13 November 2017
DESY Theory, Hamburg

# How we fell in love with WIMPs

## and should not dump them (yet)

Marco Cirelli
(CNRS LPTHE Jussieu Paris)

Based on: Cirelli, Fornengo, Strumia 'Minimal Dark Matter', NPB 2006 +…
Cirelli, Sala, Taoso, JHEP 2014
Cirelli, Hambye, Panci, Sala, Taoso, JCAP 2015
Cirelli, Sala et al + HESS collaboration 2017 to appear

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LPTHE
LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

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# Introduction

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DM exists

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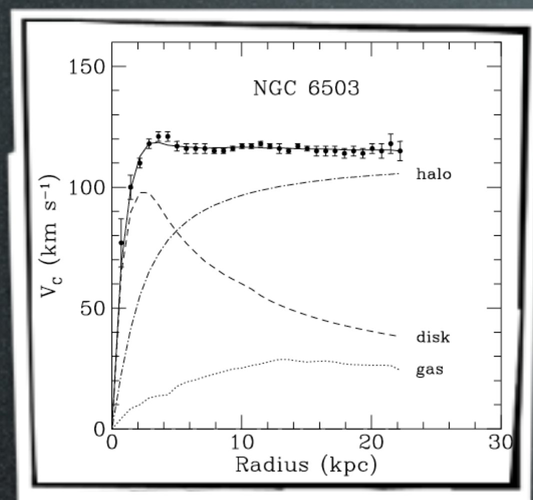
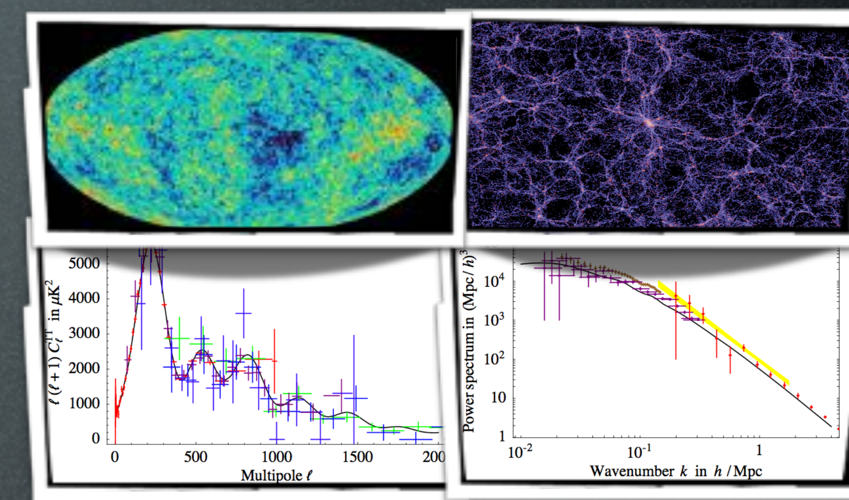
## DM exists




galactic rotation curves


weak lensing (e.g. in clusters)




‘precision cosmology’ (CMB, LSS)

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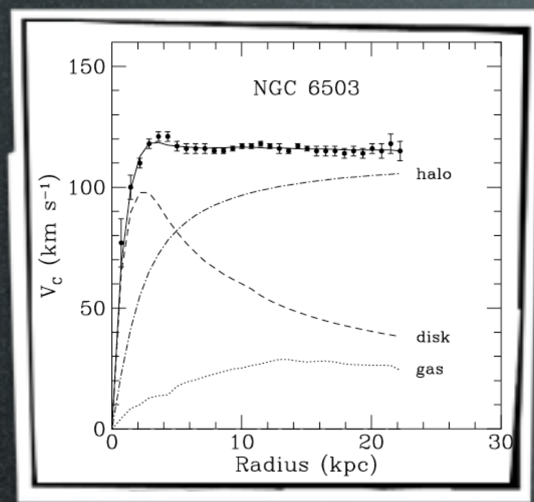
## DM exists

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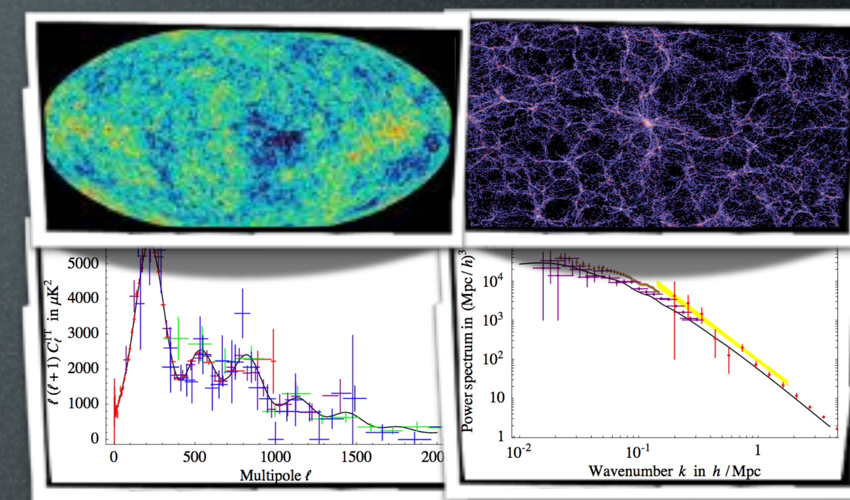



'precision cosmology' (CMB, LSS)

## But: **what** is it?

# Candidates

WIMPs

# Candidates

WIMPs

$SU(2)_L$

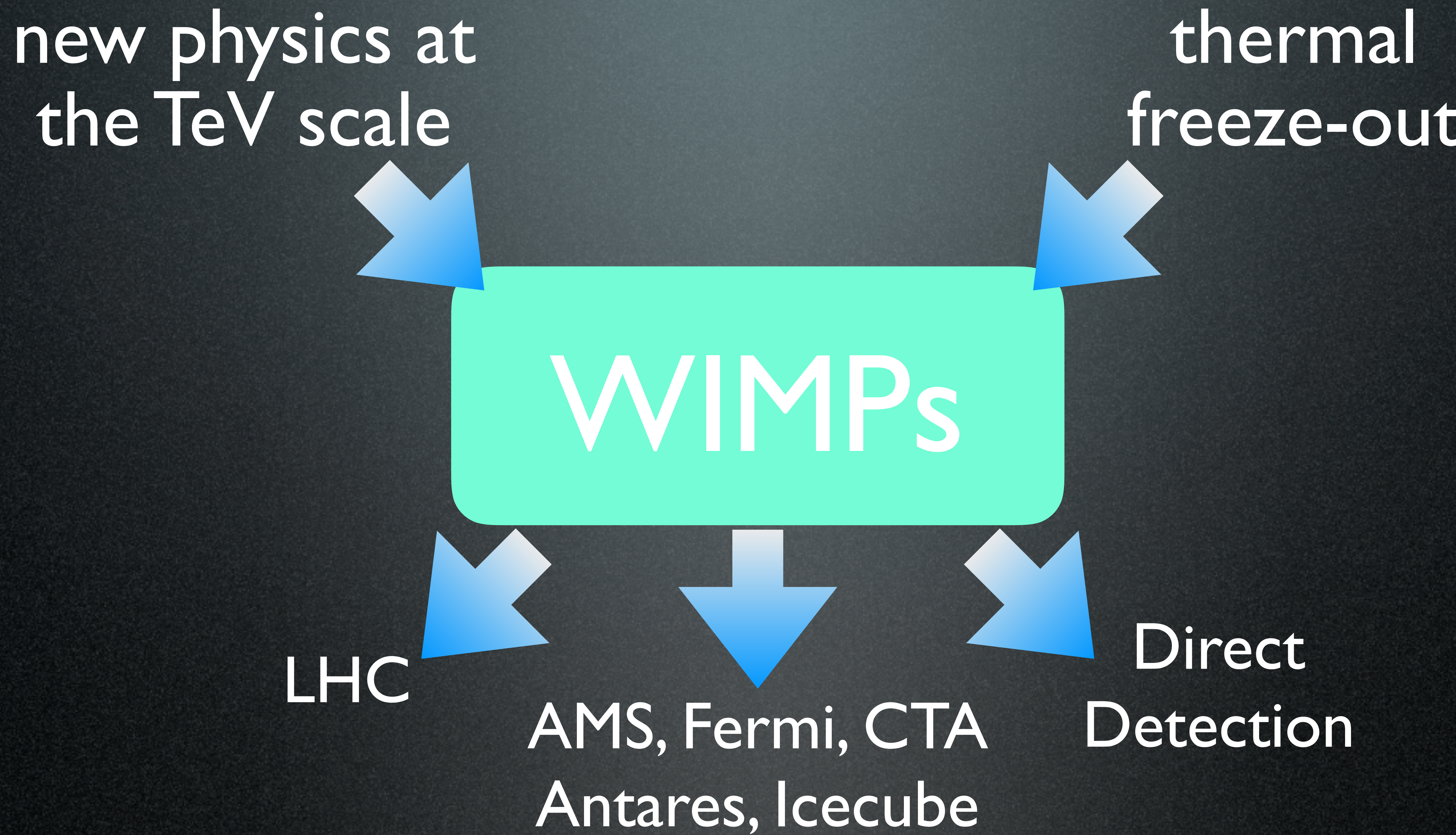
# Candidates

new physics at the TeV scale

thermal freeze-out

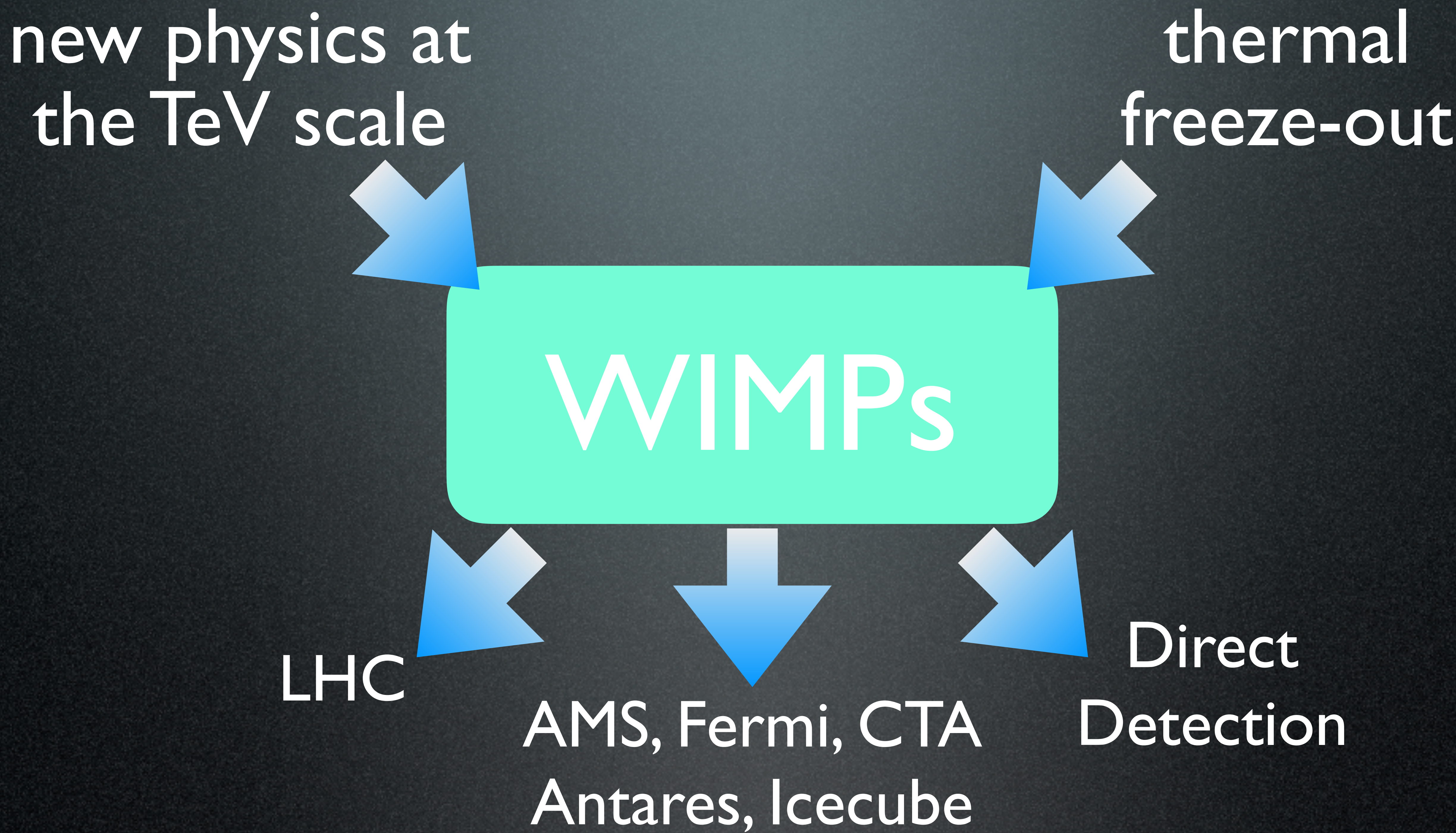
WIMPs

# Candidates



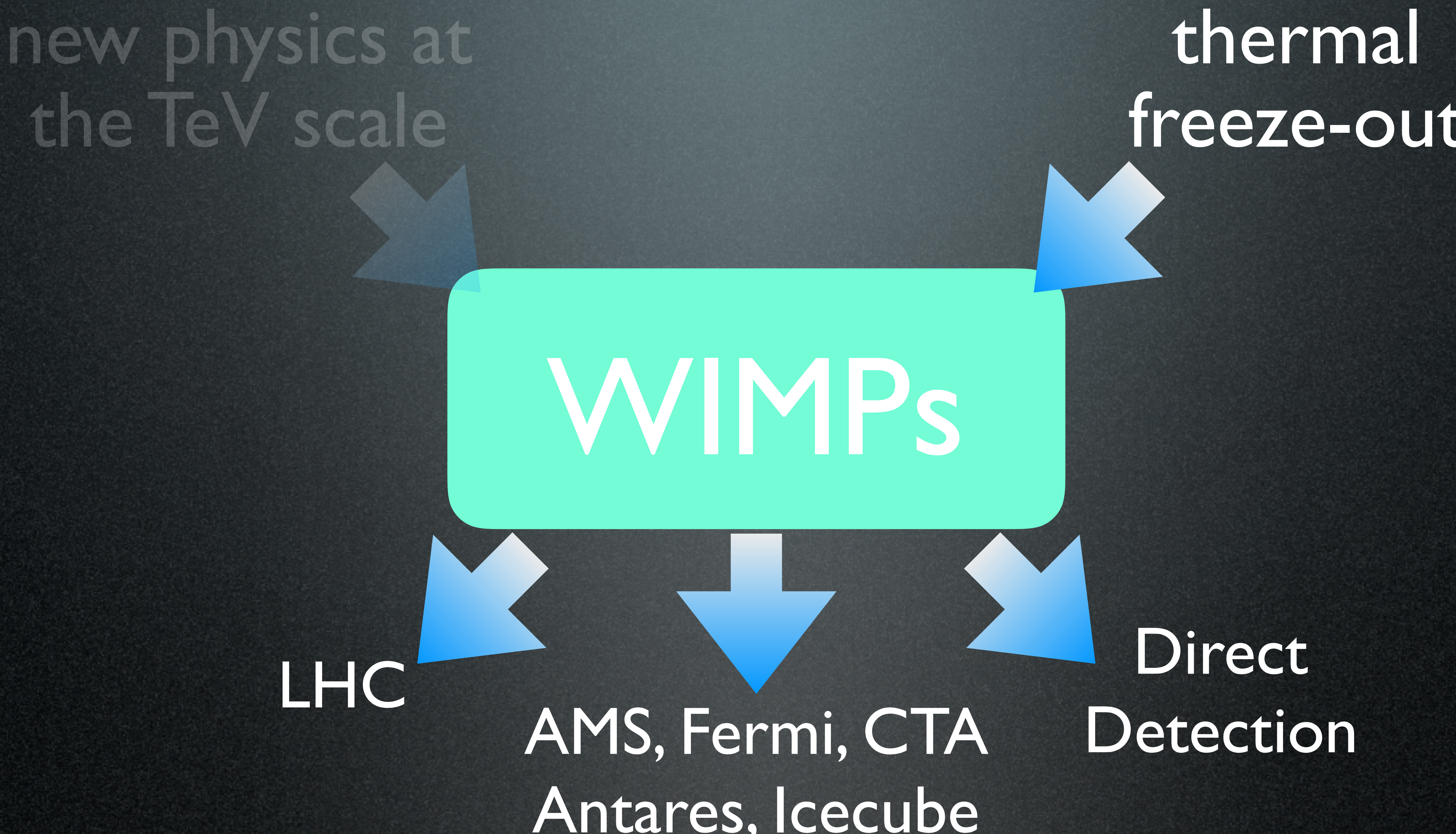
new physics at the TeV scale
thermal freeze-out
WIMPs
LHC
AMS, Fermi, CTA
Antares, Icecube
Direct Detection

# Candidates




1.
2.
3.

# Candidates




1. even without a larger framework, WIMPs are still appealing
2.
3.

# Candidates

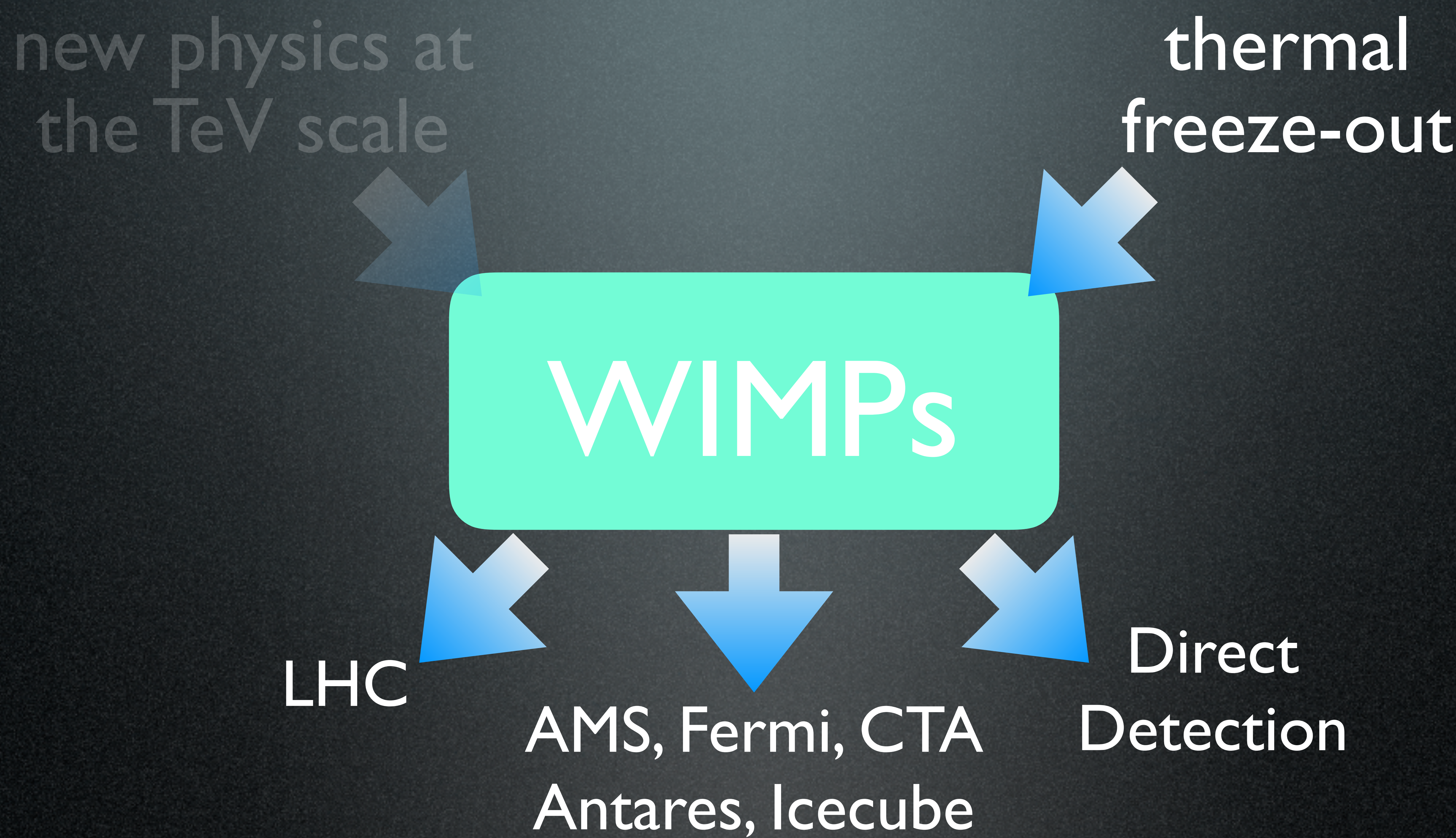
new physics at the TeV scale

thermal freeze-out

WIMPs

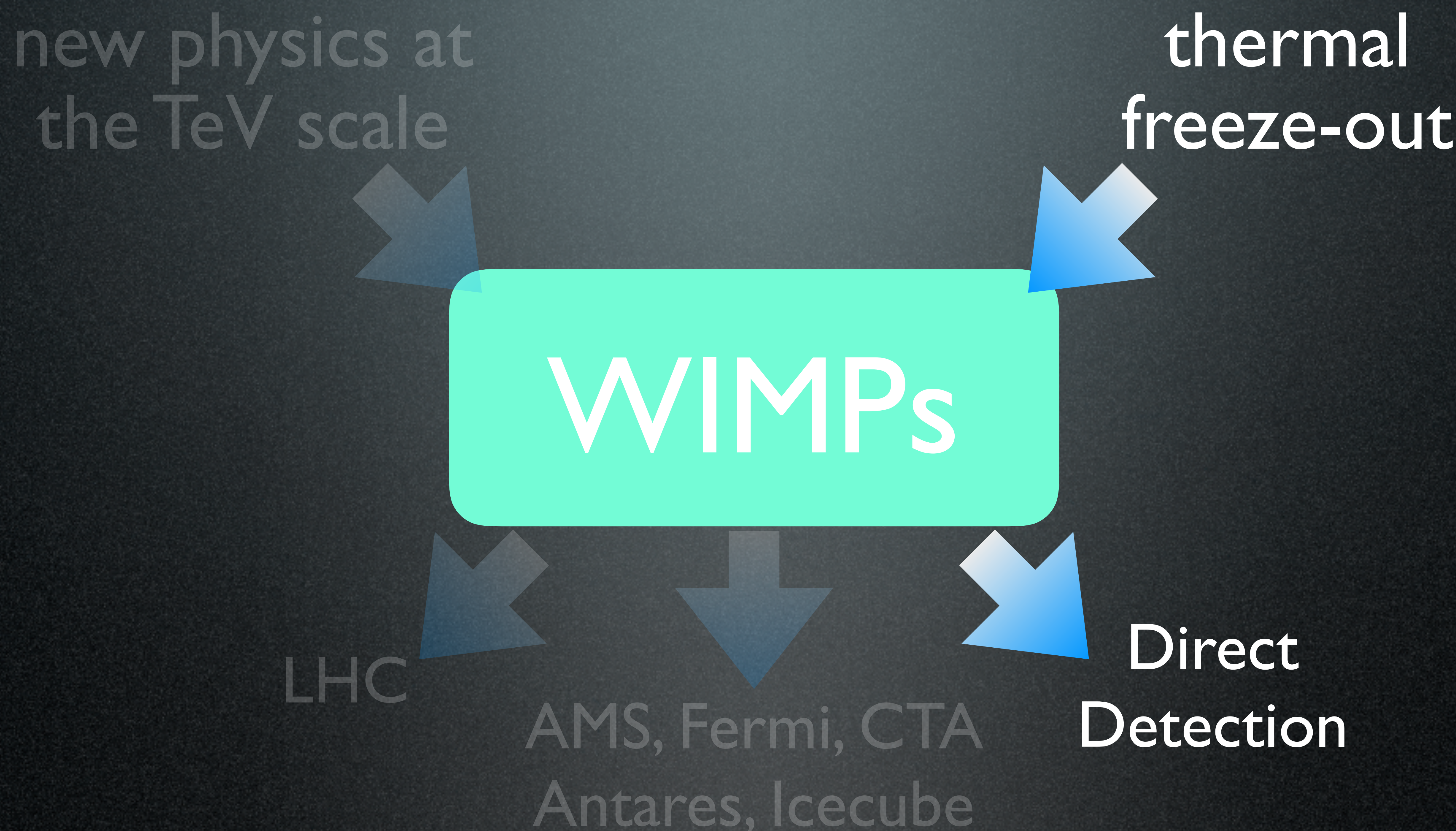
Aside:
Asking ‘Is New Physics at the TeV (still) exciting?’ is a bit like asking ‘Are french movies nice?’. If consistently, over many years, the large majority of movies from France are nice, this is strong motivation to build a new movie theatre and invest a lot in them. If, after many years, most french movies turn out to be horribly boring and self-centered, it’s OK to lose interest in them. That does not imply that there can be one beautiful french movie one day that wins the Oscar (or a point in the SuSy parameter space that turns out to be The Truth.)

# Candidates




1. even without a larger framework, WIMPs are still appealing
2. the frontier is multi-TeV
3.

# Candidates



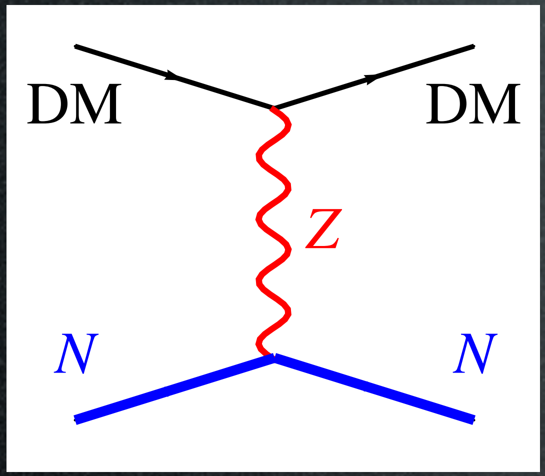

1. even without a larger framework, WIMPs are still appealing
2. the frontier is multi-TeV
3. searches are complementary and still have ground to cover

# WIMP DD: ‘**theory**’

SM weak scale SI interactions

# WIMP DD: 'theory'

SM weak scale SI interactions




tree level,
vector

$$\sigma_{\rm SI} \sim \frac{\alpha^2 \; m_N^2}{M_Z^4}$$

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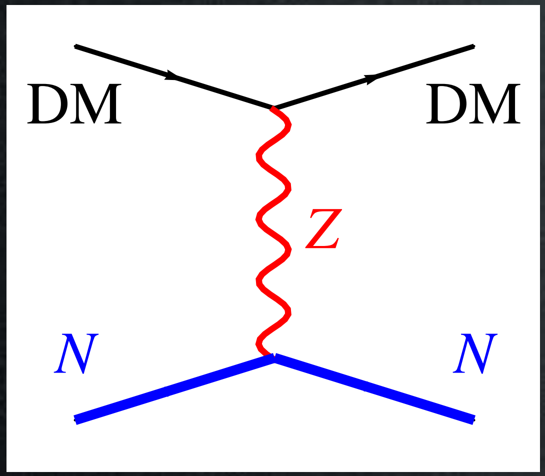
SM weak scale SI interactions

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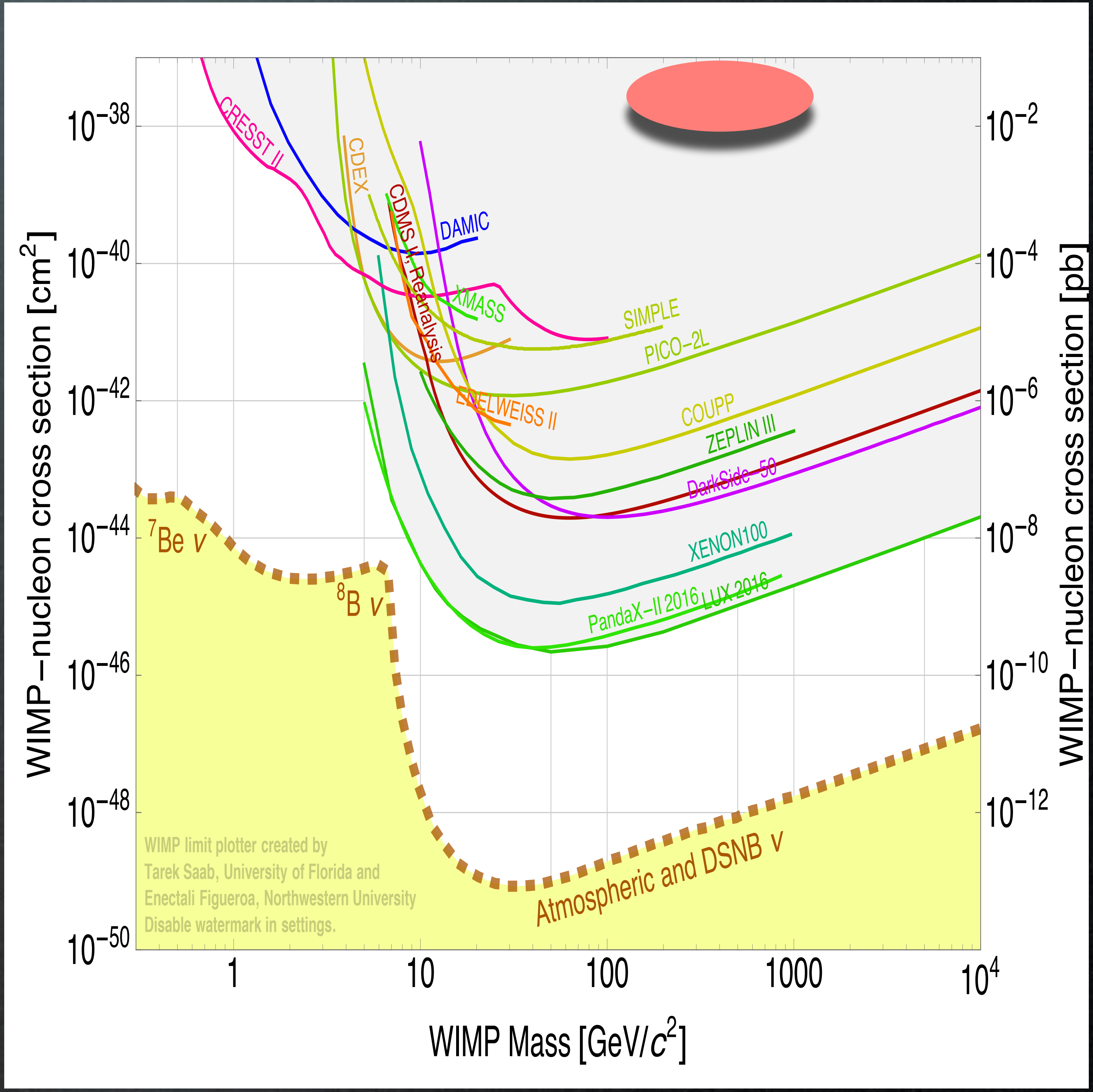

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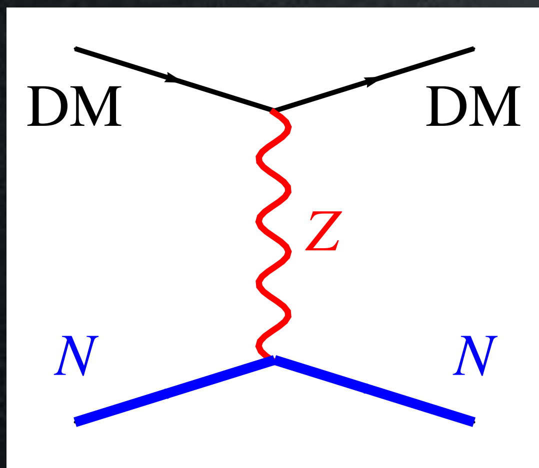


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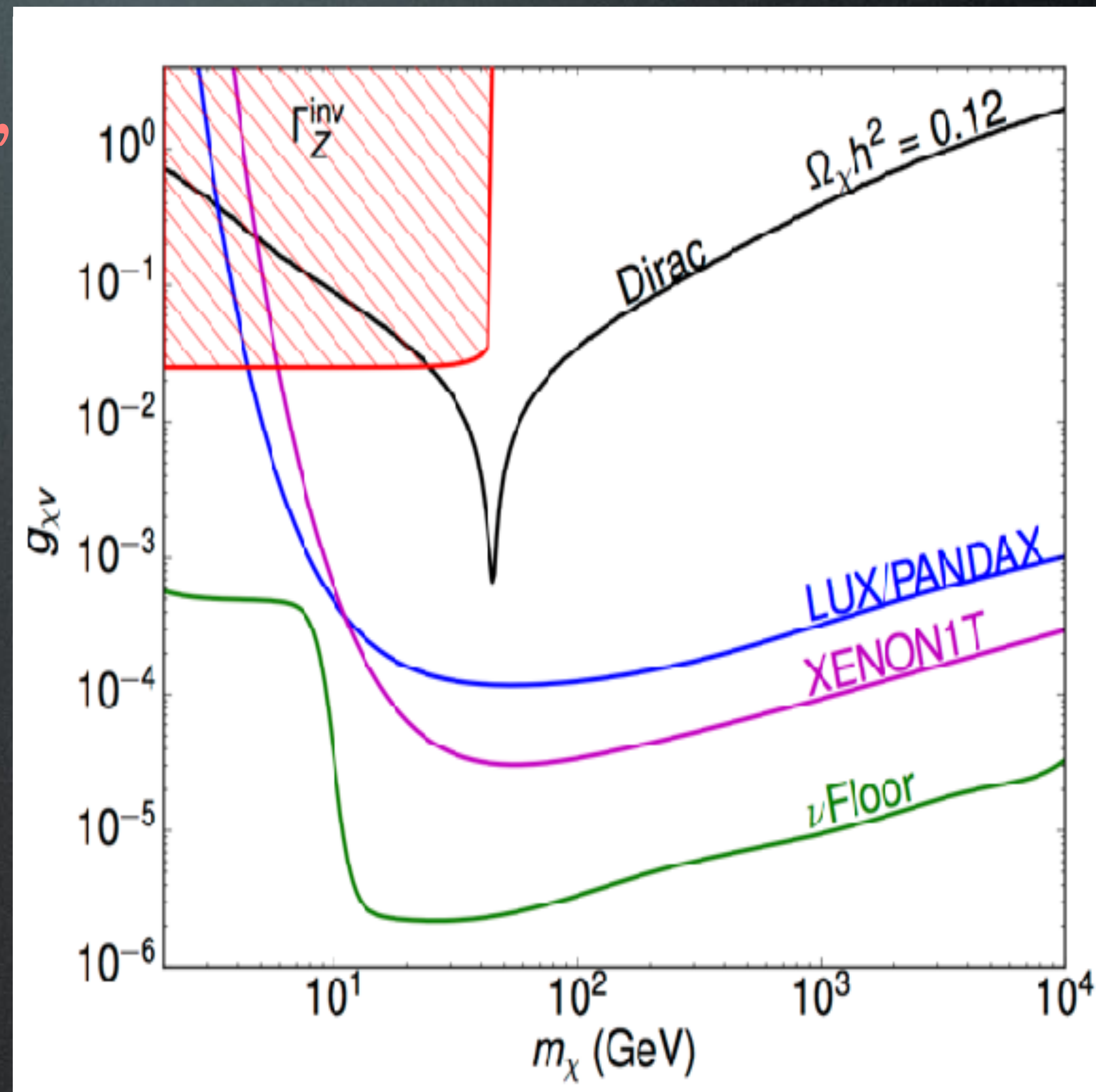


Escudero, Berlin, Hooper, Lin 1609.09079

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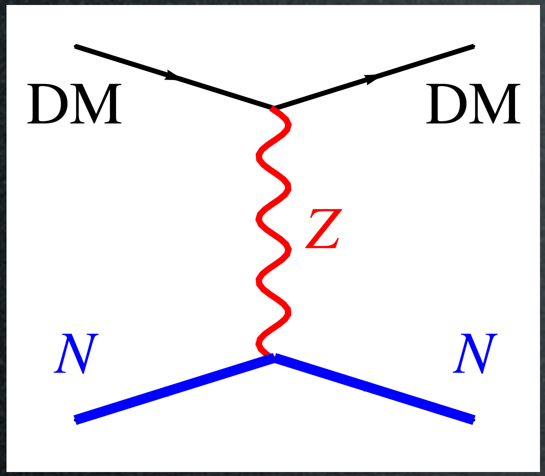


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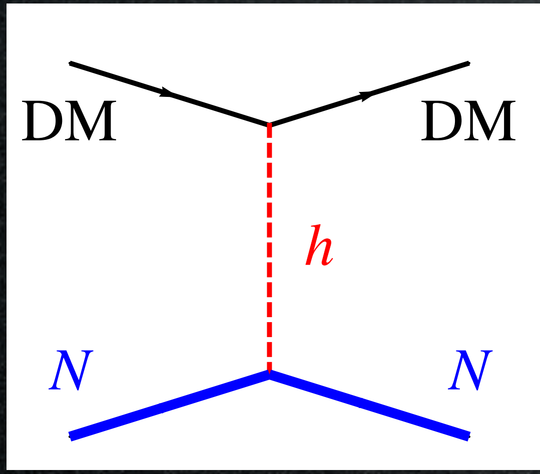


tree level, scalar

$$\sigma_{\rm SI} \sim \frac{\alpha^2\ m_N^4}{M_h^6}$$

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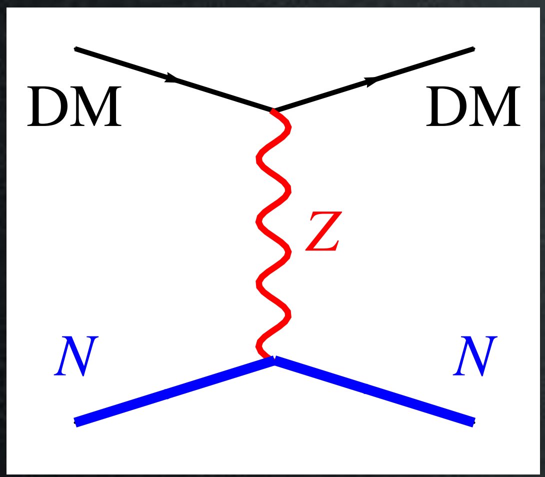
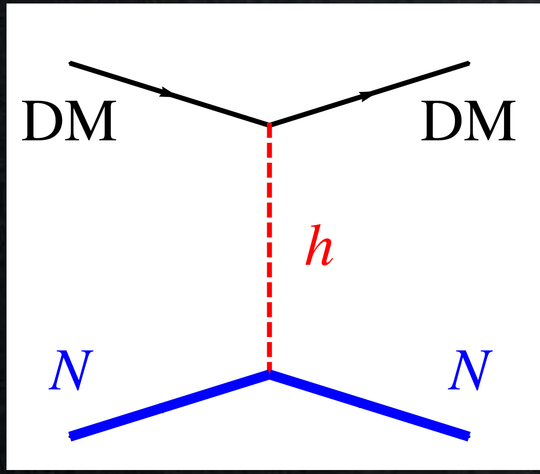



tree level, vector

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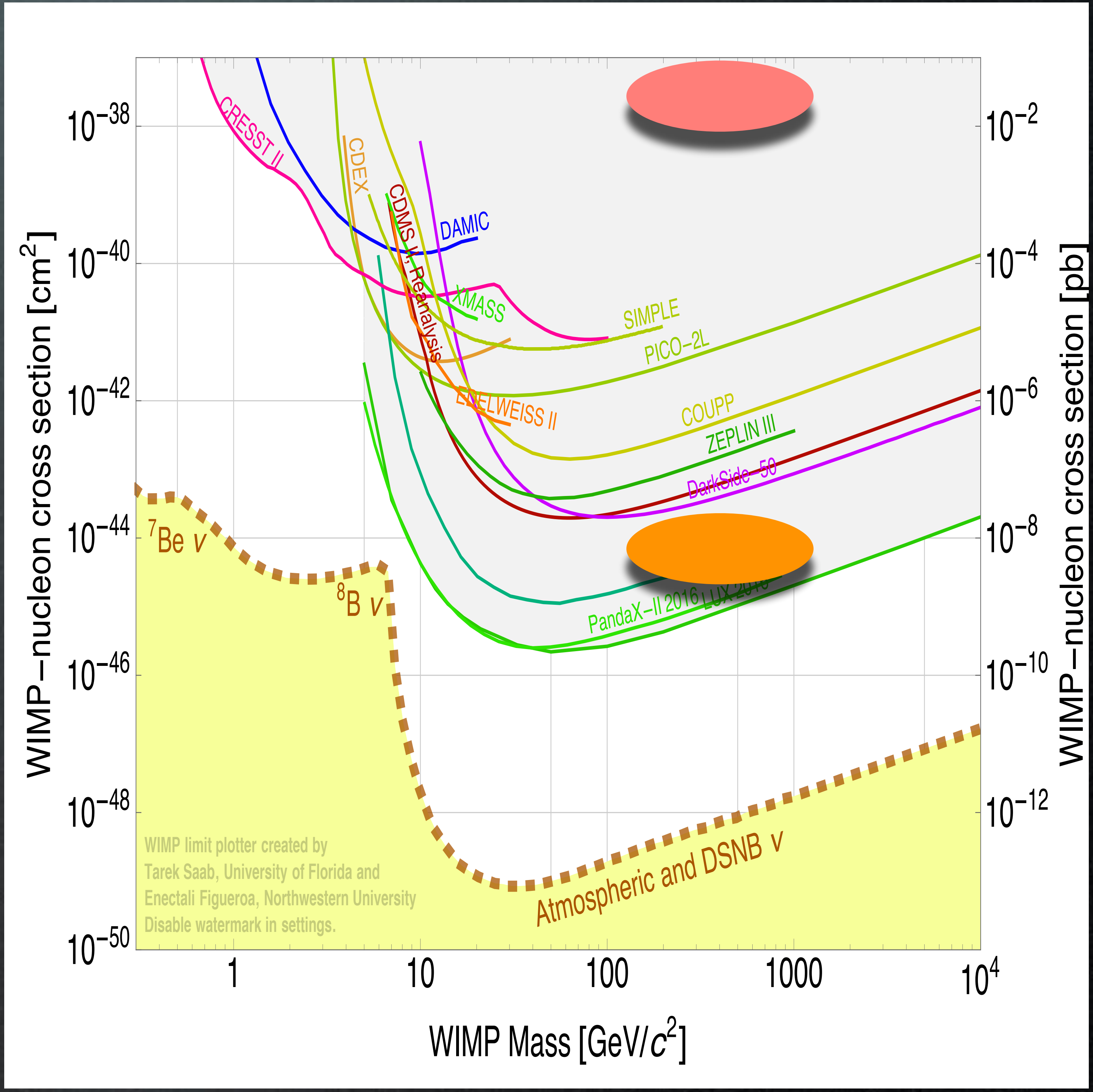

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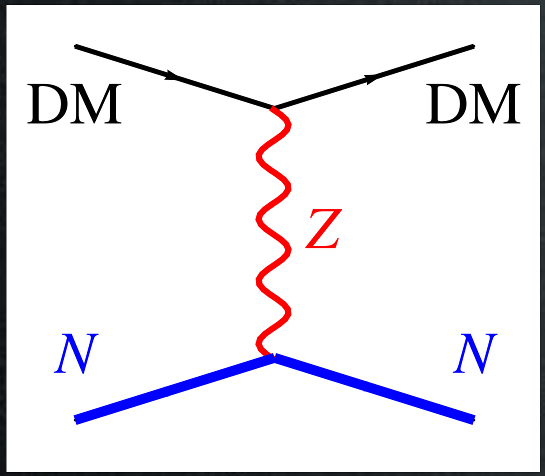
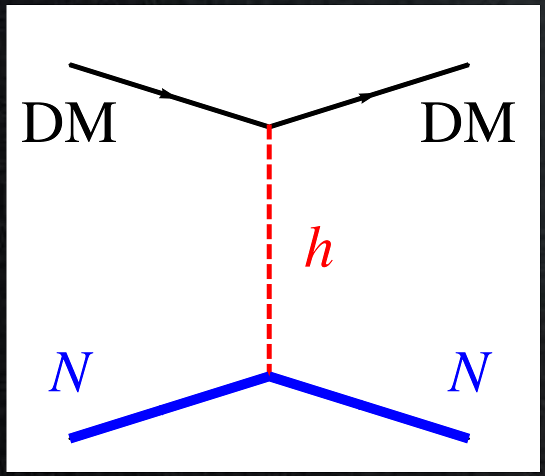



tree level, vector

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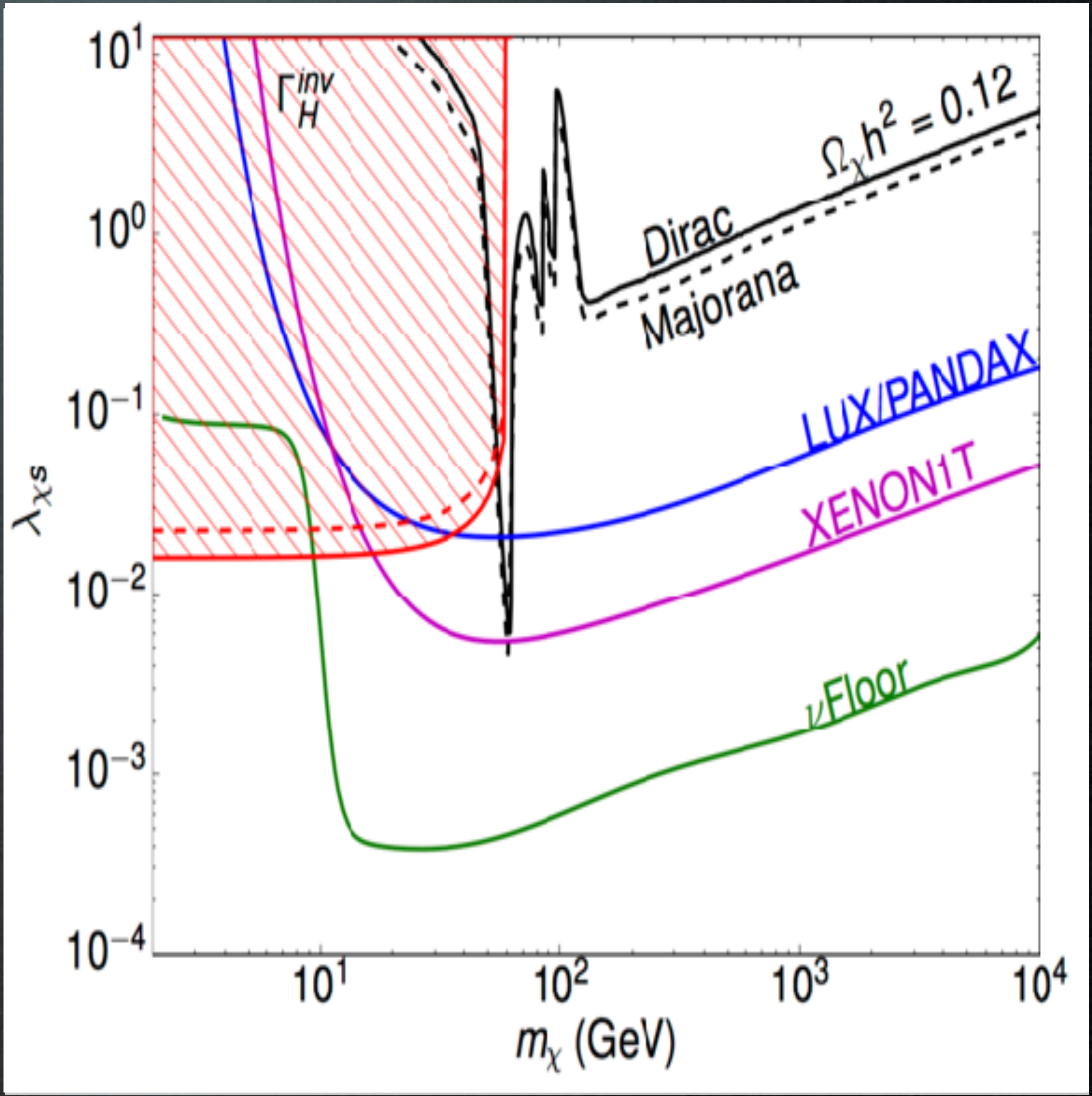


Escudero, Berlin, Hooper, Lin 1609.09079

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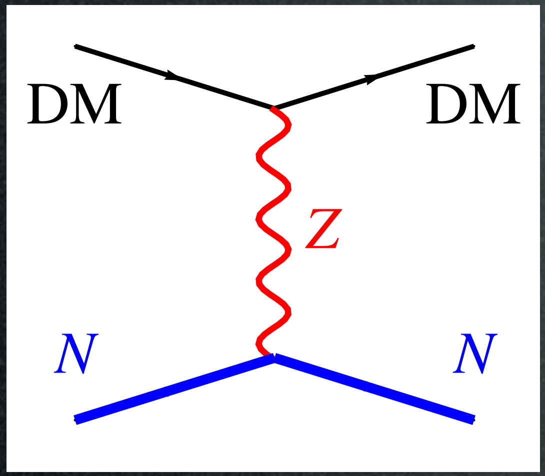


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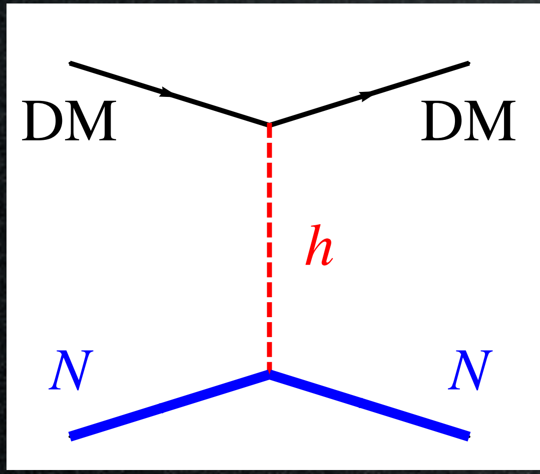


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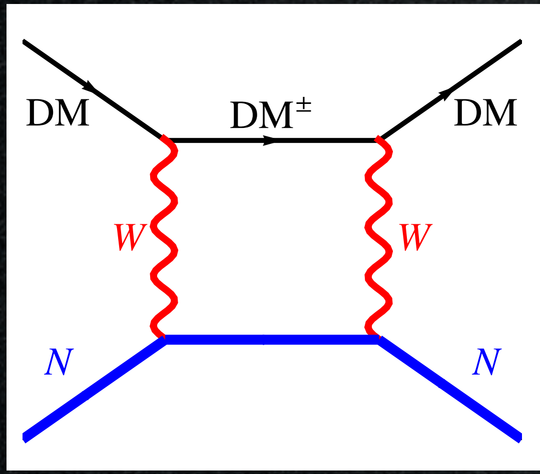
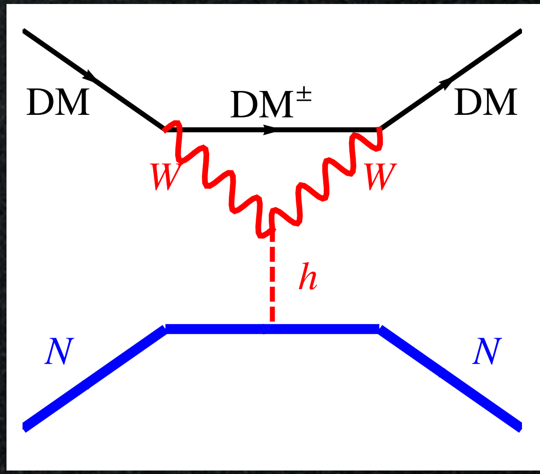



one loop

$$\sigma_{\rm SI} \sim \frac{\alpha^4\ m_N^4}{M_W^6}$$



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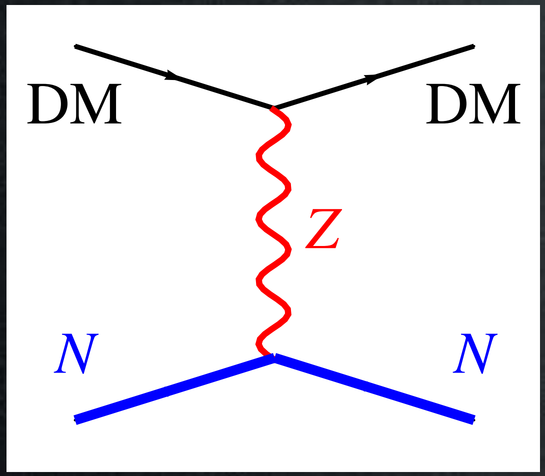
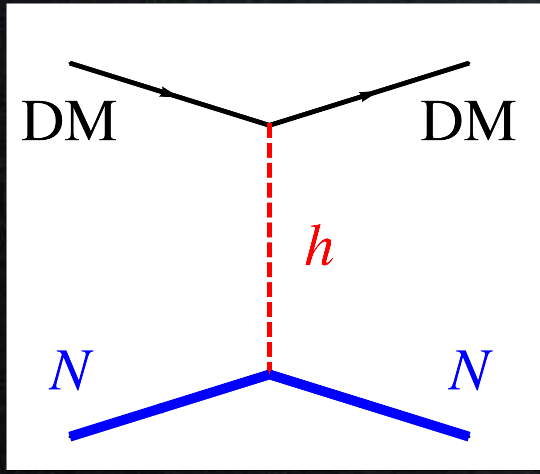



tree level, vector

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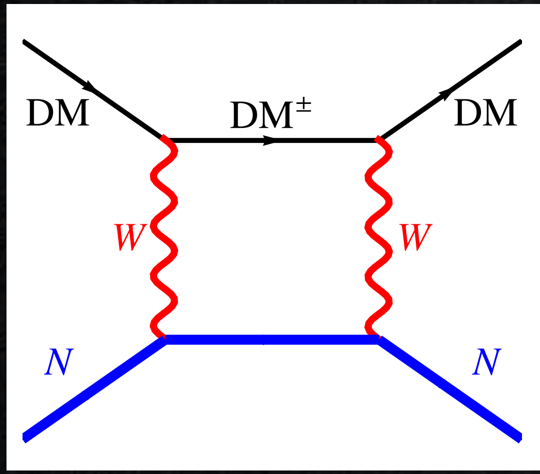


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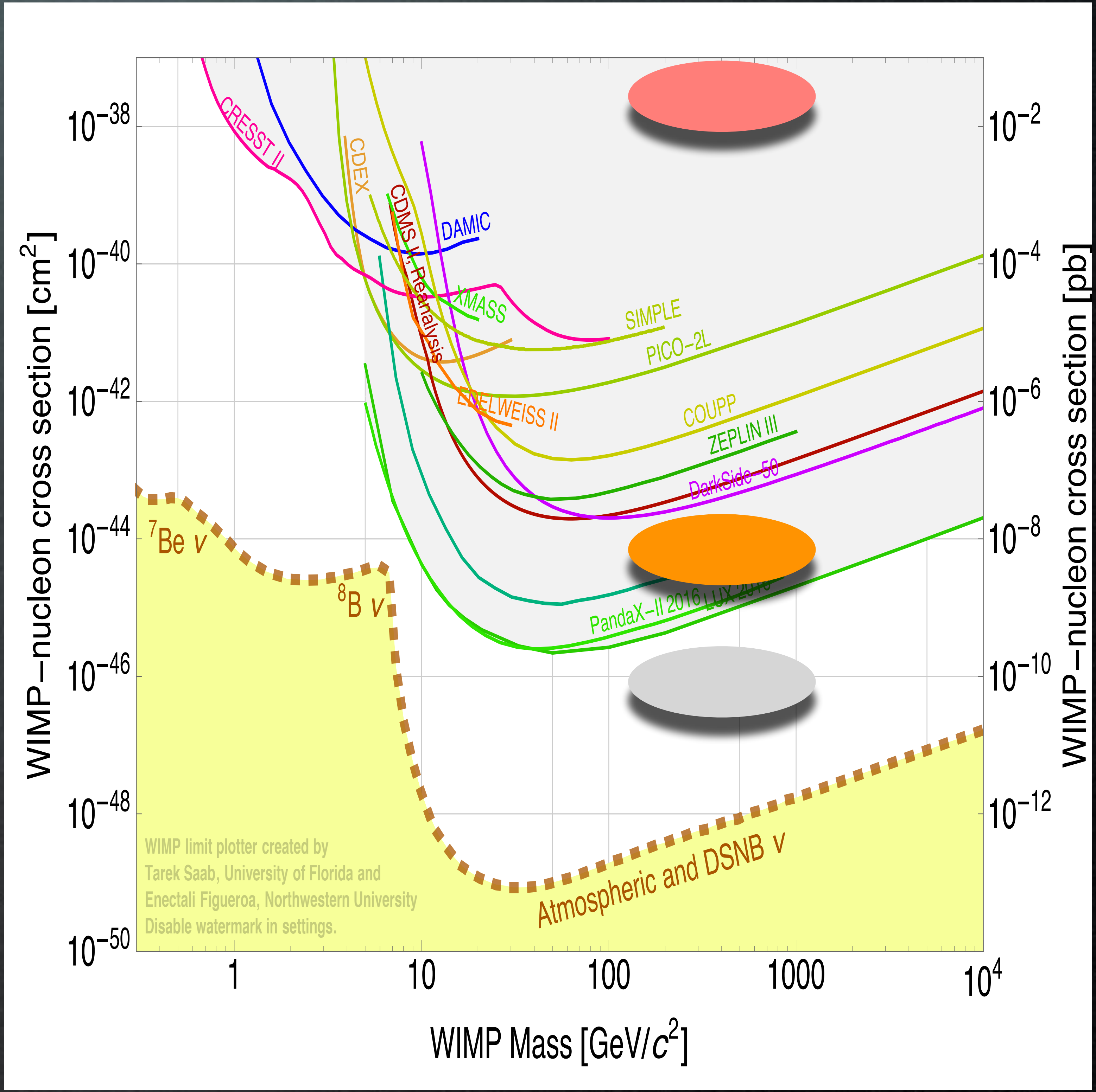

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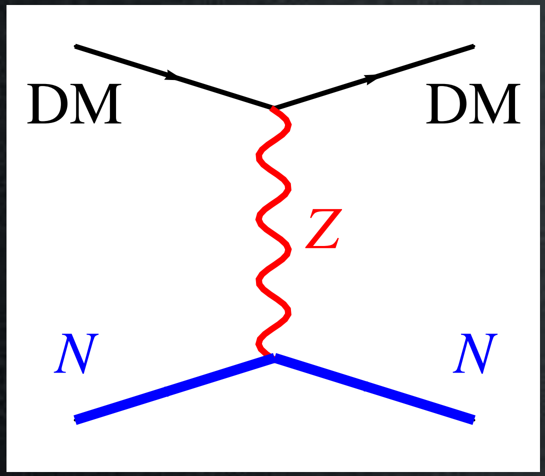


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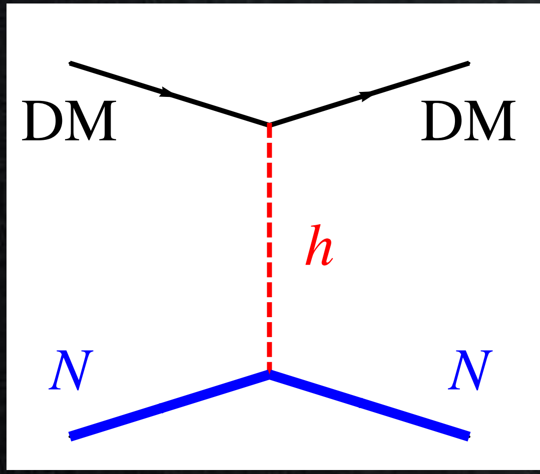


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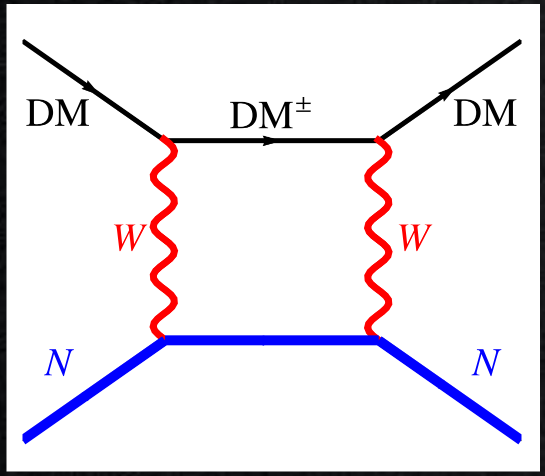


one loop

Still viable under which conditions?

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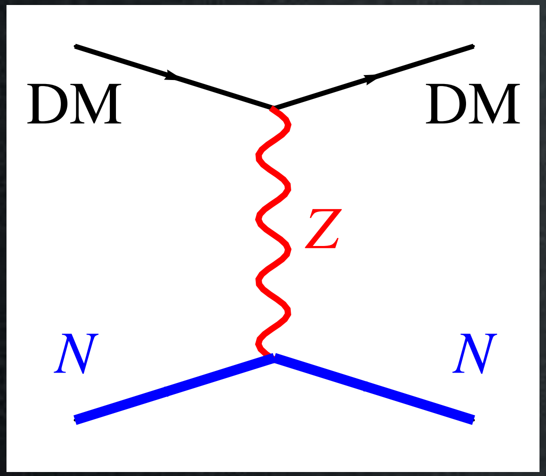
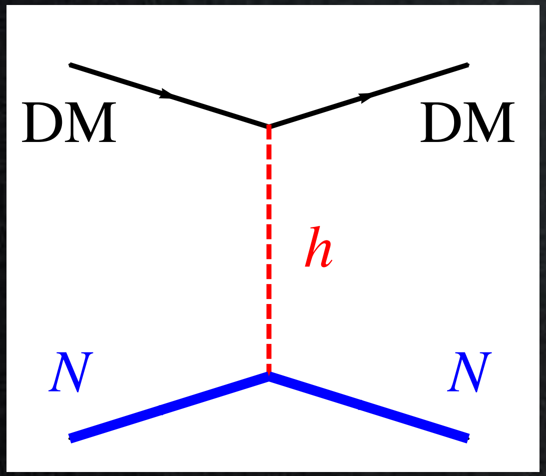


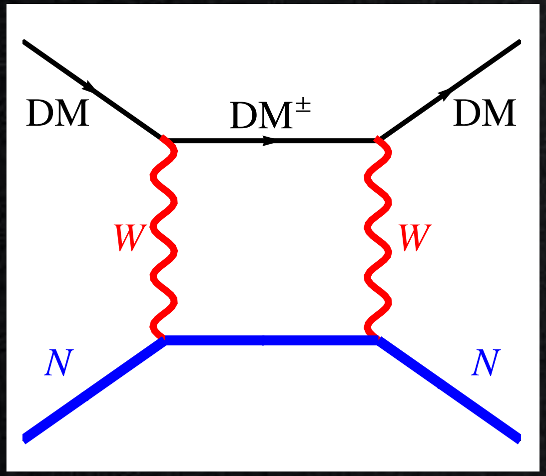

~~tree level, vector~~

Still viable under which conditions?

- real particle
  (Majorana fermion, real scalar)




tree level, scalar




one loop

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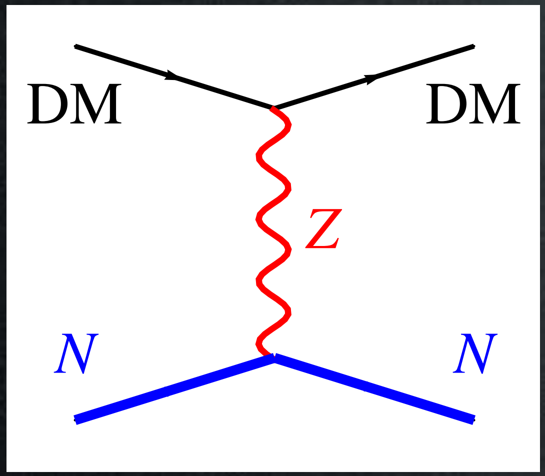


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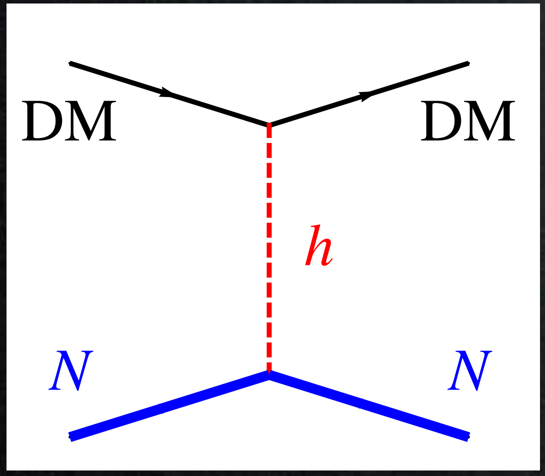


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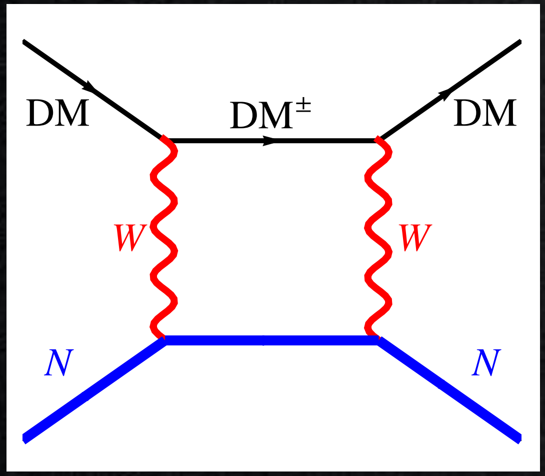


one loop

Still viable under which conditions?

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- hypercharge $Y = 0$

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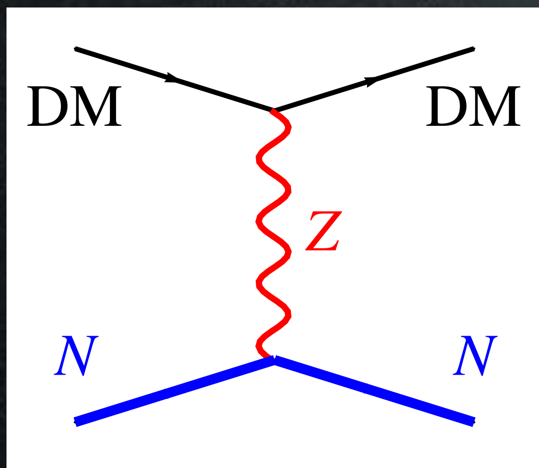


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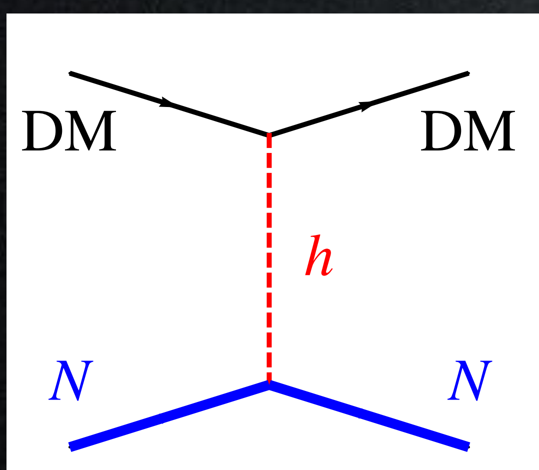


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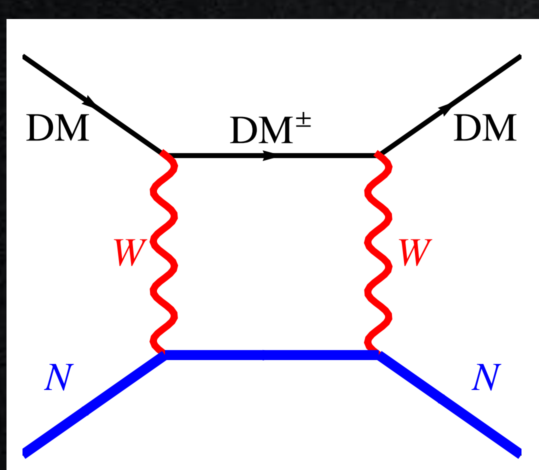
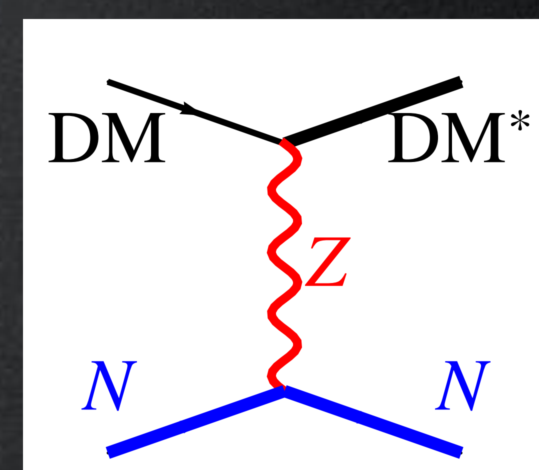


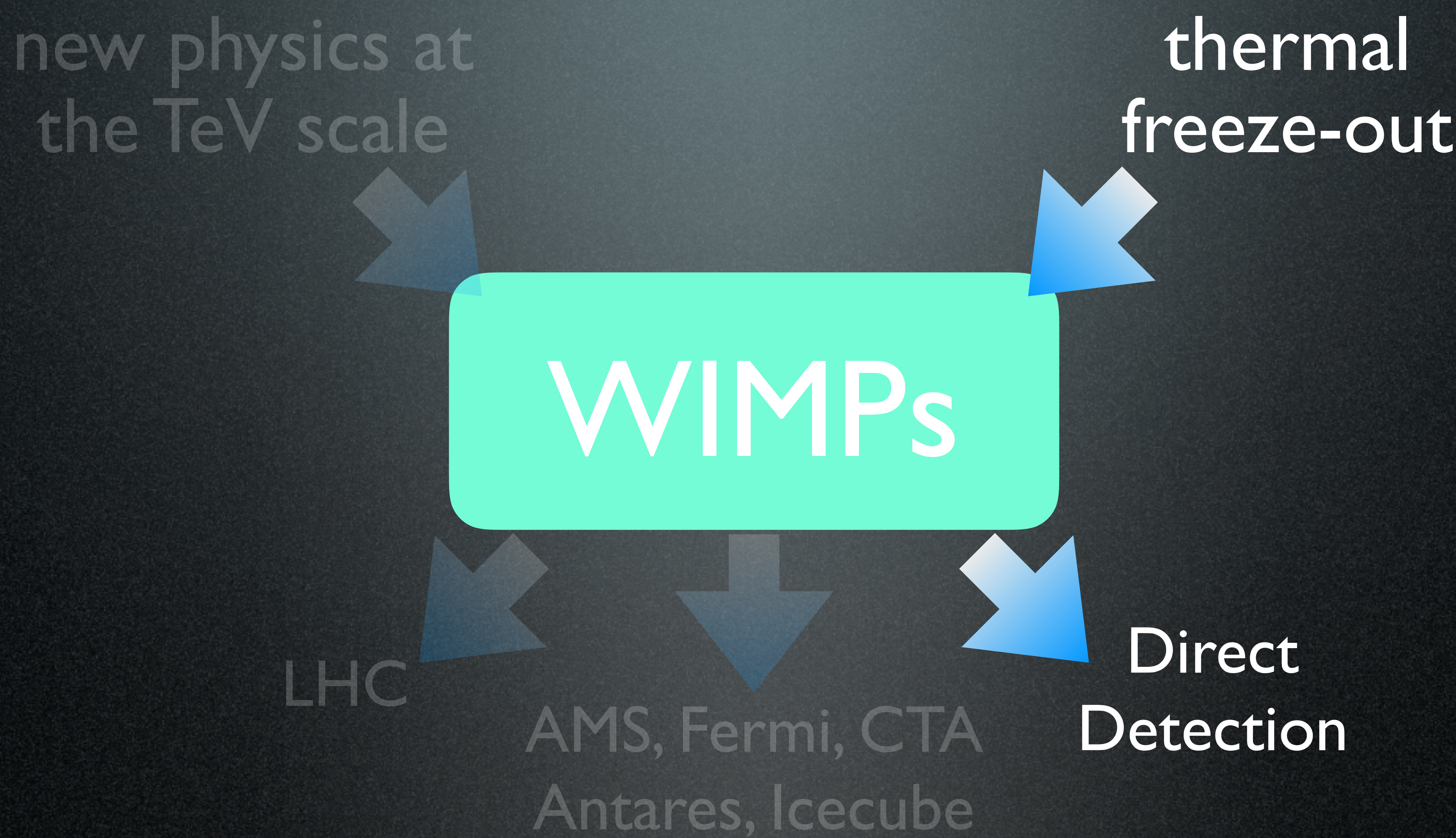

one loop

Still viable under which conditions?

- real particle
  (Majorana fermion, real scalar)
- hypercharge $Y = 0$
- SD interactions only
- inelastic scattering



# Candidates




1. even without a larger framework, WIMPs are still appealing
2. the frontier is multi-TeV
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# Minimalistic approach

# Minimalistic approach

On top of the SM, add only one extra multiplet $\mathcal{X} = \begin{pmatrix} \mathcal{X}_1 \\ \mathcal{X}_2 \\ \vdots \end{pmatrix}$

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \bar{\mathcal{X}}(i\not{D} + M)\mathcal{X}$$ if $\mathcal{X}$ is a fermion

$$\mathscr{L} = \mathscr{L}_{\rm SM} + |D_\mu \mathcal{X}|^2 - M^2|\mathcal{X}|^2$$ if $\mathcal{X}$ is a scalar

and systematically search for the ideal DM candidate...

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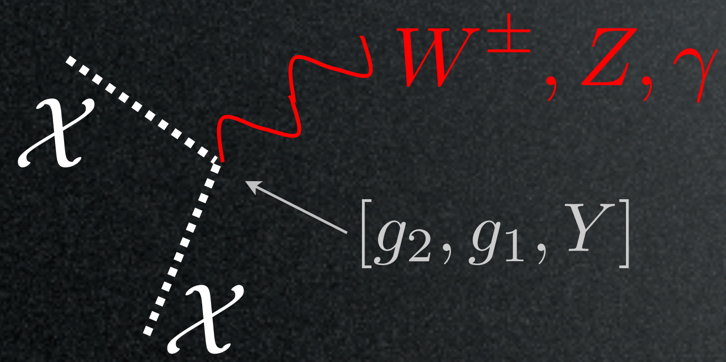
gauge interactions




the only parameter,
and will be fixed by $\Omega_{\rm DM}$.

(other terms in the scalar potential)

(one loop mass splitting)

and systematically search for the ideal DM candidate...

The ideal DM candidate is

# weakly int., massive, neutral, stable

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# weakly int., massive, neutral, stable

| $SU(2)_L$ | $U(1)_Y$ | spin |
|---|---|---|
| $\underline{2}$ | | |
| $\underline{3}$ | | |
| $\underline{4}$ | | |
| $\underline{5}$ | | |
| $\underline{7}$ | | |

← ($\underline{6}$ is similar to $\underline{4}$)

$$\chi = \begin{pmatrix} \chi_1 \\ \chi_2 \\ \vdots \\ \chi_n \end{pmatrix}$$

these are all possible choices:

$n \leq 5$ for fermions

$n \leq 7$ for scalars

to avoid explosion in the running coupling

$$\alpha_2^{-1}(E') = \alpha_2^{-1}(M) - \frac{b_2(n)}{2\pi} \ln \frac{E'}{M}$$

(actually, including 2-loops,
$n \leq 6$ ($n \leq 4$) for real (complex) scalars)

Di Luzio, Nardecchia et al., 1504.00359

The ideal DM candidate is

# weakly int., massive, neutral, stable

| $SU(2)_L$ | $U(1)_Y$ | spin |
|---|---|---|
| $\underline{2}$ | $1/2$ | |
| $\underline{3}$ | $0$ | |
| | $1$ | |
| $\underline{4}$ | $1/2$ | |
| | $3/2$ | |
| $\underline{5}$ | $0$ | |
| | $1$ | |
| | $2$ | |
| $\underline{7}$ | $0$ | |

Each multiplet contains a neutral component with a proper assignment of the hypercharge, according to

$$Q = T_3 + Y \equiv 0$$

e.g. for $n = 2$: $T_3 = \begin{pmatrix} +\frac{1}{2} \\ \\ -\frac{1}{2} \end{pmatrix} \Rightarrow |Y| = \frac{1}{2}$

e.g. for $n = 3$ : $T_3 = \begin{pmatrix} +1 \\ 0 \\ -1 \end{pmatrix} \Rightarrow |Y| = 0 \text{ or } 1$

etc.

The ideal DM candidate is

# weakly int., massive, neutral, stable

| $SU(2)_L$ | $U(1)_Y$ | spin |
|---|---|---|
| $\underline{2}$ | $1/2$ | $S$ |
| | | $F$ |
| $\underline{3}$ | $0$ | $S$ |
| | | $F$ |
| | $1$ | $S$ |
| | | $F$ |
| $\underline{4}$ | $1/2$ | $S$ |
| | | $F$ |
| | $3/2$ | $S$ |
| | | $F$ |
| $\underline{5}$ | $0$ | $S$ |
| | | $F$ |
| | $1$ | $S$ |
| | | $F$ |
| | $2$ | $S$ |
| | | $F$ |
| $\underline{7}$ | $0$ | $S$ |

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etc.

# The ideal DM candidate is
# weakly int., massive, neutral, stable

| $SU(2)_L$ | $U(1)_Y$ | spin | $M$ (TeV) |
|---|---|---|---|
| $\underline{2}$ | 1/2 | $S$ | 0.43 |
| | | $F$ | 1.2 |
| $\underline{3}$ | 0 | $S$ | 2.0 |
| | | $F$ | 2.6 |
| | 1 | $S$ | 1.4 |
| | | $F$ | 1.8 |
| $\underline{4}$ | 1/2 | $S$ | 2.4 |
| | | $F$ | 2.5 |
| | 3/2 | $S$ | 2.4 |
| | | $F$ | 2.5 |
| $\underline{5}$ | 0 | $S$ | 5.0 |
| | | $F$ | 4.2 |
| | 1 | $S$ | 3.5 |
| | | $F$ | 3.2 |
| | 2 | $S$ | 3.5 |
| | | $F$ | 3.2 |
| $\underline{7}$ | 0 | $S$ | 8.5 |

The mass $M$ is determined by the relic abundance:

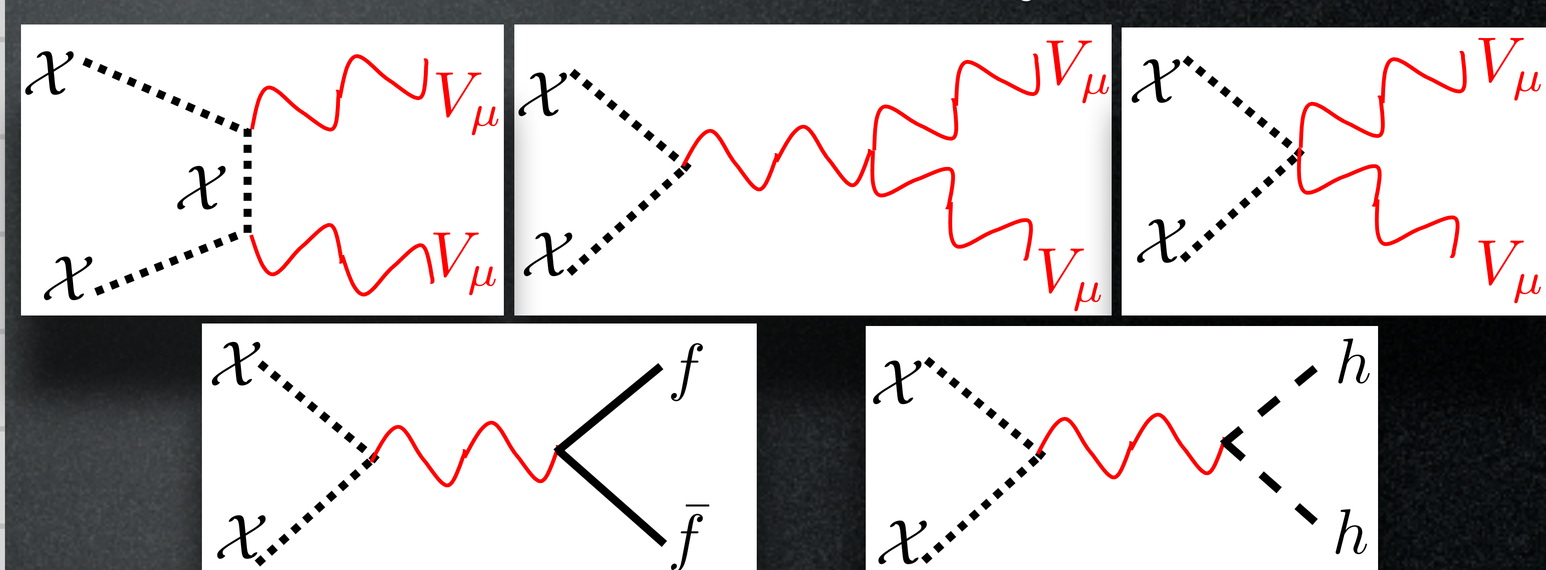
$$\Omega_{\rm DM} = \frac{6\ 10^{-27}{\rm cm}^3{\rm s}^{-1}}{\langle \sigma_{\rm ann} v\rangle} \cong 0.24$$

for $\mathcal{X}$ scalar

$$\langle \sigma_A v\rangle \simeq \frac{g_2^4\ (3-4n^2+n^4)+16\ Y^4 g_Y^4 + 8 g_2^2 g_Y^2 Y^2 (n^2-1)}{64\pi\ M^2\ g_{\mathcal{X}}}$$

for $\mathcal{X}$ fermion

$$\langle \sigma_A v\rangle \simeq \frac{g_2^4\ (2n^4+17n^2-19)+4Y^2 g_Y^4 (41+8Y^2)+16 g_2^2 g_Y^2 Y^2 (n^2-1)}{128\pi\ M^2\ g_{\mathcal{X}}}$$




(- include co-annihilations)
(- computed for $M \gg M_{Z,W}$)

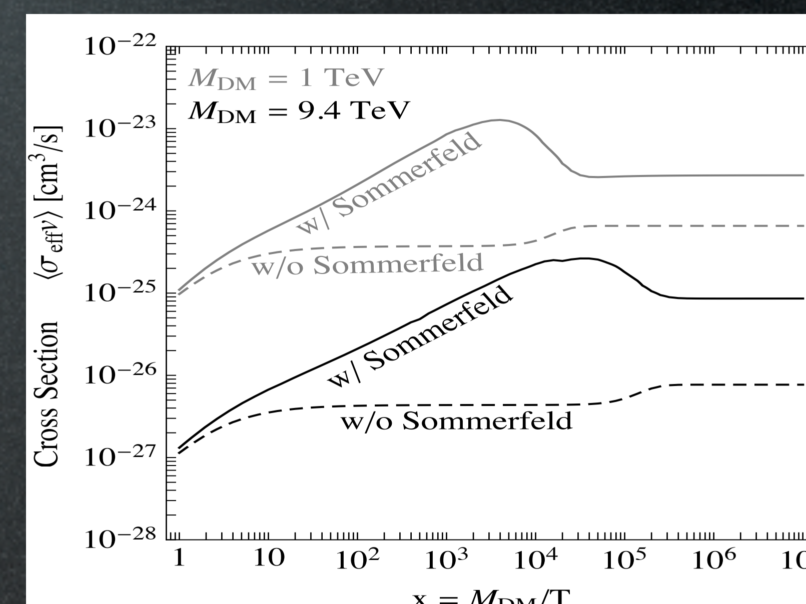
# The ideal DM candidate is
# weakly int., massive, neutral, stable

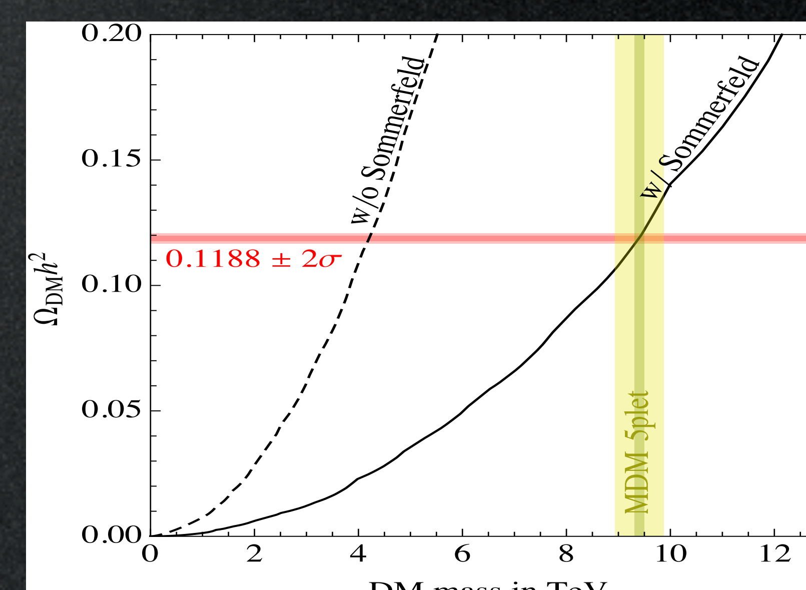
| $SU(2)_L$ | $U(1)_Y$ | spin | $M$ (TeV) |
|---|---|---|---|
| $\underline{2}$ | $1/2$ | $S$ | |
| | | $F$ | 1.0 |
| $\underline{3}$ | $0$ | $S$ | 2.5 |
| | | $F$ | 2.7 |
| | $1$ | $S$ | |
| | | $F$ | |
| $\underline{4}$ | $1/2$ | $S$ | |
| | | $F$ | |
| | $3/2$ | $S$ | |
| | | $F$ | |
| $\underline{5}$ | $0$ | $S$ | |
| | | $F$ | 9.4 |
| | $1$ | $S$ | |
| | | $F$ | |
| | $2$ | $S$ | |
| | | $F$ | |
| $\underline{7}$ | $0$ | $S$ | 25 |

**Non-perturbative corrections**
(and other smaller corrections) ← (more later)
**induce modifications:**

$$\langle \sigma_{\rm ann} v \rangle \rightsquigarrow R \cdot \langle \sigma_{\rm ann} v \rangle + \langle \sigma_{\rm ann} v \rangle_{p-{\rm wave}}$$

with $R \sim \mathcal{O}(\text{few}) \to \mathcal{O}(10^2)$

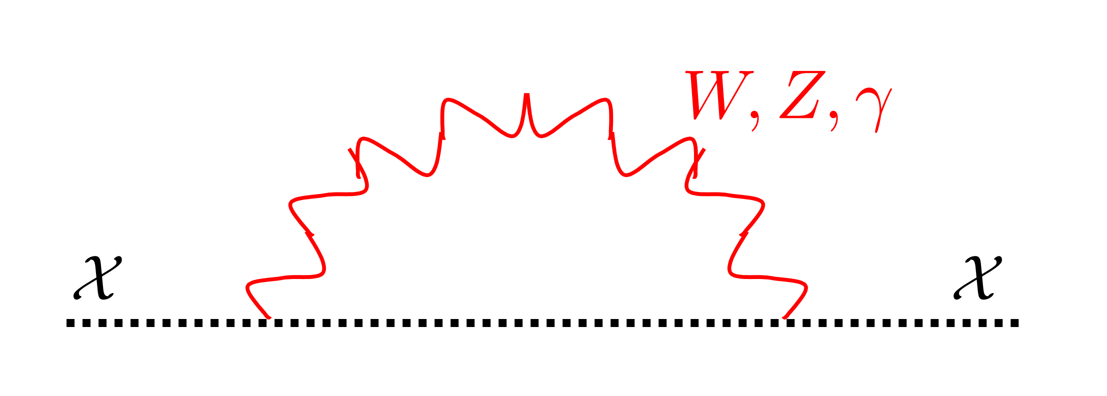


# The ideal DM candidate is
# weakly int., massive, neutral, stable

| $SU(2)_L$ | $U(1)_Y$ | spin | $M$ (TeV) | $\Delta M$(MeV) |
|---|---|---|---|---|
| 2 | 1/2 | $S$ | | 348 |
| | | $F$ | 1.0 | 342 |
| 3 | 0 | $S$ | 2.5 | 166 |
| | | $F$ | 2.7 | 166 |
| | 1 | $S$ | | 540 |
| | | $F$ | | 526 |
| 4 | 1/2 | $S$ | | 353 |
| | | $F$ | | 347 |
| | 3/2 | $S$ | | 729 |
| | | $F$ | | 712 |
| 5 | 0 | $S$ | | 166 |
| | | $F$ | 9.4 | 166 |
| | 1 | $S$ | | 537 |
| | | $F$ | | 534 |
| | 2 | $S$ | | 906 |
| | | $F$ | | 900 |
| 7 | 0 | $S$ | 25 | 166 |

EW loops induce a mass splitting $\Delta M$ inside the n-uplet: tree level




$$M_Q - M_{Q'} = \frac{\alpha_2 M}{4\pi}\left\{(Q^2 - Q'^2)s_W^2 f(\tfrac{M_Z}{M}) + (Q-Q')(Q+Q'-2Y)\left[f(\tfrac{M_W}{M}) - f(\tfrac{M_Z}{M})\right]\right\}$$

with $f(r) \stackrel{r\to 0}{\longrightarrow} -2\pi r$

The neutral component is the lightest

# The ideal DM candidate is
# weakly int., massive, neutral, stable

| $SU(2)_L$ | $U(1)_Y$ | spin | $M$ (TeV) | $\Delta M$(MeV) | decay ch. |
|---|---|---|---|---|---|
| $\underline{2}$ | 1/2 | $S$ | | 348 | $EL$ |
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| $\underline{3}$ | 0 | $S$ | 2.5 | 166 | $HH^*$ |
| | | $F$ | 2.7 | 166 | $LH$ |
| | 1 | $S$ | | 540 | $HH, LH$ |
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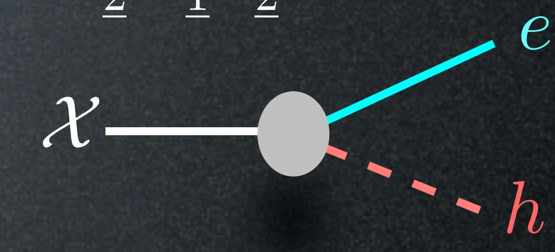
| $\underline{4}$ | 1/2 | $S$ | | 353 | $HHH^*$ |
| | | $F$ | | 347 | $(LHH^*)$ |
| | 3/2 | $S$ | | 729 | $HHH$ |
| | | $F$ | | 712 | $(LHH)$ |
| $\underline{5}$ | 0 | $S$ | | 166 | $(HHH^*H^*)$ |
| | | $F$ | 9.4 | 166 | — |
| | 1 | $S$ | | 537 | $(HH^*H^*H^*)$ |
| | | $F$ | | 534 | — |
| | 2 | $S$ | | 906 | $(H^*H^*H^*H^*)$ |
| | | $F$ | | 900 | — |
| $\underline{7}$ | 0 | $S$ | 25 | 166 | $(\chi\chi H^*H)$ |

List all allowed SM couplings:

← e.g. $\overset{1/2}{\underset{\underline{2}}{\chi}}\ \overset{-1}{\underset{\underline{1}}{E}}\ \overset{1/2}{\underset{\underline{2}}{H}}$




← e.g. $\overset{1/2}{\underset{\underline{4}}{\chi}}\ \overset{-1/2}{\underset{\underline{2}}{L}}\ \overset{1/2}{\underset{\underline{2}}{H}}\ \overset{-1/2}{\underset{\underline{2}}{H^*}}$

dim=5 operator, induces

$\tau \sim \Lambda^2 \mathrm{TeV}^{-3} \ll t_{\mathrm{universe}}$

for $\Lambda \sim M_{\mathrm{Pl}}$

← dim=5, loop decay

Di Luzio, Nardecchia et al., 1504.00359

# The ideal DM candidate is
# weakly int., massive, neutral, stable

| $SU(2)_L$ | $U(1)_Y$ | spin | $M$ (TeV) | $\Delta M$(MeV) | decay ch. |
|---|---|---|---|---|---|
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| | | $F$ | 9.4 | 166 | — |
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| | | $F$ | | 534 | — |
| | $2$ | $S$ | | 906 | $(H^*H^*H^*H^*)$ |
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| $\underline{7}$ | $0$ | $S$ | 25 | 166 | $(\chi\chi H^*H)$ |

List all allowed SM couplings:

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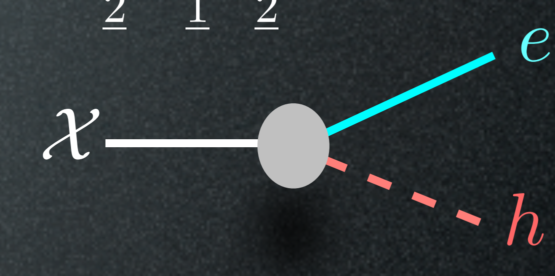


e.g. $\overset{1/2}{\underset{\underline{4}}{\mathcal{X}}}\ \overset{-1/2}{\underset{\underline{2}}{L}}\ \overset{1/2}{\underset{\underline{2}}{H}}\ \overset{-1/2}{\underset{\underline{2}}{H^*}}$

dim=5 operator, induces

$\tau \sim \Lambda^2 \mathrm{TeV}^{-3} \ll t_{\mathrm{universe}}$

for $\Lambda \sim M_{\mathrm{Pl}}$

No allowed decay!

*Automatically* stable!

The ideal DM candidate is

**weakly int., massive, neutral, stable**

and

**not excluded**

by direct searches!

| $SU(2)_L$ | $U(1)_Y$ | spin | $M$ (TeV) | $\Delta M$(MeV) | decay ch. |
|---|---|---|---|---|---|
| $\underline{2}$ | 1/2 | $S$ | | 348 | $EL$ |
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| | 1 | $S$ | | 537 | $(HH^*H^*H^*)$ |
| | | $F$ | | 534 | — |
| | 2 | $S$ | | 906 | $(H^*H^*H^*H^*)$ |
| | | $F$ | | 900 | — |
| $\underline{7}$ | 0 | $S$ | 25 | 166 | $(\chi\chi H^*H)$ |

# The ideal DM candidate is weakly int., massive, neutral, stable and not excluded by direct searches!

| $SU(2)_L$ | $U(1)_Y$ | spin | $M$ (TeV) | $\Delta M$(MeV) | decay ch. |
|---|---|---|---|---|---|
| $\underline{2}$ | $1/2$ | $S$ | | 348 | $EL$ |
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| | | $F$ | | 900 | — |
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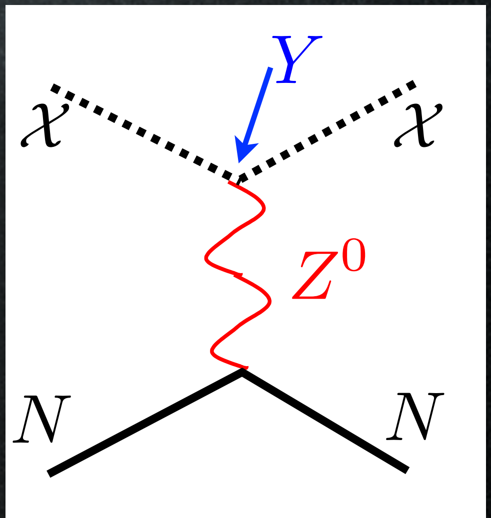
Candidates with $Y \neq 0$ interact as




$\sigma \simeq G_F^2 M_N^2 Y^2$ $\gg$ present bounds

Goodman Witten 1985

e.g. LUX, Xenon, PandaX

need $Y = 0$

The ideal DM candidate is

**weakly int., massive, neutral, stable**

and

**not excluded**

by direct searches!

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| | | $F$ | | 534 | — |
| | 2 | $S$ | | 906 | $(H^*H^*H^*H^*)$ |
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The ideal DM candidate is

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and

**not excluded**

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# The ideal DM candidate is

**weakly int., massive, neutral, stable** and **not excluded**

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| | | $F$ | | 900 | — |
| 7 | 0 | $S$ | 25 | 166 | — |

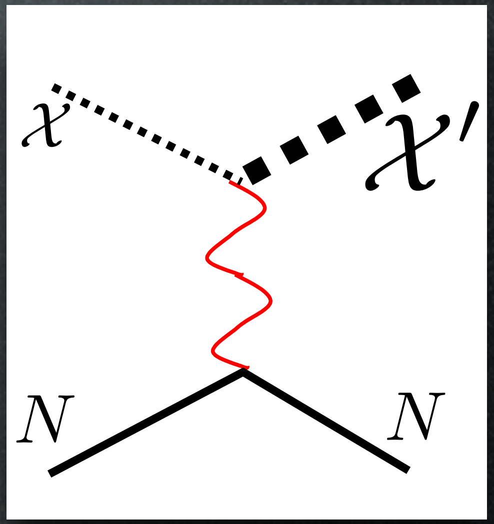
We have a winner!

(other terms in the scalar potential)

# If you want to cure ill candidates...

$Y \neq 0$ : introduce some mechanism to forbid coupling with $Z^0$ anyway

e.g. mixing with an extra state splits the 2 components of $\mathcal{X}$; if splitting is large enough, NC scattering is kinematically forbidden...




stability: impose some symmetry to forbid decays (e.g. R-parity)...

...the case of SuSy higgsino

mixing is with bino;
even for pure higgsino,
some mixing is 'inevitable'
due to higher dim operators

The ideal DM candidate is

**weakly int., massive, neutral, stable**

and

**not excluded**

| $SU(2)_L$ | $U(1)_Y$ | spin | $M$ (TeV) | $\Delta M$(MeV) | decay ch. |
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| | | $F$ | | 900 | — |
| $\underline{7}$ | 0 | $S$ | 25 | 166 | — |

And a second place

We have a winner!

(other terms in the scalar potential)

# Recap:

A fermionic $SU(2)_L$ quintuplet with $Y = 0$
provides a DM candidate with $M = 9.4$ TeV,
which is fully successful:

- neutral
- ***automatically*** stable ← like proton stability in SM!

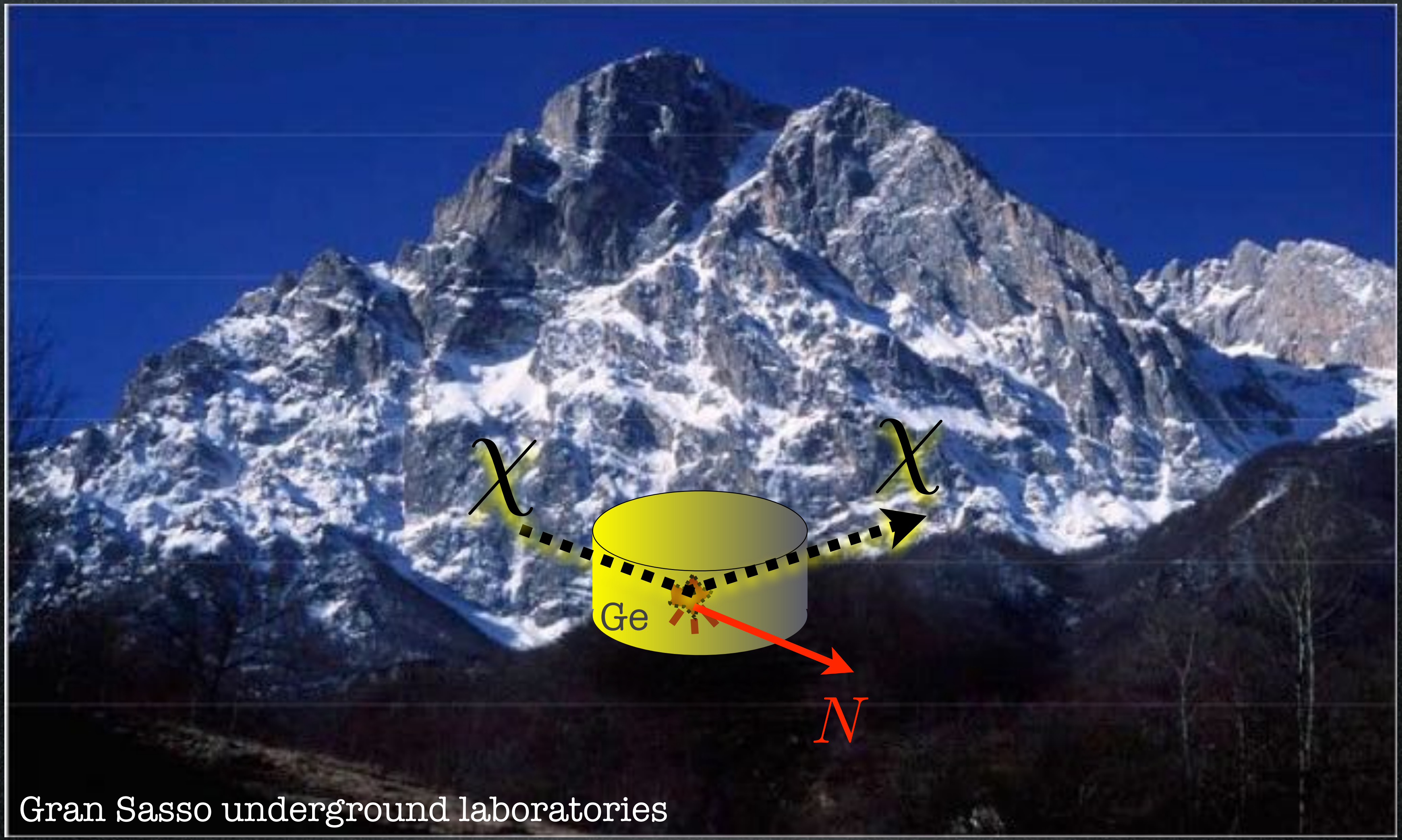
and

not yet discovered by DM searches.

(Other candidates can be cured via non-minimalities.)

# Detection and Phenomenology

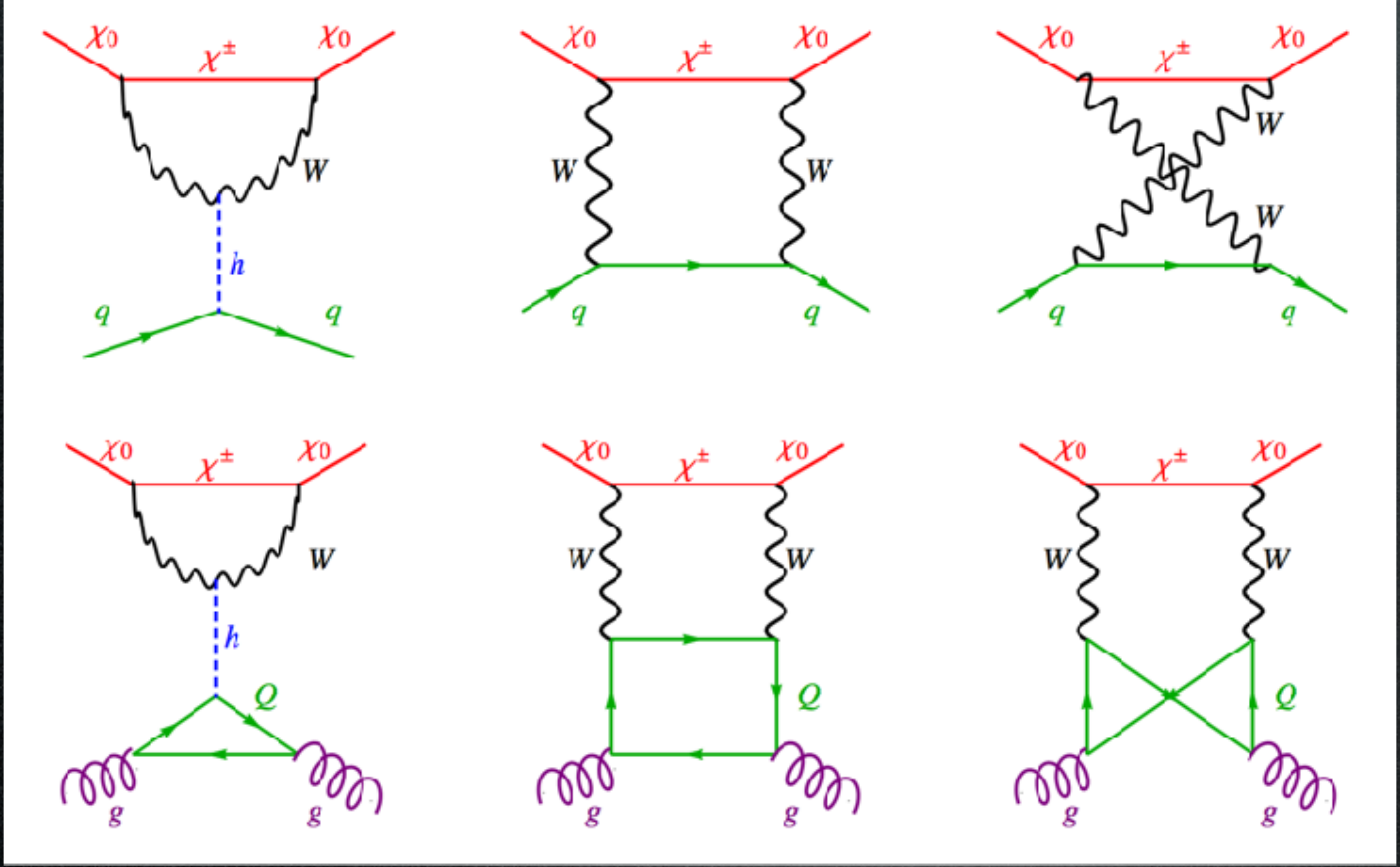
# Direct Detection



# Direct Detection

No tree level scattering.

1-loop and 2-loops:




$$\sigma_{\rm SI}^{n} = 2 \cdot 10^{-46}\ {\rm cm}^2$$


Cirelli, Fornengo, Strumia hep-ph/0512090

Essig 0710.1668

Hisano, Ishiwata, Nagata 1007.2601

Hisano, Ishiwata, Nagata, Takesano 1104.0228

Hill, Solon 1111.0016

Hisano, Ishiwata, Nagata 1010.5985

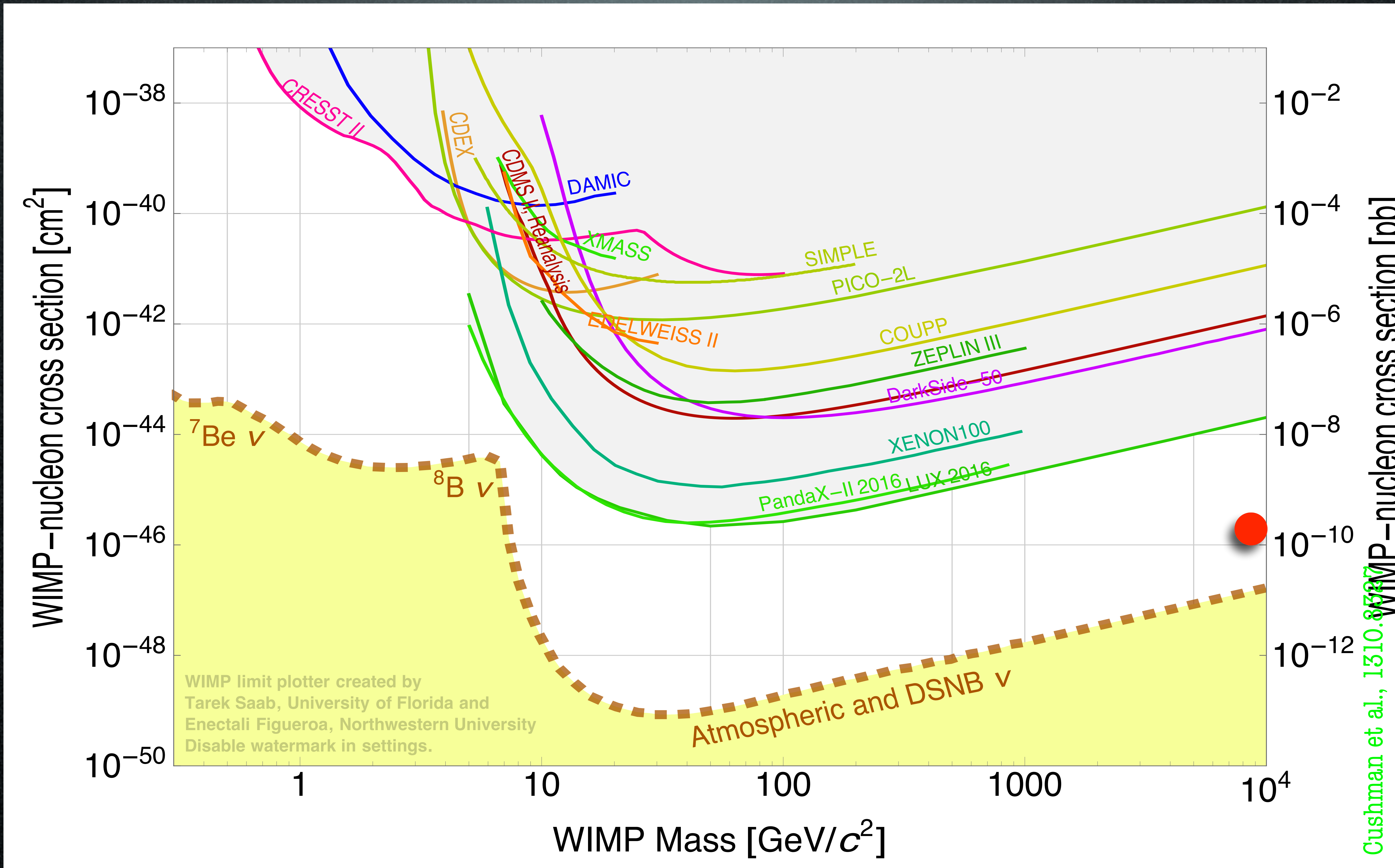
Farina, Pappadopulo, Strumia 1303.7244

Hill, Solon 1309.4092

Hill, Solon 1401.3339

Hisano, Ishiwata, Nagata 1504.00915

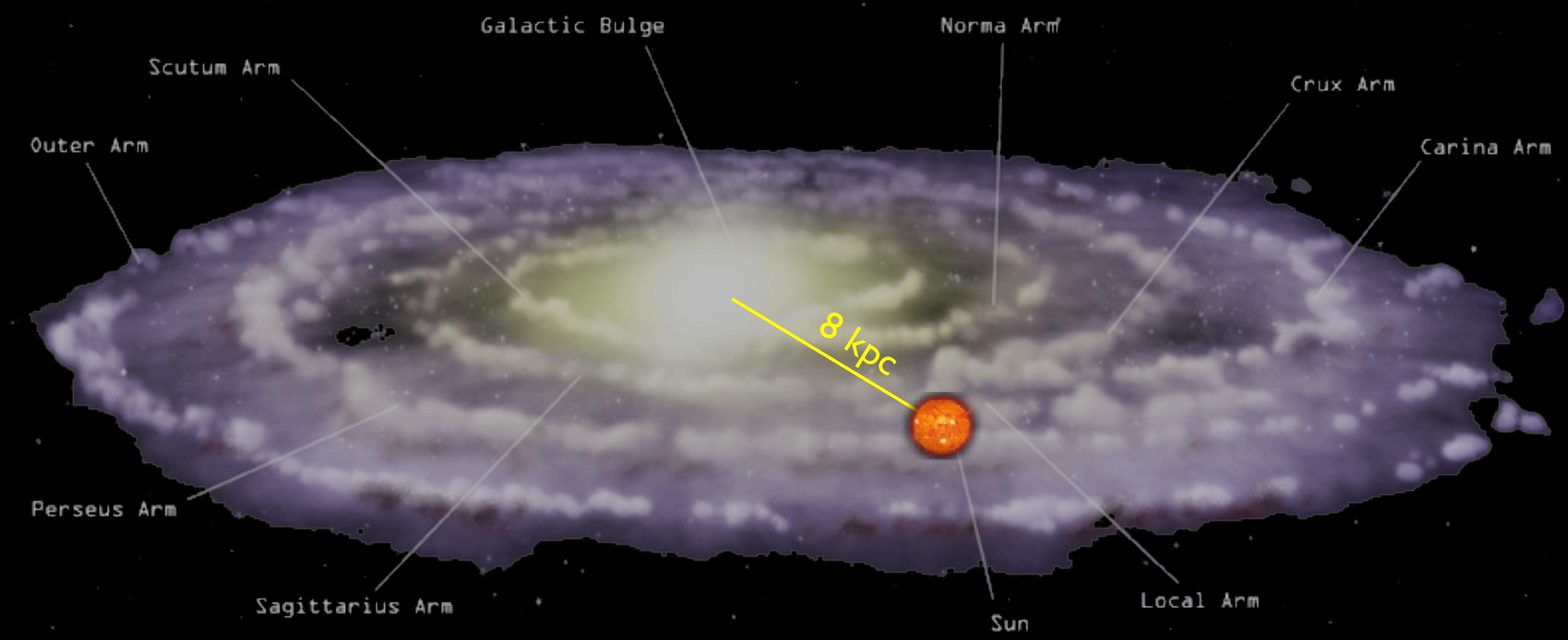
# Direct Detection




PS: SD cross section equally challenging Hisano, Ishiwata, Nagata 1010.5985

# Indirect Detection

i.e. $\nu, \bar{p}, e^+, \gamma, \bar{D}$ from MDM annihilations in MW halo.



# Indirect Detection

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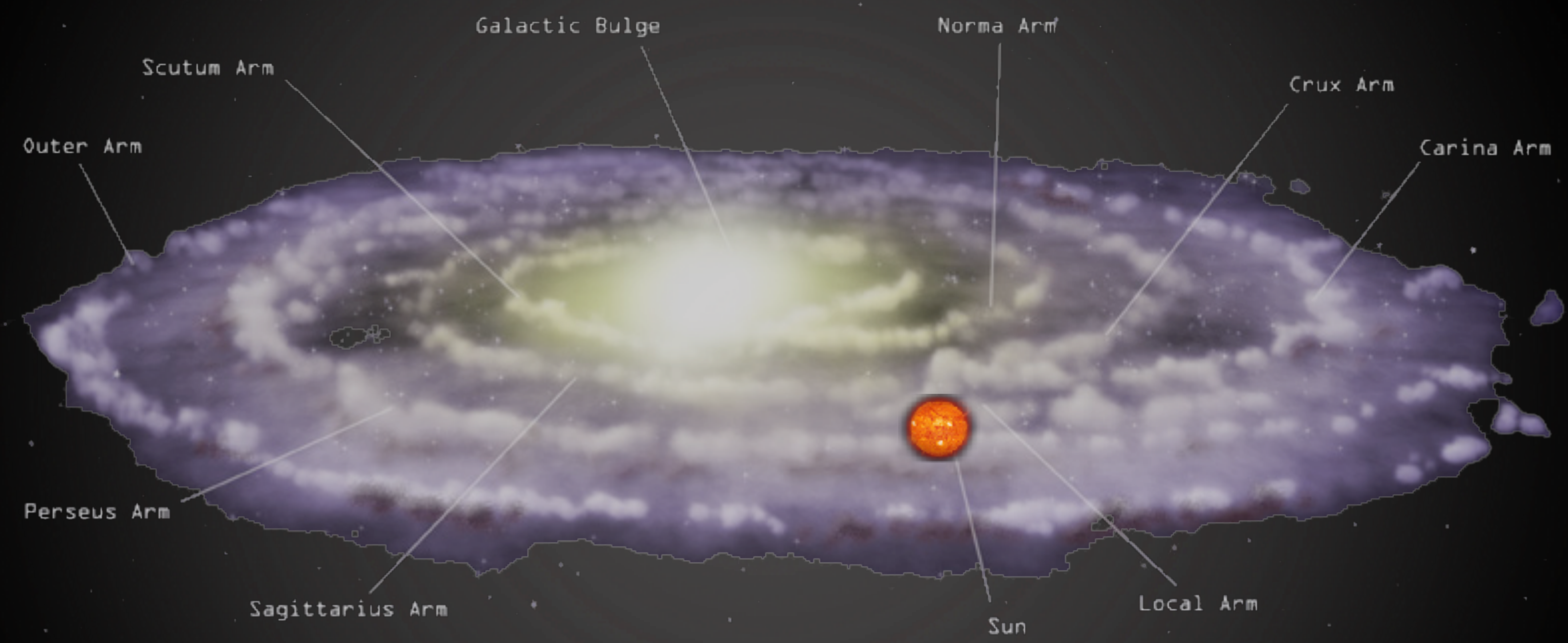
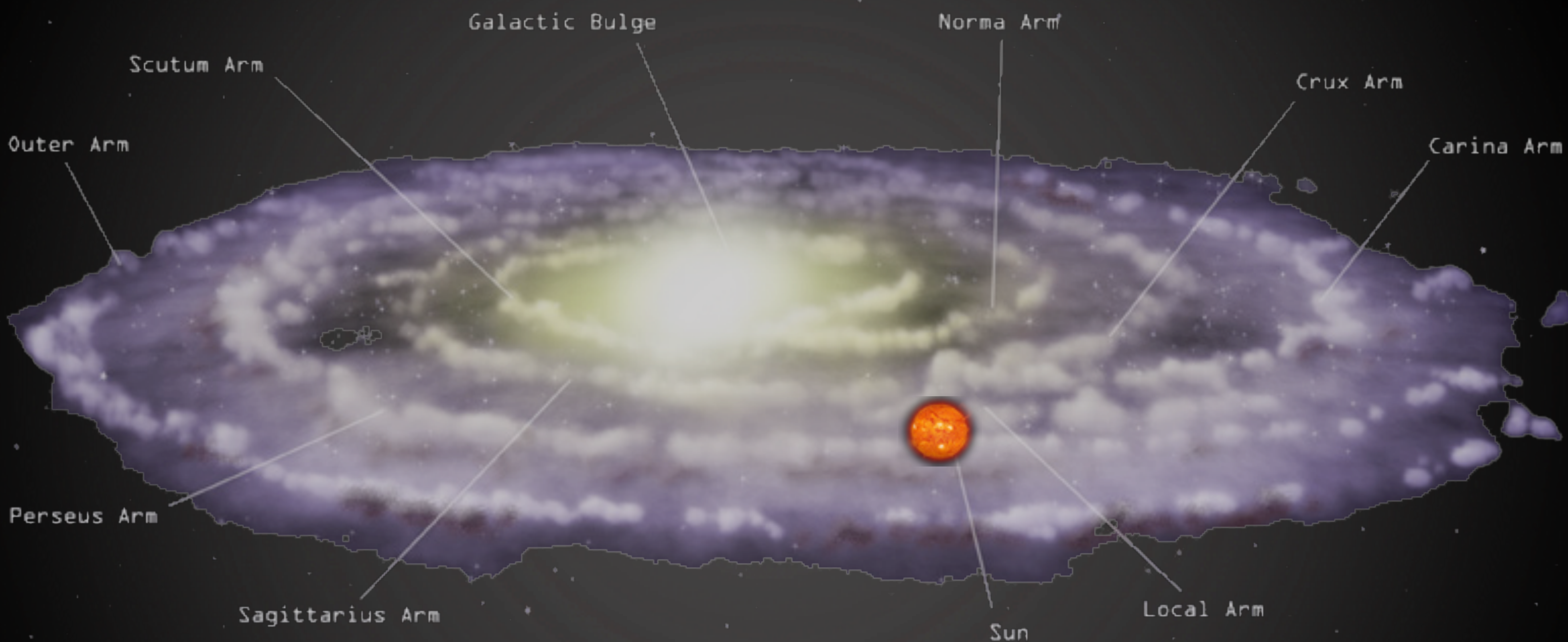


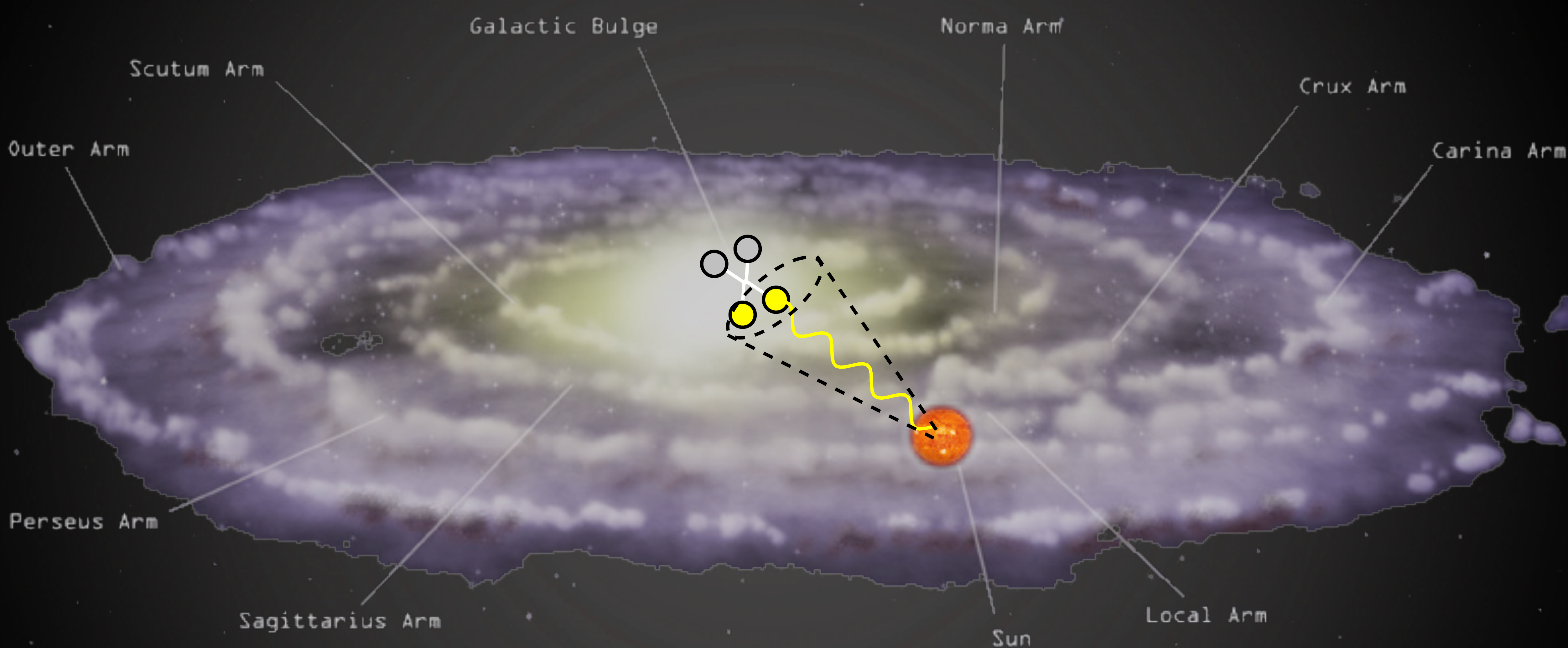
# Indirect Detection

$\gamma$ from MDM annihilations



# Indirect Detection

$\gamma$ from MDM annihilations in galactic center

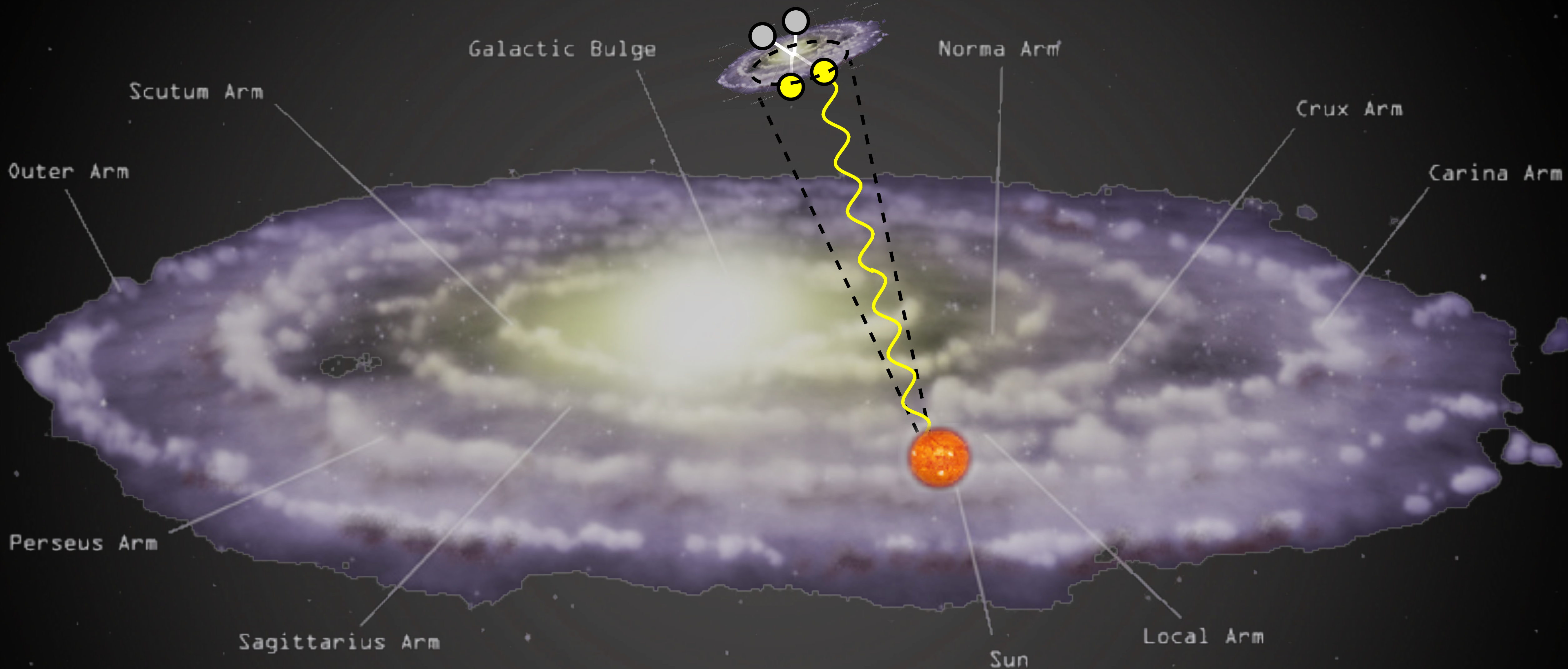


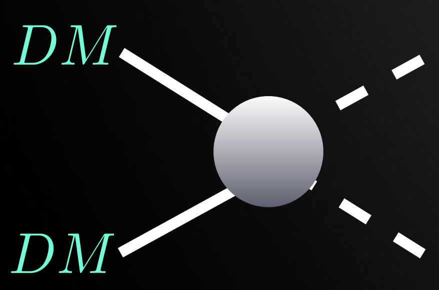

$$DM\ DM \to W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \gamma$$

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

# Indirect Detection

## $\gamma$ from MDM annihilations in dwarf galaxies



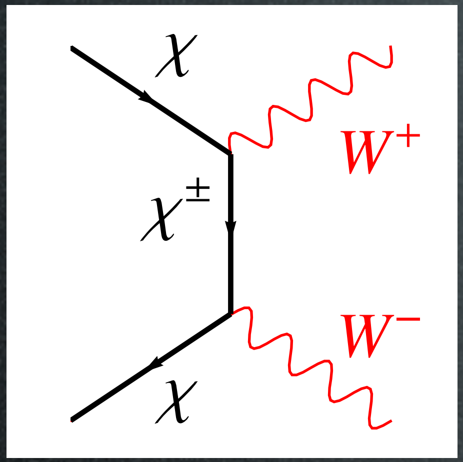




$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots \ \text{and } \gamma$$

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

# Indirect Detection

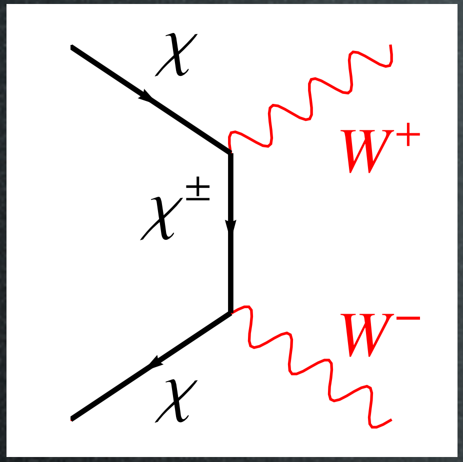
$\gamma$ from MDM annihilations




**+** $W^\pm, Z \to \bar{p}, e^+, \gamma \ldots$

# Indirect Detection

$\gamma$ from MDM annihilations




continuum

$+ \quad W^\pm, Z \to \bar{p}, e^+, \gamma \ldots$

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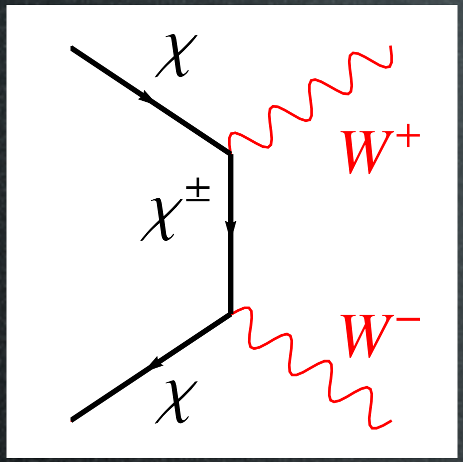
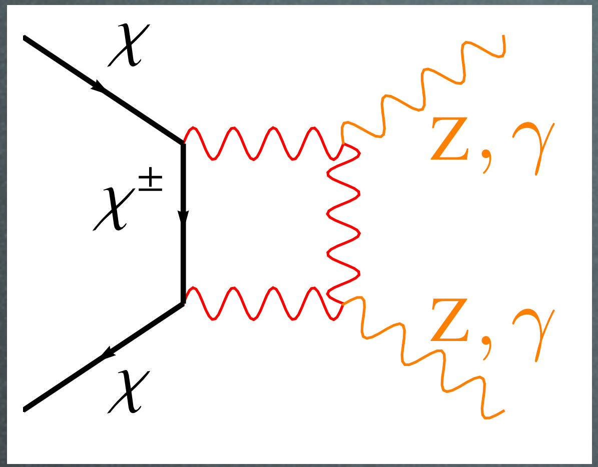



+ $W^\pm, Z \to \bar{p}, e^+, \gamma \ldots$

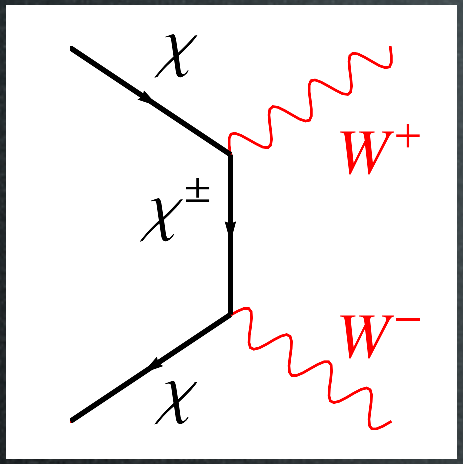
(channels for MDM with Y=0)

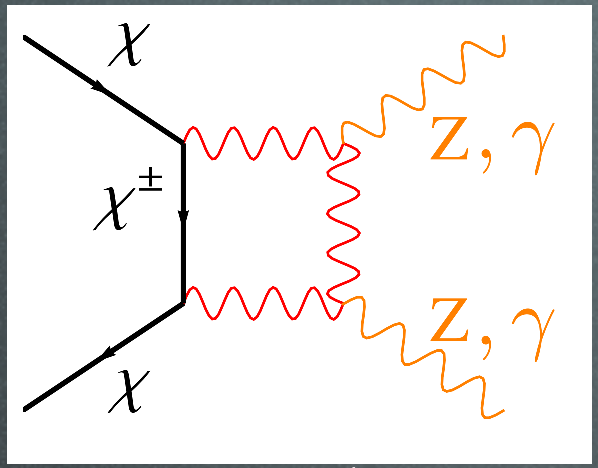
continuum

line(s)
(+ continuum)

# Indirect Detection

$\gamma$ from MDM annihilations

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continuum

line(s)
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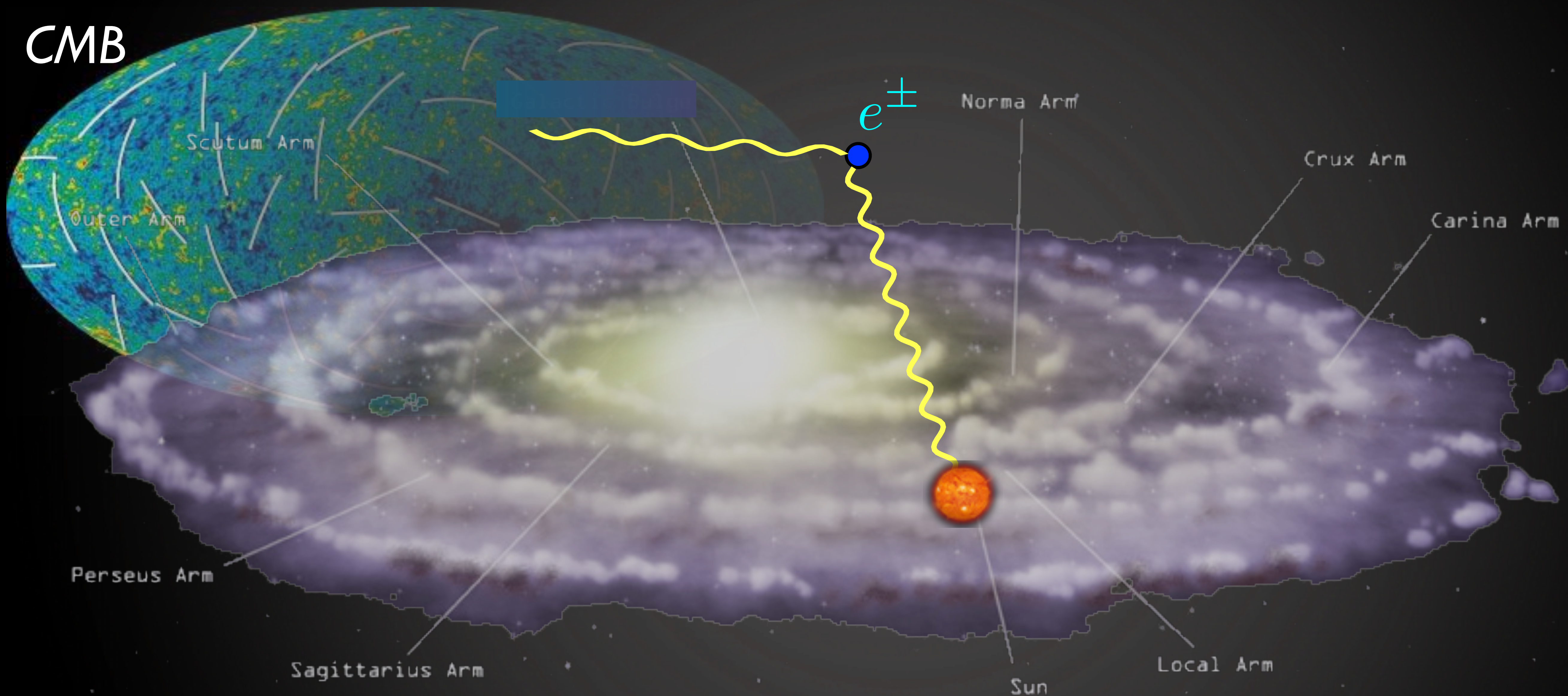
# Secondary emission

$\gamma$ from Inverse Compton on $e^{\pm}$ in halo




- upscatter of CMB, infrared and starlight photons on energetic $e^{\pm}$
- probes regions outside of Galactic Center

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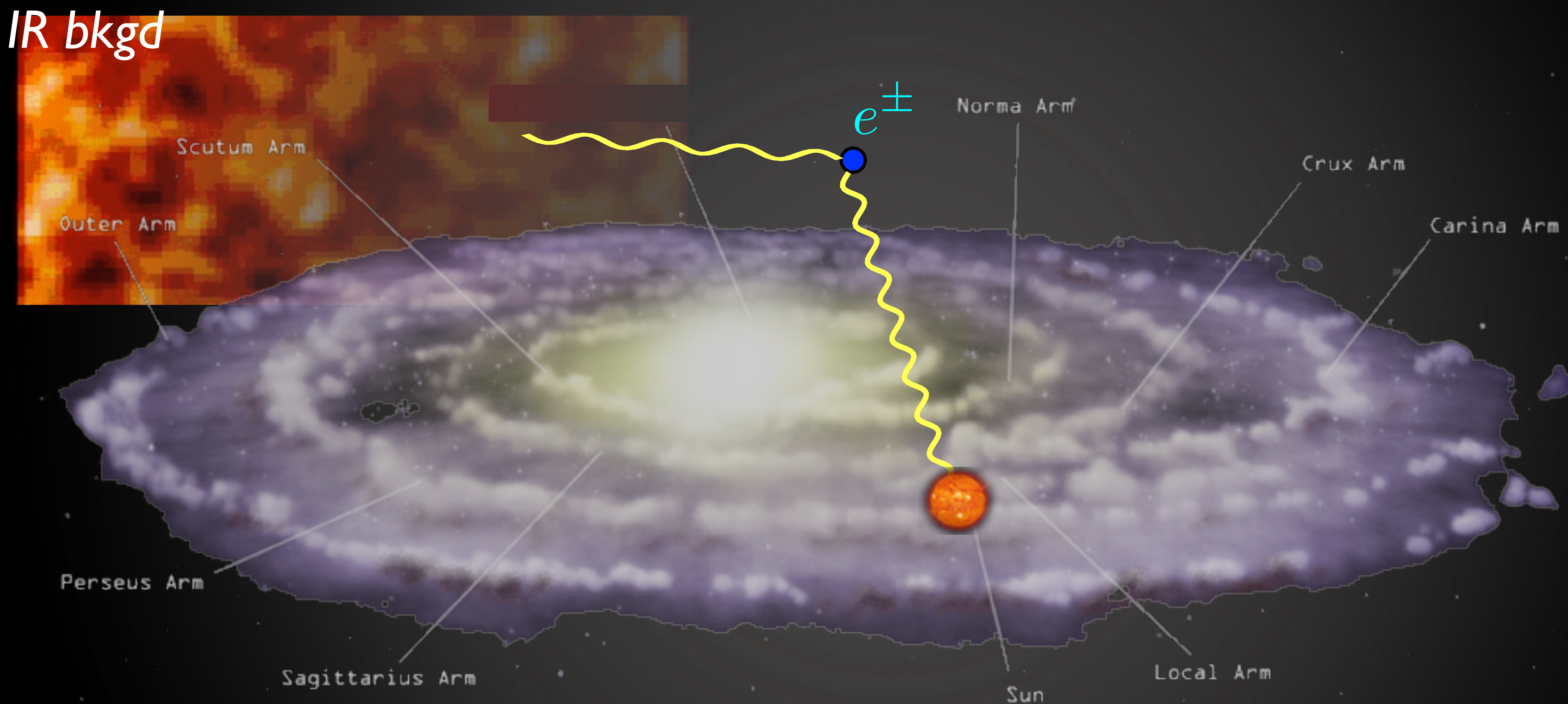


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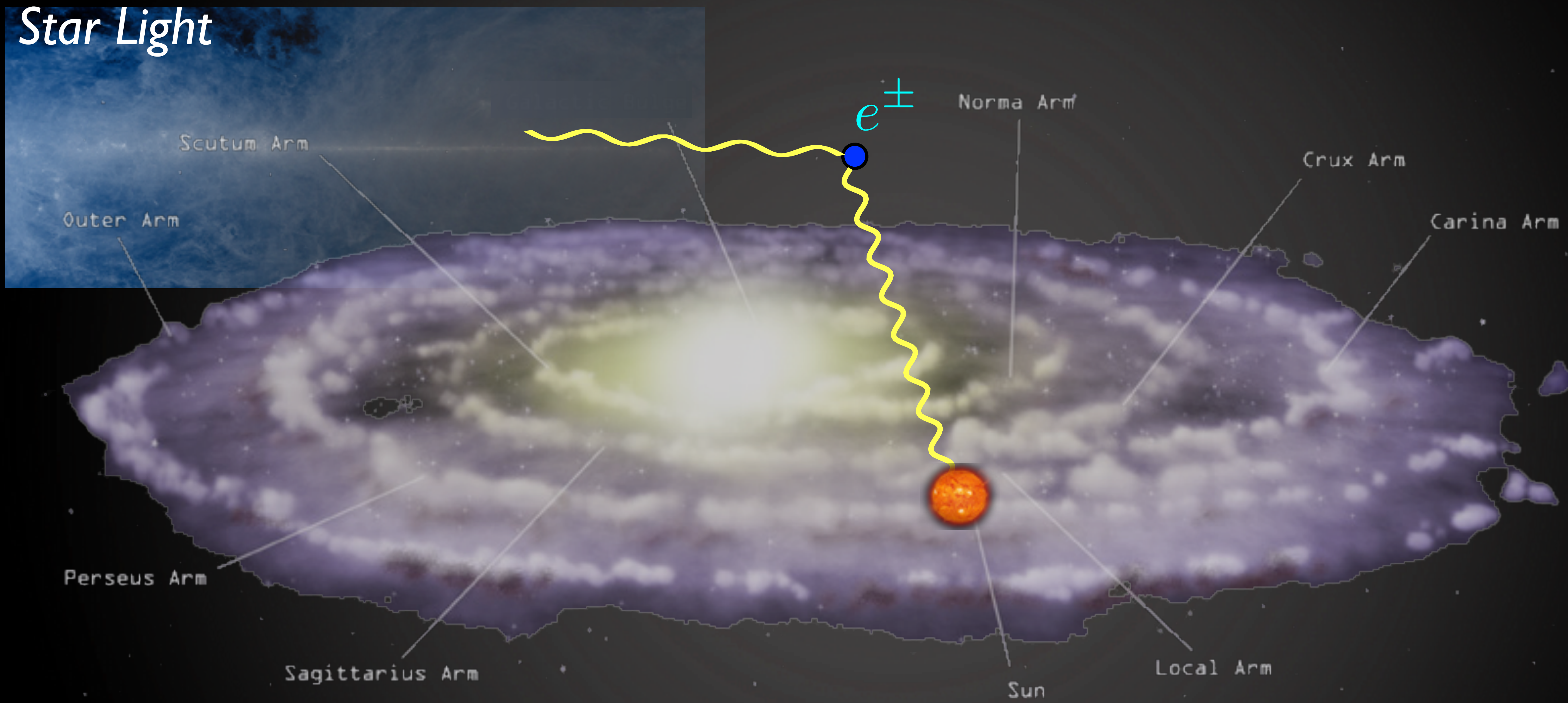


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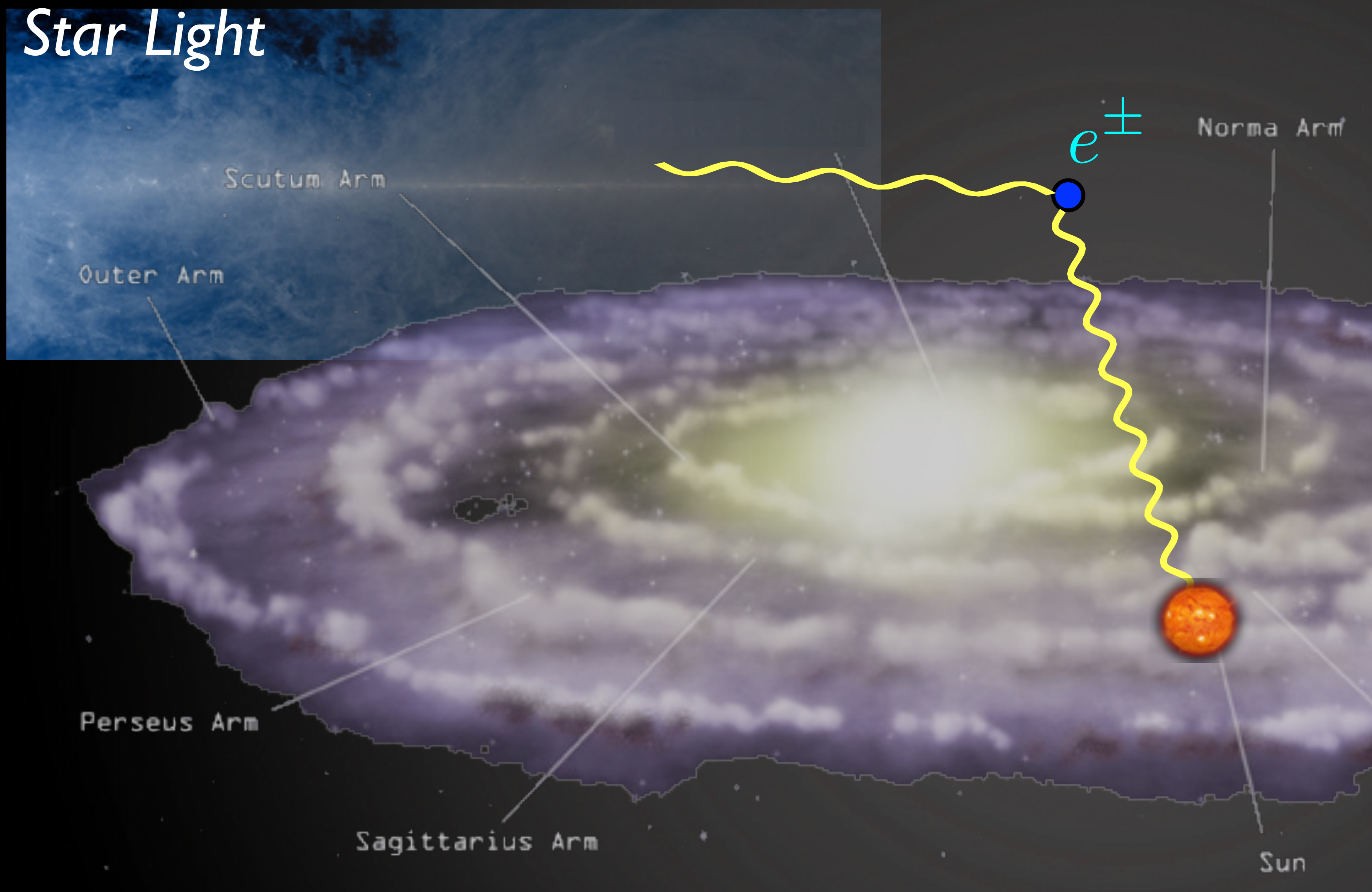


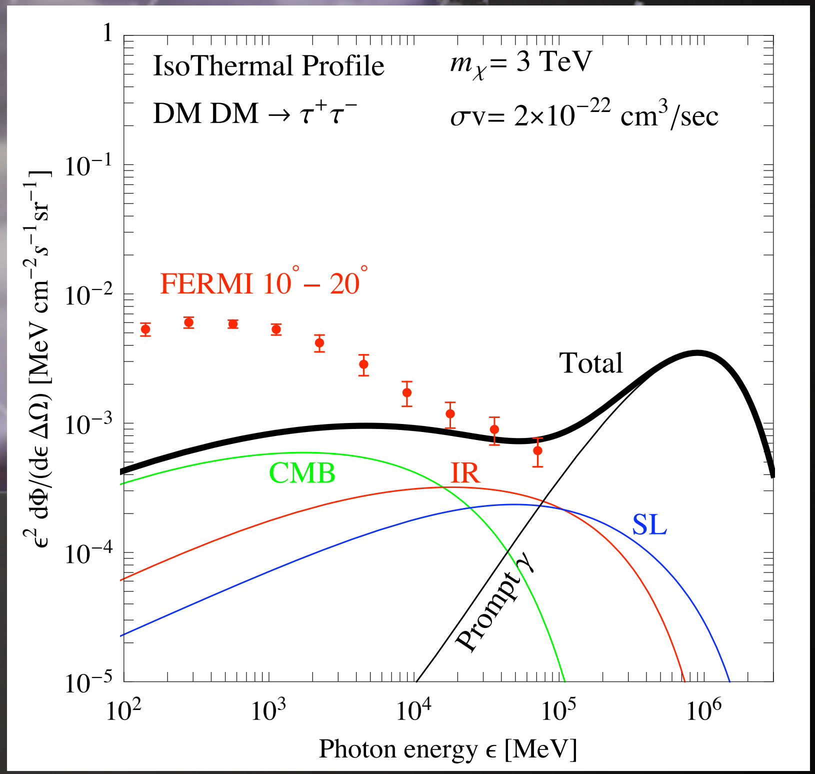


Cirelli, Panci, Serpico 0912.0663

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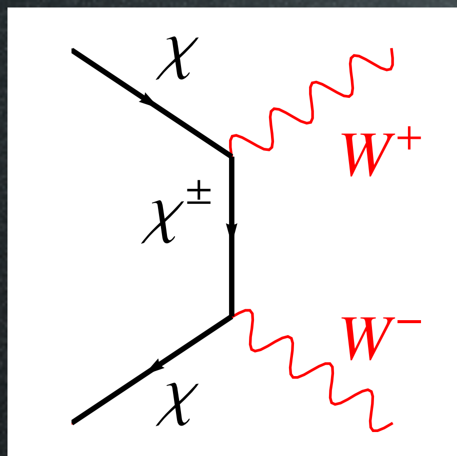


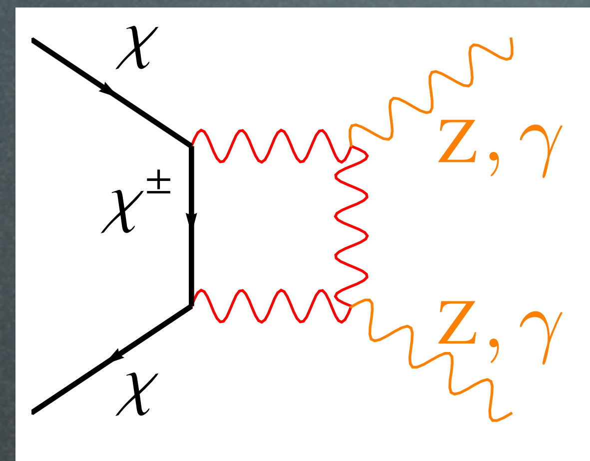


$+ \quad W^{\pm}, Z \to \bar{p}, e^{+}, \gamma \ldots$

(channels for MDM with Y=0)

continuum

line(s)
(+ continuum)

+ ICS

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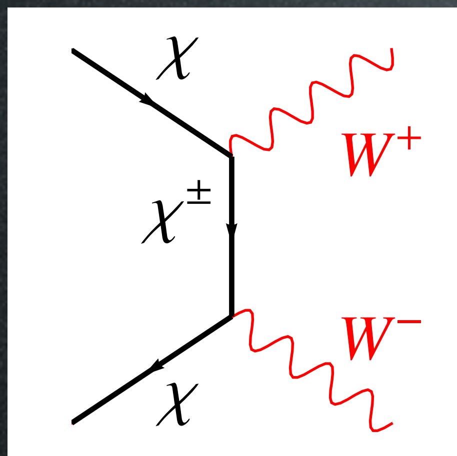


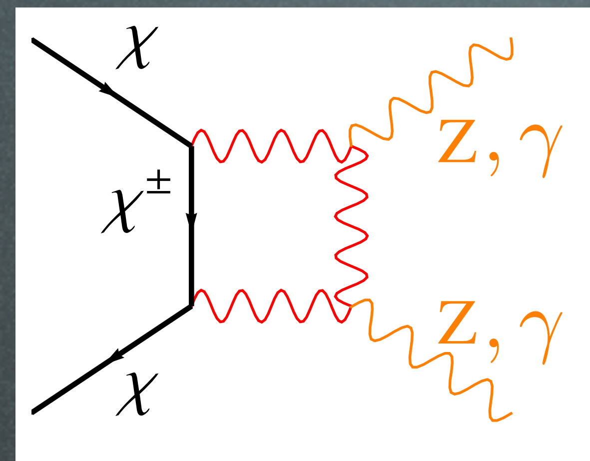


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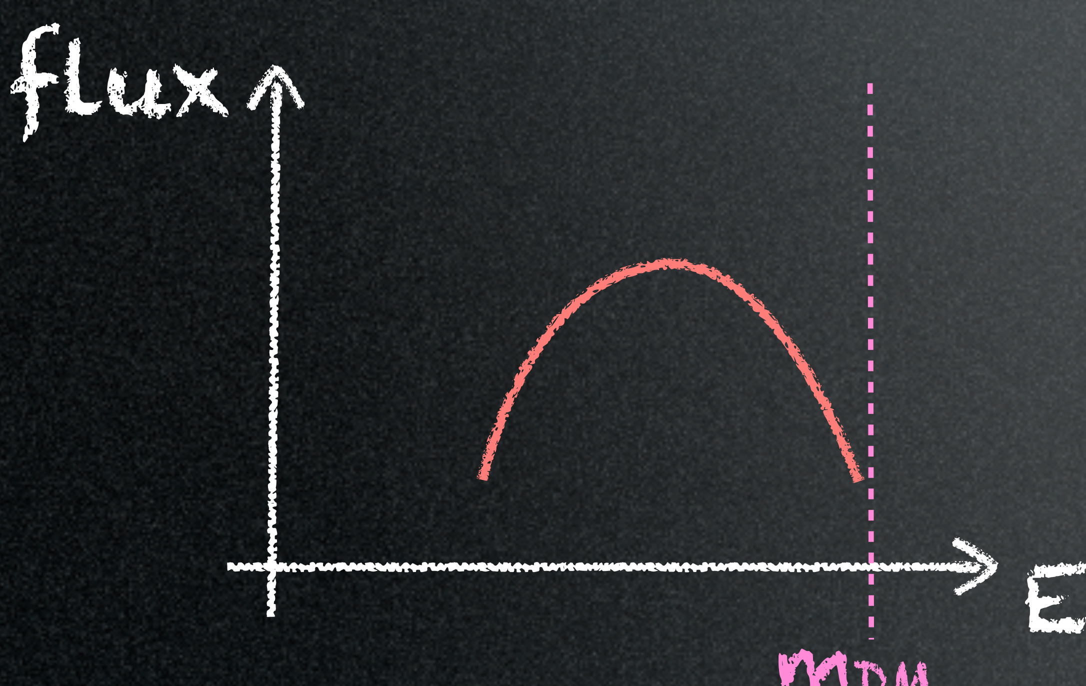

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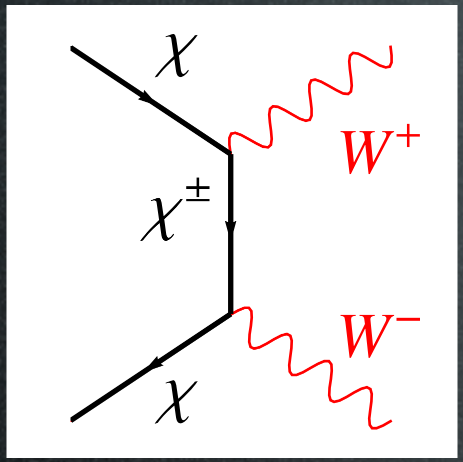


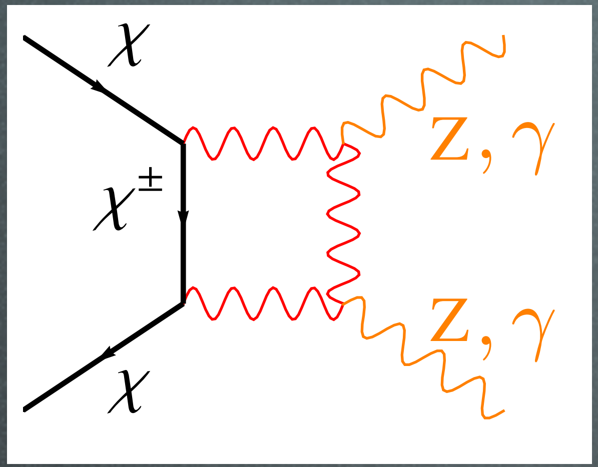


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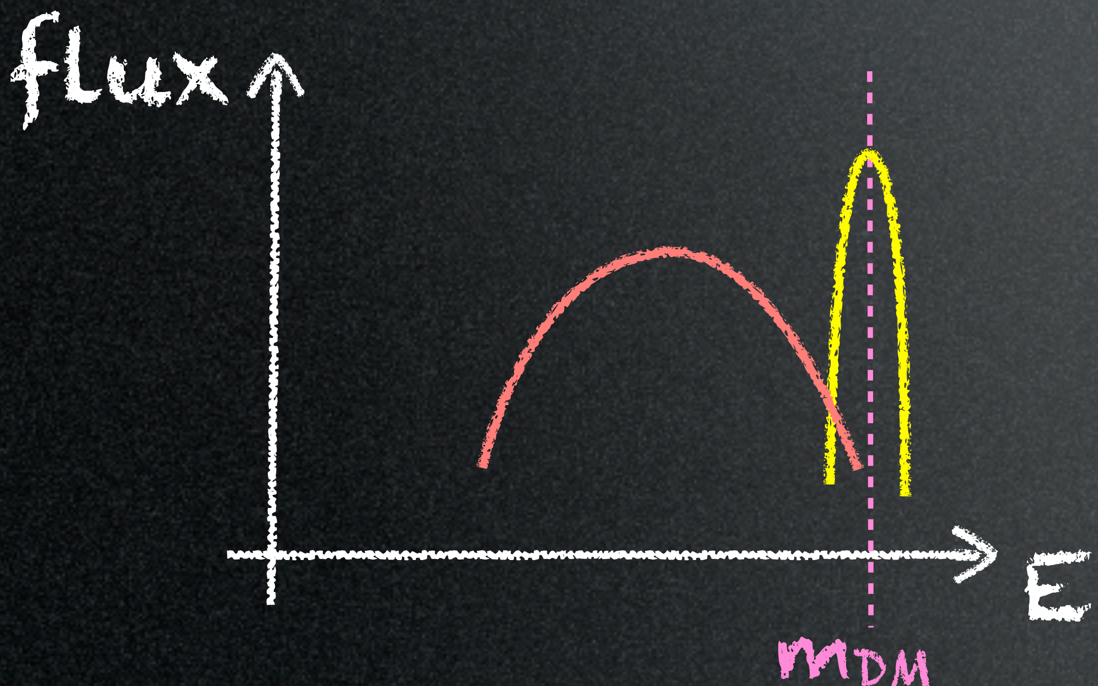

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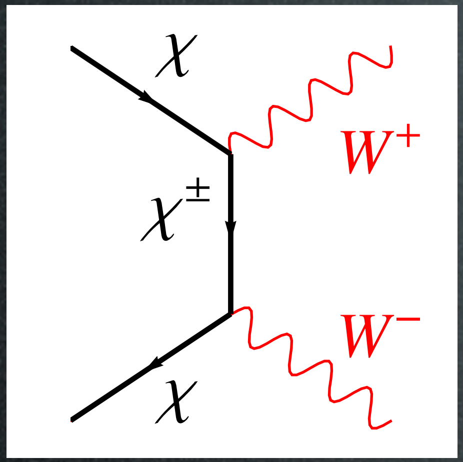


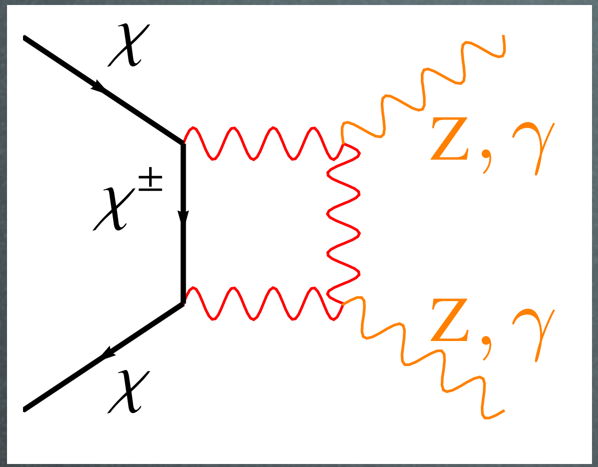


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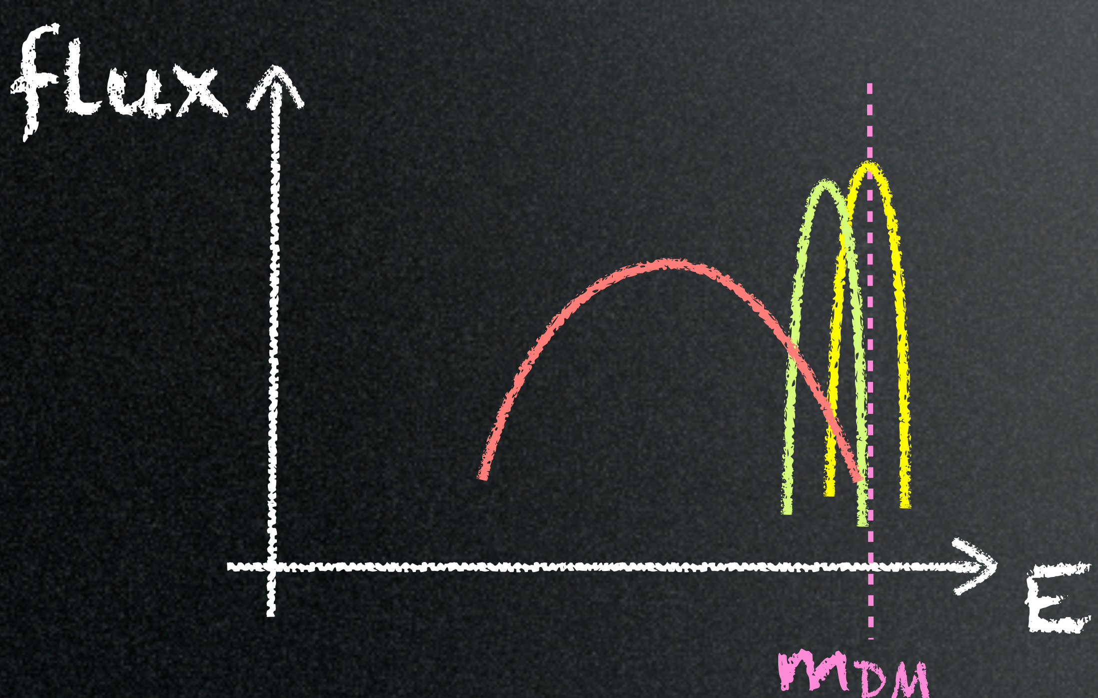

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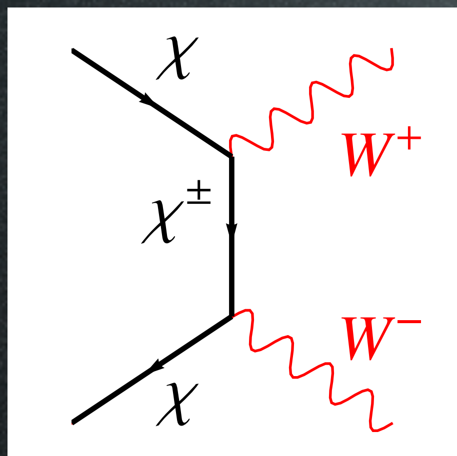


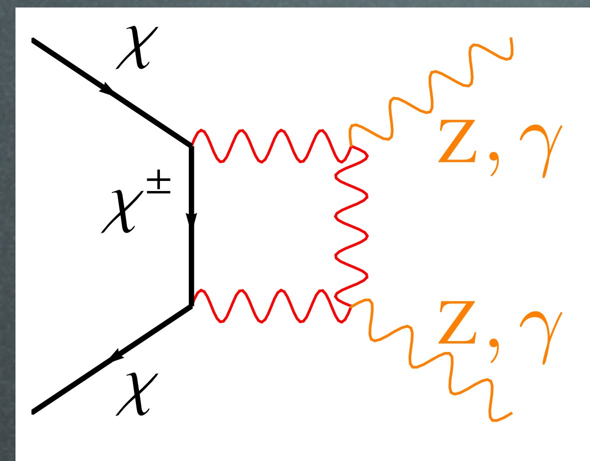


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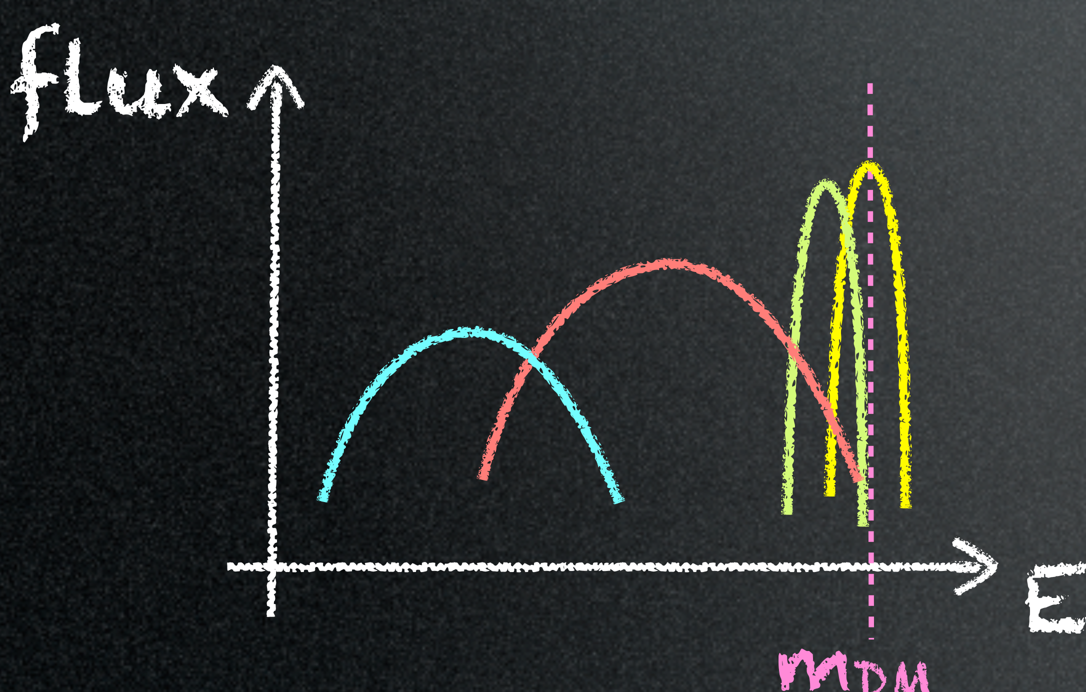

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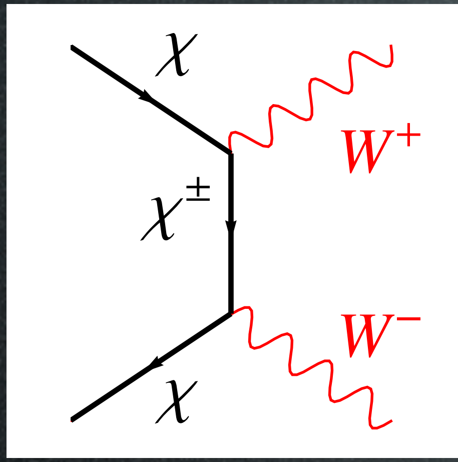


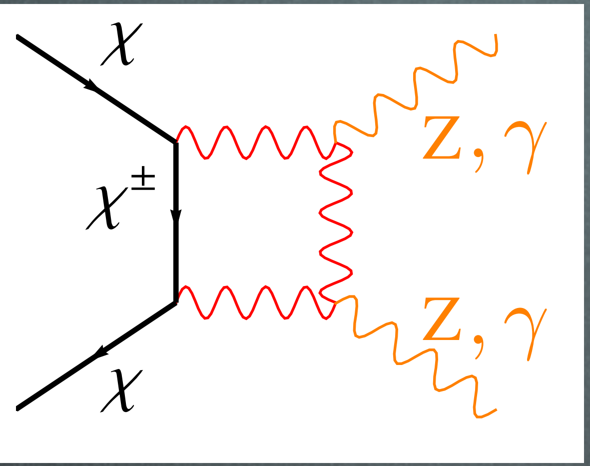


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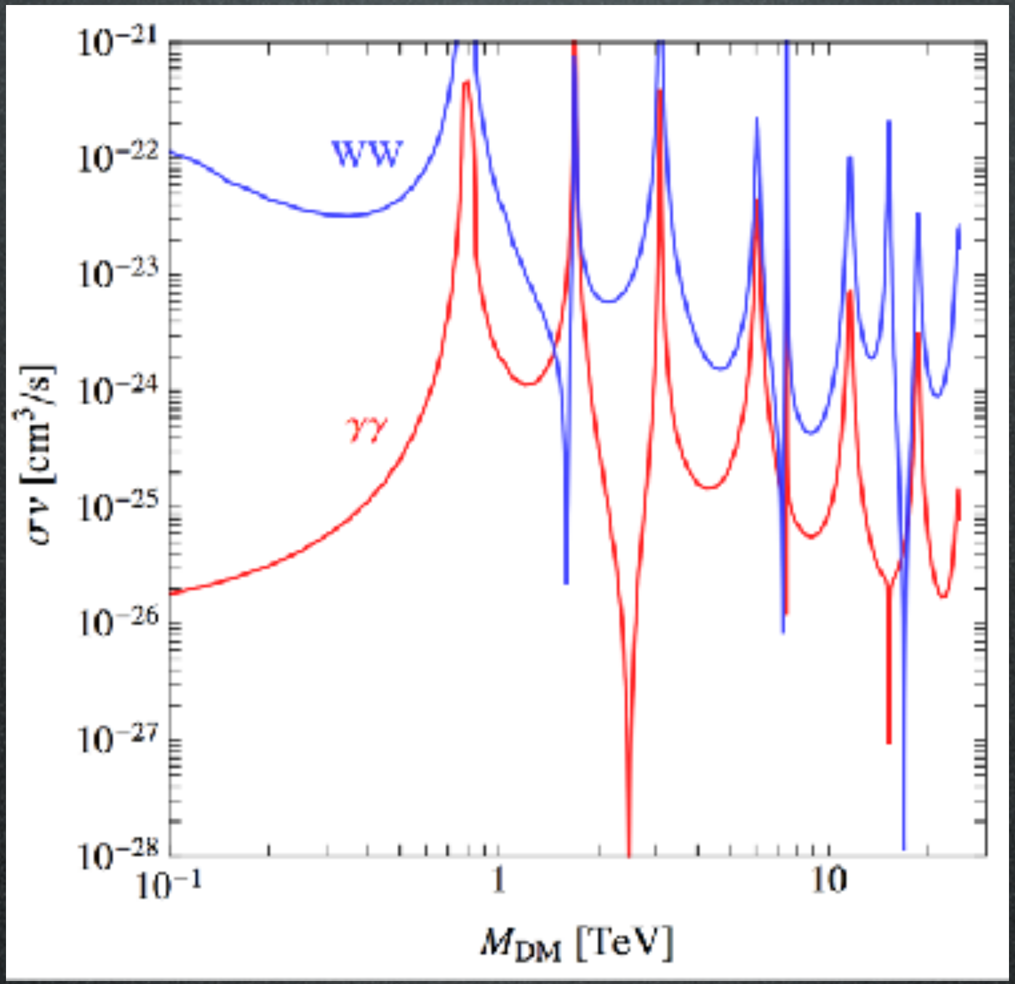
(channels for MDM with Y=0)

Enhanced cross section due to 'Sommerfeld corrections'

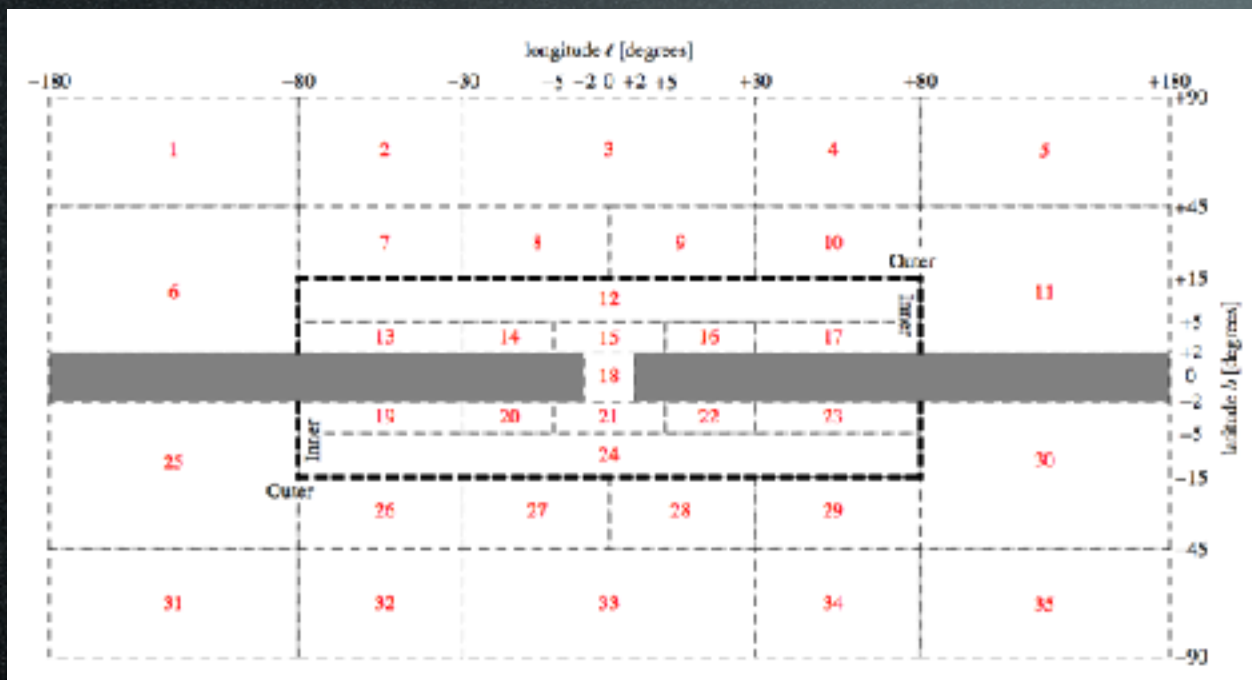
Hisano et al., 2004, 2005
Cirelli, Strumia, Tamburini 2007

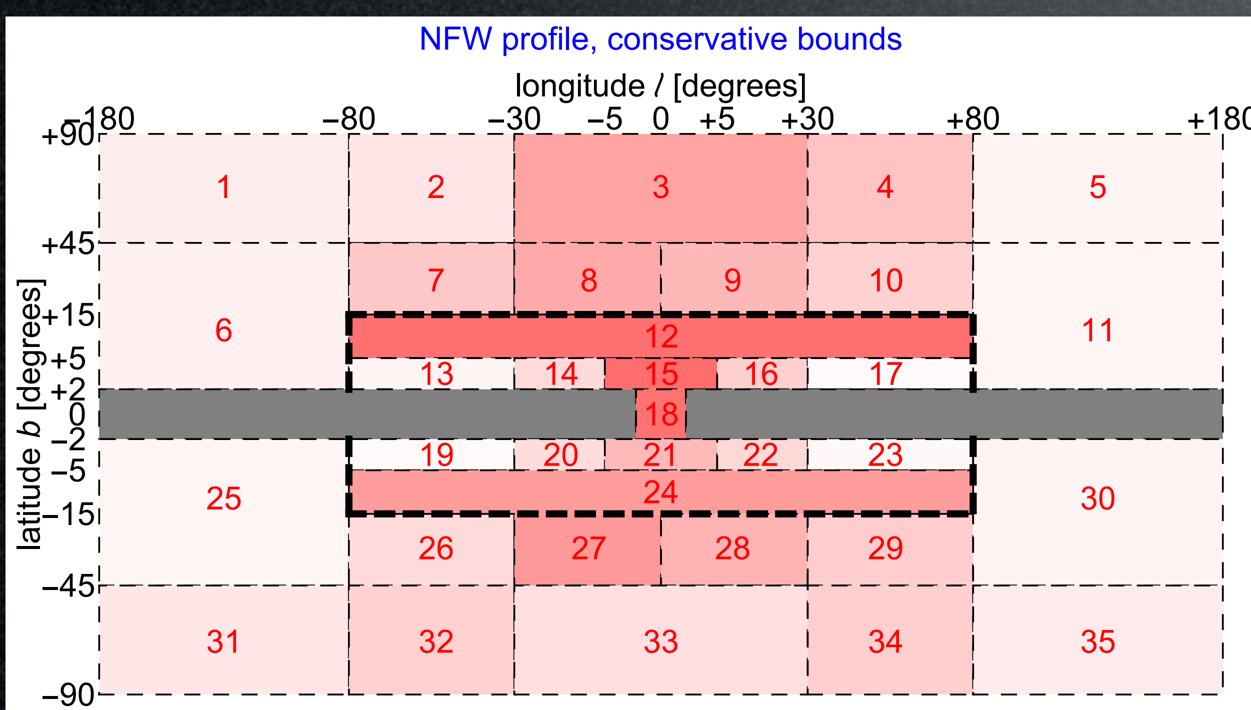


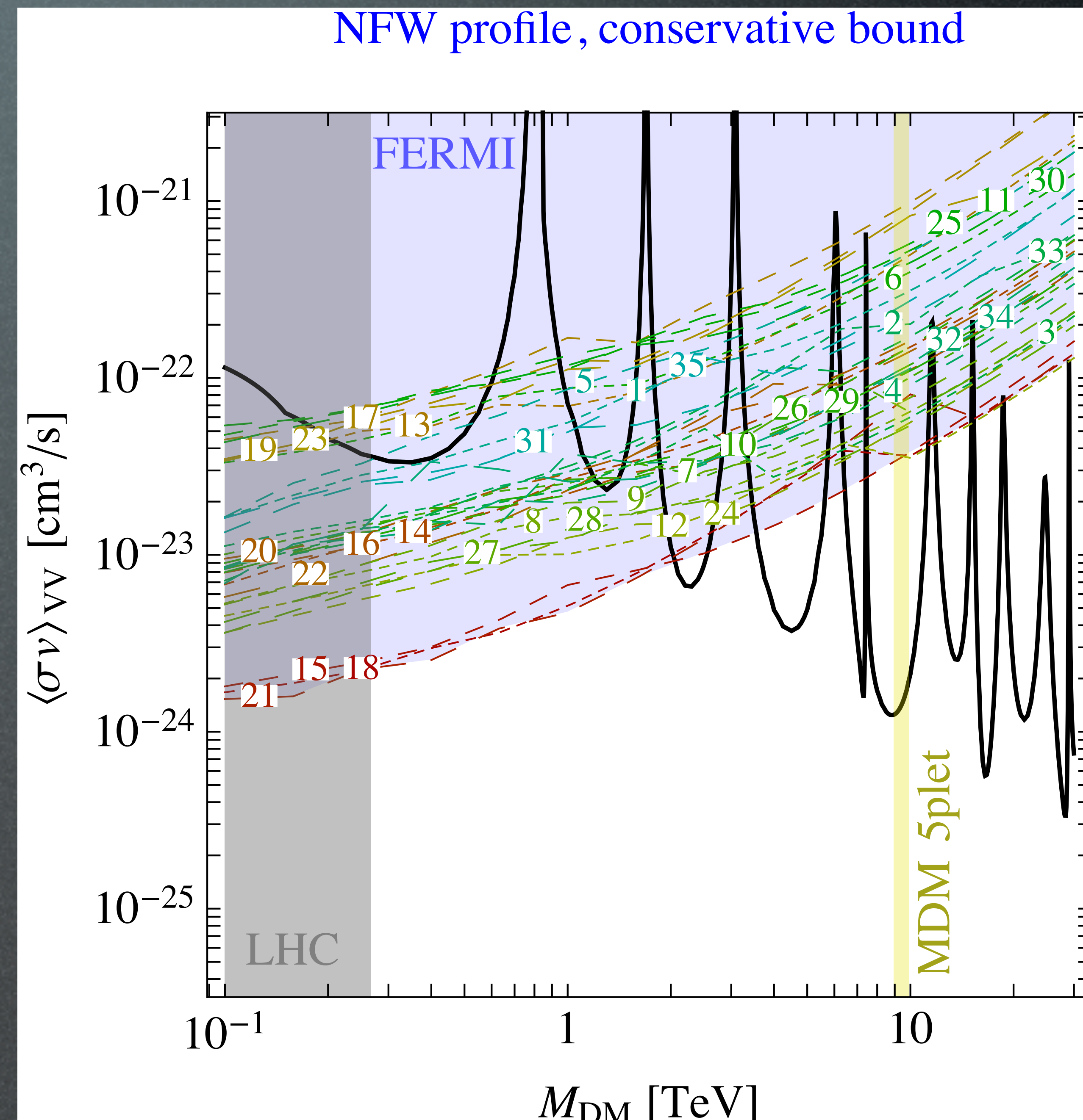

Cirelli, Hambye, Panci, Sala, Taoso
1507.05519

# Indirect Detection

## FERMI diffuse galactic:




Cirelli, Hambye, Panci, Sala, Taoso 1507.05519

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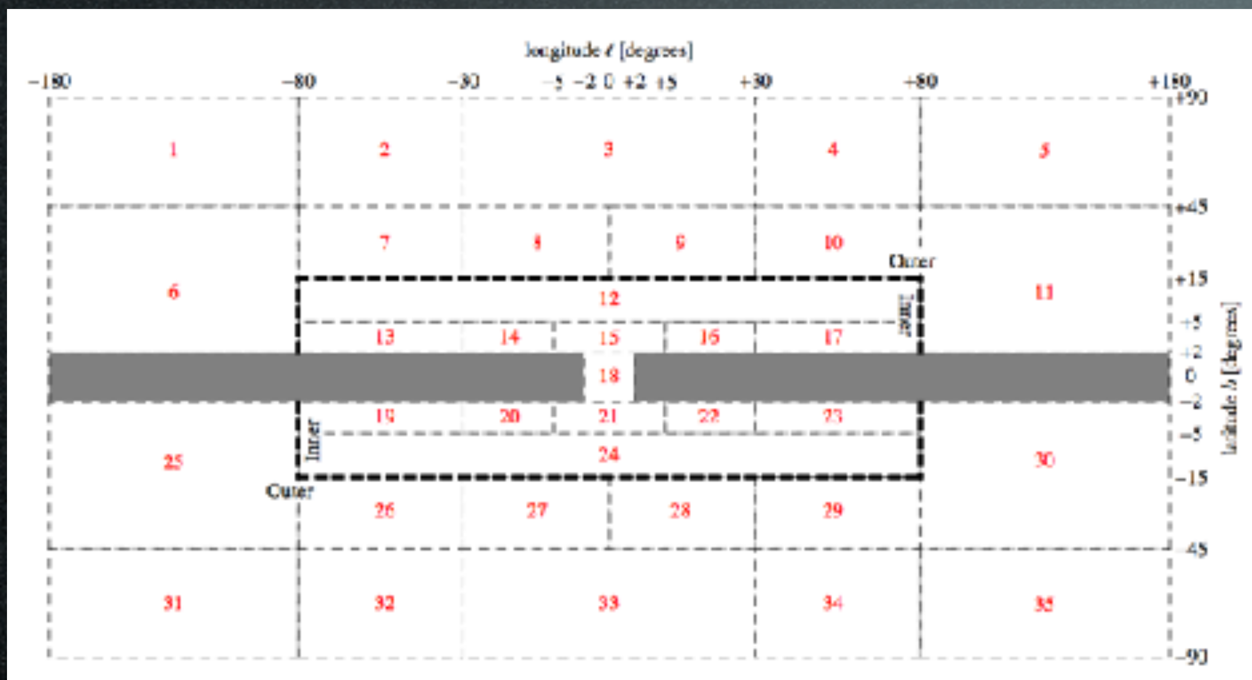

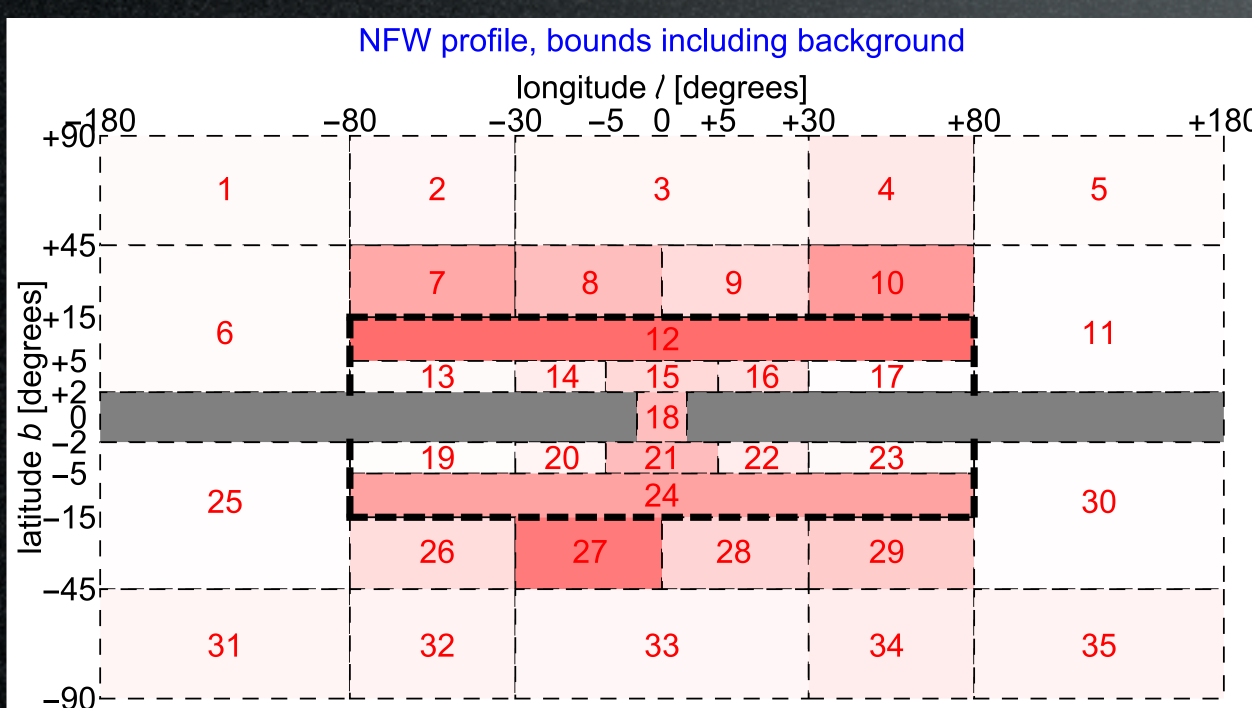


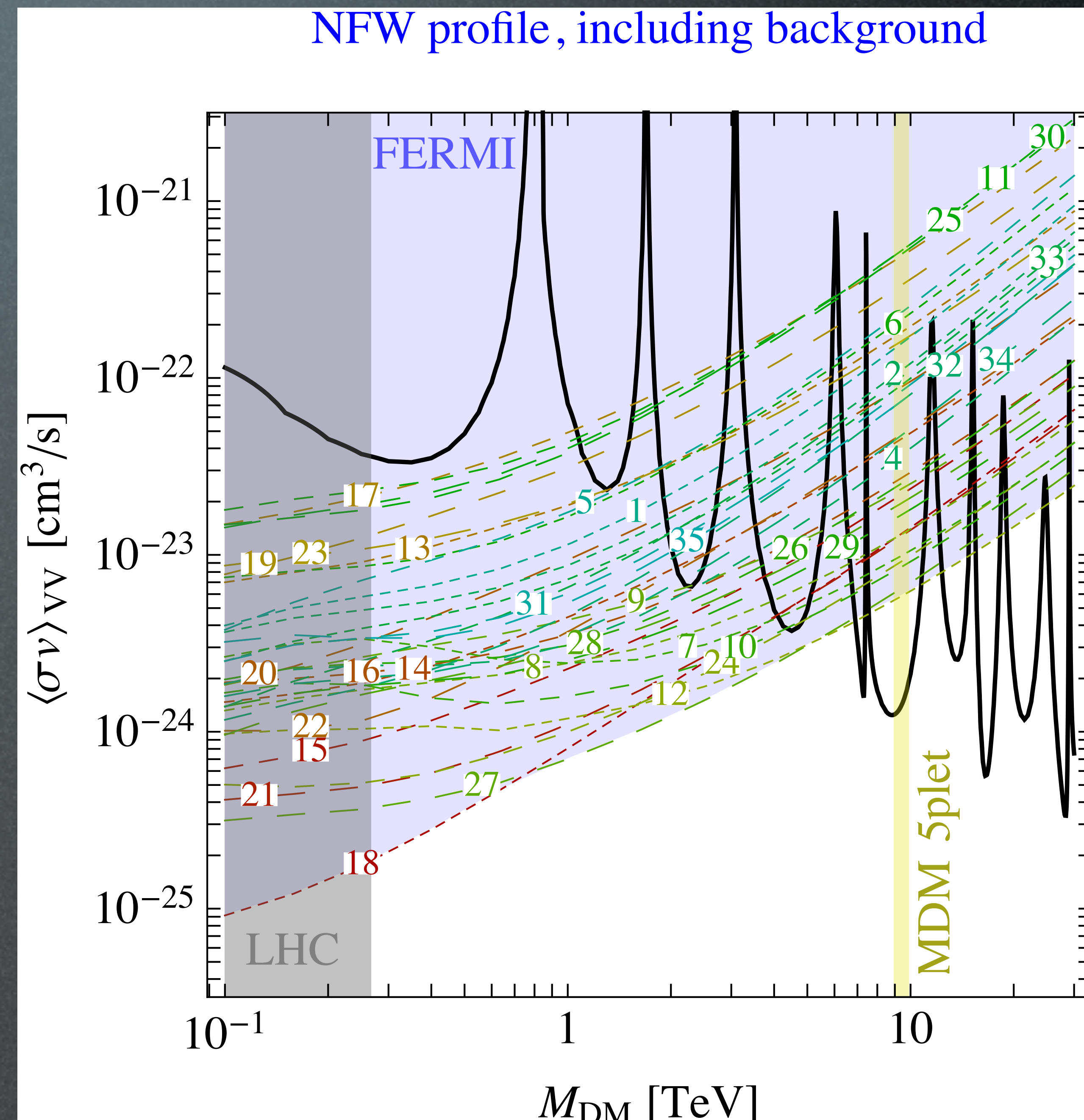


Cirelli, Hambye, Panci, Sala, Taoso 1507.05519

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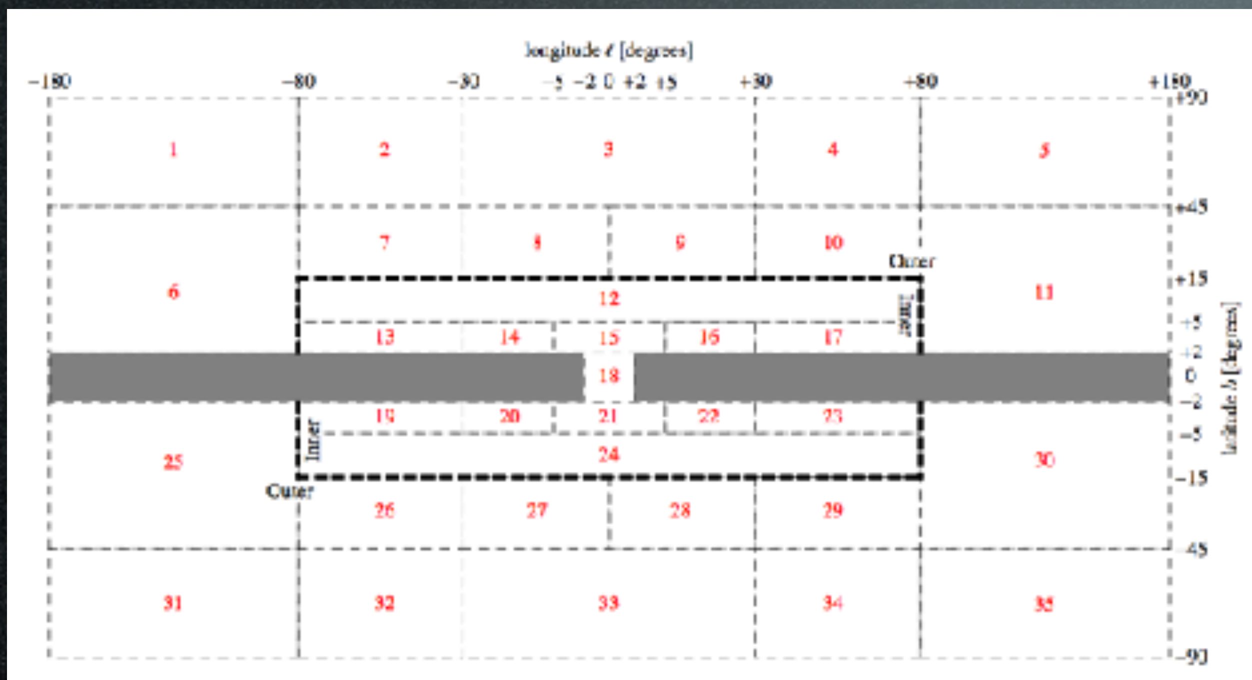


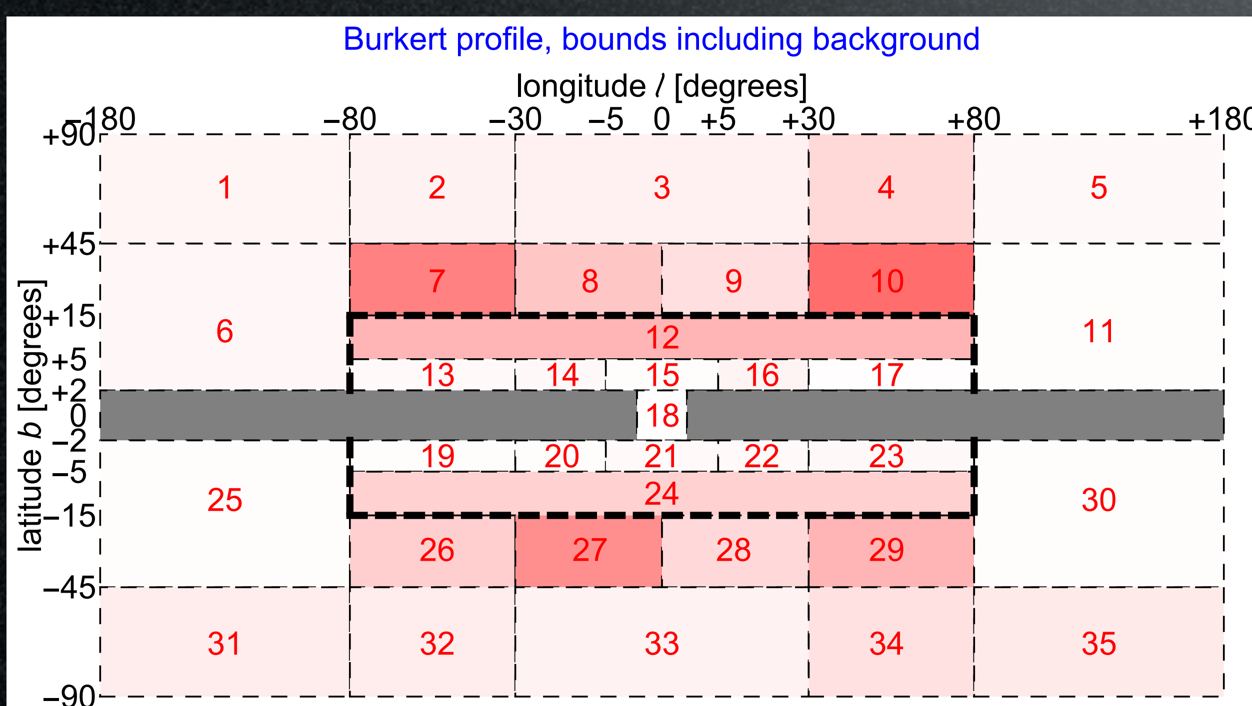


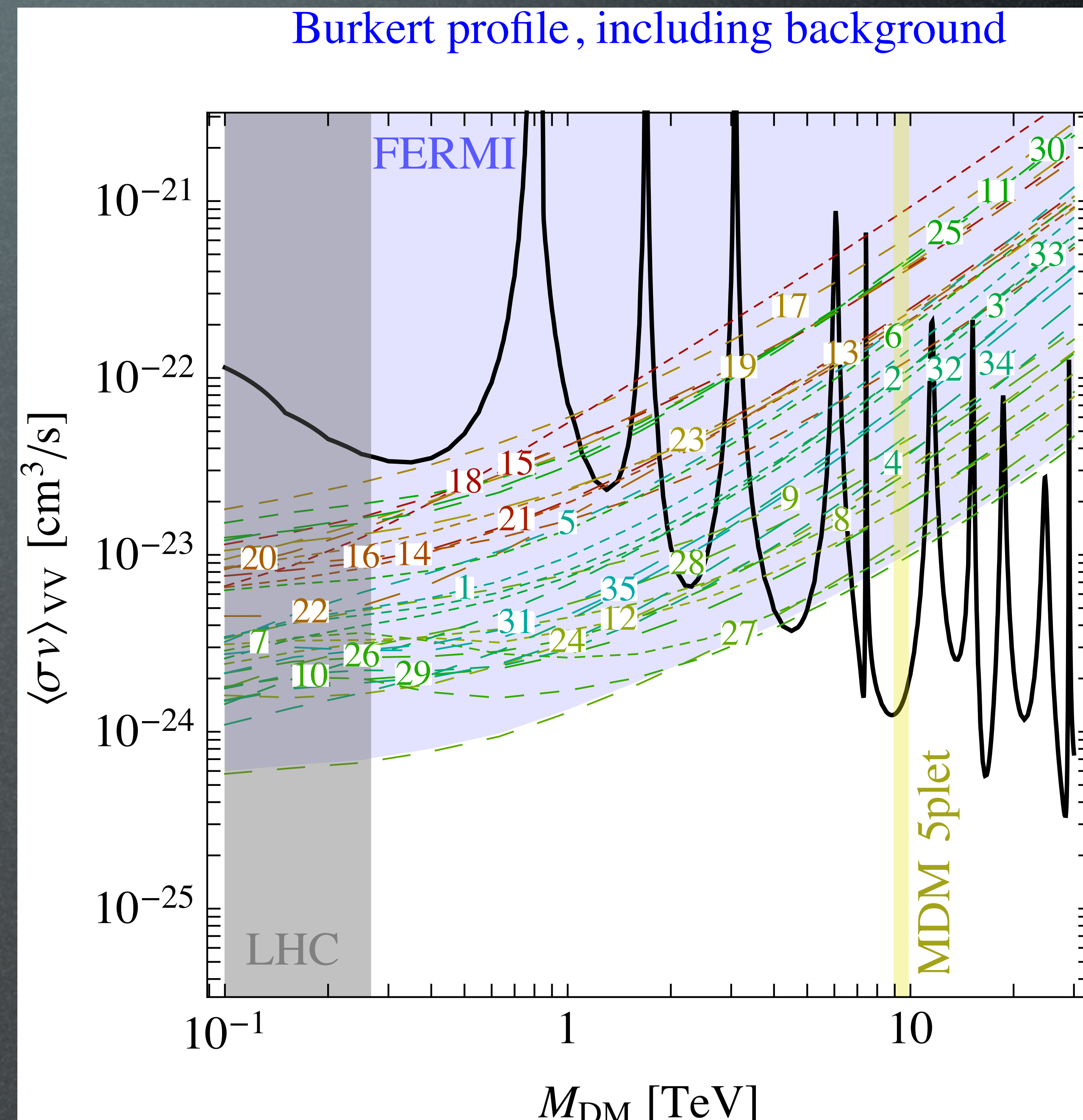


Cirelli, Hambye, Panci, Sala, Taoso 1507.05519

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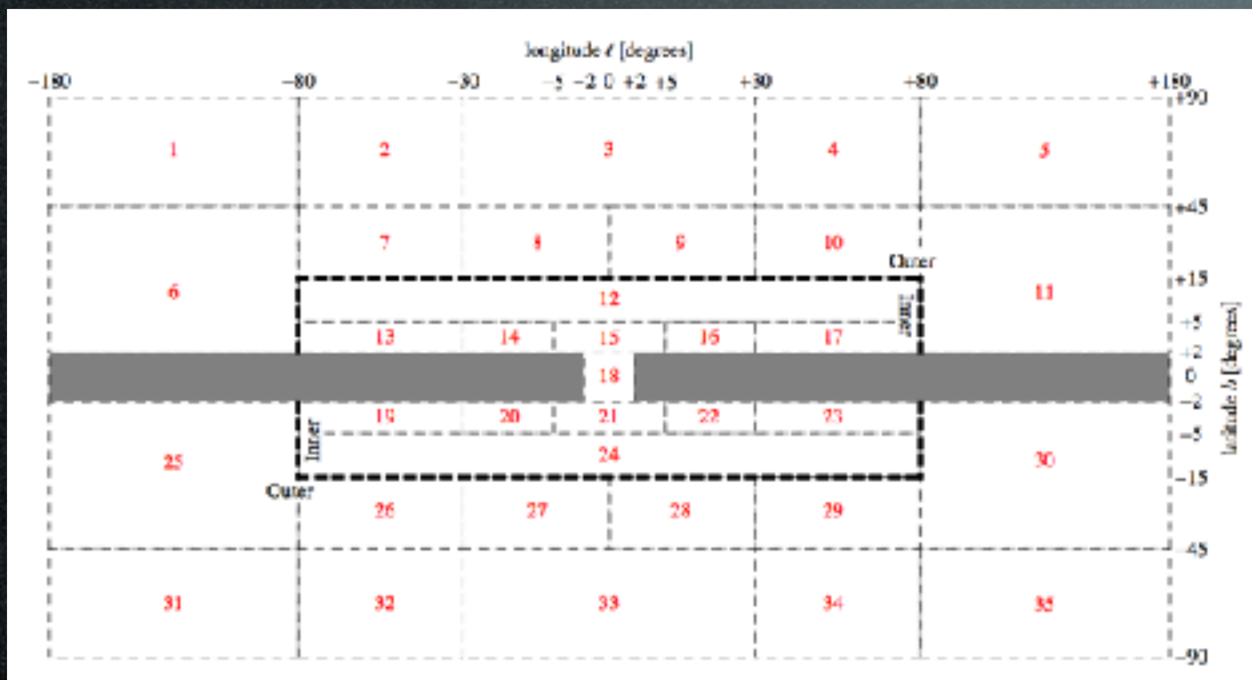
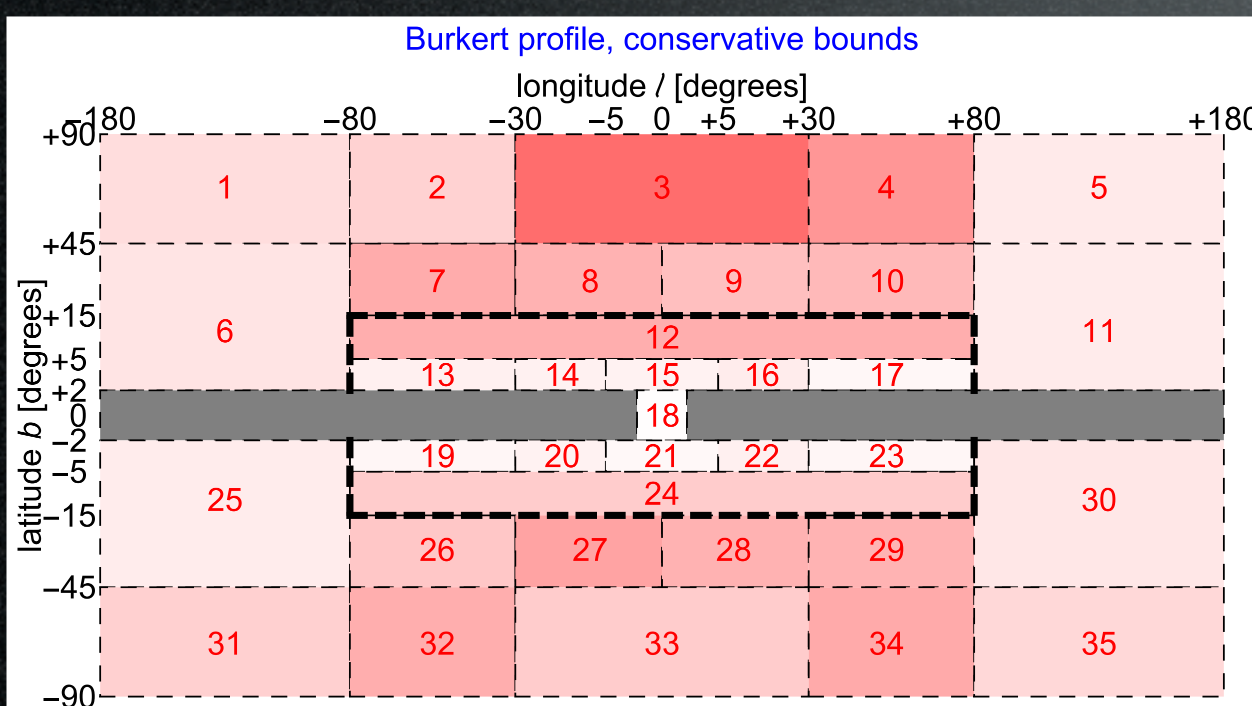
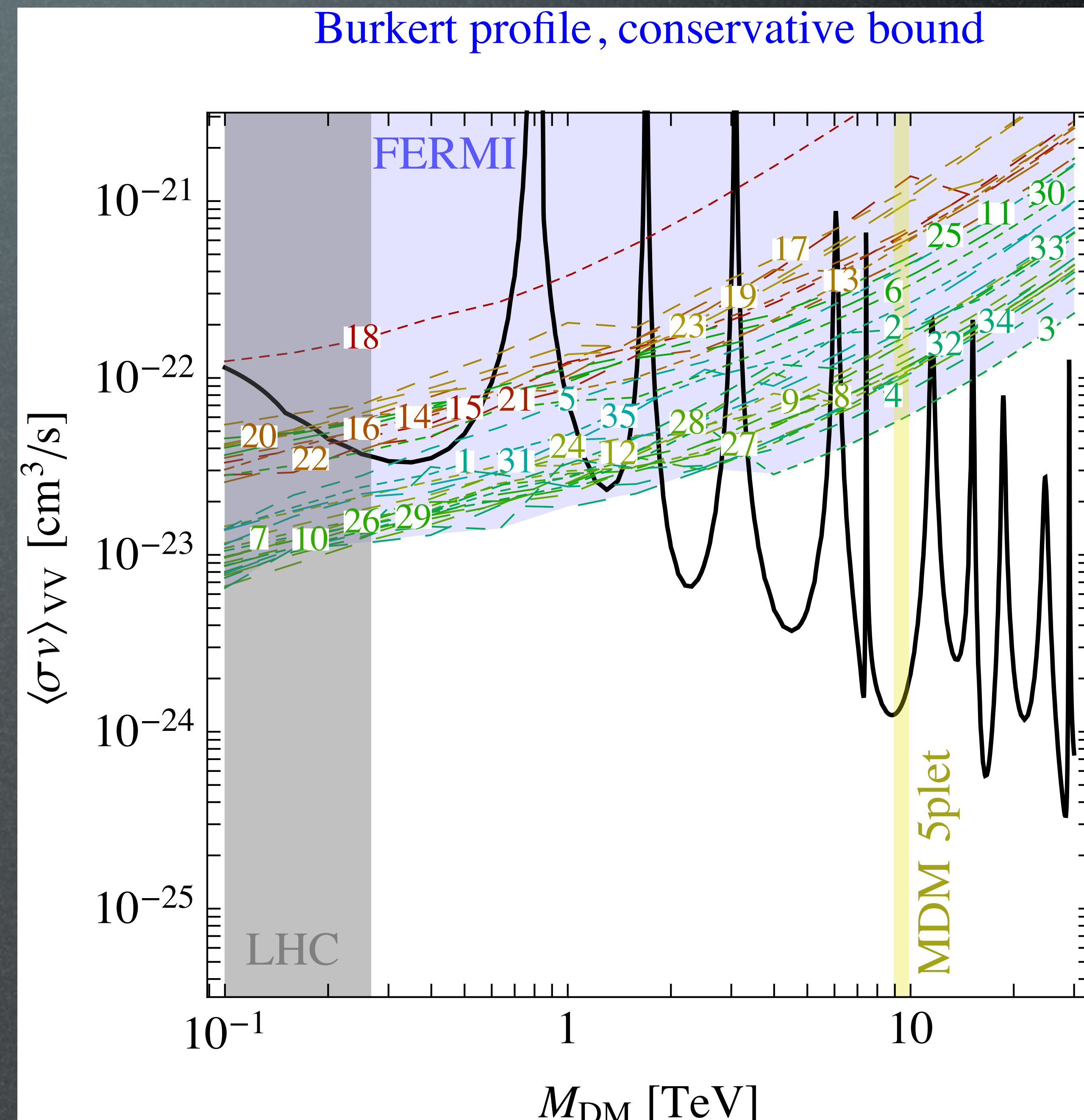



Cirelli, Hambye, Panci, Sala, Taoso 1507.05519

→ relevant constraints but MDM 5plet not probed

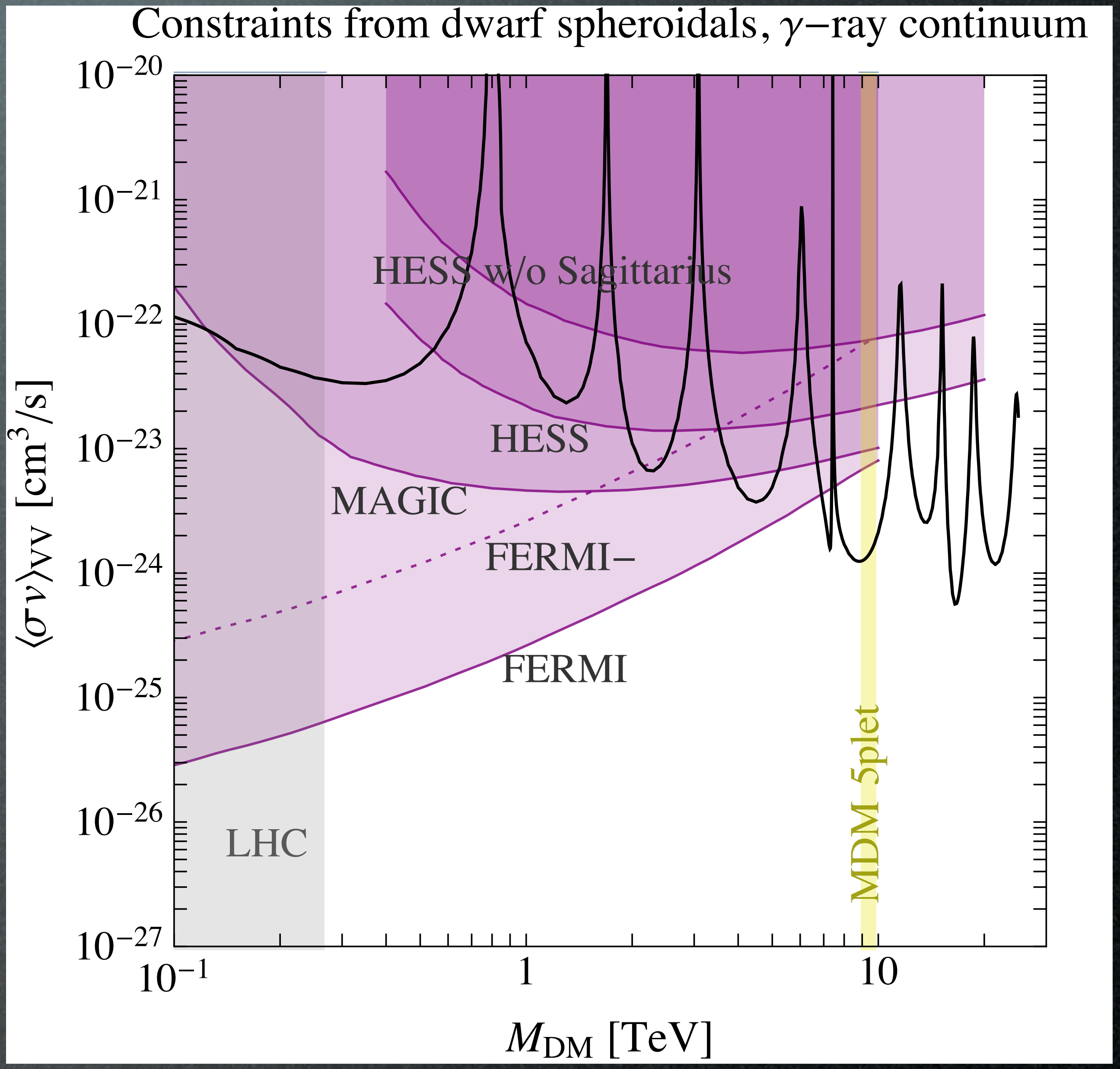
# Indirect Detection

## dSphs galaxies, search for continuum $\gamma$-rays:

FERMI: 15 dSphs, 6yrs, 'Pass-8' - 1503.02641

HESS: 4 dSphs, incl Sagittarius - 1410.2589

MAGIC: Segue1 - 1312.1535




Cirelli, Hambye, Panci, Sala, Taoso 1507.05519

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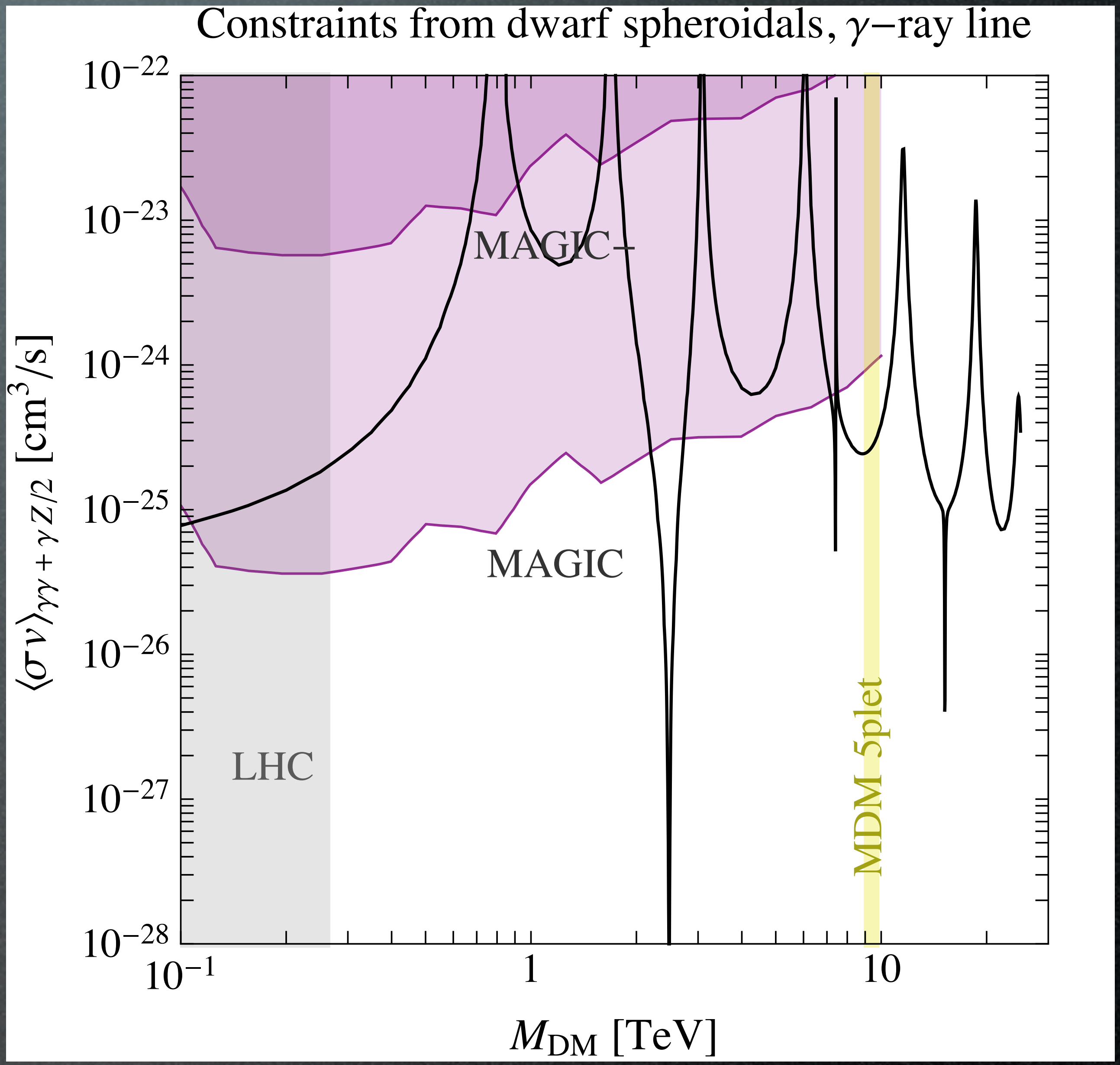
# Indirect Detection

## dSphs galaxies, search for $\gamma$-ray lines:

MAGIC: Segue1 - 1312.1535




Cirelli, Hambye, Panci, Sala, Taoso 1507.05519

NB large uncertainties in dSPhs 'J factor', i.e. DM-brightness

e.g. Bonnivard et al., 1504.02048

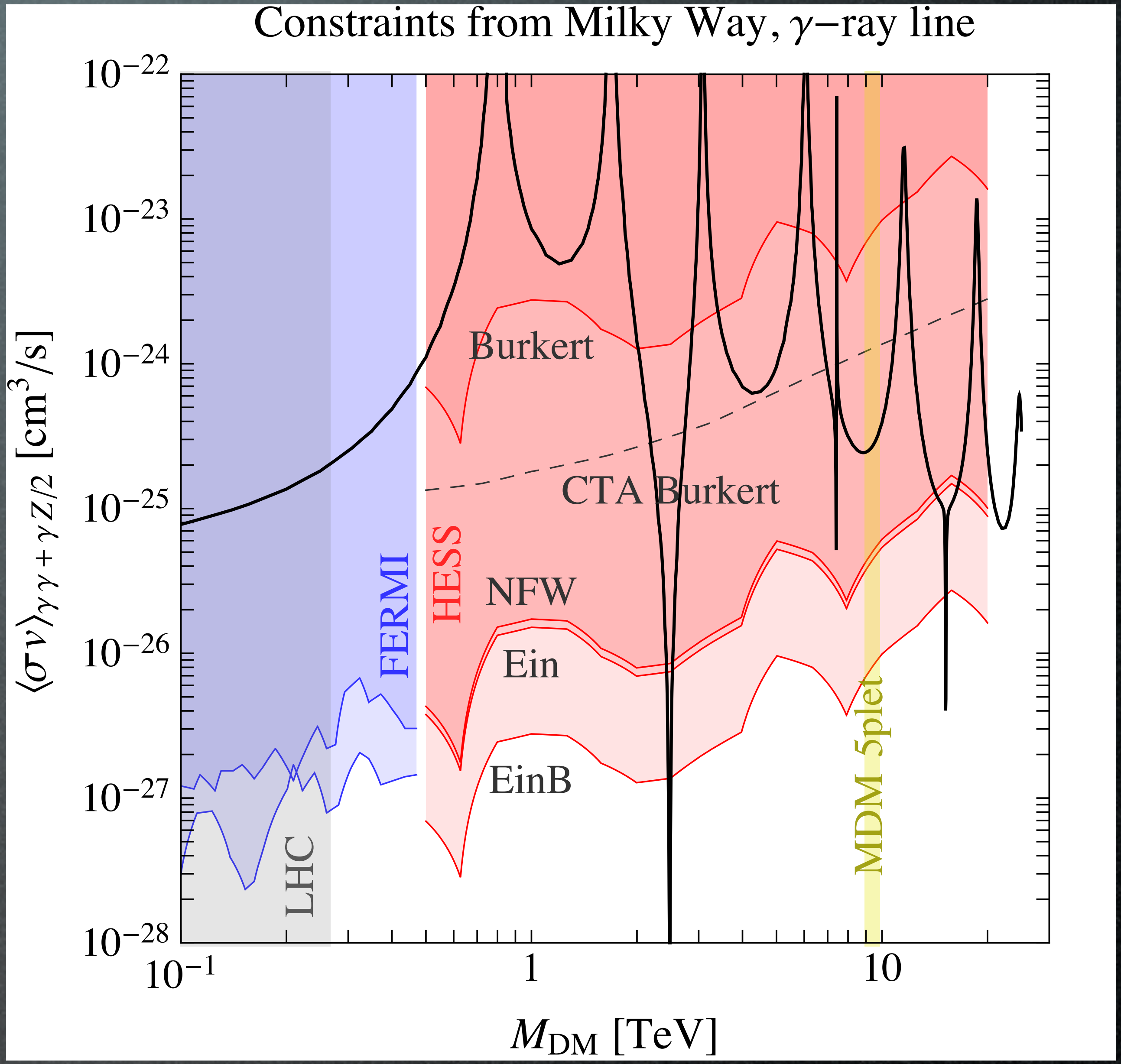
relevant constraints but MDM 5plet not probed

# Indirect Detection

MW center area, search for $\gamma$-ray lines:

FERMI: 1506.00013

HESS: 1301.1173




Cirelli, Hambye, Panci, Sala, Taoso 1507.05519

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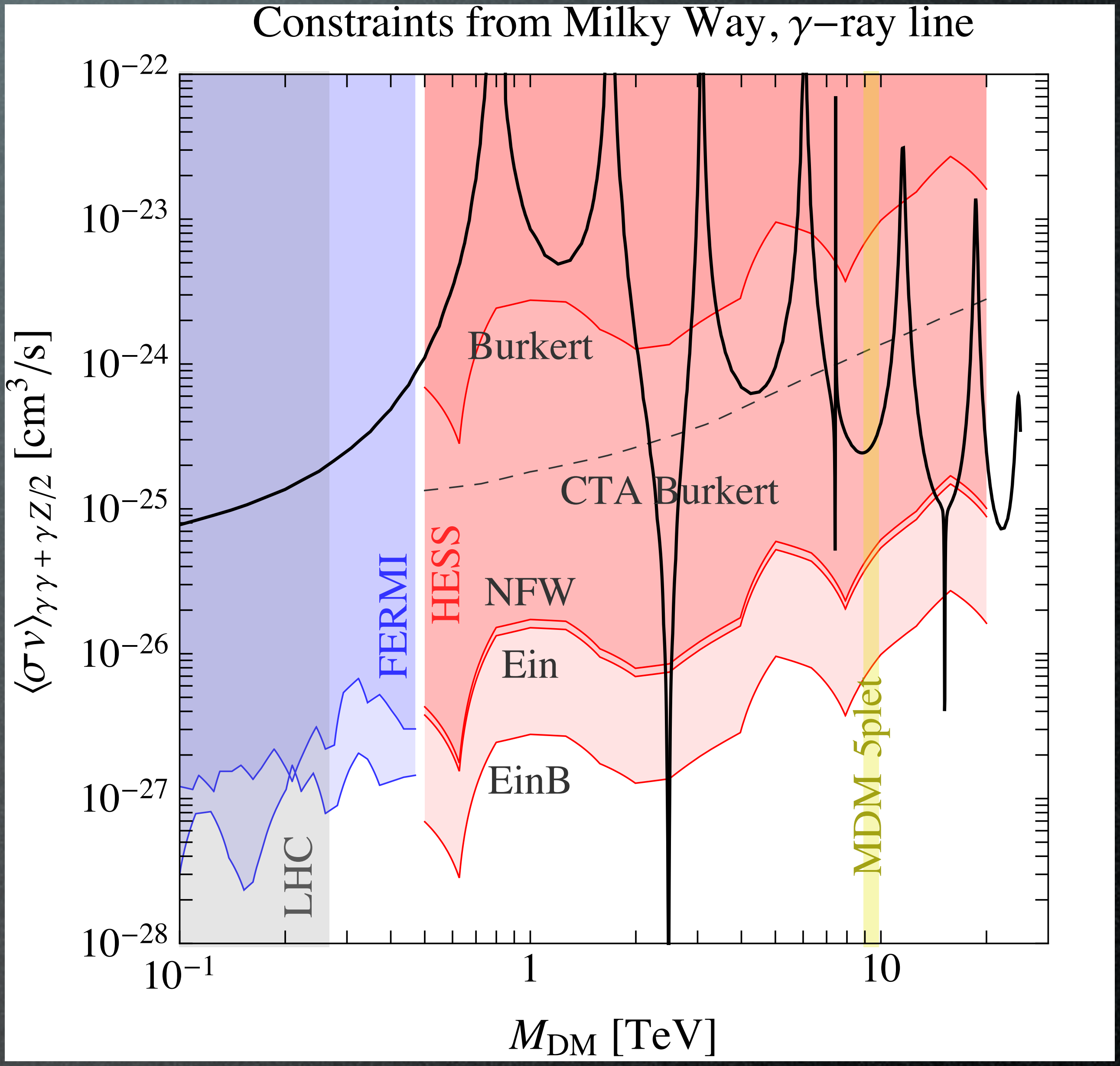
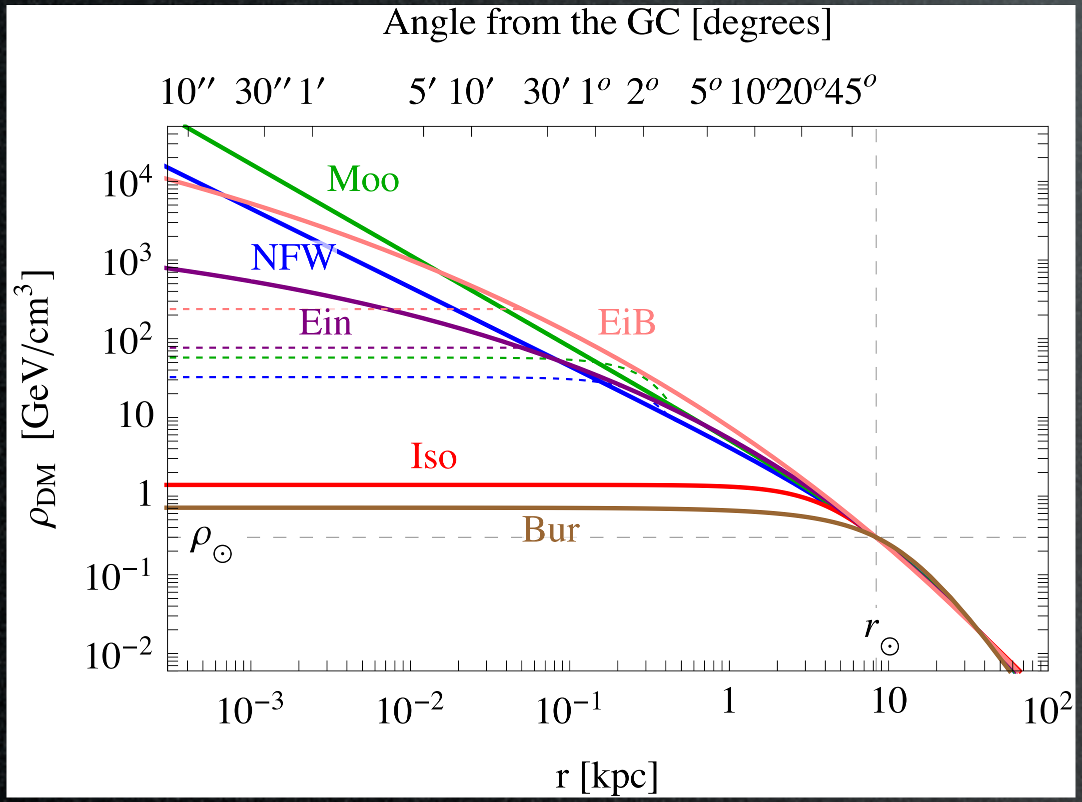



Cirelli, Hambye, Panci, Sala, Taoso 1507.05519

## Uncertainties in DM profile:




e.g. Cirelli et al., 1012.4515

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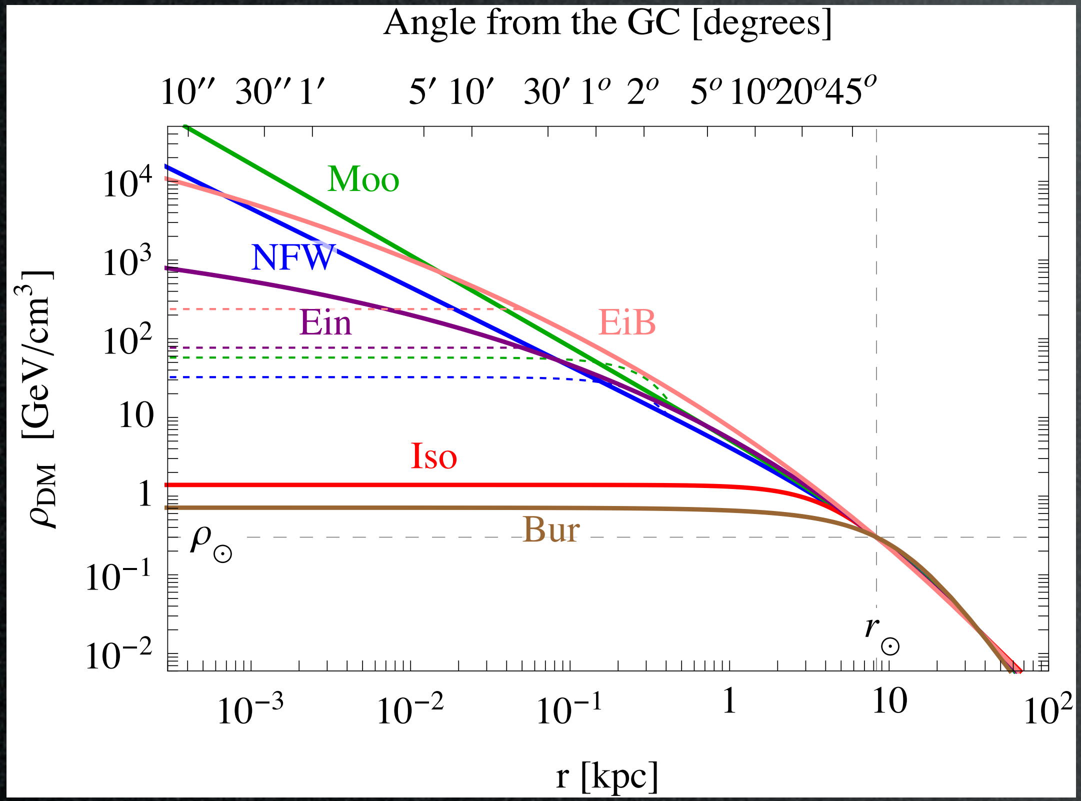


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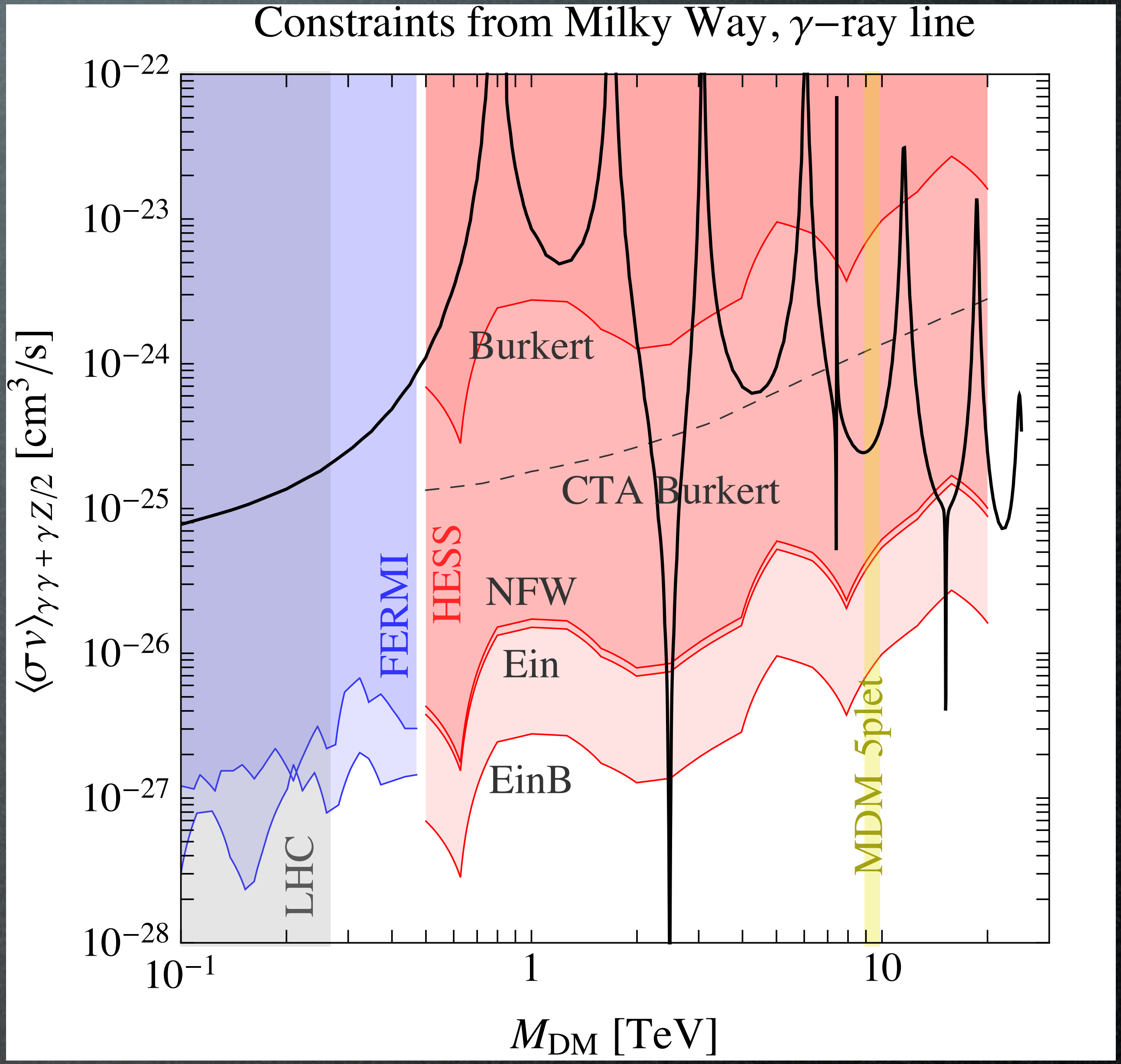


Cirelli, Hambye, Panci, Sala, Taoso 1507.05519

MDM excluded if cuspy

MDM not probed if cored

Consistent conclusions in: Garcia-Cely et al. 1507.05536

# Post scriptum

Bound state formation is relevant

Pospelov, Ritz 2009
March-Russell, West 2009
Shepherd, Tait, Zaharijas 2009
K.Petraki+, 2014+

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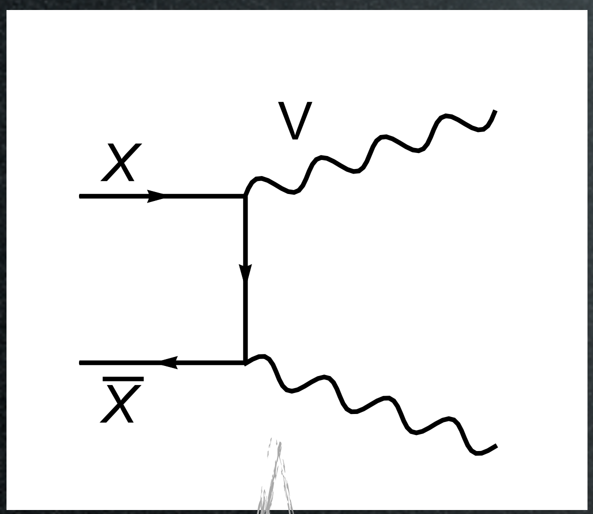


tree level annihilation

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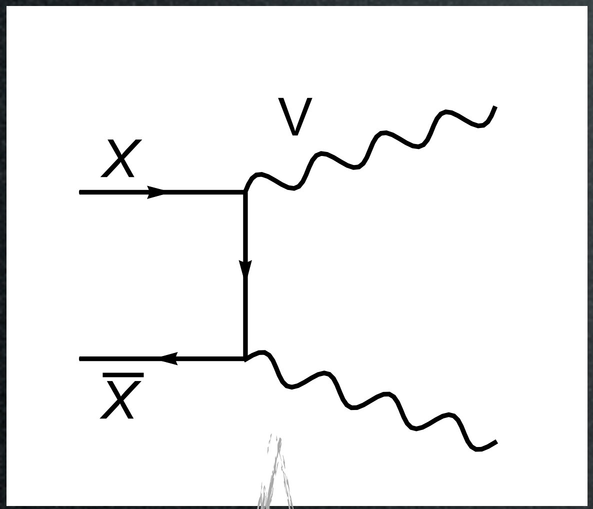


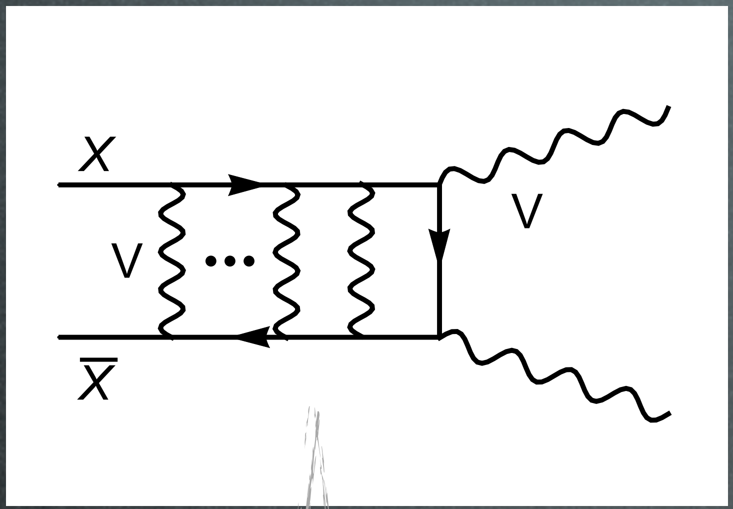


tree level annihilation

size of the XX system

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

range

Sommerfeld enhanced

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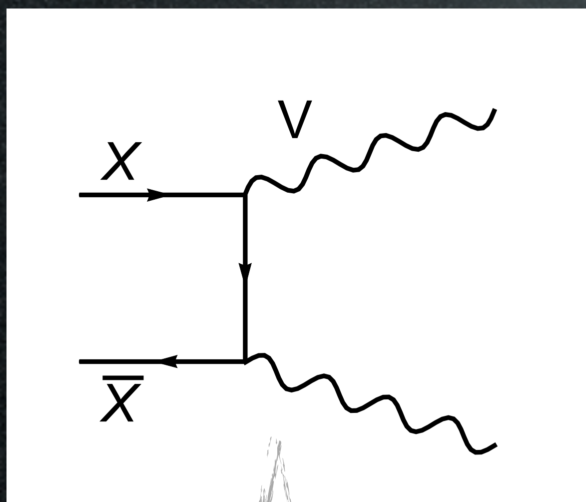


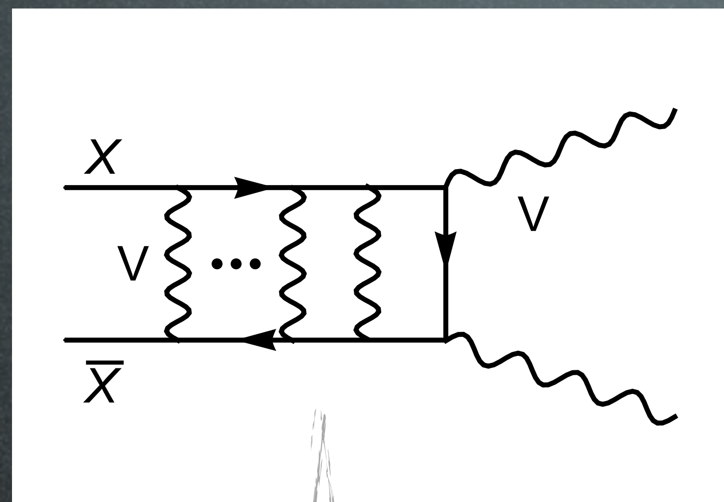


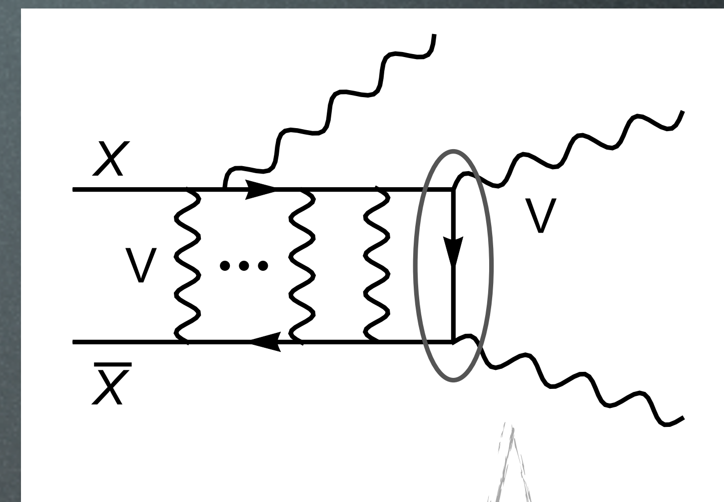


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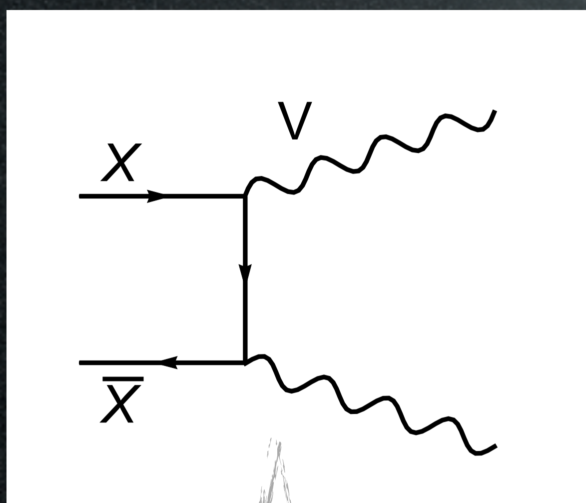


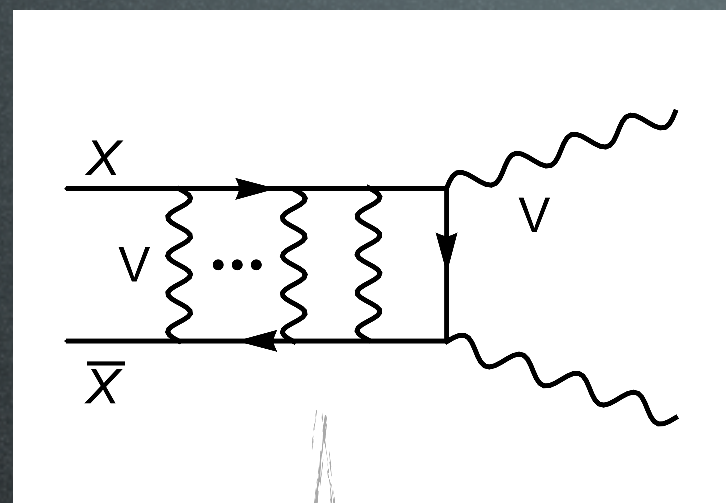


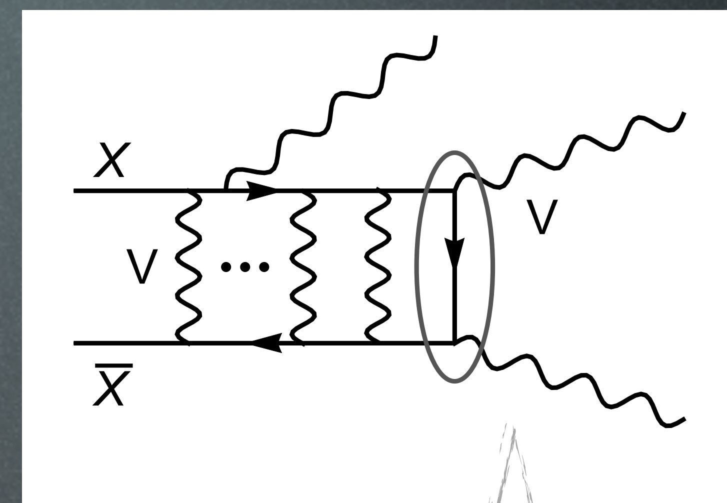


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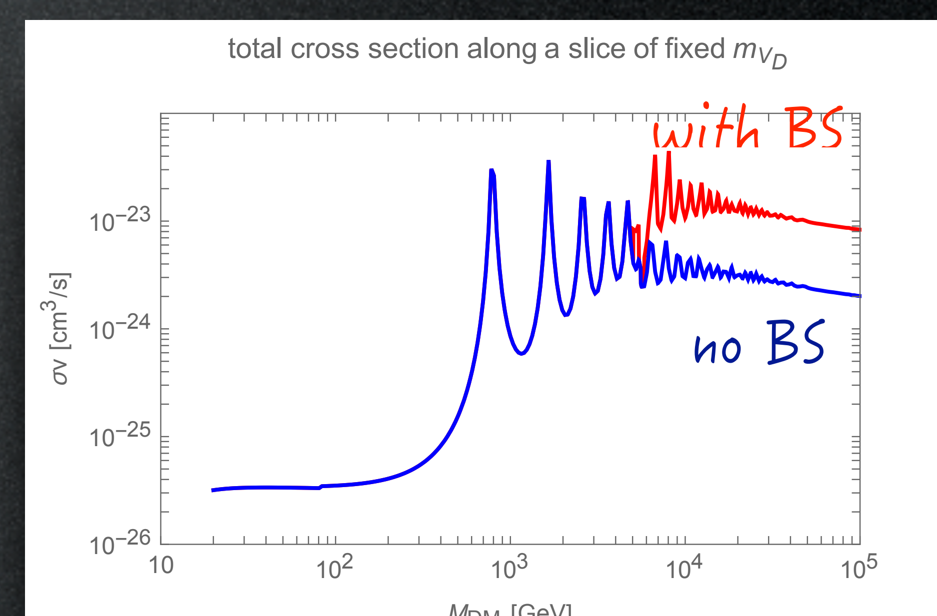

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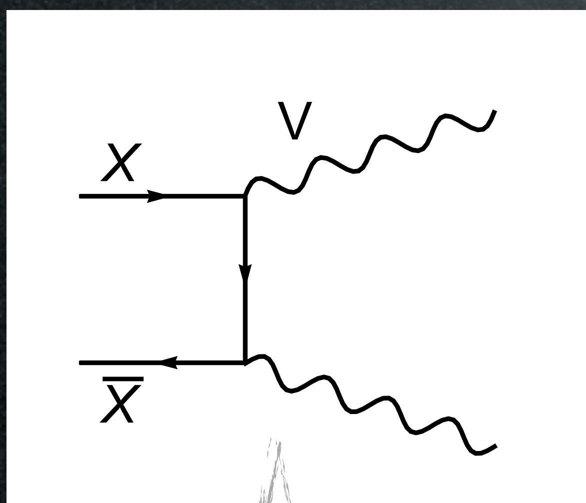
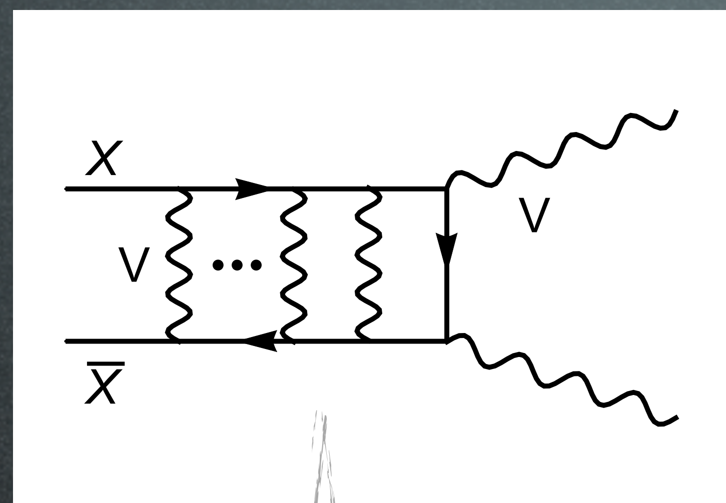
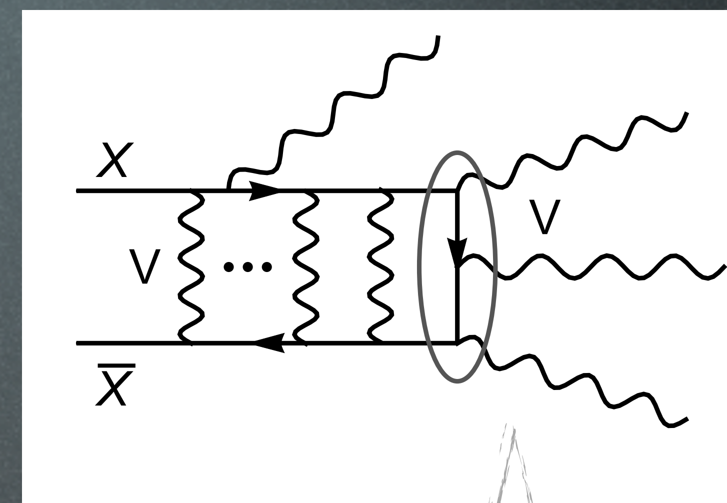



tree level annihilation

size of the XX system

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

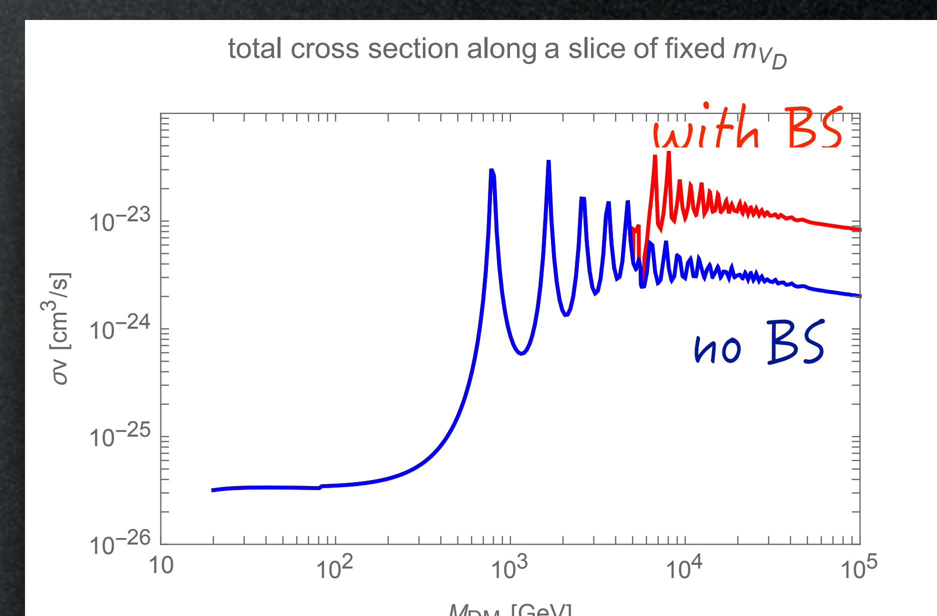
range

Sommerfeld enhanced

binding energy of the XX system

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

emitted mediator

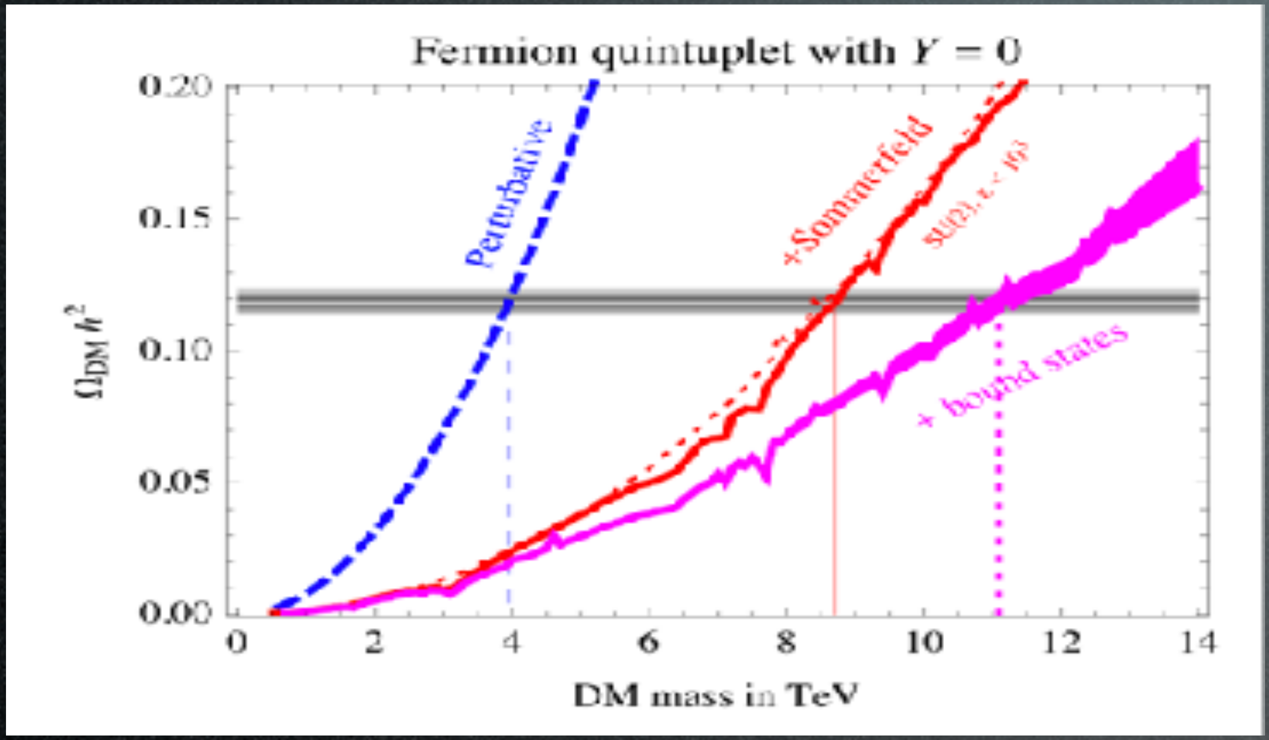


# Post scriptum

Bound state formation

Mitridate, Redi, Smirnov, Strumia 1702.01141

impact on thermal mass and indirect detection



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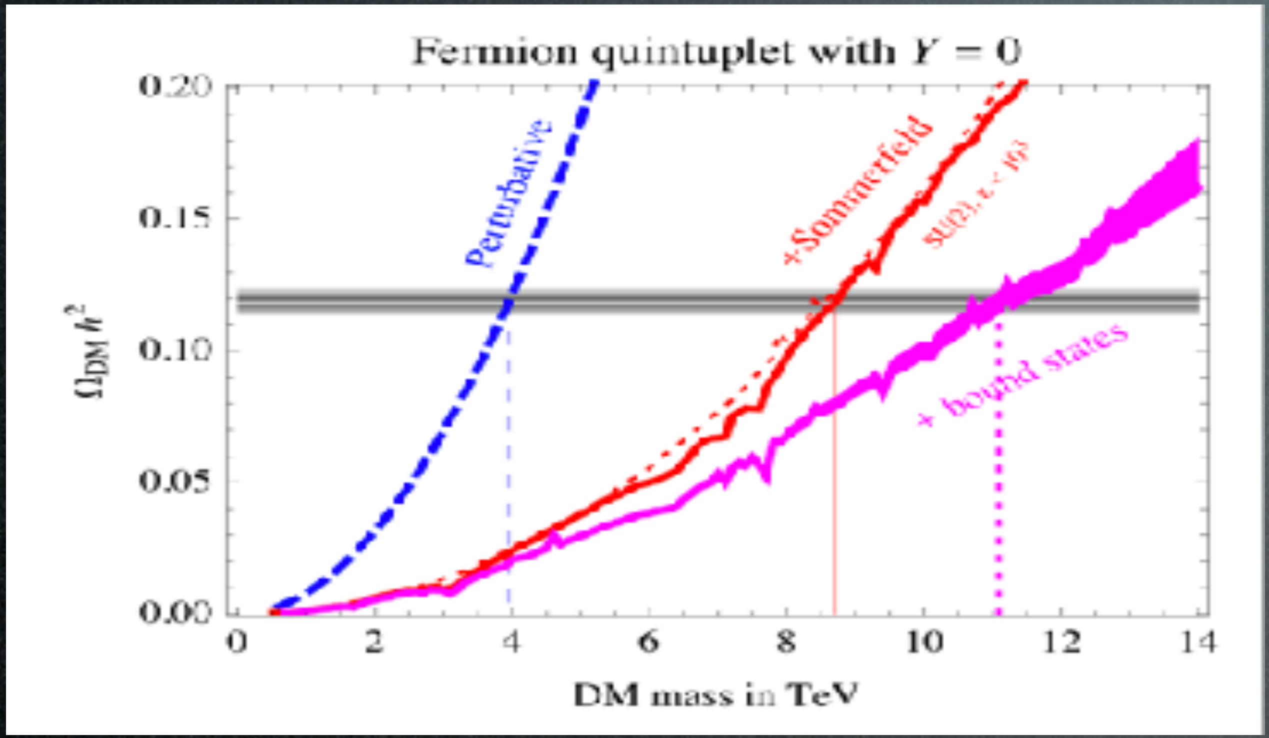


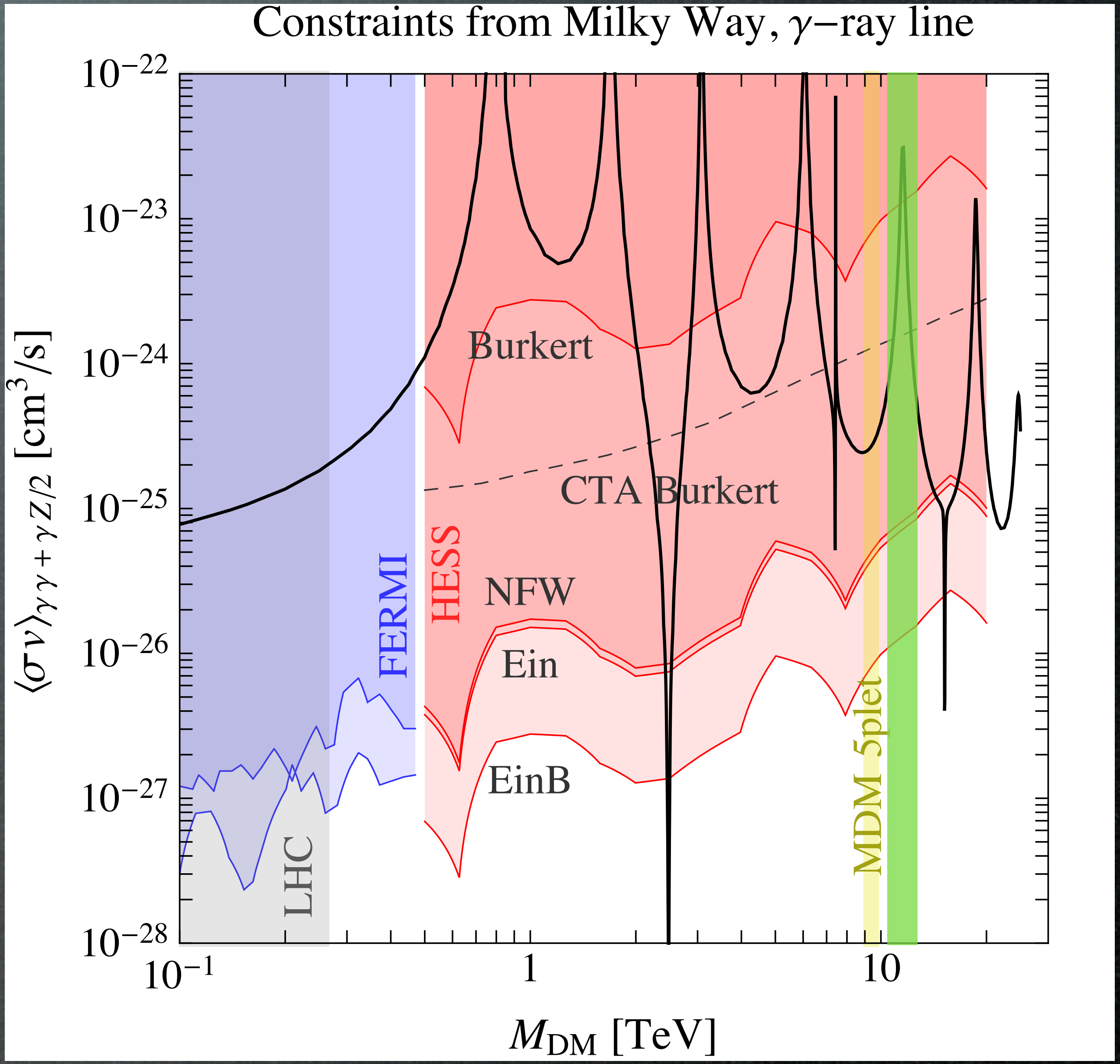

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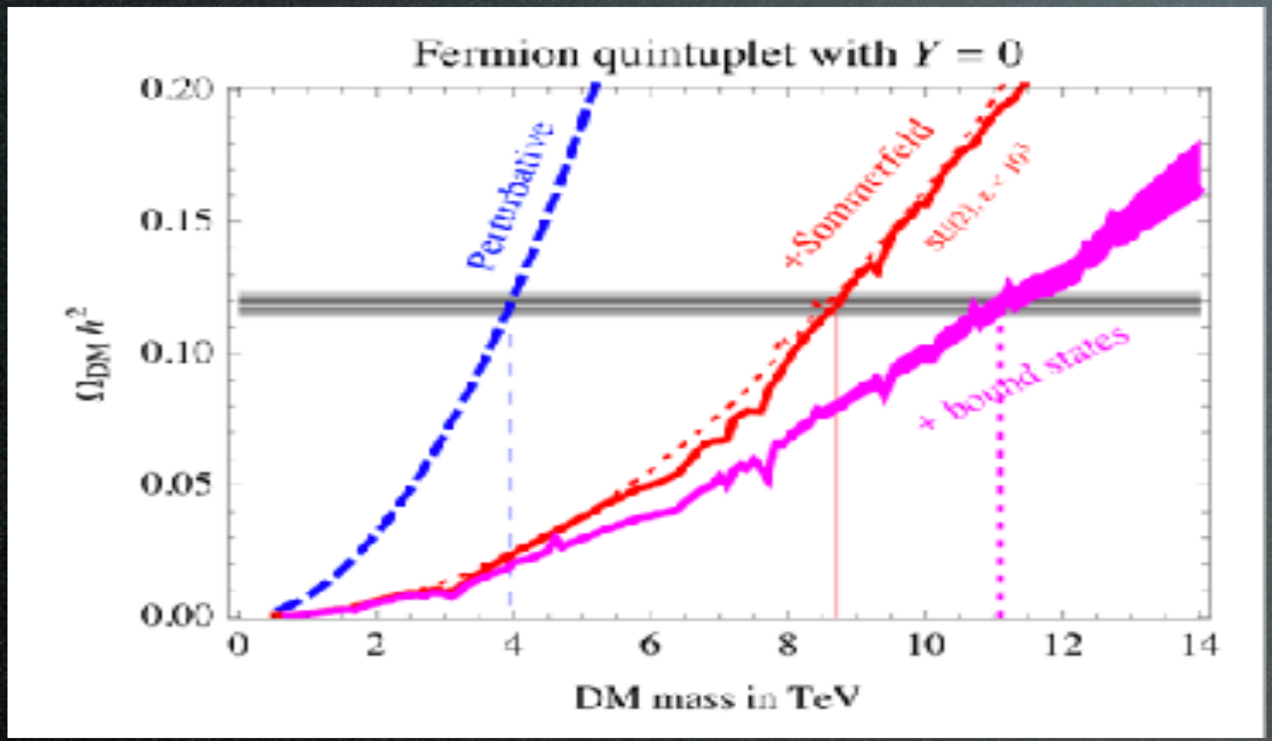
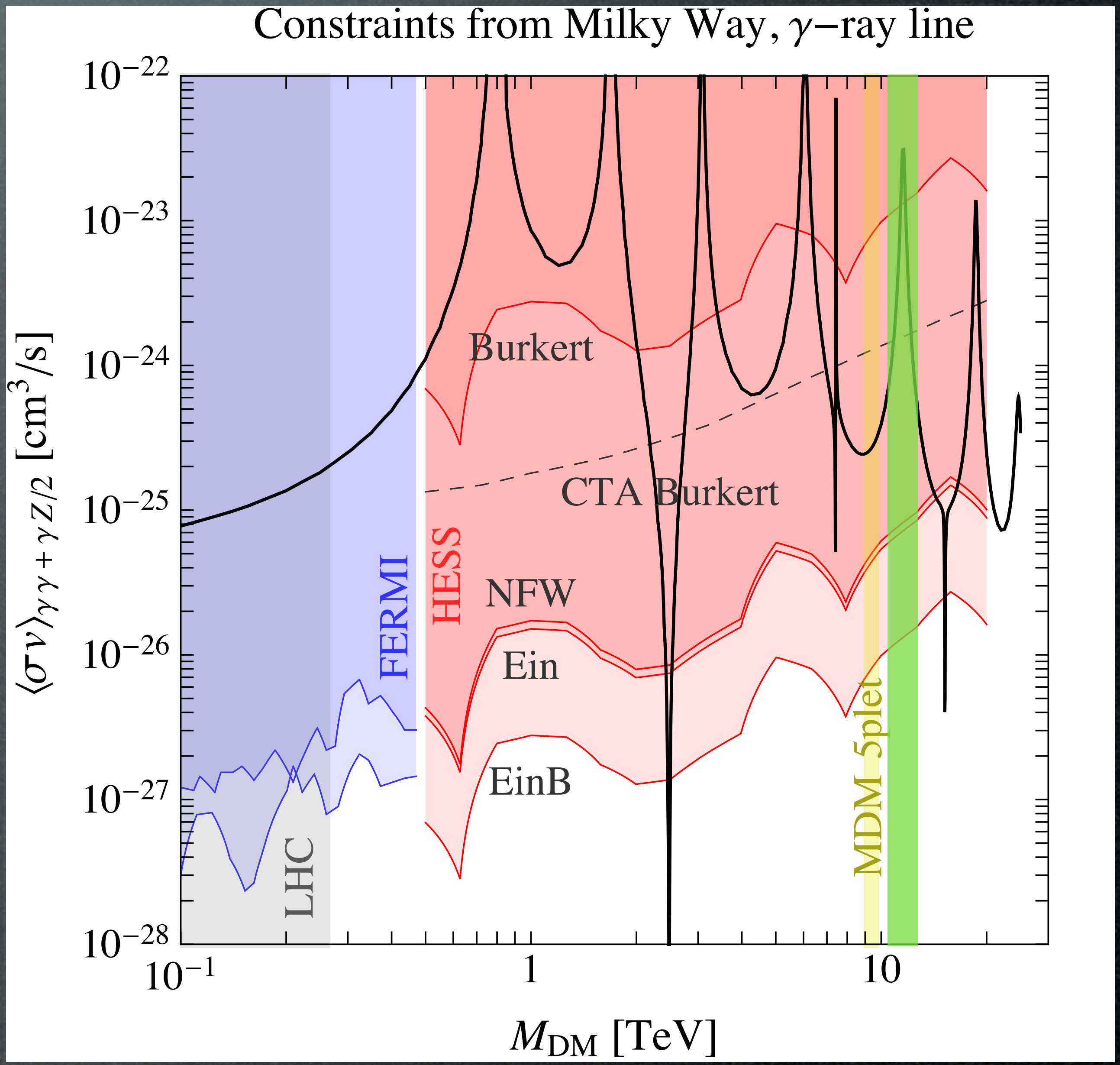
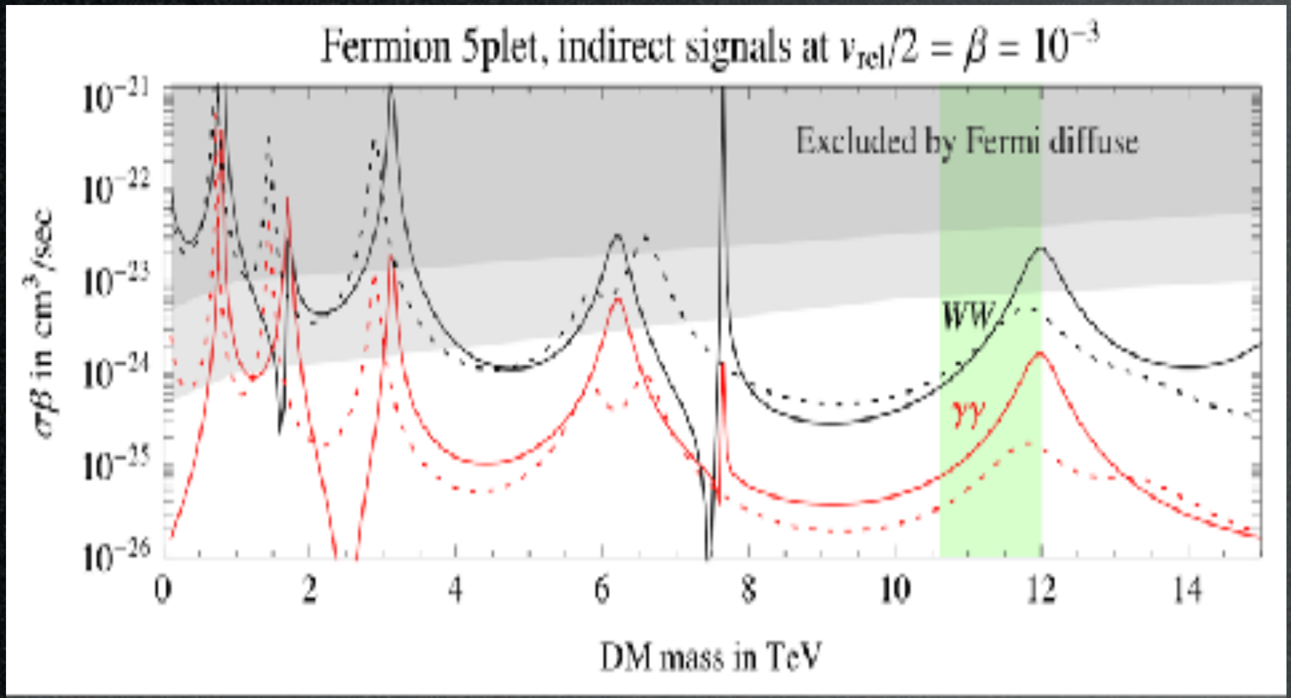


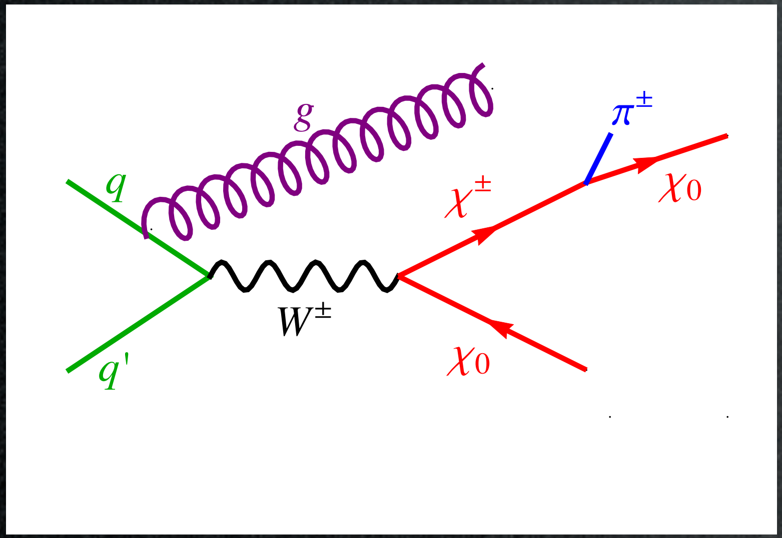

<--
Mitridate, Redi, Smirnov, Strumia 1702.01141**v2**

# Collider searches

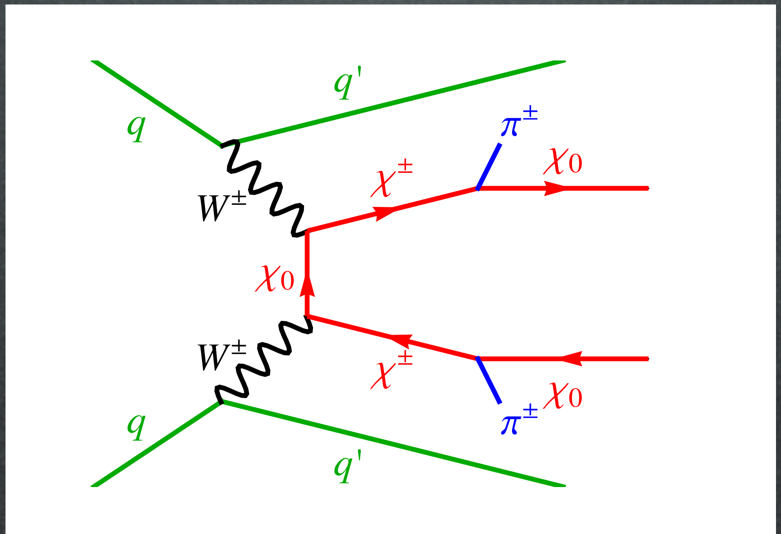
At 9.4 TeV, no hope at the LHC.

- relax the mass constraint
- consider next-to-minimal cases (e.g. the triplet = pure wino)
- explore reach of 100 TeV future collider

## Mono-X

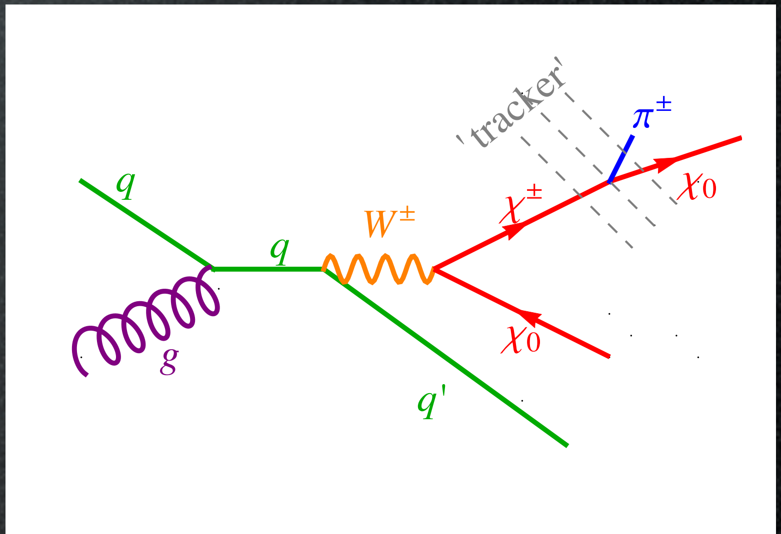



## VBF




*di-jets + MET*

## Disappearing tracks




or: indirect searches

# Collider searches

At 9.4 TeV, no hope at the LHC.

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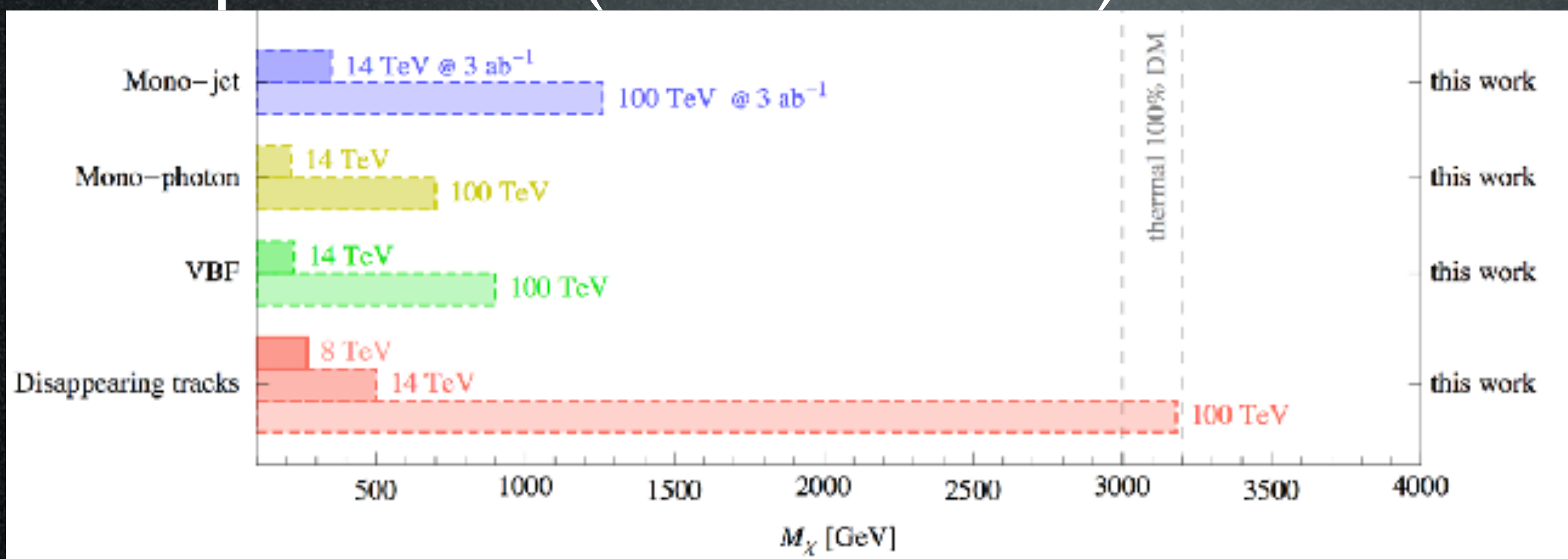
For triplet MDM (a.k.a. wino DM)




Cirelli, Sala, Taoso 1407.7058

For 5plet MDM

| Model | $\sqrt{s} = 8$ TeV | | | | $\sqrt{s} = 14$ TeV | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ATLAS | | CMS | | Exclude | | | Discover | | |
| | Expected | Observed | Expected | Observed | 500% | 100% | 20% | 500% | 100% | 20% |
| Wino | 224 | 238 | 203 | 195 | 354 | 483 | 635 | 287 | 394 | 514 |
| Majorana Fiveplet | 256 | 267 | 234 | 226 | 410 | 524 | 668 | 340 | 448 | 576 |
| Dirac Fiveplet | 283 | 293 | 259 | 251 | 465 | 599 | 743 | 381 | 503 | 639 |

Ostdiek, 1506.03445

# Collider searches

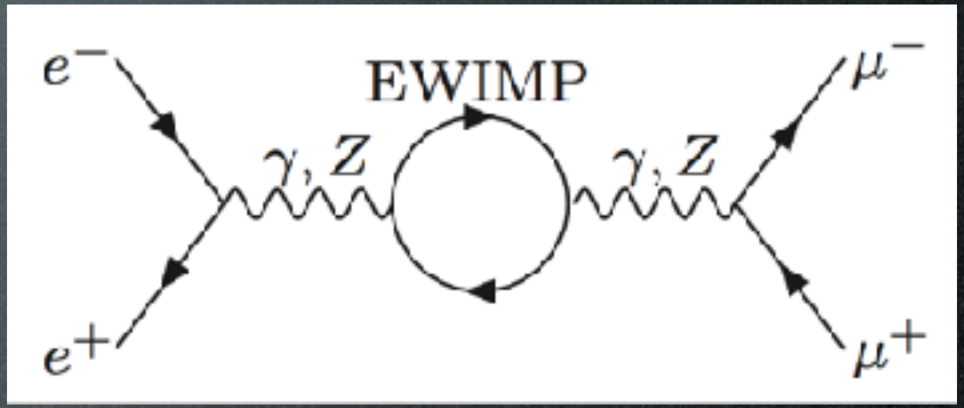
Indirect searches at a future Linear Collider:

# Collider searches

Indirect searches at a future Linear Collider:

Harigaya, Ichikawa, Matsumoto..., 1504.03402

Even if $\sqrt{s} < M_{\rm DM}$, one can see the effects in precision measurements



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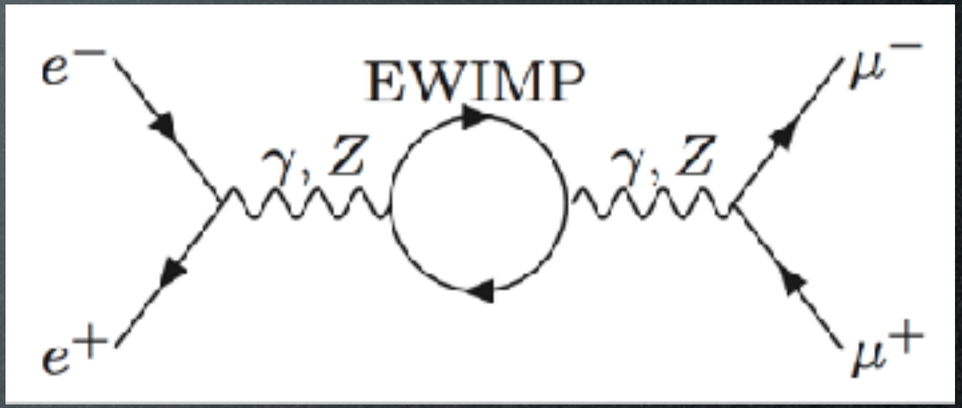
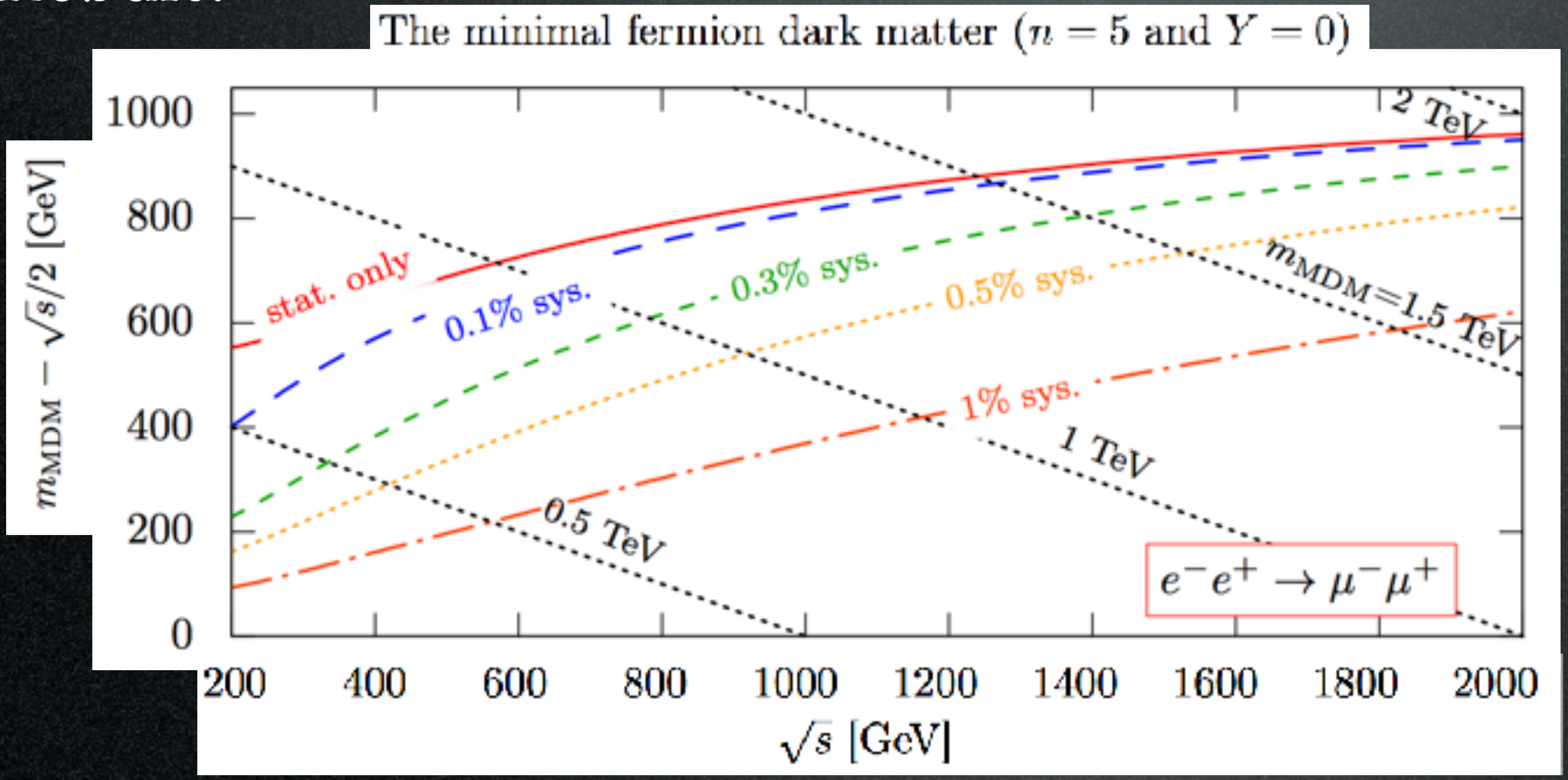



Result:



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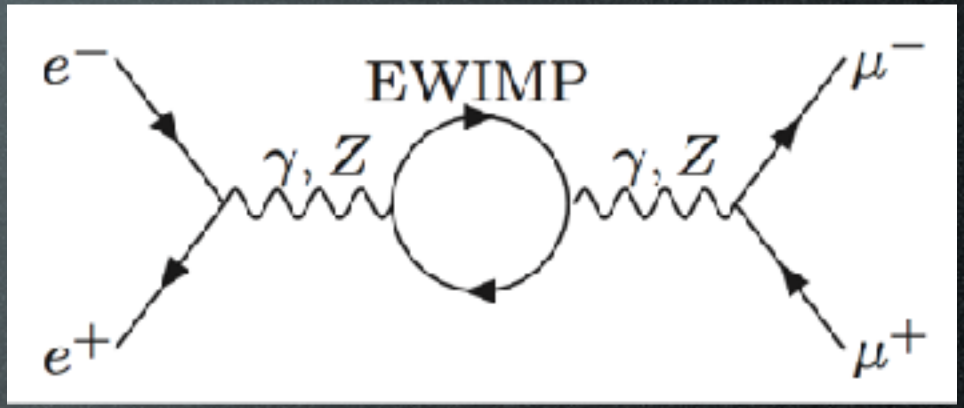


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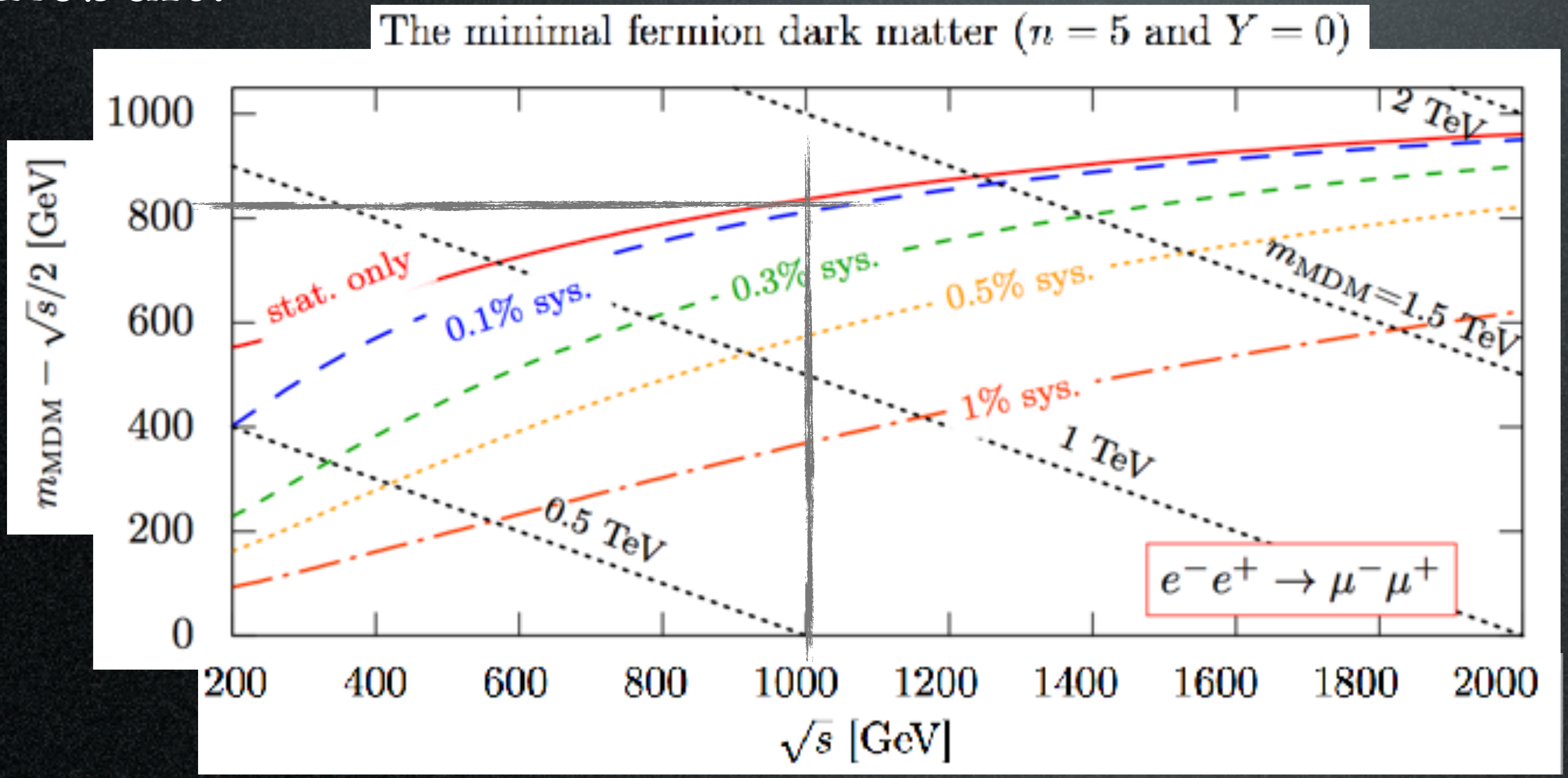


How to read the plot:
a LC with $\sqrt{s}$ = 1 TeV,
assuming only stat uncertainties,
will be sensitive to $m_{\rm DM} - \sqrt{s}/2 \sim 800$ GeV
i.e. $m_{\rm DM} \sim 1.3$ TeV (indeed see the dotted isocontours of the DM mass)

similar plots for other channels
& for other candidates

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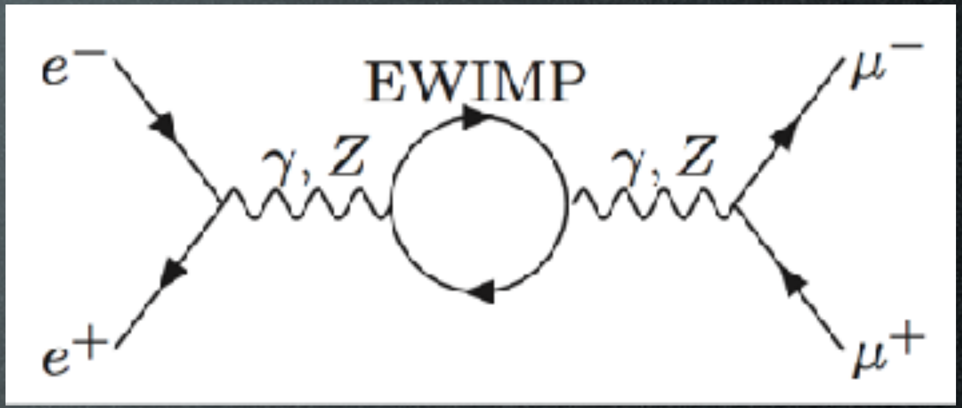
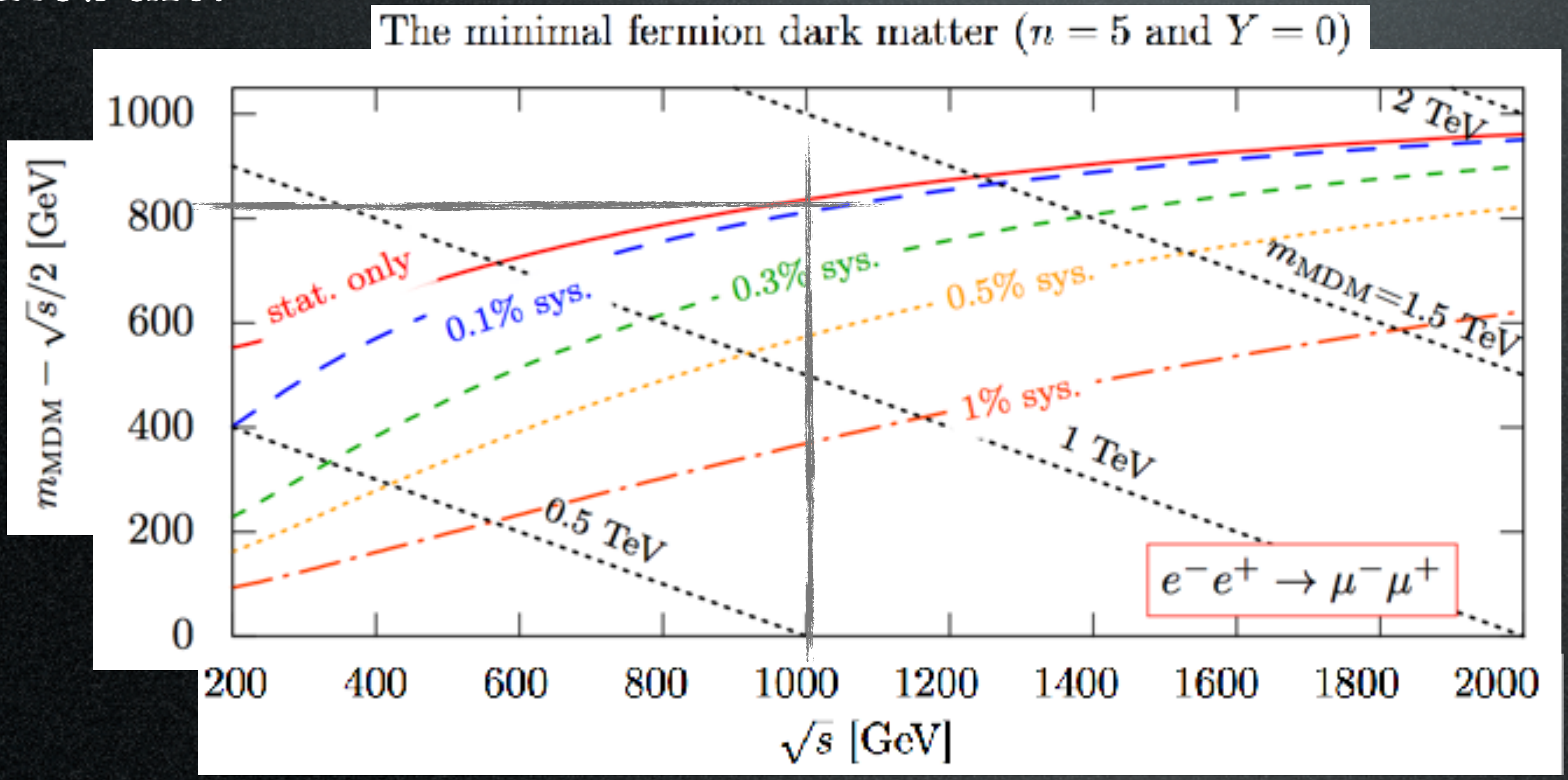



Result:

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similar plots for other channels
& for other candidates

one can go beyond the collider energy, but not by much

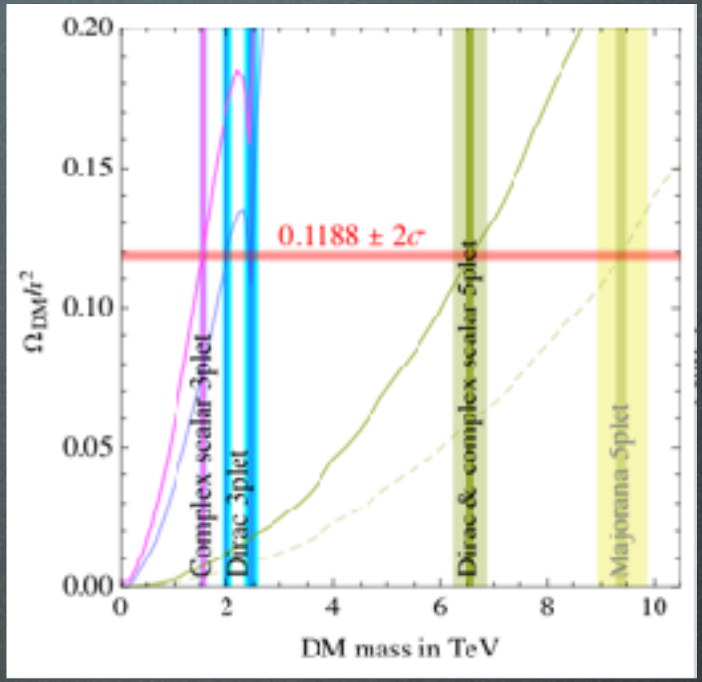
# Bonus track

Some interesting recent extensions:

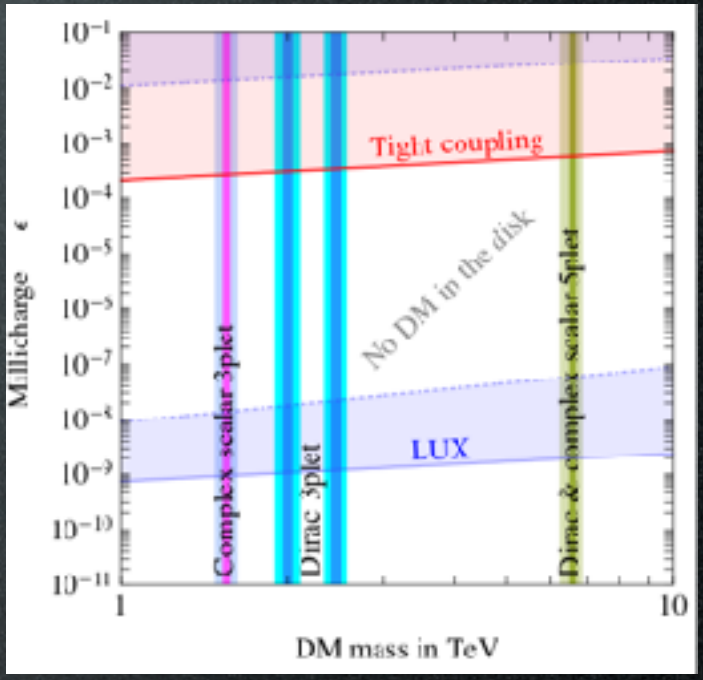
- **millicharged** MDM

Del Nobile, Nardecchia, Panci 1512.05353

assume $Y = \varepsilon \neq 0$,
-> implies stability
-> for suitable $\varepsilon$, no DD



relic abundance



constraints

- **decaying** MDM, if $\Lambda < M_{Planck}$

Del Nobile, Nardecchia, Panci 1512.05353

-> observable consequences in gamma rays

- **'natural'** MDM

Fabbrichesi, Urbano 1510.03861

MDM induces (at 2-loops) $m_h$ corrections => small hierarchy prob
-> supersymmetrize it!:
- fermion/boson cancellations restore naturalness
- stability preserved by SuSy

# Bonus track

Some interesting recent extensions:

-asymmetric MDM

Boucenna, Krauss, Nardi 1503.01119

-MDM and vacuum stability

Cai,Ramsey-Musolf et al., 1108.0969
Cai et al., 1508.04034

-non-thermally produced MDM

Aoki, Toma, Vicente 1507.01591

-incorporating neutrino masses

Cai, Schmidt 1603.00255
Ahriche, McDonald, Nasri, Picek 1603.01247

# Conclusions 1/2

The DM problem requires physics beyond the SM.

(*) unless it's Primordial Black Holes generated by higgs perturbations!
Espinosa, Racco, Riotto 1710.11196

# Conclusions 1/2

The DM problem requires physics beyond the SM.

WIMPs:

# Conclusions 1/2

The DM problem requires physics beyond the SM.

WIMPs:

1. even without a larger framework, they are still appealing
2. the frontier is multi-TeV
3. searches are complementary and still have ground to cover

# Conclusions 2/2

The DM problem requires physics beyond the SM.

Focussing on pure WIMPs,
we find one fully successful DM candidate:
massive, neutral, *automatically* stable.

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fermionic $SU(2)_L$ quintuplet with $Y = 0$,
mass = 9.4 TeV
(or 11 TeV with bound states)

The phenomenology is precisely computable:

- tested by indirect detection (γ ray) exp's:
  - excluded if cuspy
  - not probed if cored

# Back-up slides

# Production at colliders

OK, given what we (do not) see, how do we interpret?

effectively | simplified models | a simple model | a full theory

# Production at colliders

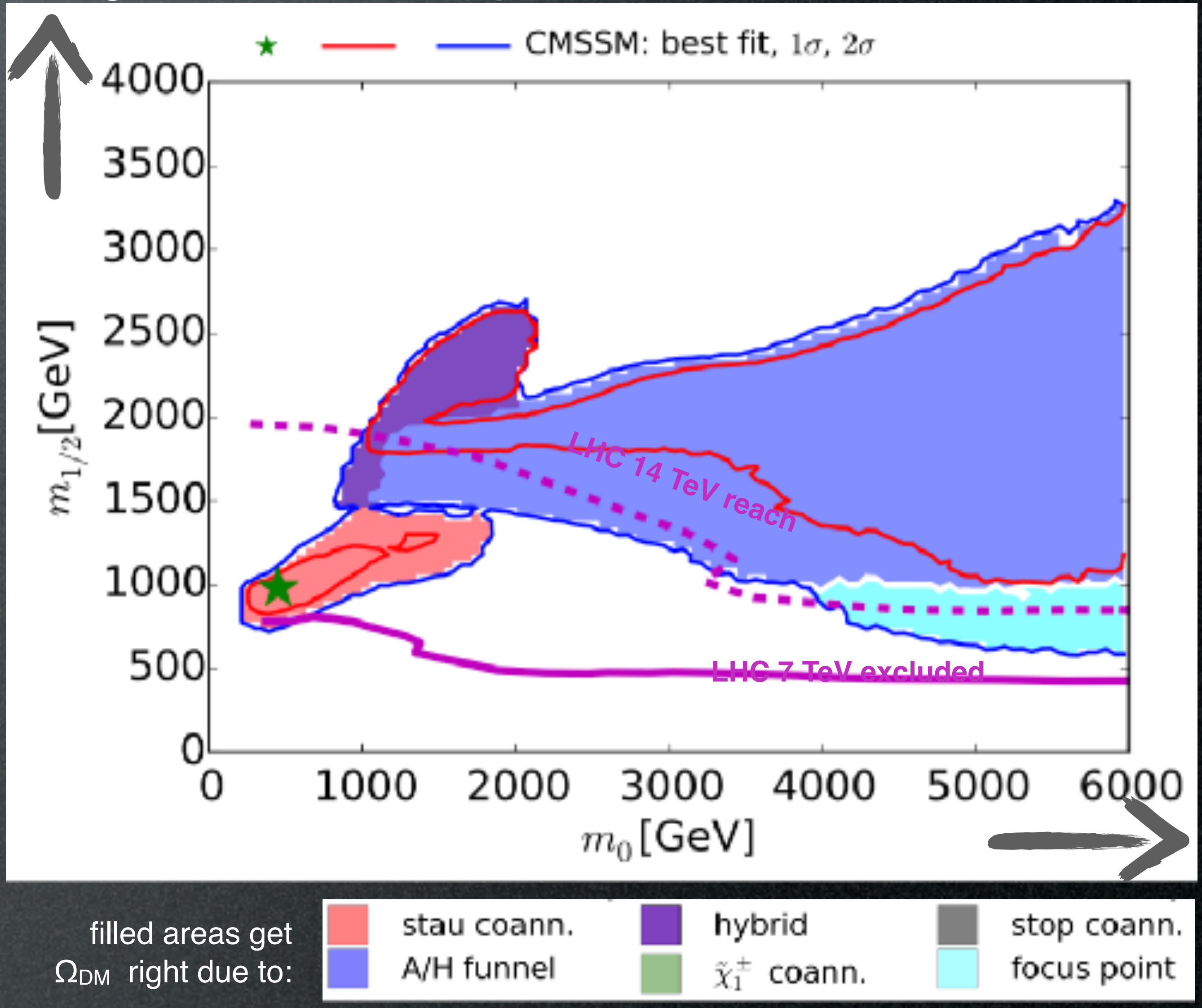
OK, given what we (do not) see, how do we interpret?

*effectively* *simplified models* *a simple model* *a full theory*

E.g. SUSY: cMSSM, pMSSM...

parameters: tens (or even hundreds!)

the glorious $m_0/m_{1/2}$ plane:




Bagnaschi, Buchmuller, Ellis, Heinemeyer, Olive, Weiglein... 1508.01173

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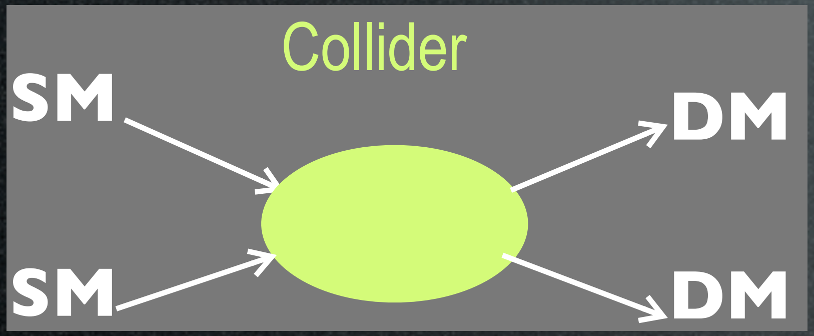

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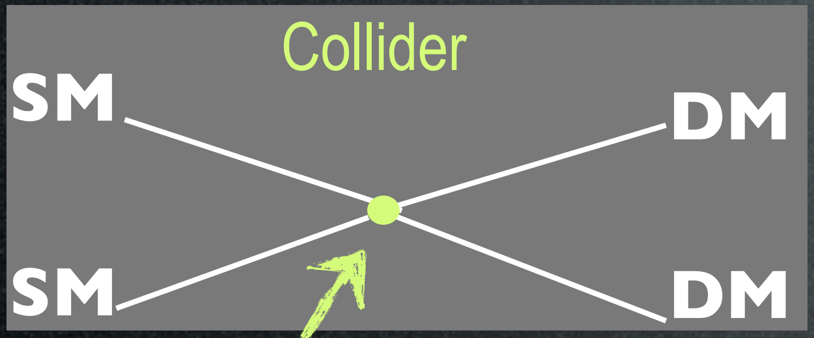


$$\frac{g}{\Lambda^n}$$

$$\frac{1}{\Lambda_1^2}[q\bar{q}][\chi\bar{\chi}]$$

$$\frac{1}{\Lambda_2^2}[q\gamma_\mu\bar{q}][\chi\gamma^\mu\bar{\chi}]$$

parameters: $\Lambda$ (assuming $g \simeq 1$)

# Production at colliders

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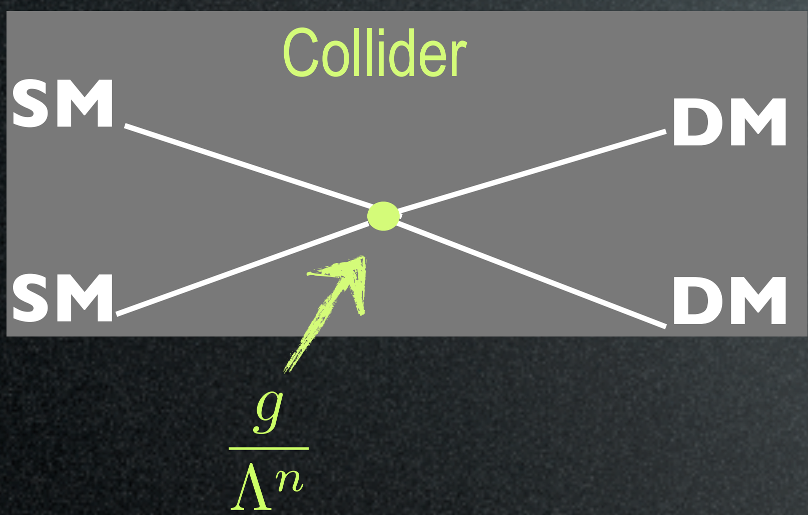


(a) Operators for Dirac fermion DM

| Name | Operator | Dimension | SI/SD |
|---|---|---|---|
| D1 | $\frac{m_q}{\Lambda^3}\bar\chi\chi\bar q q$ | 7 | SI |
| D2 | $\frac{im_q}{\Lambda^3}\bar\chi\gamma^5\chi\bar q q$ | 7 | N/A |
| D3 | $\frac{im_q}{\Lambda^3}\bar\chi\chi\bar q\gamma^5 q$ | 7 | N/A |
| D4 | $\frac{m_q}{\Lambda^3}\bar\chi\gamma^5\chi\bar q\gamma^5 q$ | 7 | N/A |
| D5 | $\frac{1}{\Lambda^2}\bar\chi\gamma^\mu\chi\bar q\gamma_\mu q$ | 6 | SI |
| D6 | $\frac{1}{\Lambda^2}\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu q$ | 6 | N/A |
| D7 | $\frac{1}{\Lambda^2}\bar\chi\gamma^\mu\chi\bar q\gamma_\mu\gamma^5 q$ | 6 | N/A |
| D8 | $\frac{1}{\Lambda^2}\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu\gamma^5 q$ | 6 | SD |
| D9 | $\frac{1}{\Lambda^2}\bar\chi\sigma^{\mu\nu}\chi\bar q\sigma_{\mu\nu}q$ | 6 | SD |
| D10 | $\frac{i}{\Lambda^2}\bar\chi\sigma^{\mu\nu}\gamma^5\chi\bar q\sigma_{\mu\nu}q$ | 6 | N/A |
| D11 | $\frac{\alpha_s}{4\Lambda^3}\bar\chi\chi G^{\mu\nu}G_{\mu\nu}$ | 7 | SI |
| D12 | $\frac{i\alpha_s}{4\Lambda^3}\bar\chi\gamma^5\chi G^{\mu\nu}G_{\mu\nu}$ | 7 | N/A |
| D13 | $\frac{i\alpha_s}{4\Lambda^3}\bar\chi\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$ | 7 | N/A |
| D14 | $\frac{\alpha_s}{4\Lambda^3}\bar\chi\gamma^5\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$ | 7 | N/A |

(b) Operators for Complex scalar DM

| Name | Operator | Dimension | SI/SD |
|---|---|---|---|
| C1 | $\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar q q$ | 6 | SI |
| C2 | $\frac{im_q}{\Lambda^2}\phi^\dagger\phi\bar q\gamma^5 q$ | 6 | N/A |
| C3 | $\frac{1}{\Lambda^2}\phi^\dagger\overleftrightarrow{\partial}_\mu\phi\bar q\gamma^\mu q$ | 6 | SI |
| C4 | $\frac{1}{\Lambda^2}\phi^\dagger\overleftrightarrow{\partial}_\mu\phi\bar q\gamma^\mu\gamma^5 q$ | 6 | N/A |
| C5 | $\frac{\alpha_s}{4\Lambda^2}\phi^\dagger\phi G^{\mu\nu}G_{\mu\nu}$ | 6 | SI |
| C6 | $\frac{i\alpha_s}{4\Lambda^2}\phi^\dagger\phi G^{\mu\nu}\tilde{G}_{\mu\nu}$ | 6 | N/A |

Tim Tait, 2010+

and many many **many** others

# Production at colliders

OK, given what we (do not) see, how do we interpret?

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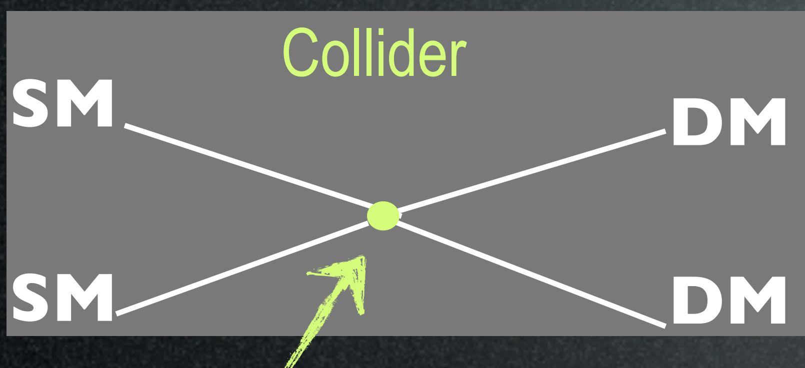
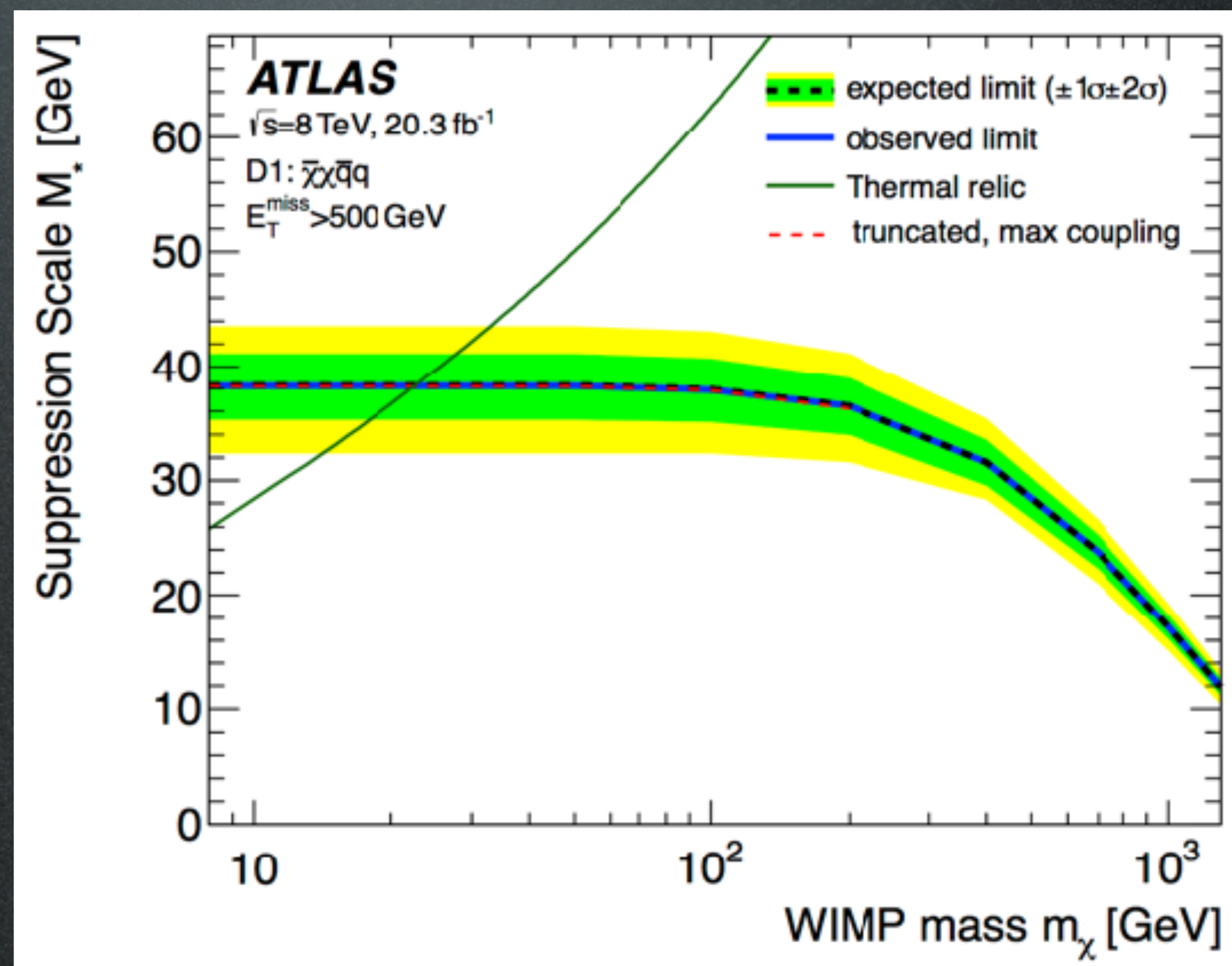



$\frac{g}{\Lambda^n}$

limits on $\Lambda$




ATLAS, 1502.01518

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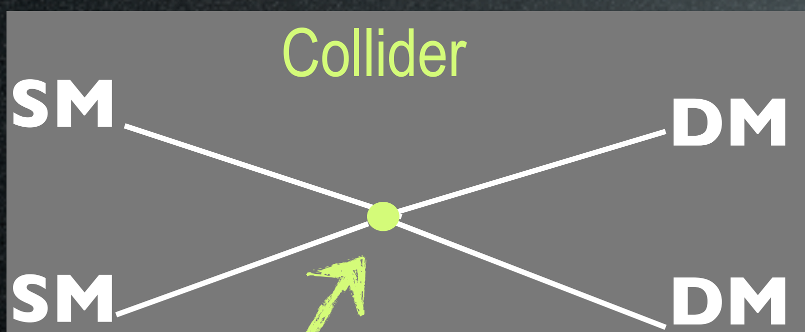
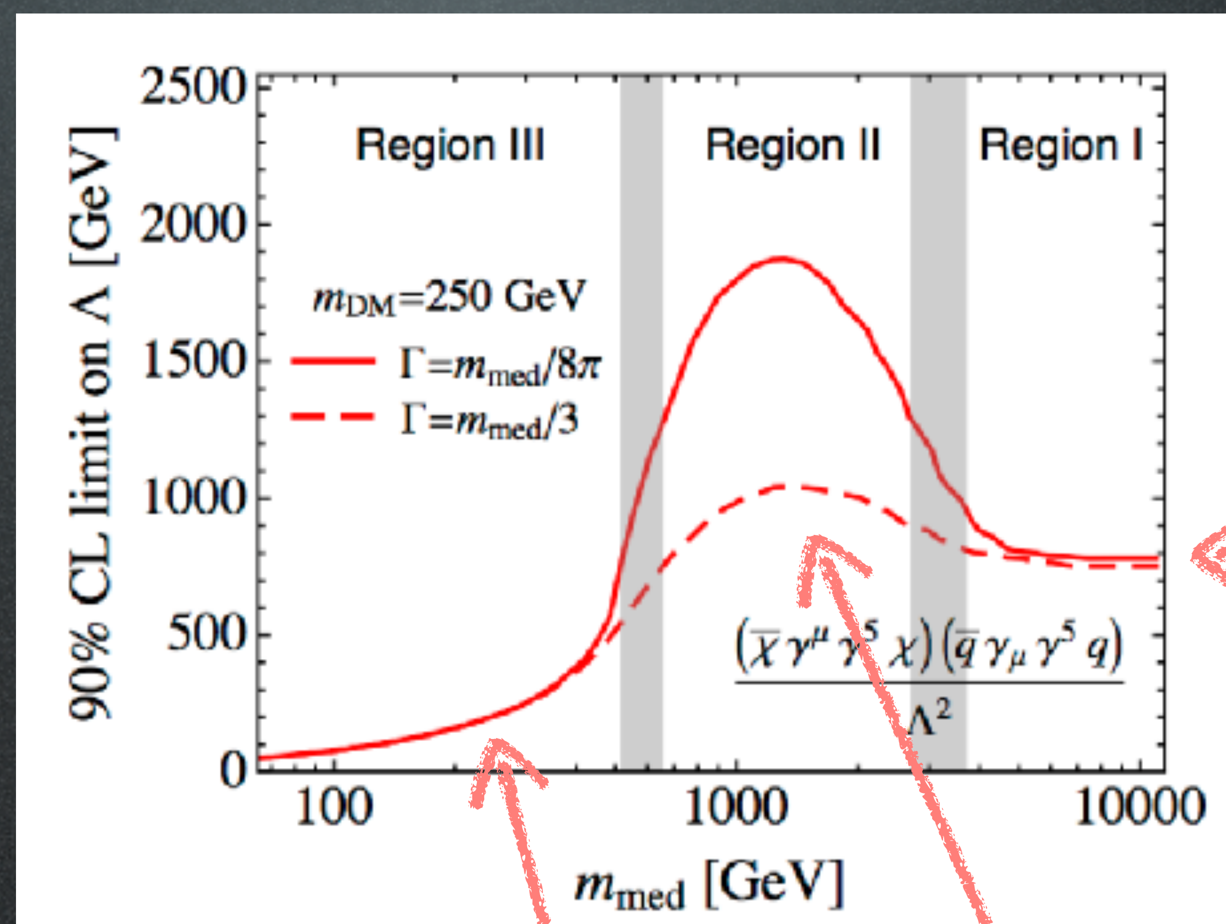



$\frac{g}{\Lambda^n}$

but how 'sensible' are they?




Buchmuller, Dolan, McCabe 1308.6799

EFT puts bounds on Λ

but Λ is actually $\Lambda = \frac{m_{med}}{\sqrt{g_q\, g_\chi}}$

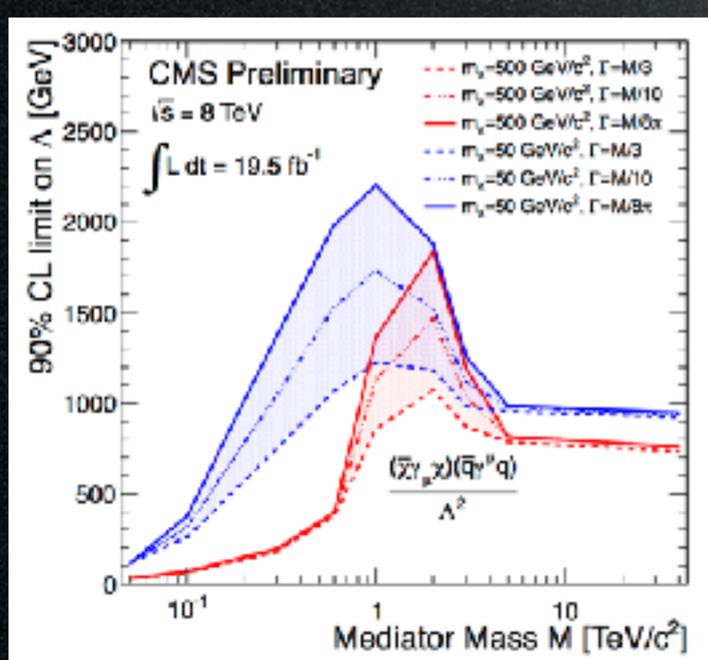
at large $m_{med}$, the two agree

resolving, at small $m_{med}$, what is the discrepancy?
i.e. what is the limit deduced on Λ, defined as above?

limits agree

EFT bound is much larger

EFT underestimates bound by some % up to factor 2 or more




CMS, CMS PAS EXO-12-048

# Production at colliders

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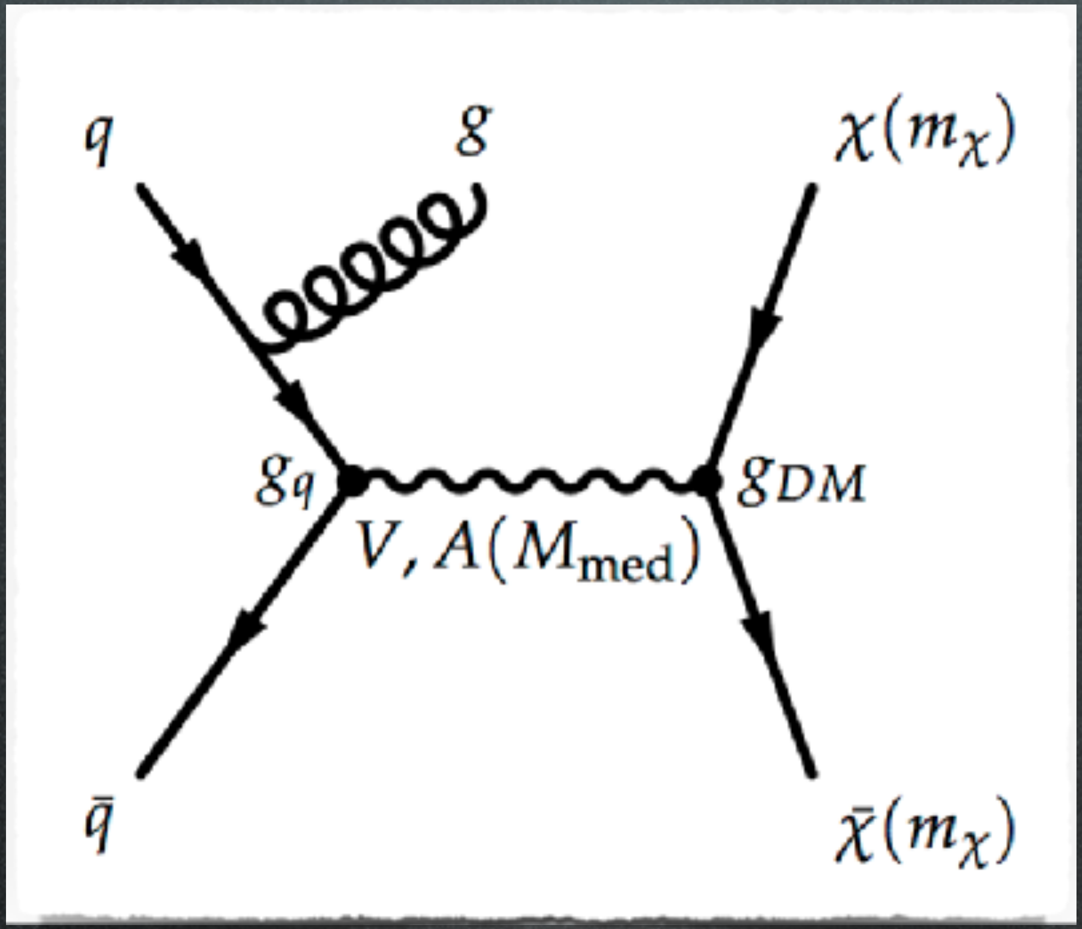
ATLAS+CMS DM forum, 1507.00966




parameters:

$m_\chi, m_{\text{med}}, g_q, g_{\text{DM}}$

$$\mathcal{L}_{\text{vector}} = g_{\text{q}} \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \chi$$

$$\mathcal{L}_{\text{axial-vector}} = g_{\text{q}} \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu \gamma^5 q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \gamma^5 \chi.$$

(and similarly for t-channel, scalar mediator, scalar DM etc...)

# Production at colliders

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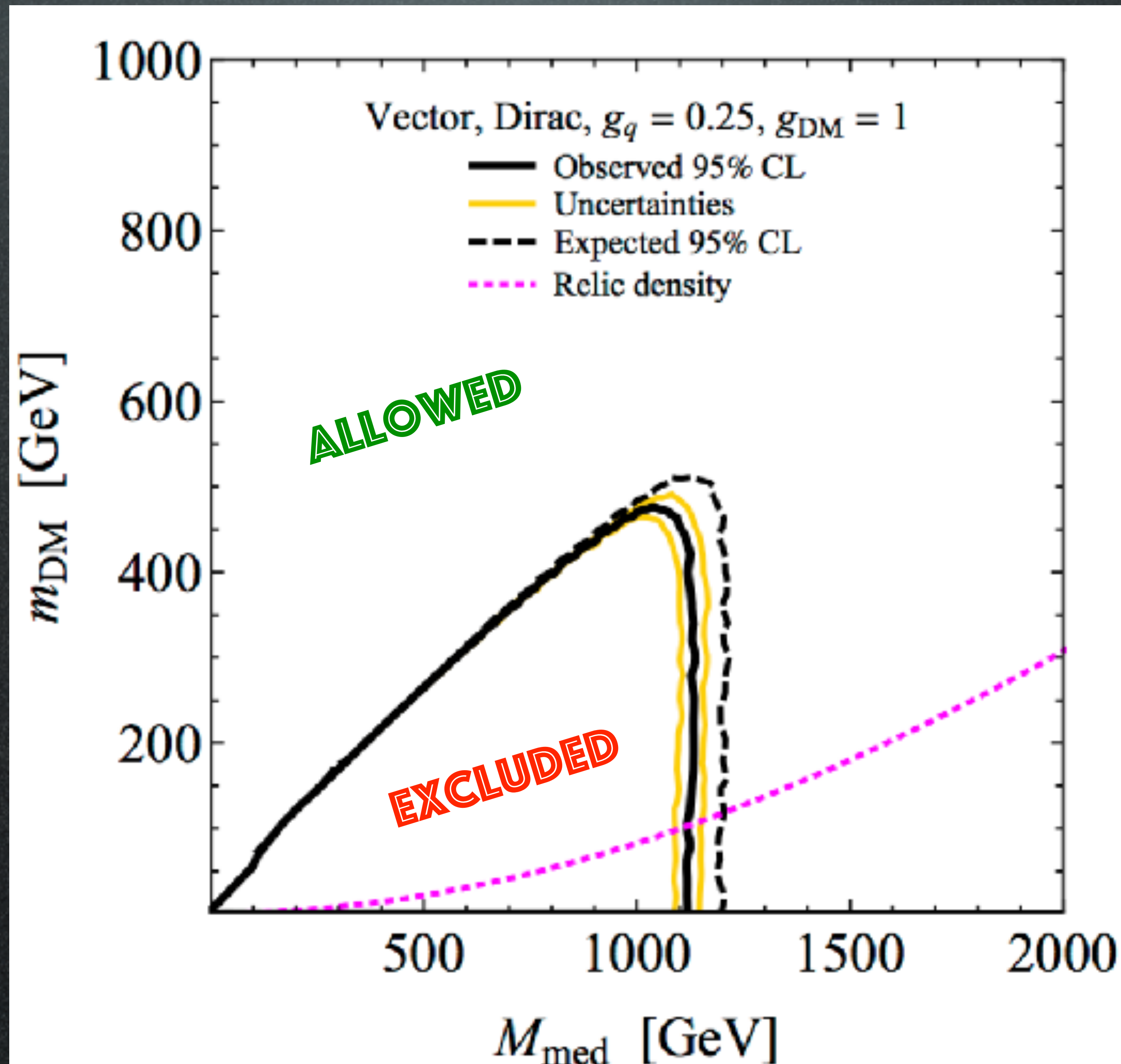
*effectively* — *simplified models* — *a simple model* — *a full theory*

mock plot:




LHCDMWG, 1603.04156

# Production at colliders

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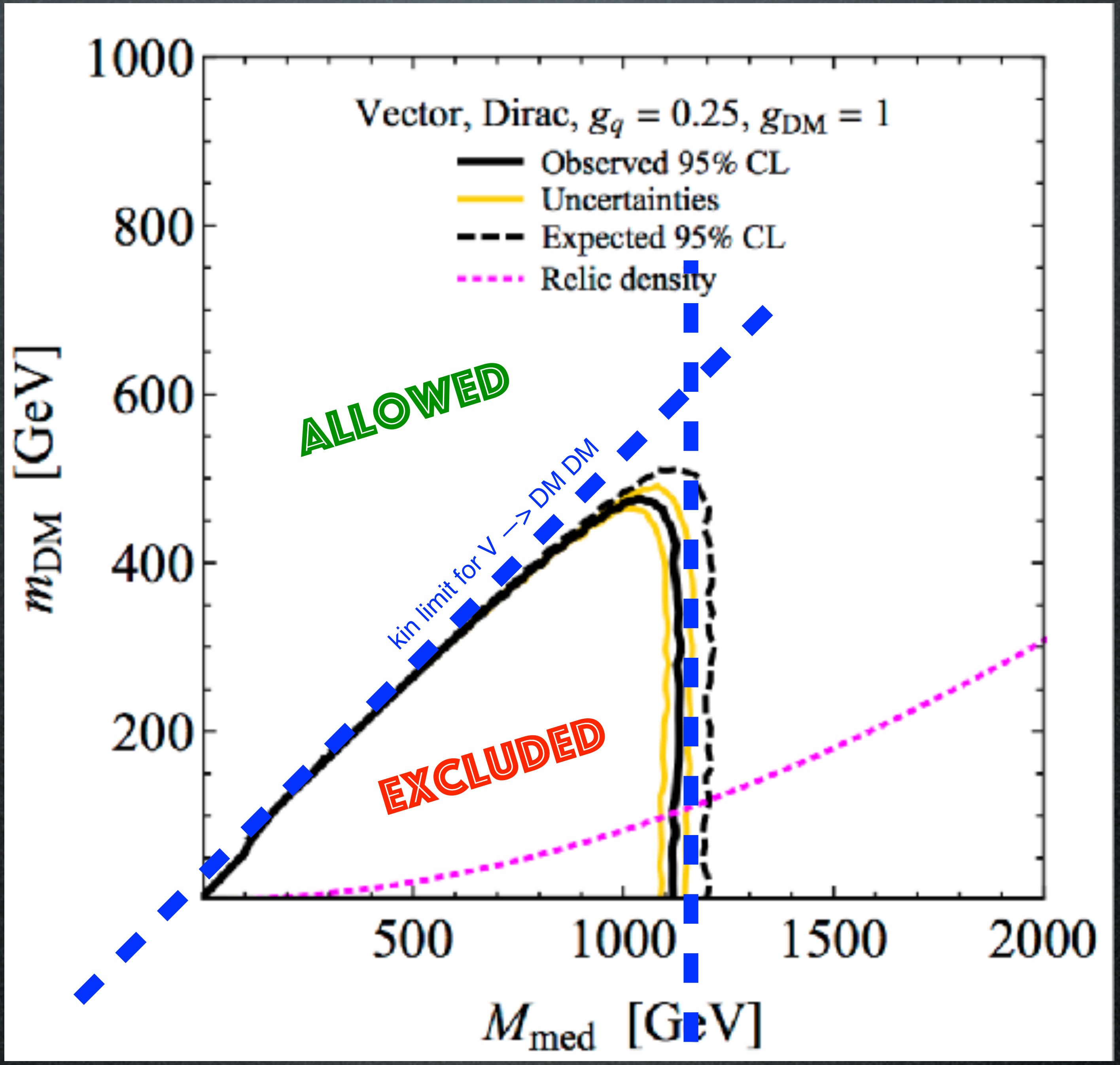


LHCDMWG, 1603.04156

# Production at colliders

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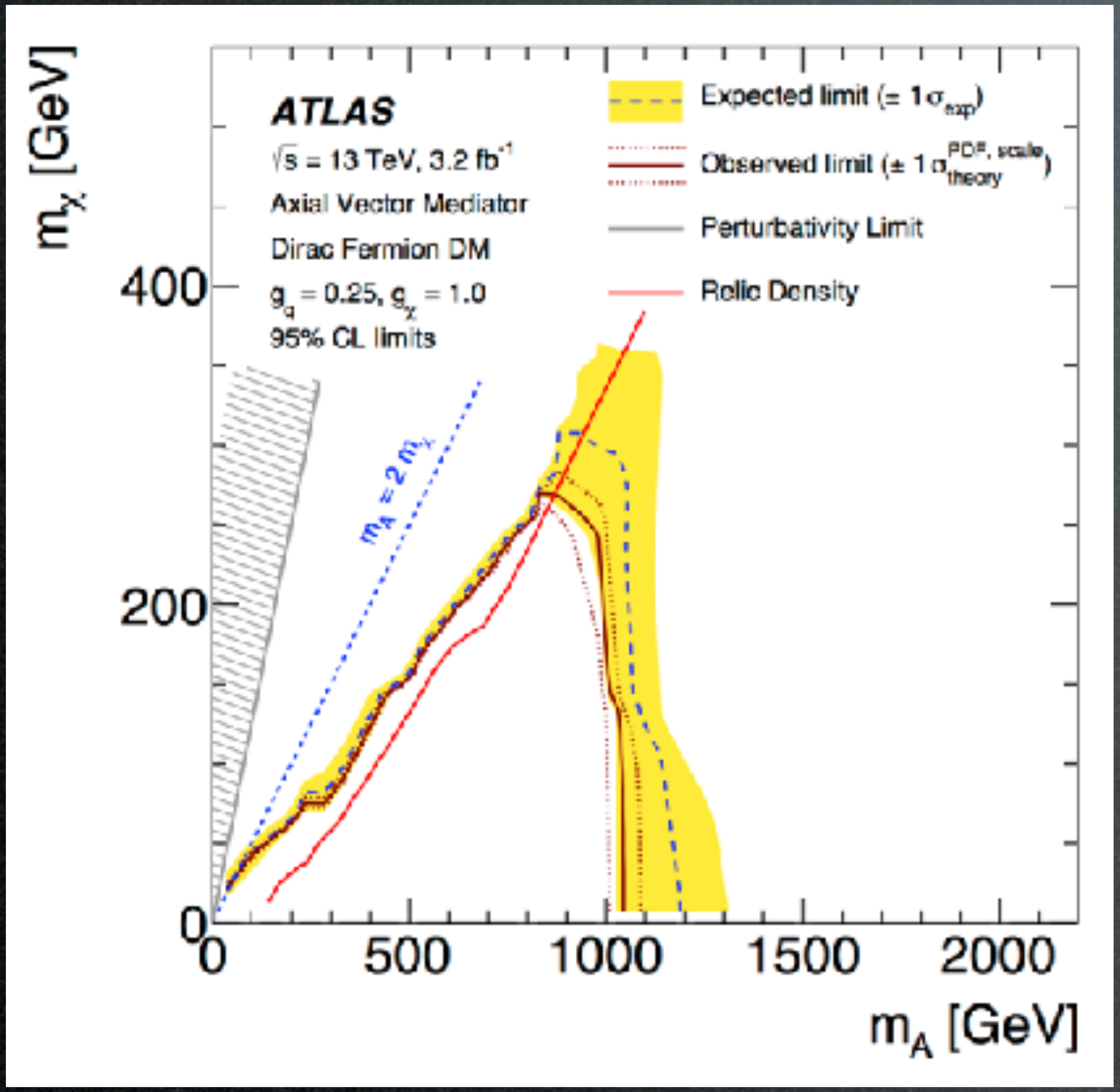
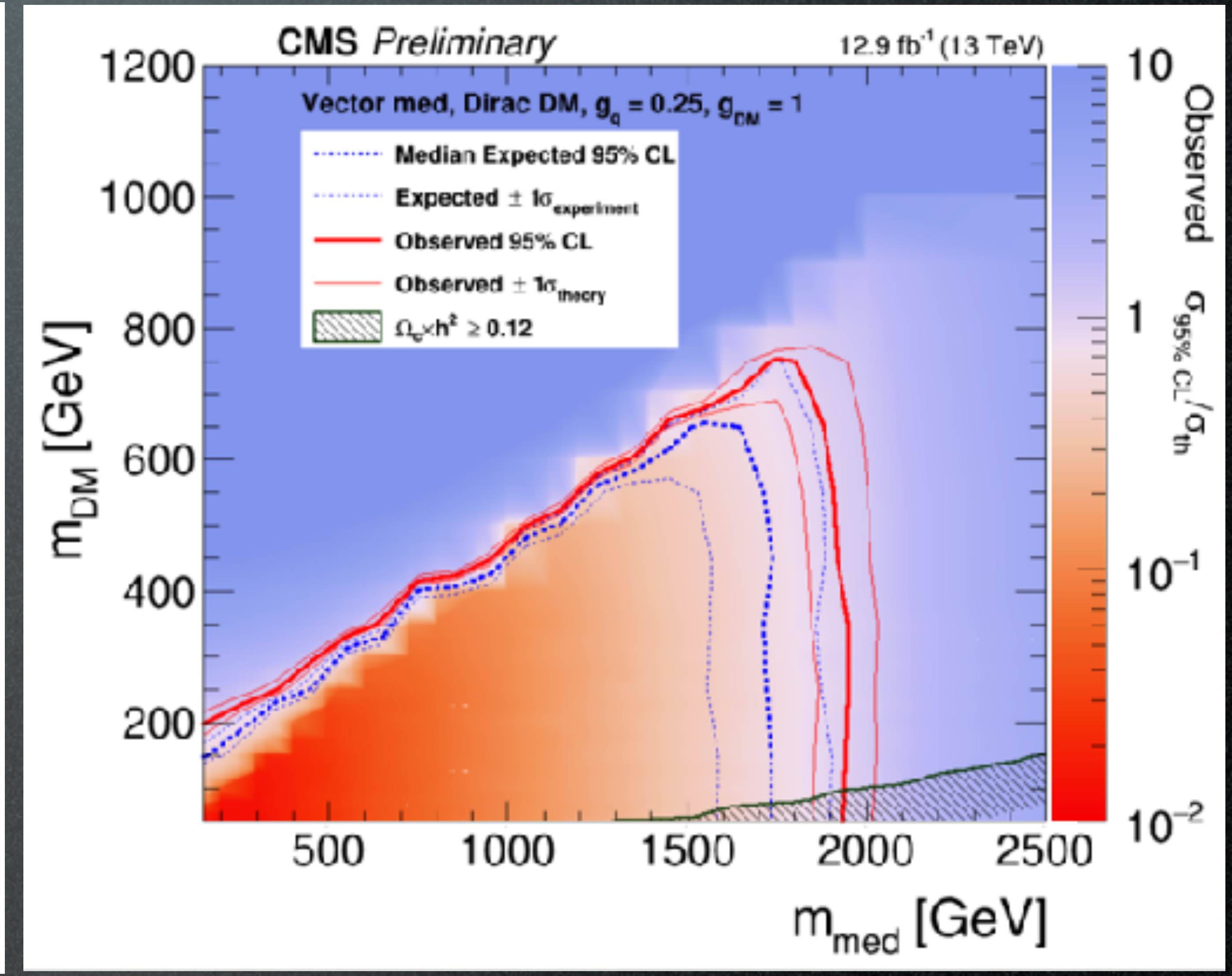
actual plots:




ATLAS coll., 1604.07773v2




CMS coll., CMS PAS EXO-16-037

# Production at colliders

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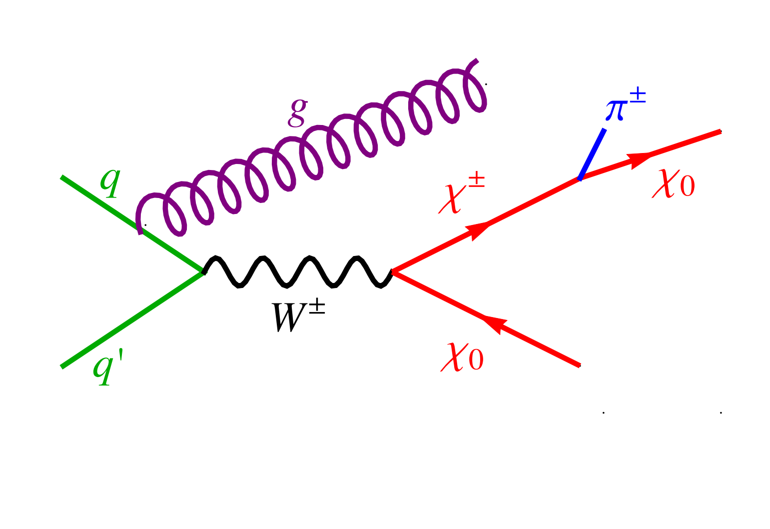
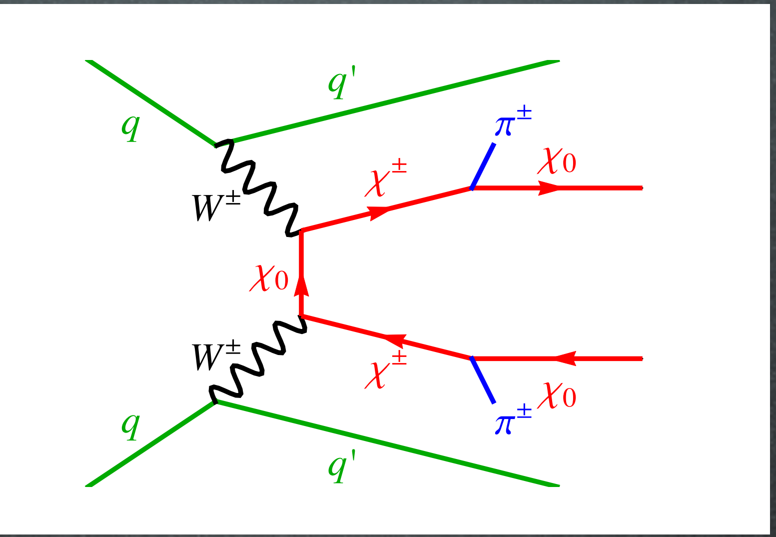
e.g. pure WIMP model (a.k.a. 'Minimal DM')



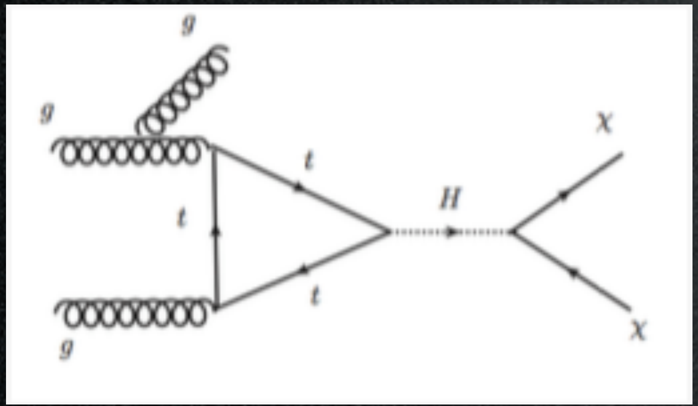

mono-jet



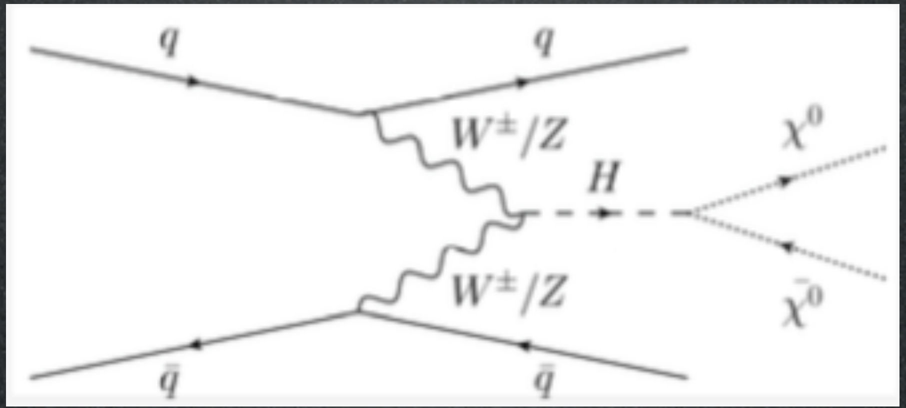

Vector Boson Fusion (VBF)

parameters: $M_{\rm DM}$

e.g. higgs portal models




mono-jet




Vector Boson Fusion (VBF)

parameters: $g_{h\chi}$

# 3. Indirect Detection

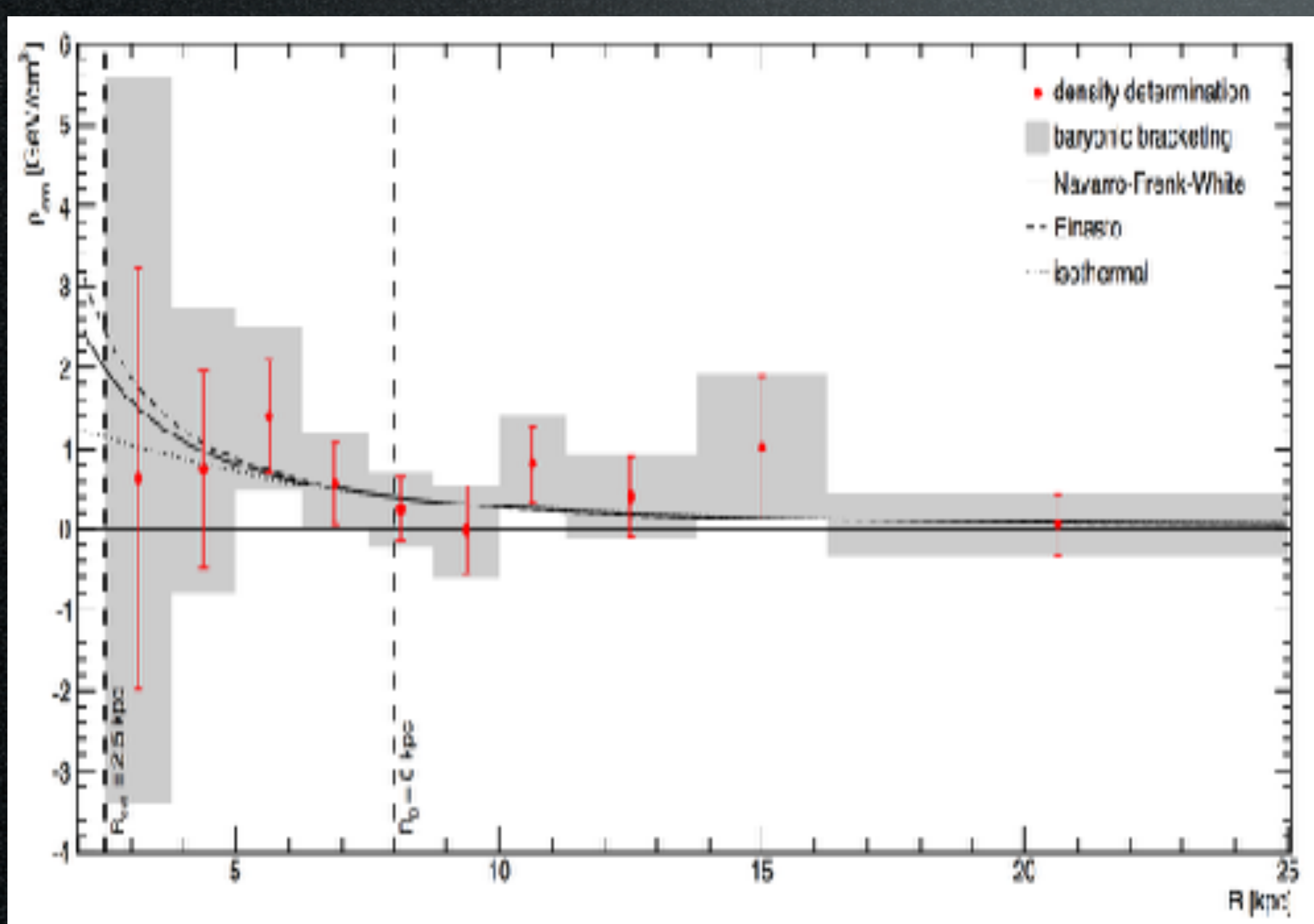
## So is the Milky Way profile peaked or cored?

**Observations:**

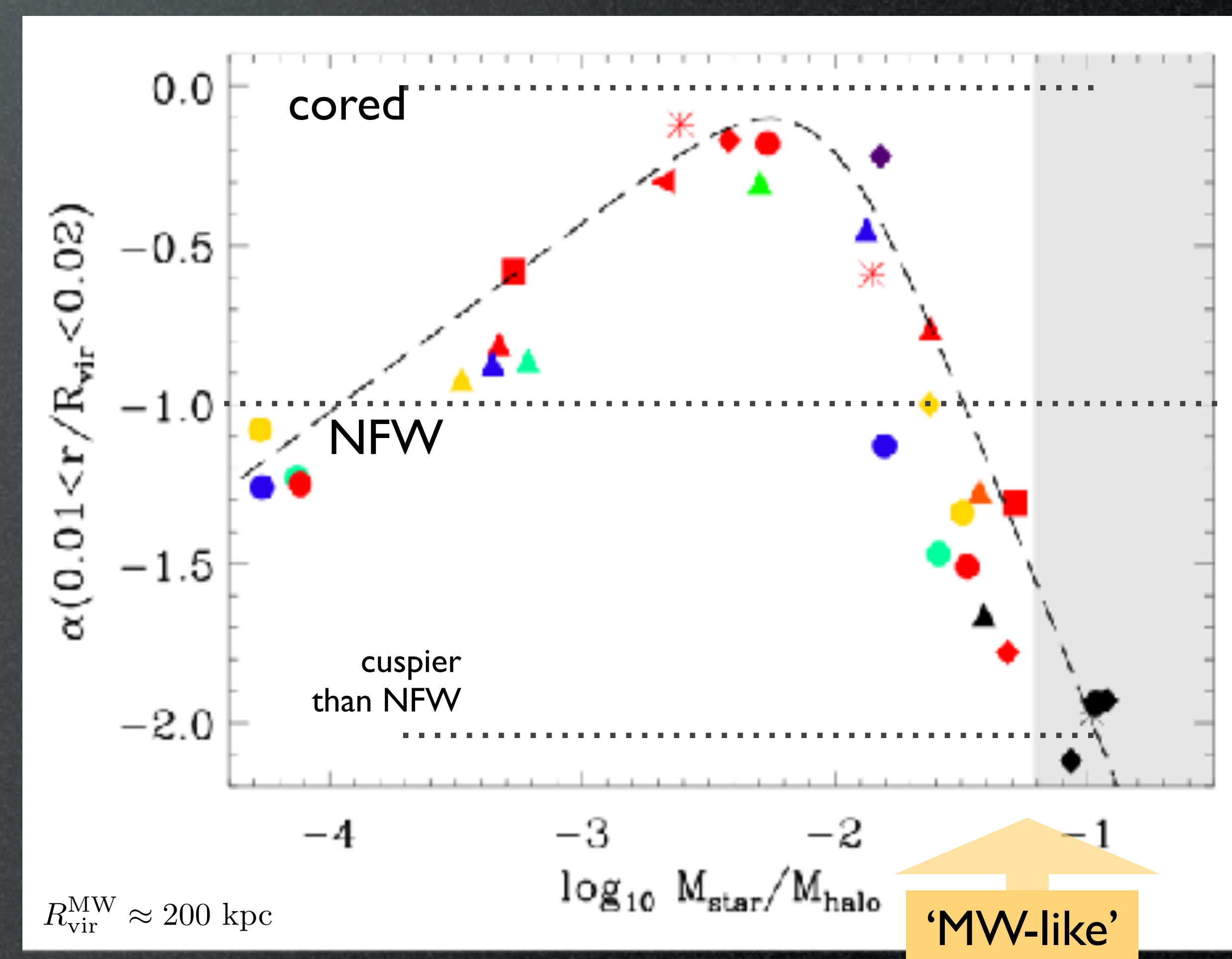
- (difficult from inside)
- no discriminating power
- anyway, no resolution < 2.5 kpc

**Simulations:**

- (still open debate, but)
- prefer cuspy
- but: no resolution < 2 kpc




Pato, Iocco 1504.03317




Di Cintio ... Macciò1306.0898

# 3. Indirect Detection

MW center area, search for $\gamma$-ray lines:

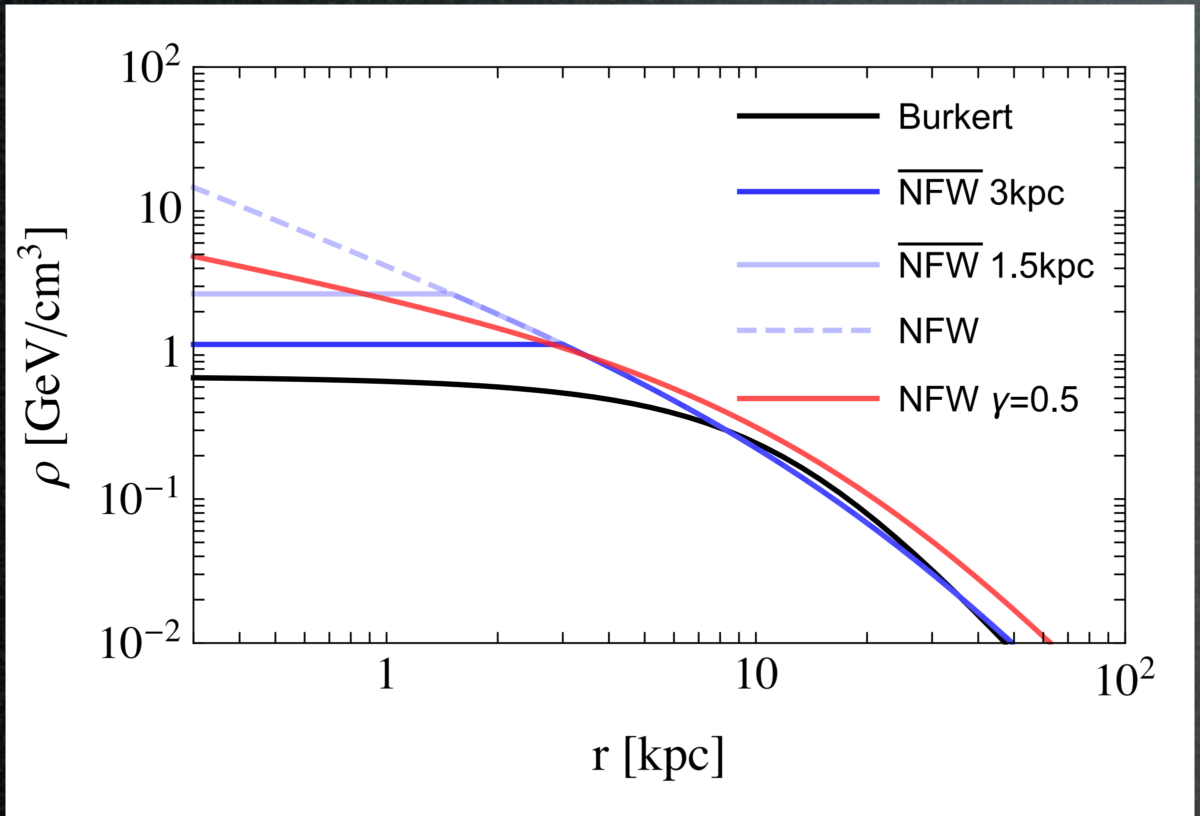
Simulations and observations
do not resolve $\lesssim 2$ kpc

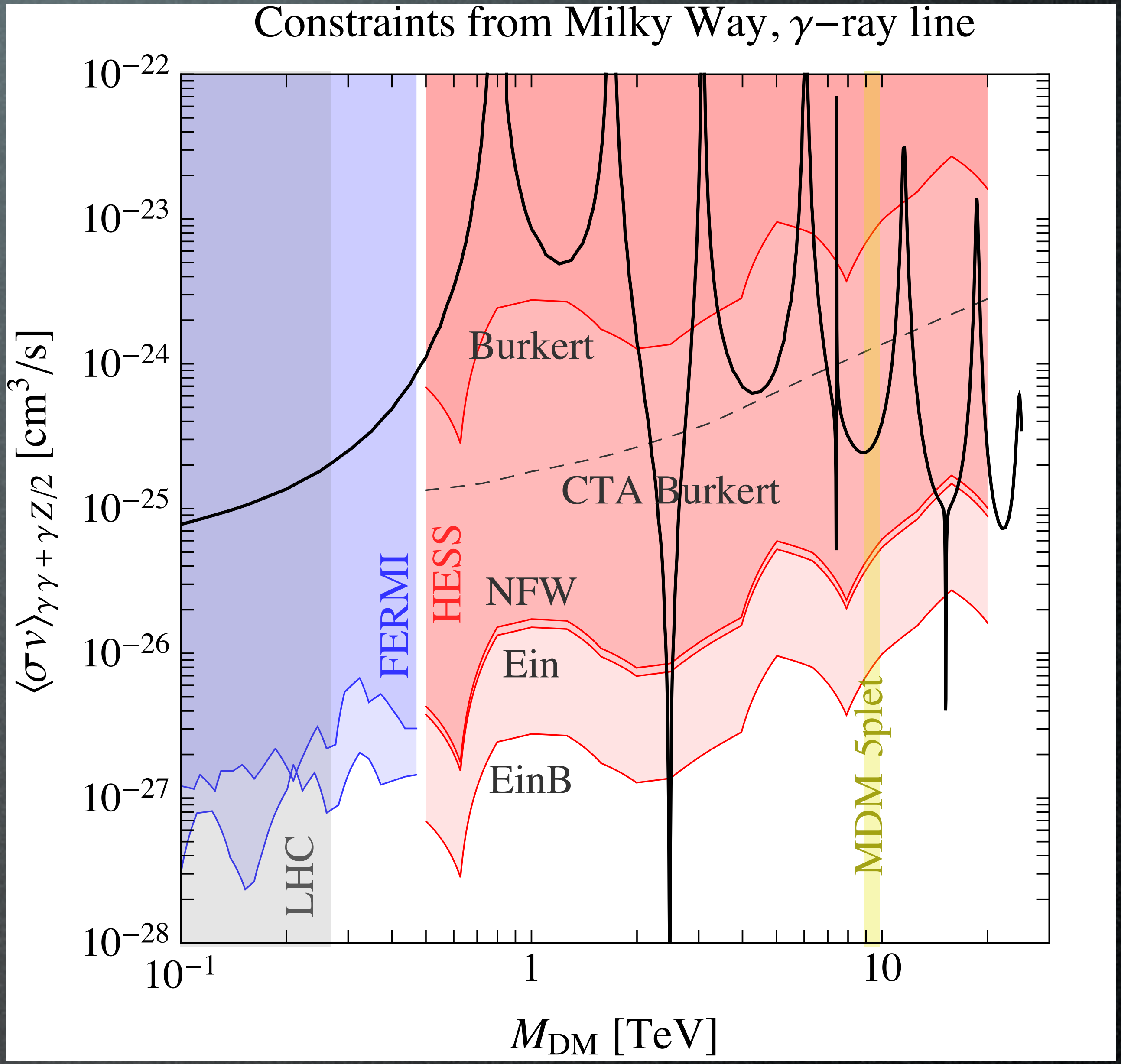
# 3. Indirect Detection

MW center area, search for $\gamma$-ray lines:

Simulations and observations do not resolve $\lesssim 2$ kpc

Uncertainties in DM profile:



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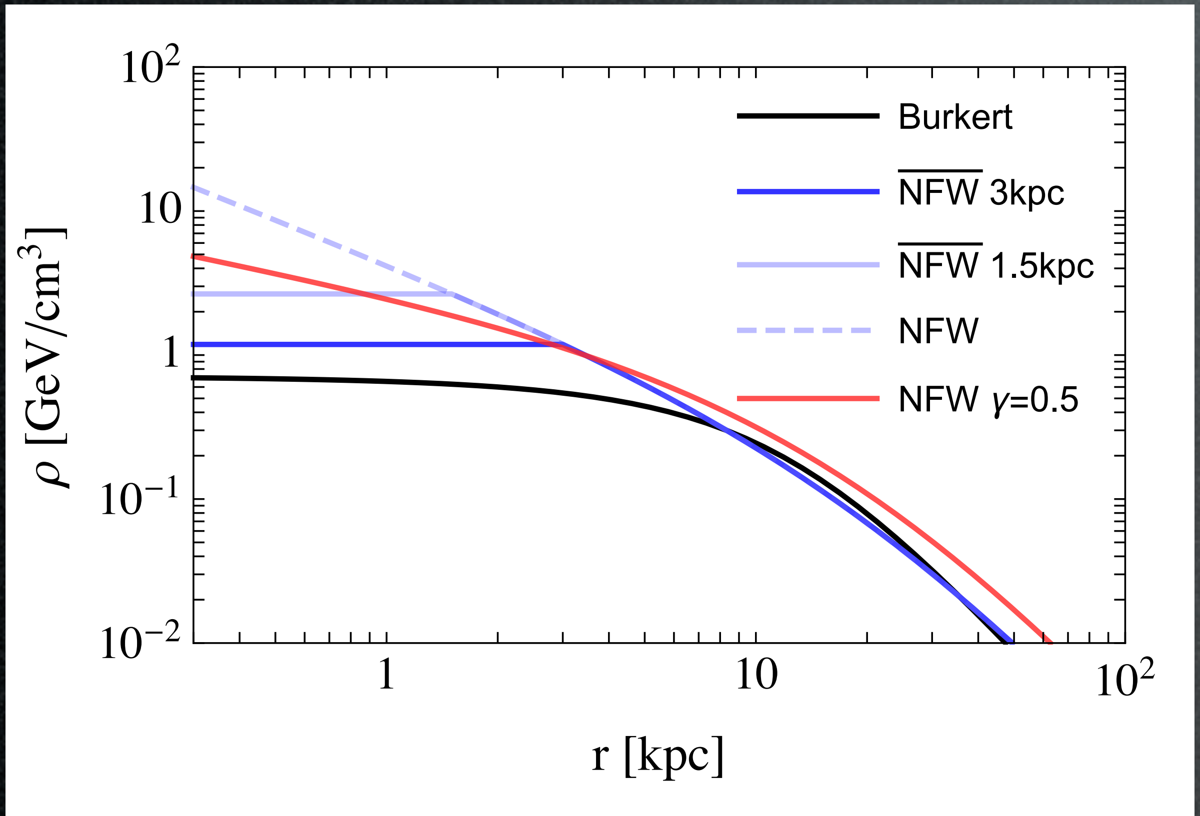
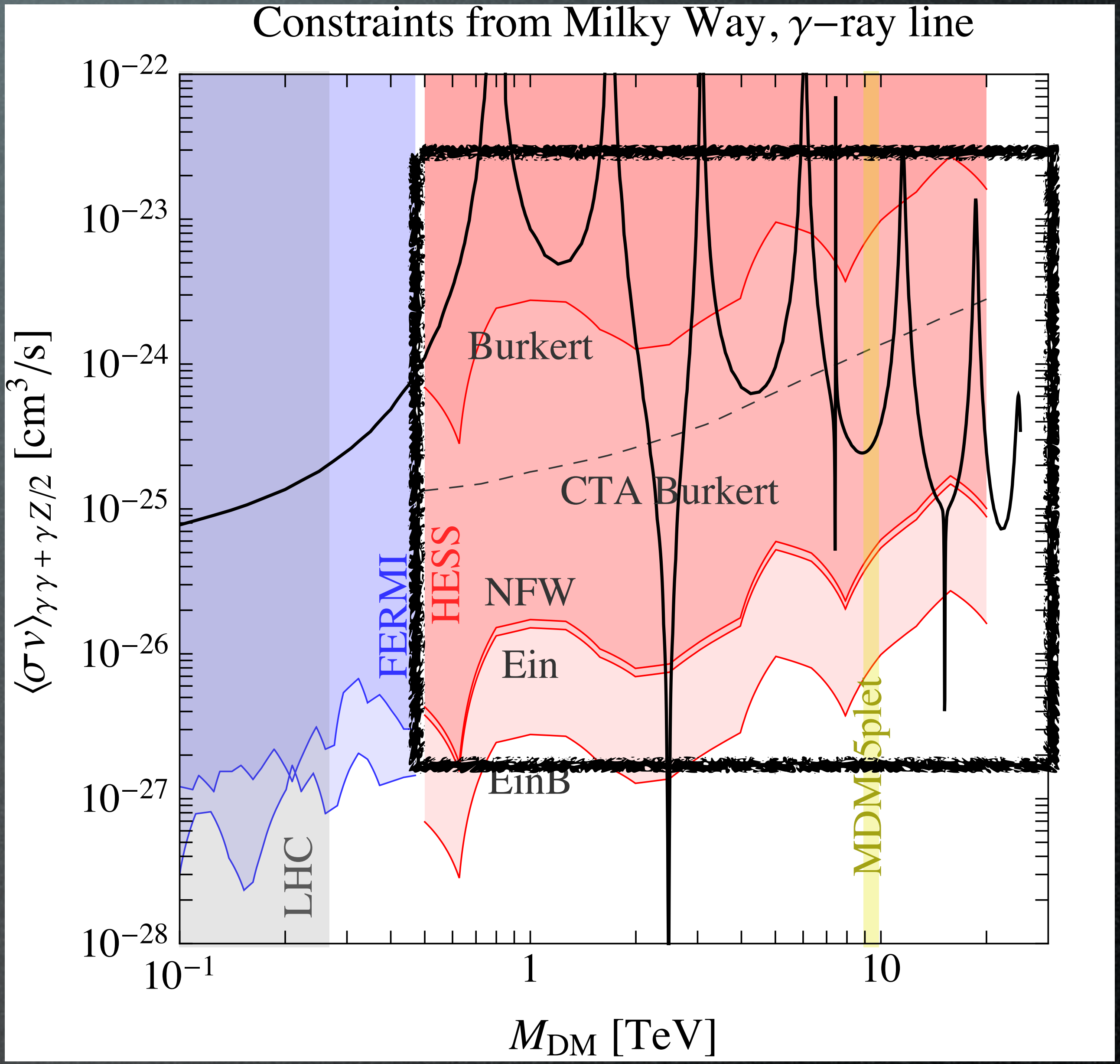
MW center area, search for $\gamma$-ray lines:

Simulations and observations do not resolve $\lesssim$ 2 kpc

Uncertainties in DM profile:



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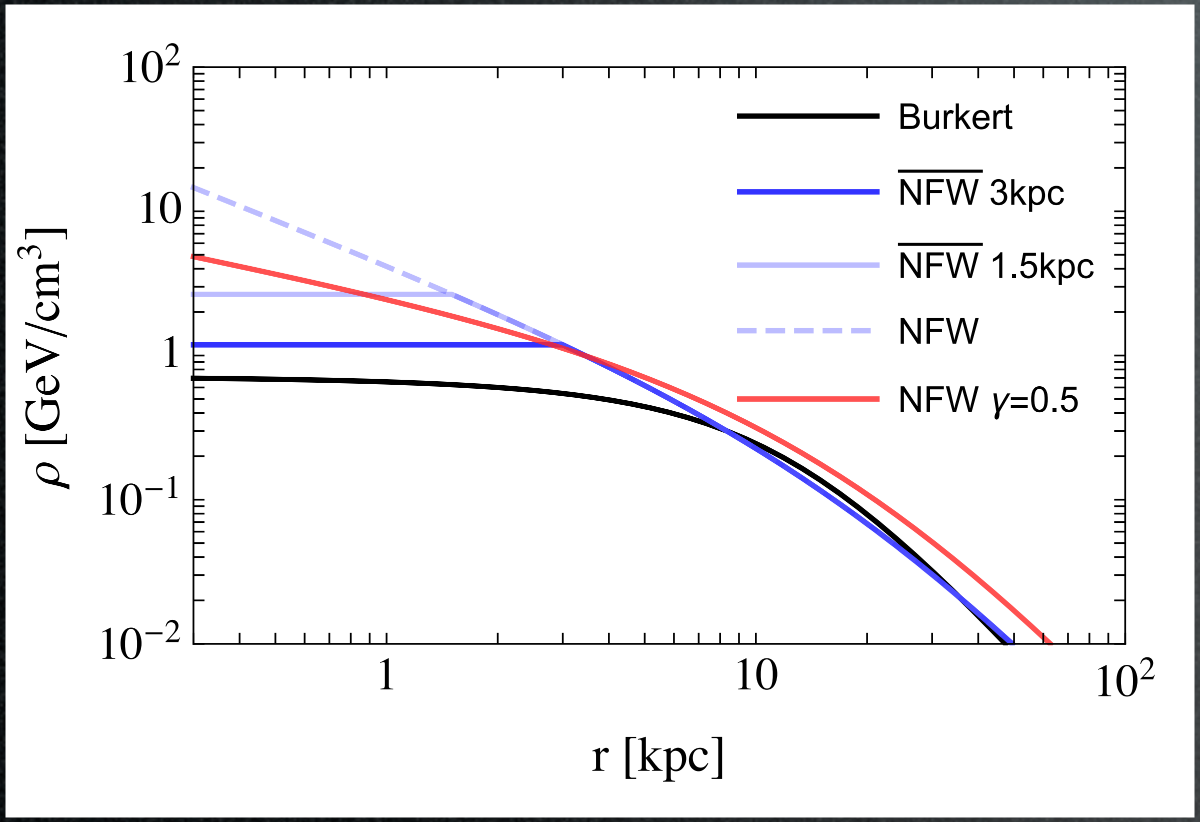


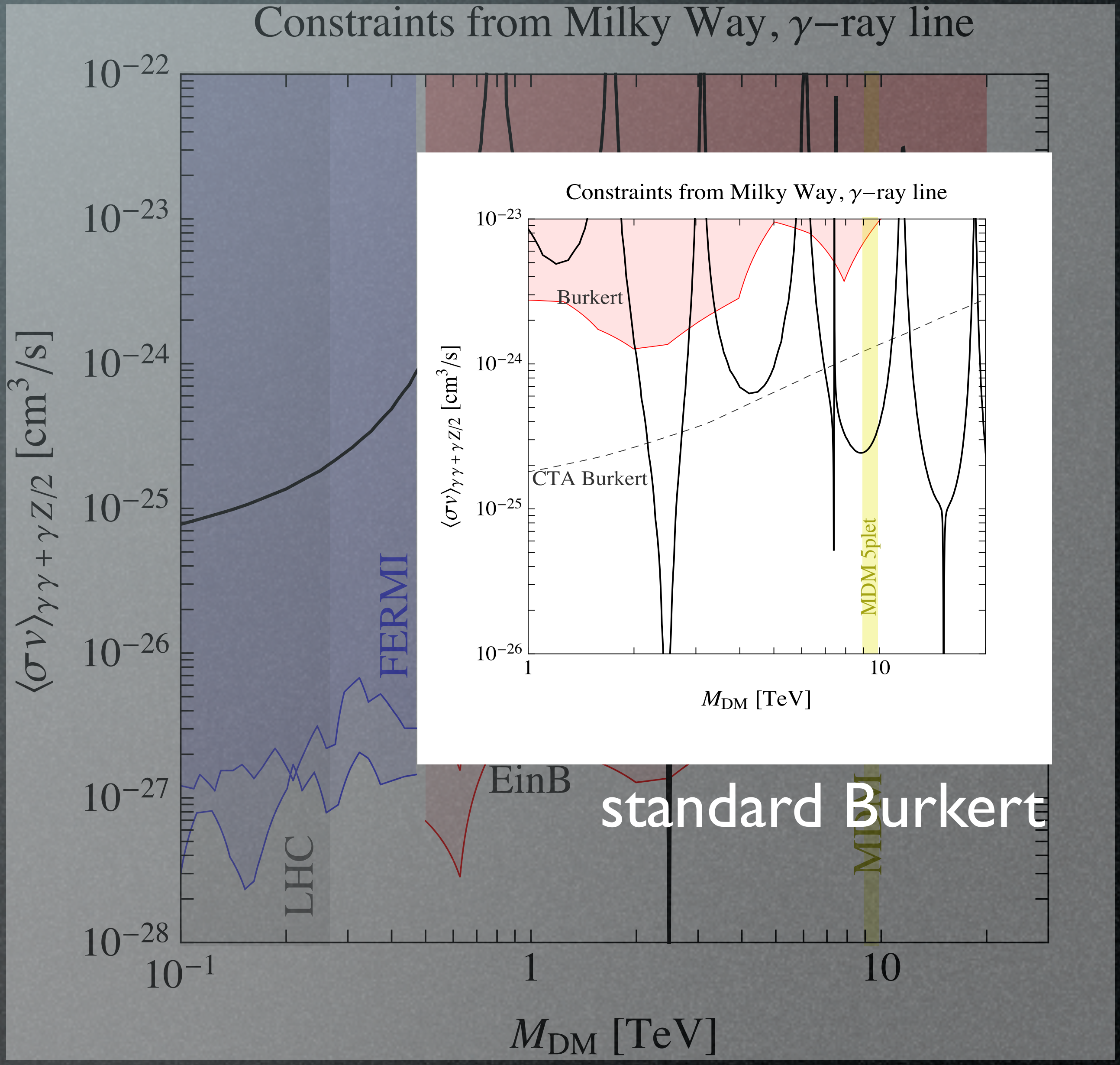

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MW center area, search for $\gamma$-ray lines:

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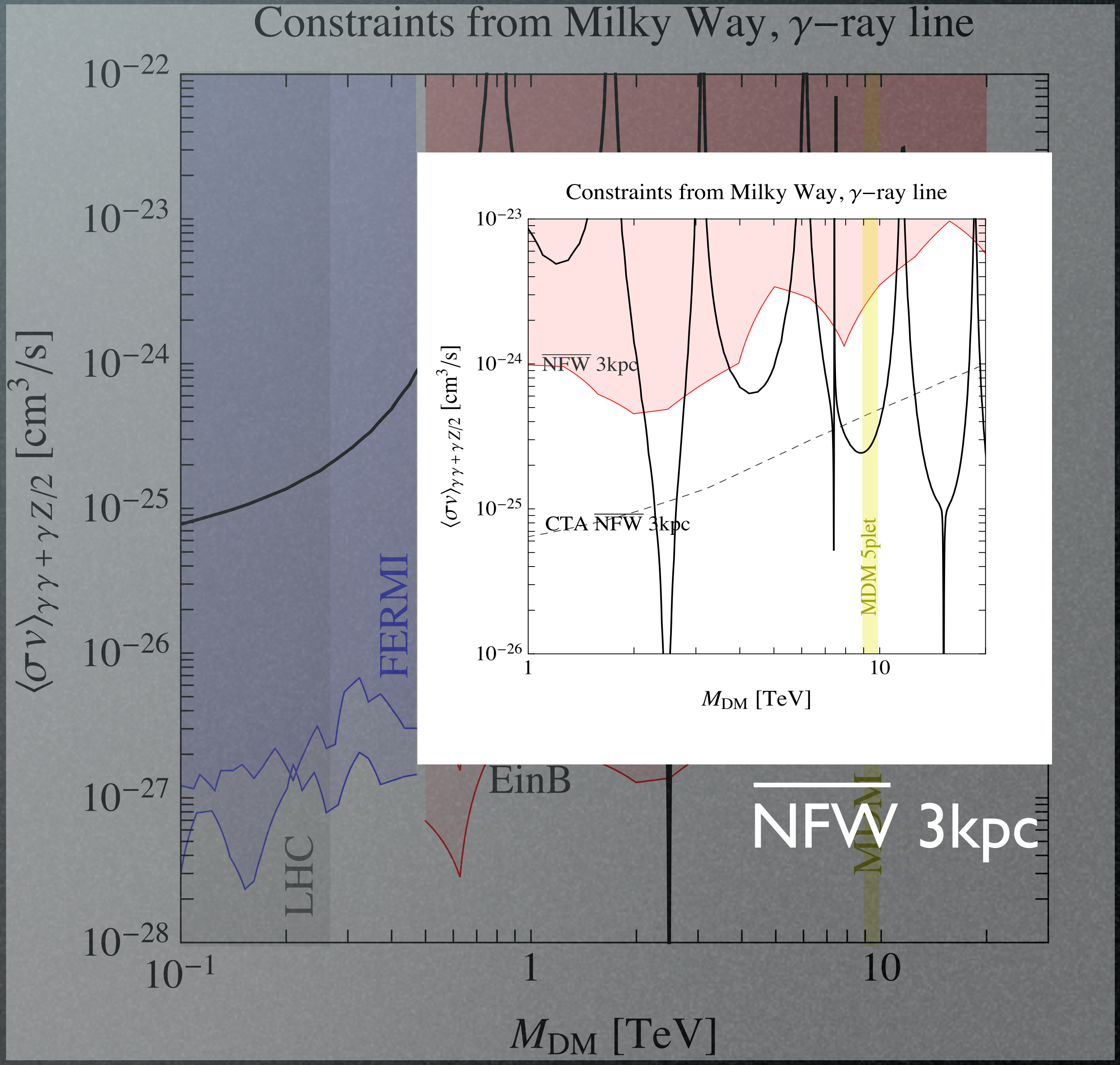
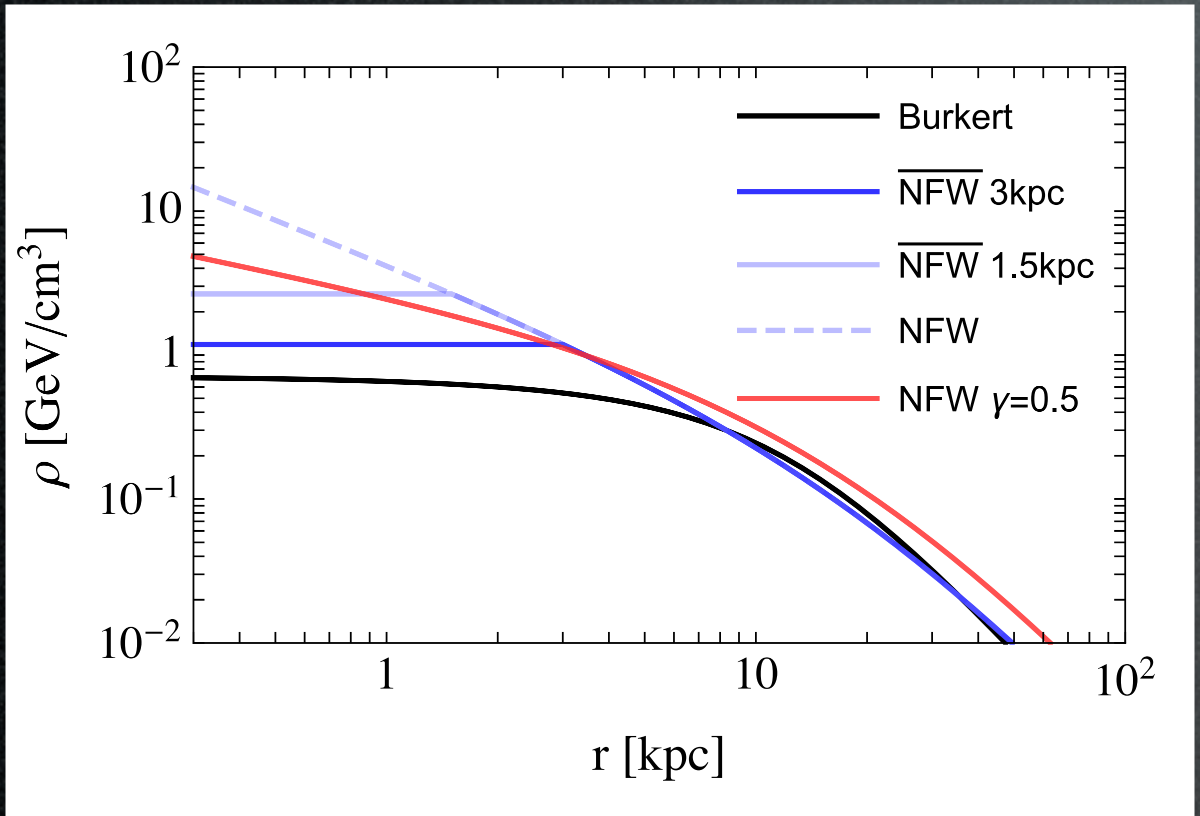



Uncertainties in DM profile:



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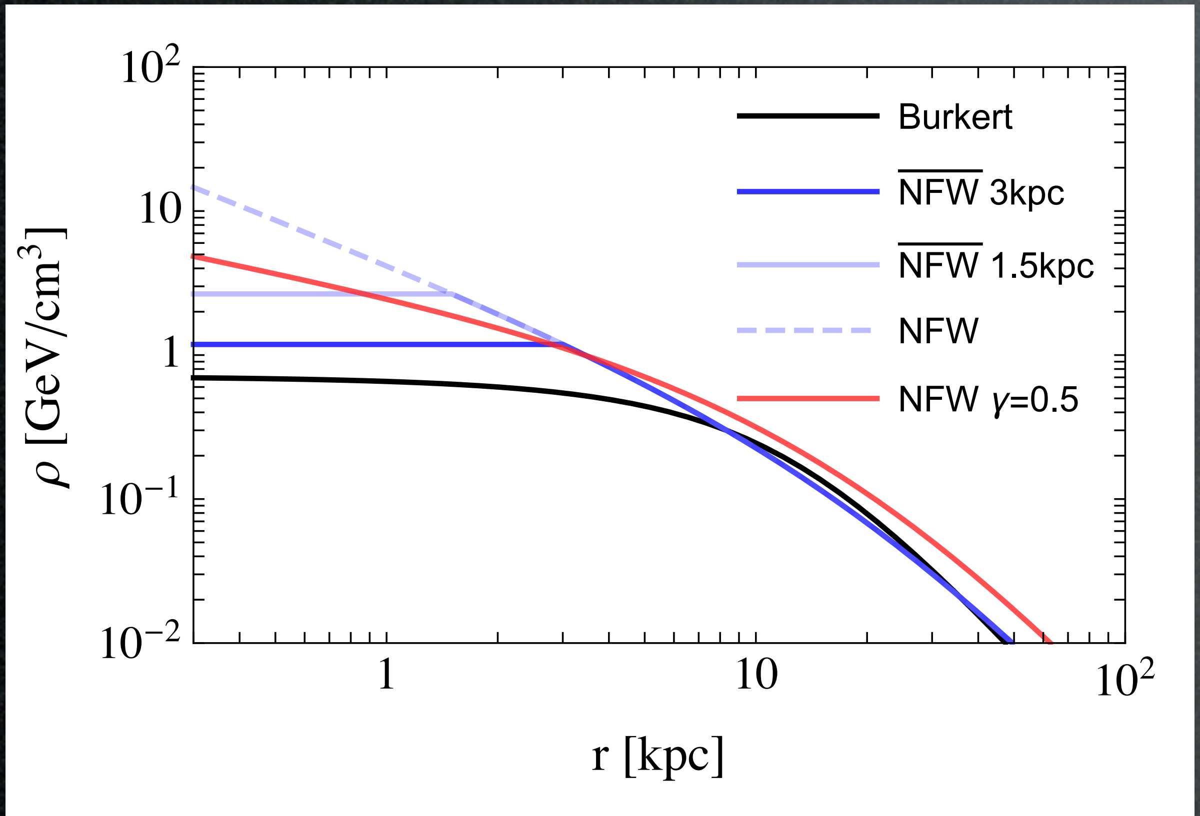


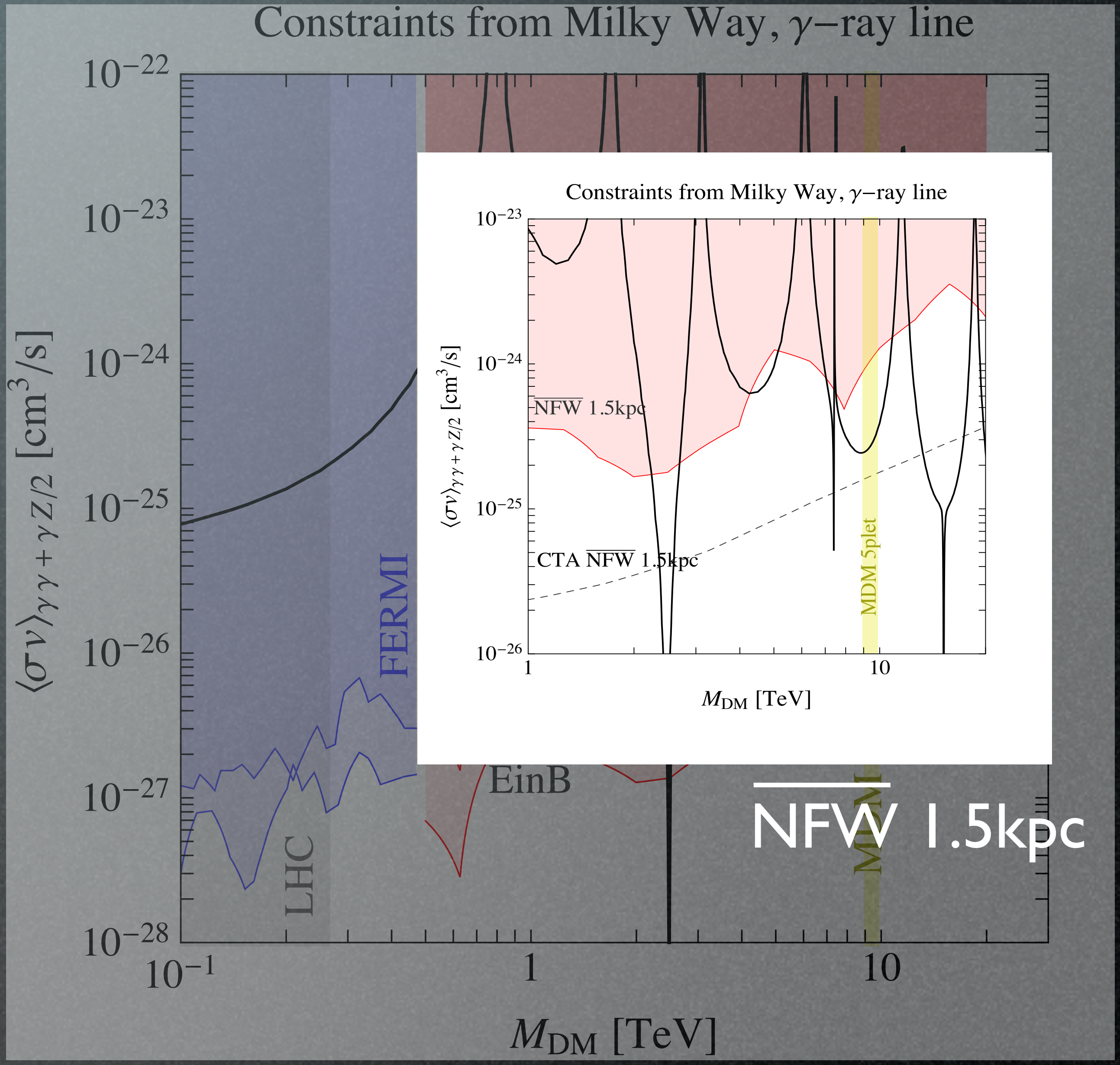

# 3. Indirect Detection

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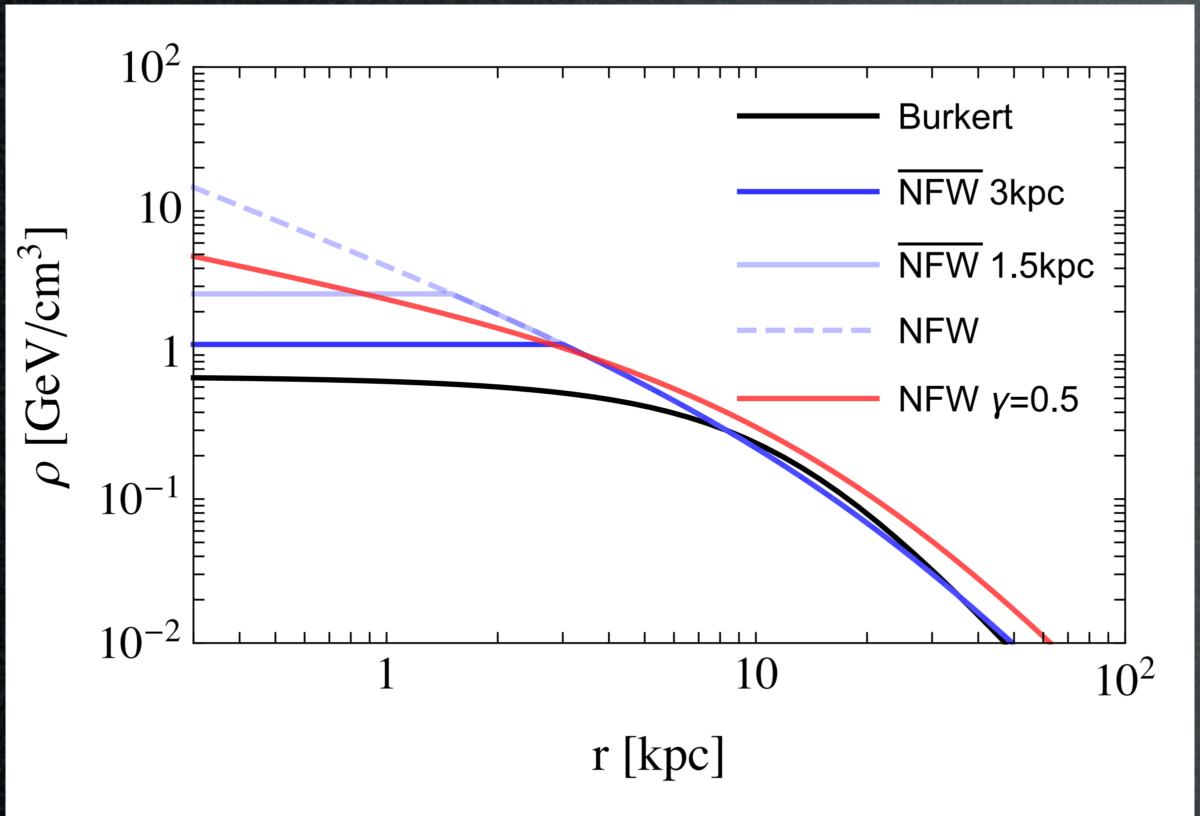
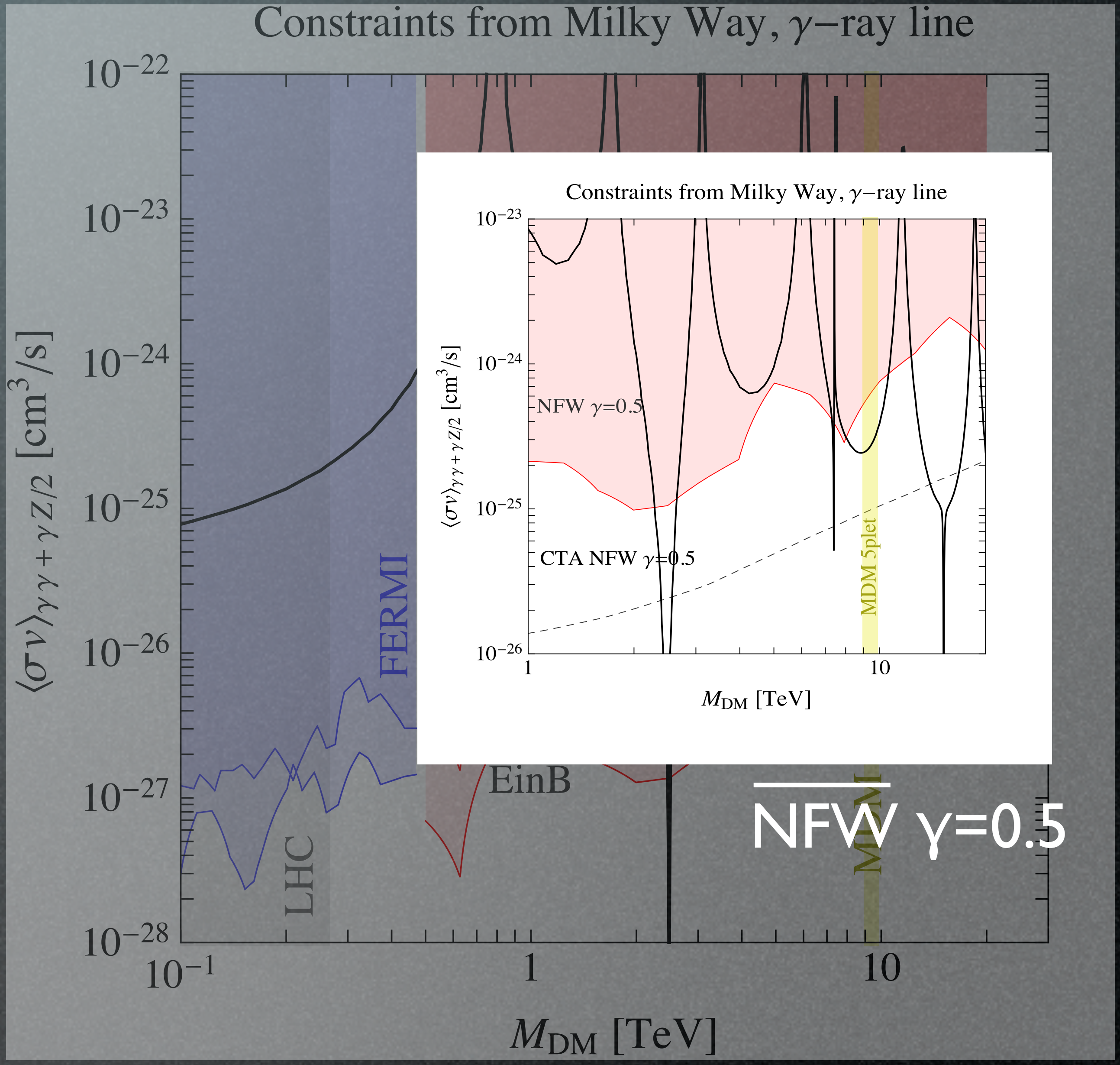
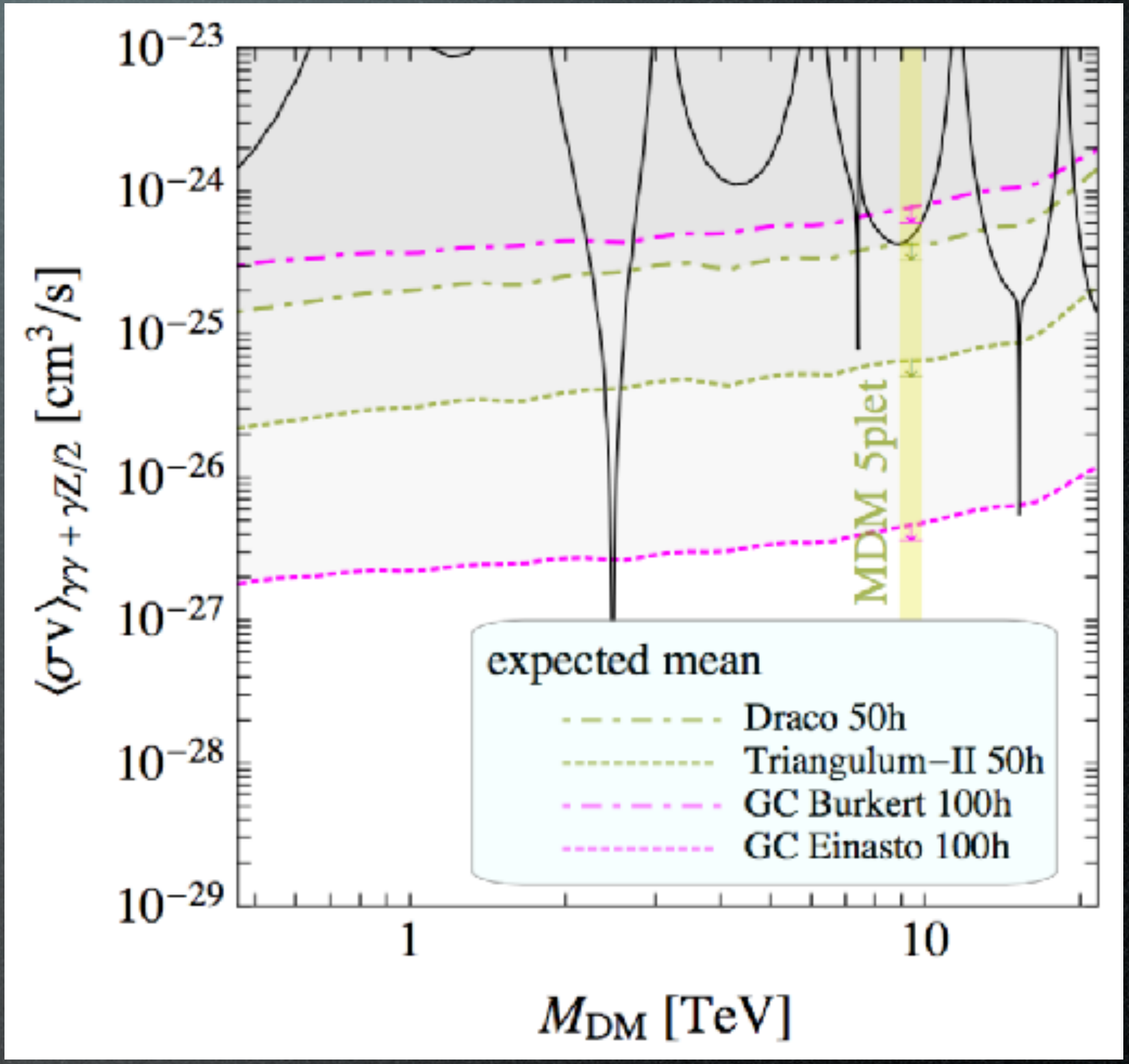
Uncertainties in DM profile:



# 3. Indirect Detection

Updated future sensitivity with CTA, search for $\gamma$-ray lines:




Lefranc, Moulin, Panci, Sala, Silk 1608.00786

Btw, dwarfs do better than GC (if GC is cored).