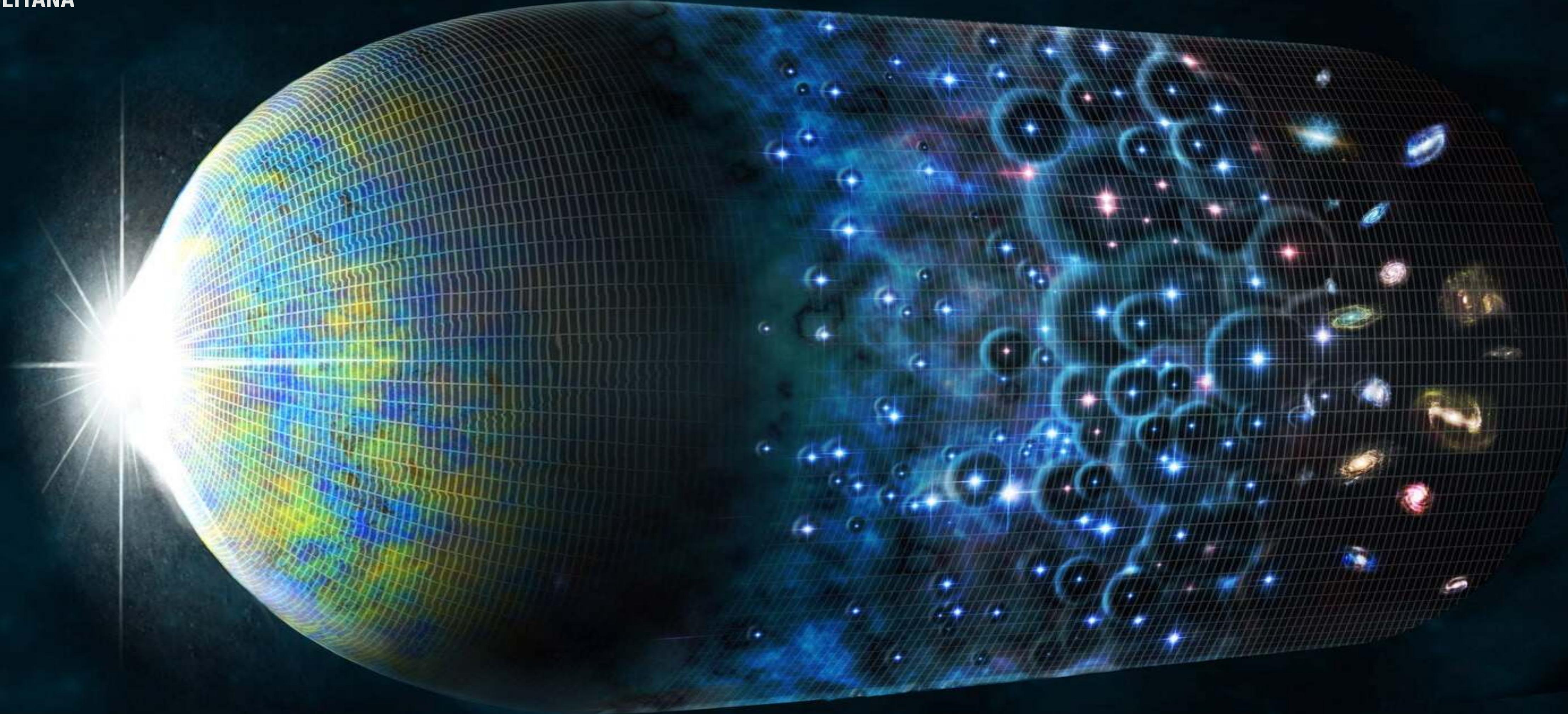


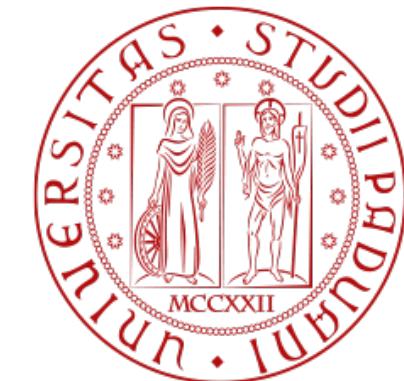
Dark Matter from Inflation

Marcos A. G. García

11/10/2021



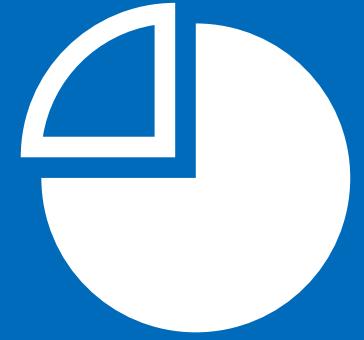
8¹²²²⁻²⁰²²
00 ANNI



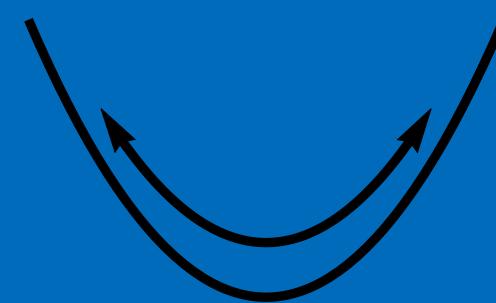
UNIVERSITÀ
DEGLI STUDI
DI PADOVA


Istituto Nazionale di Fisica Nucleare
Sezione di Padova

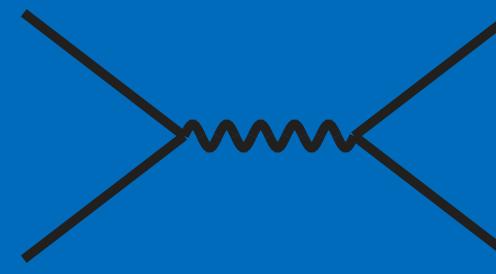
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs

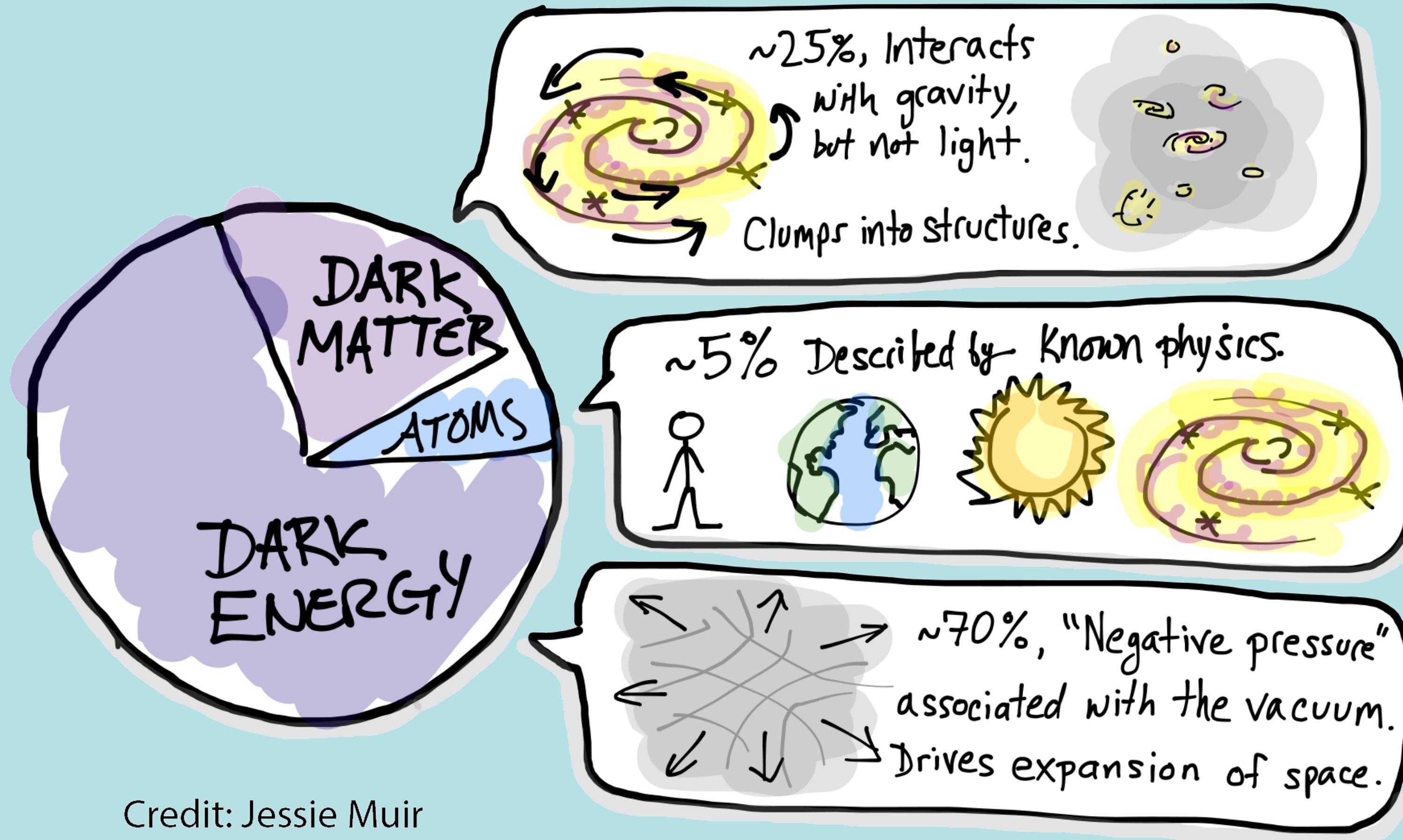


4. Compact objects

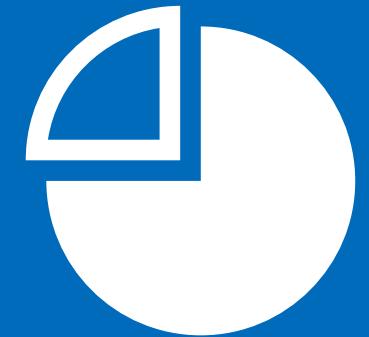


5. Prospects

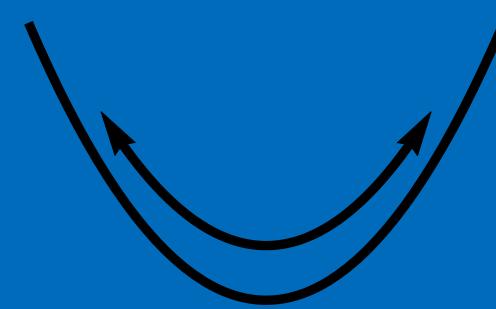
Solid evidence for Dark Matter



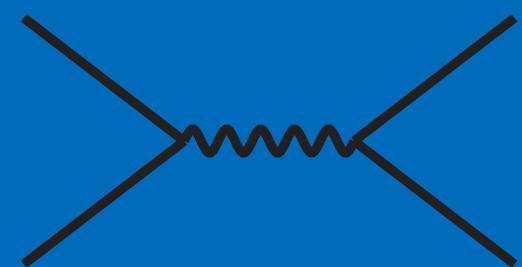
**1. Beyond
WIMPs**



**2. Inflation &
reheating**



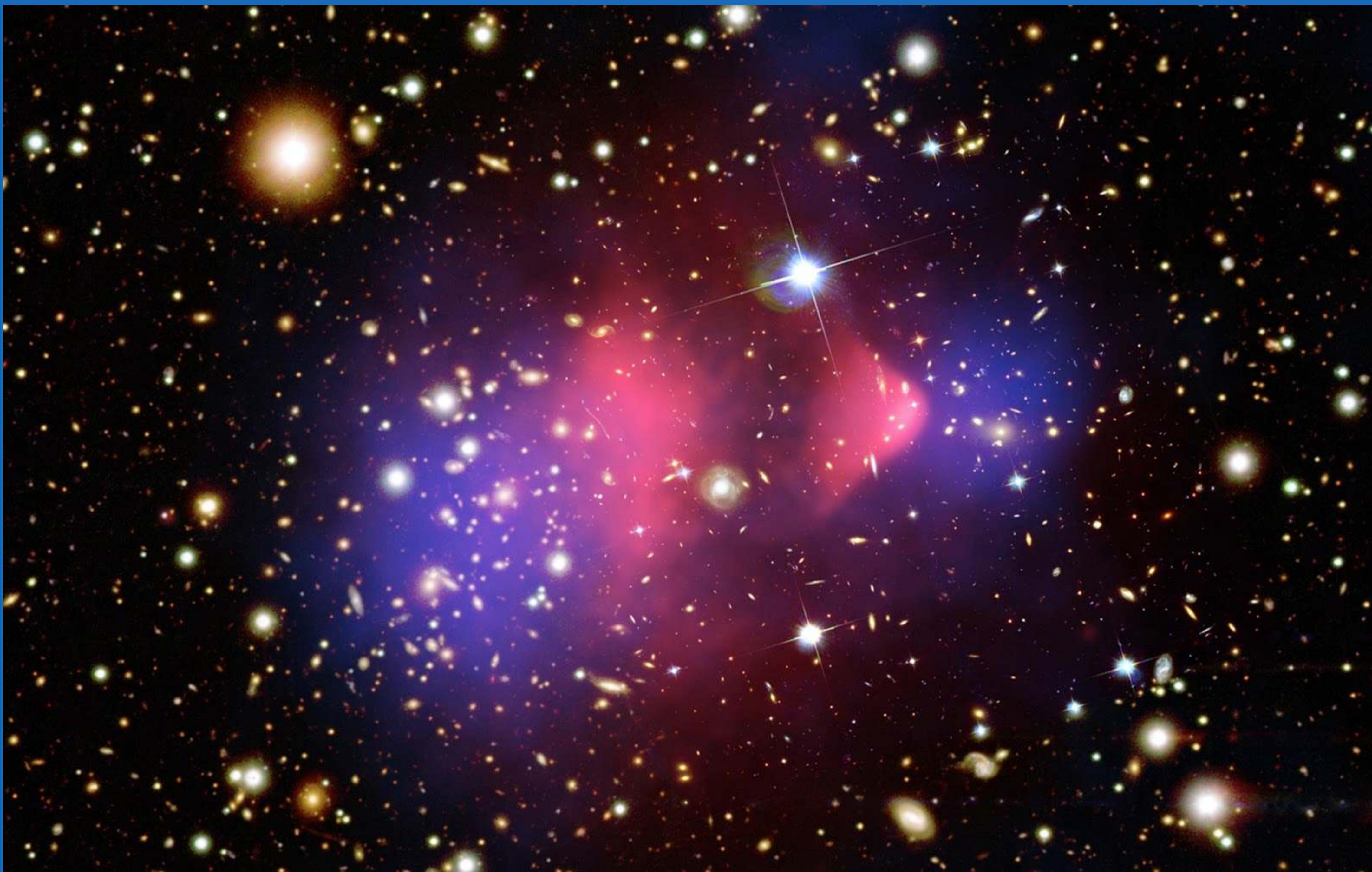
3. FIMPs



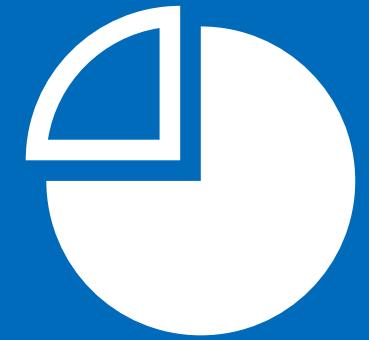
**4. Compact
objects**



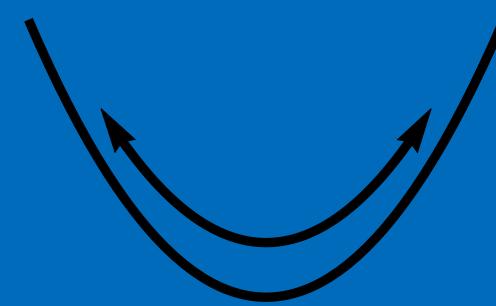
5. Prospects



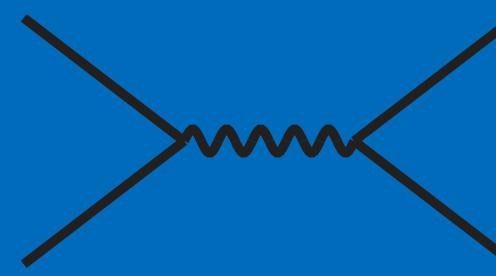
1. Beyond WIMPs



2. Inflation & reheating



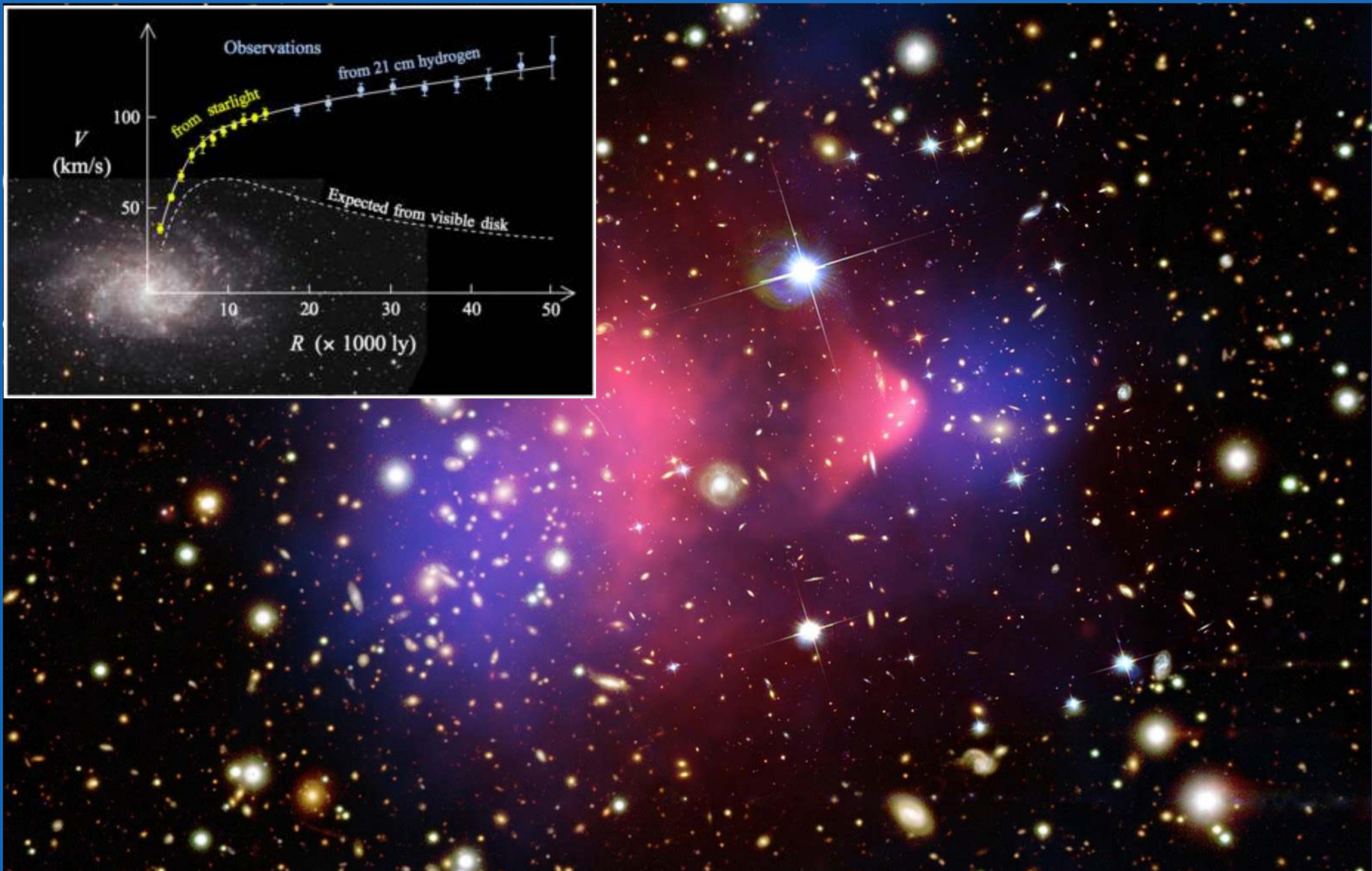
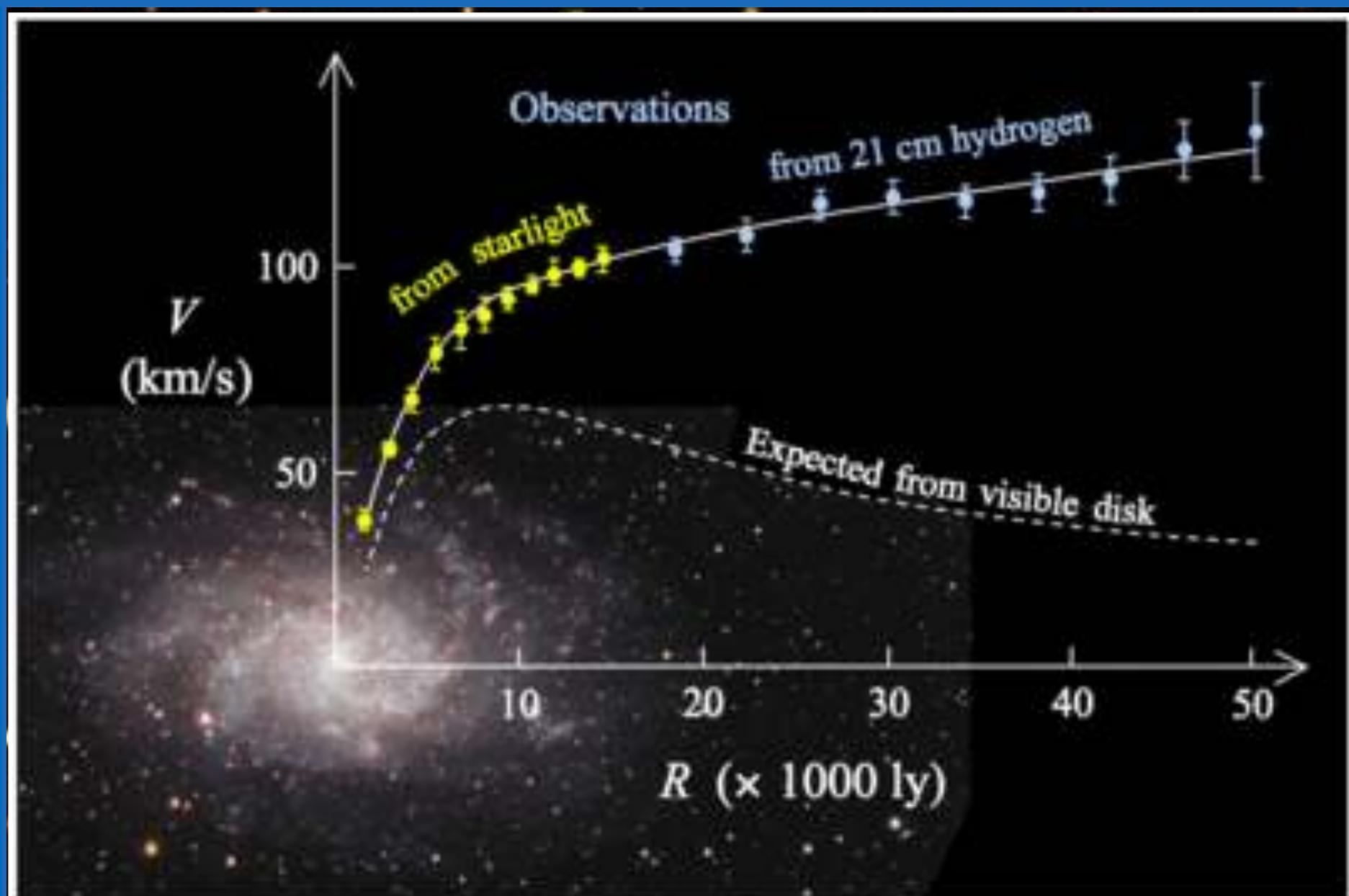
3. FIMPs



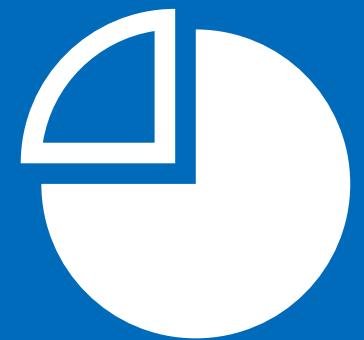
4. Compact objects



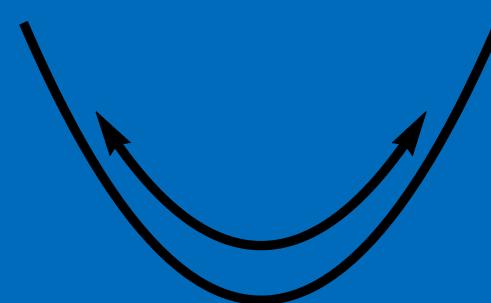
5. Prospects



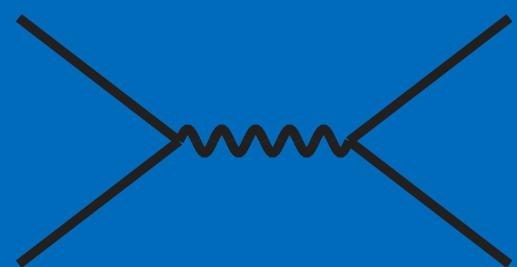
1. Beyond WIMPs



2. Inflation & reheating



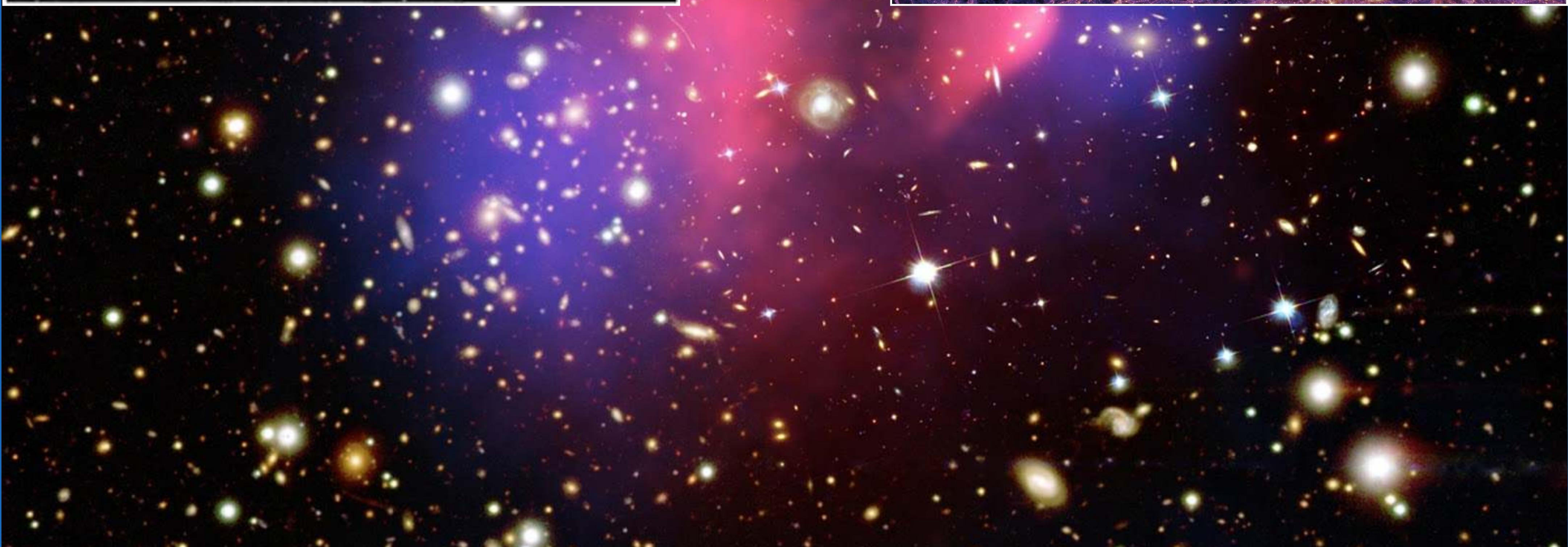
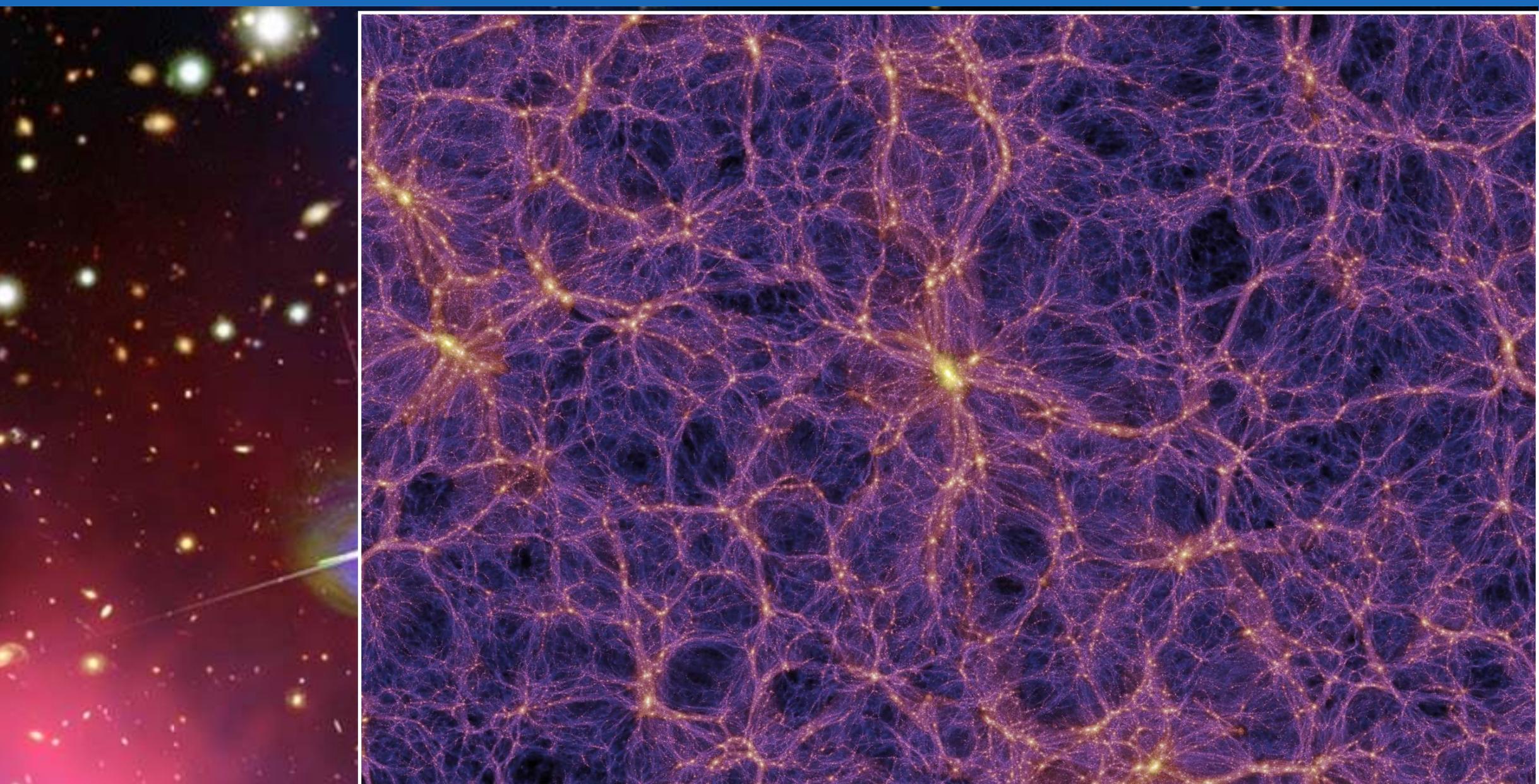
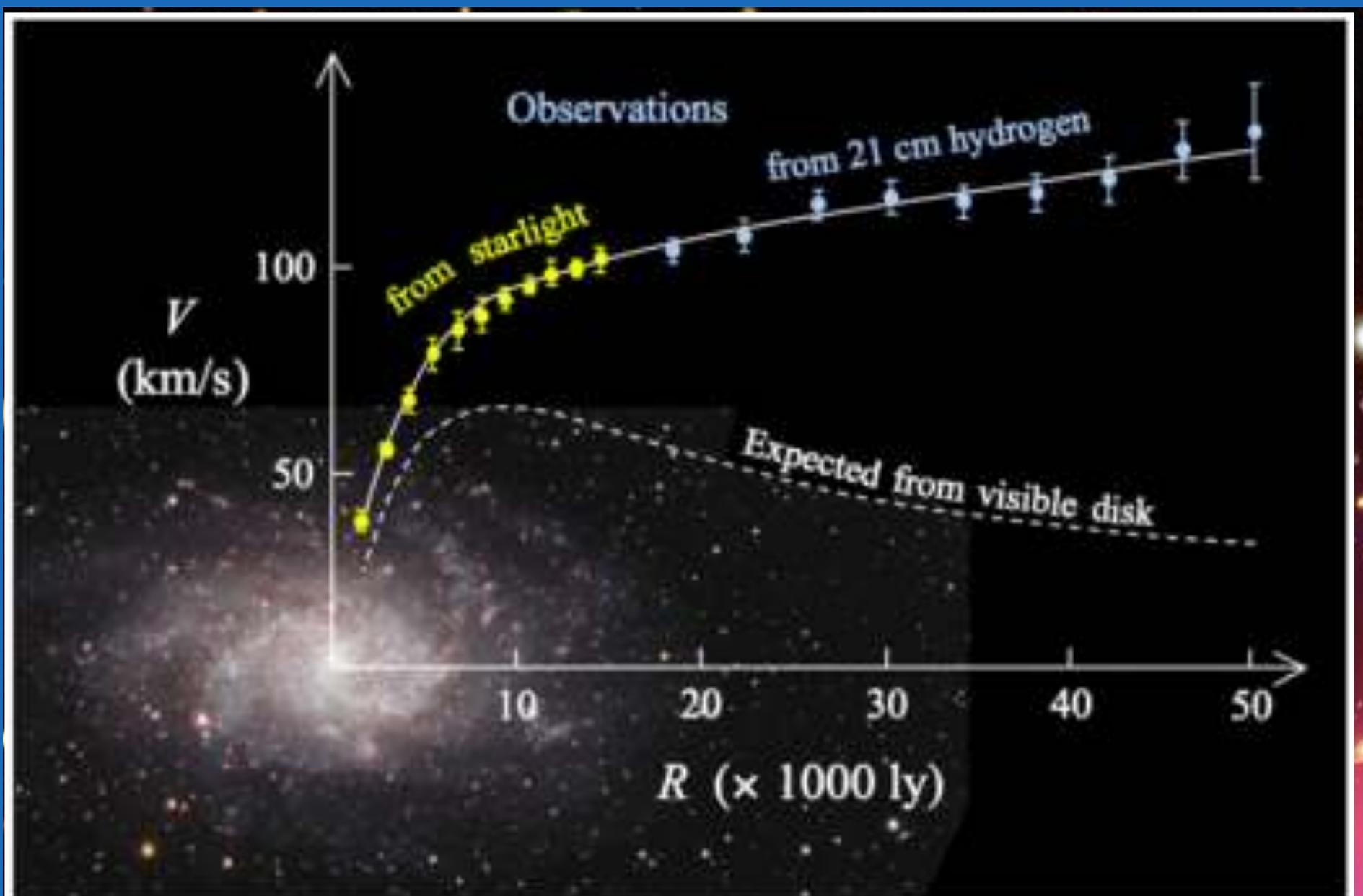
3. FIMPs



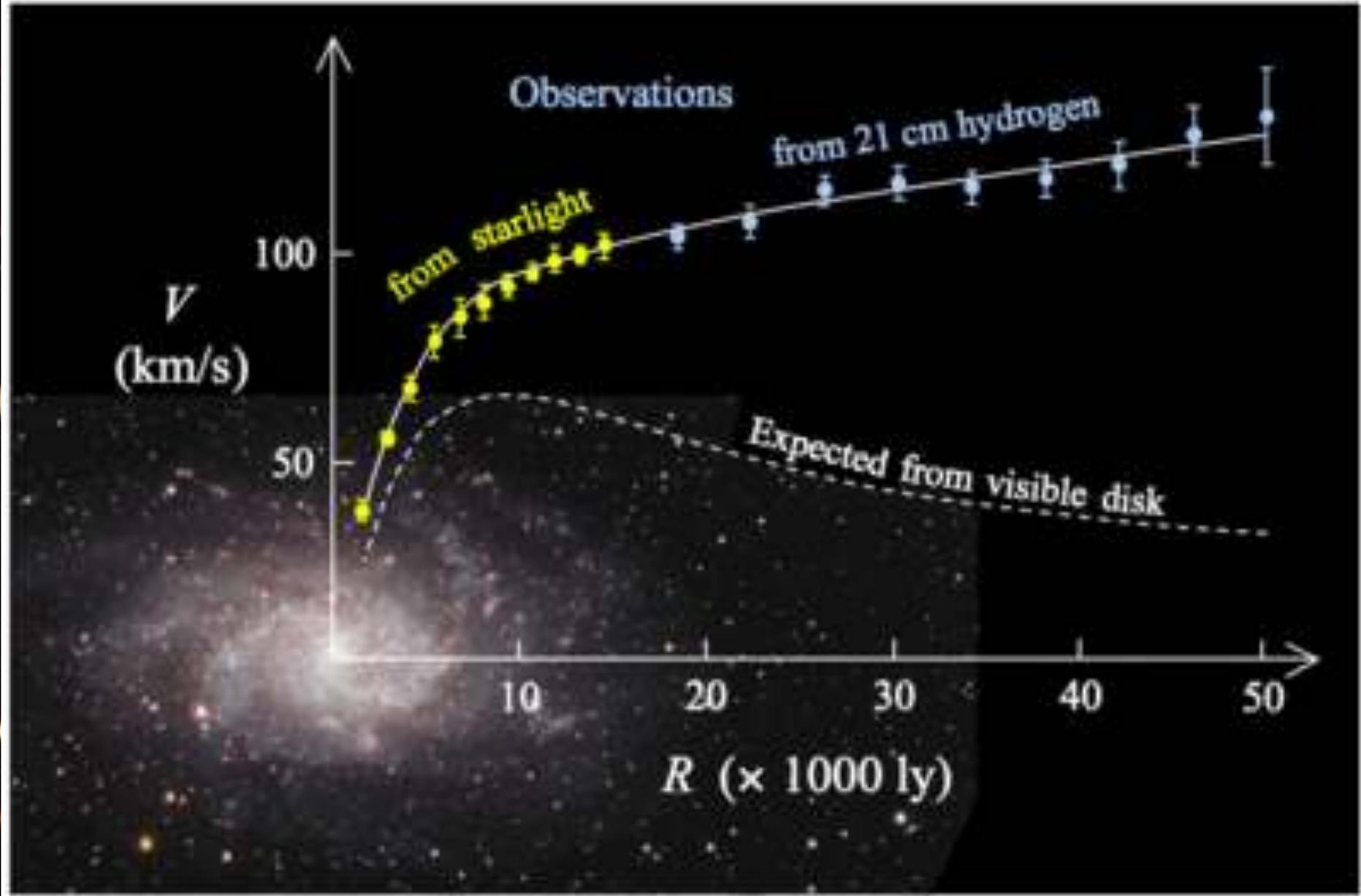
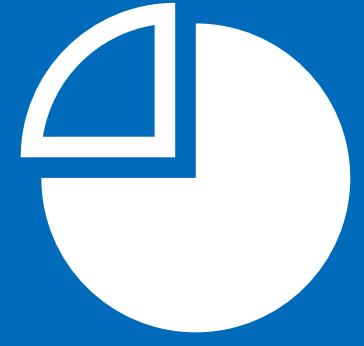
4. Compact objects



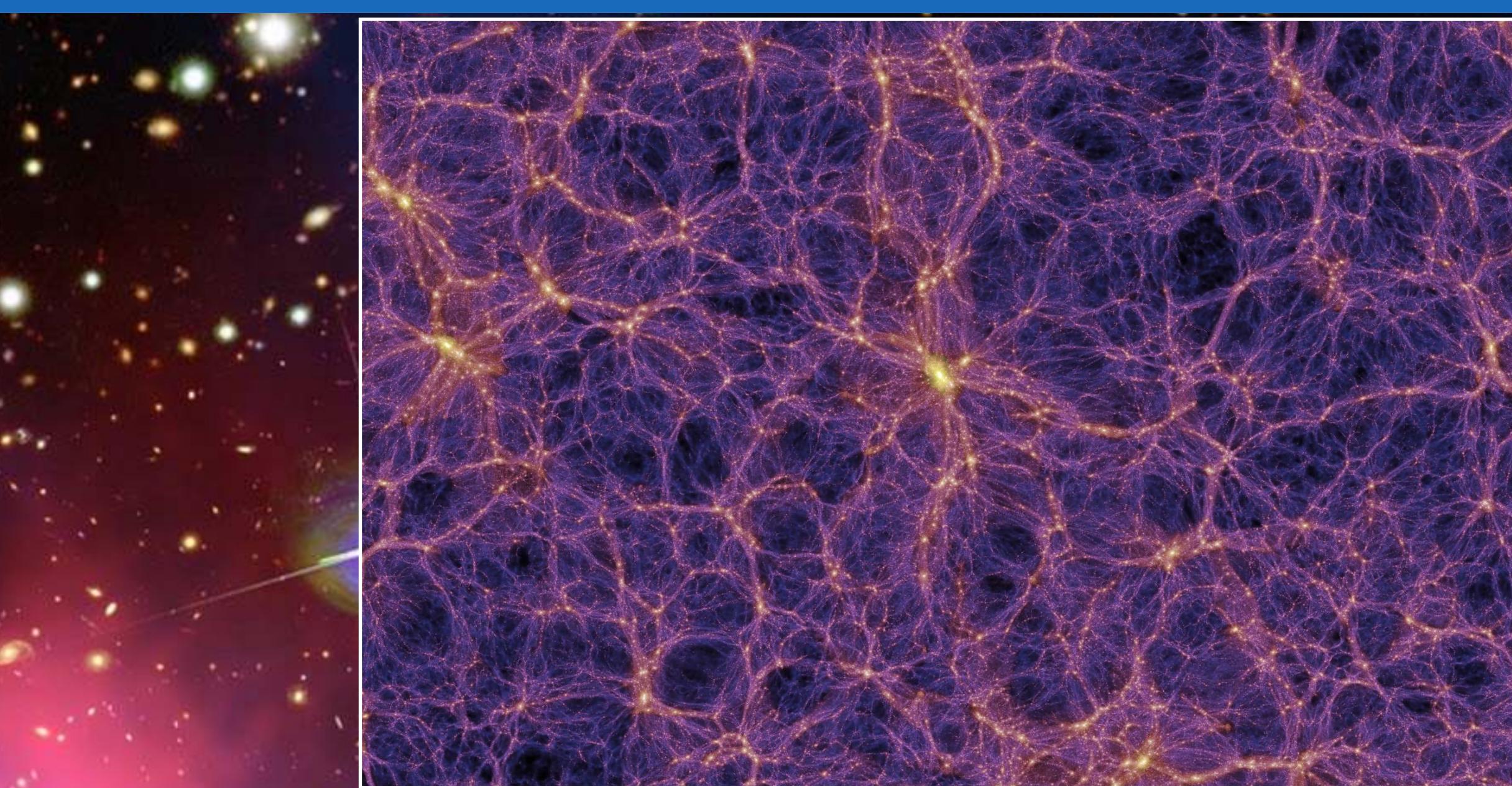
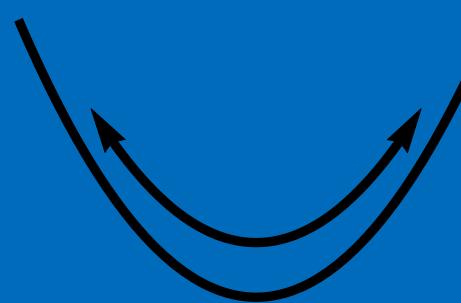
5. Prospects



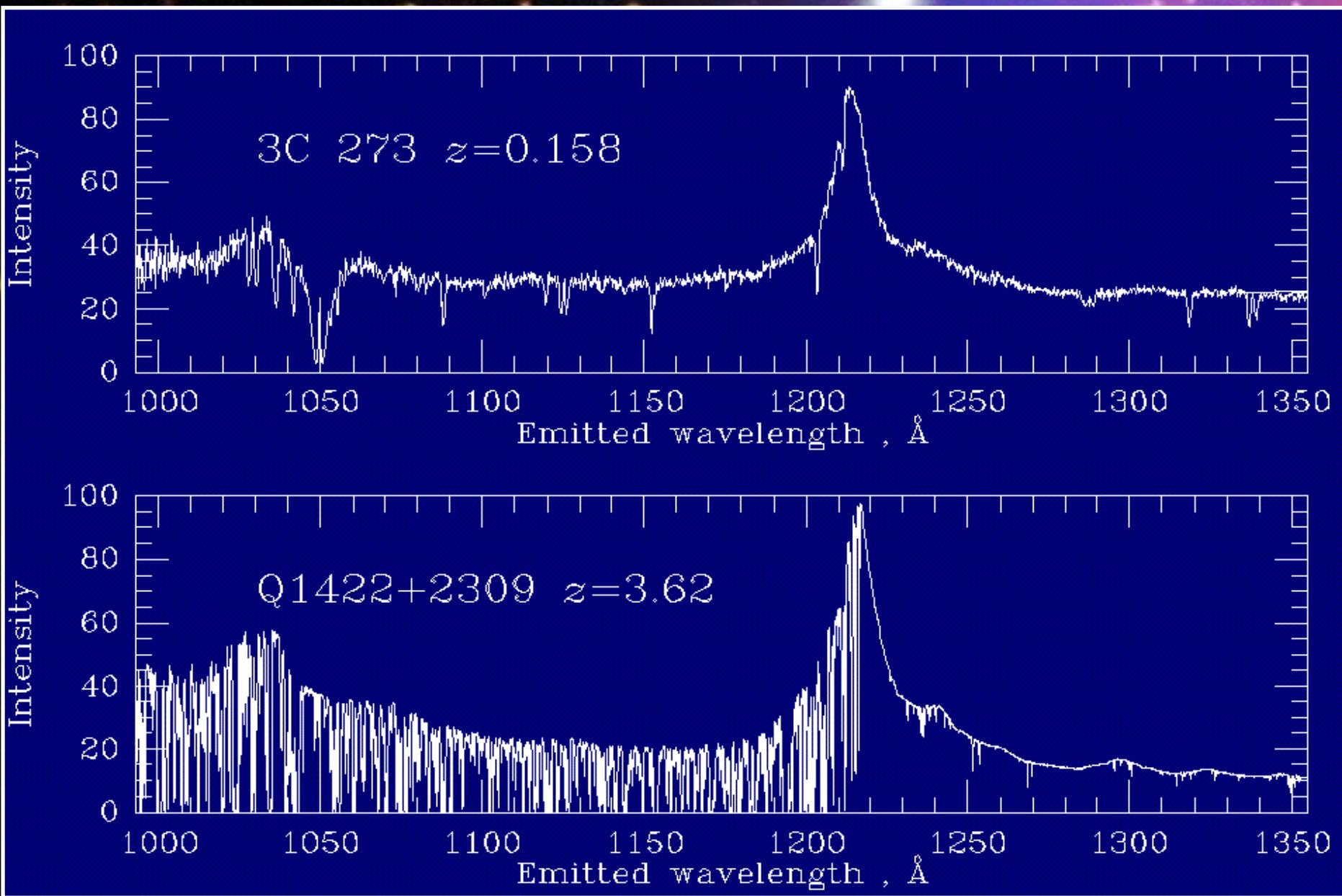
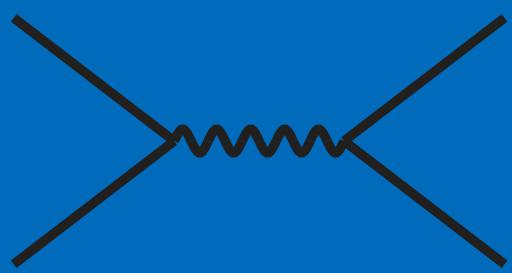
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs

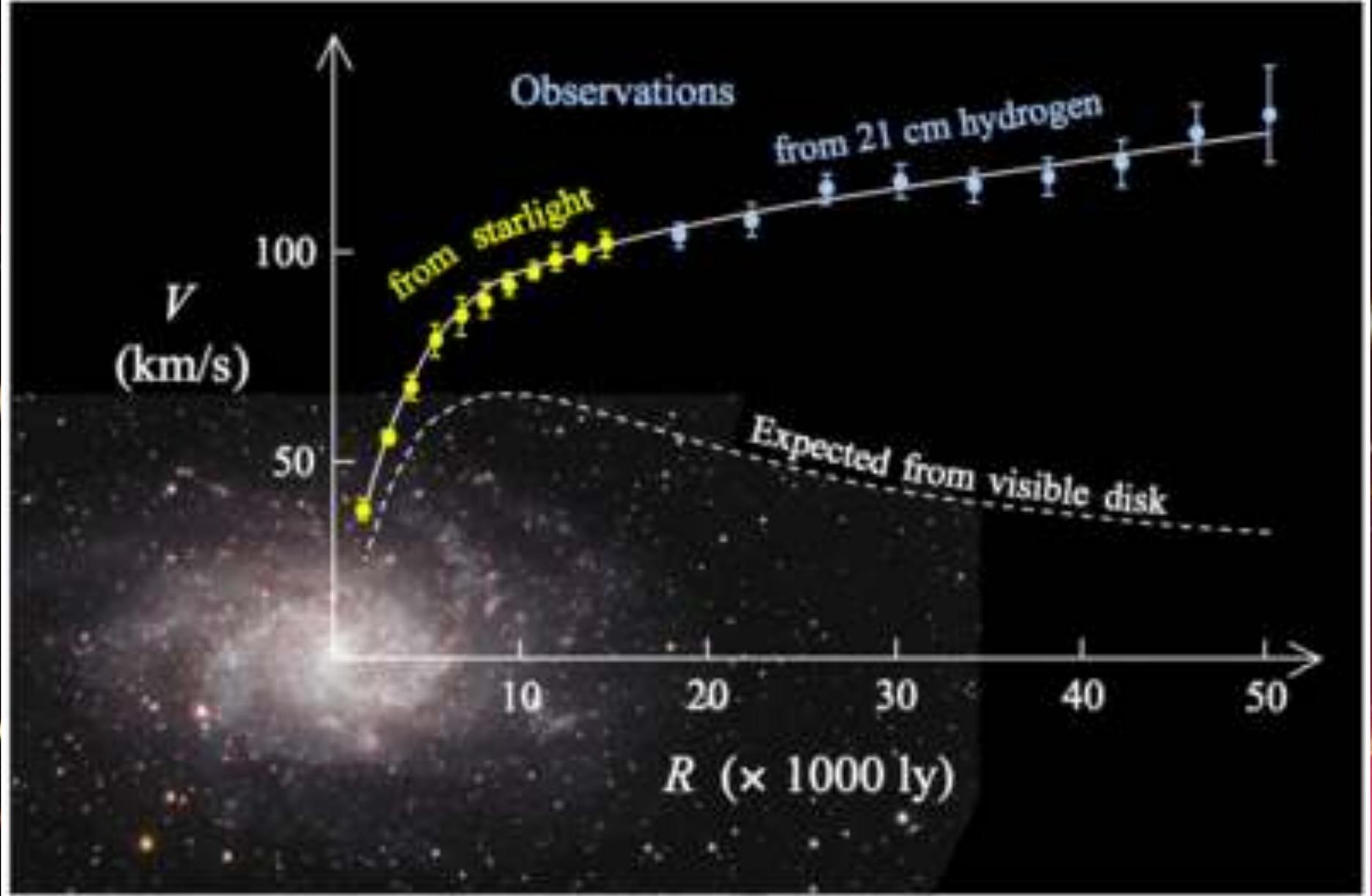
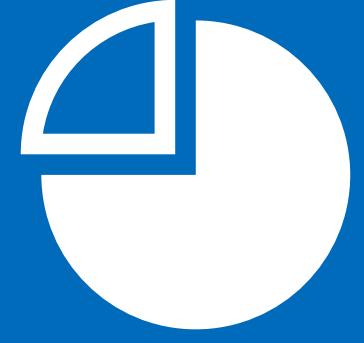


4. Compact objects

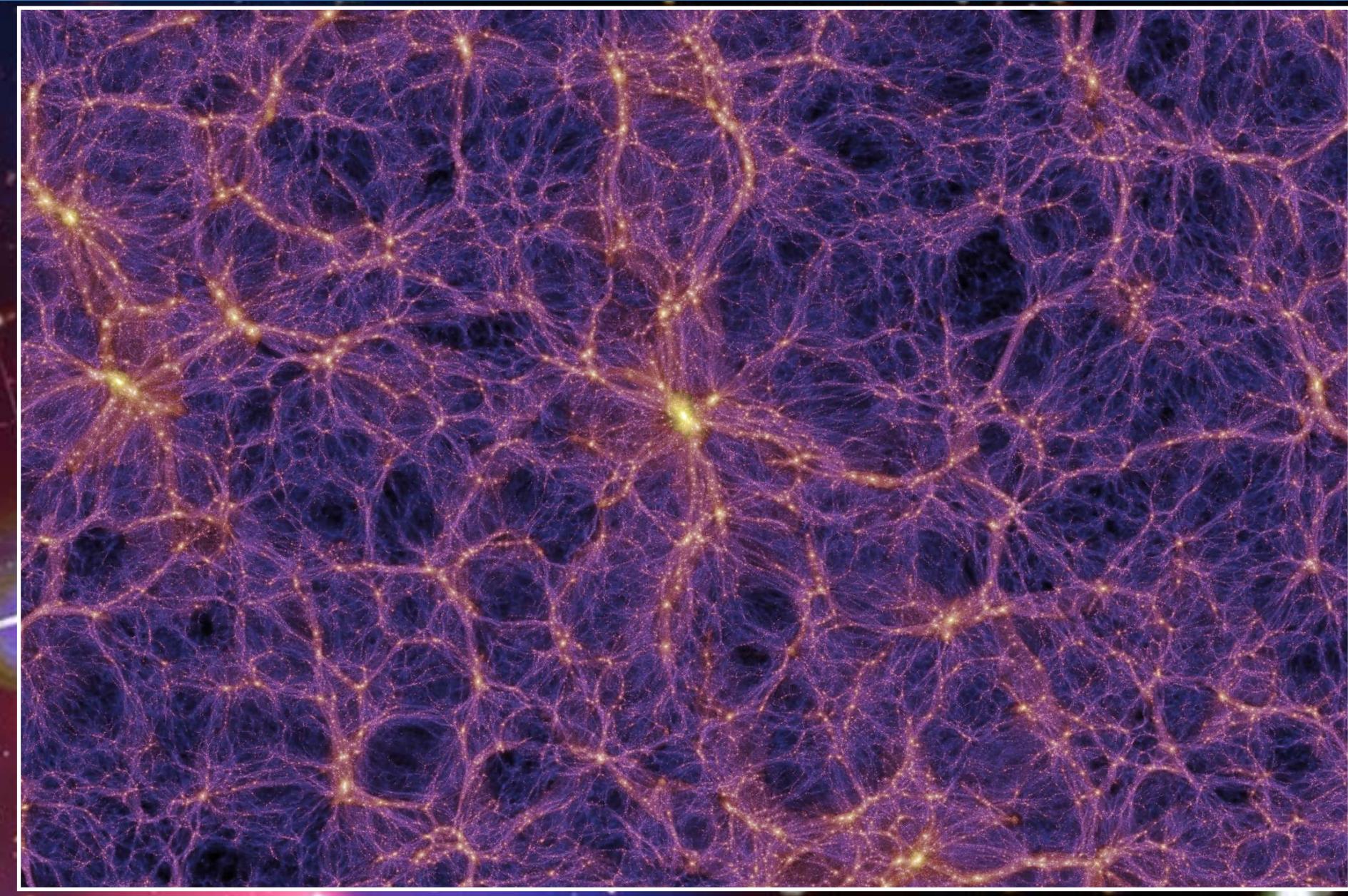
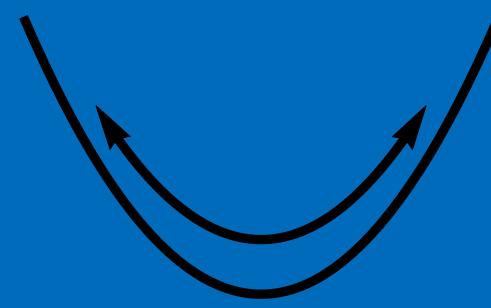


5. Prospects

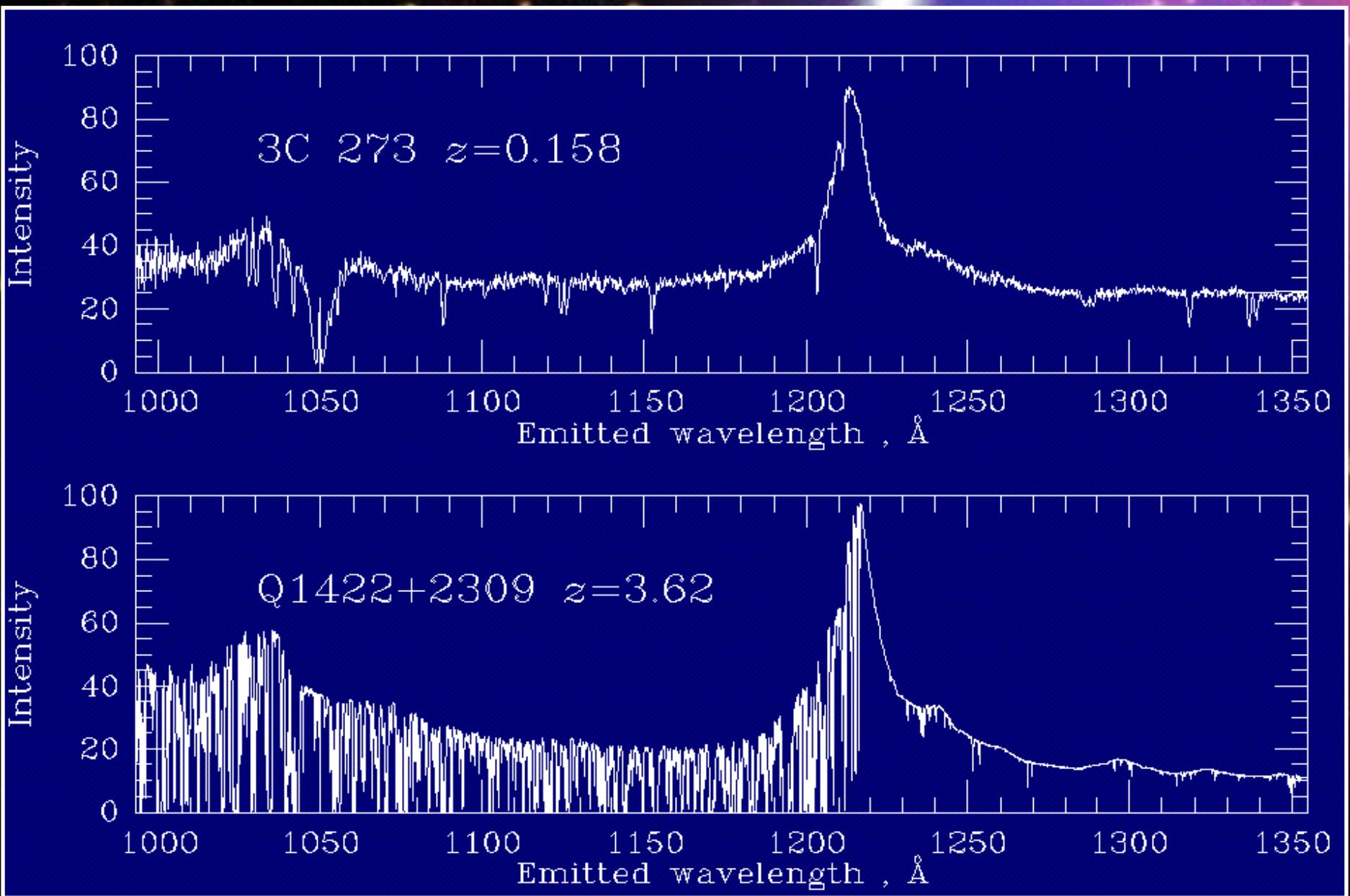
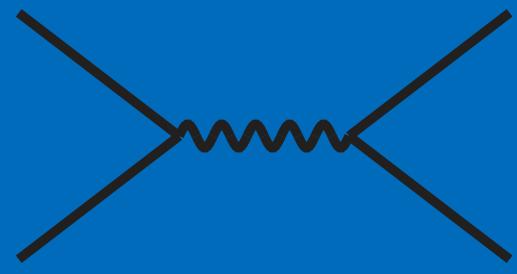
1. Beyond WIMPs



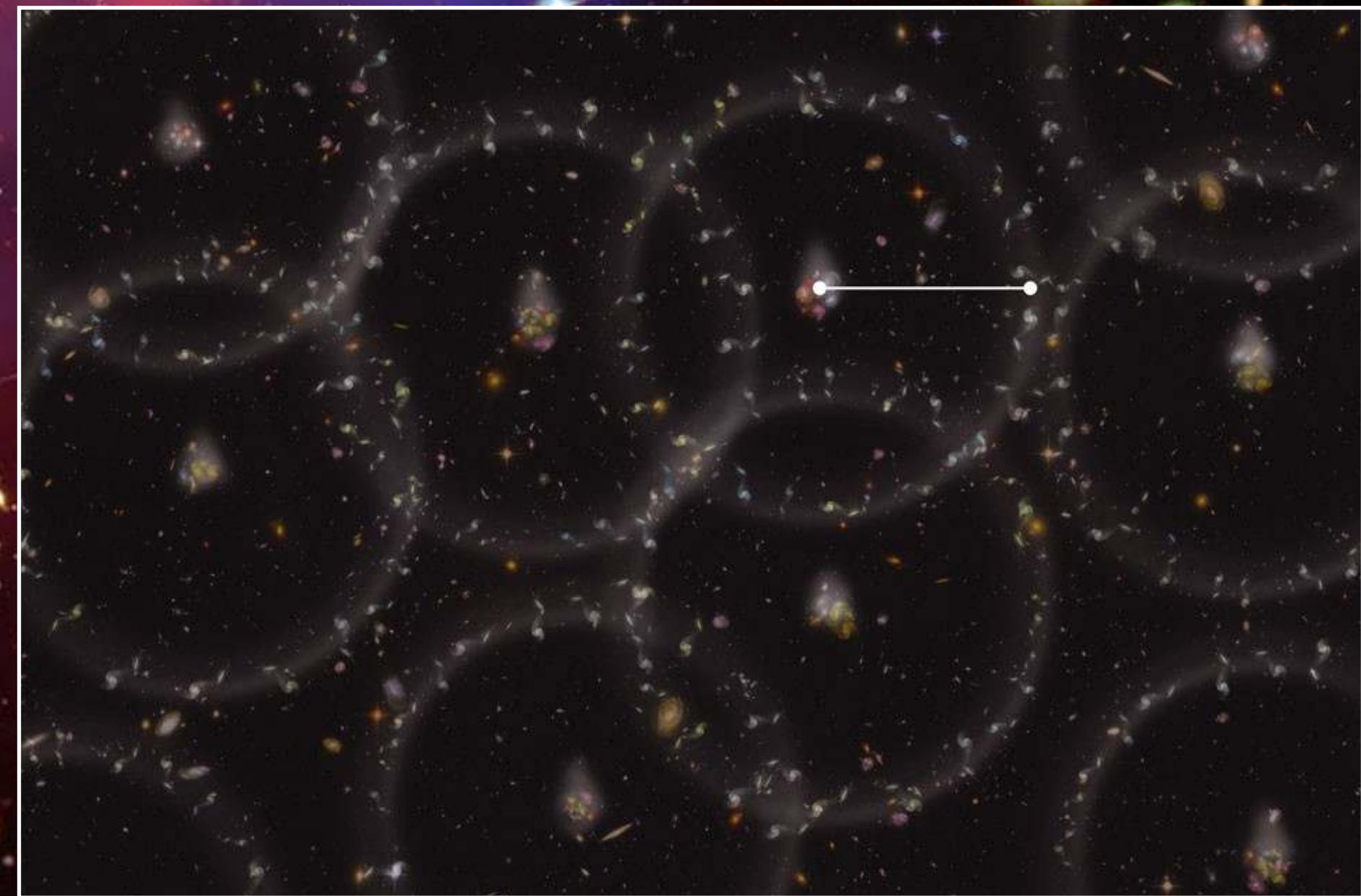
2. Inflation & reheating



3. FIMPs

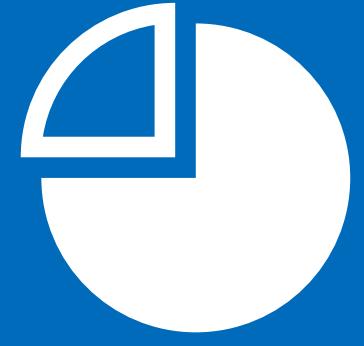


4. Compact objects

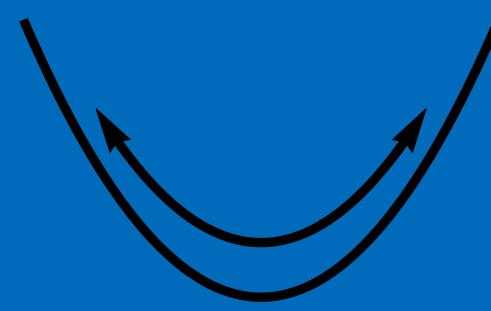


5. Prospects

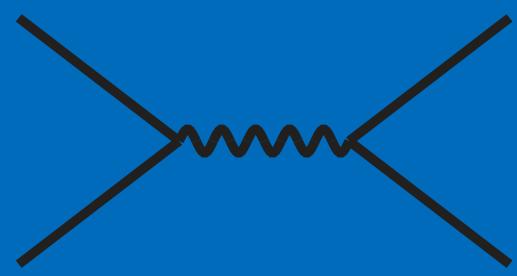
1. Beyond WIMPs



2. Inflation & reheating



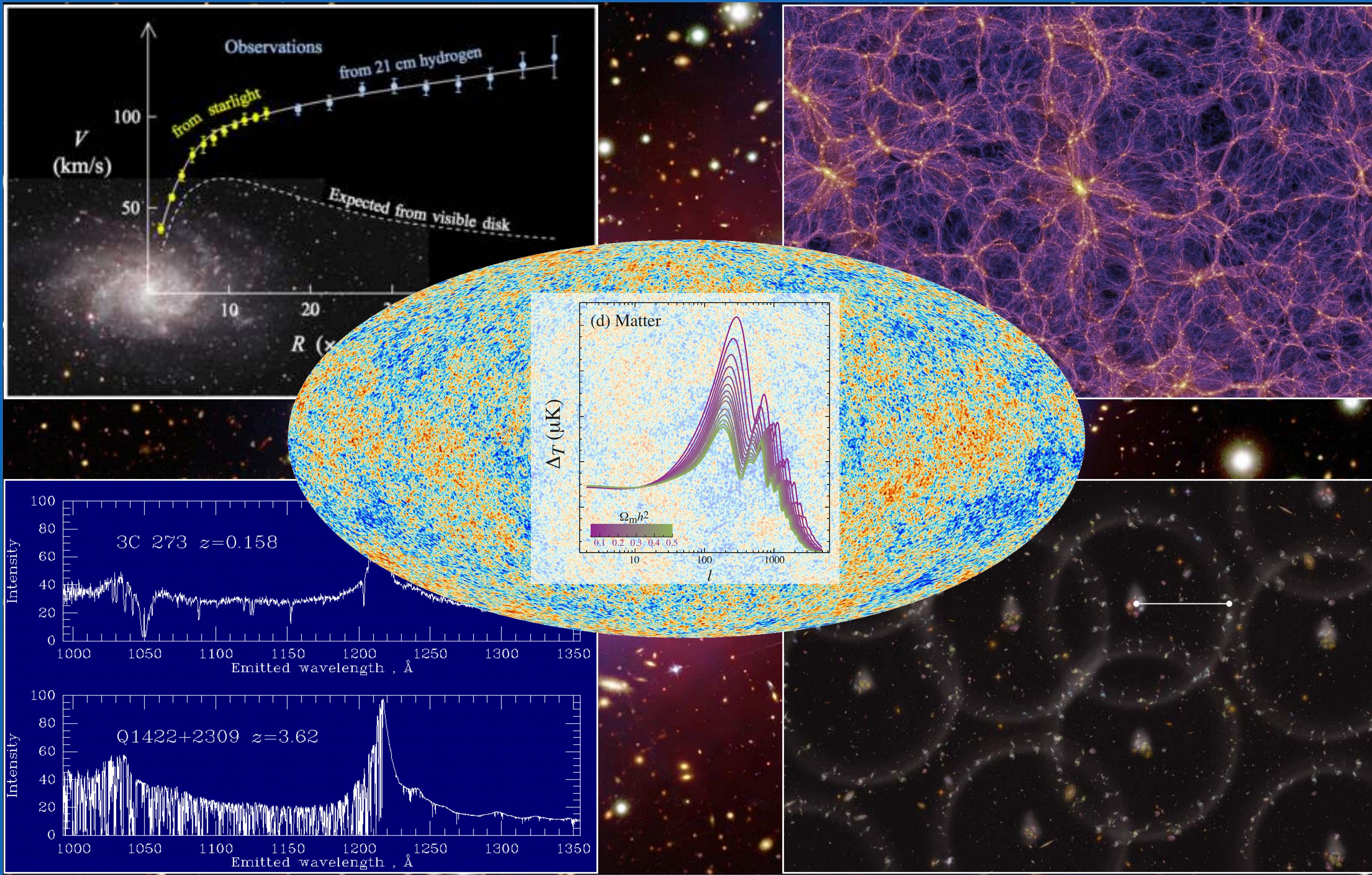
3. FIMPs



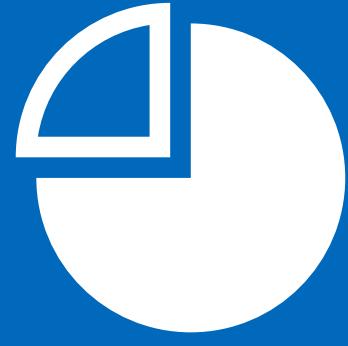
4. Compact objects



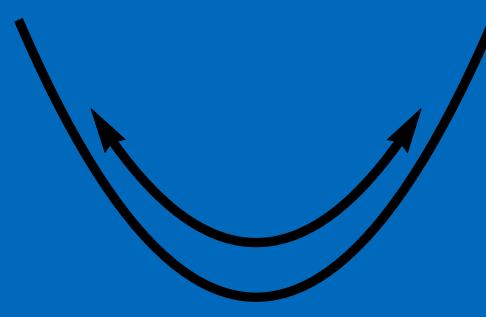
5. Prospects



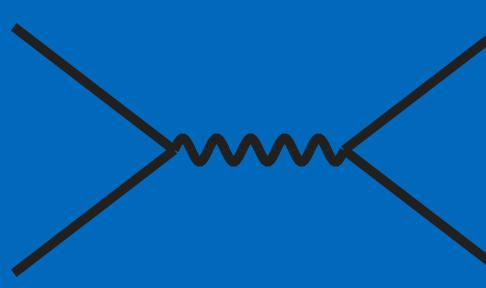
1. Beyond WIMPs



2. Inflation & reheating



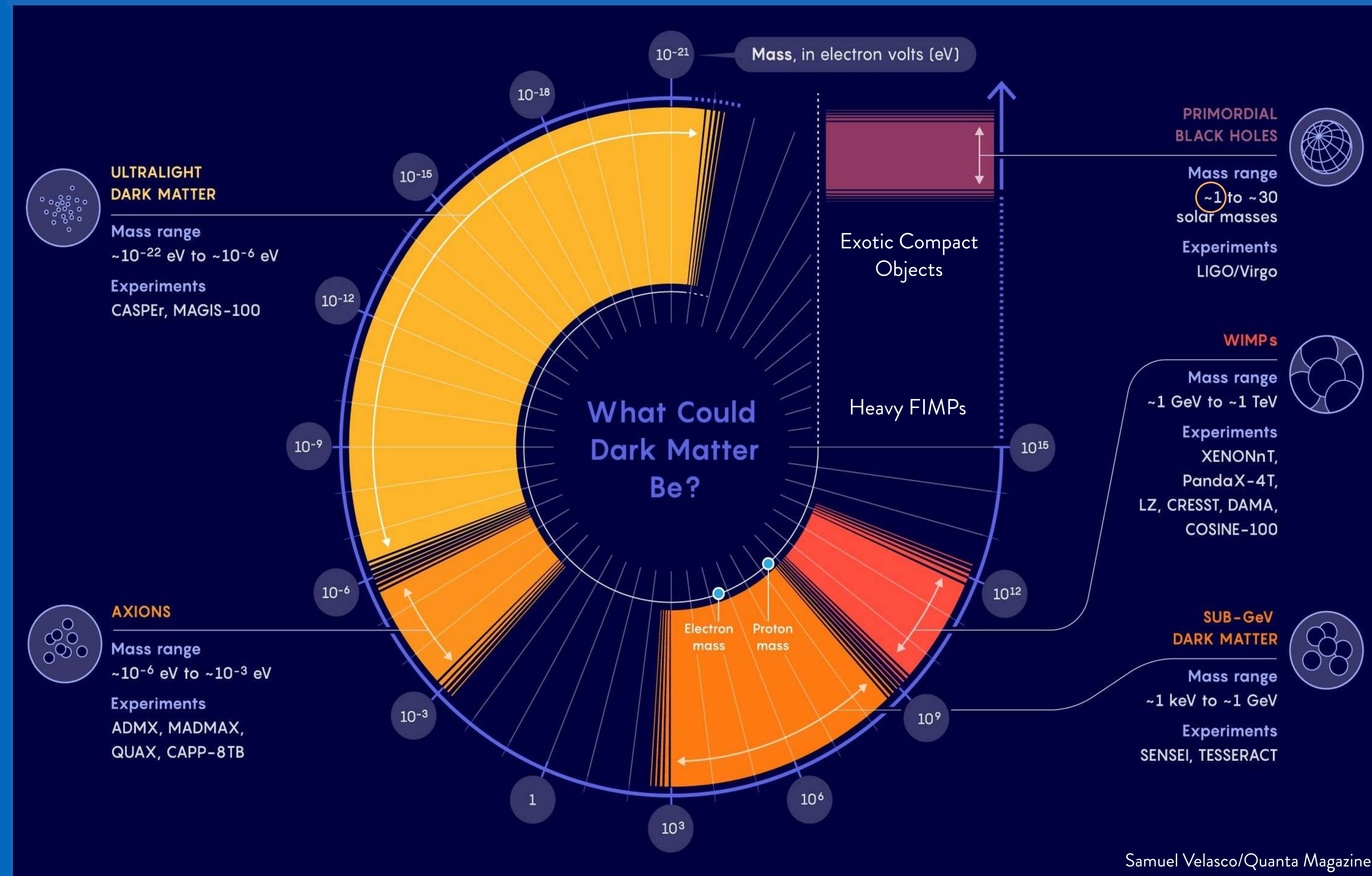
3. FIMPs



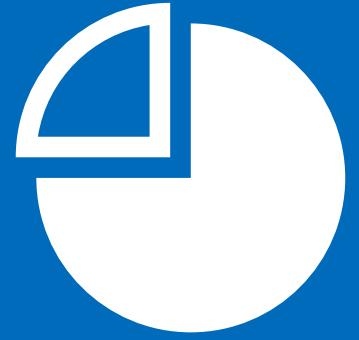
4. Compact objects



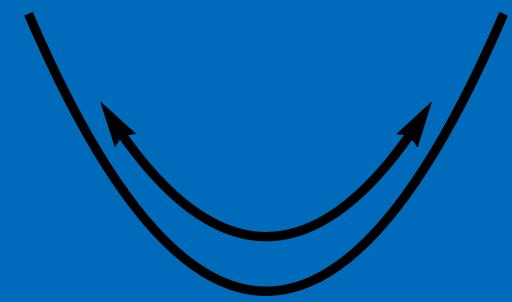
5. Prospects



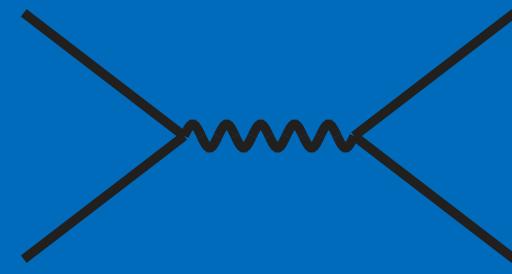
1. Beyond WIMPs



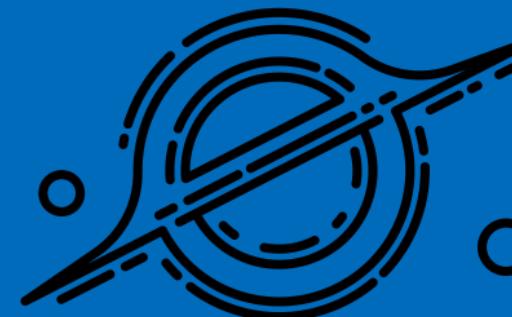
2. Inflation & reheating



3. FIMPs

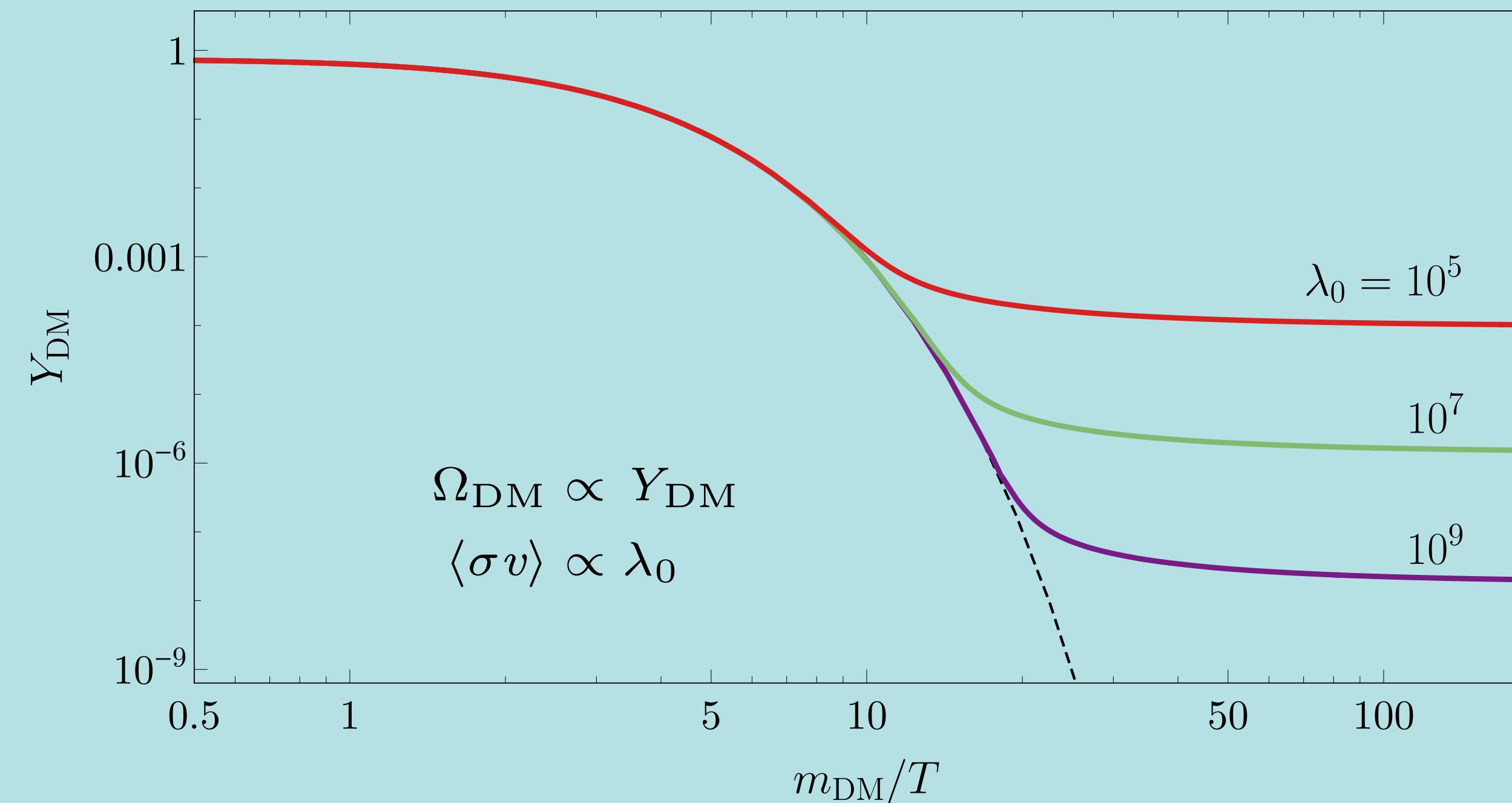
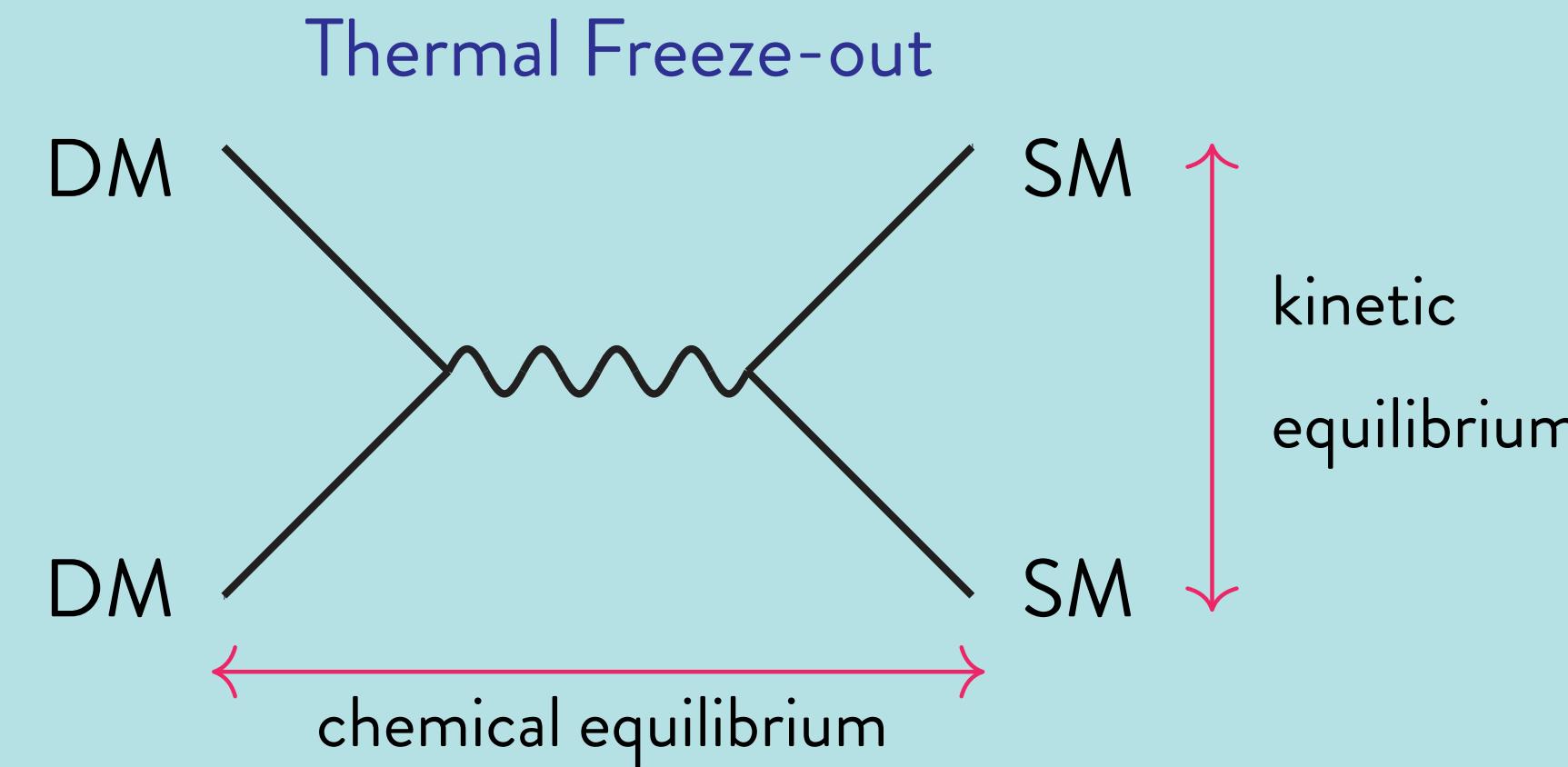


4. Compact objects

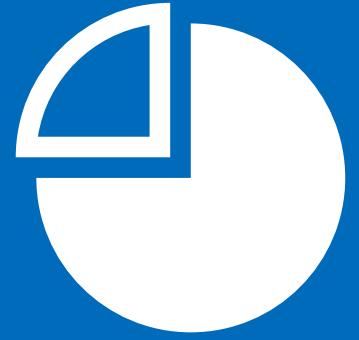


5. Prospects

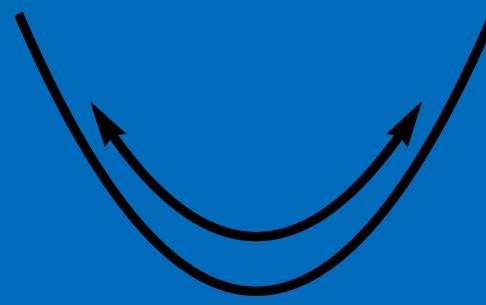
The many virtues of the WIMP



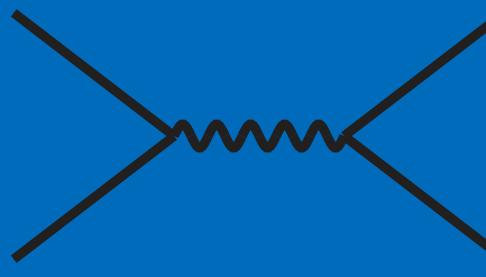
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs

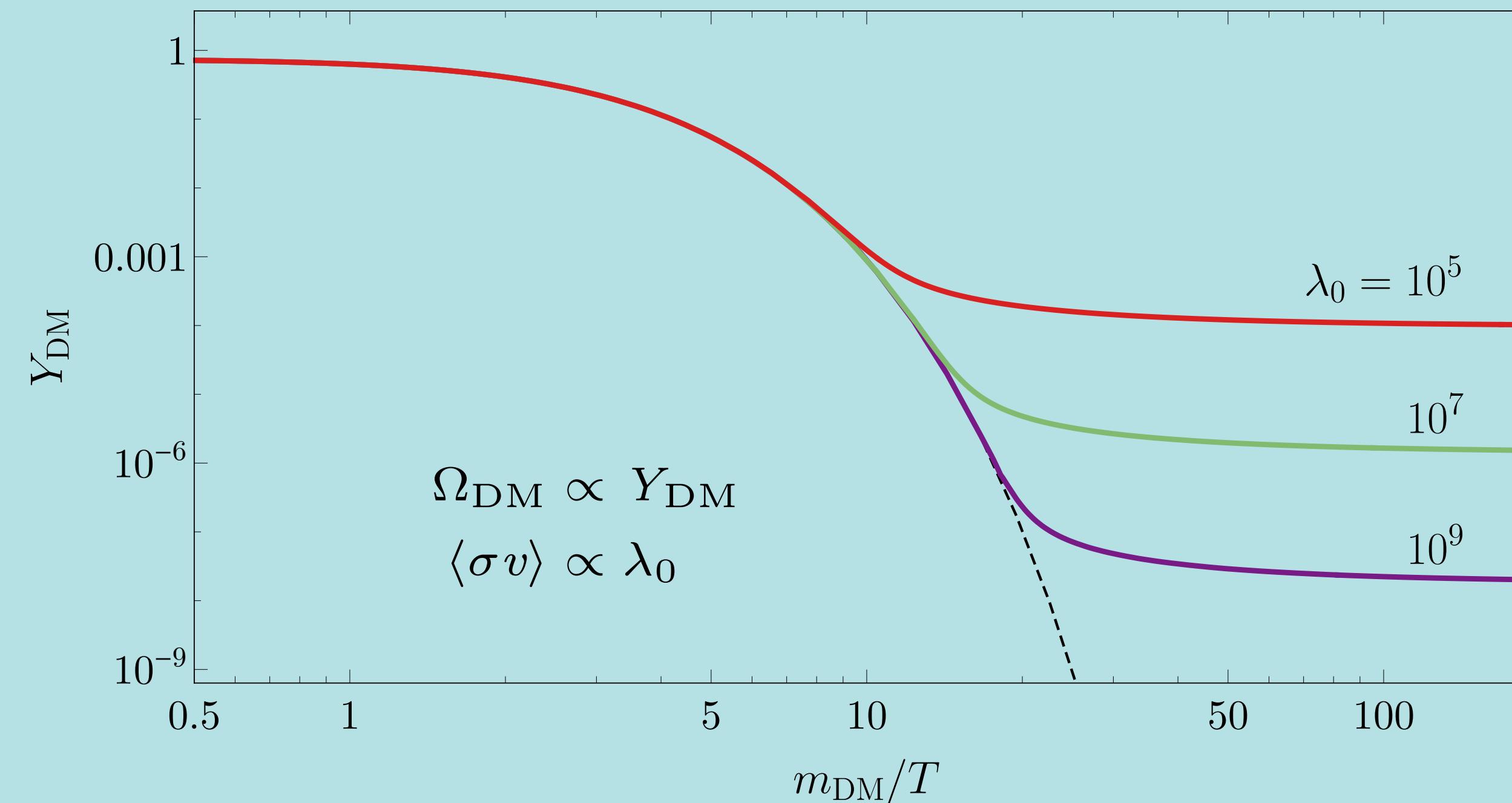
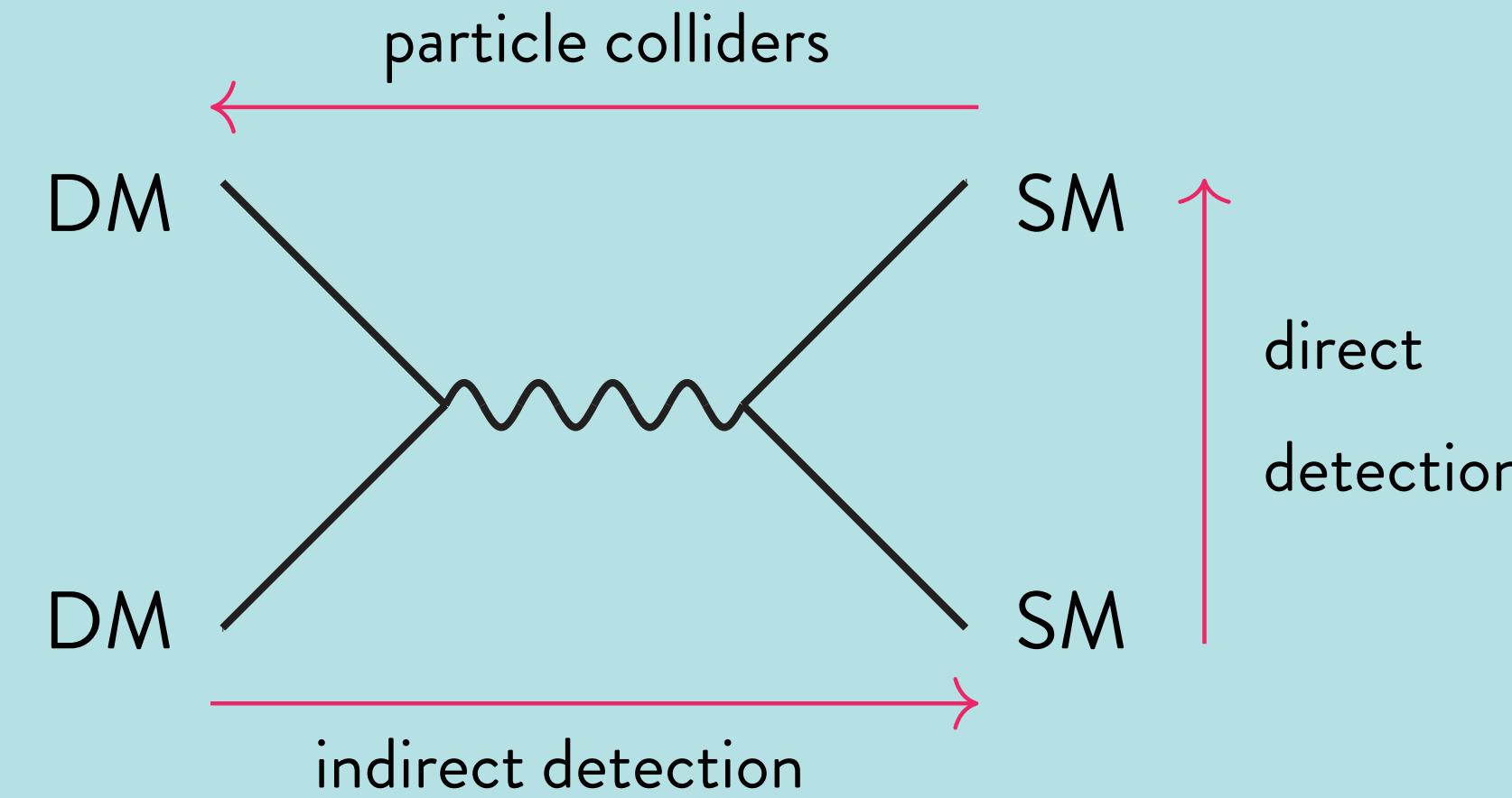


4. Compact objects

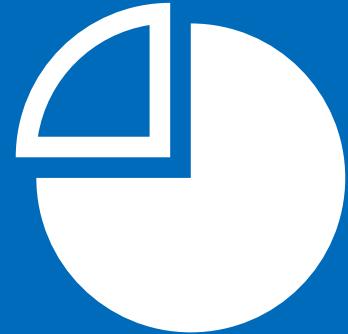


5. Prospects

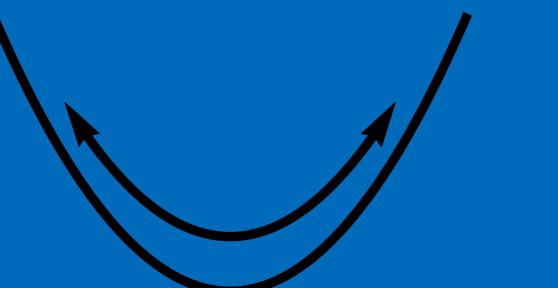
The many virtues of the WIMP



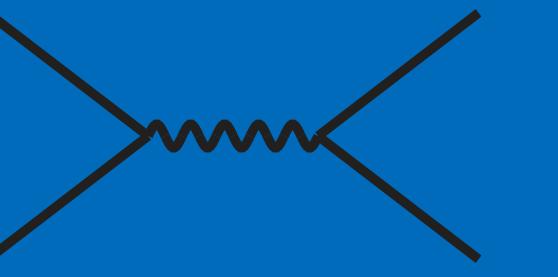
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs



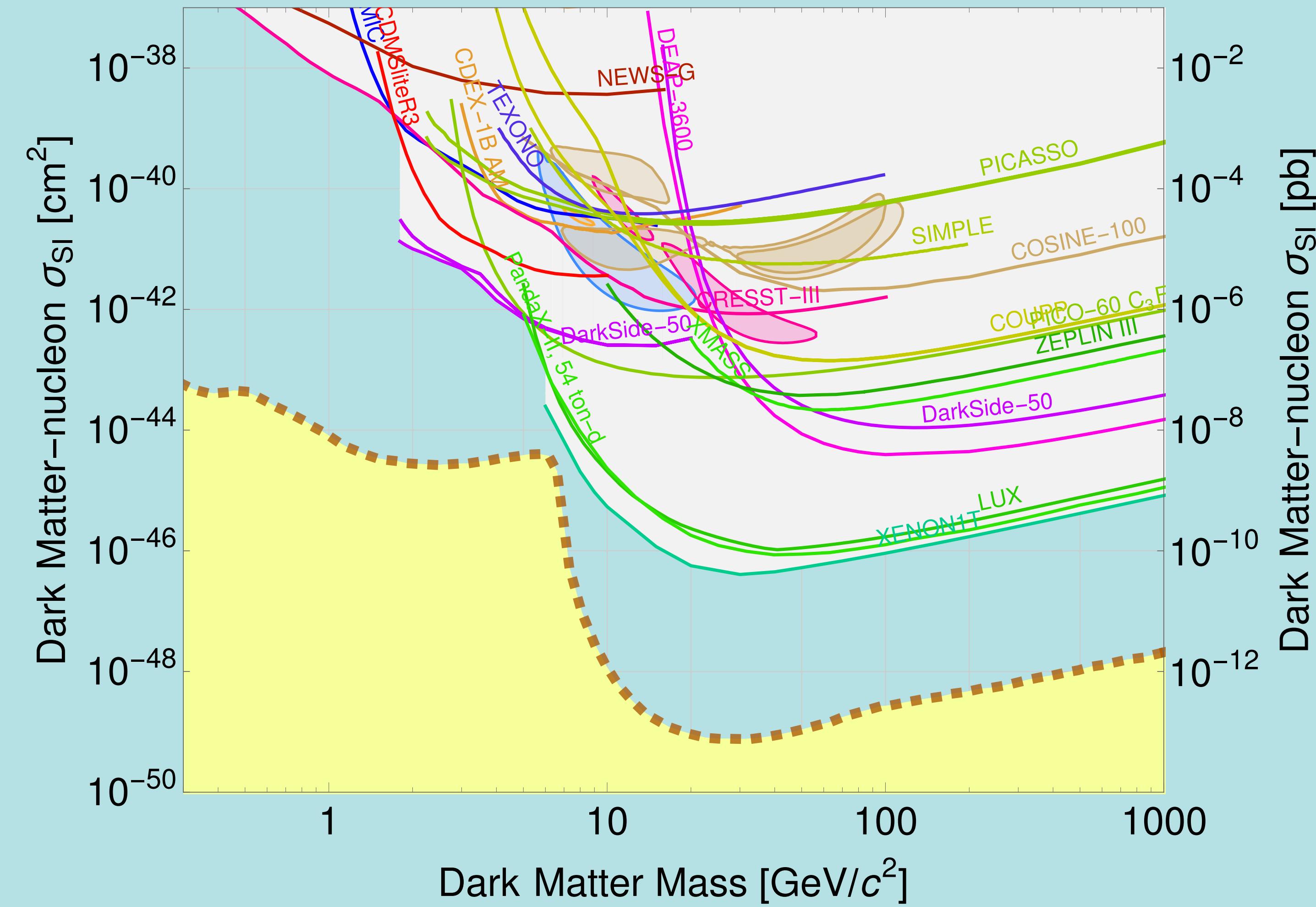
4. Compact objects



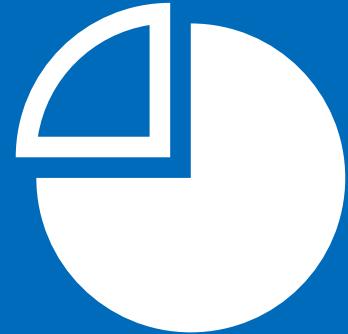
5. Prospects

Where are the WIMPs?

Direct detection



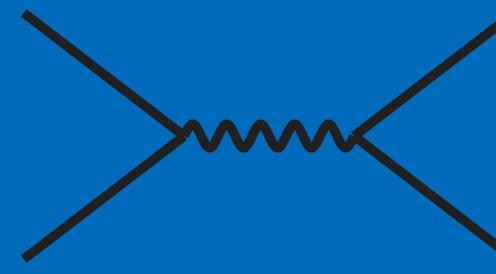
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs



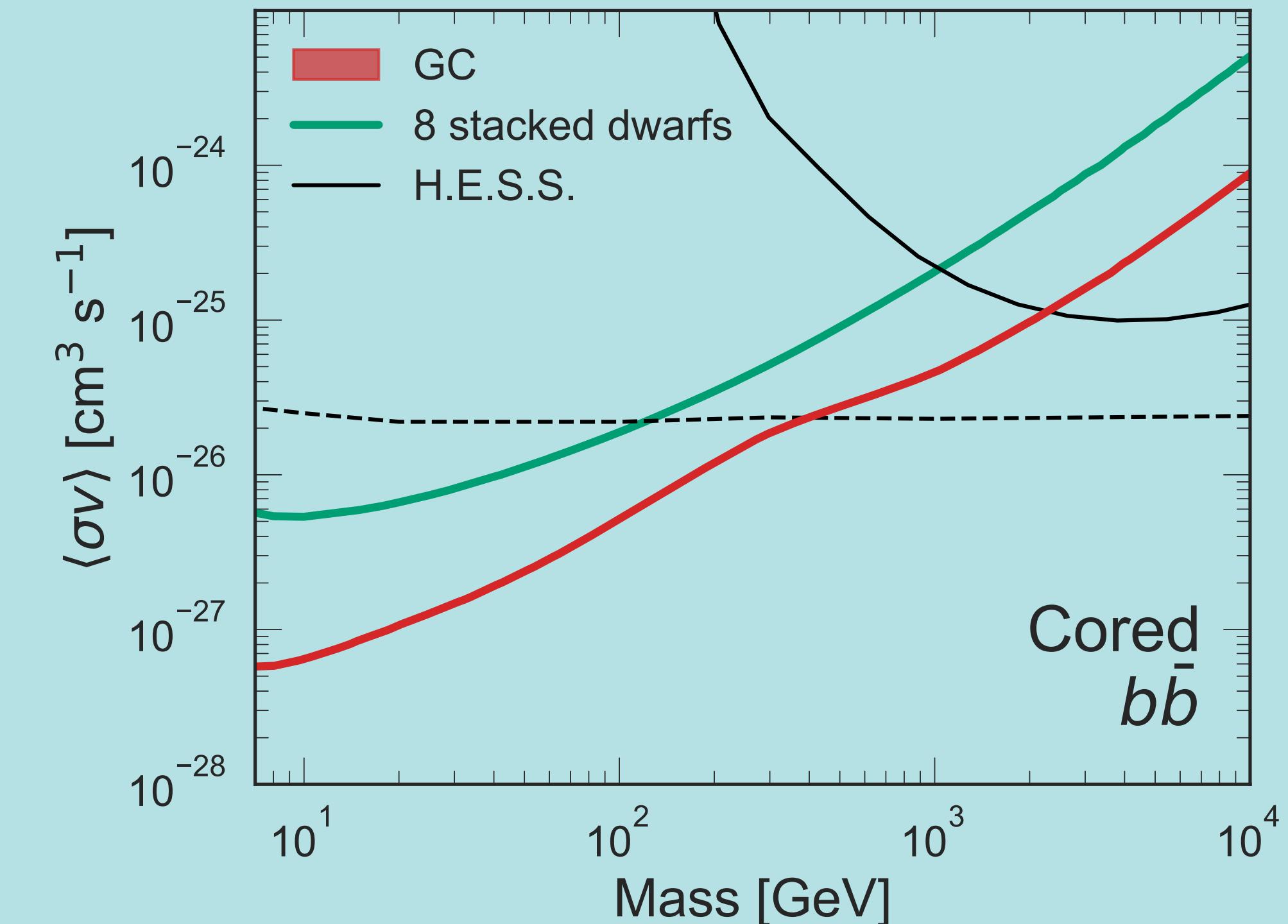
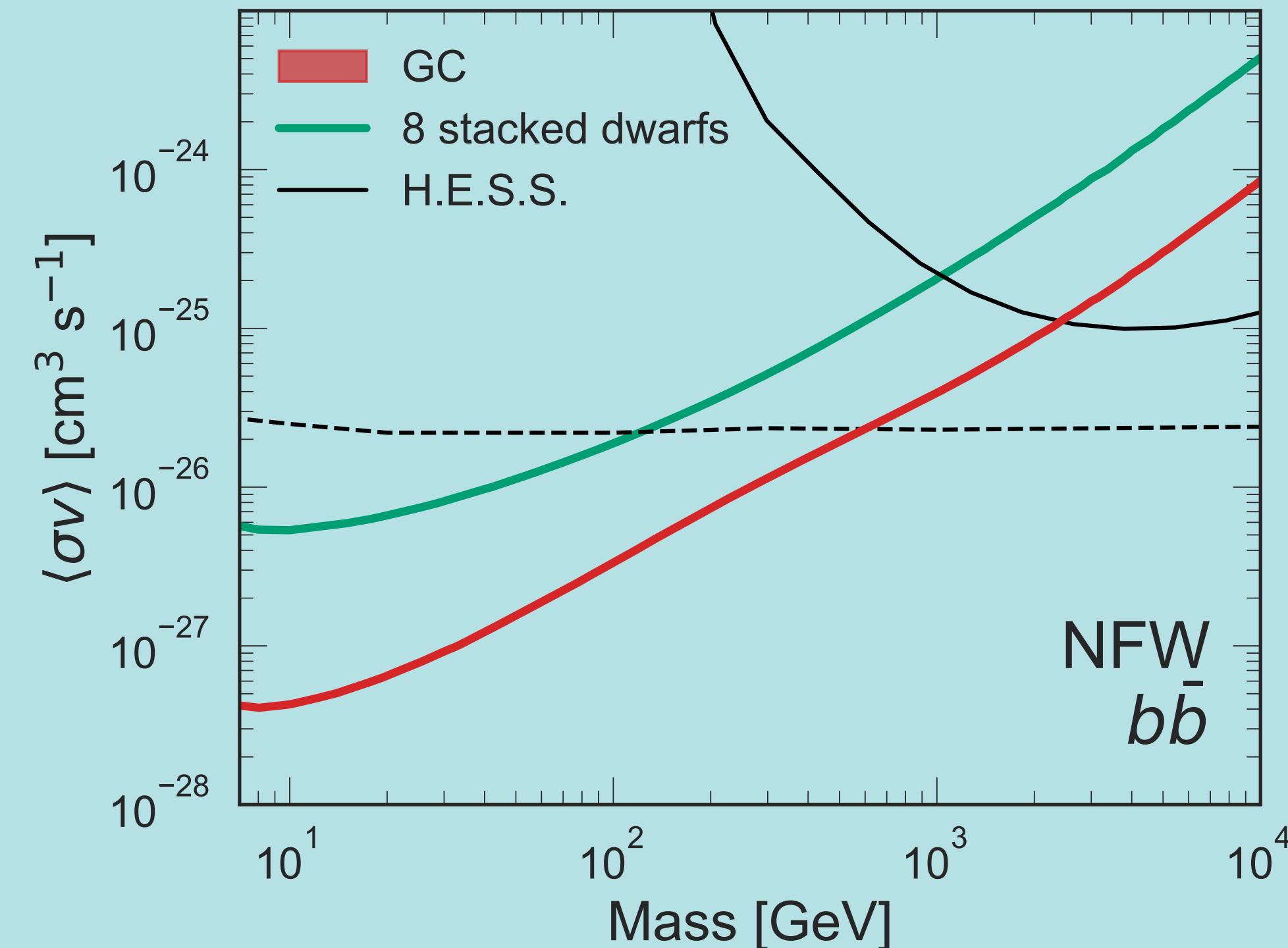
4. Compact objects



5. Prospects

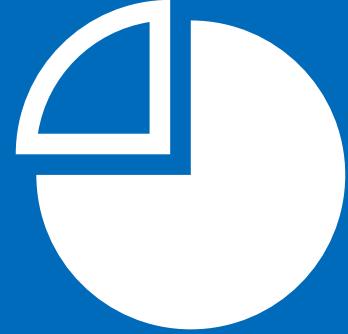
Where are the WIMPs?

DM annihilation in the Galactic Center



K. Abazajian et al., PRD 102 (2020), 043012 (Fermi-LAT)

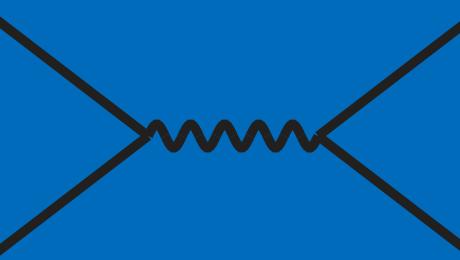
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs



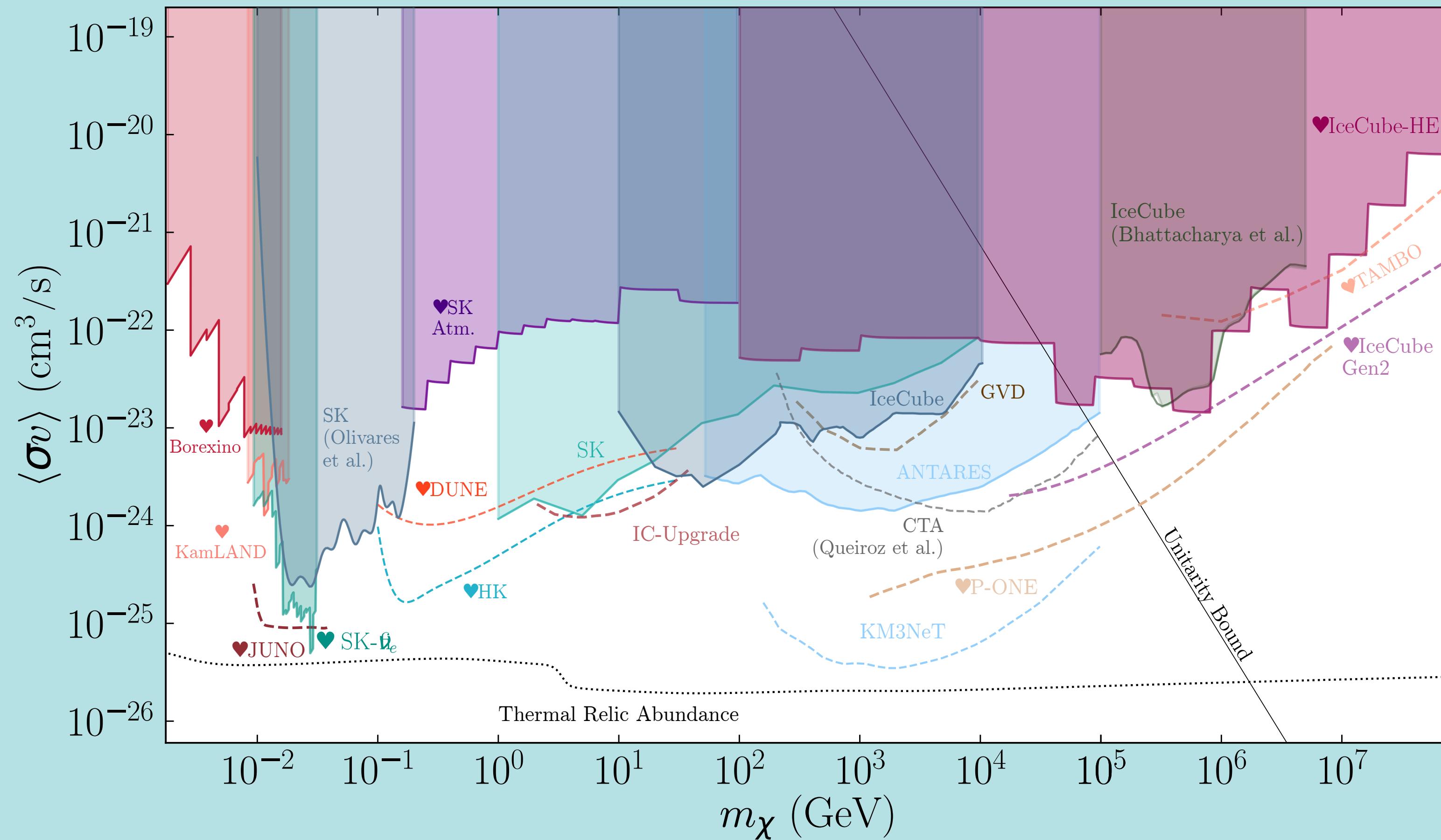
4. Compact objects



5. Prospects

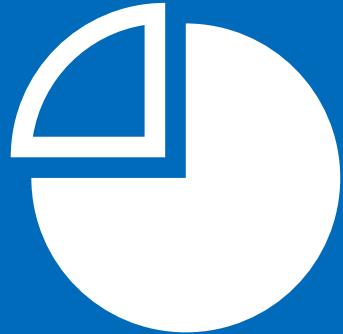
Where are the WIMPs?

DM annihilation to neutrinos

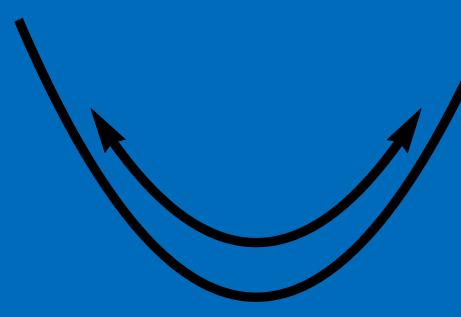


C. Argüelles et al., arXiv:1912.09486 [hep-ph]

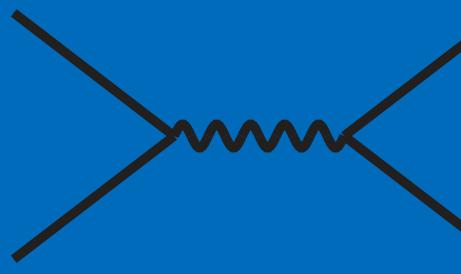
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs

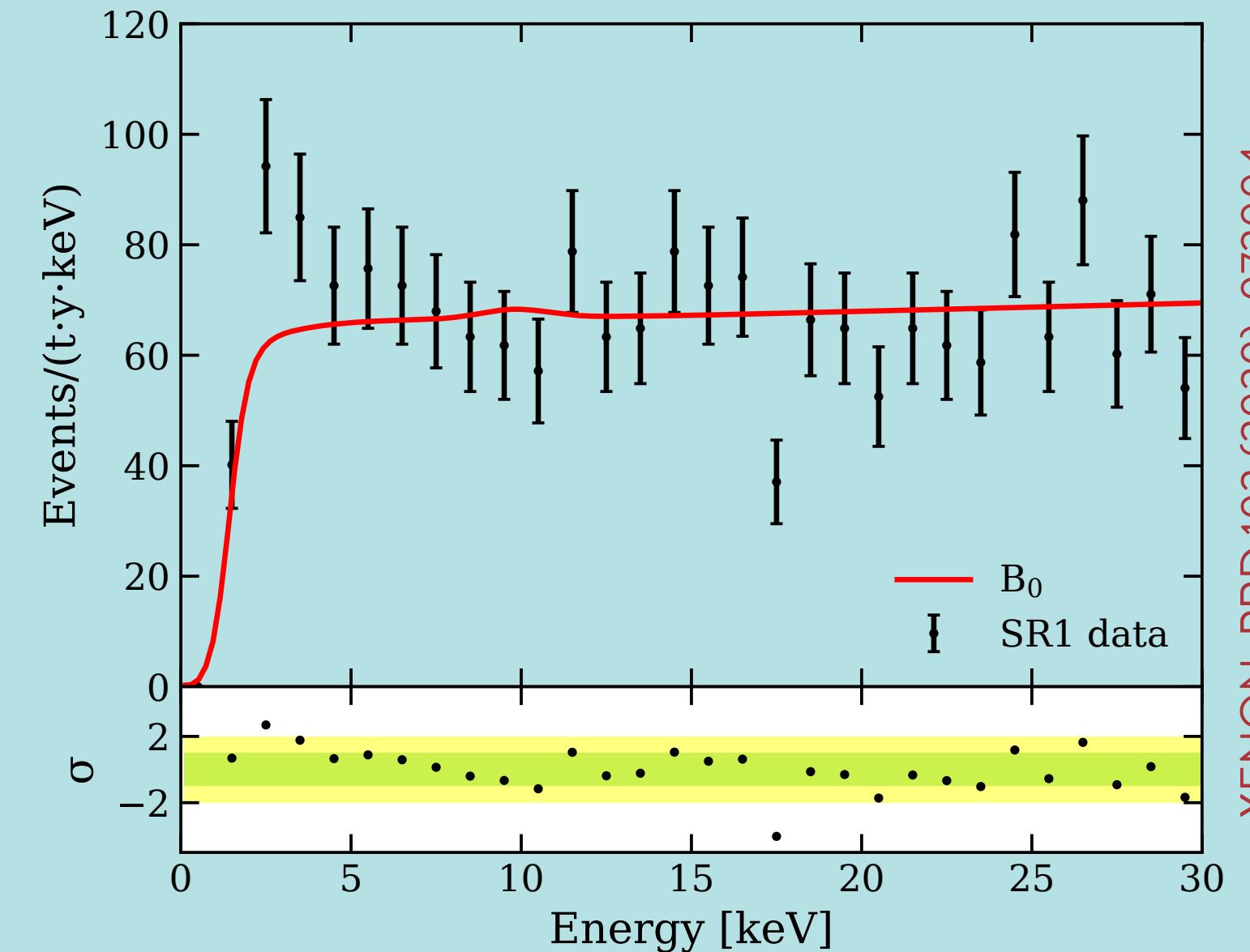


4. Compact objects

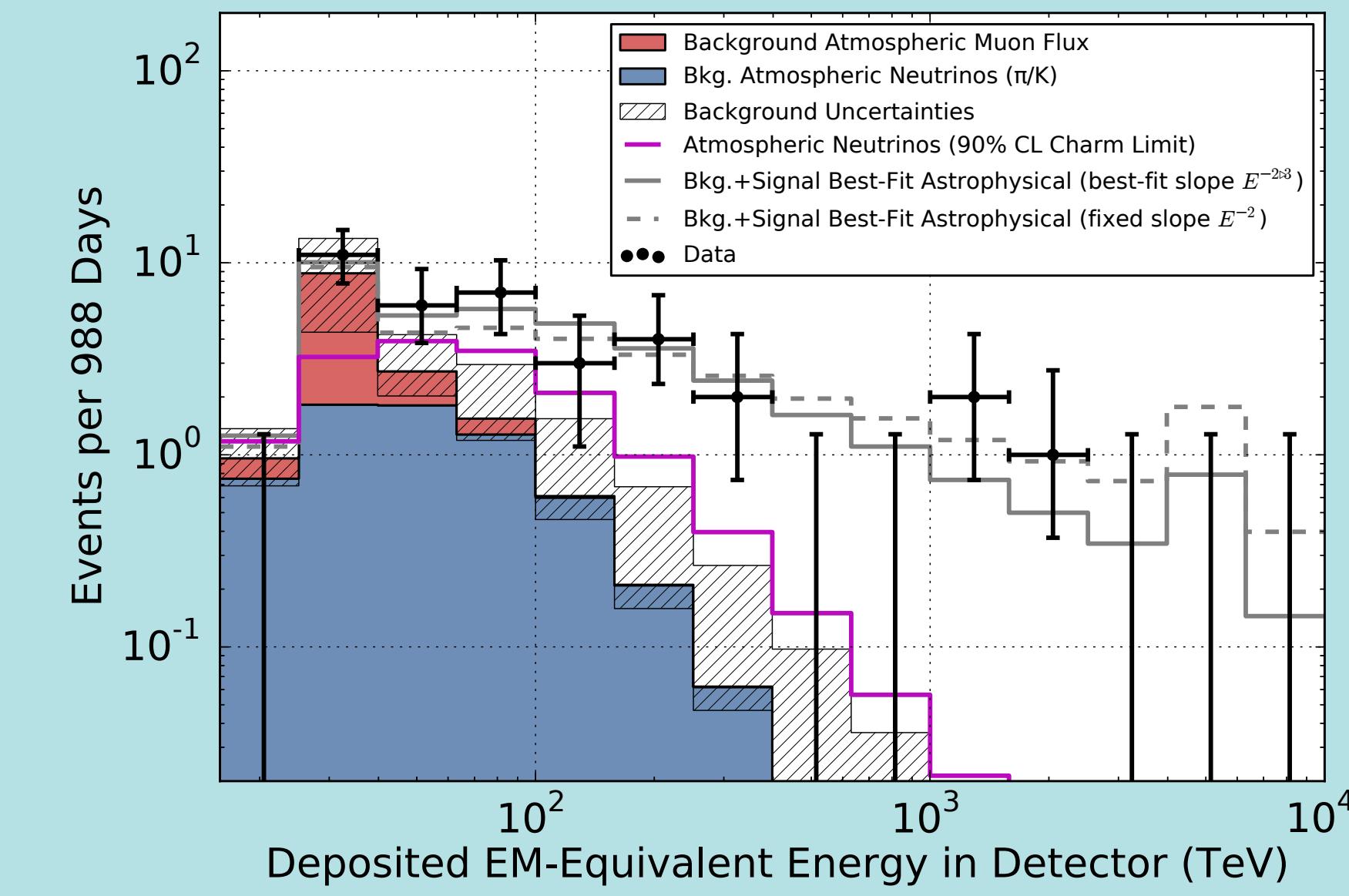


5. Prospects

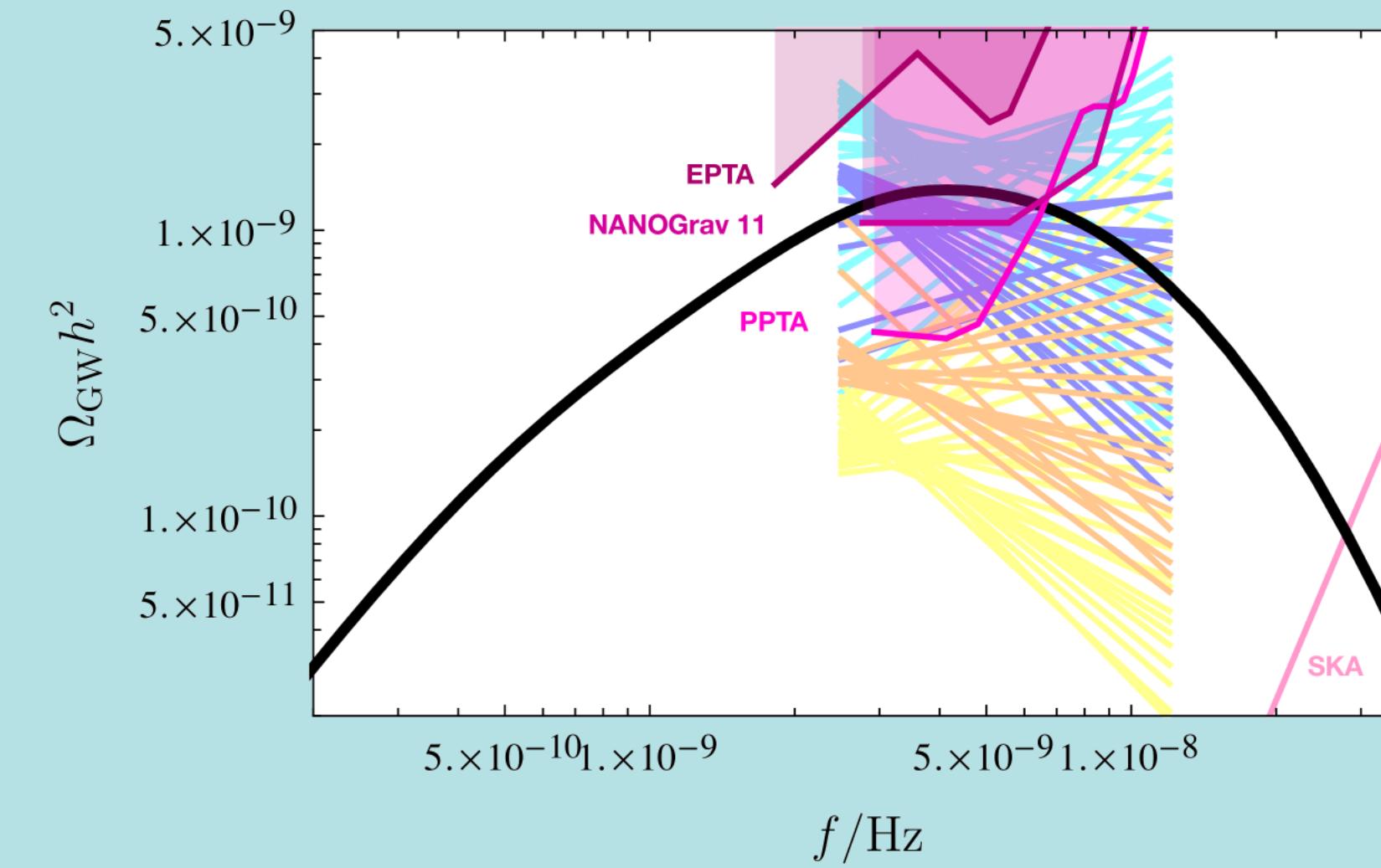
Other evidence for Dark Matter?



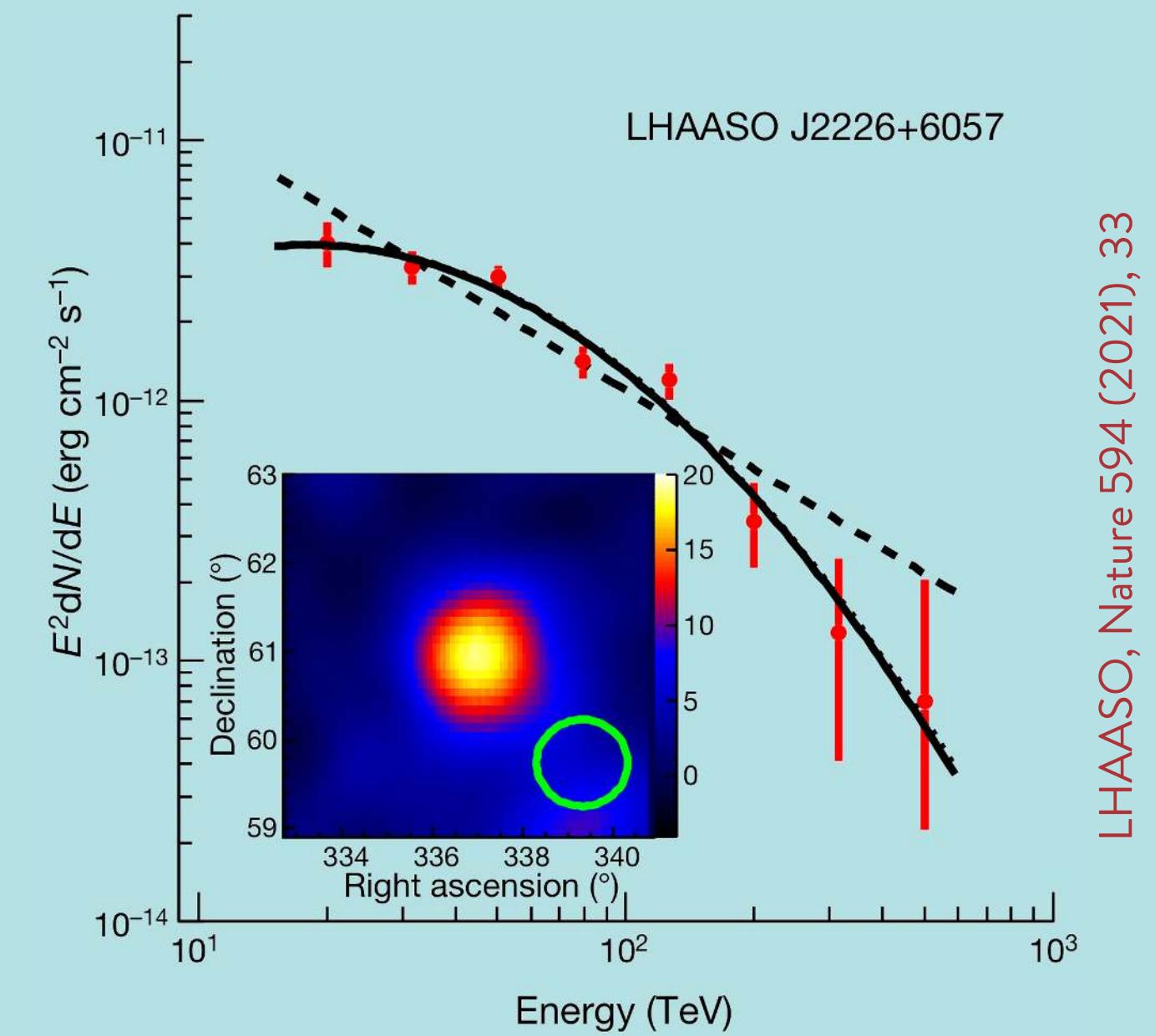
XENON, PRD 102 (2020), 072004



IceCube, PRL 113 (2014), 101101

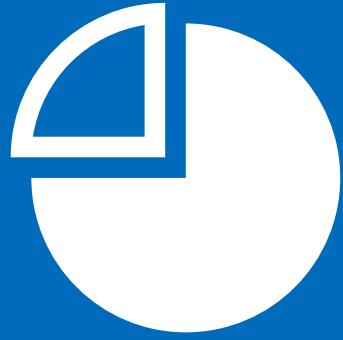


K. Kohri and T. Terada, PLB 813 (2021), 136040



LHAASO, Nature 594 (2021), 33

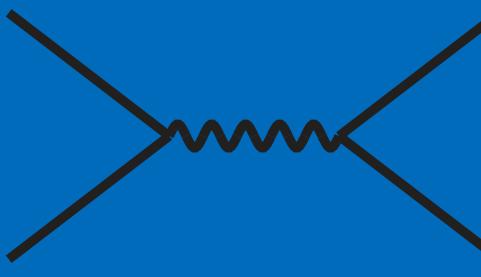
1. Beyond WIMPs



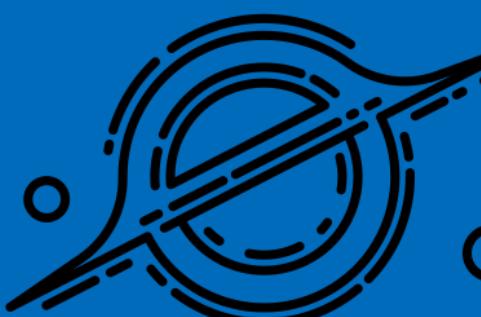
2. Inflation & reheating



3. FIMPs

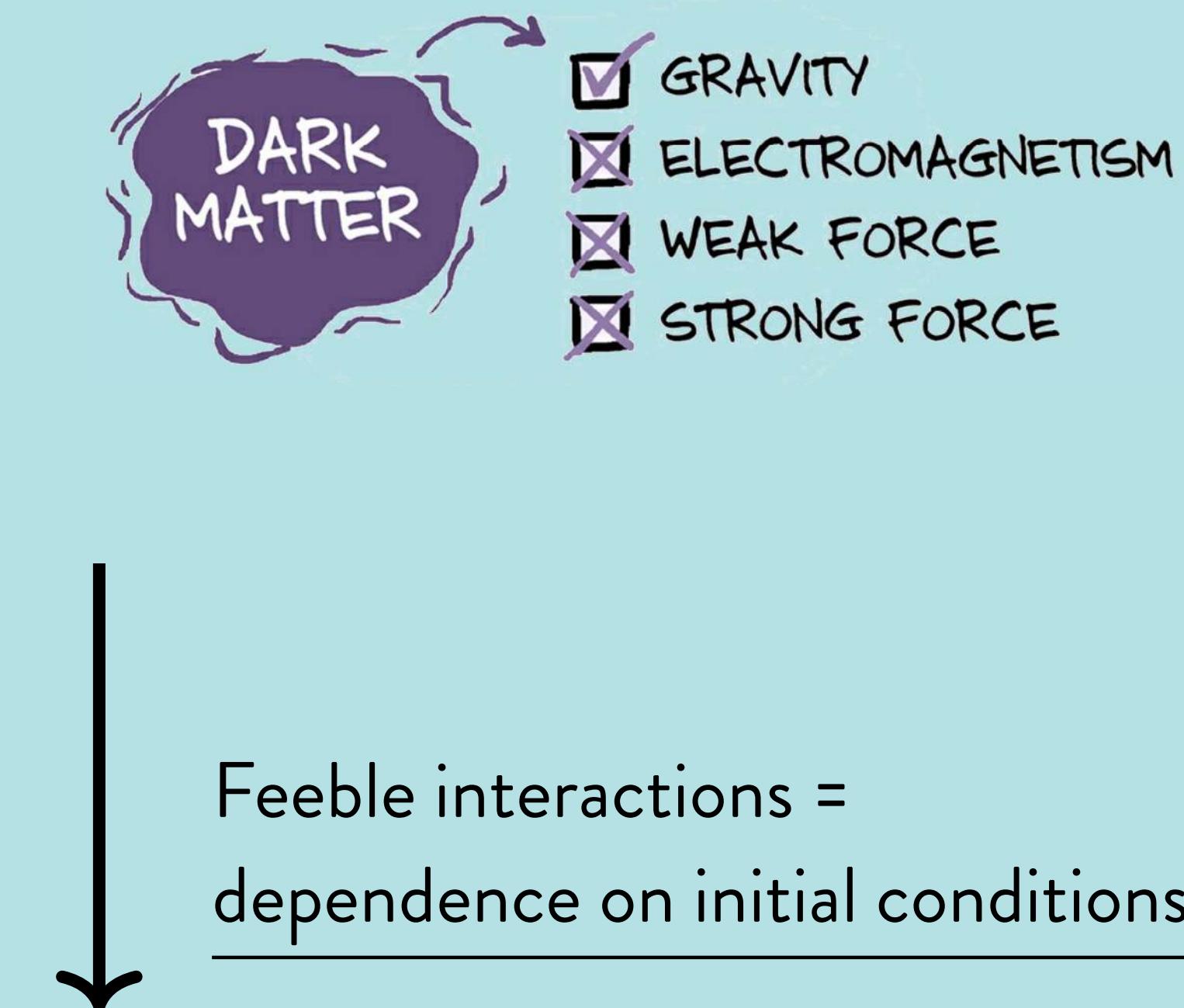
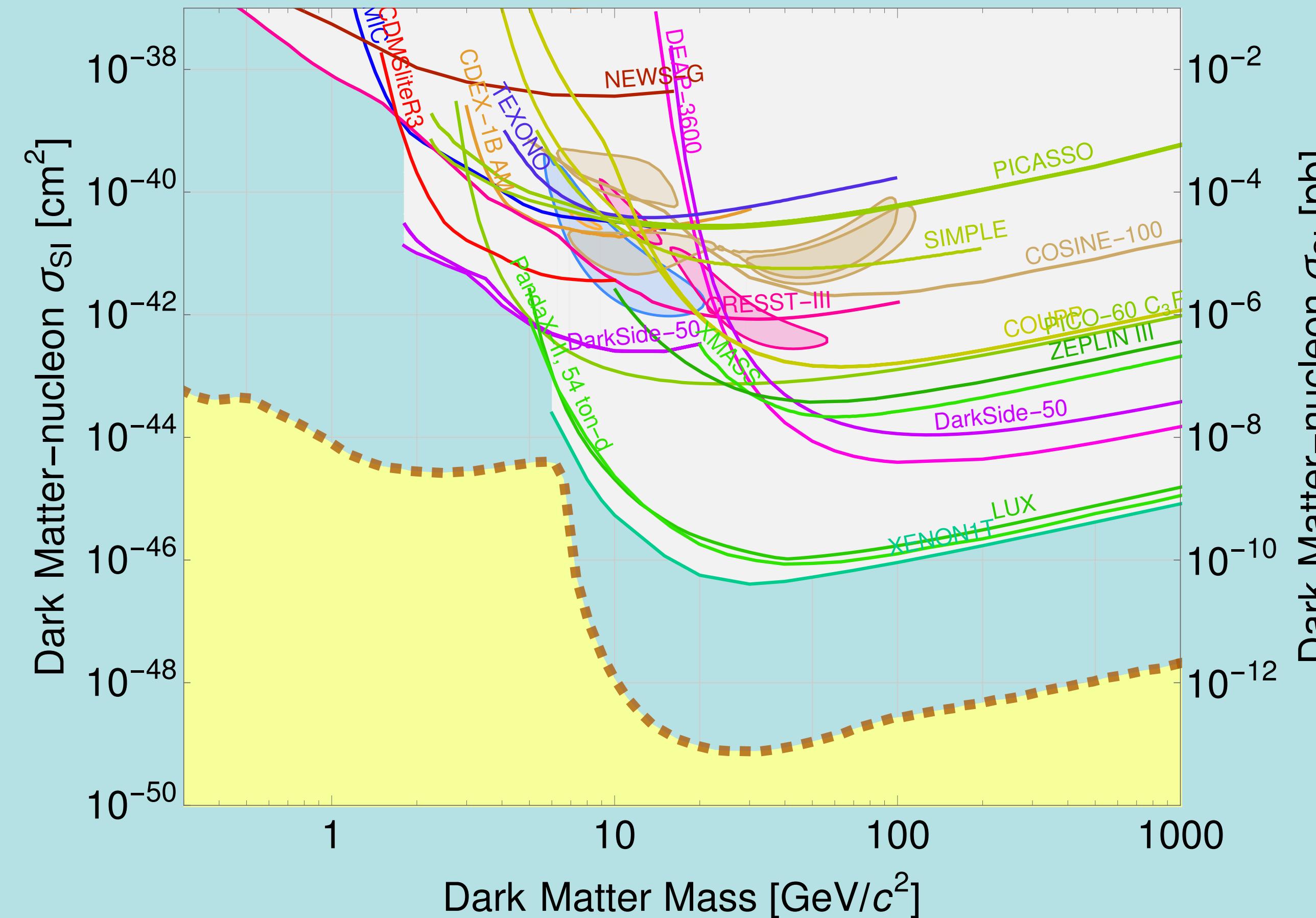


4. Compact objects

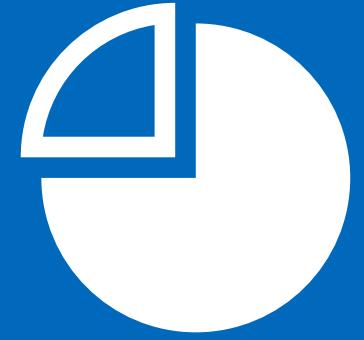


5. Prospects

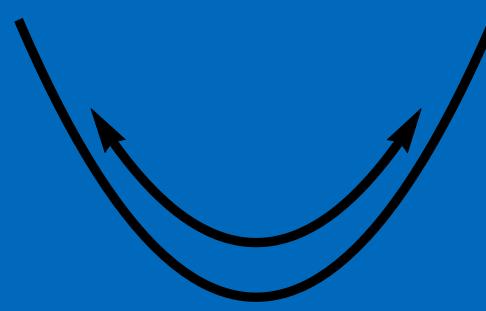
Beyond the WIMP



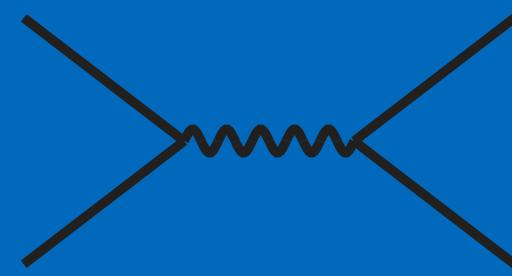
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs

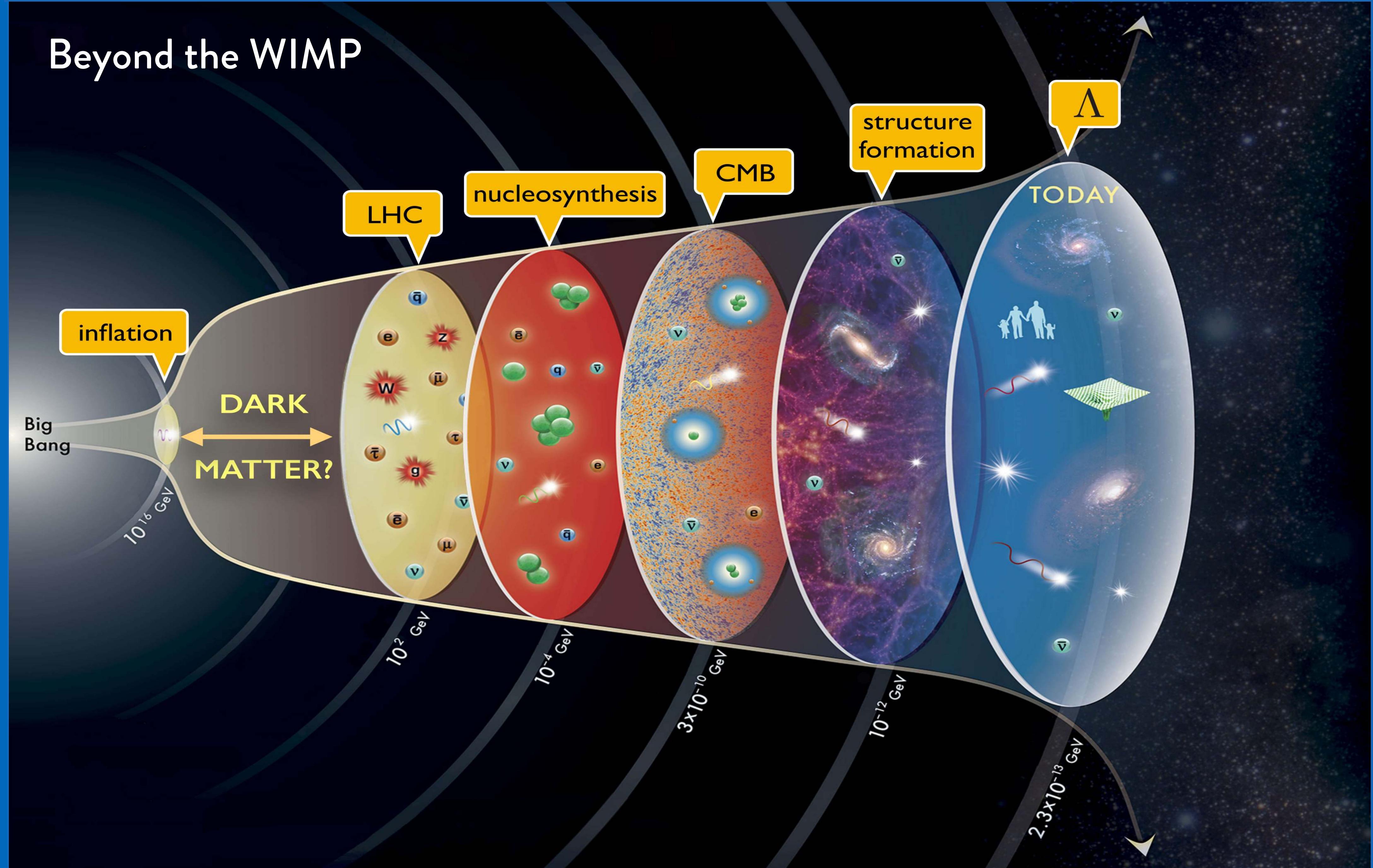


4. Compact objects

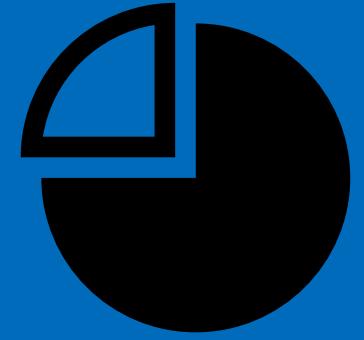


5. Prospects

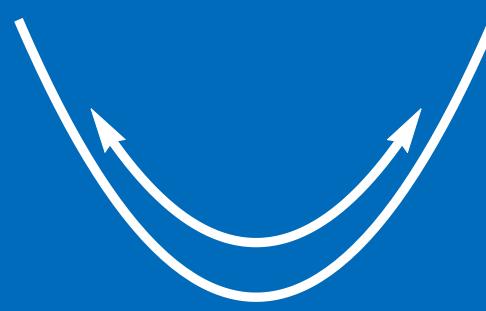
Beyond the WIMP



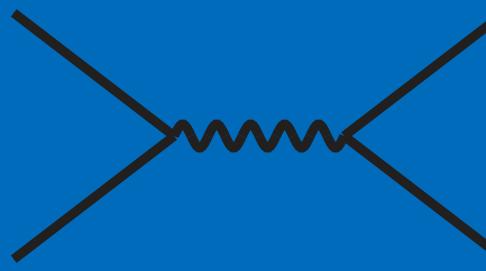
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs



4. Compact objects



5. Prospects

Inflating spacetime

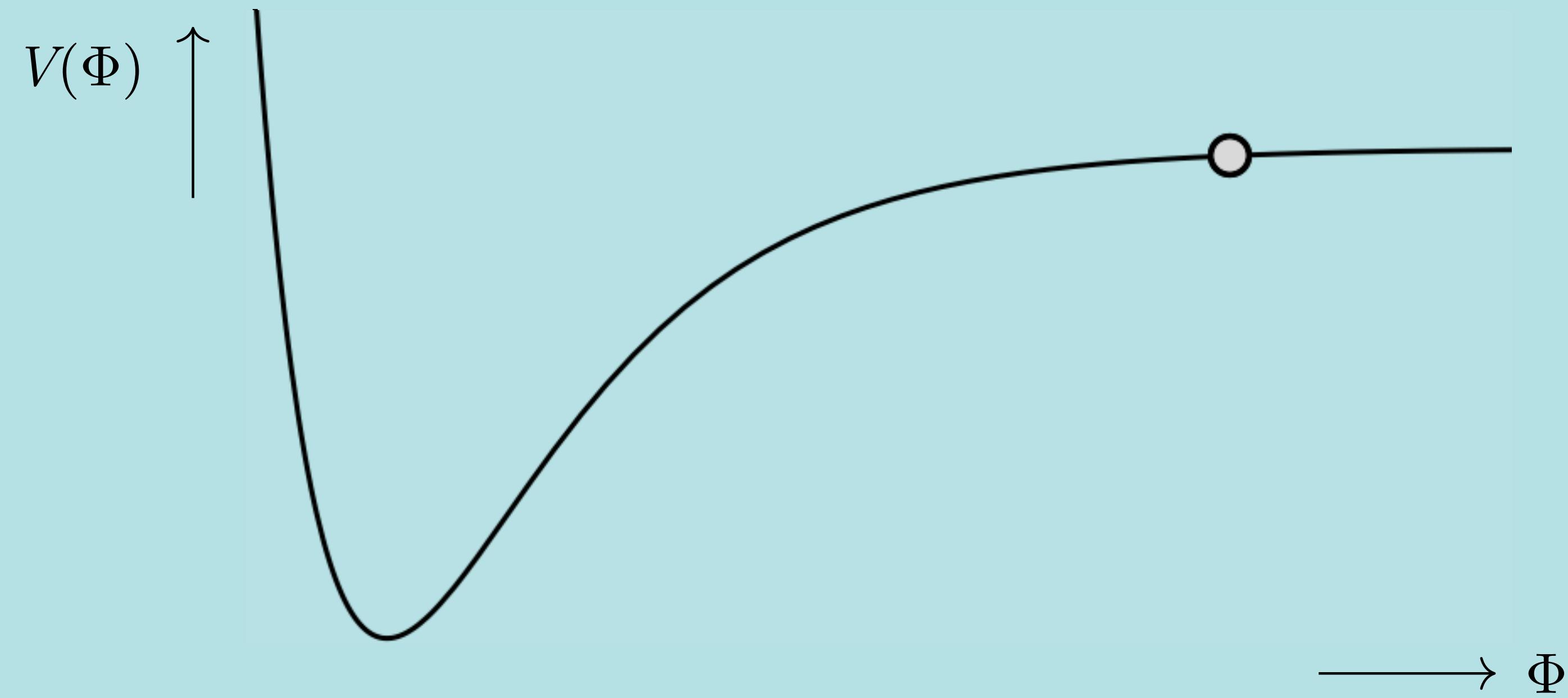
Simplest incarnation: a slowly rolling scalar field in FRW spacetime, $ds^2 = dt^2 - a(t)^2 dx^2$

$$\ddot{\Phi} + 3H\dot{\Phi} + V'(\Phi) = 0$$

$$H \equiv \frac{\dot{a}}{a} = \left(\frac{\rho_\Phi}{3M_P^2} \right)^{1/2} \quad \text{with}$$

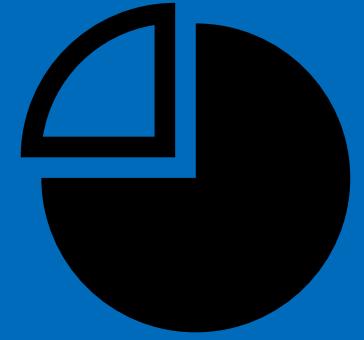
$$\rho_\Phi = \frac{1}{2}\dot{\Phi}^2 + V(\Phi)$$

$$P_\Phi = \frac{1}{2}\dot{\Phi}^2 - V(\Phi)$$



When inflation ends, reheating begins

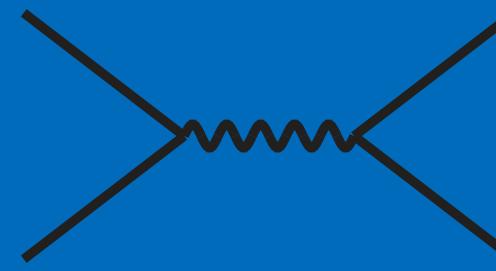
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs



4. Compact objects

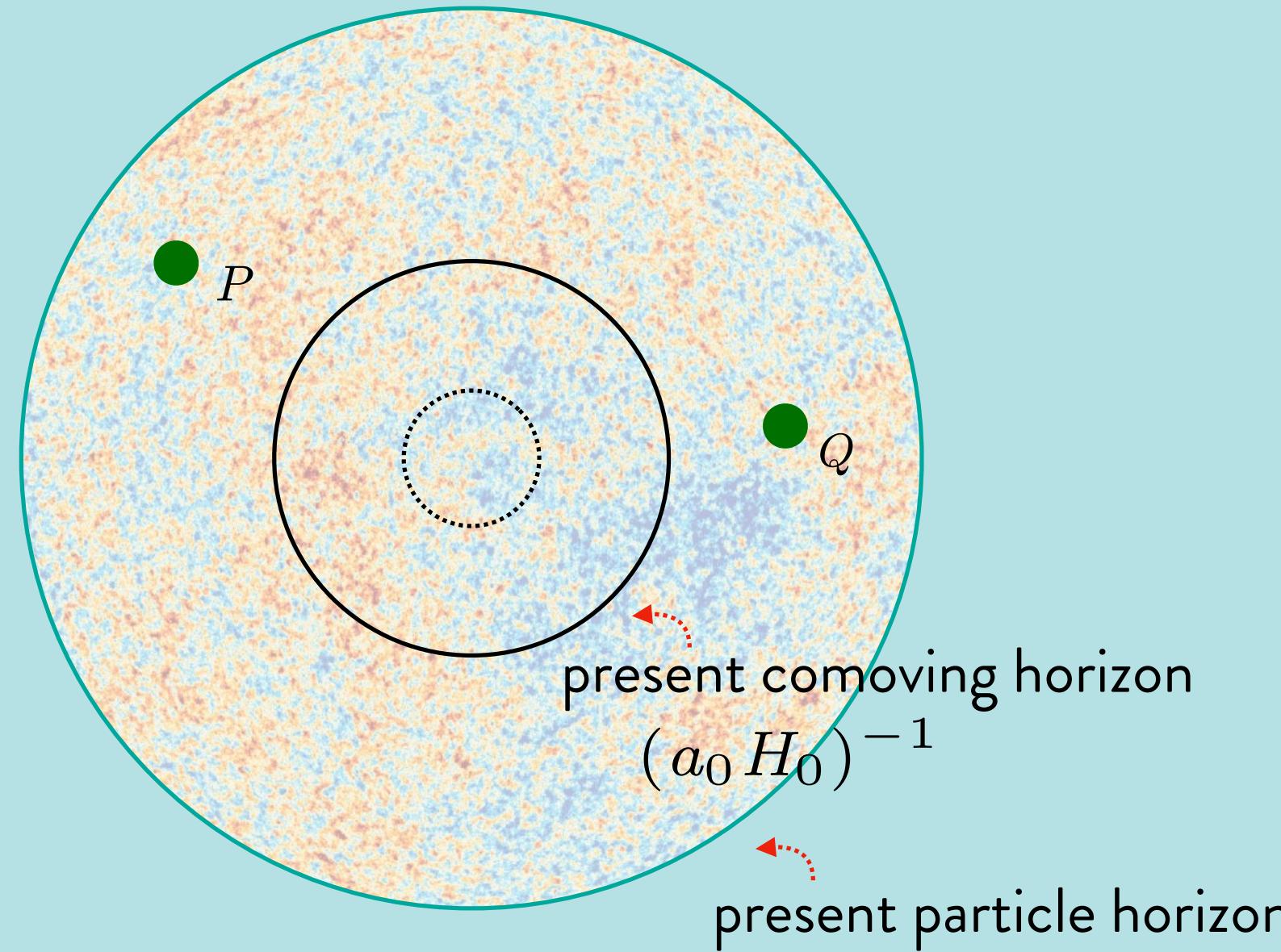


5. Prospects

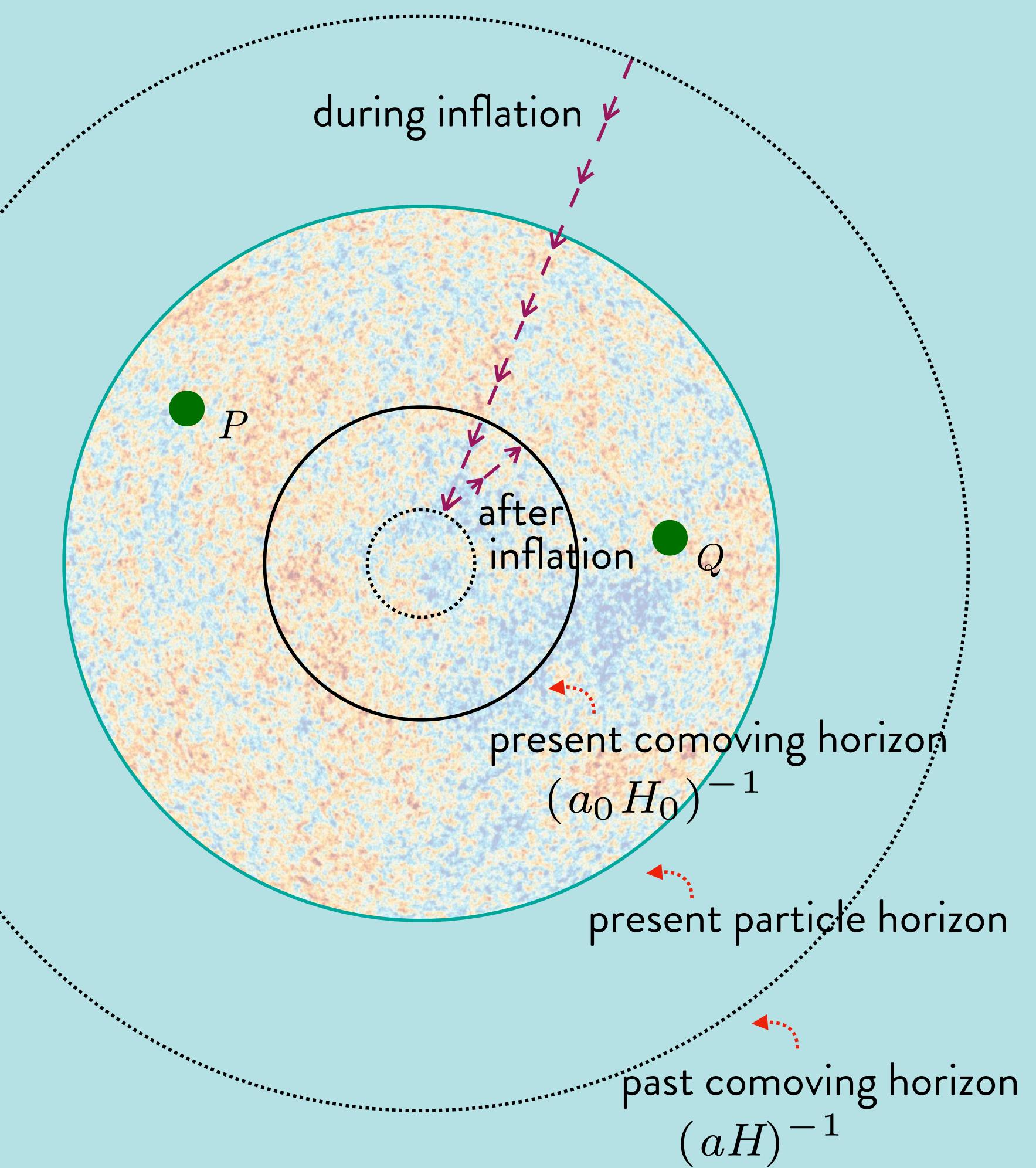
The horizon problem

$\Delta T / T \sim 10^{-5}$ in the CMB

Without inflation

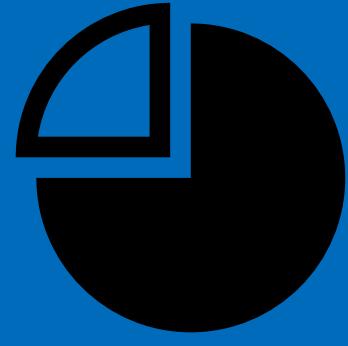


With inflation

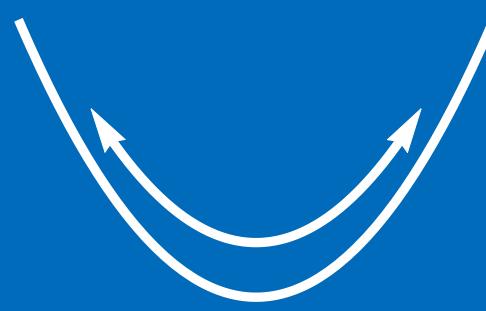


Credit: Héctor Ramírez

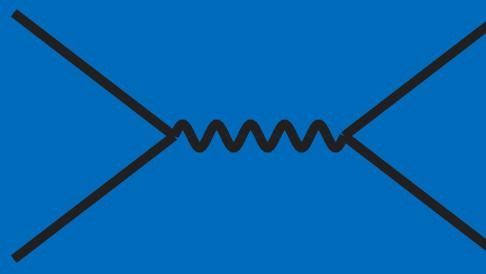
1. Beyond WIMPs



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3. FIMPs

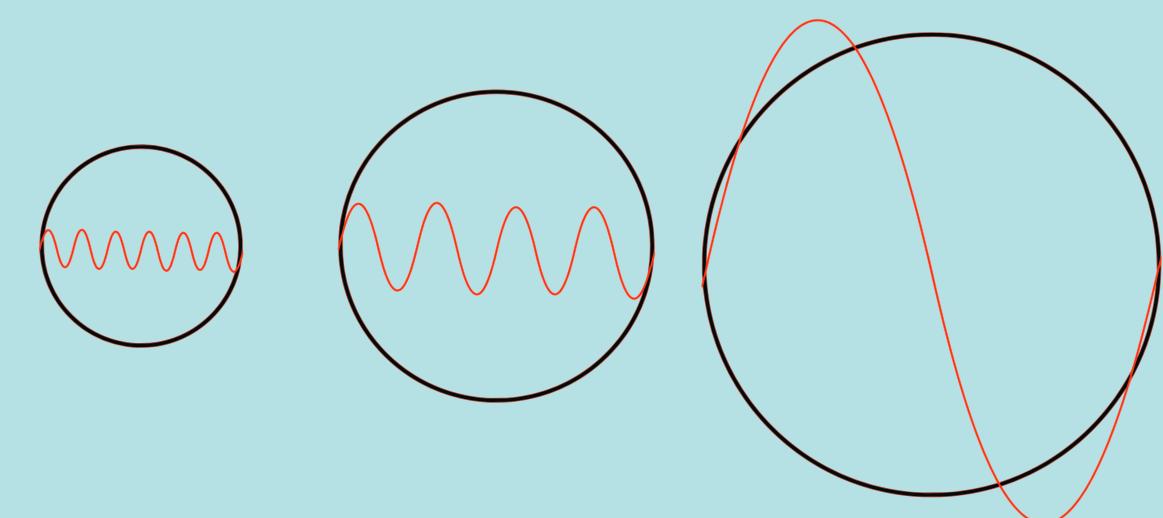


4. Compact objects



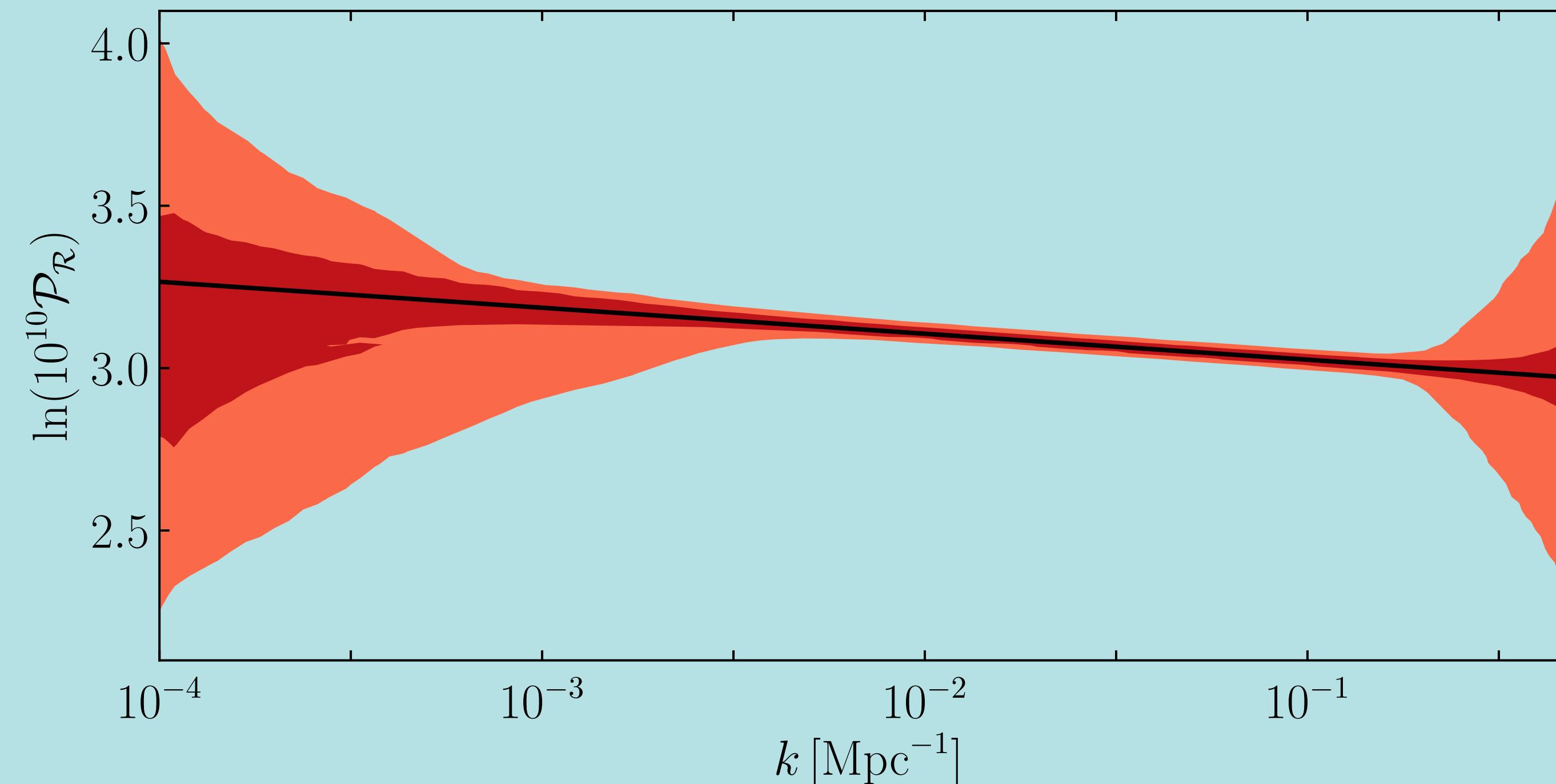
5. Prospects

The primordial fluctuations



Quantum fluctuations in Φ, g , are stretched by expansion

Planck TT, TE, EE + lowE + lensing + BK15 (■ 1σ , ■ 2σ)

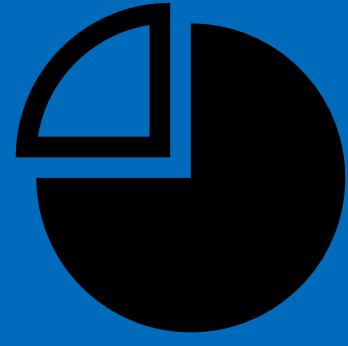


Y. Akrami et al. [Planck], Astron.
Astrophys. 641 (2020) A10

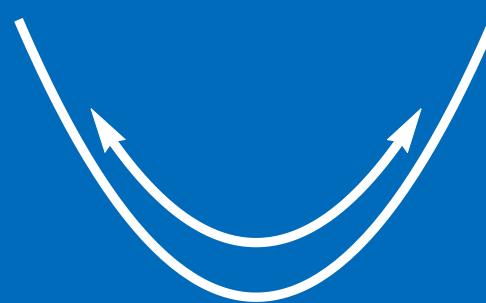
$$\mathcal{P}_{\mathcal{R}} = \frac{H_*^4}{4\pi^2 \dot{\Phi}_*^2} \left(\frac{k}{aH} \right)^{n_s - 1}$$

$$\mathcal{P}_{\mathcal{T}} = \frac{2H_*^2}{\pi^2} \left(\frac{k}{aH} \right)^{n_T}$$

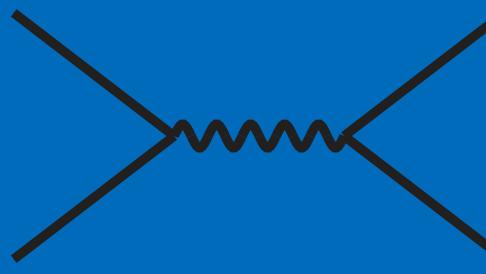
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs

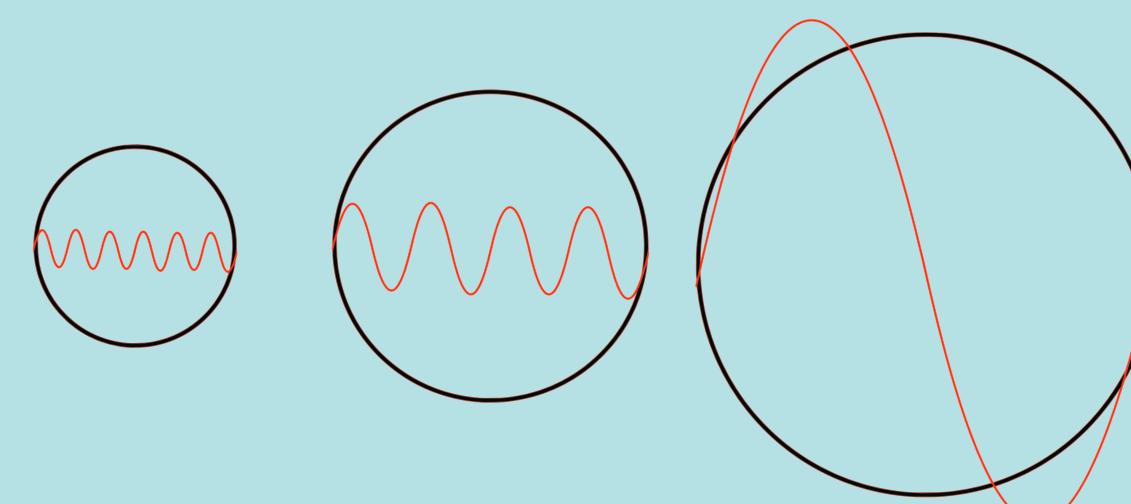


4. Compact objects

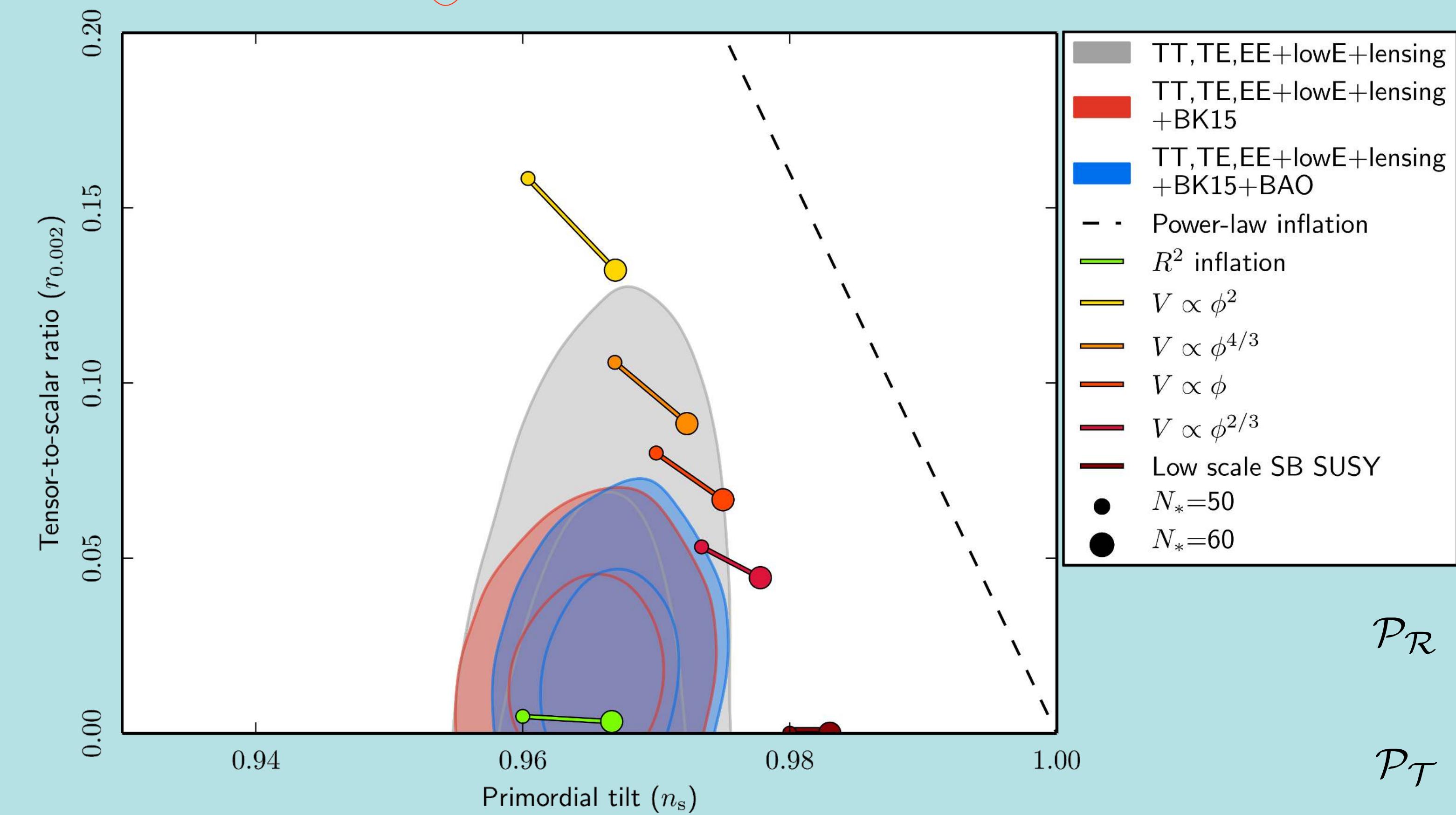


5. Prospects

The primordial fluctuations



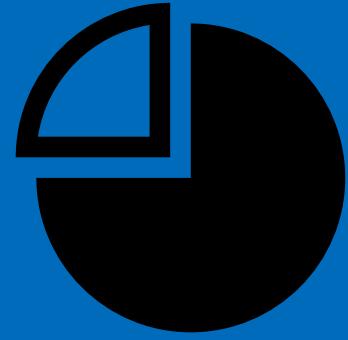
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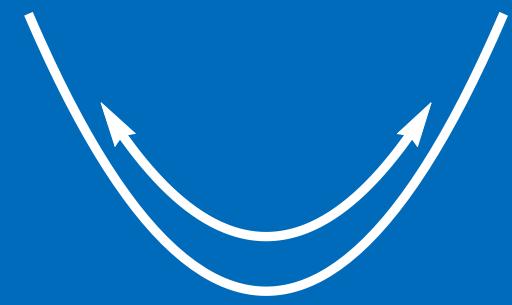
$$\mathcal{P}_{\mathcal{R}} = \frac{H_*^4}{4\pi^2 \dot{\Phi}_*^2} \left(\frac{k}{aH} \right)^{n_s - 1}$$

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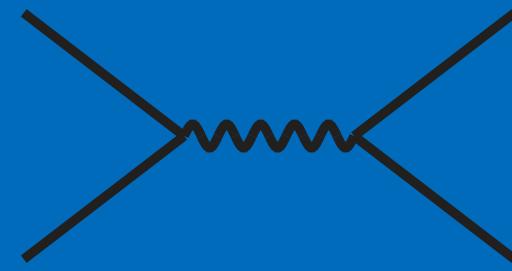
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs



4. Compact objects



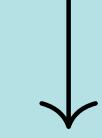
5. Prospects

The vacuum can be excited!

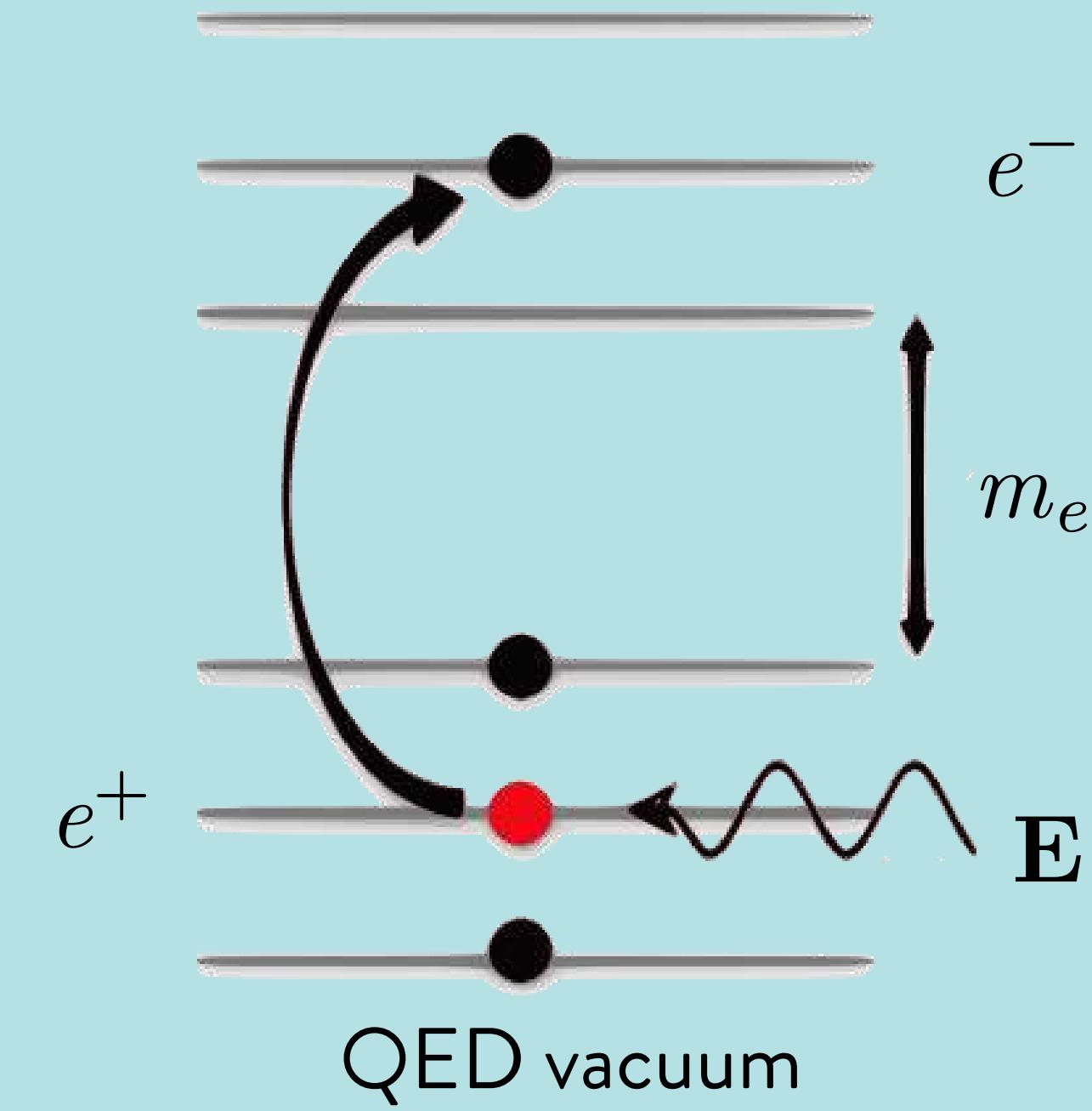
$$A_\mu = (0, 0, 0, Et)$$

$$\omega^2(t) = (p_z + gEt)^2 + \mathbf{p}_T^2 + m^2$$

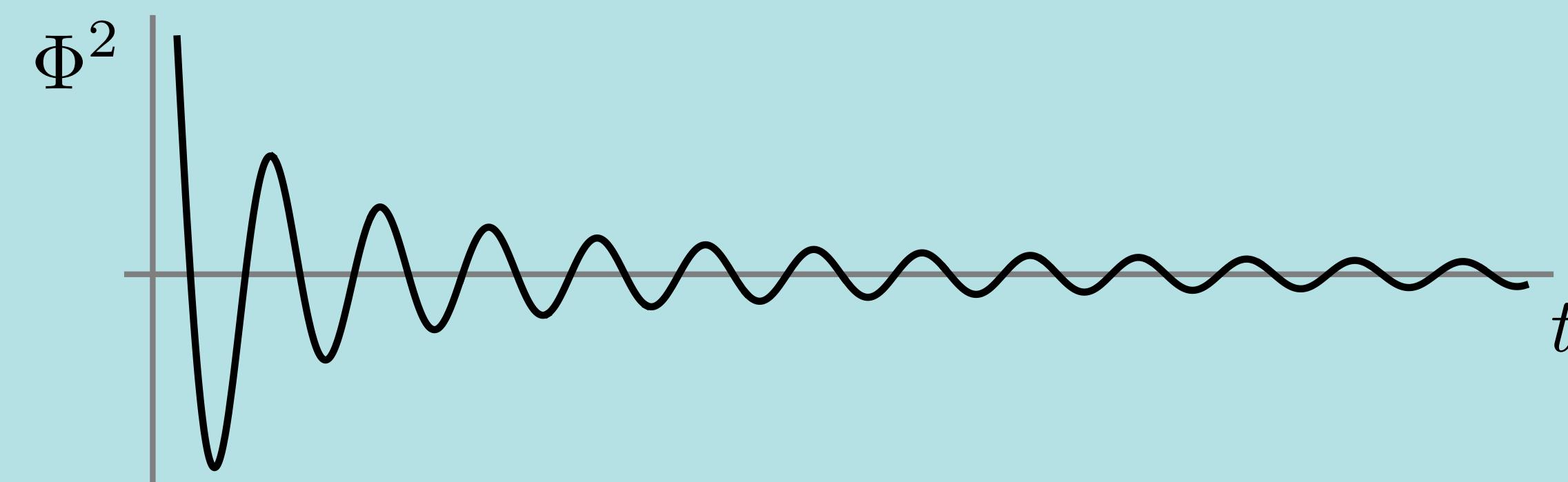
mixing of +/- frequency modes



particle production! (Schwinger effect)



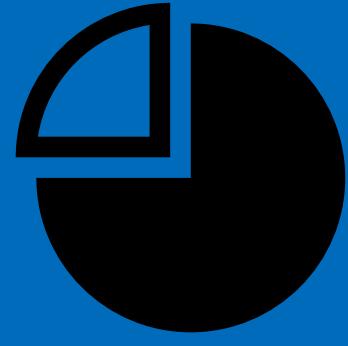
During reheating, the inflaton provides an oscillating background



$$\mathcal{L}_\psi = y \Phi \bar{\psi} \psi \equiv m_\psi(t) \bar{\psi} \psi$$

$$\mathcal{L}_\chi = \frac{1}{2} \sigma \Phi^2 \chi^2 \equiv \frac{1}{2} m_\chi^2(t) \chi^2$$

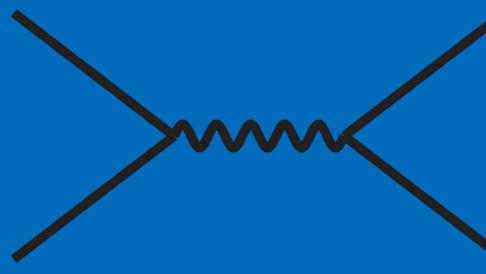
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs



4. Compact objects

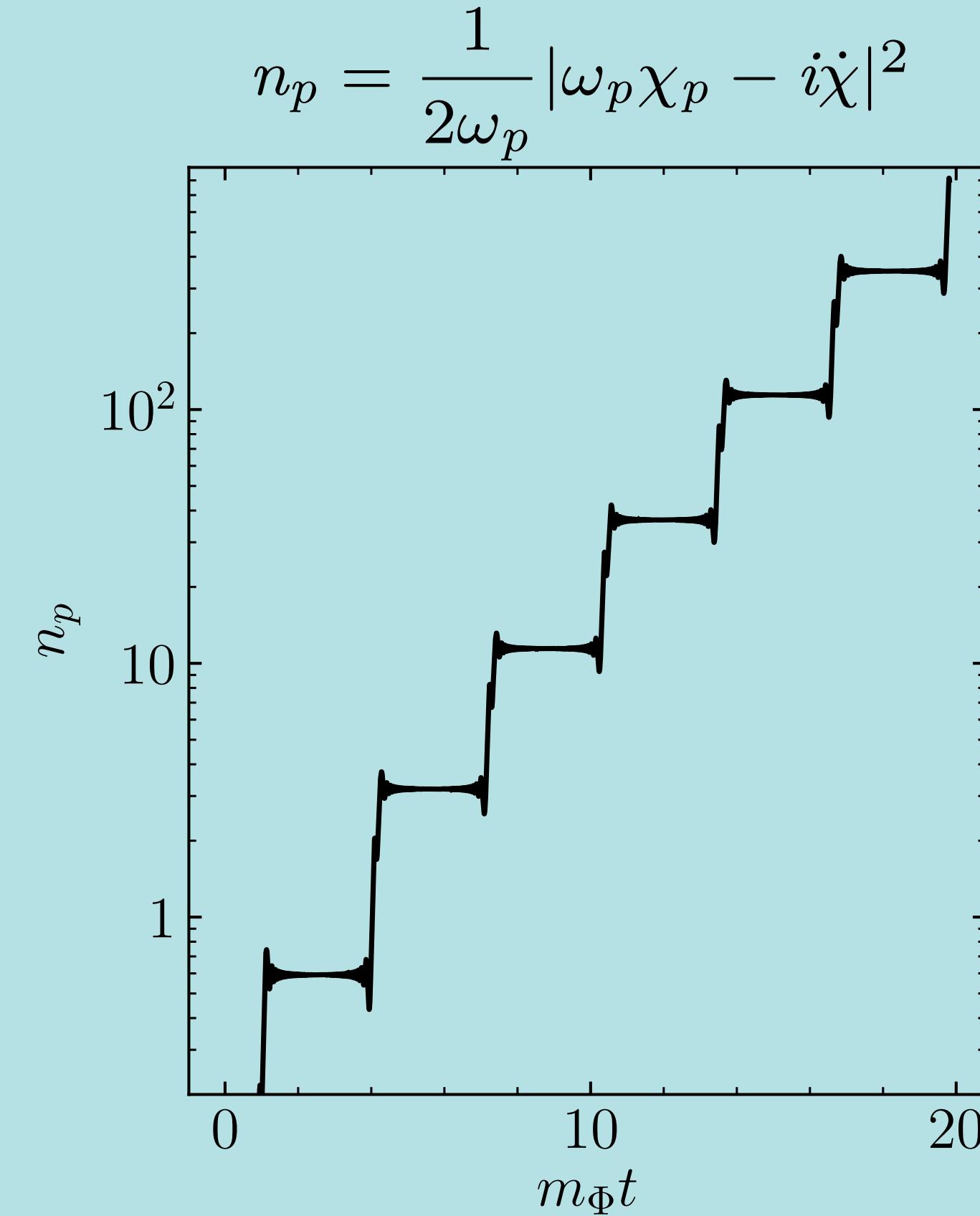
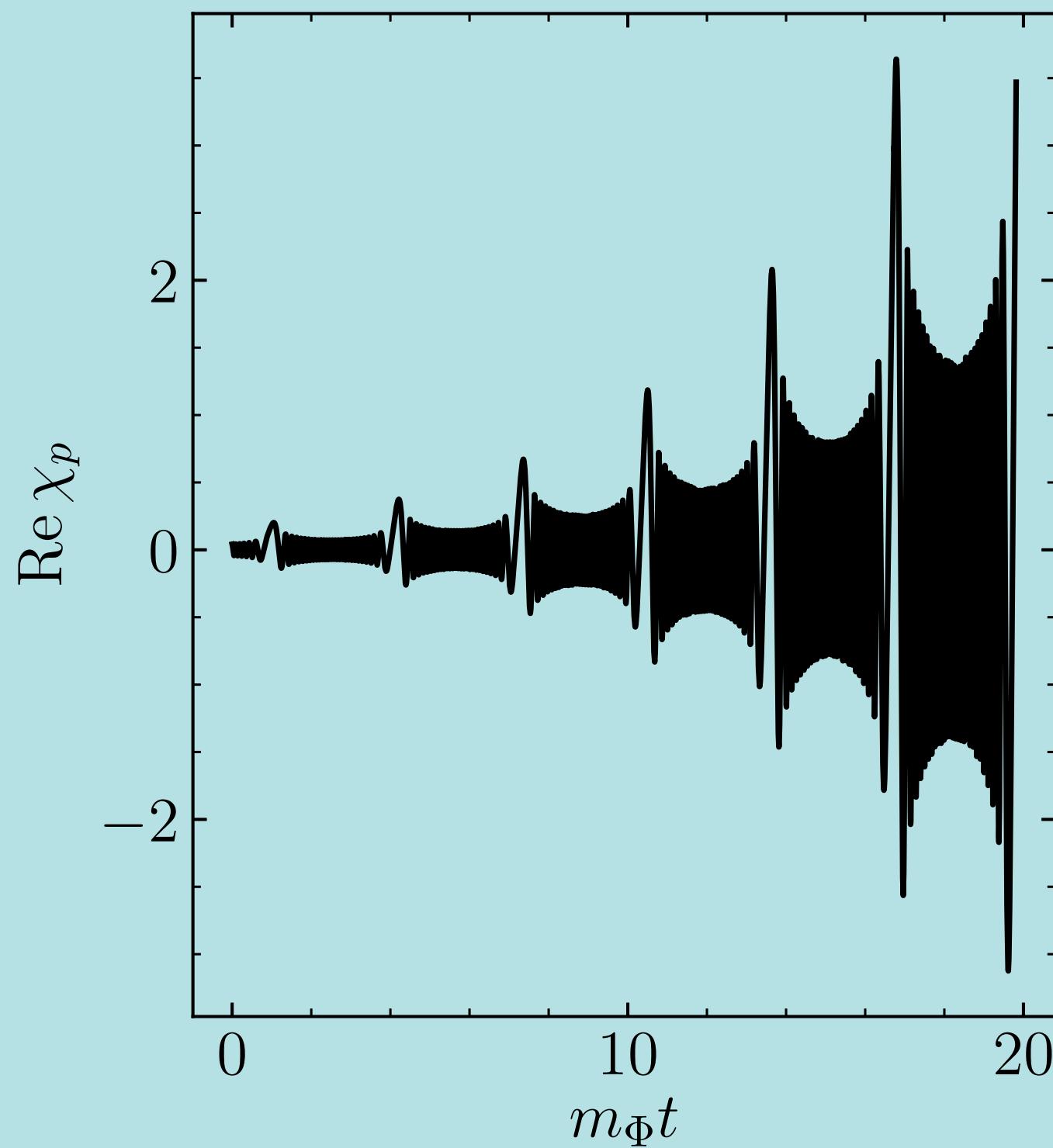
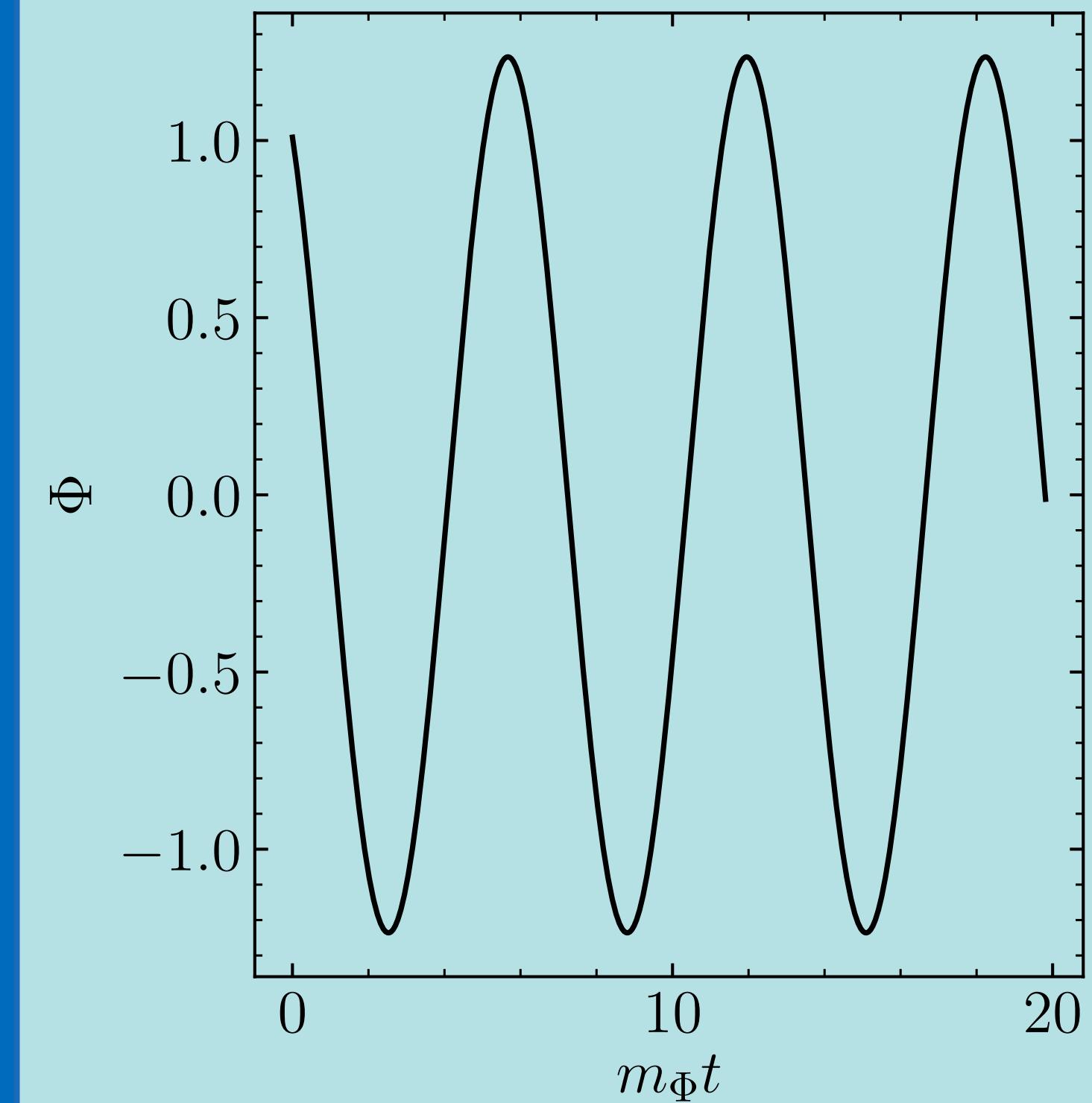


5. Prospects

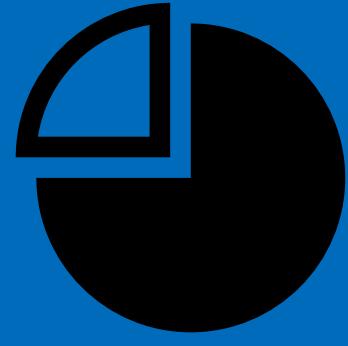
Scalar (p)reheating

$$\ddot{\chi}_p + 3H\dot{\chi}_p + \left[\frac{p^2}{a^2} + m_\chi^2(t) \right] \chi_p = 0, \quad m_\chi^2(t) = \sigma\Phi^2 + m_{\chi,0}^2$$

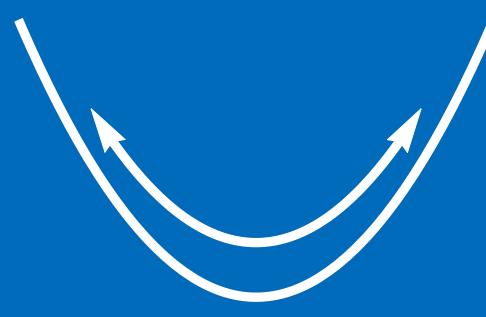
Neglecting expansion,



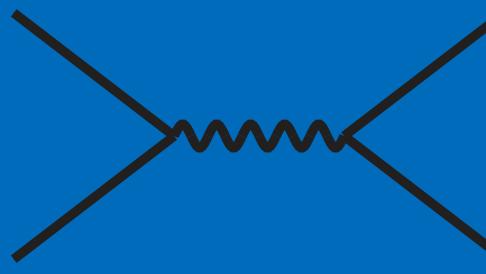
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs



4. Compact objects

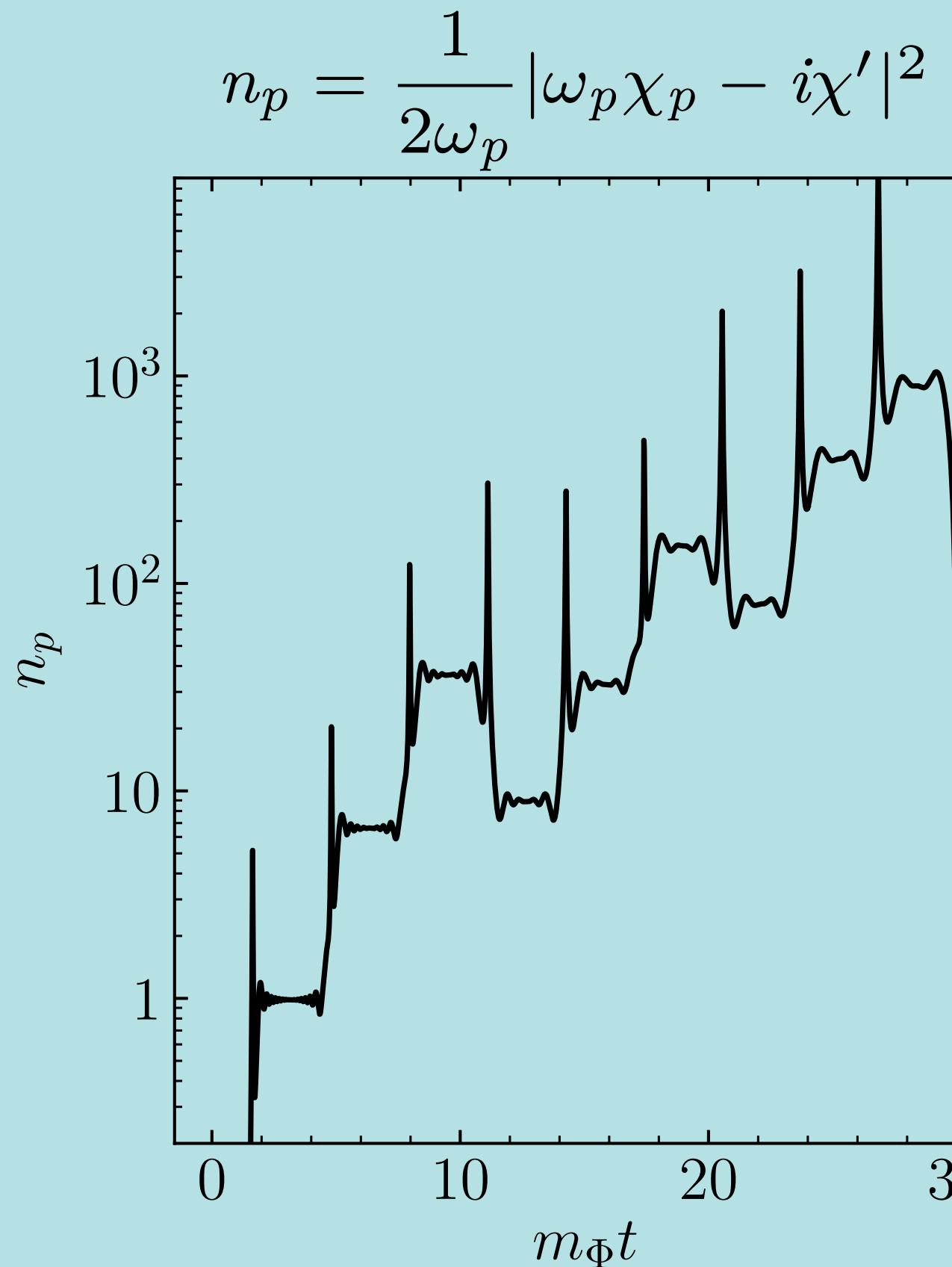
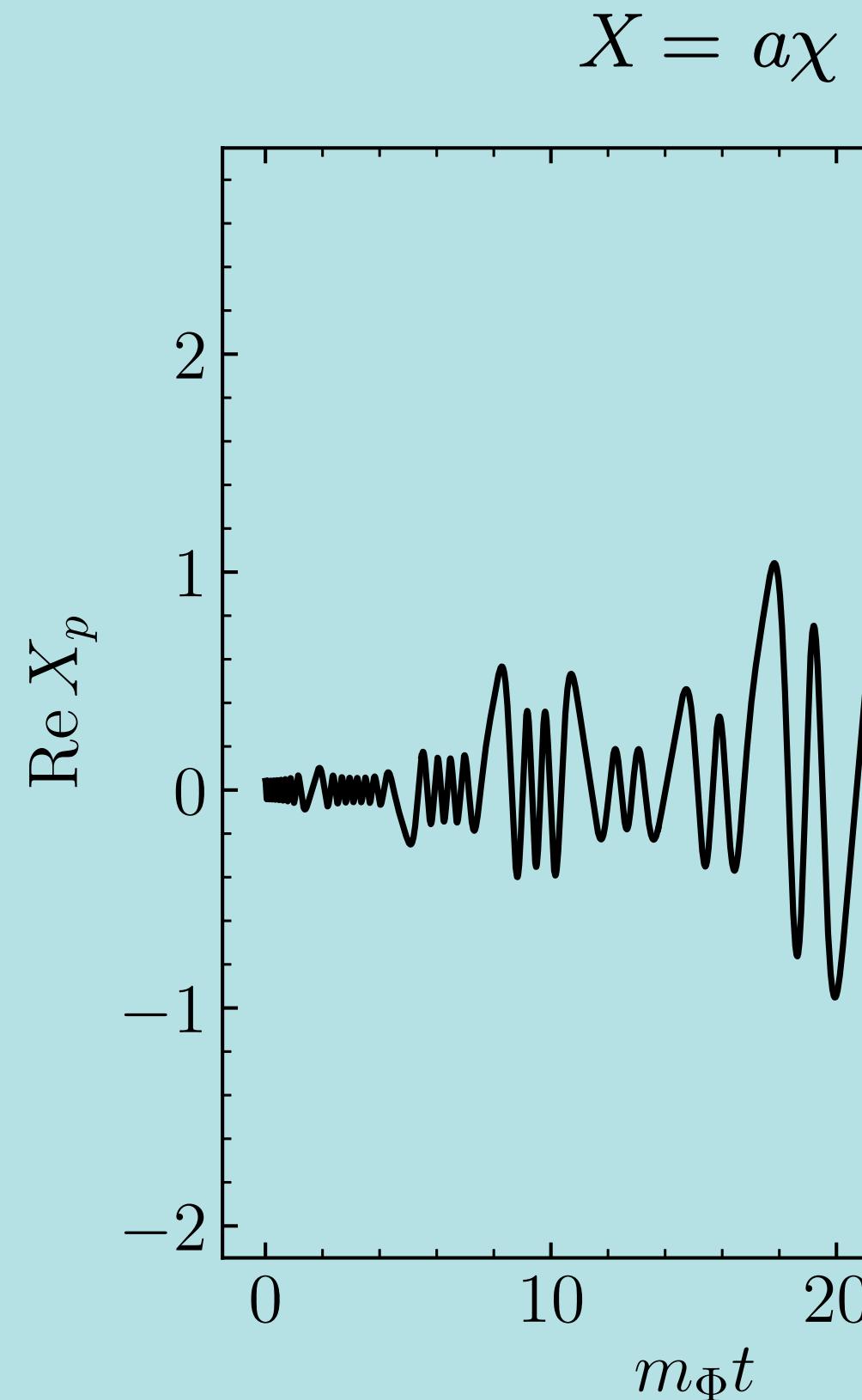
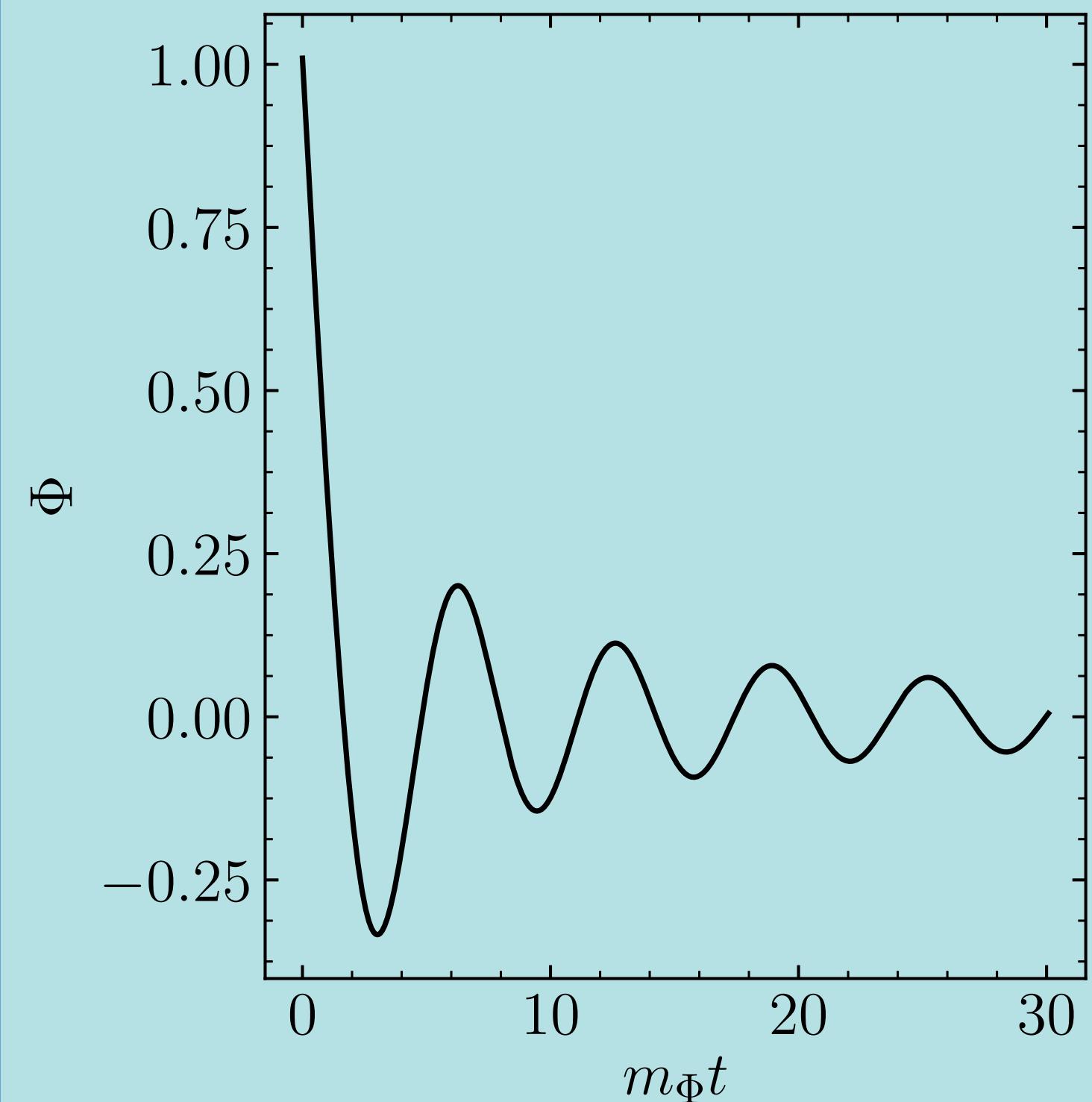


5. Prospects

Scalar (p)reheating

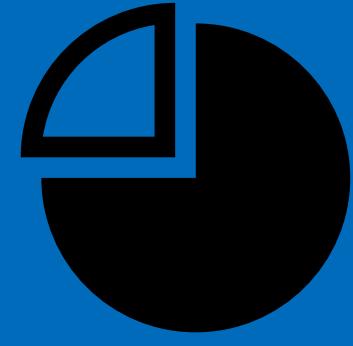
$$\ddot{\chi}_p + 3H\dot{\chi}_p + \left[\frac{p^2}{a^2} + m_\chi^2(t) \right] \chi_p = 0, \quad m_\chi^2(t) = \sigma \Phi^2 + m_{\chi,0}^2$$

With expansion,



$$n_p = \frac{1}{2\omega_p} |\omega_p \chi_p - i\chi'|^2$$

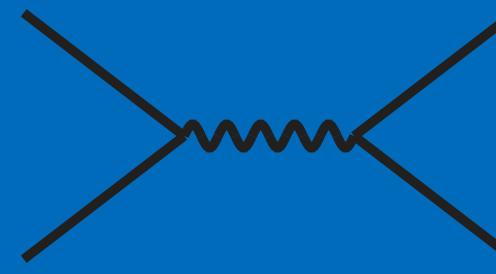
1. Beyond WIMPs



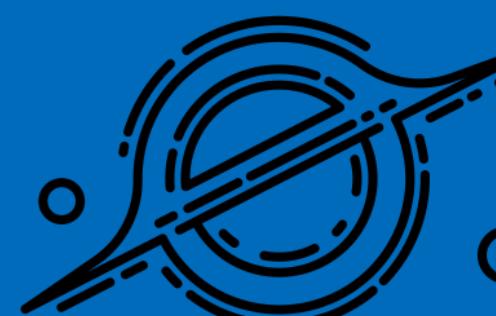
2. Inflation & reheating



3. FIMPs



4. Compact objects

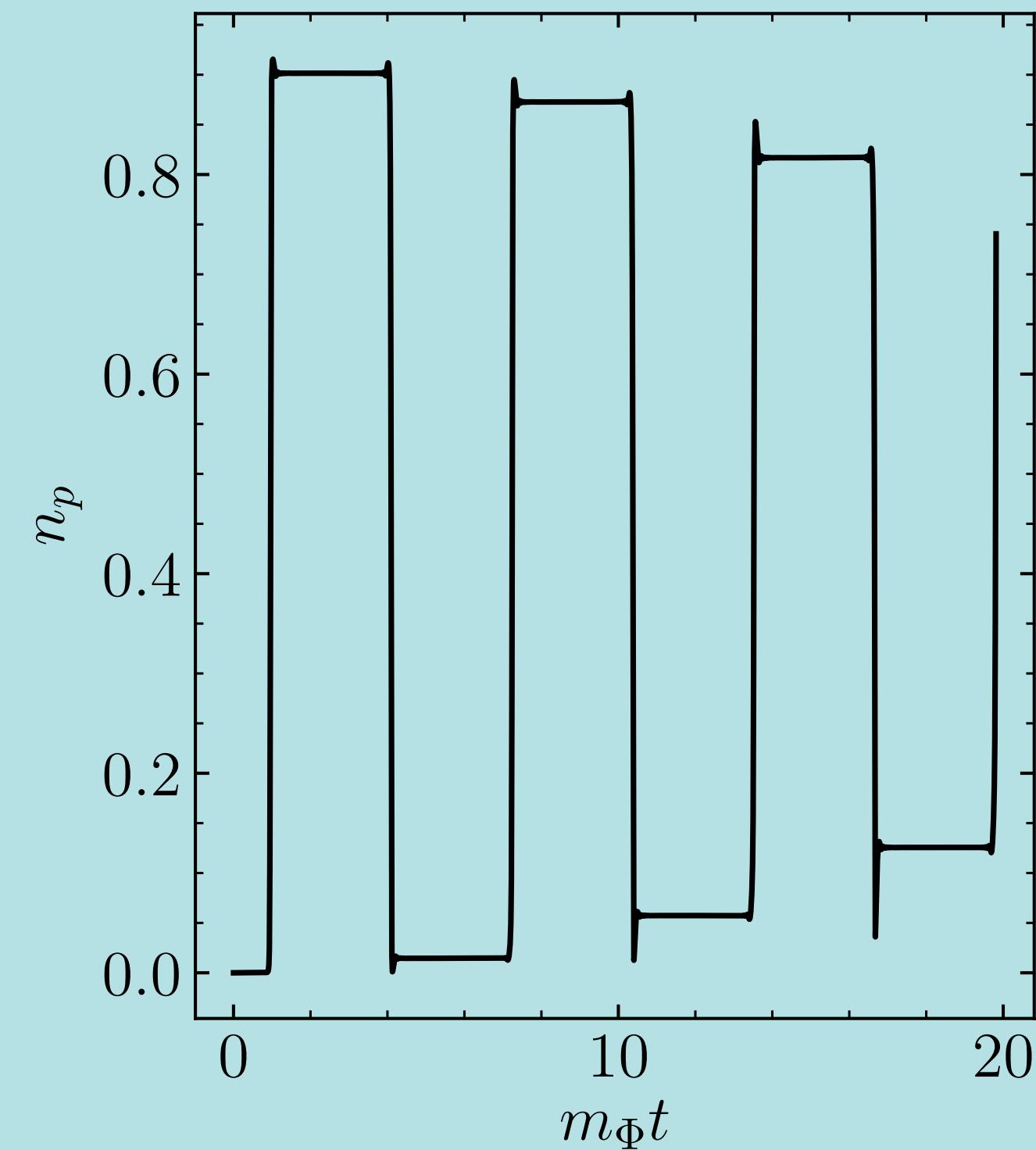
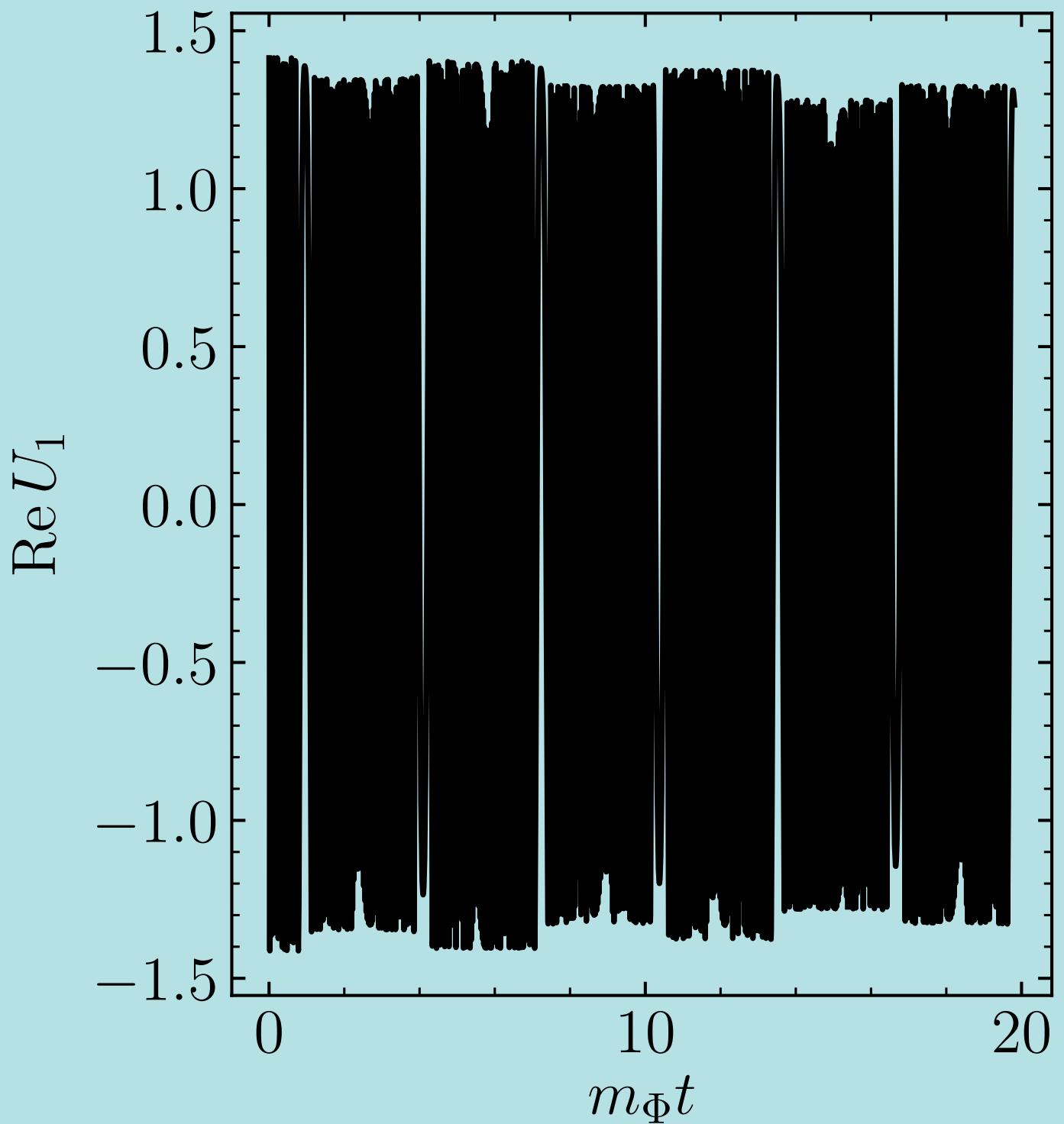
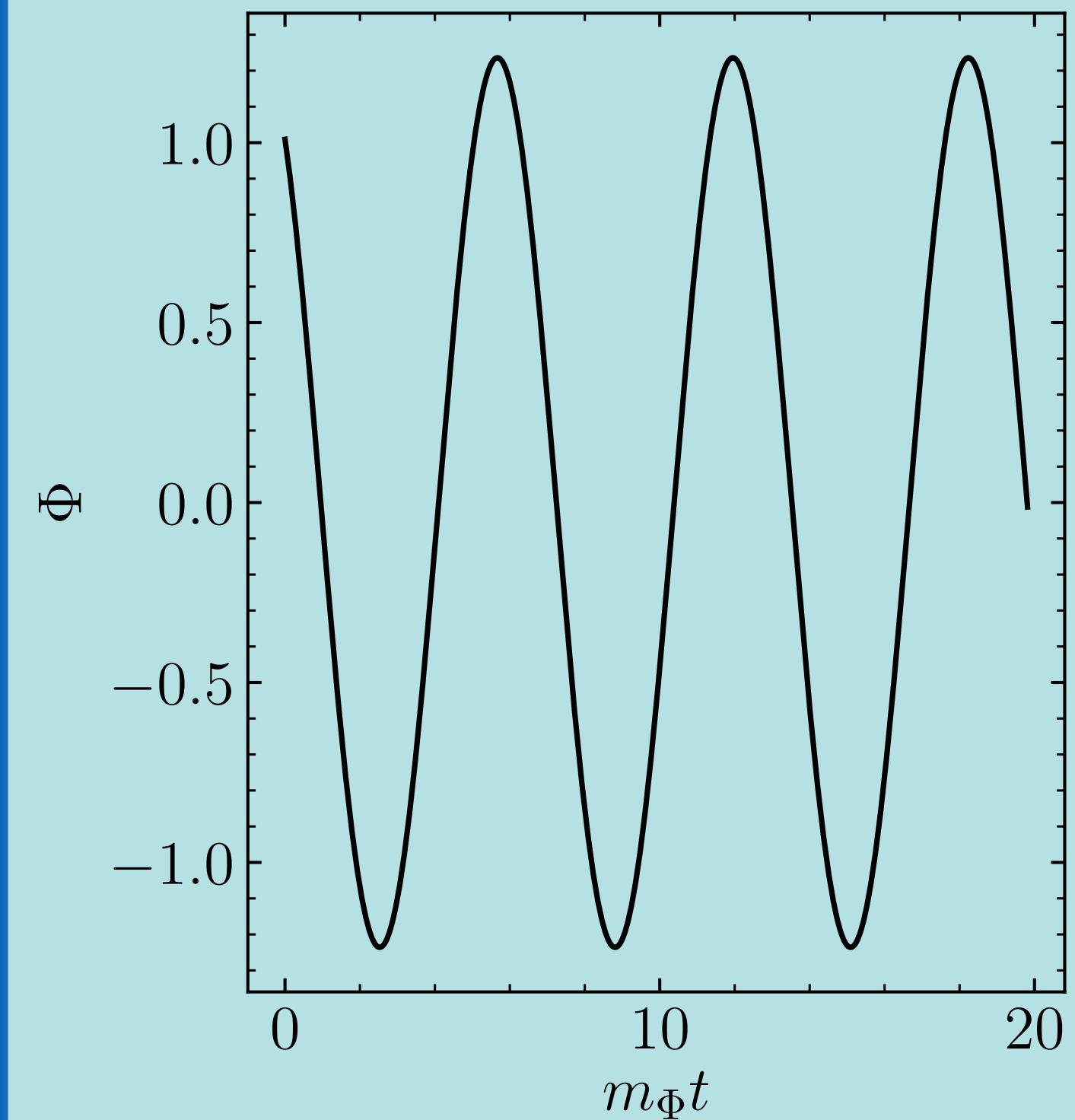


5. Prospects

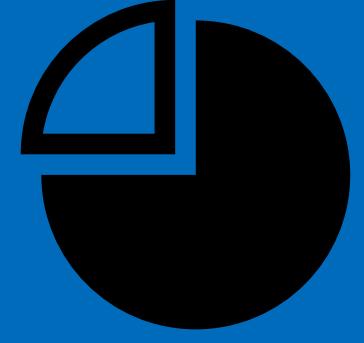
Fermion (p)reheating

$$\left[i\gamma^\mu \partial_\mu + i\frac{3a'}{2a} \gamma^0 - am_\psi(\tau) \right] \psi = 0, \quad m_\psi^2(\tau) = (y\Phi + m_{\psi,0})^2$$

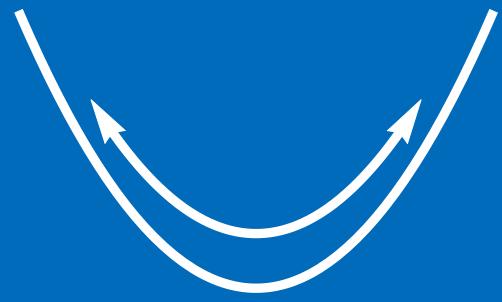
Neglecting expansion,*



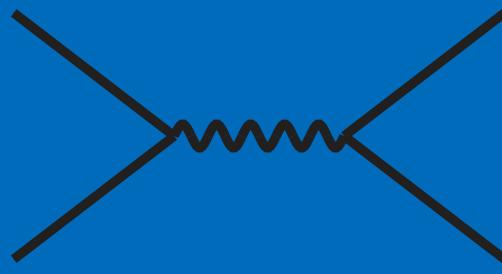
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs



4. Compact objects



5. Prospects

Fermion (p)reheating

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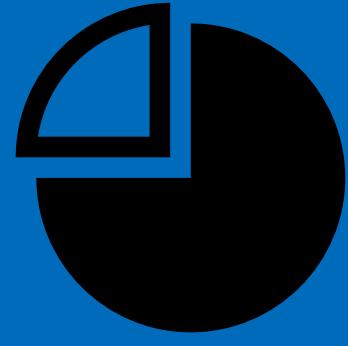
* $dt/d\tau = a$ and

$$\psi(\tau, \mathbf{x}) = a^{-3/2} \sum_{r=\pm} \int \frac{d^3 p}{(2\pi)^{3/2}} e^{-ip \cdot x} \left[u_p^{(r)}(\tau) \hat{a}_p^{(r)} + v_p^{(r)}(\tau) \hat{b}_{-\mathbf{p}}^{(r)\dagger} \right]$$

with

$$u_p^{(r)}(\tau) = \begin{pmatrix} U_1(\tau) \xi_r(\mathbf{p}) \\ U_2(\tau) \frac{\boldsymbol{\sigma} \cdot \mathbf{p}}{p} \xi_r(\mathbf{p}) \end{pmatrix}$$

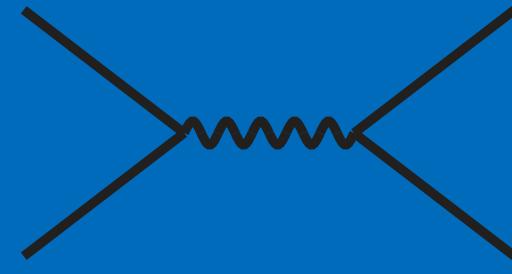
1. Beyond WIMPs



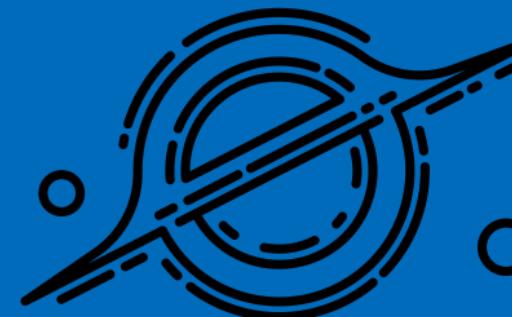
2. Inflation & reheating



3. FIMPs



4. Compact objects

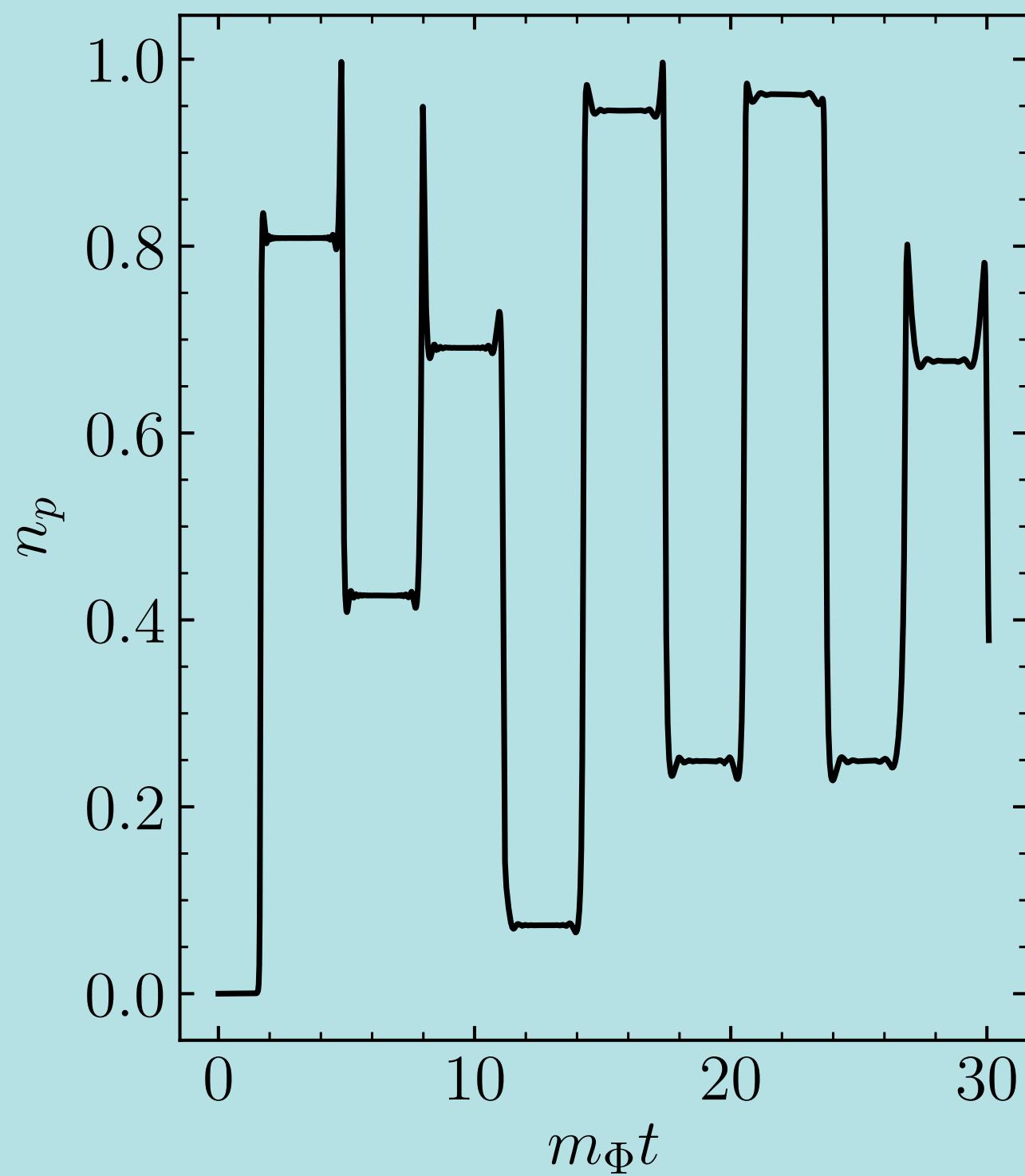
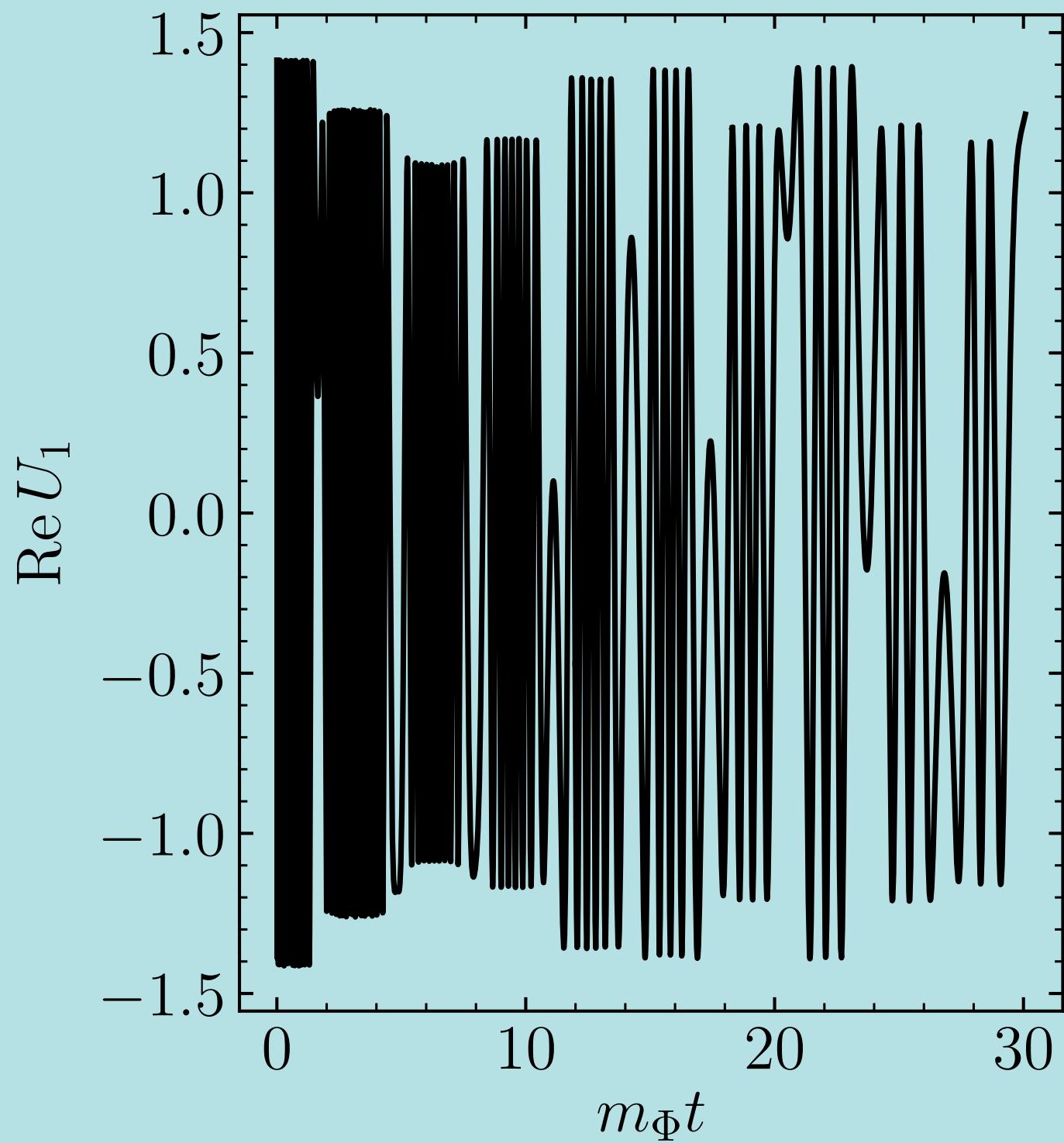
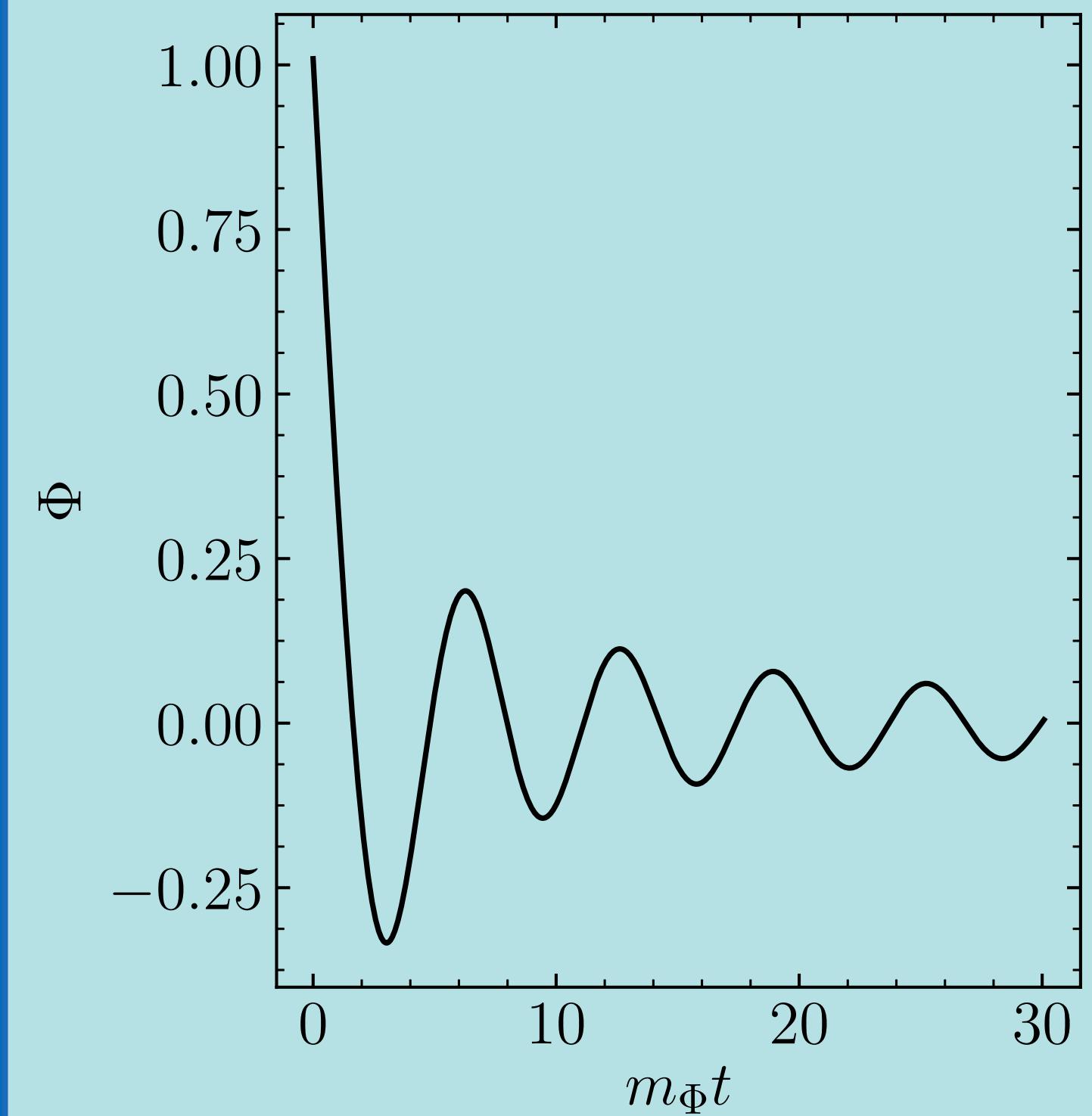


5. Prospects

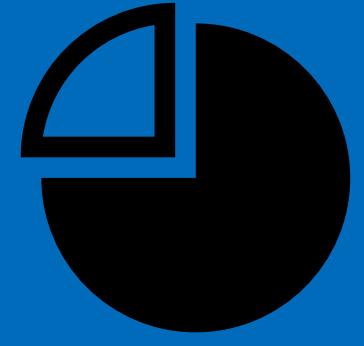
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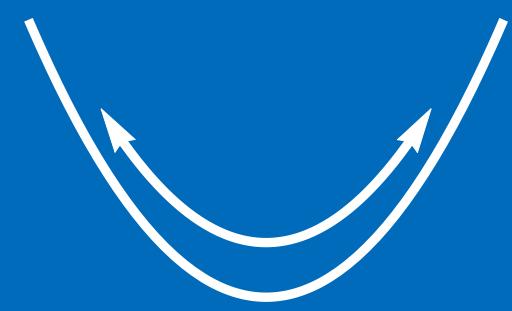
With expansion,



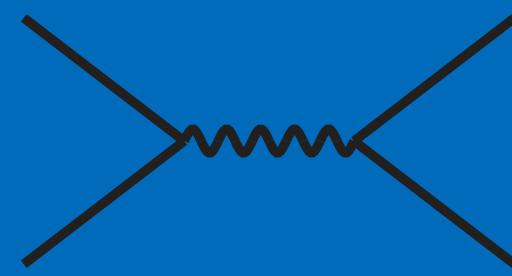
1. Beyond WIMPs



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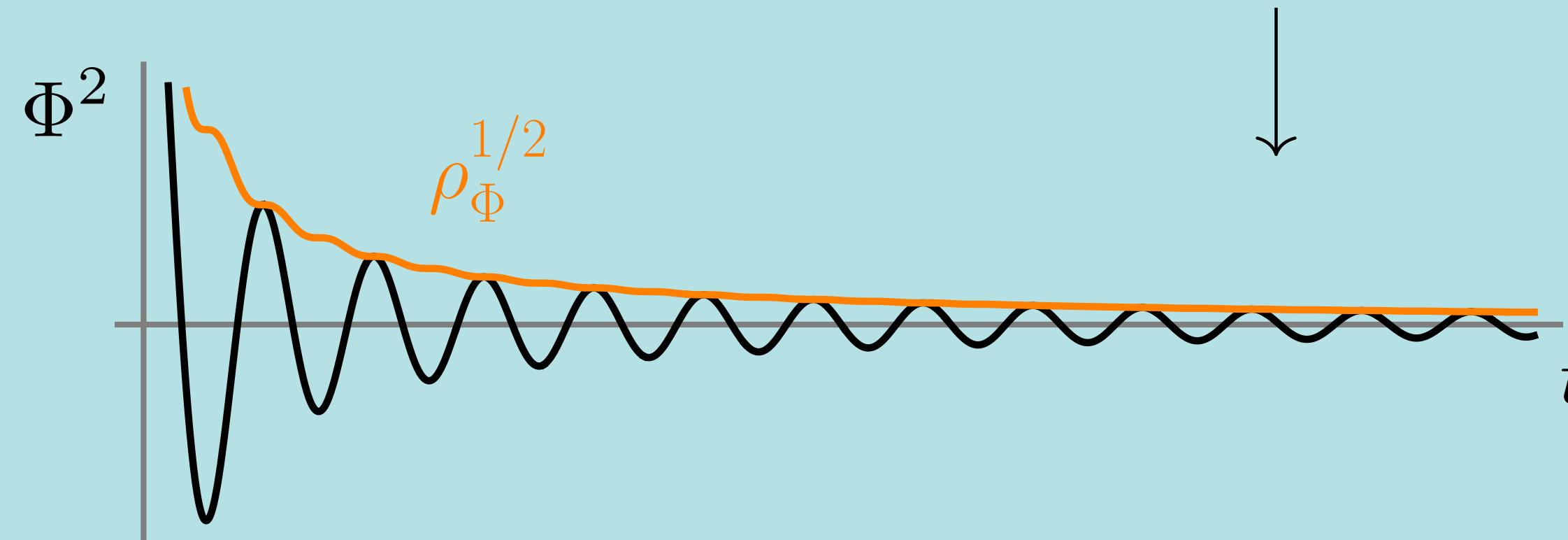


5. Prospects

The perturbative (dissipative) picture

Reheating as the exchange of energy between two ideal fluids

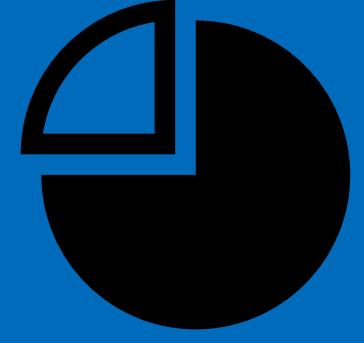
$$T^{\mu\nu} = T_{\Phi}^{\mu\nu} + T_R^{\mu\nu} = \begin{pmatrix} \rho_{\Phi} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} + \frac{1}{3} \begin{pmatrix} 3\rho_R & 0 & 0 & 0 \\ 0 & \rho_R & 0 & 0 \\ 0 & 0 & \rho_R & 0 \\ 0 & 0 & 0 & \rho_R \end{pmatrix}$$



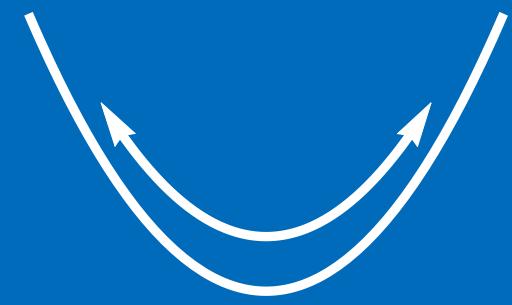
$$\langle p_{\Phi} \rangle = \frac{1}{2} \langle \dot{\Phi}^2 + m_{\Phi}^2 \Phi^2 \rangle \simeq 0$$

(matter)

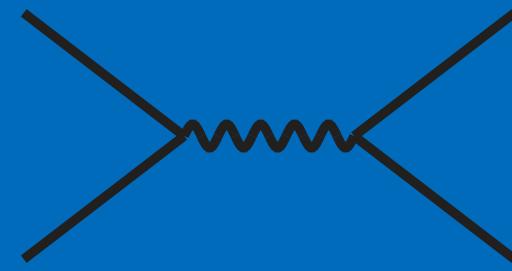
1. Beyond WIMPs



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5. Prospects

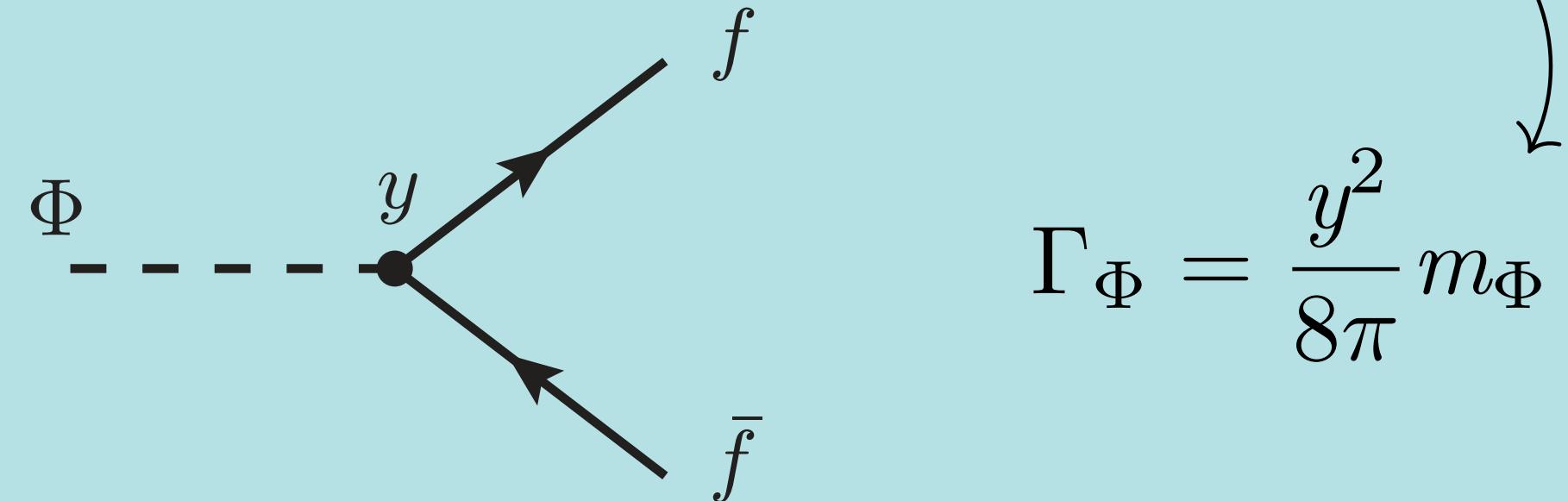
The perturbative (dissipative) picture

Reheating as the exchange of energy between two ideal fluids

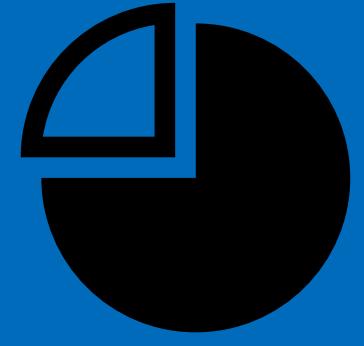
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Conservation $\nabla_{\mu} T^{\mu\nu} = 0$,

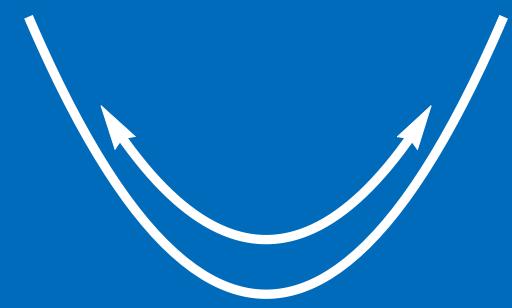
$$\dot{\rho}_R + 4H\rho_R = -(\dot{\rho}_{\Phi} + 3H\rho_{\Phi}) \equiv \Gamma_{\Phi}\rho_{\Phi}$$



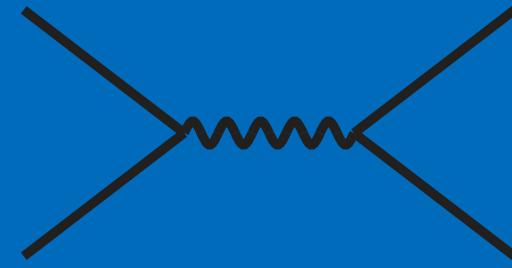
1. Beyond WIMPs



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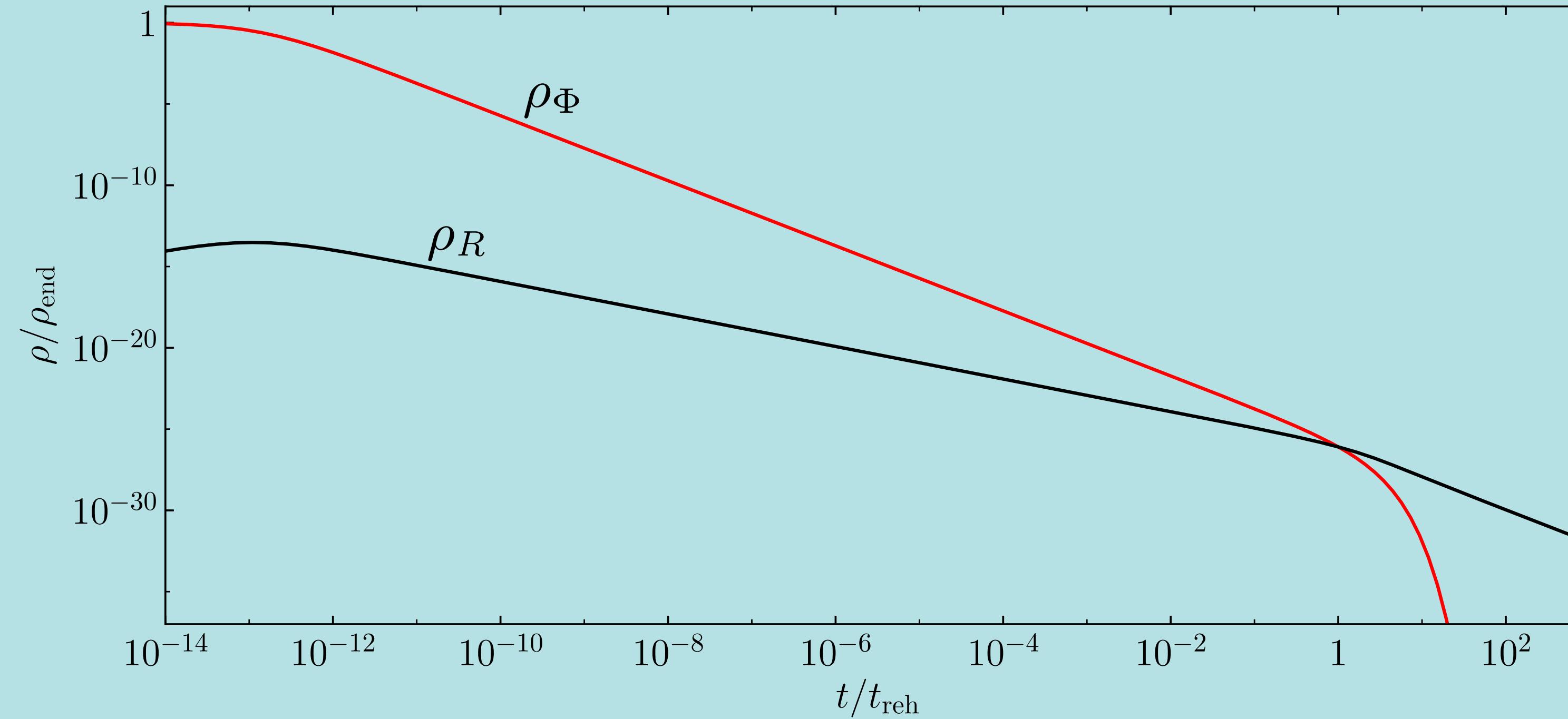


5. Prospects

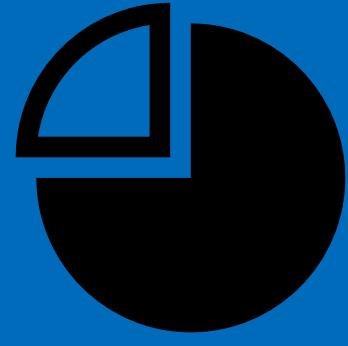
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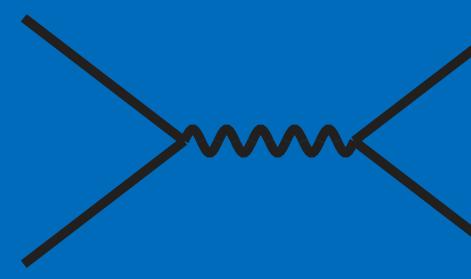
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2. Inflation & reheating



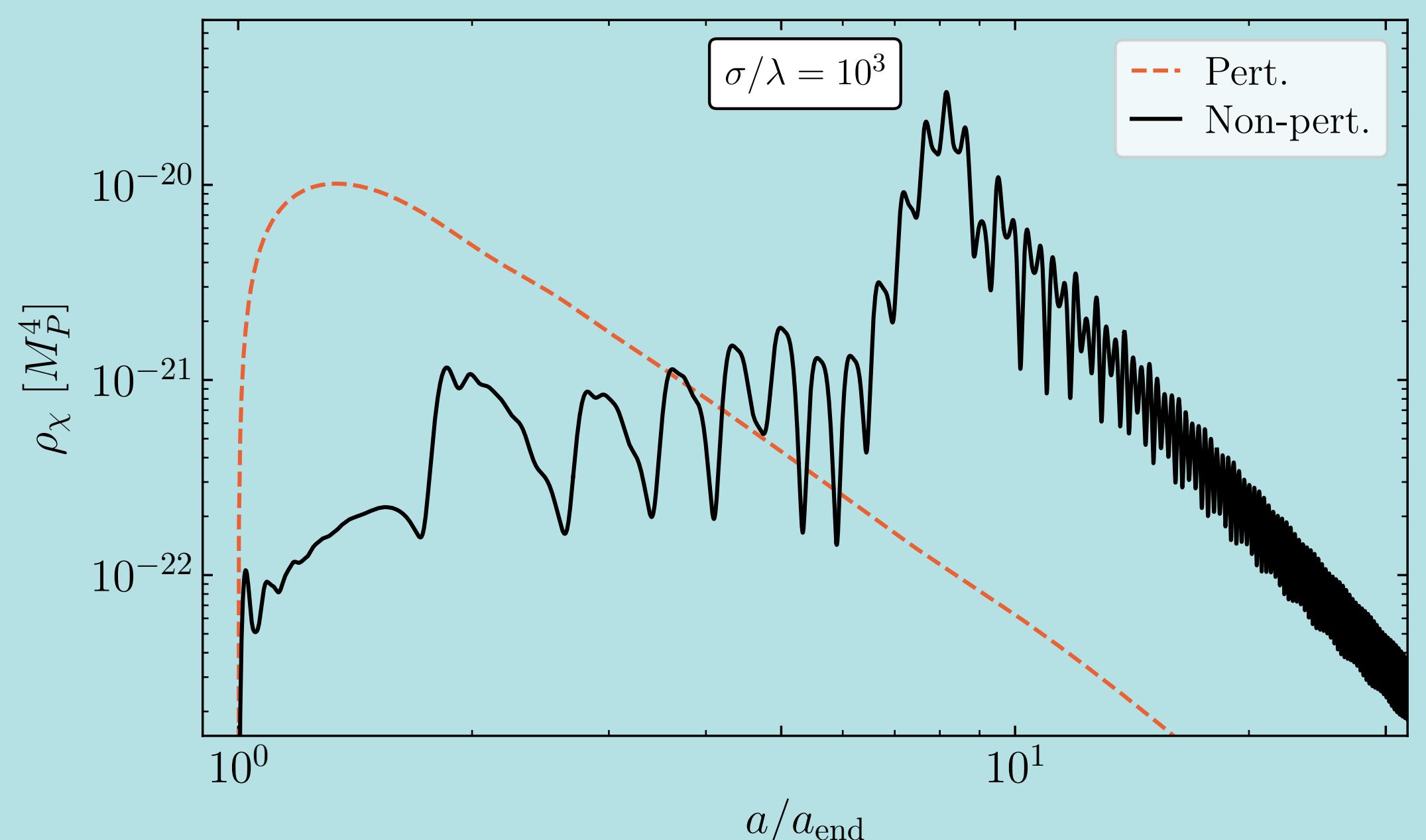
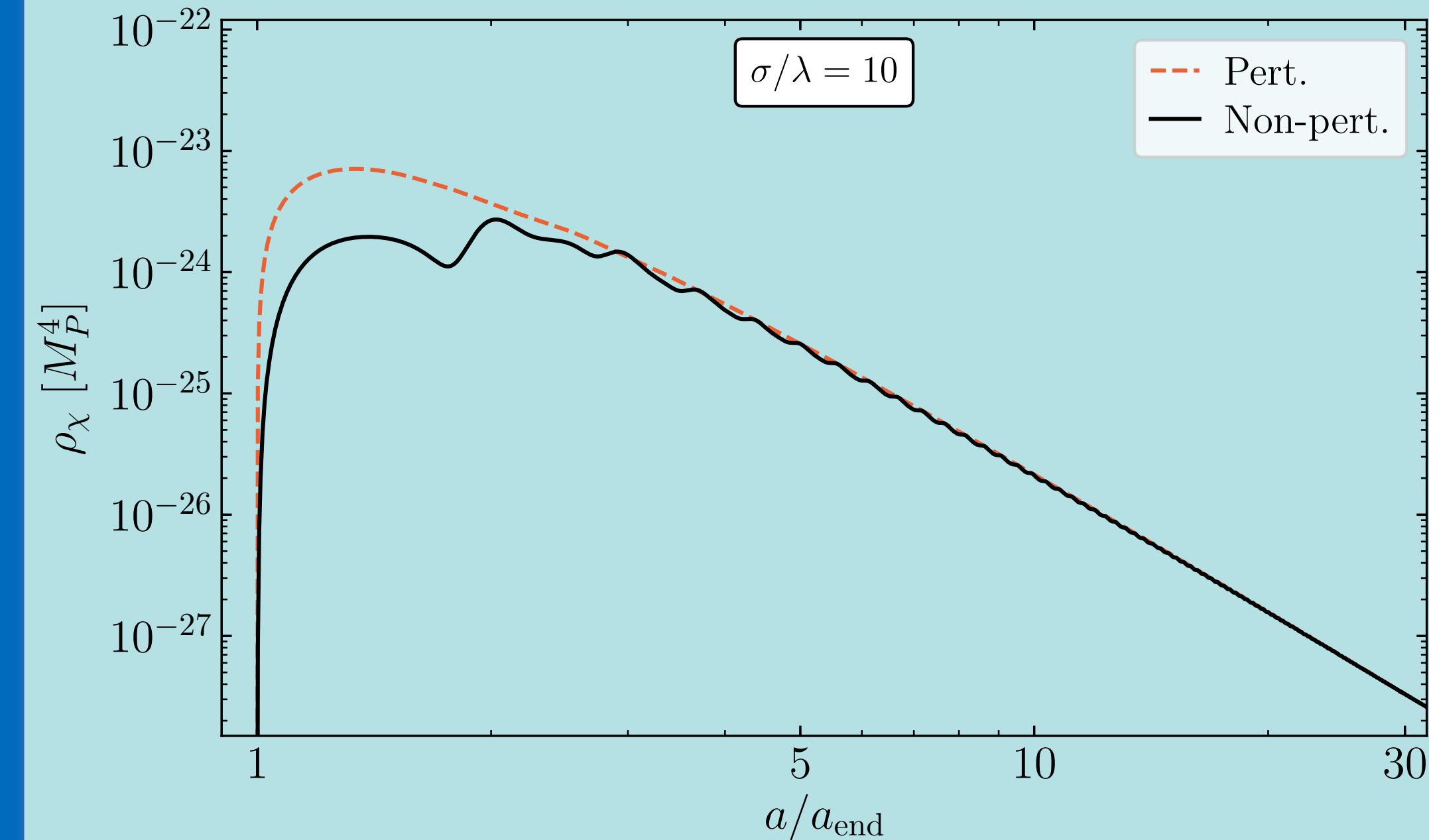
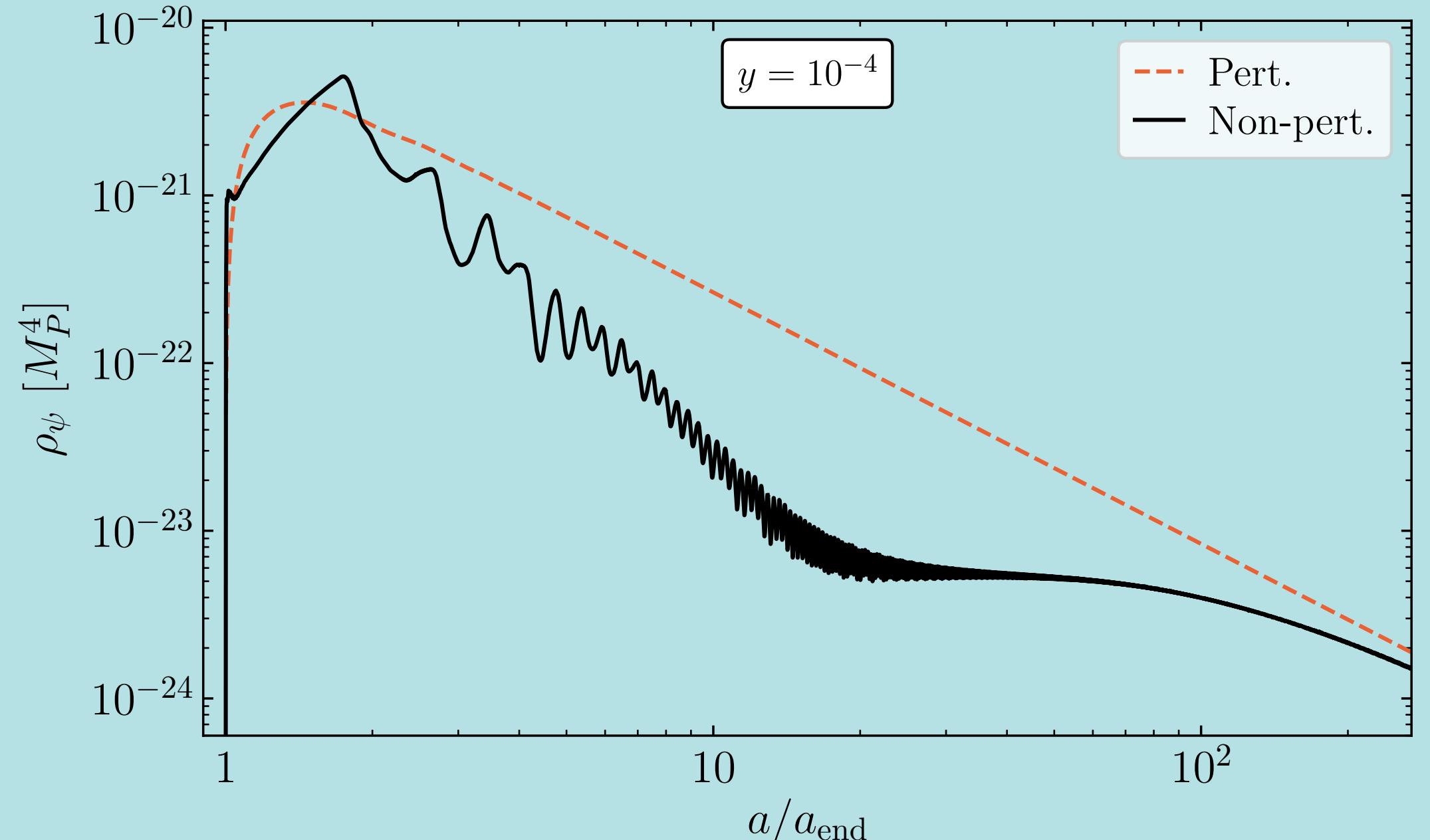
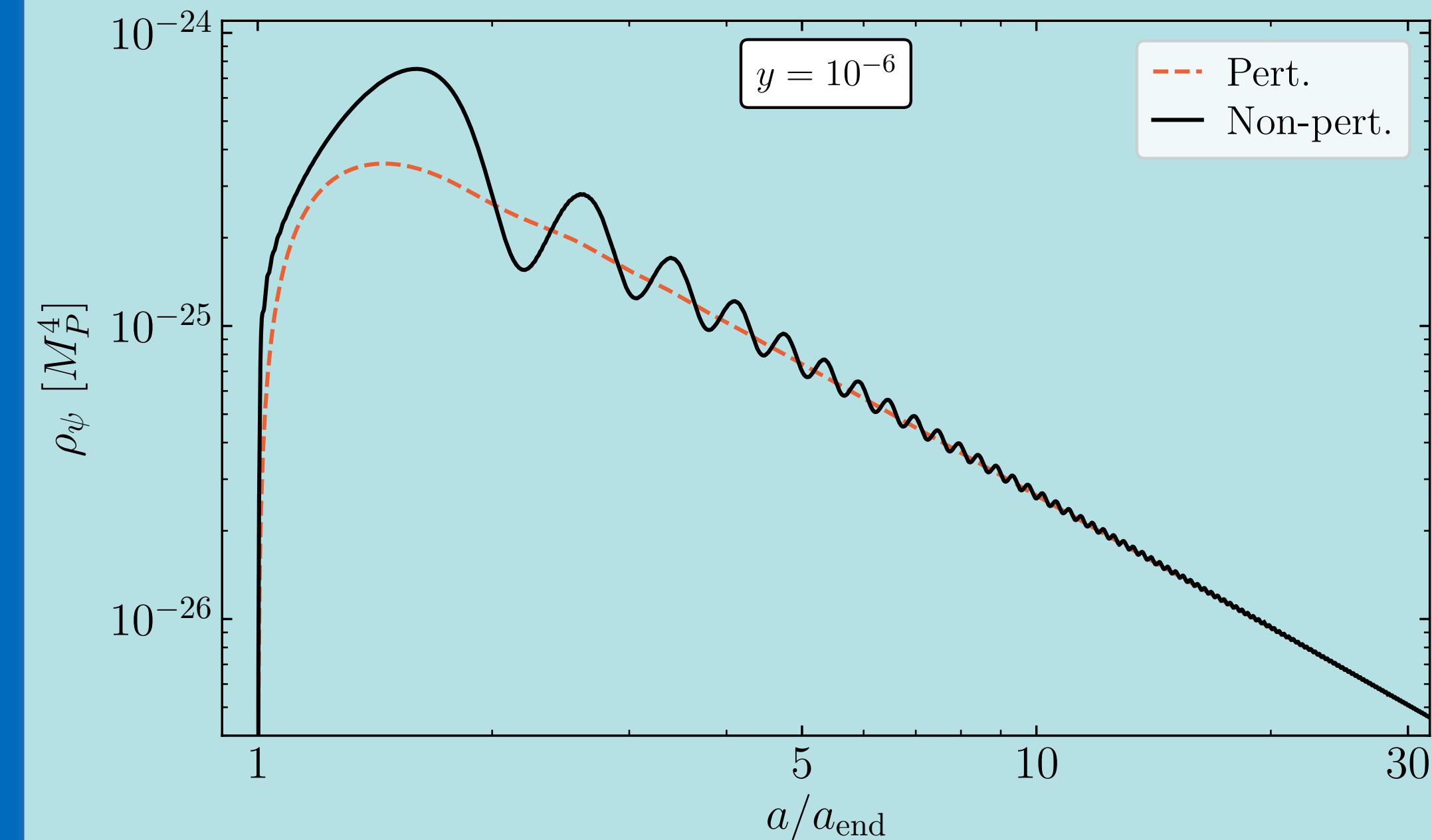
3. FIMPs



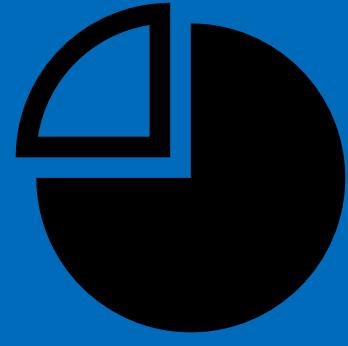
4. Compact objects



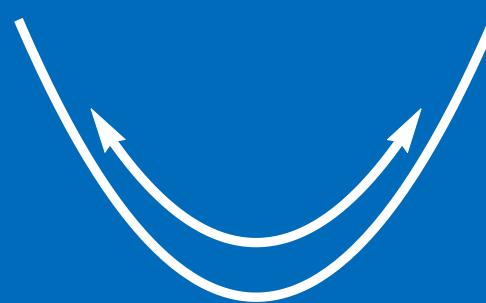
5. Prospects



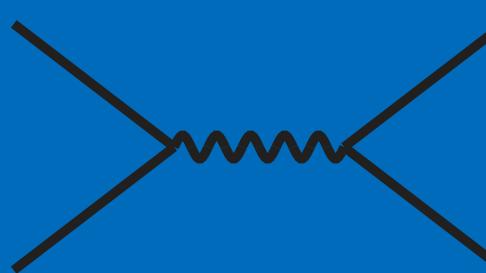
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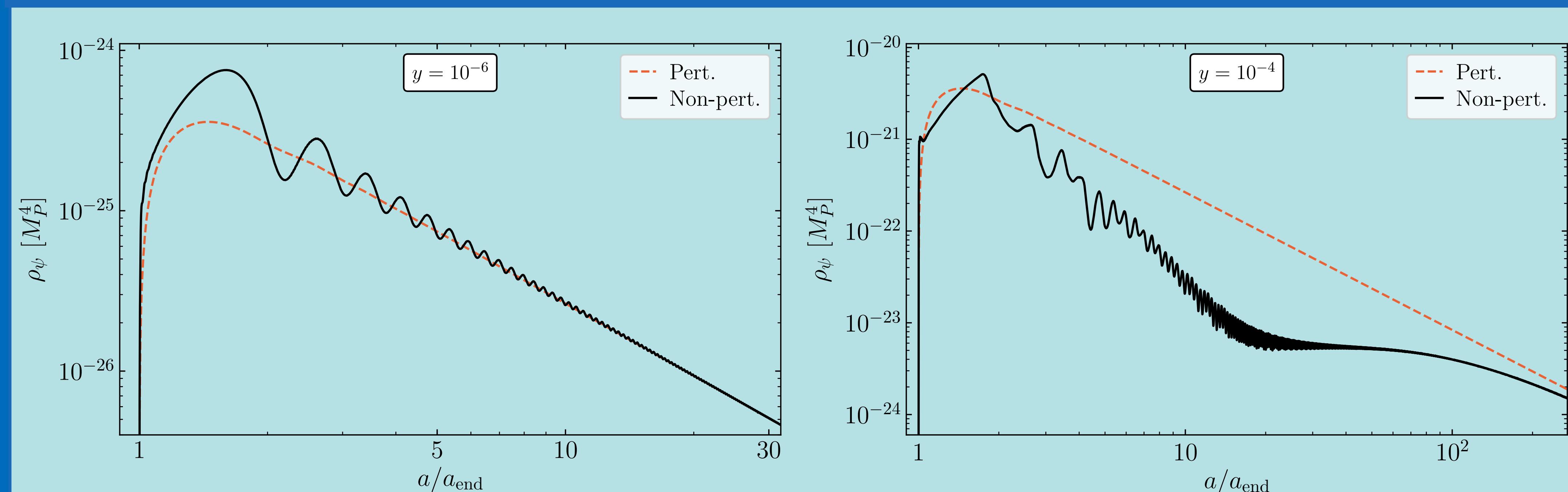
3. FIMPs



4. Compact objects



5. Prospects



Early times:

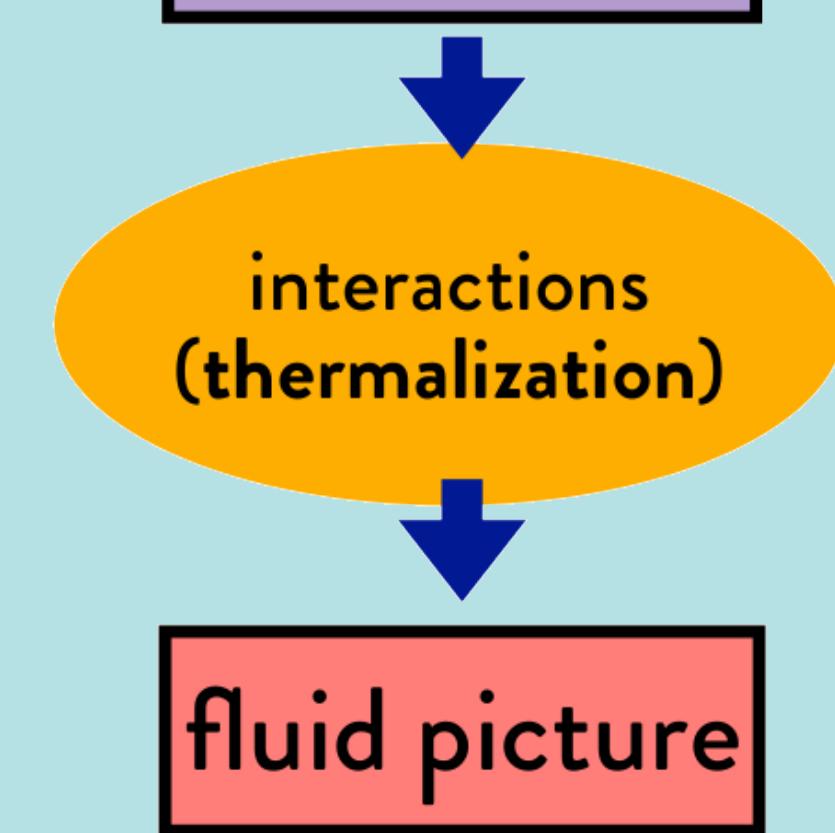
field picture

(limited dissipation)

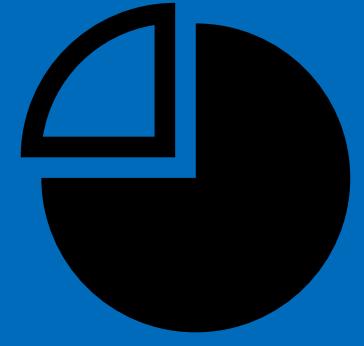
Late times:

fluid picture

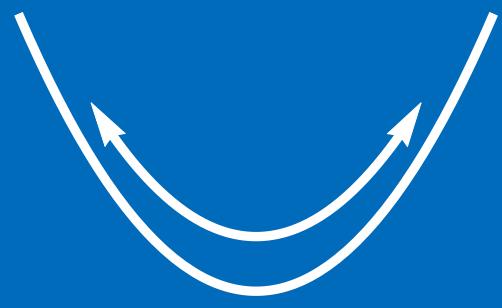
(no fluctuations)



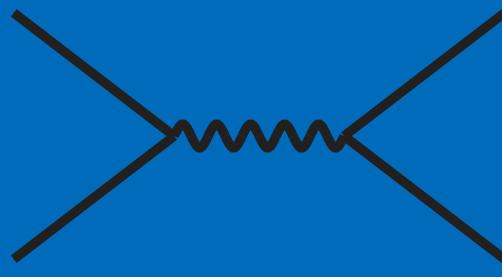
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs



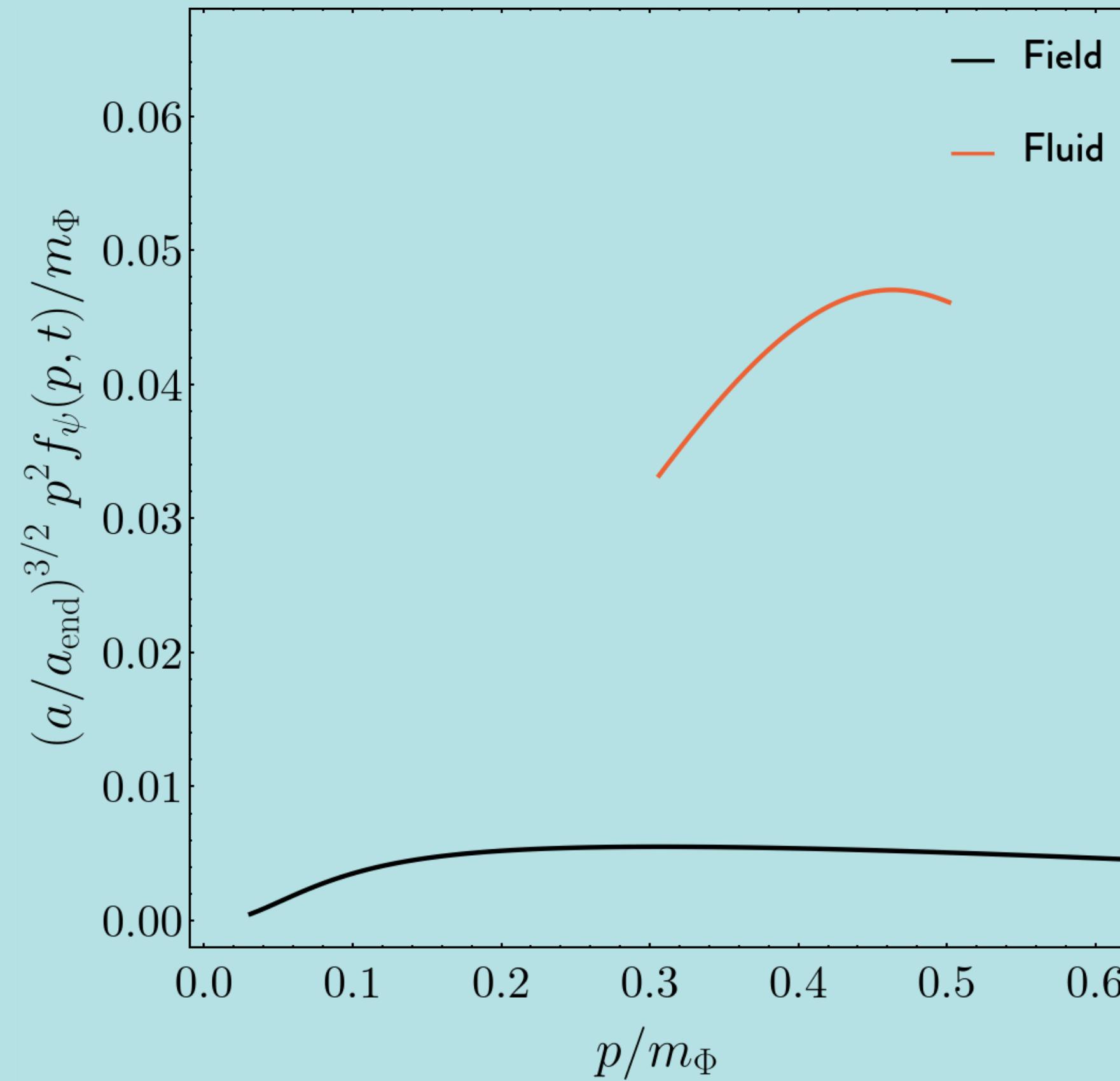
4. Compact objects



5. Prospects

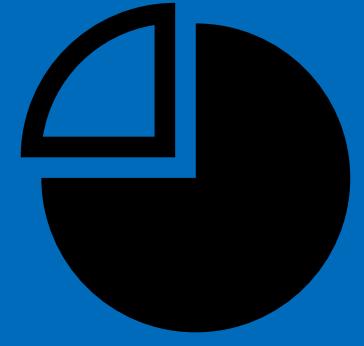
The phase space distribution

$$n_\psi = \int \frac{d^3 p}{(2\pi)^3} f_\psi(p, t)$$

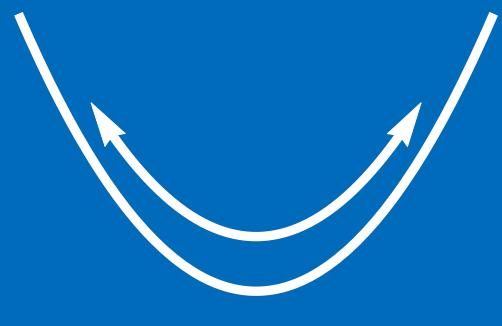


$$\begin{aligned} \frac{\partial f_\psi}{\partial t} - H|\mathbf{p}| \frac{\partial f_\psi}{\partial |\mathbf{p}|} \\ = \frac{1}{2p_0} \int d\Pi |\mathcal{M}|_{\Phi \rightarrow \bar{\psi}\psi}^2 n_\Phi \delta^{(3)}(\mathbf{P}) + \mathcal{C}^{\text{int}}[f_\psi] \end{aligned}$$

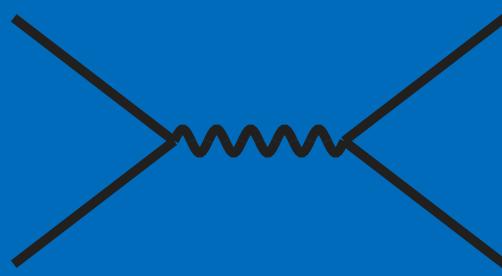
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs



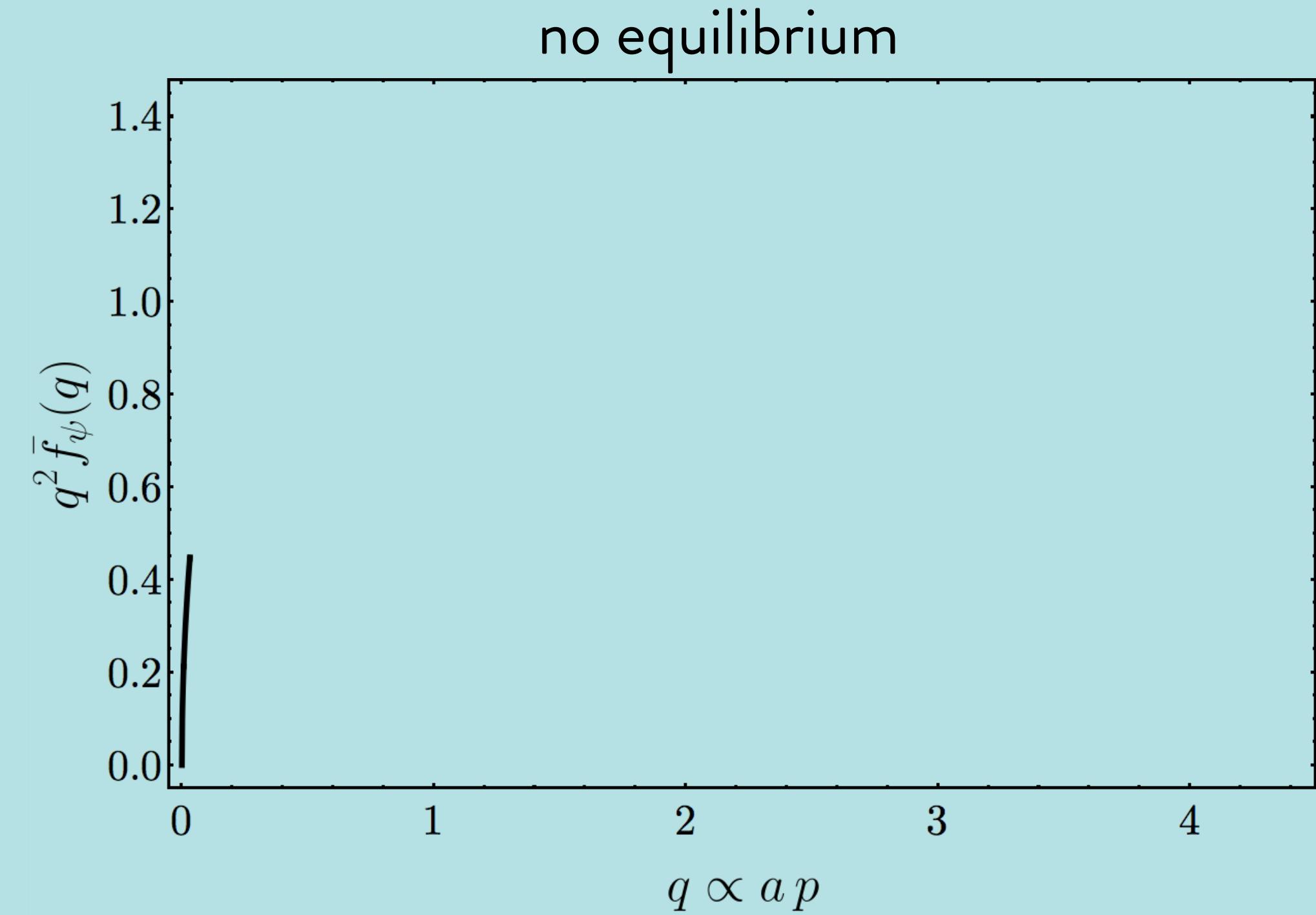
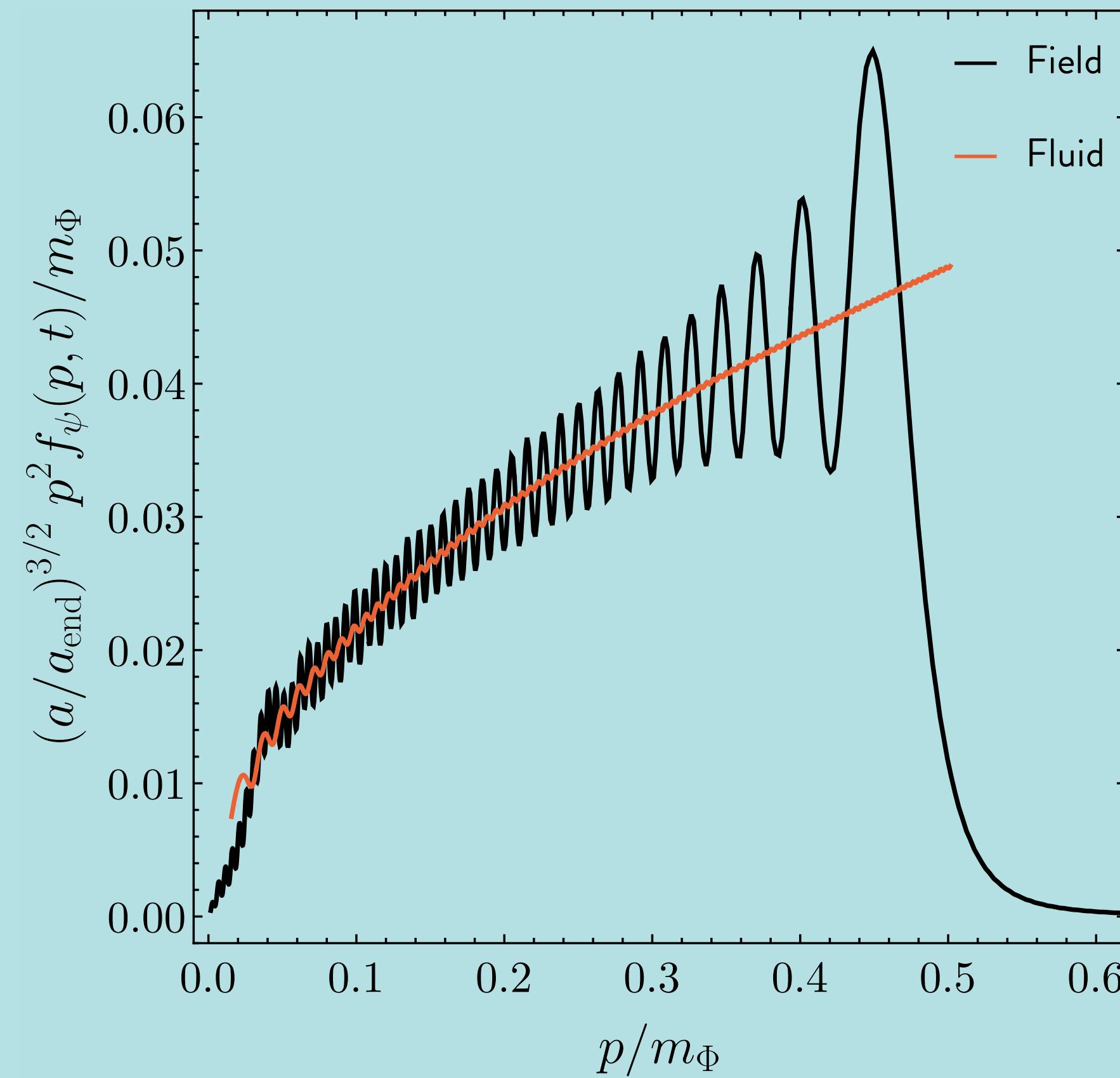
4. Compact objects



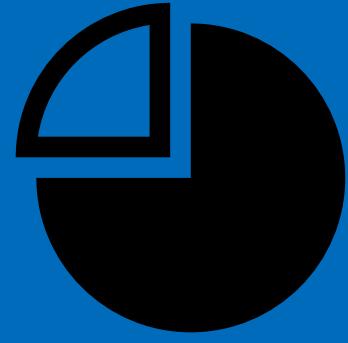
5. Prospects

The phase space distribution

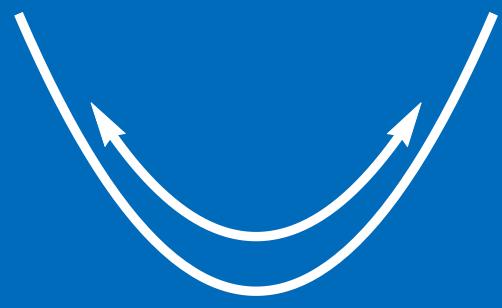
$$n_\psi = \int \frac{d^3 p}{(2\pi)^3} f_\psi(p, t)$$



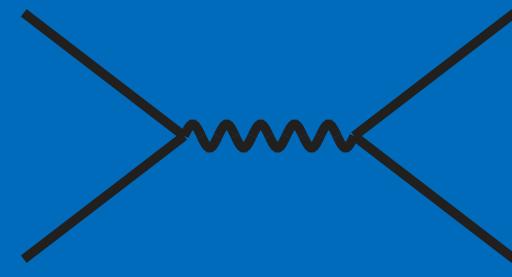
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs



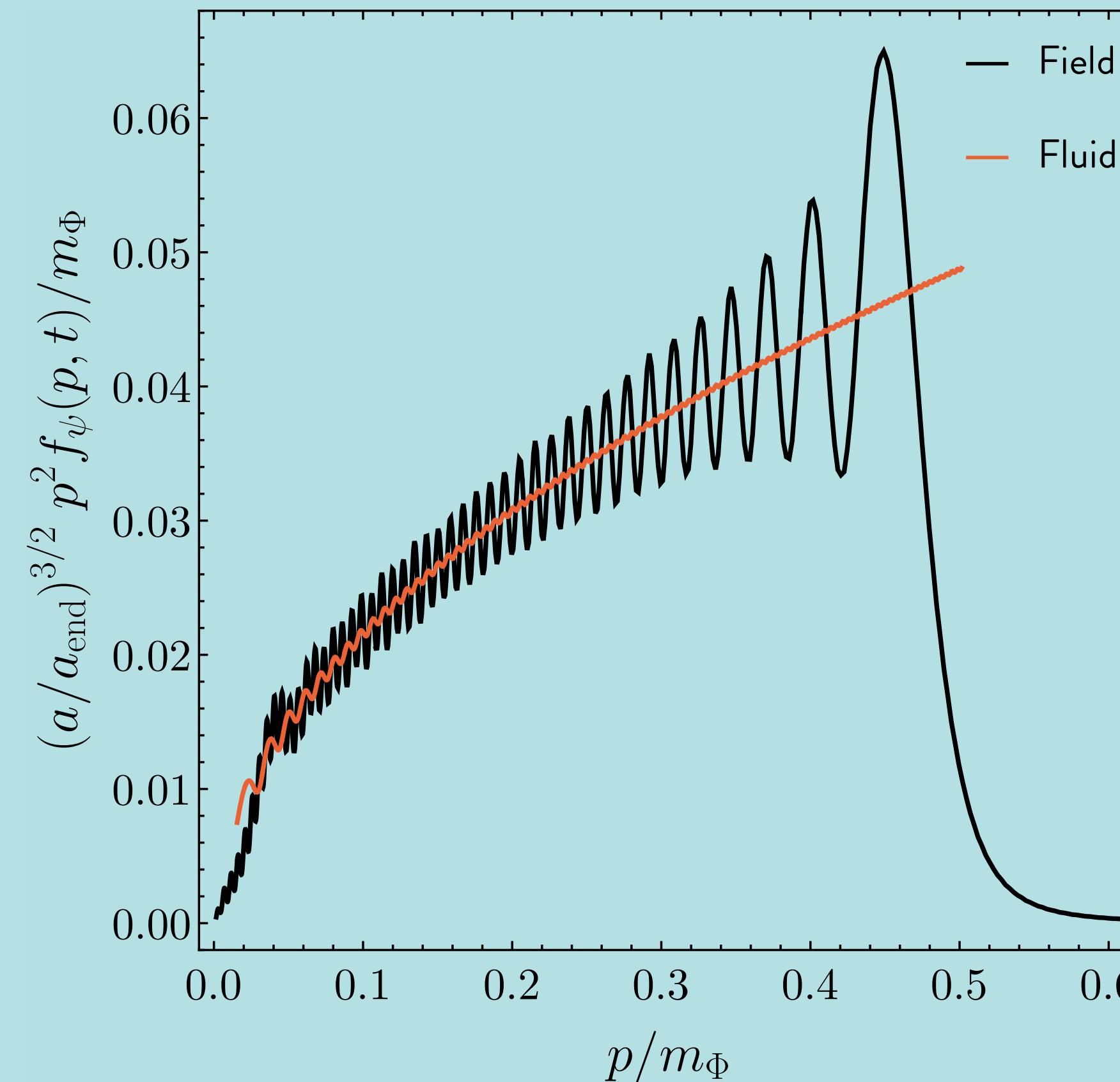
4. Compact objects



5. Prospects

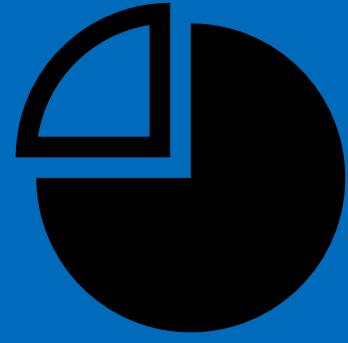
The phase space distribution

$$n_\psi = \int \frac{d^3 p}{(2\pi)^3} f_\psi(p, t)$$

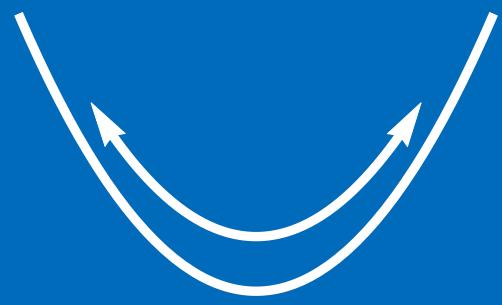


$$\mathcal{C}^{\text{int}}[f_\psi] = \left| \text{---} \right|^2 + \left| \text{---} \right|^2 + \dots$$

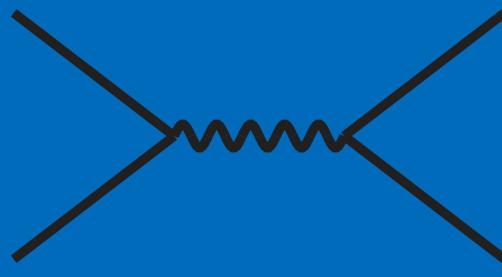
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs



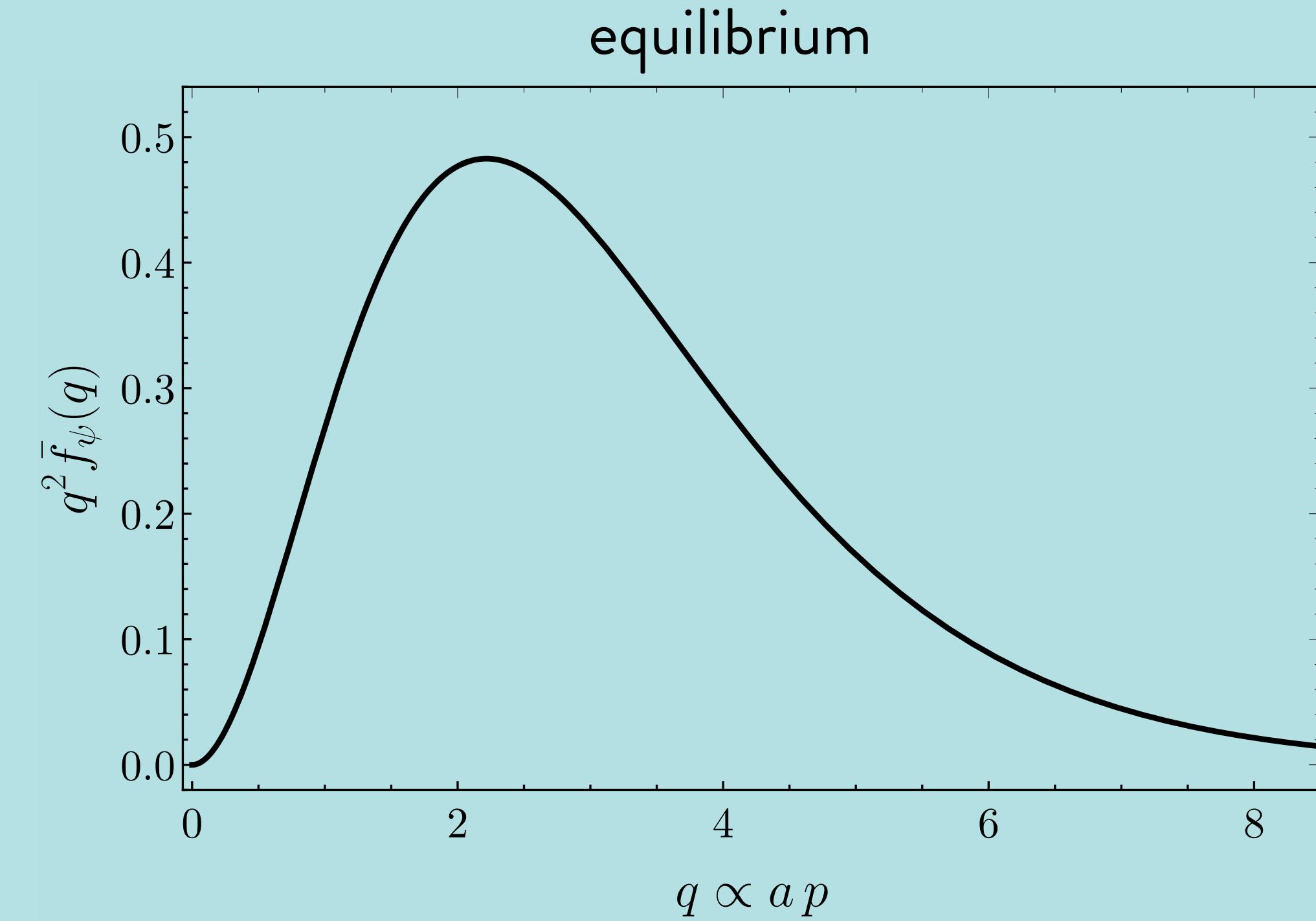
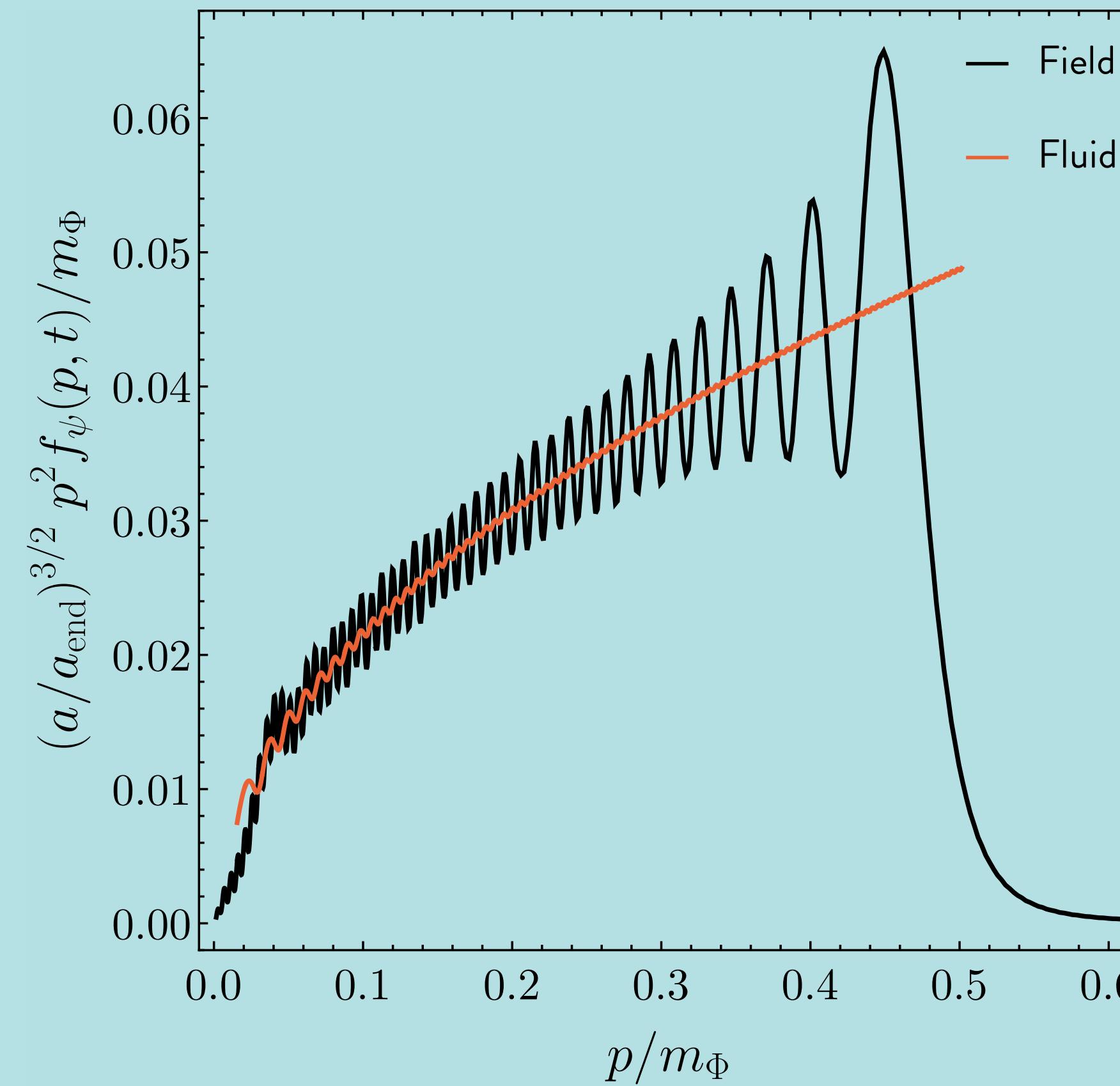
4. Compact objects



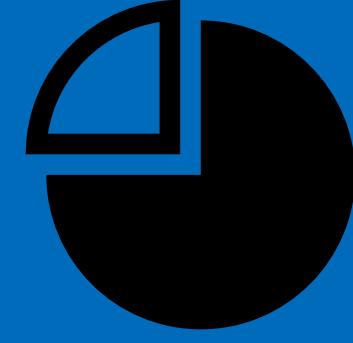
5. Prospects

The phase space distribution

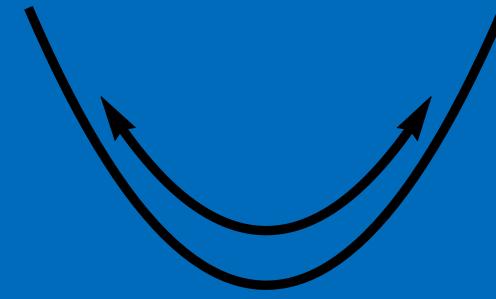
$$n_\psi = \int \frac{d^3 p}{(2\pi)^3} f_\psi(p, t)$$



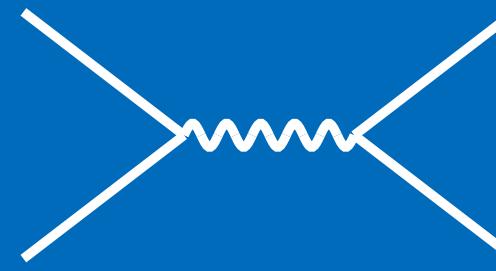
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs



4. Compact objects

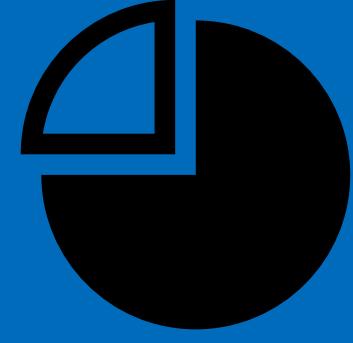


5. Prospects

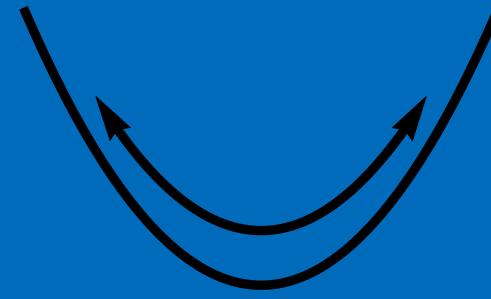
Is a spin- $\frac{3}{2}$ dark matter particle the missing piece in the puzzle?



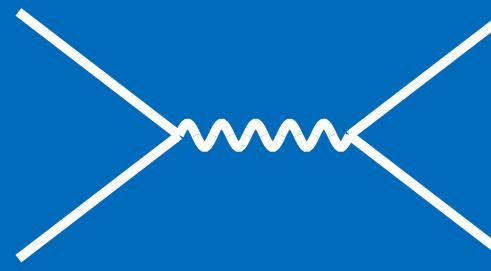
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs



4. Compact objects



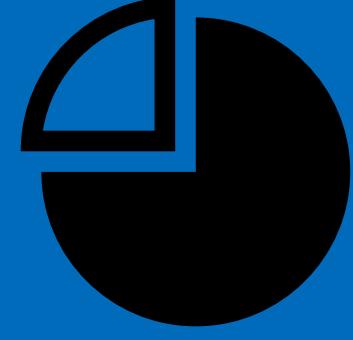
5. Prospects

Is a spin- $\frac{3}{2}$ dark matter particle the missing piece in the puzzle?

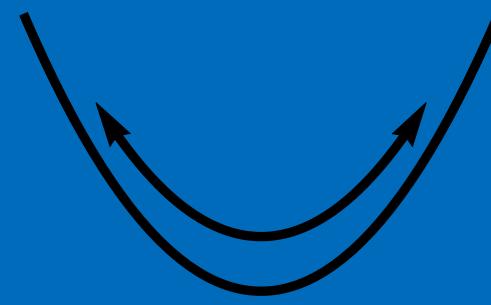
	spin 0	spin 1/2	spin 1	spin 3/2	spin 2
SM+DM:					

$$\mathcal{L} = -\frac{1}{2}\bar{\Psi}_\mu \left(i\gamma^{[\mu}\gamma^\nu\gamma^{\rho]}\partial_\rho + m_{3/2}\gamma^{[\mu}\gamma^{\nu]} \right) \Psi_\nu \quad (\text{Rarita-Schwinger})$$

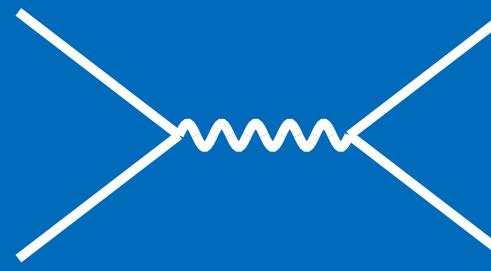
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs



4. Compact objects



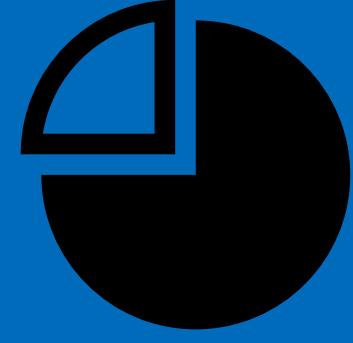
5. Prospects

Is a spin- $\frac{3}{2}$ dark matter particle the missing piece in the puzzle?

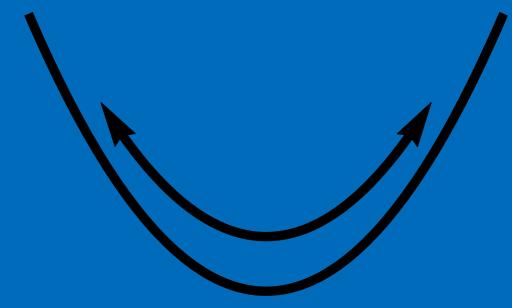
	spin 0	spin 1/2	spin 1	spin 3/2	spin 2
SM+DM:	H	u_L	W^0	Ψ	G
	Φ	ν_R			<i>raritron</i>

$$\begin{aligned}\mathcal{L} = & -\frac{1}{2}\bar{\Psi}_\mu \left(i\gamma^{[\mu}\gamma^\nu\gamma^{\rho]}\partial_\rho + m_{3/2}\gamma^{[\mu}\gamma^{\nu]} \right) \Psi_\nu \\ & + yH\bar{\nu}_L\nu_R + \frac{M_R}{2}\bar{\nu}_R^c\nu_R \quad (\nu \text{ masses through see-saw}) \\ & + y_\nu\Phi\bar{\nu}_R\nu_R \quad (\text{reheating})\end{aligned}$$

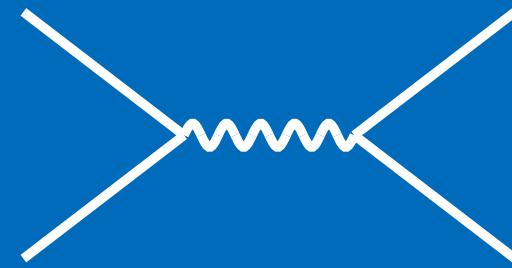
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs

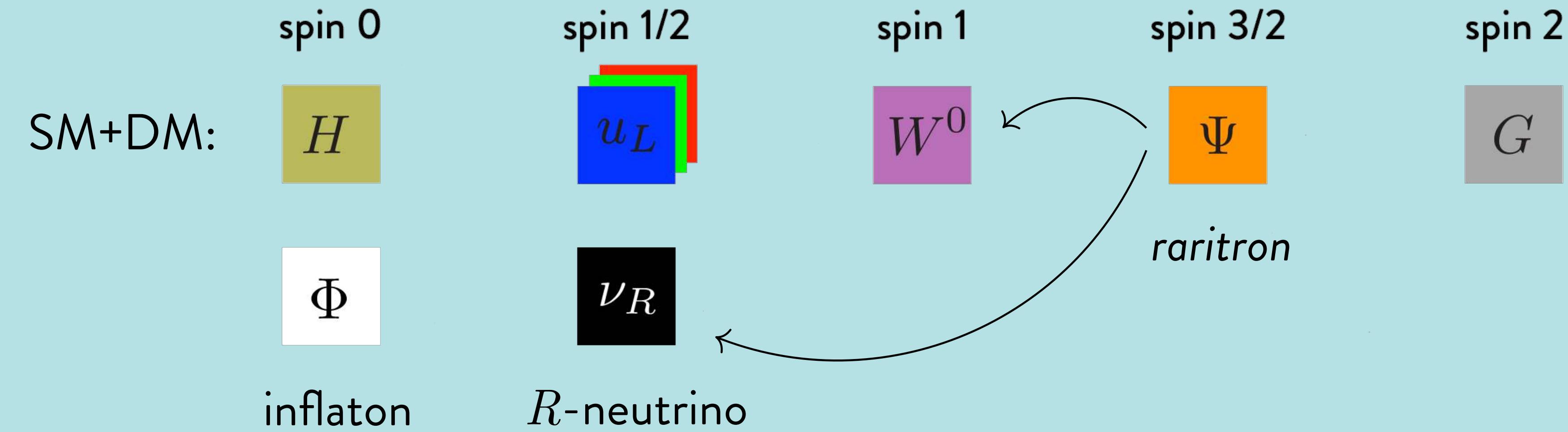


4. Compact objects



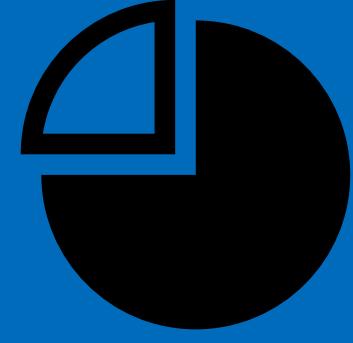
5. Prospects

Is a spin- $\frac{3}{2}$ dark matter particle the missing piece in the puzzle?

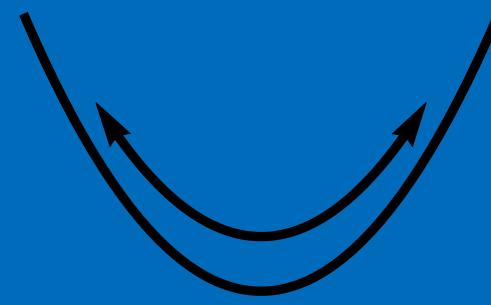


$$\begin{aligned}\mathcal{L} = & -\frac{1}{2}\bar{\Psi}_\mu \left(i\gamma^{[\mu}\gamma^\nu\gamma^{\rho]}\partial_\rho + m_{3/2}\gamma^{[\mu}\gamma^{\nu]}\right) \Psi_\nu \\ & + yH\bar{\nu}_L\nu_R + \frac{M_R}{2}\bar{\nu}_R^c\nu_R \\ & + y_\nu\Phi\bar{\nu}_R\nu_R \\ & + i\frac{\alpha_1}{2M_P}\bar{\nu}_R\gamma^\mu[\gamma^\rho,\gamma^\sigma]\Psi_\mu F_{\rho\sigma}\end{aligned}$$

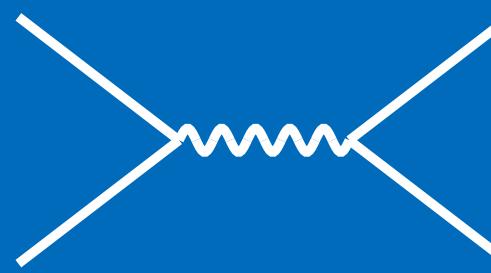
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs

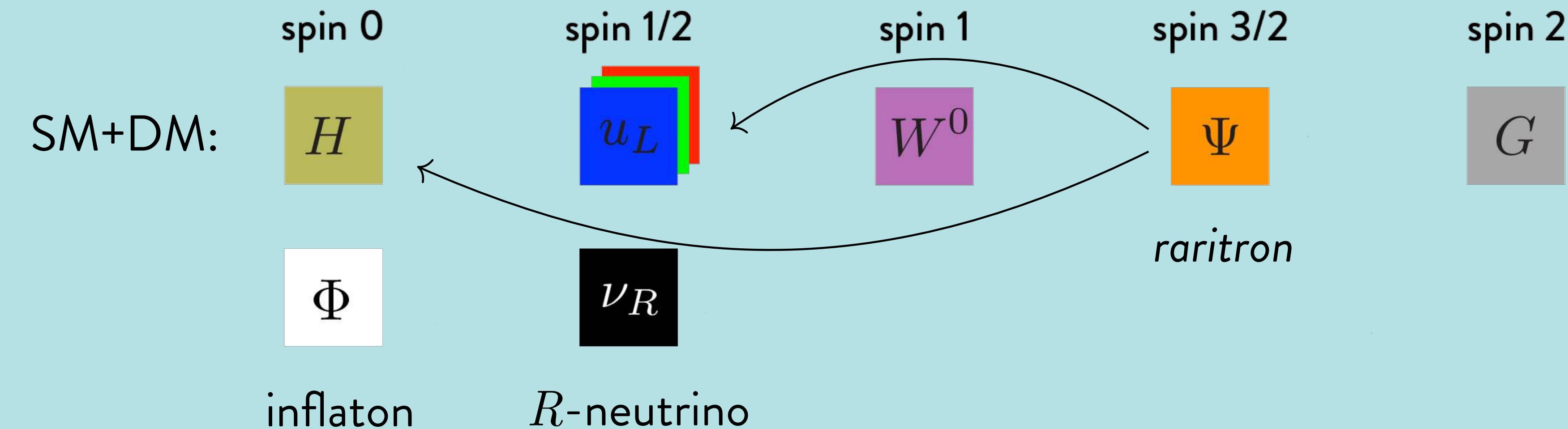


4. Compact objects



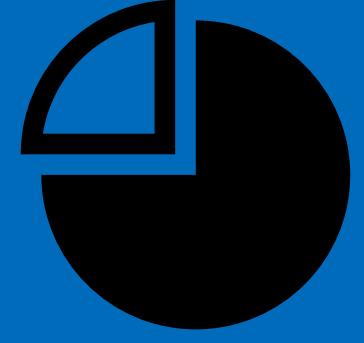
5. Prospects

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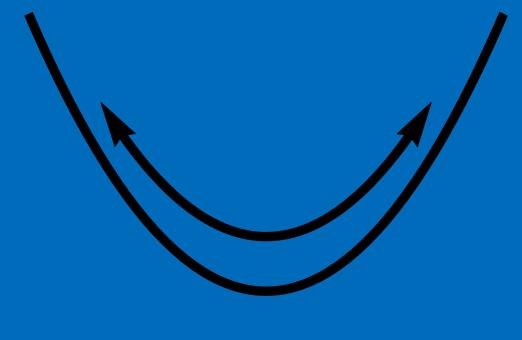


$$\begin{aligned}\mathcal{L} = & -\frac{1}{2}\bar{\Psi}_\mu \left(i\gamma^{[\mu}\gamma^\nu\gamma^{\rho]}\partial_\rho + m_{3/2}\gamma^{[\mu}\gamma^{\nu]} \right) \Psi_\nu \\ & + yH\bar{\nu}_L\nu_R + \frac{M_R}{2}\bar{\nu}_R^c\nu_R \\ & + y_\nu\Phi\bar{\nu}_R\nu_R \\ & + i\frac{\alpha_1}{2M_P}\bar{\nu}_R\gamma^\mu[\gamma^\rho,\gamma^\sigma]\Psi_\mu F_{\rho\sigma} + i\frac{\alpha_2}{2M_P}i\sigma_2(D^\mu H)^*\bar{L}\Psi_\mu + \dots\end{aligned}$$

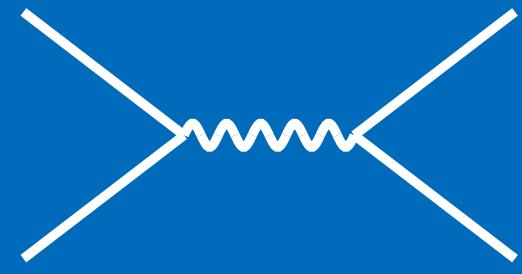
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs



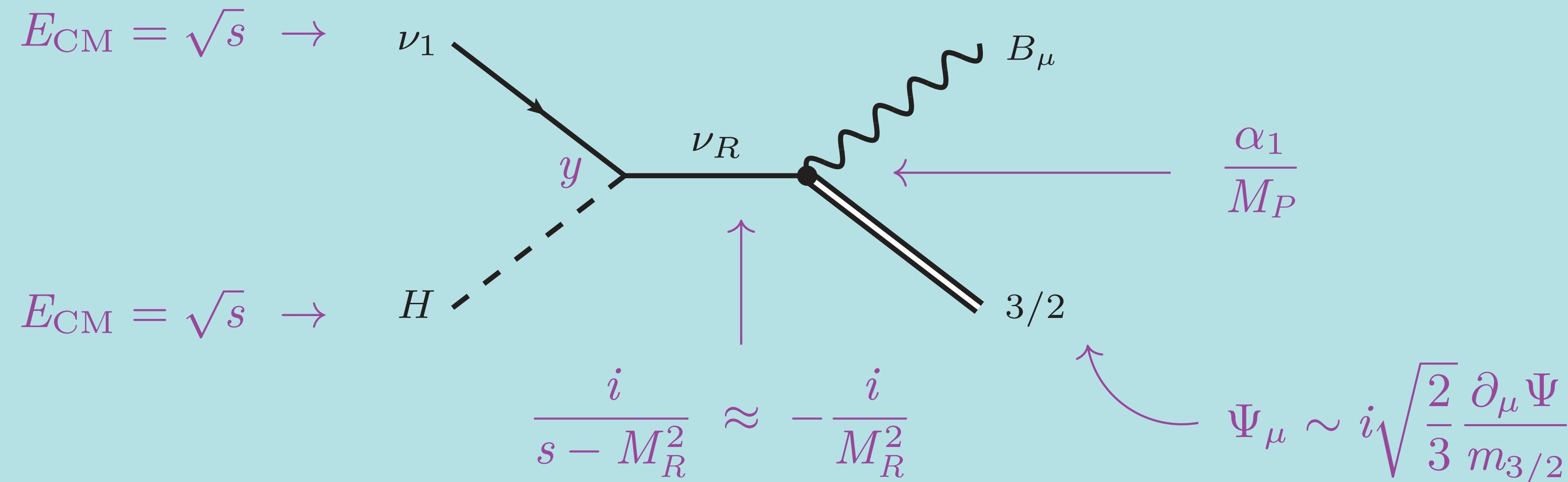
4. Compact objects



5. Prospects

Scatterings and decays

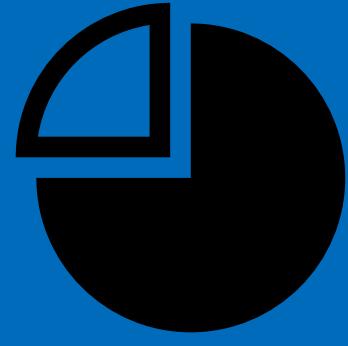
$$\mathcal{L}_{3/2} = \boxed{i\frac{\alpha_1}{2M_P}\bar{\nu}_R\gamma^\mu[\gamma^\rho, \gamma^\sigma]\Psi_\mu F_{\rho\sigma}} + i\frac{\alpha_2}{2M_P}i\sigma_2(D^\mu H)^*\bar{L}\Psi_\mu + \text{h.c.}$$



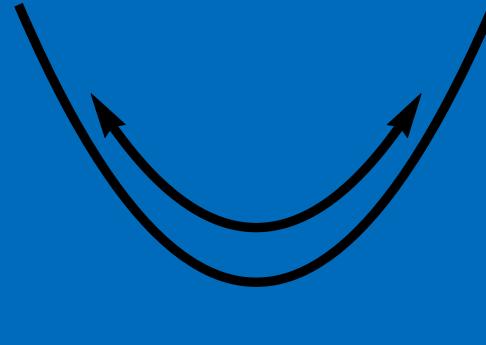
$$\Rightarrow \sigma(s) \propto \frac{\alpha_1^2 y^2 s^2}{m_{3/2}^2 M_R^2 M_P^2}$$

- Production peaked at high energies → reheating
- Ψ is never in thermal equilibrium (freeze-in)

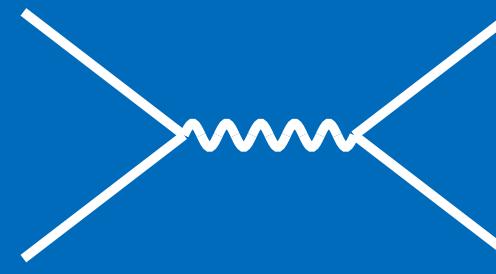
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs

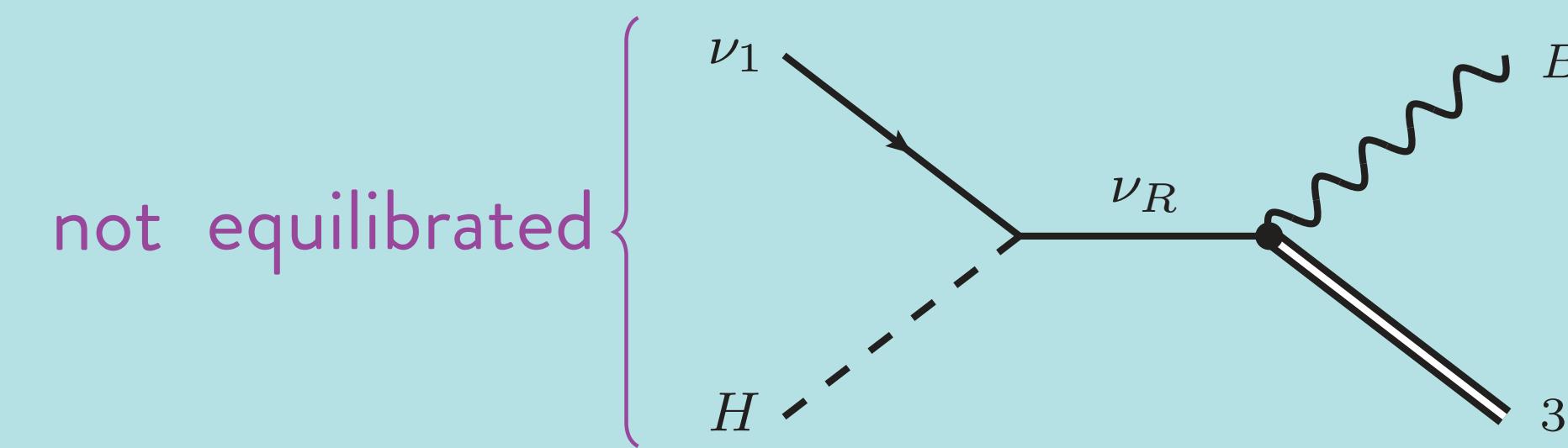


4. Compact objects

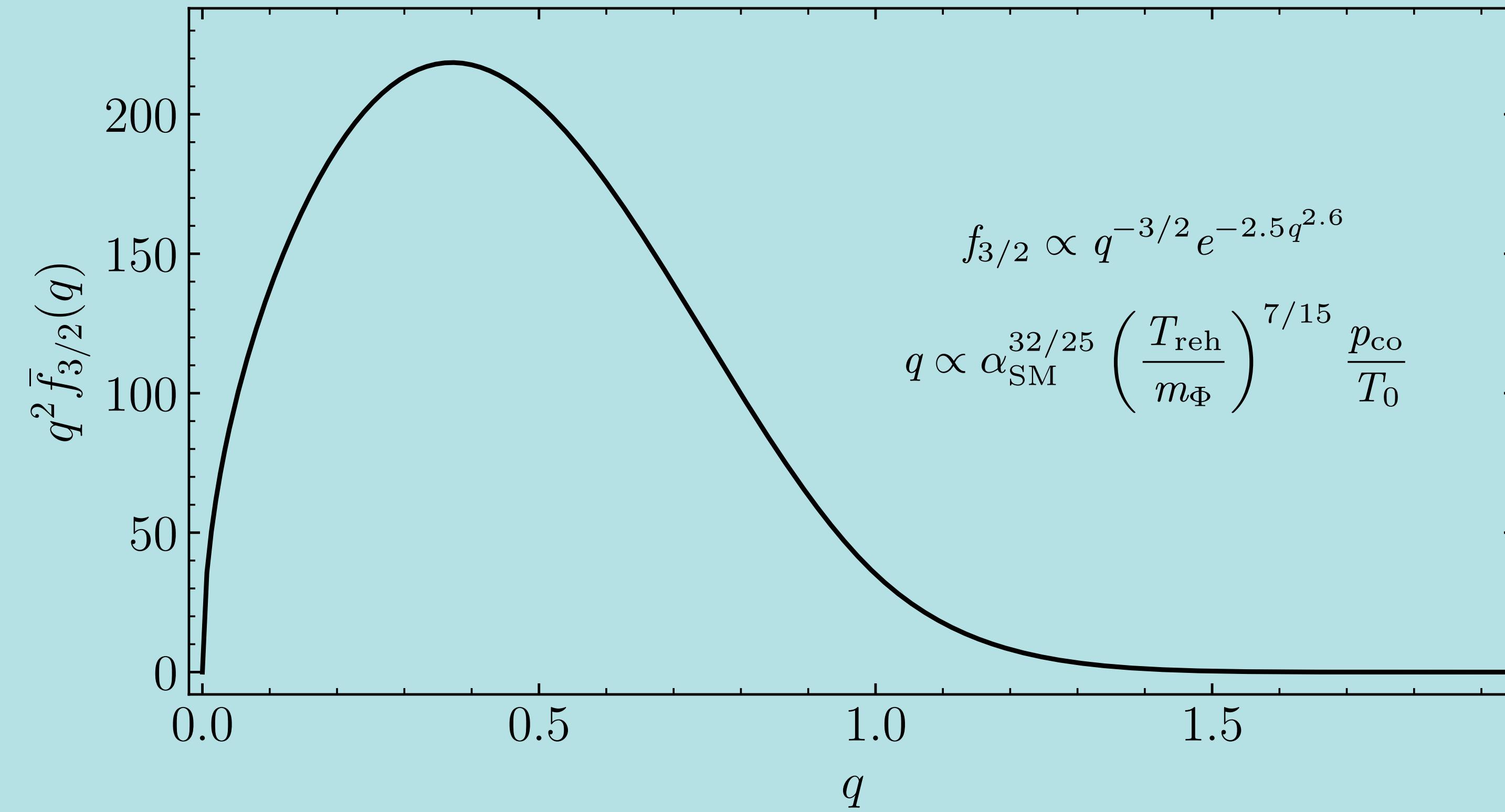


5. Prospects

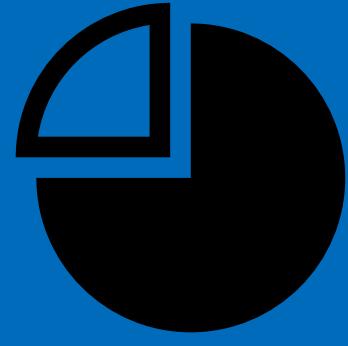
Scatterings and decays



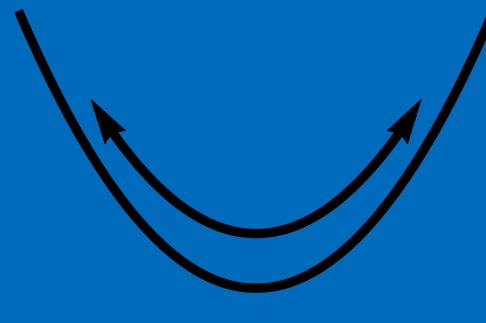
$$\Omega_{3/2} \propto \alpha_1 \frac{m_\nu m_\Phi^2 T_{\text{reh}}^3}{m_{3/2} M_R t_{\text{therm}}}$$



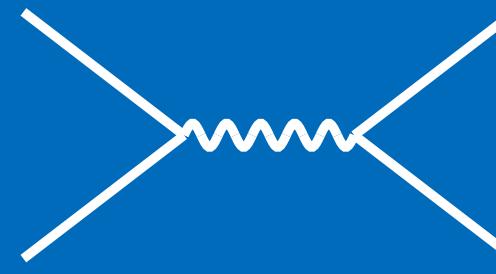
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs

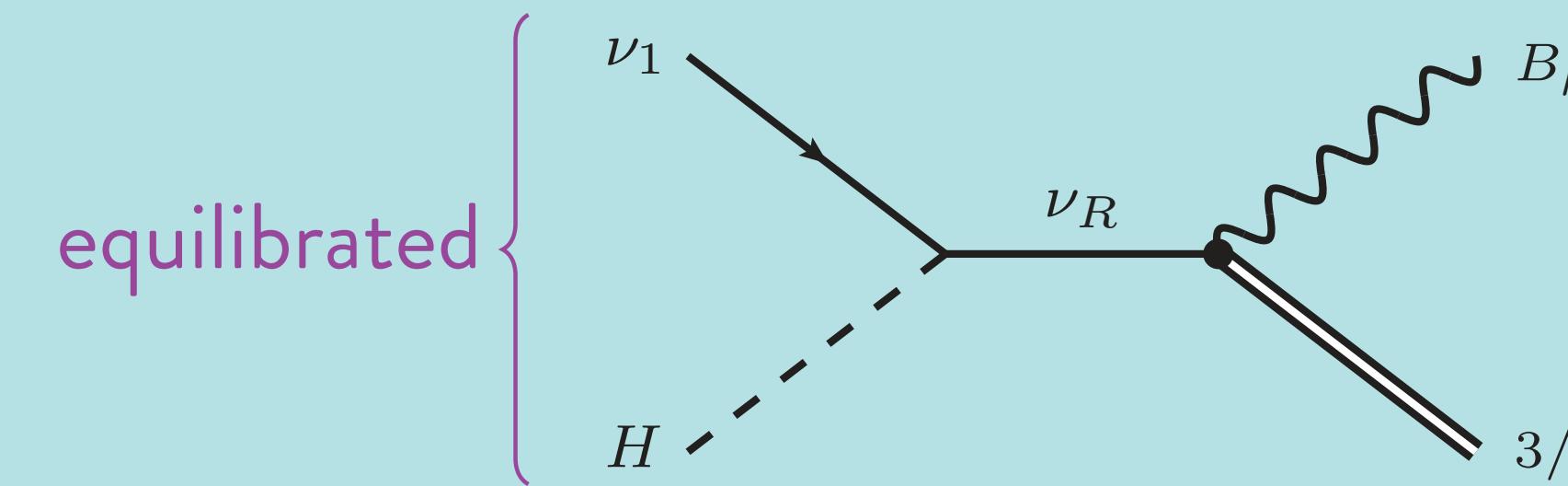


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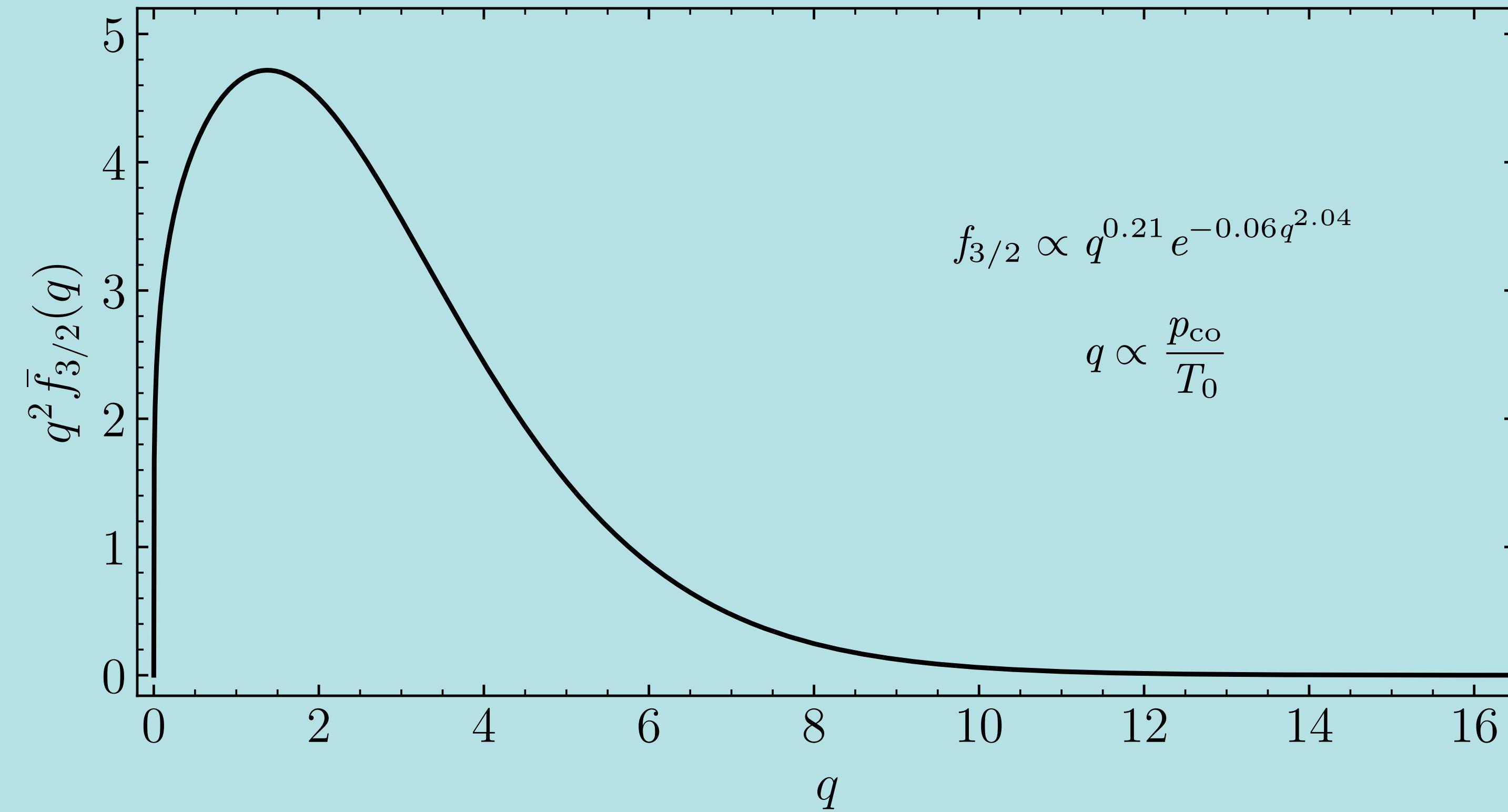


5. Prospects

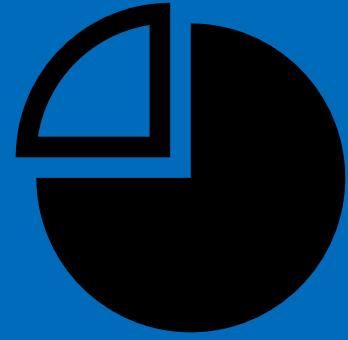
Scatterings and decays



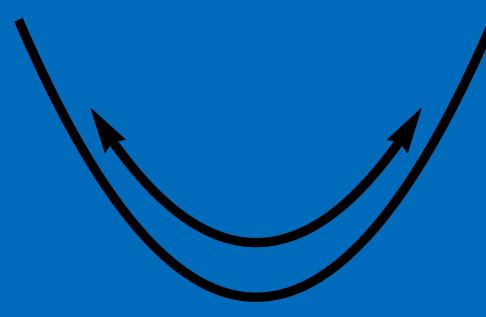
$$\Omega_{3/2} \propto \alpha_1 \frac{m_\nu T_{\text{reh}}^5}{m_{3/2} M_R}$$



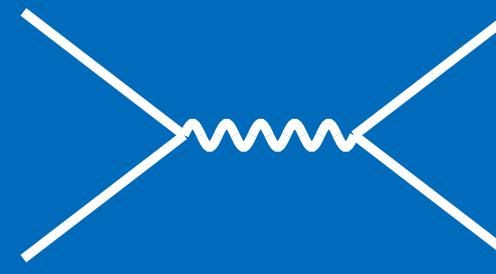
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs

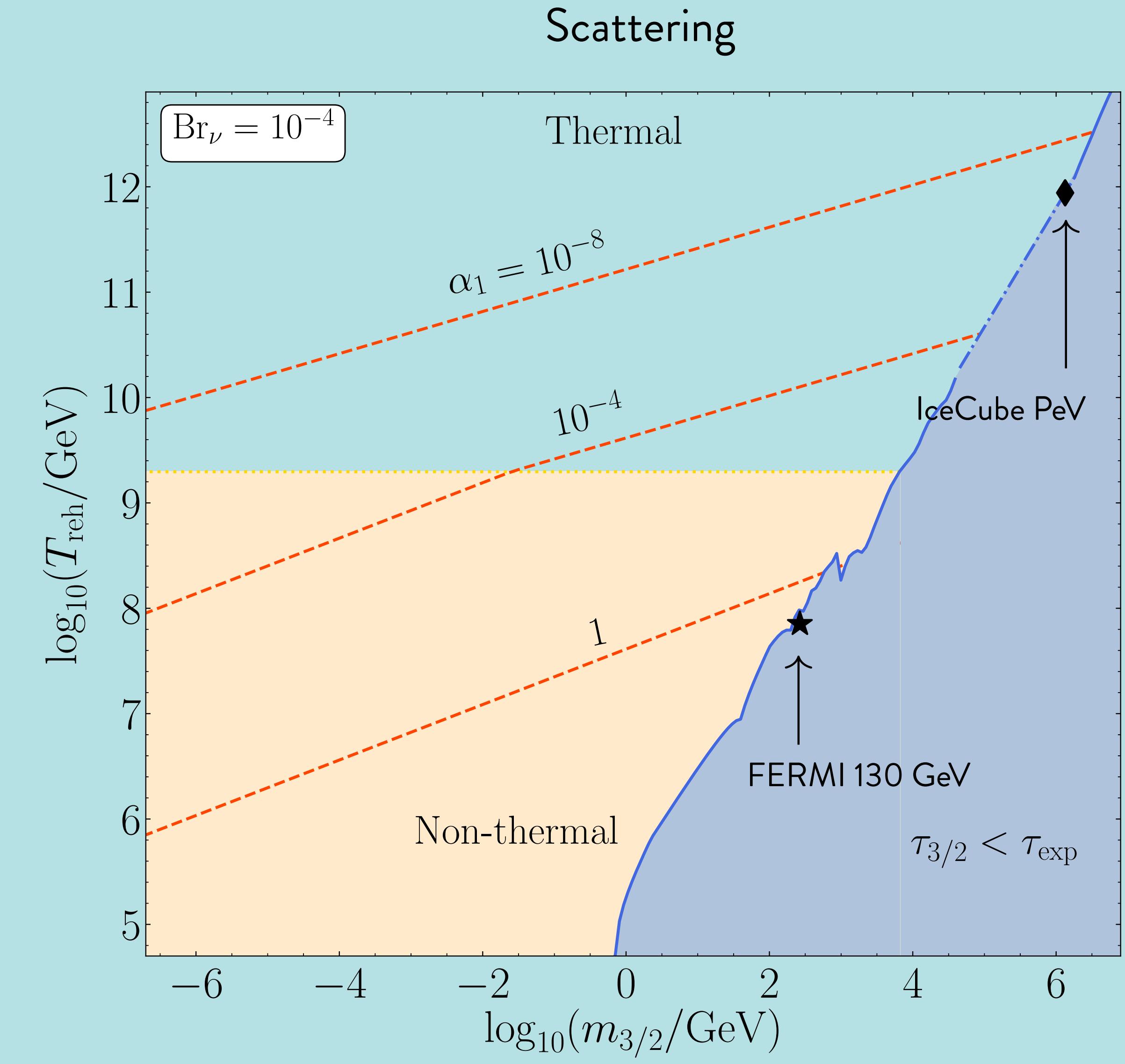
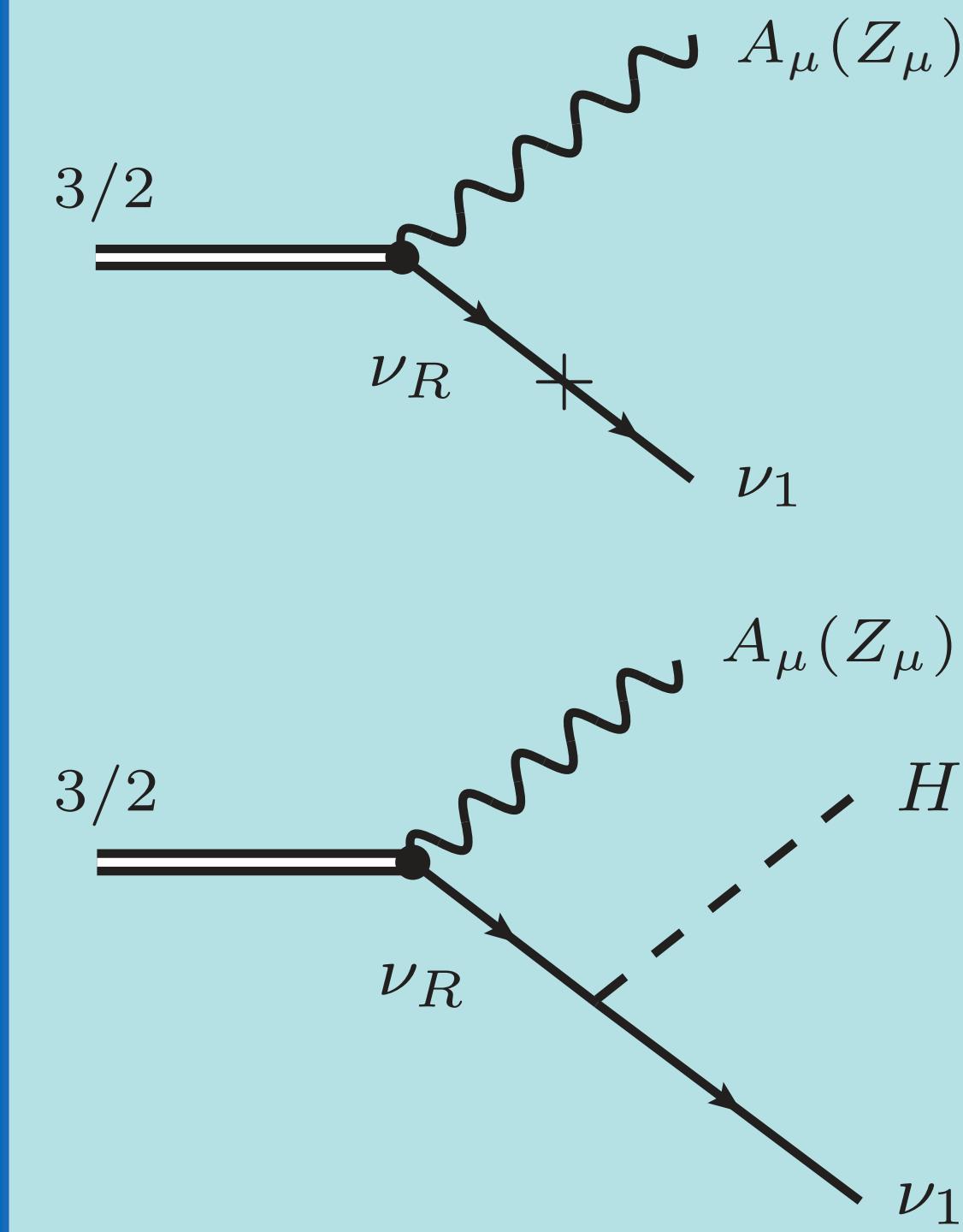


4. Compact objects

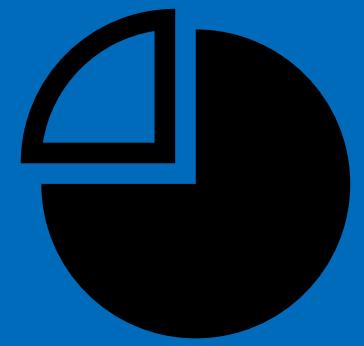


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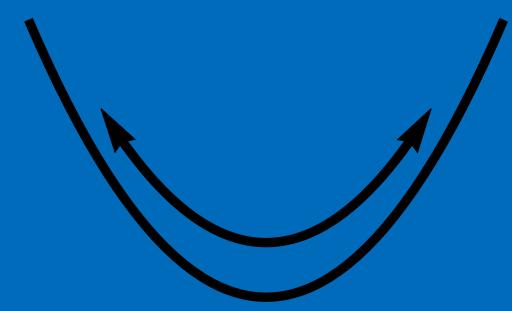
Scatterings and decays



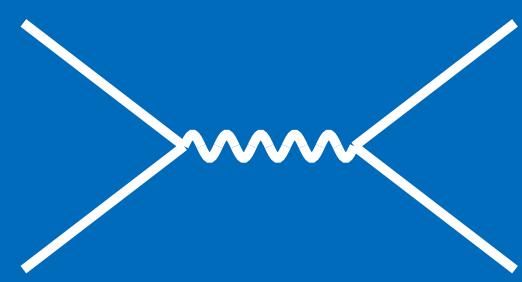
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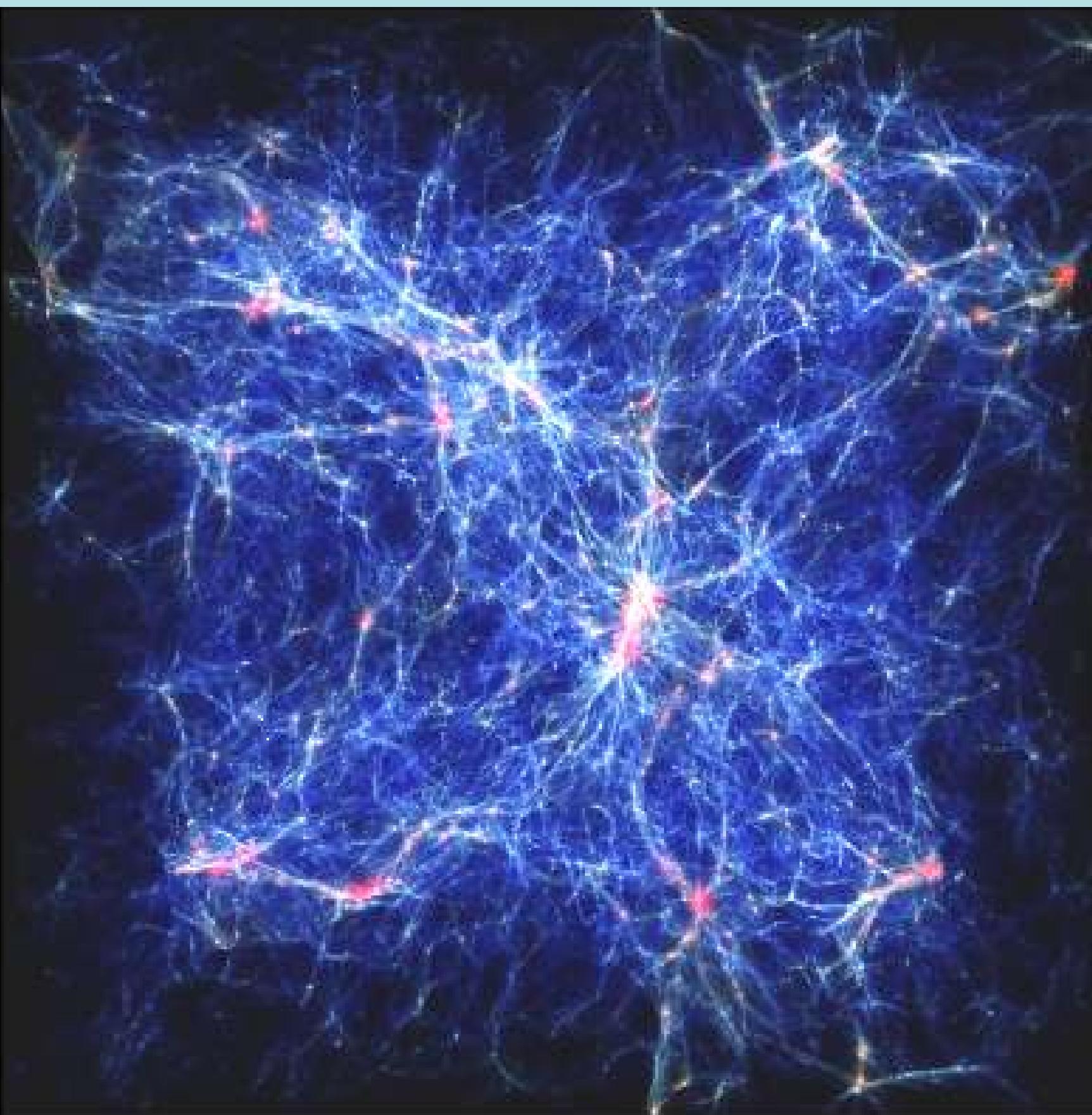


4. Compact objects

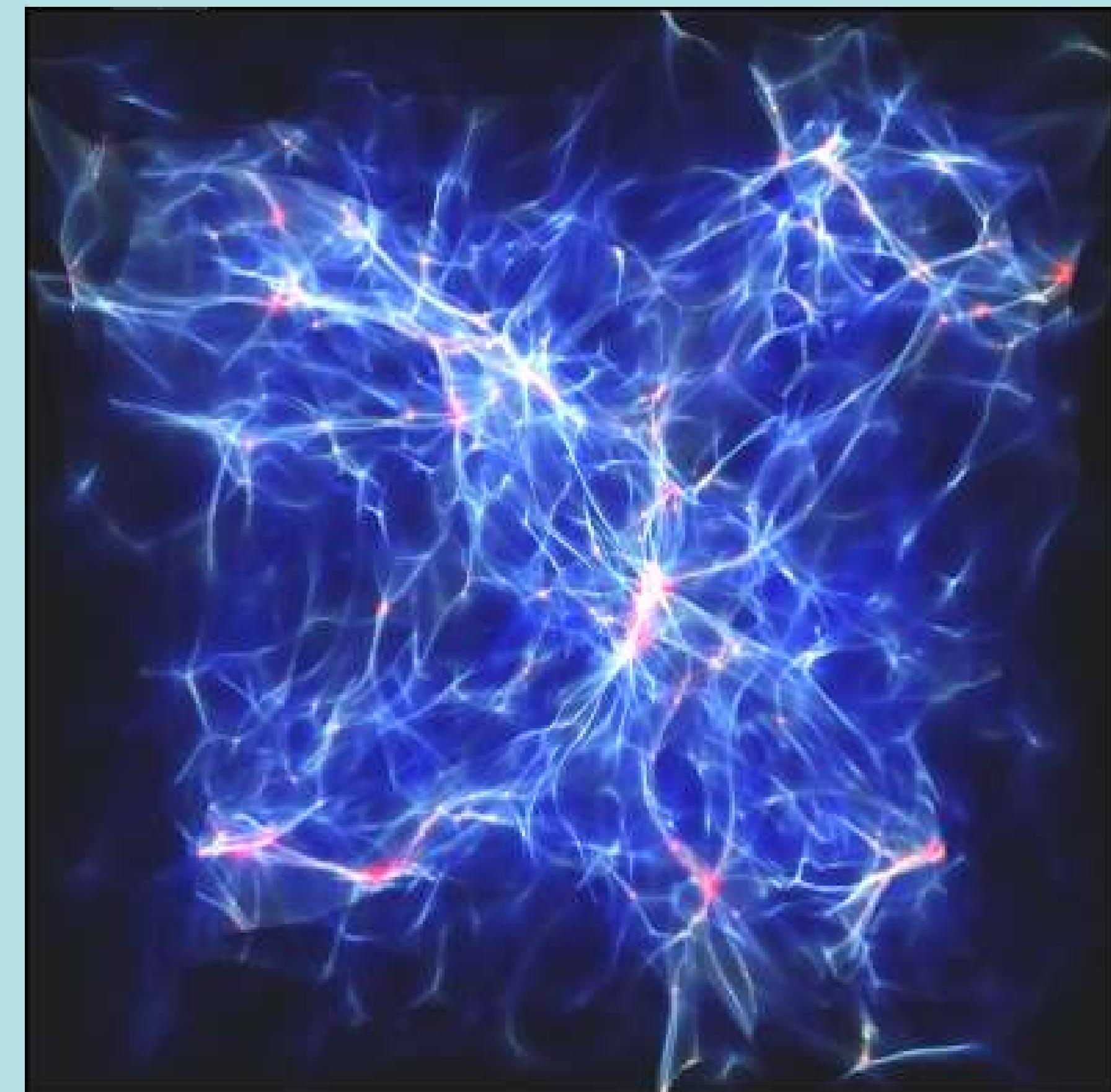


5. Prospects

How warm is out-of-equilibrium dark matter?

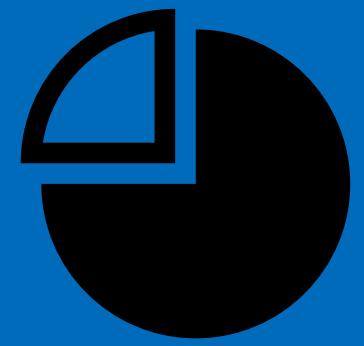


CDM

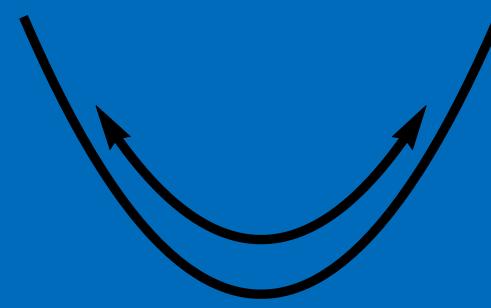


WDM (0.5 keV)

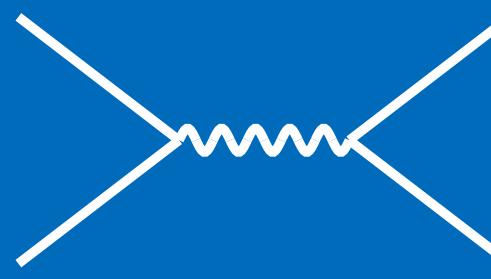
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs

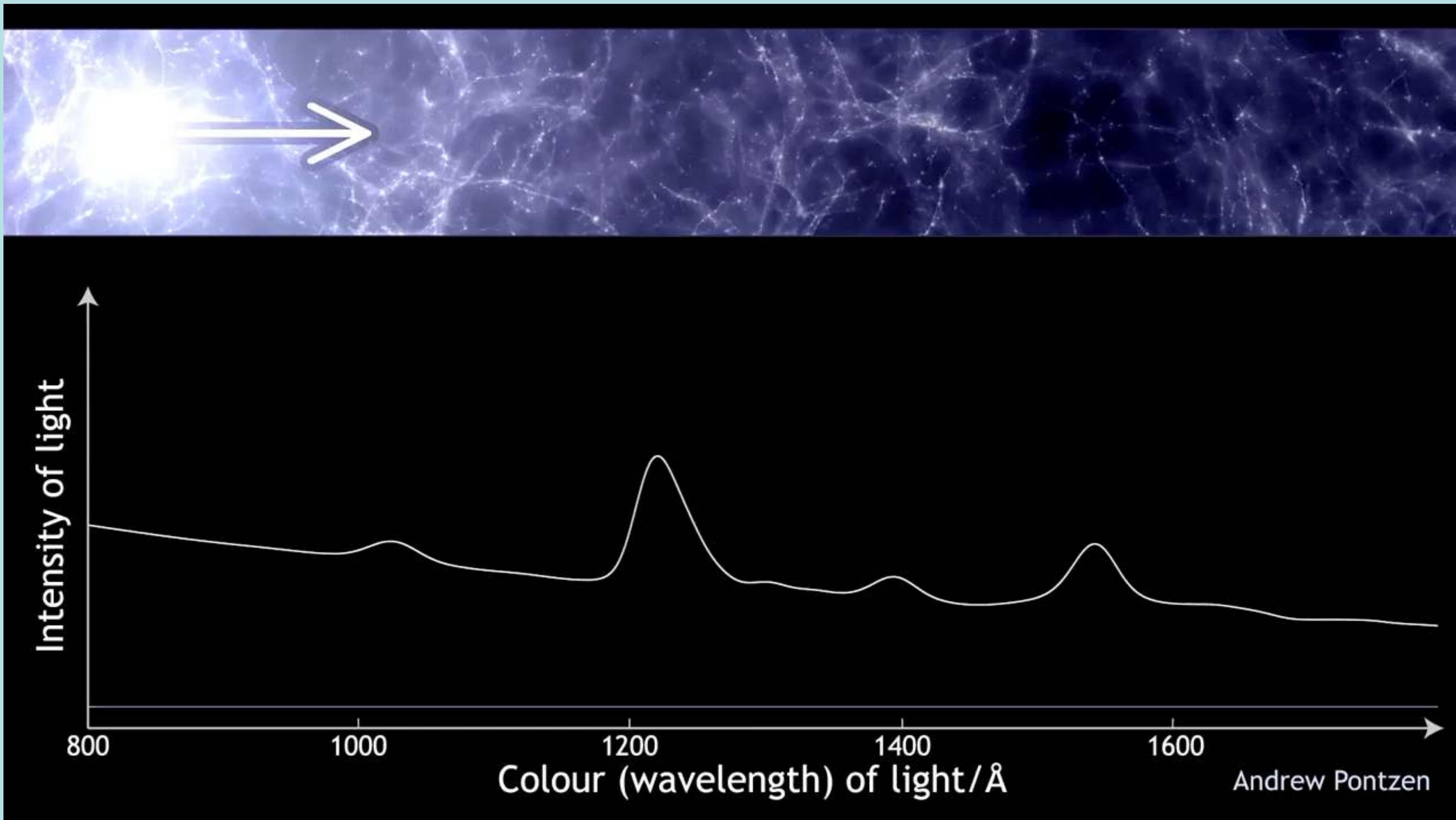


4. Compact objects

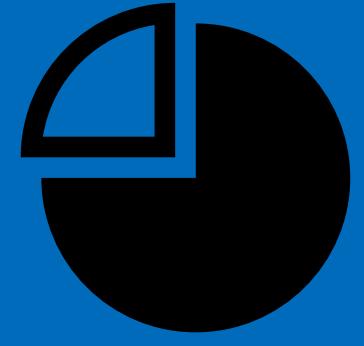


5. Prospects

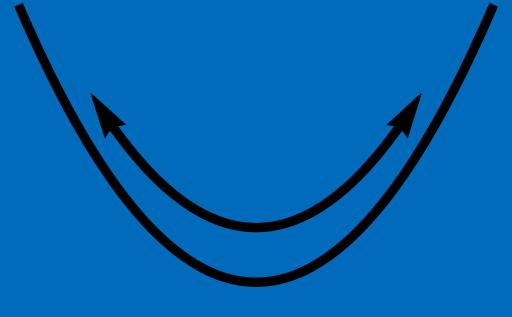
How warm is out-of-equilibrium dark matter?



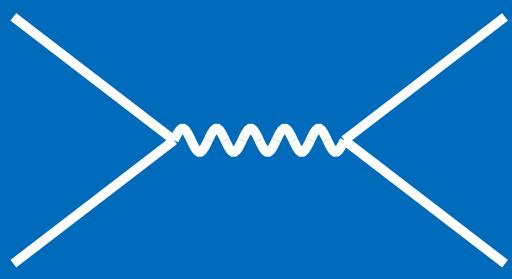
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs



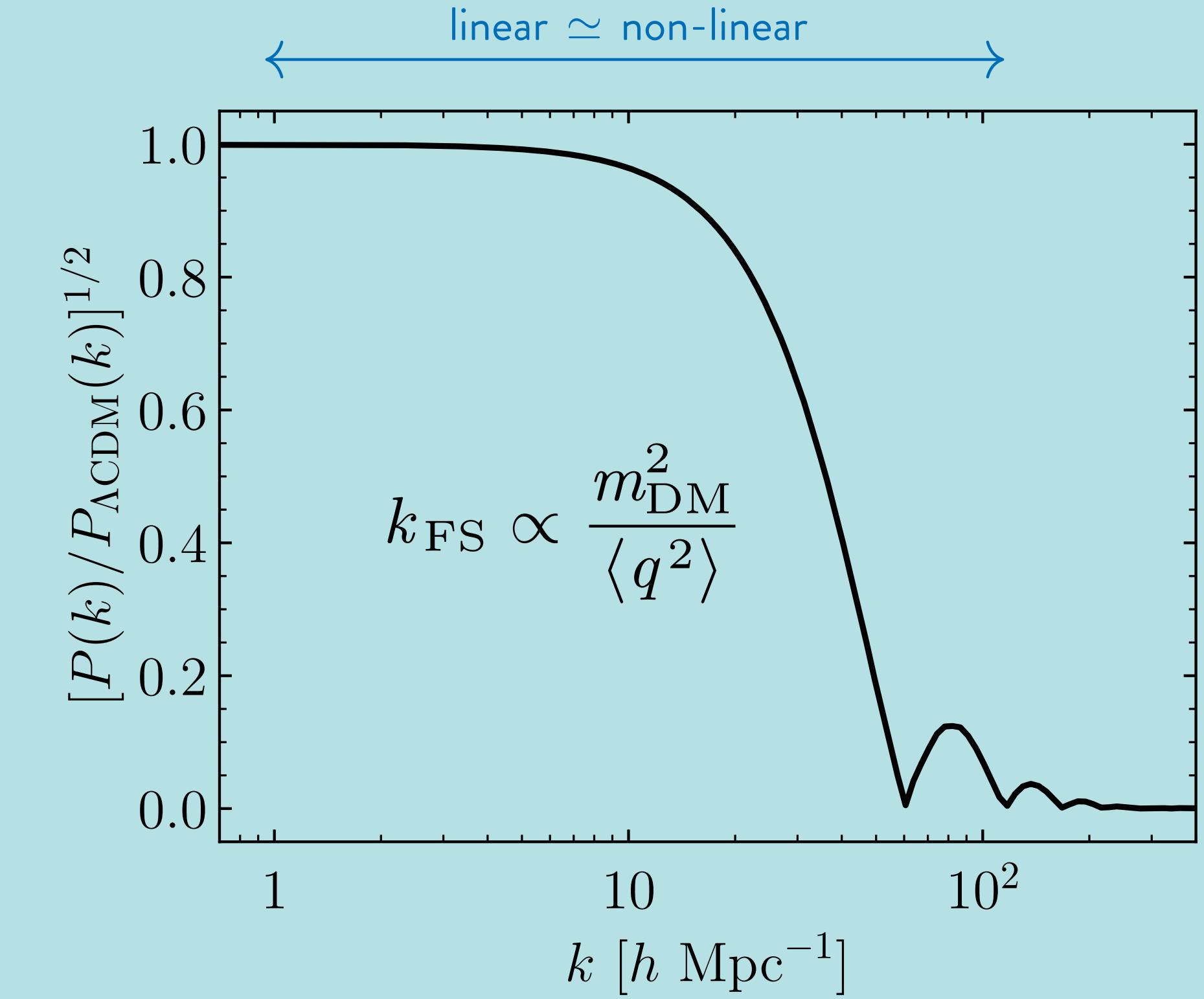
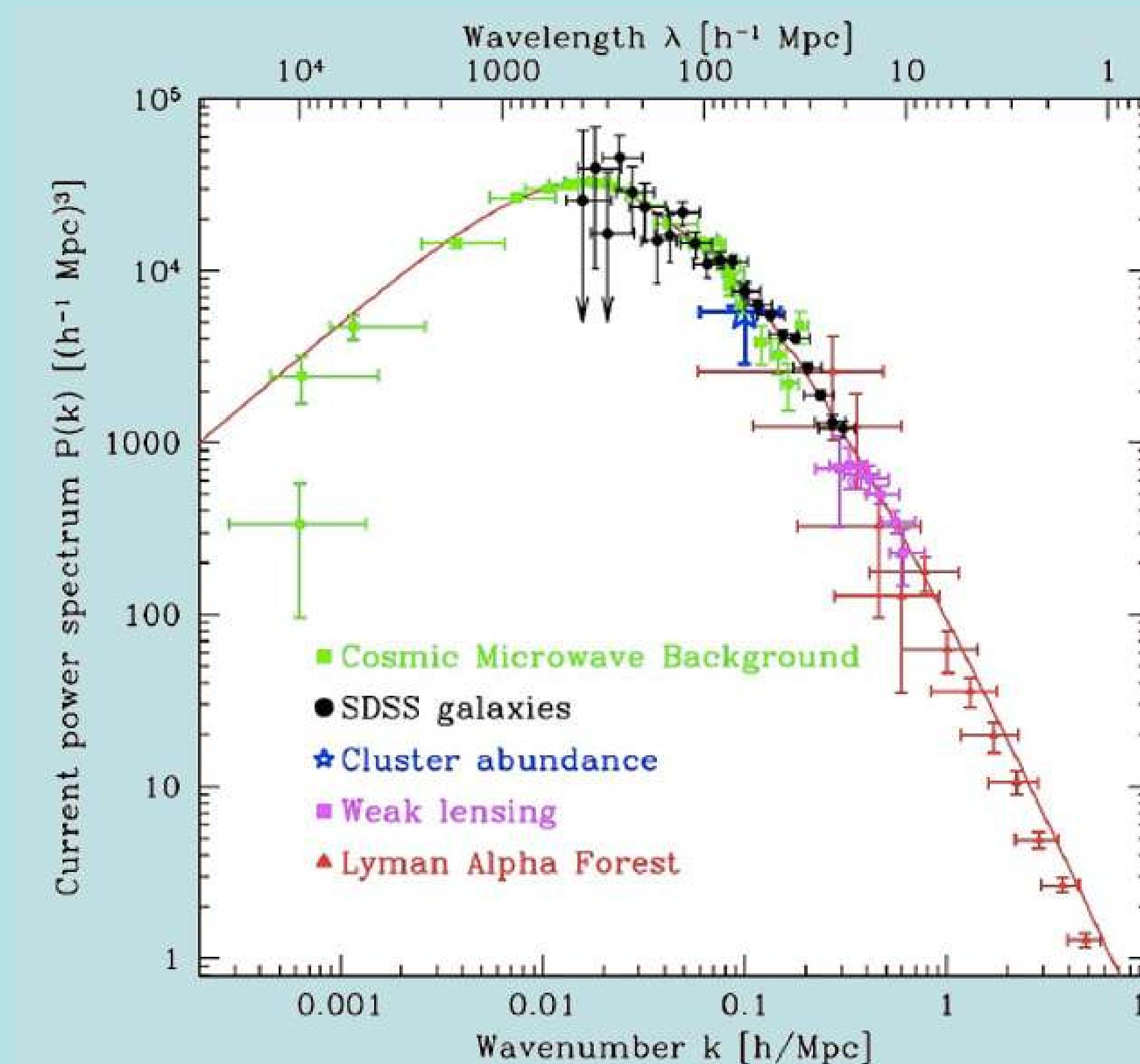
4. Compact objects



5. Prospects

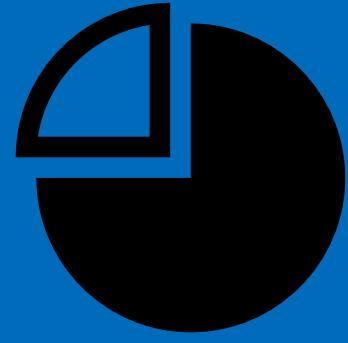
How warm is out-of-equilibrium dark matter?

R. Murgia, V. Iršič and M. Viel, PRD 98 (2018), 083540



G. Ballesteros, MG and M. Pierre, JCAP 03 (2021), 101

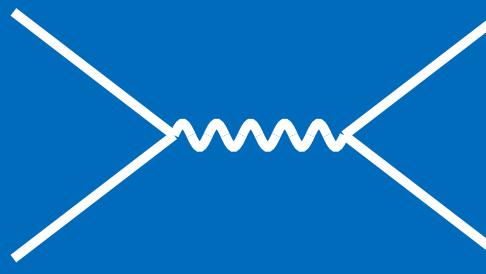
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs

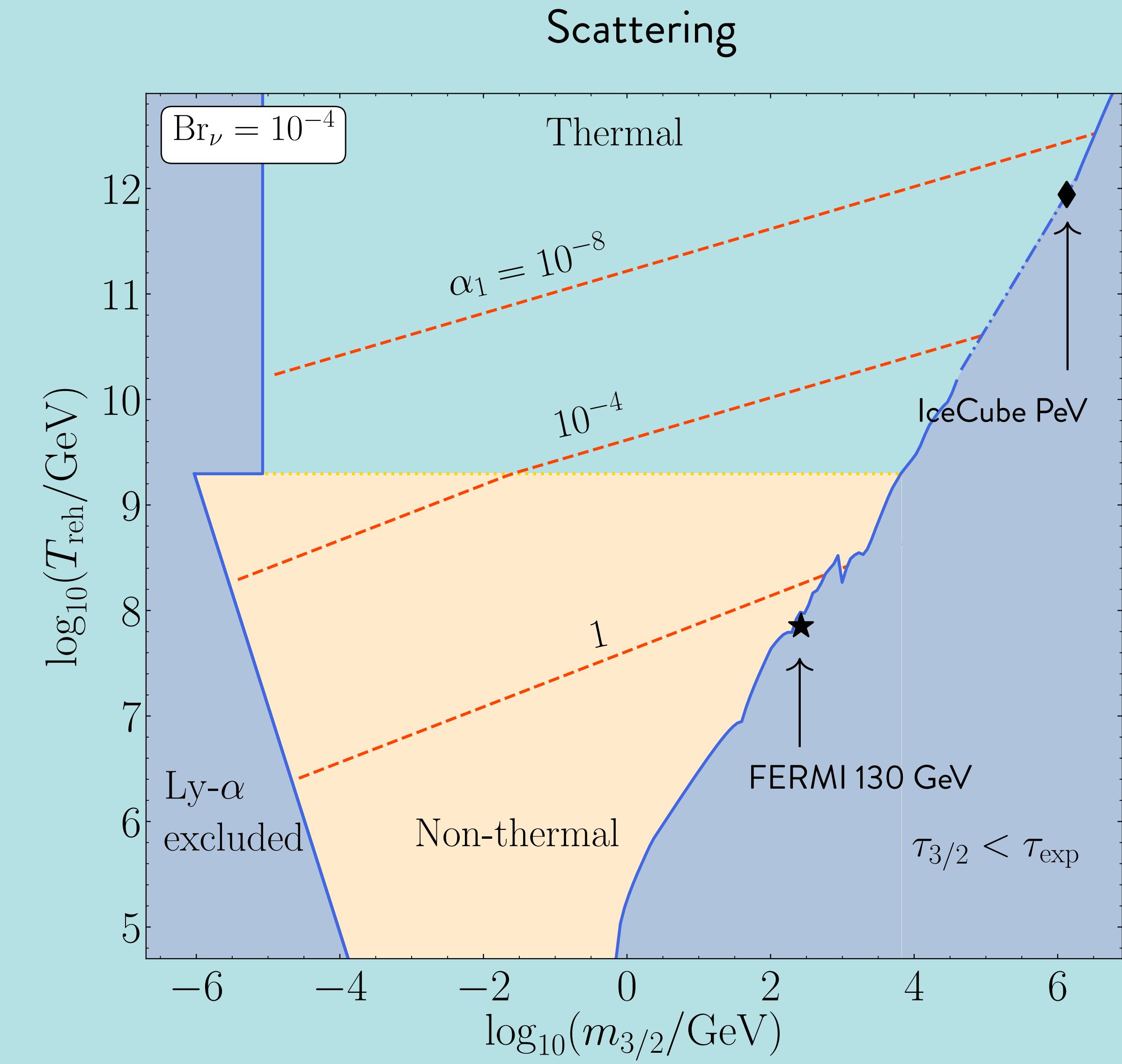
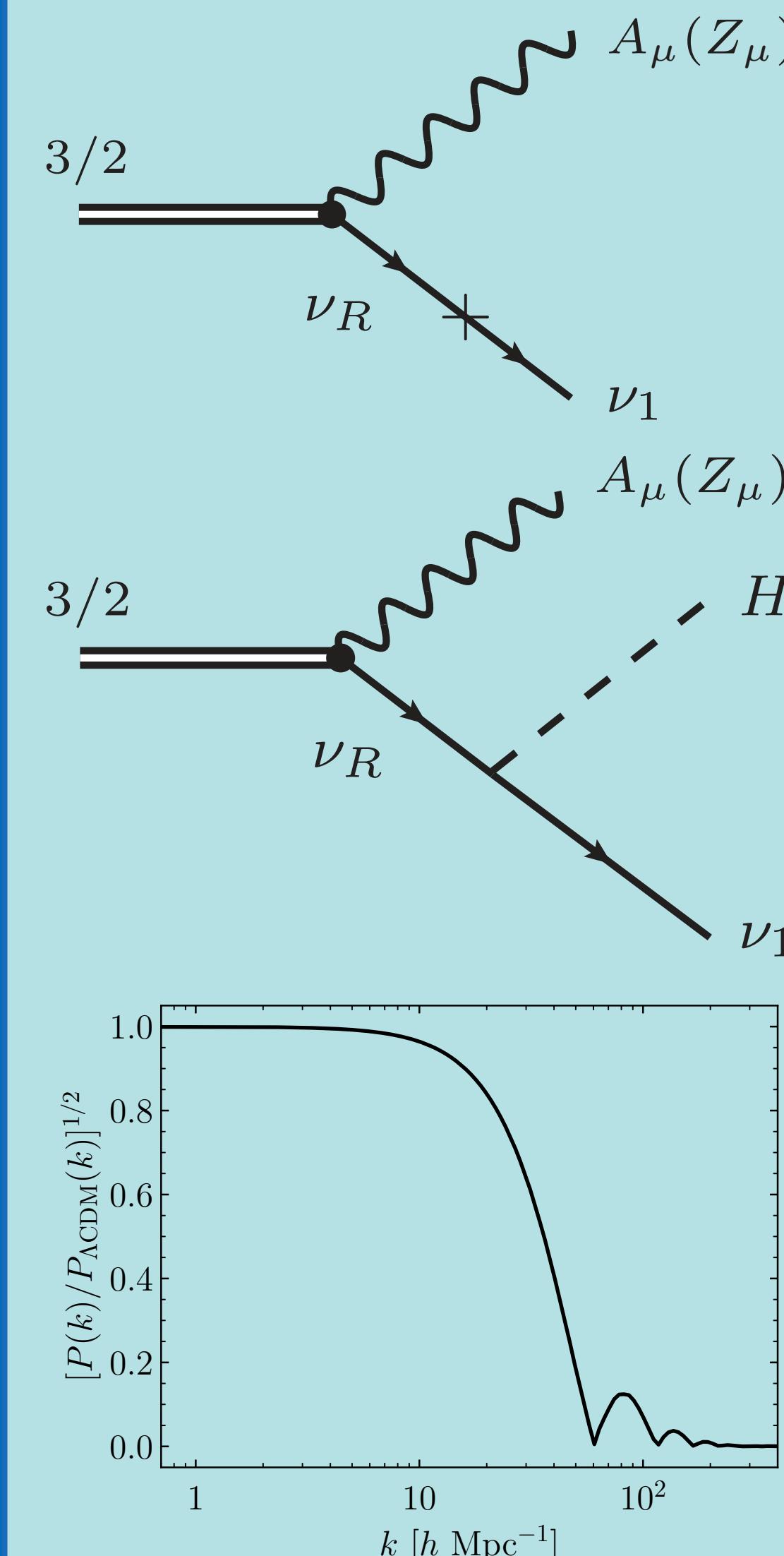


4. Compact objects

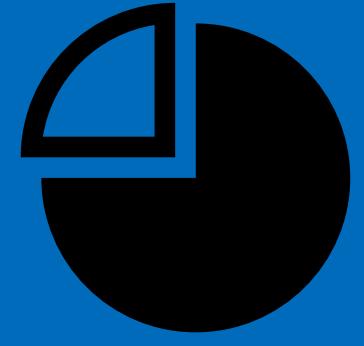


5. Prospects

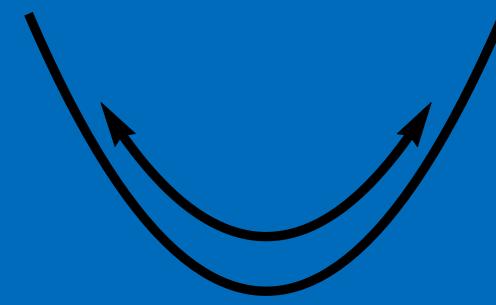
Constraints: $\Omega_{\text{DM}} + \gamma + \nu + \text{Lyman-}\alpha$



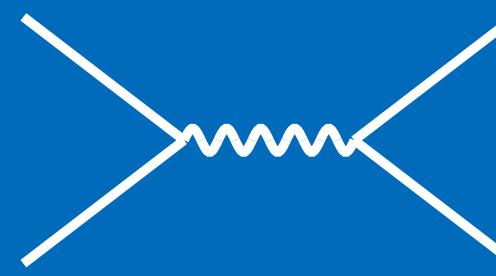
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs



4. Compact objects

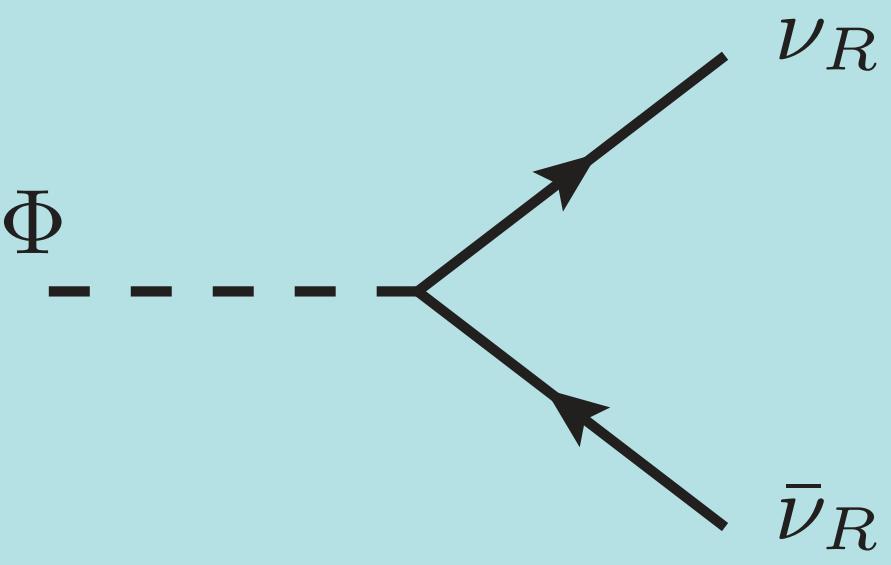


5. Prospects

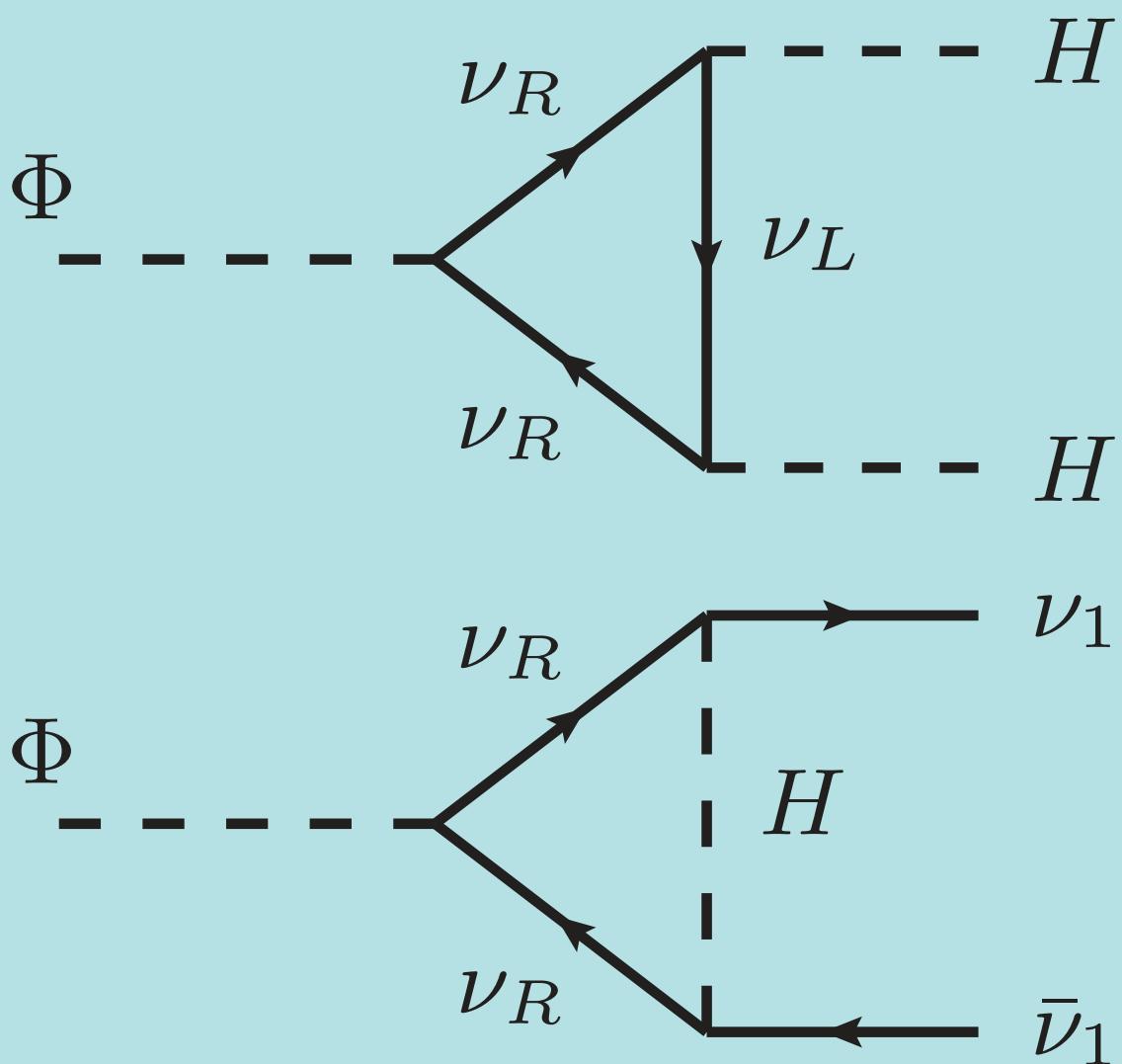
Production (via inflaton decay)

Via α_1 ,

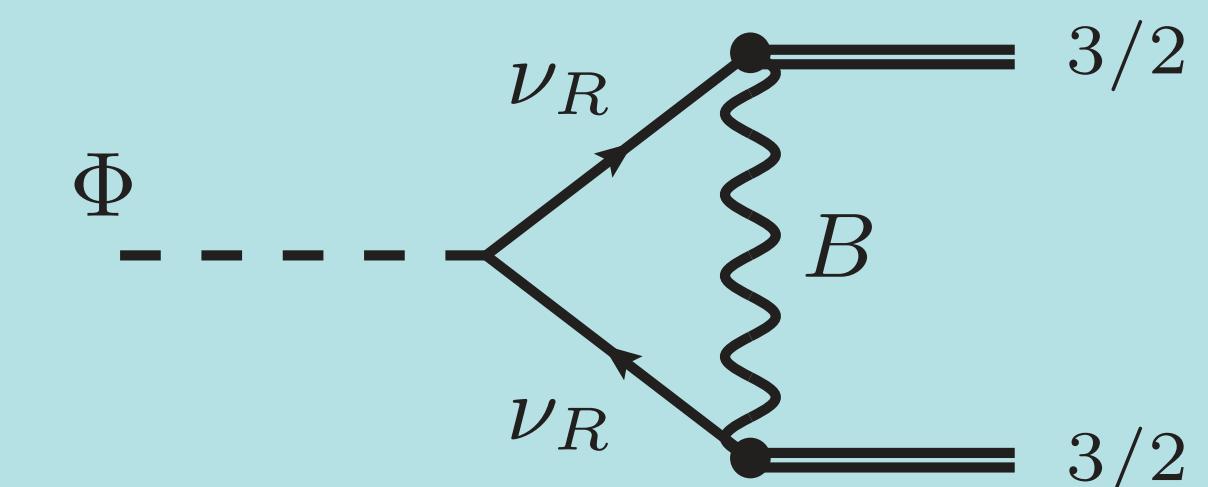
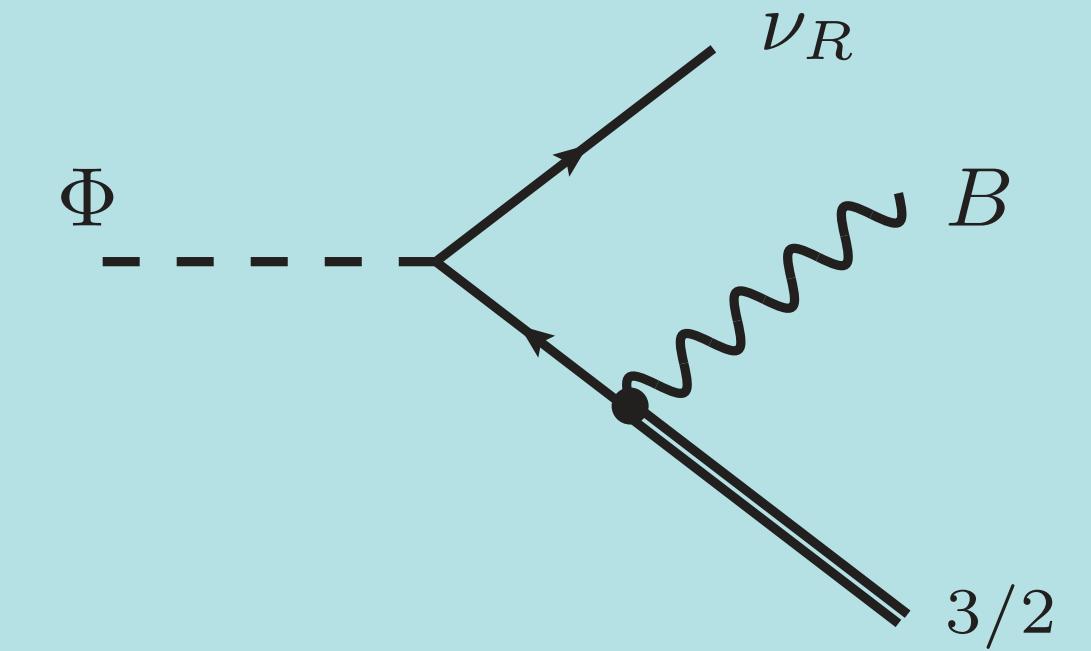
$M_R \ll m_\Phi$:



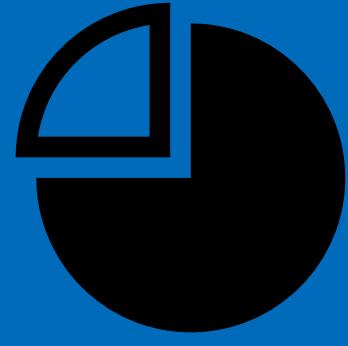
$M_R \gg m_\Phi$:



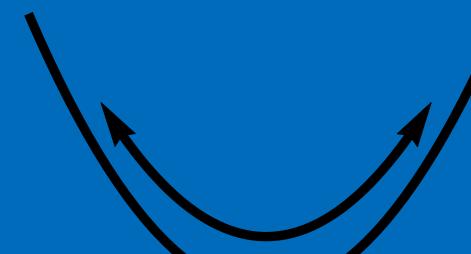
(via α_2 are 2-loop suppressed)



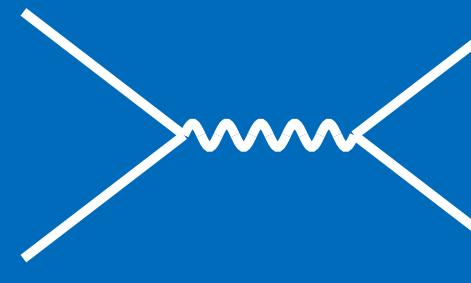
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs

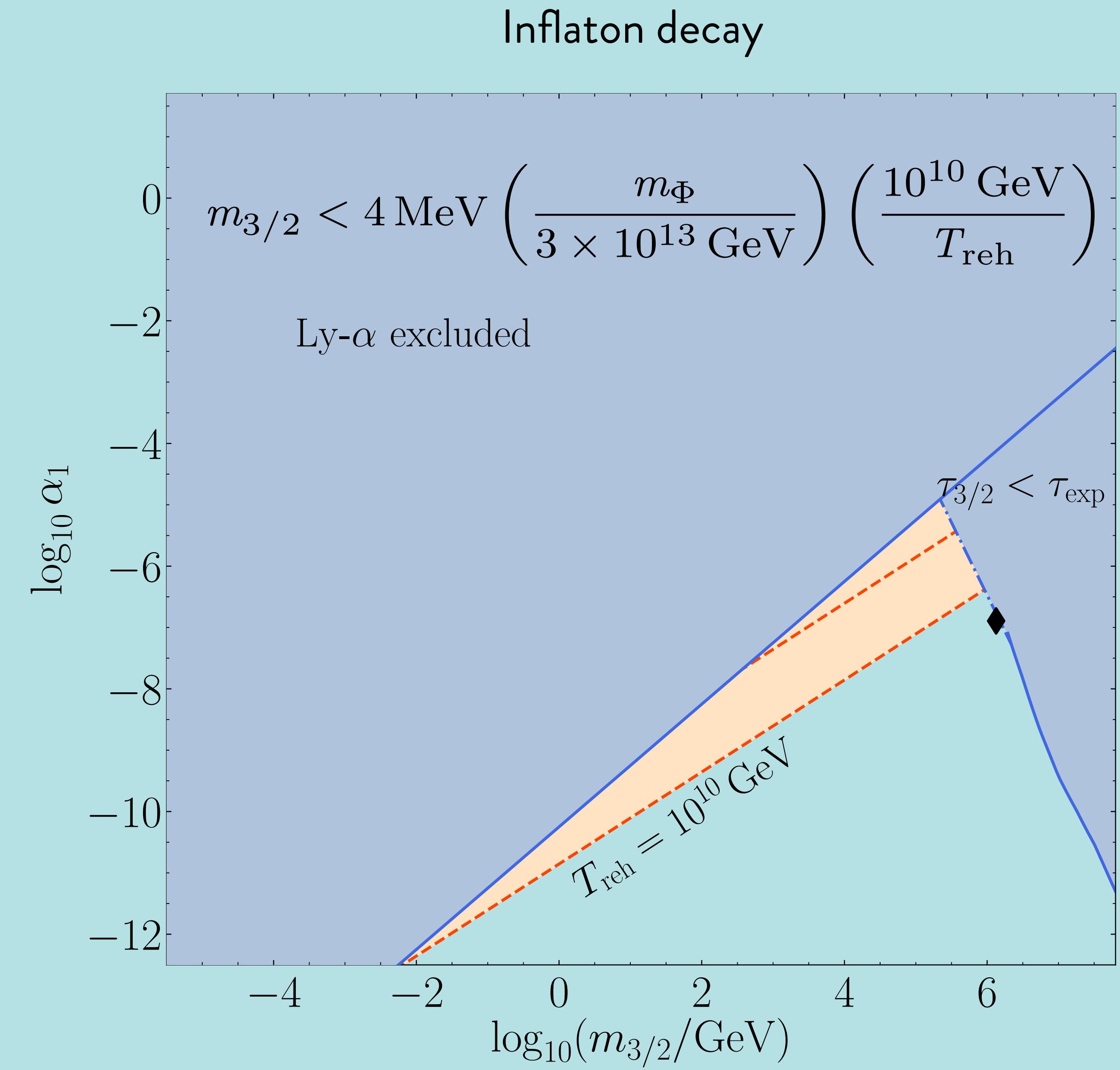
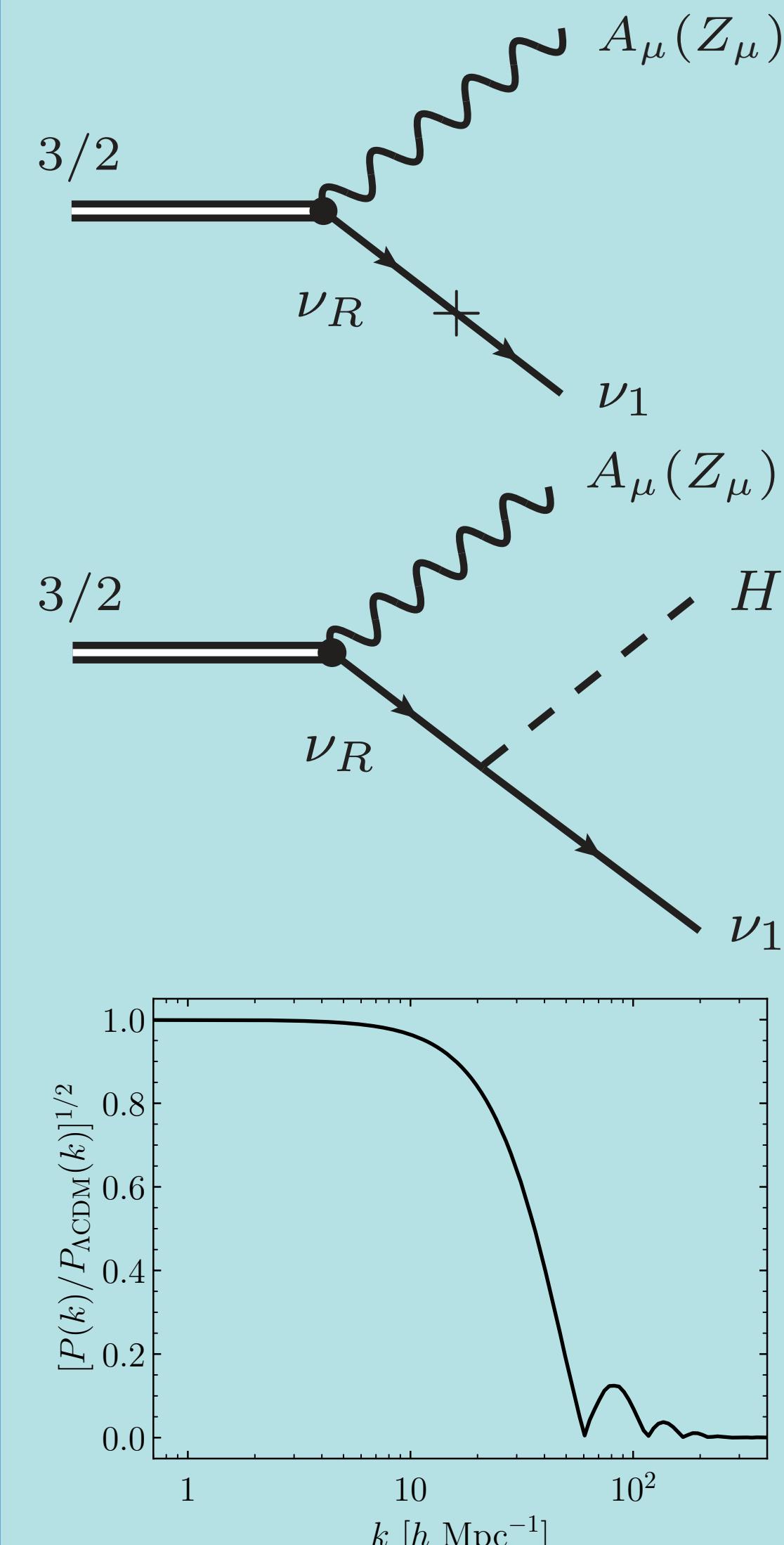


4. Compact objects

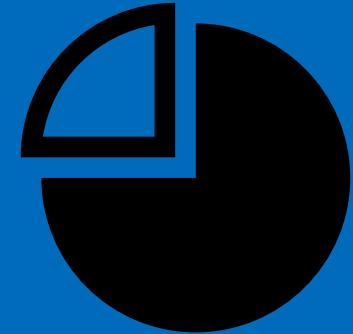


5. Prospects

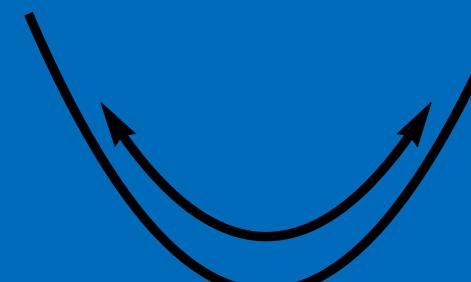
Constraints: $\Omega_{\text{DM}} + \gamma + \nu + \text{Lyman-}\alpha$



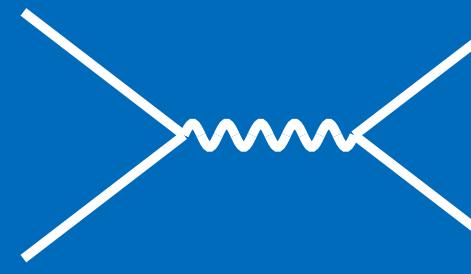
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs



4. Compact objects

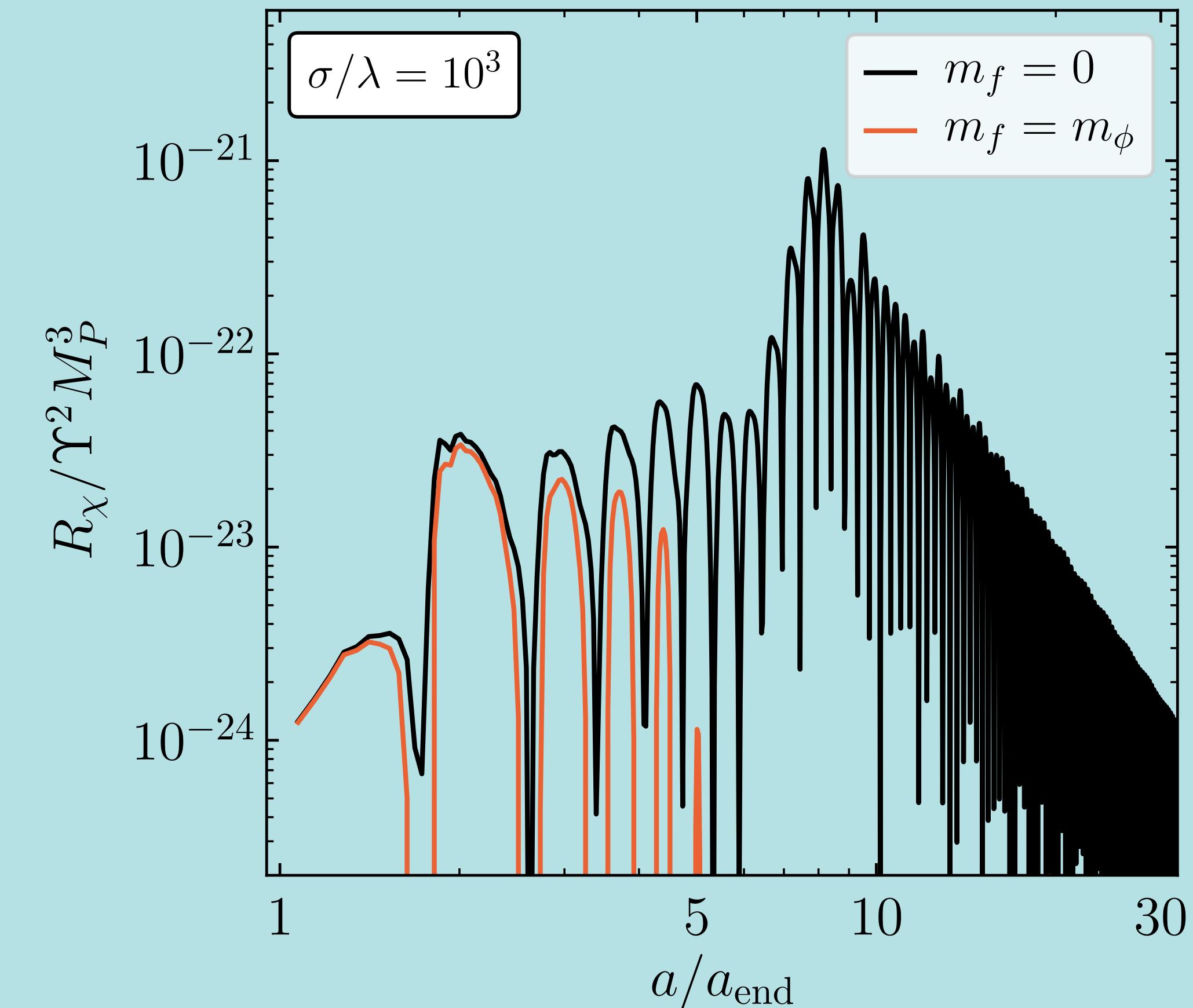
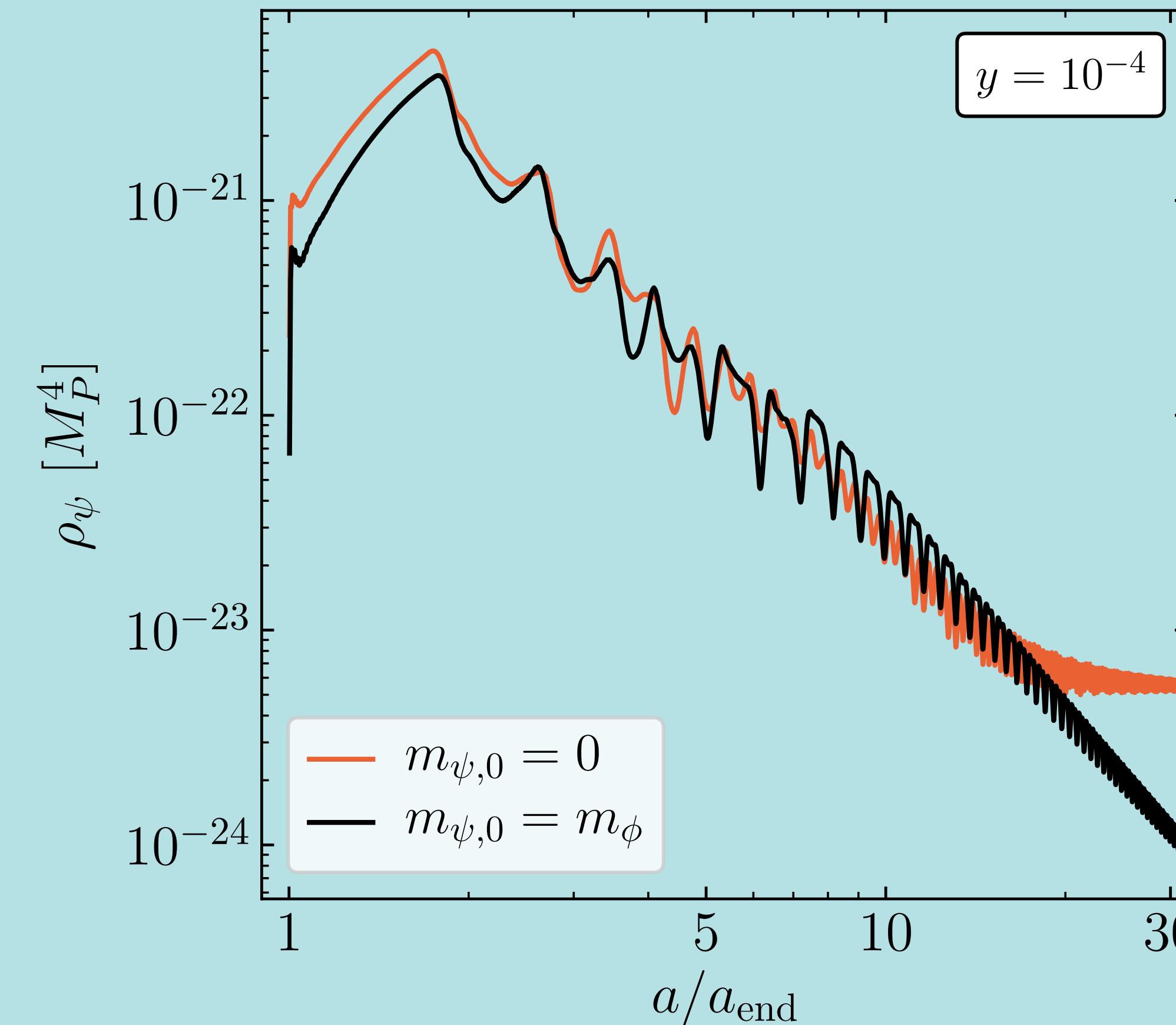


5. Prospects

Beyond perturbation theory

Super-heavy dark matter (WIMPzillas, ...)

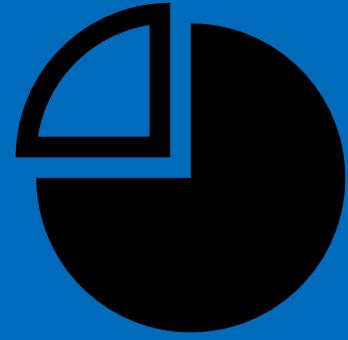
E. Kolb, D. Chung and A. Riotto, AIP Conf. Proc. 484 (1999), 91



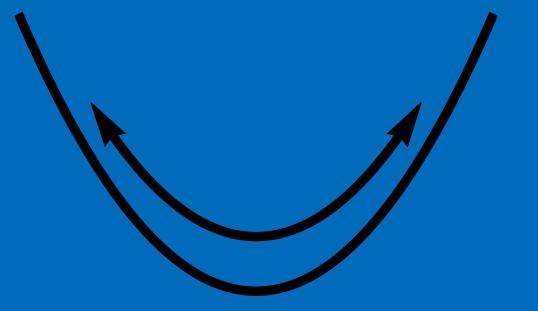
(but not thermally though)

MG, K. Kaneta, Y. Mambrini and K. Olive, JCAP 04 (2021), 012

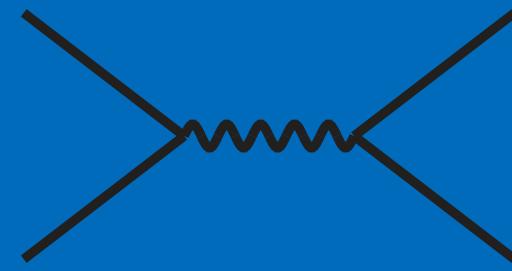
1. Beyond WIMPs



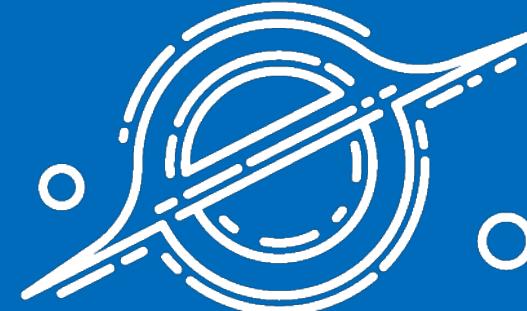
2. Inflation & reheating



3. FIMPs

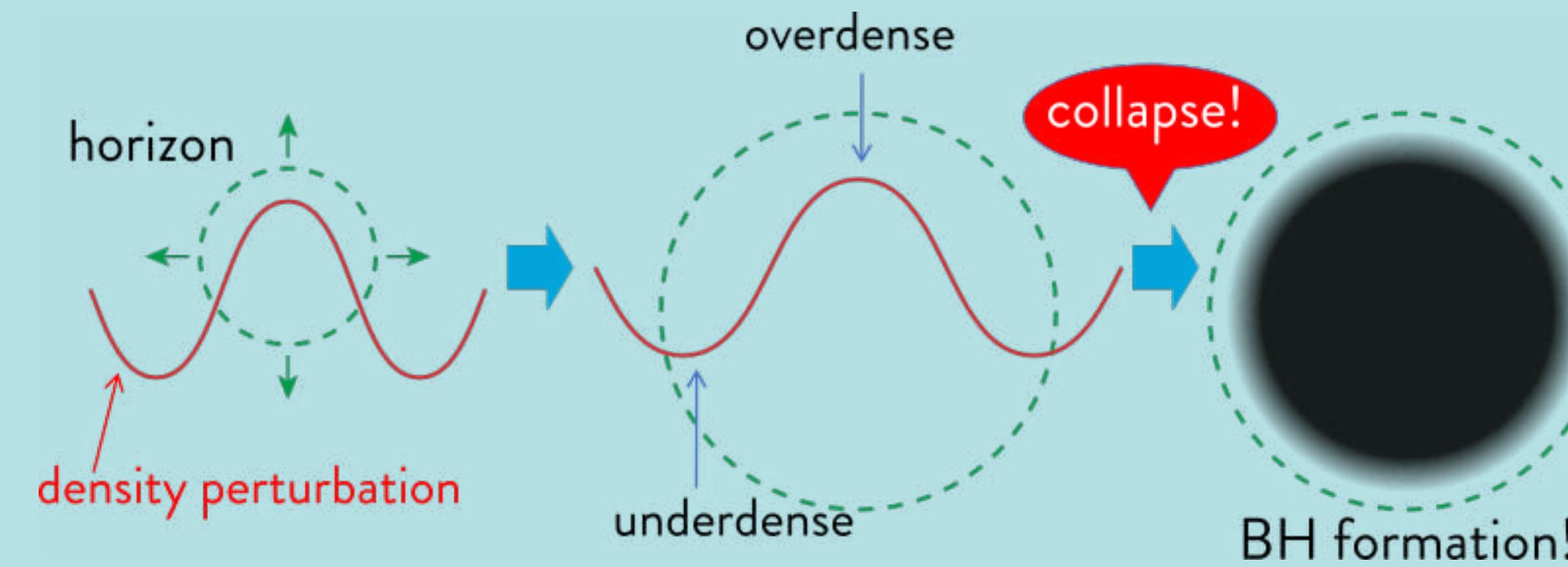


4. Compact objects



5. Prospects

Large metric fluctuations?



Credit: Naoya Kitajima

Metric preheating \rightarrow overdensities \rightarrow light PBHs \rightarrow (Hawking) reheating

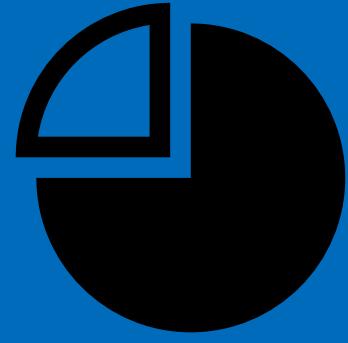
M_{BH}	τ_{BH}
A man	10^{-12} s
10^{15} g	10^{10} y
Earth	10^{49} y
Sun	10^{66} y
Milky Way	10^{99} y

$$\frac{\delta\rho_C}{\rho} \gtrsim 0.5$$

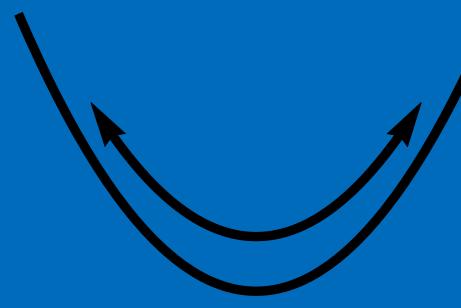
$$M_{\text{BH}} \propto \rho_{\text{form}} / H_{\text{form}}^3 < 10^9 \text{ g}$$

$$\tau_{\text{BH}} \approx 10^{64} \left(\frac{M}{M_{\odot}} \right)^3 \text{ y}$$

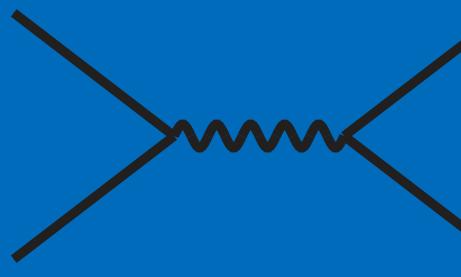
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs

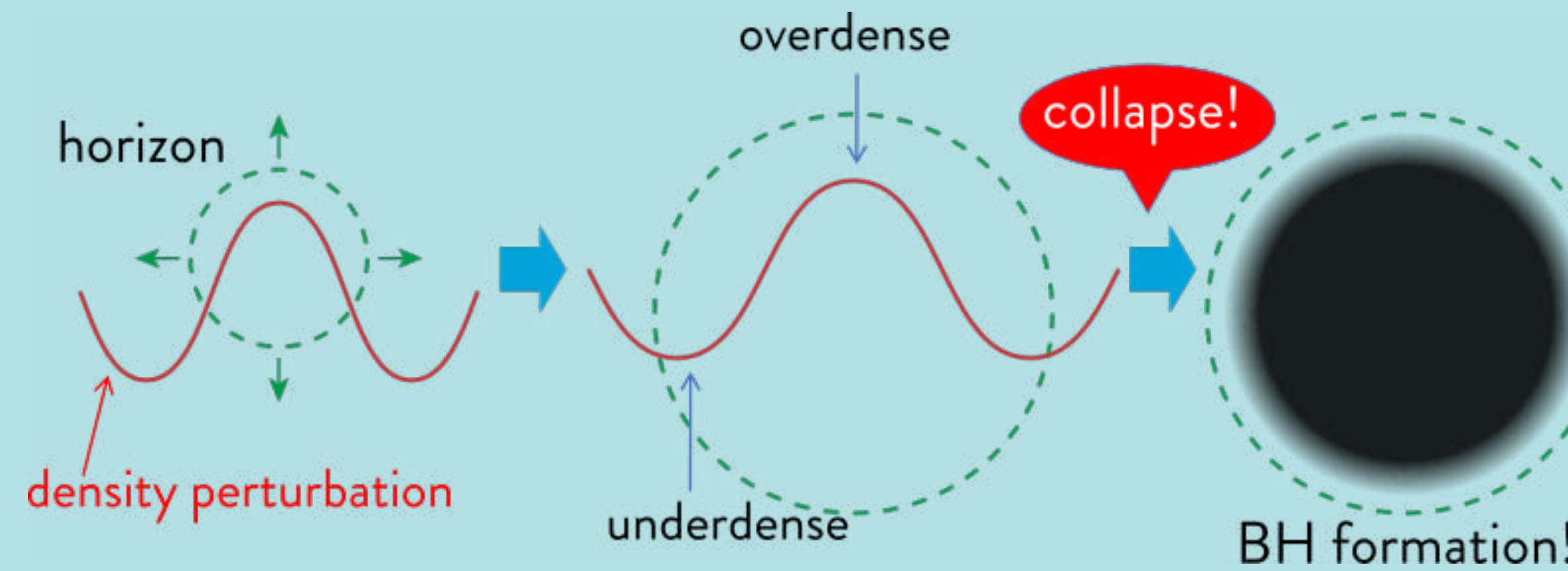


4. Compact objects

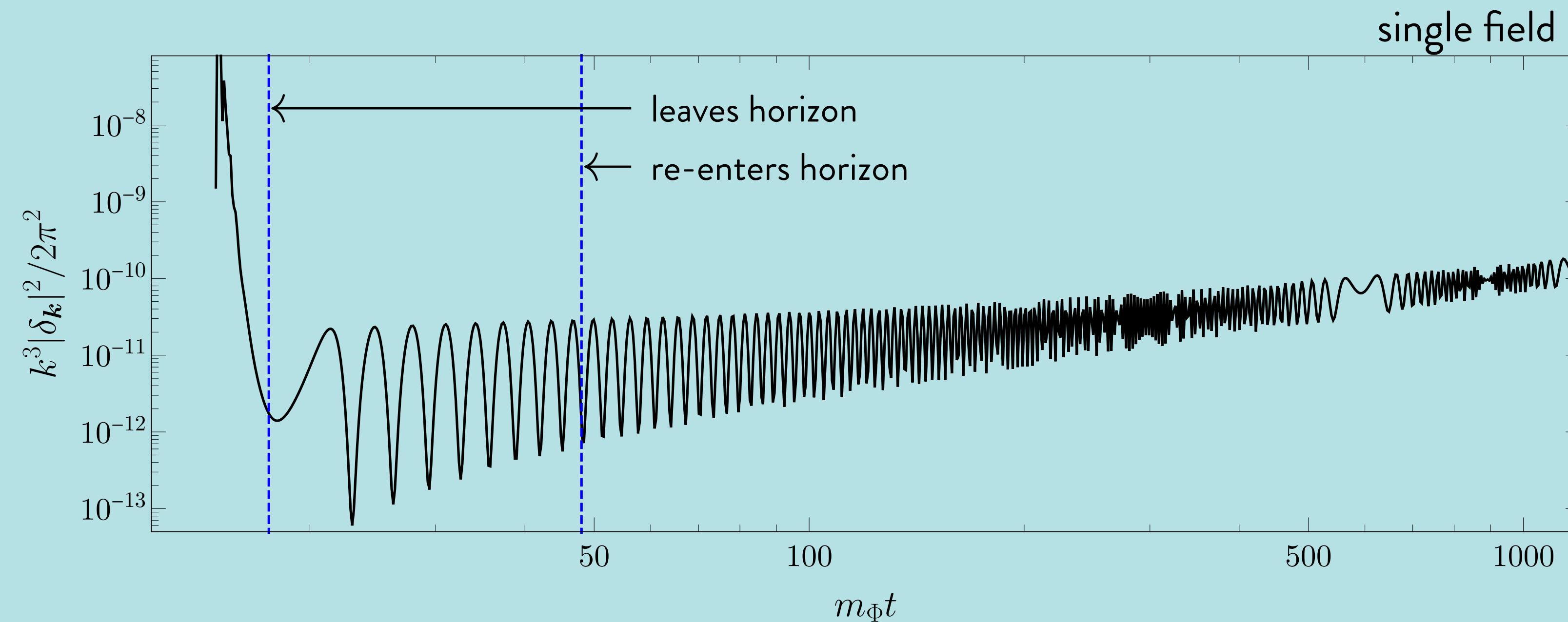


5. Prospects

Large metric fluctuations?



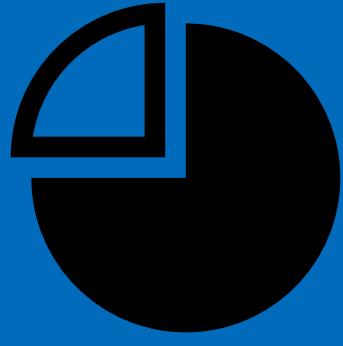
Credit: Naoya Kitajima



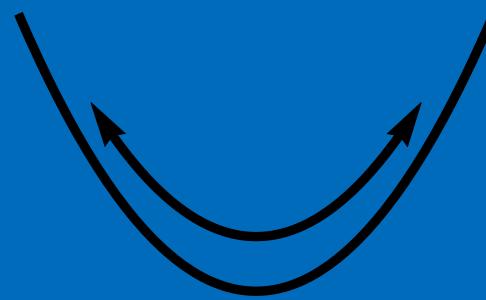
K. Jedamzik, M. Lemoine and J. Martin, JCAP 09 (2010), 034;

A. Gómez, MG, G. Ballesteros, M. Pierre, on it

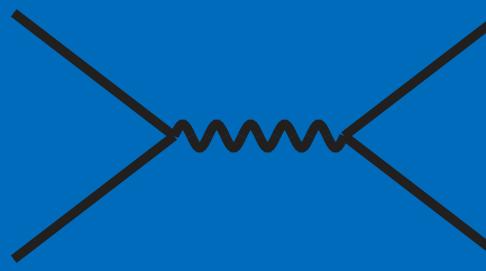
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs

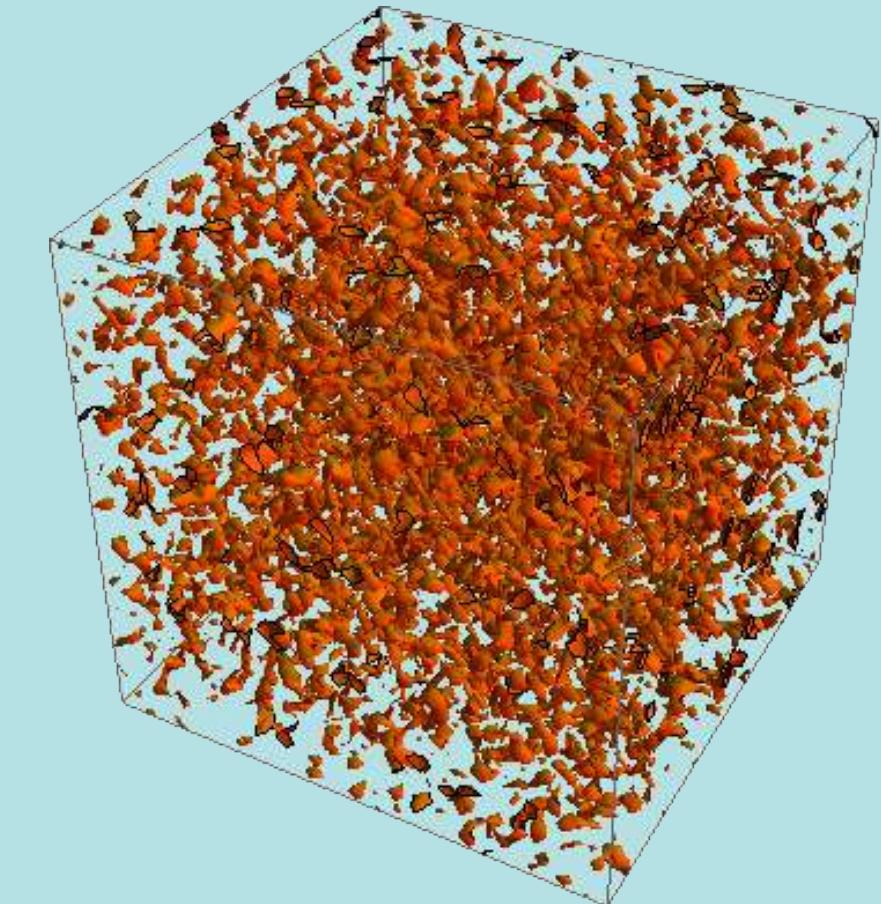
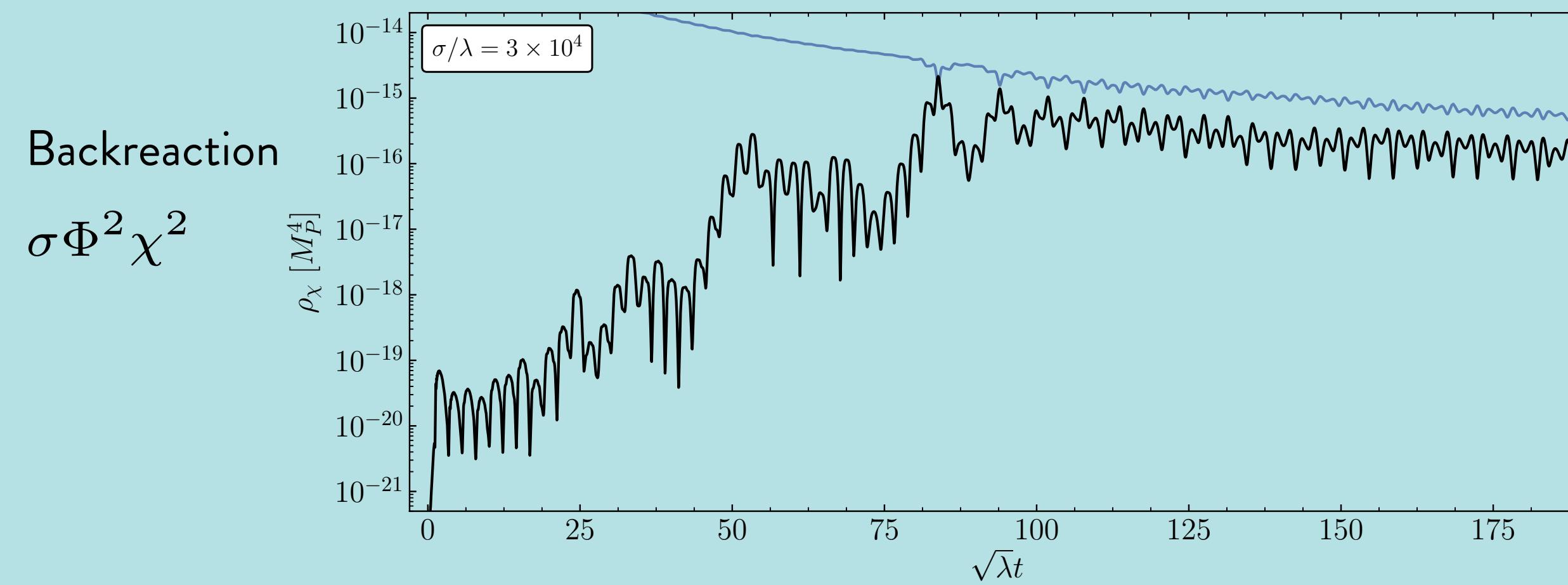


4. Compact objects



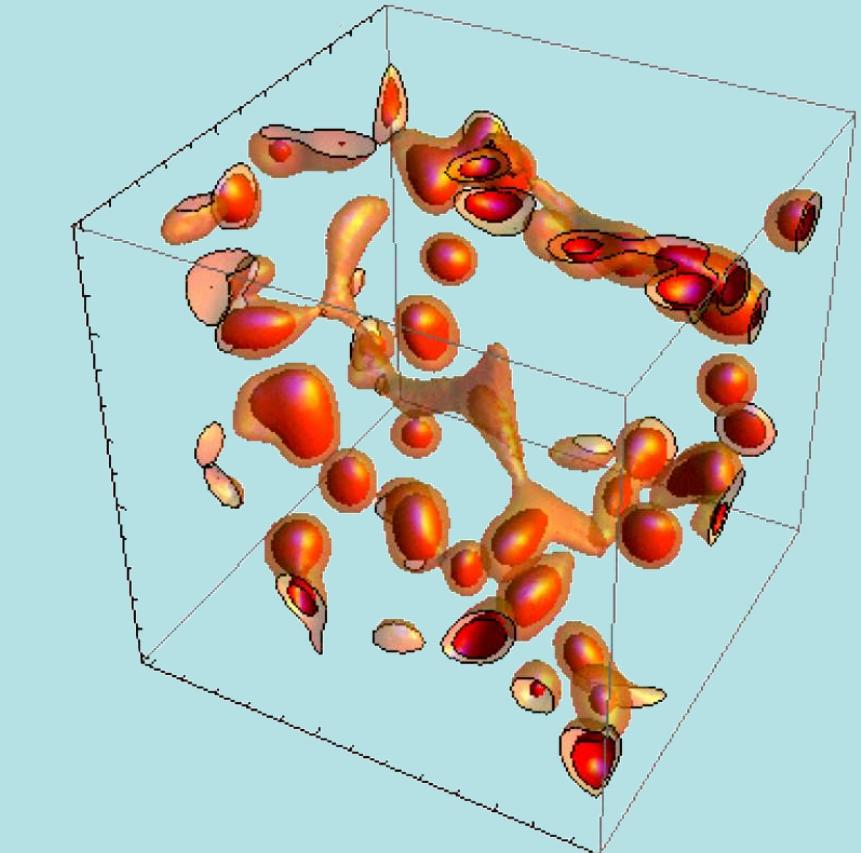
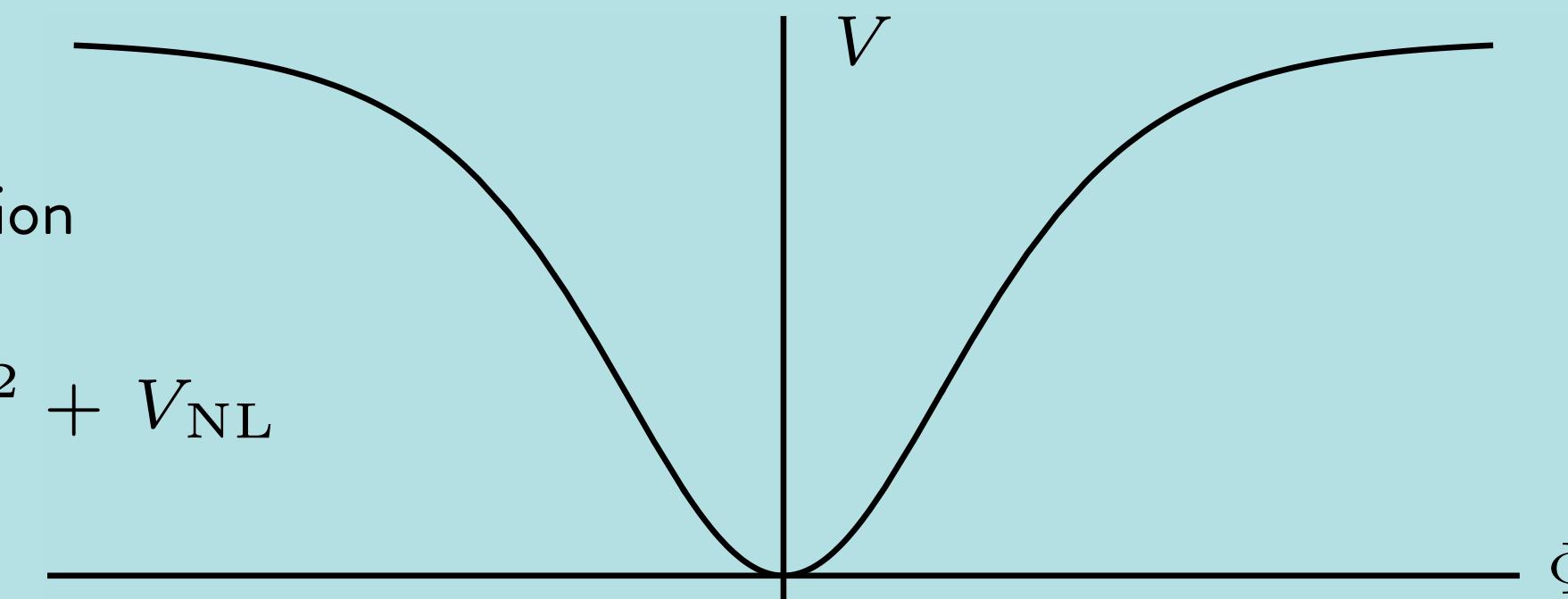
5. Prospects

Fragmenting the condensate



“opening up” =
attractive interaction

$$V = \frac{1}{2} m_\Phi^2 \Phi^2 + V_{NL}$$



Complex, U(1):

Q-Balls

Real: Oscillons

self-interaction ← → gravity

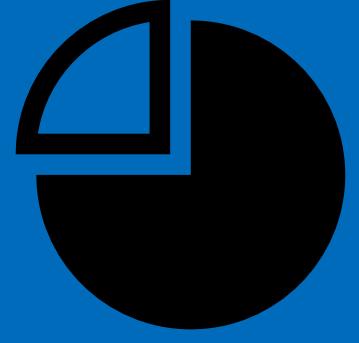


Boson stars

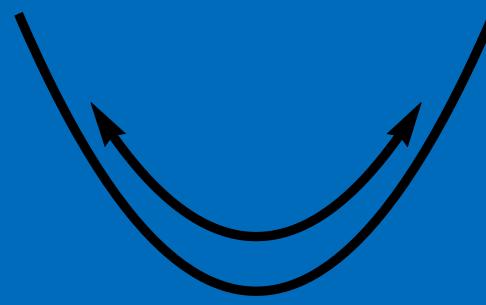


Oscillatons

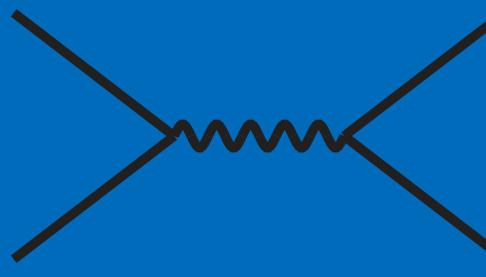
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs

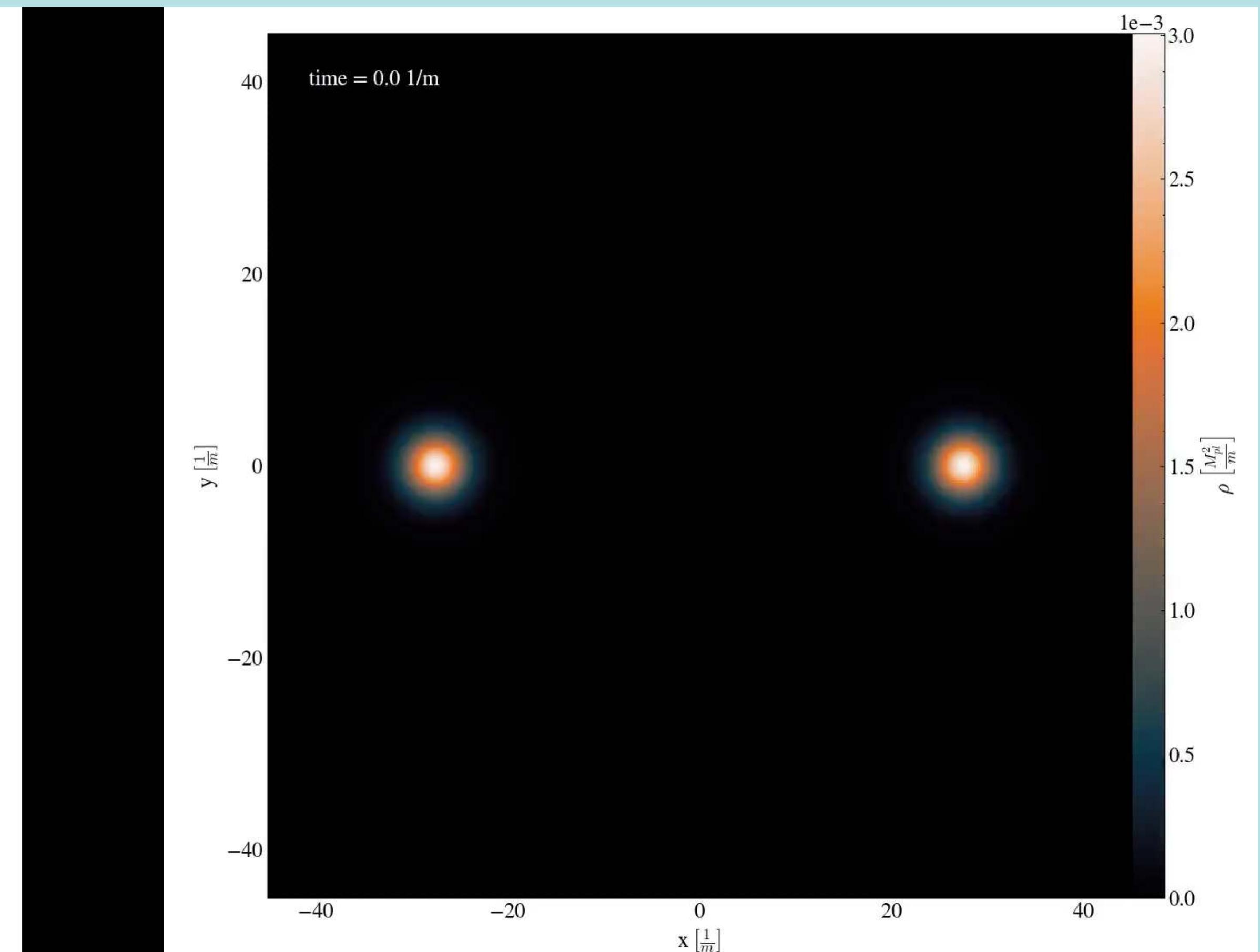
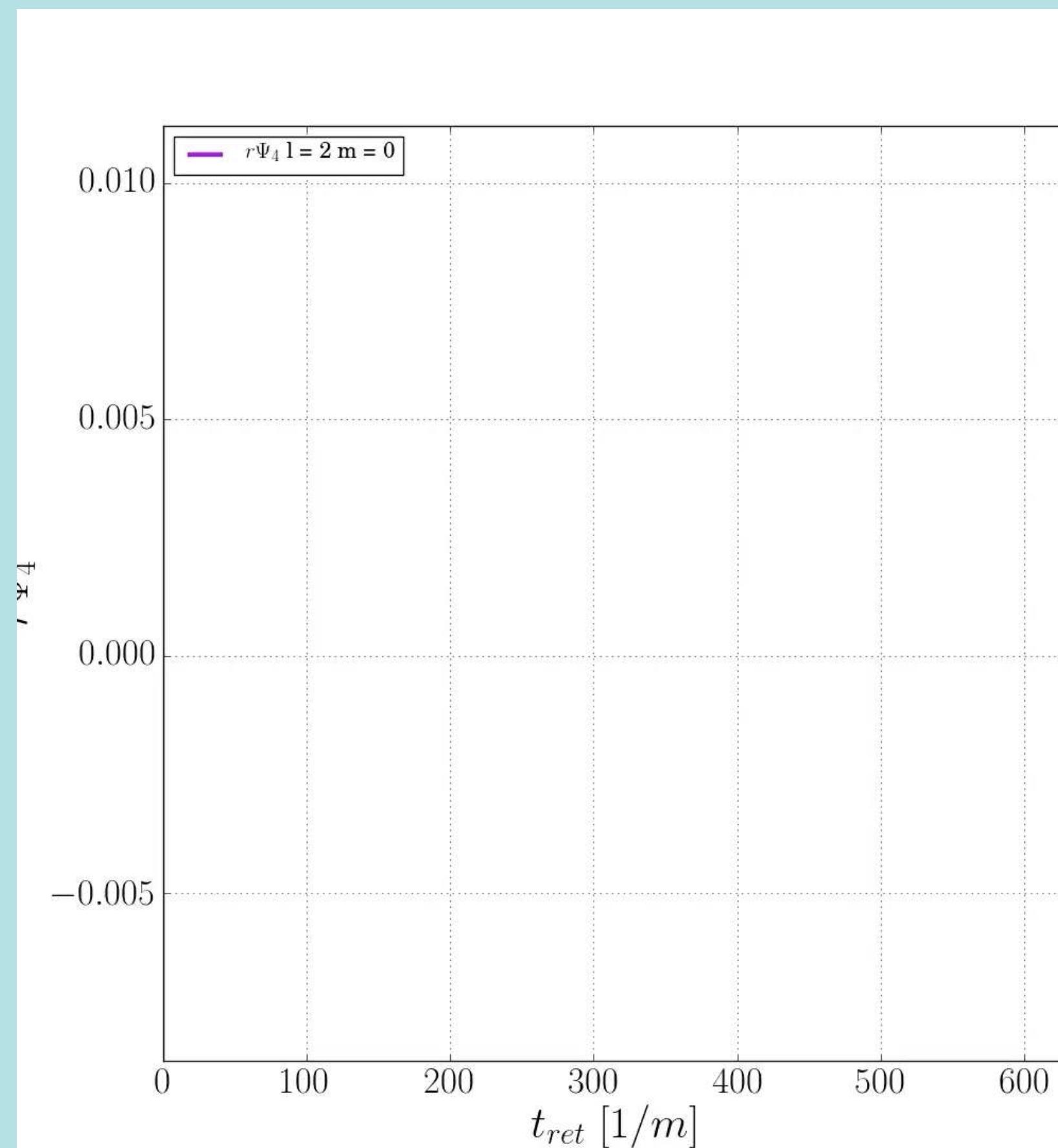


4. Compact objects



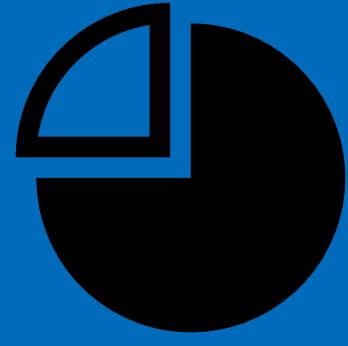
5. Prospects

Oscillaton collisions

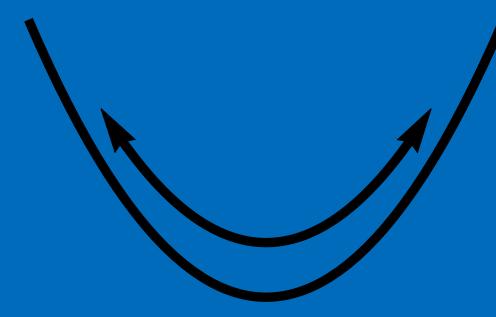


T. Helfer, E. A. Lim, MG and M. A. Amin, PRD 99 (2019), 044046

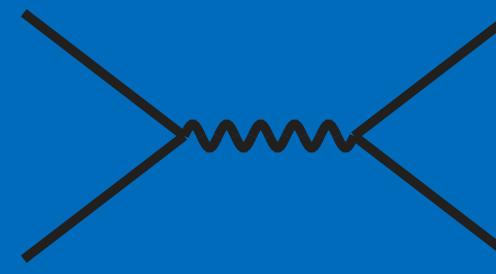
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs

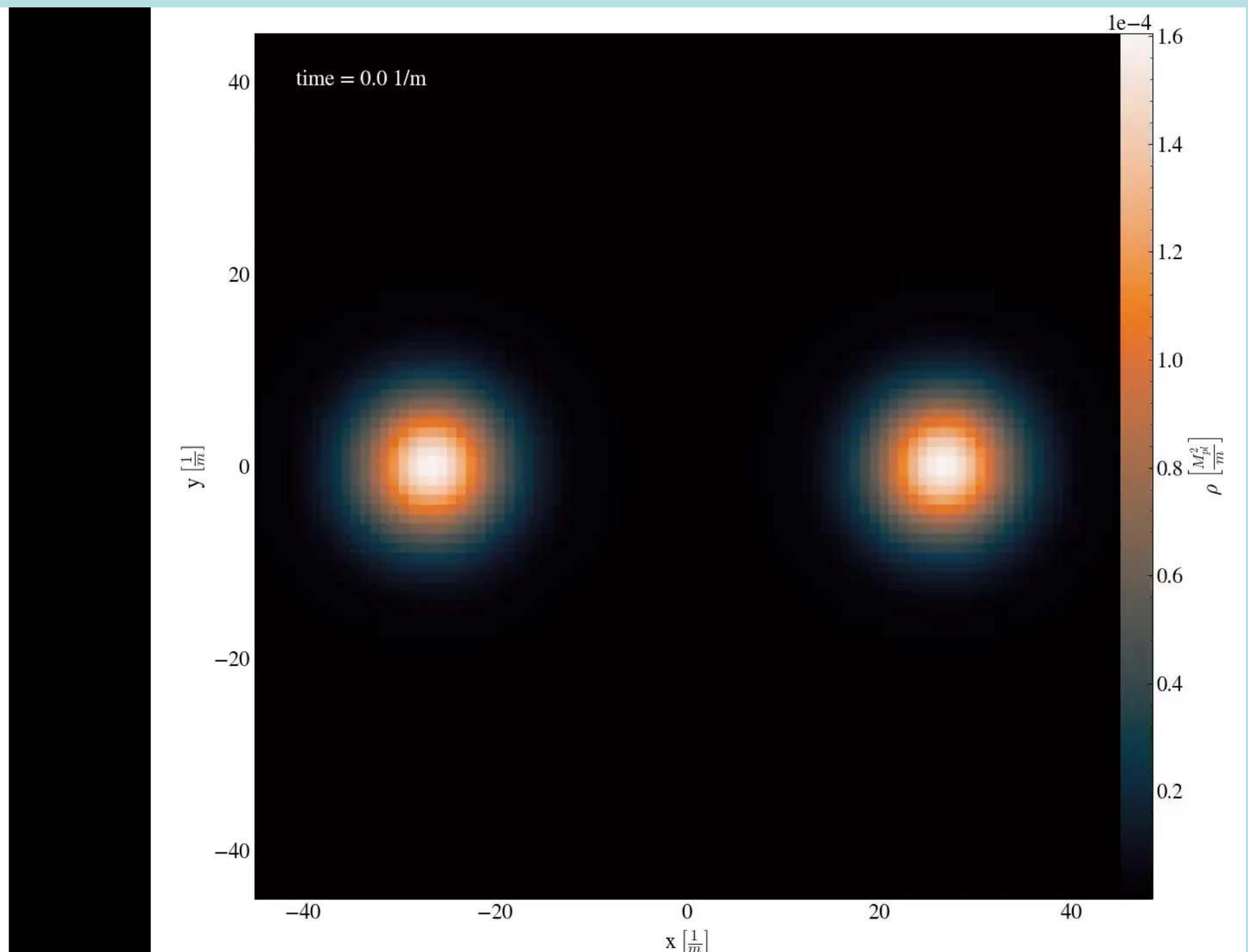
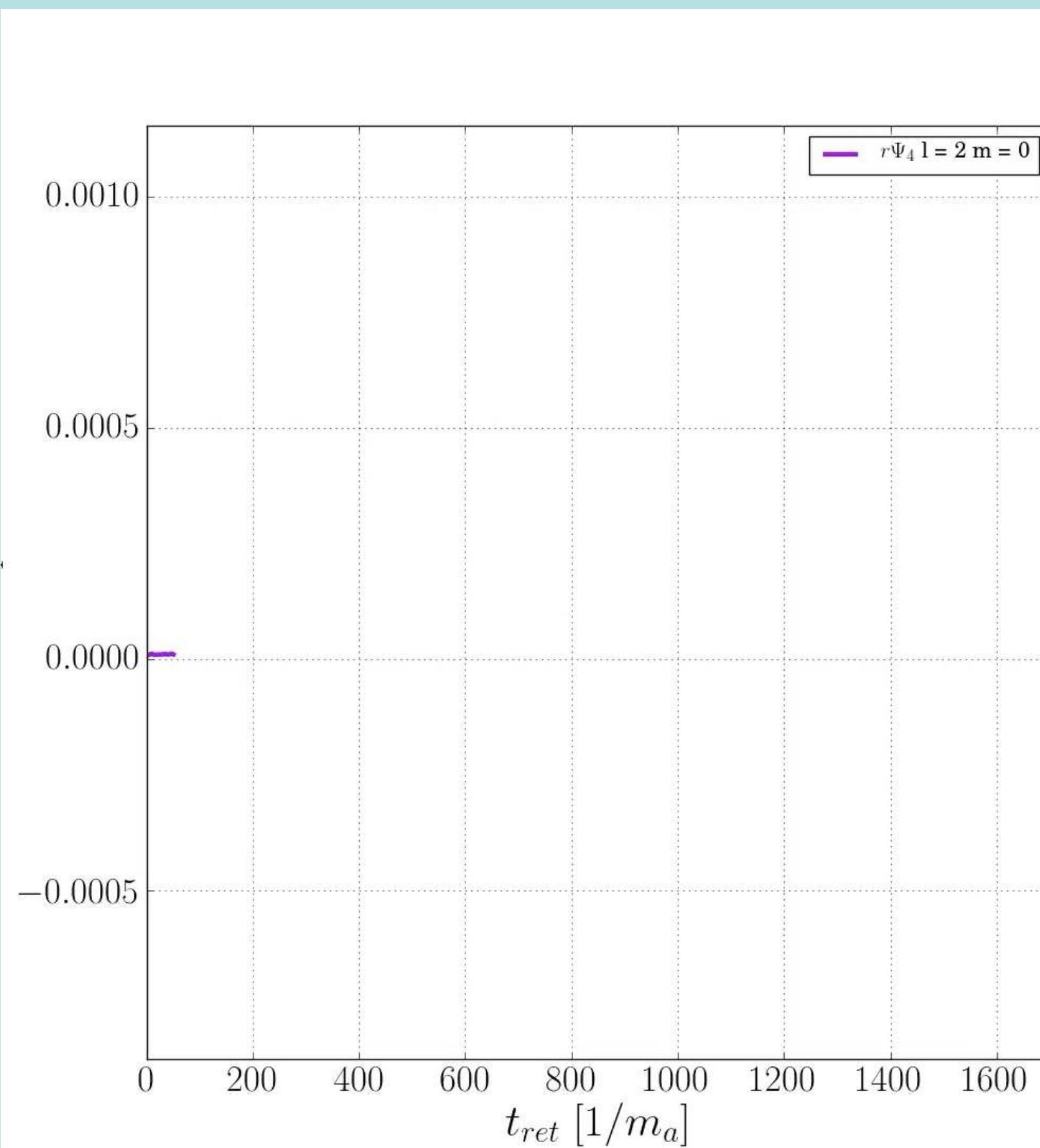


4. Compact objects



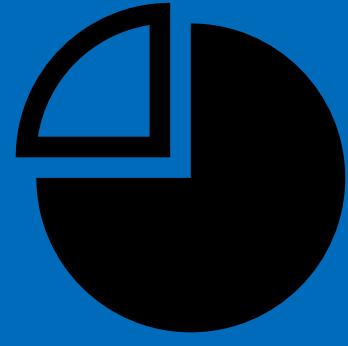
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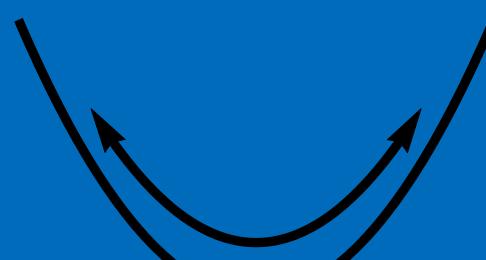


T. Helfer, E. A. Lim, MG and M. A. Amin, PRD 99 (2019), 044046

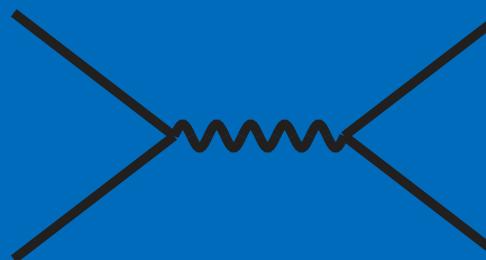
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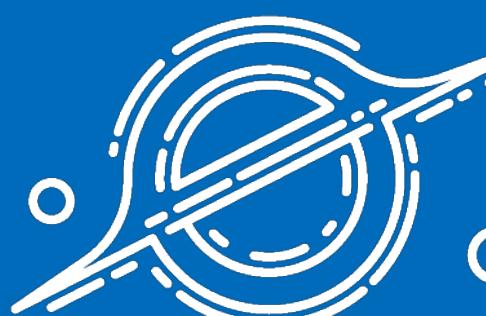
2. Inflation & reheating



3. FIMPs

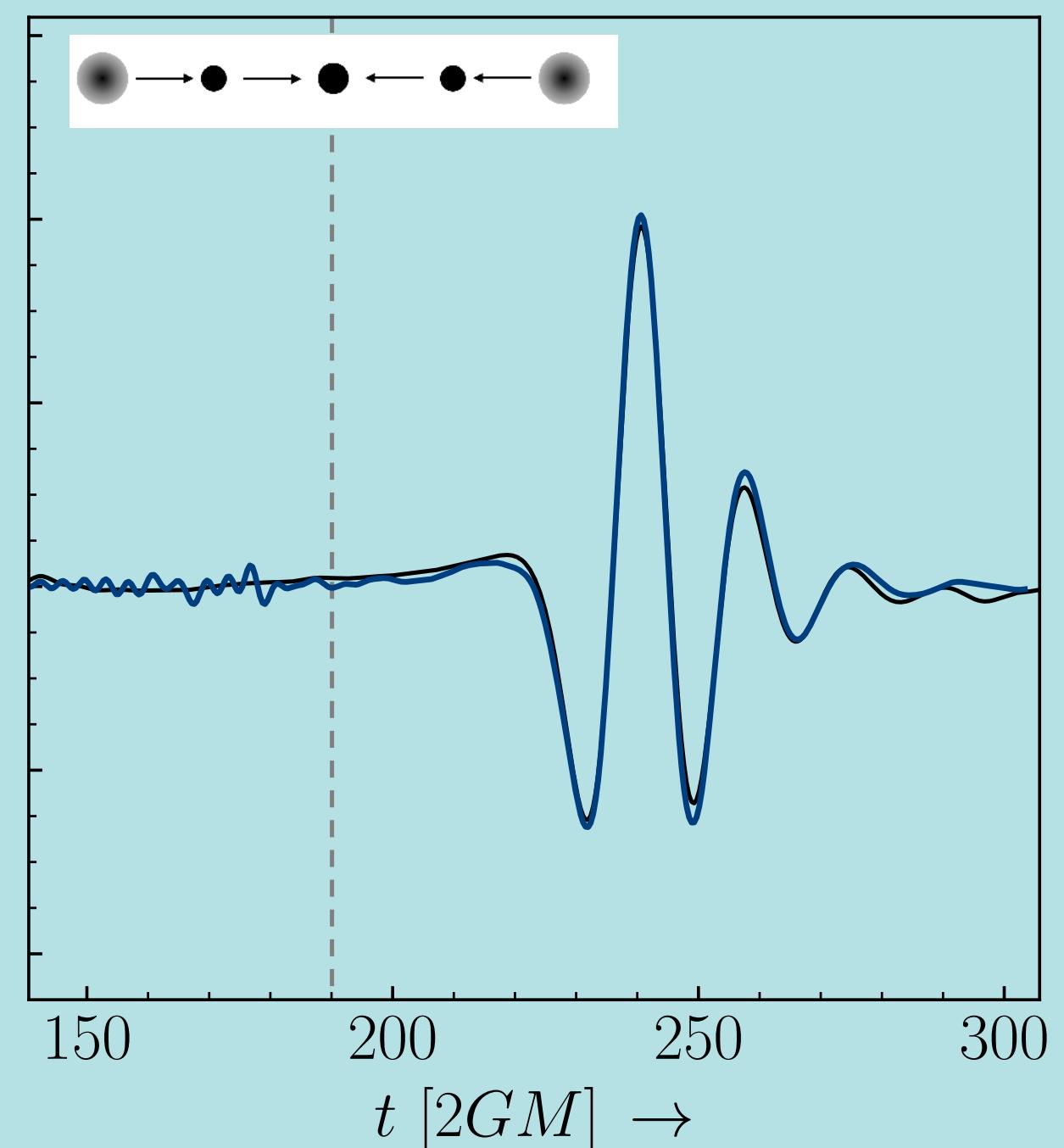
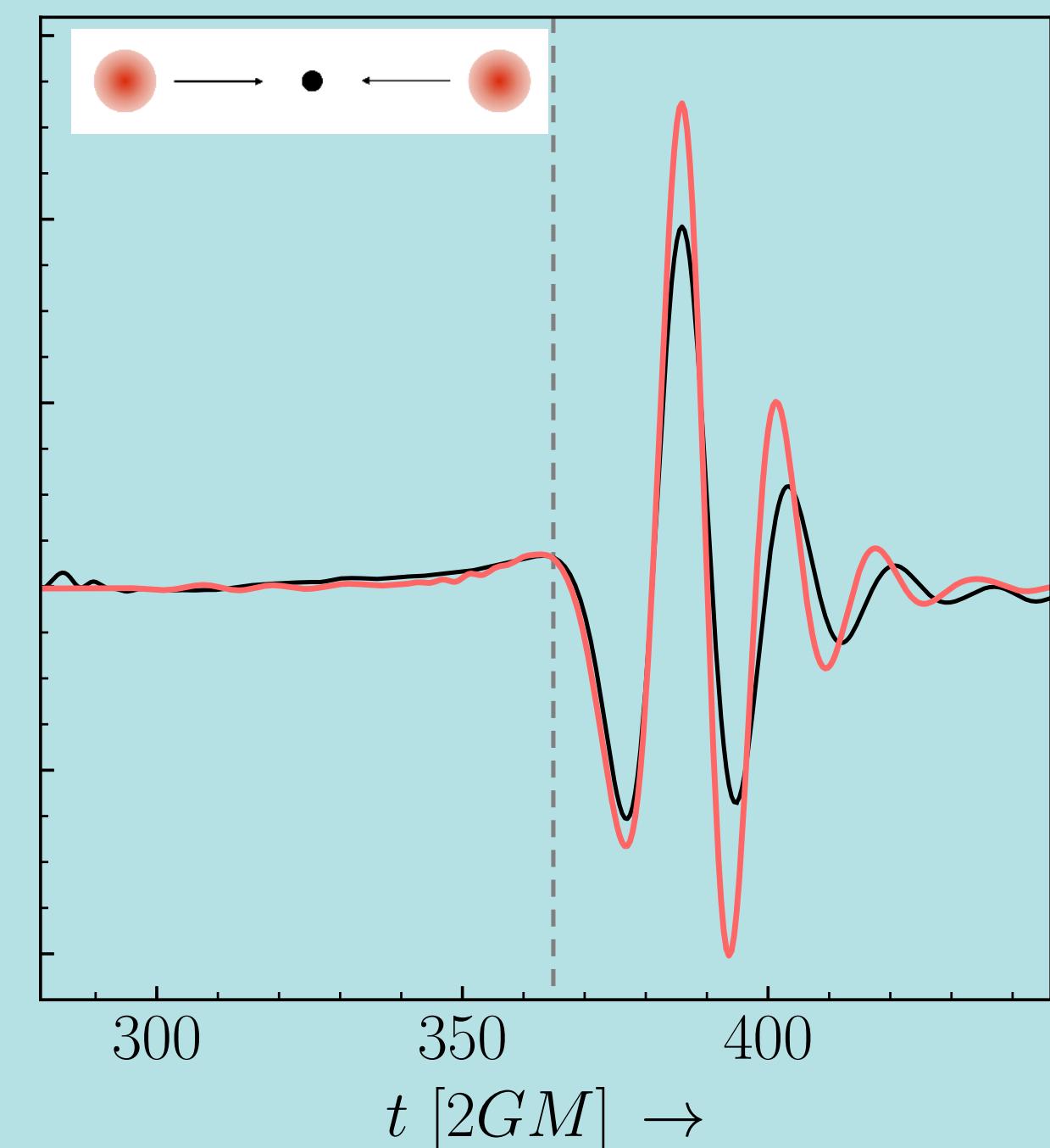
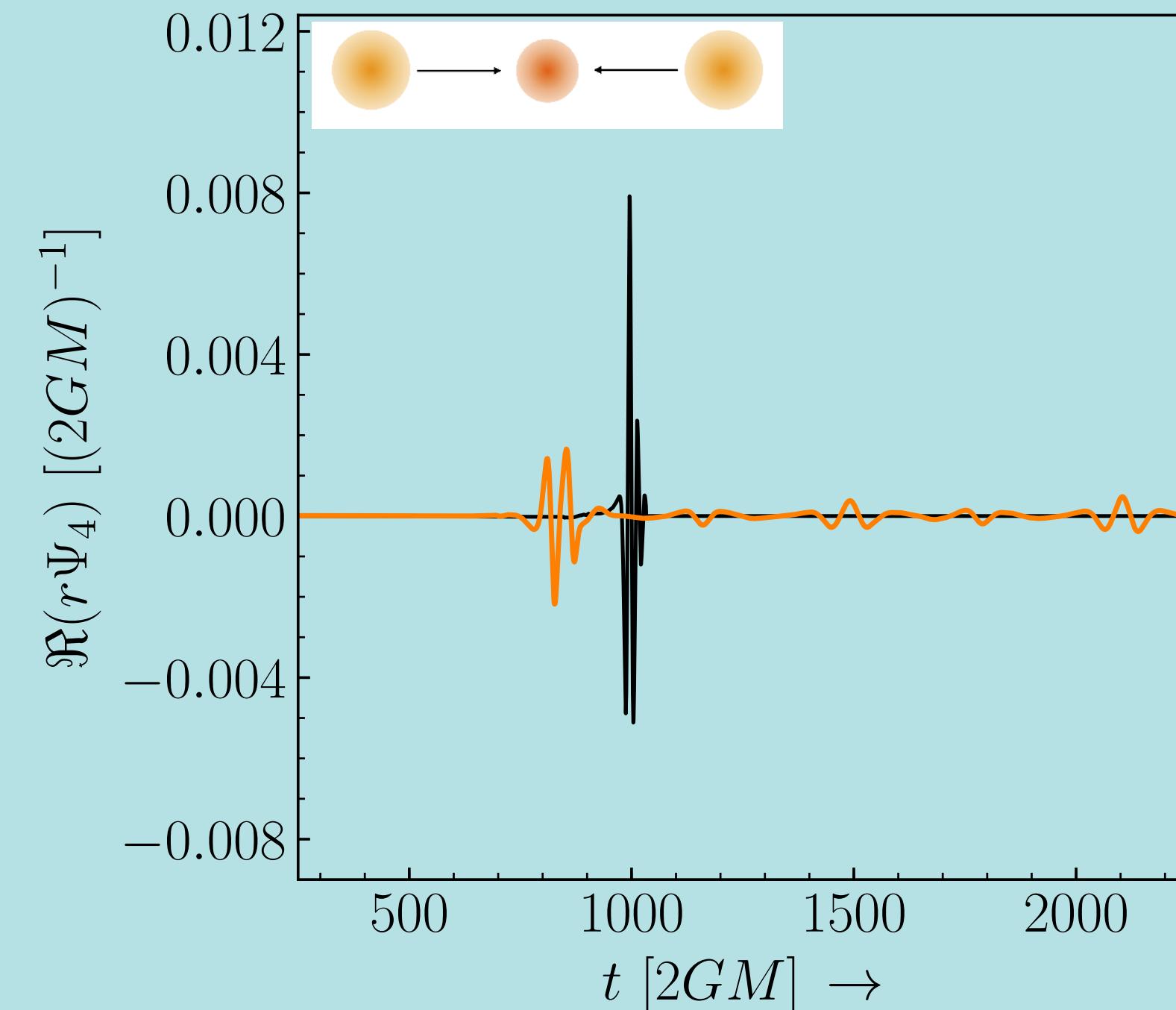


4. Compact objects



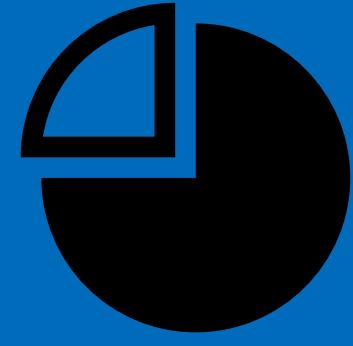
5. Prospects

Oscillaton collisions

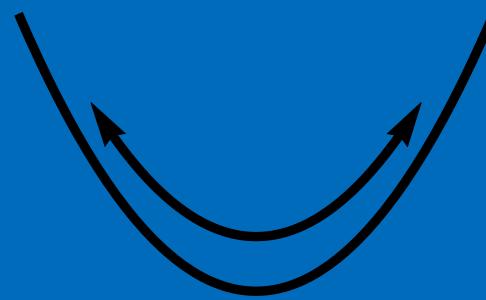


LIGO range $10^{-12} \text{ eV} \lesssim m \lesssim 10^{-10} \text{ eV}$

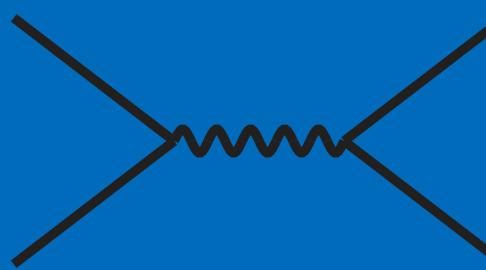
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs



4. Compact objects



5. Prospects

Dark matter from inflation

ON THE CONCENTRATION OF RELIC MAGNETIC MONOPOLES IN THE UNIVERSE

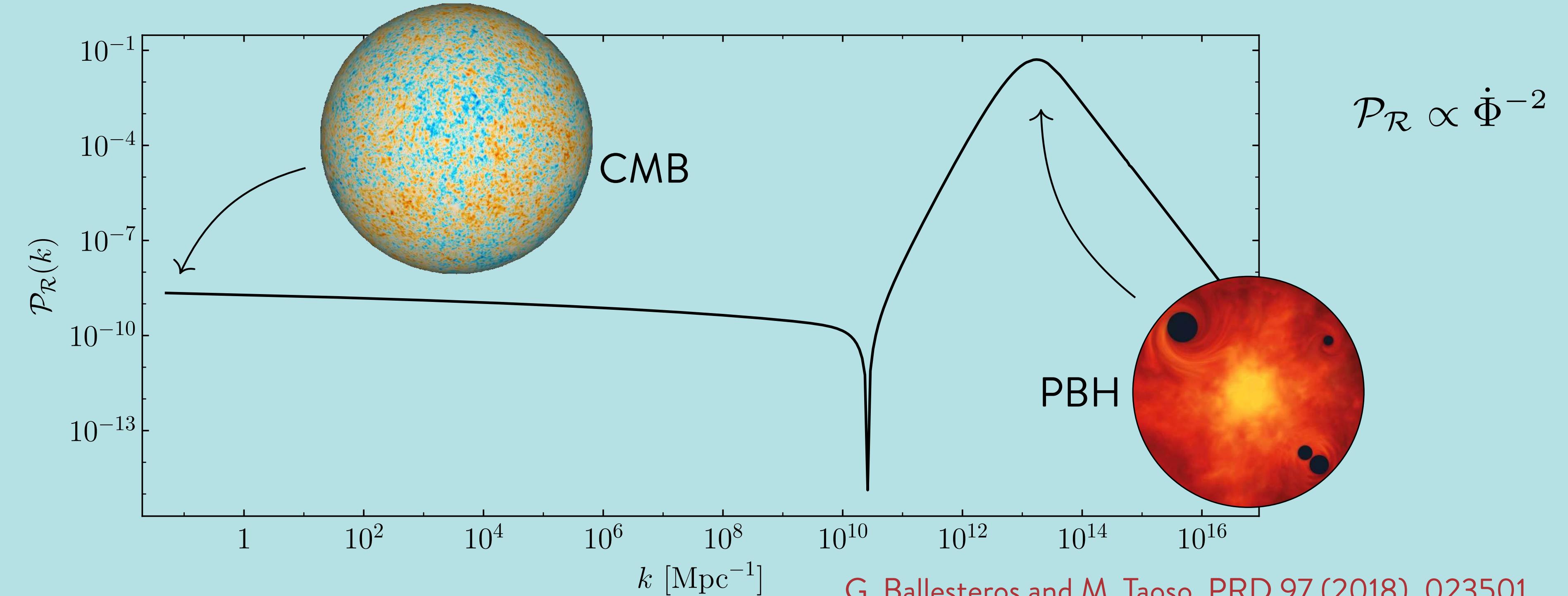
Ya.B. ZELDOVICH and M.Yu. KHOPOV

Institute of Applied Mathematics, Academy of Sciences of the USSR, Moscow 125047, USSR

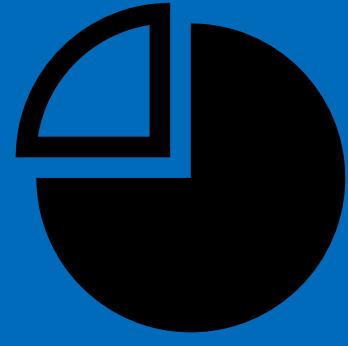
PLB 79 (1978), 239

Inflation efficiently dilutes
relics, dangerous or not

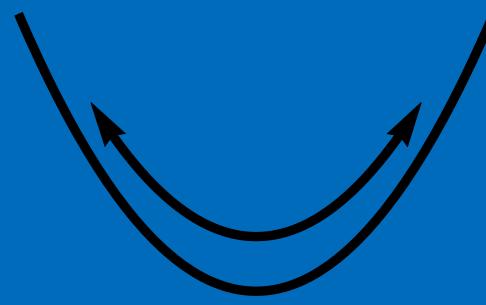
But inflation can lead to overdensities



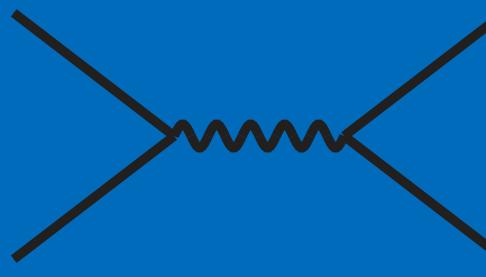
1. Beyond WIMPs



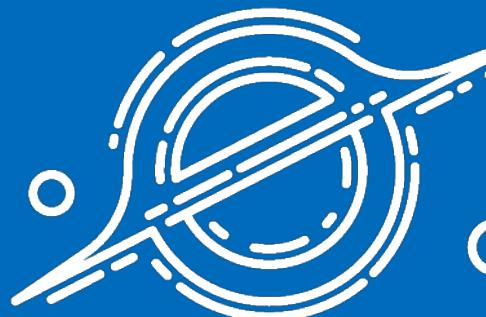
2. Inflation & reheating



3. FIMPs



4. Compact objects



5. Prospects

Dark matter from inflation

ON THE CONCENTRATION OF RELIC MAGNETIC MONOPOLES IN THE UNIVERSE

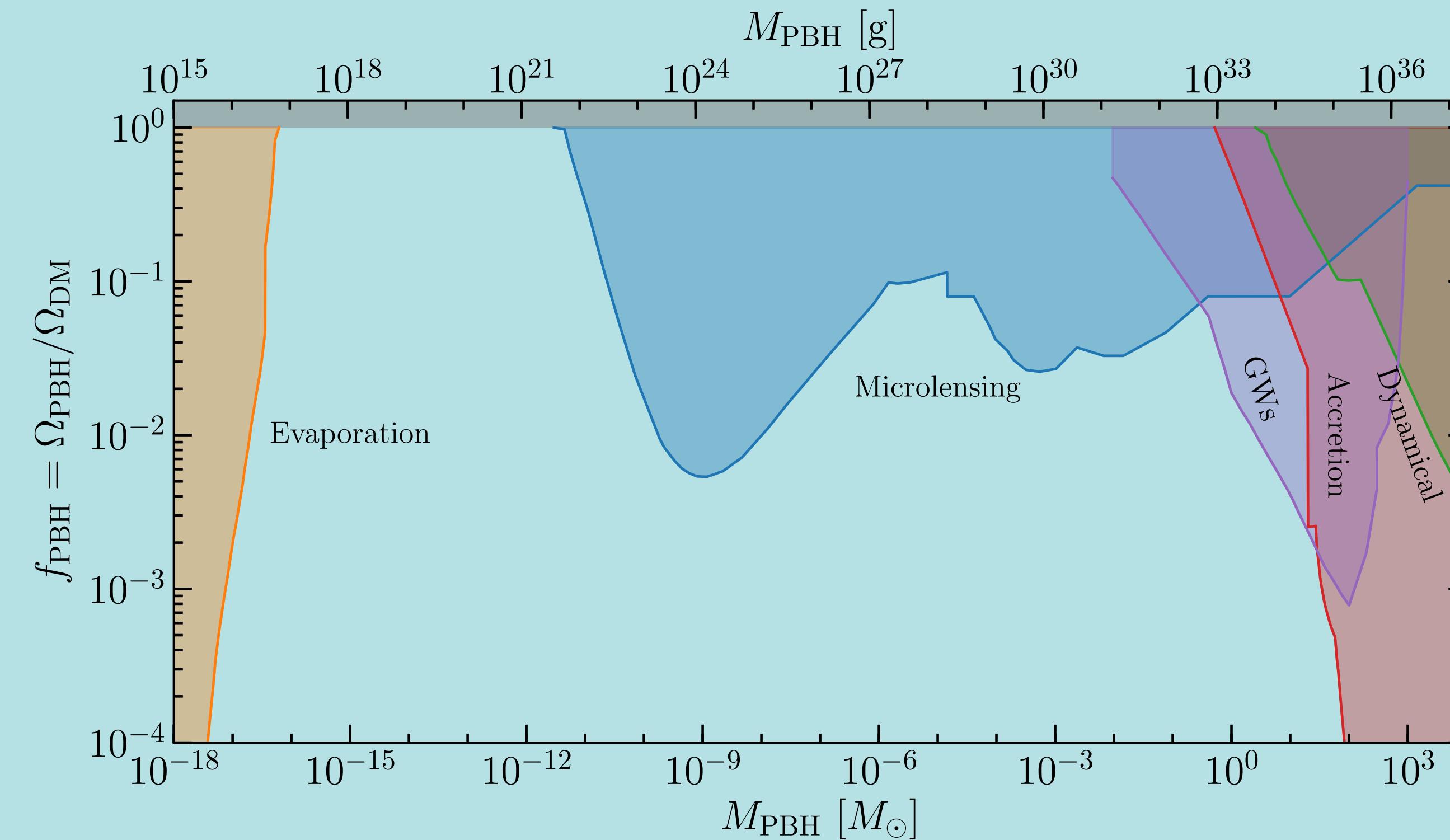
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PLB 79 (1978), 239

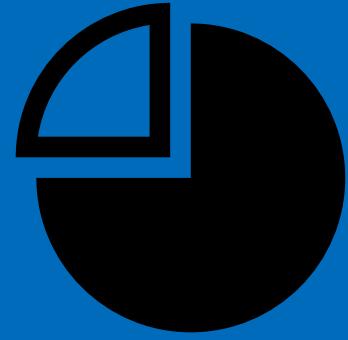
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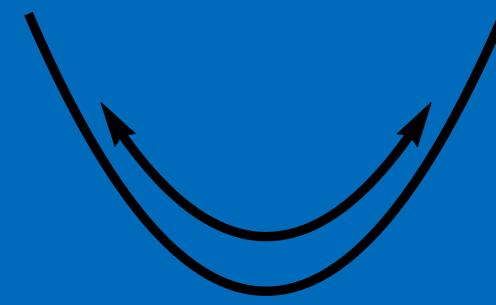


github.com/bradkav/PBHbounds

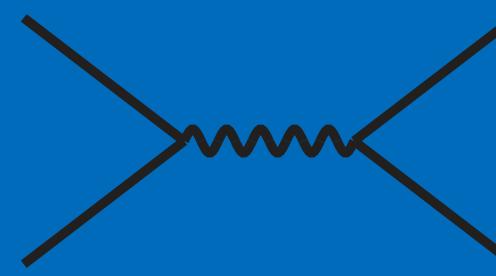
1. Beyond WIMPs



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3. FIMPs

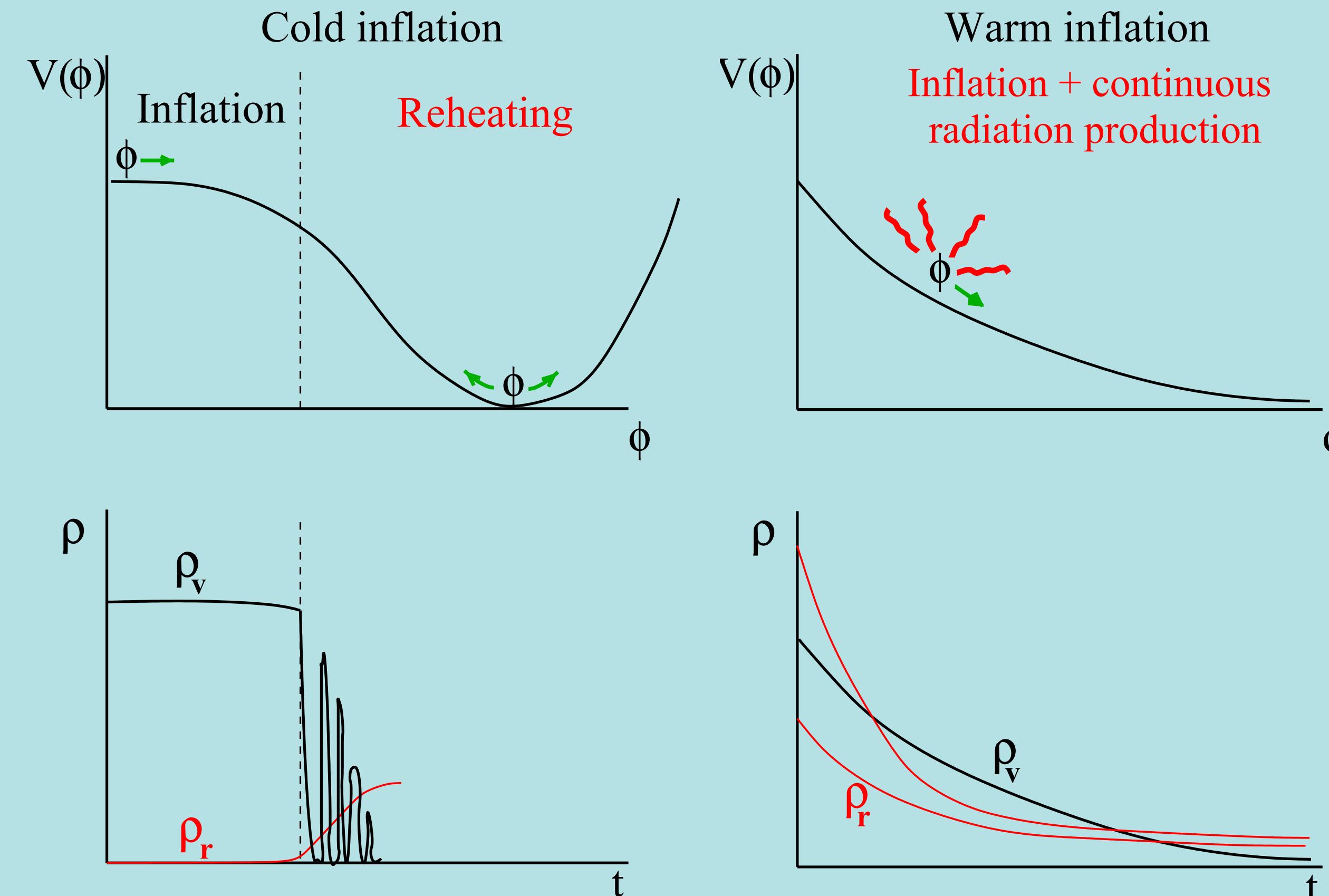


4. Compact objects



5. Prospects

Warm inflation?



A. Berera, PRL 75 (1995), 3218

A. Berera, I. G. Moss and R. O. Ramos, Rept. Prog. Phys. 72 (2009), 026901

Inflaton slows down by thermal friction

$$\ddot{\Phi} + (3H + \Gamma)\dot{\Phi} + V_{\Phi} = 0$$

$$\dot{\rho}_r + 4H\rho_r - \Gamma\dot{\Phi}^2 = 0$$

Thermal noise is an extra source of density fluctuations

$$\delta\ddot{\Phi}_k + (3H + \Gamma)\delta\dot{\Phi}_k = \xi_k + \dots$$



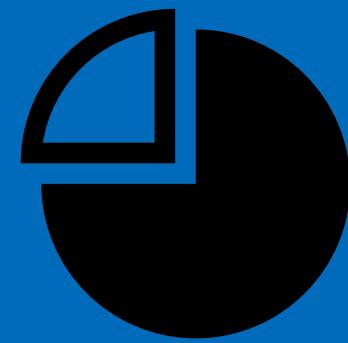
Daniel Green @nu_phases · 1 jun. ...
3/8 The inflaton needs to continually produce particles

Problem: most couplings that do this will destroy inflation / scale invariance

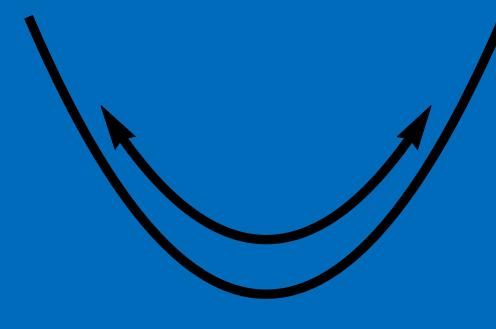
Worse problem: If you write a coupling that preserves scale invariance, it was shown you don't get normal friction

arxiv.org/abs/1109.4192

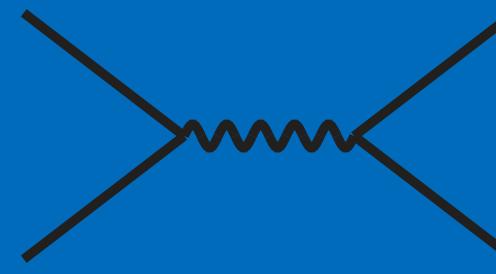
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs



4. Compact objects



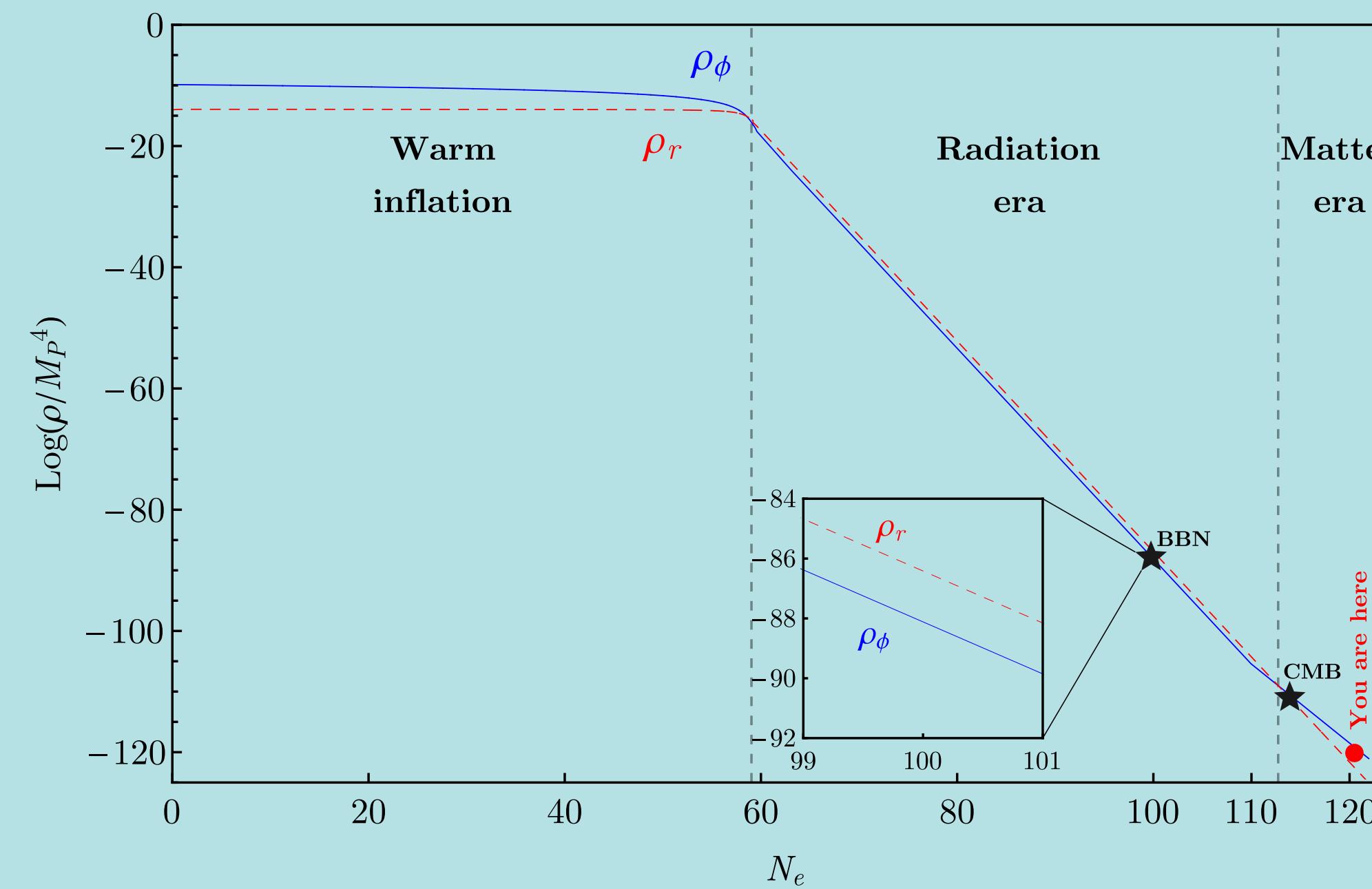
5. Prospects

Warm inflation?

A way around? Warm Little Inflation

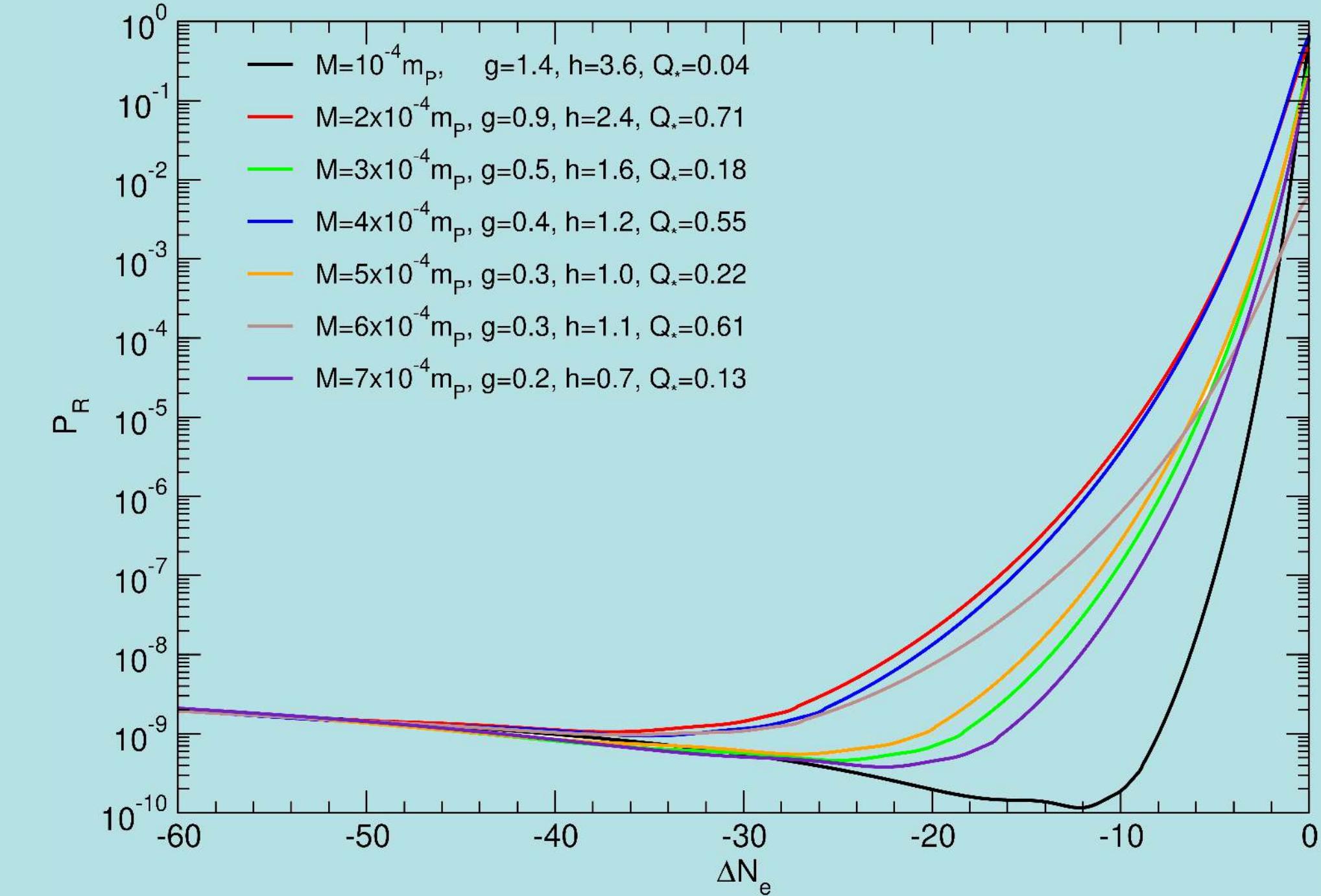
(Φ as a pseudo-Nambu-Goldstone boson)

Leftover Φ as DM



J. Rosa and L. Ventura, PRL 122 (2019), 161301

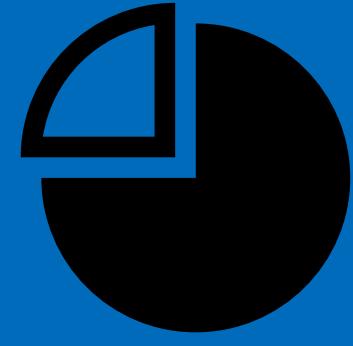
PBH from WLI



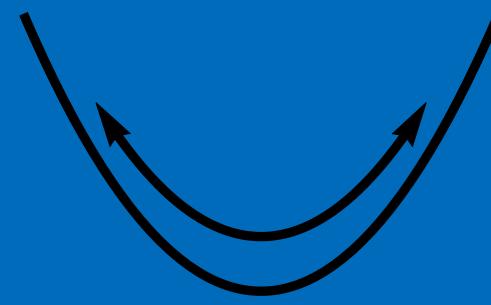
M. Bastero-Gil and M. Díaz-Blanco, arXiv:2105.08045 [hep-ph]

A. Pérez, MG, G. Ballesteros, M. Pierre, J. Rey, on it

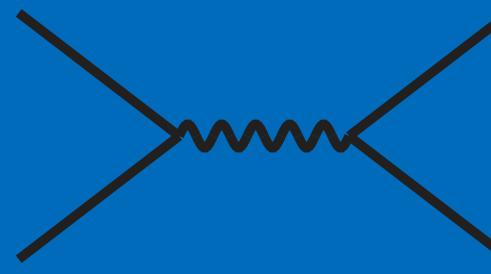
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2. Inflation & reheating



3. FIMPs



4. Compact objects

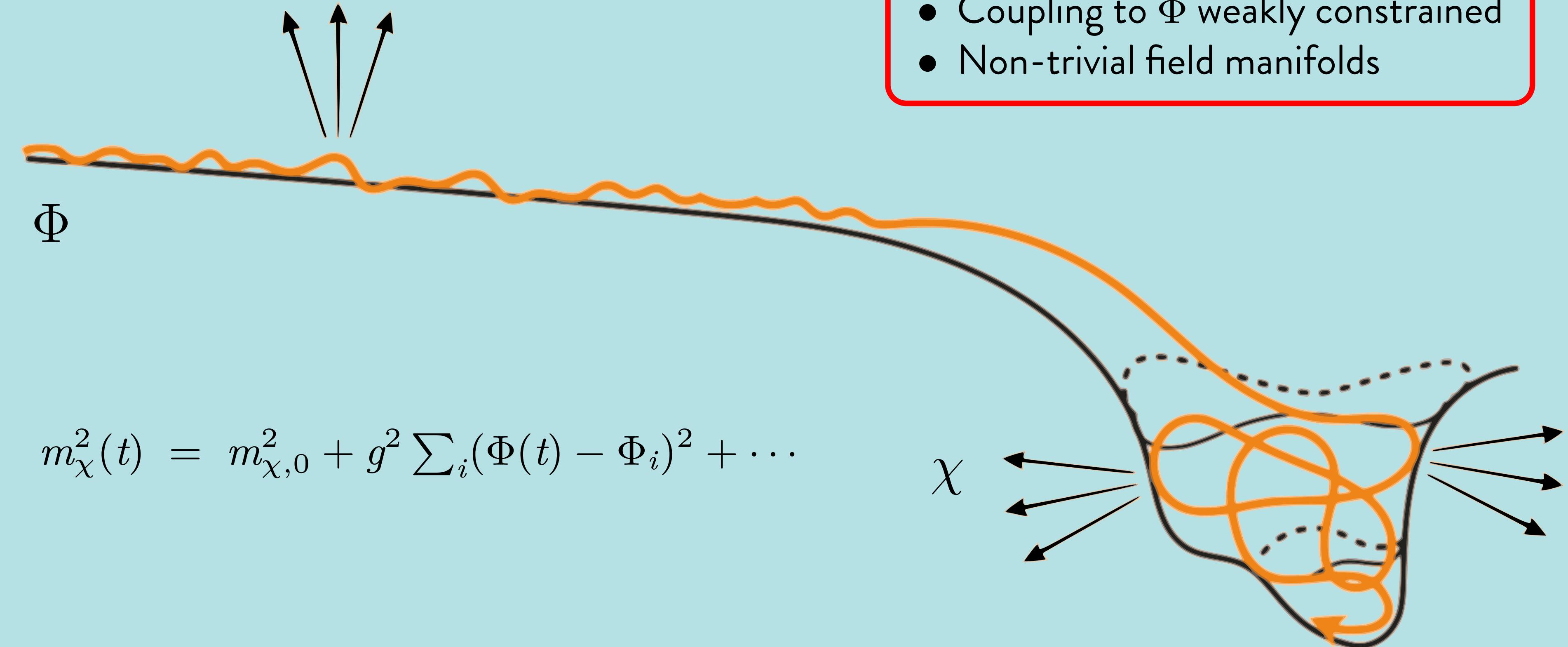


5. Prospects

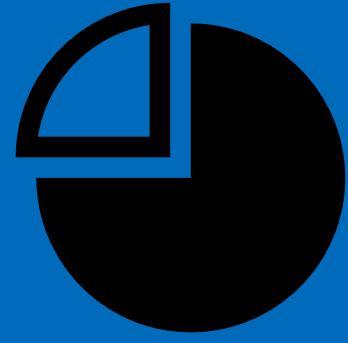
Complexity in the early Universe

Particle theory

- SM UV completions $N_F \gg 1$
- Coupling to Φ weakly constrained
- Non-trivial field manifolds



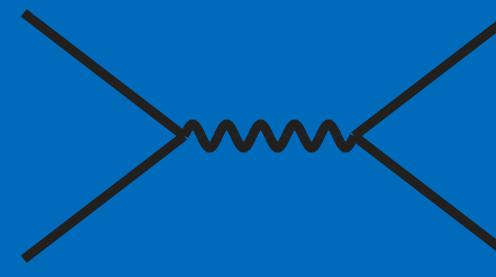
1. Beyond WIMPs



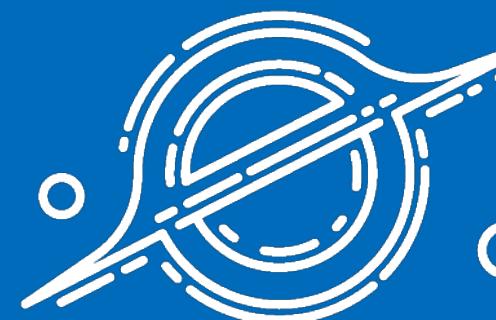
2. Inflation & reheating



3. FIMPs



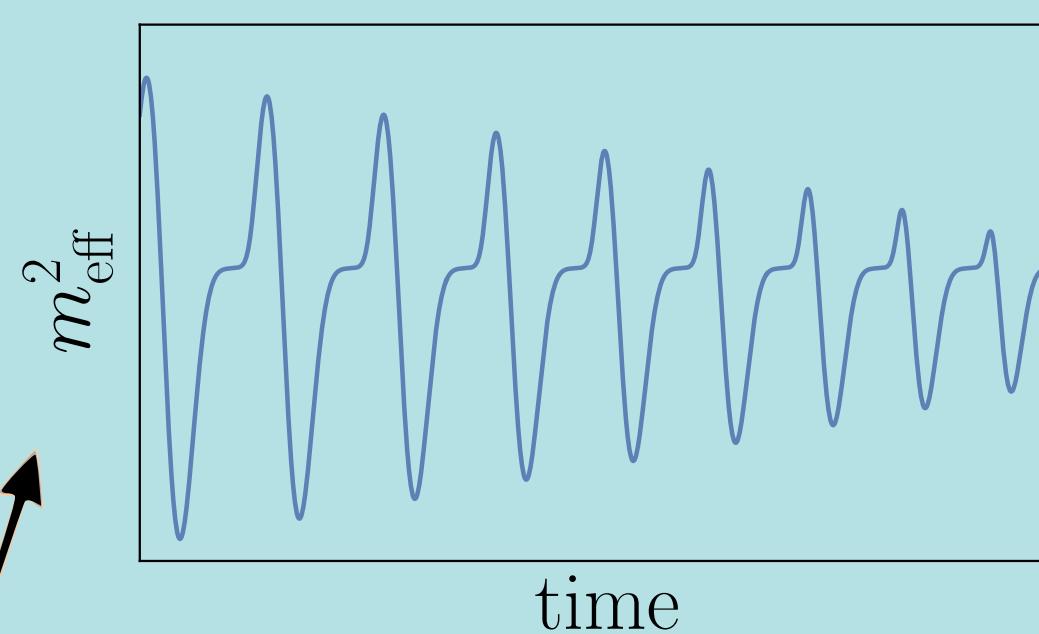
4. Compact objects



5. Prospects

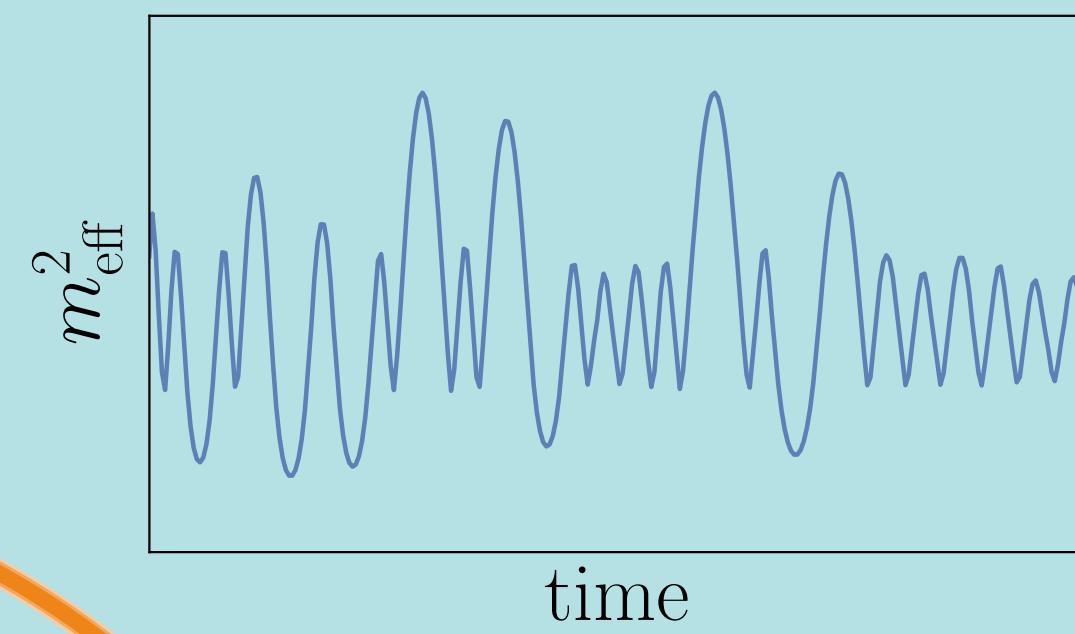
Complexity in the early Universe

(axion monodromy)



R. Flauger et al., JCAP 10 (2017), 058
J. Ellis, MG et al., JCAP 07 (2017), 006

(flipped SU(5))



Φ

χ

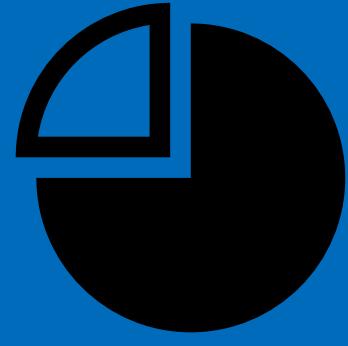
$$m_\chi^2(t) = m_{\chi,0}^2 + g^2 \sum_i (\Phi(t) - \Phi_i)^2 + \dots$$

R. Easter and L. McAllister, JCAP 05 (2006), 018

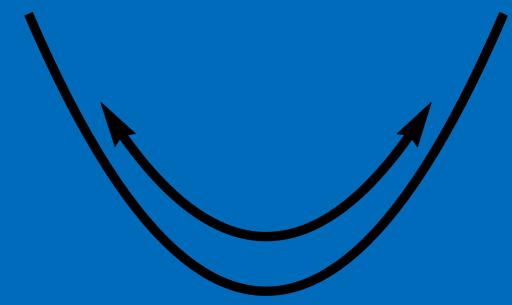
D. Green et al., PRD 80 (2009), 063533

Y. Nakai, R. Namba and Z. Wang, JHEP 12 (2020), 170

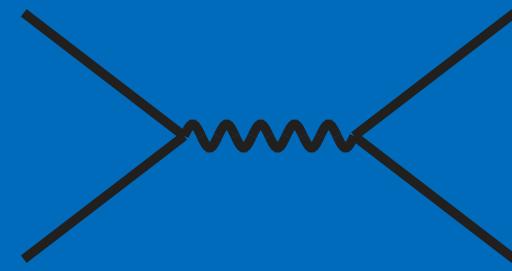
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs



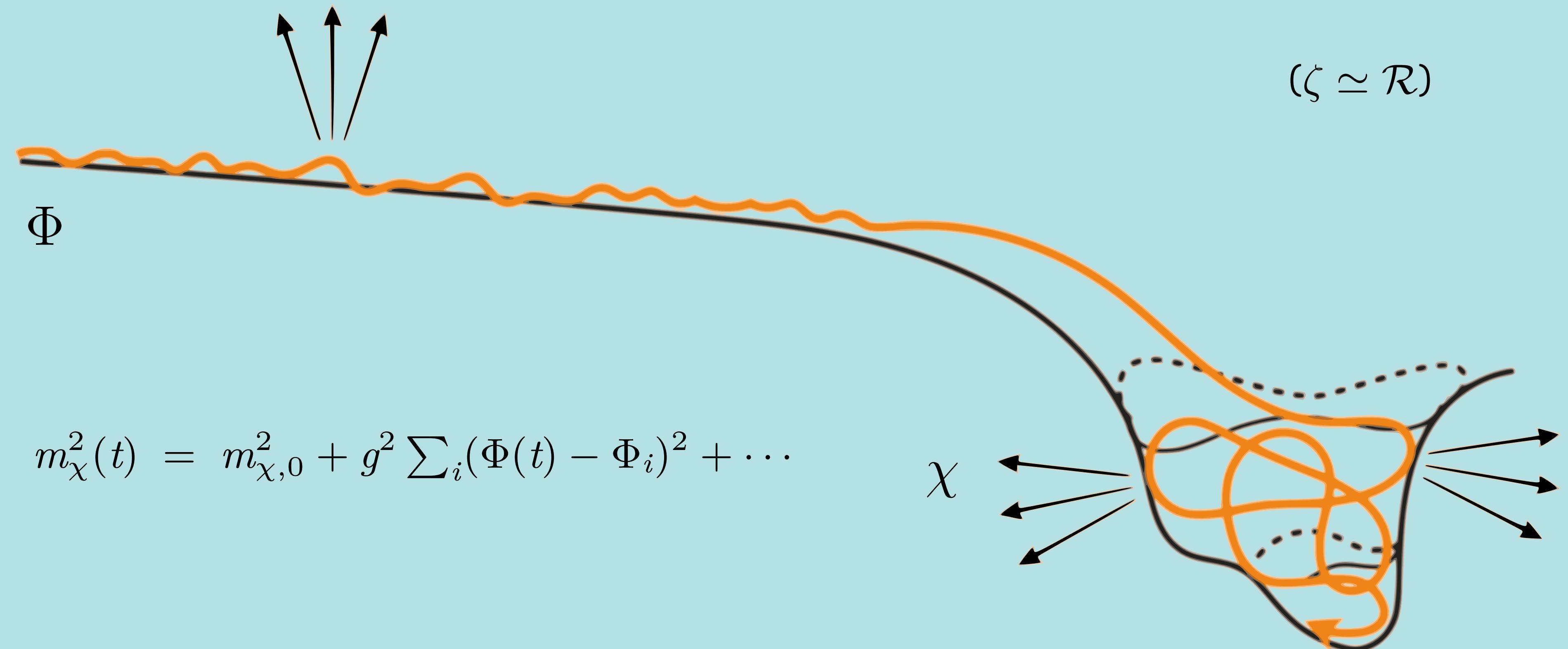
4. Compact objects



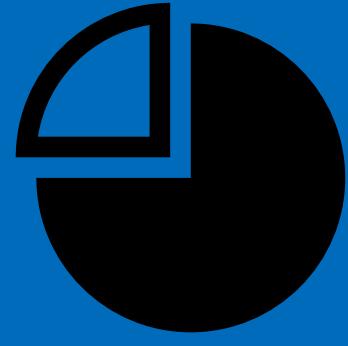
5. Prospects

Complexity in the early Universe

background dynamics \longrightarrow particle production $\langle \chi_{k_1} \chi_{k_2} \cdots \rangle$ \longleftrightarrow curvature fluctuations $\langle \zeta_{k_1} \zeta_{k_2} \cdots \rangle$



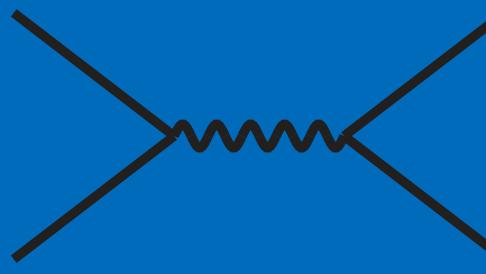
1. Beyond WIMPs



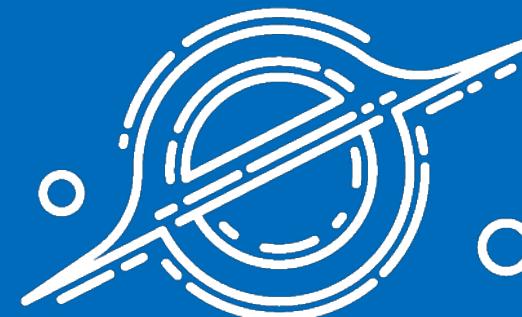
2. Inflation & reheating



3. FIMPs



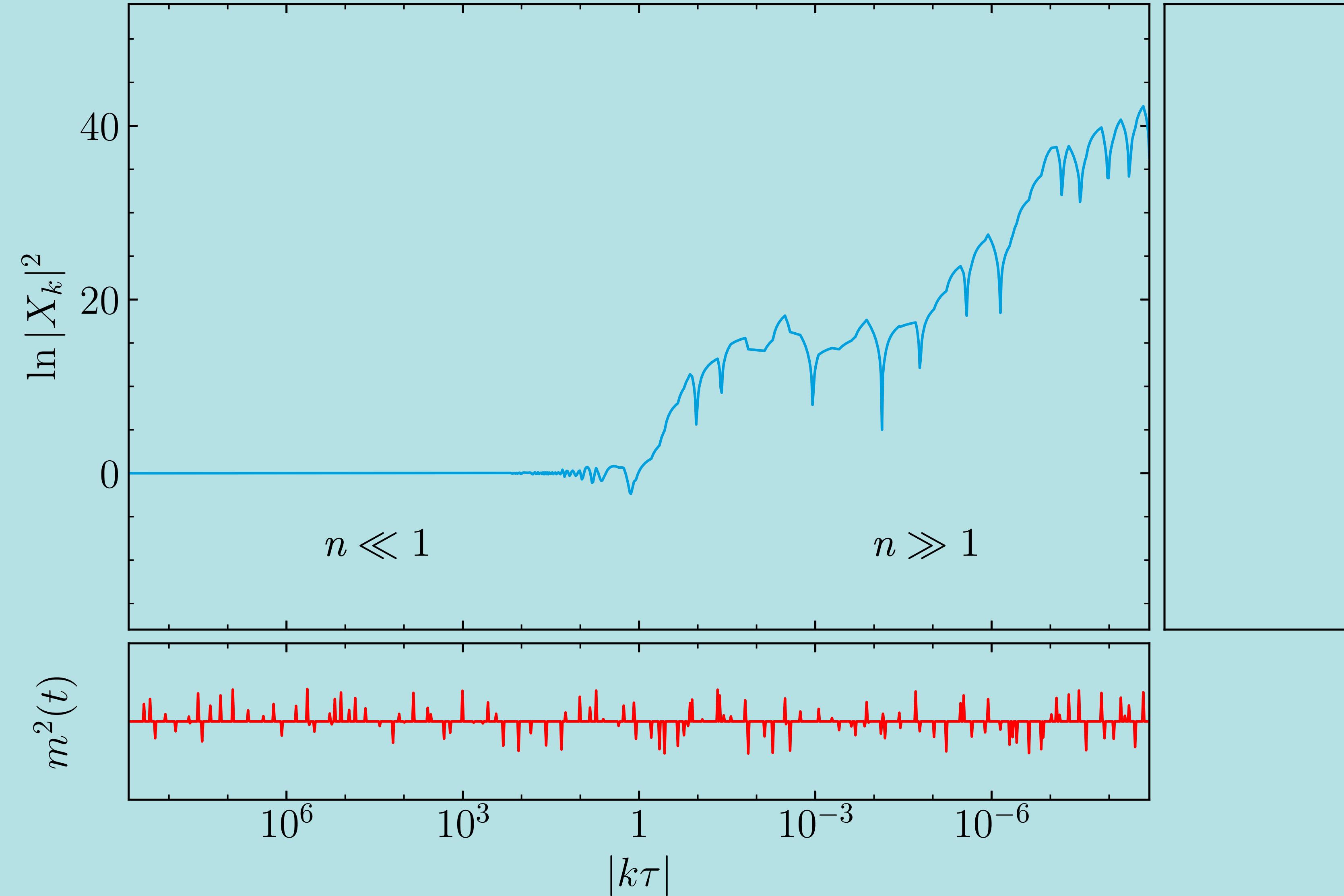
4. Compact objects



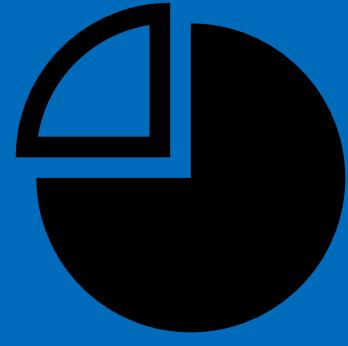
5. Prospects

A (conformal) spectator in dS

MG, M. Amin, S. Carlsten and D. Green, JCAP 05 (2019), 012



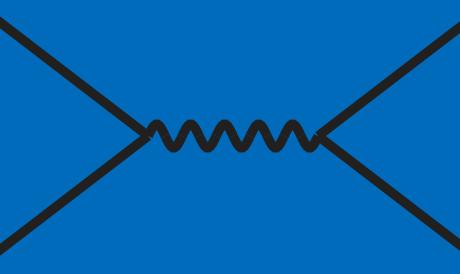
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs

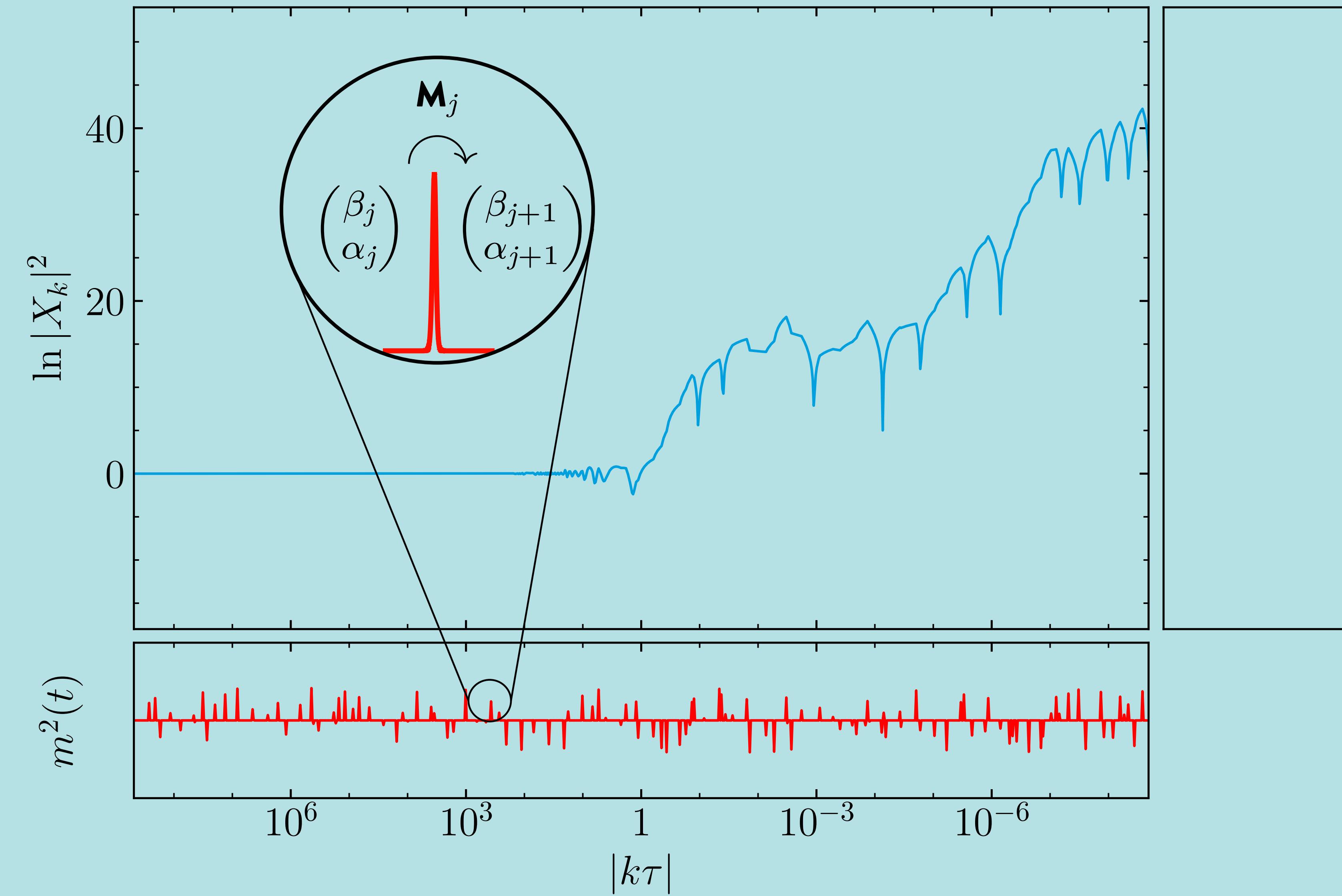


4. Compact objects

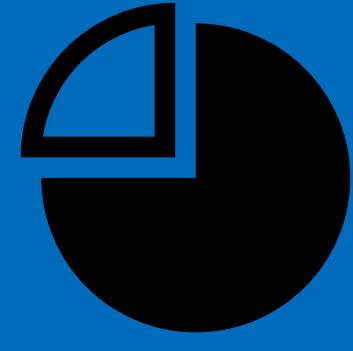


5. Prospects

A (conformal) spectator in dS



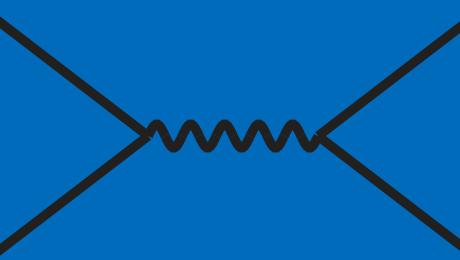
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs

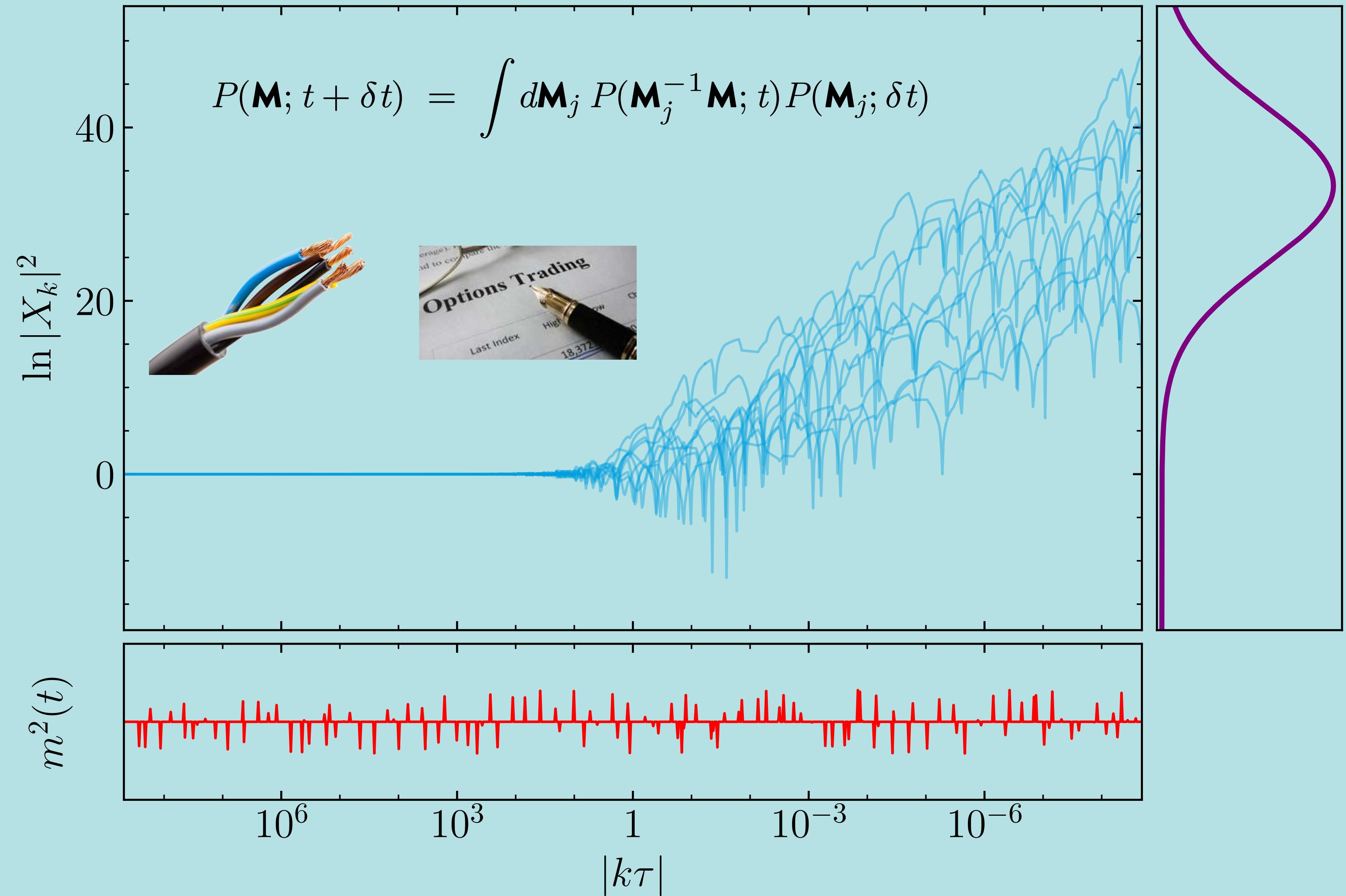


4. Compact objects

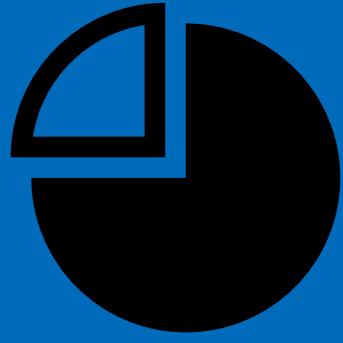


5. Prospects

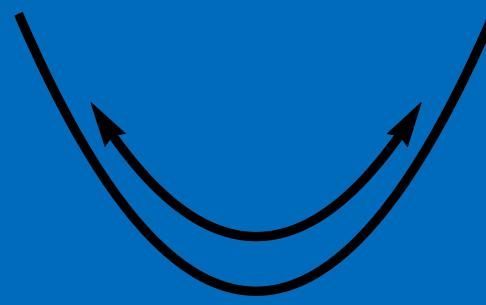
A (conformal) spectator in dS



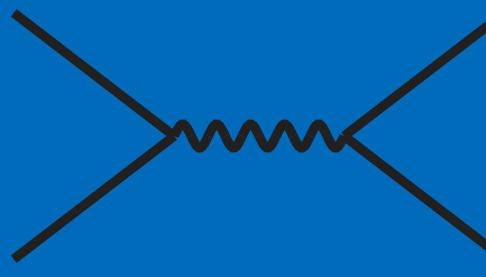
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs



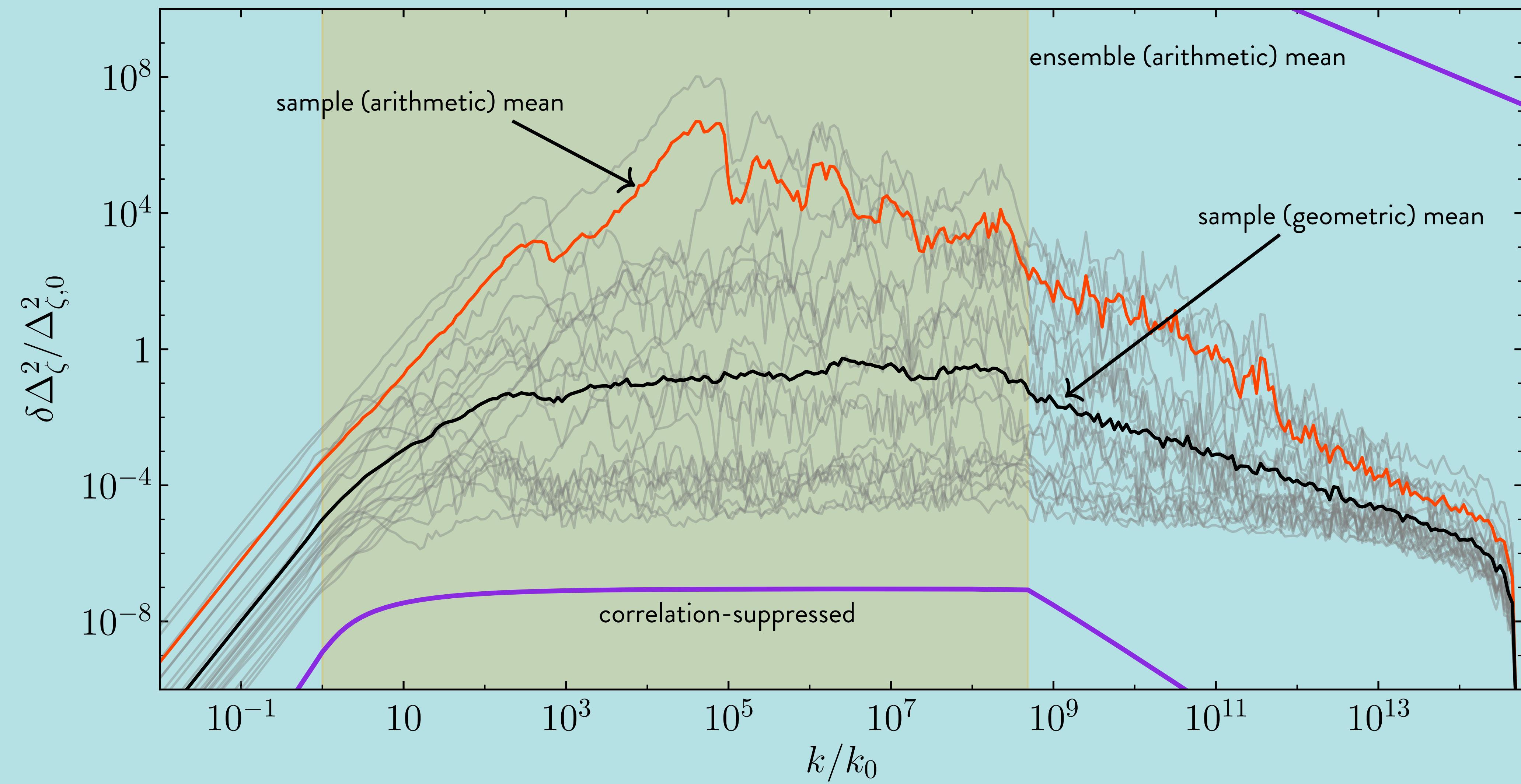
4. Compact objects



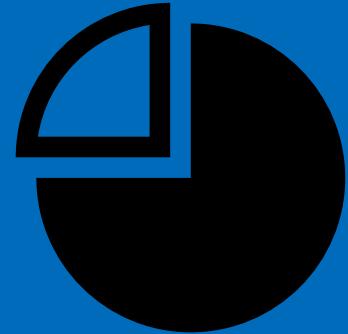
5. Prospects

A stochastically sourced power spectrum

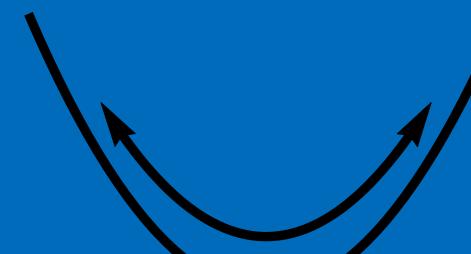
MG, M. A. Amin and D. Green, JCAP 06 (2020), 039



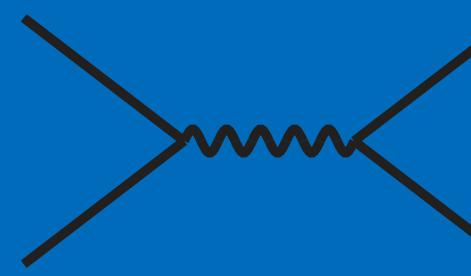
1. Beyond WIMPs



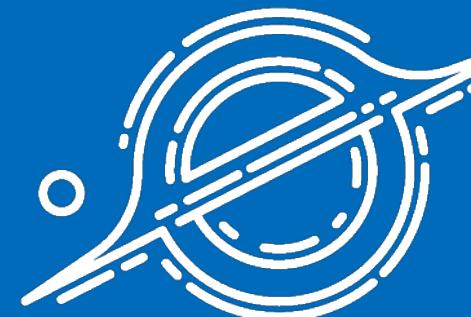
2. Inflation & reheating



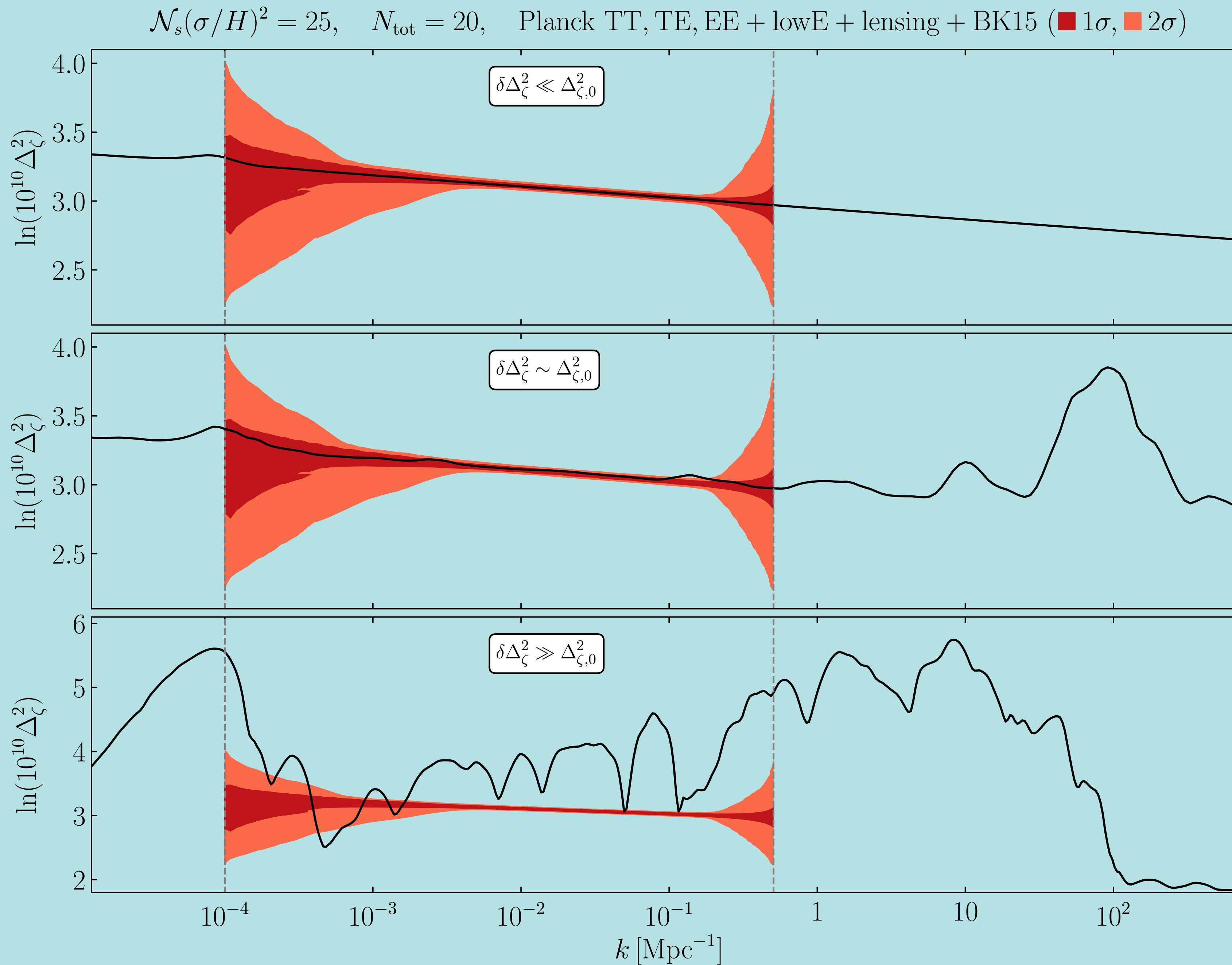
3. FIMPs



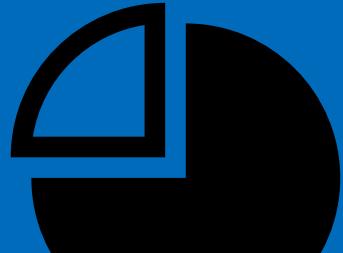
4. Compact objects



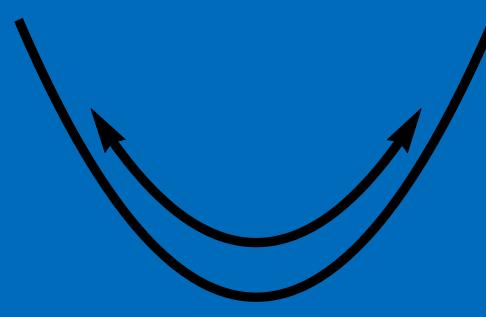
5. Prospects



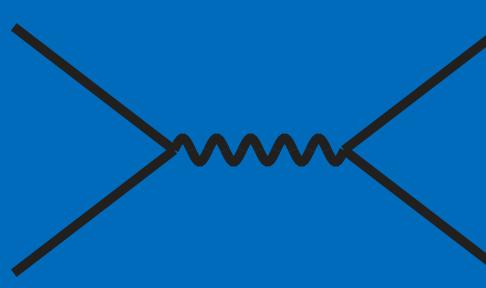
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs

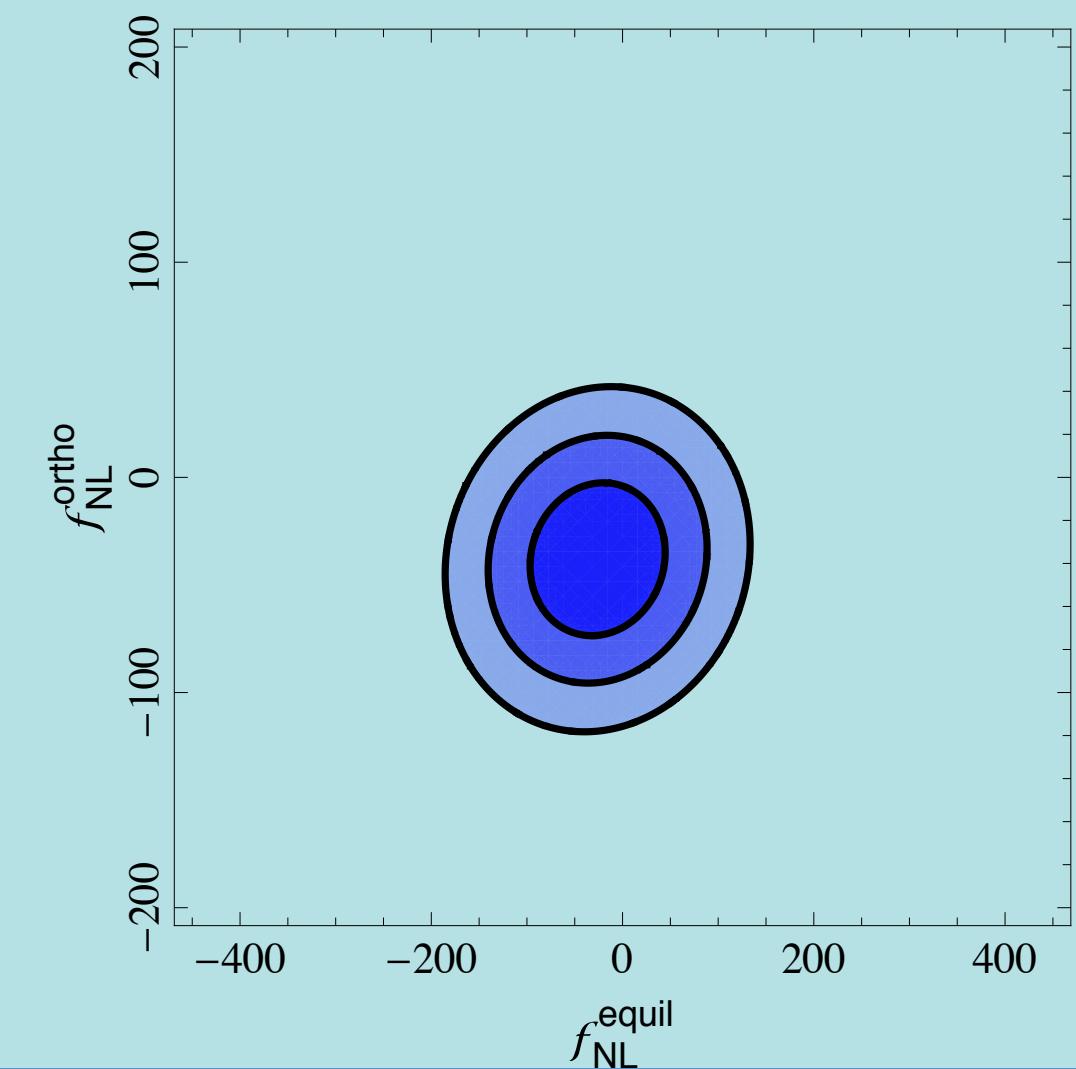
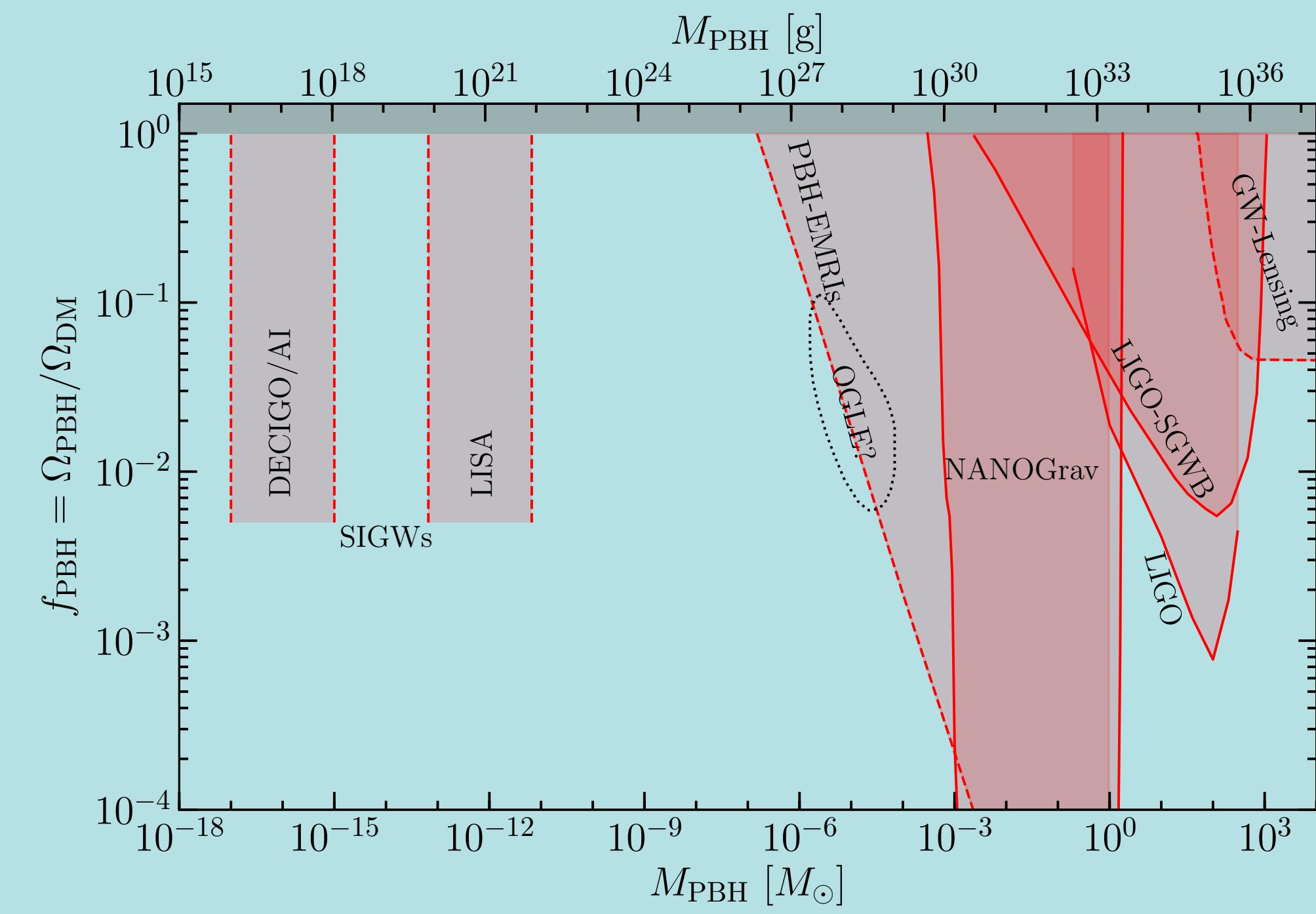
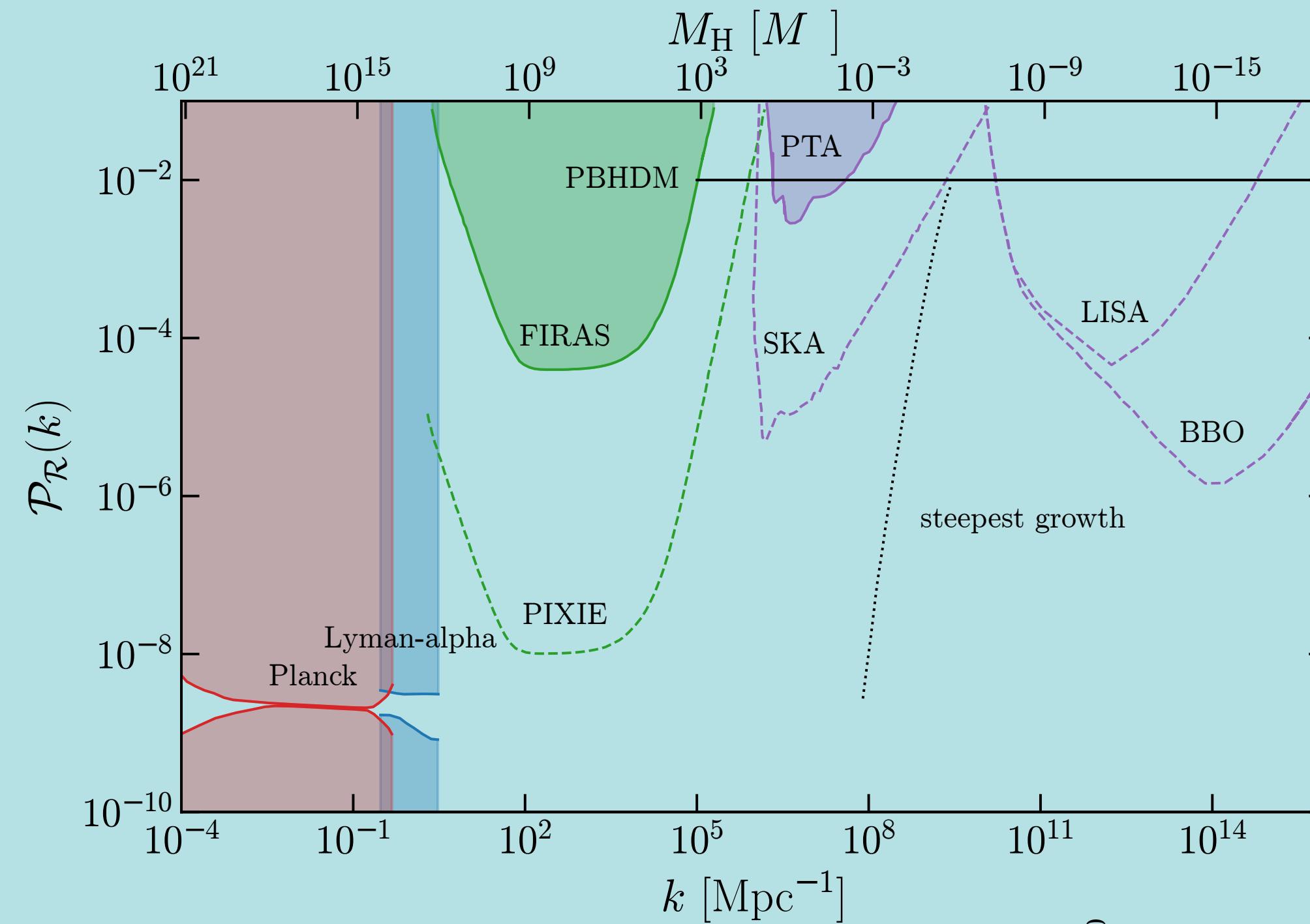


4. Compact objects

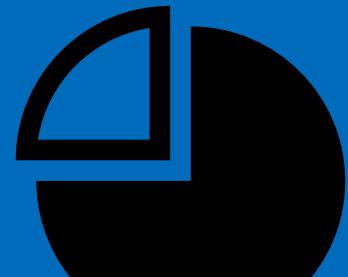


5. Prospects

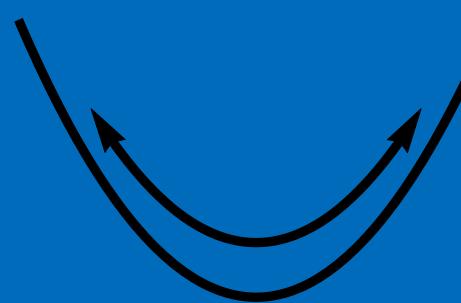
Prospects



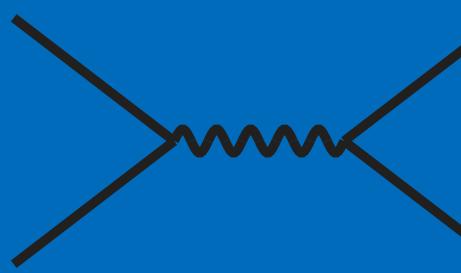
1. Beyond WIMPs



2. Inflation & reheating



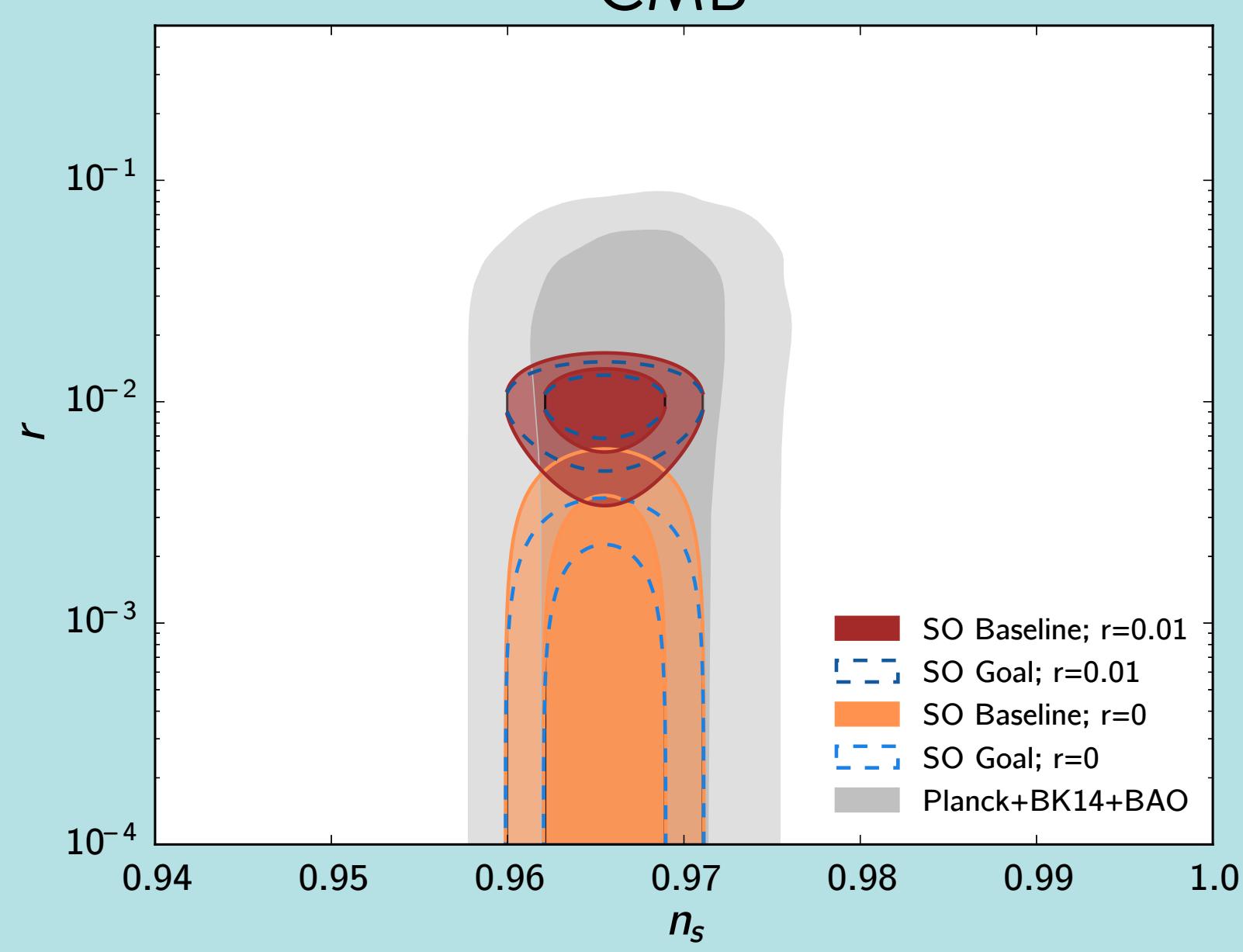
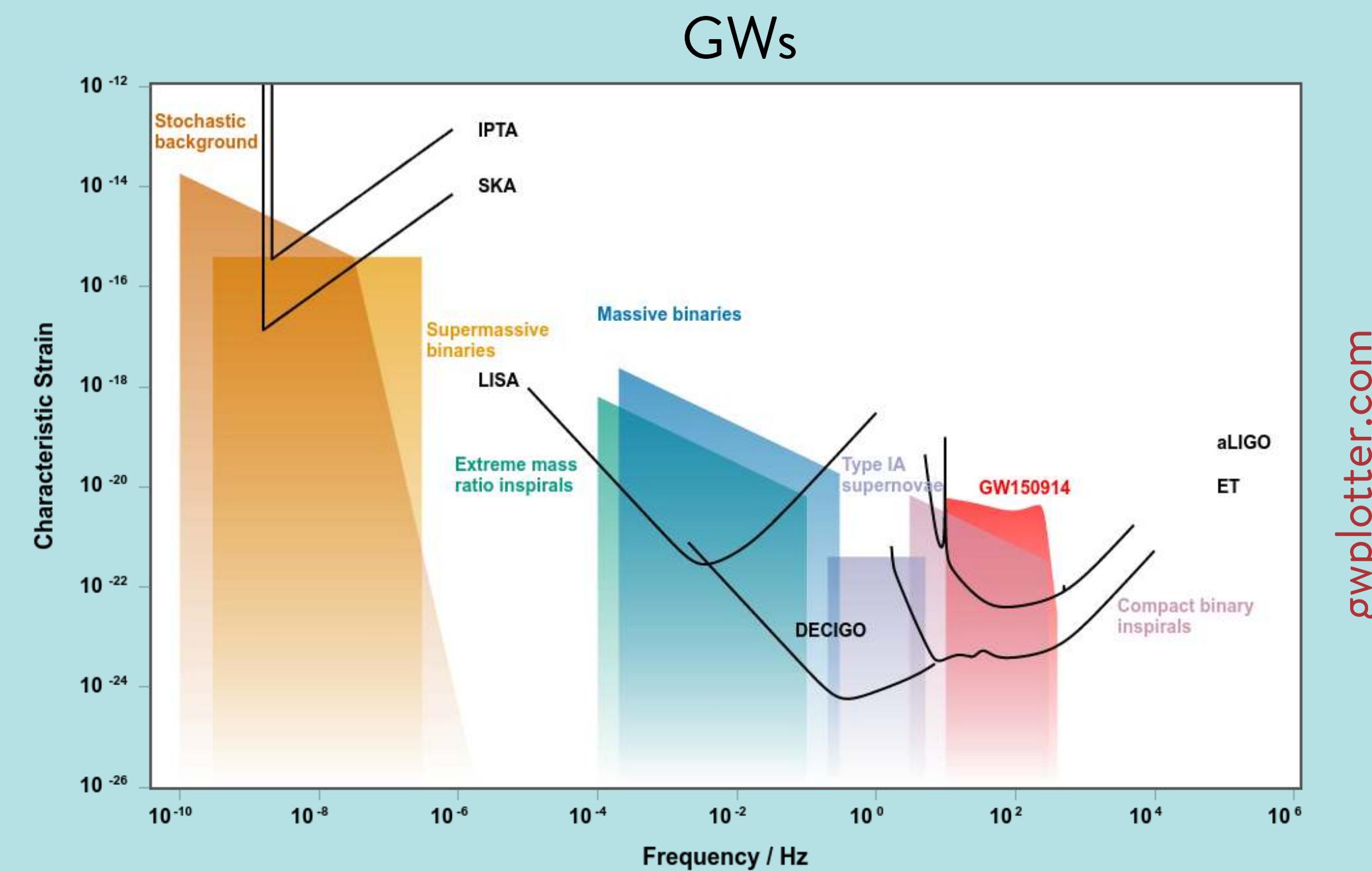
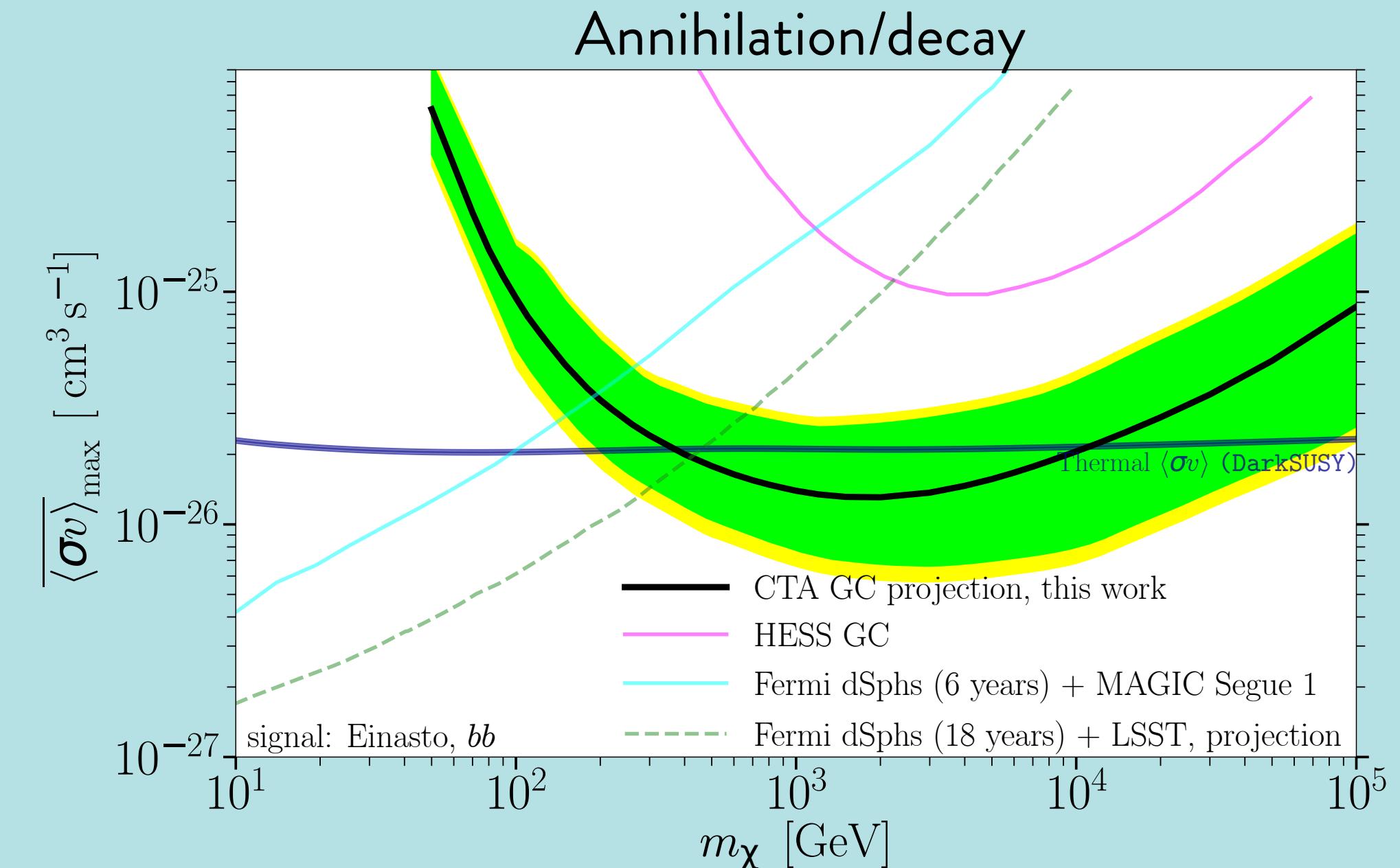
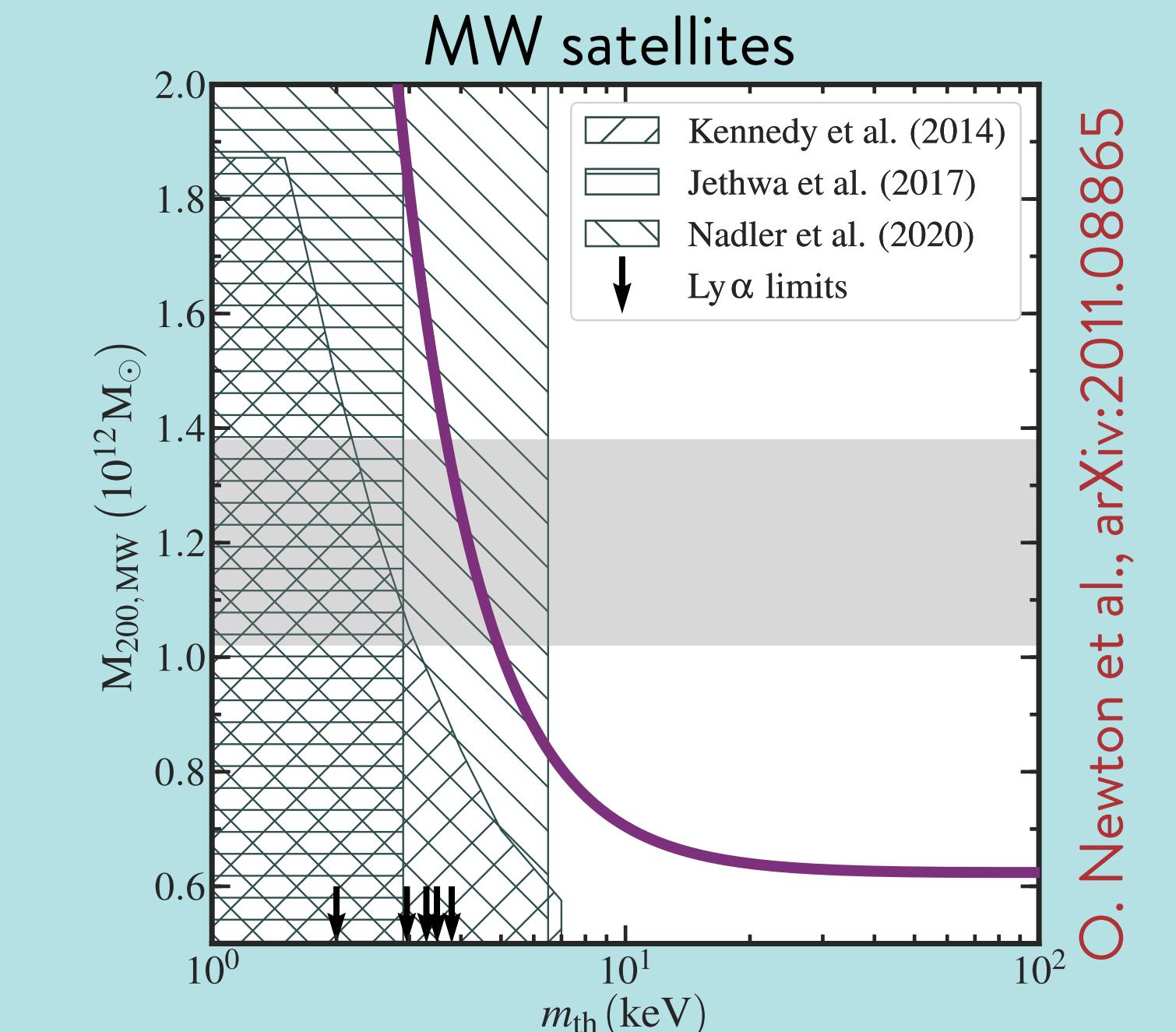
3. FIMPs



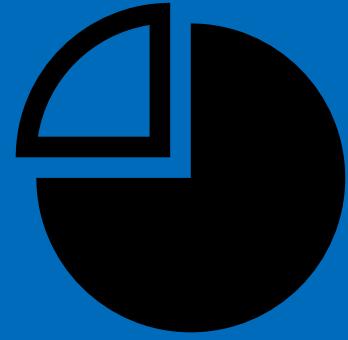
4. Compact objects



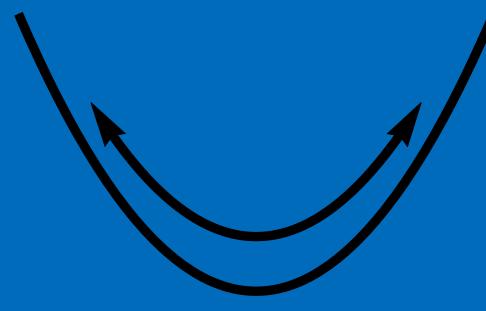
5. Prospects



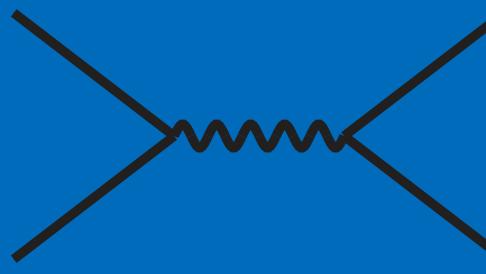
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs



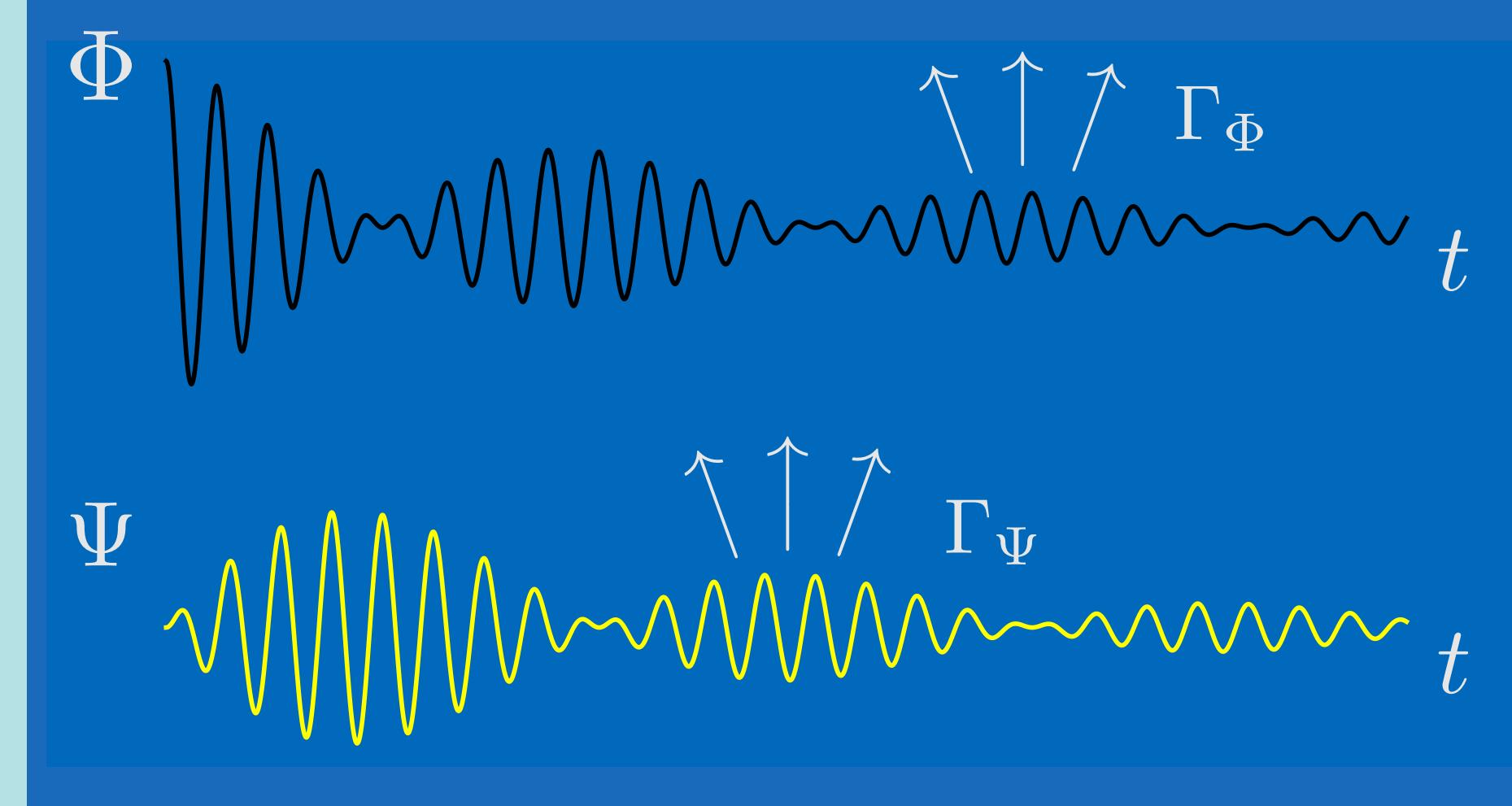
4. Compact objects



5. Prospects

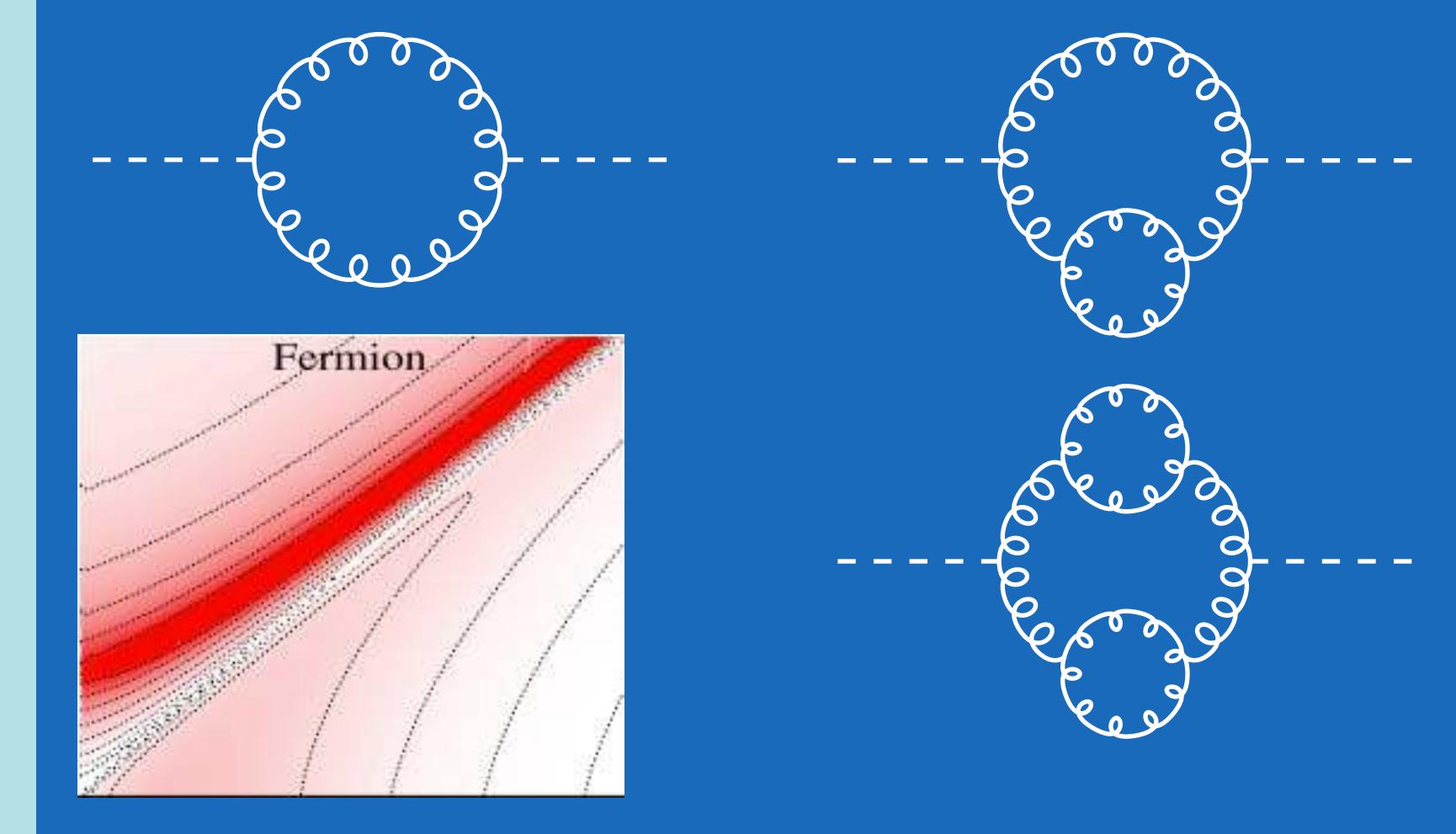
Reheating + BSM is not always simple

Multifield effects



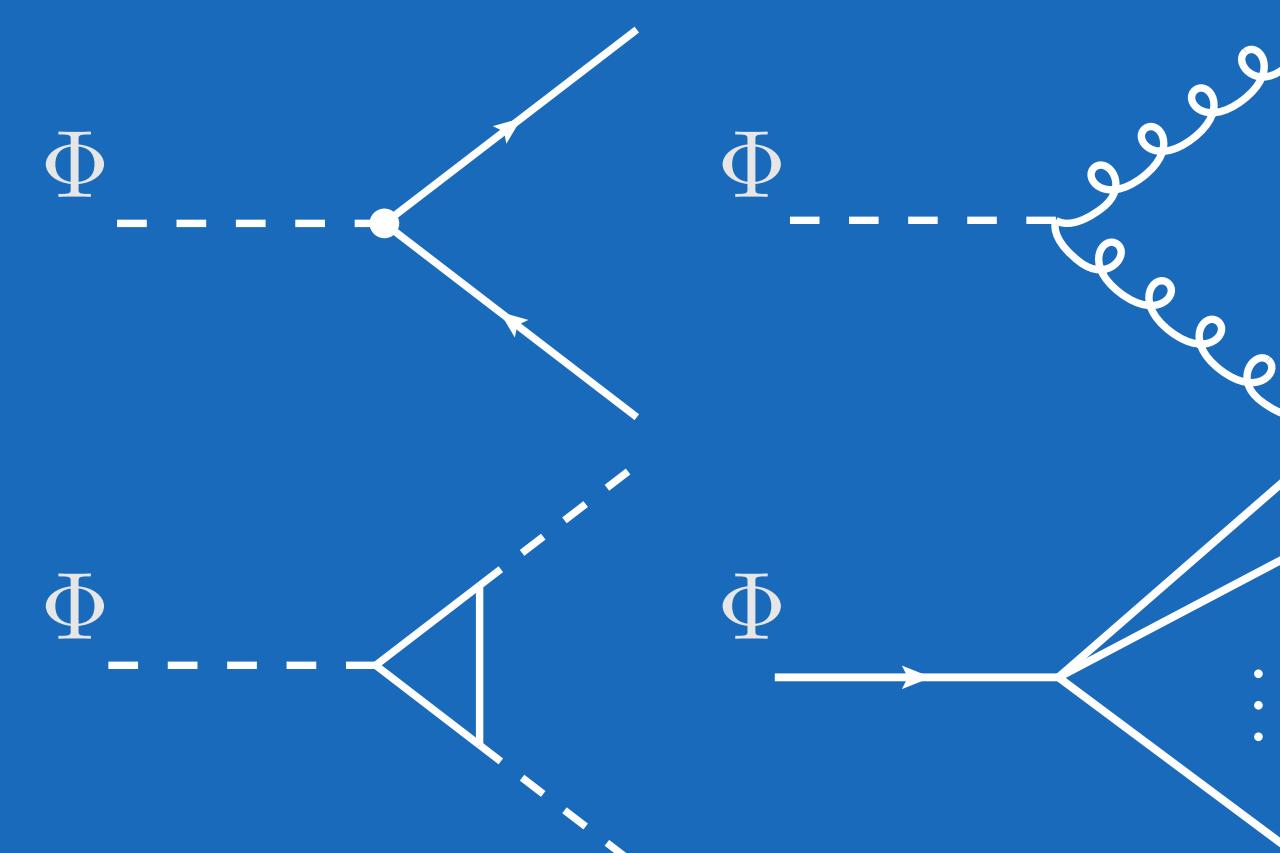
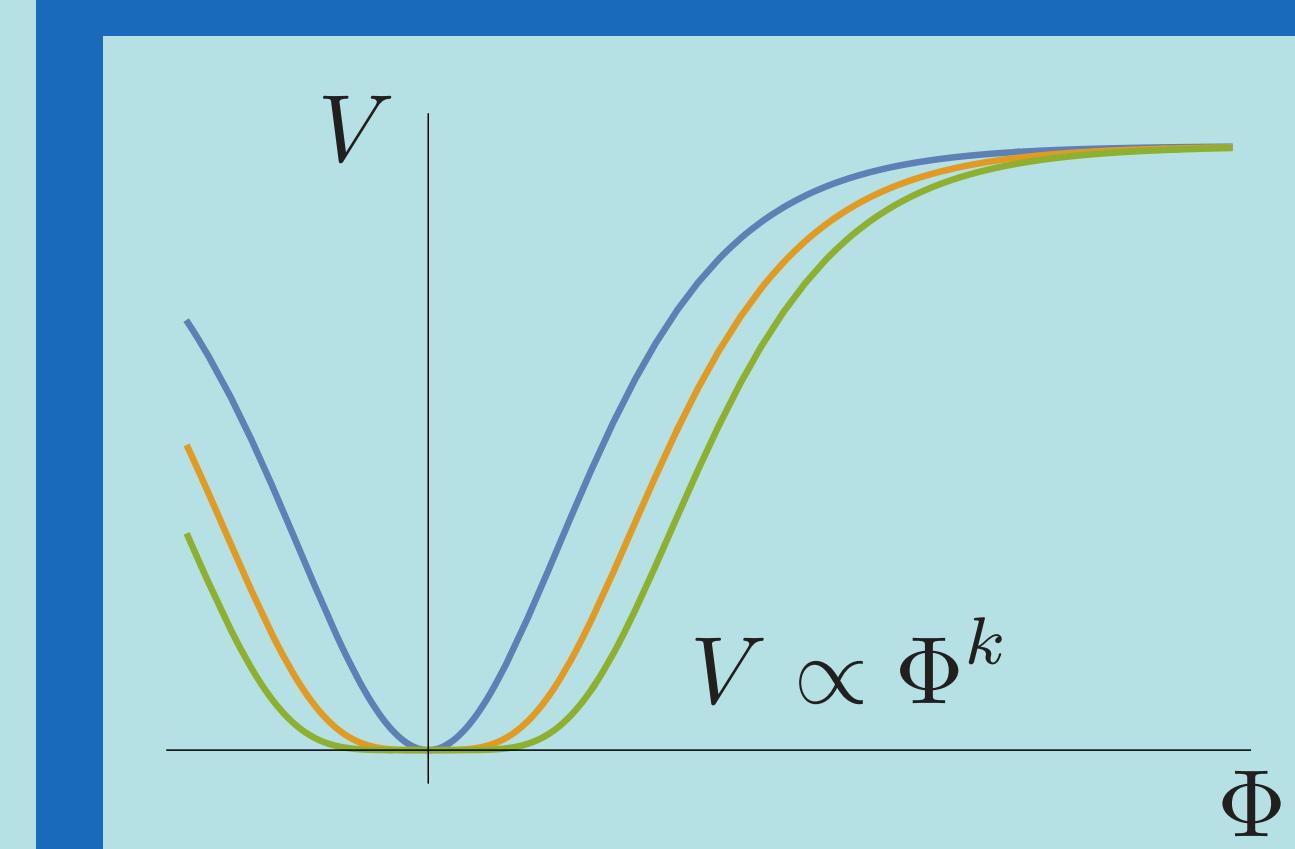
J. Ellis, MG, N. Nagata, D. Nanopoulos and K. Olive, JCAP 07 (2017), 006

In-medium effects



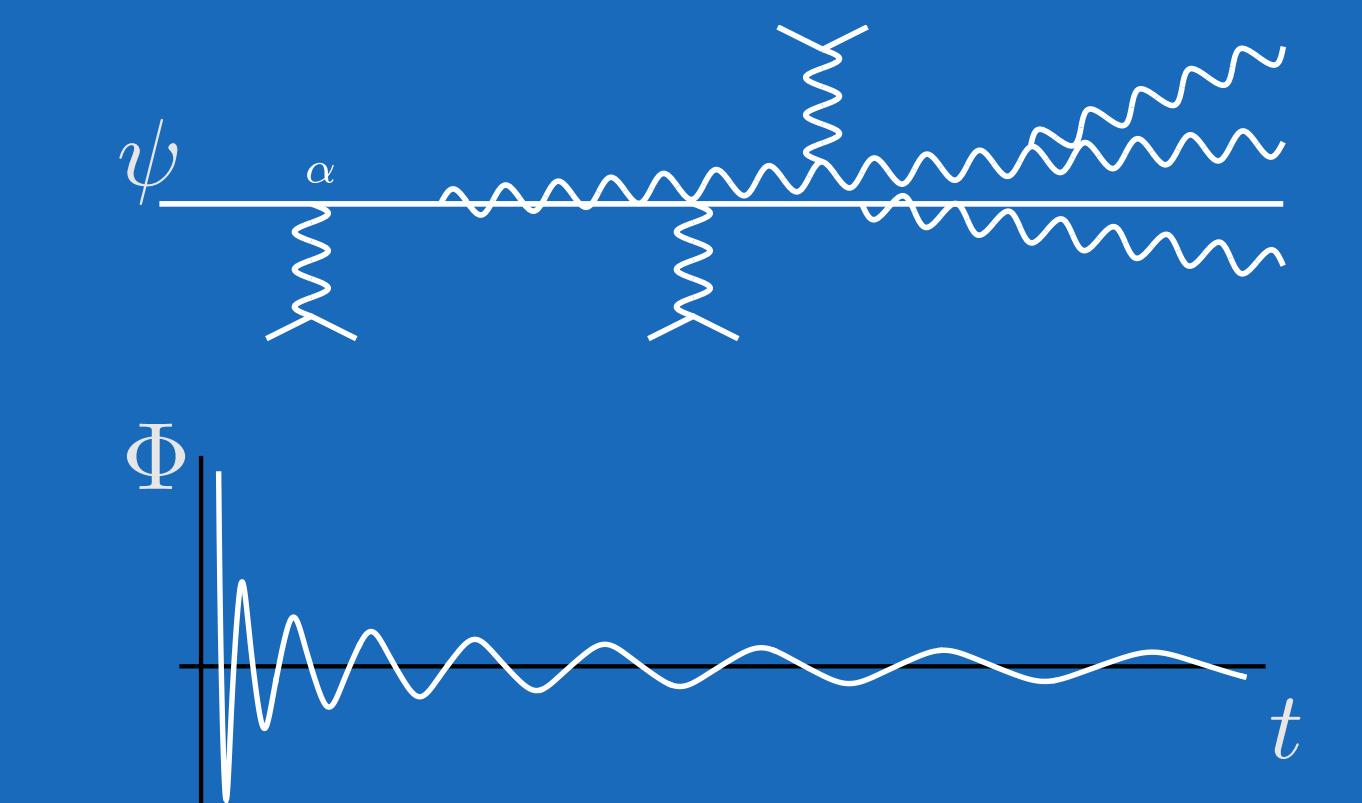
V. Rychkov and A. Strumia, PRD 75 (2007), 075011

More general potentials

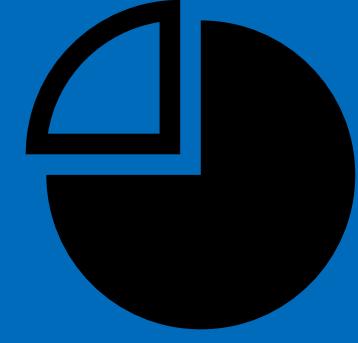


MG, K. Kaneta, Y. Mambrini and K. A. Olive, PRD 101 (2020), 123507 ;

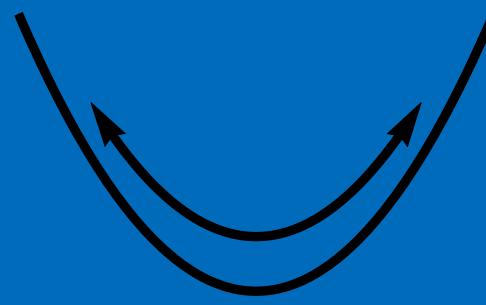
MG, K. Kaneta, Y. Mambrini and K. A. Olive, JCAP 04 (2021), 012



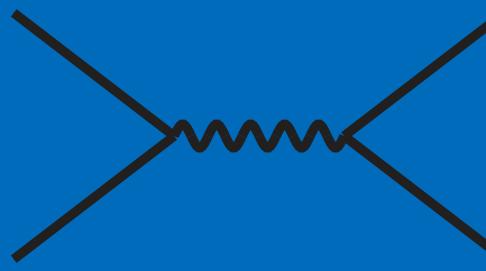
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs



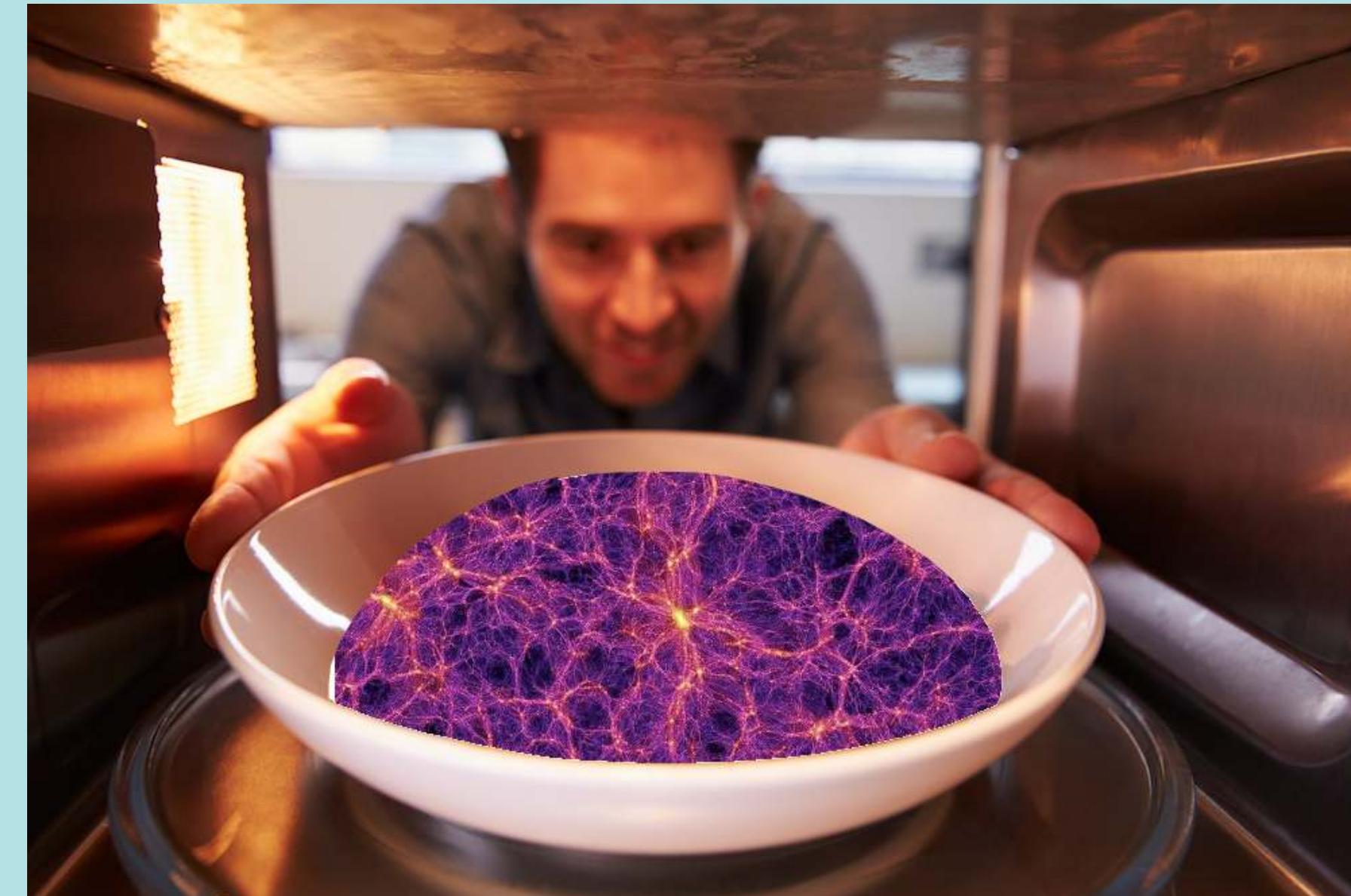
4. Compact objects



5. Prospects

Conclusion

- The light beyond the WIMP: the Big Bang itself?
- Dark matter as a probe of early dynamics
- Indirect connection with low energy physics (neutrinos, CMB, proton decay, ...)
- Same ideas, different applications (condensed matter, baryon asymmetry, finance, ...)



¡Gracias!