Dark Matter from Dark Sectors
Phenomenology and Challenges

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DESY Hamburg

Università di Firenze 14 Feb 2018

Beyond the SM: which future?

stop

gluino

fermionic top partner

deviations from SM flavour

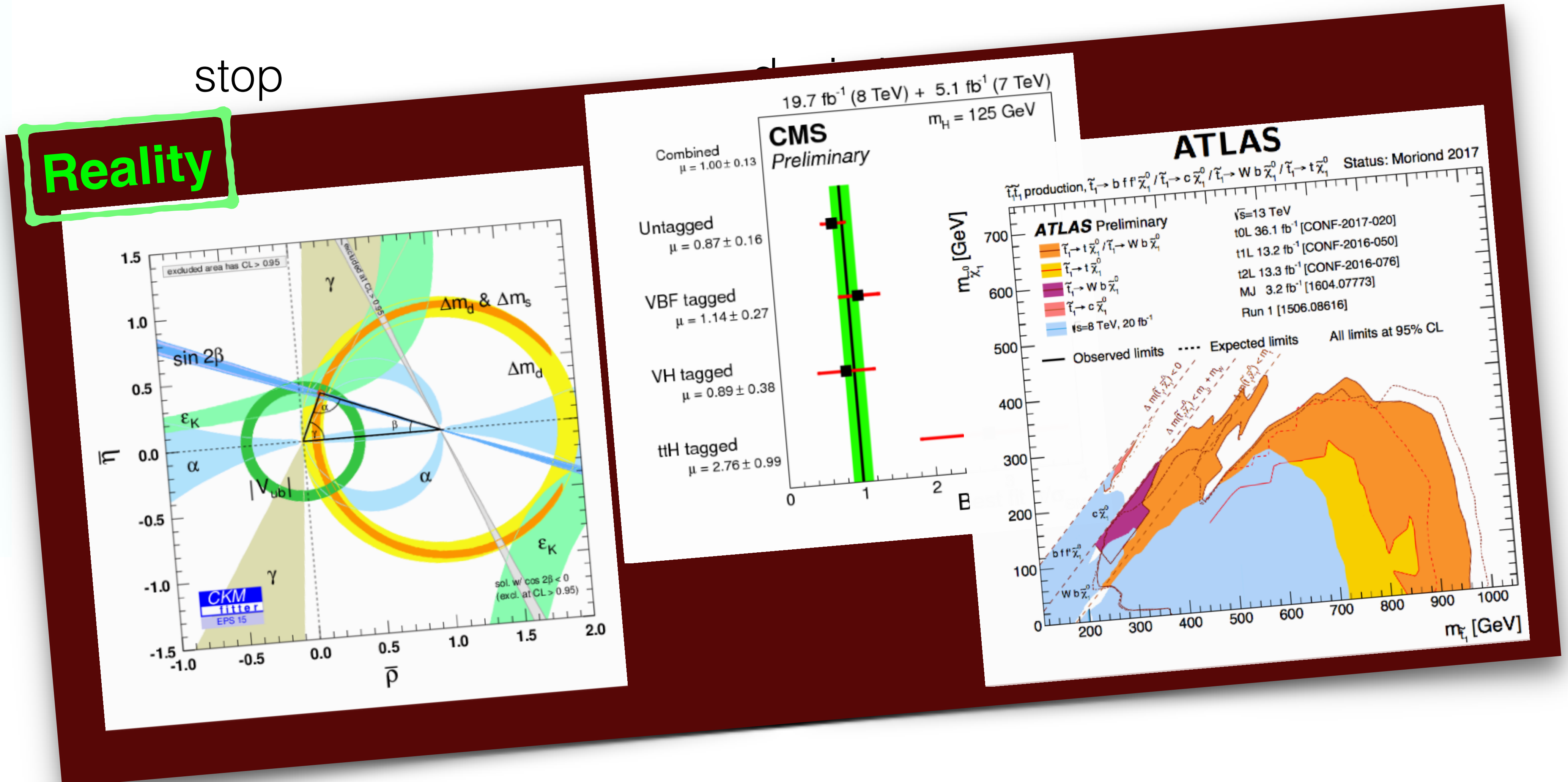
deviations in Higgs couplings

in Z-pole observables

.....

Beyond the SM: which future?

stop



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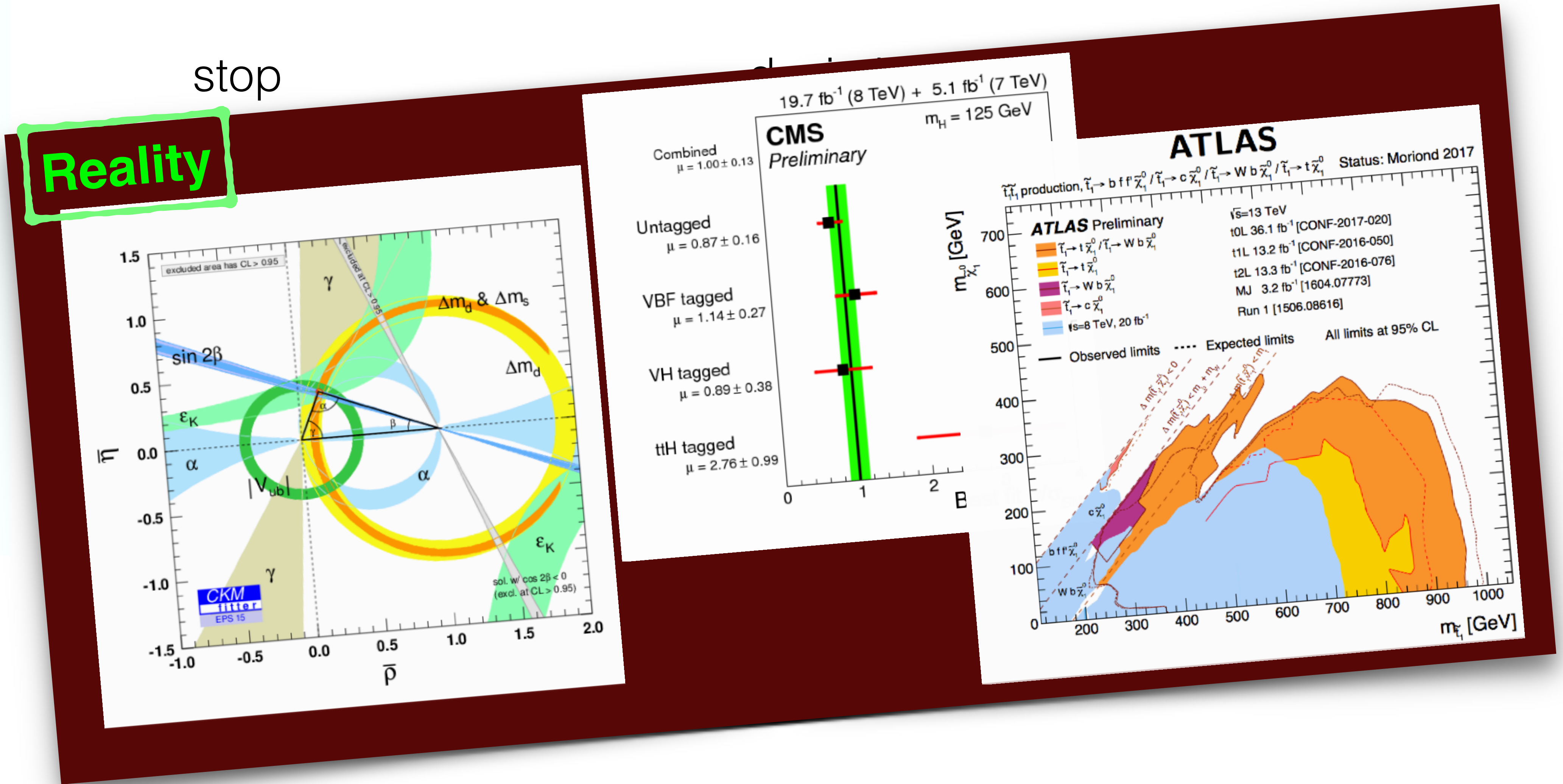

IMO above expectations still hold…but:

Reality strongly motivates to pursue alternative inspirations

This talk: **pheno-driven** motivations for Dark Matter models

Non-Minimal Dark Sectors

Dark Matter widely believed to be a new particle

A legitimate attitude:

Our sector (SM) is very involved, why should the dark sector be so simple?

Example

New force in the dark sector New dark gauge boson(s), that can be light

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Various **Extensions of the SM** predict new (necessarily "dark") vector bosons

Twin Higgs/mirror world Chacko+ hep-ph/0506256

Gauging $U(1)_{B-L}$, $U(1)_{L_\mu - L_\tau}$ Langacker 1981 He+1991,…

Gauging flavour (sub)group Froggatt Nielsen 1978,…. Grinstein+ 1009.2049

……….

Dark sectors with scalar mediators also motivated (e.g. SUSY-breaking sector…)

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Dark sectors with scalar mediators also motivated (e.g. SUSY-breaking sector…)

On top of those, plenty of other **pheno motivations** (see next slides)

DM Signals beyond 10 TeV

DM Signals in Structures?

Dark Sectors & self interactions

DM Signals beyond 10 TeV

Motivations for DM beyond 10-100 TeV

…Pheno

Origin of **IceCube PeV neutrinos**? ~ only studies of heavy DM so far

Bhattacharya+ 1706.05746,….

Theory…

Motivations for DM beyond 10-100 TeV

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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

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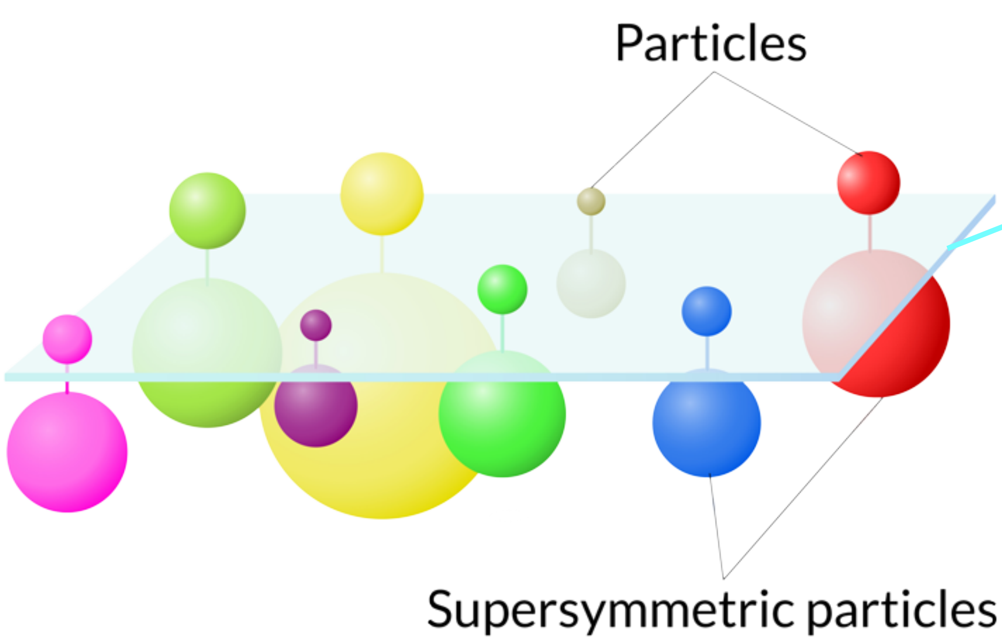
Supersymmetry



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

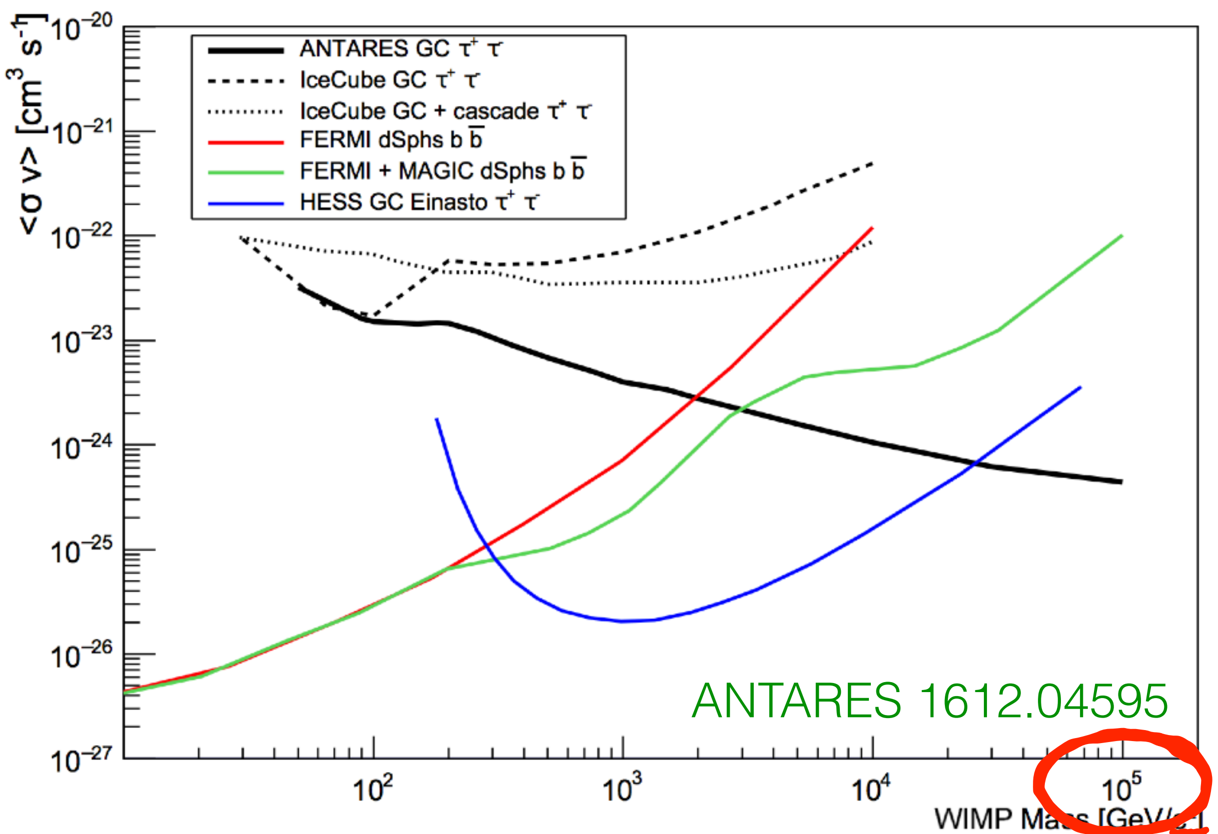
[breaking/mediation sector]

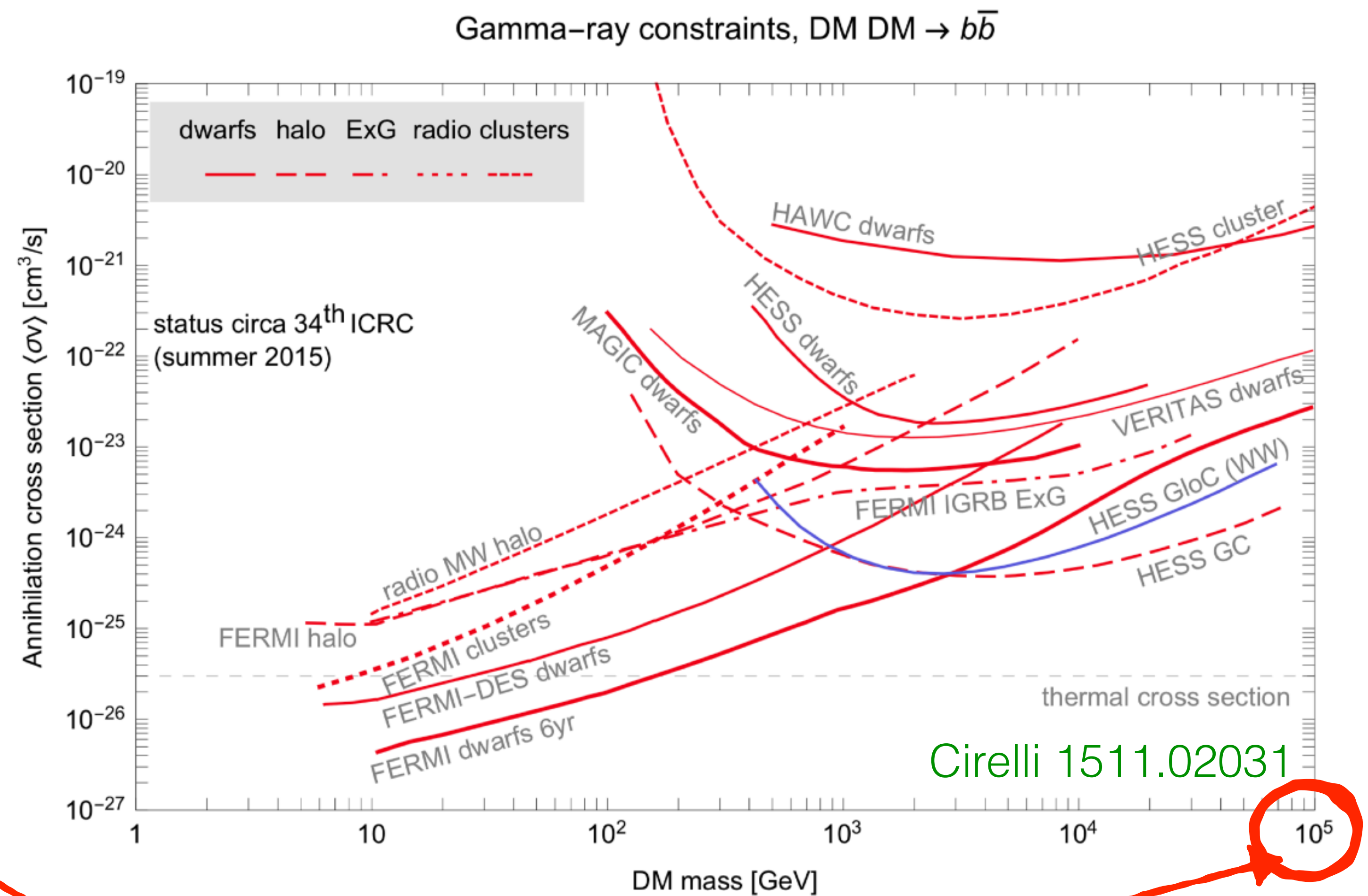
Naturally hosts DM!

Dimopoulos Giudice Pomarol hep-ph/9607225

Theory…

Telescopes have unique opportunity!





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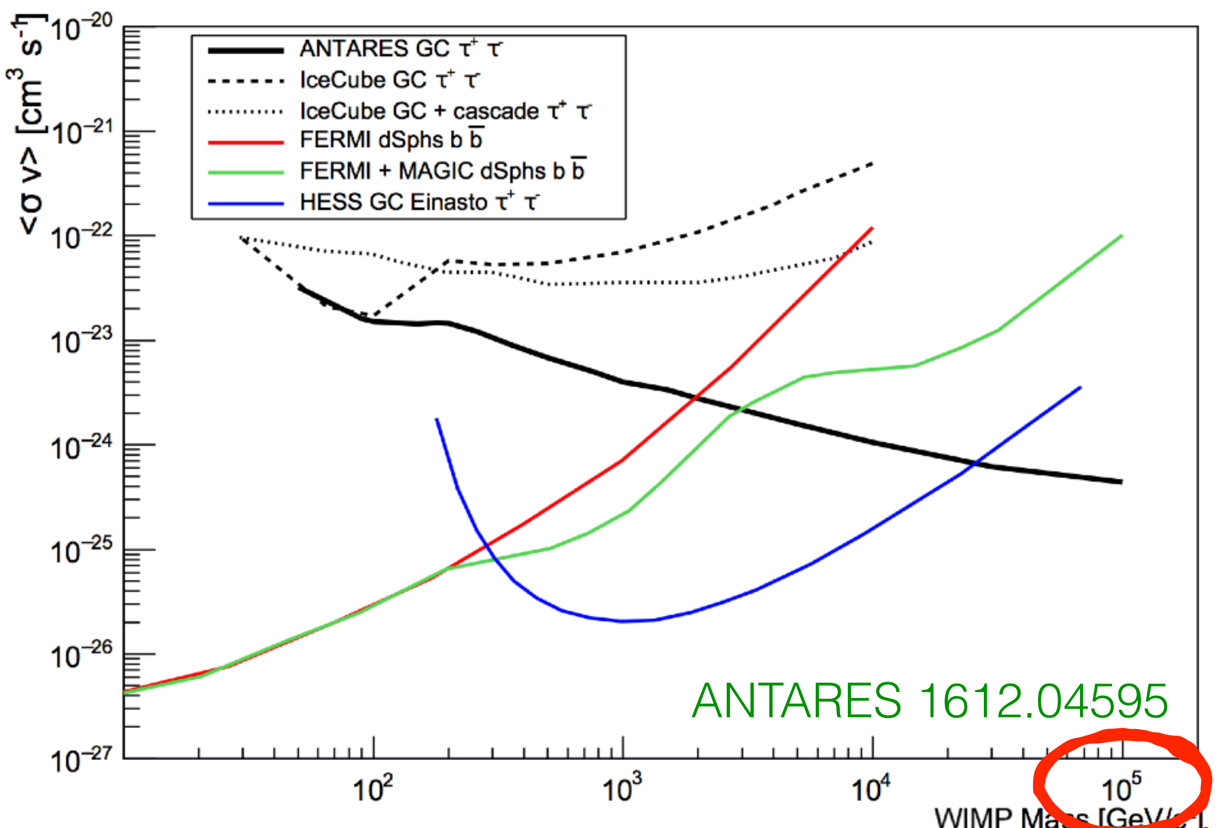
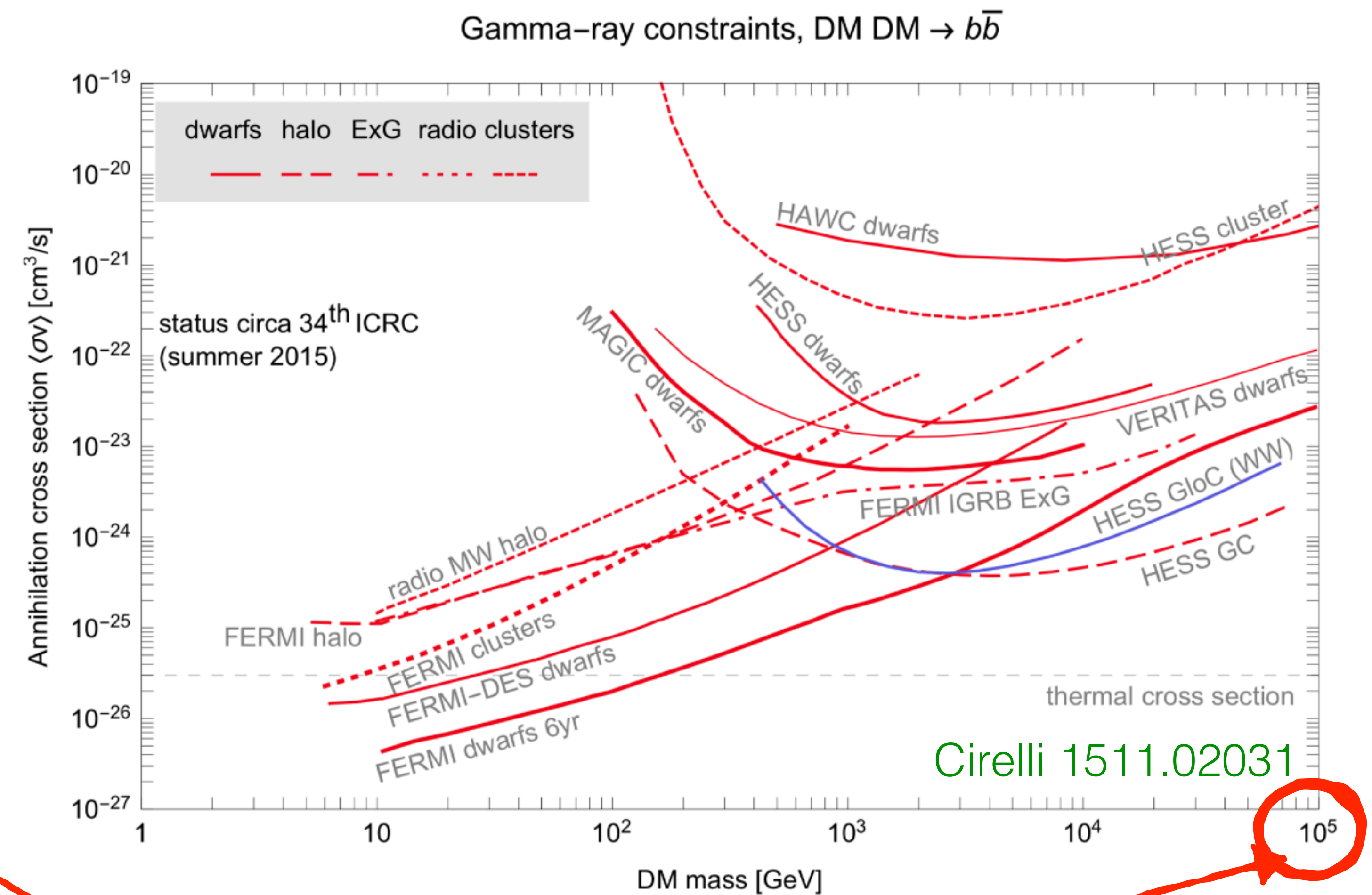




…but do not test DM annihilations beyond 100 TeV

Why not beyond 10-100 TeV?

ElectroWeak radiation should be resummed, ~ like QCD at the LHC

PPPC [Cirelli+ 1012.4515] only 1st order, & stops at 100 TeV

Pythia not entirely reliable, lacks vector splittings

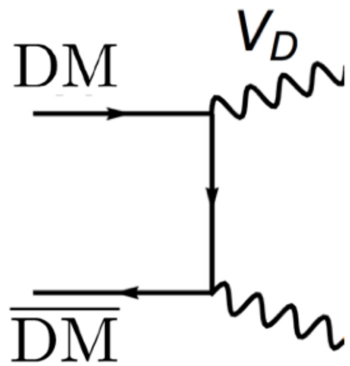
Unitarity bound thermal cross section becomes too large for consistency of QFT

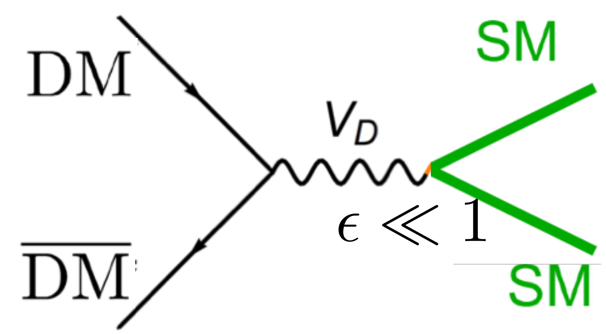
Secluded DM Models address both challenges

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

Thermal production possible with tiny interactions with SM

Pospelov+ 0711.4866,...





~ avoid bounds from direct detection & LHC

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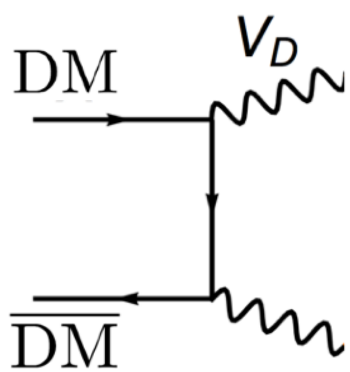
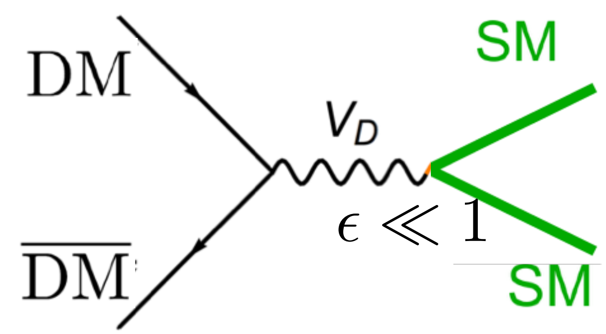




~ avoid bounds from direct detection & LHC

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

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

Mediators can dominate the energy density of the Universe

and decay after DM freeze-out, and enough before BBN $\Rightarrow$ Can **evade the unitarity bound**

Berlin Hooper Krnjac 1602.08490

Cirelli Panci Petraki FS Taoso 1612.07295

Entropy injection in the SM bath **dilutes** the DM abundance

A prototype: Dark U(1) Dark Matter

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

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

Free parameters α_D $M_{\rm DM}$ m_V ϵ

Cosmology For small enough ϵ the dark sector evolves independently of the SM

$T_{\rm SM} = T_D \equiv T_{\rm eq}$ Assume Dark sector in equilibrium with SM at high temperatures

$T_D = T_{\rm SM}\left(\frac{g_{\rm SM}/g_{\rm SM}^{\rm eq}}{g_D/g_D^{\rm eq}}\right)^{\frac{1}{3}}$ then evolution set by separate entropy conservation

Constraints: Dark photons decay well before **BBN**, low DM annihilations at **CMB**, …

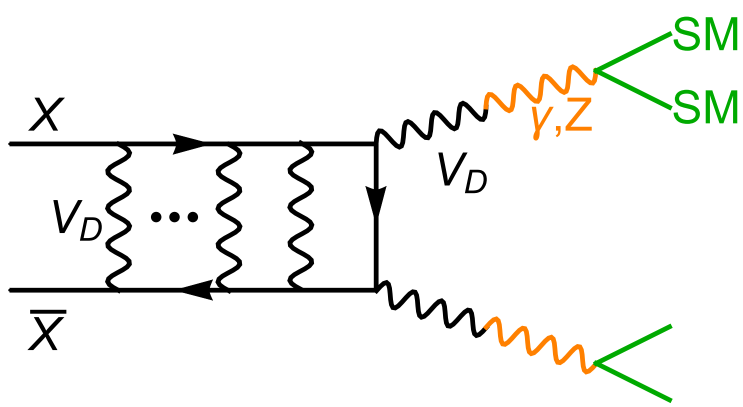
Dark U(1) DM & long-range interactions

~ 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
....



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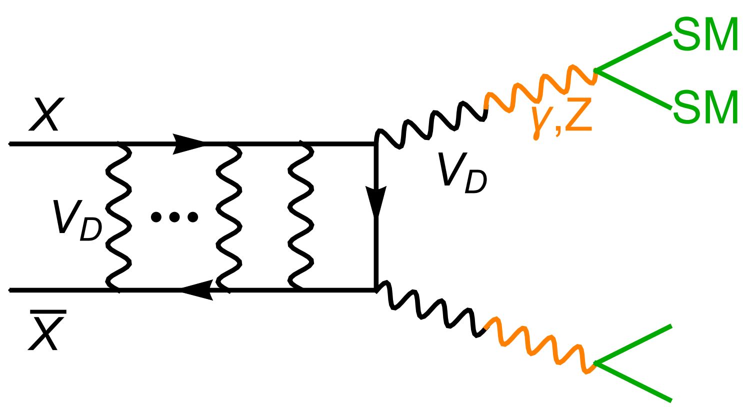

Dark U(1) w/ Sommerfeld explains **cosmic ray anomalies**

Positron fraction (PAMELA etc) Arkani-Hamed+ 0810.0713
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GeV Galactic Center gamma excess Hooper+ 1206.2929
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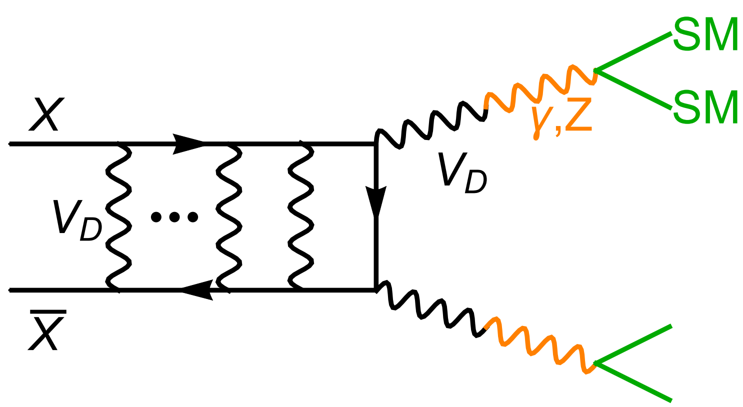

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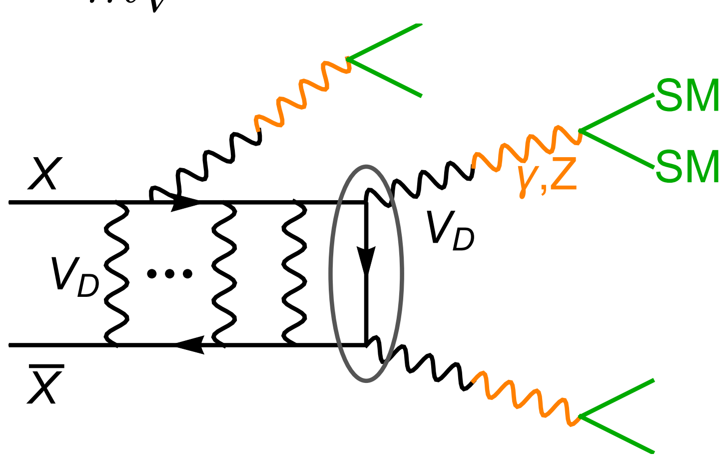
DM **bound states** can form



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

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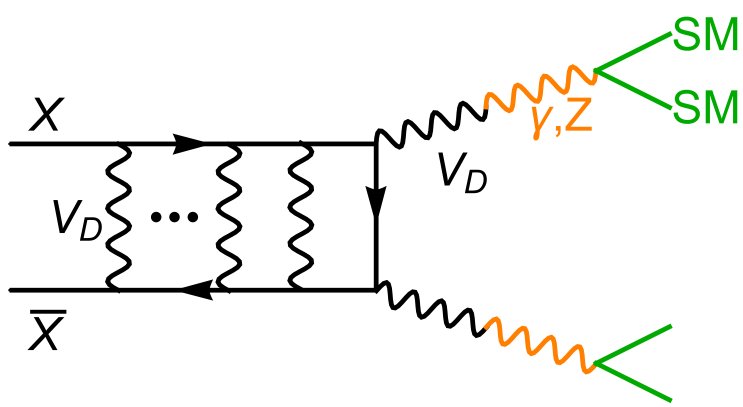

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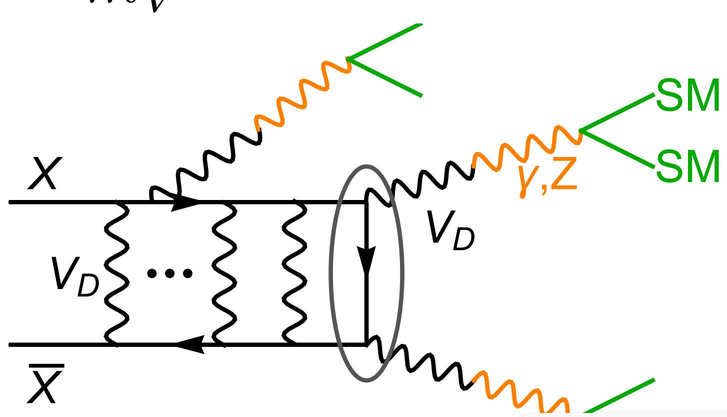

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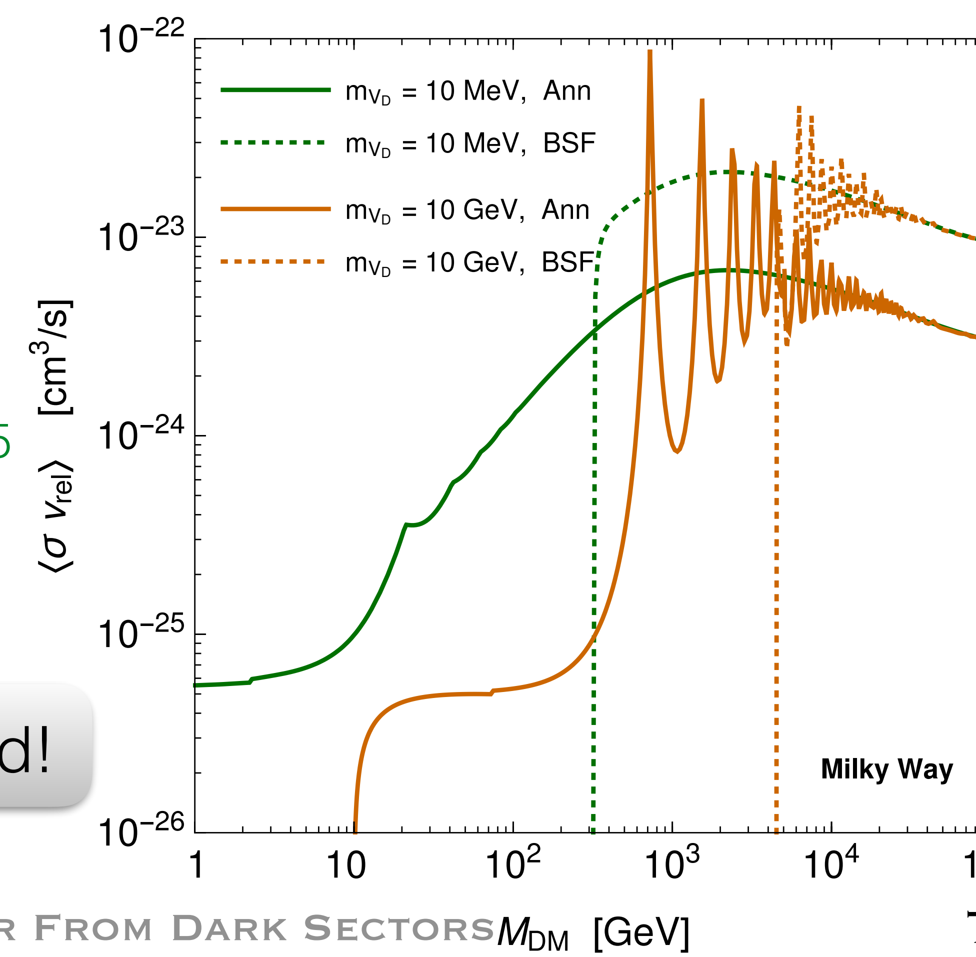
BS can dominate over Sommerfeld!



Petraki+ 1611.01394

Pheno in the ϵ - m_V plane

α_D fixed to reproduce thermal relic abundance

von Harling Petraki 1407.7874 + minor refinement

3 free parameters

$M_{\rm DM}$ m_V ϵ

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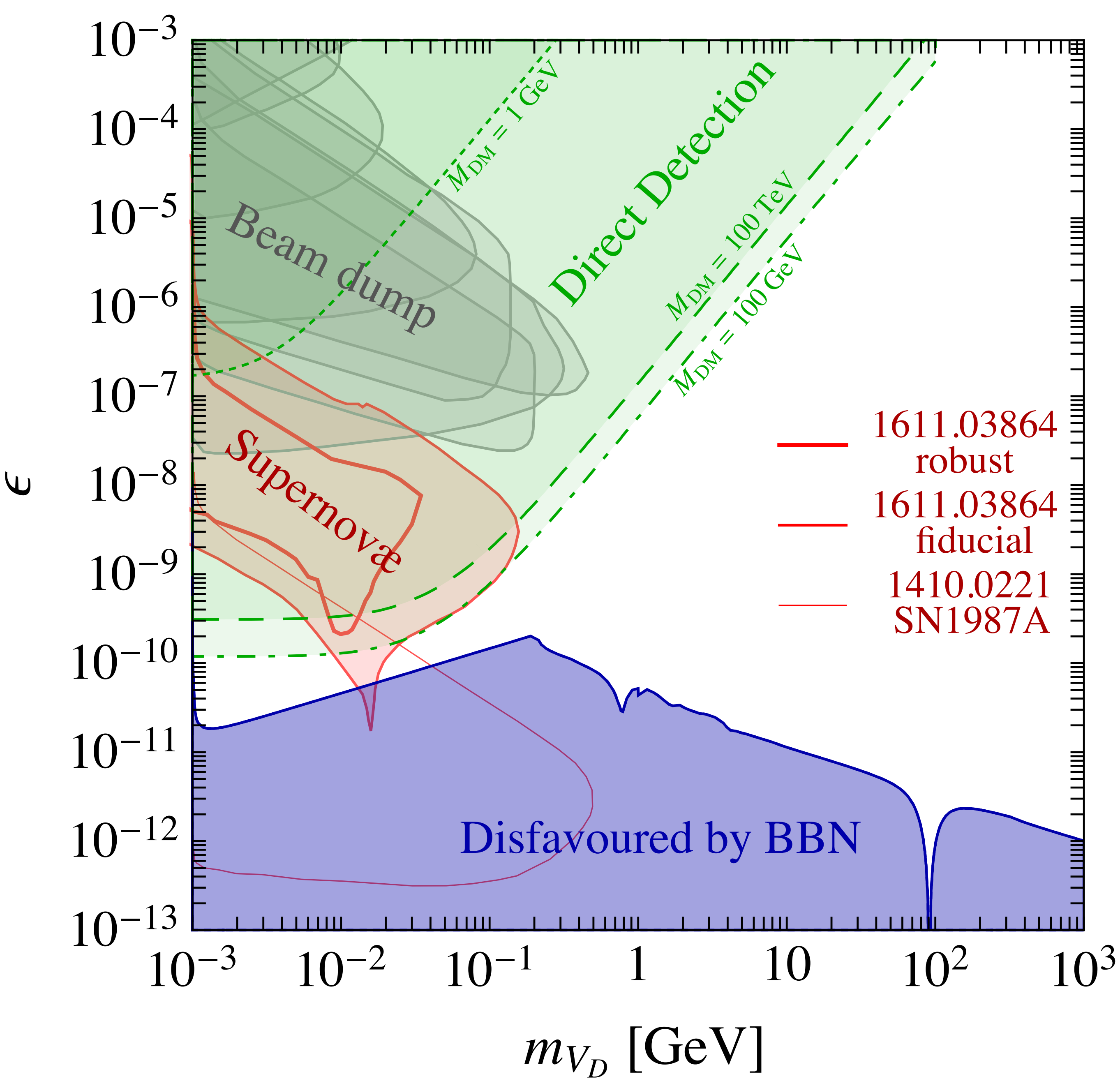
$M_{\mathrm{DM}} \quad m_V \quad \epsilon$



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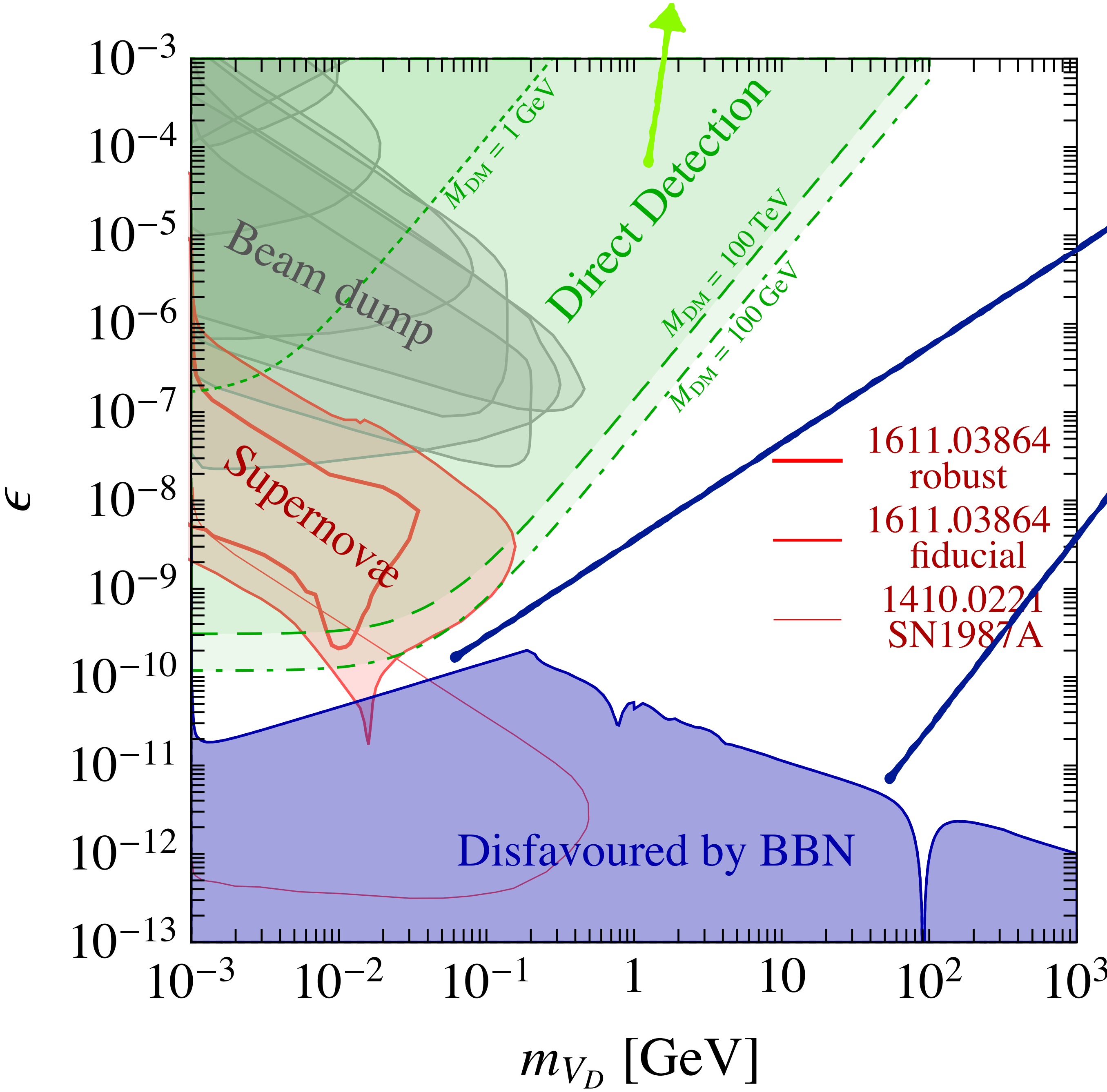
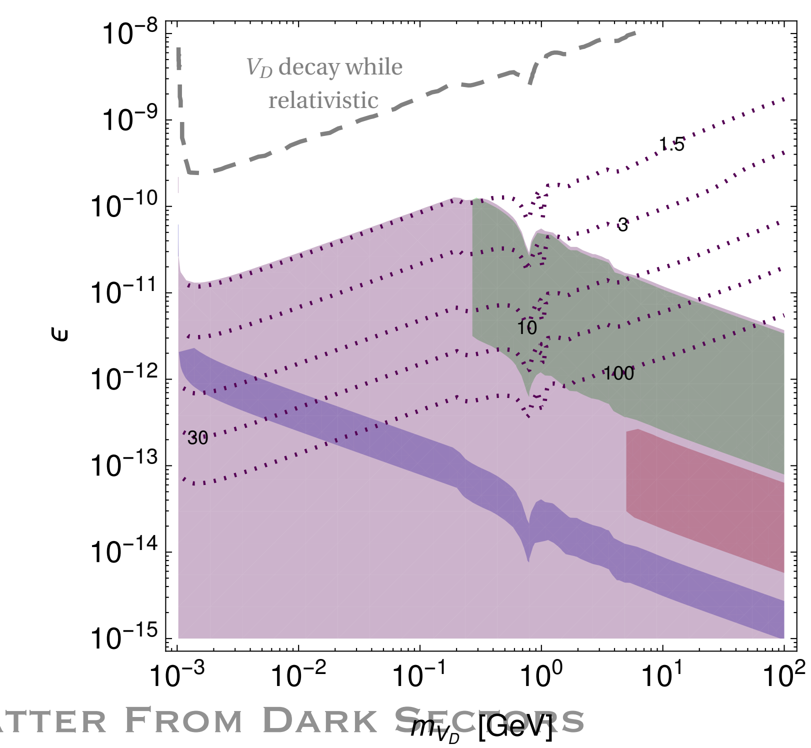
Only constraint that would vanish w/o Dark Matter



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

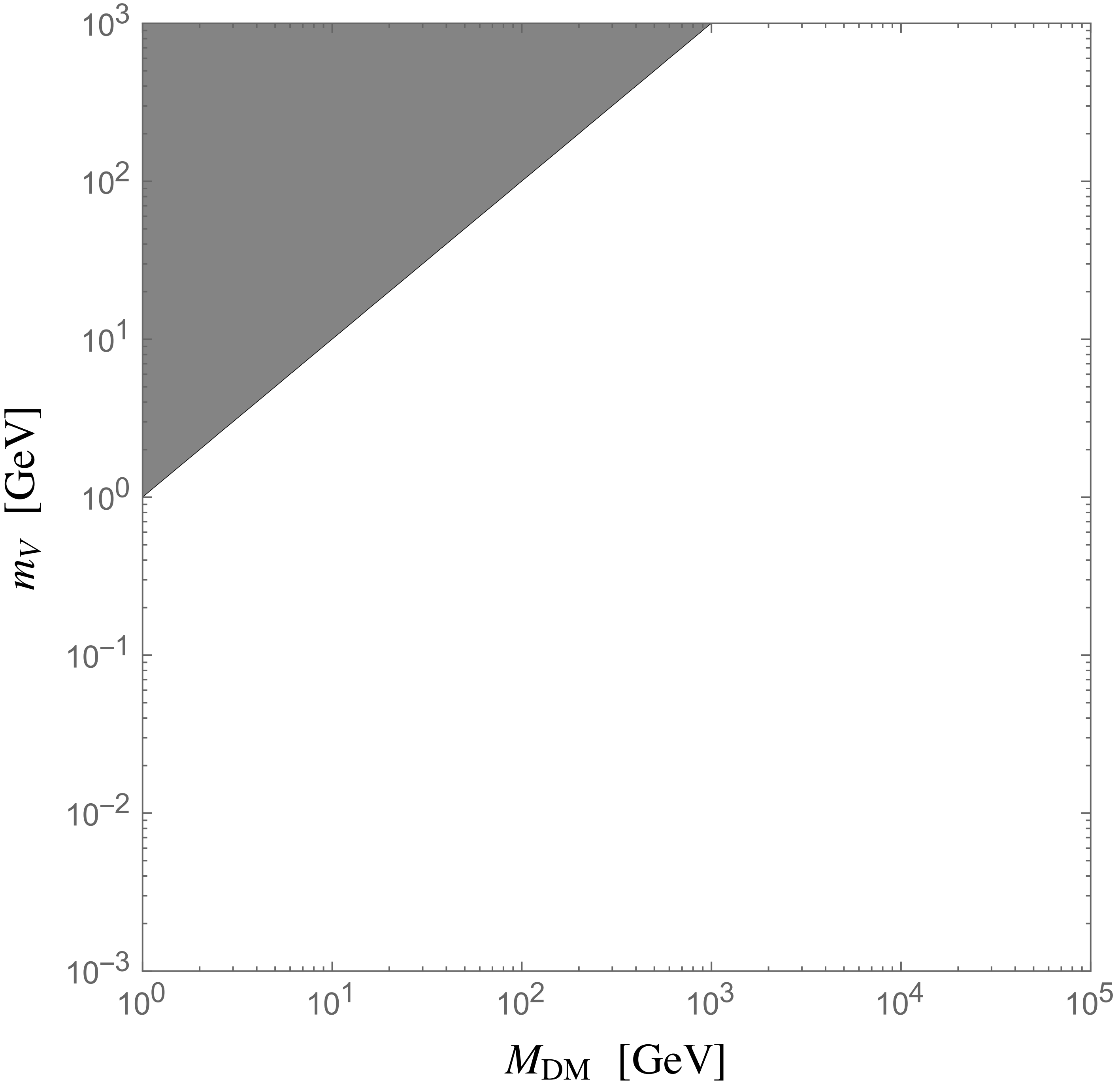
$\text{Lifetime}(V_D) < 0.03$ sec

Values chosen to match the more detailed study Berger+ 1605.07195



Pheno in the $M_{\rm DM}$ - m_V plane

Take home: ~ for any $M_{\rm DM}$ - m_V point $\exists$ ϵ that is allowed



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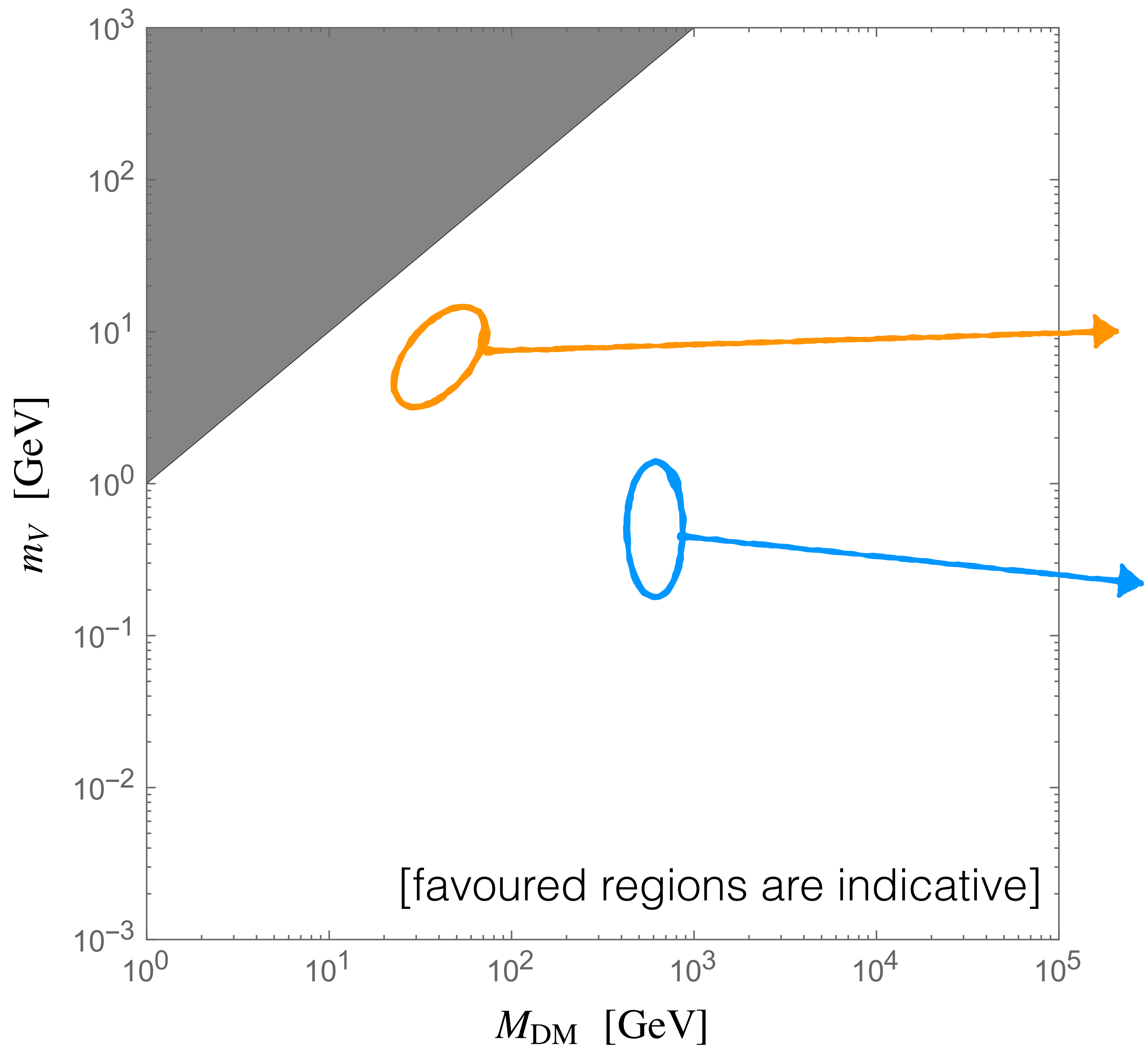
If you believe any cosmic-ray anomaly



GeV Galactic Center gamma excess

Hooper+ 1206.2929, ….

Elor Rodd Slatyer 1503.01773

Positron fraction (PAMELA etc)

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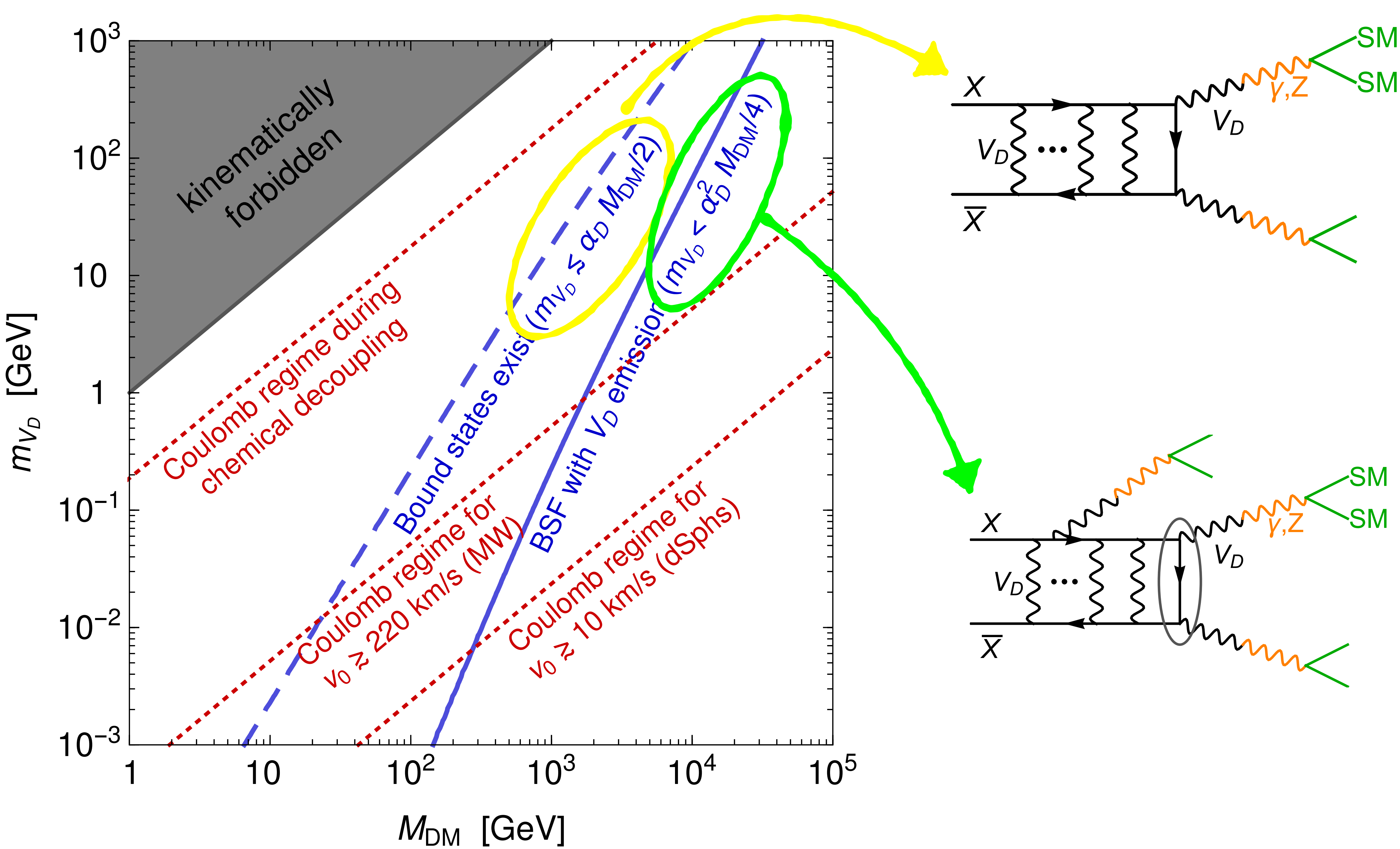
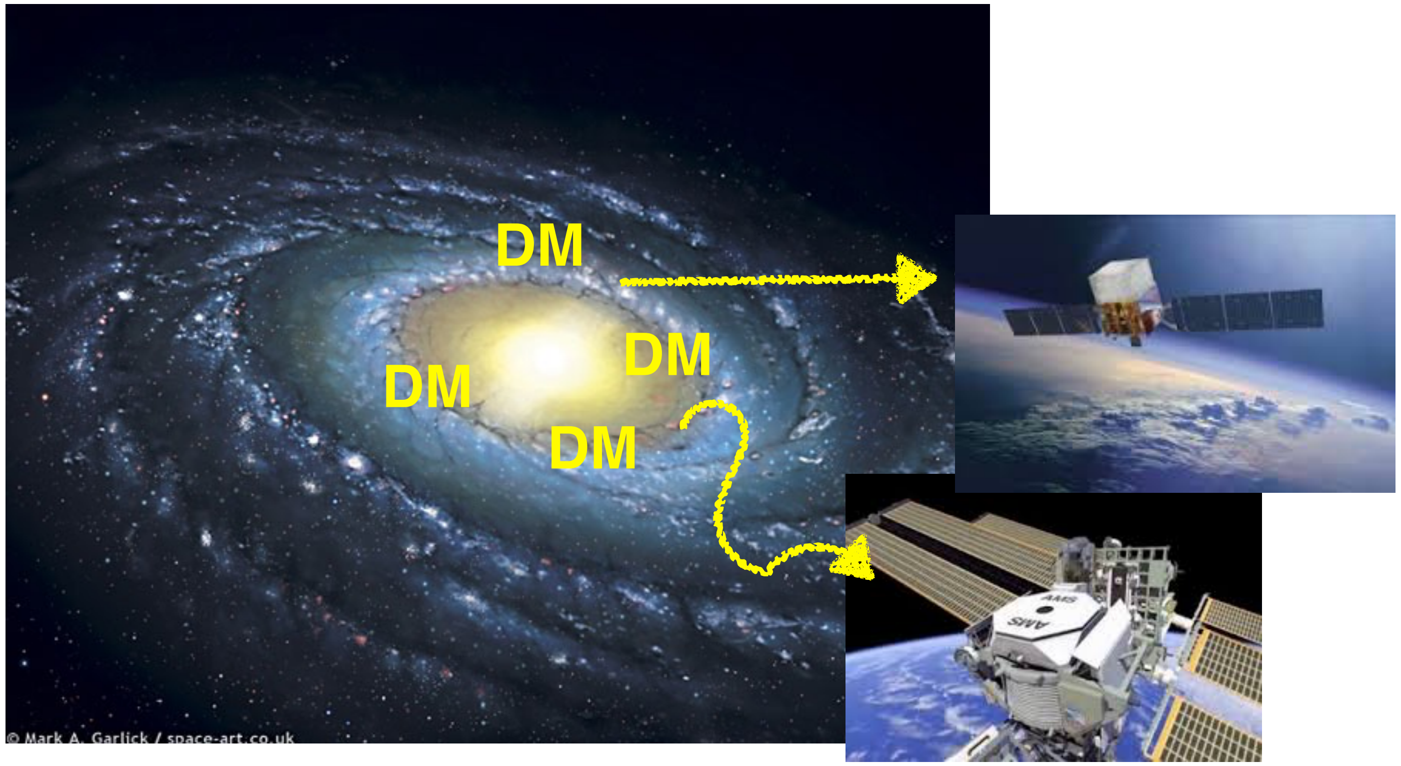
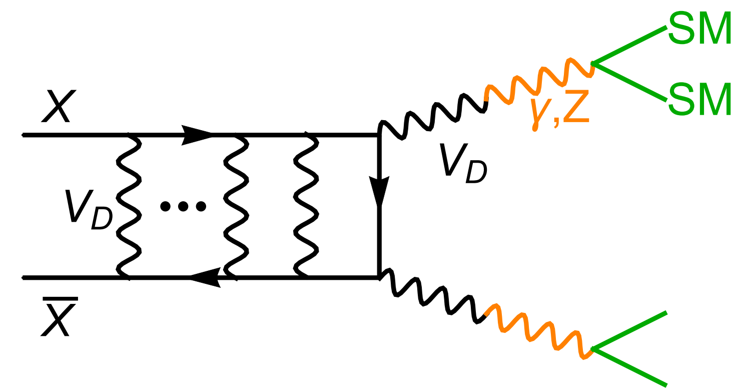
Pheno in the $M_{\rm DM}$ - m_V plane

What matters where:



Indirect detection: ingredients





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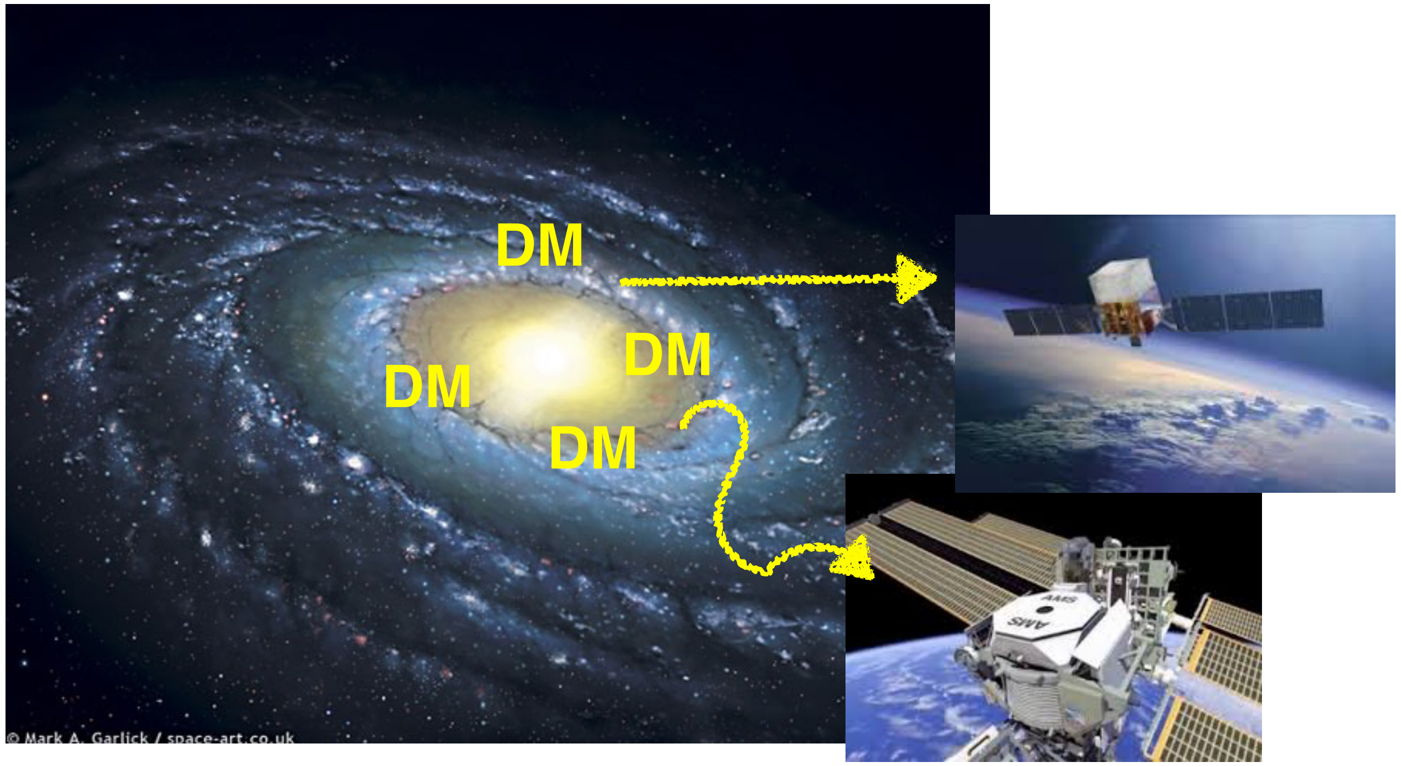

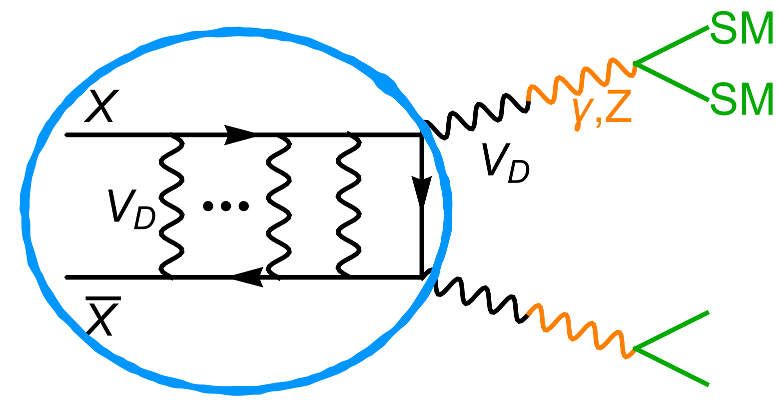

1. Sommerfeld and BS formation Petraki+ 1611.01394

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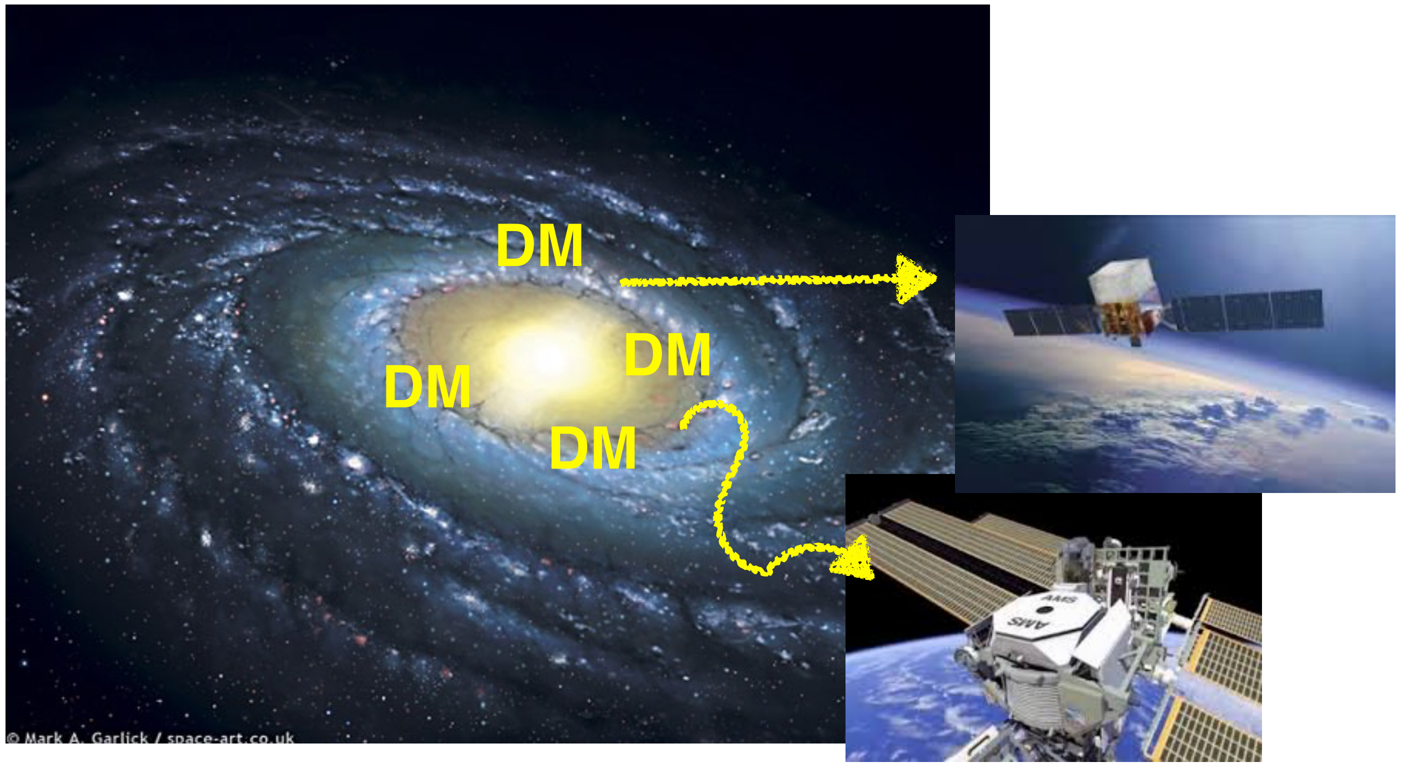

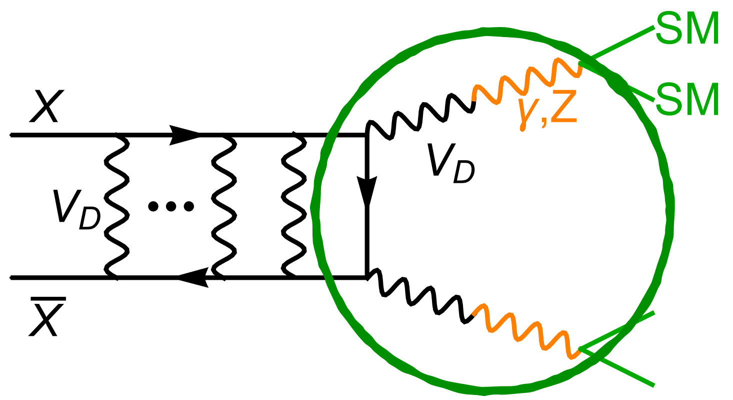

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2. Cascade decays: one step softens the spectra
Elor Rodd Slatyer 1511.08787

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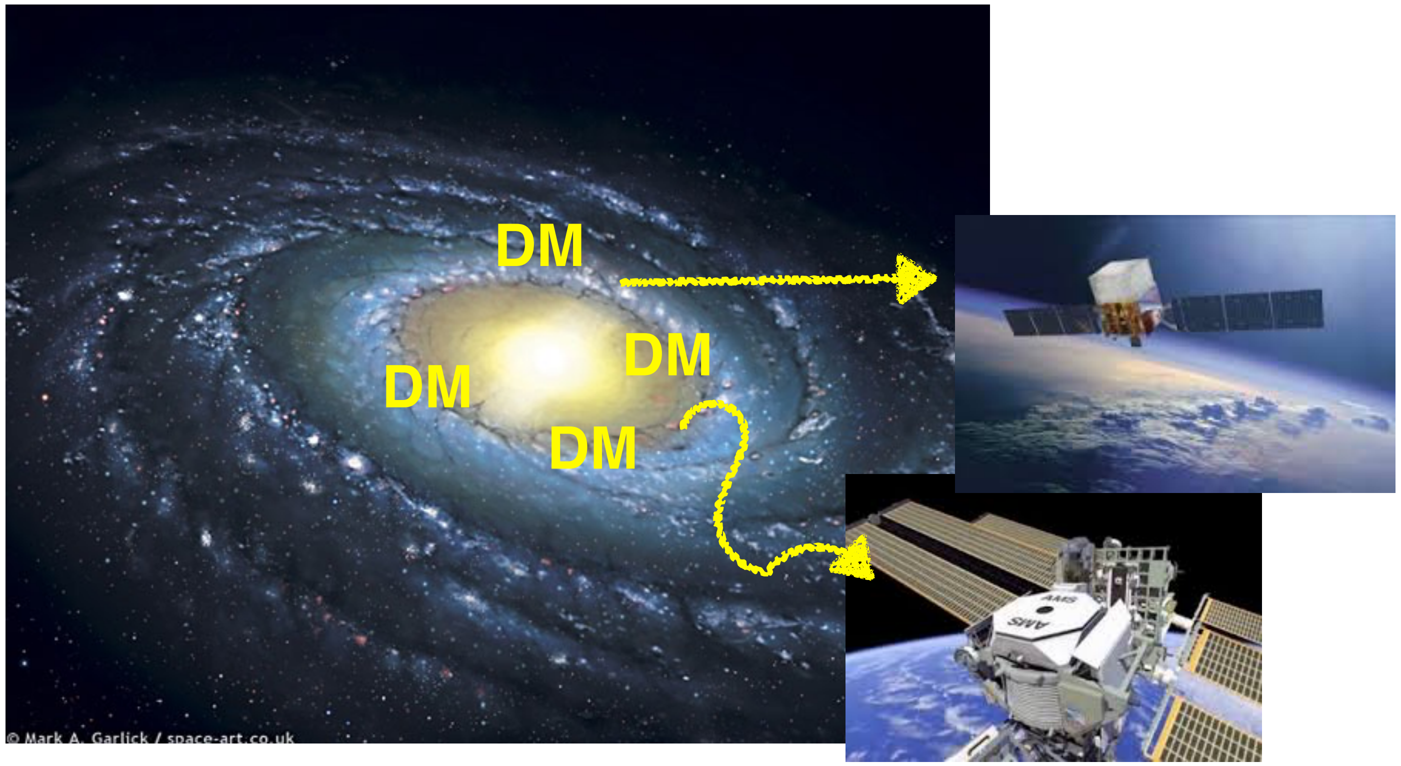

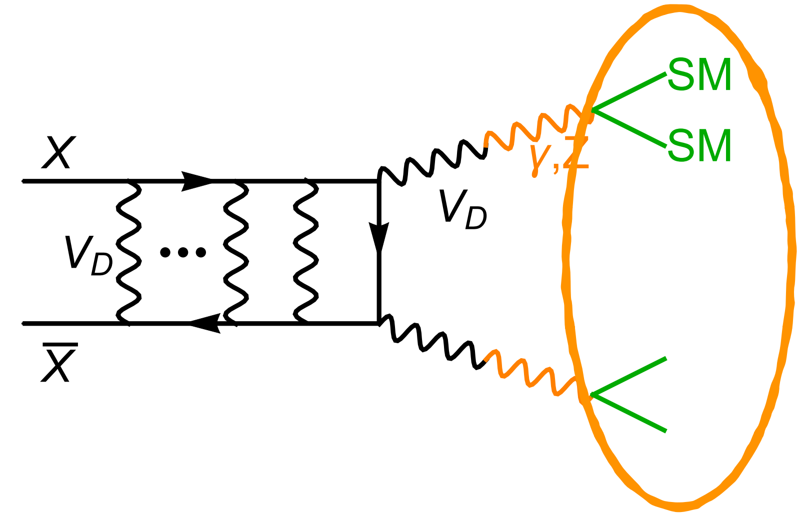

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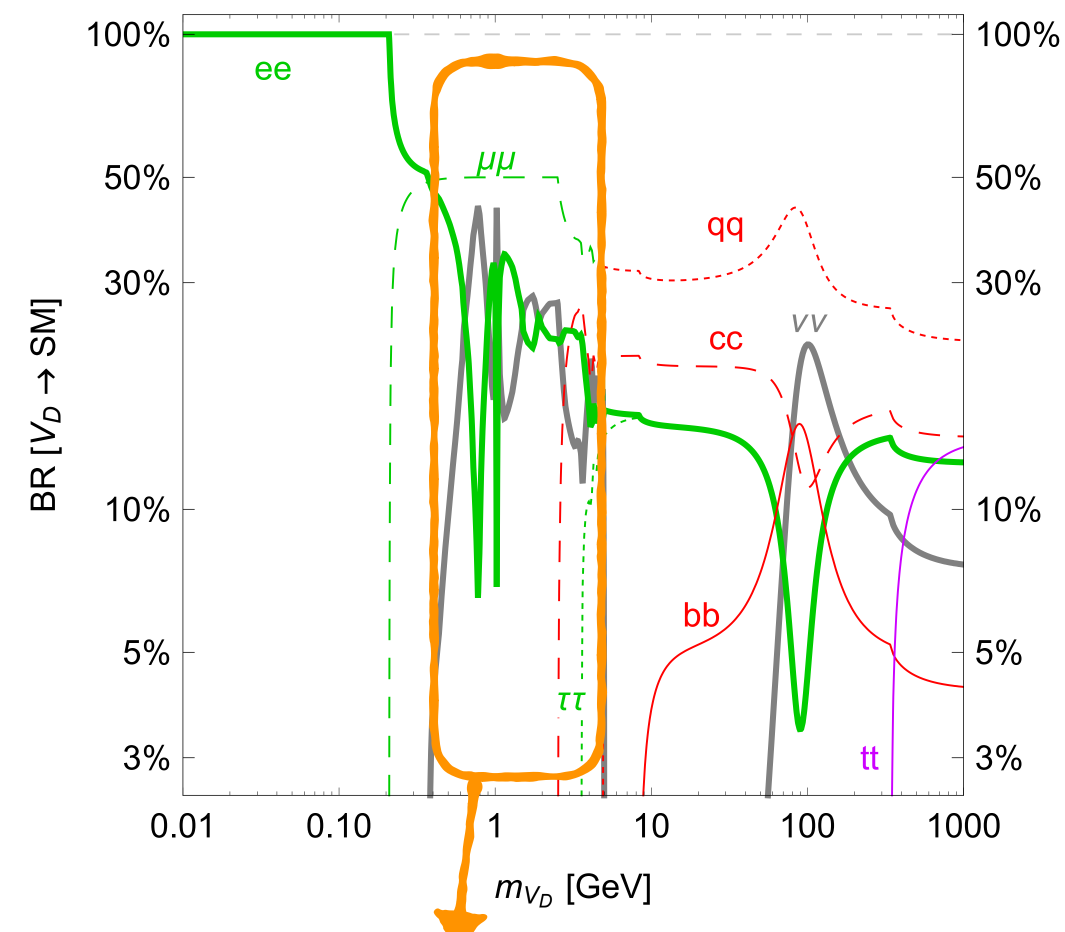
3. Dark Photon decays $\mathcal{L} \supset g_f V_D^\mu (\bar{f}\gamma_\mu f)$

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

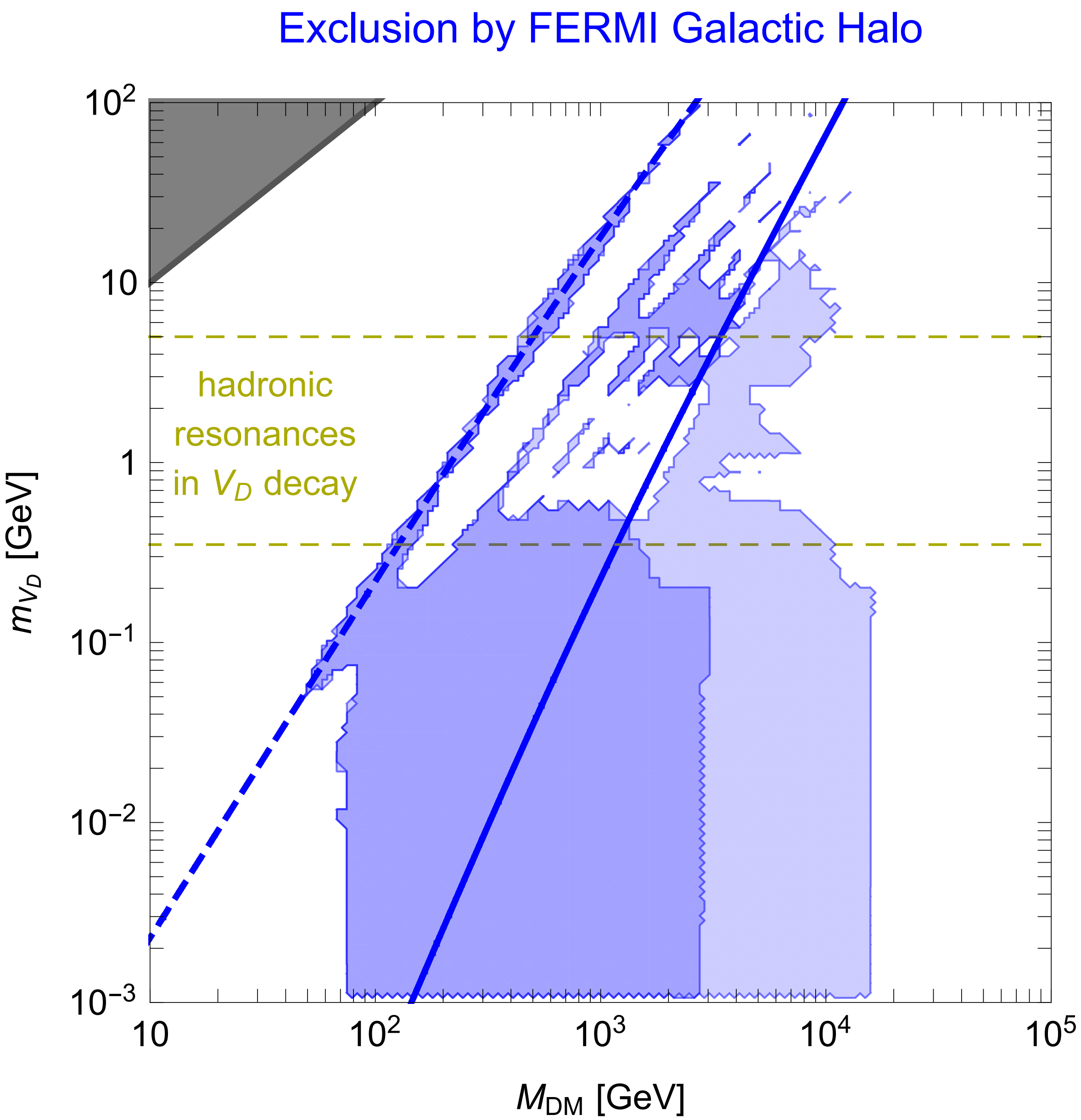
$$\delta = \frac{m_V}{m_Z}$$

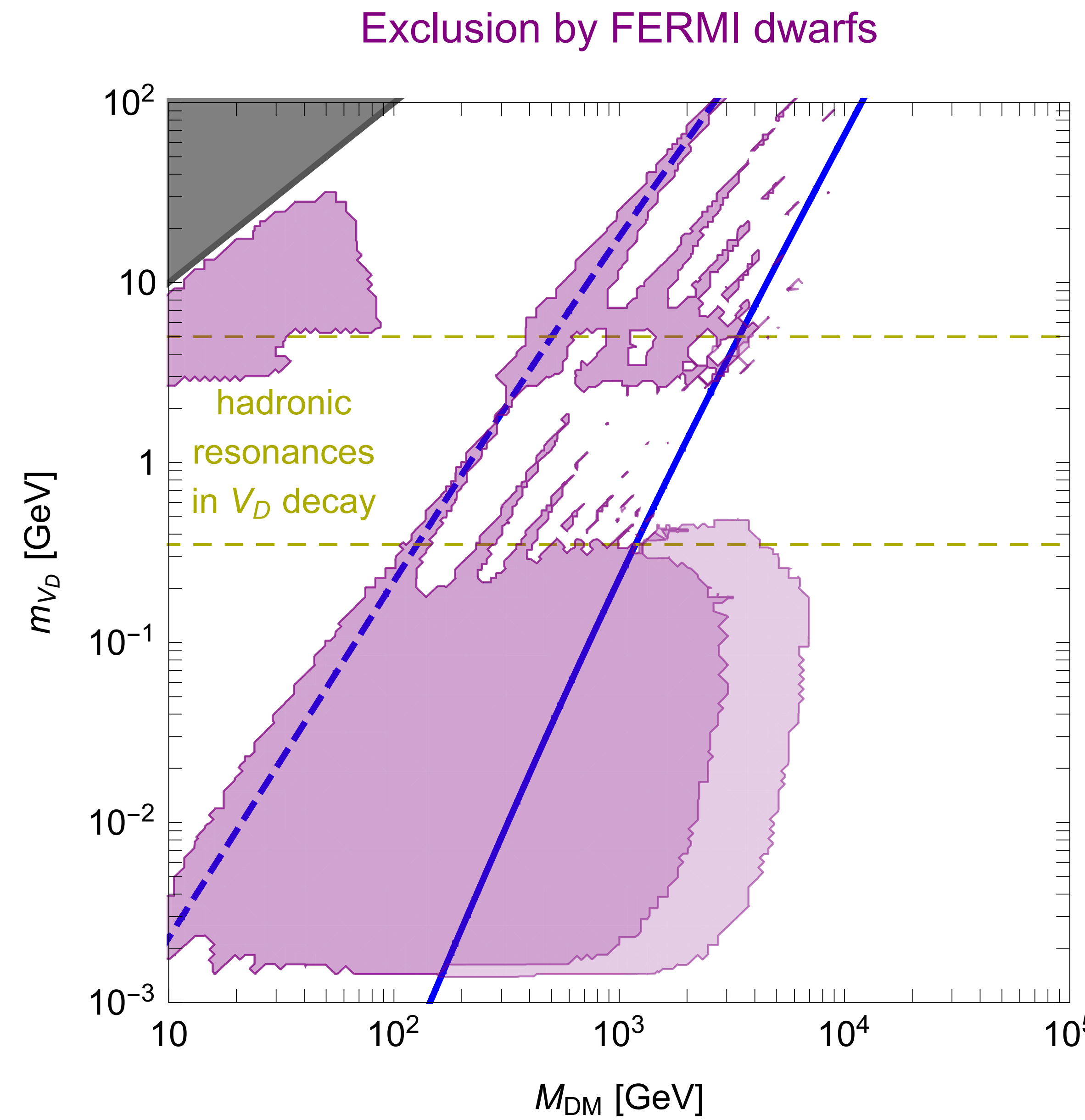


from measurements of $e^+e^- \to$ hadrons

Results: Gamma rays

Dark: w/o BS formation
Light: w/ BS formation





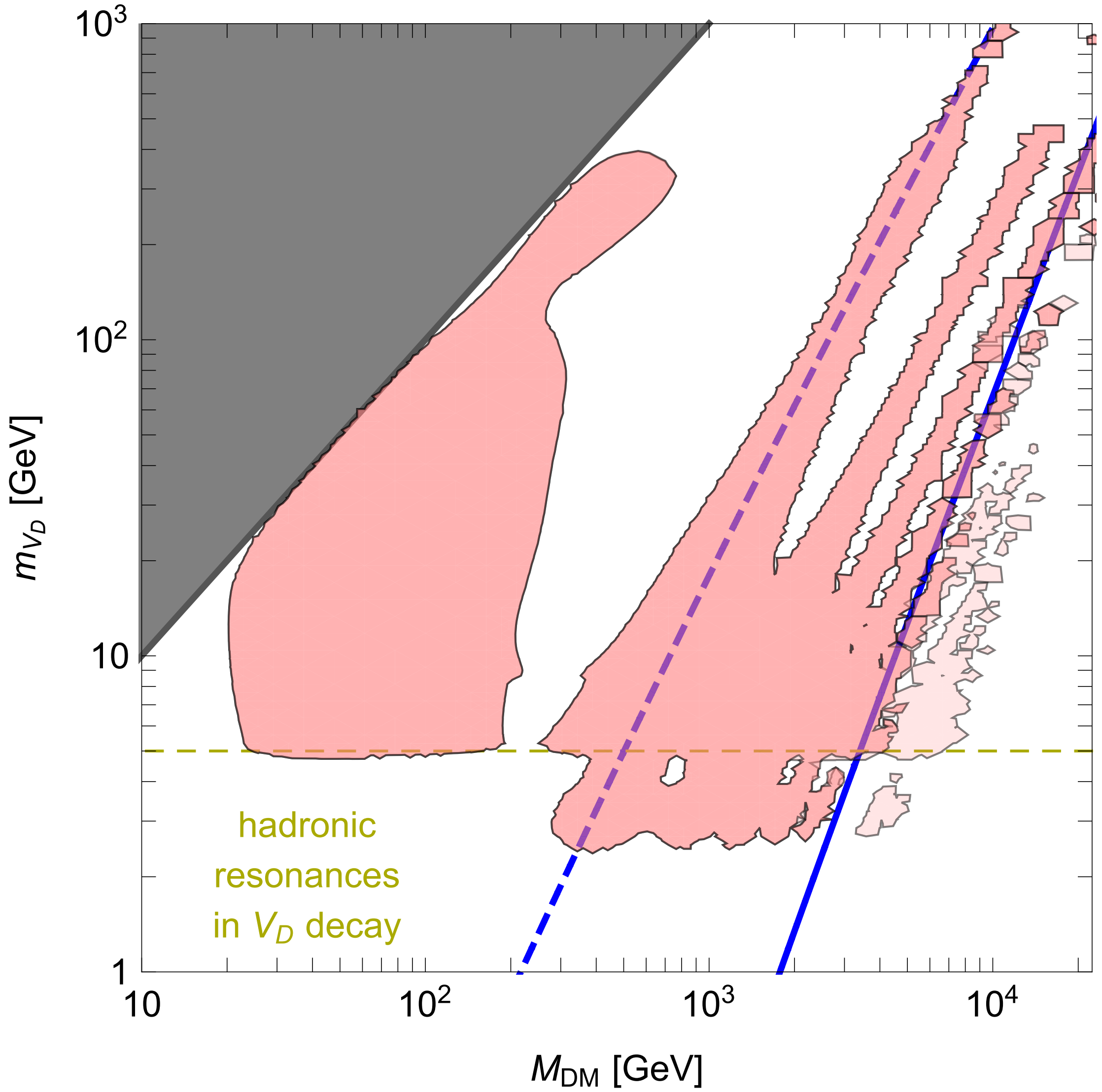
From our analysis Cirelli+ 1507.05519

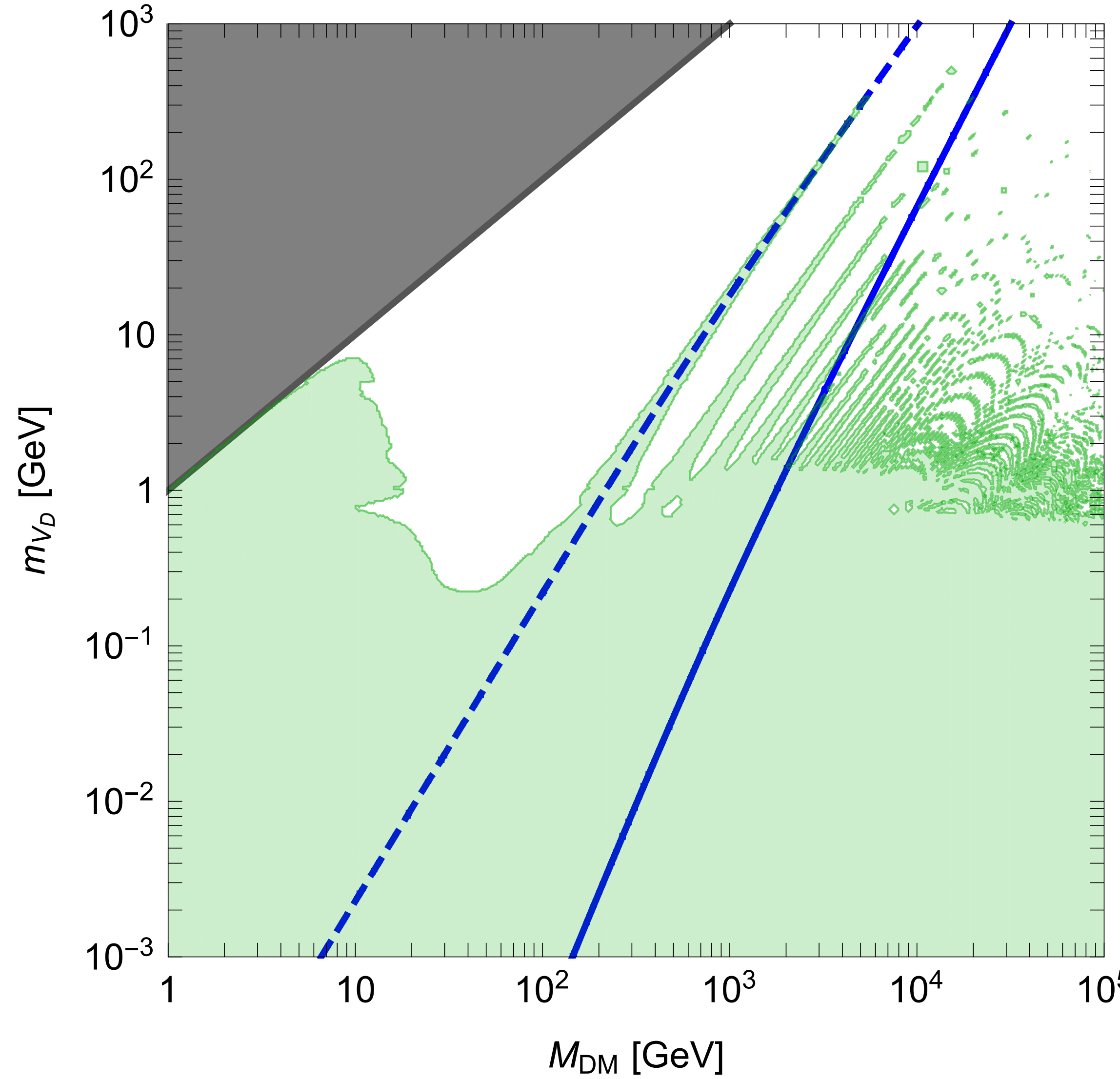
Photons from the "Fermi Strips" [robust vs DM profile]

$$|\ell| < 80^\circ \qquad 5^\circ < |b| < 15^\circ$$

Both data and J-factors from FERMI 1503.02641

Results: Antiprotons and CMB





Data of AMS 2016

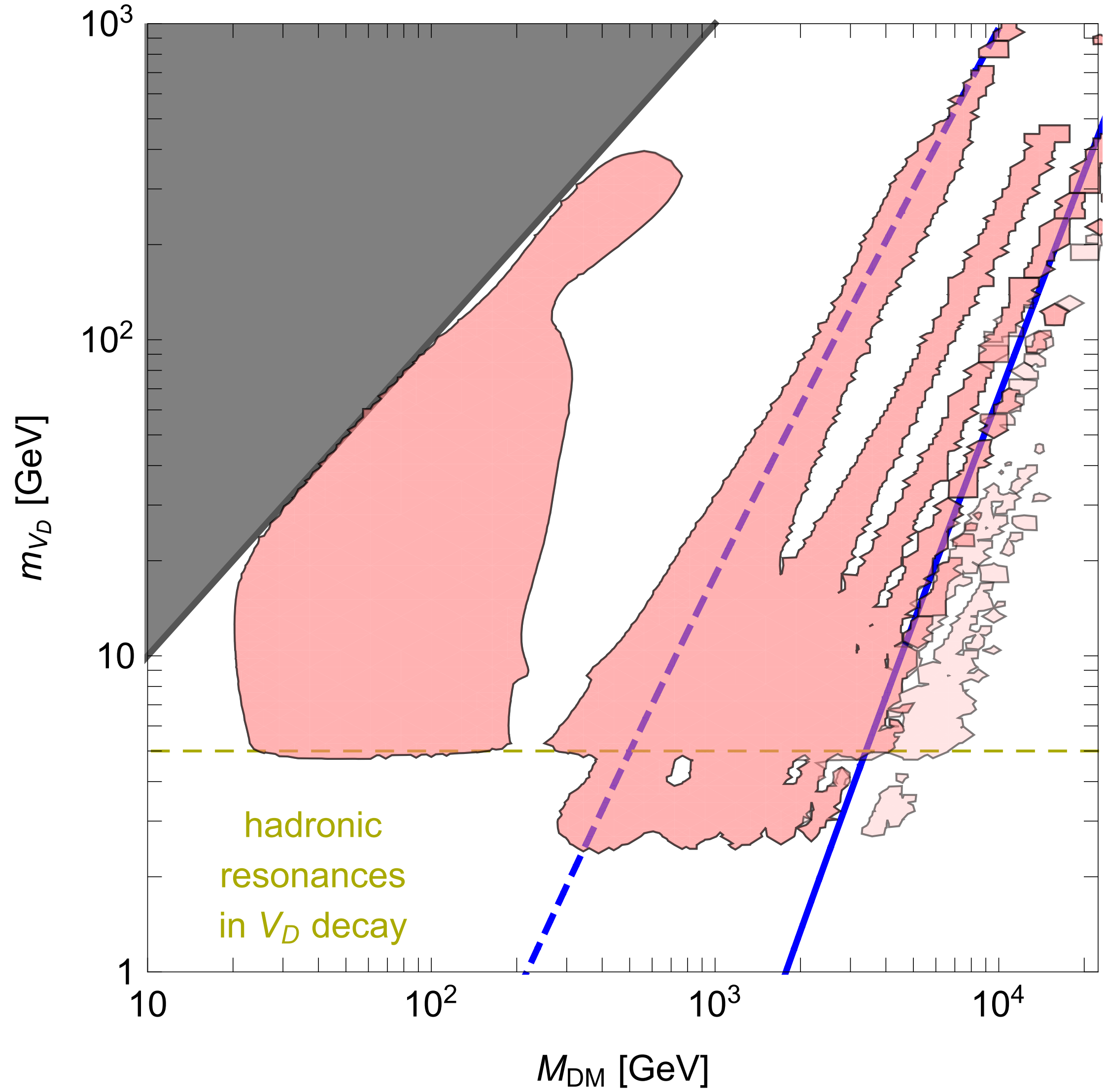
Analysis of Giesen+ 1504.04276

Data of PLANCK 1502.01589

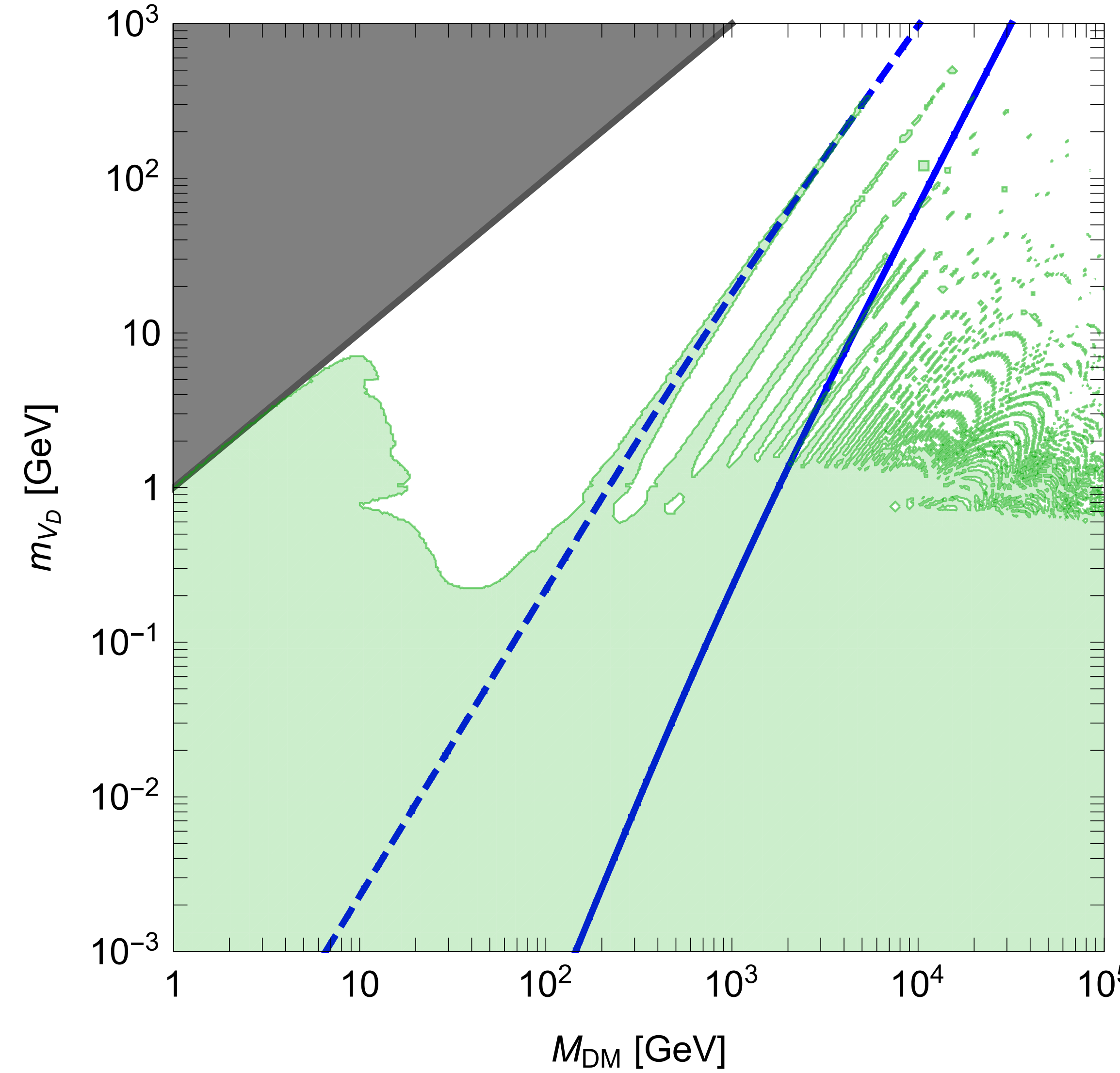
Effect on CMB (ionization etc) from Slatyer 1506.03811

Results: Antiprotons and CMB

Exclusion by AMS−02 antiprotons



Exclusion by CMB



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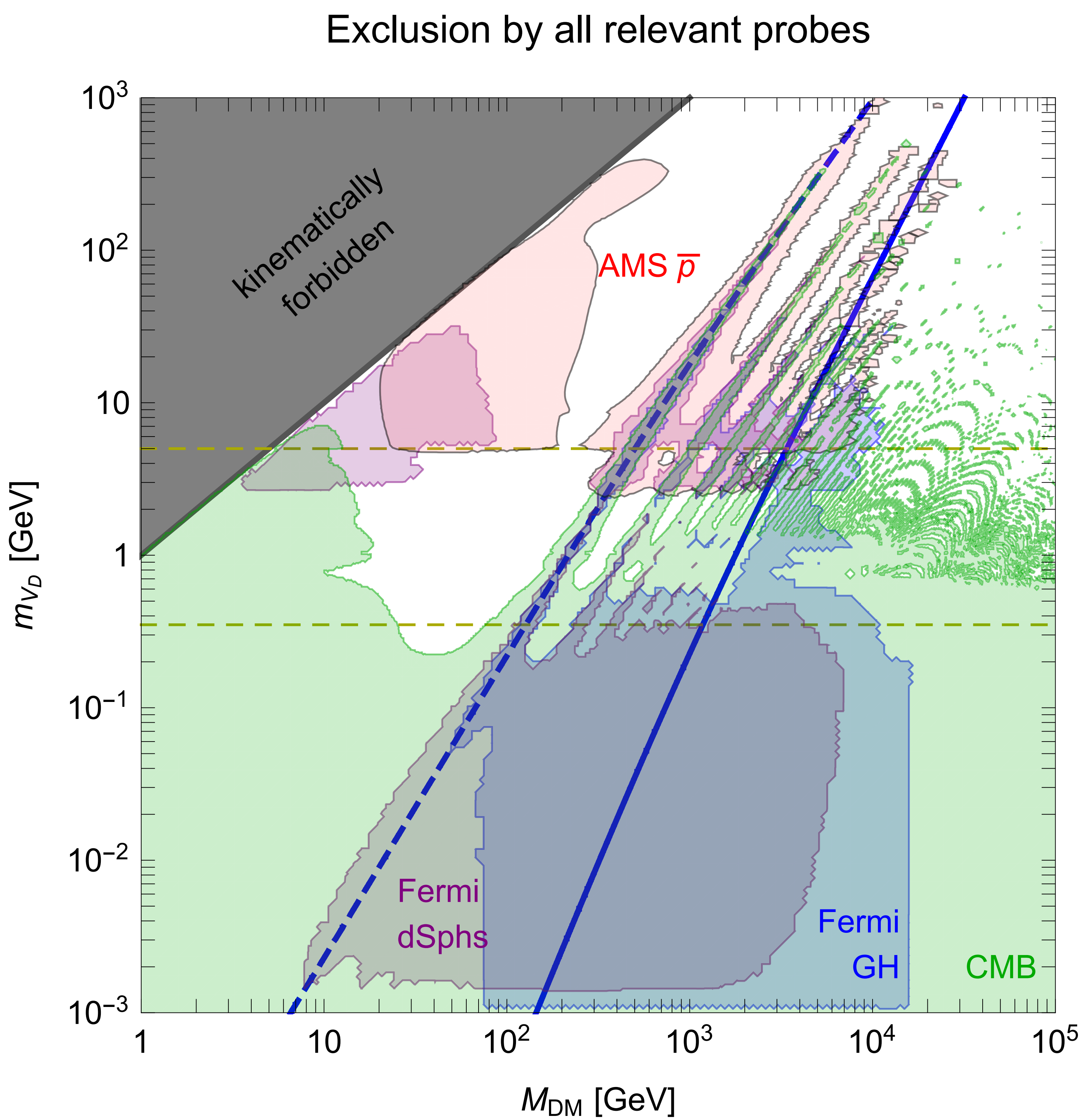
Effect on CMB (ionization etc) from Slatyer 1506.03811

$\langle v_X \rangle = \sqrt{2\,T_X/M_{\rm DM}}$ saturates Somm. & BS enhancements: rel. V_D $T_X \propto a^{-1}$

$T_D^{\rm f.o.} \approx M_{\rm DM}/30$ then kinetic eq. with V_D keeps $T_X = T_D$ non-rel. V_D $T_X \propto a^{-2}$

Summary of indirect detection

Cirelli Panci Petraki FS Taoso 1612.07295



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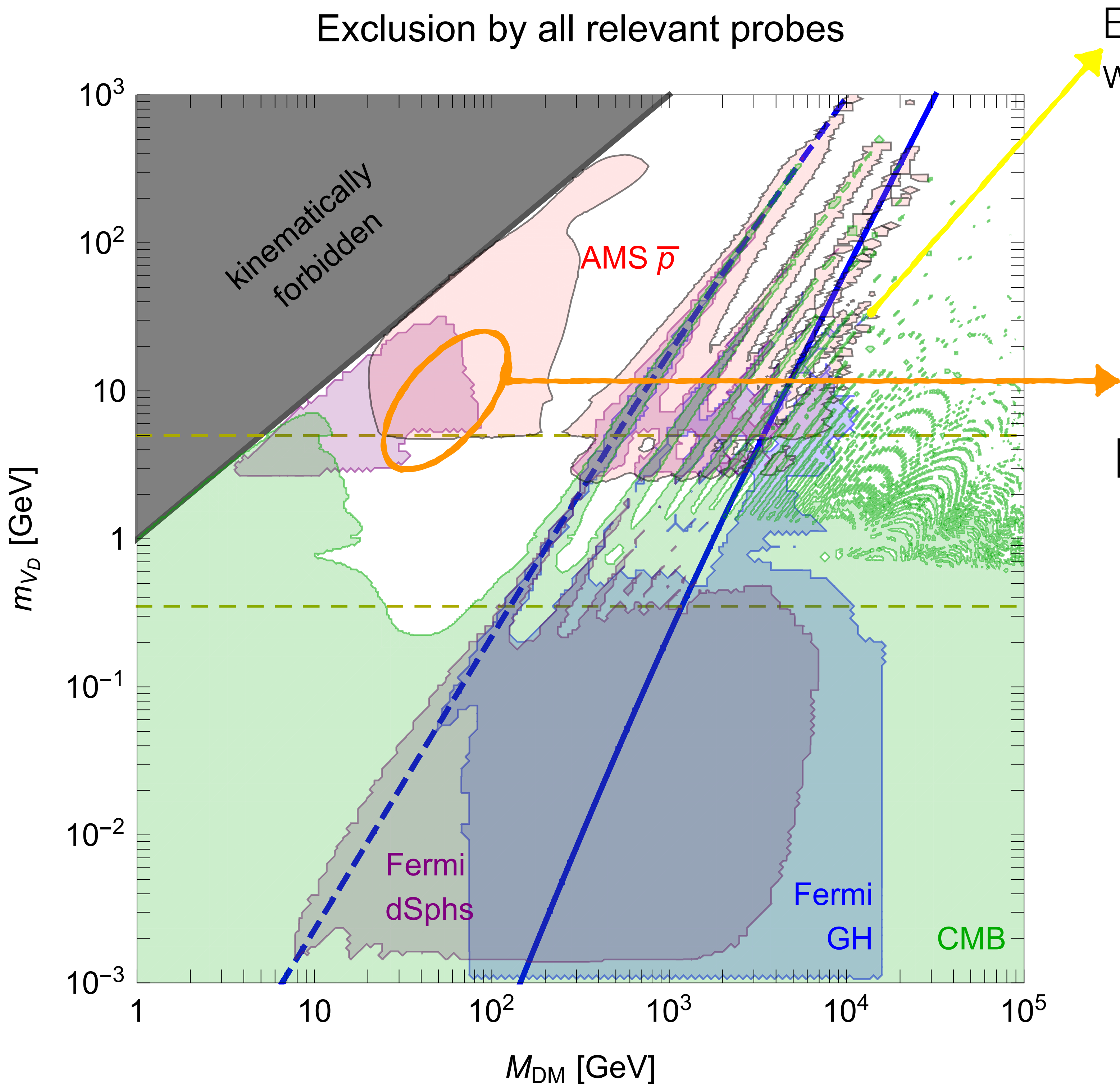


Explore for the first time a region where Bound State formation is crucial

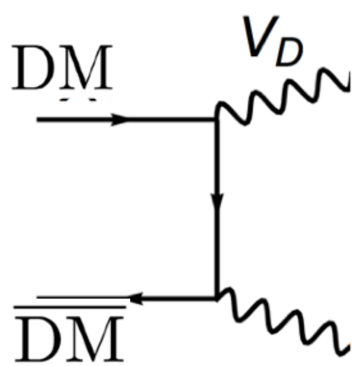
~ excludes this model as explanation of GC excess

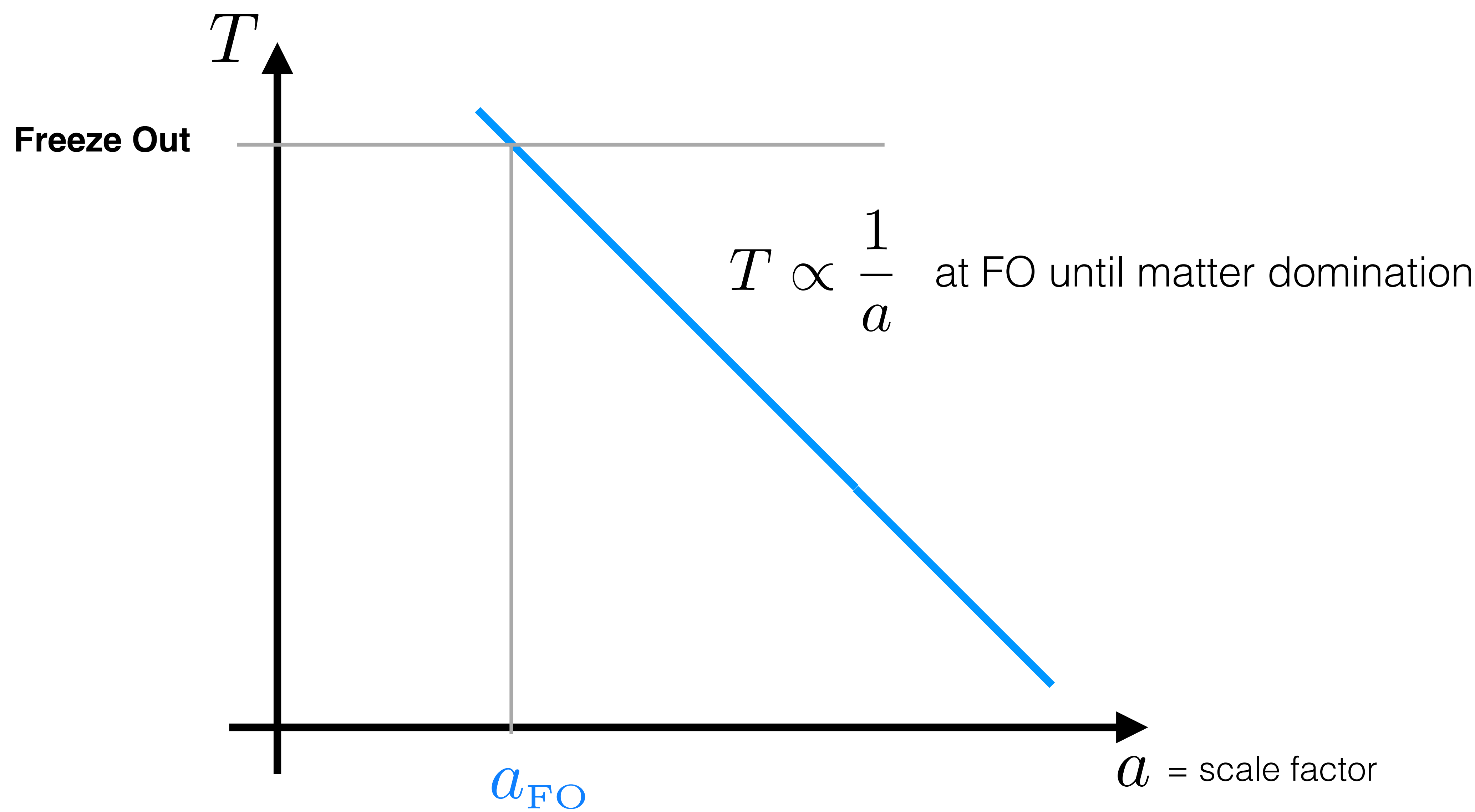
[caveat: large astro uncertainties]

Secluded DM Models & Unitarity bound

Berlin+1602.08490
Cirelli+1612.07295

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





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Cirelli+1612.07295

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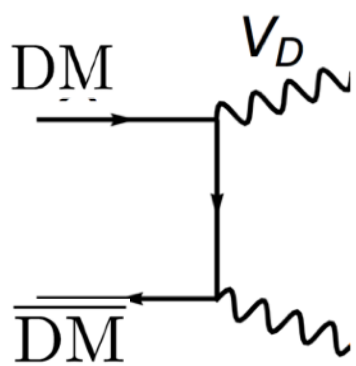
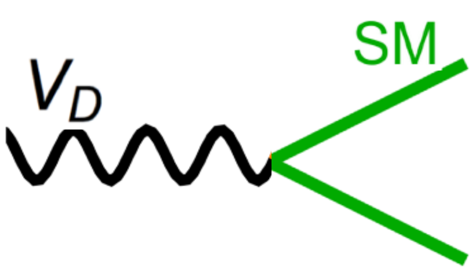
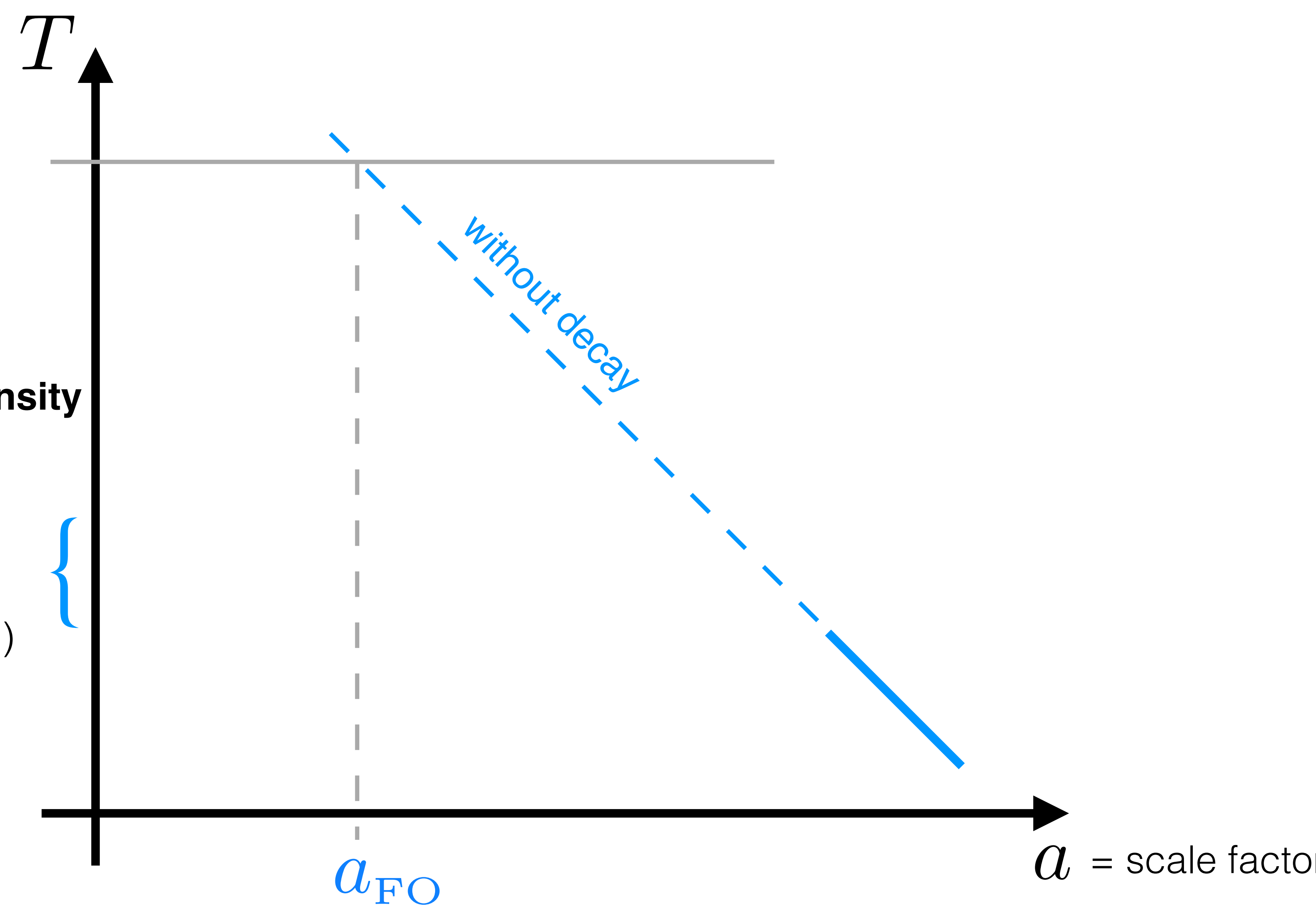


$\boxed{\epsilon \lll 1}$ **V_D's dominate energy density**



V_D's decay
(before BBN)



Secluded DM Models & Unitarity bound

Berlin+1602.08490
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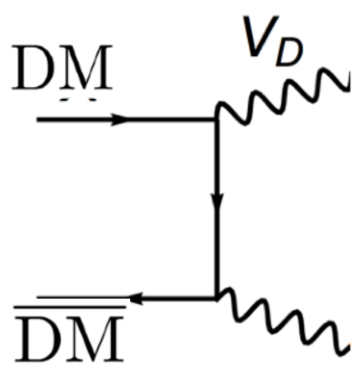

Freeze Out

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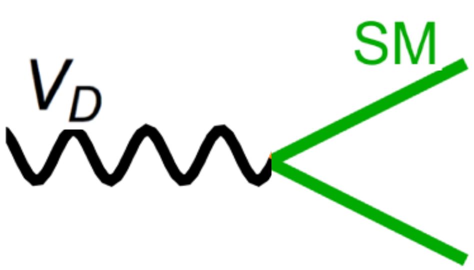

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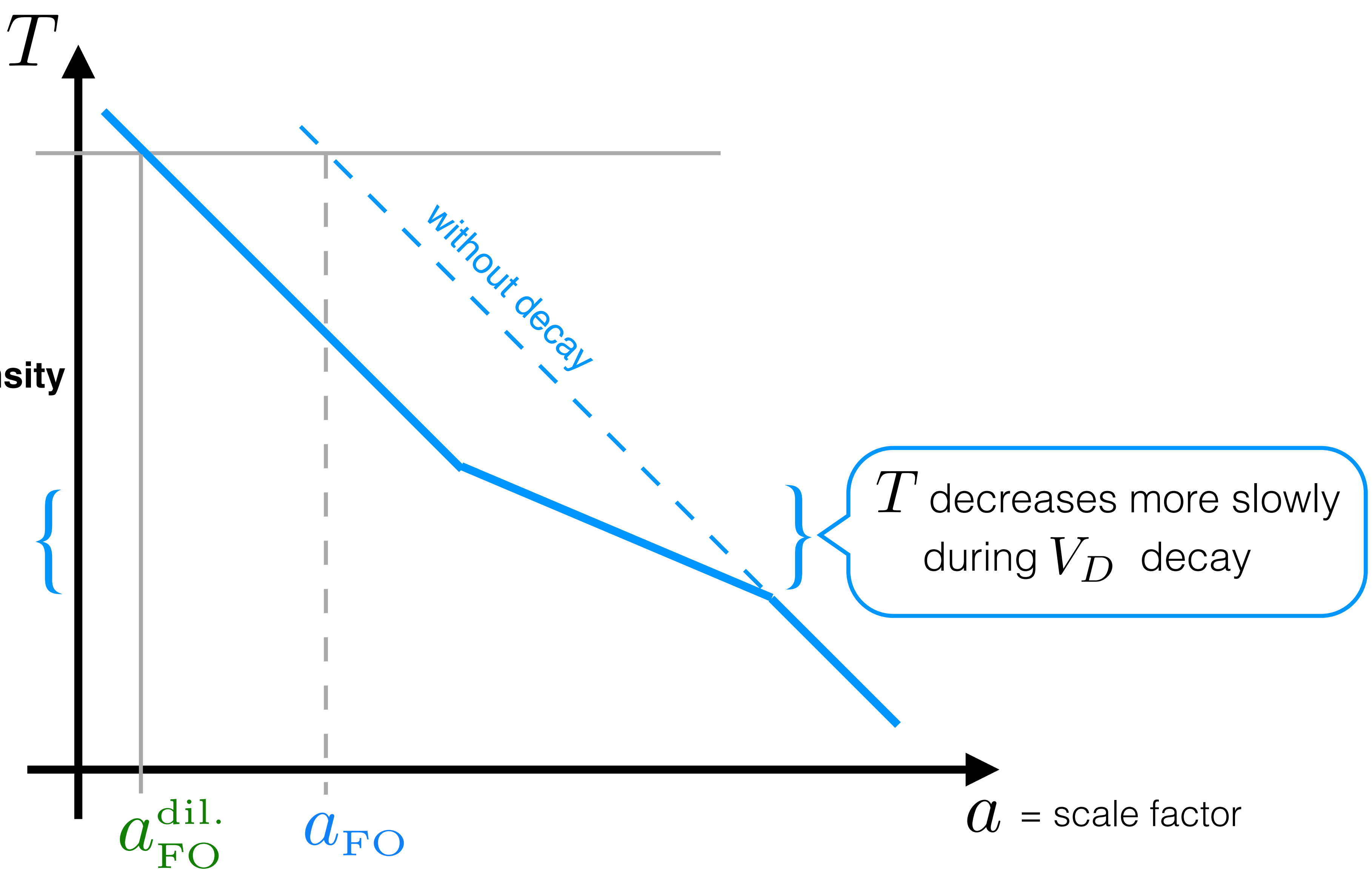

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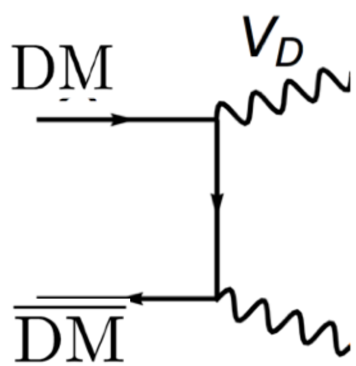
1/dilution factor
Scherrer Turner 1985



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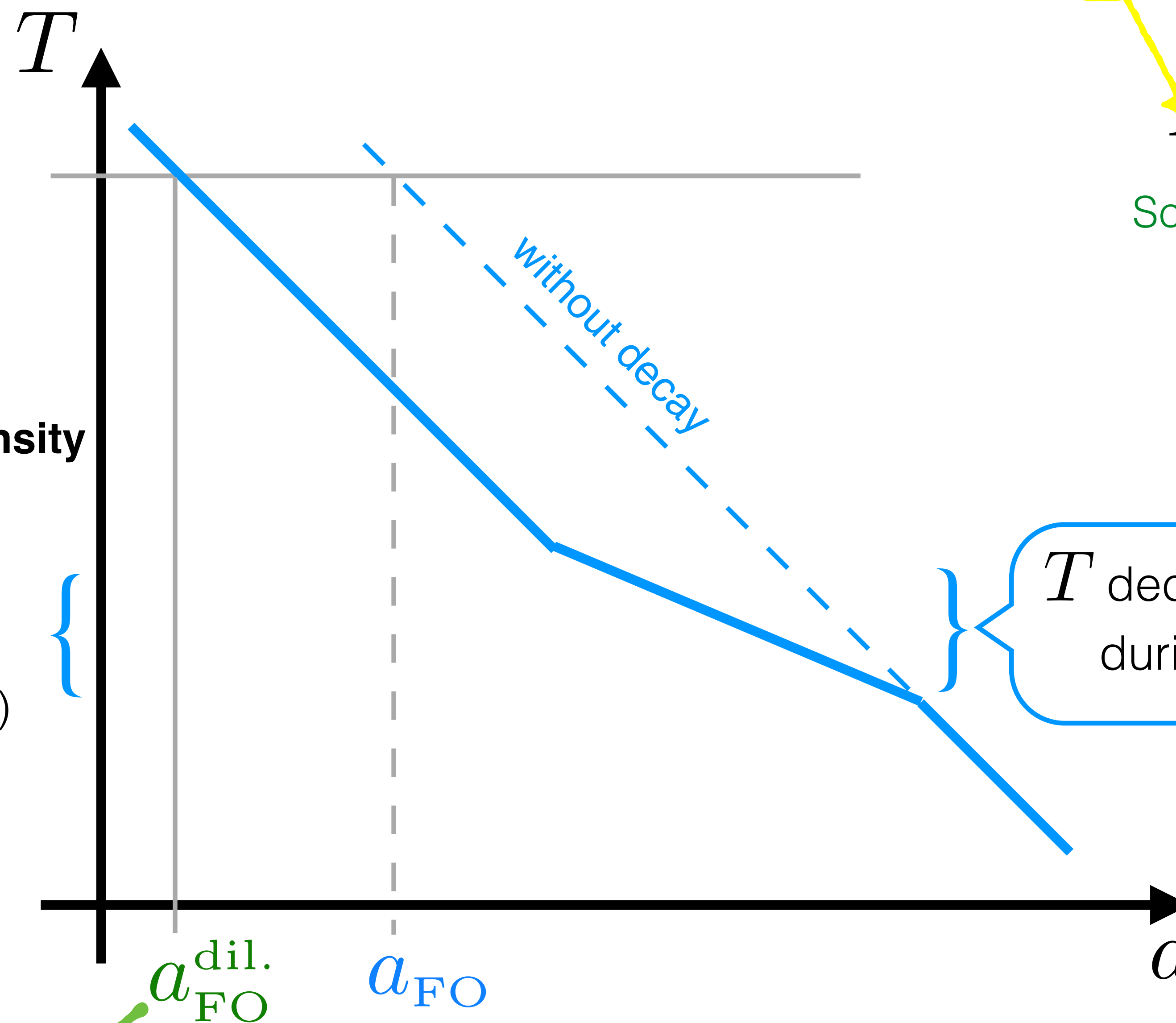
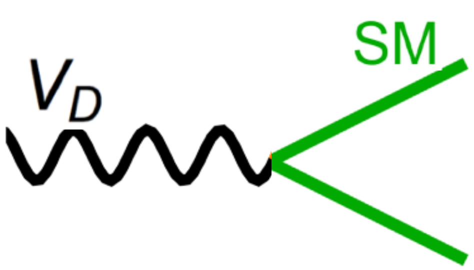


= scale factor

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



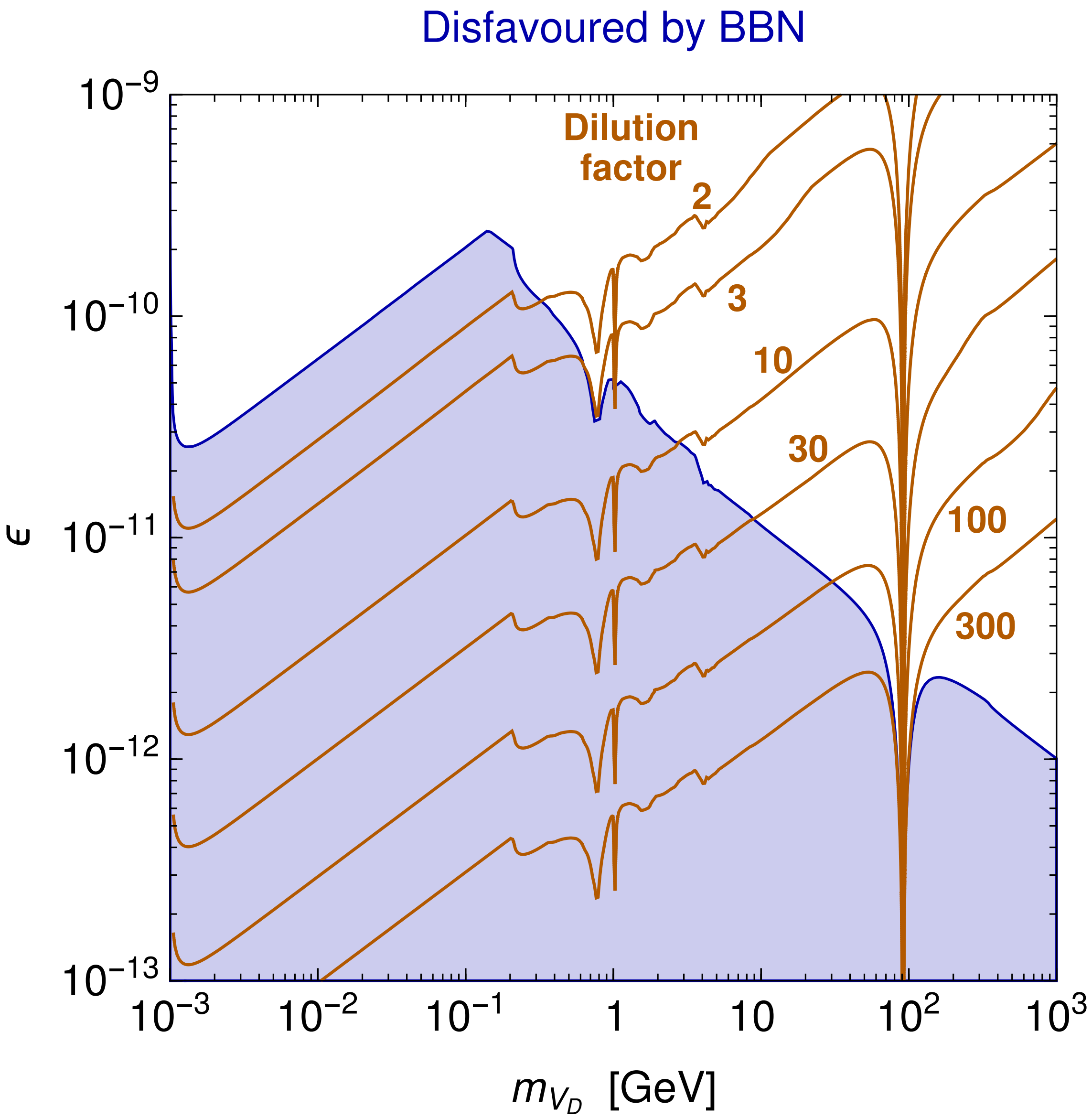
V_D's decay
(before BBN)

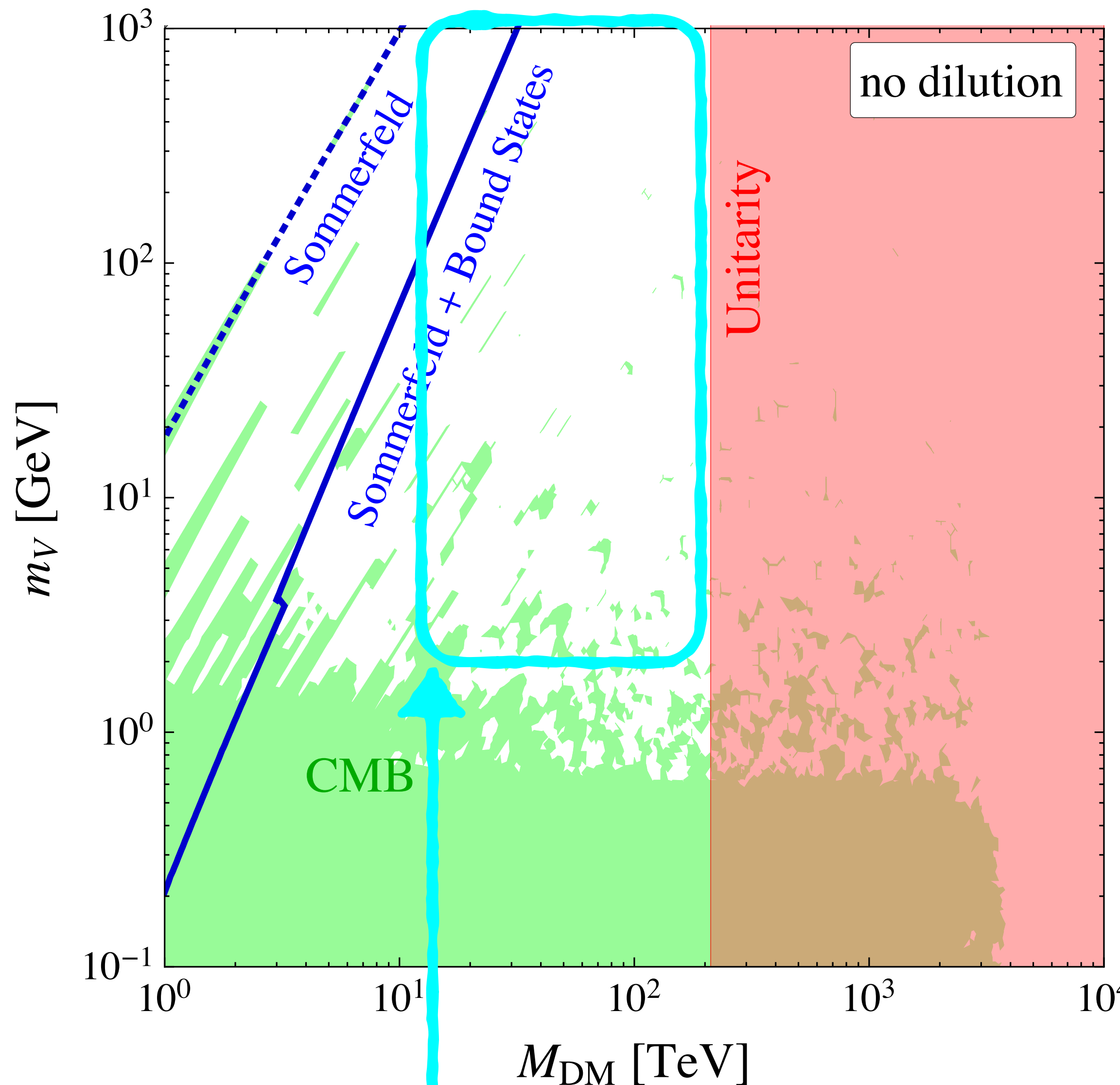
T decreases more slowly during V_D decay

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!

Secluded DM Models & dilution

Cirelli+1612.07295
Cirelli Gouttenoire Petraki FS work in progress





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1/dilution factor

Allowed region

Opportunity for ANTARES, IceCUBE, CTA,…

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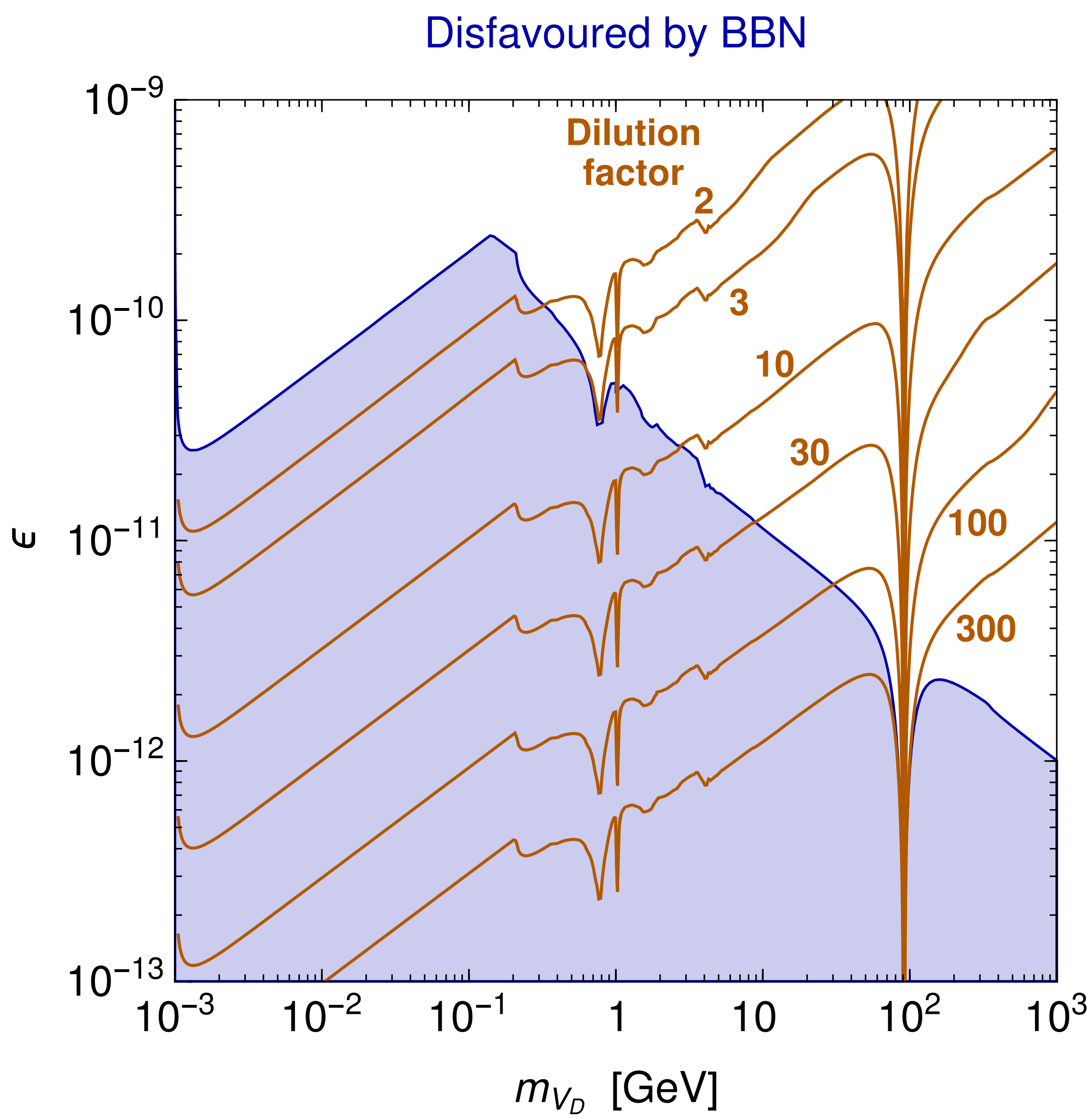

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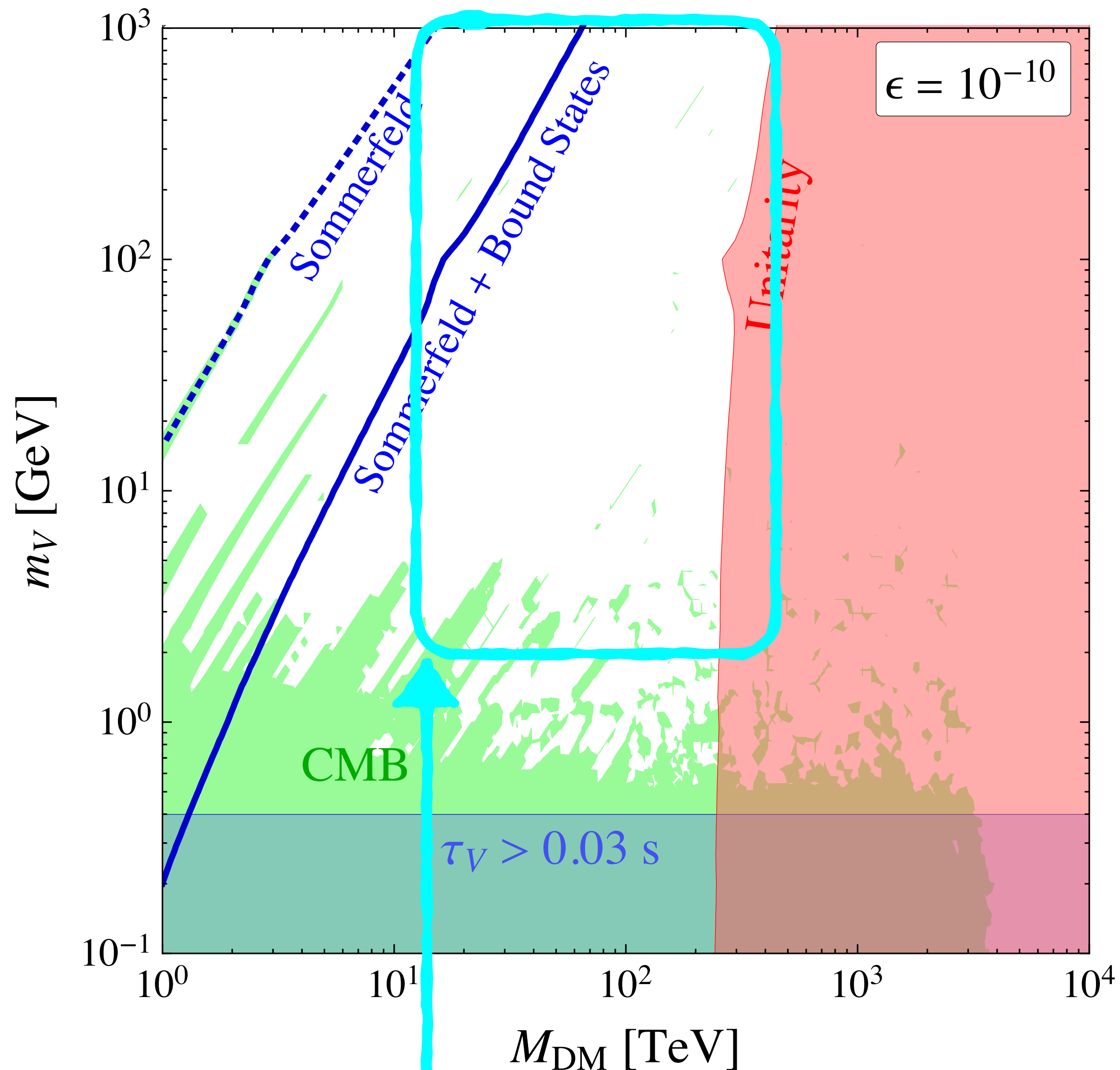

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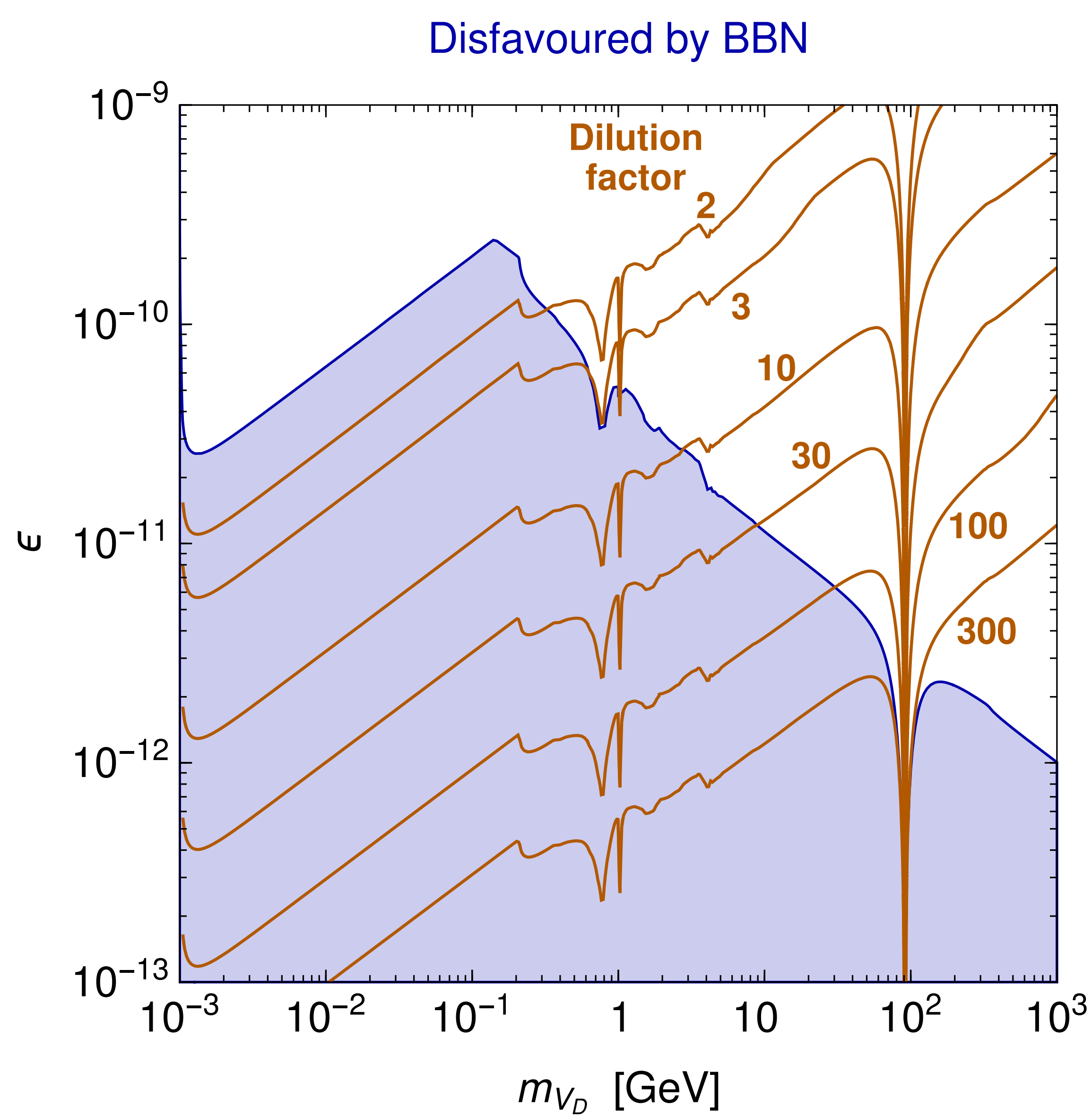

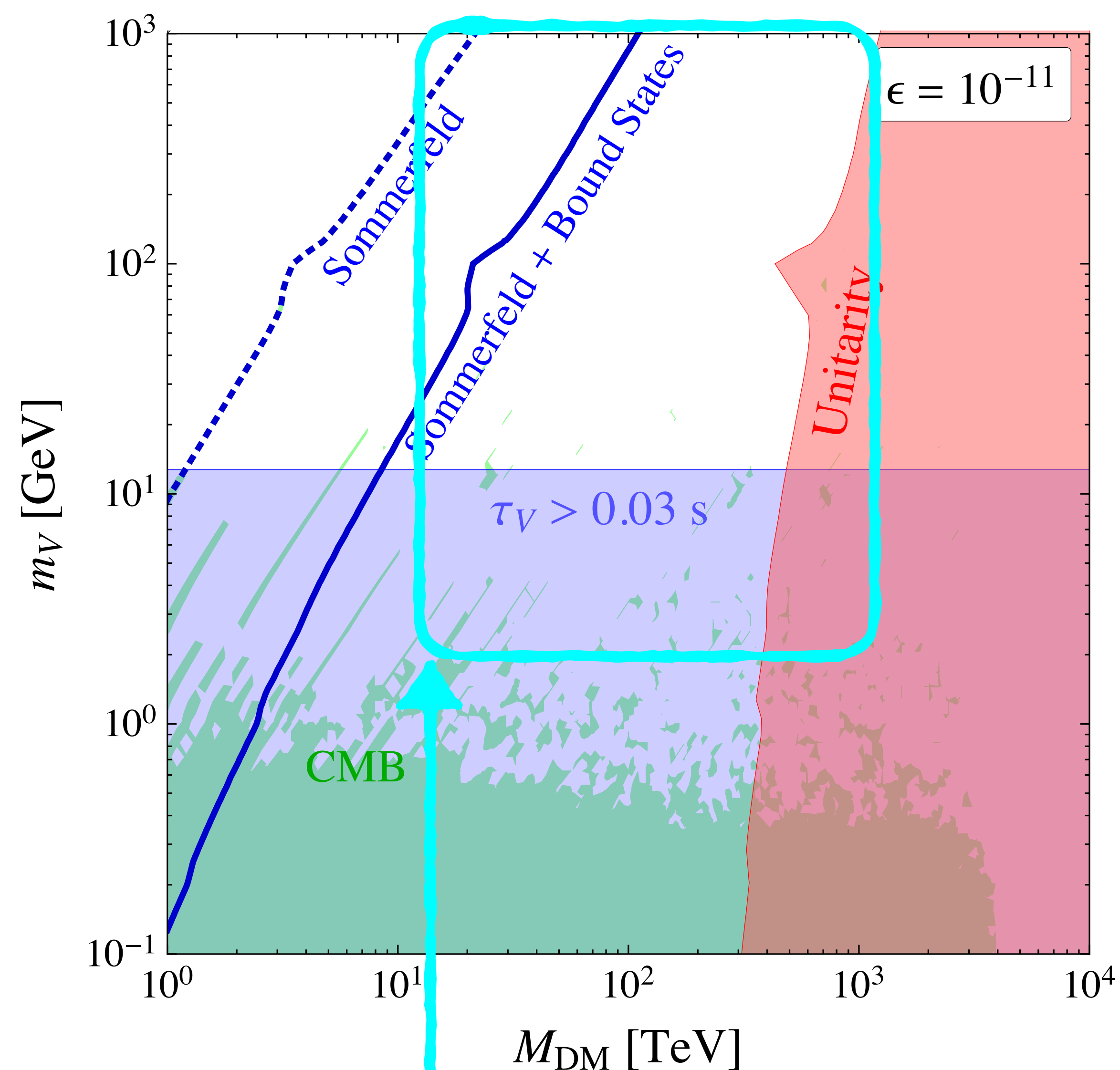

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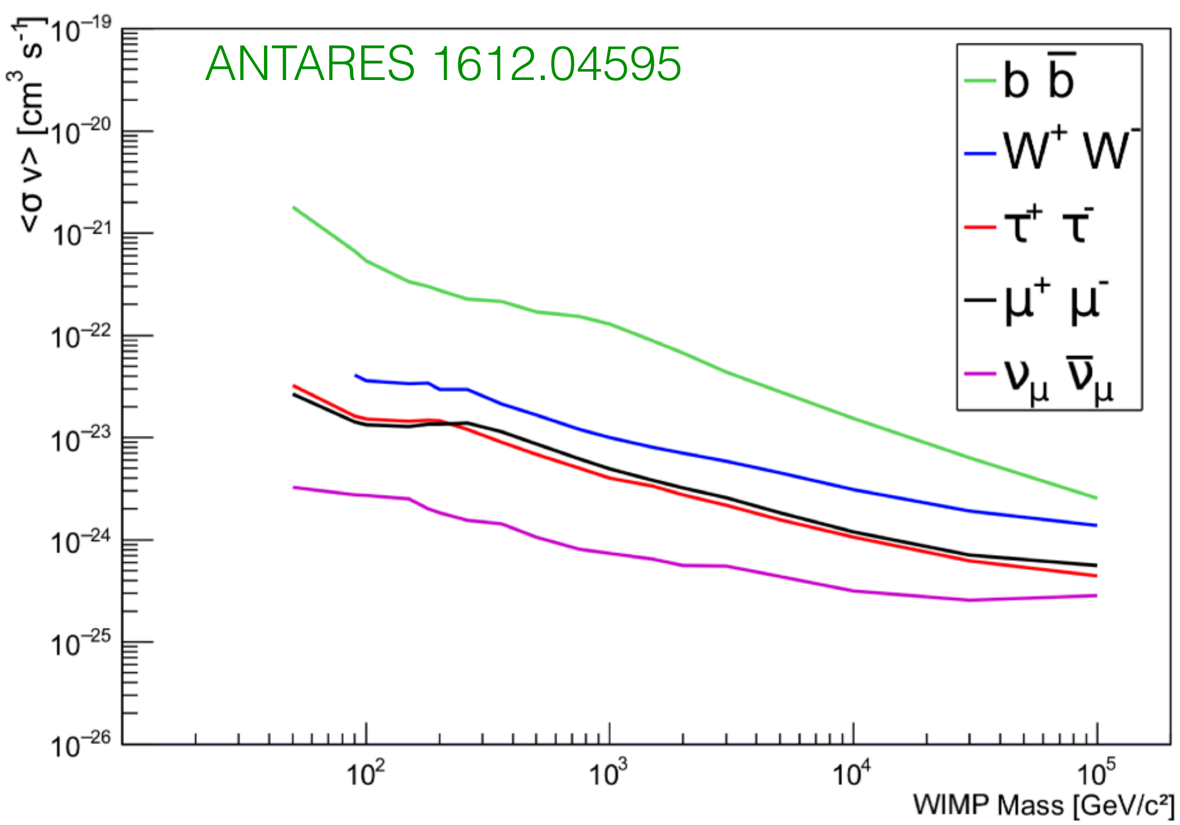
Estimate of ANTARES capabilities



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!

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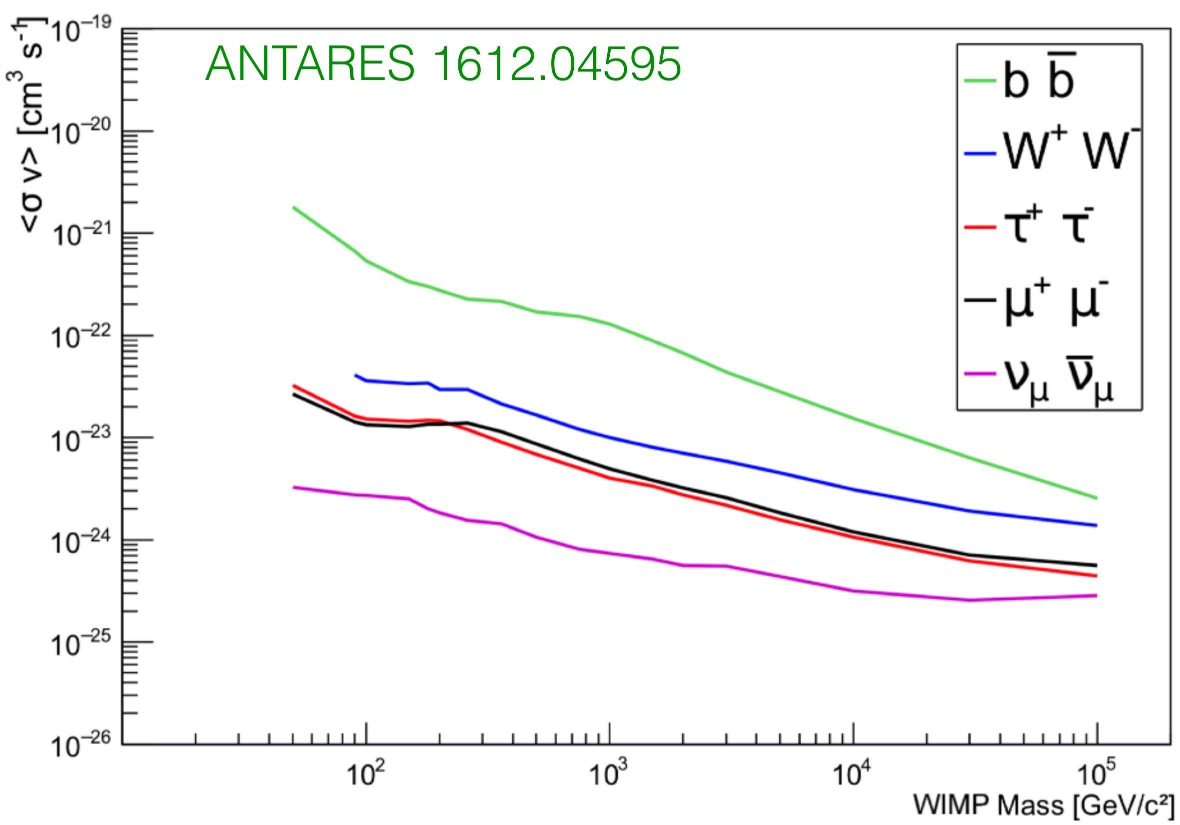

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How to still get a rough idea

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

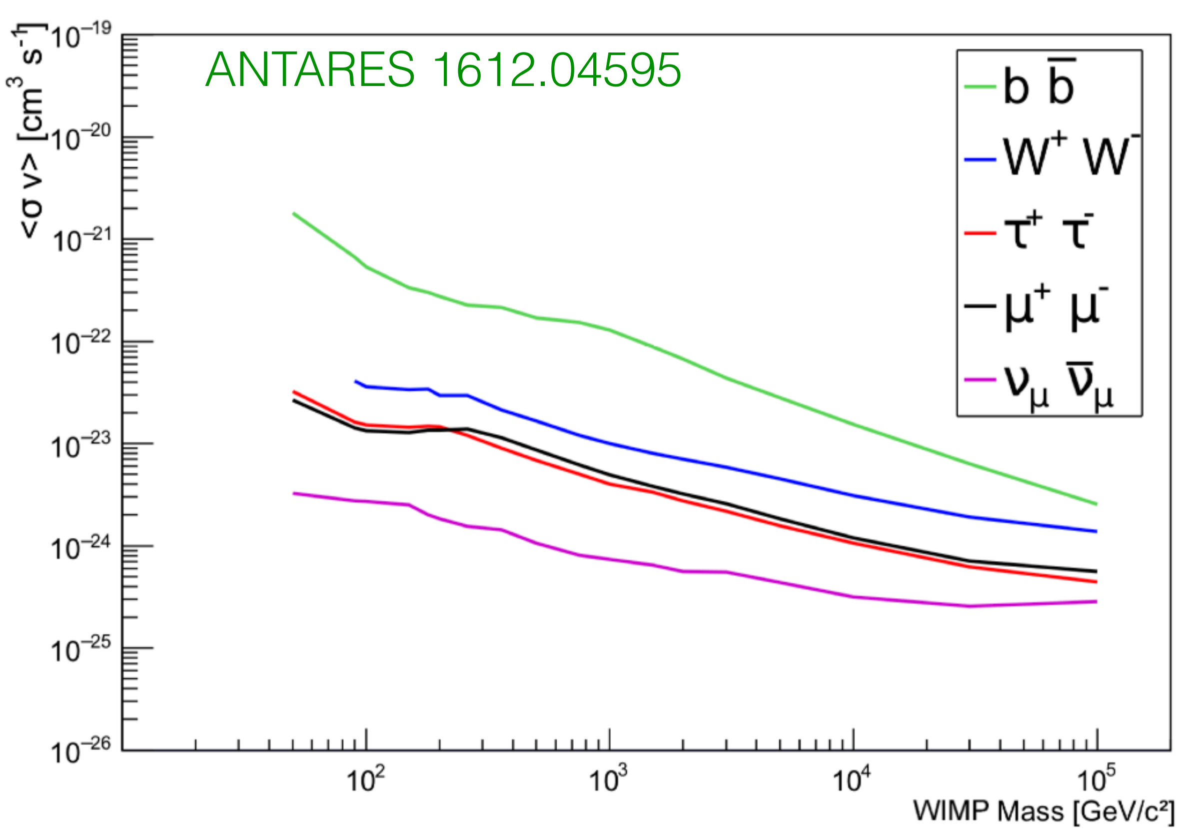
Educated guess from the fact limits are

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}

Estimate of ANTARES capabilities



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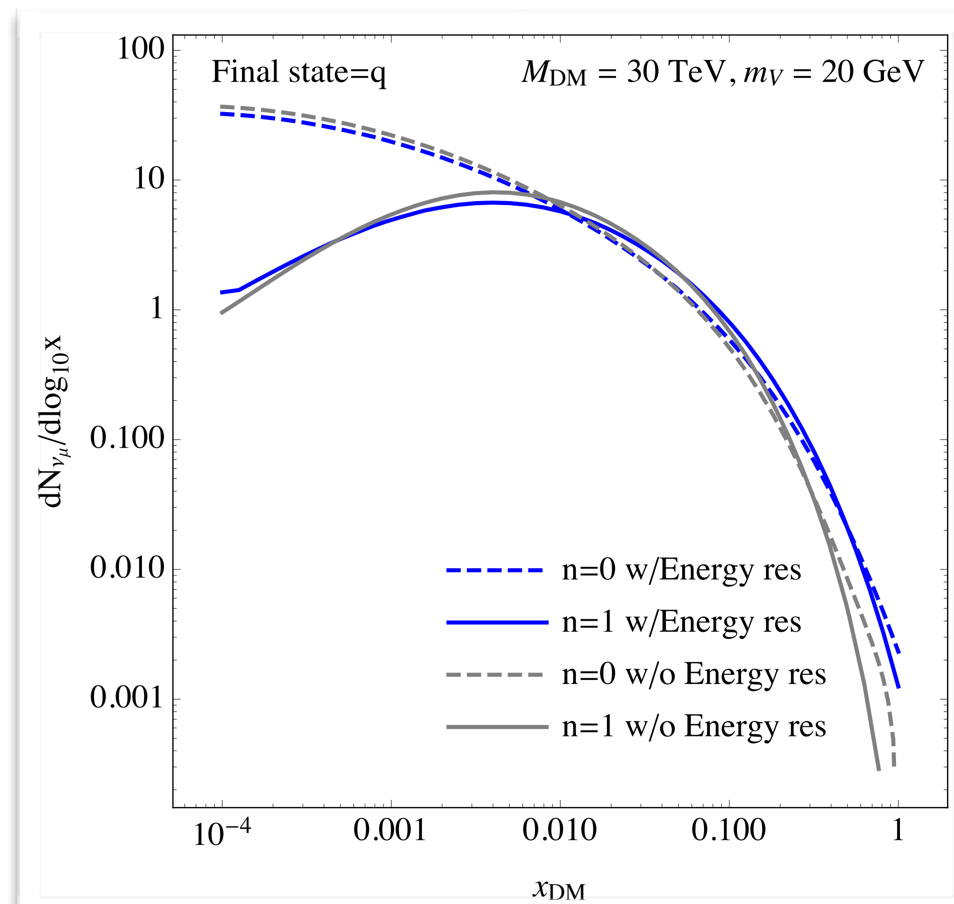
1. ANTARES limits are driven by **higher energy** ν's

2. 0- and 1- step spectra of quarks and neutrinos

are ~ **similar at higher energies**



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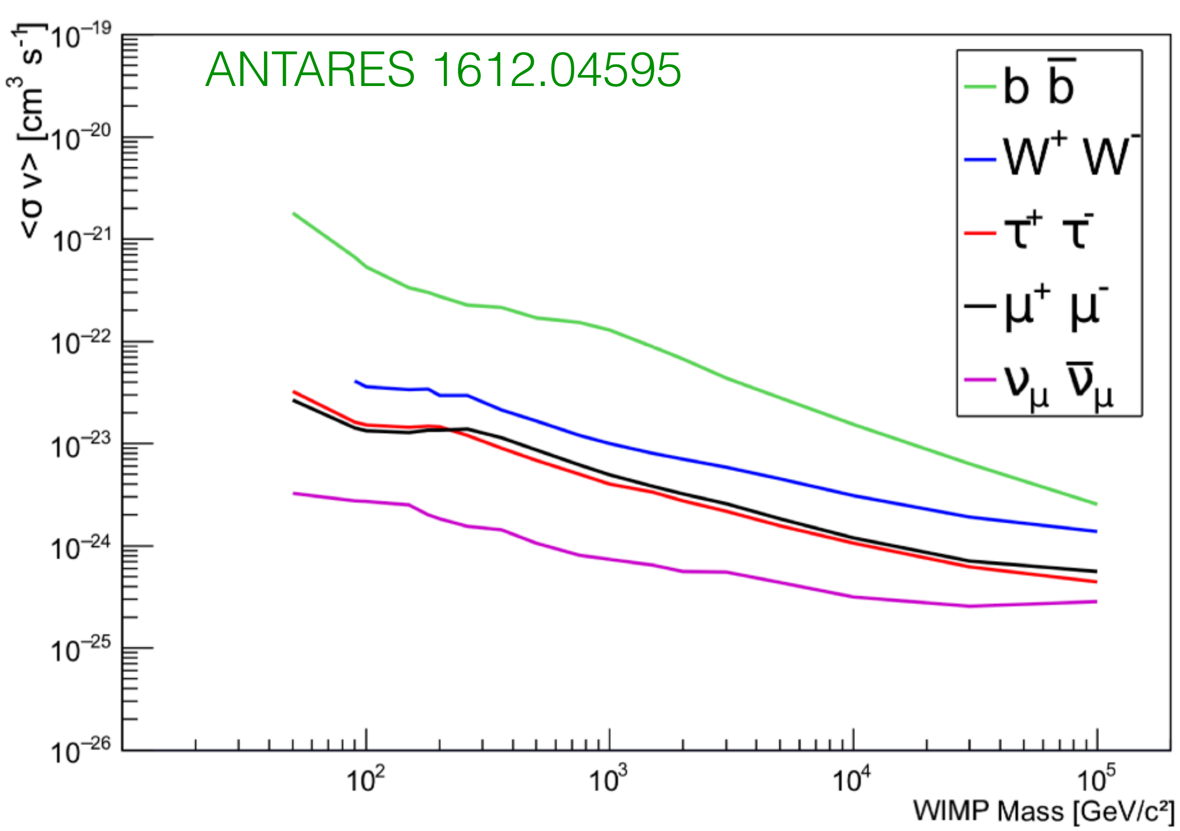

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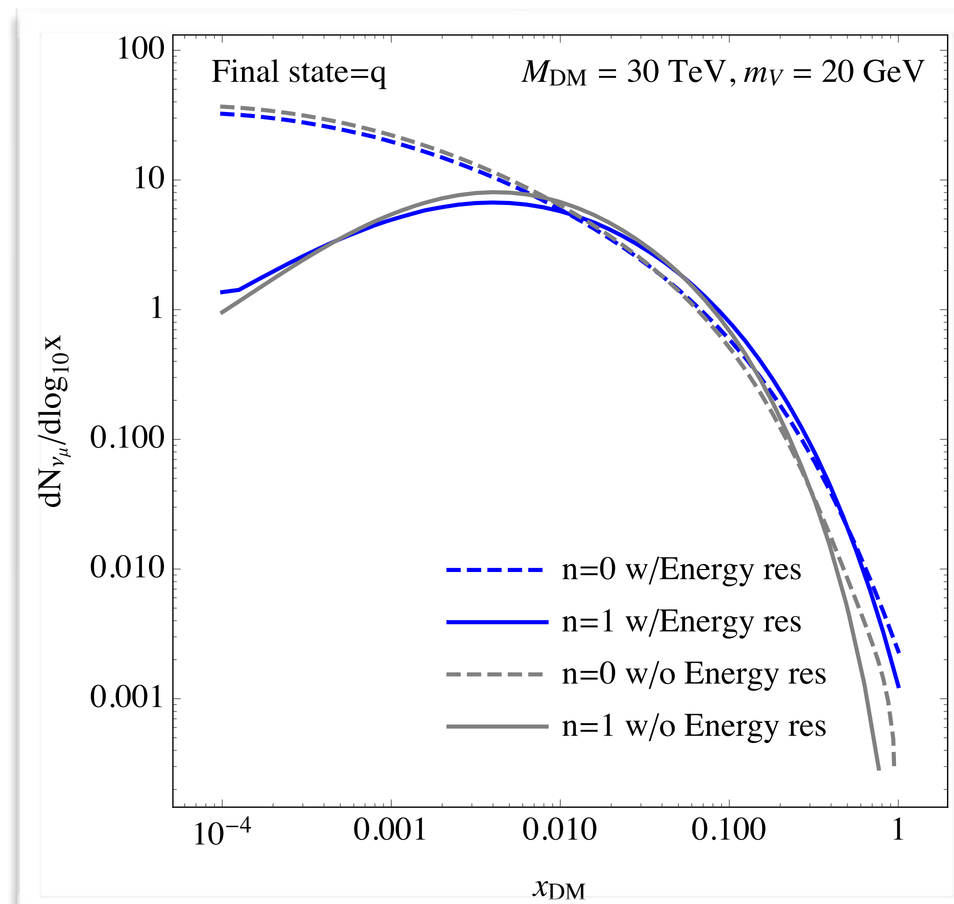
How to still get a rough idea

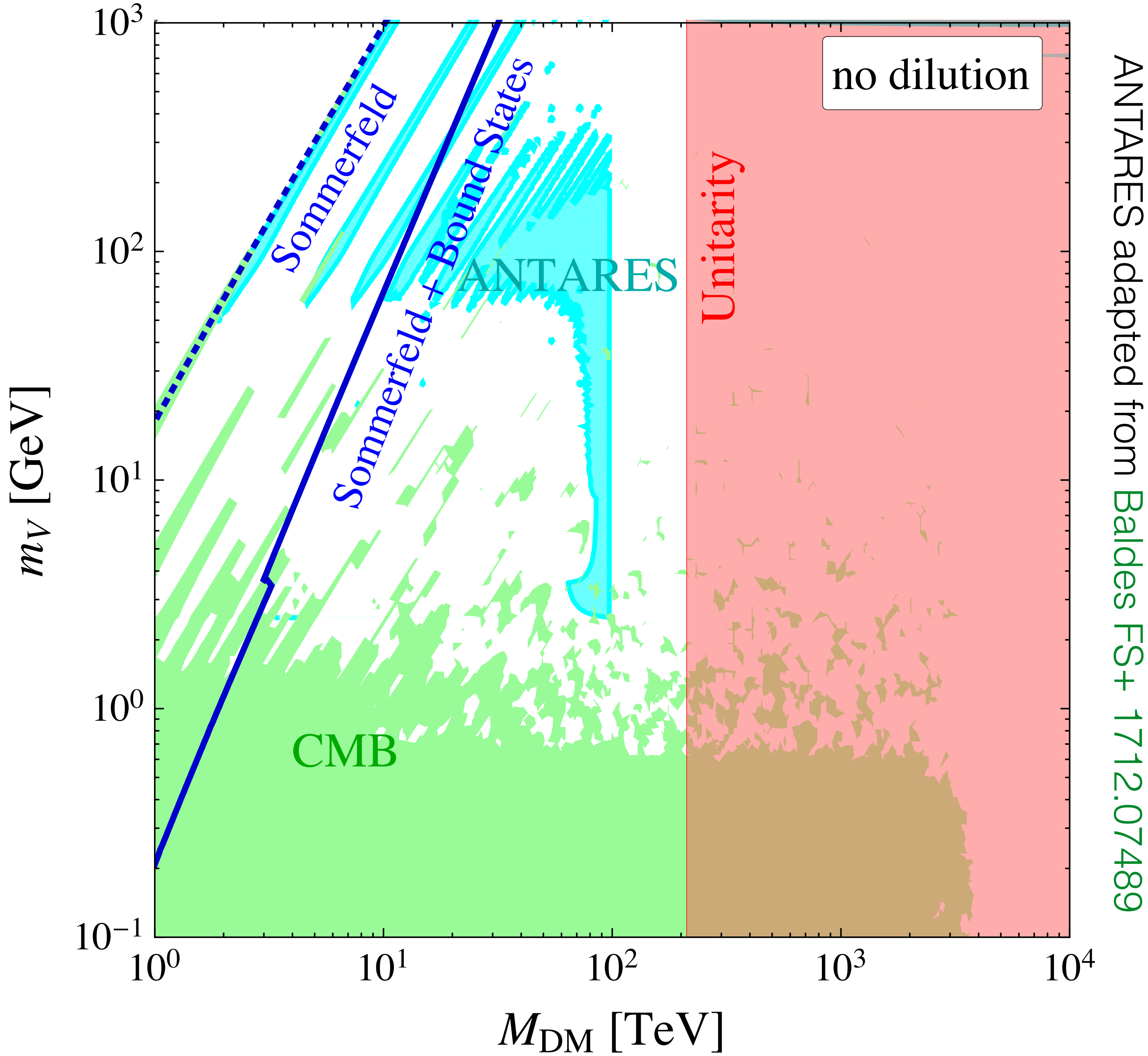
1. ANTARES limits are driven by **higher energy** ν's

2. 0- and 1- step spectra of quarks and neutrinos are ~ **similar at higher energies**

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



ANTARES current reach



Conservative because

- we should have included final states other than quarks and neutrinos
- we should have summed over them

Aggressive because

of choice of peaked NFW DM profile

OK in the logic of this being a new opportunity

DM Signals beyond 10 TeV

DM Signals in Structures?

Dark Sectors & self interactions

DM Signals in Structures?

CDM “problems” at small scales

Collisionless Cold DM works at large scales

$\gtrsim \mathrm{Mpc}$ = galaxy clusters & larger

N-body simulations reproduce observed distribution of matter

A few problems claimed at **small** scales

[WARNING: my particle physicist’s understanding]
see Tulin Yu 1705.02358 for recent review

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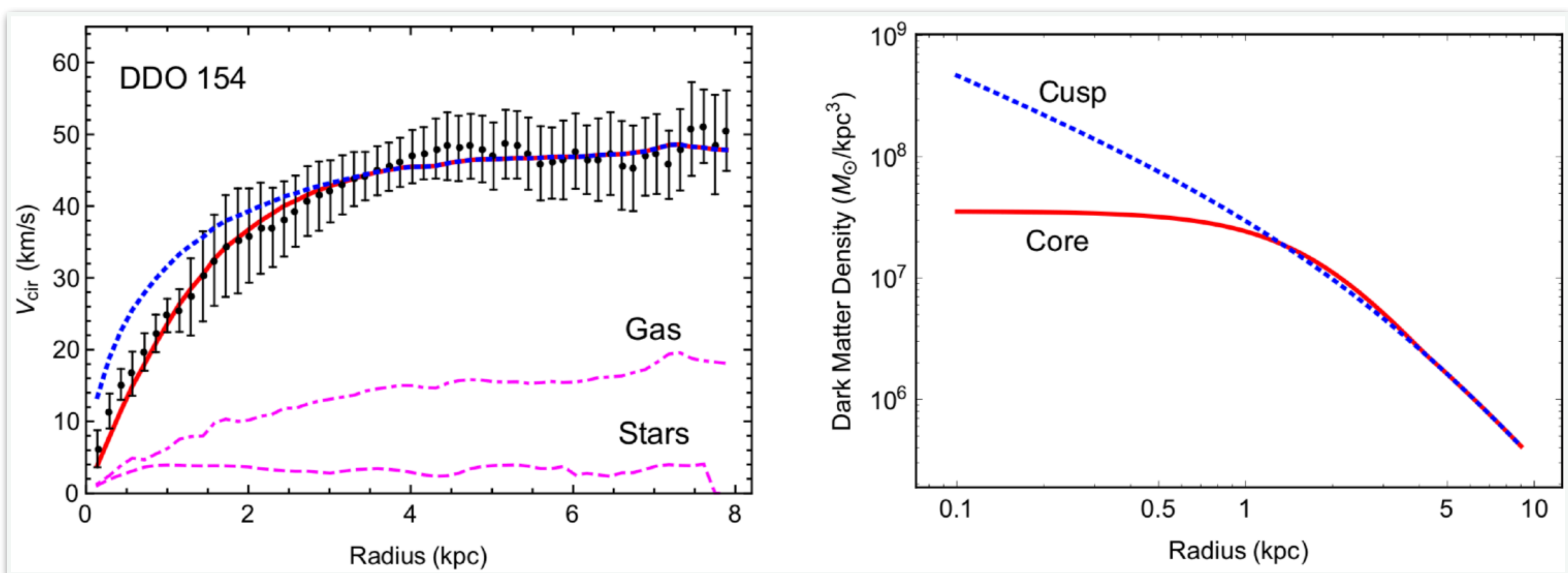
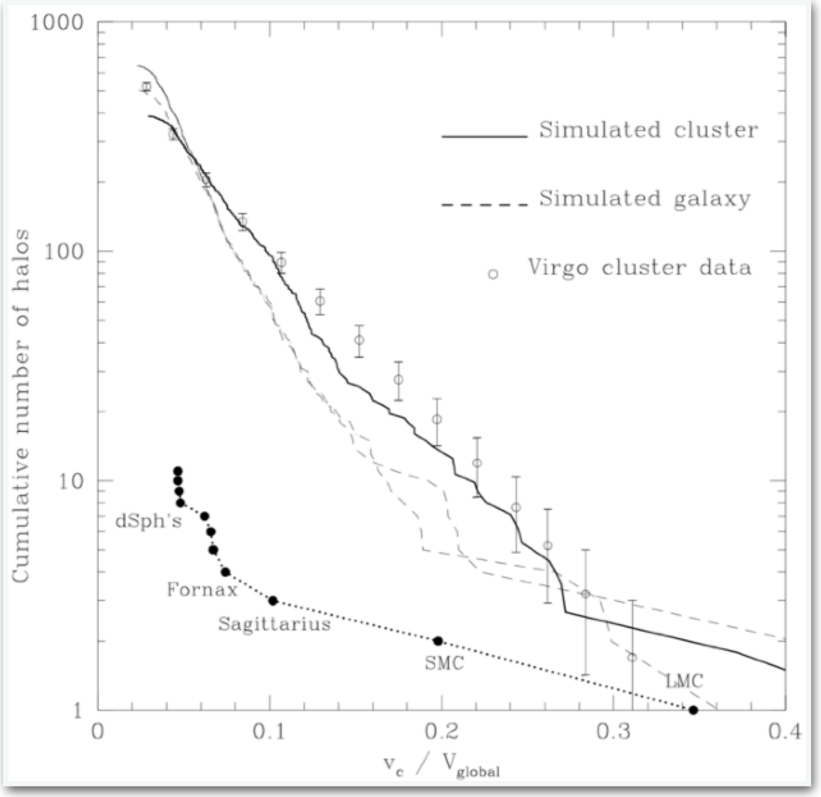
1. Core vs cusp ~ large observational consensus that **small galaxies** (e.g. dSphs) have cores but DM simulations predict cusps

Circular velocity profile measures gravitational potential



CDM “problems” at small scales

2. Missing satellites of the large galaxies, w.r.t. simulations



Moore+ astro-ph/9907411

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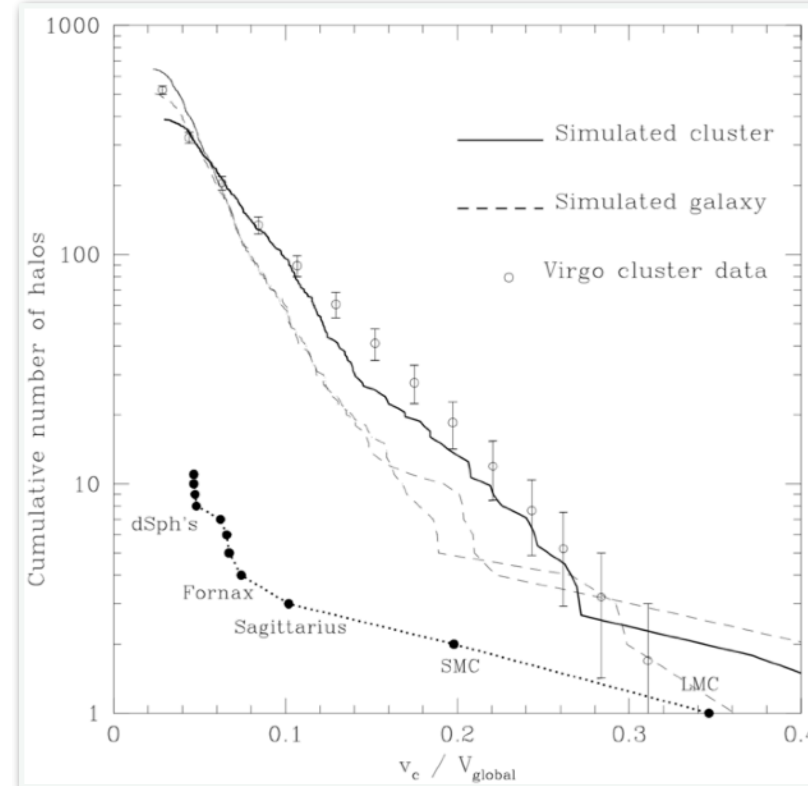
More satellites observed since then

Smaller satellites may not host enough stars to be seen



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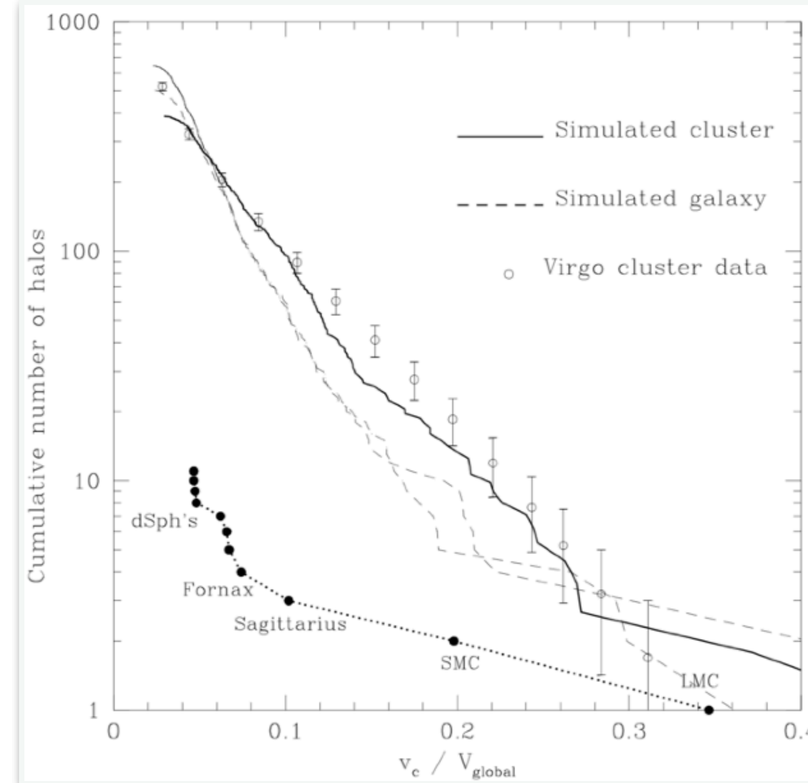
Predicted satellites are too big to fail in producing stars

Circular vel. profile vs distance from center of dSph

Points: observations, where vel. measured at half-light radius



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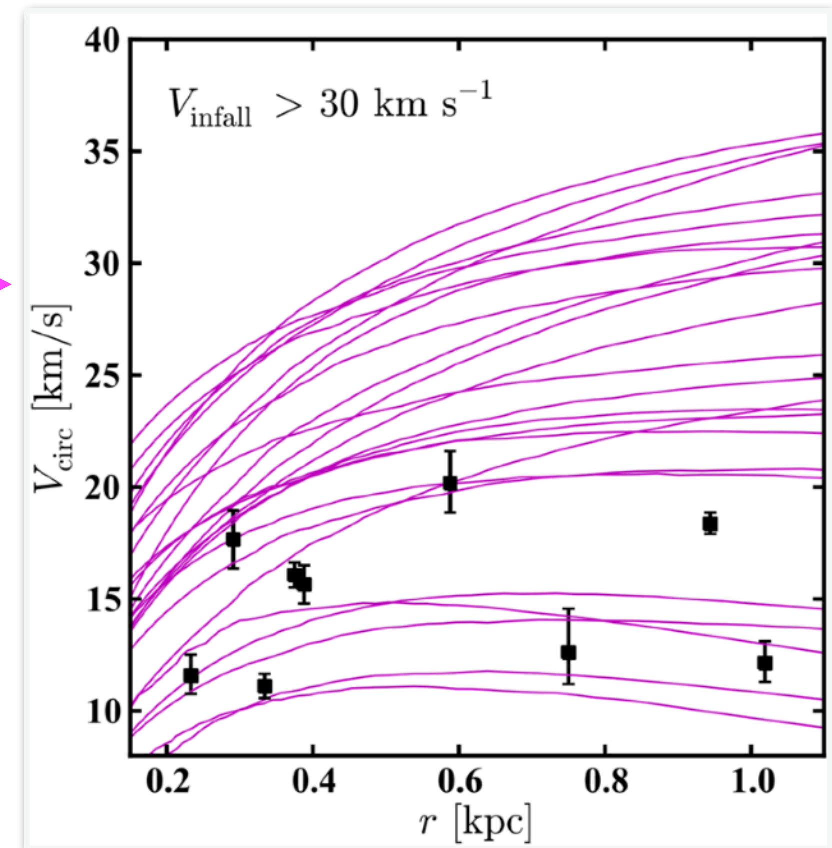

Boylan-Kolchin+ 1111.2048

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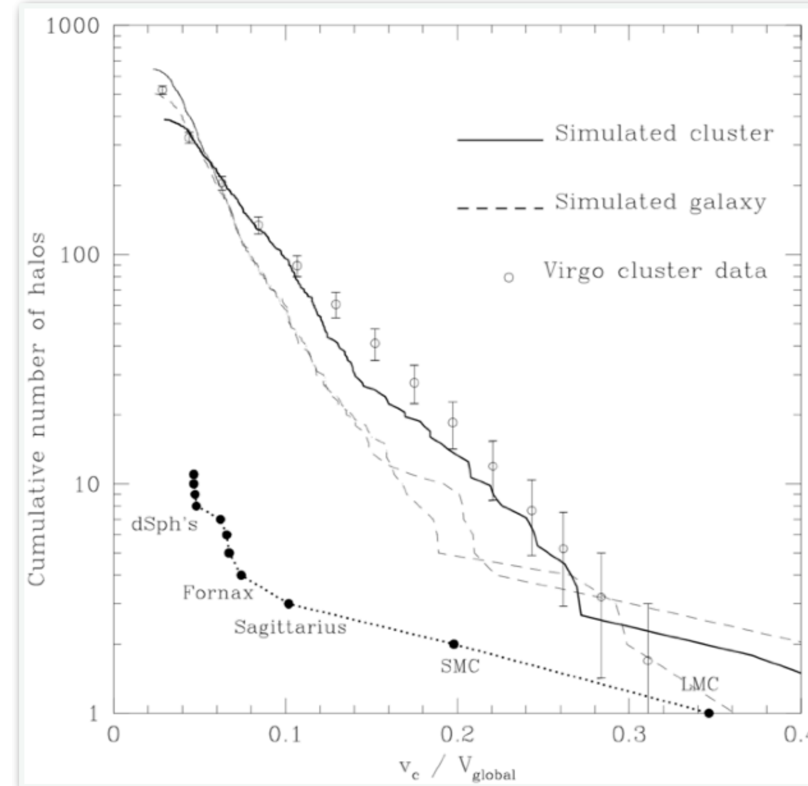

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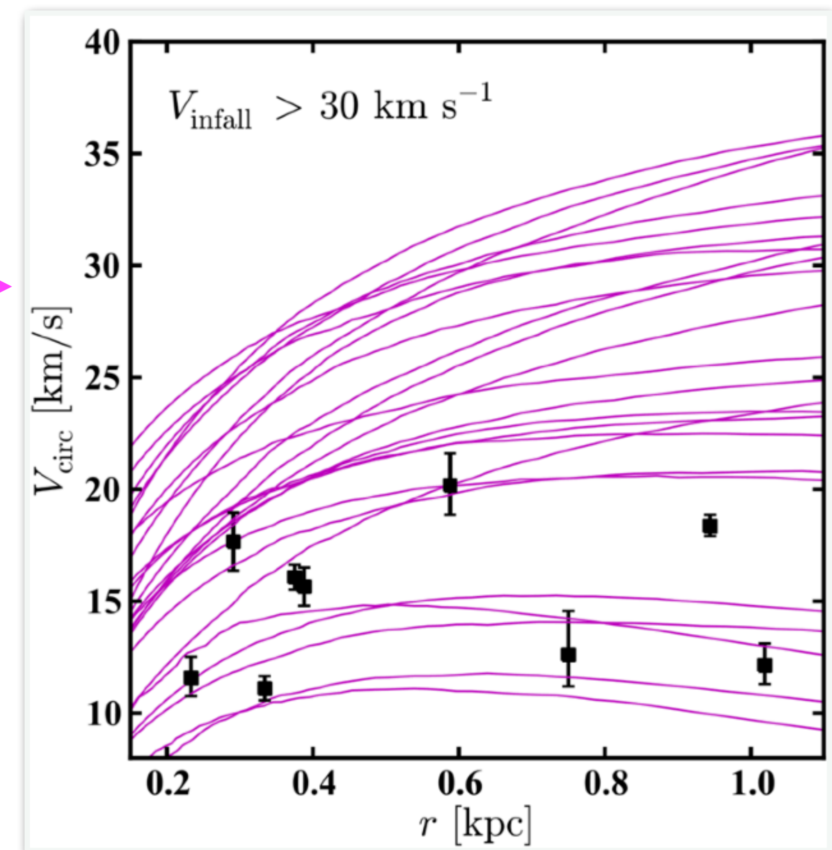

Boylan-Kolchin+ 1111.2048

4. Diversity Oman+ 1504.01437

CDM ~ predicts self-similar density profiles

but in some galaxies those profiles exhibit "too large" scatter

Do baryons explain everything?

A "particle" in numerical simulations weights ~ $10^6\ \mathrm{M_{sun}}$

$\Longrightarrow$ "**Baryonic feedback**" modelled as fluid in **hydrodynamical simulations**

Model → Star Formation
→ Supernovae explosions [send baryons out of center, baryons drag DM via gravity]
→ ....

Many free parameters, fitted to some "criteria"

e.g. Abundance Matching $\approx$ impose the observed relation $\mathrm{M_{star}}$ vs $\mathrm{M_{DM}}$

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1. Core vs cusp

Some groups find cores in fainter galaxies

e.g. Di Cintio+ 1306.0898

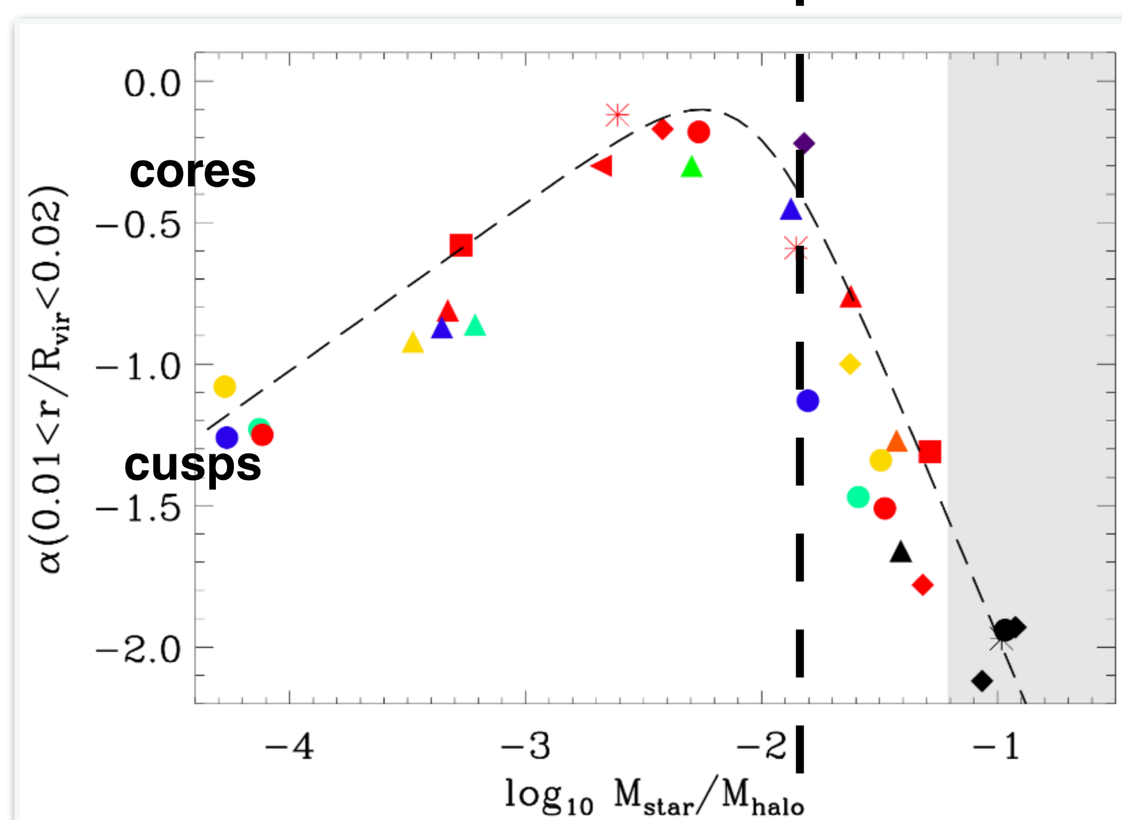
But others don't e.g. Sawala, Frenk+ 1511.01098, …

Reasons not clear, intense activity …

[other groups even question observational evidence for cores]

e.g. Genina, Frenk+ 1707.06303

~ Dwarves | ~ Milky Way



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3. Too big to fail Brook Di Cintio 1410.3825

Hydro simulations that find **cores** also ameliorate this

naively: cored profile $\Rightarrow$ less star formation, more tidal stripping…

… but do not solve the problem

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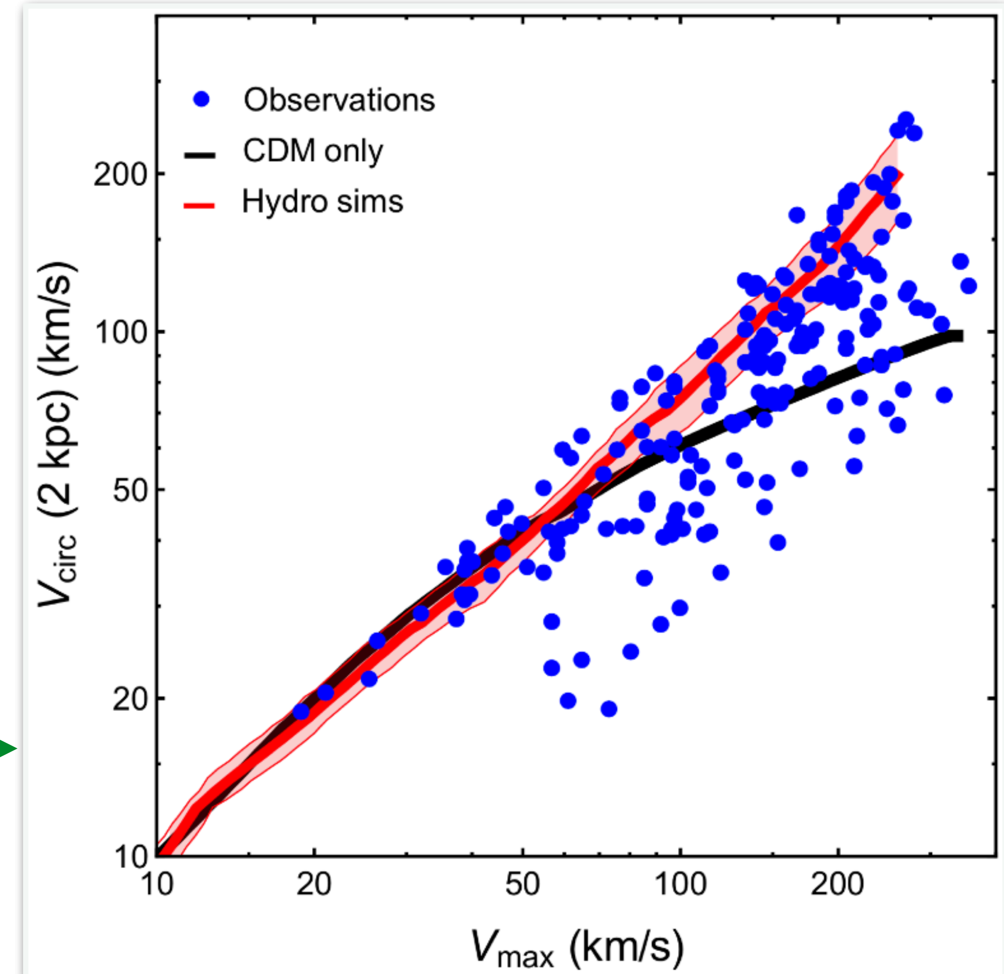
Hydro simulations seem to fail here → Oman+ 1504.01437

Still, this problem is much "younger" …



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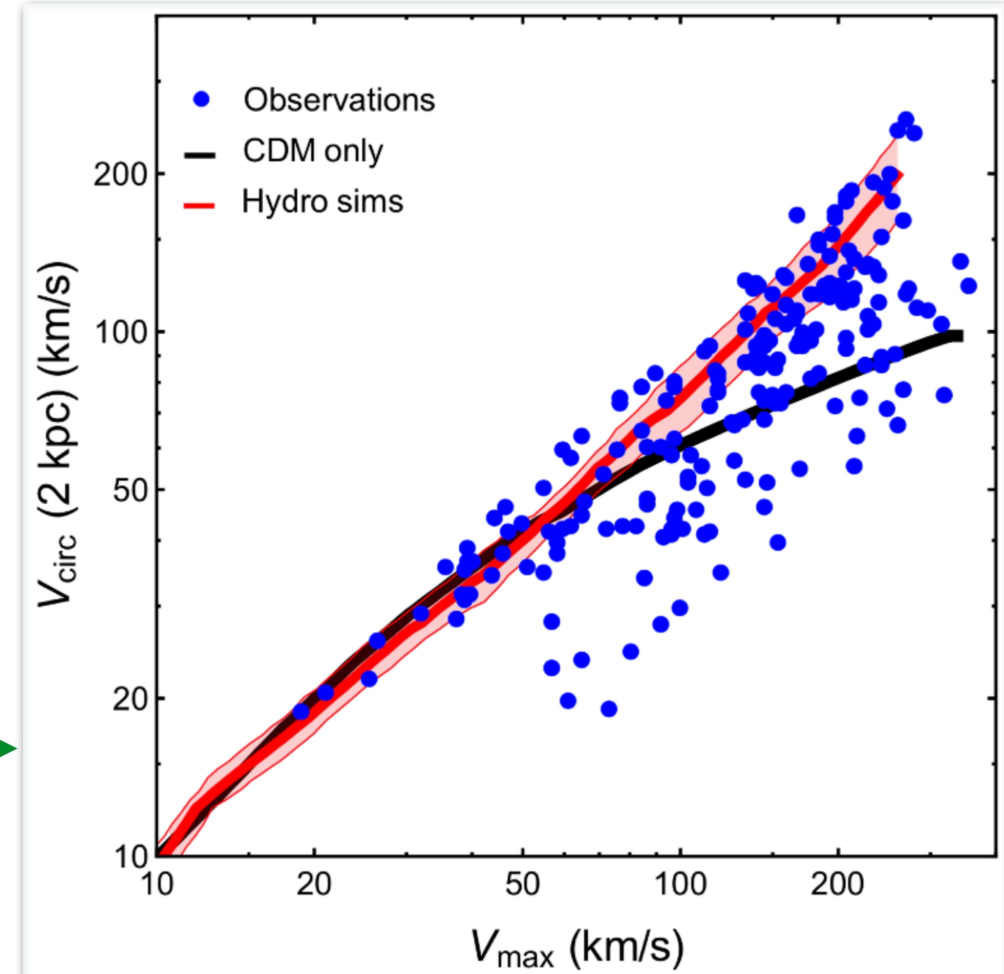

(My) Take Too early to say if baryon effects are (not) enough to explain observations

Attitude here: Let's study DM models that could give "signals" in structures

Baryon simulations may eventually converge

These DM models may give signals elsewhere

Dark Matter “Signals” in Structures?

Here **Signal** = deviation from collisionless CDM = evidence for DM interaction (beyond gravity)

$$R_{\rm scat} = \sigma v_{\rm rel}\rho_{\rm dm}/m \approx 0.1\ {\rm Gyr}^{-1} \times \left(\frac{\rho_{\rm dm}}{0.1\ \ {\rm M}_\odot/{\rm pc}^3}\right)\left(\frac{v_{\rm rel}}{50\ {\rm km/s}}\right)\left(\frac{\sigma/m}{1\ {\rm cm}^2/{\rm g}}\right) \approx\ 1\ {\rm barn/GeV}$$

Spergel Steinhardt astro-ph/9909386,….

O(1) **self-scatter** per DM particle ~ solve problems

If more, “heat” transfer inefficient

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Simulations of Self-Interacting DM

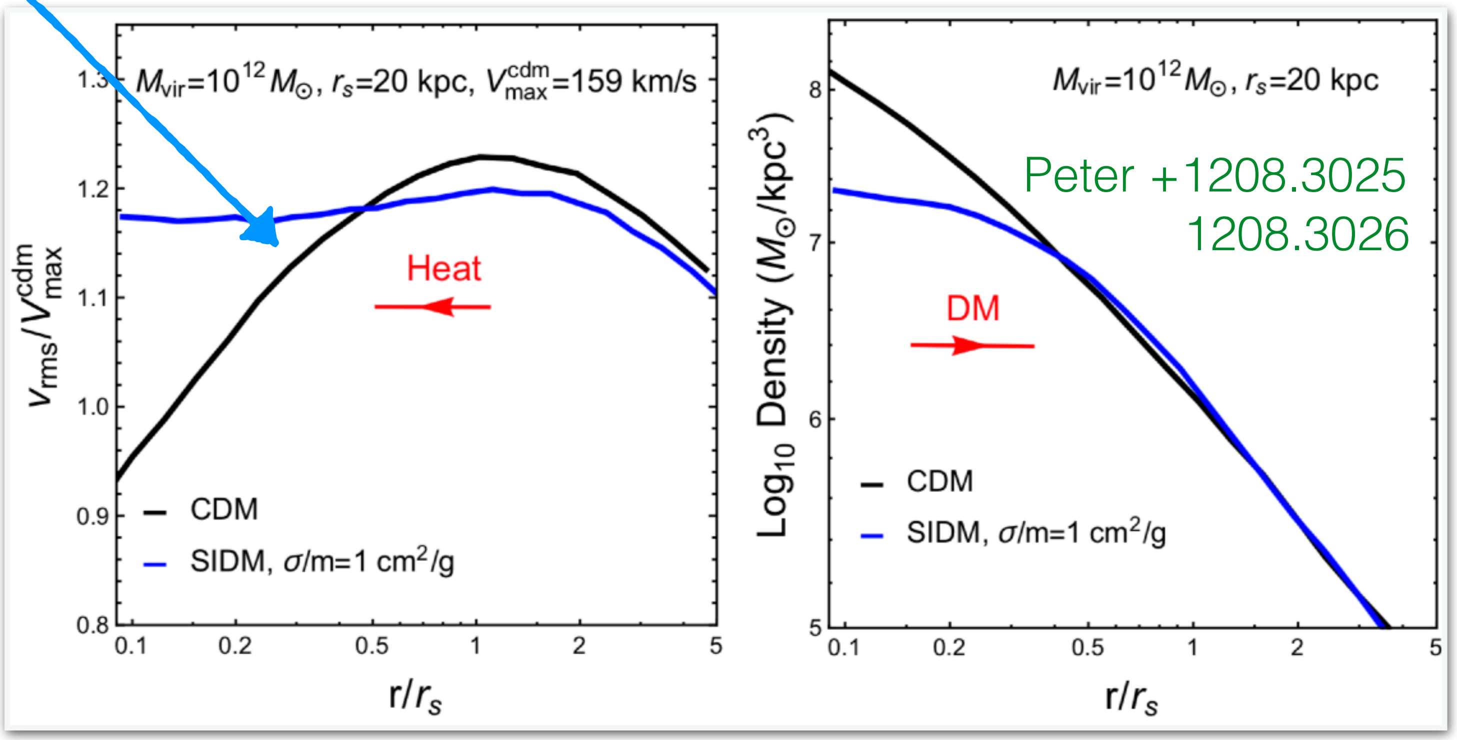
SIDM + baryons are in early stage

see e.g.

Vogelsberger+ 1405.5216 for **cores vs cusps**

Kamada+ 1611.02716 for **diversity**

Very roughly: less DM in center $\Rightarrow$
> importance of baryons, that are "less regular"



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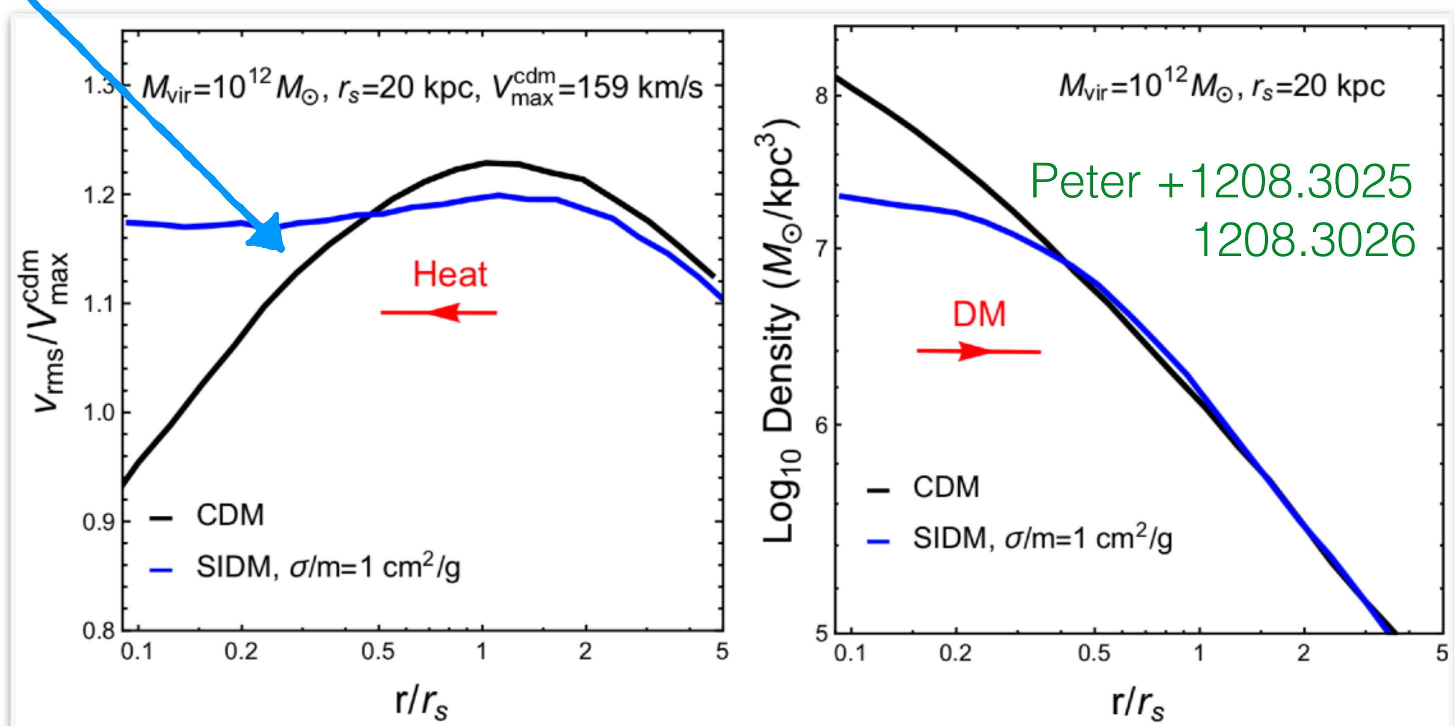


Constraints on larger scales $\dfrac{\sigma}{m} \lesssim 0.5\,\dfrac{{\rm cm}^2}{g}$ e.g. from Bullet cluster SW Randall+ 0704.0261

(

Problems on larger scales?

Disclaimer: my particle physicist understanding

Disclaimer2: seem less solid, might well be a false alarm…still, any feedback?

Pawlowski Kroupa Jerjen 1307.6210

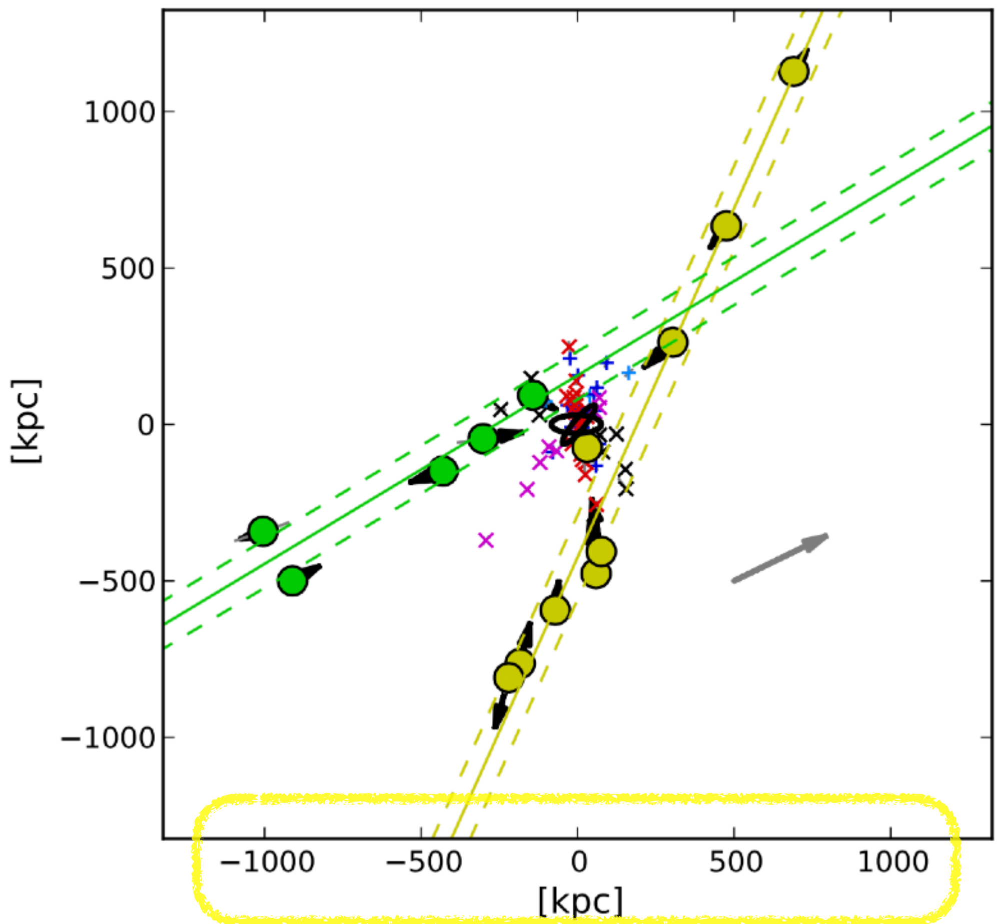
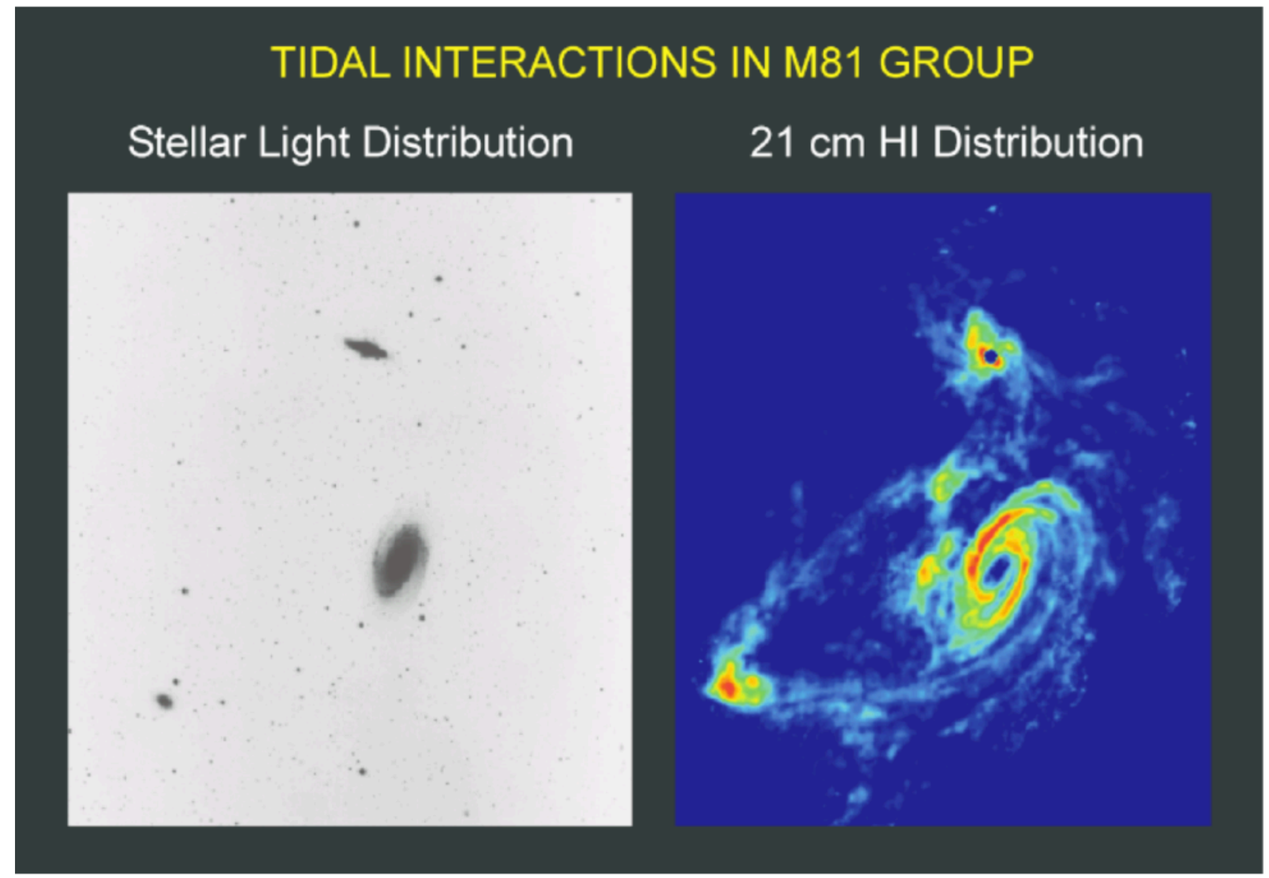


Figure 9. Edge-on view of both LG planes. The orientation of the MW and M31 are indicted as black ellipses in the centre. Members of the LGP1 are plotted as yellow points, those of LGP2 as green points. MW galaxies are plotted as plus signs (+), all other galaxies as crosses (×), the colours code their plane membership as in

Galaxies in the local group seem to be aligned in two planes

Too big scales to explain w/Galaxy formation

from Pavel Kroupa @ Jussieu 2017



(Old) dynamical analysis do not find solutions compatible with the observation that this galaxies have not merged

)

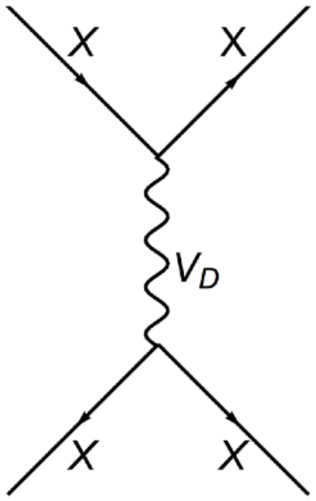
DM Signals beyond 10 TeV

DM Signals in Structures?

Dark Sectors & self interactions

Dark Sectors & self interactions

Dark U(1) DM & self-interactions



Prototype of **Self-Interacting DM**

Long-range self-interactions "reconcile" dSphs and clusters Feng+ 0905.3039

Buckley Fox arXiv:0911.3898,…

Larger in systems with smaller velocities

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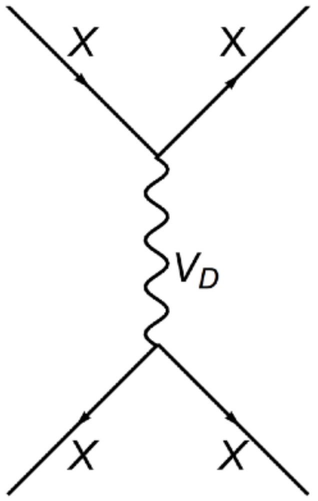

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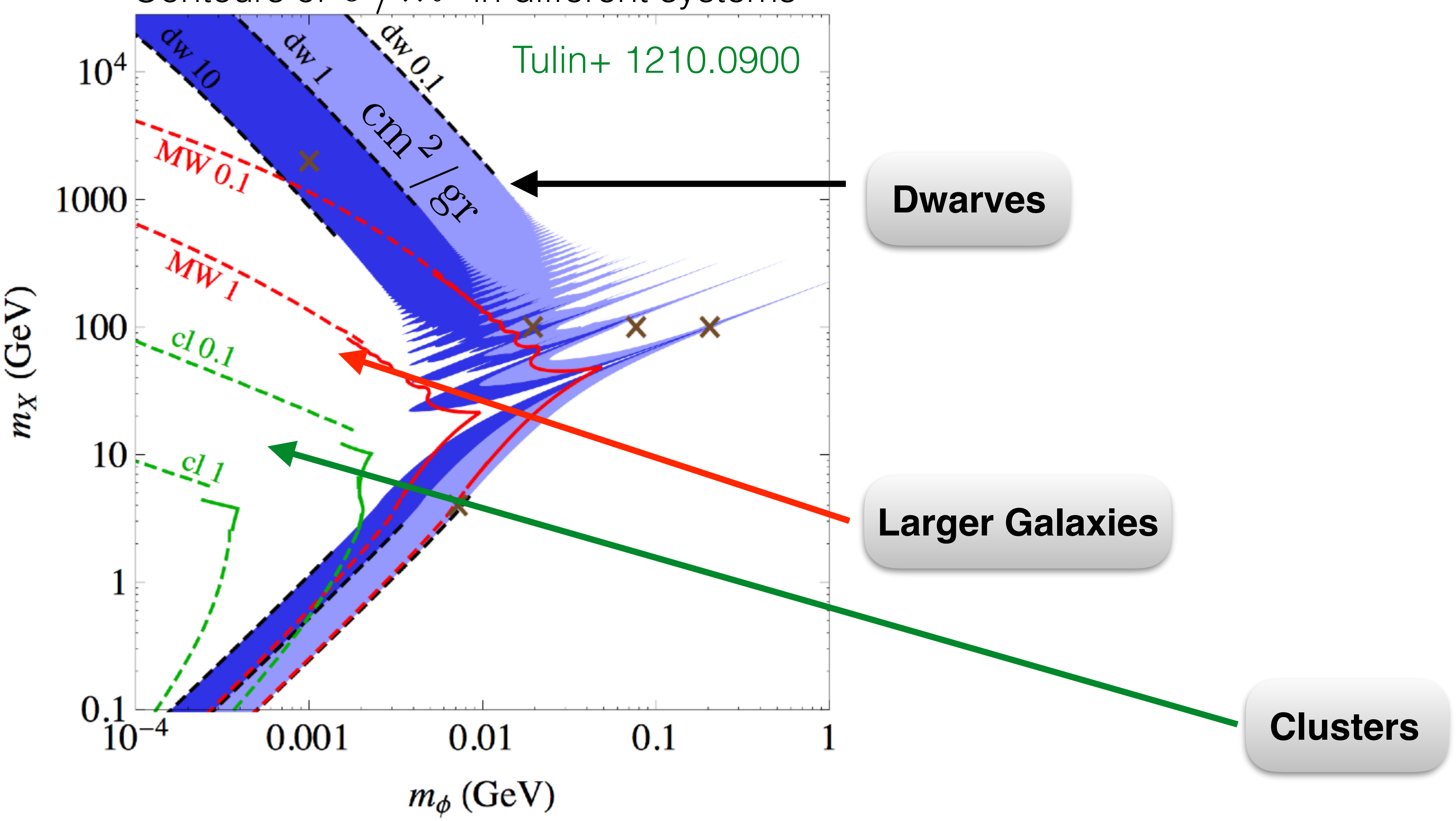
Contours of σ/m in different systems



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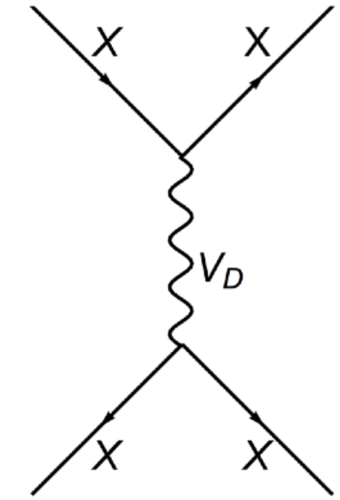

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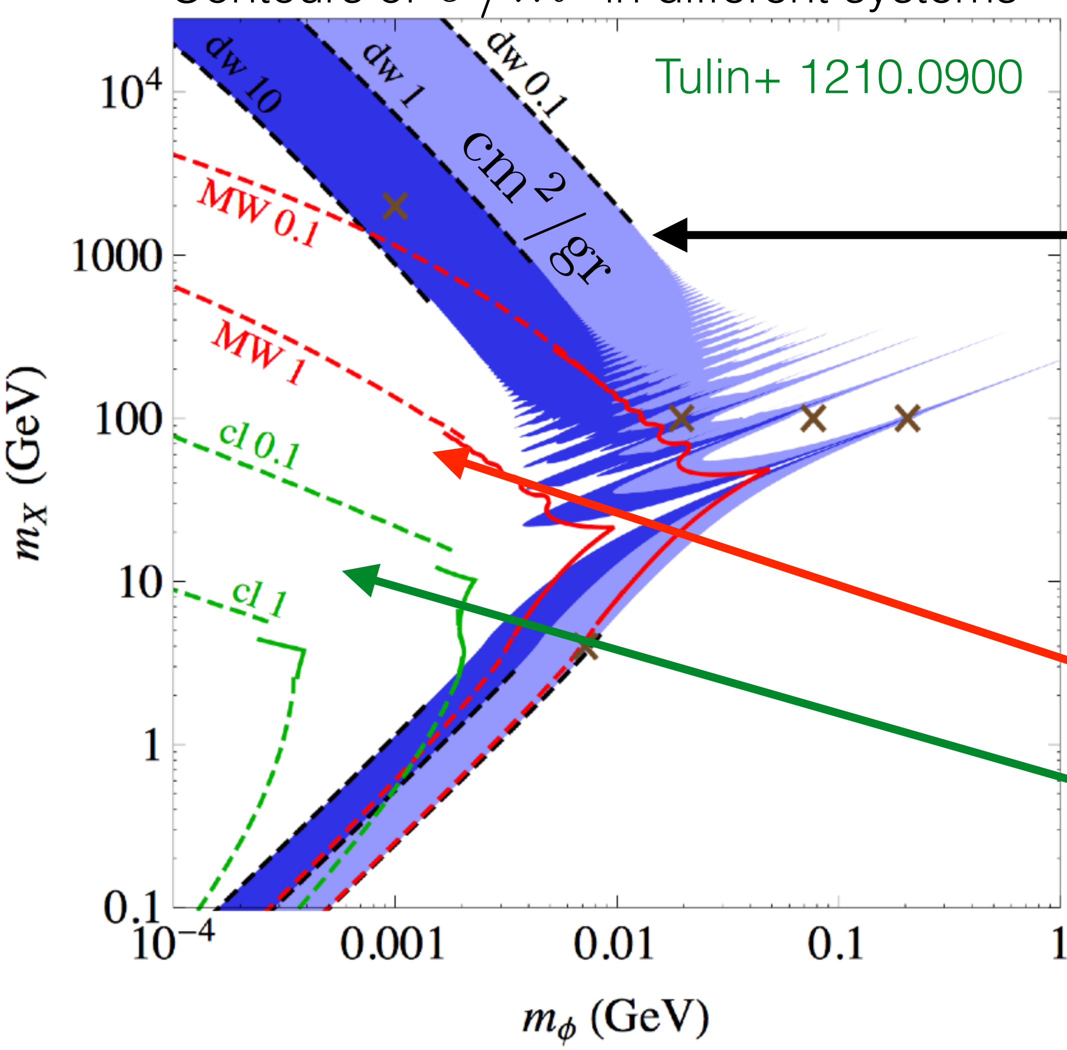
Larger in systems with smaller velocities

Contours of σ/m in different systems

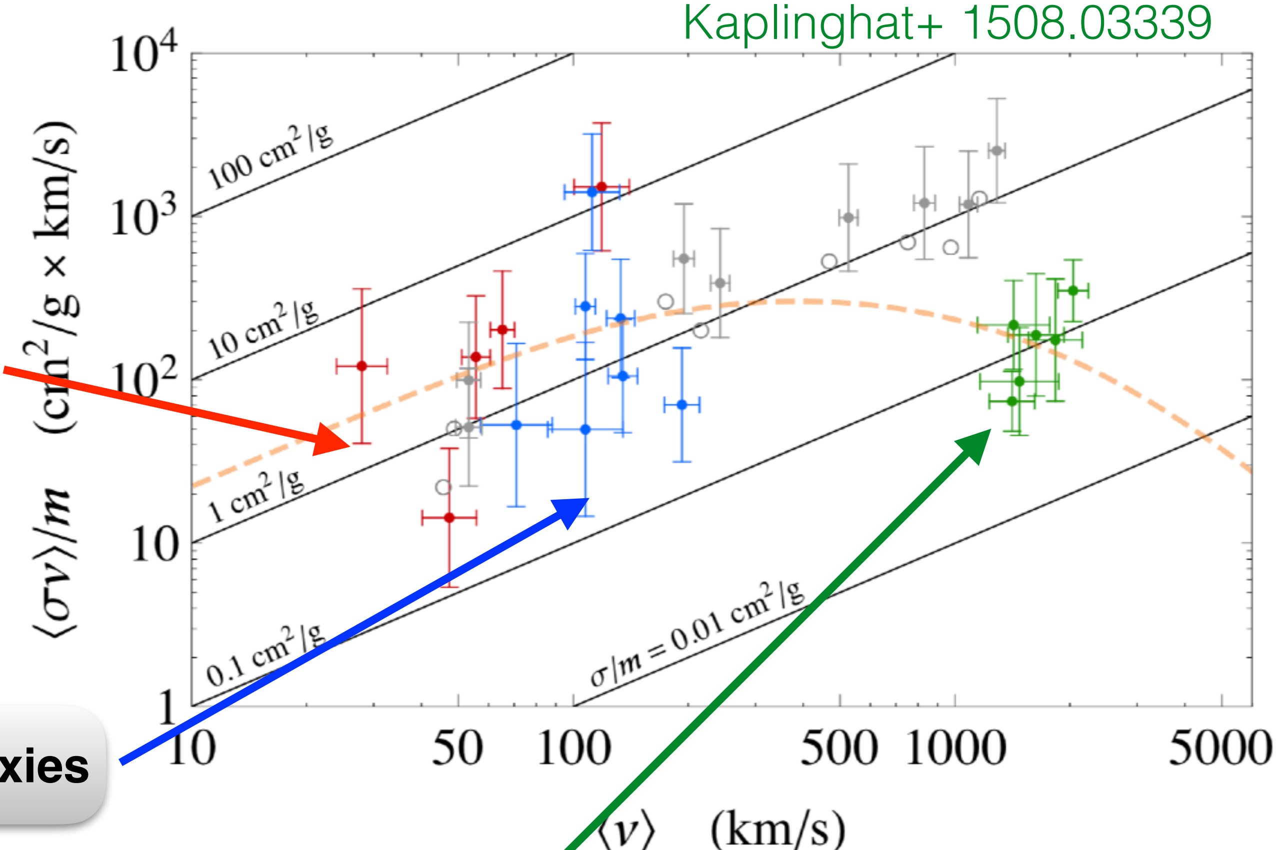


Dwarves

Larger Galaxies

Clusters

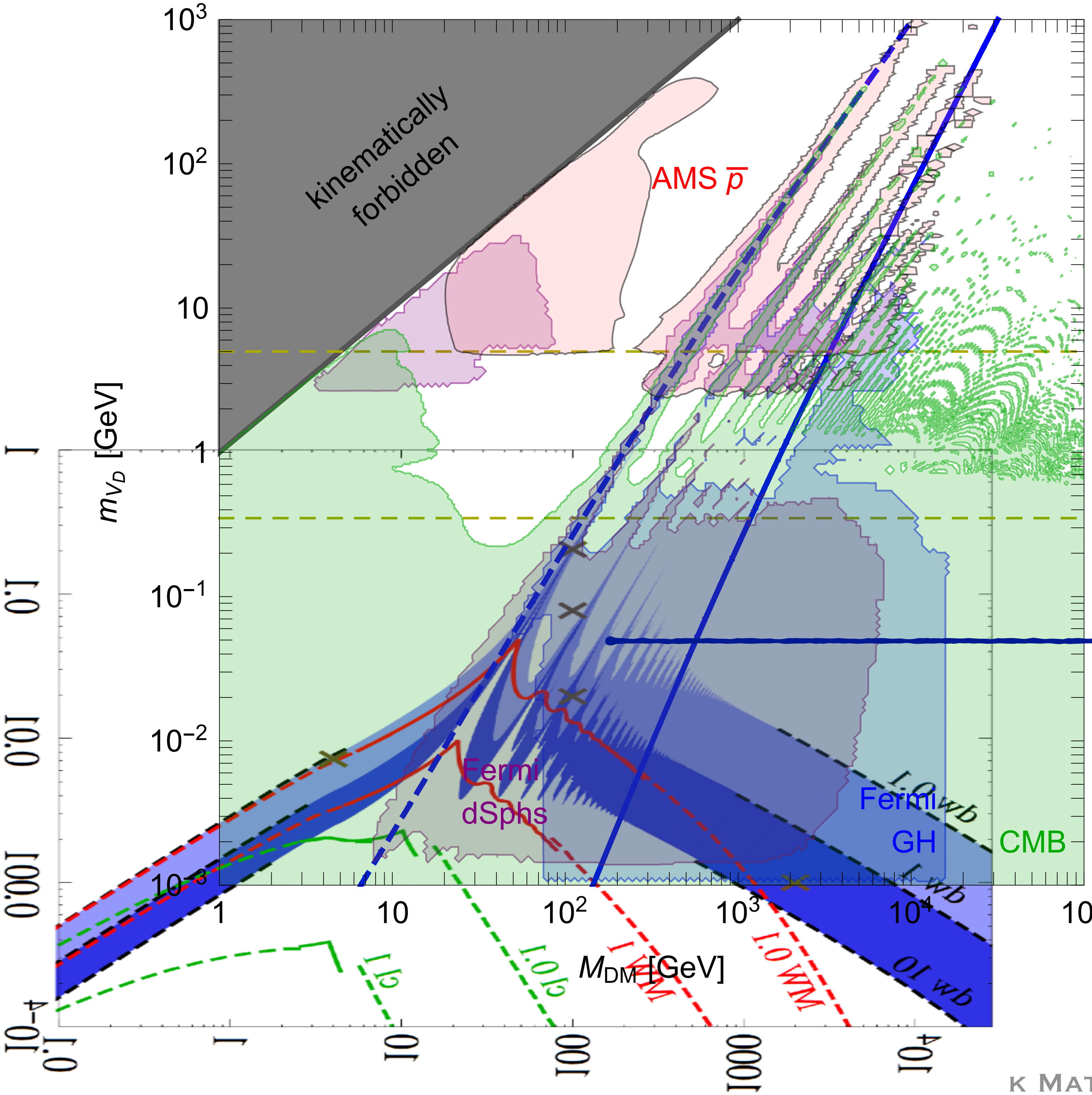
Kaplinghat+ 1508.03339



Summary of indirect detection

Cirelli Panci Petraki FS Taoso 1612.07295

Exclusion by all relevant probes



Excludes this DM model as explanation of "anomalies"

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

see also Bringmann+1612.00845

How to Recover Self Interactions

General Messages from our study of a specific model

If observable Self-Interactions from long-range interactions of symmetric DM

then **CMB** is a challenge

Ways-out Mediator decays into **neutrinos**

Annihilation dominantly **p-wave**

e.g. with scalar mediators
although not in good shape (CRESST, BBN,…)
see Kahlhoefer+ 1704.02149

…

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…

Or abandon some hypothesis:

Asymmetric DM

Inelastic Self-Interactions

Atomic DM

…

How to Recover Self Interactions

Asymmetric DM

Baldes Cirelli Panci Petraki FS Taoso 1712.07489

Asymmetric Dark U(1) DM

Goal How big of an asymmetry to not have Indirect Detection?

Other challenges?

Recently realised that ID signals are larger than previously thought
Baldes Petraki 1712.07489

Asymmetric Dark Matter

DM abundance from Asymmetry (like baryons) rather from Thermal Freeze Out (like neutrinos)

$$Y_X = \frac{n_X}{s} \qquad Y_D \equiv Y_+ - Y_- \qquad \boxed{r_\infty \equiv (Y_-/Y_+)_{t\to\infty}}$$

DM renamed "**Dark Proton**" $M_{p_D} = m_p \frac{Y_B}{Y_D}\frac{\Omega_{\rm DM}}{\Omega_{\rm B}}\left(\frac{1-r_\infty}{1+r_\infty}\right)$

Needs large DM annihilations

to realise $r_\infty \to 0$

[i.e. to kill symmetric population]

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U(1) exact → no way to generate a charge imbalance

→ a single species cannot be asymmetric (unless weird initial conditions)

→ population of "**Dark Electrons**" is ~ necessary

U(1) broken → same, unless asymmetry generated between U(1) breaking and freeze-out

Effects of Dark Electrons

Here Assume population of **dark electrons**

Mechanism for generating the asymmetry unspecified

$M_{e_D} < (<) M_{p_D}$

by definition

Dark Atoms form if $\frac{\alpha_D^2}{2} \frac{M_{p_D} m_{e_D}}{(M_{p_D} + m_{e_D})} > M_V$

interesting, but not here see e.g. Cyr-Racine Sigurdson 1209.5752

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Indirect Detection Larger $e_D^+ - e_D^-$ annihilation cross sections

→ much suppressed symmetric relic population

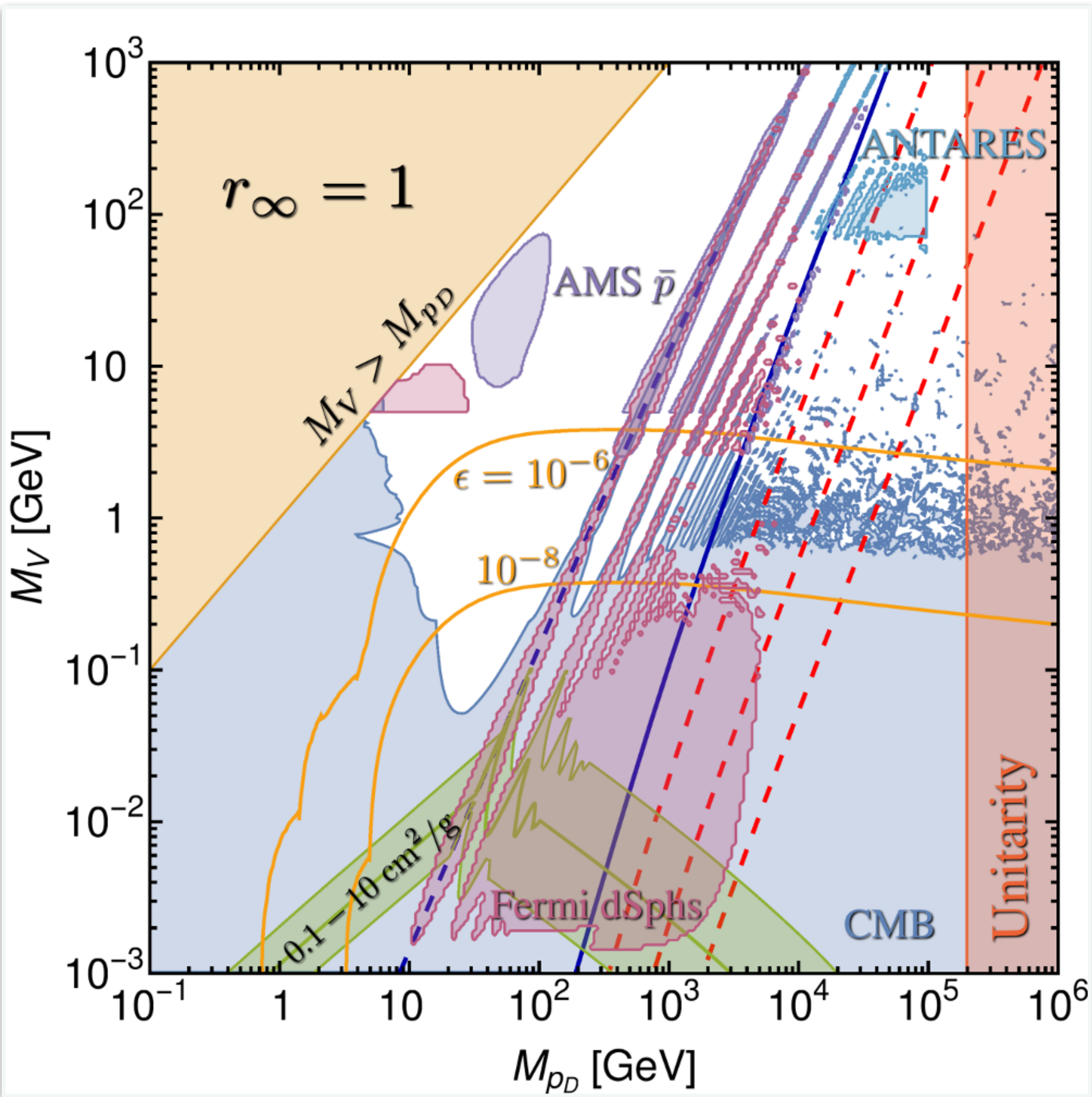
+ annihilation products ~ outside energy domain of telescopes

+ less energy depositi in medium (relevant for CMB)

Extra annihilation channels for $p_D - \bar{p}_D$ → suppress ID signals

Indirect Detection of Asymmetric DM

$$\sigma_{\rm ID}\, v_{\rm rel} \equiv \frac{n_\infty^+ n_\infty^-}{(n_\infty^{\rm sym})^2}\sigma_{\rm inel}\, v_{\rm rel} = \frac{4 r_\infty}{(1+r_\infty)^2}\,\sigma_{\rm inel}\, v_{\rm rel}$$



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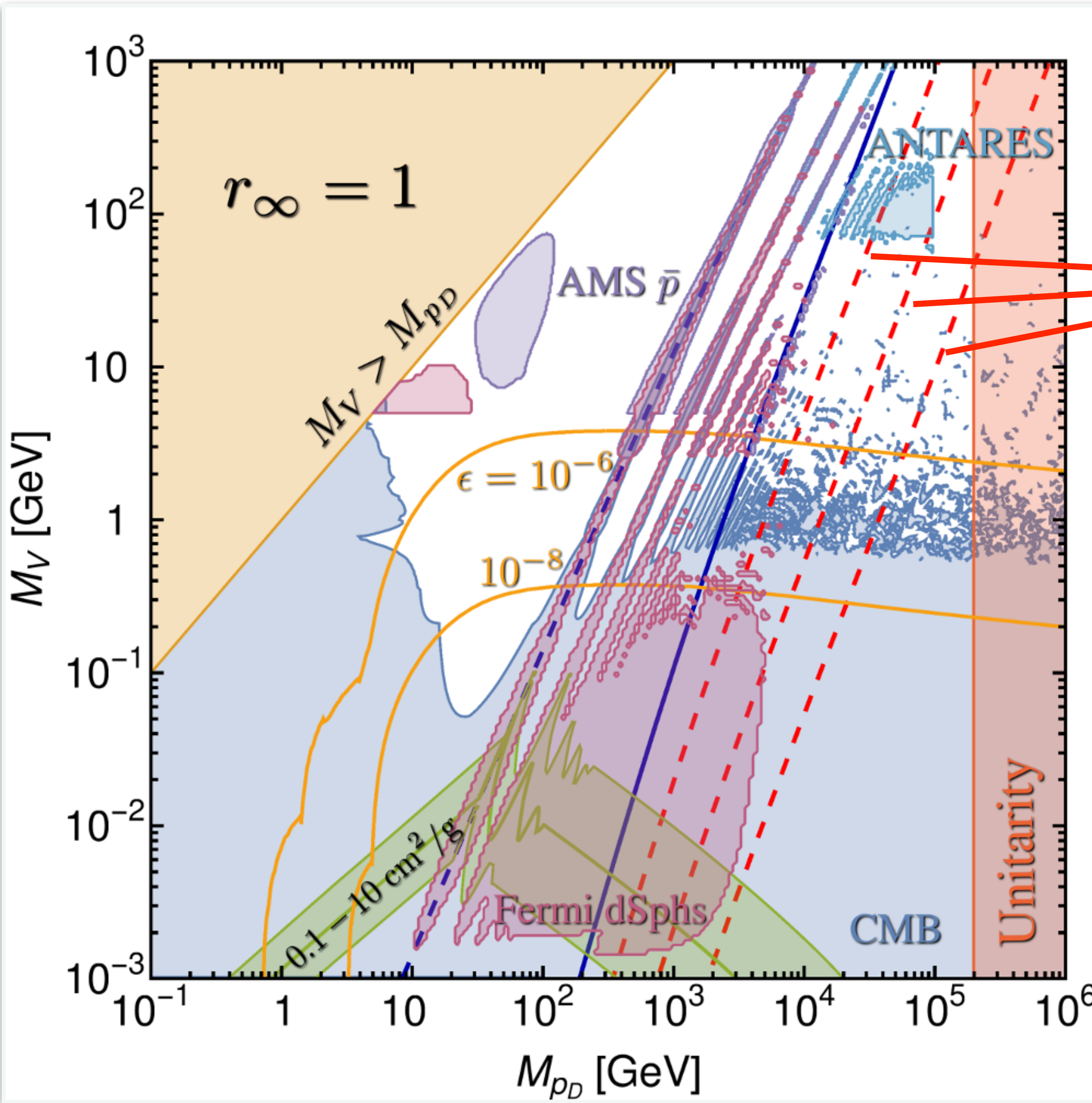

Dark atoms form right of red lines

$\Longrightarrow$ our study does not apply

Lines: $m_{e_D} = M_{p_D}/10, 100, 1000$

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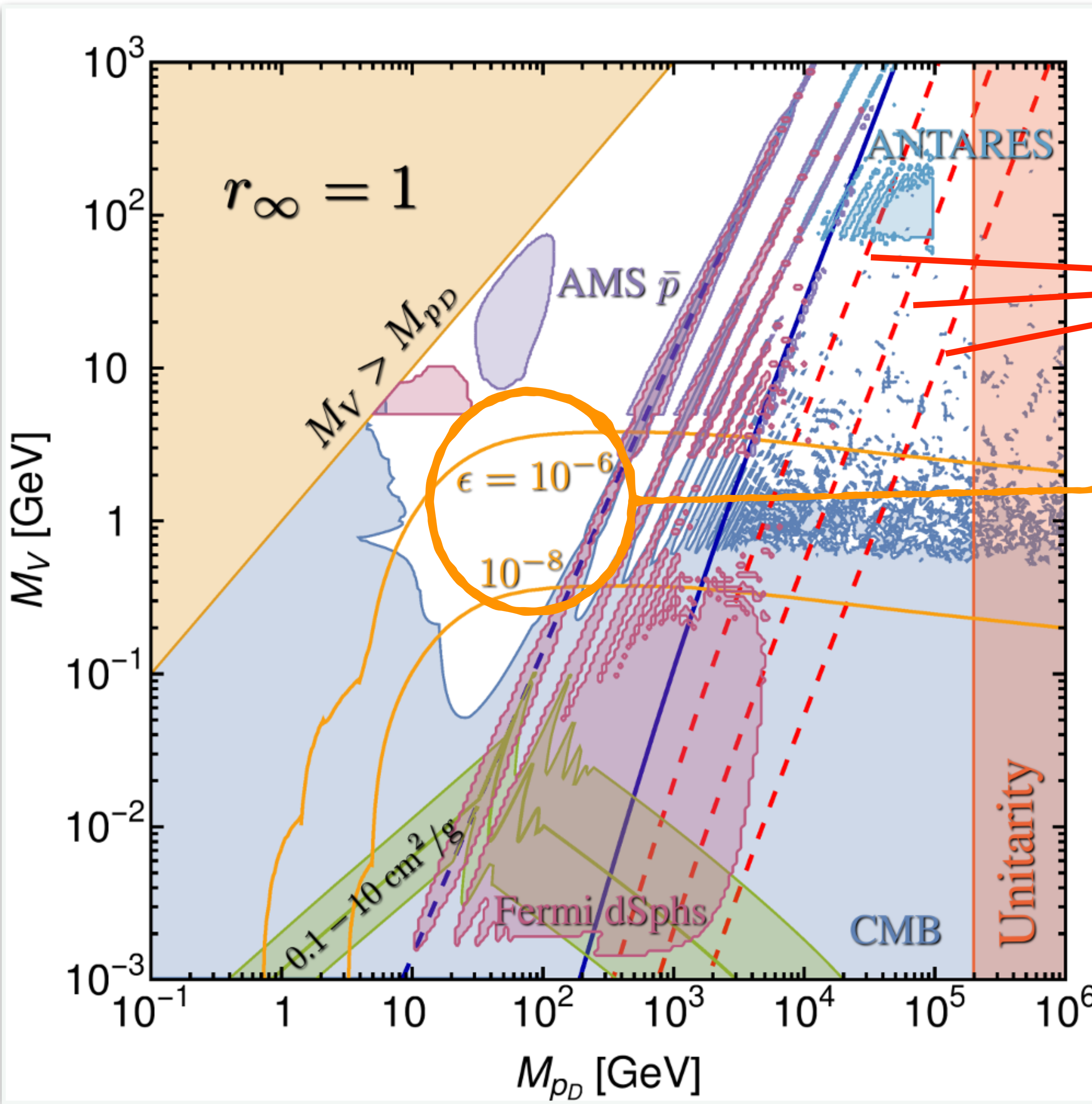

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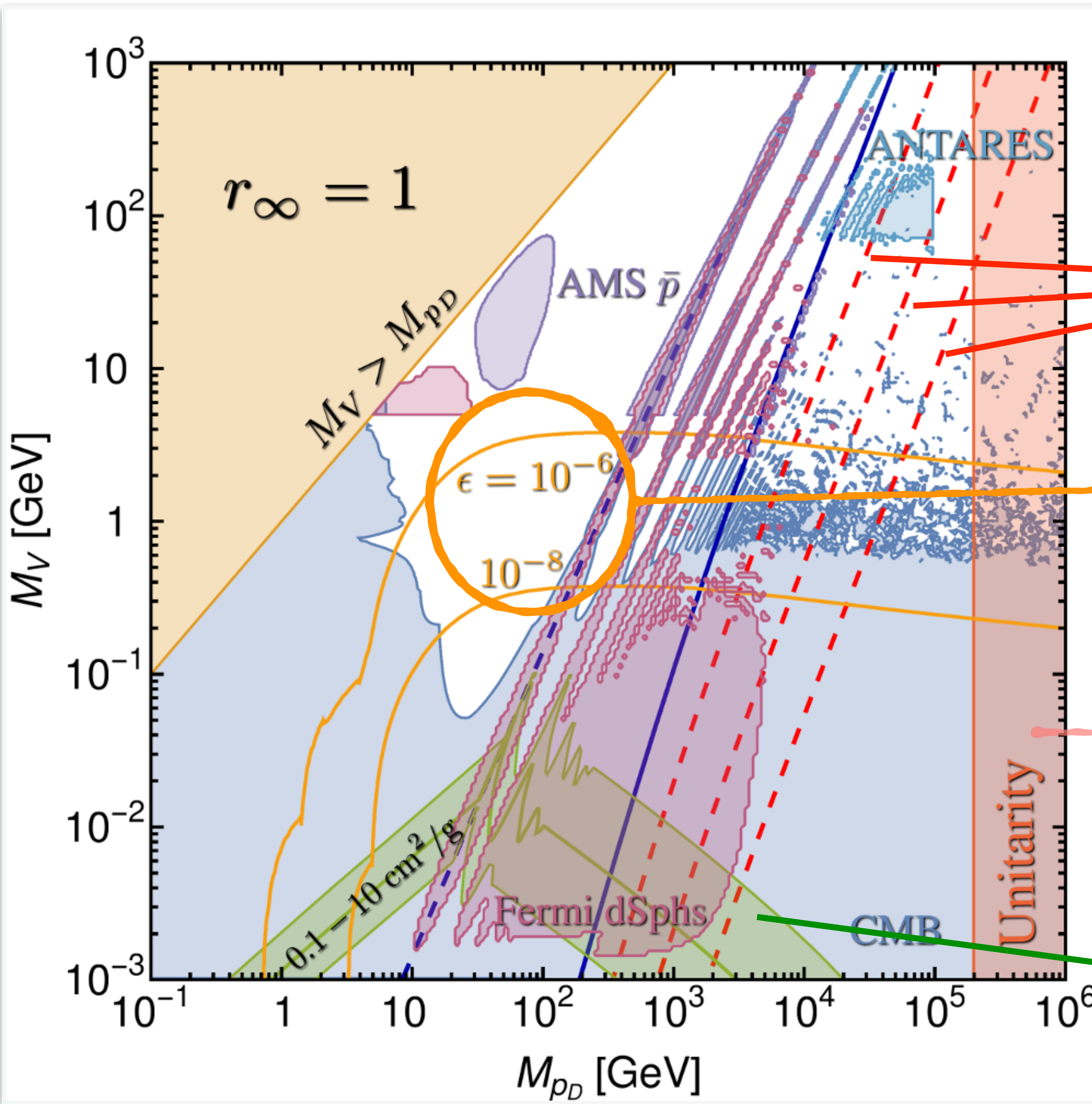

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Perturbative Unitarity Bound

self-scatter cross section in dSphs

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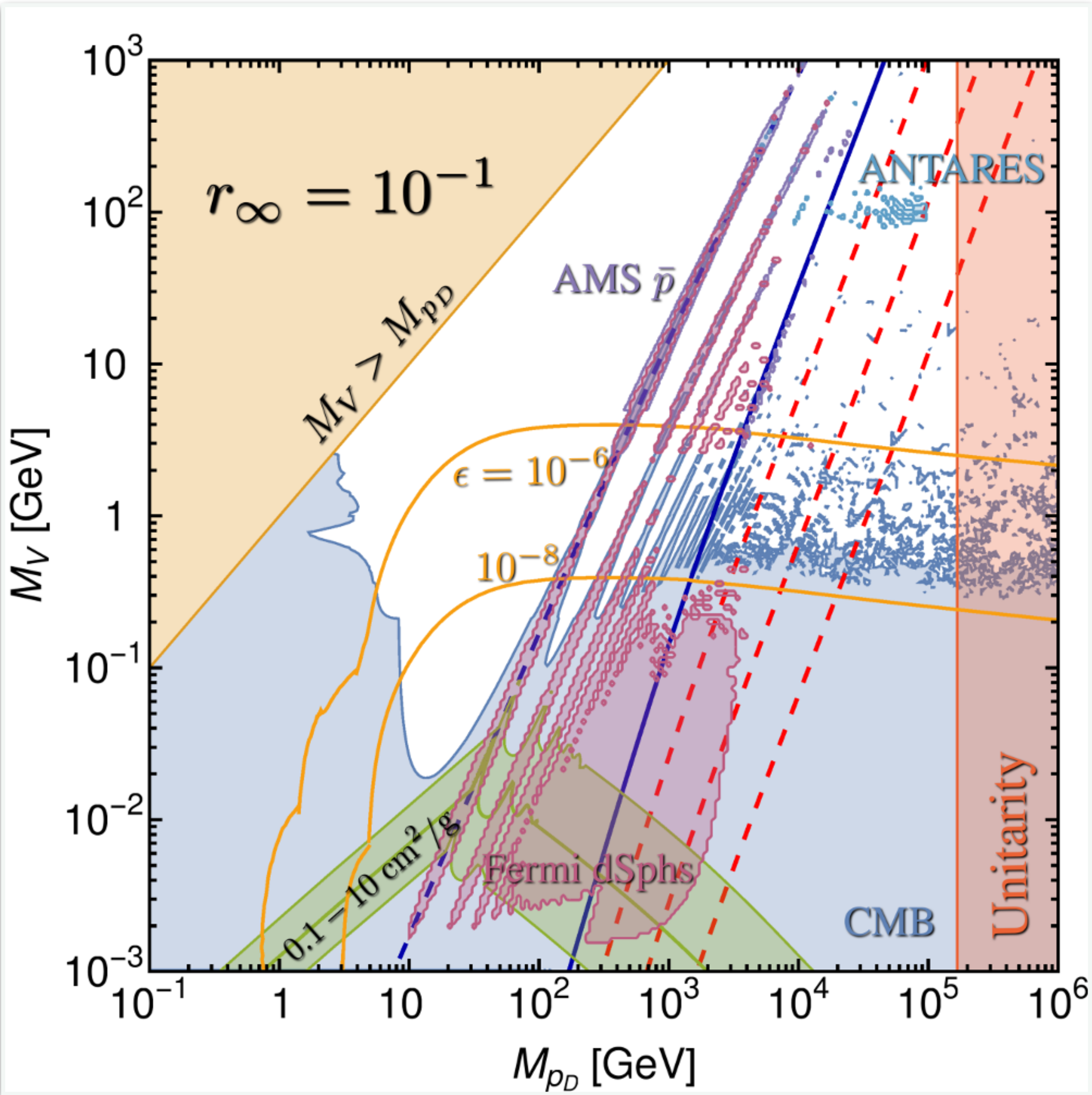

Smaller $r_\infty \Rightarrow$ Larger α_D

(Mild) changes also in

Direct Detection

Self scatter

Unitarity Bound

Indirect Detection of Asymmetric DM

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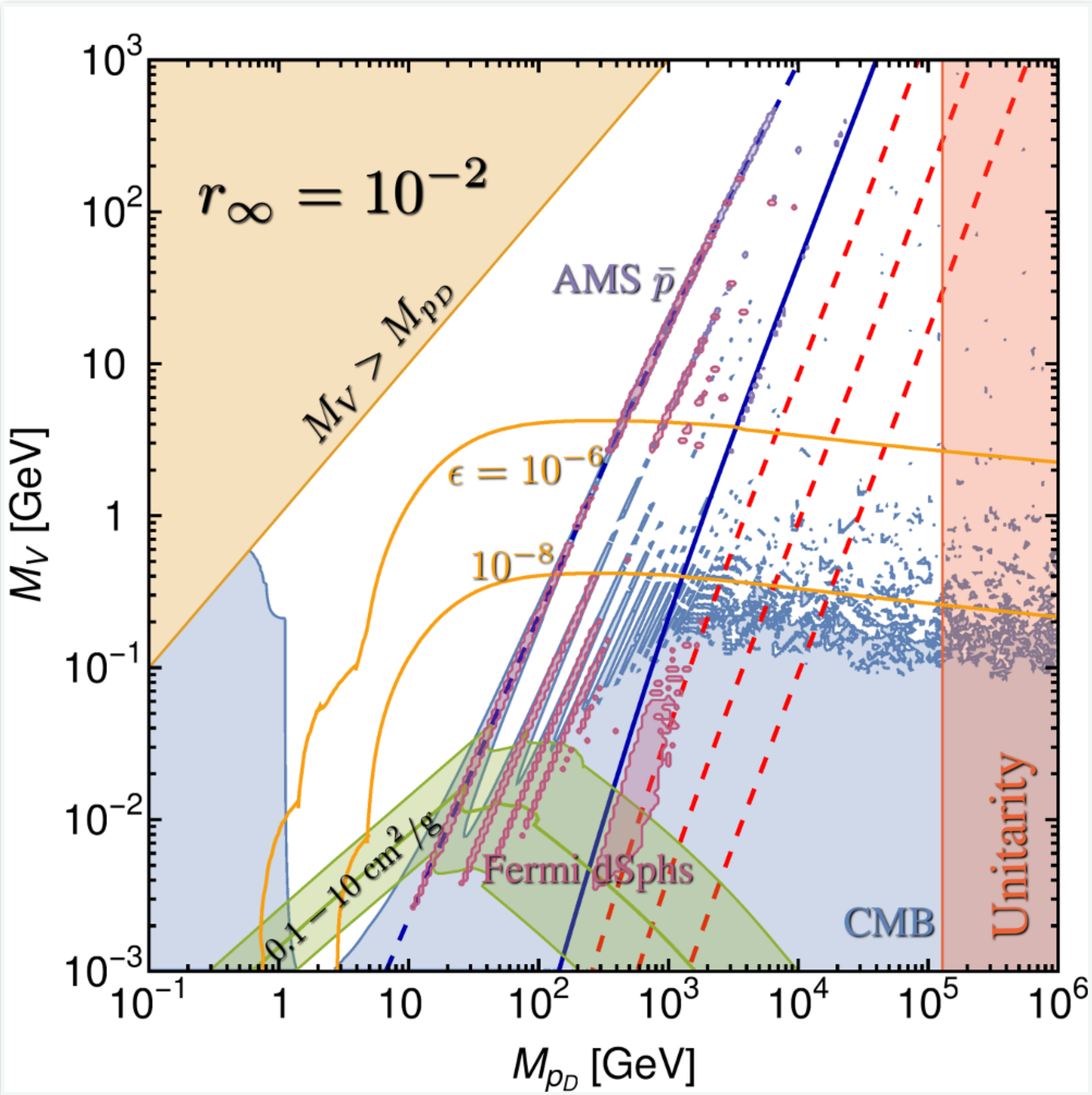

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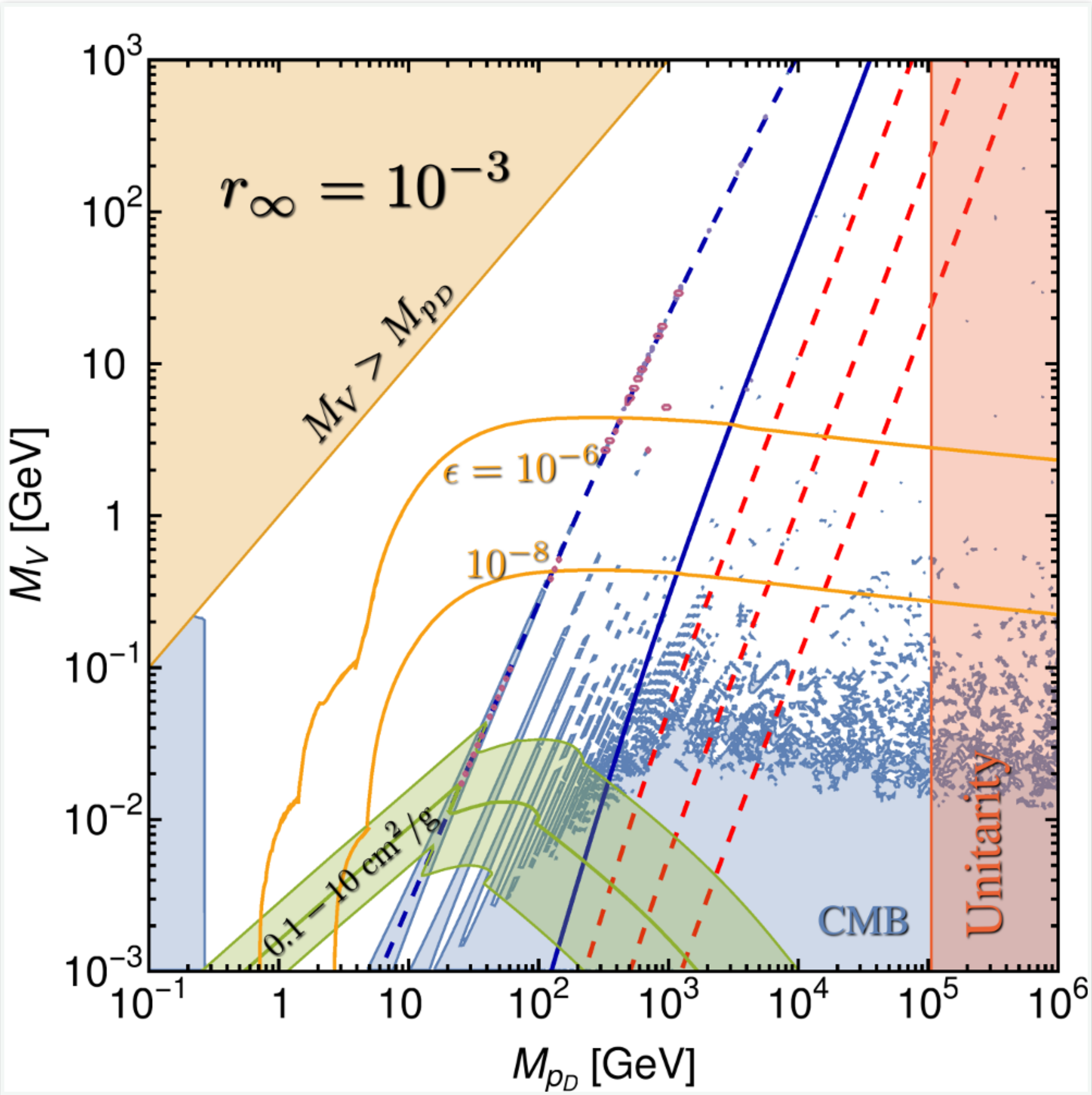

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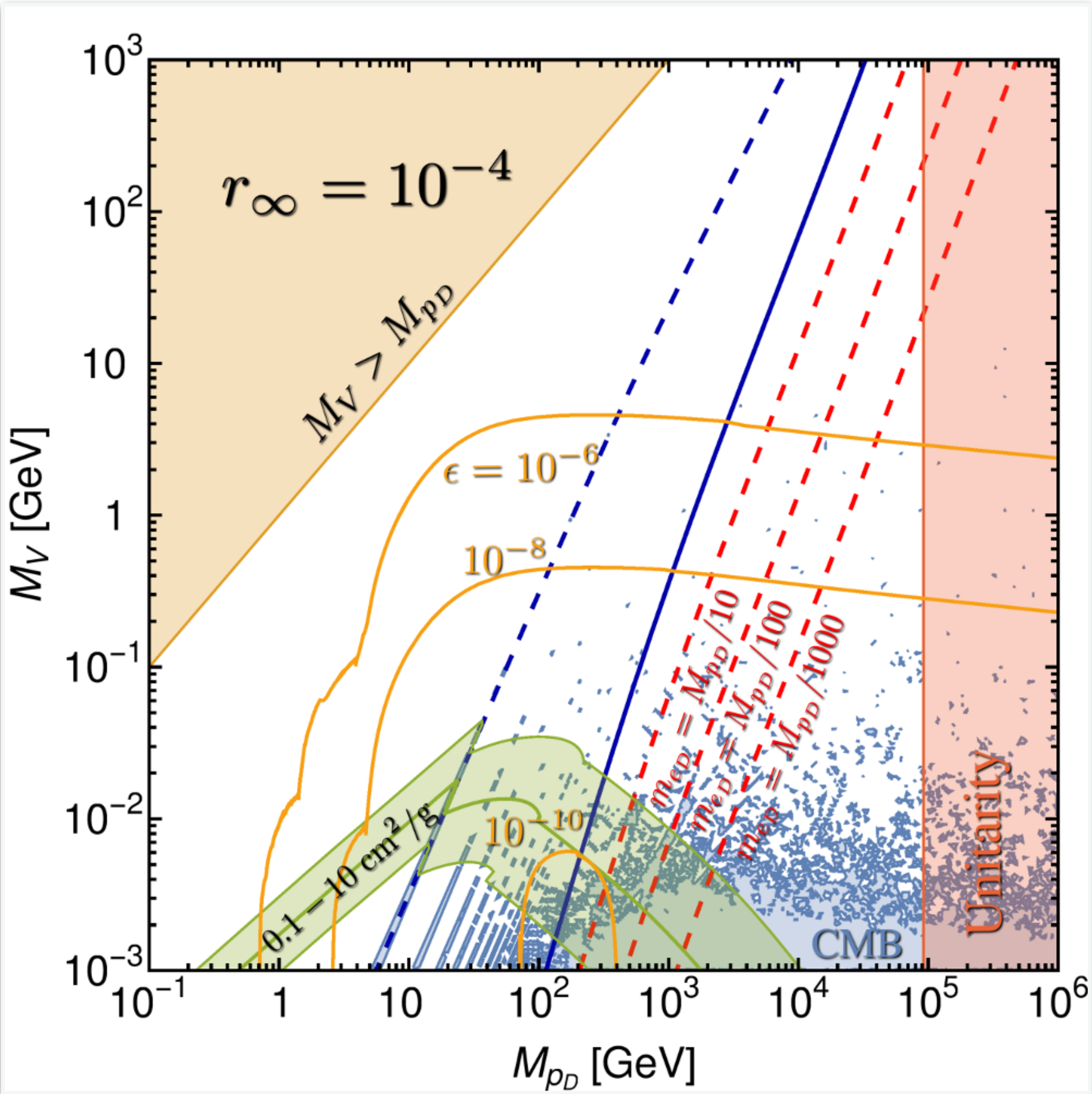

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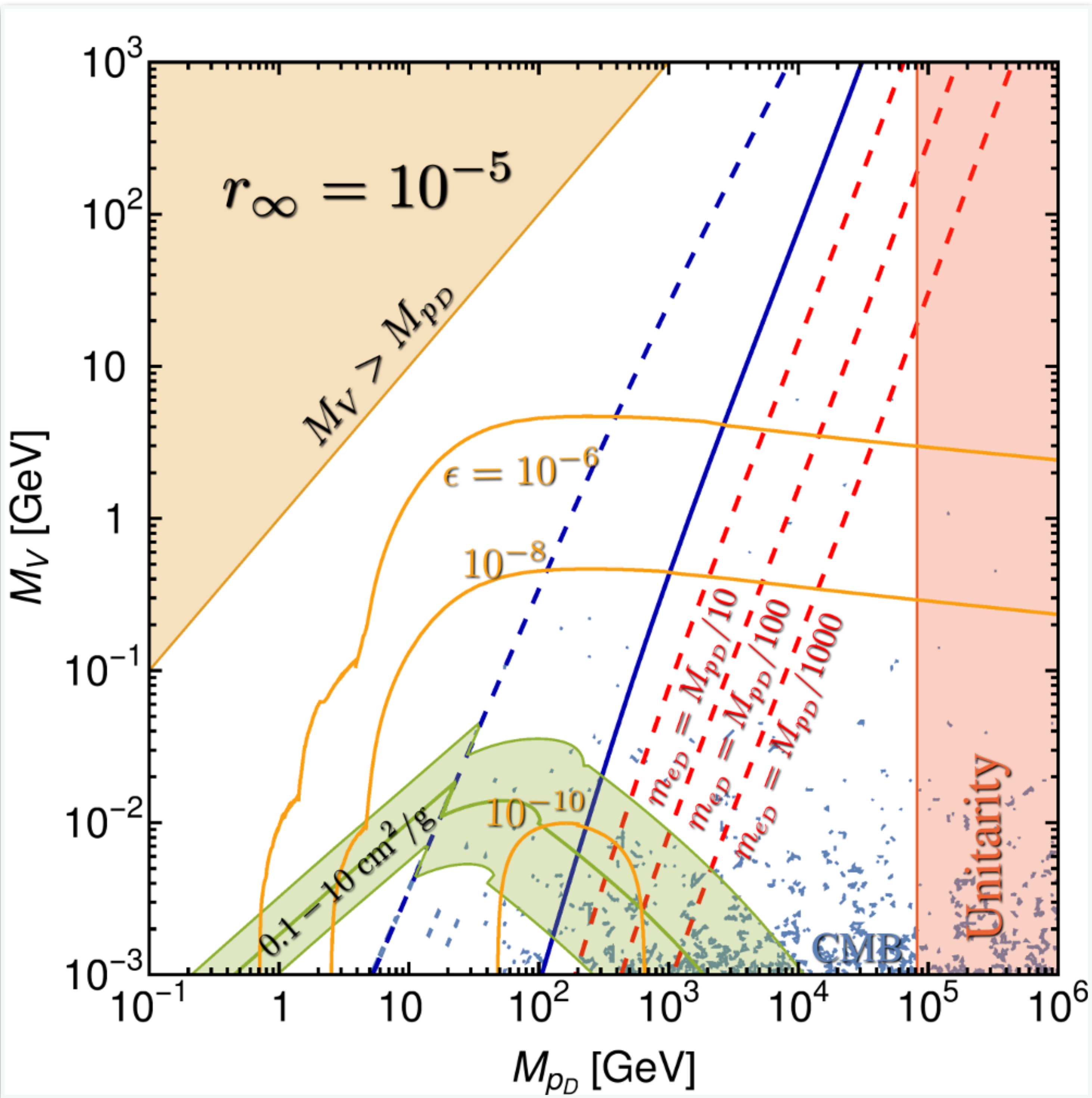

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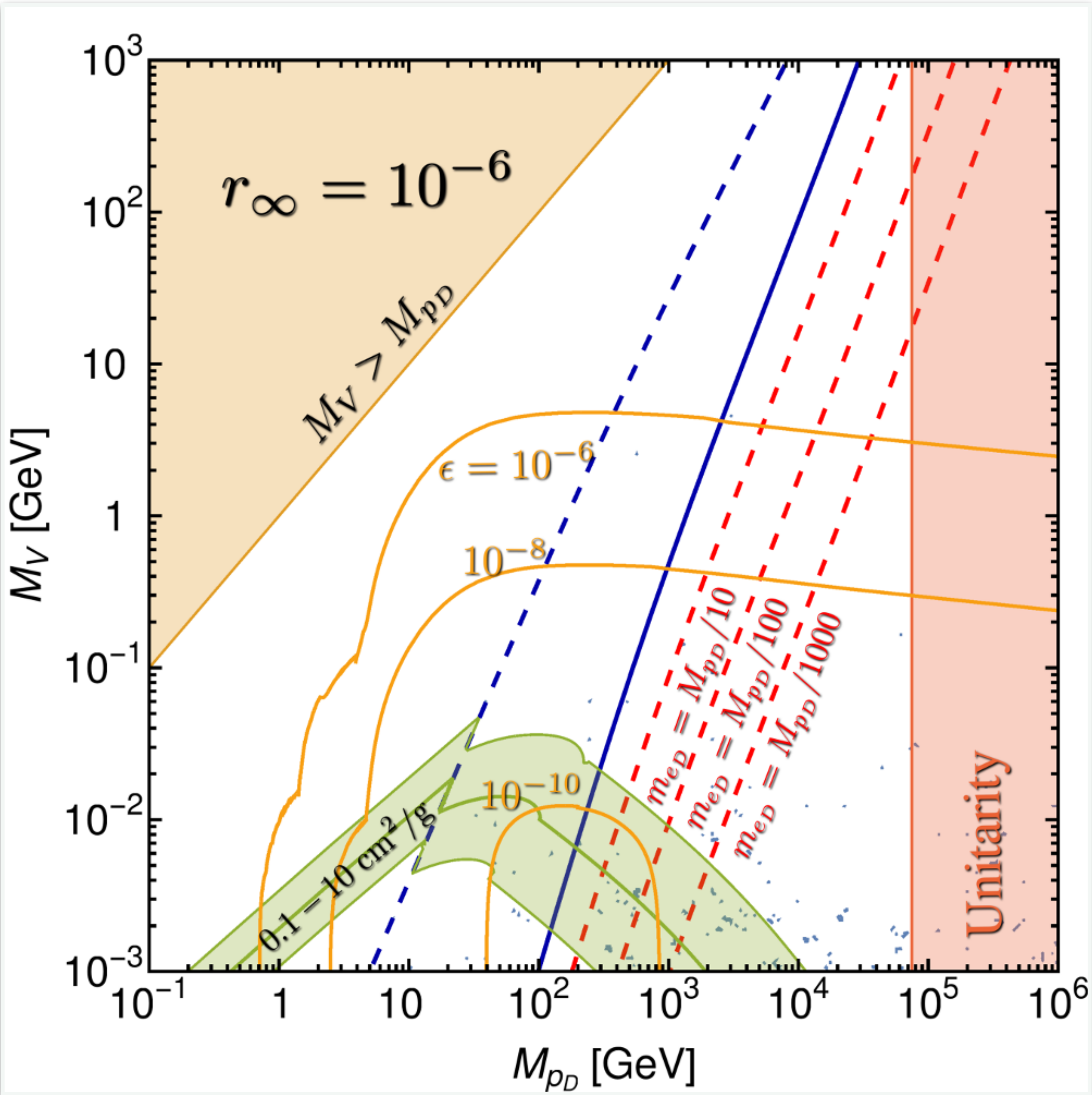


Conclusions & Outlook

Dark Matter from Dark Sectors

theoretically motivated

addresses challenges to exploring beyond 10-100 TeV

"Simple" case study: thermal DM charged under a dark U(1)

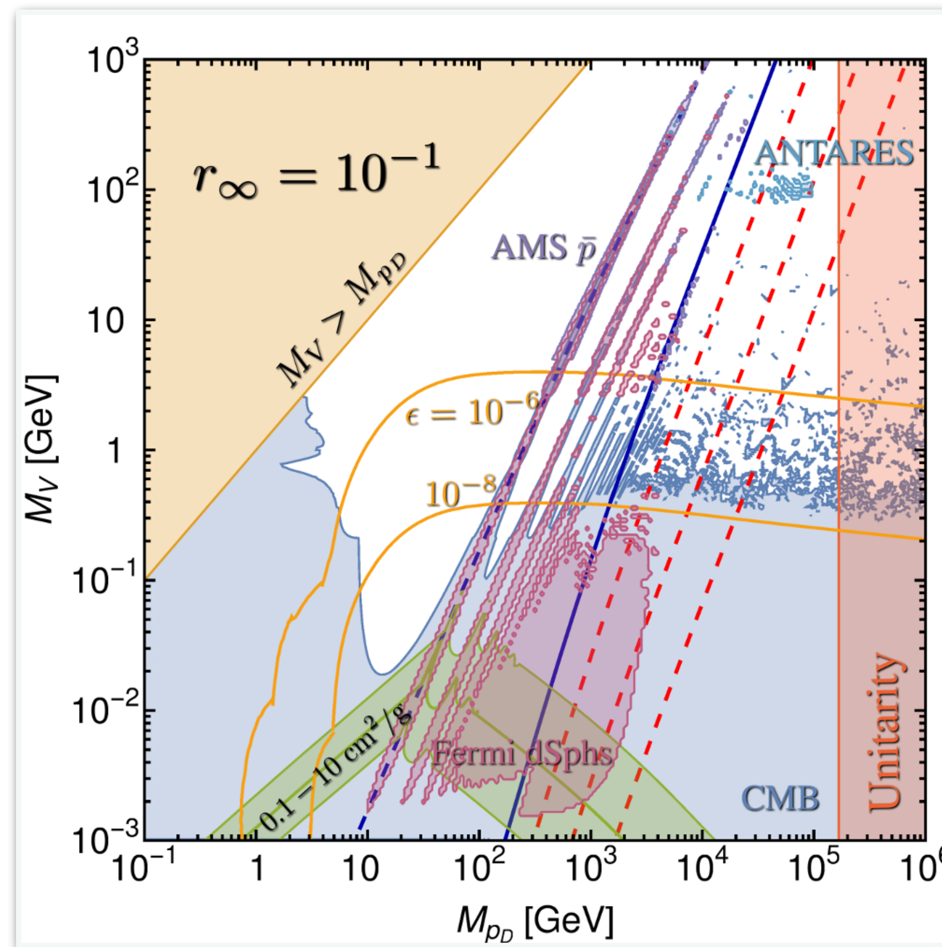
Our work Cirelli Panci Petraki FS Taoso 1612.07295
+Baldes 1712.07489

First systematic inclusion of bound state formation

This model as symm. Self-Interacting DM is excluded

CMB constrains Asymmetries down to 10^{-6}

Future: how to probe PeV thermal Dark Matter?



BACK UP

Origin of mediator mass

If from **Higgs mechanism**

$$V(S,H) = -\frac{\mu_h^2}{2}|H|^2 + \lambda_h|H|^4 - \frac{\mu_s^2}{2}|S|^2 + \lambda_s|S|^4 + \kappa|S|^2|H|^2$$

$$m_s^2 = 2\lambda_s v_s^2 = 2\lambda_s \frac{m_{V_D}^2}{q_s^2 g_D^2} = \frac{\lambda_s}{2\pi}\frac{1}{q_s^2\,\alpha_D} m_{V_D}^2$$

one can choose $q_s \ll 1$

to make S heavy enough

Otherwise

$2m_h > m_s \geq 2m_{V_D}$ $\quad S \to VV$ fast

$m_s < 2m_{V_D}$ $\quad S \to \mathrm{SM\,SM}$ via mixing with SM Higgs

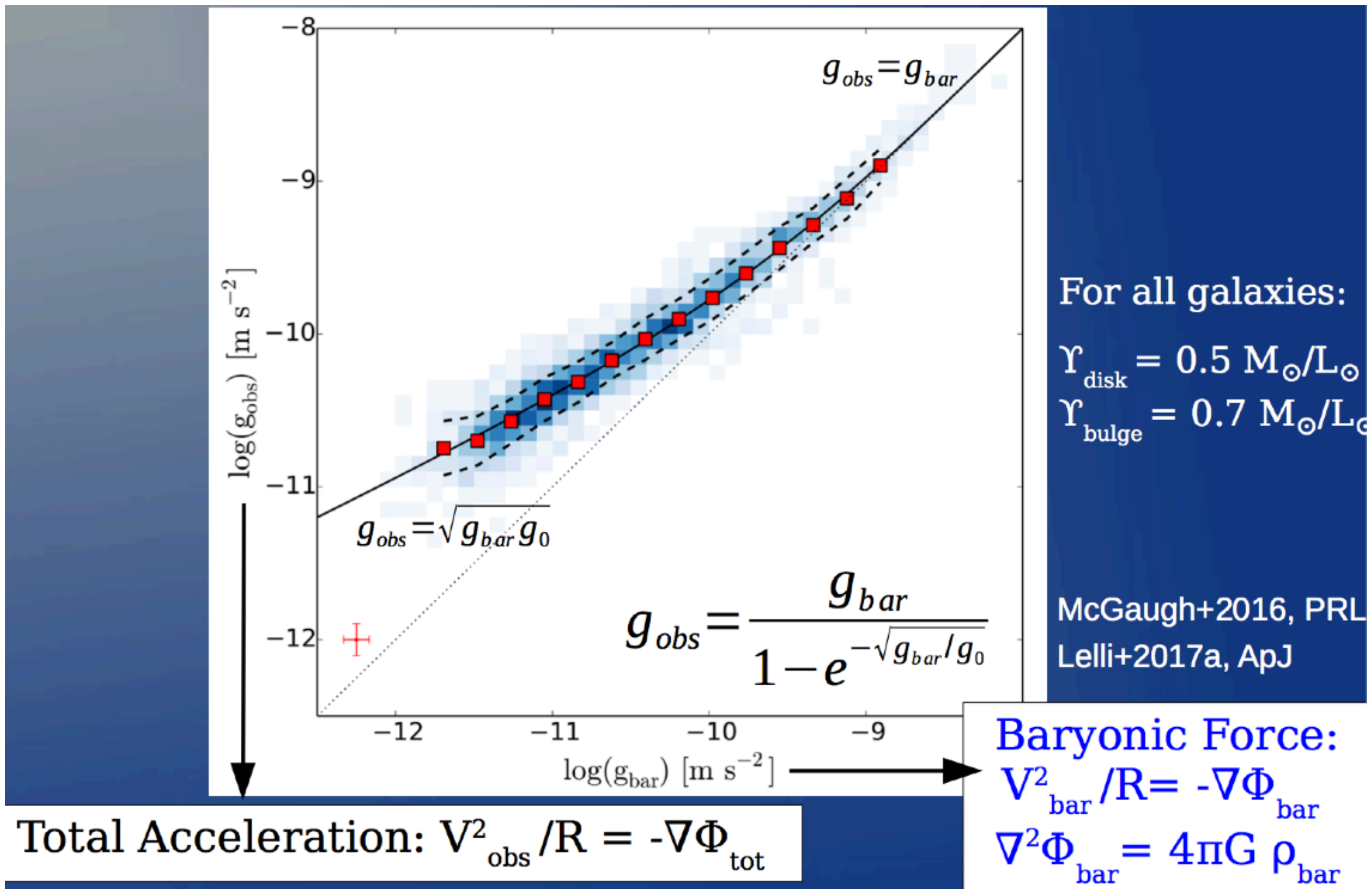
could be large from Higgs data
will be constrained by Direct Detection

$\boxed{\bar{\chi}\chi\,|S|^2}$ generated at one loop

[use $(g_D^2/2)\, s^2\, V_{D\mu} V_D^{\mu}$]

A fifth problem in structures?

New arrival: **MDAR** [= mass discrepancy vs acceleration relation]



from Federico Lelli @ Jussieu 2017

Could also point to modified gravity

Understanding w/baryon physics shown to be possible

Di Cintio Lelli 1511.06616

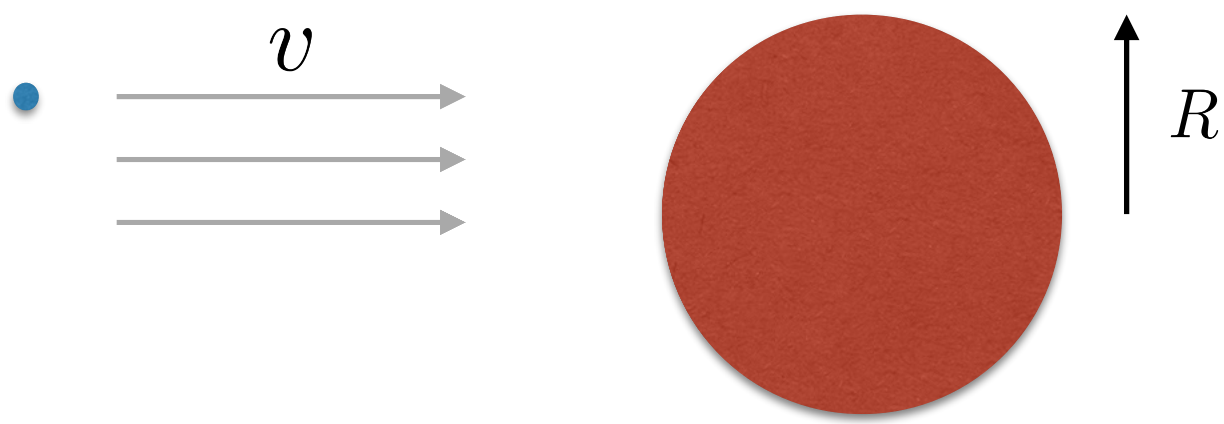
Ludlow+ 1610.07663

still observers are worried by small scatter of points

Sommerfeld enhancement

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

Classical analogous



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

If slow, gravity becomes important:

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

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

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

DM mass for SM weak force? $\alpha_{\text{w}} \sim 1/30$ $\boxed{M_{\text{DM}} \gtrsim 30\, M_{W,Z} \simeq 2.5\ \text{TeV}}$

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.**