Beyond WIMPs at Neutrino Experiments
Heavy & Light Dark Matter

Filippo Sala

DESY Hamburg

Dark Ghosts, Brussels 13 Nov 2018

What is Dark Matter?

WIMPs

Weakly Interacting Massive Particles

Naturally at the ~ TeV scale

connection with hierarchy problem,…

Motivated plenty of experimental activity!

Cosmic rays | Colliders | Recoils vs nuclei on Earth

What is Dark Matter?

WIMPs

W ... , . . .

Mo

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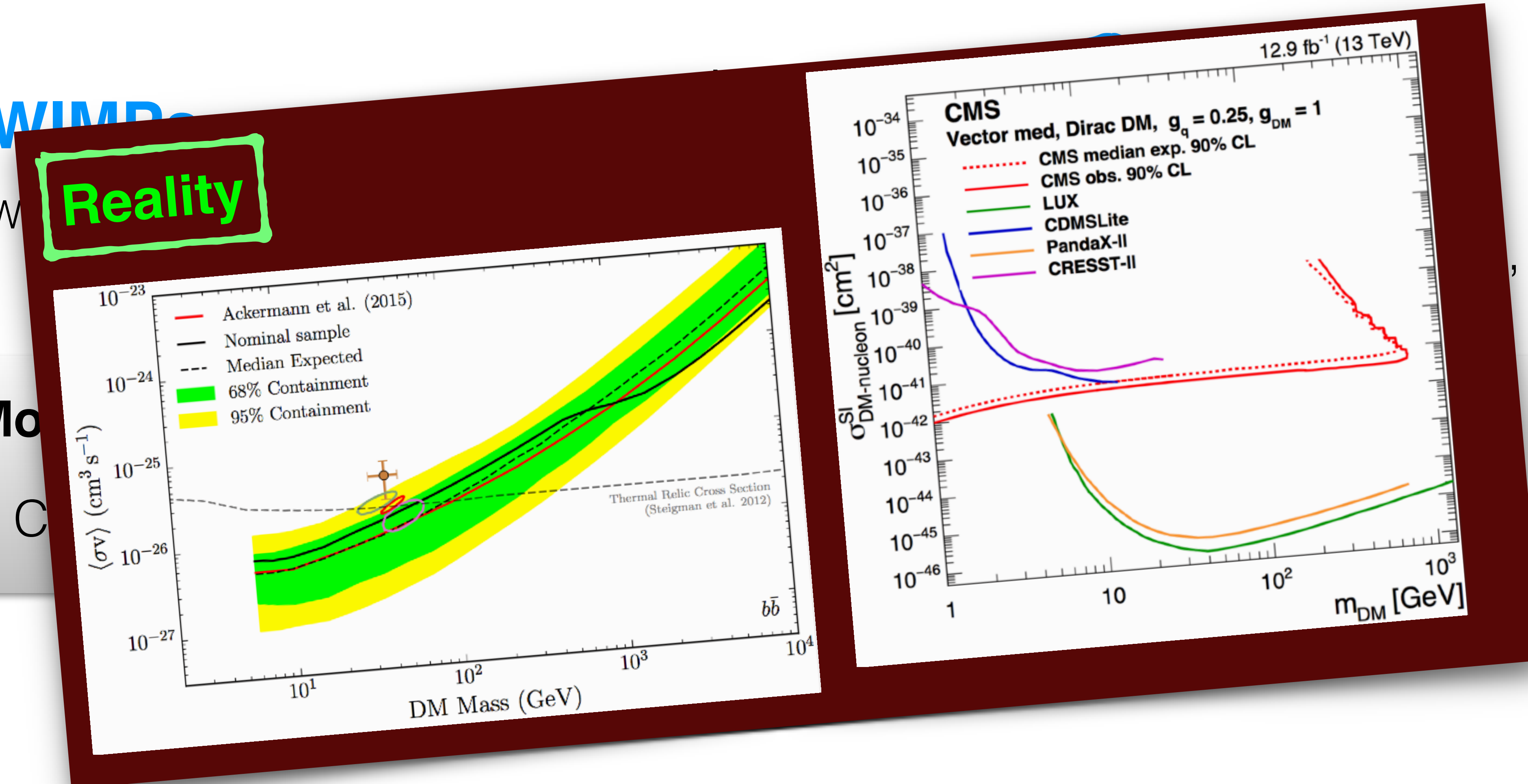

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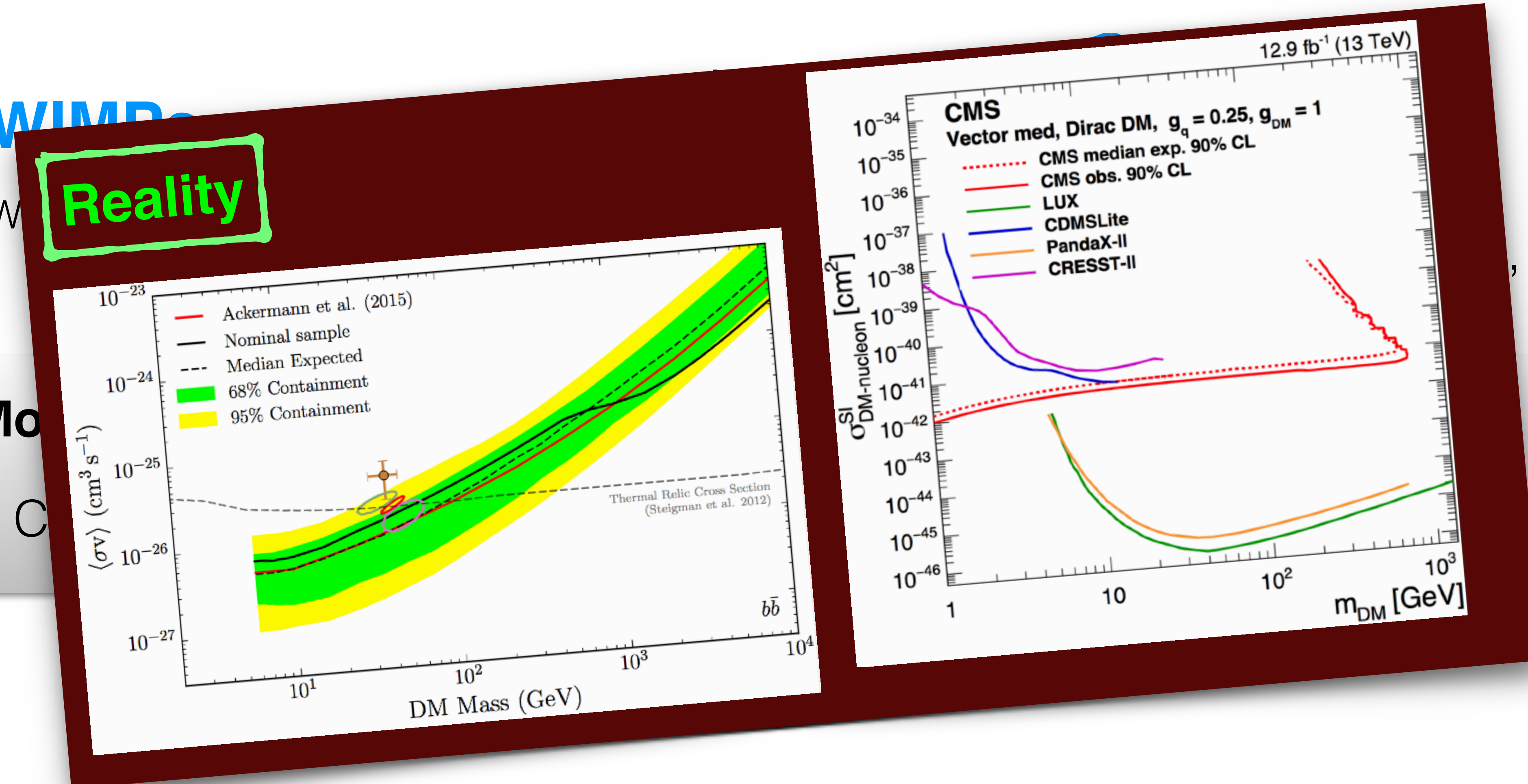
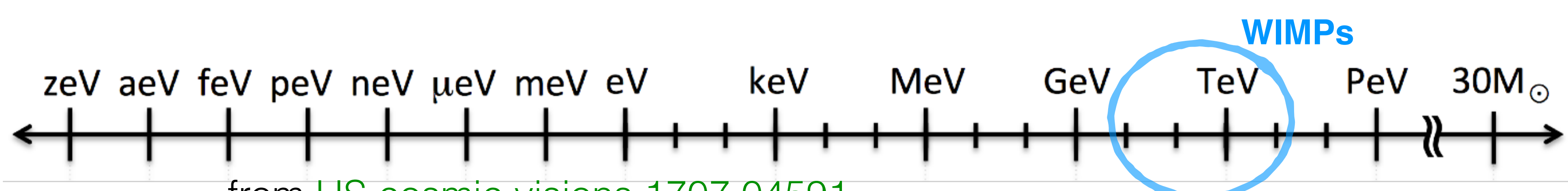




from US cosmic visions 1707.04591

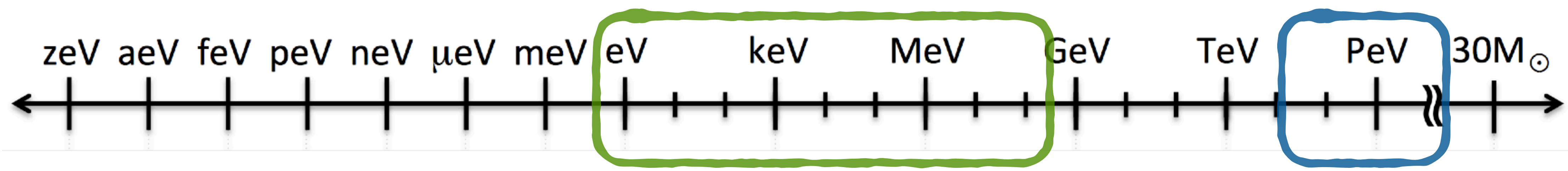
Most attention so far:

DM mass <(<) GeV

DM as Primordial Black hole

New Directions in Dark Matter

Attitude: take “more” **Risk**, but **Diversify it**



Light DM

Heavy DM

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Light DM

Ema FS Sato 1811.00520

Heavy DM

Cirelli **Gouttenoire** Petraki FS 1811.03608

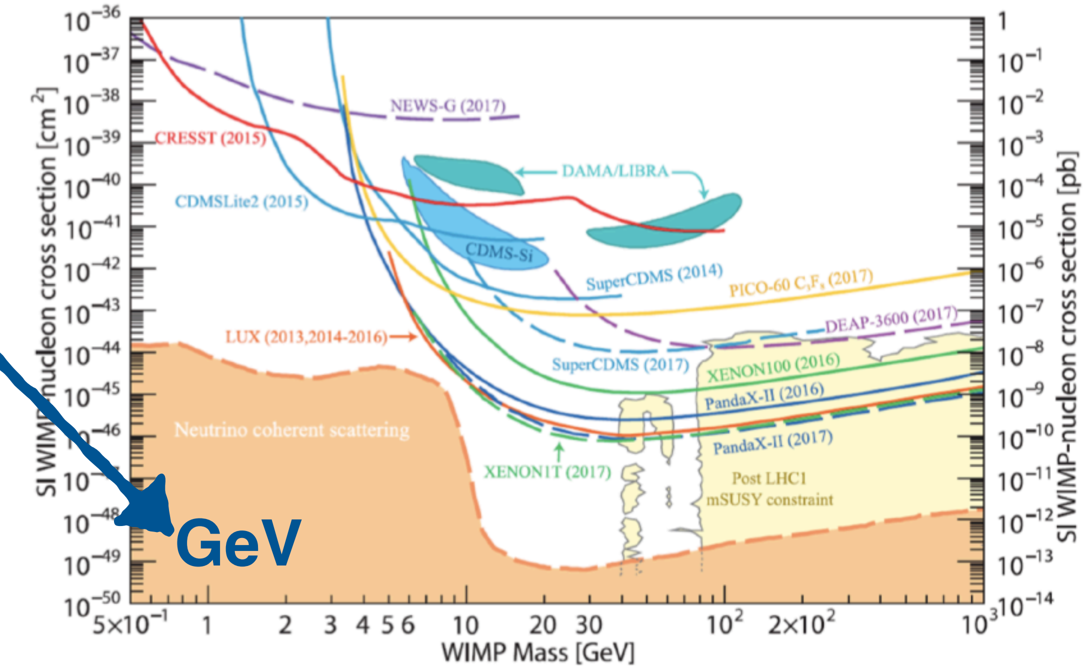
Why sub-GeV Dark Matter?

Pheno…

~ **unconstrained** by current experiments

but **lots of new ideas** to test it!

US cosmic visions 1707.04591



…Theory

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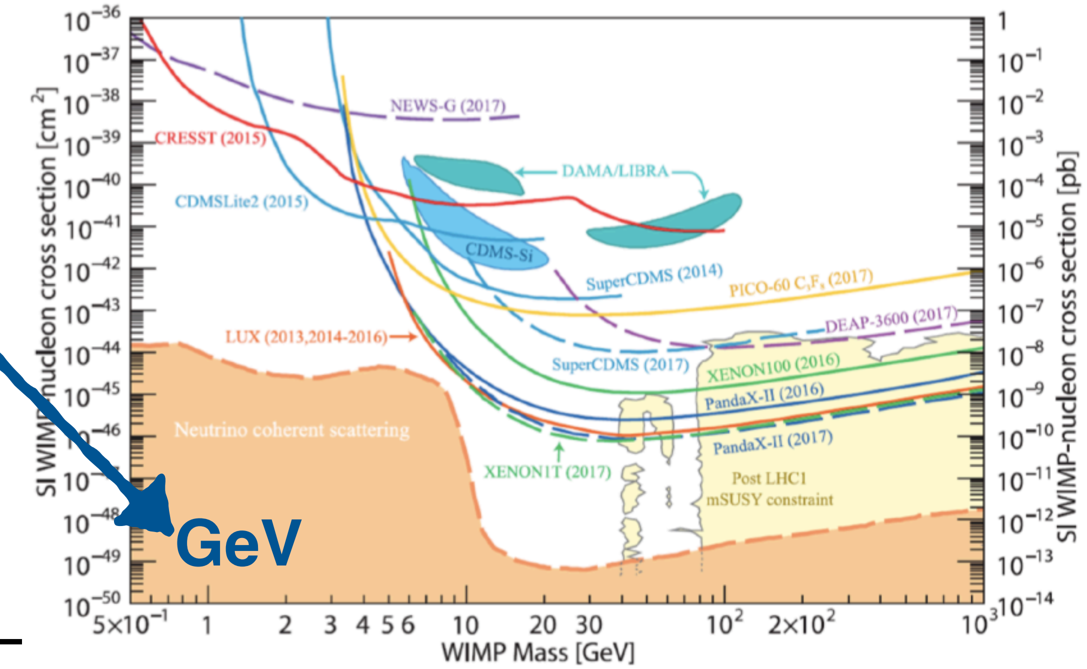

Connection with **observed anomalies**

e.g. in B decays and/or in muon g-2

FS Straub 1704.06188, 1809.11061

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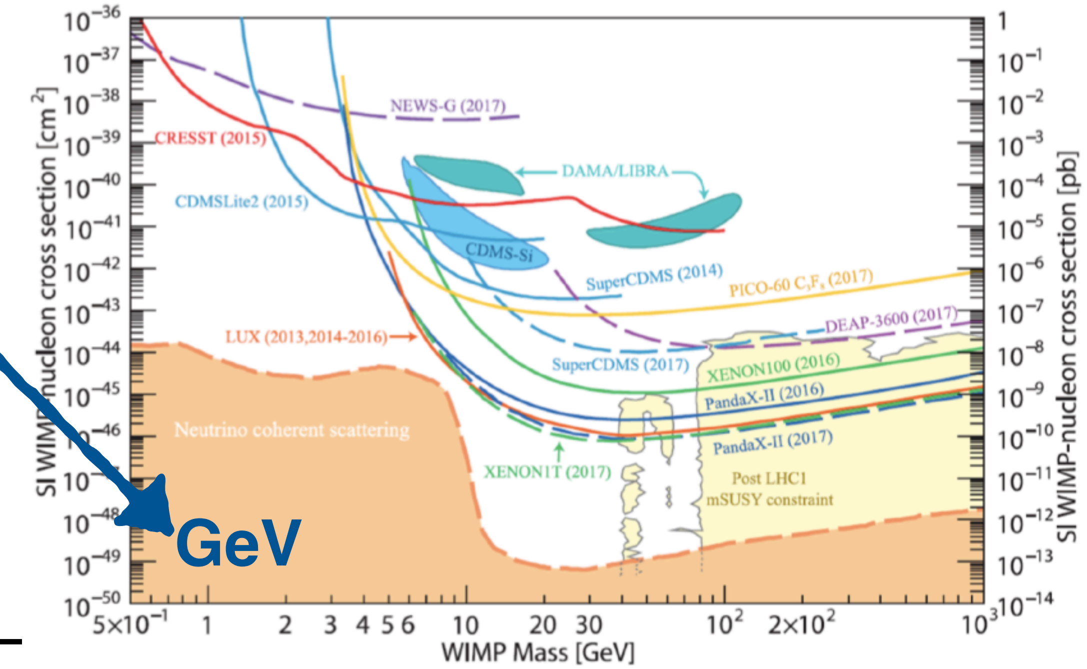

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Lots of proposals for DM abundance, e.g. SIMPs Hochberg+ 1402.5143,…

Connection with Hierarchy Problem (Relaxion DM) Fonseca Morgante 1809.04534 Banerjee Kim Perez 1810.01889

Leptogenesis Falkowski+ 1712.07652

Theory…

A New Idea for Direct Detection

Ema FS Sato 1811.00520

"Standard" Direct Detection challenged by low DM masses

$$v_{\rm DM}^{\rm halo} \simeq 10^{-3}\, c \longrightarrow E_{\rm NR} = \frac{q^2}{2m_N} \leq \frac{2\mu_{\chi N}^2 v_\chi^2}{m_N} \lesssim 190 \text{ eV} \times \left(\frac{m_\chi}{500 \text{ MeV}}\right)^2 \left(\frac{16 \text{ GeV}}{m_N}\right)$$

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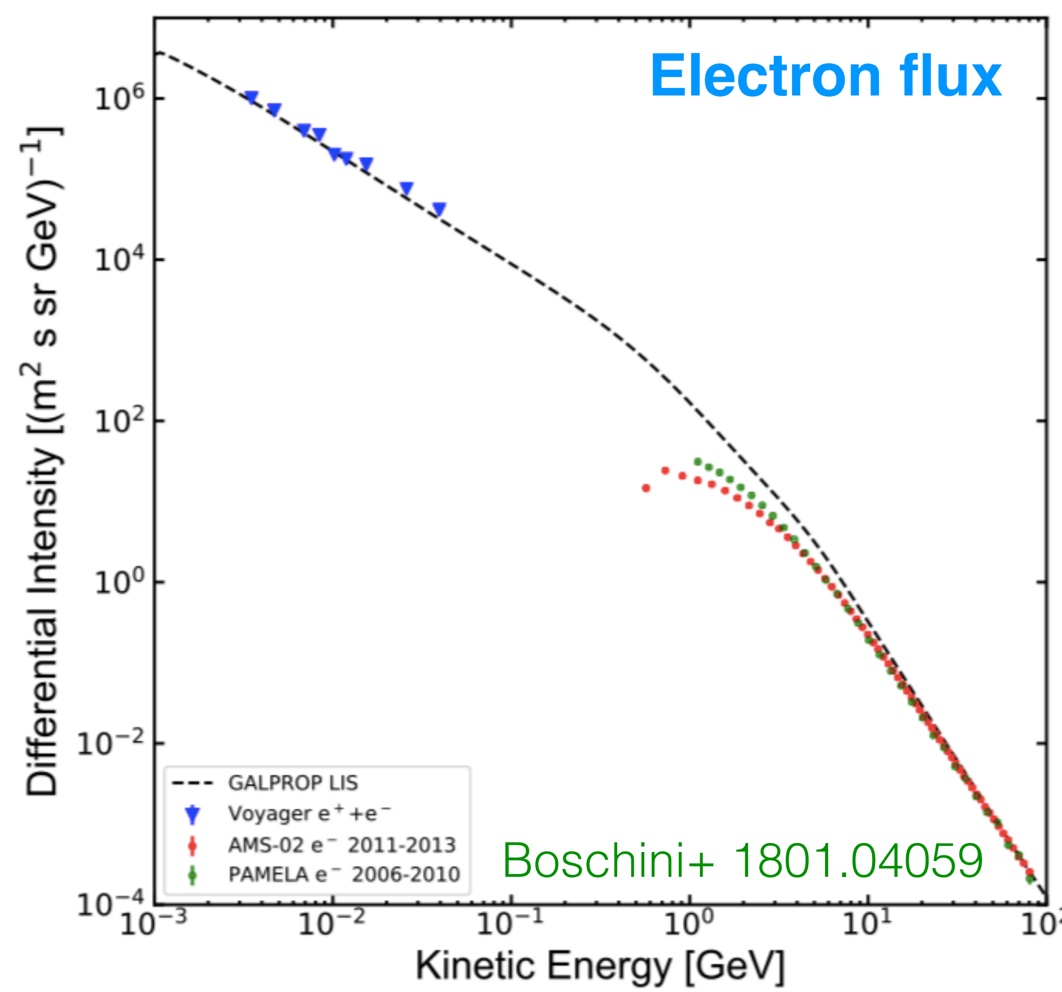
Our way-out:

Detection possible if DM interacts with SM

↓

High-velocity DM component unavoidably generated by **Cosmic-ray scatterings**!

see Bringmann Pospelov 1810.10543
for analogous idea for DM-nucleon interactions



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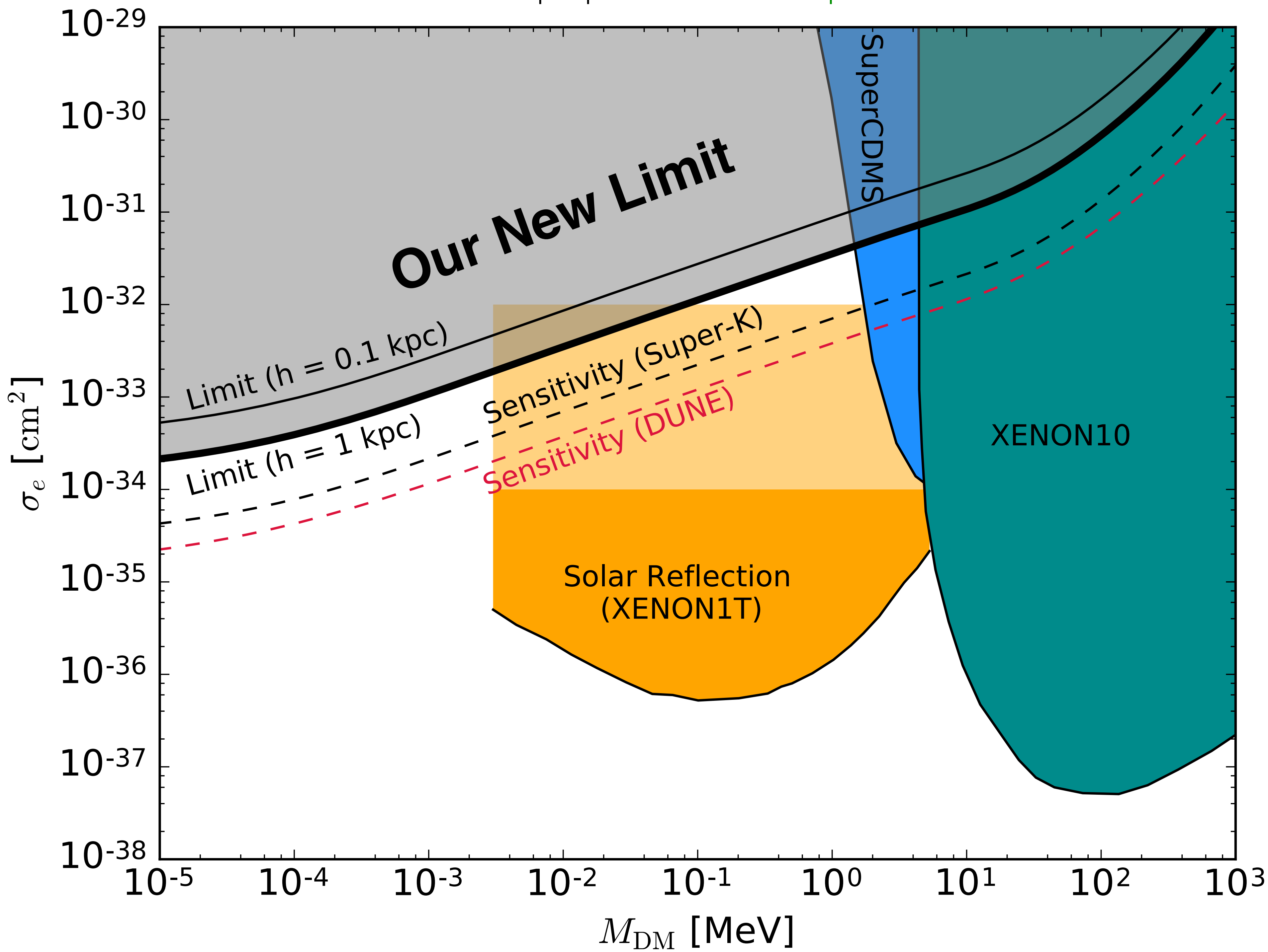

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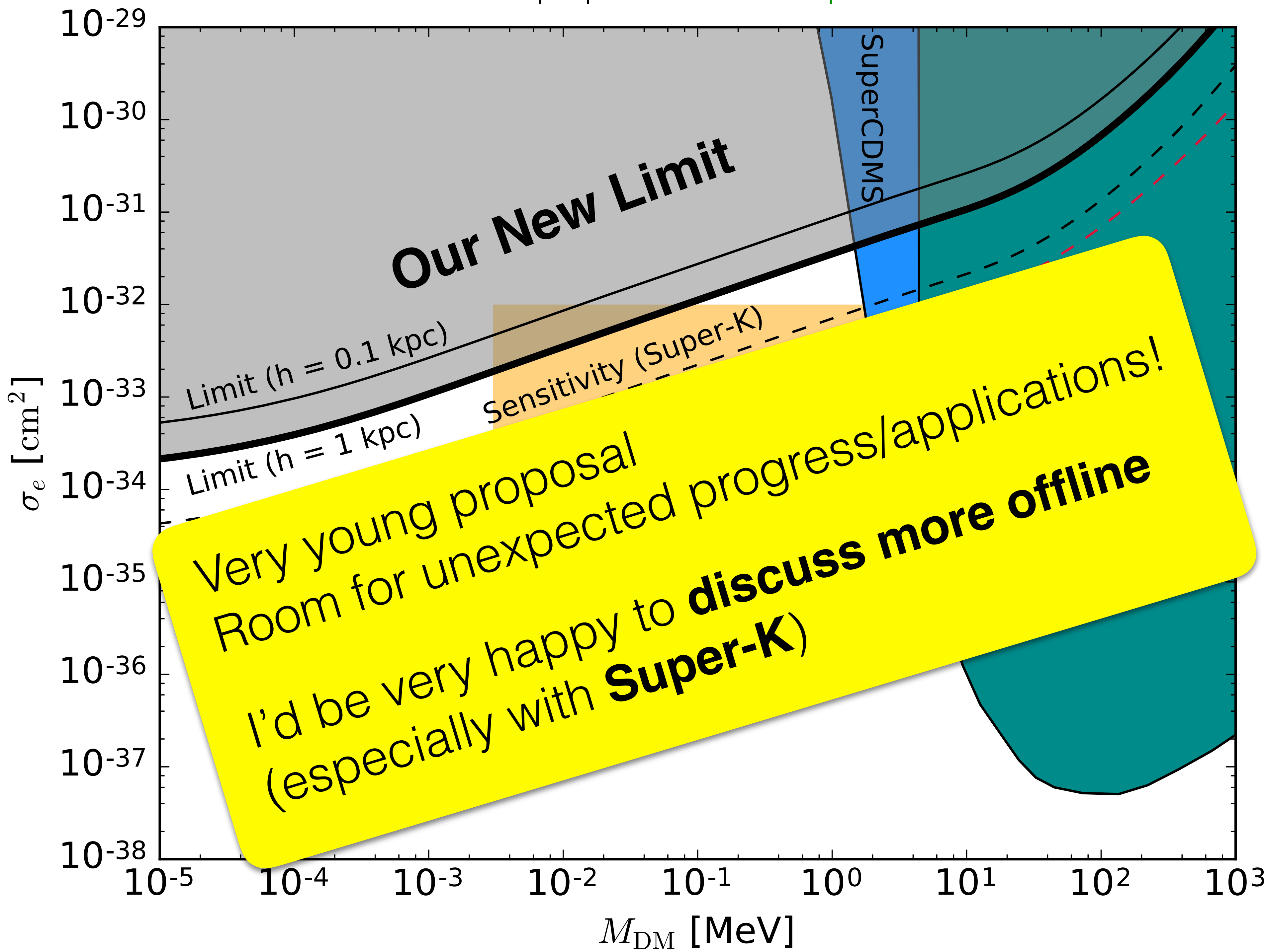

Very young proposal
Room for unexpected progress/applications!

I'd be very happy to **discuss more offline**
(especially with **Super-K**)

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Why DM beyond 10-100 TeV?

Almost **virgin territory**

Most studies of heavy DM so far followed IceCube "anomalies"

Bhattacharya+ 1706.05746,....

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LHC is pushing **solutions to SM problems** (hierarchy, flavour, …) to **>> TeV**

Richer sectors could exist there

e.g. new confining sector w/DM Antipin Redi Strumia 1410.1817,…+Mitridate Smirnov 1707.05380

…Theory

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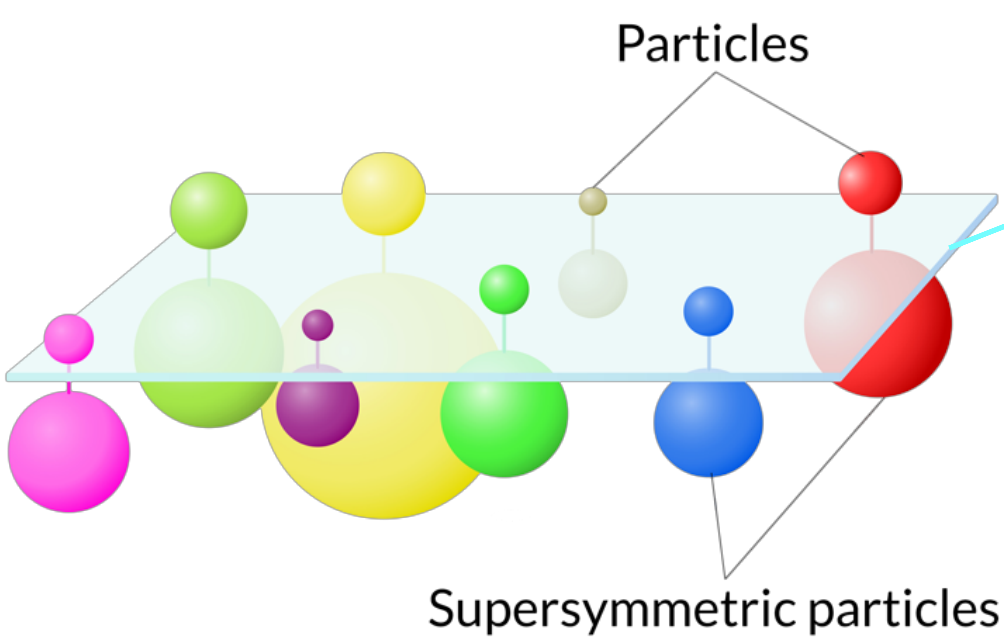
Supersymmetry



This sector is necessary, and **>(>) 10 TeV**

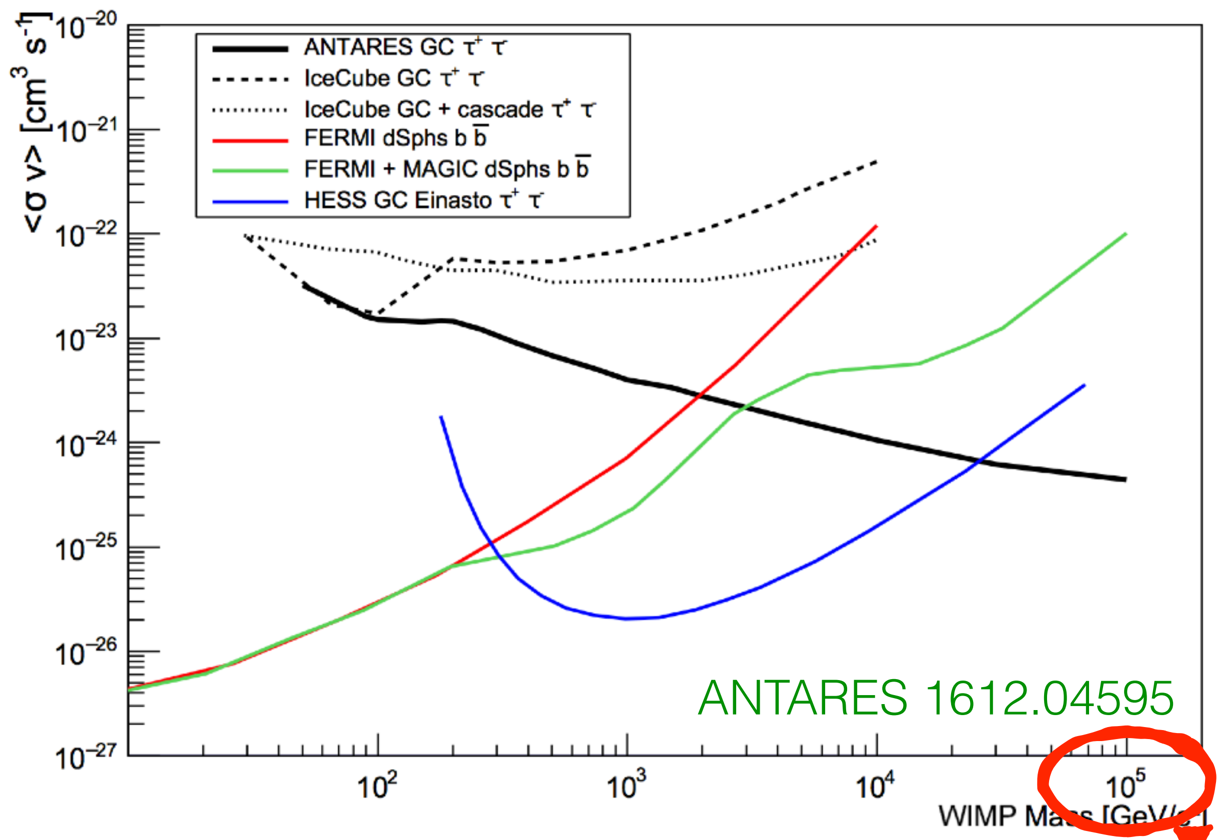
[breaking/mediation sector]

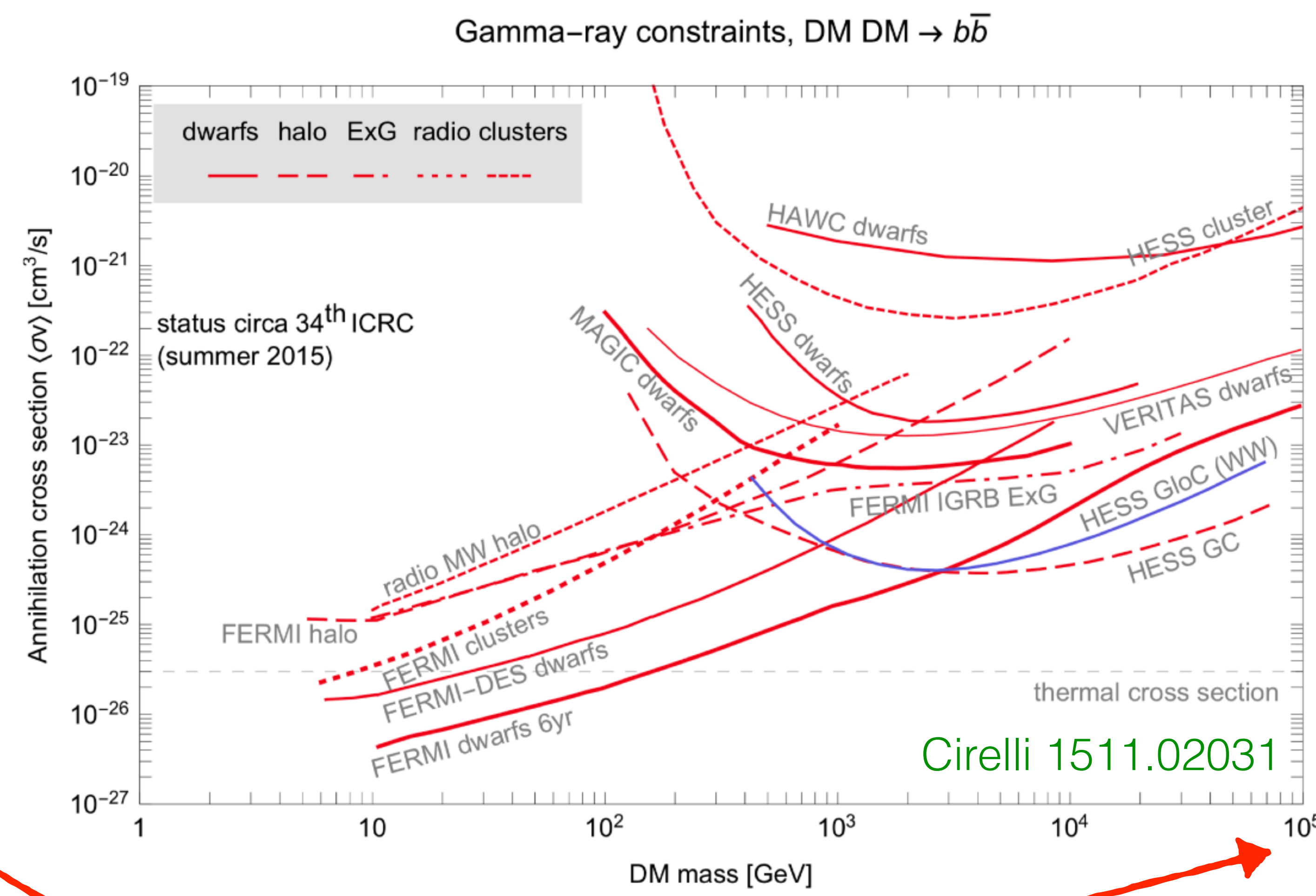
Naturally hosts DM!

Dimopoulos Giudice Pomarol hep-ph/9607225

Theory...

Telescopes have Unique Opportunity!





…but do not test DM annihilations beyond 100 TeV

Why not beyond 10-100 TeV?

The Usual Objections

ElectroWeak radiation

Controlled by $\frac{\alpha_2}{\pi} \log^2 \frac{M_{\rm DM}}{m_W}$ ≈ 1 for $M_{\rm DM} \simeq 100$ TeV

$\Rightarrow$ it should be resummed, ~ like QCD at the LHC

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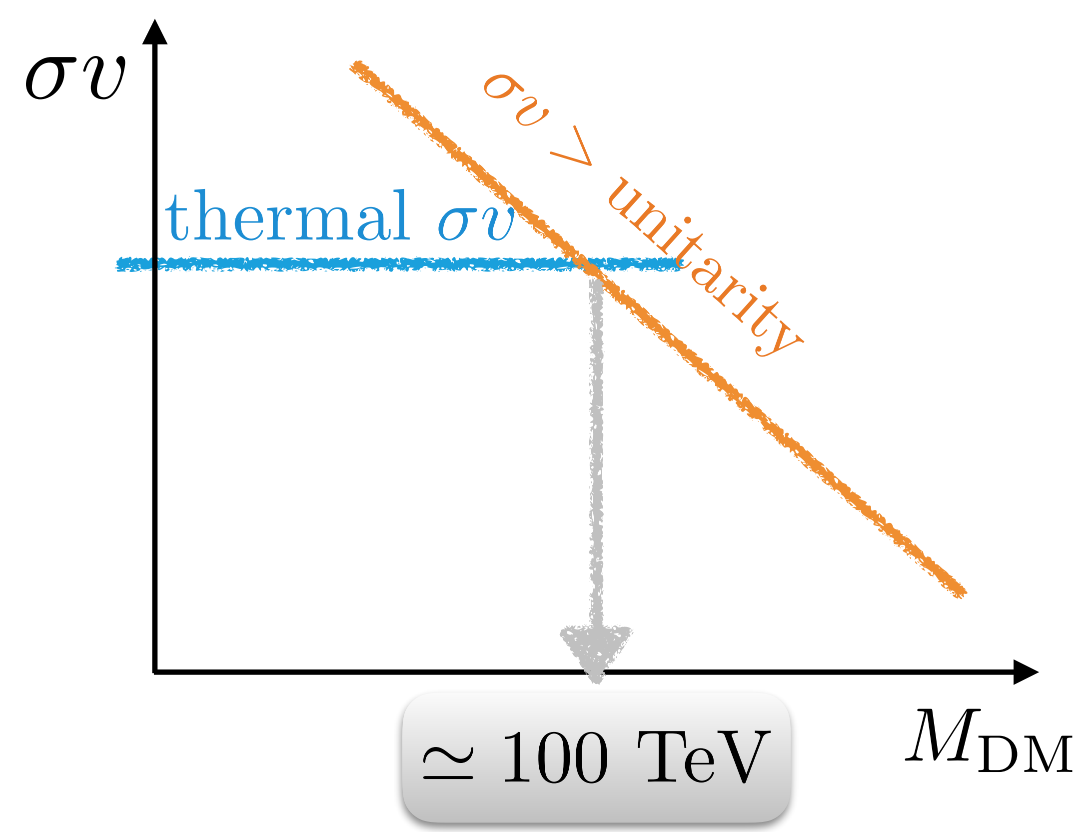
Unitarity bound

$$SS^\dagger = 1$$

$$\Downarrow$$

$$\sigma^j v_{\rm rel} \leq \frac{4\pi(2j+1)}{v_{\rm rel}}\frac{1}{M_{\rm DM}^2}$$

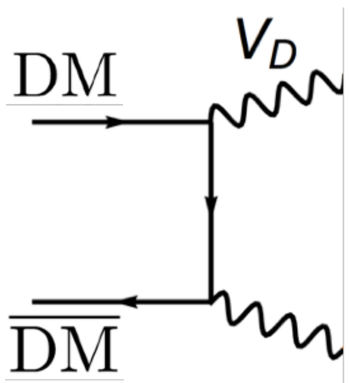
[Griest Kamionkowski PRL 1990]

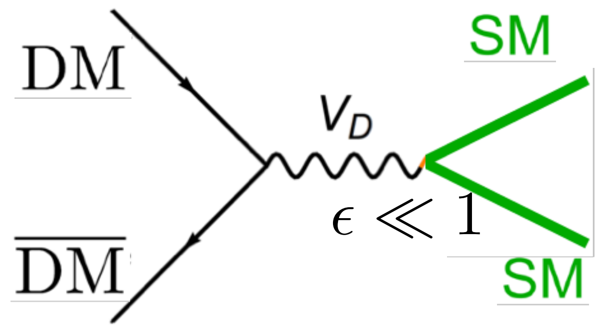


Secluded DM & Electroweak Radiation

Secluded DM $\mathcal{L} \sim g_{\rm D} V_{\rm D} (\overline{\rm DM}\,{\rm DM} + \epsilon\, \overline{\rm SM}\,{\rm SM})$

Thermal production possible with tiny interactions with SM   Pospelov+ 0711.4866,...





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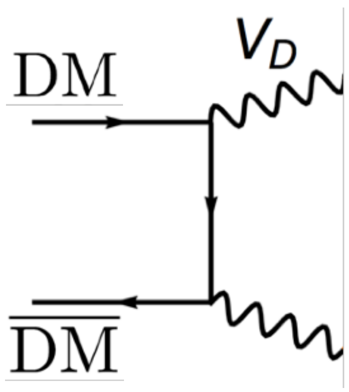

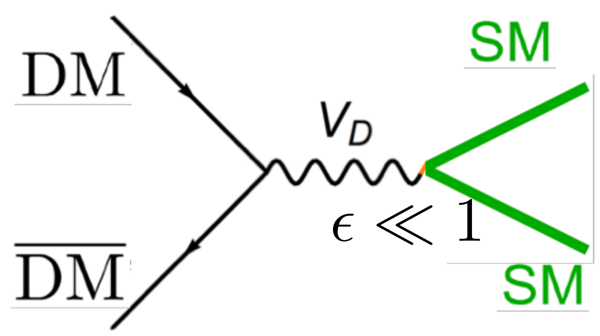

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Center of mass energy = $m_V \ll 100$ TeV $\Rightarrow$ **EW radiation @ first order is OK!**

[can use PPPC even for $M_{\rm DM} > 10 - 100$ TeV]

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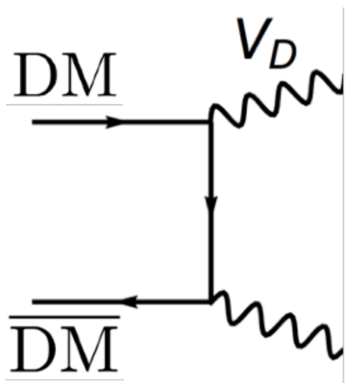

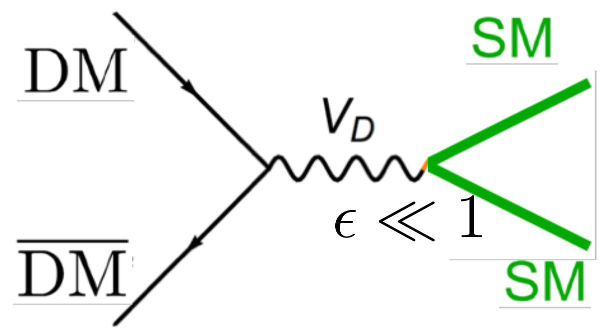

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Explicit Example: $\mathcal{L} = \bar{X}(i\hat{D} - M_{\rm DM})X - \frac{1}{4} F_{D\,\mu\nu} F_D^{\mu\nu} - \frac{\epsilon}{2c_w} F_{D\,\mu\nu} B^{\mu\nu}$

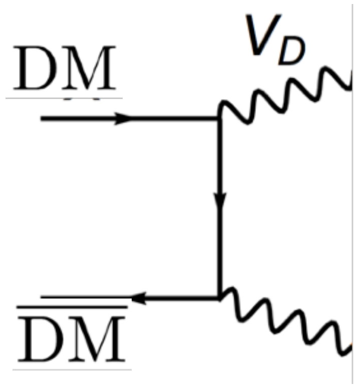
$X = {\rm DM}$ charged under a dark U(1)

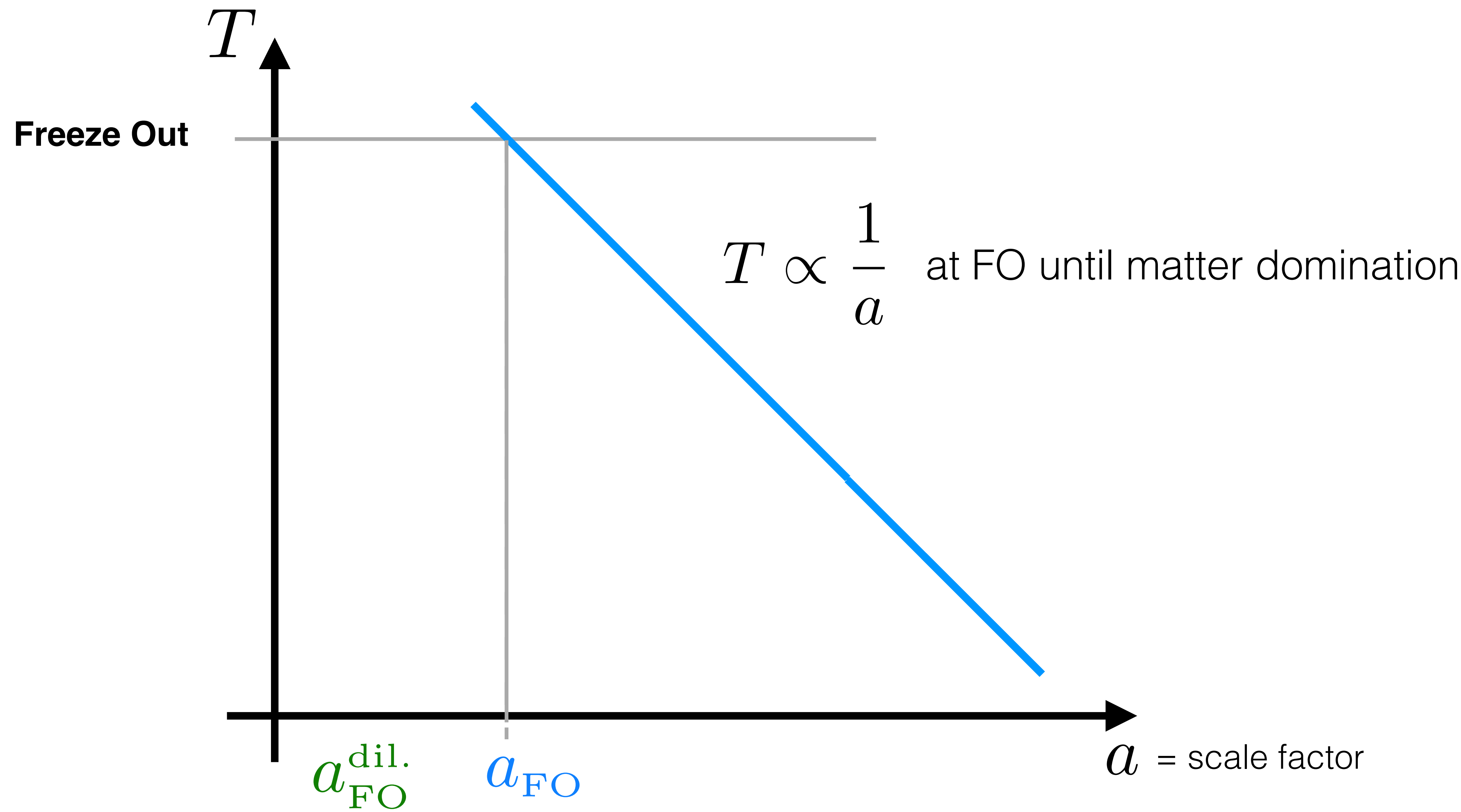
E.g. from heavy new particles charged under both U(1)'s

Secluded DM & the Unitarity Bound

Berlin+1602.08490
Cirelli+1612.07295

"Standard" Cosmological Evolution: $\Omega_{\rm DM} \propto \frac{1}{\sigma v}$





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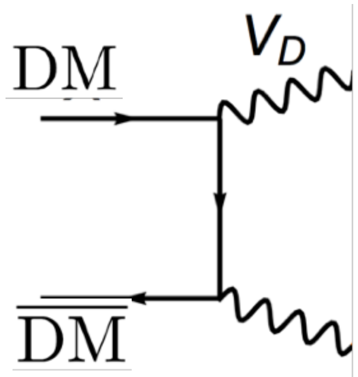
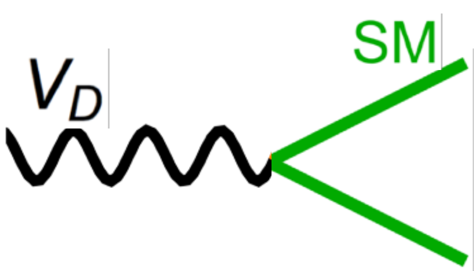
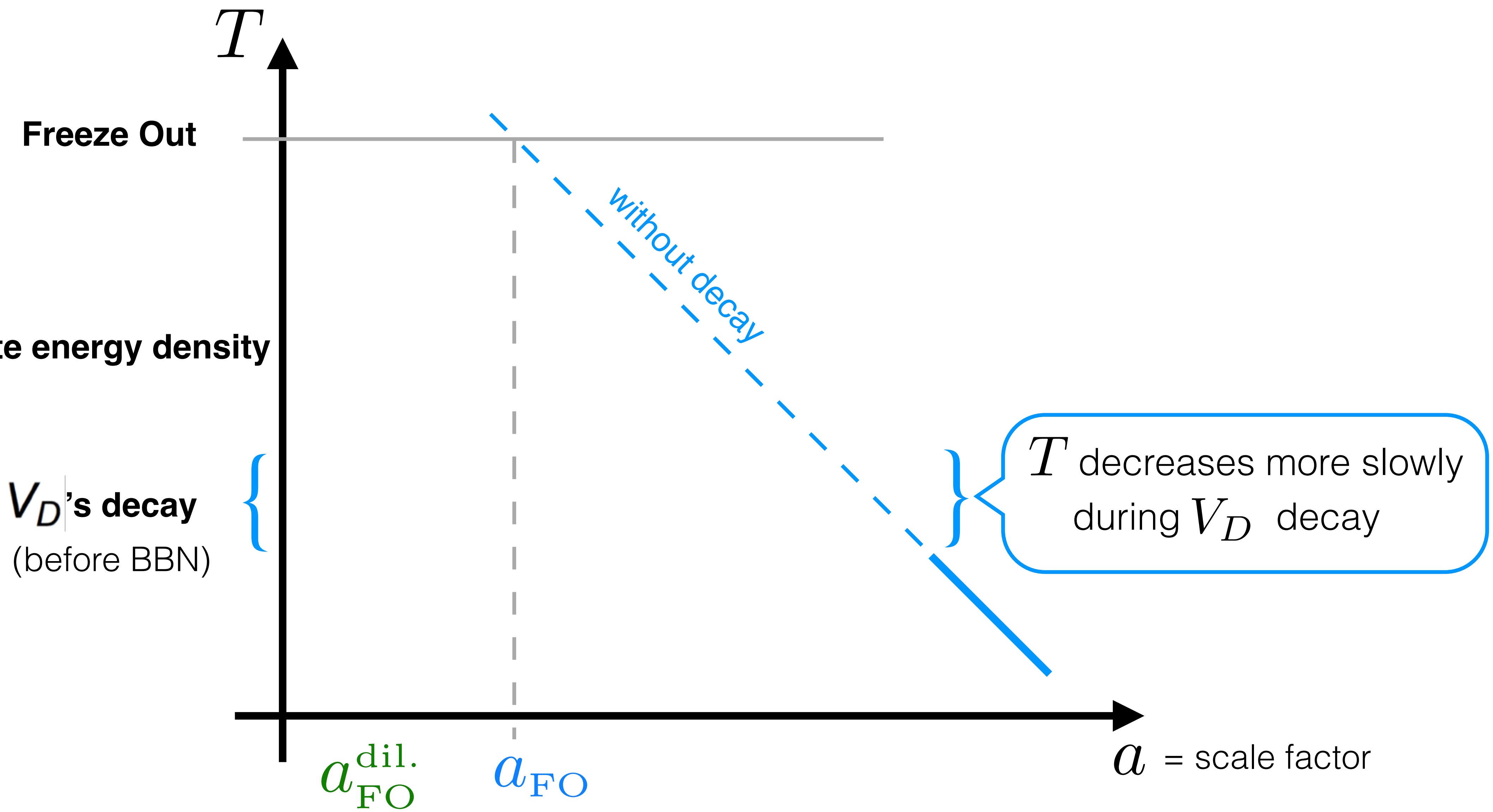


$\epsilon \lll 1$ **V_D's dominate energy density**



V_D's decay
(before BBN)



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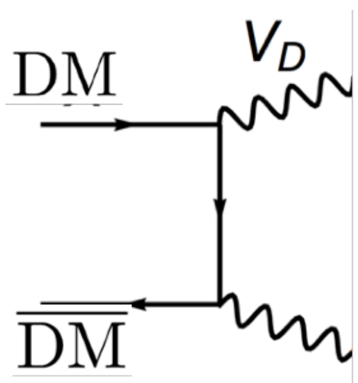

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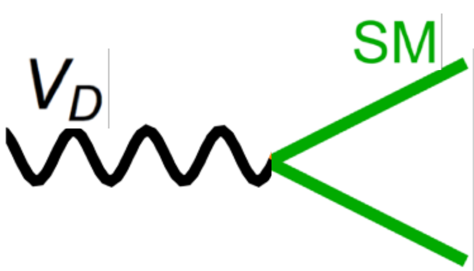

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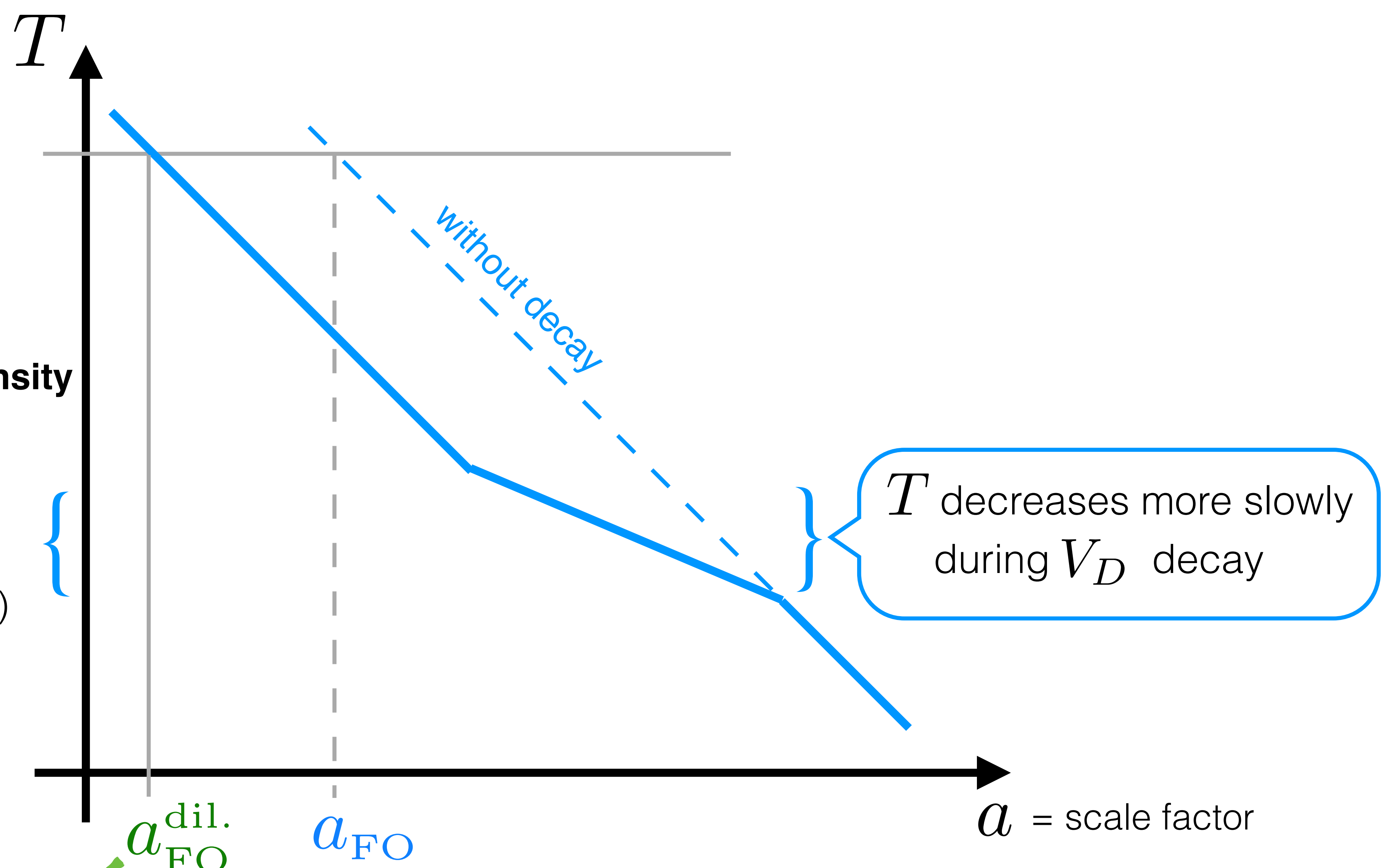
Freeze Out



Universe @freeze-out is smaller than w/o decay $\Rightarrow$ The same amount of relic DM is later more diluted $\Rightarrow$ $\sigma v^{\rm FO}_{\rm DM\,\overline{DM}\to V\,V}$ smaller and DM can be heavier!

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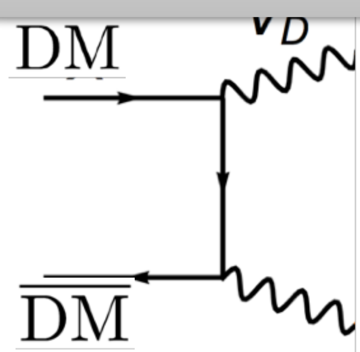

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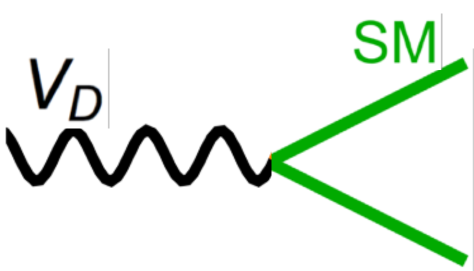

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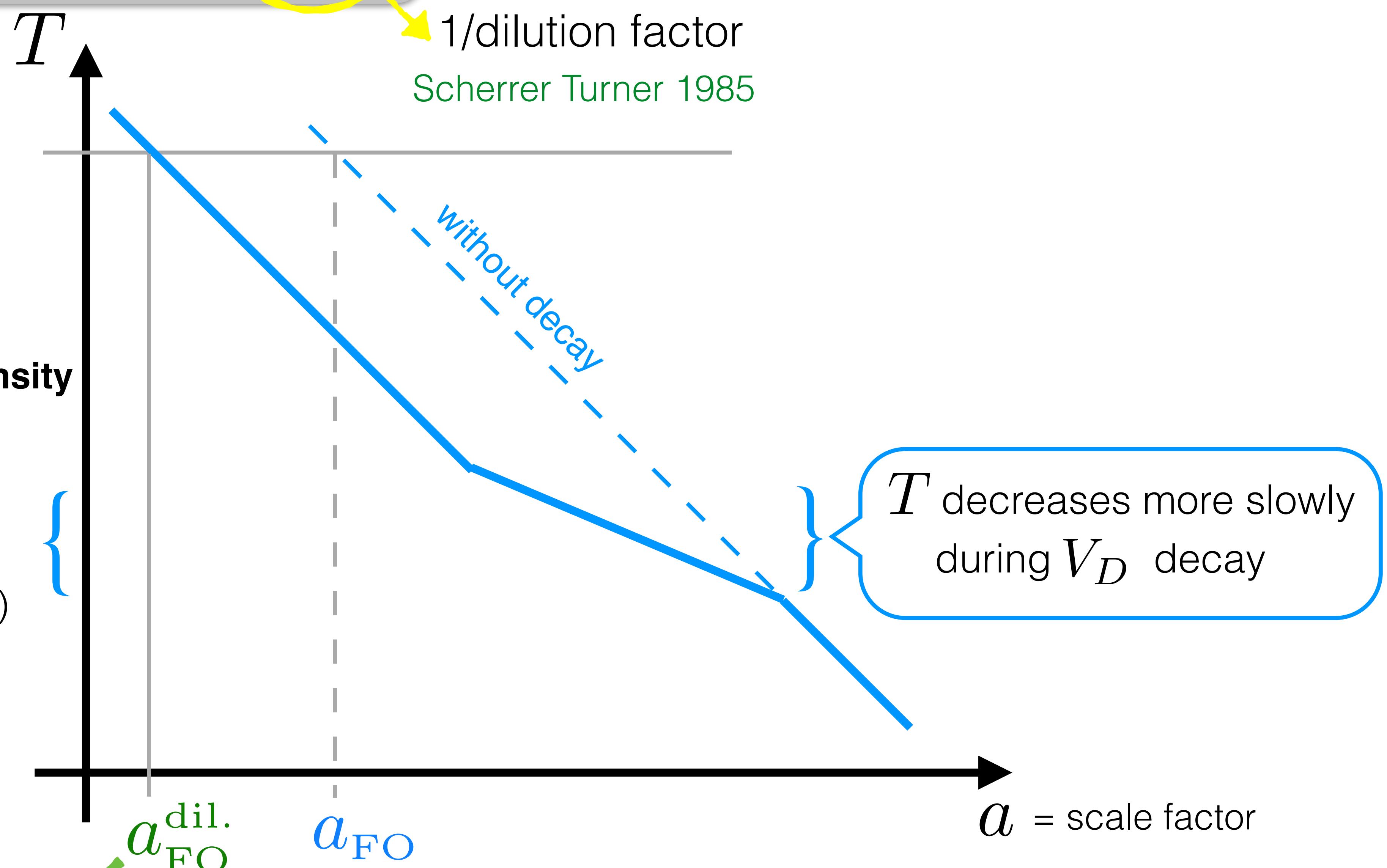

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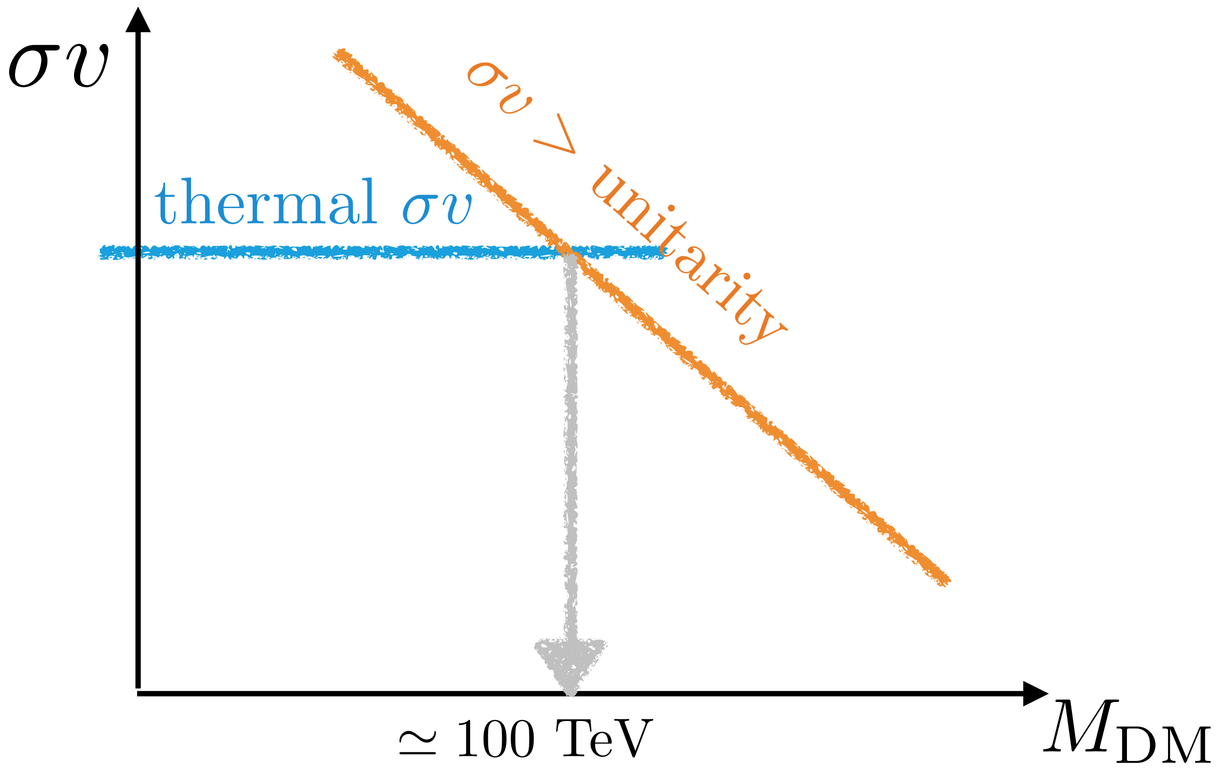
How Heavy?

Cirelli Gouttenoire Petraki FS 1811.03608



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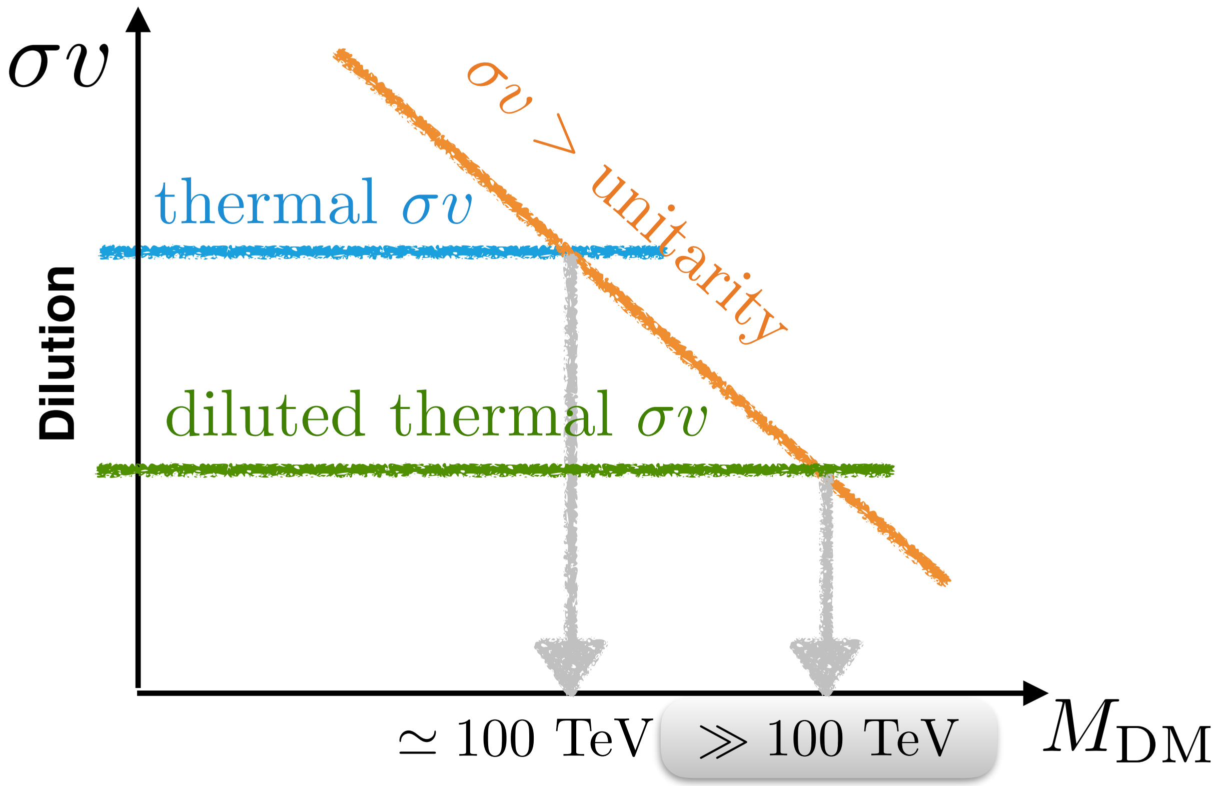

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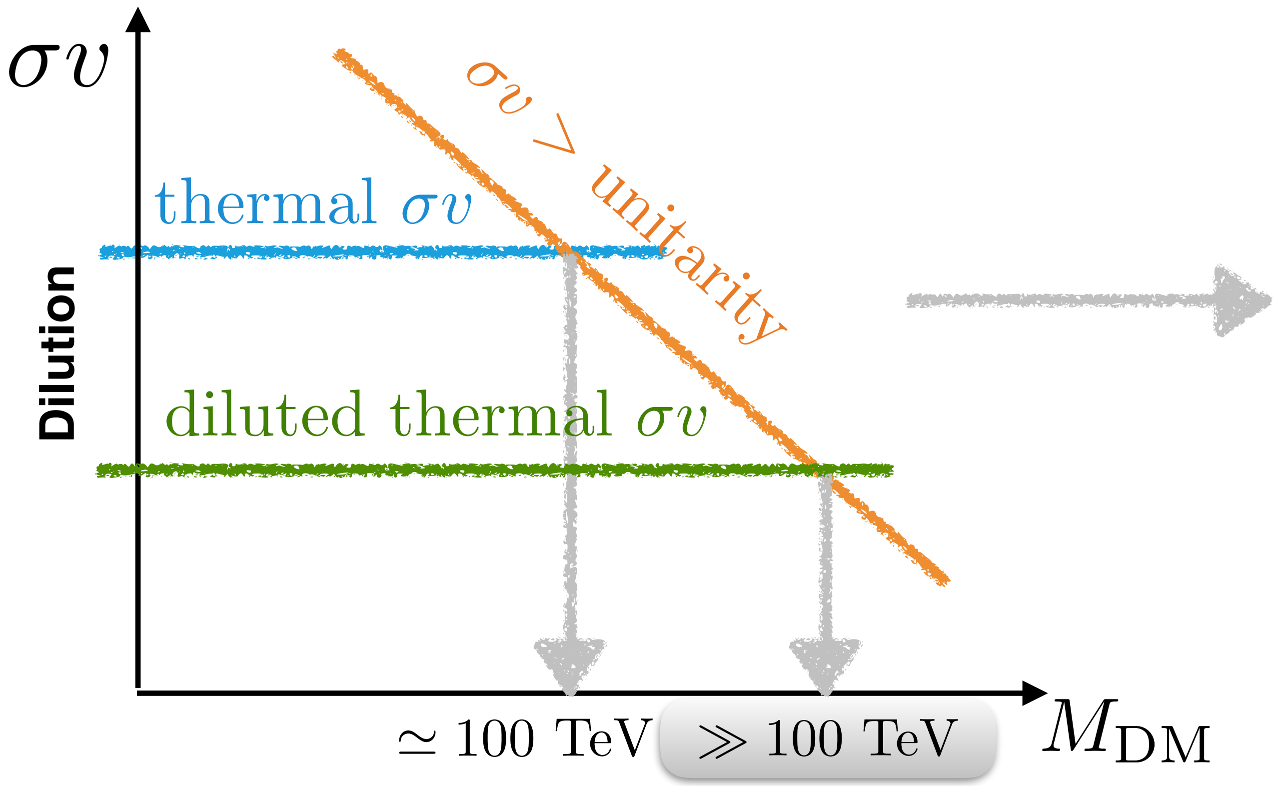

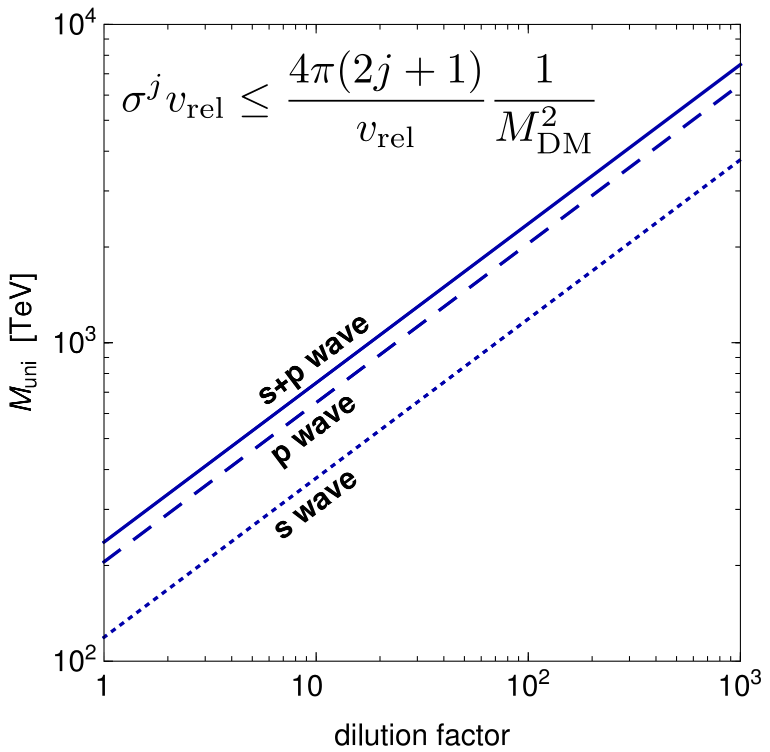

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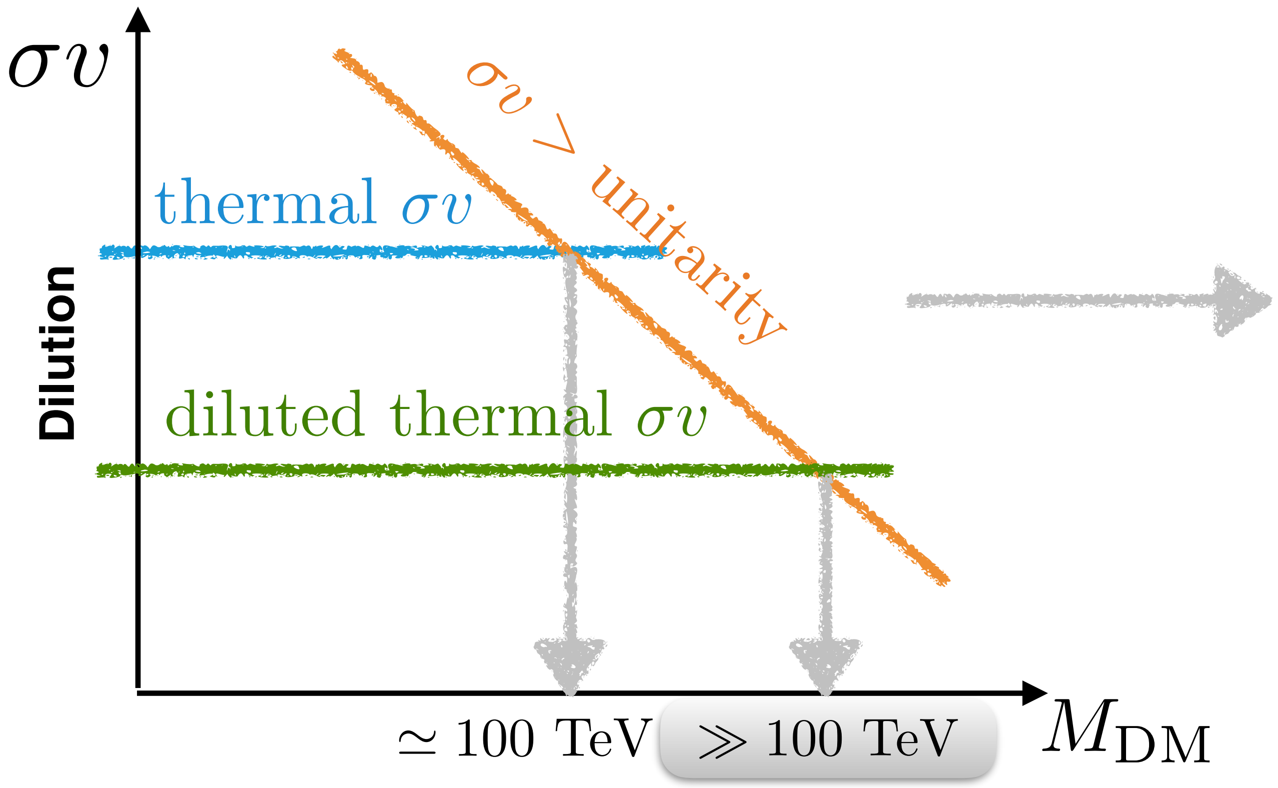

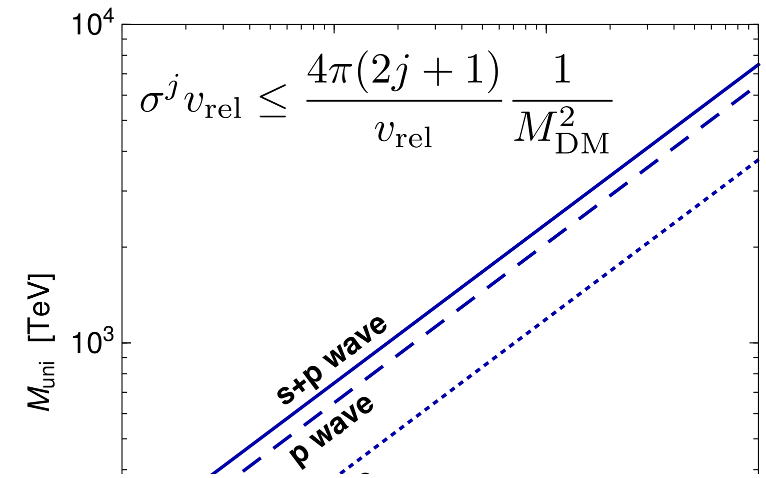

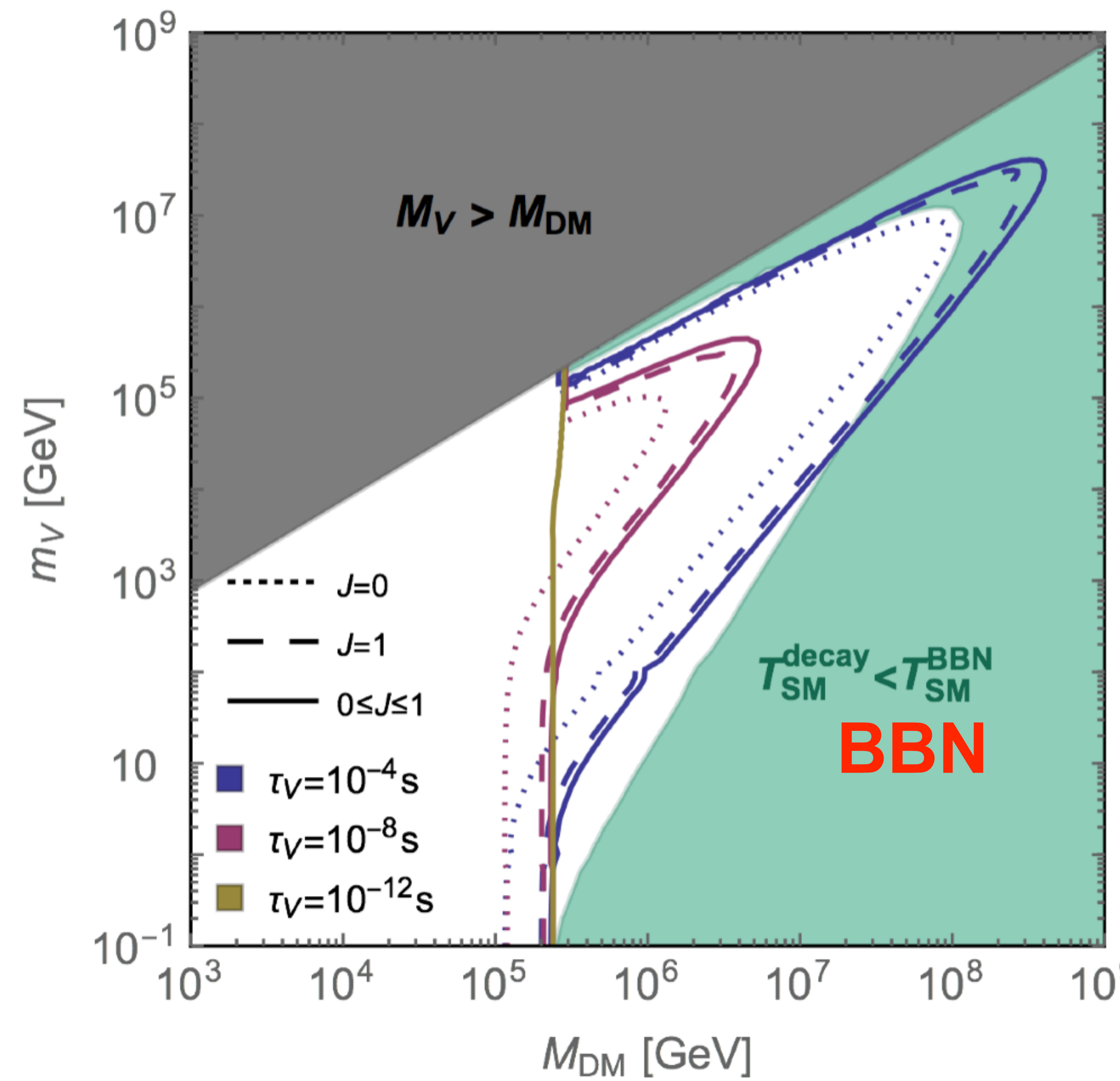

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$$\text{Dilution} \propto m_V \sqrt{\tau_V}$$

Experimental Tests

Cirelli+ 1612.07295, Baldes+ 1712.07489

Cirelli Gouttenoire Petraki FS 1811.03608

Tiny portal with the SM + Heavy → Direct Detection & Collider put no constraints

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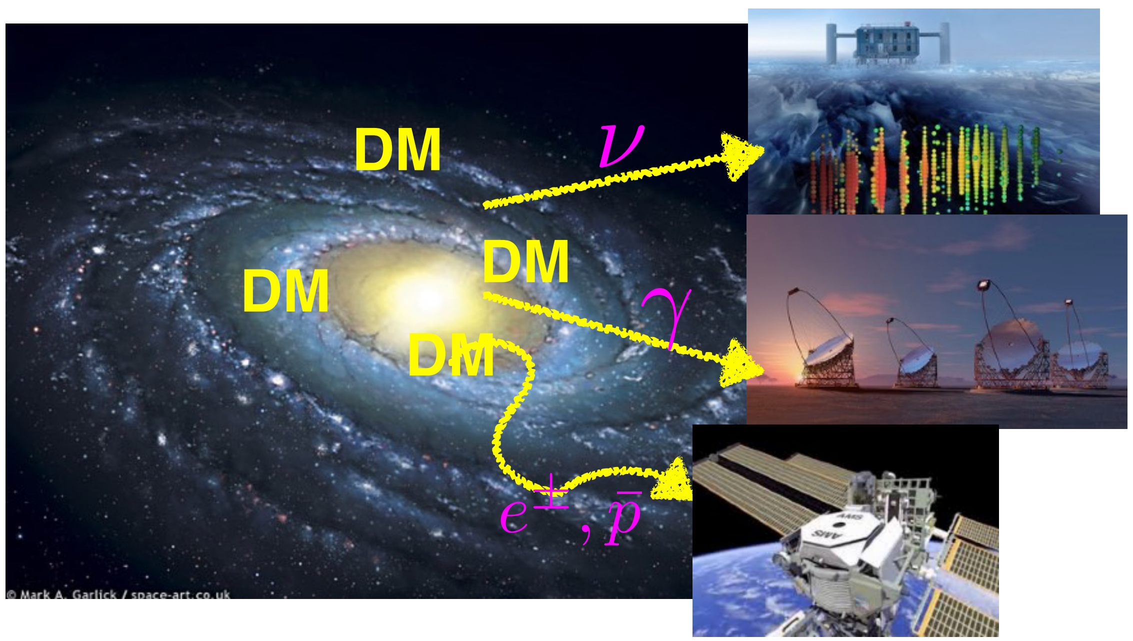

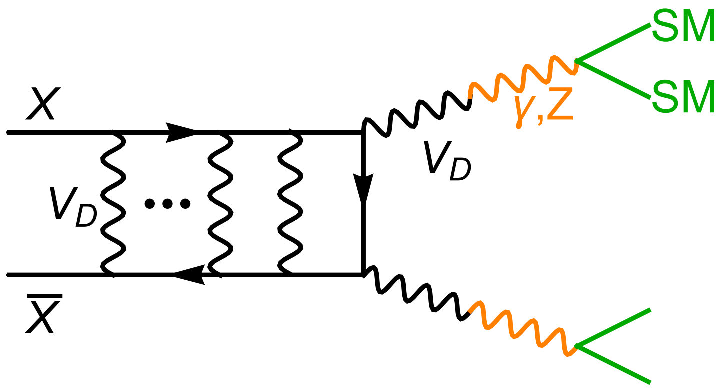

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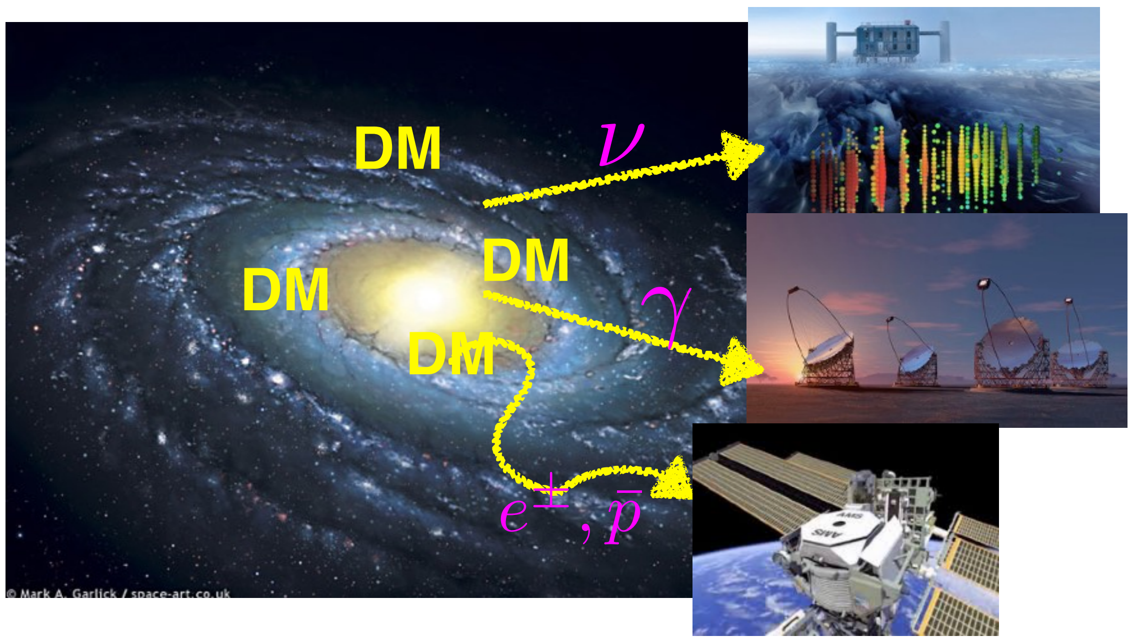

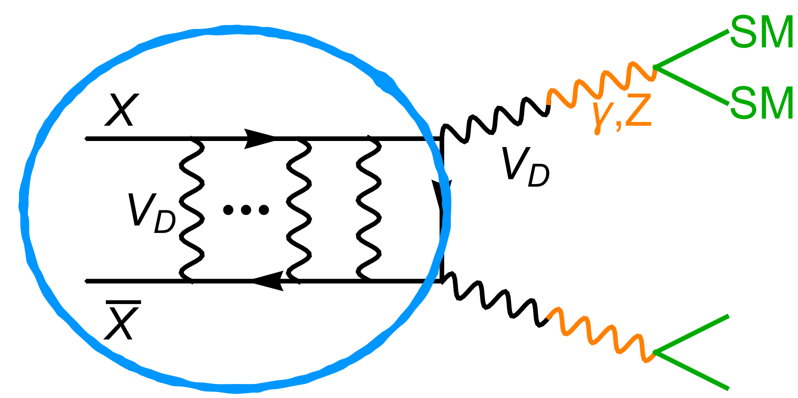

1. Sommerfeld and Bound State formation

Petraki+ 1611.01394

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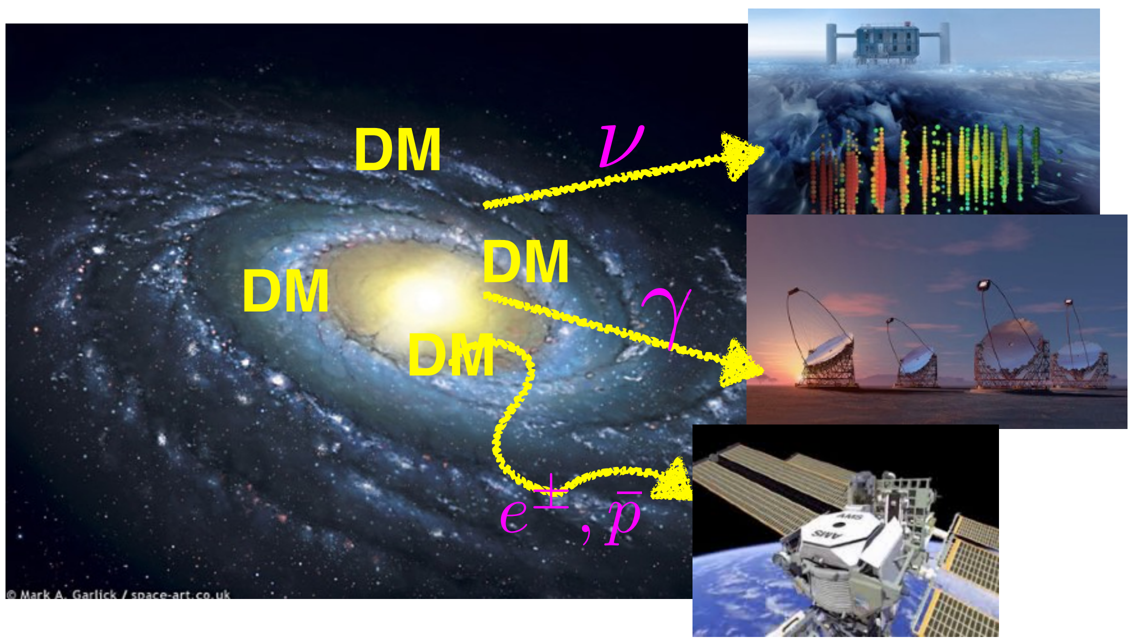

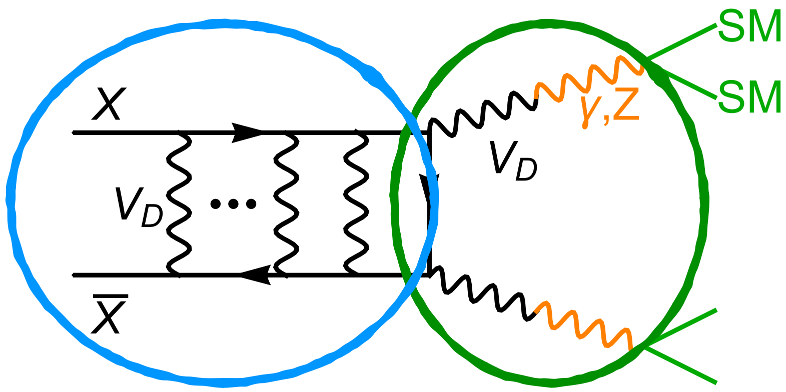

1. Sommerfeld and Bound State formation
Petraki+ 1611.01394

2. Cascade decays: one step softens the spectra
Elor Rodd Slatyer 1511.08787

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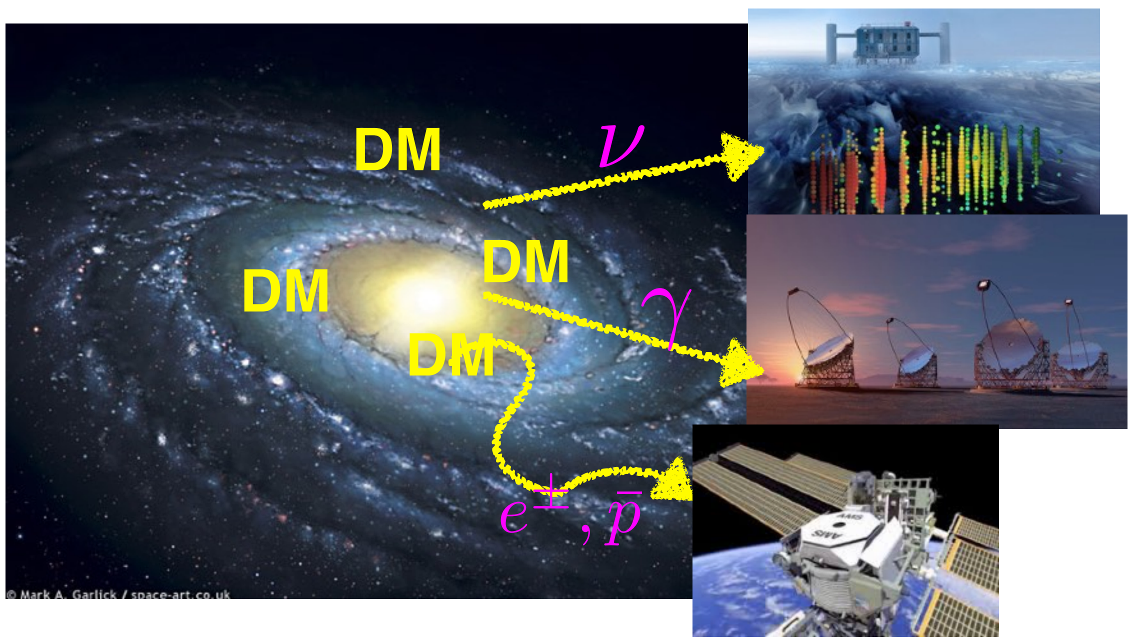
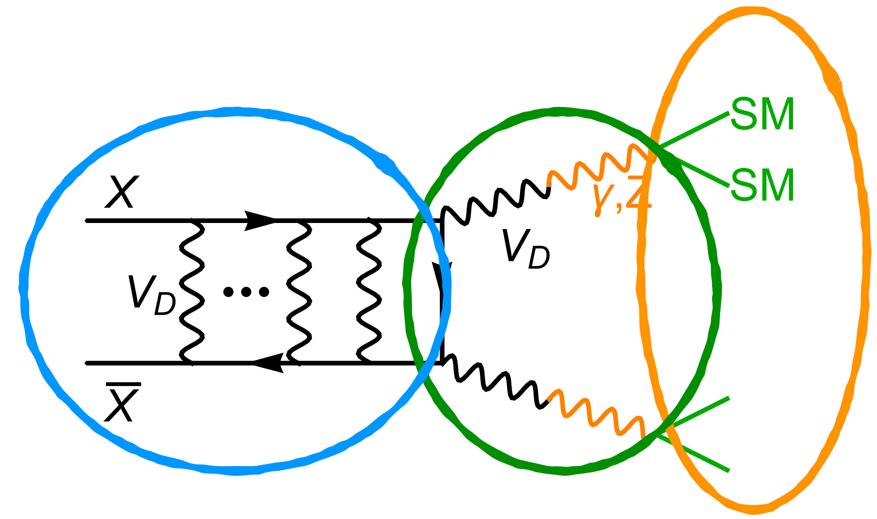
Cirelli Gouttenoire Petraki FS 1811.03608

Tiny portal with the SM + Heavy → Direct Detection & Collider put no constraints



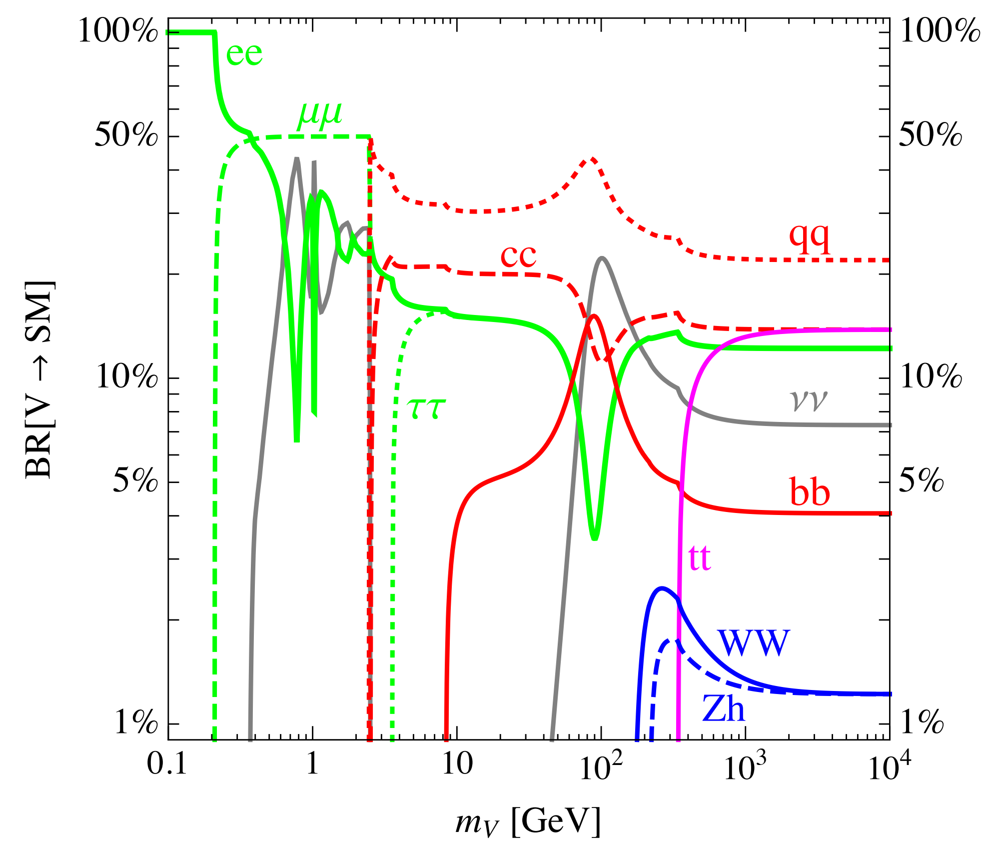


1. Sommerfeld and Bound State formation
Petraki+ 1611.01394

2. Cascade decays: one step softens the spectra
Elor Rodd Slatyer 1511.08787

3. Dark Photon decays $\mathcal{L} \supset g_f V_D^\mu (\bar{f} \gamma_\mu f)$

$$g_f = \epsilon\, e \left(Q_f \frac{1}{1-\delta^2} + \frac{Y_f}{c_w^2} \frac{\delta^2}{\delta^2 - 1} \right) + O(\epsilon^2) \qquad \delta = \frac{m_V}{m_Z}$$



Signals of ~ 100 TeV DM

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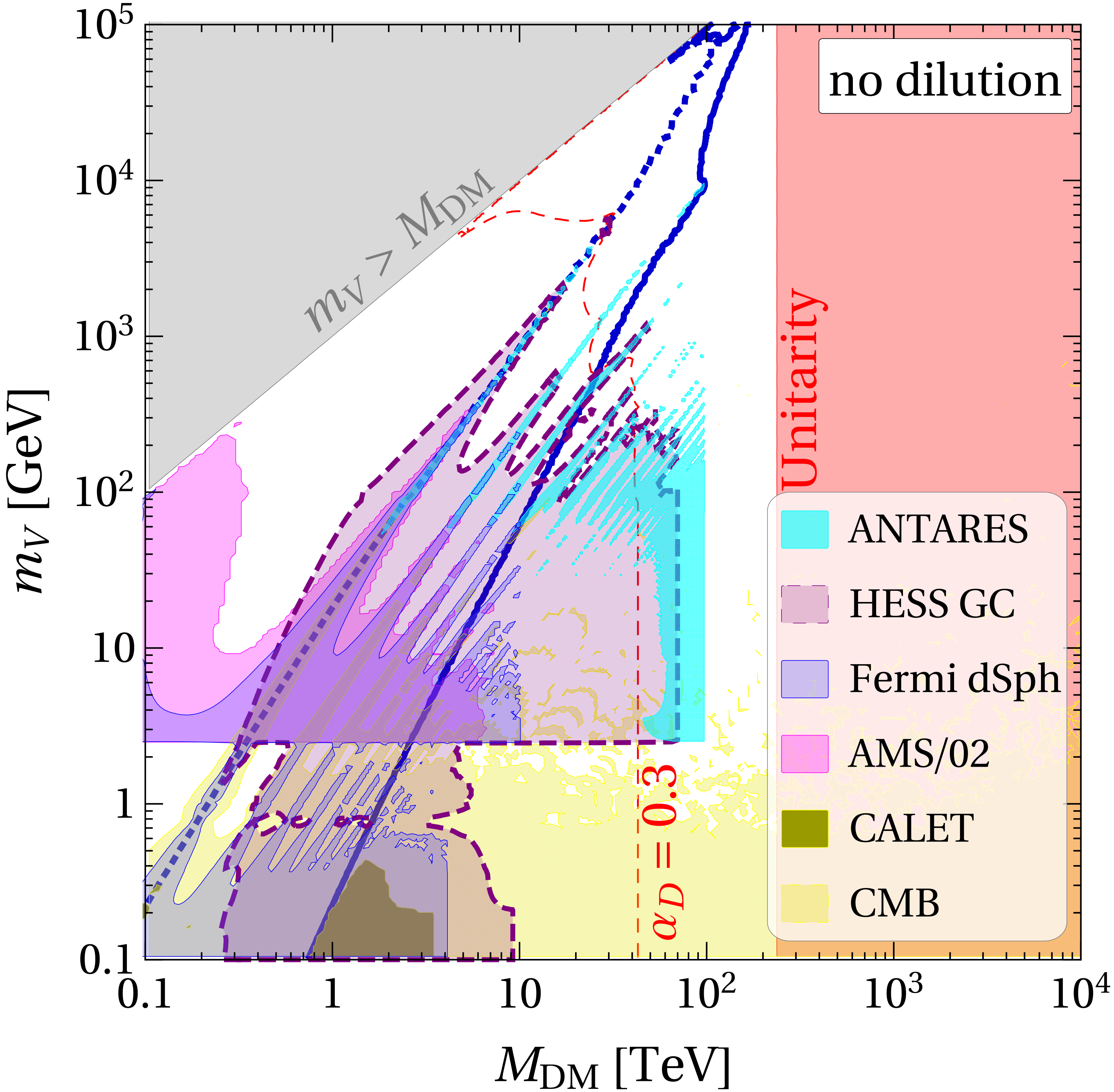

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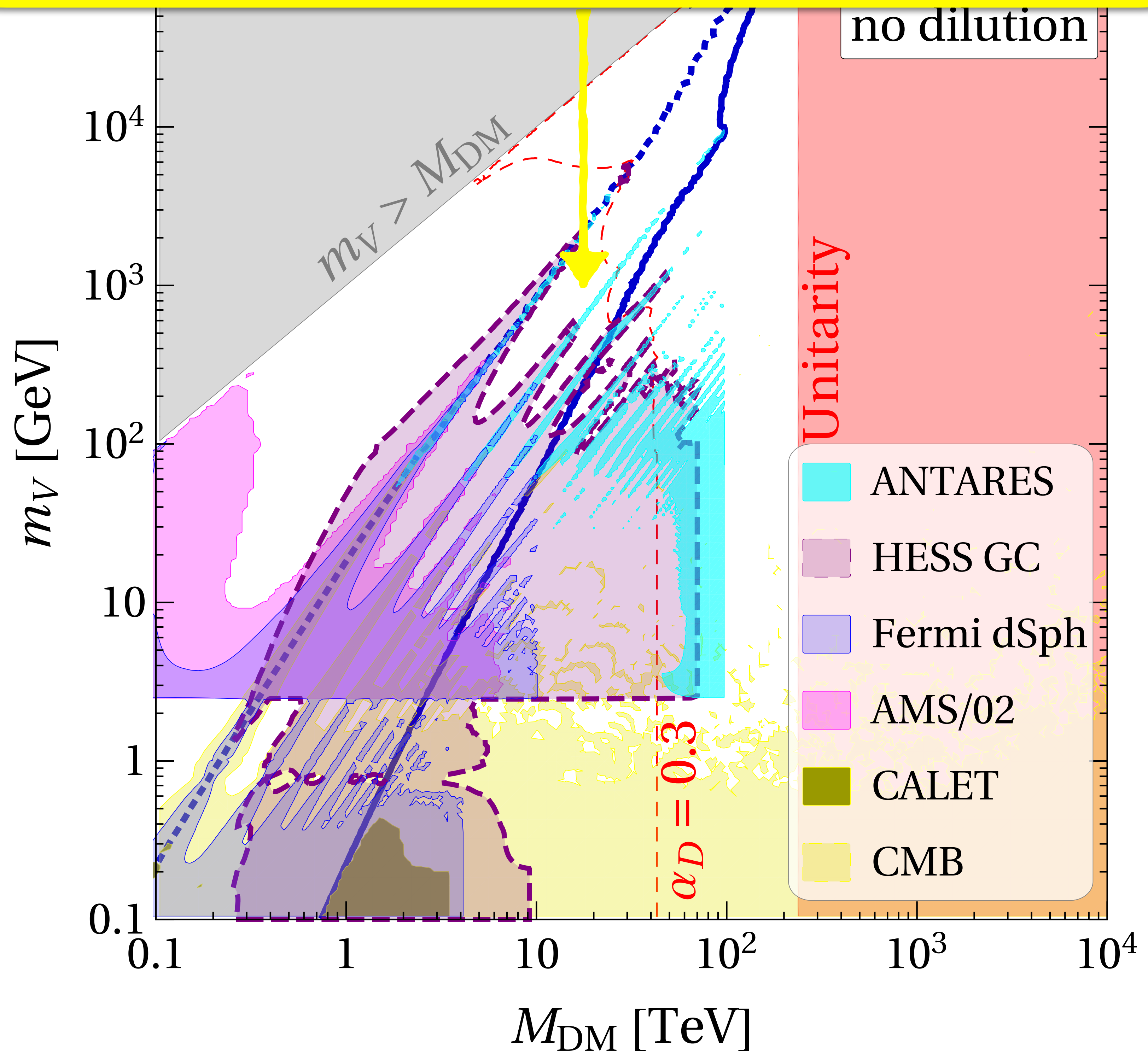
Multimessanger hunt for **Heavy DM** is possible!



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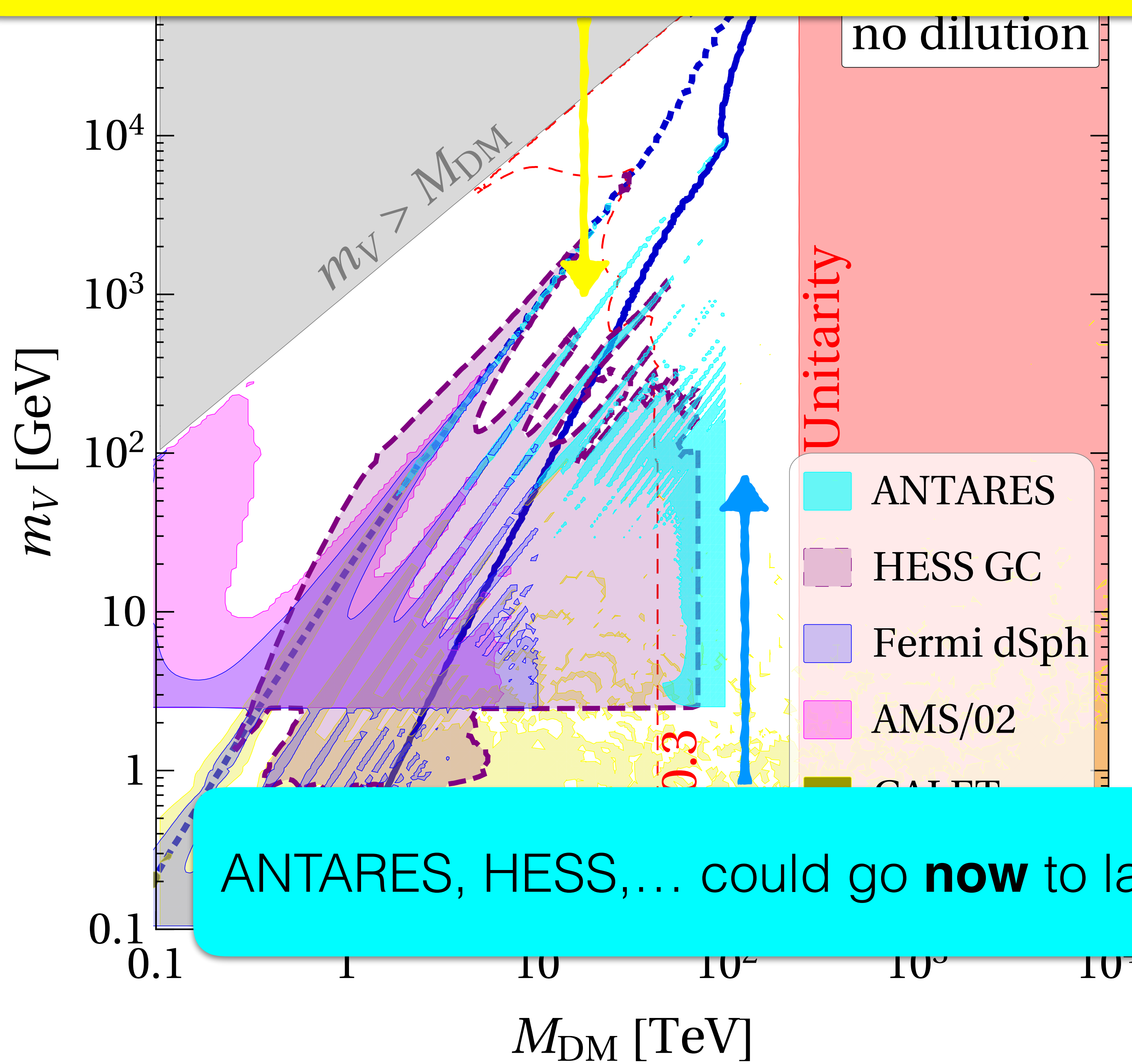
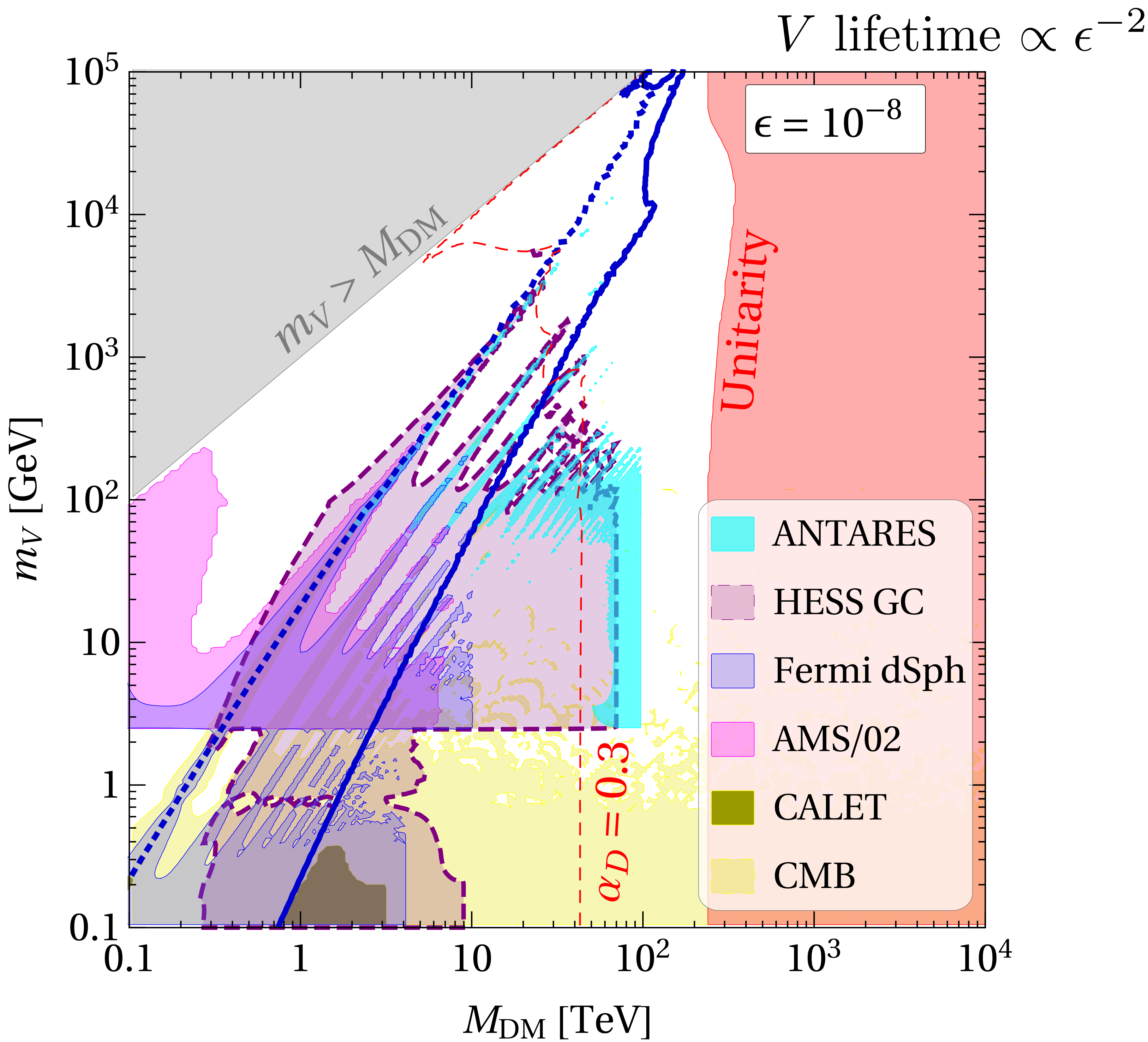


ANTARES, HESS,… could go **now** to larger DM mass

Signals of ~ 100 TeV DM

Cirelli Gouttenoire Petraki FS 1811.03608



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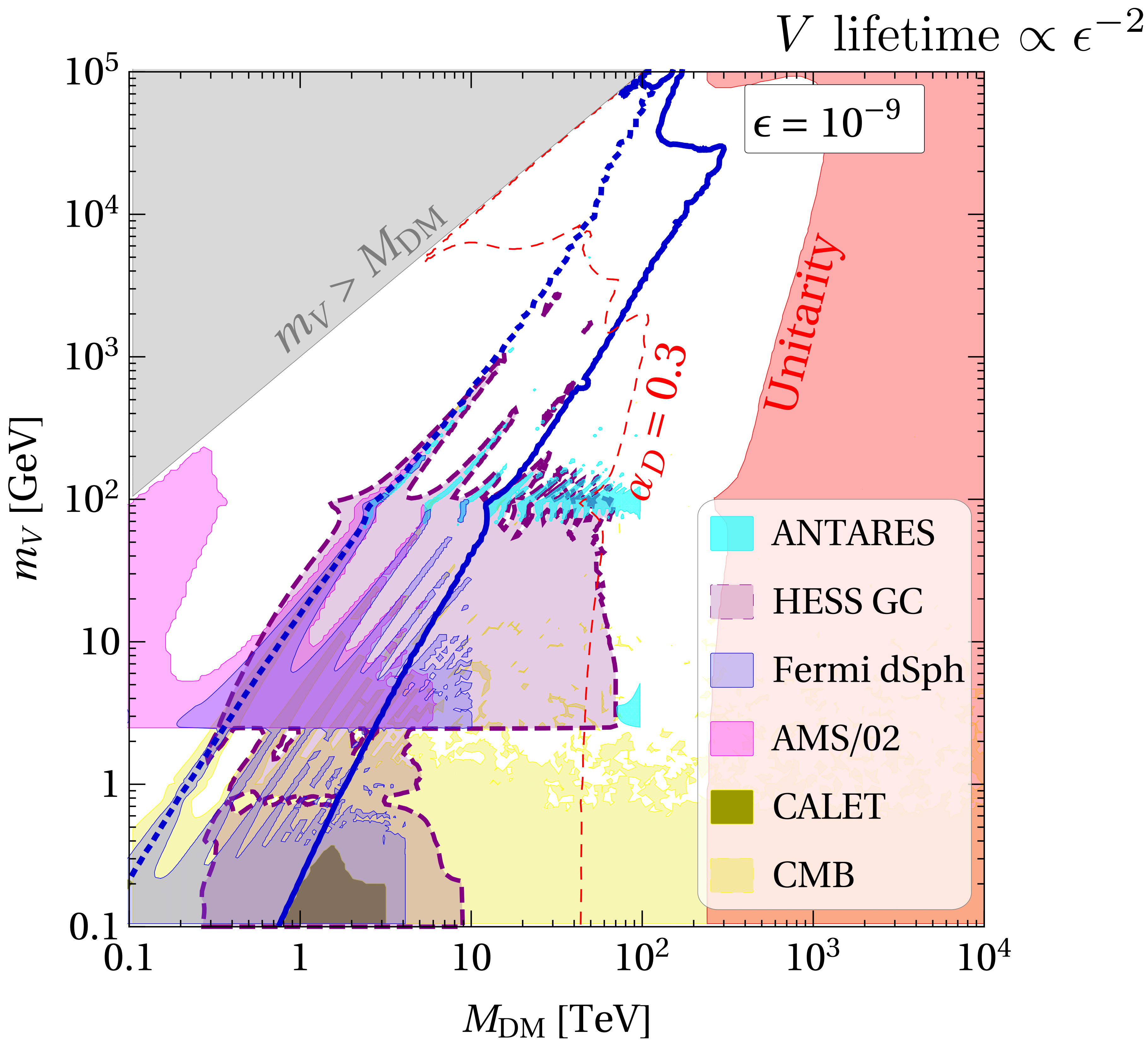

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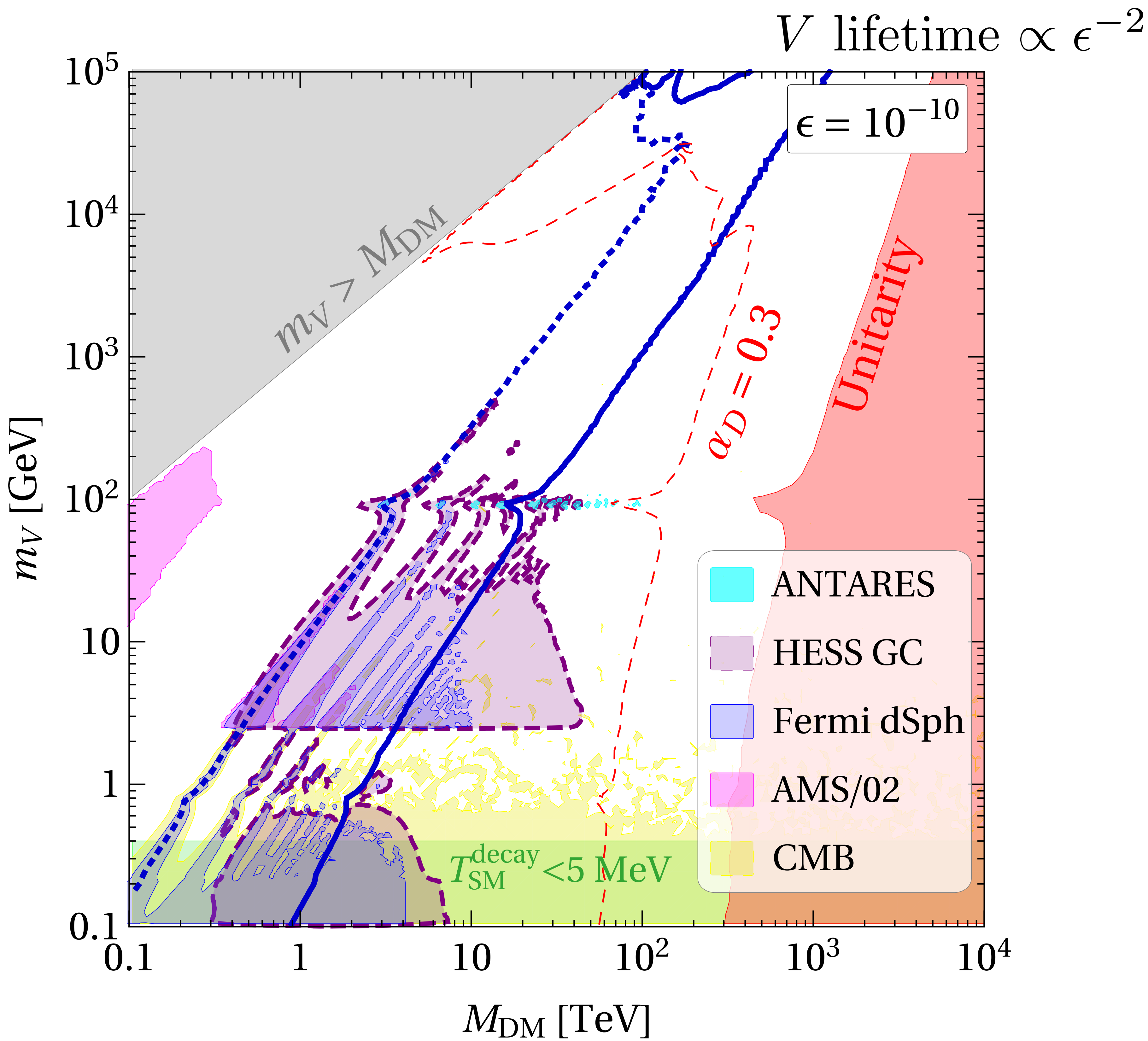

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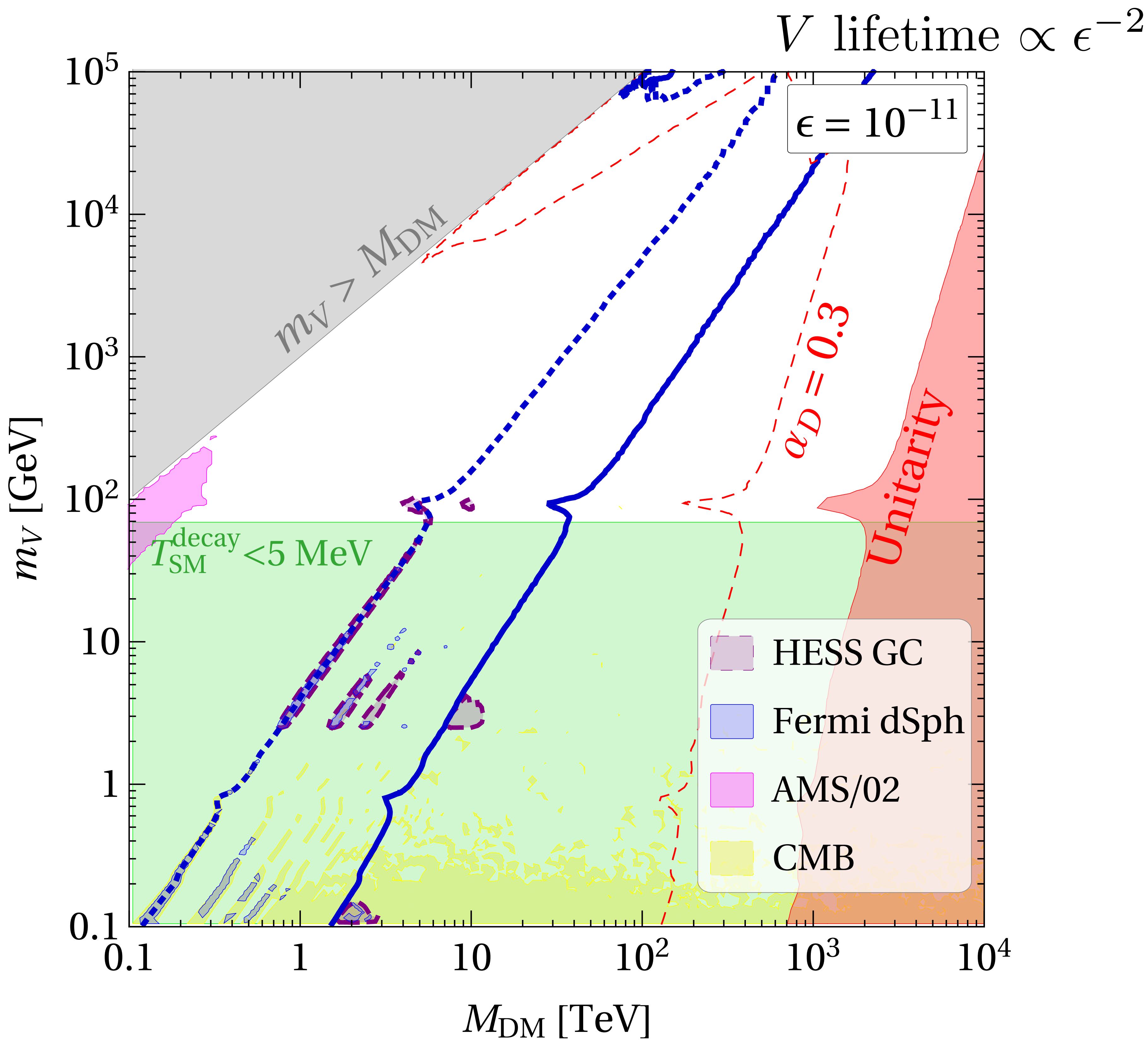

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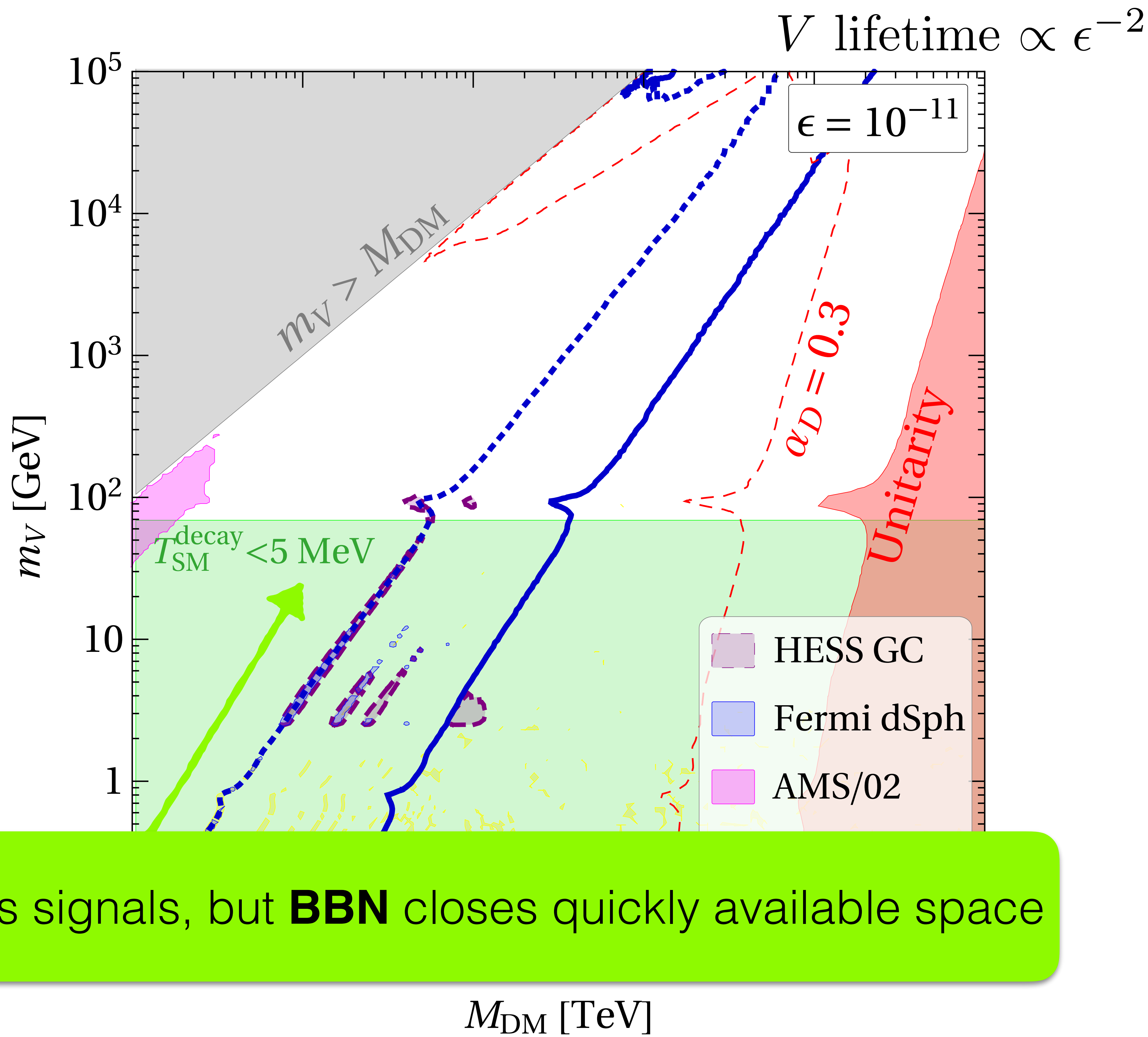
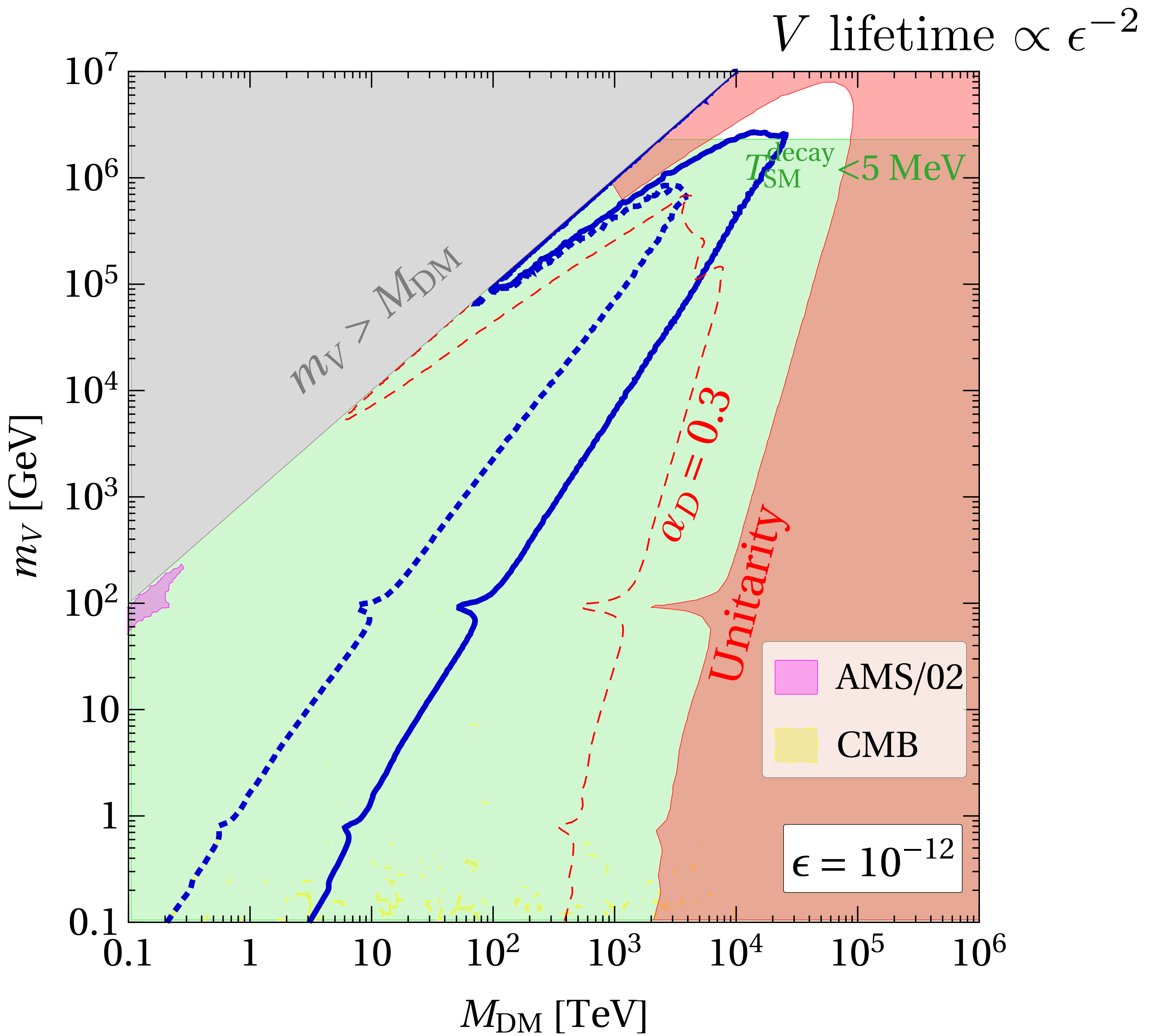


Dilution inhibits signals, but **BBN** closes quickly available space

Signals of ~ 100 TeV DM

Cirelli Gouttenoire Petraki FS 1811.03608



A Partial Recap

Cirelli Gouttenoire Petraki FS 1811.03608

Results

- ✓ **Heavy Dark Matter is testable!**
- ✓ Secluded DM Models as ideal playground for **Early Matter domination**

A Partial Recap

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Results

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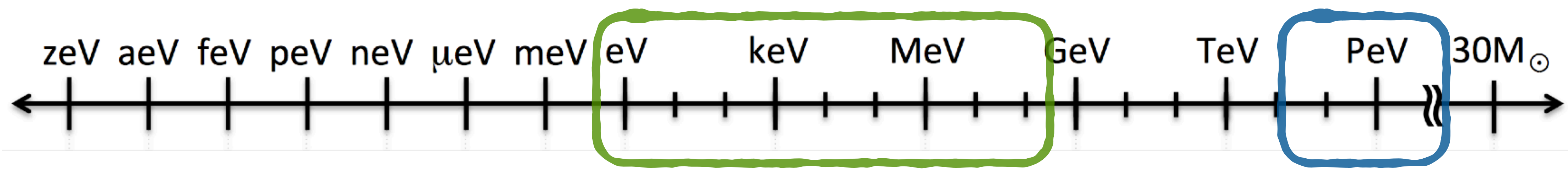
Outlook

- Public access to Telescope data would help!
- Sensitivity of Future Experiments? (KM3NeT, CTA, LHAASO, TAIGA,…)
- Other effects of Decay of Mediators? (e.g. on baryon asymmetry)
- Origin of Dark Matter mass? (e.g. SUSY breaking sector)
- Origin of small portal with SM? (e.g. Neutrino Masses)
- ….

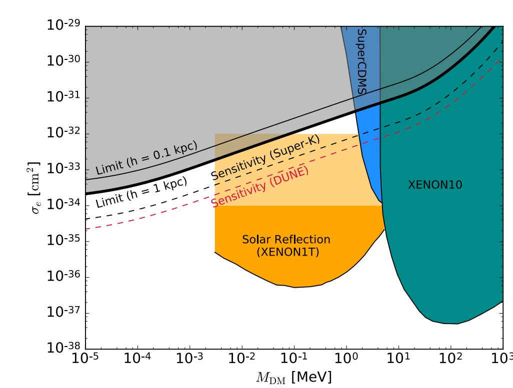
New Directions in Dark Matter

Both involve **Neutrino Experiments!**



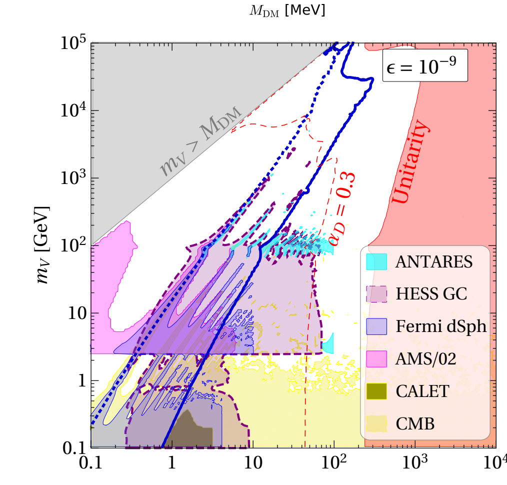
Light DM

Ema FS Sato 1811.00520



Heavy DM

Cirelli Gouttenoire Petraki FS 1811.03608



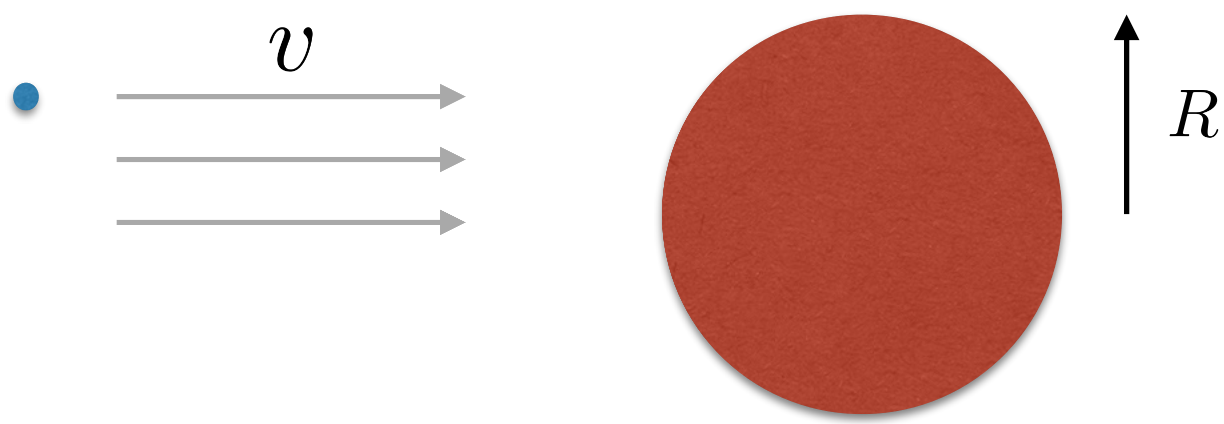
Back up

More on Heavy DM

Sommerfeld Enhancement

Sommerfeld 1931,
Hisano+ hep-ph0412403 (first time DM), ….
Arkani-Hamed+ 0810.0713 for nice explanation

Classical analogous



$$\sigma_0 = \pi R^2$$

If slow, gravity becomes important:

$$\sigma = \sigma_0 \left(1 + \frac{v_{\rm esc}^2}{v^2}\right)$$

Quantum: like in classical example, to have (Sommerfeld) enhancement requires

- slow particles $v \ll c$
- long-range attractive force $M_{\rm mediator} < \alpha\, M_{\rm DM}$

DM mass for SM weak force? $\alpha_{\rm w} \sim 1/30$

$$M_{\rm DM} \gtrsim 30\, M_{W,Z} \simeq 2.5\ {\rm TeV}$$

A bit more technical:
quantum field theory computations assume particles are “free" (=plain waves) at $r = +\infty$
BUT: if potential V is important also there (long-range!) you have to **solve Schroedinger eq.**

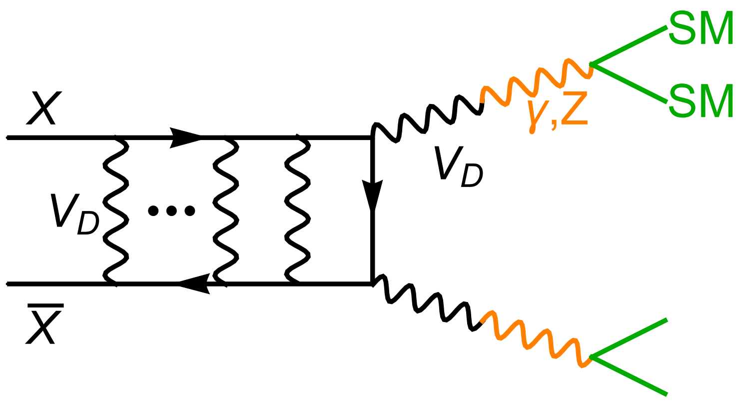
Dark U(1) DM & long-range interactions

~ size of XX system

$$\frac{\alpha_D M_{\rm DM}}{m_V} \gtrsim 1$$

Interaction is long-range: Sommerfeld enhanced

Hisano+ hep-ph/0412403
hep-ph/0610249



Explains anomalies in **cosmic-rays** & **structures**

Self-interacting DM compatibly w/all limits
for recent review see Tulin Yu 1705.02358

GeV Galactic Center gamma excess Hooper+ 1206.2929

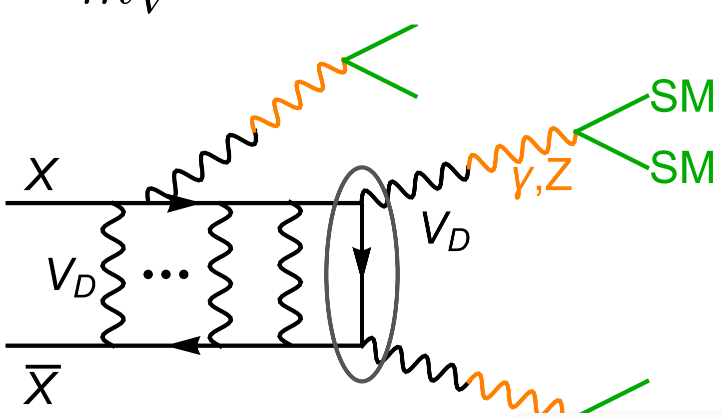
....

~ binding energy

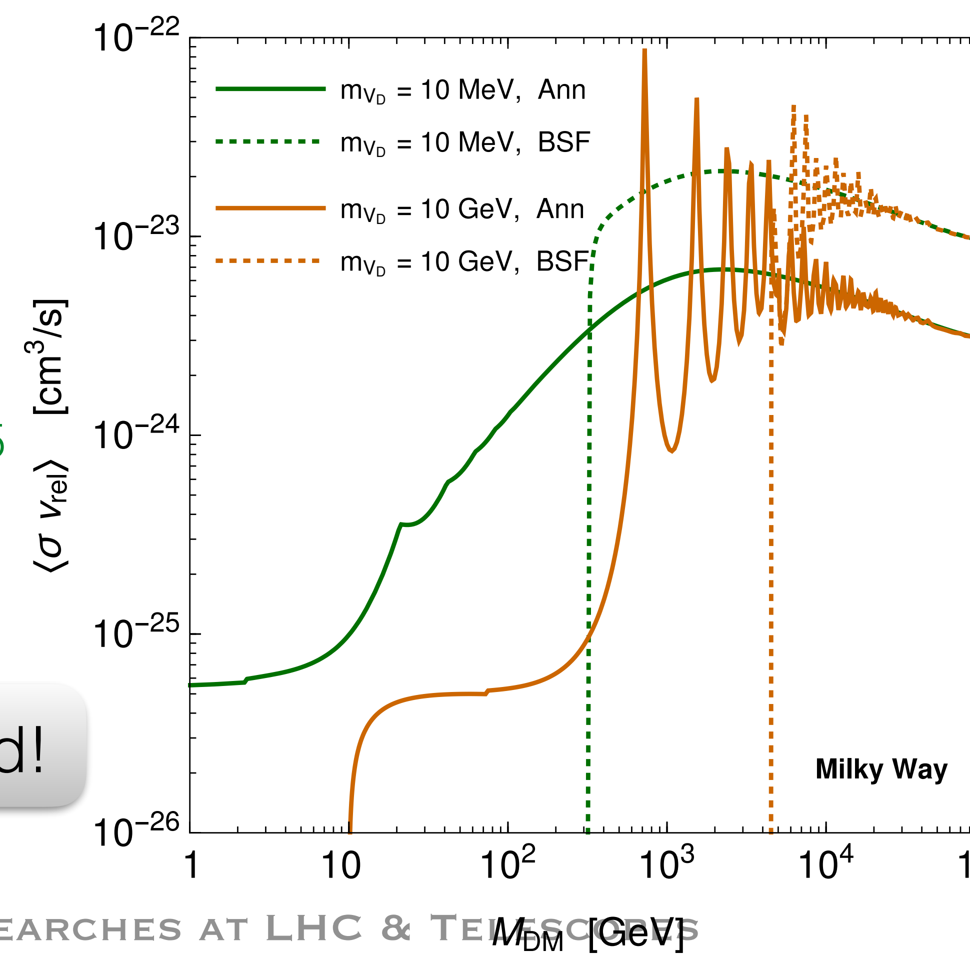
$$\frac{\alpha_D^2 M_{\rm DM}}{m_V} \gtrsim 1$$

DM **bound states** can form

Pospelov Ritz 0810.1502
March-Russel West 0812.0559
Shepherd Tait Zaharijas 0901.2125



BS can dominate over Sommerfeld!



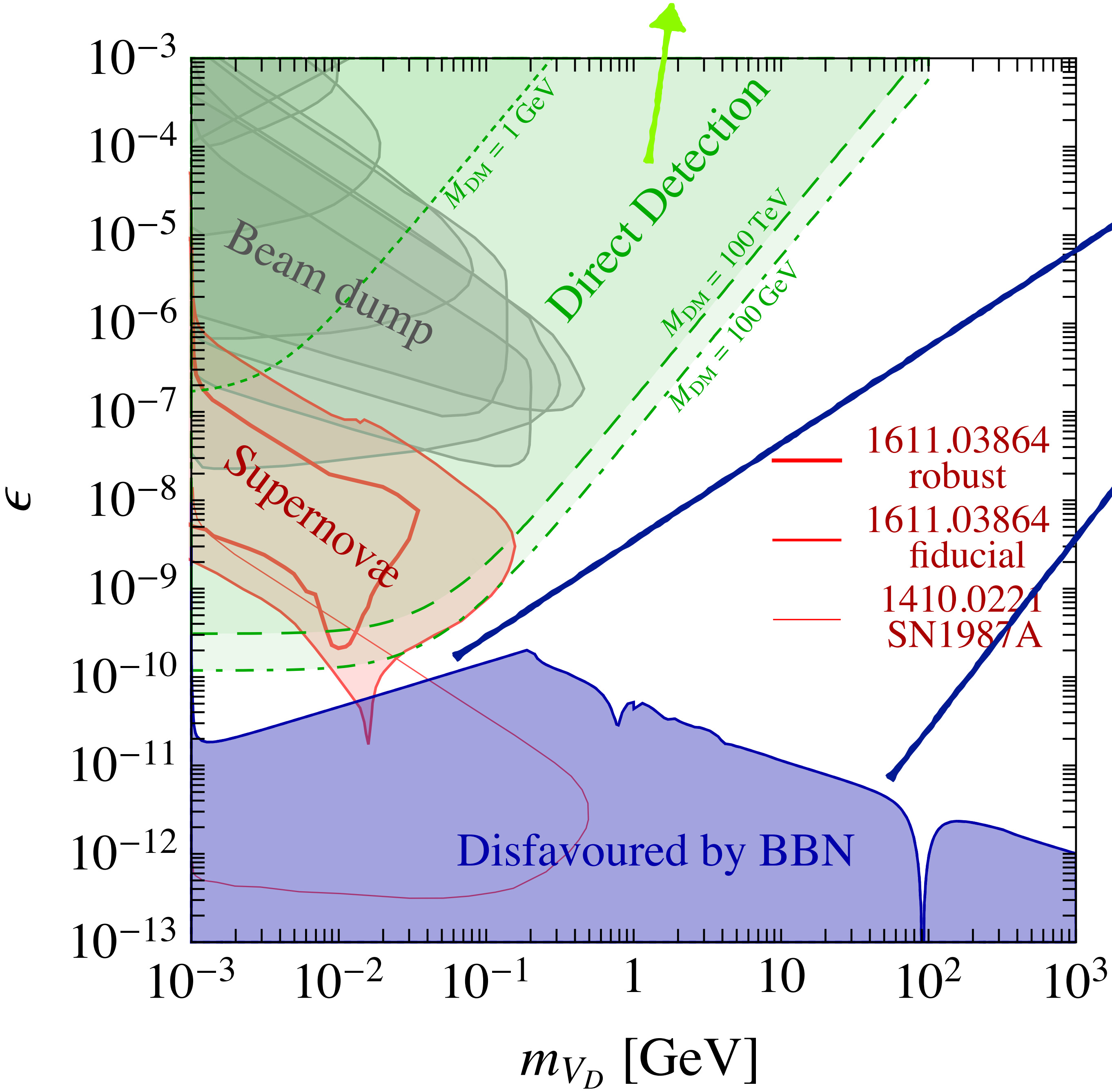
Petraki+ 1611.01394

Pheno in the ϵ - m_V plane

α_D fixed to reproduce thermal relic abundance → 3 free parameters: $M_{\rm DM}$ m_V ϵ

von Harling Petraki 1407.7874 + minor refinement

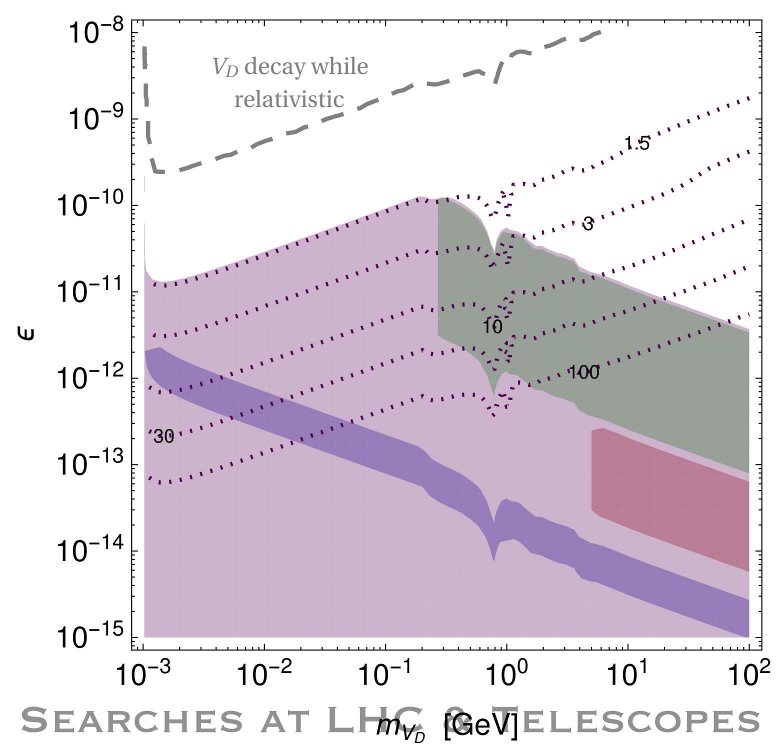
Only constraint that would vanish w/o Dark Matter



Dark photons are not > 50% of energy density of the universe

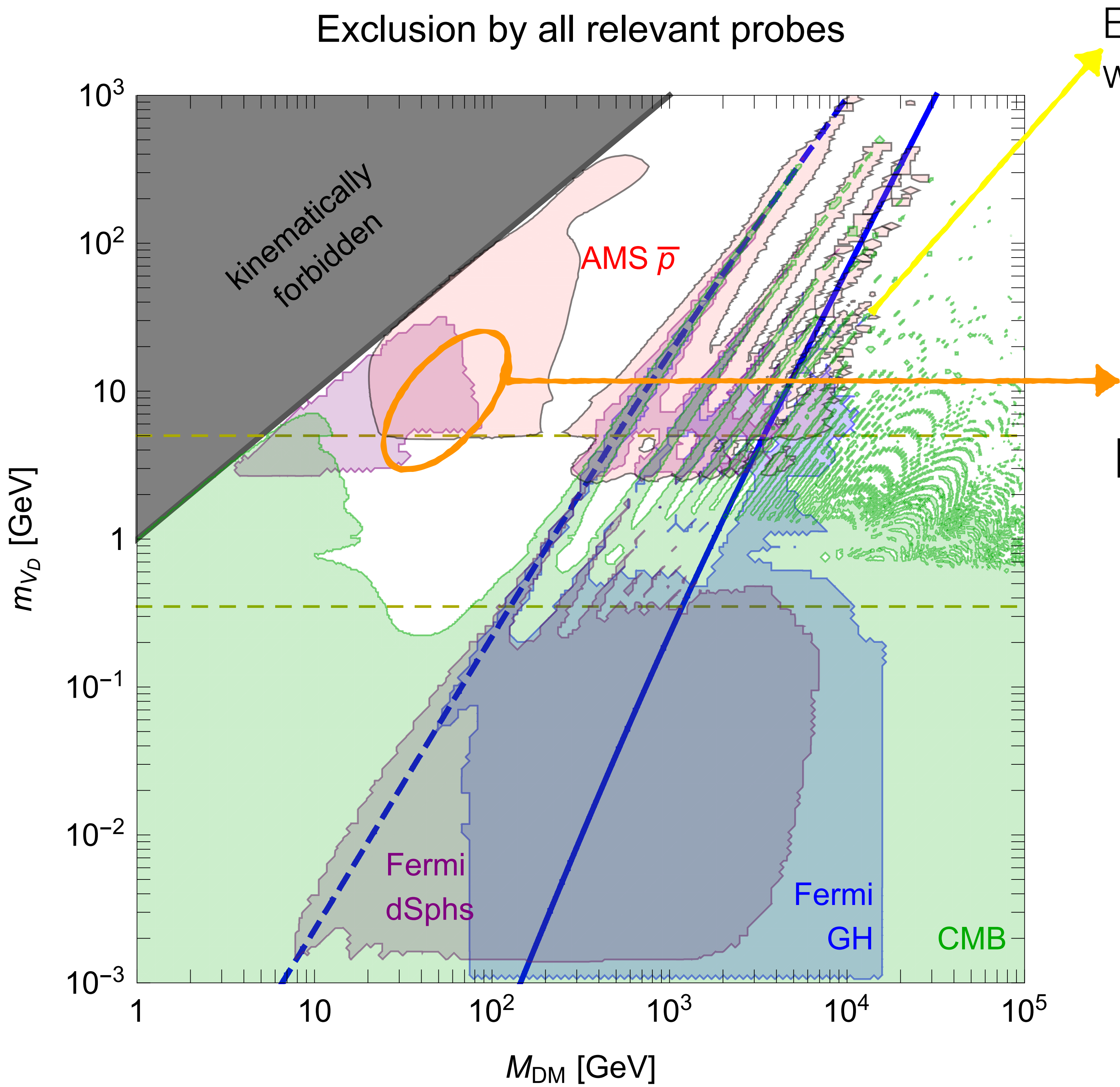
$\text{Lifetime}(V_D) < 0.03$ sec

Values chosen to match the more detailed study Berger+ 1605.07195



Summary of indirect detection

Cirelli Panci Petraki FS Taoso 1612.07295



Explore for the first time a region where Bound State formation is crucial

~ excludes this model as explanation of GC excess

[caveat: large astro uncertainties]

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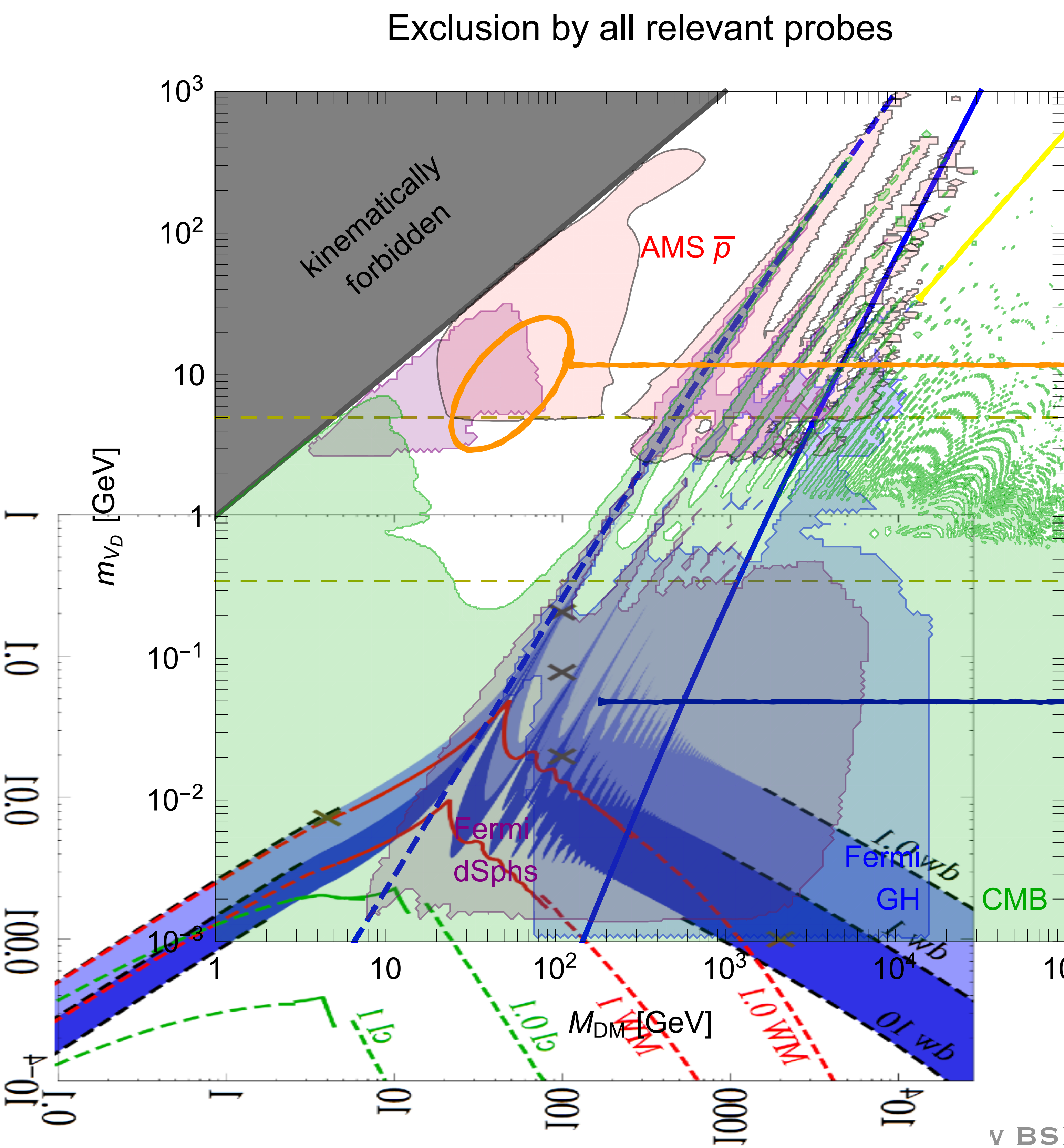

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~ excludes this model as explanation of GC excess

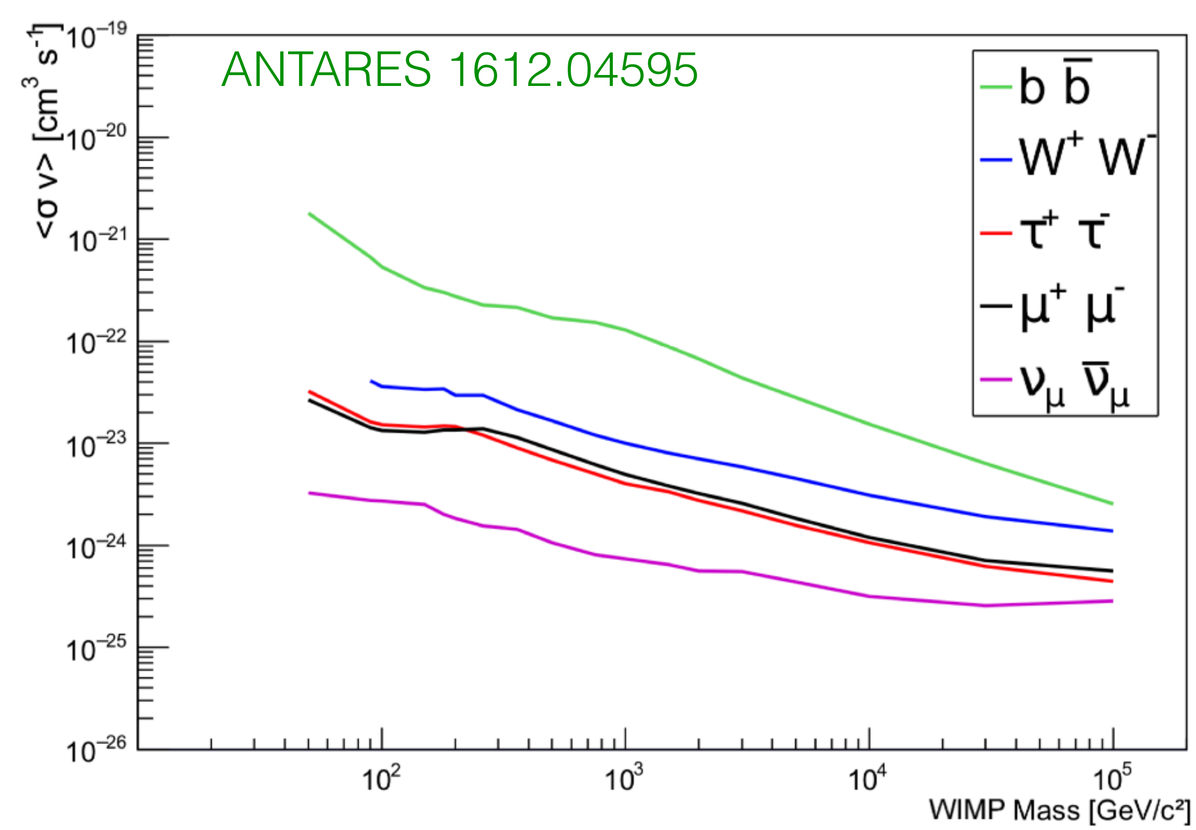
[caveat: large astro uncertainties]

Excludes this DM model as explanation of “anomalies”

[or: CMB prevents signals of this DM in structures]

see also Bringmann+1612.00845

Estimate of ANTARES capabilities



Limits for annihilation $\mathrm{DM}\,\overline{\mathrm{DM}} \to \mathrm{SM}\,\overline{\mathrm{SM}}$

But we need $\mathrm{DM}\,\overline{\mathrm{DM}} \to V\,V \to 2\mathrm{SM}\,2\overline{\mathrm{SM}}$

I do not find a way to reinterpret their search

from the way they give limits on neutrino fluxes

thanks a lot Christoph Toennis for useful discussions!

How to still get a rough idea

1. ANTARES limits are driven by **higher energy** ν's

Educated guess from the fact limits are

1.1 stronger for $\nu\bar{\nu},\ \mu\bar{\mu},\ \tau\bar{\tau}$
which have ν spectra peaked
at higher energies than $b\bar{b},\ W^+W^-$

1.2 very similar for $\mu\bar{\mu},\ \tau\bar{\tau}$
whose ν spectra are very different
at low energies, similar at higher ones

1.3 stronger at larger M_{DM}

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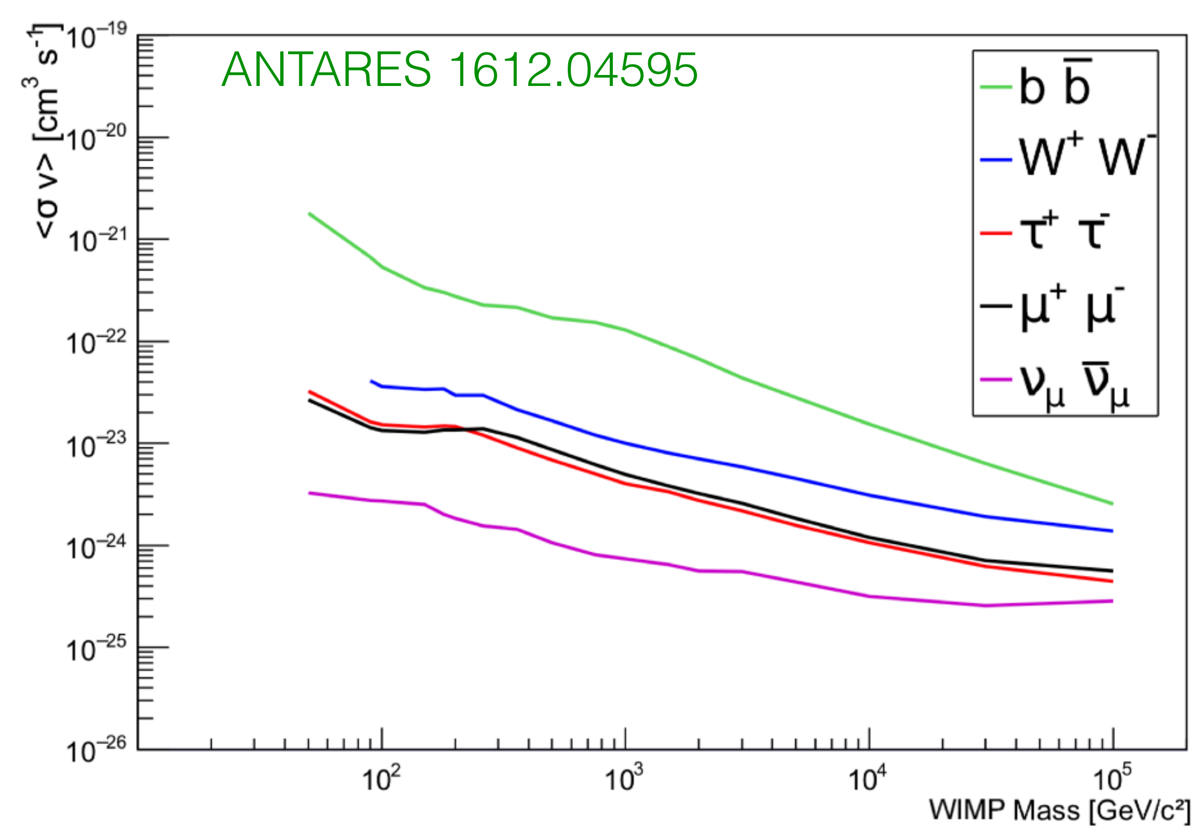

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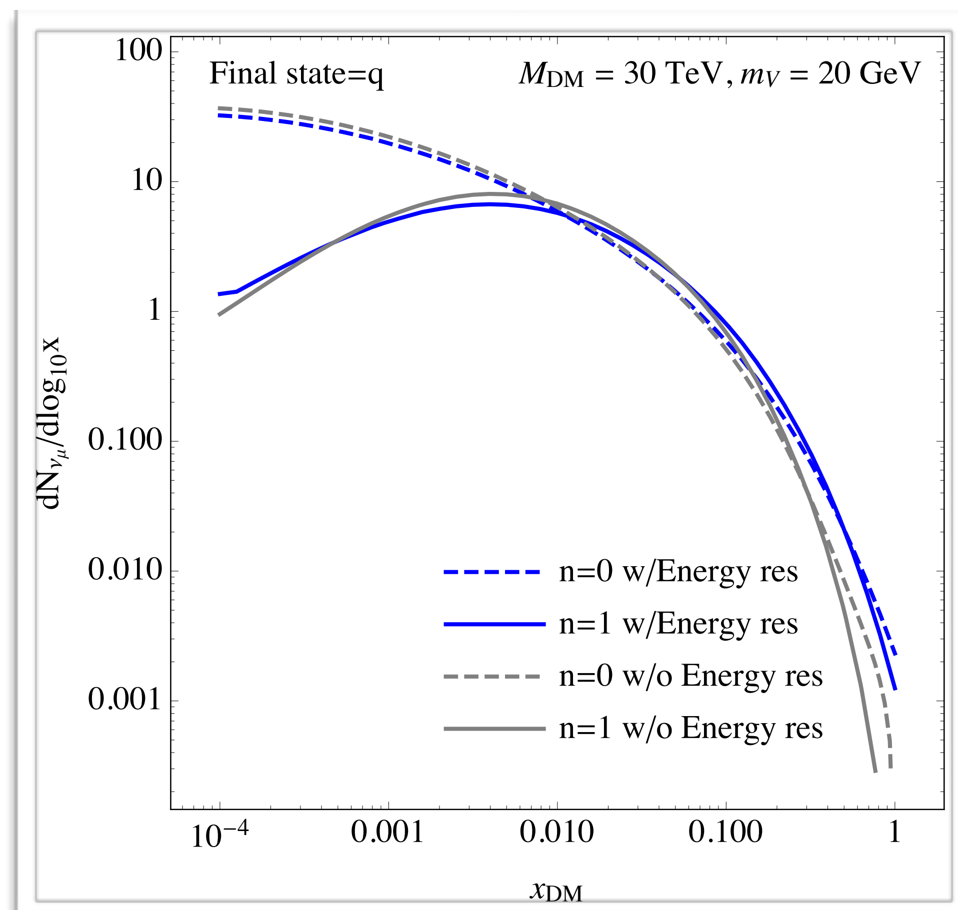

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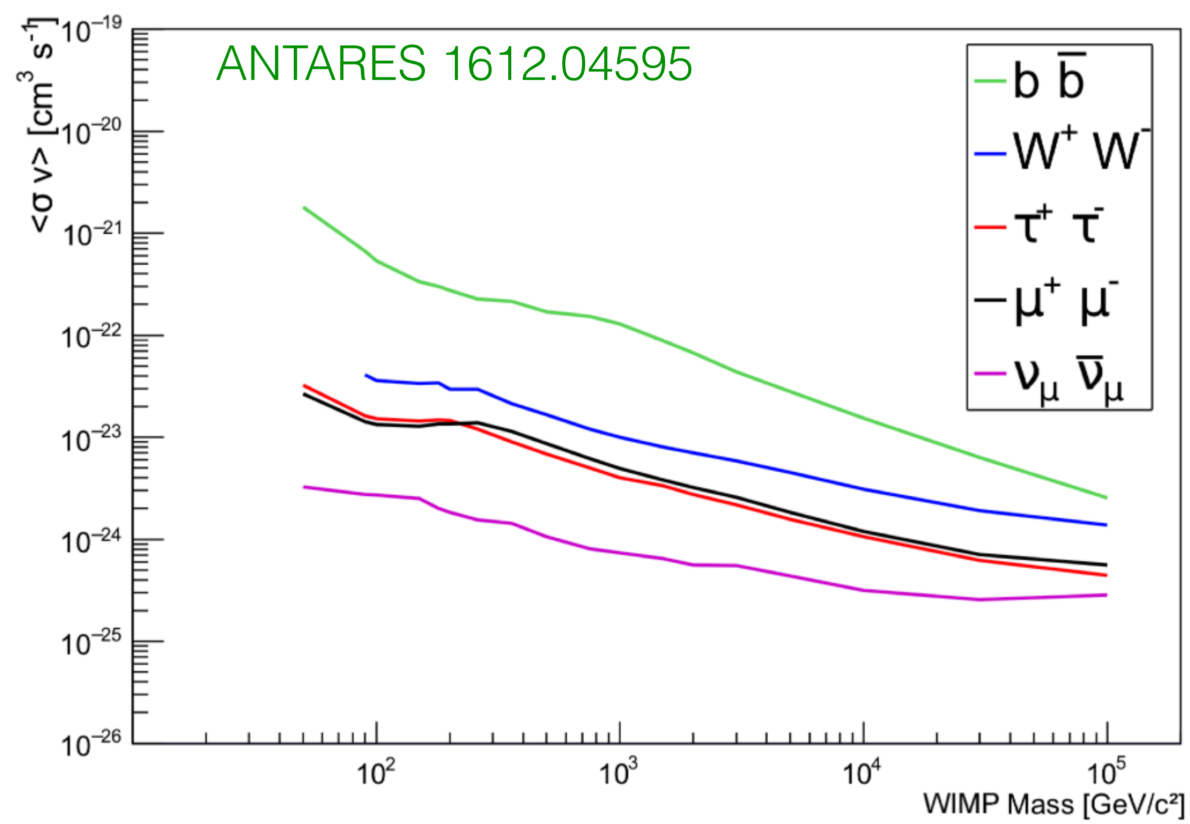

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$\Rightarrow$ Apply ANTARES 0-step limit to q, ν final states