5 February 2016
IPMU, Kashiwa, Japan

# Minimal Dark Matter,

## reloaded

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LPTHE PARIS

erc NewDark

Based on: Cirelli, Fornengo, Strumia 'Minimal Dark Matter', NPB 2006 +…
Cirelli, Sala, Taoso, JHEP 2014
Cirelli, Hambye, Panci, Sala, Taoso, JCAP 2015

# Introduction

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DM exists

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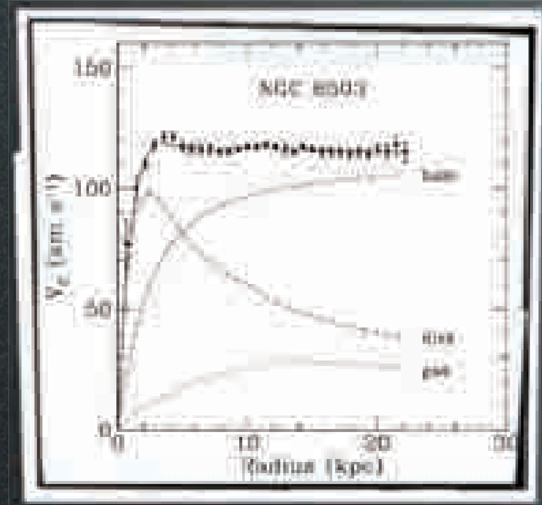
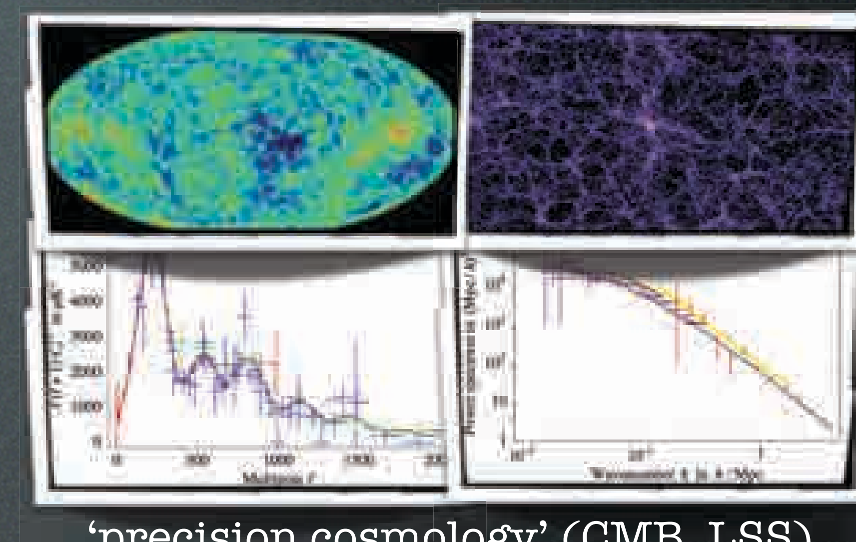
## DM exists



galactic rotation curves

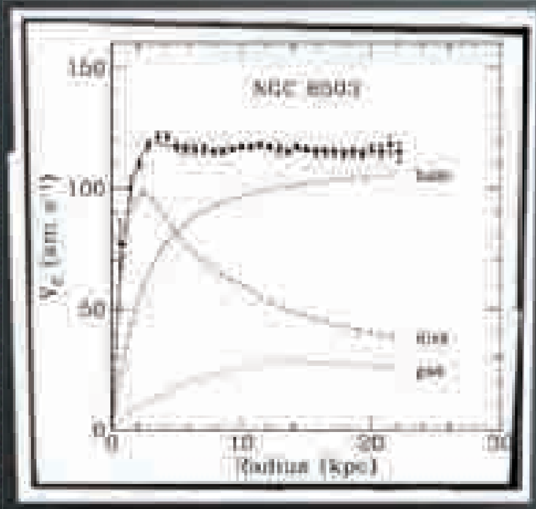
weak lensing (e.g. in clusters)



‘precision cosmology’ (CMB, LSS)

# Introduction

## DM **exists**

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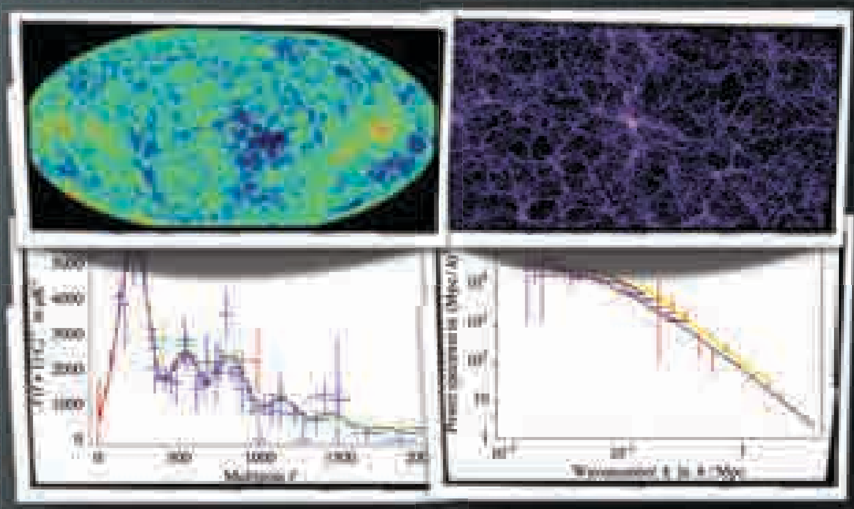


‘precision cosmology’ (CMB, LSS)

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

Most likely a

weakly int., massive, neutral, stable

relic particle.

Most likely a

# weakly int., massive, neutral, stable

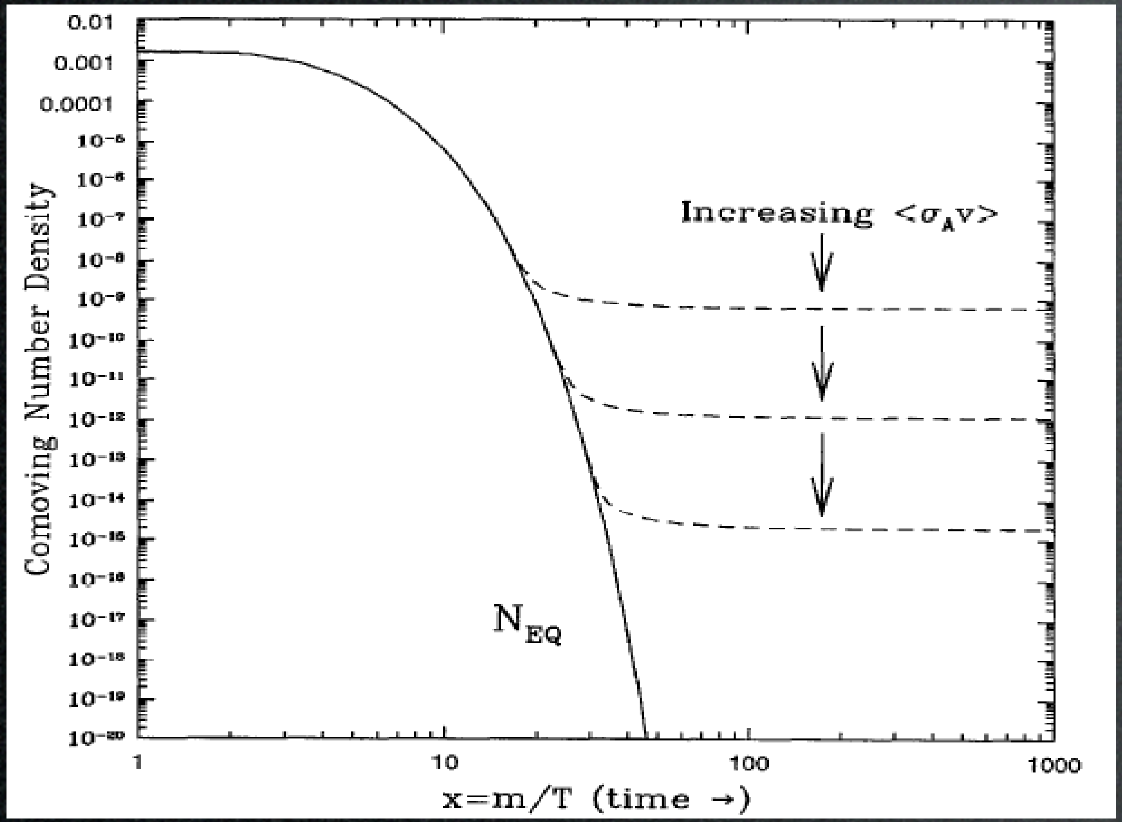
has the correct
**relic abundance** today!

Boltzmann eq. in the Early Universe:

$$\Omega_X \approx \frac{6\ 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle \sigma_{\mathrm{ann}} v \rangle}$$

Weak cross section:

$$\langle \sigma_{\mathrm{ann}} v \rangle \approx \frac{\alpha_w^2}{M^2} \approx \frac{\alpha_w^2}{\mathbf{1\ TeV}^2} \quad \Rightarrow \Omega_X \sim \mathcal{O}(\mathrm{few}\ 0.1)$$




Kolb,Turner, The Early Universe, 1995

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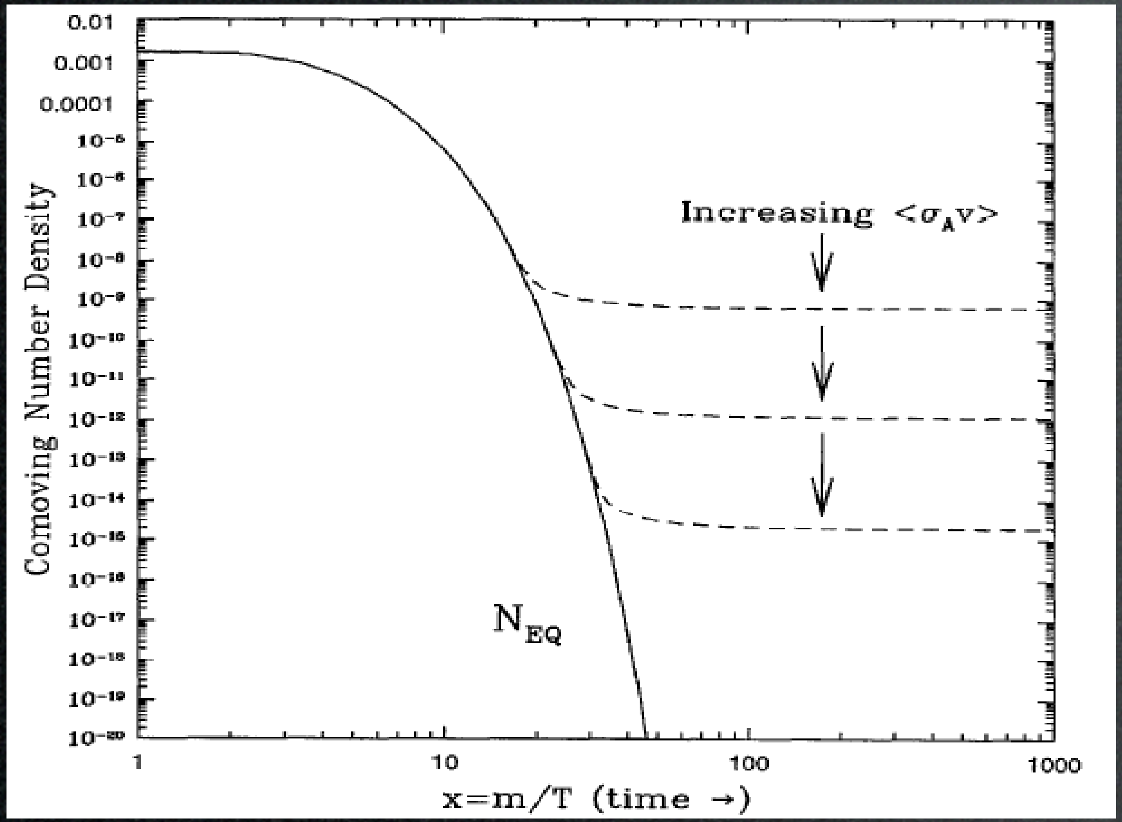


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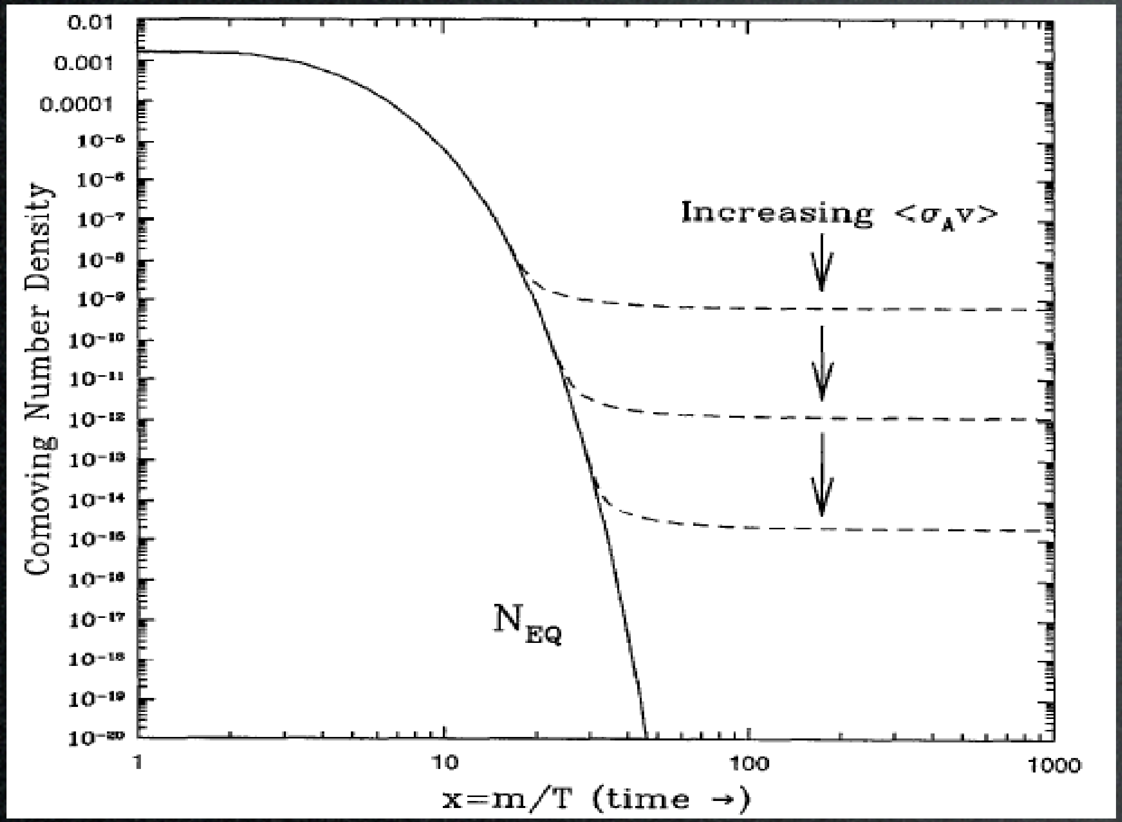


Kolb,Turner, The Early Universe, 1995

at least on cosmological time scales, i.e.

$\tau > t_{\mathrm{universe}}$

Most likely a

# weakly int., massive, neutral, stable

Theories beyond the SM have ambitious goals (hierarchy prob, EWSB, unification).
As a *byproduct*, they can provide DM candidates at the EW scale.

Popular candidates:

SuperSymmetric LSP,
Extra dimensional LKP...

...BUT:

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(the LHC did not find New Physics, at least yet)

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DM phenomenology is unclear (scatter plots)

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(ii) these theories have many parameters,
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(iii) DM stability is imposed by hand
(R-parity, T-parity, KK parity)

# Minimalistic approach

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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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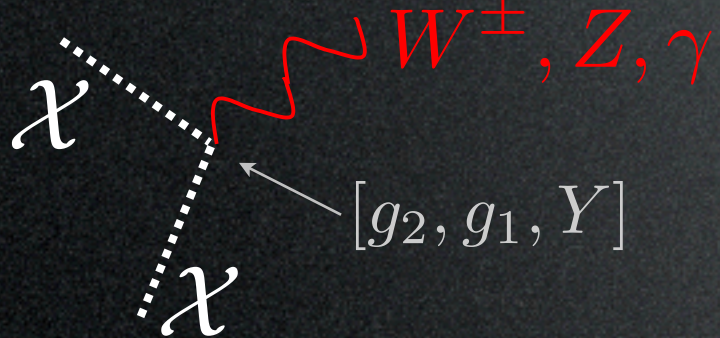
gauge interactions

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

## The ideal DM candidate is

# weakly int., massive, neutral, stable

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

$$\mathcal{X} = \begin{pmatrix} \mathcal{X}_1 \\ \mathcal{X}_2 \\ \vdots \\ \mathcal{X}_n \end{pmatrix}$$

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

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

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:

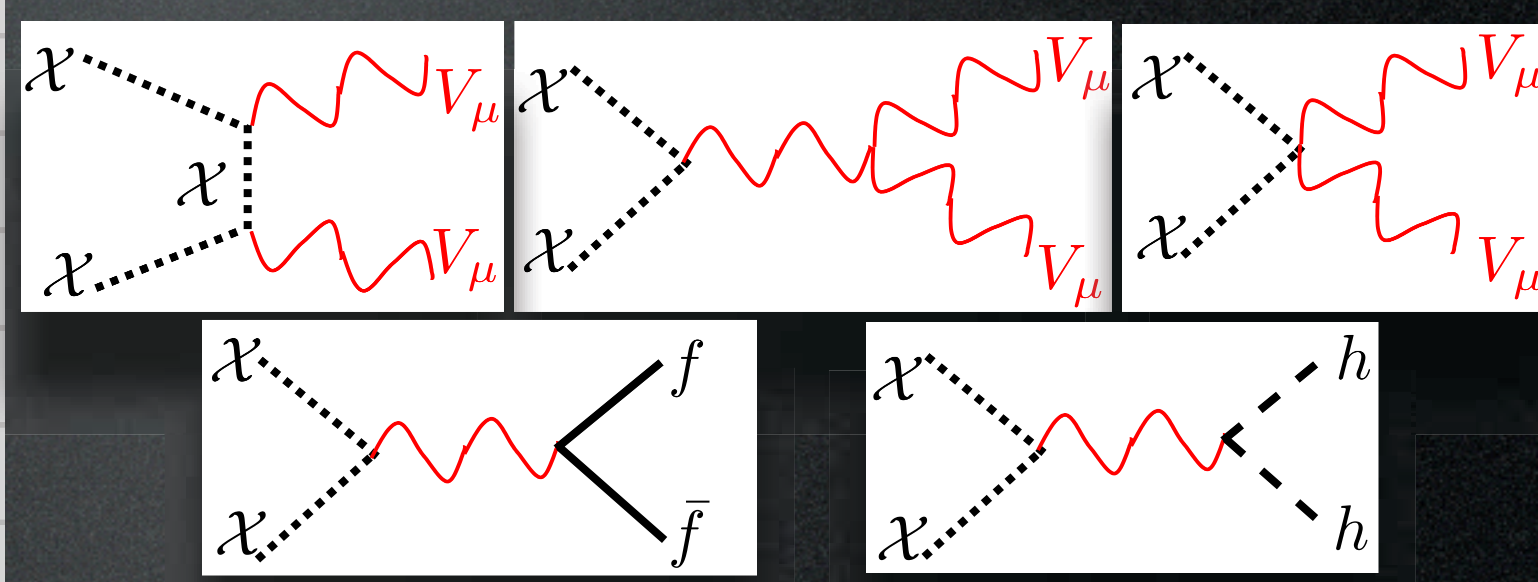
$$\Omega_{\rm DM} = \frac{6\ 10^{-27}{\rm cm}^3{\rm s}^{-1}}{\langle\sigma_{\rm ann} v\rangle} \simeq 0.24$$

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

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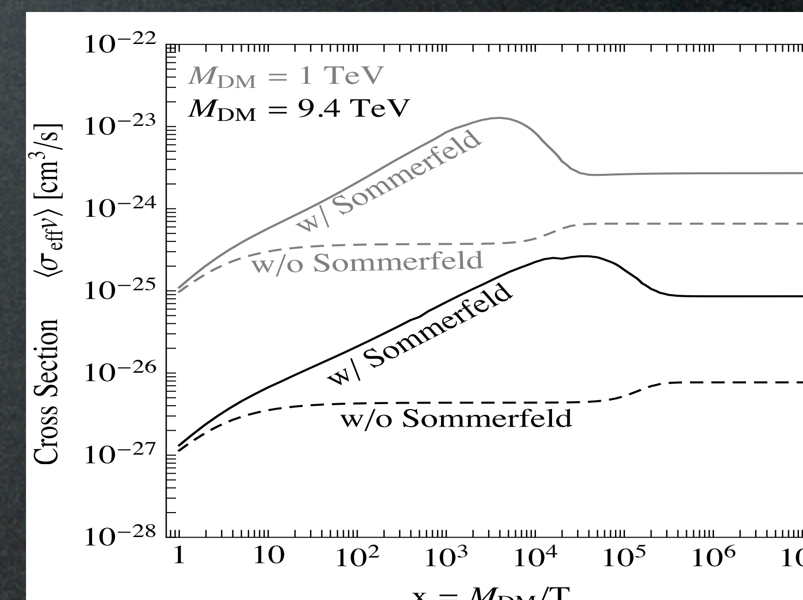
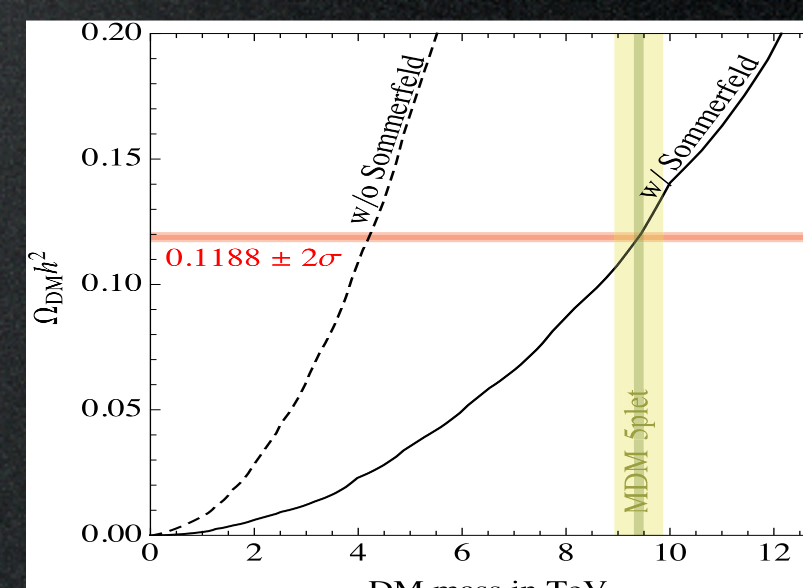
| $SU(2)_L$ | $U(1)_Y$ | spin | $M$ (TeV) |
|---|---|---|---|
| $\underline{2}$ | $1/2$ | $S$ | |
| | | $F$ | 1.0 |
| $\underline{3}$ | $0$ | $S$ | 2.5 |
| | | $F$ | 2.7 |
| | $1$ | $S$ | |
| | | $F$ | |
| $\underline{4}$ | $1/2$ | $S$ | |
| | | $F$ | |
| | $3/2$ | $S$ | |
| | | $F$ | |
| $\underline{5}$ | $0$ | $S$ | |
| | | $F$ | 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 $R \sim \mathcal{O}(\text{few}) \to \mathcal{O}(10^2)$



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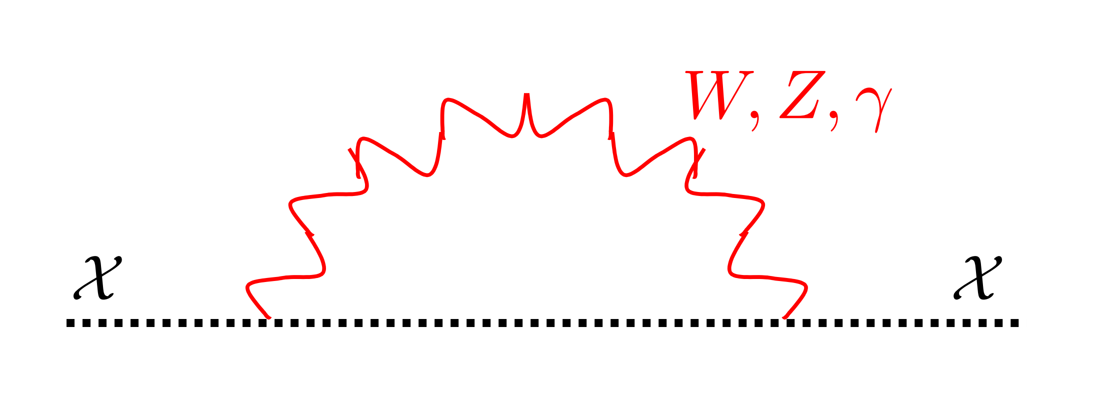
| $SU(2)_L$ | $U(1)_Y$ | spin | $M$ (TeV) | $\Delta M$(MeV) |
|---|---|---|---|---|
| 2 | 1/2 | $S$ | | 348 |
| | | $F$ | 1.0 | 342 |
| 3 | 0 | $S$ | 2.5 | 166 |
| | | $F$ | 2.7 | 166 |
| | 1 | $S$ | | 540 |
| | | $F$ | | 526 |
| 4 | 1/2 | $S$ | | 353 |
| | | $F$ | | 347 |
| | 3/2 | $S$ | | 729 |
| | | $F$ | | 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:

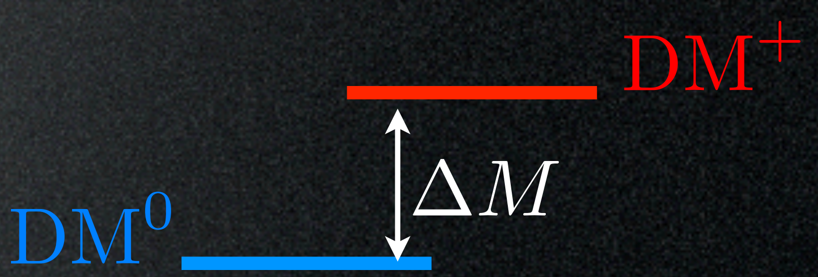
tree level




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

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

The neutral component is the lightest



# The ideal DM candidate is

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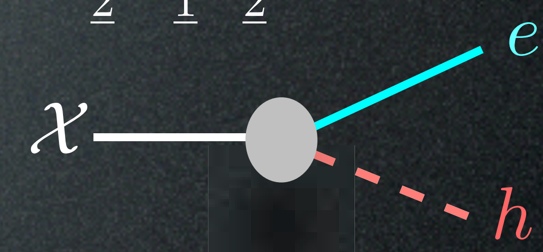
| $SU(2)_L$ | $U(1)_Y$ | spin | $M$ (TeV) | $\Delta M$(MeV) | decay ch. |
|---|---|---|---|---|---|
| $\underline{2}$ | $1/2$ | $S$ | | 348 | $EL$ |
| | | $F$ | 1.0 | 342 | $EH$ |
| $\underline{3}$ | $0$ | $S$ | 2.5 | 166 | $HH^*$ |
| | | $F$ | 2.7 | 166 | $LH$ |
| | $1$ | $S$ | | 540 | $HH, LH$ |
| | | $F$ | | 526 | $LH$ |
| $\underline{4}$ | $1/2$ | $S$ | | 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

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List all allowed SM couplings:

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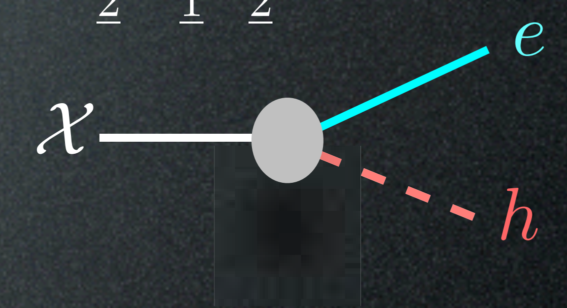


e.g. $\overset{1/2\ -1/2\ 1/2\ -1/2}{\underset{\underline{4}\ \ \underline{2}\ \ \underline{2}\ \ \underline{2}}{\chi L H H^*}}$

dim=5 operator, induces

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

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

No allowed decay!

*Automatically* stable!

The ideal DM candidate is

weakly int., massive, neutral, stable

and

not excluded

by direct searches!

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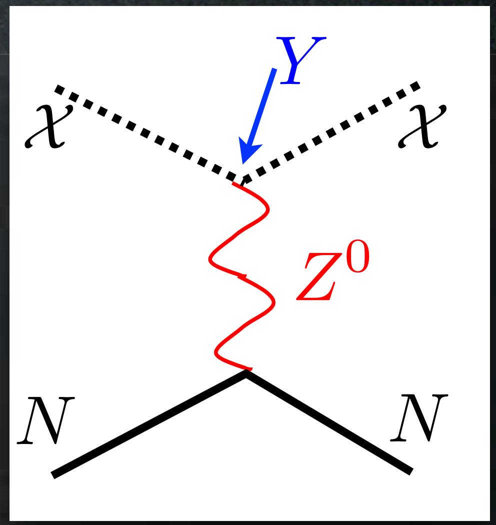
and
**not excluded**
by direct searches!

Candidates with $Y \neq 0$ interact as




$\sigma \simeq G_F^2 M_N^2 Y^2$

Goodman Witten 1985

$\gg$ present bounds
e.g. LUX

need $Y = 0$

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| | | $F$ | | 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 | $(\chi\chi H^*H)$ |

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. |
|---|---|---|---|---|---|
| $\underline{2}$ | 1/2 | $S$ | | 348 | $EL$ |
| | | $F$ | 1.0 | 342 | $EH$ |
| $\underline{3}$ | 0 | $S$ | 2.5 | 166 | $HH^*$ |
| | | $F$ | 2.7 | 166 | $LH$ |
| | 1 | $S$ | | 540 | $HH, LH$ |
| | | $F$ | | 526 | $LH$ |
| $\underline{4}$ | 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 | $(H^*H^*H^*H^*)$ |
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# 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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| | | $F$ | | 526 | $LH$ |
| 4 | 1/2 | $S$ | | 353 | $HHH^*$ |
| | | $F$ | | 347 | $(LHH^*)$ |
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| | | $F$ | | 712 | $(LHH)$ |
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| | | $F$ | 9.4 | 166 | — |
| | 1 | $S$ | | 537 | $(HH^*H^*H^*)$ |
| | | $F$ | | 534 | — |
| | 2 | $S$ | | 906 | $(H^*H^*H^*H^*)$ |
| | | $F$ | | 900 | — |
| 7 | 0 | $S$ | 25 | 166 | — |

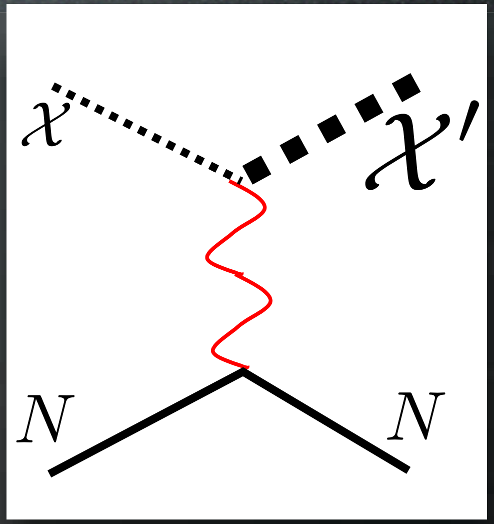
← We have a winner!

(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

# Recap:

A fermionic $SU(2)_L$ quintuplet with $Y = 0$
provides a DM candidate with $M = 9.4\ \mathrm{TeV}$,
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.)

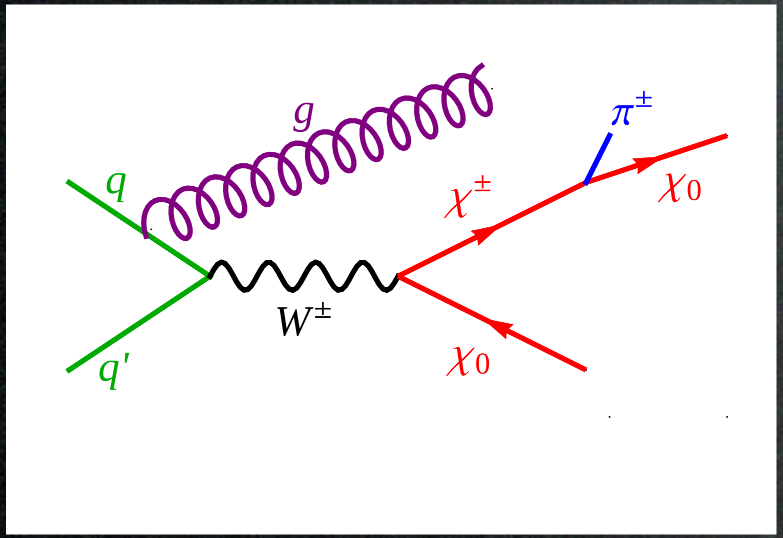
# Detection and Phenomenology

# 1. Collider searches

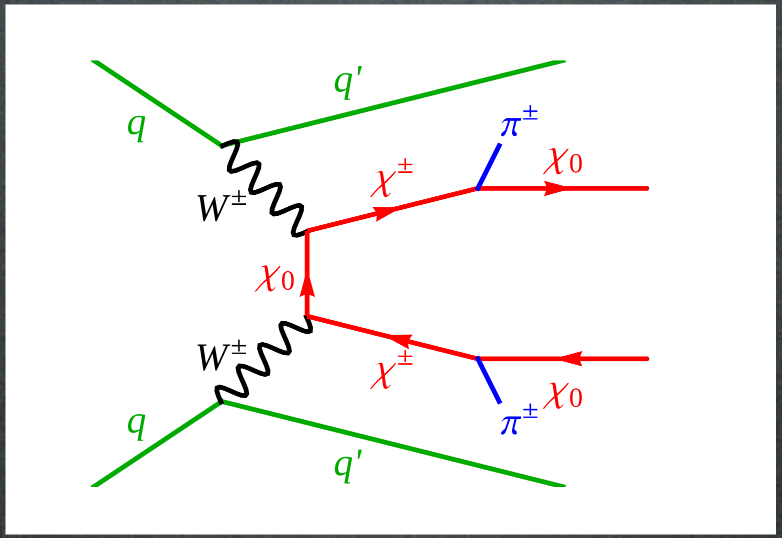
At 9.4 TeV, no hope at the LHC.

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

## Mono-X

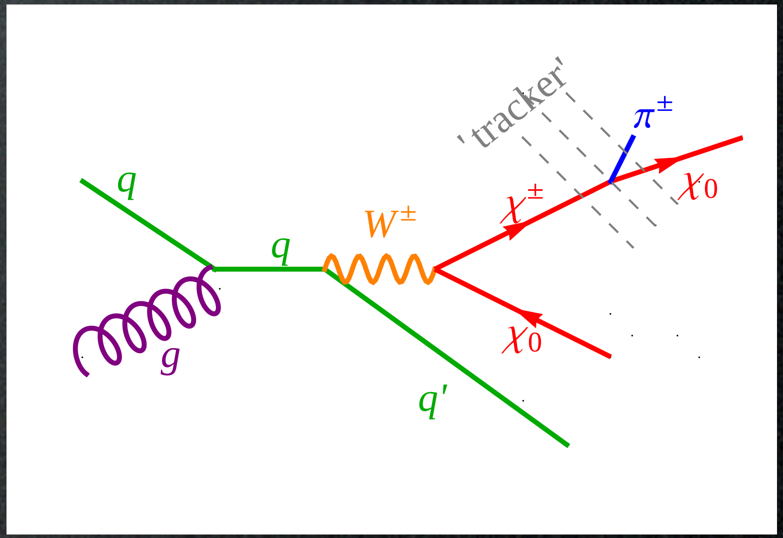



## VBF




*di-jets + MET*

## Disappearing tracks

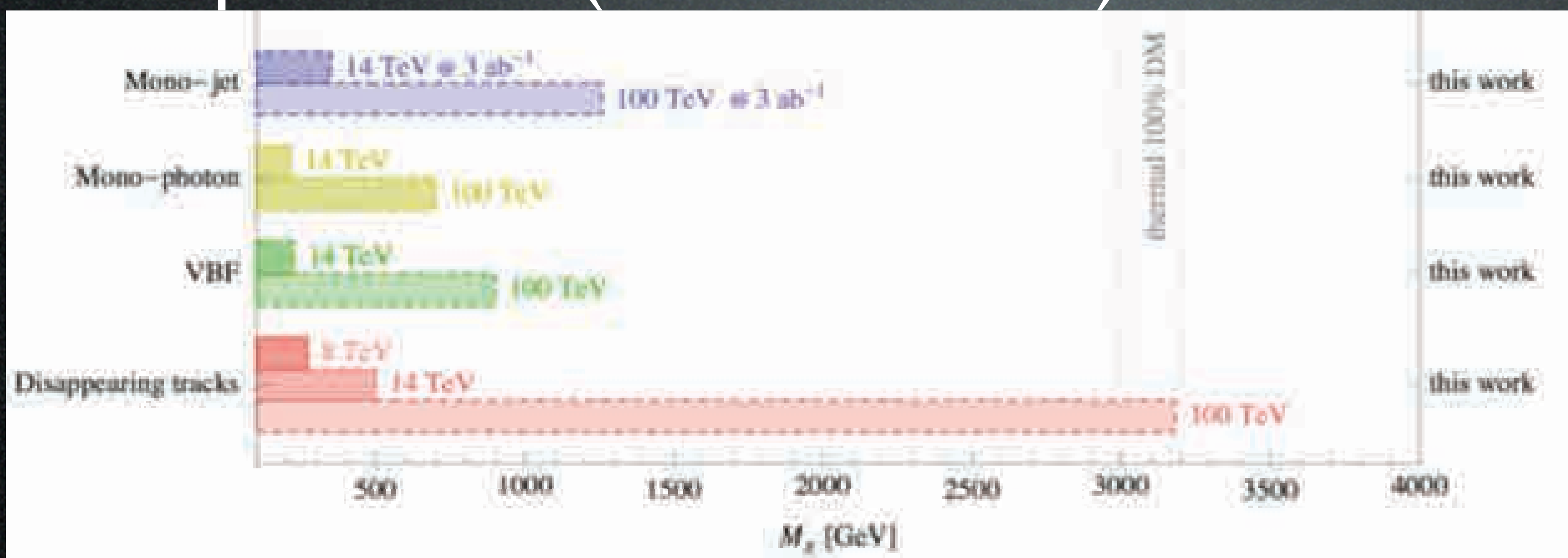


# 1. Collider searches

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

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




Cirelli, Sala, Taoso 1407.7058

For 5plet MDM

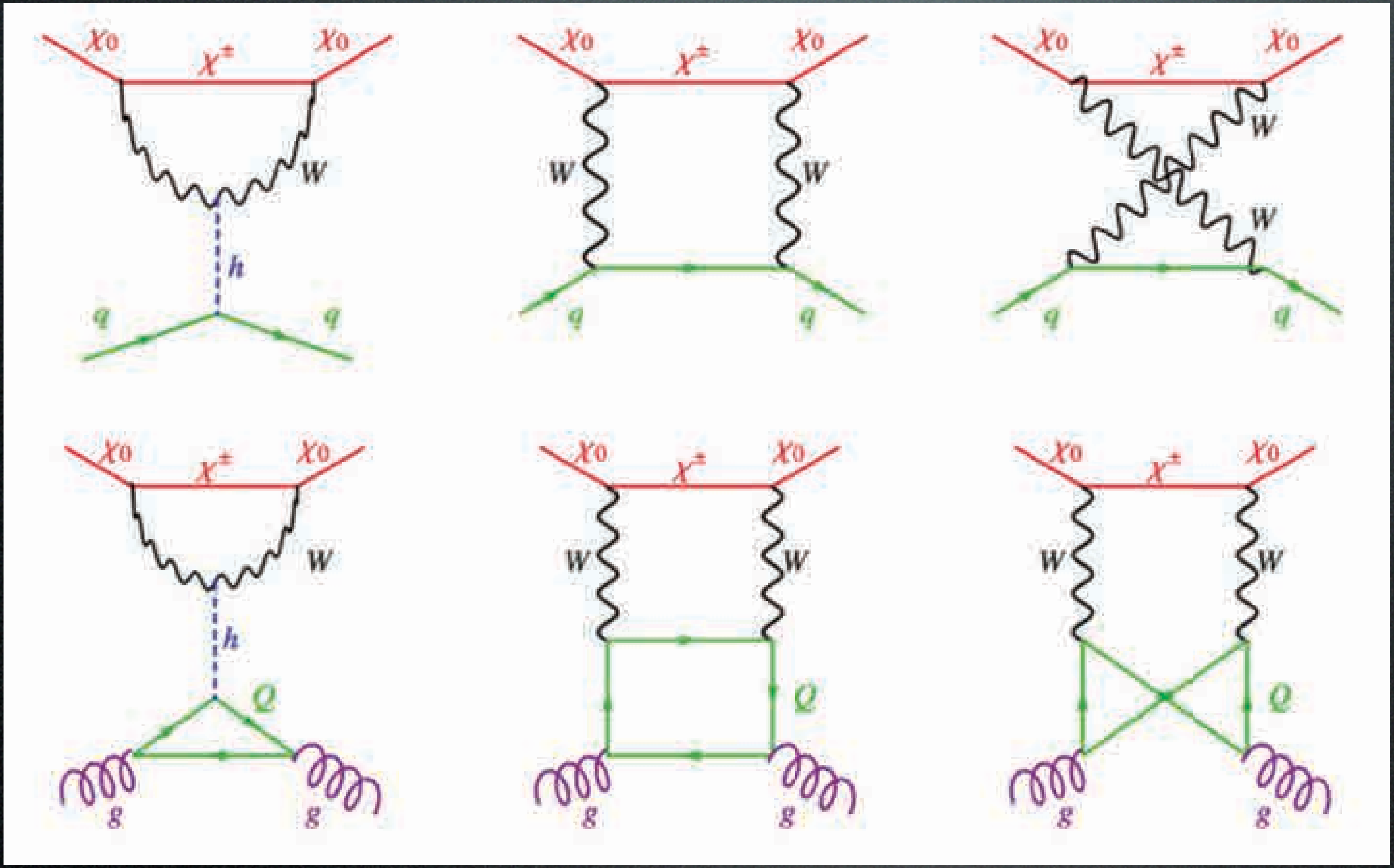
| Model | $\sqrt{s} = 8$ TeV | | | | $\sqrt{s} = 14$ TeV | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ATLAS | | CMS | | Exclude | | | Discover | | |
| | Expected | Observed | Expected | Observed | 500% | 100% | 20% | 500% | 100% | 20% |
| Wino | 224 | 238 | 203 | 195 | 354 | 483 | 635 | 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

# 2. Direct Detection

No tree level scattering.

1-loop and 2-loops:




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

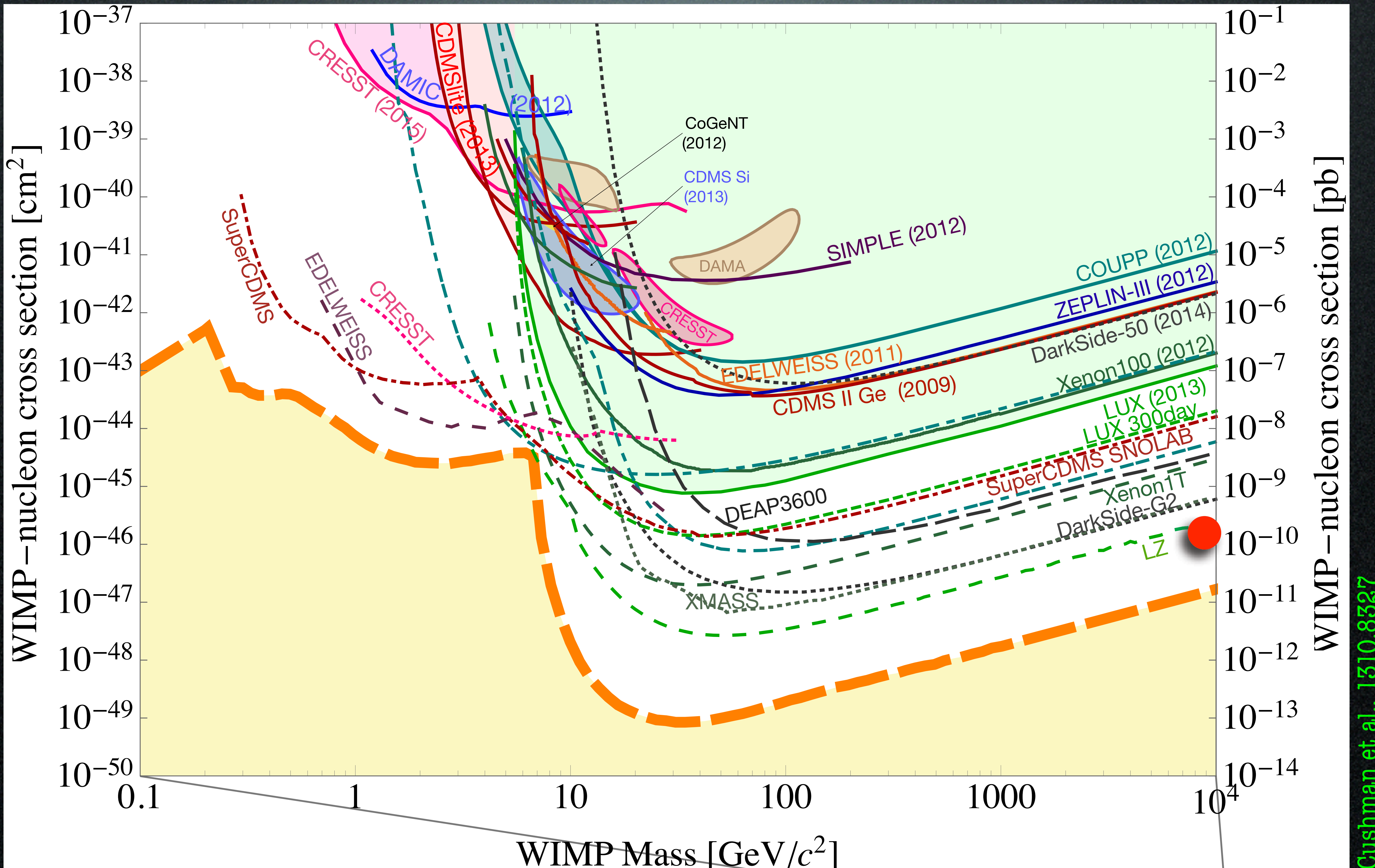
Hill, Solon 1309.4092

Hill, Solon 1401.3339

Hisano, Ishiwata, Nagata
1504.00915

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

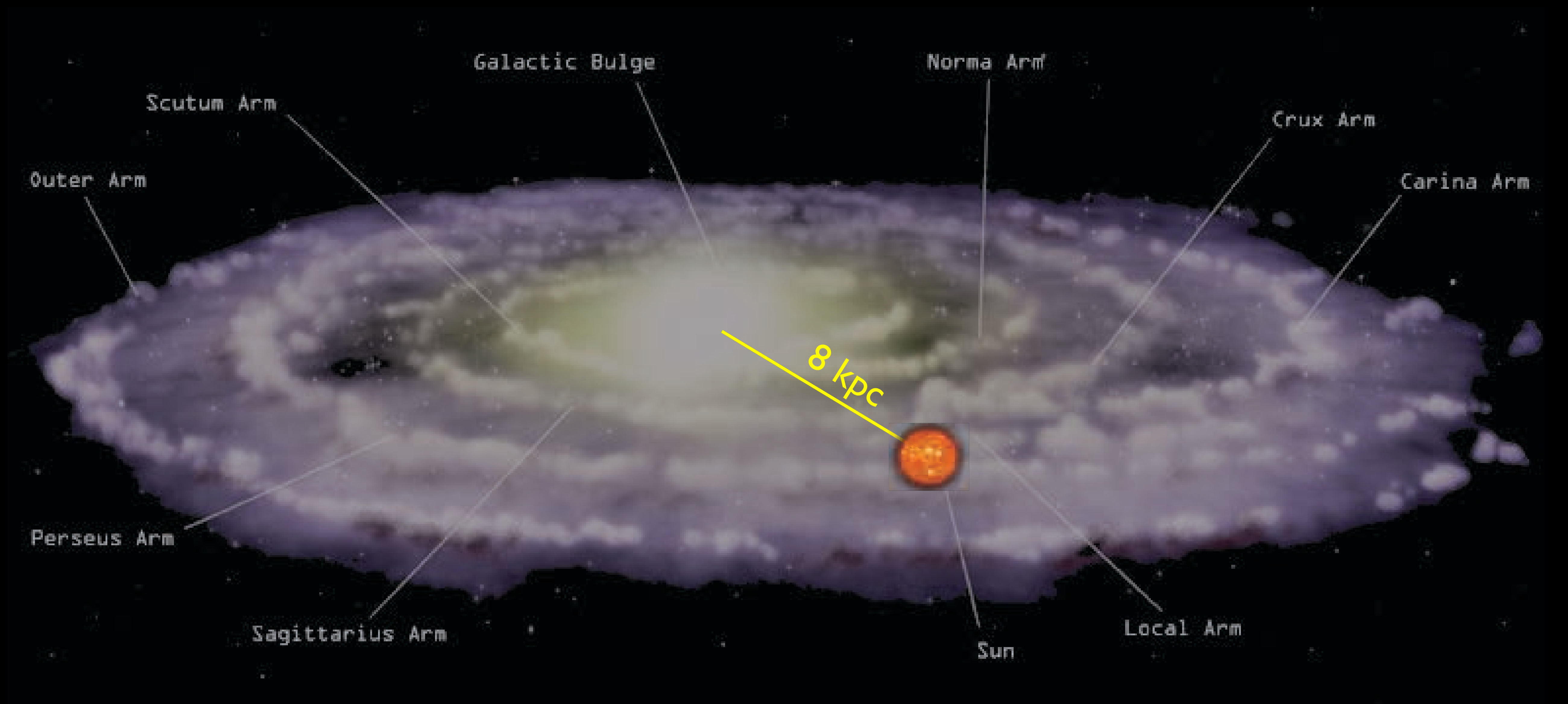
# 2. Direct Detection




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

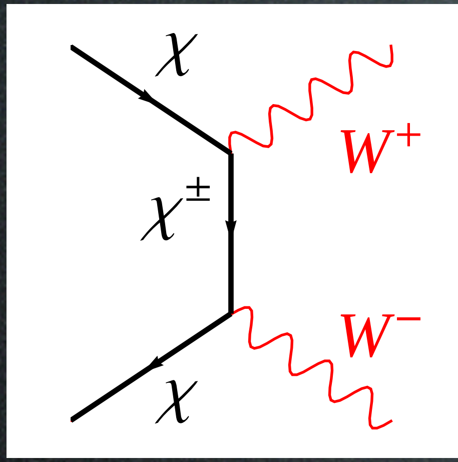
# 3. Indirect Detection

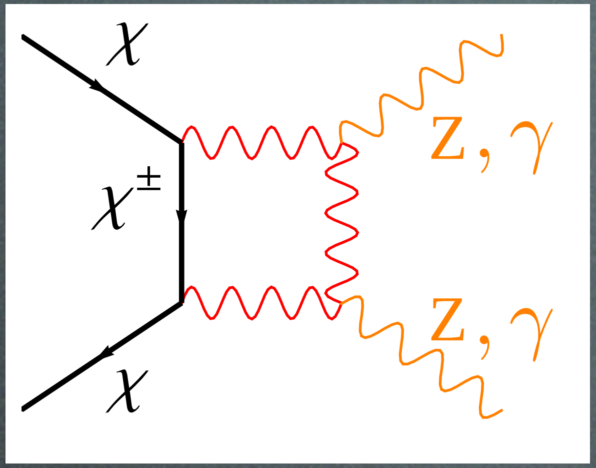
i.e. $\nu, \bar{p}, e^+, \gamma, \bar{D}$ from MDM annihilations in MW halo.



# 3. Indirect Detection

i.e. , , , $\gamma$, from MDM annihilations in MW halo.




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

(channels for MDM with Y=0)

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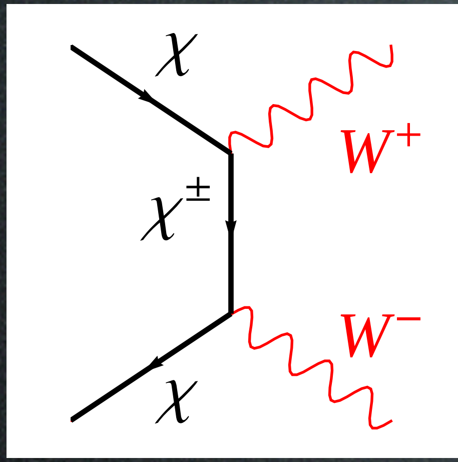
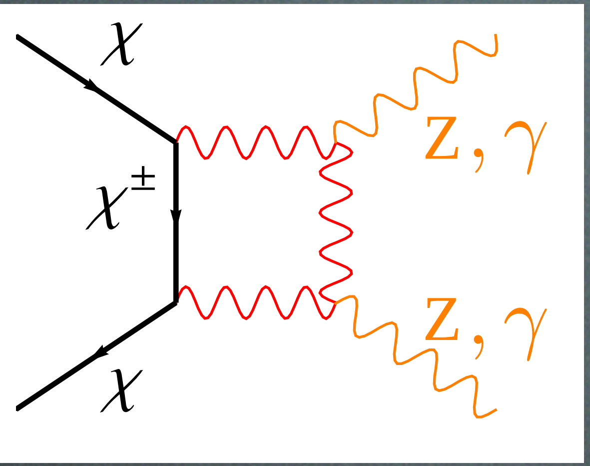


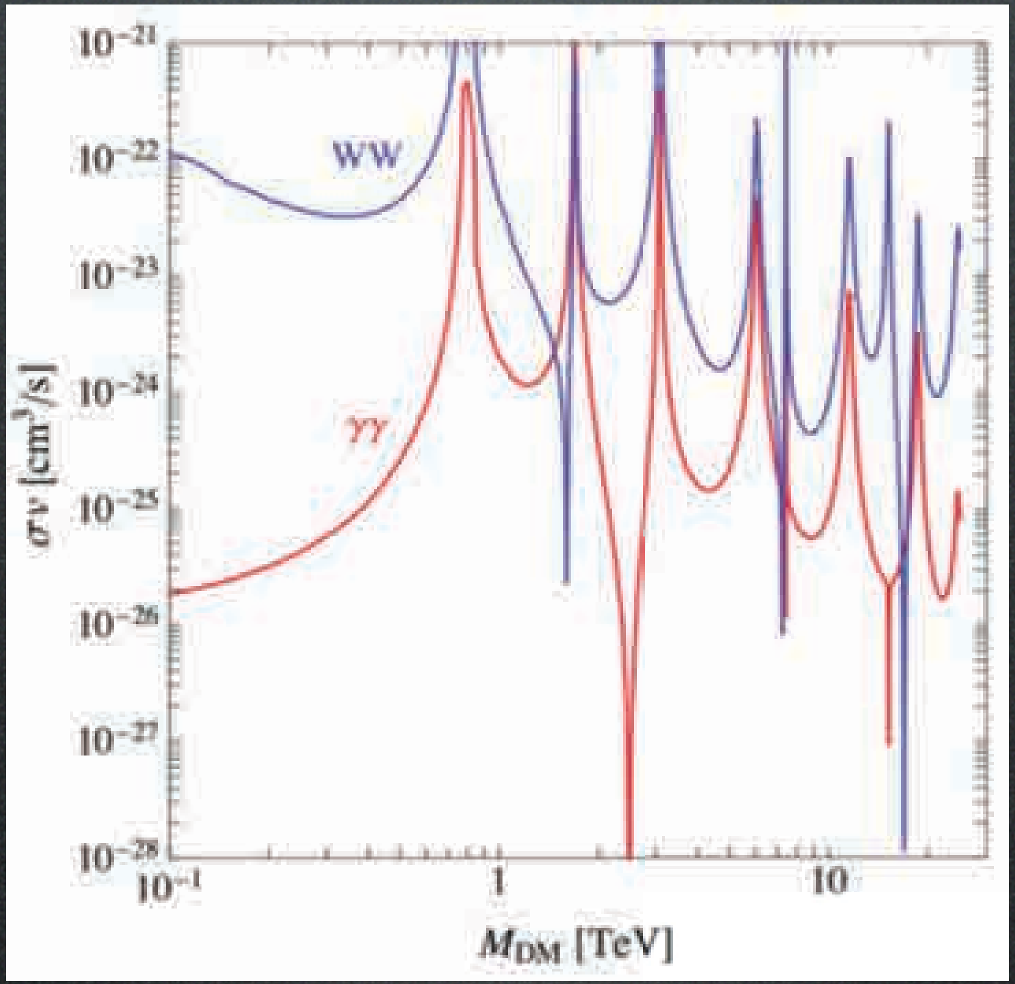




$+ \quad W^{\pm}, Z \to \bar{p}, e^{+}, \gamma \ldots$

(channels for MDM with Y=0)

Enhanced cross section due to 'Sommerfeld corrections'

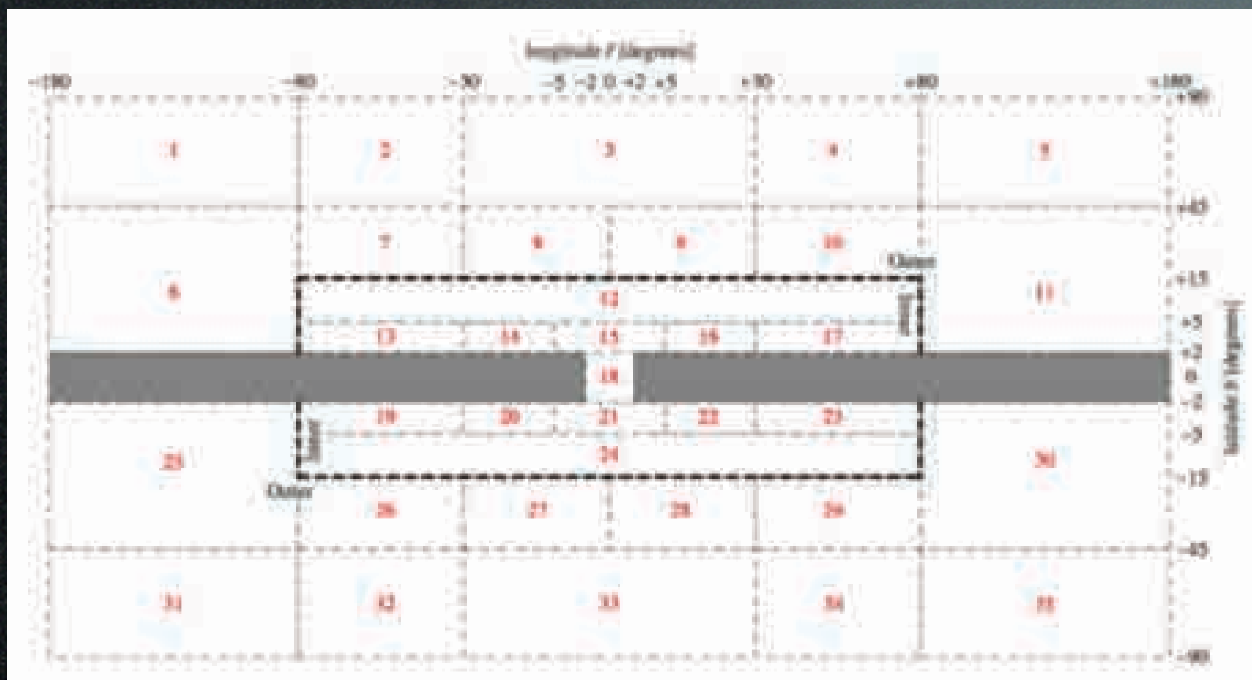
Hisano et al., 2004, 2005
Cirelli, Strumia, Tamburini 2007

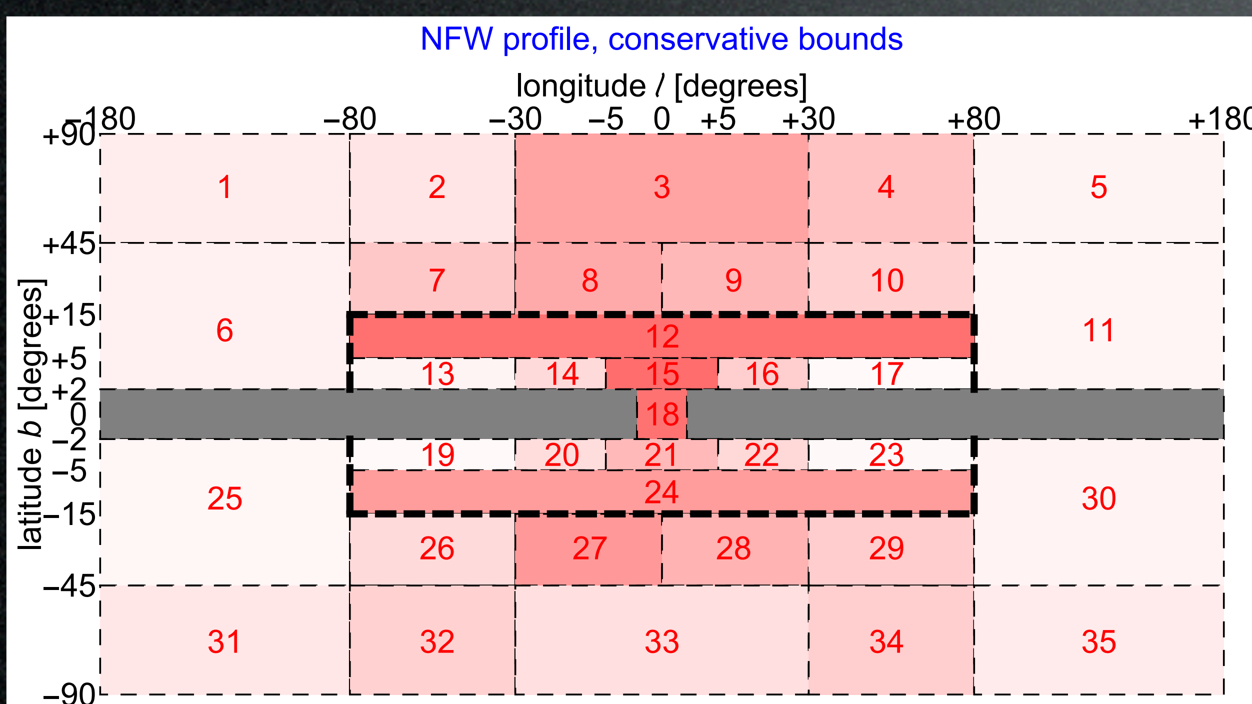


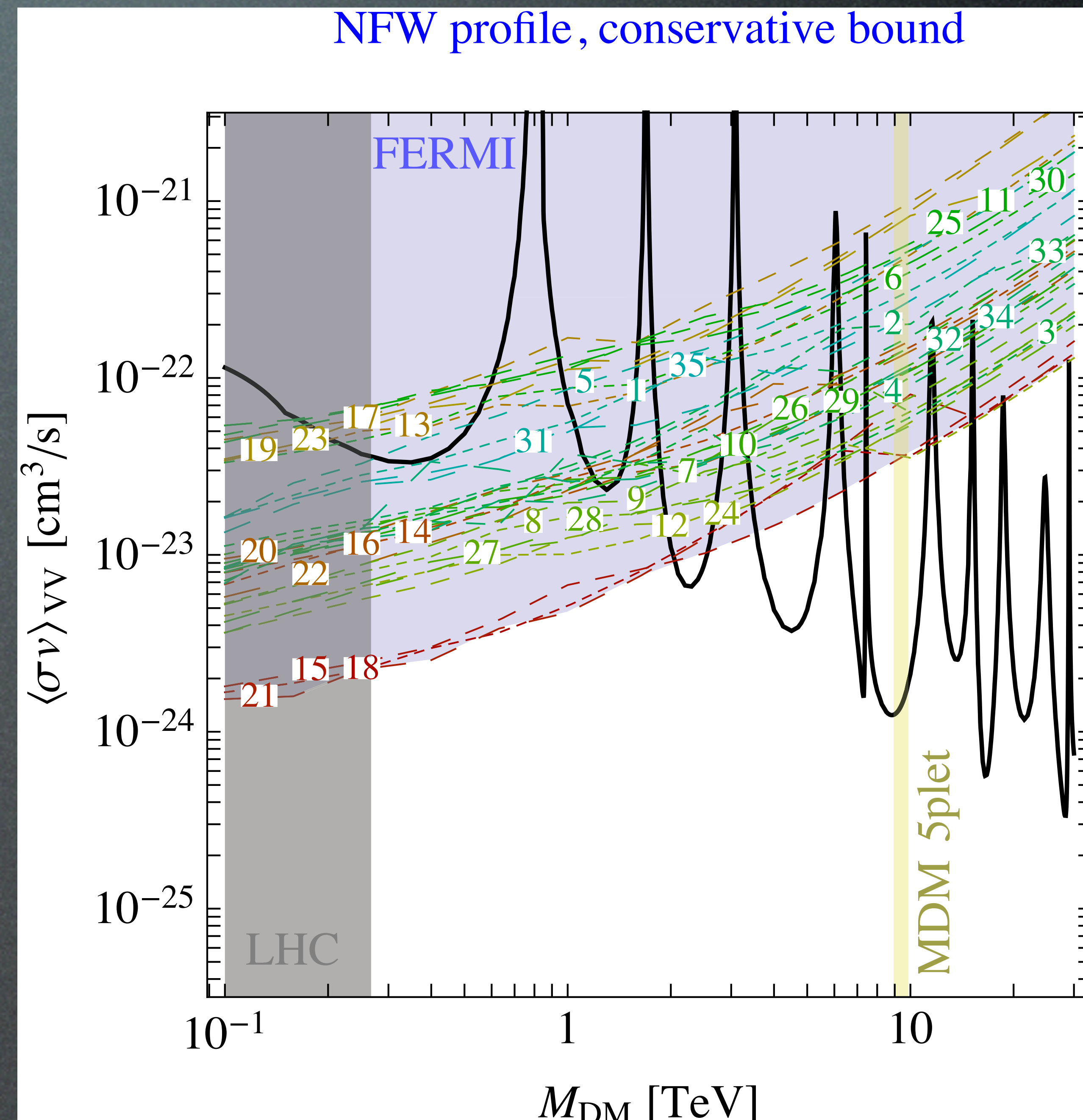

Cirelli, Hambye, Panci, Sala, Taoso
1507.05519

# 3. Indirect Detection

## FERMI diffuse galactic:






Cirelli, Hambye, Panci, Sala, Taoso 1507.05519

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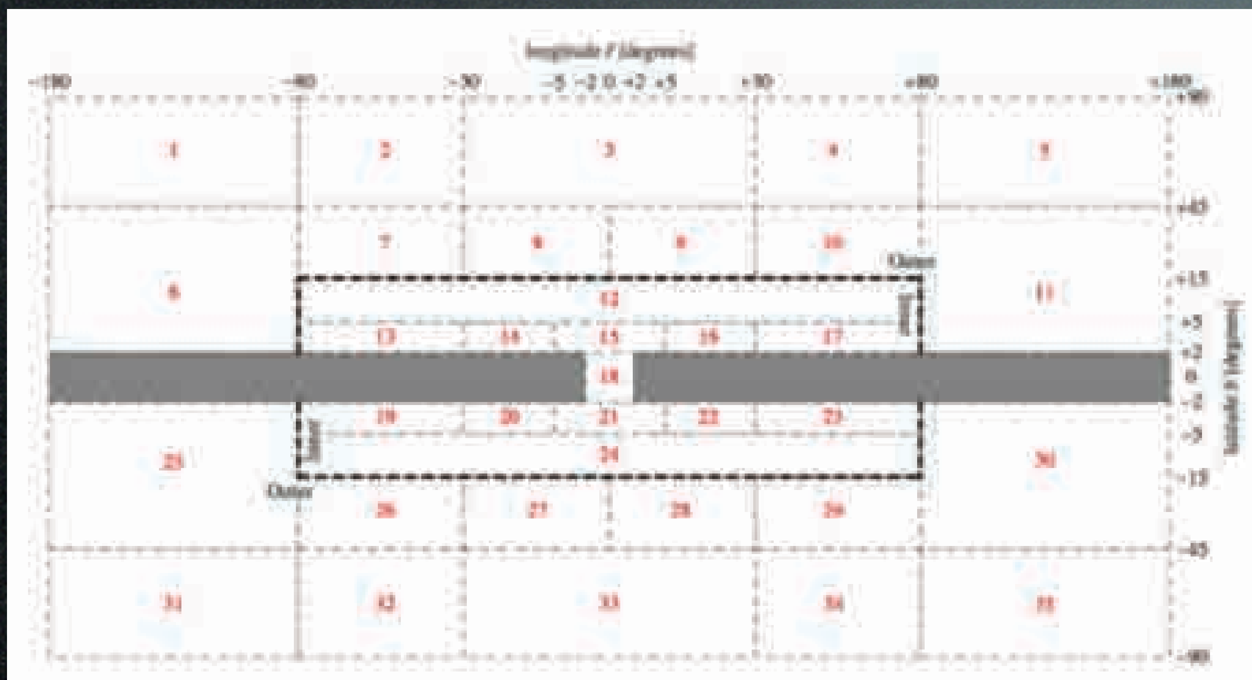

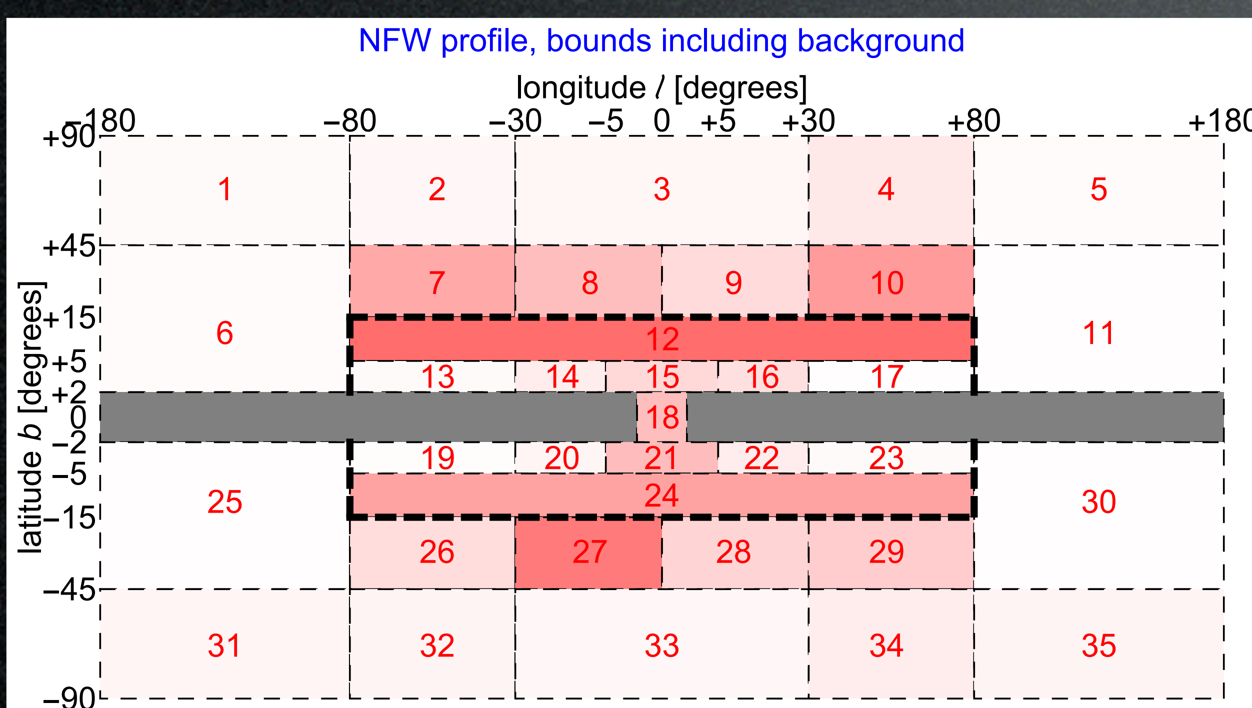


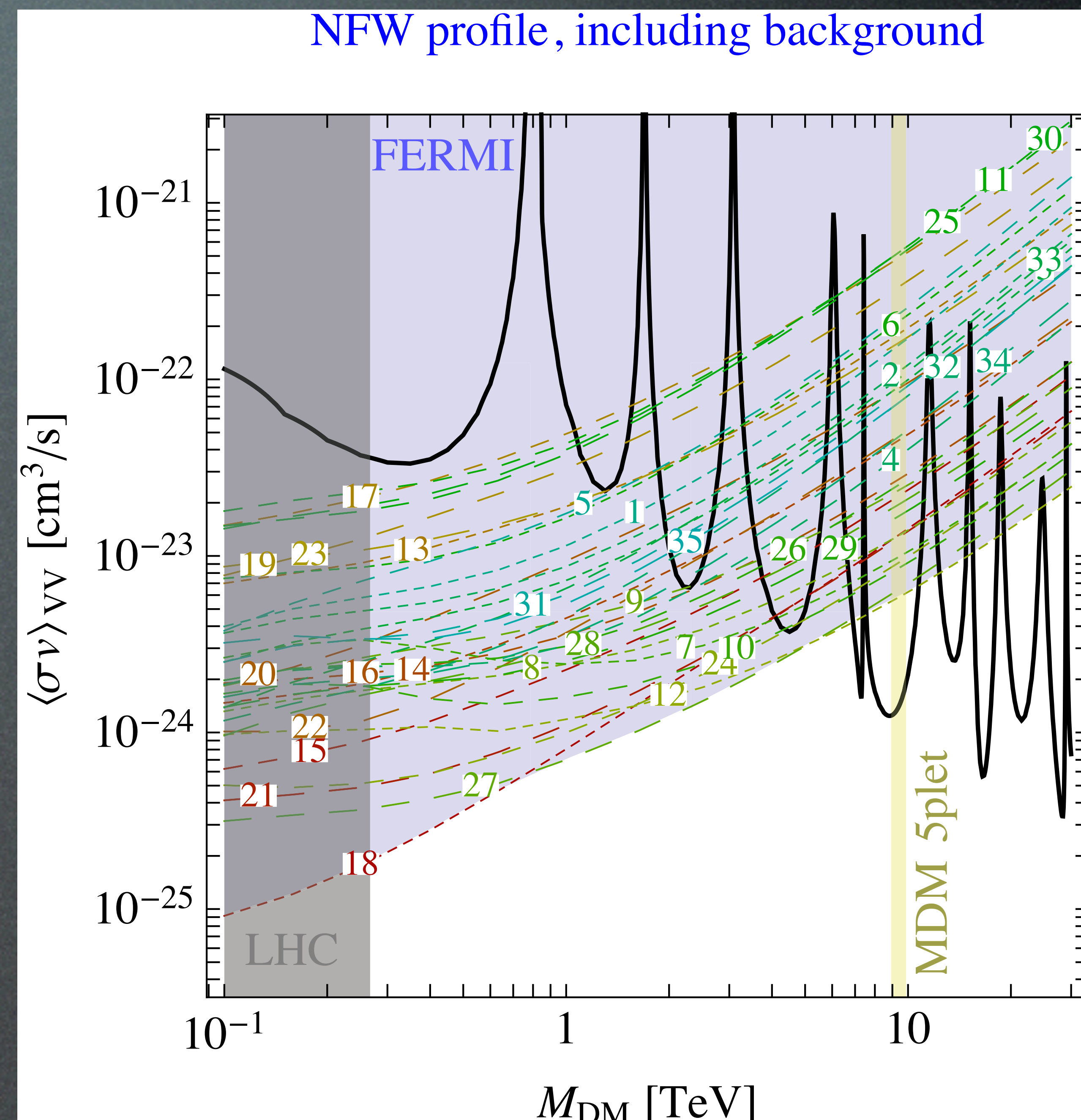


Cirelli, Hambye, Panci, Sala, Taoso 1507.05519

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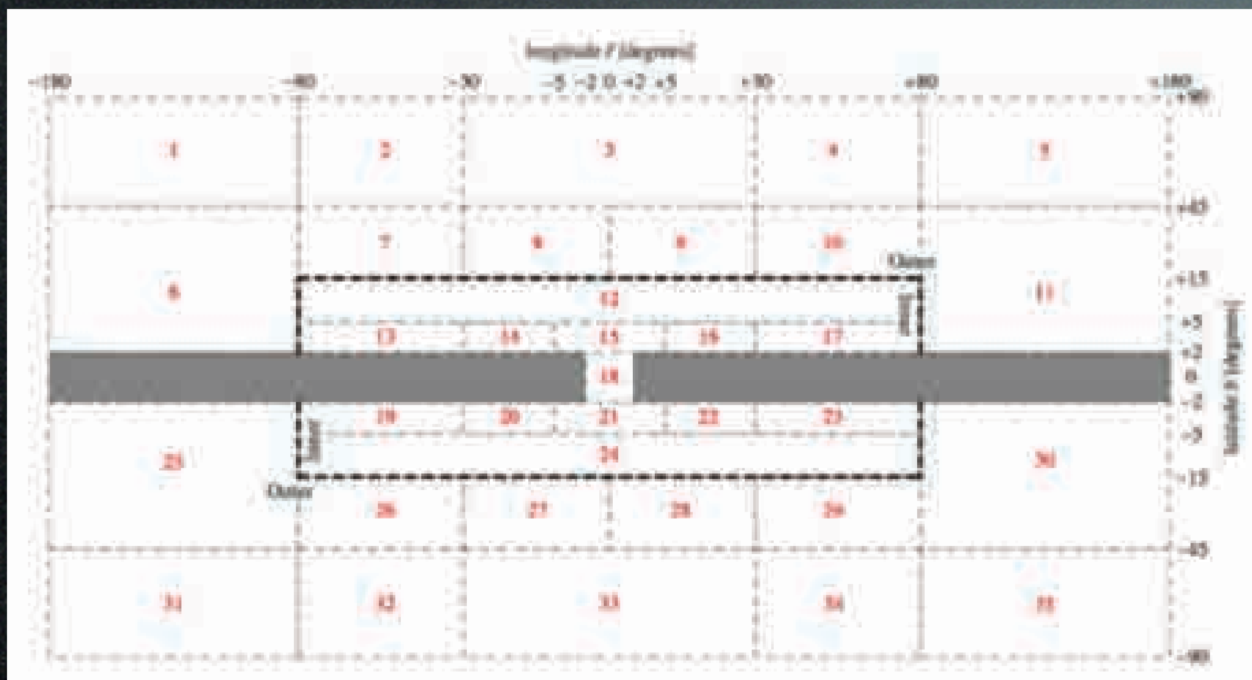

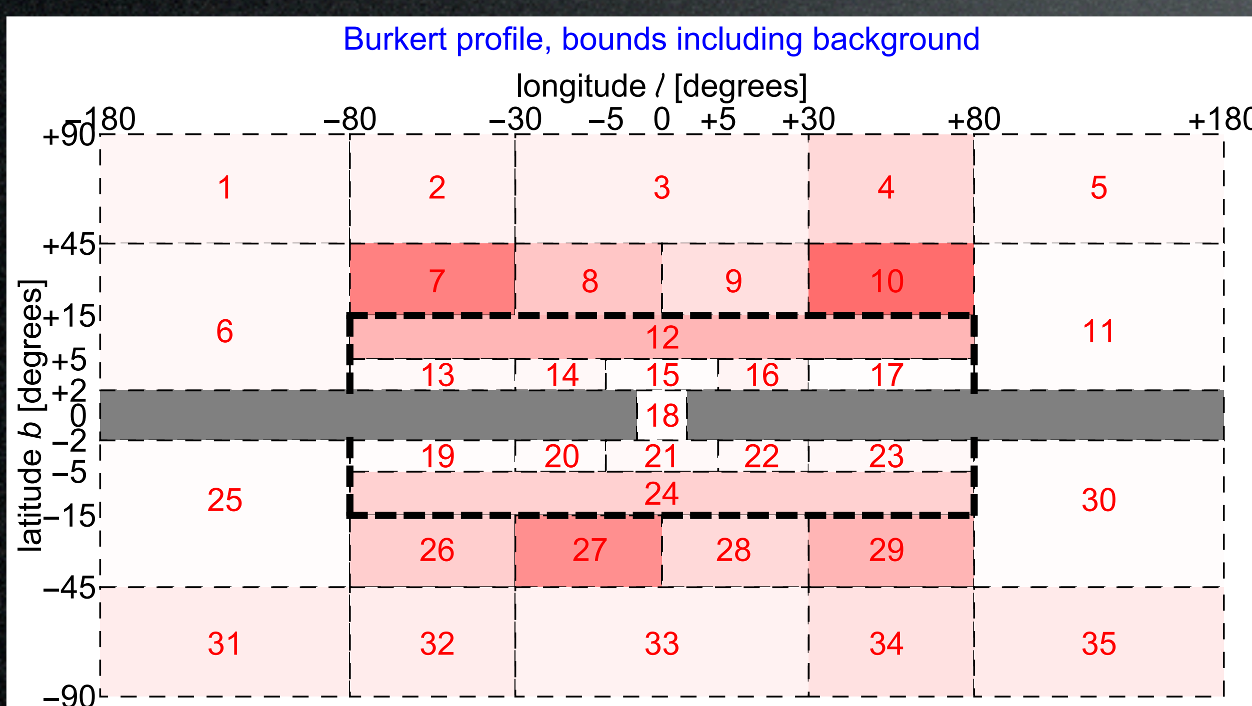


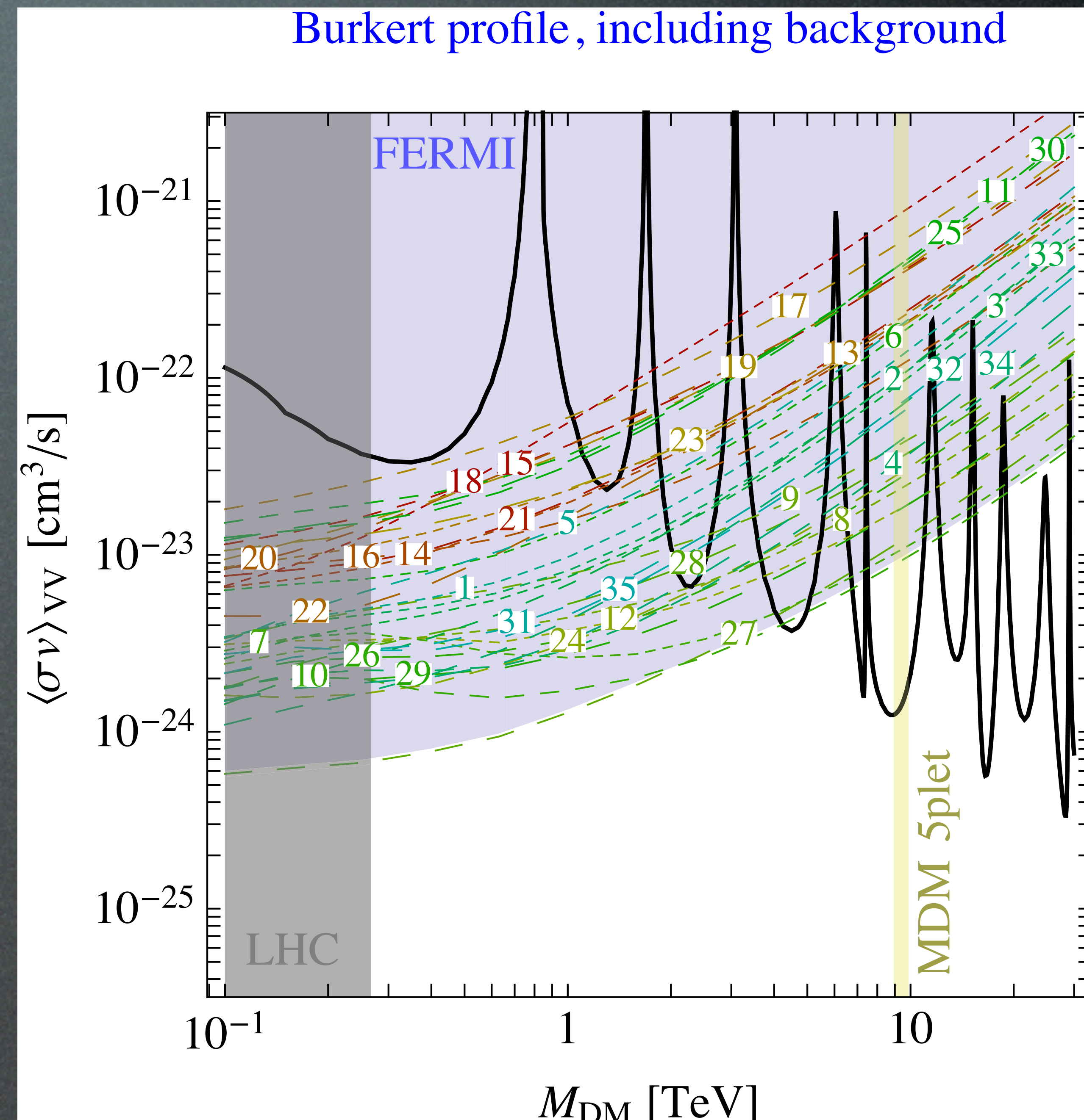


Cirelli, Hambye, Panci, Sala, Taoso 1507.05519

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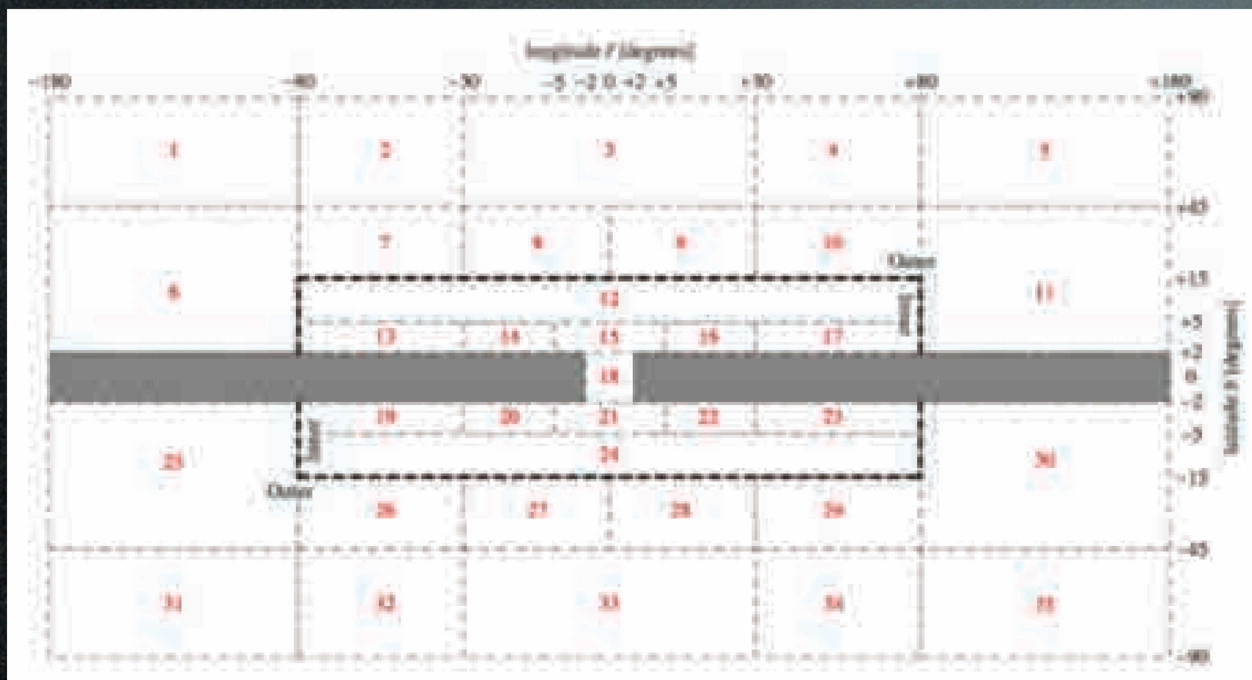
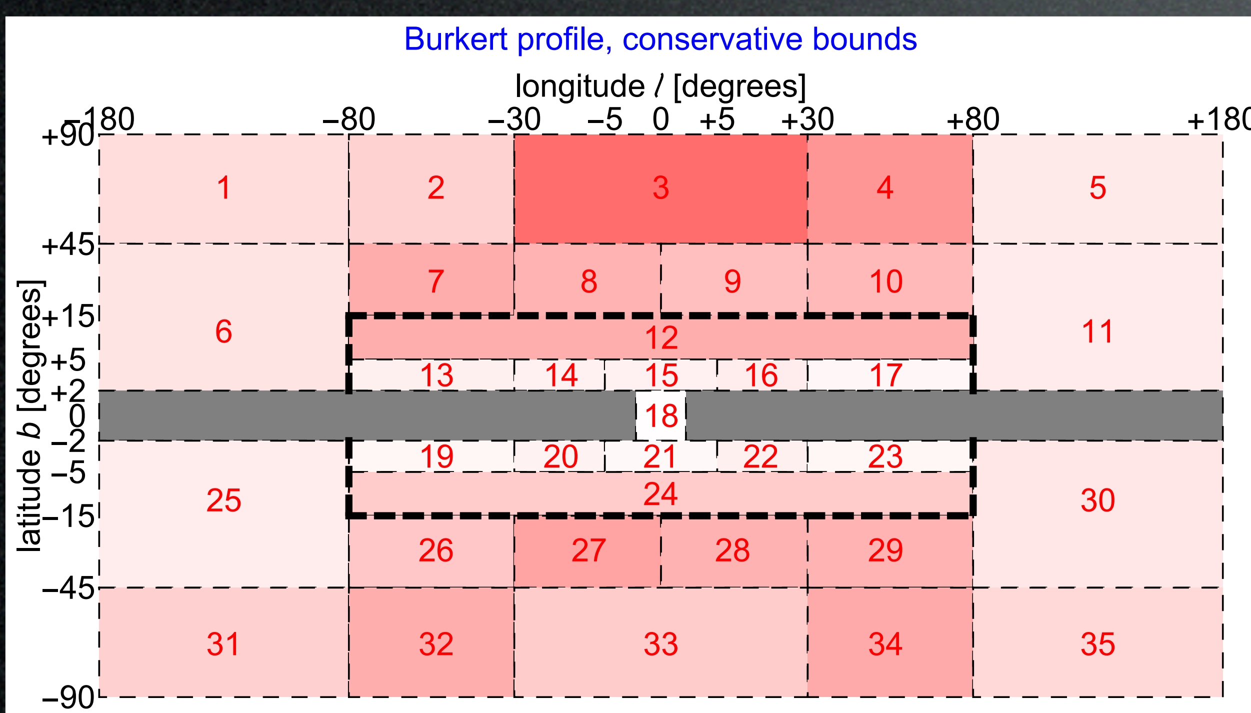
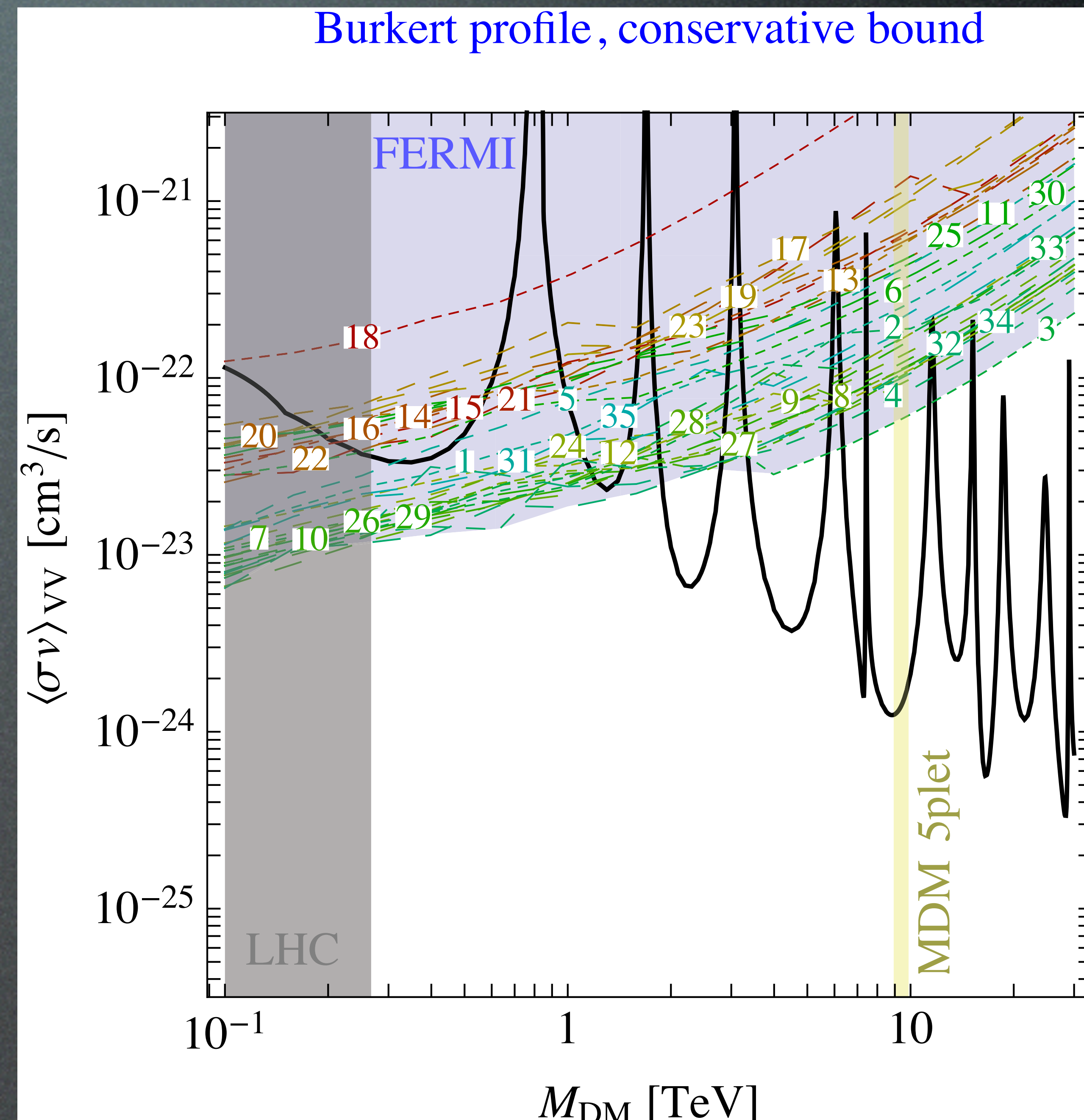





Cirelli, Hambye, Panci, Sala, Taoso 1507.05519

relevant constraints but MDM 5plet not probed

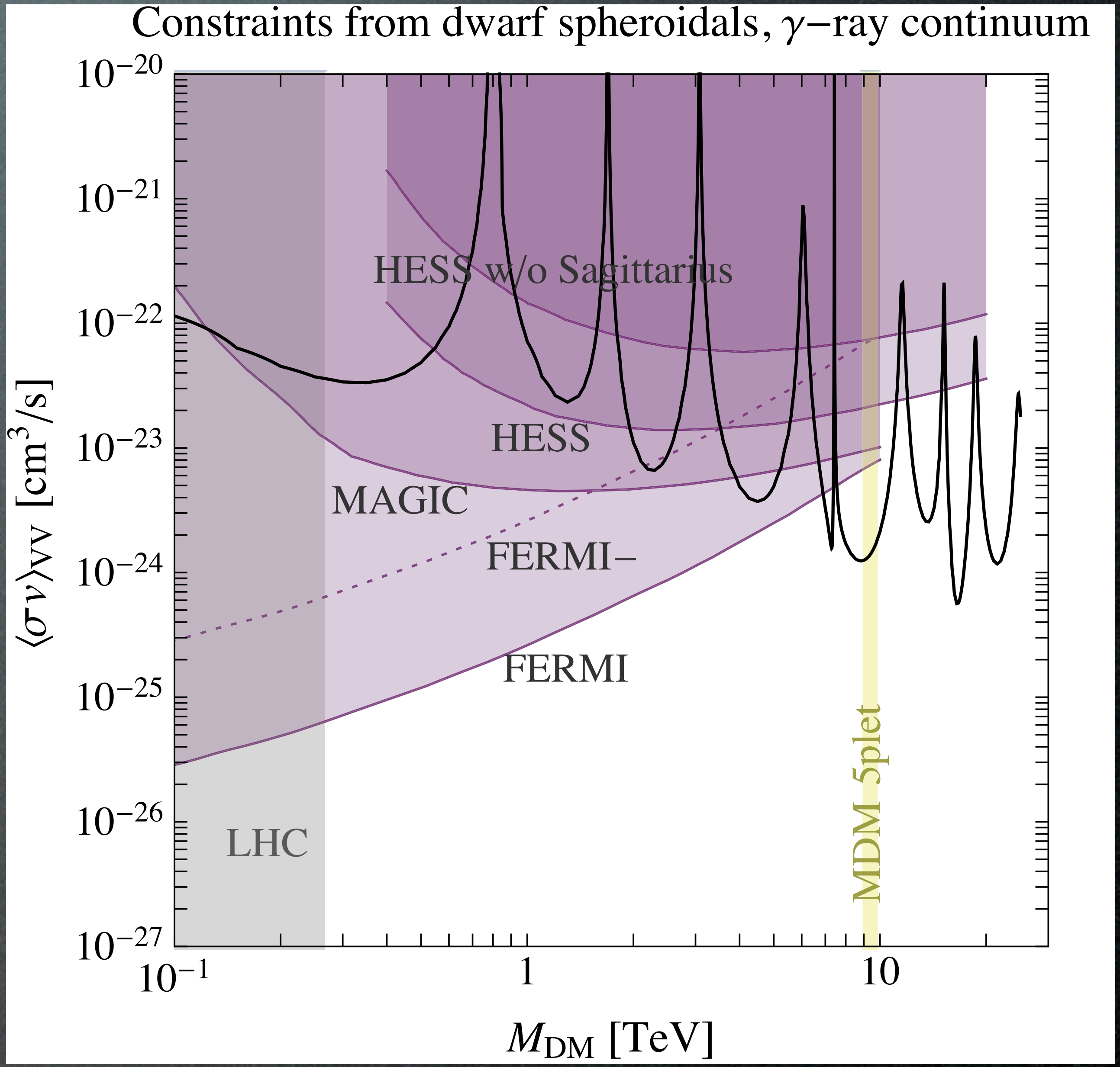
# 3. Indirect Detection

## 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

relevant constraints but
MDM 5plet not probed

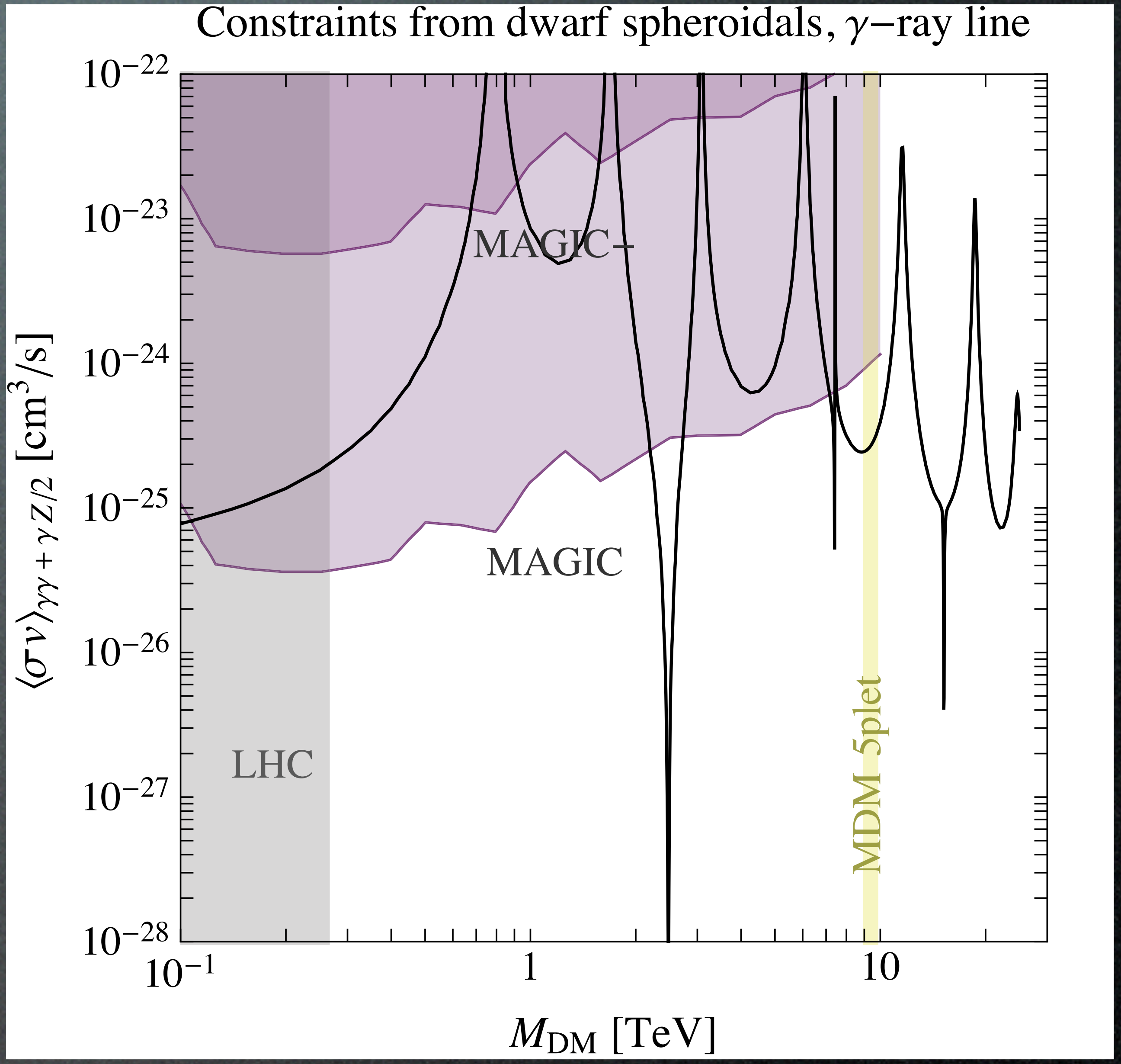
# 3. Indirect Detection

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

MAGIC: Segue1 - 1312.1535

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

e.g. Bonnivard et al., 1504.02048




Cirelli, Hambye, Panci, Sala, Taoso 1507.05519

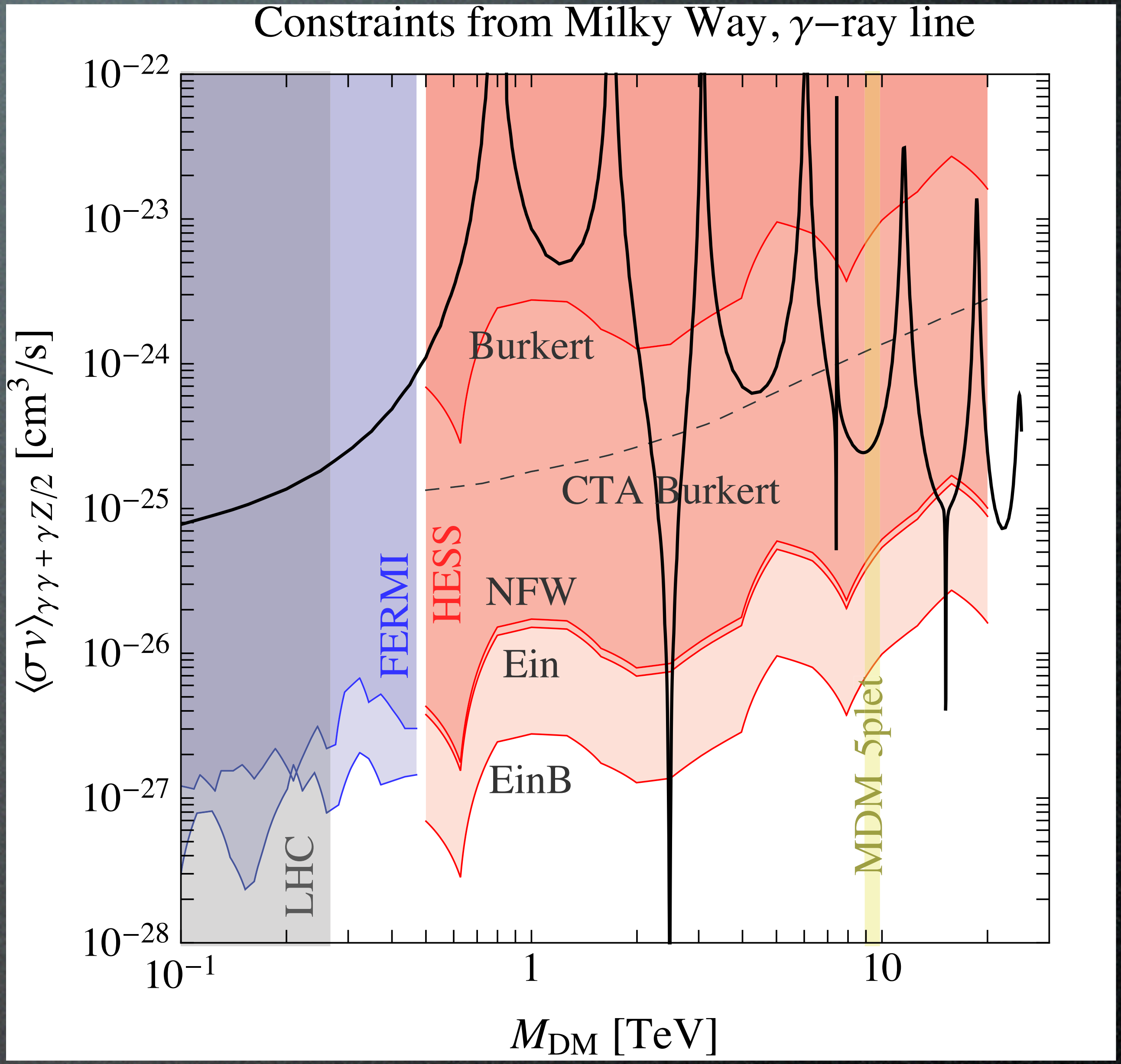
relevant constraints but MDM 5plet not probed

# 3. 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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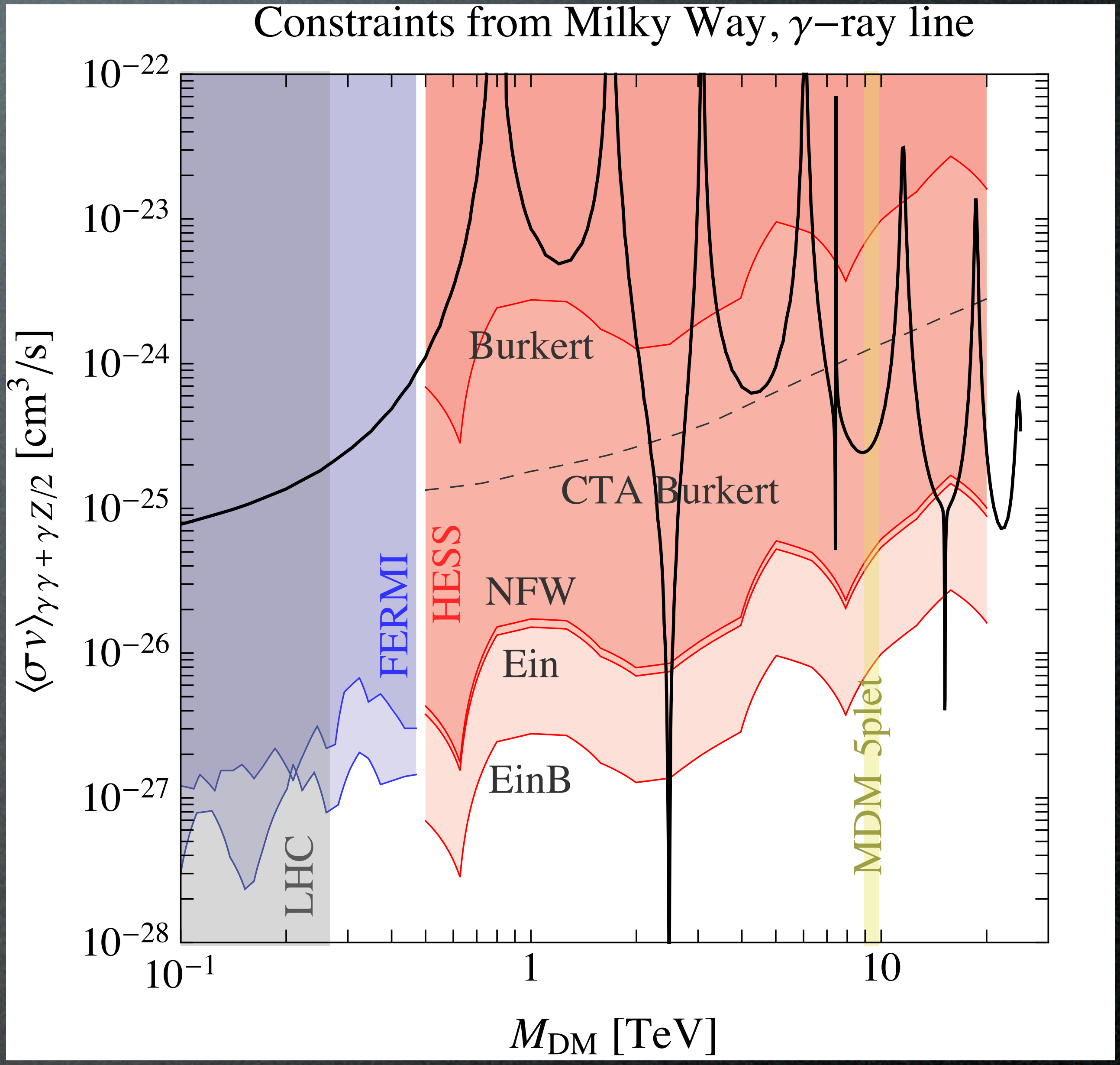
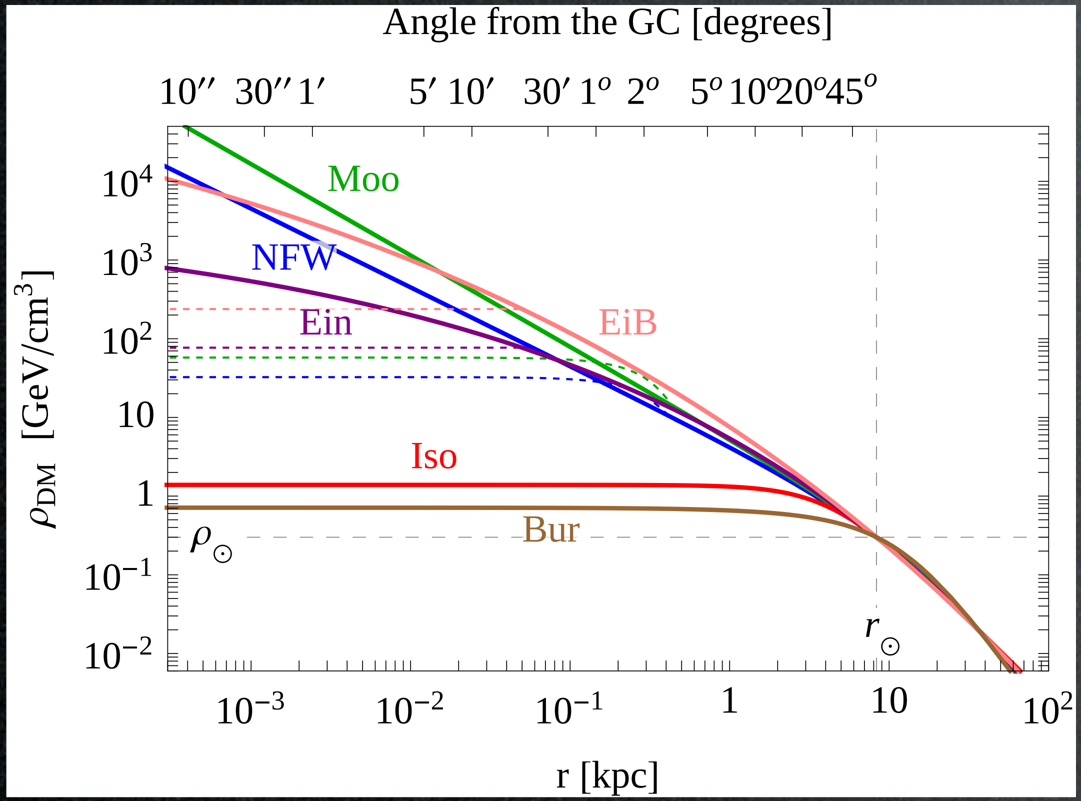



Cirelli, Hambye, Panci, Sala, Taoso 1507.05519

## Uncertainties in DM profile:




e.g. Cirelli et al., 1012.4515

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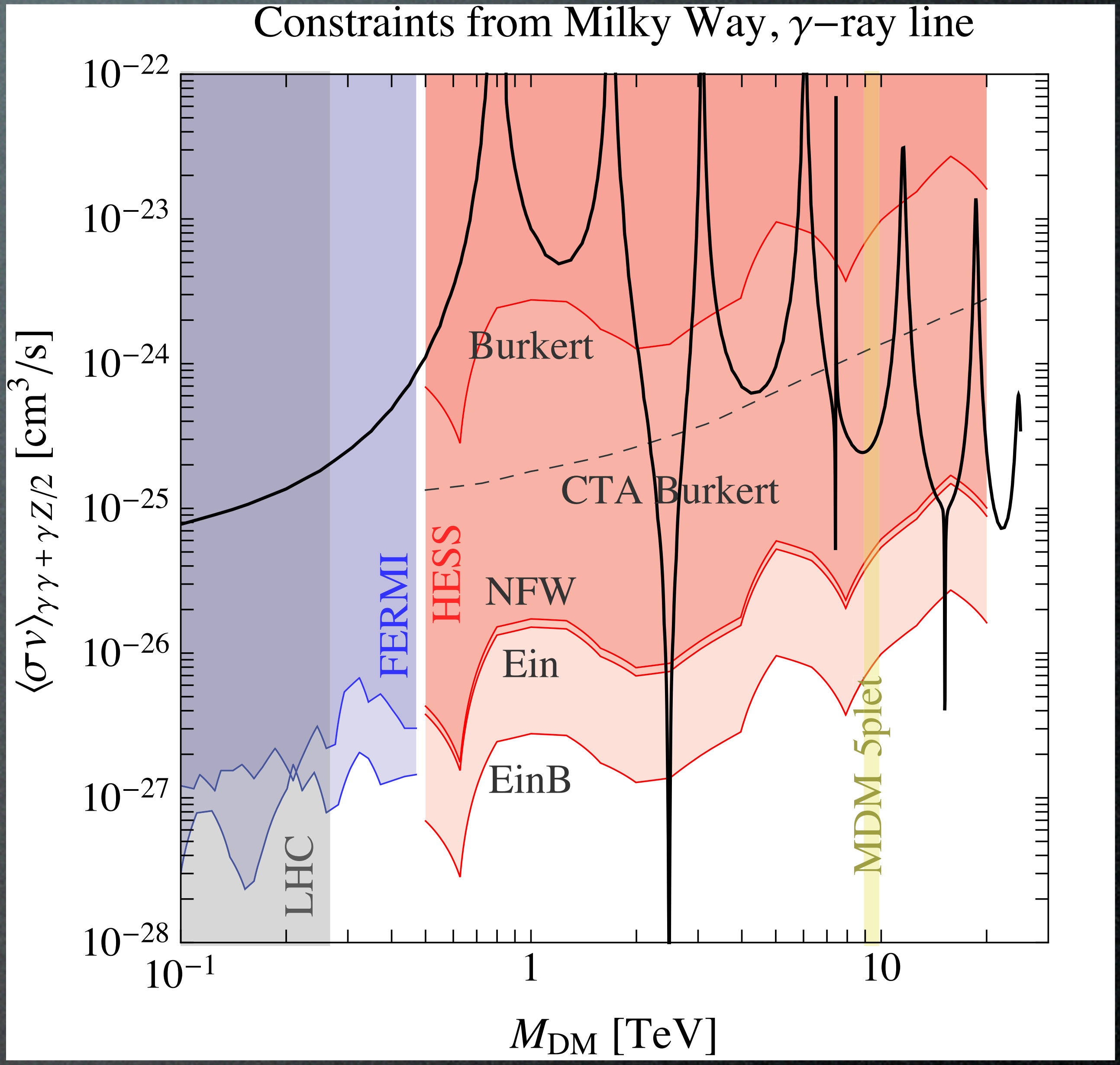


Cirelli, Hambye, Panci, Sala, Taoso 1507.05519

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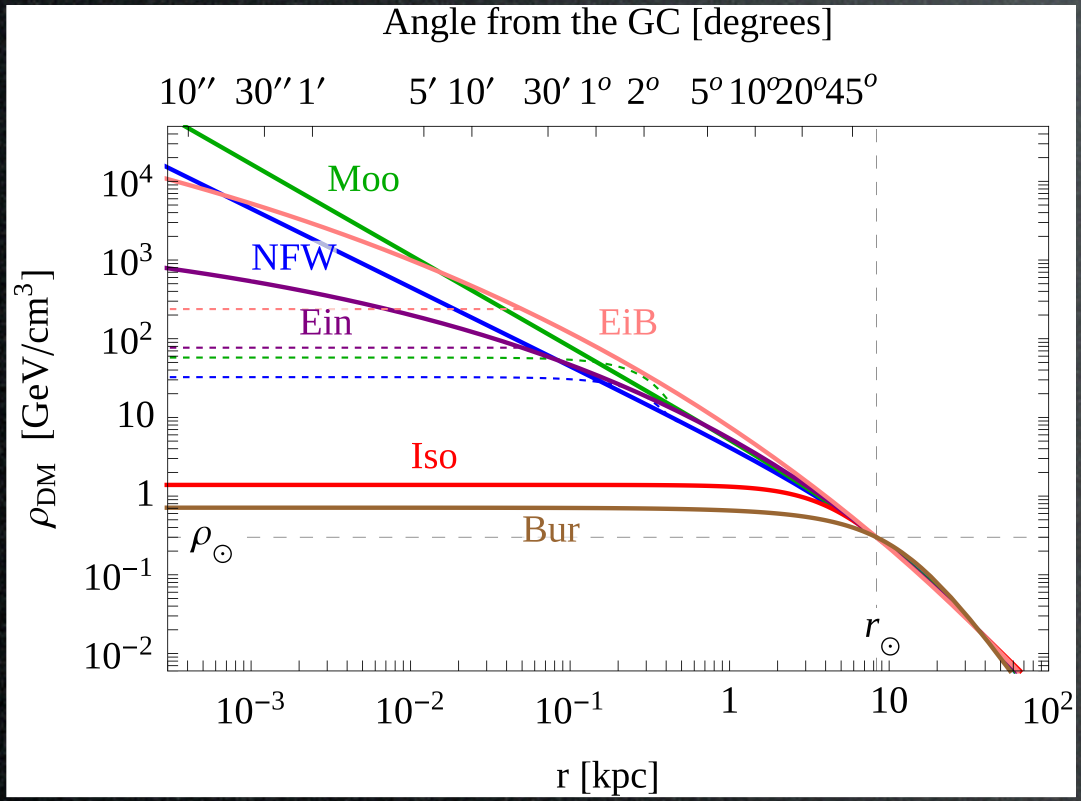



e.g. Cirelli et al., 1012.4515

MDM excluded if cuspy

MDM not probed if cored

Consistent conclusions in: Garcia-Cely et al. 1507.05536

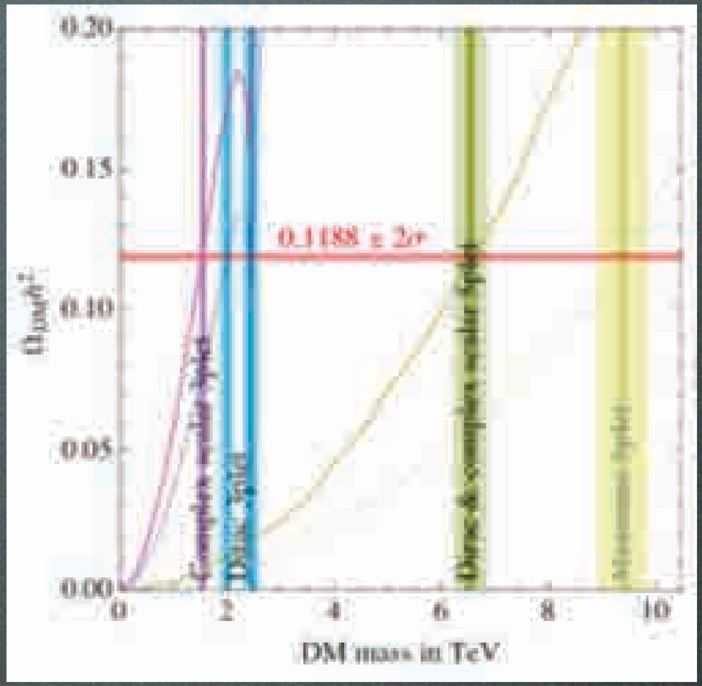
# Bonus track

Some interesting recent extensions:

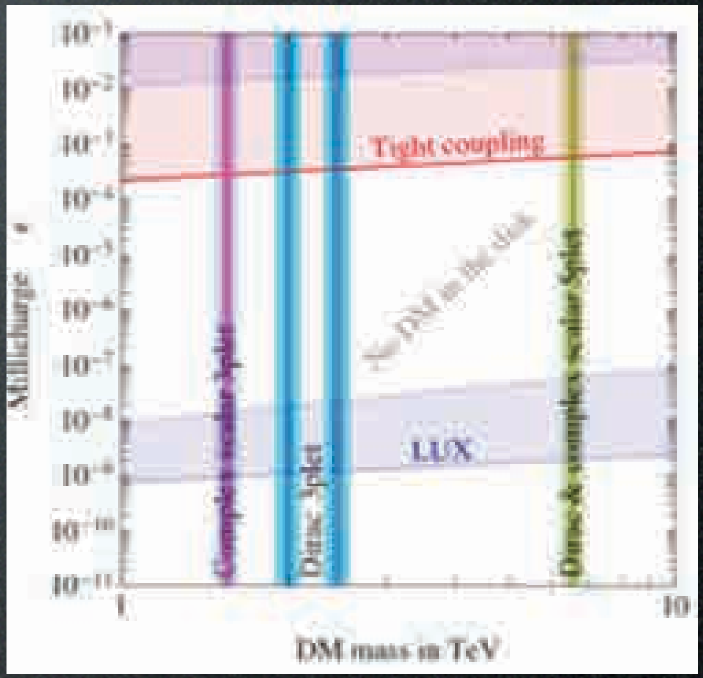
- millicharged MDM

Del Nobile, Nardecchia, Panci 1512.05353

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




relic abundance




constraints

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

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

# Conclusions

The DM problem requires physics beyond the SM.

Introducing the minimal amount of it,
we find one fully successful DM candidate:
massive, neutral, *automatically* stable.

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

Its phenomenology is precisely computable:

- too heavy to be produced at LHC,
- challenging in next gen direct detection exp's,
- tested by indirect detection (γ ray) exp's:
  - excluded if cuspy
  - not probed if cored

(Other candidates have different properties.)

# Conclusions

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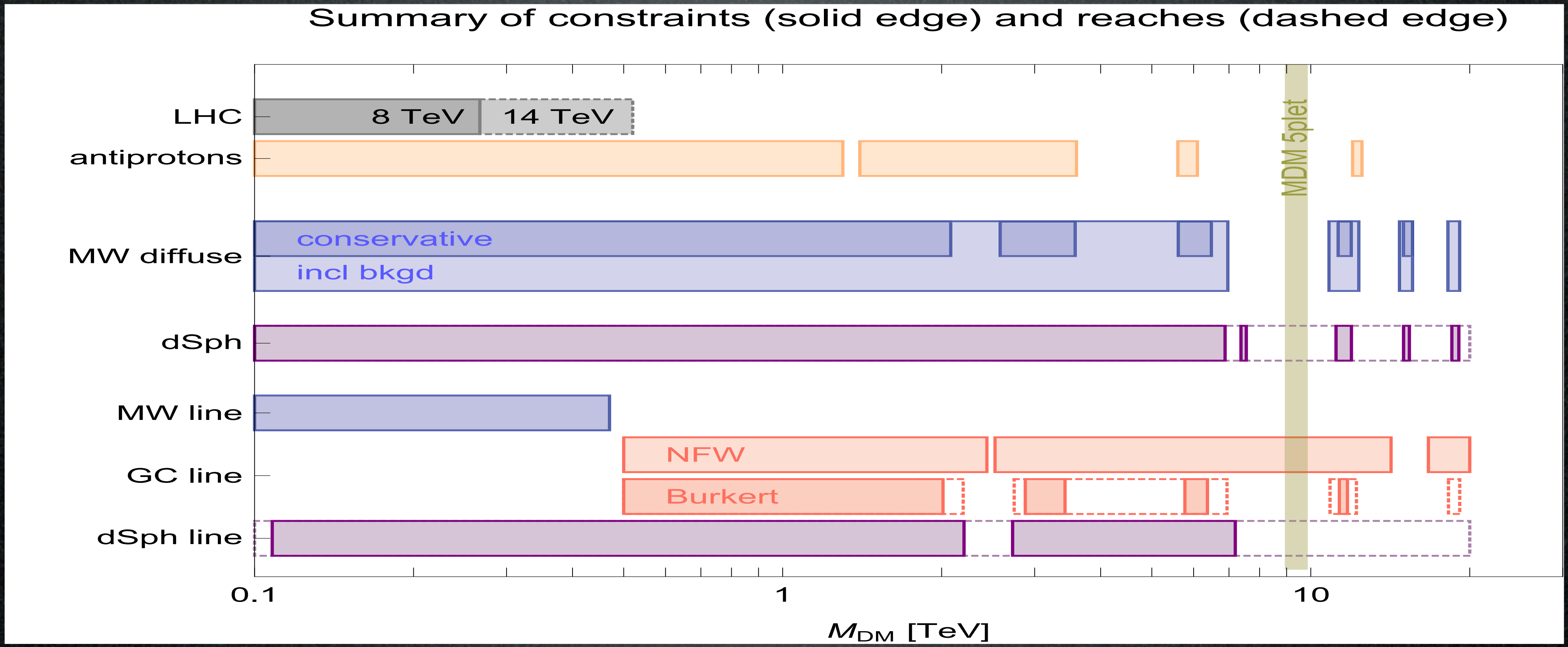


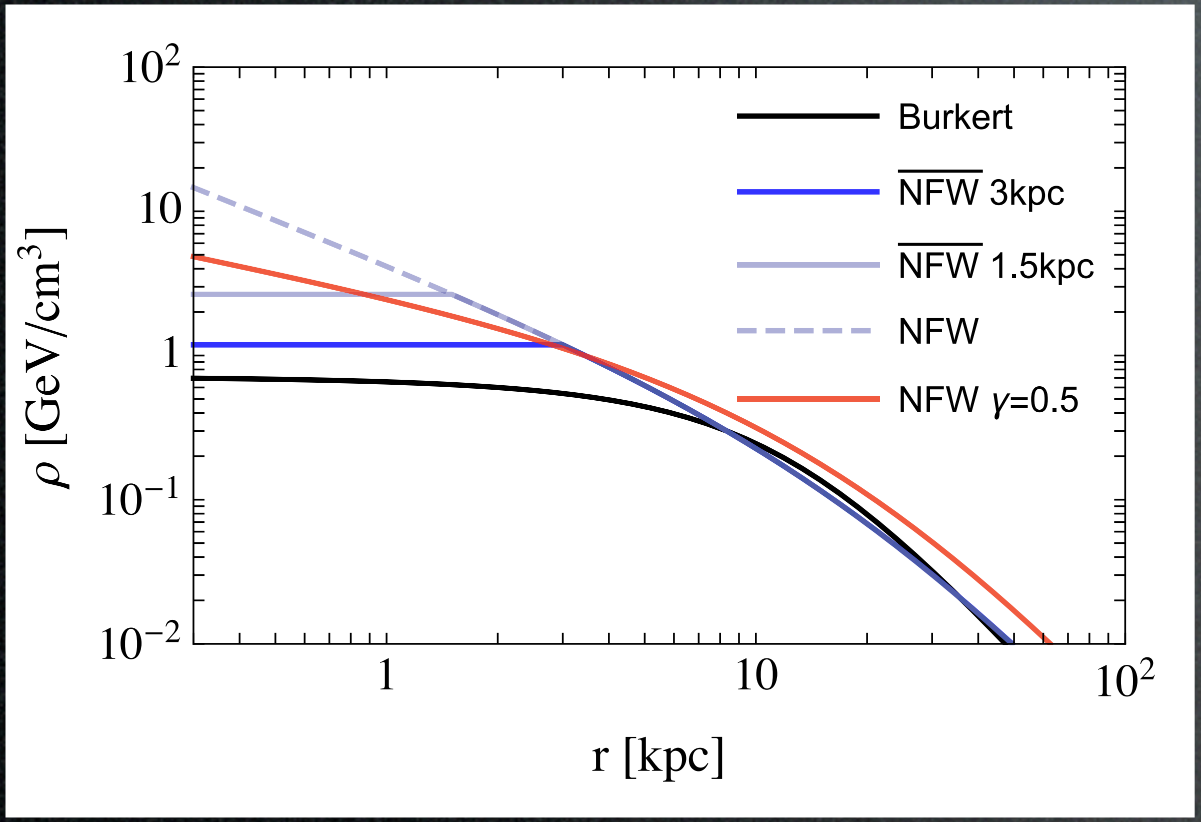
# Back-up slides

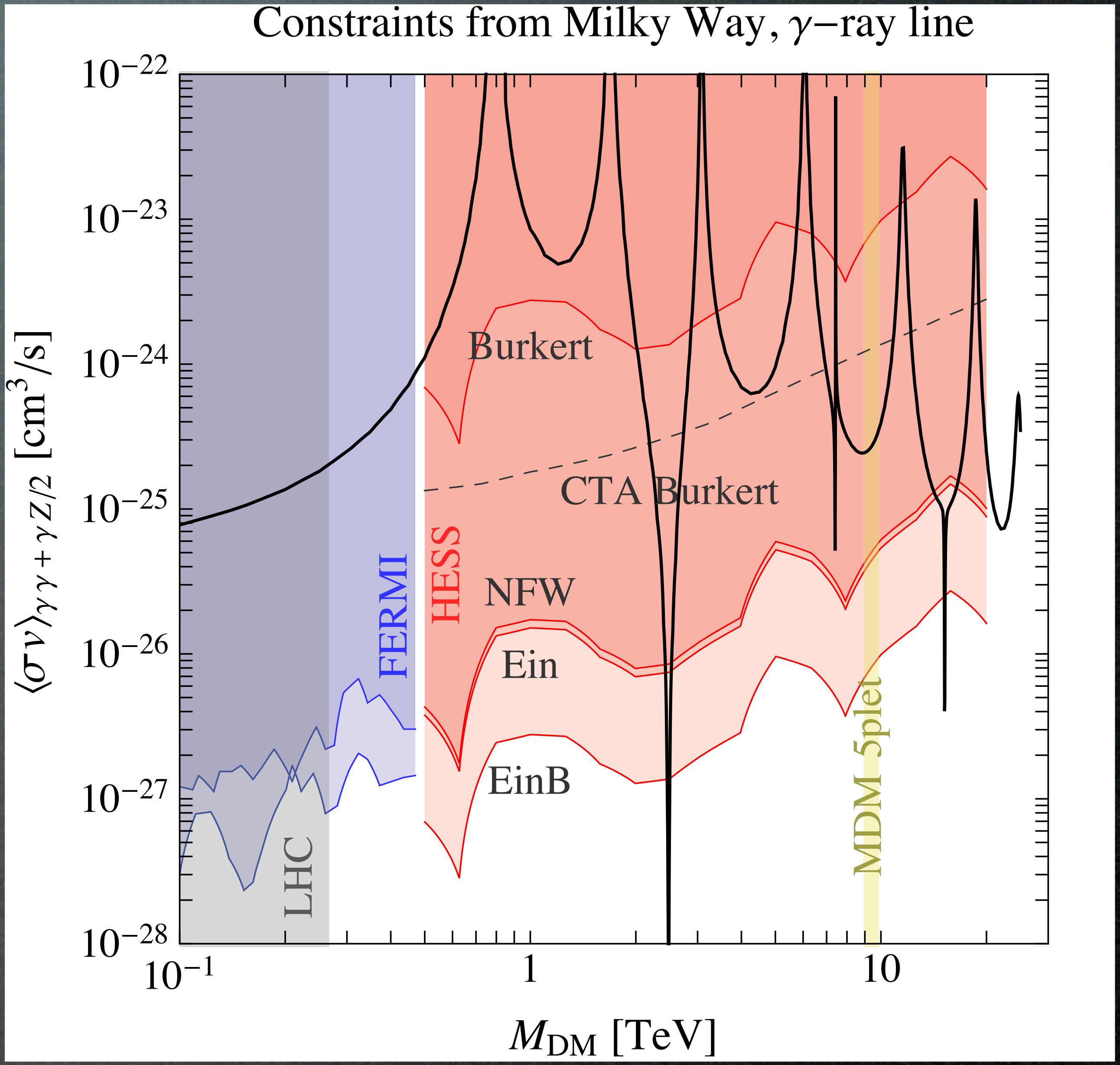
# 3. Indirect Detection

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

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

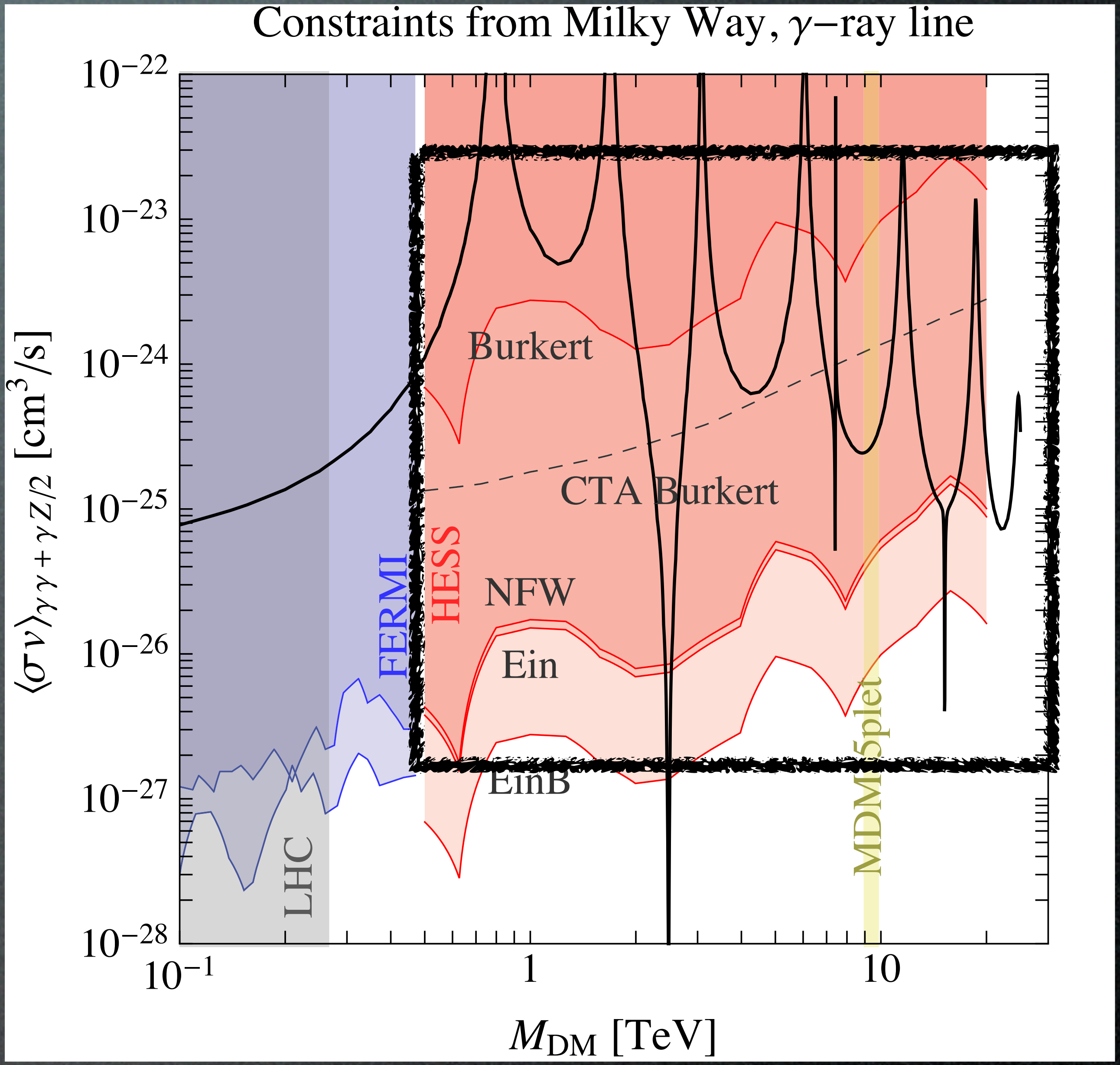
Uncertainties in DM profile:



# 3. Indirect Detection

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

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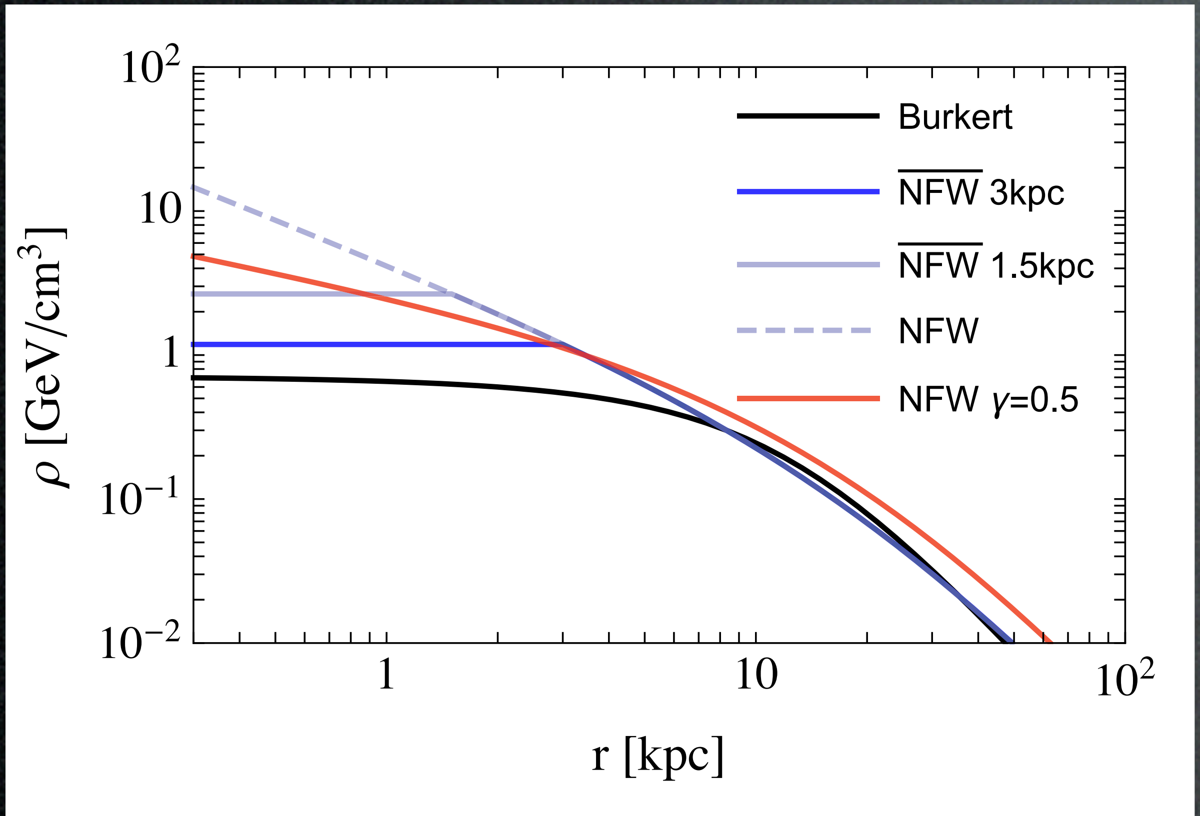

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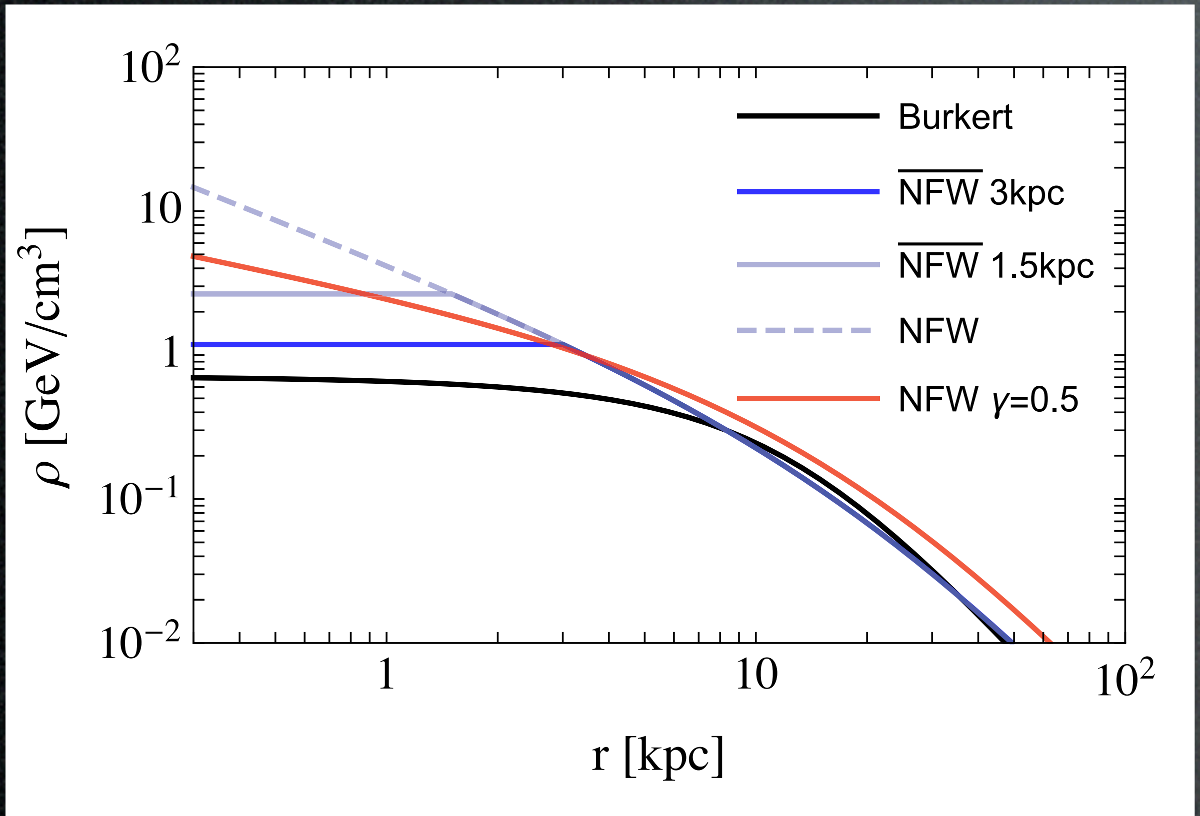
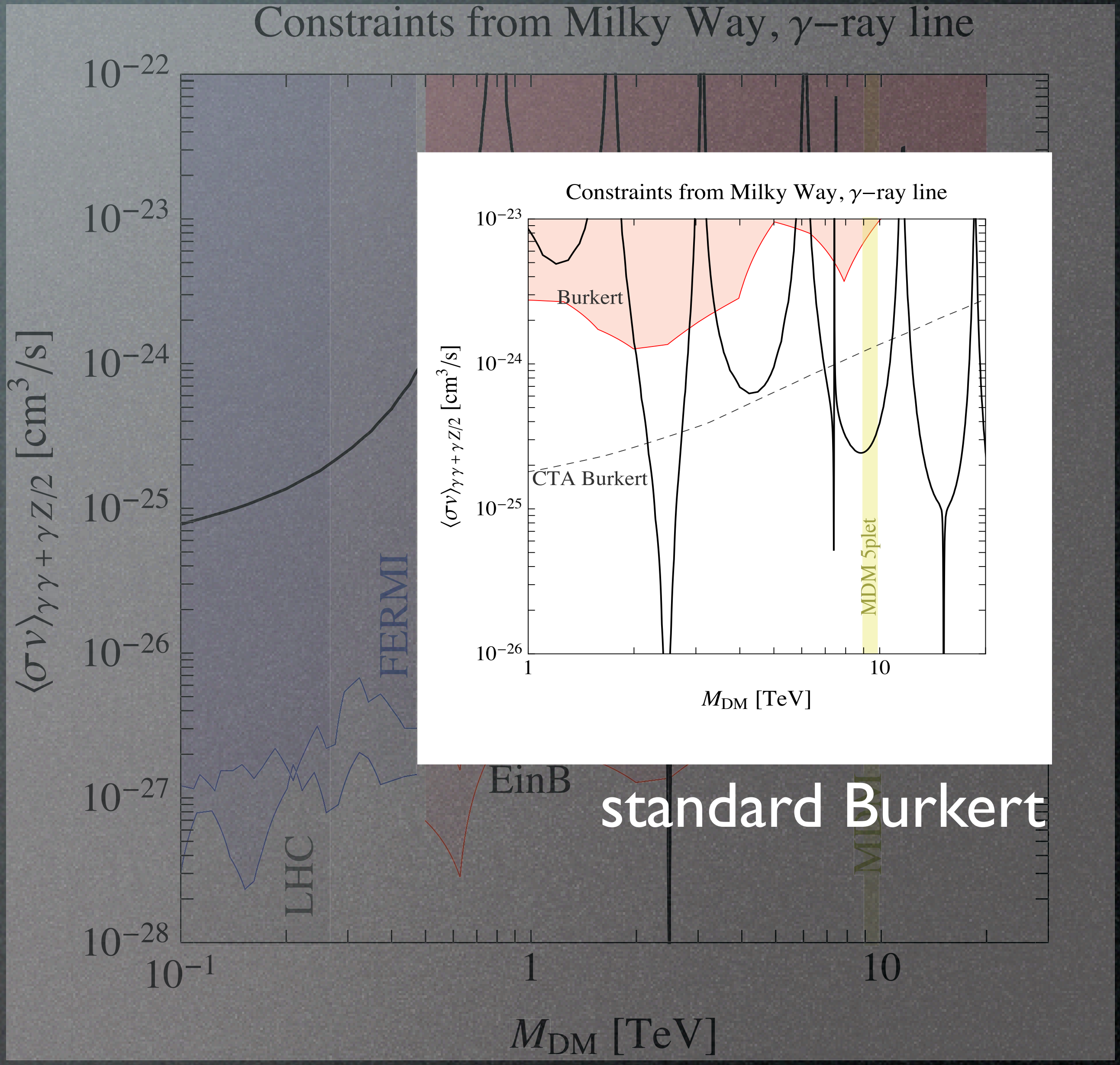


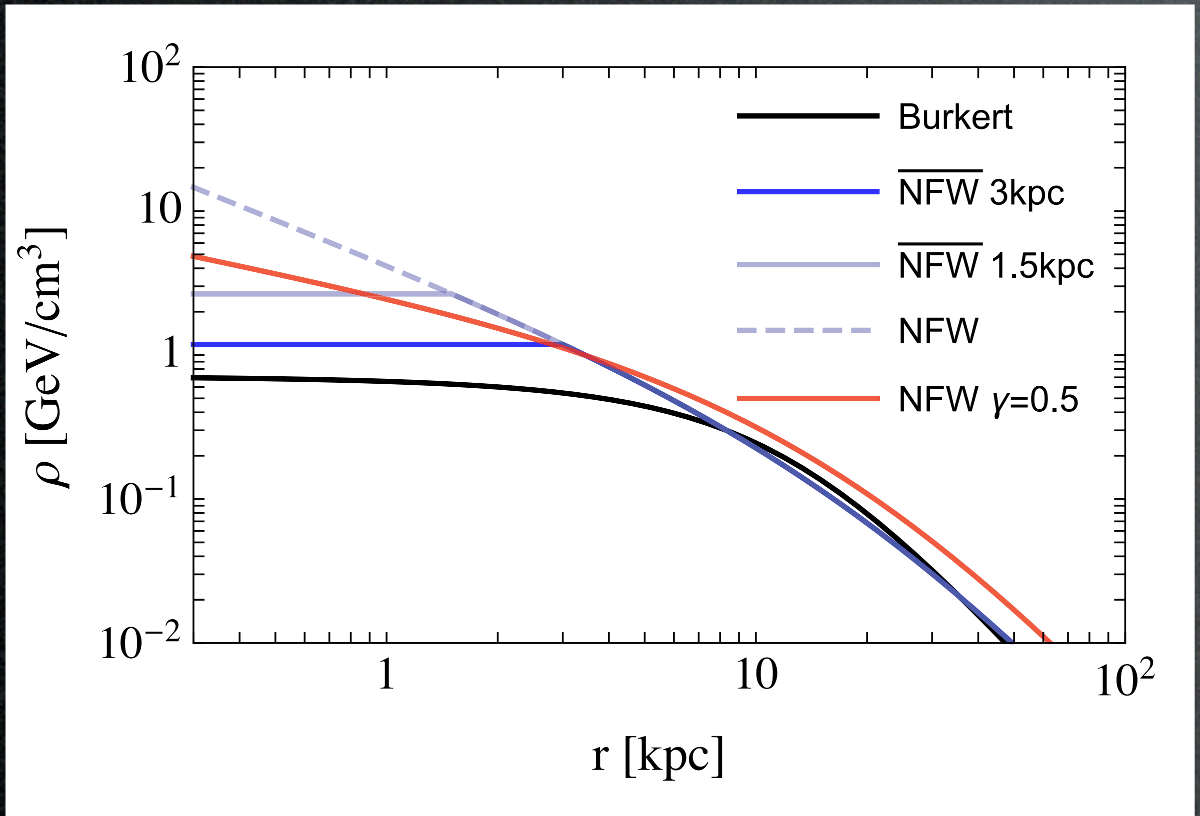



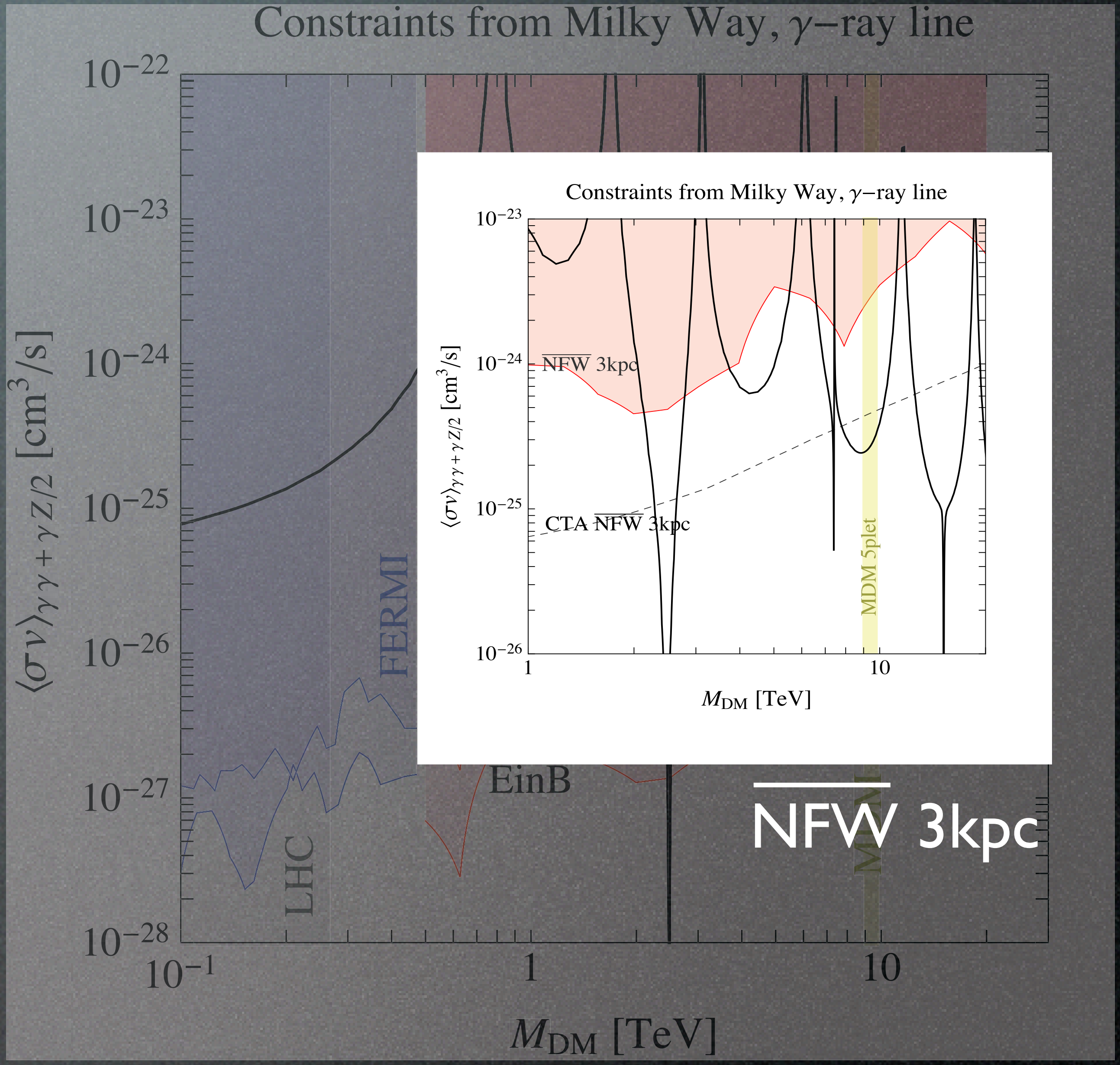
# 3. Indirect Detection

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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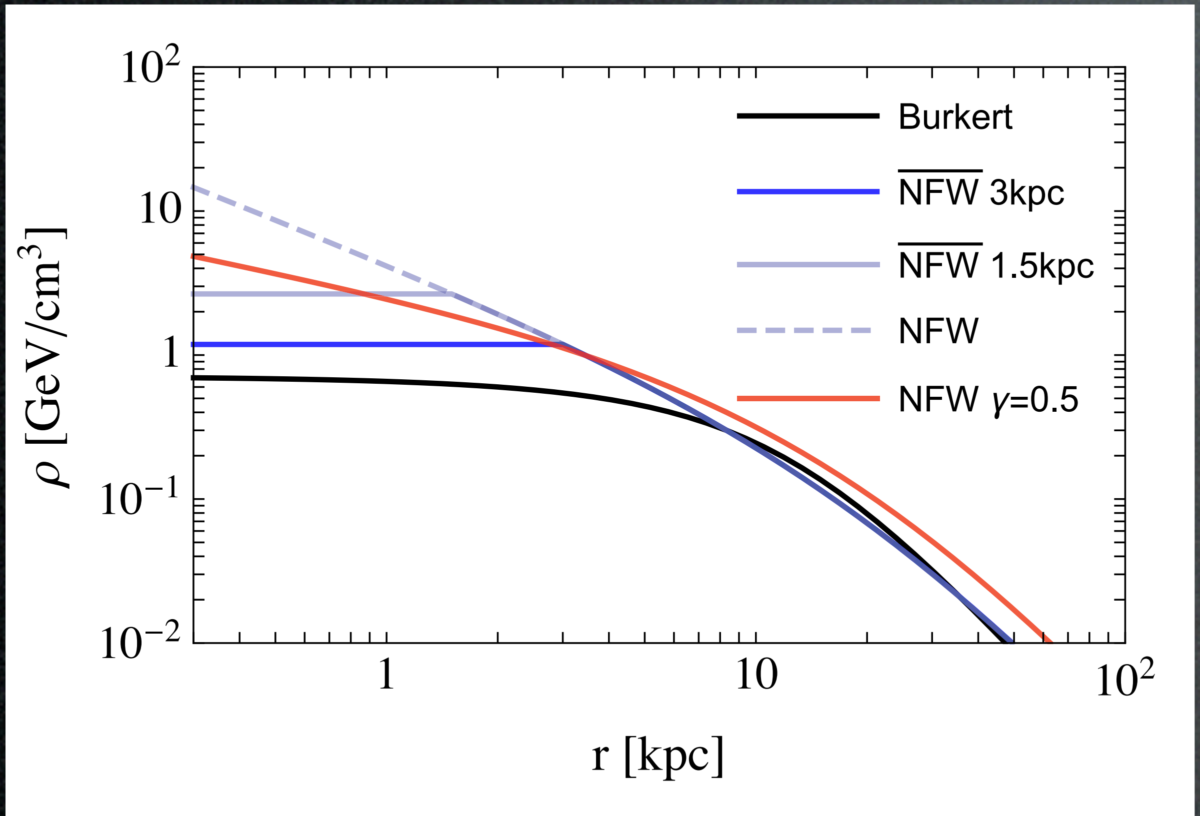


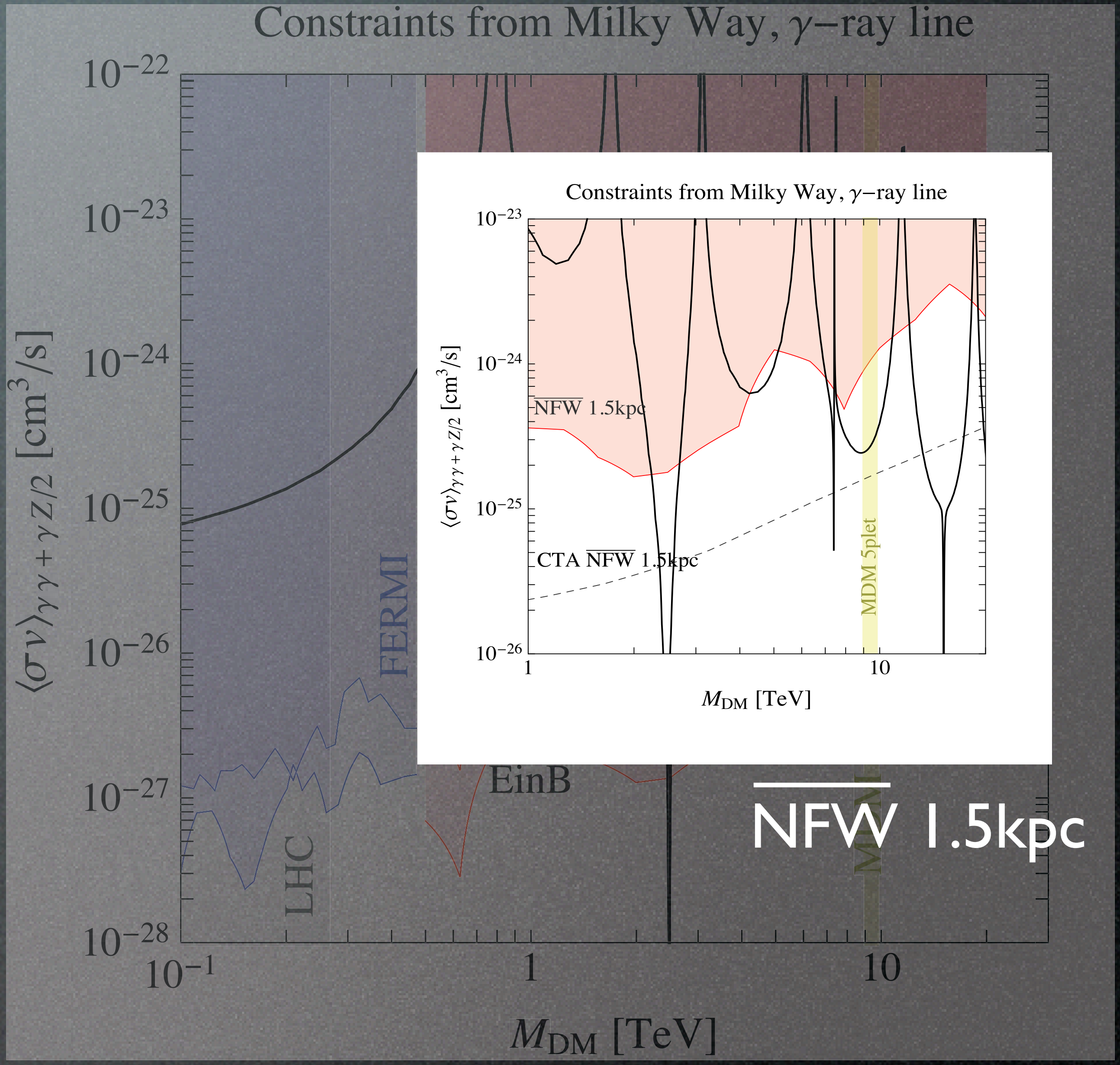

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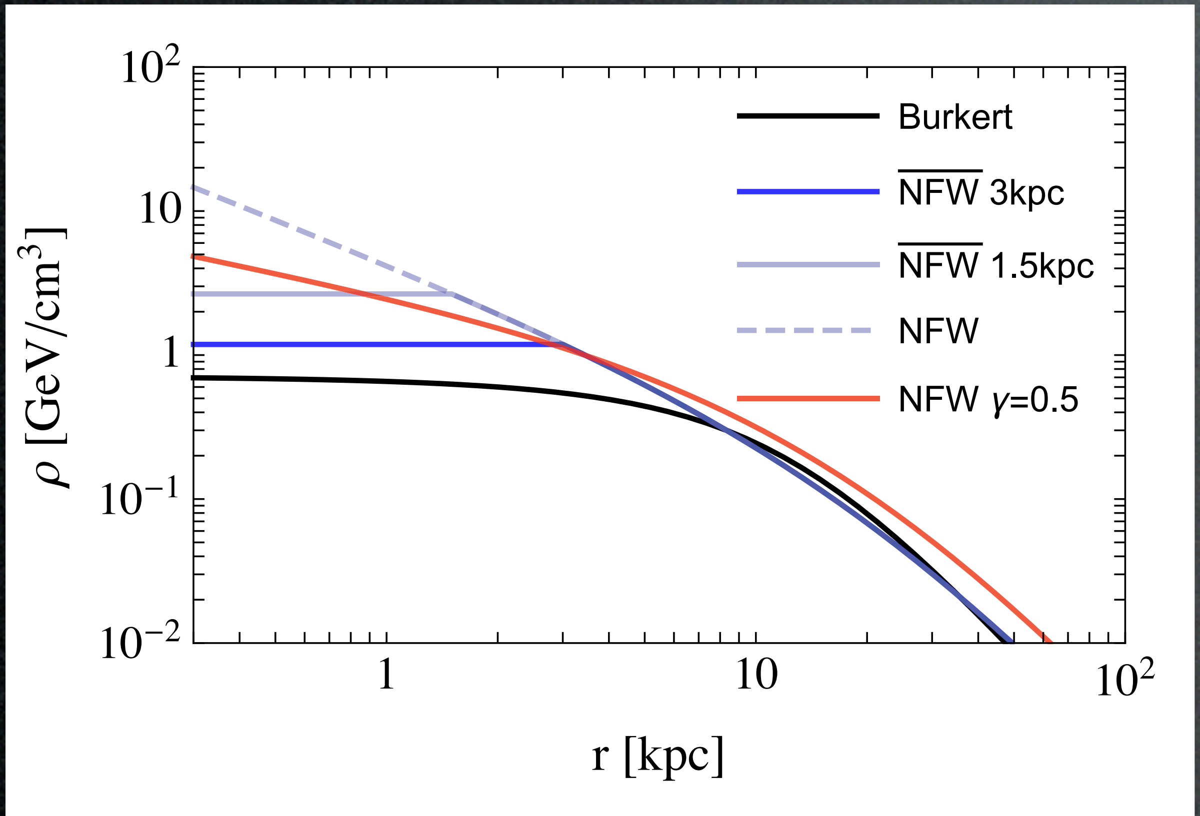
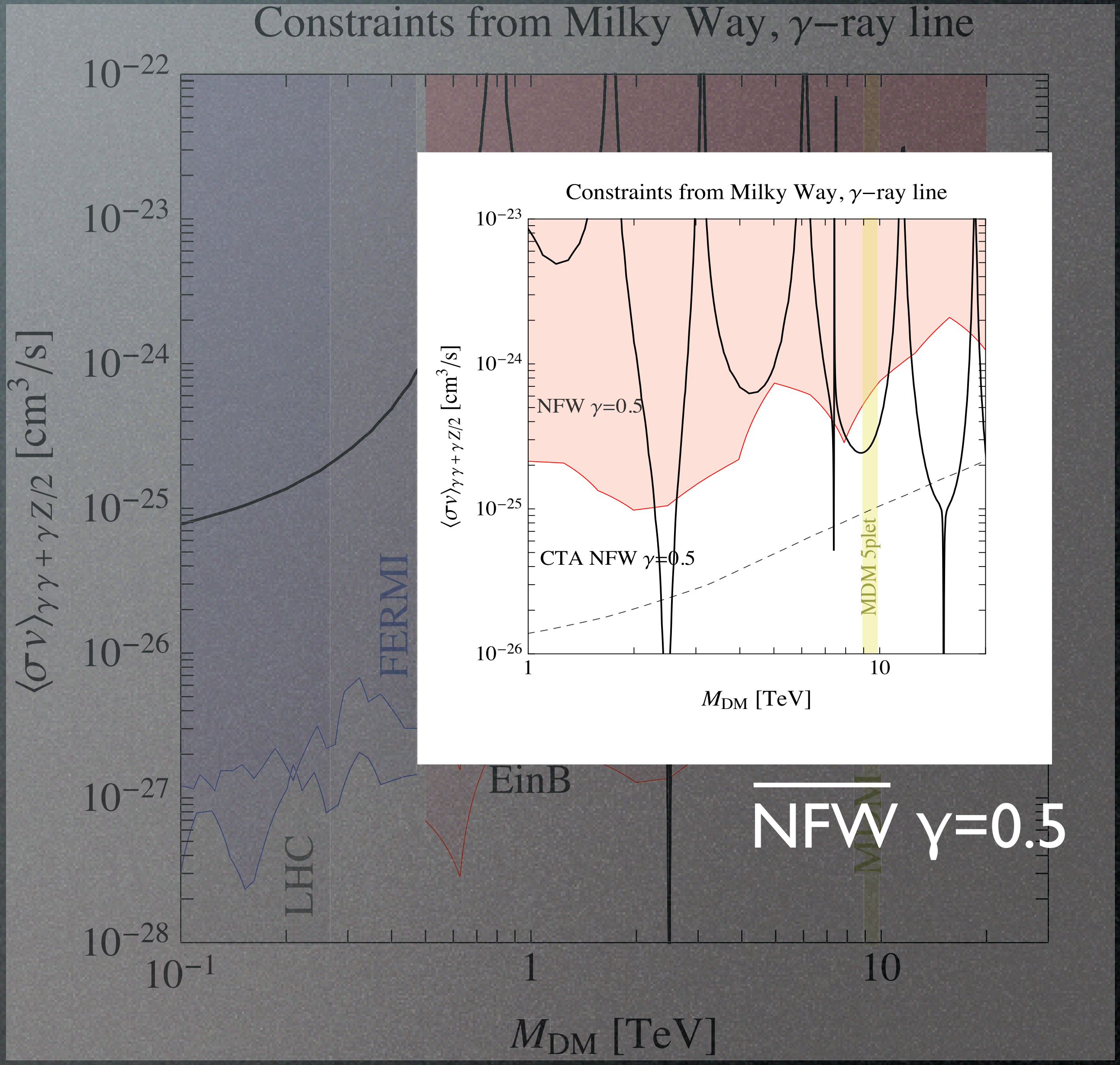
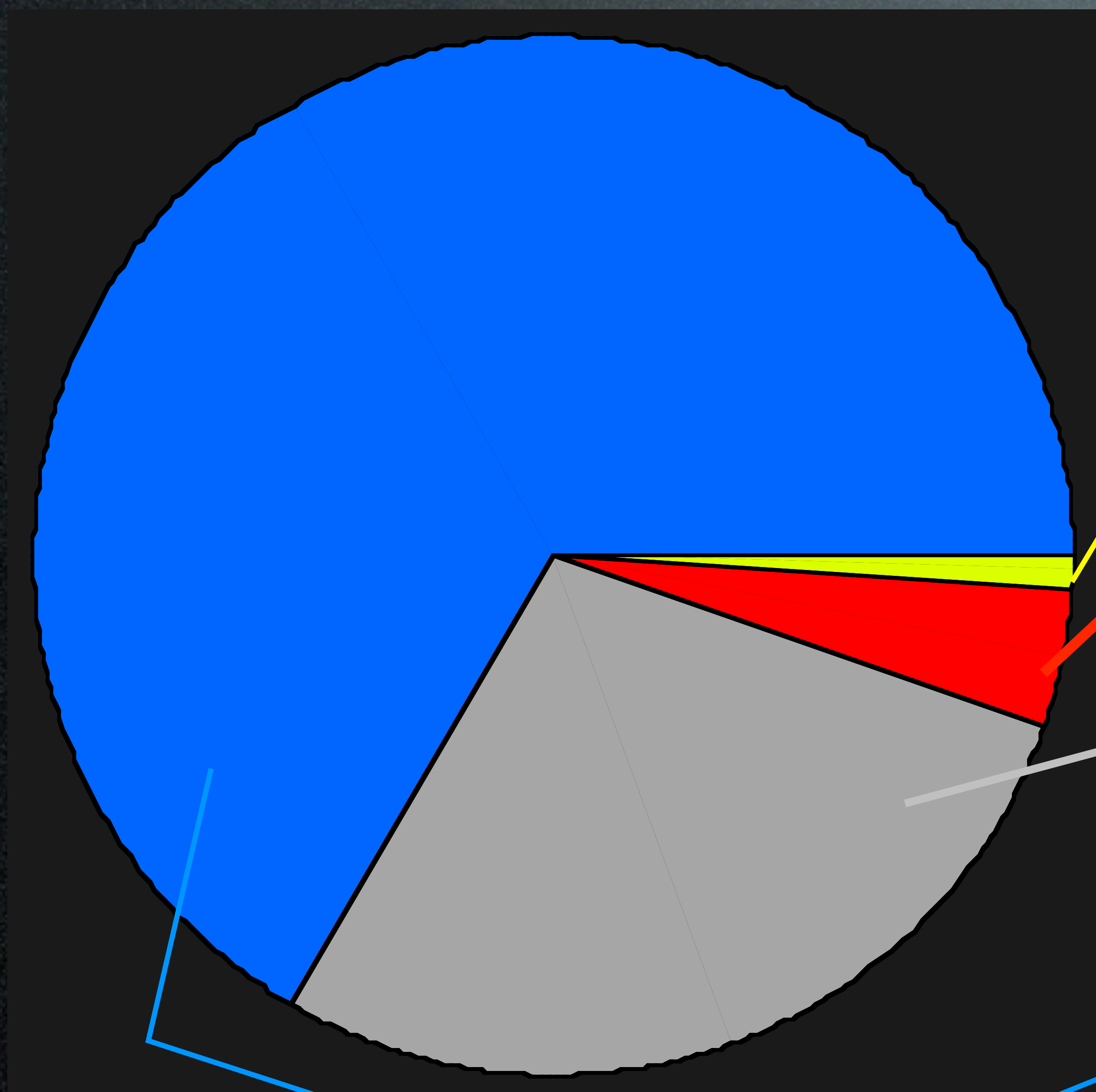


# The cosmic inventory

## Most of the Universe is Dark



$\Omega_{\rm lum} \sim 0.01$ -mass to light ratio in typical systems

$\Omega_{\rm b} \simeq 0.040 \pm 0.005$ -BBN -CMB

$\Omega_{\rm DM} \sim 0.24$ ⟵ particle physics $\bigcap$ cosmology

$\Omega_{\rm de} \sim 0.7$
- CMB + SNIa
- CMB - DM
- acoustic peak in baryons

$\left(\Omega_x = \frac{\rho_x}{\rho_c}\right.$; CMB first peak $\Rightarrow \Omega_{\rm tot} = 1$ (flat); HST $\left. h = 0.71 \pm 0.07 \right)$

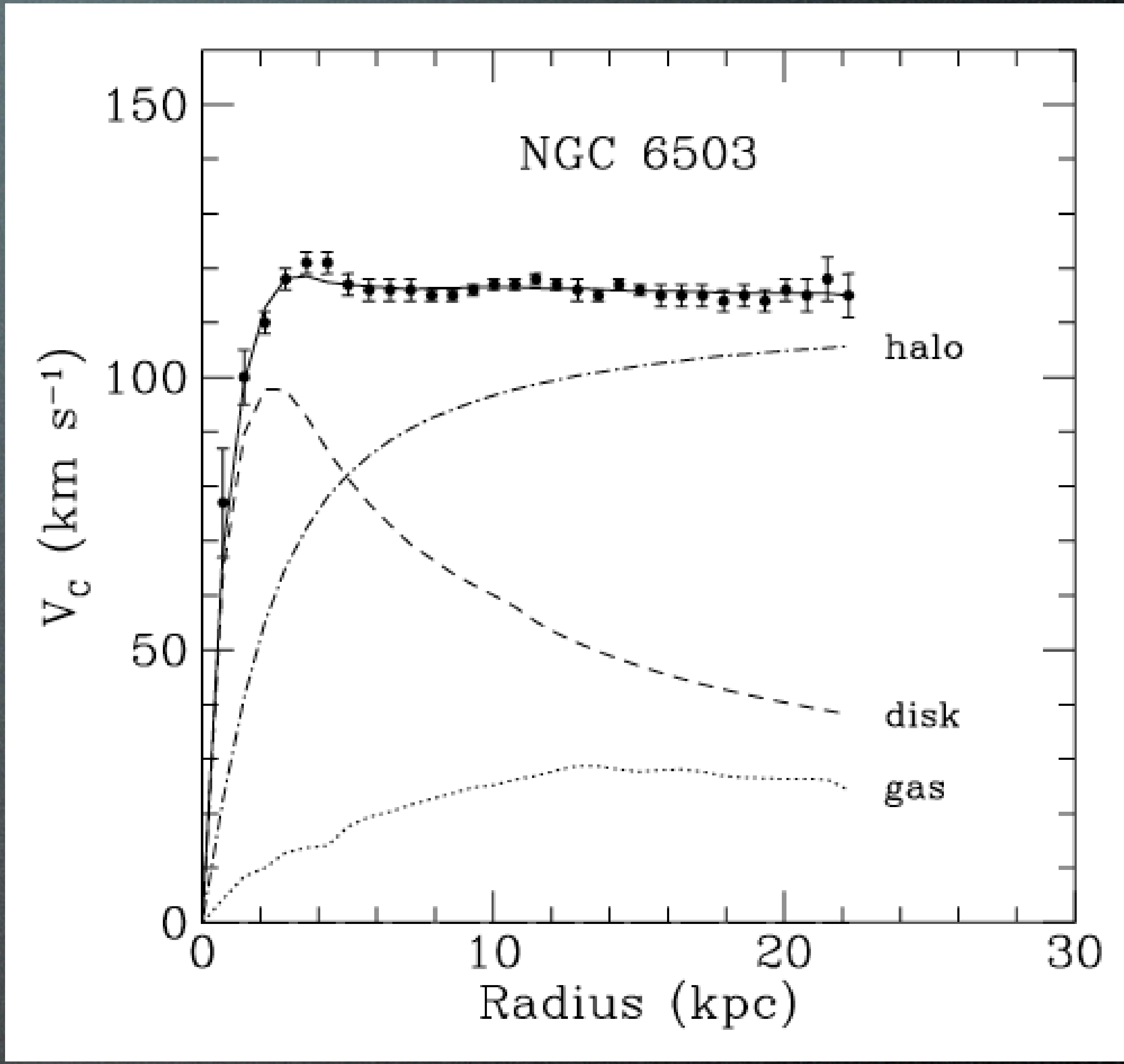
# The Evidence for DM

1) galaxy rotation curves

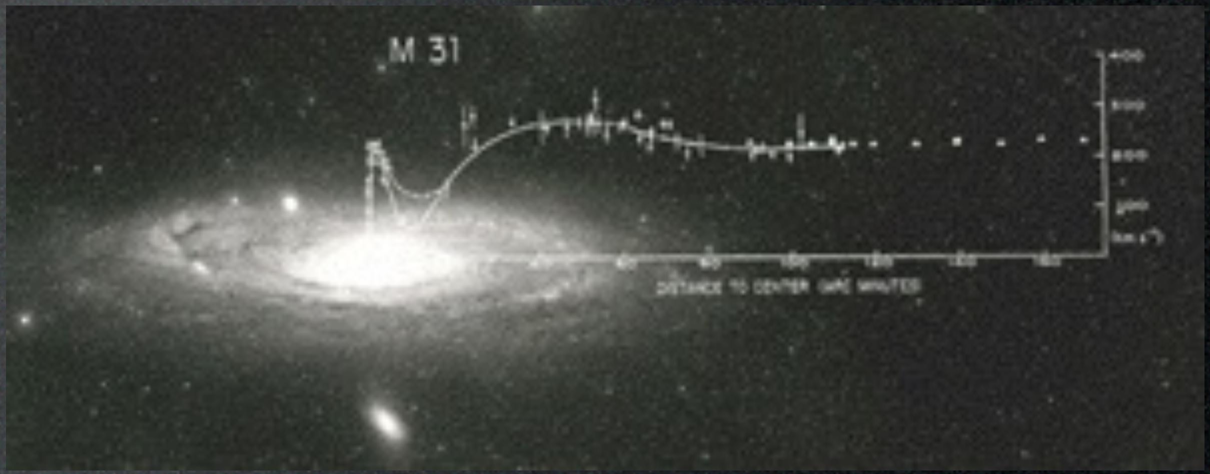
$$v_c(r) = \sqrt{\frac{2G_N M(r)}{r}}$$

$$v_c(r) \sim \text{const} \Rightarrow \rho_M(r) \sim \frac{1}{r^2}$$

$$\Omega_M \gtrsim 0.1$$



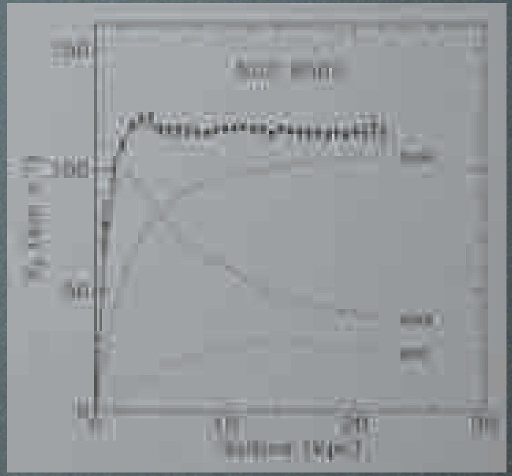

Begeman et al., MNRAS 249 (1991)




[back to main slide]

# The Evidence for DM

1) galaxy rotation curves



$\Omega_M \gtrsim 0.1$

2) clusters of galaxies

- "rotation curves"
- gravitation lensing
- X-ray gas temperature

$$\Omega_M \sim 0.2 \div 0.4$$

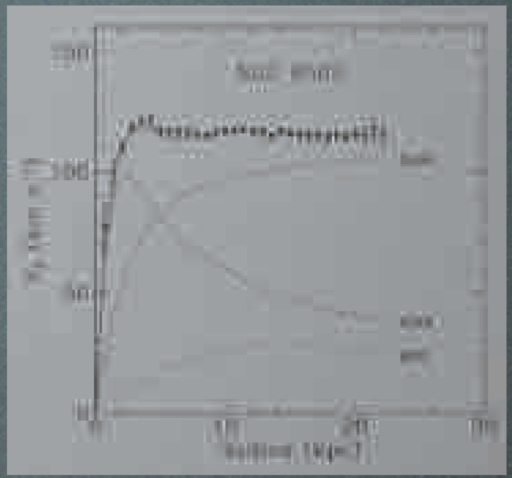

"bullet cluster" - NASA
astro-ph/0608247

[further developments]

[back to main slide]

# The Evidence for DM

1) galaxy rotation curves



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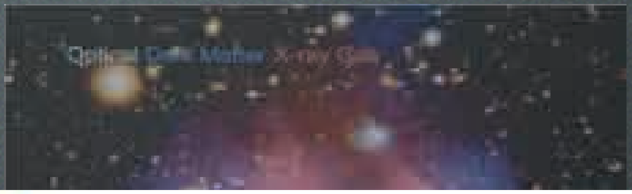
2) clusters of galaxies



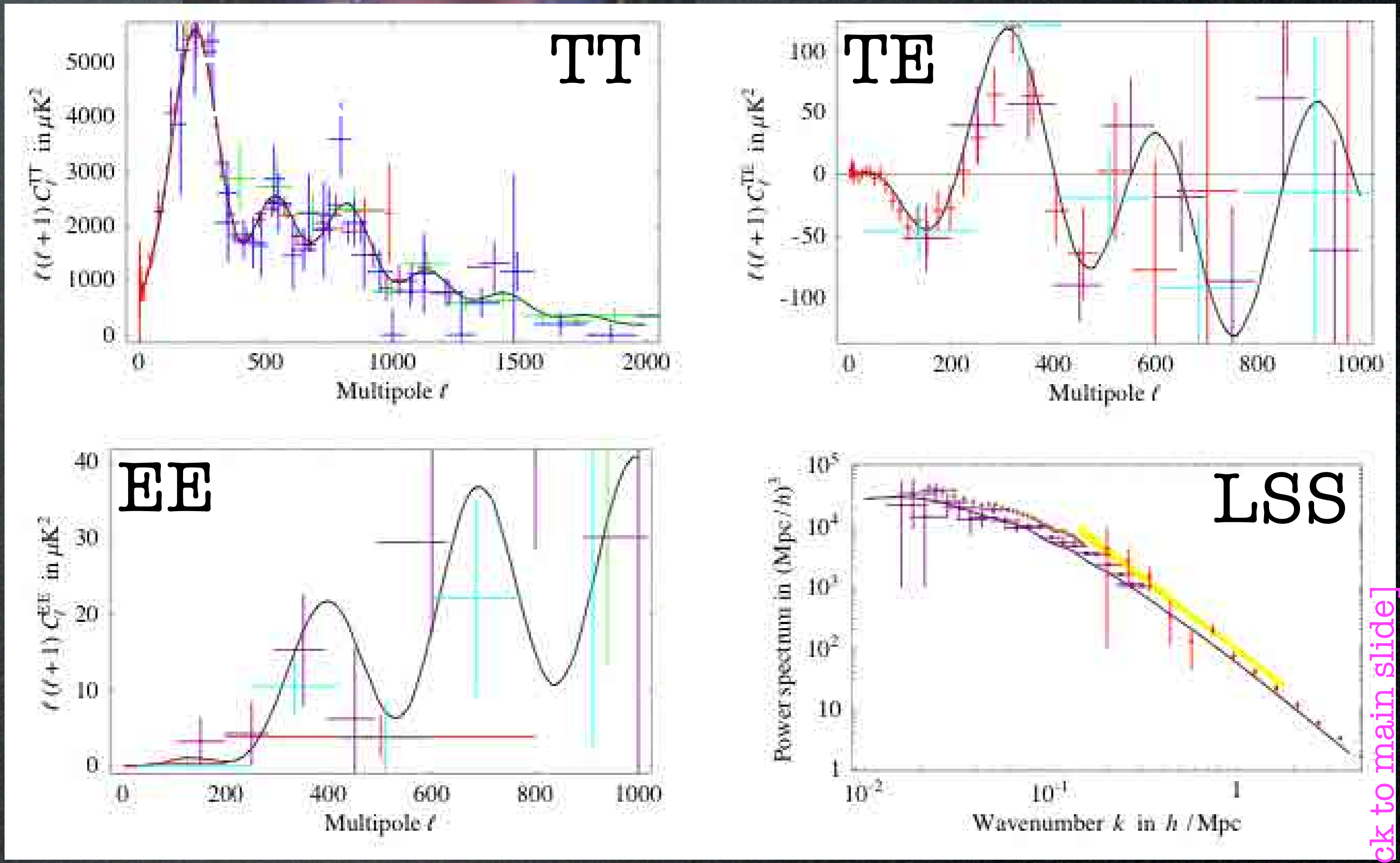
$\Omega_M \sim 0.2 \div 0.4$

3) CMB+LSS(+SNIa:)

WMAP-3yr
ACbar
CBI

Boomerang
DASI
VSA

SDSS, 2dFRGS
LyA Forest Croft
LyA Forest SDSS




$\Omega_M \approx 0.26 \pm 0.05$

M.Cirelli and A.Strumia, astro-ph/0607086

[back to main slide]

# Comparison with SplitSuSy-like models

A-H, Dimopoulos and/or Giudice, Romanino 2004
Pierce 2004; Arkani-Hamed, Dimopoulos, Kachru 2005
Mahbubani, Senatore 2005

| SplitSuSy-like | MDM |
|---|---|
| - Higgsino (a fermion doublet) | - arbitrary multiplet, scalar or fermion |
| - + something else (a singlet) | - nothing else (with Y=0) |
| - stabilization by R-parity | - automatically stable |
| - want unification also | - forget unification, it's SM |
| - unification scale is low, need to embed in 5D to avoid proton decay (Mahbubani, Senatore 2005) | - nothing |

Common feature: the focus is on DM, not on SM hierarchy problem.

# Non-Minimal terms in the scalar case

Quadratic and quartic terms in $\mathcal{X}$ and $H$ :

$$\lambda_H (\mathcal{X}^* T^a_{\mathcal{X}} \mathcal{X})\,(H^* T^a_H H) + \lambda'_H |\mathcal{X}|^2 |H|^2 + \frac{\lambda_{\mathcal{X}}}{2} (\mathcal{X}^* T^a_{\mathcal{X}} \mathcal{X})^2 + \frac{\lambda'_{\mathcal{X}}}{2} |\mathcal{X}|^4$$

[1] [2] [3] [4]

- do not induce decays (even number of $\mathcal{X}$, and $\langle \mathcal{X} \rangle = 0$ )
- [3] and [4] do not give mass terms
- after EWSB, [2] gives a common mass $\sqrt{\lambda'_H} v \approx \mathcal{O}(\lesssim 100 \text{ GeV})$ to all $\mathcal{X}_i$ components; negligible for $M = \mathcal{O}(\text{TeV})$
- after EWSB, [1] gives mass splitting $\Delta M_{\text{tree}} = \frac{\lambda_H v^2 |\Delta T^3_{\mathcal{X}}|}{4M} = \lambda_H \cdot 7.6 \text{ GeV} \frac{\text{TeV}}{M}$ between $\mathcal{X}_i$ components;
  assume $\lambda_H \lesssim 0.01$ so that $\Delta M_{\text{tree}} \ll \Delta M$
- [1] (and [2]) gives annihilations $\bar{\mathcal{X}}\mathcal{X} \to \bar{H} H$
  assume $|\lambda'_H| \ll g_Y^2, g_2^2$ so that these are subdominant

(Anyway, scalar MDM is less interesting.)

[back to Lagrangian]
[back to table]

# Neutralino “properties”

neutralino mass matrix in MSSM ($\tilde{B} - \tilde{W}^3 - \tilde{H}_1^0 - \tilde{H}_2^0$ basis)

$$M_\chi = \begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\ 0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\ -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0 \end{pmatrix}$$

superpotential

$$\mathcal{W} = -\mu \mathcal{H}_1 \mathcal{H}_2 + \mathcal{H}_1 h_e^{ij} \mathcal{L}_{Li} \mathcal{E}_{Rj} + \mathcal{H}_1 h_d^{ij} \mathcal{Q}_{Li} \mathcal{D}_{Rj} - \mathcal{H}_2 h_u^{ij} \mathcal{Q}_{Li} \mathcal{U}_{Rj}$$

soft SUSYB terms

$$\mathcal{L}_{\rm soft} = -\frac{1}{2}\left( M_1 \bar{\tilde{B}} \tilde{B} + M_2 \bar{\tilde{W}}^a \tilde{W}^a + M_3 \bar{\tilde{G}}^a \tilde{G}^a \right) + \ldots$$

$$\tan\beta = \frac{\langle v_1 \rangle}{\langle v_2 \rangle}$$

# 3. Indirect Detection

## Propagation for positrons:

$$\frac{\partial f}{\partial t} - K(E) \cdot \nabla^2 f - \frac{\partial}{\partial E}\left(b(E) f\right) = Q$$

diffusion
$K(E) = K_0 (E/\mathrm{GeV})^\delta$

energy loss
$b(E) = (E/\mathrm{GeV})^2/\tau_E$
$\tau_E = 10^{16}\,\mathrm{s}$

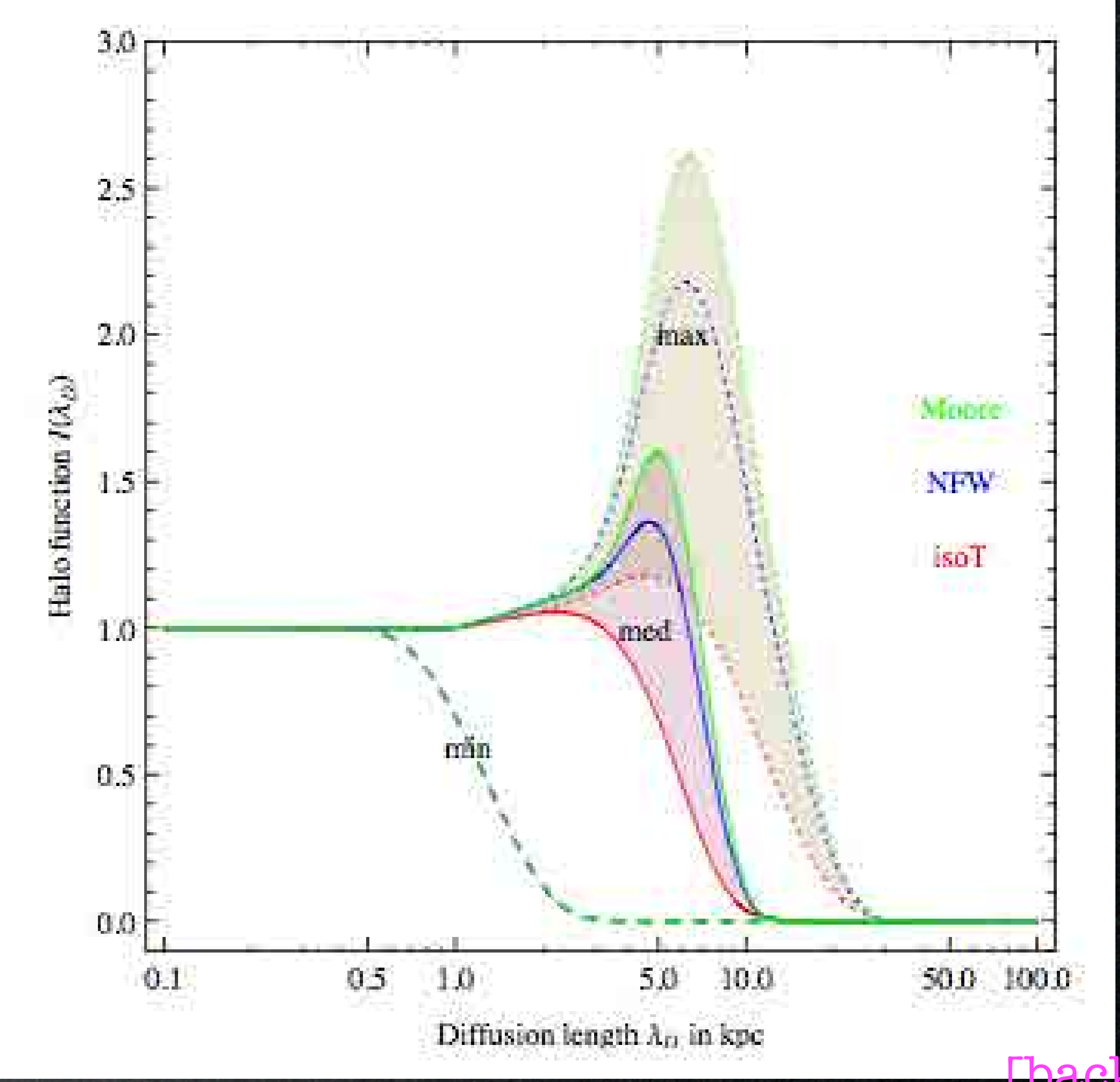
$$Q = \frac{1}{2}\left(\frac{\rho}{M_{\rm DM}}\right)^2 f_{\rm inj}, \qquad f_{\rm inj} = \sum_k \langle \sigma v \rangle_k \frac{dN^k_{e^+}}{dE}$$

| Model | $\delta$ | $K_0$ in kpc$^2$/Myr | $L$ in kpc |
|---|---|---|---|
| min (M2) | 0.55 | 0.00595 | 1 |
| med | 0.70 | 0.0112 | 4 |
| max (M1) | 0.46 | 0.0765 | 15 |

Solution:

$$\Phi_{e^+}(E, \vec{r}_\odot) = B \frac{v_{e^+}}{4\pi} \frac{\tau_E}{E^2} \int_E^{M_{\rm DM}} dE'\; Q(E') \cdot I\left(\lambda_D(E, E')\right)$$

$$\lambda_D^2 = 4 K_0 \tau_E \left[\frac{(E/\mathrm{GeV})^{\delta-1} - (E'/\mathrm{GeV})^{\delta-1}}{\delta - 1}\right]$$




[back]

# 3. Indirect Detection

## Propagation for antiprotons:

$$\frac{\partial f}{\partial t} - K(T)\cdot\nabla^2 f + \frac{\partial}{\partial z}\left(\mathrm{sign}(z)\, f\, V_{\rm conv}\right) = Q - 2h\,\delta(z)\,\Gamma_{\rm ann} f$$

diffusion — convective wind — spallations

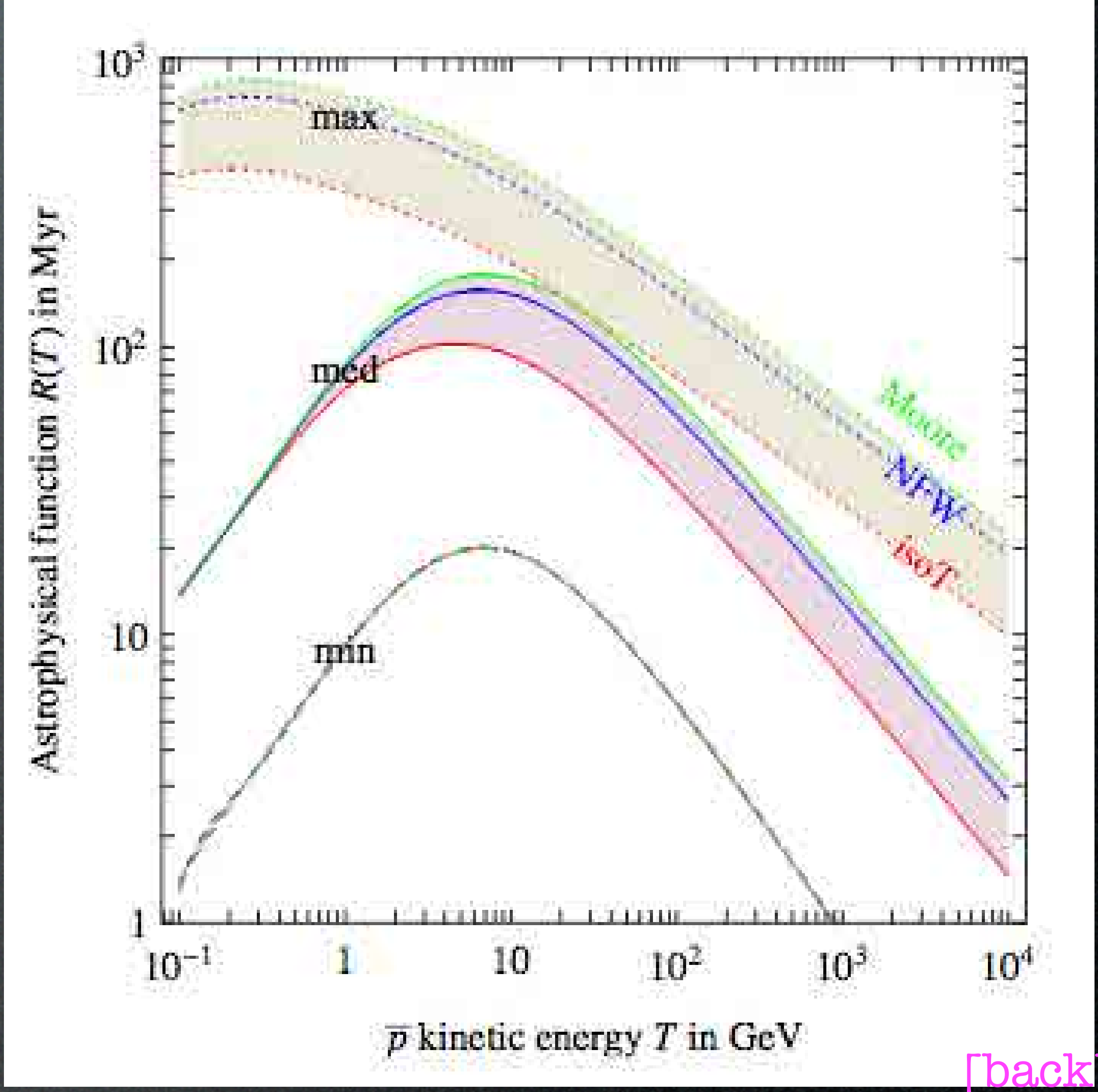
$K(T) = K_0 \beta\, (p/\mathrm{GeV})^\delta$

$T$ kinetic energy

| Model | $\delta$ | $K_0$ in kpc$^2$/Myr | $L$ in kpc | $V_{\rm conv}$ in km/s |
|---|---|---|---|---|
| min | 0.85 | 0.0016 | 1 | 13.5 |
| med | 0.70 | 0.0112 | 4 | 12 |
| max | 0.46 | 0.0765 | 15 | 5 |

Solution:

$$\Phi_{\bar p}(T,\vec r_\odot) = B\,\frac{v_{\bar p}}{4\pi}\left(\frac{\rho_\odot}{M_{\rm DM}}\right)^2 R(T)\sum_k \frac{1}{2}\langle\sigma v\rangle_k \frac{dN^k_{\bar p}}{dT}$$




[back]

# Indirect Detection

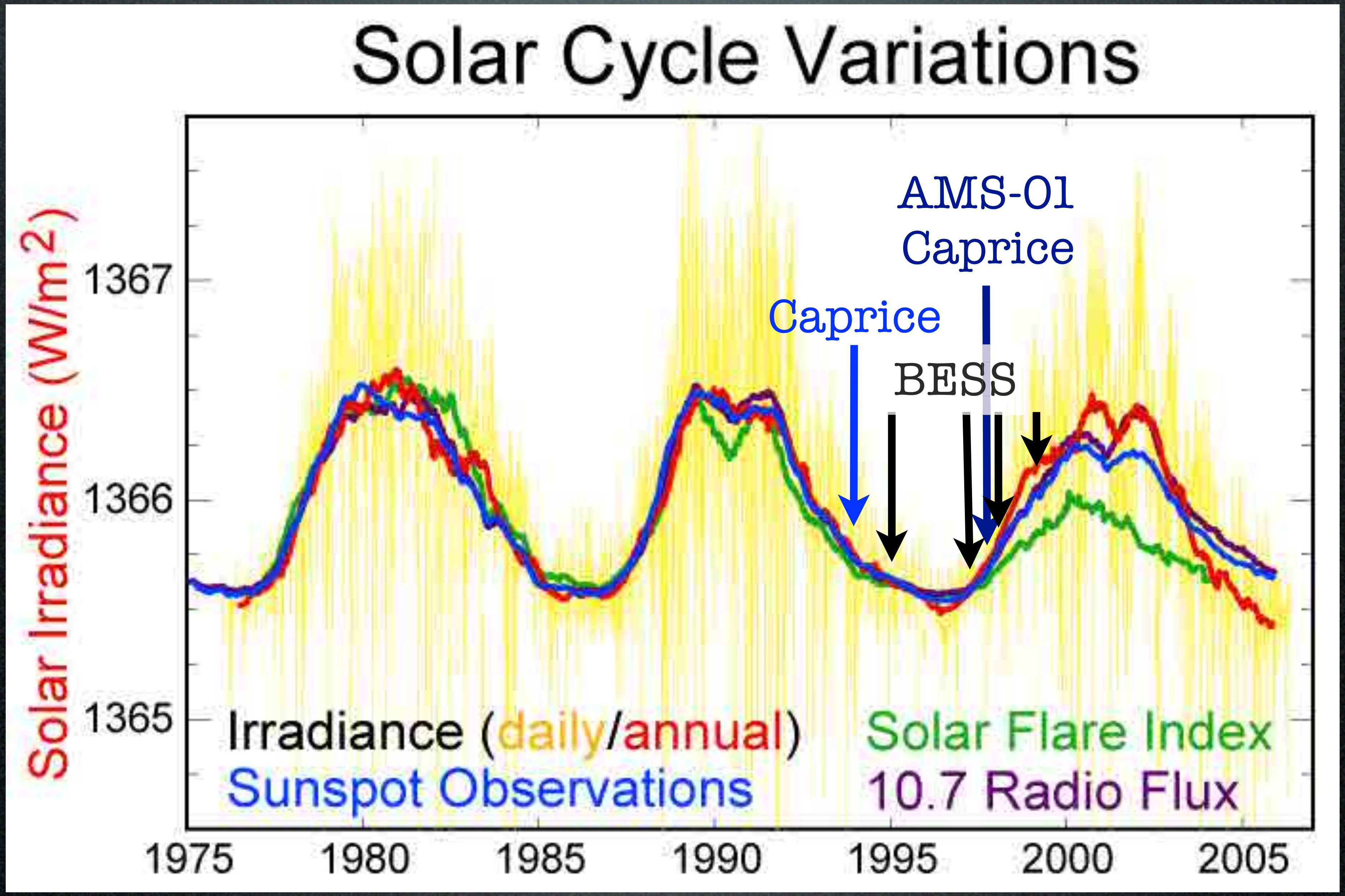
Solar wind Modulation of cosmic rays:

$$\frac{d\Phi_{\bar{p}\oplus}}{dT_\oplus} = \frac{p_\oplus^2}{p^2}\frac{d\Phi_{\bar{p}}}{dT}, \qquad T = T_\oplus + |Ze|\phi_F$$

spectrum at Earth

spectrum far from Earth

Fisk potential $\phi_F \simeq 500$ MV

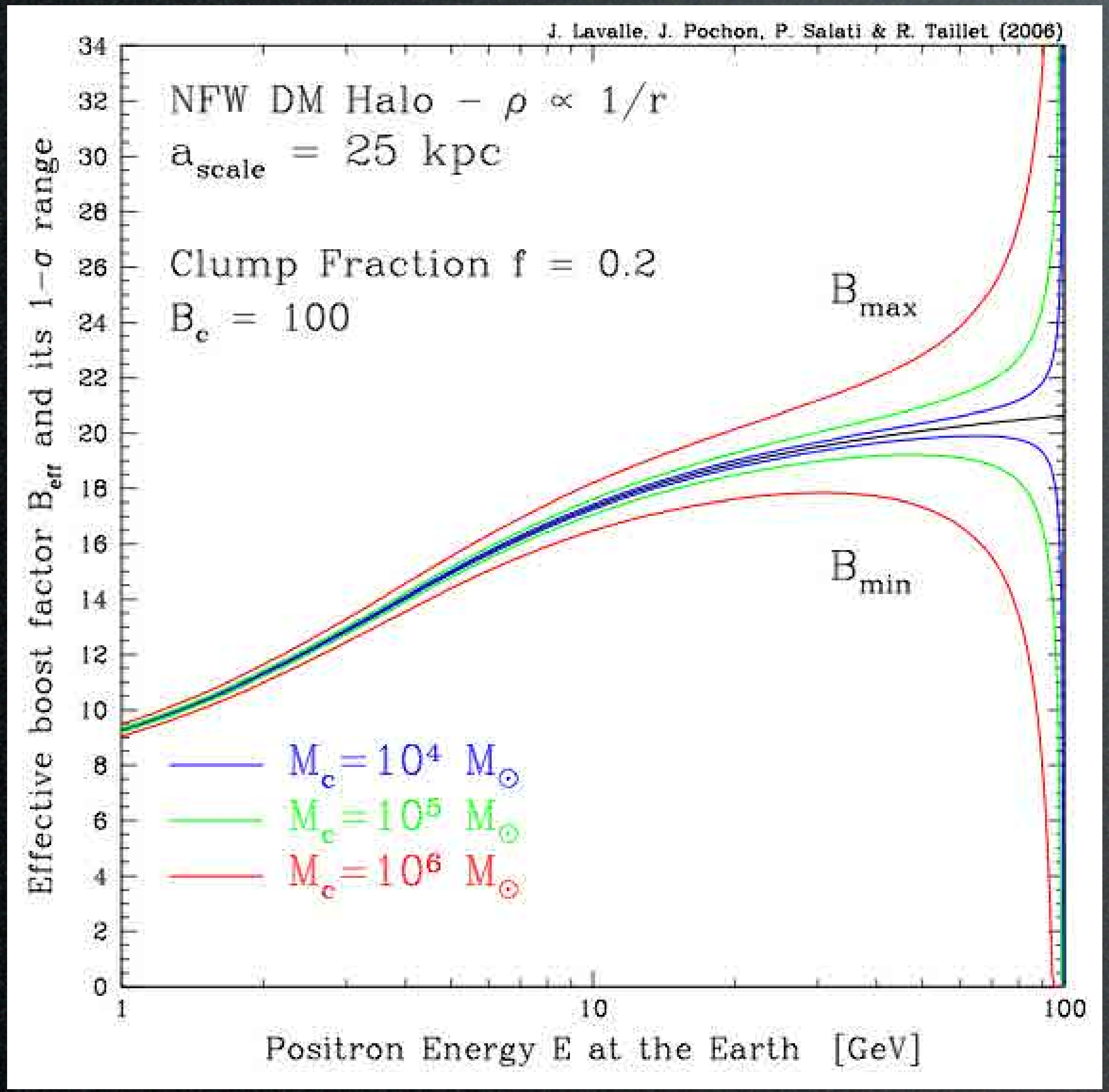


# Indirect Detection

**Boost Factor**: local clumps in the DM halo enhance the density, boost the flux from annihilations. Typically: $B \simeq 1 \rightarrow 20 \quad (10^4)$

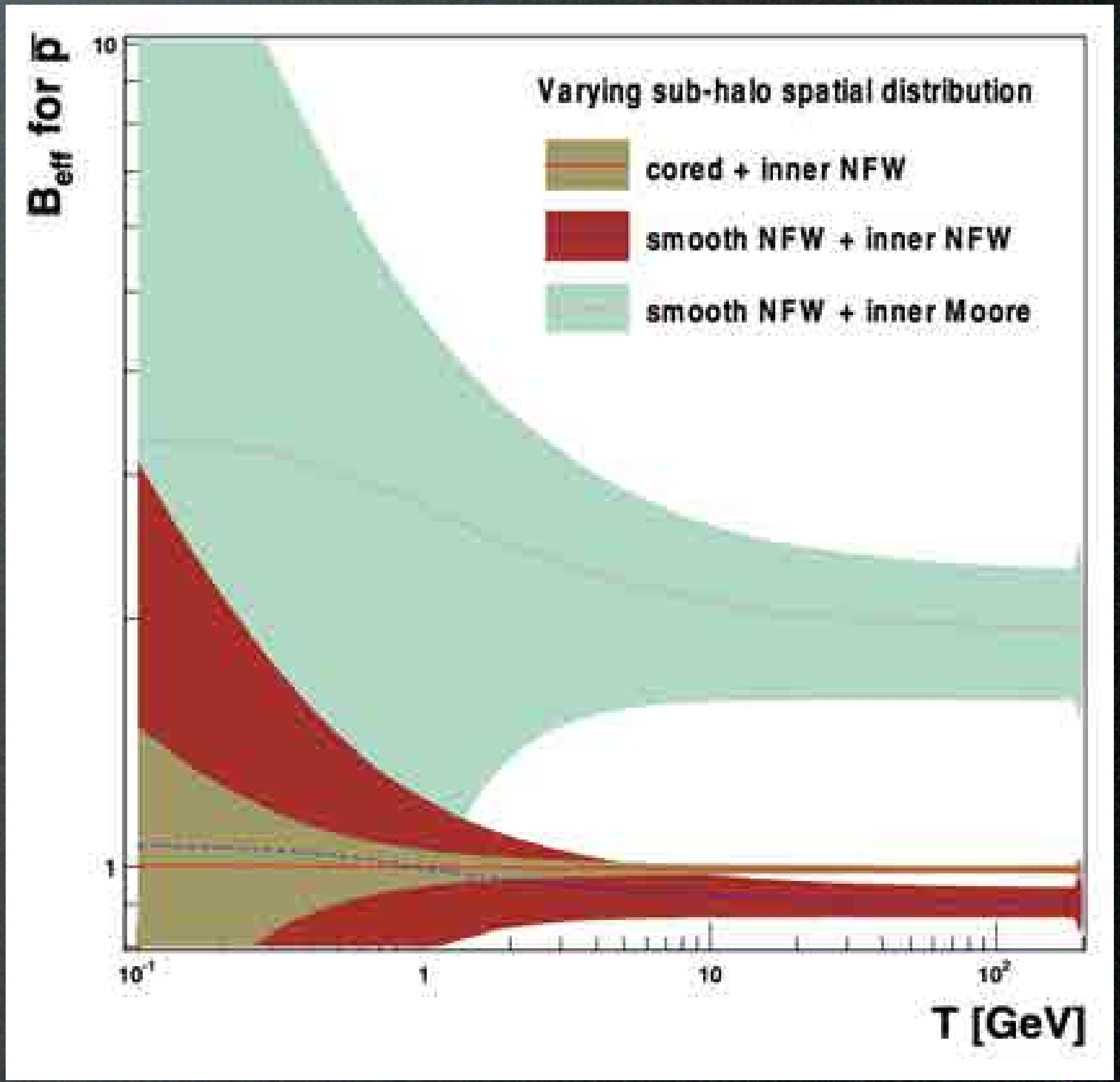
In principle, B is different for $e^+$, anti-p and gammas,
energy dependent,
dependent on many astro assumptions,
with an energy dependent variance, at high energy for $e^+$, at low energy for anti-p.

## positrons




Lavalle et al. 2006

## antiprotons




Lavalle et al. 2007

[back]

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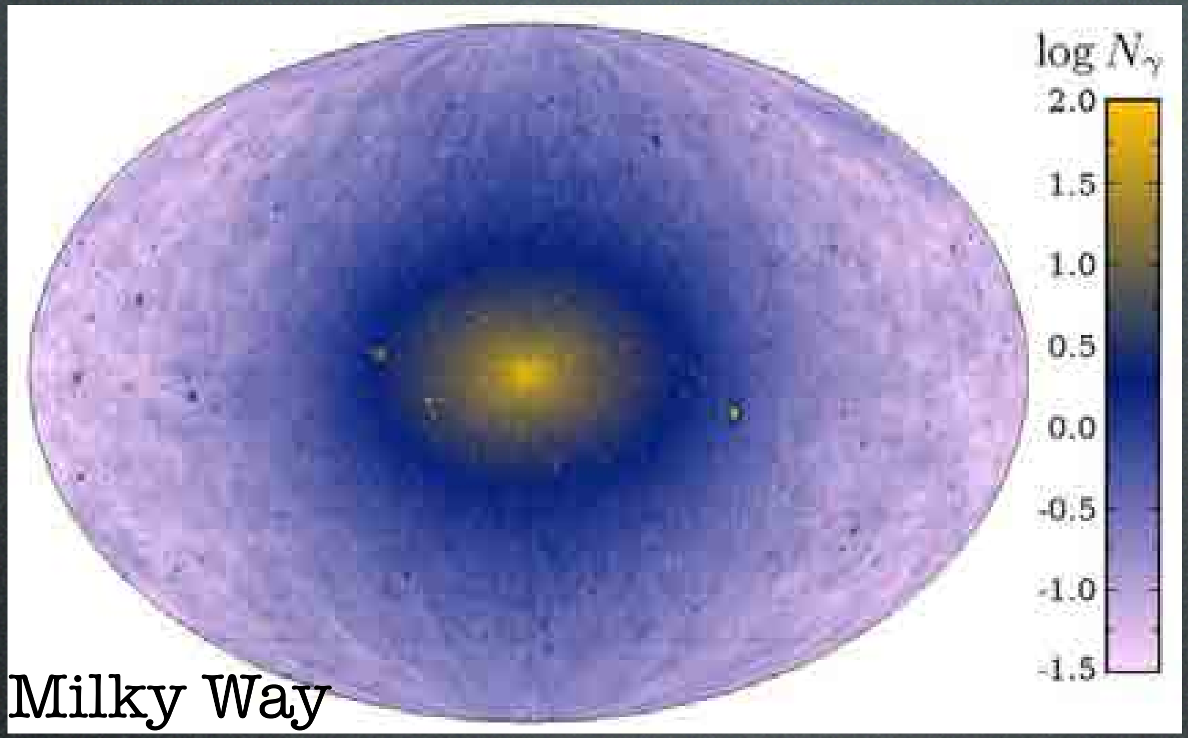
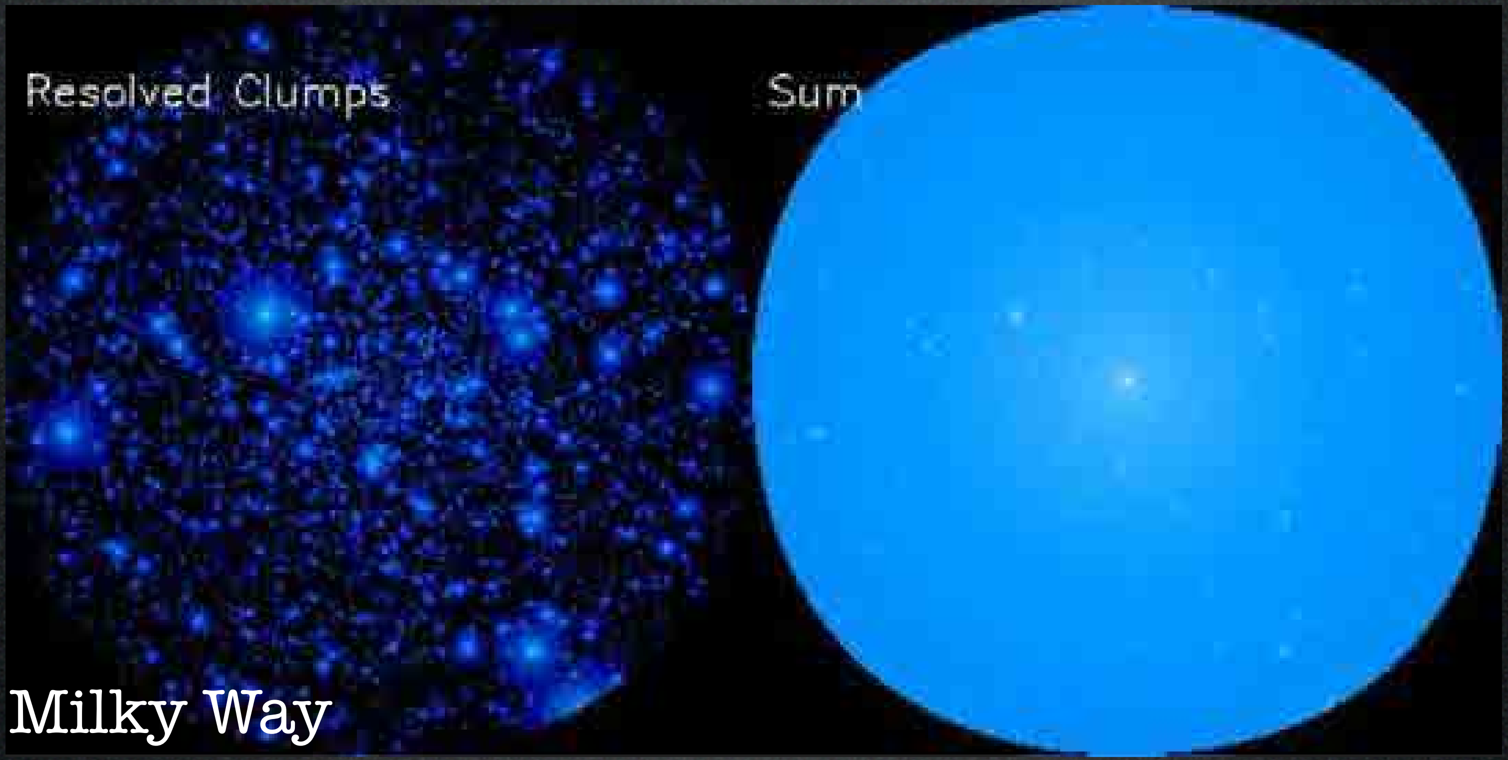
For illustration:




Kuhlen, Diemand, Madau 2007



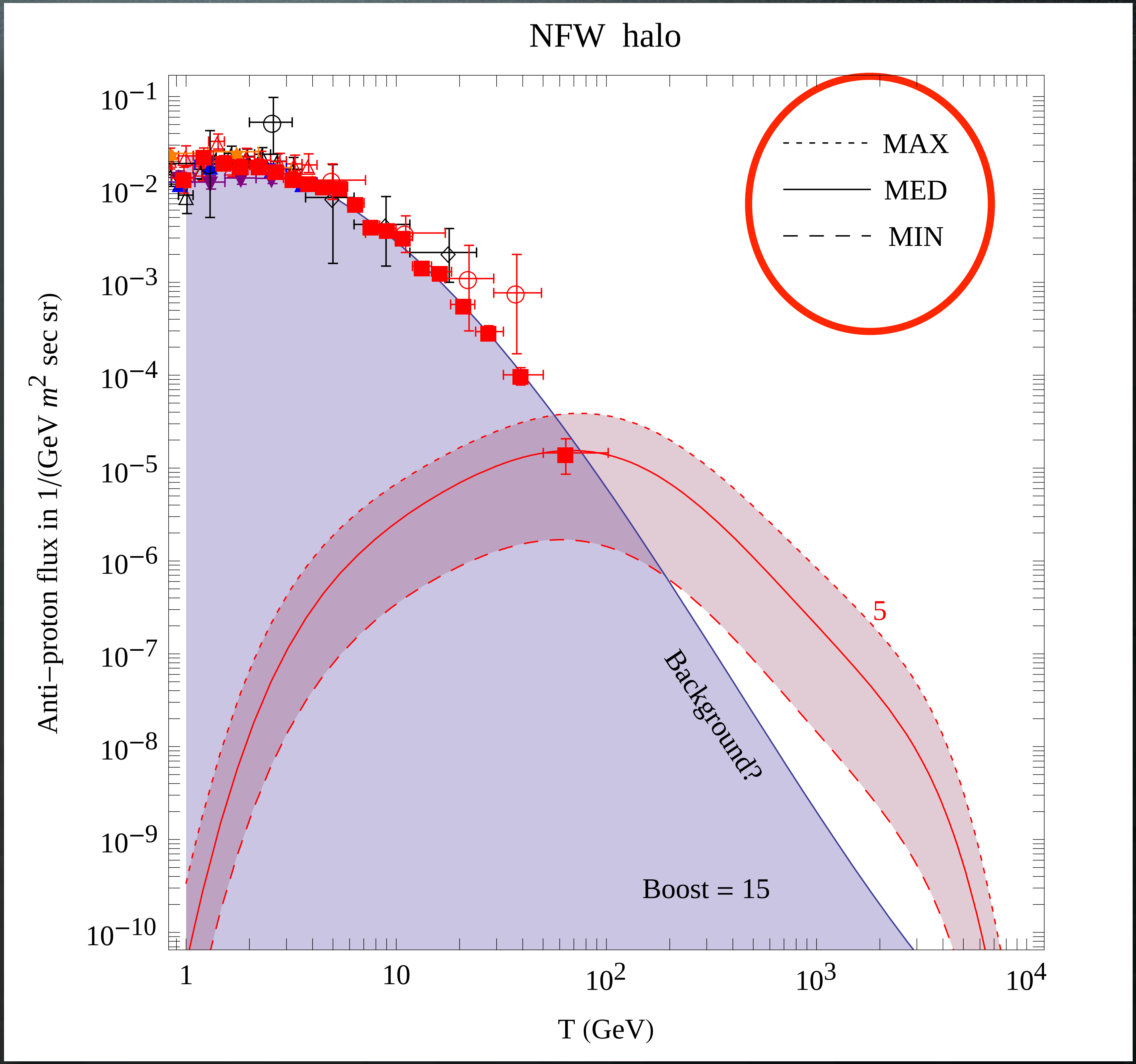

Bertone, Branchini, Pieri 2007

# 3. Indirect Detection

Results for anti-protons:

Astro uncertainties:

- propagation model
- DM halo profile
- boost factor B



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