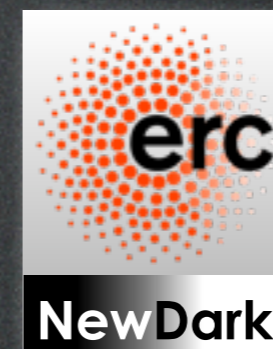


24 June 2016
RICAP 2016 Frascati

Gamma-ray signatures of Dark Matter

Marco Cirelli

(CNRS LPTHE Jussieu Paris)

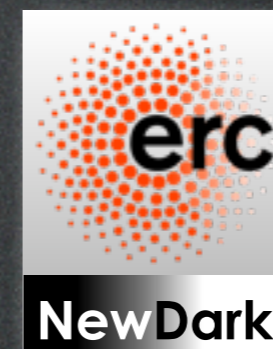


24 June 2016
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Photon signatures of Dark Matter

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How does DM produce γ -rays?

1. prompt emission

2. secondary emission

How does DM produce γ -rays?

1. prompt emission

1a. continuum

1b. line(s)

1c. sharp features

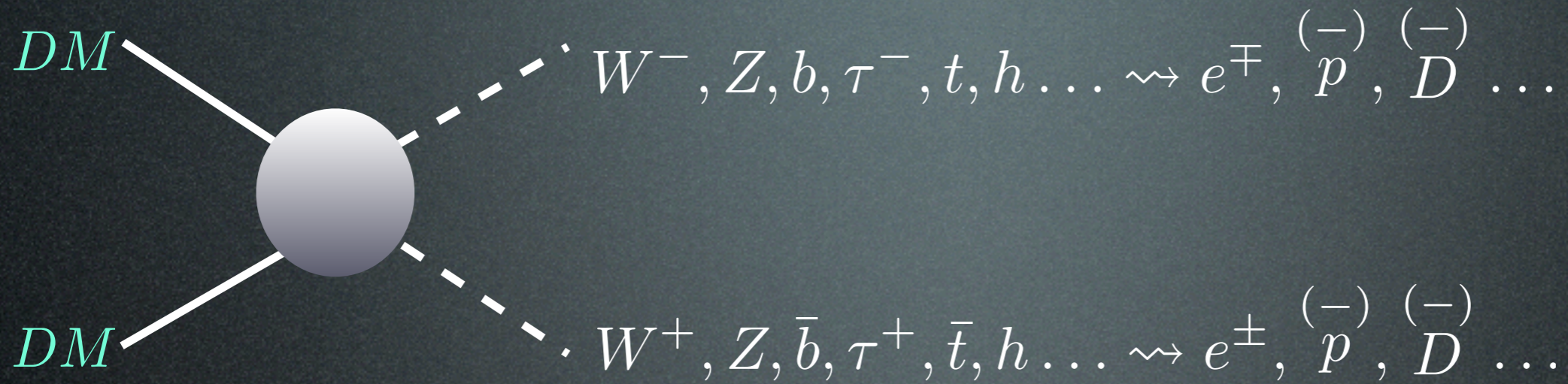
2. secondary emission

2a. ICS

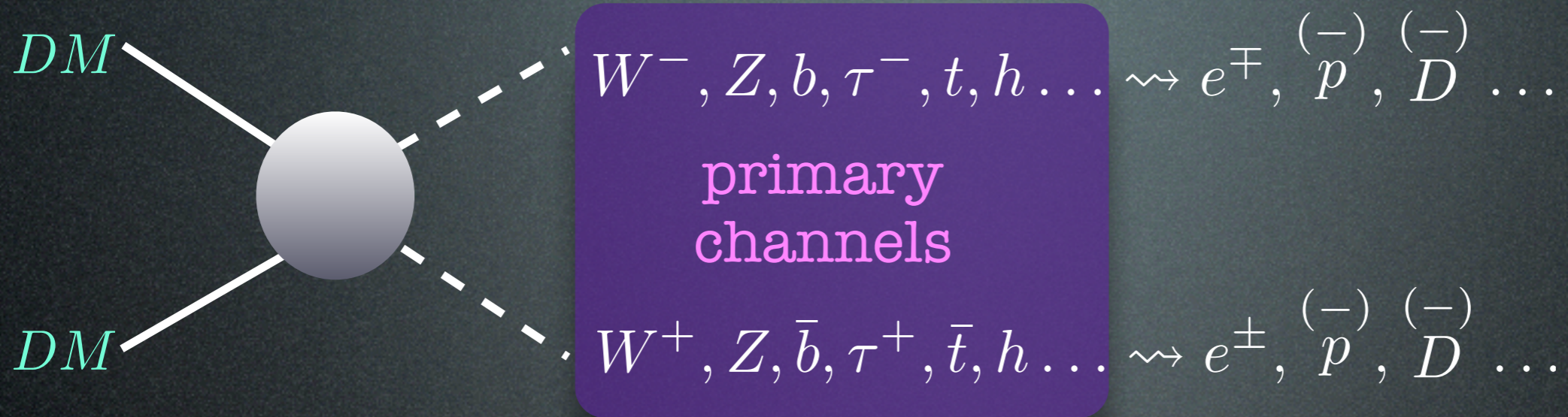
2b. bremsstrahlung

2c. synchrotron

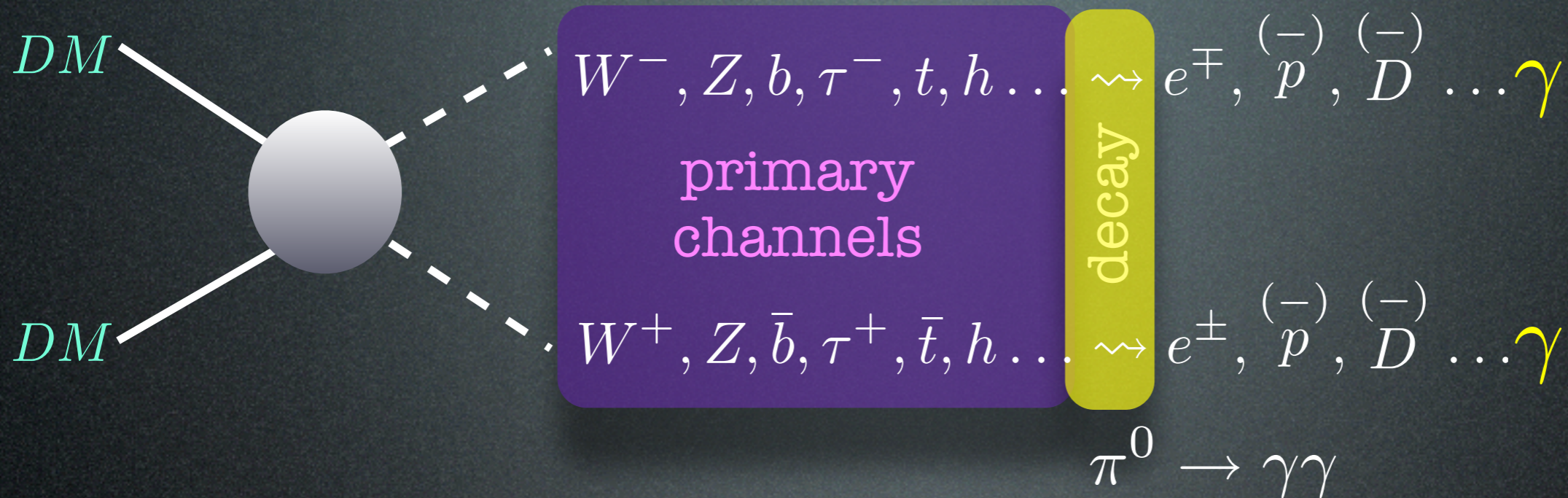
Prompt emission: continuum



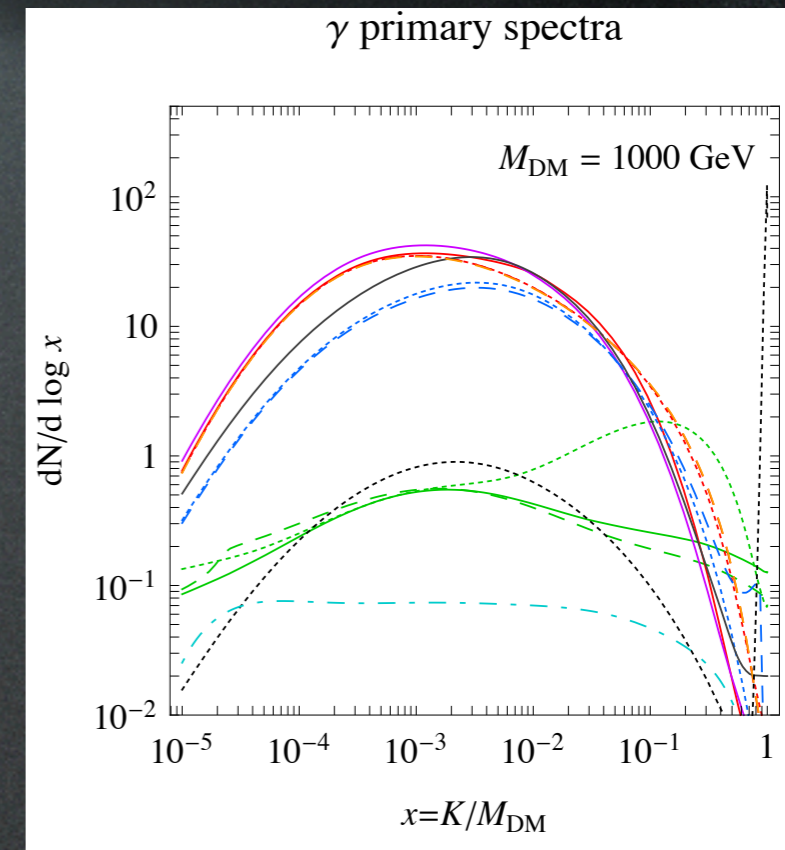
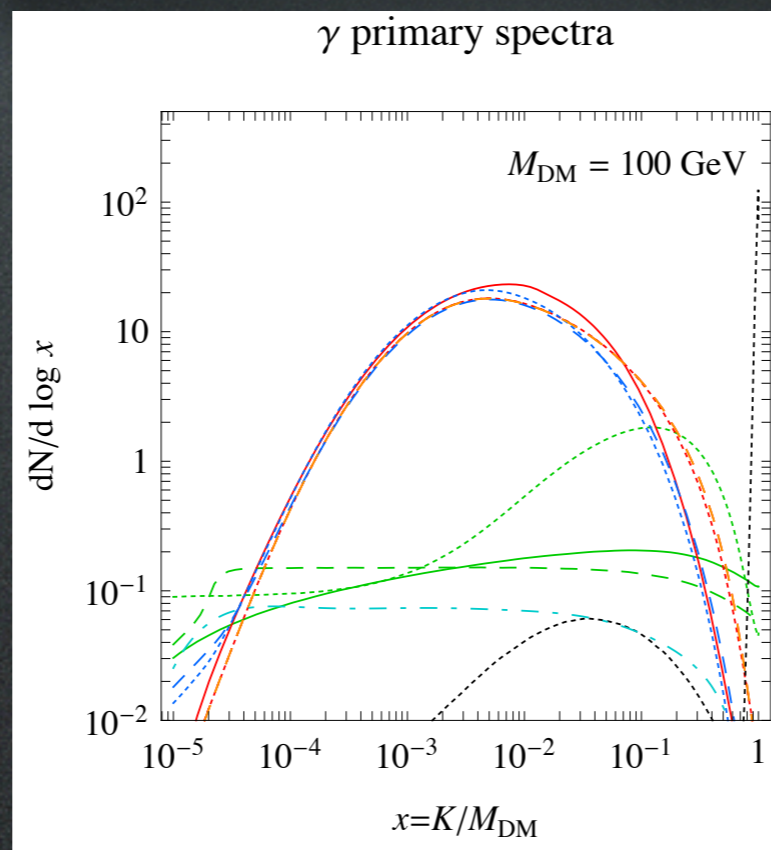
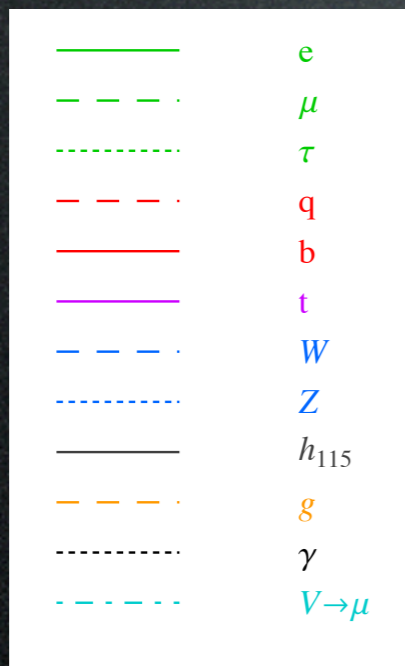
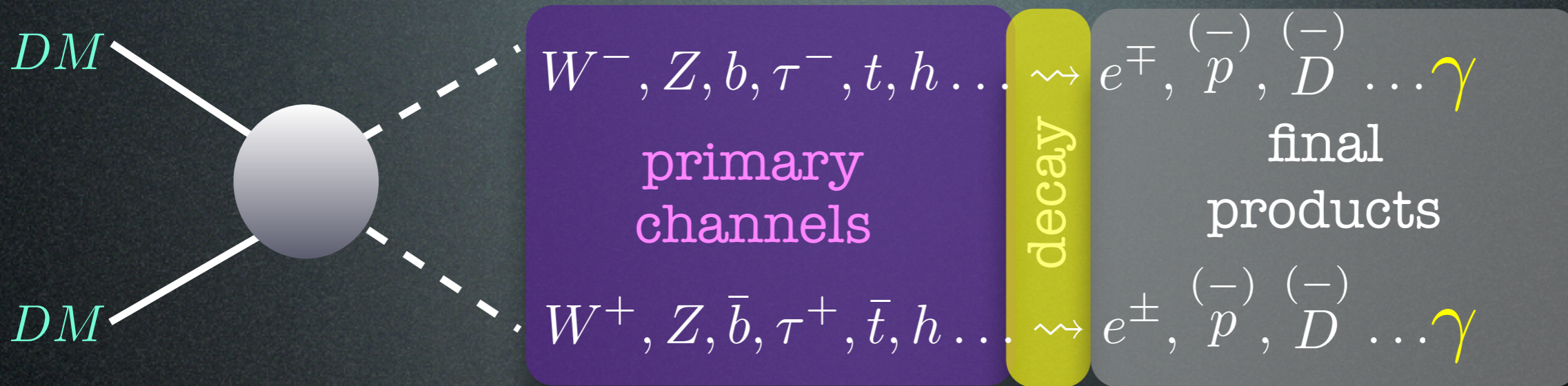
Prompt emission: continuum



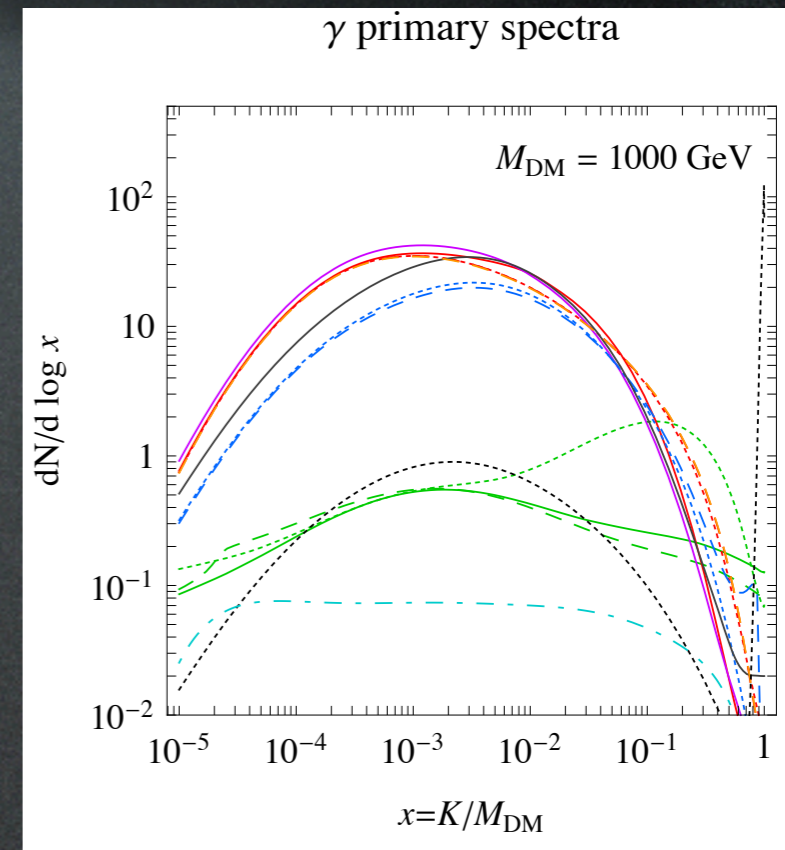
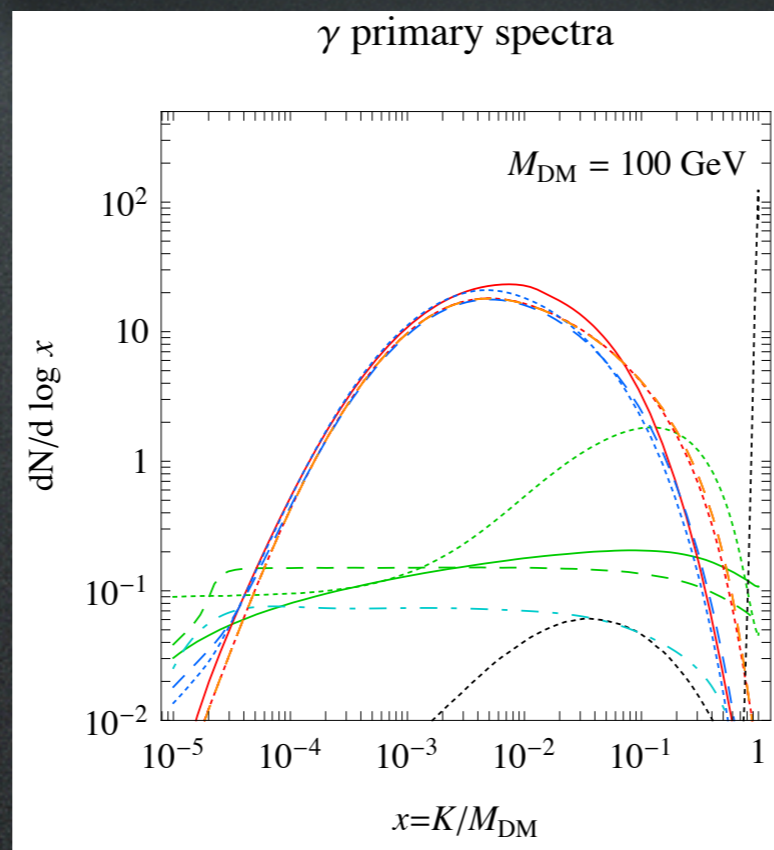
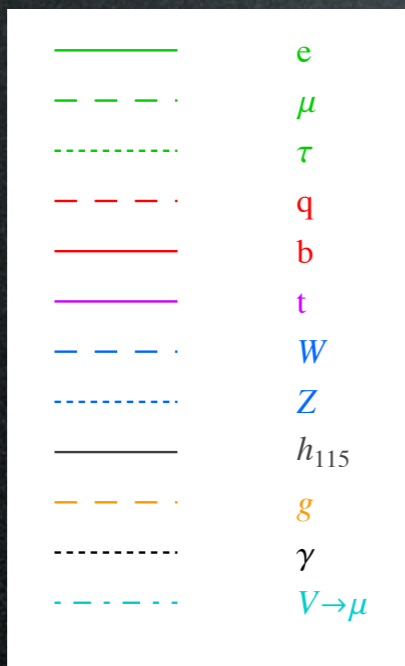
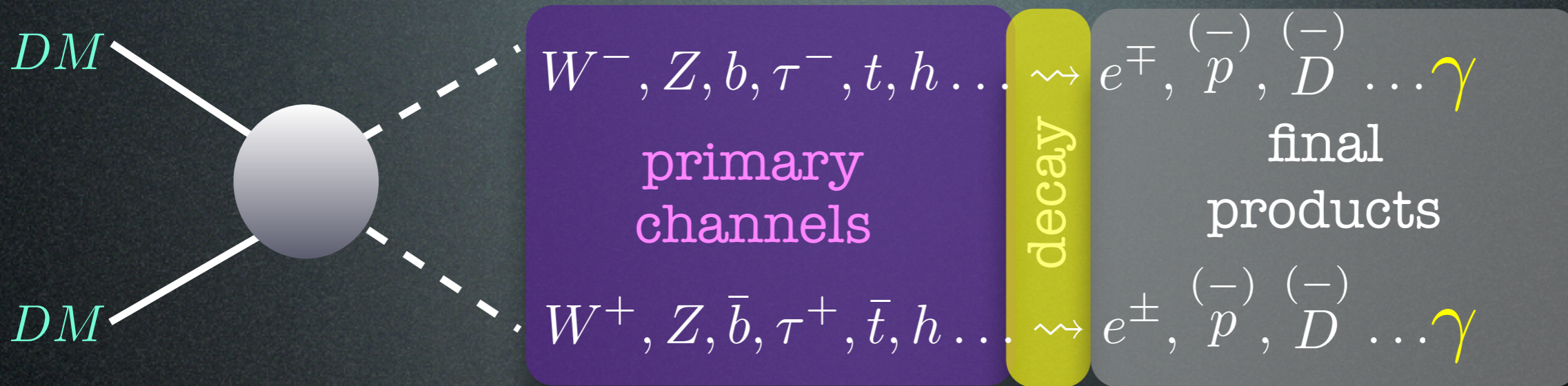
Prompt emission: continuum



Prompt emission: continuum



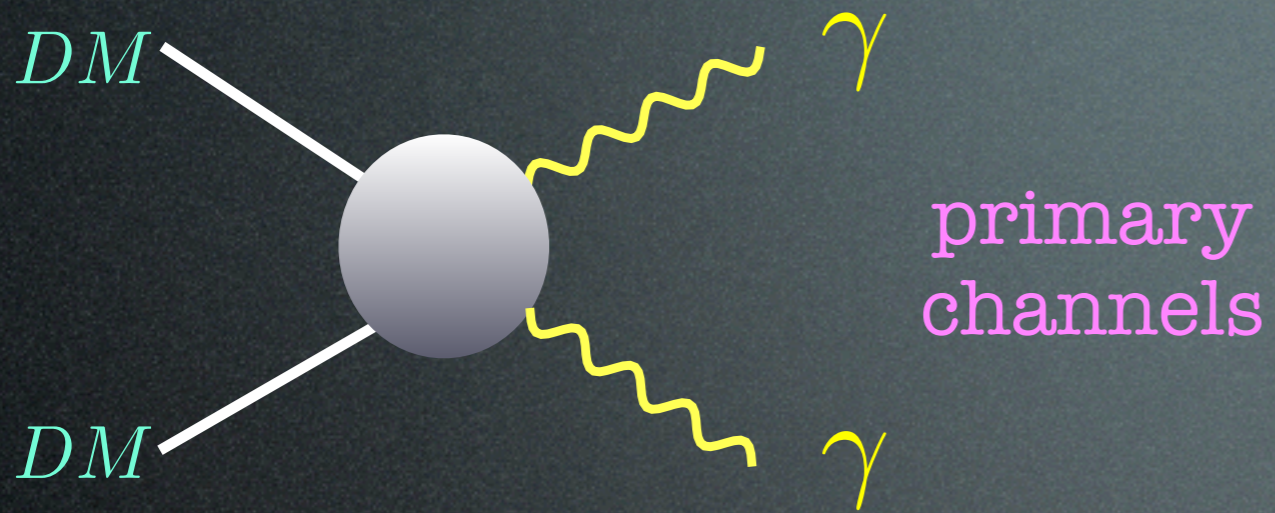
Prompt emission: continuum



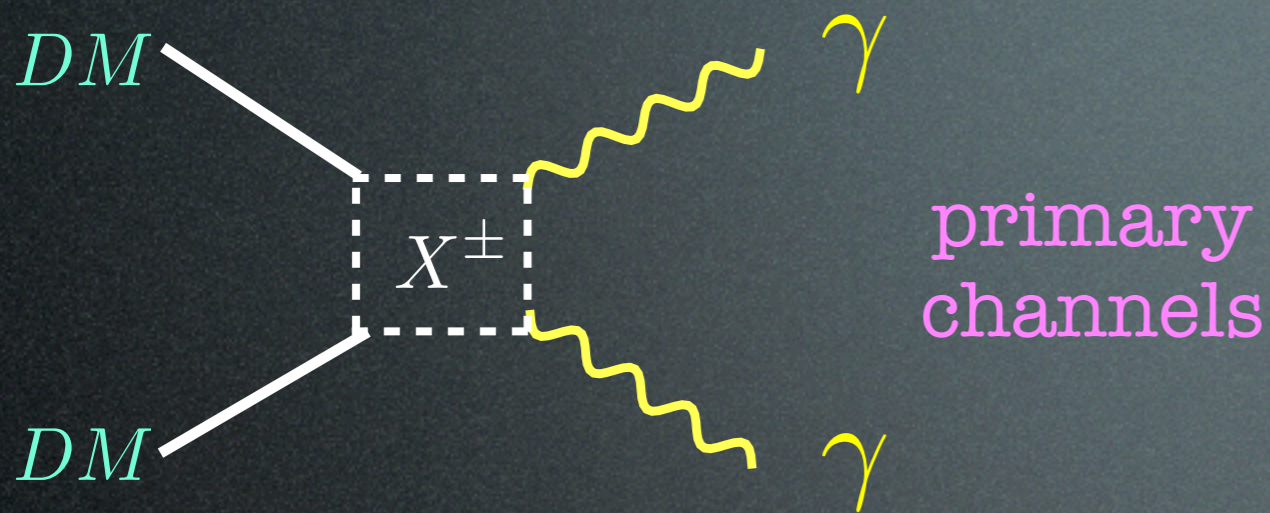
So what are the particle physics parameters?

1. Dark Matter mass
2. primary channel(s)
3. annihilation cross section σ_{ann}

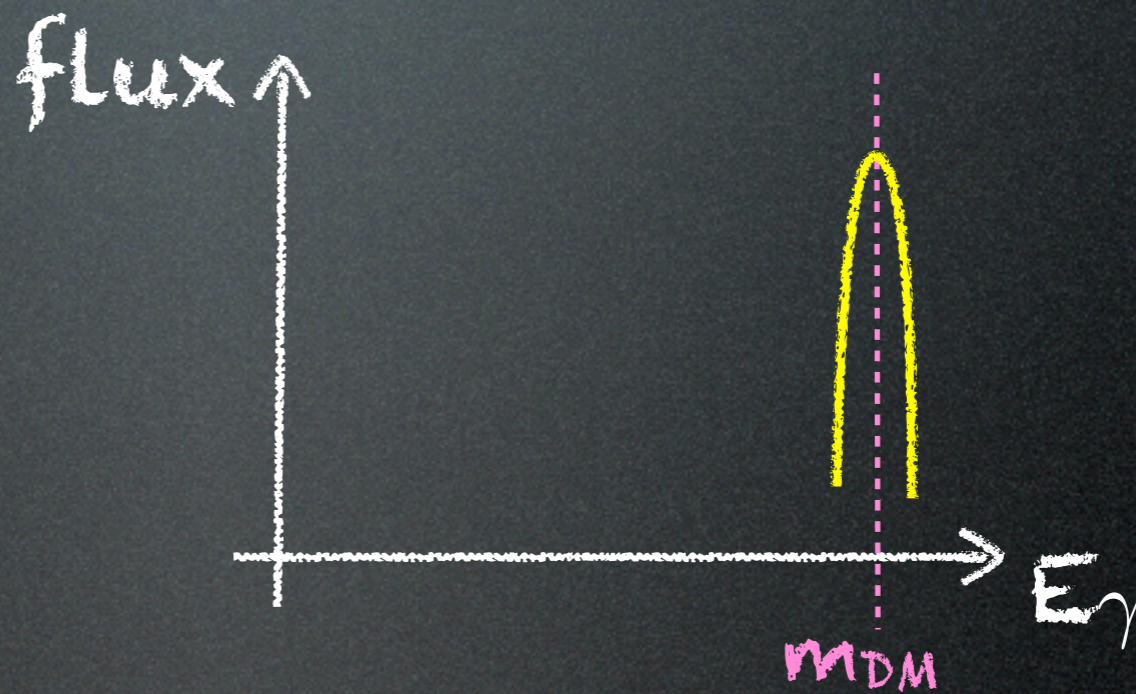
Prompt emission: line(s)



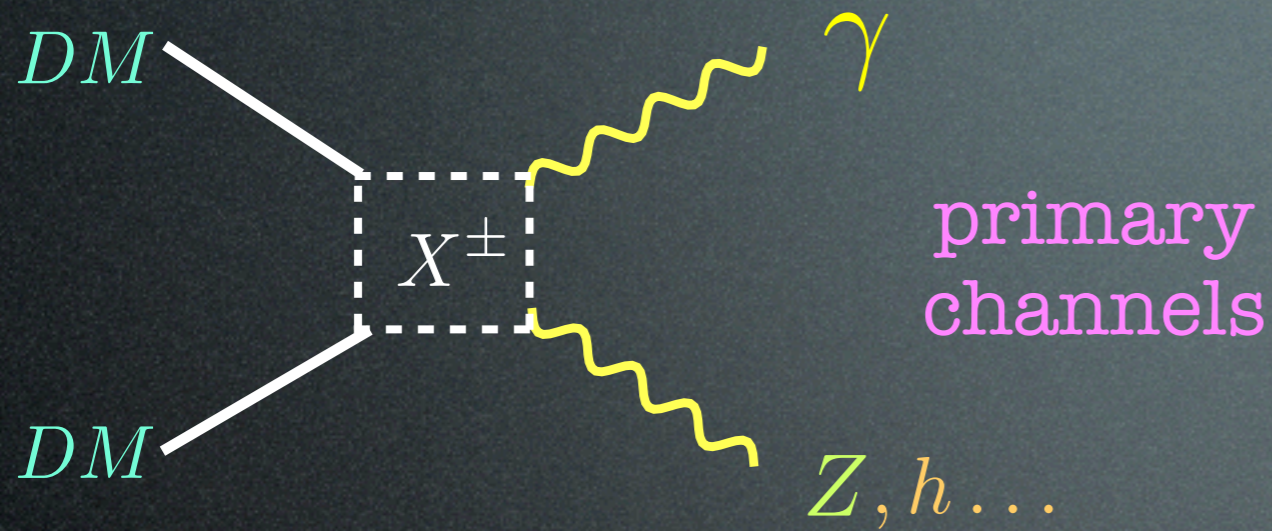
Prompt emission: line(s)



$$E_\gamma = m_{DM}$$

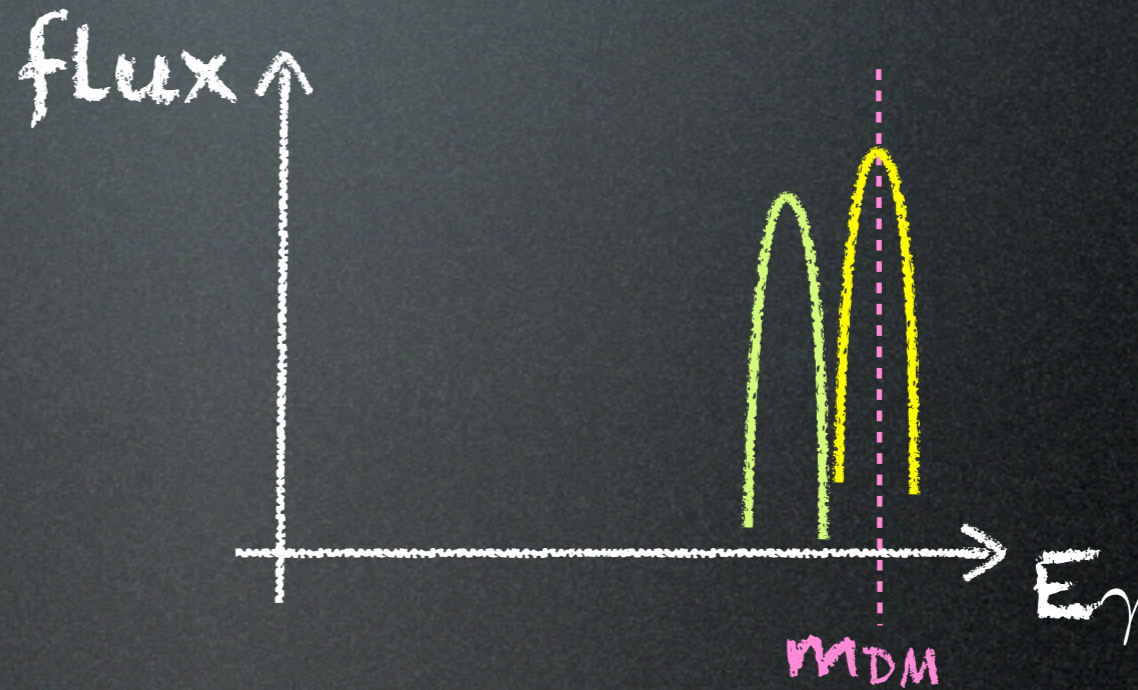


Prompt emission: line(s)

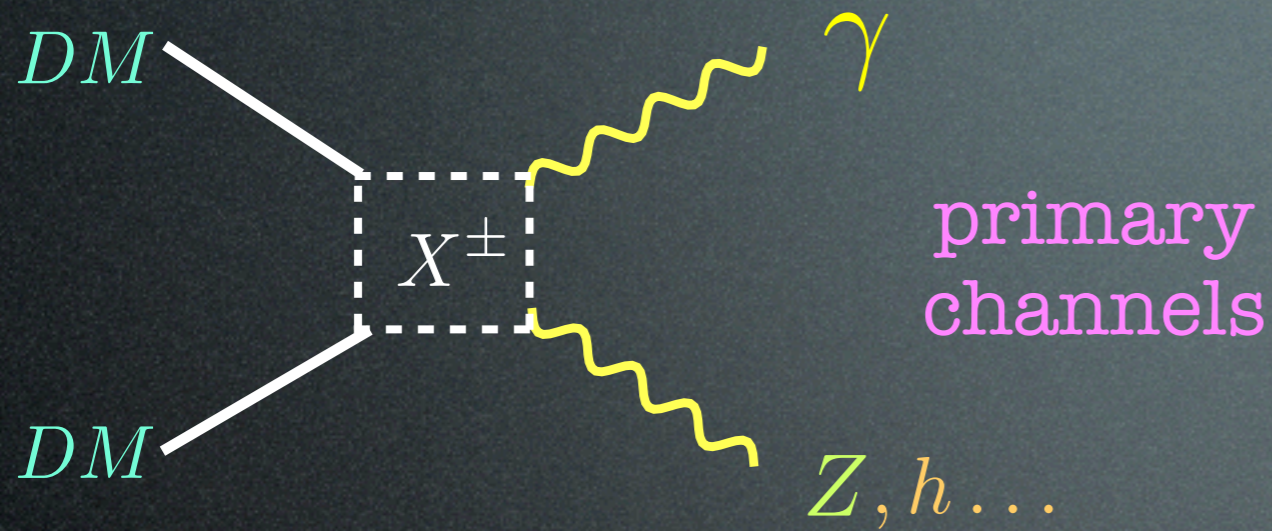


$$E_\gamma = m_{DM}$$

$$E_\gamma = m_{DM} \left(1 - \frac{m_Z^2}{4m_{DM}^2} \right)$$

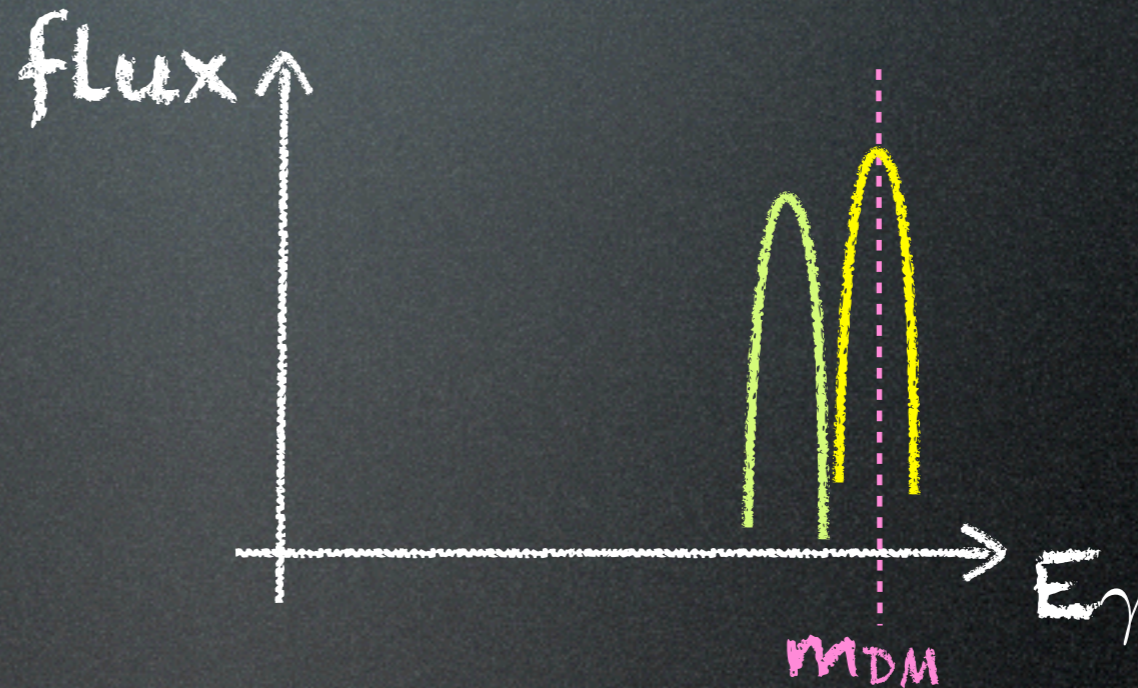


Prompt emission: line(s)



$$E_\gamma = m_{\text{DM}}$$

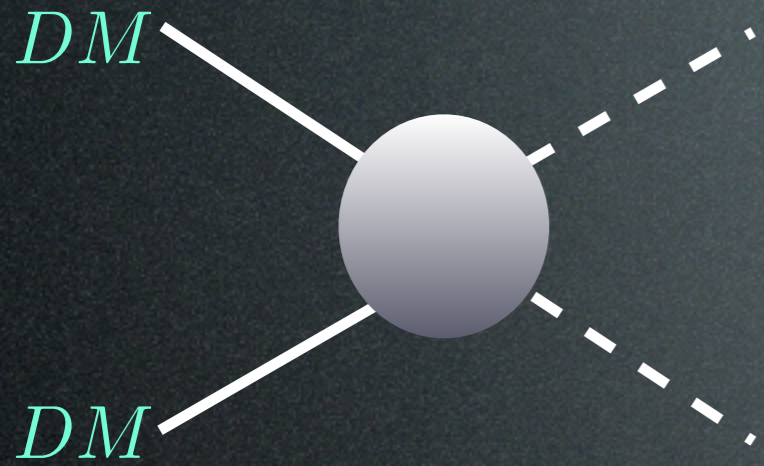
$$E_\gamma = m_{\text{DM}} \left(1 - \frac{m_Z^2}{4m_{\text{DM}}^2} \right)$$



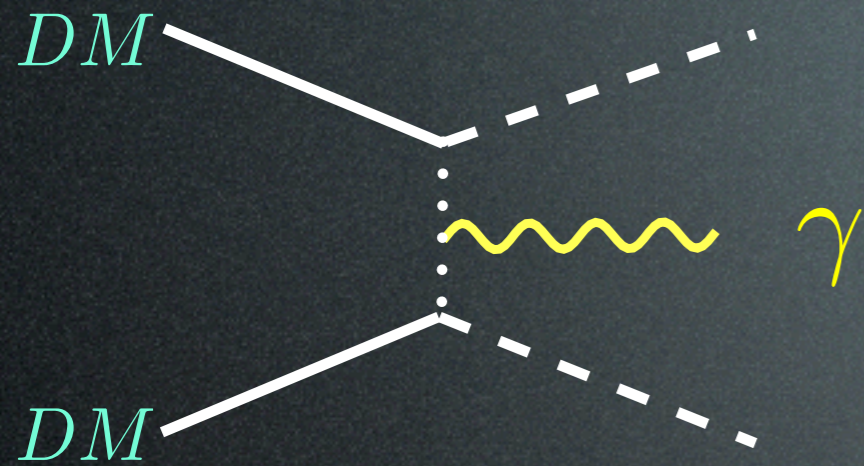
So what are the particle physics parameters?

1. Dark Matter **mass**
2. **annihilation** cross section σ_{ann}

Prompt emission: sharp features



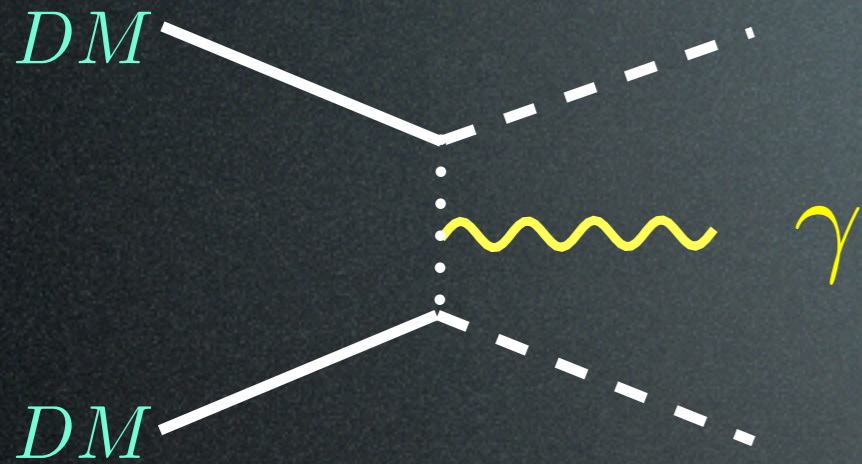
Prompt emission: sharp features



Internal Bremsstrahlung

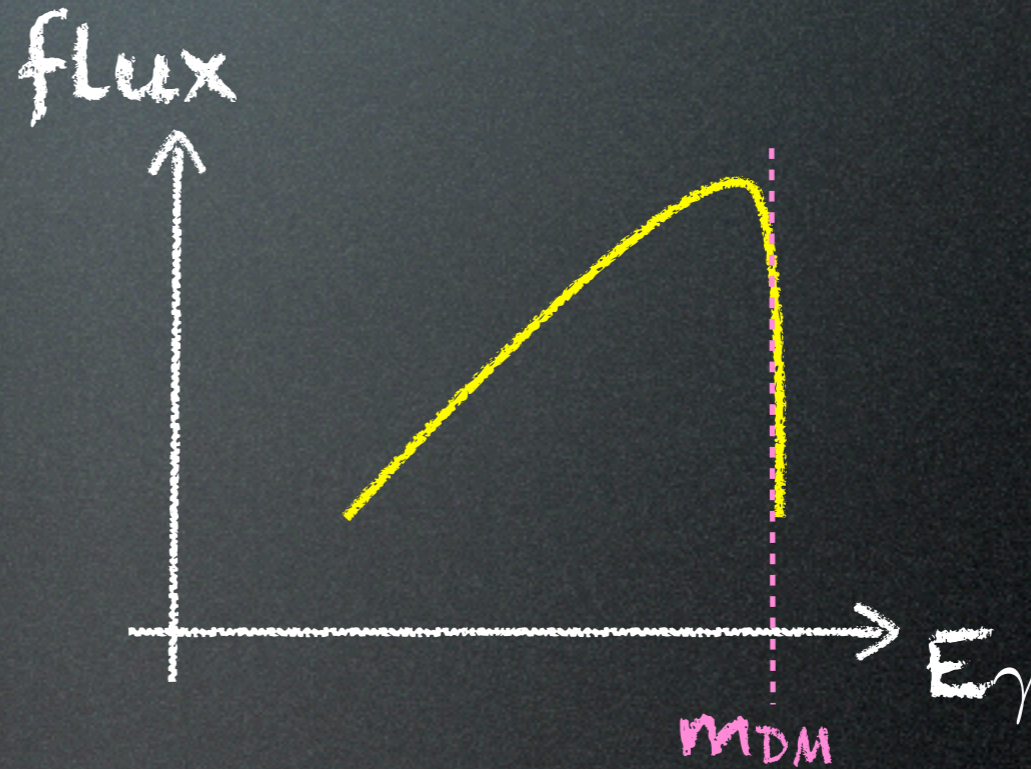
Bergström 1989

Prompt emission: sharp features

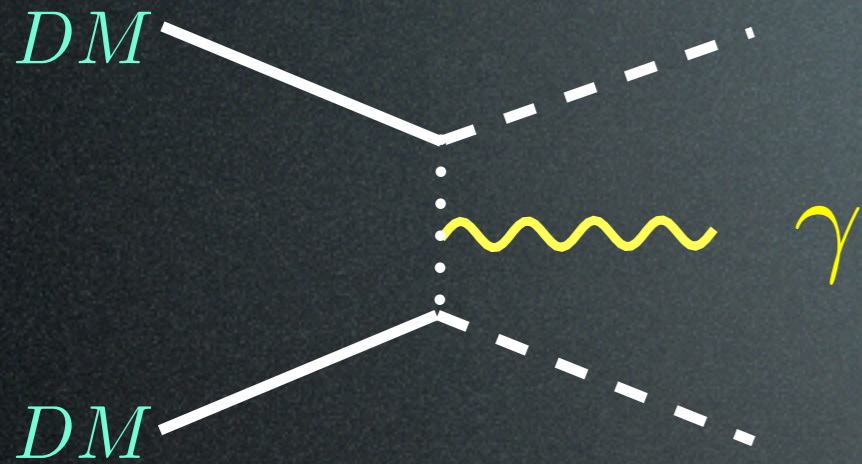


Internal Bremsstrahlung

Bergström 1989



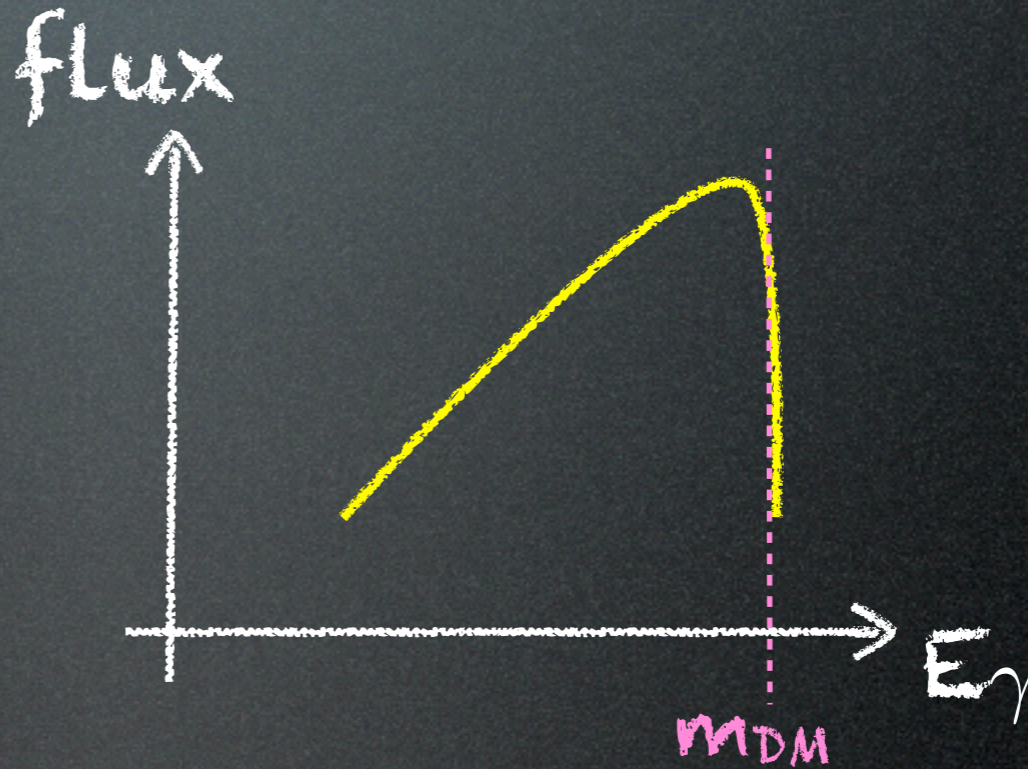
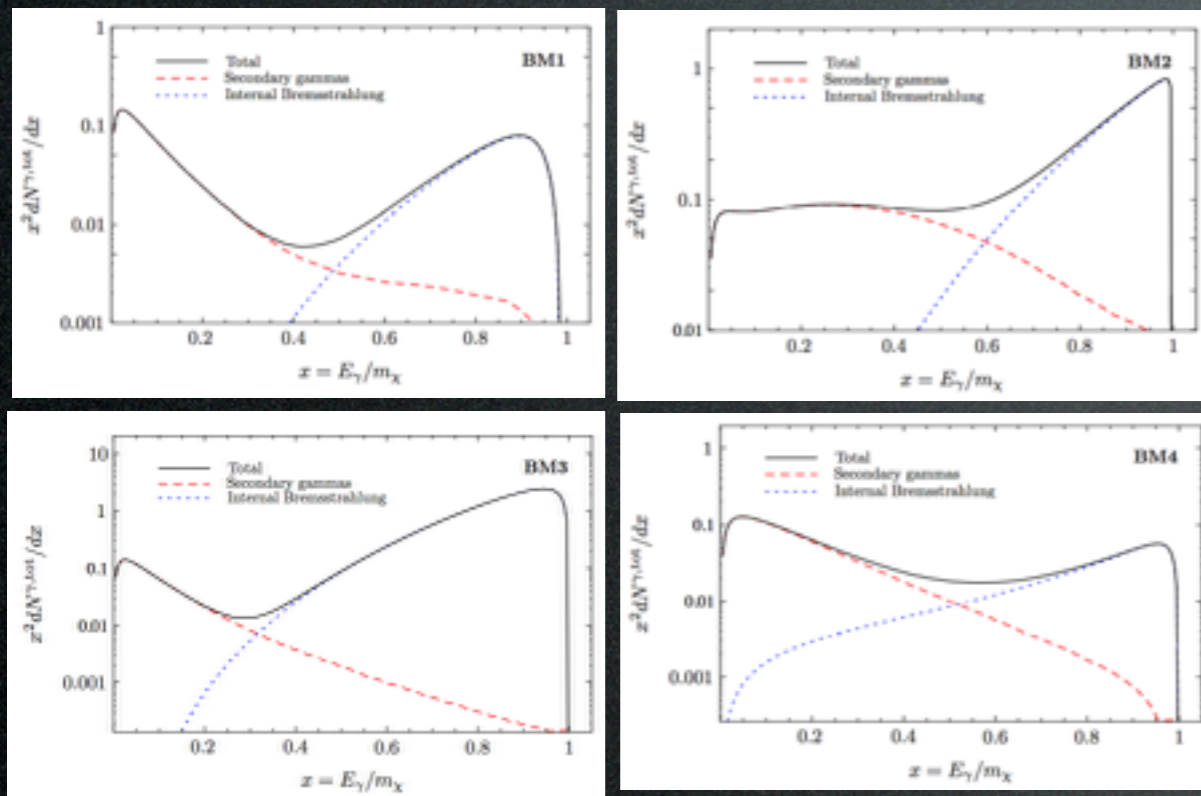
Prompt emission: sharp features



Internal Bremsstrahlung

Bergström 1989

Bringmann, Bergstrom, Edsjo 0710.3169

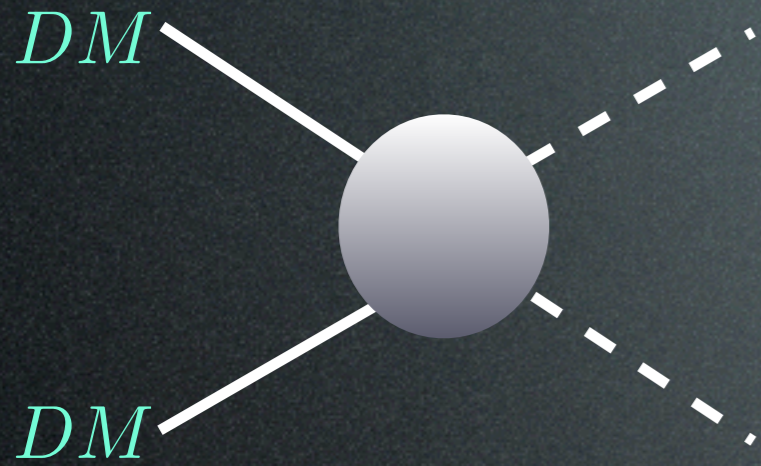


So what are the particle physics parameters?

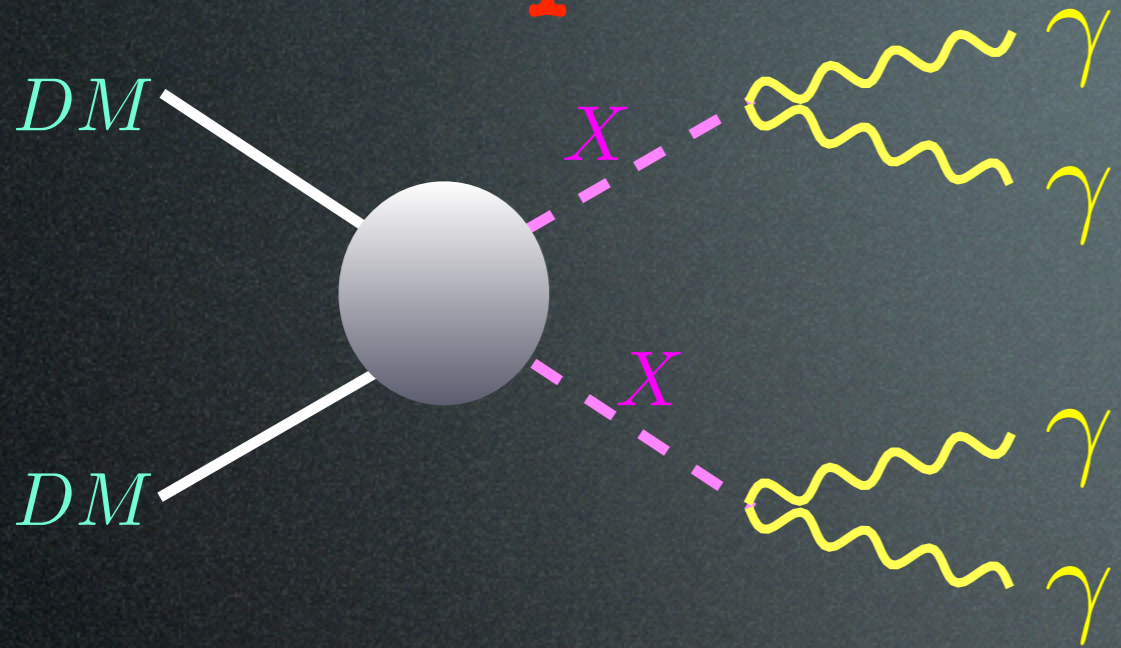
1. Dark Matter mass.

The rest depends on the model

Prompt emission: sharp features



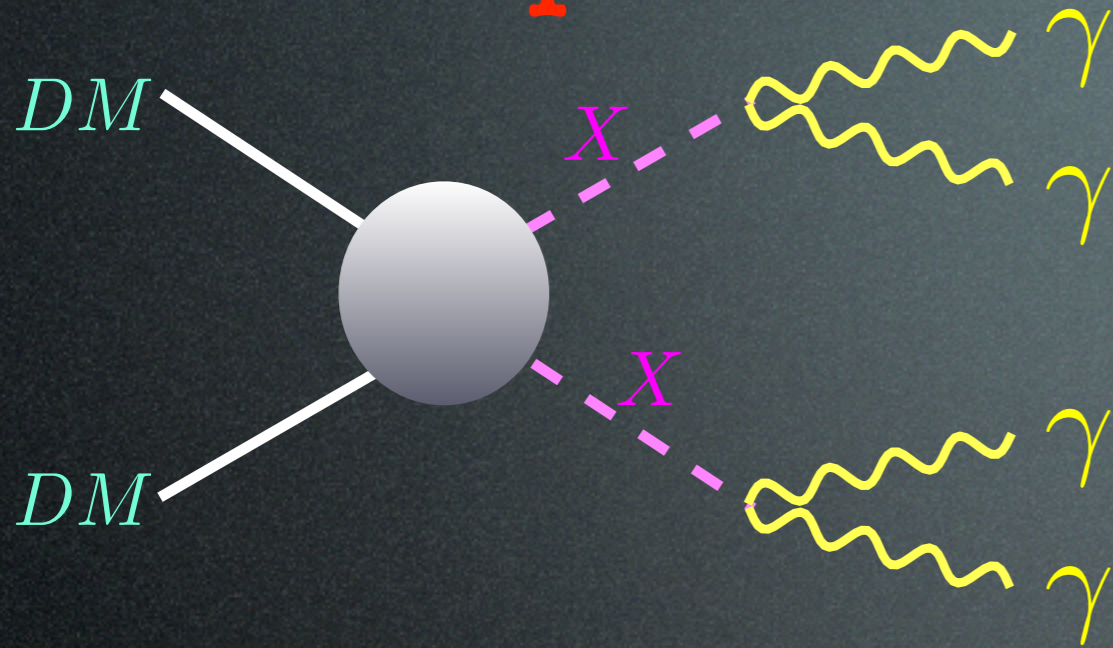
Prompt emission: sharp features



Metastable intermediate states

Ibarra, Lopez Gehler, Pato 1205.0007
Fan, Reece 1209.1097

Prompt emission: sharp features

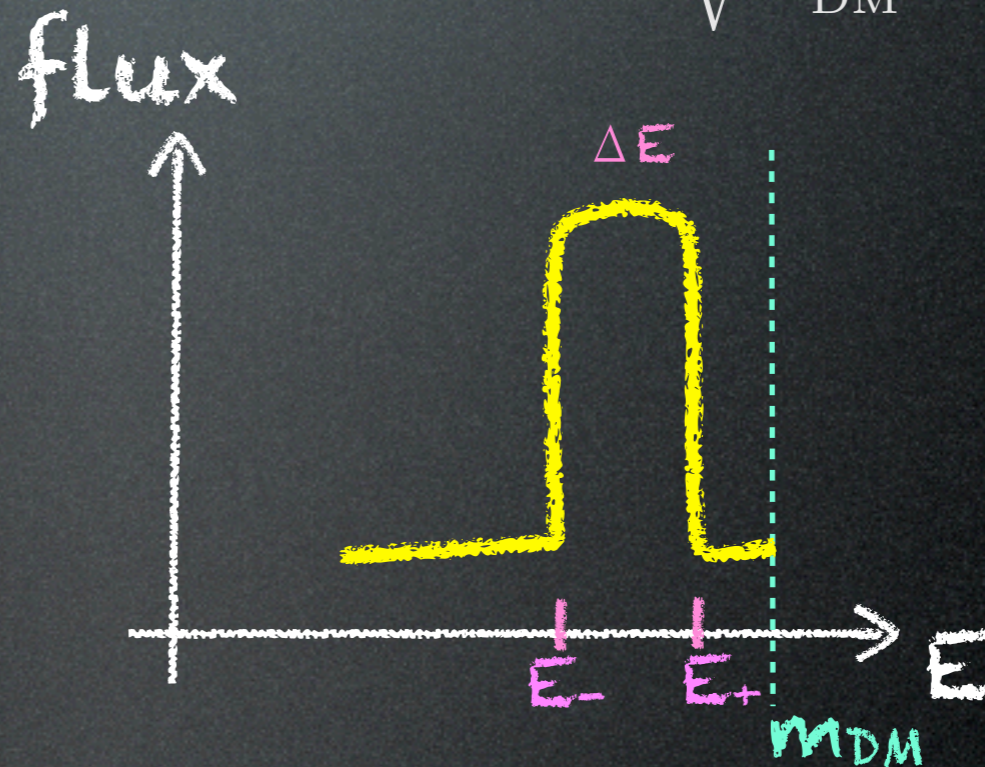


Metastable intermediate states

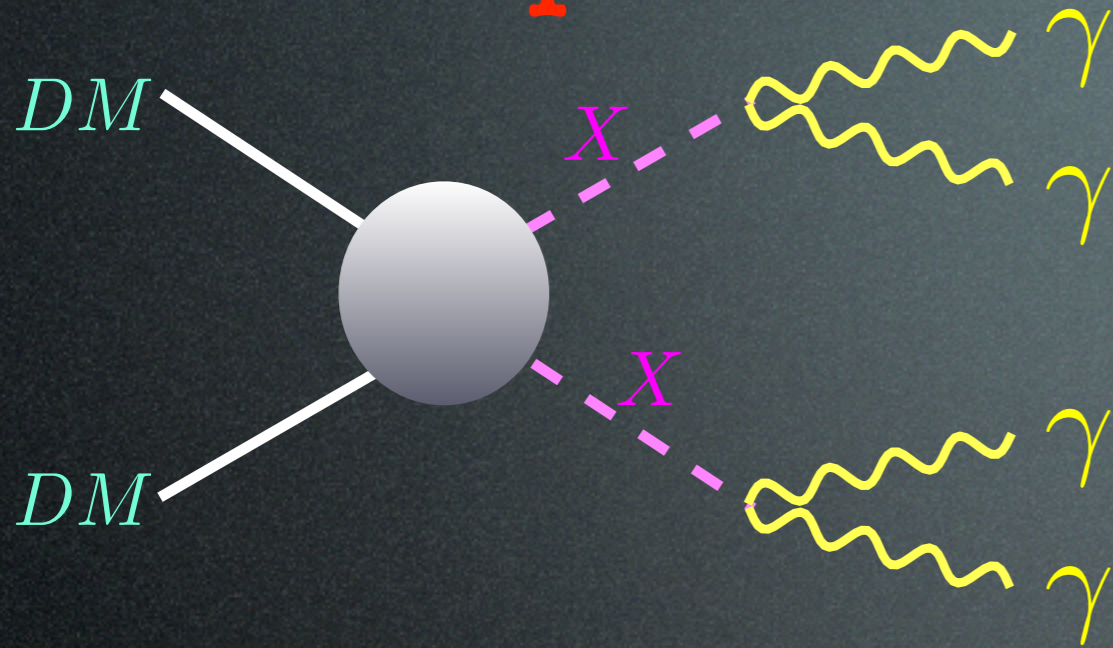
$$E_{\pm} = \frac{m_{\text{DM}}}{2} \left(1 \pm \sqrt{1 - \frac{m_X^2}{m_{\text{DM}}^2}} \right)$$

$$\Delta E = \sqrt{m_{\text{DM}}^2 - m_X^2}$$

Ibarra, Lopez Gehler, Pato 1205.0007
Fan, Reece 1209.1097



Prompt emission: sharp features

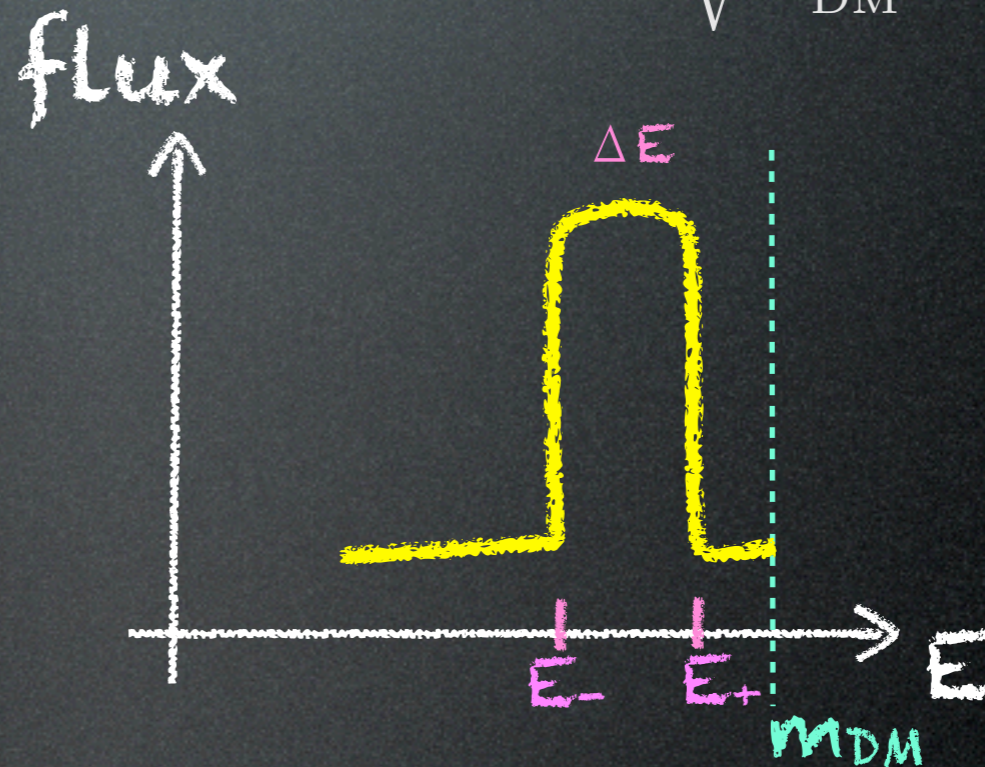


Metastable intermediate states

$$E_{\pm} = \frac{m_{\text{DM}}}{2} \left(1 \pm \sqrt{1 - \frac{m_X^2}{m_{\text{DM}}^2}} \right)$$

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Ibarra, Lopez Gehler, Pato 1205.0007
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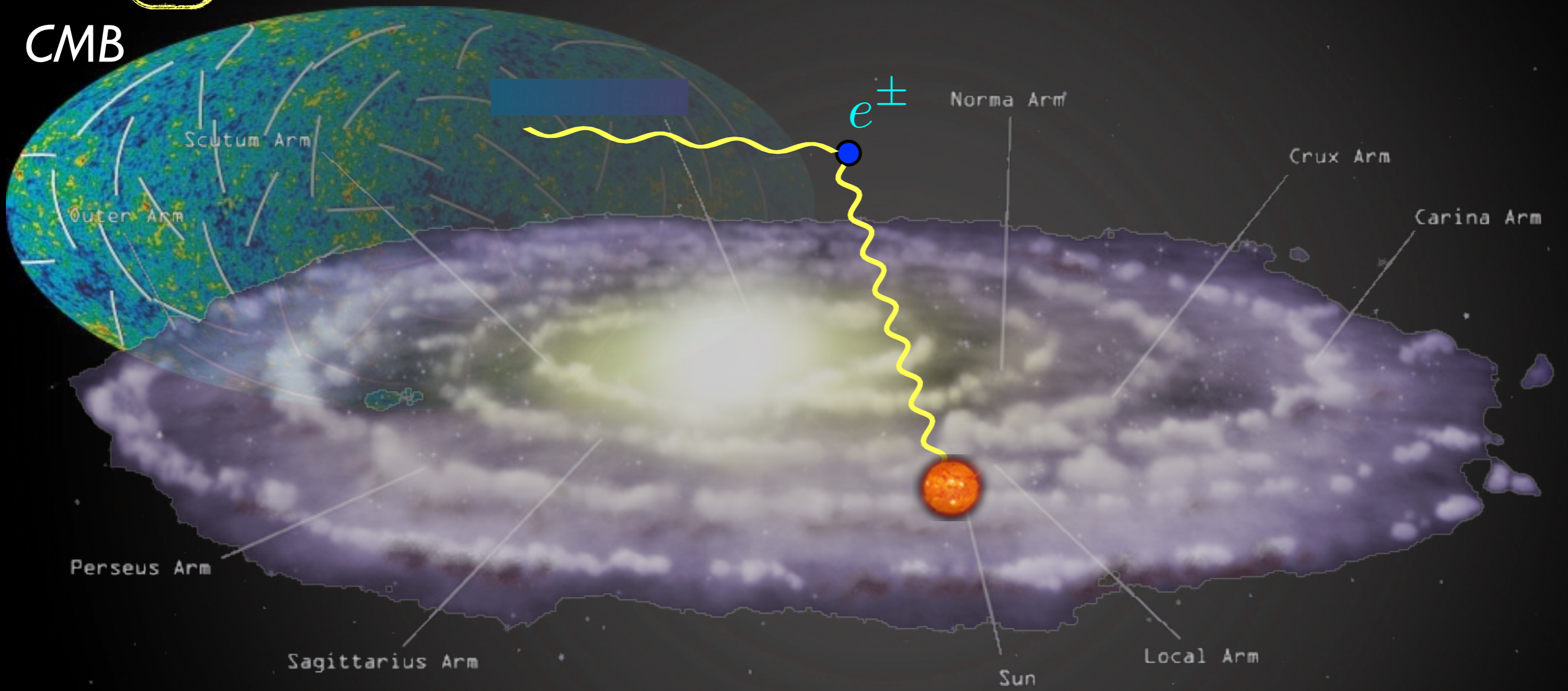
So what are the particle physics parameters?

1. Dark Matter mass
2. The mediator mass

Secondary emission

a. γ from Inverse Compton on e^\pm in halo

CMB



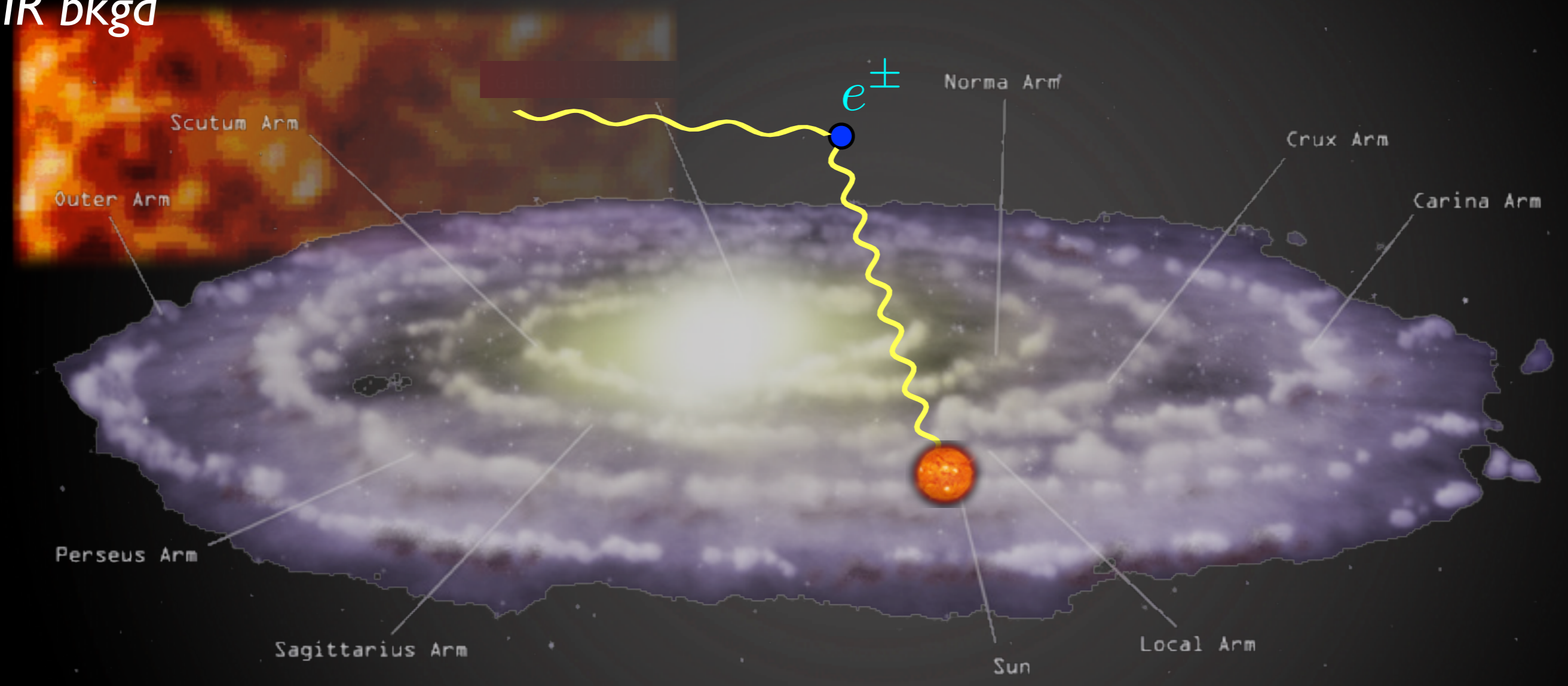
- upscatter of CMB, infrared and starlight photons on energetic e^\pm
- probes regions outside of Galactic Center

Secondary emission

a.

γ from Inverse Compton on e^\pm in halo

IR bkgd



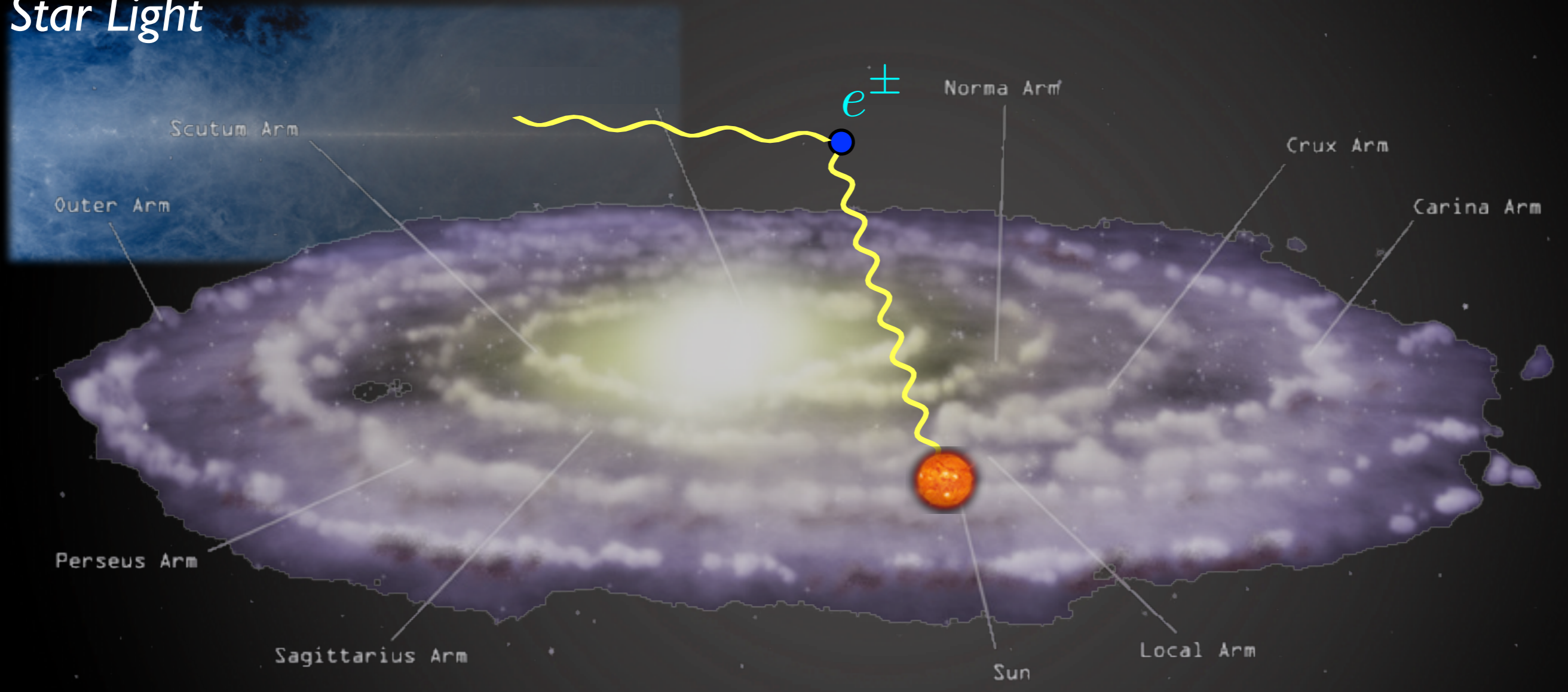
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Secondary emission

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γ from Inverse Compton on e^\pm in halo

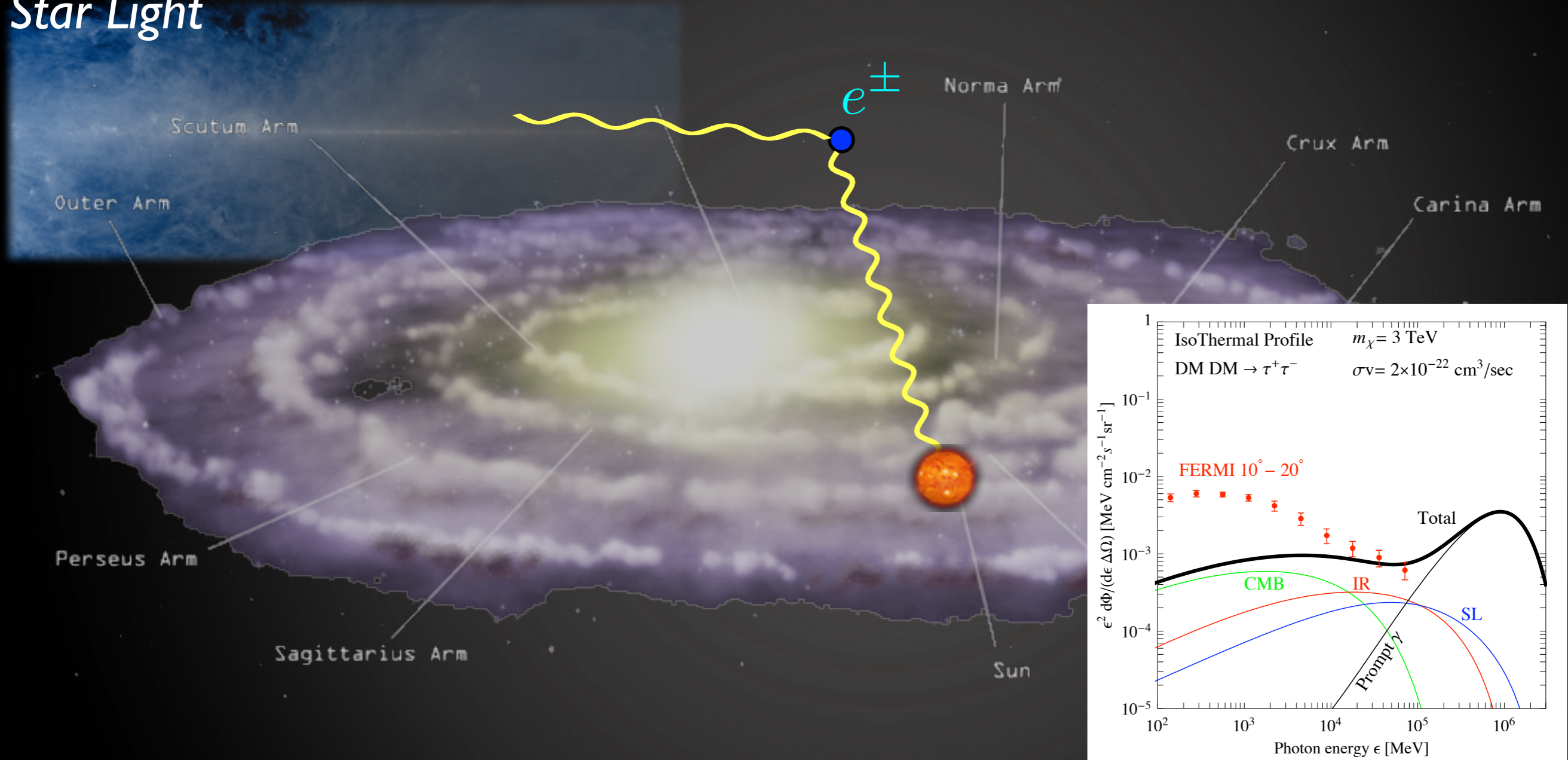
Star Light



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

Secondary emission

a. γ from Inverse Compton on e^\pm in halo
Star Light

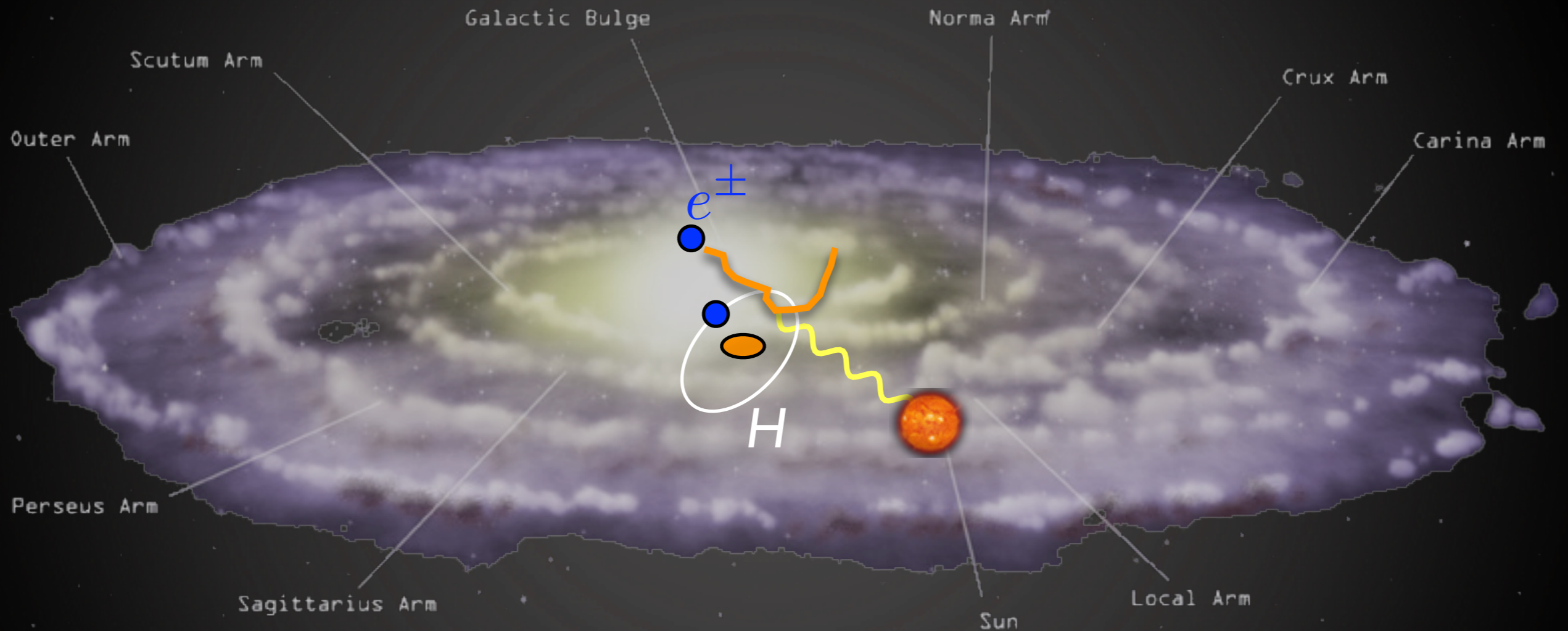


Cirelli, Panci, Serpico 0912.0663

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

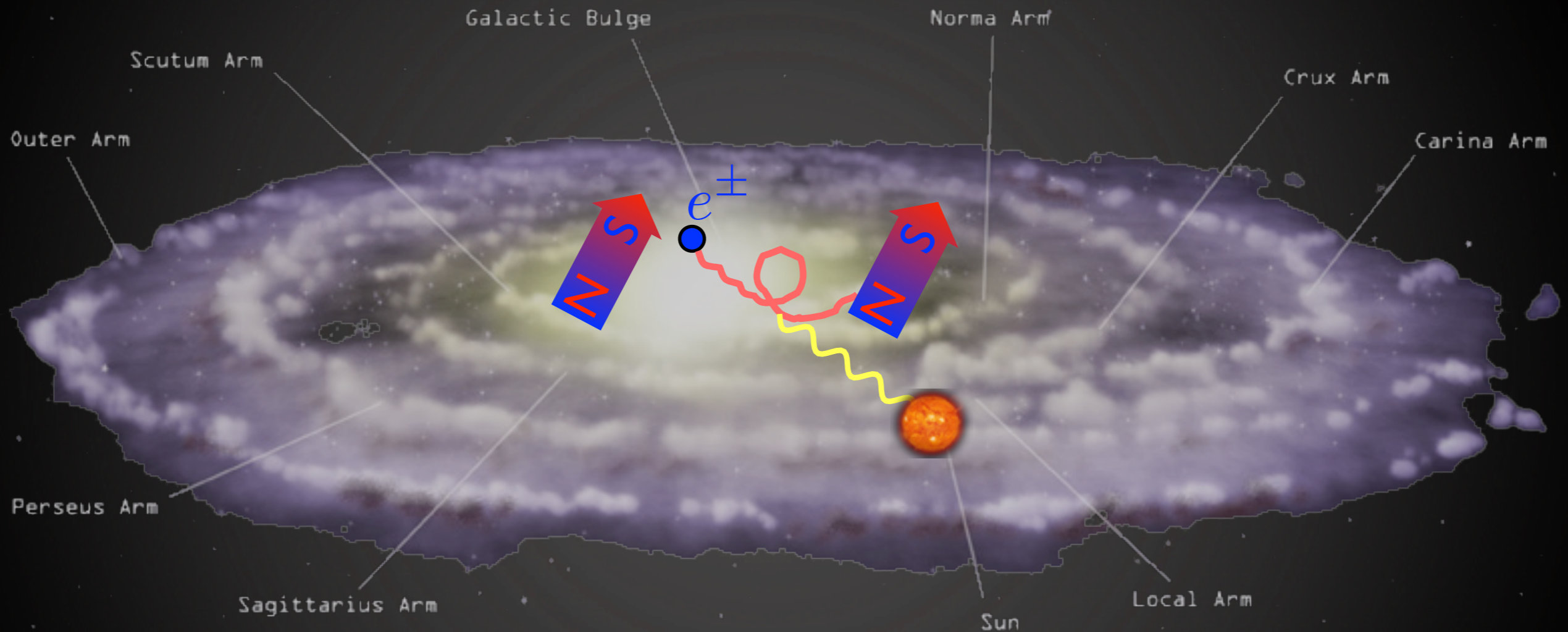
Secondary emission

b. soft gammas from bremsstrahlung of e^\pm on ISM



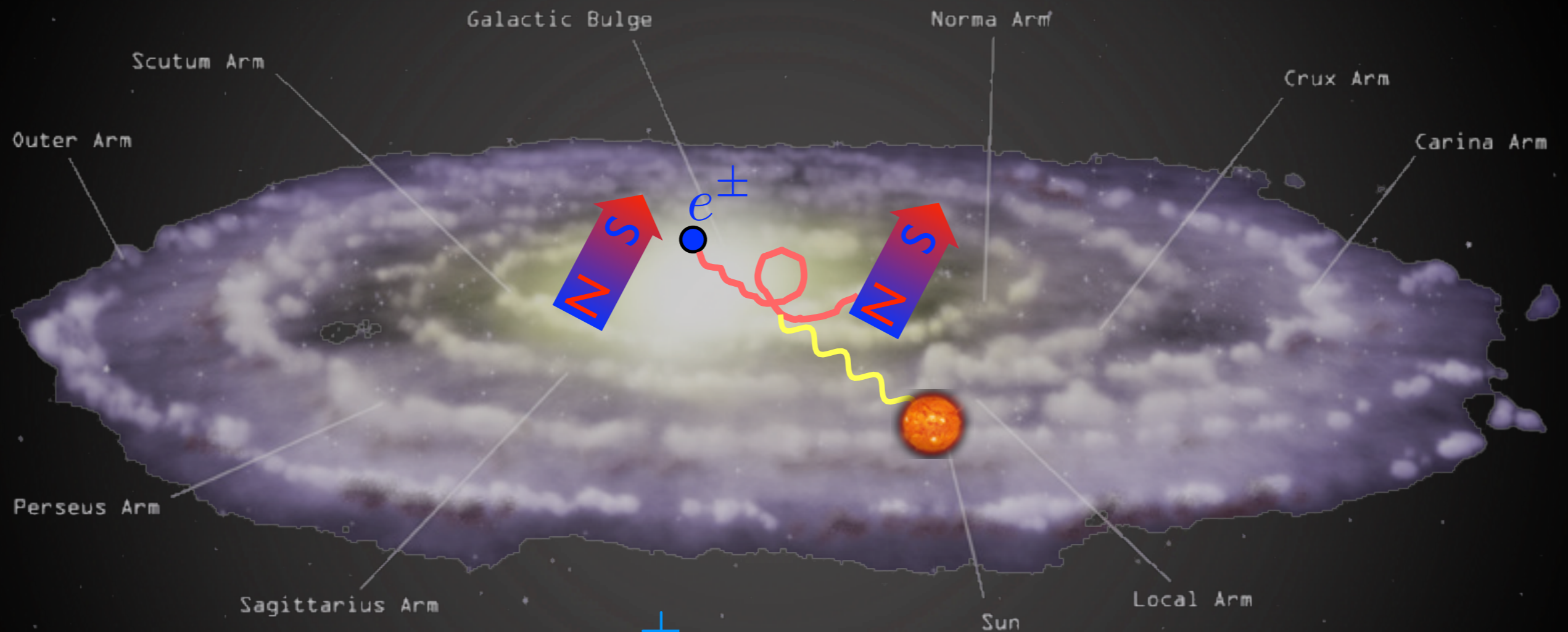
Secondary emission

c. radio-waves from synchro radiation of e^\pm in GC



Secondary emission

c. radio-waves from synchro radiation of e^\pm in GC



- compute the population of e^\pm from DM annihilations in the GC
- compute the synchrotron emitted power for different configurations of galactic \vec{B}

(assuming 'scrambled' B ; in principle, directionality could focus emission, lift bounds by $O(\text{some})$)

How does DM produce γ -rays?

1. prompt emission

1a. continuum

1b. line(s)

1c. sharp features

2. secondary emission

2a. ICS

2b. bremsstrahlung

2c. synchrotron

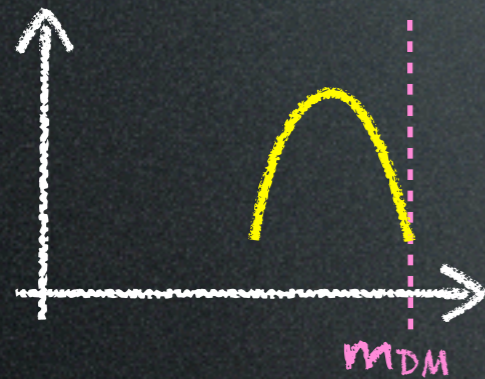
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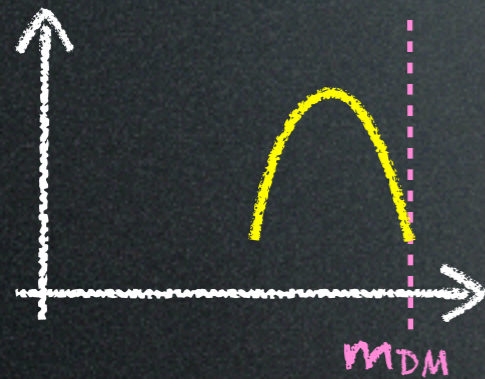
2b. bremsstrahlung

2c. synchrotron

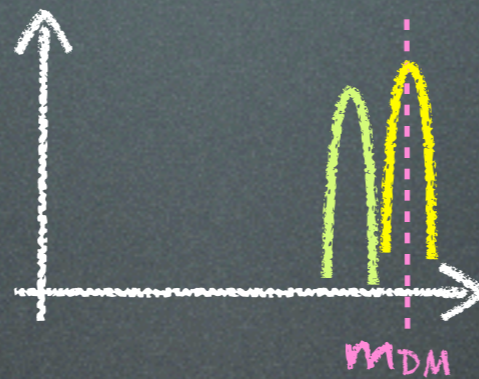
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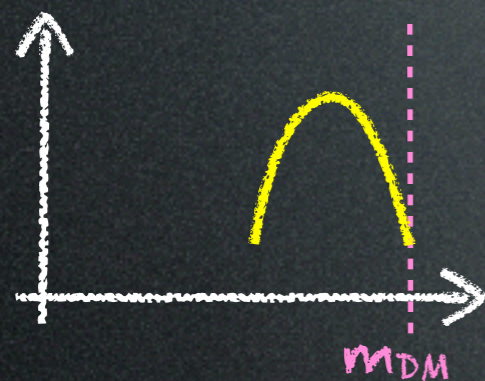
2b. bremsstrahlung

2c. synchrotron

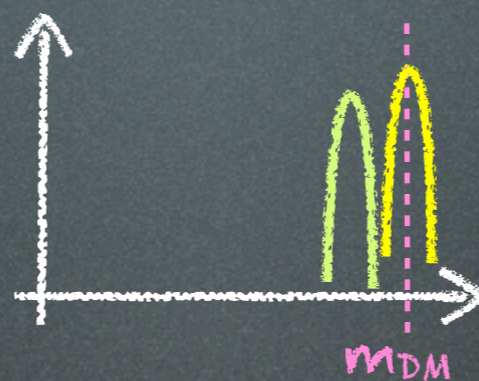
How does DM produce γ -rays?

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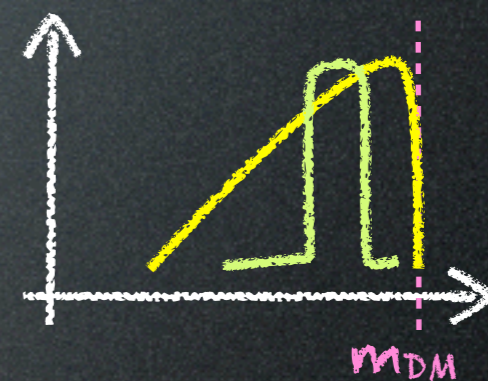
1a. continuum



1b. line(s)



1c. sharp features



2. secondary emission

2a. ICS

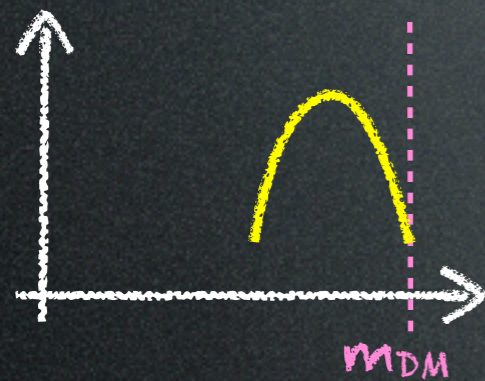
2b. bremsstrahlung

2c. synchrotron

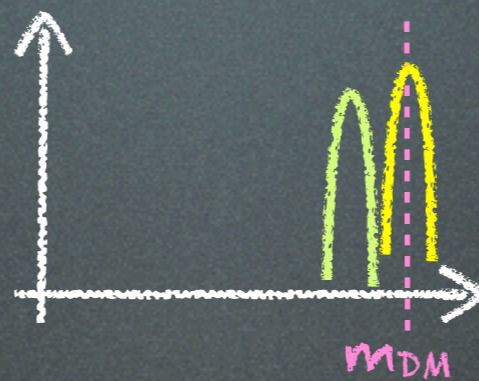
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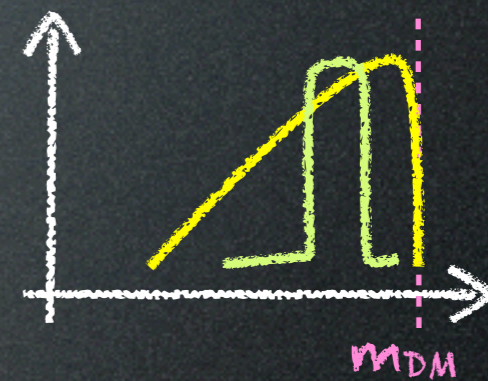
1a. continuum



1b. line(s)

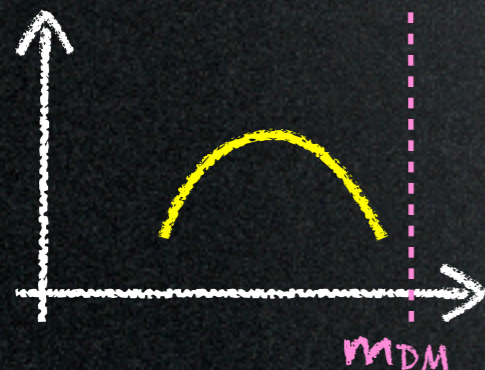


1c. sharp features



2. secondary emission

2a. ICS



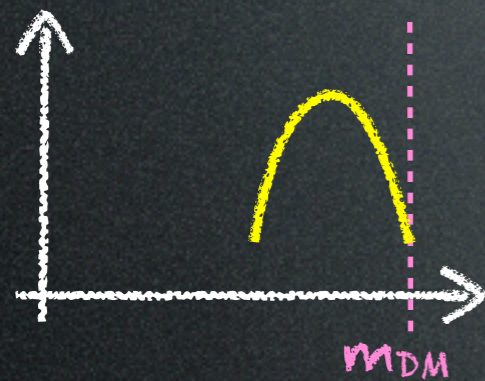
2b. bremsstrahlung

2c. synchrotron

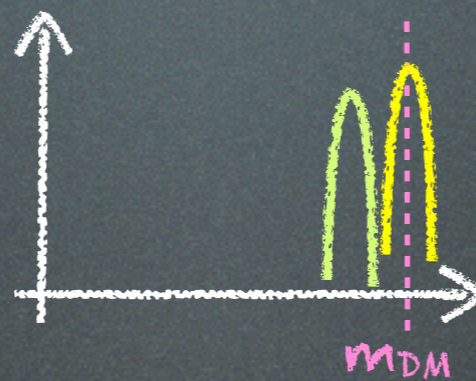
How does DM produce γ -rays?

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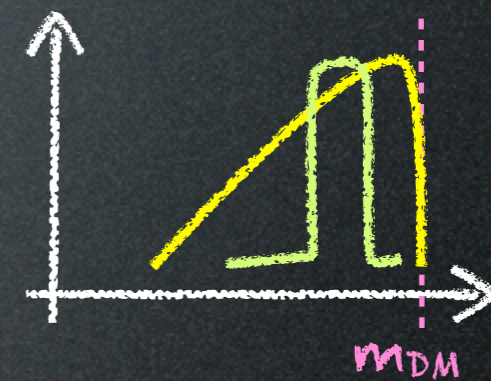
1a. continuum



1b. line(s)

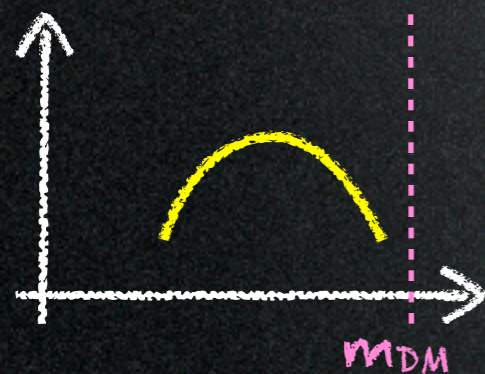


1c. sharp features

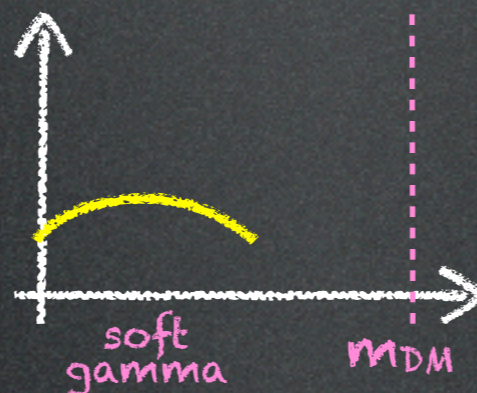


2. secondary emission

2a. ICS



2b. bremsstrahlung

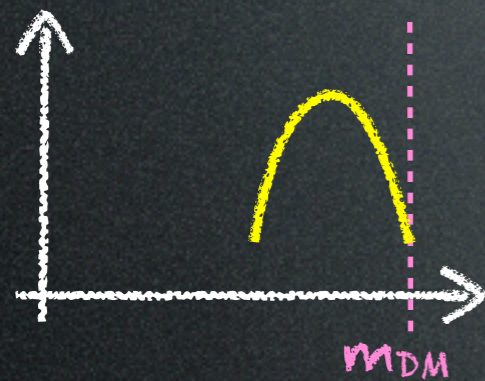


2c. synchrotron

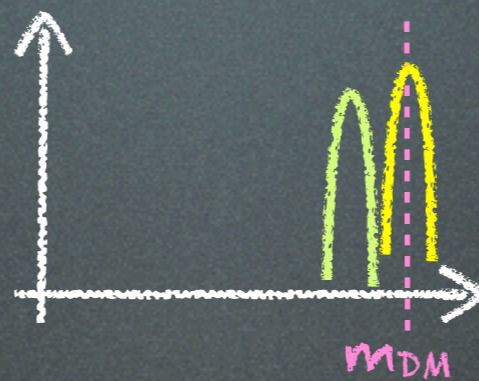
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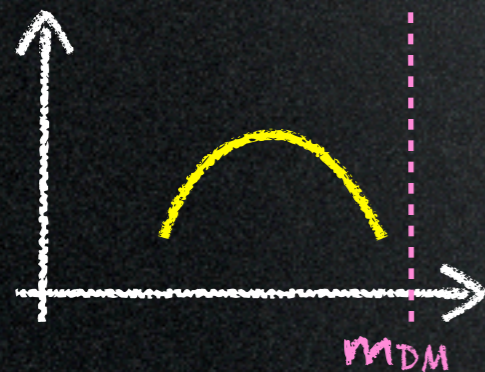


1c. sharp features

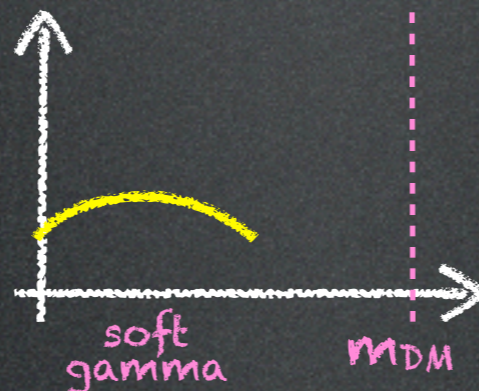


2. secondary emission

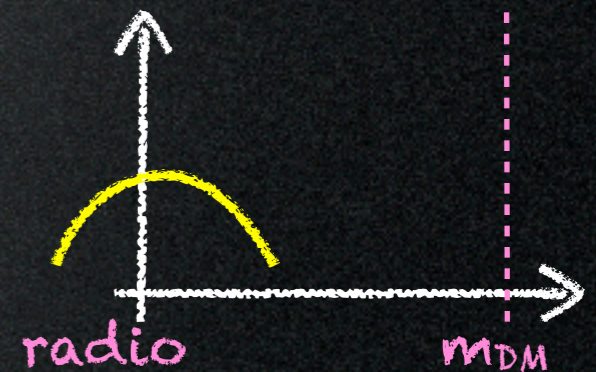
2a. ICS



2b. bremsstrahlung



2c. synchrotron

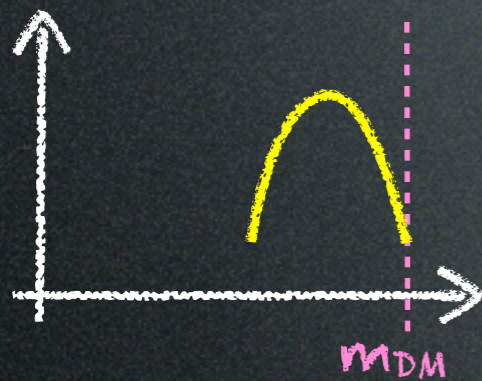


How does DM produce γ -rays?

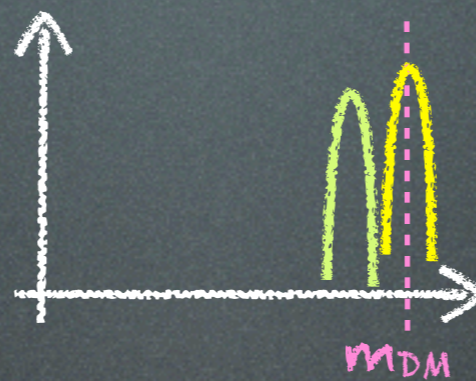
1. prompt emission

environment-independent

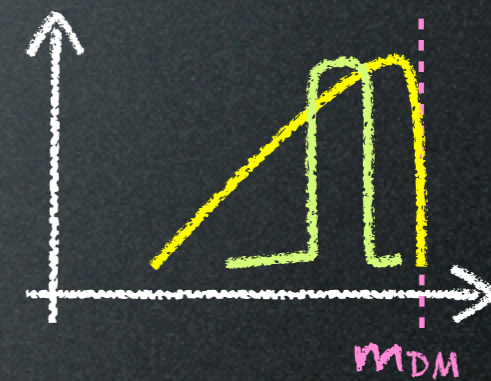
1a. continuum



1b. line(s)



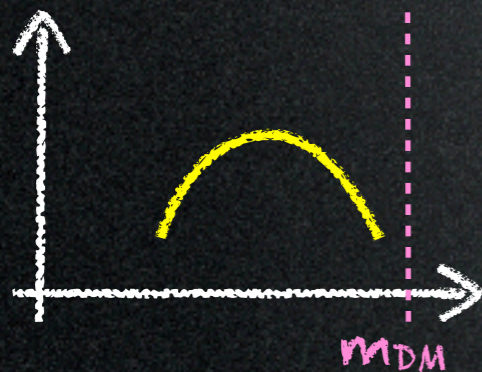
1c. sharp features



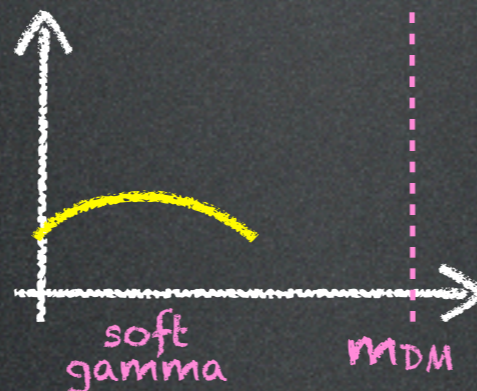
2. secondary emission

environment-dependent

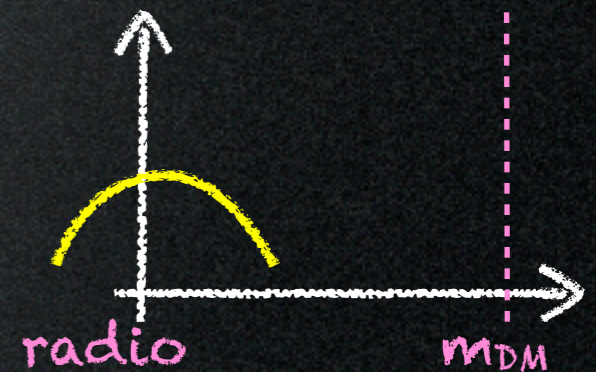
2a. ICS



2b. bremsstrahlung



2c. synchrotron



Application #1

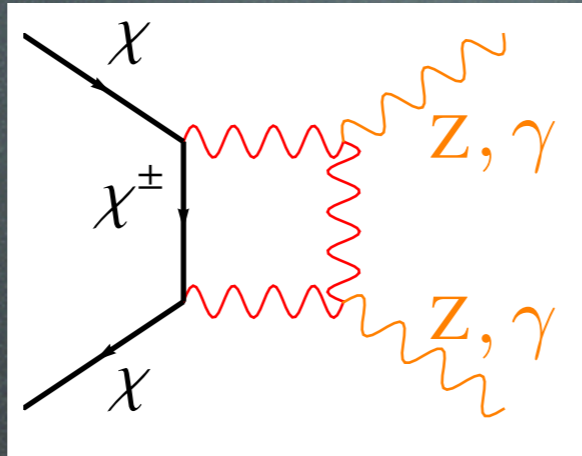
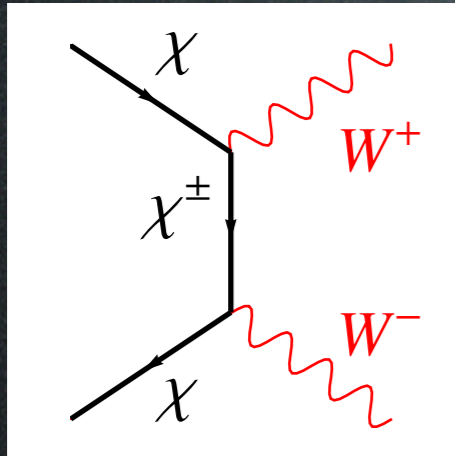
High energy γ -rays constrain pure WIMP multi-TeV DM

based on:

Cirelli, Hambye, Panci, Sala, Taoso
1507.05519

Application #1

High energy γ -rays constrain pure WIMP multi-TeV DM

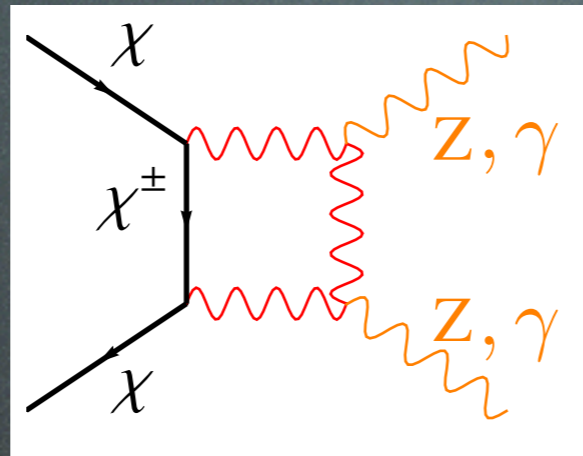
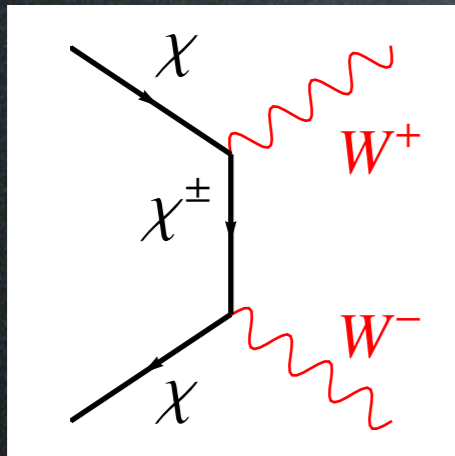


$$+ W^\pm, Z \rightarrow \bar{p}, e^+, \gamma \dots$$

(channels for MDM with $Y=0$)

Application #1

High energy γ -rays constrain pure WIMP multi-TeV DM

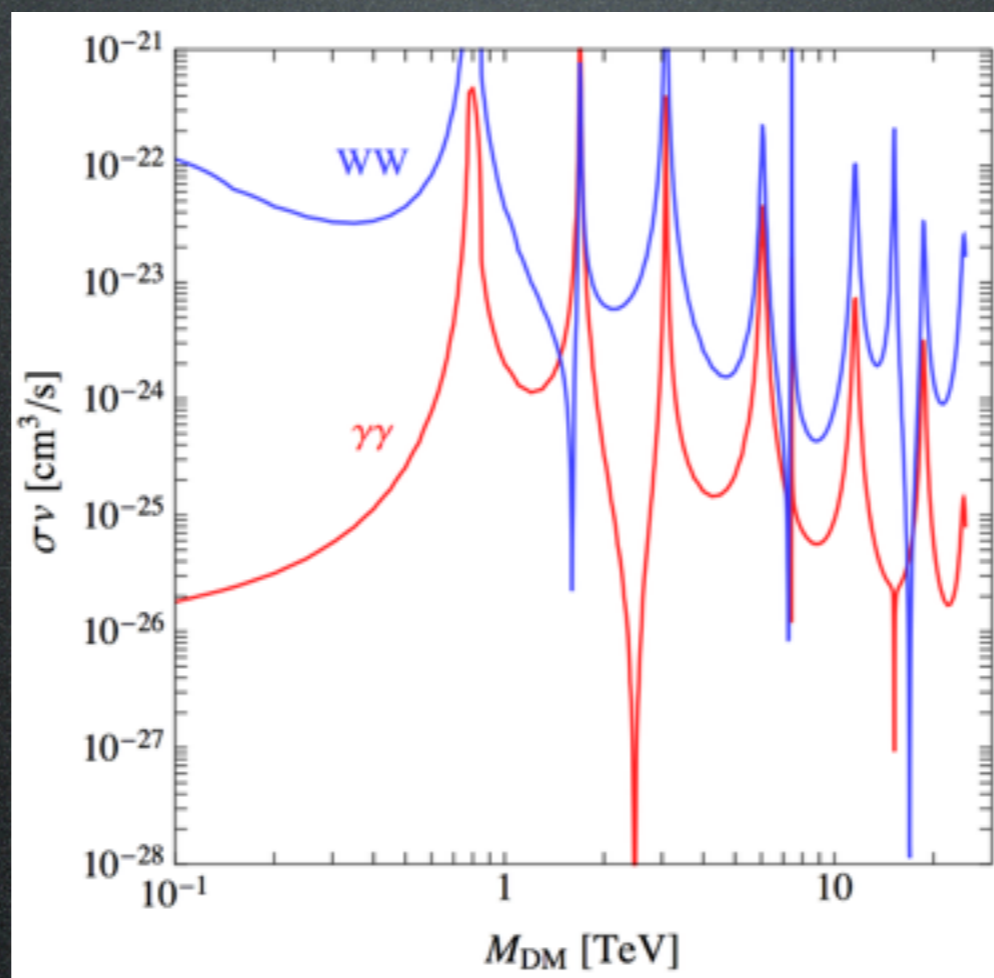


$$+ W^\pm, Z \rightarrow \bar{p}, e^+, \gamma \dots$$

(channels for MDM with $Y=0$)

Enhanced cross section due to 'Sommerfeld corrections'

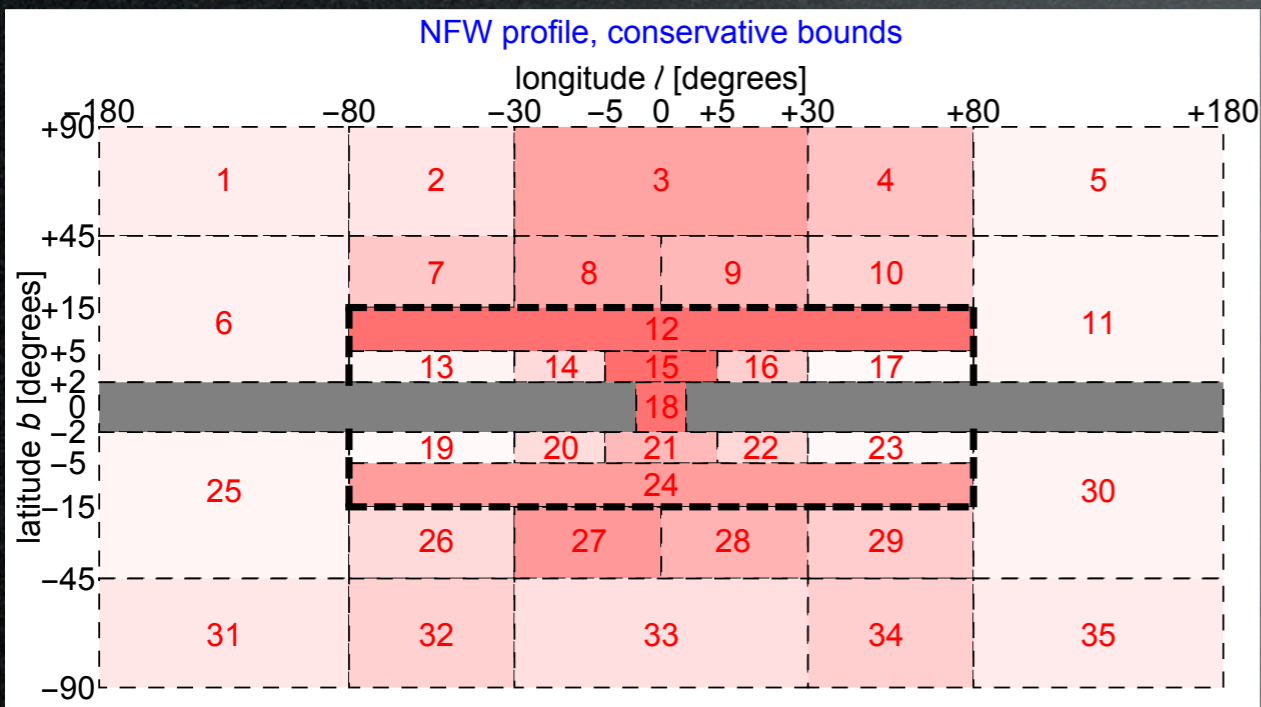
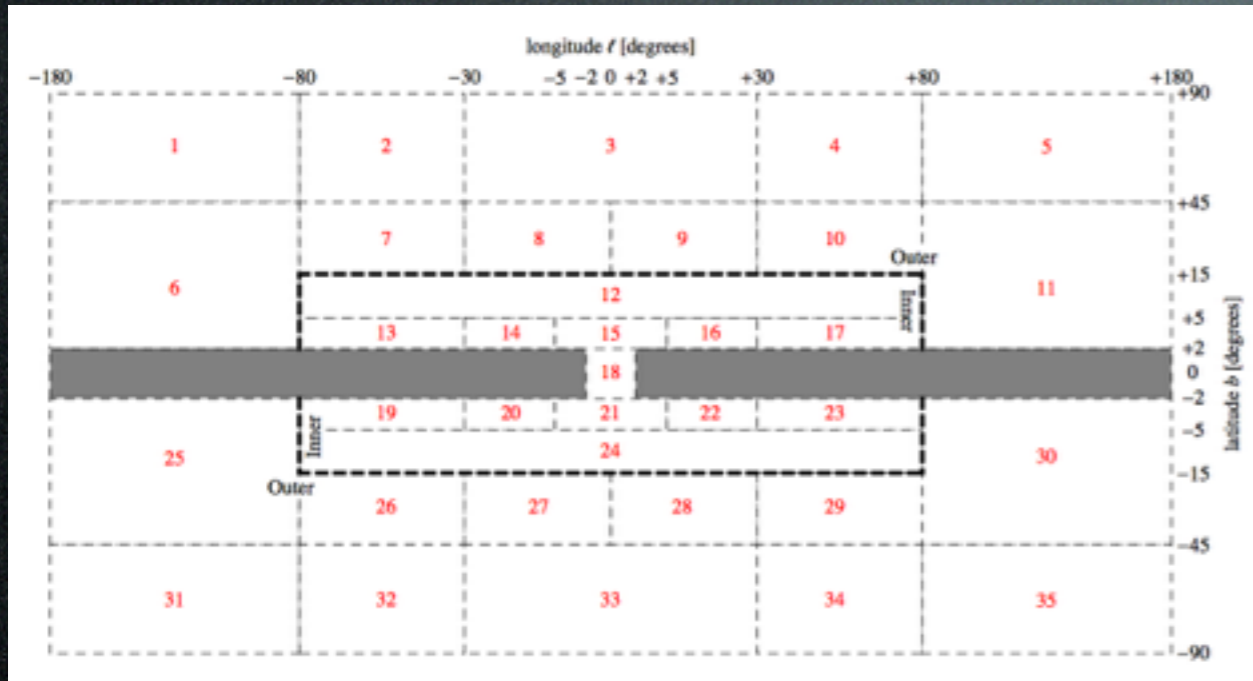
Hisano et al., 2004, 2005
Cirelli, Strumia, Tamburini 2007



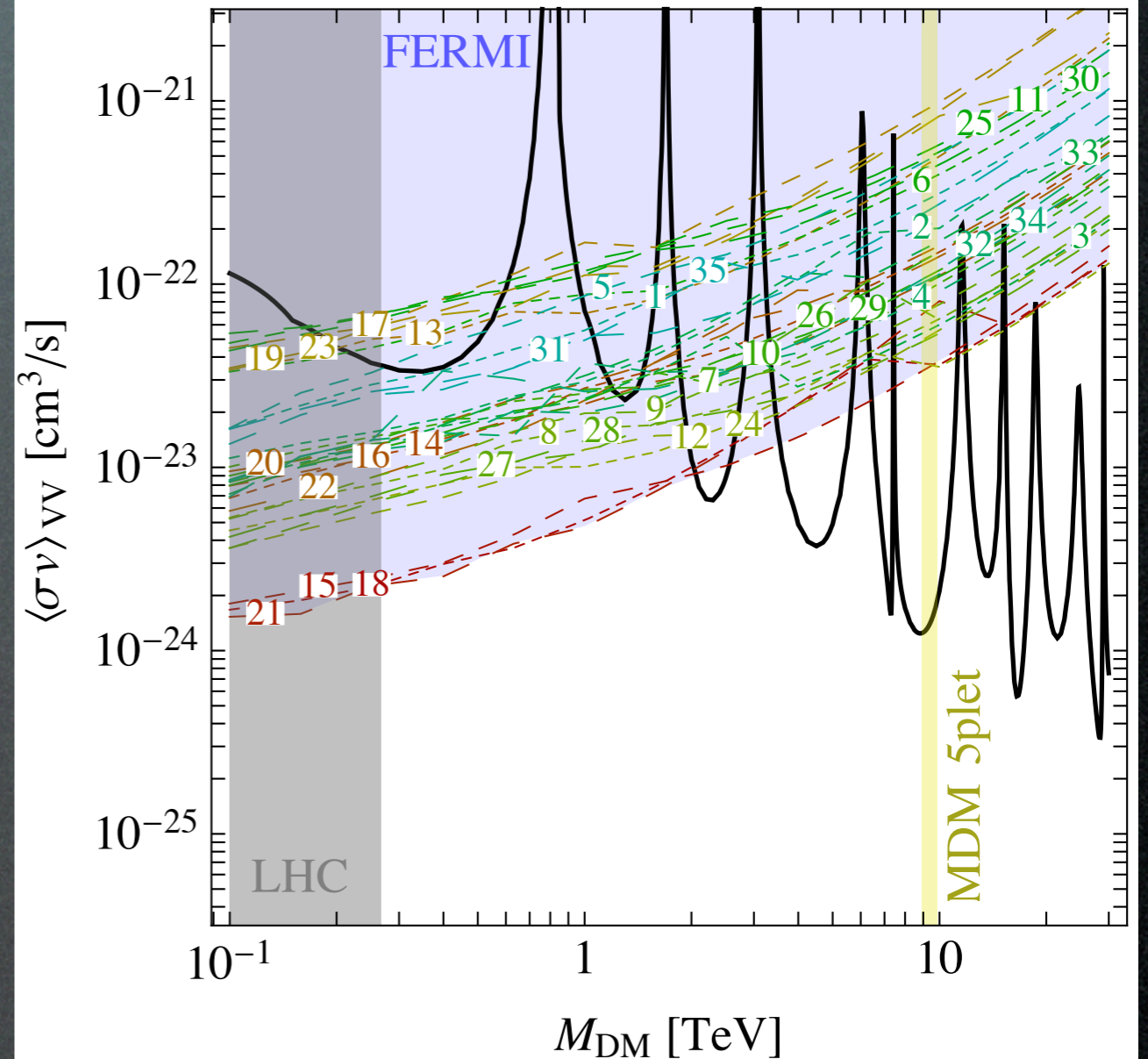
Cirelli, Hambye, Panci, Sala, Taoso
1507.05519

Application #1

FERMI diffuse galactic:

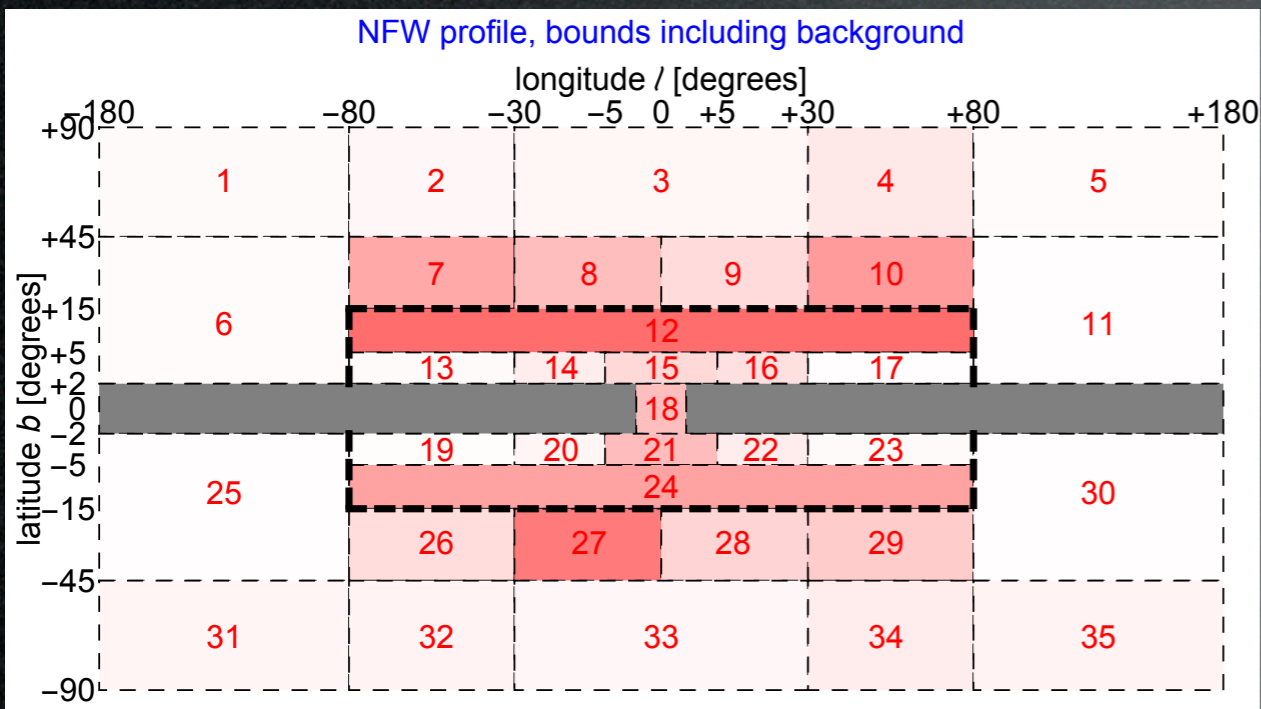
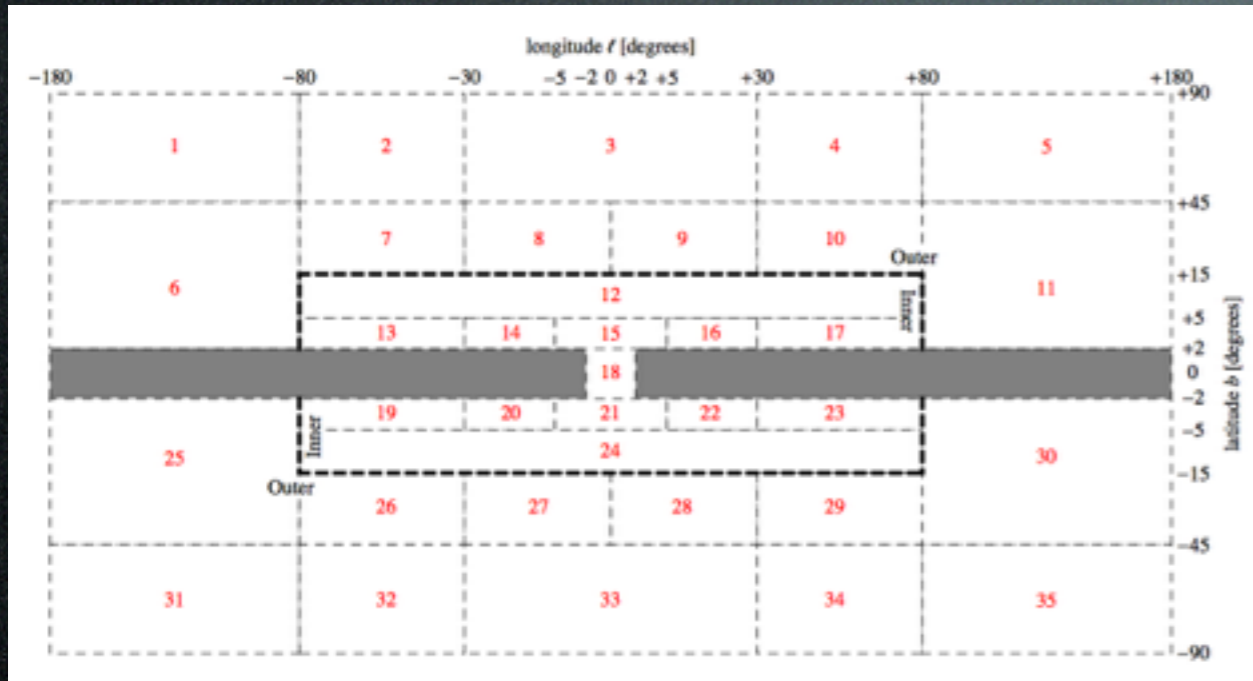


NFW profile, conservative bound

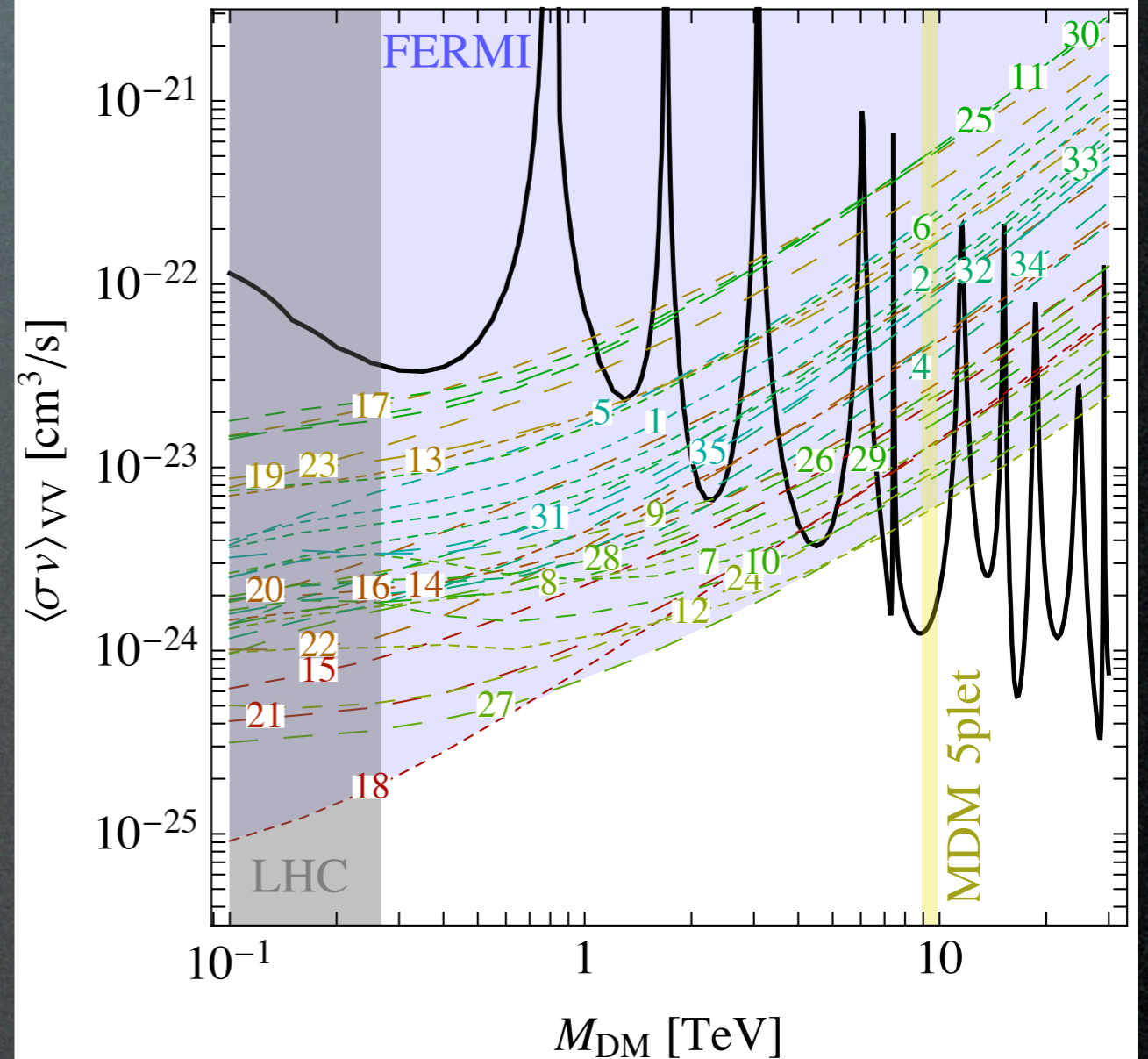


Application #1

FERMI diffuse galactic:

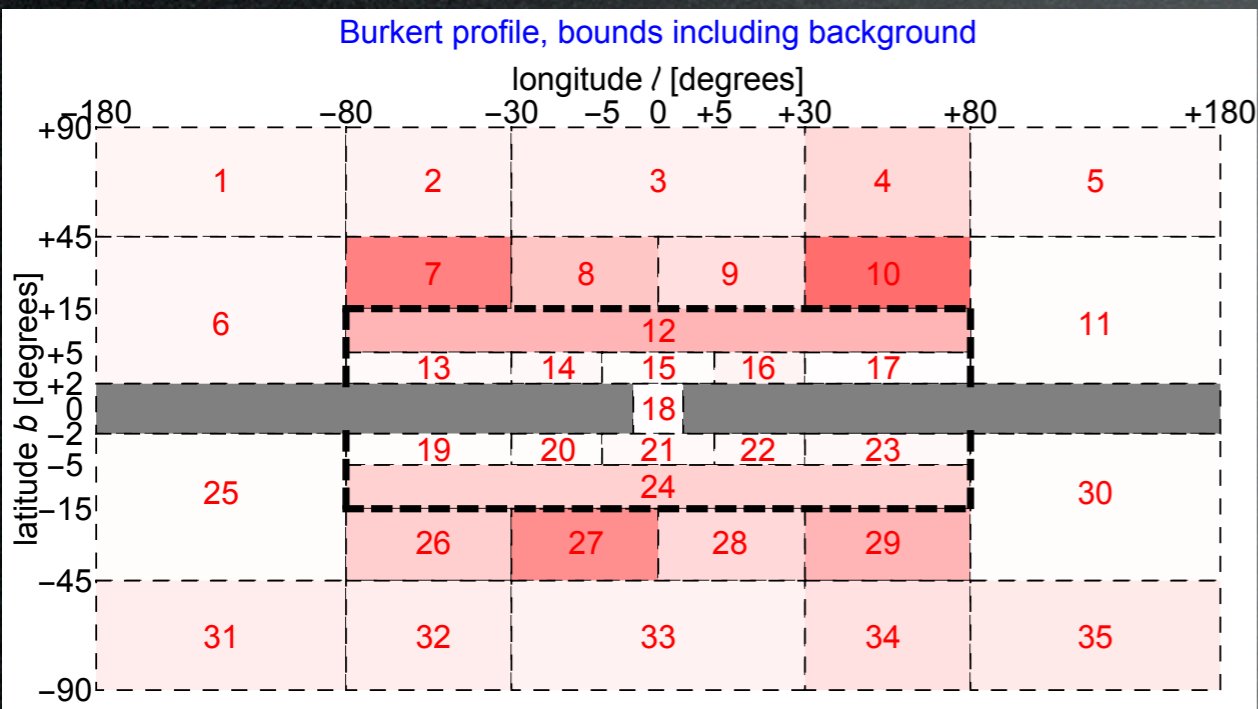
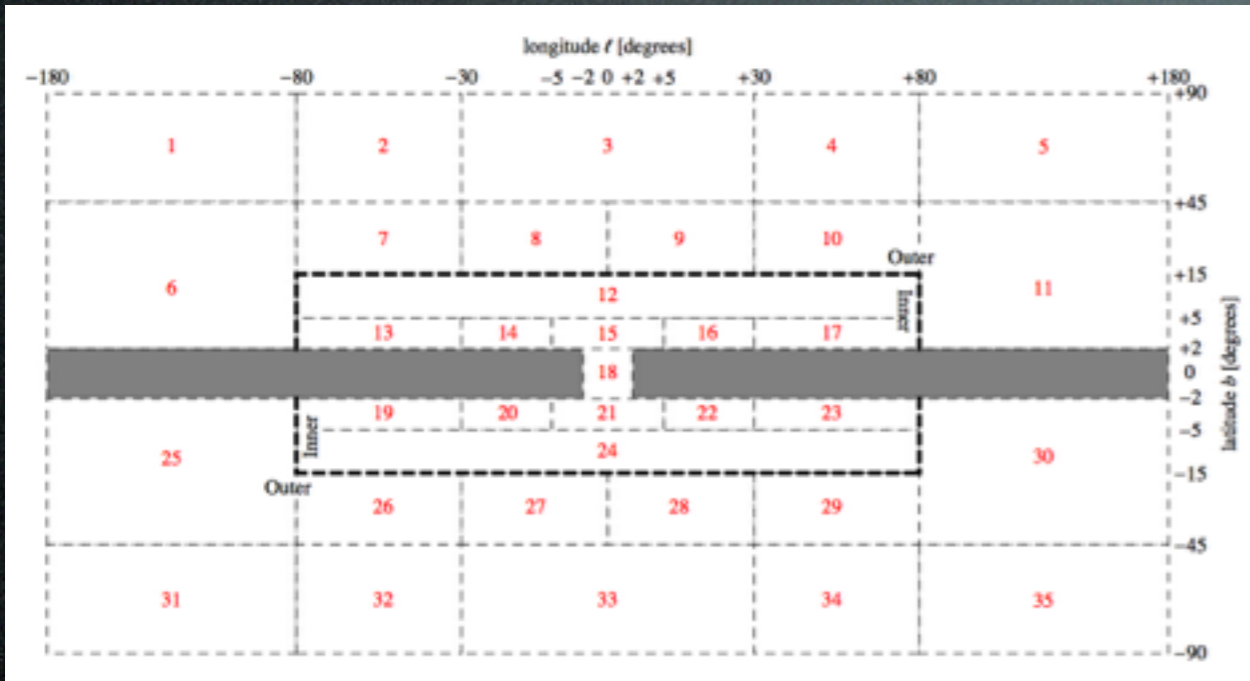


NFW profile, including background

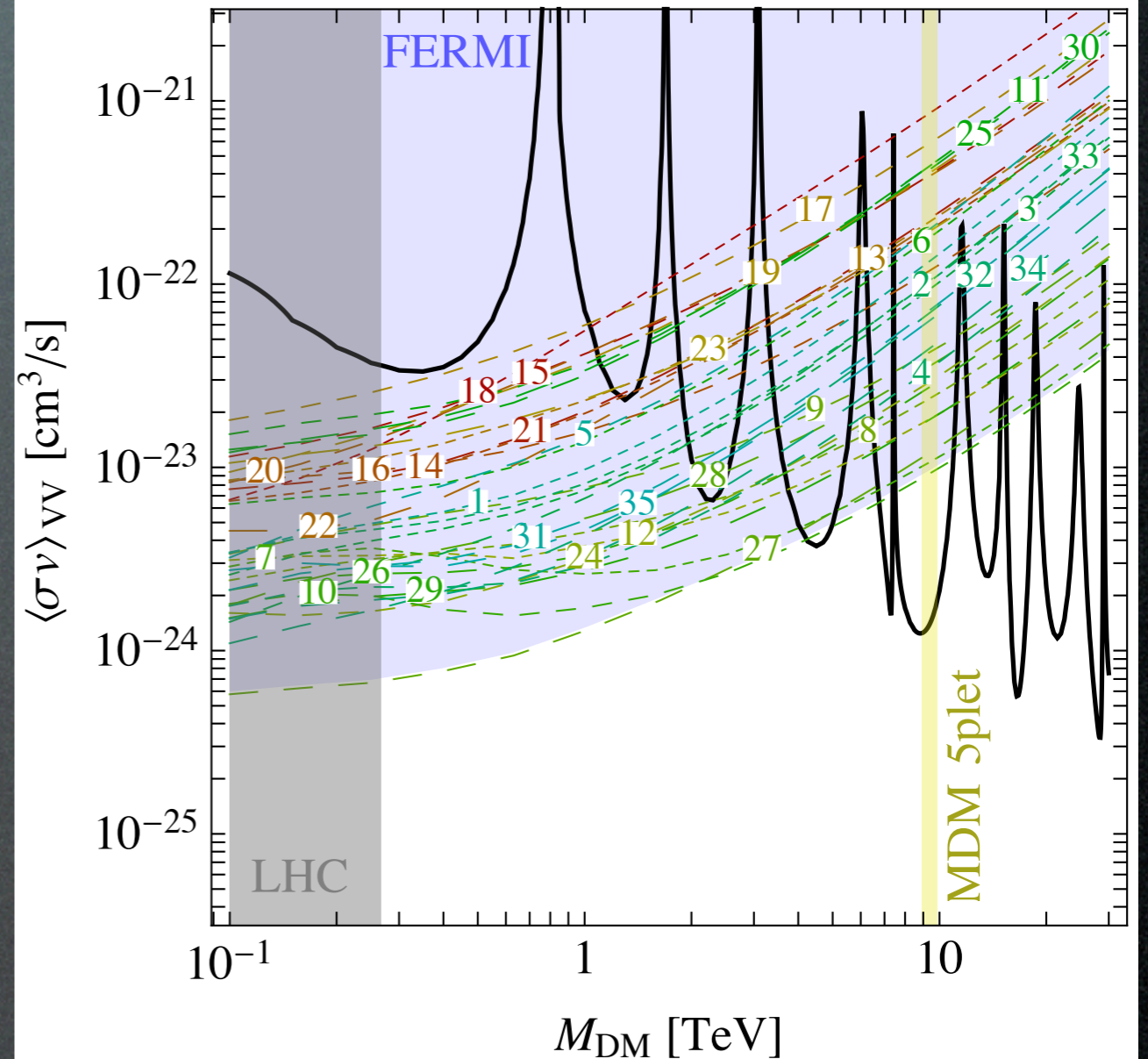


Application #1

FERMI diffuse galactic:

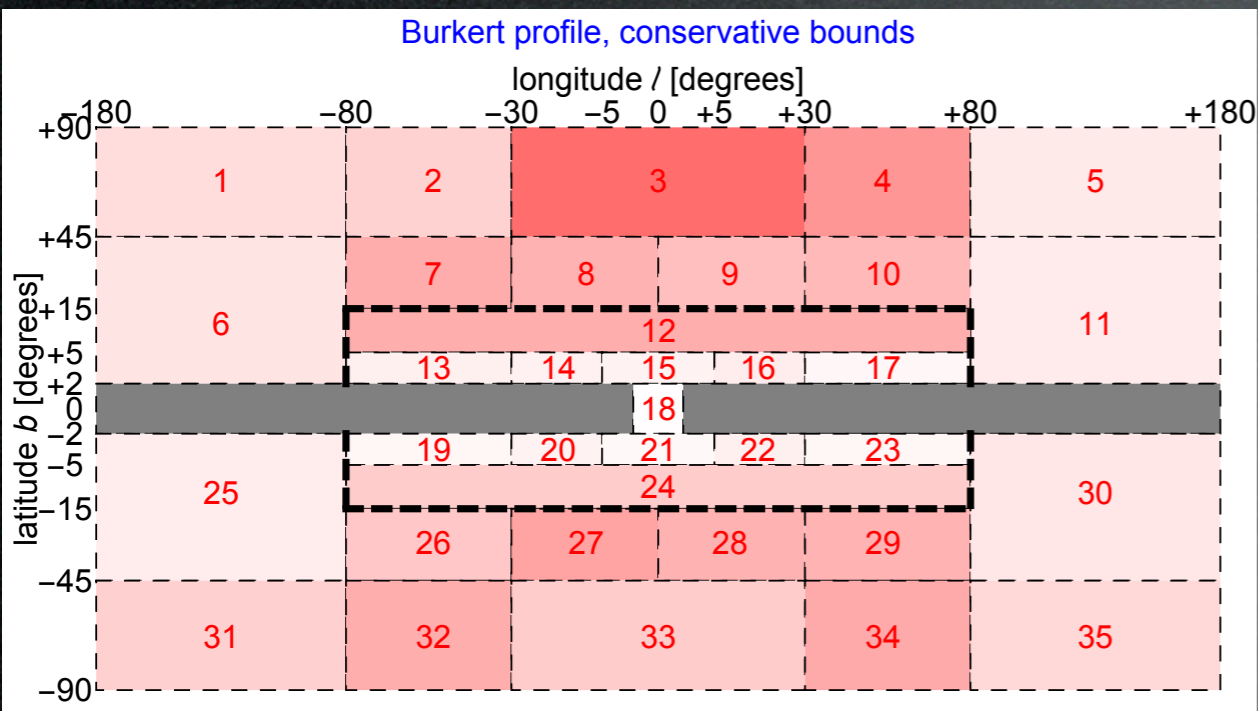
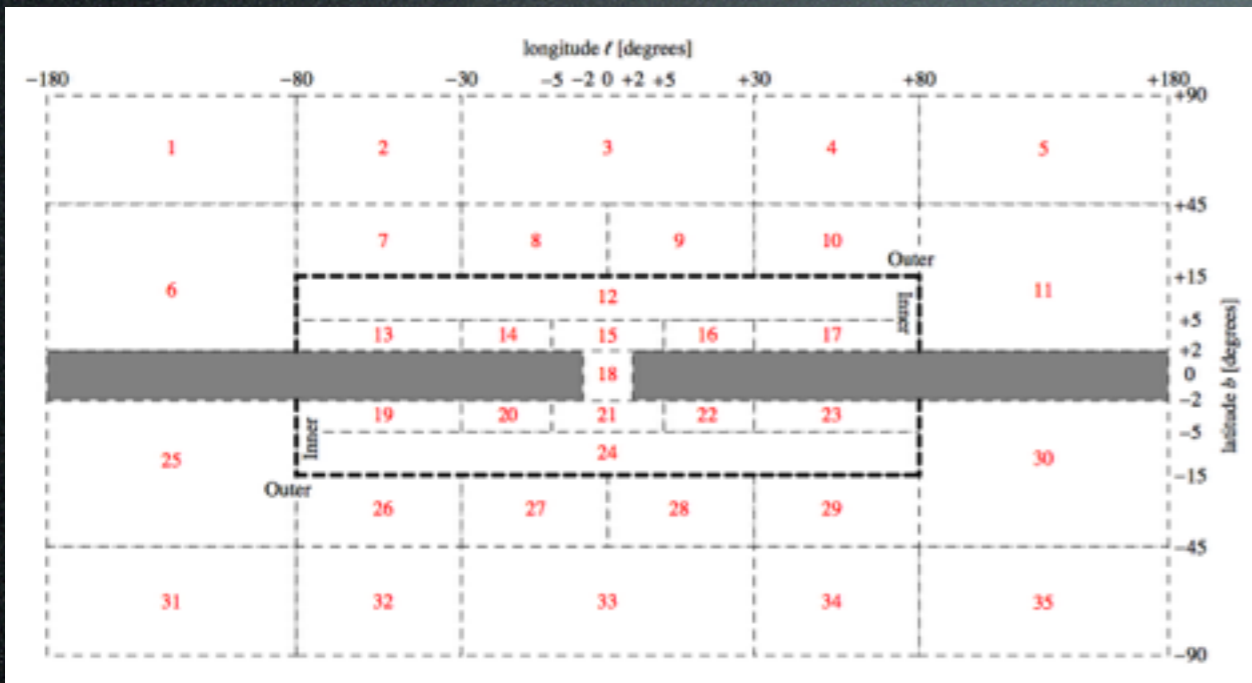


Burkert profile, including background

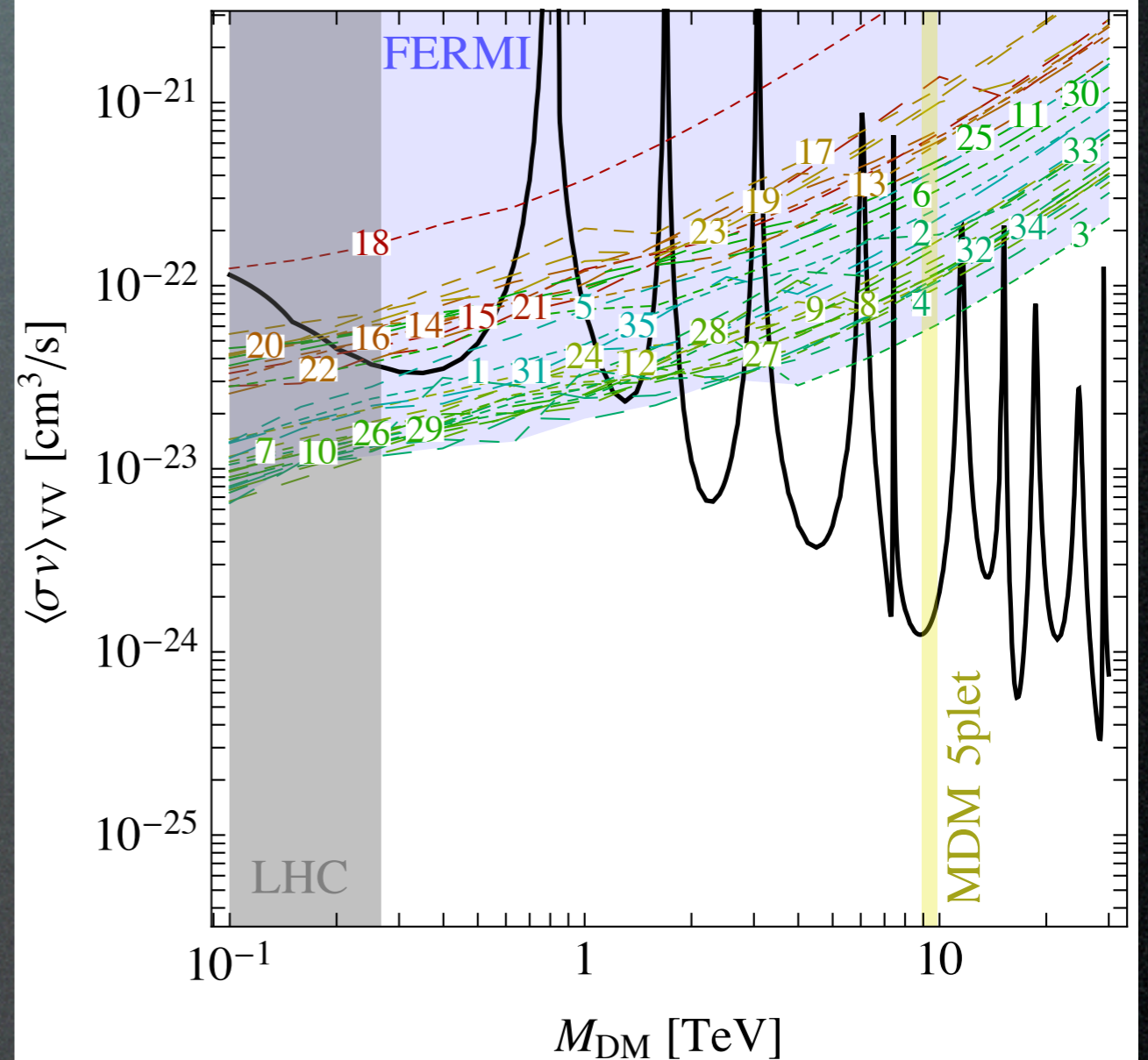


Application #1

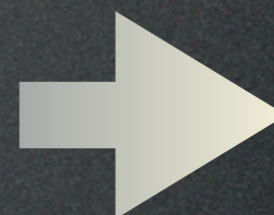
FERMI diffuse galactic:



Burkert profile, conservative bound



Cirelli, Hambye, Panci, Sala, Taoso 1507.05519



relevant constraints but
MDM 5plet not probed

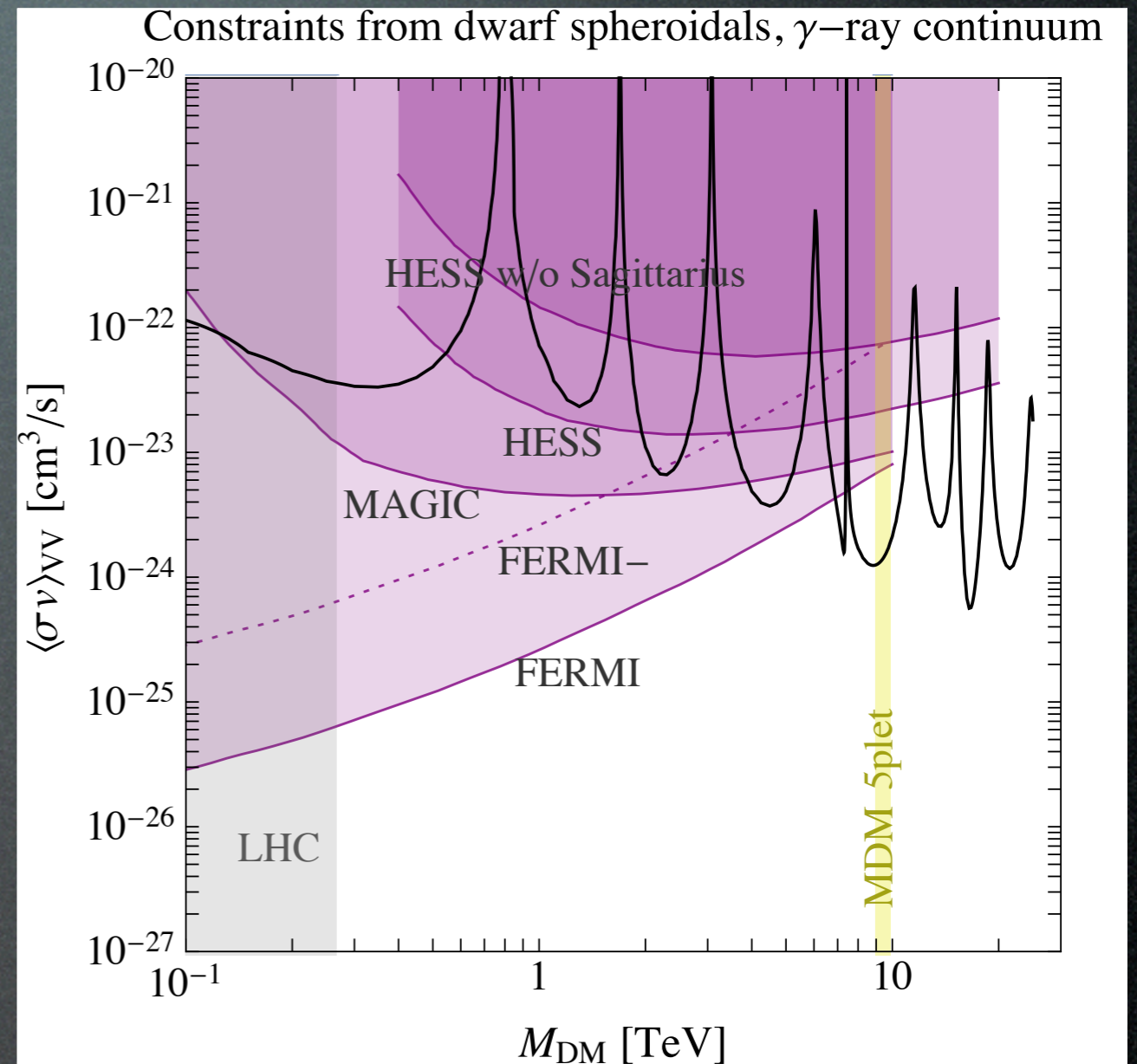
Application #1

dSphs galaxies, search for **continuum** γ -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

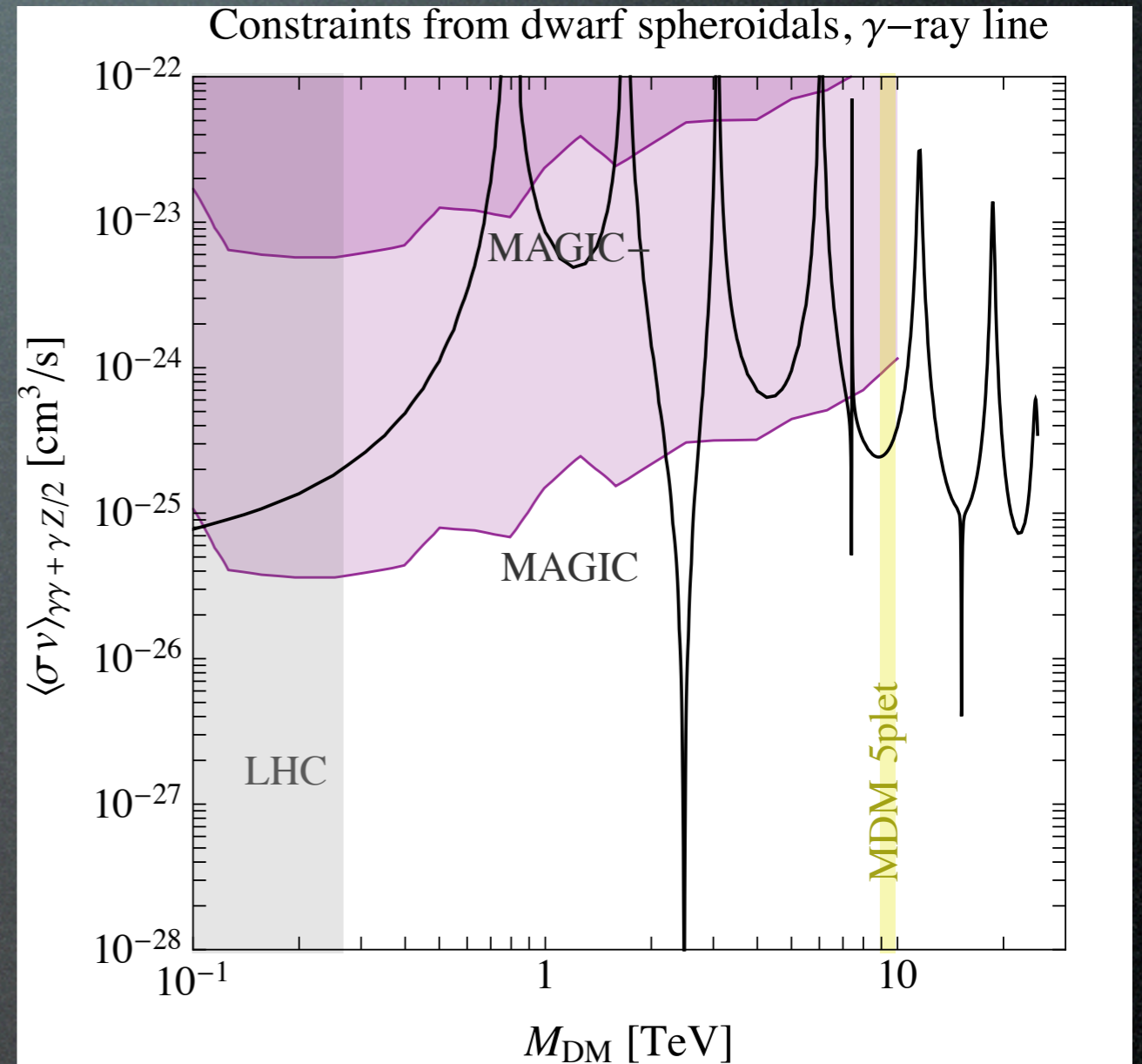
Application #1

dSphs galaxies, search for γ -ray lines:

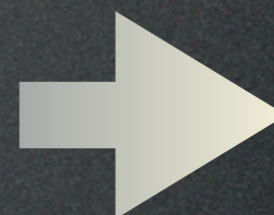
MAGIC: Segue1 - 1312.1535

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



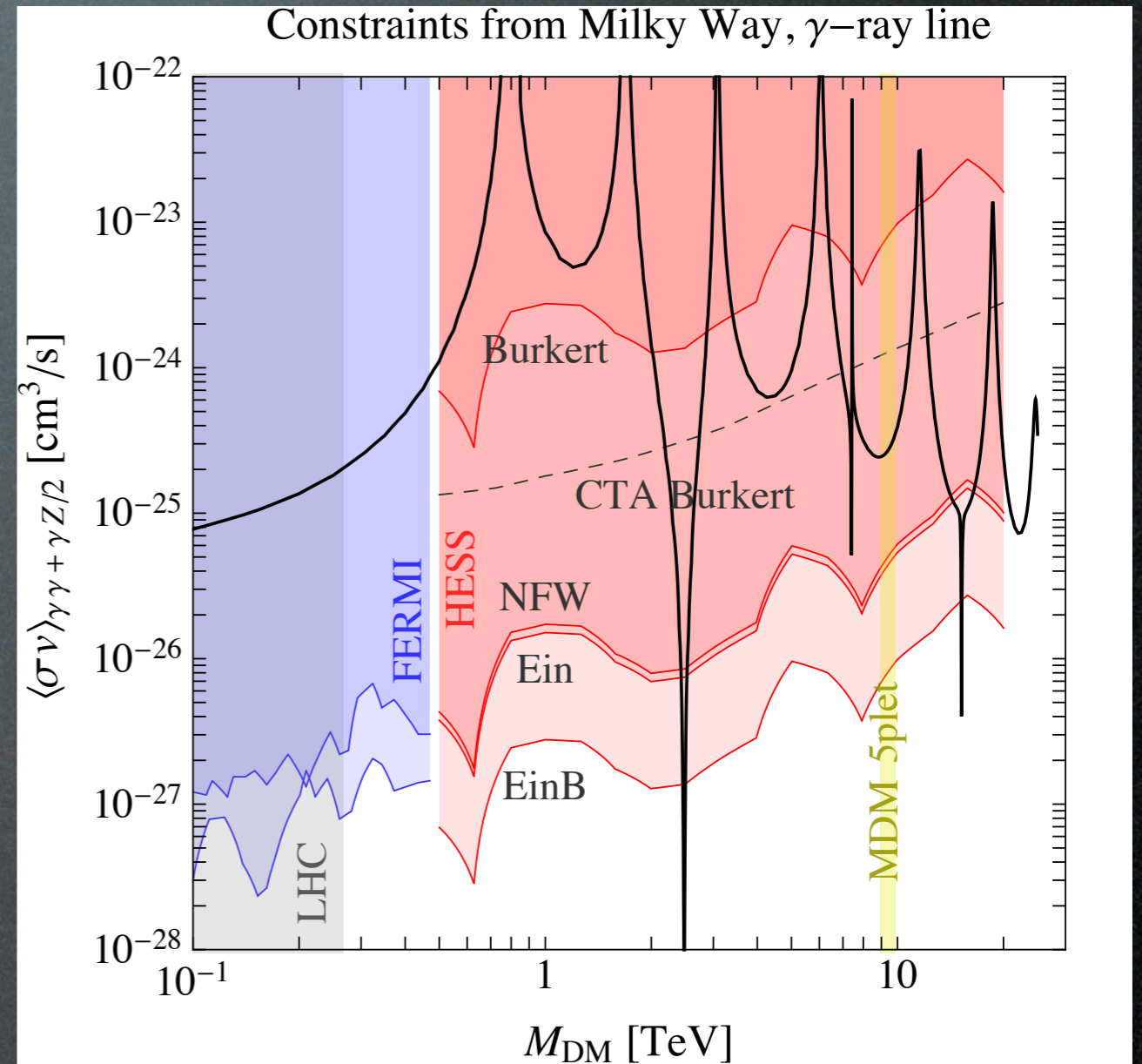
relevant constraints but
MDM 5plet not probed

Application #1

MW center area, search for γ -ray lines:

FERMI: 1506.00013

HESS: 1301.1173



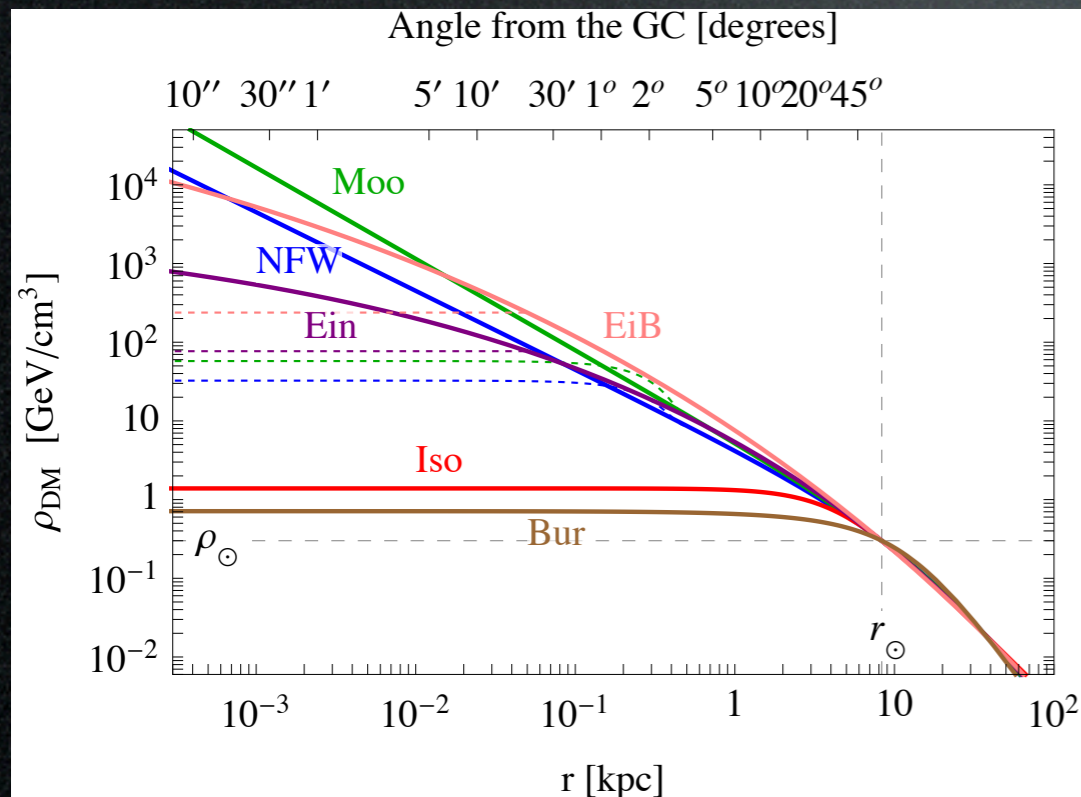
Application #1

MW center area, search for γ -ray lines:

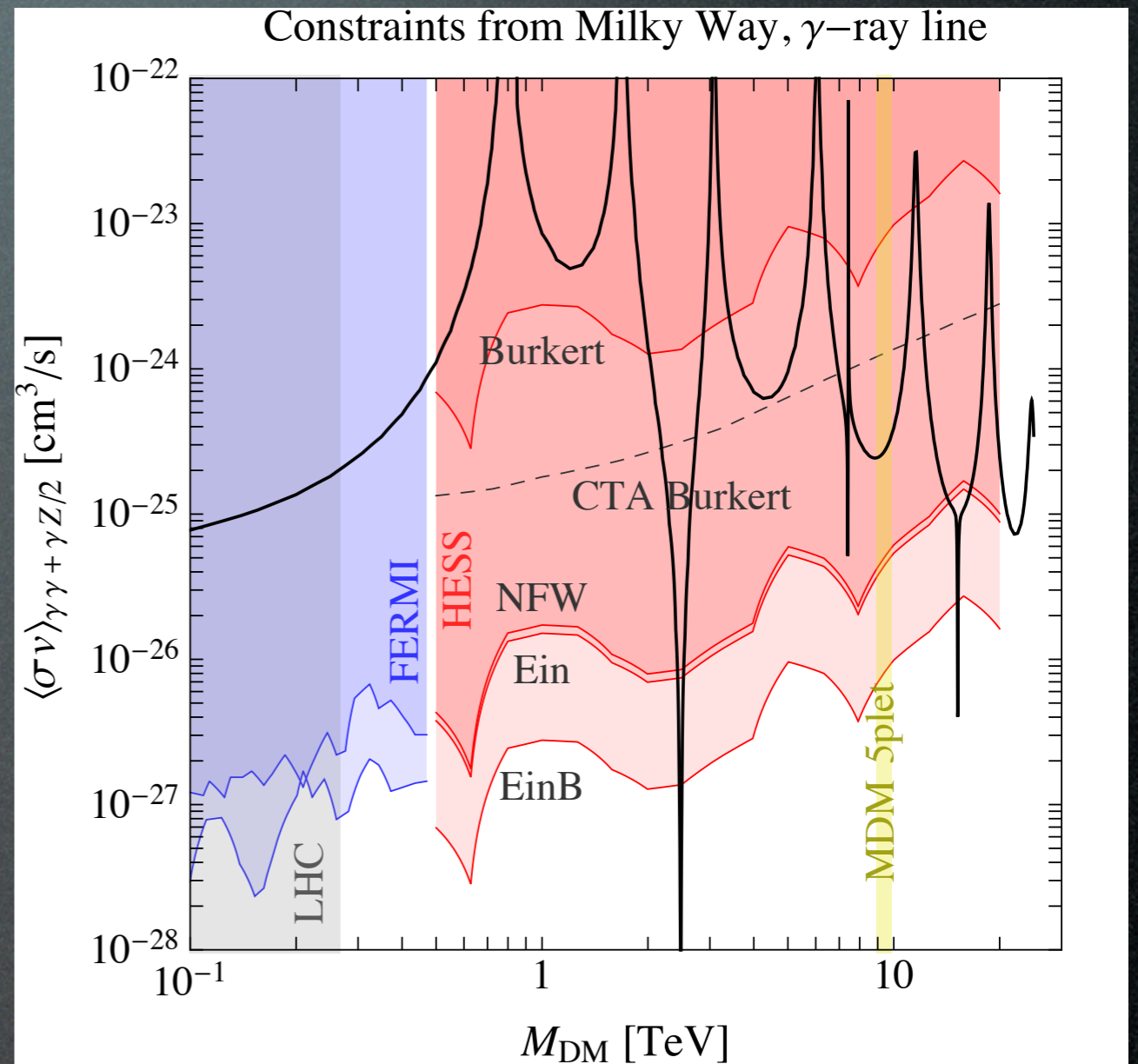
FERMI: 1506.00013

HESS: 1301.1173

Uncertainties in DM profile:



e.g. Cirelli et al., 1012.4515



Cirelli, Hambye, Panci, Sala, Taoso 1507.05519

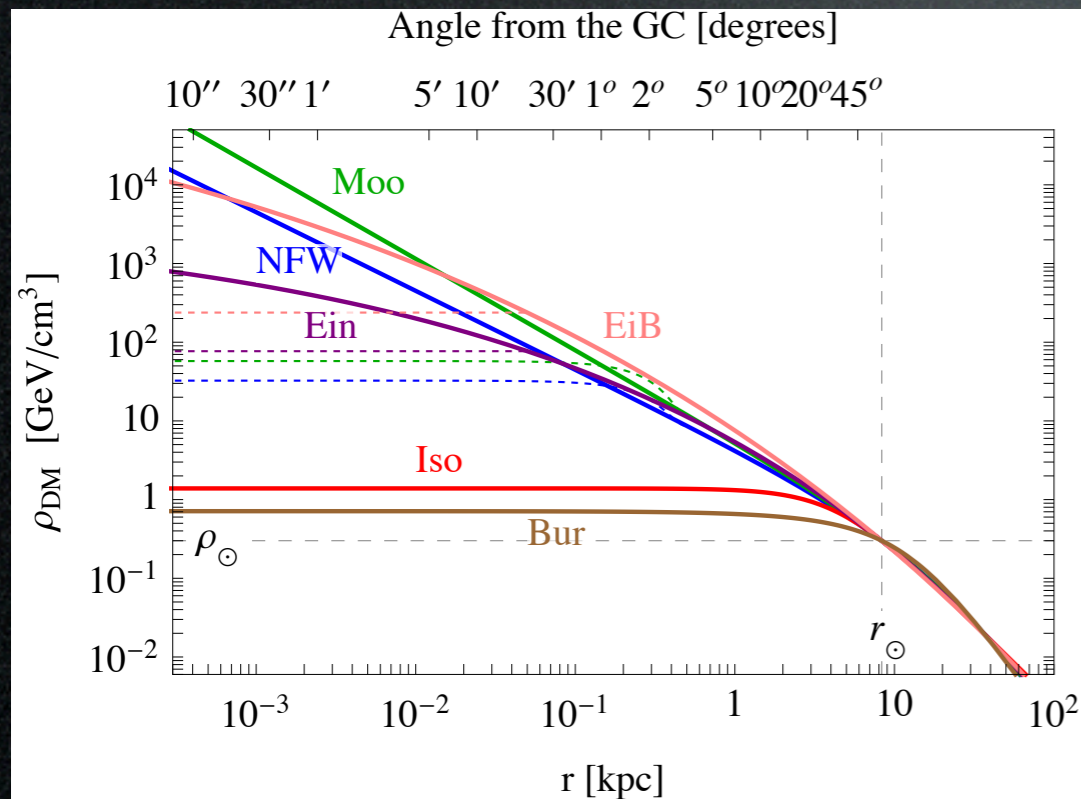
Application #1

MW center area, search for γ -ray lines:

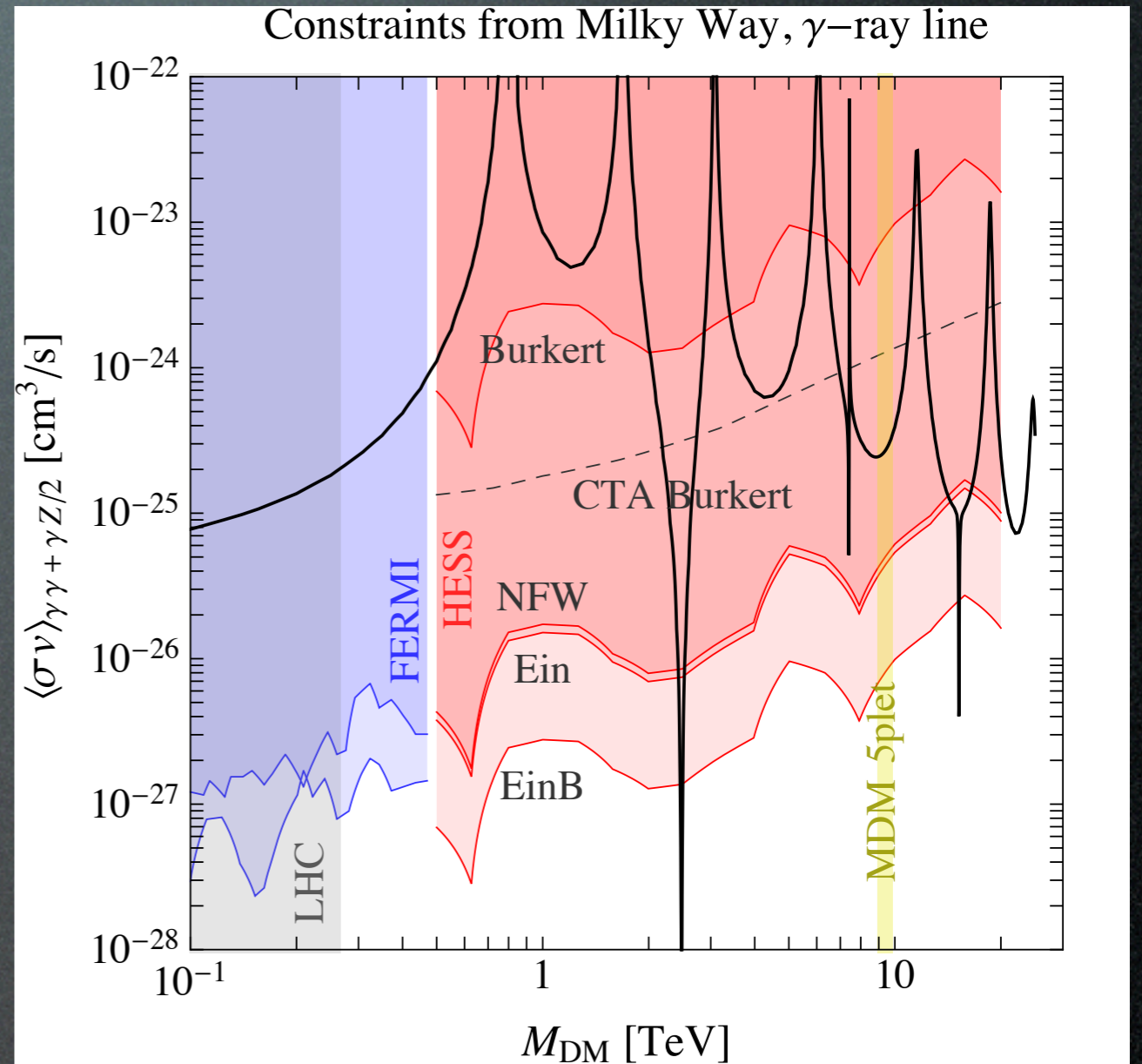
FERMI: 1506.00013

HESS: 1301.1173

Uncertainties in DM profile:



e.g. Cirelli et al., 1012.4515



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

Application #2

Bremsstrahlung γ -rays are relevant for light DM

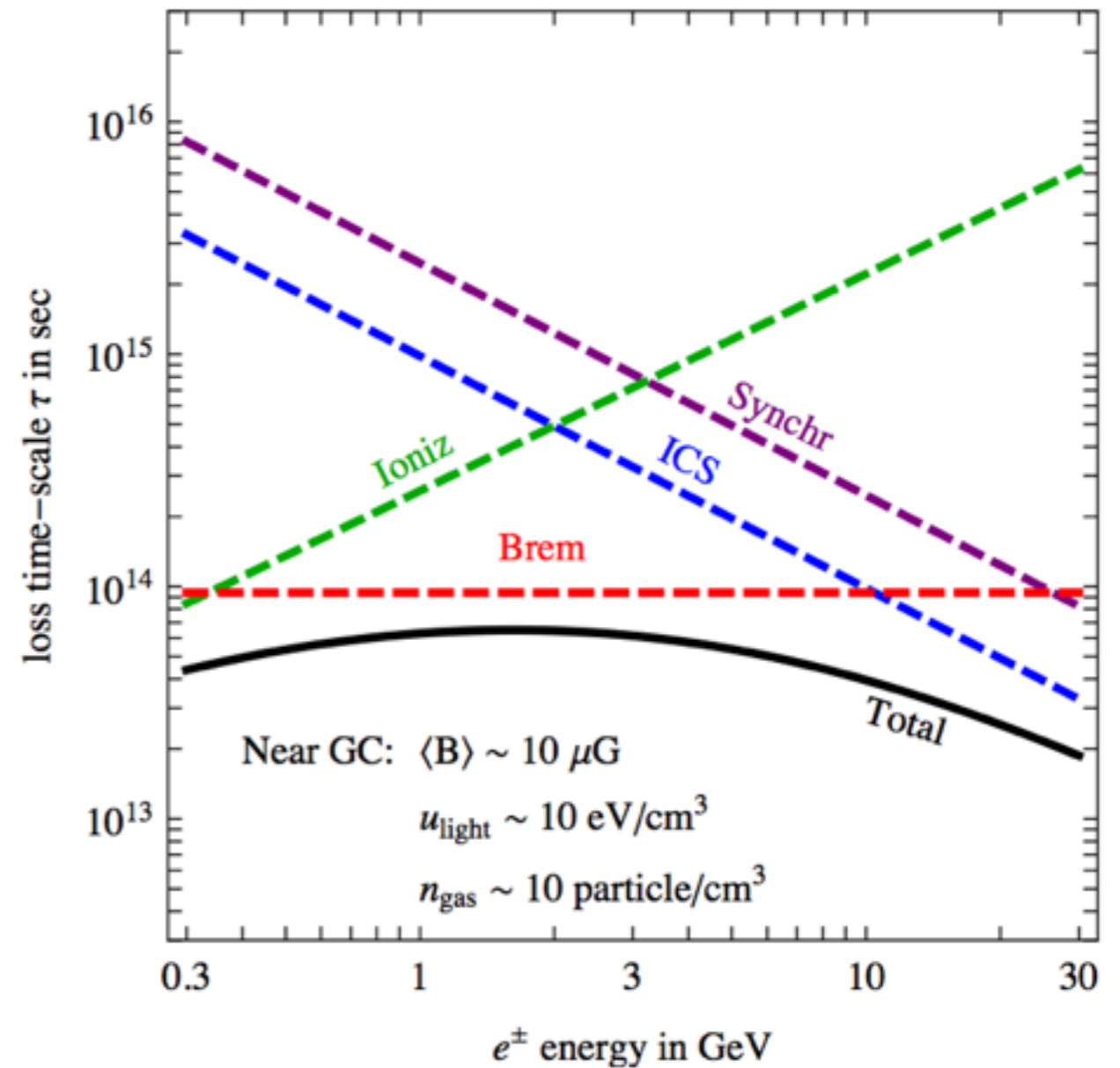
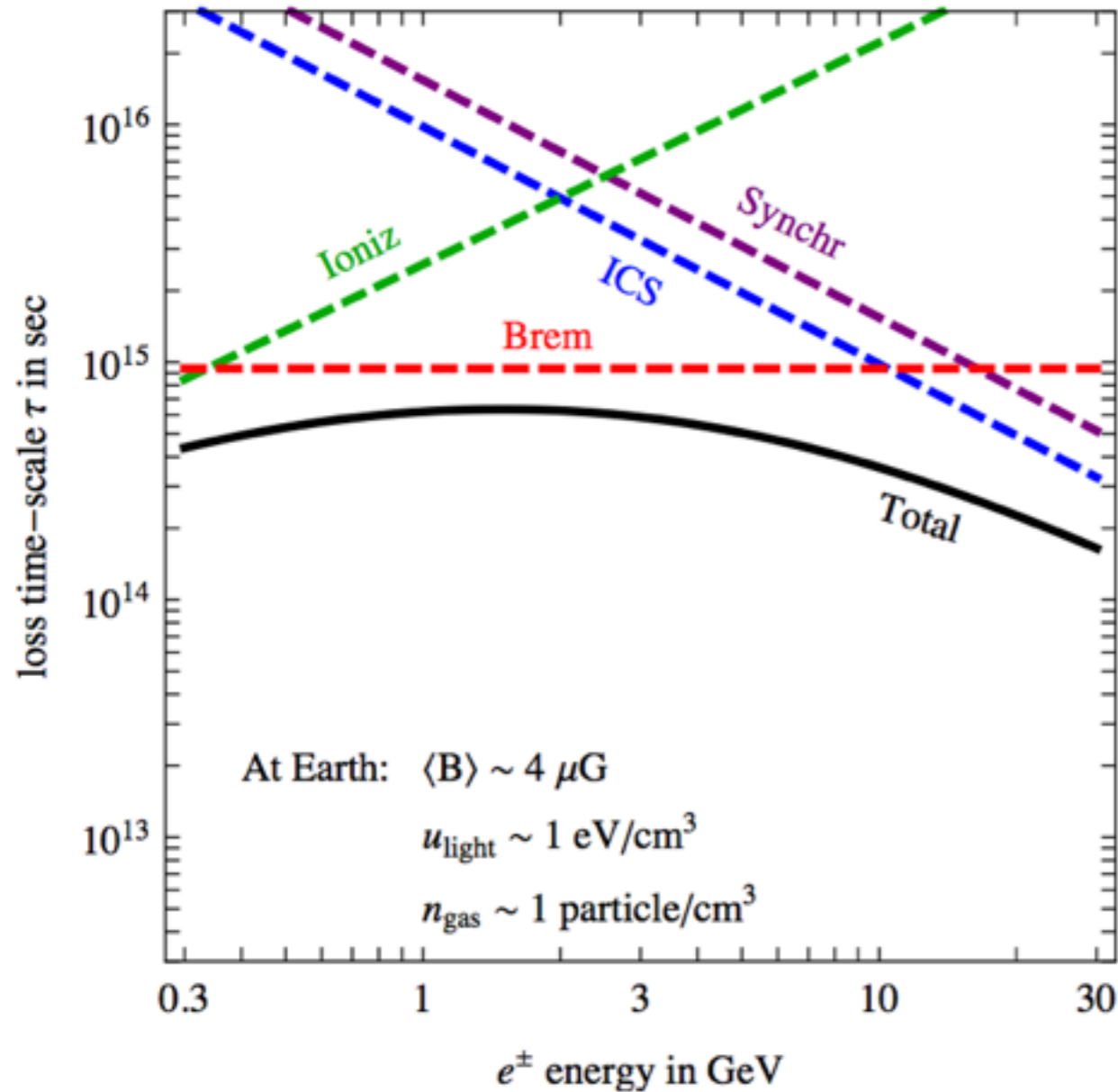
based on:

Cirelli, Serpico, Zaharijas
1307.7152

Application #2

Bremsstrahlung γ -rays are relevant for light DM

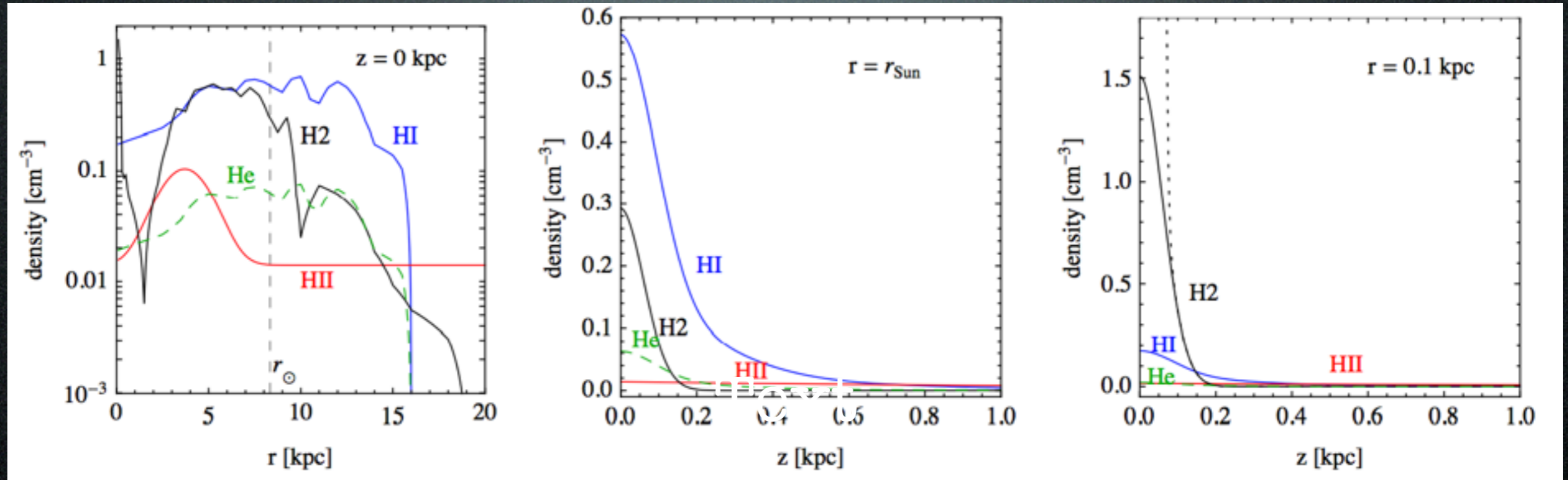
Relative importance of energy losses:



\Rightarrow brem is the **dominant** energy loss for low energy e^\pm !

Application #2

Bremsstrahlung γ -rays are relevant for light DM



Gas-tronomy 101:

HI = neutral atomic hydrogen

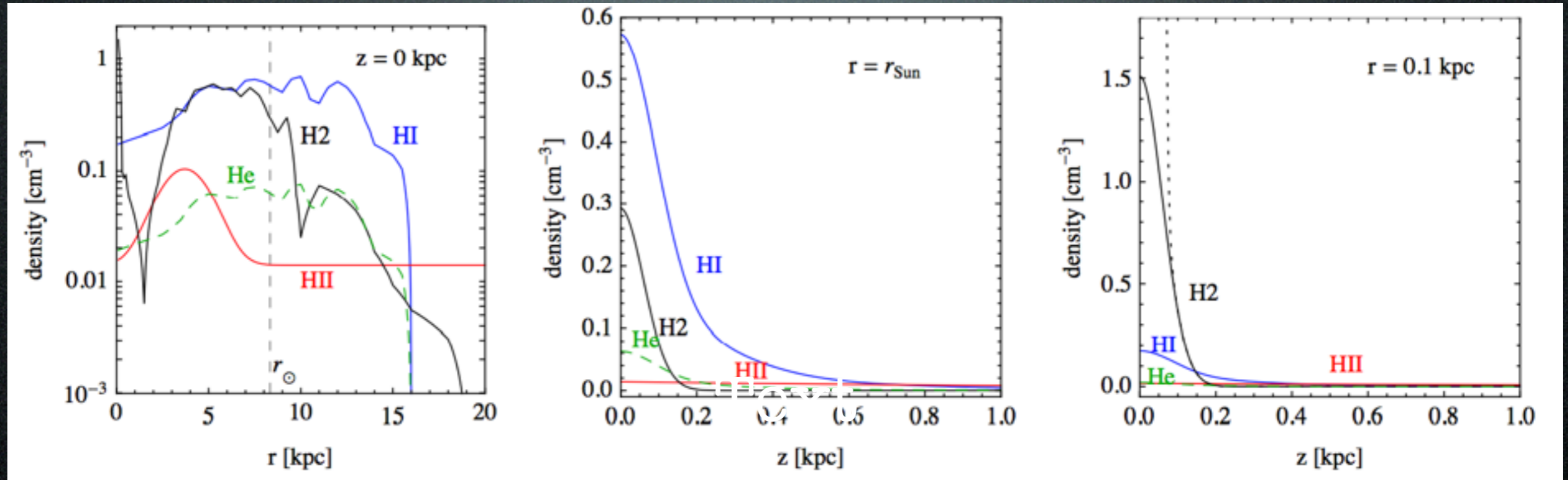
HII = ionized hydrogen

H2 = neutral molecular hydrogen

(He = Helium)

Application #2

Bremsstrahlung γ -rays are relevant for light DM



But: inner kpc of the Galaxy is denser
(and more uncertain)

SNB

Stellar Nuclear Bulge

< 1 kpc

?

CMZ

Central Molecular Zone

< 200 pc

10^2 - 10^3 /cm³

CNR

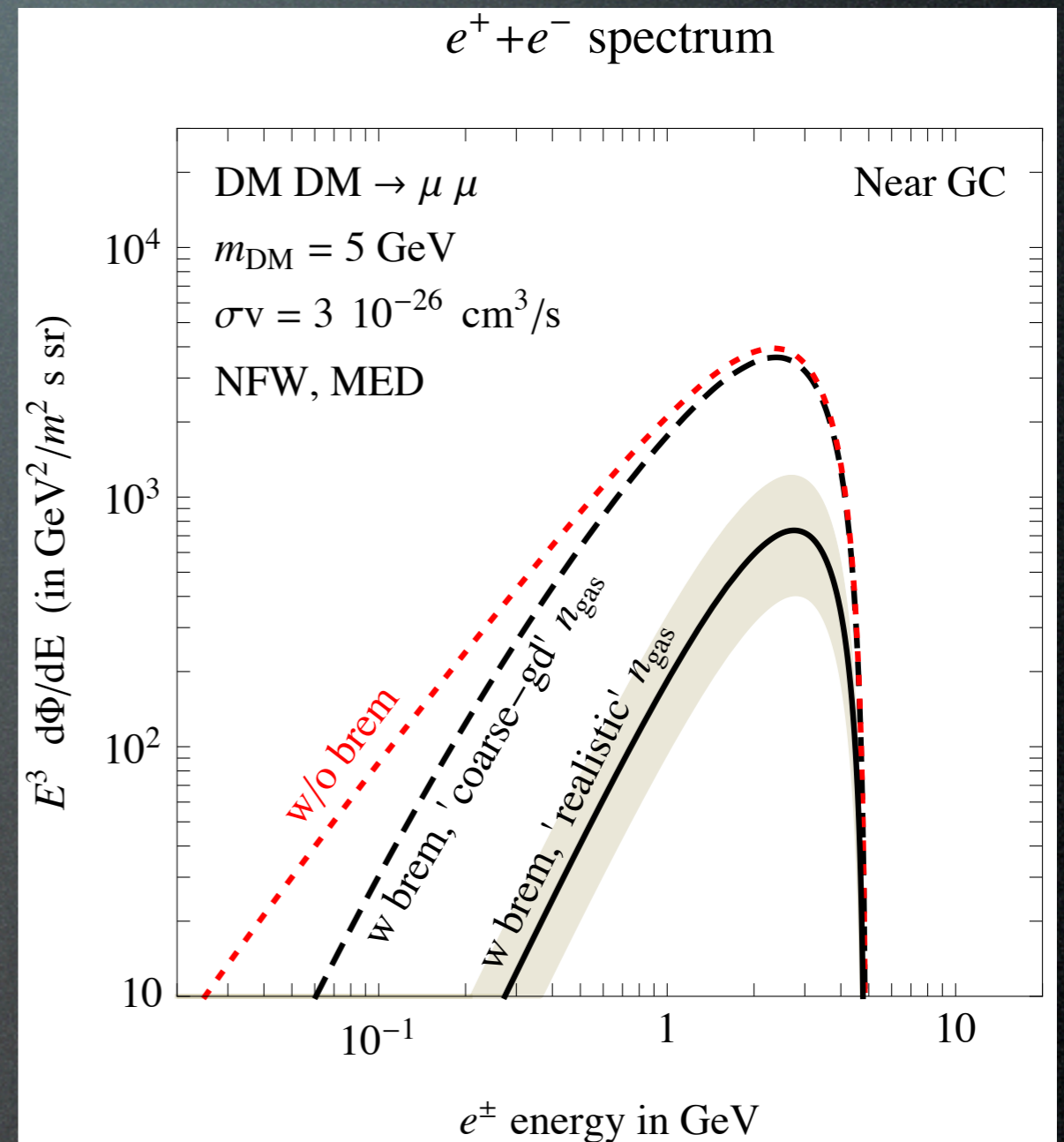
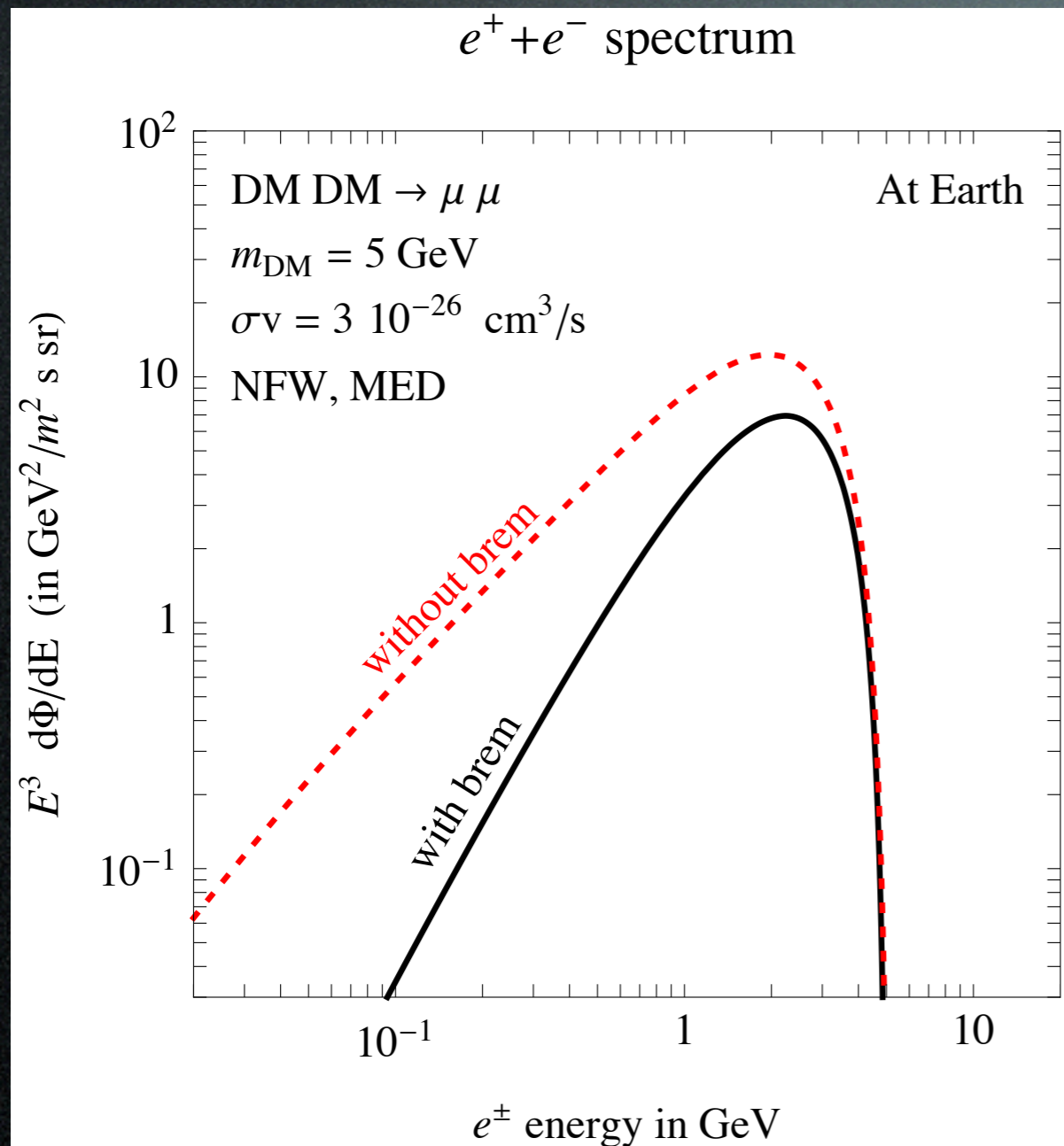
Circum-Nuclear Ring

< 3 pc

10^5 /cm³

Application #2

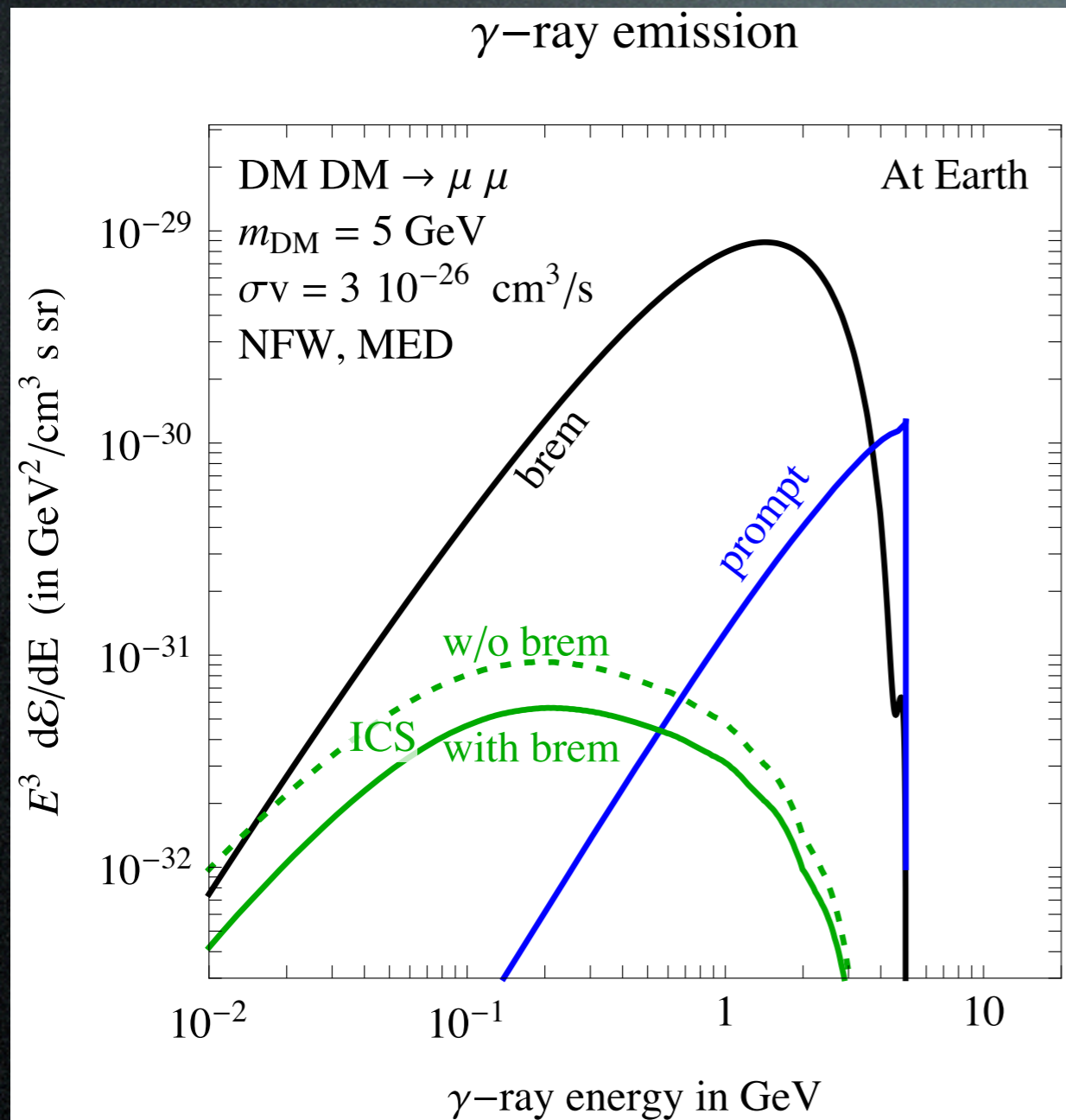
The e^\pm population is affected by bremsstrahlung



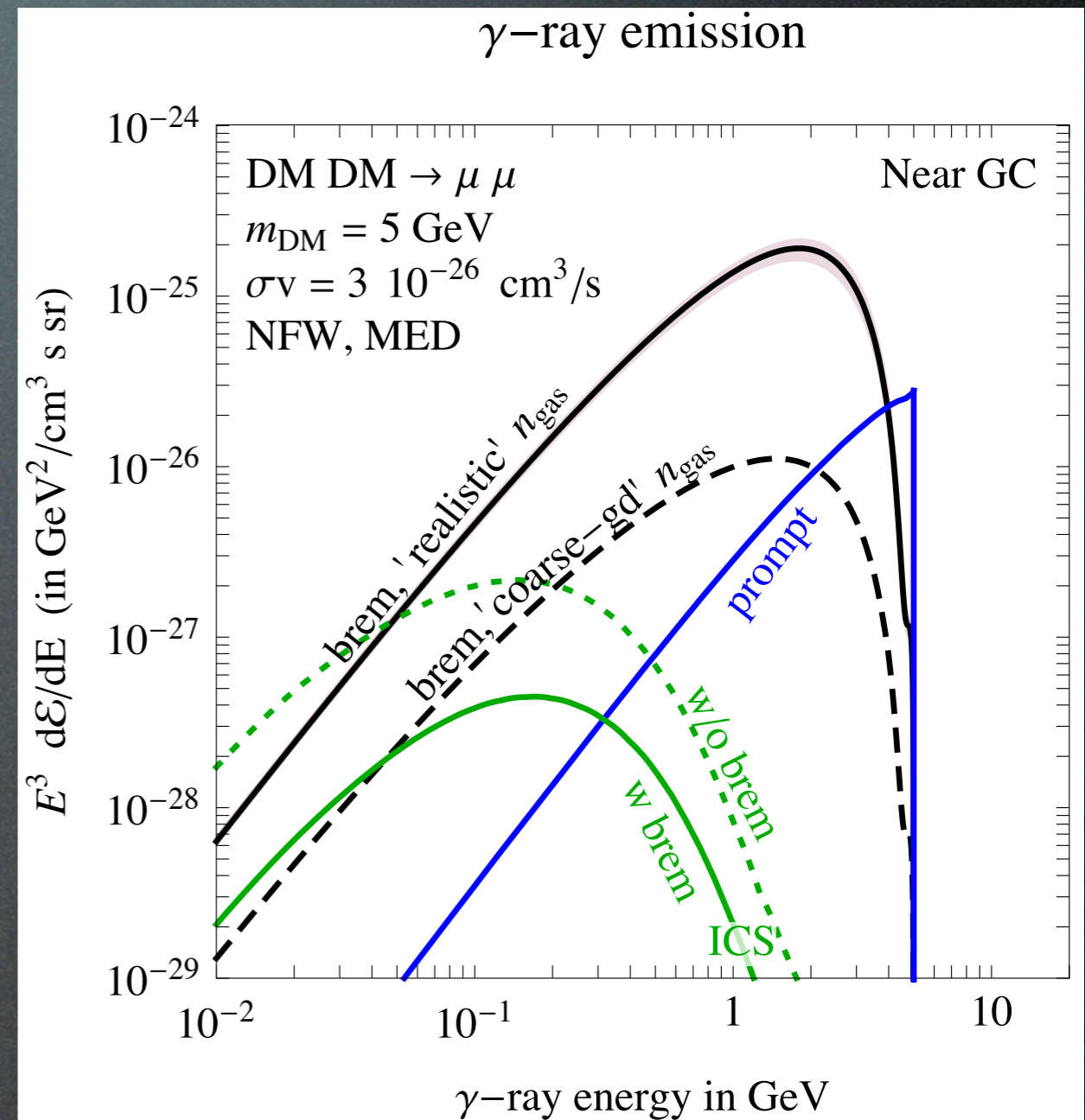
 = factor 2 uncertainty in n_{gas}

Application #2

The total γ ray spectrum



- brem is dominant
- ICS is affected



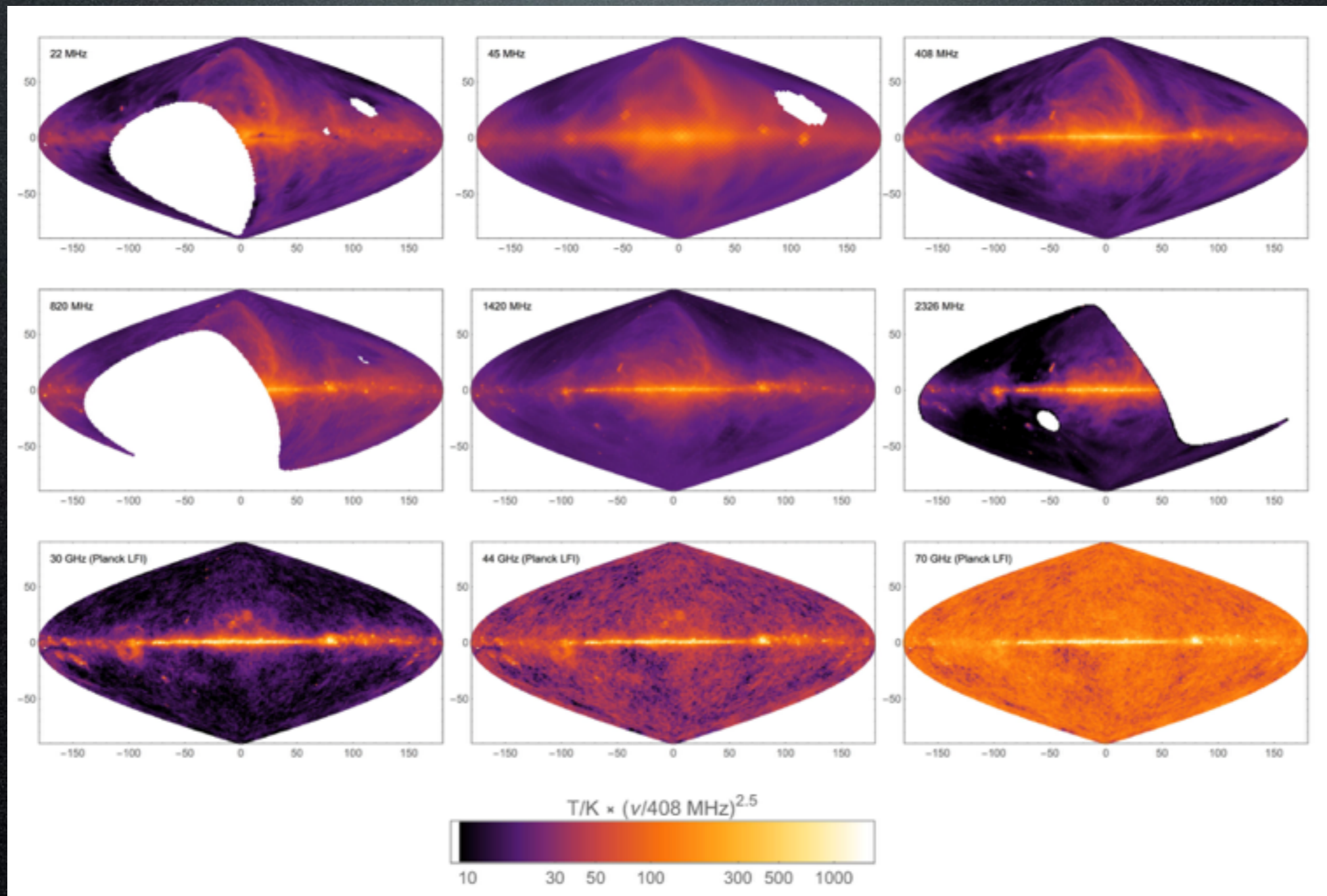
- uncertainty is somewhat reabsorbed:
large $n_{\text{gas}} \Rightarrow$ more loss **and** more emission

Application #3

Galactic radio measurements constrain DM

based on:
Cirelli, Taoso 1604.06267

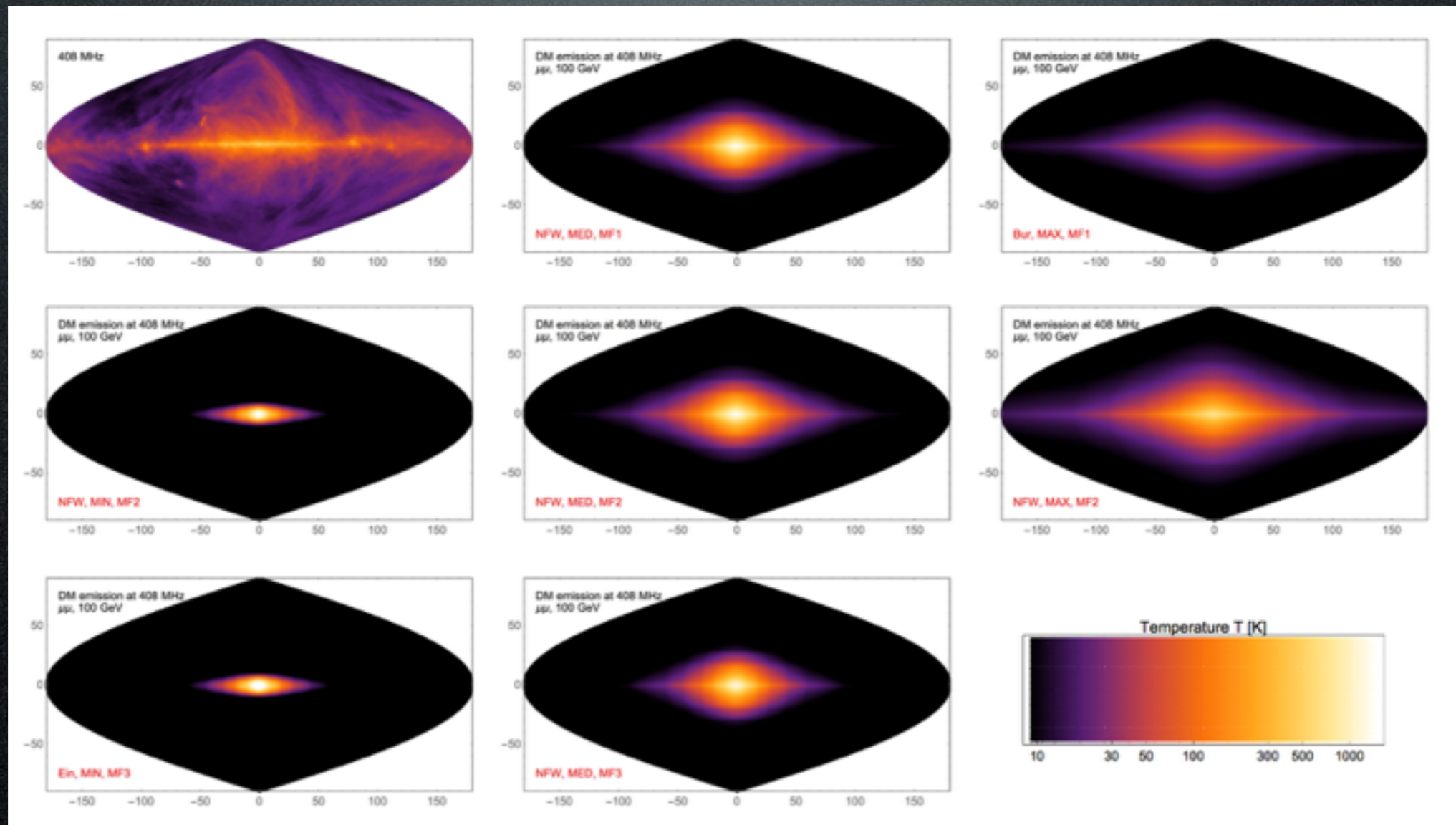
Galactic radio surveys



Application #3

Galactic radio measurements constrain DM

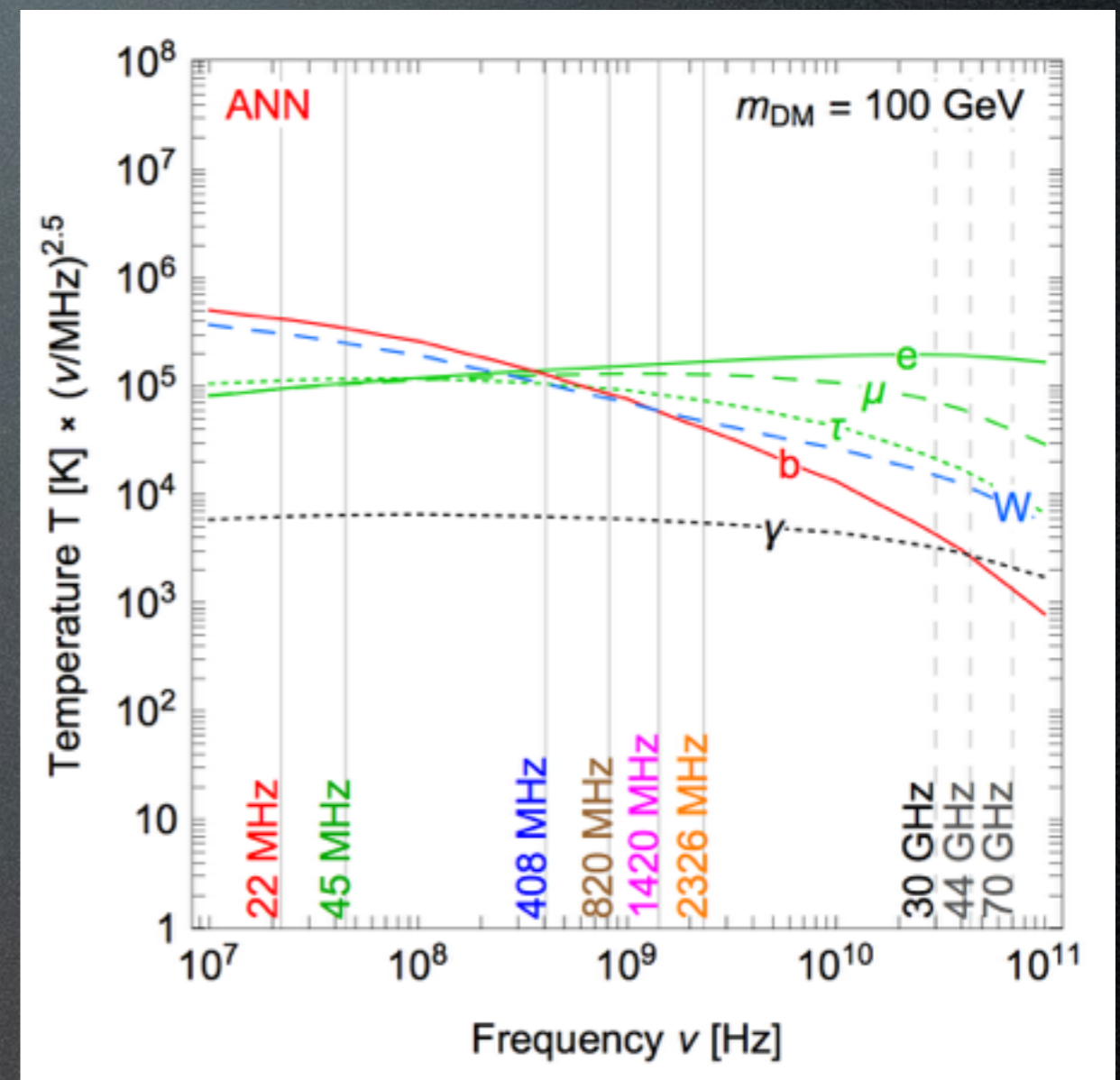
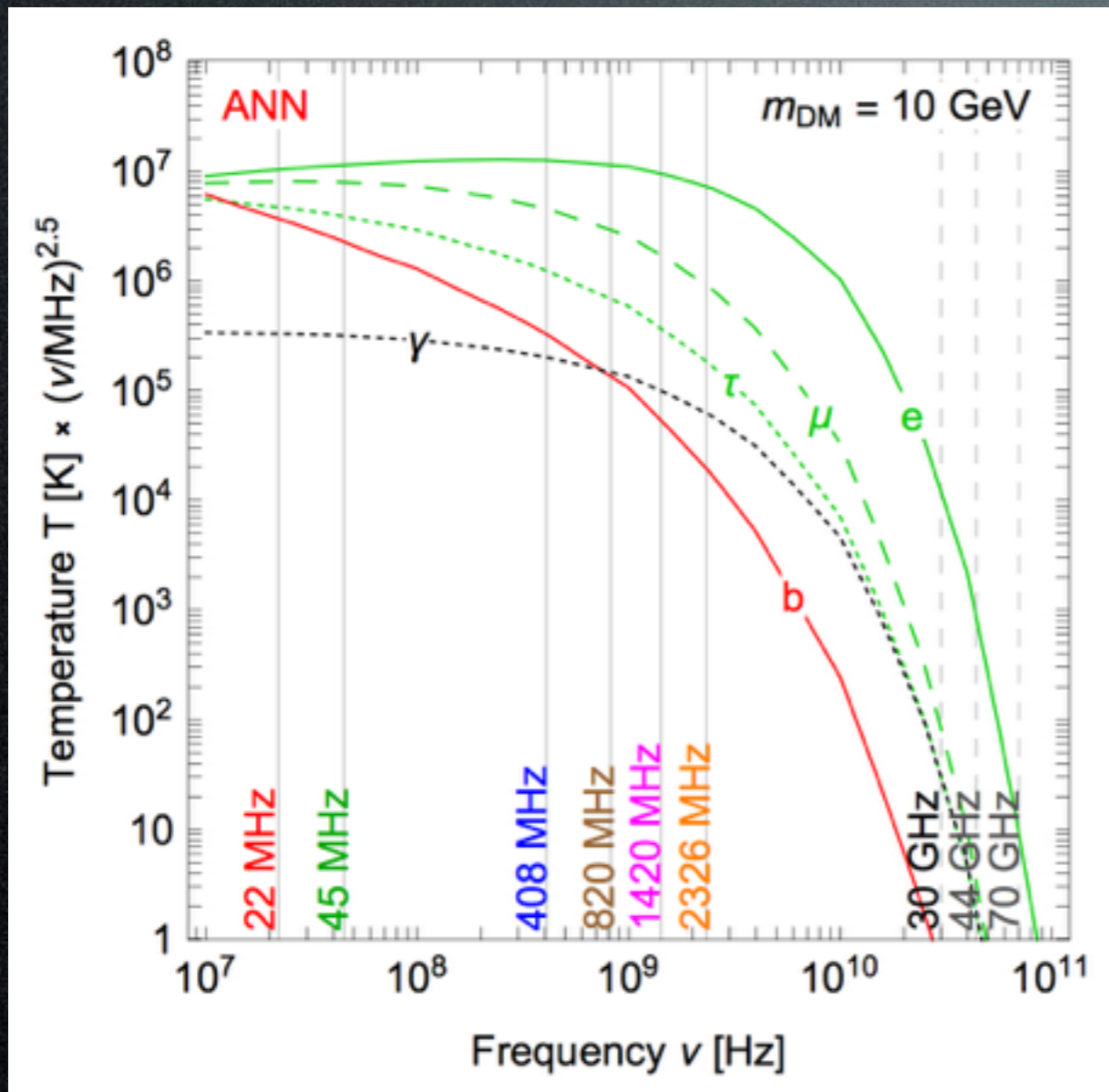
DM radio emission



Application #3

Galactic radio measurements constrain DM

Cirelli, Taoso 1604.06267

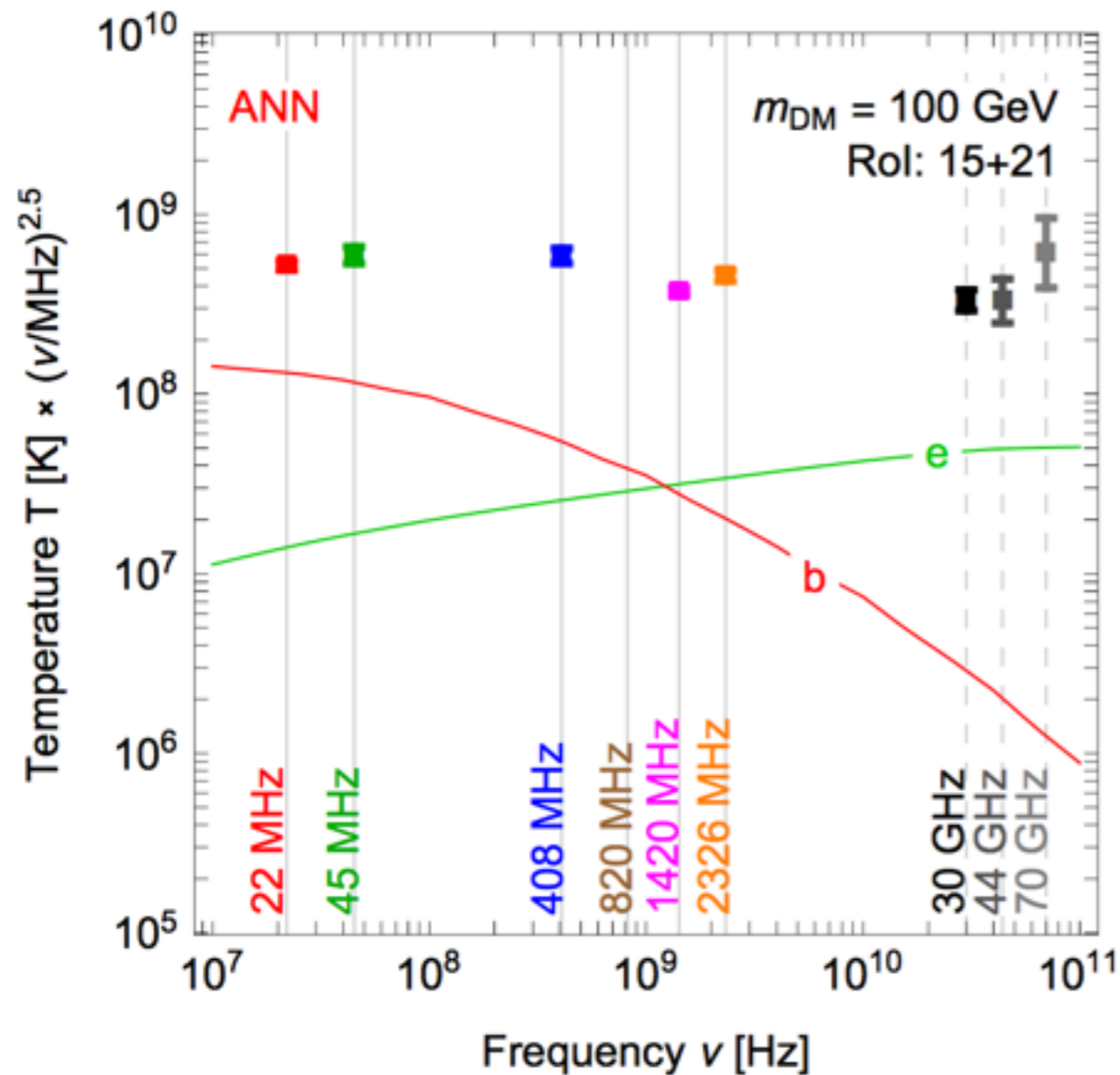


light DM emits
at low frequency

heavier DM emits
at all frequencies

Application #3

Galactic radio measurements constrain DM

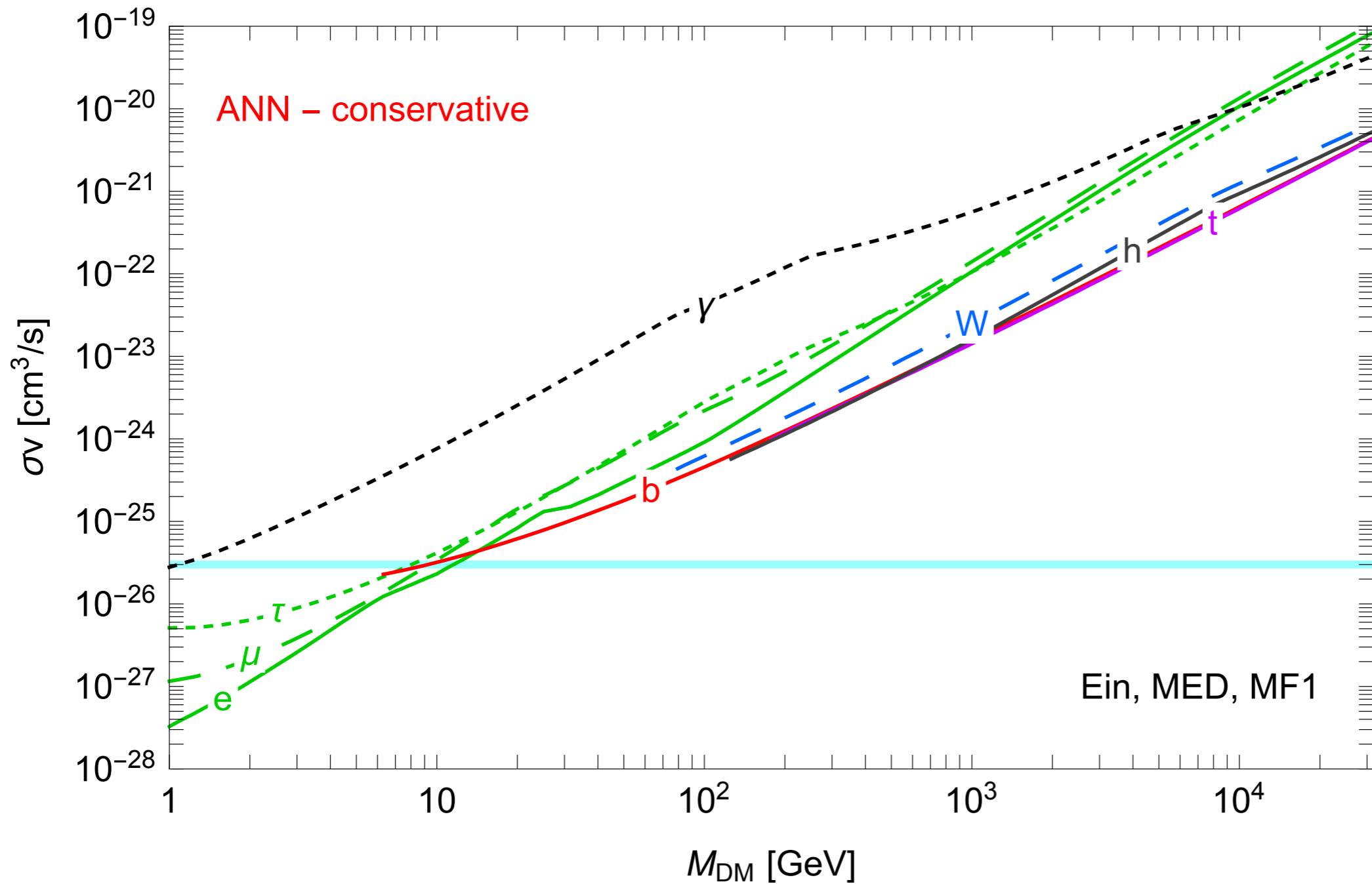


- low frequencies constrain hadronic (soft) spectra, high frequencies constrain leptonic (hard) spectra

Application #3

Galactic radio measurements constrain DM

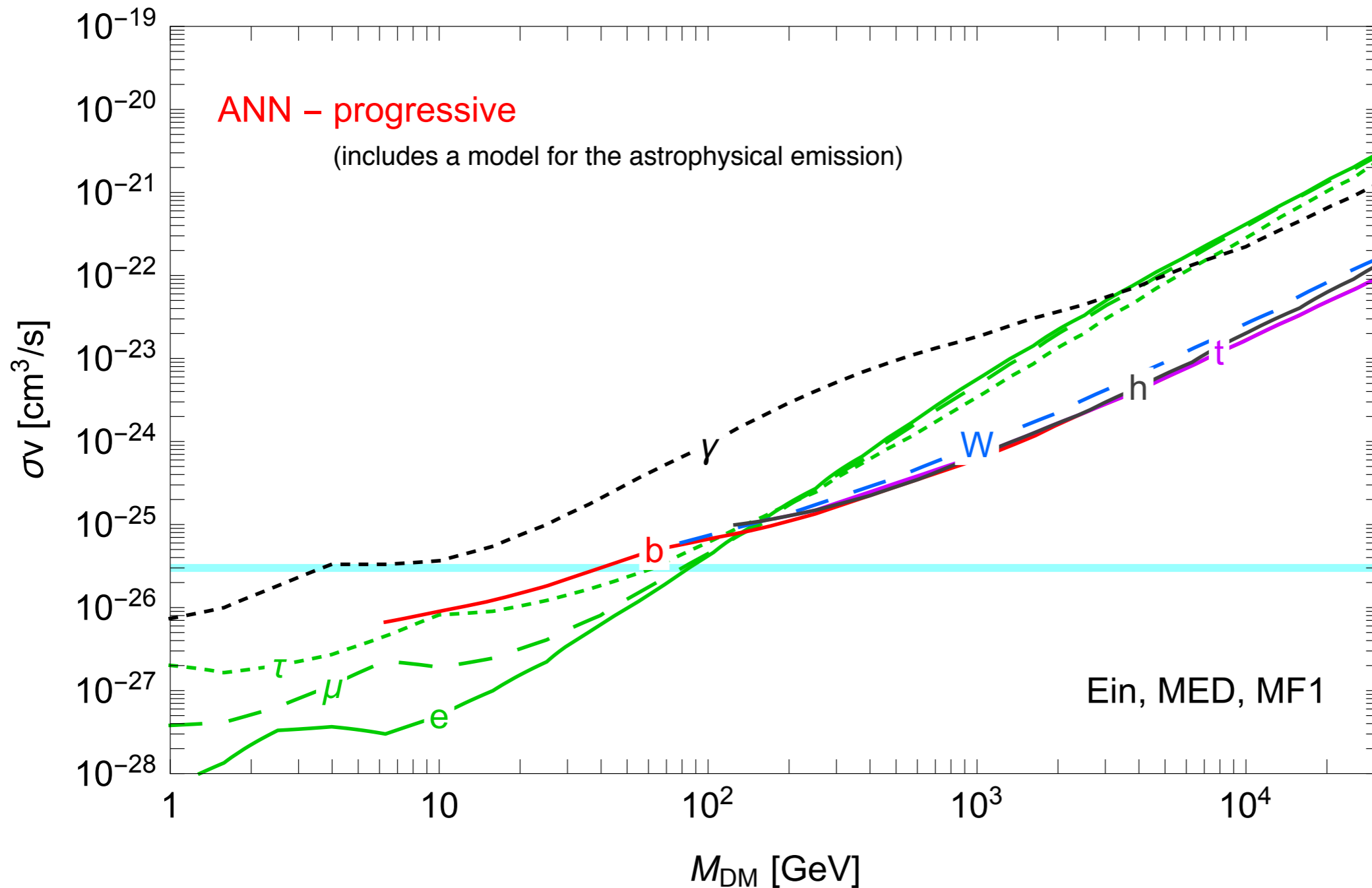
Bounds:



Application #3

Galactic radio measurements constrain DM

Bounds:



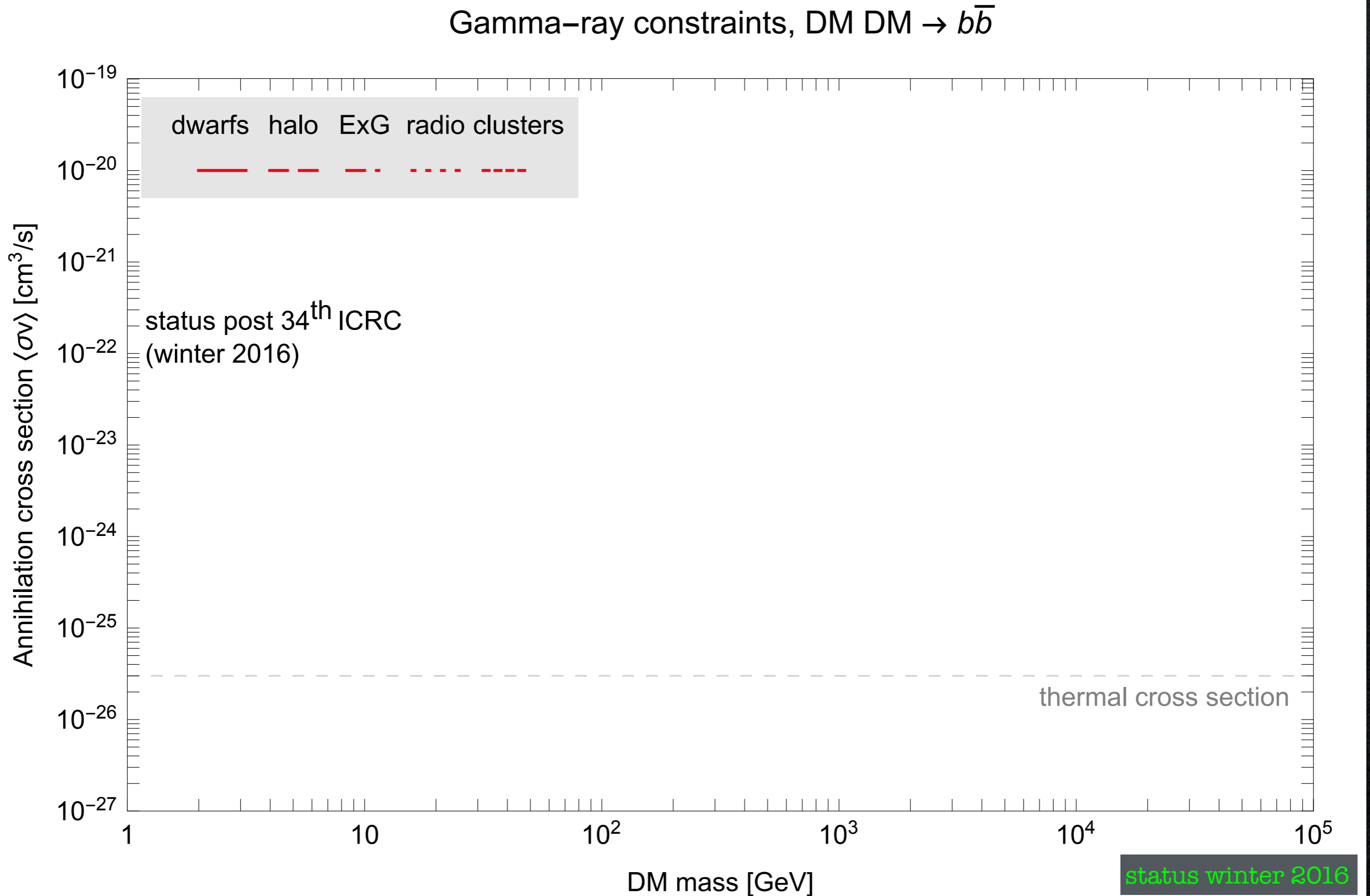
Combined gamma constraints

Gamma ray searches - DM annihilation

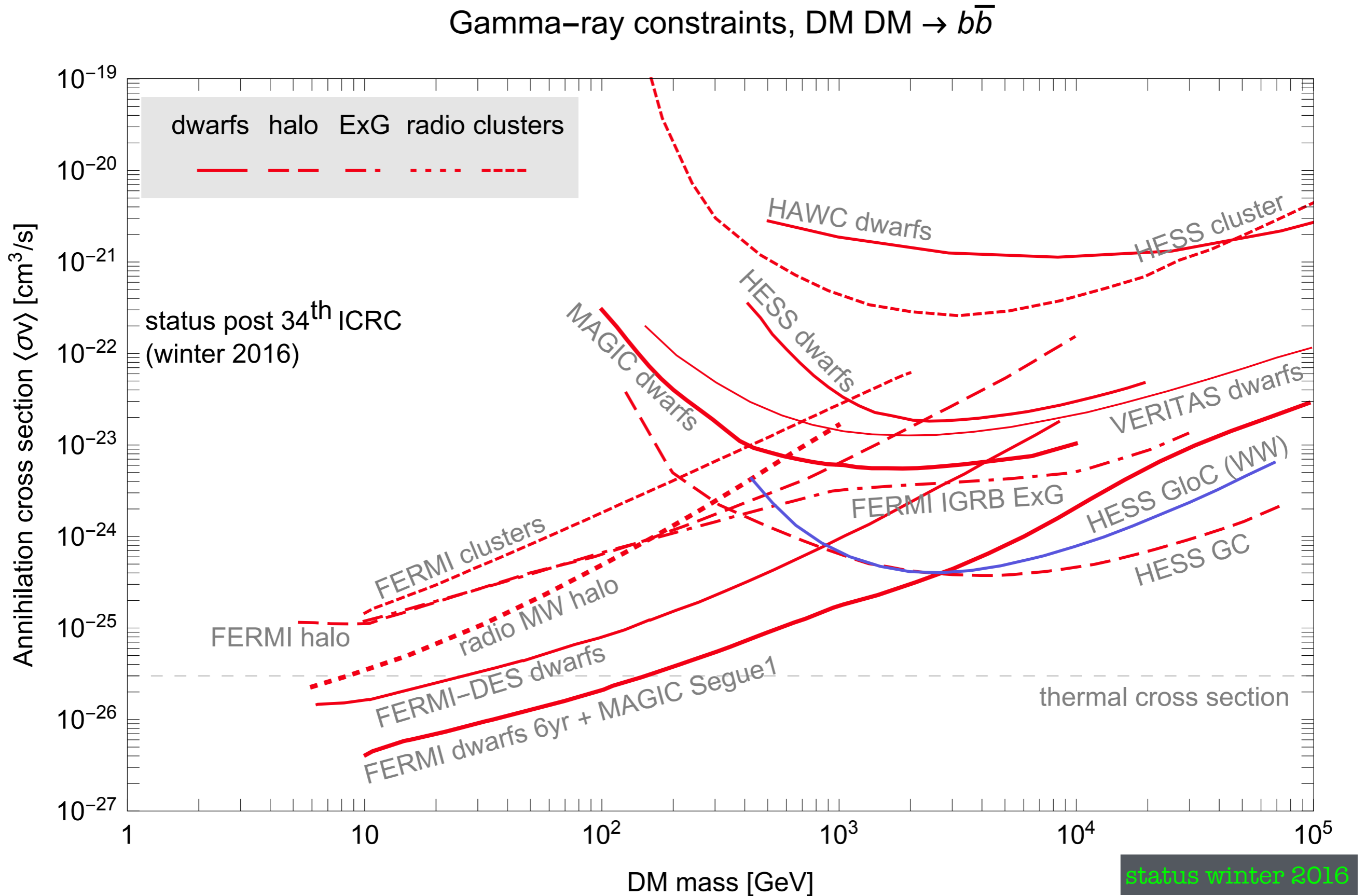
	GC / GCH	MW halo	Dwarfs	Clusters	Extragalactic	other
continuum	HESS [60, 61] (FERMI [91])	FERMI [62]	MAGIC [63]	FERMI [70, 73] HESS [71] VERITAS [72]	FERMI [74]	FERMI [79] (dark satellites)
			HESS [64]			HESS [80] (GloCs)
			FERMI [65] FERMI+MAGIC [66] FERMI-DES [67] HAWC [68] VERITAS [69]			VERITAS [81] (subhalos)
lines	HESS [75, 76]	FERMI [77]	MAGIC [63]	FERMI [78]		

Figure 7: A collection of the currently most relevant γ -ray searches for DM annihilation, as produced by the different experimental collaborations.

Combined gamma constraints



Combined gamma constraints



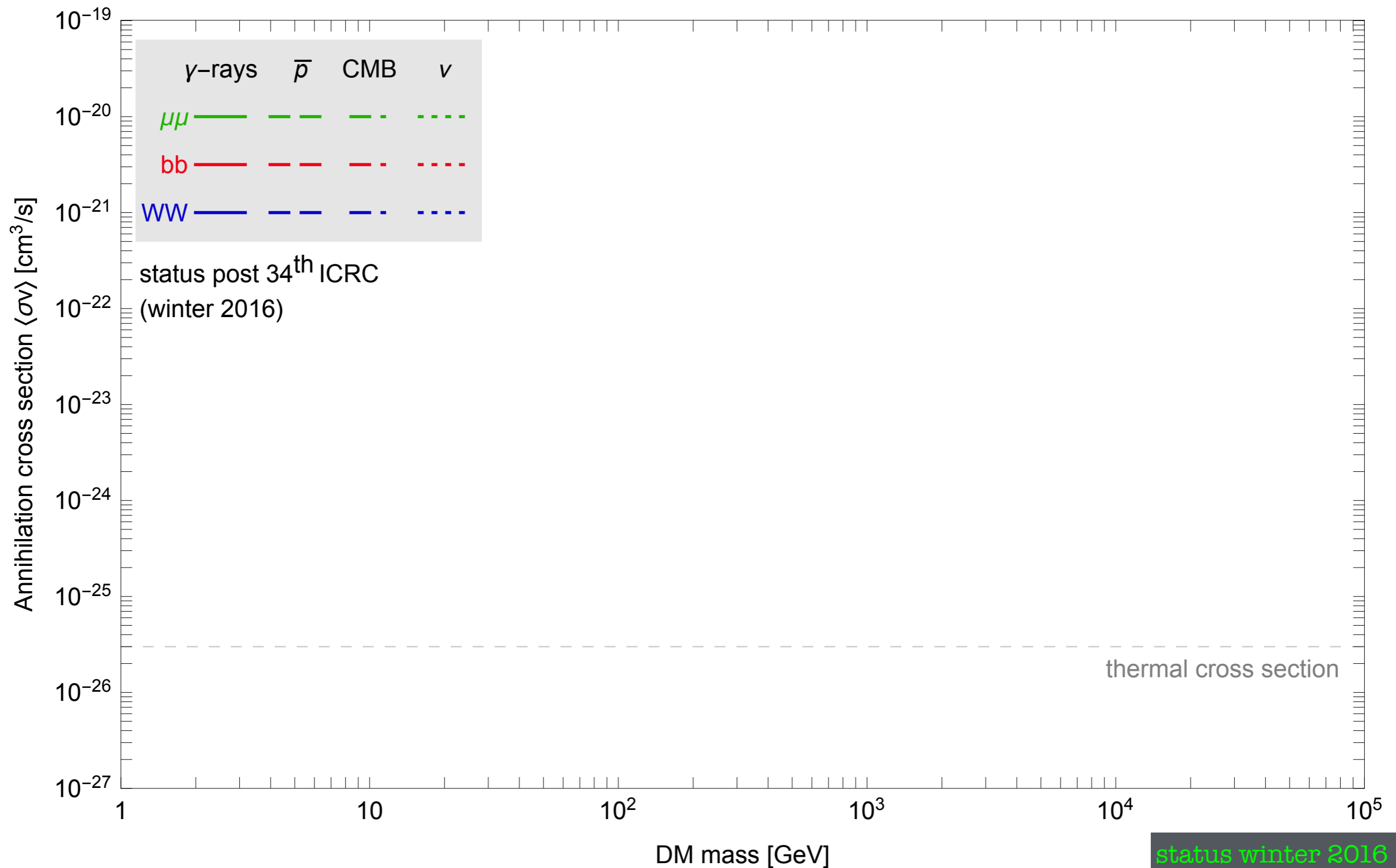
Combined DM ID constraints

antiprotons, gammas, neutrinos, CMB...

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antiprotons, gammas, neutrinos, CMB...

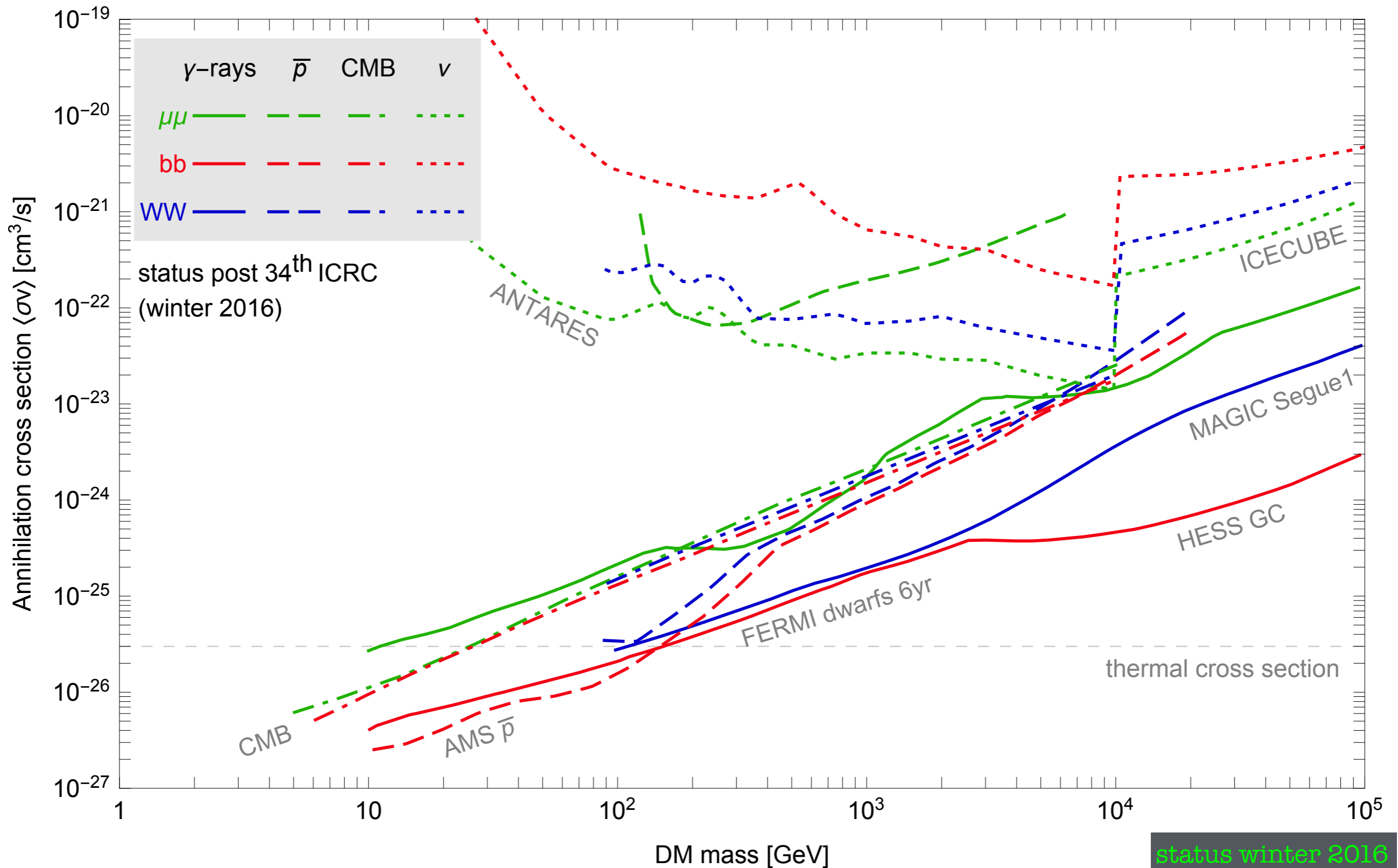
All ID constraints



Combined DM ID constraints

antiprotons, gammas, neutrinos, CMB...

All ID constraints



Conclusions

DM not seen yet (Damn!...)

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Indirect detection is in principle
a very powerful tool

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in e^\pm : long standing 'excesses'

in p : still large uncertainties

in d : challenging flux

in γ : unknown backgrounds

in ν : challenging detection

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Solution:

- multimessenger

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Solution:

- multimessenger & multiwavelength
- switch off astrophysics

Conclusions

DM not seen yet (Damn!...)

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