9 December 2016
Fayet-fest
ENS Paris

Dark Matter then and now

Marco Cirelli
(CNRS LPTHE Jussieu)

LPTHE
LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

erc
NewDark

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Introduction

The Dark Matter theory space:

Introduction

The Dark Matter theory space:

SuSy DM

Non SuSy DM

Introduction

The Dark Matter theory space:

SuSy DM

Non SuSy DM



?

Introduction

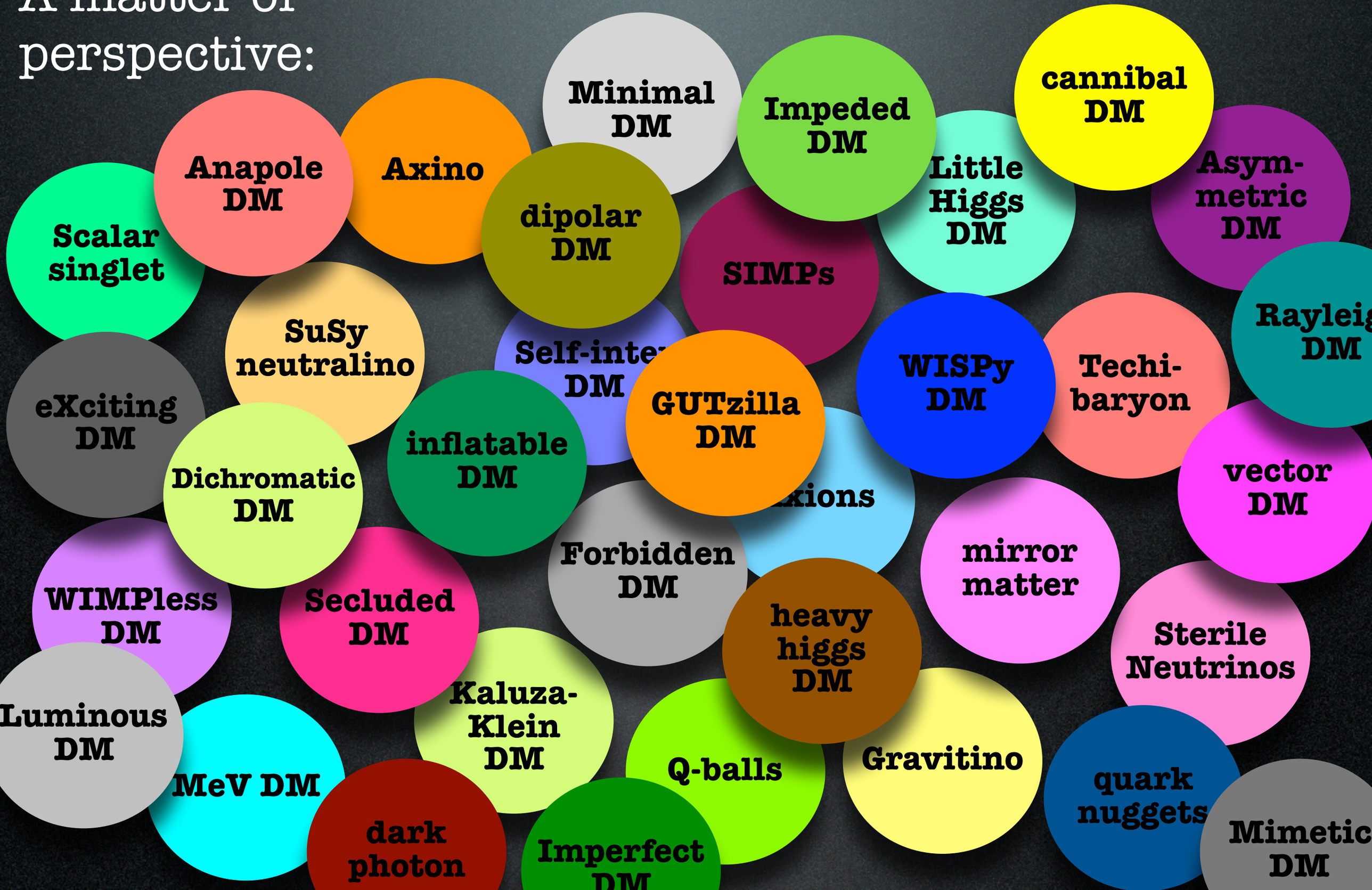
The Dark Matter theory space:

SuSy neutralino

other exotic candi-dates

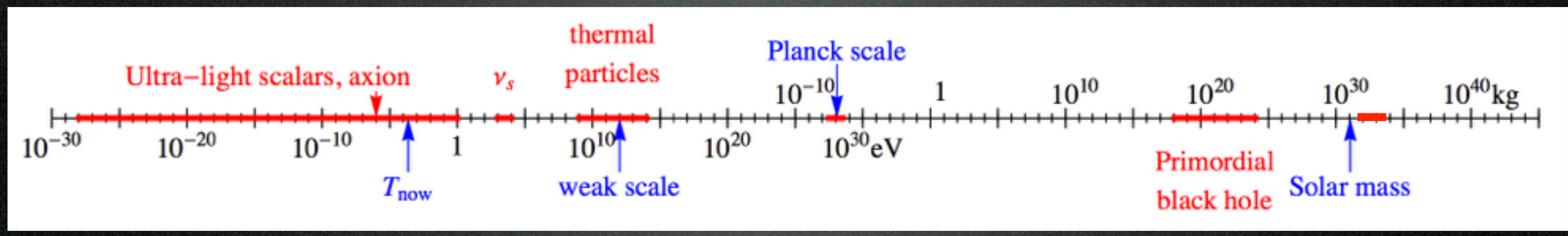
Candidates

A matter of perspective:



Candidates

A matter of perspective: plausible mass ranges



‘only’ 90 orders of magnitude!

Introduction

The Dark Matter theory space:

Caveat: no categorization is perfect.

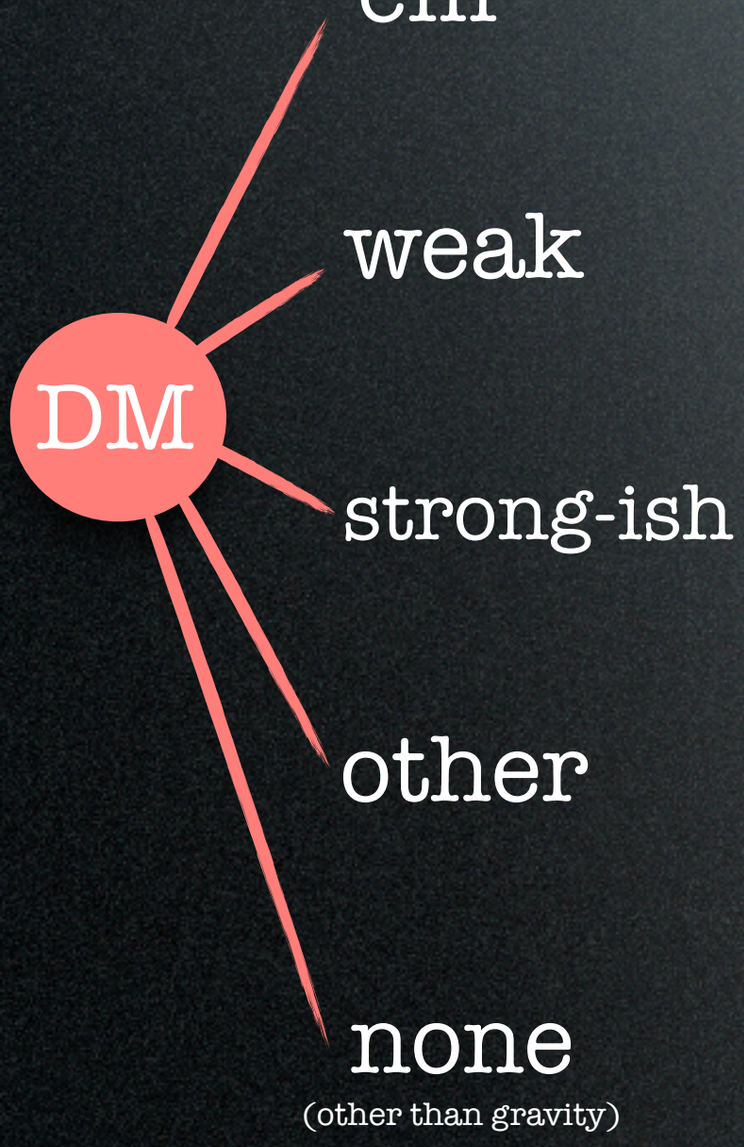
DM

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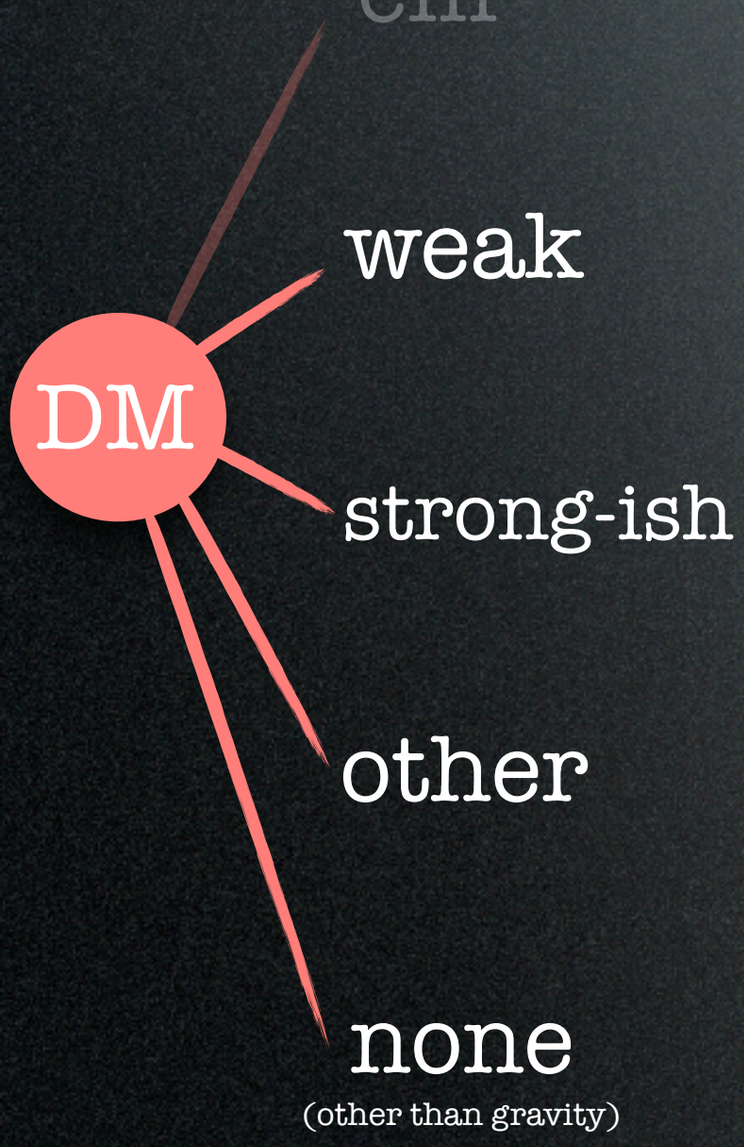


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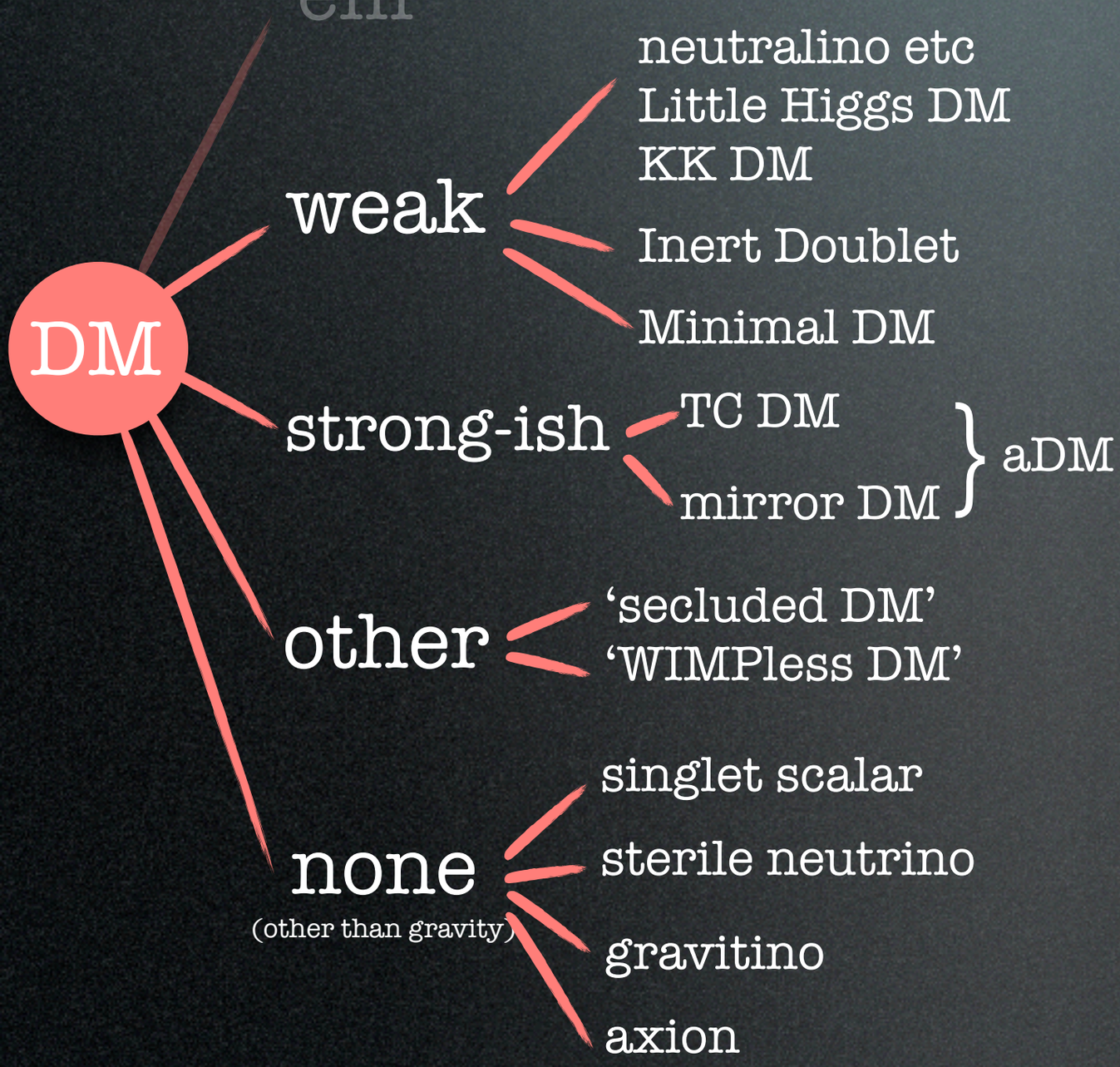


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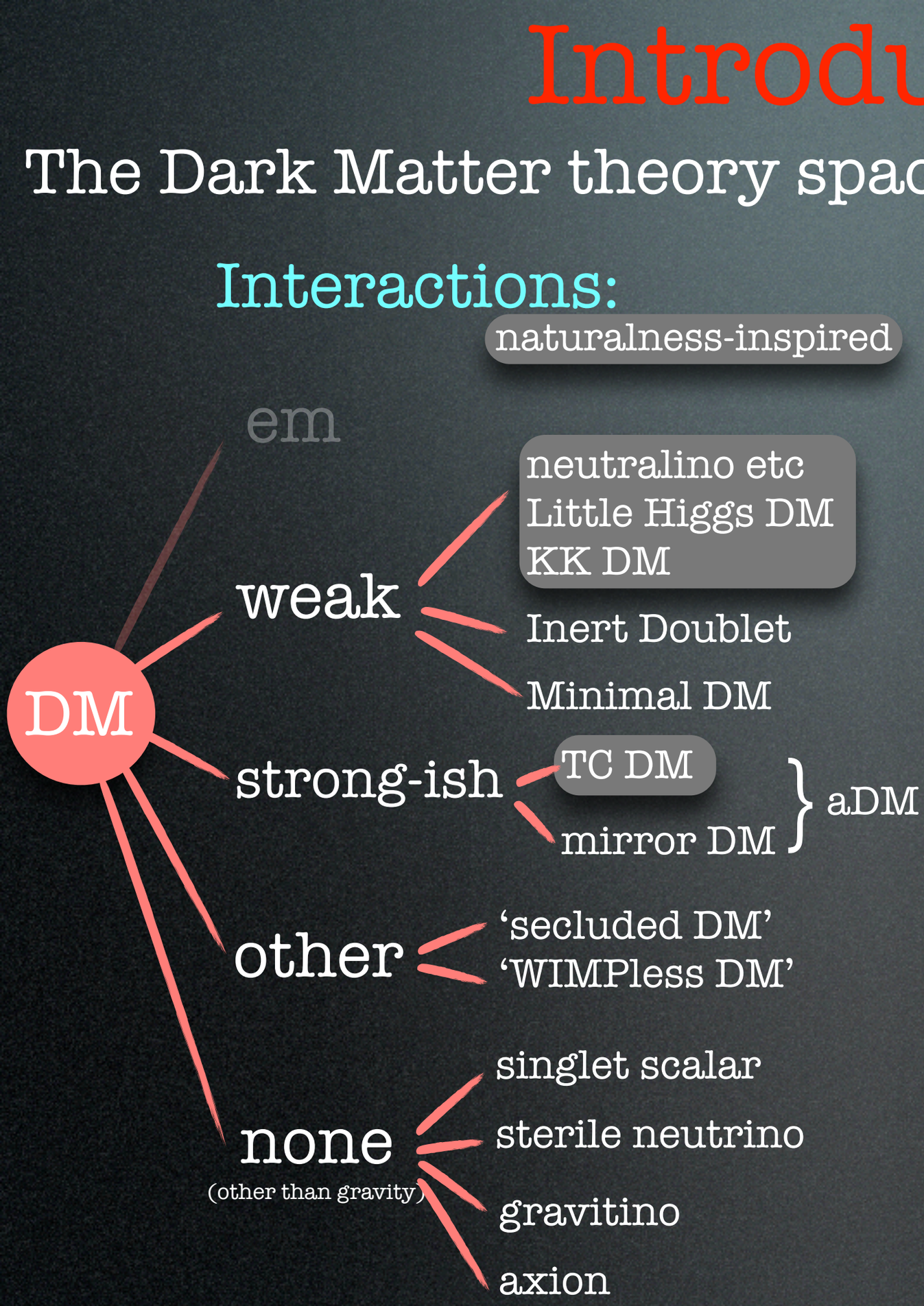
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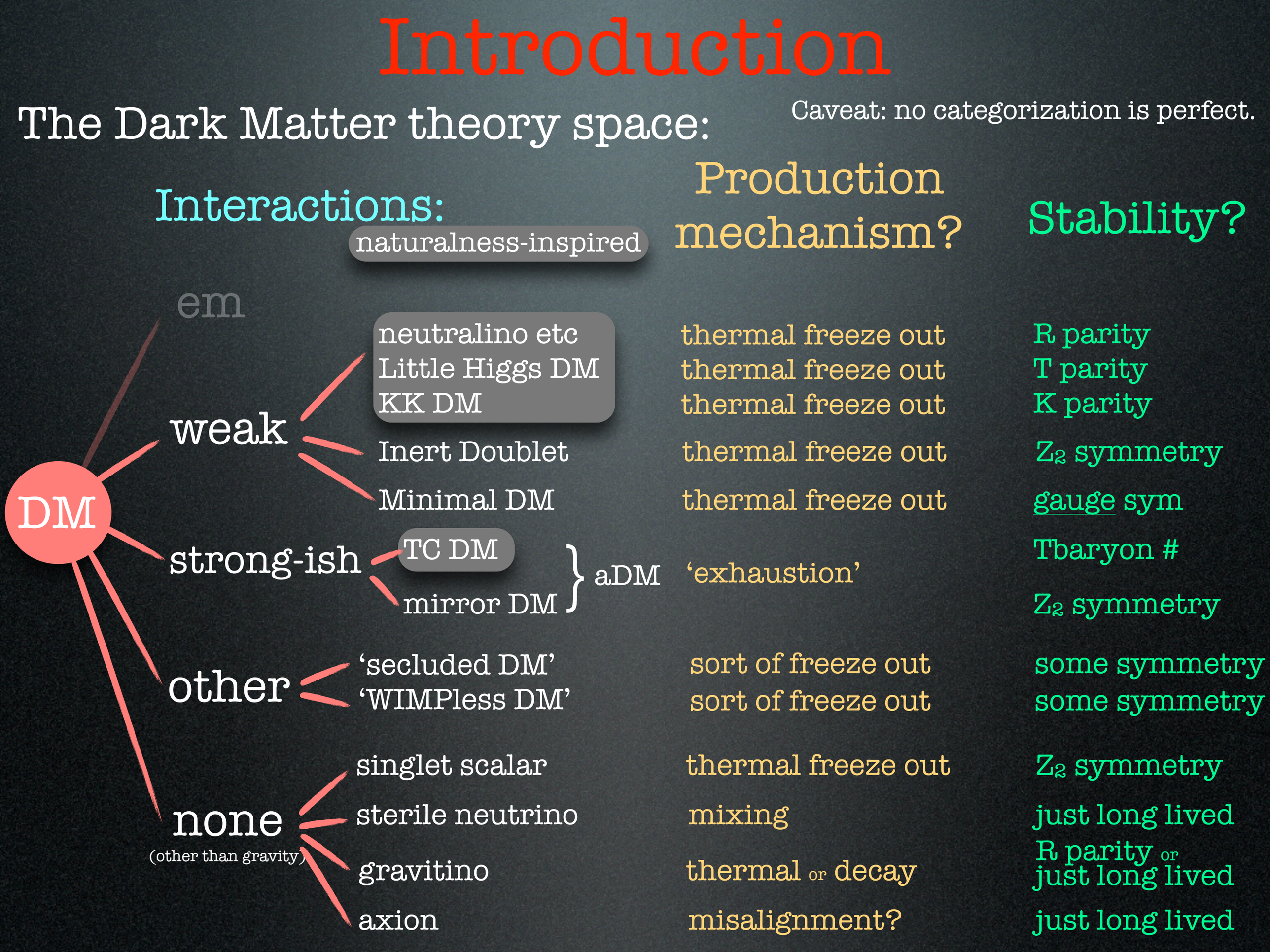
naturalness-inspired



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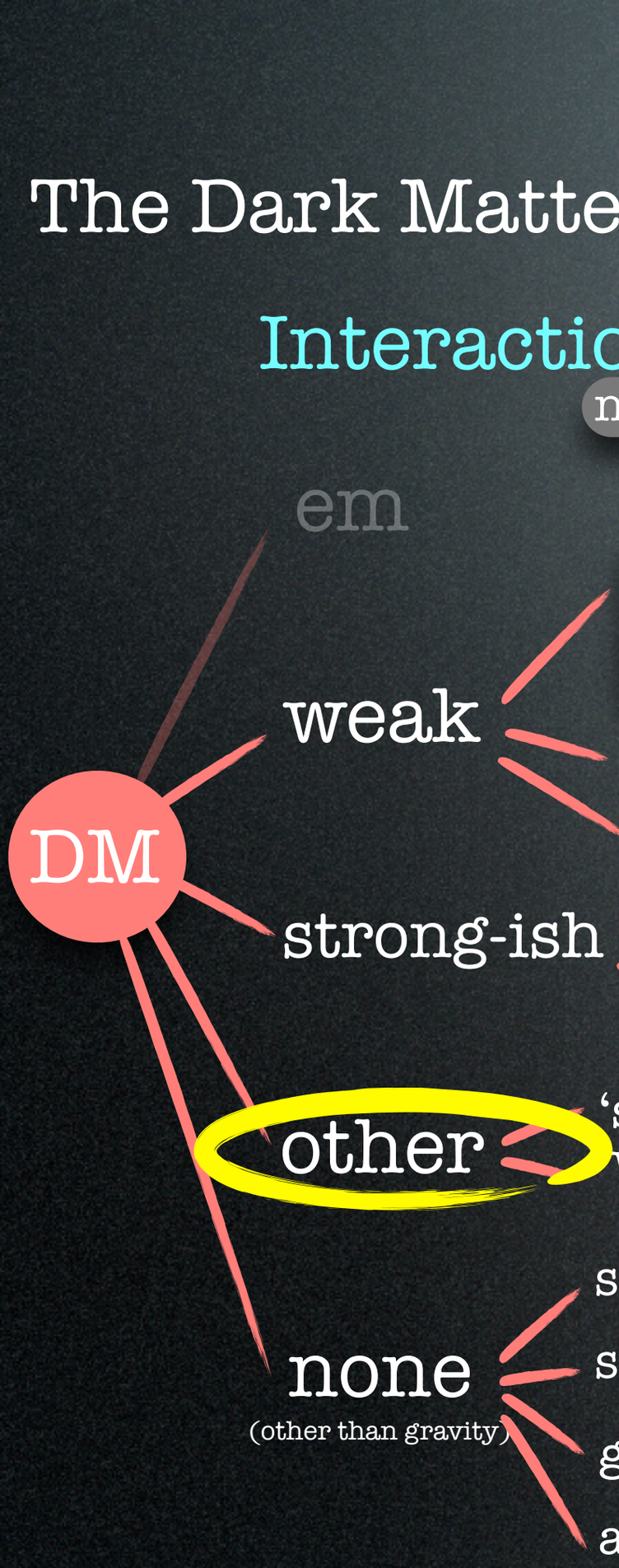
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Introduction

The Dark Matter theory space:

Caveat: no categorization is perfect.



Interactions: (naturalness-inspired)	Production mechanism?	Stability?
neutralino etc	thermal freeze out	R parity
Little Higgs DM	thermal freeze out	T parity
KK DM	thermal freeze out	K parity
Inert Doublet	thermal freeze out	Z_2 symmetry
Minimal DM	thermal freeze out	gauge sym
TC DM	‘exhaustion’	Tbaryon #
mirror DM	‘exhaustion’	Z_2 symmetry
‘secluded DM’	sort of freeze out	some symmetry
WIMPless DM’	sort of freeze out	some symmetry
singlet scalar	thermal freeze out	Z_2 symmetry
sterile neutrino	mixing	just long lived
gravitino	thermal or decay	R parity or just long lived
axion	misalignment?	just long lived

aDM

Dark U(1) DM

inspired by:
Boehm, **Fayet** 2003+

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Boehm, **Fayet** 2003+

$$\mathcal{L} = \bar{X}(i\not{\partial} - M_{\rm DM})X - \frac{1}{4}F_{D\mu\nu}F_D^{\mu\nu} - \frac{\epsilon}{2}F_{D\mu\nu}F_Y^{\mu\nu}$$

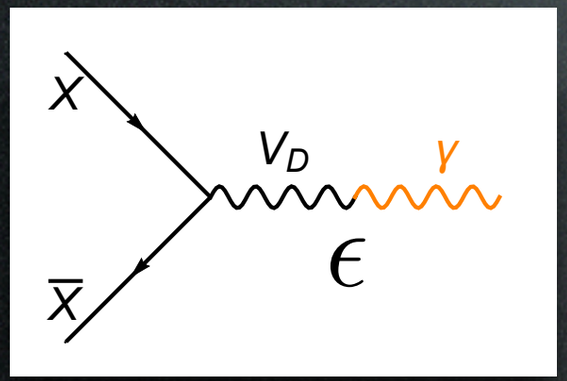
parameters are: α, ν, m_V, M

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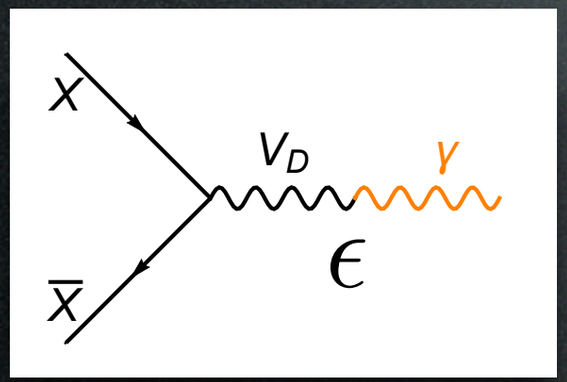


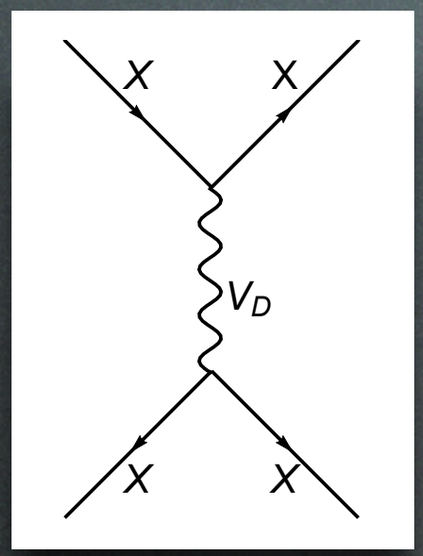
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Inspiration from astro/cosmo

An old idea

"we suggest that the dark matter particles should have an elastic scattering cross-section"

Spergel, Steinhardt 1999

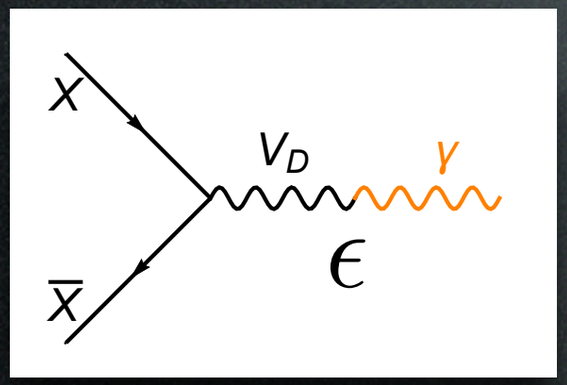
$$\sigma_{XX} = 8.1 \times 10^{-25}\,\mathrm{cm}^2 \left(\frac{m_x}{\mathrm{GeV}}\right)\left(\frac{\lambda}{1\mathrm{Mpc}}\right)^{-1}$$

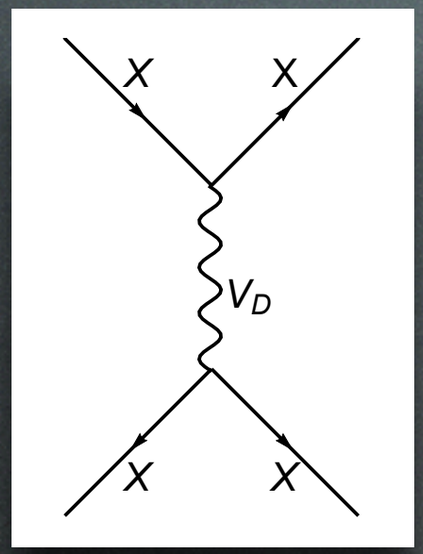
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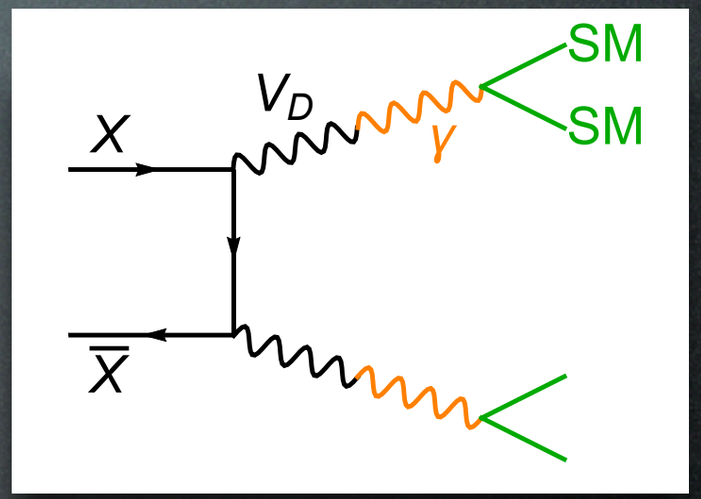
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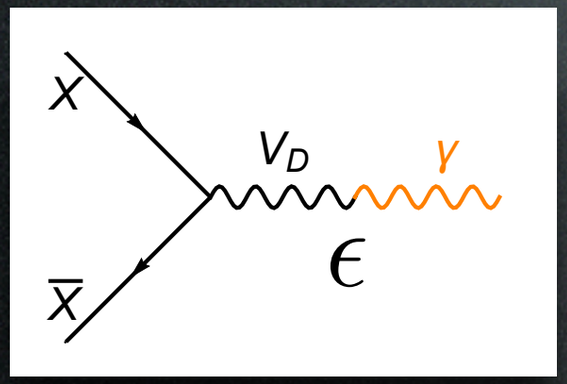


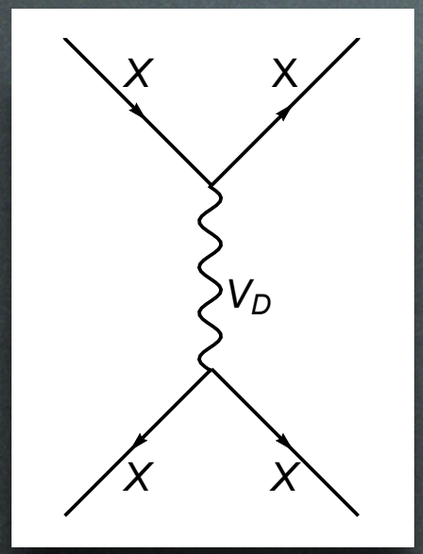
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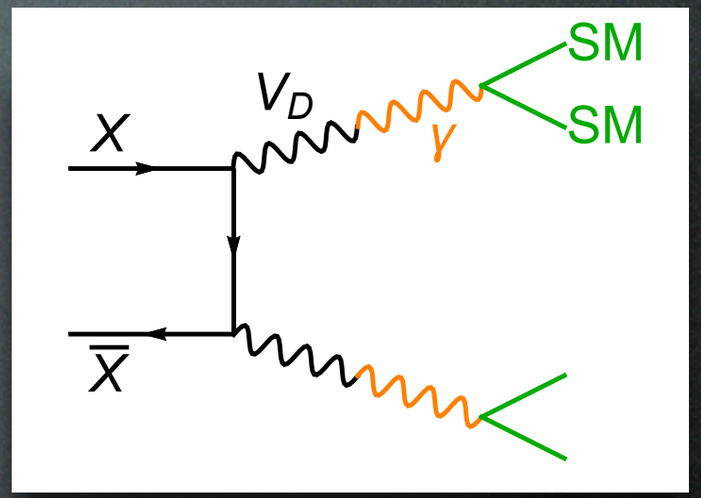
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size of the XX system

If $\alpha M/m_V \gtrsim 1$, the force is long range:

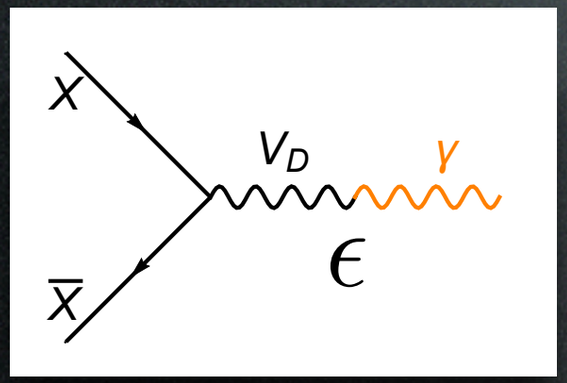
range

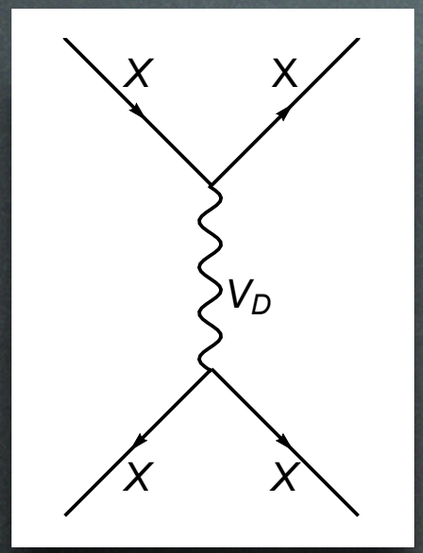
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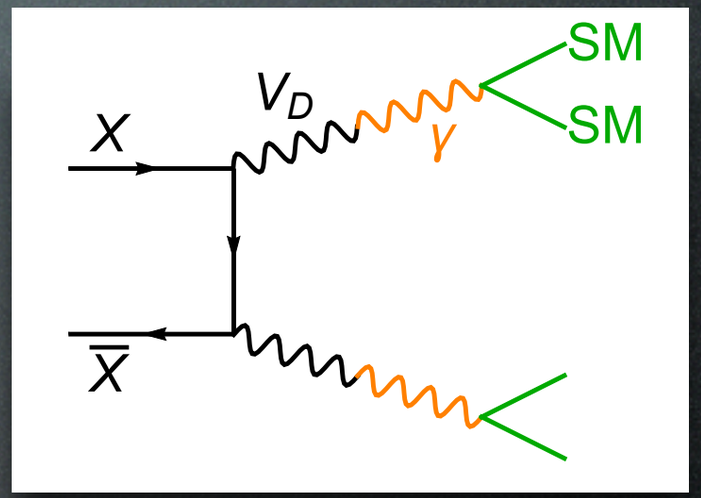
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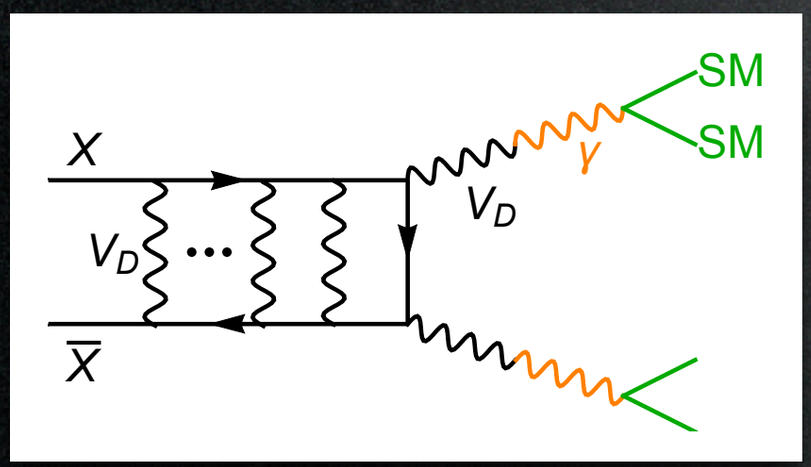




size of the XX system

If $\alpha M/m_V \gtrsim 1$, the force is long range:
(range)

Sommerfeld enhanced

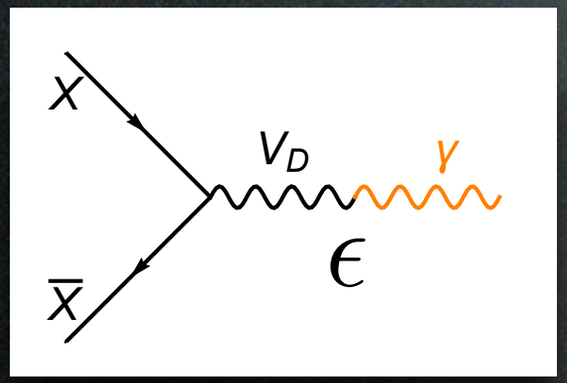


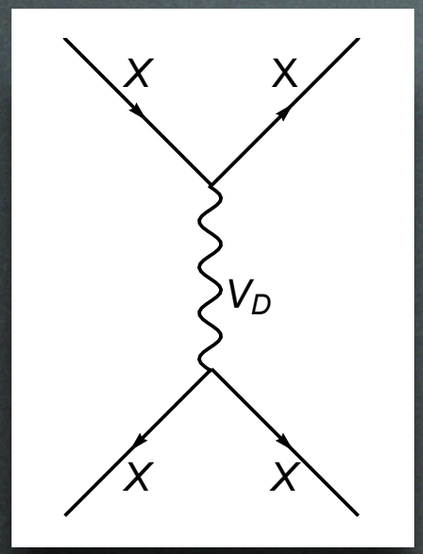
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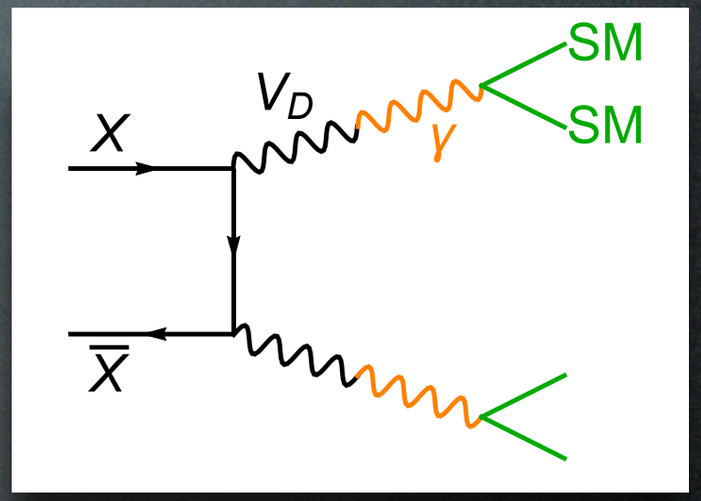
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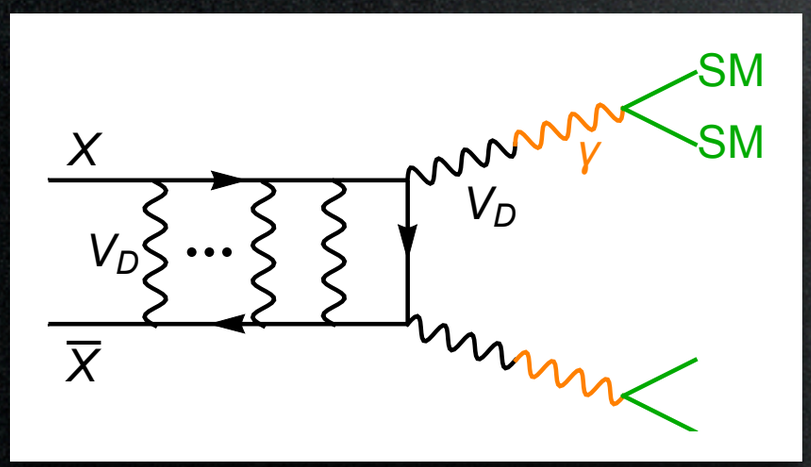
Cirelli, Strumia, Tamburini 0706.4071
Cirelli, Franceschini, Strumia 0802.3378

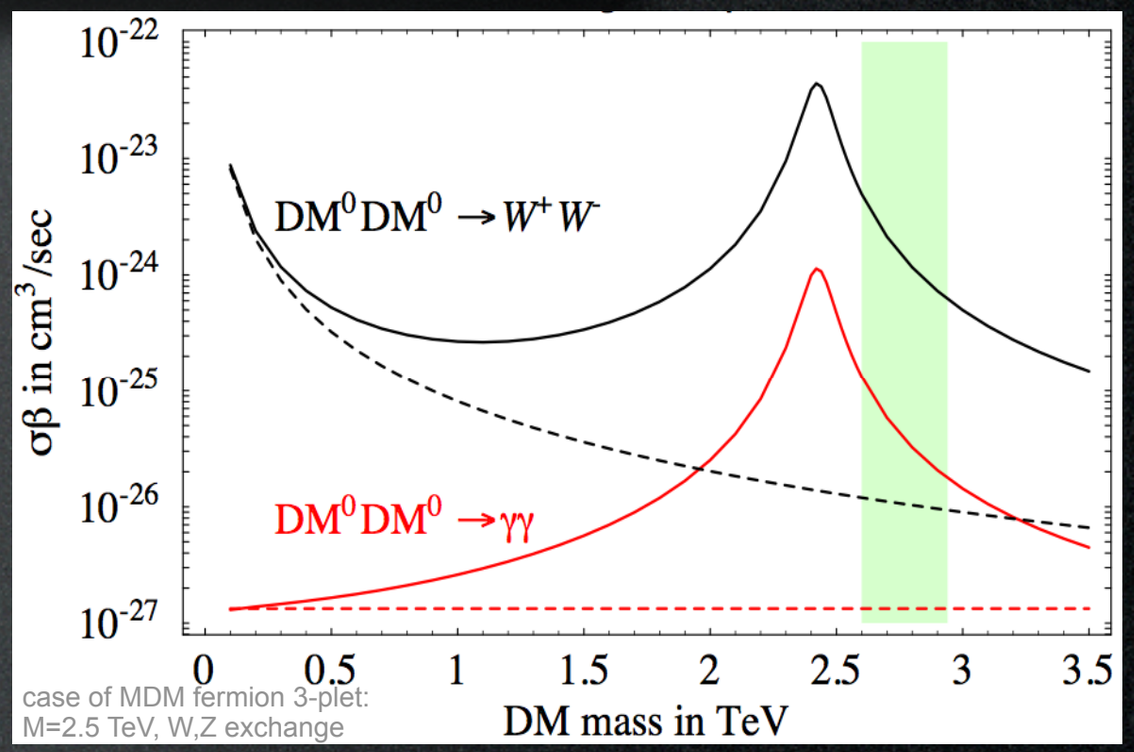
size of the XX system

If $\alpha M/m_V \gtrsim 1$, the force is long range:

range

Sommerfeld enhanced





case of MDM fermion 3-plet:
M=2.5 TeV, W,Z exchange

Inspiration from astro/cosmo

An old idea

"we suggest that the dark matter particles should have an elastic scattering cross-section"

Spergel, Steinhardt 1999

$$\sigma_{XX} = 8.1 \times 10^{-25}\,\mathrm{cm}^2 \left(\frac{m_x}{\mathrm{GeV}}\right)\left(\frac{\lambda}{1\mathrm{Mpc}}\right)^{-1}$$

with a modern incarnation:
'secluded Dark Matter' or 'hidden sector DM'

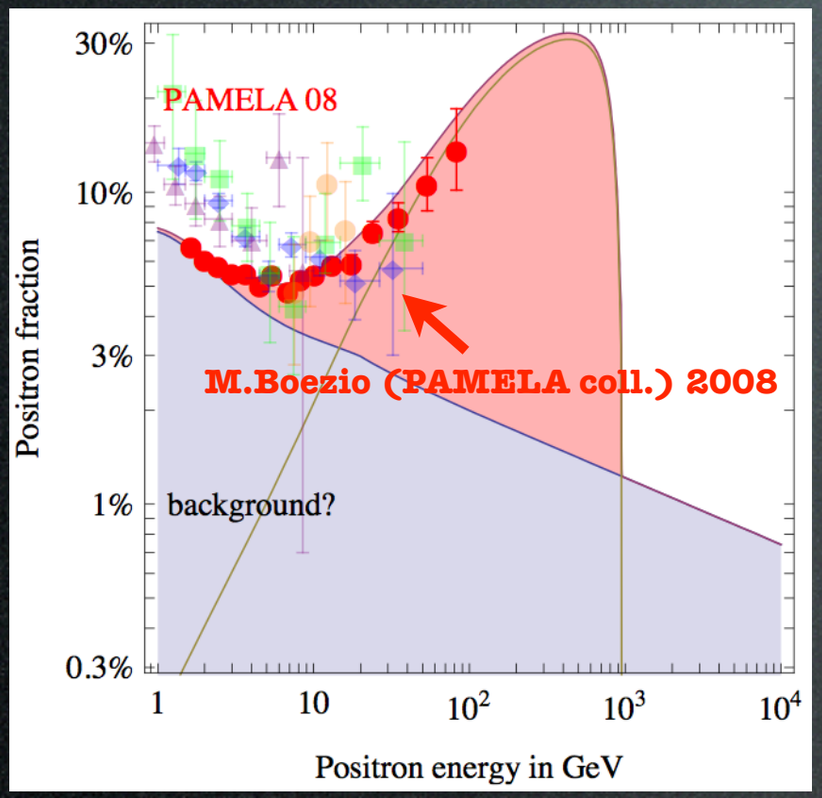
Pospelov, Ritz et al 0711.4866

Arkani-Hamed, Weiner, Finkbeiner et al. 0810.0713
0811.3641

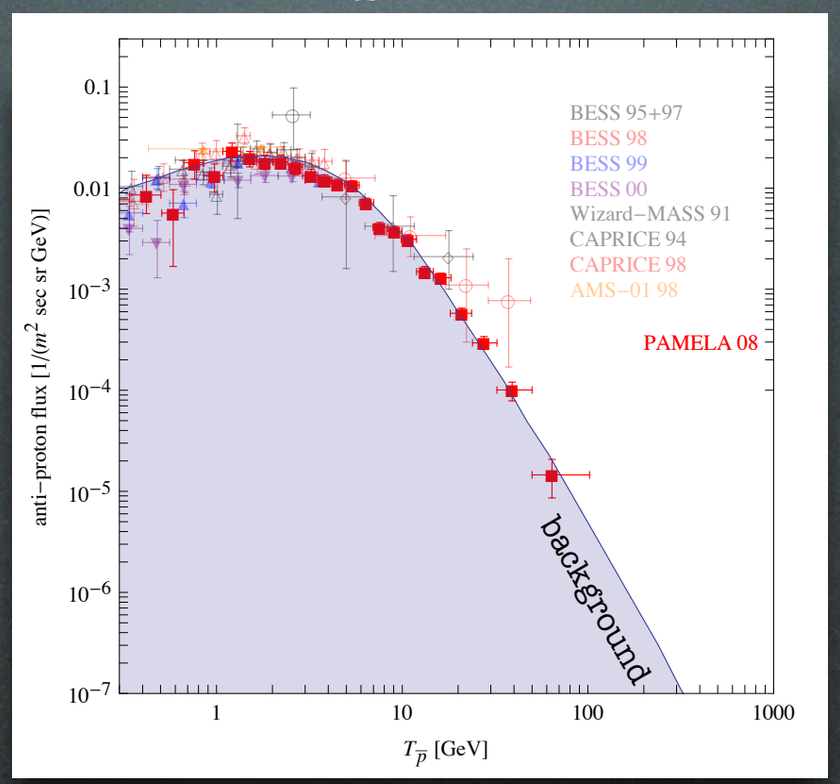
Nomura, Thaler 0810.539

Phenomenological motivation

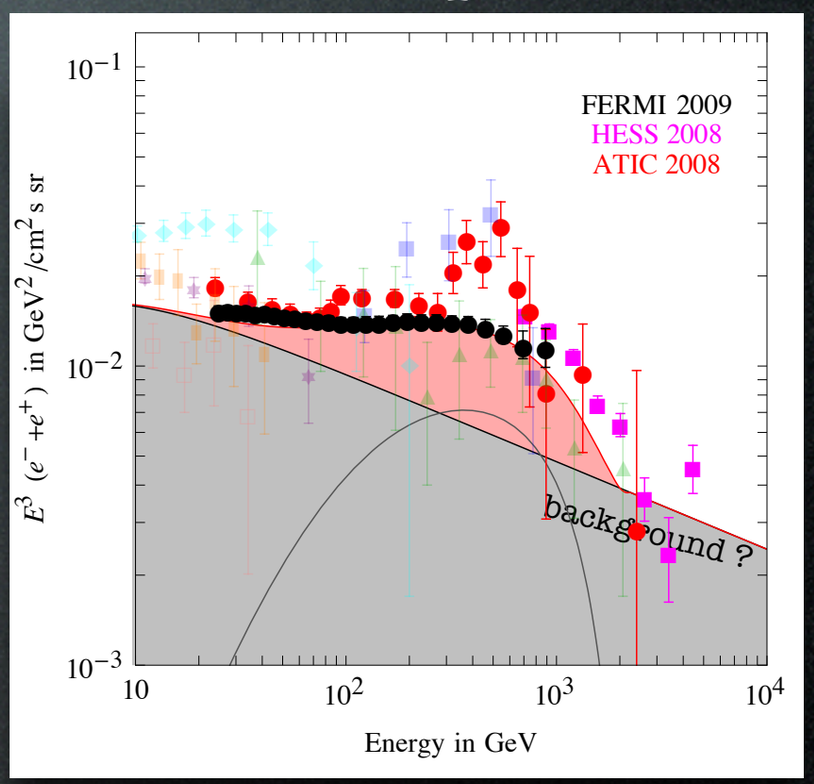
positron fraction



antiprotons



electrons + positrons

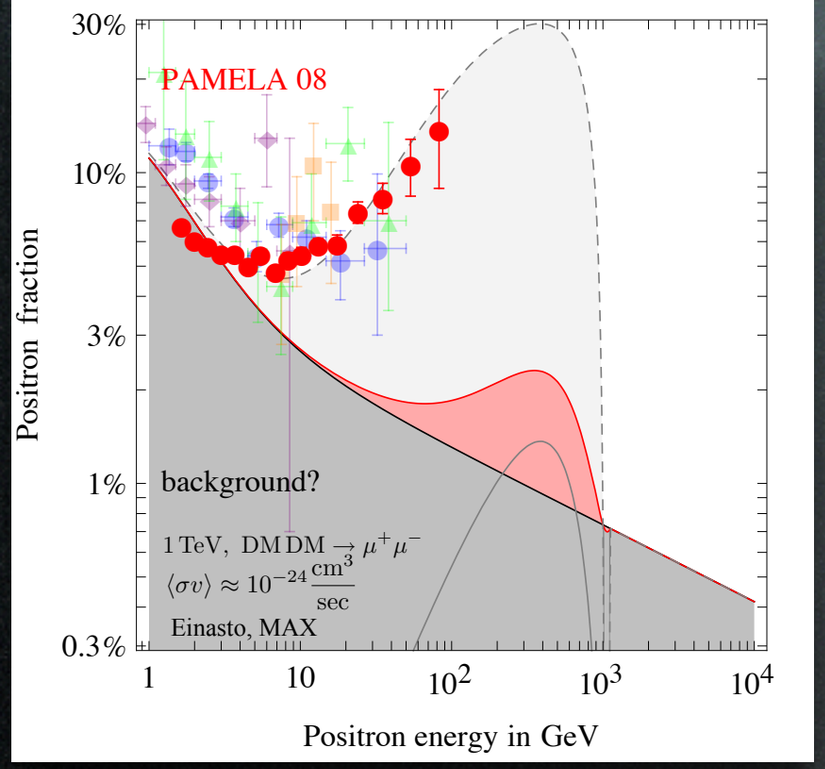


Are these signals of Dark Matter?

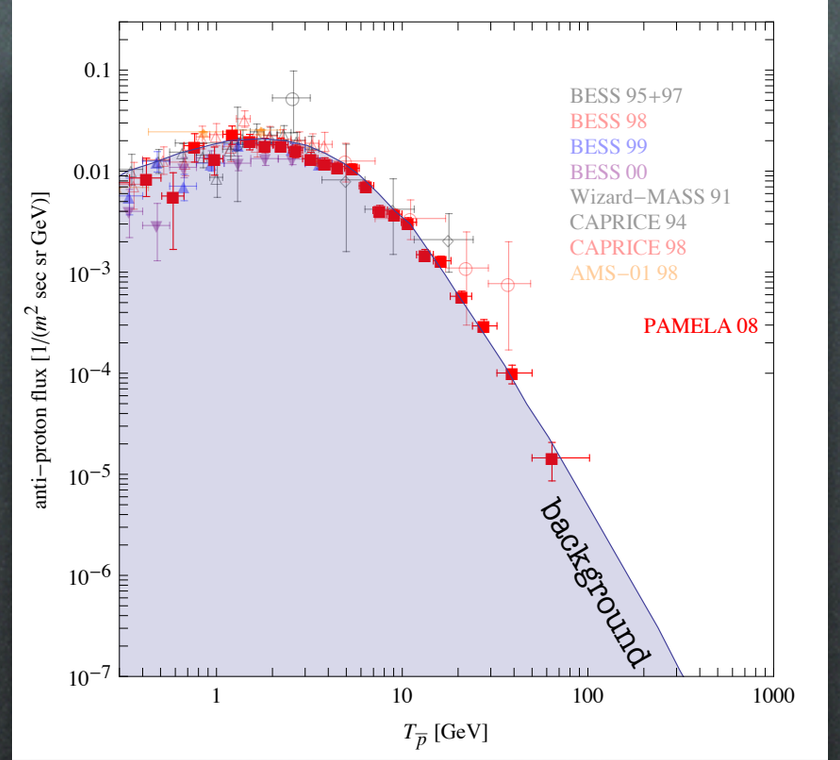
YES: few TeV, leptophilic DM
with huge $\langle \sigma v \rangle \approx 10^{-23}\,\mathrm{cm}^3/\mathrm{sec}$

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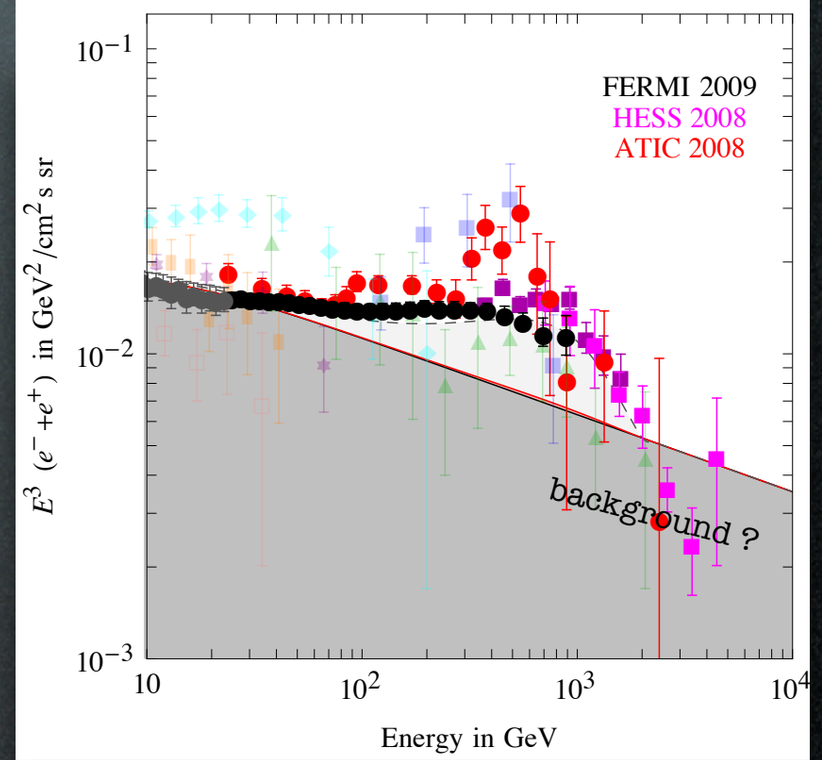
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Are these signals of Dark Matter?

YES: few TeV, leptophilic DM
with huge $\langle\sigma v\rangle \approx 10^{-23}\,\text{cm}^3/\text{sec}$

NO: a formidable 'background' for future searches

The "Theory of DM"

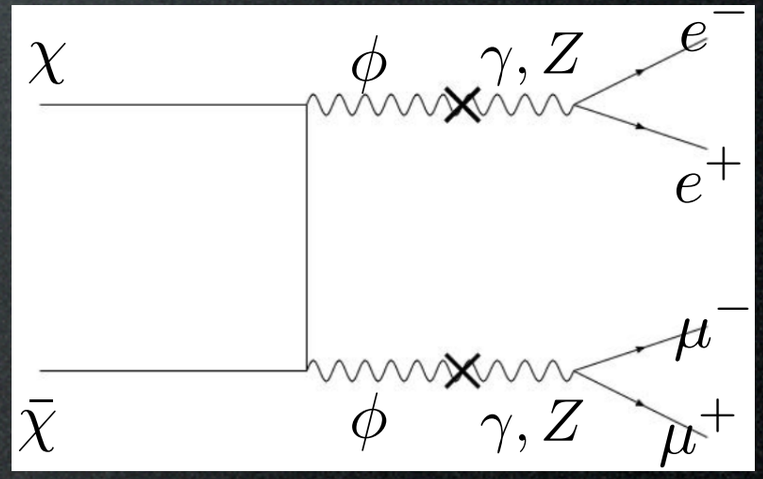
Arkani-Hamed, Weiner, Finkbeiner et al. 0810.0713
0811.3641

Basic ingredients:

χ Dark Matter particle, decoupled from SM, mass $M \sim 700+$ GeV

ϕ new gauge boson ("Dark photon"),
couples only to DM, with typical gauge strength, $m_\phi \sim$ few GeV
- mediates Sommerfeld enhancement of $\chi\bar{\chi}$ annihilation:
$\alpha M/m_V \gtrsim 1$ fulfilled

- decays only into e^+e^- or $\mu^+\mu^-$
for kinematical limit



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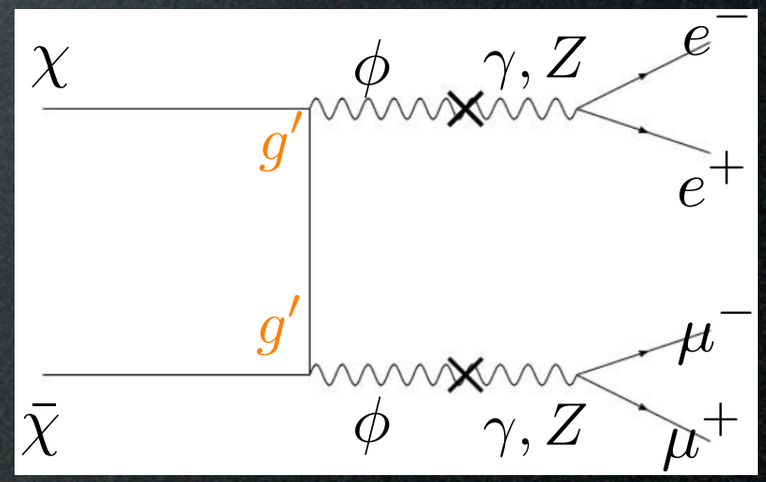
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Production mechanism:

just thermal freeze-out
of these annihilations

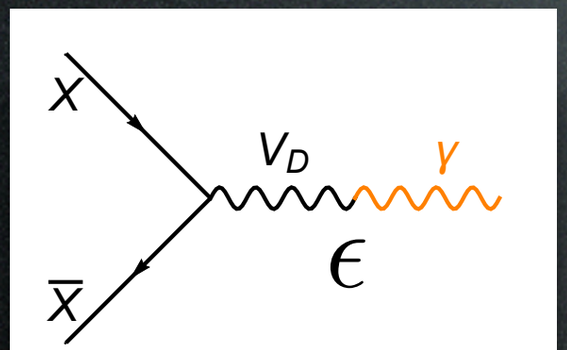
same idea in: WIMPless DM Feng, Kumar 2008

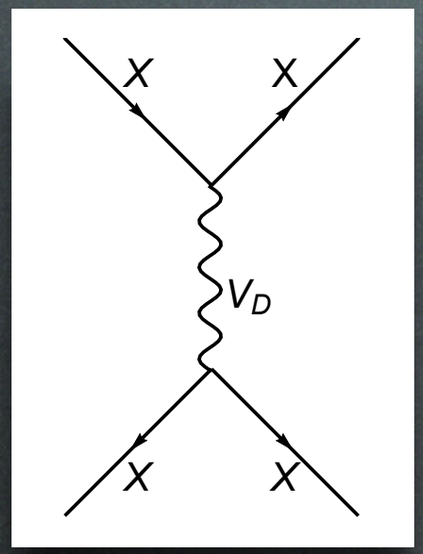
Dark U(1) DM

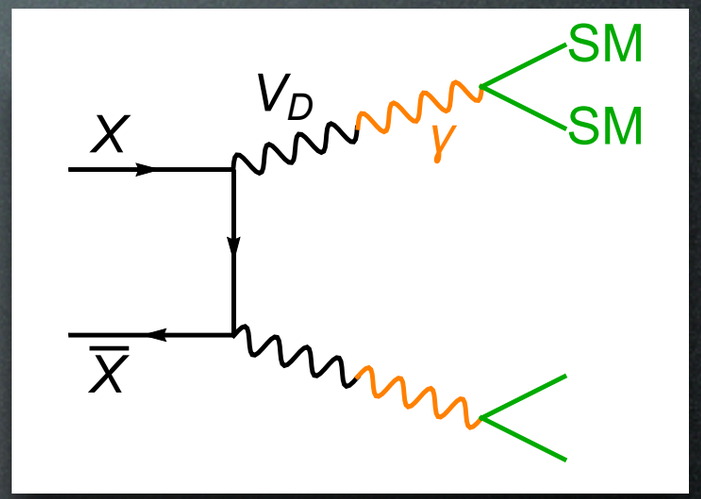
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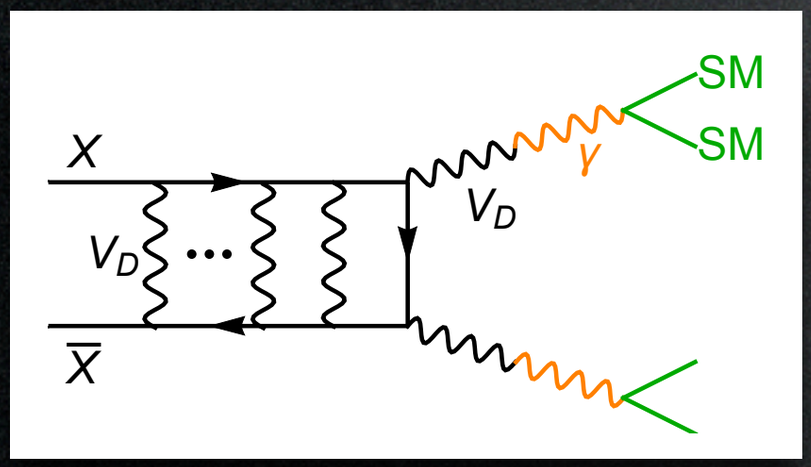




size of the XX system

If $\alpha M/m_V \gtrsim 1$, the force is long range:
(range)

Sommerfeld enhanced

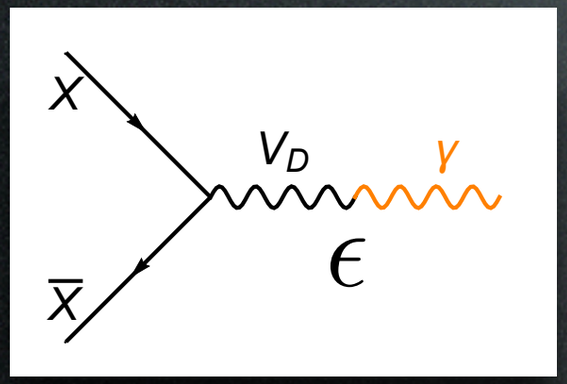


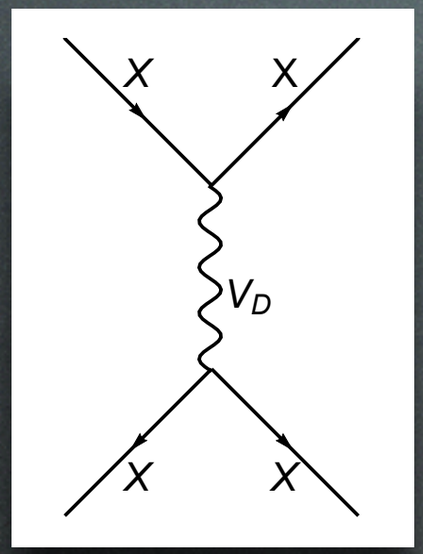
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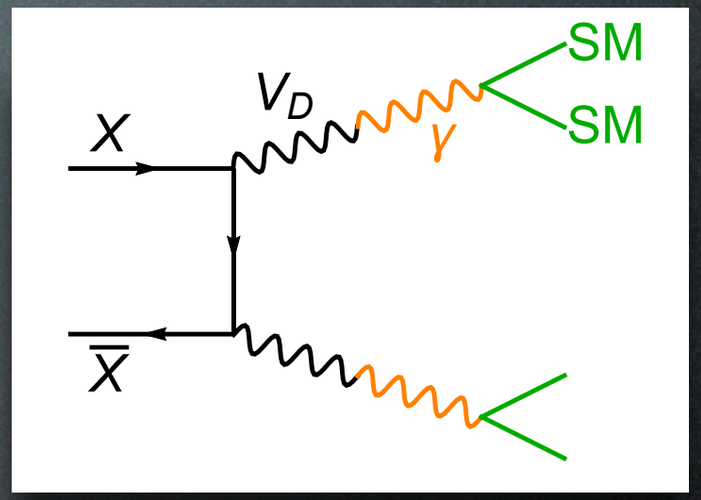
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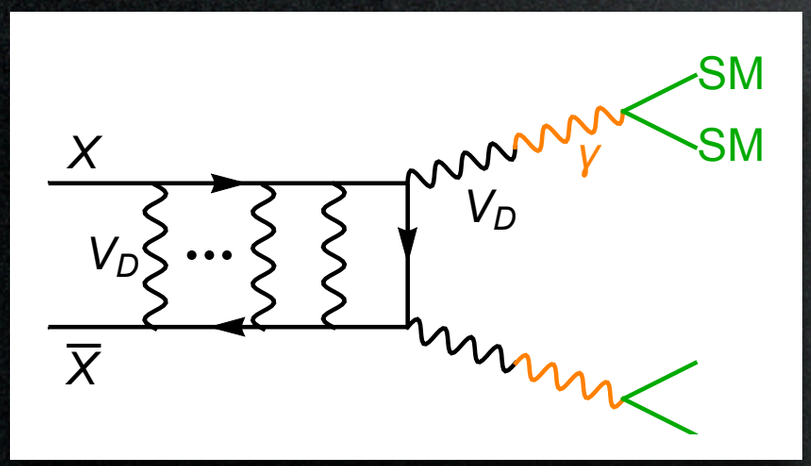


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range

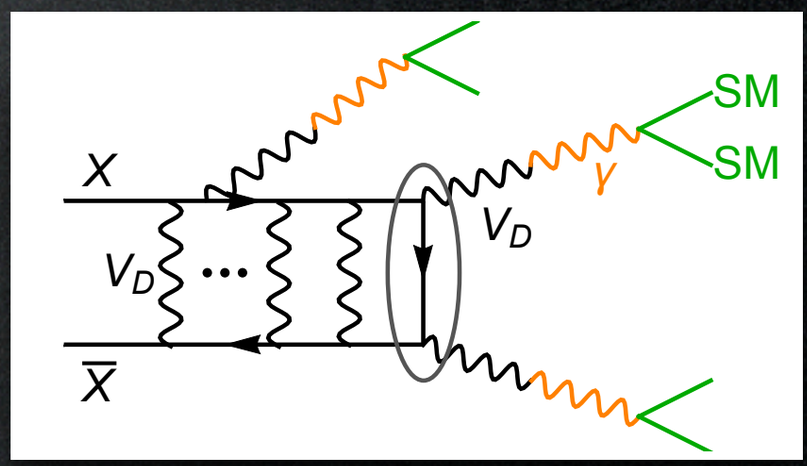
Sommerfeld enhanced



binding energy of the XX system

If $\alpha^2 M/2m_V \gtrsim 1$, bound states form

emitted dark photon

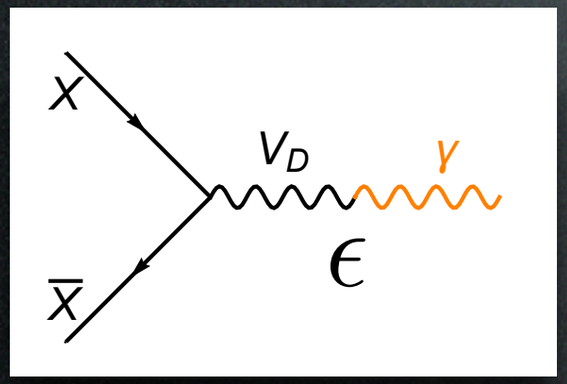


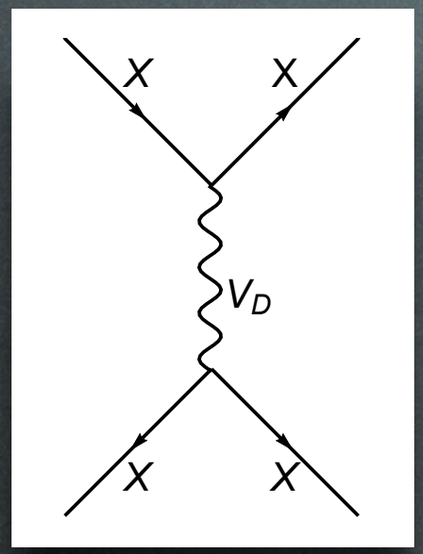
Dark U(1) DM

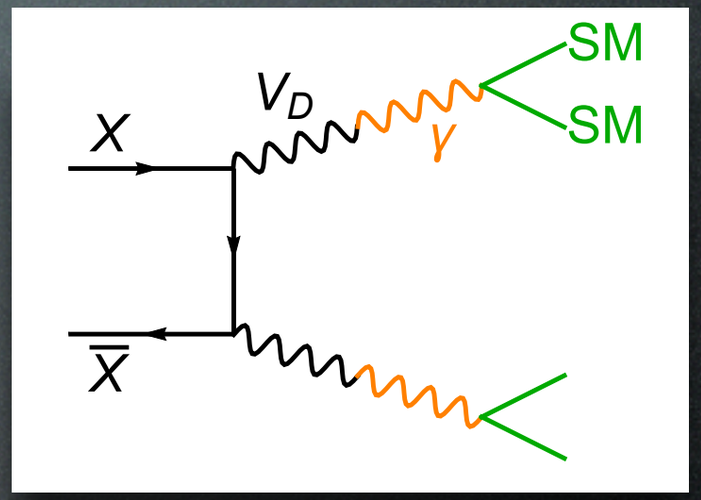
inspired by:
Boehm, **Fayet** 2003+

$$\mathcal{L} = \bar{X}(i\not{\partial} - M_{\rm DM})X - \frac{1}{4}F_{D\mu\nu}F_D^{\mu\nu} - \frac{\epsilon}{2}F_{D\mu\nu}F_Y^{\mu\nu}$$

parameters are: α, ν, m_V, M





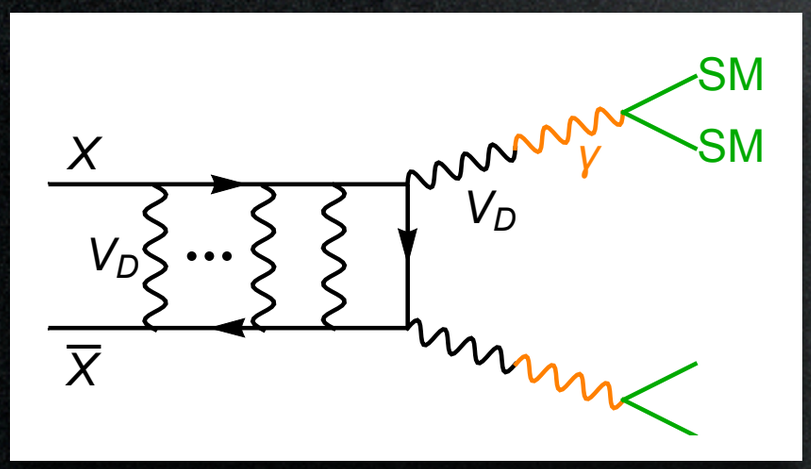


size of the XX system

If $\alpha M/m_V \gtrsim 1$, the force is long range:

range

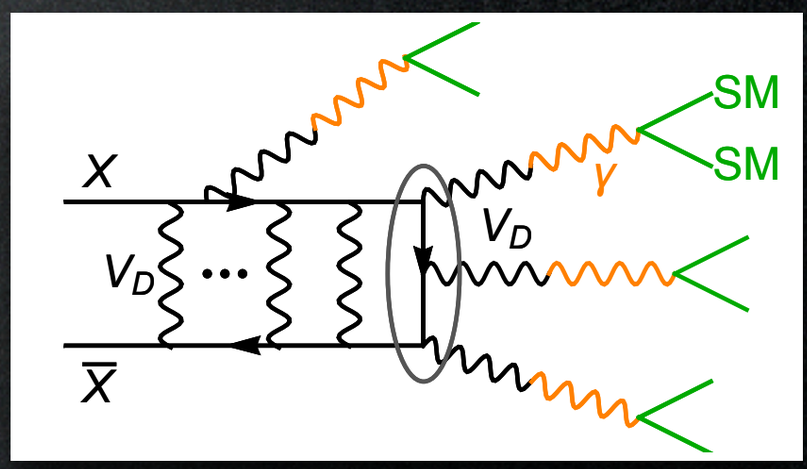
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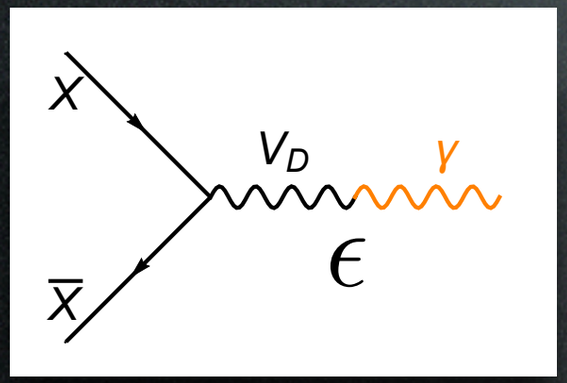


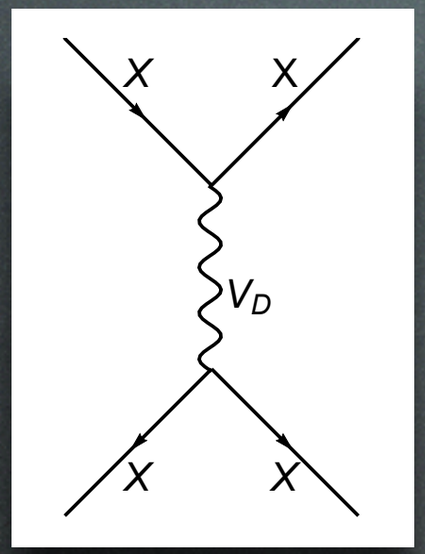
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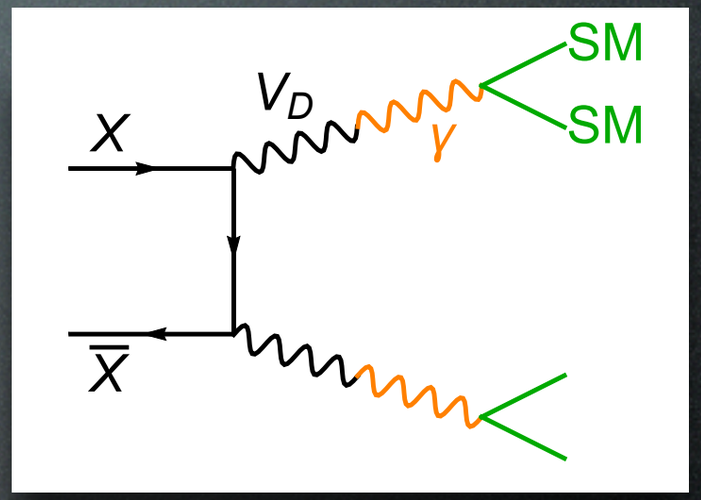
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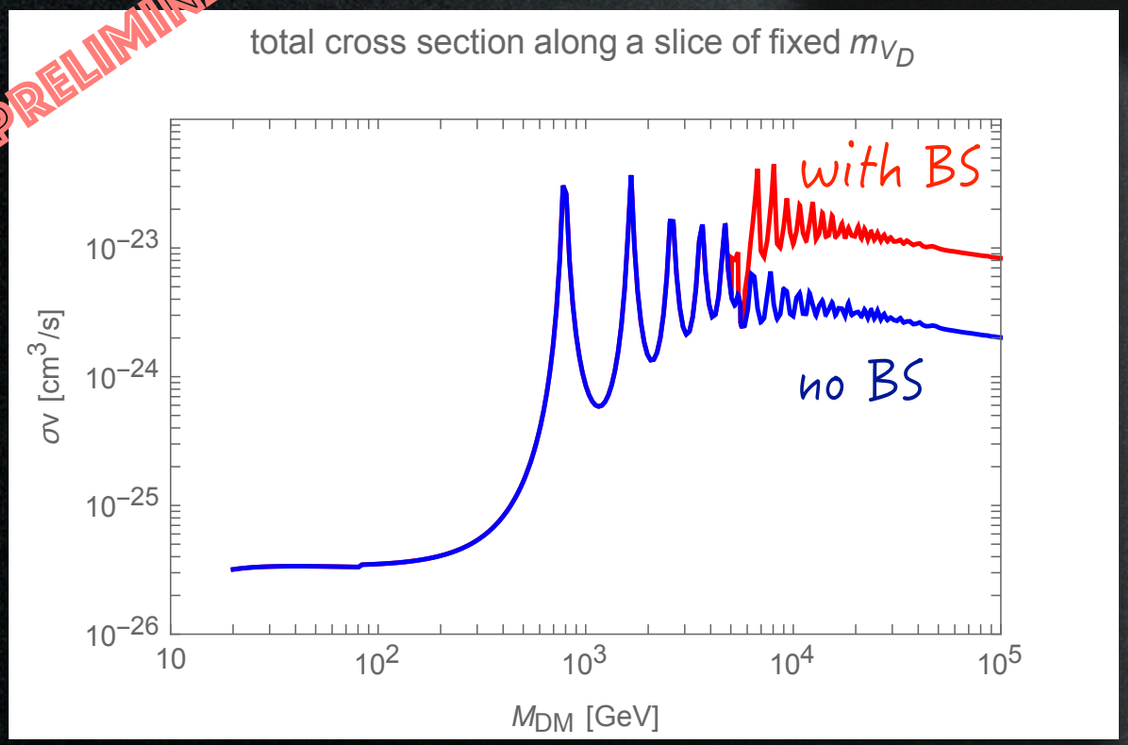
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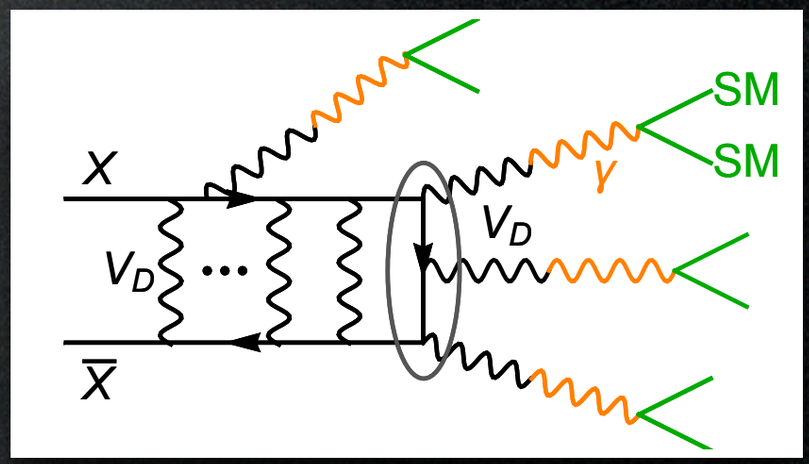
PRELIMINARY



binding energy of the XX system

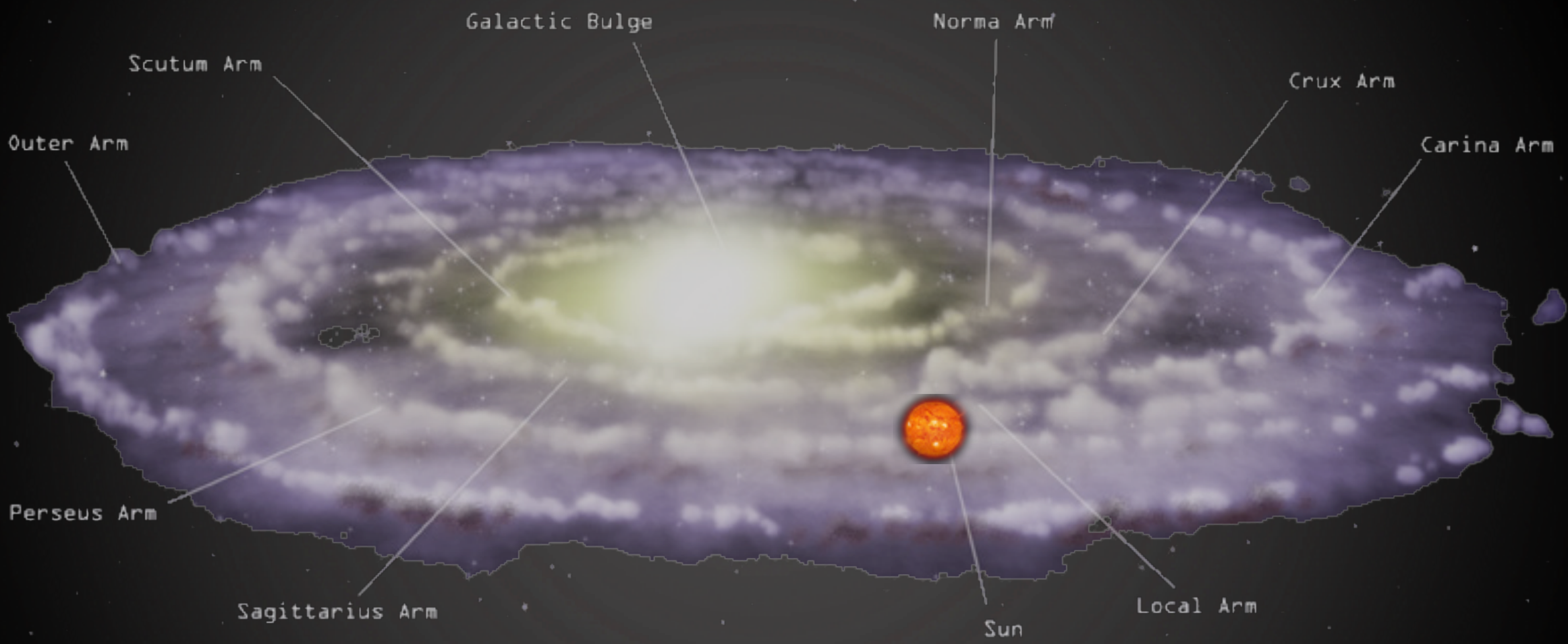
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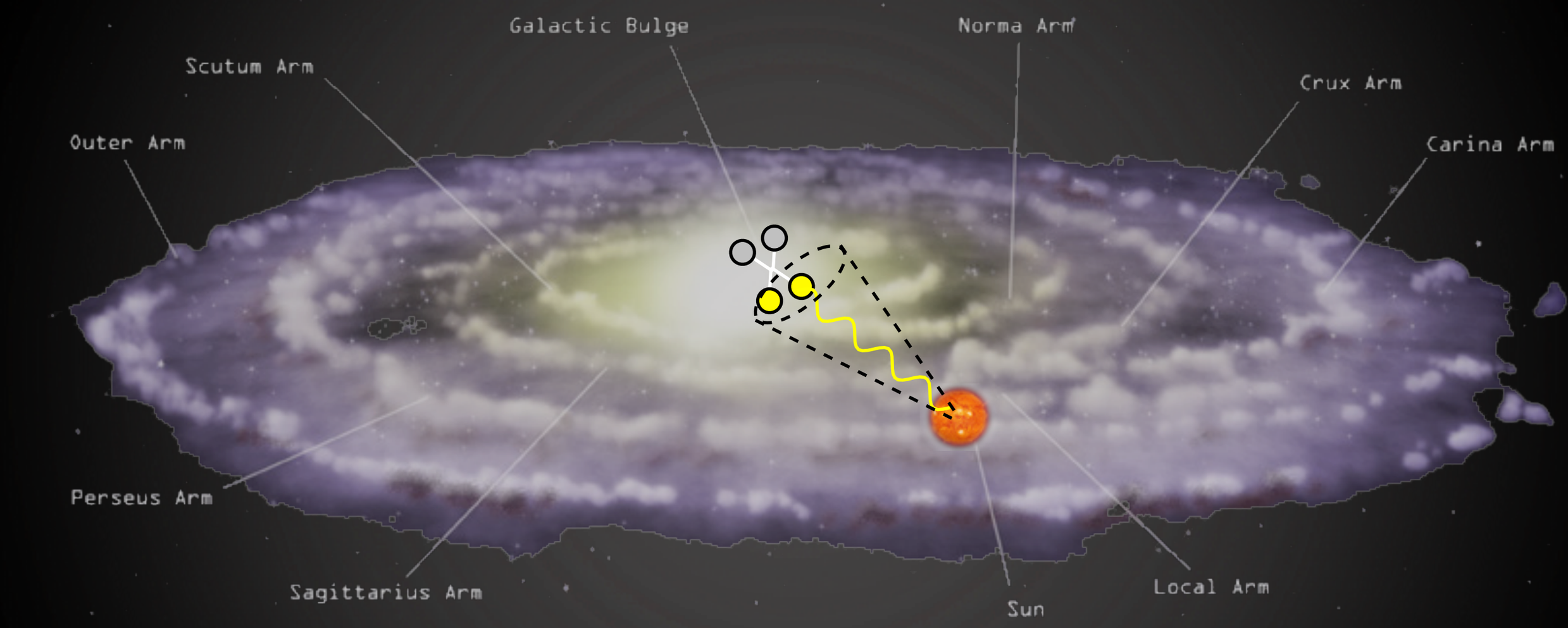
Indirect Detection

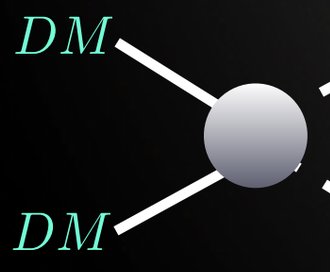
γ from DM annihilations



Indirect Detection

γ from DM annihilations in galactic center



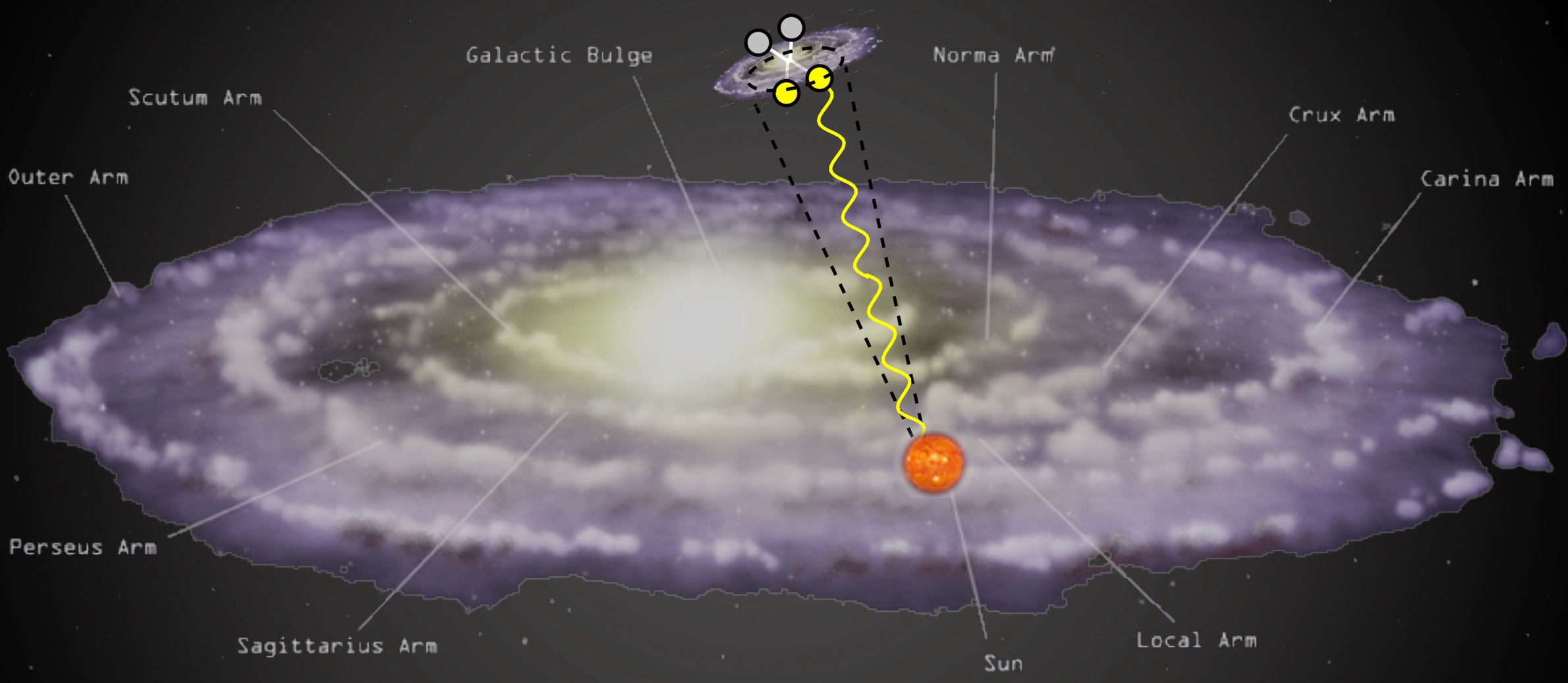


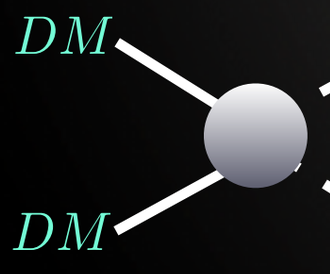
$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp},\ \overset{(-)}{p},\ \overset{(-)}{D}\ \ldots \text{ and } \gamma$$

$$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^{\pm},\ \overset{(-)}{p},\ \overset{(-)}{D}\ \ldots \text{ and } \gamma$$

Indirect Detection

γ from DM annihilations in dwarf galaxies



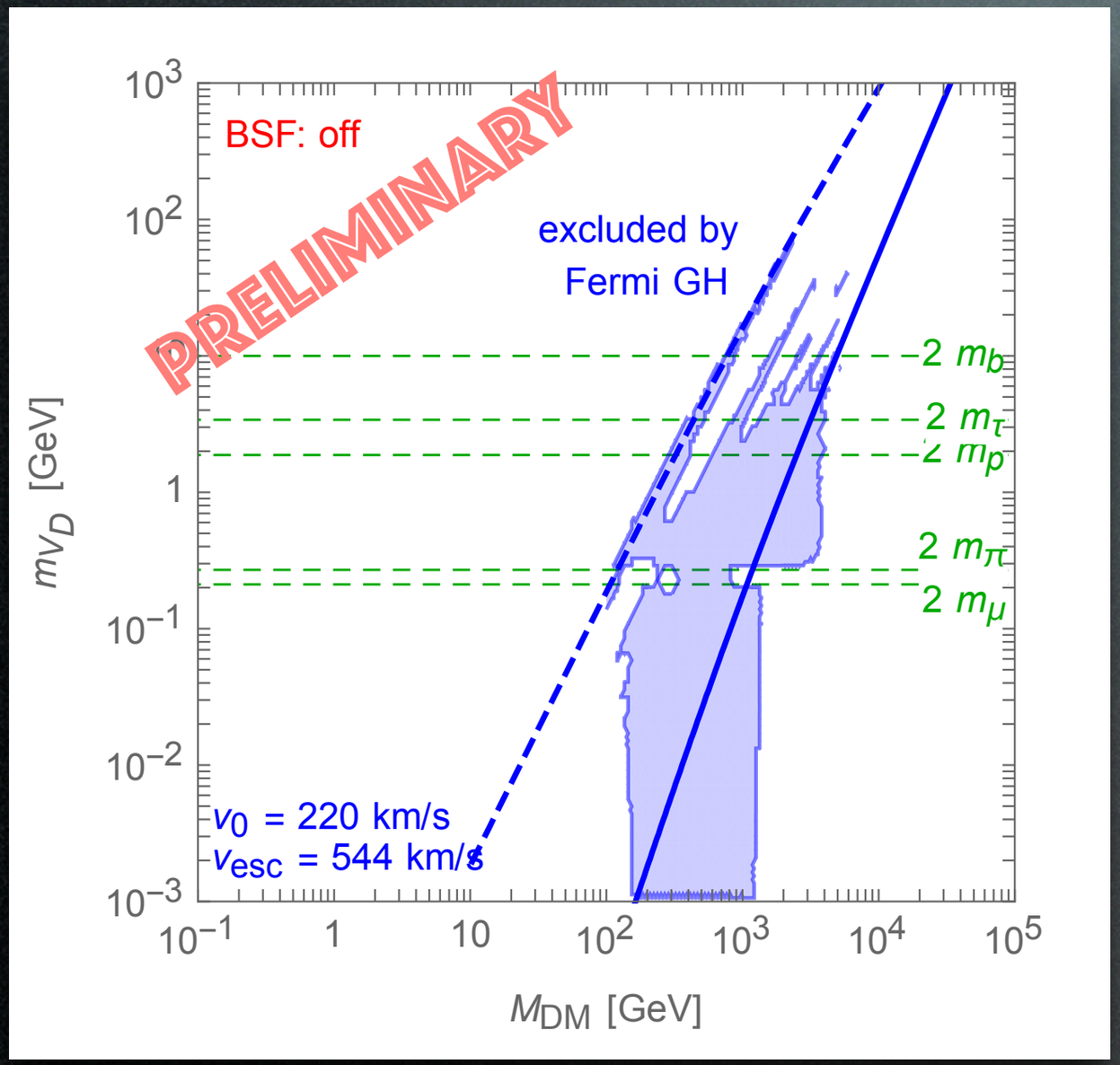


$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp},\ \overset{(-)}{p},\ \overset{(-)}{D}\ \ldots \text{ and } \gamma$$

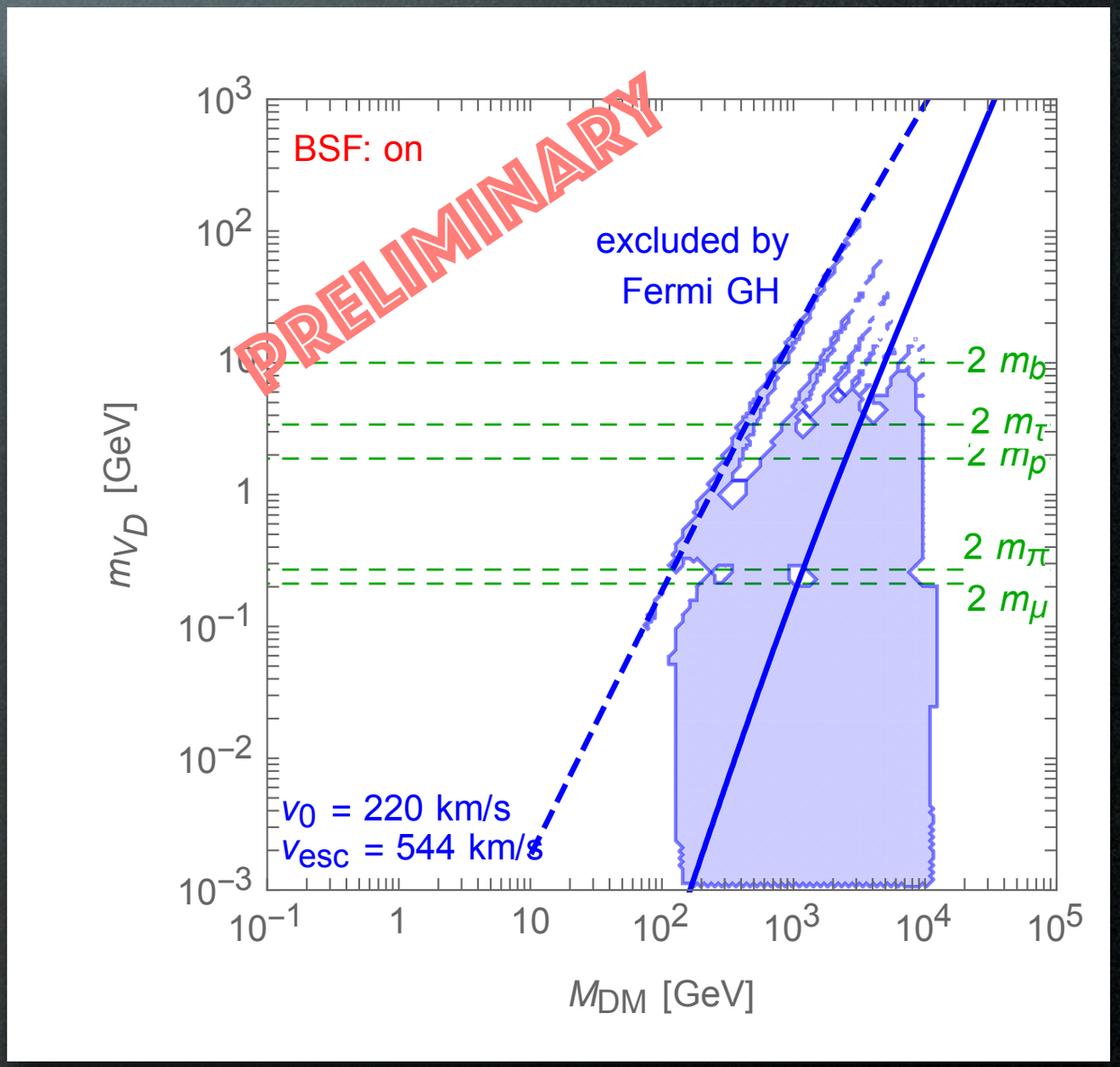
$$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^{\pm},\ \overset{(-)}{p},\ \overset{(-)}{D}\ \ldots \text{ and } \gamma$$

Indirect Detection

without bound states



with bound states



Cirelli, Panci, Petraki, Sala, Taoso,
1612.xxxxx

Conclusions

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Dark Matter exists

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Perhaps in form of SuSy LSP

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Perhaps within a rich ‘Dark Sector’

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In both cases Pierre's ideas resonate.

Thank You!

Backup slides

Sommerfeld Enhancement

NP QM effect that can enhance the annihilation cross section by orders of magnitude in the regime of small velocity and relatively long range force.

Sommerfeld, Ann.Phys. 403, 257 (1931)

Hisano et al., 2003-2006:
in part. hep-ph/0307216, 0412403, 0610249

Cirelli, Tamburini, Strumia 0706.4071

Arkani-Hamed et al., 0810.0713

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A classical analogy:

Arkani-Hamed et al. 0810.0713



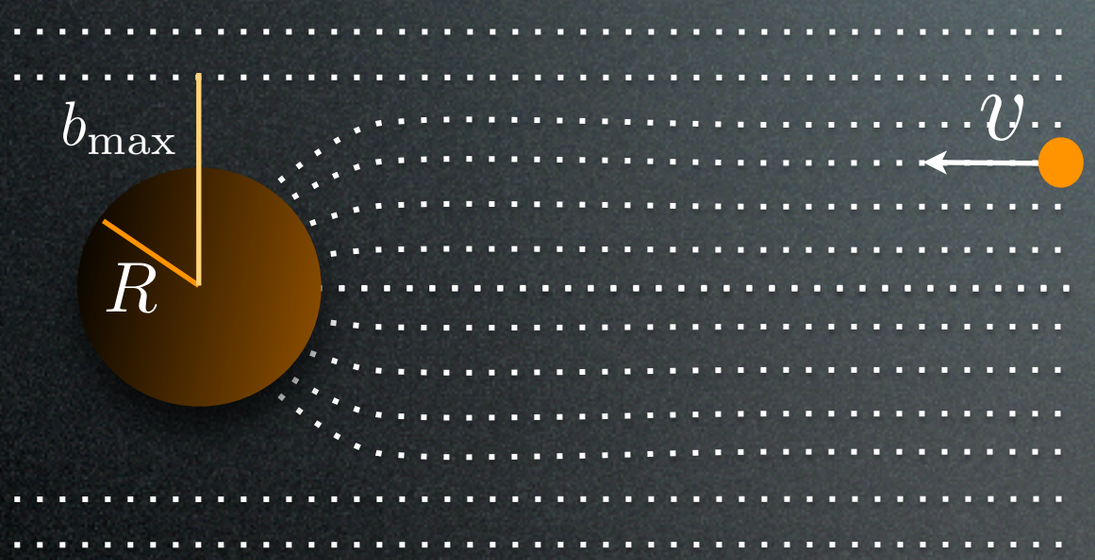
$$\sigma_0 = \pi R^2$$

Sommerfeld Enhancement

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A classical analogy:

Arkani-Hamed et al. 0810.0713



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

$$\sigma = \pi R^2 \left(1 + \frac{2G_N M/R}{v^2}\right)$$

with $v_{\rm esc}^2 = 2G_N M/R$

For $v \gg v_{\rm esc}$ then $\sigma \to \sigma_0$

For $v \ll v_{\rm esc}$ then $\sigma \gg \sigma_0$

i.e. $E_{\rm kin} < U_{\rm pot}$ (i.e. the deforming potential is not negligible)

[jump to conclusions]

Sommerfeld Enhancement

NP QM effect that can enhance the annihilation cross section by orders of magnitude in the regime of small velocity and relatively long range force.

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$\psi(\vec{r})$ wave function of two DM particles ($\vec{r} = \vec{r}_1 - \vec{r}_2$)
obeys (reduced) Schrödinger equation:

(V does not depend on time)

$$-\frac{1}{M}\frac{d^2\psi}{dr^2} + V \cdot \psi = M\nu^2\psi$$

ν: velocity

V: potential due to exchange of force carriers

At $r = 0$: annihilation

$$\sigma_{\text{ann}} \propto \psi\Gamma\psi \qquad \text{with } \Gamma \text{ such that } \langle \text{DM DM}|\Gamma|\text{final}\rangle$$

Sommerfeld enhancement:

$$R = \frac{\sigma_{\text{ann}}}{\sigma^0_{\text{ann}}} = \left|\frac{\psi(\infty)}{\psi(0)}\right|^2$$

σ^0_{ann}: unperturbed cross section

Sommerfeld Enhancement

NP QM effect that can enhance the annihilation cross section by orders of magnitude in the regime of small velocity and relatively long range force.

Yukawa potential:

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$$-\frac{1}{M}\frac{d^2\psi}{dr^2} + V\cdot\psi = M\nu^2\psi$$

with $V = -\frac{\alpha}{r}e^{-m_V r}$

parameters are: α, ν, m_V, M $\left(\alpha = \frac{g^2}{4\pi} \approx \frac{1}{137}\right)$

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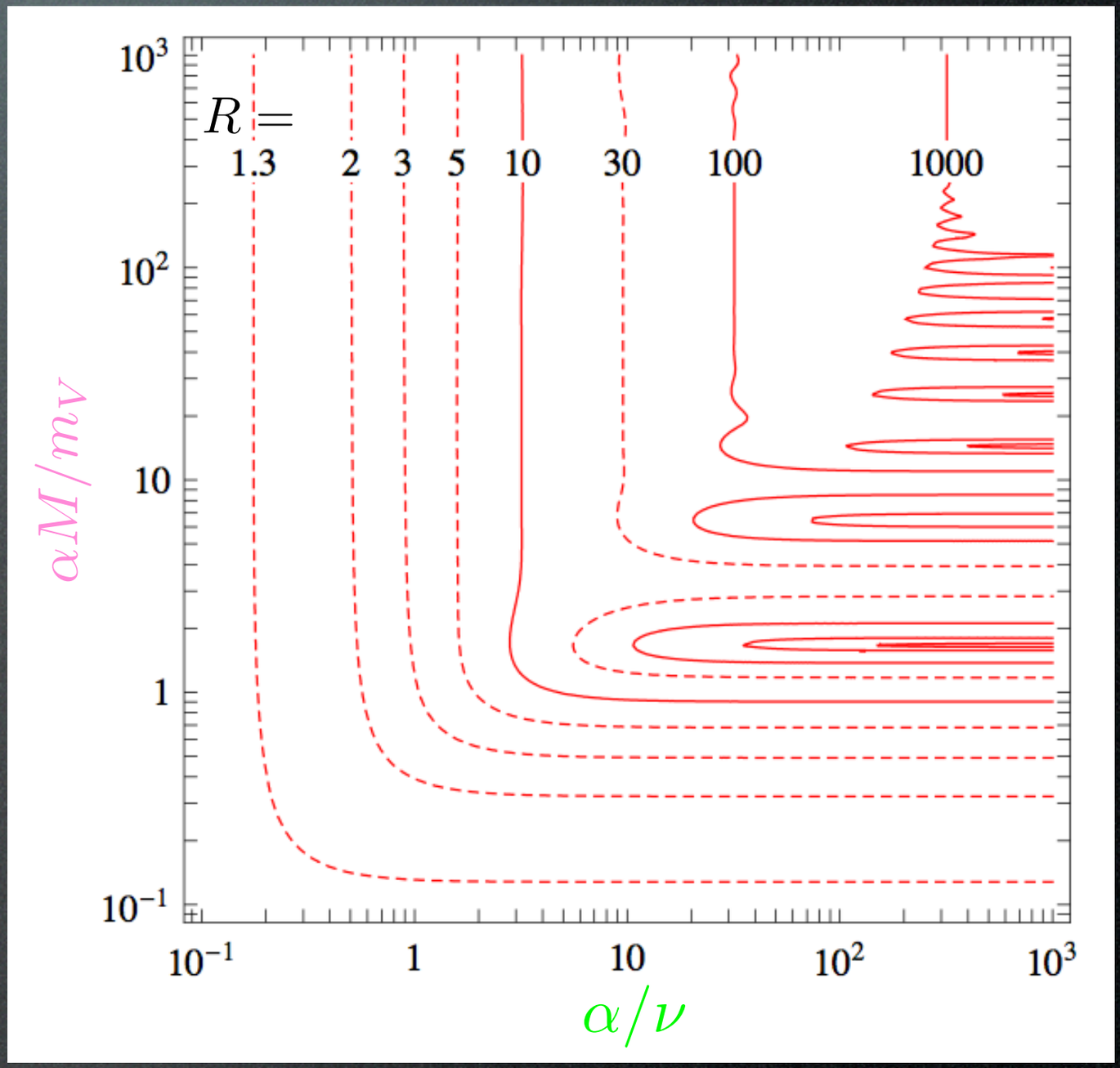
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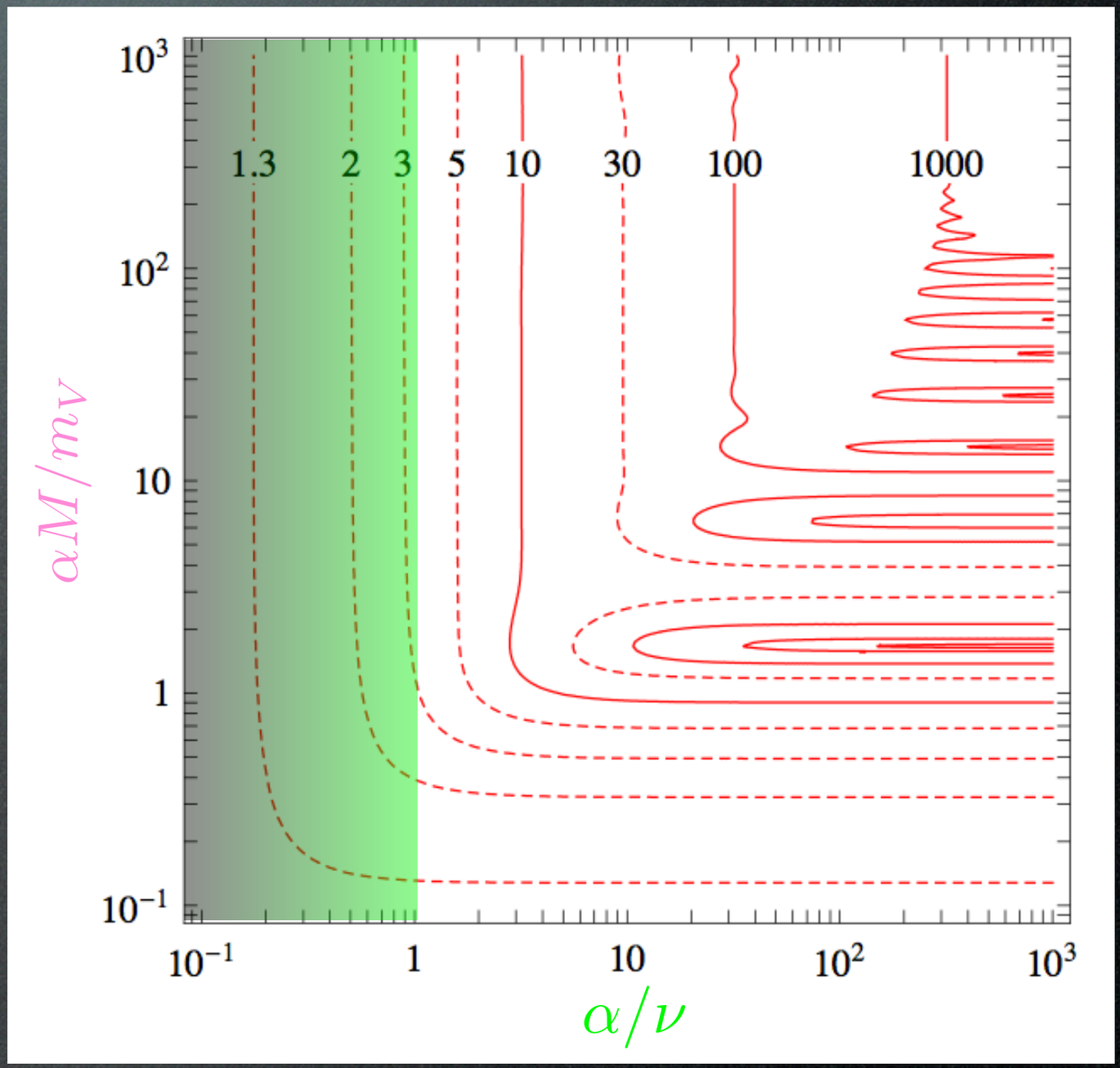
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The effect is relevant for:

$\alpha/\nu \gtrsim 1$ i.e. small velocities
i.e today but not at f.o.

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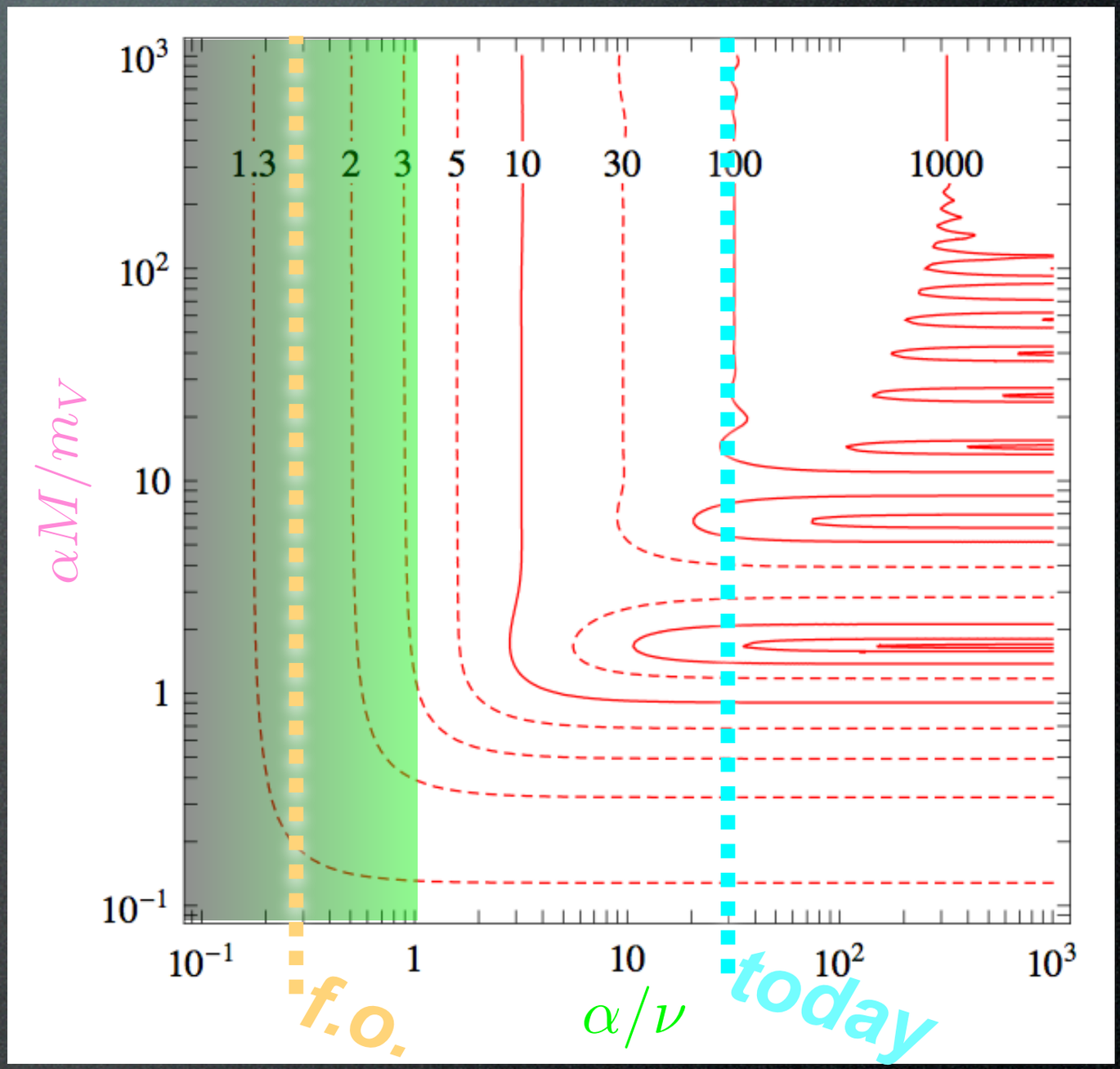
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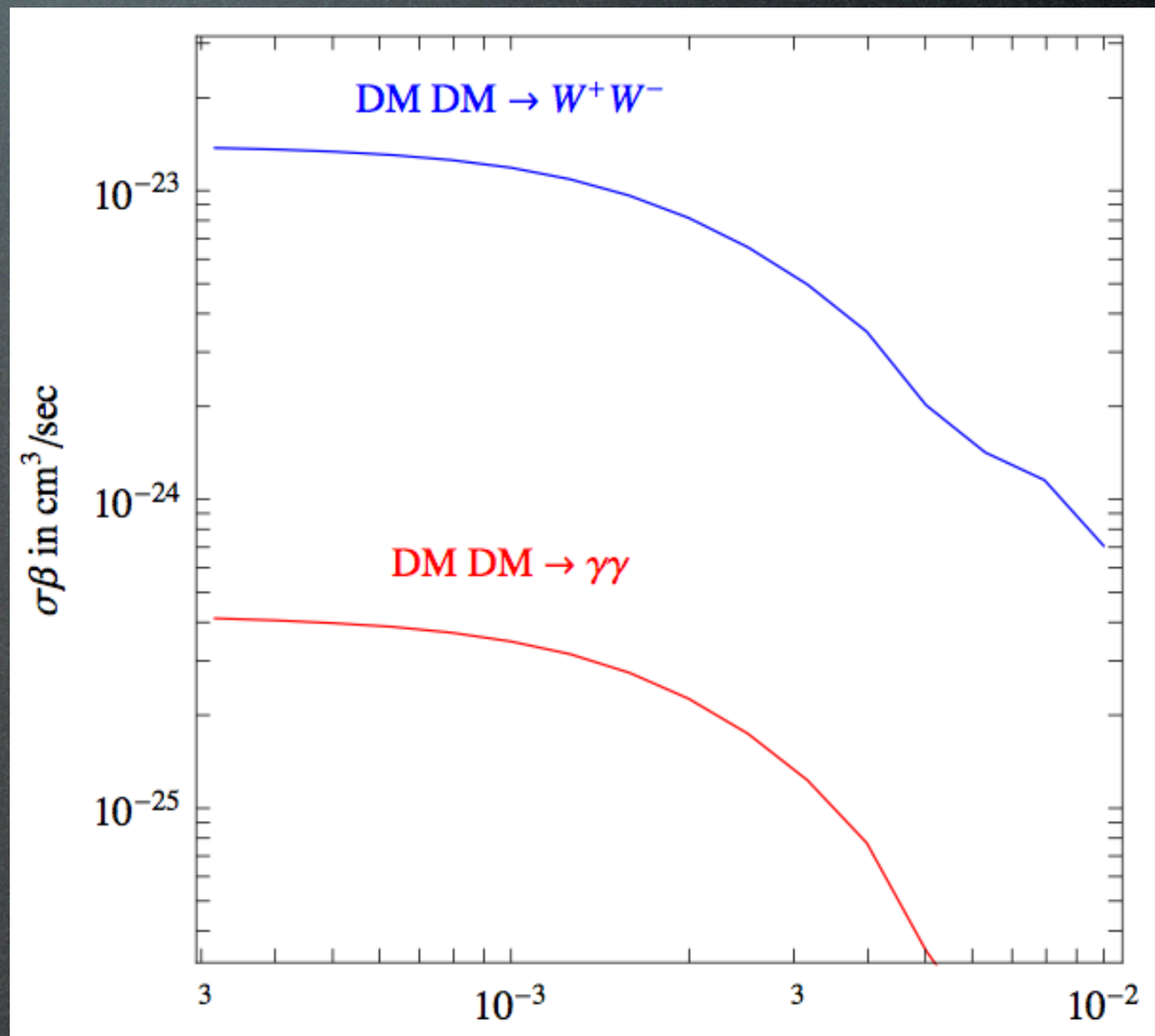
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Cirelli, Franceschini, Strumia 0802.3378



case of MDM fermion 5-plet:
M=9.7 TeV, W,Z exchange

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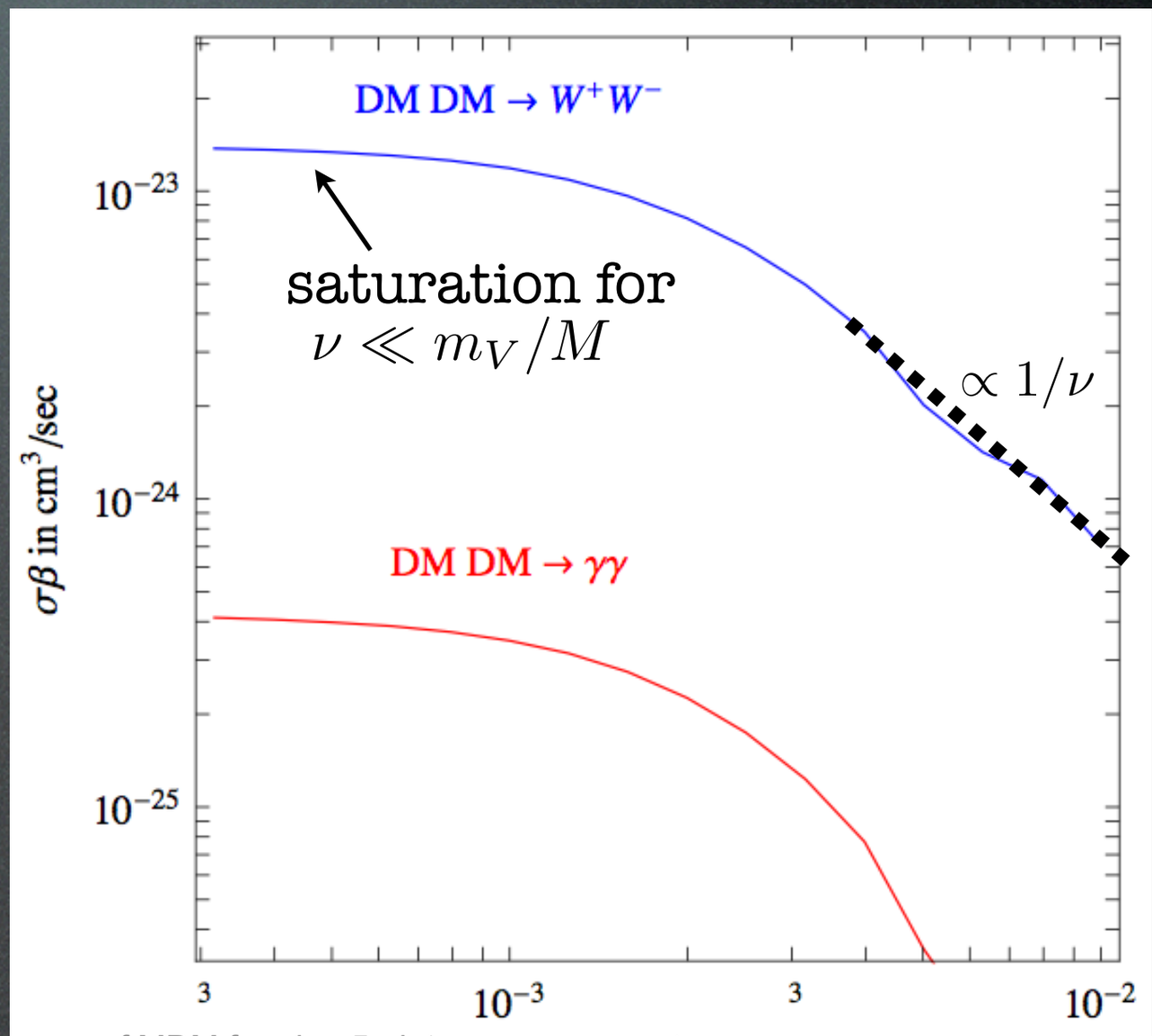
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Cirelli, Franceschini, Strumia 0802.3378



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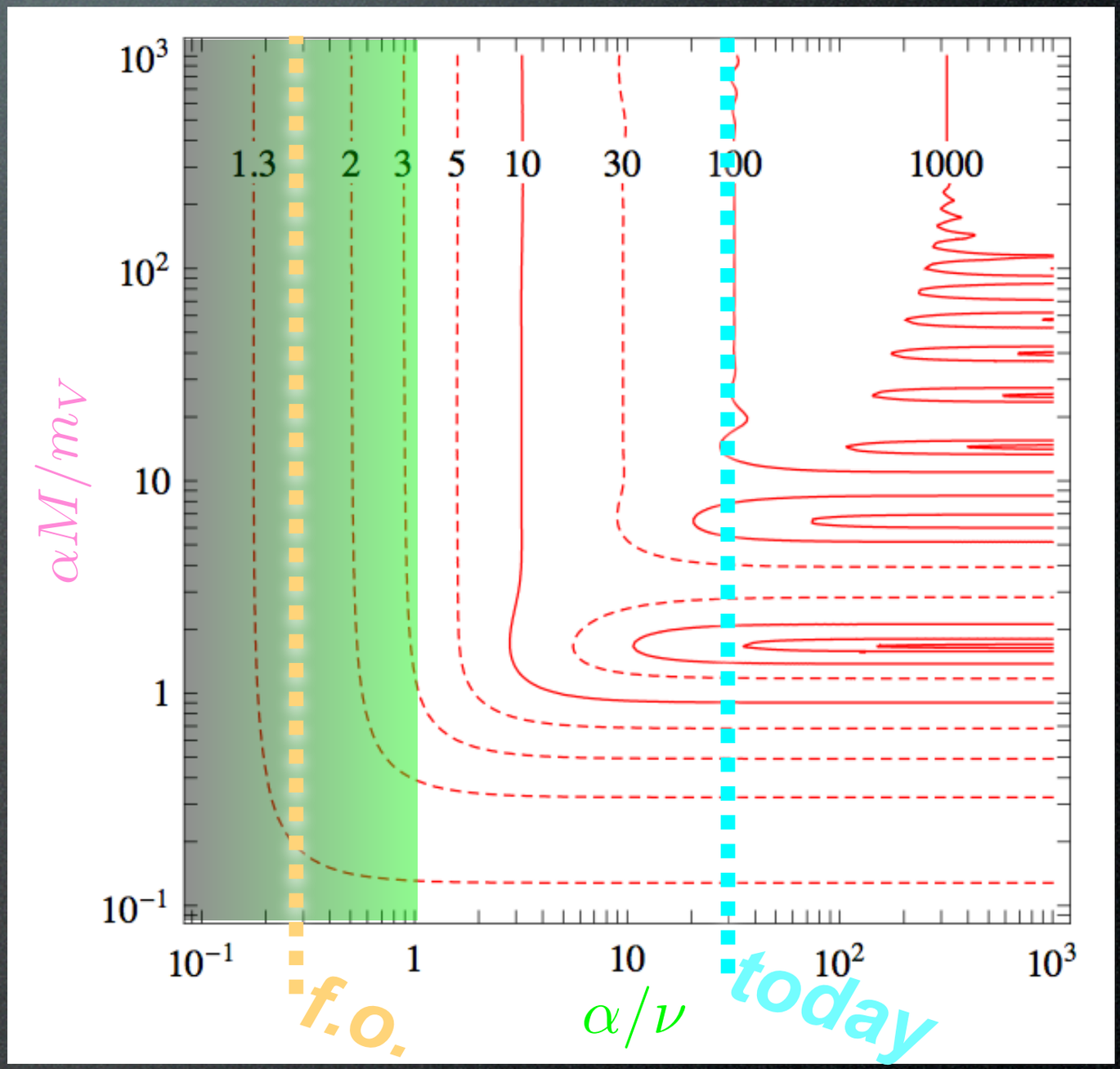
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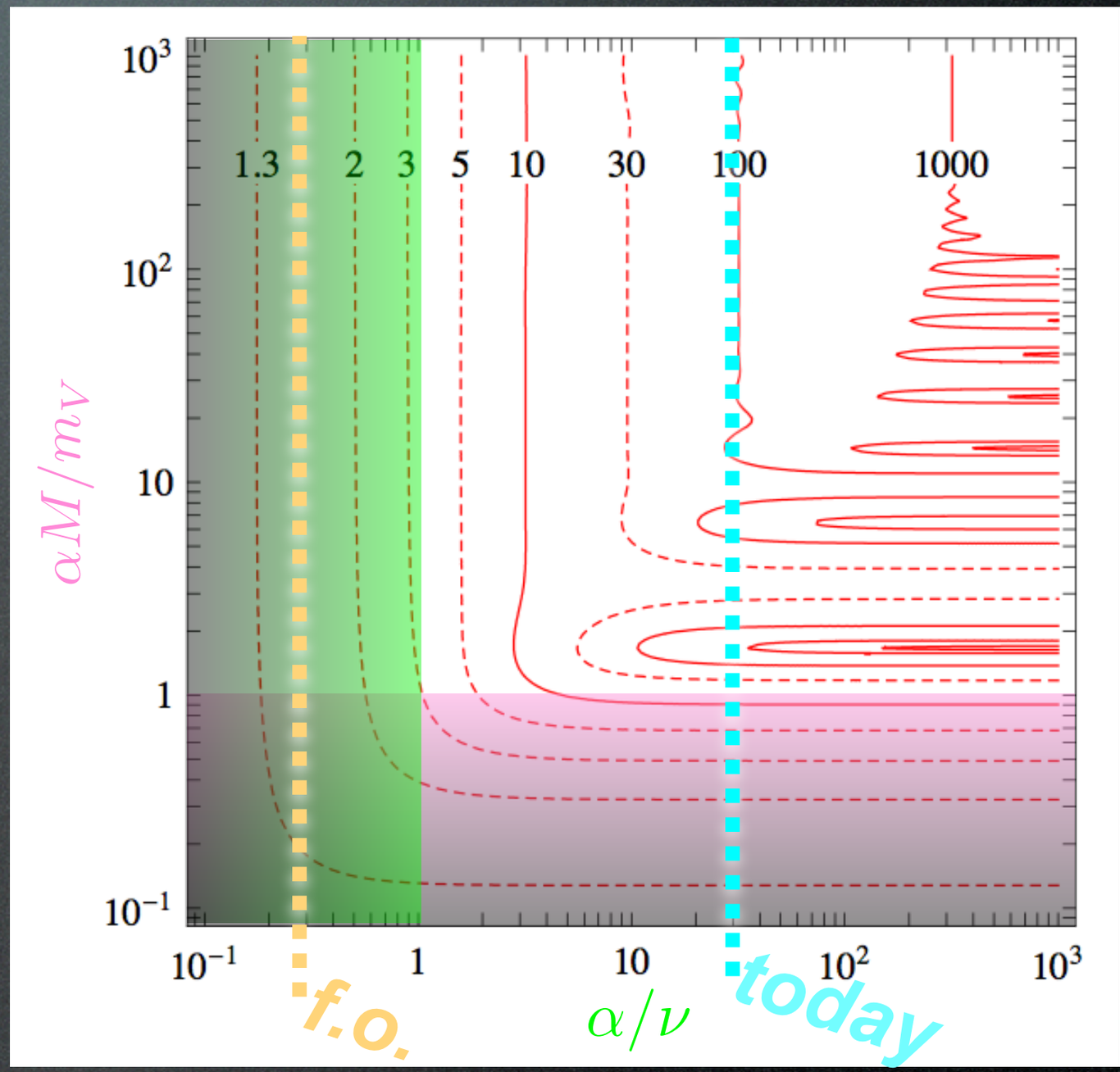
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i.e today but not at f.o.

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for SM weak: $m_V \to M_{W,z}$
$M \to \text{multi}-\text{TeV}$

for 1 TeV DM: need $m_V \to \text{GeV}$



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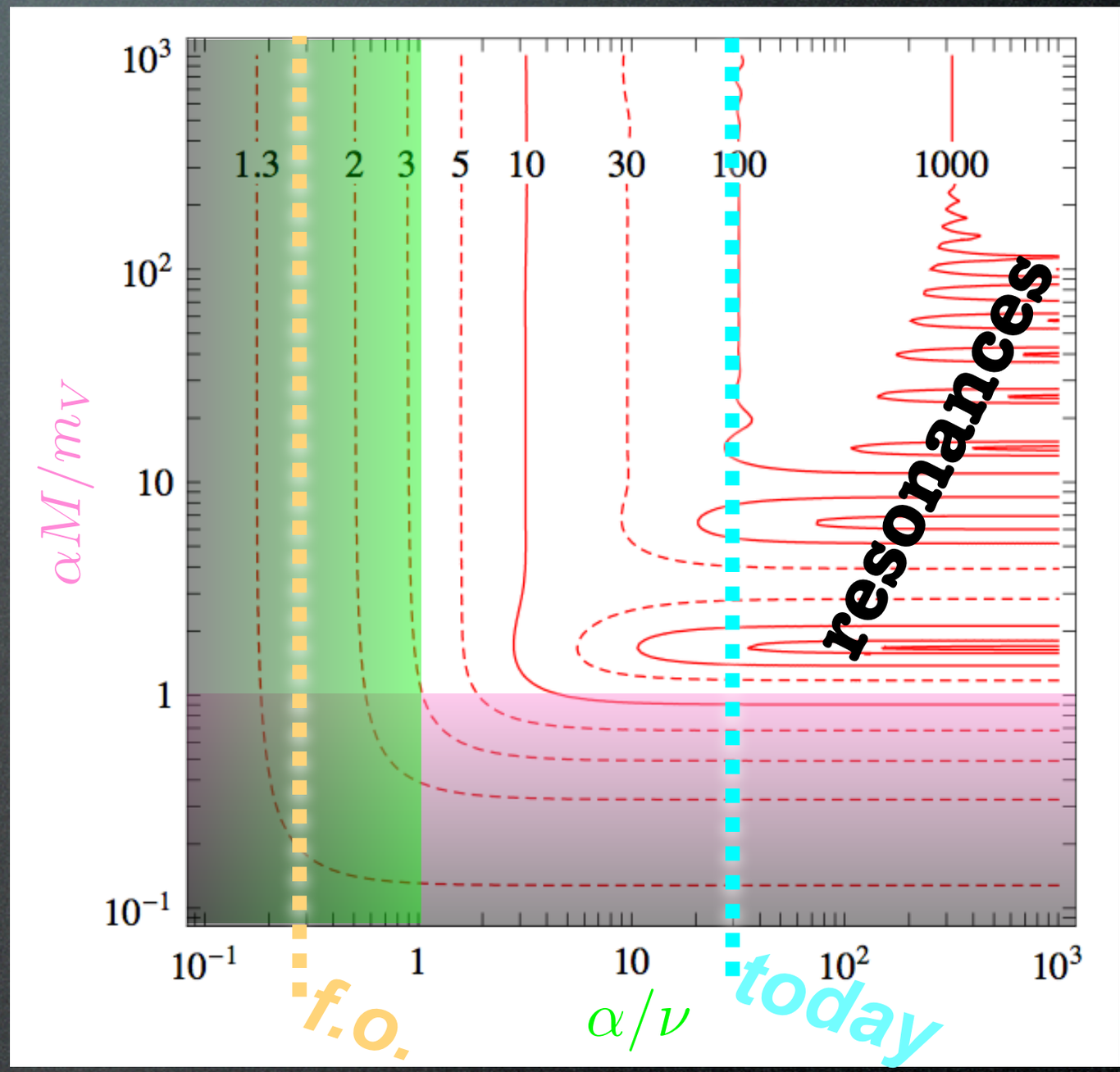
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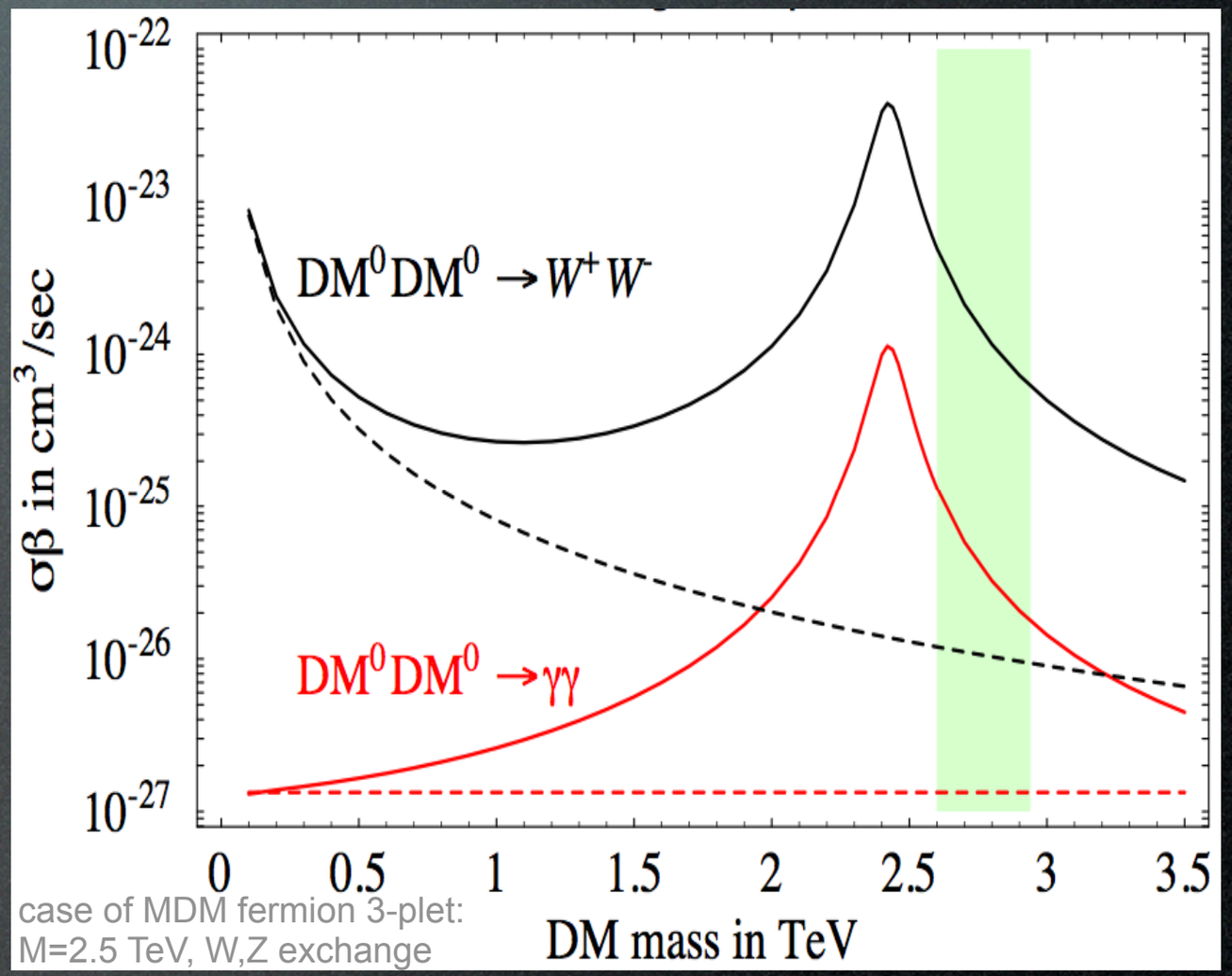
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case of MDM fermion 3-plet:
M=2.5 TeV, W,Z exchange

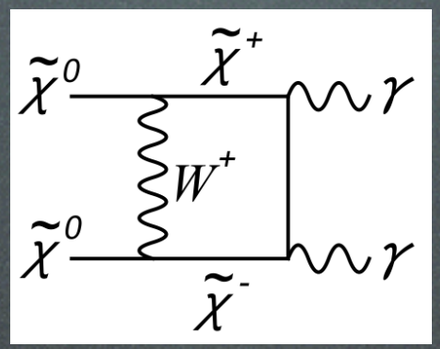
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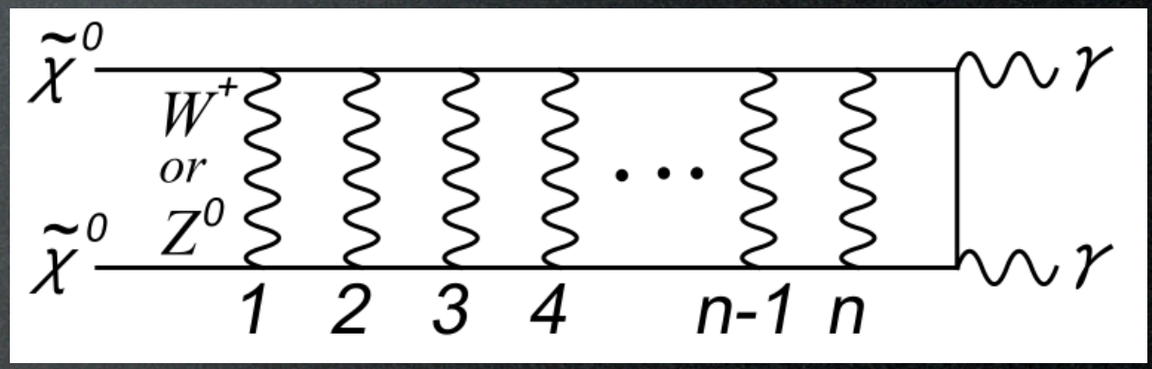
In terms of Feynman diagrams:

Hisano et al. hep-ph/0412403

First order cross section:



Adding a rung to the ladder: $\times \left(\frac{\alpha M}{m_W}\right)$



For $\alpha M/m_V \gtrsim 1$ the perturbative expansion breaks down, need to resum all orders
i.e.: keep the full interaction potential.

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Recap:

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Cirelli, Strumia, Tamburini 0706.4071

