Indirect Detection of Neutrino Portal Dark Matter

Barmak Shams Es Haghi
U. Pittsburgh

with Brian Batell, Tao Han - arXiv:1704.08708

TeVPA
Aug 9, 2017

Non-gravitational Interaction of DM: Renormalizable Portals

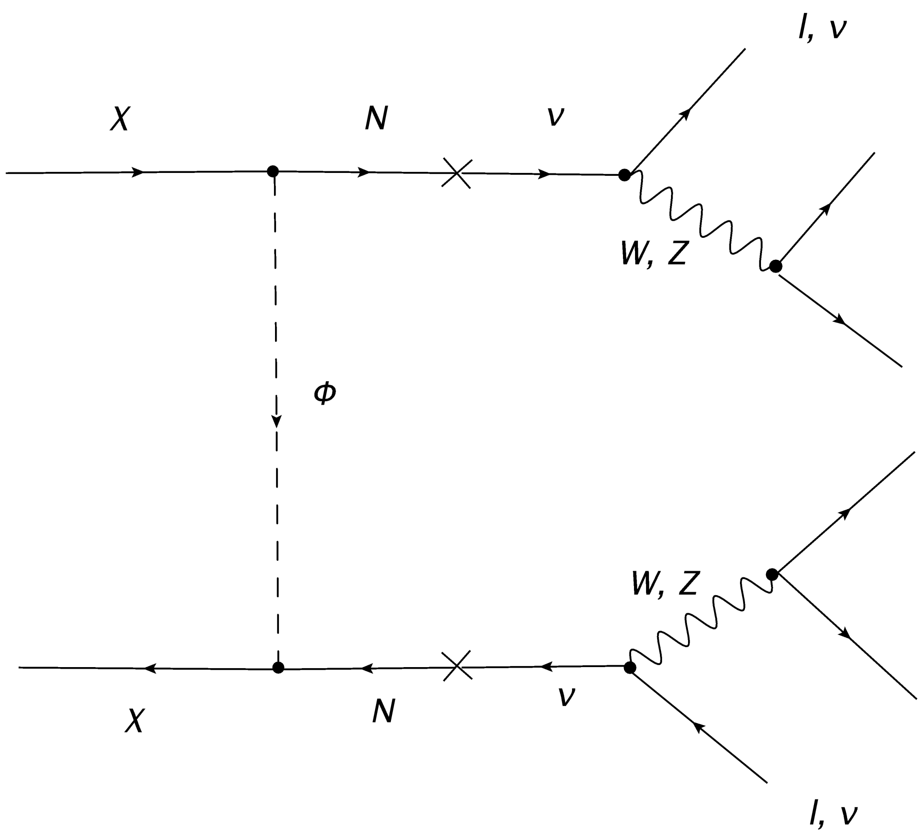
- Scalar portal $(\lambda_1 S + \lambda_2 S^2)|H|^2$
- Vector portal $B_{\mu\nu} V^{\mu\nu}$
- Neutrino portal LHN

Motivations For Neutrino Portal:

- Explains neutrino mass (via seesaw mechanism)
- Baryogengesis through leptogenesis
- Dark Matter

Model: $\mathcal{L} \supset -\frac{1}{2}m_\phi^2\phi^2 - \left[\frac{1}{2}m_N NN + \frac{1}{2}m_\chi\chi\chi + yLHN + \lambda N\phi\chi + \text{h.c.}\right]$

Z_2 symmetry $m_N < m_\chi < m_\phi$



Parameters: $\{\lambda, m_\phi, m_\chi, m_N\} \longrightarrow \{\langle\sigma v\rangle, m_\chi, m_N\}$

$$\langle\sigma v\rangle = \frac{\left[\text{Re}(\lambda)^2(m_\chi + m_N) + \text{Im}(\lambda)^2(m_\chi - m_N)\right]^2}{16\pi[m_\phi^2 + m_\chi^2 - m_N^2]^2}\left(1 - \frac{m_N^2}{m_\chi^2}\right)^{1/2}$$

Relic Abundance & Cosmology:

Thermal equilibrium: $\langle\sigma v\rangle \sim \langle\sigma v\rangle_{\text{thermal}}$

$$\langle\sigma v\rangle_{\text{thermal}} = 2.2 \times 10^{-26}\,\text{cm}^3\ \text{s}^{-1}$$

Mass range: Unitarity + Thermal WIMP + BBN

$$1\ \text{GeV} < m_N < m_\chi \lesssim 20\ \text{TeV}$$

Seesaw:

$$m_\nu \sim \sqrt{(\Delta m_\nu)^{\text{atm}}} \sim 0.05\,\text{eV} \rightarrow y \simeq 10^{-6}\left(\frac{m_N}{246\,\text{GeV}}\right)^{1/2}$$

Yukawa coupling is small, Direct Detection/Production at Collider are challenging.

Indirect Detection:

DM can have multiple annihilation channels

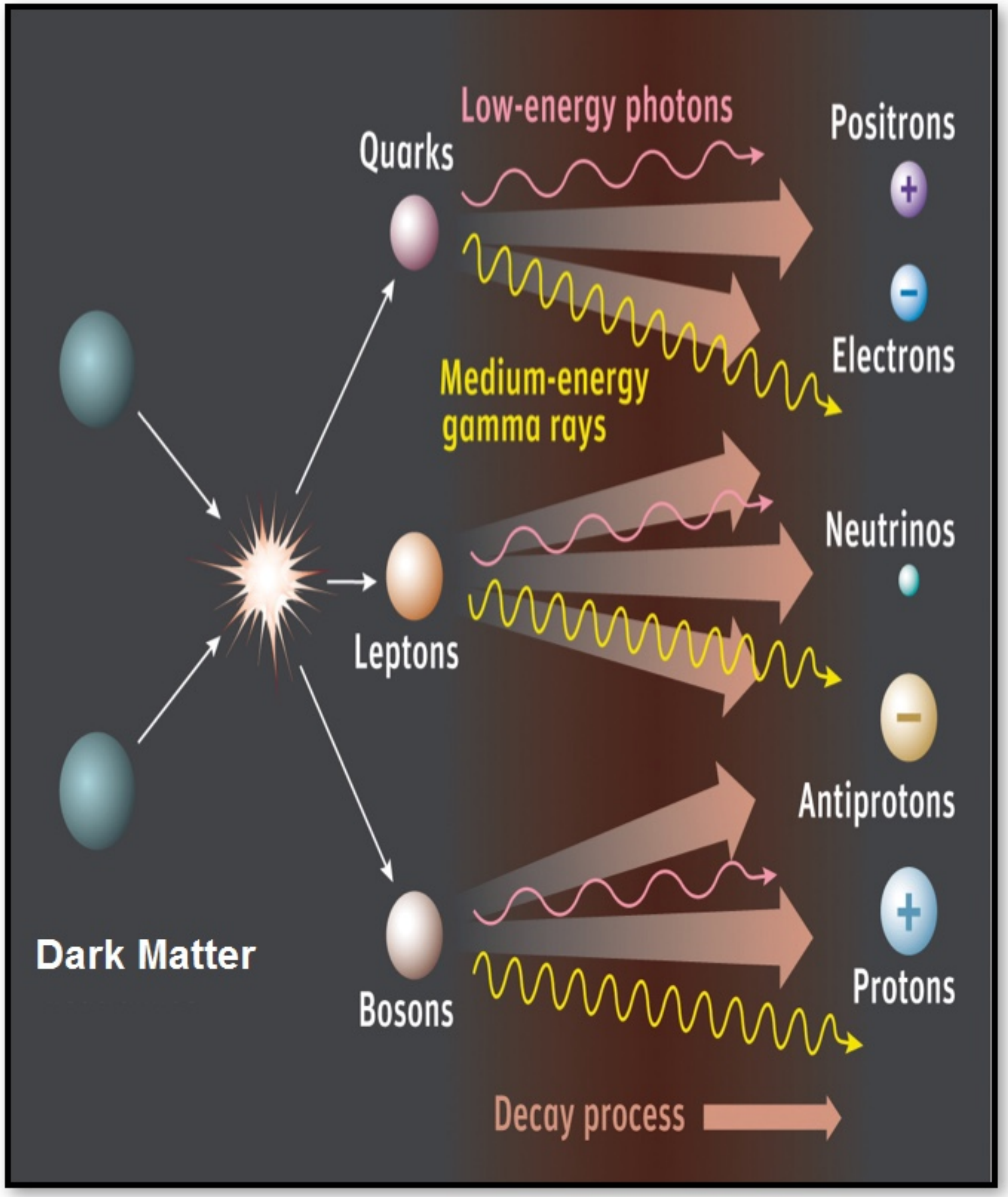


Image Credit:
Sky & Telescope /
Gregg Dinderman

Quantity of interest:

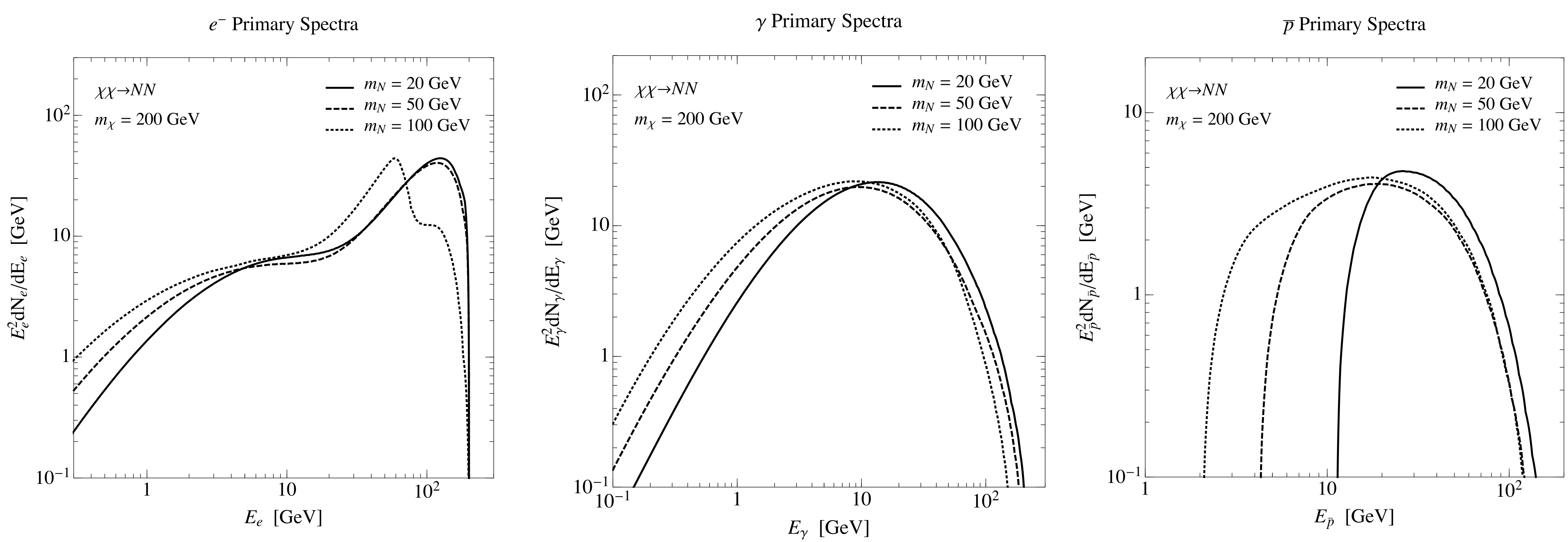
Energy spectrum per DM annihilation in the photon, electron,... channels

Simulation → **Spectrum**

Simulation Chain:

SM_HeavyN_NLO Model Files (SM+ 3 heavy neutrinos) → MadGraph5_aMC@NLO (Generating Events) → Pythia (Hadronize + Shower) → $\frac{dN_{a,f}}{dE_a}$ (Spectrum)

Alva, Han, Ruiz 2015
Degrande, Mattelaer, Ruiz , Turner 2016



CMB

z ~1100 $$e^- + p \rightleftharpoons H + \gamma$$ binding energy : 13.6 eV

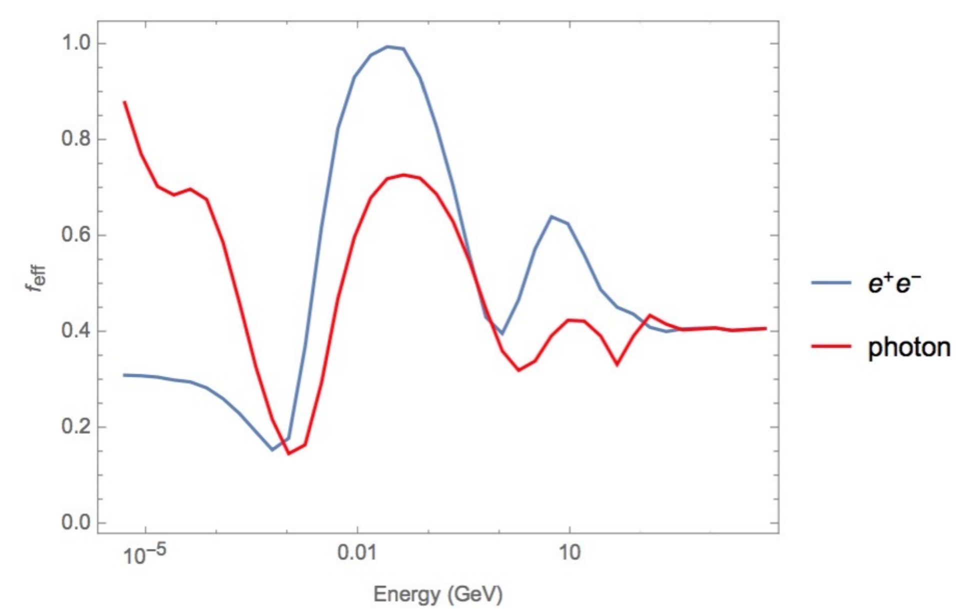
DM annihilation products:

- neutrino: weakly interacting, so they escape
- protons: highly penetrating and poor at transferring energy
- electron/positron & photon: heating and ionization occurs primarily through them

$$\left(\frac{dE}{dV\,dt}\right)_{\text{injected}} = \rho^2_{\text{DM}}(z)\frac{\langle\sigma v\rangle}{m_{\text{DM}}} = (1+z)^6\rho^2_{crit}\Omega^2_{DM,0}\frac{\langle\sigma v\rangle}{m_{\text{DM}}}$$

$$\left(\frac{dE}{dV\,dt}\right)_{\text{deposited}} = f(z)\left(\frac{dE}{dV\,dt}\right)_{\text{injected}}$$

Slatyer, 2016



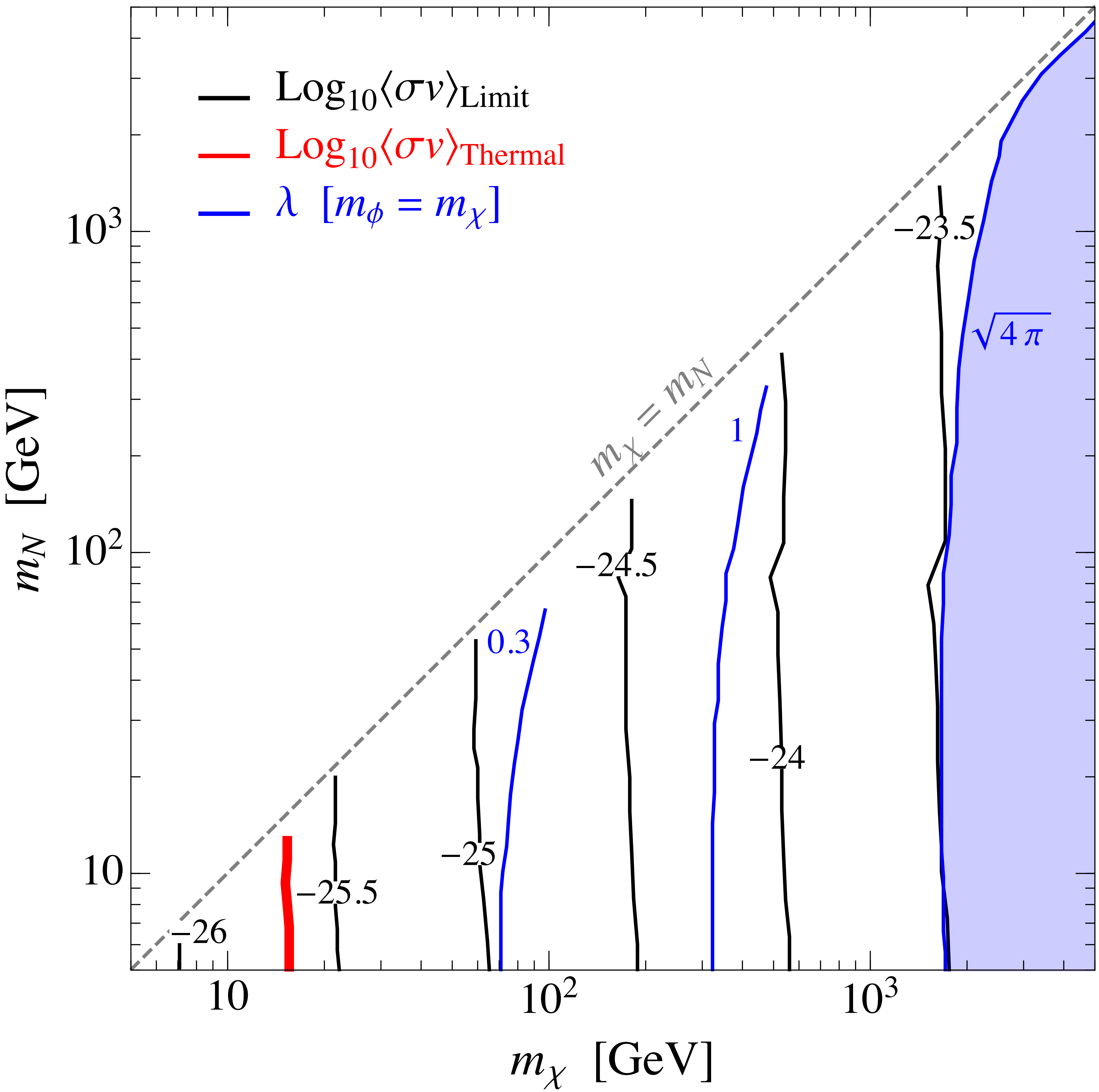
Introducing Efficiency factor: (universal: redshift-independent, model-independent)

$$f_{\text{eff}}(m_{\text{DM}}) = \frac{\int_0^{m_{\text{DM}}} E dE\left[2f^{e^+}_{\text{eff}}(E)(\frac{dN}{dE})_{e^+} + f^{\gamma}_{\text{eff}}(E)(\frac{dN}{dE})_{\gamma}\right]}{2m_{\text{DM}}}$$

***Planck* limit:** $$f_{\text{eff}}(m_{\text{DM}})\frac{\langle\sigma v\rangle}{m_{\text{DM}}} < 4.1\times10^{-28}\text{cm}^3/\text{s}/\text{GeV}$$

Ade et al. ,2016

Planck CMB 95% C.L. Limit



Gamma rays from dwarf spheroidal galaxies (dSphs)

very clean sources for indirect detection:

- Large DM content
- Having few stars and little gas, negligible background

6 years of Fermi Large Area Telescope (LAT) data:

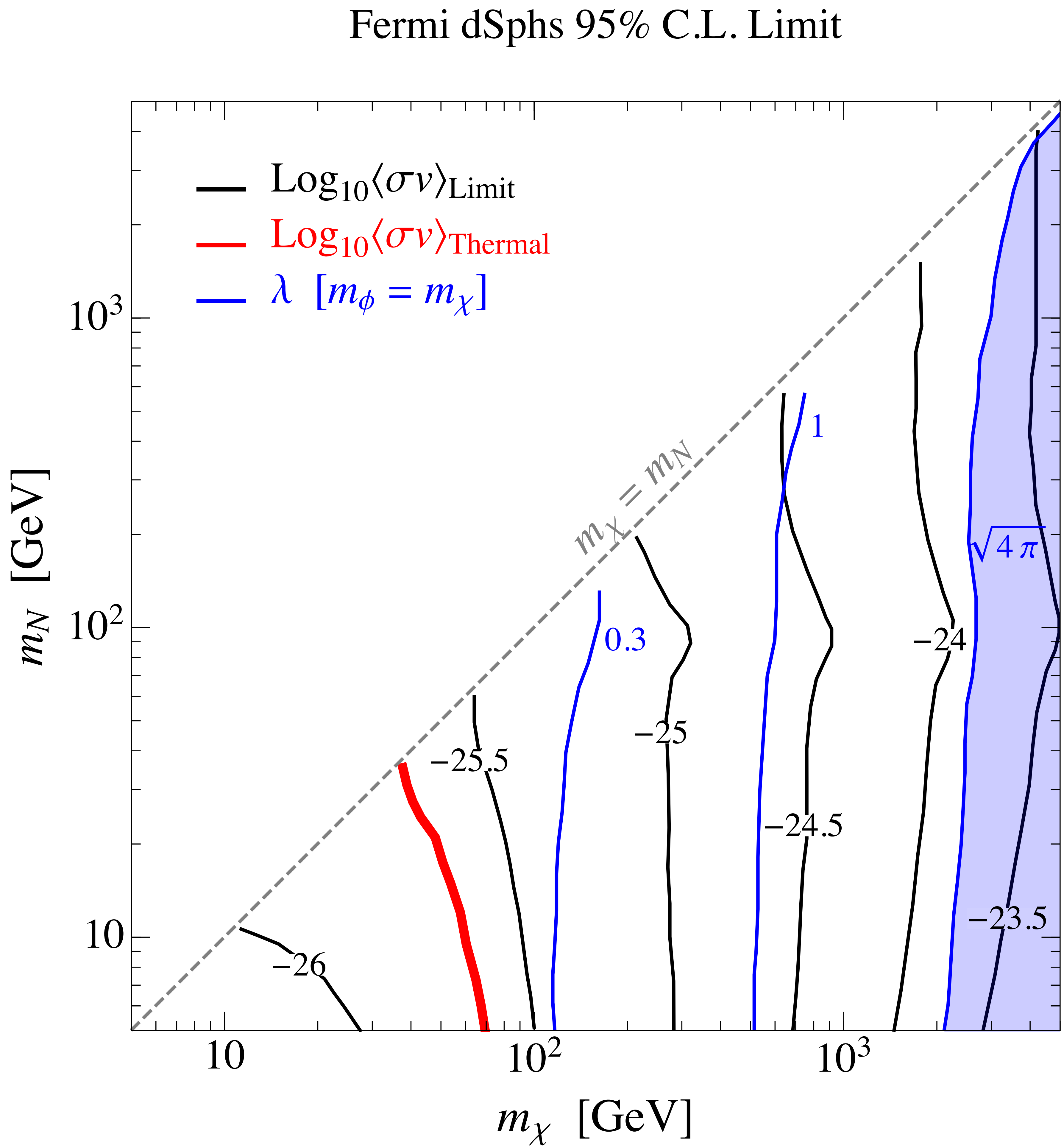
The Fermi analysis is based on a joint maximum likelihood analysis of 15 dSphs for gamma ray energies in the 500 MeV - 500 GeV range.

$$\frac{d\Phi_a}{dE_a} = \frac{1}{4\pi}\frac{\langle\sigma_{ann}v\rangle}{2m_{DM}^2}\sum_f \frac{dN_{a,f}}{dE_a}B_f \times \int_V \rho^2_{\rm DM}(\vec{x})\,dV$$

Flux

Particle Physics

Astrophysics (*J* - factor)



Fermi dSphs 95% C.L. Limit
$\mathrm{Log}_{10}\langle\sigma v\rangle_{\mathrm{Limit}}$
$\mathrm{Log}_{10}\langle\sigma v\rangle_{\mathrm{Thermal}}$
$\lambda\ [m_\phi = m_\chi]$
$m_\chi = m_N$
−26
−25.5
0.3
−25
1
−24.5
−24
$\sqrt{4\pi}$
−23.5
m_N [GeV]
m_χ [GeV]
10
10^2
10^3

Antiprotons

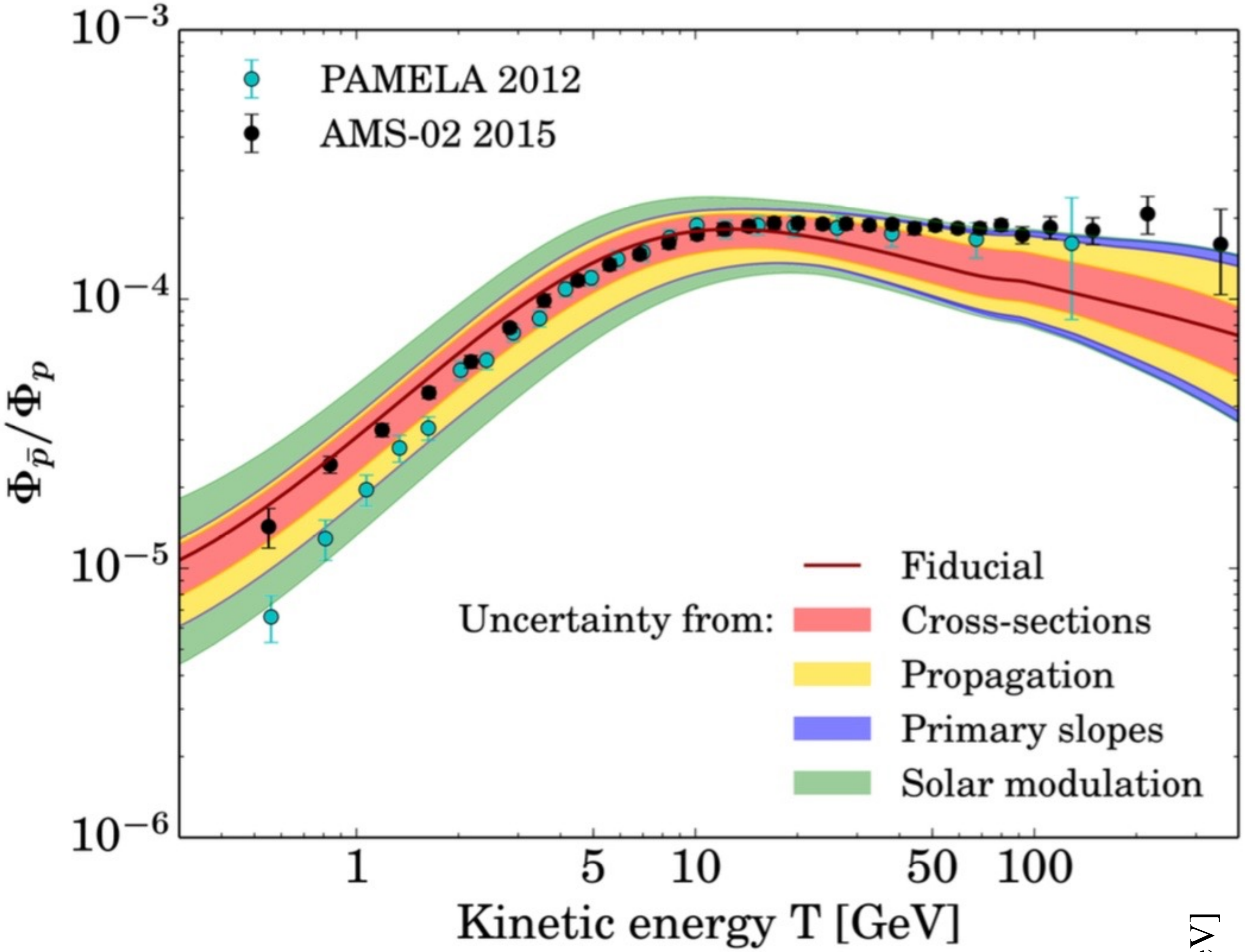
Antiproton content of the astrophysical background is rare:

- its production costs us a lot of energy $\sim 7\, m_P$
- energy flux of cosmic rays is very steep peaked around 0.1 GeV

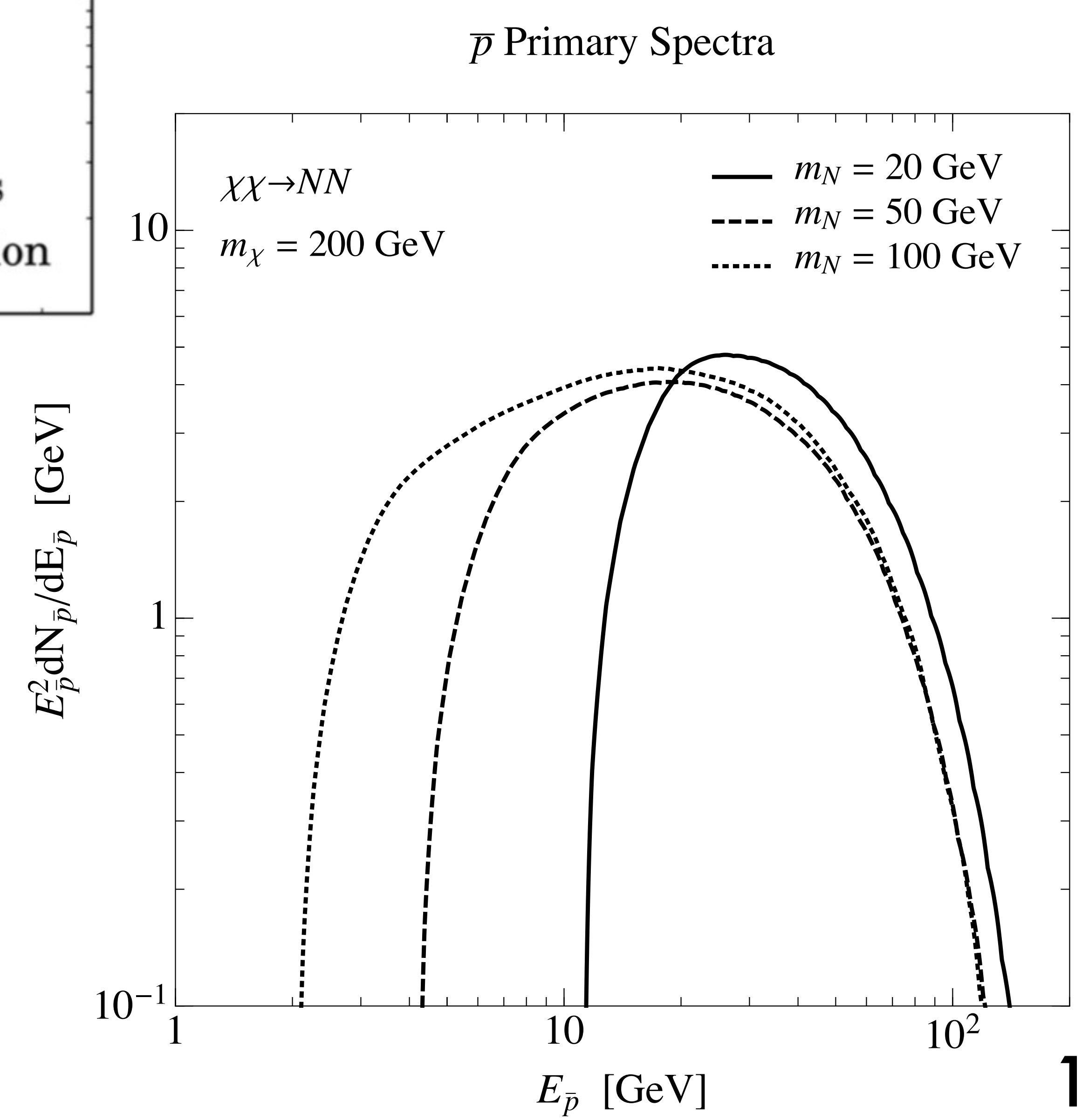
DM annihilation will produce as much antiproton as proton!

Antiprotons deflection by the Galactic magnetic field and their propagation may be seen as a diffusion process.

The Alpha Magnetic Spectrometer (AMS-02) has provided the most precise measurements of the cosmic ray proton and antiproton flux to date.



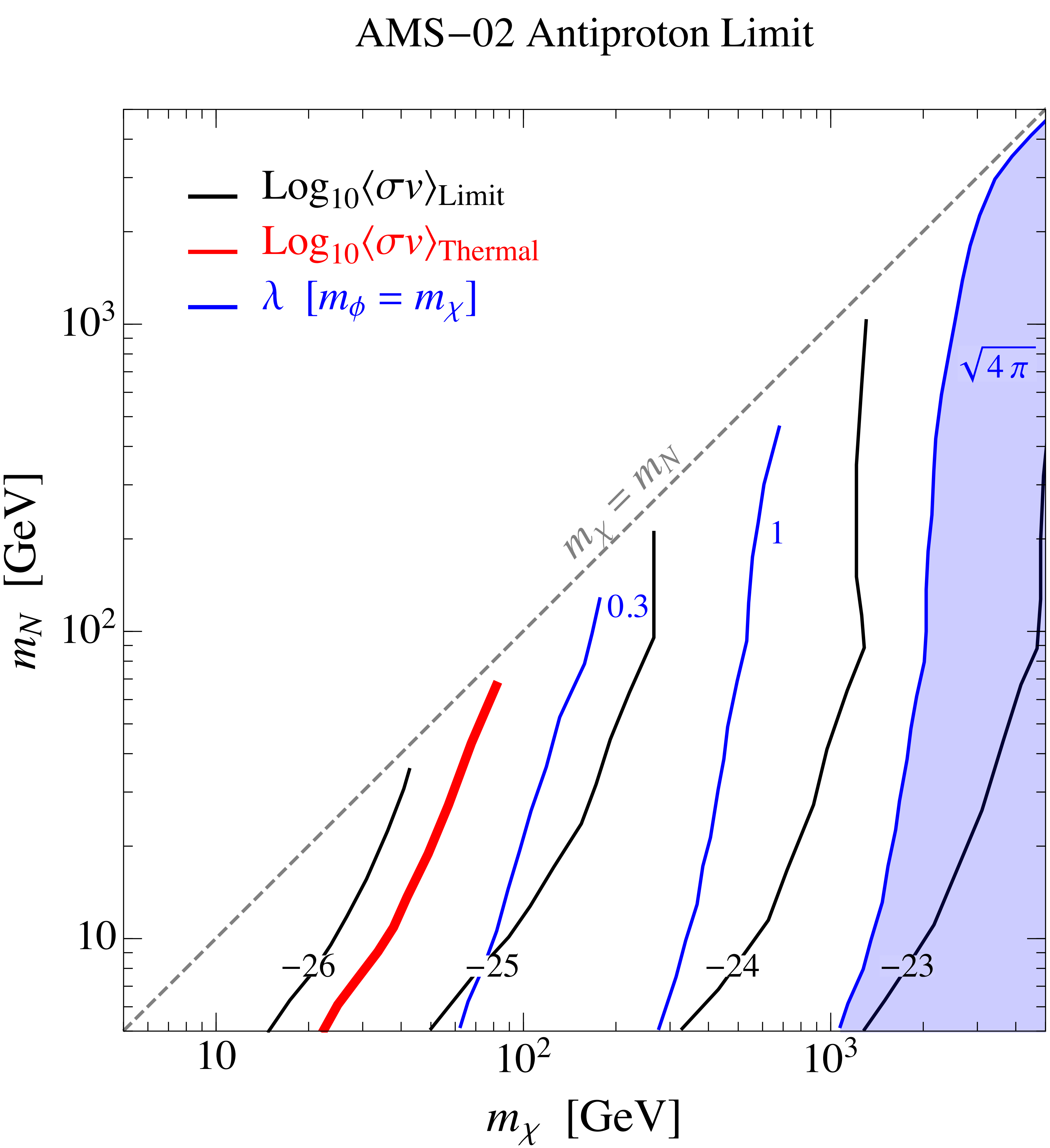
Giesen, *et al.* 2015



Used Einasto profile & the MED propagation scheme

$$\chi^2(m_\chi, \langle\sigma v\rangle) - \chi_0^2 \leq 4$$

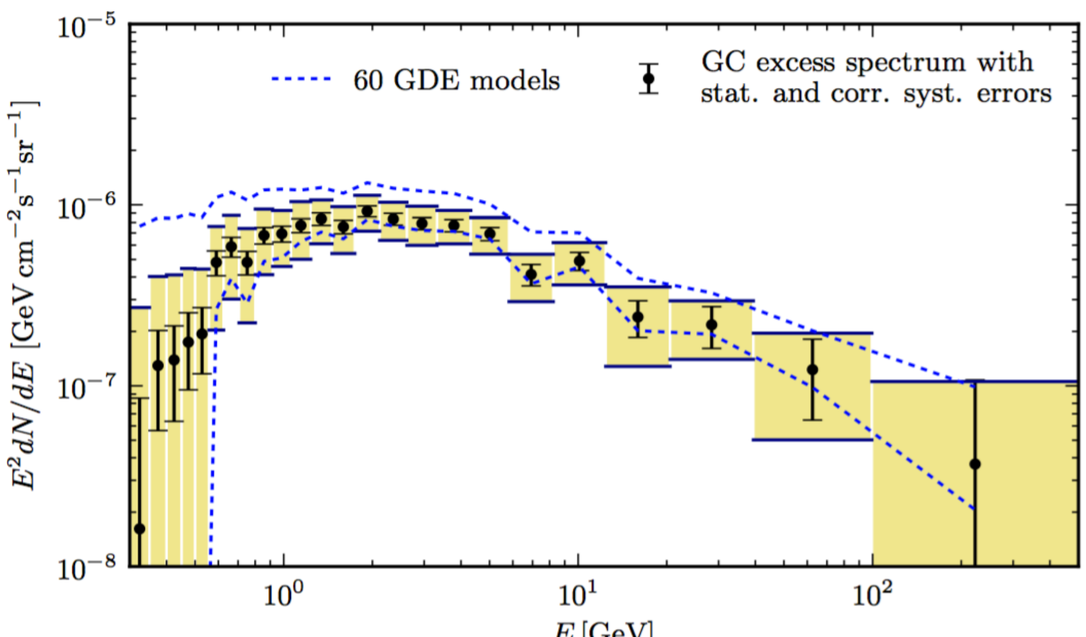
χ_0^2 is the best fit assuming no primary DM antiproton source


AMS−02 Antiproton Limit
$\mathrm{Log}_{10}\langle\sigma v\rangle_{\mathrm{Limit}}$
$\mathrm{Log}_{10}\langle\sigma v\rangle_{\mathrm{Thermal}}$
$\lambda\ [m_\phi = m_\chi]$
$m_\chi = m_N$
$\sqrt{4\pi}$
1
0.3
−26
−25
−24
−23
10^3
10^2
10
m_N [GeV]
m_χ [GeV]

Galactic Center Gamma Ray Excess Interpretation

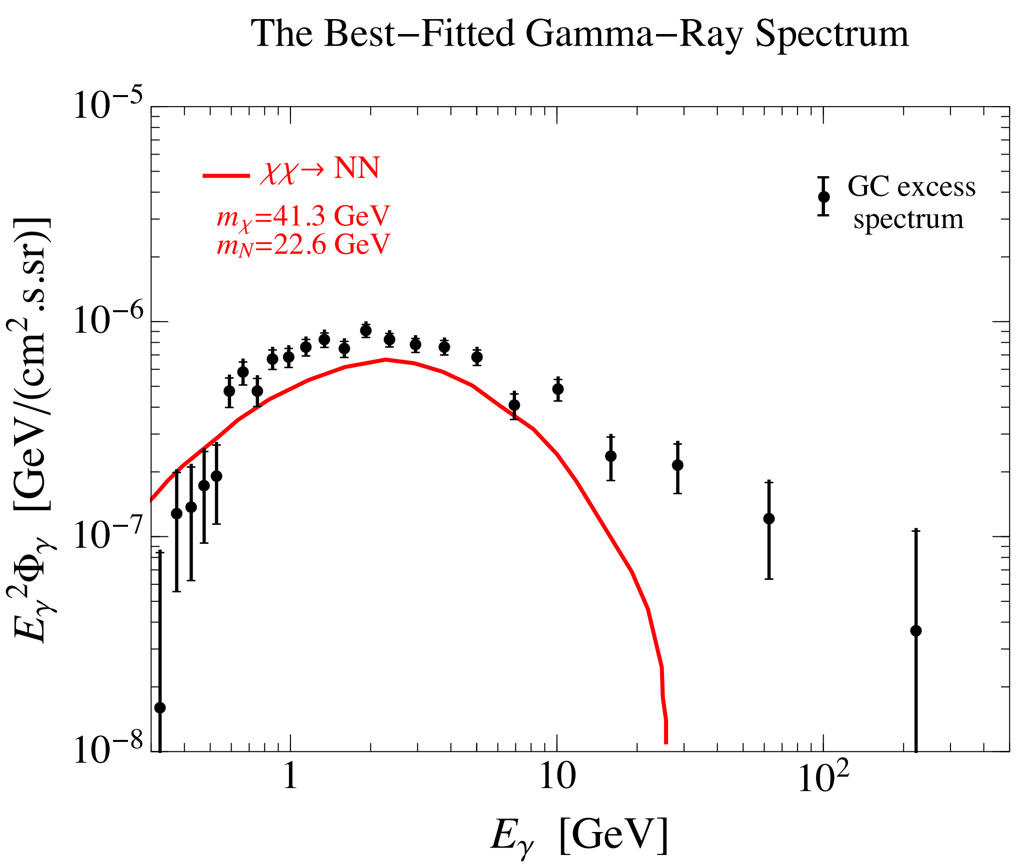
Various analyses of Fermi-LAT data show an excess
of gamma rays coming from the central region of the Milky Way

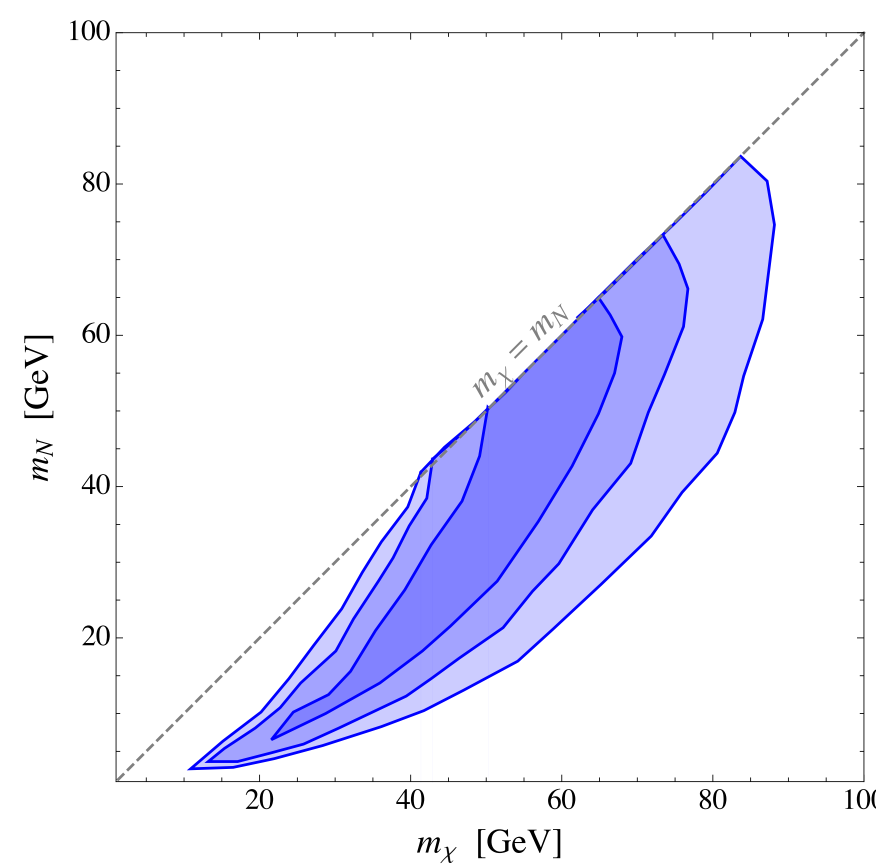
Goodenough, Hooper 2009

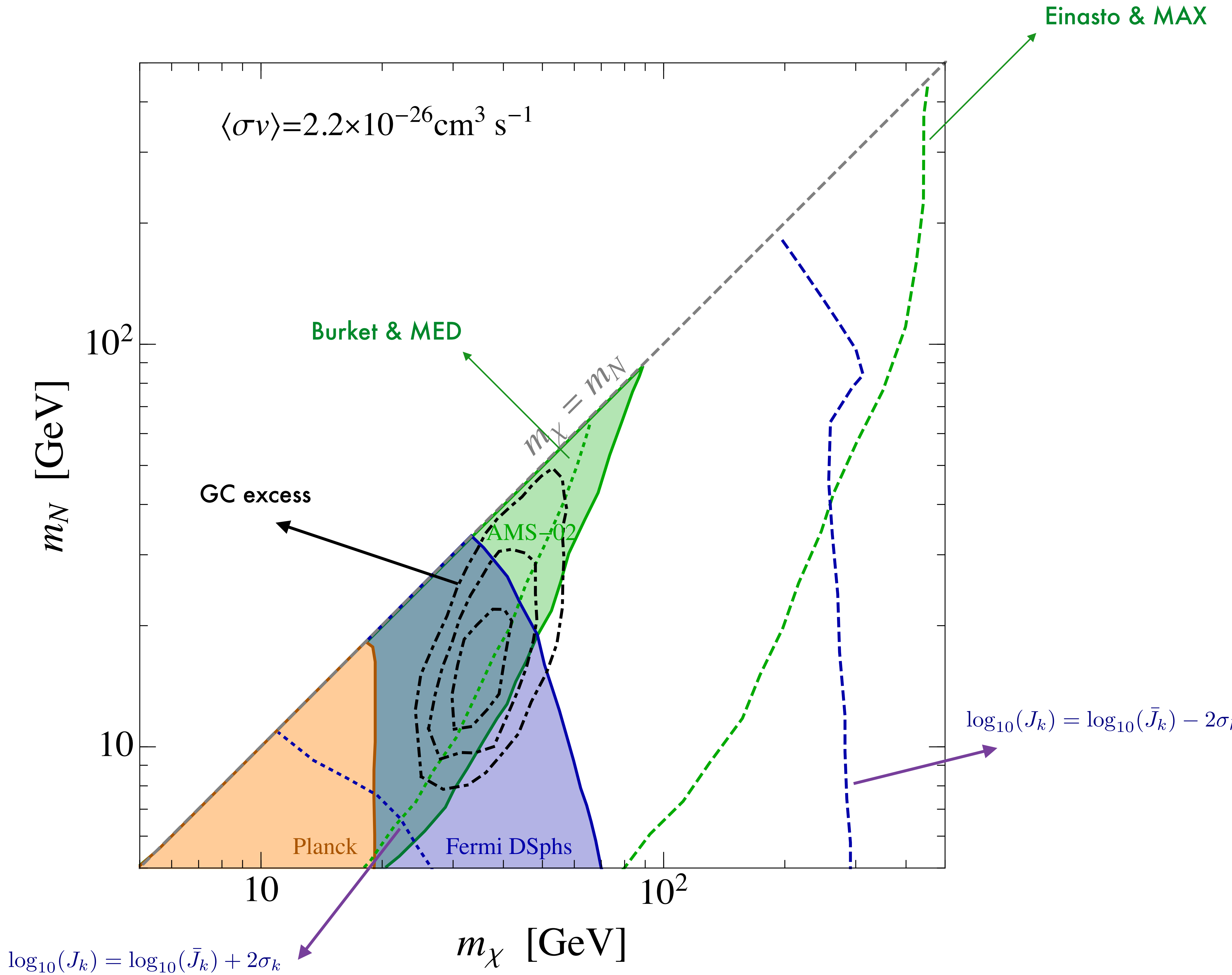


Calore, Cholis, Weniger 2014

best-fit point
$$\begin{cases} \langle \sigma v \rangle = 3.08 \times 10^{-26}\ \text{cm}^3\ \text{s}^{-1} \\ m_\chi = 41.3\ \text{GeV} \\ m_N = 22.6\ \text{GeV} \\ \chi^2/\text{dof} = 14.12/23 \end{cases}$$






Einasto & MAX
$\langle\sigma v\rangle$=2.2×10^{-26}cm^3 s^{-1}
Burket & MED
$m_\chi = m_N$
GC excess
AMS−02
Planck
Fermi DSphs
$\log_{10}(J_k) = \log_{10}(\bar{J}_k) - 2\sigma_k$
$\log_{10}(J_k) = \log_{10}(\bar{J}_k) + 2\sigma_k$
m_N [GeV]
m_χ [GeV]
10
10^2

Future prospects

Fermi-LAT:

The upcoming change: fast discovery of new dSphs

Fermi-LAT 15 years observations:

improvement on the cross section by a factor of a few,
probing DM with masses larger than 100 GeV in neutrino portal.

Ground-based imaging air Cherenkov telescopes like CTA:

will be able to probe heavy TeV-scale DM annihilation
improve cross section sensitivity by an order of magnitude

Summary

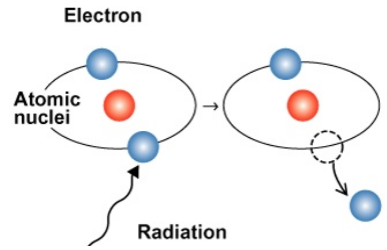
- Neutrino portal is an economical and predictive model to explain thermal WIMP DM.
- Type-I seesaw model necessitates exploring indirect detection methods.
- Astrophysical data constrain the model, and it provides an interpretation of Galactic Center Gamma Ray Excess.
- Future detectors will be able to further probe heavy TeV-scale DM annihilation.

Thank you!

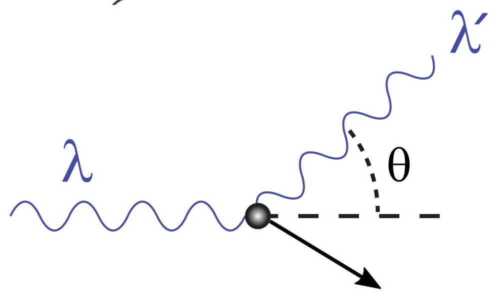
Backups

Photon Cooling Processes (ordered by increasing photon energy)

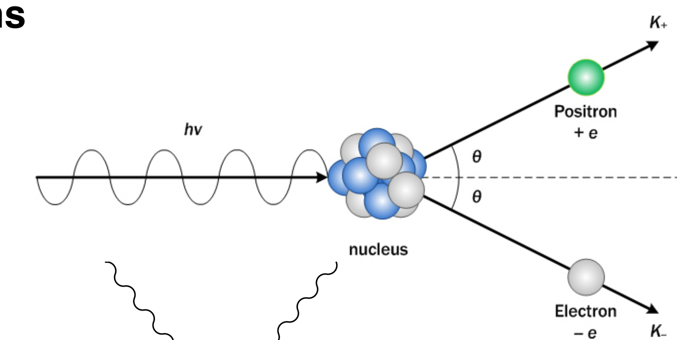
- **Photoionization**



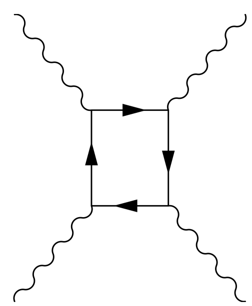
- **Compton scattering**



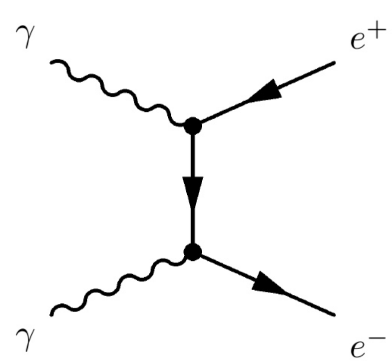
- **Pair production off nuclei and atoms**



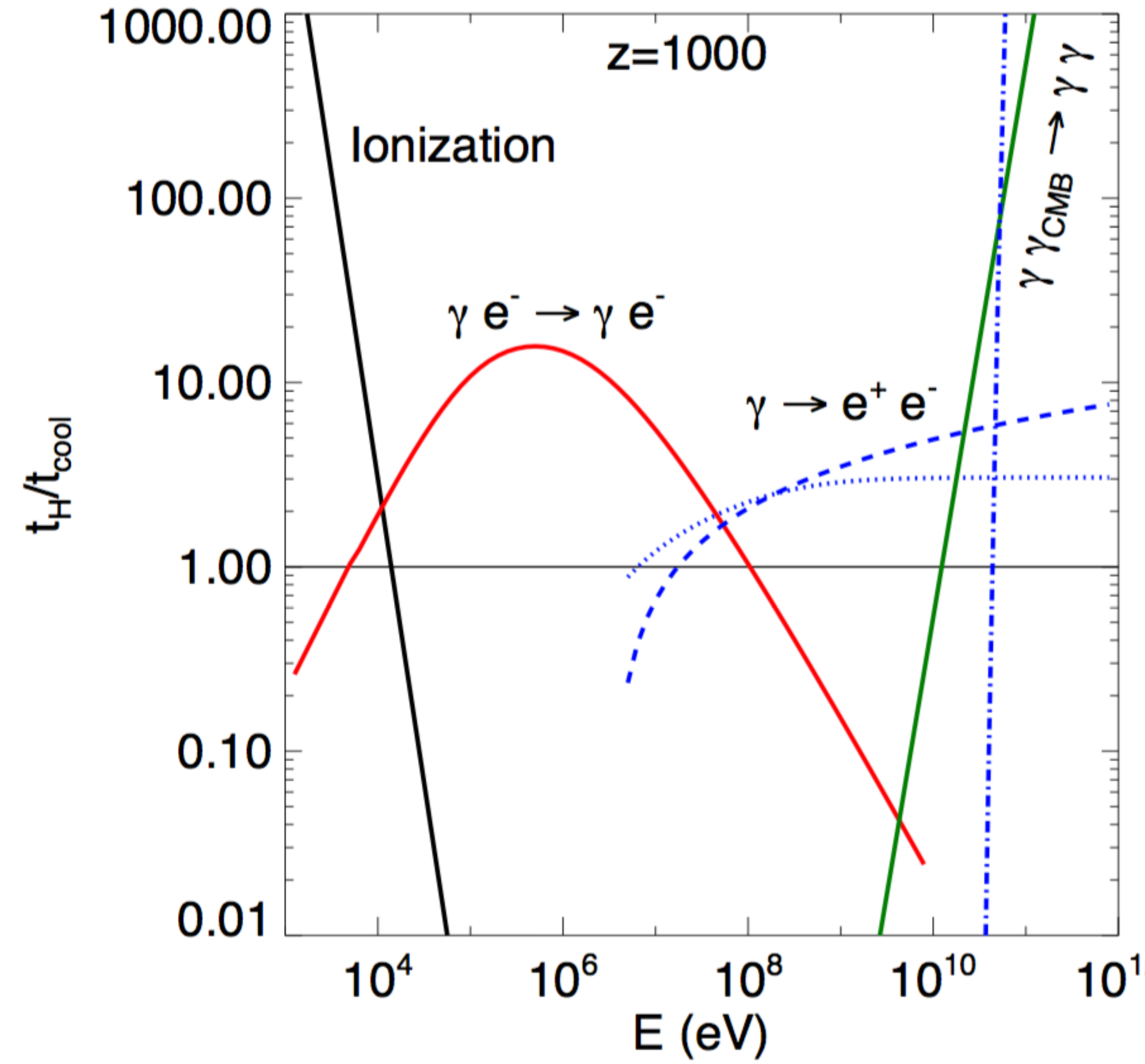
- **photon-photon scattering**



- **pair production off CMB photons**



Slatyer, Padmanabhan, Finkbeiner 2009



$$t_{cool} \equiv 1/(d \ln E/dt)$$

$$t_H \equiv 1/H(z)$$

Electron cooling process: electrons from the annihilation products, or from Compton scattering and pair production considered above lose their energy largely by inverse Compton scattering CMB photons.

The quantity of interest in the likelihood analysis : the energy flux for kth dwarf and jth energy bin

$$\varphi_{k,j} = \int_{E_{j,\min}}^{E_{j,\max}} E\Phi_{\gamma,k}(E)dE$$

For each dwarf and energy bin, Fermi/LAT provides likelihood, as a function of flux

$$\mathcal{L}_k(m_{DM}, \langle\sigma v\rangle, J_k) = \mathcal{LN}(J_k|\bar{J}_k, \sigma_k) \prod_j \mathcal{L}_{k,j}(\varphi_{k,j}(m_{DM}, \langle\sigma v\rangle, J_k))$$

J-factor, introduced as as a nuisance parameter

$$\mathcal{LN}(J_k|\bar{J}_k, \sigma_k) = \frac{1}{\ln(10) J_k \sqrt{2\pi}\sigma_k} e^{-(\log_{10}(J_k) - \log_{10}(\bar{J}_k))^2/2\sigma_k^2}$$

$$\mathcal{L}(m_{DM}, \langle\sigma v\rangle, \{J_i\}) = \prod_k \mathcal{L}_k(m_{DM}, \langle\sigma v\rangle, J_k)$$

$$\Delta \ln \mathcal{L}(m_{DM}, \langle\sigma v\rangle) = \ln \mathcal{L}(m_{DM}, \langle\sigma v\rangle, \{\hat{\hat{J}}_i\}) - \ln \mathcal{L}(m_{DM}, \widehat{\langle\sigma v\rangle}, \{\hat{J}_i\})$$

$$\Delta \ln \mathcal{L}(m_{DM}, \langle\sigma v\rangle) \leq 2.71/2$$

DM density profile (in the galaxy) from N-body simulations:

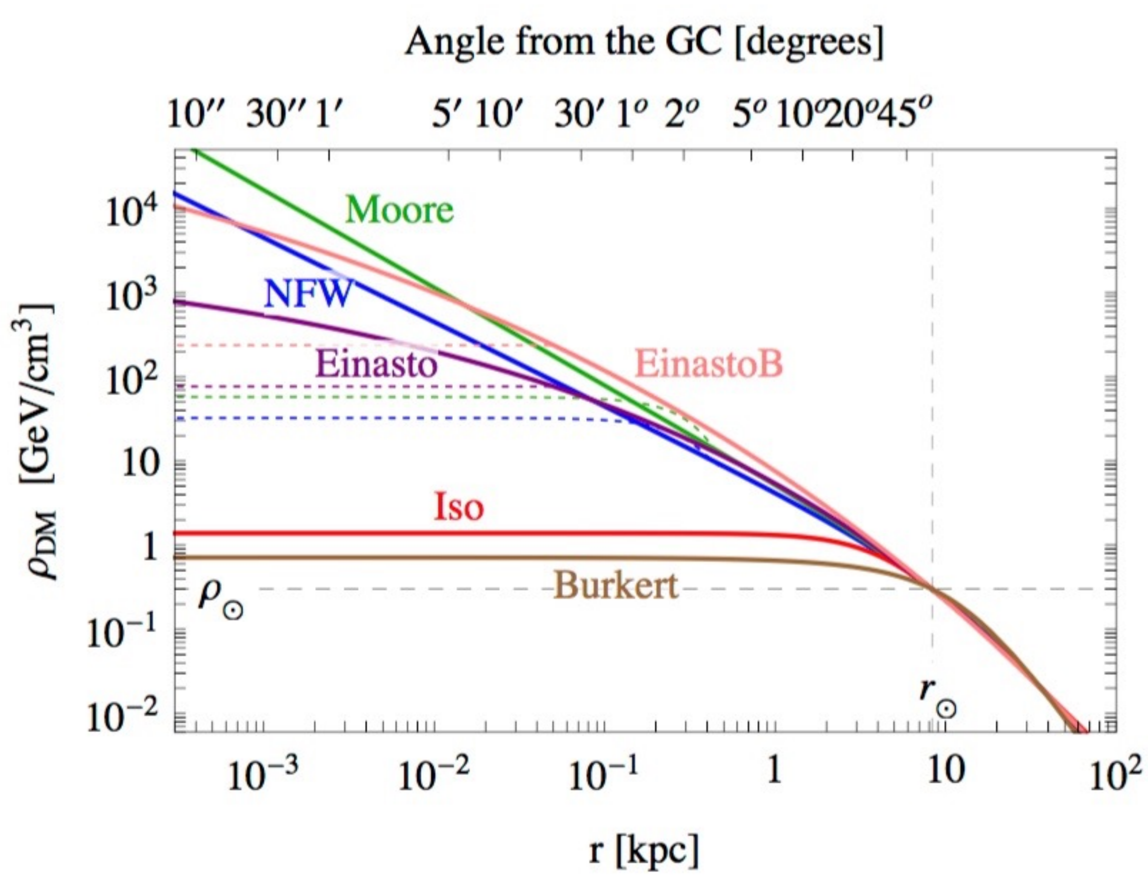
$$\text{NFW}: \quad \rho_{\rm NFW}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$$

$$\text{Einasto}: \quad \rho_{\rm Ein}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\}$$

$$\text{Isothermal}: \quad \rho_{\rm Iso}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

$$\text{Burkert}: \quad \rho_{\rm Bur}(r) = \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)}$$

$$\text{Moore}: \quad \rho_{\rm Moo}(r) = \rho_s \left(\frac{r_s}{r}\right)^{1.16}\left(1+\frac{r}{r_s}\right)^{-1.84}$$



DM halo	α	r_s [kpc]	ρ_s [GeV/cm^3]
NFW	−	24.42	0.184
Einasto	0.17	28.44	0.033
EinastoB	0.11	35.24	0.021
Isothermal	−	4.38	1.387
Burkert	−	12.67	0.712
Moore	−	30.28	0.105

PPPC 4 DM ID

Antiproton diffusion process

$$\frac{\partial f}{\partial t} - \mathcal{K}(K).\nabla^2 f + \frac{\partial f}{\partial z}(\text{sign}(z)\, f\, V_{\text{conv}}) = Q - 2h\delta(z)(\Gamma_{\text{ann}} + \Gamma_{\text{non-ann}})$$

$$f(t, \vec{r}, K) = dN_{\bar{p}}/dK \qquad\qquad K = E - m_p$$

diffusion coefficient function : $\mathcal{K}(K) = \mathcal{K}_0 \beta (p/\text{GeV})^\delta$

source term from DM annihilation: $Q = \frac{1}{2}\left(\frac{\rho(\vec{x})}{m_{\text{DM}}}\right)^2 \sum_f \langle \sigma v \rangle_f \frac{dN^f_{\bar{p}}}{dK}$

$$\Phi_{\bar{p}}(K, \vec{r}_\odot) = \frac{v_{\bar{p}}}{4\pi}\left(\frac{\rho(\vec{x})}{m_{\text{DM}}}\right)^2 R(K) \sum_f \frac{1}{2}\langle \sigma v \rangle_f \frac{dN^f_{\bar{p}}}{dK}$$

Model	δ	$\mathcal{K}_0(\text{kpc}^2/\text{Myr})$	$V_{\text{conv}}(\text{km/s})$	$R(\text{kpc})$	$L(\text{kpc})$
MIN	0.85	0.0016	13.5	20	1
MED	0.70	0.0112	12	20	4
MAX	0.46	0.0765	5	20	15

PPPC 4 DM ID