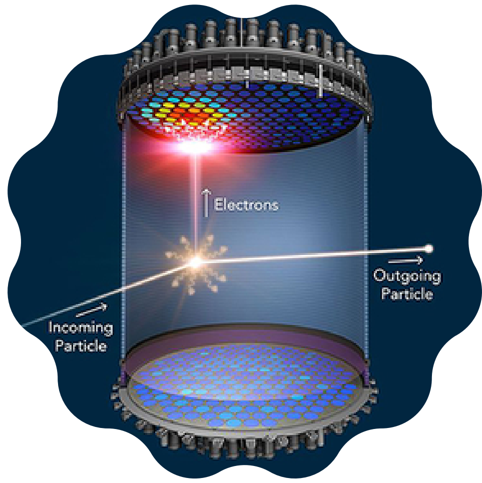
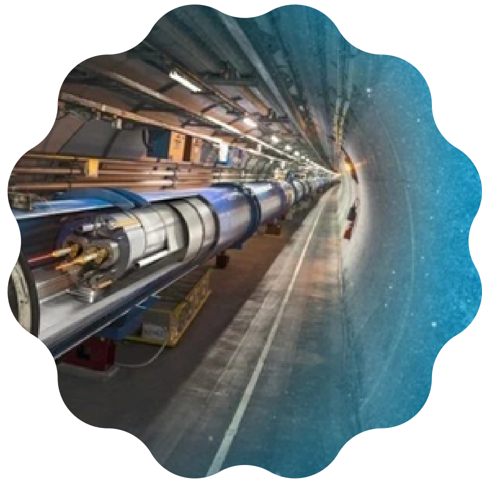
Complementarity of direct detection, indirect detection and collider searches (LHC)

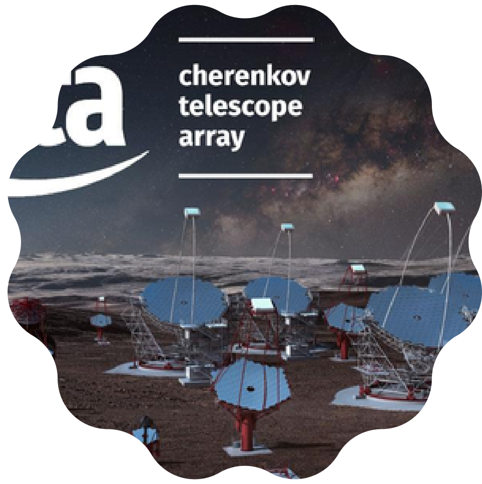
Farinaldo Queiroz

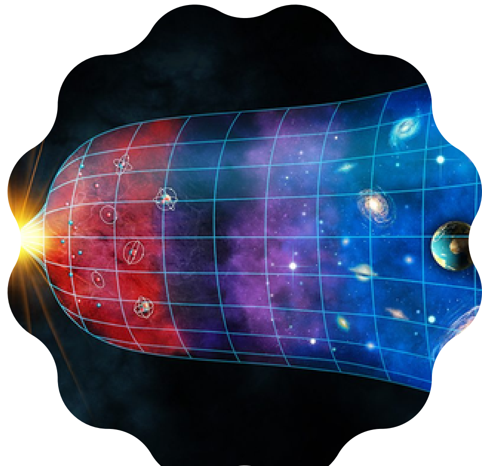
UFRN

The 2nd DMNet International Symposium, Heidelberg 2022









What you've seen so far...

DM models, properties and particle physics candidates, Takashi Toma

Searching for Dark Matter with HyperK, Nicole Bell

Dark matter in galaxy clusters from X-ray & SZ effect, Stefano Ettori

Some gamma-ray talks

Astrophysical anomalies

Direct and Indirect Detection of Dark Matter

The 2nd DMNet International Symposium

Sep 13 – 15, 2022
Max Planck Institute for Nuclear Physics, Heidelberg, Germany
Europe/Zurich timezone

Emphasize the importance of complementarity

Dark matter sensitivity of neutrino detectors

Take away messages

Without interdisciplinary searches one cannot claim the discovery of dark matter particles

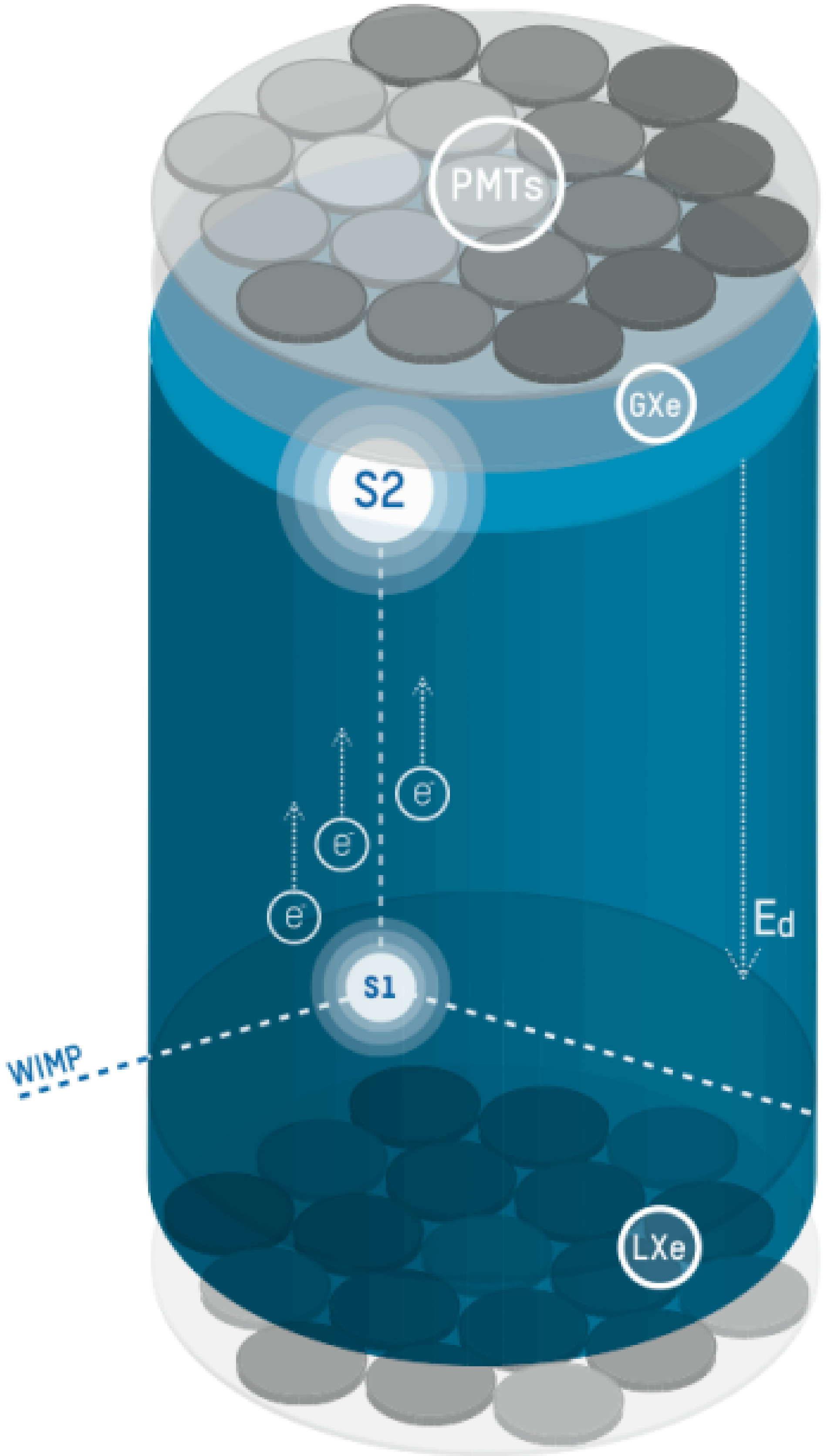
The next generation of experiments will exclude most simplified models, but not the WIMP paradigm

The progress on the direct, indirect and collider experiments will move at very different paces in the near future

Part of the field is moving to a multifold dark matter search: Direct, indirect, collider, *neutron stars, *gravitational waves

Part of the field is moving to alternative dark matter production mechanisms motivated by "Why not? "

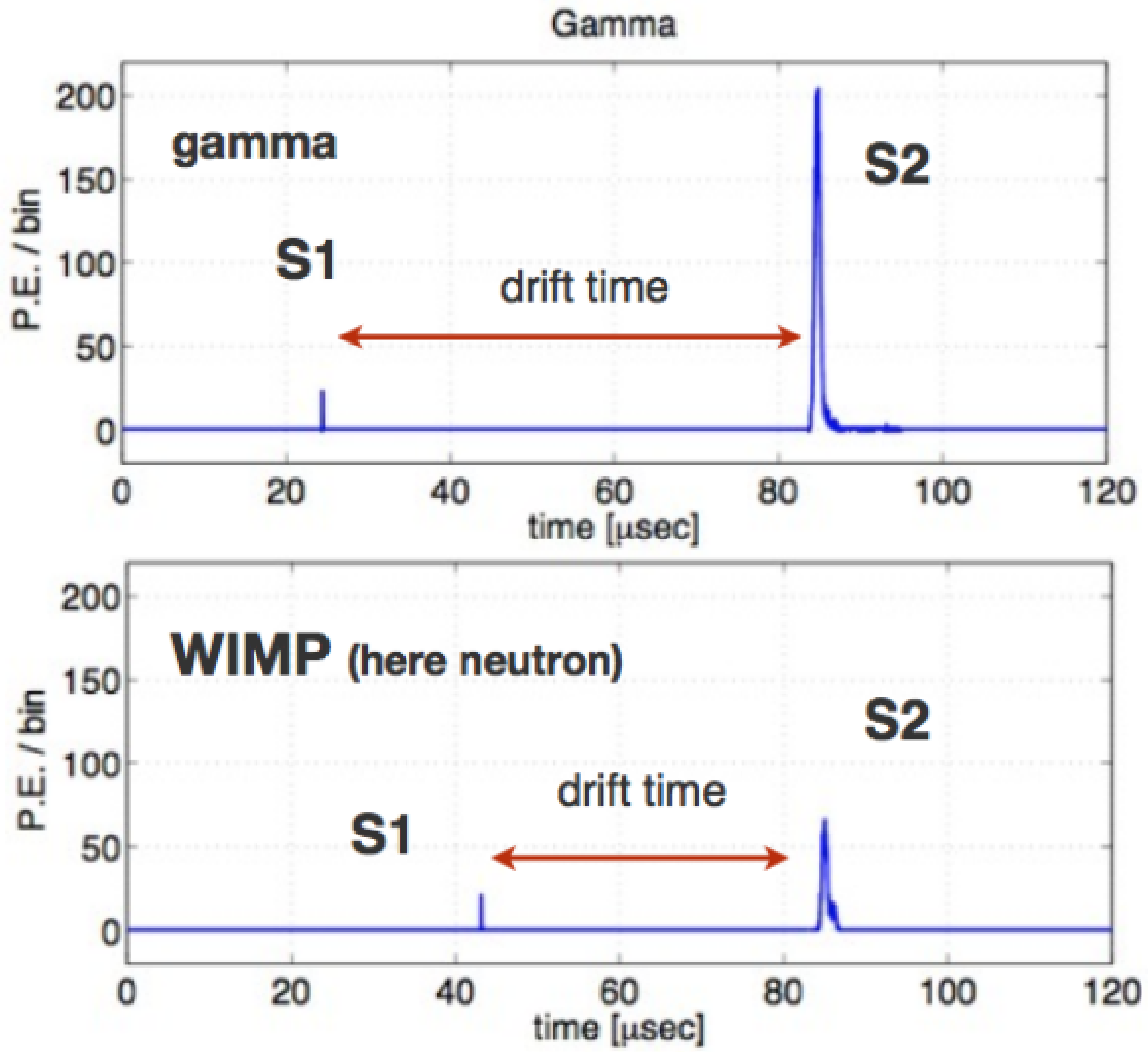
Direct Detection



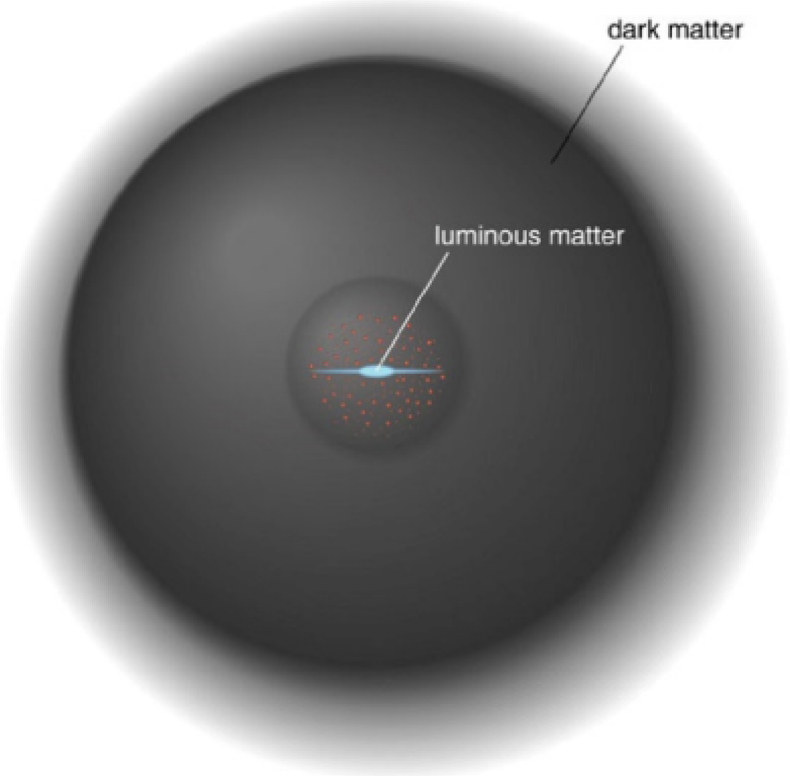
SIGNAL x Background

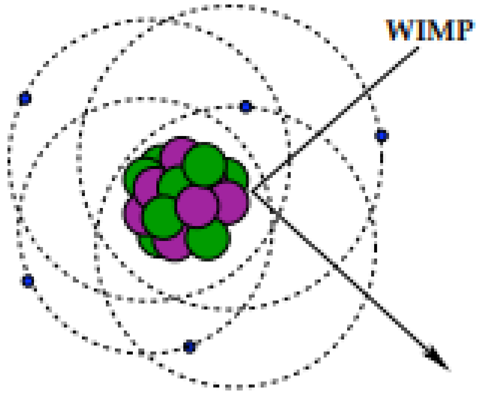
It is related to the dark matter local density.

I don't want to run from it



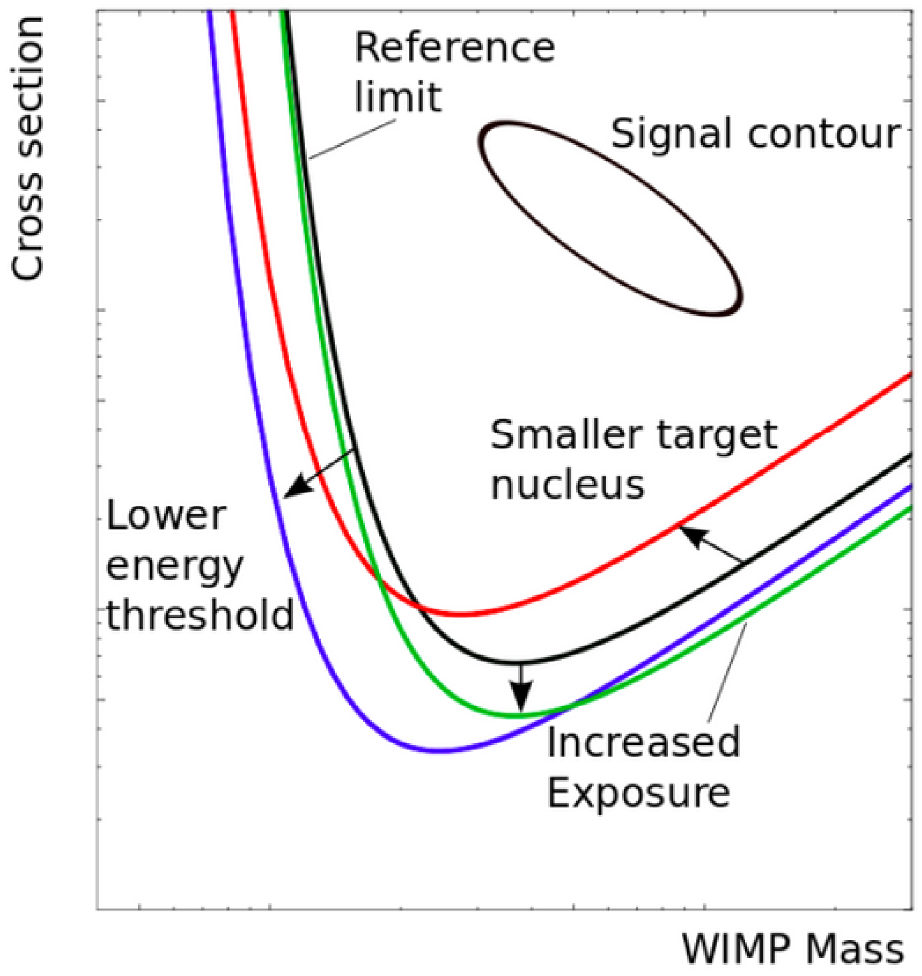
Manfred and Teresa talks

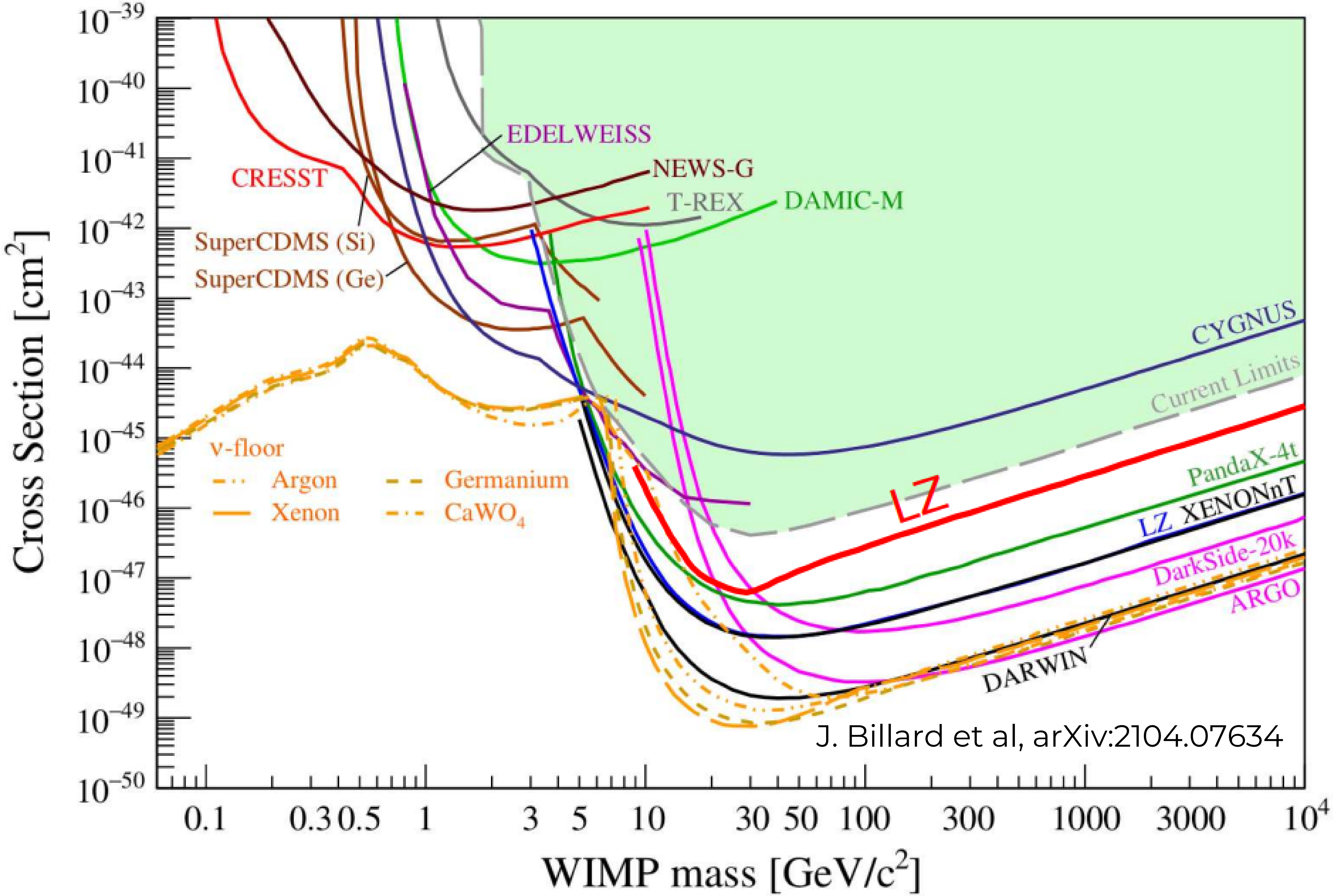




$E_R \sim \mathcal{O}(10\,\mathrm{keV})$

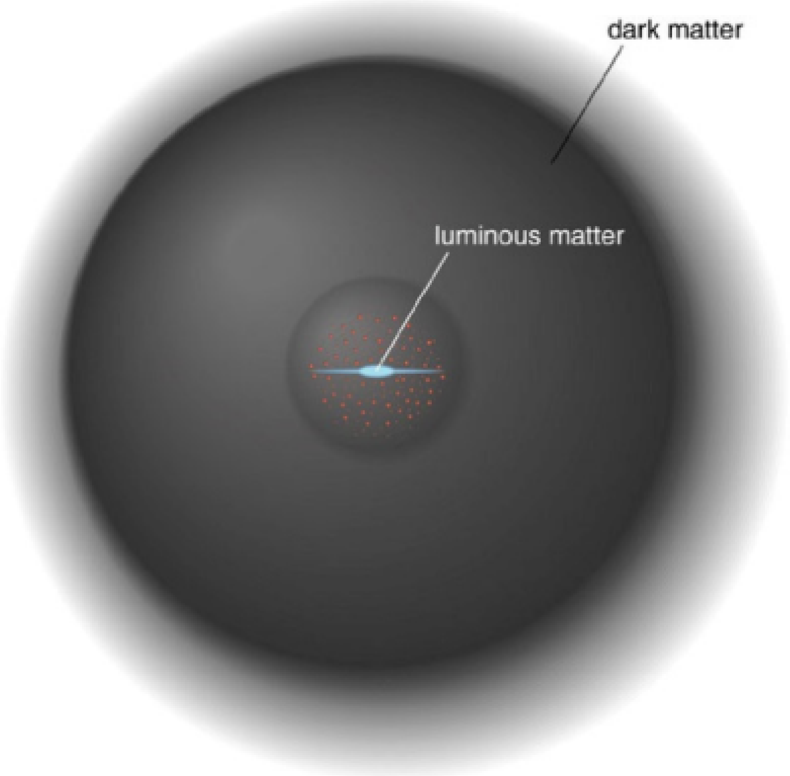
$$\frac{dR}{dE}(E,t) = \frac{\rho_0}{m_\chi \cdot m_A} \cdot \int v \cdot f(\mathbf{v},t) \cdot \frac{d\sigma}{dE}(E,v)\, d^3v$$

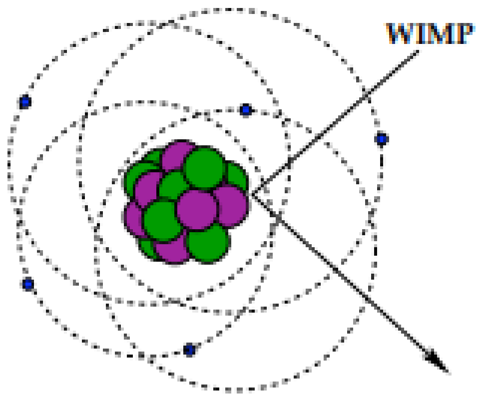




J. Billard et al, arXiv:2104.07634

Marrodan Undagoitia, Rauch, arxiv:1509.08767





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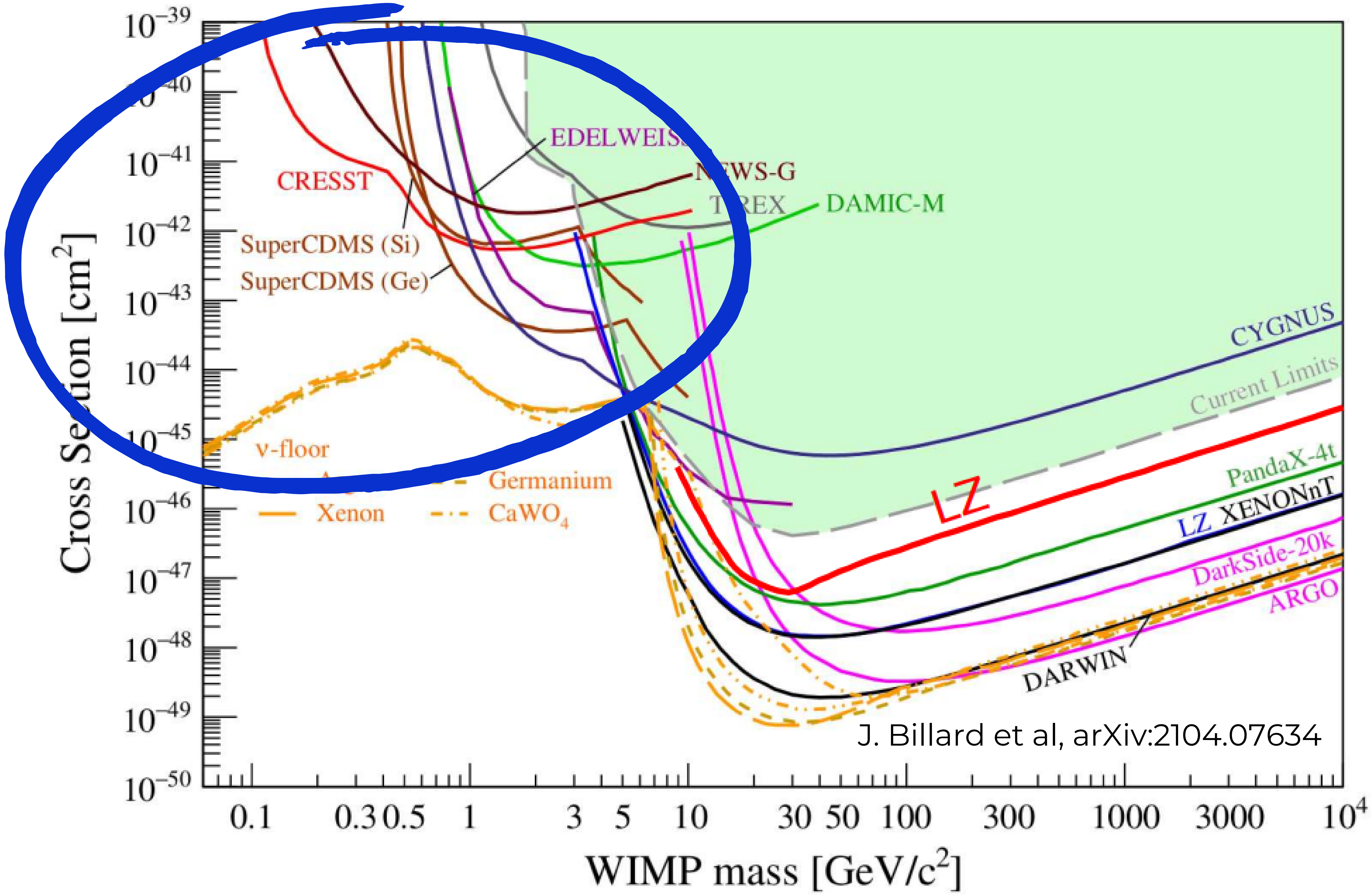
Sub-GeV dark matter?

pseudoscalar mediators

Non-standard Cosmologies



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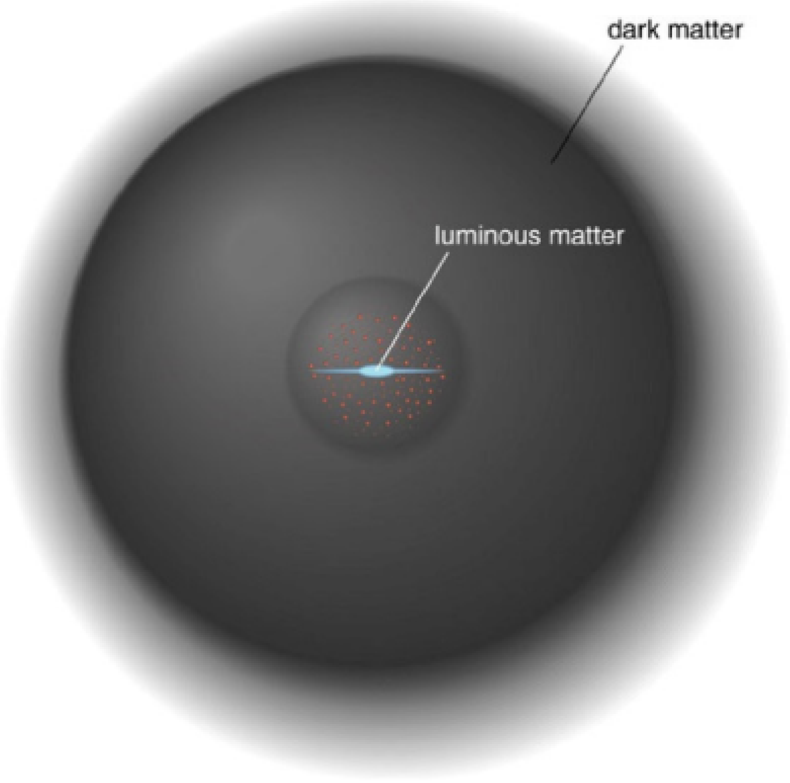

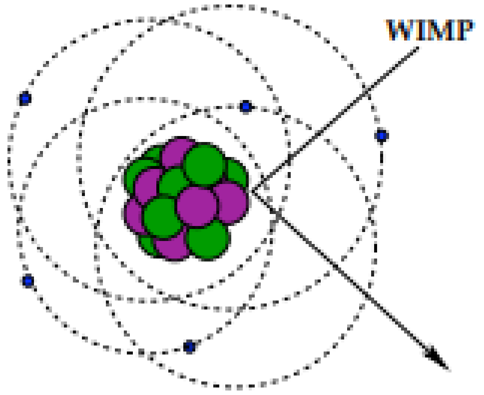

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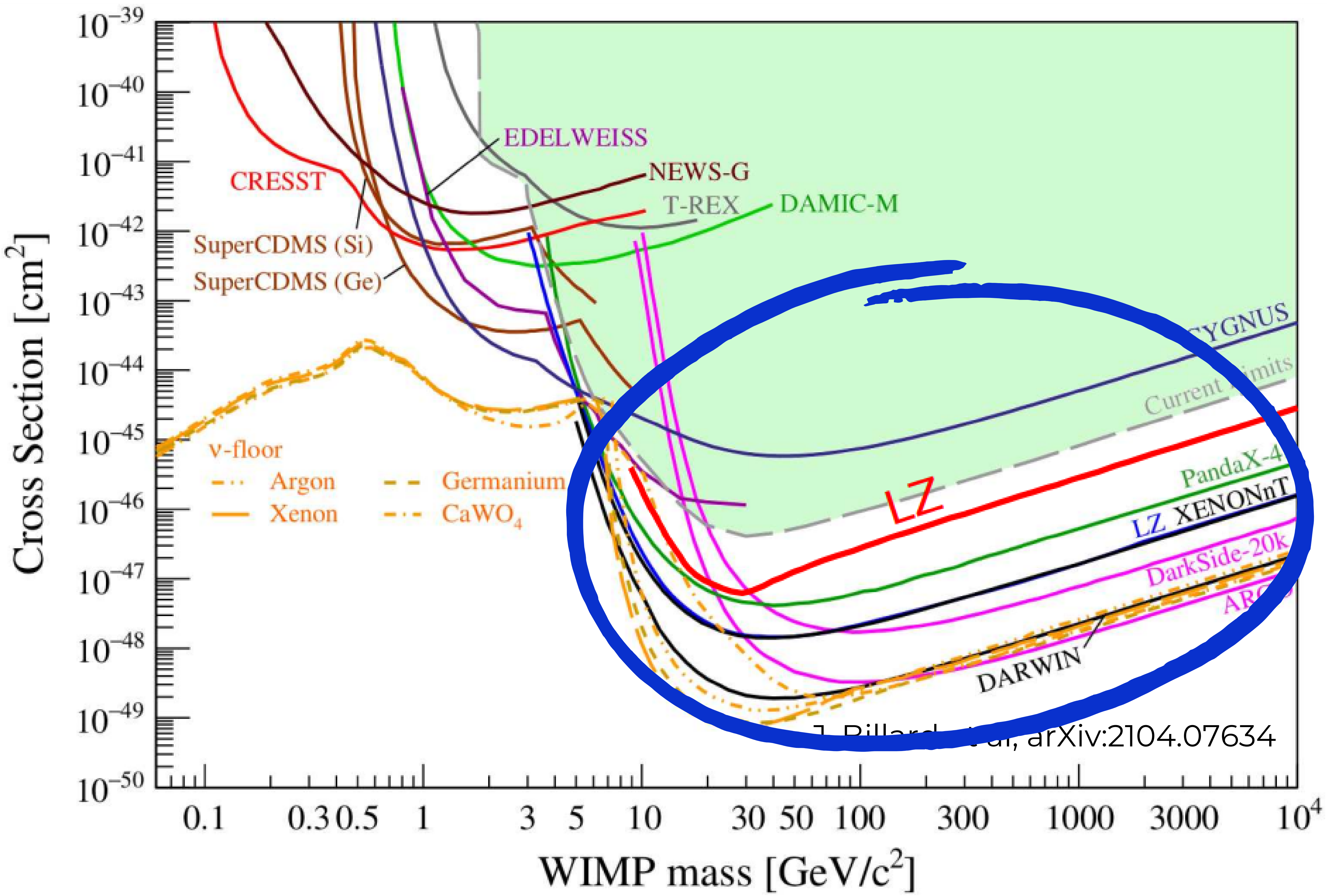

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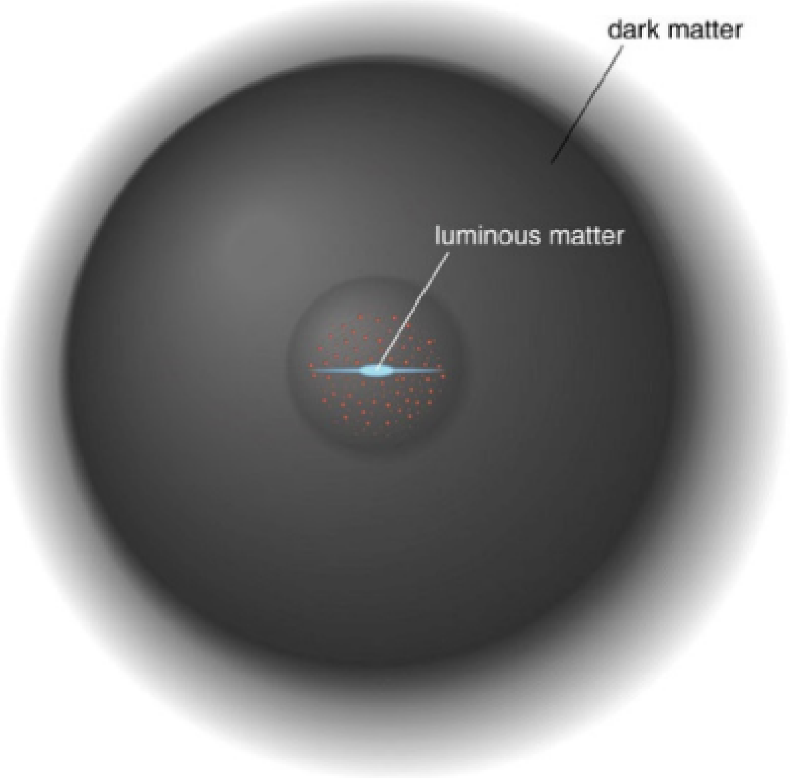
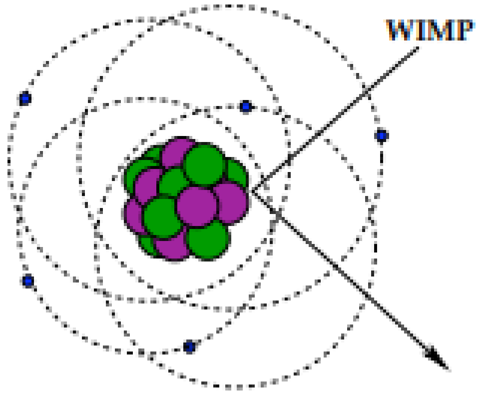
Marrodan Undagoitia, Rauch, arxiv:1509.08767





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Sub-GeV dark matter?

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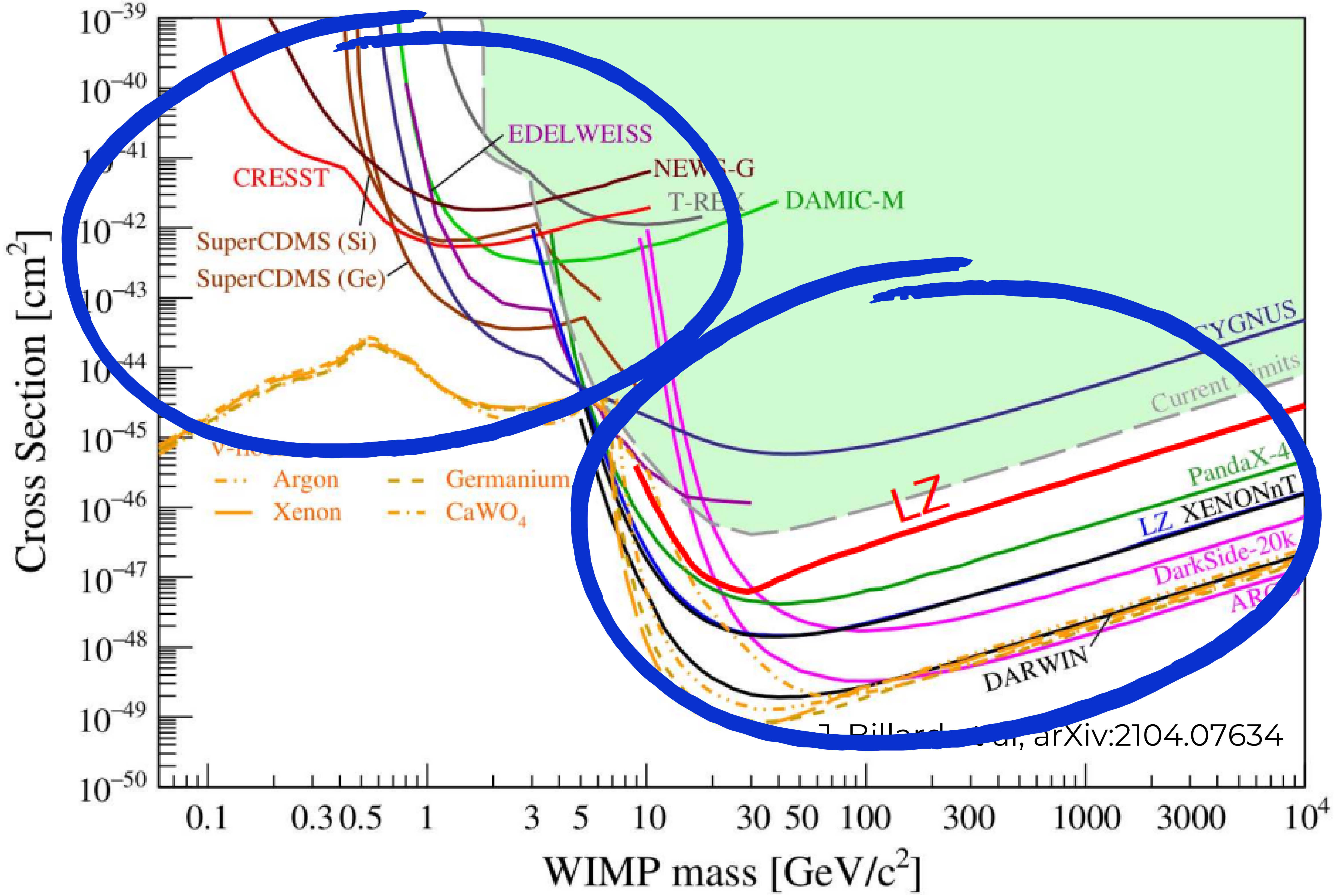
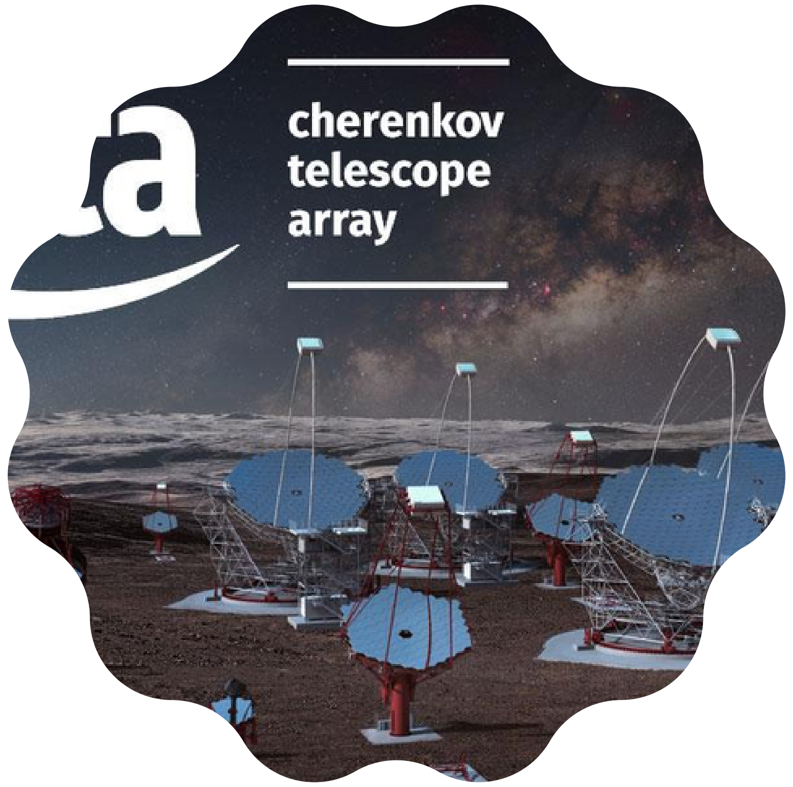


Marrodan Undagoitia, Rauch, arxiv:1509.08767

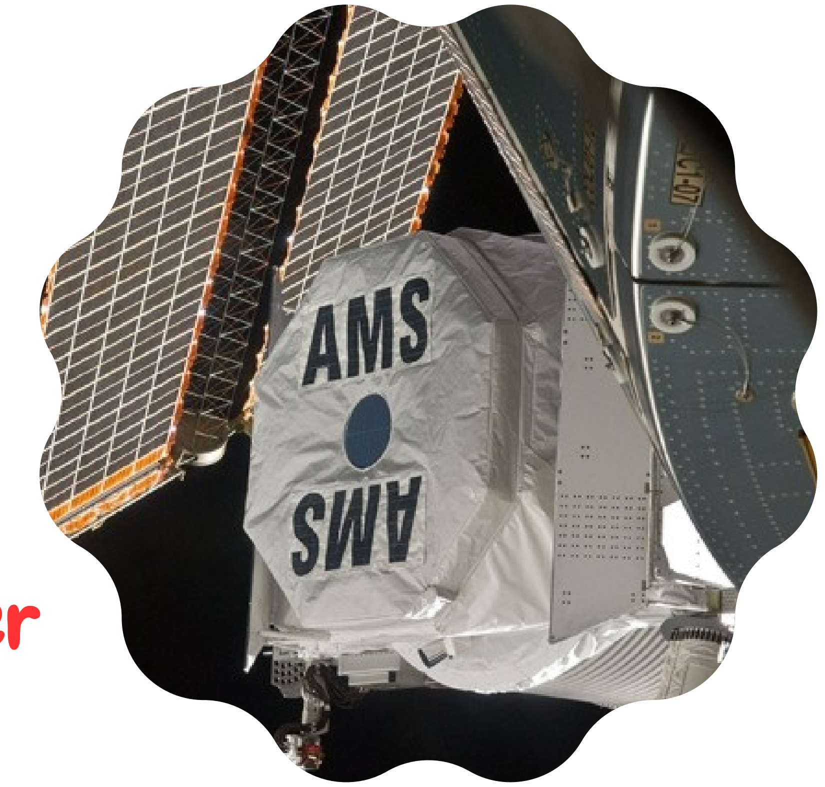
Indirect Detection

*Fermi-LAT



CTA

It is related to the dark matter local density.



AMS

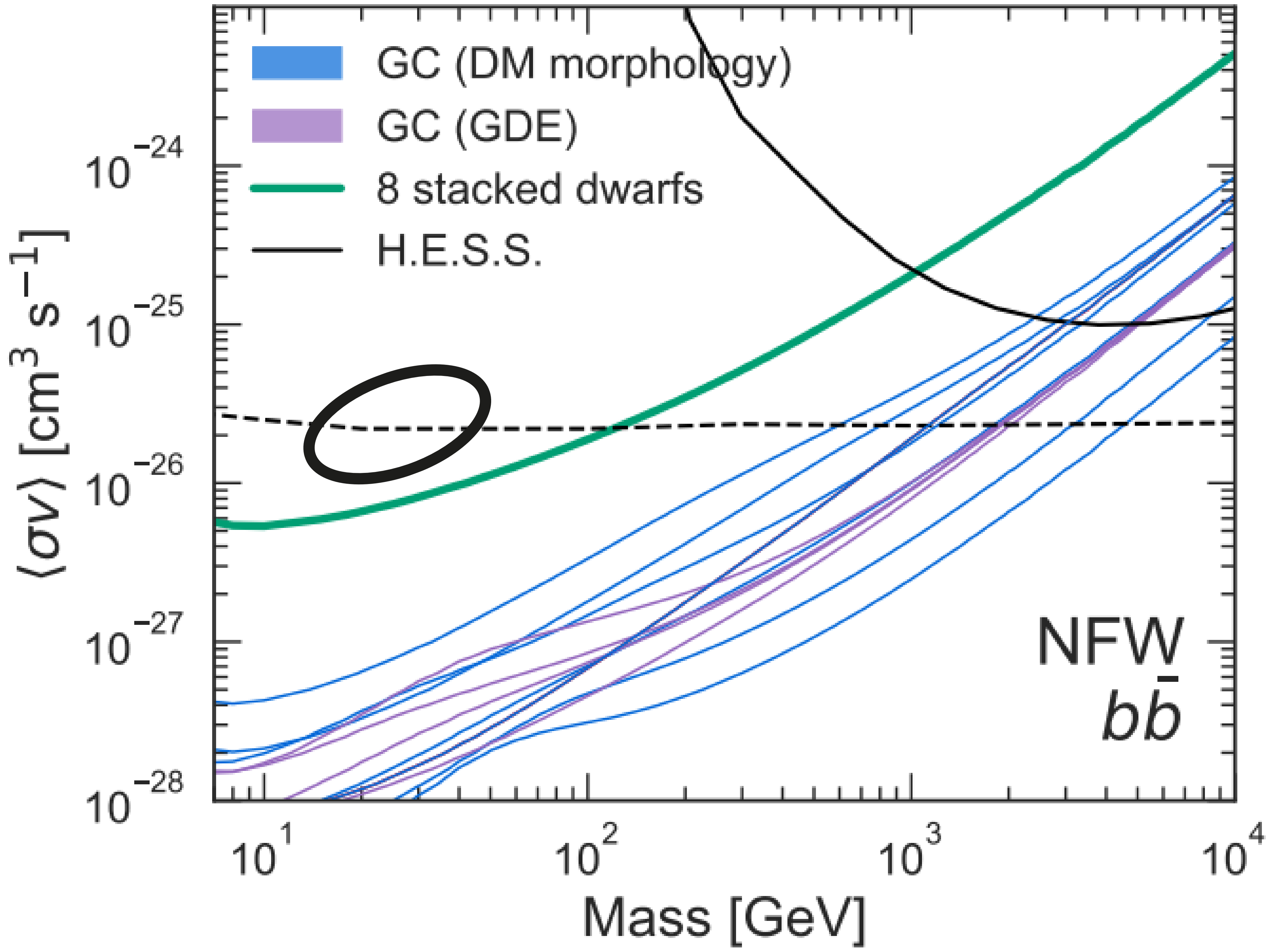
I don't want to run from it

*Neutrino telescopes

$$\overbrace{\frac{d\Phi}{d\Omega dE}}^{Diff.Flux} = \frac{\overbrace{\sigma v}^{Anni.\,Cross\,Section}}{8\pi m_\chi^2} \times \underbrace{\frac{dN}{dE}}_{Energy\,Spectrum} \times \int_{l.o.s} ds \underbrace{\rho^2(\vec{r}(s,\Omega))}_{Dark\,Matter\,Distribution}$$

Where are we?

***Fermi-LAT**
through 2022,
possibly will
cotinue



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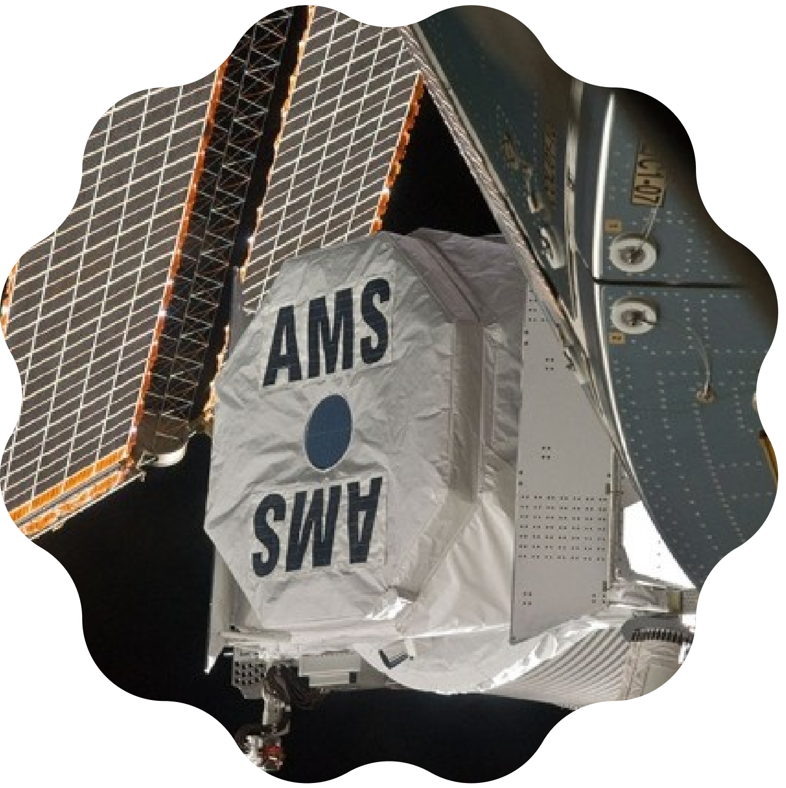
Abazajian, Horiuchi, Kaplinghat,Keeley, Macias 2003.10416

Where are we?

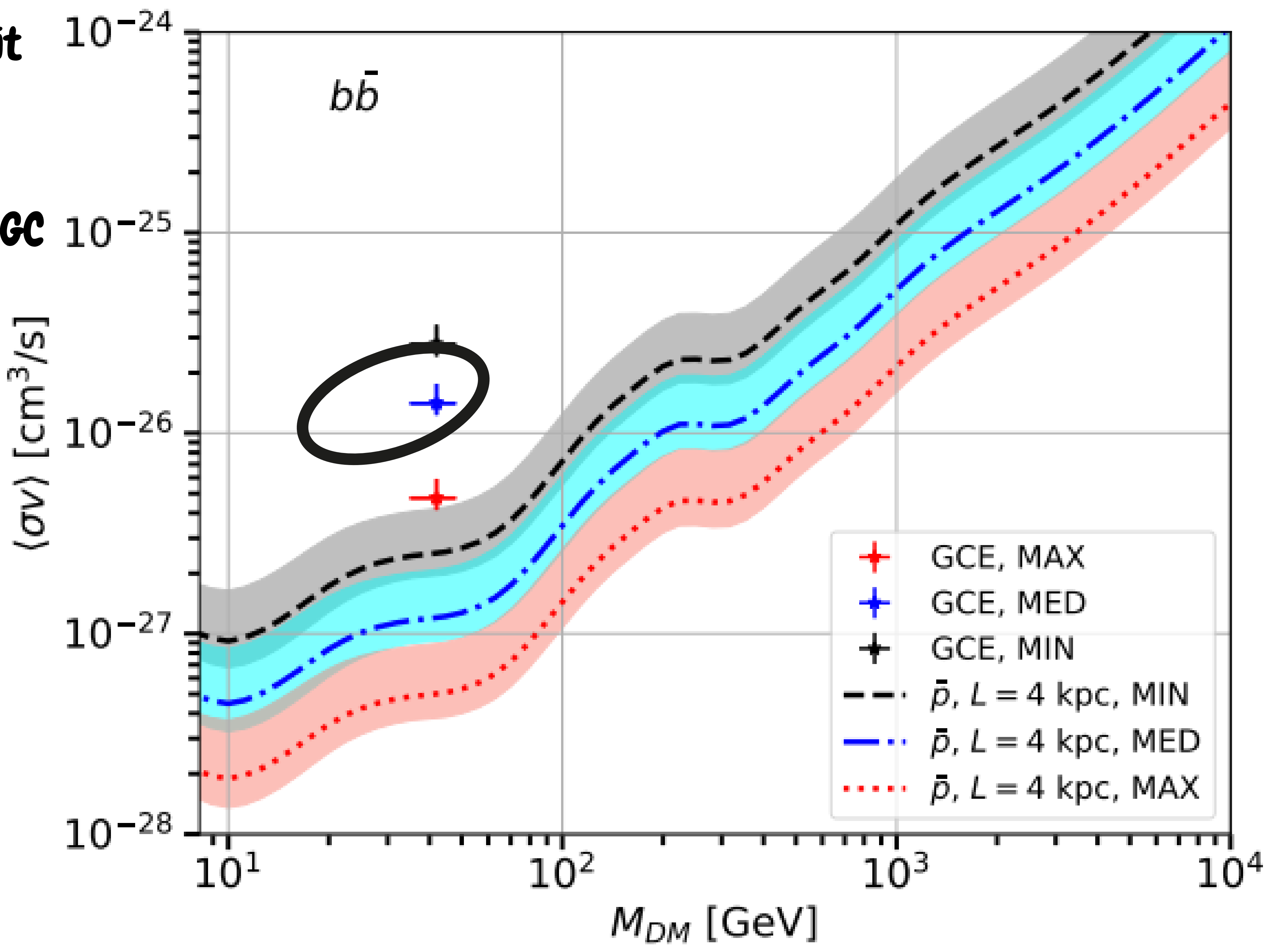


AMS

Our plans are to keep AMS operating on the International Space Station as long as there is a space station.

It is fair to say that the DM interpretation does provide a good fit to the Fermi-LAT data but is disfavored by other probes. The neutron stars interpretation for the GC excess is debatable

Leane and Slatyer, arXiv:1904.08430



Mauro, Winkler arxiv: 2101.11027

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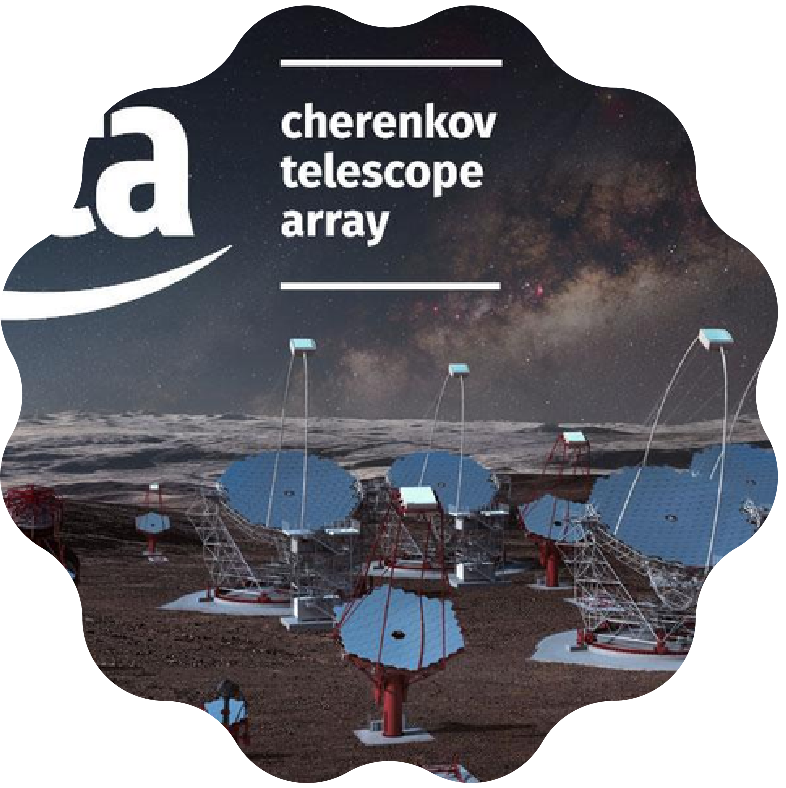
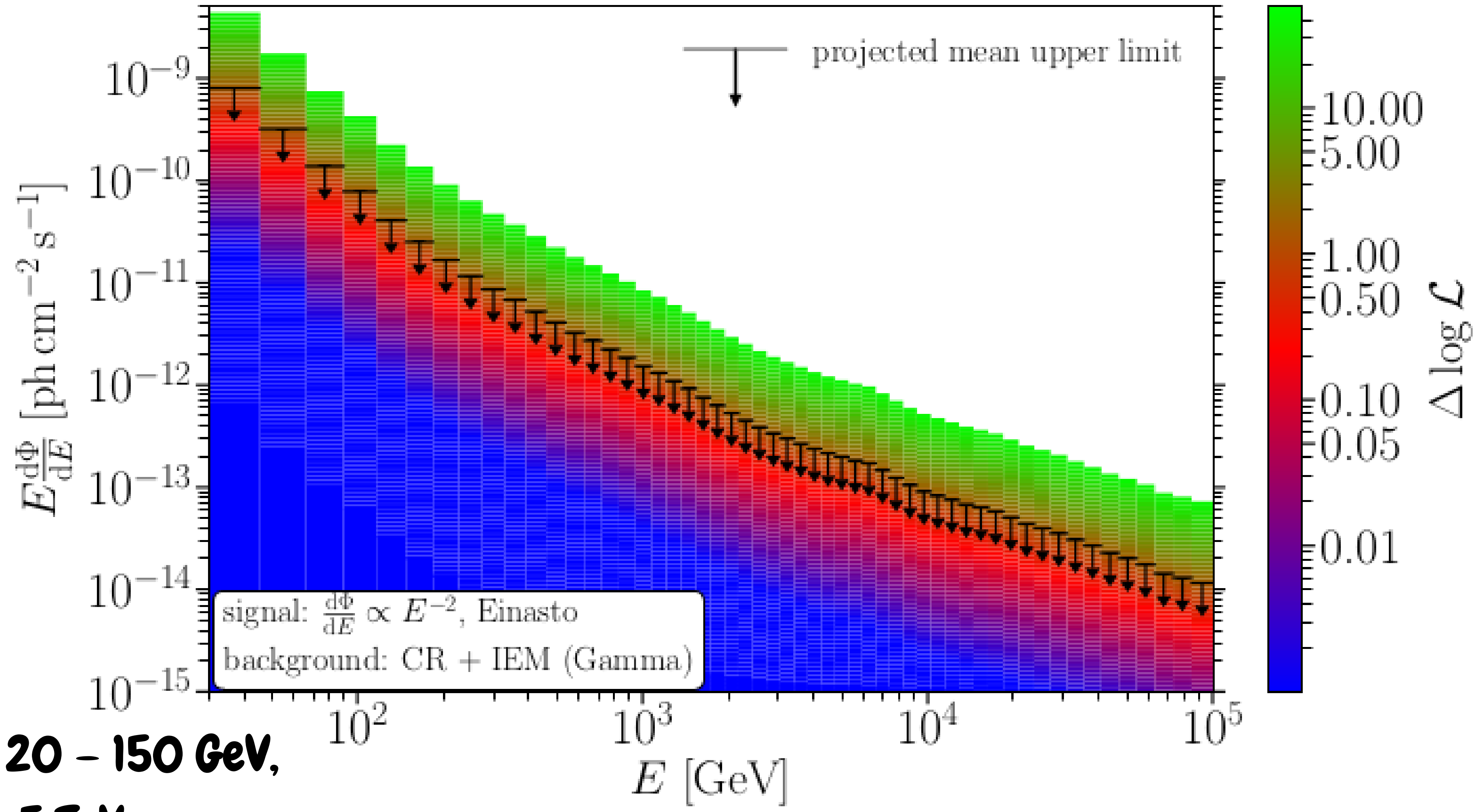


CTA

Hopefully in the coming years

Forecast



The CTA design concept :

i) LSTs (Large-Sized Telescopes, 23 m in diameter) E= 20 – 150 GeV,

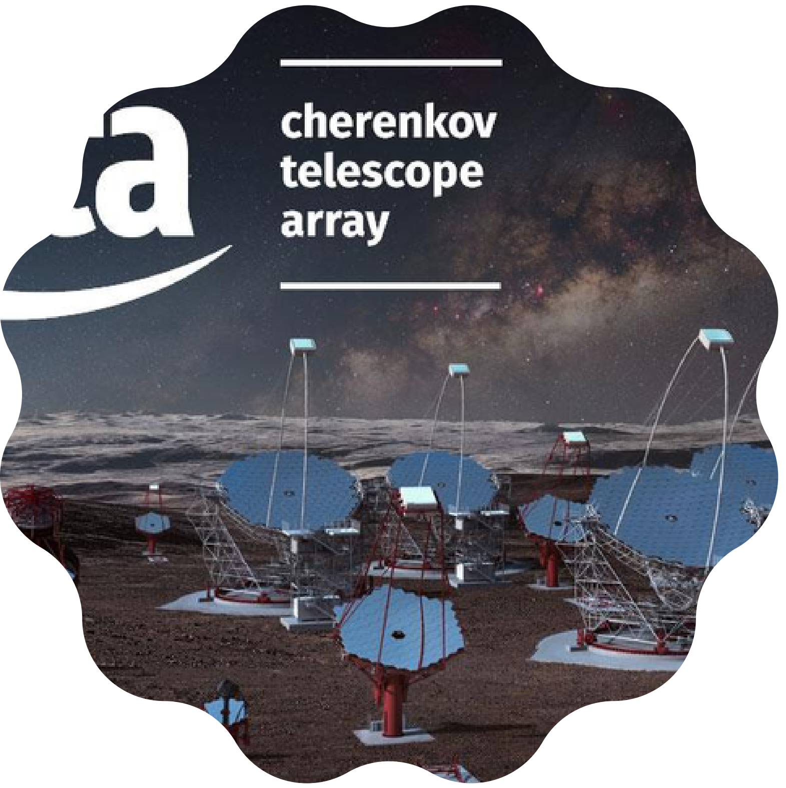
ii) MSTs (Medium-Sized Telescopes, 11.5 m) E=150 GeV-5 TeV

iii) a large number of SSTs (Small-Sized Telescope, 4 m) E> 5TeV

$$\overbrace{\frac{d\Phi}{d\Omega dE}}^{Diff.Flux} = \frac{\overbrace{\sigma v}^{Anni.\,Cross\,Section}}{8\pi m_\chi^2} \times \underbrace{\frac{dN}{dE}}_{Energy\,Spectrum} \times \int_{l.o.s} ds \underbrace{\rho^2(\vec{r}(s,\Omega))}_{Dark\,Matter\,Distribution}$$

CTA consortium,arxiv: 2007.16129

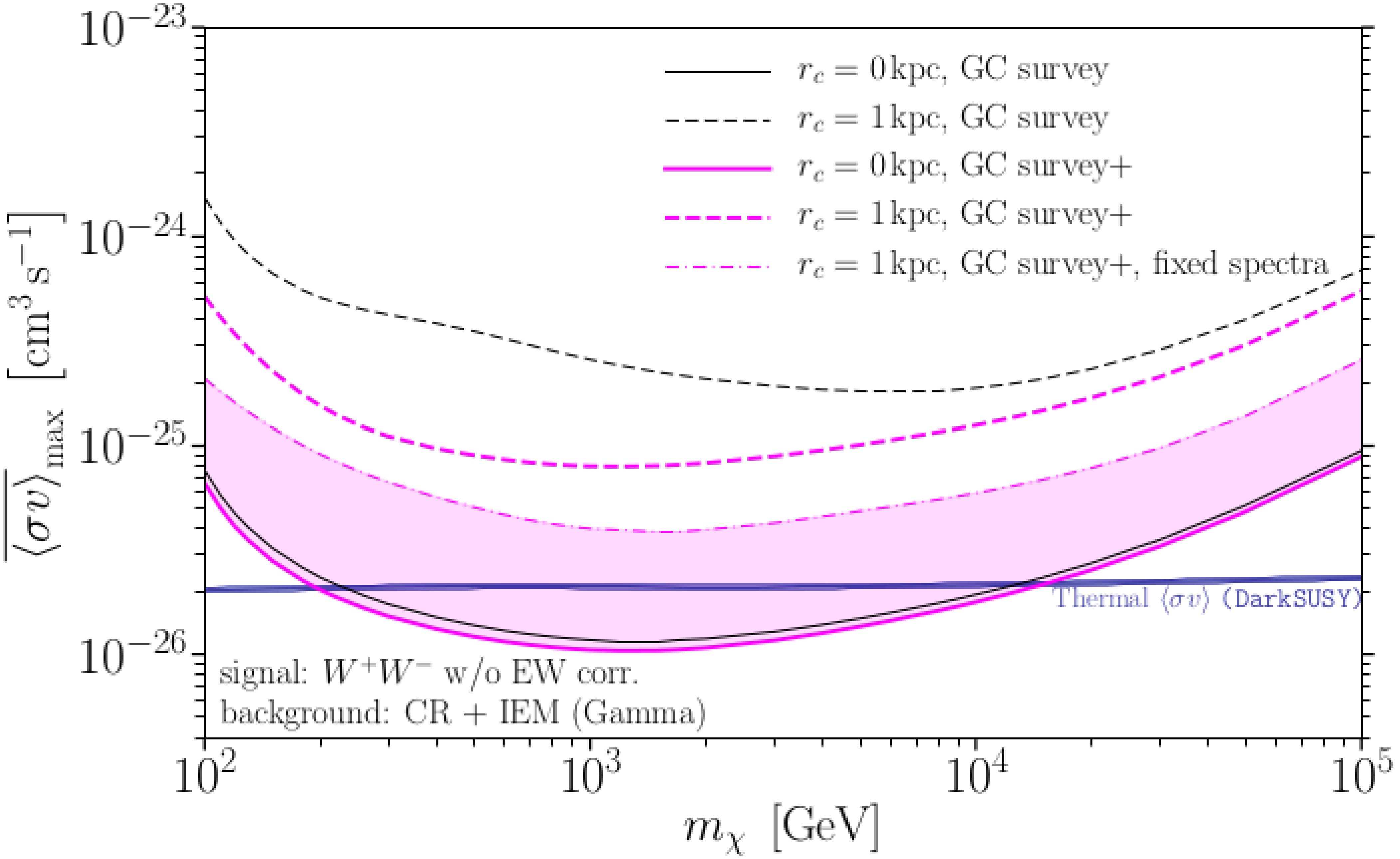
Where are we?



CTA

Hopefully in the coming years

CTA is expected to improve by 1-2 orders of magnitude the limits (masses > 300GeV)



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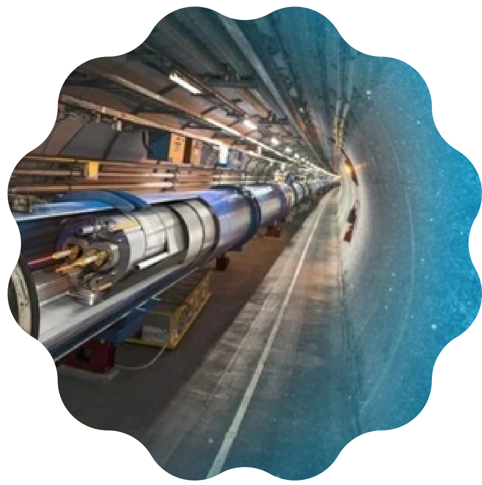
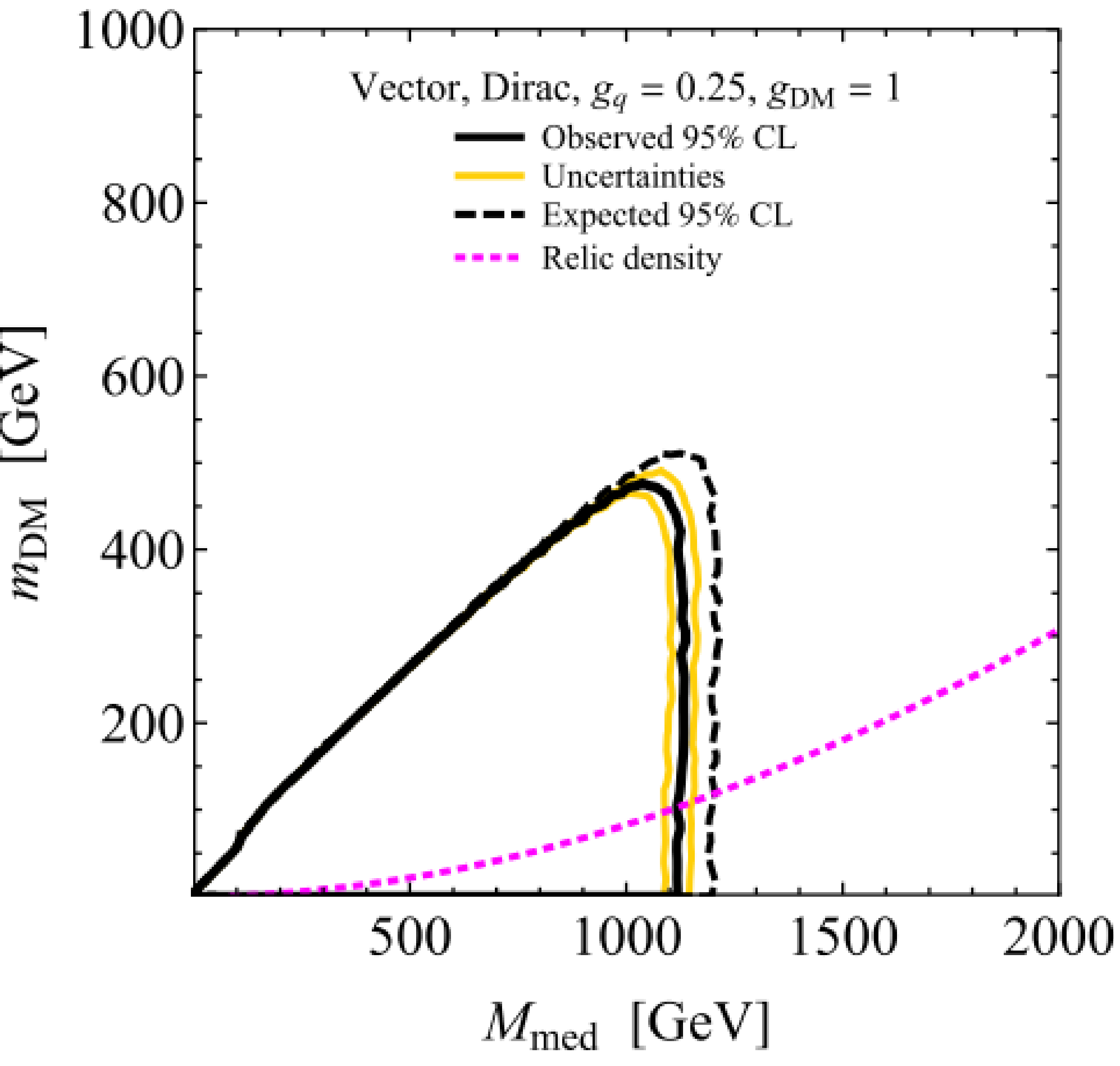
Colliders

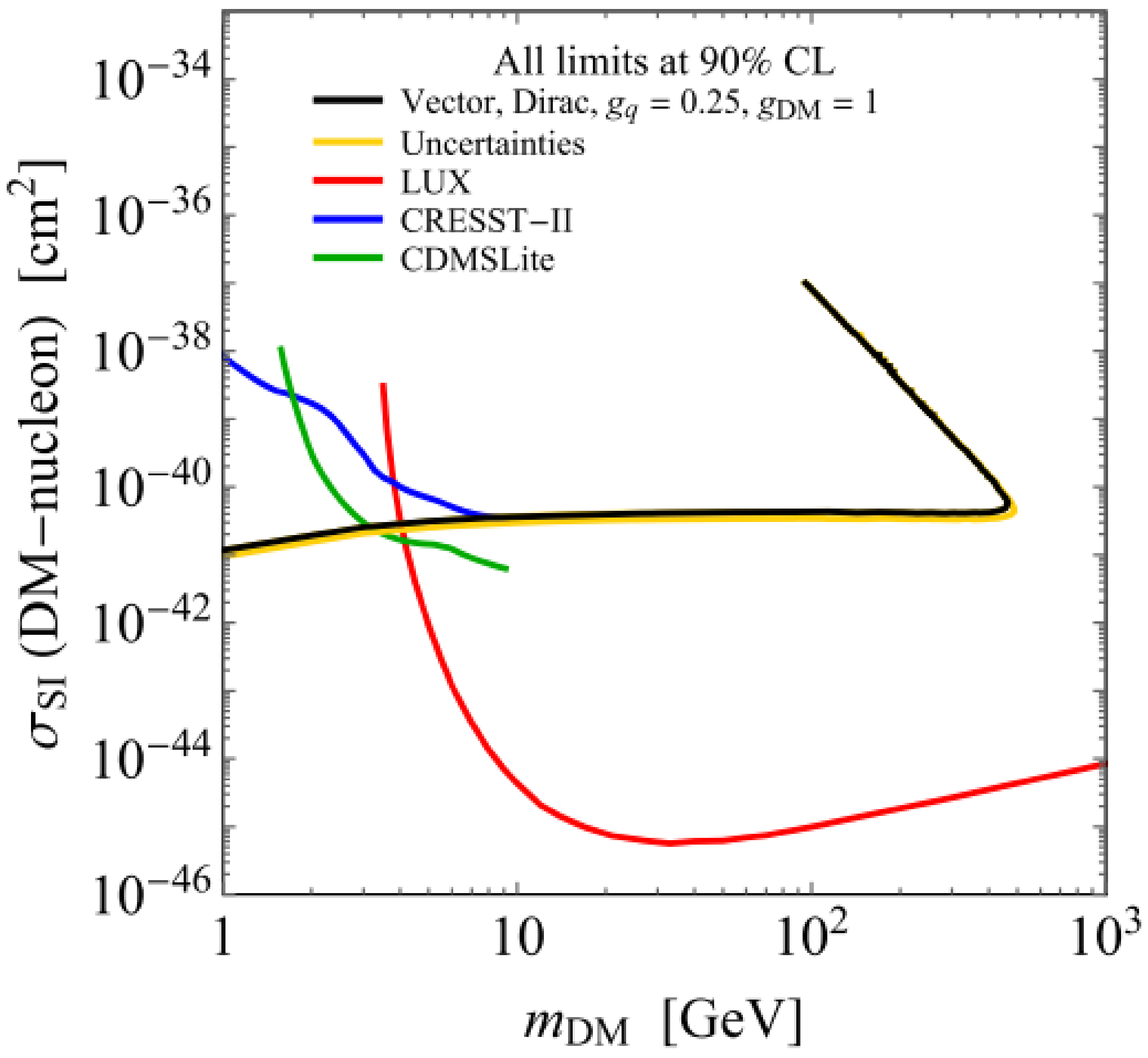


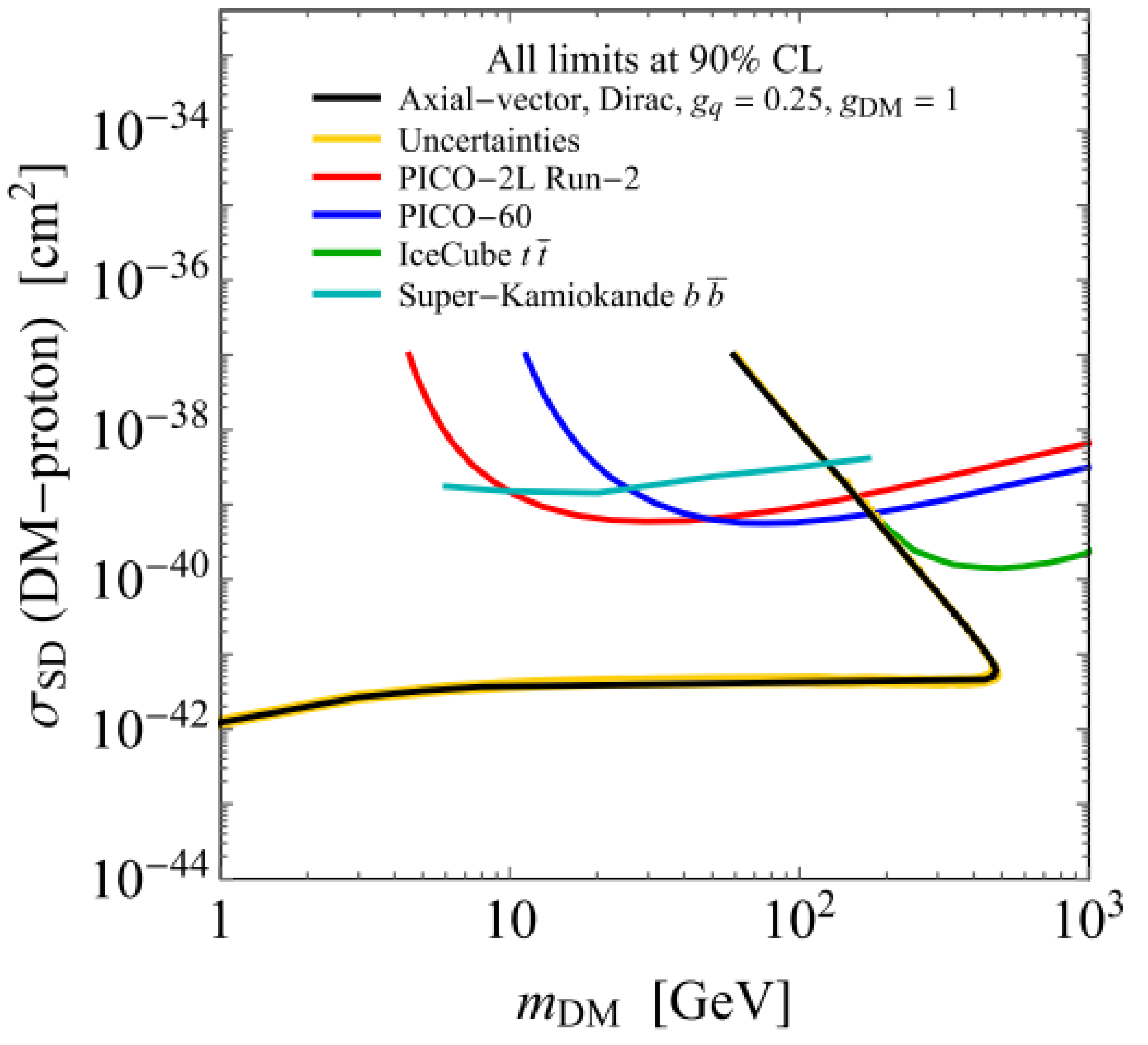
Represent an important cross-check

Cover regions of parameter unexplored by direct (indirect) detection experiments

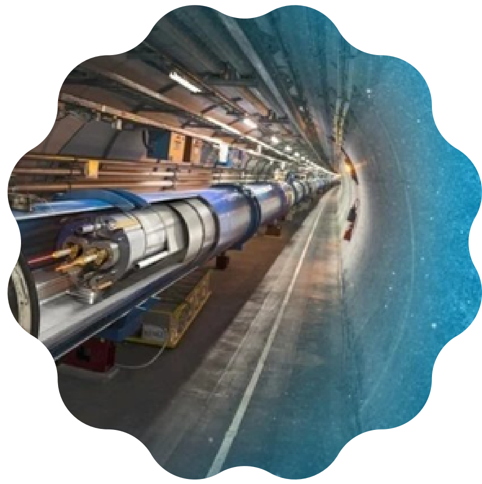
A. Boveia, 2022 Snowmass Summer Study, 2206.03456







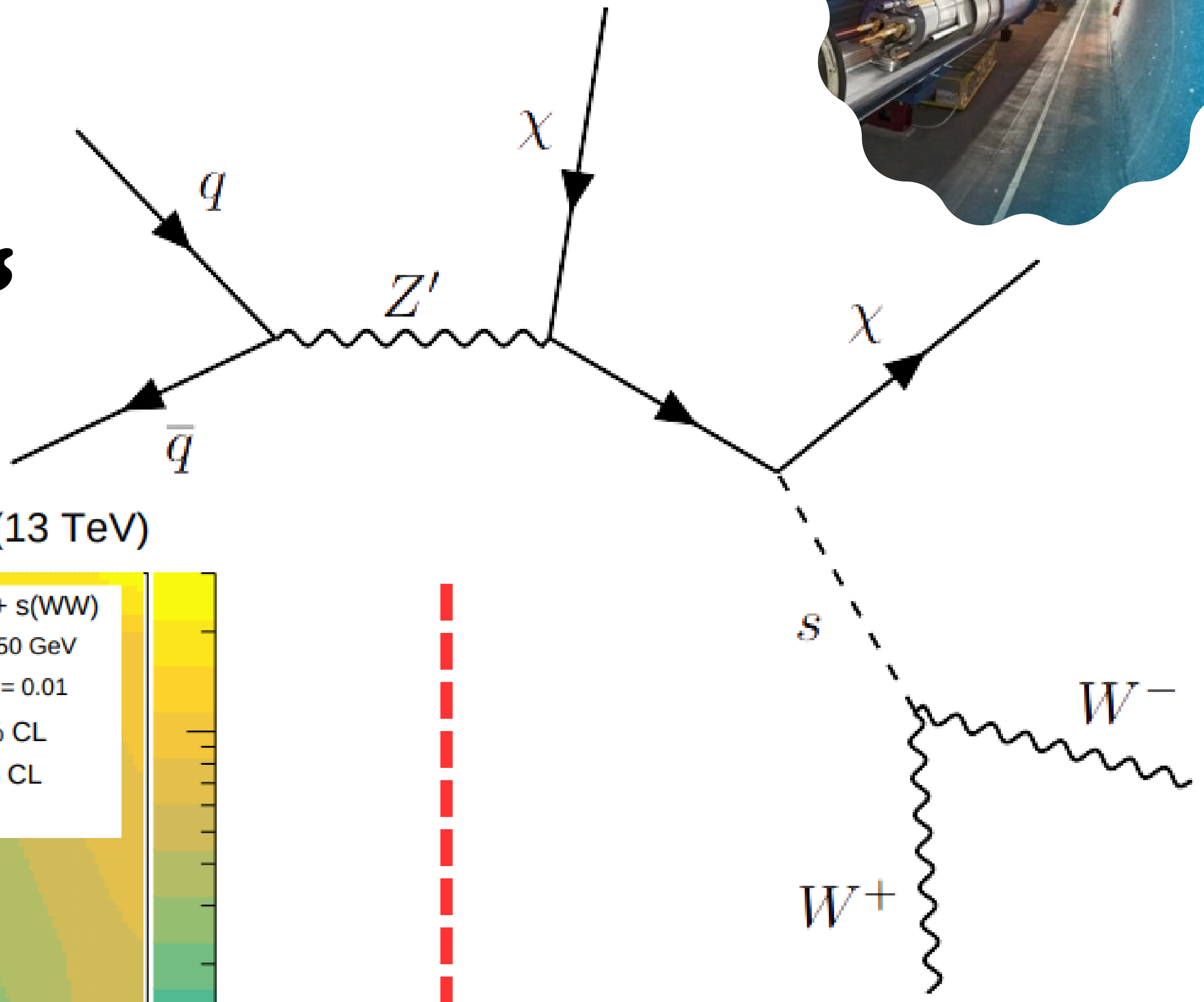
Colliders

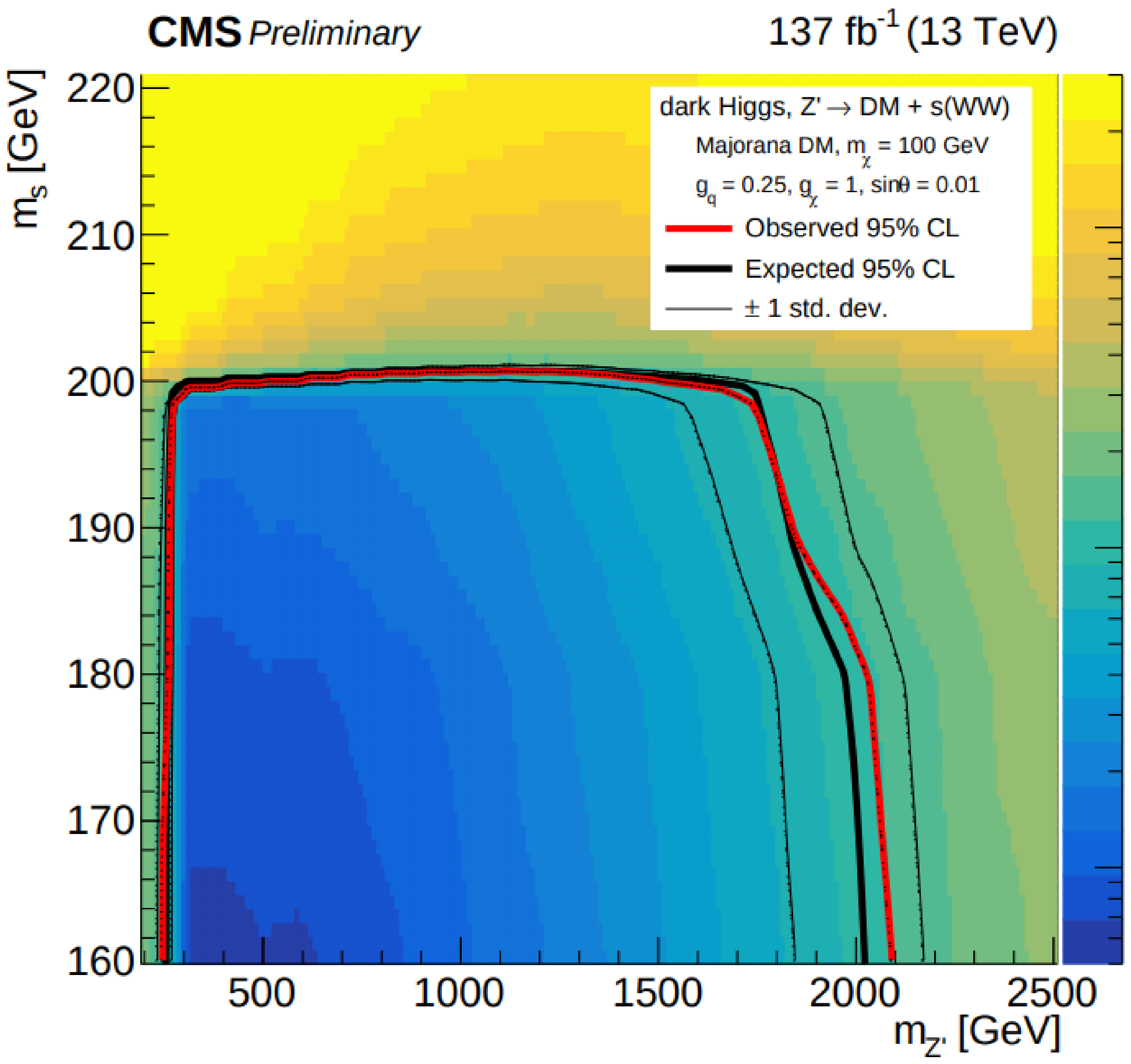


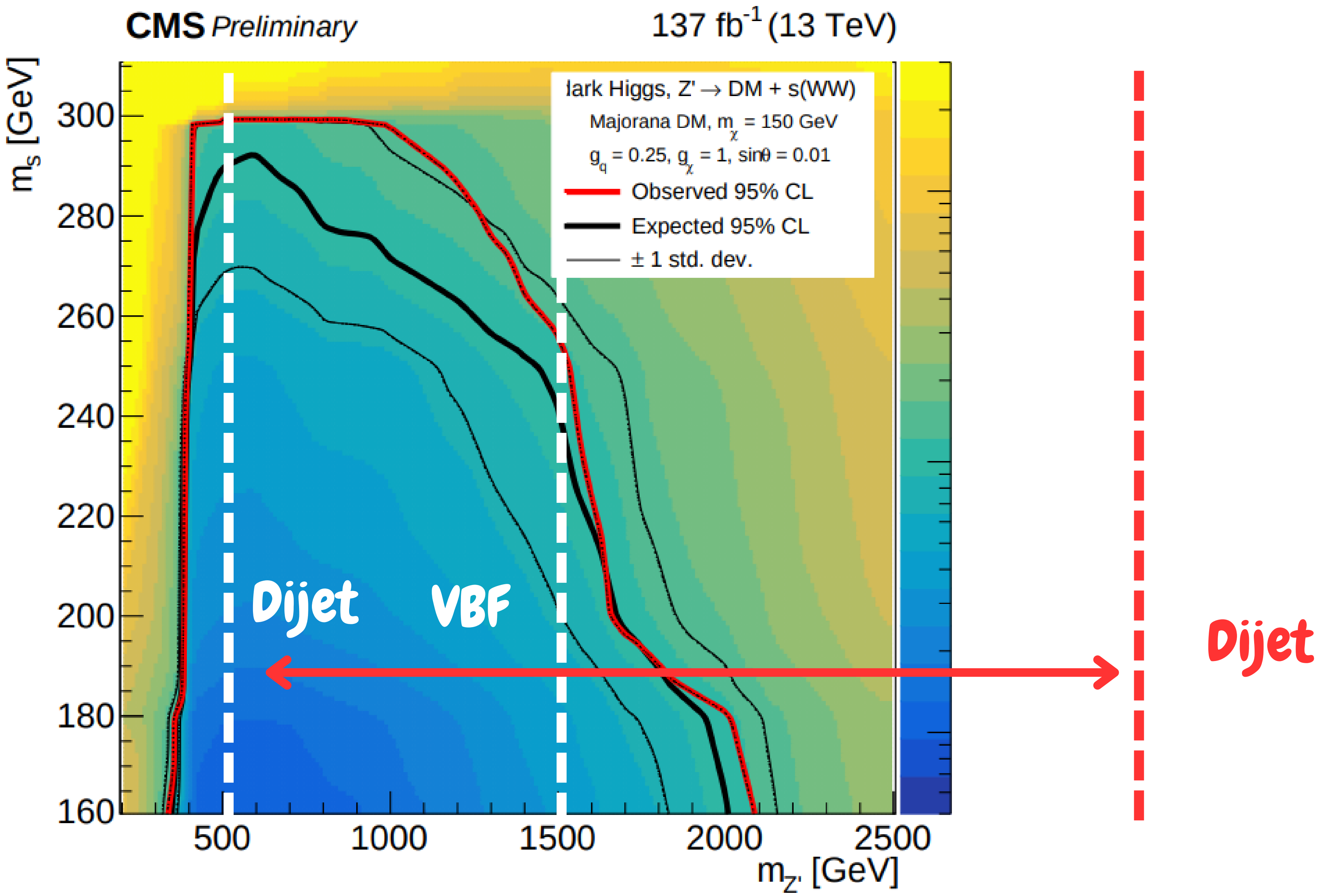
Represent an important cross-check

Cover regions of parameter unexplored by direct detection experiments

CMS, arxiv: 1908.01713







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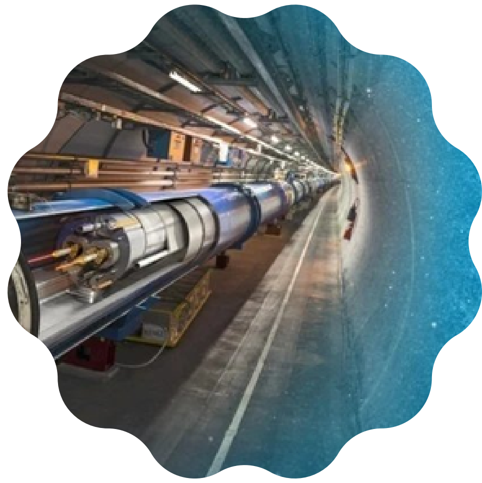


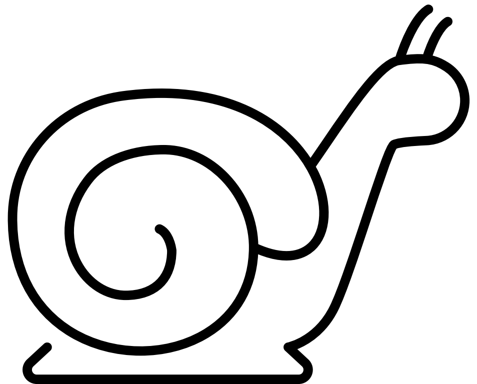
What's the future?

HL-LHC in 2030: it will not improve by one order of magnitude the sensitivity on dark sector

HE-LHC in 2050 ?

Colliders will continue to be important searches for dark sectors but the progress will occur at a very different pace

Muon collider? LHeC?

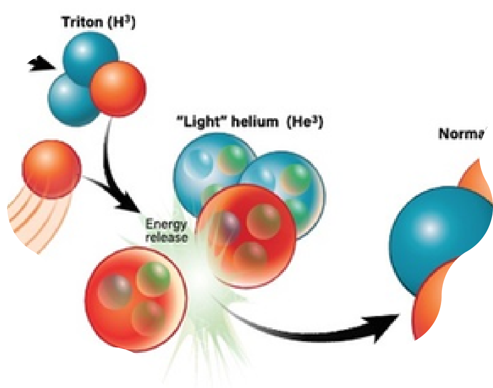


CoGENT
CDMS anomaly
DAMA
The GeV Fermi excess
AMS02 data
DAMPE
PAMELA
Xenon1T anomaly
x-ray signals.....
Shunsaku Horiuchi's tak

Pandora box

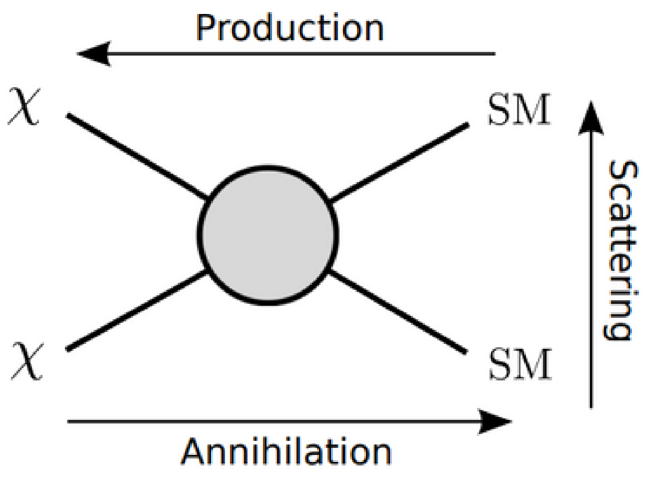
If it is hard to observe a clear dark matter signal within the thermal relic paradigm, imagine if we depart from it

Standard Darkness

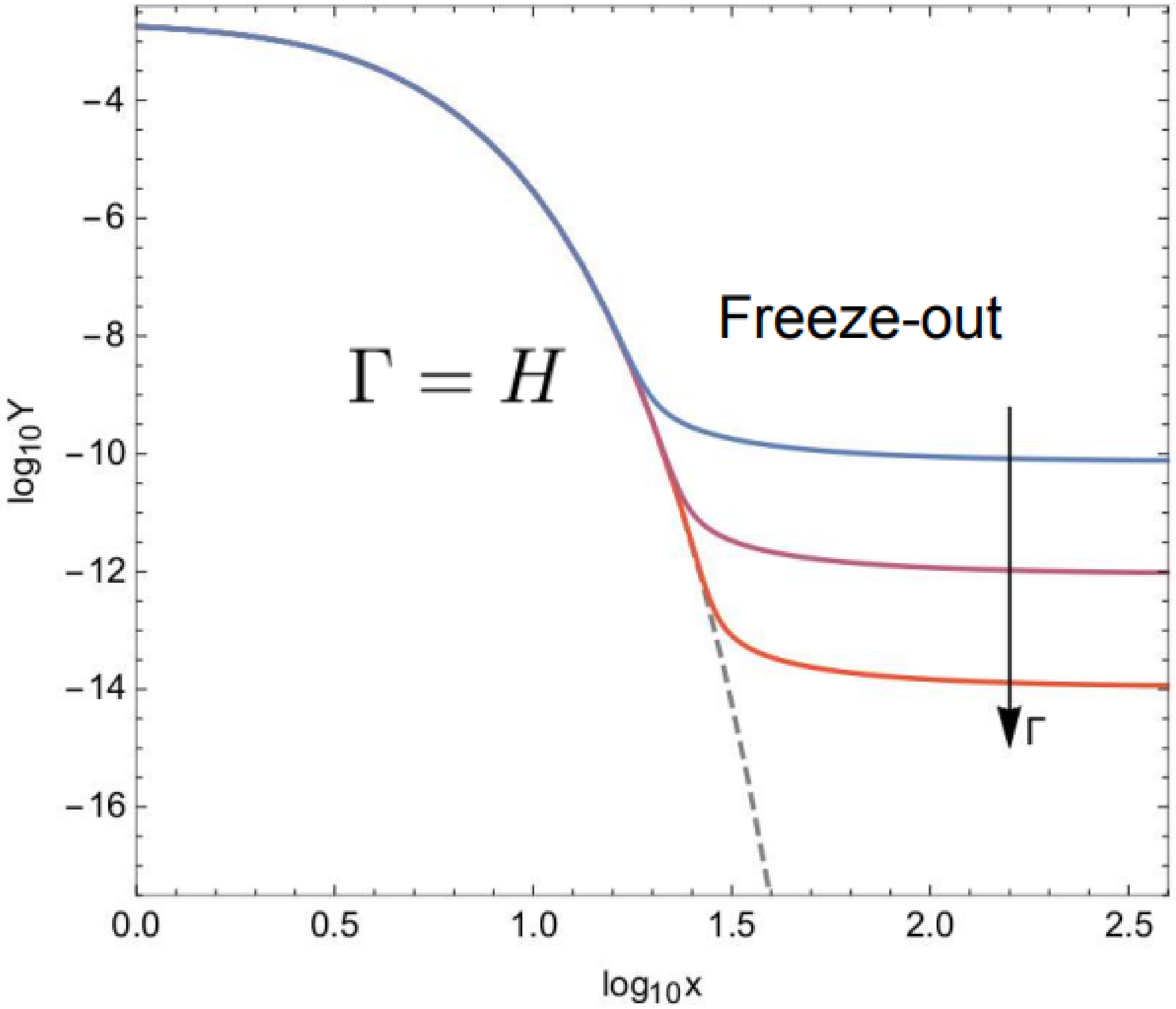


We often use as evidence for dark matter

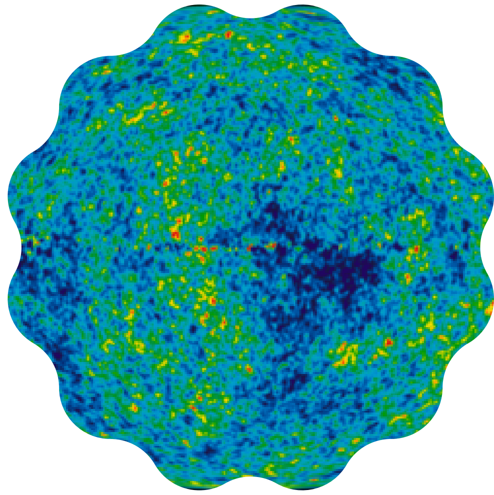
Galaxy rotation curves
Cosmic Microwave Background
Collision of Clusters
Baryon Acoustic Oscillations
Gravitational Lensing
Cosmic Shear
Structure Formation
*Fermi GeV excess
*AMS-02 results

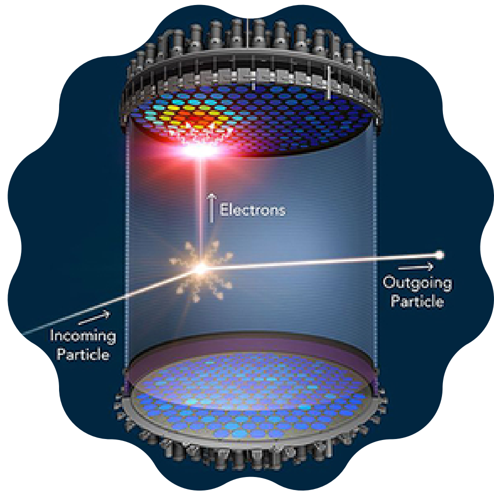


Thermal relic



smaller CS
standard CS
large CS





$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle \left(n_\chi^2 - n_\chi^{\text{eq}2} \right)$$

Standard Darkness

We often use as evidence for dark matter

Galaxy rotation curves
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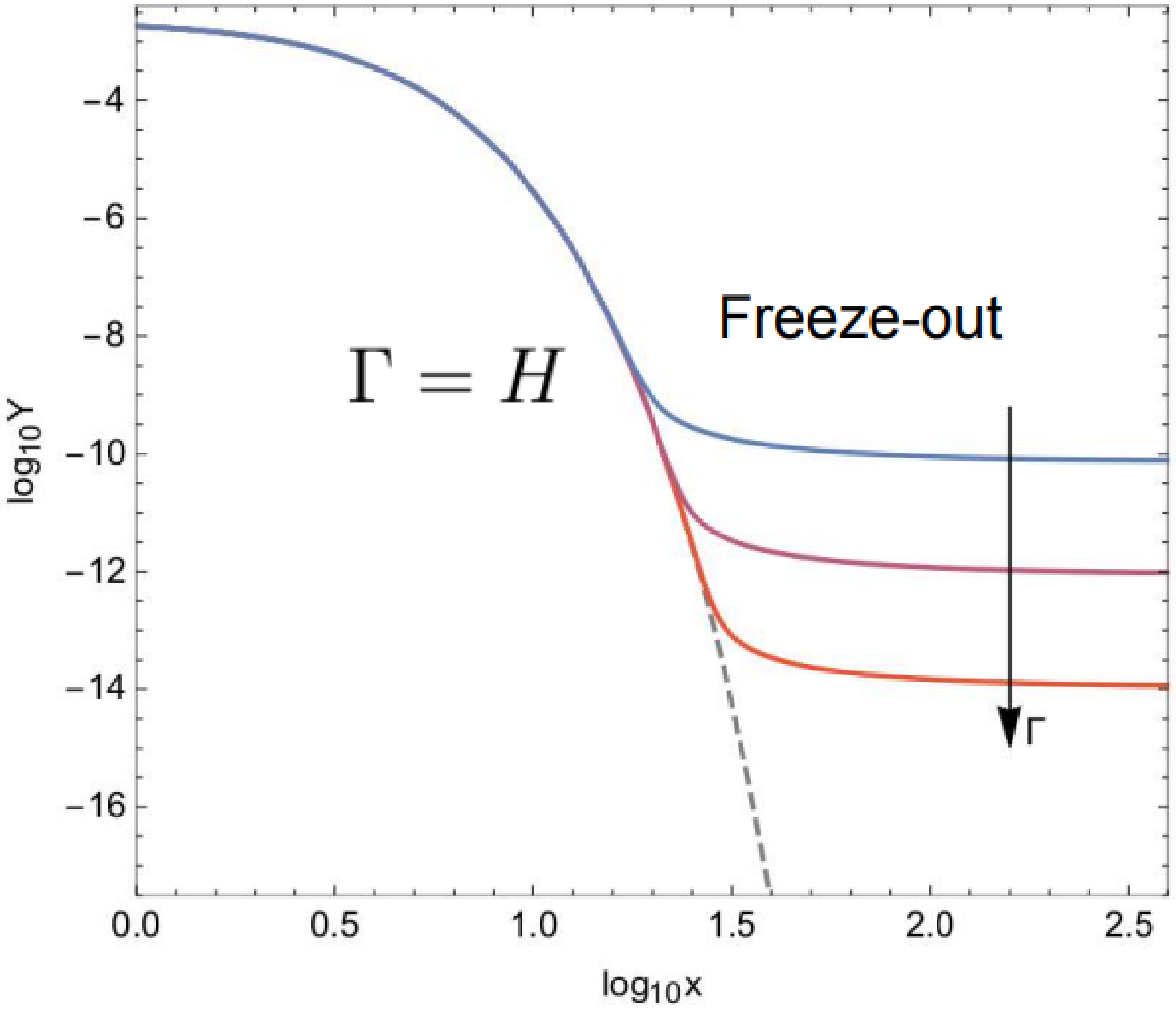
*AMS-02 results
Neutrino Masses
Lepton Flavor Violation
Hierarchy Problem
Grand Unification

} Extra

Thermal relic



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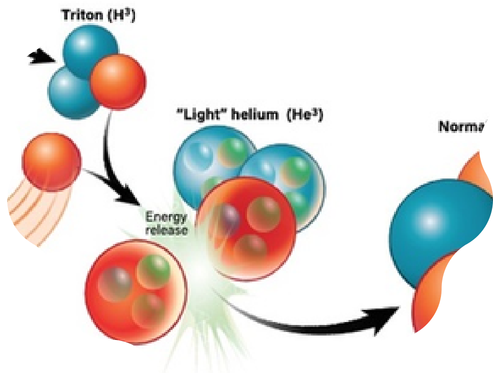
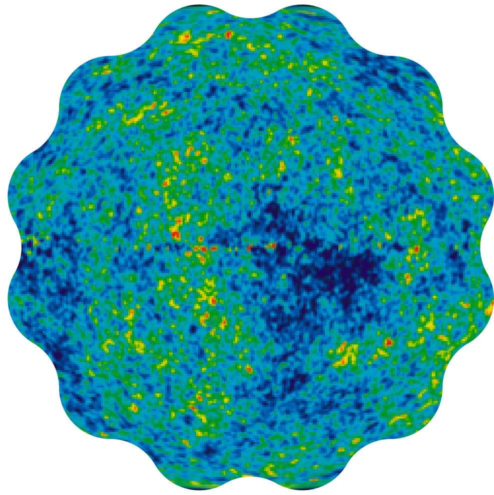
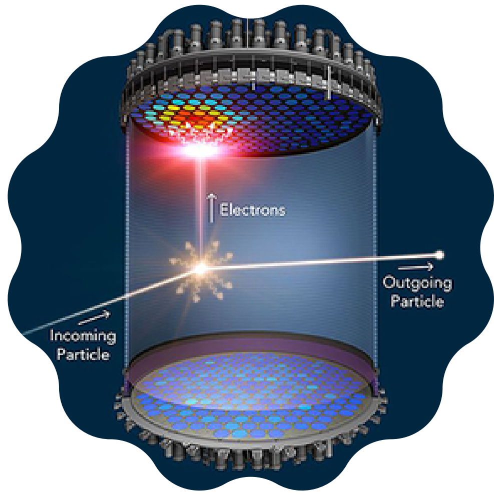






Bear in mind that I will play the devil's advocate

Standard Darkness

Stranger Darkness

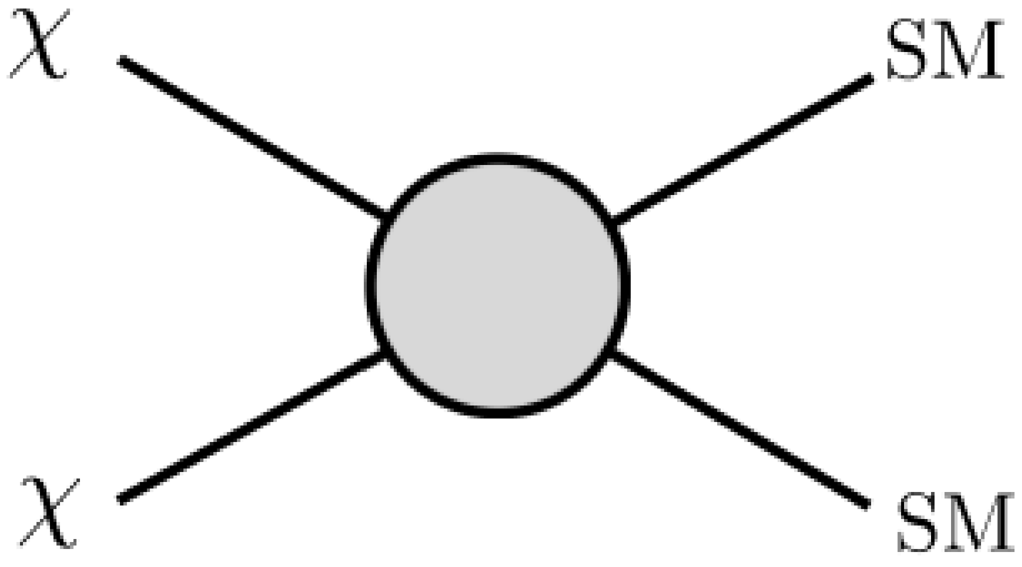
Stranger Darkness

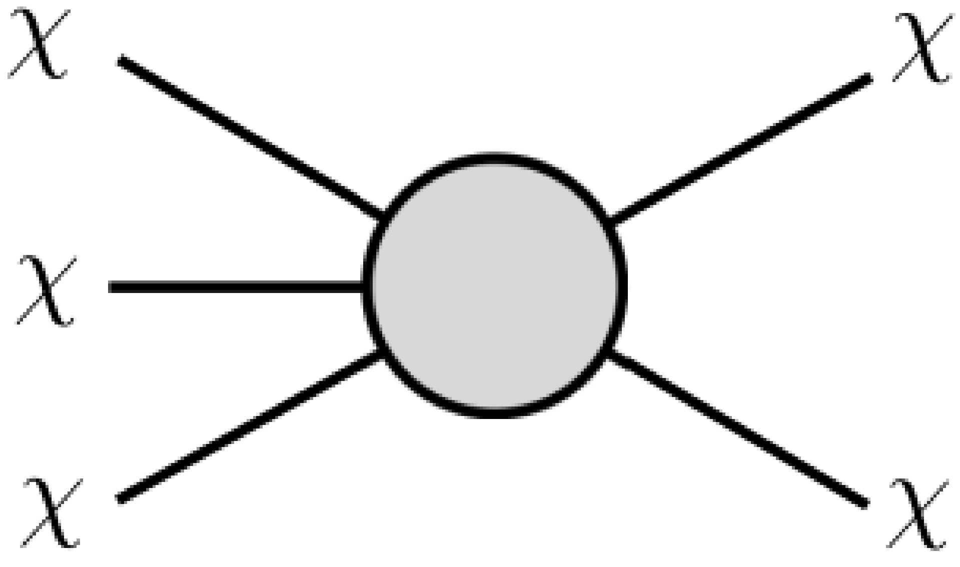
Before we where motivated by "signals" now by why not?

SIMP (Strongly Interacting Massive Particle)

DM abundance is determined by number changing interactions

Takashi's talk on Tuesday





Helps to solve the small scale problem (cusp x core)

Large self-interactions are required for observed abundance

How can I prove to my experimental colleague that a SIMP was observed?

Hochberg, Kuflik, VolanskyWacker, arxiv:1402.5143

Stranger Darkness

Before we where motivated by "signals" now by why not?

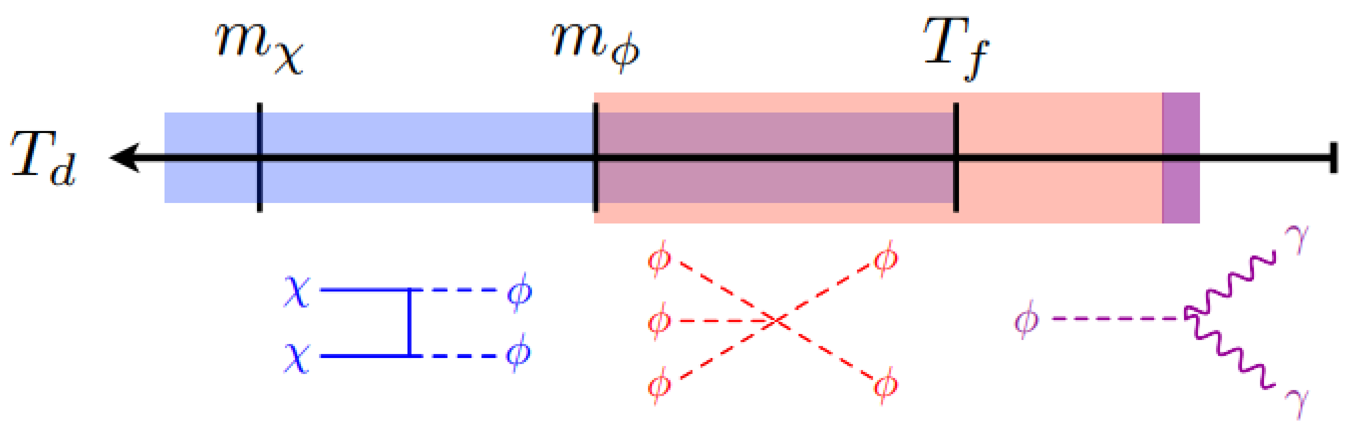
Cannibal DM

1. The dark sector is kinetically decoupled from the SM sector.
2. The dark sector has a mass gap.
3. The dark sector remains in chemical equilibrium, through number changing interactions, at temperatures below the mass of the LDP.

4*. The scalar field phi decays into radiation

5* The scalar field dominated the energy density

6* Assume that DM annihilations decouple during cannibalism



A boosted rate for indirect detection

Dark fields are kinematically decoupled from SM

The dark sector remains in chemical equilibrium, through number changing interactions,

How can I prove to my experimental colleague that a Cannibal DM was observed?

Pappadopulo, Ruderman, Trevisan, 1602.04219

Stranger Darkness

Before we where motivated by "signals" now by why not?

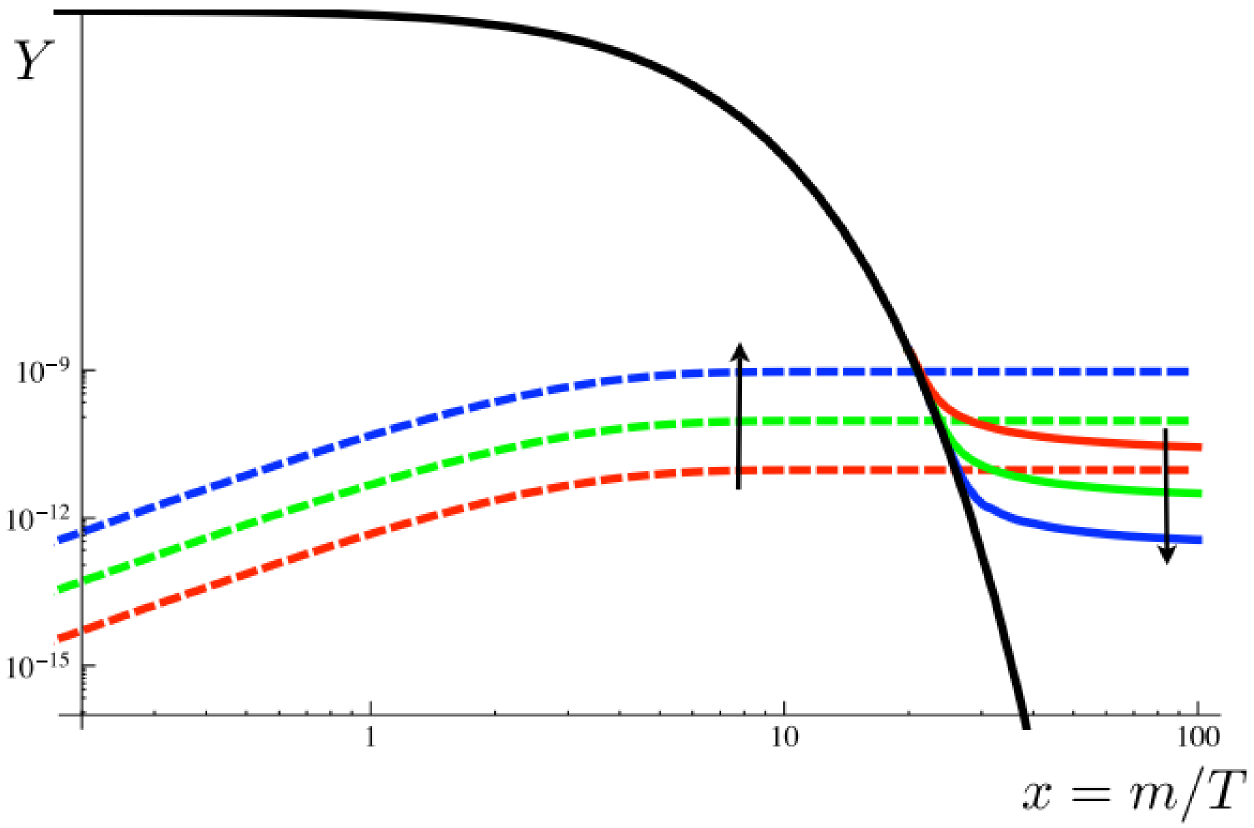
Hope to observe the companions

FIMP Feebly Interacting Massive Particle)

1. Never thermalized with SM sector,
2. Produced slowly by decays or scatterings
3. tiny couplings are needed

$$\Omega_\chi h^2 \simeq 4.48 \times 10^8 \frac{g_\sigma}{g_{*s}\sqrt{g_*}} \frac{m_\chi}{\mathrm{GeV}} \frac{M_{\mathrm{P}}\,\Gamma_{\sigma\to\chi\chi}}{m_\sigma^2}$$

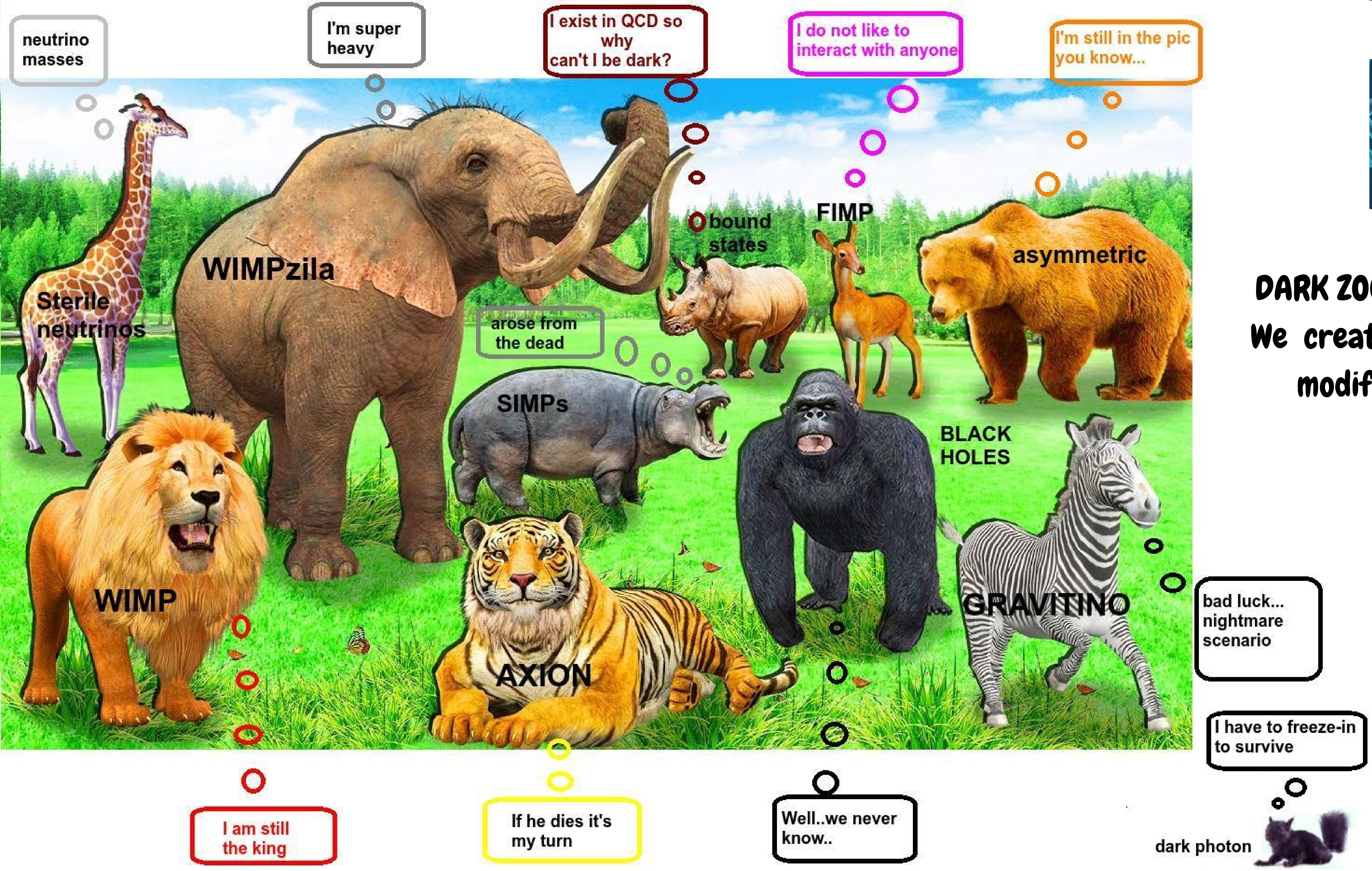
$$y \simeq 10^{-12} \left(\frac{\Omega_\chi h^2}{0.12}\right)^{1/2} \left(\frac{g_*}{100}\right)^{3/4} \left(\frac{m_\sigma}{m_\chi}\right)^{1/2}$$



Good luck proving it has anything to do with dark matter

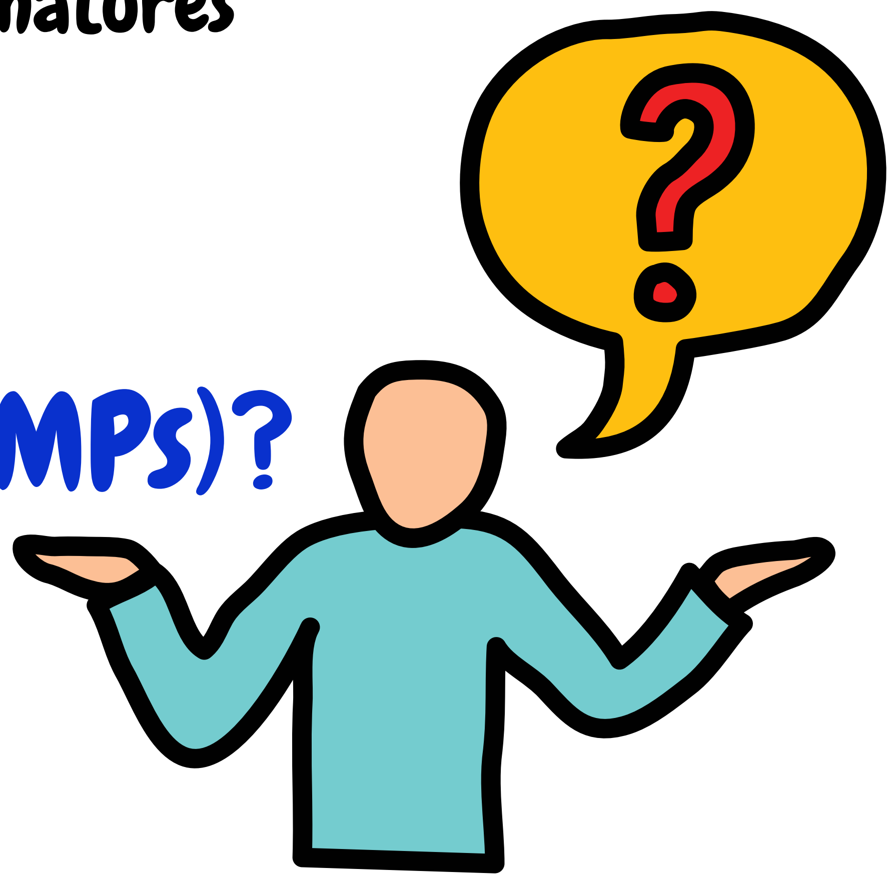
Hall,Jedamzik, March-Russell, West, arxiv: 0911.1120

Bernal, Heikinheimo,Tenkanen,Tuominen,Vaskonen, 1706.07442



DARK ZOO is not enough.
We created a genetically modified dark zoo

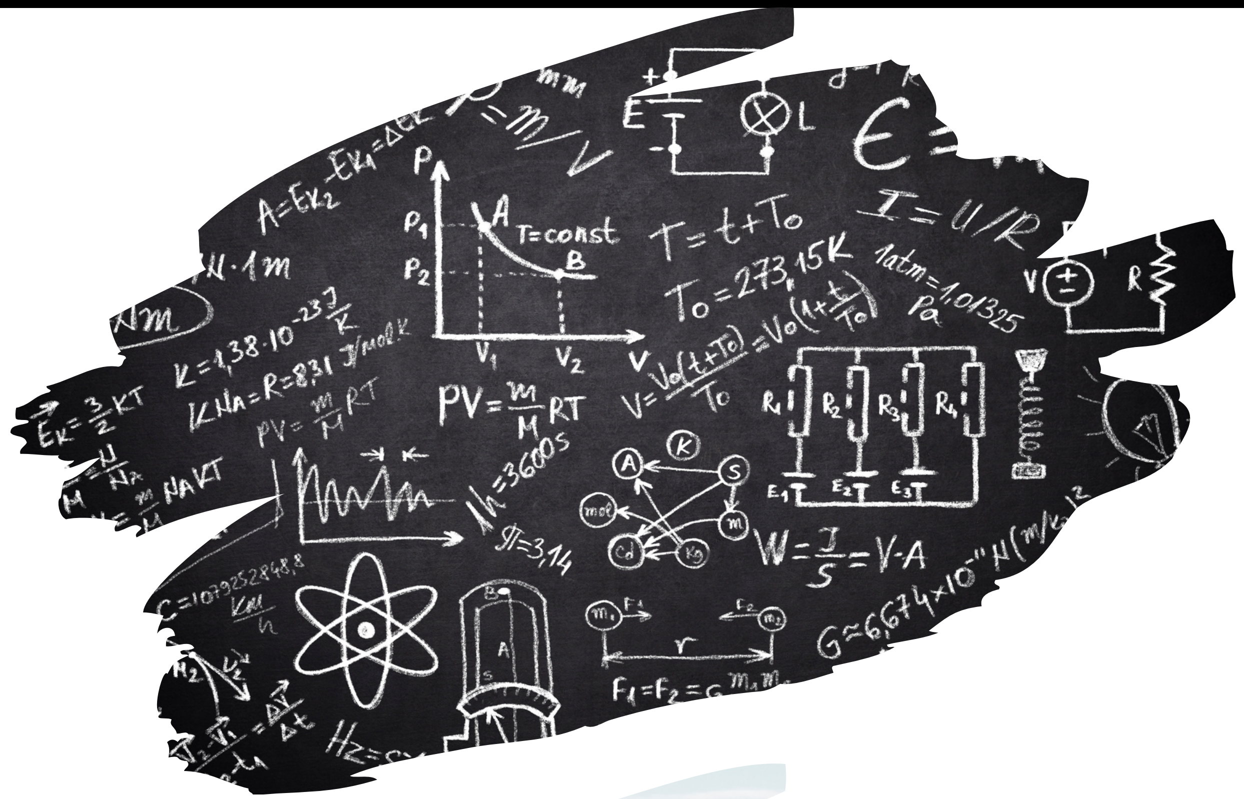
If you think is plausible to assume tiny couplings, tuned mass differences
several assumptions about complex dark sectors, and lack of smoking gun signatures



What can you say against thermal relics (or WIMPs)?

If are near resonances, assume a tiny mass gap (coannihilation,inelastic), matter domination periods, we do the same game above, while keeping the IMPORTANT multifaceted search going

For theorists this is fun though



For experimentalists, the question is:

which road should I take?

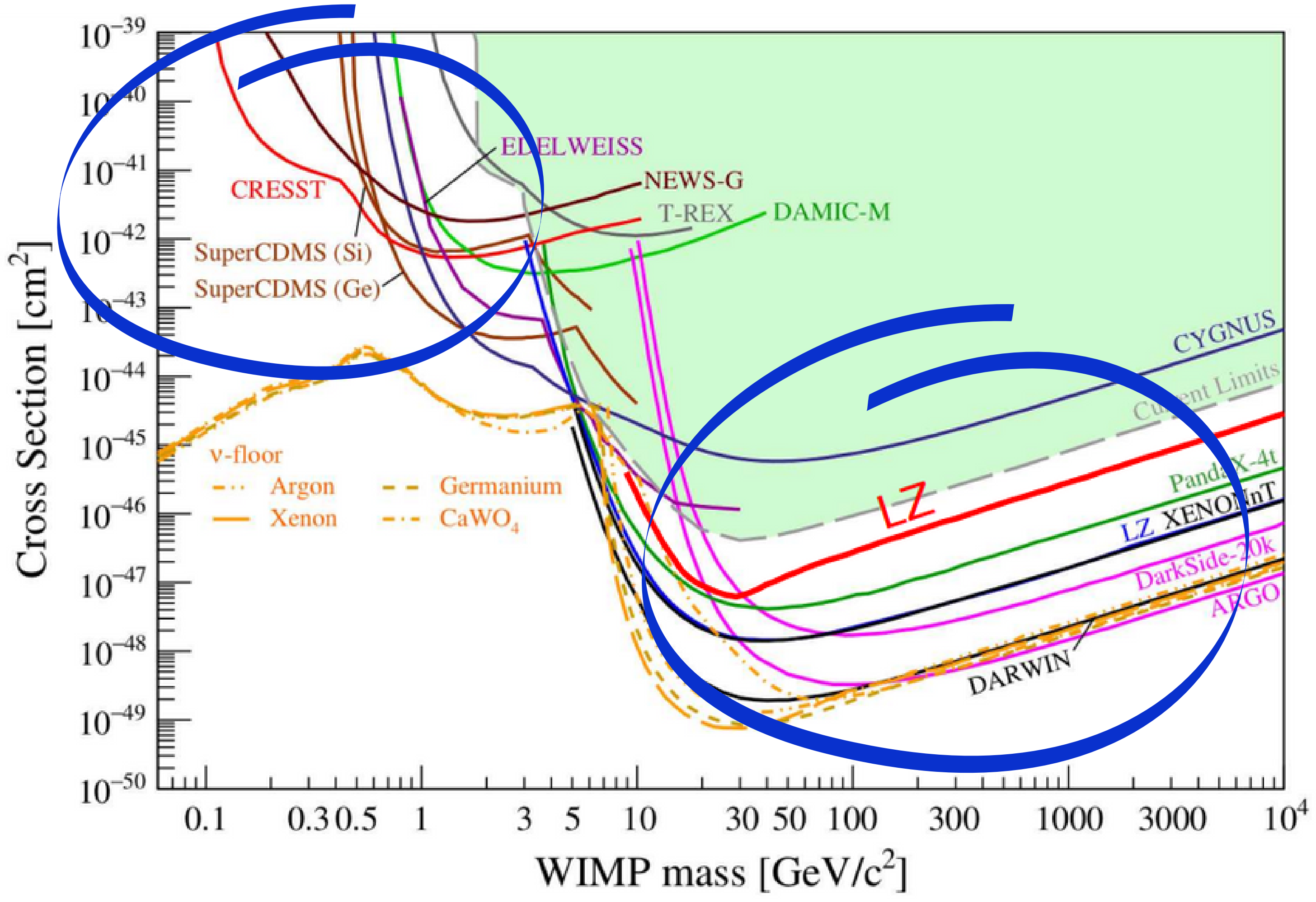
Alternative dark sectors

Thermal relics

Back to Standard Darkness

Thermal Particles

DM bilinear	*SM fermion bilinear*			
fermion DM	$\bar{f}f$	$\bar{f}\gamma^5 f$	$\bar{f}\gamma^\mu f$	$\bar{f}\gamma^\mu\gamma^5 f$
$\bar{\chi}\chi$	$\sigma v \sim v^2,\ \sigma_{SI} \sim 1$	$\sigma v \sim v^2,\ \sigma_{SD} \sim q^2$	–	–
$\bar{\chi}\gamma^5\chi$	$\sigma v \sim 1,\ \sigma_{SI} \sim q^2$	$\sigma v \sim 1,\ \sigma_{SD} \sim q^4$	–	–
$\bar{\chi}\gamma^\mu\chi$ (Dirac only)	–	–	$\sigma v \sim 1,\ \sigma_{SI} \sim 1$	$\sigma v \sim 1,\ \sigma_{SD} \sim v_\perp^2$
$\bar{\chi}\gamma^\mu\gamma^5\chi$	–	–	$\sigma v \sim v^2,\ \sigma_{SI} \sim v_\perp^2$	$\sigma v \sim 1,\ \sigma_{SD} \sim 1$



This translates to the rates at direct detection experiments being suppressed by several orders of magnitude

Sure there are ways to circumvent bounds using particle physics but let's

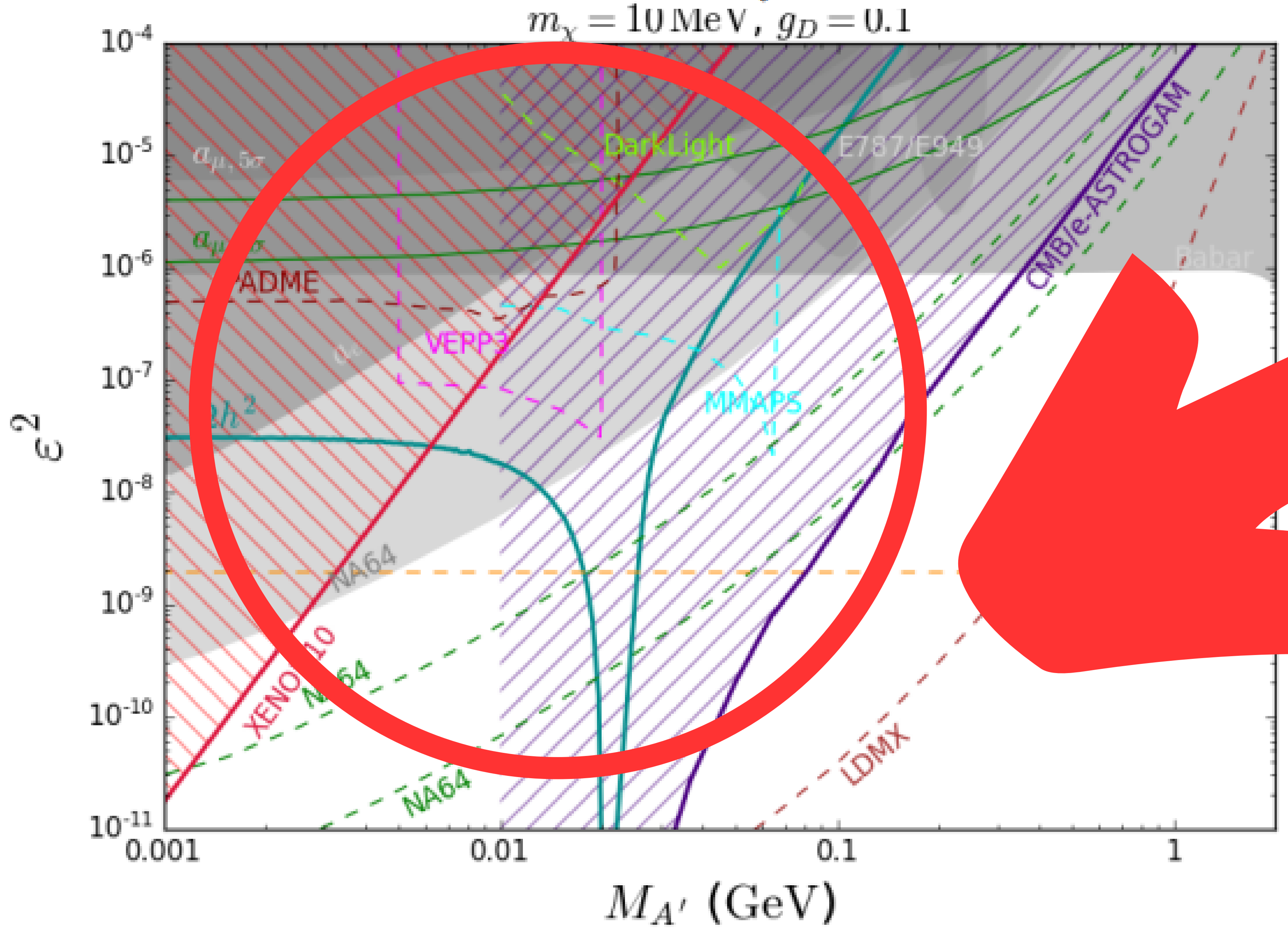
take very constrained models and see what happens when we play with cosmology

Berlin, Hooper, McDermott,arxiv: 1404.0022

Back to Standard Darkness

Taking a very constrained scenario: dark photon

$$\overline{\chi}(-g_D \not{A}' - m_\chi)\chi + \sum_i \overline{f}_i(-e q_{f_i} \not{A} - \varepsilon e q_{f_i} \not{A}' - m_{f_i}) f_i$$



Thermal relic

+

Direct detection

+

Indirect Detection

+

Accelerator

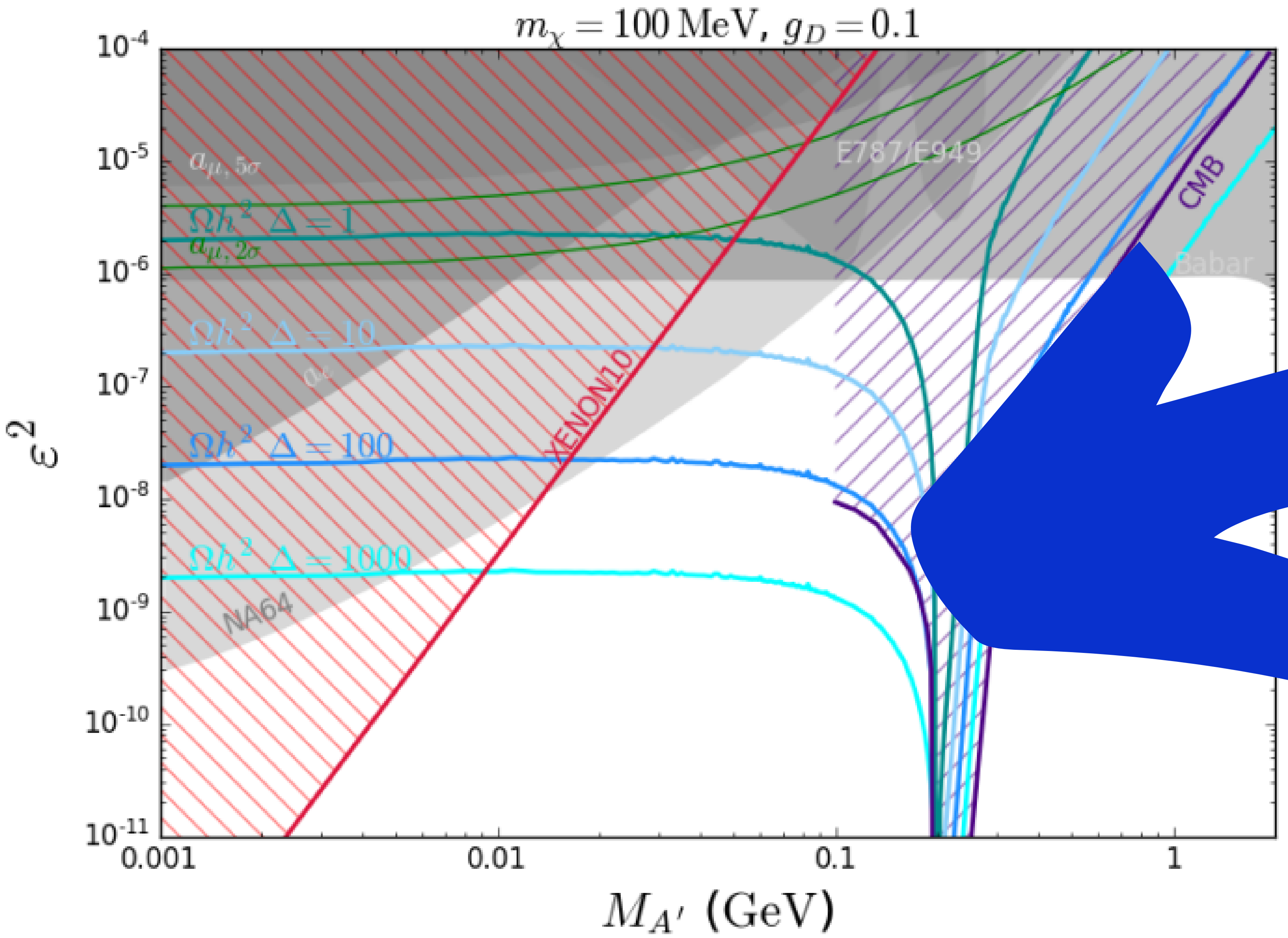
It has been excluded already by several experiments

Dutra, Lindner, Profumo, FSQ, Rodejohann, 1801.05447

Back to Standard Darkness

Taking a very constrained scenario: dark photon

$$\bar{\chi}(-g_D \not{A}' - m_\chi)\chi + \sum \bar{f}_i(-e q_{f_i} \not{A} - \varepsilon e q_{f_i} \not{A}' - m_{f_i}) f_i$$



Thermal relic

+

Direct detection

+

Indirect Detection

+

Accelerator

+

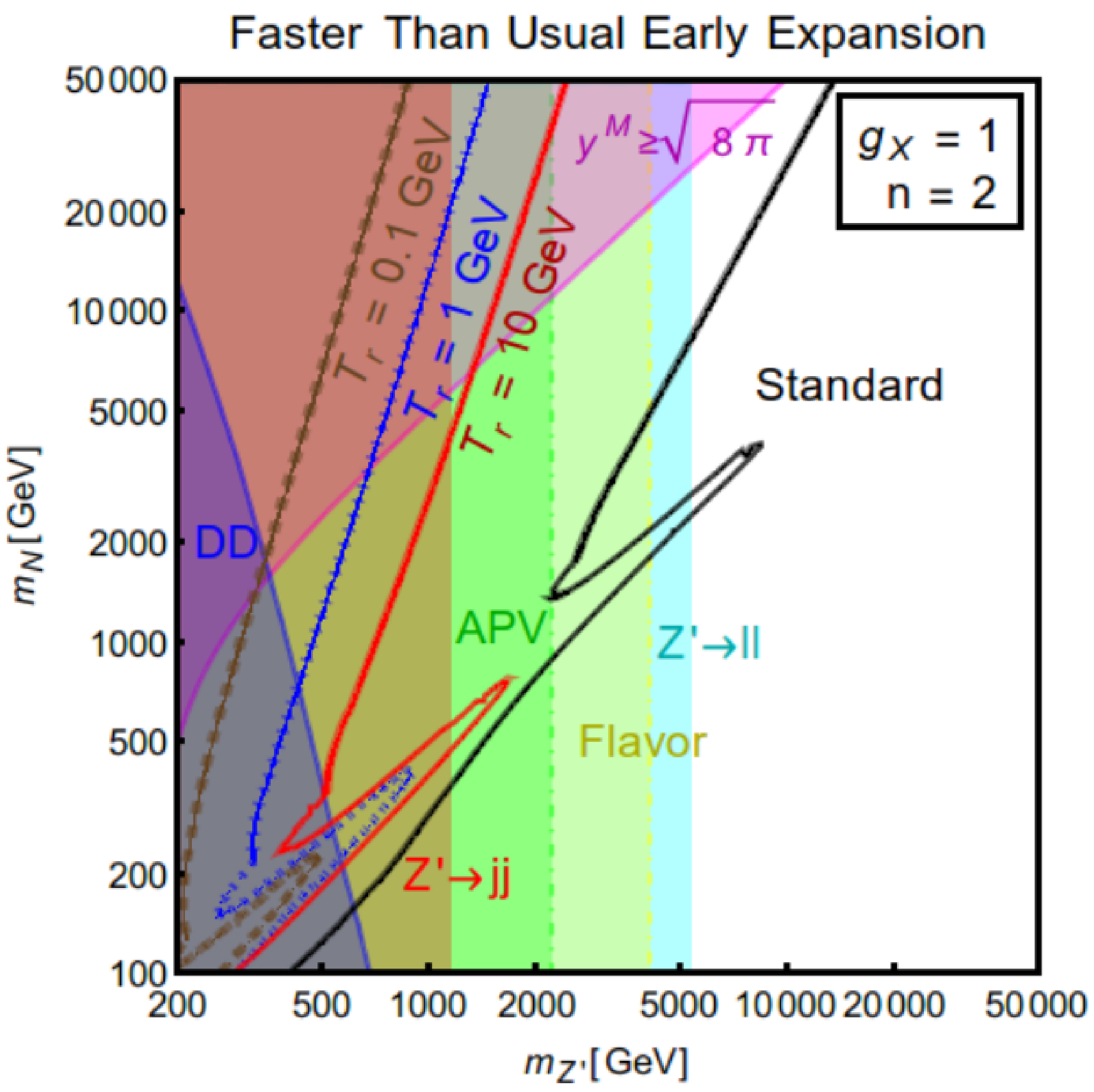
Non-standard Cosmologies

Dutra, Lindner, Profumo, FSQ, Rodejohann, 1801.05447

Back to Standard Darkness

Taking a very constrained scenario: Z'

$$+\frac{1}{4} g_X \left(N_{1R}\gamma^{\mu}\gamma_5 N_{1R}\right) Z'_{\mu} \quad - \frac{g_X}{2} Q_{X_f} \left(\bar{\psi}_f \gamma^{\mu}\psi_f\right) Z'_{\mu}$$

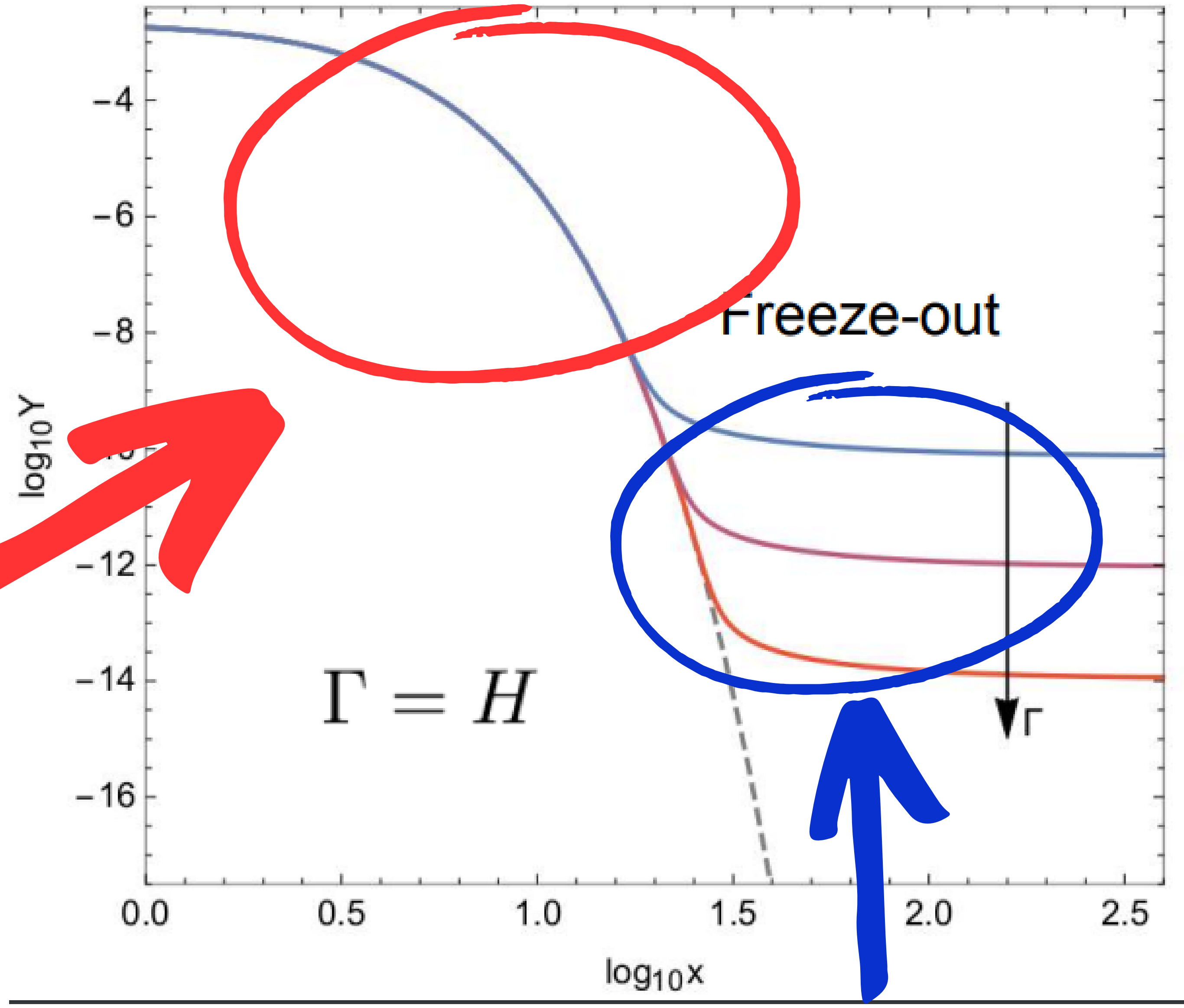


Arcadi, Neto, Siqueira, FSQ 2108.11398

Was the universe expanding too fast?

$$H(T) \approx \frac{\pi}{3}\sqrt{\frac{g_\star}{10}}\frac{T^2}{M_{Pl}}\left(\frac{T}{T_r}\right)^{n/2}$$

A way to make under-abundant dark matter consistent with the data

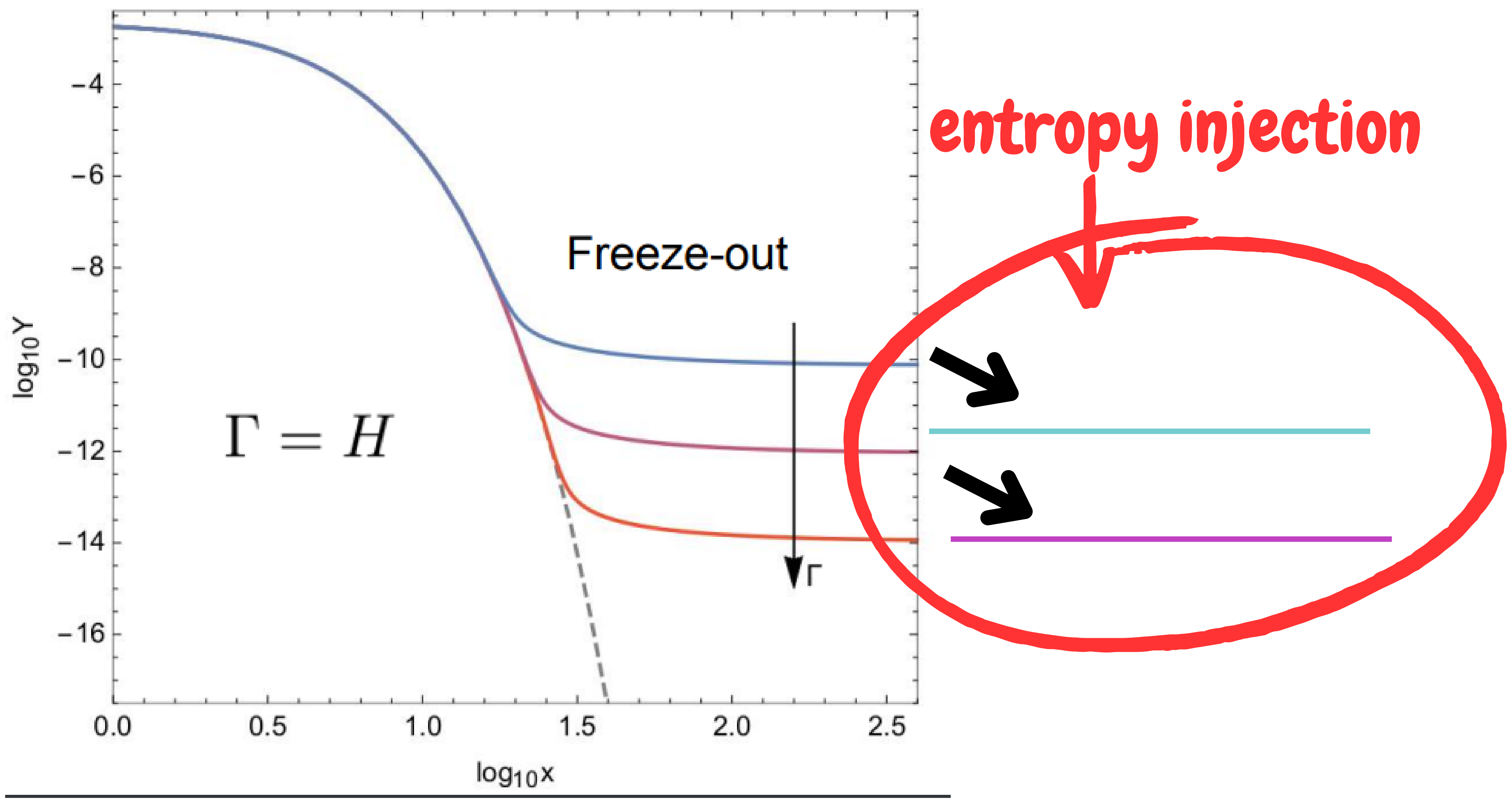


$$H_R(T) = \frac{\pi}{3}\sqrt{\frac{g_\star}{10}}\frac{T^2}{M_{Pl}}$$

Back to Standard Darkness

Taking a very constrained scenario: Z'

$$+\frac{1}{4}g_X\left(N_{1R}\gamma^{\mu}\gamma_5 N_{1R}\right)Z'_{\mu} \quad -\frac{g_X}{2}Q_{X_f}\left(\bar{\psi}_f\gamma^{\mu}\psi_f\right)Z'_{\mu}$$



Arcadi, Neto, Siqueira, FSQ 2108.11398

Back to Standard Darkness

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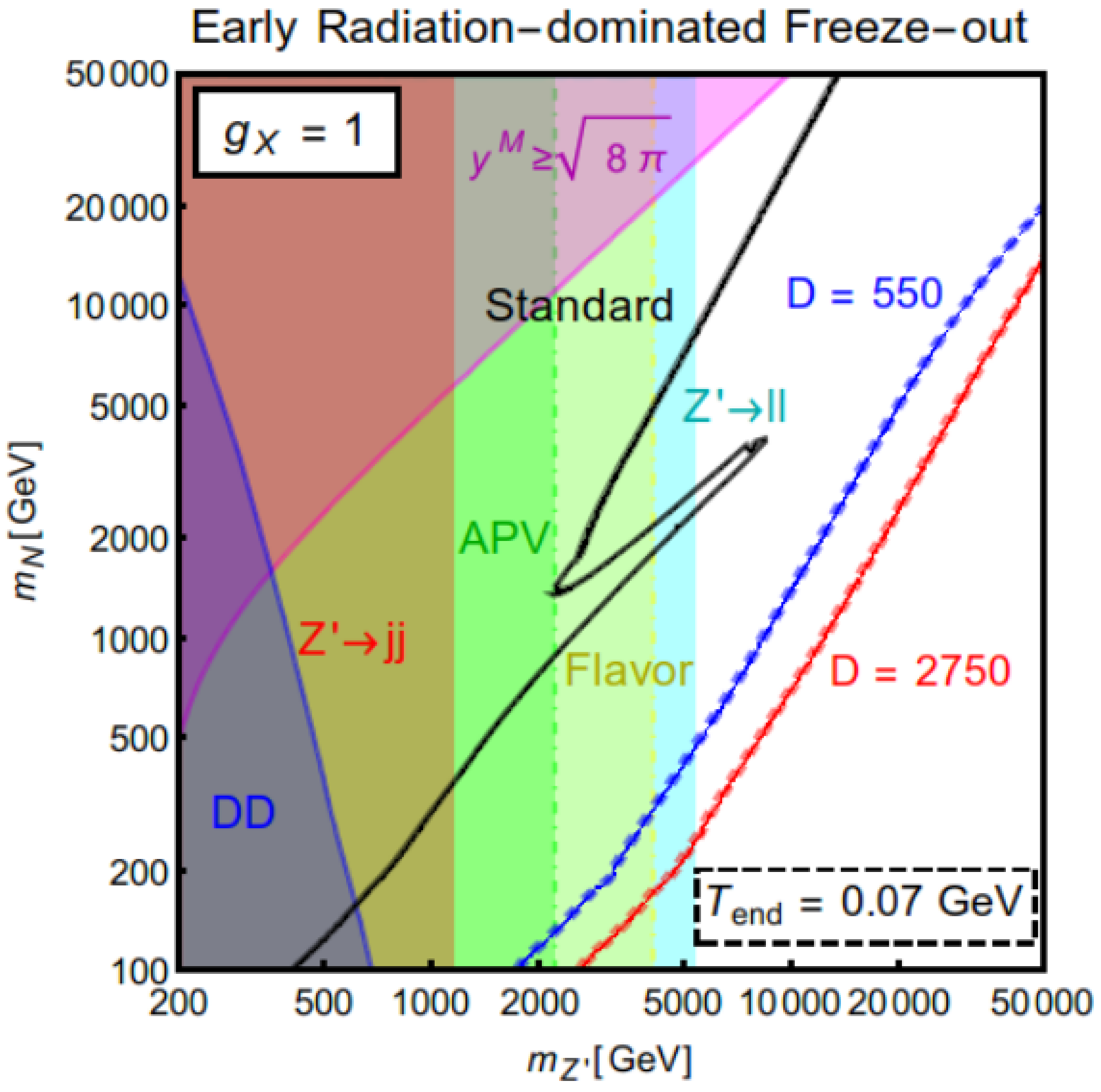
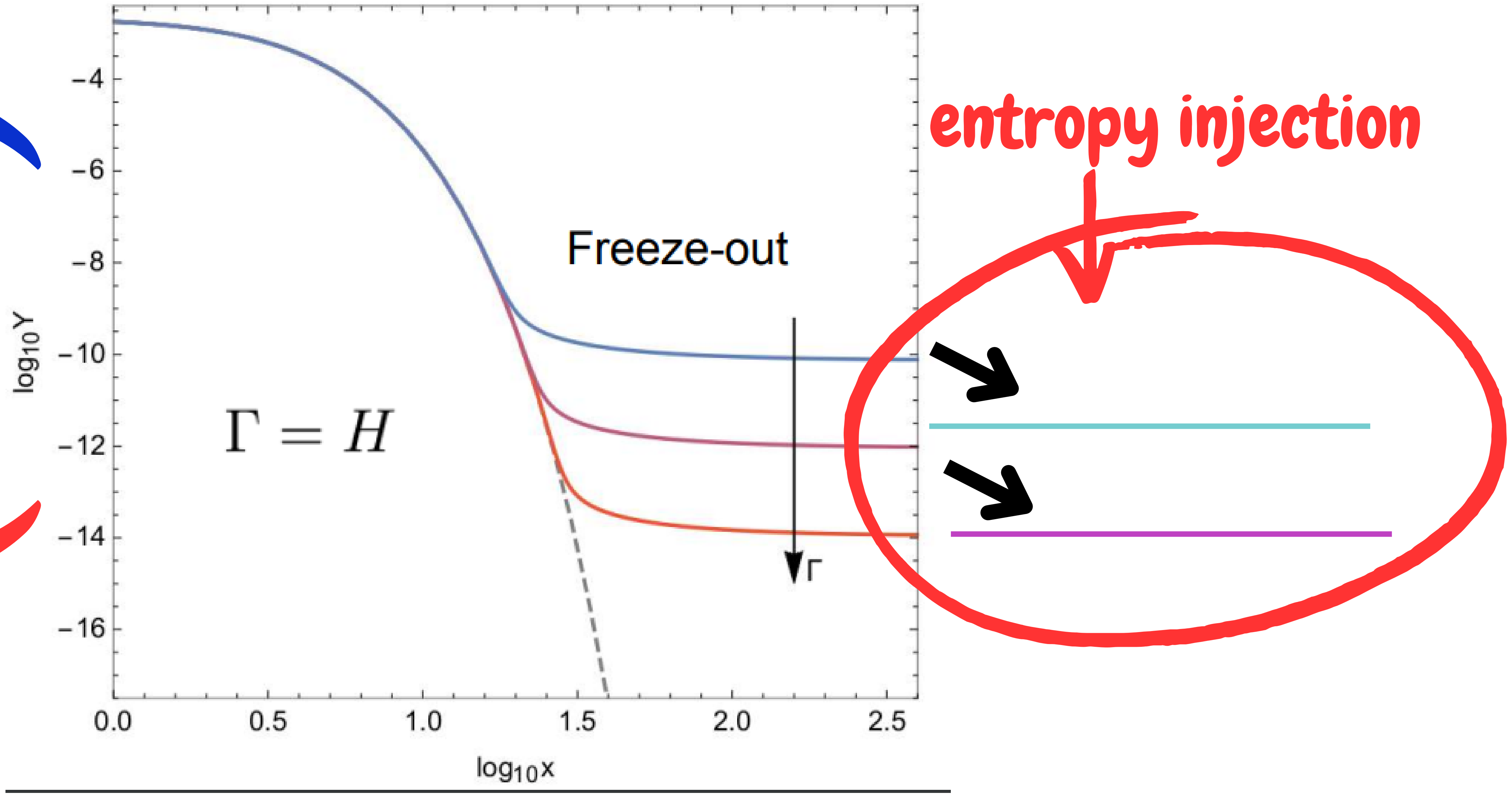
PROGRESS IS NEEDED HERE:

Scalar dominates the energy density and decays into radiation



Dilution factors



Arcadi, Neto, Siqueira, FSQ 2108.11398

Back to Standard Darkness

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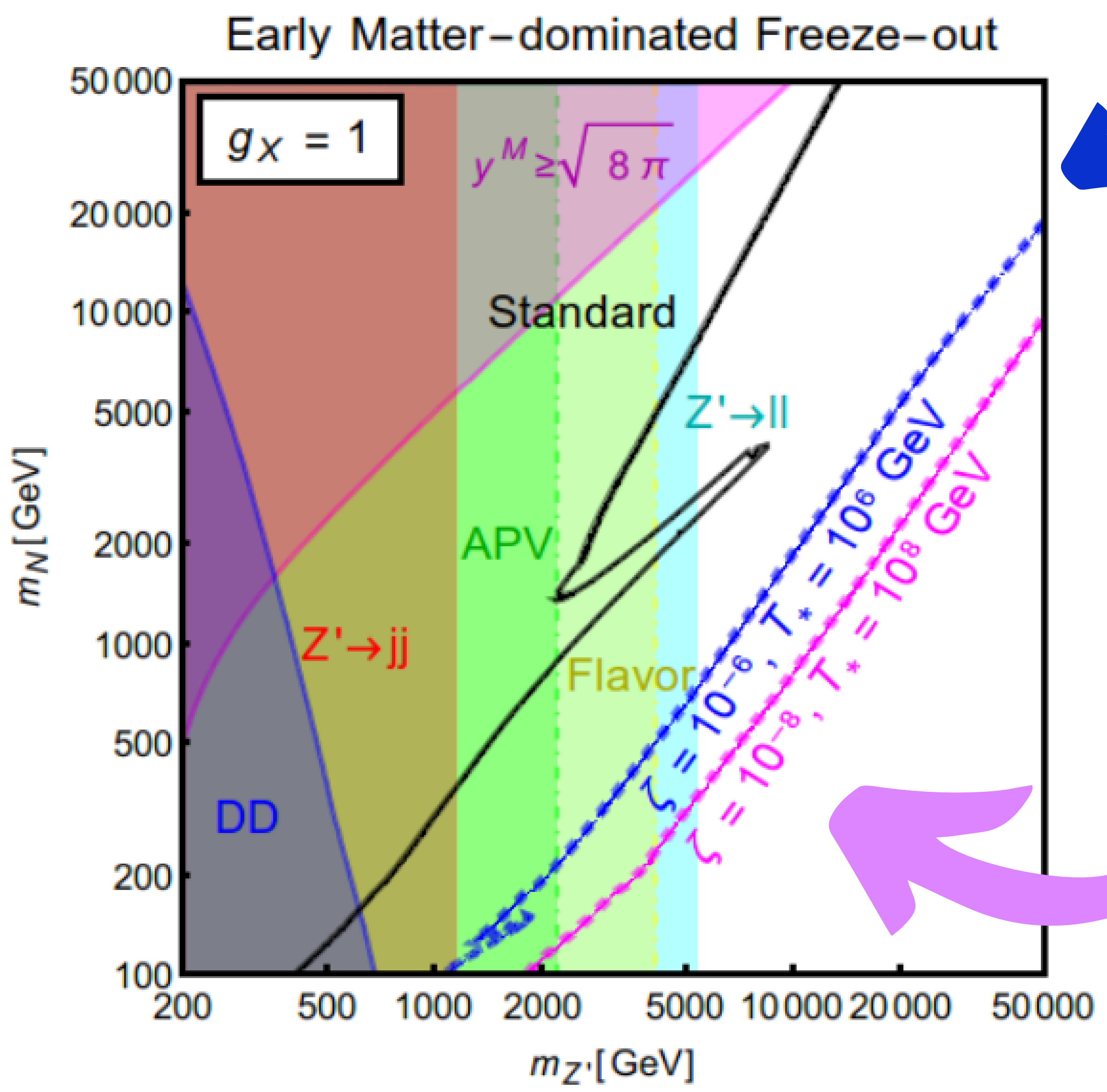
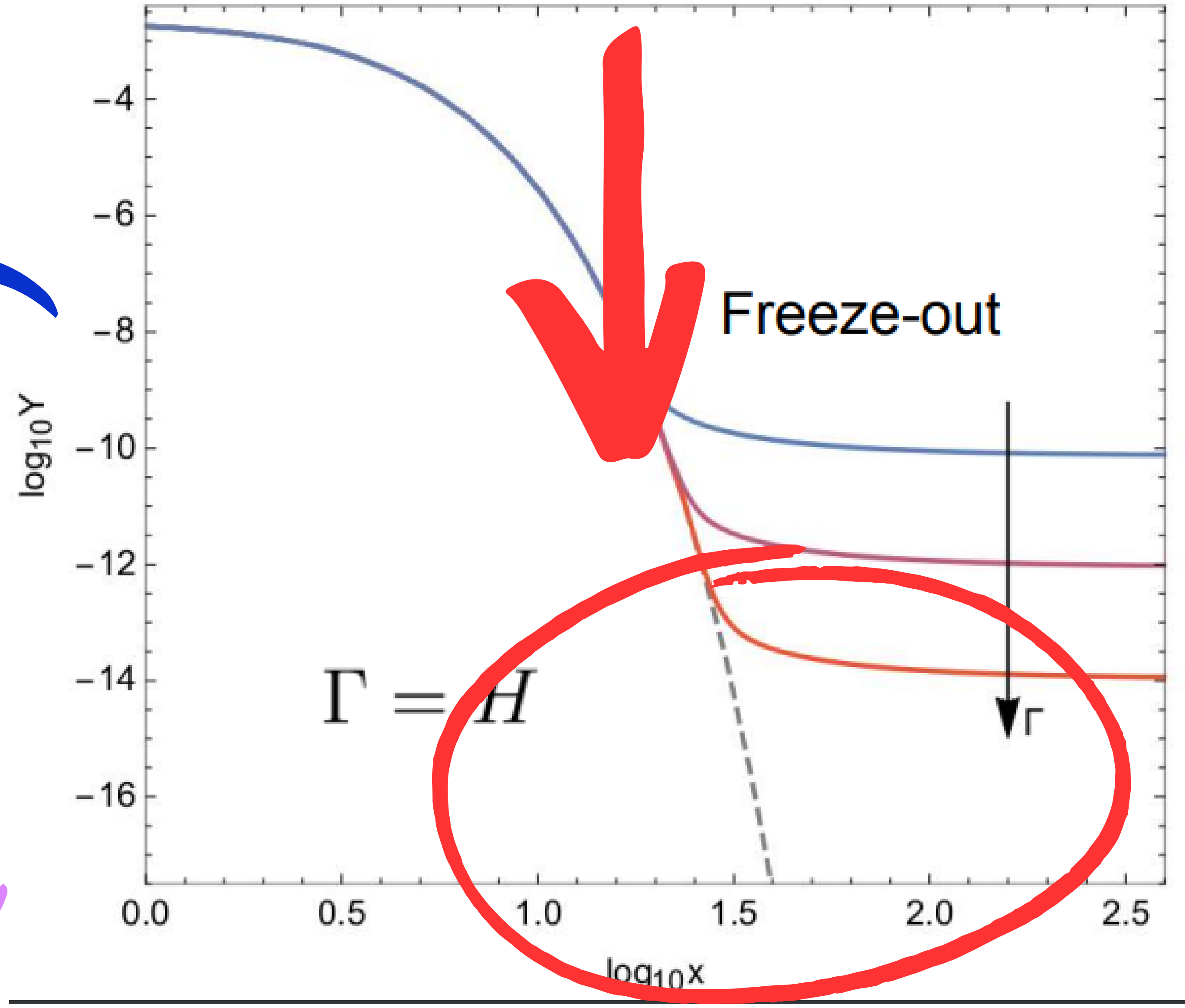
$H \propto T^{3/2}$ **slower**

$$\zeta = \frac{s(T_1)}{s(T_2)} \sim \frac{T_{end}}{T_\star}$$

$$T_{eq} \equiv T_\star\left(\frac{a_\star}{a(T_{eq})}\right)$$





Arcadi, Neto, Siqueira, FSQ 2108.11398

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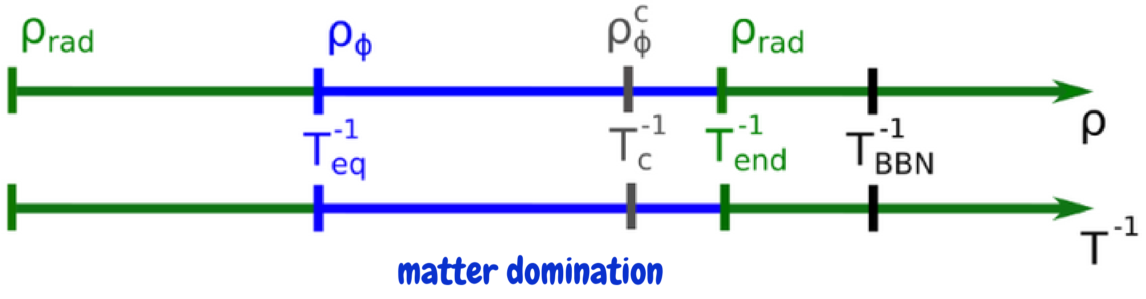
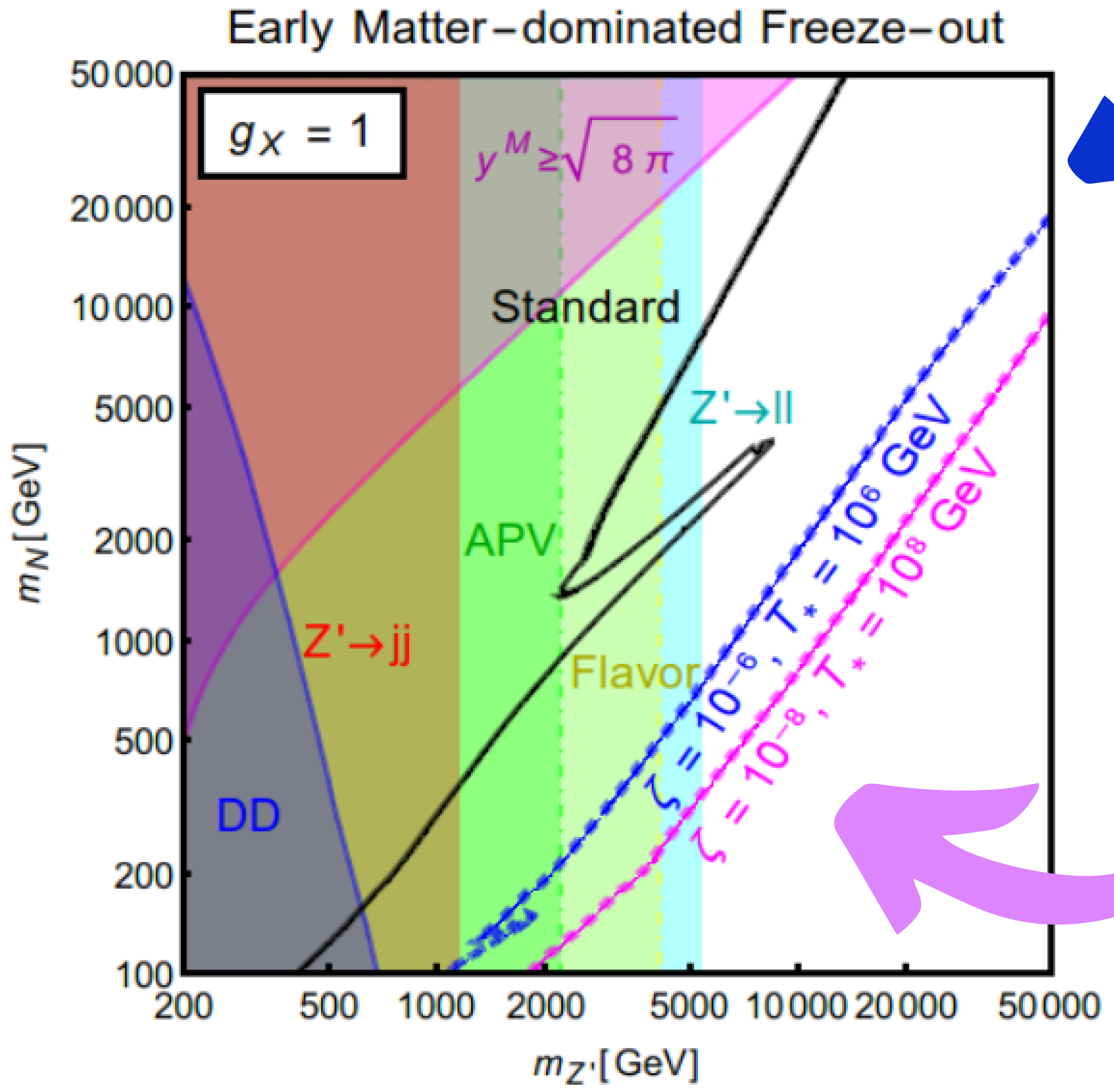
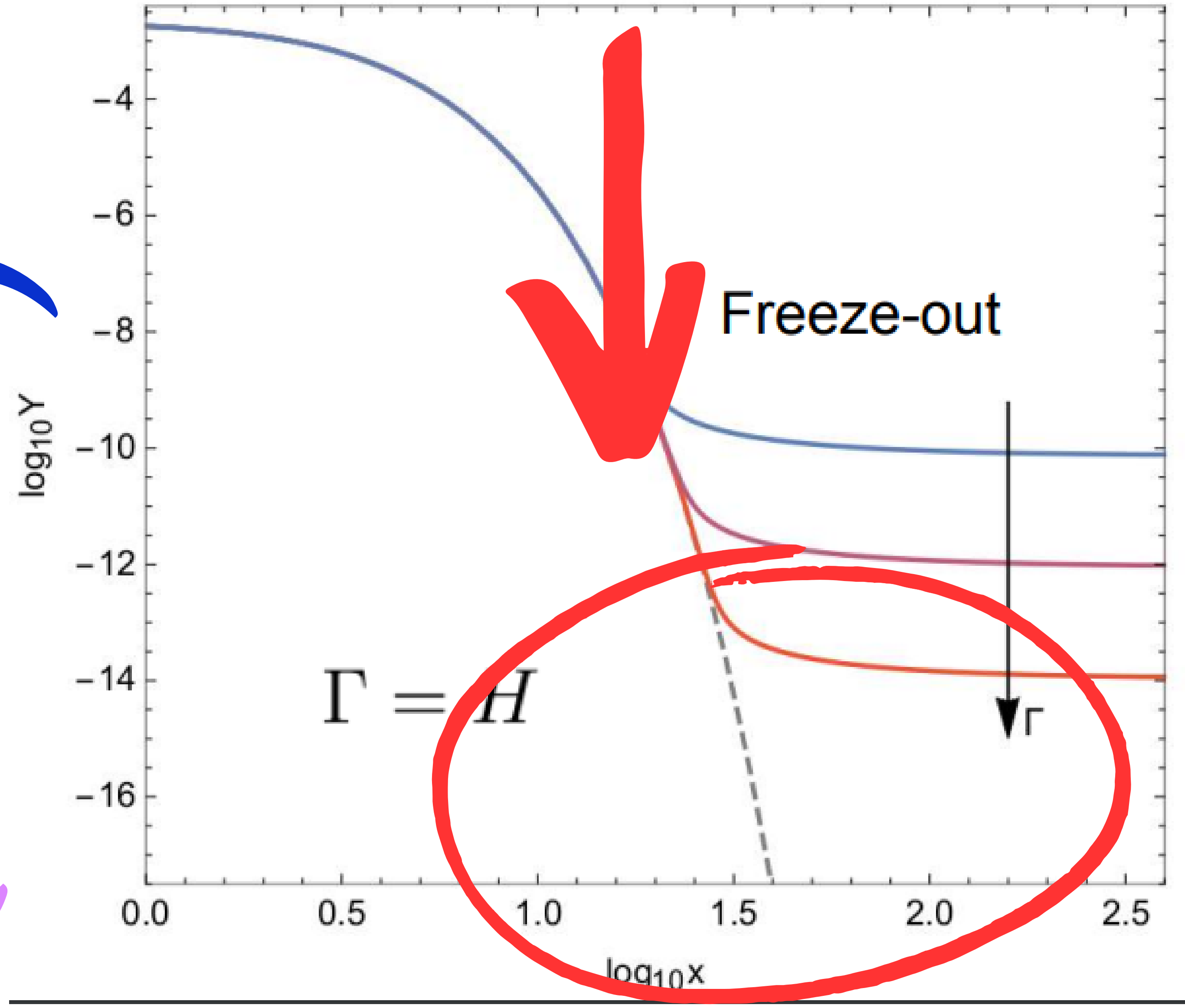


The universe is radiation-dominated at $T=T_*$

$$T_{end} \equiv \left[\frac{90\,M_{Pl}^2}{\pi^2 g_\star(T_{end})}\right]^{1/4}\Gamma_\phi^{1/2}$$

$$\Omega_N h^2 = \zeta\,\Omega_N^{MD} h^2$$





Arcadi, Neto, Siqueira, FSQ, arxiv:2108.11398

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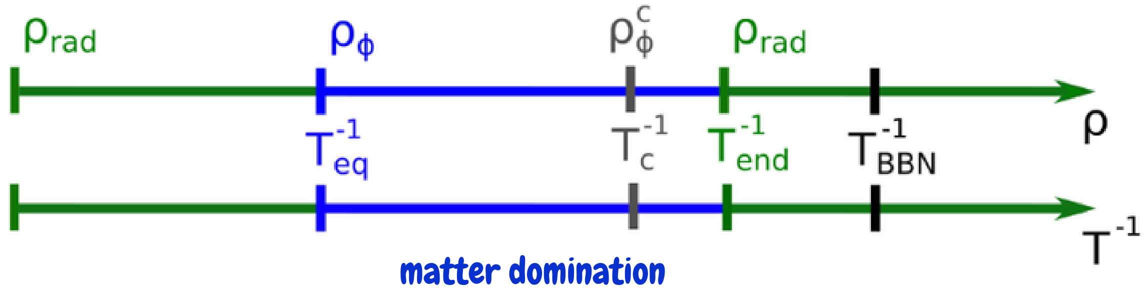

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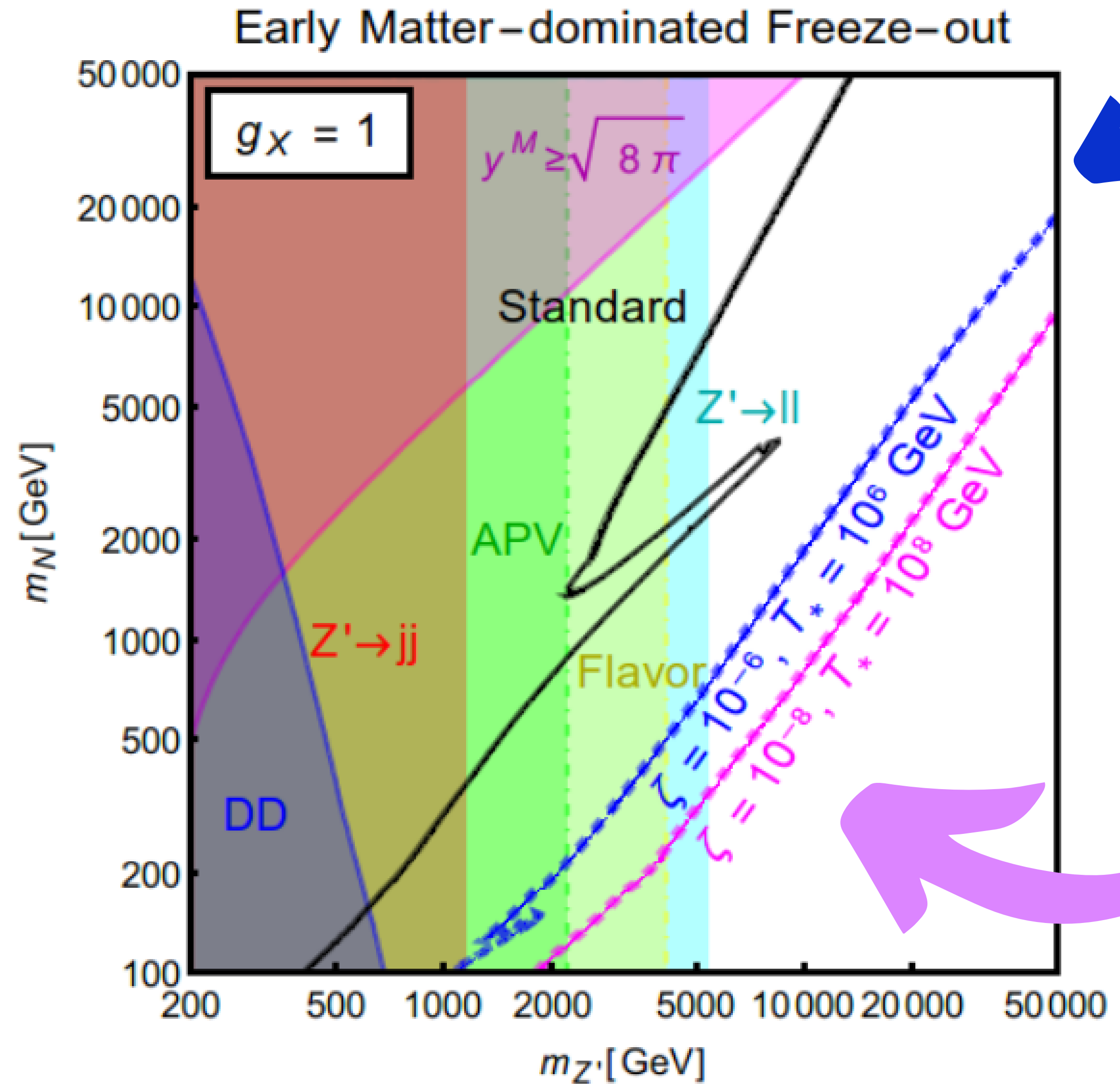


Thermal relic

+

Direct detection

+

Indirect Detection

+

Colliders

+

Non-standard Cosmologies

Arcadi, Neto, Siqueira, FSQ, arxiv:2108.11398

Neutron stars as laboratories

Rate at which energy is transfered

$$\dot{E} = \frac{E_\chi^R \dot{m}}{m_\chi} f$$

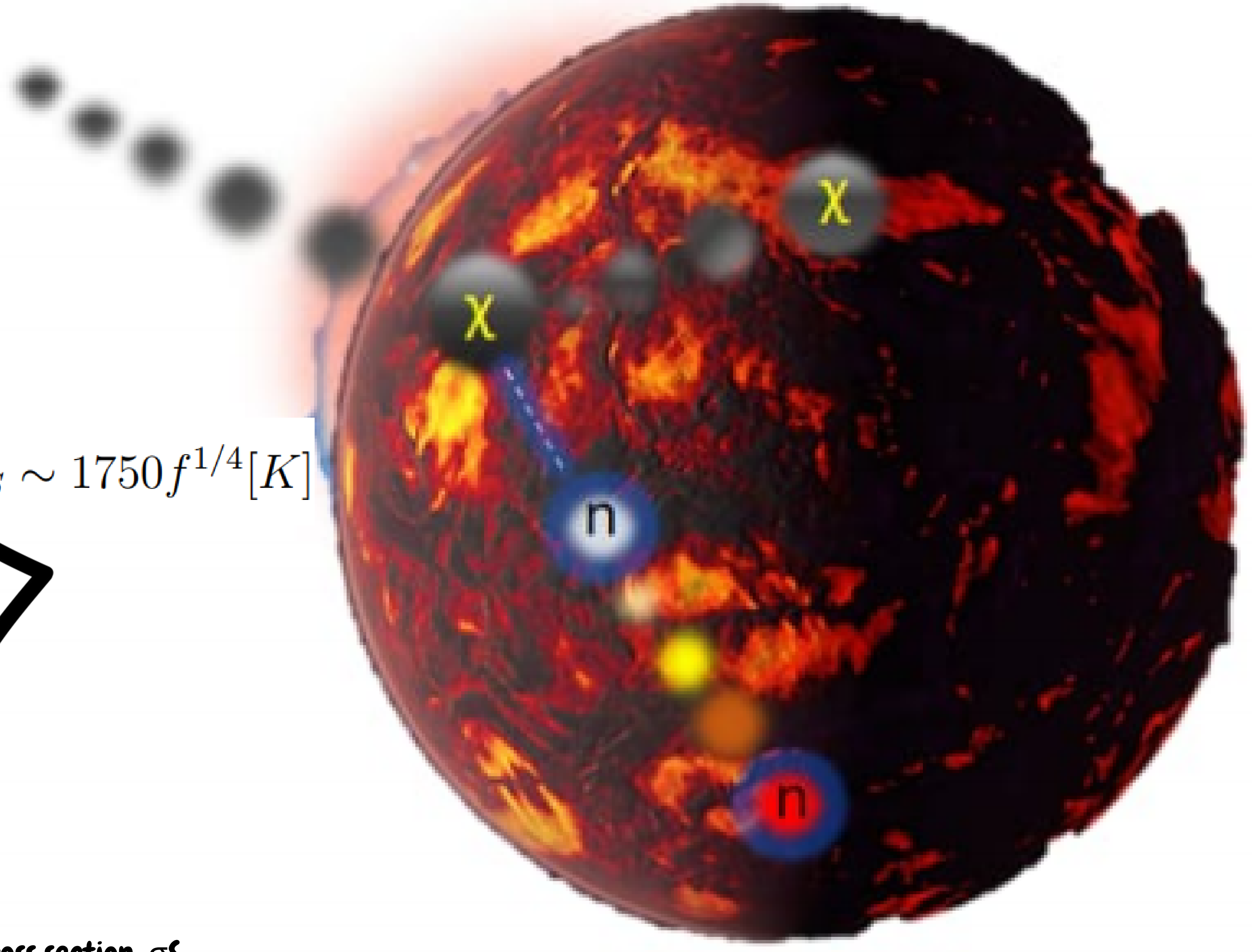
- $\dot{m}$ → Flux of DM
- f → is the capture efficiency
- m_χ → DM mass

Heating

$$T_{NS} = \left[\frac{(\gamma^R - 1) b_{max}^2 v_\chi \rho_\chi}{\sigma_B R^2}\right]^{1/4} \left(1 - \frac{2GM_\star}{R}\right)^{\frac{1}{2}} f^{1/4}$$

Astrophysics

$$T_{NS} \sim 1750 f^{1/4} [K]$$



Bell, Busoni, Robles, Virgator, arxiv: 2004.14888

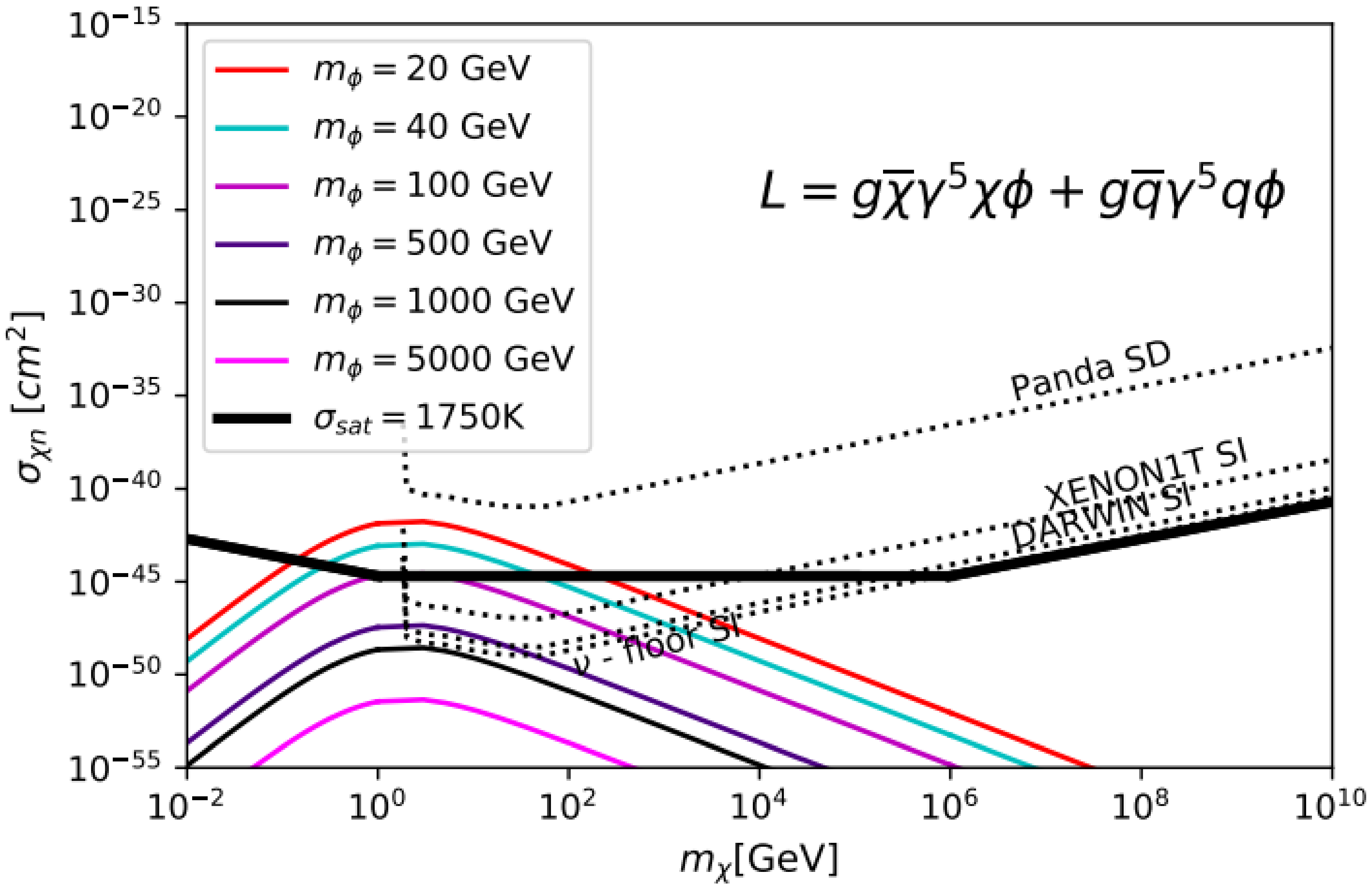
Connection to Particle Physics

It depends on the relation between dark matter-nucleon scattering cross section (σn) and a saturation cross section, σS, above which all the transient dark matter is captured so that

$$f = min(\sigma_{\chi n}/\sigma_S, 1)$$

SCATTERING CROSS SECTION

Fermion DM + pseudoscalar Mediator

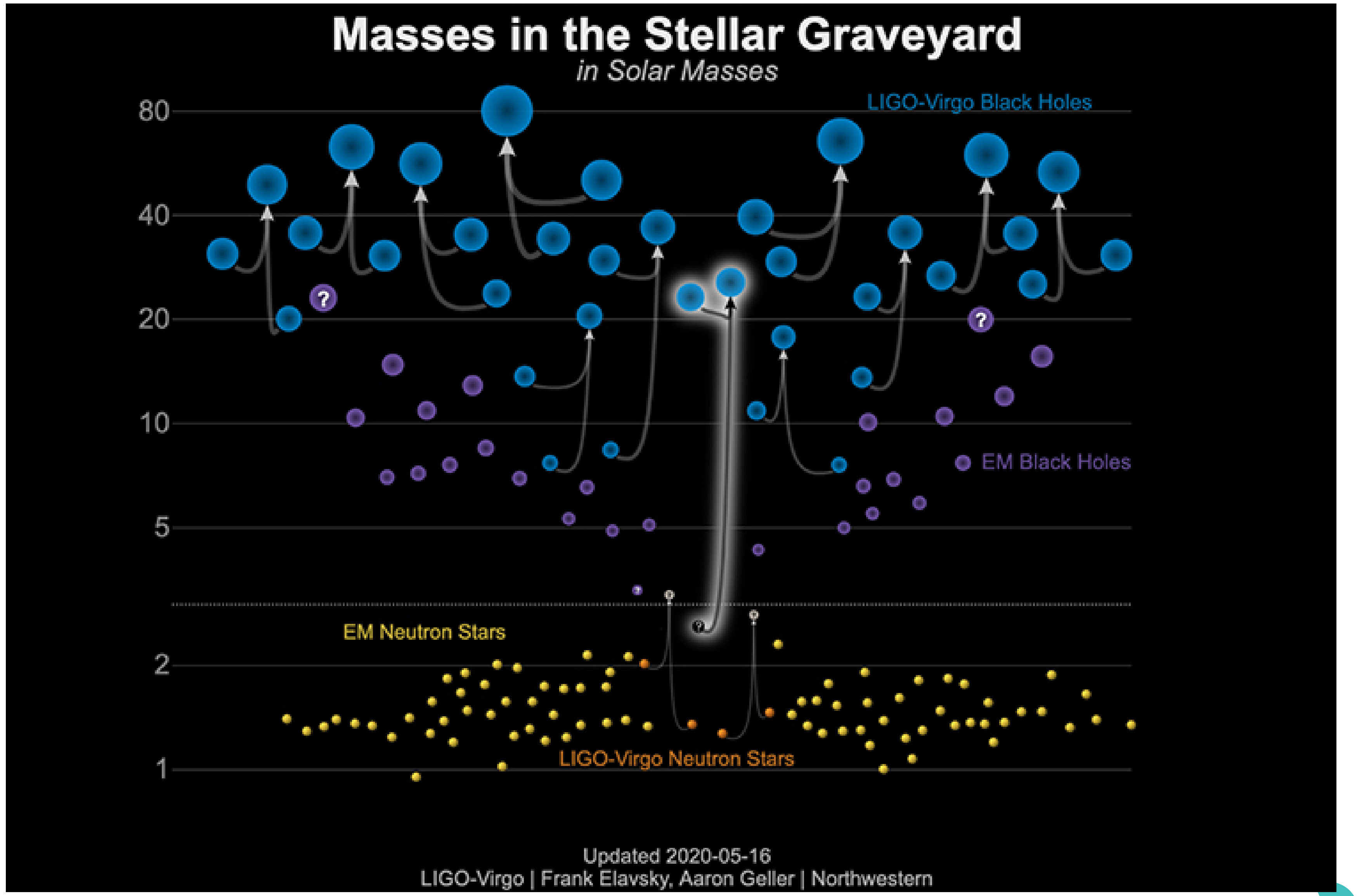


Neutron stars with temperatures around 2000 K located 10 pc away could be detected at the JWST. Owing to the compact (R ∼ 10 km) size of NS, they will appear as unresolved, extremely faint point sources, even for a cutting-edge facility such as the JWST. The Near-Infrared Camera has the potential to discover such neutron stars with 24h of exposure.

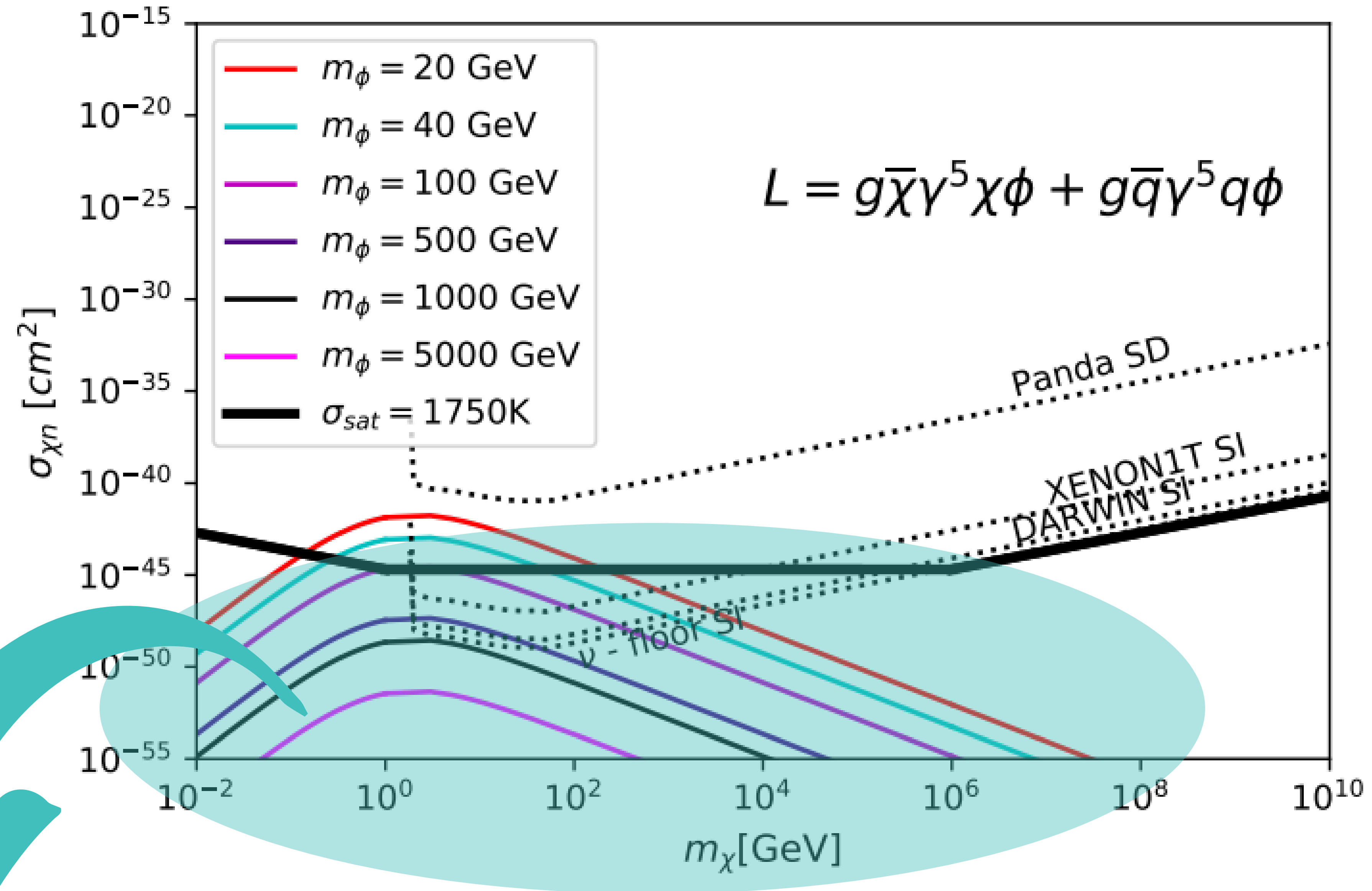
MASS

Maity, FSQ ariv: 2104.02700

Collective effect is needed



Fermion DM + pseudoscalar Mediator

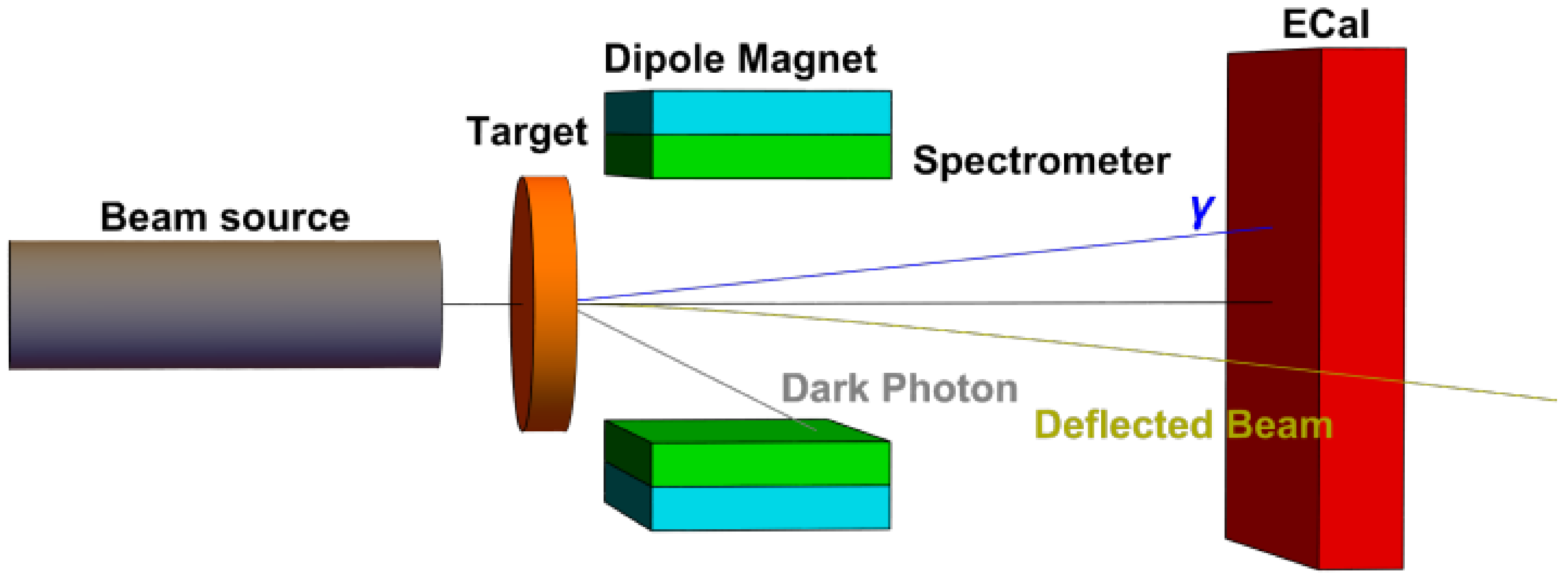


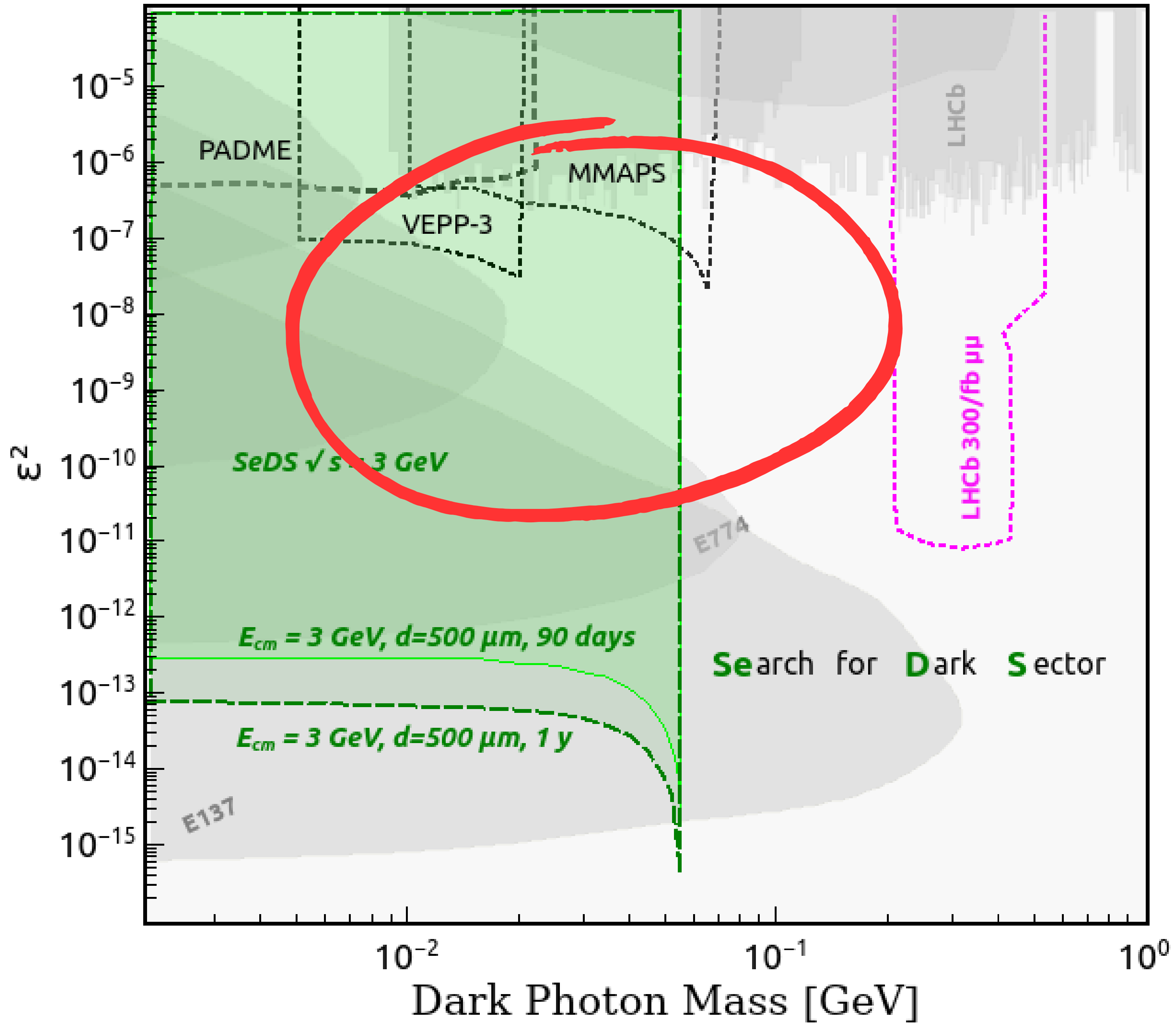
Neutron stars will constitute an important probe!

Search for Dark Sector by Repurposing the UVX Brazilian Synchrotron

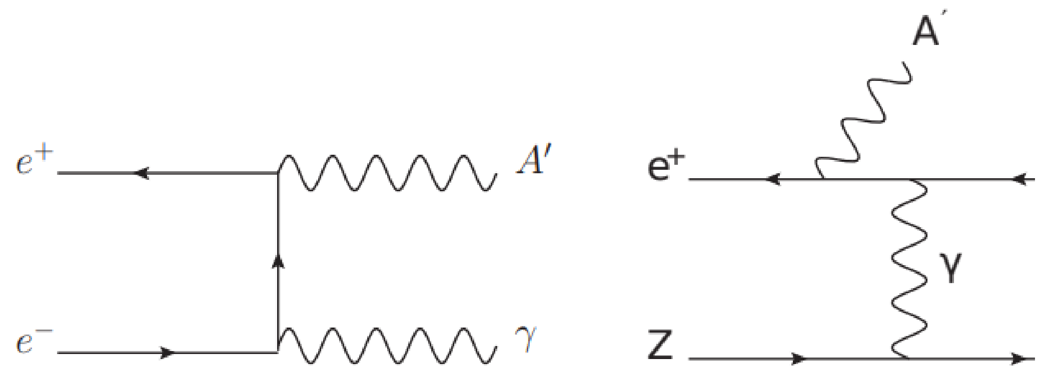
L. Duarte (IIP, Brazil), L. Lin (LNLS, Campinas), M. Lindner (Heidelberg, Max Planck Inst.), V. Kozhuharov (Sofiya U. and INFN, Italy), S.V. Kuleshov (Andres Bello Natl. U. and Unlisted, CL) et al. (Jun 10, 2022)

e-Print: 2206.05305 [hep-ph]





e+e- collisions competitive probe In Latin-America



Thank you

Without interdisciplinary searches one cannot claim the discovery of dark matter particles. Alternatives models for particle dark matter are welcome but without a strong experimental program involved discoveries are not expected