Dark Matter beyond WIMPs

Nicolás BERNAL

جامعة نيويورك أبوظبي

NYU ABU DHABI

CPT & CPPM, Marseille

March 11th, 2024

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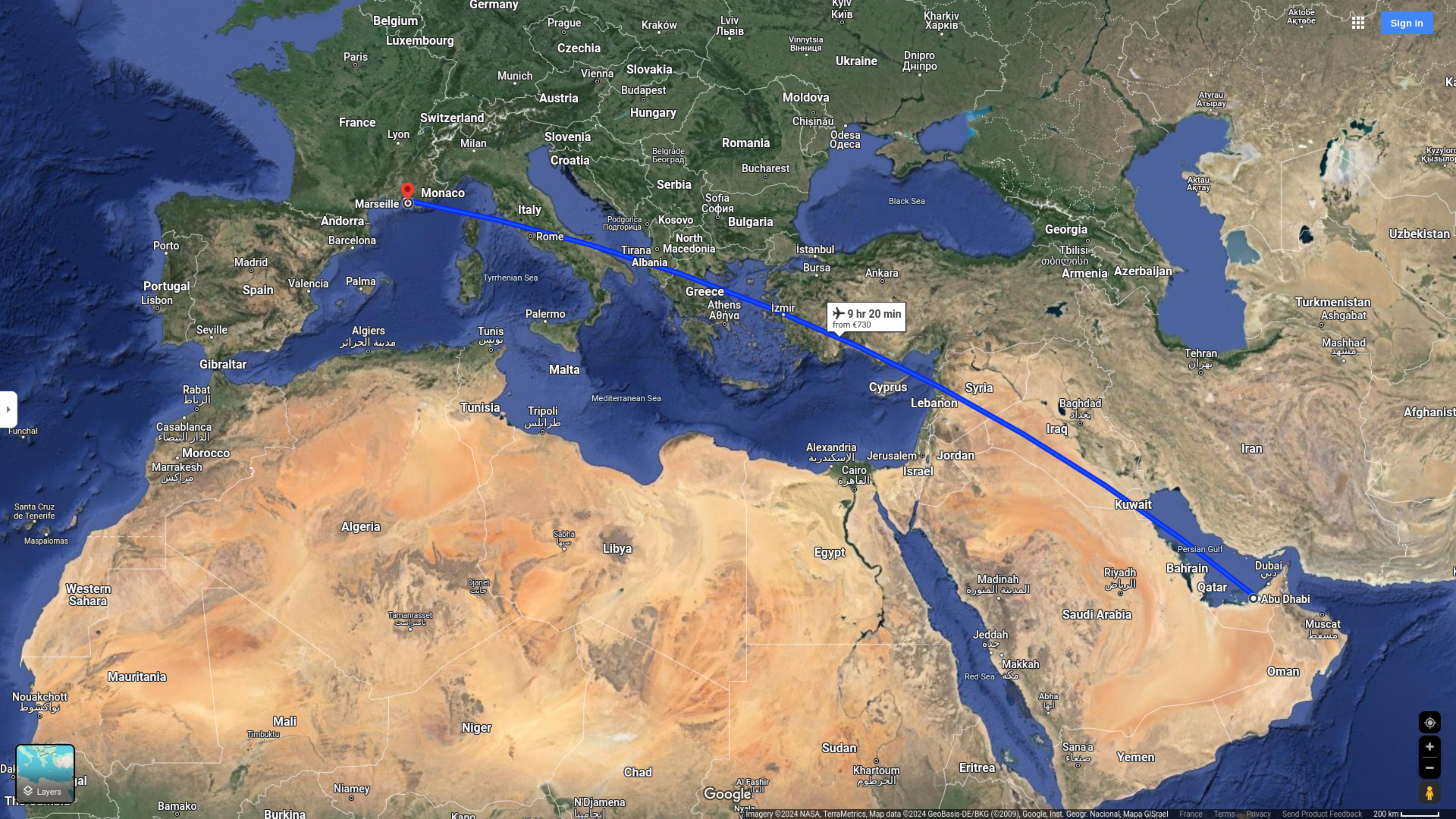
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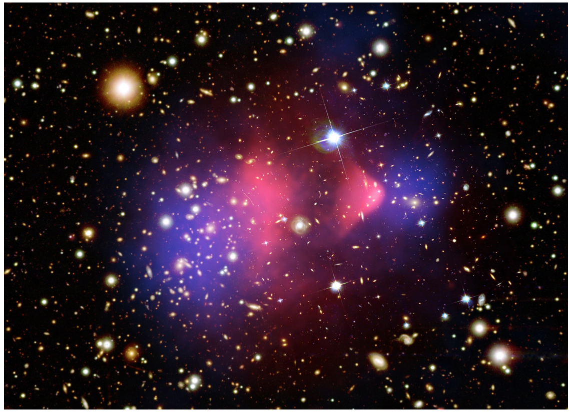
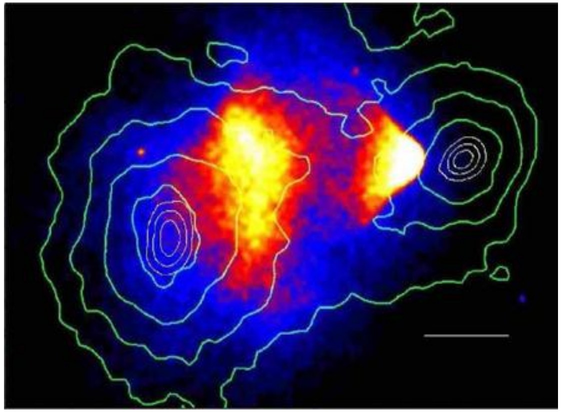
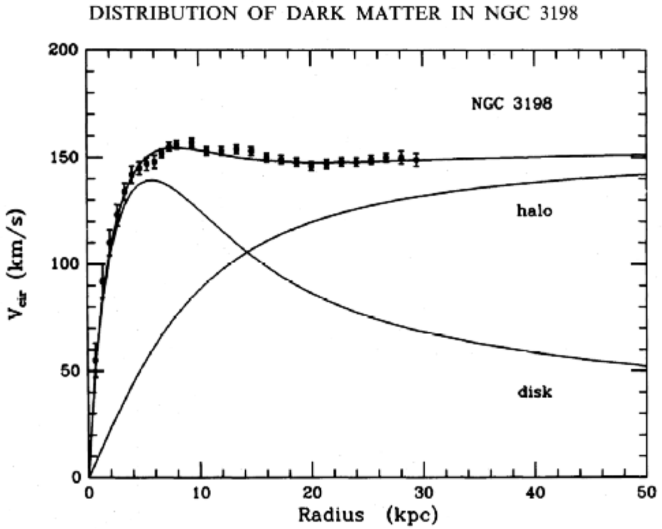
Evidences for Dark Matter

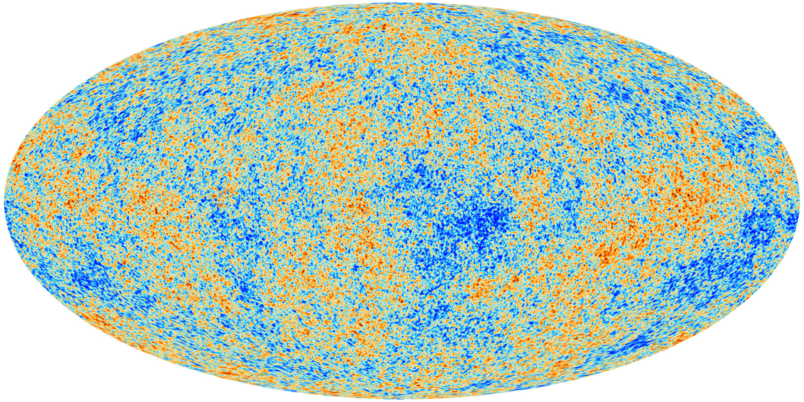
Several observations indicate the existence of non-luminous Dark Matter (*missing gravitational force*) at very different scales!

* Galactic rotation curves
* RC in Clusters of galaxies
* Clusters of galaxies
* CMB anisotropies









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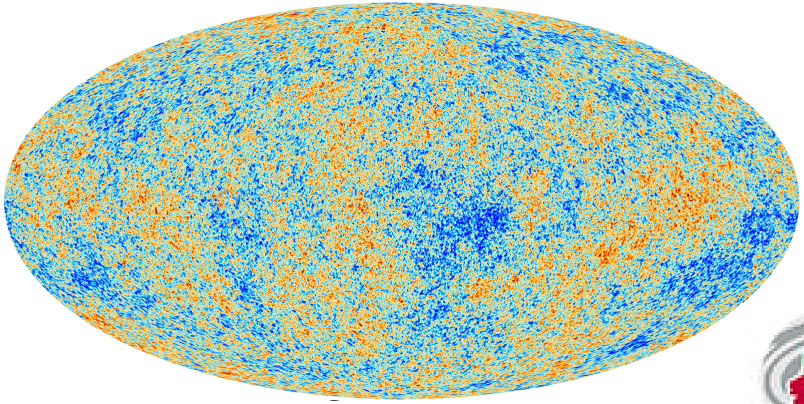

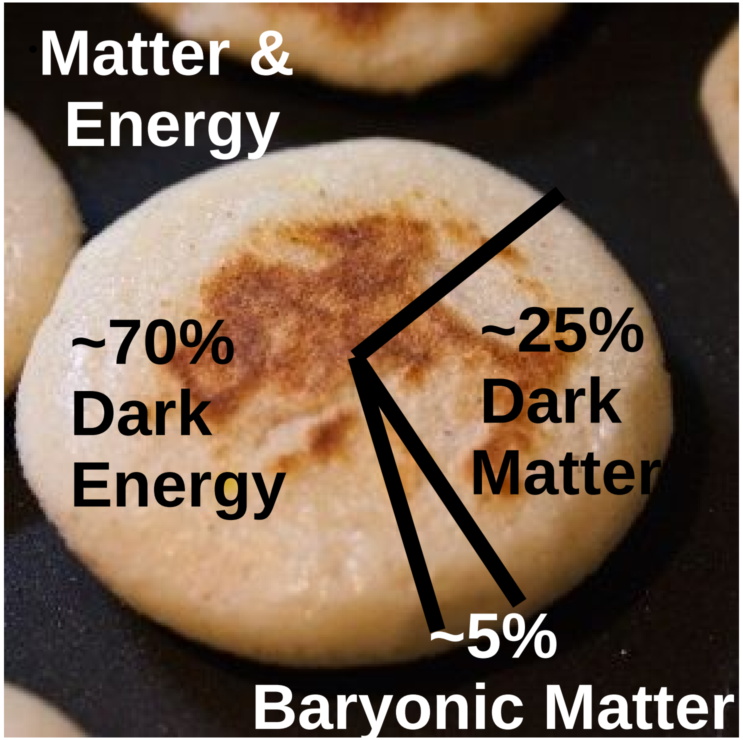

Evidences for Dark Matter

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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

Evidences for Dark Matter

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

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Dark Matter needs New Physics beyond the Standard Model!

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Place Général de Gaulle

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ARTISTIQUE & SCIENTIFIQUE

LA SCIENCE TAILLE XX ELLES

Aoife Bharucha
Physicienne

Toucher l'intouchable, saisir l'insaisissable

cnrs

FEMMES & SCIENCES association

What is the Dark Matter?

What is the Dark Matter?

How was Dark Matter produced in the Early Universe?

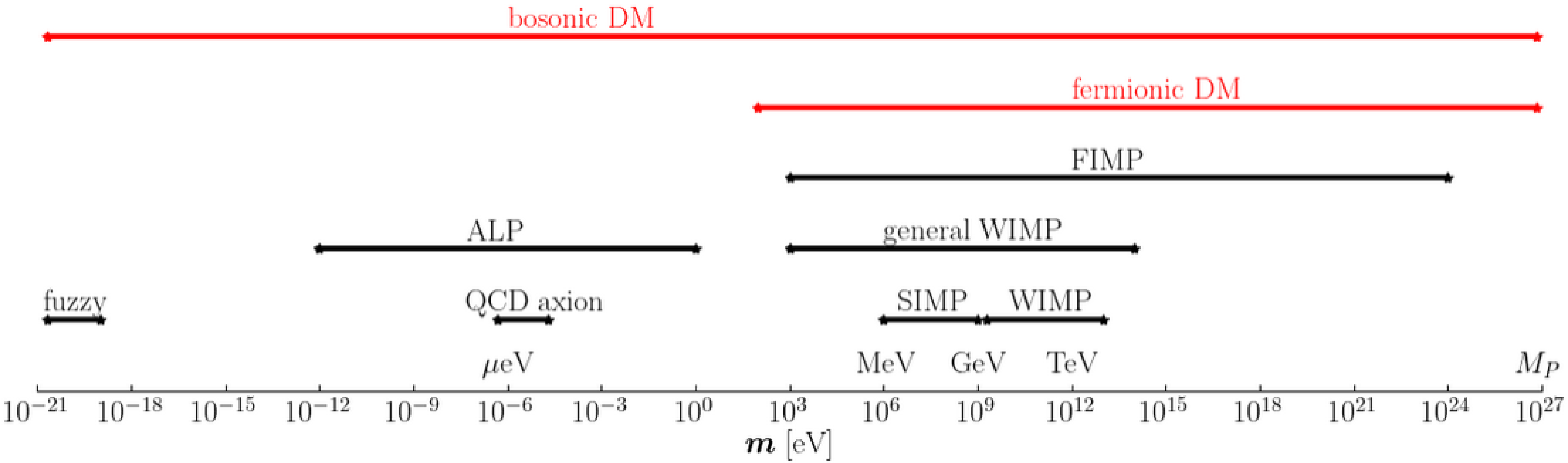
How was Dark Matter produced in the Early Universe?

WIMP

Cannibal FIMP SIMP Axion WISP ALP MACHO PBHs

Asymmetric DM ELDER Non-thermal DM Composite DM

Dark Matter Mass



Menu of the Day

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

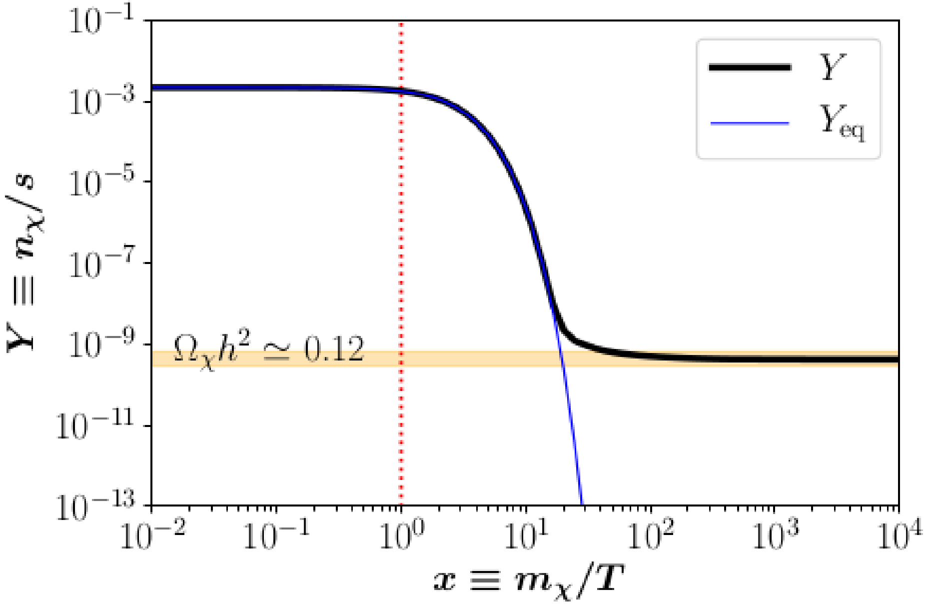
\+ Entr’acte 2: Testing reheating

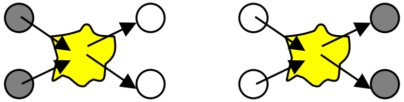
3. **SIMP** DM
   Self-interacting Massive Particles

1. WIMP DM
Weakly Interacting Massive Particle

WIMP Dark Matter

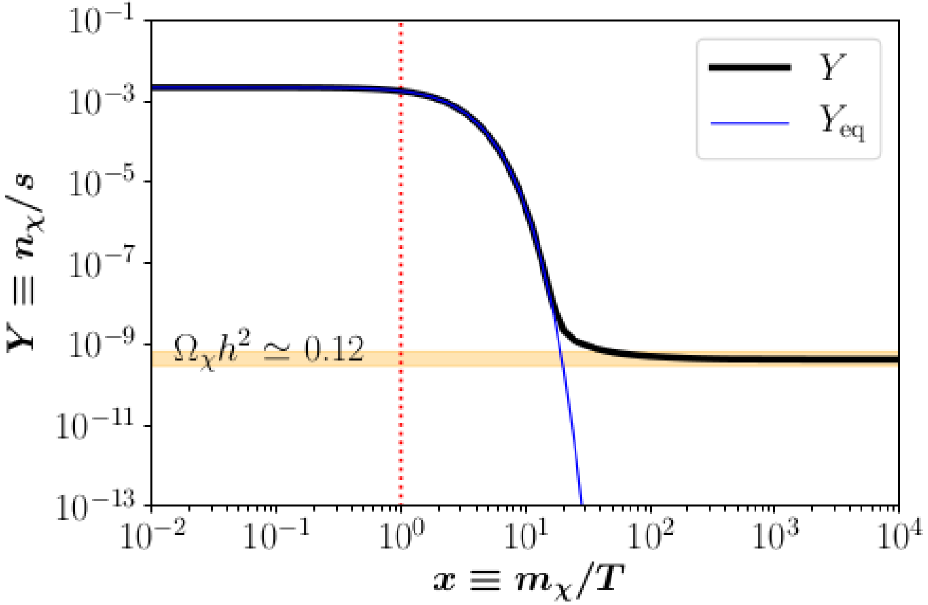
$$\frac{dn_\chi}{dt} + 3\,H\,n_\chi = -\langle v\sigma_\chi\rangle\left[n_\chi^2 - (n_\chi^{\rm eq})^2\right]$$





WIMP Dark Matter

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



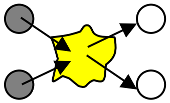
WIMP DM typically requires:

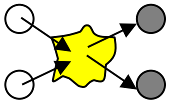
<*σv*> ~ few 10^{-26} cm^3/s

* 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





WIMP Dark Matter

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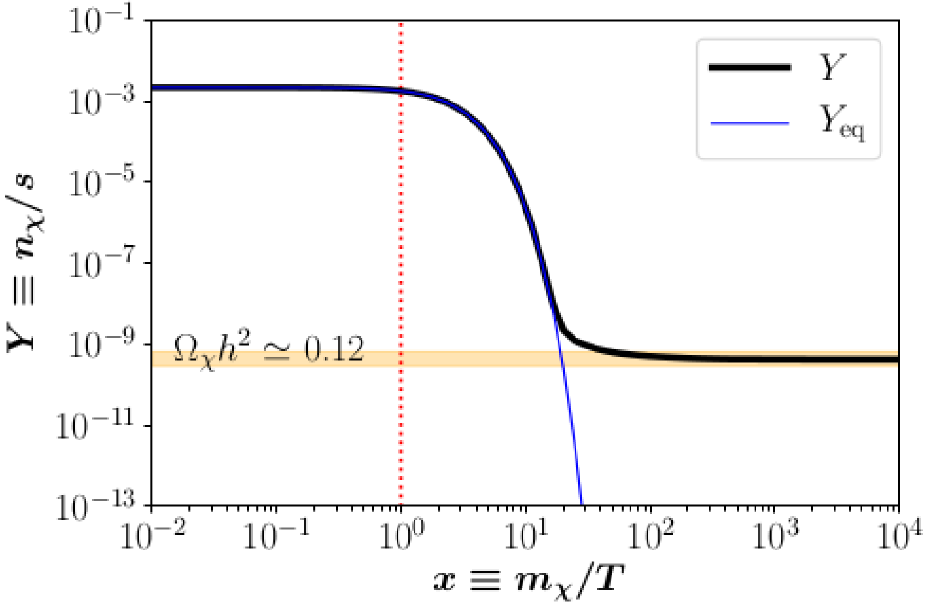


WIMP DM typically requires:

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

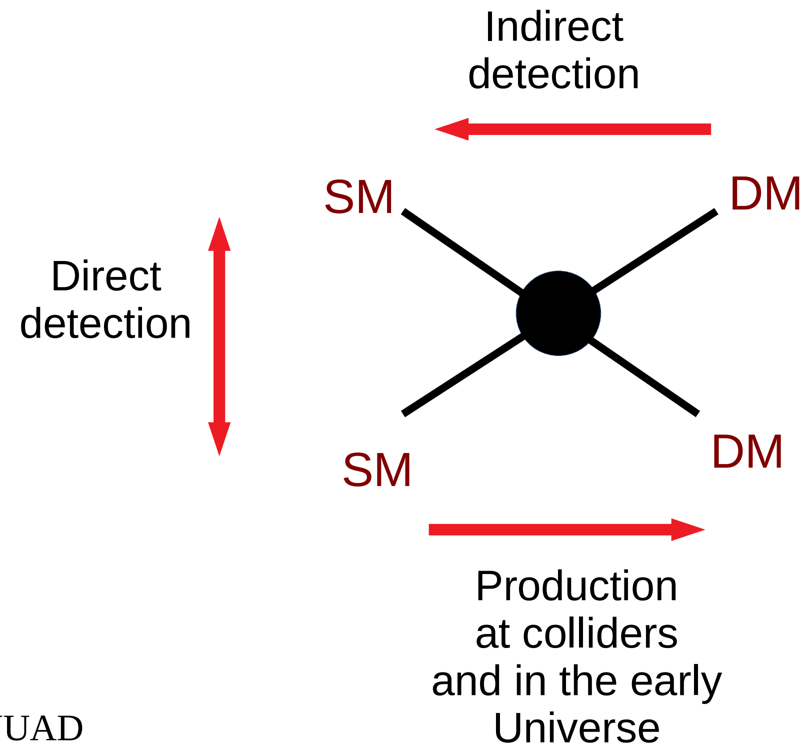
* GeV to TeV masses
* *O*(1) couplings DM-SM

→ Independent on initial conditions!

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

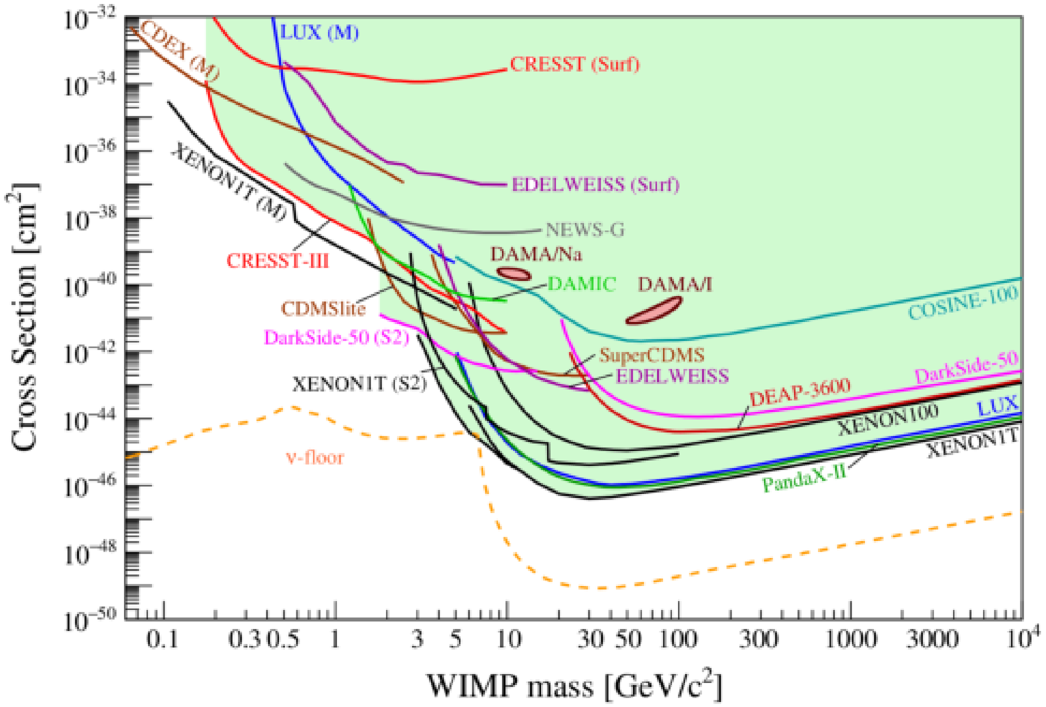
but no compelling detection so far! :-(

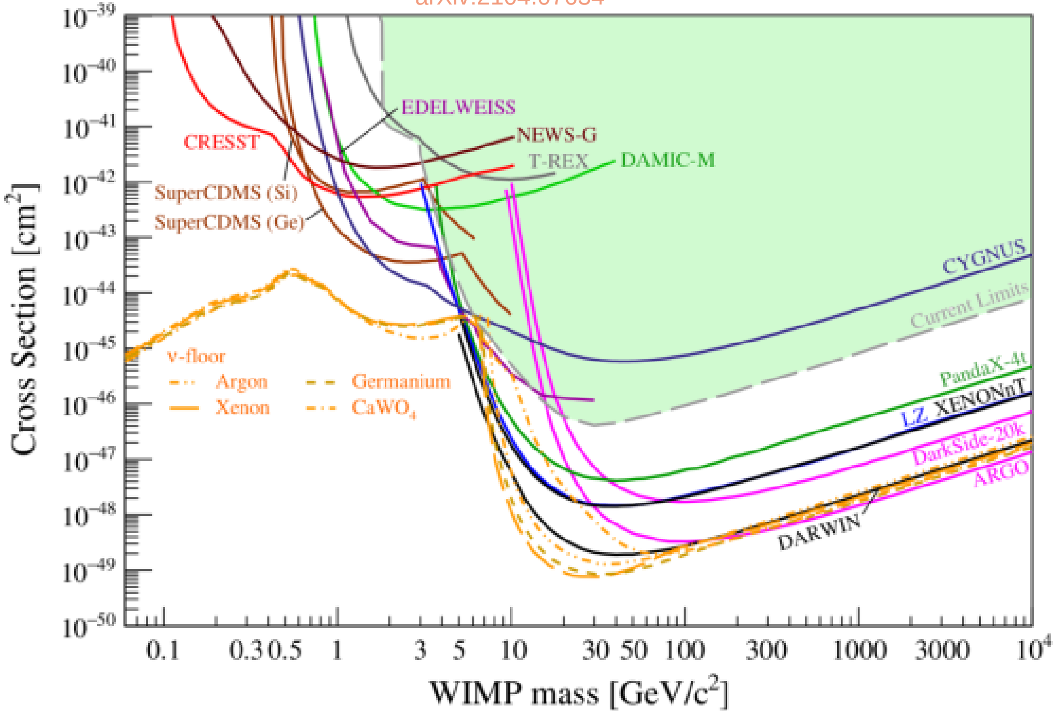
Detecting WIMPs



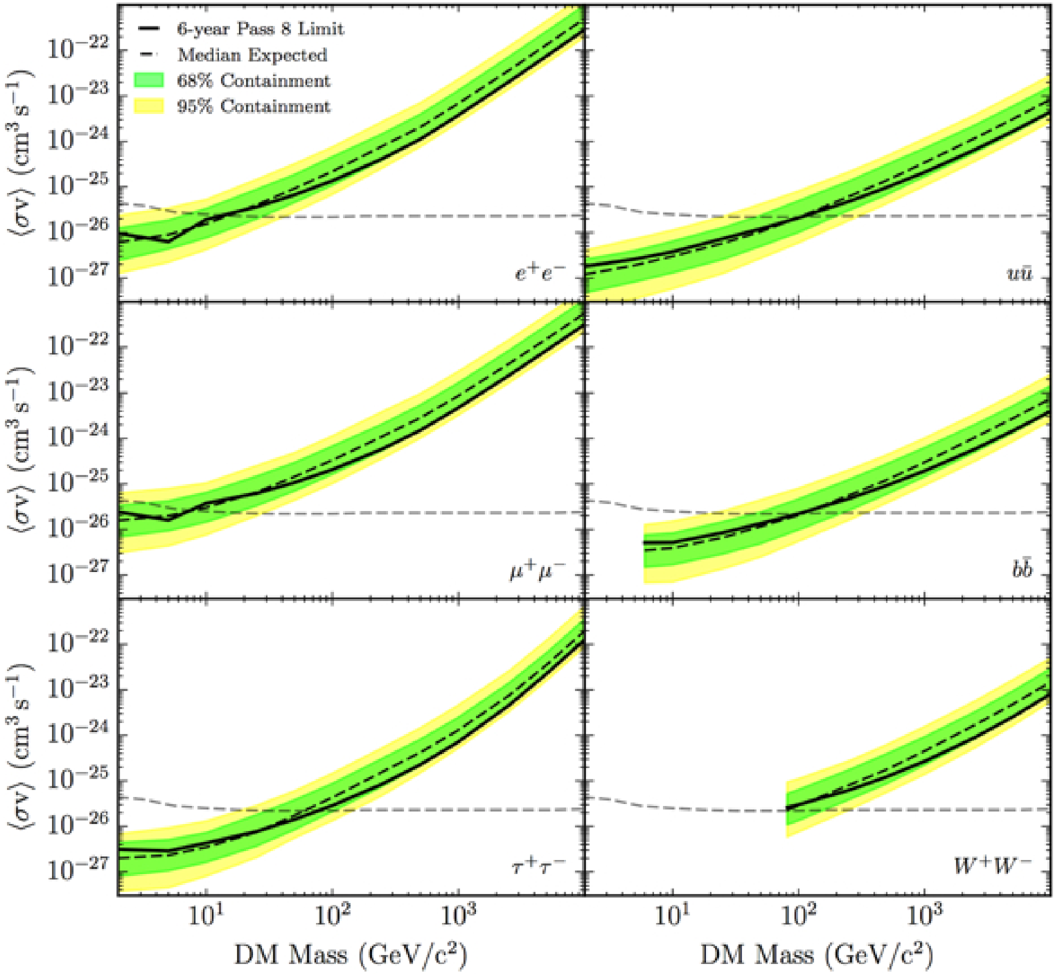
WIMP Dark Matter under Tension

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

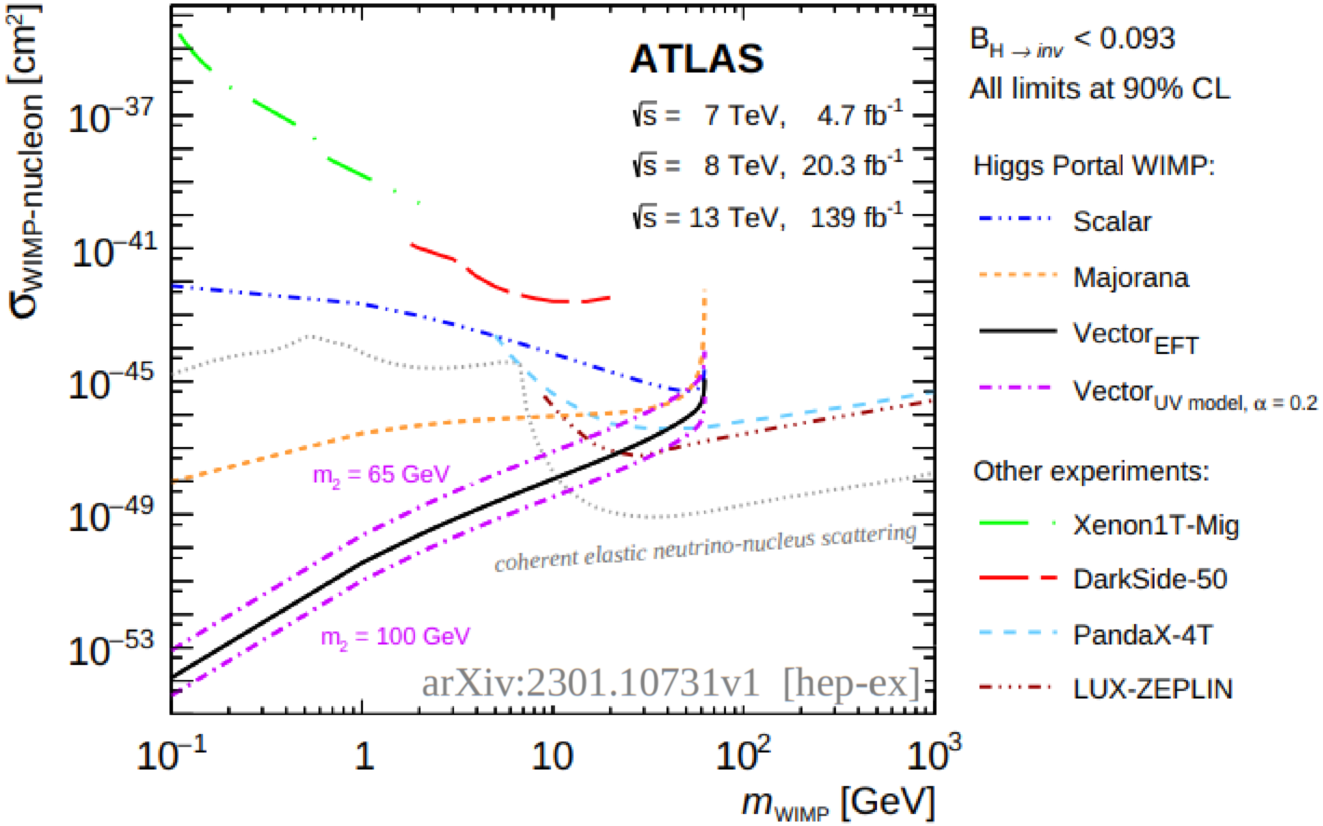




WIMP Dark Matter under Tension



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, $T \sim O(\text{MeV})$, 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!

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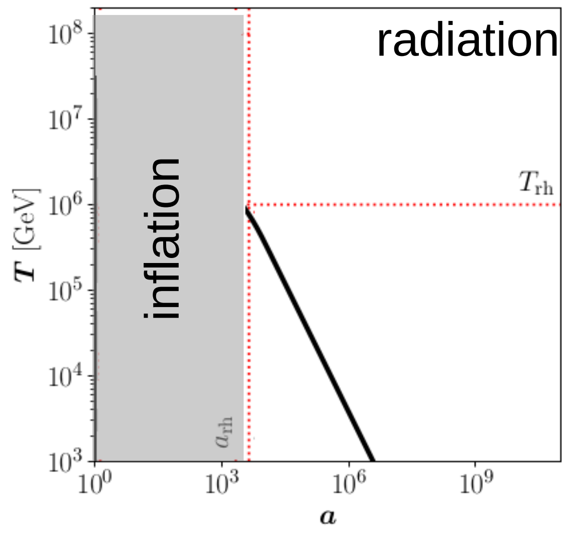
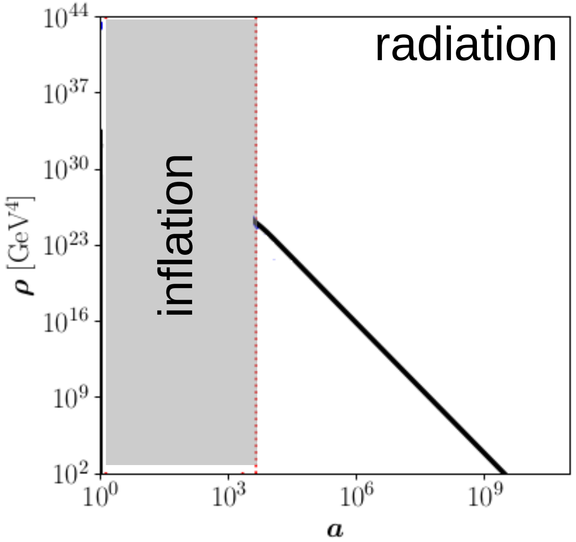
Standard Cosmology



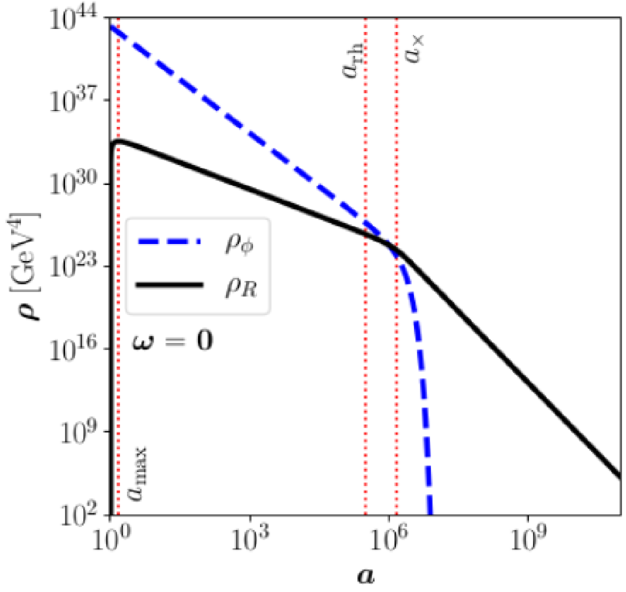
$T \sim 1/a$

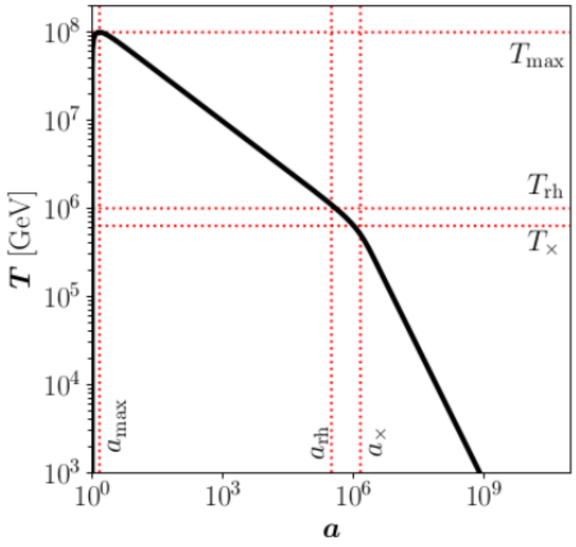


$\rho_R \sim T^4 \sim a^{-4}$

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

Non-instantaneous Reheating



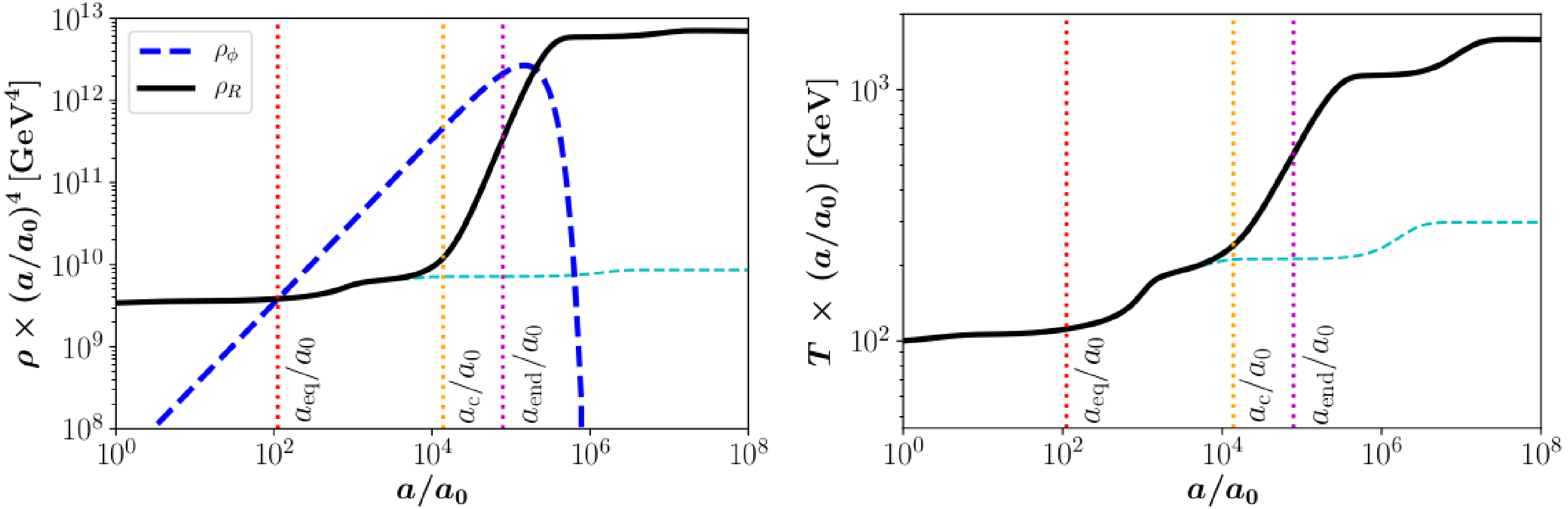


Decay or annihilation of inflatons into SM radiation is a *continuous process*

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

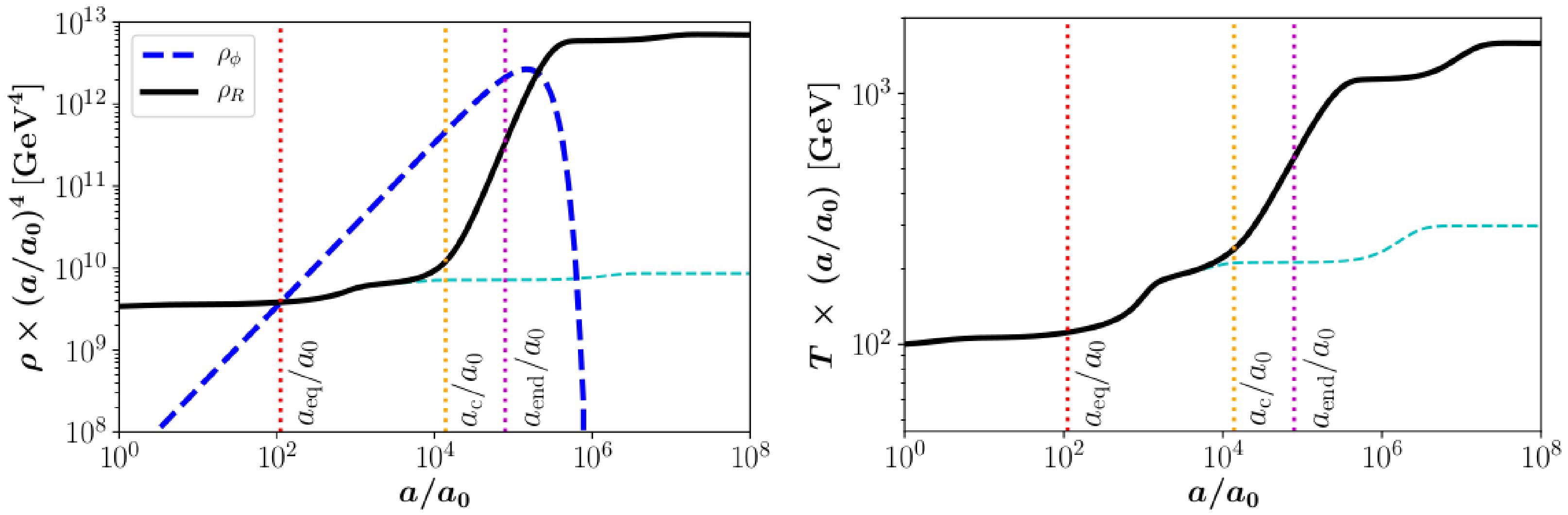
$$\frac{d\rho_R}{dt} + 4\, H\, \rho_R = +\Gamma_\phi\, \rho_\phi$$

Non-standard Cosmologies



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

Non-standard Cosmologies



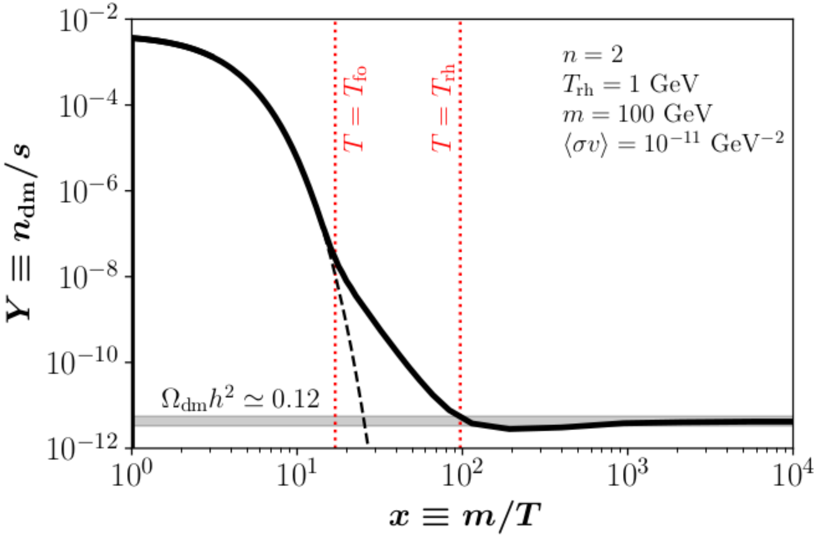
* Total energy density of the Universe could have been dominated by another non-SM component
* Entropy injection

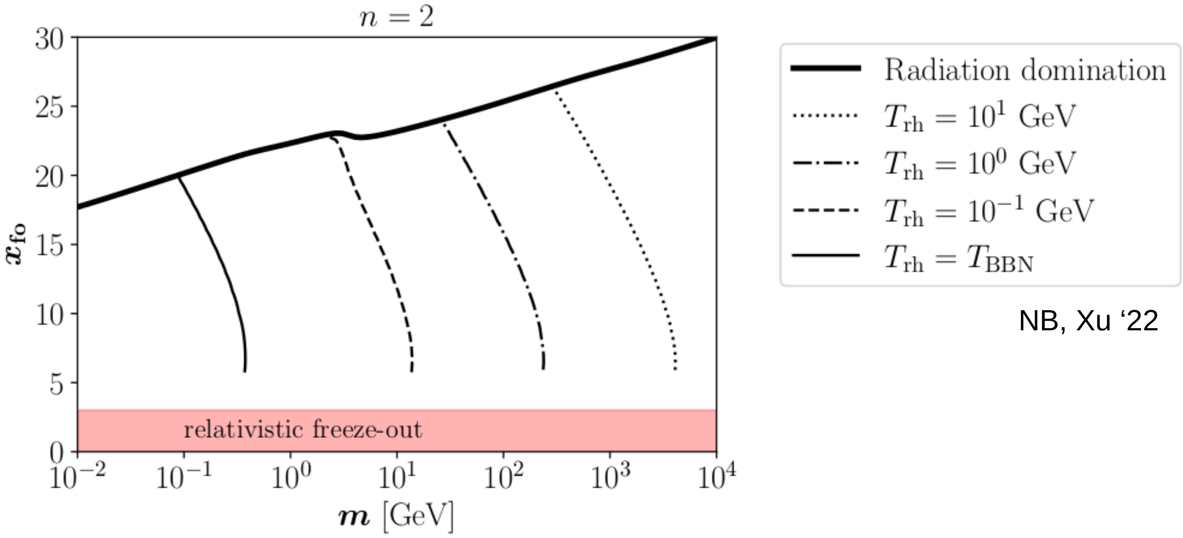
Multiple possible sources:
* heavy longlived particle (moduli, GUTs, RHNs, …)
* Primordial black holes
* ...

Entr'acte 1:
Standard vs Non-standard Cosmologies

WIMPs in Non-standard Cosmologies

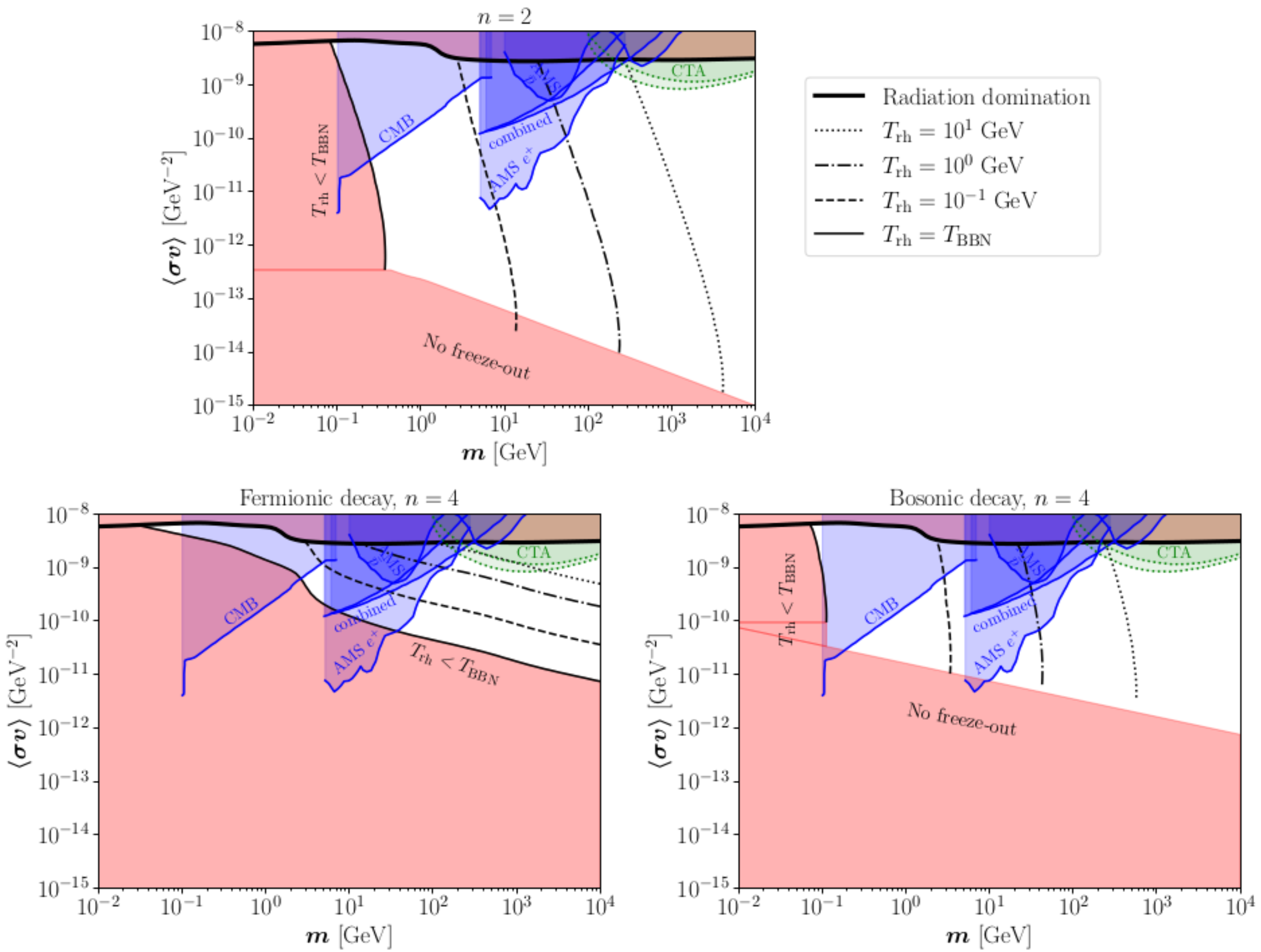
$$\frac{dn_\chi}{dt} + 3\,H\,n_\chi = -\langle v\sigma_\chi\rangle\left[n_\chi^2 - (n_\chi^{\rm eq})^2\right]$$





NB, Xu ‘22

WIMPs in Non-standard Cosmologies



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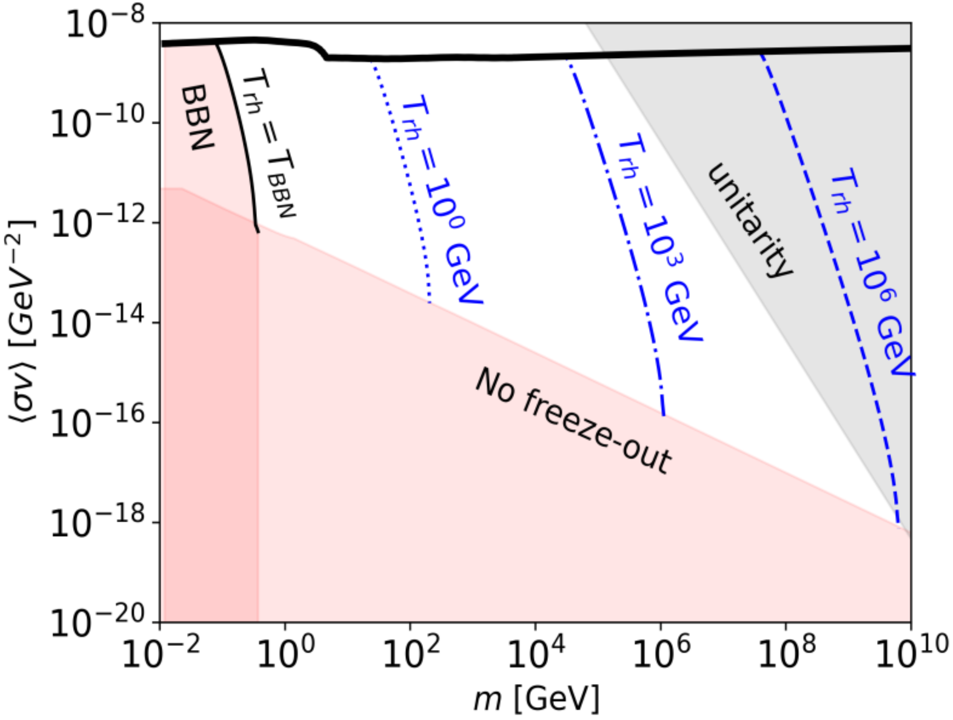
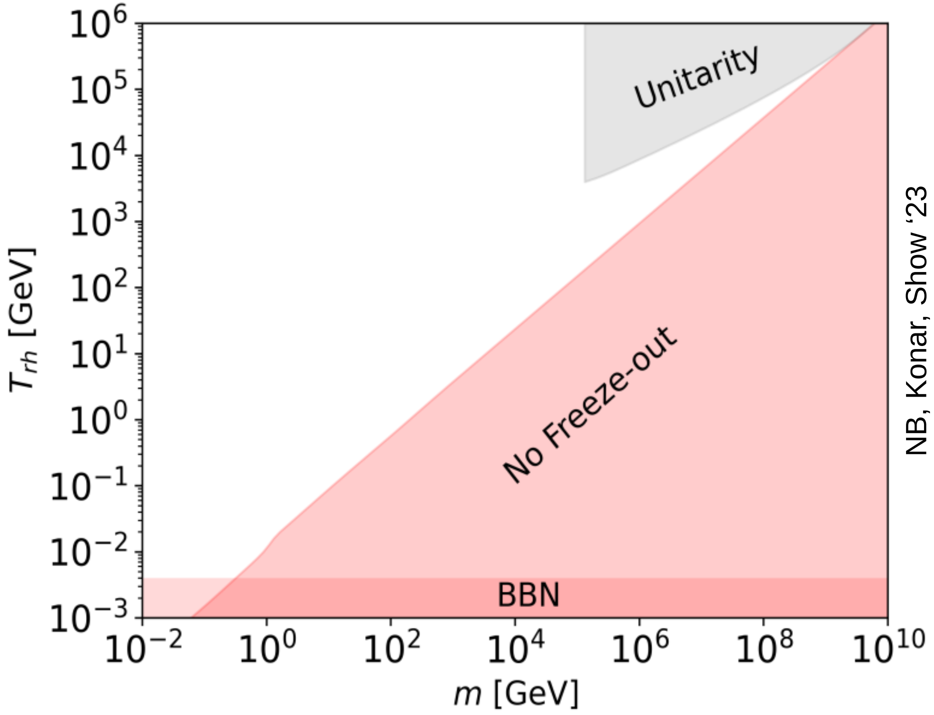
WIMPs in Non-standard Cosmologies

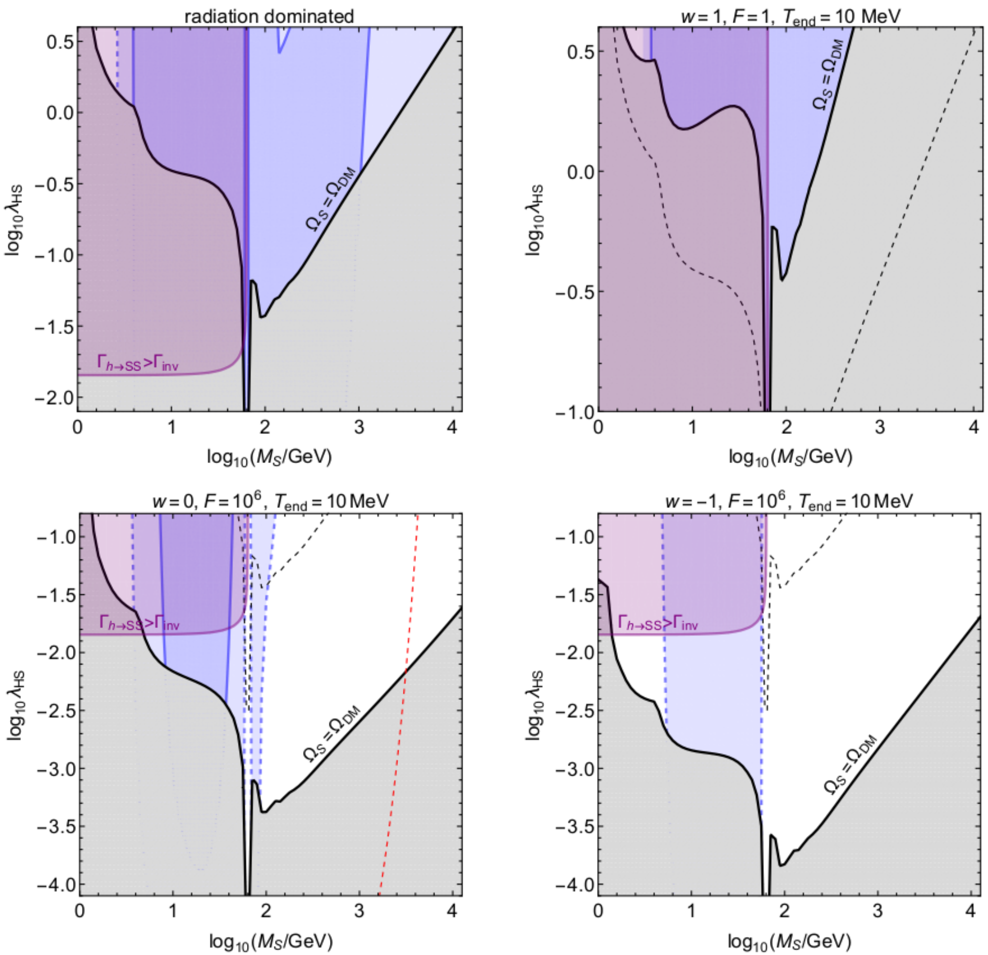




NB, Konar, Show '23

WIMPs in Non-standard Cosmologies

Singlet scalar
DM model



NB, Cosme, Tenkanen, Vaskonen '19

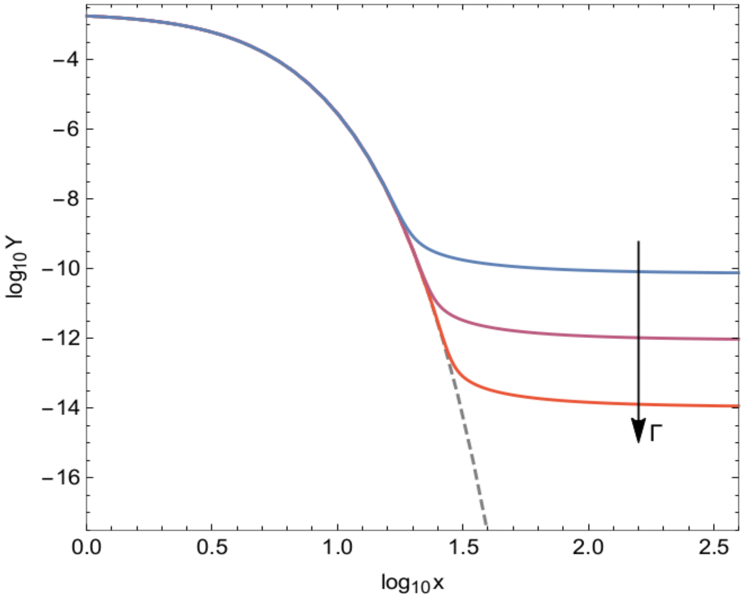
2. FIMP DM
Feebly Interacting Massive Particle

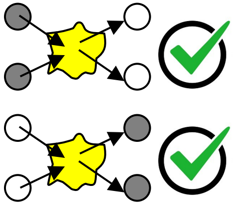
The Dawn of FIMP Dark Matter:
A Review of Models and Constraints

NB, Heikinheimo,Tenkanen,Tuominen, Vaskonen ‘17

WIMP vs FIMP Dark Matter

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





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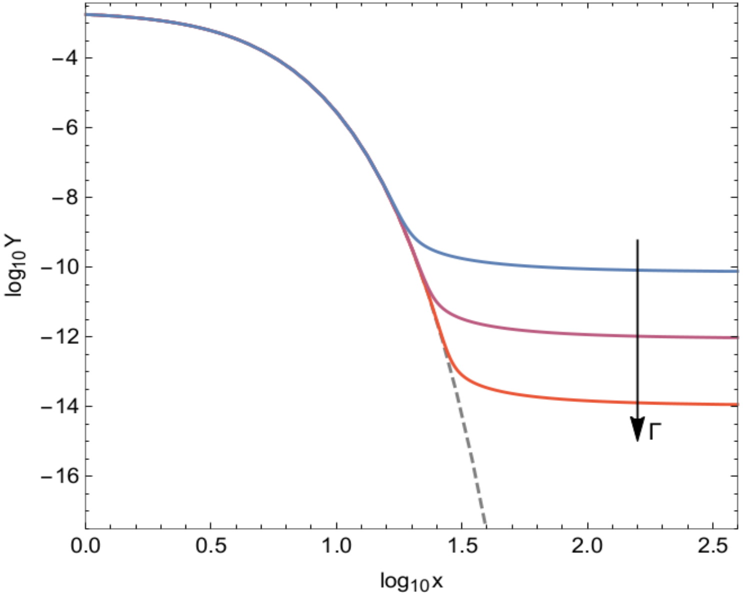
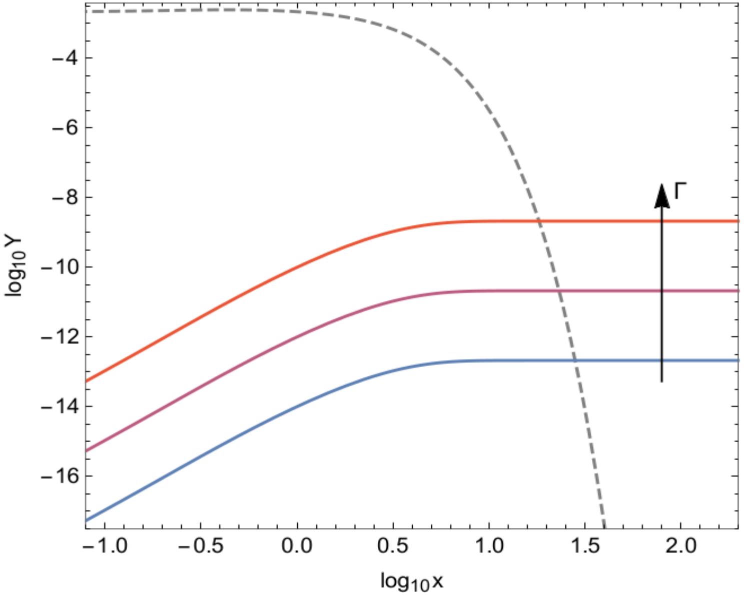
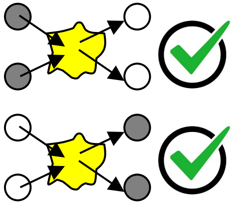
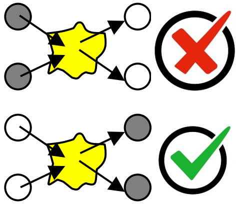








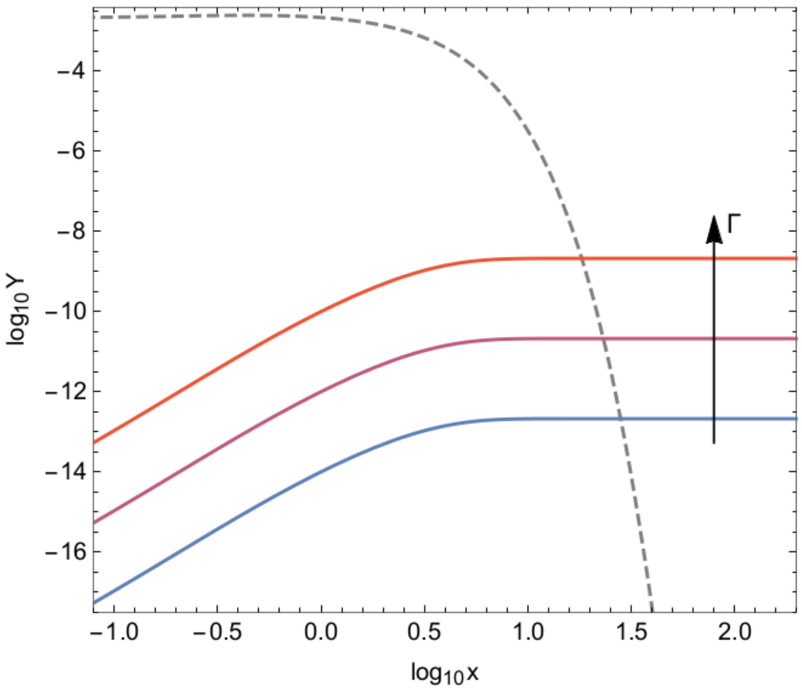
FIMP Dark Matter

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

FIMP DM typically requires:

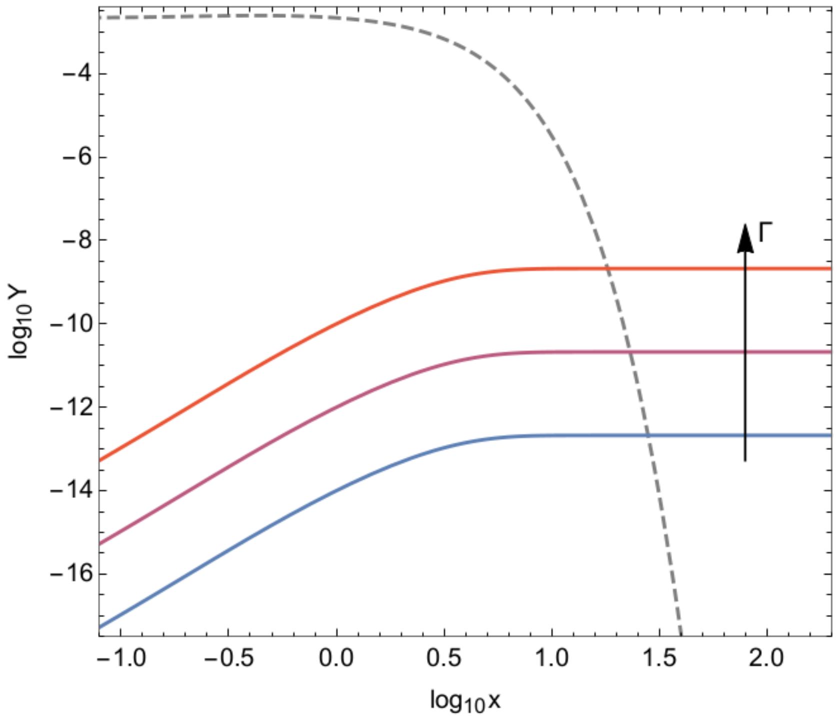
* Very suppressed DM-SM interaction rates
  to avoid thermalization between
  the dark and the visible sectors
* masses > keV (!)
* Usually *assumed* a dark sector
  with a negligible initial population

→ Dependent of initial conditions!

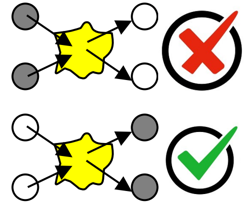


2a. Infrared FIMPs
Feebly Interacting Massive Particles

IR FIMP paradigm



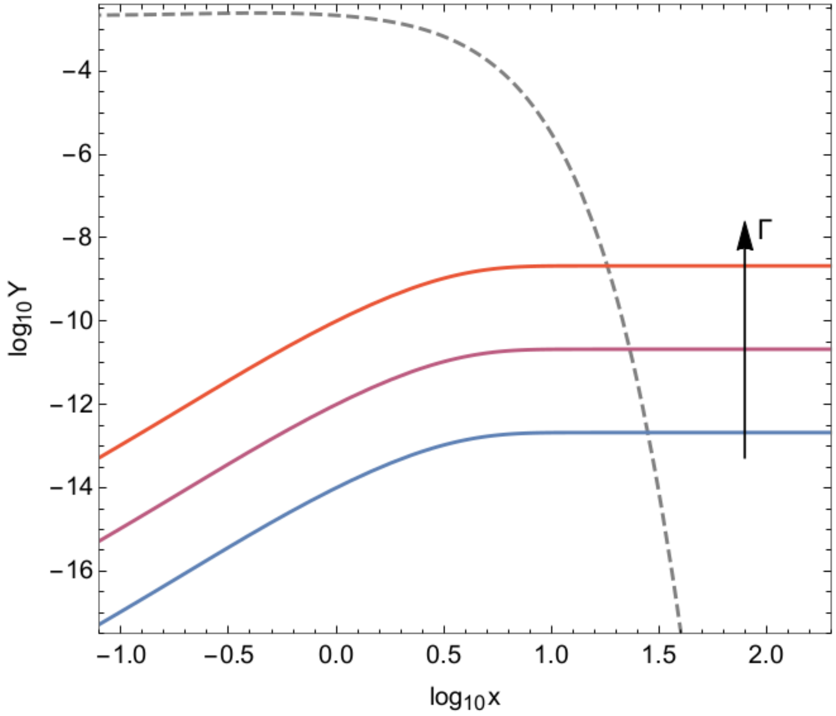
$$\frac{dn}{dt} + 3\,H\,n = -\langle\sigma v\rangle\,\left(\cancel{n^2} - n_{\rm eq}^2\right)$$



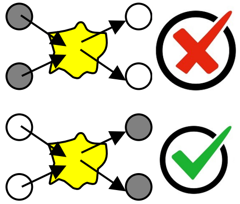
* chemical equilibrium never reached
* **renormalizable** operators
* masses: keV to ~M_P
* $\lambda_{\text{DM-SM}} \sim 10^{-11}$
* $T_{\rm fi} \sim m$

→ (mild) dependence from initial conditions

IR FIMP paradigm



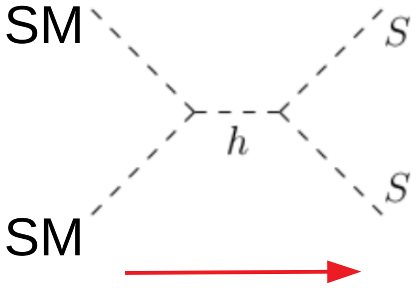
$$\frac{dn}{dt} + 3\,H\,n = -\langle \sigma v \rangle \left(\cancel{n^2} - n_{\rm eq}^2 \right)$$

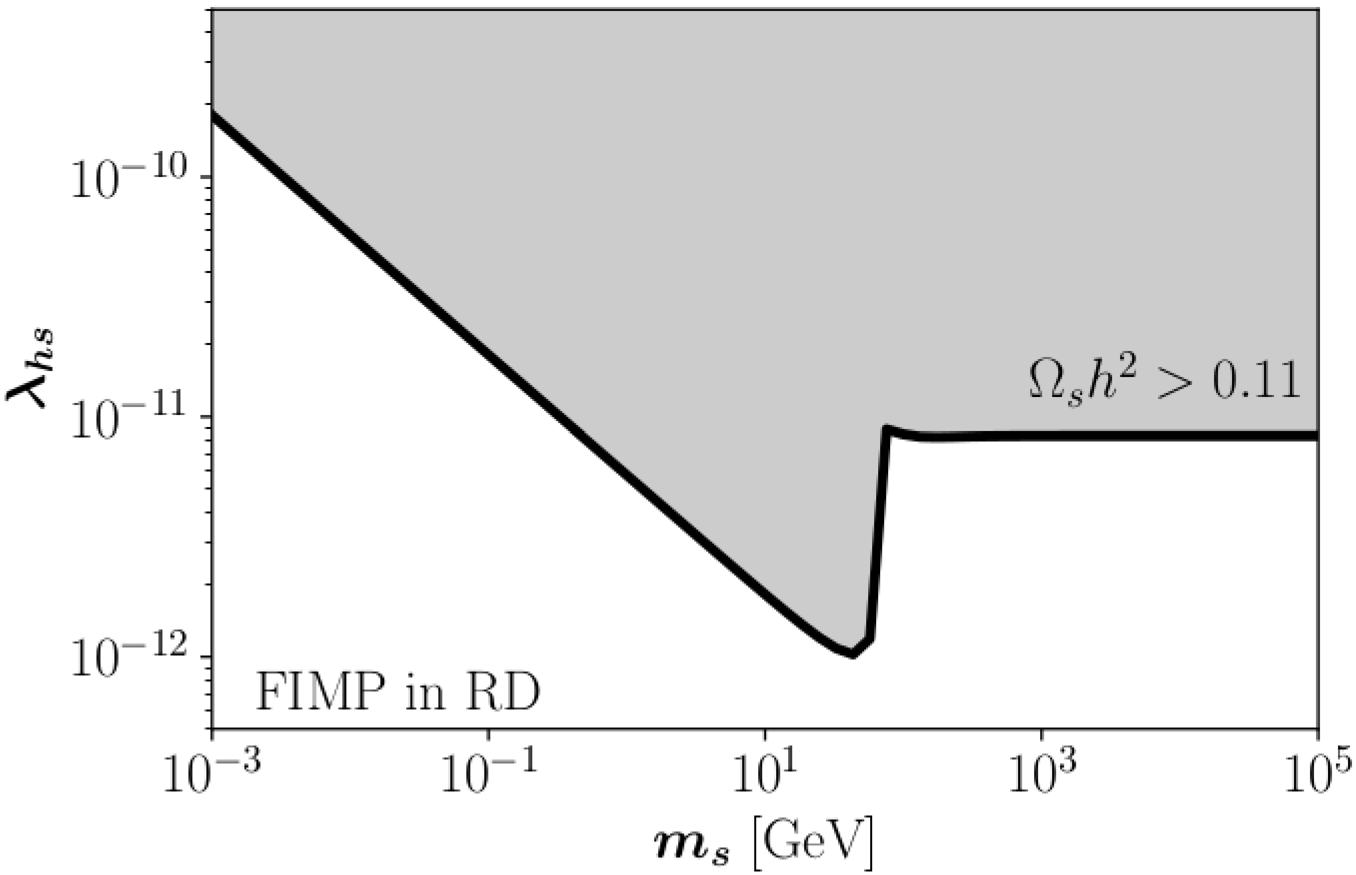


* chemical equilibrium never reached
* **renormalizable** operators
* masses: keV to ~M_P
* $\lambda_{\text{DM-SM}} \sim 10^{-11}$ ← "Unnaturally" small… but could be *technically natural*!
* $T_\mathrm{fi} \sim m$

→ (mild) dependence from initial conditions

Singlet Scalar DM - FIMP

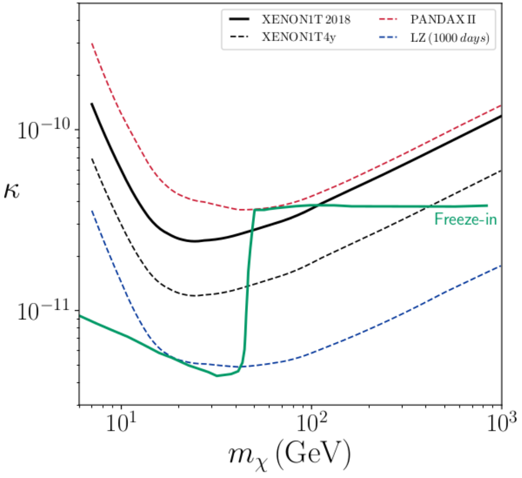




Detecting FIMPs

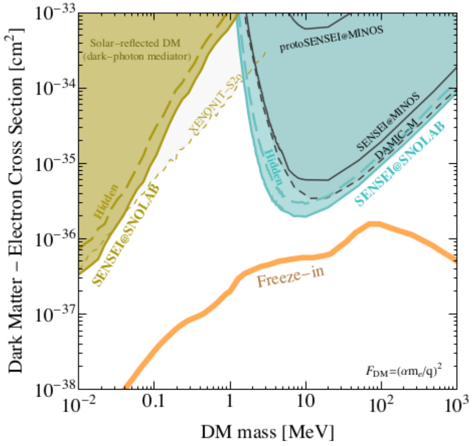
By construction, very challenging to test...

Hambye+ ‘18



Light mediators

Sensei ‘23

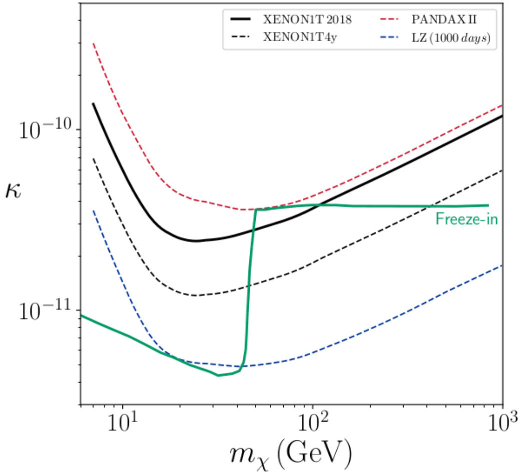


MeV dark matter

Detecting FIMPs

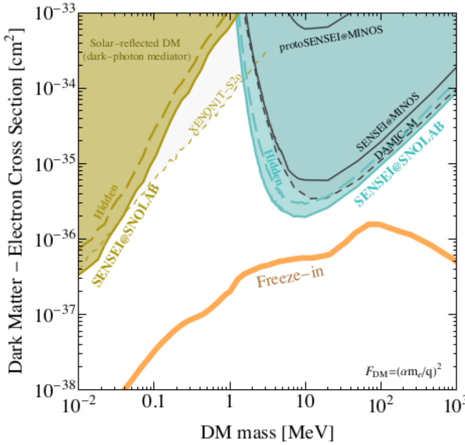
By construction, very challenging to test...

Hambye+ '18



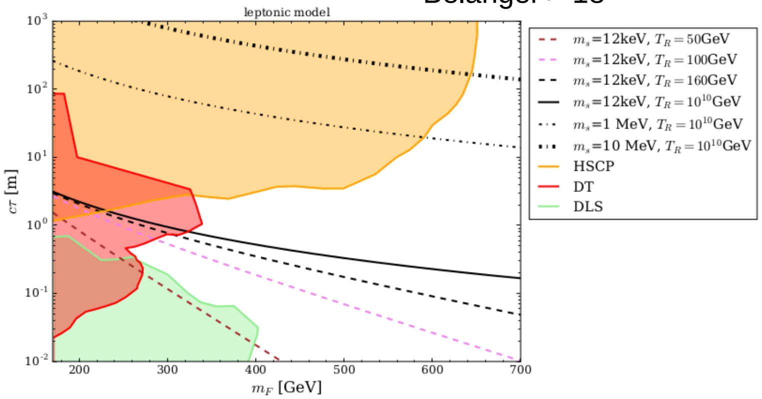
Light mediators

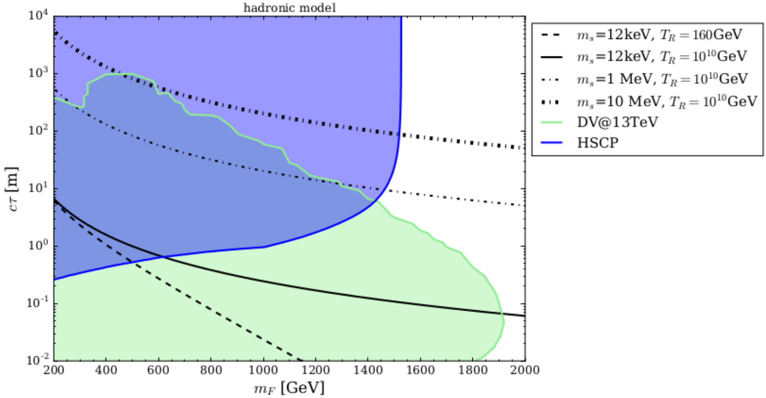
Sensei '23



MeV dark matter

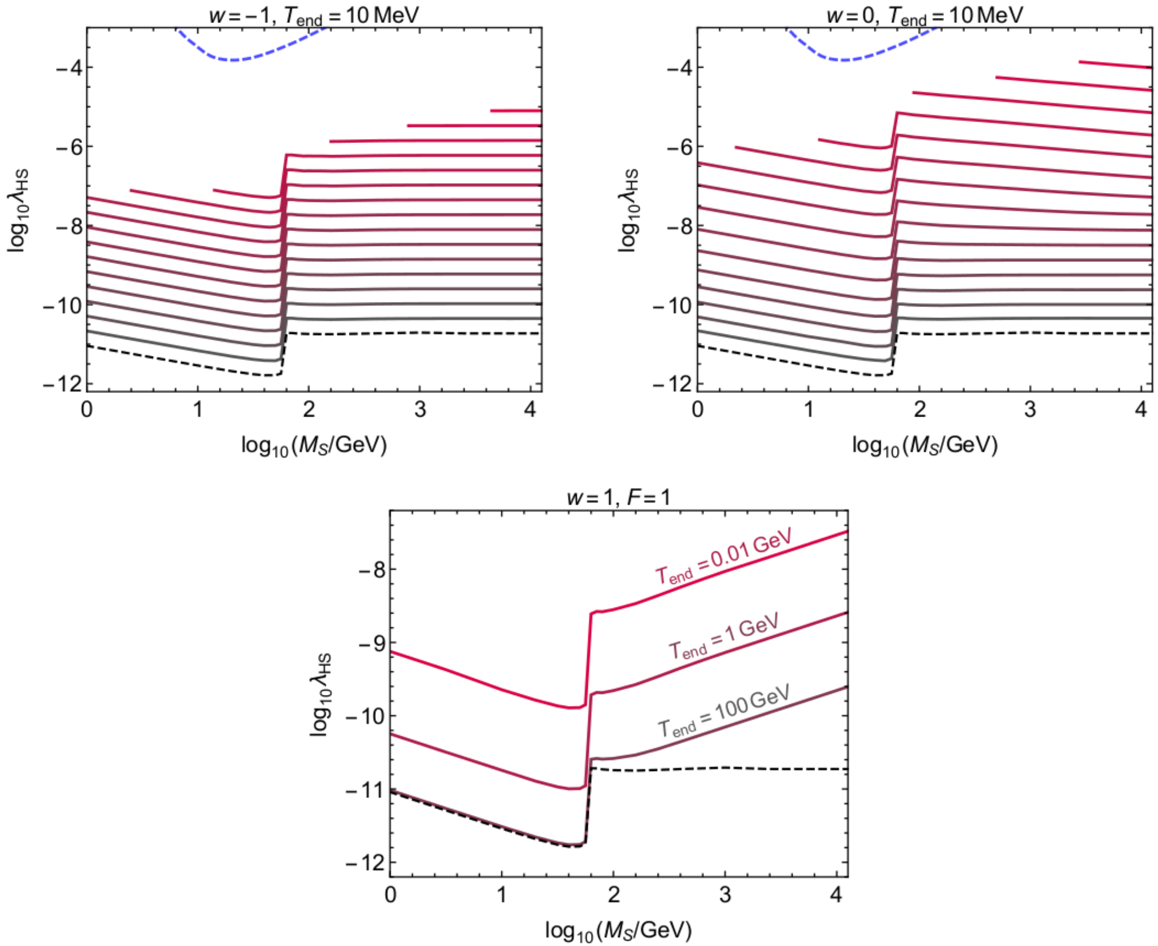
Bélanger+ '18





IR FIMPs in Non-standard Cosmologies

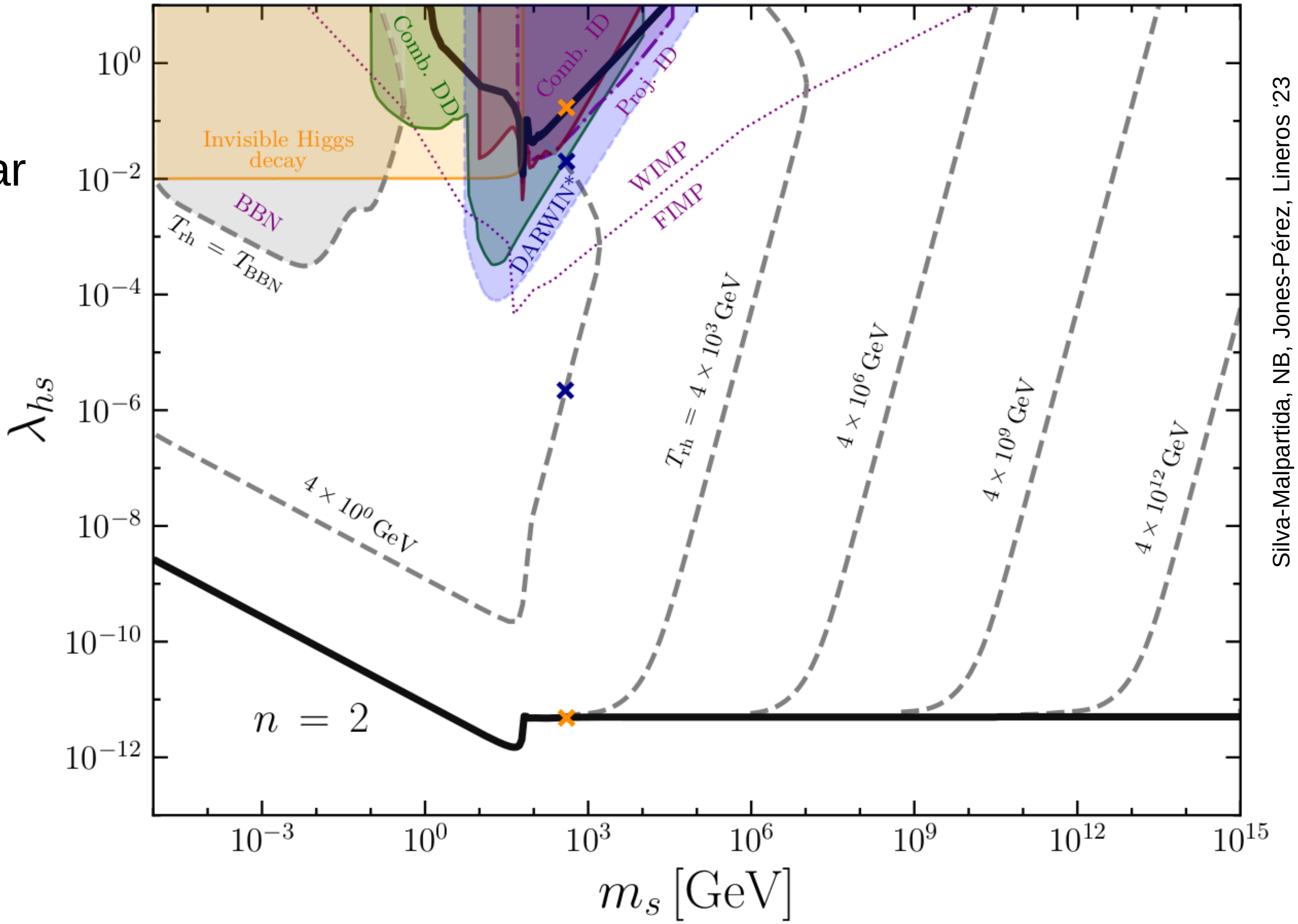
Singlet scalar
DM model



NB, Cosme, Tenkanen, Vaskonen '19

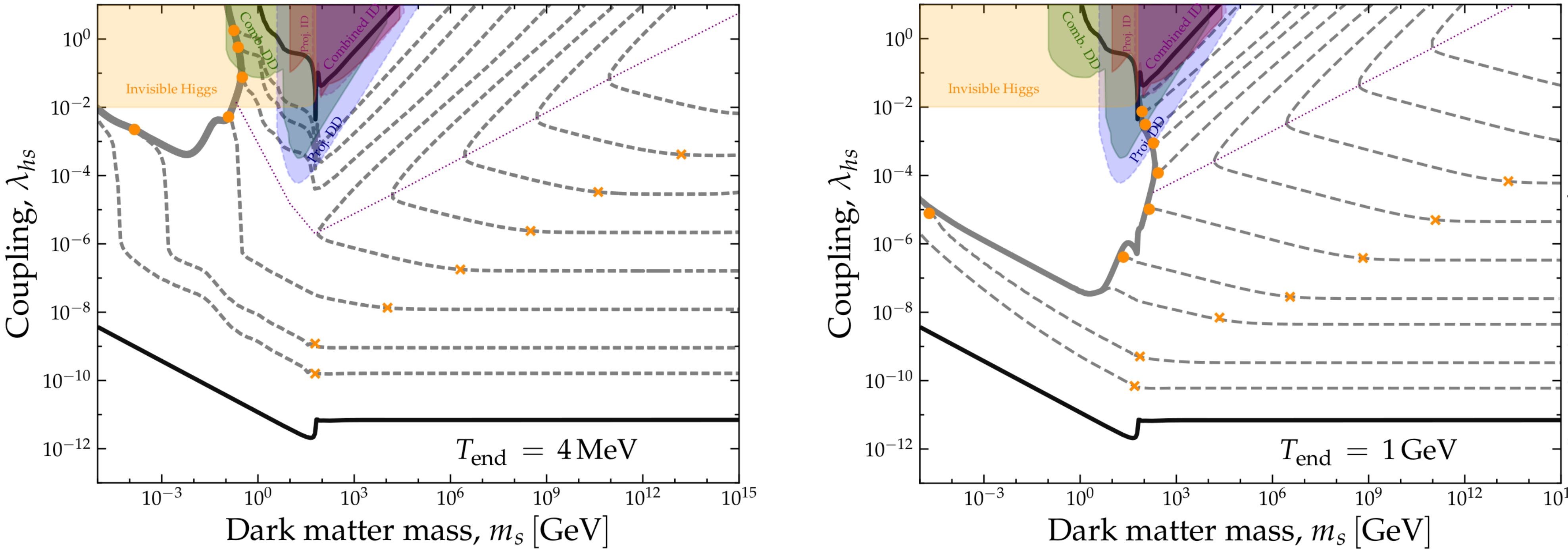
WIMPs and FIMPs with Low-temperature reheating

Singlet scalar DM model



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

WIMPs and FIMPs in Non-standard Cosmologies

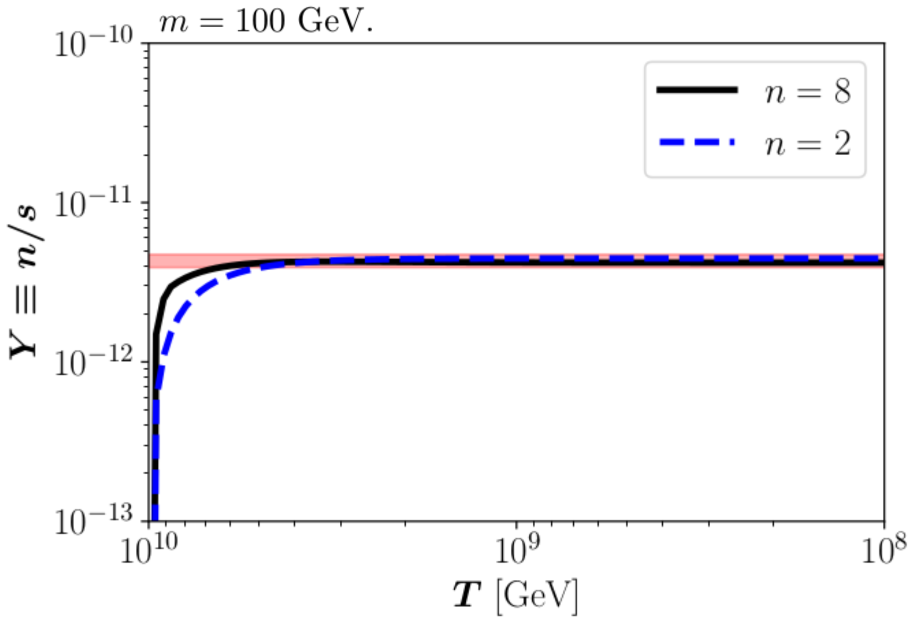


Silva-Malpartida, NB, Jones-Pérez, Lineros, Soon!

Singlet scalar
DM model

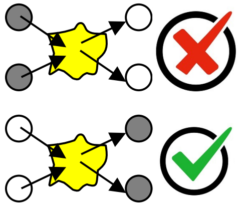
2b. Ultraviolet FIMPs
Feebly Interacting Massive Particles

UV FIMP paradigm



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

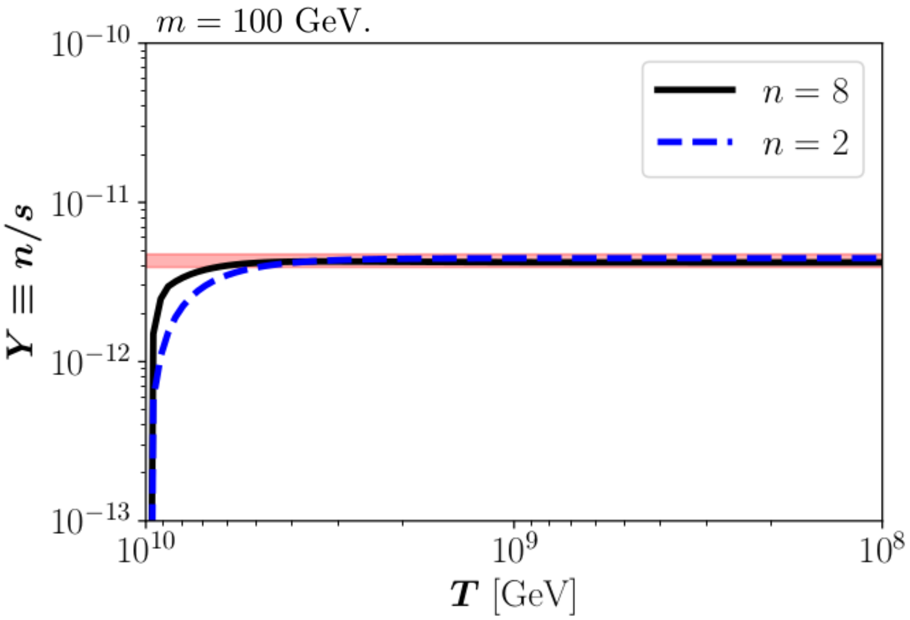
$$\frac{dn}{dt} + 3\,H\,n = -\langle \sigma v \rangle \left(\cancel{n^2} - n_{\rm eq}^2 \right)$$

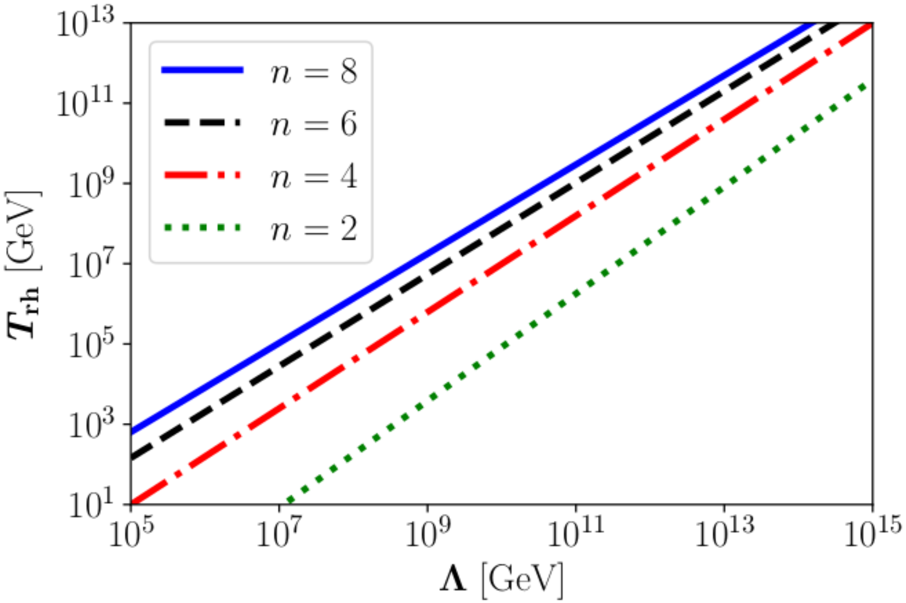


* chemical equilibrium never reached
* ***non*-renormalizable** operators
* masses: keV to ~M_P
* $\Lambda > T_{rh}$
* $T_{fi} \sim T_{rh}$

→ (strong) dependence from initial conditions

UV FIMP paradigm





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

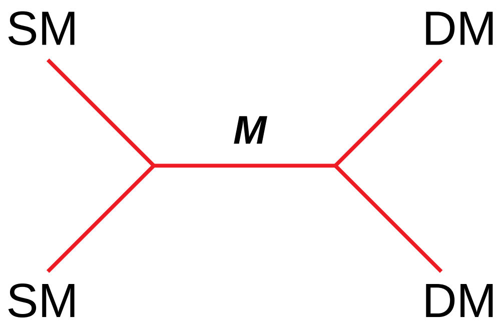
$$Y \sim \int_0^{T_{\rm RH}} \frac{M_{\rm Pl}\, T^n}{\Lambda^{n+2}} \sim \frac{M_{\rm Pl}\, T_{\rm RH}^{n+1}}{\Lambda^{n+2}}$$

UV FIMP paradigm

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

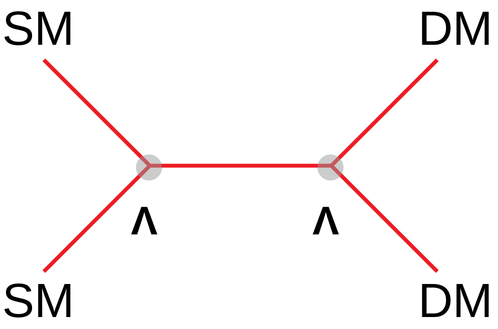
- **Heavy mediator** (*M* >> T_{rh})

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



UV FIMP paradigm

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



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

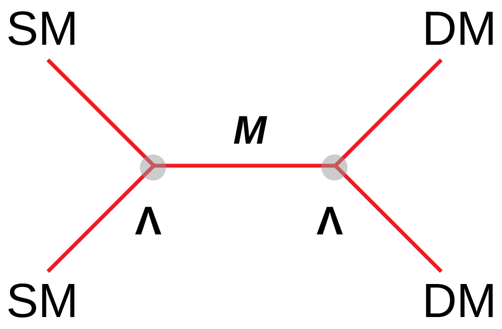
$$\langle \sigma v \rangle \propto g^4 \frac{T^2}{M^4}$$

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

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

UV FIMP paradigm

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



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

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

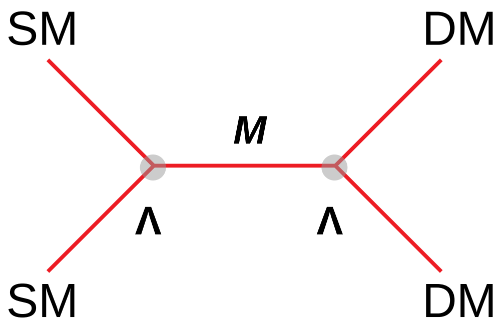
- **Suppressed couplings** ($\Lambda \gg T_{rh}$)

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

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

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

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** ($\Lambda >> T_{rh}$)

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

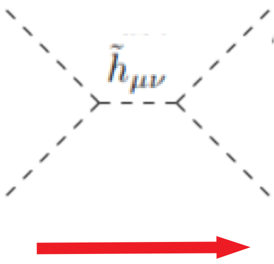
← **Gravitational UV freeze-in**

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

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

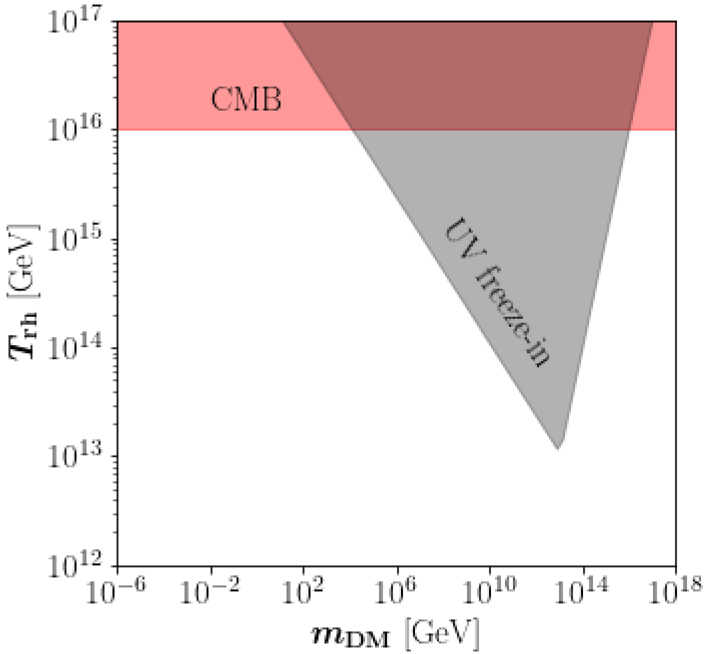
Gravitational FIMPs

An example of UV FIMP, mediated by massless SM gravitons



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

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



Depends on:

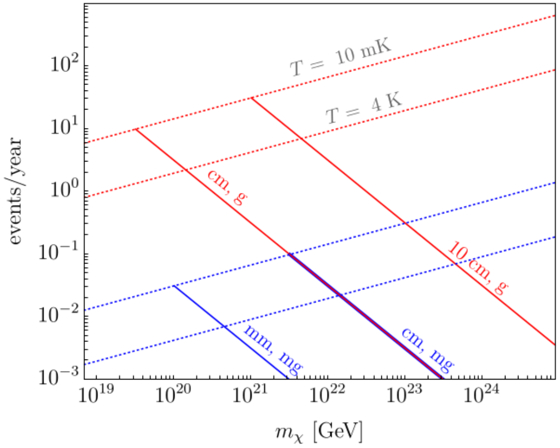
* DM mass and spin
* Reheating temperature
* No free couplings: M_P

Gravitational FIMPs

By construction, nightmare scenario to test!

http://windchimeproject.org/

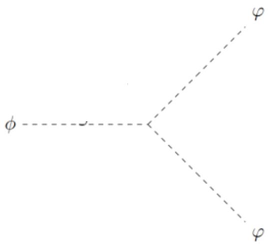
Carney, Ghosh, Krnjaic, Taylor ‘19



Entr'acte 2:
Testing reheating

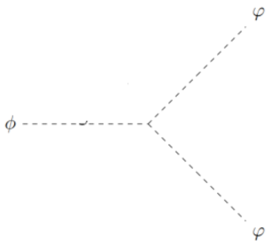
Probing Reheating
with Graviton Bremsstrahlung

Inflaton decay

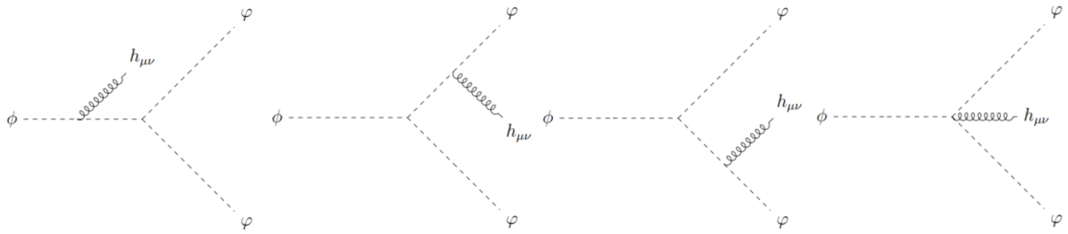


Probing Reheating with Graviton Bremsstrahlung

Inflaton decay

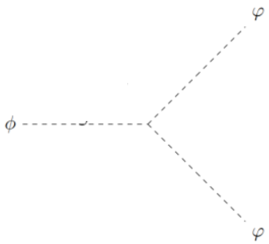


$\rightarrow$

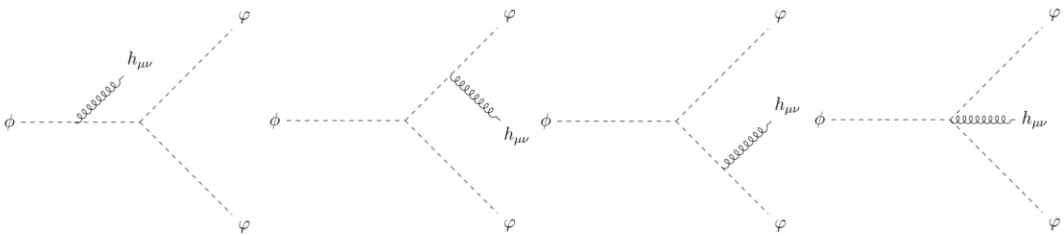


Probing Reheating with Graviton Bremsstrahlung

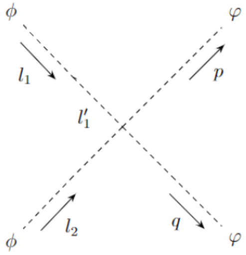
Inflaton decay



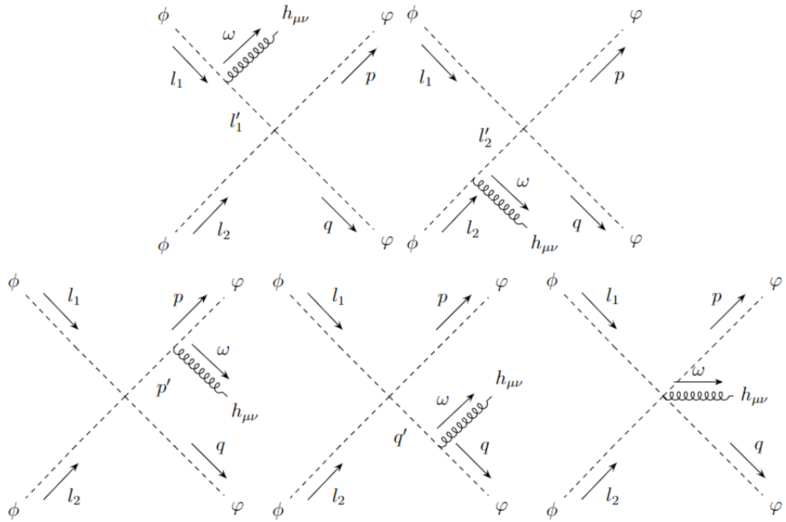
→



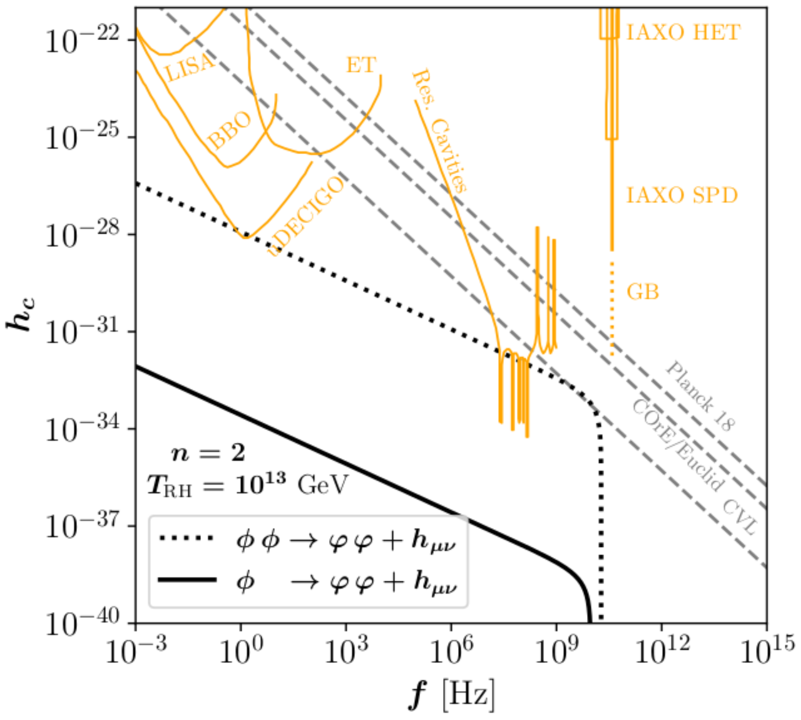
Inflaton annihilation

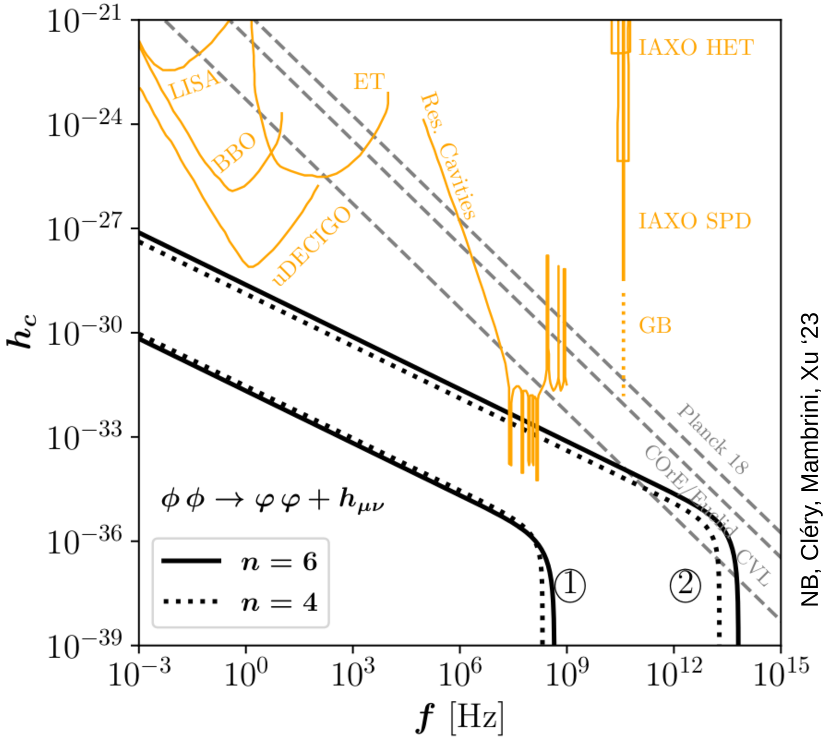


→



Probing Reheating with Graviton Bremsstrahlung





NB, Cléry, Mambrini, Xu '23

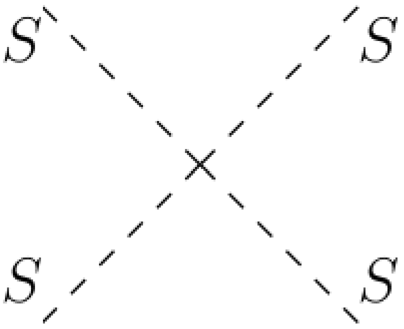
Entr'acte 2:
Testing reheating

What about possible DM self-interactions?

3. SIMP DM
Self-Interacting Massive Particle

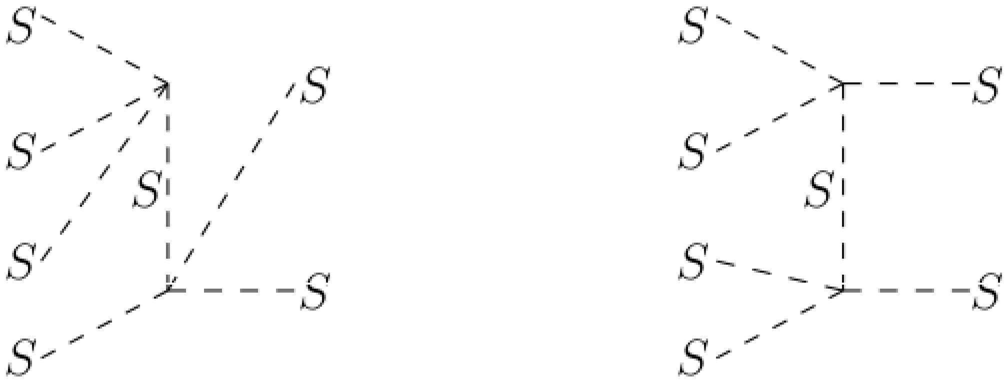
DM self-interactions

Elastic scattering



Kinetic equilibrium:
DM temperature

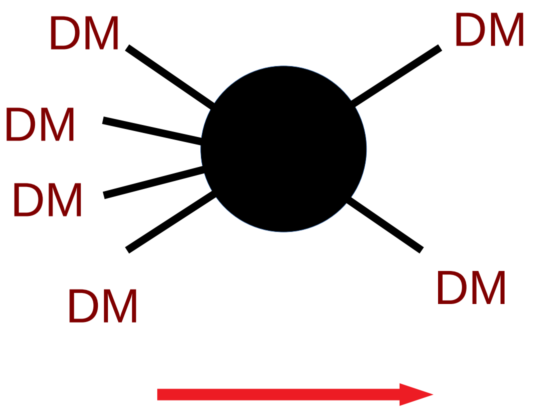
Number-changing interactions



Chemical equilibrium:
4 → 2 and 2 → 4

SIMP DM
4 → 2 annihilations

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



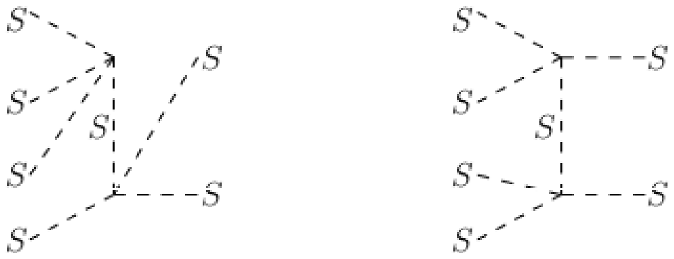
A Z_2 symmetry forbids 3 → 2 annihilations...
but allows 4 → 2 annihilations!

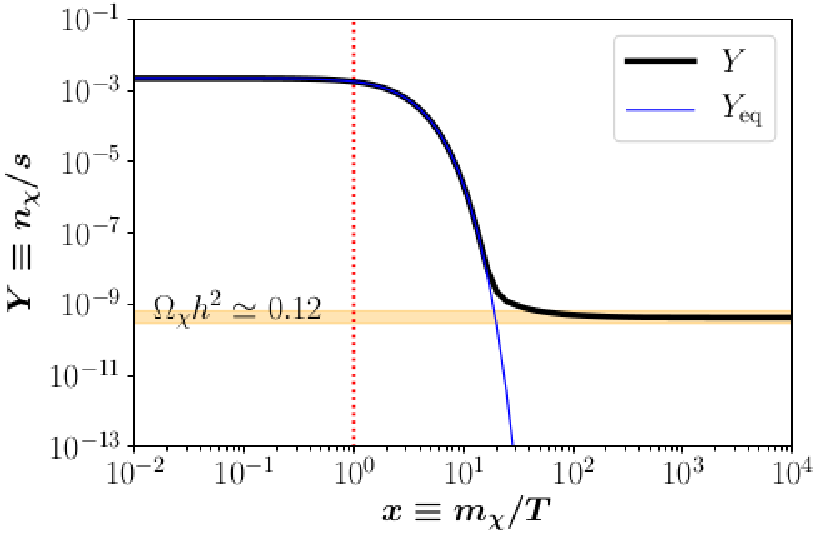
Could be the dominant channel if
the SM-DM portal is very suppressed…

… like in the FIMP scenario!

Singlet Scalar DM
4 → 2 annihilations

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





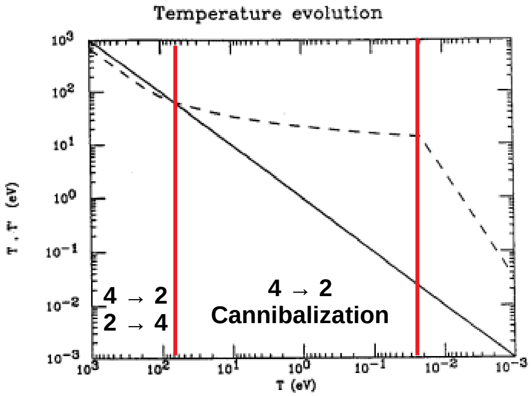
$$\langle\sigma v^3\rangle_{4\to 2} \sim \frac{27\sqrt{3}}{8\pi}\,\frac{\lambda_S^4}{m_S^8}$$

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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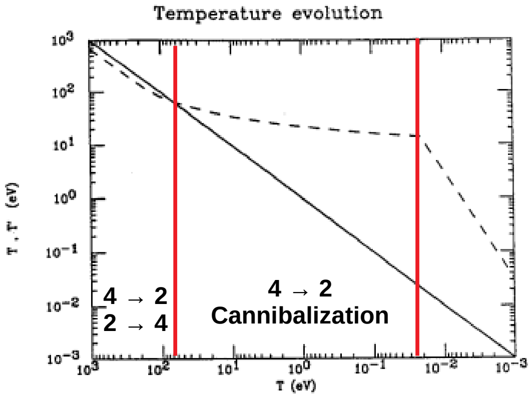


Perturbativity implies

$m \sim O(100)$ eV

* Avoid increase of temperature

→ SIMP DM

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

* Control the increase of temperature

→ ELDER DM

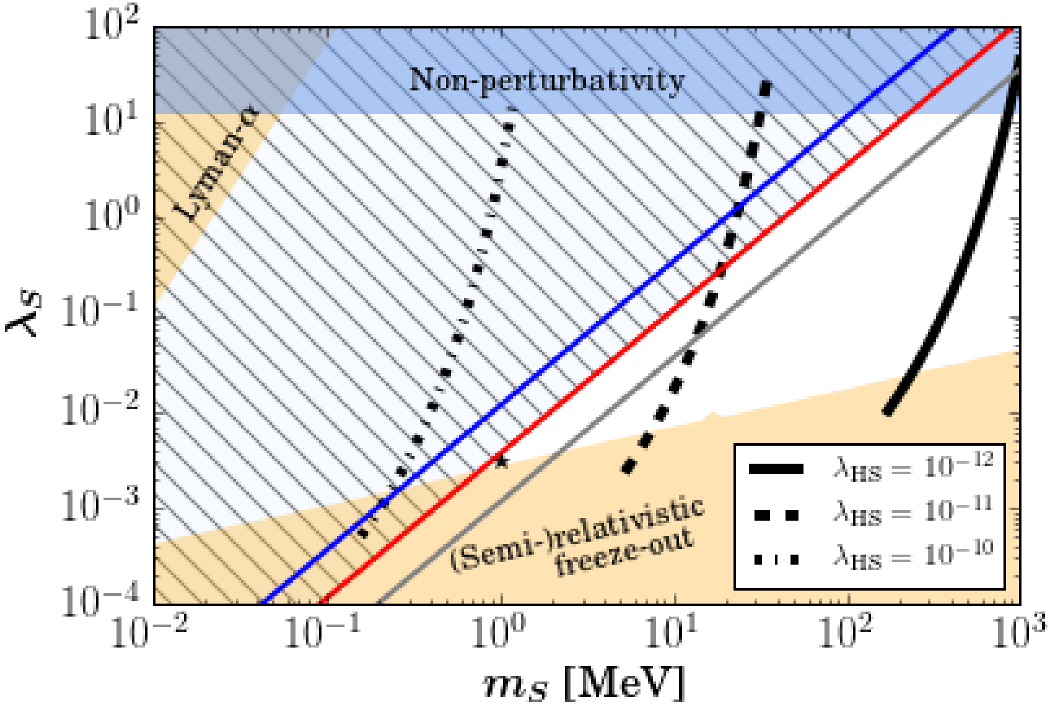
Kuflik, Perelstein, Rey-Le Lorier, Tsai ‘15

* Start with a colder dark sector

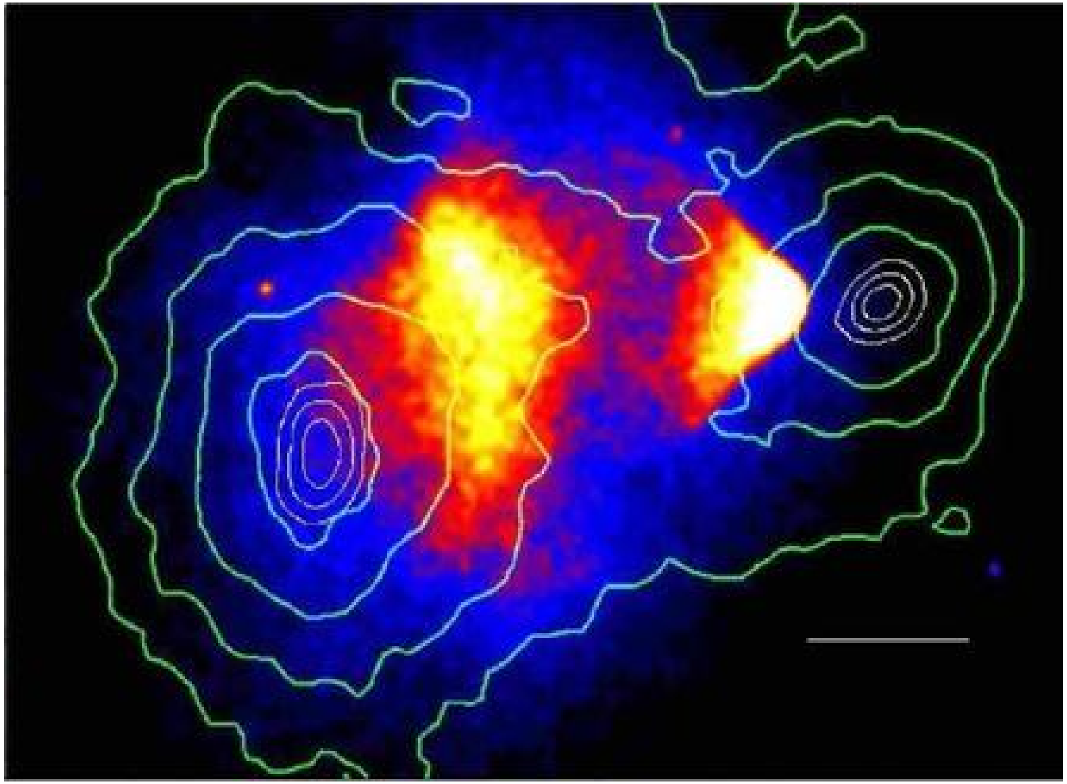
NB, Chu ‘15
NB, Chu, Garcia-Cely, Hambye, Zaldivar ‘15

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

Singlet Scalar DM
Dark Freeze-out via a FIMP mechanism

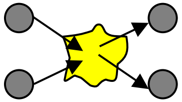


Detecting SIMPs



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...
- Continue searches for WIMPs, FIMPs, and other DM candidates

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

Muchas gracias