*November, 7* *Dark Days*

# Gamma rays from Dark Matter in light of CMB constraints

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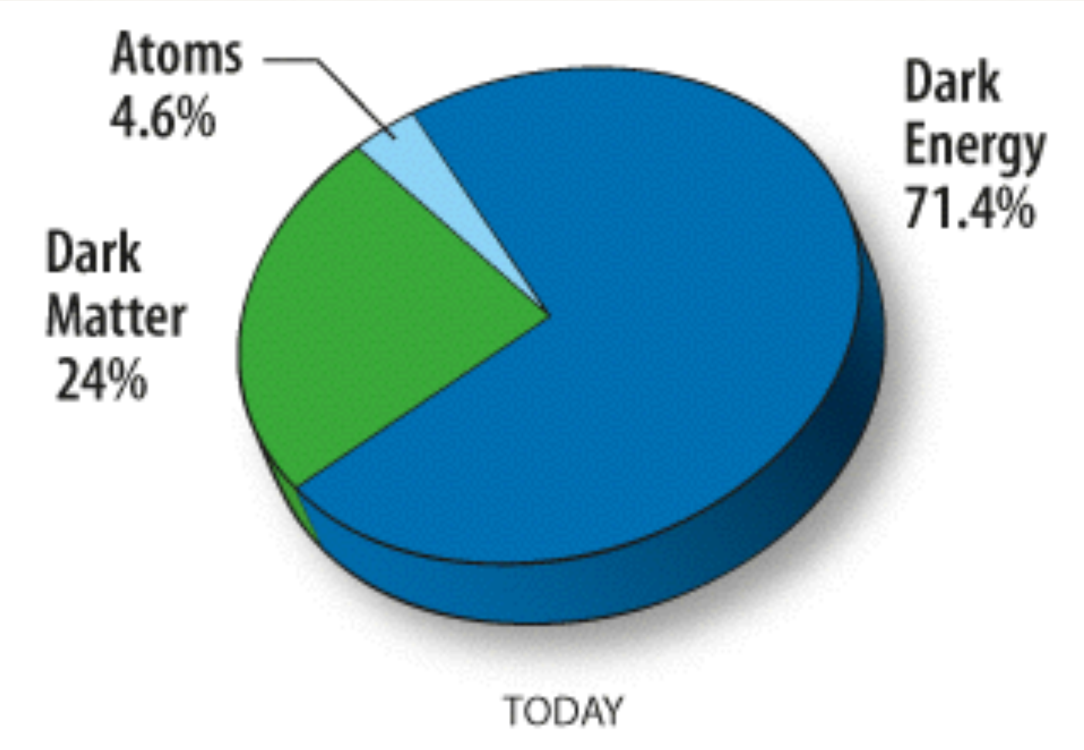
based on arxiv:1705.00777v2
Phys. Rev. D **96**, 063520

# Introduction

# Introduction

- Dark matter is key in the $\Lambda$CDM model, consistent with most cosmological observations

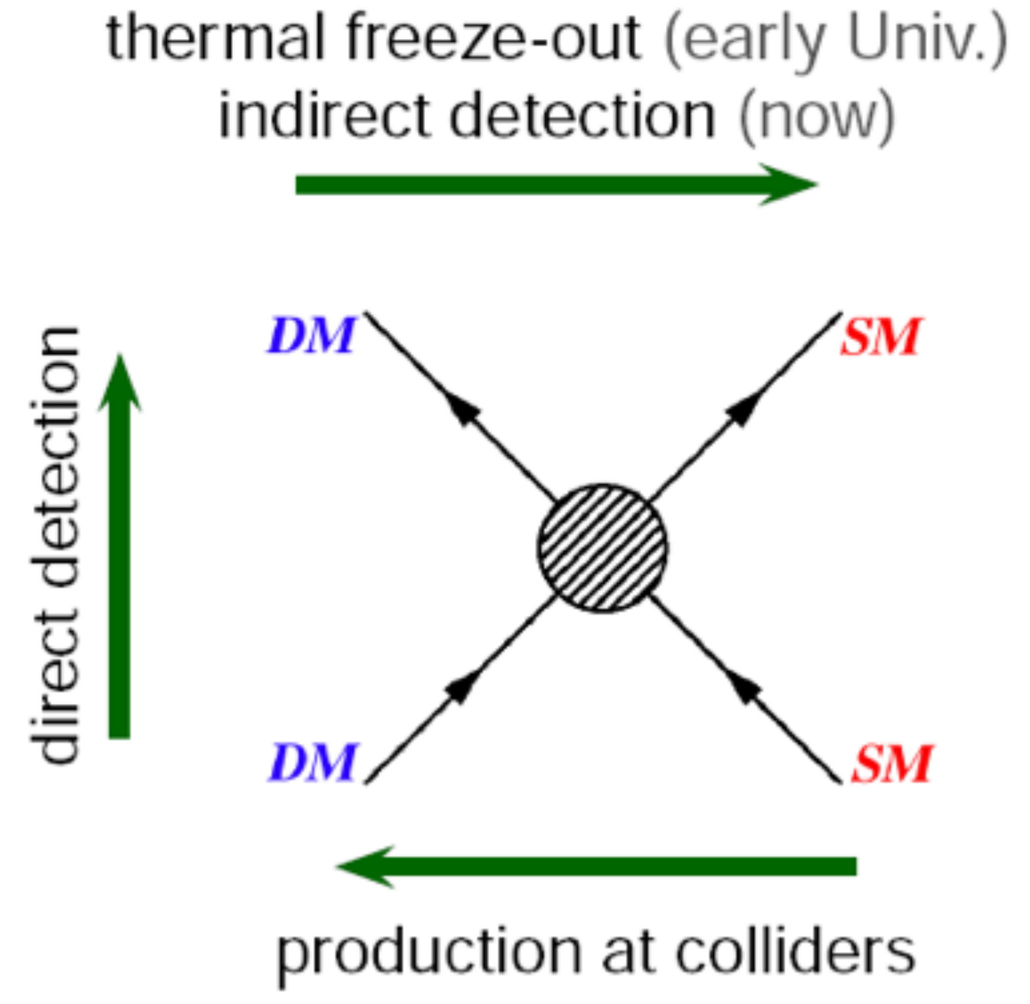


https://map.gsfc.nasa.gov/universe/uni_matter.html

# Introduction

- So far we have no non-gravitational detection…
- We hope for direct or indirect signals…

we focus on indirect detection !



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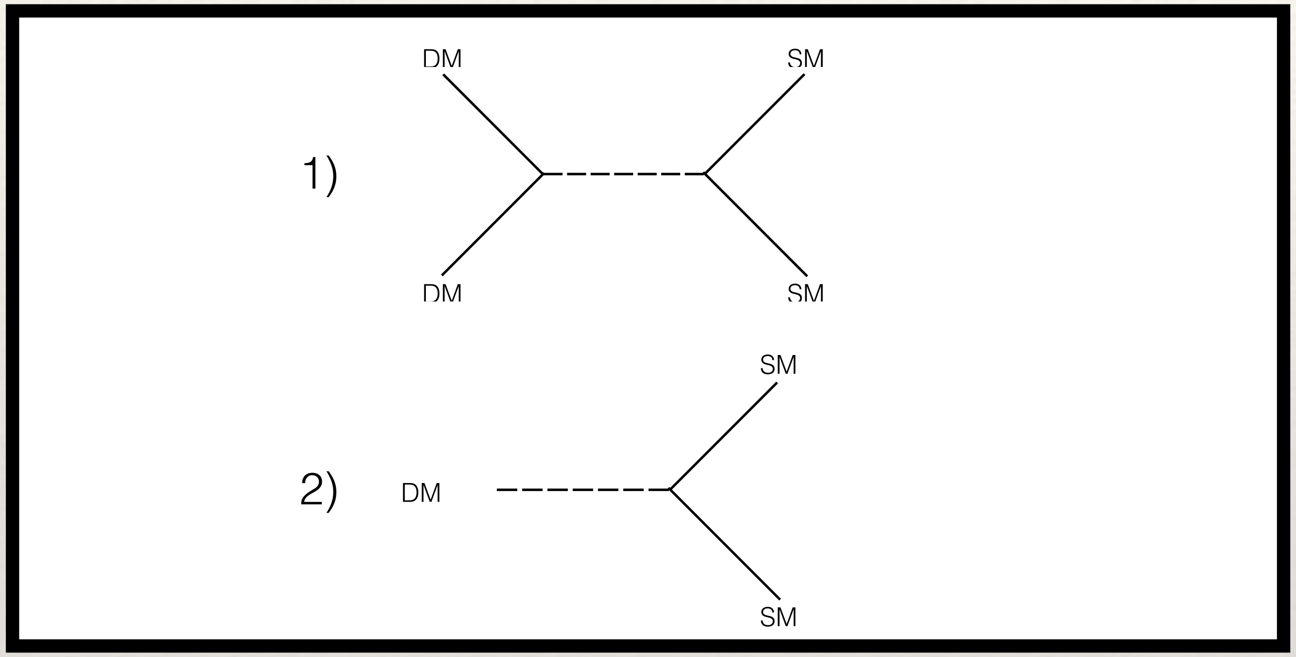


we focus on annihilation!

# Introduction

- Searches for gamma rays as DM probe have been extensively pursued (Fermi-LAT)

$$5\text{GeV} \sim 300\text{GeV}$$

- New generation of gamma ray detectors have been proposed to explore the low MeV and overlap some of the Fermi energy regime such as the e-ASTROGAM, GRIPS, PANGU, ACT, and others

A. A. Abdo et al. 2010

A. A. Abdo et al. 2010

M. Ackermann et al. 2012

V. Tatischeff et al. 2016

J. Greiner, K., et al. 2011

X. Wu, et al. 2014

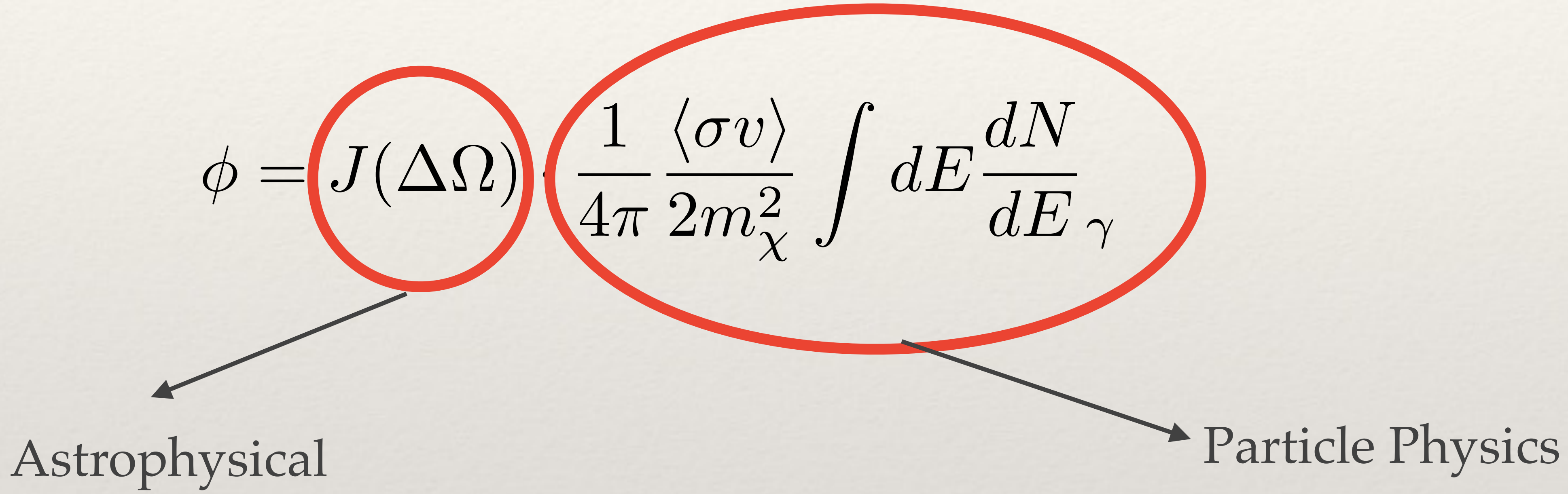
S. E. Boggs et al. 2006

e-ATROGAM

$$0.2 \sim 100\text{MeV}$$

# Introduction

Indirect detection → particle physics and astrophysical contribution



$$\phi = J(\Delta\Omega) \cdot \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_\chi^2}\int dE\frac{dN}{dE}_\gamma$$

Astrophysical

Particle Physics

$$J(\Delta\Omega) = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega \int_0^{l(\hat{\theta}_{\mathrm{max}})} \rho^2(r(l))dl(\theta)$$

# Introduction

$J(\Delta\Omega) \longrightarrow$ depends on the target !

**Galactic Center** $\xrightarrow{J(\Delta\Omega)}$ Simulations

**Dwarf spheroidal Draco** $\xrightarrow{J(\Delta\Omega)}$ Jeans analysis

We explored values that are already in the literature !

# Introduction

- In this work we focus on the possibility of having a $5\sigma$ detection in the $\langle \sigma v \rangle \; m_\chi$ plane, considering the current constraints from the CMB (Cosmic Microwave Background) for future experiment (e-ASTROGAM)

Targets → Galactic center

Targets → Dwarf Galaxy Draco

The CMB constraints come from altering the thermal history of the Universe by injecting energy (DM annihilation.)

# Gamma-rays from DM

# Gamma-rays from DM

$$m_{\pi^0} \lesssim m_\chi \lesssim 1\ \mathrm{GeV}$$

- 6 annihilation channels:

$$\chi\chi \rightarrow \gamma\gamma$$
$$\chi\chi \rightarrow \gamma\pi^0$$
$$\chi\chi \rightarrow \pi^0\pi^0$$
$$\chi\chi \rightarrow \bar{l}l \quad (l = e, \mu)$$
$$\chi\chi \rightarrow \pi^+\pi^-$$

- With energy spectra:

$$\frac{dN}{dE}_{\gamma\gamma} = 2\delta(E - m_\chi)$$

$$\frac{dN}{dE}_{\gamma\pi^0} = \delta\left(E - \left(m_\chi - \frac{m_{\pi^0}^2}{4m_\chi}\right)\right) + \frac{2}{m_\chi - \frac{m_{\pi^0}^2}{4m_\chi}}$$

$$\frac{dN}{dE}_{\pi^0\pi^0} = \frac{4}{\sqrt{\frac{s}{4} - m_{\pi^0}^2}}$$

$$\frac{dN}{dE}_{\bar{l}l} = \frac{\alpha}{\pi}\left(\frac{1-(1-y)^2}{y}\right)\left(\ln\frac{s(1-y)}{m_l^2}\right)$$

The spectra for charged pions was provided by [8] !

[8] D.-F. M. L. Coogan, A and S. Profumo 2017

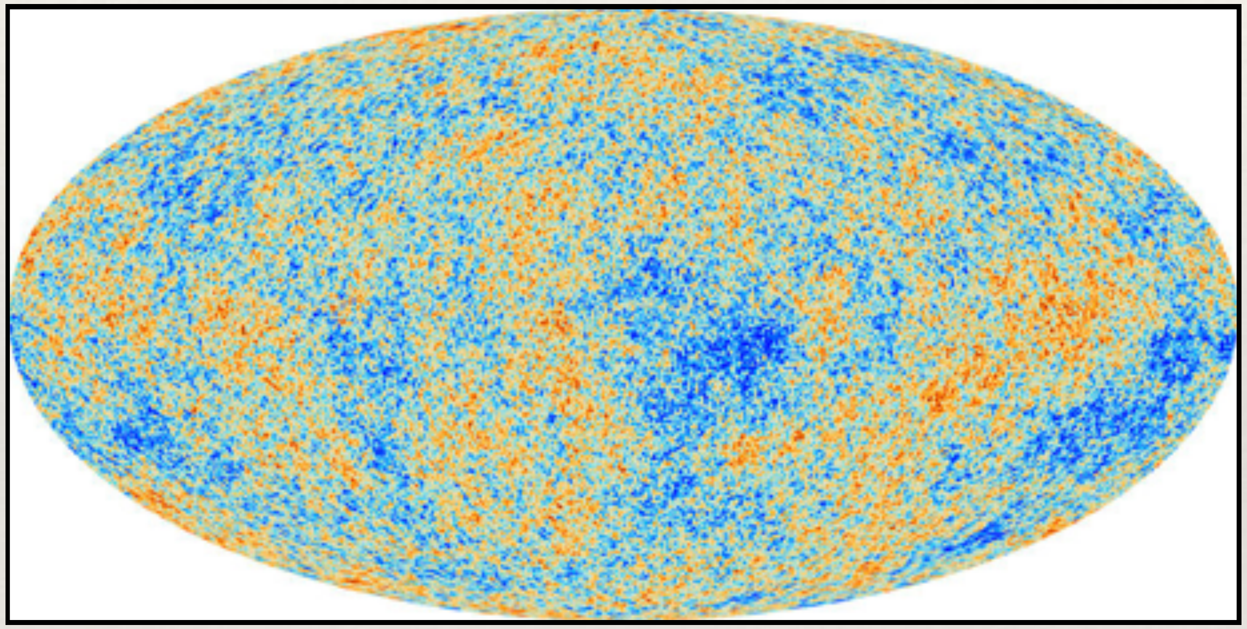
# Thermal history and CMB constraints

# Thermal history

$e^- + p^+ \leftrightarrow H + \gamma$ $\xrightarrow[\text{Universe's expansion}]{}$ falls out of equilibrium

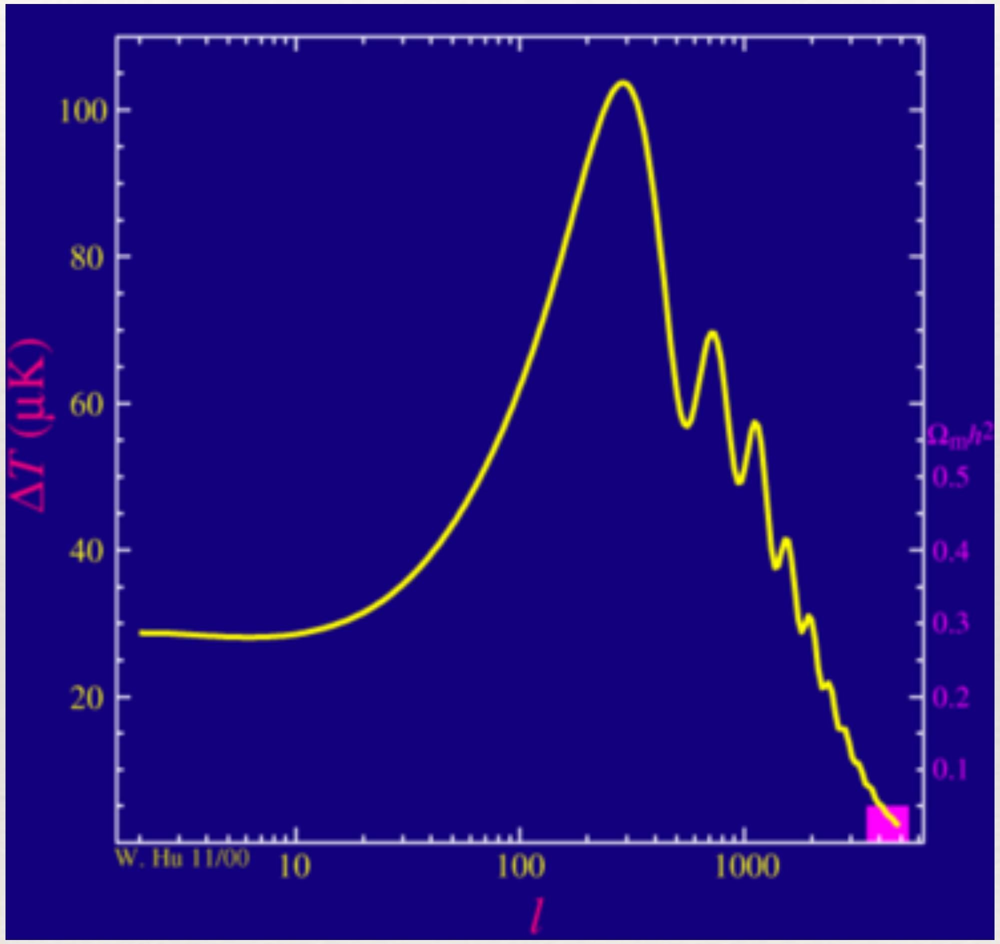
we are left with

$e^-$ $\gamma$ HI



$$\frac{\delta T}{T} \sim 10^{-5}$$

http://www.esa.int/spaceinimages/Images/2013/03/



Wayne Hu, http://background.uchicago.edu/~whu/

# Thermal history

- what happens if we inject extra energy in the medium?

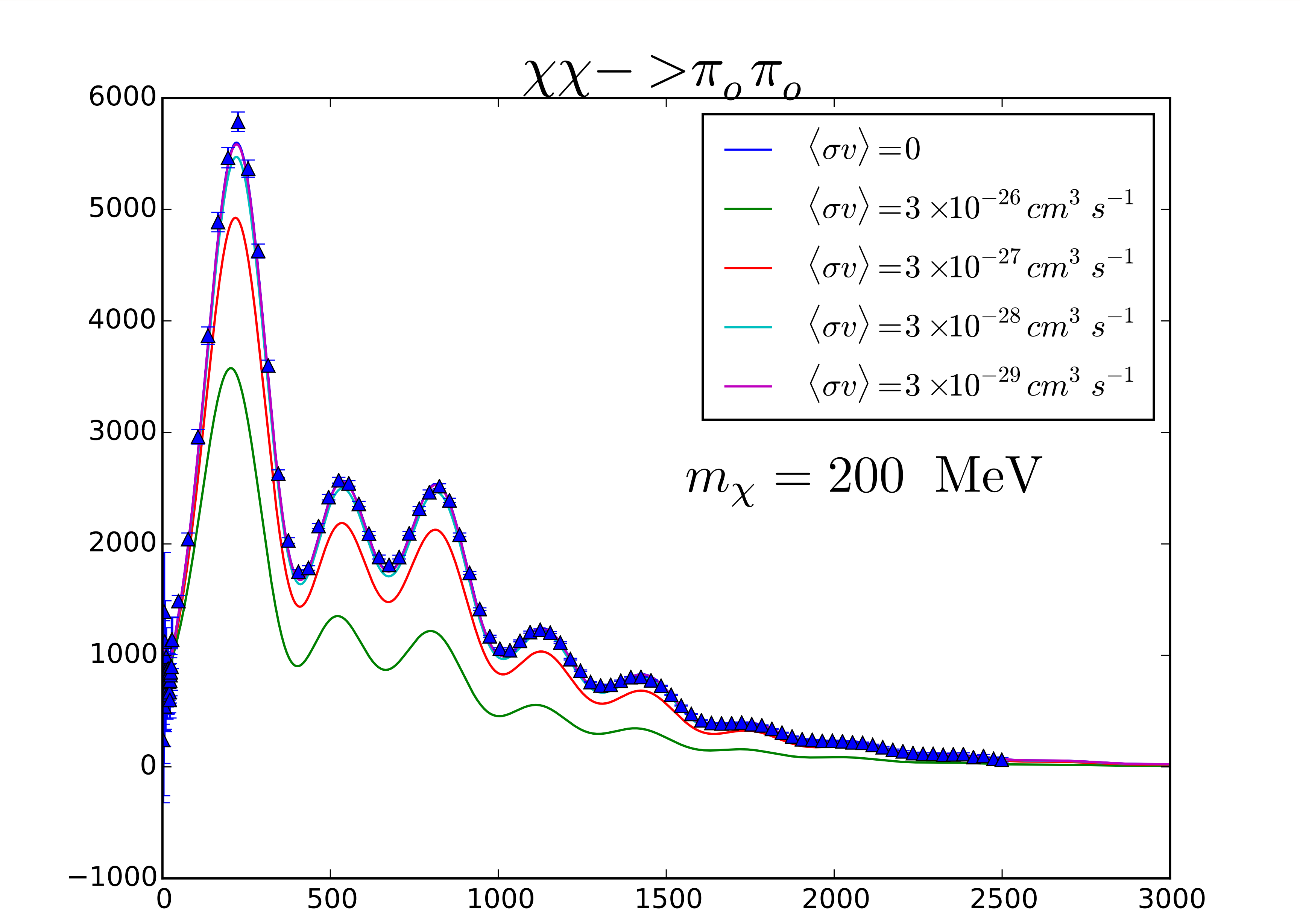
extra energy ionizes neutral hydrogen → the fraction of free-electrons increases

free electrons interact with CMB photons

↓

**change in the power spectrum !**

# Thermal History



# Thermal History

- DM particle annihilation can inject energy in the IGM

Energy injected !

$$\frac{dE}{dtdV} = \rho_c^2 c^2 \Omega_\chi^2 (1+z)^6 \frac{\langle \sigma v \rangle}{m_\chi}$$

Change in the thermal history of the Universe due to DM !

- Account for the absorbed energy

$$\frac{dE}{dtdV}_{\mathrm{absorbed}} = f(z) \frac{dE}{dtdV}_{\mathrm{injected}}$$

# Thermal History

$$f(z) \rightarrow f_{\text{eff}}$$

$$\boxed{P_{\text{ann}} \equiv f_{\text{eff}} \frac{\langle \sigma v \rangle}{m_\chi}}$$

$$f_{\text{eff}} = \frac{1}{2m_\chi} = \int_0^{m_\chi} dE\ E \left( f_{\text{eff}}^{\gamma}(E) \frac{dN}{dE}_{\gamma}(E) + 2 f_{\text{eff}}^{e^{-(+)}}(E) \frac{dN}{dE}_{e^{-(+)}} \right)$$

Effective efficiency function

**Mathematica: http://nebel.rc.fas.harvard.edu/epsilon**

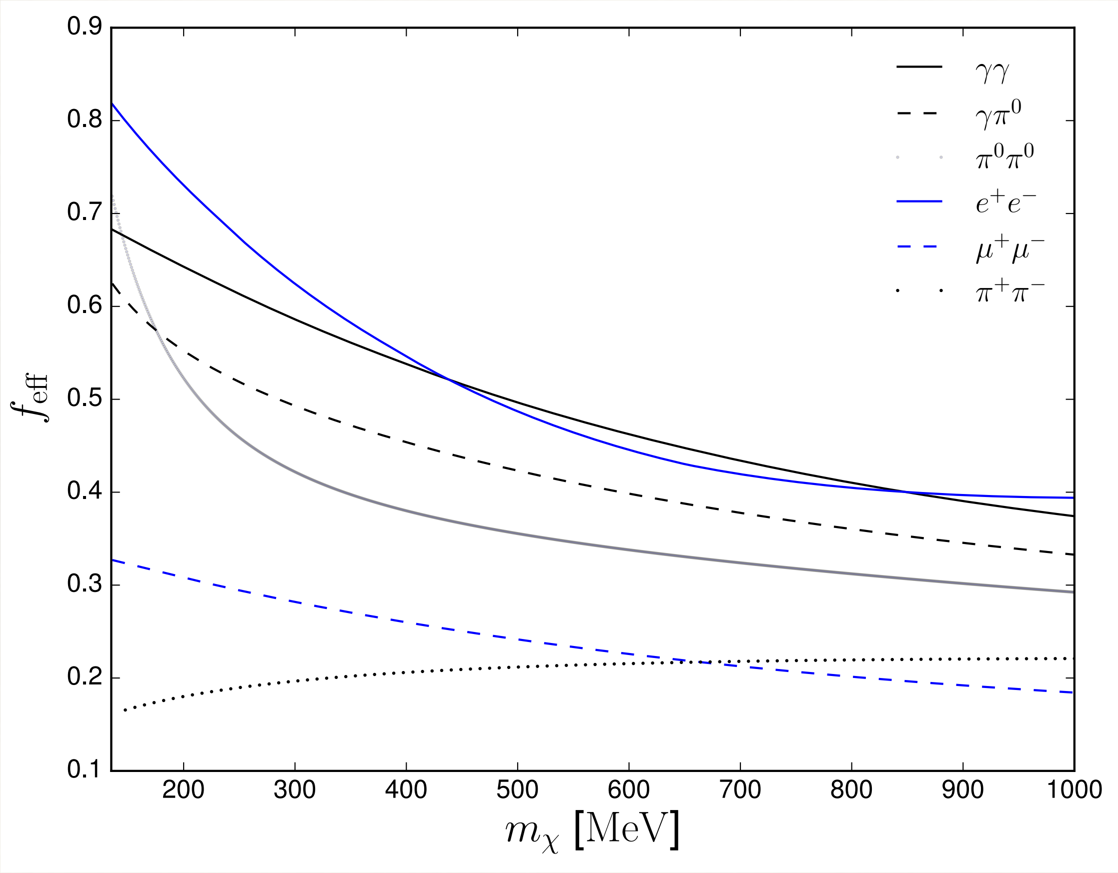
**Python: https://github.com/JavierReynoso/feff.git**

- T. R. Slatyer, Phys. Rev. D93, 023527 (2016), 1506.03811.

# Thermal history

DM annihilation channels $\longrightarrow$ $$\frac{dN^{e^-(e^+)}}{dE} \quad \frac{dN^{(\gamma)}}{dE} \quad \longrightarrow \quad f_{\text{eff}}$$

Input in the code



$$P_{\text{ann}} < 4.1 \times 10^{-28} \text{cm}^3\text{s}^{-1}\text{GeV}^{-1}$$

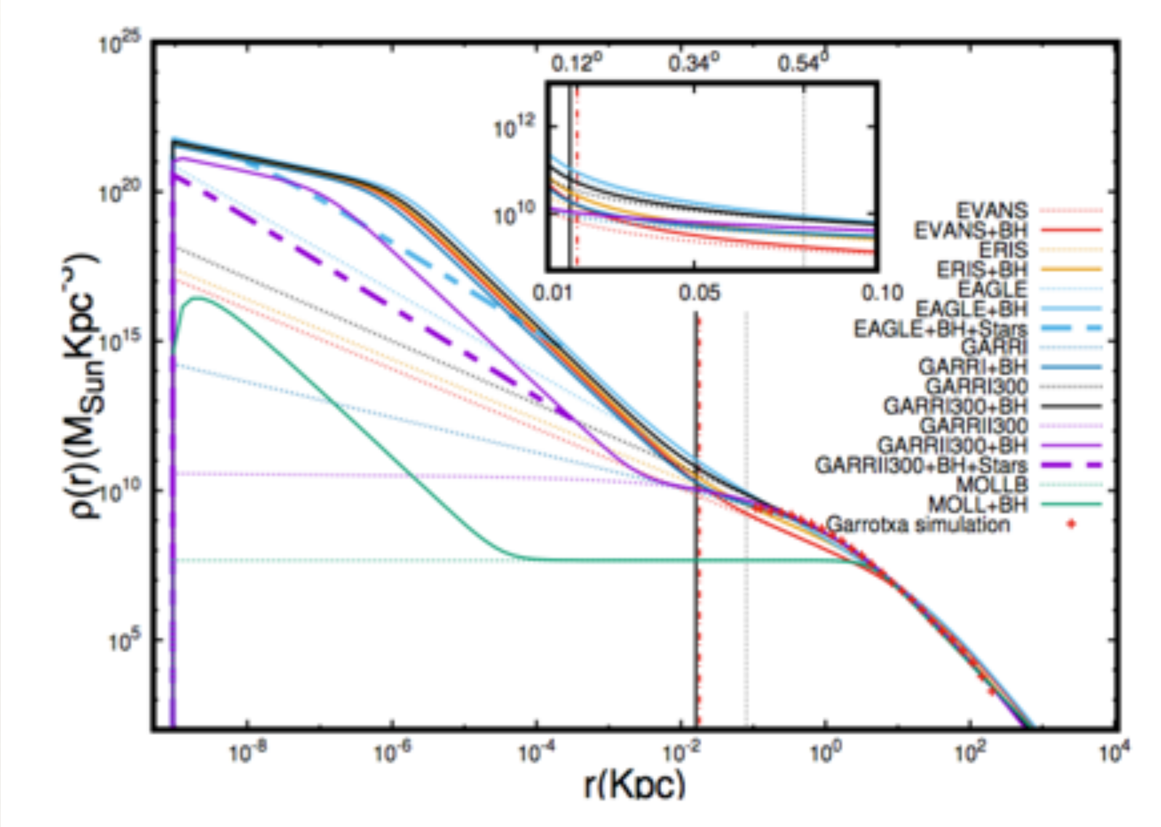
$$\boxed{\langle \sigma v \rangle < \frac{m_\chi}{f_{\text{eff}}} P_{\text{ann}}}$$

P. A. R. Ade et al. 2016

# Gamma-ray detection

# Gamma-ray detection

- Photon flux from DM annihilation



$$\phi = J(\Delta\Omega) \cdot \frac{1}{4\pi} \frac{\langle\sigma v\rangle}{2m_\chi^2} \int dE \frac{dN}{dE}_\gamma$$

$$\log_{10}(J_{\rm Draco}/{\rm GeV}^2{\rm cm}^{-5}) = 19.05^{+0.22}_{-0.21}[10]$$

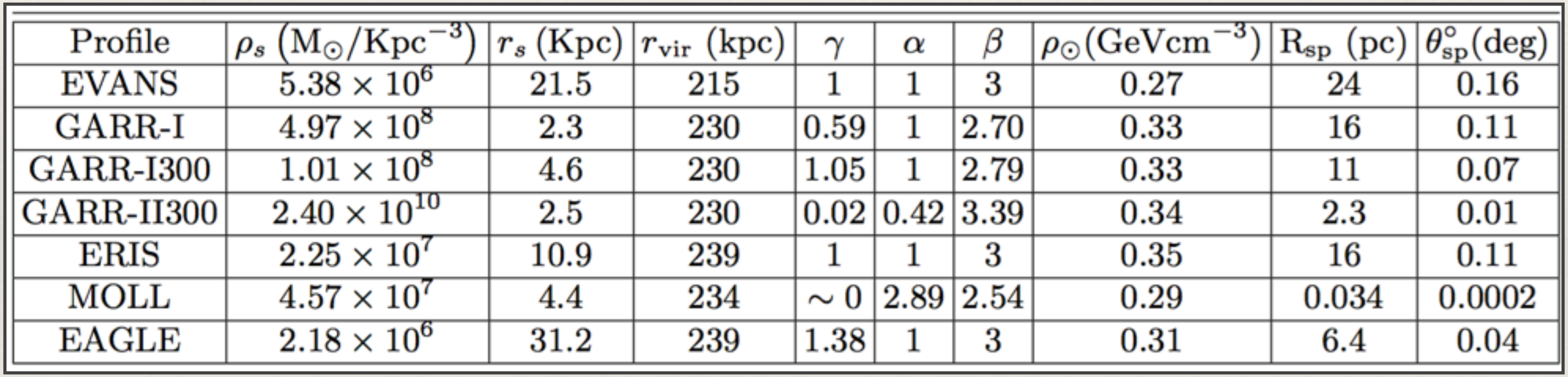
$$\log_{10}(J_{\rm GC}/{\rm GeV}^2{\rm cm}^{-5}) \sim 19 - -23[9]$$

[9] V. Gammaldi, V. Avila-Reese, O. Valenzuela, and A. X. Gonzales-Morales, Phys. Rev. D94, 121301 (2016), 1607.02012.

[10] K. K. Boddy, K. R. Dienes, D. Kim, J. Kumar, J.-C. Park, and B. Thomas, Phys. Rev. D94, 095027 (2016), 1606.07440.

# Gamma-ray detection

$$\rho_h(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^{\gamma}\left(1+\frac{r}{r_s}^{\alpha}\right)^{\frac{\beta-\gamma}{\alpha}}}$$



| Profile | $\rho_s$ $(M_\odot/\mathrm{Kpc}^{-3})$ | $r_s$ (Kpc) | $r_{\mathrm{vir}}$ (kpc) | $\gamma$ | $\alpha$ | $\beta$ | $\rho_\odot(\mathrm{GeVcm}^{-3})$ | $\mathrm{R_{sp}}$ (pc) | $\theta^\circ_{\mathrm{sp}}$(deg) |
|---|---|---|---|---|---|---|---|---|---|
| EVANS | $5.38 \times 10^6$ | 21.5 | 215 | 1 | 1 | 3 | 0.27 | 24 | 0.16 |
| GARR-I | $4.97 \times 10^8$ | 2.3 | 230 | 0.59 | 1 | 2.70 | 0.33 | 16 | 0.11 |
| GARR-I300 | $1.01 \times 10^8$ | 4.6 | 230 | 1.05 | 1 | 2.79 | 0.33 | 11 | 0.07 |
| GARR-II300 | $2.40 \times 10^{10}$ | 2.5 | 230 | 0.02 | 0.42 | 3.39 | 0.34 | 2.3 | 0.01 |
| ERIS | $2.25 \times 10^7$ | 10.9 | 239 | 1 | 1 | 3 | 0.35 | 16 | 0.11 |
| MOLL | $4.57 \times 10^7$ | 4.4 | 234 | $\sim 0$ | 2.89 | 2.54 | 0.29 | 0.034 | 0.0002 |
| EAGLE | $2.18 \times 10^6$ | 31.2 | 239 | 1.38 | 1 | 3 | 0.31 | 6.4 | 0.04 |

[9] V. Gammaldi, V. Avila-Reese, O. Valenzuela, and A. X. Gonzales-Morales, Phys. Rev. D94, 121301 (2016), 1607.02012.

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# Gamma-ray detection

$$N_s \sim N_\sigma \sqrt{N_b}$$

$$N_\sigma = 5$$

we built an hypothetical detector
~ eASTROGAM

$$N_s = \phi \cdot T_{\rm obs} \cdot A_{\rm eff}$$

$$N_b \propto \int dE \frac{d\phi_b}{dE}$$

$$\boxed{\langle \sigma v \rangle > 10\sqrt{N_b}\frac{1}{\int_{E^-}^{E^+} dE \frac{dN}{dE}} \frac{4\pi}{A_{\rm eff} T_{\rm obs} J} m_\chi^2}$$

- To have a 5 sigma detection !

# Gamma-ray detection

$$\frac{d\phi}{d\Omega dE} = (2.74) \times 10^{-3} \left(\frac{\mathrm{MeV}}{E}\right)^{-2.0} \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{MeV}^{-1}$$

Draco [10]

$$E^2 \frac{d\phi}{dE} \sim 1.1 \times 10^{-2} E^{0.23} \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{MeV}$$

GC [11]

Analysis → Optimize energy range of observation

[10] K. K. Boddy, K. R. Dienes, D. Kim, J. Kumar, J.-C. Park, and B. Thomas, Phys. Rev. D94, 095027 (2016), 1606.07440.

[11] A. W. Strong, I. V. Moskalenko, and O. Reimer, Astro- phys. J. 613, 962 (2004), astro-ph/0406254

# Gamma-ray detection

$$\int_{\Delta E - m_\chi}^{m_\chi} dE \frac{dN}{dE} \quad \longrightarrow \quad \Delta E$$ maximizes the detection

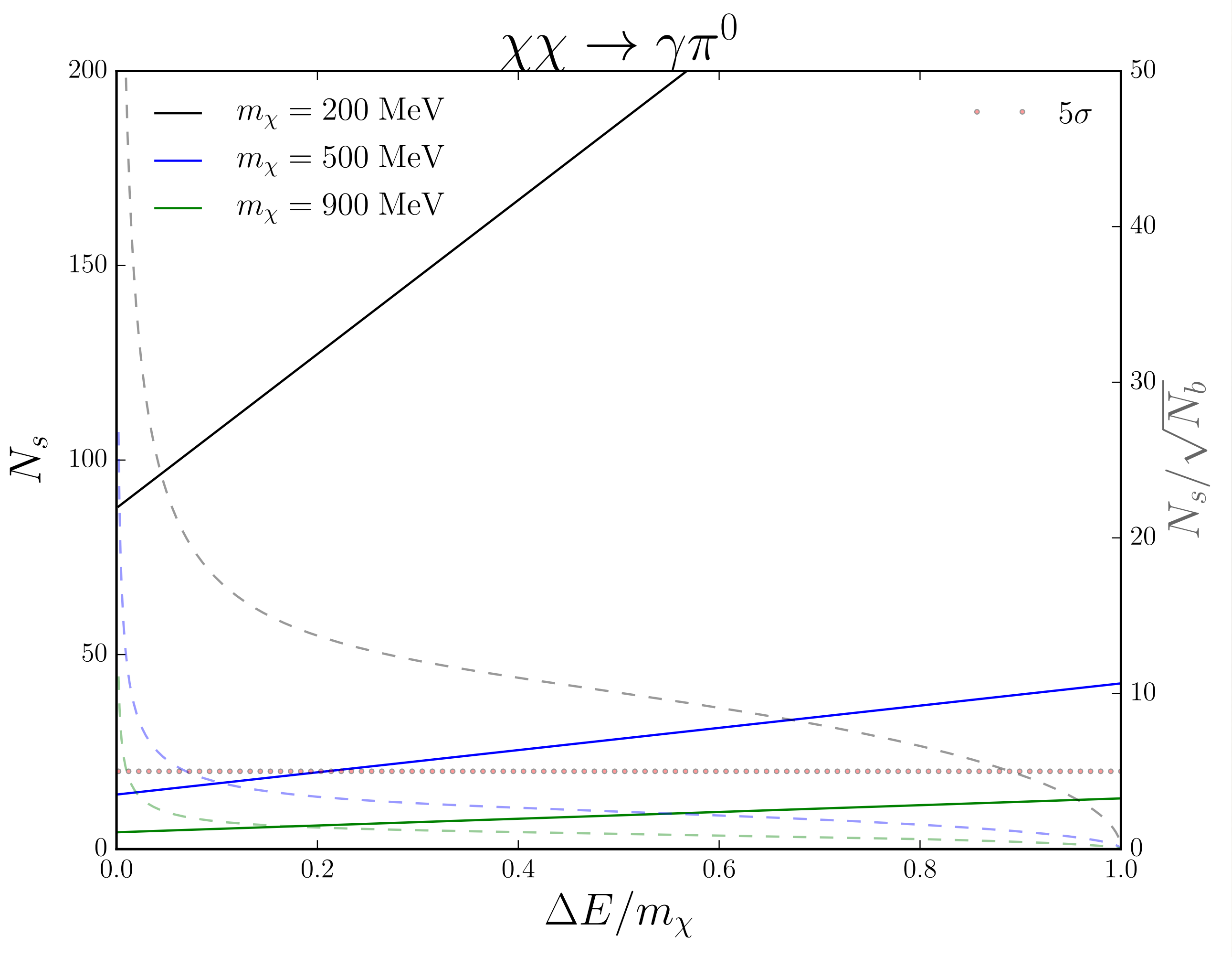
$$\frac{N_s}{\sqrt{N_b}} \propto f(\langle \sigma v \rangle_o, m_{\chi_o}, \Delta E) > 5$$

$$\gamma\pi^0 \to \Delta E/m_\chi \sim 0.01$$

$$\gamma\gamma \to \Delta E/m_\chi \sim 0.01$$

$$\pi^0\pi^0 \to \Delta E/m_\chi = \sqrt{\frac{s}{4} - m_{\pi^0}^2}$$

$$l\bar{l}, \pi^+\pi^- \to \Delta E/m_\chi \sim 0.95$$



# Results

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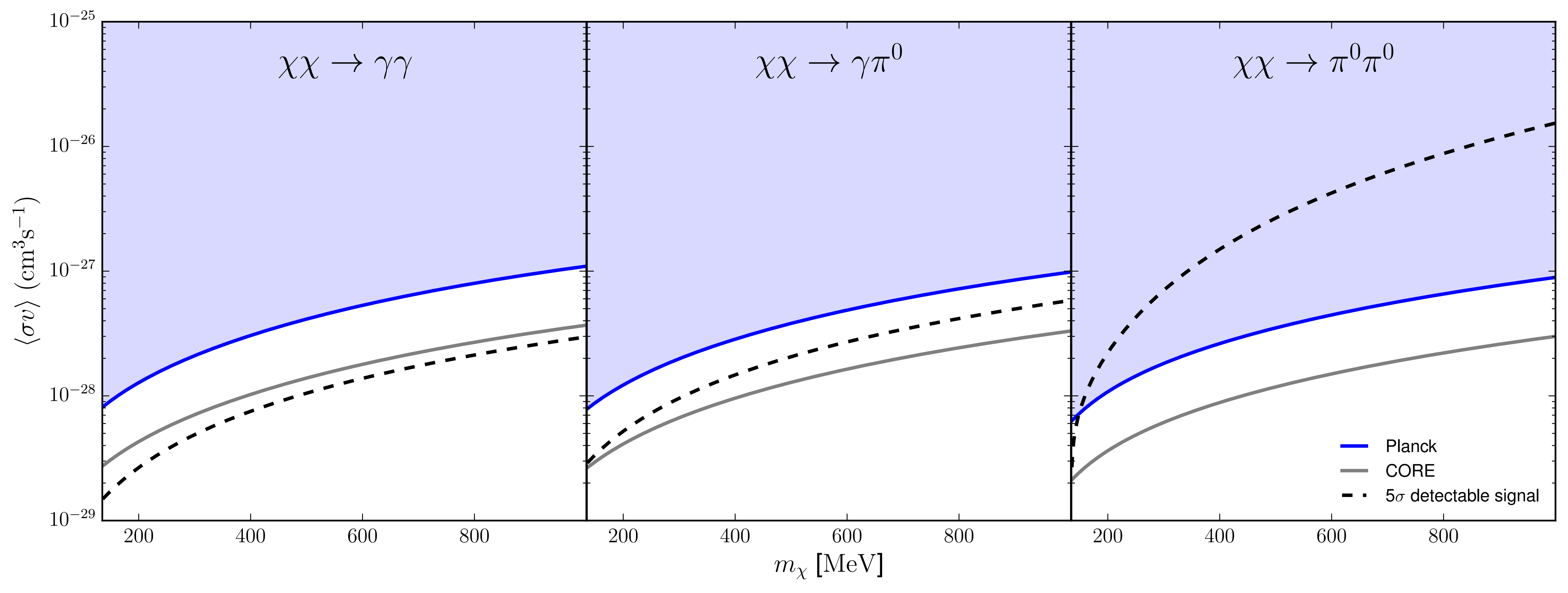
Projected constraint from CORE+ [12] $P_{\rm ann} < 1.38 \times 10^{-28} {\rm cm}^3 {\rm s}^{-1} {\rm GeV}^{-1}$

Planck [13] $P_{\rm ann} < 4.1 \times 10^{-28} {\rm cm}^3 {\rm s}^{-1} {\rm GeV}^{-1}$



[12] E. Di Valentino et al. (CORE) (2016), 1612.00021.

[13] P. A. R. Ade et al. (Planck), Astron. Astrophys. 594, A13 (2016), 1502.01589.

Draco

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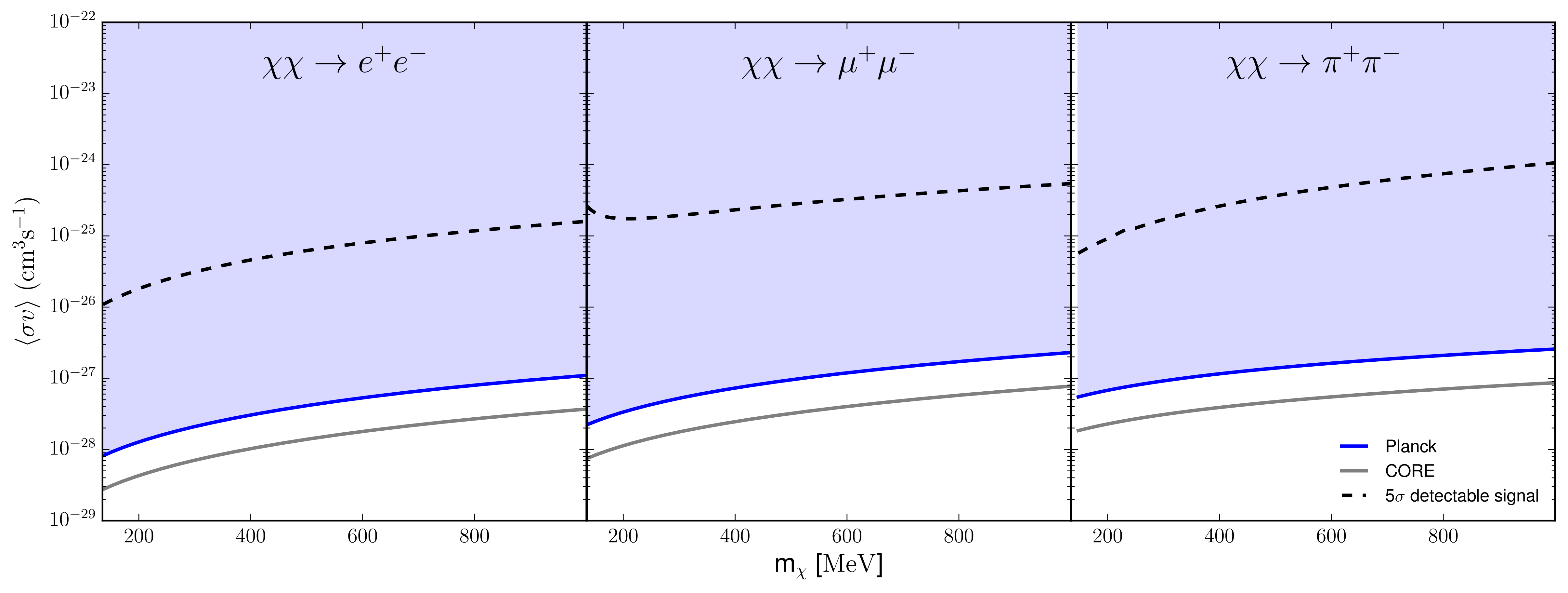

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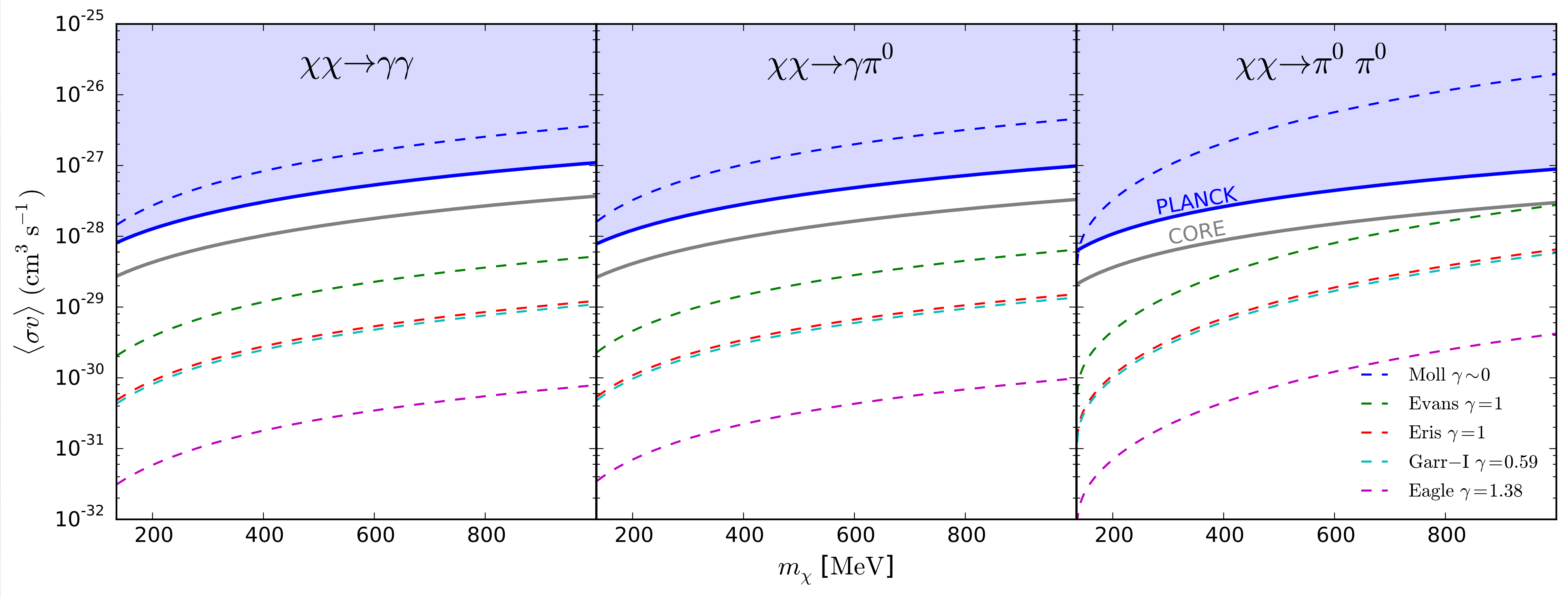

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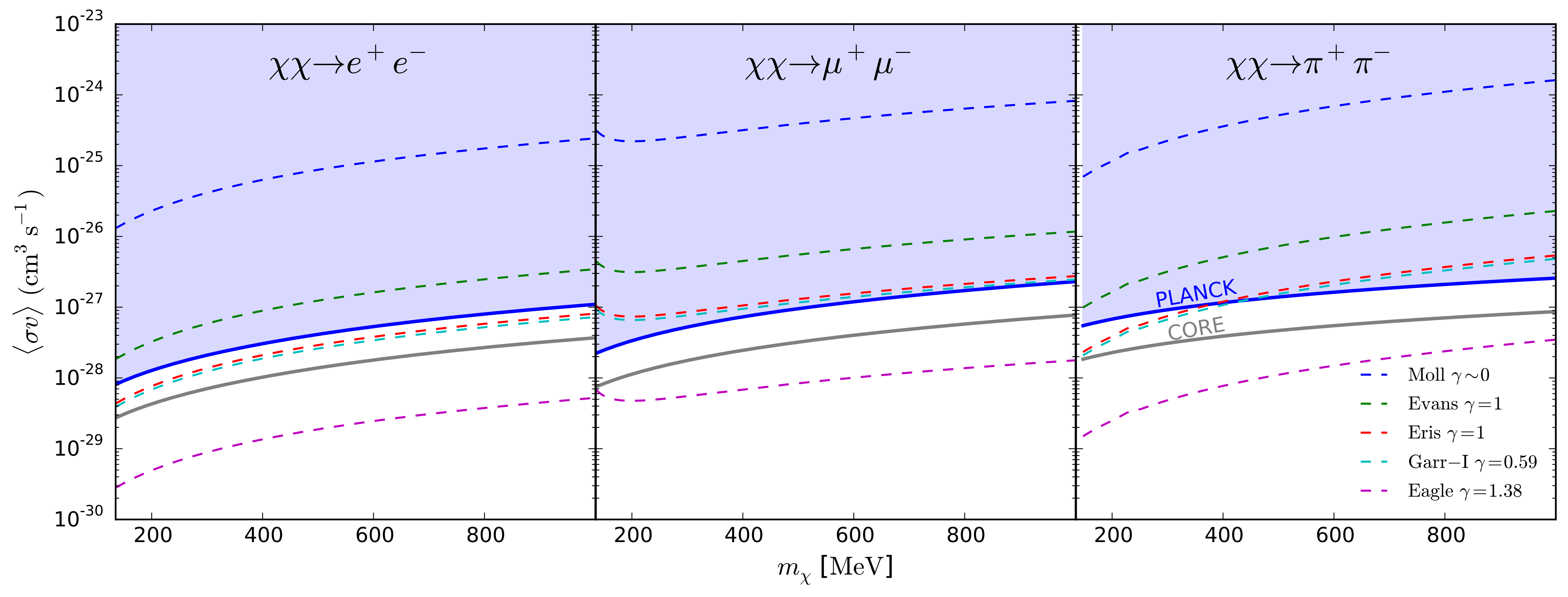

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GC

# Discussion

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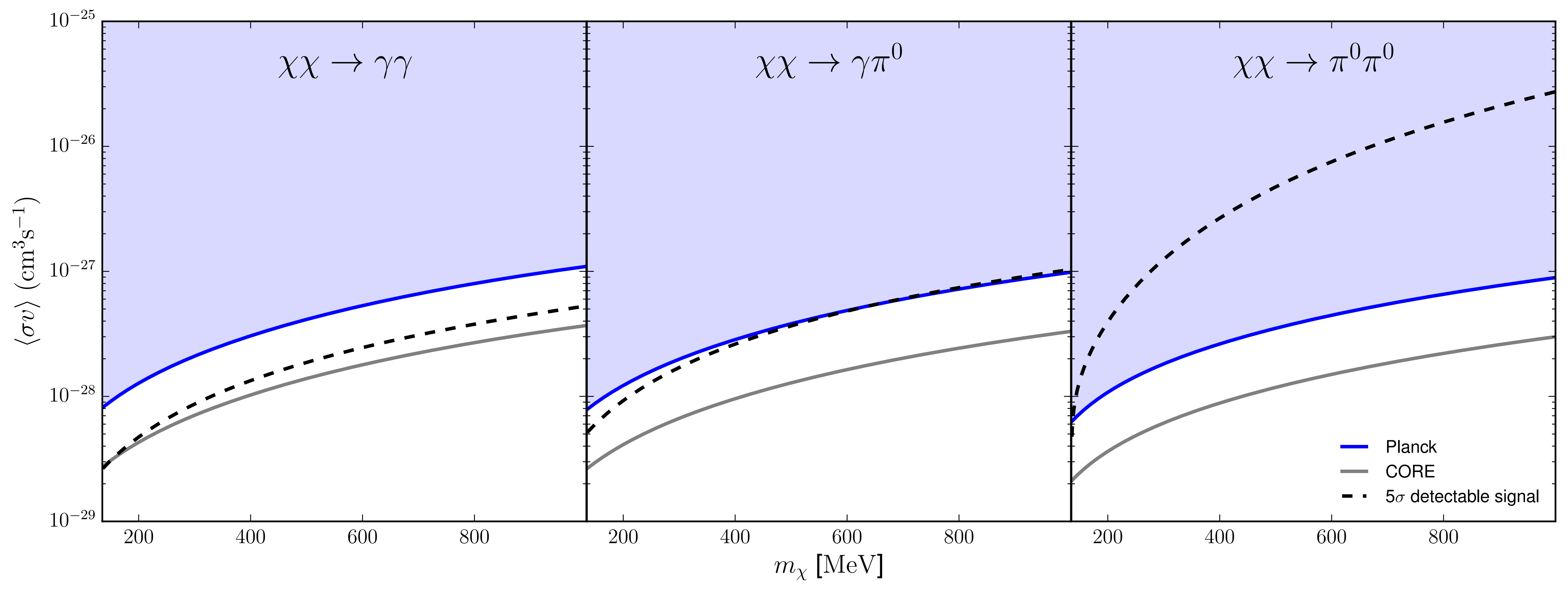
- We investigated the possible detection of DM annihilation in the MeV regime
- 6 annihilation channels
- Compared constraints and detection limits
- For Draco 3 channels are totally excluded and the neutral pions channel have a small window of possible detection
- The GC detection depends strongly on the DM density profile used to compute the astrophysical factor "J", yet it is more optimistic

# Thanks!

# Support material

$$\log_{10}(J_{\mathrm{Draco}}/\mathrm{GeV}^2\mathrm{cm}^{-5}) \sim 18.8[13]$$



[13] A. Geringer-Sameth, S. M. Koushiappas, and M. Walker, Astrophys. J. 801, 74 (2015) [arXiv:1408.0002 [astro- ph.CO]].

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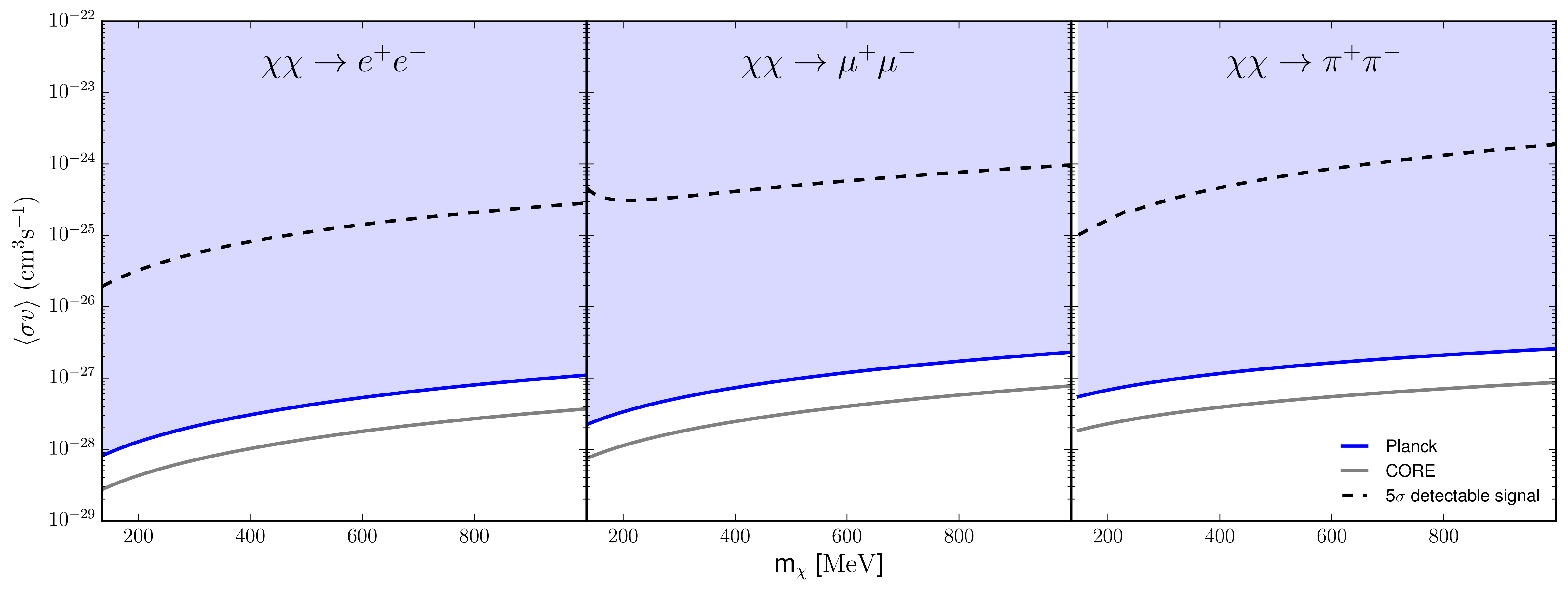

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**http://nebel.rc.fas.harvard.edu/epsilon**

$$f(z) \to f_{\rm eff}$$

$$E^{-} = \frac{m_{\pi^0}^2}{4m_\chi} \qquad E^{+} = \frac{m_\chi}{2}$$

$$\frac{dN}{dE} = \frac{4}{E^{+} - E^{-}} \theta(E_\gamma - E^{-}) \theta(E^{+} - E_\gamma)$$

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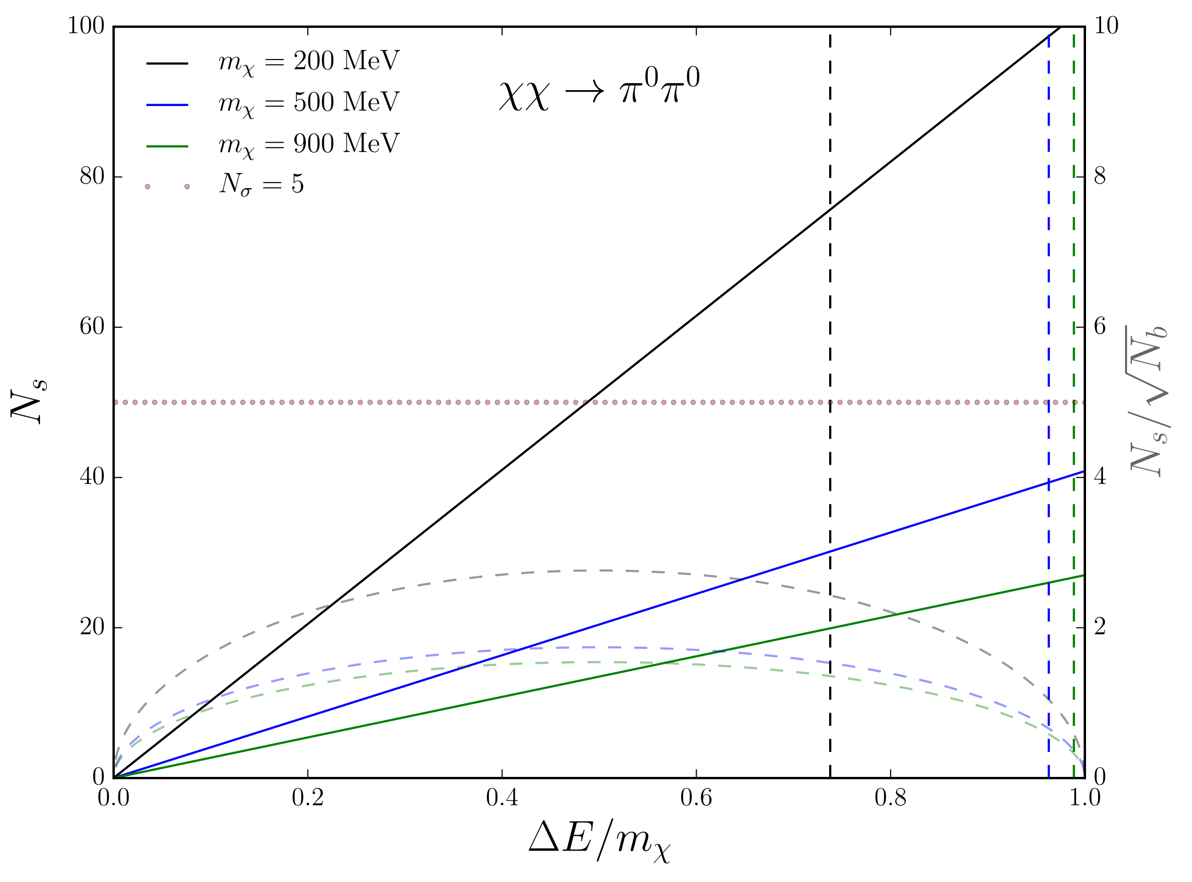

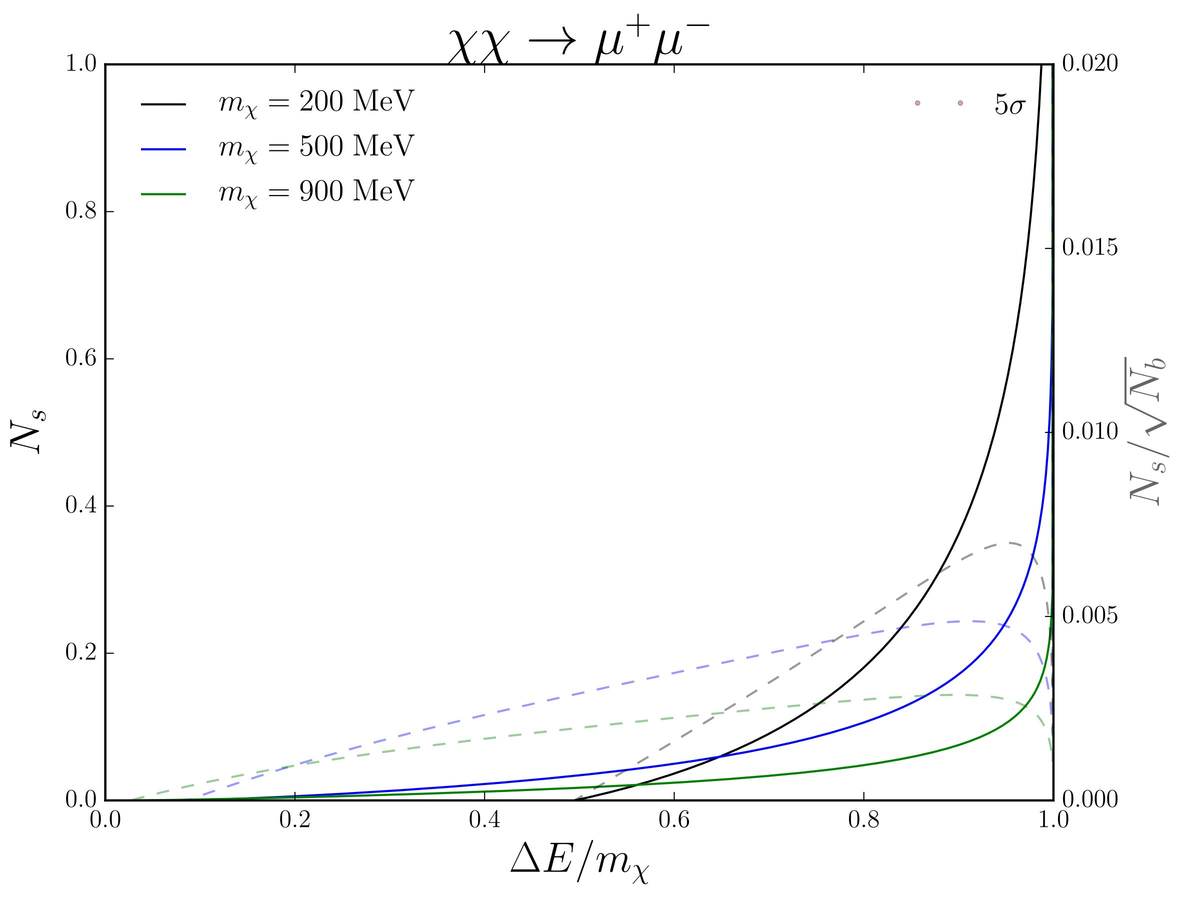

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