

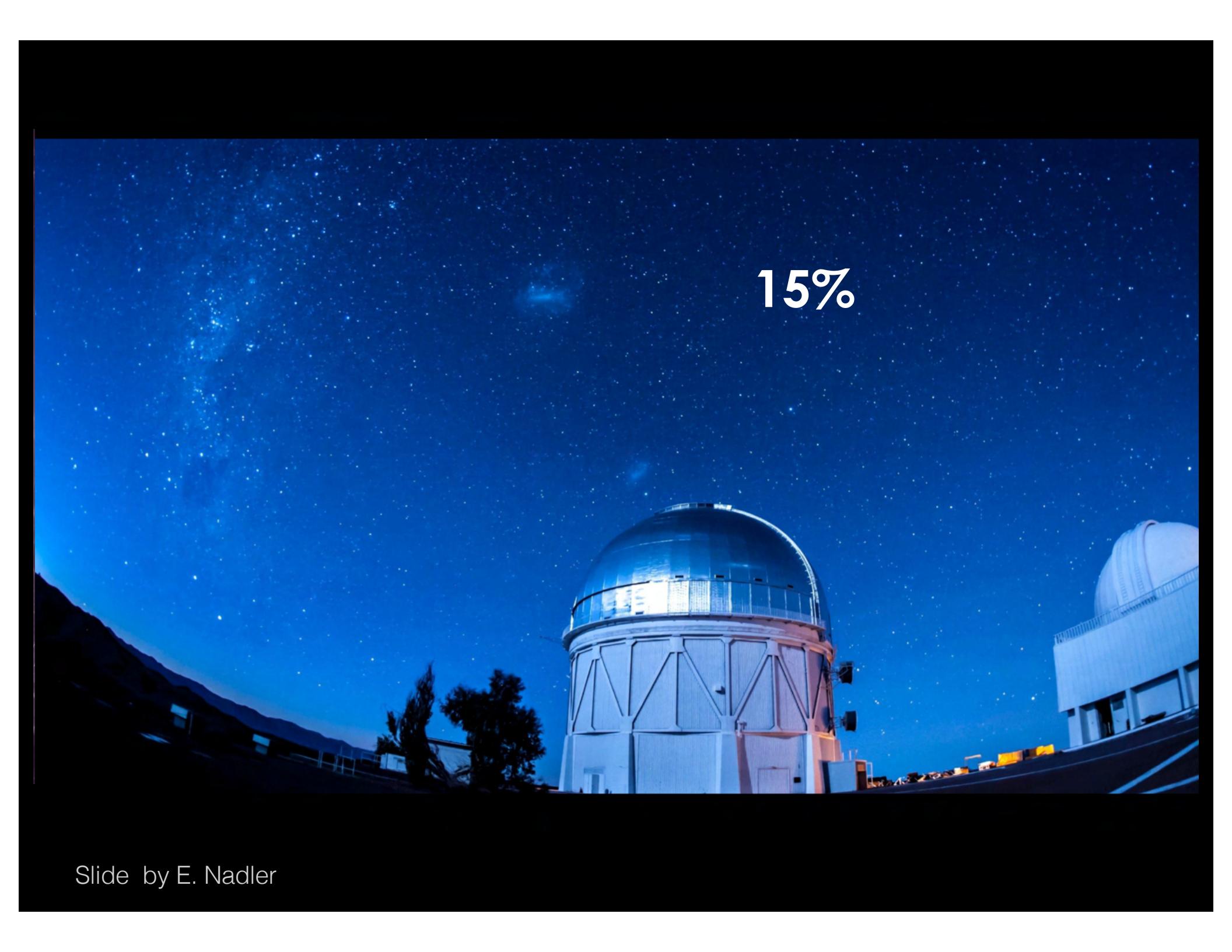


Dark matter cosmology

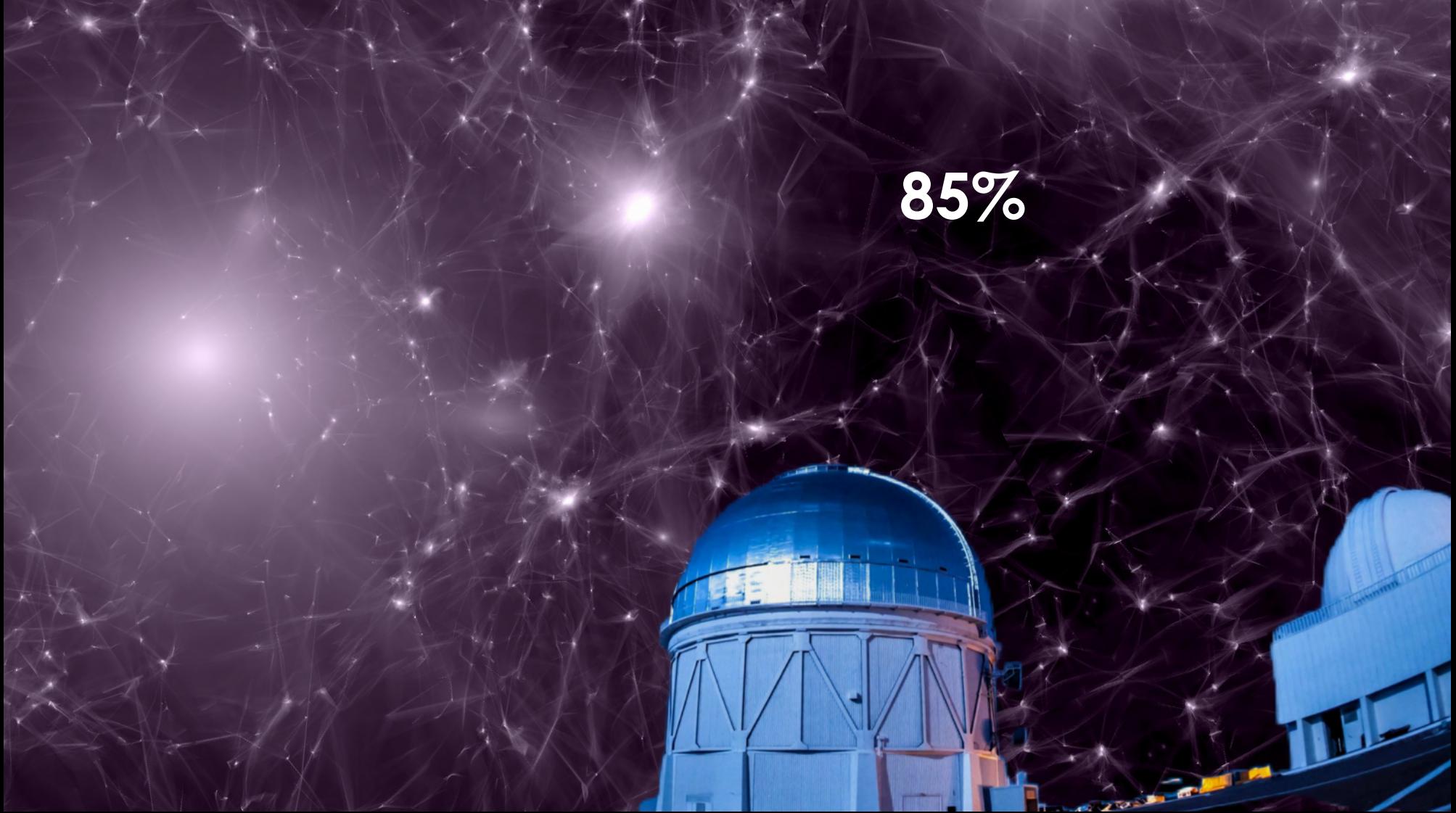
from the early Universe to the Milky Way

Vera Gluscevic

University of Southern California

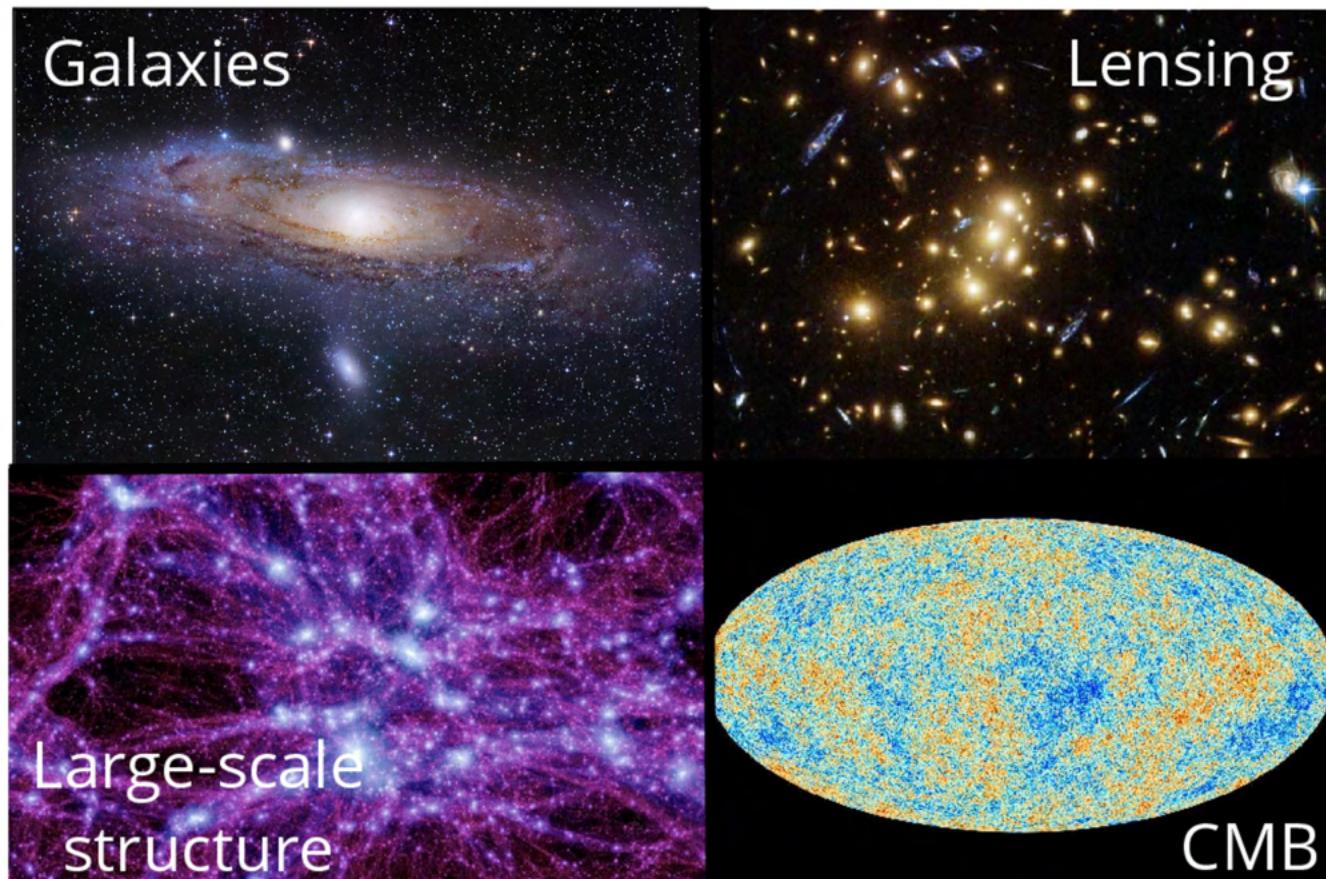
A photograph of a clear night sky filled with stars. In the foreground, the dark silhouette of a mountain range is visible on the left. On the right, there are two large observatory domes. The dome on the right is white, while the one in the center is blue. The blue dome has a circular window at the top and a metal railing around its base. The sky is a deep blue, transitioning to black at the bottom.

15%



85%

Lots of evidence points to a **consistent picture**:
there is **~6x more gravity** in the Universe than visible matter.



CMB and dark matter

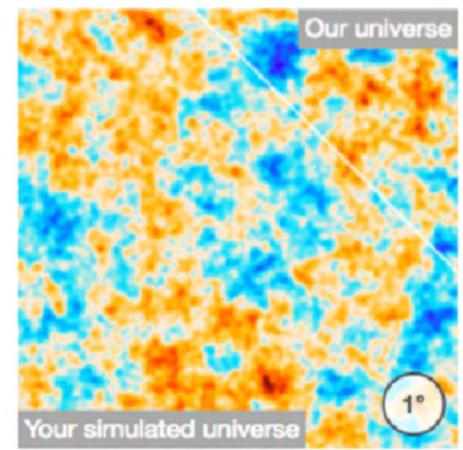
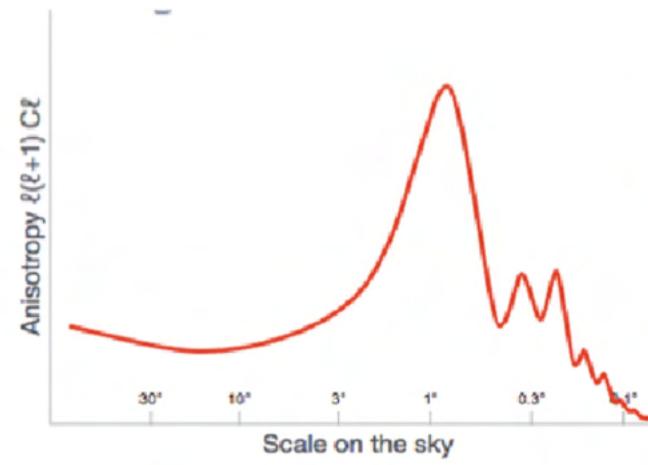
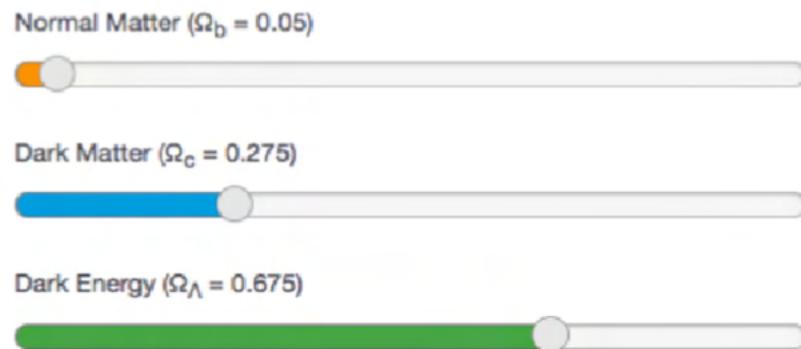


Image credits: Amanda Yoho, Planck

CMB and dark matter

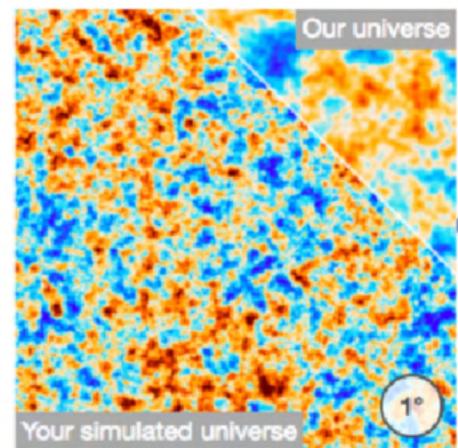
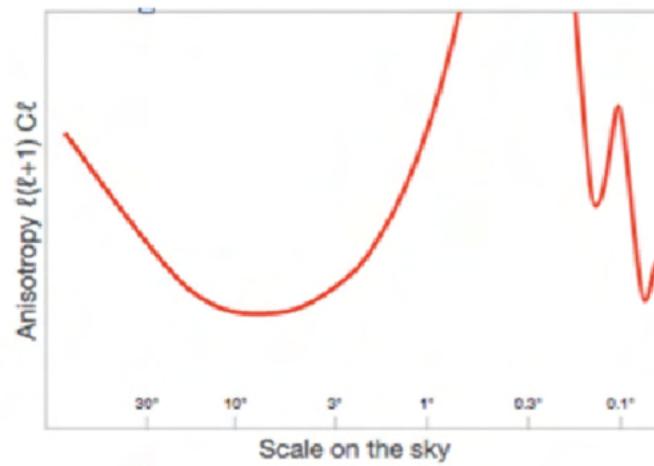
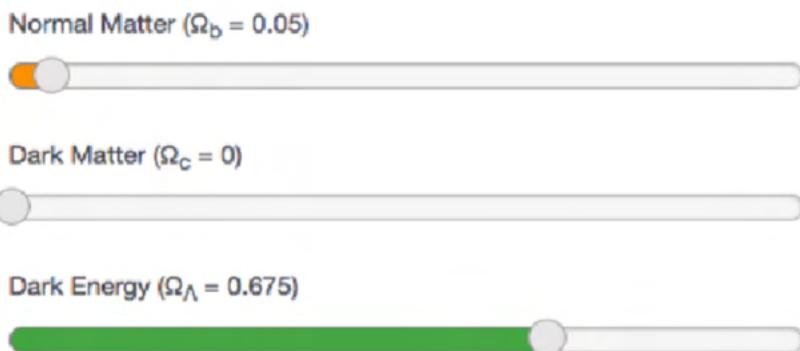


Image credits: Amanda Yoho, Planck

CMB and dark matter

Normal Matter ($\Omega_b = 0.325$)



Dark Matter ($\Omega_c = 0$)



Dark Energy ($\Omega_\Lambda = 0.675$)

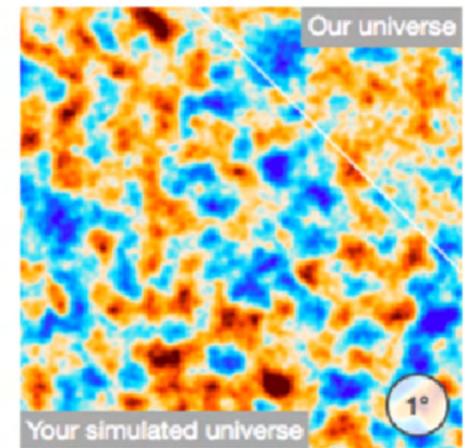
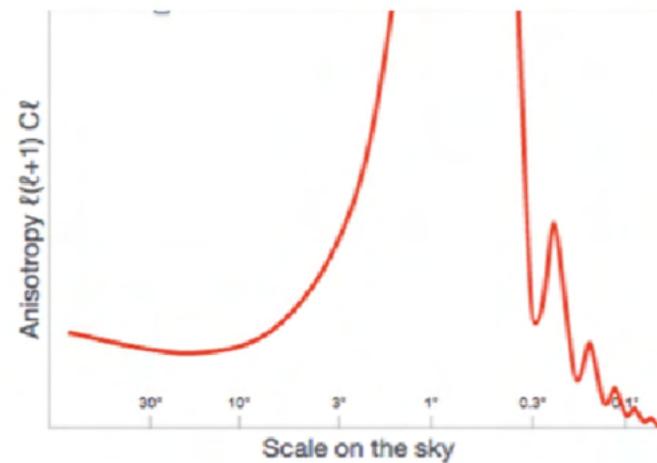


Image credits: Amanda Yoho, Planck

Direct detection – status of nuclear recoil searches

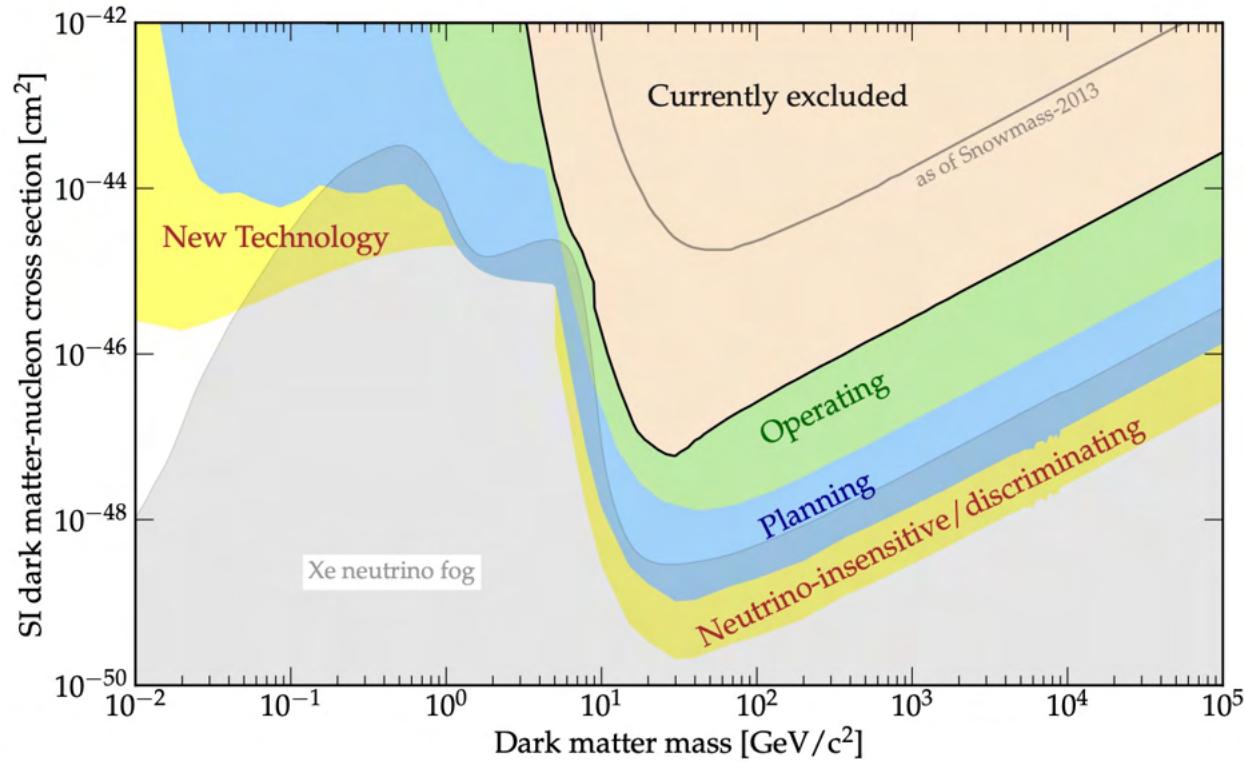
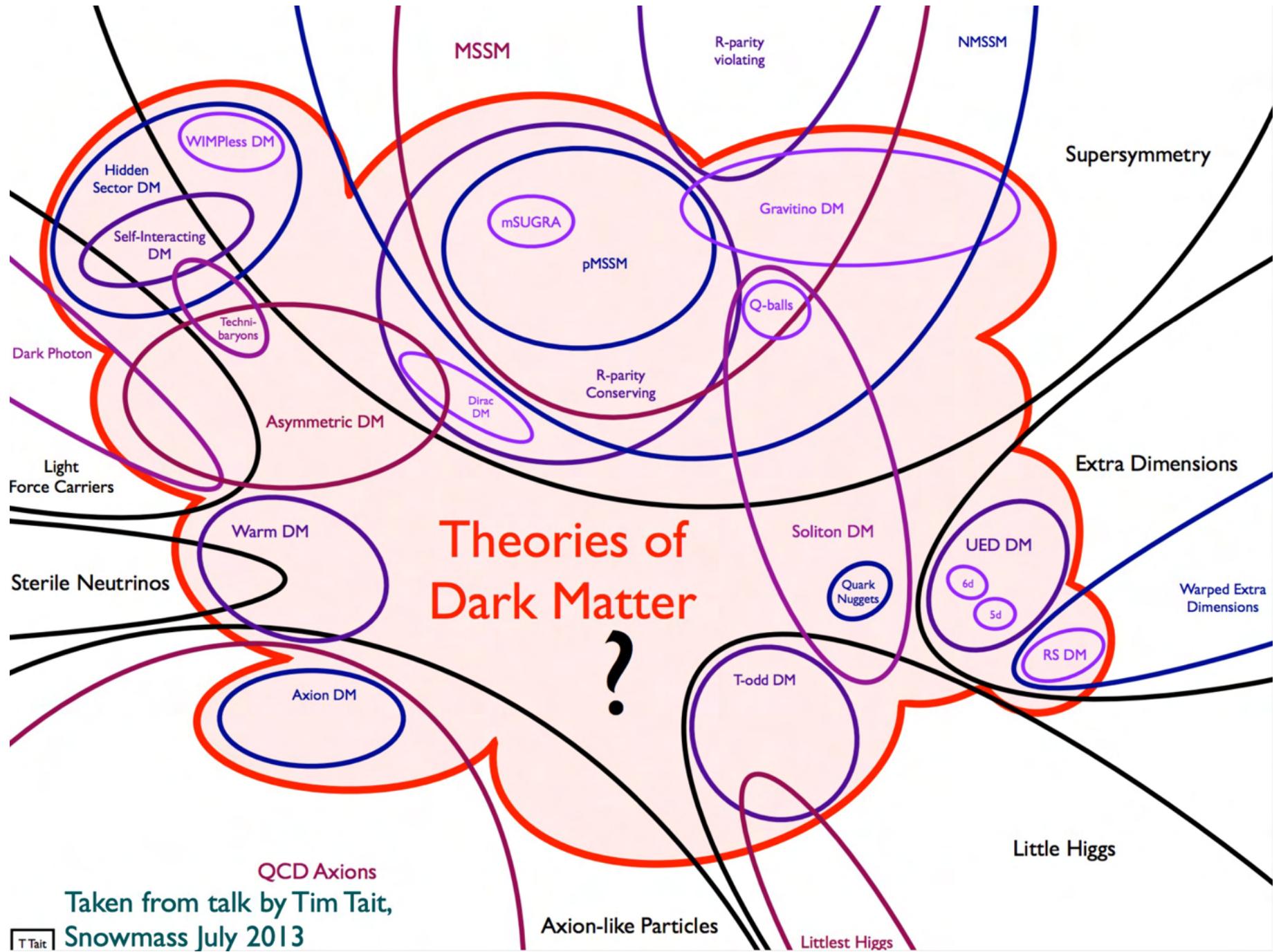


Figure 5-18. Combined Spin-independent dark-matter nucleon scattering cross section space. Current 90% c.l. constraints are shaded beige, while the reach of currently operating experiments are shown in green (LZ, XENONnT, PandaX-4T, SuperCDMS SNOLAB, SBC). Future experiments are shown in blue (SuperCDMS, DarkSide-20k, DarkSide-LowMass, SBC, XLZD, ARGO) and yellow (Snowball and Planned \times 5). The neutrino fog for a xenon target is shaded light grey. From Ref. [97].



State of knowledge

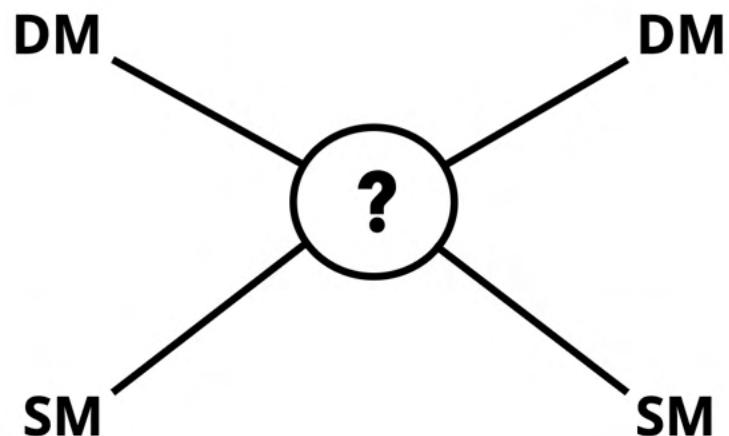
It's **not** a lot of things
~~(relativistic, interacting much, decaying fast)~~



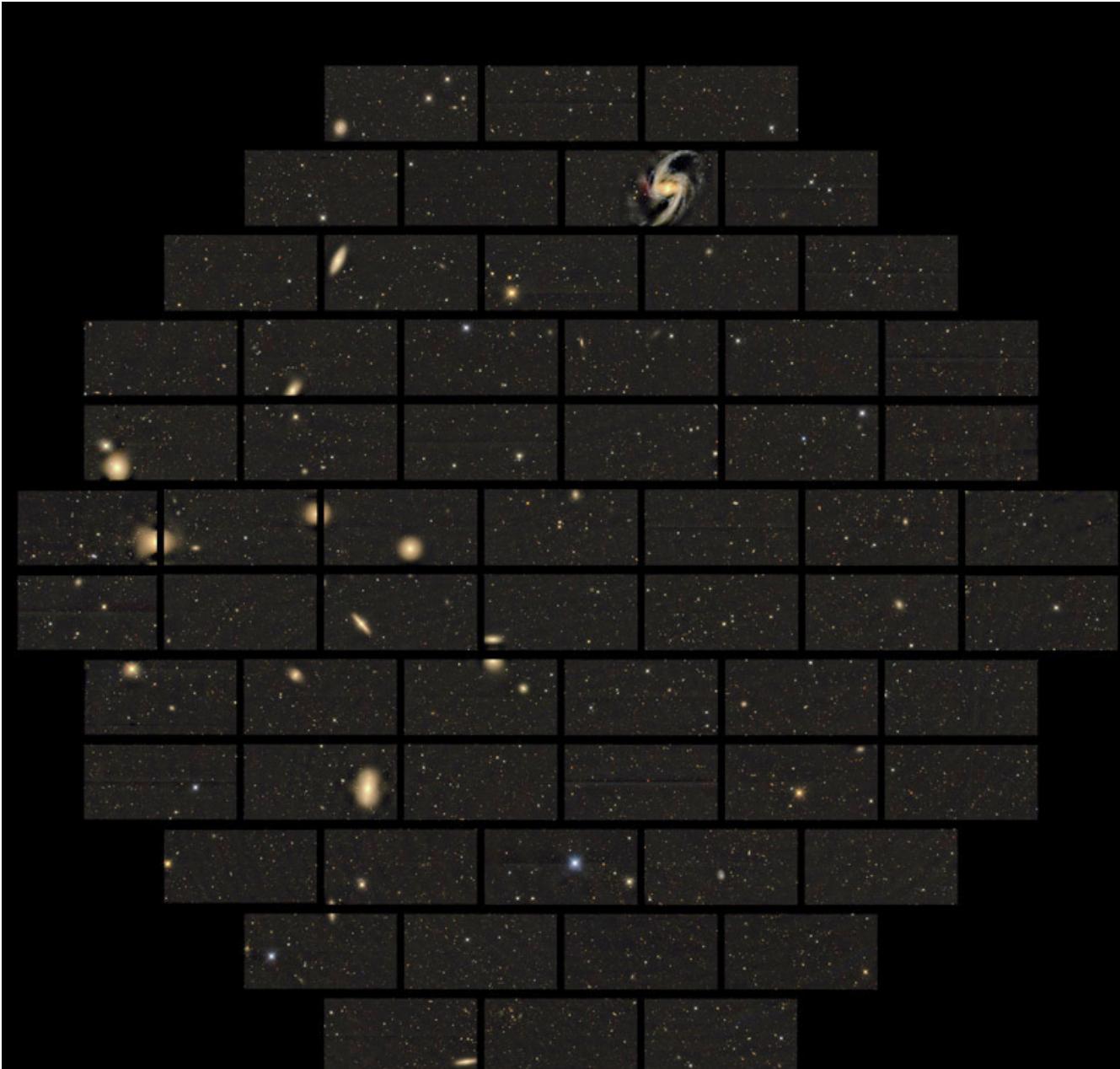
It could be a lot of things
(WIMPs, axions, hidden sector, etc.)



? mass, spin, interactions, production ?

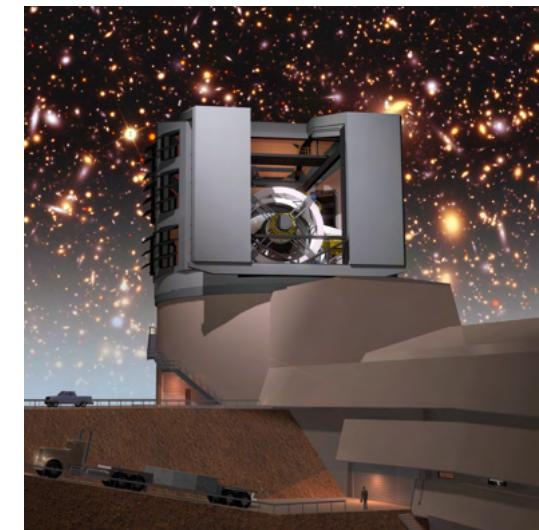
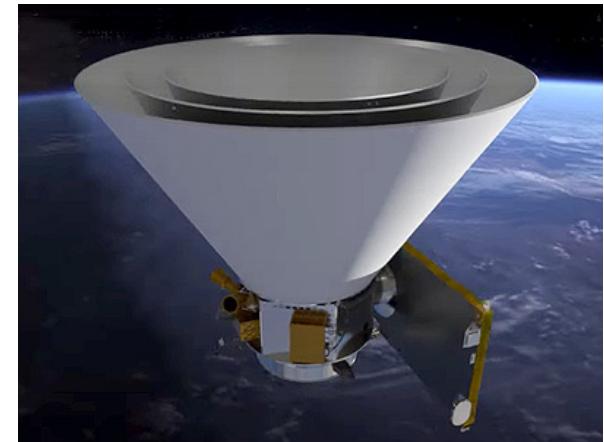
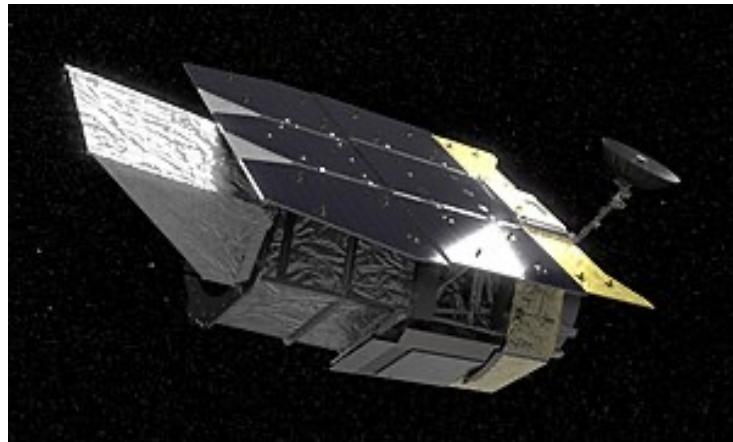
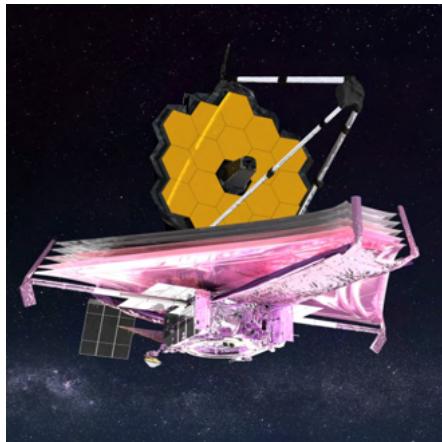


Data

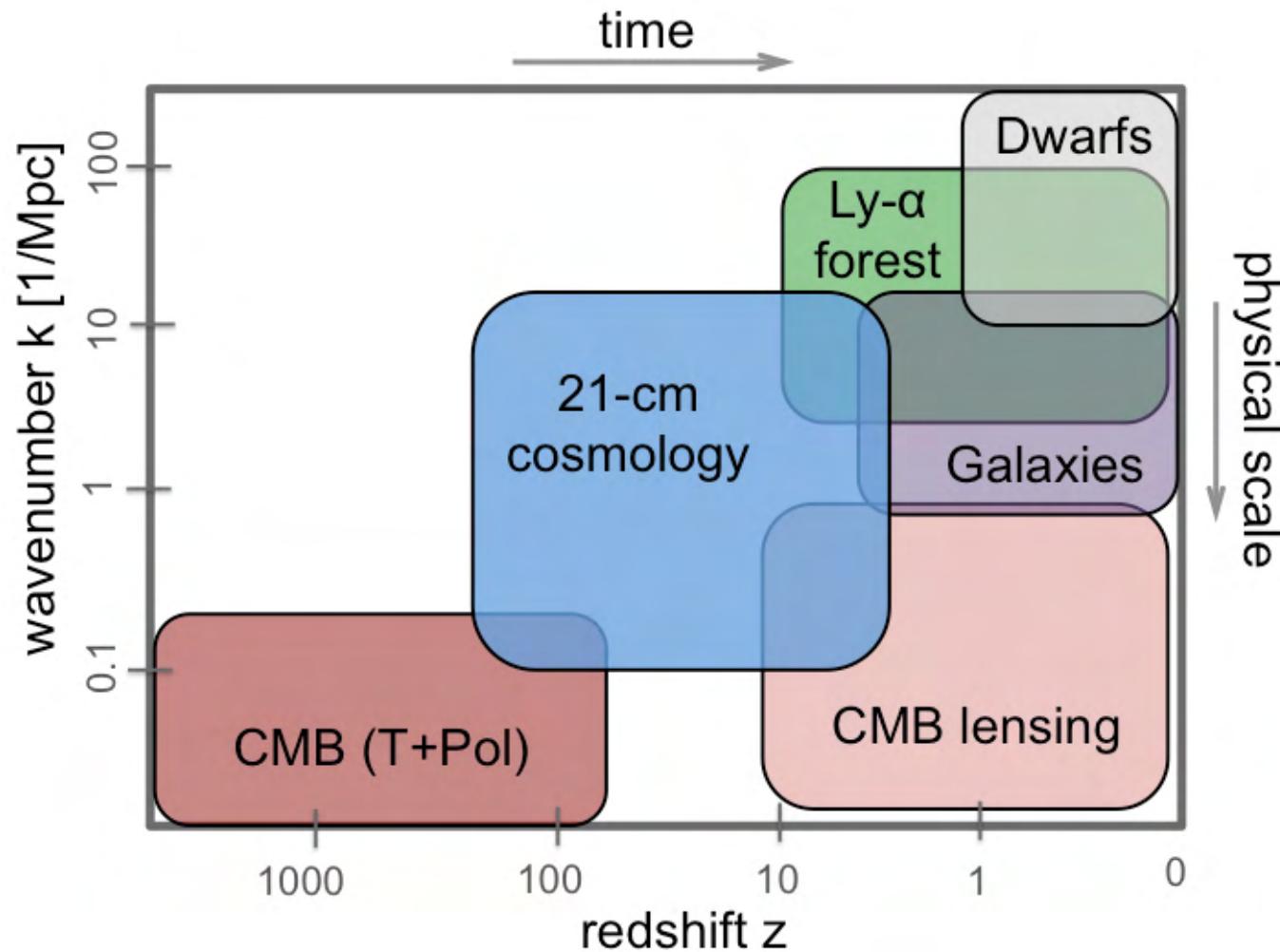


Images taken by the DES Collaboration with the DECam mounted on the Blanco Telescope. (DES Collaboration.)

Data



Observables



The plan

recap

- **Ultra-brief overview of computational tools**
- **Mass** -- Lessons from BBN
- **Spin** -- Lessons from cosmic structures
- **Interactions** -- Lessons from large and small scales
- **Thermal history** -- Lessons from 21-cm cosmology

Computational tools

ultra-brief review

Linear cosmology --- CLASS/CAMB

<https://arxiv.org/abs/1104.2932>

The screenshot shows a GitHub repository page for 'lesgourg / class_public'. The repository is public, has 28 pulls, 249 forks, and 187 stars. It contains 284 issues, 29 pull requests, and various projects like Wiki, Security, and Insights. The master branch is selected. The repository has a large number of commits from 'lesgourg' and others, including updates to .github/workflows, cpp, doc, and external files. The 'About' section describes it as a public repository for the Cosmic Linear Anisotropy Solving System, mentioning branches for different purposes like ExoCLASS and FFTlog.

Search or jump to... / Pulls Issues Codespaces Marketplace Explore

lesgourg / class_public Public Watch 28 Fork 249 Star 187

Code Issues 284 Pull requests 29 Projects Wiki Security Insights

master Go to file Add file Code

lesgourg Implement interacting dark matter follo... on Mar 29, 2022 2,004

.github/workflows Changed reference branch from master to ... 2 years ago

cpp updated doc, cpp, output, test 2 years ago

doc doc updated for 3.2.0 (#93) last year

external defined Omega0_nfsm (non-free-streamin... 2 years ago

About

Public repository of the Cosmic Linear Anisotropy Solving System (master for the most recent version of the standard code; classnet branch for acceleration with neutral networks; ExoCLASS branch for exotic energy injection; class_matter branch for FFTlog)

Cosmological background

fluids + gravity

Dark matter
& Baryons (p+e+nuclei)

$$\rho_m \sim (1+z)^3$$

Friedmann equations

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2}$$

Radiation

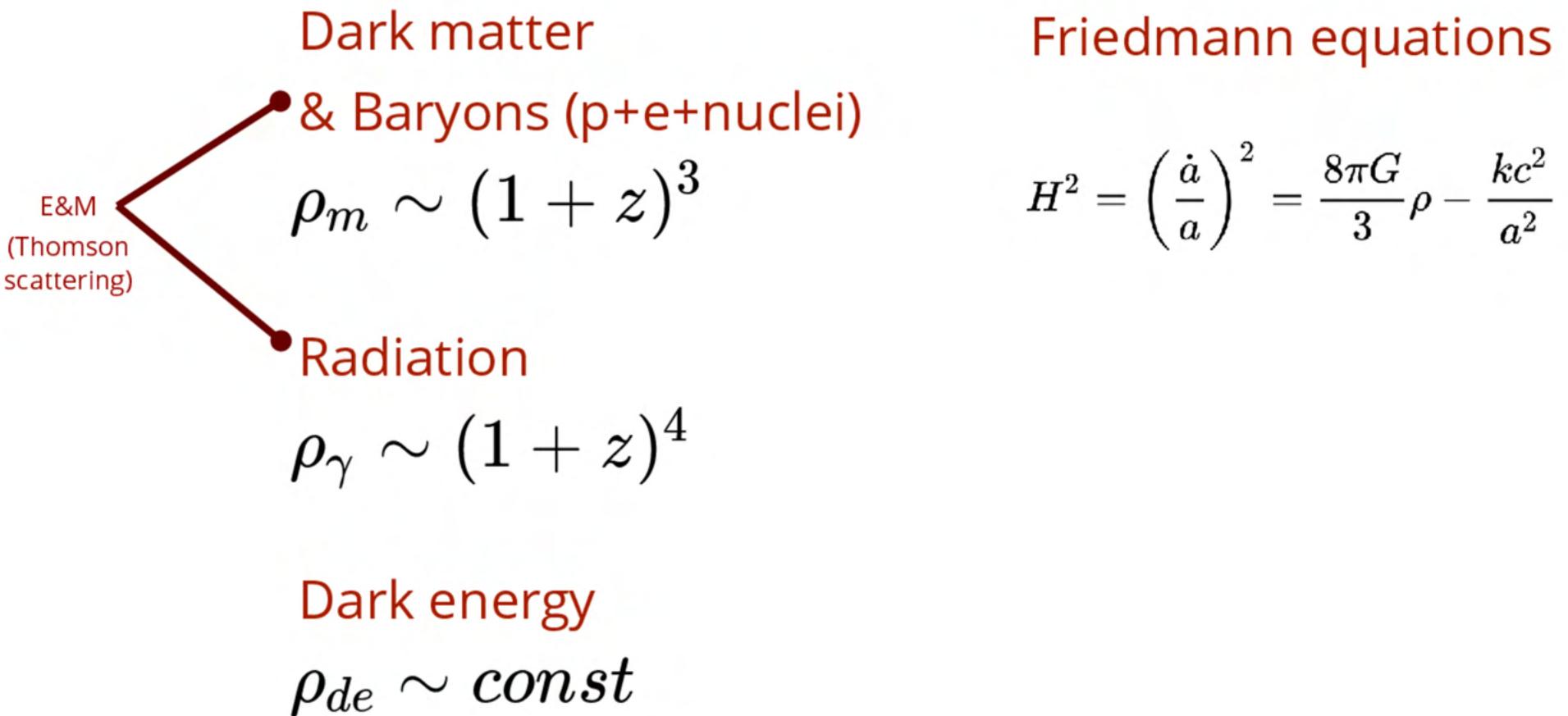
$$\rho_\gamma \sim (1+z)^4$$

Dark energy

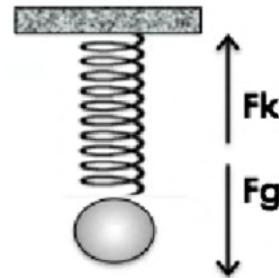
$$\rho_{de} \sim \text{const}$$

Cosmological background

fluids + gravity



Matter perturbations



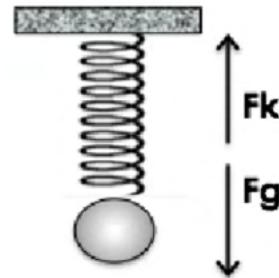
$$\dot{\delta}_\chi = -\frac{\dot{h}}{2}, \quad \dot{\delta}_b = -\theta_b - \frac{\dot{h}}{2},$$

$$\frac{df}{dt} = C[f] \quad \Rightarrow$$

$$\dot{\theta}_b = -\frac{\dot{a}}{a}\theta_b + c_b^2 k^2 \delta_b + R_\gamma (\theta_\gamma - \theta_b)$$

e.g. arxiv:1803.00070, arxiv:9506072

Matter perturbations



$$\dot{\delta}_\chi = -\frac{\dot{h}}{2}, \quad \dot{\delta}_b = -\theta_b - \frac{\dot{h}}{2},$$

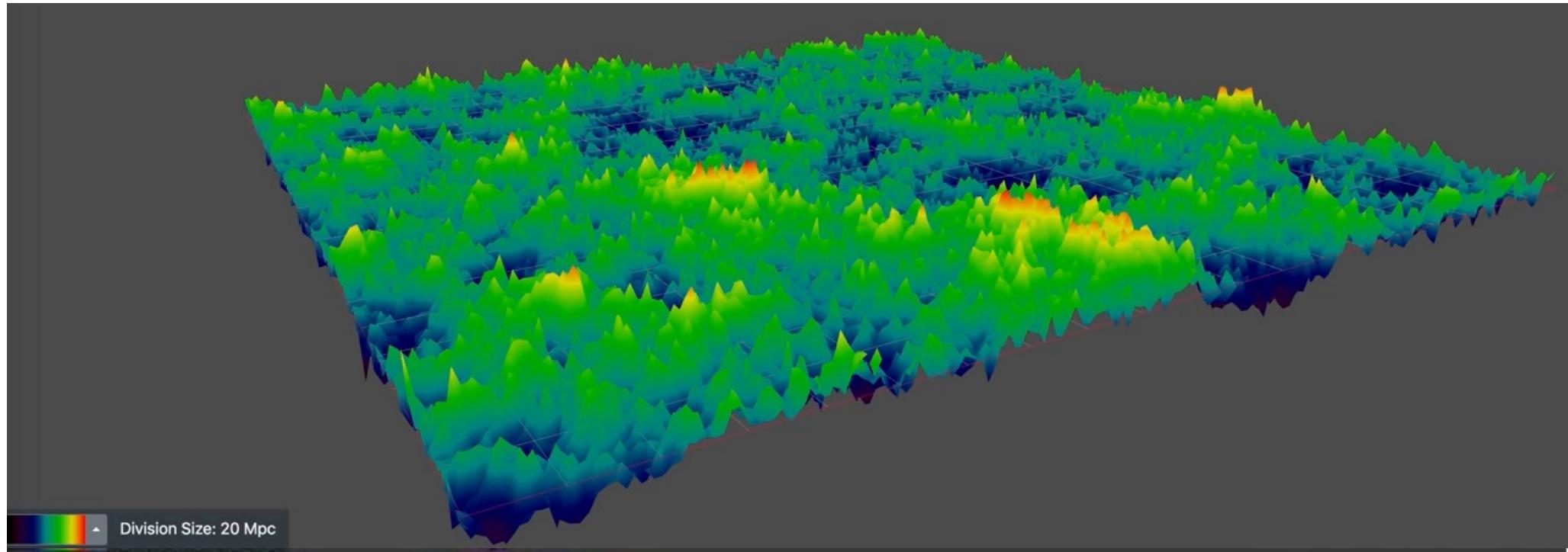
$$\frac{df}{dt} = C[f] \quad \Rightarrow$$

$$\dot{\theta}_b = -\frac{\dot{a}}{a}\theta_b + c_b^2 k^2 \delta_b + R_\gamma (\theta_\gamma - \theta_b)$$

Early universe is a linear system!

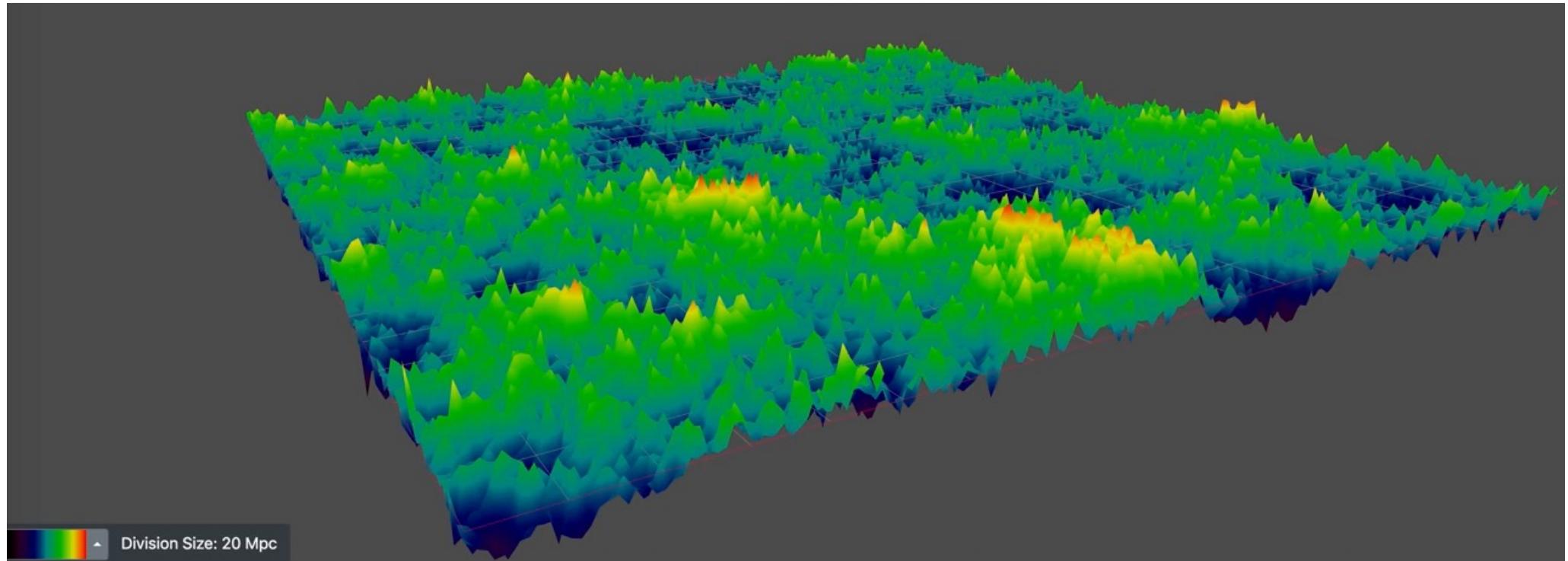
e.g. arxiv:1803.00070, arxiv:9506072

Matter perturbations: baryons



Created using CLASS Real Space Interface [J. Lesgourges]

Matter perturbations: CDM

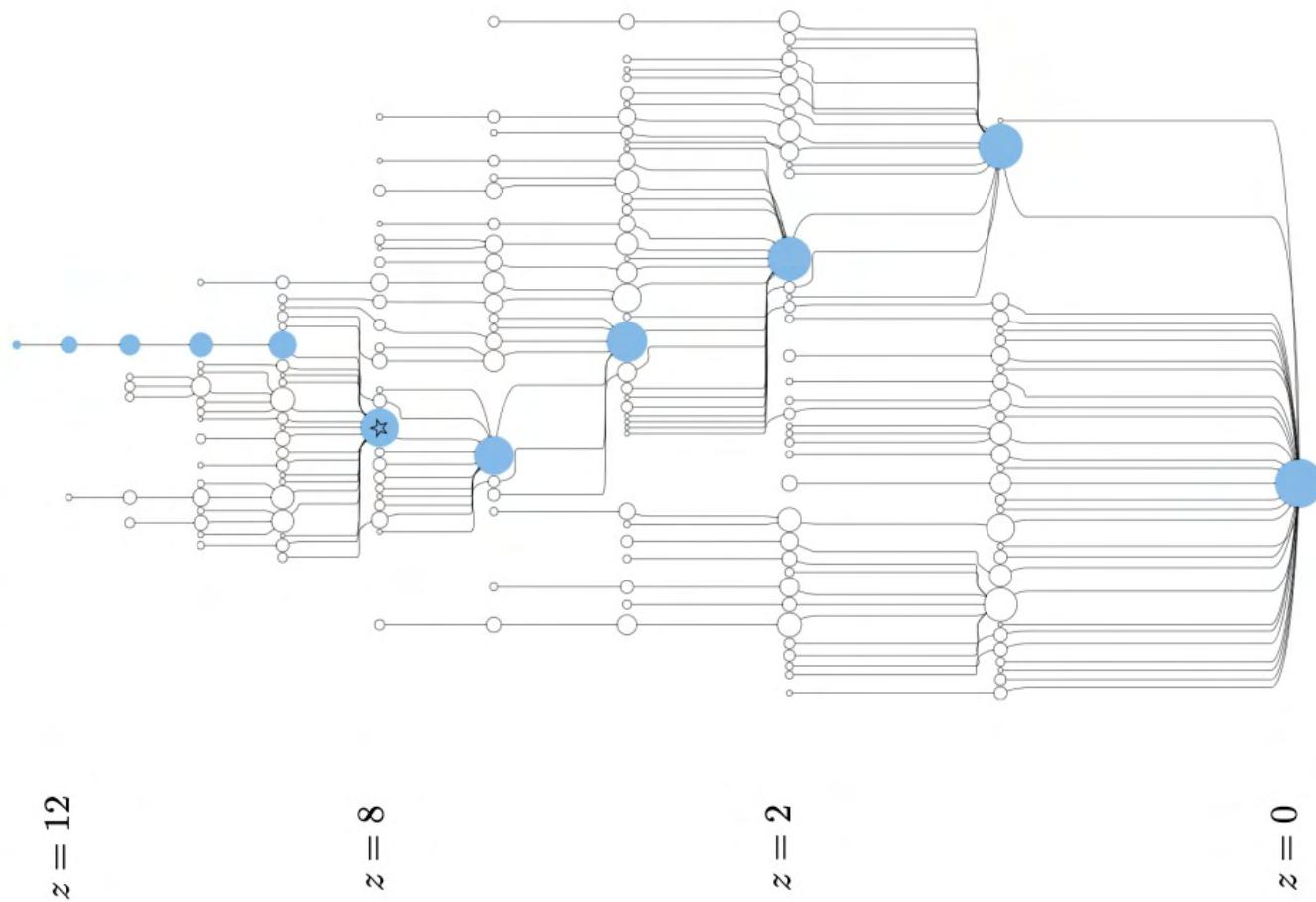


Created using CLASS Real Space Interface [J. Lesgourges]

Structure formation --- simulations



Structure formation --- semi analytic models



Nadler+ 2022

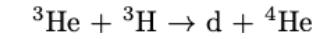
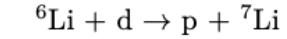
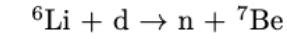
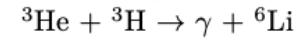
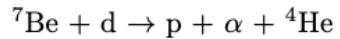
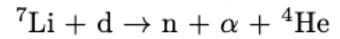
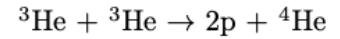
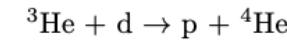
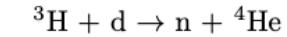
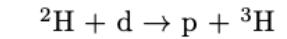
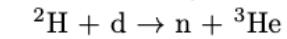
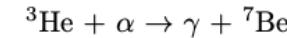
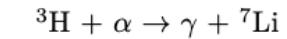
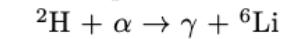
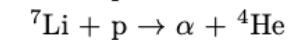
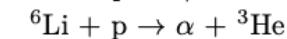
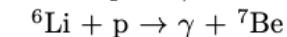
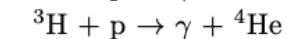
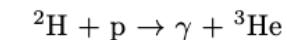
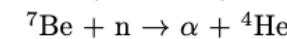
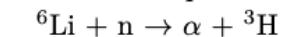
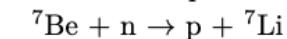
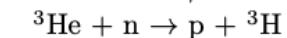
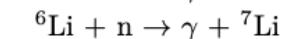
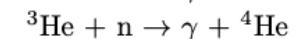
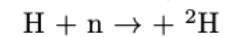
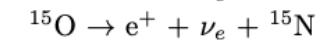
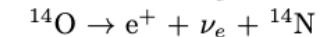
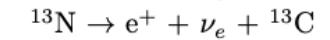
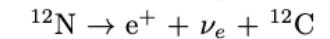
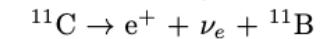
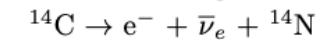
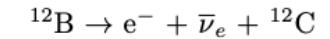
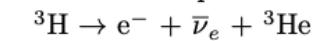


And also... baryons....

Need to compute/measure
nuclear reaction rates for BBN:

<https://alterbbn.hepforge.org/>
<https://parthenope.na.infn.it/>

n decay



I. Spin

lessons from cosmic structures

Tremaine-Gunn bound (~1970s)

- Measure LOS velocity dispersion => mass profile $\mathbf{M}(\mathbf{r})$ and density profile $\rho(\mathbf{r})$.

- +Jeans stability => escape velocity

$$v_{esc} \approx \sqrt{\frac{2GM(r)}{r}}$$

- +Pauli exclusion => fermi velocity

$$v_F(r) = \left(\frac{6\pi^2\rho(r)}{gm^4} \right)^{1/3}$$

$$v_F < v_{esc}$$

Teamwork time





Teamwork time

Estimate the lower bound on fermionic dark matter mass, from Leo II dwarf spheroidal galaxy, using the measurements of the escape velocity and density at half light radius, shown in the figure.

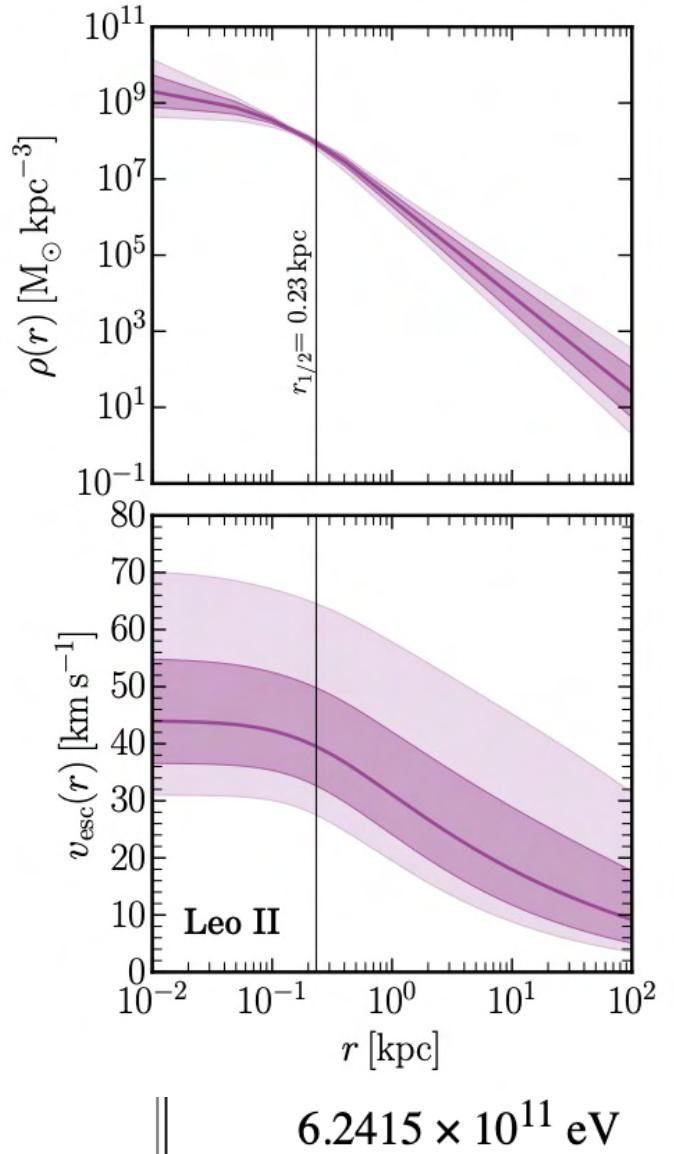
How does your result compare to the result of the paper linked at the top of the figure?

How would you improve this bound?

Hint: You will need formulas from the previous slide, and possibly also the following constants:

parsec		pc		3.086×10^{18} cm		
reduced Planck's constant		$\hbar = h/2\pi$		1.0546×10^{-27} cm ² g s ⁻¹		
Solar mass		M_{\odot}		1.989×10^{33} g		
erg (unit of energy)		erg		$1 \text{ cm}^2 \text{ g s}^{-2}$		6.2415×10^{11} eV

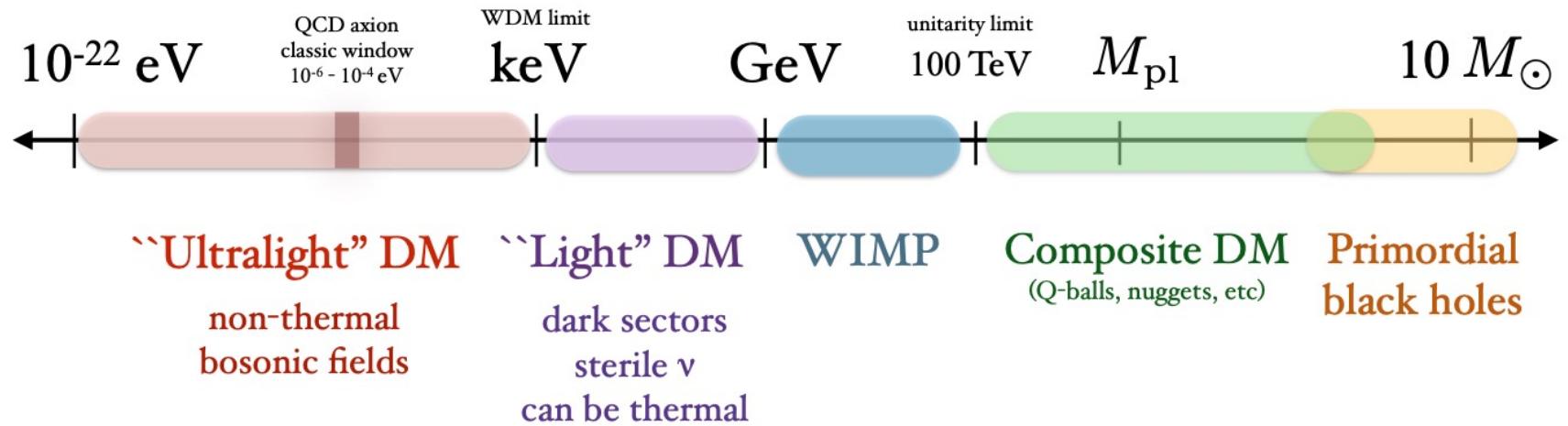
<https://arxiv.org/pdf/2010.03572.pdf>



II. Mass

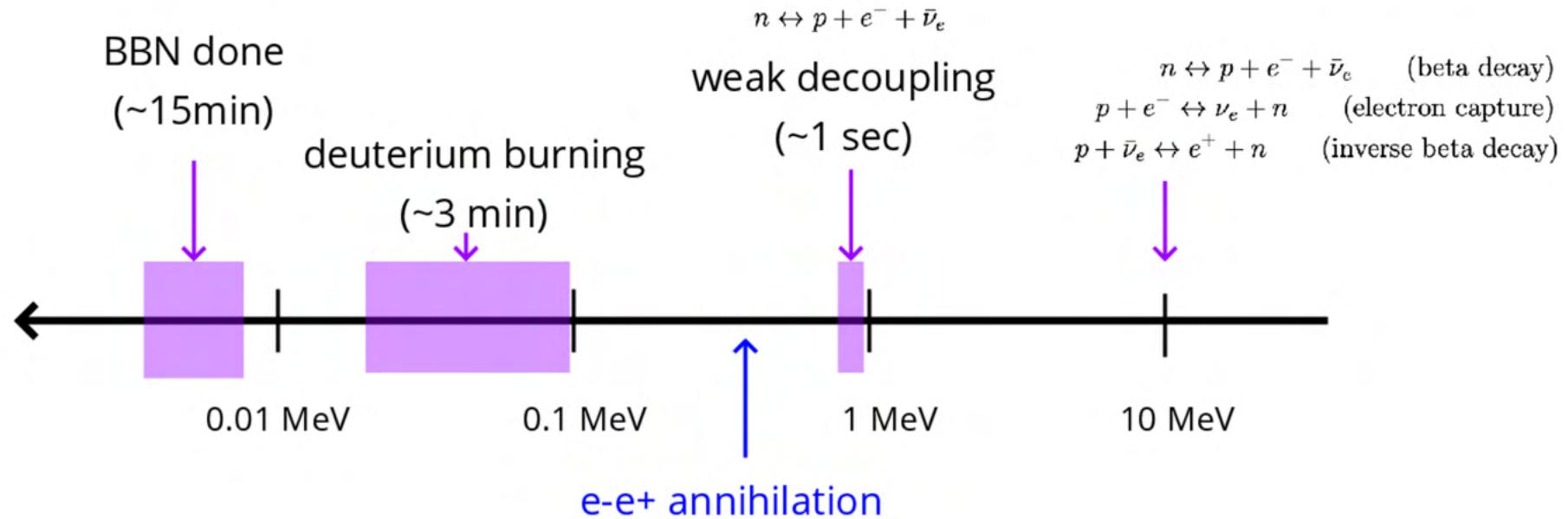
lessons from BBN

Allowed range of DM mass is huge.

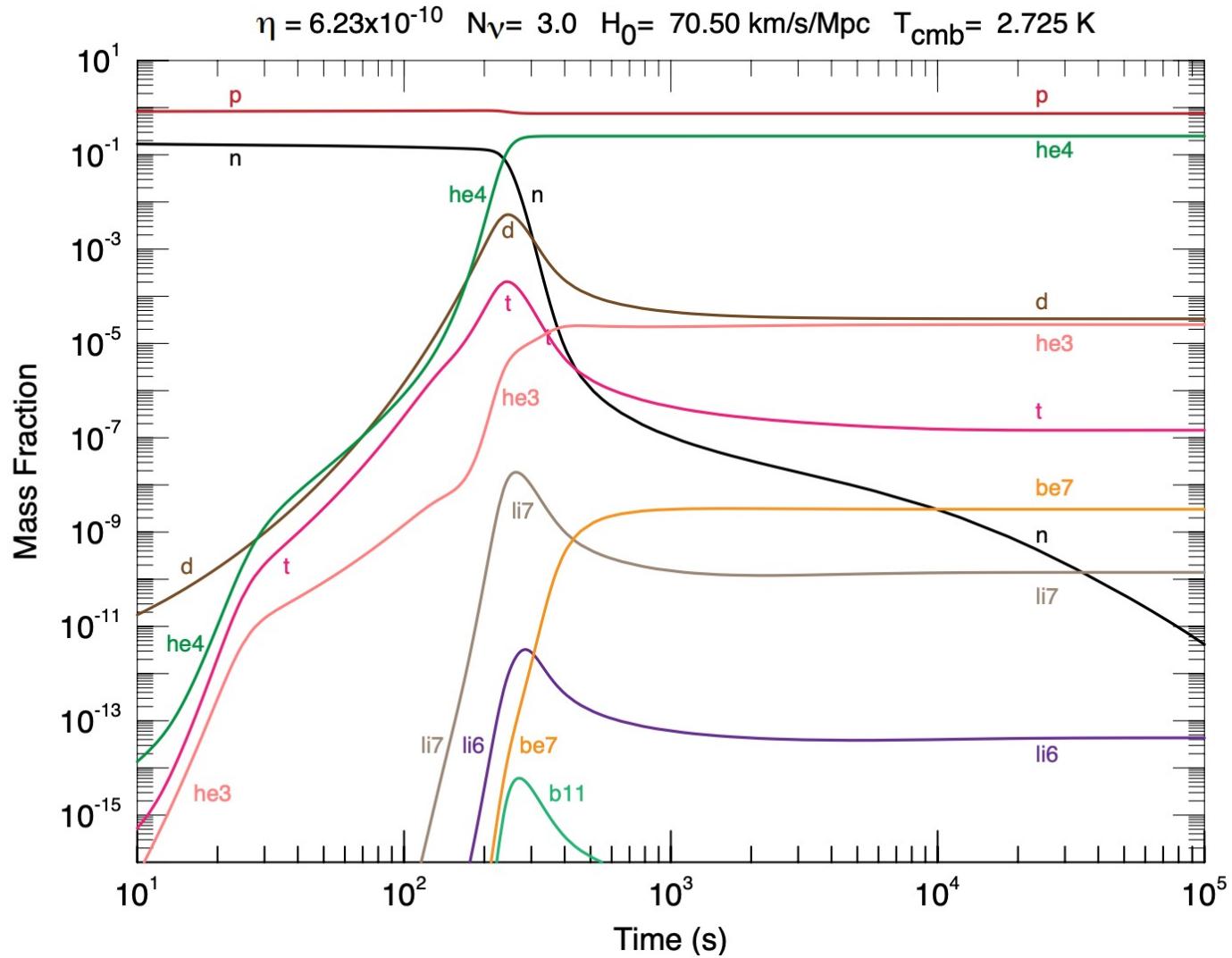


Plot by T. Lin.

BBN



Primordial element abundances



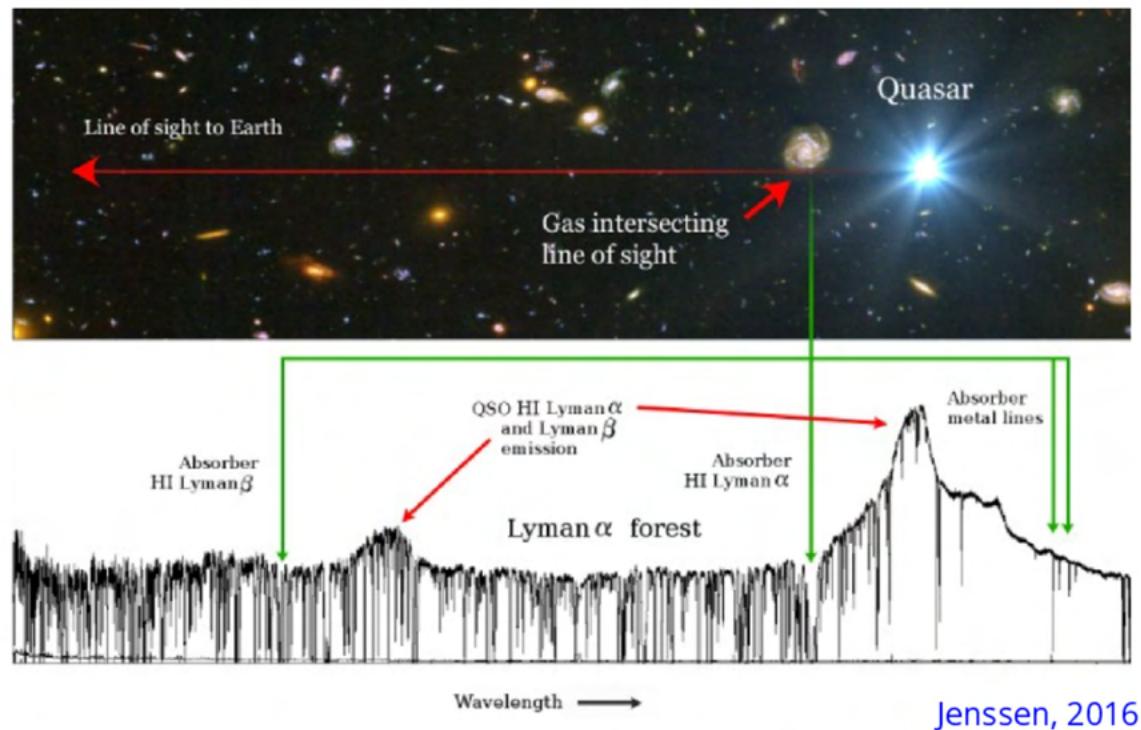
Jenssen, 2016

<https://arxiv.org/abs/1803.00070>

For a review: <https://arxiv.org/pdf/1903.09187.pdf>

We can measure primordial element abundances in pristine circumgalactic gas
(using Lyman-alpha forest absorption in quasar spectra)

D, He-4, He-3, Li-7



For a review: <https://arxiv.org/pdf/1903.09187.pdf>

What about dark matter?

Thermal relic

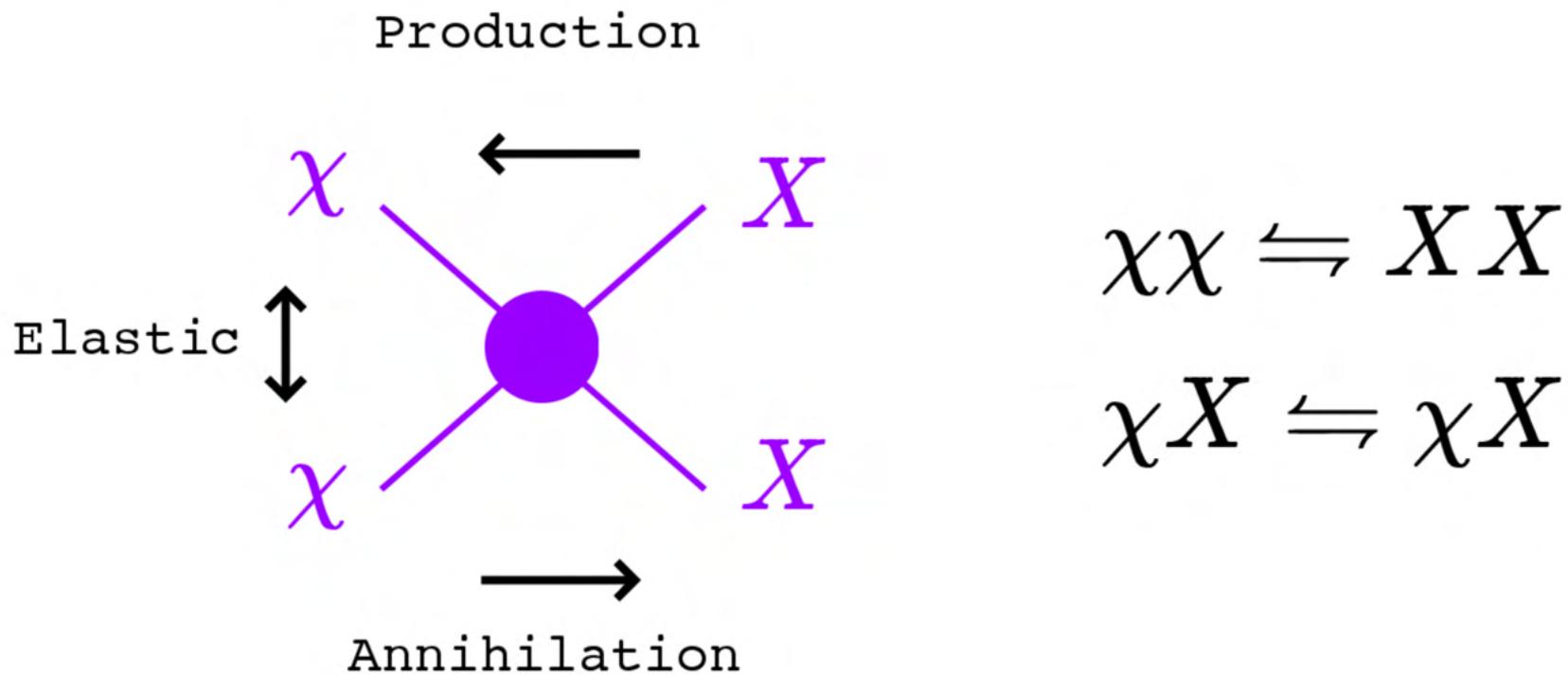
~concepts of **decoupling** and **freeze-out**~

Thermal relic particle starts off in thermal, kinetic, and chemical equilibrium with the rest of the universe at early times.

Thermal relic

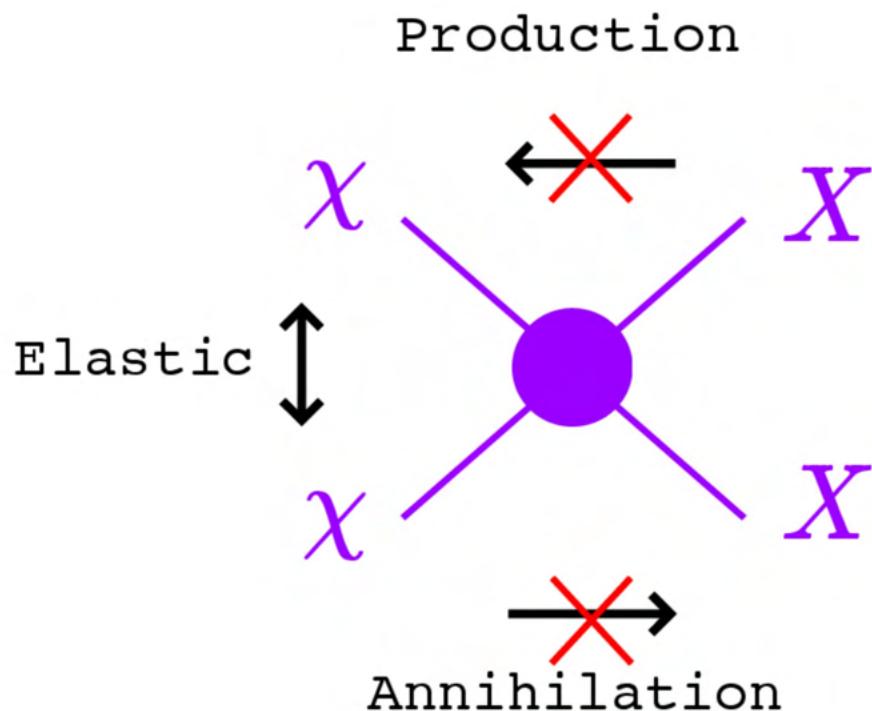
~concepts of **decoupling** and **freeze-out**~

Thermal relic particle starts off in thermal, kinetic, and chemical equilibrium with the rest of the universe at early times.



Thermal relic

chemical decoupling → freeze-out



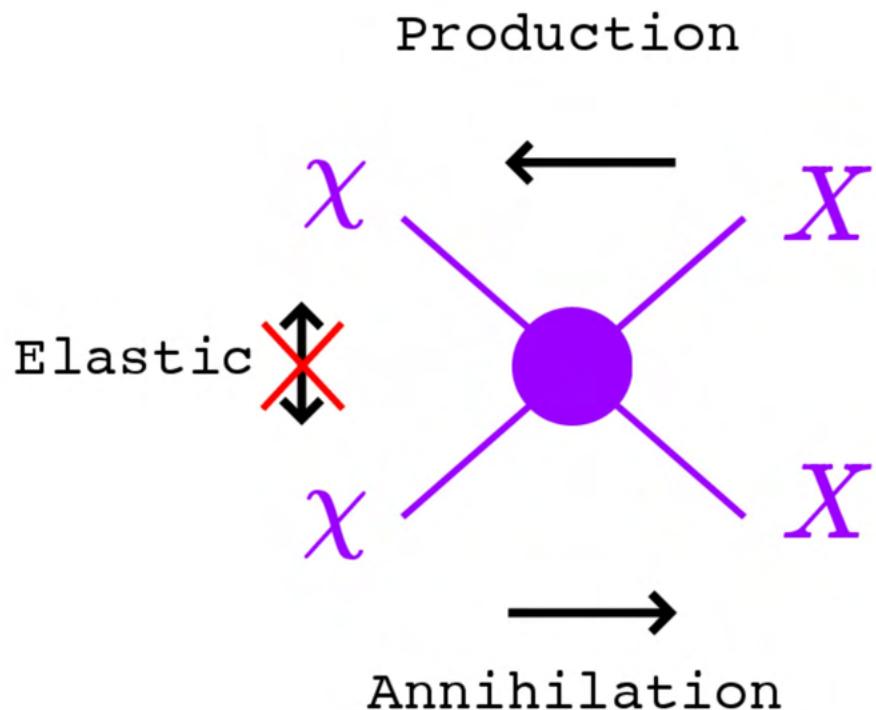
$$\chi\chi \not\rightarrow XX$$

$$\Gamma_{\text{inelastic}} = n_\chi \langle \sigma v \rangle \sim H$$

$$H \sim \frac{T^2}{M_{\text{pl}}}$$

Thermal relic

kinetic decoupling



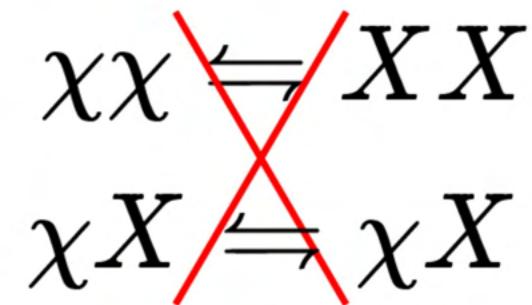
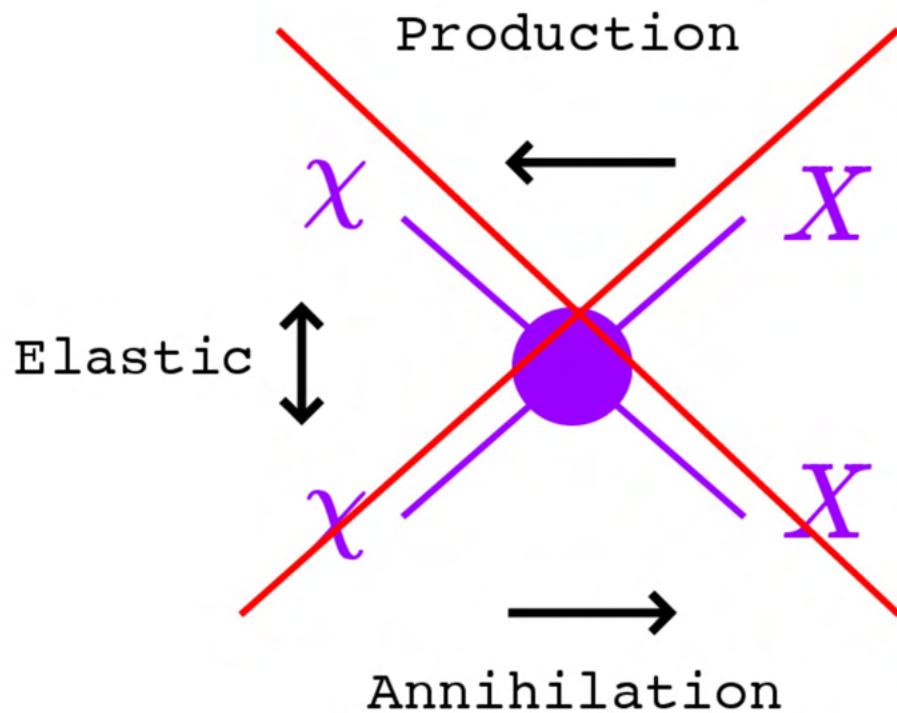
$$\chi X \not\cong \chi X$$

$$\Gamma_{\text{elastic}} = n_X \langle \sigma v \rangle \sim H$$

$$H \sim \frac{T^2}{M_{\text{pl}}}$$

Thermal relic

thermal decoupling
followed by free-streaming



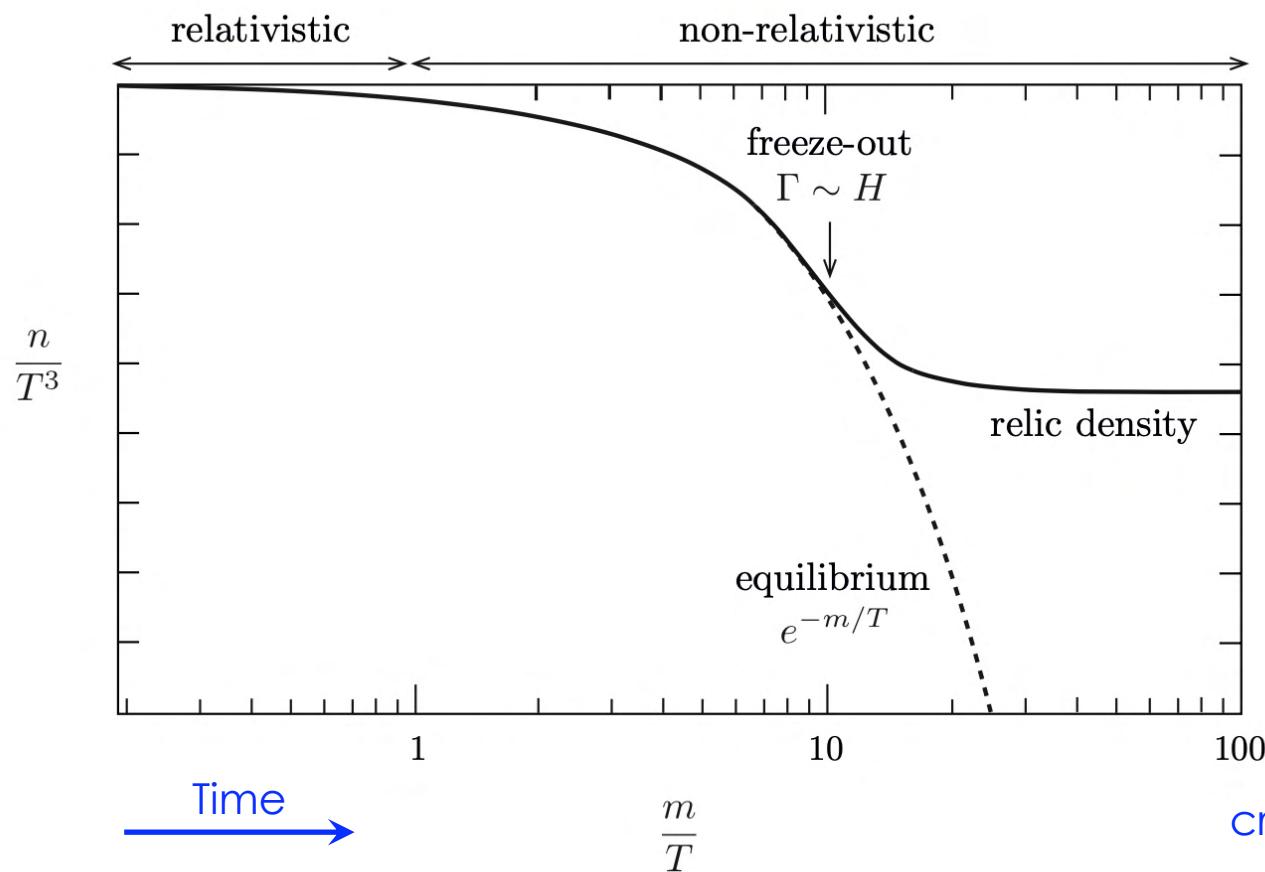
Thermal relic abundance

$$f(p) = \frac{1}{e^{(E(p)-\mu)/T} \pm 1}$$

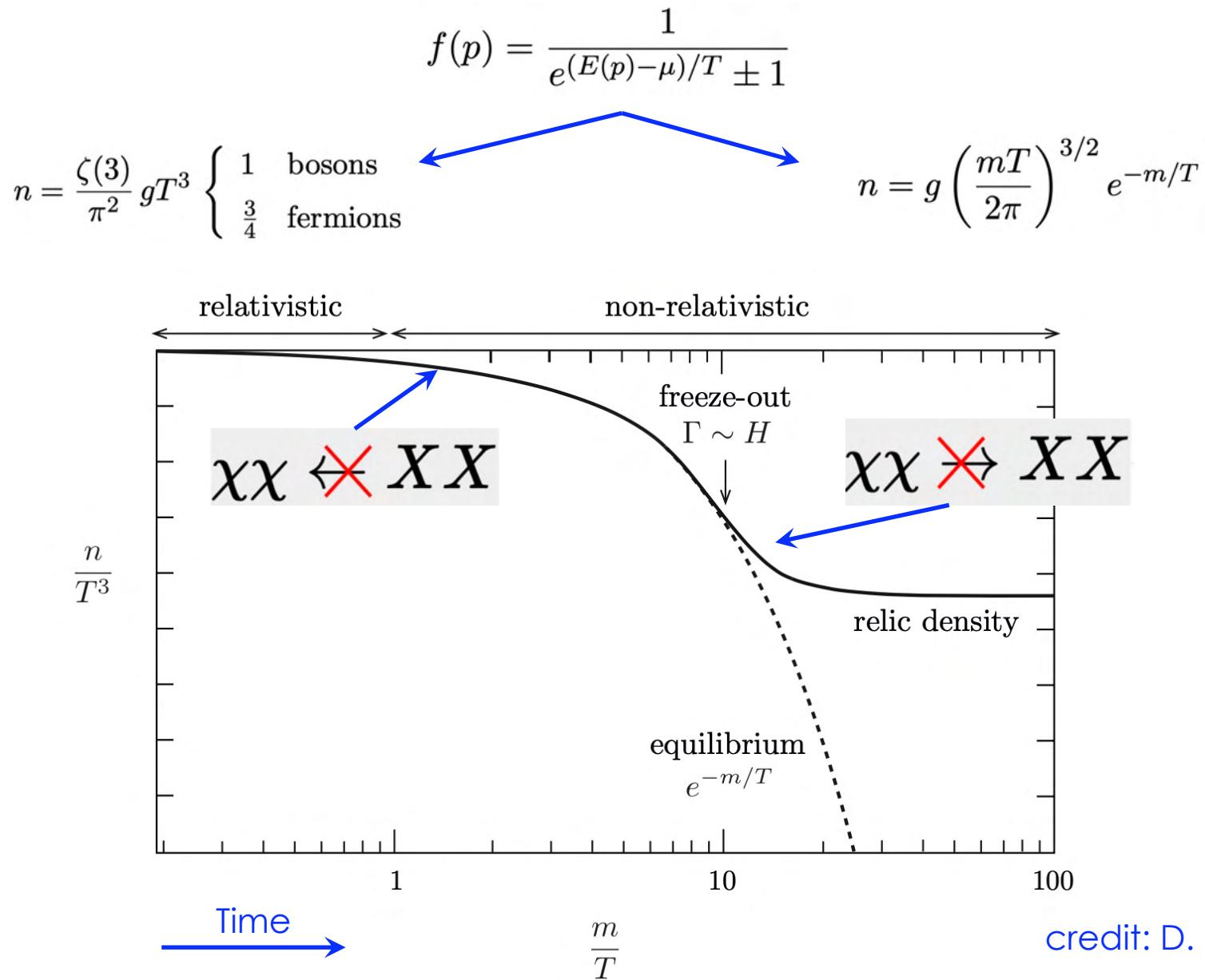
$$n = \frac{\zeta(3)}{\pi^2} g T^3 \begin{cases} 1 & \text{bosons} \\ \frac{3}{4} & \text{fermions} \end{cases} \quad \xrightarrow{\text{blue arrow}} \quad n = g \left(\frac{mT}{2\pi} \right)^{3/2} e^{-m/T}$$

Thermal relic abundance

$$f(p) = \frac{1}{e^{(E(p)-\mu)/T} \pm 1}$$
$$n = \frac{\zeta(3)}{\pi^2} g T^3 \begin{cases} 1 & \text{bosons} \\ \frac{3}{4} & \text{fermions} \end{cases}$$
$$n = g \left(\frac{mT}{2\pi} \right)^{3/2} e^{-m/T}$$



Thermal relic abundance



Question for you

A

B

C

D

A B

C D

Question for you

What happens to the temperature of the universe when a particle falls out of equilibrium?

- A) It stays constant
- B) It increases
- C) It decreases
- D) It depends on the particle interactions
- E) I have no idea

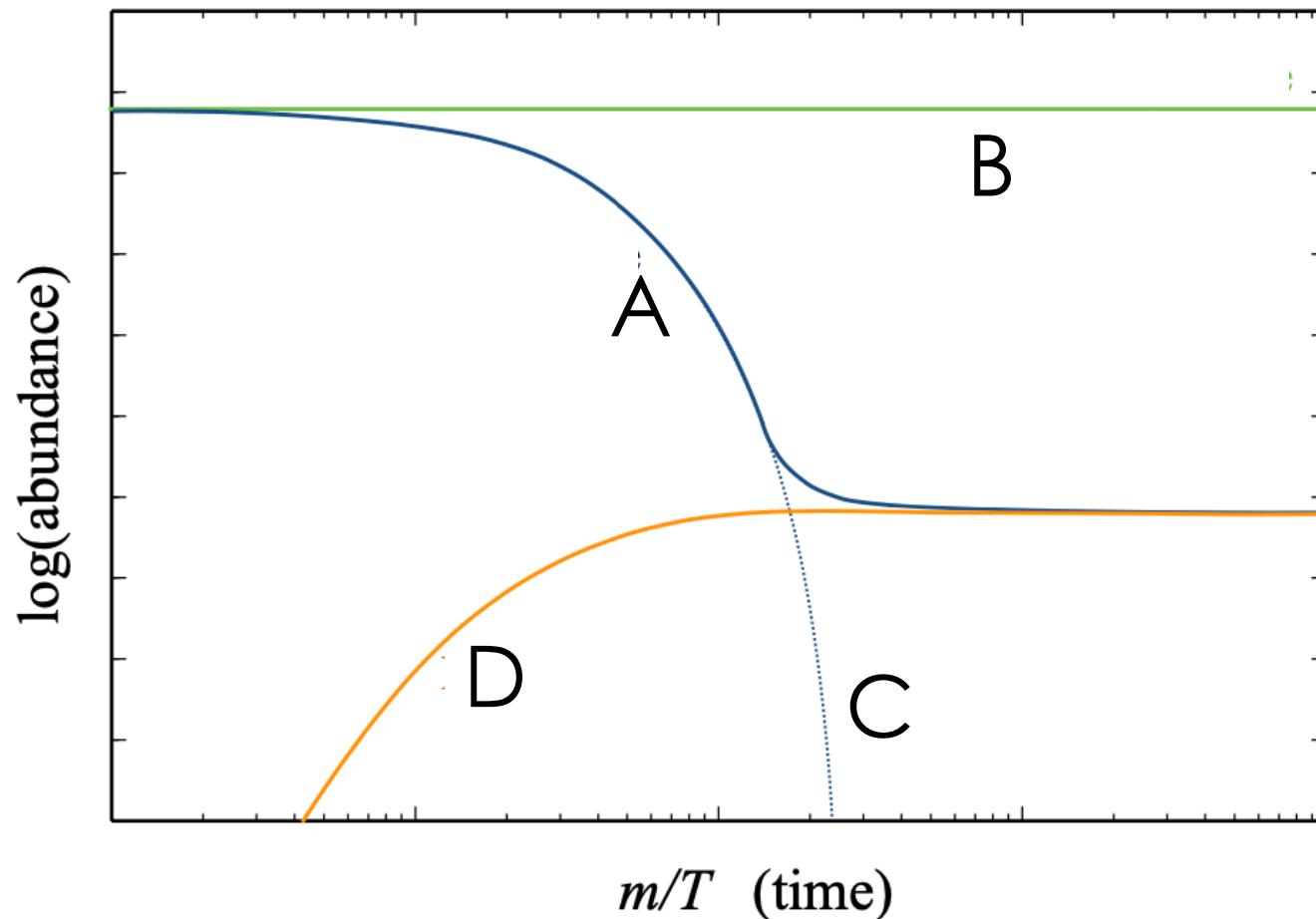
The quantity $g_{*S}(T) T^3 a^3$ is conserved throughout the expansion history of the universe.

The quantity $g_{*S}(T) T^3 a^3$ is conserved throughout the expansion history of the universe.

A B
C D

Question for you

Which of the four scenarios occurs if $H > \Gamma$ while $T \gg m$?
(m =particle mass, T =temperature, Γ =rate of particle production/annihilation)

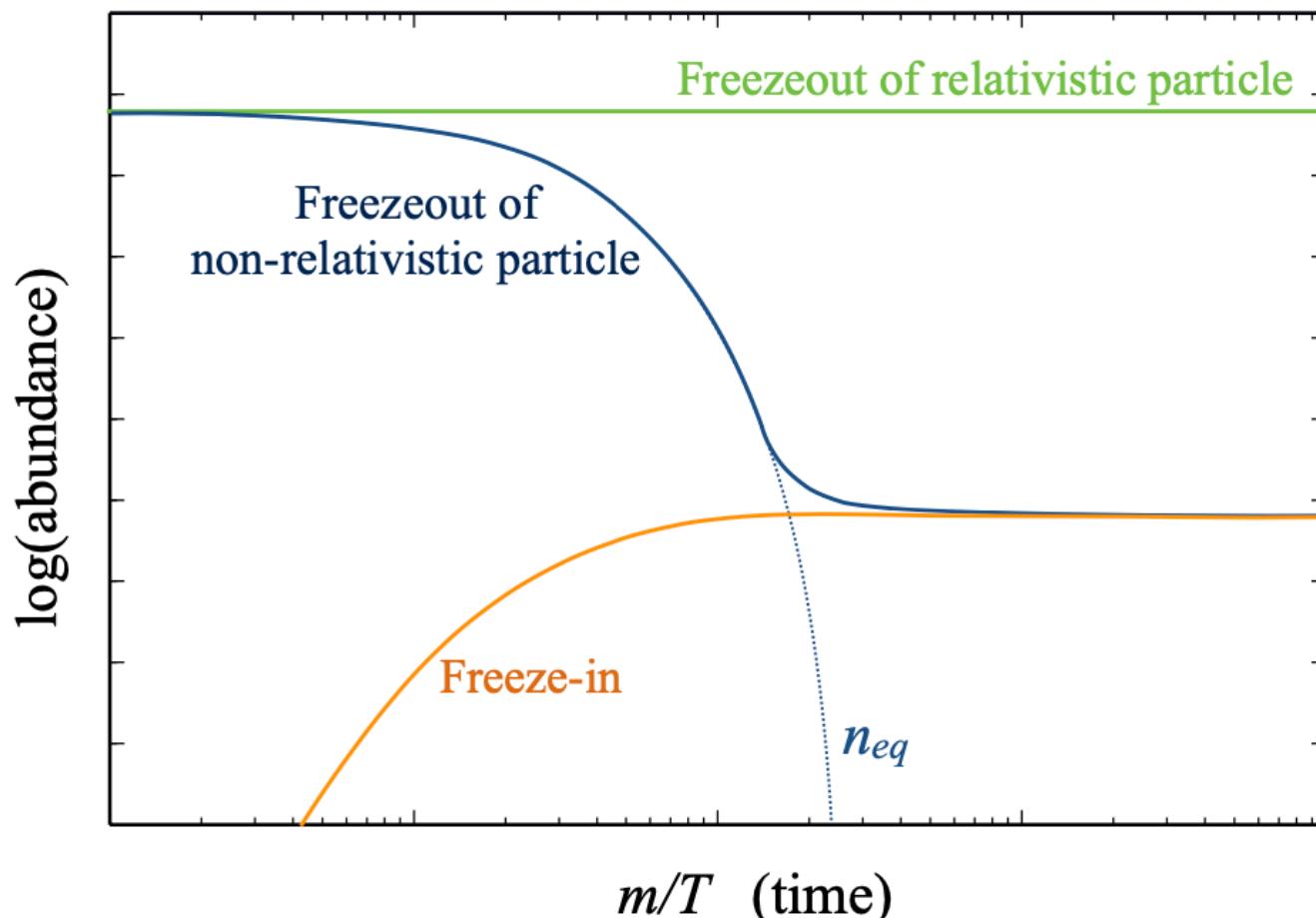


A B

C D

Question for you

Which of the four scenarios occurs if $H > \Gamma$ while $T \gg m$?
(m =particle mass, T =temperature, Γ =rate of particle production/annihilation)



Plot by T. Lin

In case of DM annihilation:

$S = \text{const}$

Heating

Expansion speeds up

Y_p increases*

Neutron half life is ~ 15 min

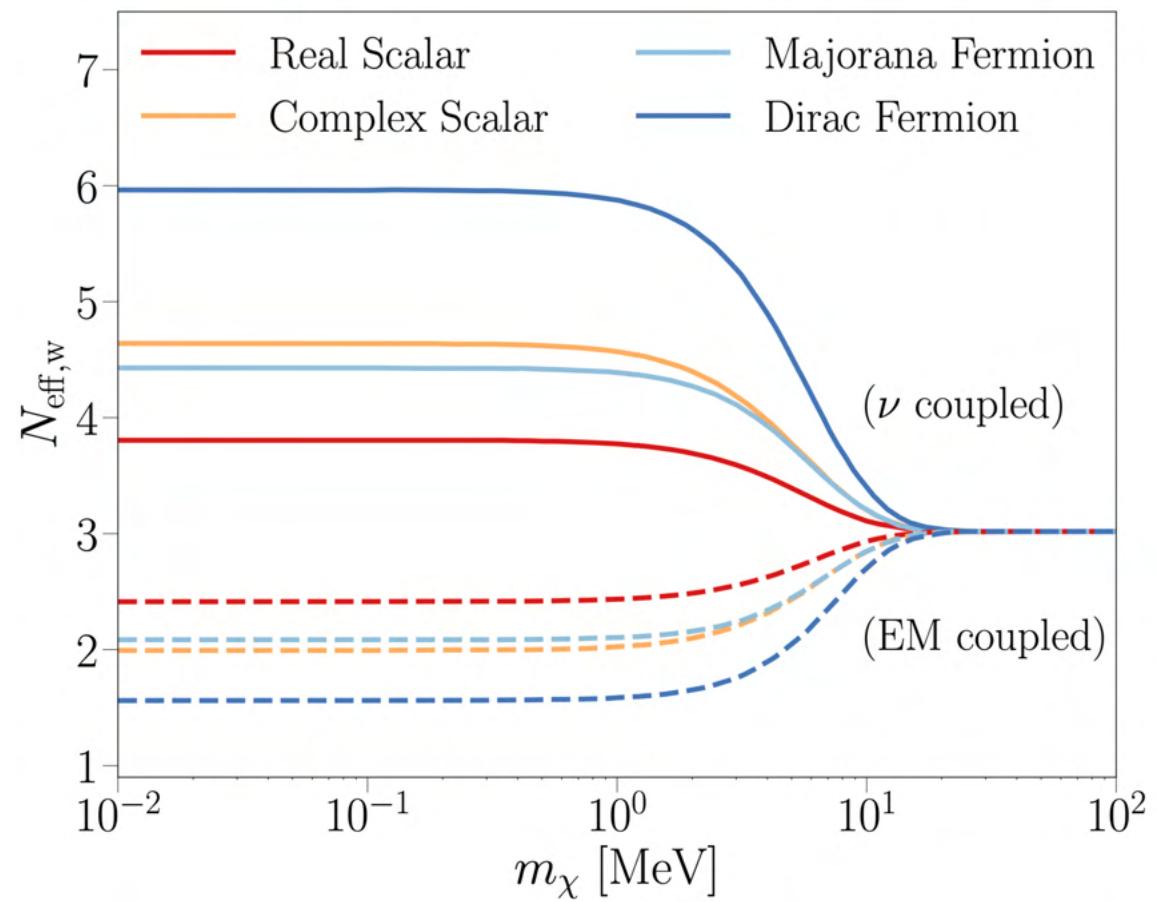
BBN with light dark matter

$$N_{\text{eff},w} \equiv 3 \left[\frac{11}{4} \left(\frac{T_\nu}{T_\gamma} \right)_0^3 \right]^{\frac{4}{3}}$$

Contribution from SM + dark matter or other light relics

Contribution from other relativistic d.o.f.

$$N_{\text{eff}}(m_\chi, \Delta N_\nu) \equiv N_{\text{eff},w}(m_\chi)(1 + \Delta N_\nu / 3)$$



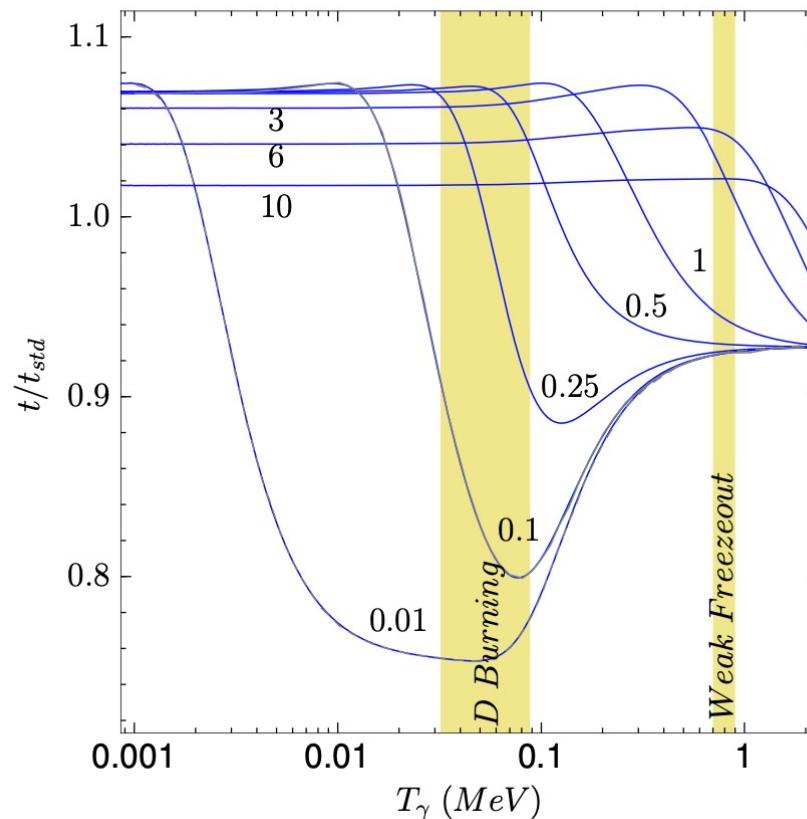
An+ 2022

Jenssen, 2016; Sabti+. 2019.

A **light thermal relic** can alter both early and late expansion history.

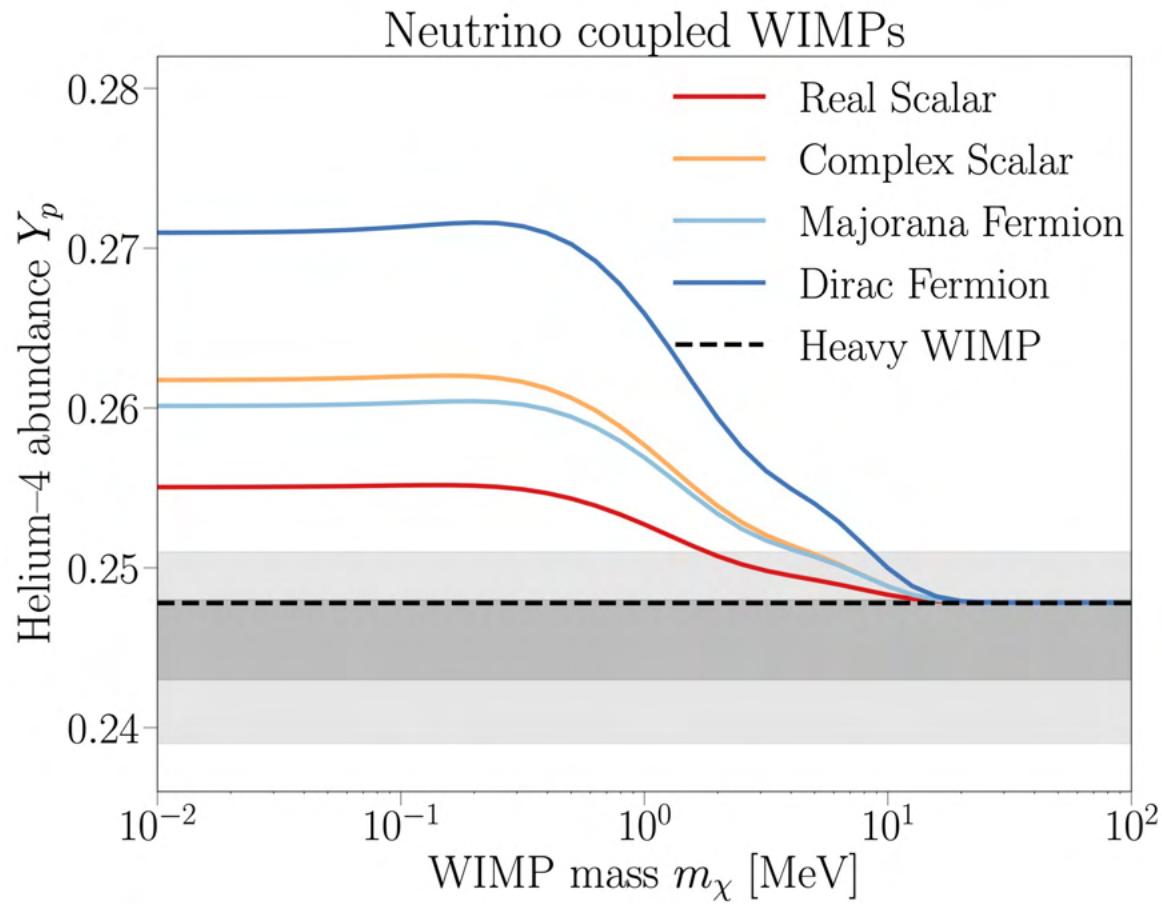
Light enough to become non-relativistic during BBN
(while annihilating into photons or neutrinos):

$$0.1 \text{ MeV} < m_\chi < 20 \text{ MeV}$$



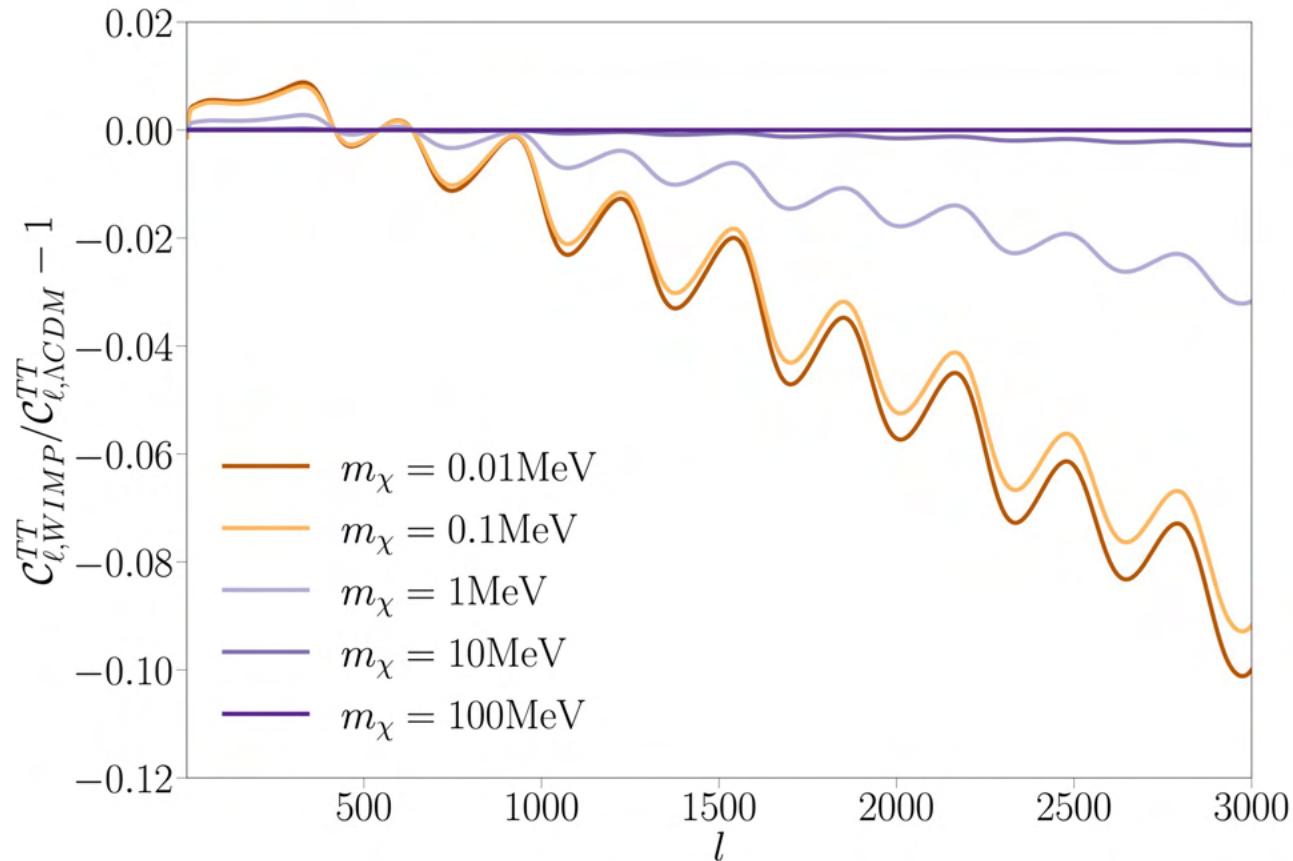
Nollett+Steigman, 2014, 2015
Jenssen, 2016
<https://arxiv.org/abs/1803.00070>

BBN with light dark matter



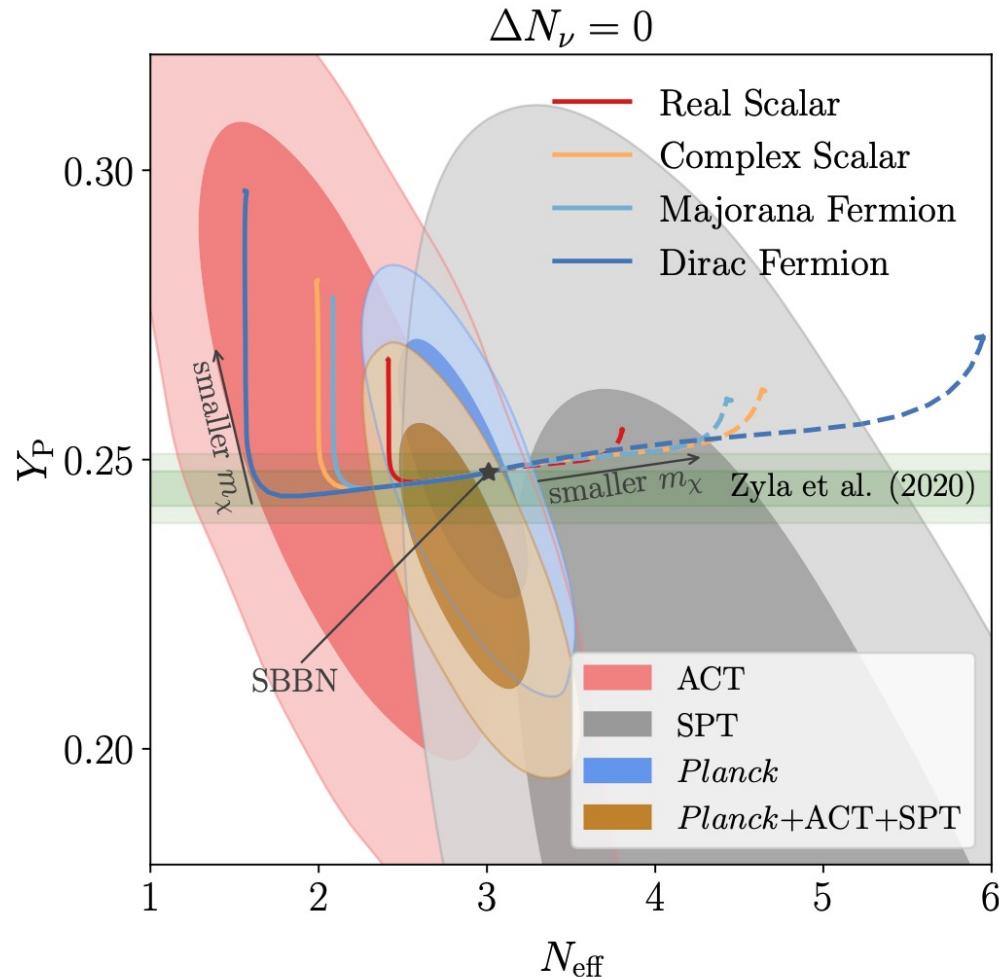
An+ 2022; Giovanetti+, 2021;
Krnjaic+McDermott, 2019;
Nollett+Steigman, 2014, 2015;
Jensen, 2016; Sabti+, 2019.

CMB with light dark matter



An+ 2022; Giovanetti+, 2021;
Krnjaic+McDermott, 2019;
Nollett+Steigman, 2014, 2015;
Jensen, 2016; Sabti+, 2019.

CMB with light dark matter



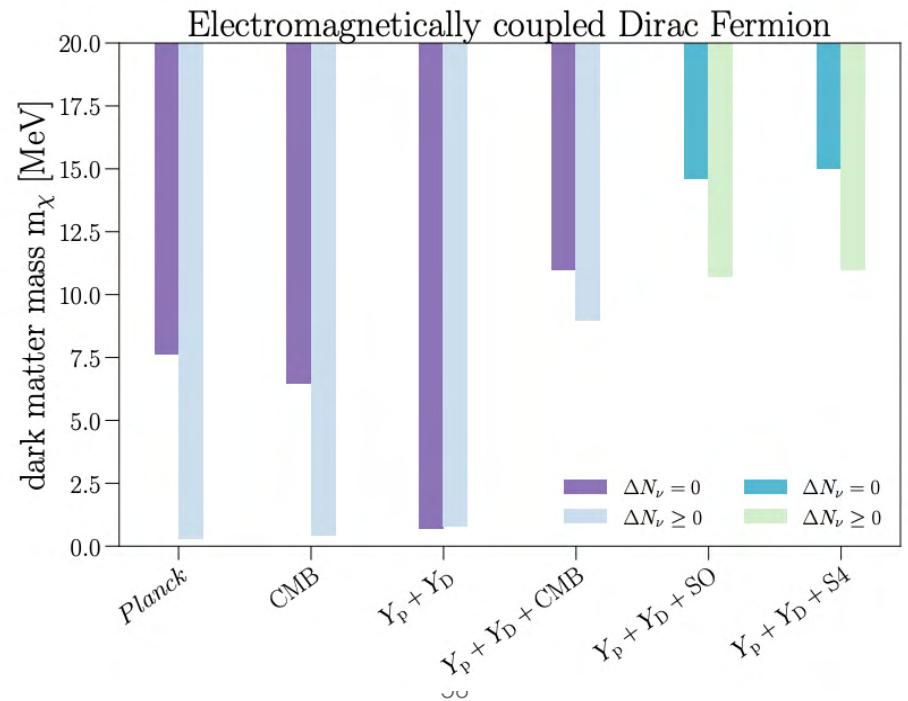
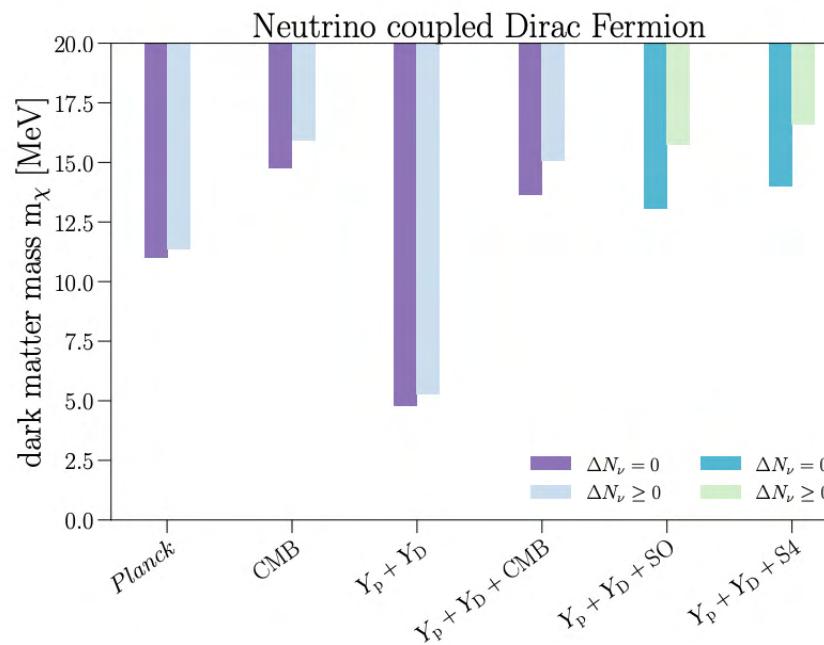
Dark matter mass bounds are sensitive to small shifts in best-fit values of N_{eff} and Y_p .

An+ 2022; Giovanetti+, 2021;
Krnjaic+McDermott, 2019;
Nollett+Steigman, 2014, 2015;
Jensen, 2016; Sabti+, 2019.

DM mass bounds

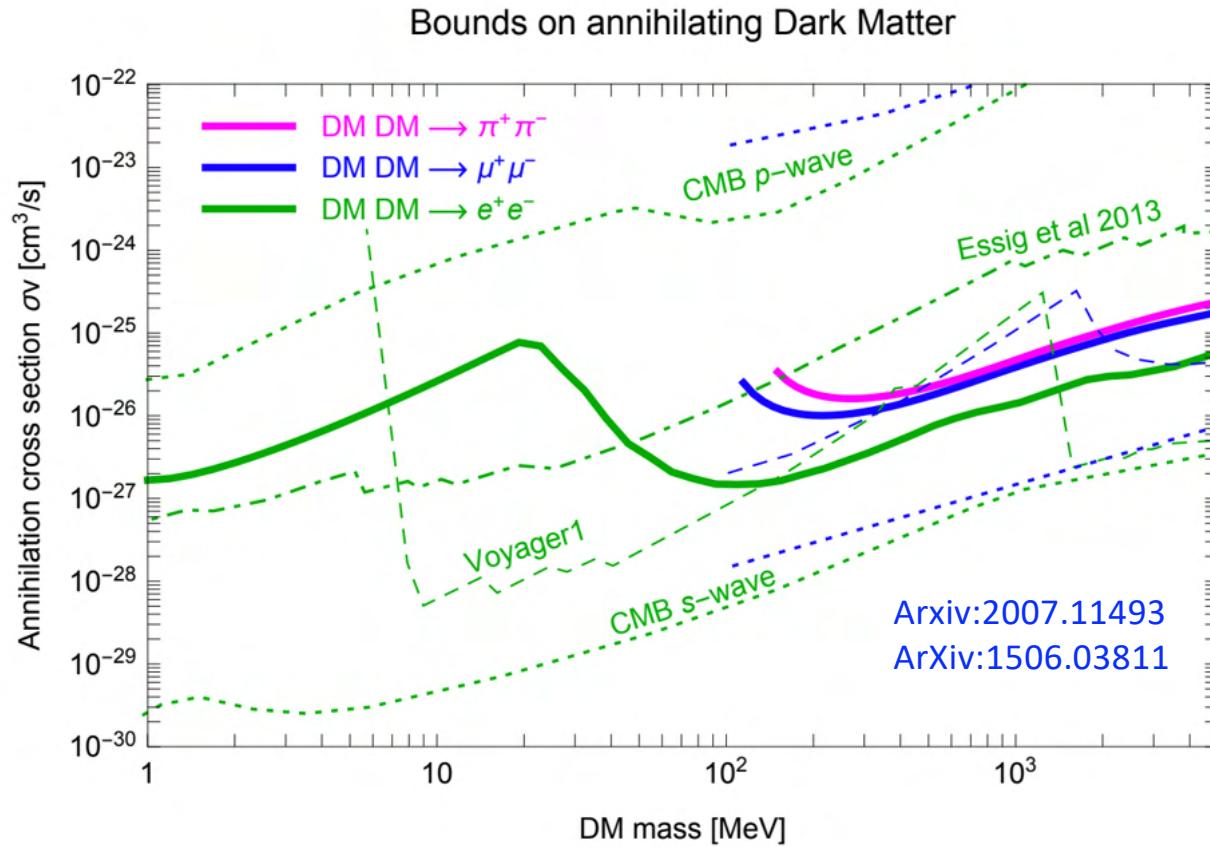
*Colored = allowed mass ranges
(95% CL)

An+ (2022)



- CMB is more constraining than primordial abundances.
 - Strongest bound is from CMB + primordial abundances, around 15 MeV
 - Weakest bound is around 100 keV
 - Addition of ACT+SPT to Planck improves bounds by up to 80% for neutrino coupled
 - Bounds on EM coupled DM sensitive to choice of data: small inconsistency between CMB data sets in value of N_{eff} .
- SO will either exclude thermal relics lighter than 20 MeV, or provide evidence for non-standard BBN.**

Digression: late-time (residual) annihilation bounds

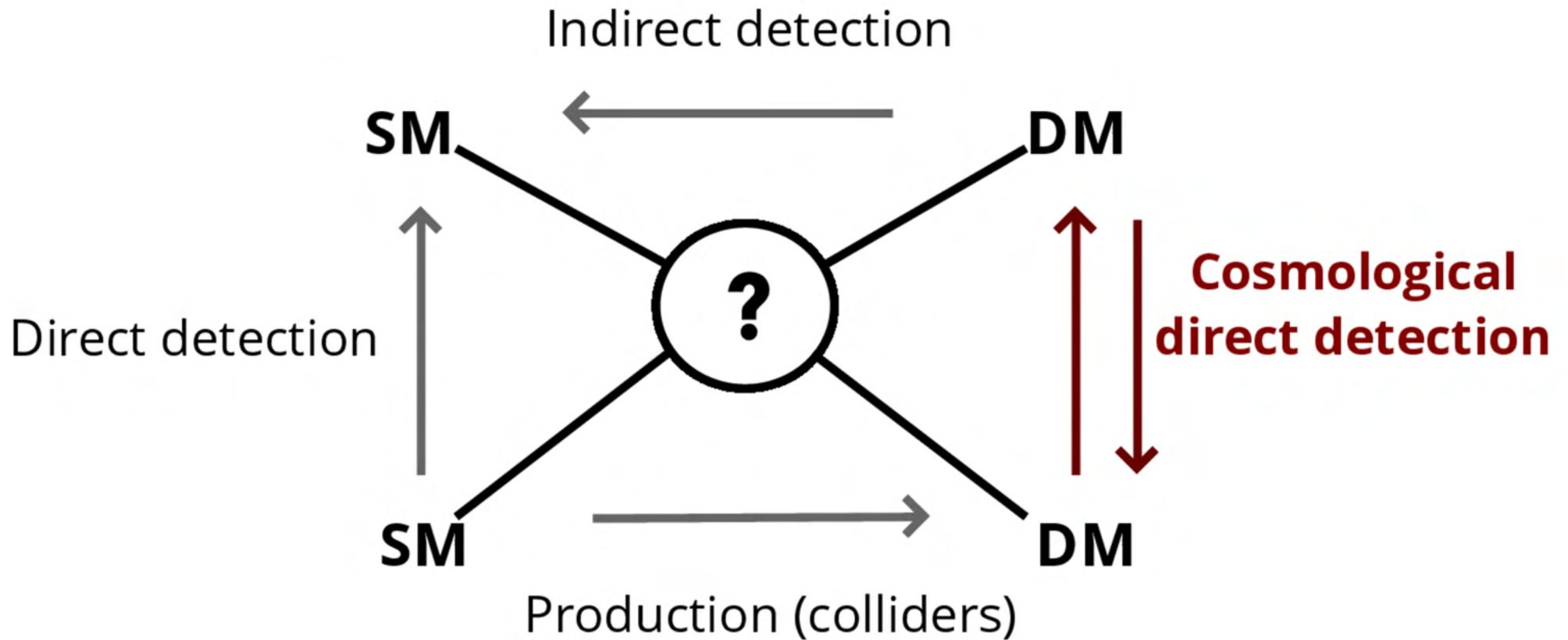


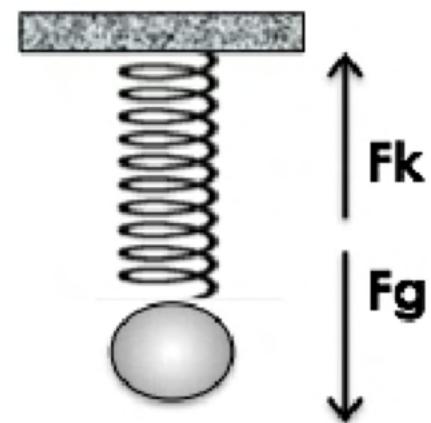
- If DM is a thermal relic, its annihilation is related to relic abundance!
- There are bounds from CMB and X-rays.

III. Interactions

lessons from small and large scales

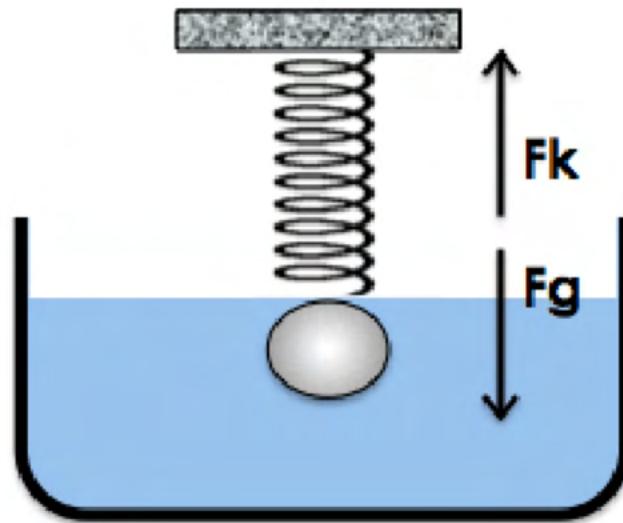
Interacting dark matter (IDM)



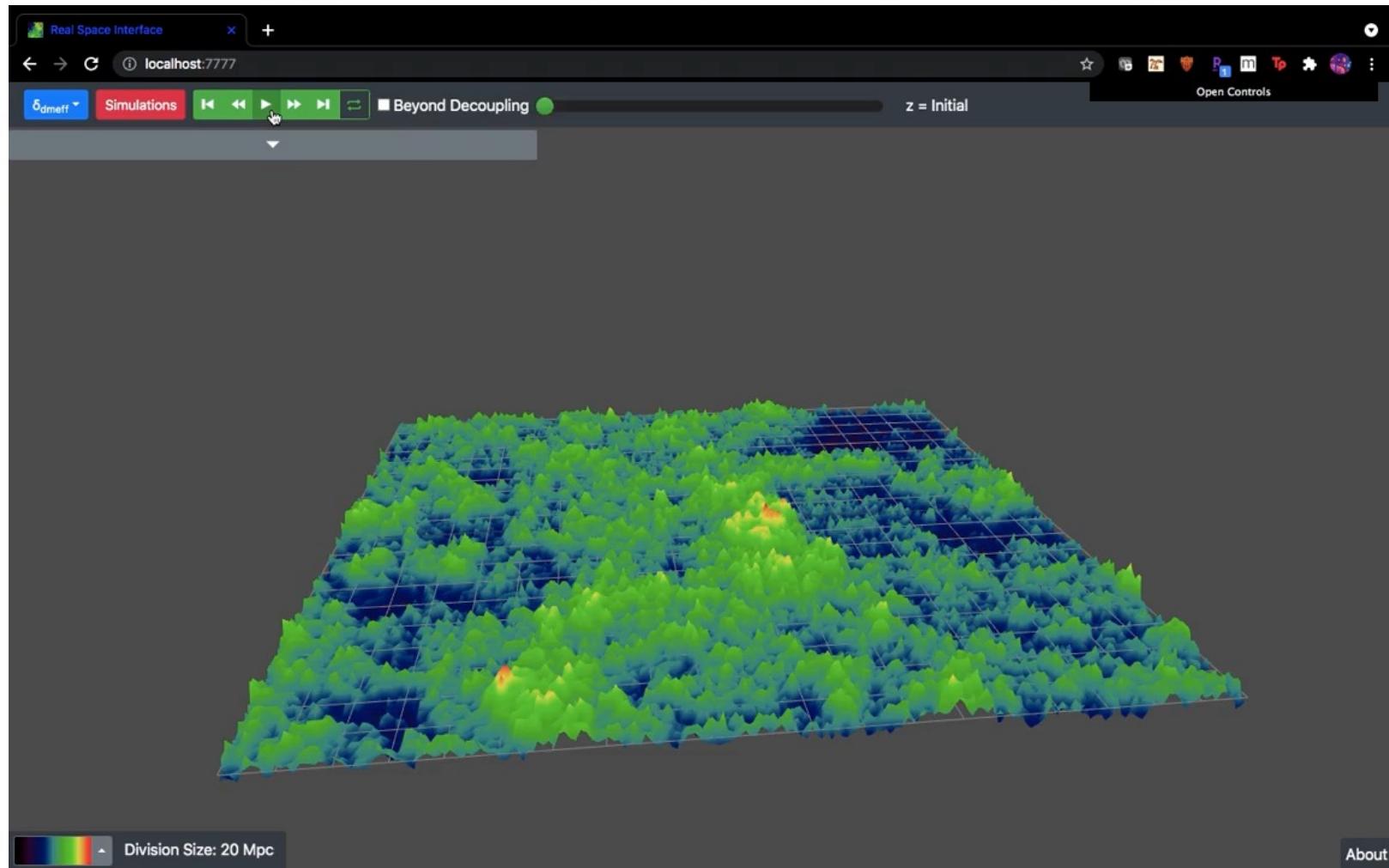


DM-baryon elastic scattering

fluids + gravity + **drag** = **damped** baryonic acoustic oscillations



IDM cosmology: dark acoustic oscillations



Credit: Dimple Sarnaik (USC), using CLASS Real Space Interface

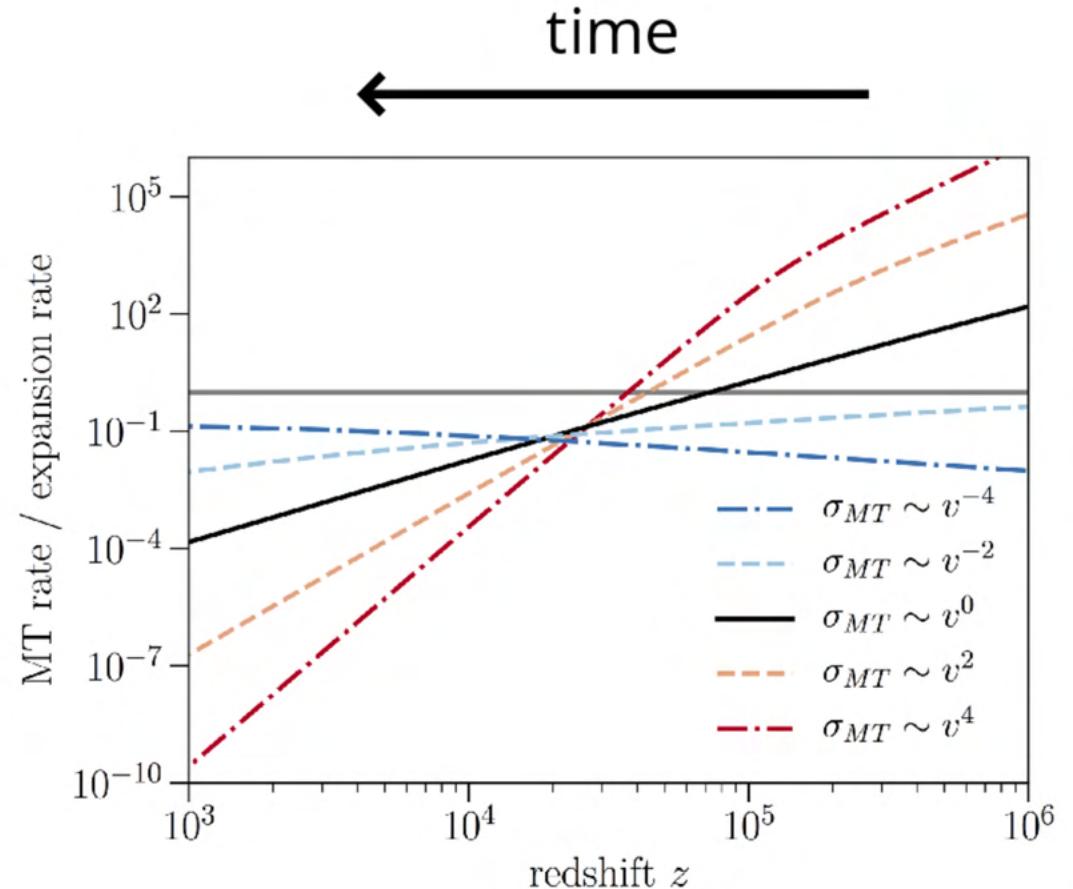
Cosmology with DM-baryon elastic scattering

momentum-transfer cross section

$$\sigma_{MT} = \sigma_0 v^n$$

momentum-transfer rate

$$R_\chi = a \rho_b \frac{\mathcal{N}_n \sigma_0}{m_\chi + m_b} \left(\frac{T_\chi}{m_\chi} + \frac{T_b}{m_b} \right)^{(n+1)/2}$$



See also: Boehm+ (2002), Chen+ (2002), Dubovsky+ (2004), Sigurdson+ (2004), Dvorkin+ (2014);

Gluscevic+ (2017); Boddy+ (2018); Xu, + (2018); Slatyer, + (2018); Wu, + (2018).

Non-relativistic EFT in a nutshell

Goal:

Model-independently categorize pheno at low energy.

Method:

Instead of a model, use Galilean Hermitian invariants:

relative particle velocity

$$\vec{v}_\perp = \vec{v} + \vec{q}/2\mu_{p\chi}$$

momentum transfer

$$i\vec{q}$$

spins

$$\vec{S}_\chi \quad \vec{S}_p$$

and construct non-relativistic operators for elastic scattering through a scalar or a vector mediator, up to second order in momentum transfer.

Result: Total of 14 operators (free: coupling and DM mass).

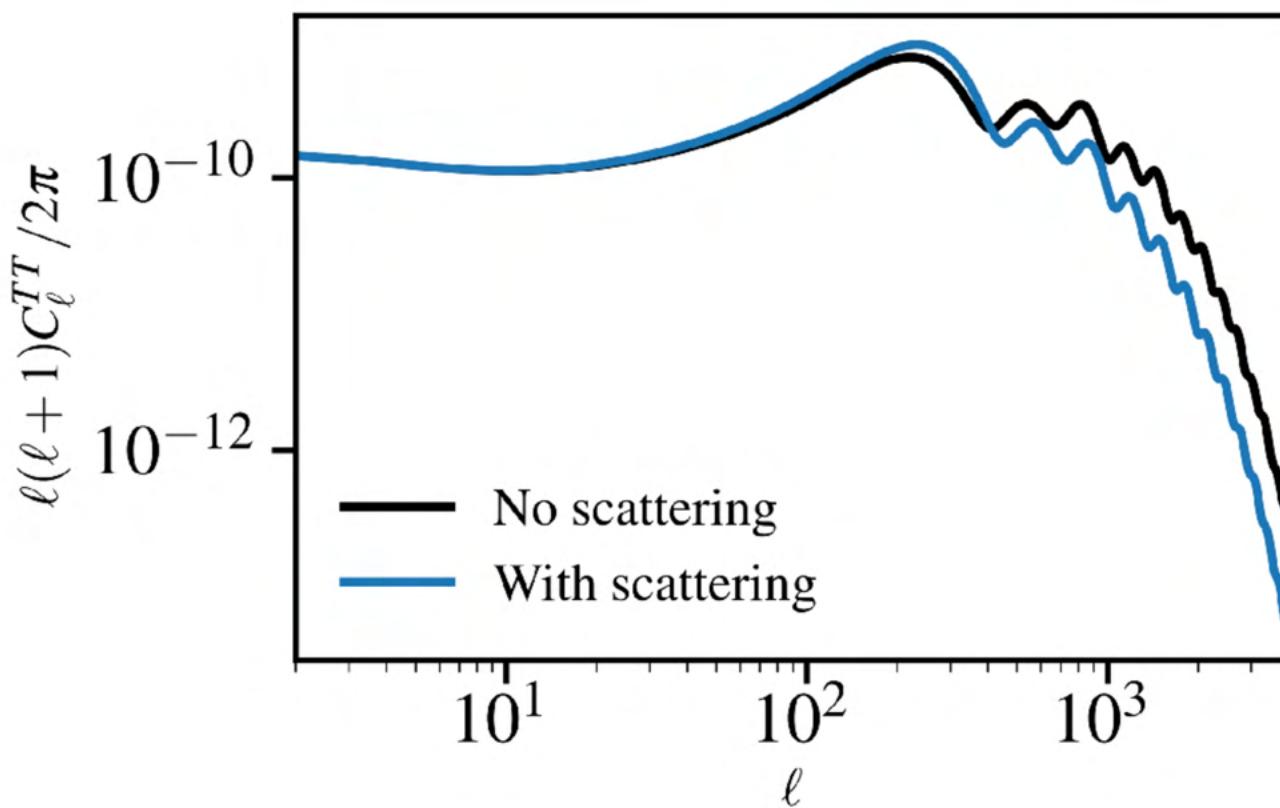
EFT in cosmological context

```

graph LR
    A["theory  
O_i(m_\chi, c_i)"] --> B["differential cross  
section  
dσ/dΩ"]
    B --> C["momentum-transfer cross section  
σ_MT(v^n) = ∫ dΩ dσ/dΩ (1 - cosθ)"]
    C --> D["R_\chi"]
    D --> E["Boltzmann Eqs."]
    E --> F["C_\ell, P(k)"]
    F --> G["momentum-transfer  
rate"]
    F --> H["evolution of  
cosmological  
perturbations"]
    F --> I["observable!"]
  
```

The diagram illustrates the flow from theoretical calculations to observable cosmological results. It starts with a theory input $O_i(m_\chi, c_i)$, which leads to a differential cross section $d\sigma/d\Omega$. This is then converted into a momentum-transfer cross section $\sigma_{MT}(v^n) = \int d\Omega \frac{d\sigma}{d\Omega} (1 - \cos\theta)$. The next step is the rate R_χ , followed by the Boltzmann Equations. These equations lead to the final observable results $C_\ell, P(k)$. Along this path, there are three intermediate steps: momentum-transfer rate, evolution of cosmological perturbations, and finally, the label "observable!".

CMB anisotropy with IDM



See also: Boehm+ (2002), Chen+ (2002), Dubovsky+ (2004), Sigurdson+ (2004), Dvorkin+ (2014);
Gluscevic+ (2017); Boddy+ (2018); Xu, + (2018); Slatyer, + (2018); Wu, + (2018).

Cosmology with DM-baryon elastic scattering

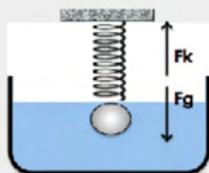
Heat and momentum transfer between DM and baryons affects:

Thermal history



$$\begin{aligned}\dot{T}_\chi &= -2 \frac{\dot{a}}{a} T_\chi + \underline{2R'_\chi(T_b - T_\chi)} \\ \dot{T}_b &= -2 \frac{\dot{a}}{a} T_b + \frac{2\mu_b}{m_\chi} \frac{\rho_\chi}{\rho_b} R'_\chi (T_\chi - T_b) + \frac{2\mu_b}{m_e} R_\gamma (T_\gamma - T_b)\end{aligned}$$

Matter distribution

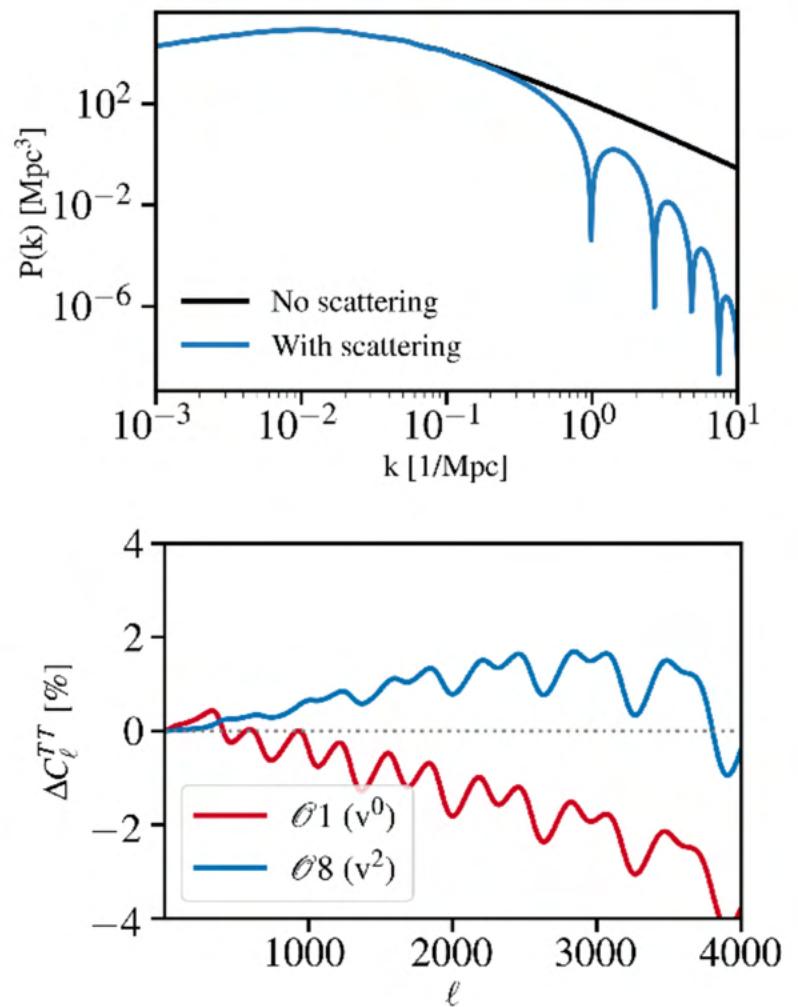
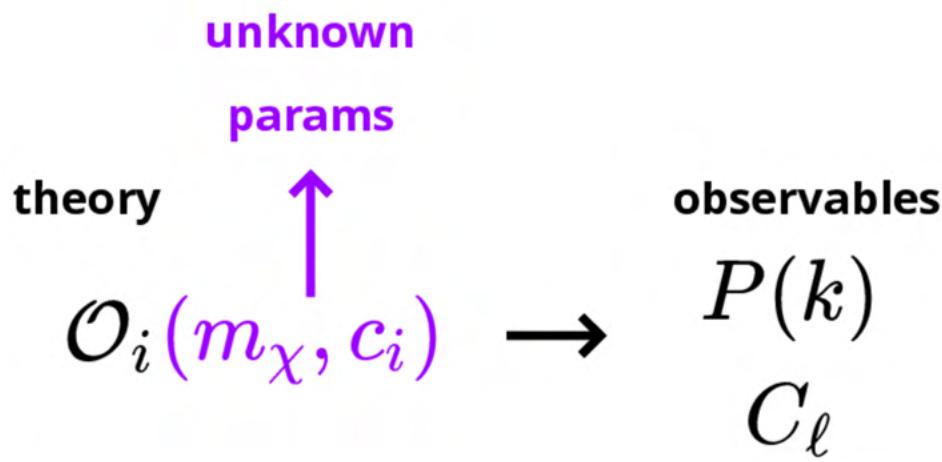


$$\begin{aligned}\dot{\delta}_\chi &= -\theta_\chi - \frac{\dot{h}}{2}, & \dot{\delta}_b &= -\theta_b - \frac{\dot{h}}{2}, \\ \dot{\theta}_\chi &= -\frac{\dot{a}}{a} \theta_\chi + c_\chi^2 k^2 \delta_\chi + \underline{R_\chi (\theta_b - \theta_\chi)}, \\ \dot{\theta}_b &= -\frac{\dot{a}}{a} \theta_b + c_b^2 k^2 \delta_b + R_\gamma (\theta_\gamma - \theta_b) + \frac{\rho_\chi}{\rho_b} R_\chi (\theta_\chi - \theta_b)\end{aligned}$$

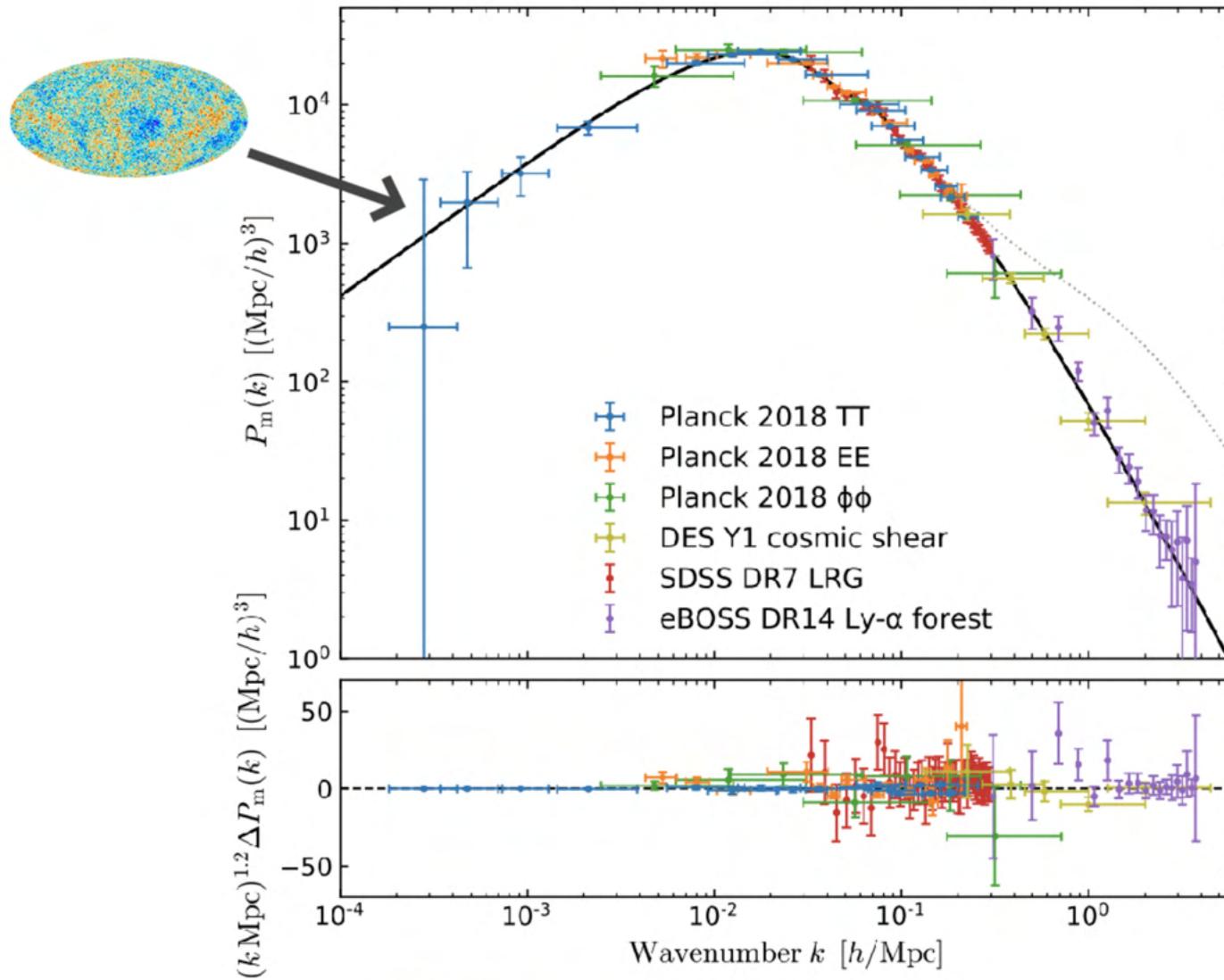
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Gluscevic+ (2017); Boddy+ (2018); Xu, + (2018); Slatyer, + (2018); Wu, + (2018).

EFT in cosmological context

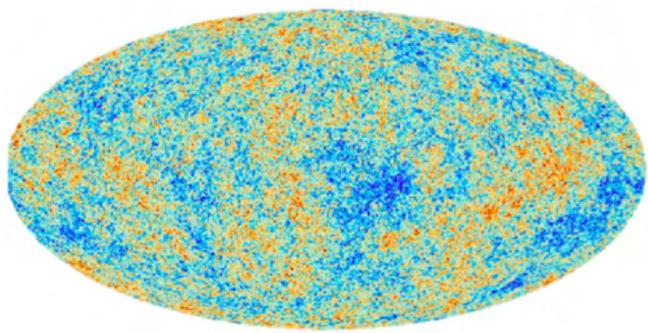


Matter distribution is captured on various scales by different visible tracers.



CMB anisotropy

Observables = temperature + polarization + lensing

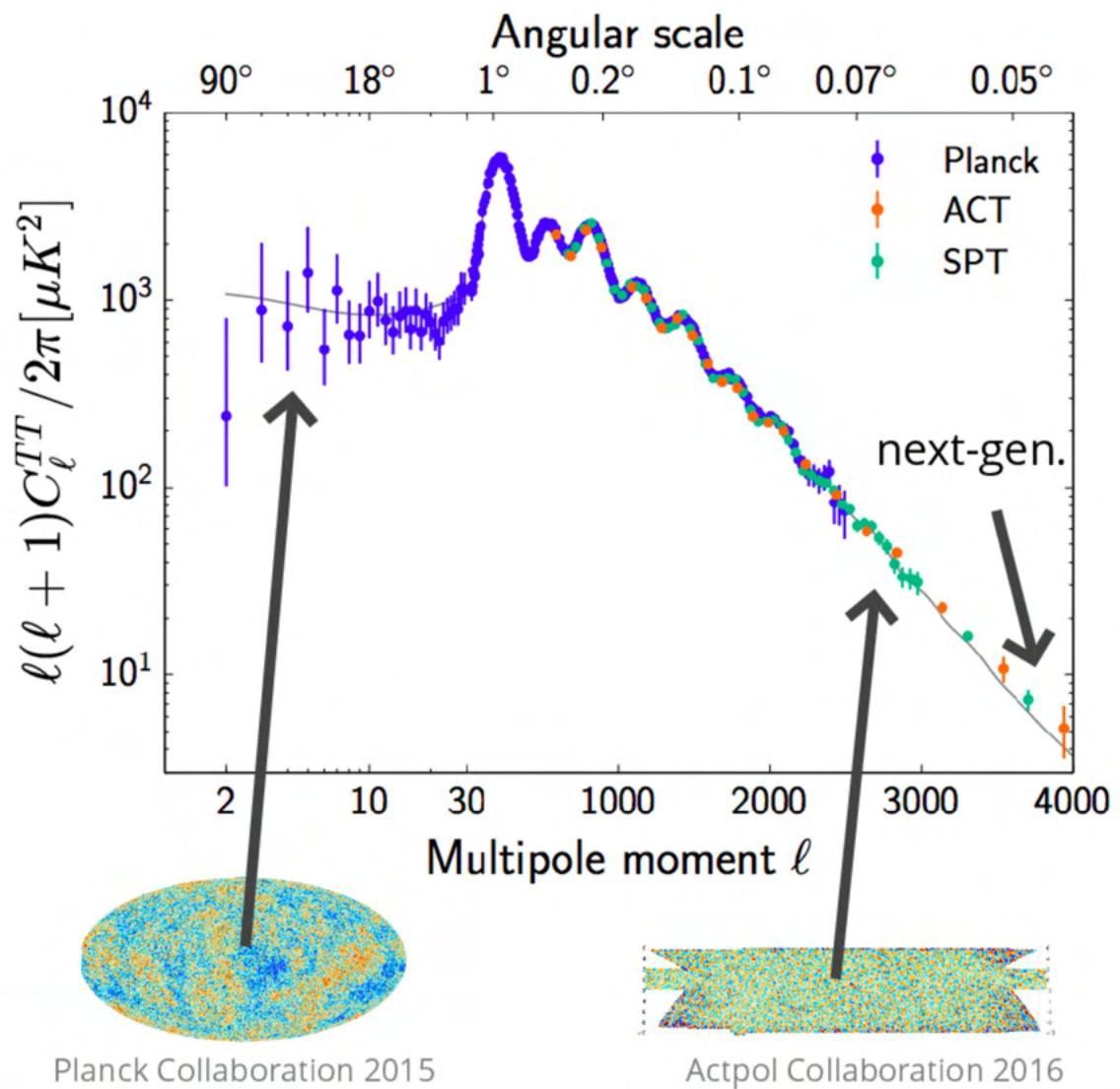


$$T(\hat{n}) = \sum a_{\ell m} Y_{\ell m}(\hat{n})$$

$$C_\ell^{TT} = \frac{1}{2\ell+1} \sum \langle |a_{\ell m}|^2 \rangle$$

<https://arxiv.org/abs/1907.12875>

<https://arxiv.org/abs/2007.07289>



Question for you

A

B

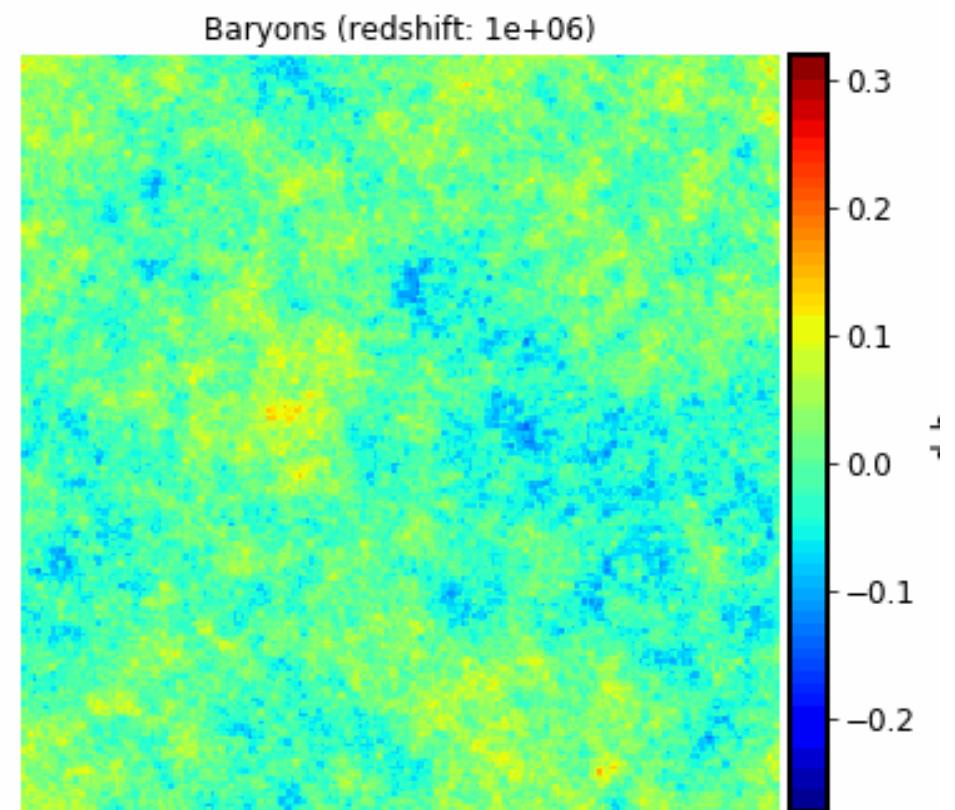
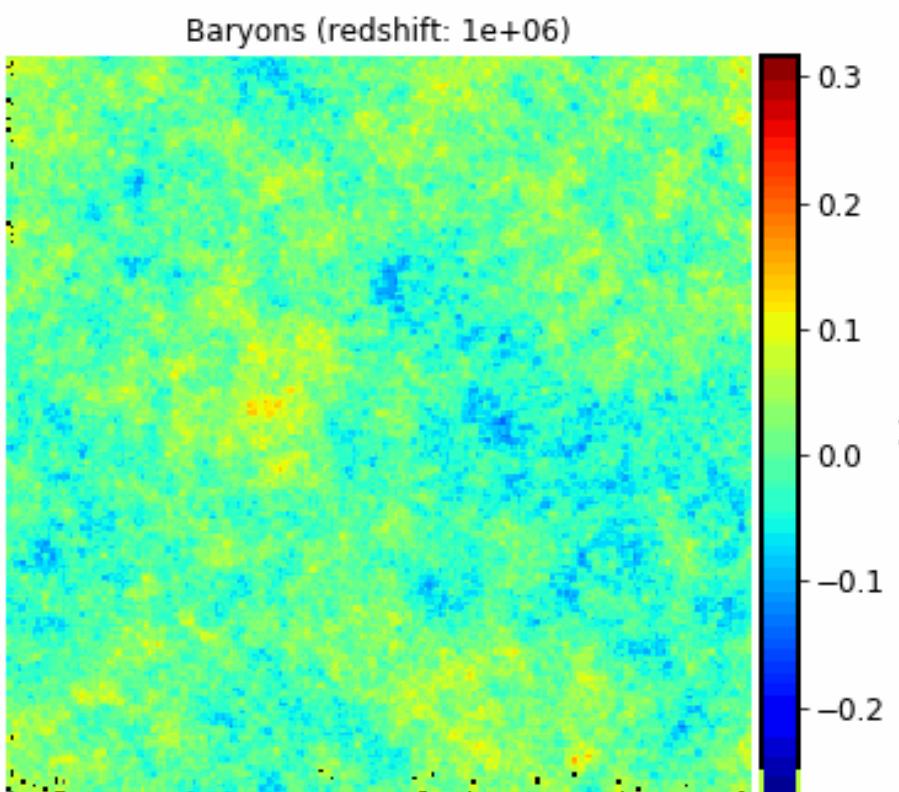
C

D

A B
C D

Question for you

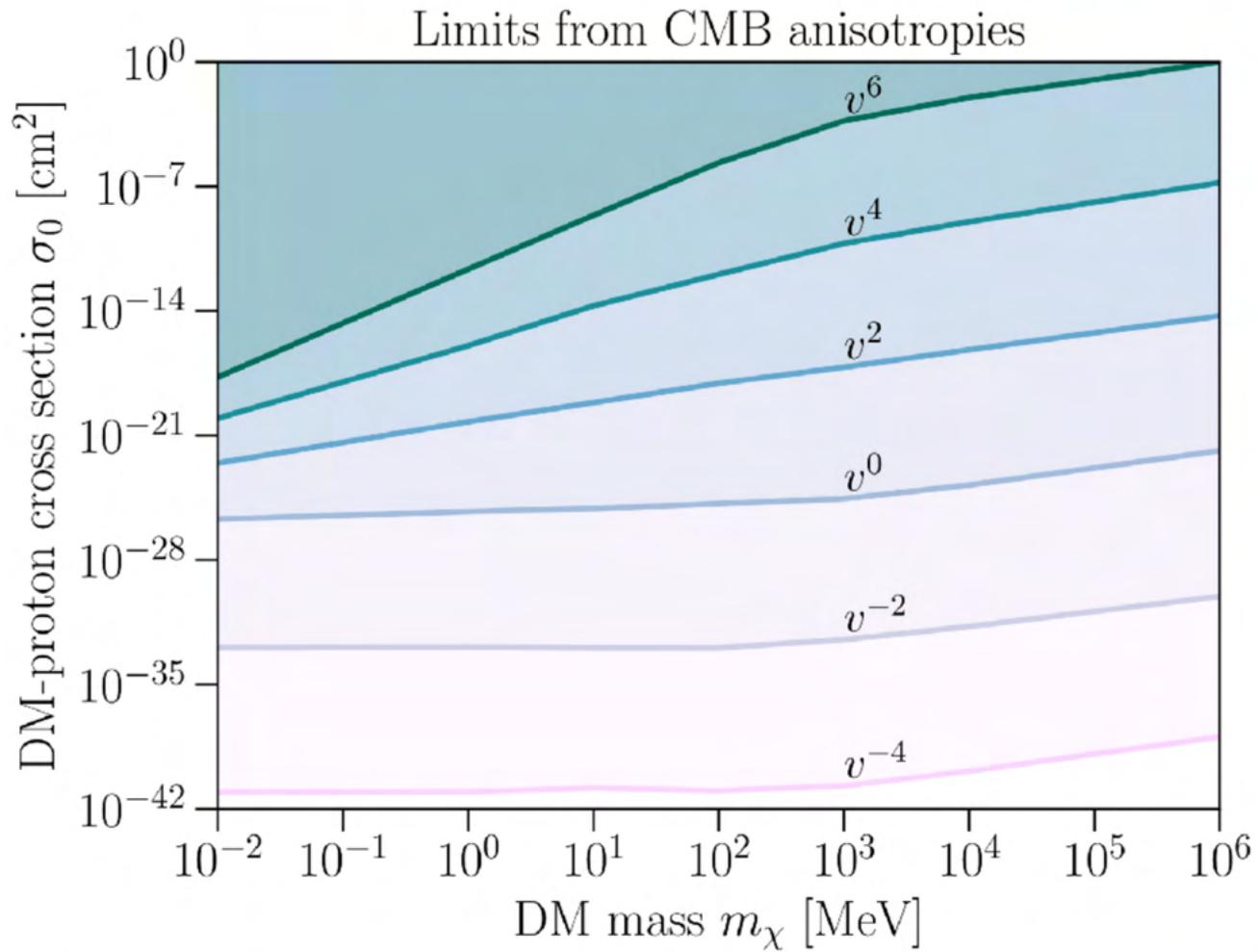
Which panel features DM-baryon scattering?



A

B

Planck limits on EFT of DM-proton scattering

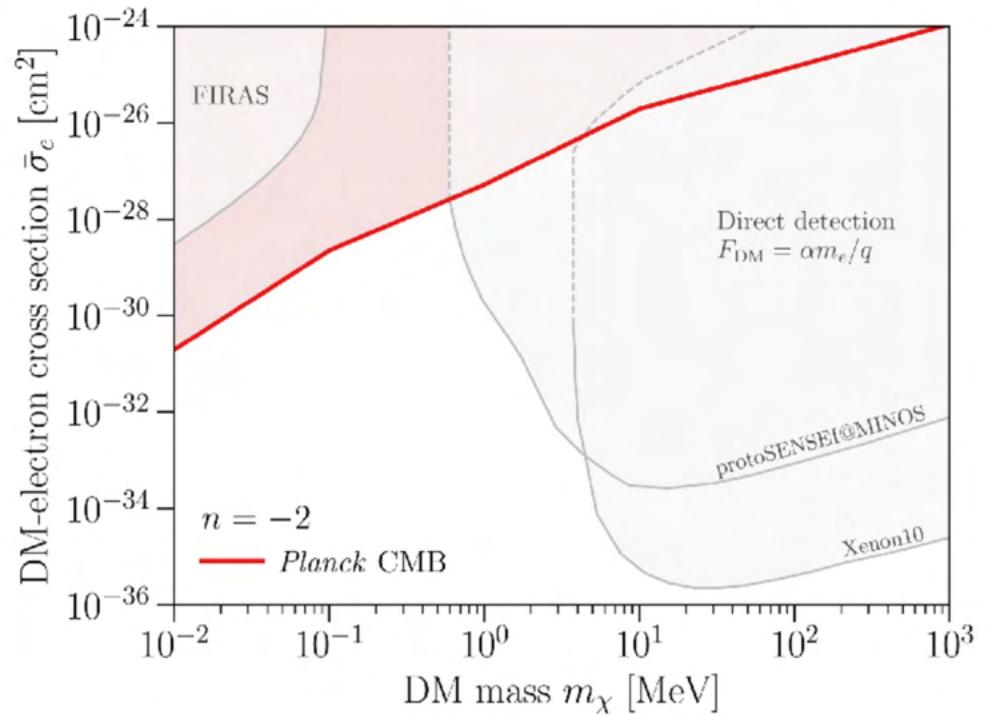
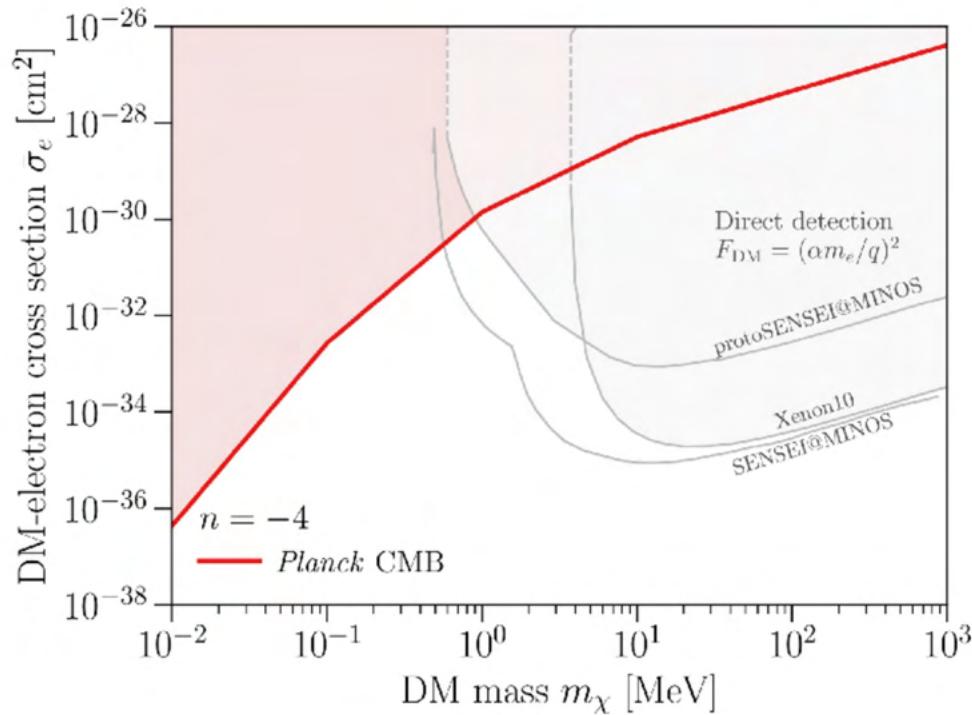


@age of the Universe ~1000 years:

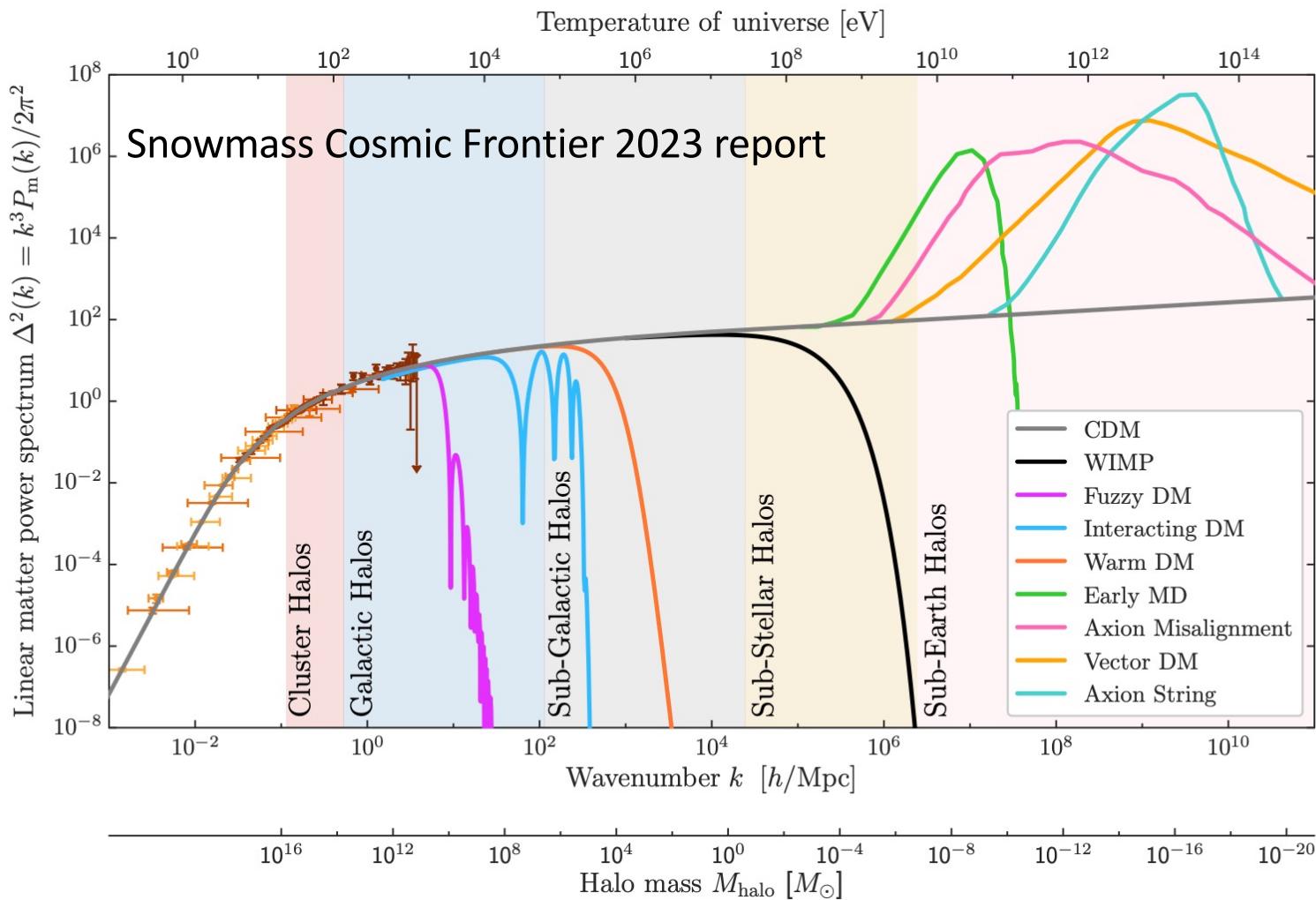
Nguyen+ (2021)

less than 1 in 100 000 proton scatterings is with DM.

Planck limits on DM-electron scattering

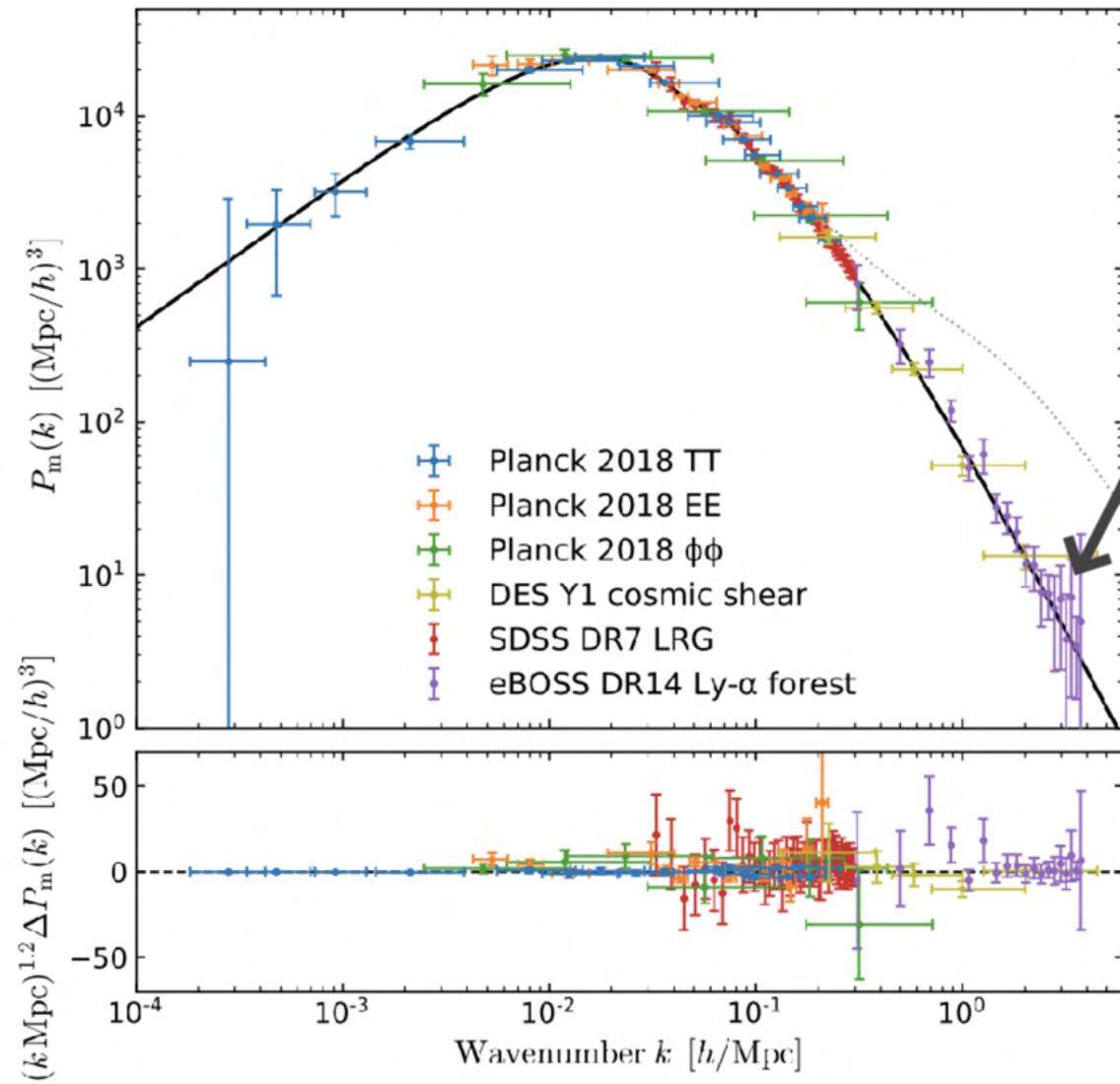


DM microphysics at the small-scale frontier



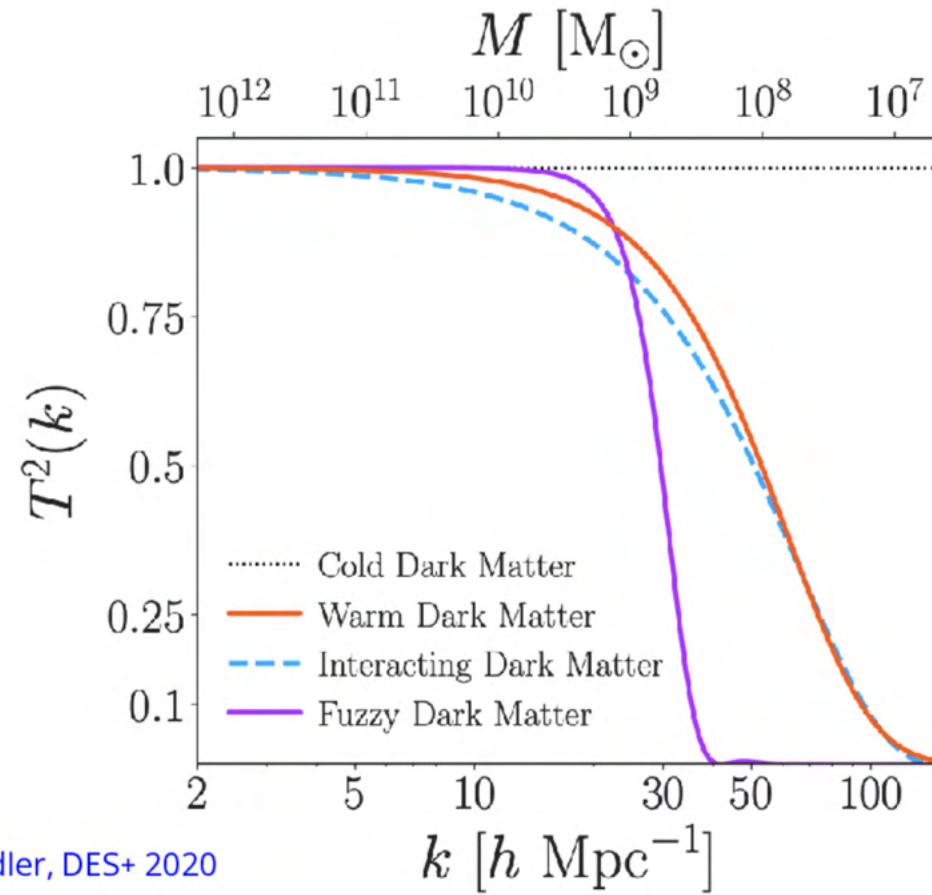
Lyman-alpha forest, dwarf galaxies, stellar streams, galaxy clustering, strong and weak lensing, intensity mapping, etc.

Observables : Lyman-alpha spectrum (from quasar spectra), dwarf galaxies, ultra-faint galaxies, stellar streams, galaxy clustering and lensing, etc.



Bullock and Boylan-Kolchin (2017)

DM microphysics can suppress structure on small scales.



Suppression of power at small scales leads to under-abundance of small dark matter halos throughout cosmic history.

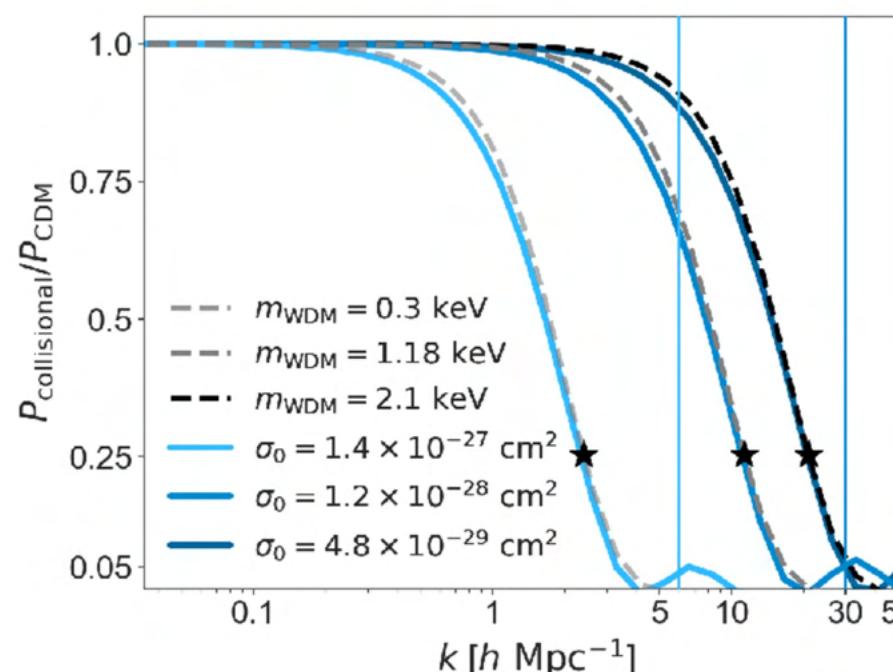
Case studies

WDM

<https://arxiv.org/abs/1702.01764>
<https://arxiv.org/pdf/1601.07553.pdf>
<https://arxiv.org/pdf/2008.00022.pdf>
<https://www.zora.uzh.ch/id/eprint/75587/1/20131701.pdf>
<https://arxiv.org/pdf/1603.03797.pdf>

IDM

<https://arxiv.org/abs/2010.02936>
<https://arxiv.org/abs/1904.10000>
<https://arxiv.org/pdf/astro-ph/0504112.pdf>
<https://arxiv.org/pdf/astro-ph/0309621.pdf>
<https://arxiv.org/pdf/astro-ph/0603373.pdf>



Nadler+ 2019

WDM = (thermal relic) warm dark matter

WDM = thermal relic that decouples while still semi-relativistic, inheriting appreciable velocity dispersion from early times.

WDM = (thermal relic) warm dark matter

*just like neutrinos!

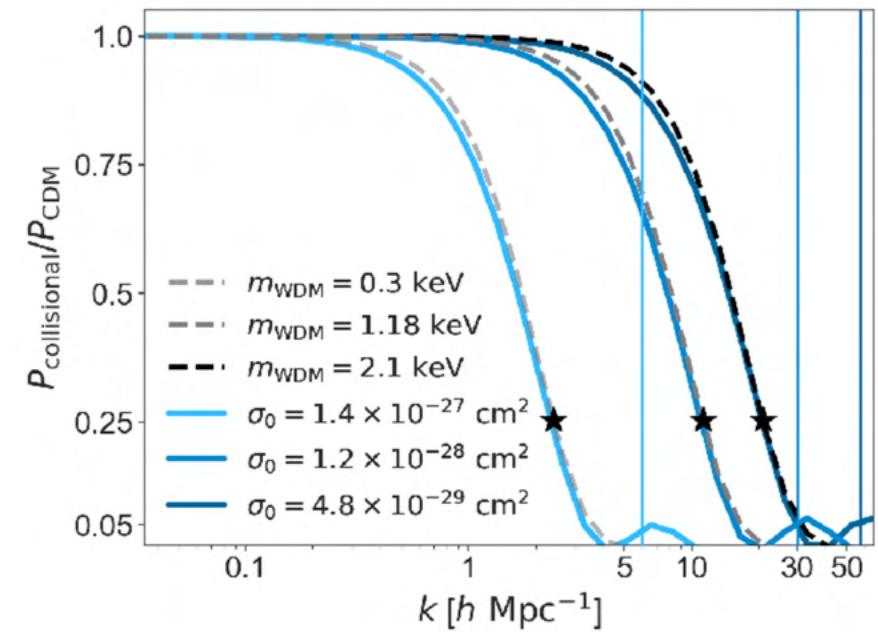
WDM = thermal relic that decouples while still semi-relativistic, inheriting appreciable velocity dispersion from early times.

WDM = (thermal relic) warm dark matter

WDM = thermal relic that decouples while still semi-relativistic, inheriting appreciable velocity dispersion from early times.

Free-streaming => **collisionless** damping of small-scale structure

$$\lambda_{fs} \equiv \int_0^{t_{eq}} \frac{\sigma(t)}{a} dt$$

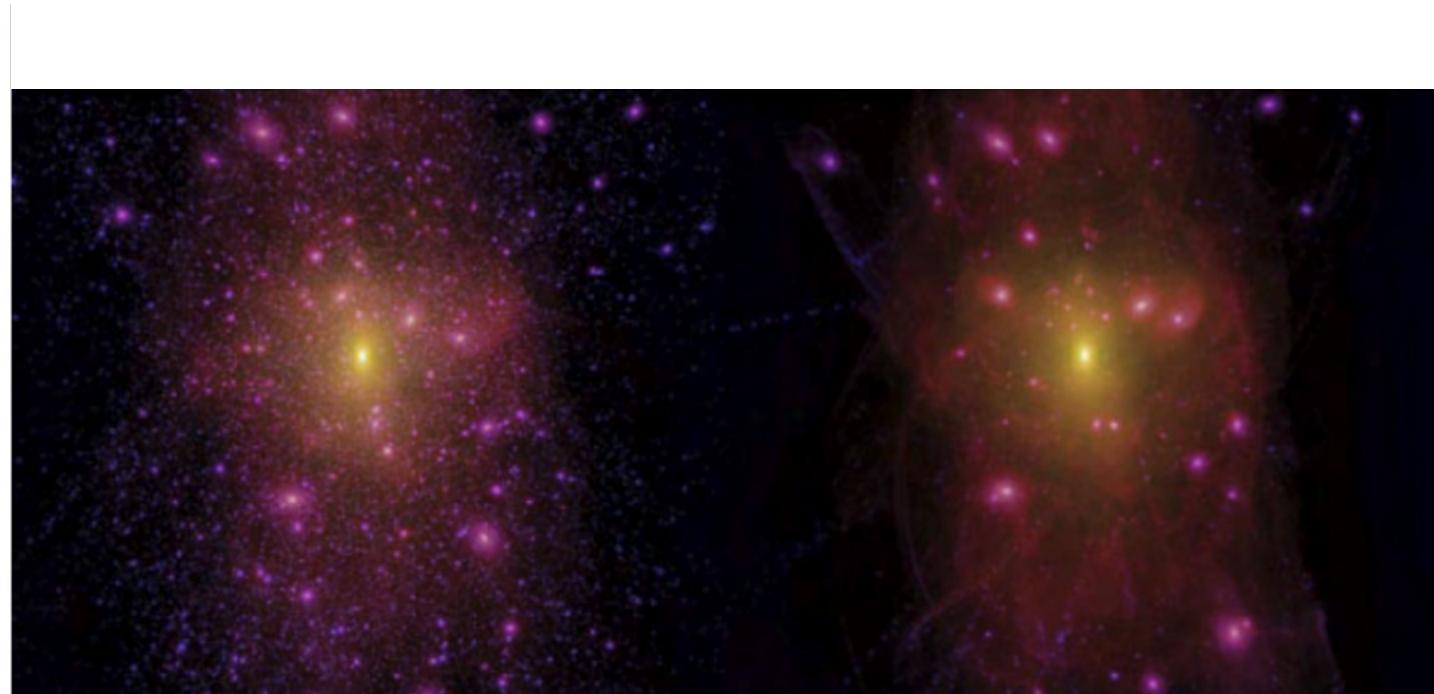


Nadler+ 2019

WDM = (thermal relic) warm dark matter

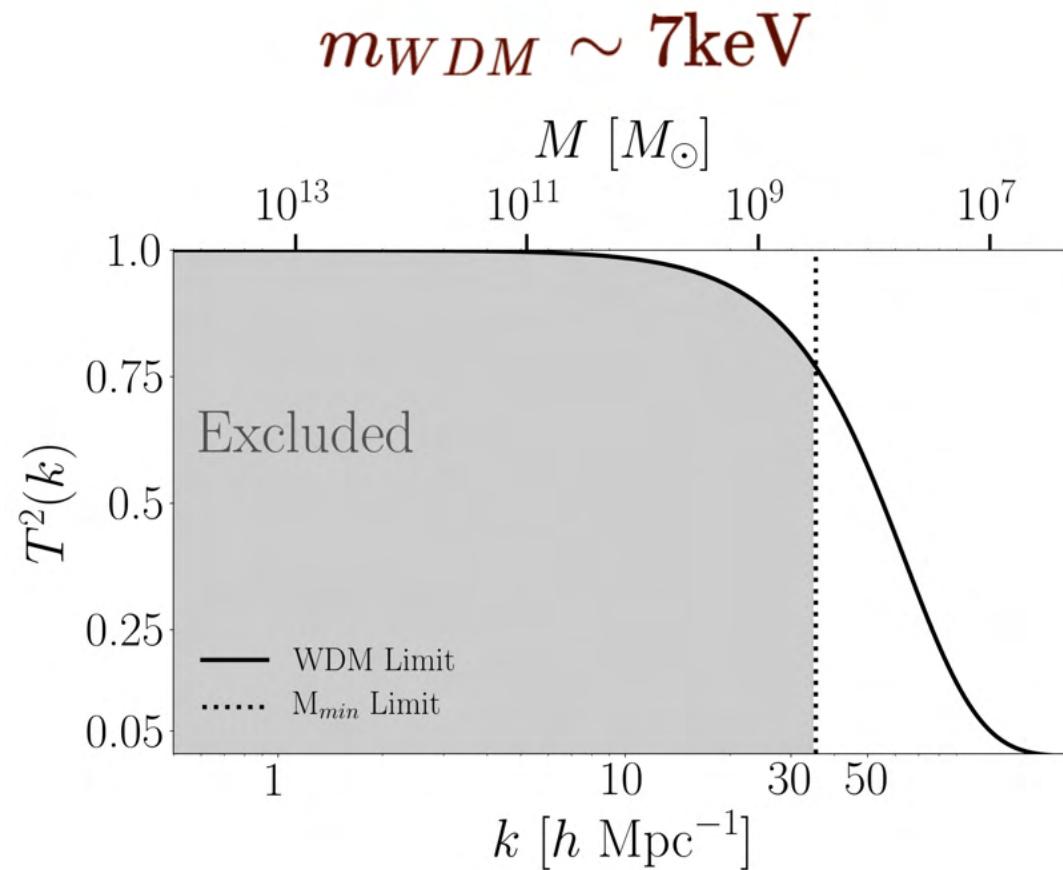
WDM = thermal relic that decouples while still semi-relativistic, inheriting appreciable velocity dispersion from early times.

Free-streaming => **collisionless** damping of small-scale structure



WDM = (thermal relic) warm dark matter

Lower bounds (Lyman-alpha forest, Milky Way substructure, 95% confidence):



<https://arxiv.org/pdf/hep-ph/0612238.pdf>

<https://arxiv.org/pdf/1702.01764.pdf>

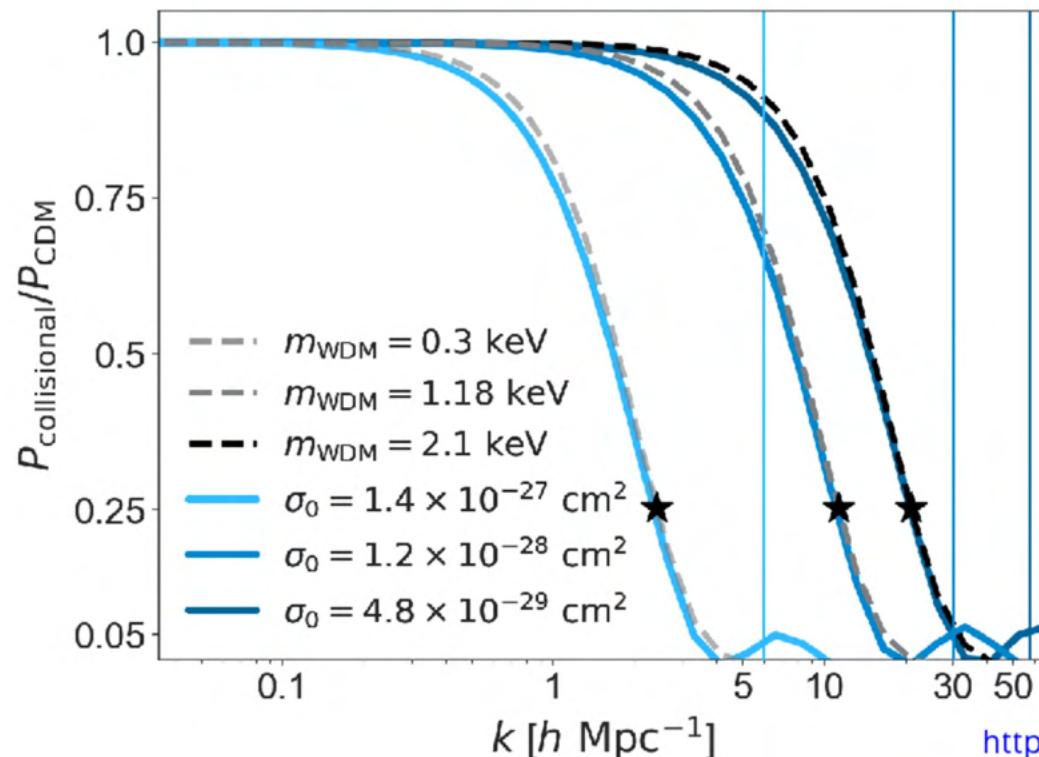
IDM = elastically interacting dark matter

Assumes elastic scattering at some point in cosmic history
(not necessary to be coupled at early times)

IDM = elastically interacting dark matter

Assumes elastic scattering at some point in cosmic history
(not necessary to be coupled at early times)

Interactions with photon-baryon fluid => **collisional** damping of small-scale structure



Teamwork time





Teamwork time

Estimate the comoving wavenumber k at which Pk is suppressed due to DM-baryon elastic scattering, assuming DM particle mass of 1 GeV and velocity-independent interaction cross section of $2e-28 \text{ cm}^2$. How does that scale compare to the scale of the modes corresponding to the smallest halos detected in galaxy surveys today?

Hints: First, assume that DM is tightly coupled to baryons until the rate of scattering (per DM particle) drops below the Hubble rate, at which point instantaneous decoupling occurs. Assume that decoupling takes place during radiation domination. Take the average mass of baryons to be about 1GeV (proton mass). What was the size of the mode that entered the horizon at this time?

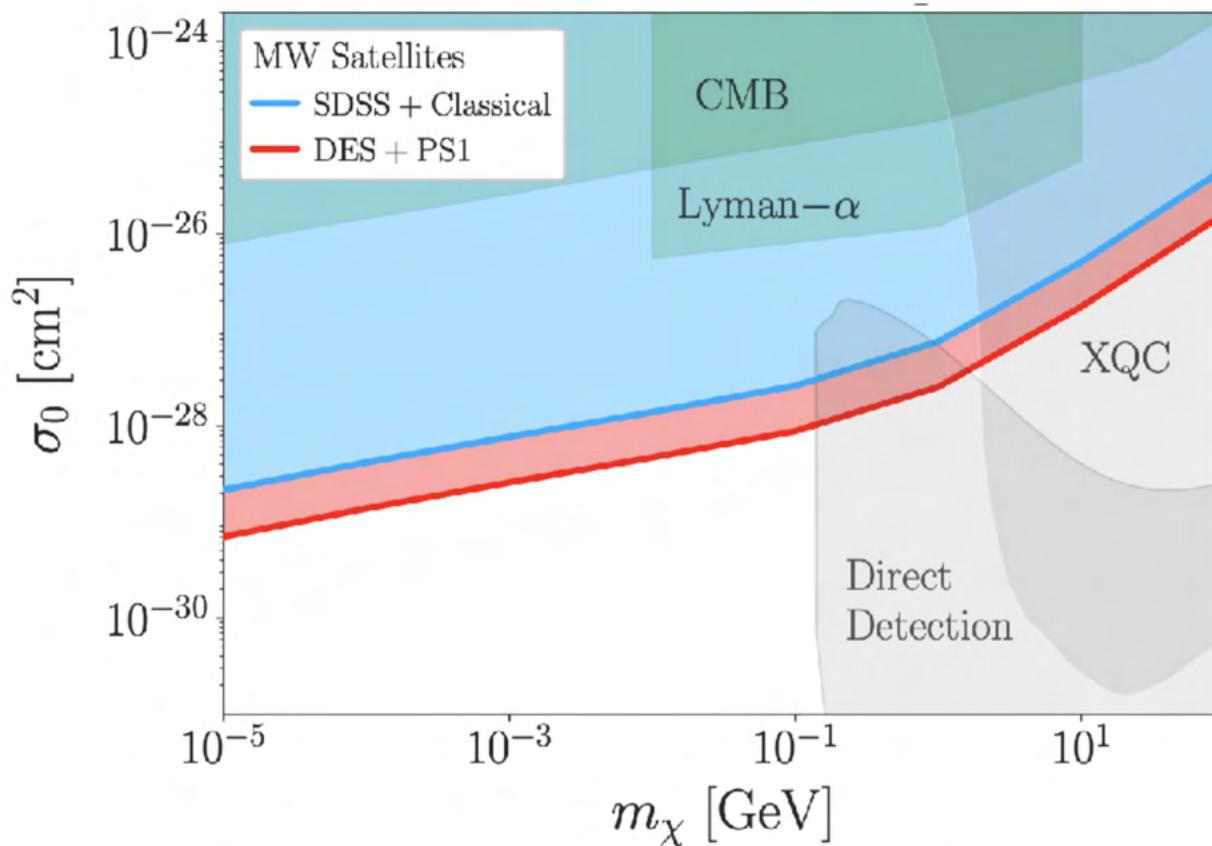
To relate this size to a halo mass scale, assume a spherical collapse of a small overdensity, $2\pi/k$ in diameter; assume that all the mass enclosed within that diameter ends up in one halo. Remember that $\sim 25\%$ of the critical density today is in dark matter. Also remember that the comoving horizon is aH , where H =Hubble parameter. Assume a flat universe.

<https://arxiv.org/pdf/1904.10000.pdf>

<https://github.com/eonadler/DMBaryonScattering/>

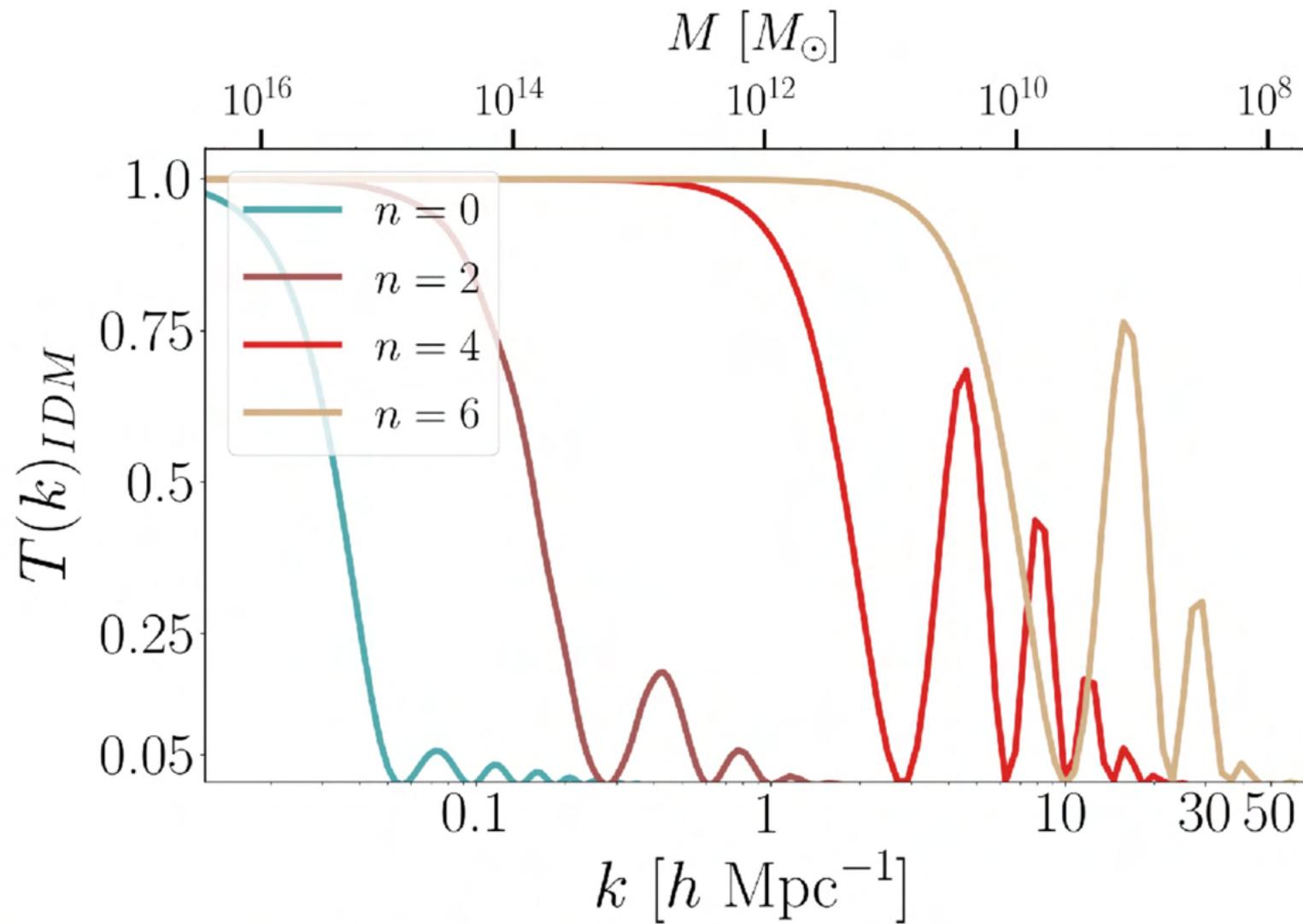
IDM limits from MW Satellites (DES+PS1)

v-independent scattering



Including: realistic modeling of galaxy-halo connection and mock observations of the satellite abundance (luminosity, size, and radial distribution)

DM-proton scattering: $\sigma \sim v^n$



Maamari, + (ApJ Letters 2020), arXiv:2010.02936
see also: 2008.00022

What if DM is NOT a thermal relic?

Case of sterile neutrinos

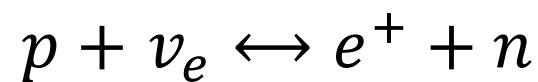
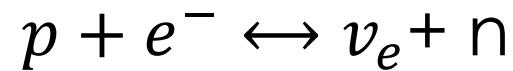
Dodelson-Widrow mechanism

$$\nu_4 = \cos \theta \nu_s + \sin \theta \nu_a$$

A diagram illustrating the Dodelson-Widrow mechanism. It shows two vectors originating from the same point. The vector labeled v_a is horizontal to the left, and the vector labeled v_s is horizontal to the right. Between them is a blue 'X' symbol, representing the angle θ between the two vectors.

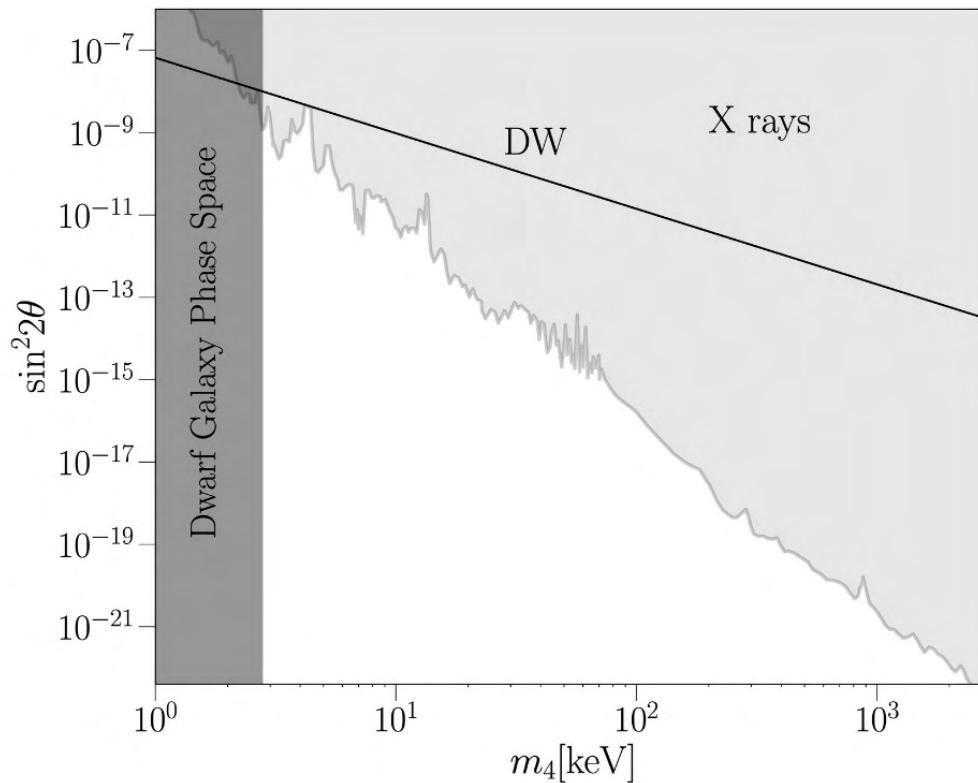
Dodelson-Widrow mechanism

$$\nu_4 = \cos \theta \nu_s + \sin \theta \nu_a$$



Dodelson-Widrow mechanism

$$\nu_4 = \cos \theta \nu_s + \sin \theta \nu_a$$



...ruled out, due to decay and X-ray production.

Question for you

A

B

C

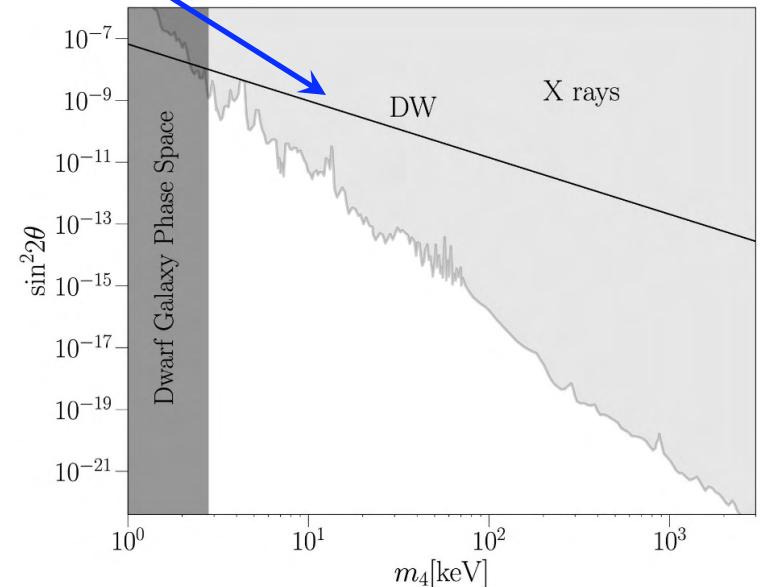
D

A B
C D

Question for you

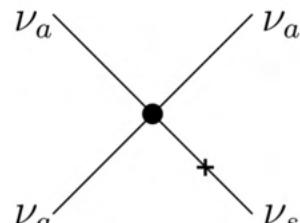
How will the abundance line in this plot change, if only 10% of DM are sterile neutrinos?

- A) It will move up.
- B) It will move down.
- C) It depends on the cosmology.

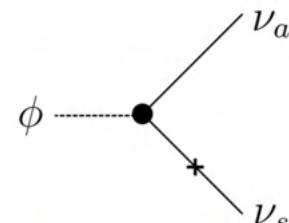


Sterile neutrinos + **neutrino self-interactions**

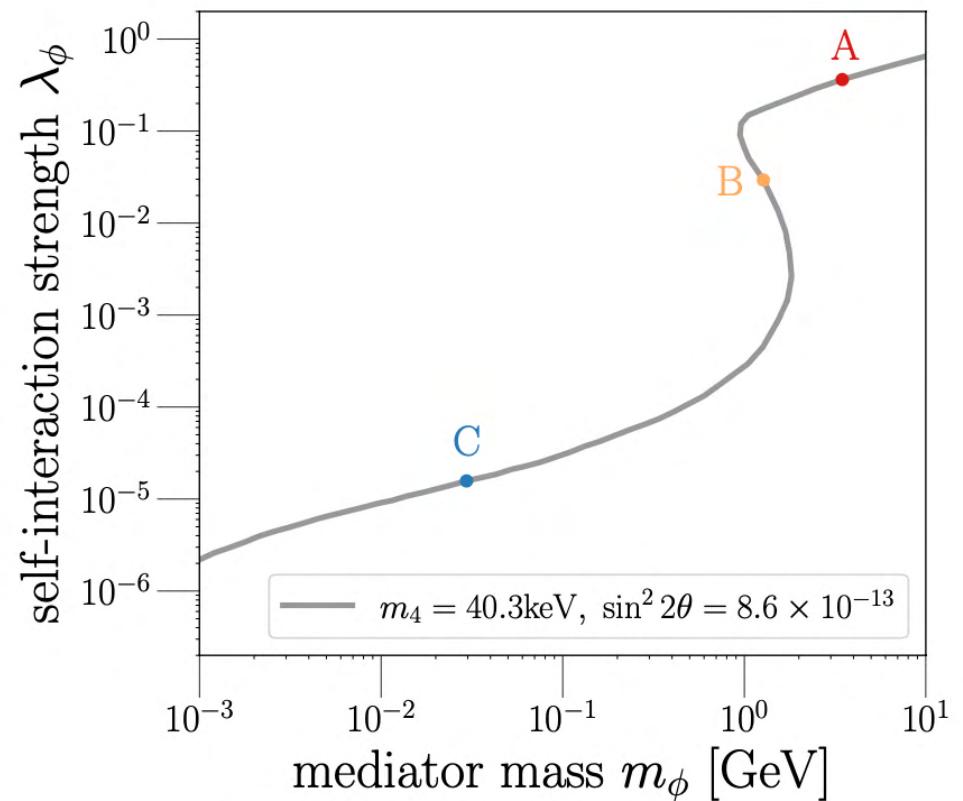
$$\mathcal{L} \supset \frac{\lambda_\phi}{2} \nu_a \nu_a \phi + \text{h.c.}$$



Case A (heavy ϕ)

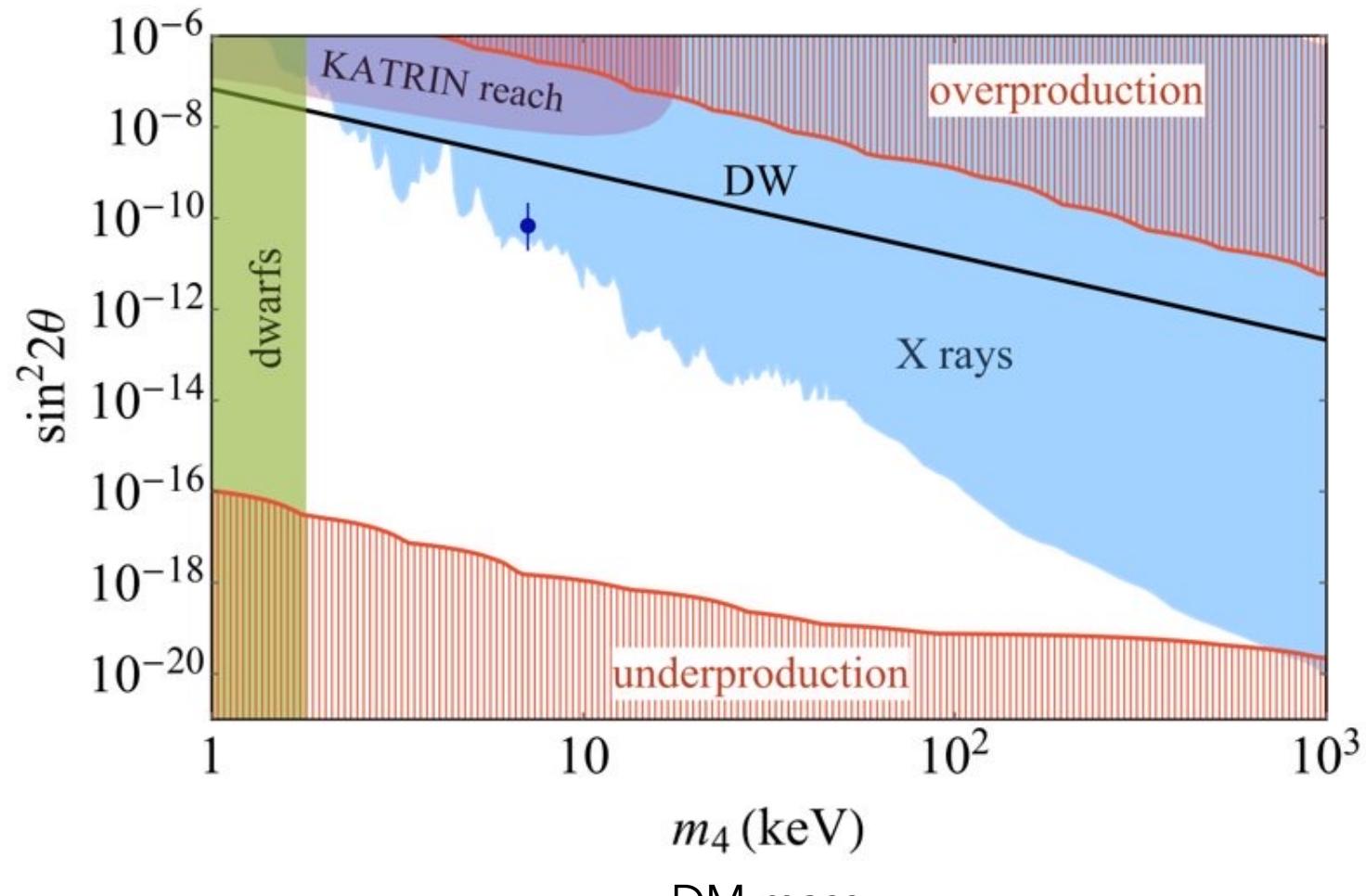


Case B (light ϕ)
Case C (light ϕ)



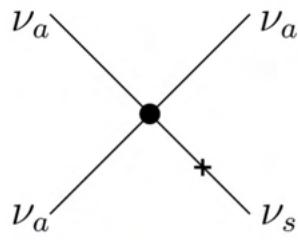
de Gouvea + (2019), etc.

Sterile neutrinos + **neutrino self-interactions** = allowed?

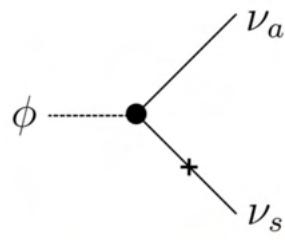


de Gouvea + (2019), etc.

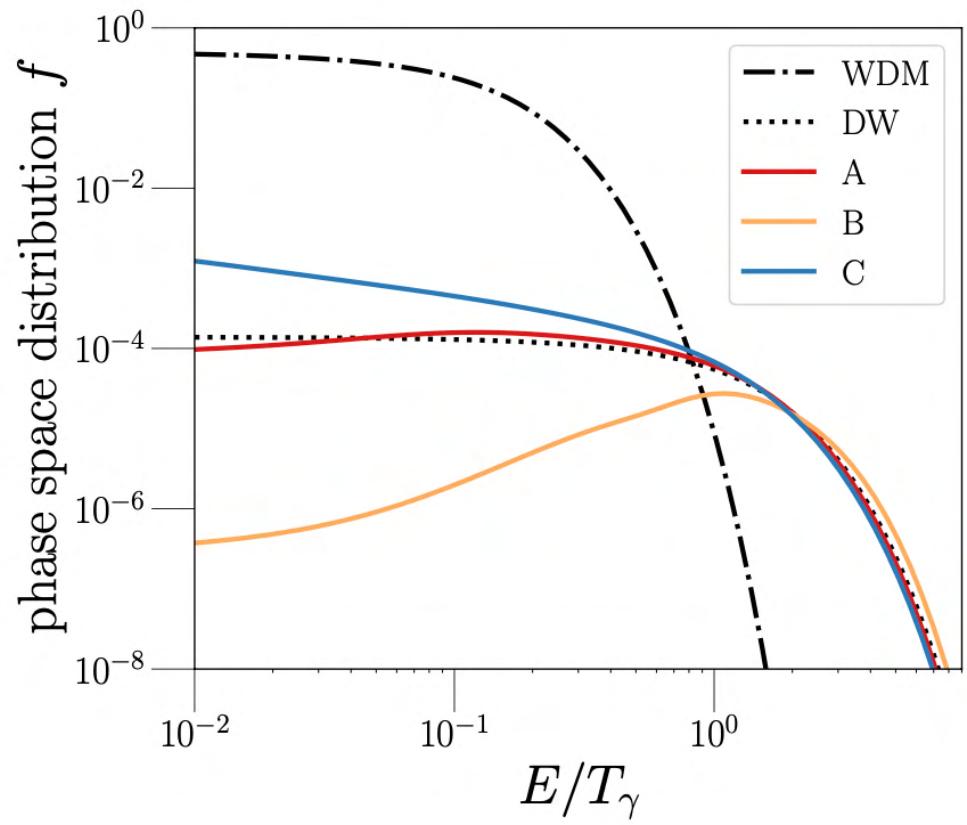
Sterile neutrinos + **neutrino self-interactions**



Case A (heavy ϕ)



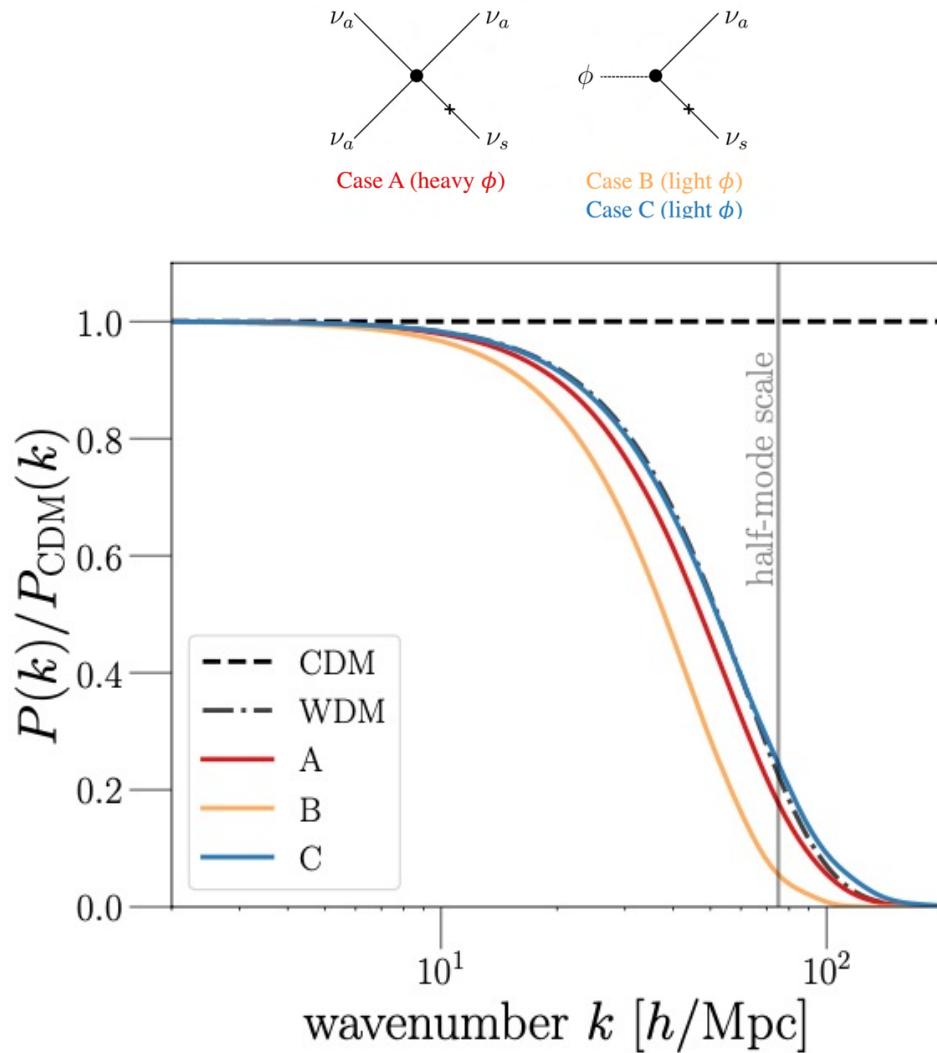
Case B (light ϕ)
Case C (light ϕ)



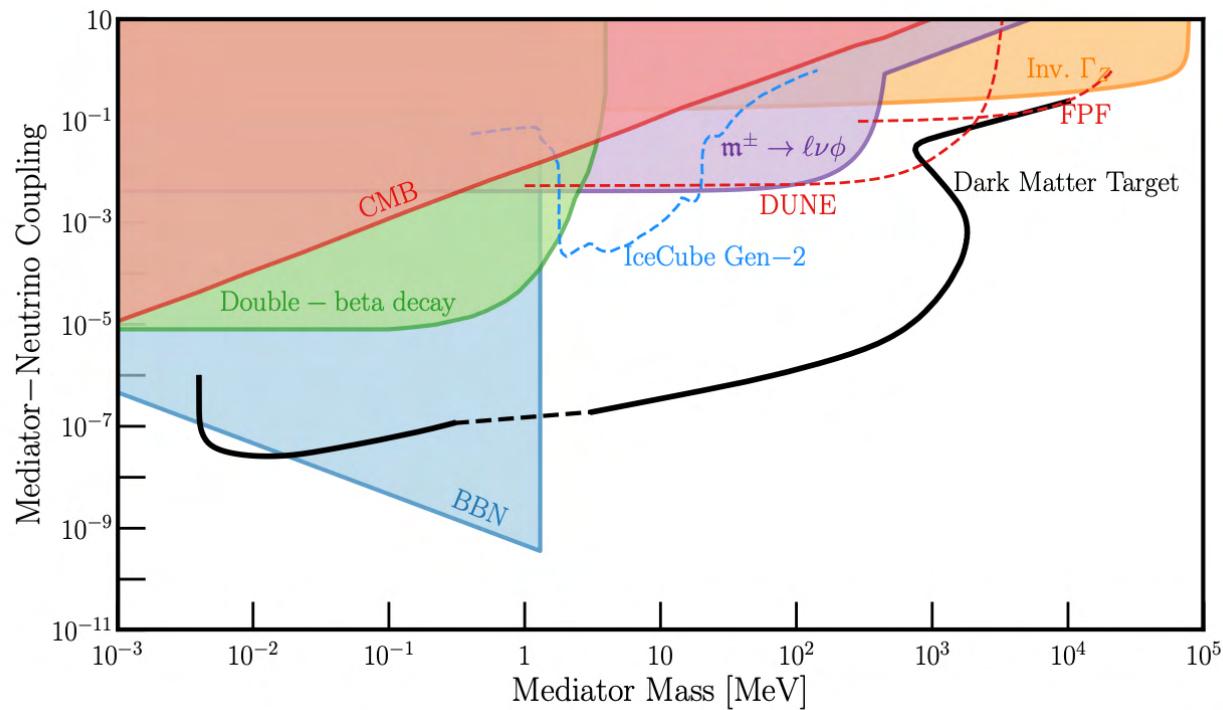
NB: Class assumes specific PSD!!

de Gouvea + (2019), etc.

Power suppression from sterile neutrino free streaming:



Lab bounds on neutrino self-interactions:

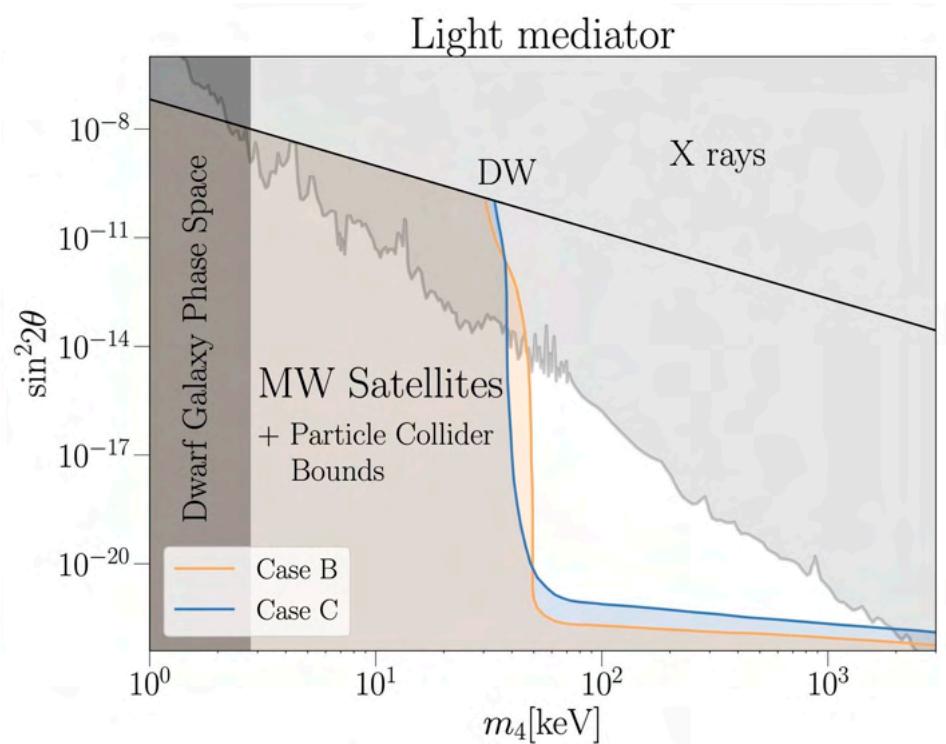
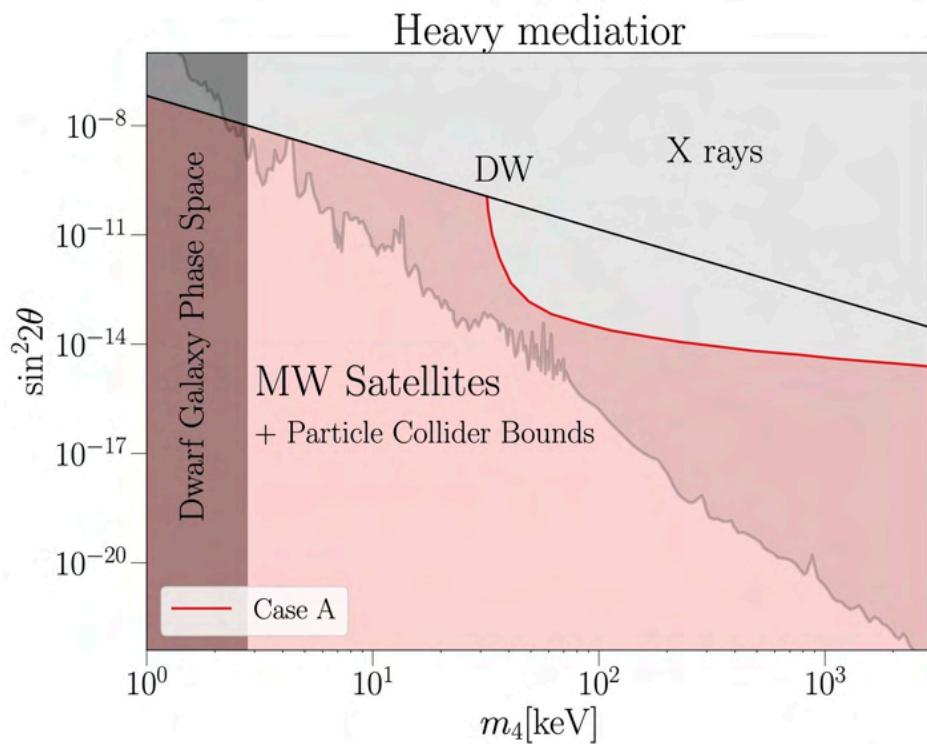


100

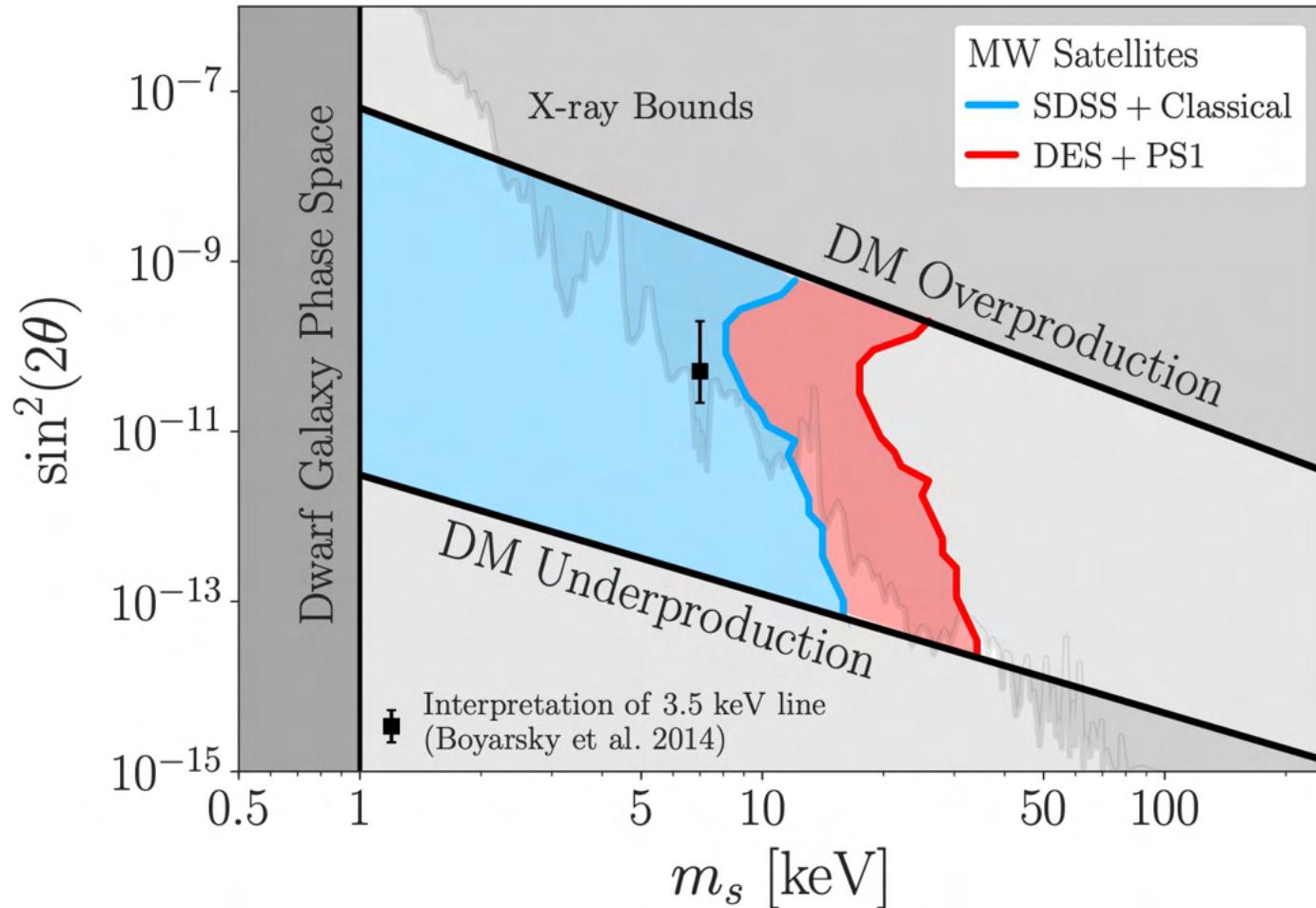
<https://arxiv.org/pdf/2203.01955.pdf>

Hard to escape thermal constraints...

Mediators > 1GeV are ruled out.



Bounds on resonantly-produced sterile neutrino



Nadler, DES+, 2021

For a review: <https://arxiv.org/pdf/1602.04816.pdf>

Near-field cosmology

Using small-scale structure to study fundamental physics

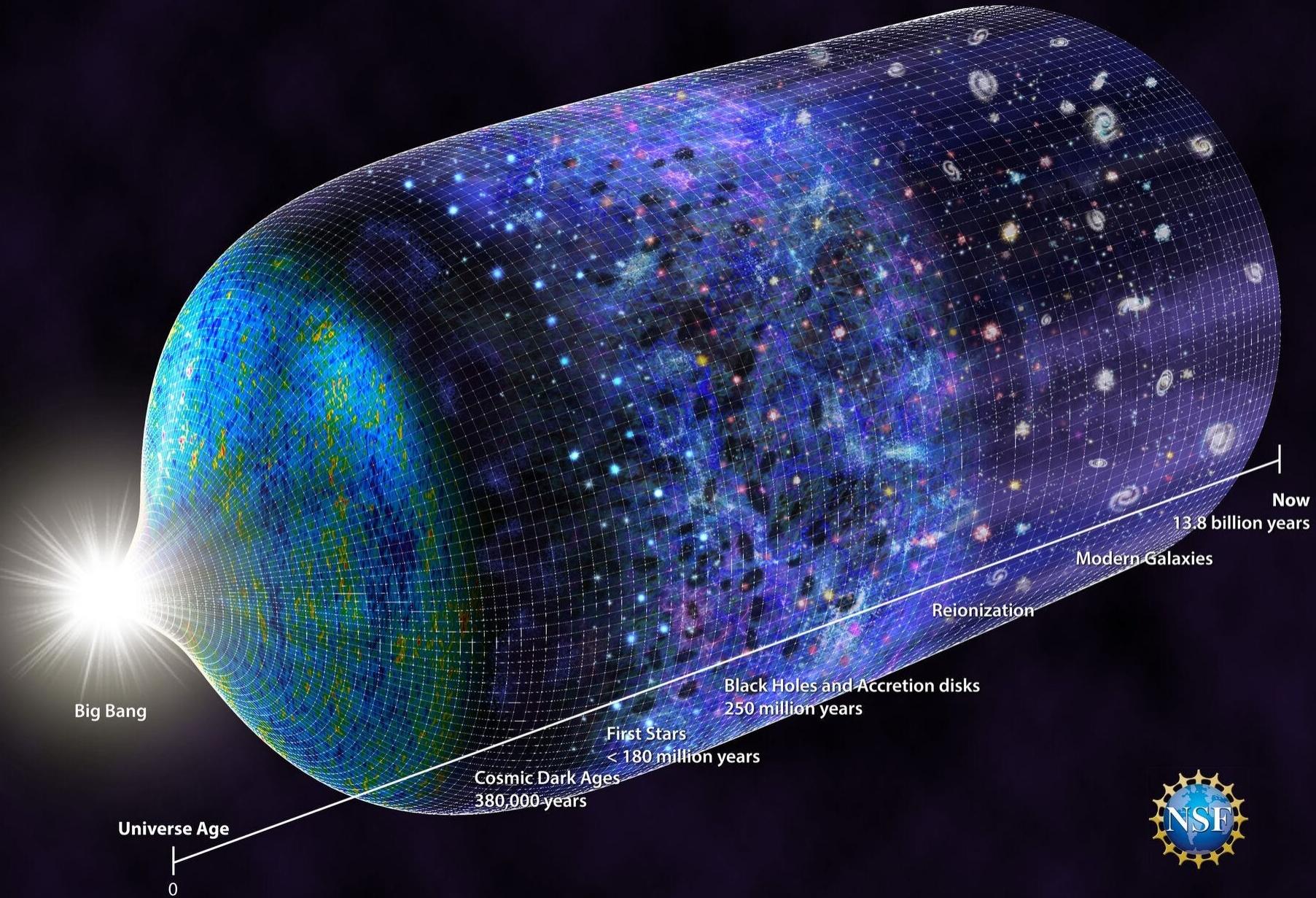
Galaxy surveys: **SDSS, DES**; Upcoming: **LSST, DESI,...**

Challenges:

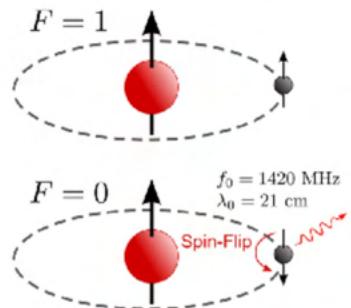
- **Observational**: smaller halos host fainter galaxies [completeness correction]
- **Theoretical**: understanding of baryonic physics and substructure formation [galaxy-halo connection]
- **Analysis**: fast forward modeling of observables [parameter inference]

BONUS!

IV. Thermal history
lessons from 21-cm cosmology

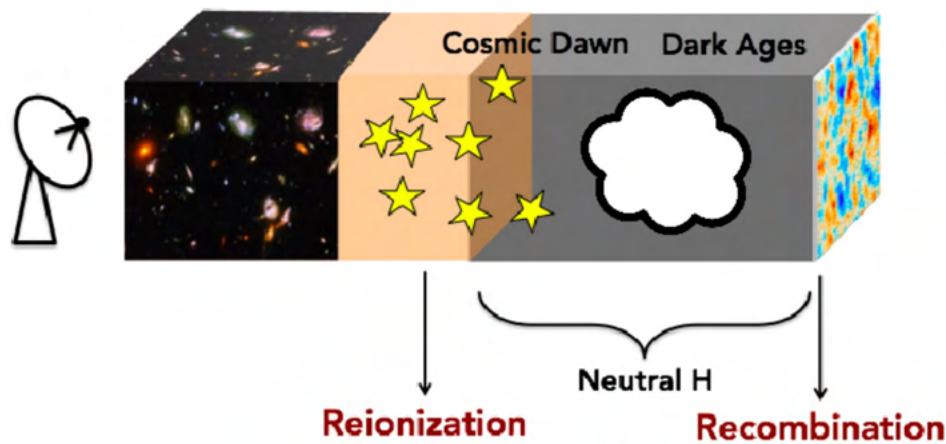


21-cm intensity mapping

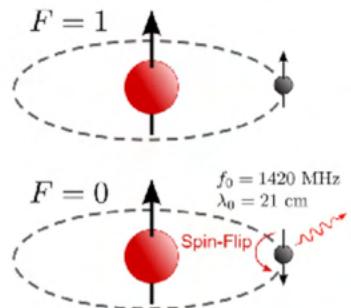


occupation number of hyperfine levels
determines intensity of 21-cm line radiation
given off by the hydrogen cloud:

$$\frac{n_1}{n_0} = 3 \exp(-T_*/T_{spin})$$

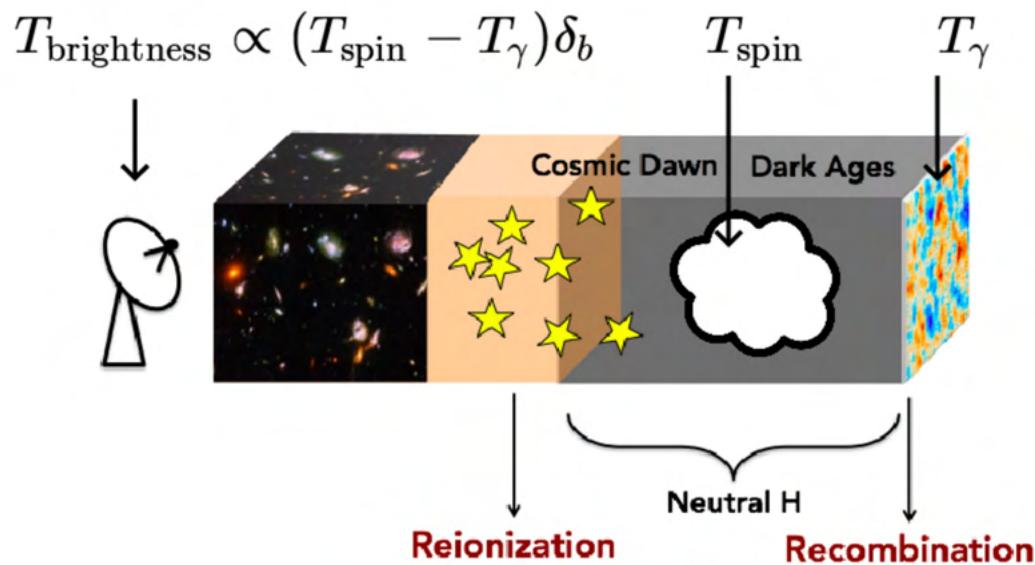


21-cm intensity mapping

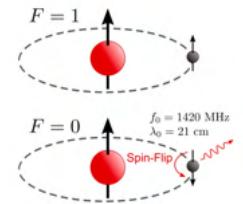
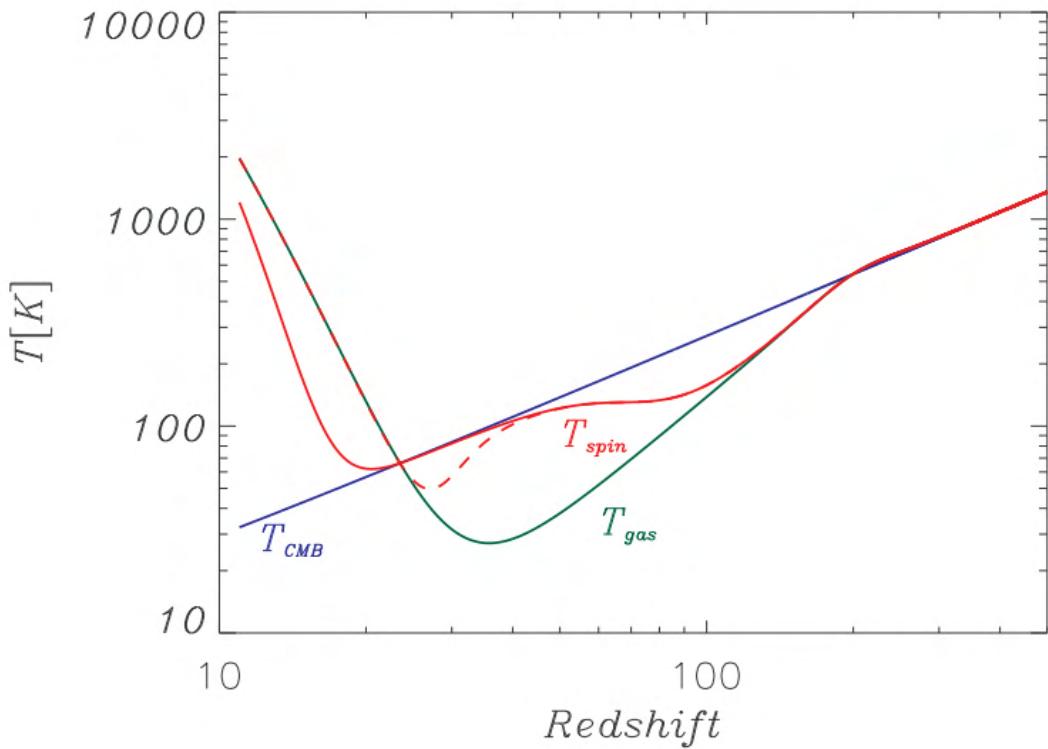


occupation number of hyperfine levels
determines intensity of 21-cm line radiation
given off by the hydrogen cloud:

$$\frac{n_1}{n_0} = 3 \exp(-T_*/T_{spin})$$



21-cm global signal



Occupation number of hyperfine levels determines the intensity of the 21-cm line.

$$\frac{n_1}{n_0} = 3 \exp(-T_*/T_{spin})$$

$$T_{\text{brightness}} \propto (T_{\text{spin}} - T_\gamma) \delta_b$$

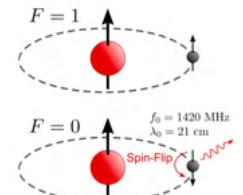
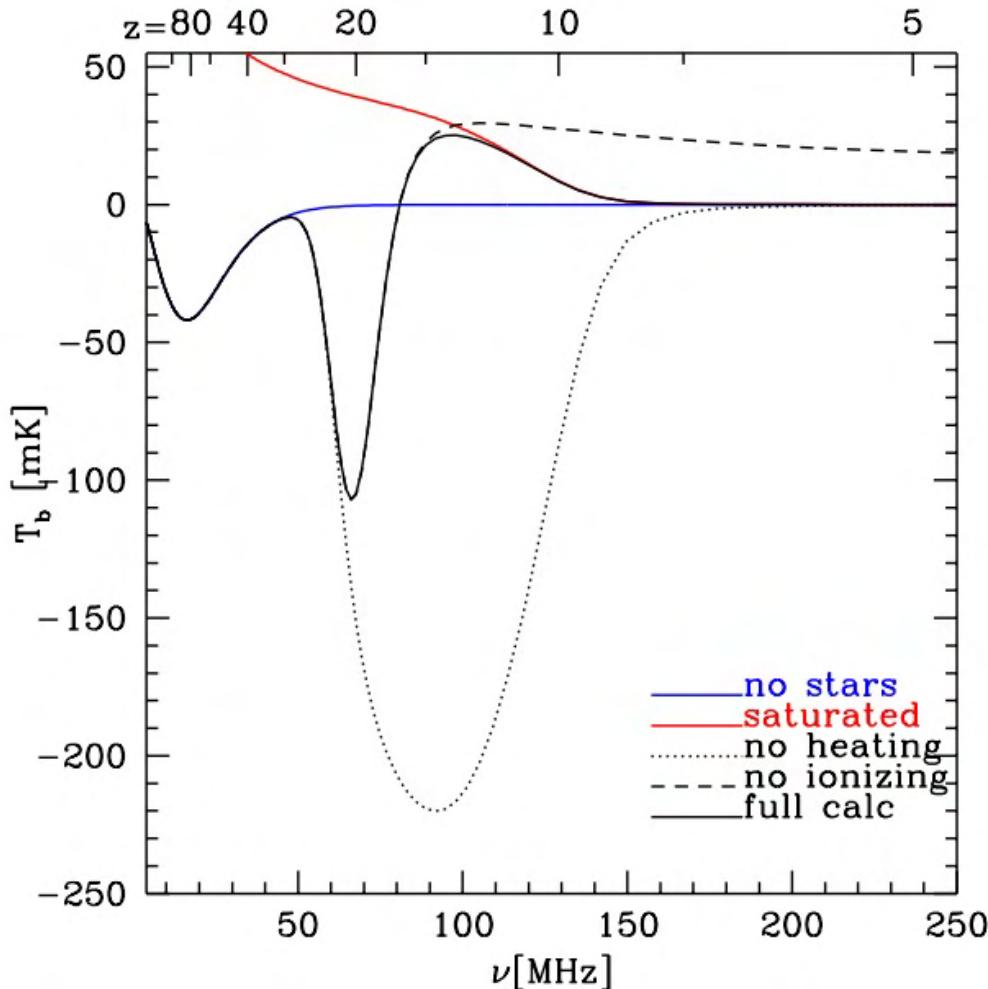
Spin temperatures is controlled by:

- radiative transitions (CMB temperature)
- atomic collisions (i.e. gas temperature)
- Lyman-alpha background (Wouthuysen–Field effect)

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<https://arxiv.org/pdf/1005.4057.pdf>
<https://arxiv.org/pdf/1206.0267.pdf>

21-cm global signal



Occupation number of hyperfine levels determines the intensity of the 21-cm line.

$$\frac{n_1}{n_0} = 3 \exp(-T_*/T_{\text{spin}})$$

$$T_{\text{brightness}} \propto (T_{\text{spin}} - T_\gamma) \delta_b$$

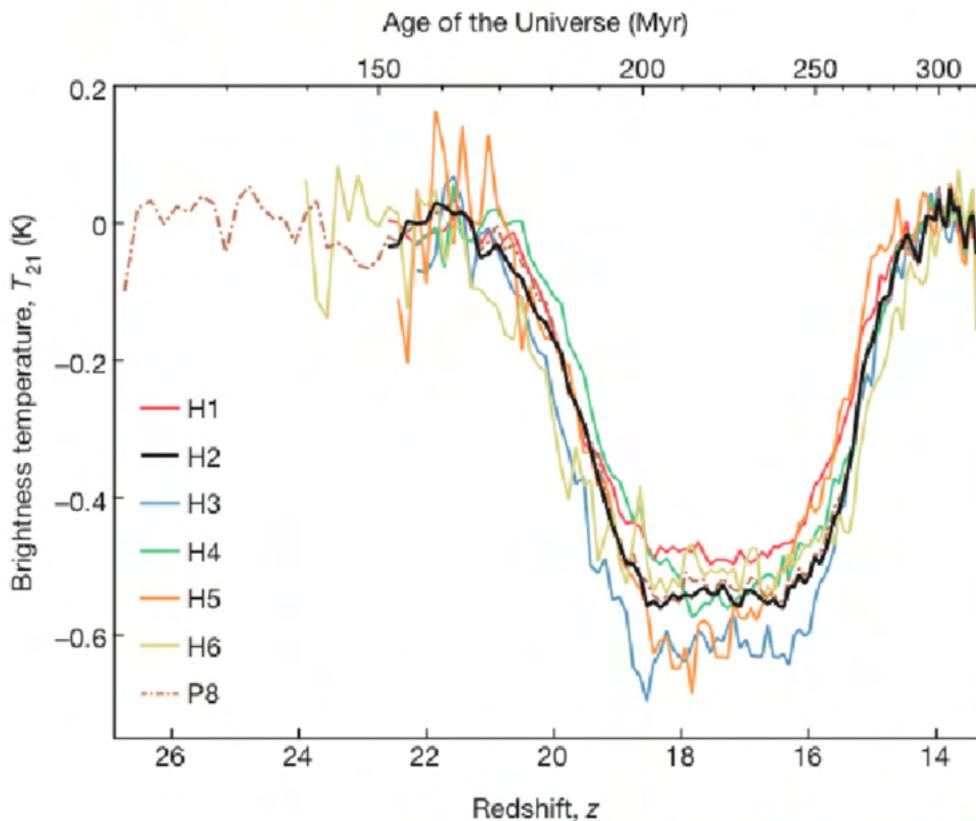
Spin temperatures is controlled by:

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Case study: EDGES

[Experiment to Detect the Global Epoch of reionization Signature]

Bowman, + (2018).



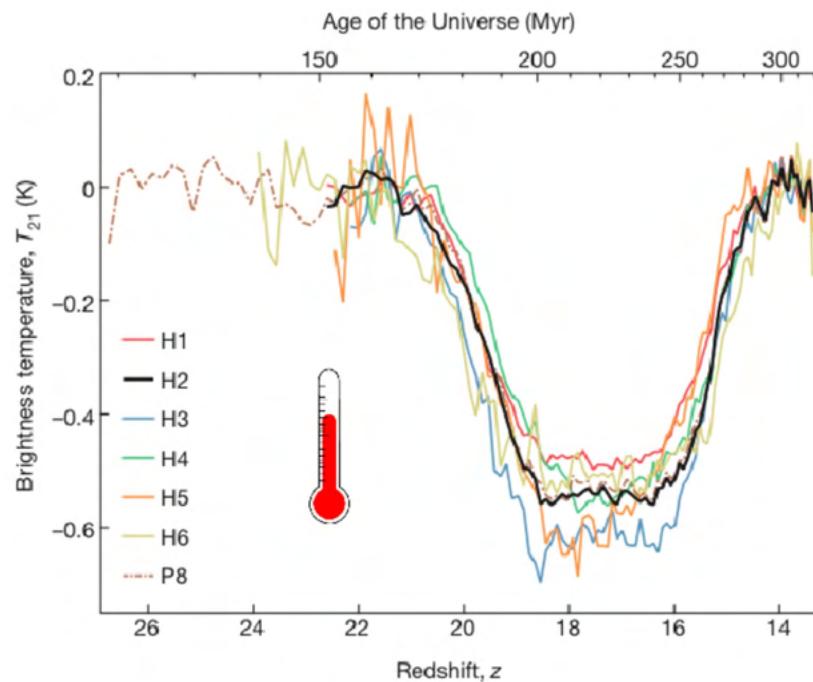
NB: Is it in the sky? Is it cosmological?
In any case: trough is too deep!

Case study: EDGES

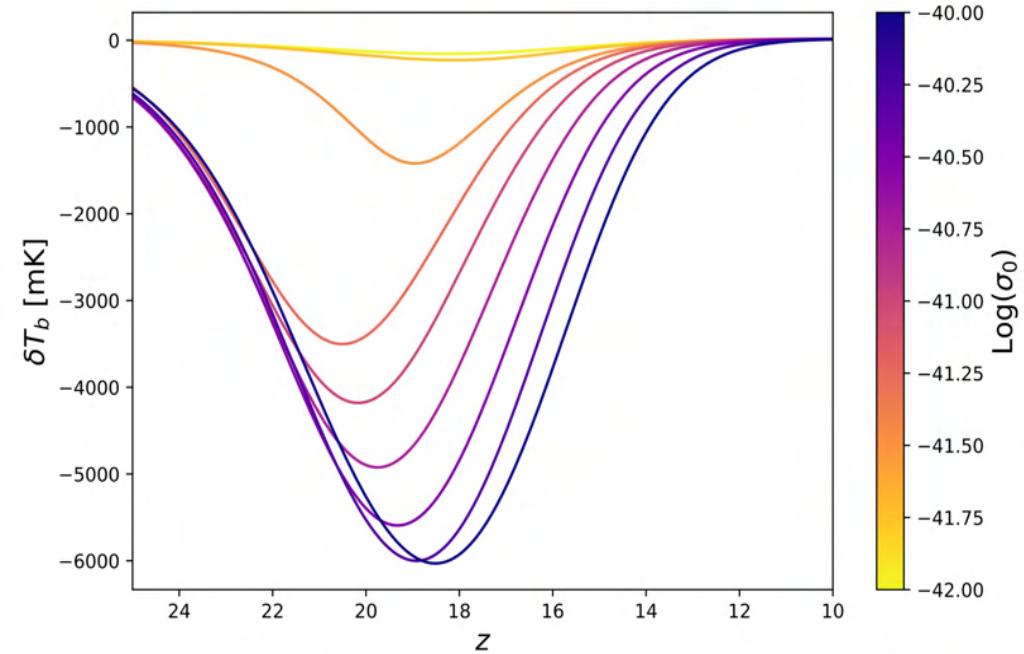
Possible interpretation: baryons are too cold.

Late-time dark matter-baryon elastic scattering?!

$$\text{Millicharge: } \sigma \sim v^{-4}$$



Bowman + (2018)
Barkana+ (2018)



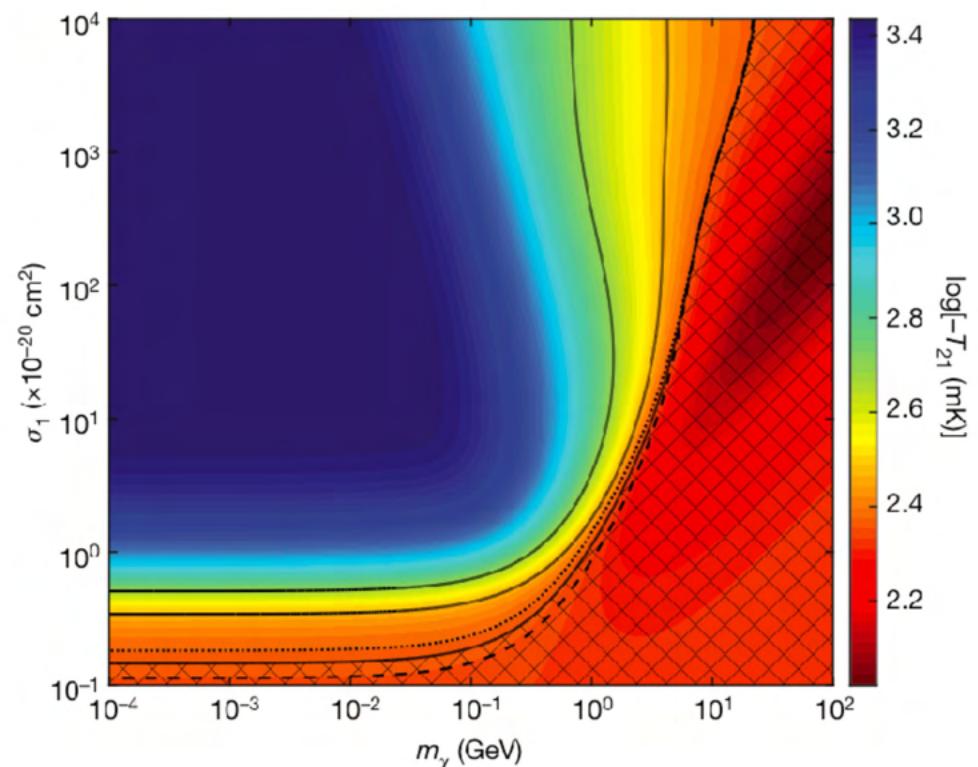
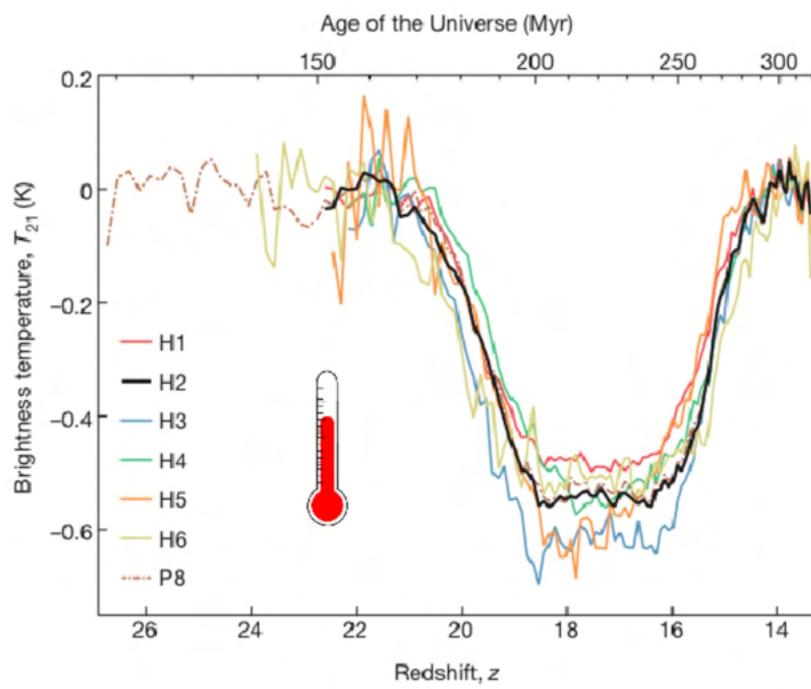
Driskell + (2022)
Munoz+ (2016)

Case study: EDGES

Possible interpretation: baryons are too cold.

Late-time dark matter-baryon elastic scattering?!

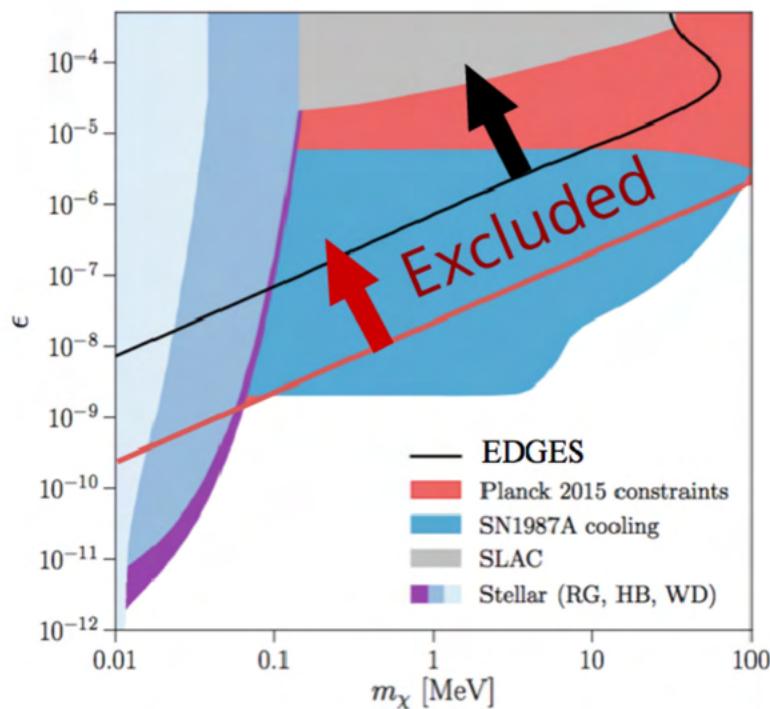
Millicharge: $\sigma \sim v^{-4}$



Bowman, + (2018)
Barkana (2018)

Planck and EDGES are *inconsistent* for millicharge accounting for >0.5% of dark matter

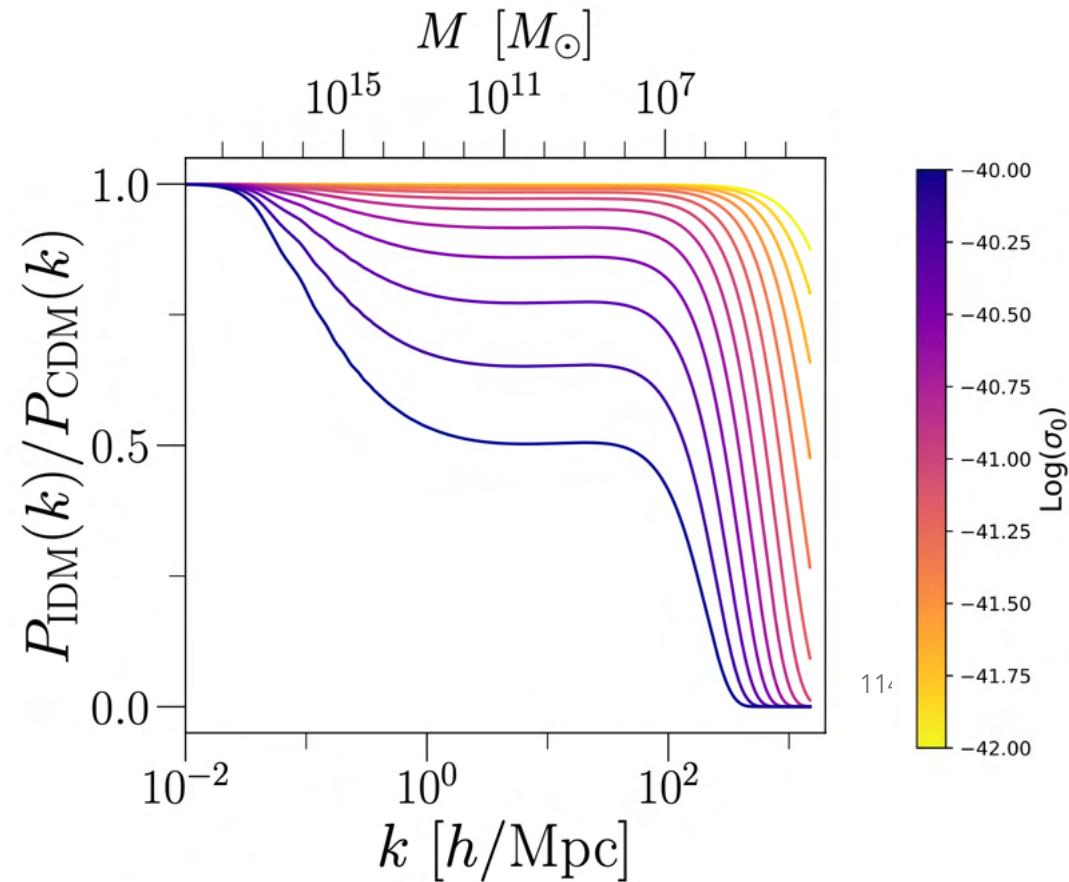
$$\sigma \sim v^{-4}$$



Boddy, + (2018); Kovetz, + (2018)

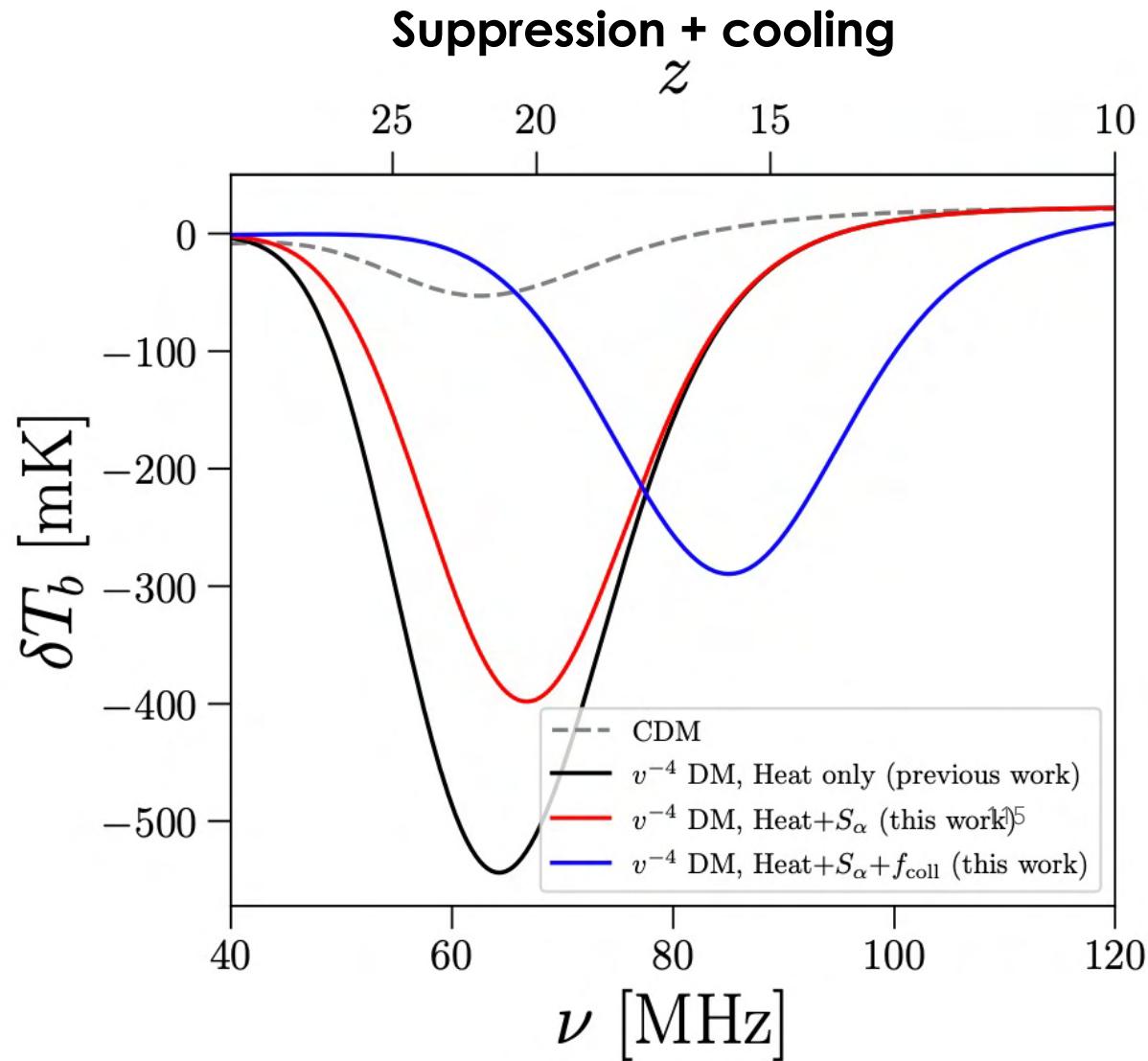
Global 21-cm signal with IDM

Suppression of structure:
(Not included in previous modeling)



Driskell + (2022)

Global 21-cm signal with IDM



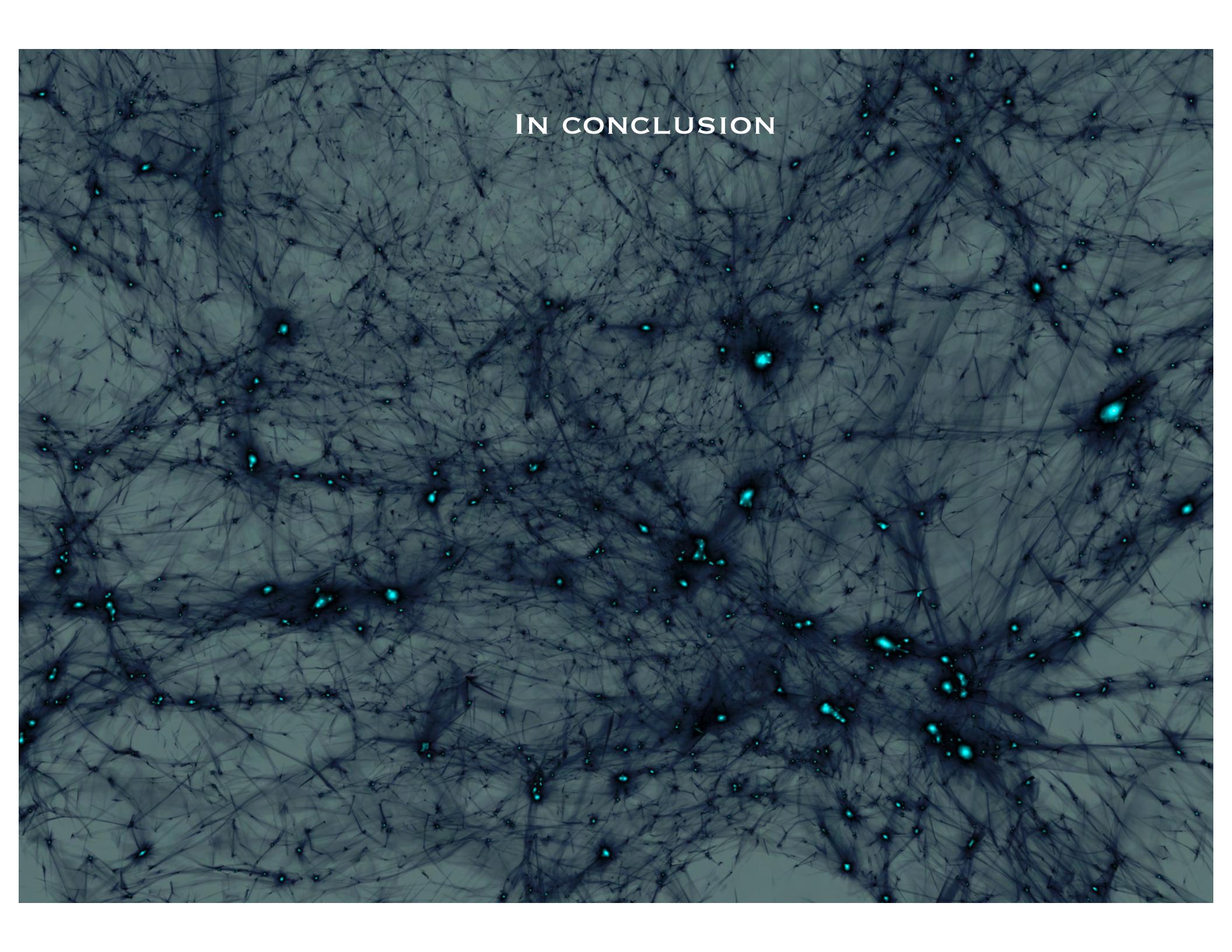
Cosmological probes are sensitive.

Comprehensive analyses are essential to establish a discovery.

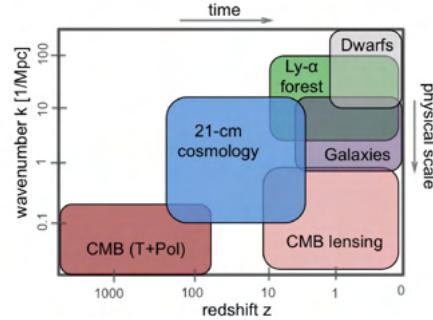
IN CONCLUSION

The following slide contains the conclusion of the presentation.

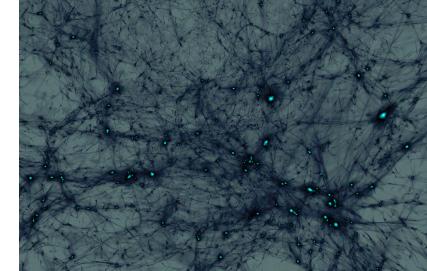
The conclusion is as follows:



IN CONCLUSION



Key points



- Dark matter dominates matter content of the universe today, and also signals existence of new physics.
- There are many viable theoretical models.
- Cosmological observables probe different aspects of DM microphysics, but smallest scales enter cosmological horizon at earliest times and thus are typically sensitive to particle physics at higher energies.
- CMB and BBN probe the early universe, mass and production mechanisms.
- LSS and 21-cm signal can probe interactions and thermal history.
- Discovery might require evidence across observables...

Cosmological discoveries* in this decade?

SO (being deployed); CMB-S4; JWST (in operation); LSS surveys: DESI (in operation), Rubin/LSST (start 2025?), Euclid (launch July 1?), Roman (2027), SphereX (2025).

* Measurements:

sum of neutrino masses (SO/CMB-S4/LSS).

minimum halo mass (Rubin, DESI, Roman etc).

Large scale B-modes (CMB).

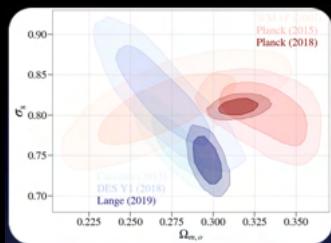
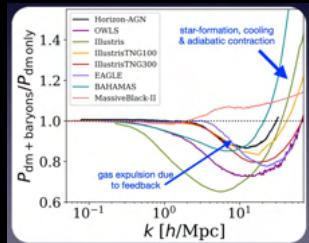
* Stress-tests:

cosmological tensions (SPT/ACT, SO + LSS surveys).

DE equation of state (LSS).

Tests of GR (LSS).

structure formation (baryonic effects, bias+) (LSS).



* Large New Open Space:

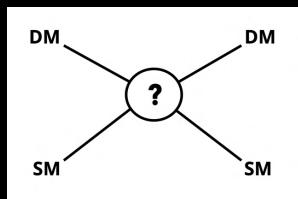
light relics and BBN (CMB).

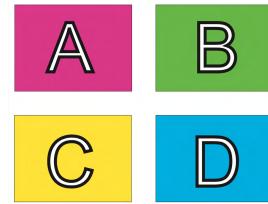
small-scale DM physics (clustering/stellar streams/lensing).

astrophysics of the first galaxies (JWST).

black holes and neutron stars (LIGO/Virgo).

Non-gaussianity (LSS+CMB).





A) Teamwork time?



B) Nap time?



<https://arxiv.org/pdf/1904.10000.pdf>

<https://github.com/eonadler/DMBaryonScattering/>

The end.