PeV thermal Dark Matter

(in cosmic rays)

Cirelli Panci Petraki FS Taoso 1612.07295 + in progress w/**Gouttenoire**

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NewDark

LPTHE
LABORATOIRE DE PHYSIQUE
THEORIQUE ET HAUTES ENERGIES

"Exploring the dark universe", 24 July 2017, Quy Nhon Vietnam

What is Dark Matter?

DM candidates from models that solve other problems of the SM

WIMPs (hierarchy,…) Axions (strong CP) [Asymmetric] (baryogenesis,…)

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WIMPs (hierarchy,…) Axions (strong CP) [Asymmetric] (baryogenesis,…)

Motivated plenty of experimental activity!

Cosmic rays

Colliders

Resonances in cavities

Recoils on nuclei on Earth

…….

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DM candidates from models th

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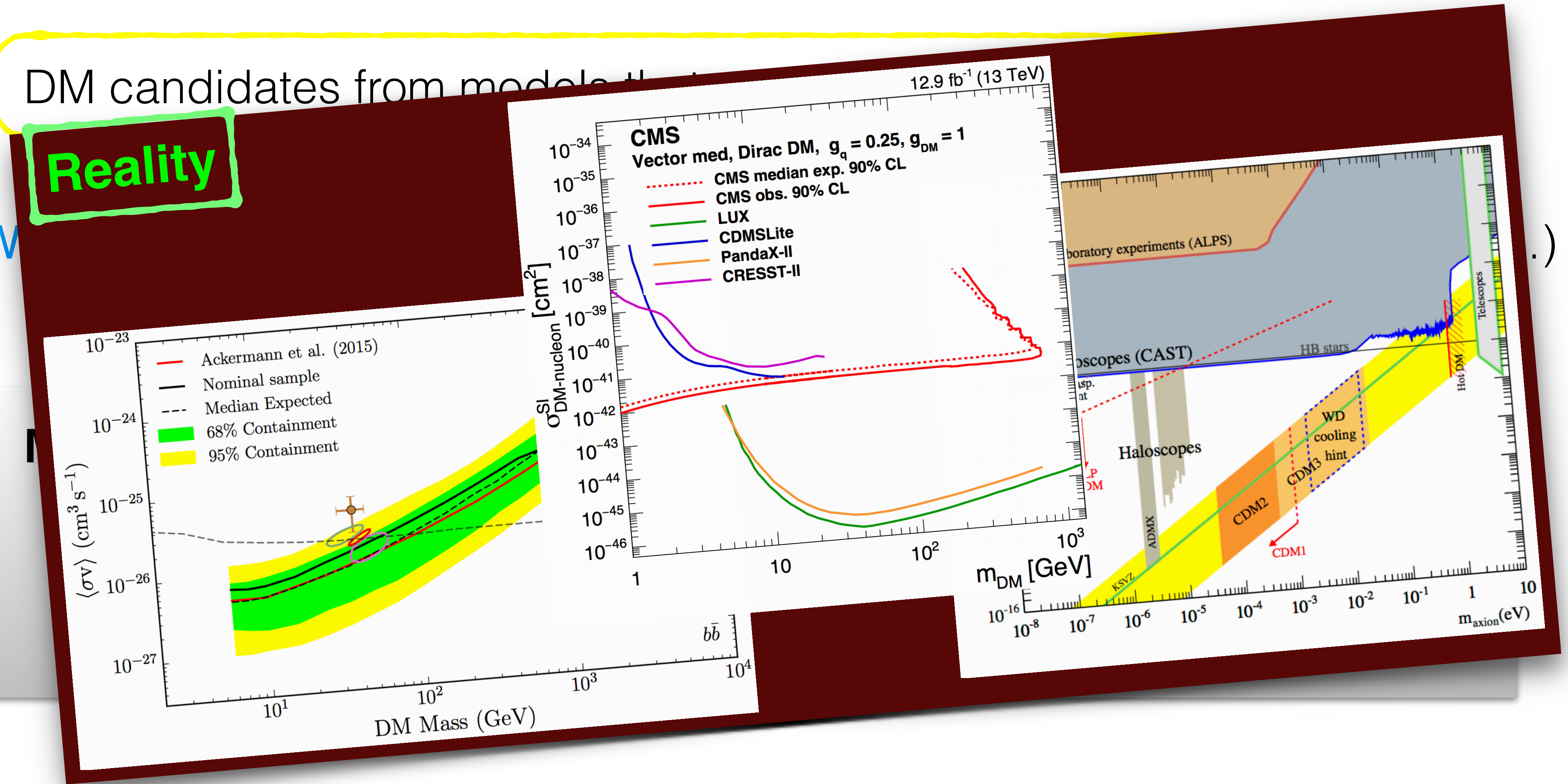
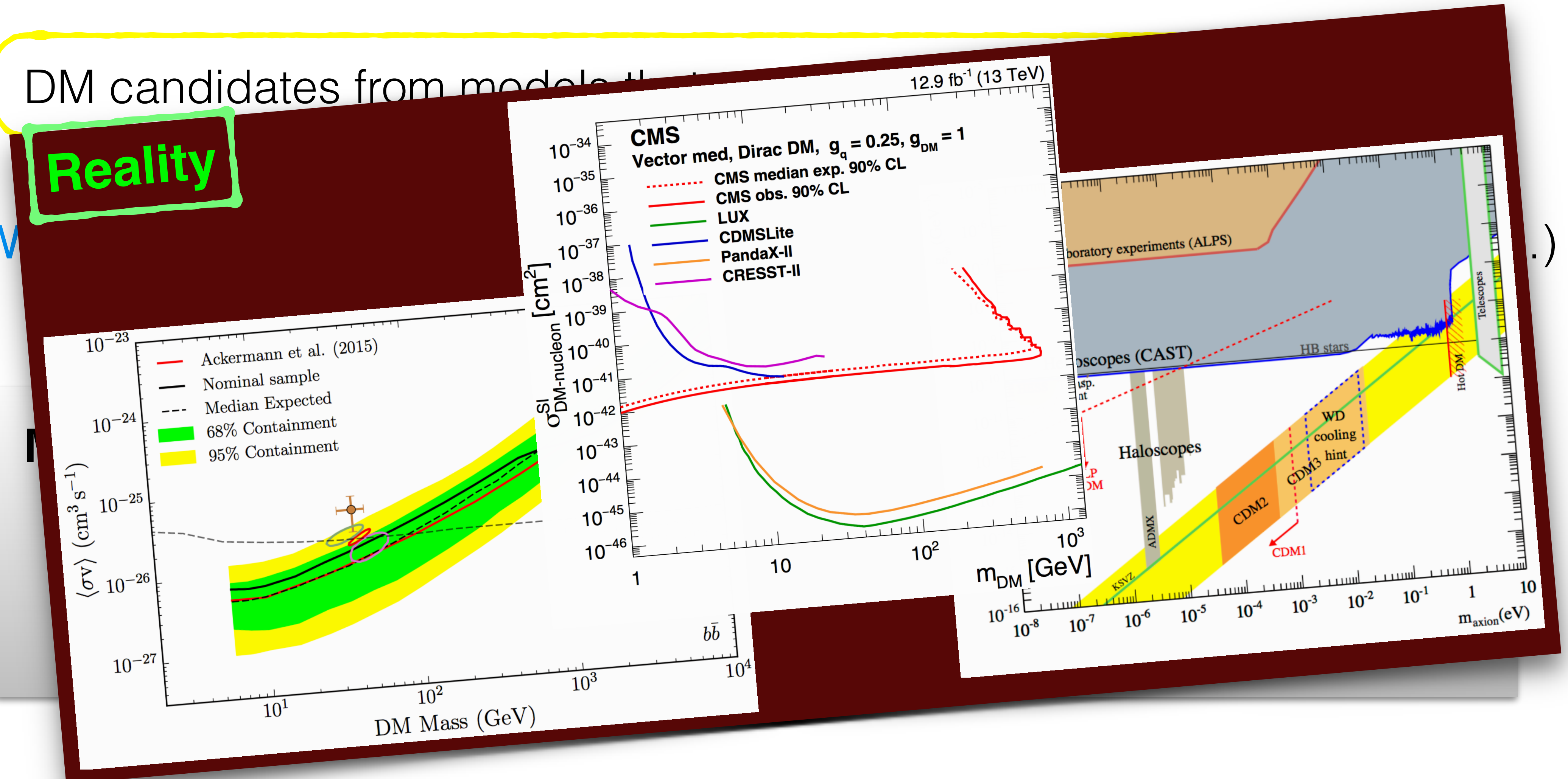


What is Dark Matter?

DM candidates from mod



DM models to solve putative anomalies

Cosmic rays (positrons, Fermi-line, Hooperon,…)

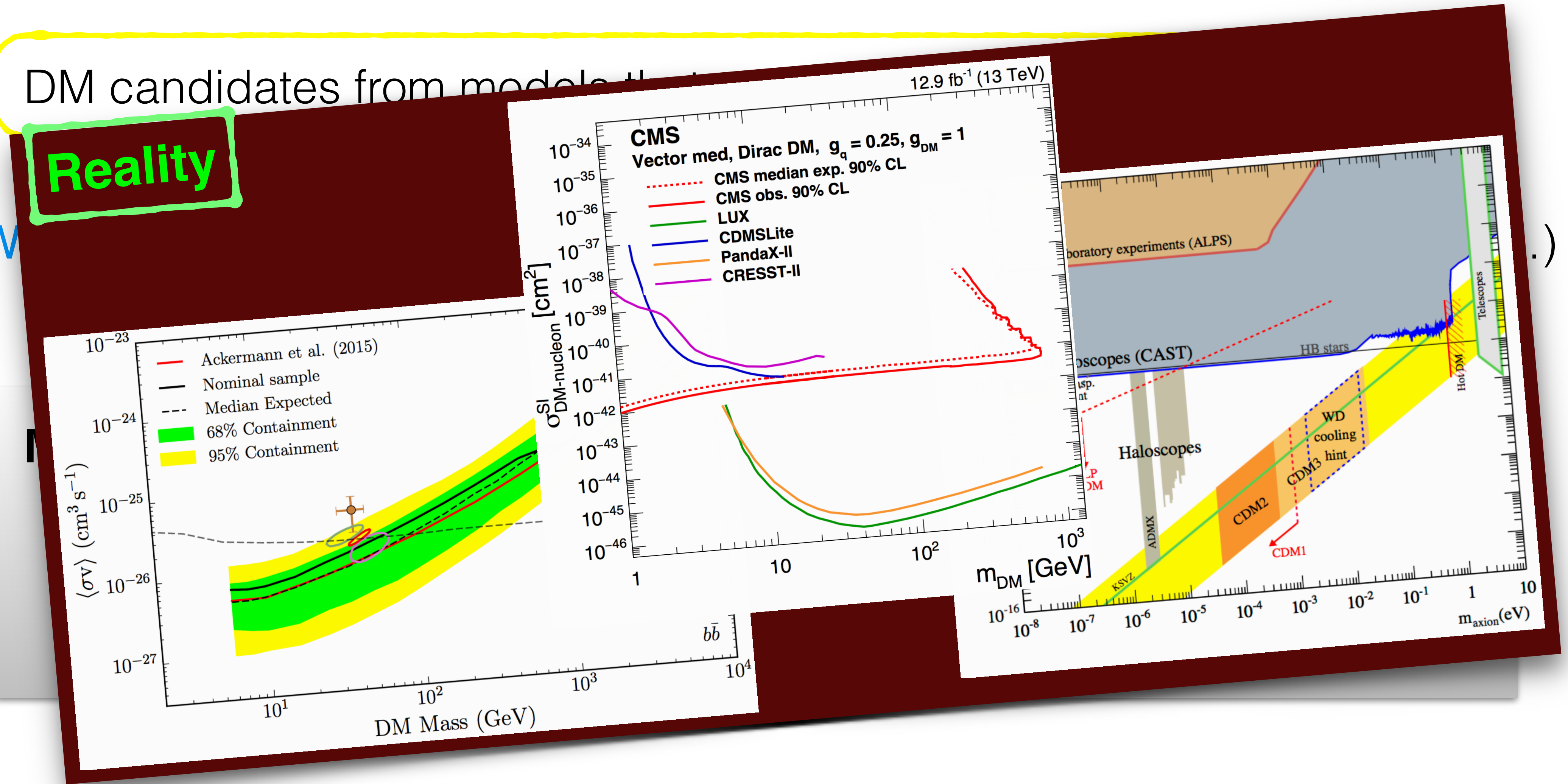
Direct Detection (DAMA,…)

Astrophysics ("Small scale crisis",…)

What is Dark Matter?

DM candidates from models th…

Reality



DM models to solve putative anomalies

Cosmic rays (positr…

Anomalies either faded away or lost credibility…

Astrophysics ("Small scale crisis",…)

Other ways to DM?

Especially since ~ 2-3 years

“No stone should be left unturned”

Accelerometers	Graham+ 1512.06165
Superfluid helium	Schutz Zurek 1604.08206,…
….	for recent report see e.g. US cosmic visions 1707.04591
ID with voyager	Boudaud+ 1612.07698

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☺ We already have many experiments
IceCube, HESS2,…(CTA, KM3NeT,…)

All* previous studies considered PeV decaying Dark Matter
& were motivated by IceCube neutrinos

* to my knowledge only one case on annihilating PeV DM: Zavala 1404.2932
[focus on astro challenges for Icecube neutrinos, **no model of DM**]

A challenge:

A limitation to quantitative predictions: center-of-mass energies > 100 TeV

$\Longrightarrow$ EW corrections should be resummed, but
- PPPC is only 1st order
- Pythia does not include all splittings

Non-Minimal Dark Sectors

A legitimate attitude: "Our sector (SM) is very involved, why should the dark sector be so simple?"

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Various **Extensions of the SM** predict populous "dark" sectors

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

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

Flavour (sub)groups Froggatt Nielsen 1978,…. Grinstein+ 1009.2049

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……….

In many of them, the dark states are (much) **heavier than SM scale**

Example: SUSY must be broken at >(>) O(100) TeV

Dark U(1) Dark Matter

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

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

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

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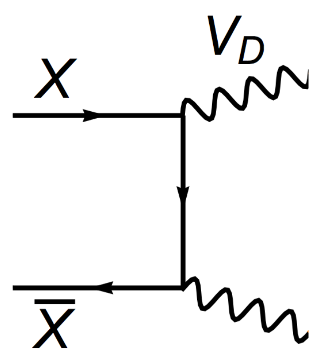
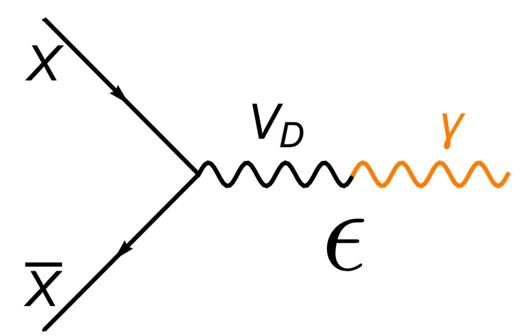
Thermal production possible with tiny interactions with SM

Pospelov+ 0711.4866,…

"Secluded WIMP DM"





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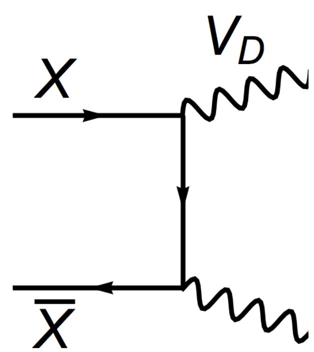
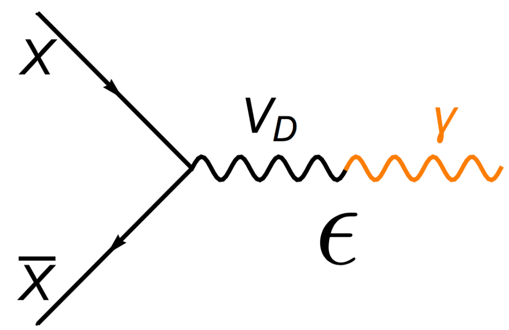




Cosmology For small enough ϵ the dark sector evolves independently of the SM

$T_{\rm SM} = T_D \equiv T_{\rm eq}$ 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

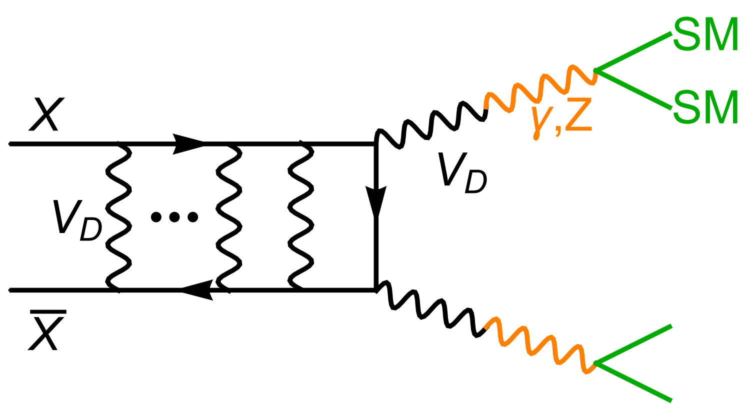
see also Kallia Petraki's talk

~ 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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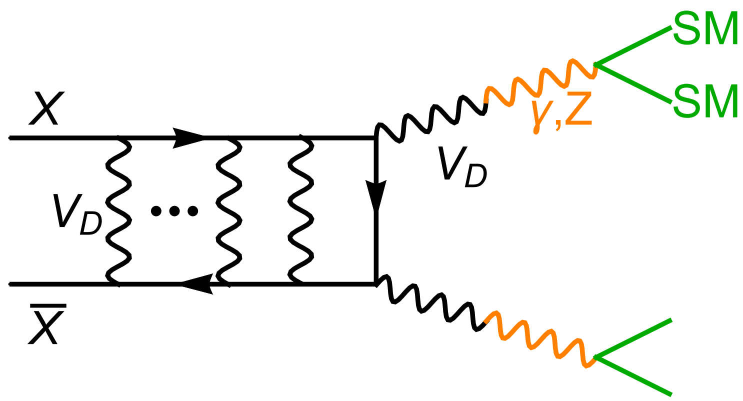
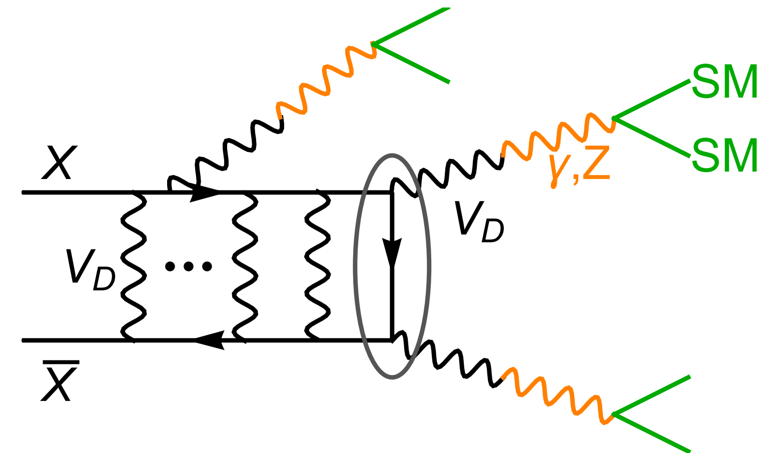




~ binding energy

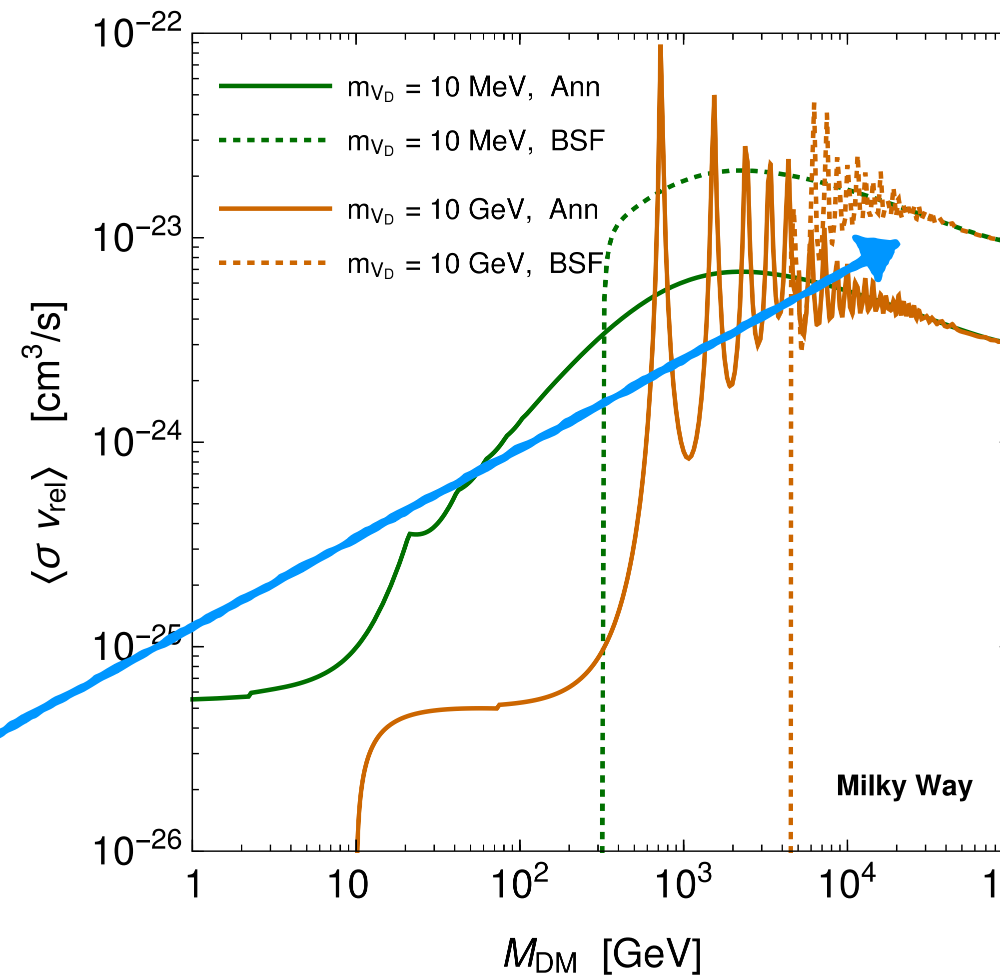
$$\frac{\alpha_D^2 M_{\rm DM}}{m_V} \gtrsim 1$$

DM **bound states** can form

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

BS formation (&decay)

can dominate over Sommerfeld!



Petraki+ 1611.01394

Pheno in the ϵ - m_V plane

see also Kallia Petraki's talk

α_D fixed to reproduce thermal relic abundance → 3 free parameters

M_{DM} m_V ϵ

von Harling Petraki 1407.7874 + minor refinement

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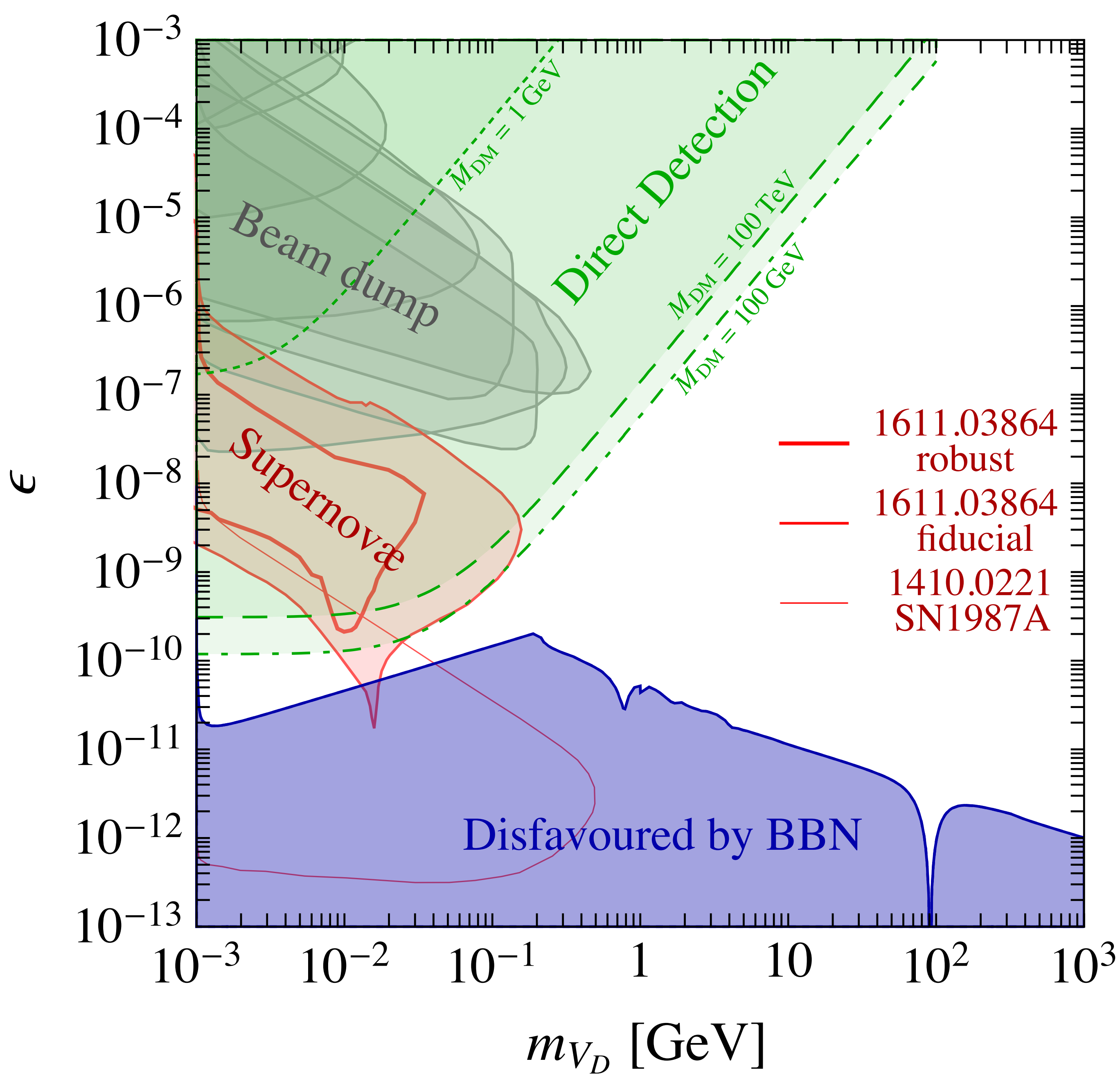
$M_{\rm DM}$ $\quad m_V$ $\quad \epsilon$



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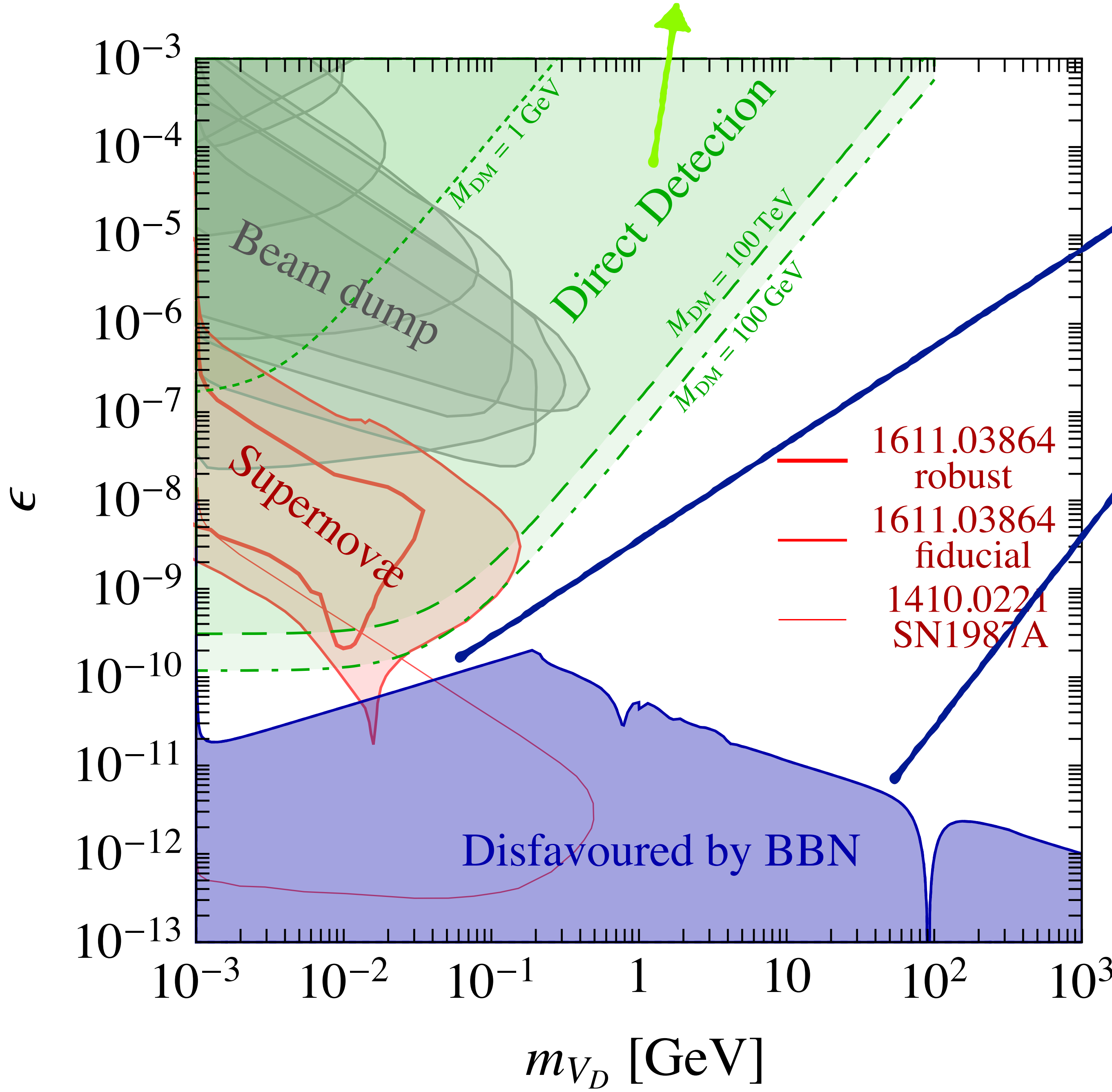
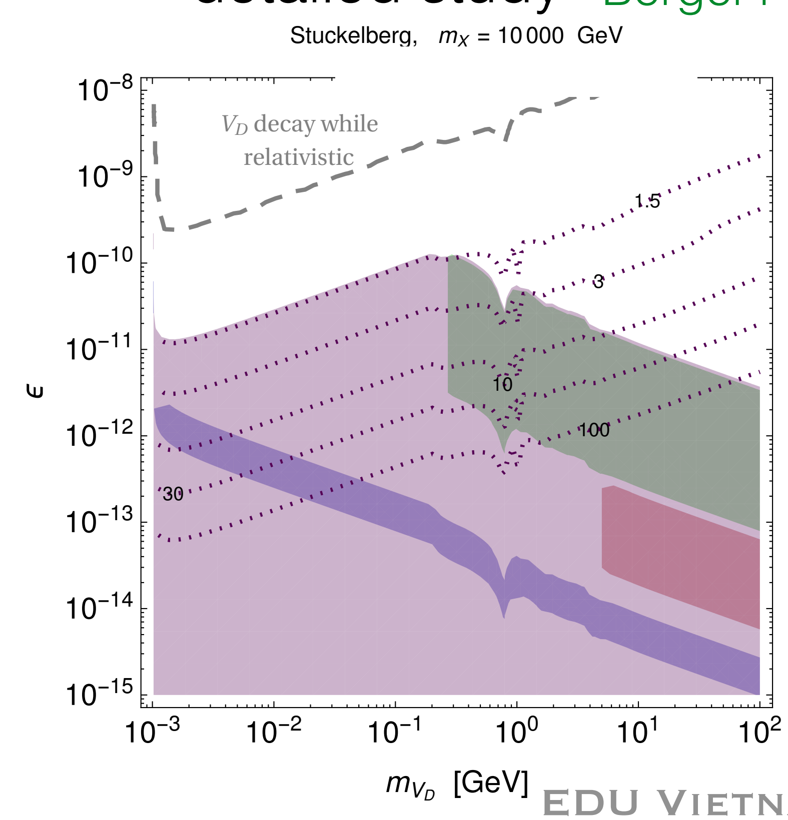
Only constraint that would vanish w/o Dark Matter



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

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

Values chosen to match the more detailed study Berger+ 1605.07195

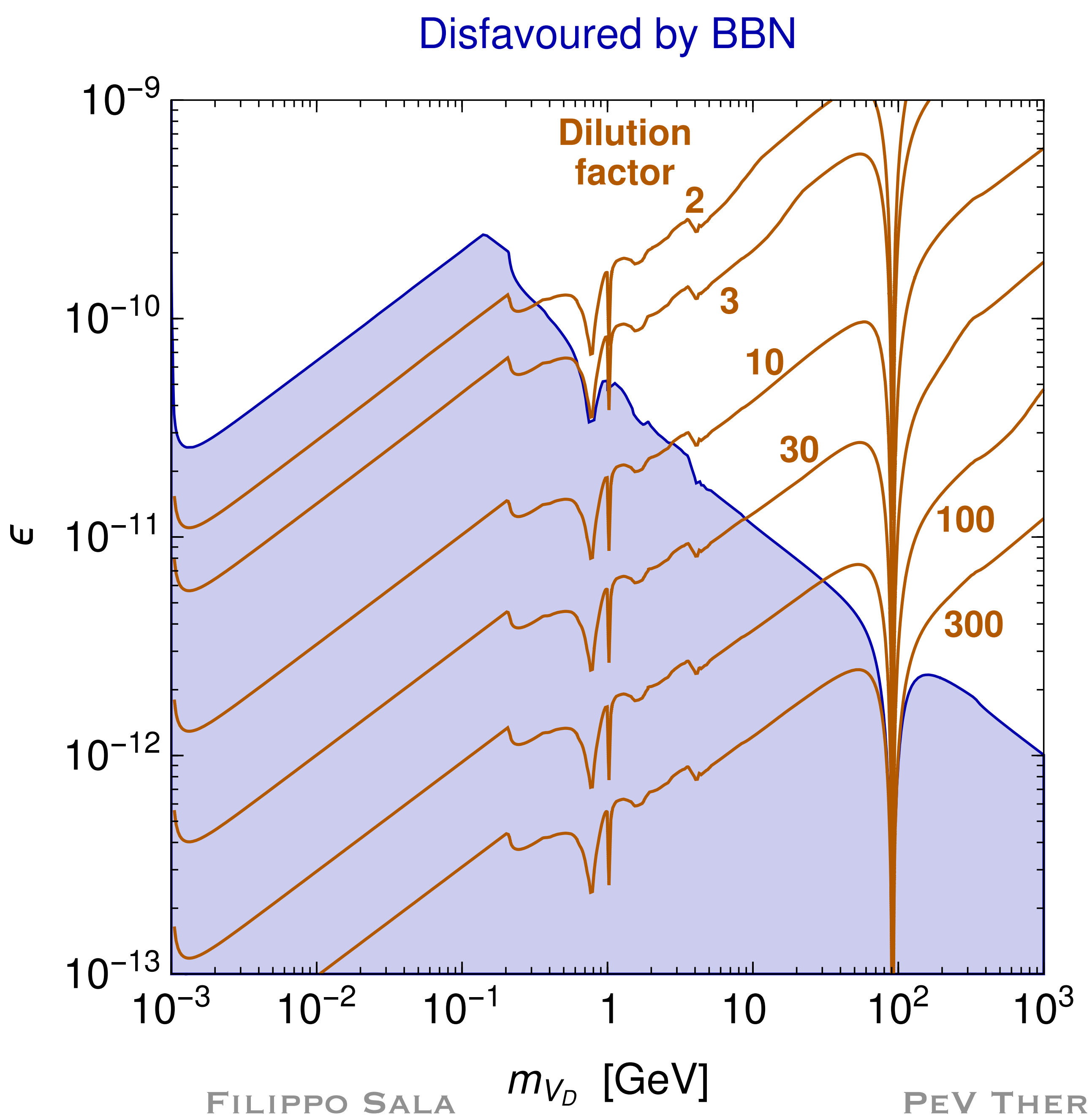


Dark Matter at a PeV and beyond

Dark Photons can dominate the energy density of the Universe

and decay after DM freeze-out, and enough before BBN

entropy injection in the SM bath dilutes the DM relic abundance!



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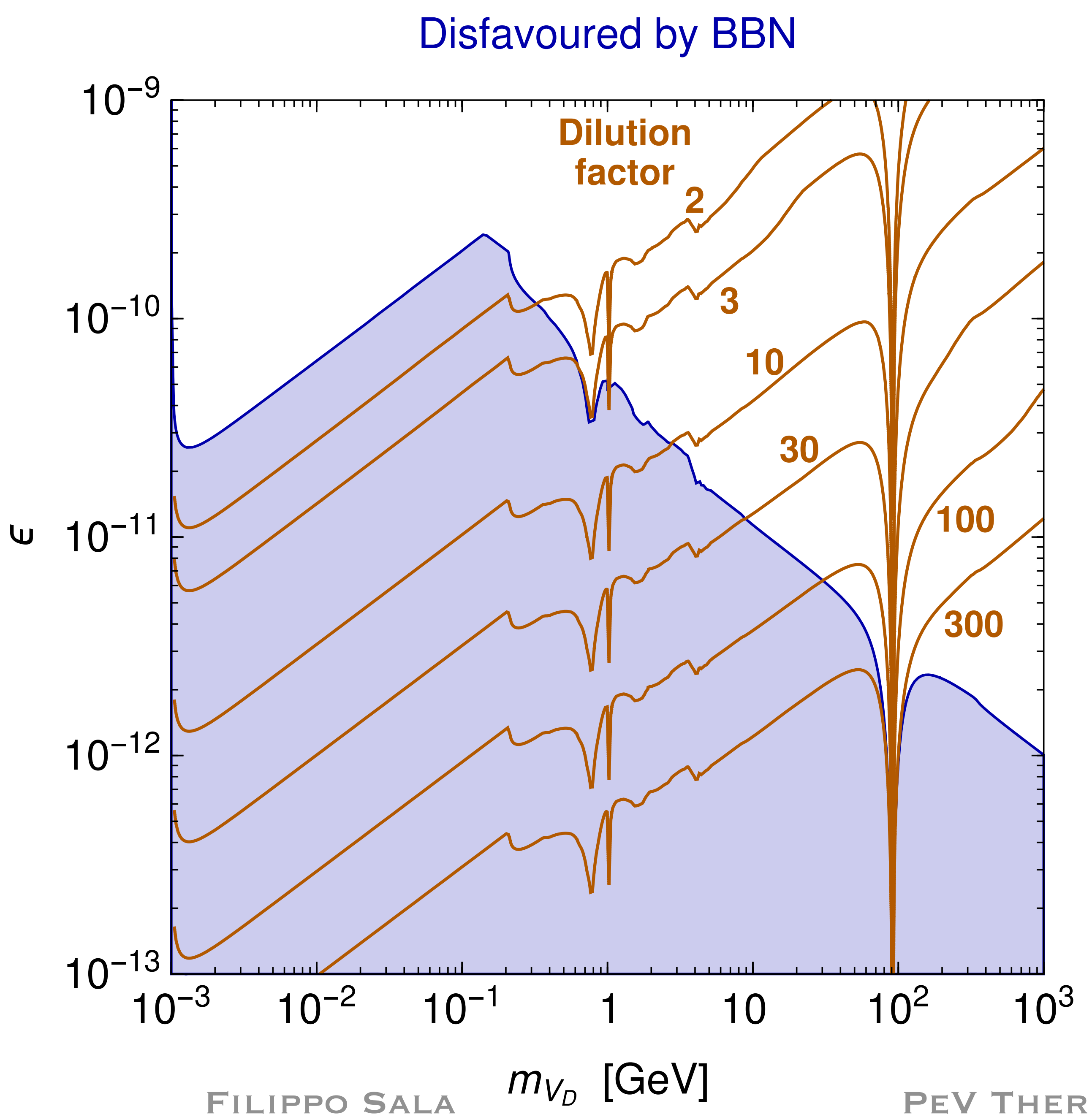
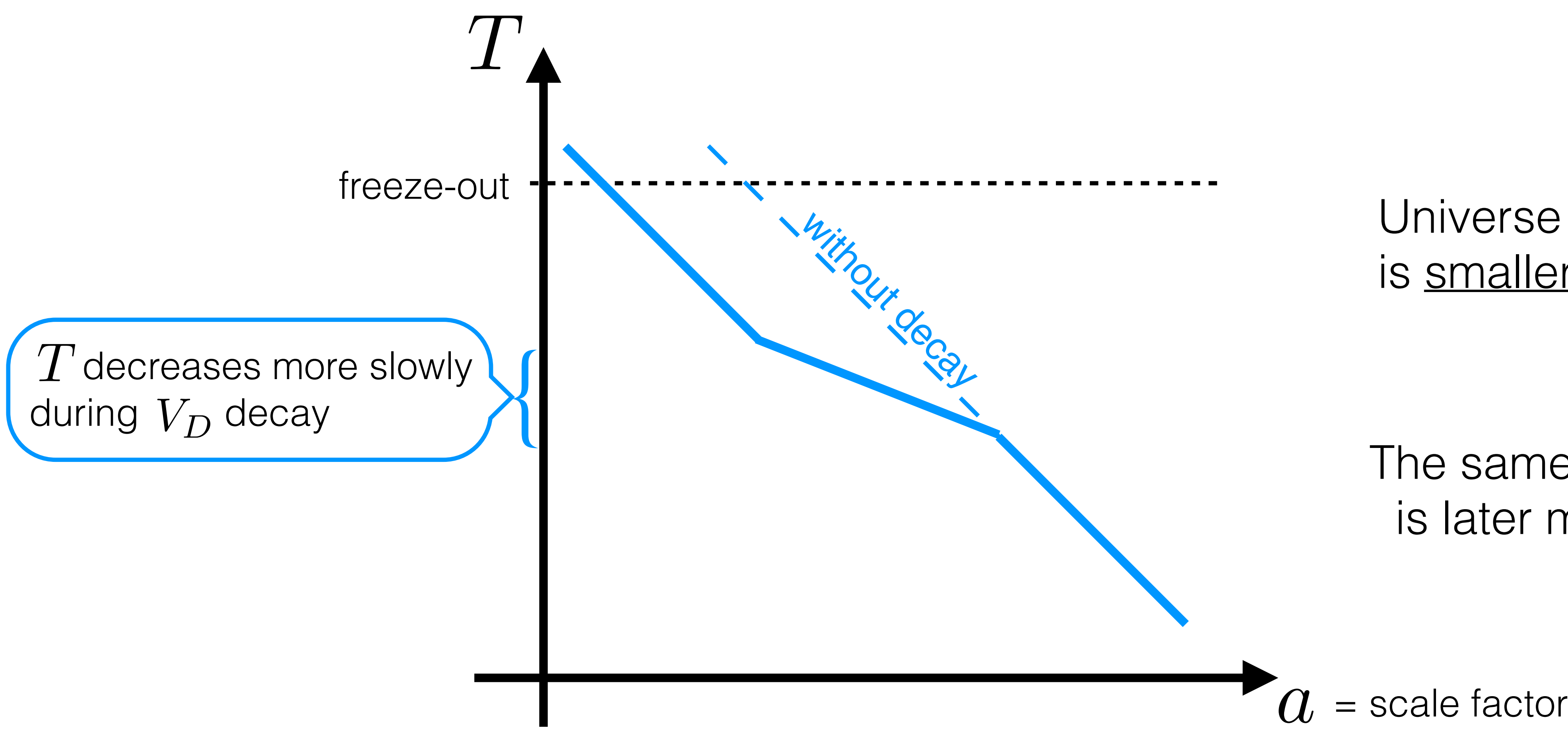


- Smaller α_D softens ID bounds
- Allows to violate the unitarity bound on $M_{\rm DM}$!

Berlin Hooper Krnjac 1602.08490

Dilution of relics

Decays from dark sector to SM make the Universe cool more slowly Scherrer Turner 1985



Universe @freeze-out is smaller than w/o decay

$\Downarrow$

The same amount of relic is later more diluted

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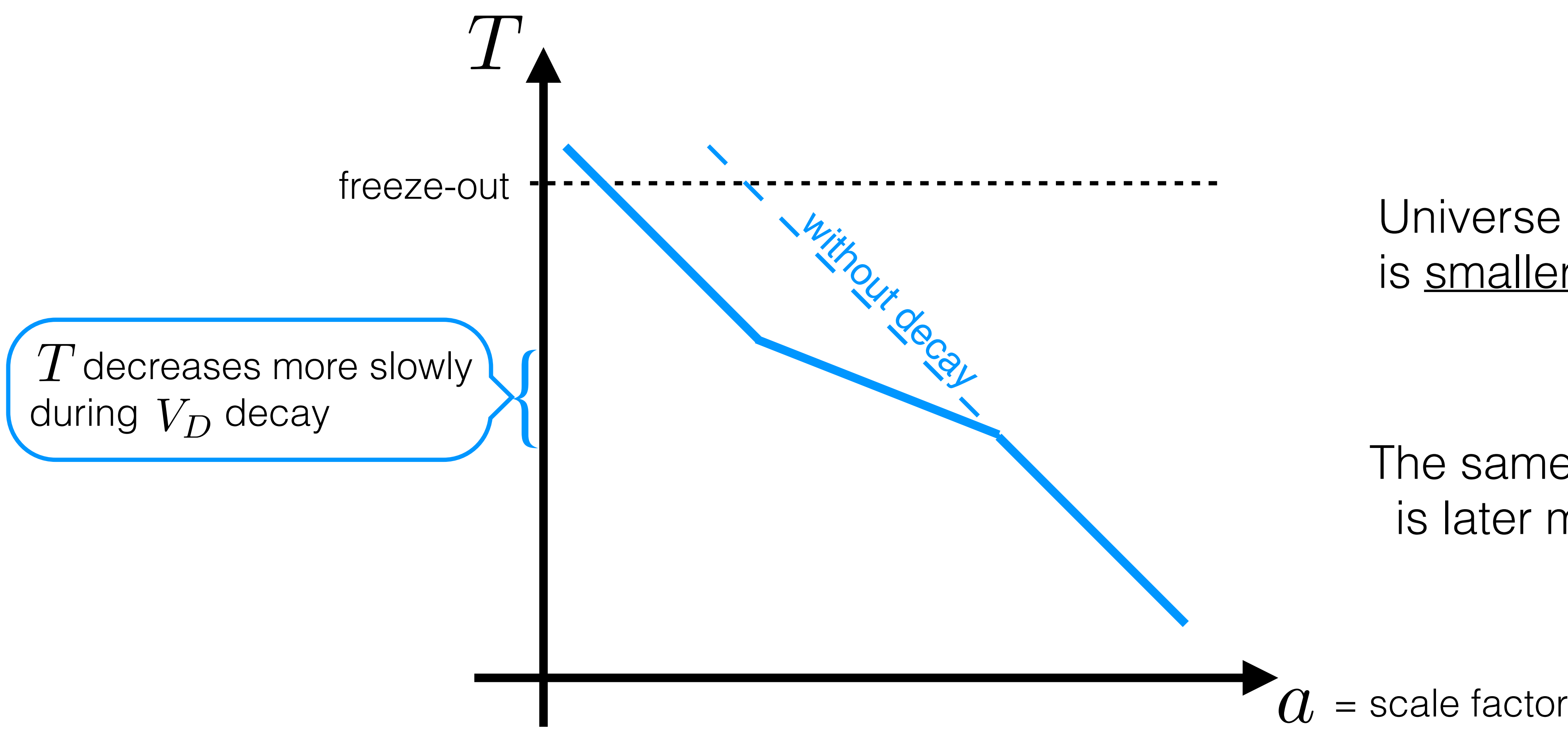

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The same amount of relic
is later more diluted

It turns out that "instantaneous" decay approx works well Scherrer Turner 1985

with T not continuous and determined from energy density conservation

$$\frac{n_0}{s_0} = \frac{n_{\text{after}}}{s_{\text{after}}} = \frac{n_{\text{before}}}{s_{\text{after}}} = \frac{n_{\text{f.o.}}}{s_{\text{f.o.}}} \frac{s_{\text{before}}}{s_{\text{after}}}$$

1/dilution factor

How to test PeV thermal Dark Matter?

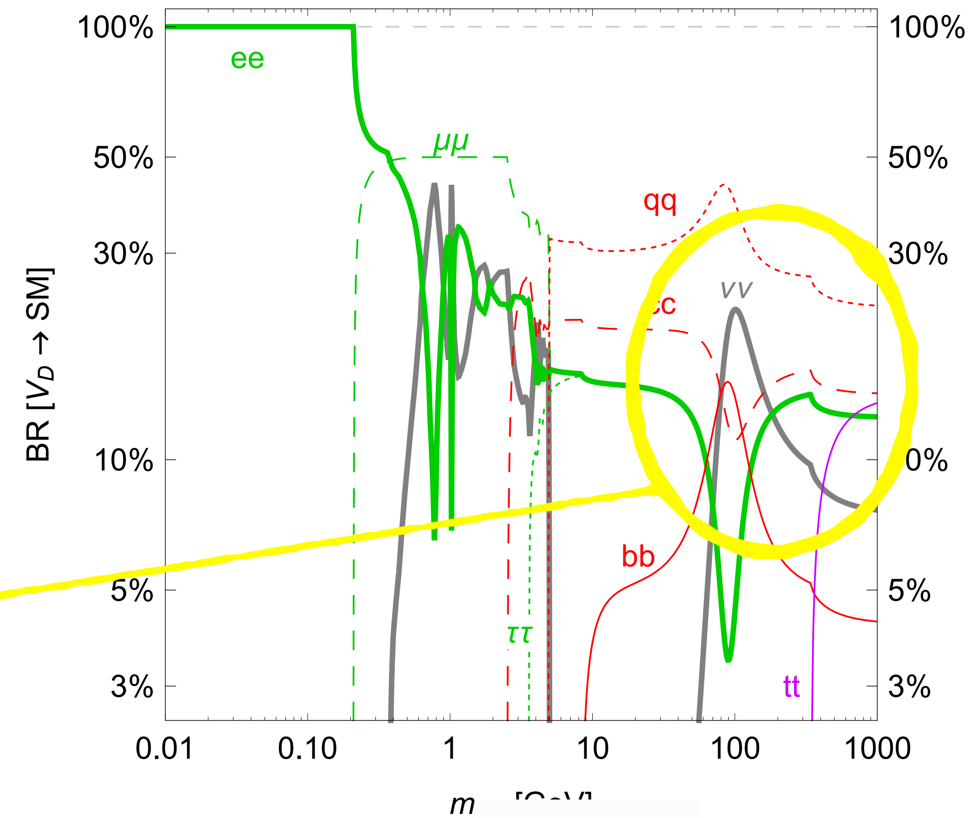
in progress

Dark U(1) Dark Matter

☺ Center-of-mass energy = $m_V \ll \mathrm{PeV}$

$\Rightarrow$ EW corrections @ first order are OK

☺ Interesting signals for IceCube, HESS2,…



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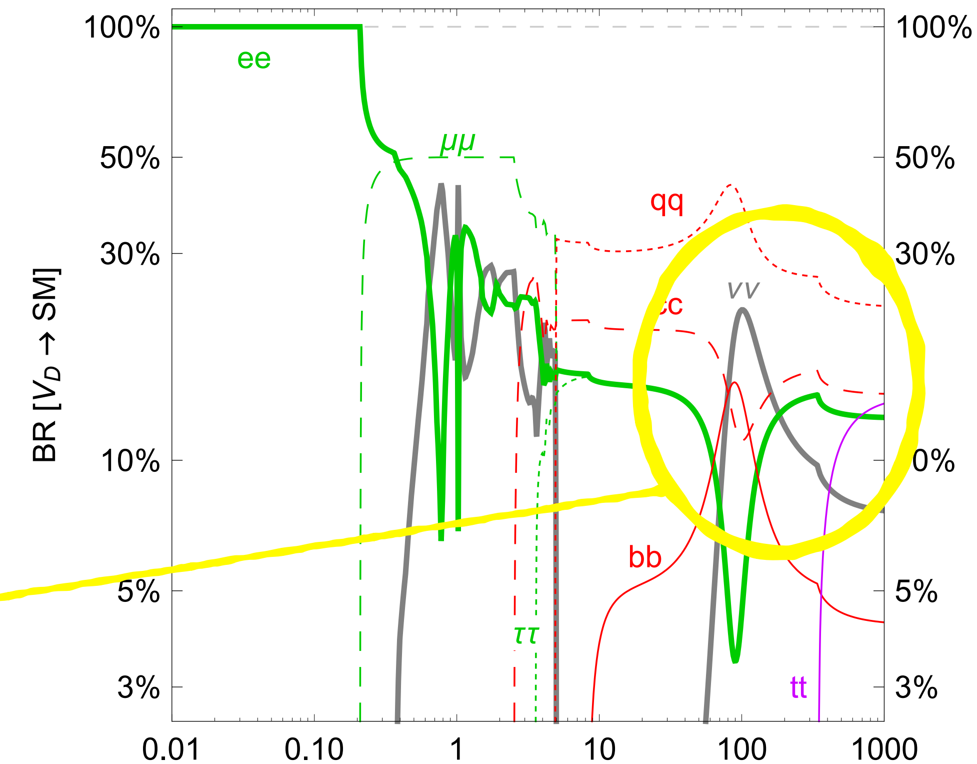
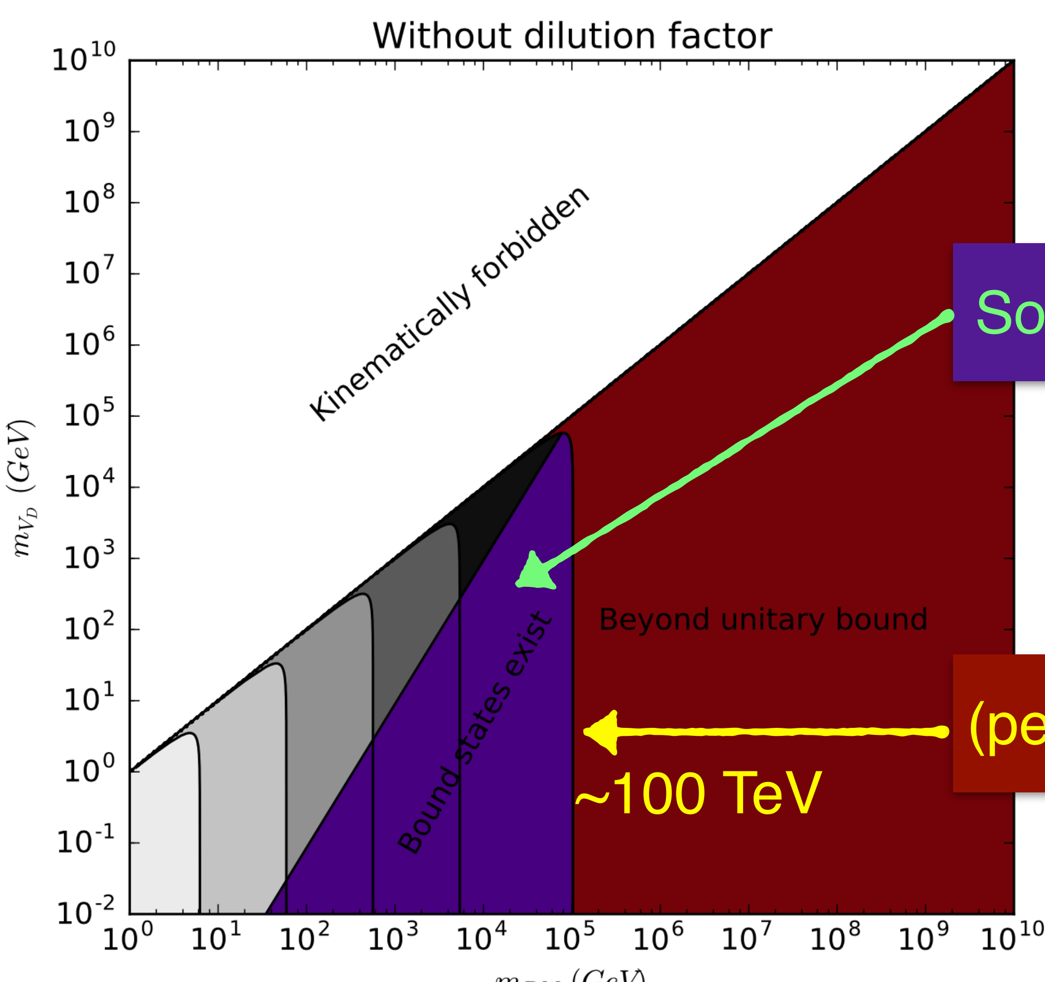


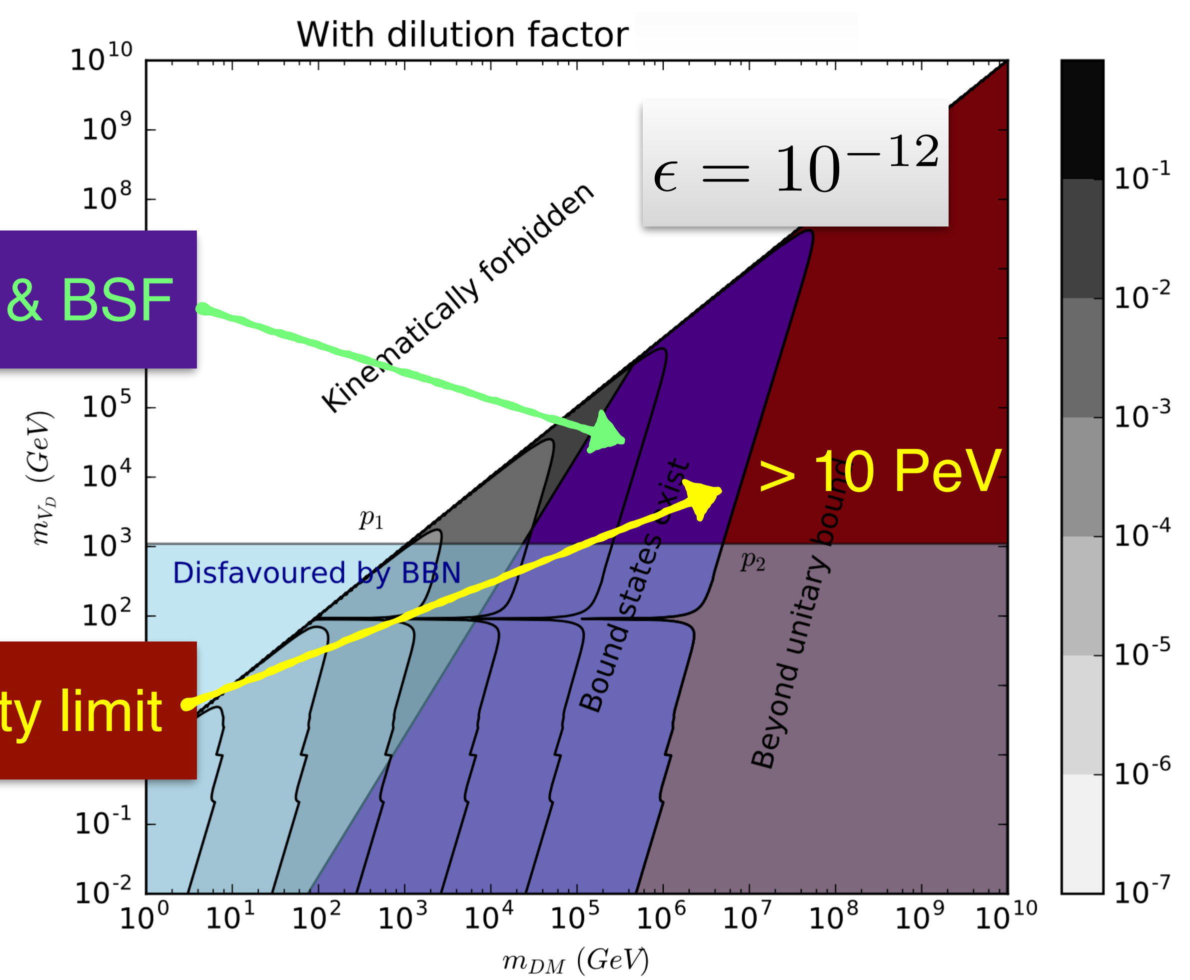


Sommerfeld & BSF

(pert.) unitarity limit

~100 TeV

> 10 PeV



plots by Yann **Gouttenoire**

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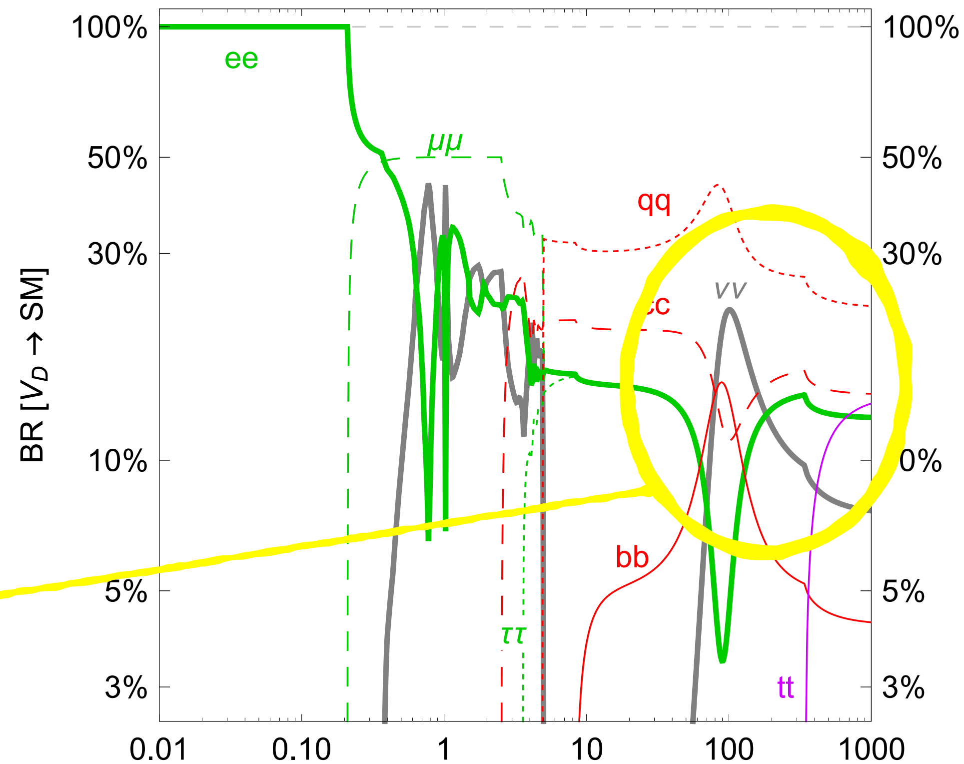

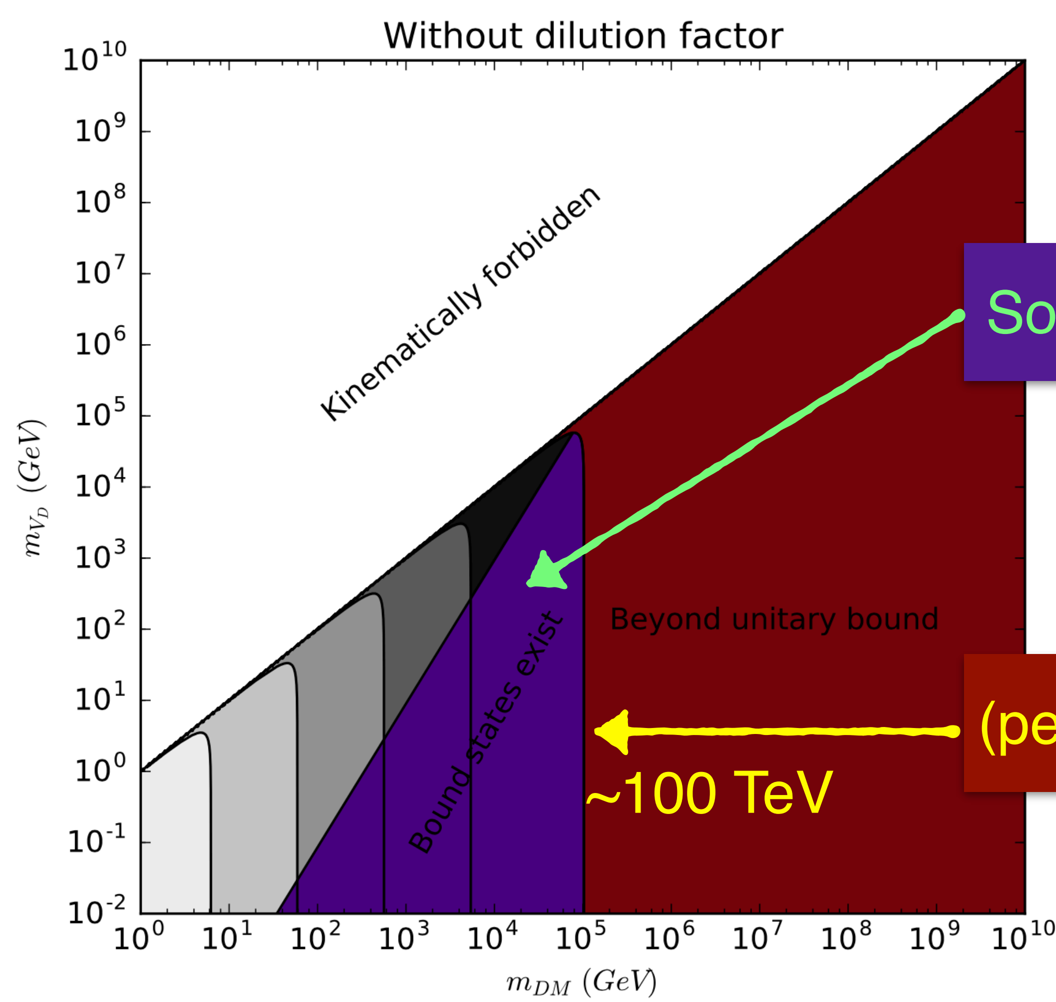

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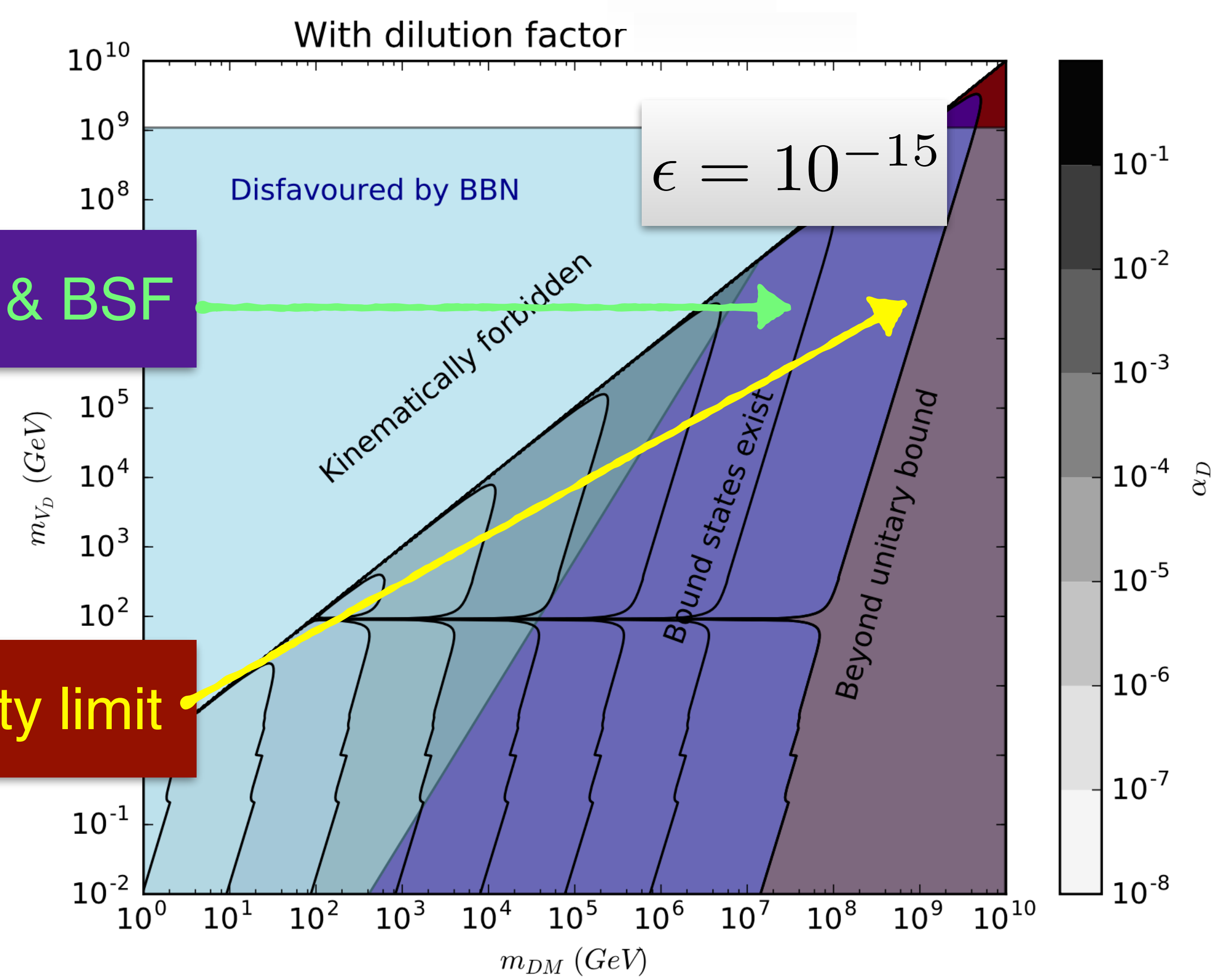


plots by Yann **Gouttenoire**

Summary & Outlook

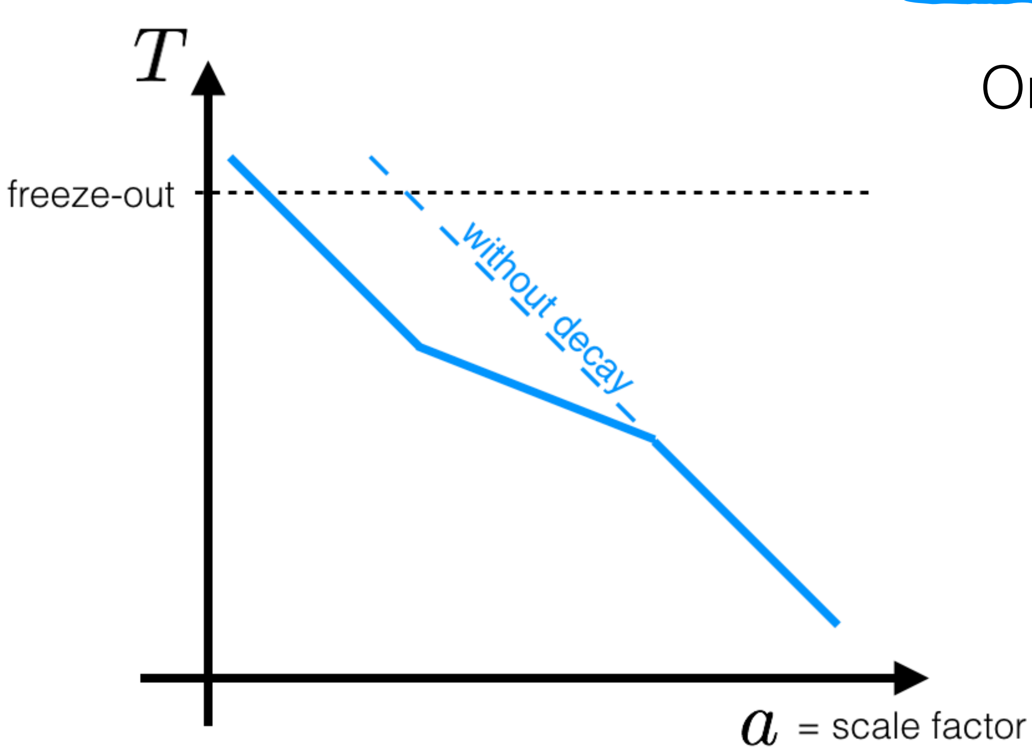
PeV Dark Matter from Dark Sectors

(almost) virgin pheno territory!

theoretically motivated

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

Realises entropy dilution of thermal relic DM via Dark Photon decays



Only limited range of parameters allowed by constraints

Future: where could it show up first?

ν IceCube Antares KM3NeT …

γ H.E.S.S. II CTA …

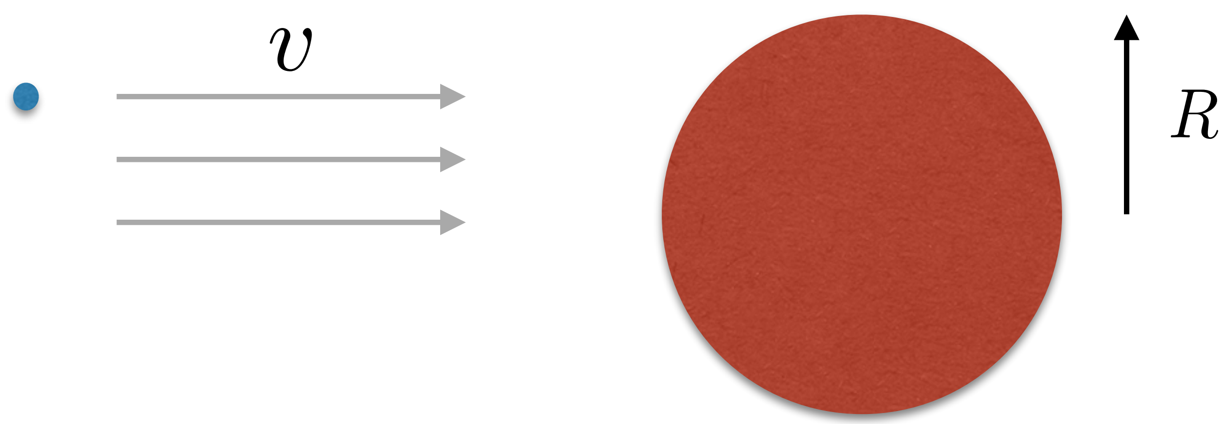
(Charged cosmic rays?)

Back-up

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:

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

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

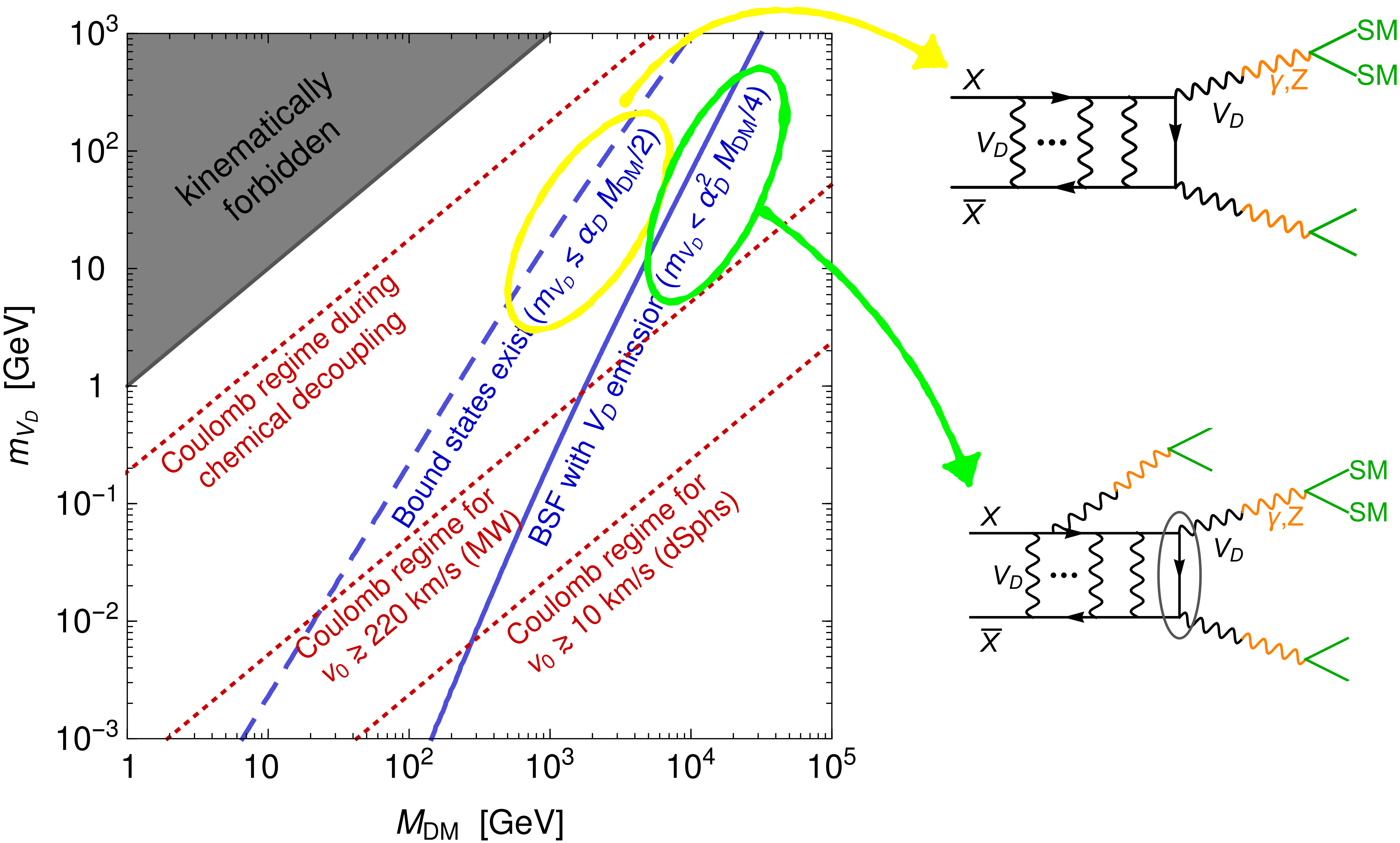
- slow particles $v \ll c$
- long-range attractive force $M_{\rm mediator} < \alpha\, M_{\rm DM}$

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

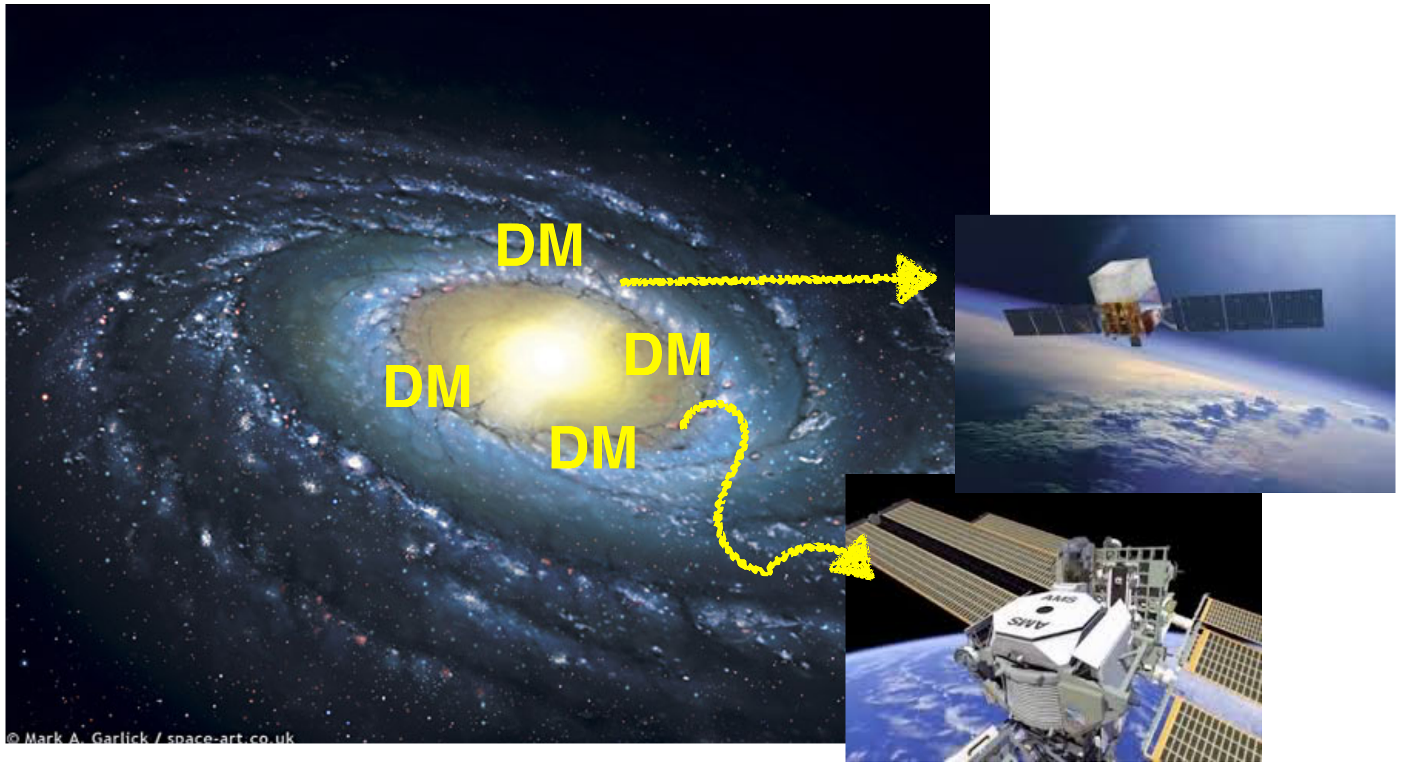
A bit more technical:
quantum field theory computations assume particles are “free" (=plain waves) at $r = +\infty$
BUT: if potential V is important also there (long-range!) you have to **solve Schroedinger eq.**

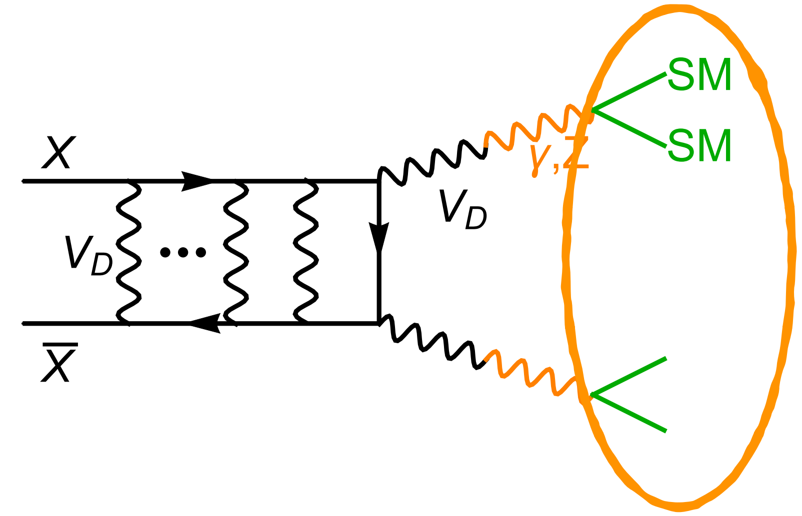
Pheno in the $M_{\rm DM}$ - m_V plane

What matters where:



Indirect detection: ingredients





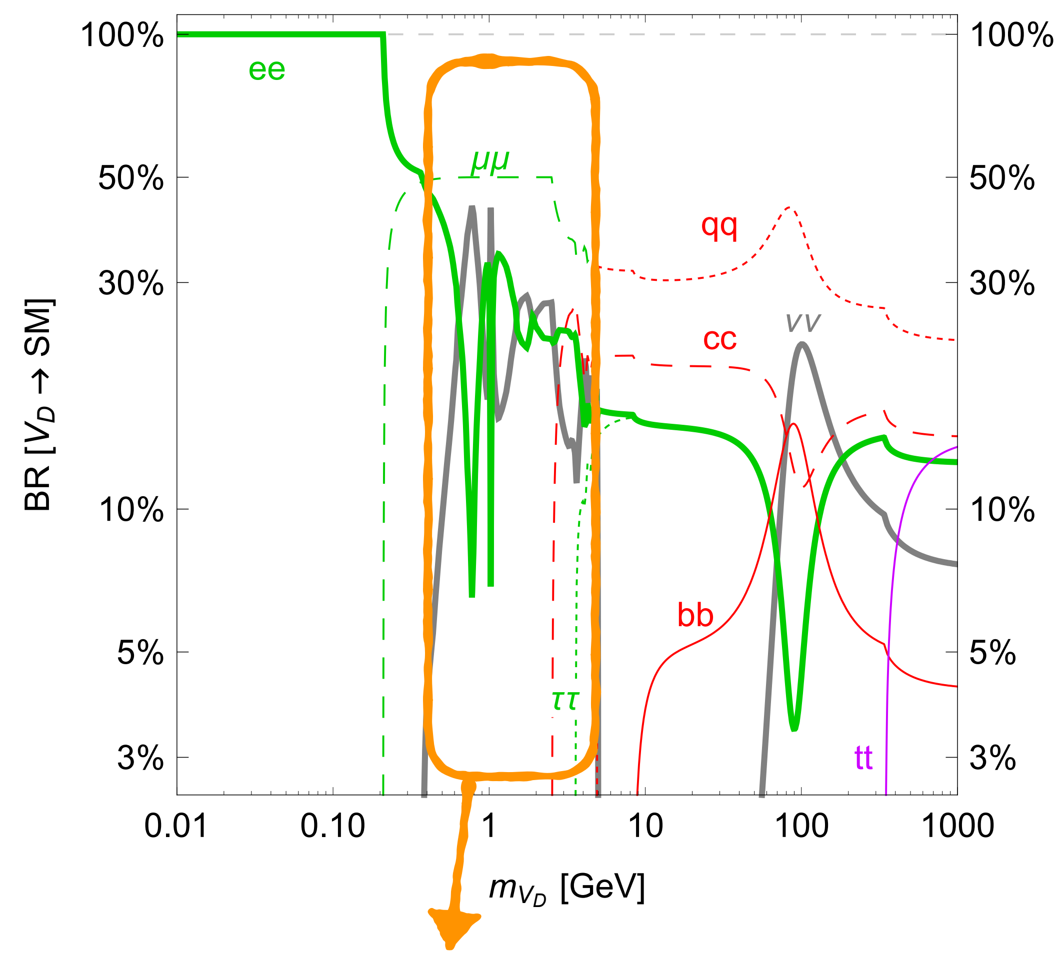
1. Sommerfeld and BS formation Petraki+ 1611.01394

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

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

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

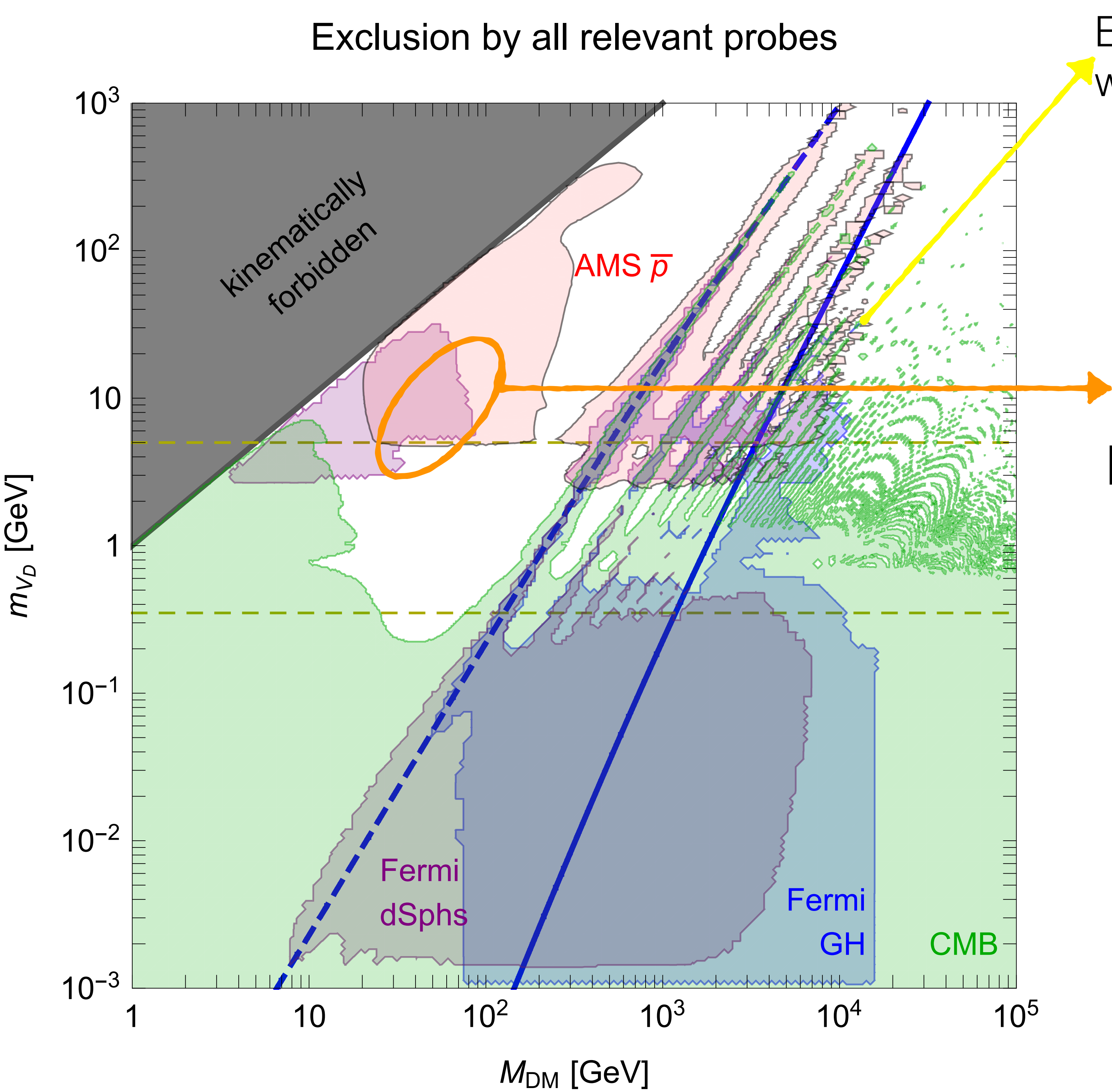
$$\delta = \frac{m_V}{m_Z}$$



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

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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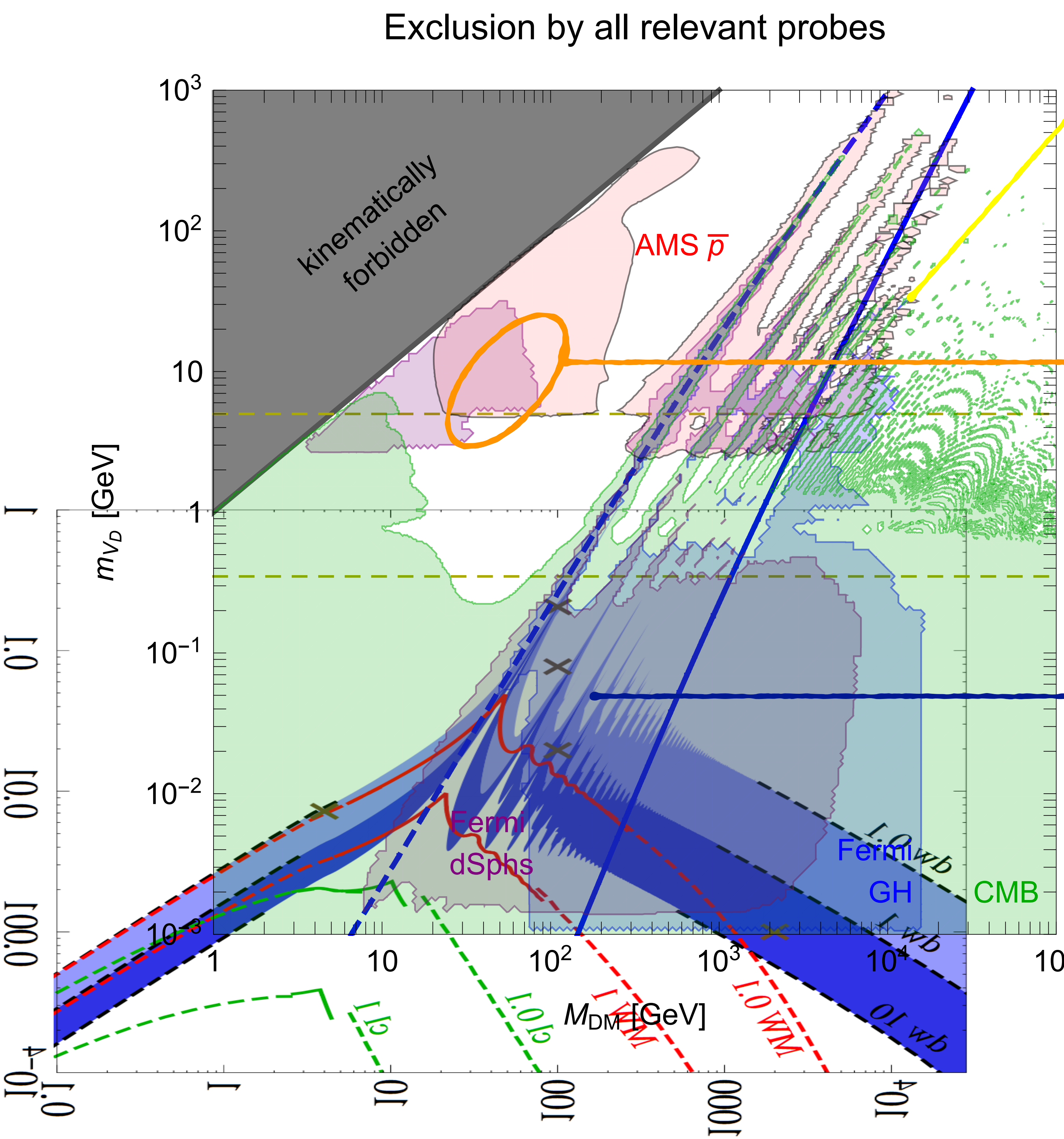

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[caveat: large astro uncertainties]

excludes this model as self-interacting DM

[caveats: in this mass range asymmetric DM .....]

see also Bringmann+1612.00845

Dark U(1) DM & self-interactions

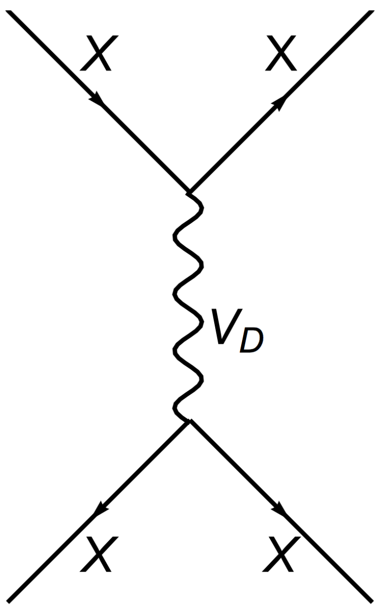
Prototype of **Self-Interacting DM** solves (putative) astro problems of cold DM

Spergel Steinhardt astro-ph/9909386,
……., Di Cintio+ 1701.04410

$$\frac{\sigma(XX \leftrightarrow XX)}{M_{\rm DM}} \sim \frac{\rm cm^2}{\rm gr} \sim 10^{12}\,\frac{\rm pb}{\rm GeV}$$

Problems on small scales:

Too-big-to-fail,…
(core vs cusp, missing satellites)



pheno motivation for a dark sector
w/ large cross sections

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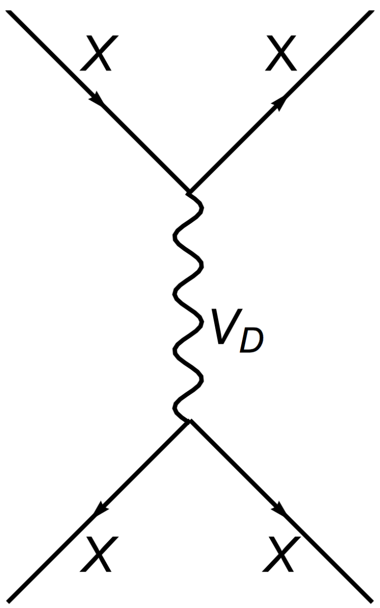


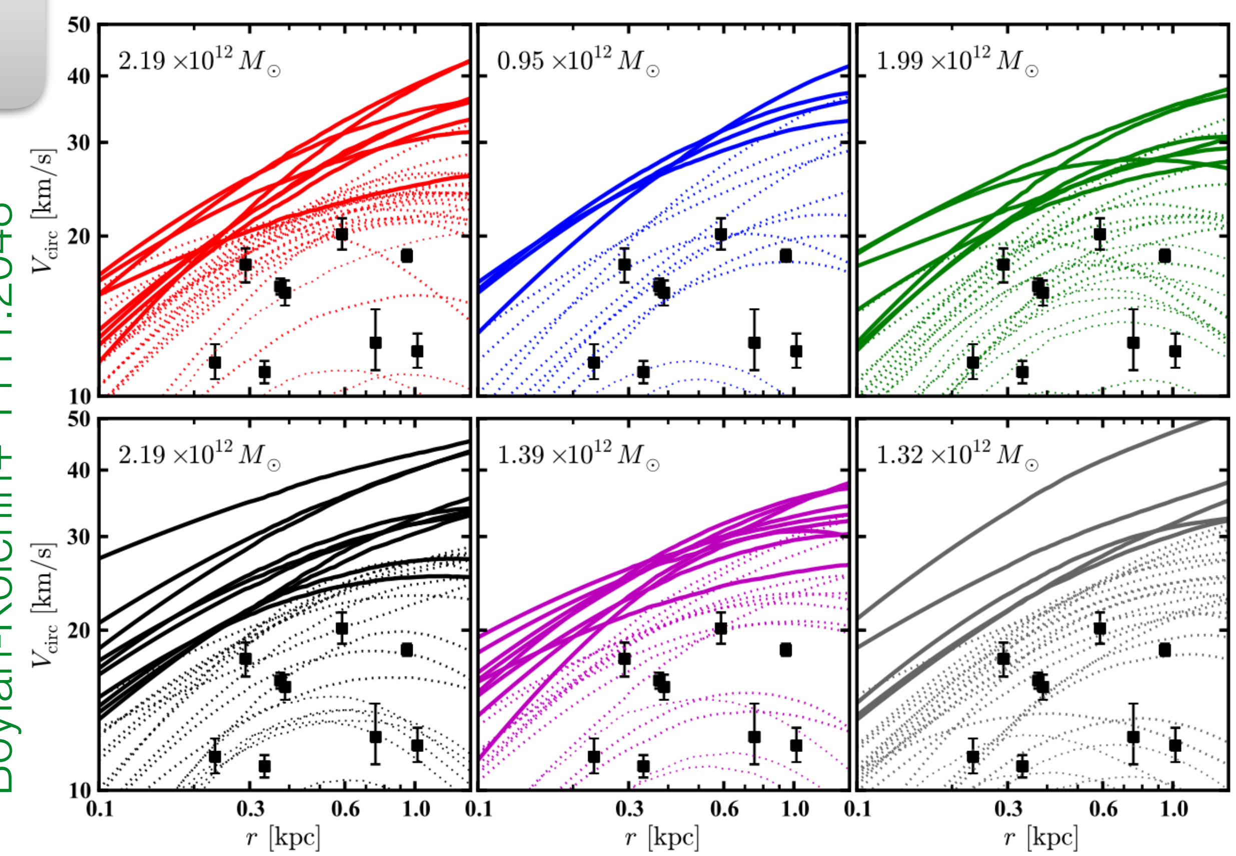
pheno motivation for a dark sector
w/ large cross sections

DM Sub-halos are expected to be <u>too big to fail</u> to produce stars

Lines: “predictions” from DM simulations

Points: observations of Milky Way satellites

Boylan-Kolchin+ 1111.2048



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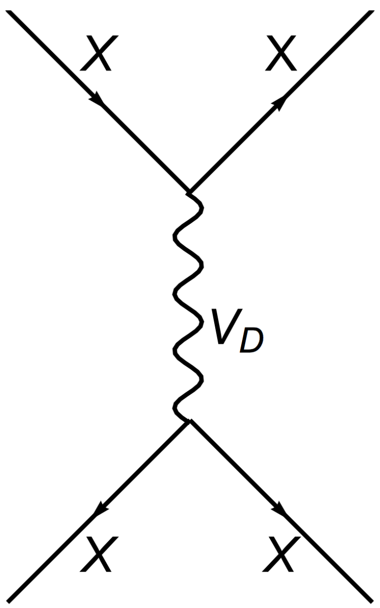


Baryon physics *could* solve them too, but not fully established

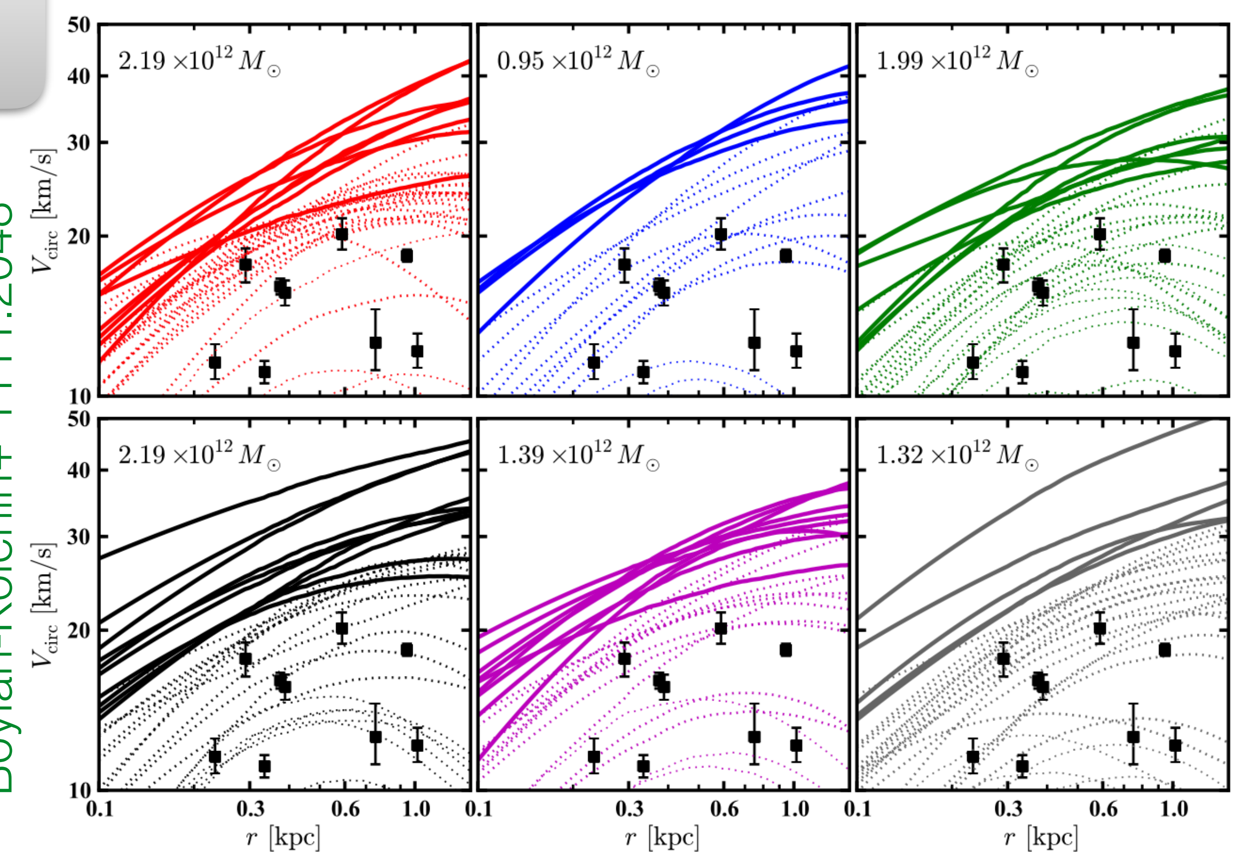
pheno motivation for a dark sector w/ large cross sections

Problems on small scales:

Too-big-to-fail,…
(core vs cusp, missing satellites)

DM Sub-halos are expected to be <u>too big to fail</u> to produce stars

Boylan-Kolchin+ 1111.2048



Lines: “predictions” from DM simulations

Points: observations of Milky Way satellites

e.g. Brook Di Cintio 1410.3825

Dwarph galaxies develop cores that bring the predictions closer to the points

Dark U(1) DM & self-interactions

Prototype of **Self-Interacting DM** solves (putative) astro problems of cold DM

Spergel Steinhardt astro-ph/9909386,
……., Di Cintio+ 1701.04410

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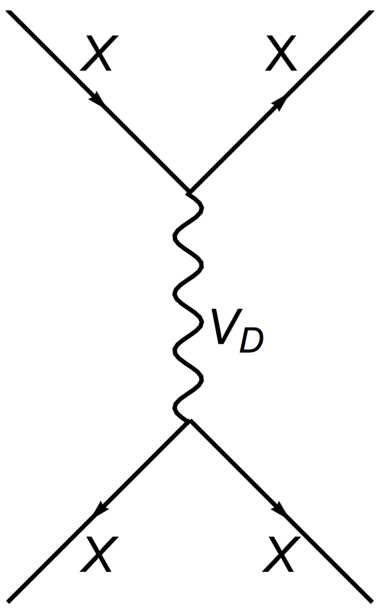

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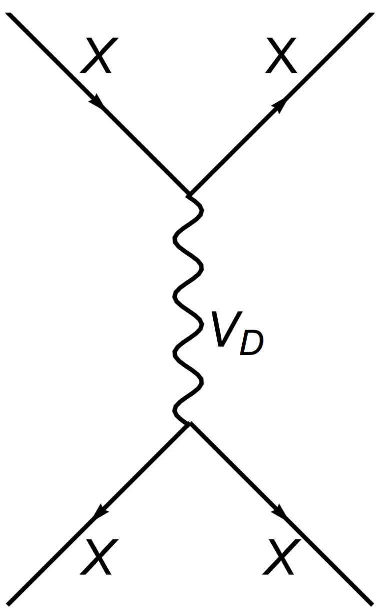


Baryon physics *could* solve them too, but not fully established

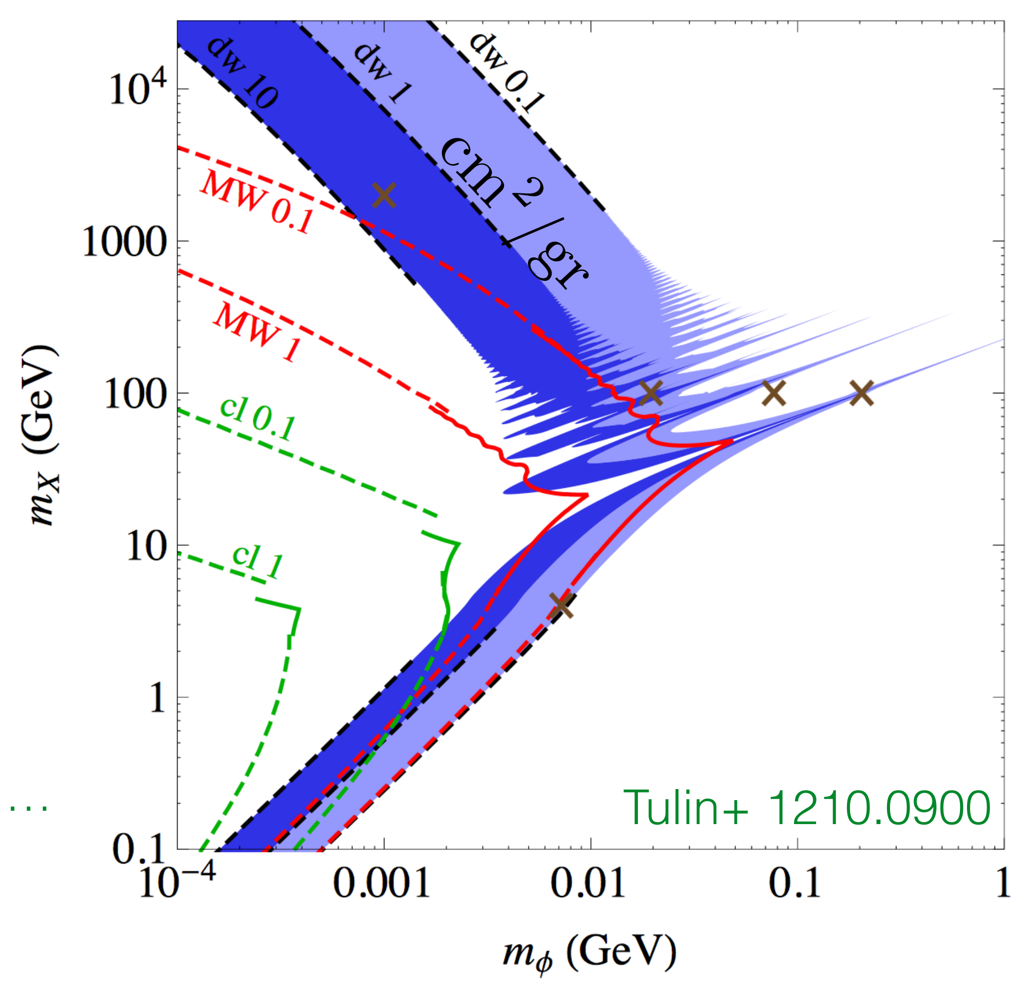
Problems on small scales:

Too-big-to-fail,…
(core vs cusp, missing satellites)

pheno motivation for a dark sector w/ large cross sections

In particular, long-range self-interactions remove problems at larger astro scales

Feng+ 0905.3039
Buckley Fox arXiv:0911.3898,…



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Problems on larger scales?

Pawlowski Kroupa Jerjen 1307.6210

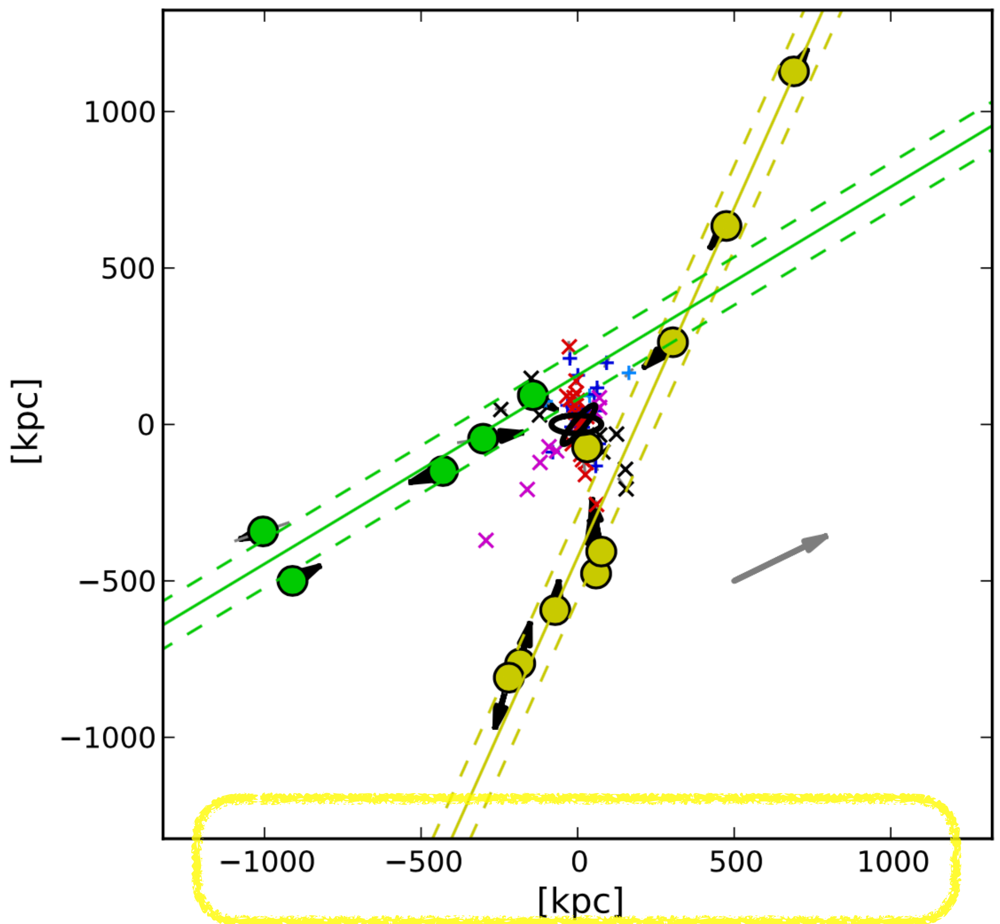


Figure 9. Edge-on view of both LG planes. The orientation of the MW and M31 are indicted as black ellipses in the centre. Members of the LGP1 are plotted as yellow points, those of LGP2 as green points. MW galaxies are plotted as plus signs (+), all other galaxies as crosses (×), the colours code their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

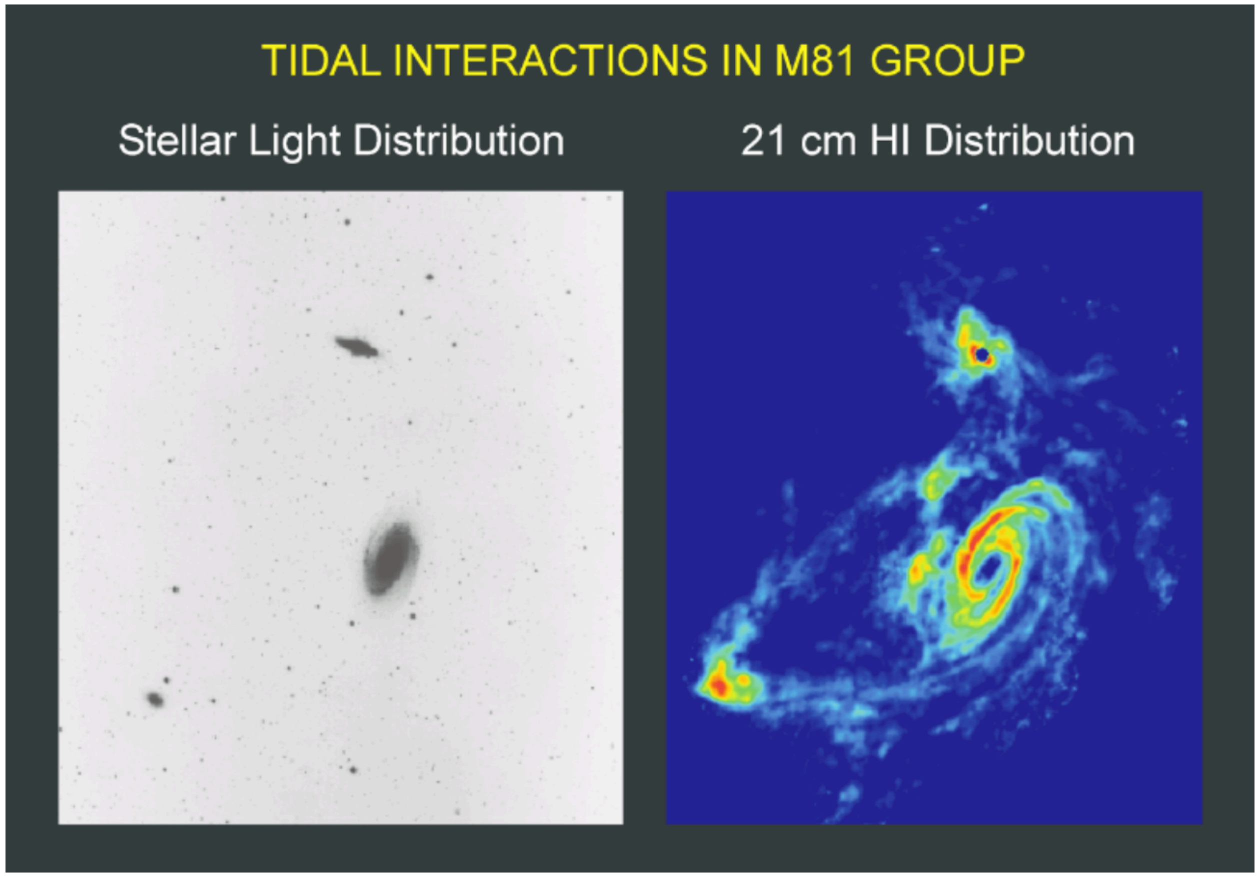
Galaxies in the local group seem to be aligned in two planes

Too big scales to explain w/Galaxy formation

Disclaimer: my particle physicist understanding

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

from Pavel Kroupa @ Jussieu 2017



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

)

Is there a “small scale crisis” of LCDM?

Disclaimer: my particle physicist understanding

Problems (of first LCDM simulations): Too-big-to-fail

Missing satellites

Cores vs cusps

Solutions: Warm DM, Self-Int DM, baryon physics

seem to me the most “natural” solution
still different groups do not entirely agree

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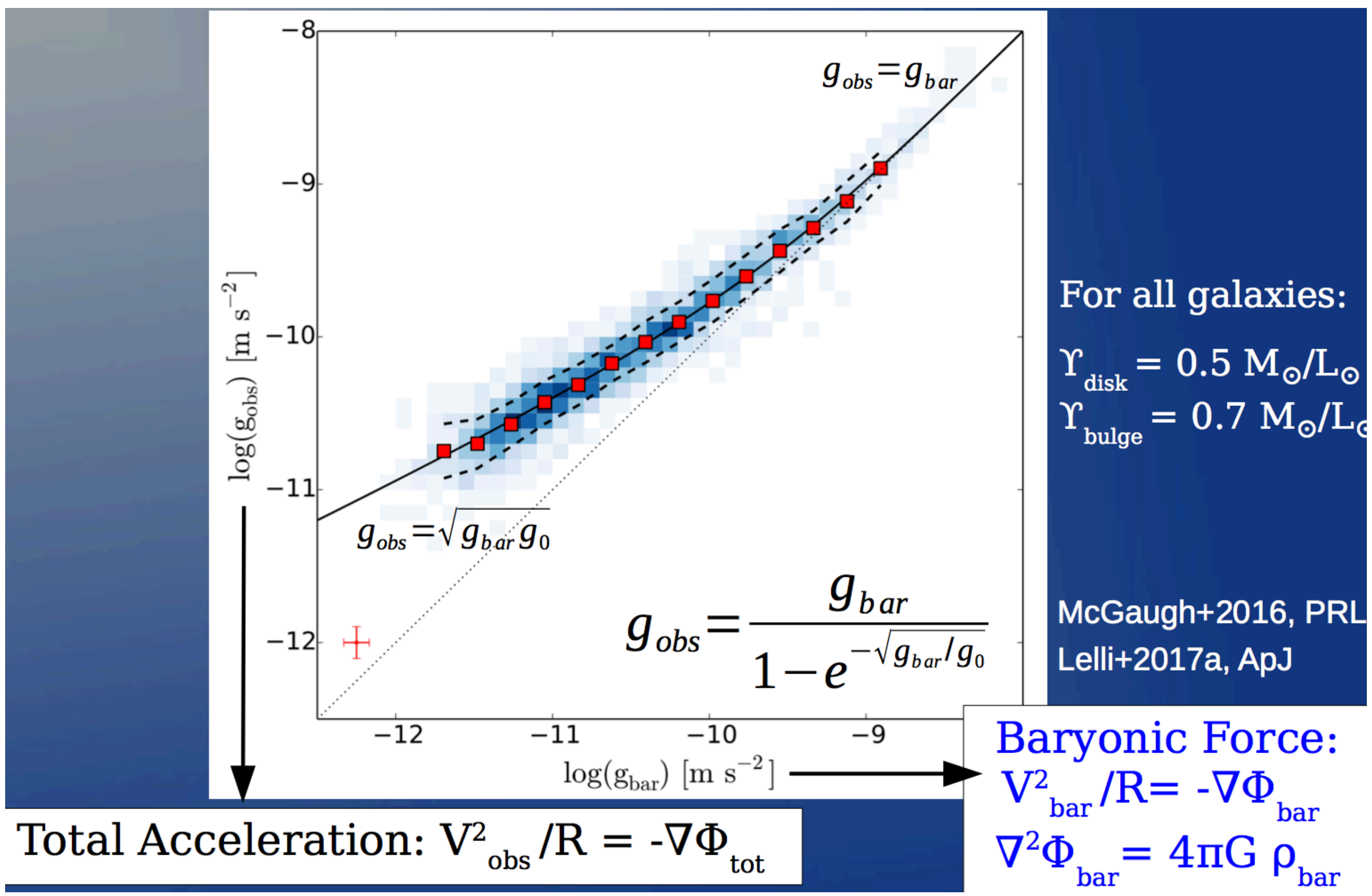
New arrival: **MDAR** [= mass discrepancy vs acceleration relation]



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