Fermi Gamma-ray line and right-handed sneutrino dark matter

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Asia Pacific Center for Theoretical Physics

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Contents

Electromagnetic spectrum

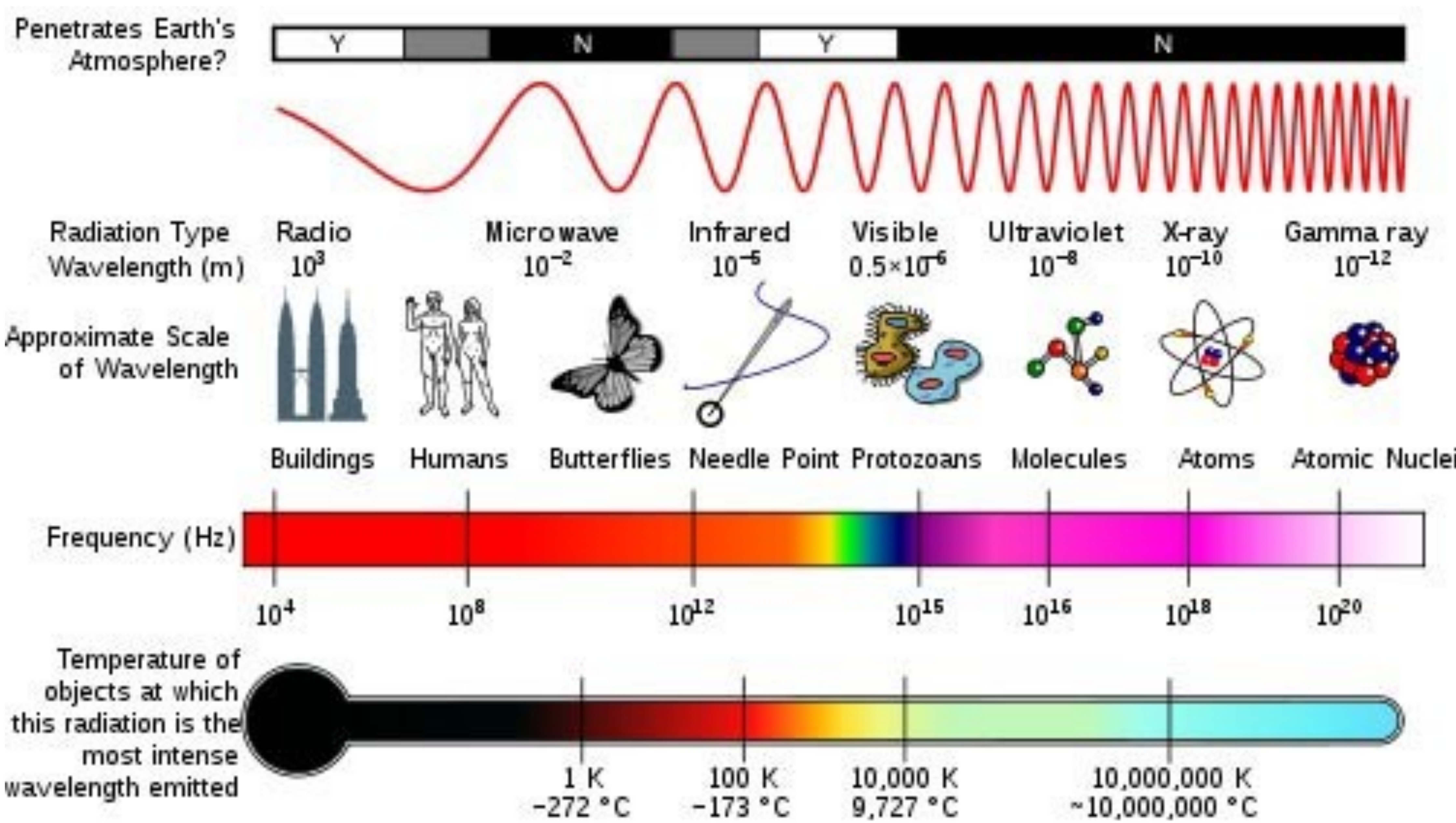
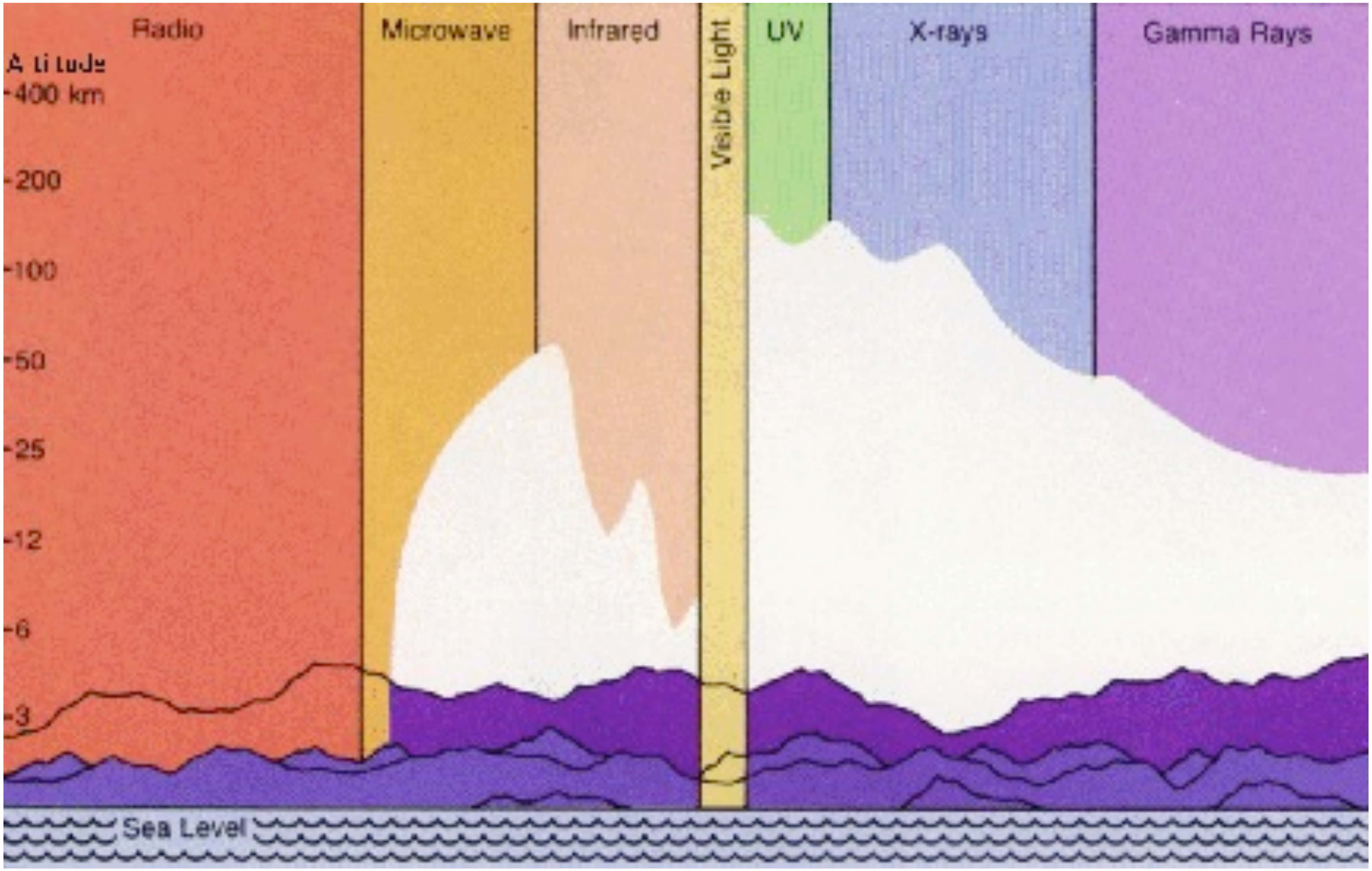


Image source : NASA

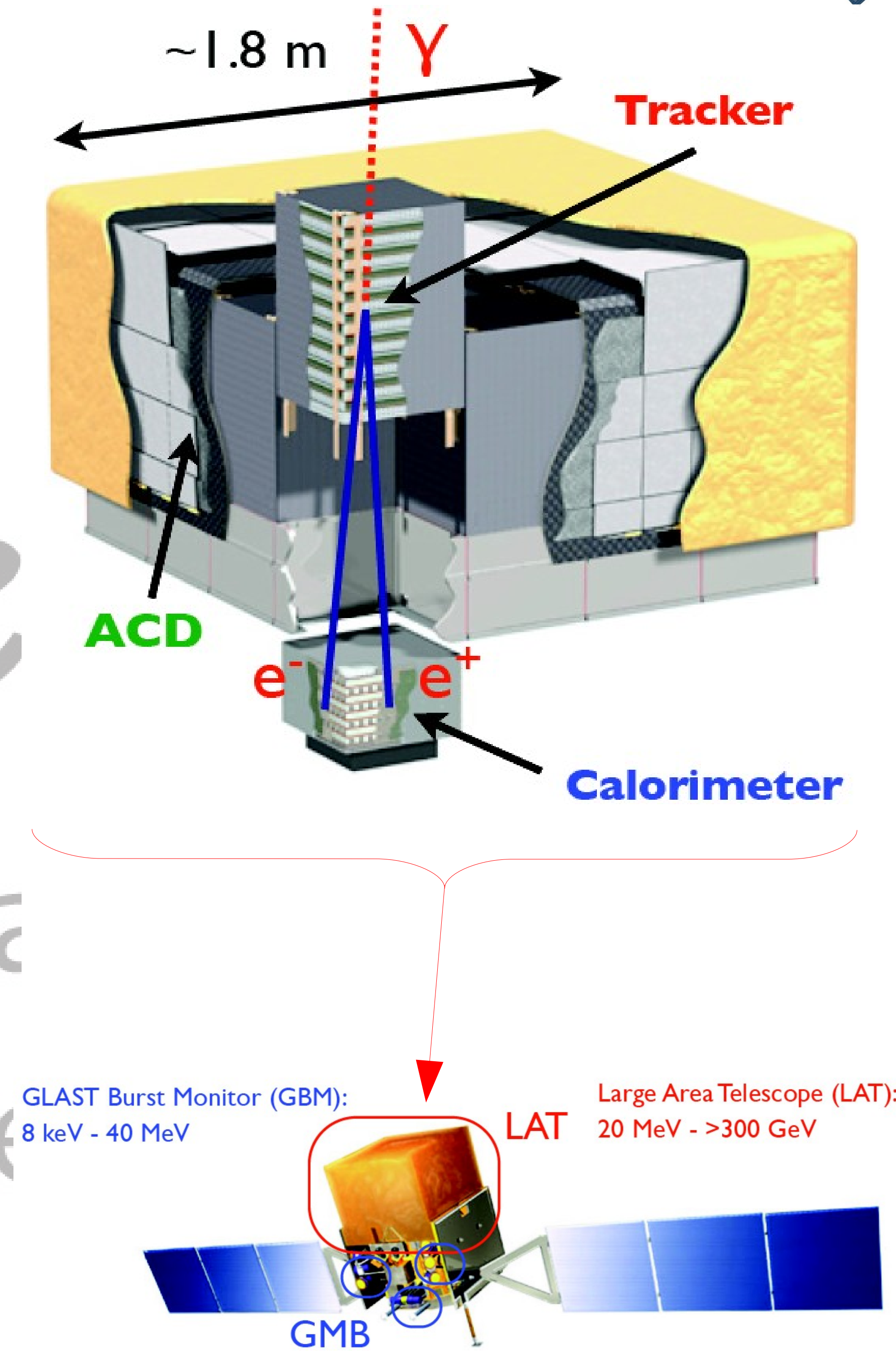
Why do we have to go to space to see the EM spectrum?



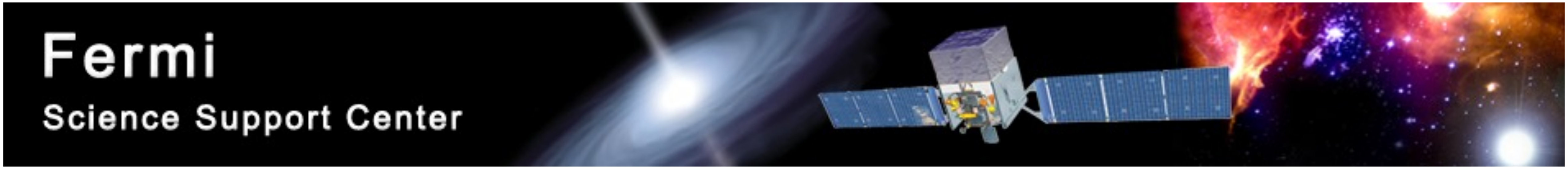
The Fermi-LAT

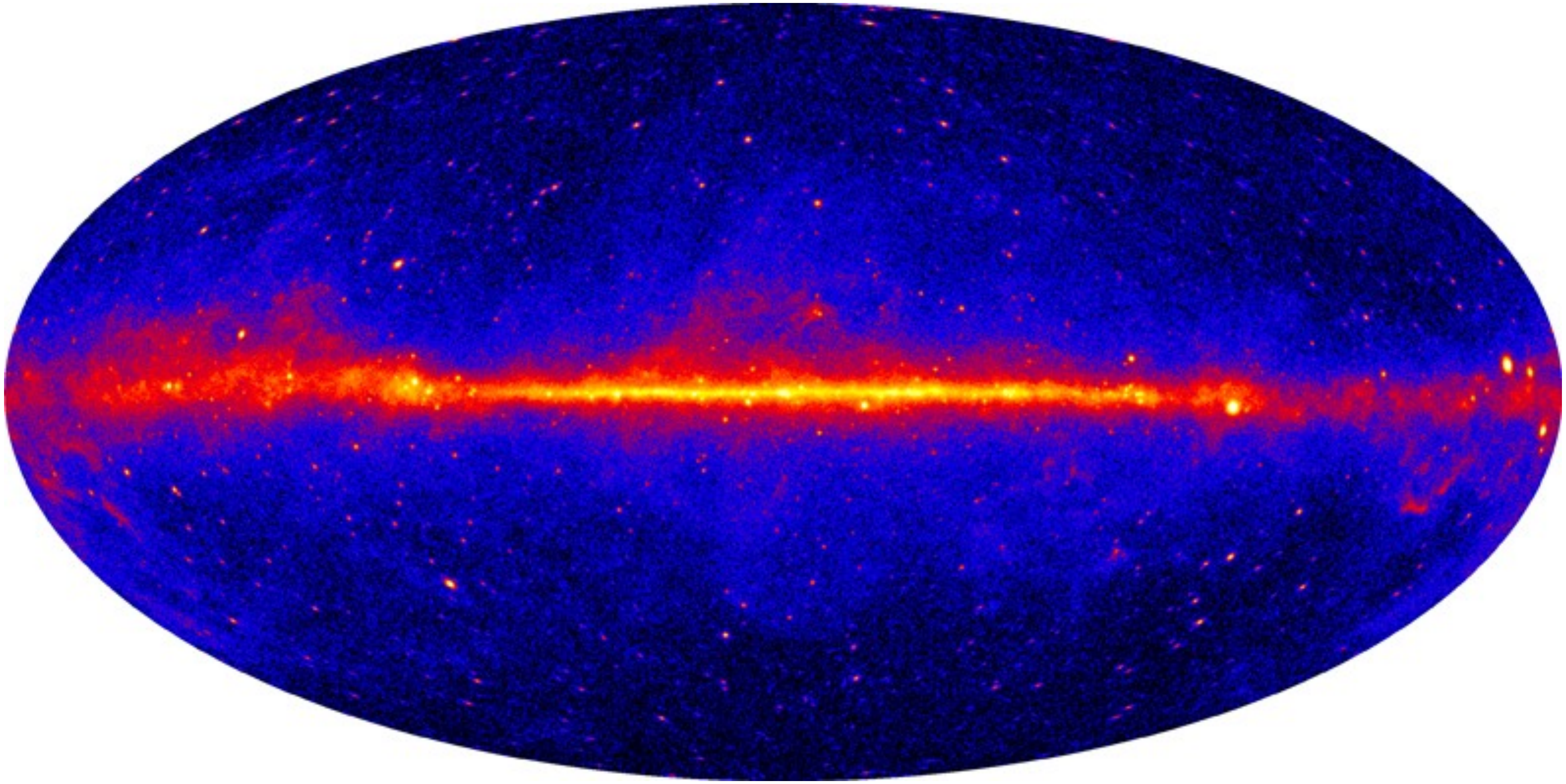
- Launched on June 11, 2008
- 16 identical modules in a 4x4 array, where each module is made up by a tracker for direction determination and a calorimeter for energy measurements
- Field of view is ~2.4 sr
- Energy range 20MeV to >300GeV
- LAT observes the entire sky every ~3 h (2 orbits)

⇨ LAT is a great instrument for DM searches!



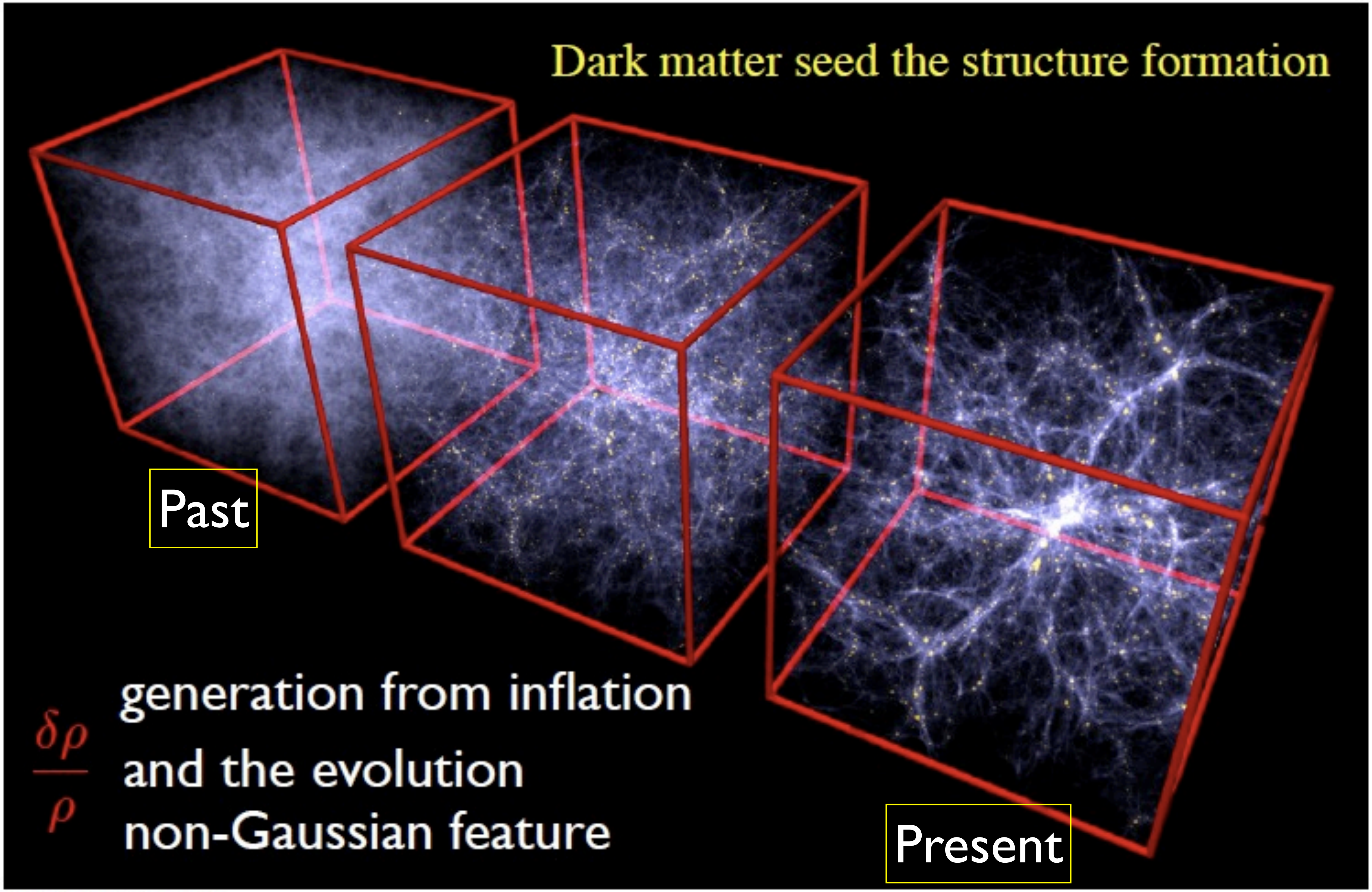
Maja Llena Garde
on behalf of the Fermi-LAT collaboration





This all-sky view from Fermi reveals bright emission in the plane of the Milky Way (center), bright pulsars and super-massive black holes.
Credit: NASA/DOE/International LAT Team

Gamma ray to probe dark matter



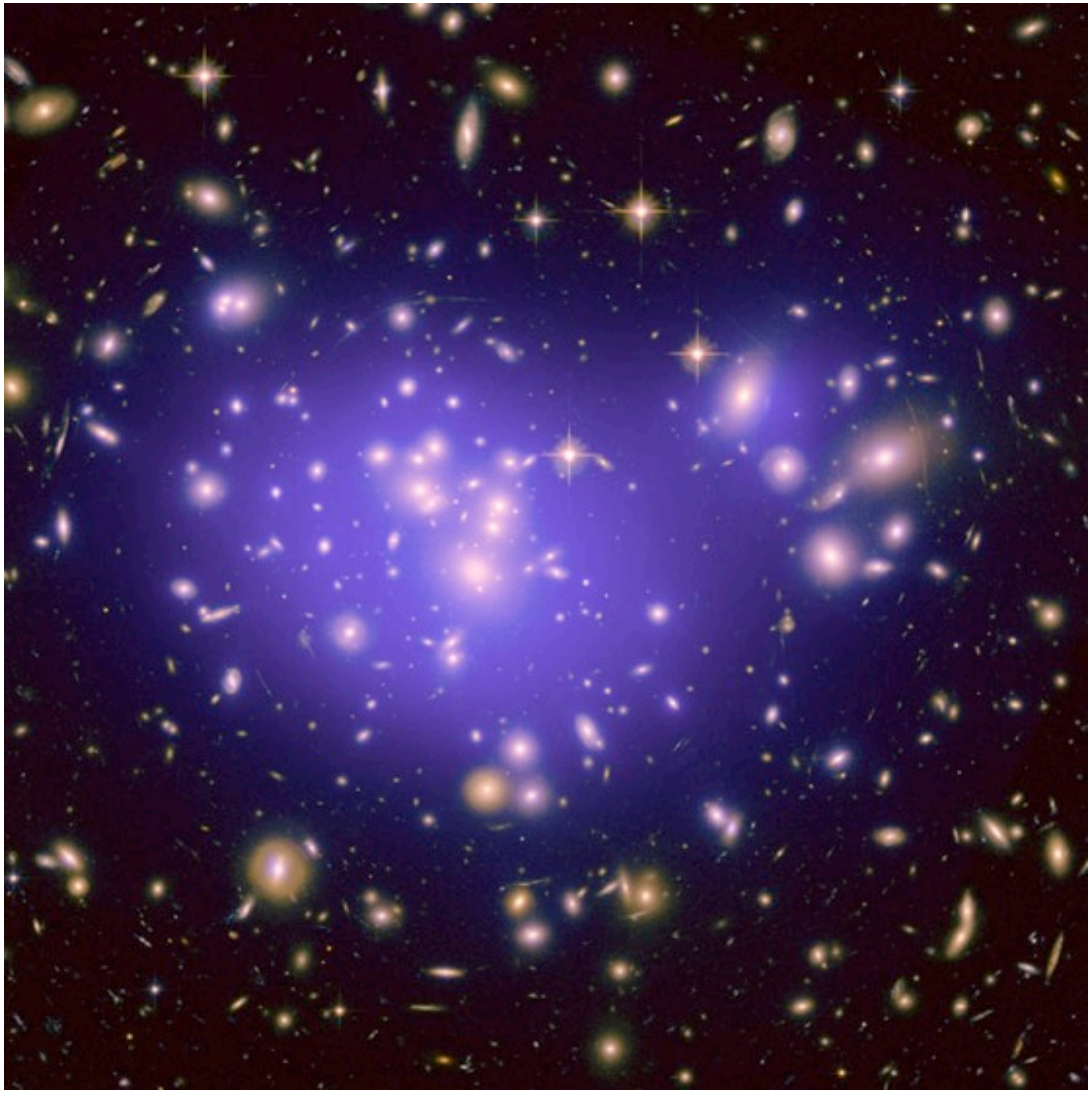
Credit: Volker Springel

Baryons and electrons are tightly coupled to the photons, thus they cannot help to form the structures until the moment of recombination.

Stable and electromagnetically neutral matters are decoupled from the photons and thus seed the formation of structures.

→ $\boxed{\text{Dark Matter}}$

After recombination, baryons are decoupled from photons and fall into the gravitational potential made by the dark matter to form the structures, such as galaxy, clusters of galaxies.



Credit: NASA/ESA/JPL-Caltech/Yale/CNRS

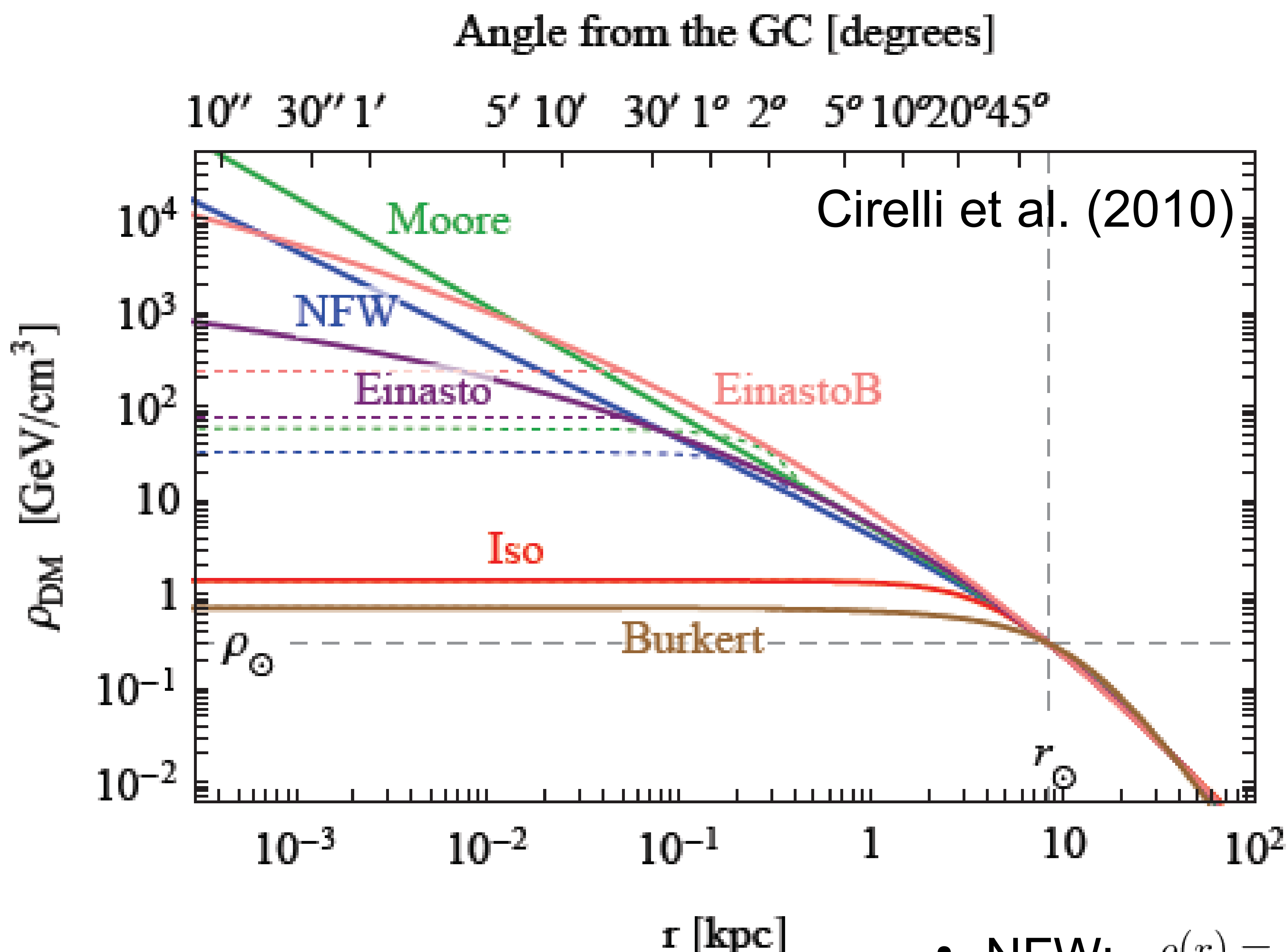
This image from NASA's Hubble Space Telescope shows the inner region of Abell 1689, an immense cluster of galaxies located 2.2 billion light-years away.

Dark matter cannot be photographed, but its distribution is shown in the blue overlay.

Around our visible galaxy

Around our visible galaxy

- Dark matter distribution in the galaxy

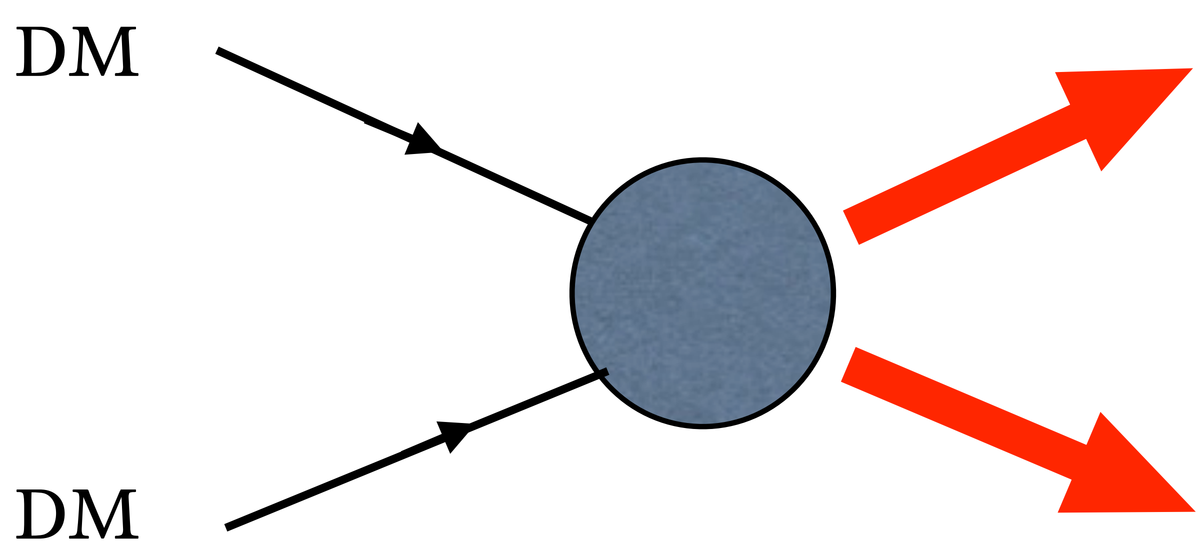


High density of DM in the galactic center region.

- NFW: $\rho(r) = \dfrac{\rho_s}{(r/r_s)(1+r/r_s)^2}$
- Einasto: $\rho(r) = \rho_s e^{\frac{-2}{\alpha}[(r/r_s)^\alpha - 1]}$
- Isothermal: $\rho(r) = \dfrac{\rho_s}{1+(r/r_s)^2}$

• Indirect detection of dark matter

WIMP dark matters in the galactic halo can annihilate (or decay) and produce other particles



Neutrinos

→ Super-K, IceCube

High energy photons

→ EGRET, Fermi, …

Antimatters:
Positrons, antiprotons

→ HEAT, PAMELA, ATIC, Fermi, AMS

Gammay-Ray Line spectrum?

Astrophysical source?

In general, it is quite difficult to obtain the sharp gamma-ray spectrum from astrophysical sources, since the relativistic particles are in a broad energy distribution or the interaction with the surrounding gas gives broad gamma-ray distribution.

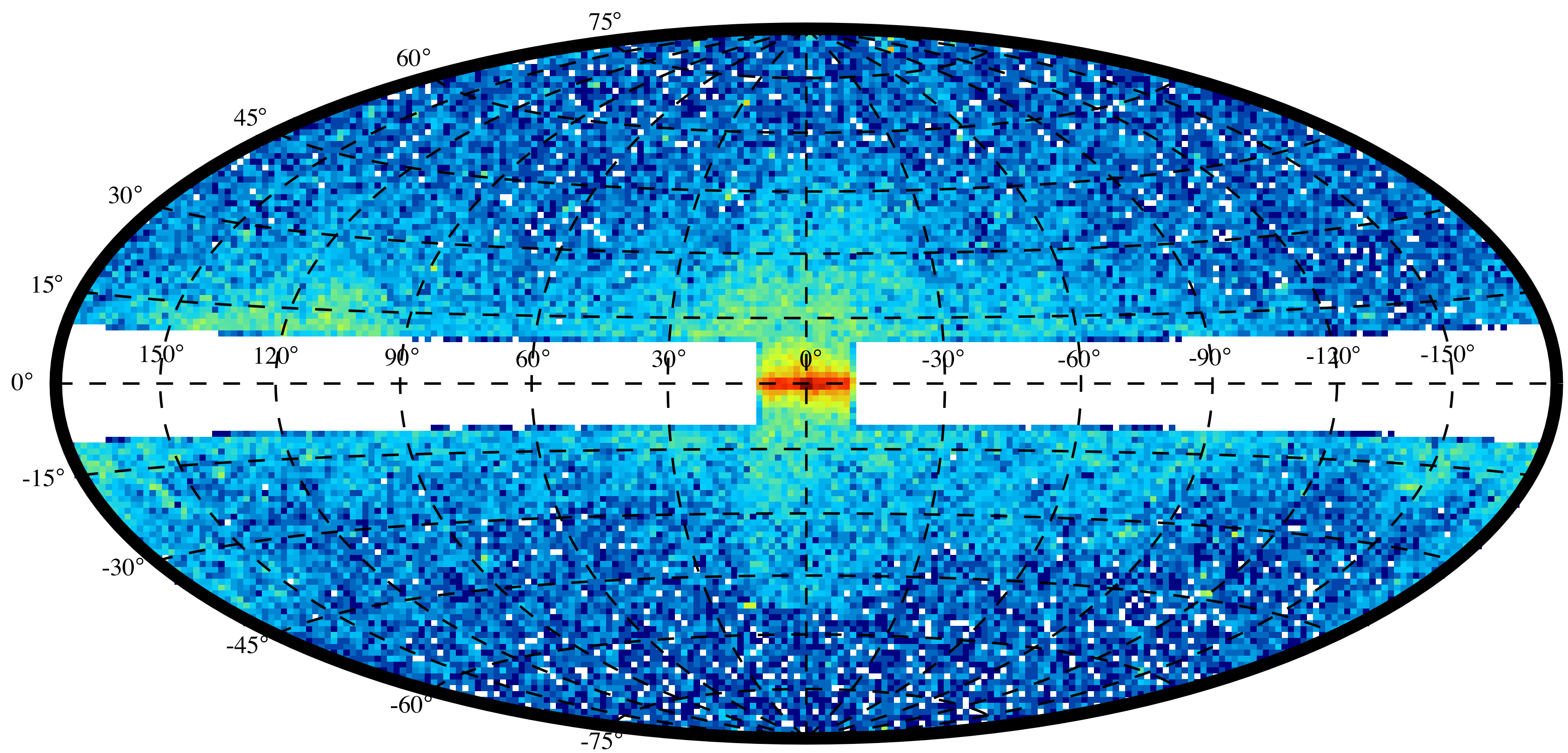
Gamma-line is a ‘smoking gun’ signature of DM

Gamma-ray line : Fermi-LAT Collaboration

[arXiv:1205.2739]

Fermi **LAT Search for Dark Matter in Gamma-ray Lines and the Inclusive Photon Spectrum**

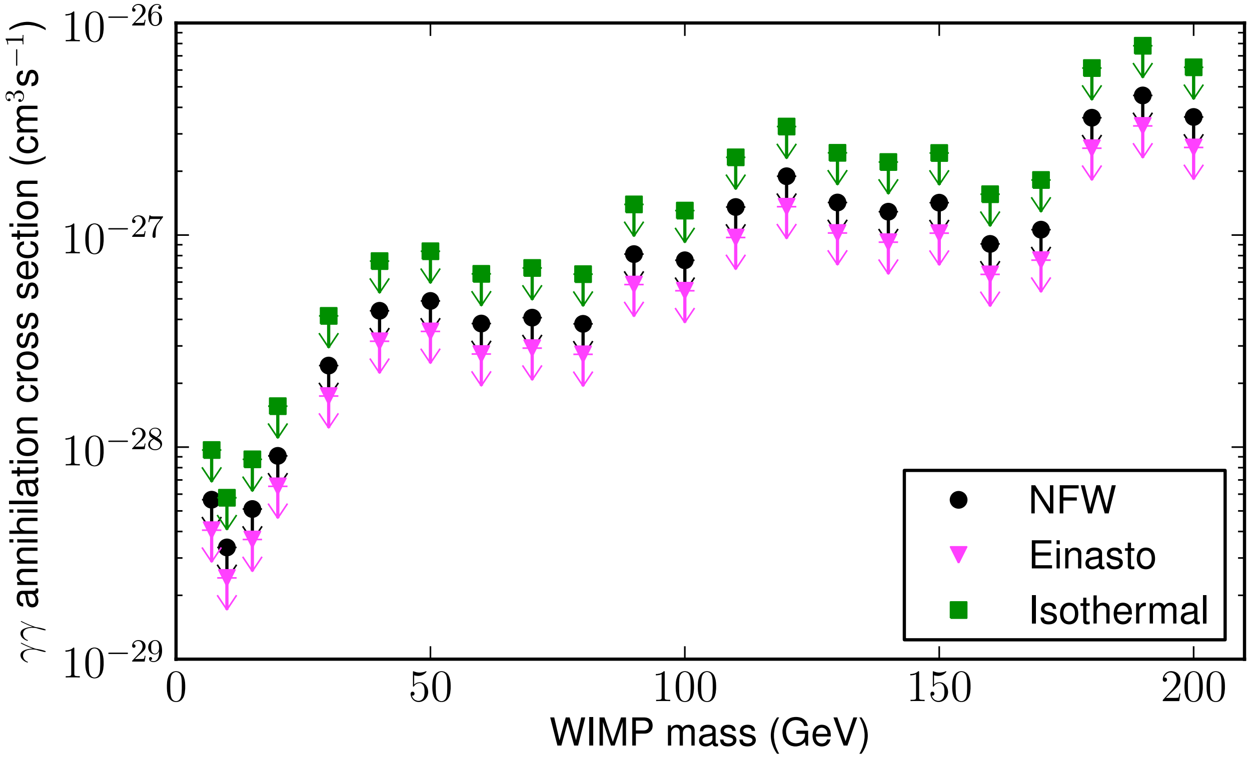
2 year data

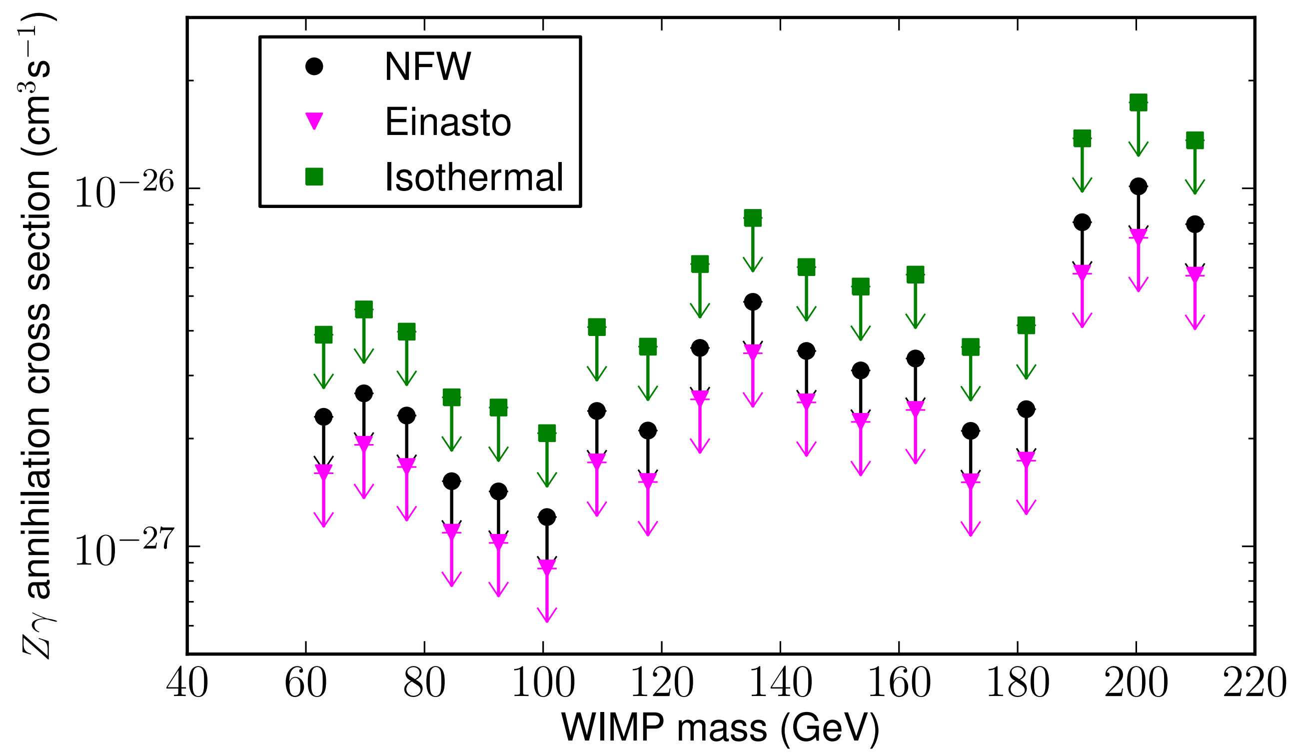


in the region of |b|>10 degrees plus |l| < 10, |b|<10, excluding the Galactic plane!

Upper limits on the gamma-ray line (NFW profile)

[arXiv:1205.2739, Fermi-LAT]



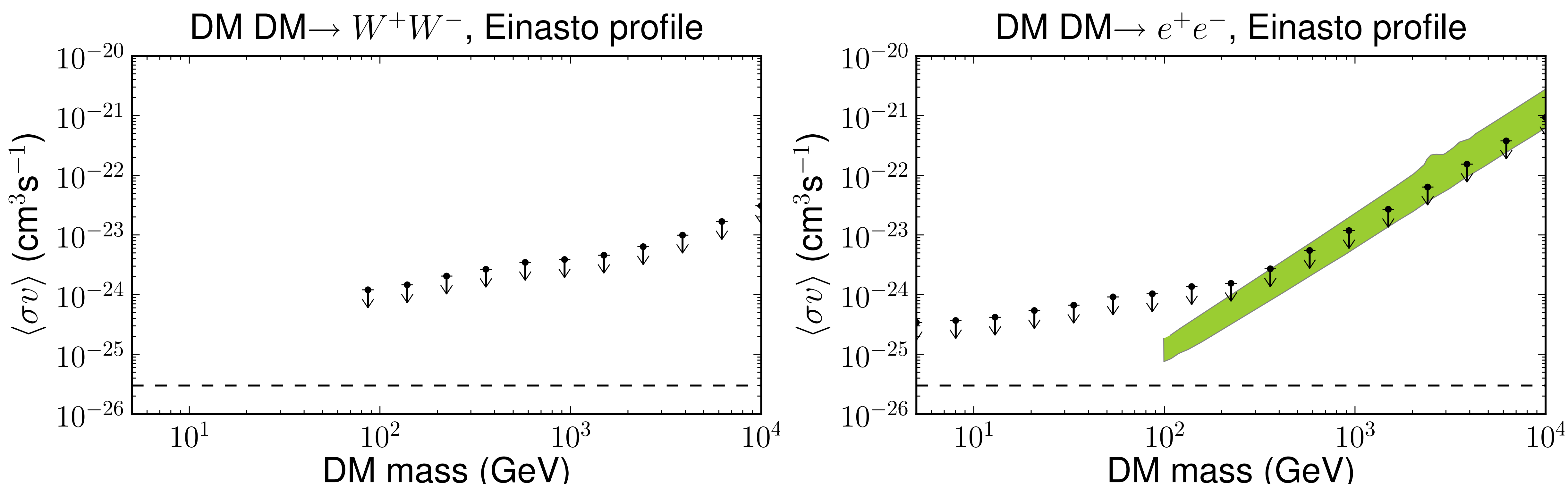


$$\langle \sigma v \rangle_{\gamma\gamma} \lesssim (0.03 \sim 4.6) \times 10^{-27}\ \mathrm{cm^3 s^{-1}} \quad \text{for} \quad m_\chi = 7 - 200\,\mathrm{GeV}$$

$$\langle \sigma v \rangle_{Z\gamma} \lesssim (0.02 \sim 10.1) \times 10^{-27}\ \mathrm{cm^3 s^{-1}} \quad \text{for} \quad m_\chi = 63 - 210\,\mathrm{GeV}$$

Upper limits on the DM annihilation

[arXiv:1205.2739, Fermi-LAT]



Dark matter annihilation into W-bosons and electron-positrons.

130 GeV gamma-line signal from public Fermi-LAT data

arising from the Galactic center

A Tentative Gamma-Ray Line from Dark Matter Annihilation at the Fermi Large Area Telescope

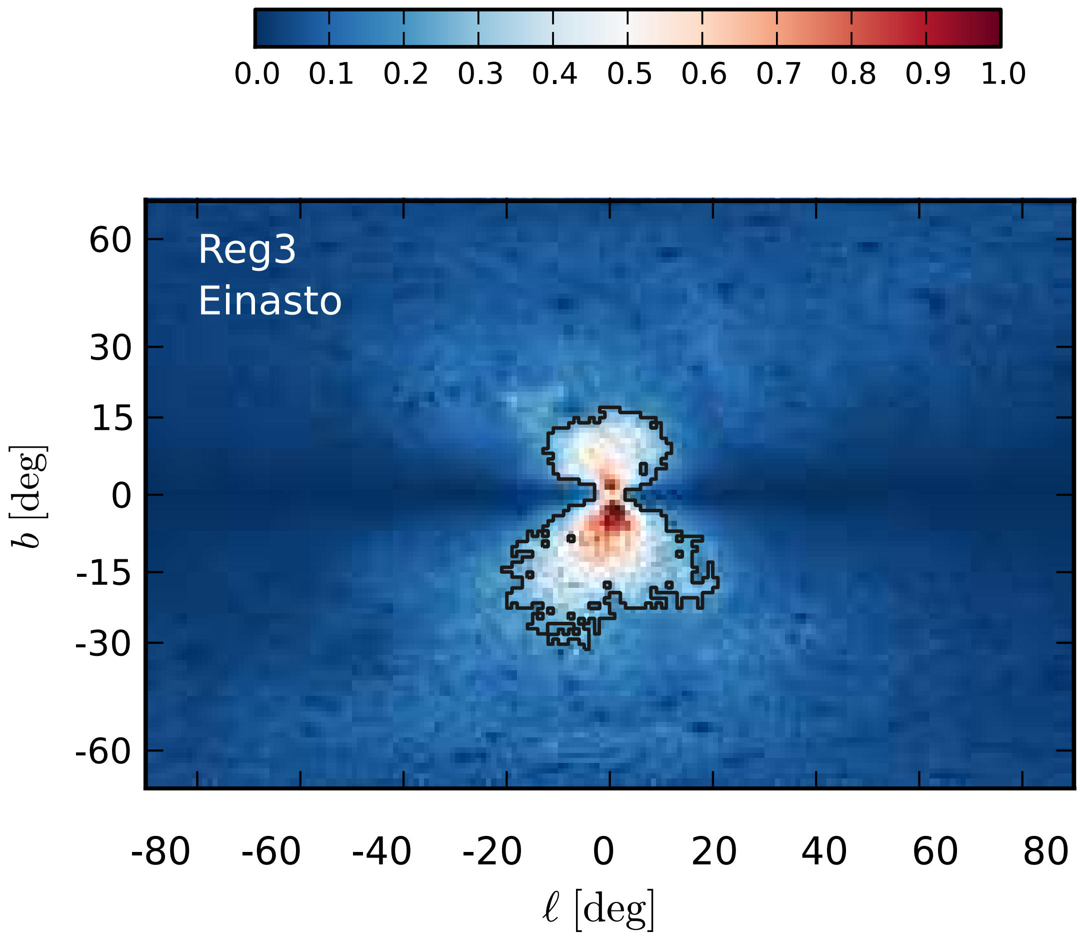
[1204.2797] C. Weniger

$$\langle \sigma v \rangle^{reqd}_{\chi\chi\to\gamma\,\gamma} \approx 1.27 \pm 0.32^{+0.18}_{-0.28} \times 10^{-27}\mathrm{cm}^3/\mathrm{s}: \quad \text{Einasto}$$
$$\approx 2.27 \pm 0.57^{+0.32}_{-0.51} \times 10^{-27}\,\mathrm{cm}^3/\mathrm{s}: \ \text{NFW}\,(1)$$

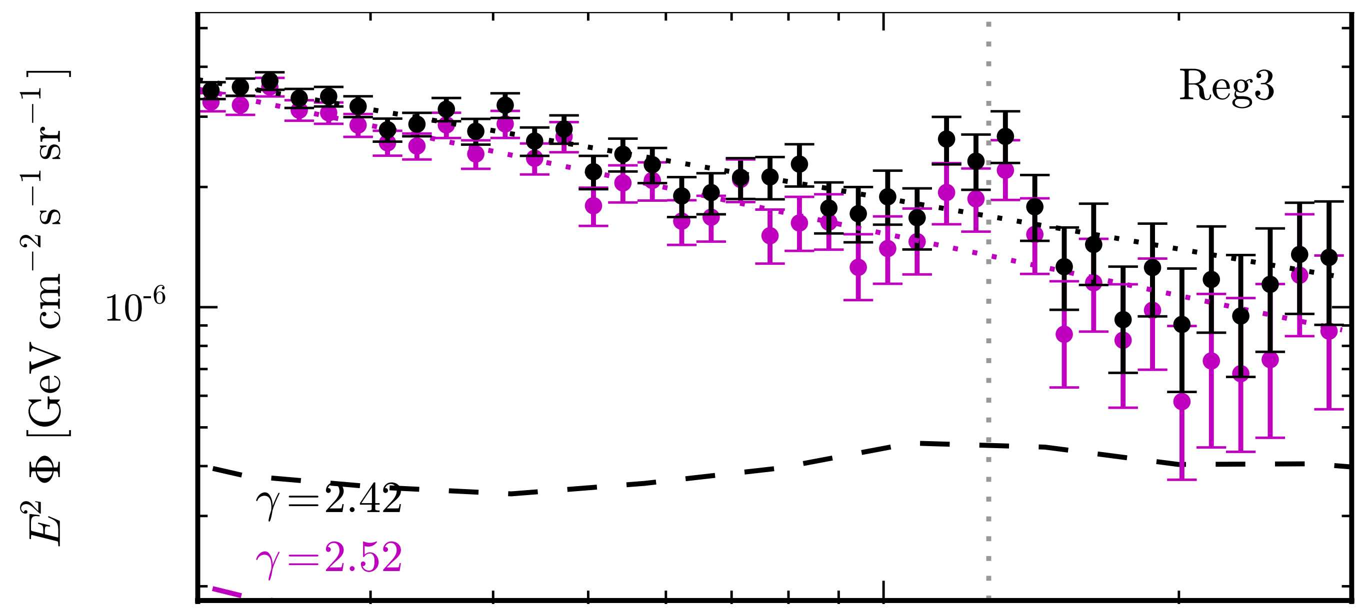
Also by

[1203.1312] Bringman, Huang, Ibarra, Vogl, Weniger

signal-to-background ratio



Gamma-ray spectrum

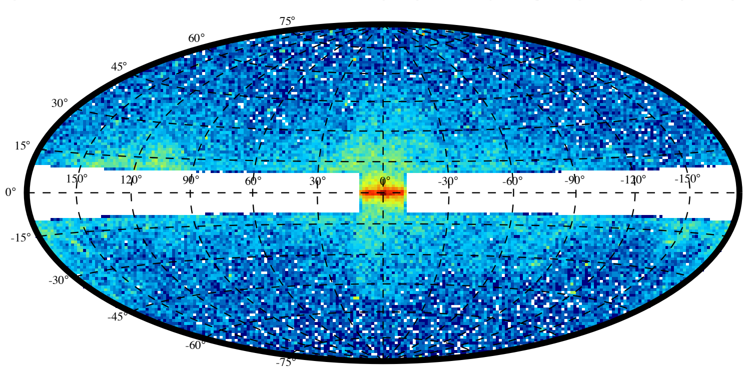


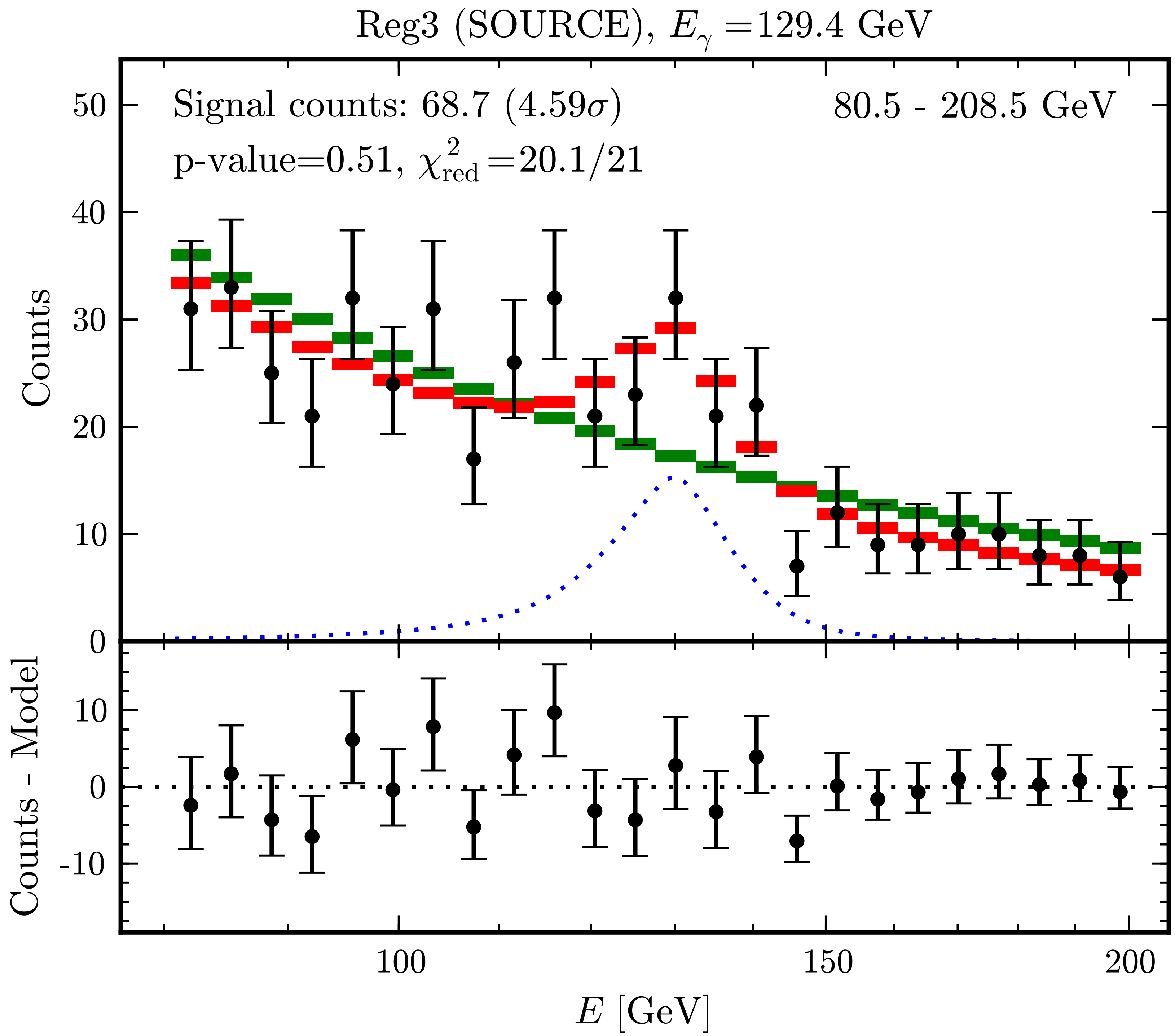
20 GeV

300

130 GeV

Fermi-LAT collaboration





black dot : measured events

horizontal bar : best fit model with DM (red) w/o DM (green)

blue dotted : line flux to fit the data

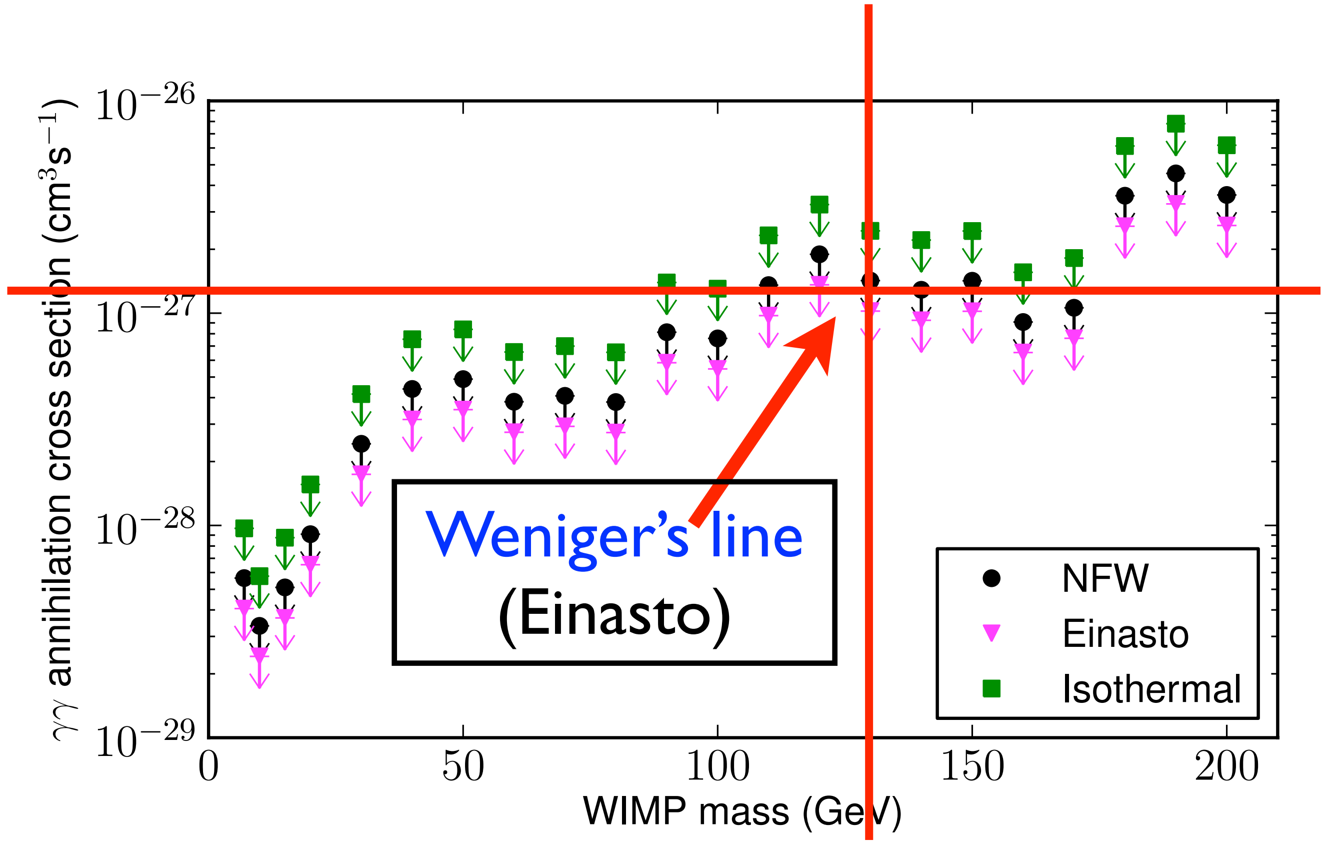
130 GeV gamma-line signal from public Fermi-LAT data

Astrophysical source?

or

Dark Matter signal?

130 GeV gamma-line : Dark Matter model of WIMP



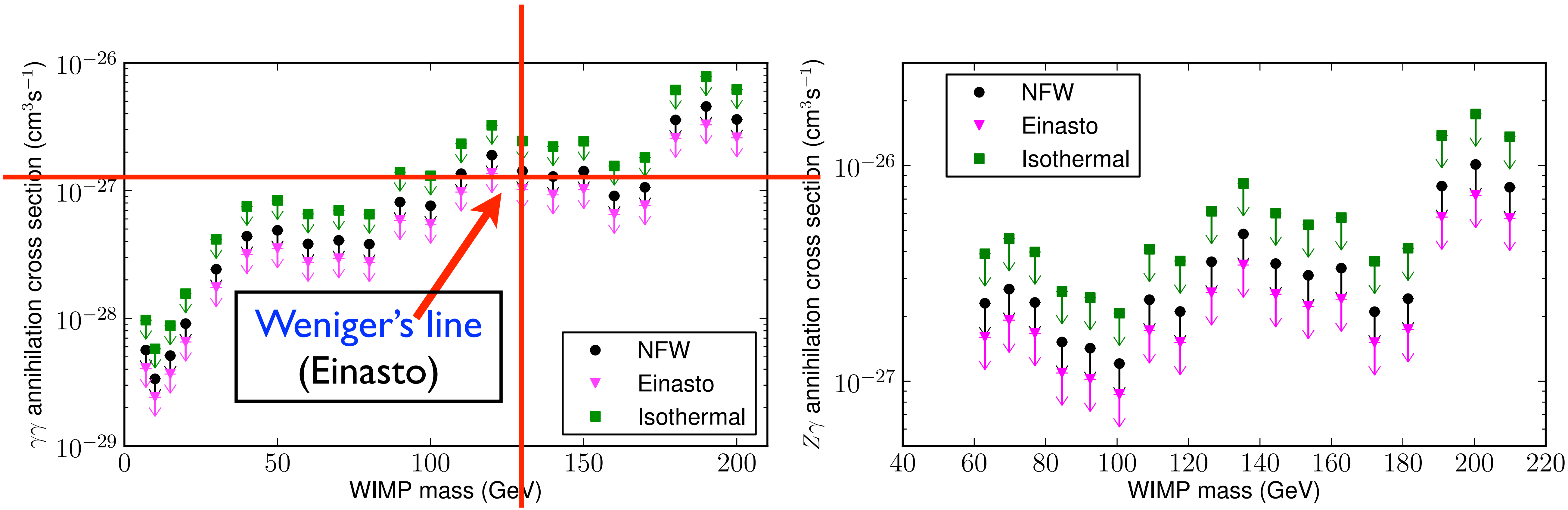
Required annihilation cross section to explain 130 GeV gamma-line

$$\begin{aligned}\langle\sigma v\rangle^{reqd}_{\chi\chi\to\gamma\,\gamma} &\approx 1.27\pm0.32^{+0.18}_{-0.28}\times10^{-27}\mathrm{cm}^3/\mathrm{s}: \quad \mathrm{Einasto}\\ &\approx 2.27\pm0.57^{+0.32}_{-0.51}\times10^{-27}\,\mathrm{cm}^3/\mathrm{s}: \ \mathrm{NFW}\,(1)\end{aligned}$$

[Weniger, 1204.2797]

[arXiv:1205.2739, FERMI-LAT]

Upper limits on the gamma-ray line



→ Marginally consistent with constraints on the line emission from Milky Way halo

→ Consistent with galaxy clusters and dwarf galaxies

Can we explain 130 GeV gamma-line with Dark Matter model of WIMP ?

Required annihilation cross section to explain 130 GeV gamma-line

$$\langle \sigma v \rangle^{reqd}_{\chi\chi\to\gamma\,\gamma} \approx 1.27 \pm 0.32^{+0.18}_{-0.28} \times 10^{-27}\mathrm{cm}^3/\mathrm{s}: \quad \mathrm{Einasto}$$

$$\approx 2.27 \pm 0.57^{+0.32}_{-0.51} \times 10^{-27}\,\mathrm{cm}^3/\mathrm{s}: \;\mathrm{NFW}\,(1)$$

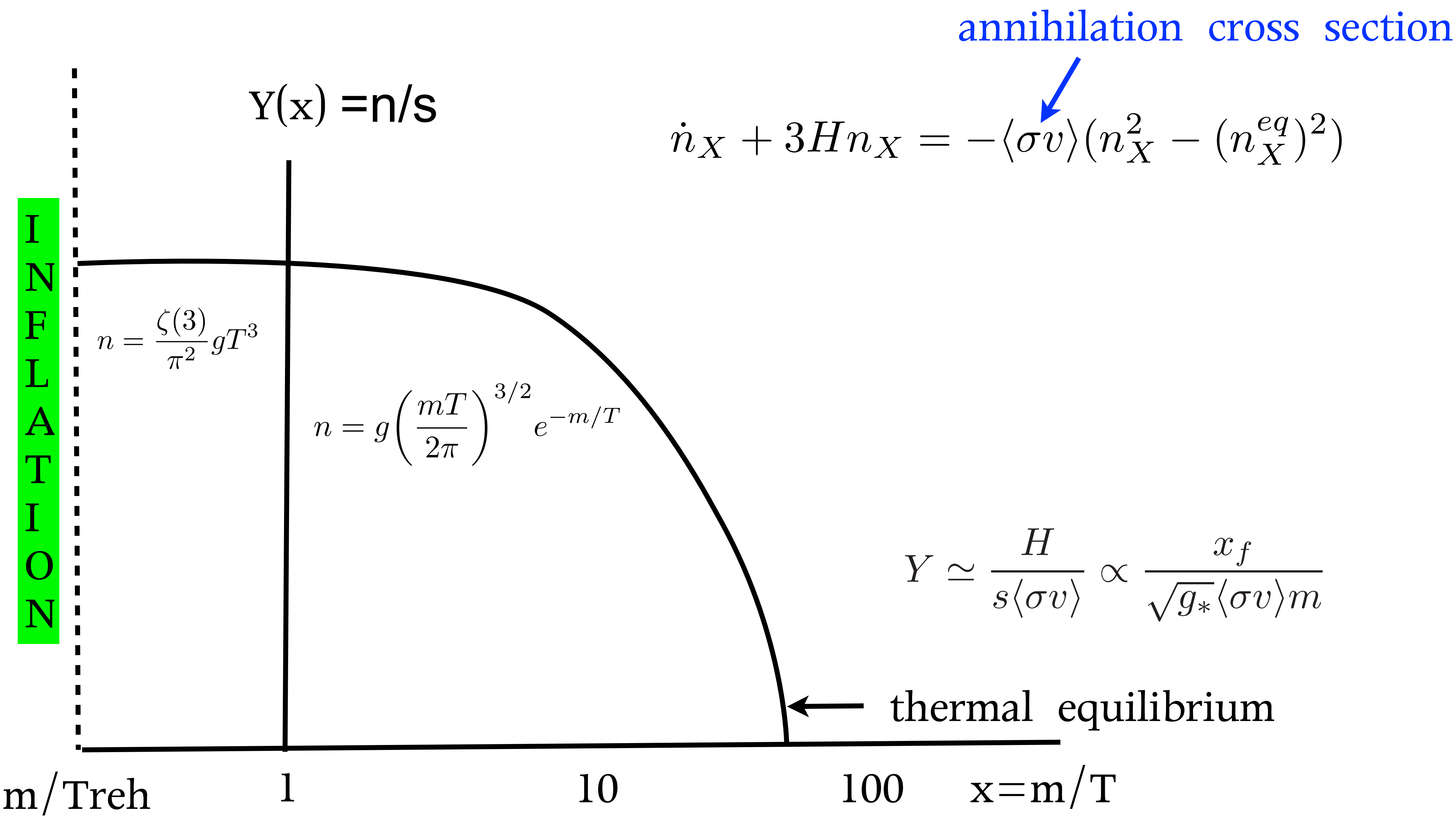
However, relic density?

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

WIMP : Weakly Interacting Massive Particle

[B. W. Lee and S. Weinberg, PRL 1977]

Initially the particles are in the thermal equilibrium and decoupled when it is non-relativistic in the expanding Universe.



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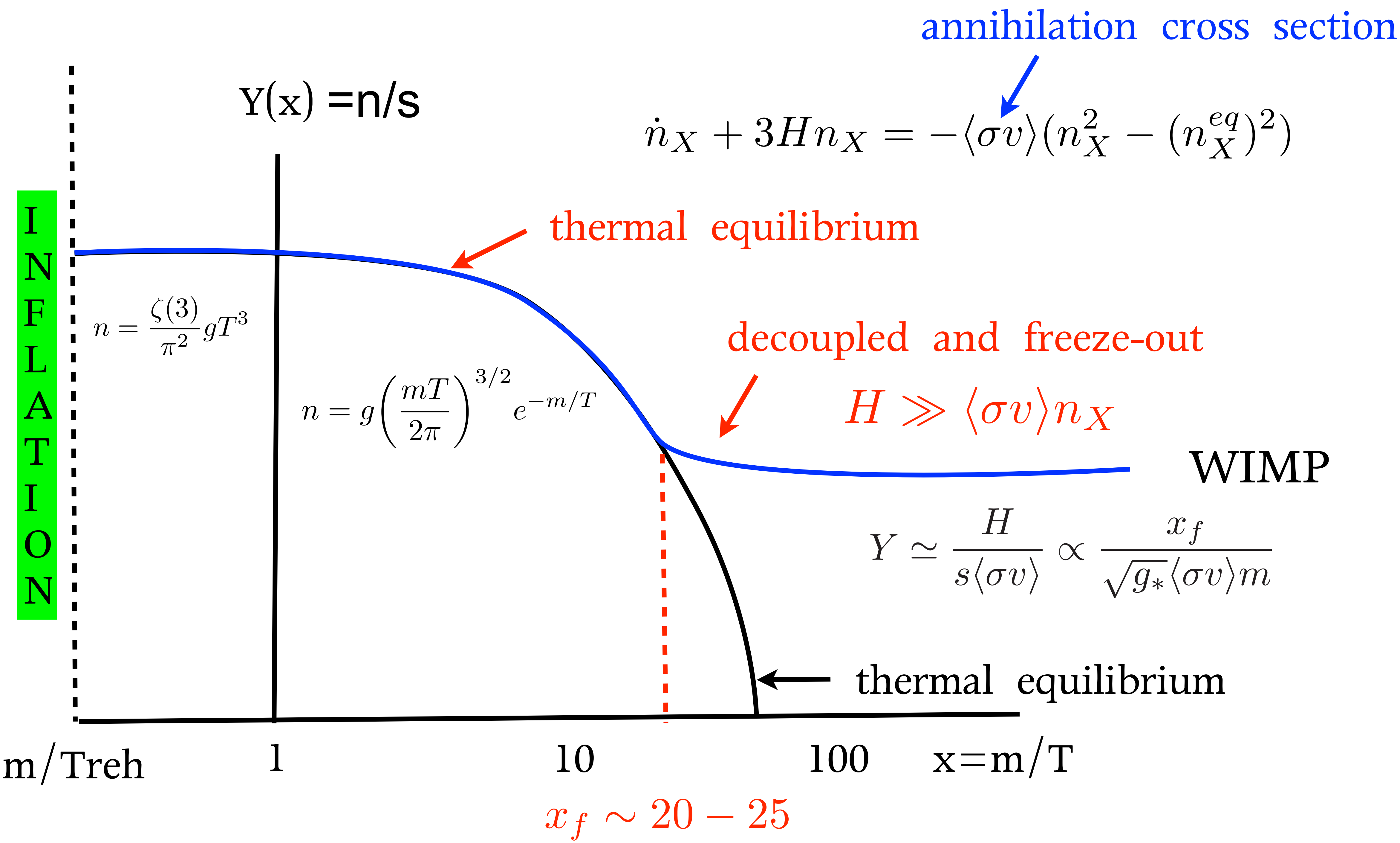
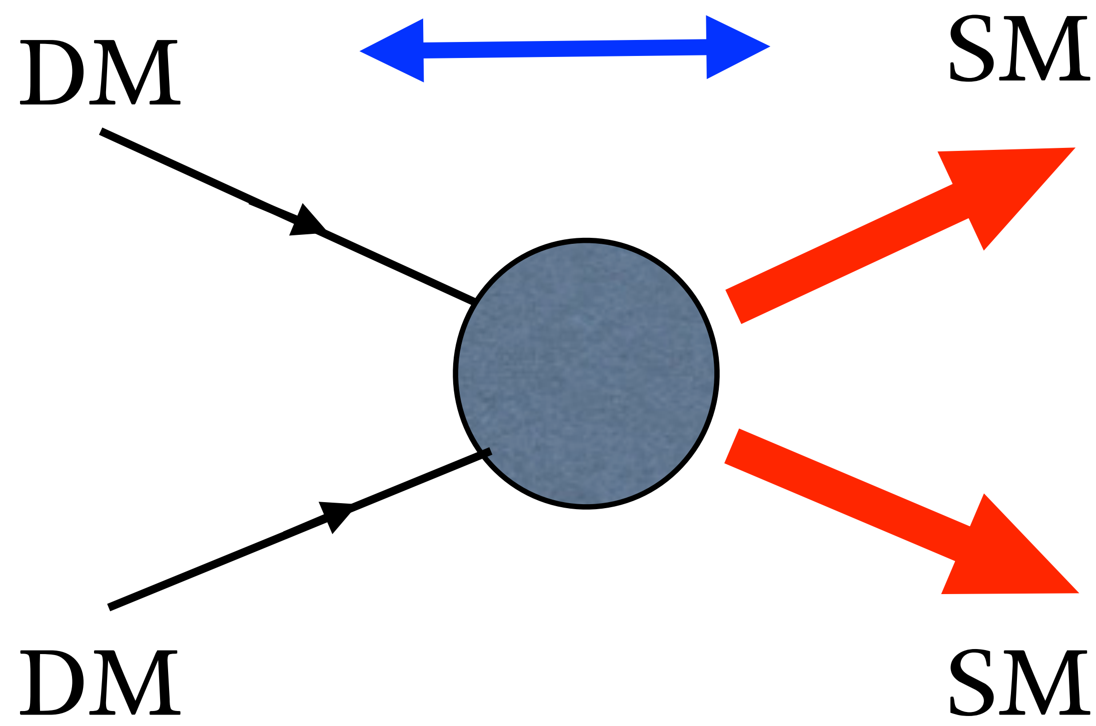


$\boxed{\text{Early Universe}}$

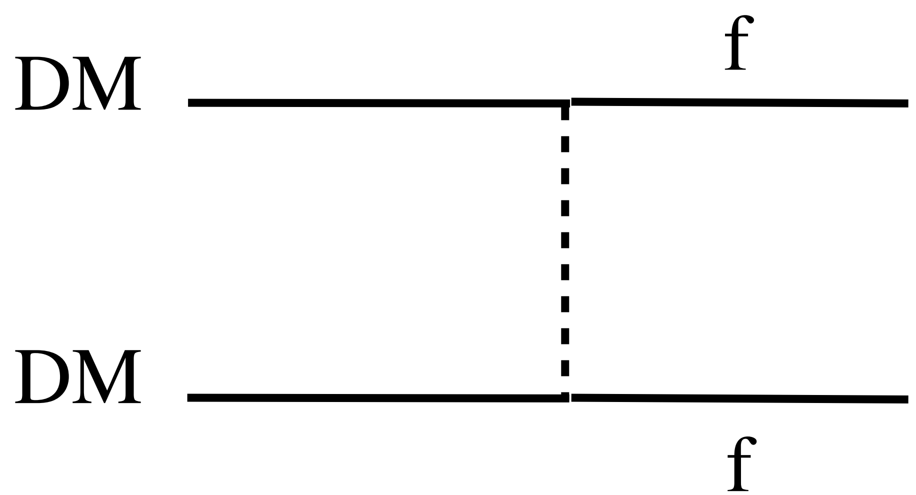
freeze-out



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

$$\text{flux} \propto n^2 \times (\text{annihilation})$$

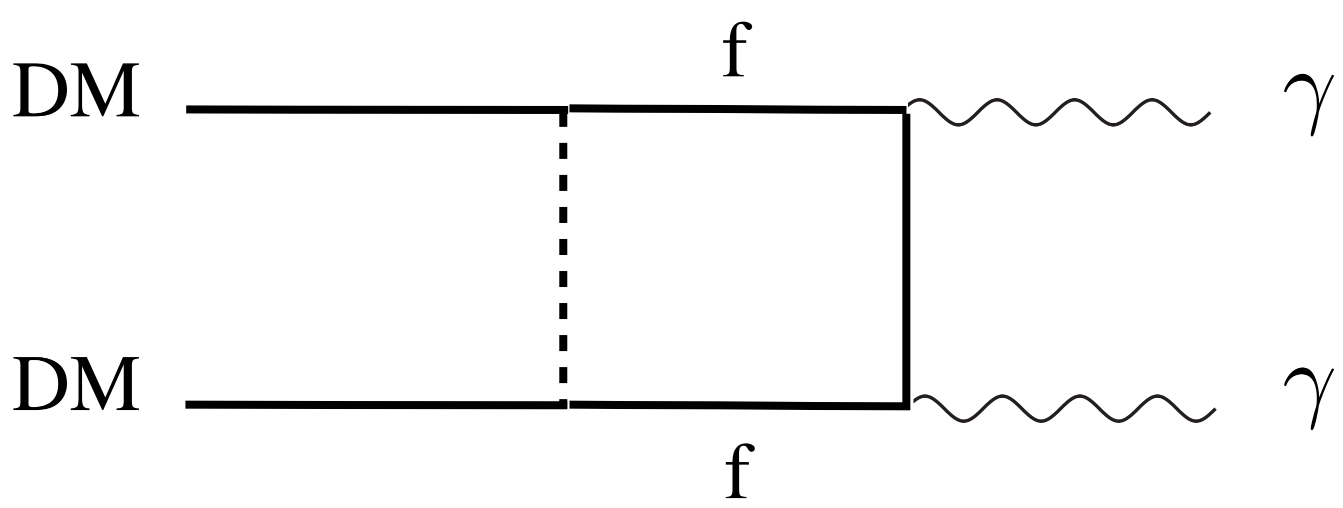
Dark Matter Annihilation



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

Photons are produced at one-loop mediated by the charged particle.

In general, the annihilation to photons are suppressed by a loop factor and gauge coupling.

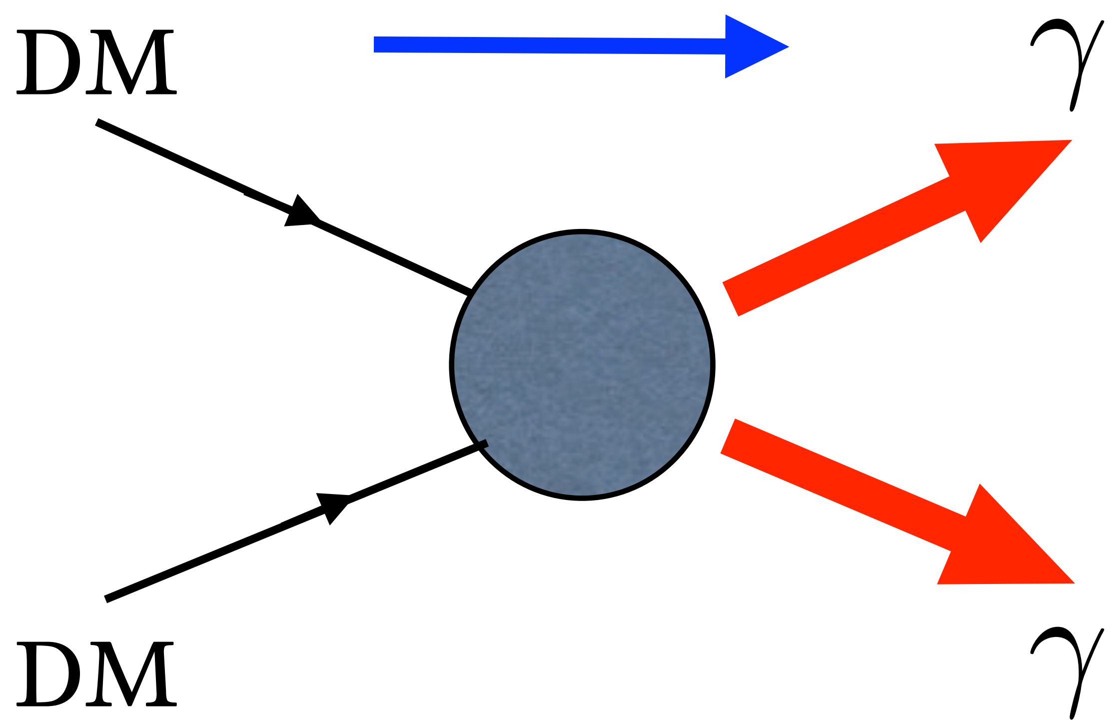


$$\langle \sigma v \rangle_{\chi\chi \to \gamma\,\gamma} \lesssim \frac{1}{16\pi^2}\,\langle \sigma\, v_{\chi\chi}^{therm} \rangle \approx 1.9 \times 10^{-28}\,\mathrm{cm}^3/\mathrm{s},$$

This is much smaller than what we need to explain 130 GeV line.

$$\langle \sigma v \rangle_{\mathrm{FERMI}} \simeq 10^{-27}\,\mathrm{cm}^3/\,\mathrm{sec}$$

$\boxed{\text{Present}}$
annihilation



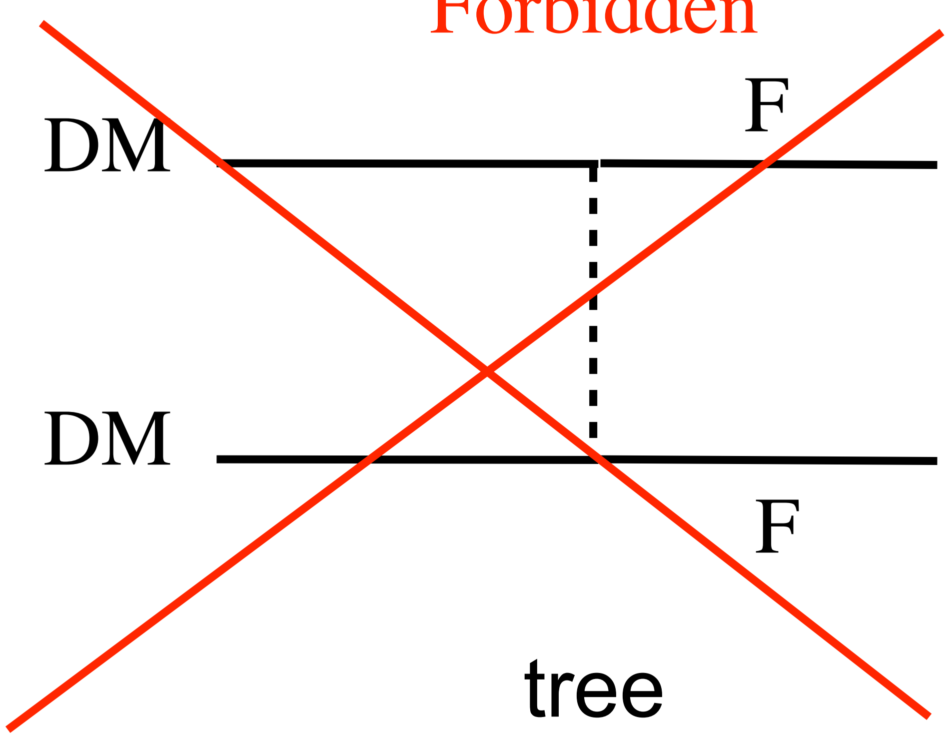
$$\langle \sigma v \rangle_{\mathrm{FERMI}} \simeq 10^{-27}\,\mathrm{cm}^3/\,\mathrm{sec}$$

Large production of photons without changing the total annihilation cross section for the relic density?

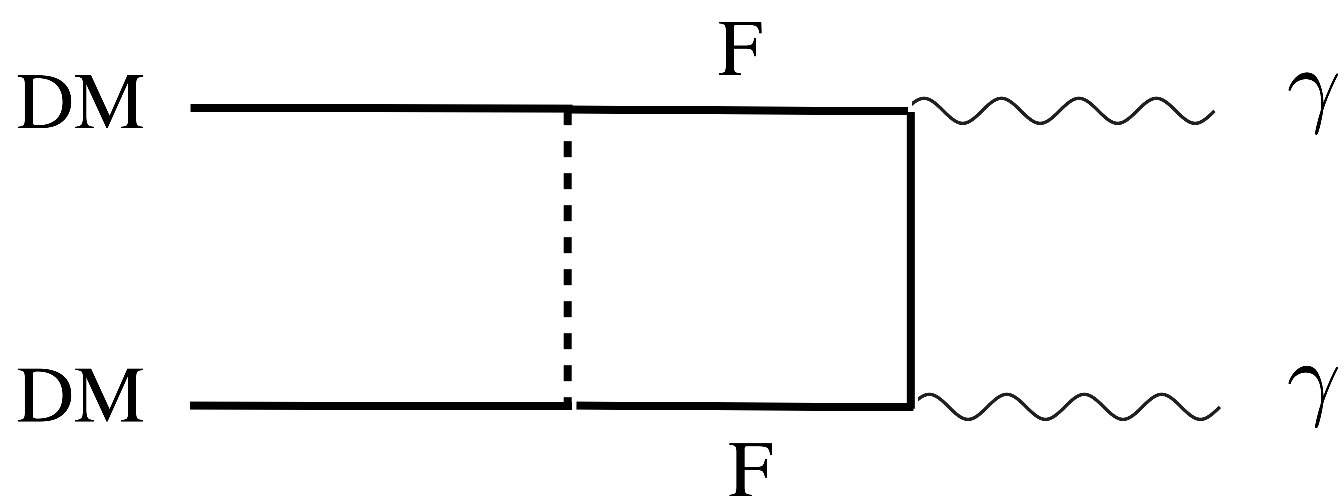
This can be done by the heavy charged particles in the loop which are coupled to the dark matter. Then the tree-level annihilation is not allowed.

$$\boxed{M_{\mathrm{DM}} < M_F}$$

Forbidden



tree



one-loop

Neutrinophilic Higgs model

[E.Ma, 2001]

Naturally Small Neutrino Mass with No New Physics Beyond the TeV Scale

Dirac neutrino $$m_\nu = y'_\nu \langle H_u \rangle = y_\nu \langle H_\nu \rangle$$

$y'_\nu \bar{L} \cdot H_u N$ **or** $y_\nu \bar{L} \cdot H_\nu N$

$y_\nu \sim 10^{-12}$ with $\langle H_u \rangle \sim 100\,\mathrm{GeV}$ $y_\nu \sim \mathcal{O}(1)$ with $\langle H_\nu \rangle \sim 0.1\,\mathrm{eV}$

Small Yukawa with large VEV or large Yukawa with small VEV

[Wang, Wang, Yang, 2006] Split Two-Higgs-Doublet Model and Neutrino Condensation

[Gabriel, Nandi, 2007] A new two Higgs doublet model

[Davidson, Logan, 2009] Dirac neutrinos from a second Higgs doublet

[Haba, Seto, 2011] Thermal leptogenesis in a supersymmetric neutrinophilic Higgs model

- Superpotential

fields	Z_2-parity	lepton number
MSSM Higgs doublets, H_u, H_d	$+$	0
new Higgs doublets, $H_\nu, H_{\nu'}$	$-$	0
right-handed neutrinos, N	$-$	1

$$\begin{aligned} W &= y_u Q \cdot H_u U_R + y_d Q \cdot H_d D_R + y_l L \cdot H_d E_R + y_\nu L \cdot H_\nu N \\ &\quad + \mu H_u \cdot H_d + \mu' H_\nu \cdot H_{\nu'} + \rho H_u \cdot H_{\nu'} + \rho' H_\nu \cdot H_d, \end{aligned}$$

break Z_2 parity, very small
generate large hierarchy of VEVs

Introduce a pair of neutrinophilic Higgs doublet, H_ν and $H_{\nu'}$

A discrete Z_2-parity, which is broken softly, ρ and $\rho'(\ll \mu, \mu')$

$$v_{u,d}(\equiv \langle H_{u,d} \rangle) \gg v_{\nu,\nu'}(\equiv \langle H_{\nu,\nu'} \rangle) = \mathcal{O}\left(\frac{\rho}{\mu'}\right) v$$

to give a small VEV for H_ν and $H_{\nu'}$

- Scalar potential of sneutrinos

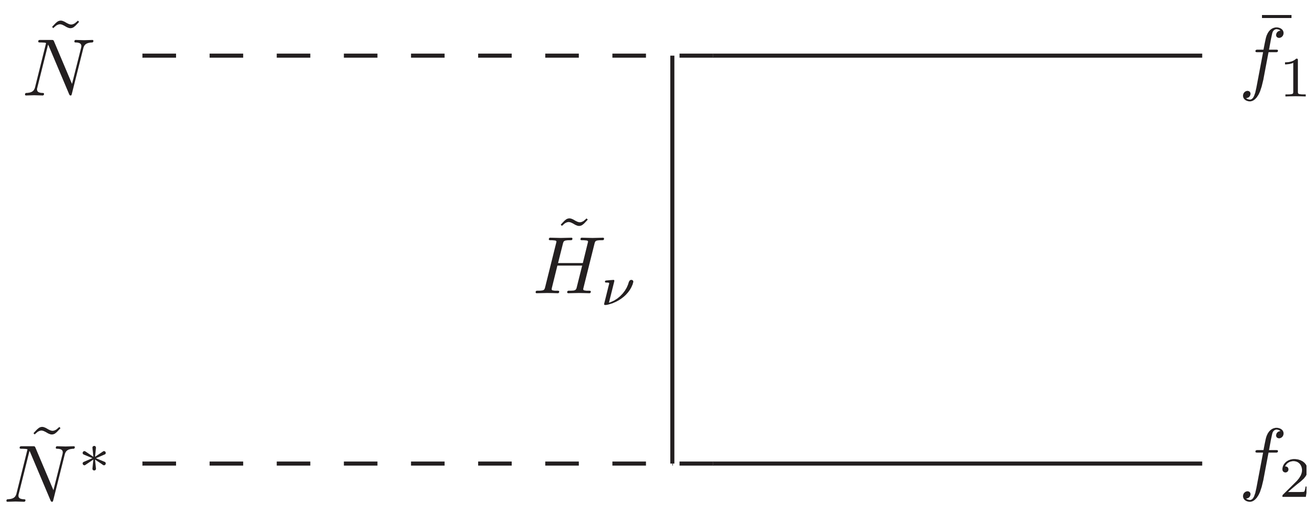
$$V = |y_\nu H_\nu \tilde{N}|^2 + |y_\nu \tilde{L}\tilde{N} - \mu' H_{\nu'} + \rho' H_d|^2 + |y_\nu \tilde{L}\cdot H_\nu|^2 + |y_l \tilde{L}\cdot H_d|^2$$
$$+ m_L^2 |\tilde{L}|^2 + m_{\tilde{N}}^2 |\tilde{N}|^2 + (y_l A_l \tilde{L}\cdot H_d \tilde{E}_R + y_\nu A_\nu \tilde{L}\cdot H_\nu \tilde{N} + h.c.) + \mathrm{D-terms}.$$

Mixing between LH and RH sneutrino is suppressed $\sin\theta_{\tilde{\nu}} = \mathcal{O}\left(\frac{m_\nu}{M_{\mathrm{SUSY}}}\right)$

Lightest RH sneutrino can be stable and Dark Matter.

- Dark matter relic density

  : RH sneutrino as Dark Matter with large Yukawa coupling $y_\nu L \cdot H_\nu N$



charged leptons
or neutrinos

$$\langle \sigma v \rangle = \sum_f \left(\frac{y_\nu^4}{16\pi} \frac{m_f^2}{(M_{\tilde{N}}^2 + M_{\tilde{H}_\nu}^2)^2} + \frac{y_\nu^4}{8\pi} \frac{M_{\tilde{N}}^2}{(M_{\tilde{N}}^2 + M_{\tilde{H}_\nu}^2)^2} \frac{T}{M_{\tilde{N}}} + \ldots \right),$$

(s-wave)
chirality suppressed

(p-wave)
at freeze-out

$$\langle v_{\rm rel}^2 \rangle = 6T/M_{DM} \sim 0.3$$

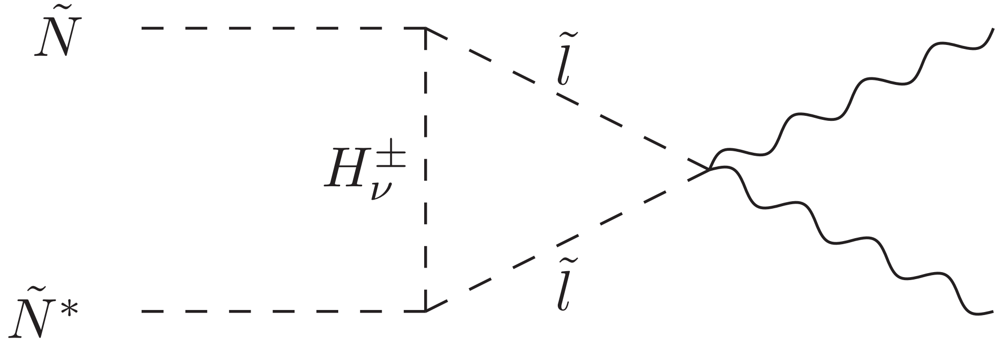
(s-wave) : RH sneutrino DM couples to only leptons, thus s-wave annihilation cross section is always subdominant

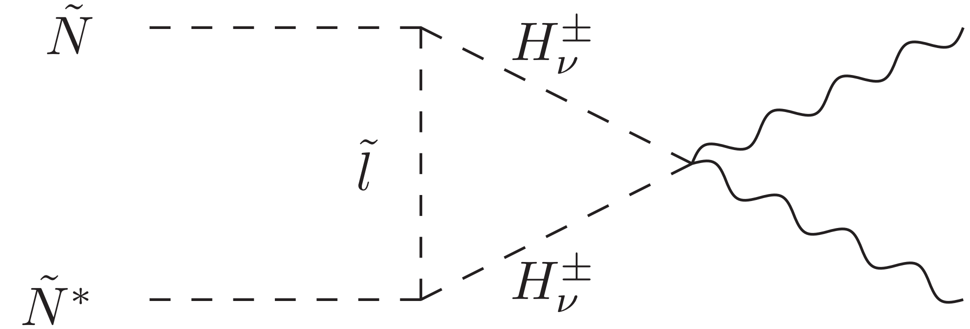
(p-wave) : the dominant annihilation at freeze-out
and give the correct relic density with large Yukawa coupling
Today, it is very suppressed by v~10^-3, thus subdominant.

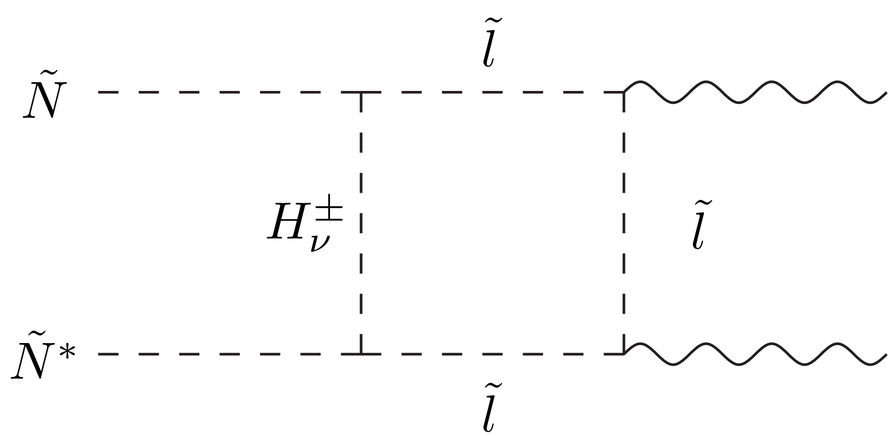
$$\boxed{y_\nu^4 \simeq 1.09 \left(\frac{130\,\mathrm{GeV}}{M_{\tilde{N}}}\right)^2 \left(\frac{M_{\tilde{H}_\nu}}{700\,\mathrm{GeV}}\right)^4 \left(\frac{\langle \sigma v\rangle_{thermal}}{2.57\times 10^{-9}\,\mathrm{GeV}^{-2}}\right) \left(\frac{1/20}{T_f/M_{\tilde{N}}}\right)}$$

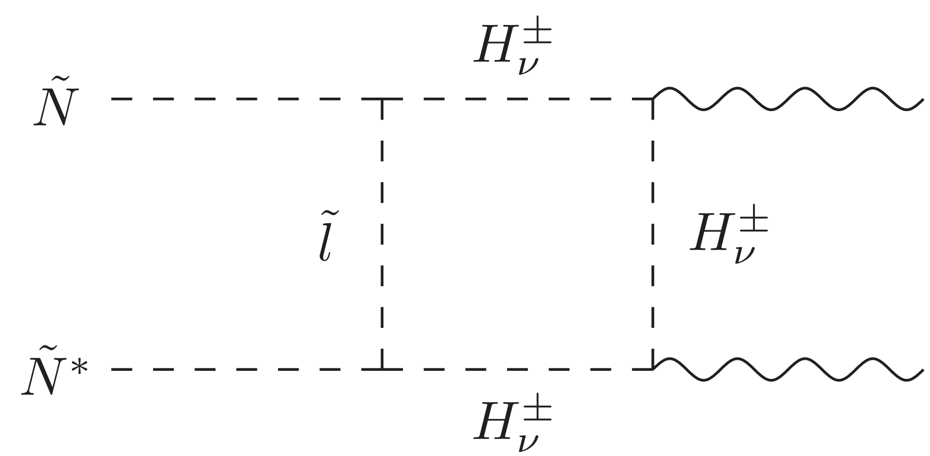
- Monochromatic gamma ray lines

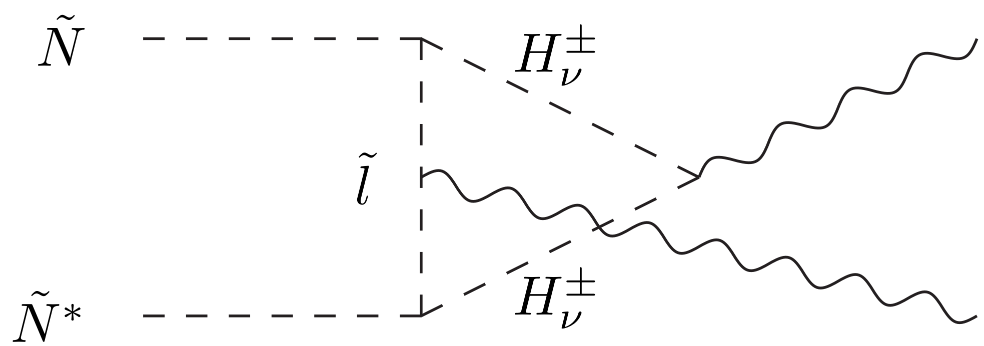
At present the tree-level annihilation is suppressed by the lepton mass or velocity in the halo. Therefore the dominant annihilation of DM in the galaxy at present comes with heavy charged particle in the one-loop.


$\tilde{N}$
$\tilde{l}$
$H_\nu^\pm$
$\tilde{l}$
$\tilde{N}^*$


$\tilde{N}$
$H_\nu^\pm$
$\tilde{l}$
$H_\nu^\pm$
$\tilde{N}^*$


$\tilde{l}$
$\tilde{N}$
$H_\nu^\pm$
$\tilde{l}$
$\tilde{N}^*$
$\tilde{l}$


$H_\nu^\pm$
$\tilde{N}$
$\tilde{l}$
$H_\nu^\pm$
$\tilde{N}^*$
$H_\nu^\pm$


$\tilde{N}$
$H_\nu^\pm$
$\tilde{l}$
$H_\nu^\pm$
$\tilde{N}^*$

130 GeV gamma-line from public Fermi-LAT data

Dark Matter signature?

If yes, then RH sneutrino DM in leptophilic Higgs model can explain.

$\boxed{\tilde{N} + \tilde{N} \to \gamma + \gamma}$ with $E_{2\gamma} = M_{\tilde{N}}$

$$\langle \sigma v \rangle_{2\gamma} \simeq \frac{4\alpha_{\rm em}^2}{\pi^2} \frac{y_\nu^4 (A_\nu^2 + \mu'^2)^2}{M_{\tilde{l}}^4} \frac{4}{M_{\tilde{N}}^2},$$

$\langle \sigma v \rangle_{(\tilde{N}\tilde{N} \to \gamma\gamma)} = \langle \sigma v \rangle^{\rm Fermi\text{-}LAT}_{(\tilde{N}\tilde{N} \to \gamma\gamma)}.$ with the parameters given by

$$\boxed{y_\nu^4 (A_\nu^2 + \mu'^2)^2 \simeq 0.018 M_{\tilde{l}}^4,}$$

Second line signal at 114 GeV

$$\boxed{\tilde{N} + \tilde{N} \to Z + \gamma} \qquad \textbf{with} \quad E_{1\gamma} \simeq M_{\tilde{N}} \left(1 - \frac{M_Z^2}{4M_{\tilde{N}}^2} \right)$$

$$\langle \sigma v \rangle_{1\gamma} \simeq \frac{4\alpha_{\rm em}^2}{\pi^2 \cos^2\theta_{\rm w}} \frac{y_\nu^4 (A_\nu^2 + \mu'^2)^2}{M_{\tilde{l}}^4} \frac{4}{M_{\tilde{N}}^2} \left(1 - \frac{M_Z^2}{4M_{\tilde{N}}^2} \right),$$

Discussion

1. Dark matters are around us and can be detected in the observation of gamma ray or cosmic rays.

2. Gamma-ray signal at Fermi-LAT may be the signature of dark matter.

3. The line signal can be explained with RH sneutrino dark matter in the neutrinophilic Higgs model.