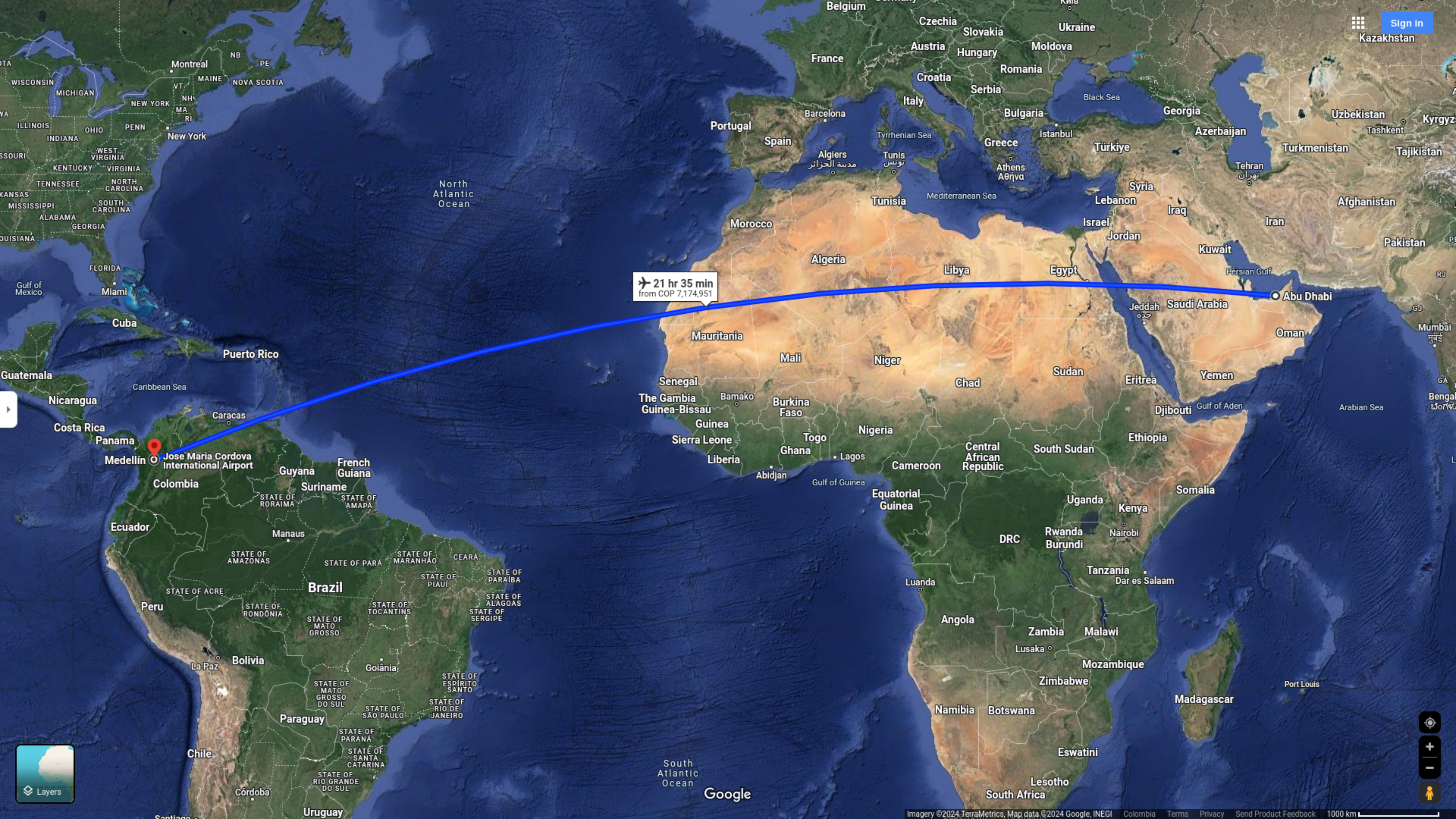
Dark Matter:
A truncated overview

Nicolás BERNAL

جامعة نيويورك أبوظبي

NYU ABU DHABI

NeMO-C 2024: Neutrinos y Materia Oscura en Colombia
July 24th-25th, 2024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Jose Maria Cordova International Airport
Medellín
Colombia
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Caribbean Sea
Mediterranean Sea
Black Sea
Tyrrhenian Sea
Persian Gulf
Gulf of Aden
Arabian Sea
Gulf of Guinea
Gulf of Mexico
Montreal
New York
Miami
Cuba
Puerto Rico
Guatemala
Nicaragua
Costa Rica
Panama
Caracas
Guyana
Suriname
French Guiana
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Peru
Brazil
Bolivia
Paraguay
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Morocco
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Libya
Egypt
Mauritania
Mali
Niger
Chad
Sudan
Eritrea
Djibouti
Senegal
The Gambia
Guinea-Bissau
Guinea
Sierra Leone
Liberia
Bamako
Burkina Faso
Togo
Ghana
Nigeria
Lagos
Abidjan
Cameroon
Central African Republic
South Sudan
Ethiopia
Somalia
Equatorial Guinea
Uganda
Kenya
Nairobi
DRC
Rwanda
Burundi
Tanzania
Dar es Salaam
Luanda
Angola
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Zimbabwe
Namibia
Botswana
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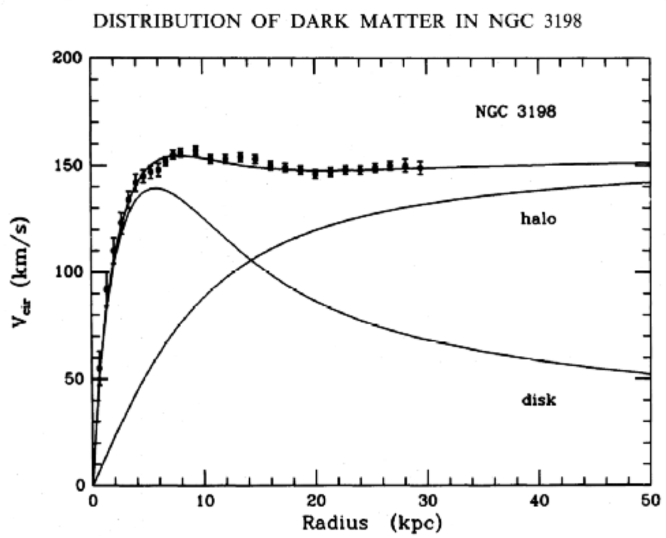
Evidences for Dark Matter

Several observations indicate the existence of non-luminous Dark Matter (*missing gravitational force*) at very different scales!

* Galactic rotation curves



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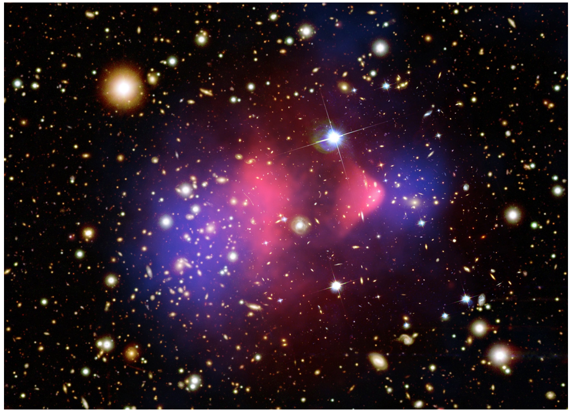
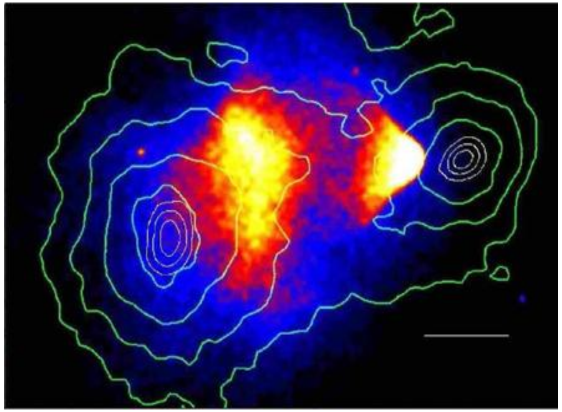
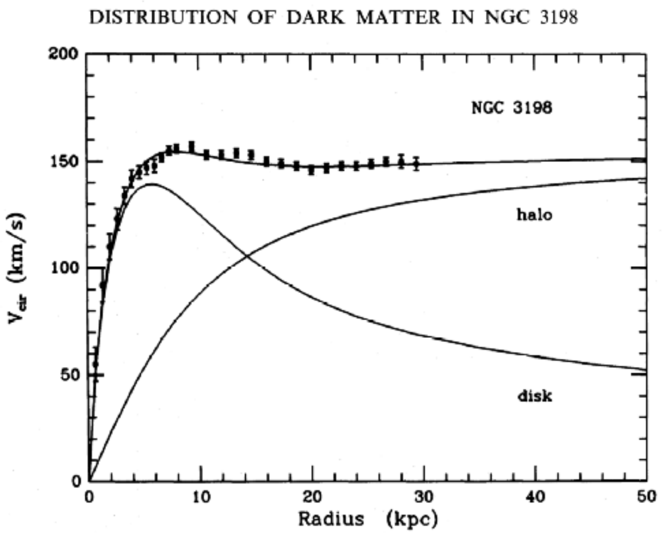
* RC in Clusters of galaxies
* Clusters of galaxies







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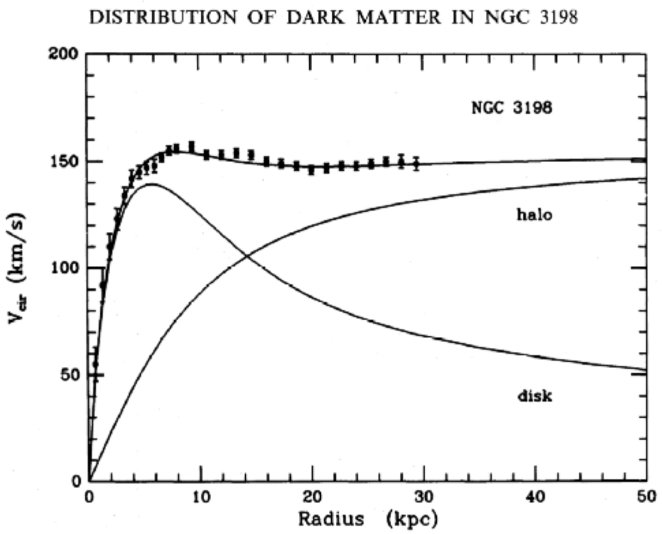

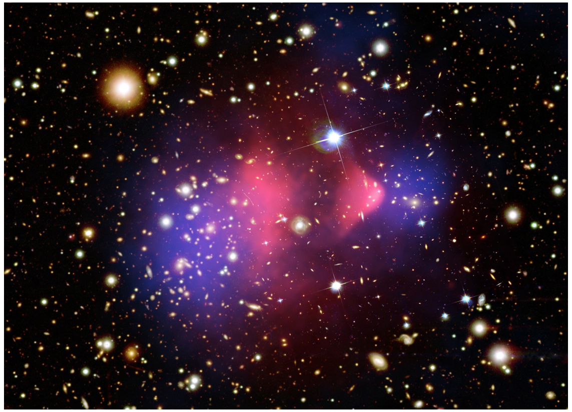

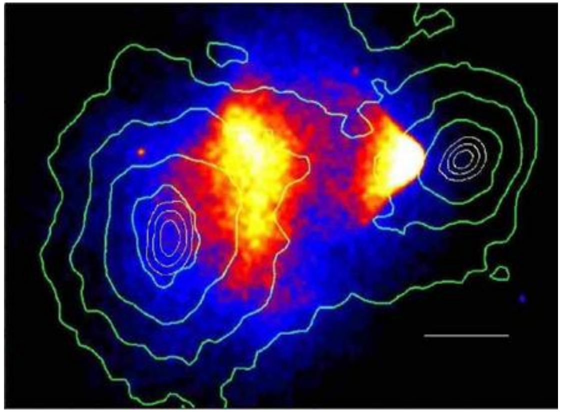

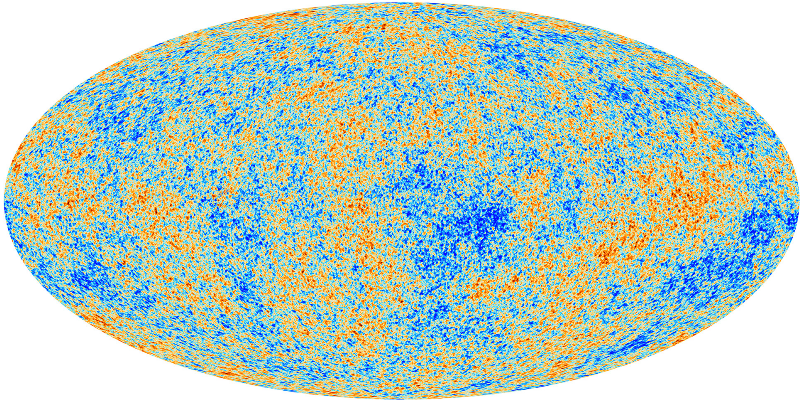

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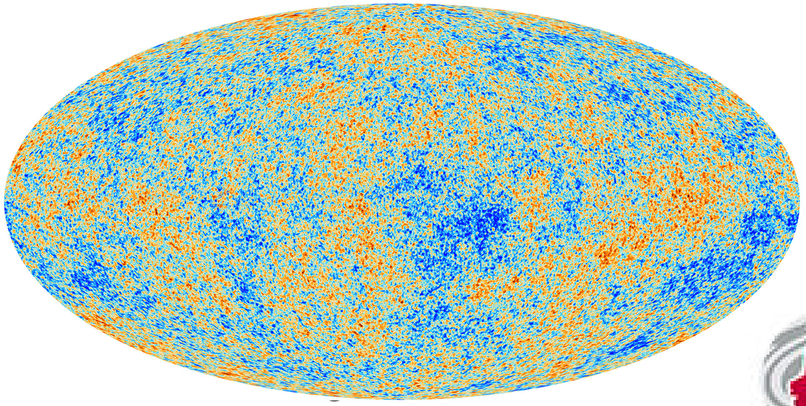

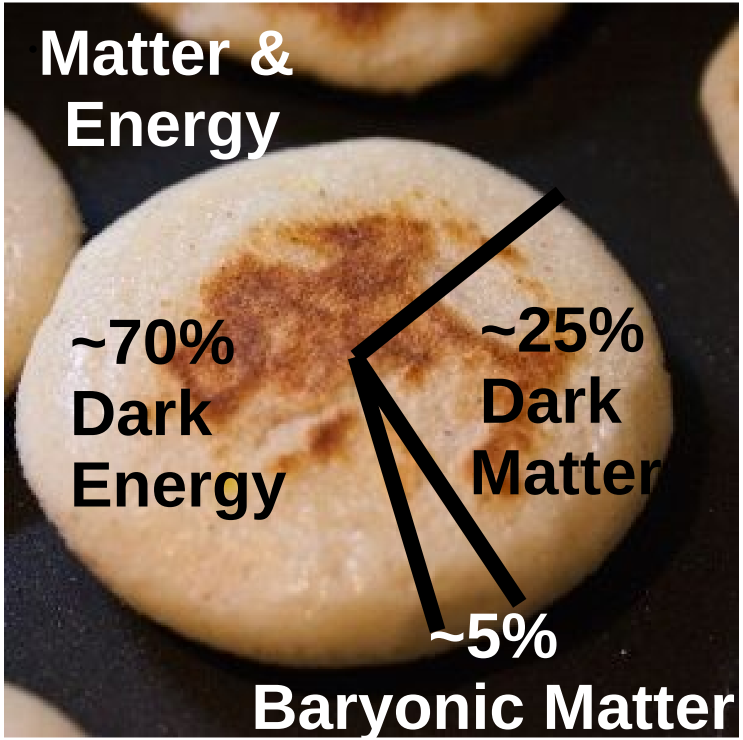

Evidences for Dark Matter

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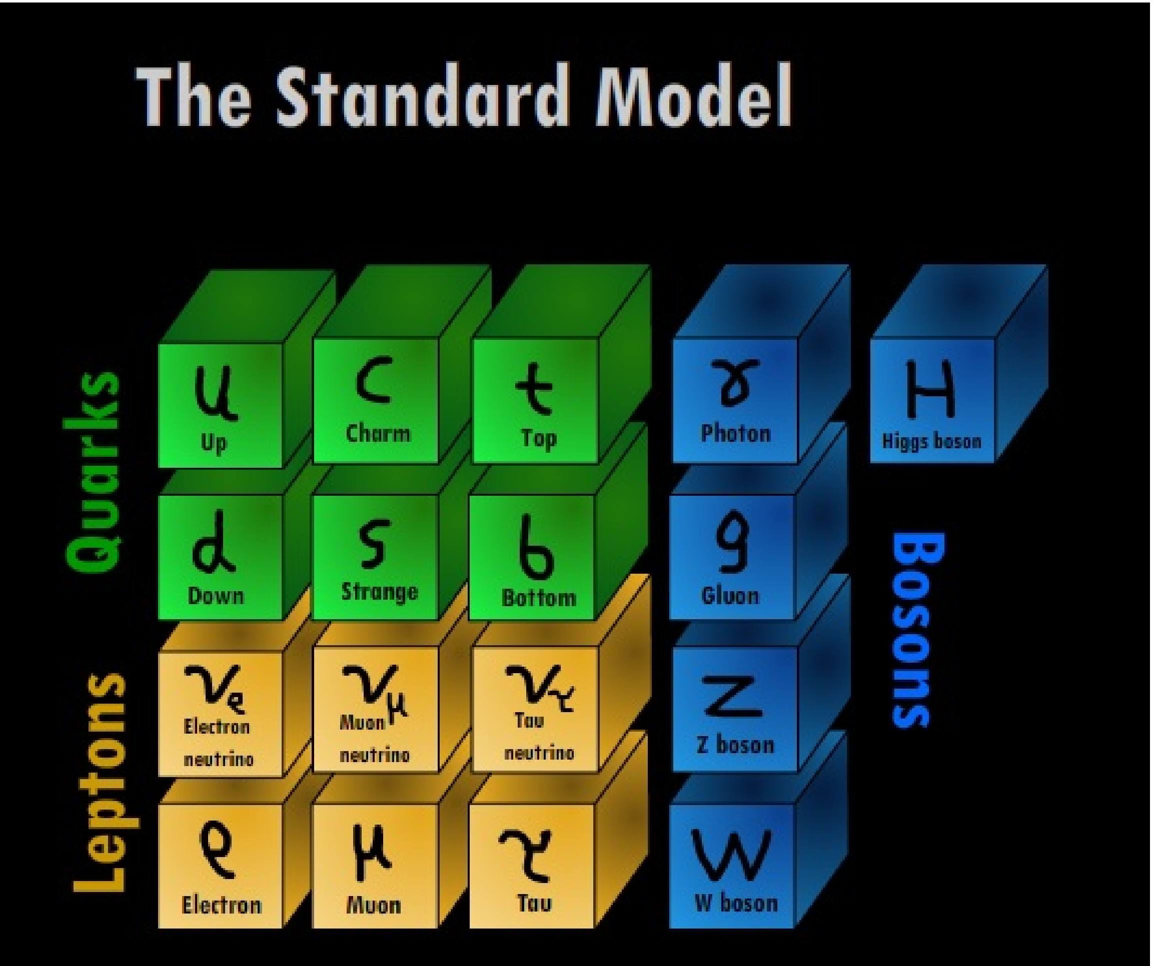
Dark Matter is there! :-)

But what is it? :-/

* Neutral (electric and color)
* Massive (non relativistic @ structure formation)
* 'Weak' interactions with the SM
* Stable or long-lived

What is Dark Matter made of?

What is Dark Matter made of?



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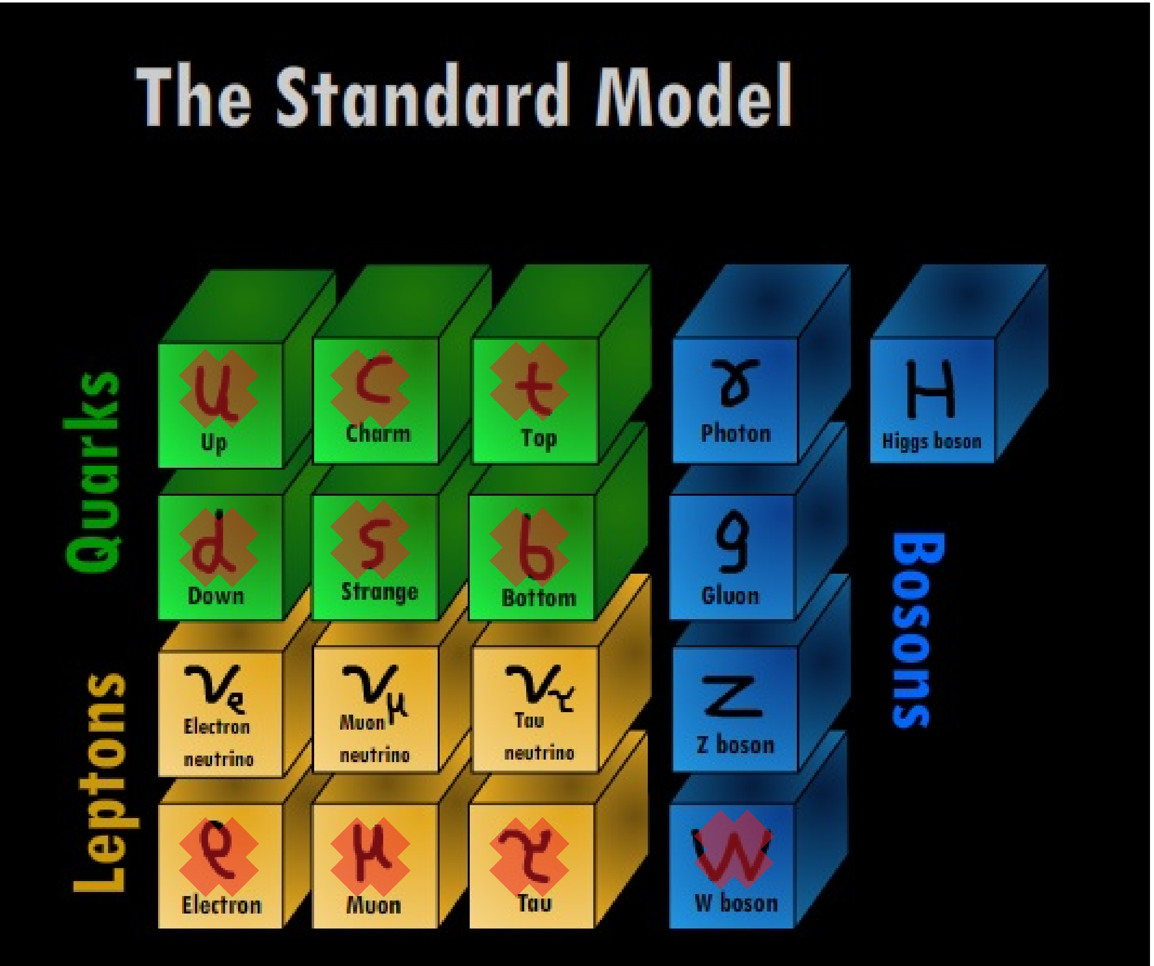
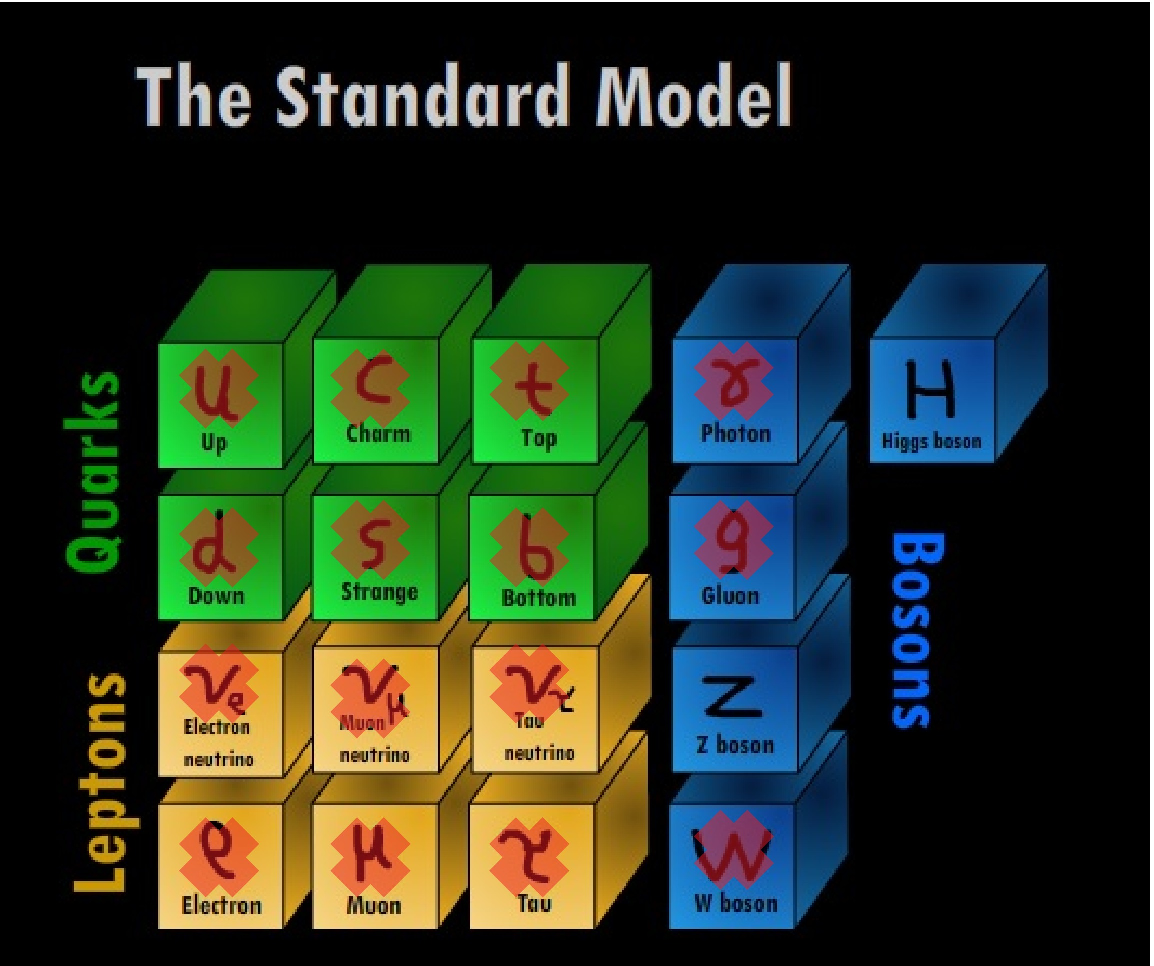


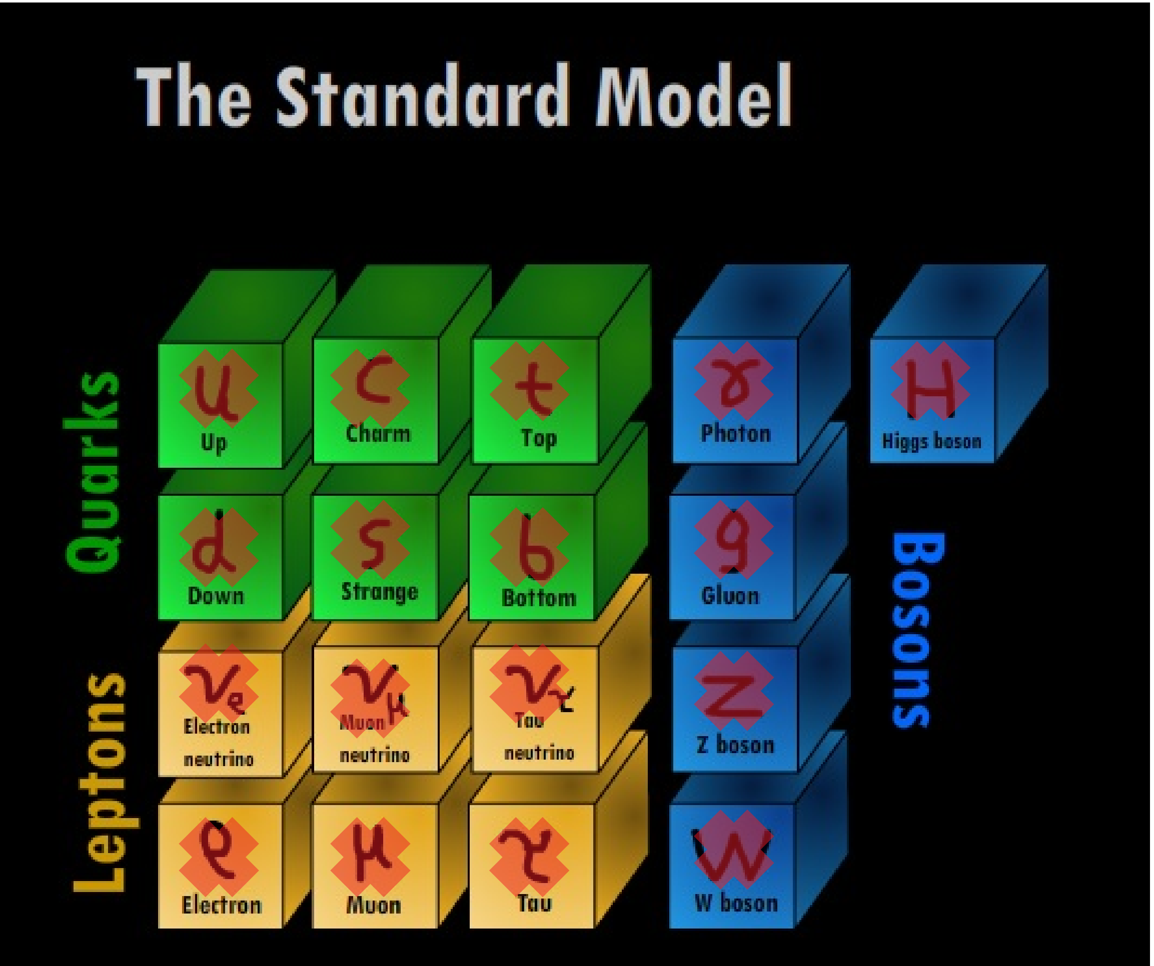
Dark → neutral

What is Dark Matter made of?



Dark Matter → neutral
→ massive

What is Dark Matter made of?



Dark Matter	→	neutral
	→	massive
Always present	→	'stable'

SM Neutrinos as Dark Matter?

* SM decouple while relativistic
  → destroy clumps of mass smaller than clusters

* They can fit the observed abundance if $$\Omega_\nu h^2 = \frac{\sum m_\nu}{93.5\mathrm{eV}}$$
  → work for Σm_ν ~ 50 eV

  → But from cosmology: $\Sigma m_\nu < 0.1$ eV

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Dark Matter needs
New Physics beyond the Standard Model!

Dark Matter @ PDG

https://pdg.lbl.gov/

$\boxed{\chi}$ $J = ?$

χ MASS

VALUE (eV)	EVTS	DOCUMENT ID	TECN	COMMENT
?±? NICK'S FIT	0			

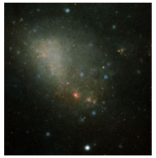
Bosonic Dark Matter

$m \gtrsim 10^{-22}$ eV 1610.08297

$\lambda \lesssim 0.5$ kpc

Fermionic Dark Matter

$m \gtrsim 800$ eV 1311.0282


χ WIDTH

VALUE (eV)	EVTS	DOCUMENT ID	TECN	COMMENT
?±? NICK'S FIT	0			

Dark Matter Existed Throughout Cosmic History

$\tau \gg 13.82$ billion years $\approx 4.36 \times 10^{17}$ s

$\Gamma \ll 1.51 \times 10^{-33}$ eV

χ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	e^+e^-	?	
Γ_2	$\mu^+\mu^-$	?	
Γ_3	$\tau^+\tau^-$	?	
Γ_4	$\ell^+\ell^-$	?	
Γ_5	$\ell^+\ell^-\ell^+\ell^-$	?	
Γ_6	invisible	?	
Γ_7	hadrons	?	
Γ_8	$(u\overline{u}+c\overline{c})/2$	?	
Γ_9	$(d\overline{d}+s\overline{s}+b\overline{b})/3$	?	
Γ_{10}	$c\overline{c}$	?	
Γ_{11}	$b\overline{b}$	?	
Γ_{12}	$b\overline{b}b\overline{b}$	?	

+47 more

Nick Rodd
https://nickrodd.com/research.html

What is the Dark Matter?

What is the Dark Matter?

How was Dark Matter produced in the Early Universe?

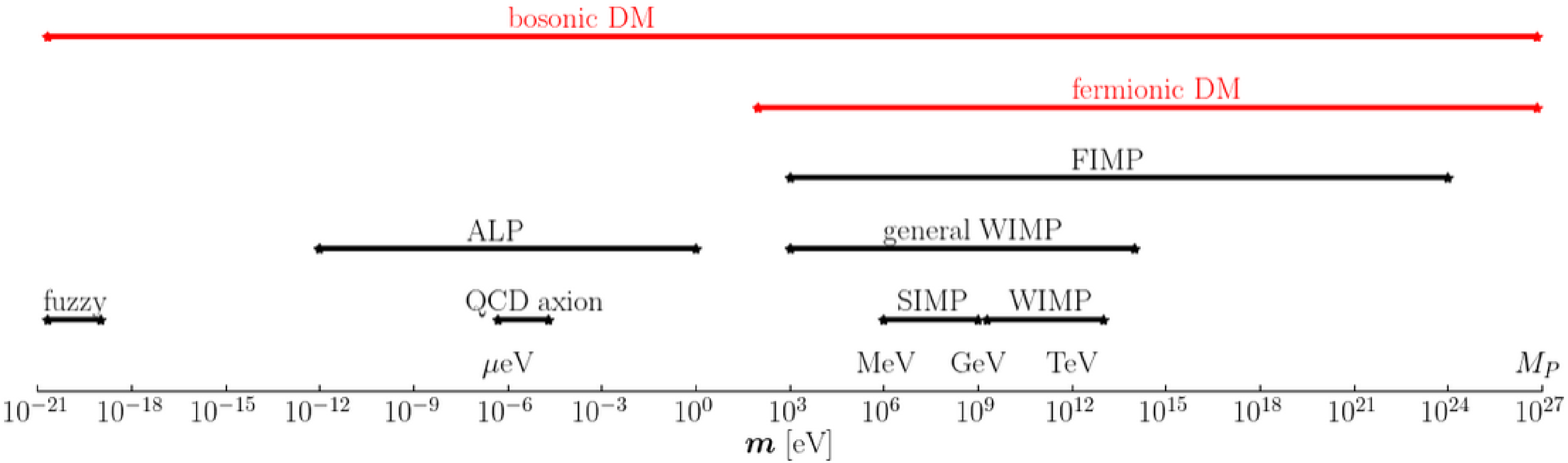
How was Dark Matter produced in the Early Universe?

WIMP

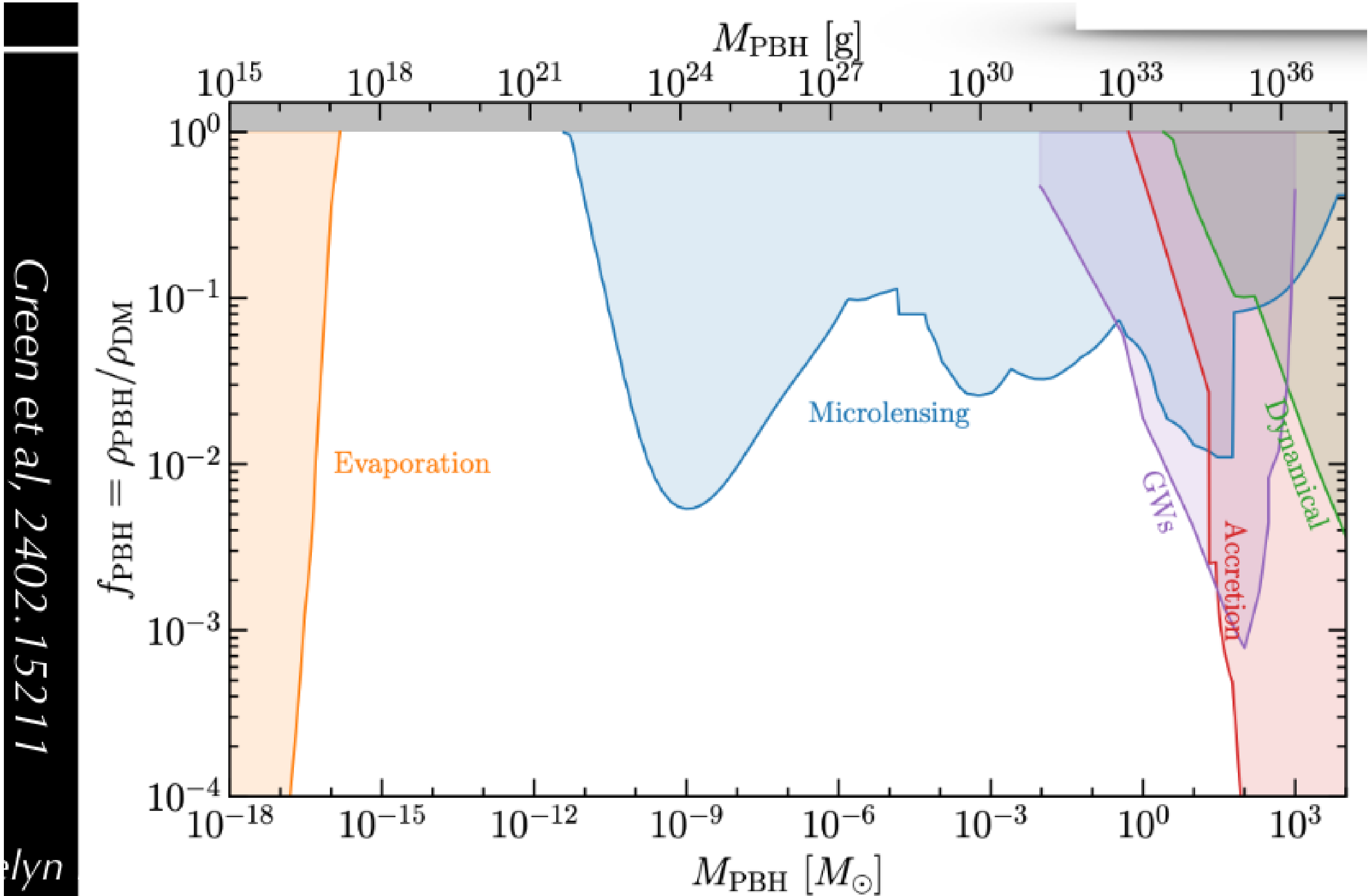
Cannibal FIMP SIMP Axion WISP ALP MACHO PBHs

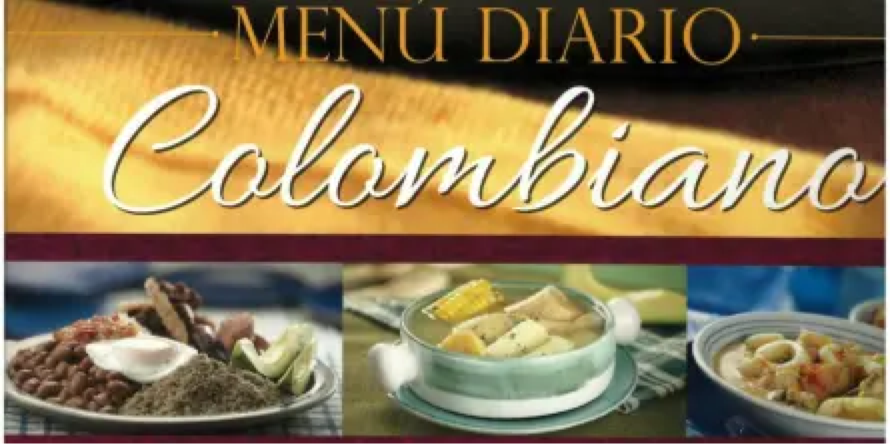
Asymmetric DM ELDER Non-thermal DM Composite DM

Dark Matter Mass



Primordial Black Holes as Dark Matter





1. **WIMP** DM
   Weakly Interacting Massive Particles

+ Entr’acte 1: Standard vs. Non-standard Cosmology

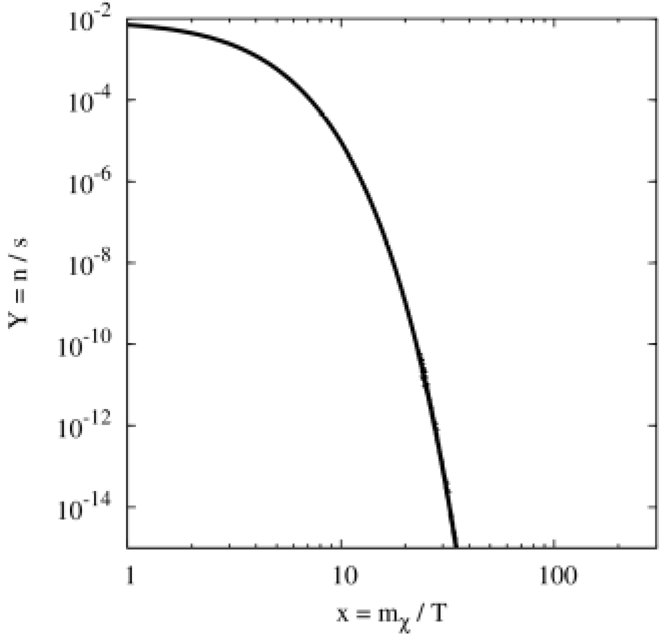
2. **FIMP** DM
   Feebly Interacting Massive Particles
   2a. Infrared FIMPs
   2b. Ultraviolet FIMPs

+ Entr’acte 2: Testing reheating

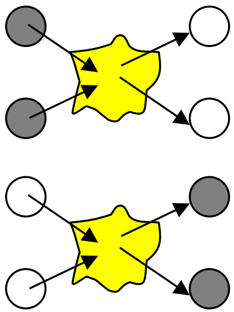
3. **SIMP** DM
   Self-interacting Massive Particles

1. WIMP DM
Weakly Interacting Massive Particle

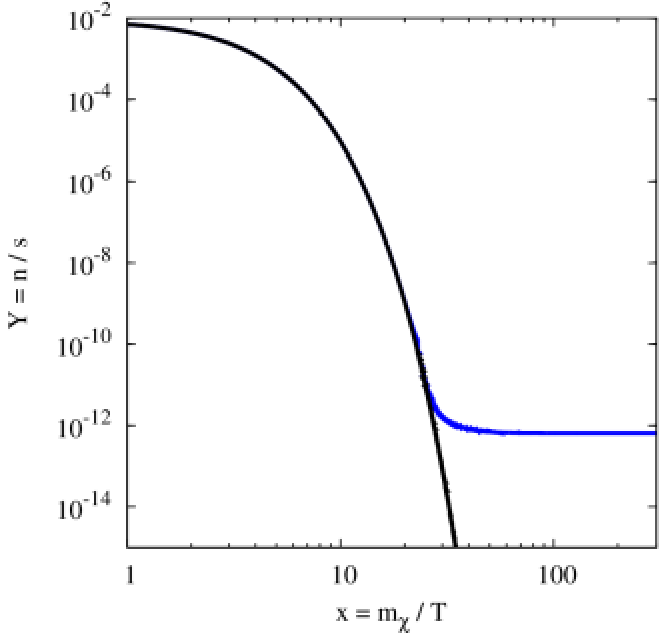
WIMP Dark Matter



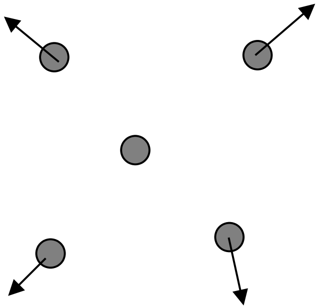
Early Universe:
DM in full **thermal equilibrium**
with the Standard Model.



WIMP Dark Matter

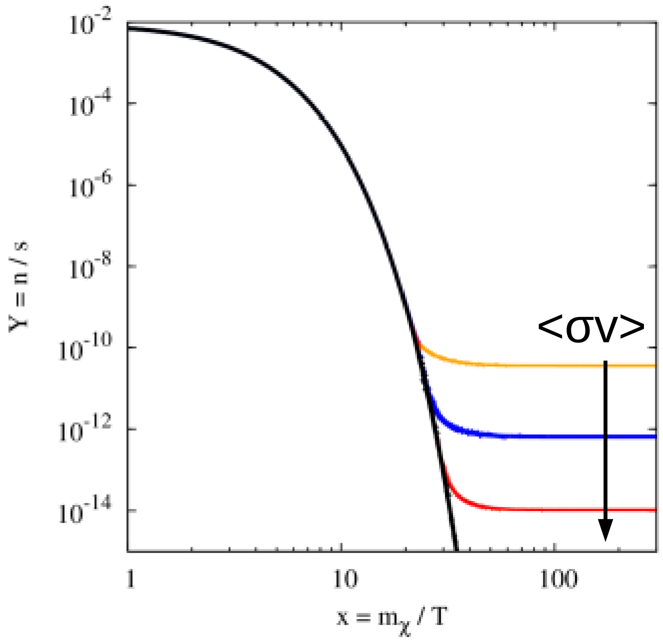


Due to the expansion of the Universe DM particles fall **out of chemical equilibrium** and cannot annihilate anymore.



A relic density of DM is obtained which remains constant.

WIMP Dark Matter



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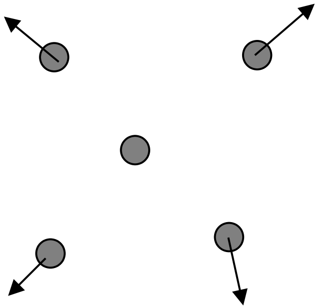
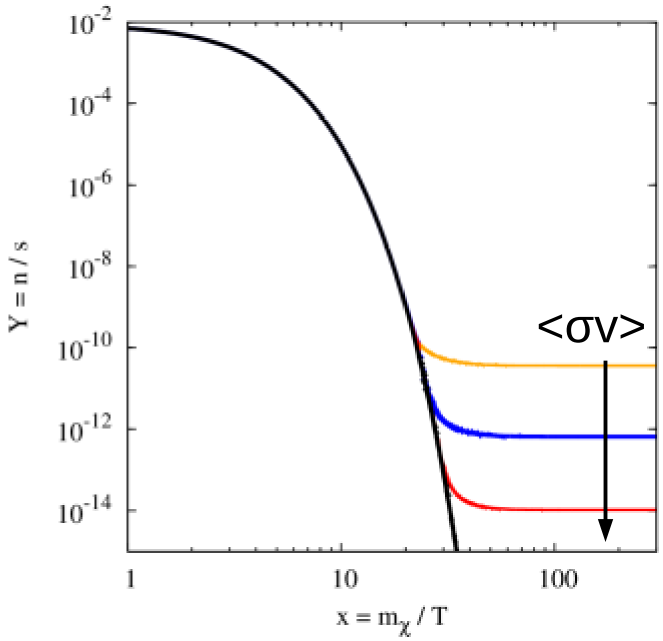


A particle with very weak interactions decouples earlier, having a larger relic density.

A relic density of DM is obtained which remains constant.

A particle with stronger interactions keeps in equilibrium for longer, and is more diluted.

WIMP Dark Matter



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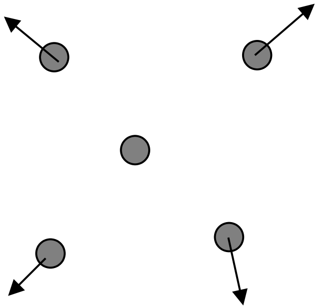

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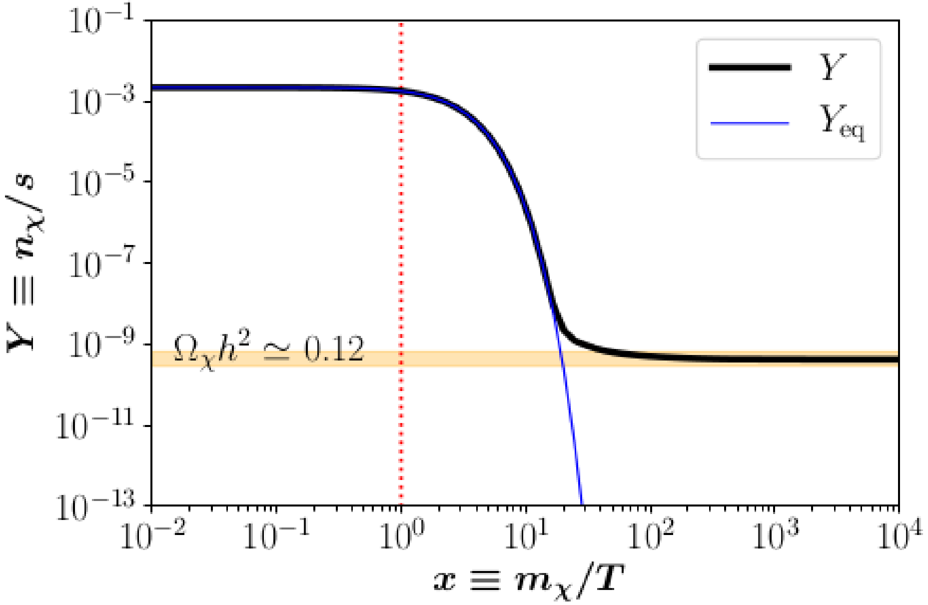
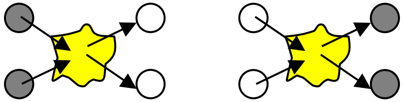
→ ***Collisionless cold WIMP*** Dark Matter

WIMP Dark Matter

$$\frac{dn_\chi}{dt} + 3\,H\,n_\chi = -\langle v\sigma_\chi\rangle\left[n_\chi^2 - (n_\chi^{\rm eq})^2\right]$$





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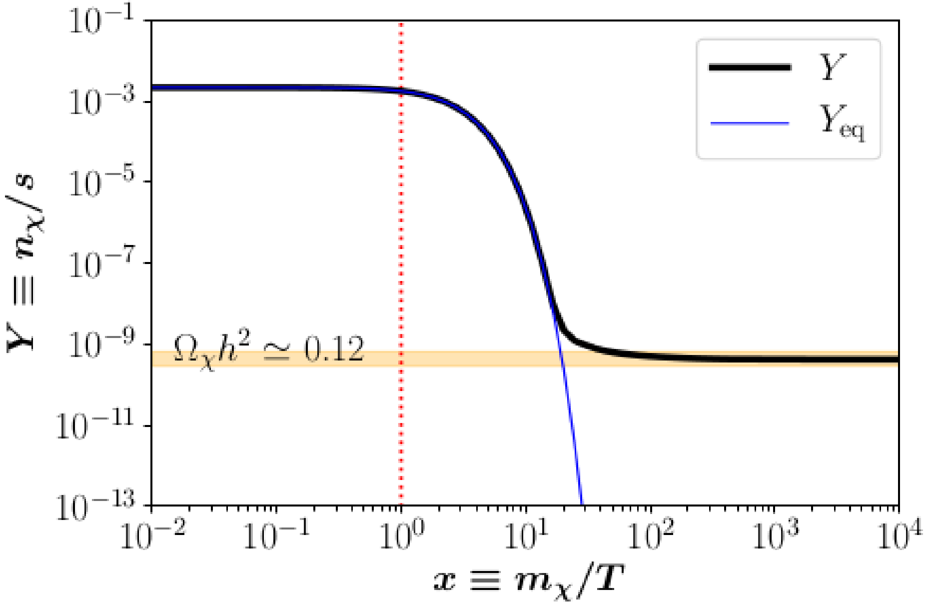


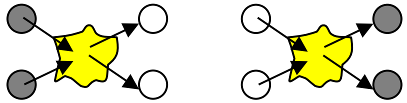
WIMP DM typically requires:

$\langle \sigma v \rangle \sim$ few 10^{-26} cm^3/s

* GeV to TeV masses
* *O*(1) couplings DM-SM

→ Independent on initial conditions!

* reheating temperature
* coupling to the inflaton
* DM density after reheating
* cosmological evolution before freeze-out



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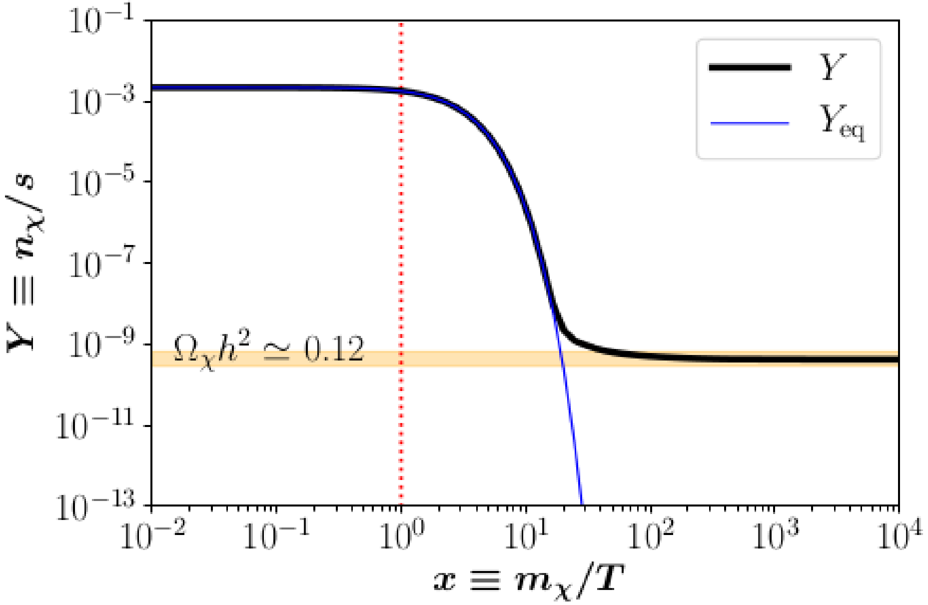

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* GeV to TeV masses
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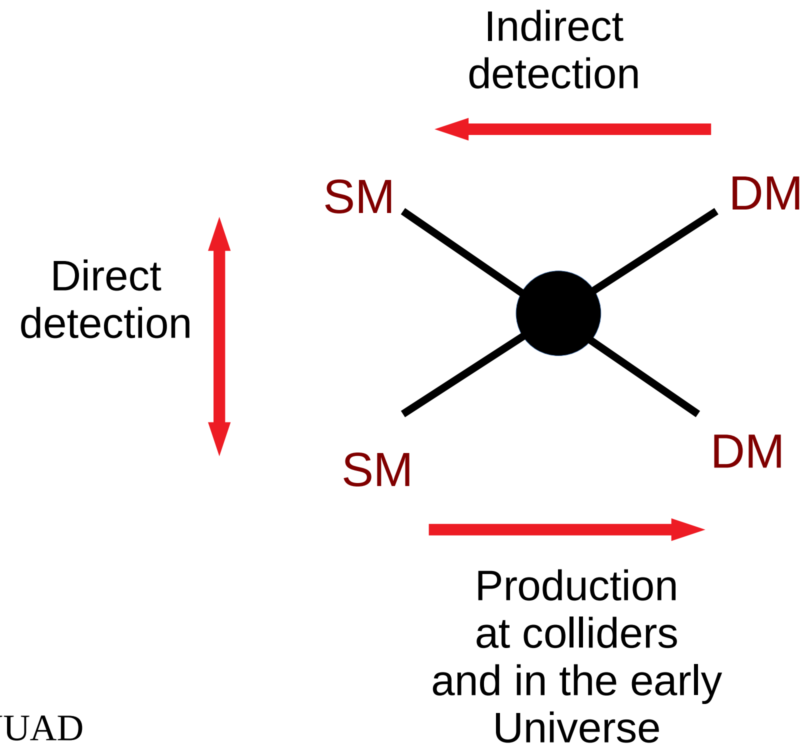
→ Independent on initial conditions!

Over the last decades a huge worldwide effort to detect WIMP DM using a multi-channel and multi-messenger approach…

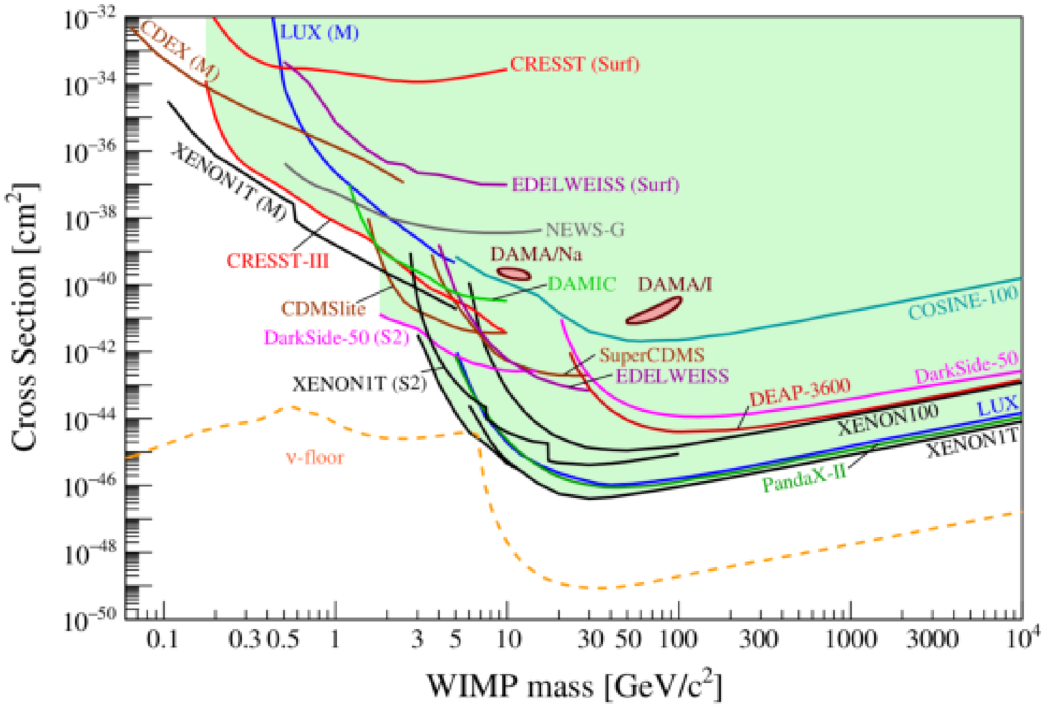
but no compelling detection so far! :-(

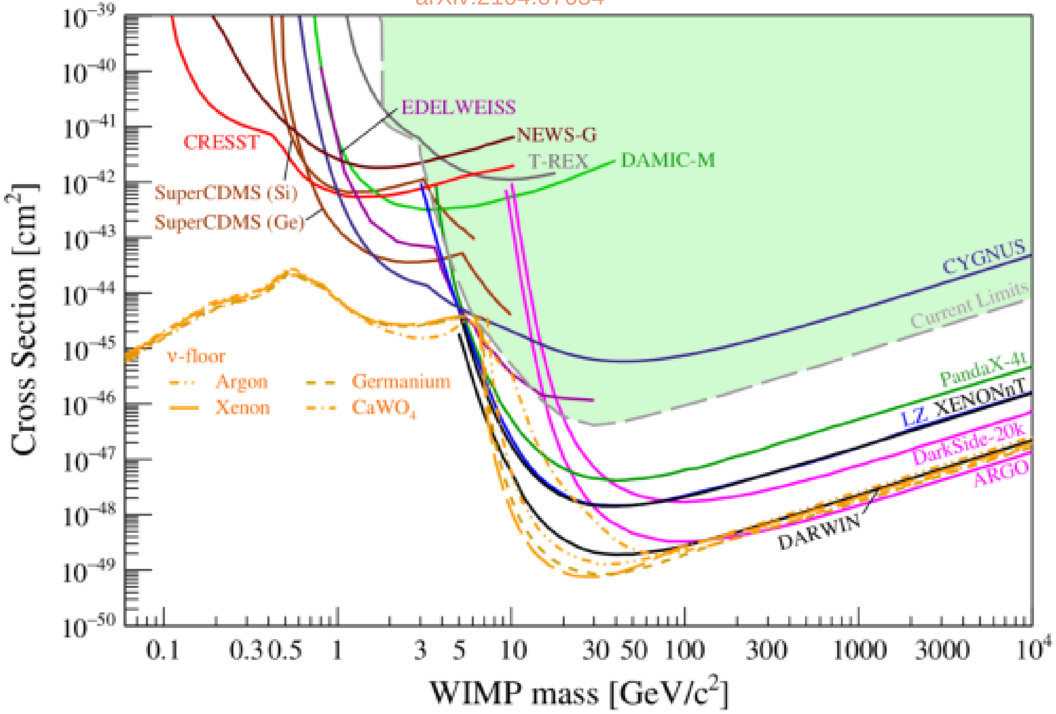
Detecting WIMPs



WIMP Dark Matter under Tension

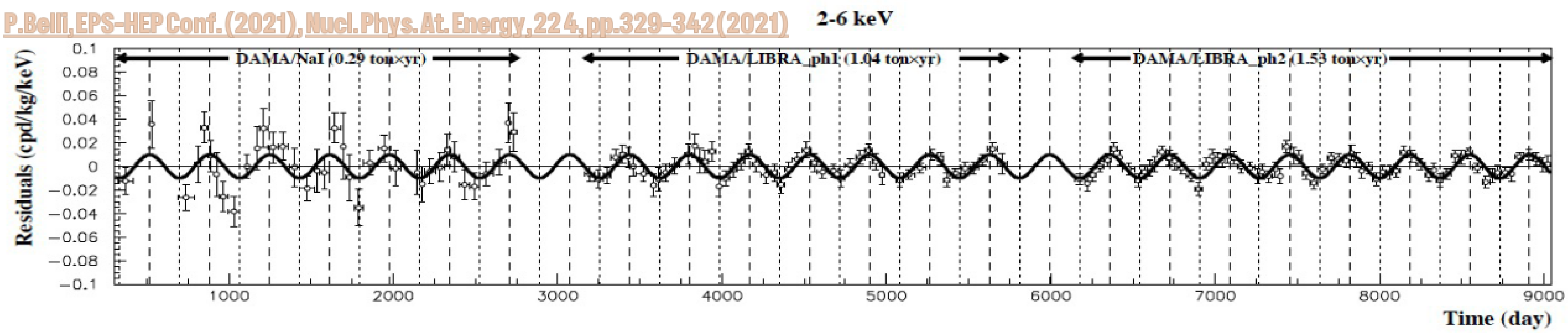
Direct detection of dark matter - APPEC committee report
arXiv:2104.07634





DAMA/LIBRA

P.Belli, EPS-HEP Conf. (2021), Nucl. Phys. At. Energy, 22 4, pp.329-342 (2021)



Dark Matter ***Annual Modulation*** Search in ***COSINE-100*** Full Dataset and ***Beyond***

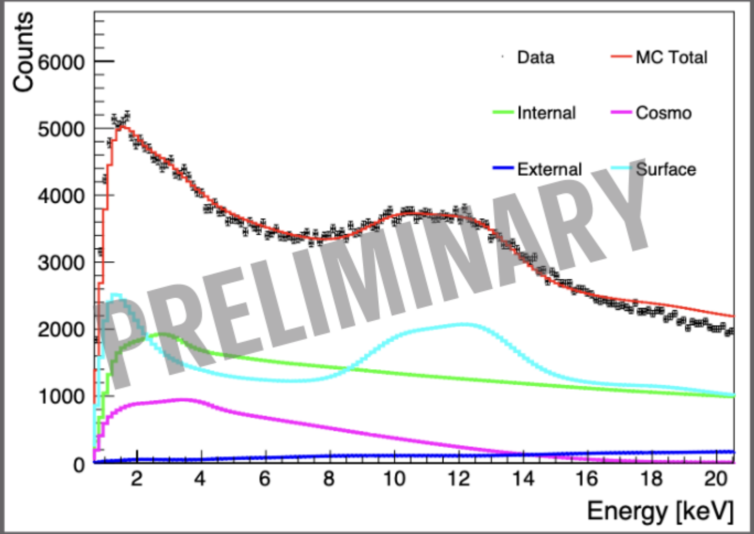
LEE Seung Mok
Department of Physics & Astronomy, Seoul National University
Center for Underground Physics, IBS
On behalf of COSINE Collaboration

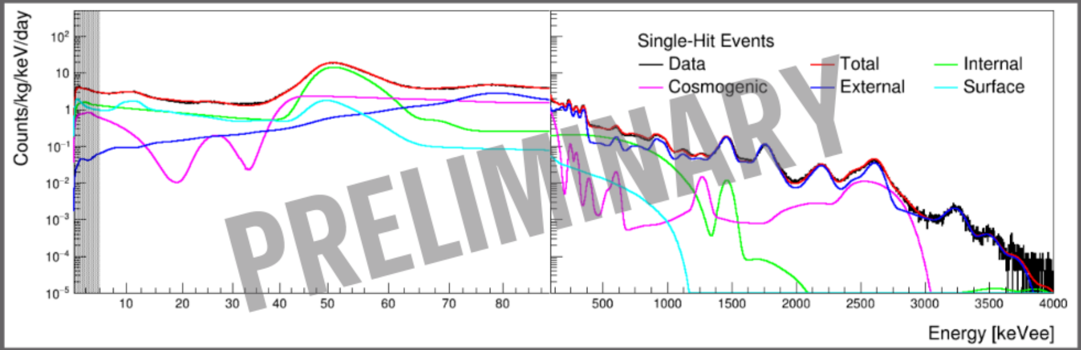
July 9th, 2024

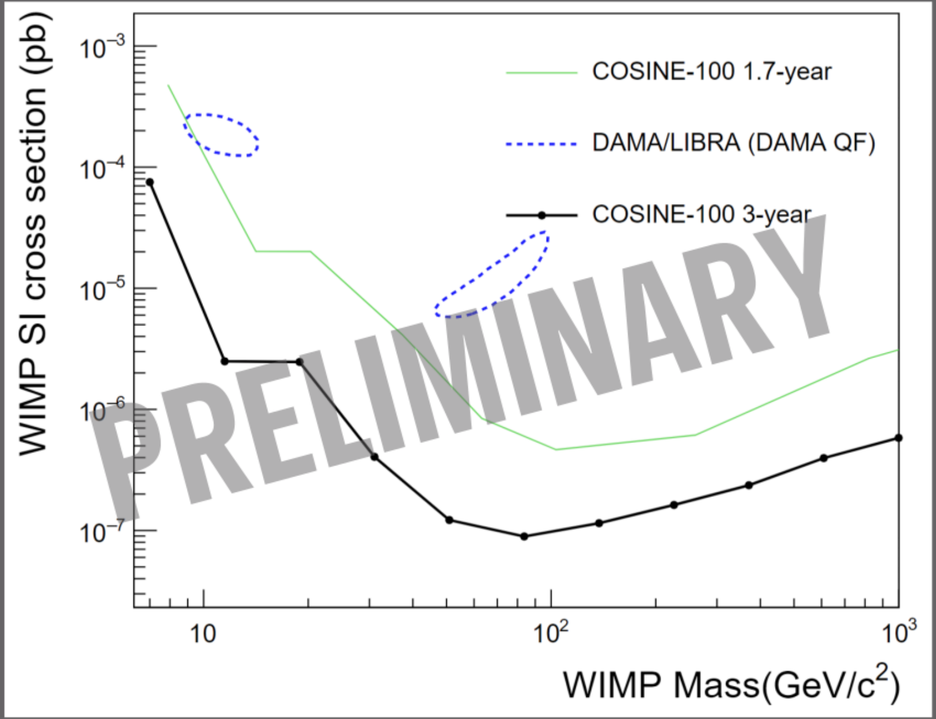
Parallel Session 1

Identification of Dark Matter 2024
Palazzo dell'Emiciclo, Sala Ipogea, L'Aquila, Italy

No DAMA-like WIMPs in NaI(Tl) Spectrum







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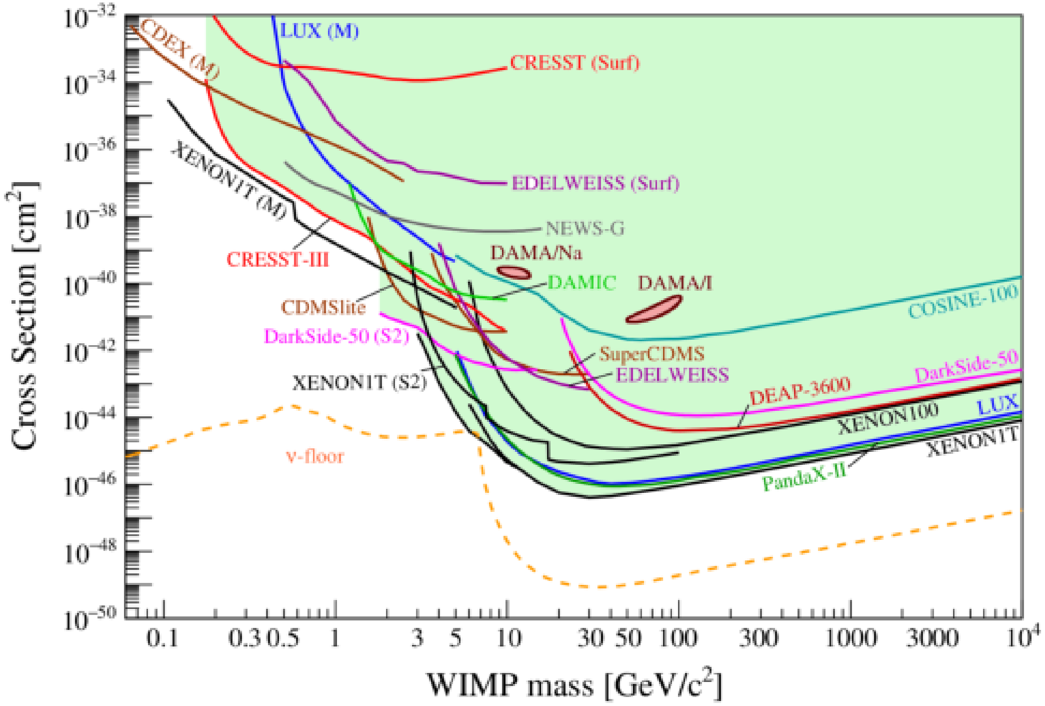
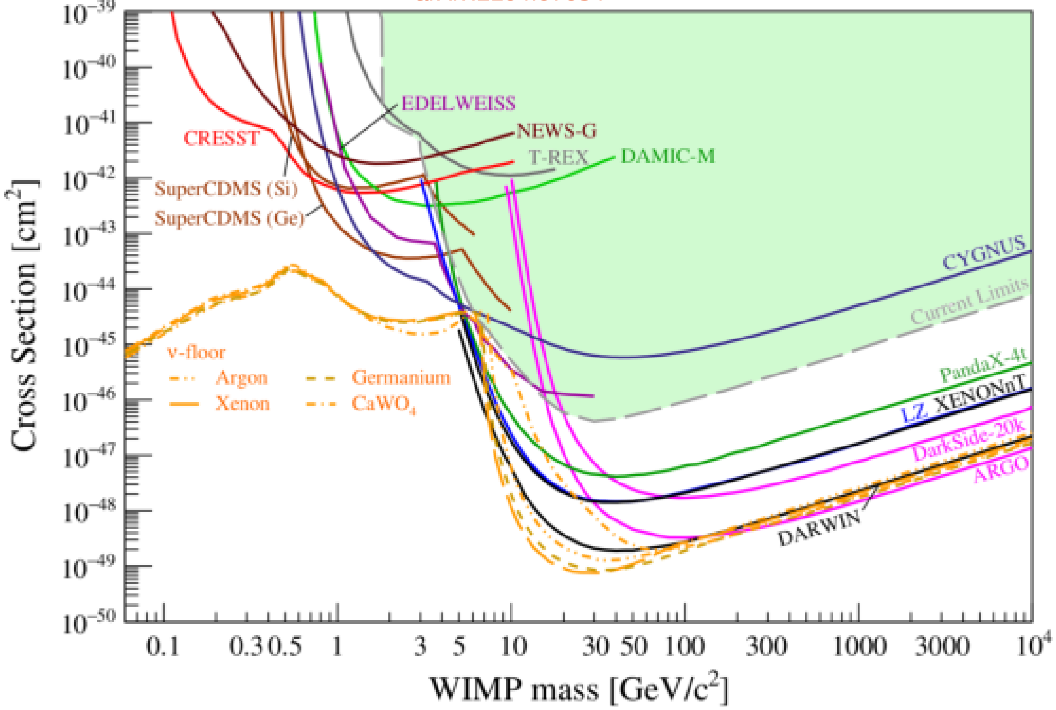




XENON

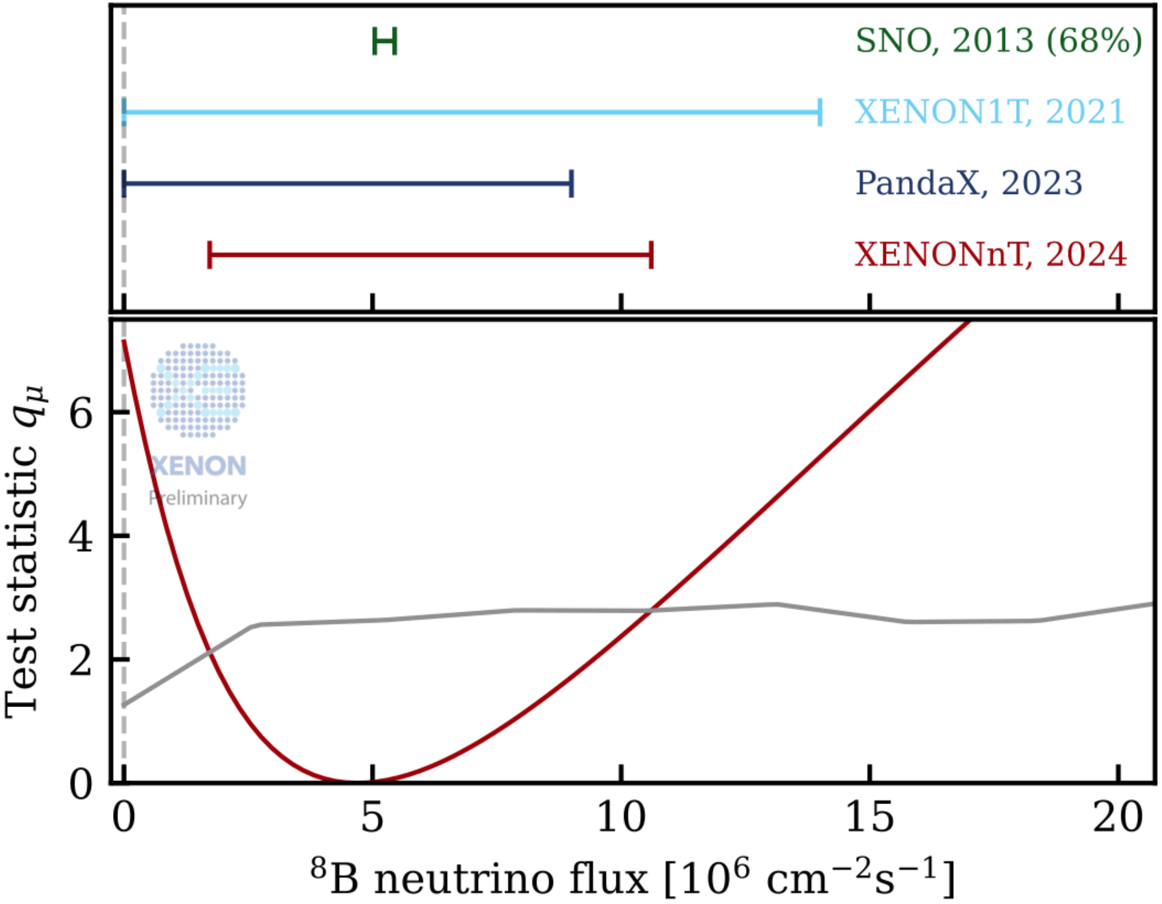
清華大學
Tsinghua University

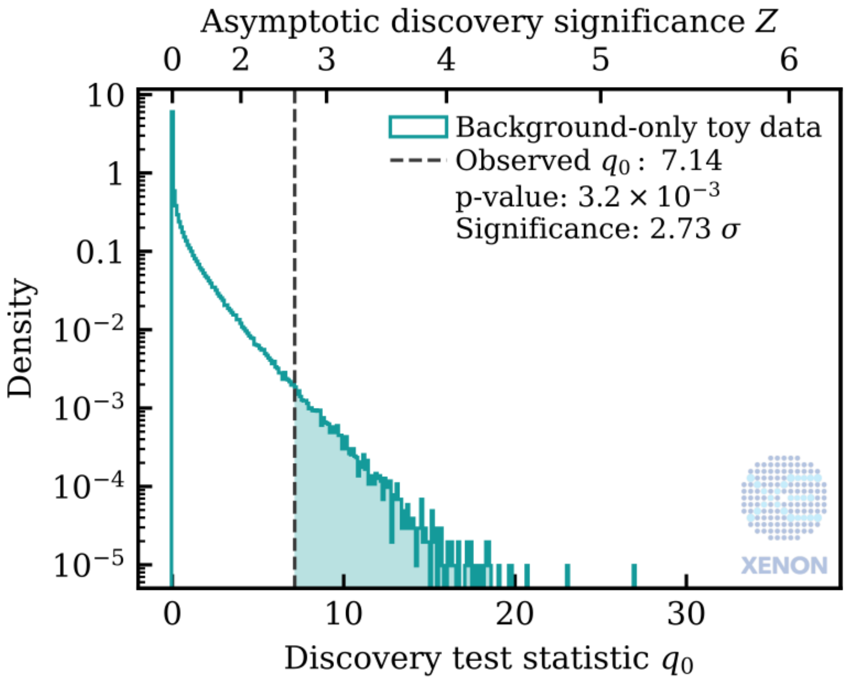
First Measurement of Coherent Elastic Neutrino Nucleus Scattering of Solar ^{8}B Neutrinos in XENONnT

Fei Gao, Tsinghua University
on behalf of the XENON Collaboration

15th International Workshop on the Identification of Dark Matter
July 8-12, 2024, L'Aquila

XENONnT Solar ^{8}B CEvNS Search Results





- We have measured the solar ^{8}B neutrinos via CEvNS in XENONnT at 2.73σ
- The first CEvNS measurement with Xe!
- The first astrophysical neutrino measurement via CEvNS

First Measurement of Solar ^{8}B Neutrino Flux through Coherent Elastic Neutrino-Nucleus Scattering in PandaX-4T

arXiv:2407.10892v1 [hep-ex] 15 Jul 2024

The PandaX-4T liquid xenon detector at the China Jinping Underground Laboratory is used to measure the solar ^{8}B neutrino flux by detecting neutrinos through coherent scattering with xenon nuclei. Data samples requiring the coincidence of scintillation and ionization signals (paired), as well as unpaired ionization-only signals (US2), are selected with energy threshold of approximately 1.1 keV (0.33 keV) nuclear recoil energy. Combining the commissioning run and the first science run of PandaX-4T, a total exposure of 1.25 and 1.04 tonne·year are collected for the paired and US2, respectively. After unblinding, 3 and 332 events are observed with an expectation of 2.8±0.5 and 251±32 background events, for the paired and US2 data, respectively. A combined analysis yields a best-fit ^{8}B neutrino signal of 3.5 (75) events from the paired (US2) data sample, with ~37% uncertainty, and the background-only hypothesis is disfavored at 2.64 σ significance. This gives a solar ^{8}B neutrino flux of $(8.4 \pm 3.1) \times 10^6$ cm^{-2}s^{-1}, consistent with the standard solar model prediction. This is the first indication of solar ^{8}B neutrino "fog" in a dark matter direct detection experiment.

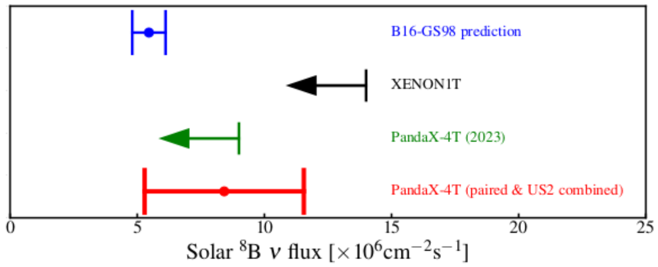
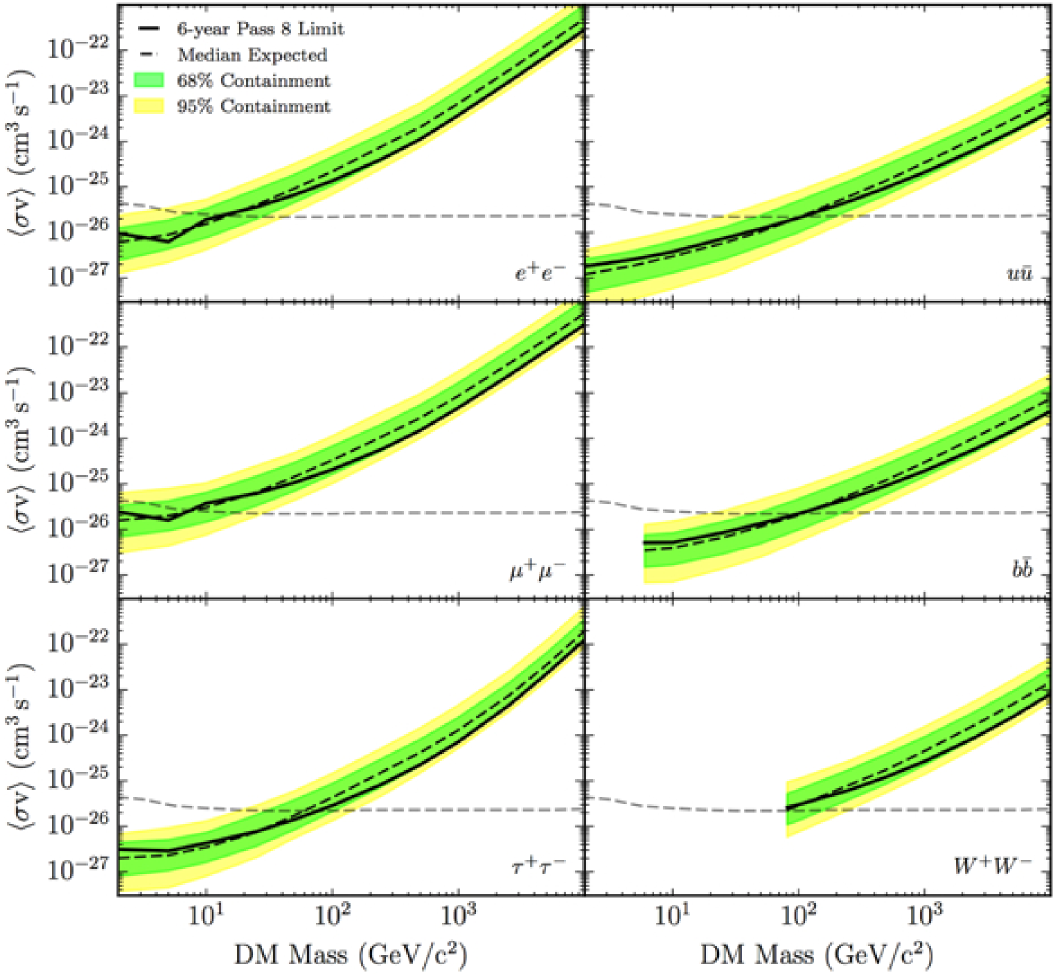
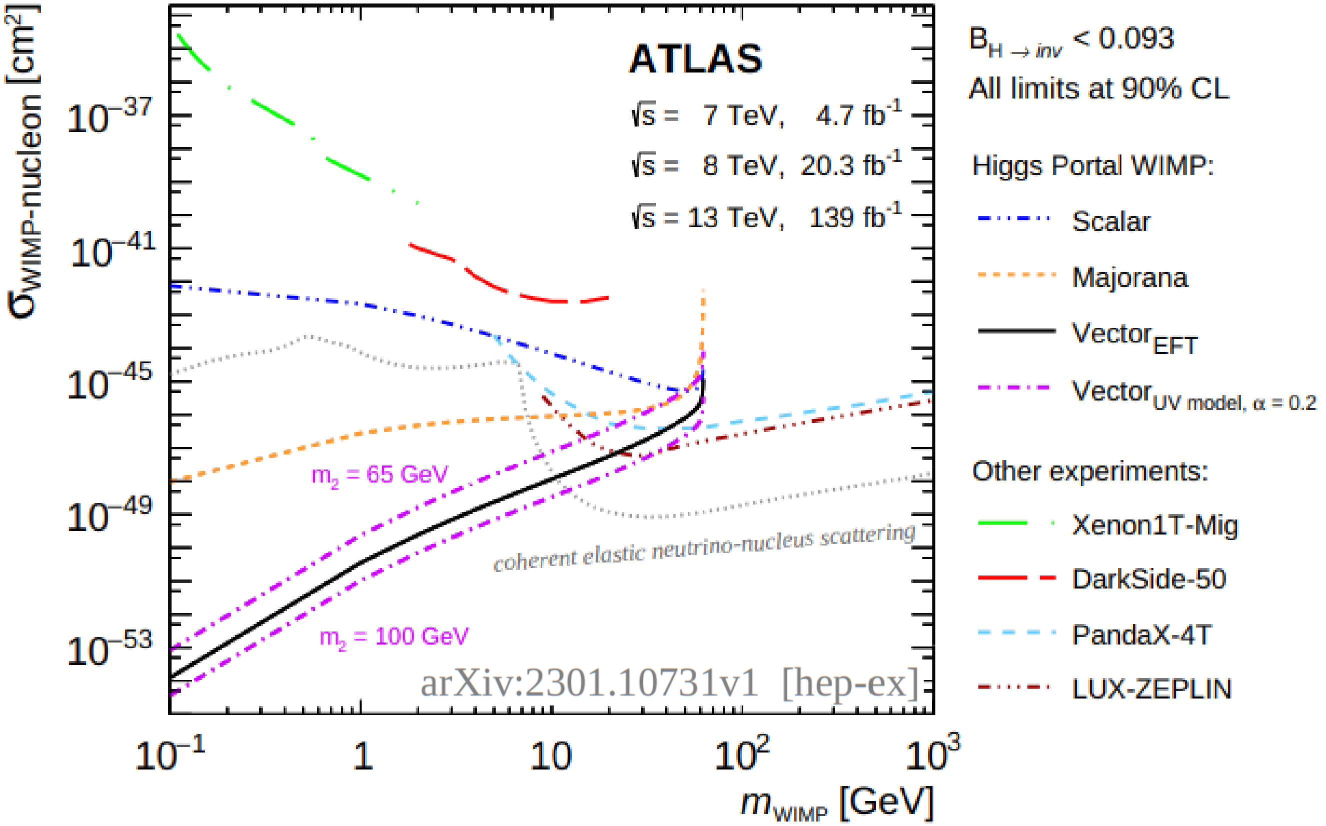


FIG. 6. The best-fit ^{8}B solar neutrino flux and 1σ uncertainty from this work (red), together with 90% C.L. regions of the PandaX-4T previous constraint [33] (green), XENON1T constraint [31] (black), and 1σ of the theoretical prediction from the standard solar model [45] (blue).

WIMP Dark Matter under Tension



WIMP Dark Matter under Tension



Entr'acte 1:
Standard vs Non-standard Cosmologies

THE FIRST THREE SECONDS:
A REVIEW OF POSSIBLE EXPANSION HISTORIES OF THE EARLY UNIVERSE

Rouzbeh Allahverdi[1], Mustafa A. Amin[2], Asher Berlin[3], Nicolás Bernal[4], Christian T. Byrnes[5], M. Sten Delos[6], Adrienne L. Erickcek[6], Miguel Escudero[7], Daniel G. Figueroa[8], Katherine Freese[9,10], Tomohiro Harada[11], Dan Hooper[12,13,14], David I. Kaiser[15], Tanvi Karwal[16], Kazunori Kohri[17,18], Gordan Krnjaic[12], Marek Lewicki[7,19], Kaloian D. Lozanov[20], Vivian Poulin[21], Kuver Sinha[22], Tristan L. Smith[23], Tomo Takahashi[24], Tommi Tenkanen[25,a], James Unwin[26], Ville Vaskonen[7,27,a], and Scott Watson[28]

arXiv:2006.16182v2 [astro-ph.CO]

Standard Cosmology

* We know that at BBN, $T \sim O(\mathrm{MeV})$, the universe was dominated by SM radiation

* Standard cosmology
  → **extrapolation** up to the reheating epoch $T \sim 10^{10}$ GeV (?)
  → SM entropy conserved
  → early universe dominated by SM radiation
  → instantaneous reheating

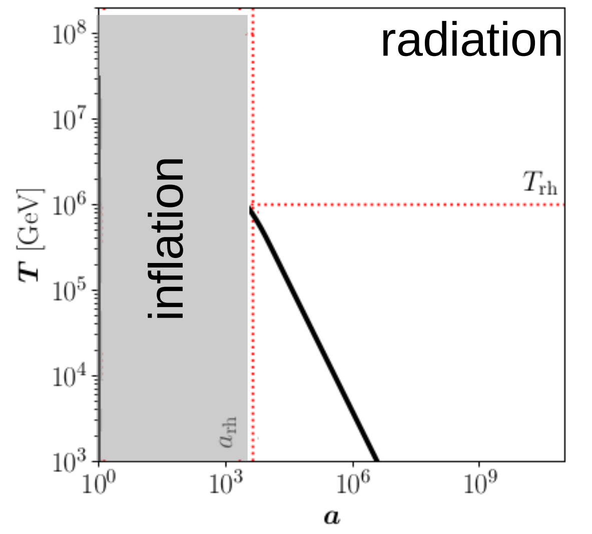
Standard Cosmology

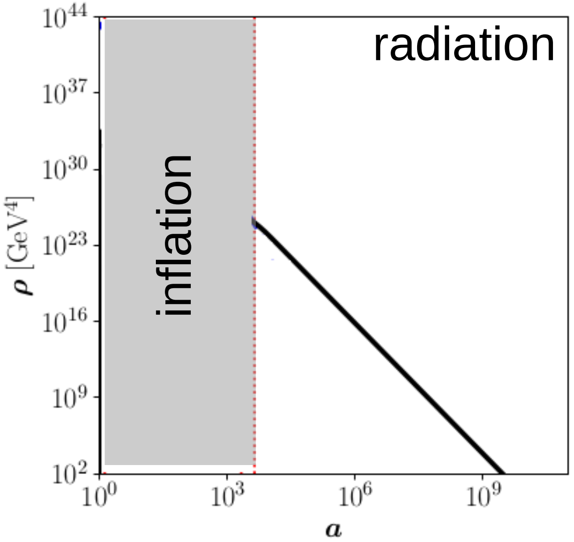
Simplest!

* We know that at BBN, $T \sim O$(MeV), the universe was dominated by SM radiation

* Standard cosmology
  → **extrapolation** up to the reheating epoch $T \sim 10^{10}$ GeV (?)
  → SM entropy conserved
  → early universe dominated by SM radiation
  → instantaneous reheating

Standard Cosmology



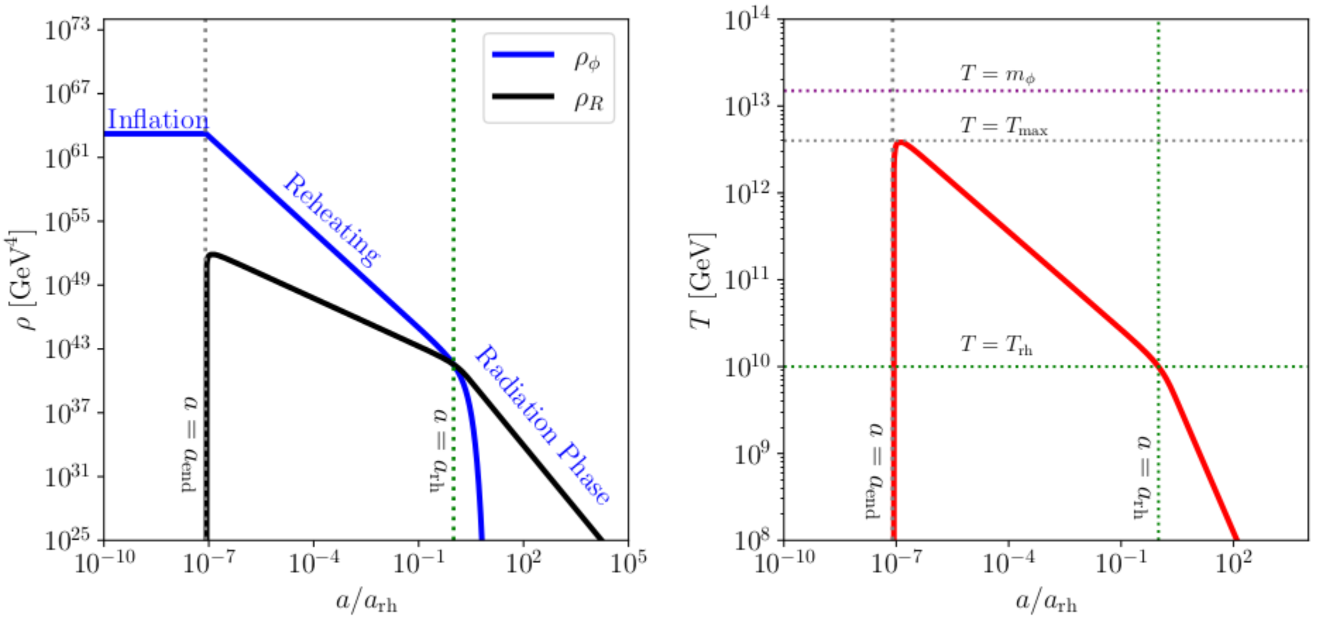


$T \sim 1/a$

$\rho_R \sim T^4 \sim a^{-4}$

This is pretty much the common lore of the particle physics community! ;-)

Non-instantaneous Reheating

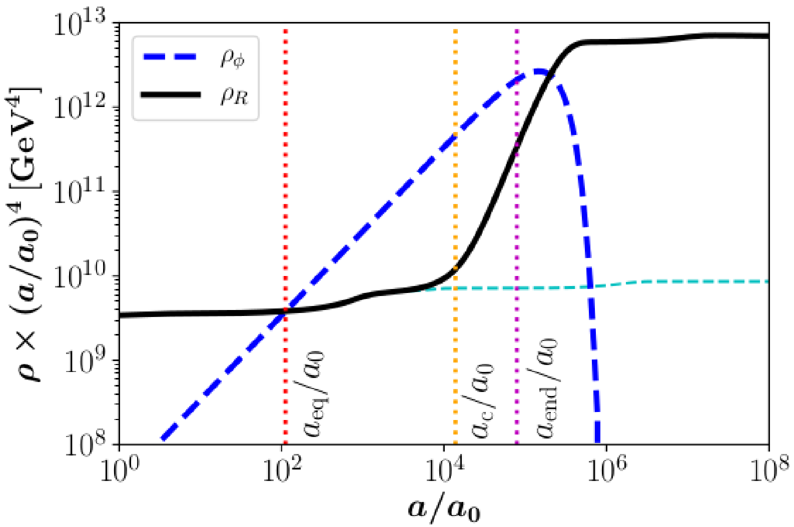


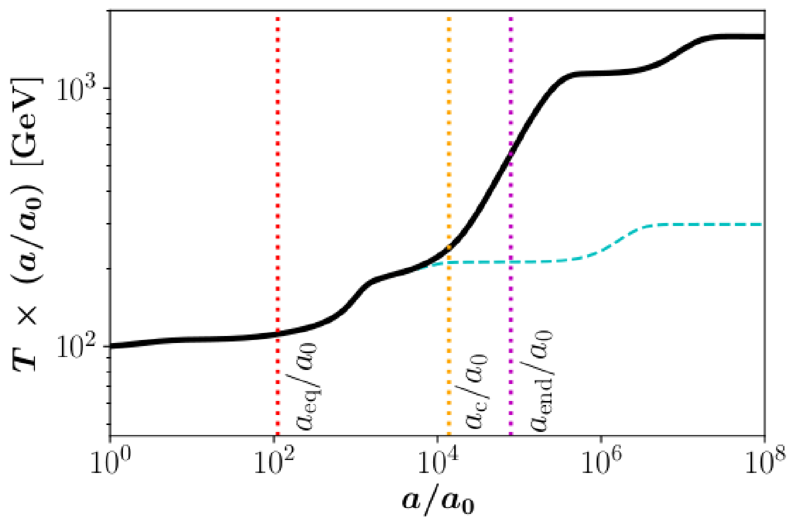
Decay or annihilation of inflatons into SM radiation is a *continuous process*

$$\frac{d\rho_\phi}{dt} + 3(1+\omega)\, H\, \rho_\phi = -\Gamma_\phi\, \rho_\phi$$

$$\frac{d\rho_R}{dt} + 4\, H\, \rho_R = +\Gamma_\phi\, \rho_\phi$$

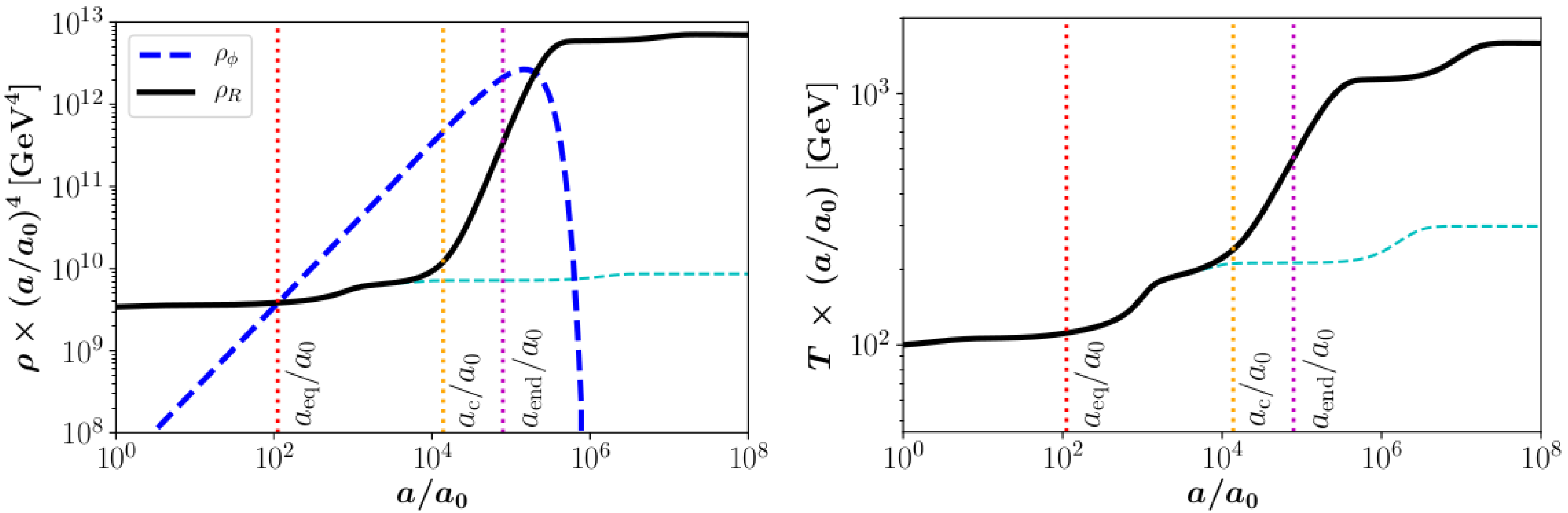
Non-standard Cosmologies





* Total energy density of the Universe could have been dominated by another non-SM component
* Entropy injection

Non-standard Cosmologies



* Total energy density of the Universe could have been dominated by another non-SM component
* Entropy injection

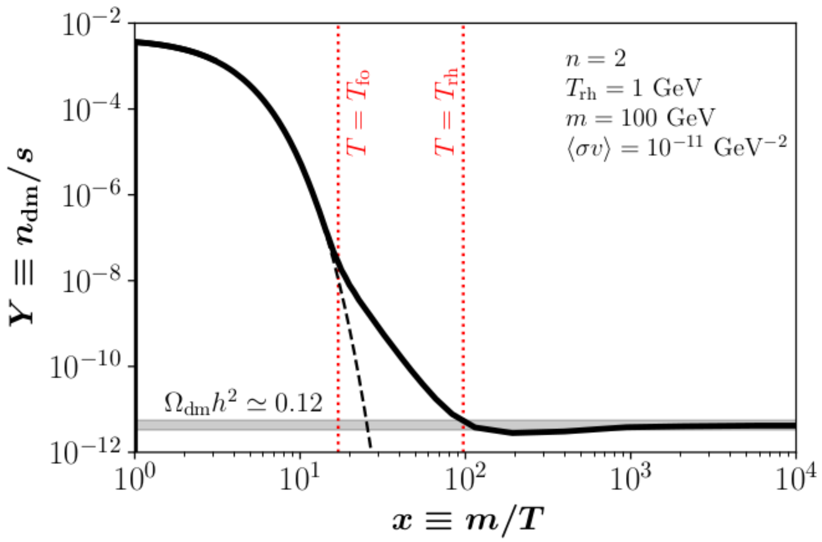
Multiple possible sources:

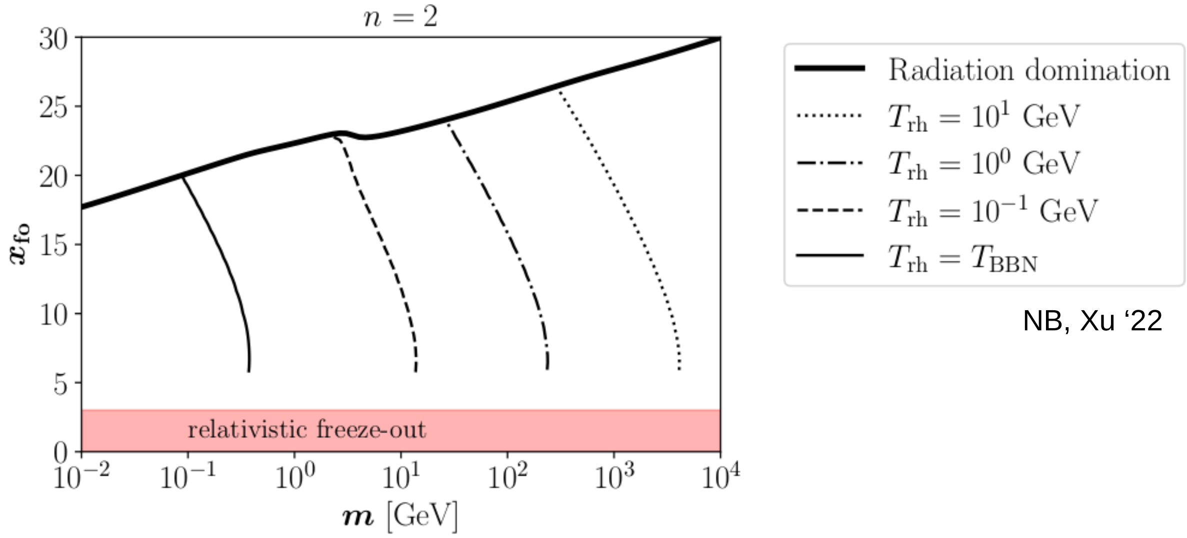
* heavy longlived particle (moduli, GUTs, RHNs, …)
* Primordial black holes
* ...

Entr'acte 1:
Standard vs Non-standard Cosmologies

WIMPs in Non-standard Cosmologies

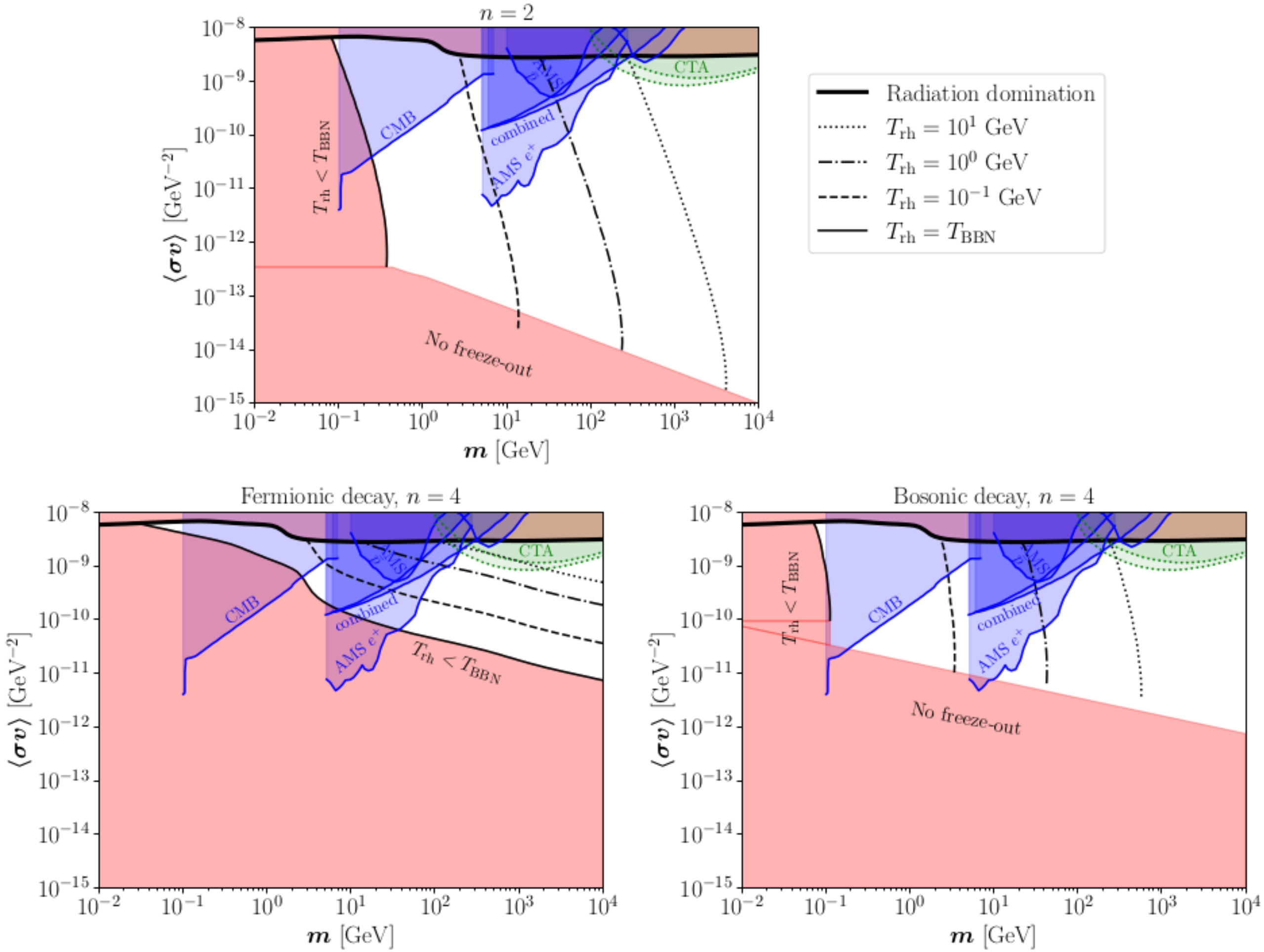
$$\frac{dn_\chi}{dt} + 3\,H\,n_\chi = -\langle v\sigma_\chi\rangle\left[n_\chi^2 - (n_\chi^{\rm eq})^2\right]$$





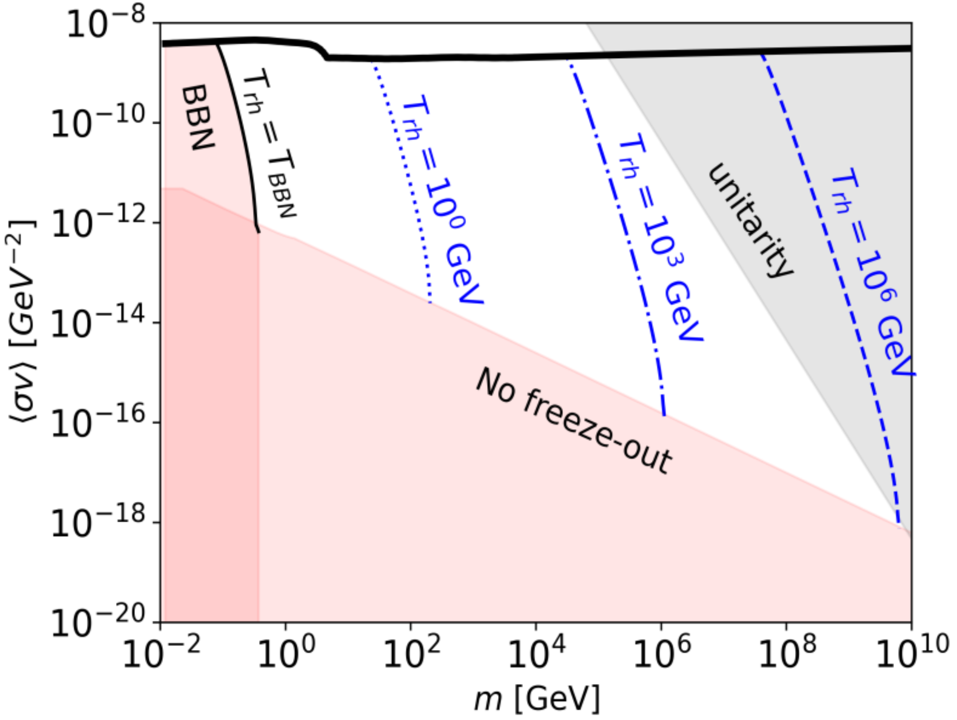
NB, Xu '22

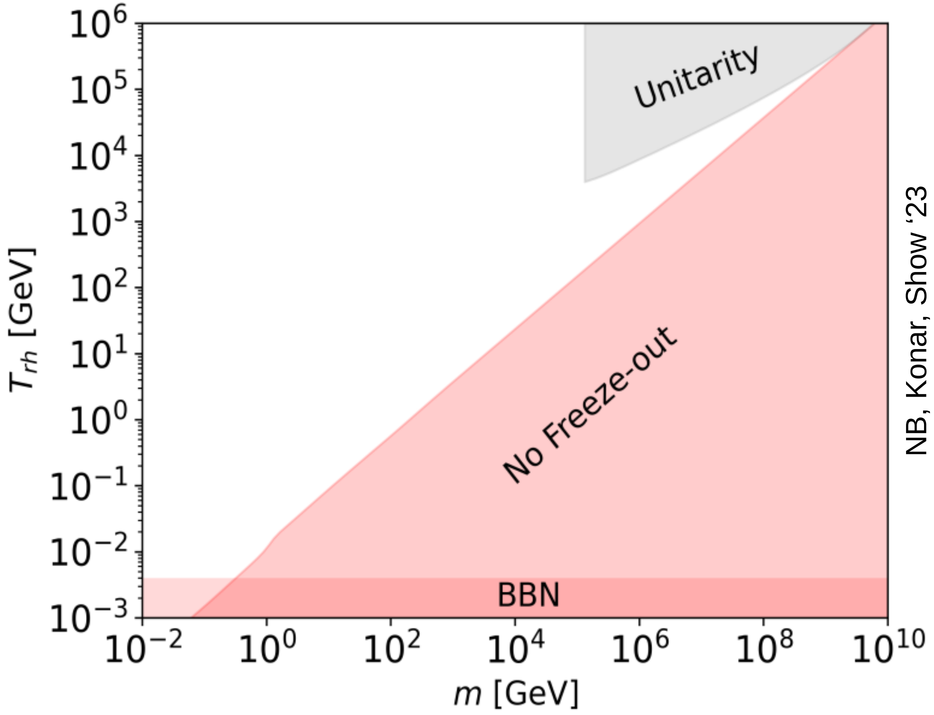
WIMPs in Non-standard Cosmologies



NB, Xu '22

WIMPs in Non-standard Cosmologies

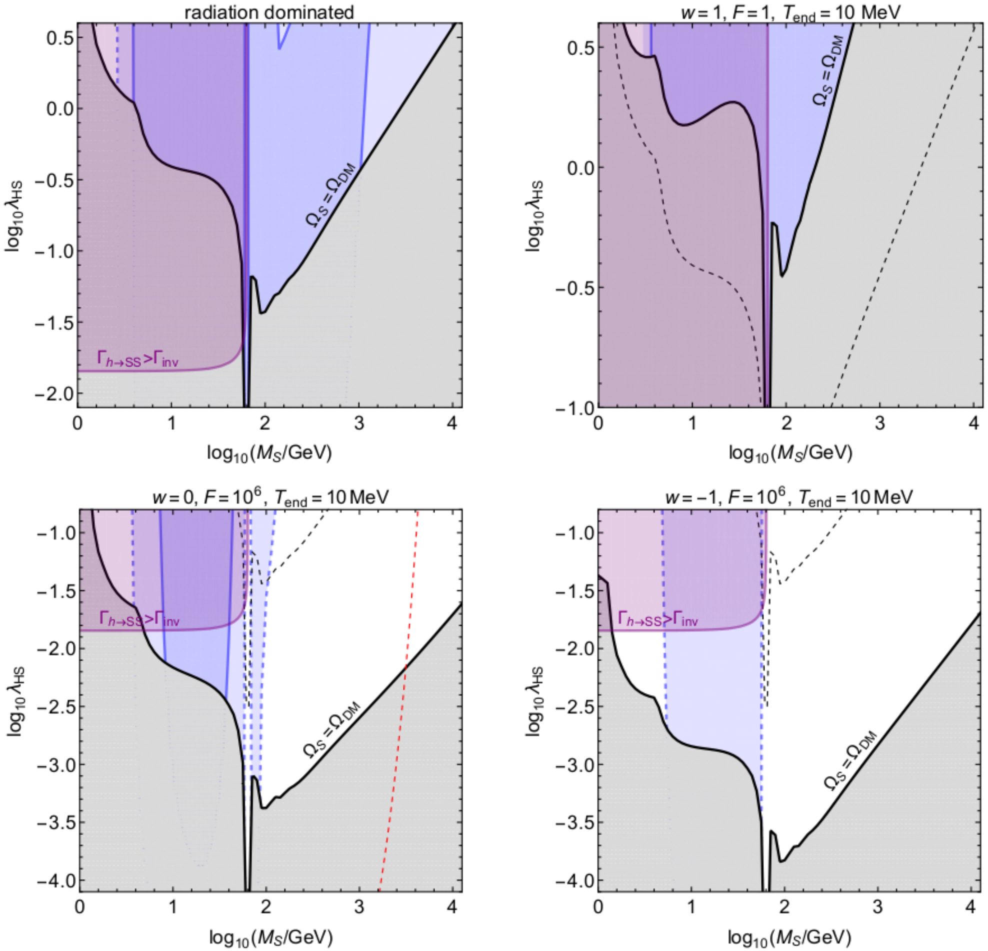




NB, Konar, Show '23

WIMPs in Non-standard Cosmologies

Singlet scalar
DM model



NB, Cosme, Tenkanen, Vaskonen '19

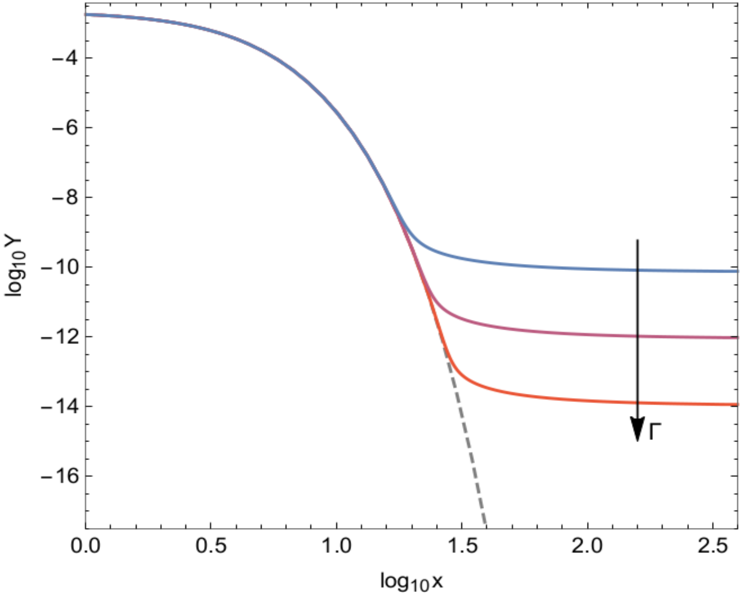
2. FIMP DM
Feebly Interacting Massive Particle

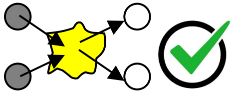
The Dawn of FIMP Dark Matter:
A Review of Models and Constraints

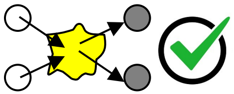
NB, Heikinheimo,Tenkanen,Tuominen, Vaskonen ‘17

WIMP vs FIMP Dark Matter

$$\frac{dn_\chi}{dt} + 3\,H\,n_\chi = -\langle v\sigma_\chi\rangle\left[n_\chi^2 - (n_\chi^{\rm eq})^2\right]$$

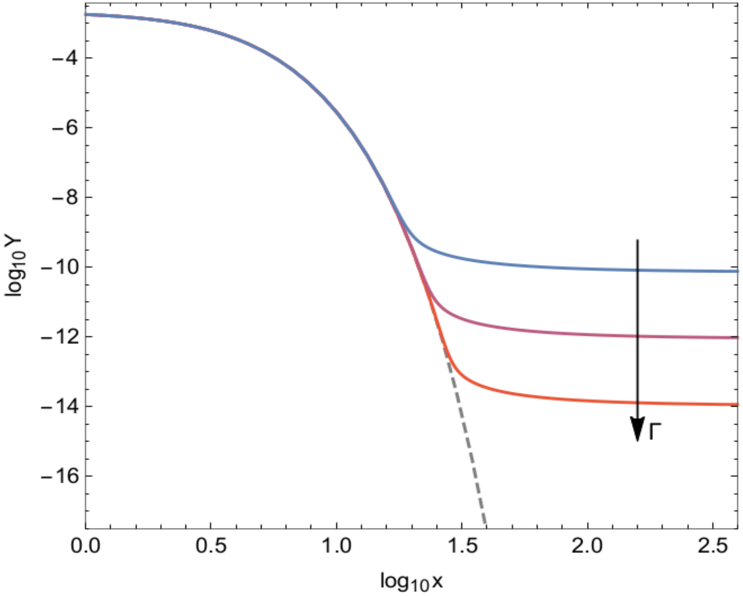


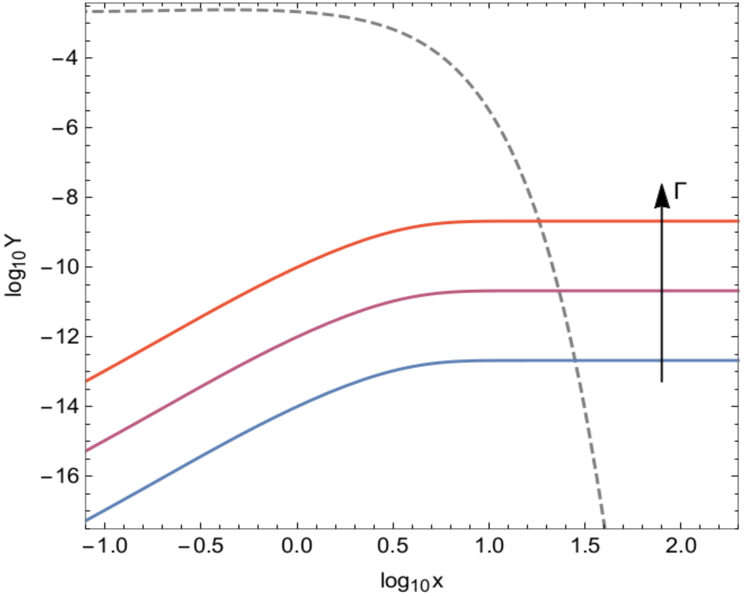


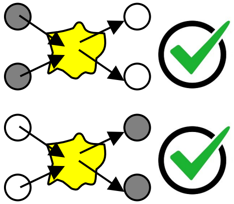


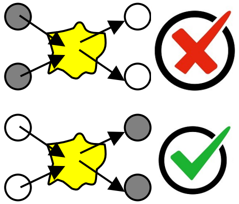
WIMP vs FIMP Dark Matter

$$\frac{dn_\chi}{dt} + 3\,H\,n_\chi = -\langle v\sigma_\chi\rangle\left[n_\chi^2 - (n_\chi^{\rm eq})^2\right]$$









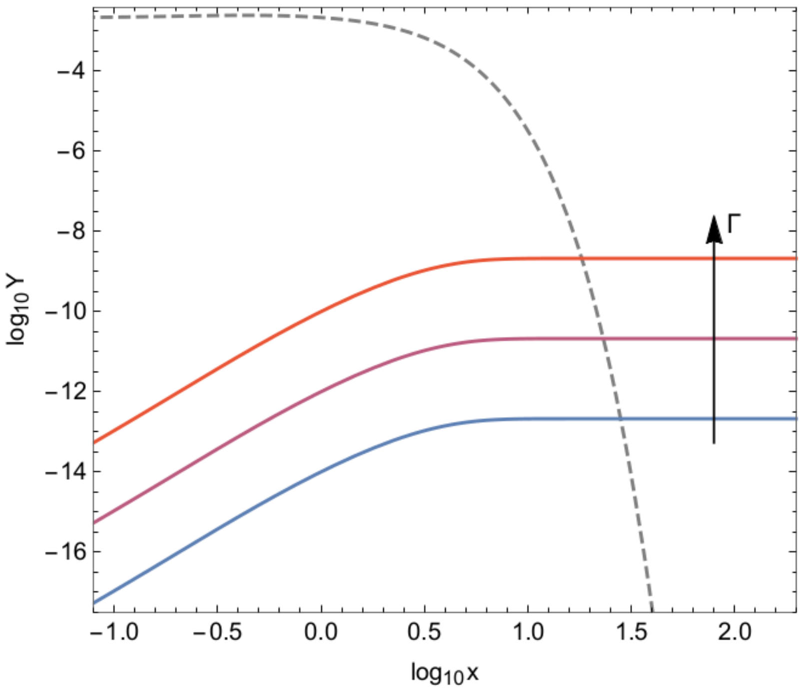
FIMP Dark Matter

$$\frac{dn_\chi}{dt} + 3\,H\,n_\chi = -\langle v\sigma_\chi\rangle\left[\cancel{n_\chi^2} - (n_\chi^{\rm eq})^2\right]$$

FIMP DM typically requires:

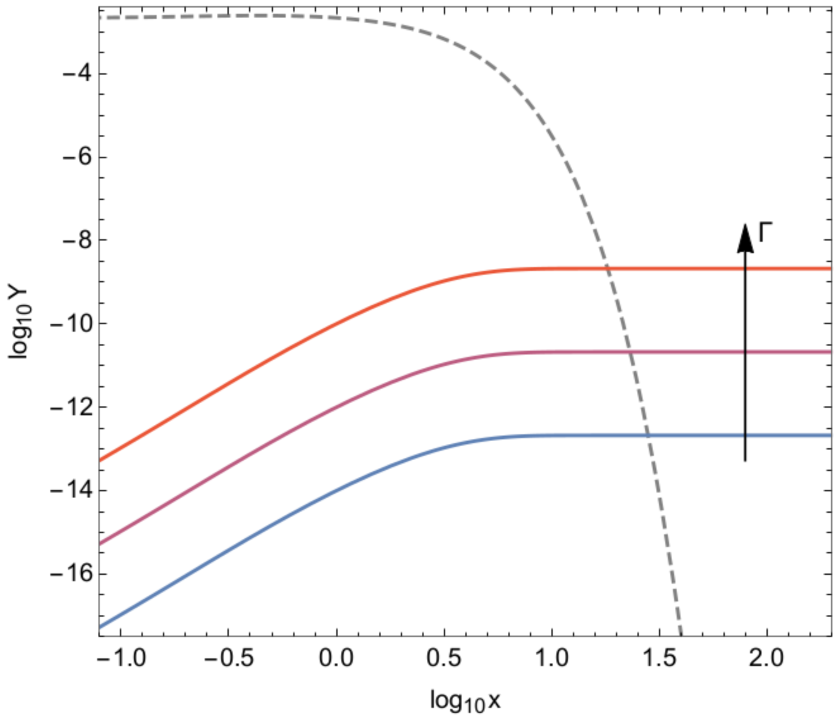
* Very suppressed DM-SM interaction rates
to avoid thermalization between
the dark and the visible sectors
* masses > keV (!)
* Usually *assumed* a dark sector
with a negligible initial population

→ Dependent of initial conditions!

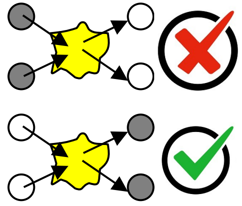


2a. Infrared FIMPs
Feebly Interacting Massive Particles

IR FIMP paradigm



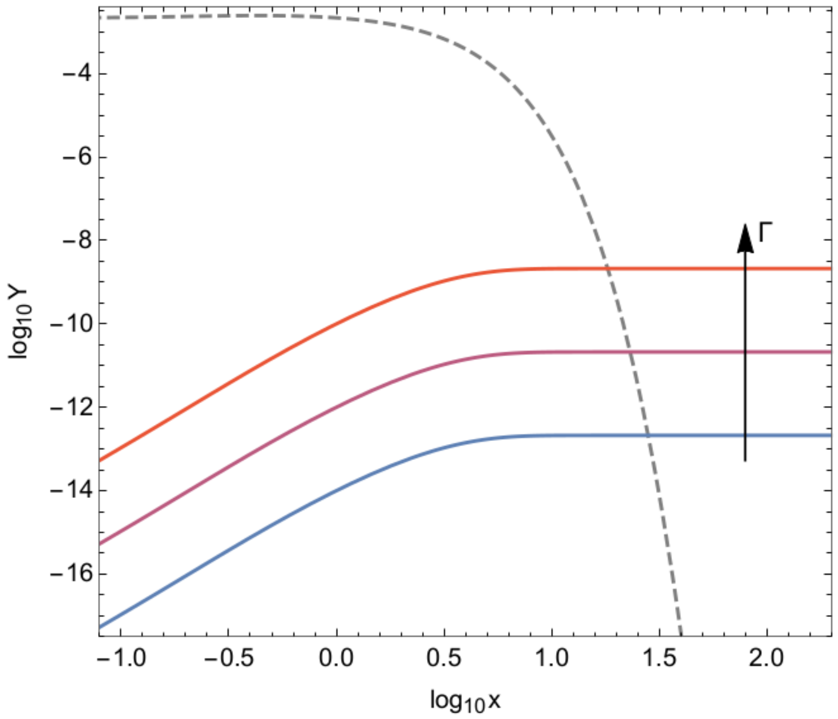
$$\frac{dn}{dt} + 3\,H\,n = -\langle\sigma v\rangle\left(\cancel{n^2} - n_{\rm eq}^2\right)$$



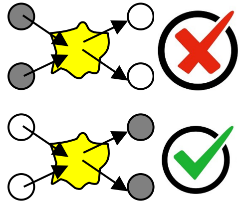
* chemical equilibrium never reached
* **renormalizable** operators
* masses: keV to $\sim M_{\rm P}$
* $\lambda_{\text{DM-SM}} \sim 10^{-11}$
* $T_{\rm fi} \sim m$

→ (mild) dependence from initial conditions

IR FIMP paradigm



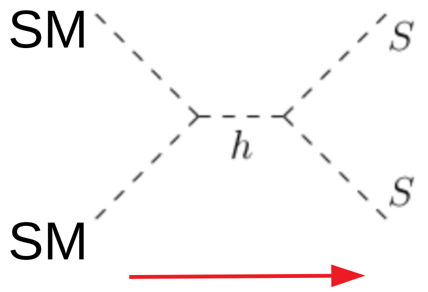
$$\frac{dn}{dt} + 3\,H\,n = -\langle\sigma v\rangle\left(\cancel{n^2} - n_{\rm eq}^2\right)$$

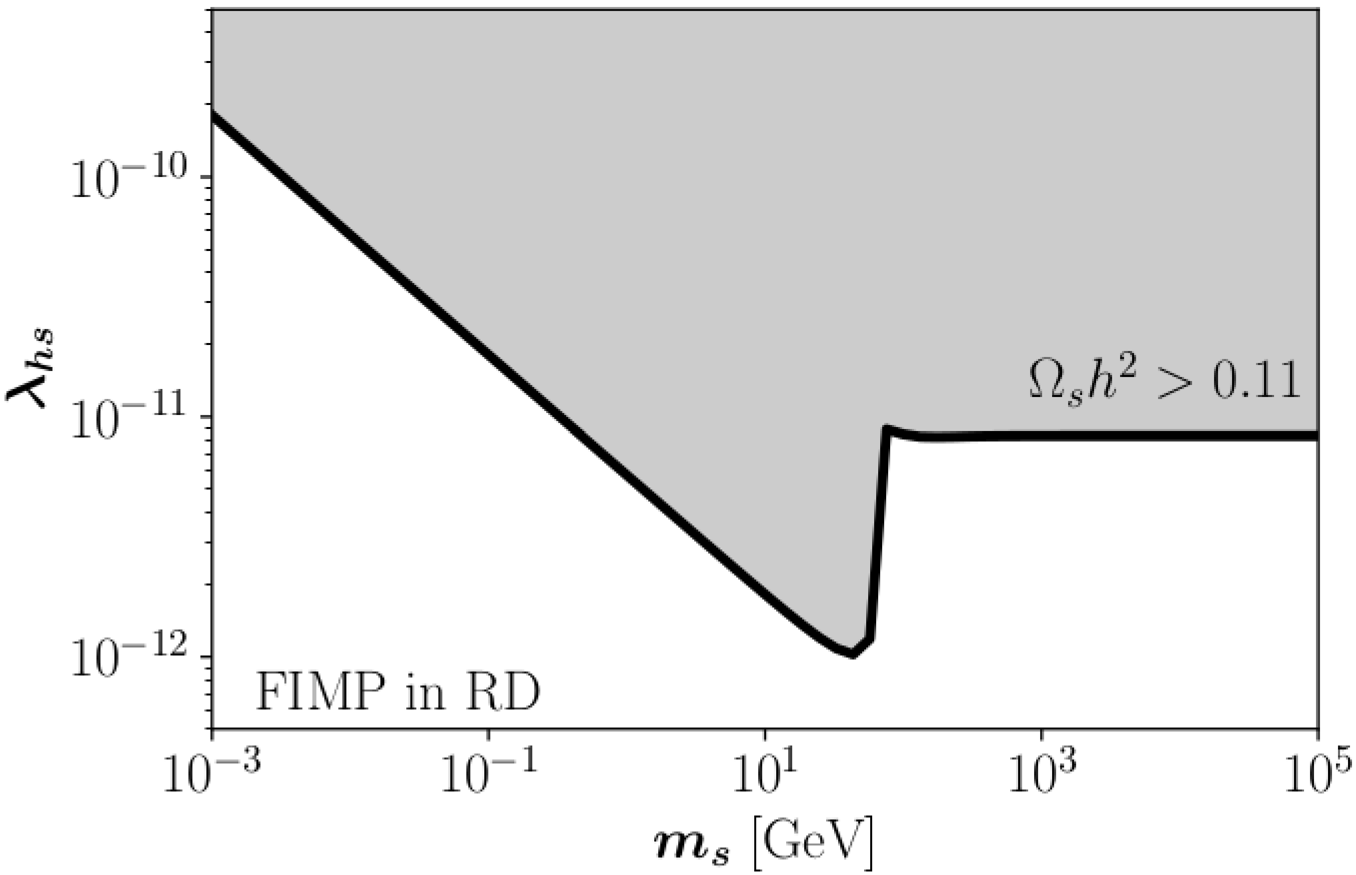


* chemical equilibrium never reached
* **renormalizable** operators
* masses: keV to ~M_P
* $\lambda_{\text{DM-SM}} \sim 10^{-11}$ ← "Unnaturally" small… but could be *technically natural*!
* $T_{\rm fi} \sim m$

→ (mild) dependence from initial conditions

Singlet Scalar DM - FIMP

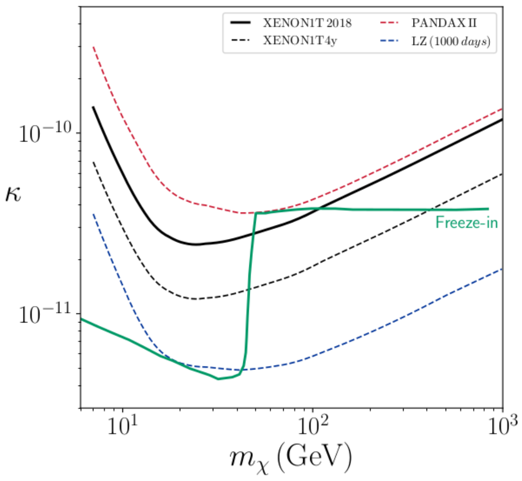




Detecting FIMPs

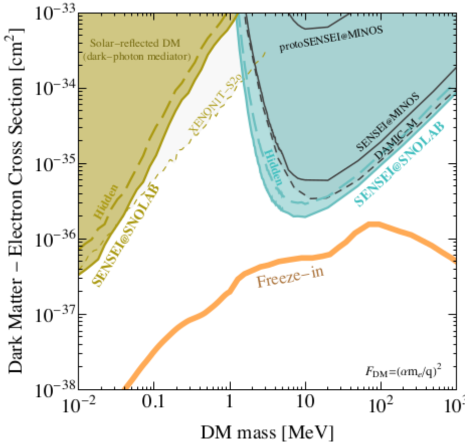
By construction, very challenging to test...

Hambye+ '18



Light mediators

Sensei '23

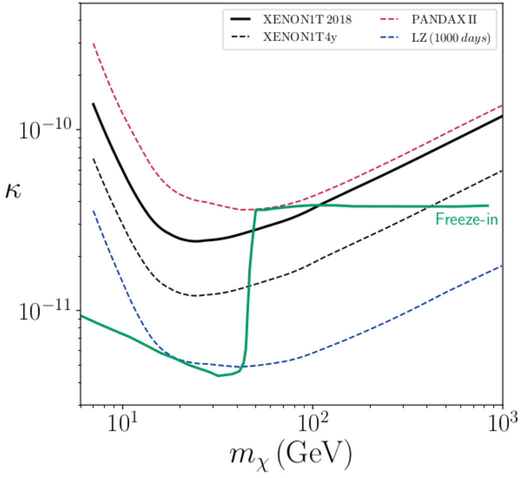


MeV dark matter

Detecting FIMPs

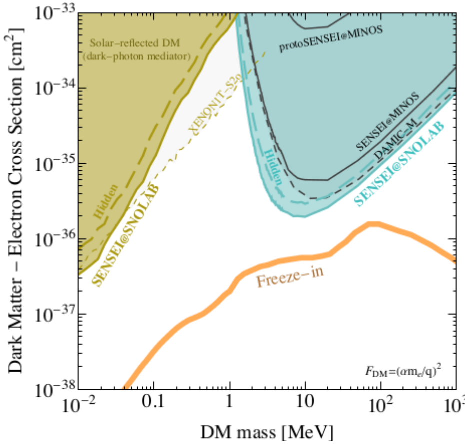
By construction, very challenging to test...

Hambye+ ‘18



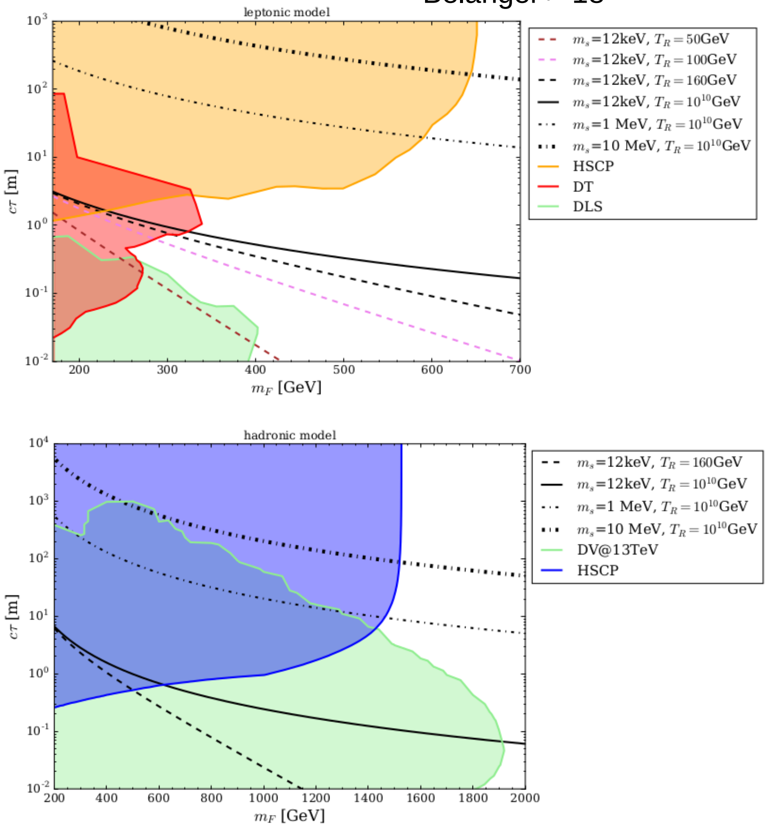
Light mediators

Sensei ‘23



MeV dark matter

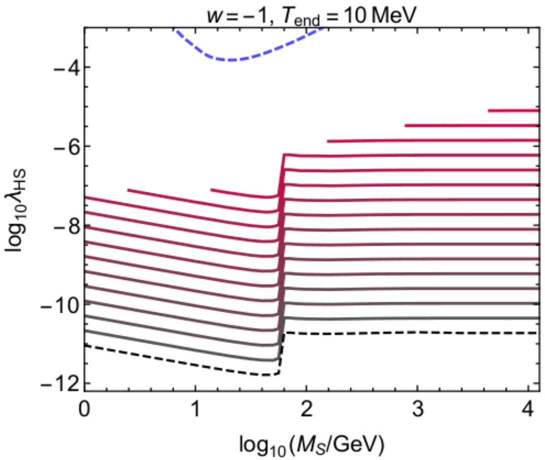
Bélanger+ ‘18

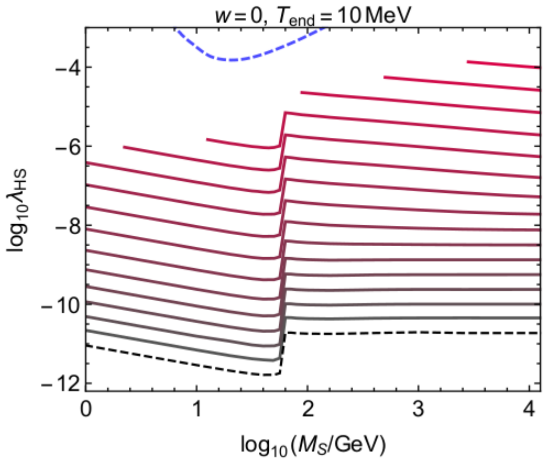


Nicolás BERNAL @ NYUAD

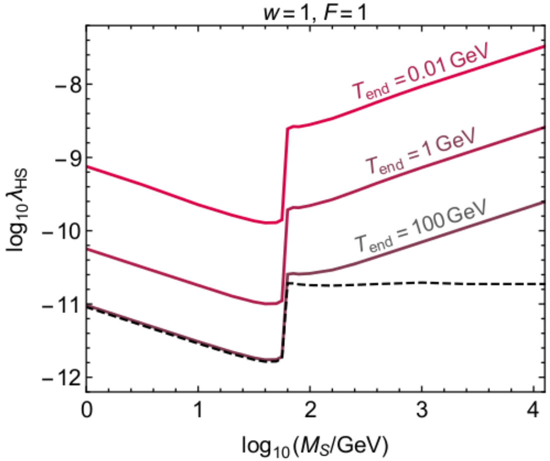
IR FIMPs in Non-standard Cosmologies

Singlet scalar
DM model



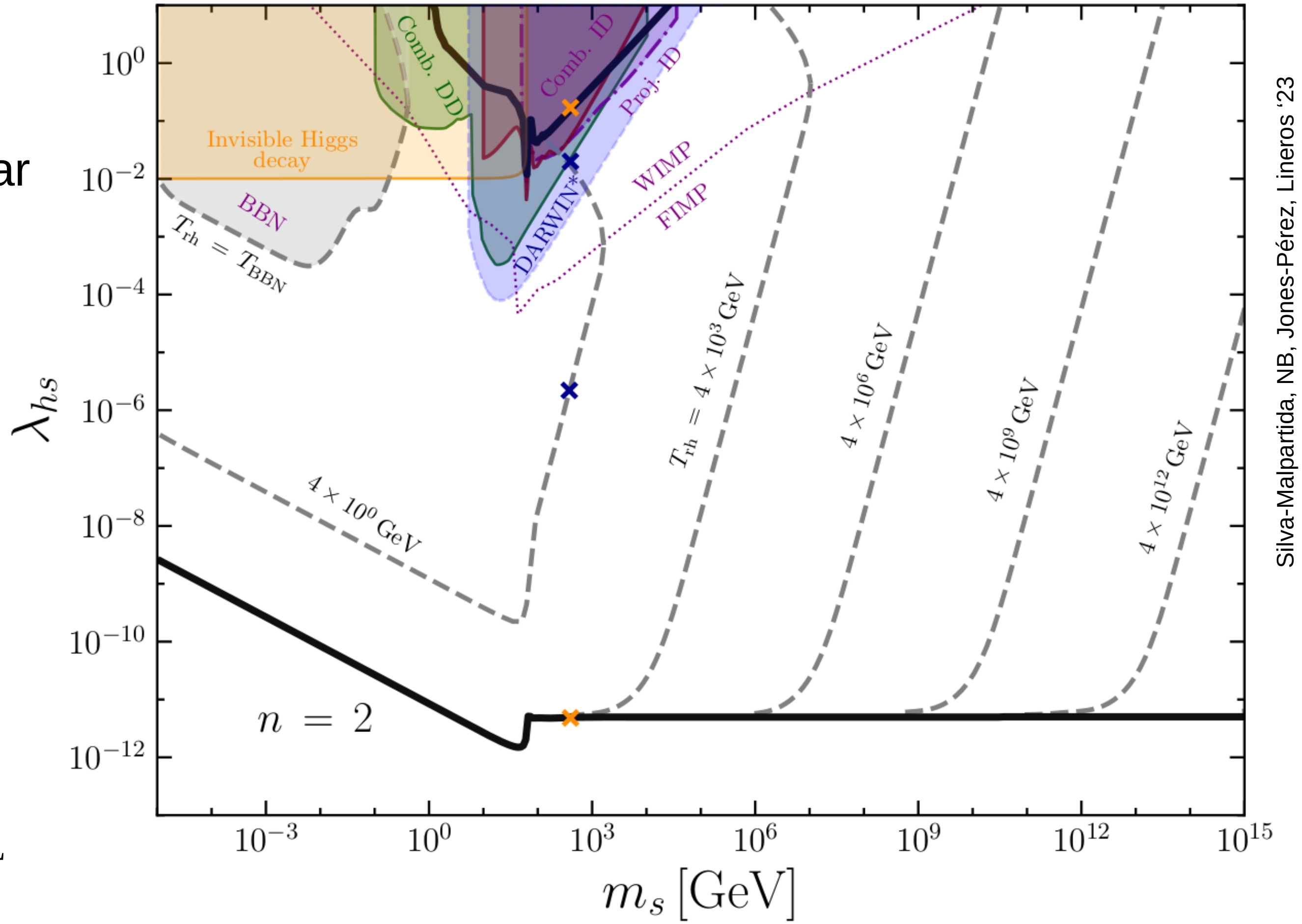


NB, Cosme, Tenkanen, Vaskonen ‘19



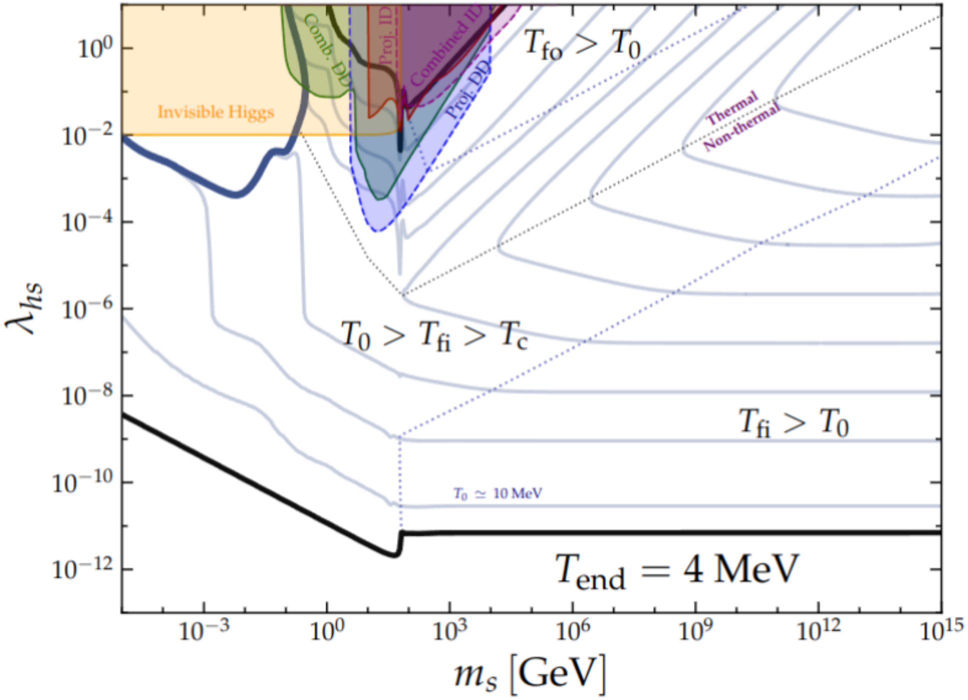
WIMPs and FIMPs with Low-temperature reheating

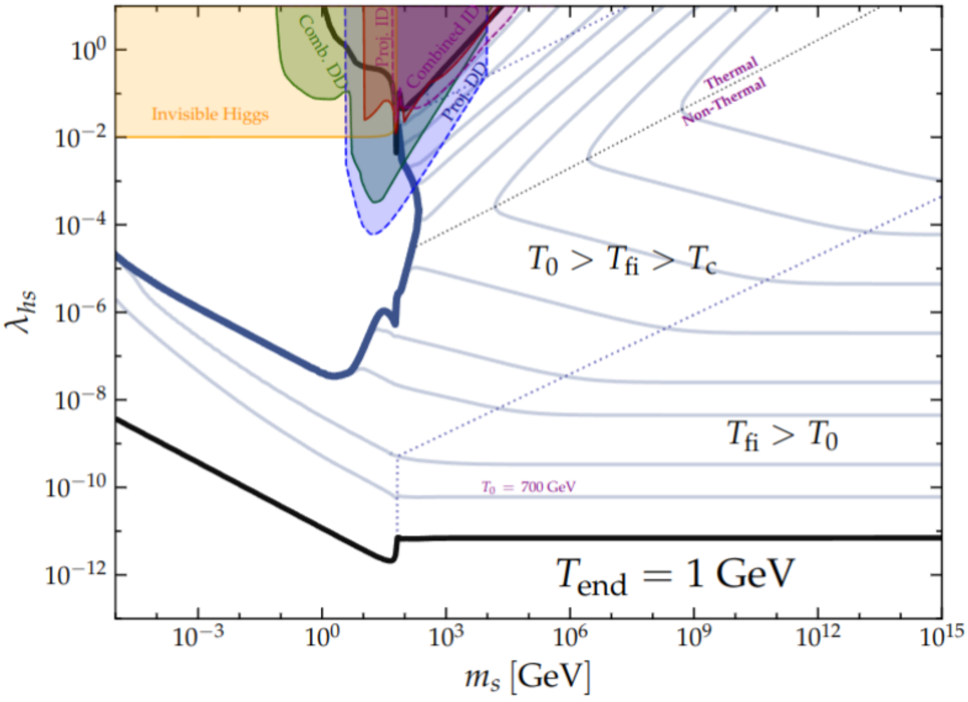
Singlet scalar DM model



Silva-Malpartida, NB, Jones-Pérez, Lineros '23

WIMPs and FIMPs in Non-standard Cosmologies



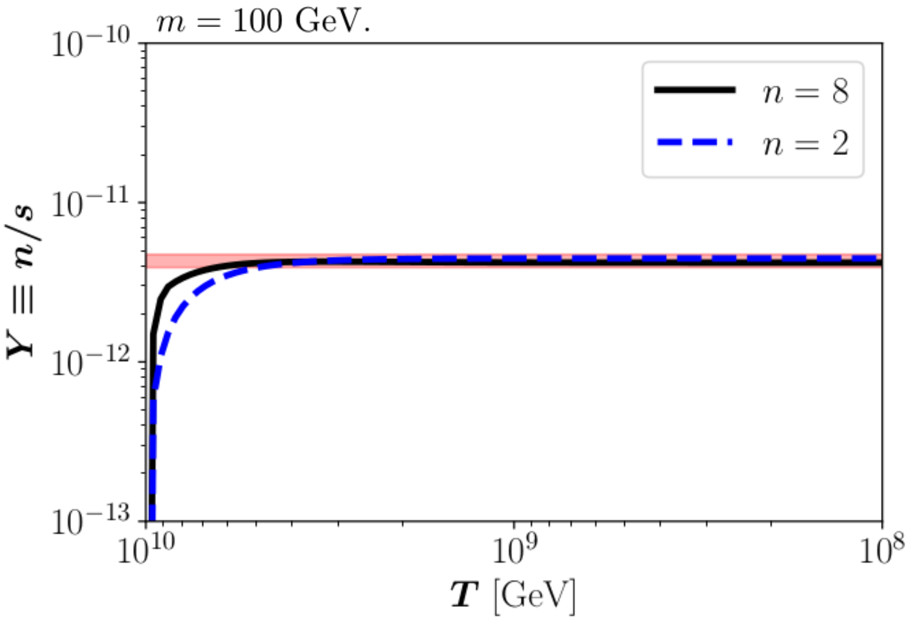


Silva-Malpartida, NB, Jones-Pérez, Lineros, Soon!

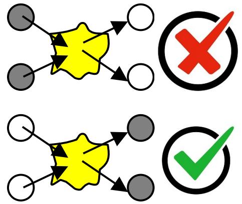
Singlet scalar
DM model

2b. Ultraviolet FIMPs
Feebly Interacting Massive Particles

UV FIMP paradigm



$$\frac{dn}{dt} + 3\,H\,n = -\langle\sigma v\rangle\left(\cancel{n^2} - n_{\rm eq}^2\right)$$

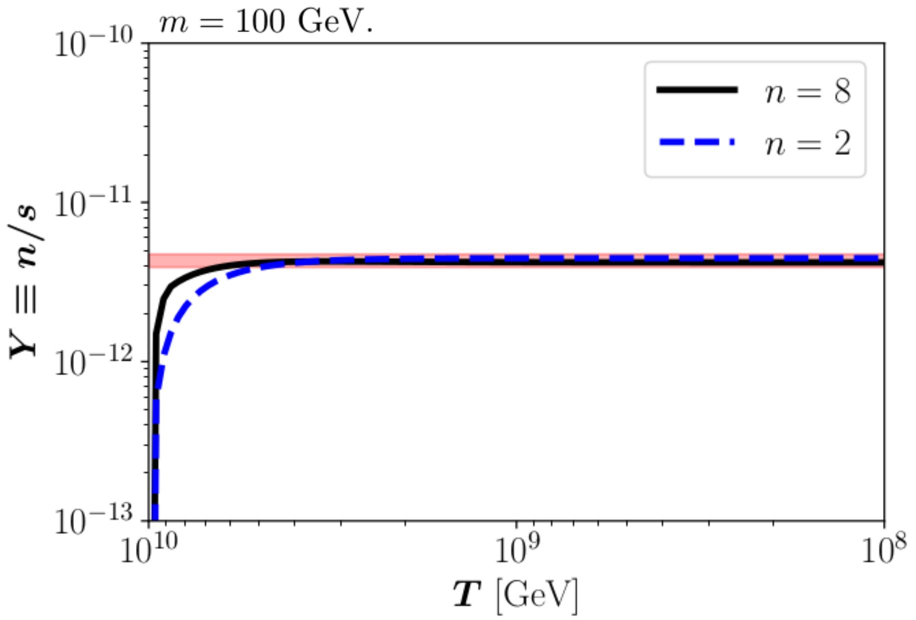


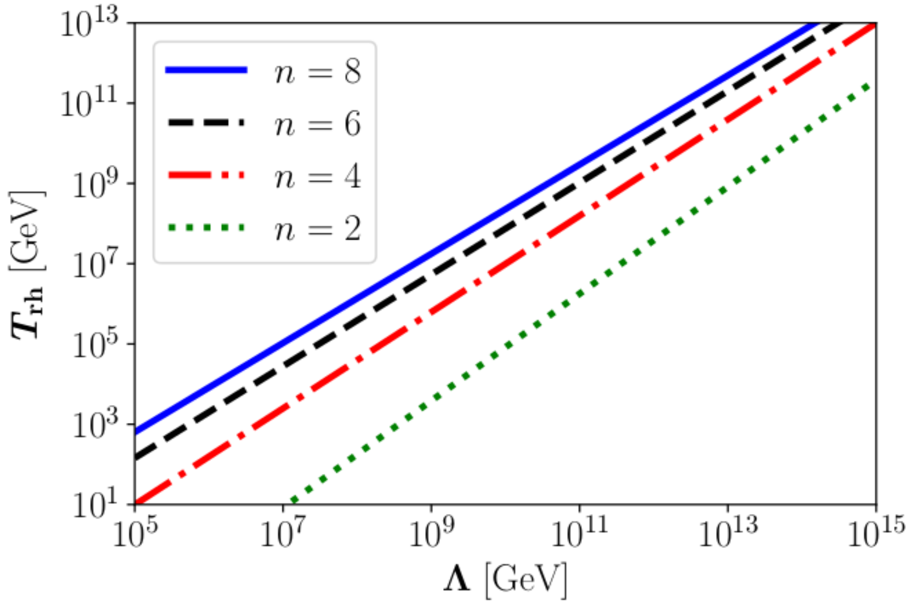
* chemical equilibrium never reached
* ***non*-renormalizable** operators
* masses: keV to ~$M_{\rm P}$
* $\Lambda > T_{\rm rh}$
* $T_{\rm fi} \sim T_{\rm rh}$

$$\langle\sigma v\rangle = \frac{T^n}{\Lambda^{2+n}}$$

→ (strong) dependence from initial conditions

UV FIMP paradigm





$$\langle \sigma v \rangle = \frac{T^n}{\Lambda^{2+n}}$$

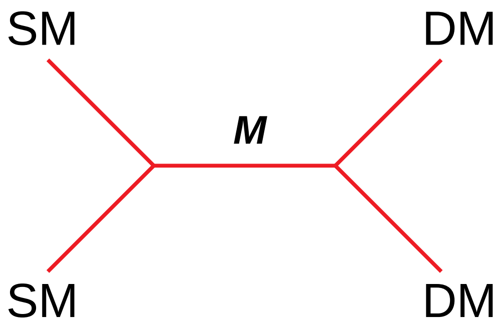
$$Y \sim \int_0^{T_{\rm RH}} \frac{M_{\rm Pl}\, T^n}{\Lambda^{n+2}} \sim \frac{M_{\rm Pl}\, T_{\rm RH}^{n+1}}{\Lambda^{n+2}}$$

UV FIMP paradigm

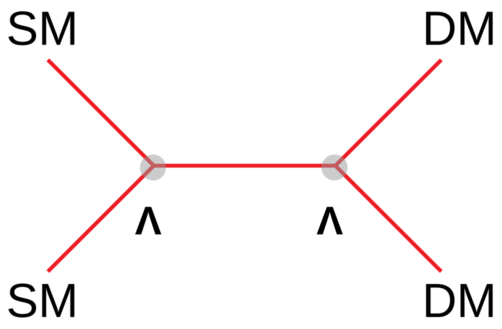
$$\langle \sigma v \rangle = \frac{T^n}{\Lambda^{2+n}}$$

- **Heavy mediator** (*M* >> T_{rh})

$$\langle \sigma v \rangle \propto g^4 \frac{T^2}{M^4}$$



UV FIMP paradigm $\langle \sigma v \rangle = \frac{T^n}{\Lambda^{2+n}}$



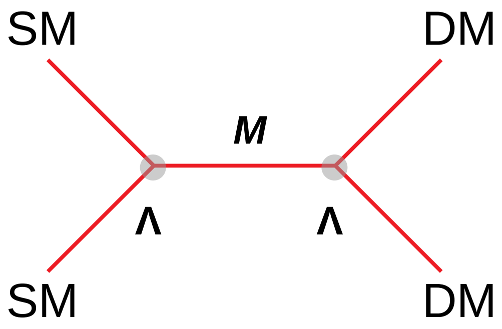
- **Heavy mediator** ($M >> T_{rh}$)

$$\langle \sigma v \rangle \propto g^4 \frac{T^2}{M^4}$$

- **Suppressed couplings** ($\Lambda >> T_{rh}$)

$$\langle \sigma v \rangle \propto \frac{T^2}{\Lambda^4}$$

UV FIMP paradigm $\langle \sigma v \rangle = \frac{T^n}{\Lambda^{2+n}}$



- **Heavy mediator** (M >> T_{rh})

$$\langle \sigma v \rangle \propto g^4 \frac{T^2}{M^4}$$

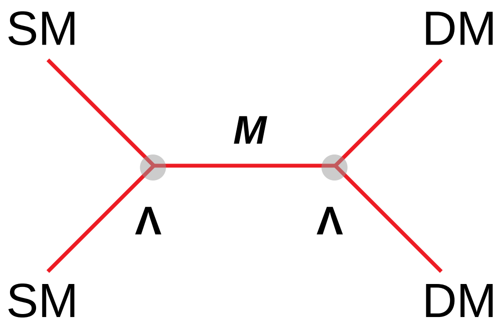
- **Suppressed couplings** (Λ >> T_{rh})

$$\langle \sigma v \rangle \propto \frac{T^2}{\Lambda^4}$$

- **Heavy mediator + suppressed couplings** (M, Λ >> T_{rh})

$$\langle \sigma v \rangle \propto \frac{T^6}{\Lambda^4 M^4}$$

UV FIMP paradigm $\langle \sigma v \rangle = \frac{T^n}{\Lambda^{2+n}}$



- **Heavy mediator** ($M >> T_{rh}$)

$$\langle \sigma v \rangle \propto g^4 \frac{T^2}{M^4}$$

- **Suppressed couplings** ($\Lambda >> T_{rh}$)

$$\langle \sigma v \rangle \propto \frac{T^2}{\Lambda^4}$$

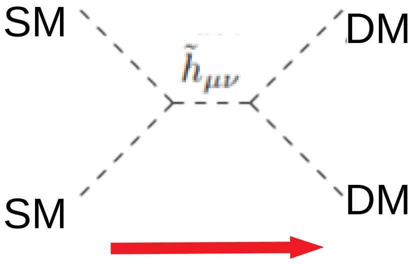
← **Gravitational UV freeze-in**

- **Heavy mediator + suppressed couplings** (M, $\Lambda >> T_{rh}$)

$$\langle \sigma v \rangle \propto \frac{T^6}{\Lambda^4 M^4}$$

Gravitational FIMPs

An example of UV FIMP, mediated by massless SM gravitons

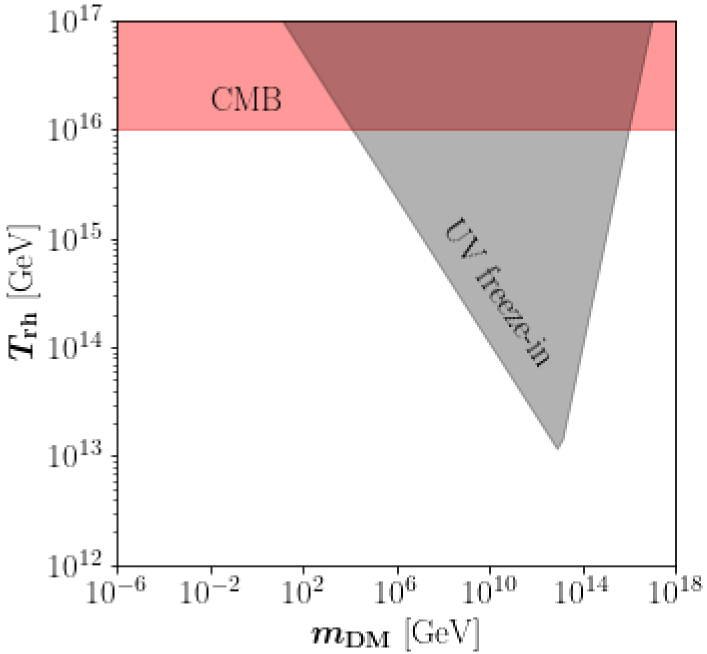


$$\langle \sigma v \rangle = \alpha_{\rm DM} \frac{T^2}{M_P^4}$$

$$\frac{\Omega_{\rm DM} h^2}{0.12} \lesssim 4.2 \times 10^{-13}\, \alpha_{\rm DM} \frac{m_{\rm DM}}{1~{\rm GeV}} \left(\frac{T_{\rm rh}}{10^{12}~{\rm GeV}}\right)^3$$

Depends on:

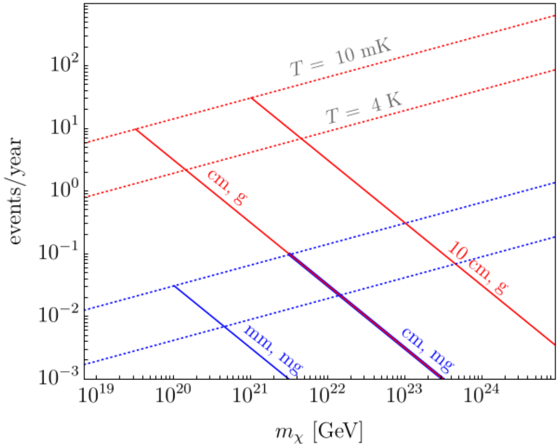
* DM mass and spin
* Reheating temperature
* No free couplings: M_P



Gravitational FIMPs

By construction, nightmare scenario to test!

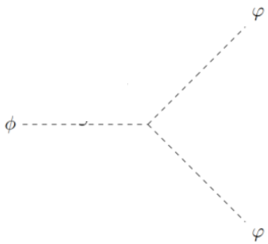
http://windchimeproject.org/
Carney, Ghosh, Krnjaic, Taylor ‘19



Entr'acte 2:
Testing reheating

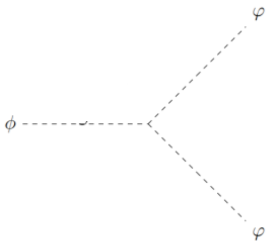
Probing Reheating with Graviton Bremsstrahlung

Inflaton decay

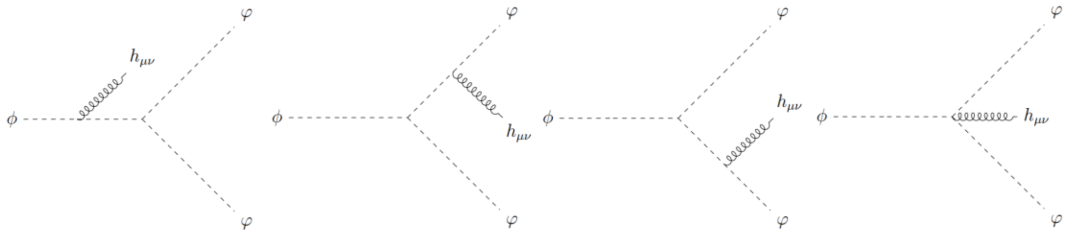


Probing Reheating with Graviton Bremsstrahlung

Inflaton decay



→



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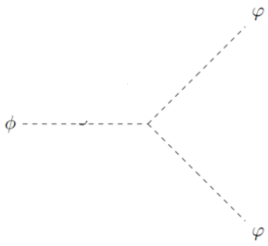
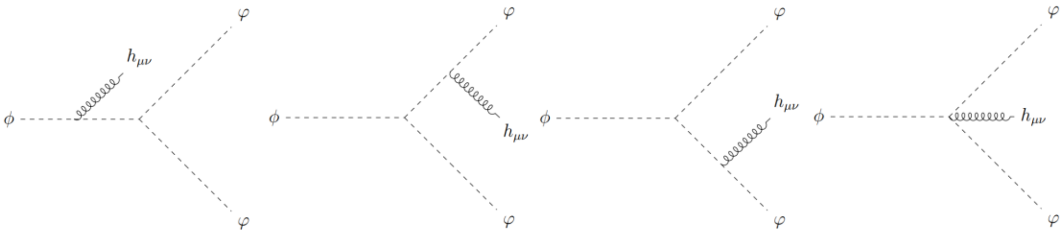
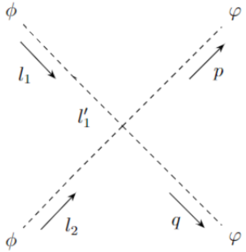


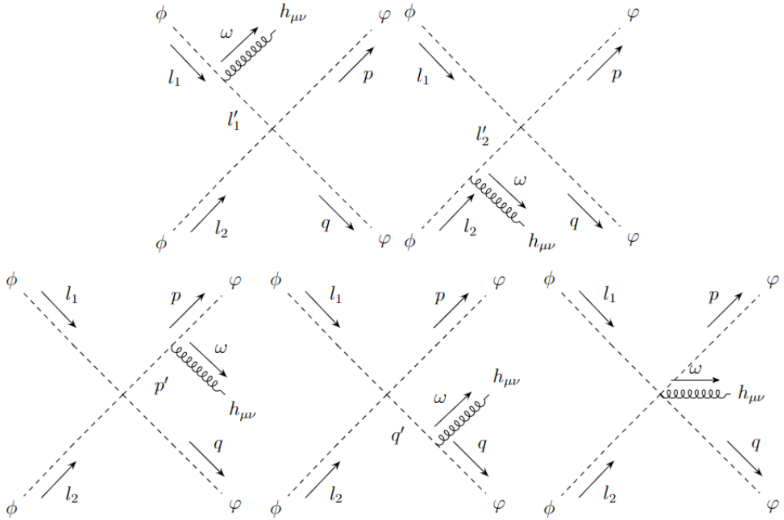
→



Inflaton annihilation



→



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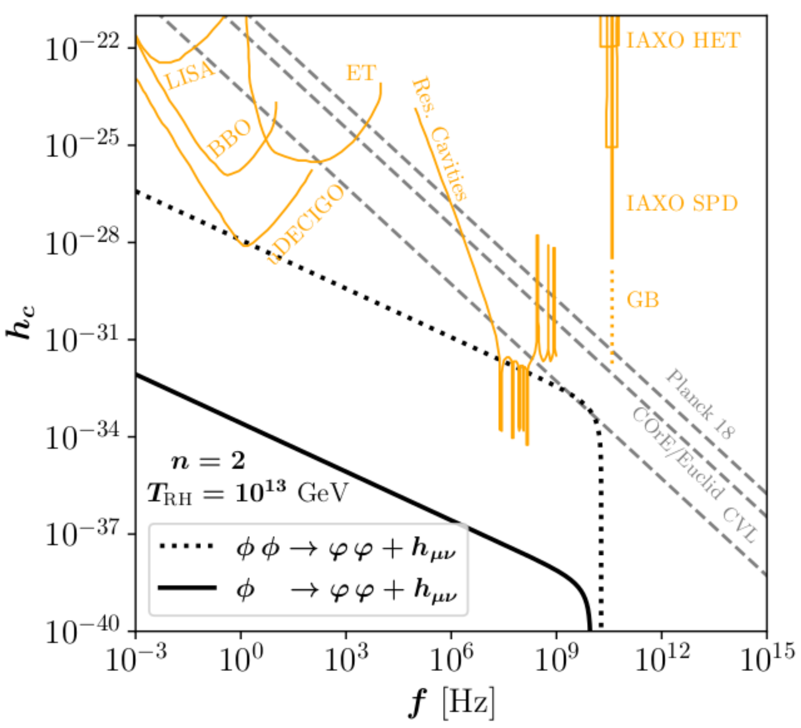
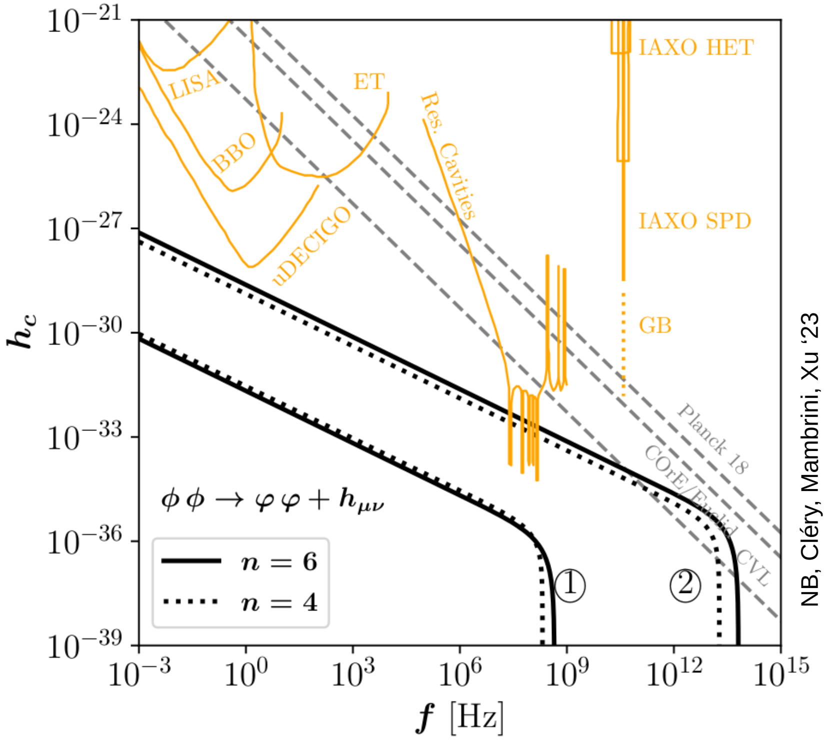




NB, Cléry, Mambrini, Xu ‘23

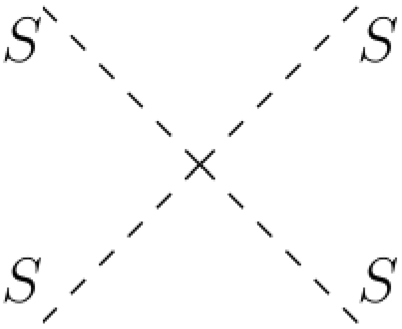
Entr'acte 2:
Testing reheating

What about possible DM self-interactions?

3. SIMP DM
Self-Interacting Massive Particle

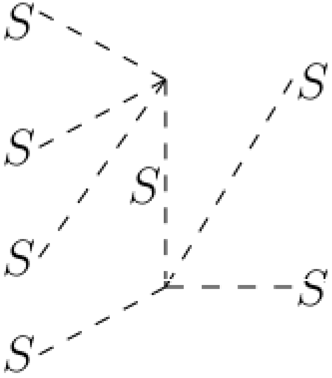
DM self-interactions

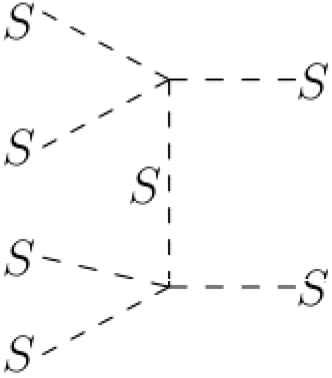
Elastic scattering



Kinetic equilibrium:
DM temperature

Number-changing interactions

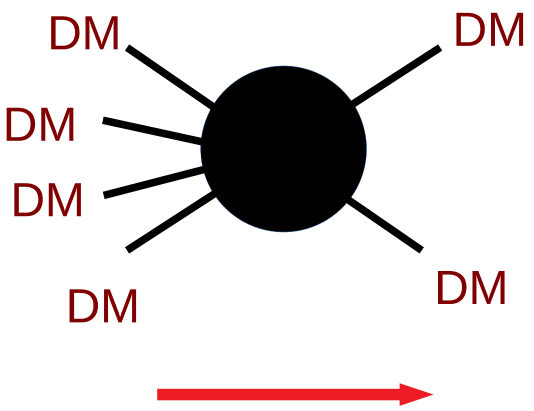




Chemical equilibrium:
$4 \to 2$ and $2 \to 4$

SIMP DM
4 → 2 annihilations

$$\frac{dn}{dt} + 3\,H\,n = -\langle\sigma v^3\rangle_{4\to 2}\,\left(n^4 - n^2\,n_{\rm eq}^2\right)$$



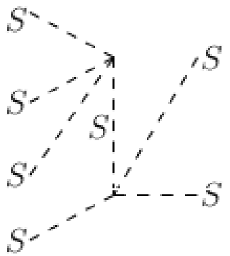
A Z_2 symmetry forbids 3 → 2 annihilations...
but allows 4 → 2 annihilations!

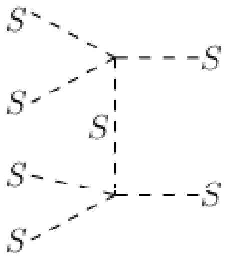
Could be the dominant channel if
the SM-DM portal is very suppressed…

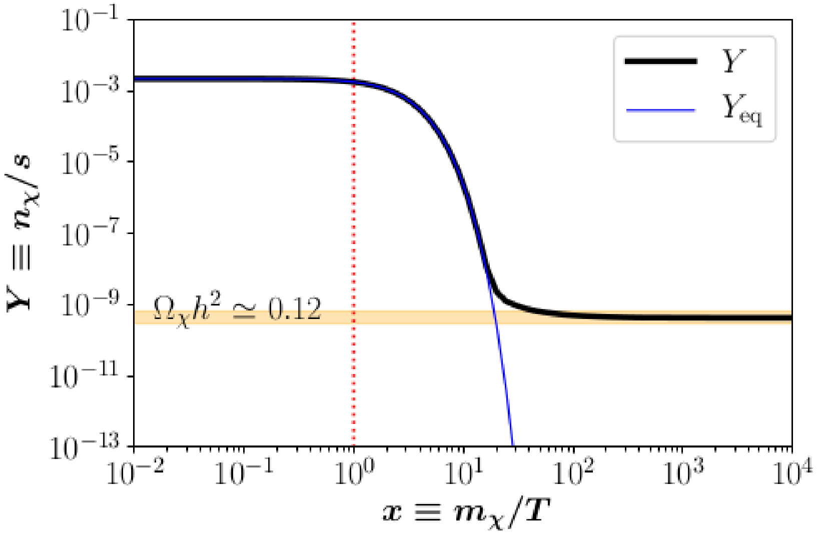
… like in the FIMP scenario!

Singlet Scalar DM
$4 \to 2$ annihilations

$$\frac{dn}{dt} + 3\,H\,n = -\langle \sigma v^3 \rangle_{4\to 2}\,\left(n^4 - n^2\,n_{\rm eq}^2\right)$$







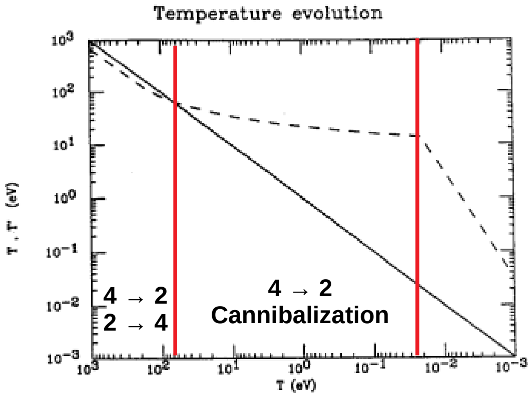
$$\langle \sigma v^3 \rangle_{4\to 2} \sim \frac{27\sqrt{3}}{8\pi}\,\frac{\lambda_S^4}{m_S^8}$$

Self-interacting DM

Self-interacting dark matter

Eric D. Carlson (Harvard U.), Marie E. Machacek (Northeastern U.), Lawrence J. Hall (UC, Berkeley and LBL, Berkeley)

Published in: *Astrophys.J.* 398 (1992) 43-52



Perturbativity implies
$m \sim O(100)$ eV

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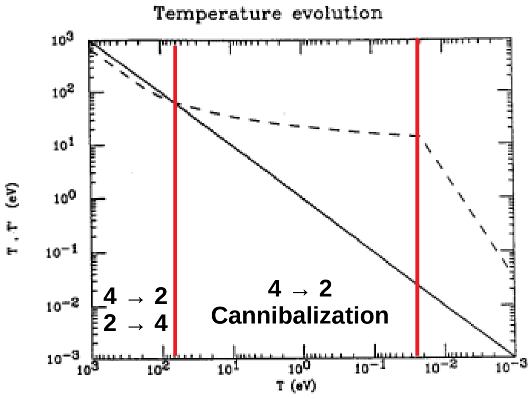


Perturbativity implies
$m \sim O(100)$ eV

* Avoid increase of temperature
→ SIMP DM

Hochberg, Kuflik, Volansky, Wacker ‘14
NB, Garcia-Cely, Rosenfeld ‘15

* Control the increase of temperature
→ ELDER DM

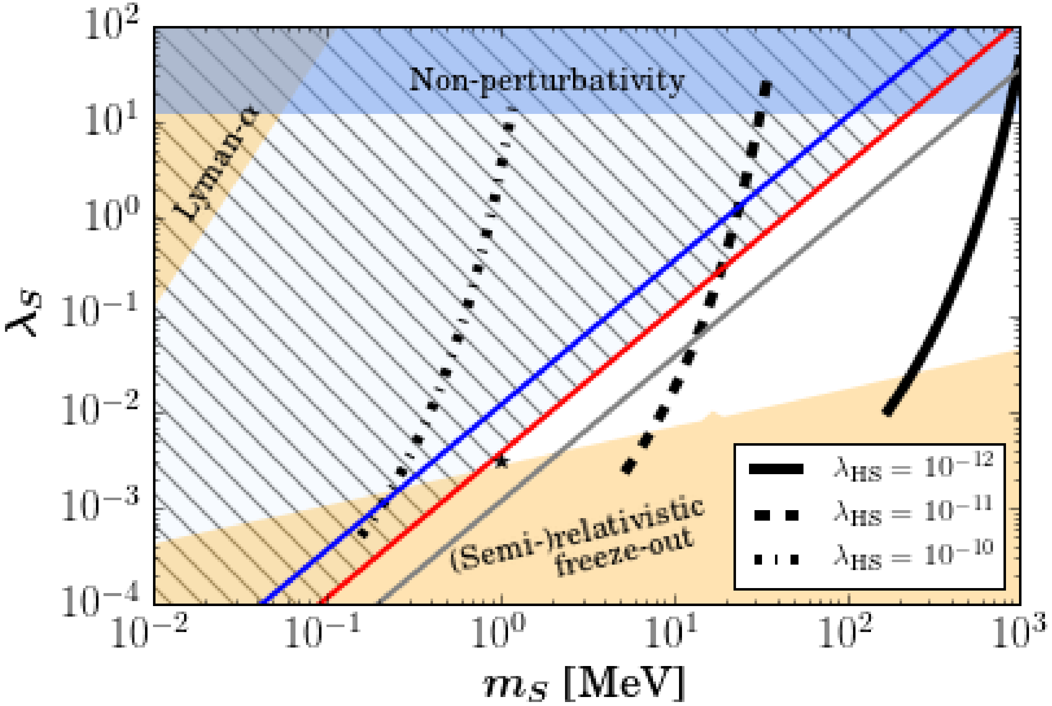
Kuflik, Perelstein, Rey-Le Lorier, Tsai ‘15

* Start with a colder dark sector

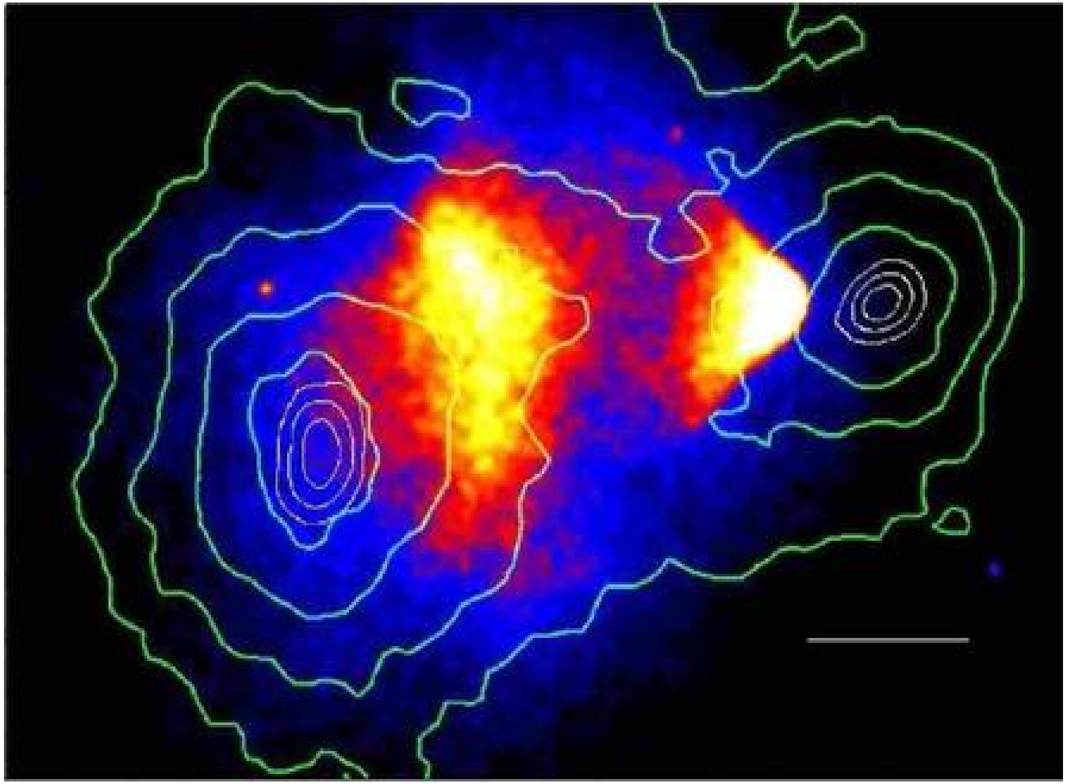
NB, Chu ‘15
NB, Chu, Garcia-Cely, Hambye, Zaldivar ‘15

$m \sim O(\text{MeV})$

Singlet Scalar DM
Dark Freeze-out via a FIMP mechanism

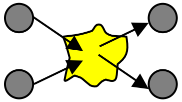


Detecting SIMPs



Very challenging to test

→ **Look at the sky!**
* Bullet cluster
* “missing satellites”
* “too-big-to-fail”
* “cusp vs core”



Conclusions & Outlook

- Dark Matter exists
- The nature of Dark Matter is still unknown
- Understanding Dark Matter is one of the major problems in particle physics
- WIMP paradigm is by far the favorite scenario ← **huge** prejudice!
- Many other mechanisms on the market:

  FIMPs, SIMPs, QCD axions, ALPs

  non-standard cosmologies & low-temperature reheating

  PBHs...
- Collaboration between complementary areas:
  particle physics, astroparticle physics, cosmology, astrophysics, instrumentation...
- Continue searches for WIMPs, FIMPs, and other DM candidates

  (Colliders, direct and indirect detection, astro + cosmo…)

Gracias ve!