

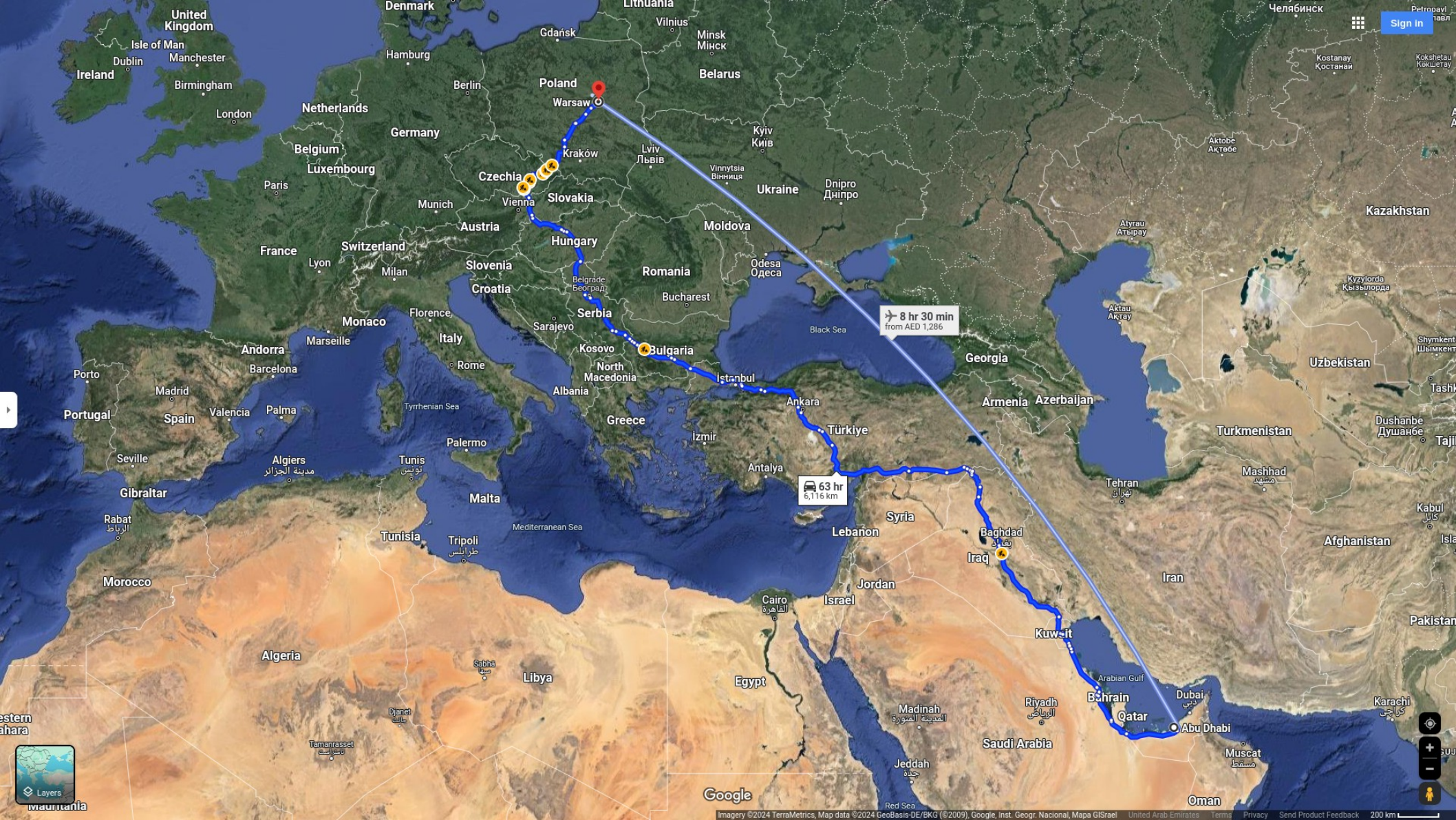
New Avenues For Dark Matter Production

Nicolás BERNAL

جامعة نيويورك أبوظبي



High Energy, Cosmology and Astro-particle physics (HECA)
Joint Seminar of the National Centre for Nuclear Research
and the Faculty of Physics of the University of Warsaw
April 23rd, 2024



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Kraków

Czechia

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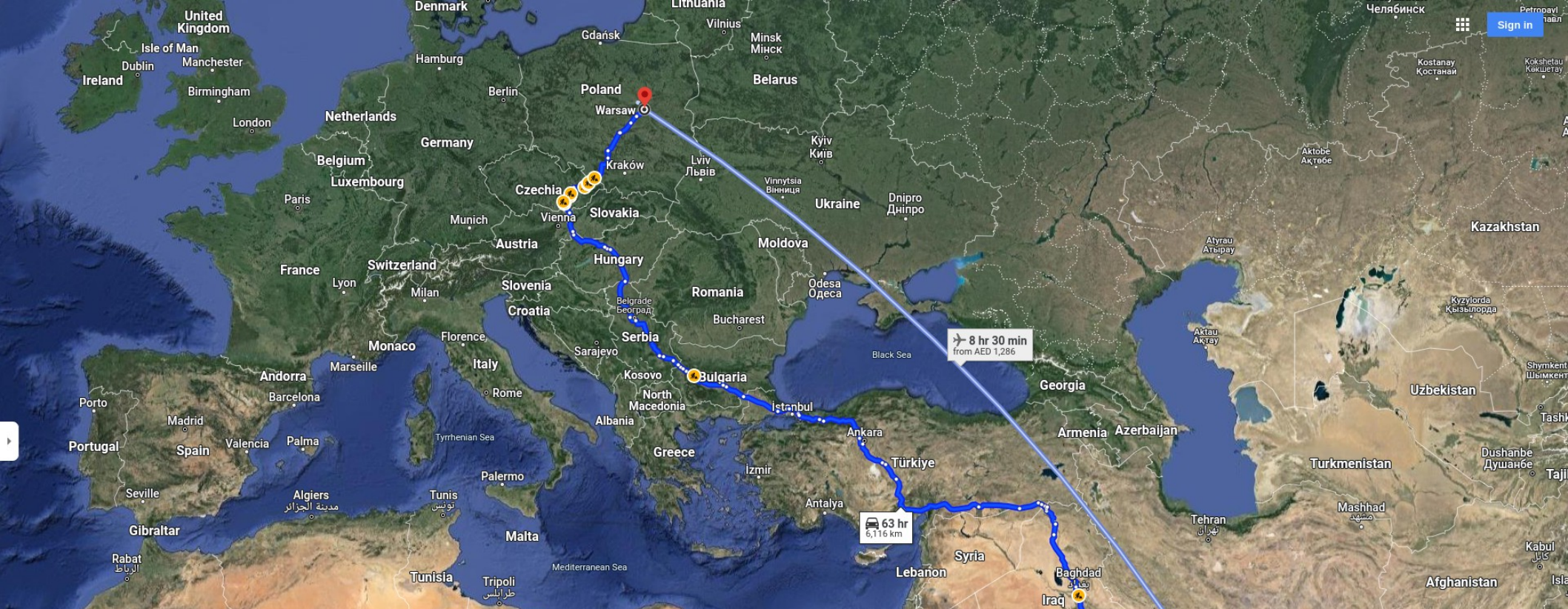
Muscat

Oman

✈ 8 hr 30 min
from AED 1,286

🚗 63 hr
6,116 km





This flight emits 38% less CO₂e than a typical flight on this route



9:10 PM
AUH

12h 25

1 stop BUD

7:35 AM⁺¹
WAW



8:10 AM
WAW

10h 25

1 stop BUD

8:35 PM
AUH

3 deals from
262 €

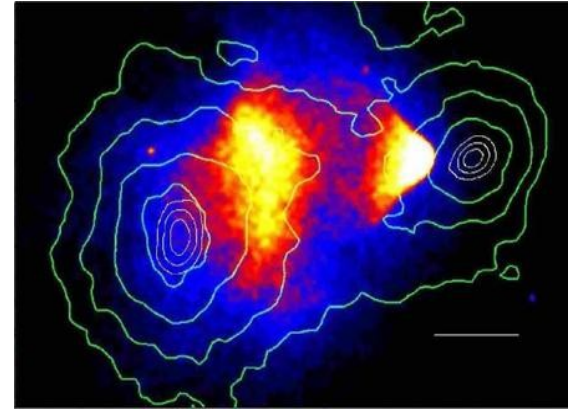
Select →

! Self-transfer

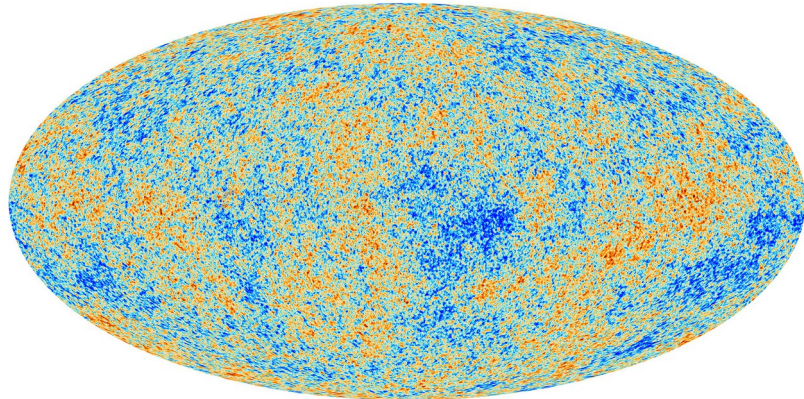
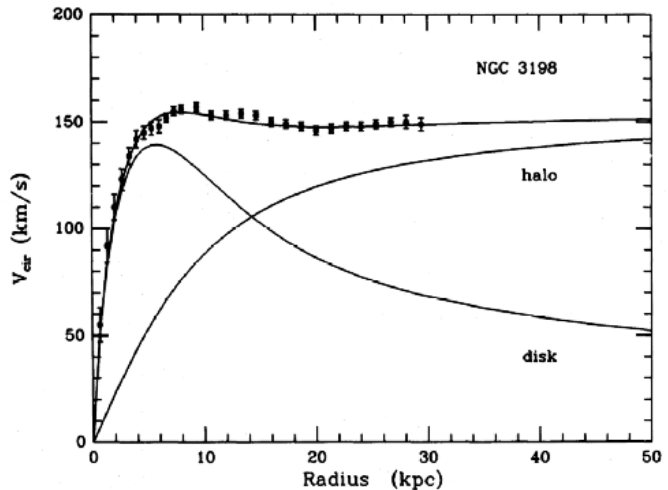
Evidences for Dark Matter

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



DISTRIBUTION OF DARK MATTER IN NGC 3198



Evidences for Dark Matter

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- * Galactic rotation curves
- * RC in Clusters of galaxies
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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

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*Dark Matter needs
New Physics beyond the Standard Model!*

What is the Dark Matter?

What is the Dark Matter?

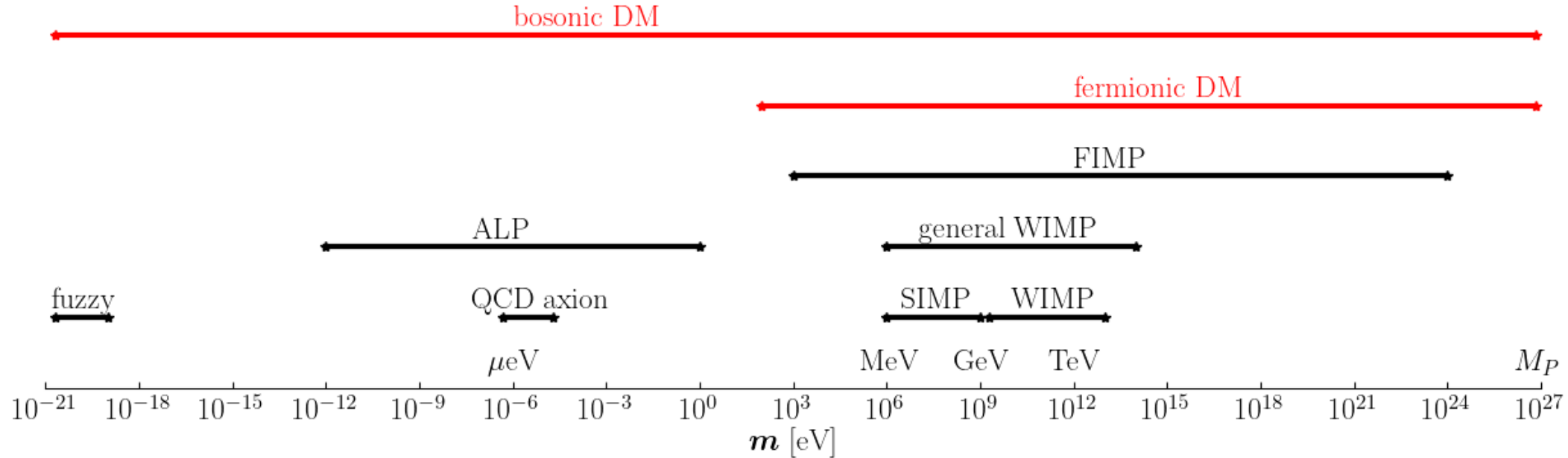
**How was Dark Matter produced
in the Early Universe?**

How was Dark Matter produced in the Early Universe?

WIMMP

Cannibal FIMP SIMP Axion WISP ALP MACHO PBHs
Asymmetric DM ELDER Non-thermal DM Composite DM

Dark Matter Mass



Le Plat du Jour

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

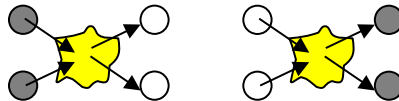
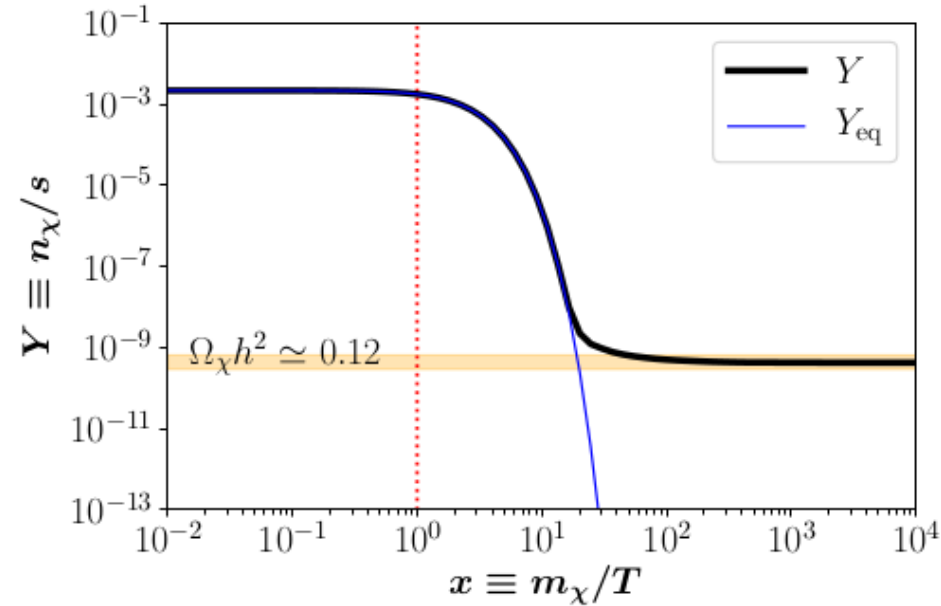
Self-interacting Massive Particles

1. WIMP DM

Weakly Interacting Massive Particle

WIMP Dark Matter

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



WIMP Dark Matter

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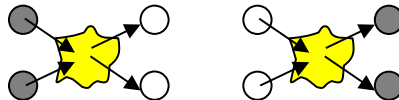
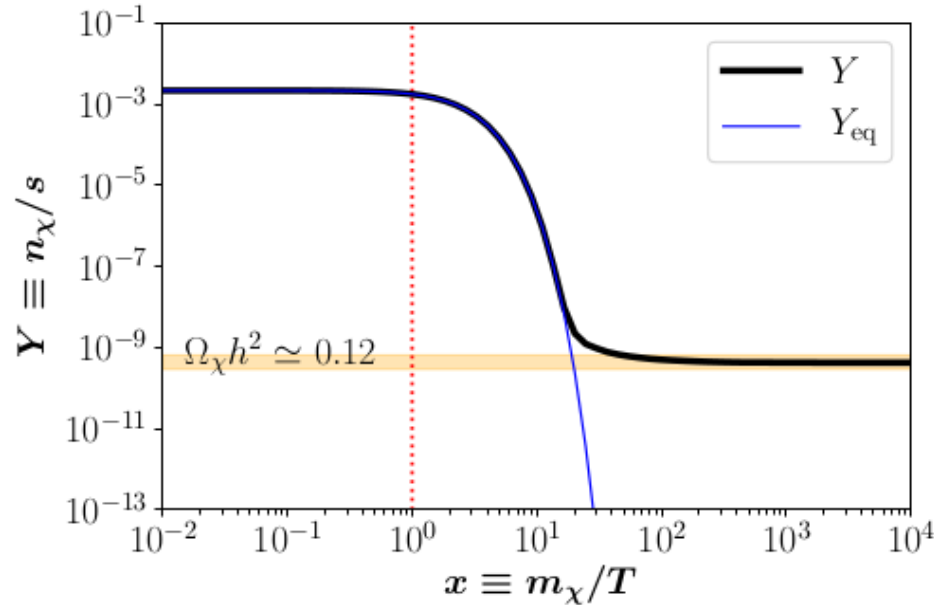
WIMP DM typically requires:

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

- * 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

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

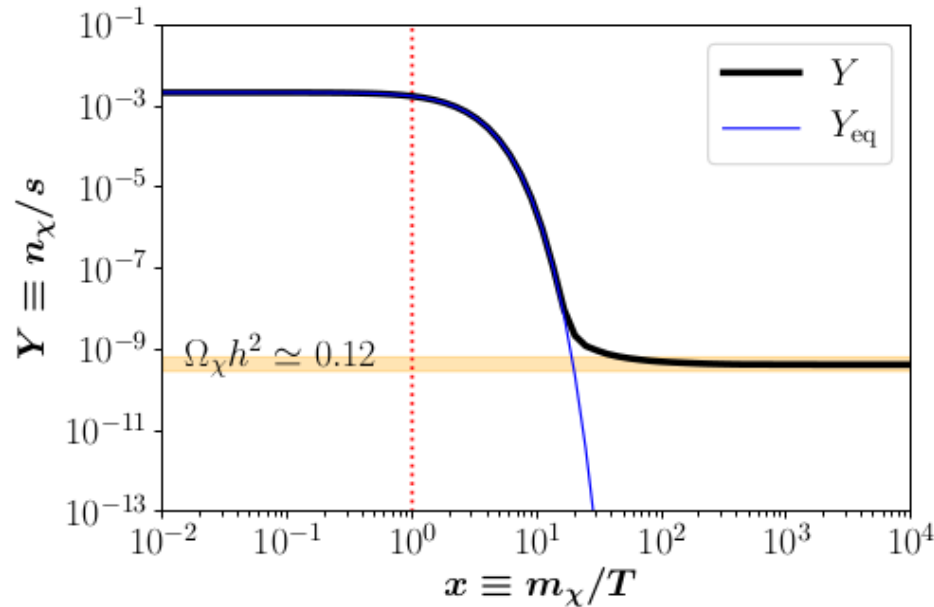
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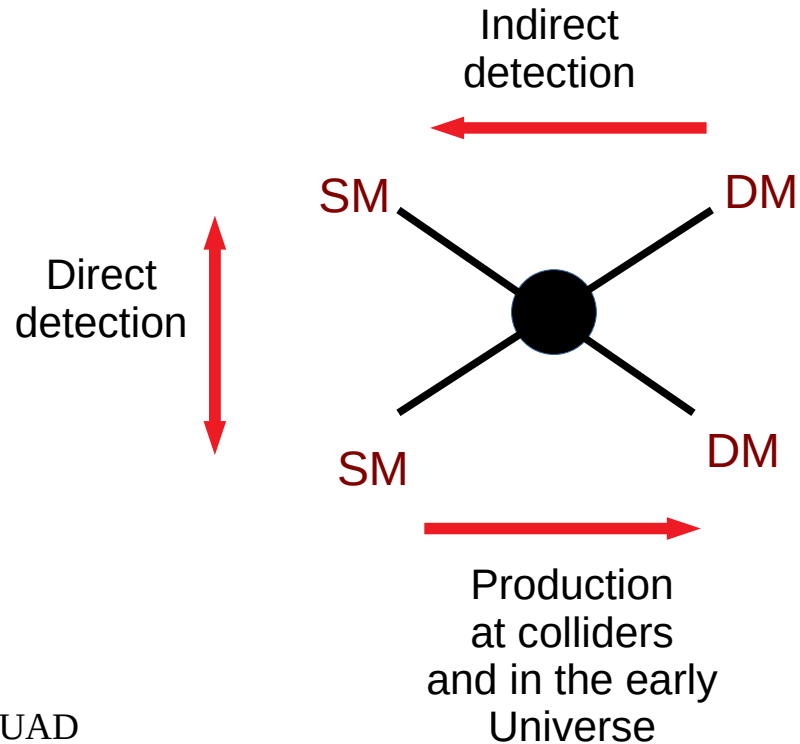
→ Independent on initial conditions!

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! :- (18

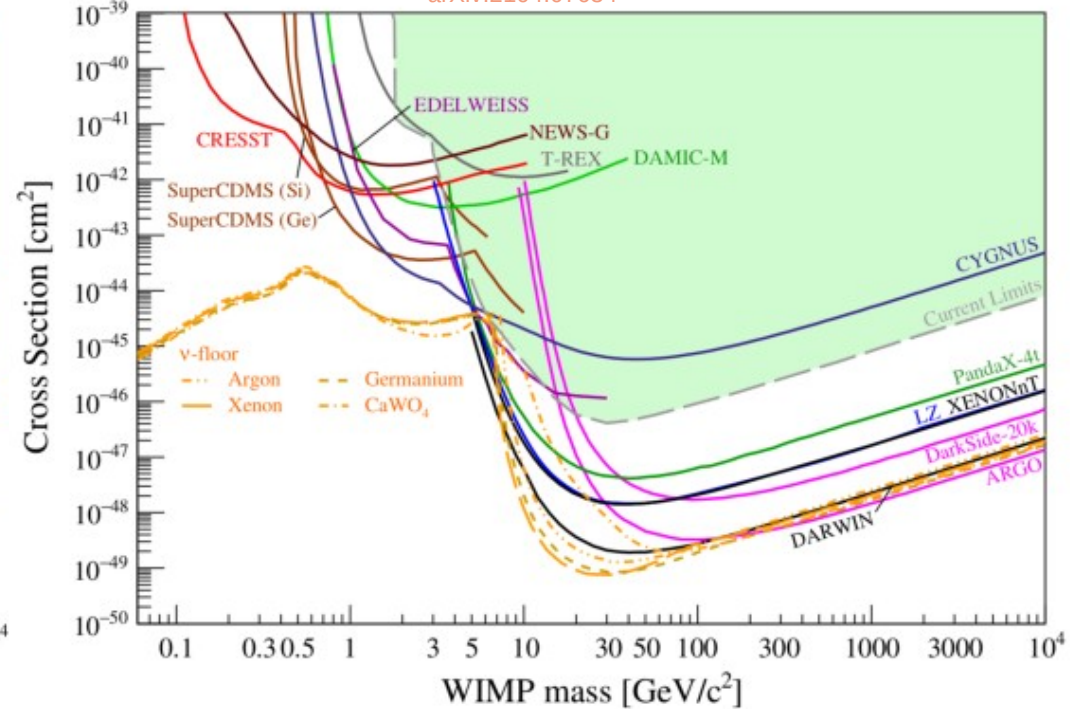
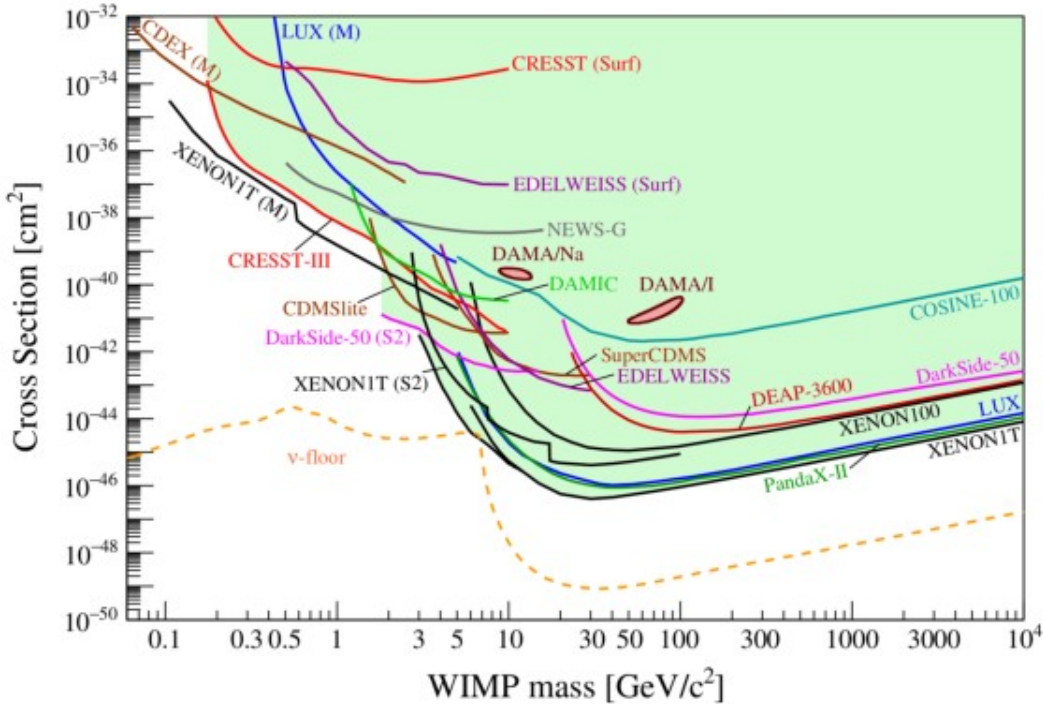


Detecting WIMPs

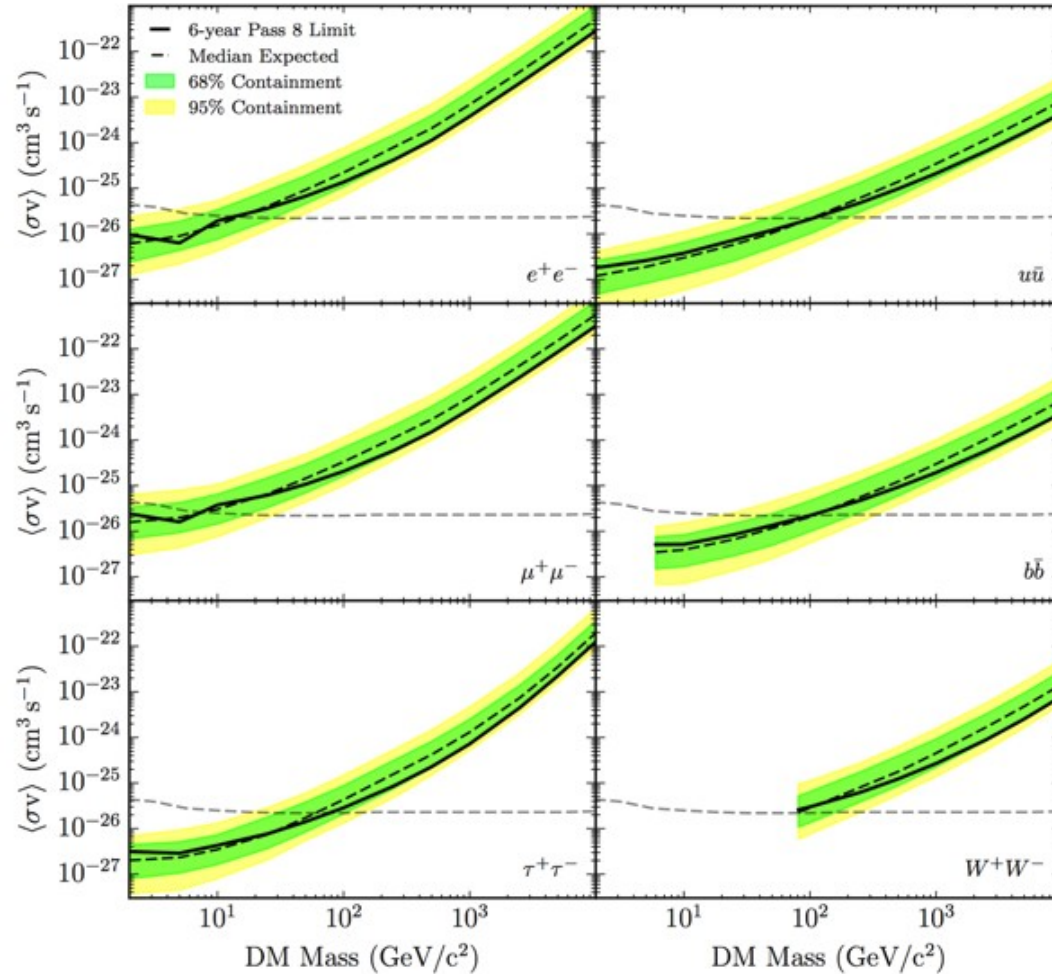


WIMP Dark Matter under Tension

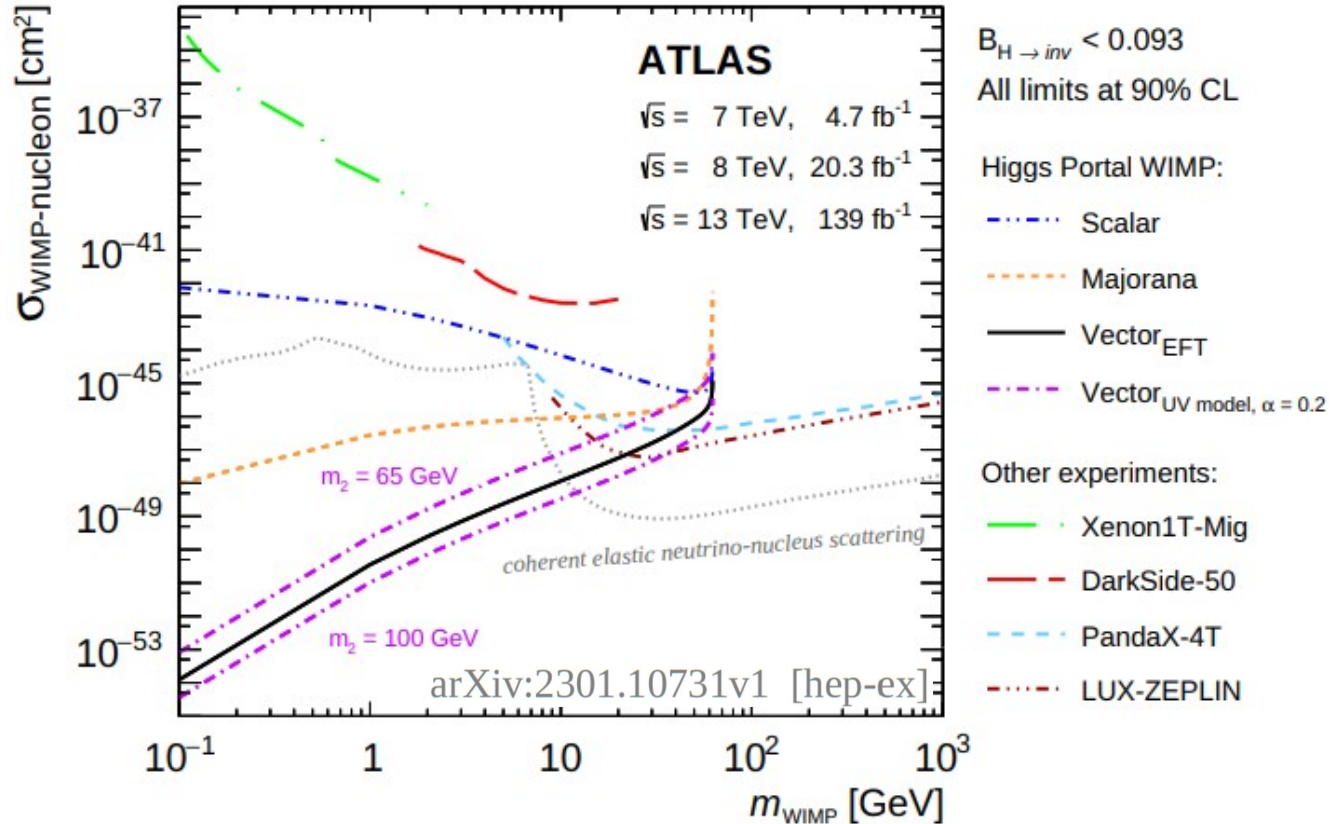
Direct detection of dark matter - APPEC committee report
arXiv:2104.07634



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 ALLAHVERDI¹, MUSTAFA A. AMIN², ASHER BERLIN³, NICOLÁS BERNAL⁴, CHRISTIAN T. BYRNES⁵, M. STEN
DELOS⁶, ADRIENNE L. ERICKCEK⁶, MIGUEL ESCUDERO⁷, DANIEL G. FIGUEROA⁸, KATHERINE FREESE^{9,10}, TOMOHIRO
HARADA¹¹, DAN HOOPER^{12,13,14}, DAVID I. KAISER¹⁵, TANVI KARWAL¹⁶, KAZUNORI KOHRI^{17,18}, GORDAN KRnjaIC¹², MAREK
LEWICKI^{7,19}, KALOIAN D. LOZANOV²⁰, VIVIAN POULIN²¹, KUVAR SINHA²², TRISTAN L. SMITH²³, TOMO TAKAHASHI²⁴,
TOMMI TENKANEN^{25,a}, JAMES UNWIN²⁶, VILLE VASKONEN^{7,27,a}, AND SCOTT WATSON²⁸

Nicolás BERNAL @ NYUAD

23

arXiv:2006.16182v2 [astro-ph.CO]

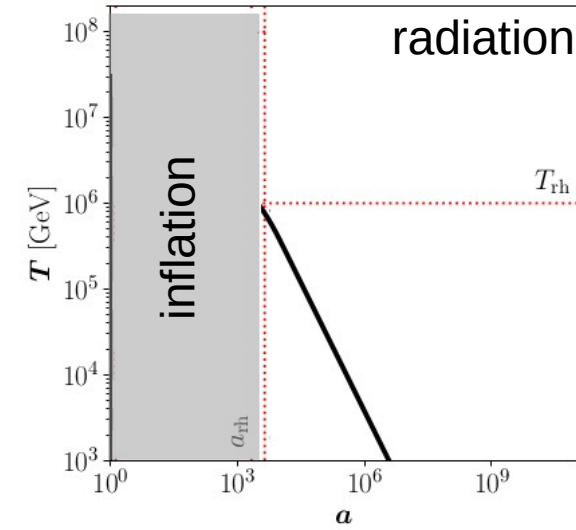
Standard Cosmology

- * 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 $T \sim 10^{10} \text{ GeV}$ (?)
 - SM entropy conserved
 - early universe dominated by SM radiation
 - instantaneous reheating

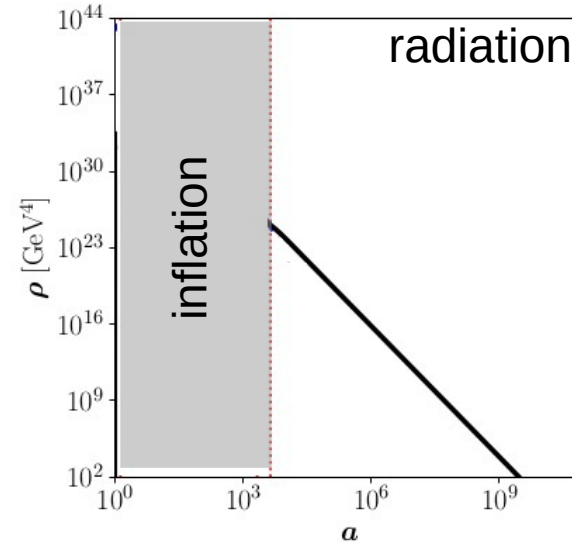
Simplest! Standard Cosmology

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Standard Cosmology

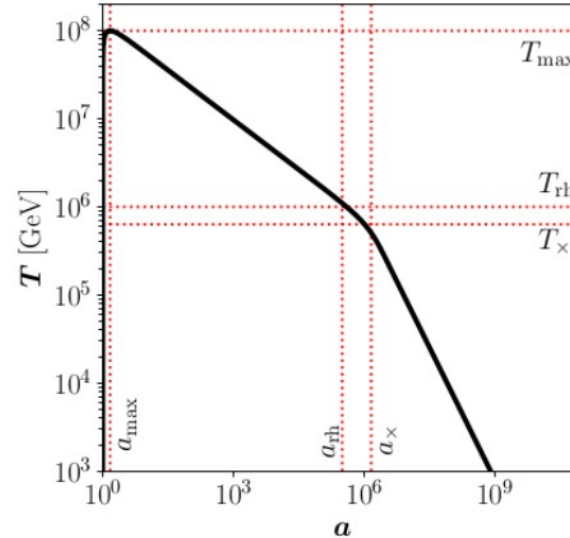
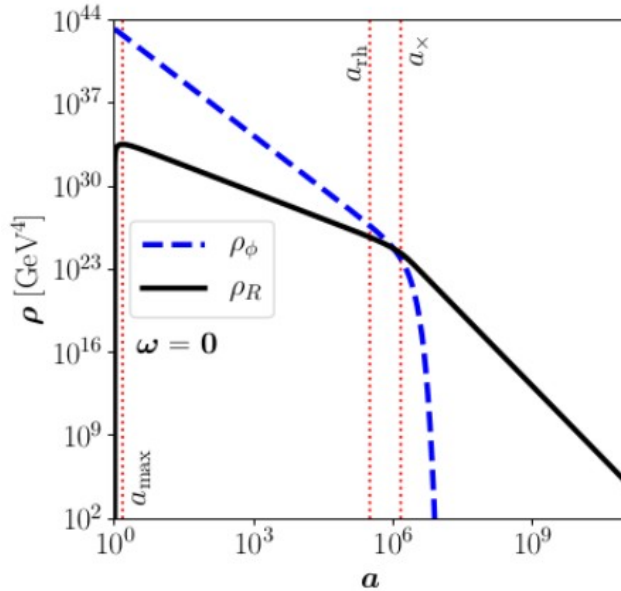


$$T \sim 1/a$$



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

Non-instantaneous Reheating

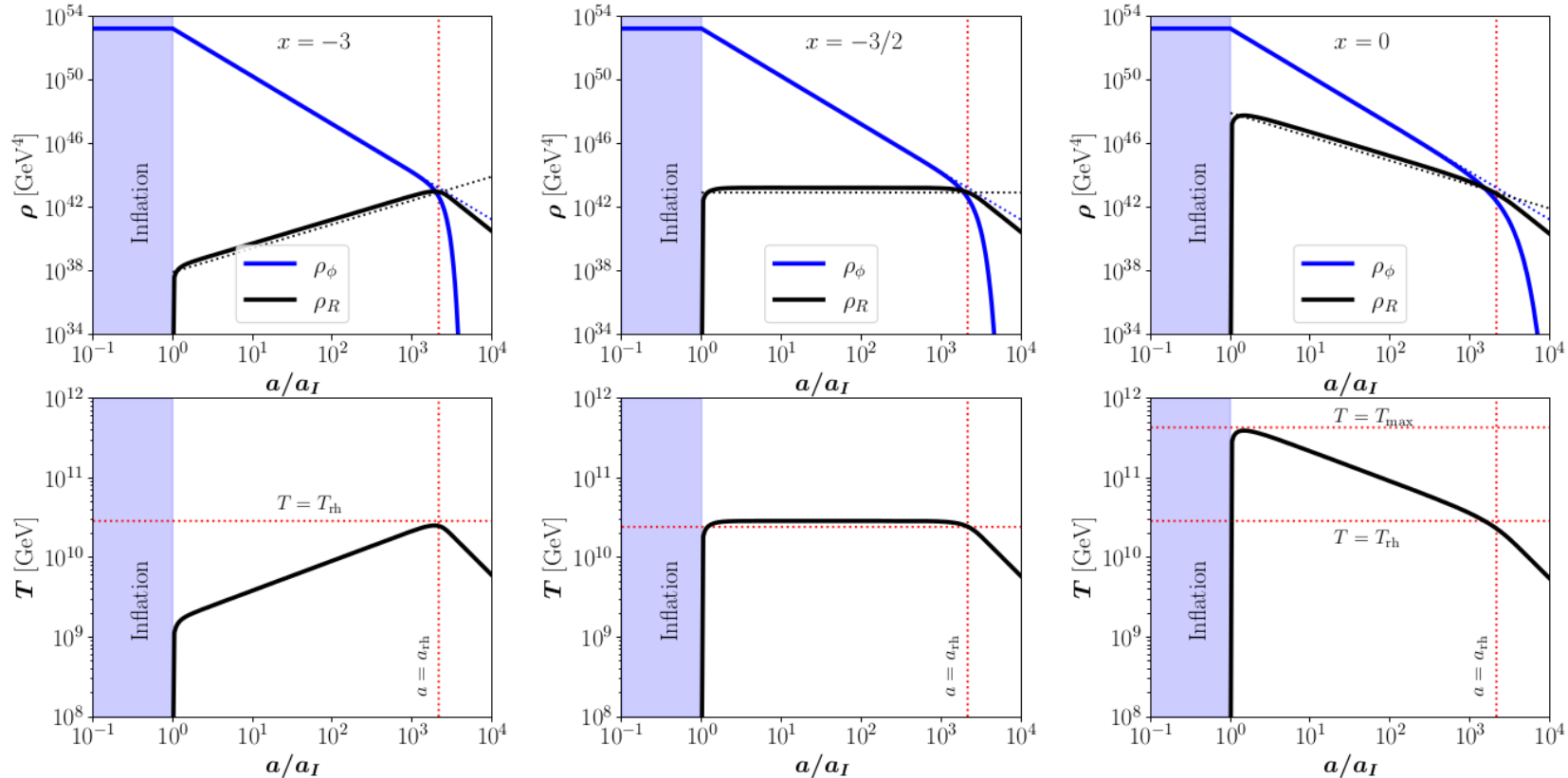


Decay or annihilation of inflatons into SM radiation is a *continuous process*

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

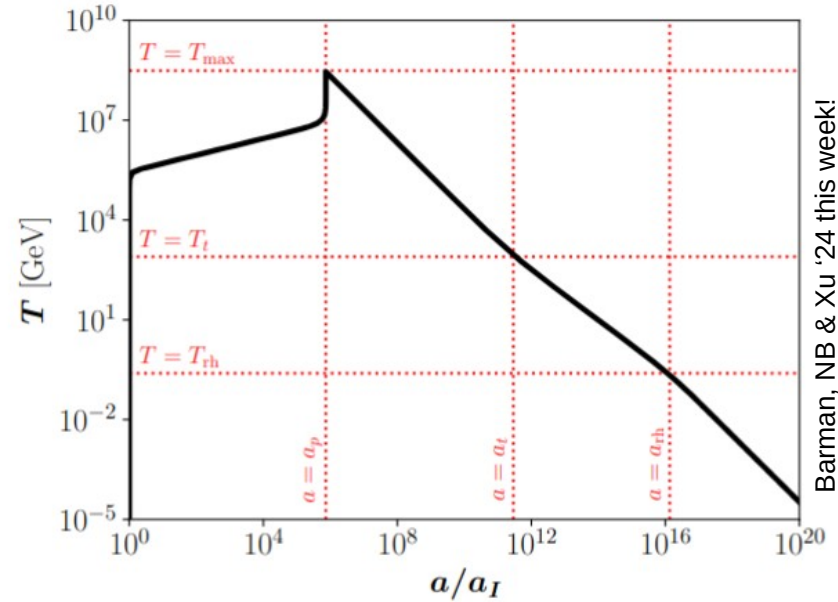
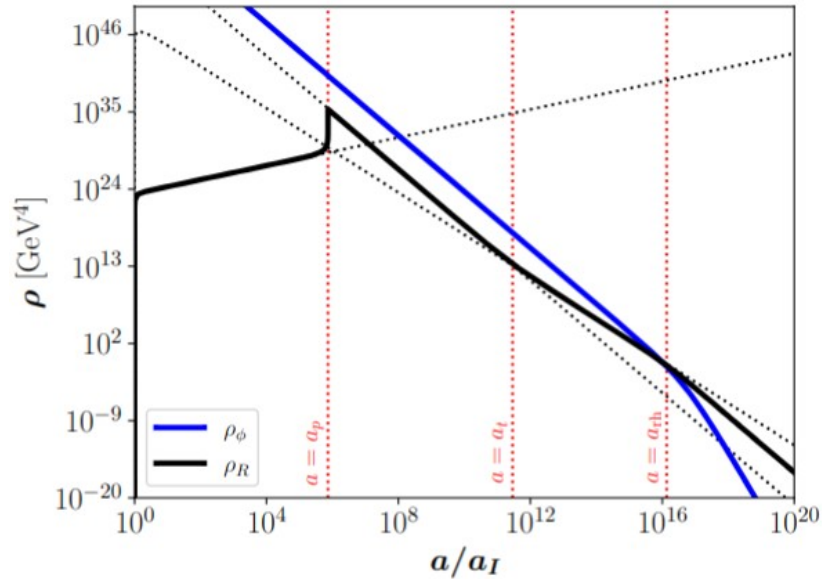
$$\frac{d\rho_R}{dt} + 4 H \rho_R = +\Gamma_\phi \rho_\phi$$

Non-instantaneous Reheating



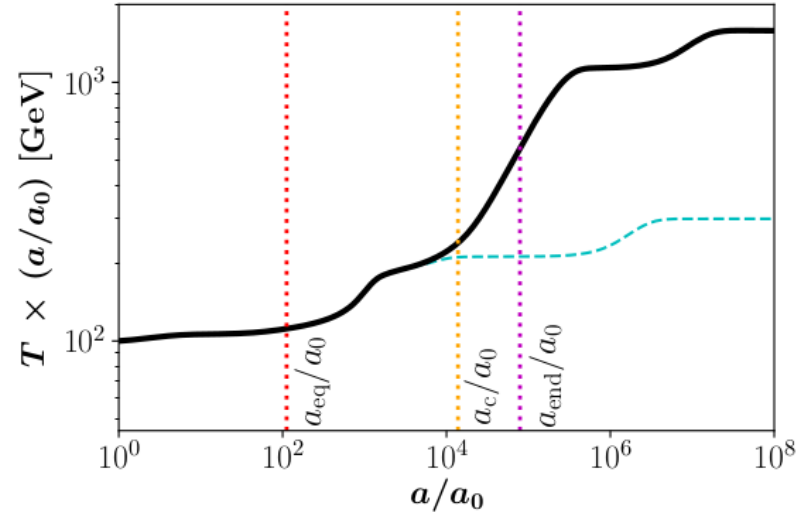
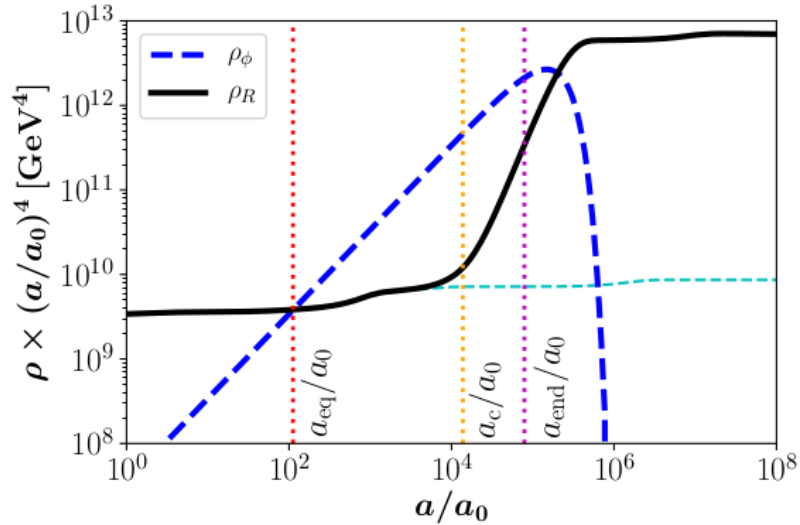
Barman, NB, Xu & Zapata '22

Non-instantaneous Reheating



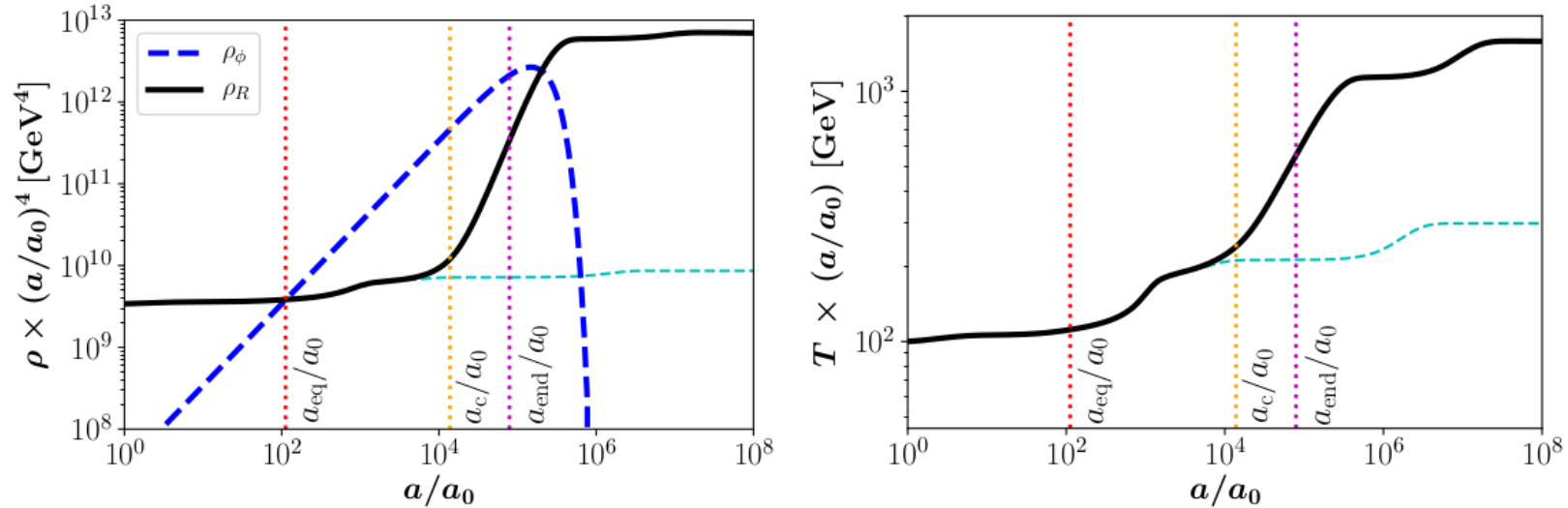
Barman, NB & Xu '24 this week!

Non-standard Cosmologies: EMD



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

Non-standard Cosmologies: EMD



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- * Entropy injection

Multiple possible sources:

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

Entr'acte 1: Standard vs Non-standard Cosmologies

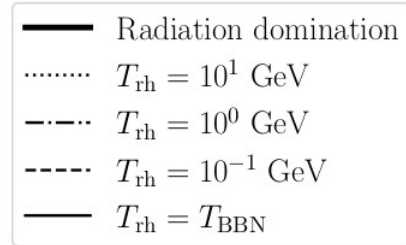
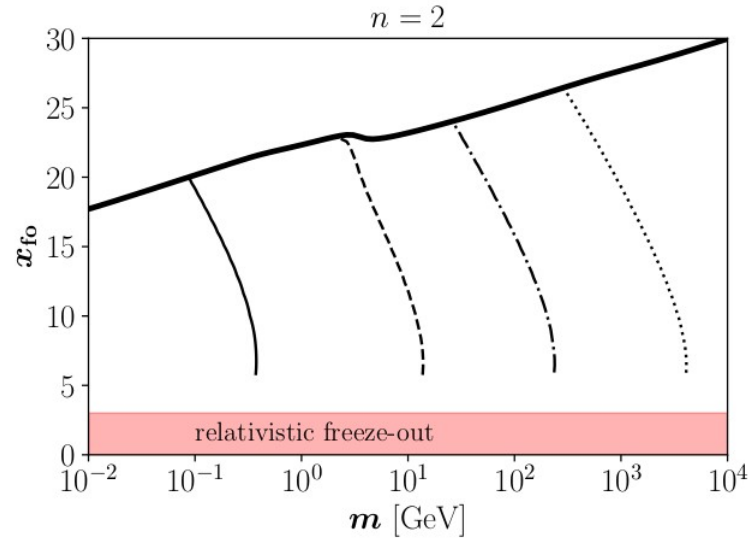
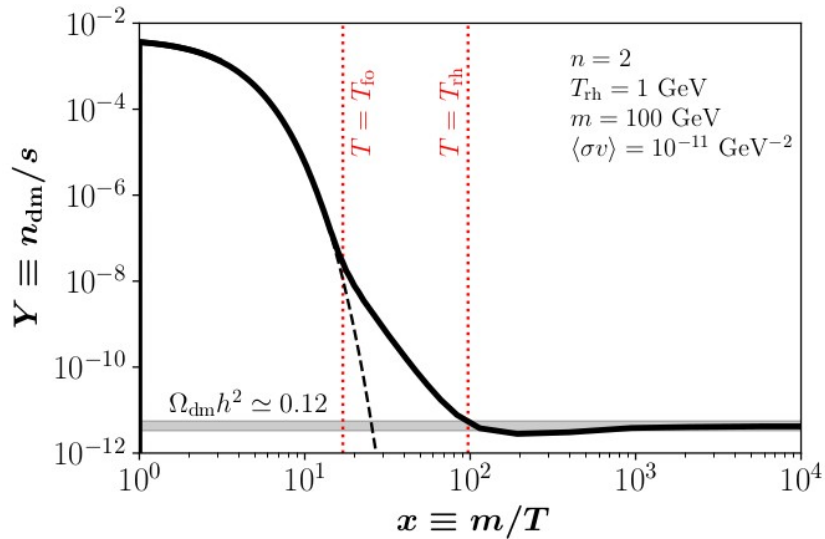


WIMPs in Non-standard Cosmologies

$$\frac{d\rho_\phi}{dt} + \frac{6n}{2+n} H \rho_\phi = -\frac{2n}{2+n} \Gamma_\phi \rho_\phi$$

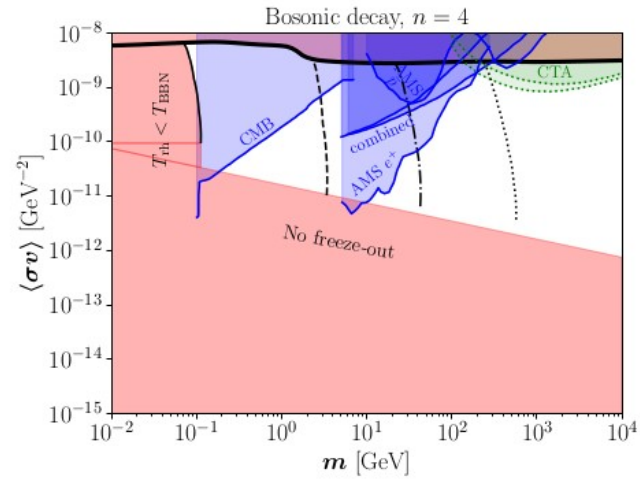
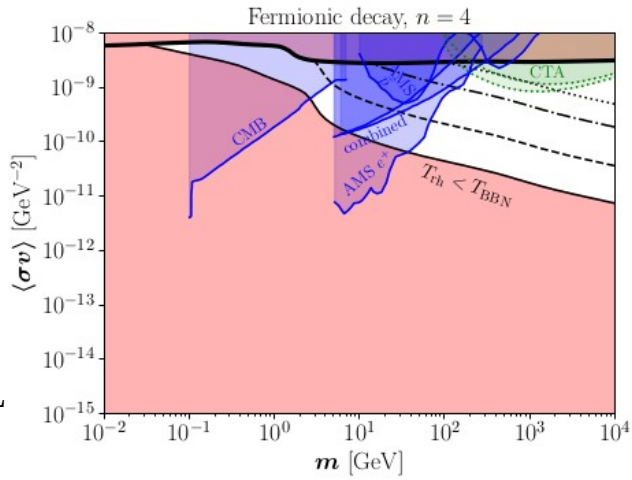
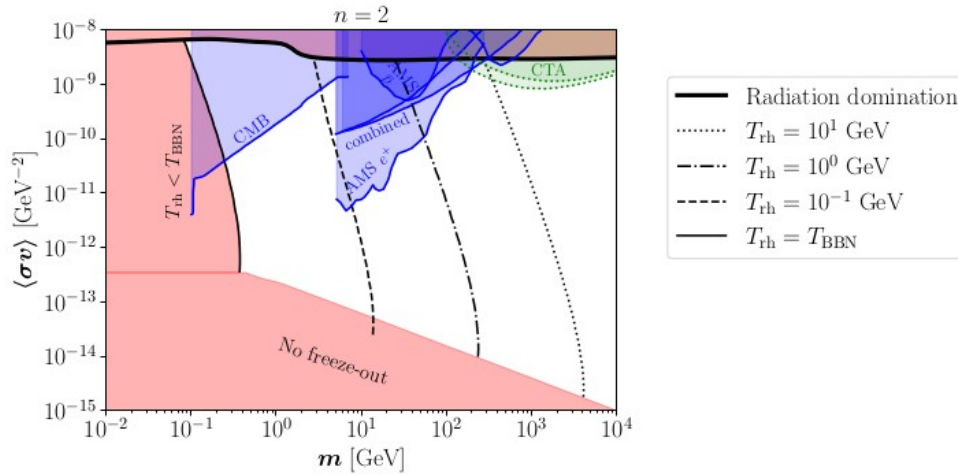
$$\frac{d\rho_R}{dt} + 4H \rho_R = +\frac{2n}{2+n} \Gamma_\phi \rho_\phi$$

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

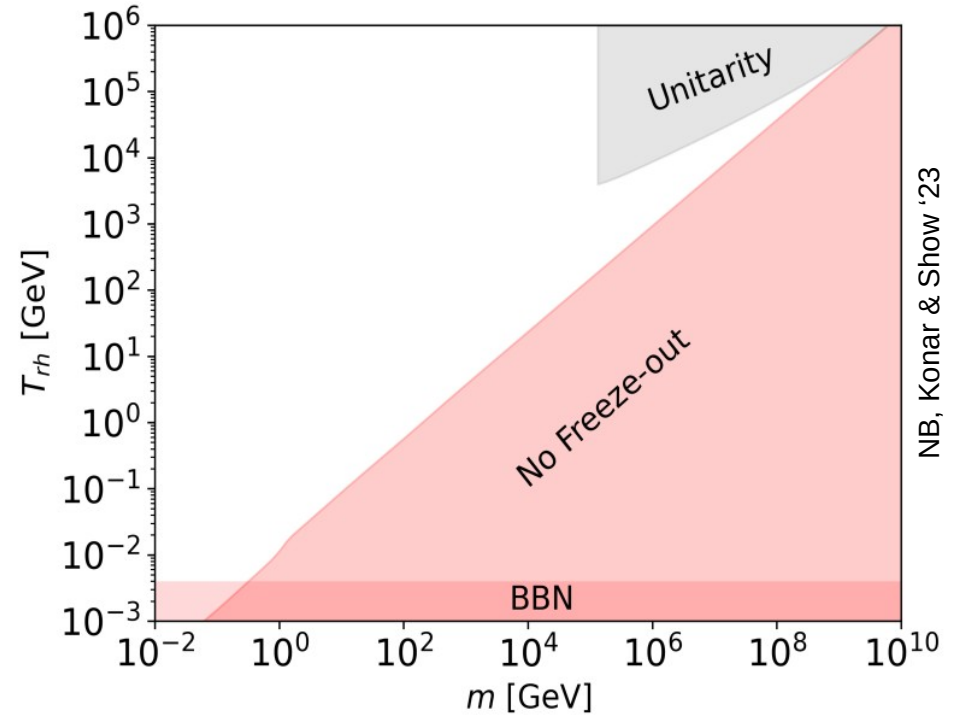
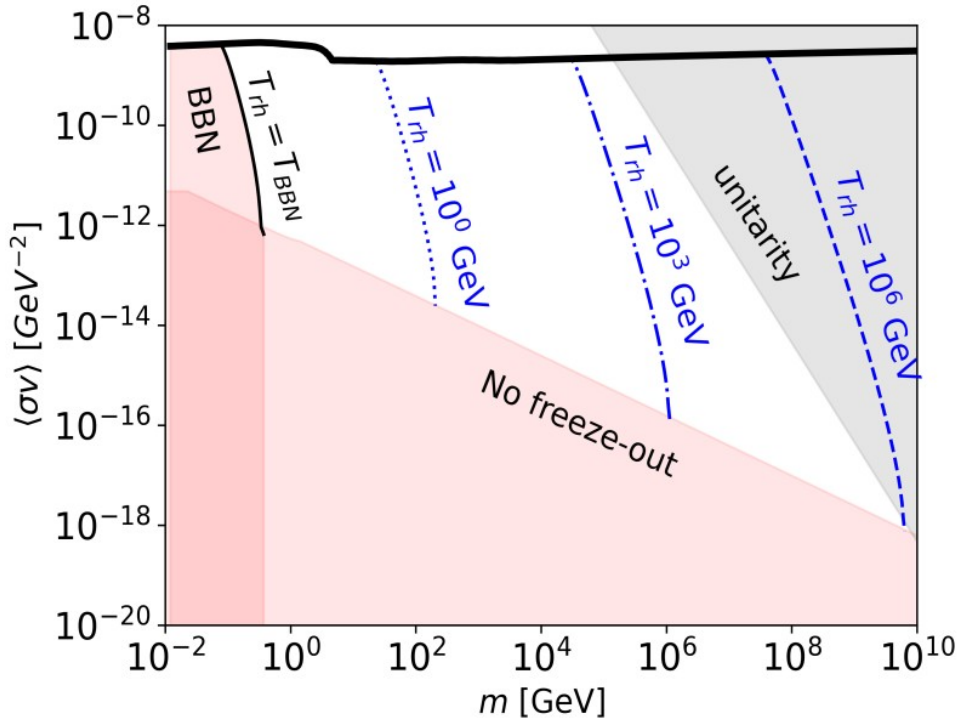


NB, Xu '22

WIMPs in Non-standard Cosmologies



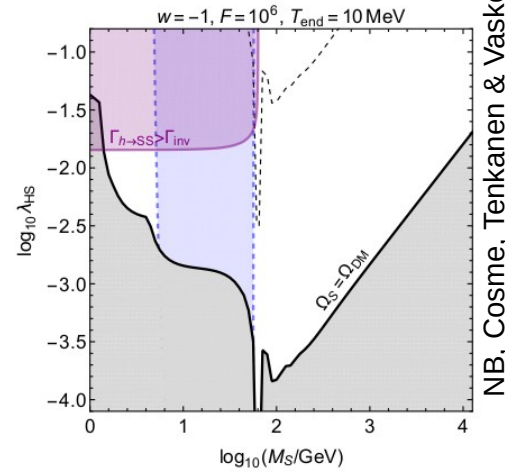
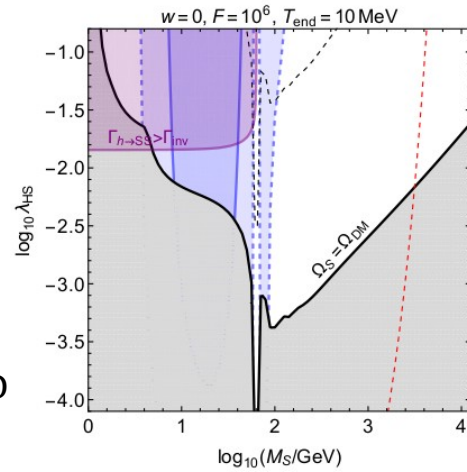
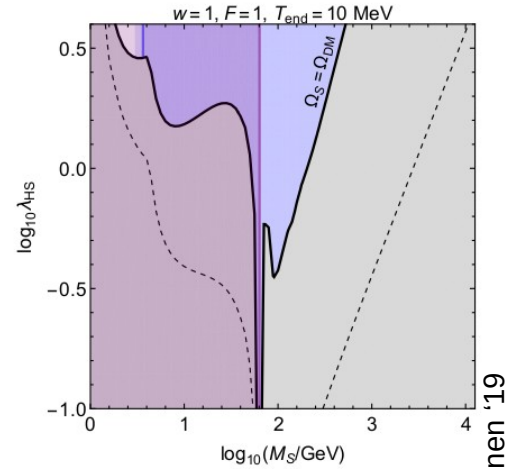
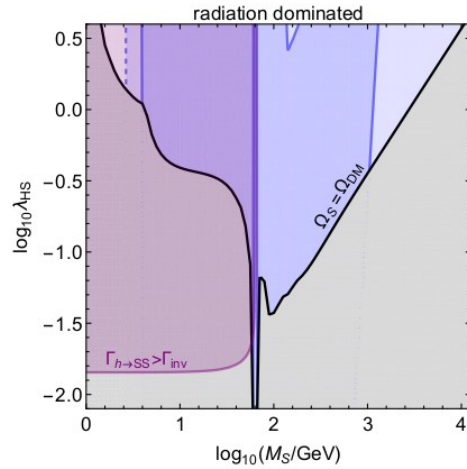
WIMPs in Non-standard Cosmologies



NB, Konar & Show '23

WIMPs in Non-standard Cosmologies

Singlet scalar
DM model



NB, Cosme, Tenkanen & Vaskonen '19

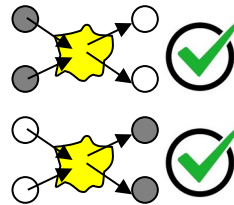
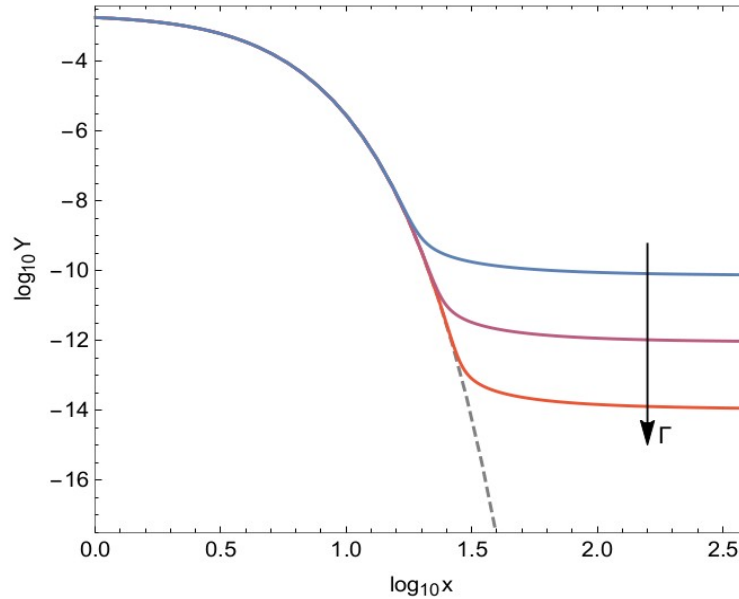
2. FIMP DM

Feebly Interacting Massive Particle

**The Dawn of FIMP Dark Matter:
A Review of Models and Constraints**
NB, Heikinheimo, Tenkanen, Tuominen & Vaskonen '17

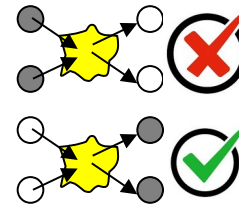
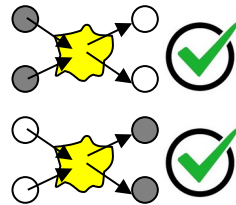
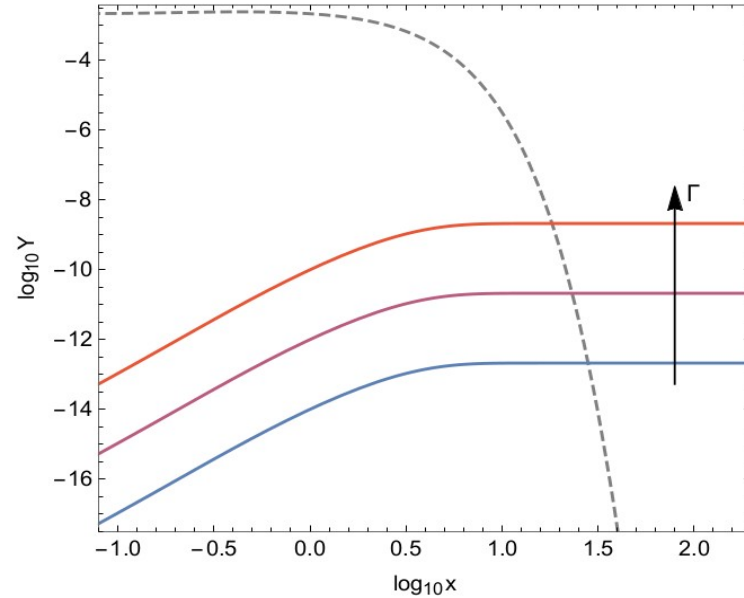
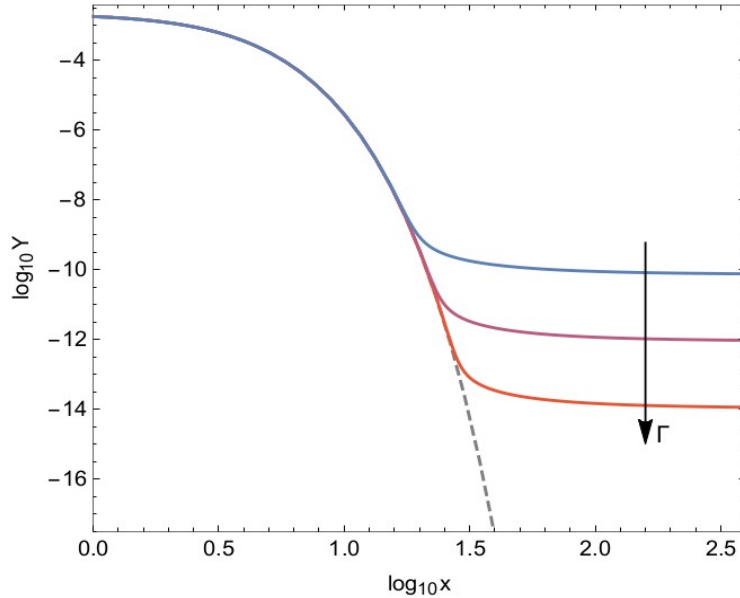
WIMP vs FIMP Dark Matter

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



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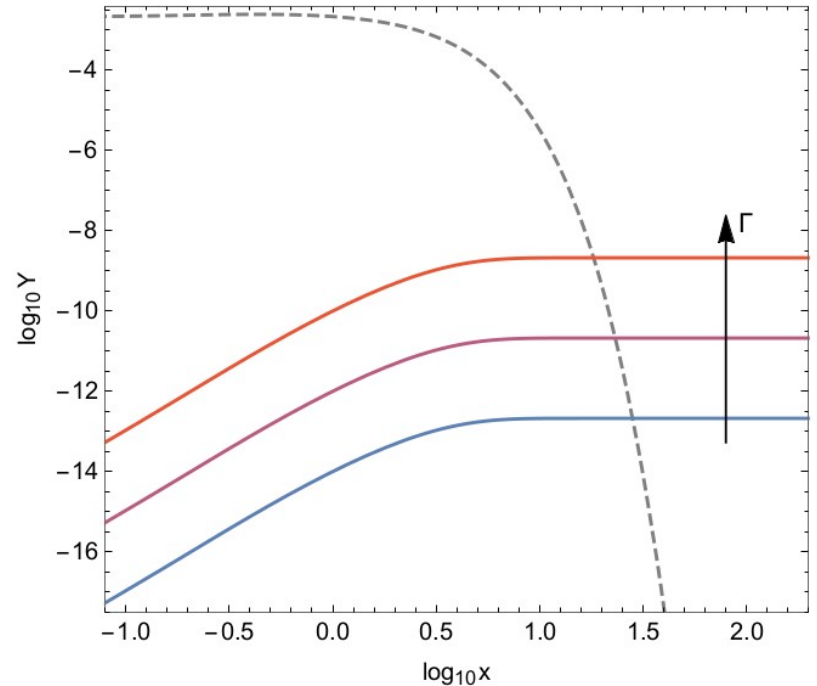
FIMP Dark Matter

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

FIMP DM typically requires:

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

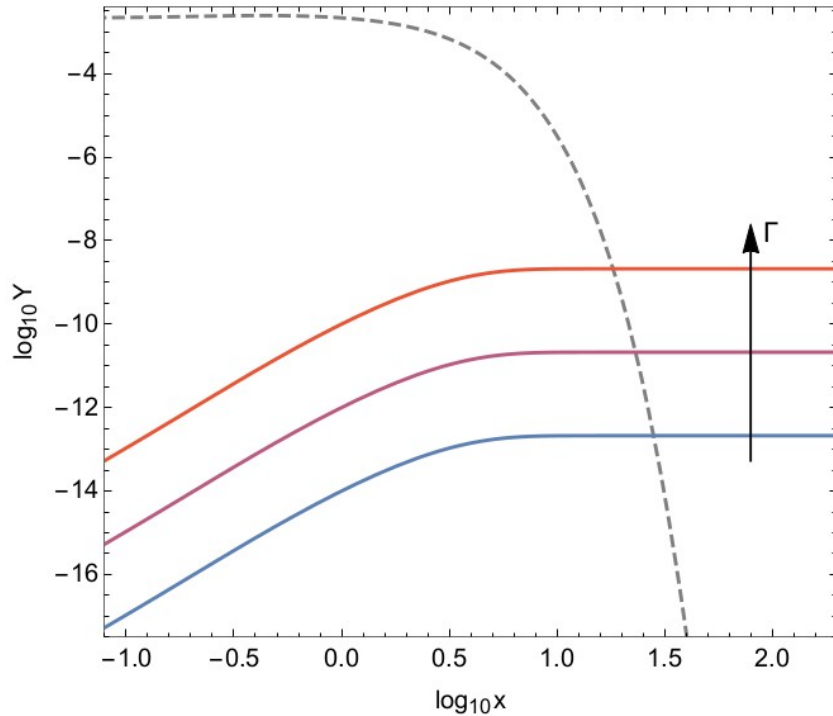
→ Dependent of initial conditions!



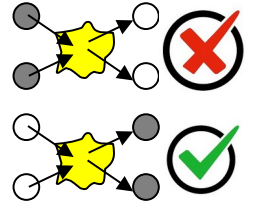
2a. Infrared FIMPs

Feebly Interacting Massive Particles

IR FIMP paradigm



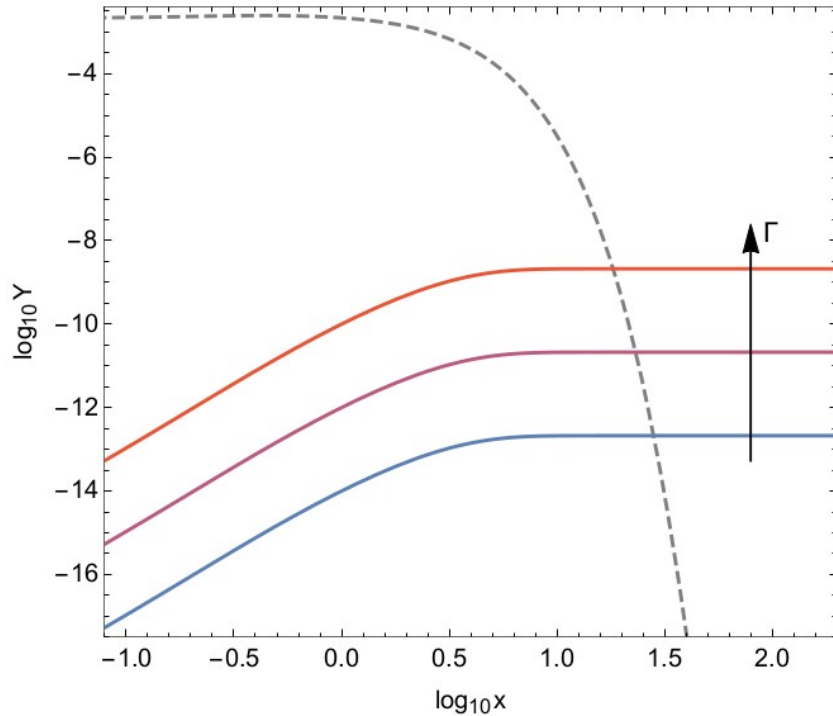
$$\frac{dn}{dt} + 3Hn = -\langle\sigma v\rangle (n^2 - n_{\text{eq}}^2)$$



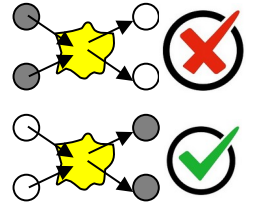
- * chemical equilibrium never reached
- * **renormalizable** operators
- * masses: keV to $\sim M_{\text{P}}$
- * $\lambda_{\text{DM-SM}} \sim 10^{-11}$
- * $T_{\text{fi}} \sim m$

→ (mild) dependence from initial conditions

IR FIMP paradigm



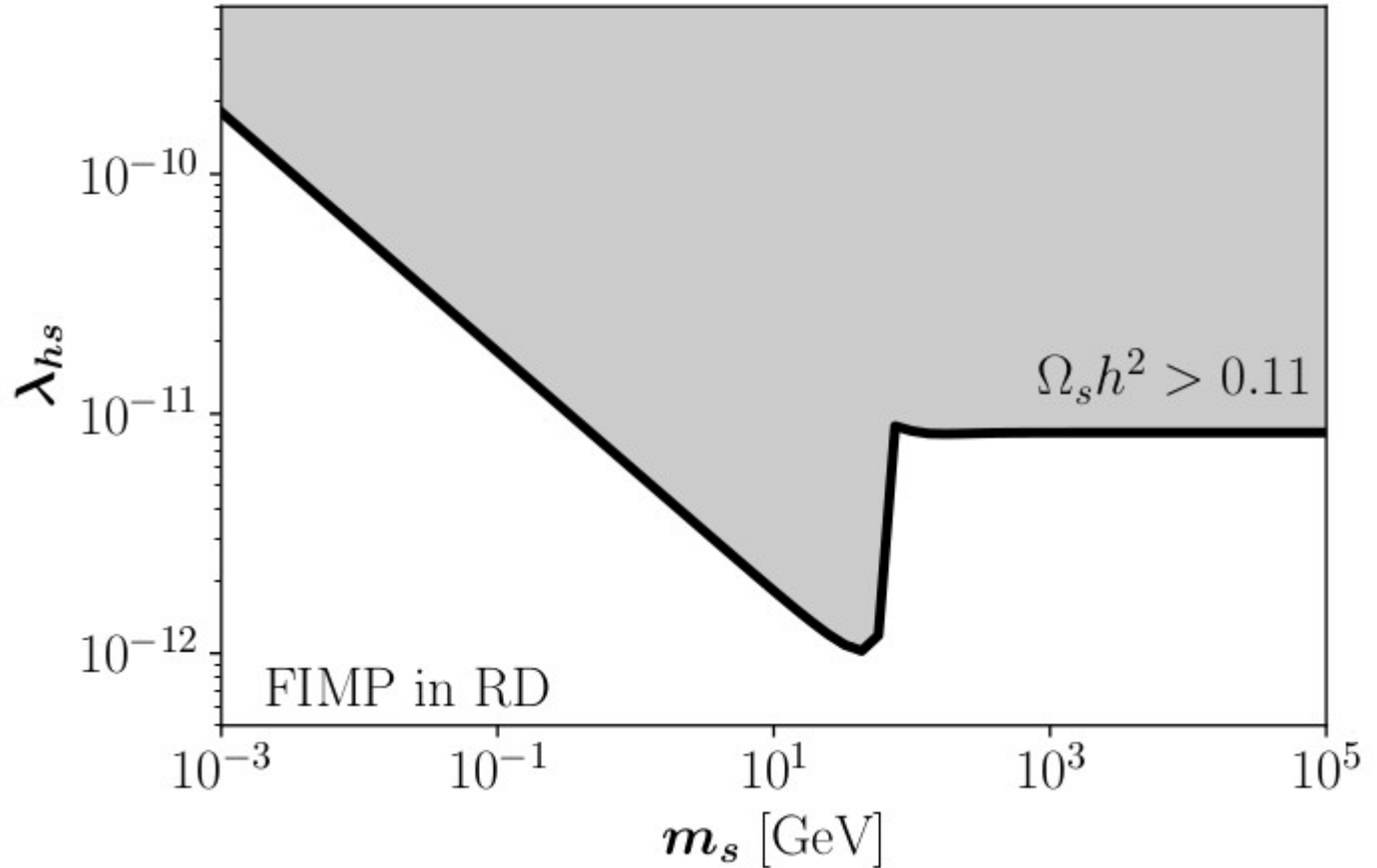
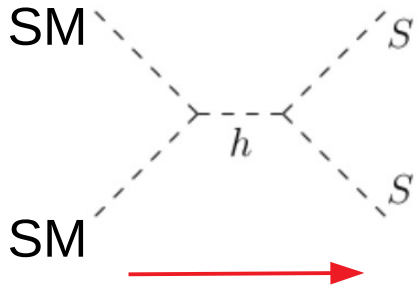
$$\frac{dn}{dt} + 3Hn = -\langle\sigma v\rangle (n^2 - n_{\text{eq}}^2)$$



- * chemical equilibrium never reached
- * **renormalizable** operators
- * masses: keV to $\sim M_{\text{P}}$
- * $\lambda_{\text{DM-SM}} \sim 10^{-11}$ ← “Unnaturally” small...
but could be *technically natural!*
- * $T_{\text{fi}} \sim m$

→ (mild) dependence from initial conditions

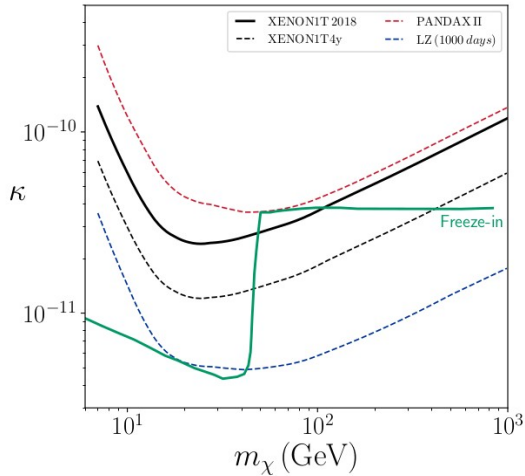
Singlet Scalar DM - FIMP



Detecting FIMPs

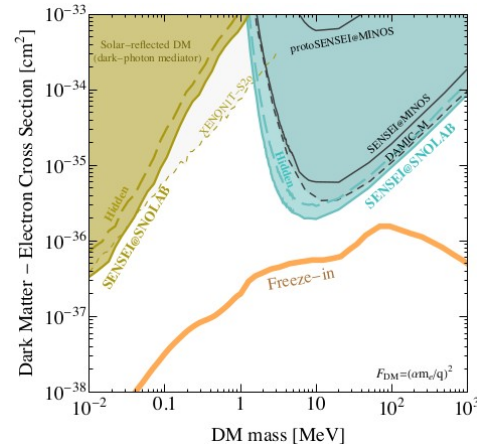
By construction, very challenging to test...

Hambye+ '18



Light mediators

Sensei '23

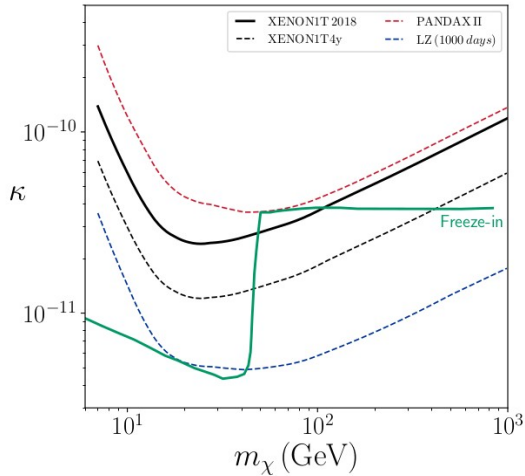


MeV dark matter

Detecting FIMPs

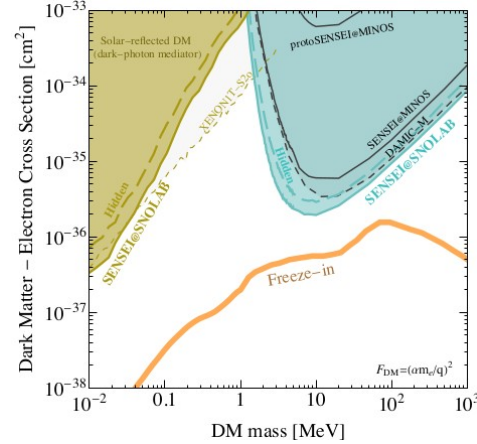
By construction, very challenging to test...

Hambye+ '18



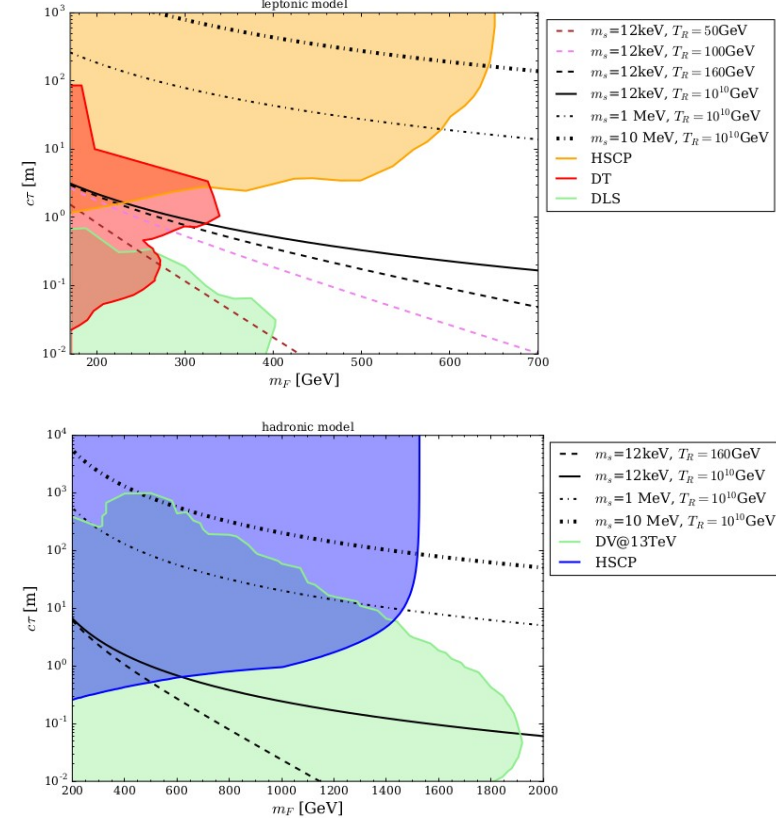
Light mediators

Sensei '23



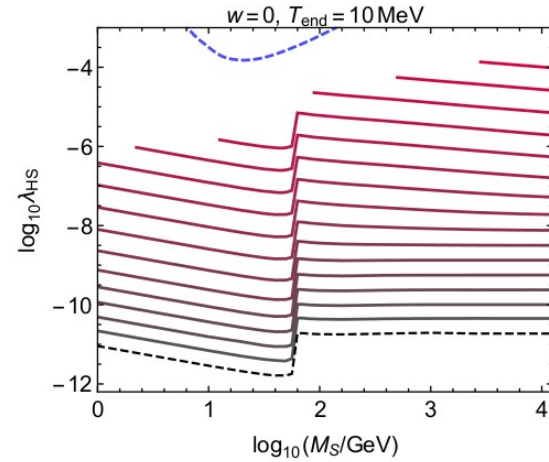
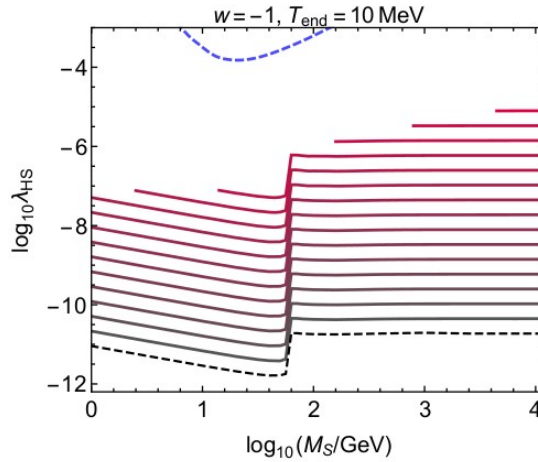
MeV dark matter

Bélangier+ '18

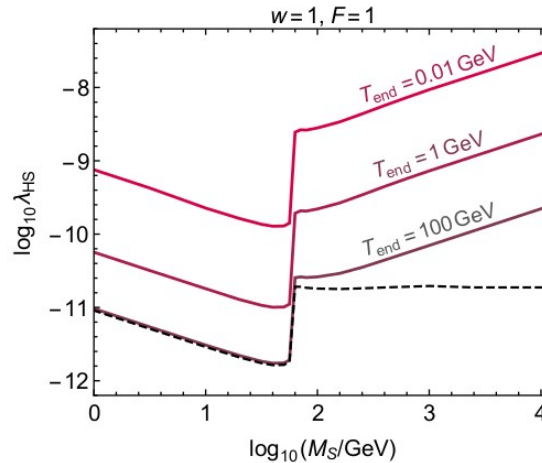


IR FIMPs in Non-standard Cosmologies

Singlet scalar
DM model

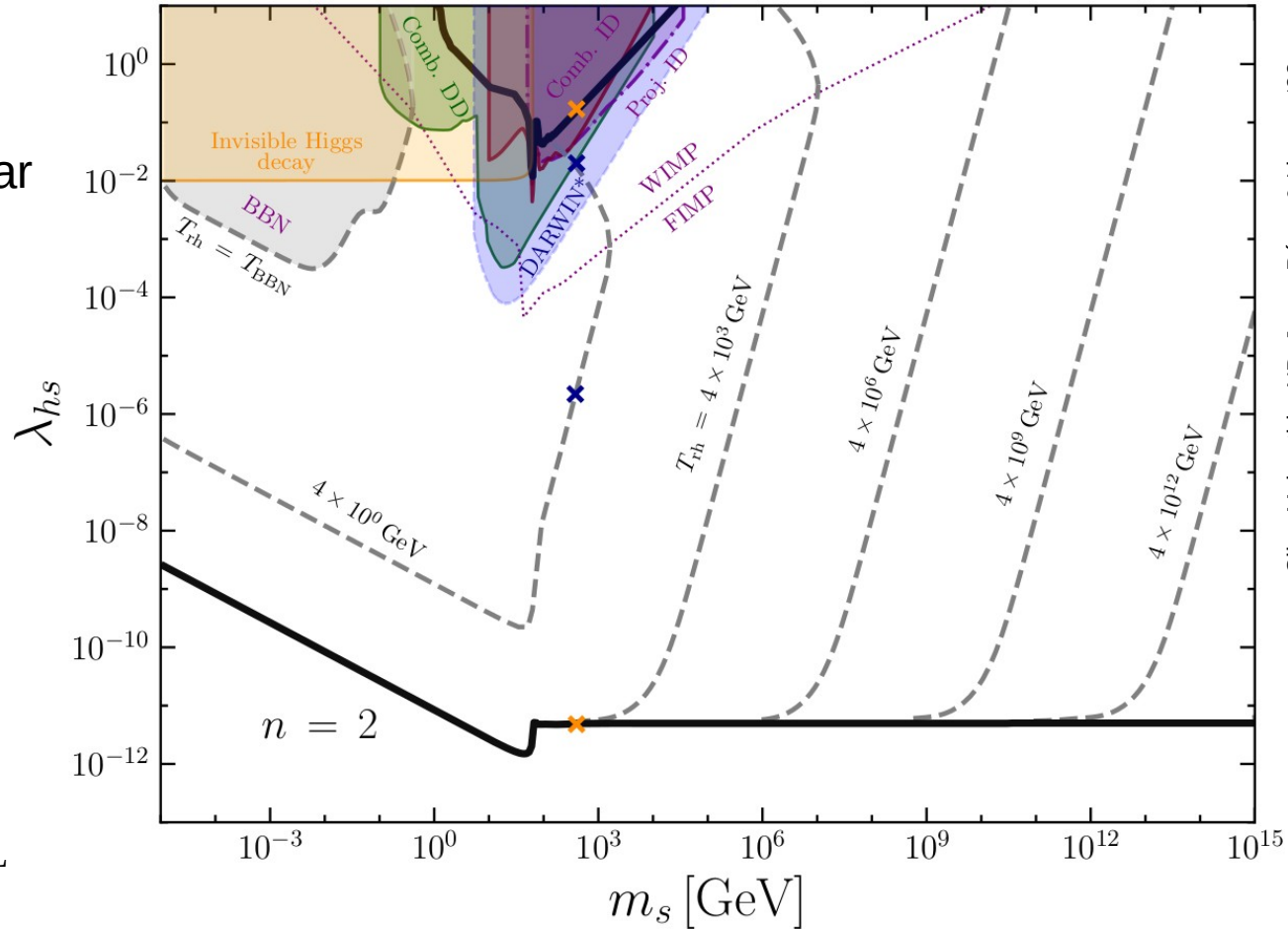


NB, Cosme, Tenkanen & Vaskonen '19



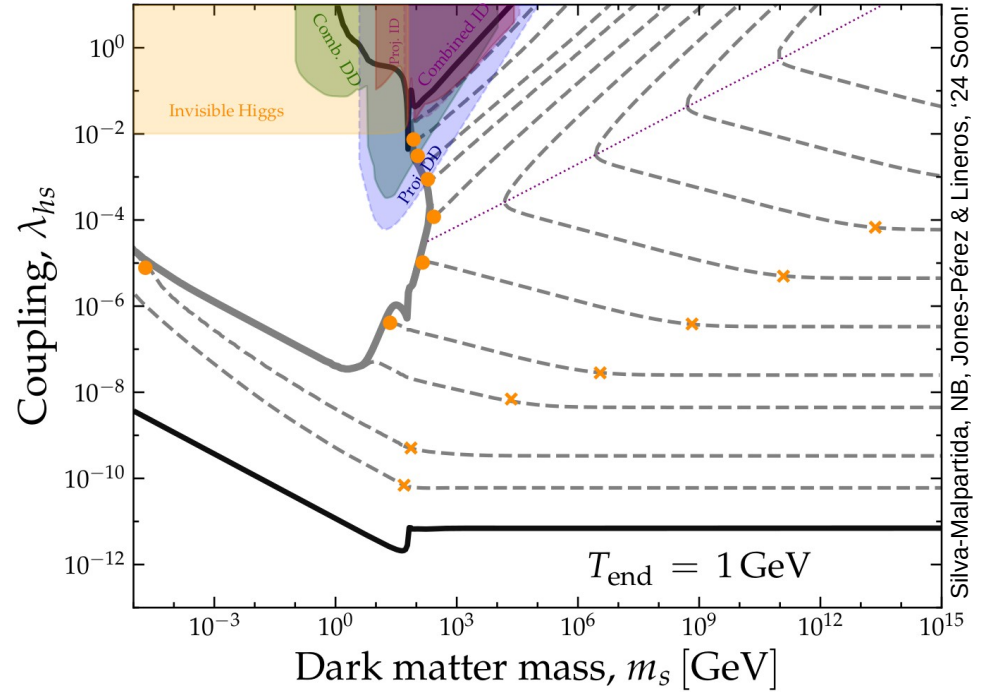
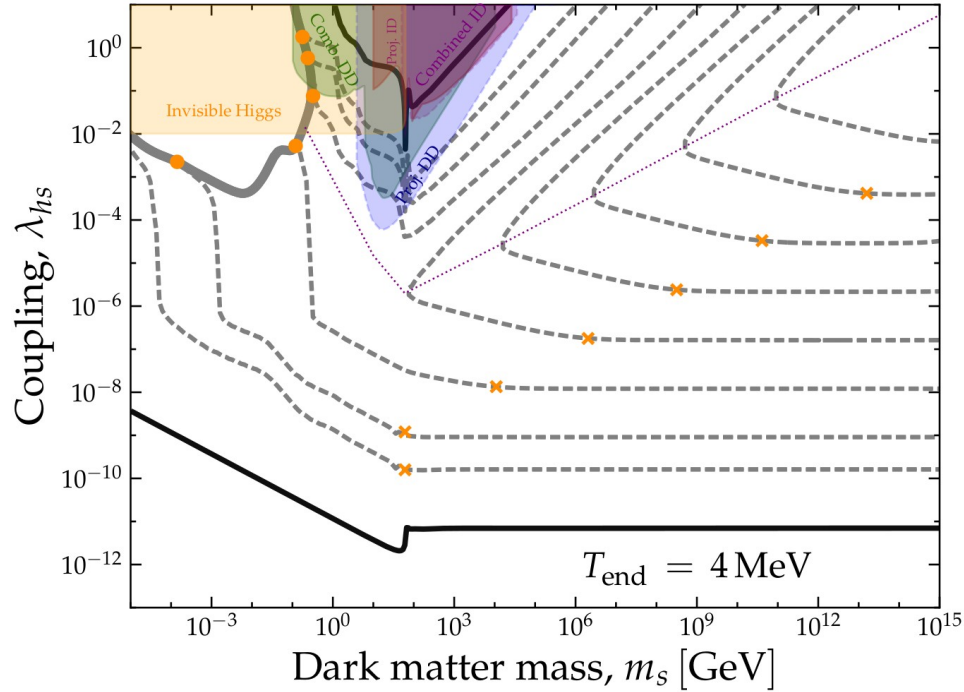
WIMPs and FIMPs with Low-temperature reheating

Singlet scalar
DM model



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

WIMPs and FIMPs in Non-standard Cosmologies

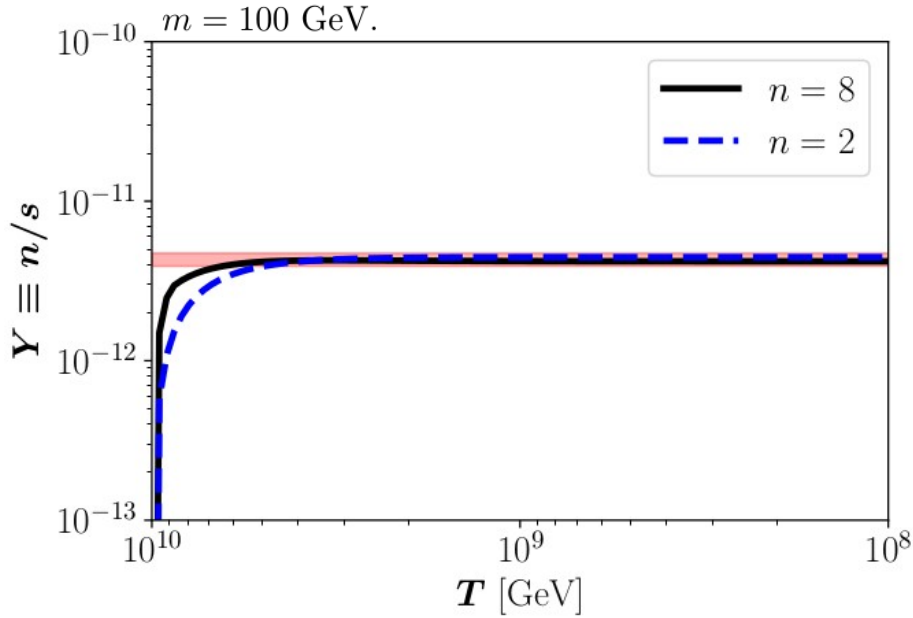


Singlet scalar
DM model

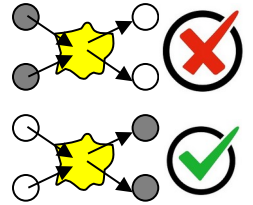
2b. Ultraviolet FIMPs

Feebly Interacting Massive Particles

UV FIMP paradigm



$$\frac{dn}{dt} + 3Hn = -\langle\sigma v\rangle (n^2 - n_{\text{eq}}^2)$$

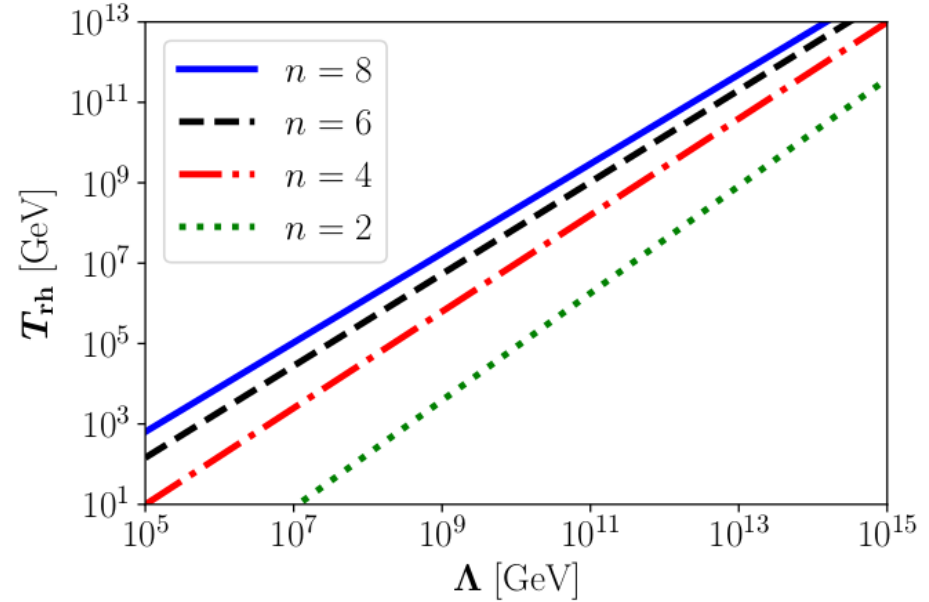
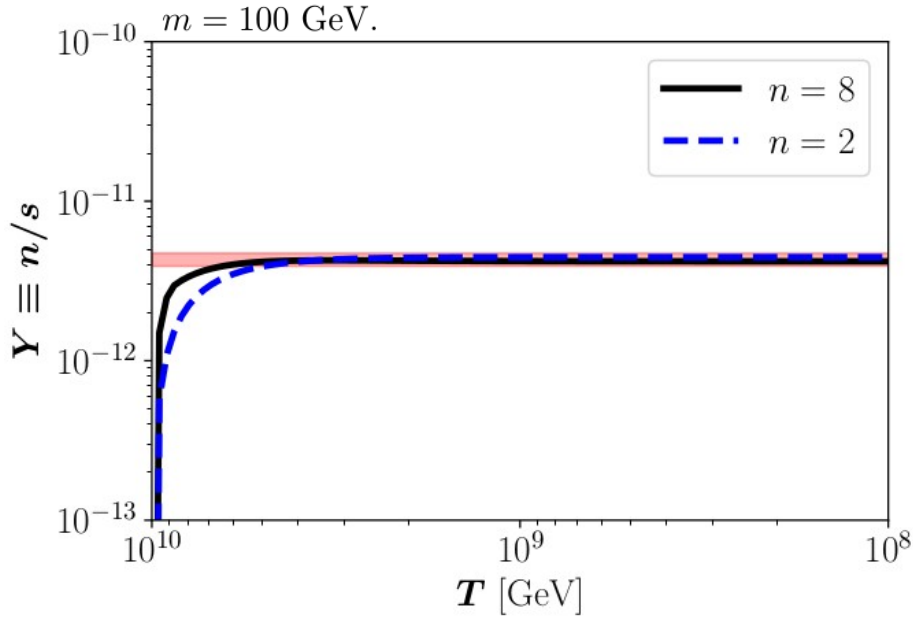


- * chemical equilibrium never reached
- * **non-renormalizable** operators
- * masses: keV to $\sim M_{\text{p}}$
- * $\Lambda > T_{\text{rh}}$
- * $T_{\text{fi}} \sim T_{\text{rh}}$

→ (strong) dependence from initial conditions

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

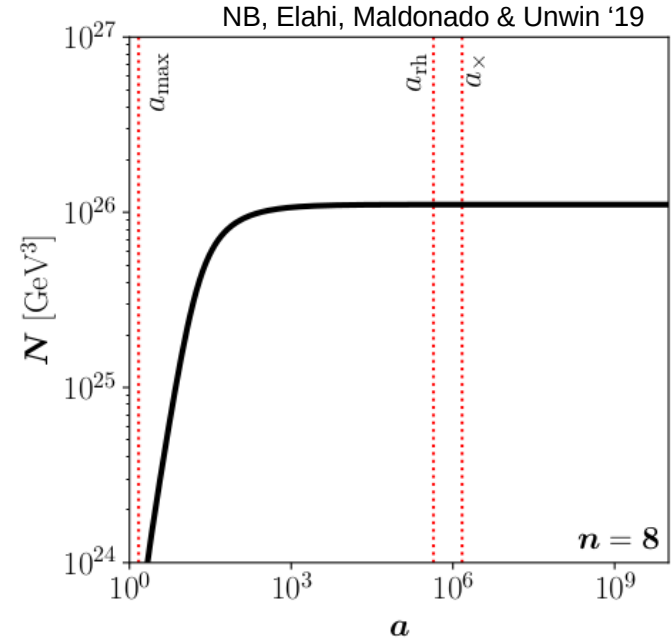
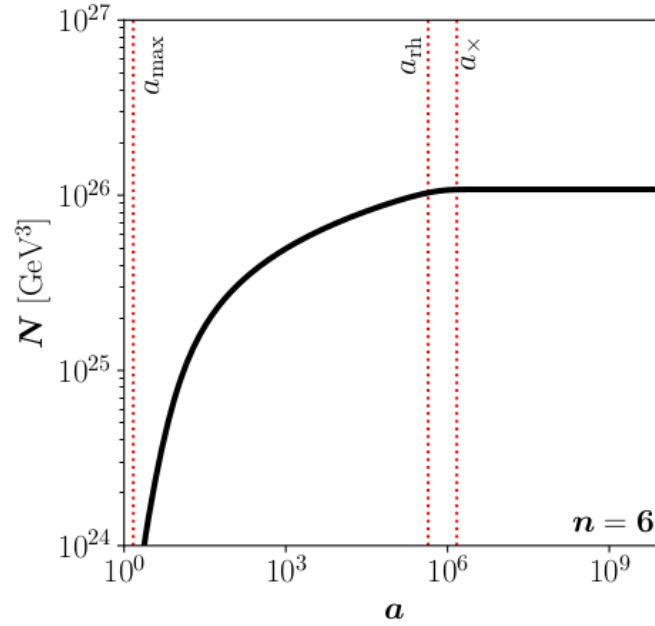
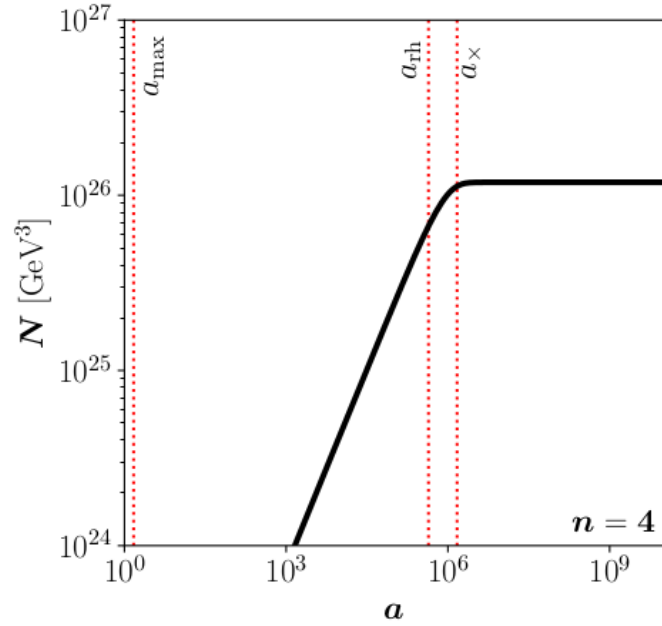
UV FIMP paradigm



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

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

UV FIMP paradigm

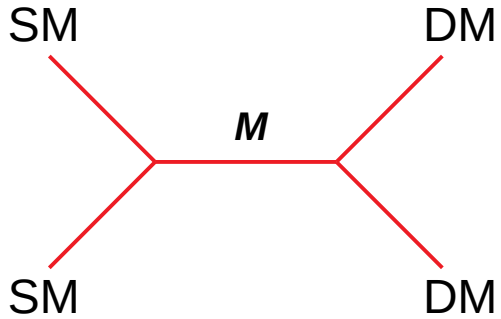


UV FIMP paradigm

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

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

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



UV FIMP paradigm

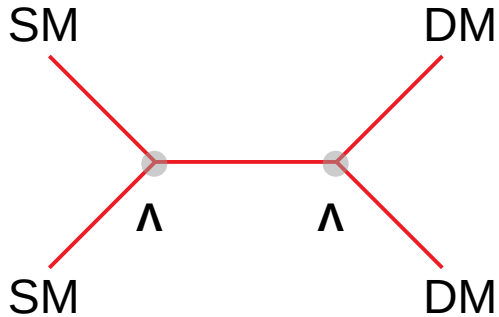
$$\langle \sigma v \rangle = \frac{T^n}{\Lambda^{2+n}}$$

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

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

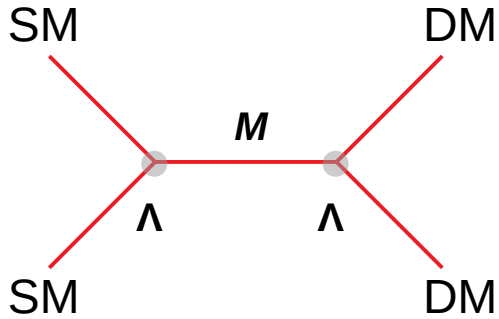
- **Suppressed couplings** ($\Lambda \gg T_{\text{rh}}$)

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



UV FIMP paradigm

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



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

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

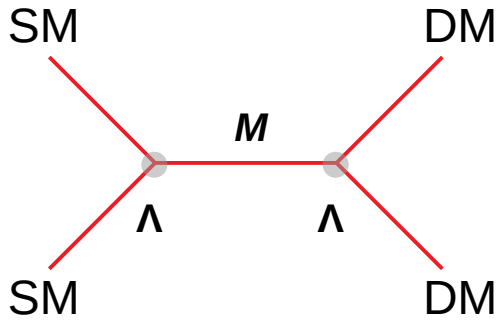
- **Suppressed couplings** ($\Lambda \gg T_{\text{rh}}$)

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

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

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

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



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

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

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

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

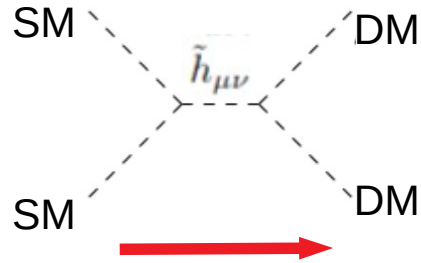
← **Gravitational UV freeze-in**

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

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

Gravitational FIMPs

An example of UV FIMP, mediated by massless SM gravitons

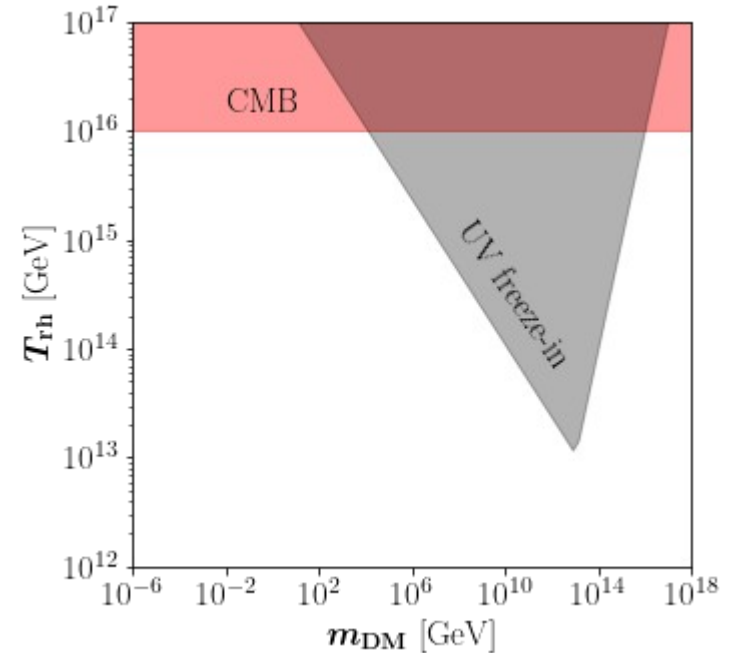


$$\langle\sigma v\rangle = \alpha_{\text{DM}} \frac{T^2}{M_P^4}$$

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

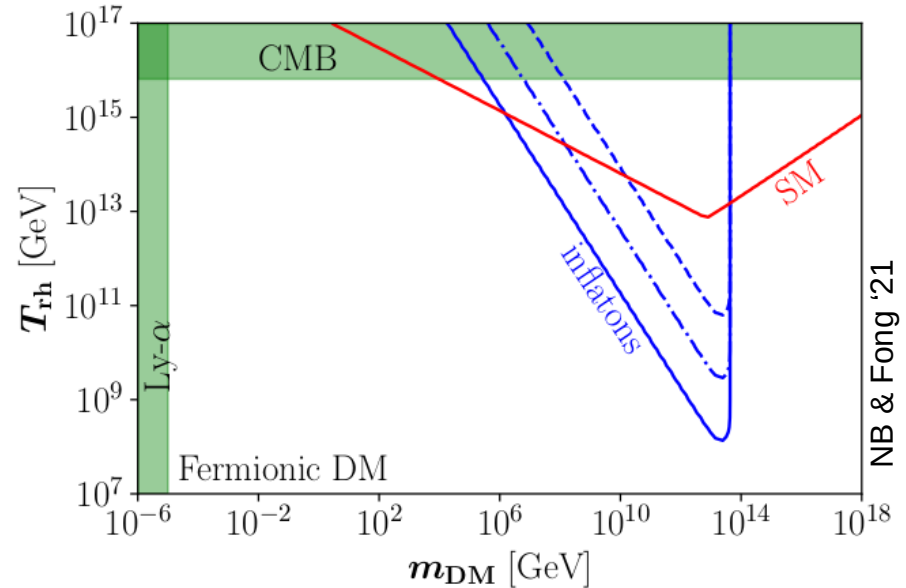
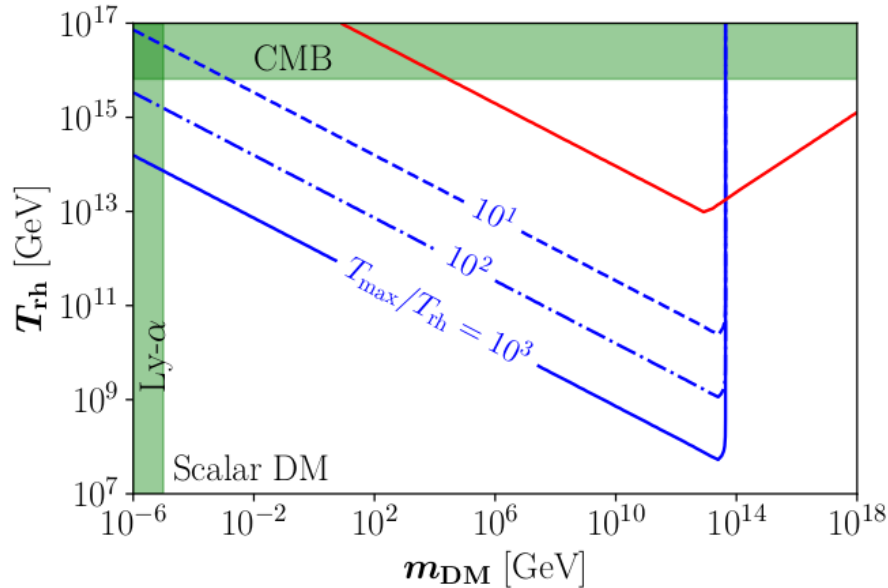
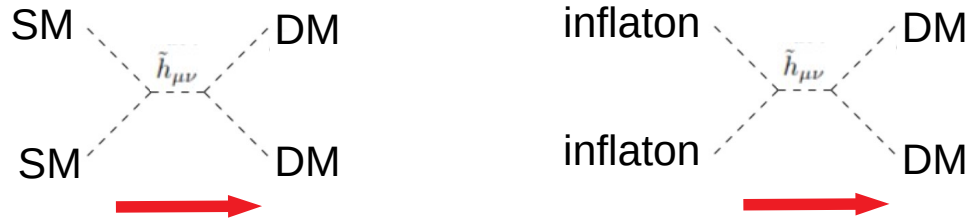
Depends on:

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



Gravitational FIMPs

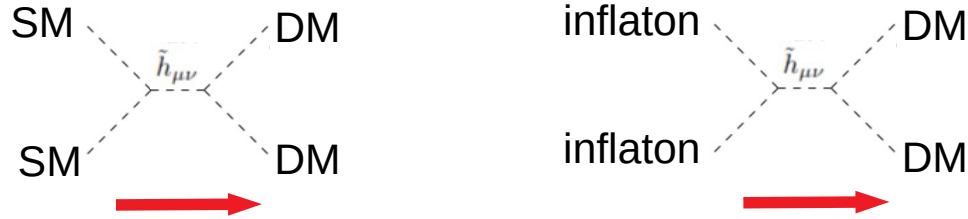
An example of UV FIMP, mediated by massless SM gravitons



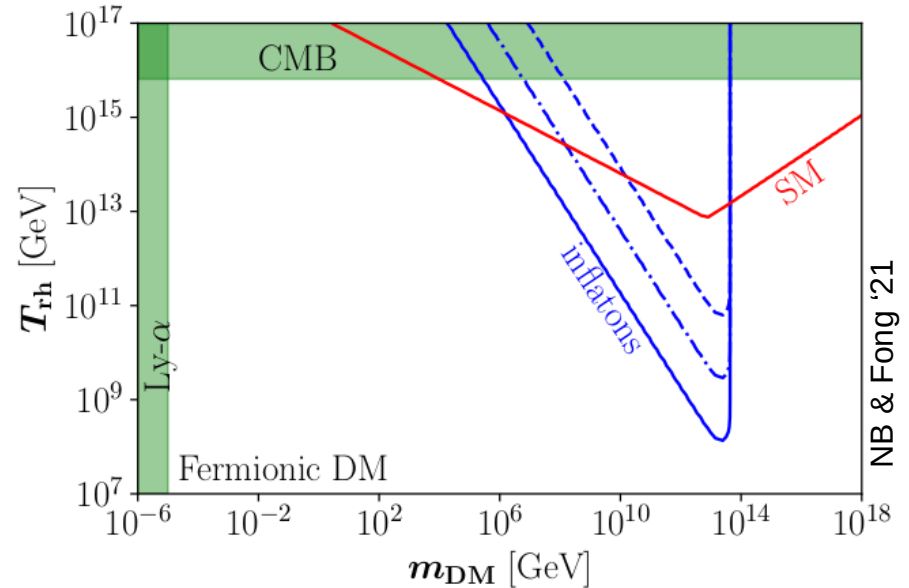
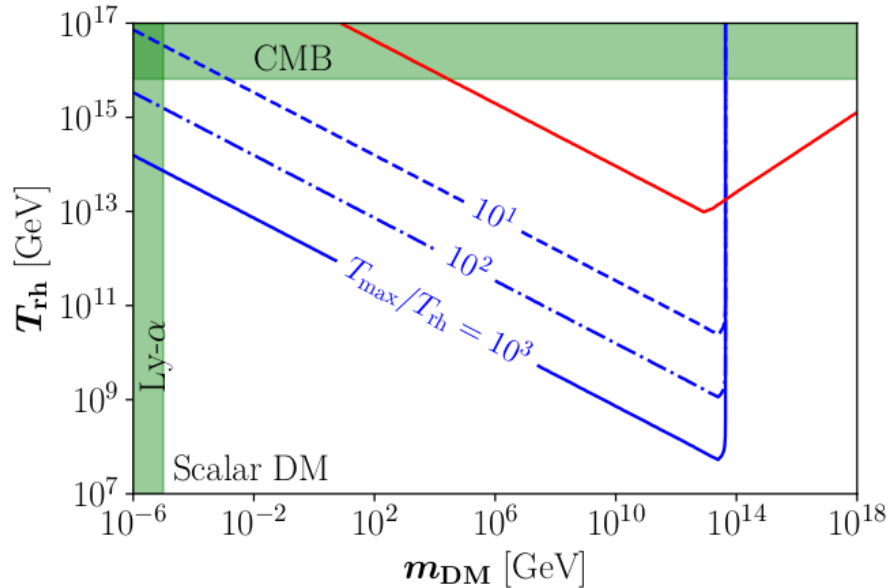
NB & Fong '21

Gravitational FIMPs

An example of UV FIMP, mediated by massless SM gravitons



Gravitational production of Matter:
RHN \rightarrow leptogenesis!

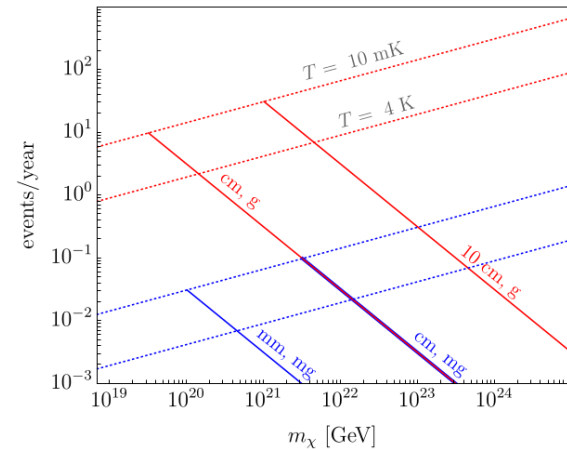


Gravitational FIMPs

By construction, nightmare scenario to test!

The Windchime Project
Gravitational Detection of Dark Matter in the Laboratory

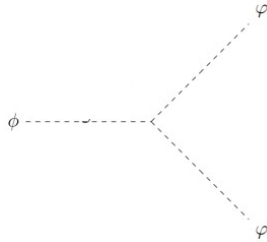
<http://windchimeproject.org/>
Carney, Ghosh, Krnjaic, Taylor '19



Entr'acte 2: Testing reheating

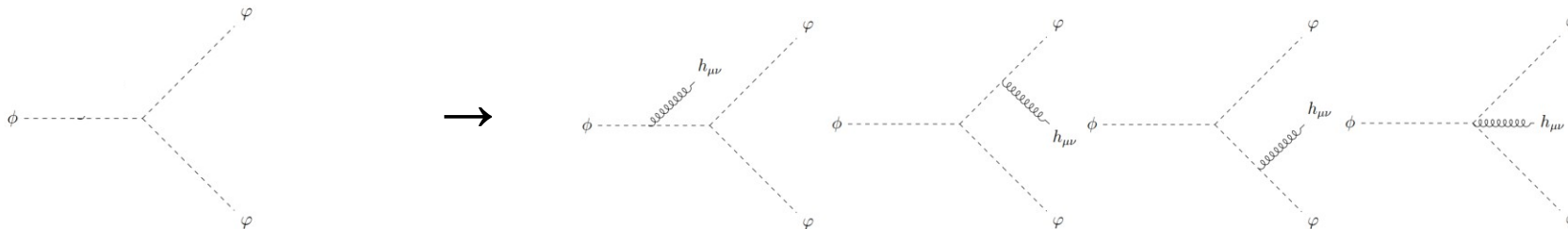
Probing Reheating with Graviton Bremsstrahlung

Inflaton
decay



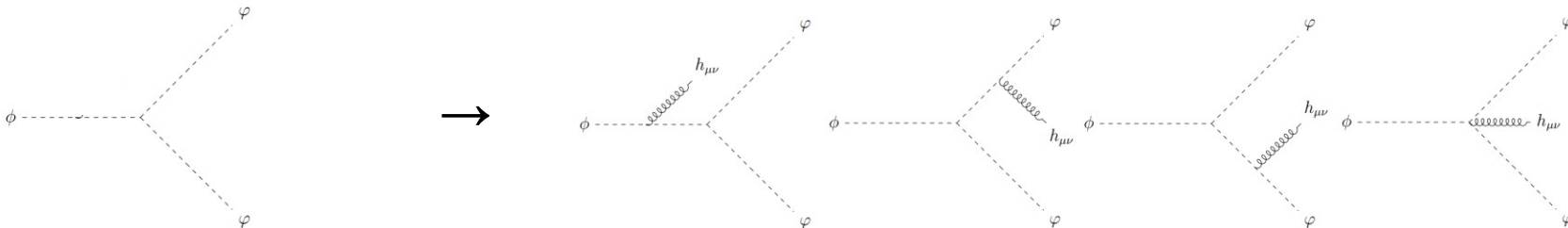
Probing Reheating with Graviton Bremsstrahlung

Inflaton
decay

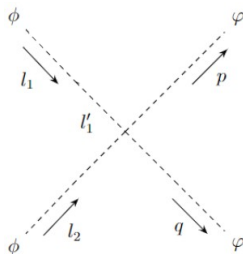


Probing Reheating with Graviton Bremsstrahlung

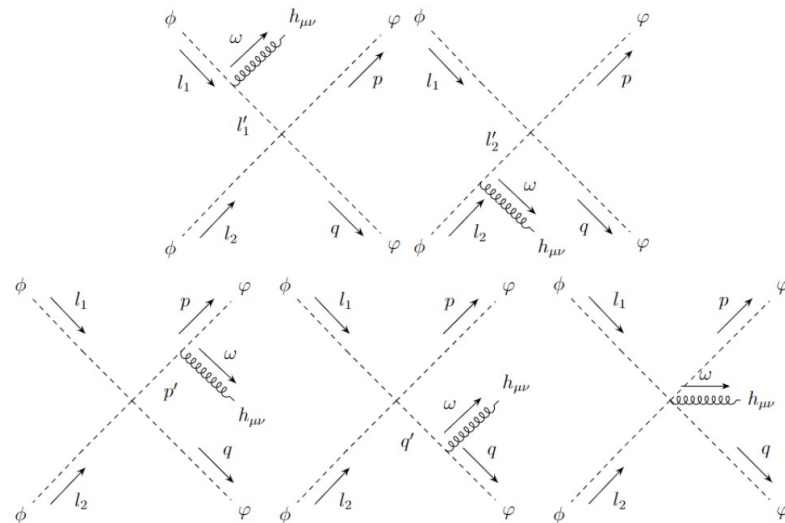
Inflaton
decay



Inflaton
annihilation



→

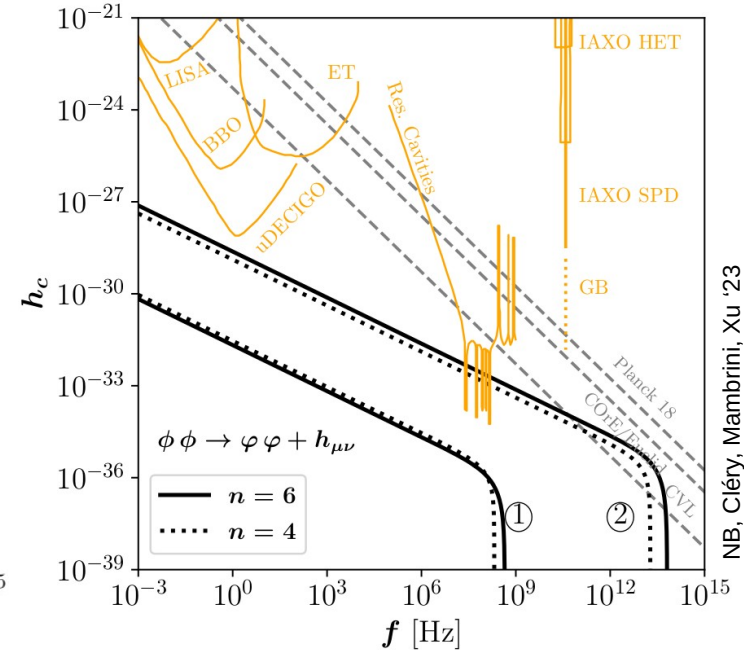
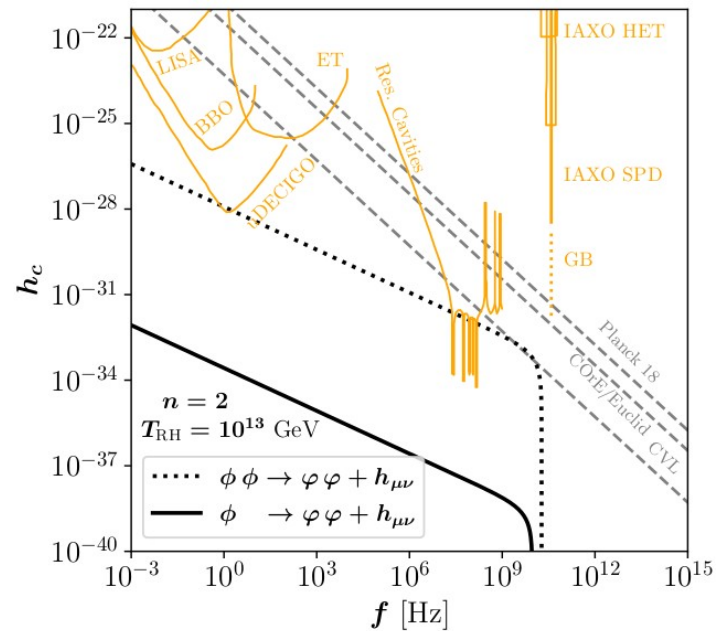


Probing Reheating with Graviton Bremsstrahlung

$$\frac{d\rho_\phi}{dt} + \frac{6n}{2+n} H \rho_\phi = -\frac{2n}{2+n} (\gamma^{(0)} + \gamma^{(1)}),$$

$$\frac{d\rho_R}{dt} + 4H \rho_R = +\frac{2n}{2+n} \gamma^{(0)} + \frac{2n}{2+n} \int \frac{d\gamma^{(1)}}{dE_\omega} \frac{E_\phi - E_\omega}{E_\phi} dE_\omega,$$

$$\frac{d\rho_{\text{GW}}}{dt} + 4H \rho_{\text{GW}} = +\frac{2n}{2+n} \int \frac{d\gamma^{(1)}}{dE_\omega} \frac{E_\omega}{E_\phi} dE_\omega,$$



Entr'acte 2: Testing reheating



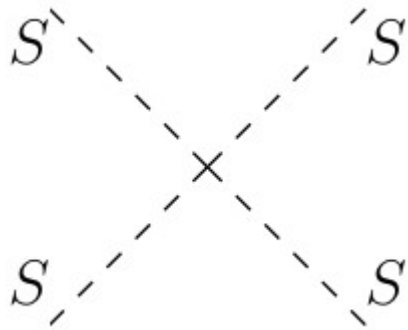
What about possible DM self-interactions?

3. SIMP DM

Self-Interacting Massive Particle

DM self-interactions

Elastic scattering



Kinetic equilibrium:
DM temperature

Number-changing interactions

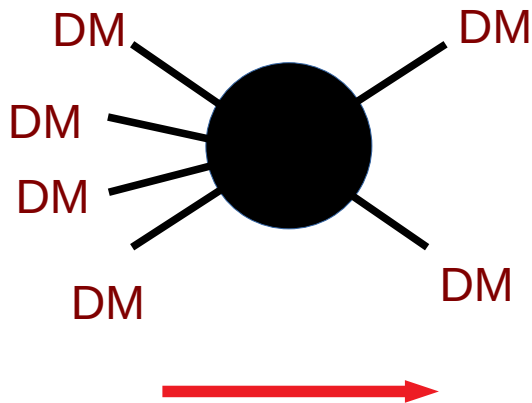


Chemical equilibrium:
 $4 \rightarrow 2$ and $2 \rightarrow 4$

SIMP DM

4 → 2 annihilations

$$\frac{dn}{dt} + 3 H n = -\langle \sigma v^3 \rangle_{4 \rightarrow 2} (n^4 - n^2 n_{\text{eq}}^2)$$



A Z_2 symmetry forbids $3 \rightarrow 2$ annihilations...
but allows $4 \rightarrow 2$ annihilations!

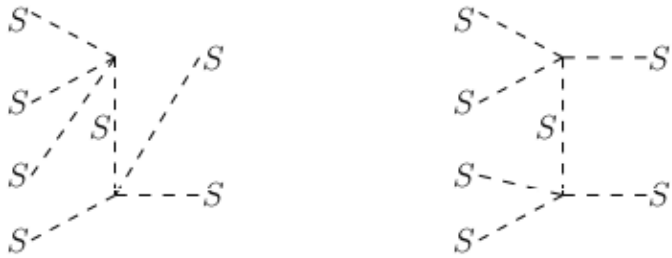
Could be the dominant channel if
the SM-DM portal is very suppressed...

... like in the FIMP scenario!

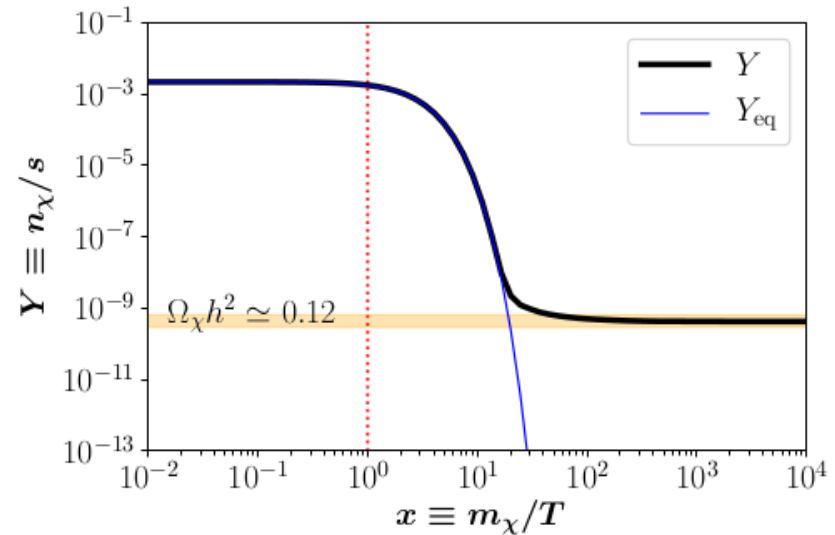
Singlet Scalar DM

$4 \rightarrow 2$ annihilations

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v^3 \rangle_{4 \rightarrow 2} (n^4 - n^2 n_{\text{eq}}^2)$$



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

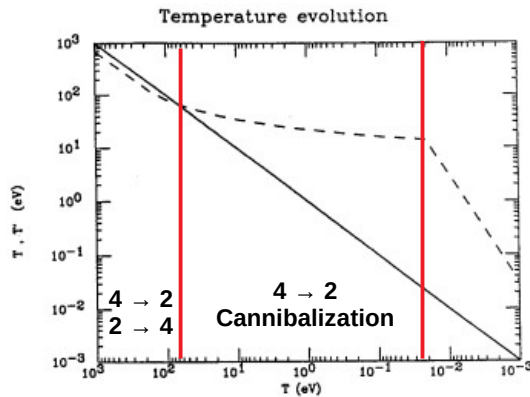


Self-interacting DM

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



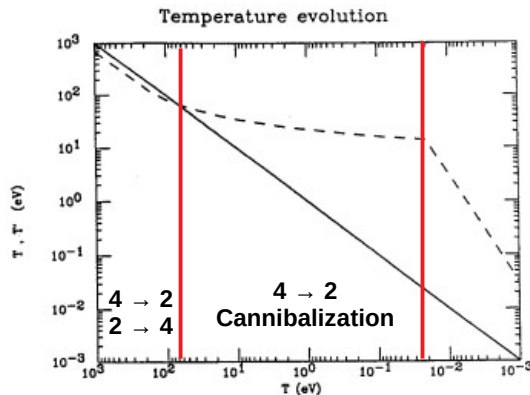
Perturbativity implies
 $m \sim O(100)$ eV

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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

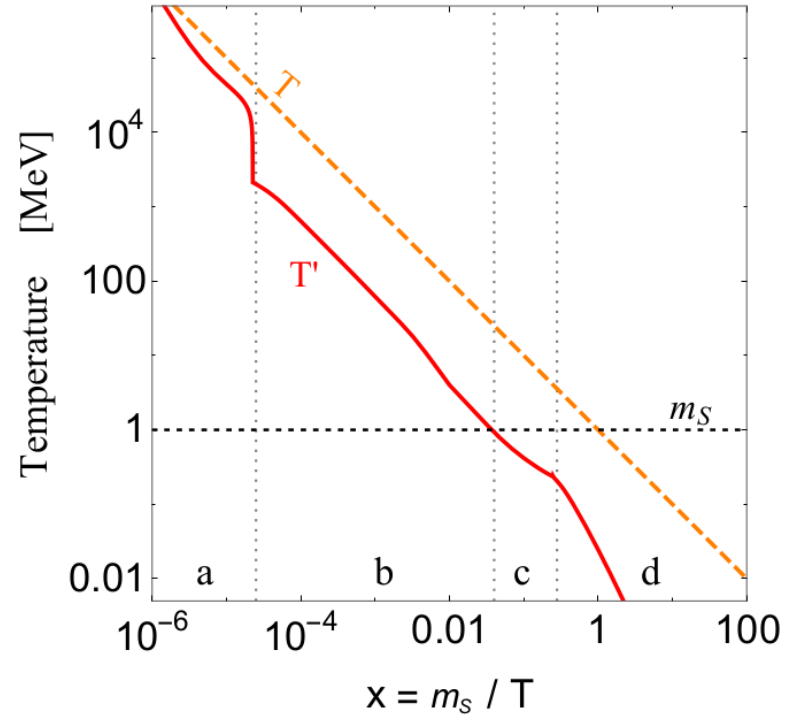
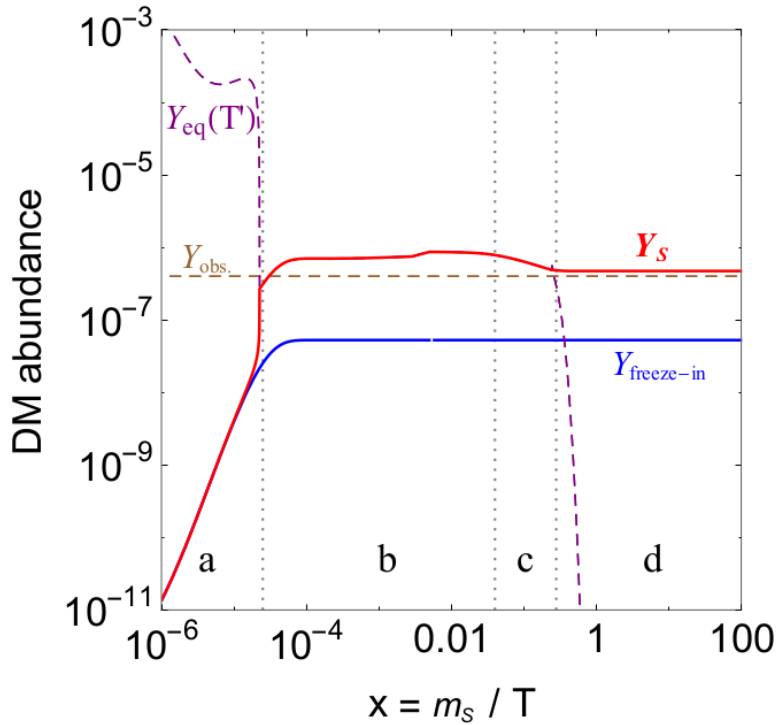
Kuflik, Perelstein, Rey-Le Lorier, Tsai '15

* Start with a colder dark sector

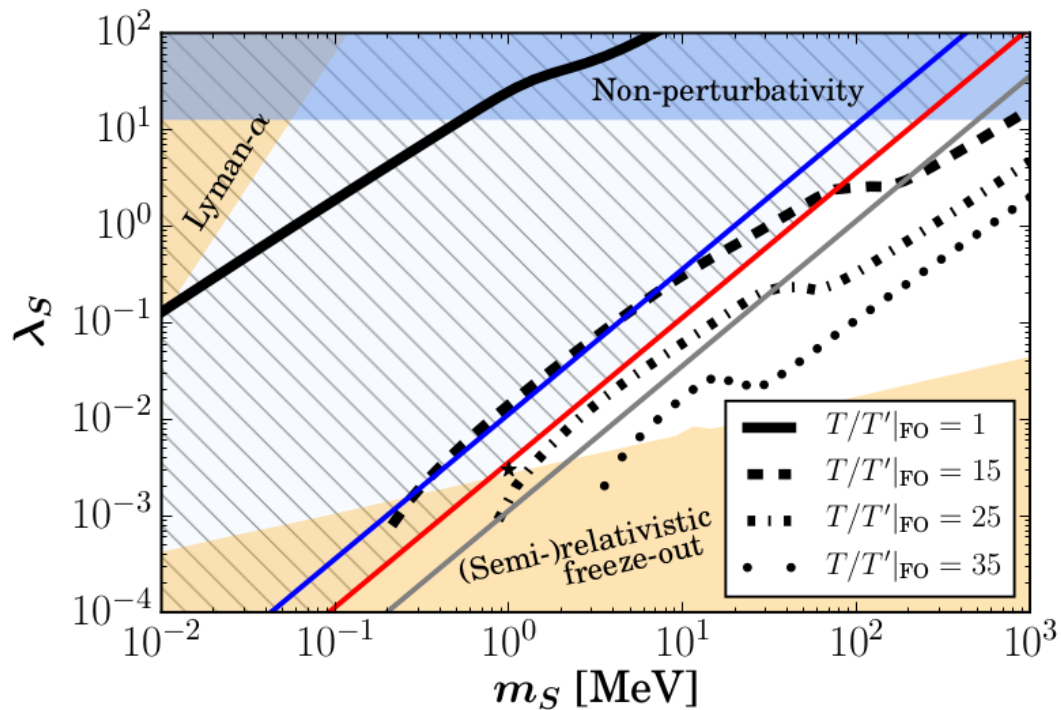
NB, Chu '15

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

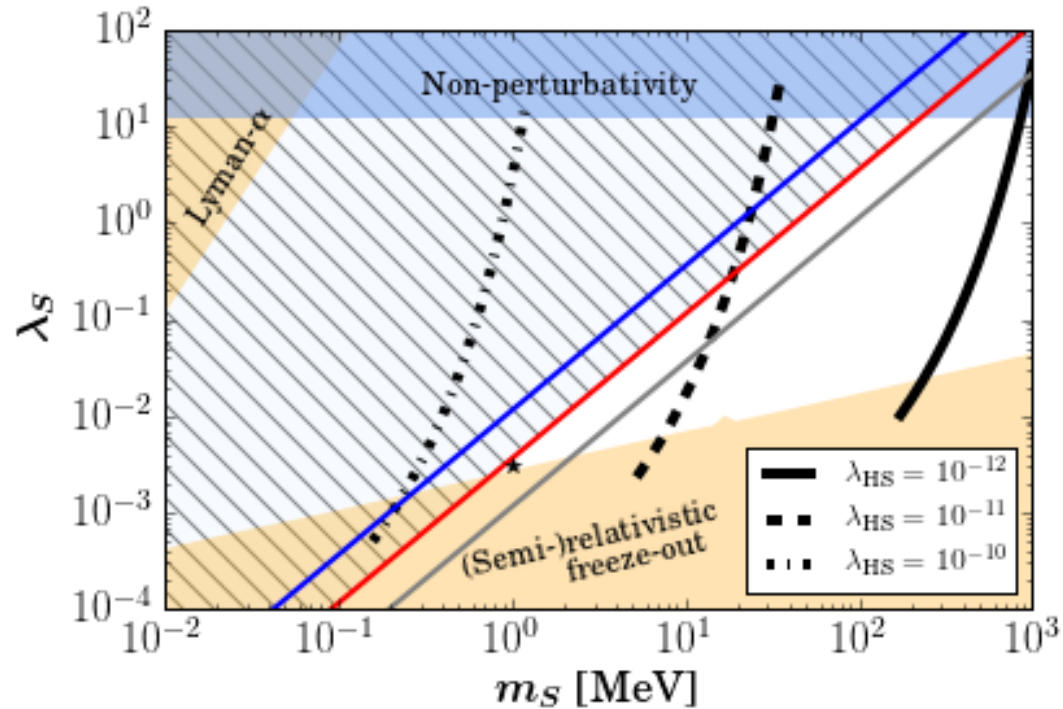
Self-interacting FIMPs



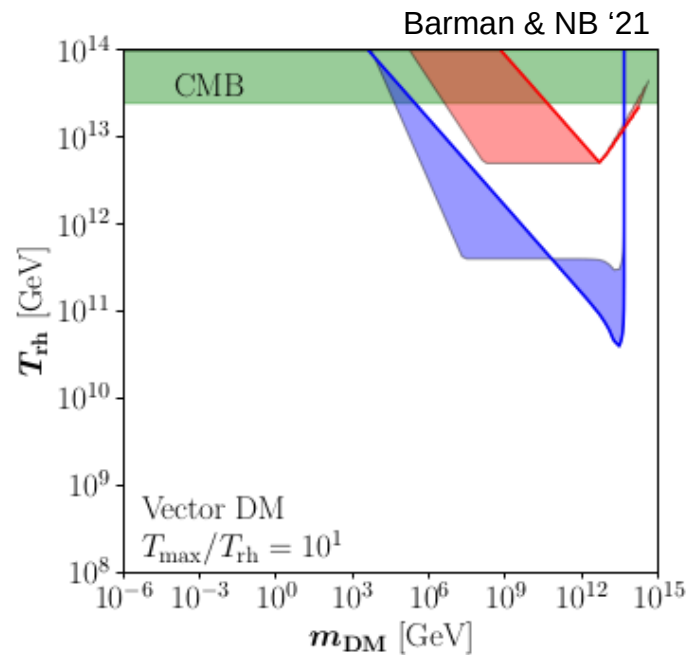
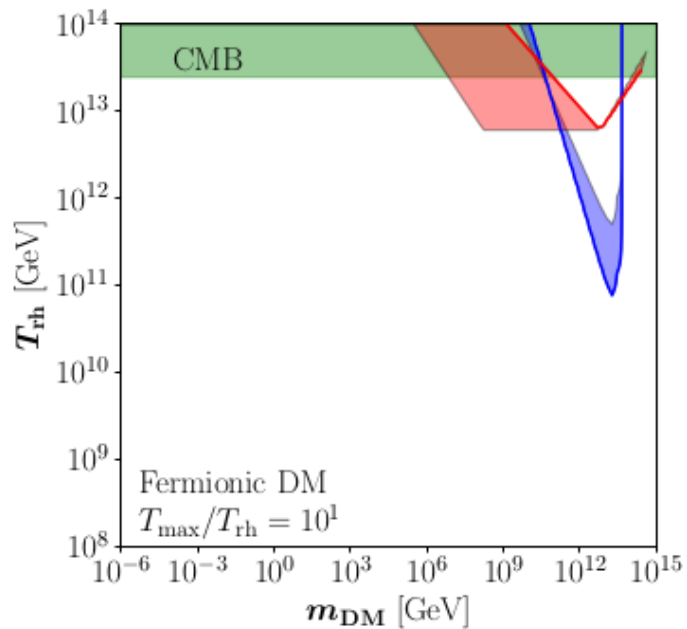
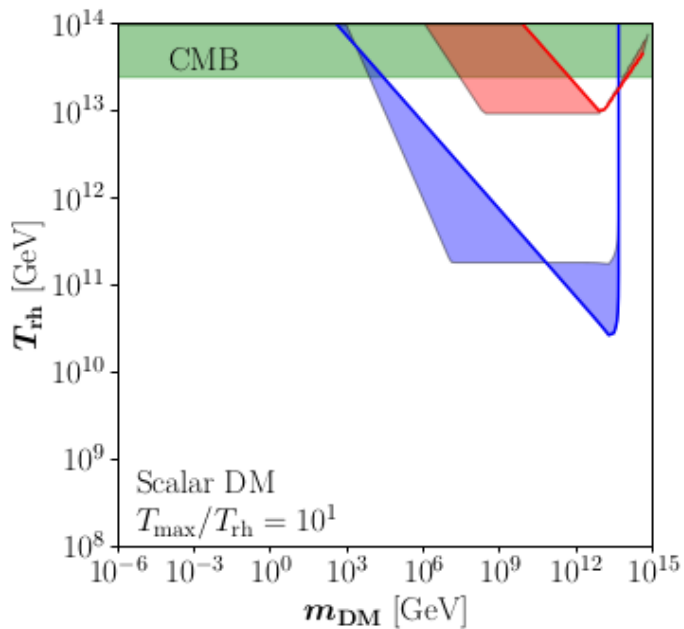
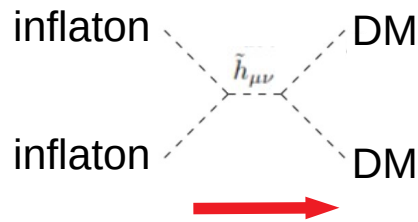
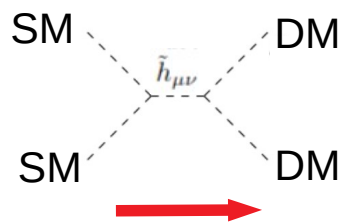
Self-interacting FIMPs



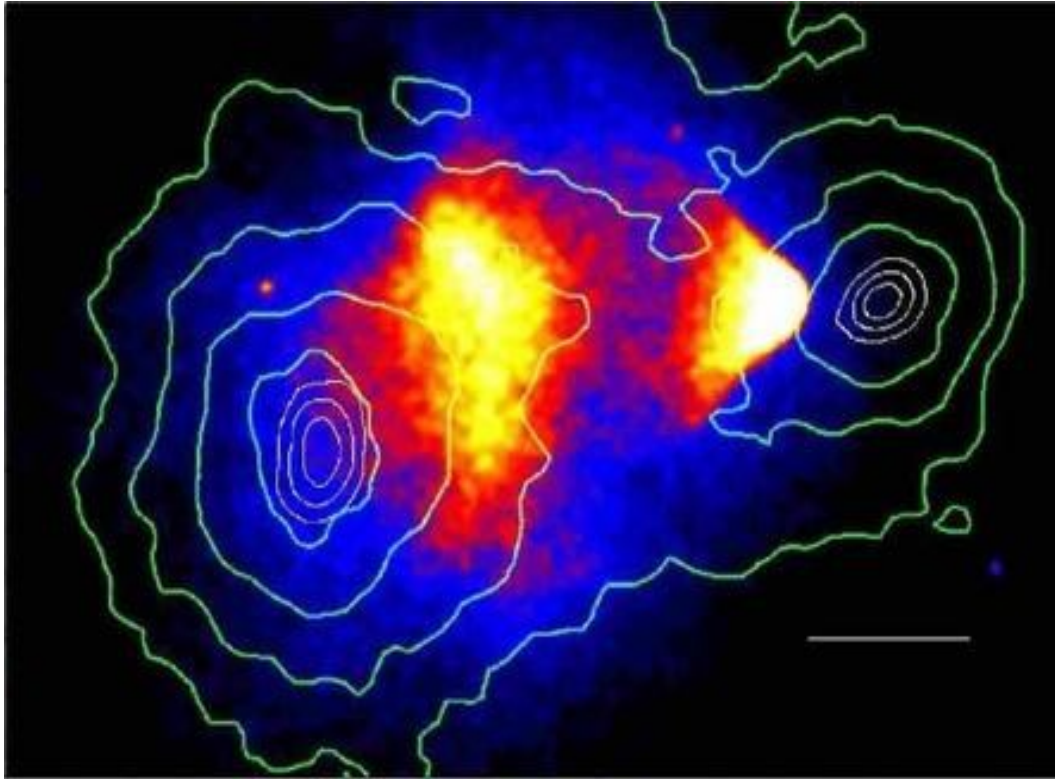
Self-interacting FIMPs



Gravitational SIMPs

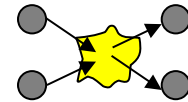


Detecting SIMPs



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...)



**Dziękuję
bardzo**