Indirect Dark Matter Searches

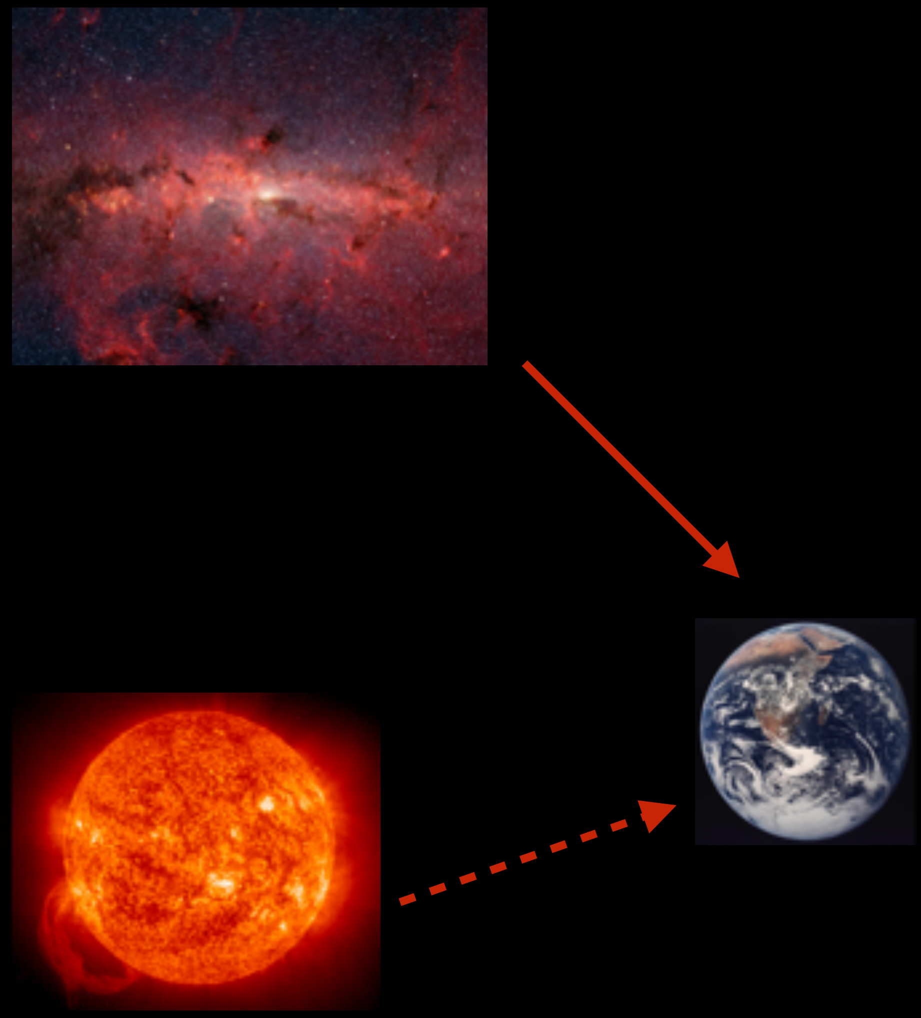
Bjoern Penning

Outline

- Indirect dark matter detection: basics.
- Searches with gamma rays: instruments and targets.
- Searches with gamma rays: results from different targets.
- Searches with charged cosmic rays and neutrinos.
- Beyond WIMPs.

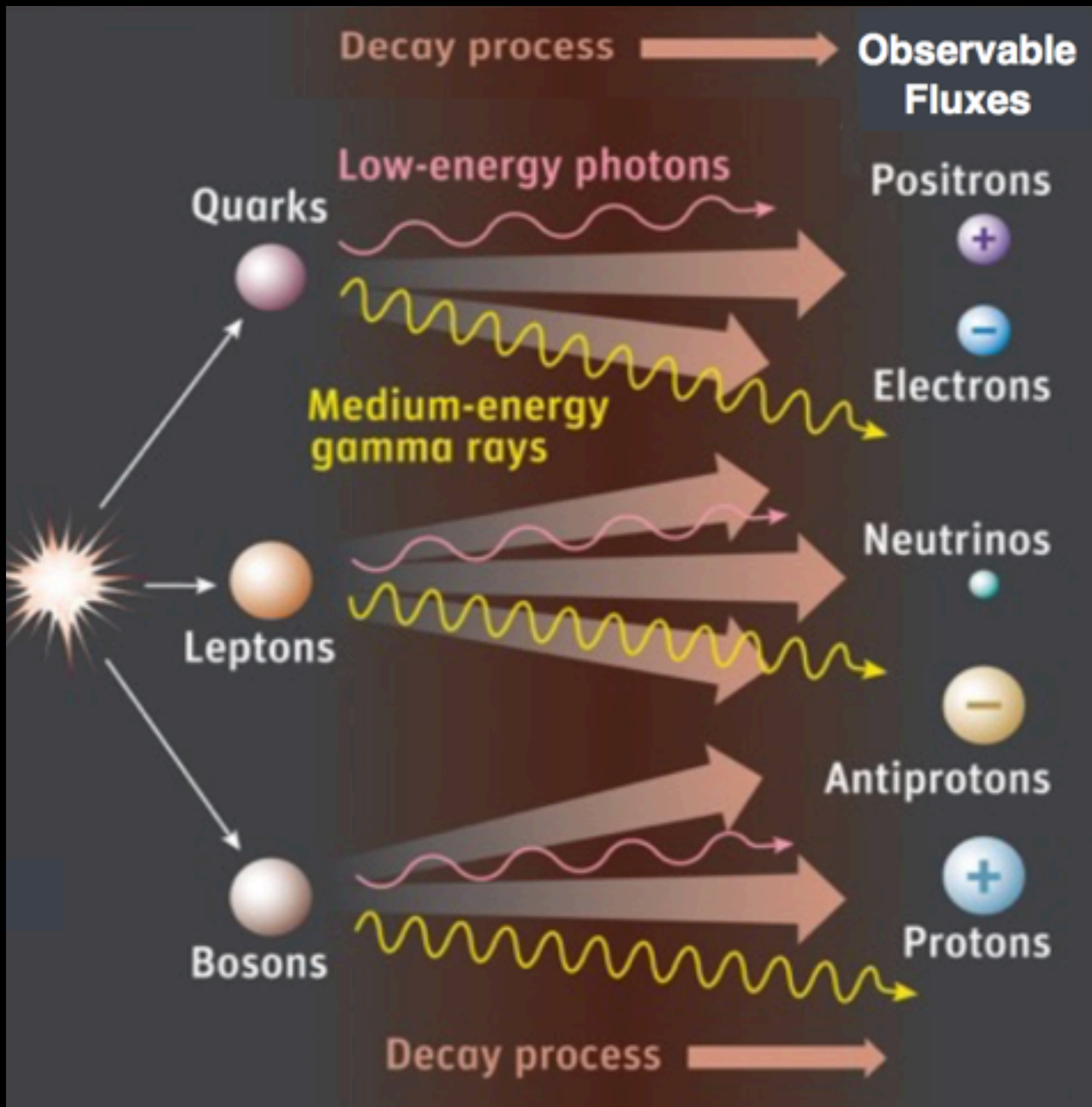
Principle of Indirect Searches

- Dark matter annihilates 'where', into 'what' and is measured 'how'?
- Where?: Objects where dark matter can have accumulated gravitationally over the evolution of the Universe
  - Galactic center, galactic halo
  - Subhalos, dwarf spheroidals, the Sun ..
- Into what?: Stable SM particles independent of DM model
  - $\chi\chi \rightarrow q/W/Z/H/lep \rightarrow \gamma, e^{\pm}, \nu, p$
- How measured?
  - Satellites or balloons measuring charged particles, γ's or X-rays
  - Cherenkov telescopes and large neutrino observatories

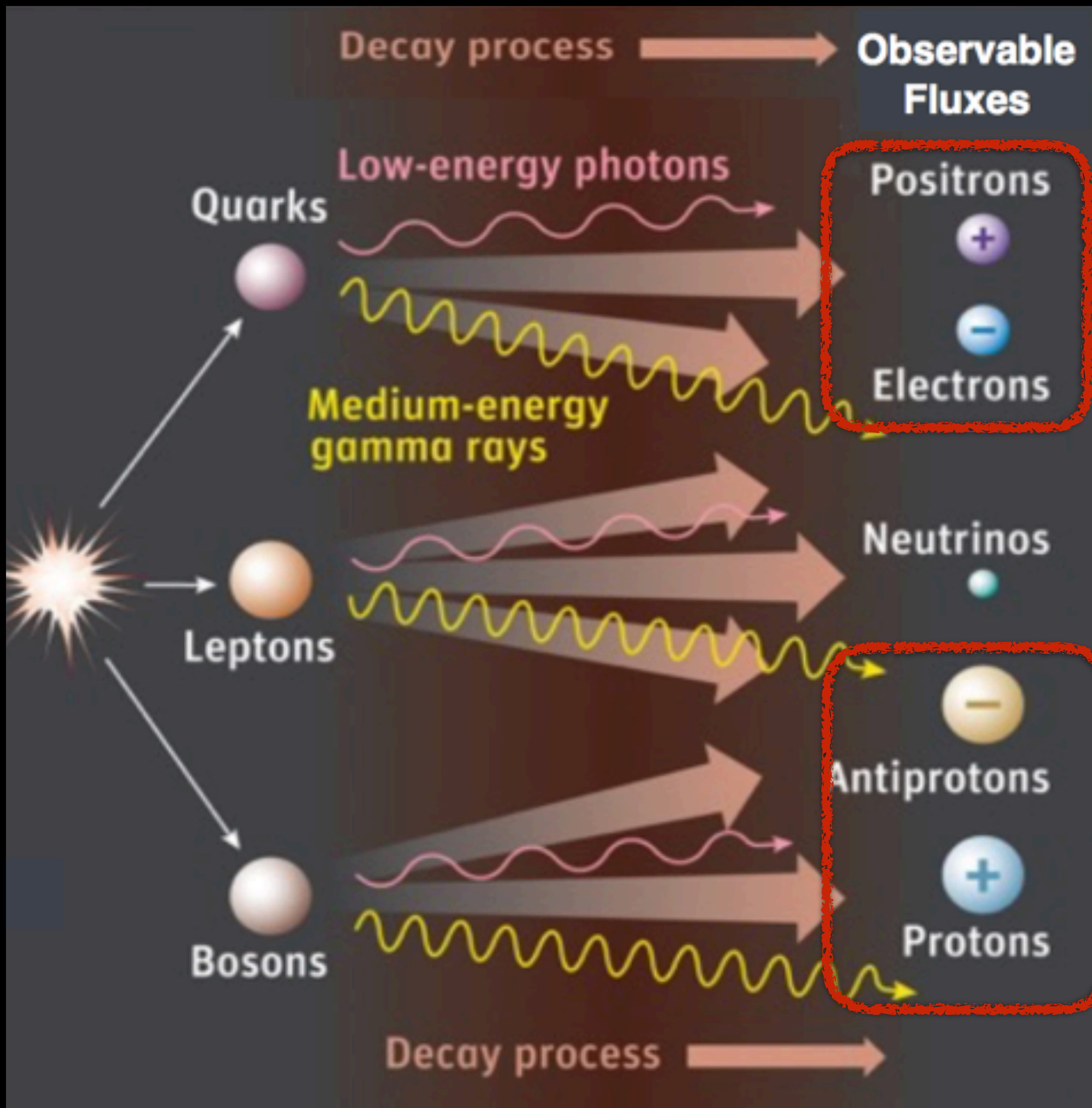


- Uncertainties:
  - DM density and velocity
  - Properties of DM & interactions
  - Relic density calculations
  - Self-interactions
  - Backgrounds

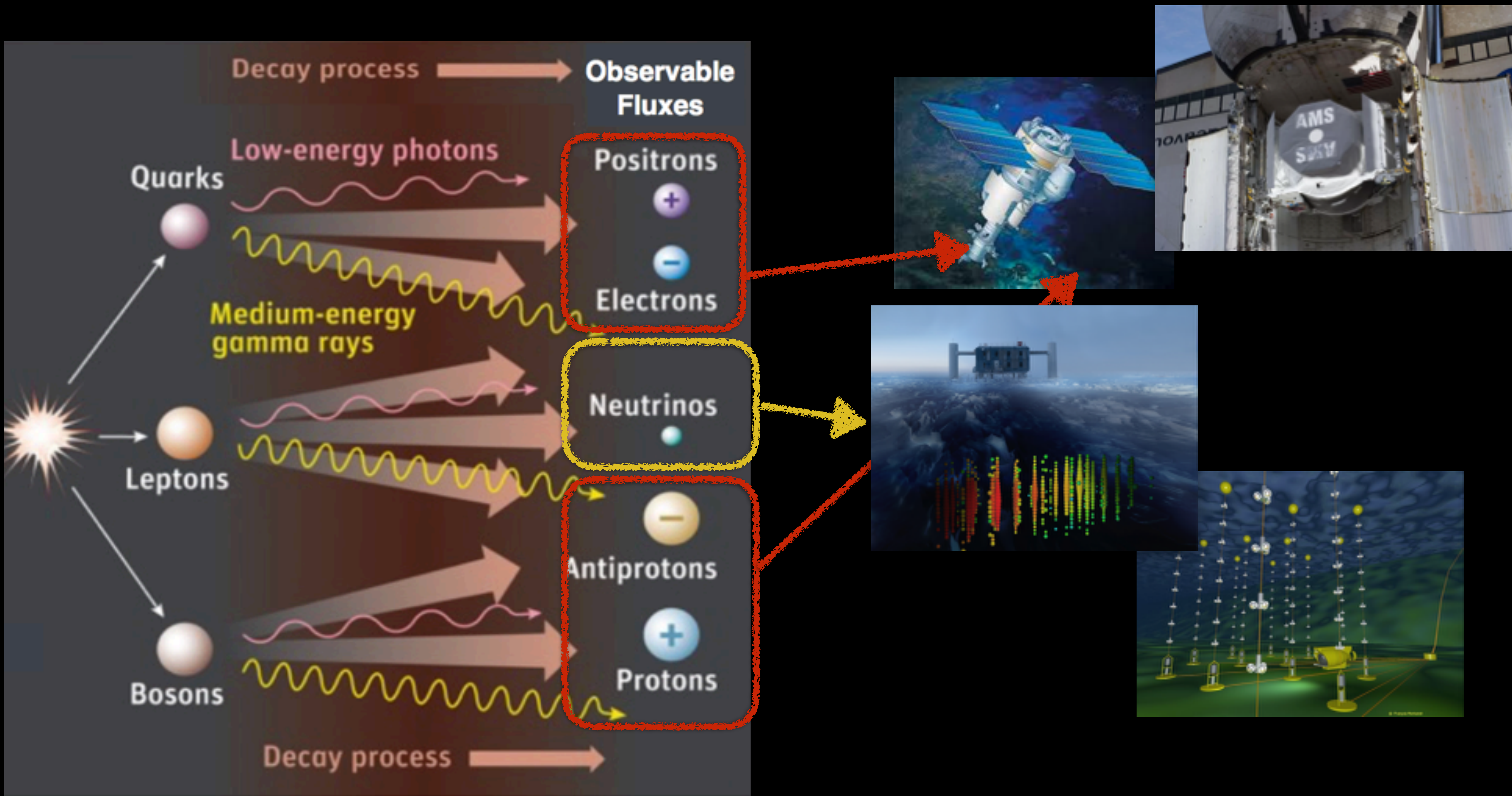
Principle of Indirect Searches



Principle of Indirect Searches



Principle of Indirect Searches



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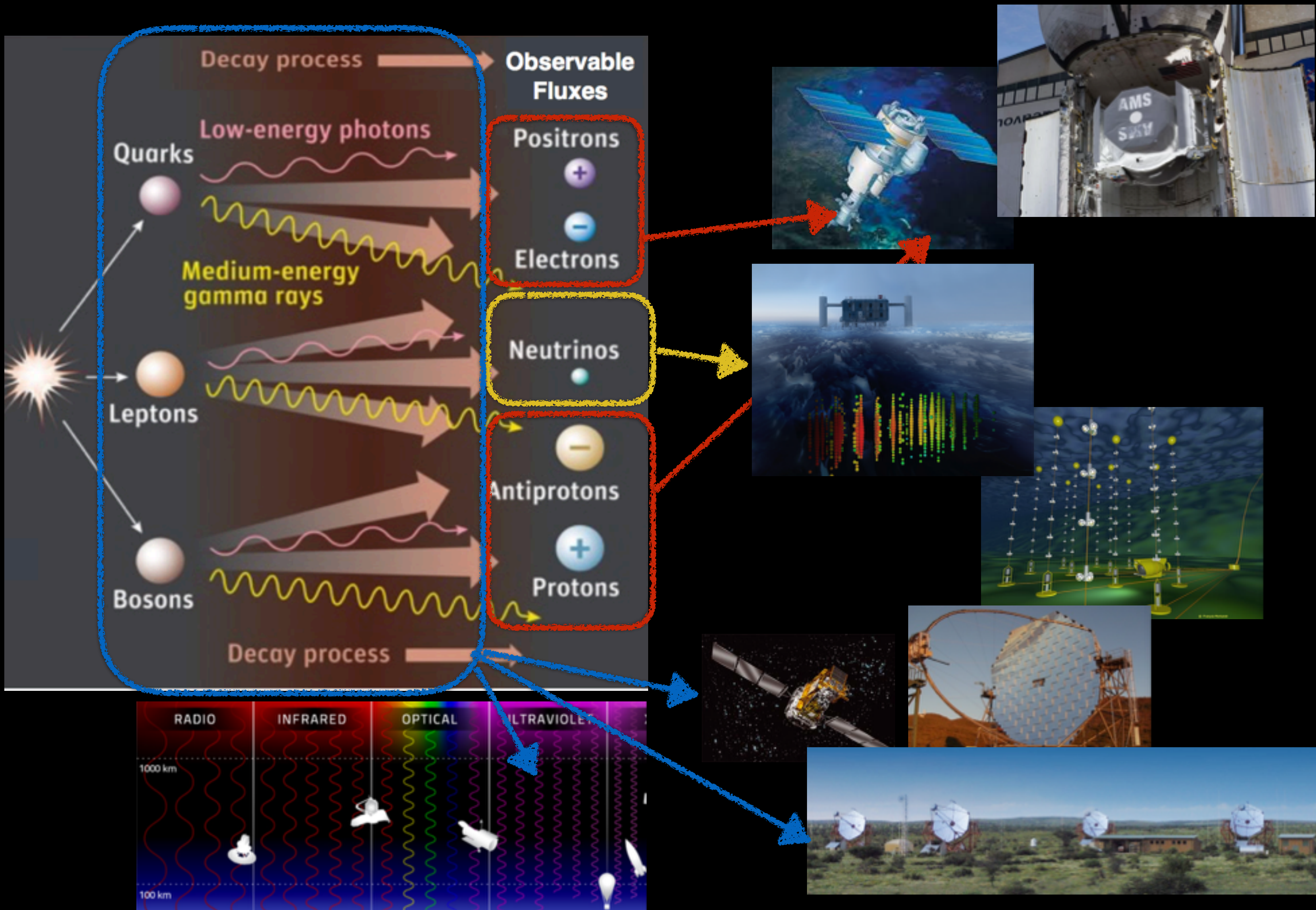
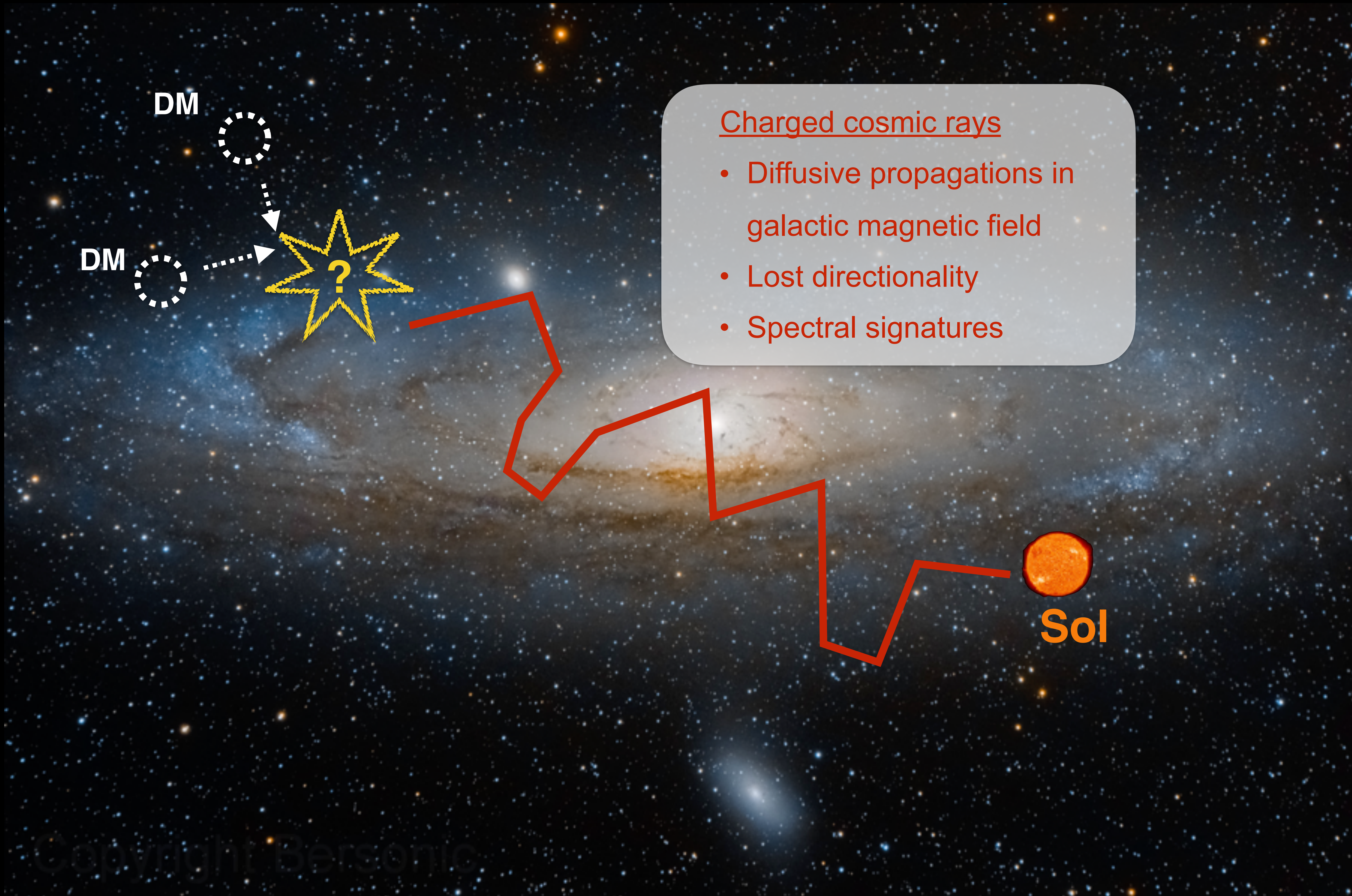
Principle of Indirect Searches



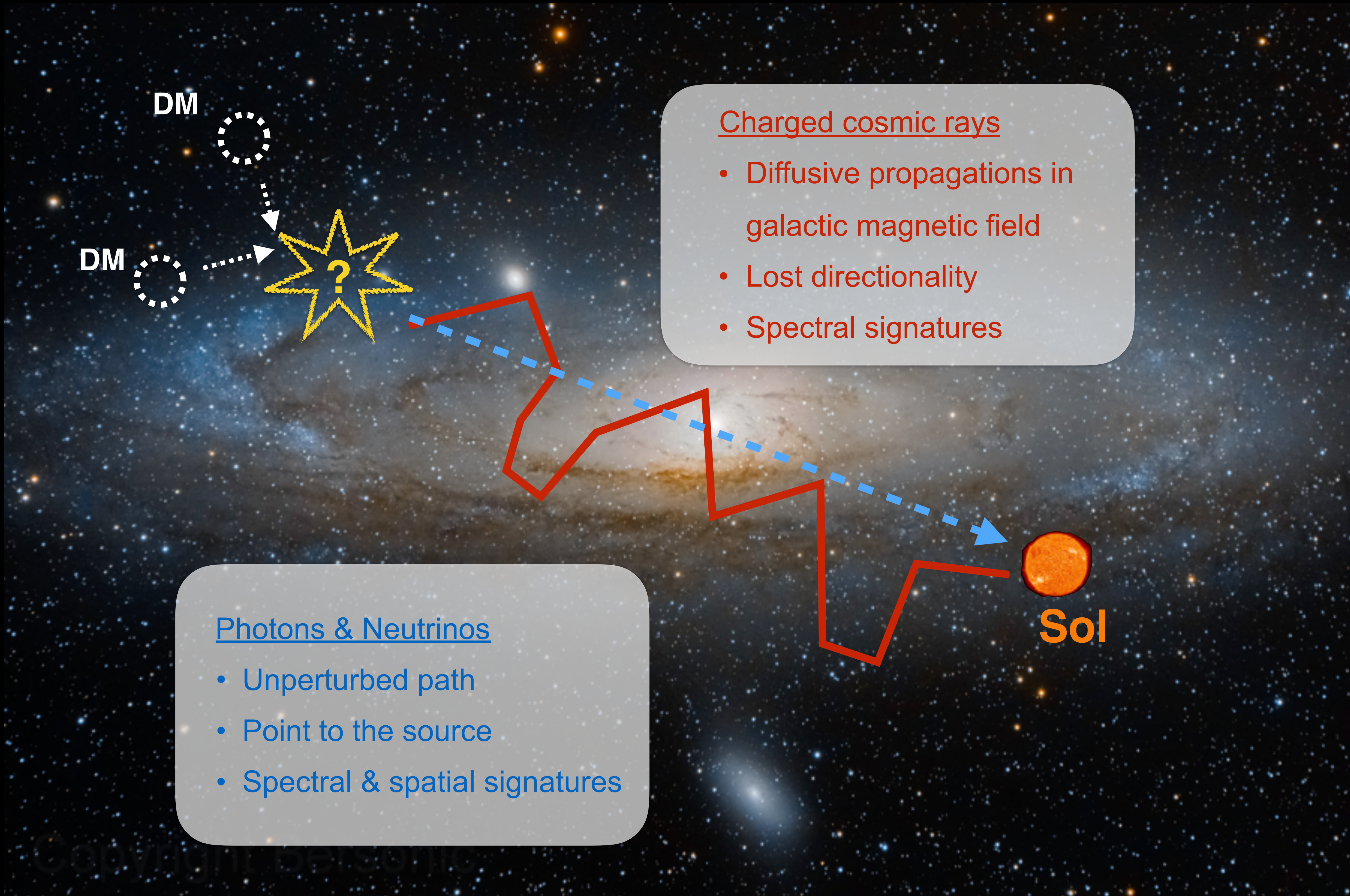
Galactic Messenger



Charged cosmic rays

- Diffusive propagations in galactic magnetic field
- Lost directionality
- Spectral signatures

Galactic Messenger



Charged cosmic rays
- Diffusive propagations in galactic magnetic field
- Lost directionality
- Spectral signatures

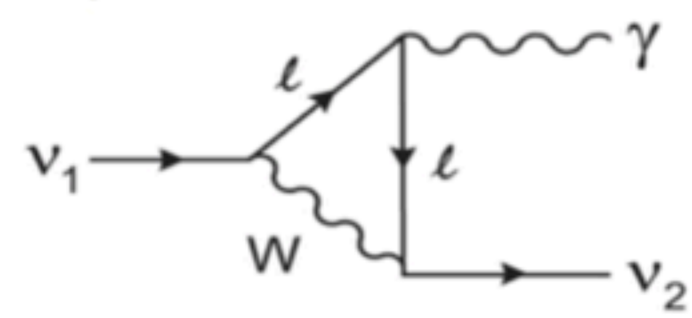
Photons & Neutrinos
- Unperturbed path
- Point to the source
- Spectral & spatial signatures

- Expected values? We know where to look for...

Annihilation

$$\langle \sigma v \rangle = 3 \times 10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1}$$

Decay



$$\tau_{\mathrm{DM}} \sim 10^{26}\,\mathrm{s}\left(\frac{\mathrm{TeV}}{m_{\mathrm{DM}}}\right)^5\left(\frac{M}{10^{15}\,\mathrm{GeV}}\right)^4$$

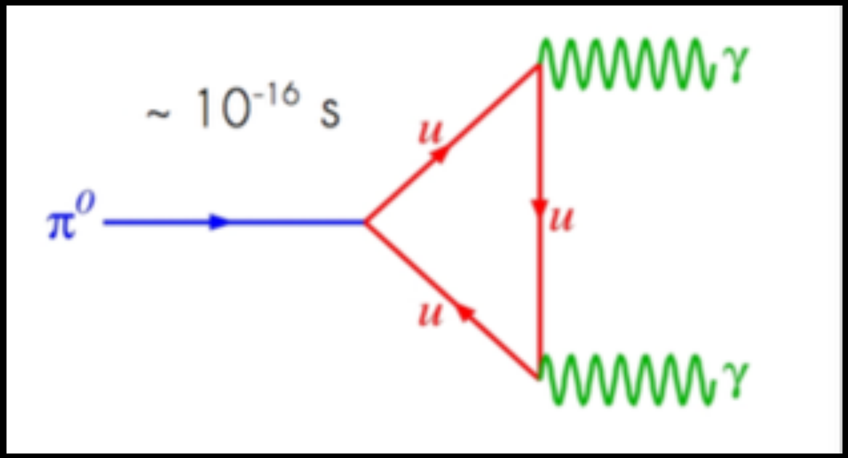
Gamma Ray Emission

- Gamma-rays are produced in potential DM interactions by SM physics

$$\chi\chi \to \left\{ \begin{array}{c} \mathrm{ZZ},\ \mathrm{W}^+\ \mathrm{W}^-,\ \gamma\gamma \\ q\bar{q},\ \ell^+\ell^-,\ \nu\bar{\nu} \end{array} \right\} \xrightarrow{\text{had./decay}} \gamma, e^\pm, \mu^\pm, p/\bar{p}, \pi^\pm, \nu/\bar{\nu} \ldots$$

π^0

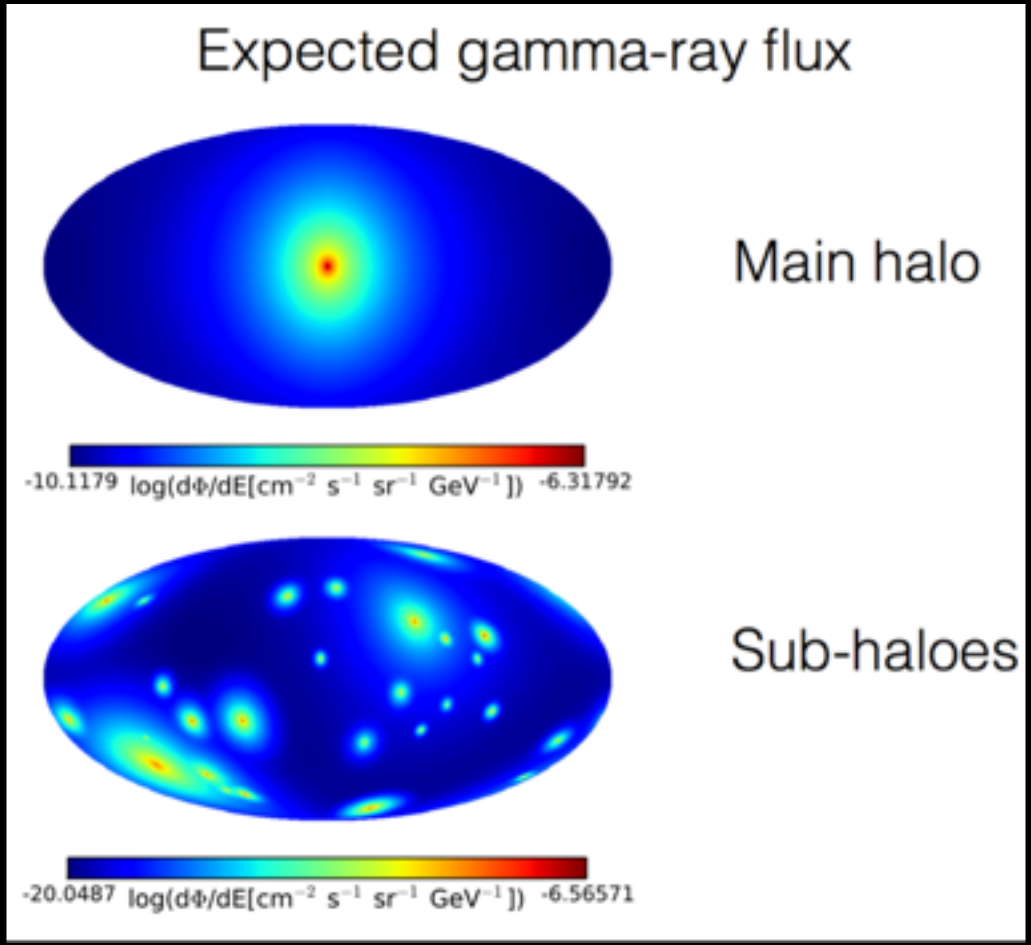
- Parton showers from initial quarks and gluons and hadronization into light colour-neutral hadrons
→ model independent "prompt" gamma-ray emission

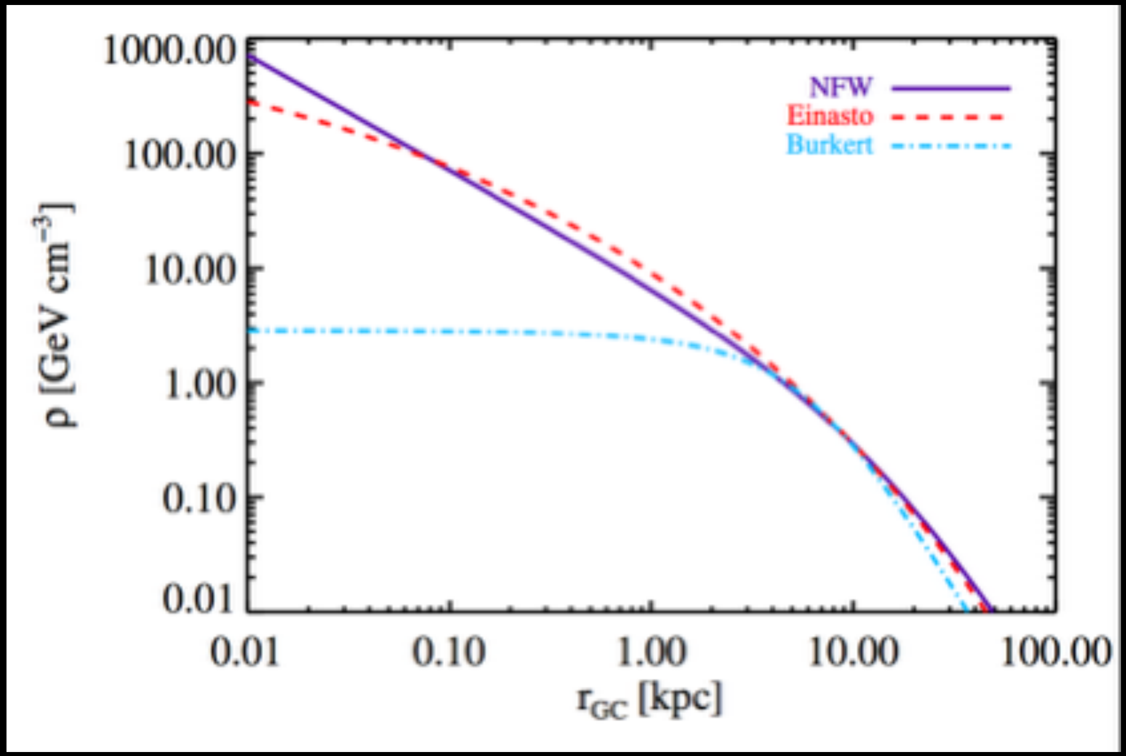


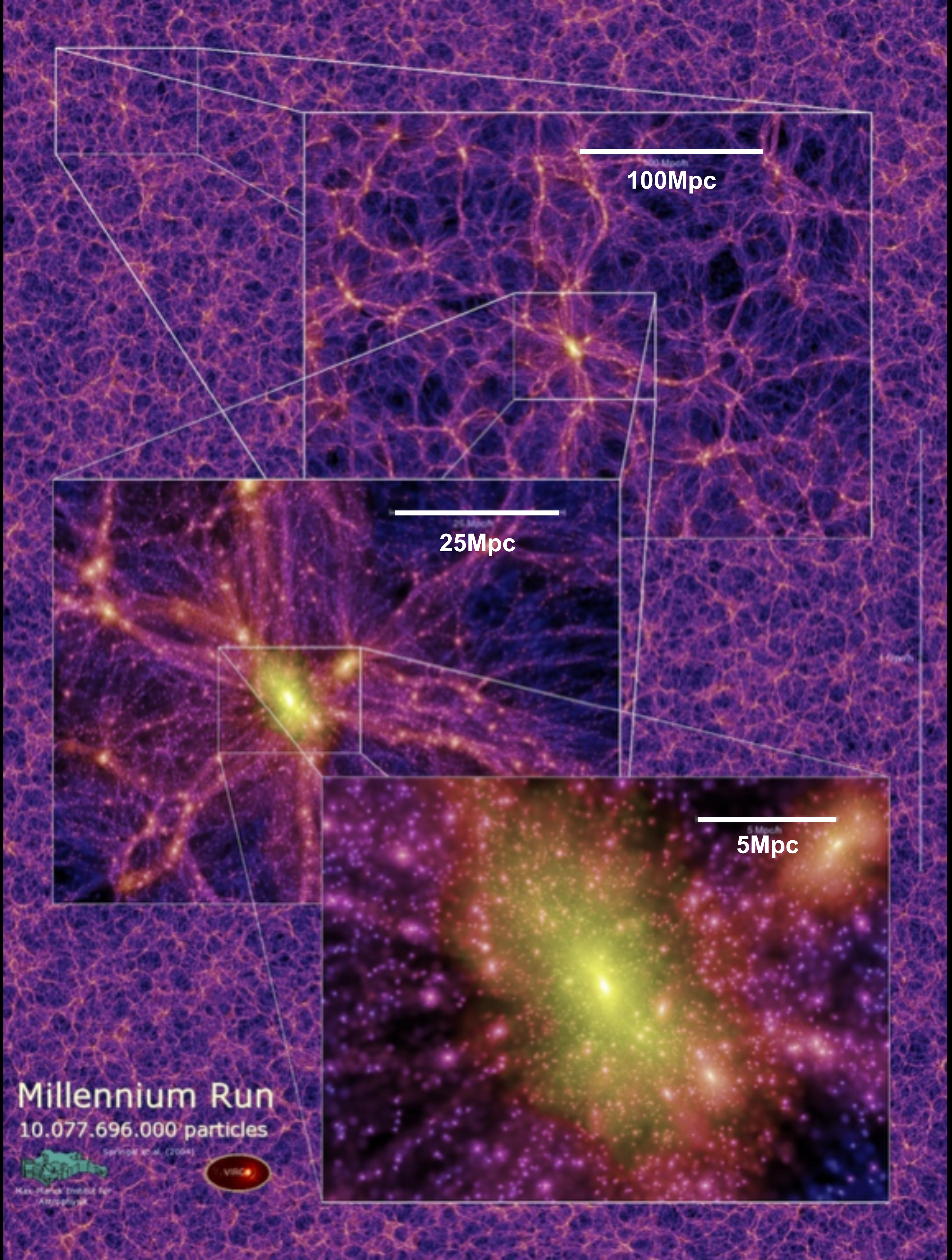
- Decay products can lead to secondary gamma-ray emission

Dark Matter Distribution in World

- From rotation curves: $\rho_{DM}(r) \sim 1/r^2$
  - Baryons interact strongly and dissipate energy → collapse into disc
  - DM is not dissipative → forms spherical halo
- Simulations and observations suggest that simple halo has to be modified
  - Baryons pulling DM
  - Feedback from supernovae
  - Interactions between an active galactic nucleus and interstellar medium
- Tri-axial distributions, similar at larger radii, modifying the core profile






100Mpc
25Mpc
5Mpc
Millennium Run
10.077.696.000 particles

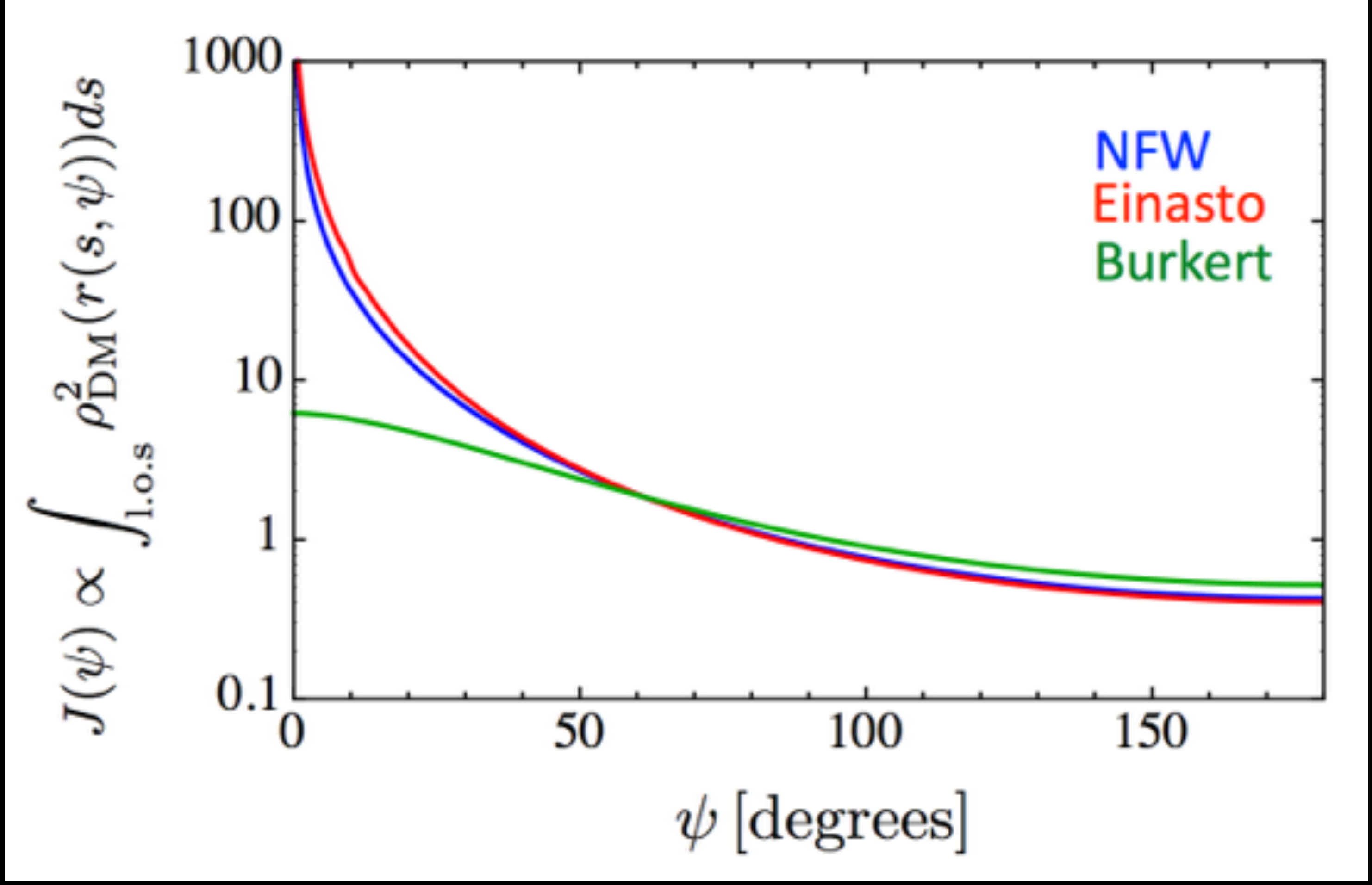
J-Factor

- Rate of annihilation scales with density squared
- Gamma flux from DM factored into DM model and DM distributions: J-Factors

$$J_{\text{dec}}(\psi) = \int_{\text{los}} \rho(\psi, l) dl$$

- Astrophys. uncertainties of the flux are absorbed by the J-factor
- The larger the J-factor the more interesting the target
  - Balance with backgrounds
  - Most favorable targets are generally nearby, high dark matter densities, low backgrounds

Target	$\log_{10}(J_{\text{ann}})$
Galactic Center	21.5
Dwarf galaxies (best)	19
Galaxy clusters (best)	18



J-factors for different DM profiles

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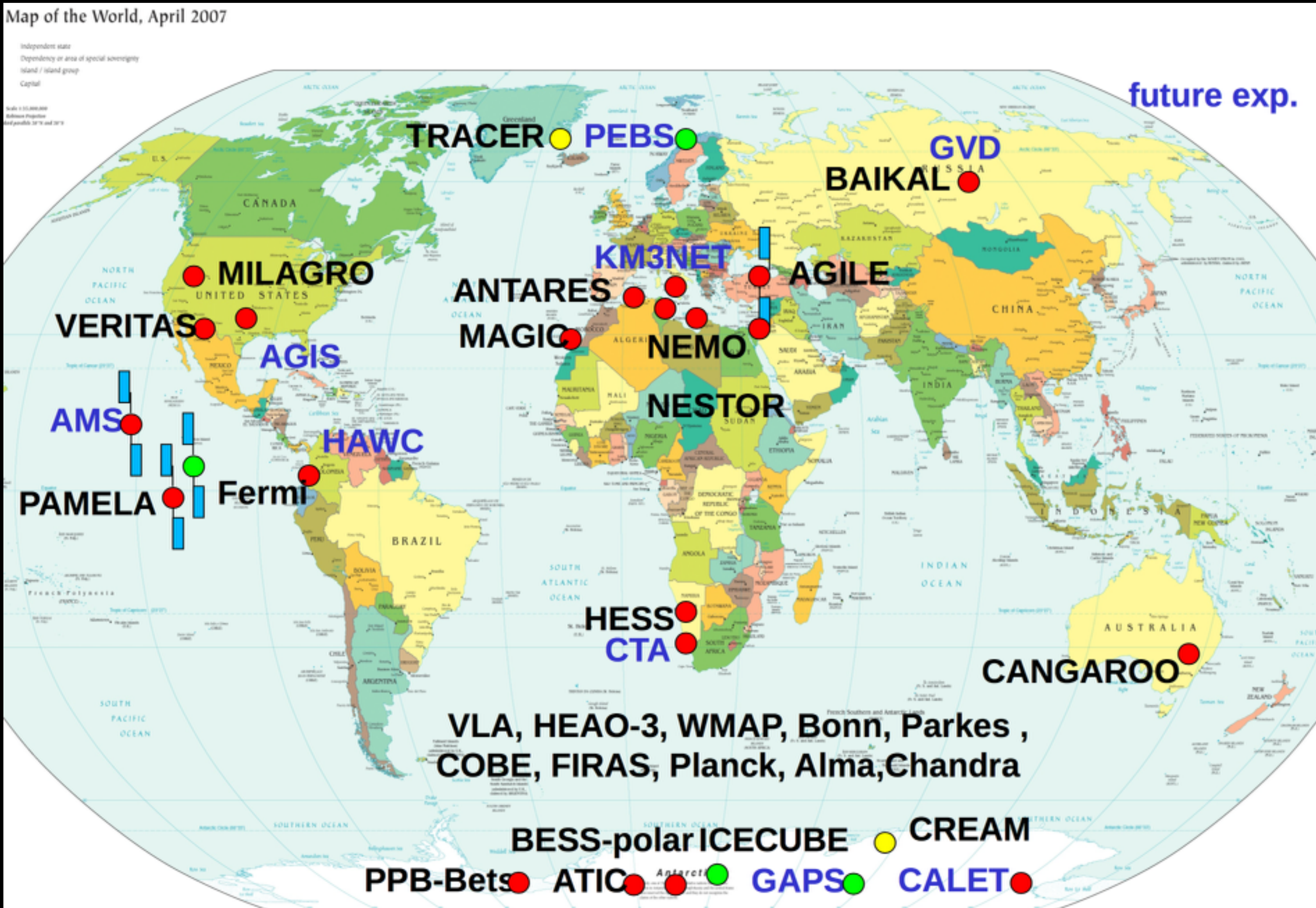
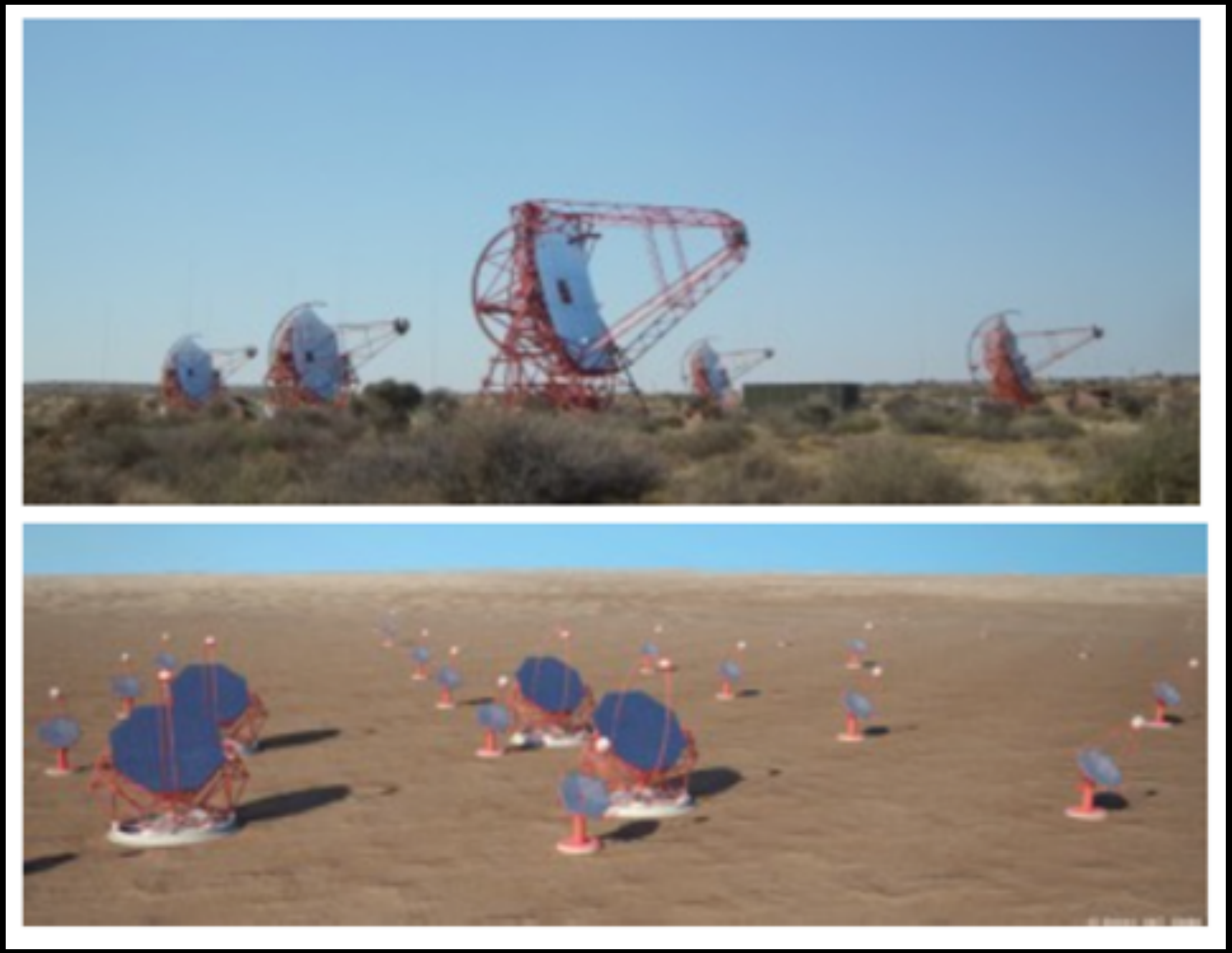
Telescopes

Cannot cover all Indirect DM searches



γ-ray detectors

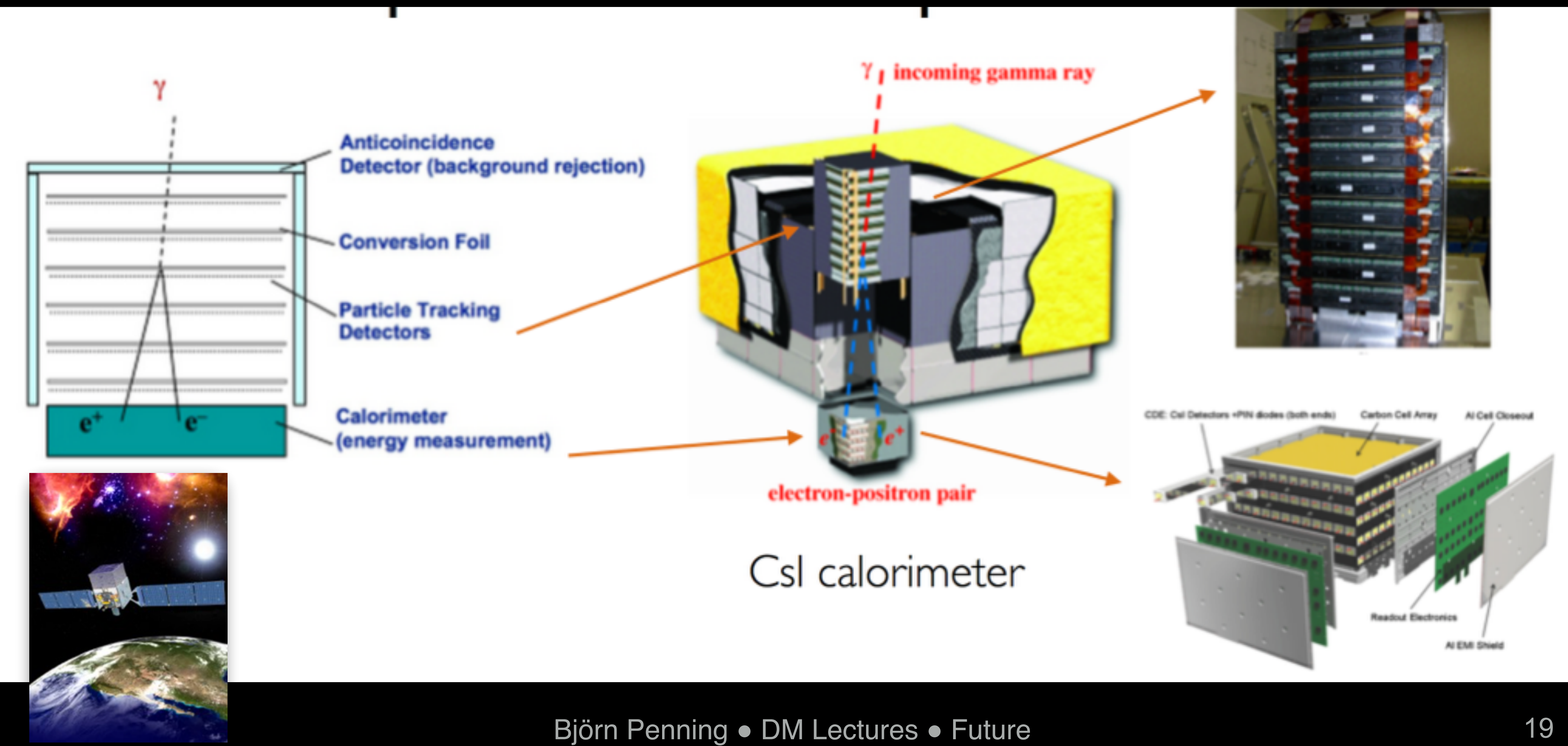
Gamma-Ray Telescopes



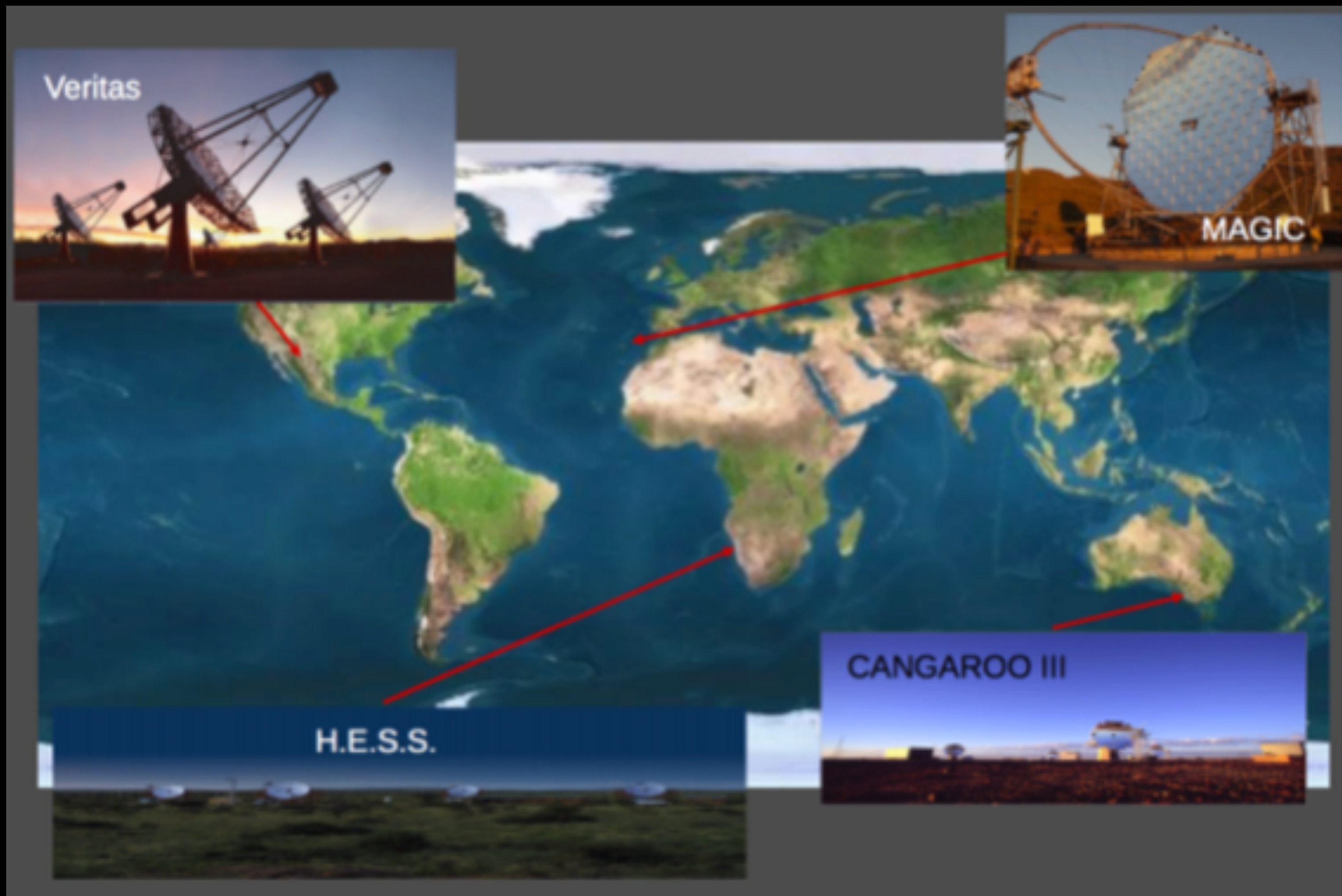
Space-based: Fermi-LAT

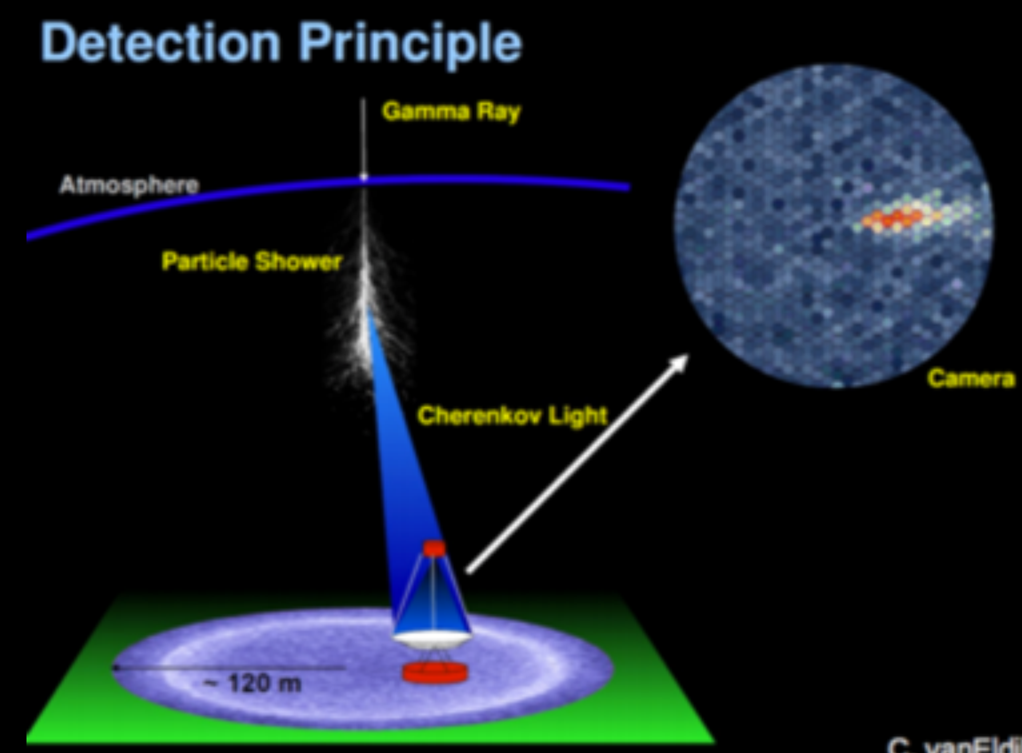
- Same techniques as in high-energy physics
- Fermi-LAT is a pair-conversion telescope
- Able to observe the entire sky

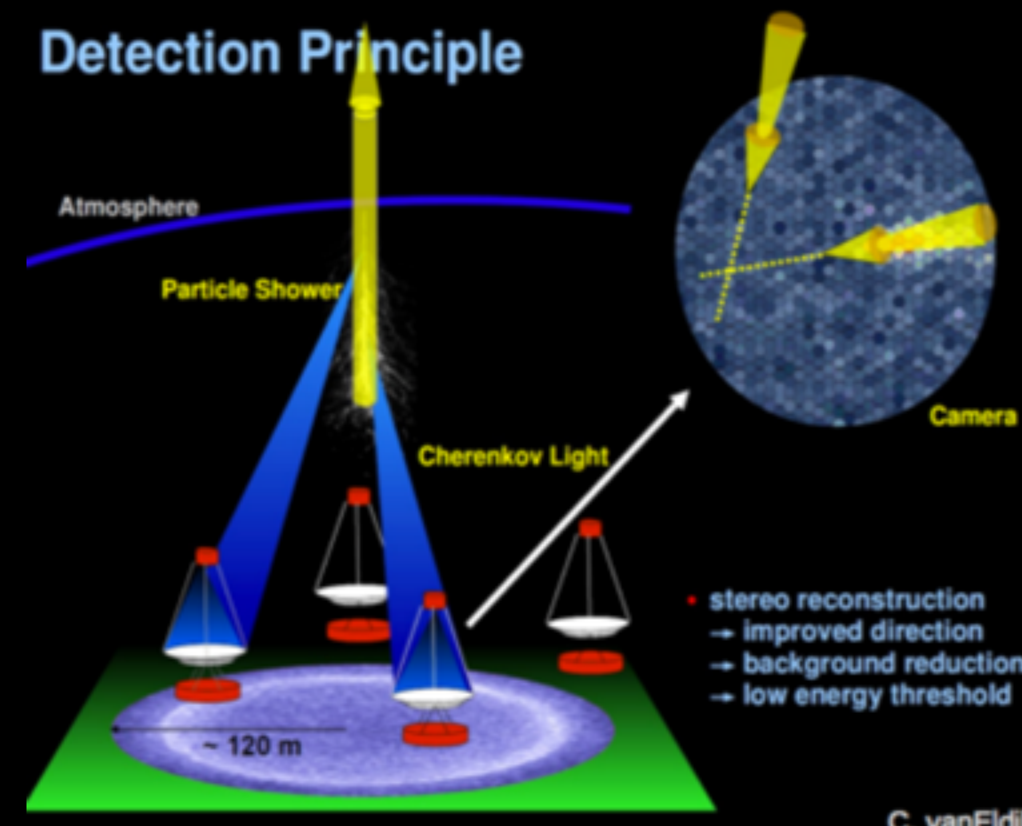
16 modular towers,
18 tungsten converting layers and 16 dual silicon tracker planes



Cherenkov Telescopes



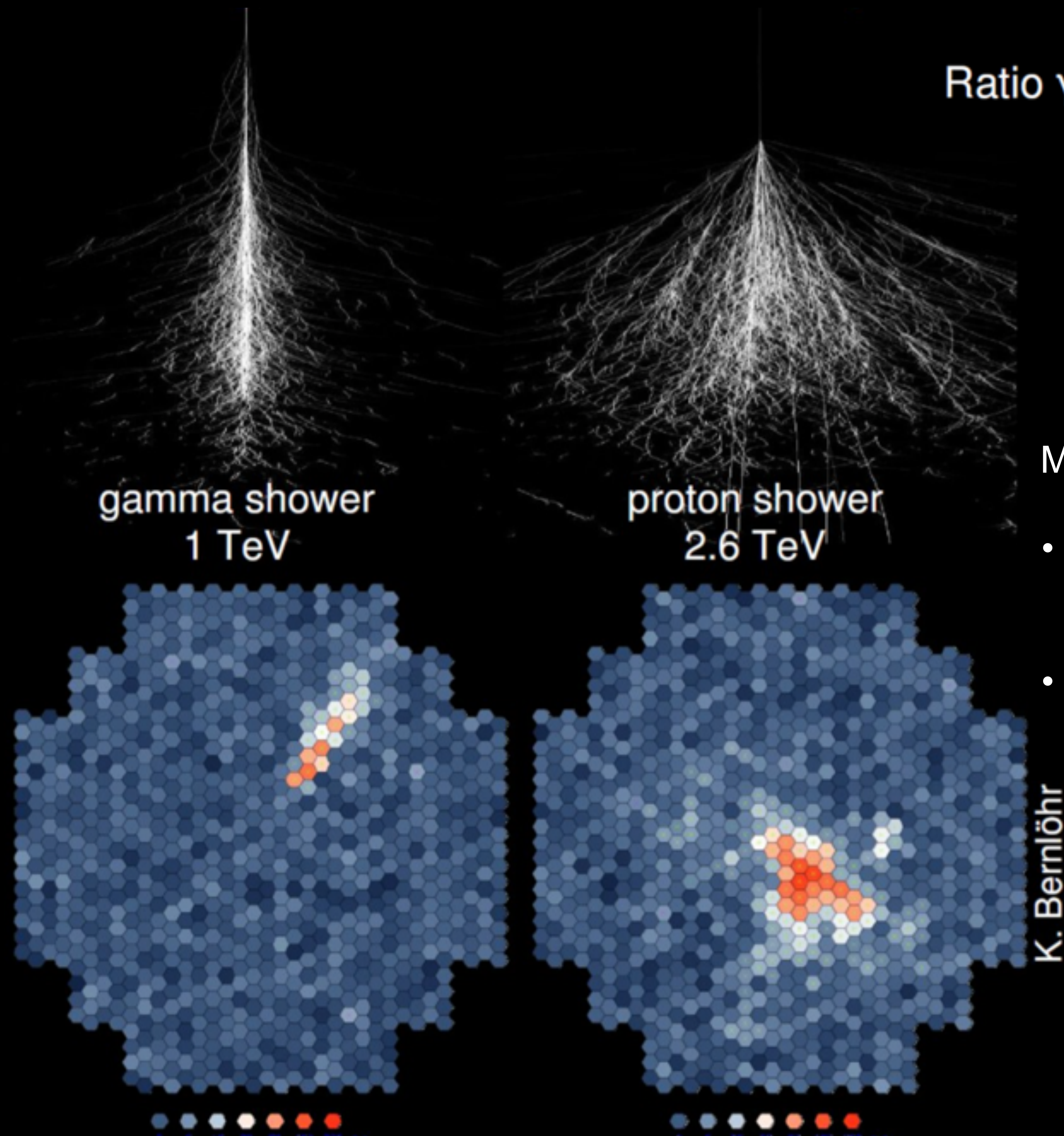




- γ rays flux at high energy decreases quickly → larger area needed than possible on space based telescopes
- γ rays (or p/nuclei) create EM shower in the atmosphere, detected via Cherenkov light
- Good angular resolution
- Obtain from image energy (image intensity), direction (image direction), type of particle (image shape)

Background

Ratio γ/hadron ≈ 1/1000



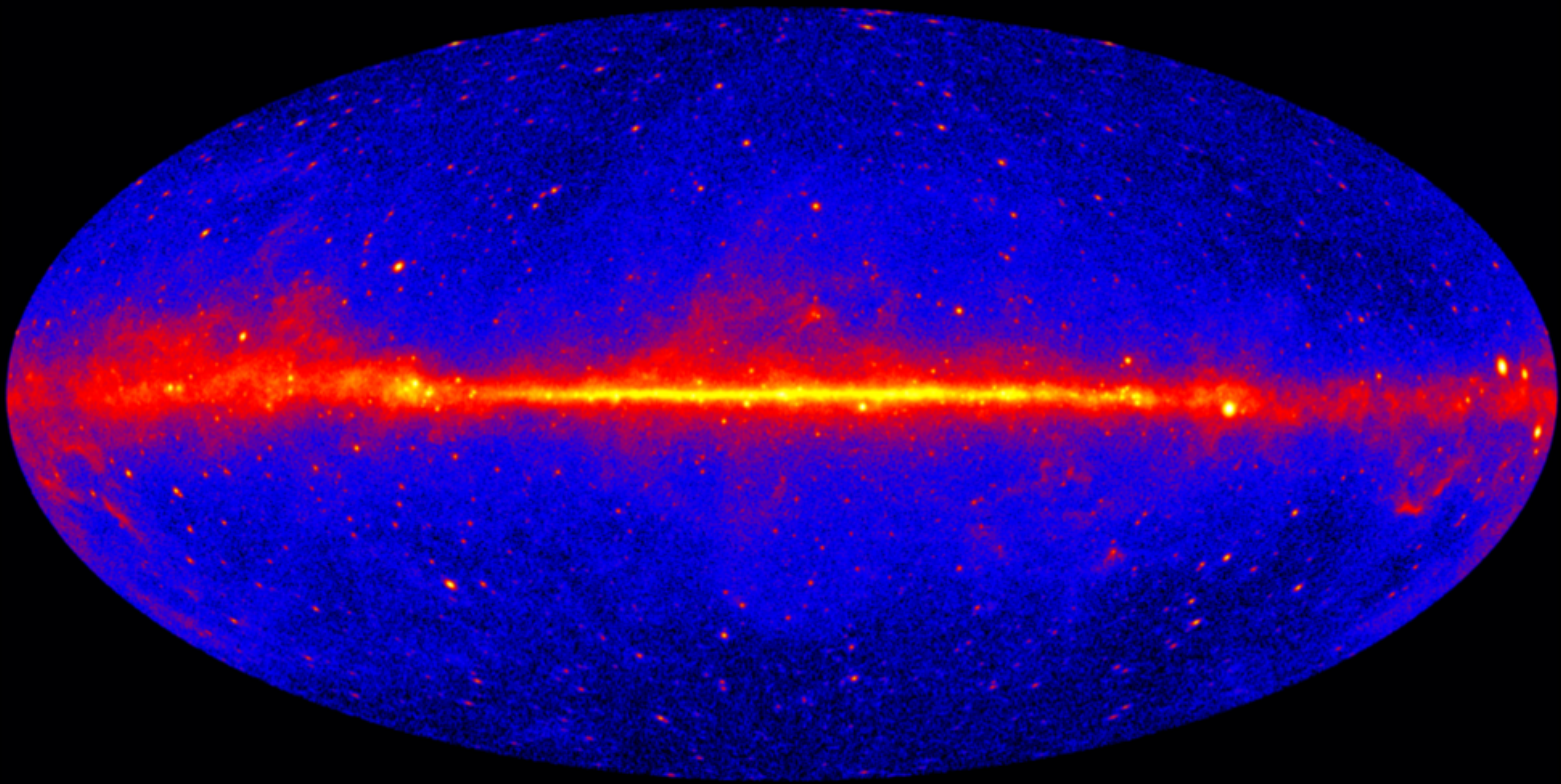
Main bkgd also CR:

- Hadronic showers eff. rejected
- Electron showers irreducible (but isotrop)

C. vanEldik

Cosmic Ray Telescopes

The Sky for Fermi-LAT



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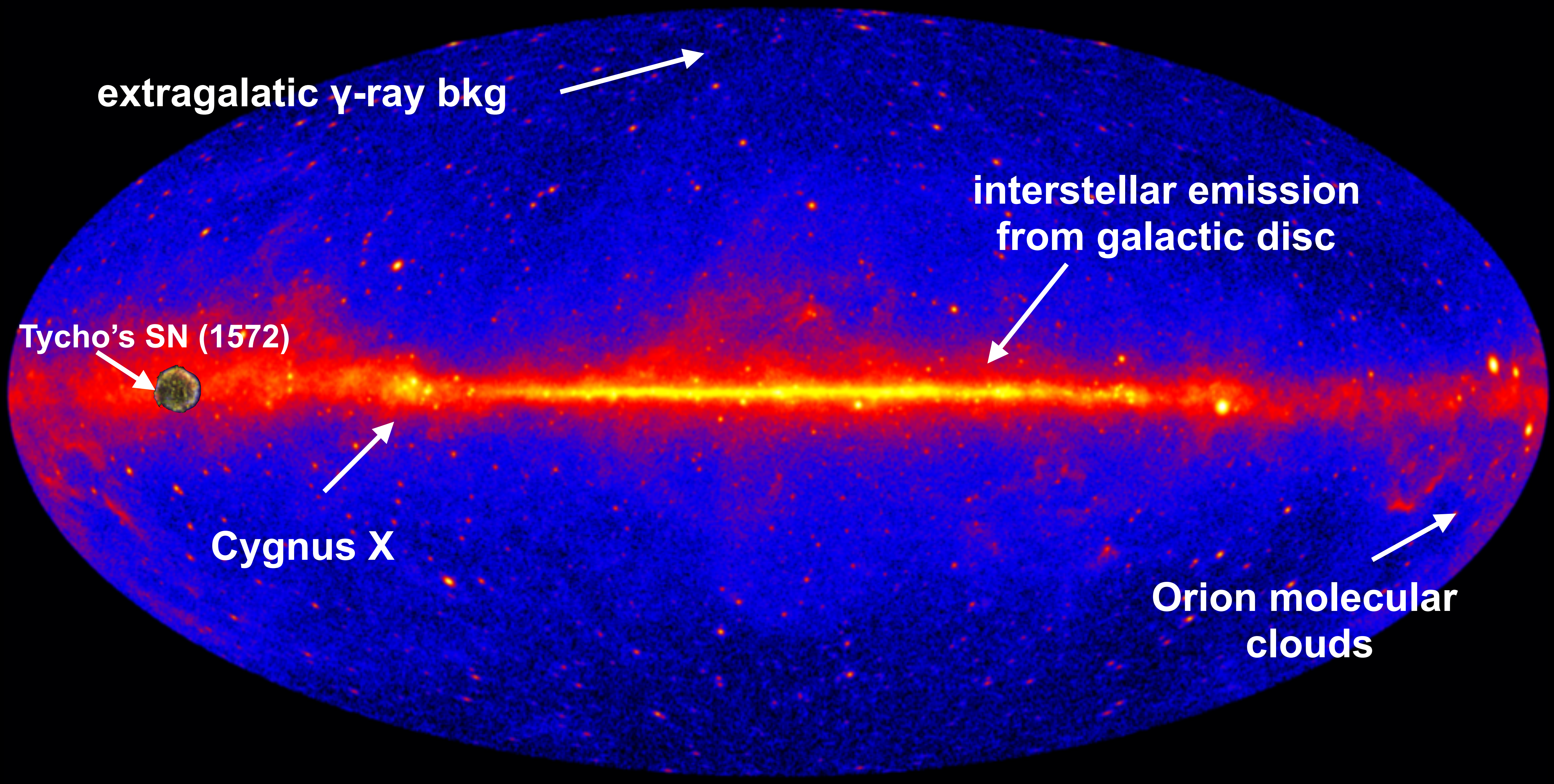

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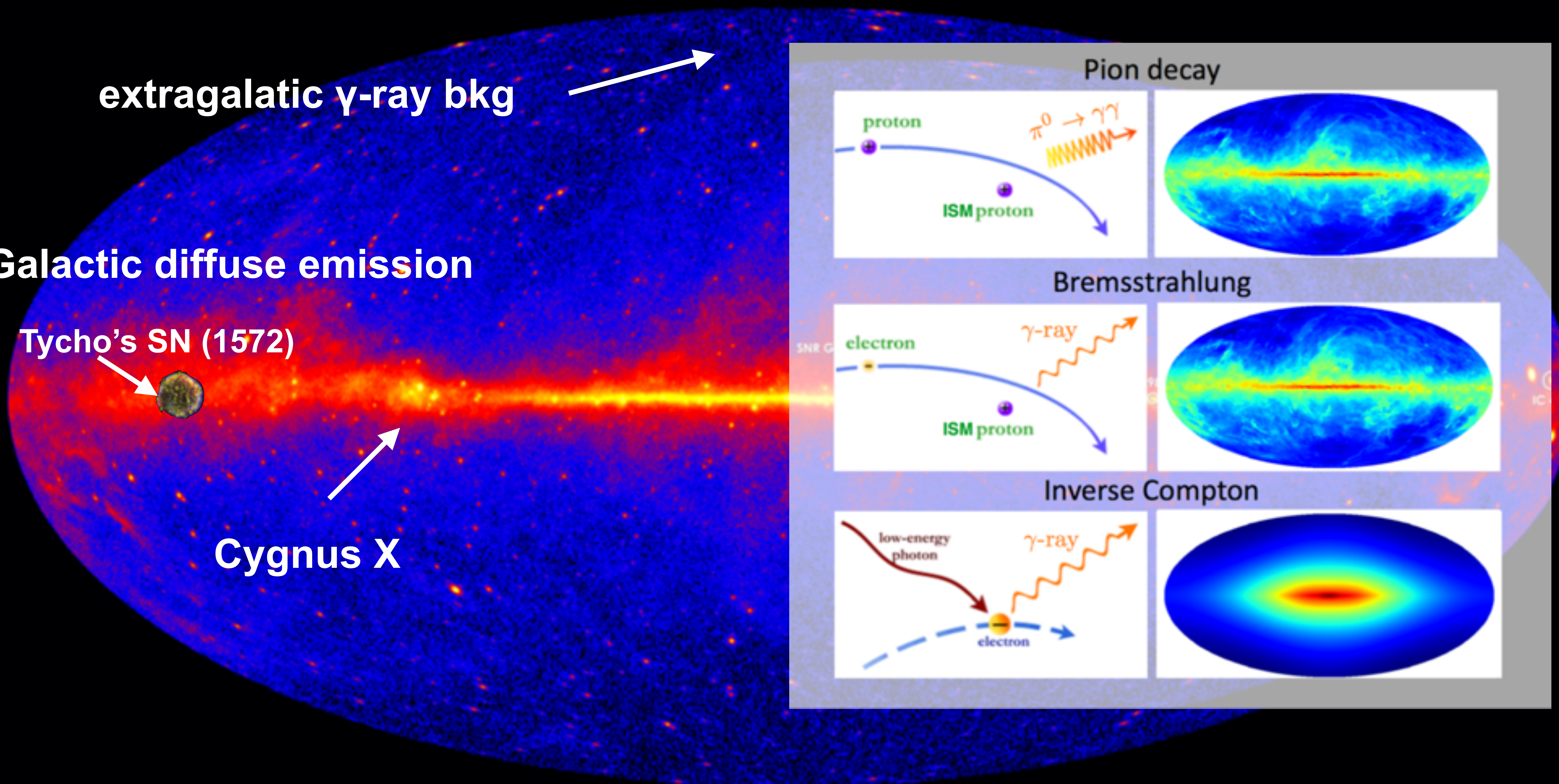

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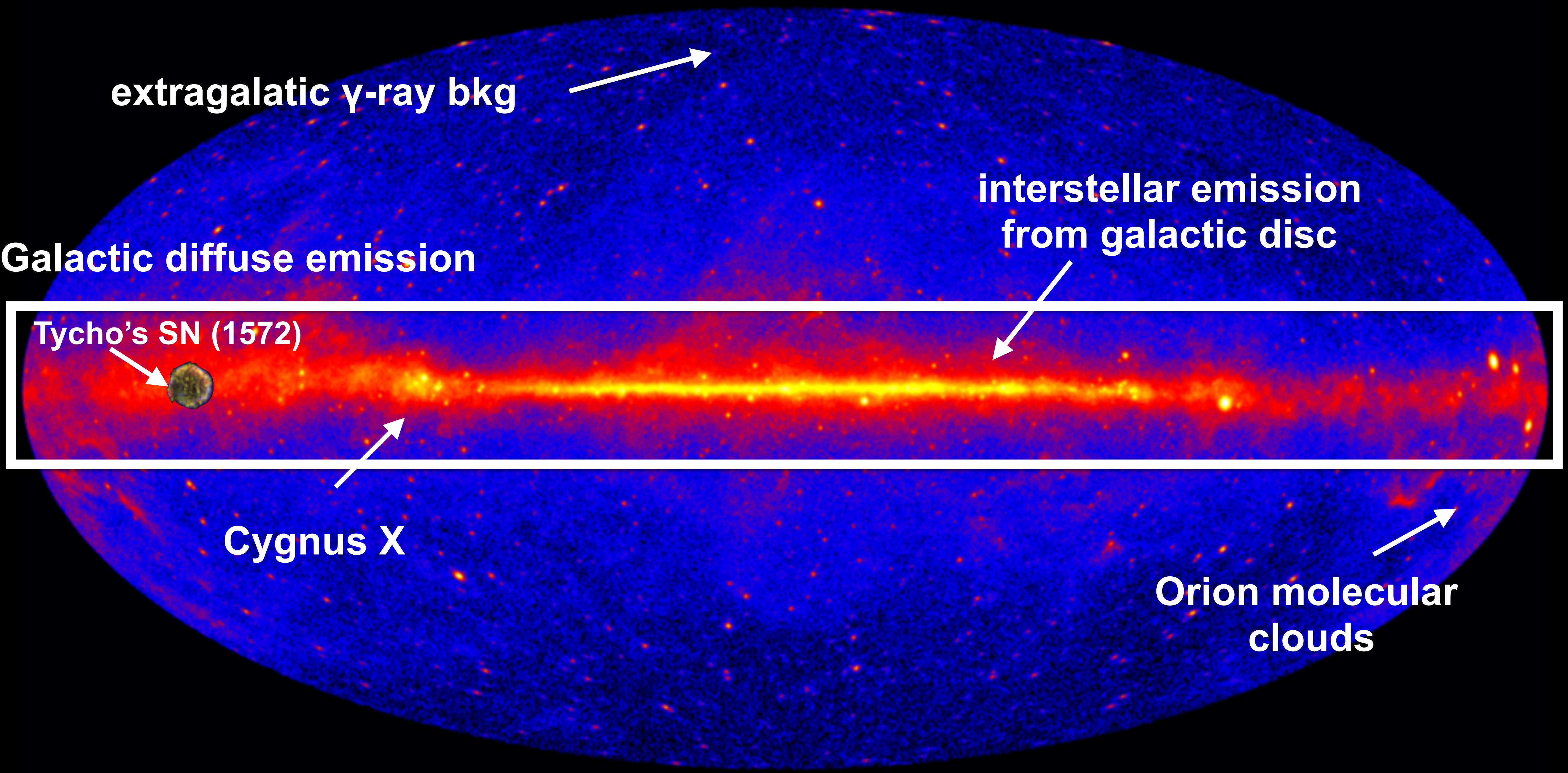
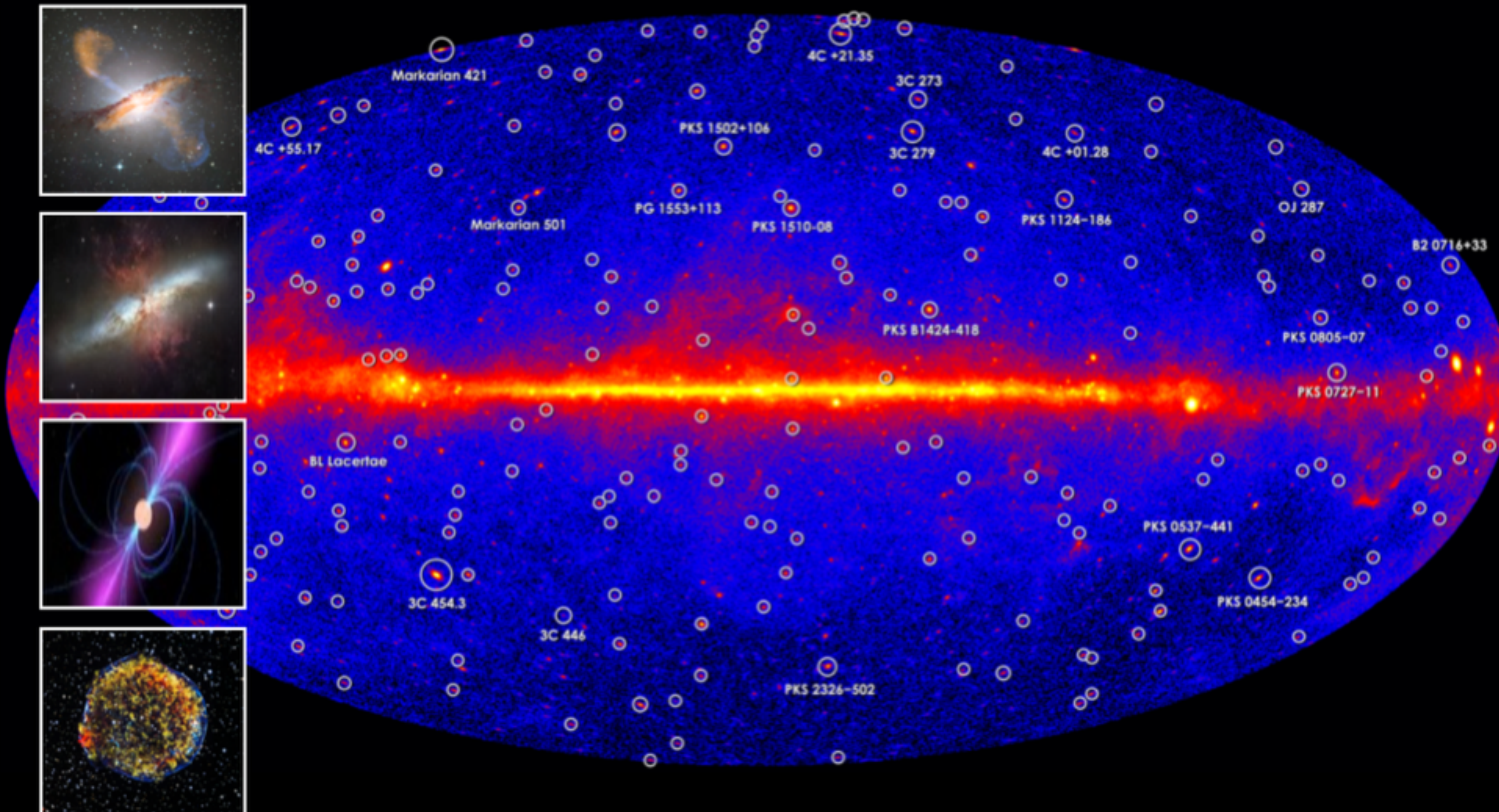


The Sky for Fermi-LAT

Detected sources



3FGL

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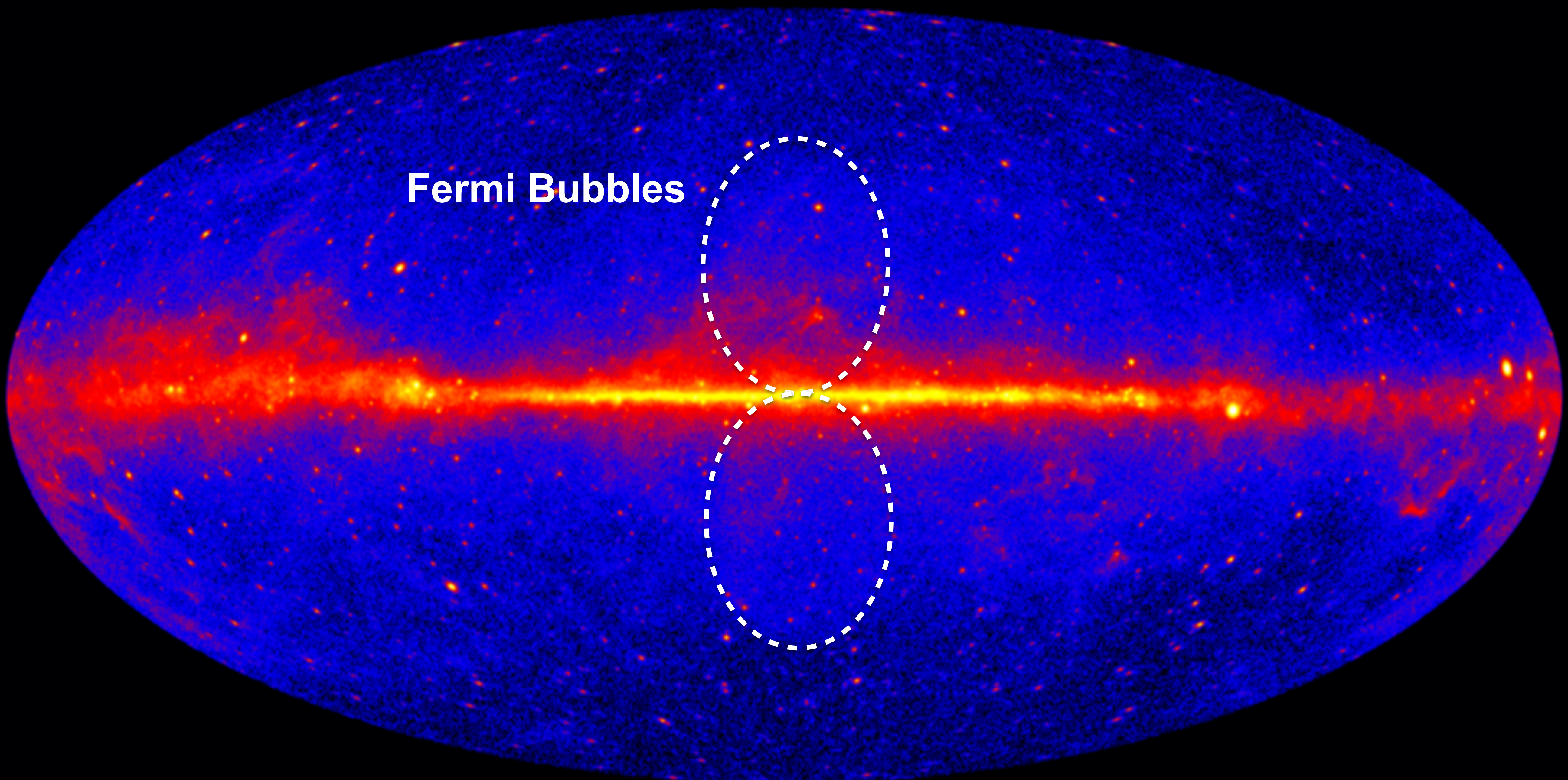
The Sky for Fermi-LAT



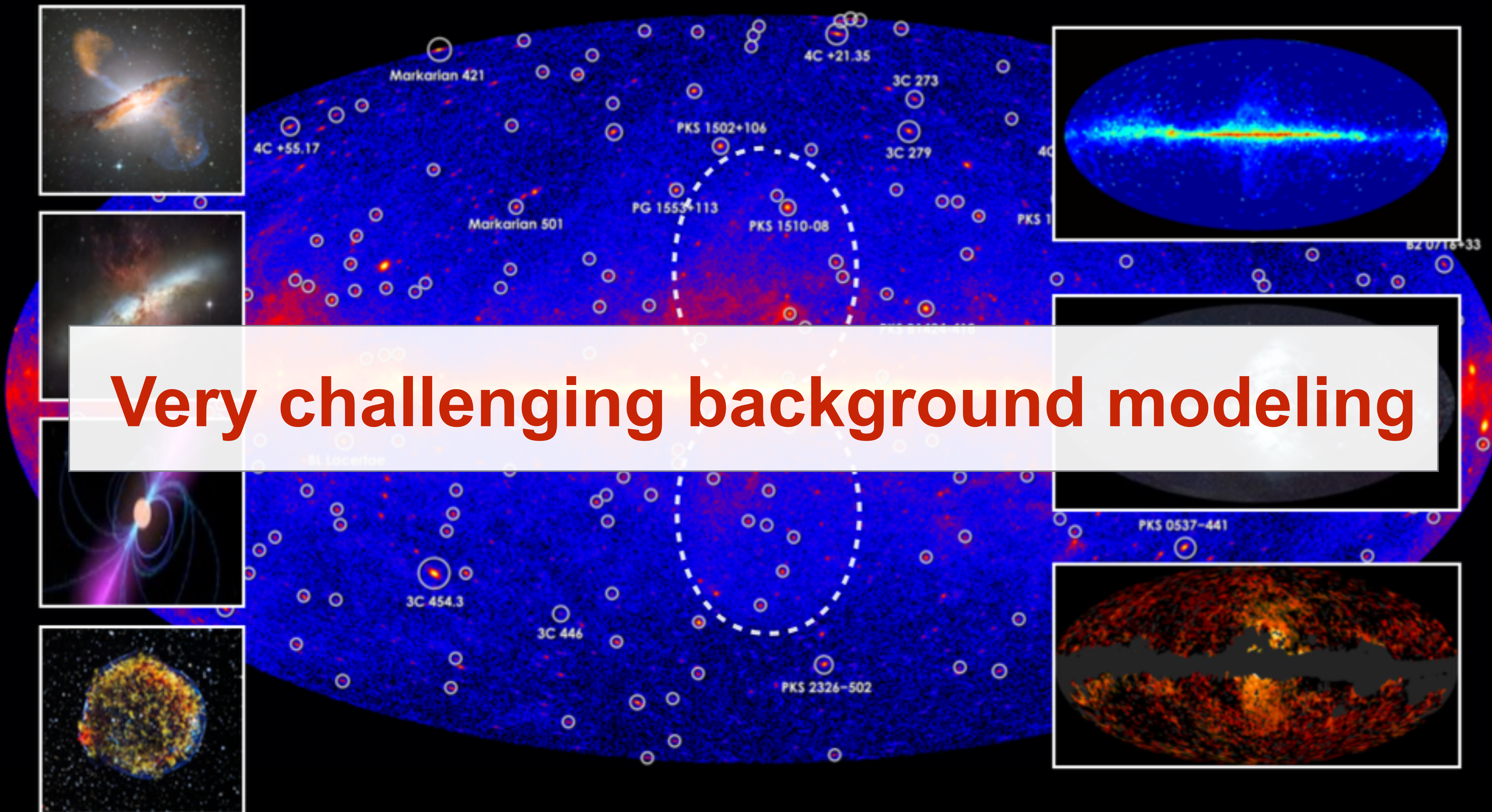
possibly remnant of a time when BH in our Galaxy was very active

The Sky for Fermi-LAT

arXiv:1502.02866

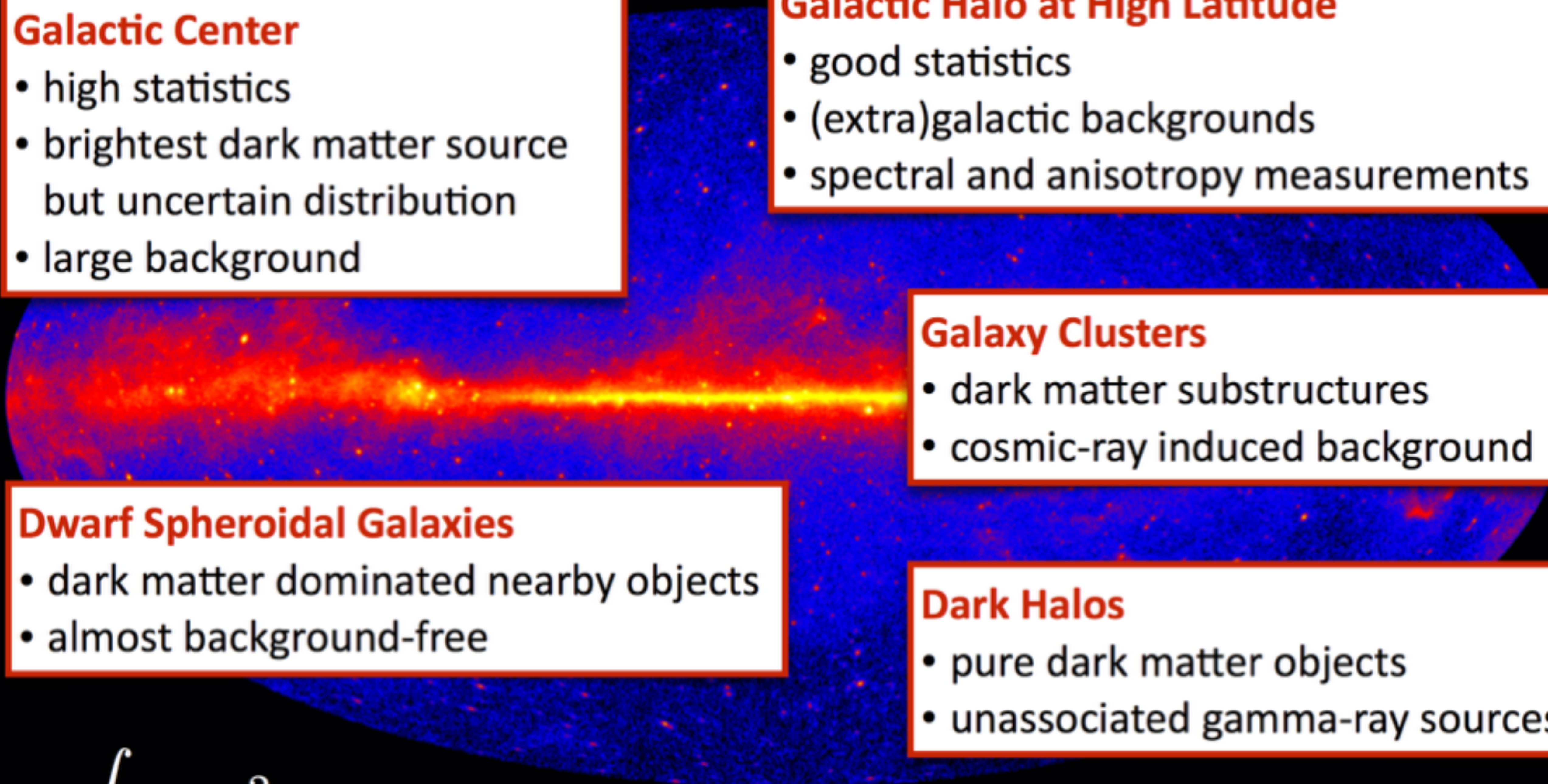
Detected sources

Fermi bubbles



Very challenging background modeling

The Sky for Fermi-LAT: Targets



Galactic Center
- high statistics
- brightest dark matter source but uncertain distribution
- large background

Galactic Halo at High Latitude
- good statistics
- (extra)galactic backgrounds
- spectral and anisotropy measurements

Galaxy Clusters
- dark matter substructures
- cosmic-ray induced background

Dwarf Spheroidal Galaxies
- dark matter dominated nearby objects
- almost background-free

Dark Halos
- pure dark matter objects
- unassociated gamma-ray sources

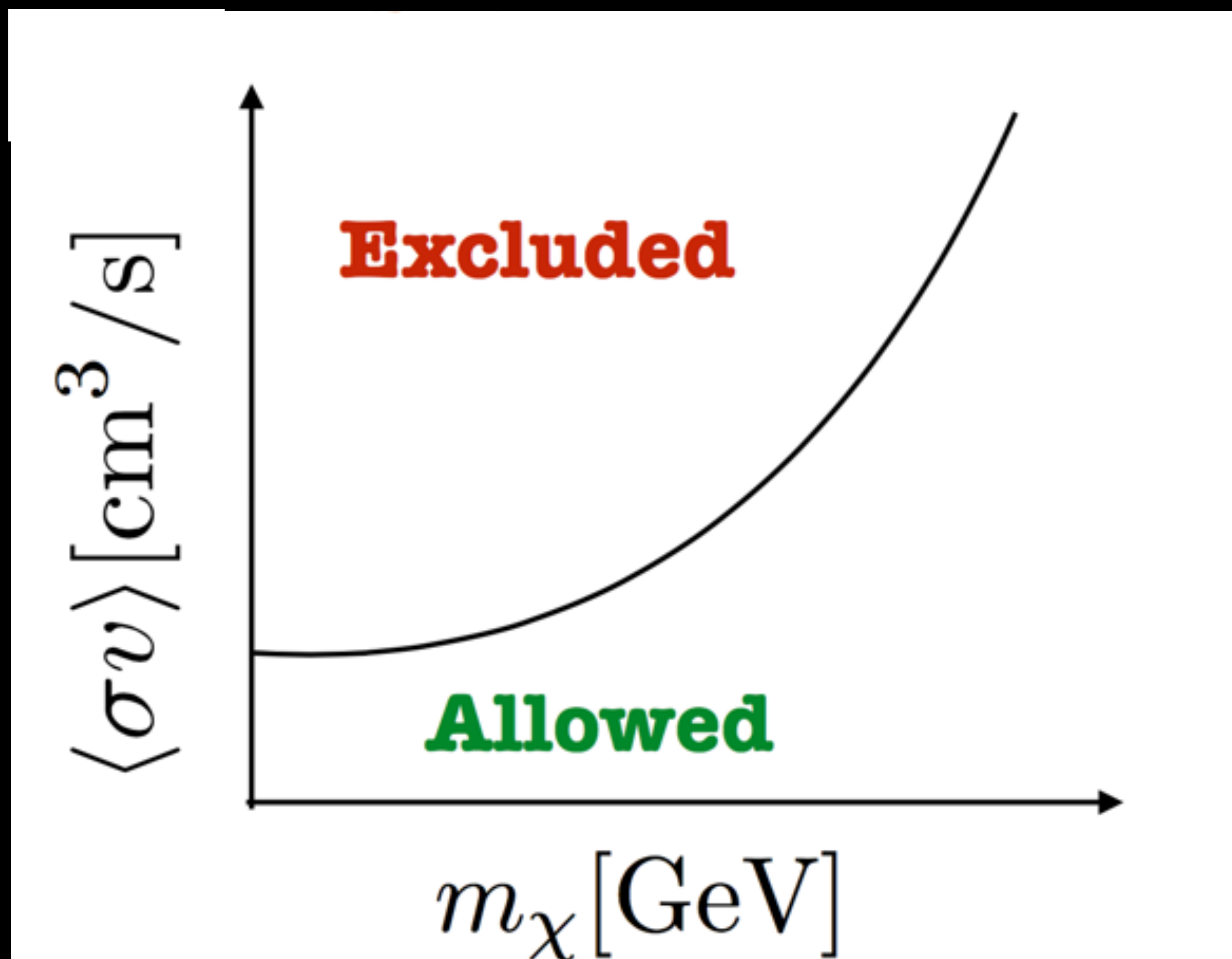
$$\propto \int_{\mathrm{l.o.s.}} \rho_{\mathrm{DM}}^2 ds$$

+ dedicated searches for gamma-ray lines

General ID Searches

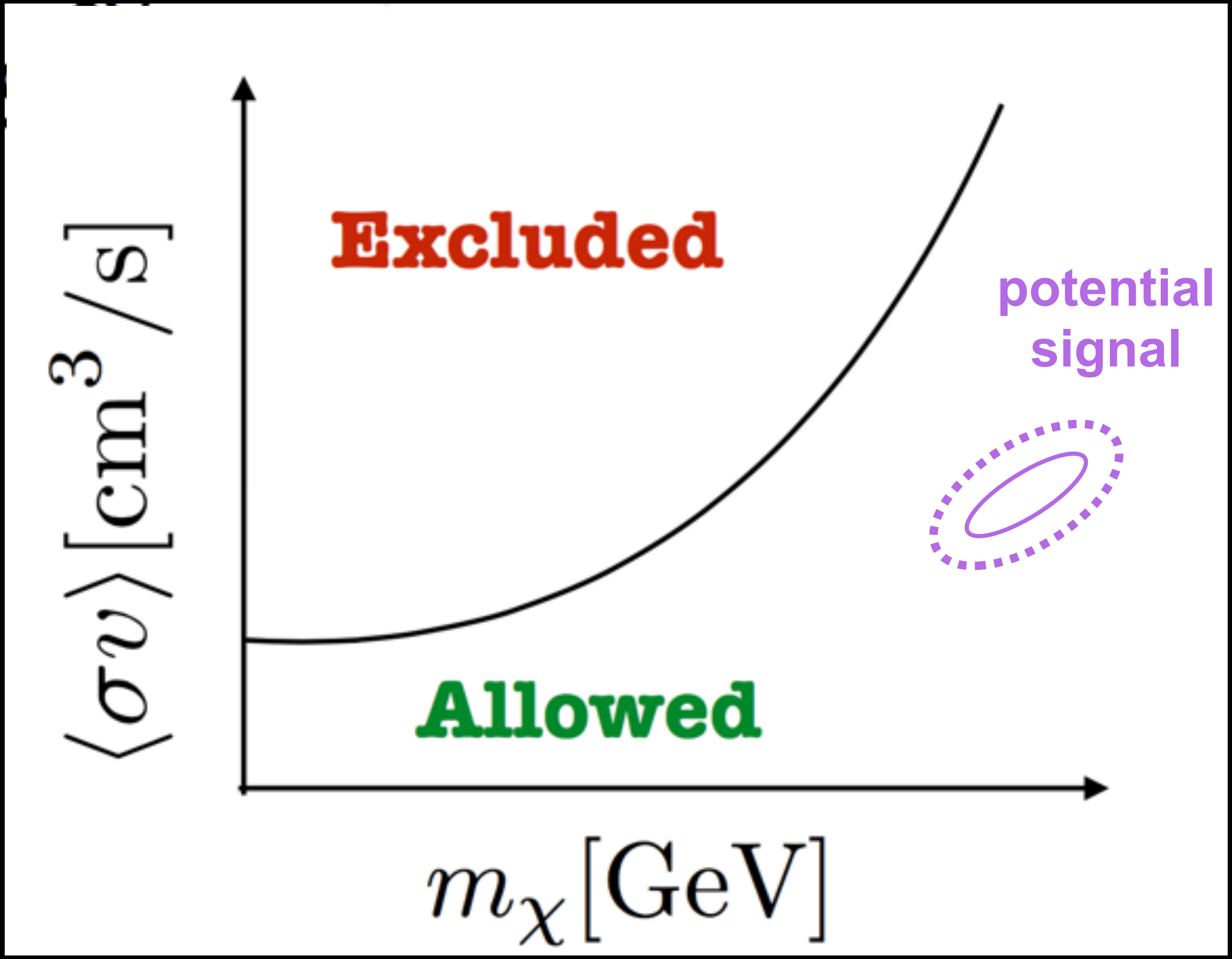
Observed Flux Expected Flux

Φ_{Obs} Φ_{Th}

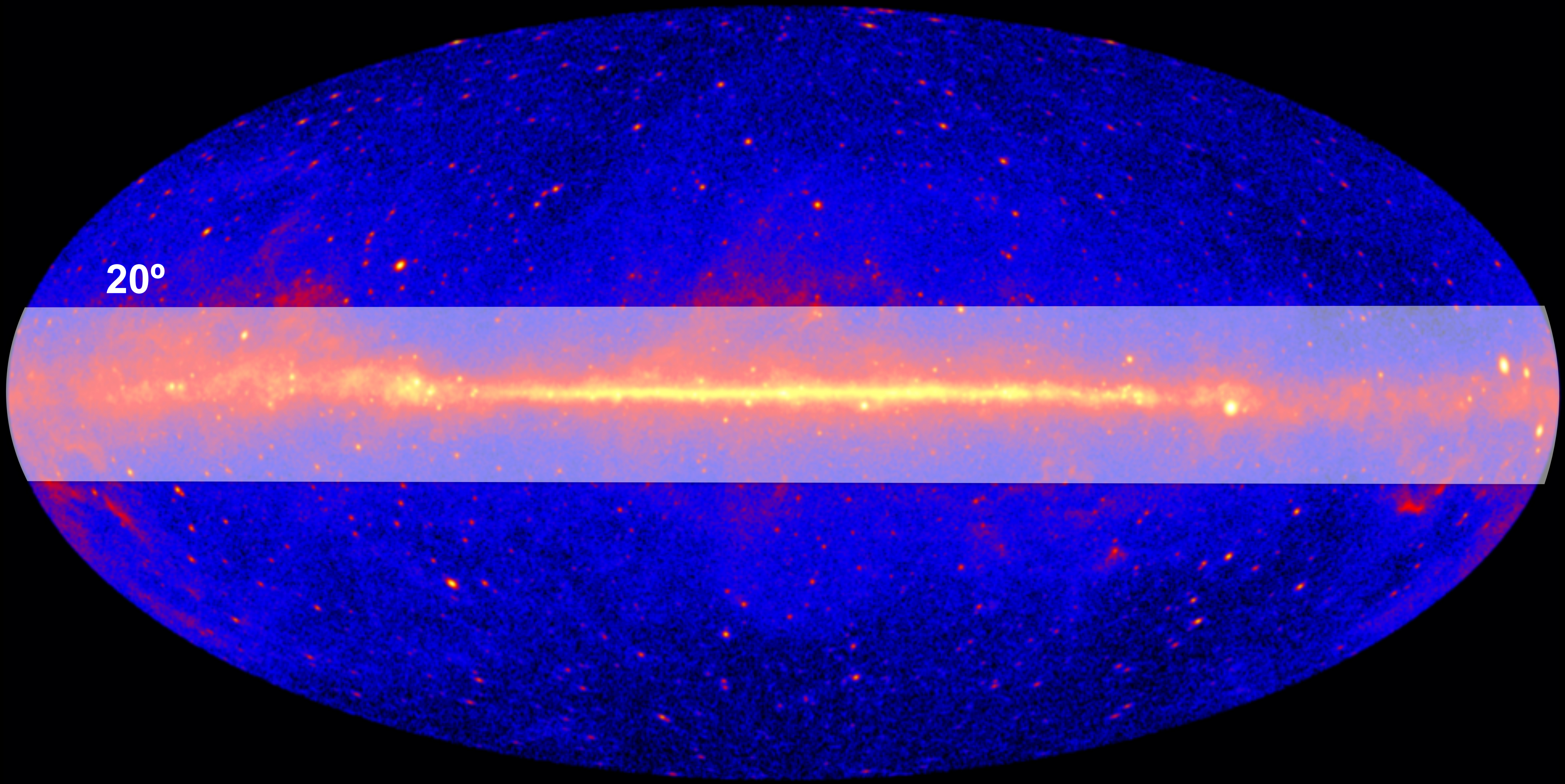


General ID Searches

Observed Flux	Expected Flux
Φ_{Obs}	Φ_{Th}

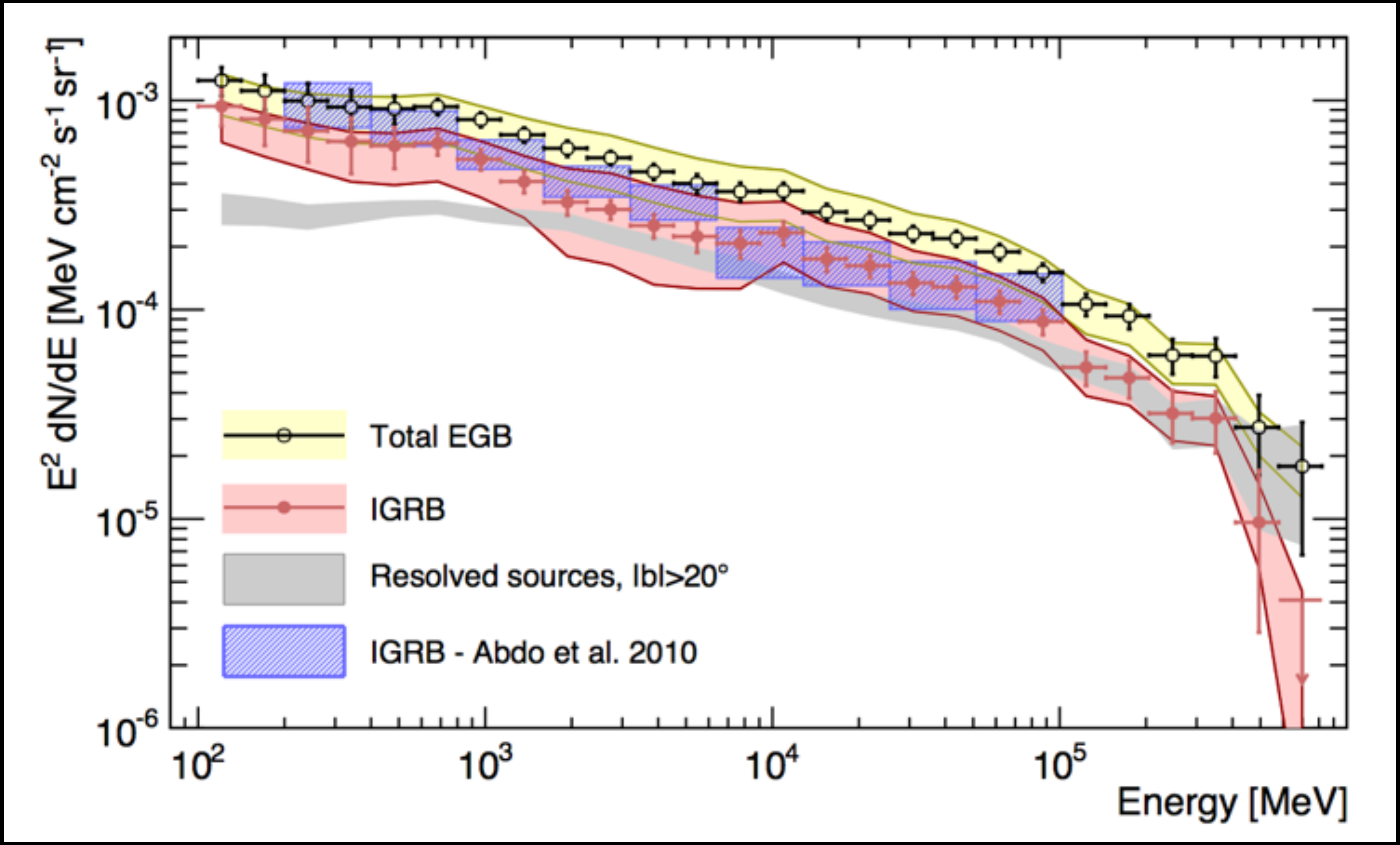


Extragalactic Searches



Extragalactic Searches

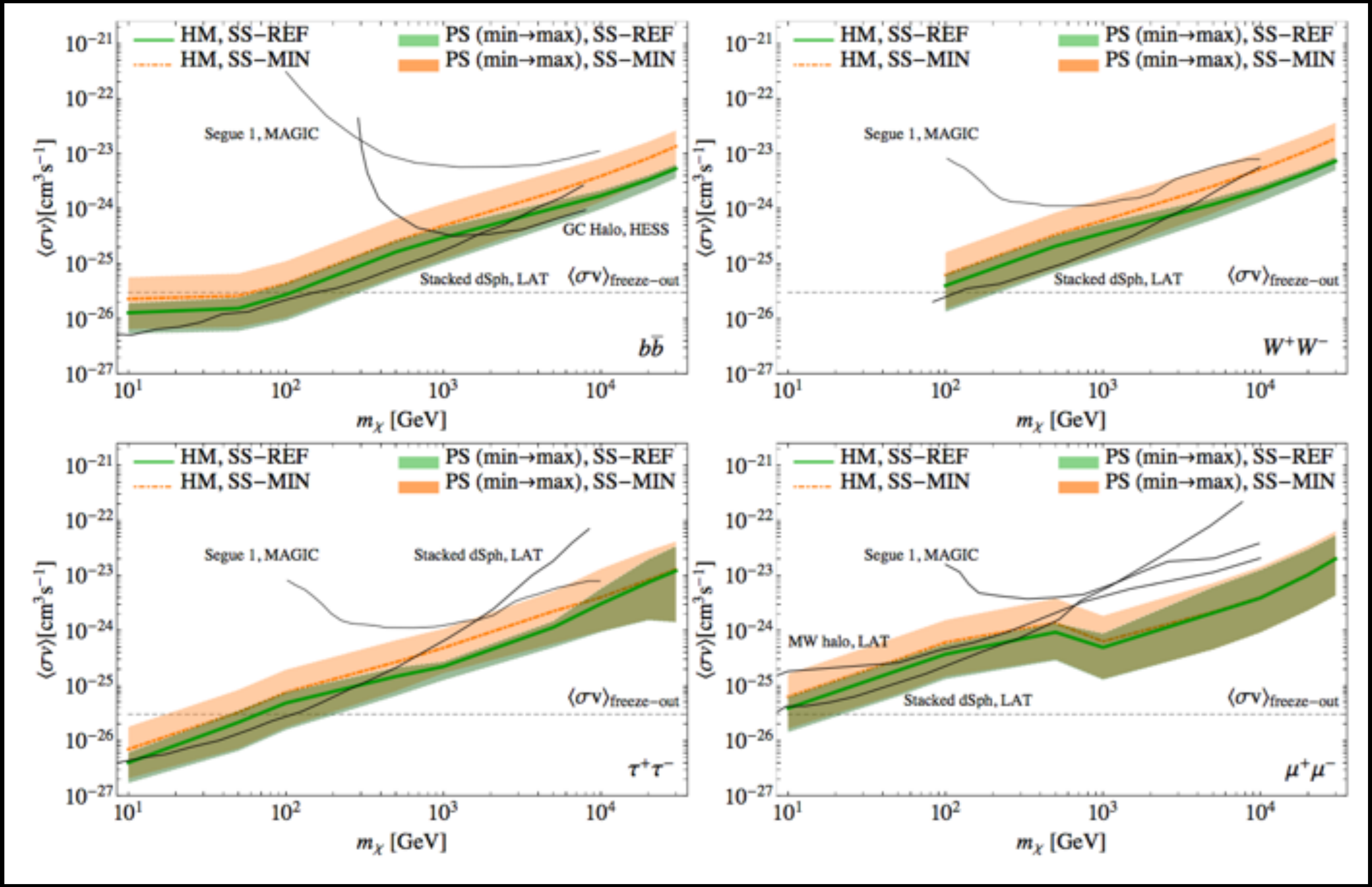
arXiv:1502.02866



- Diffuse Gamma Ray Bkgd + resolved point sources (gray) = total "Extragalactic Gamma-ray Background (EGB)" (black data points). The latter is defined here as the sum of the DGRB and of the resolved sources at |b| > 20◦ (shown in gray).
- Above 100 GeV, ~ 50% of the EGB resolved into individual LAT sources

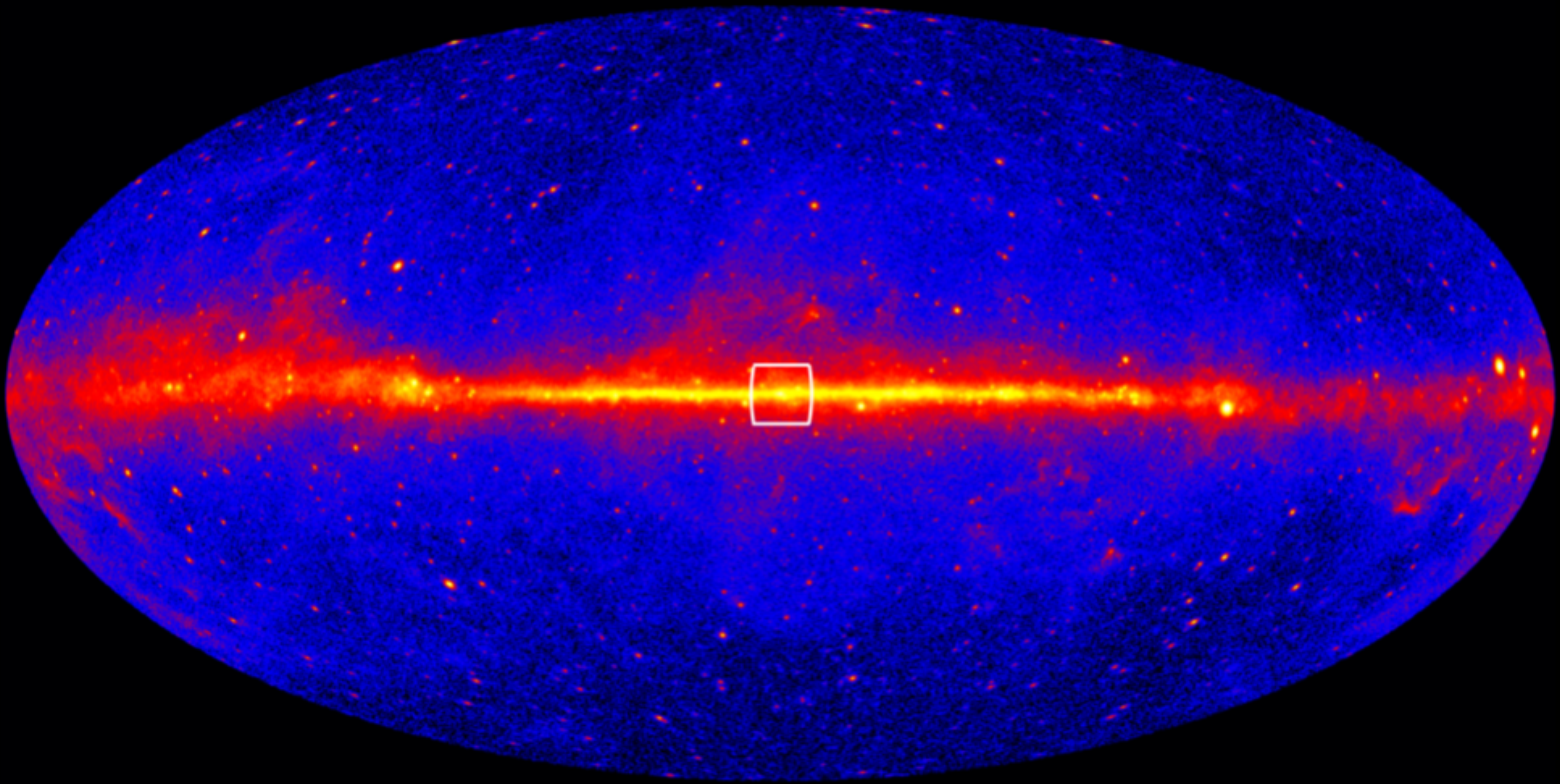
Extragalactic Searches

arXiv:1501.05464



- Limits on annihilation cross section at 2σ C.L.
  - Reference case (SS-REF): Substructures boost total Galactic annihilation signal x15
  - Minimal case (SS-MIN): signal x 3
- Constraints starting to approach interesting regions

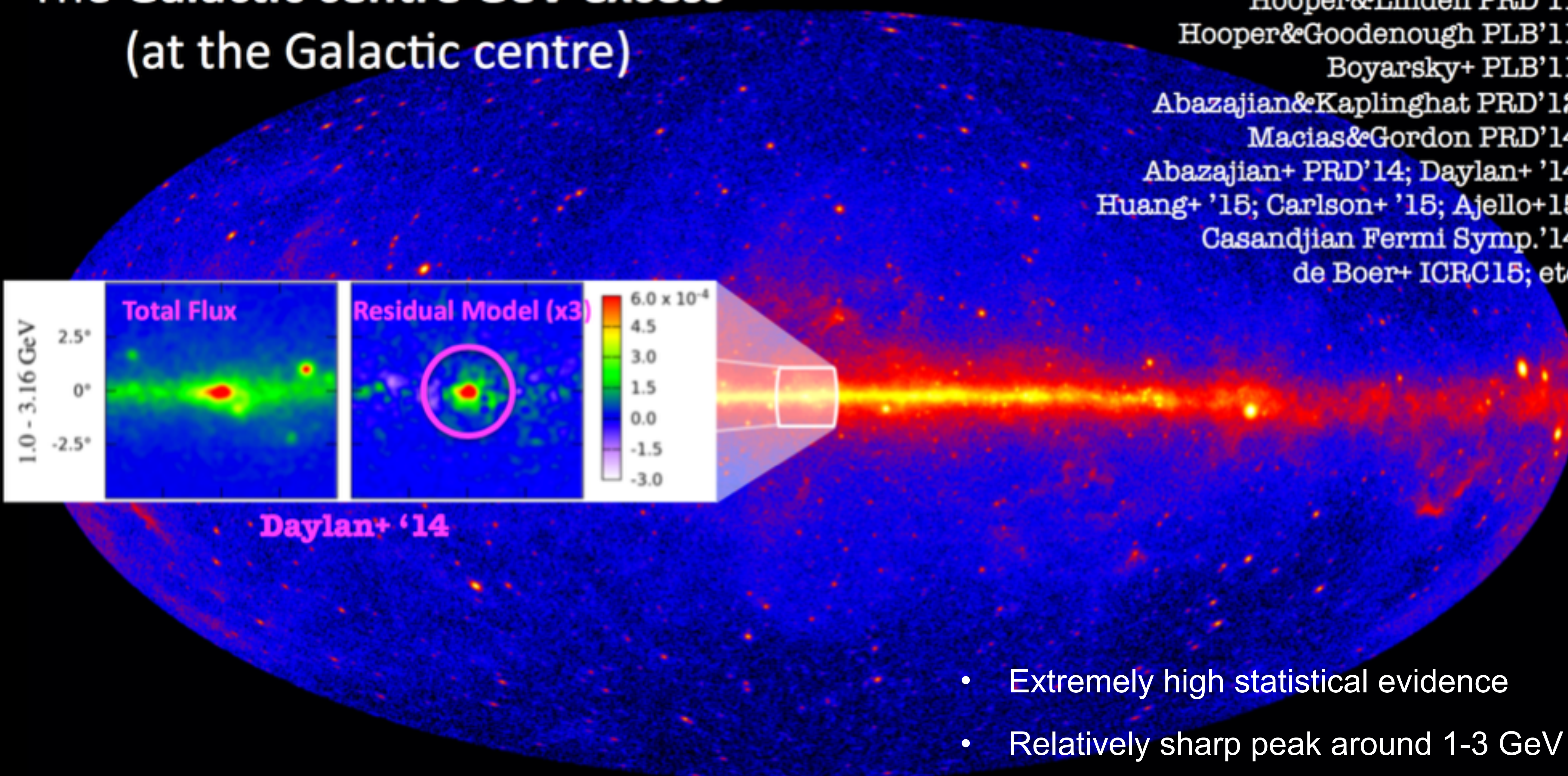
Low Latitude Fermi-LAT searches



Low Latitude Fermi-LAT searches

The **Galactic centre GeV excess** (at the Galactic centre)

Hooper&Goodenough '09; Vitale&Morselli '09;
Hooper&Linden PRD'11;
Hooper&Goodenough PLB'11;
Boyarsky+ PLB'11;
Abazajian&Kaplinghat PRD'12;
Macias&Gordon PRD'14;
Abazajian+ PRD'14; Daylan+ '14;
Huang+ '15; Carlson+ '15; Ajello+15;
Casandjian Fermi Symp.'14;
de Boer+ ICRC15; etc.

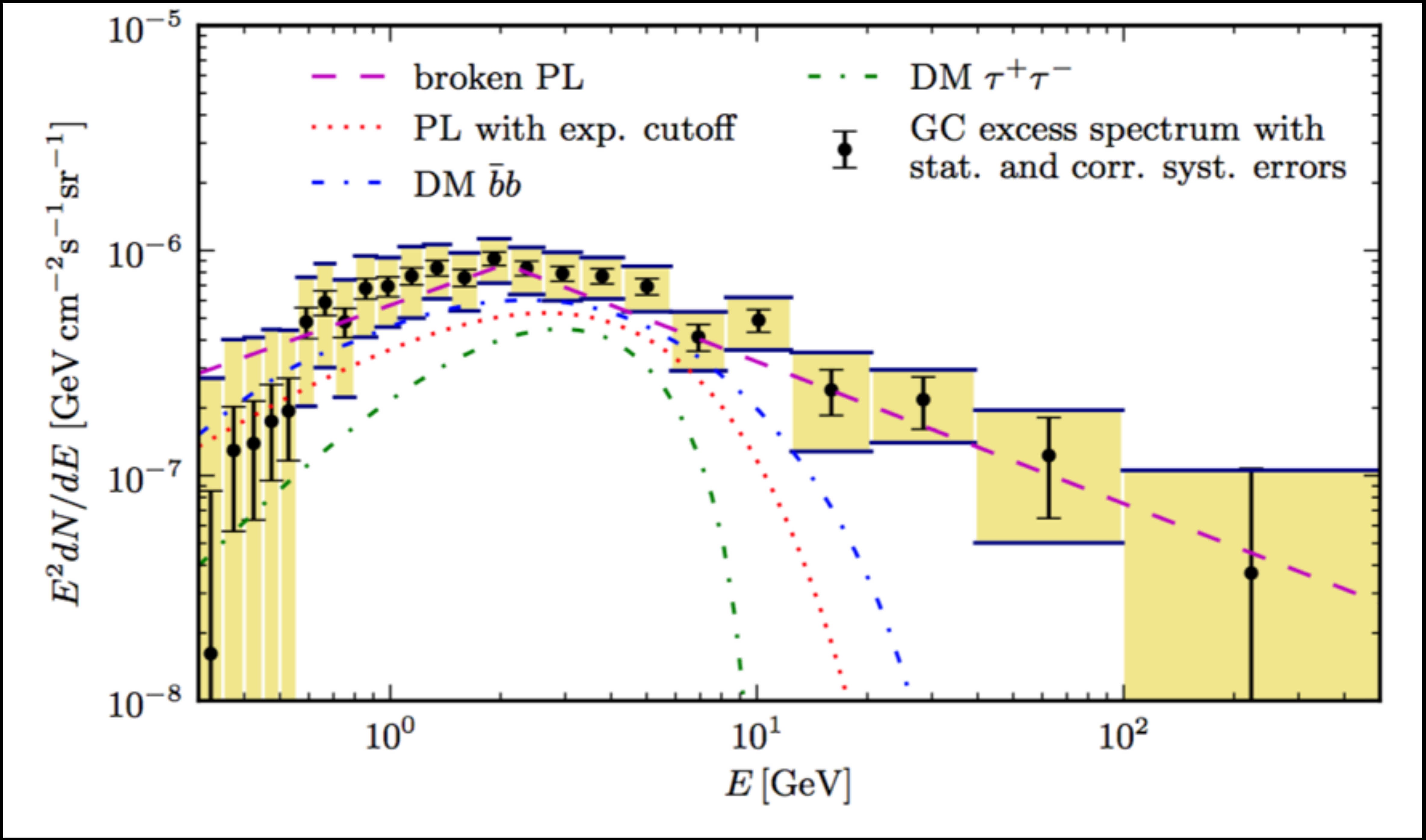


Daylan+ '14

- Extremely high statistical evidence
- Relatively sharp peak around 1-3 GeV
- Roughly $r^{-2.5}$ emission profile
- Extends at least from ~10pc to ~1kpc

Characterizing the excess: energy spectrum

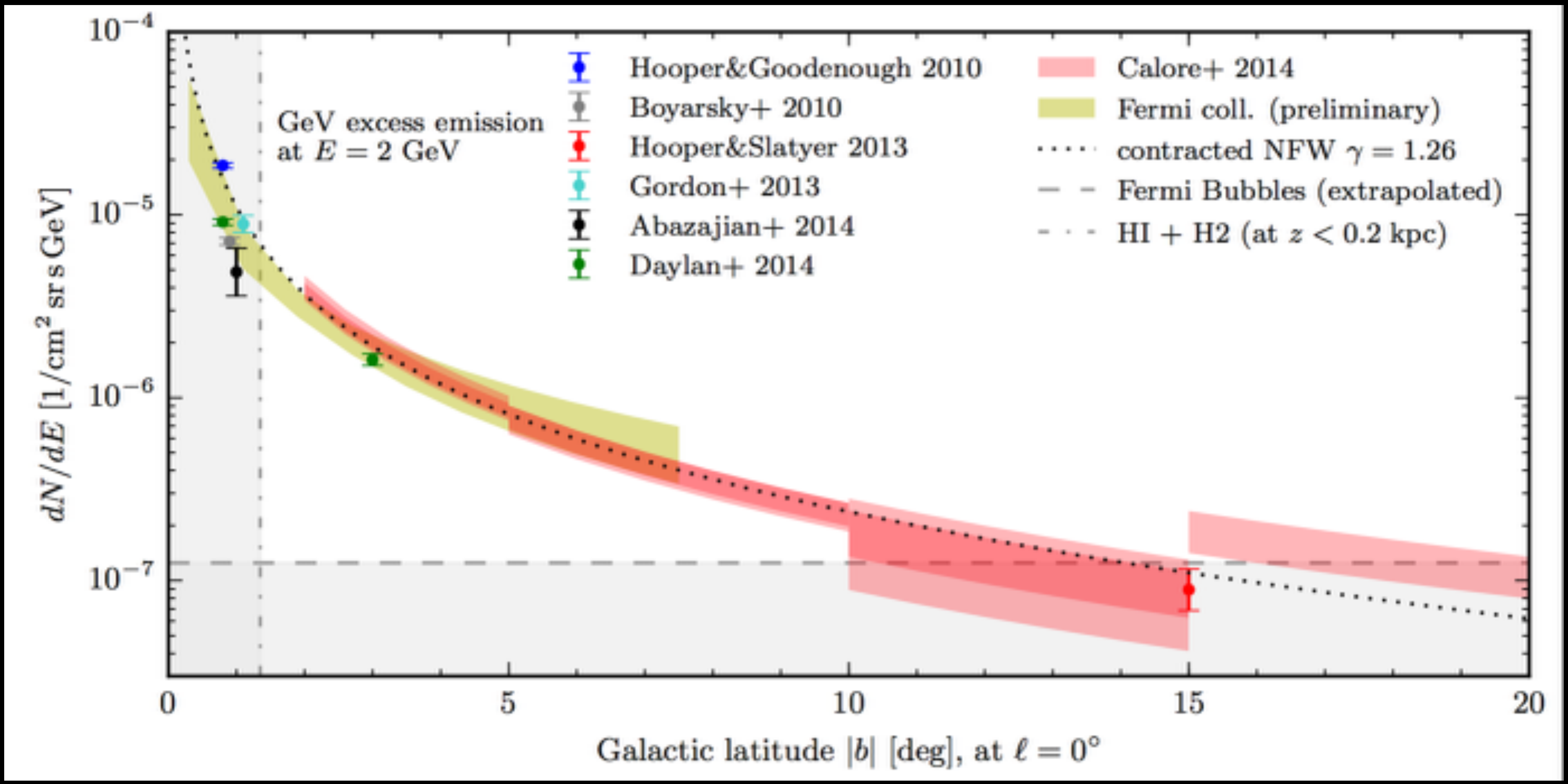
arXiv:1502.02805



- Data analyses using background and signal templates, stable against foreground variations
- Excess consistent with DM signal or broken power law
- Main uncertainties from Fermi Bubbles and unresolved point sources

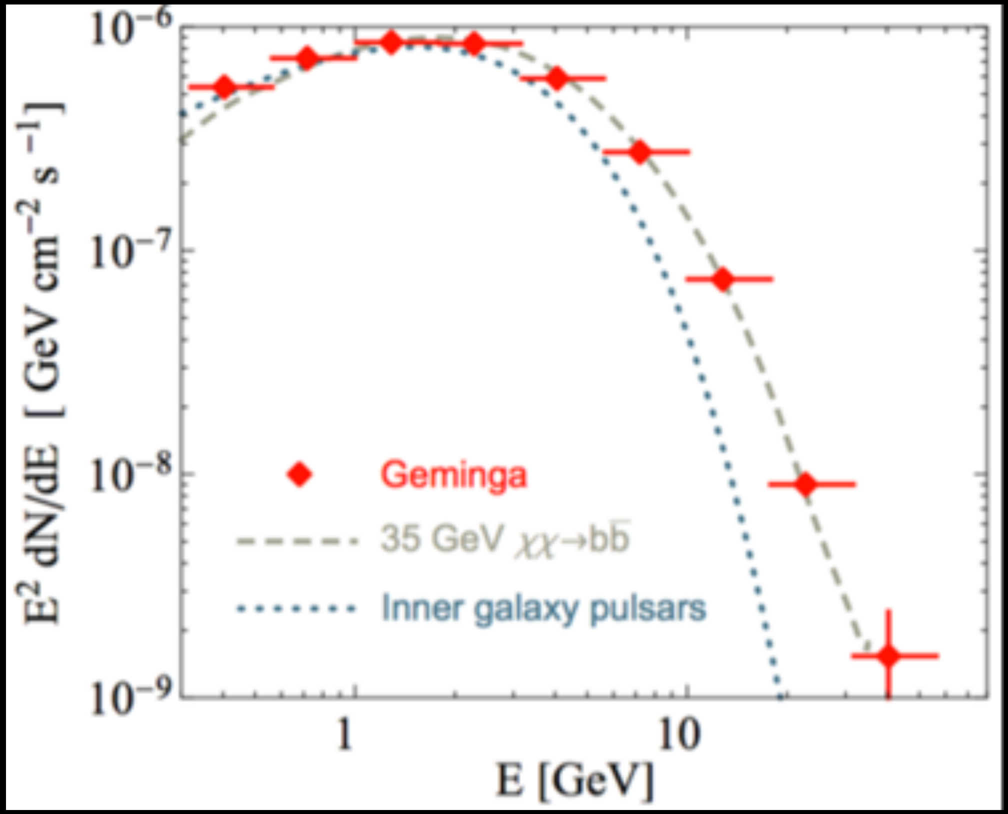
Why is the GeV excess so exciting?

arXiv:1411.4647



Possible explanations:

- Milli-second pulsars: need large population
- "Recent" bursts injecting high-energy population of electrons or protons: Spectral fit worse, spherical out to kpc scales?



- Recent strong evidence for unresolved point sources
- Future observations should allow us to discover the bulge MSP populations.

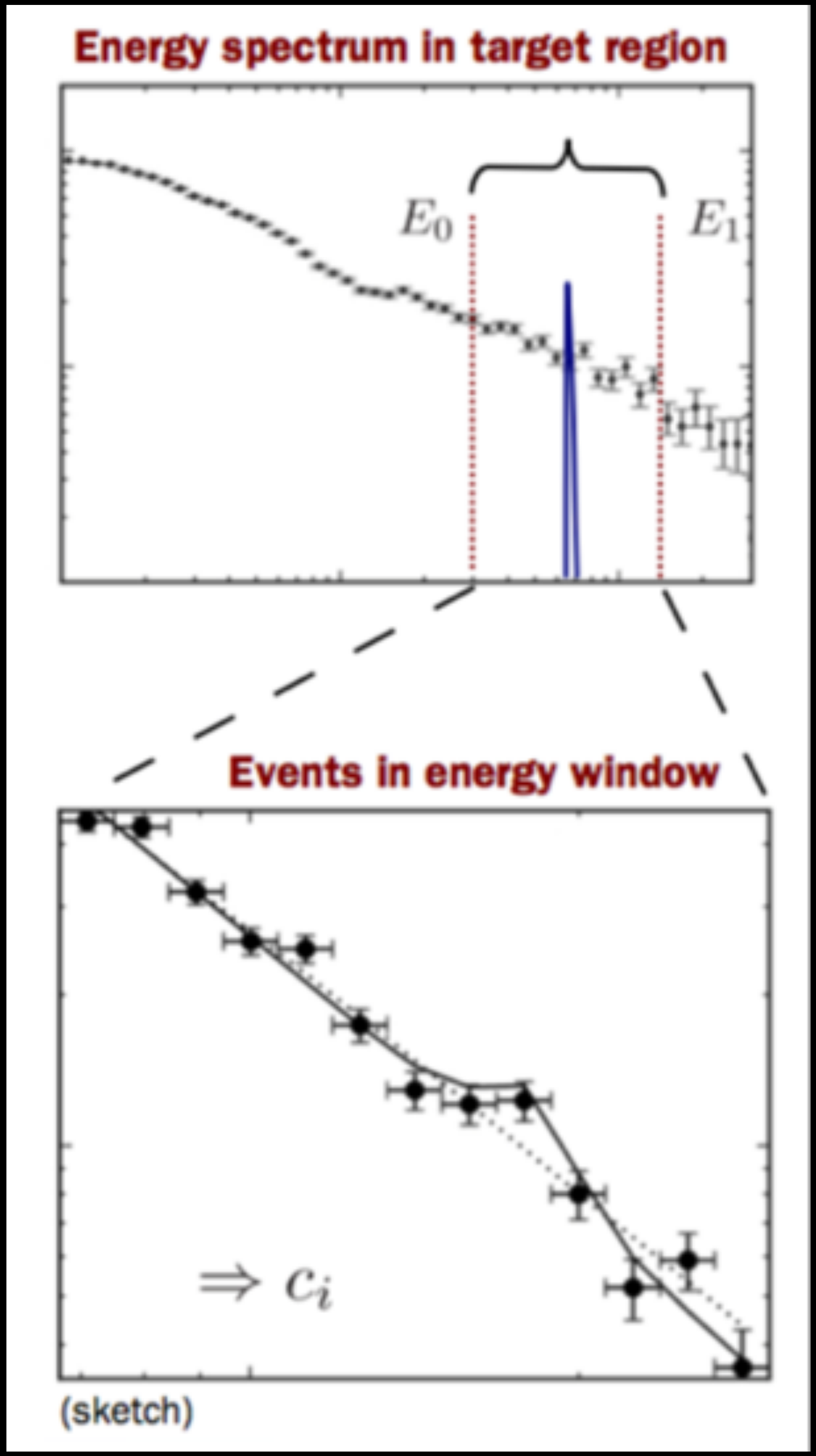
Search for Spectral Features

- Searching DM spectral features
- 'Bump-hunt' style of search
- Only three free parameters:

$$\frac{dJ}{dE} = \alpha \frac{dJ_{DM}}{dE} + \beta E^{-\gamma}$$

DM signal

astrophys. background



Bringmann+PRD'11

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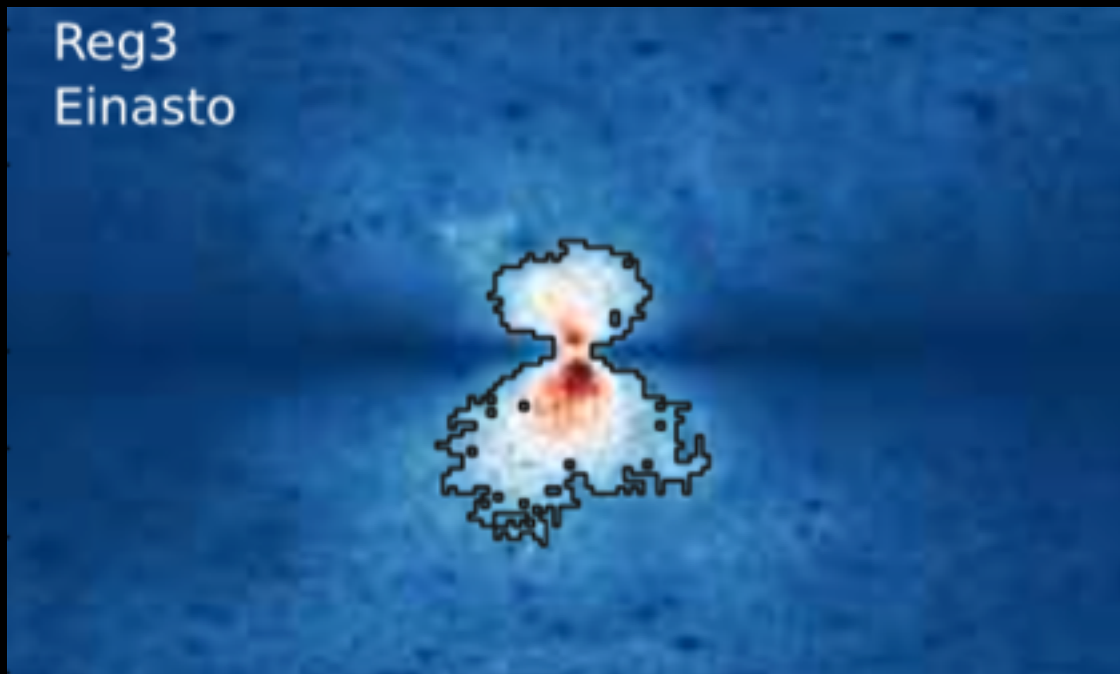
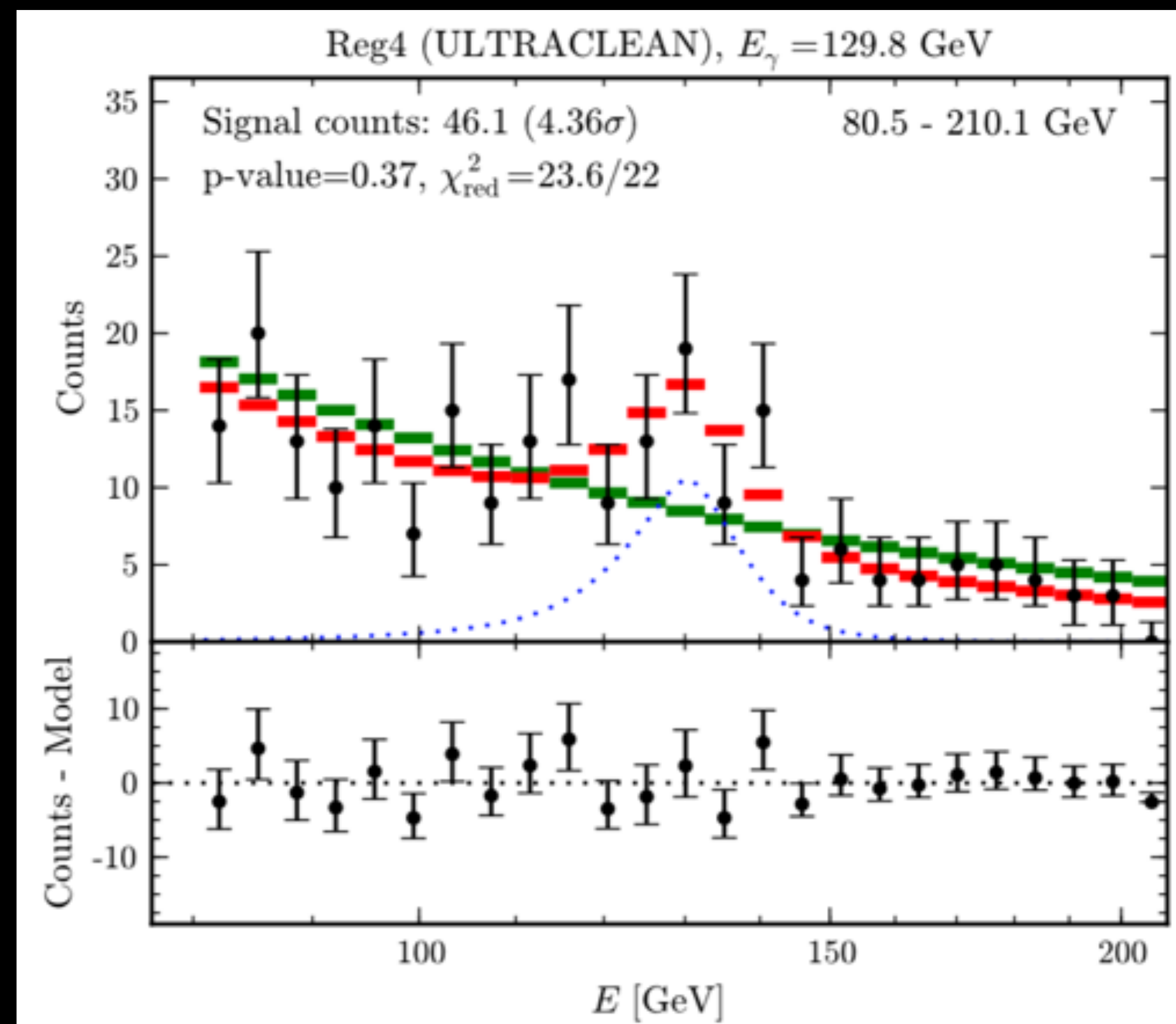
Gamma-ray line searches



- Optimised region of interest about the Galactic center, depends on the DM profile:

$$\frac{N_S}{\sqrt{N_B}}$$



- A gamma-ray line signal at 130 GeV?
- 43 months of SOURCE data (P7V6)
  - Significance: 4.6σ (local), 3.2σ (global)

Bringmann+ JCAP'12 Weniger JCAP'12
Profumo&Linden, JCAP'12; Ibarra+ JCAP'12; Dudas+'12; Cline PRD'12;
Choi&Seto PRD'12; Buckley&Hooper PRD'12; etc...

Gamma-ray line searches

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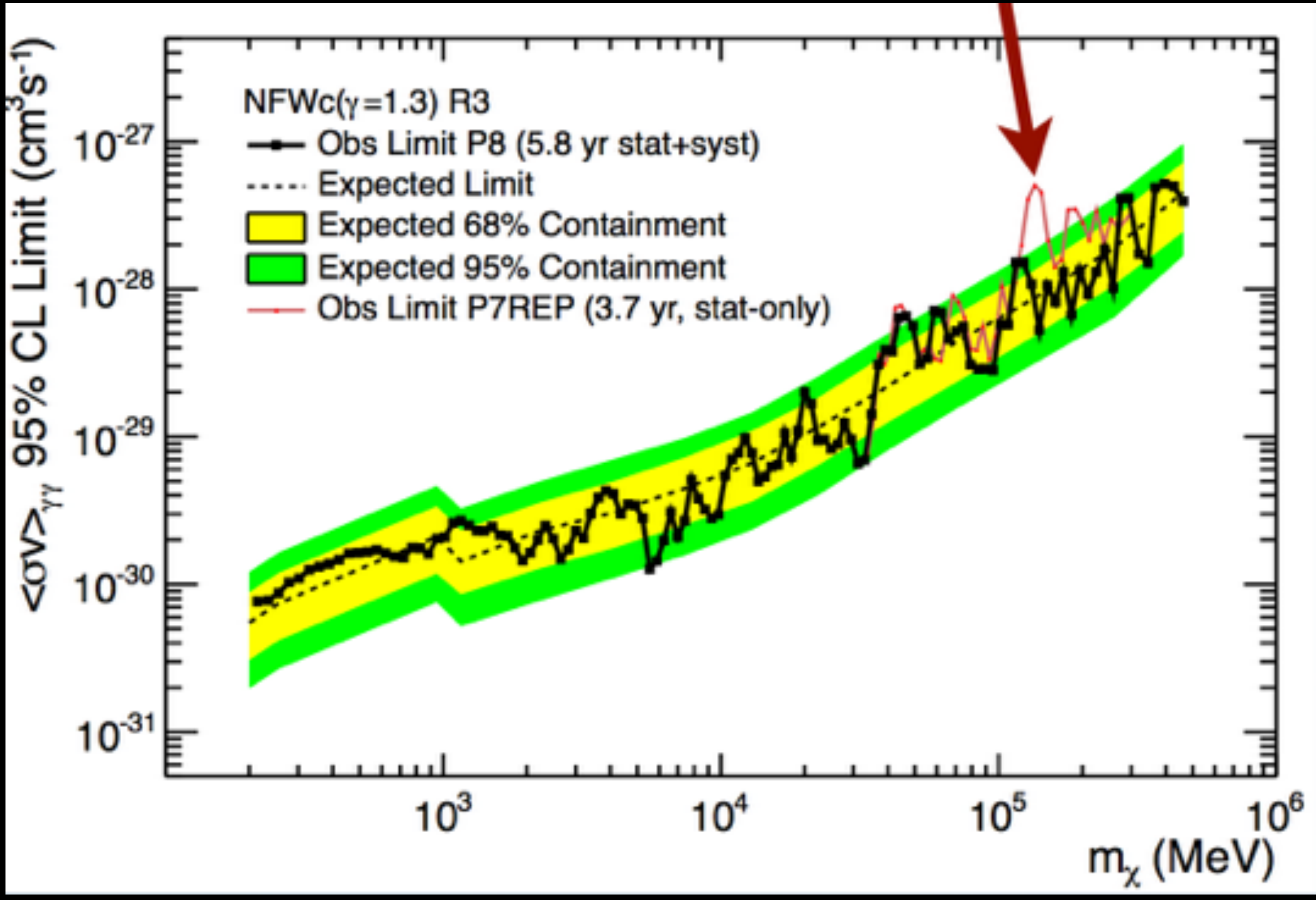
130 GeV feature now excluded



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Profumo&Linden, JCAP'12; Ibarra+ JCAP'12; Dudas+'12; Cline PRD'12; Choi&Seto PRD'12; Buckley&Hooper PRD'12; etc...

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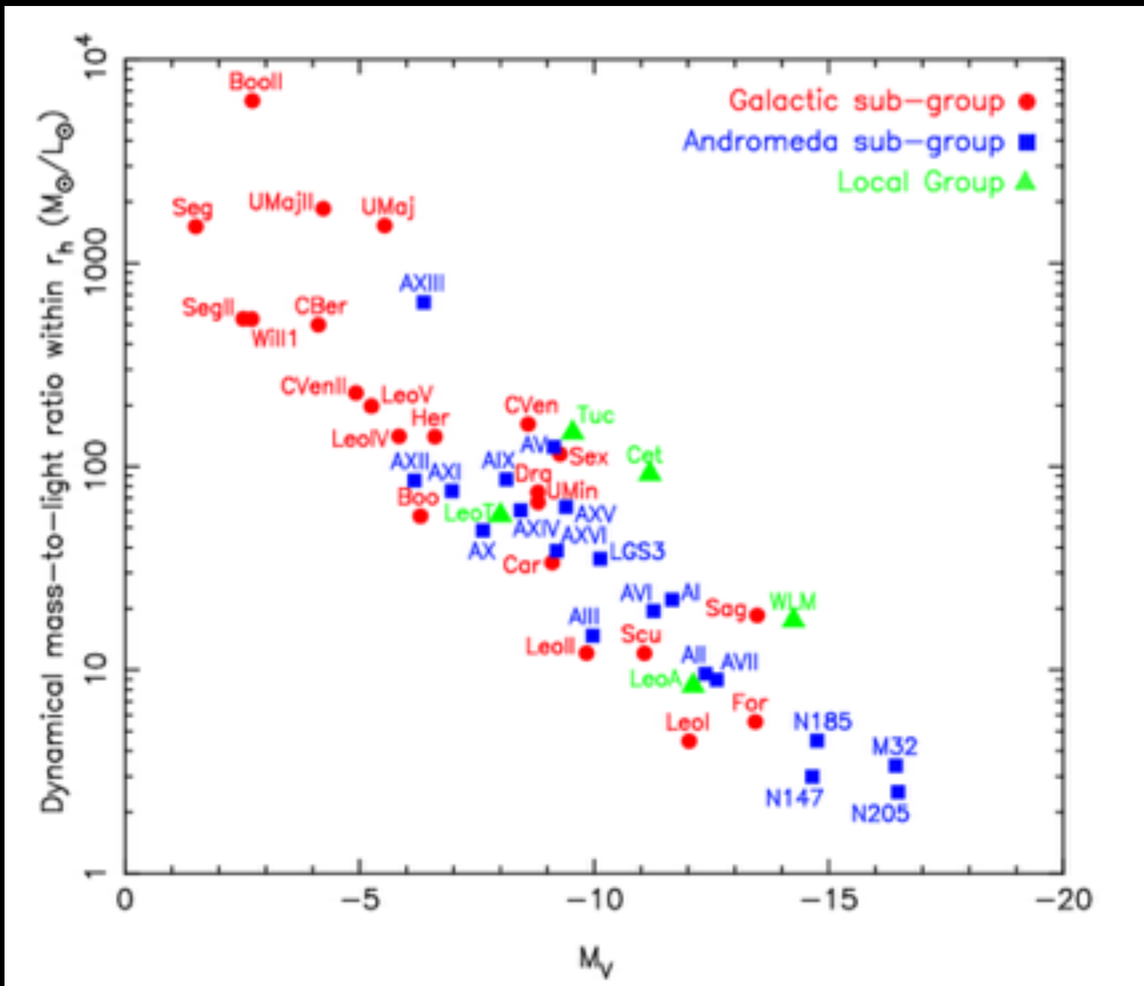
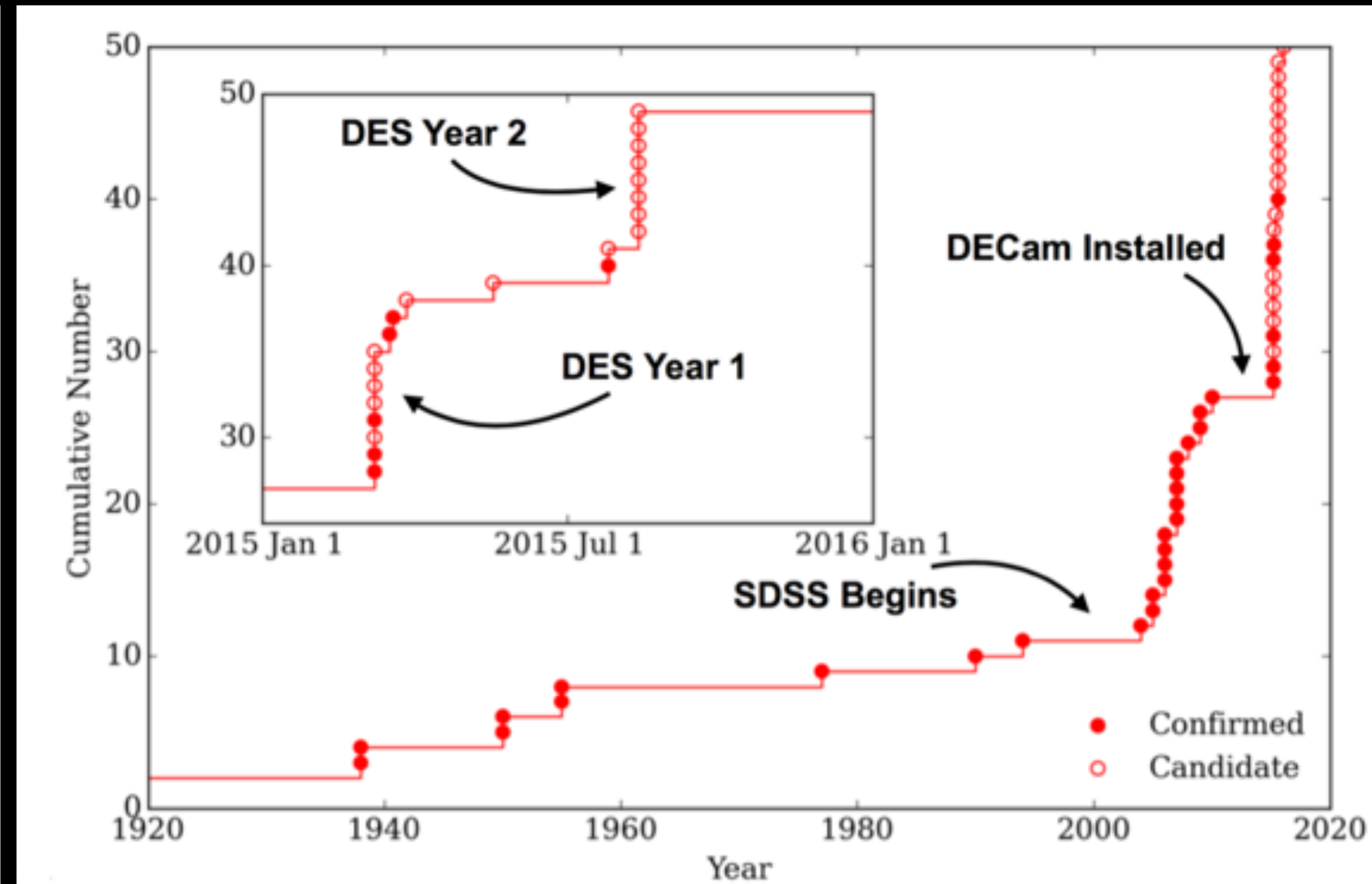
Searches using dwarf spheroidal galaxies

Dwarf spheroidal galaxies

arXiv:1204.1562



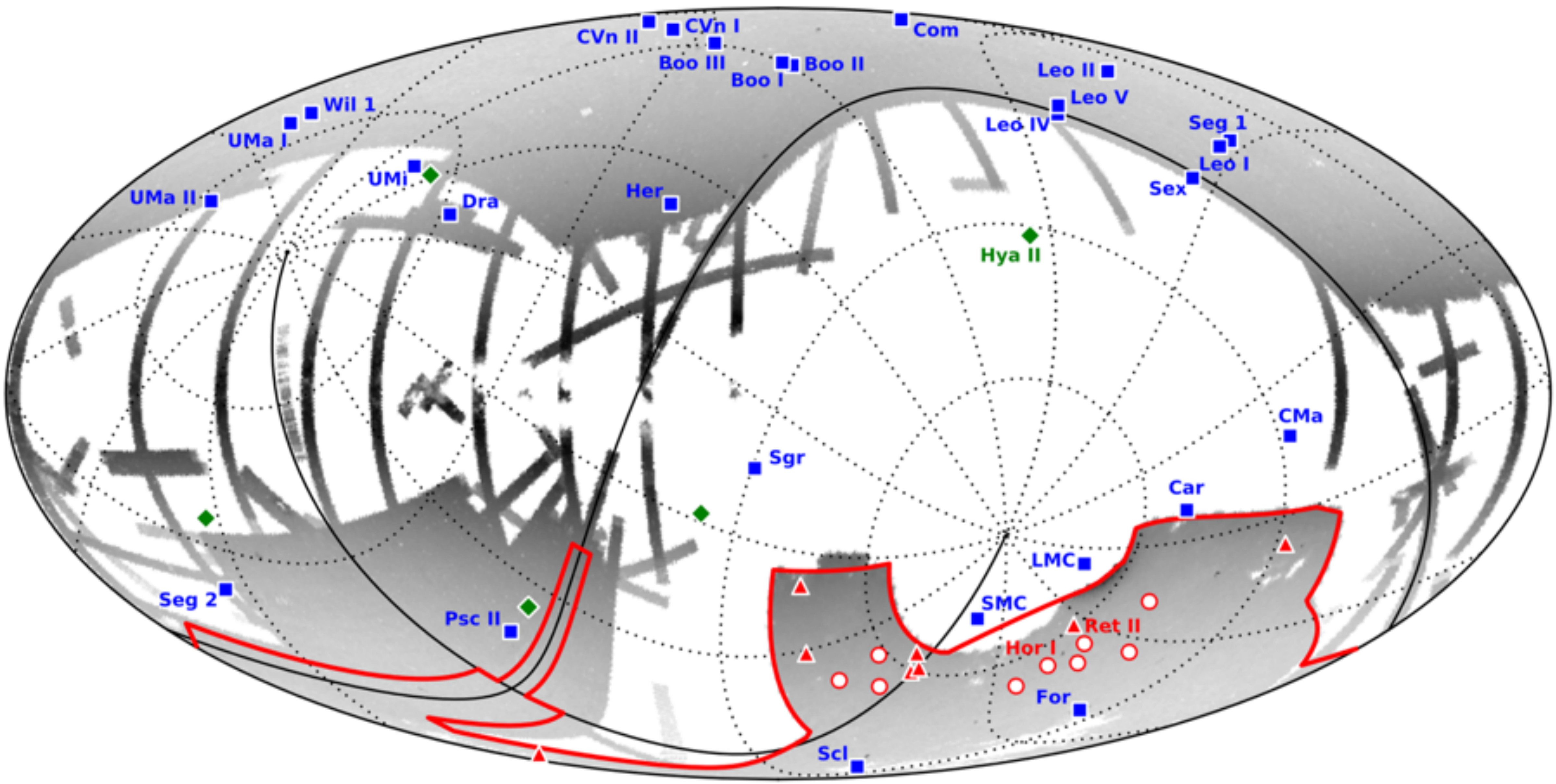


- DSpecs closest dominated DM objects, high mass-to-light ratio
- Very low background (stars and gas)
- Discovered in optical surveys (SDSS, DES)
- Robust targets for ID searches
    - Uncertainties in the halo profile might have been underestimated.

Known dwarf spheroidal galaxies

DES Collaboration, ApJ'15

Stellar density field
from SDSS & DES



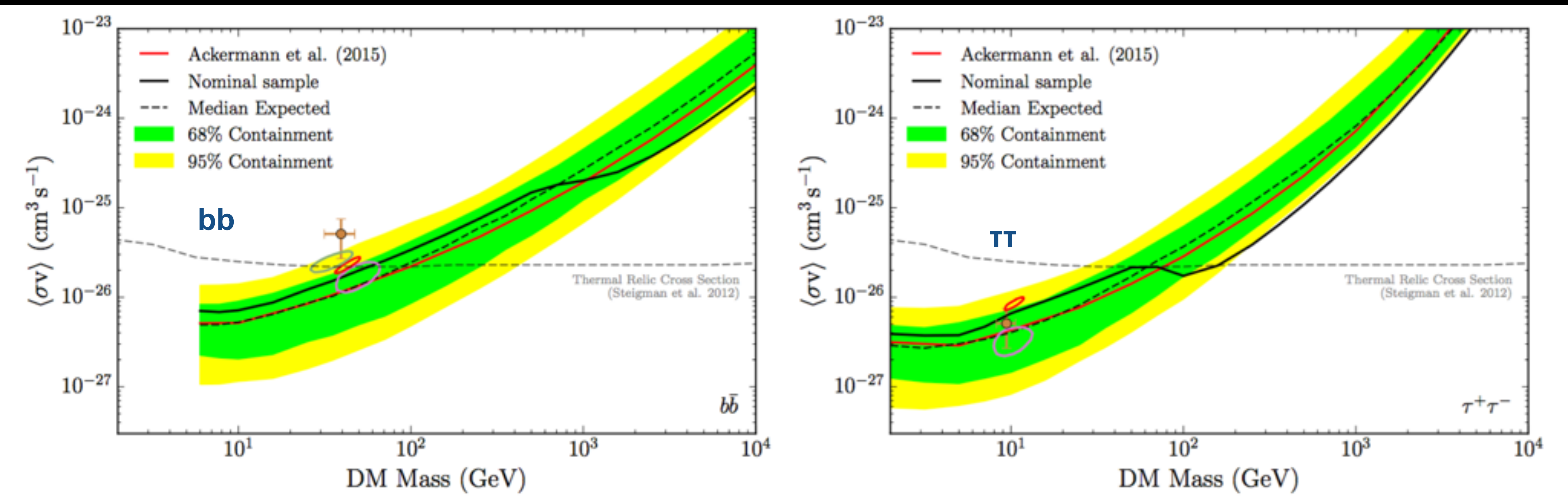
Blue - Previously discovered satellites
Green - Discovered in 2015 with PanSTARRS/SDSS

Red outline - DES footprint
Red circles - DES Y1 satellites
Red triangles - DES Y2 satellites

Latest Fermi-LAT Analysis

arXiv:1611.03184

Fermi-LAT & DES

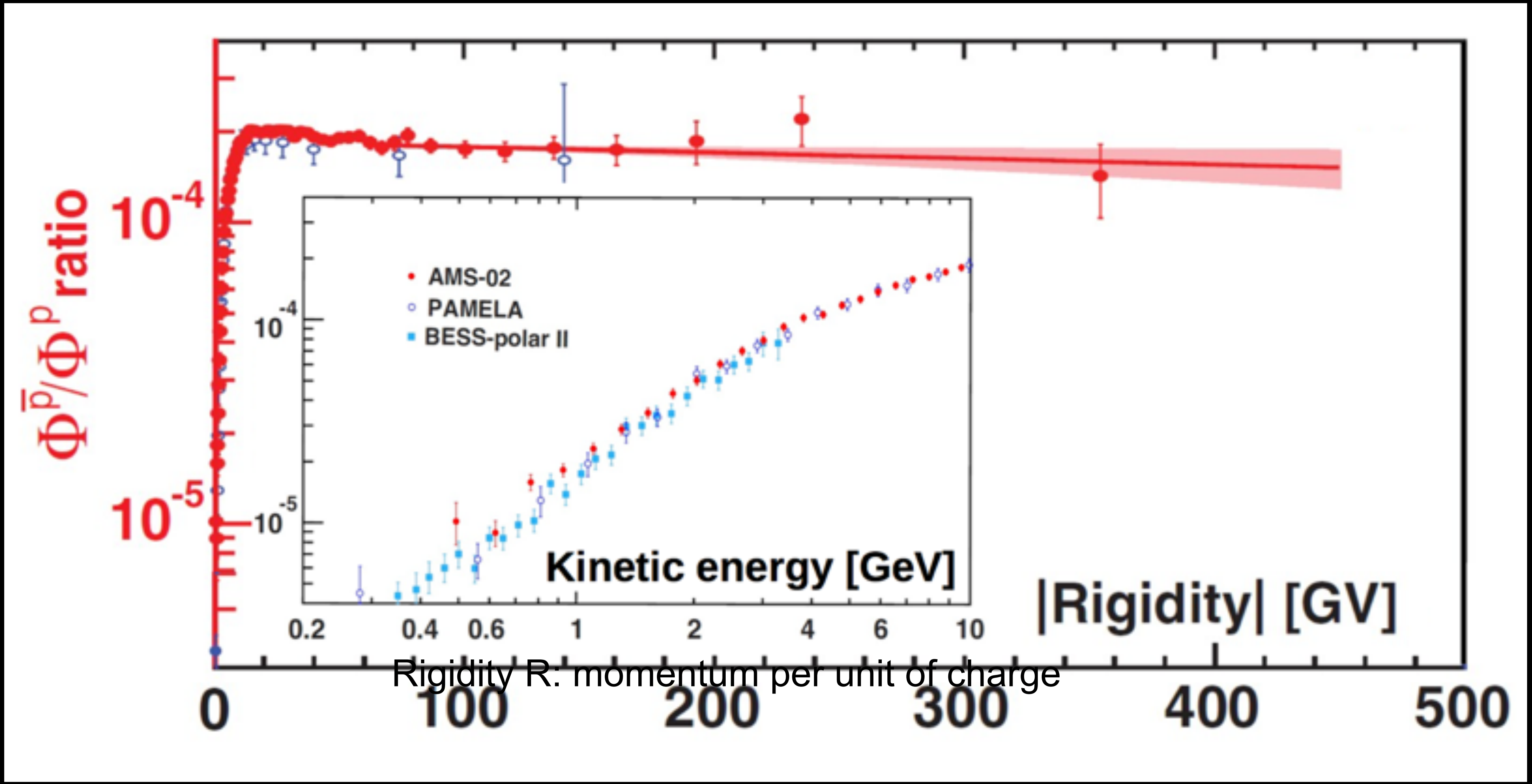


Very small excess in bb channel (again).

Searches with anti-protons

Antiproton/proton ratio

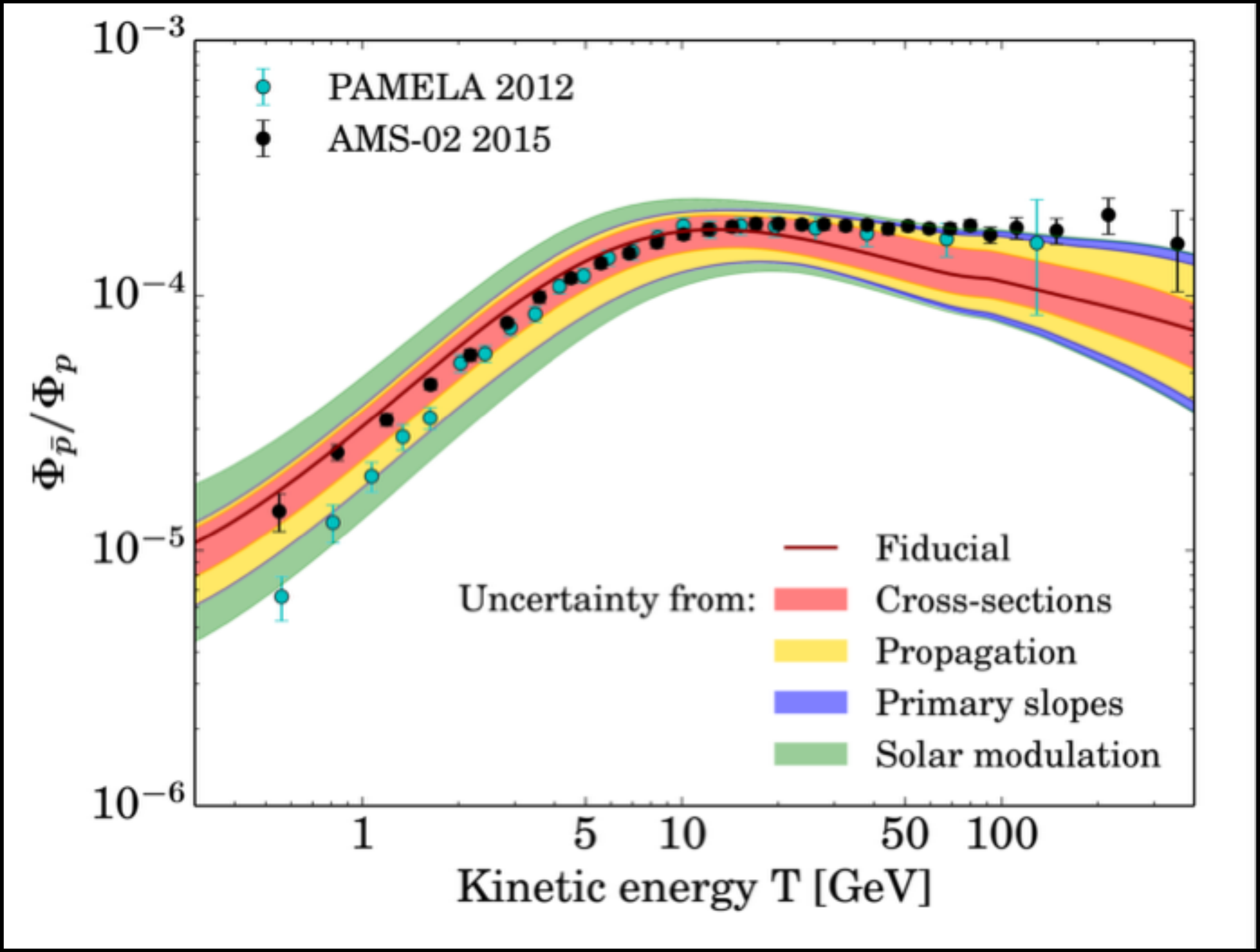
arXiv:1701.00086



Rigidity R: momentum per unit of charge

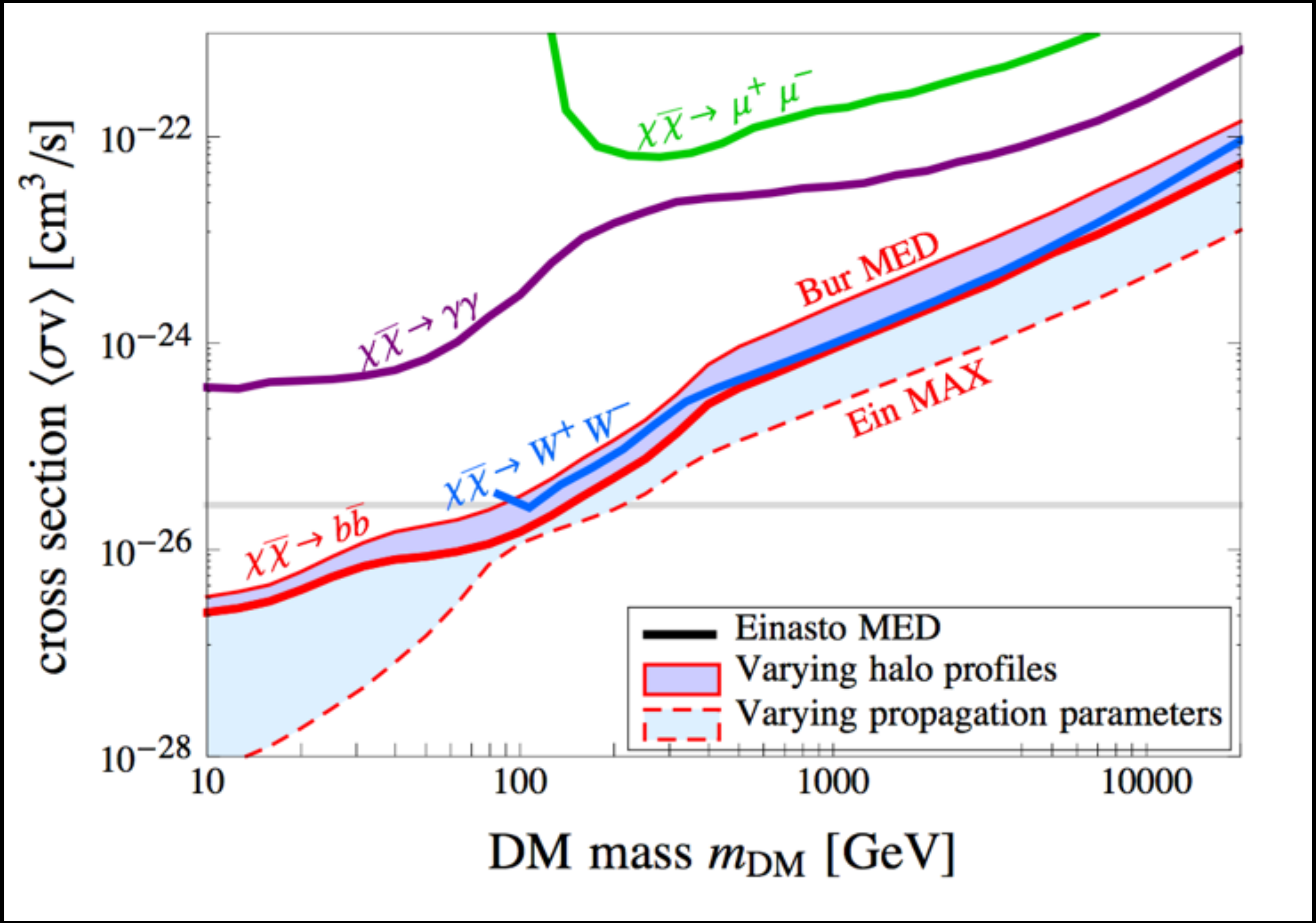
- Production of anti-protons again universal because of hadronization in DM decay/annihilation
- Background anti-proton production and propagation relatively well understood → Powerful tool for stringent constraints on DM contribution

Antiproton/proton ratio



- Quite some uncertainty affects the prediction of the astro only antiproton signal.

Constraints on DM from antiprotons

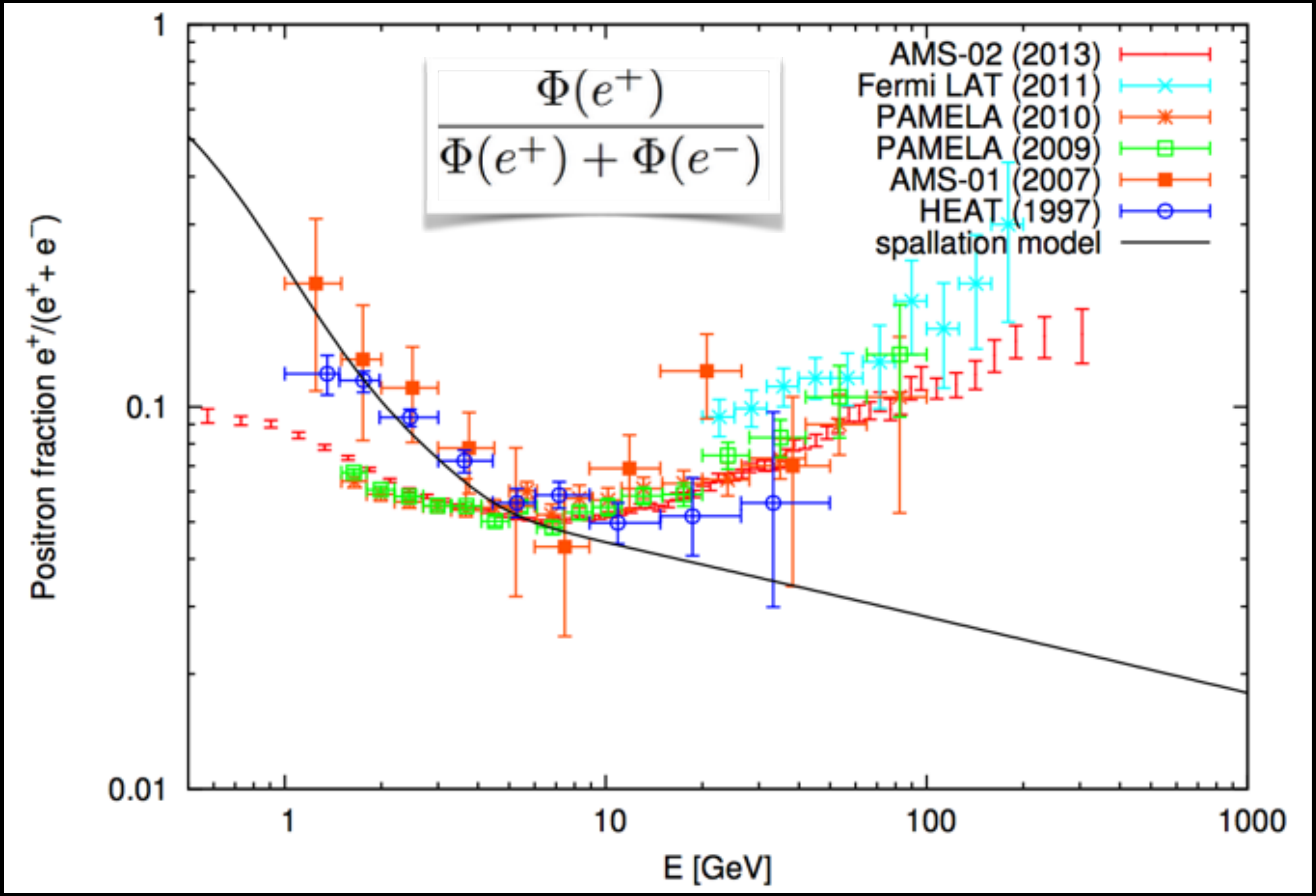


- Discussion of uncertainties in the GeV excess signal + protons & radio constraints

Bringmann+ PRD'14; Cholis+PRD'15

Positron Fraction

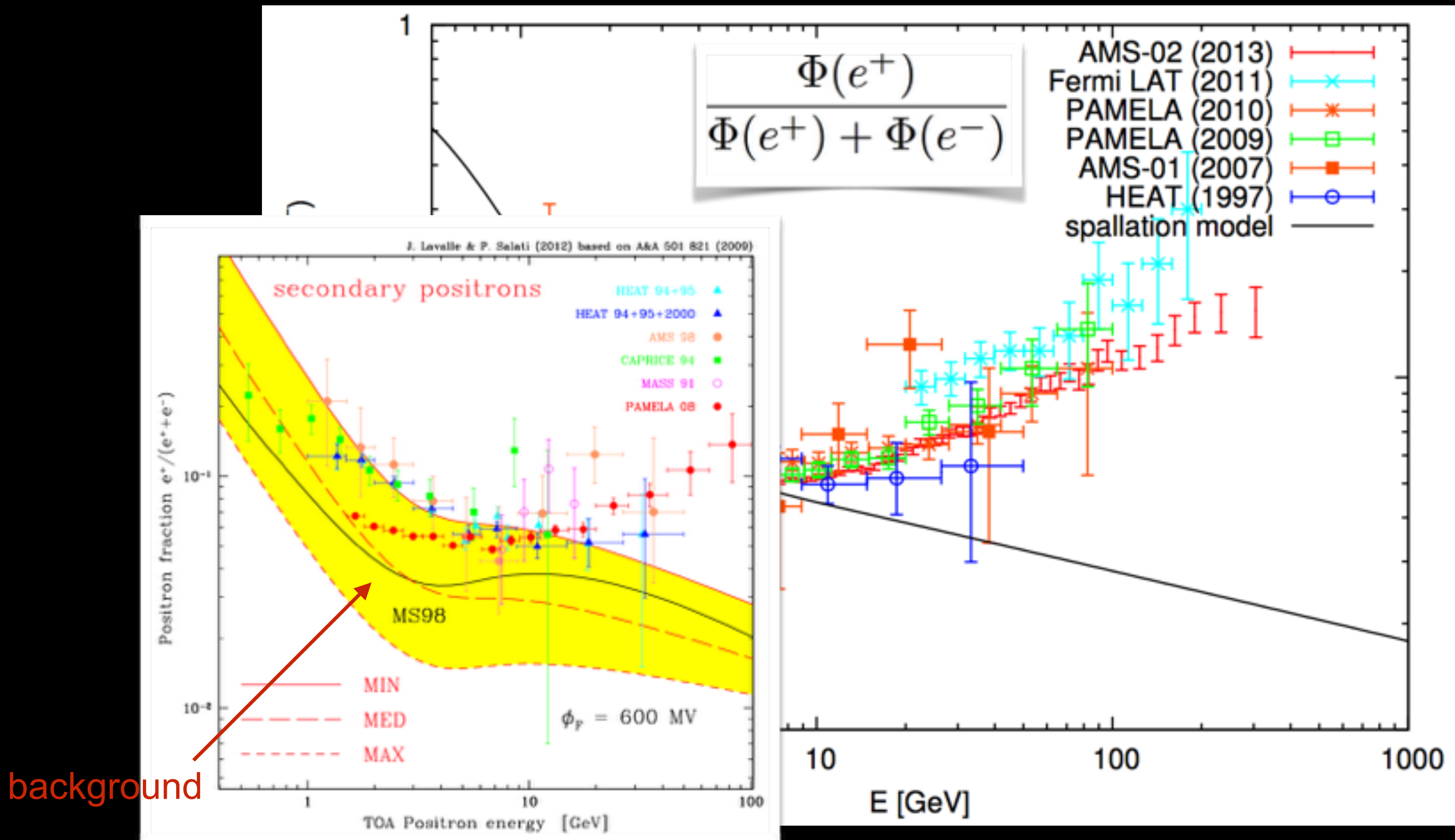
arXiv:1307.6434



- Anomaly: a rise in the positron fraction for E > 10 GeV
- From CR propagation physics, the ratio is expected to decrease for all propagation models

Positron Fraction

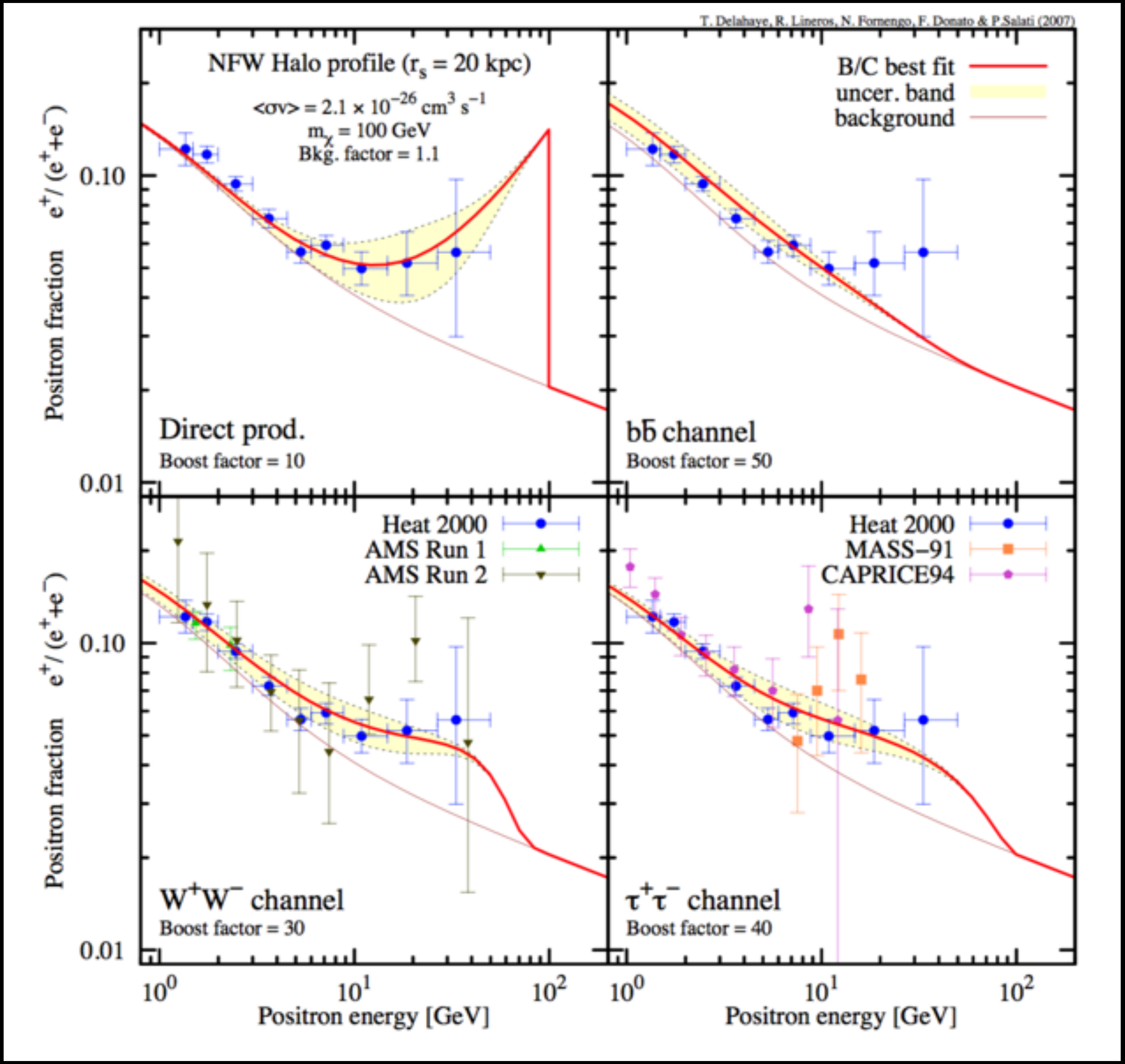
arXiv:1307.6434
arXiv:1205.1004



- Anomaly: a rise in the positron fraction for E > 10 GeV
- From CR propagation physics, the ratio is expected to decrease for all propagation models

Is it DM?

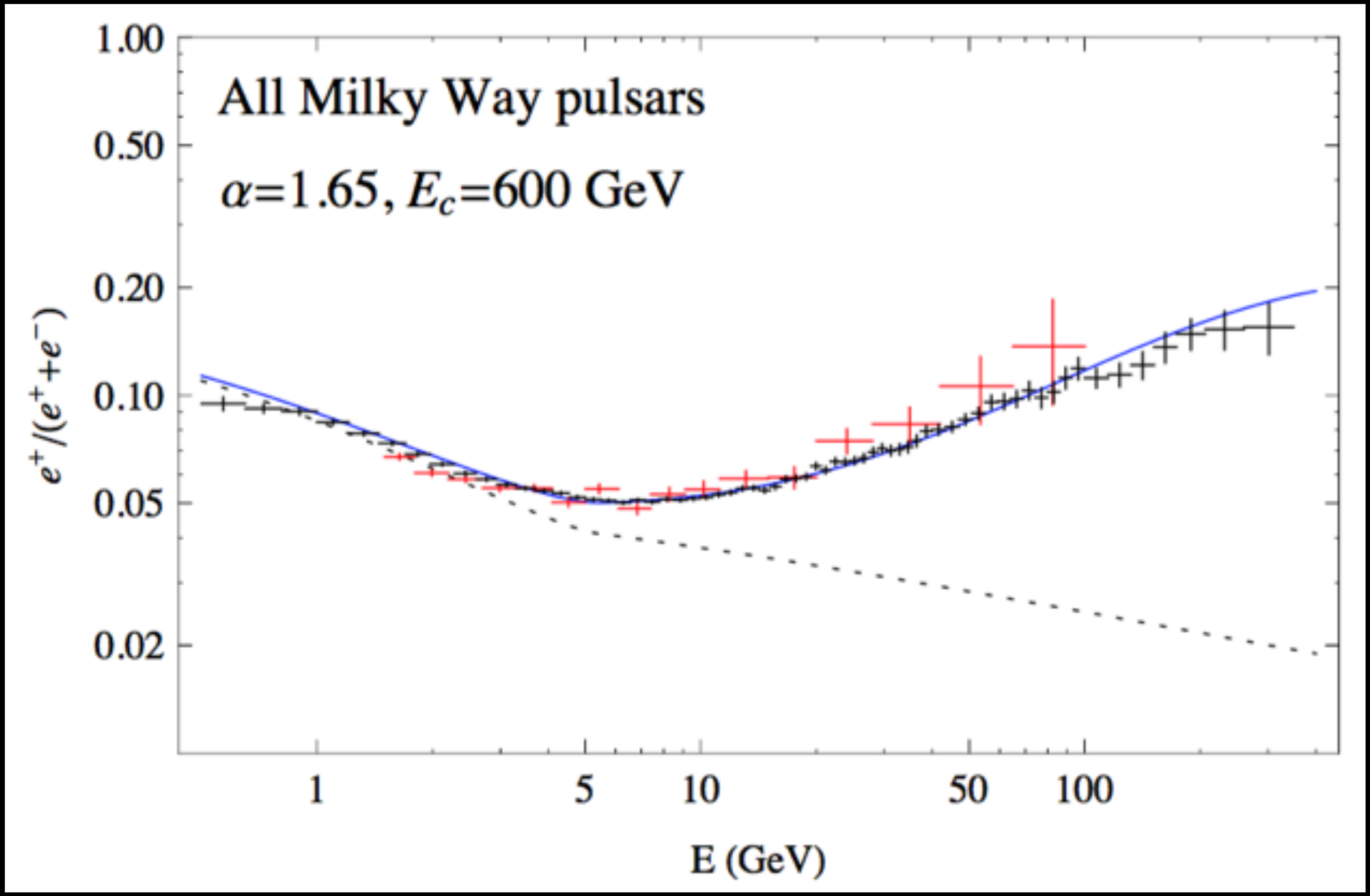
arXiv:1003.4124

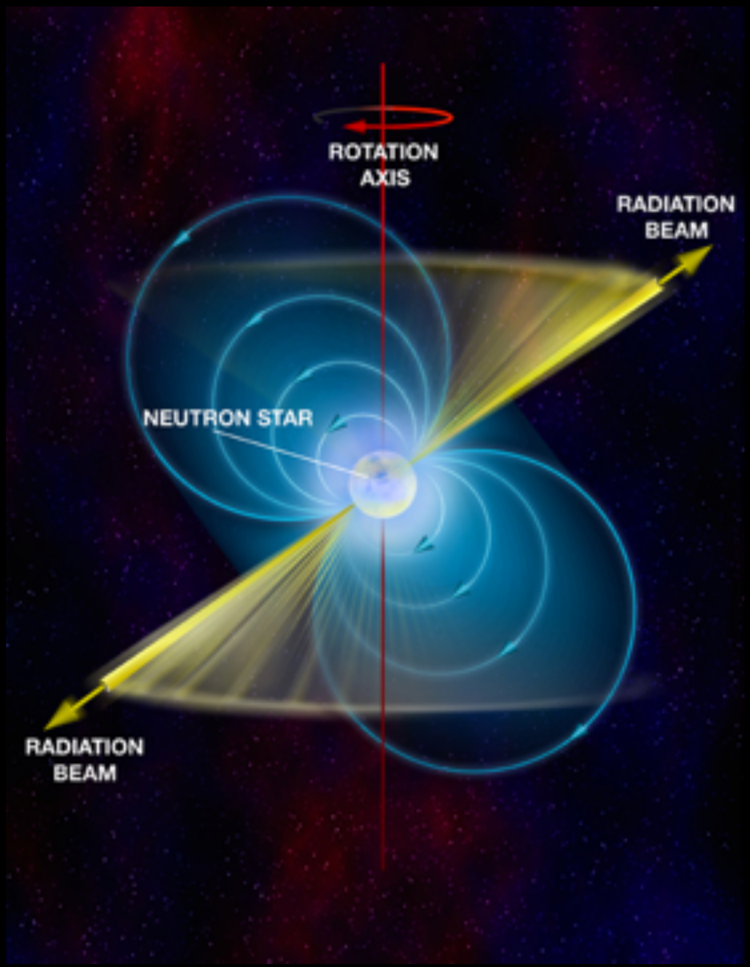


- Dark matter interpretation:
  - Annihilation into leptons only
  - Quite massive particle
  - Very large cross section

Is it DM?

arXiv:1304.1840, 0904.3830,



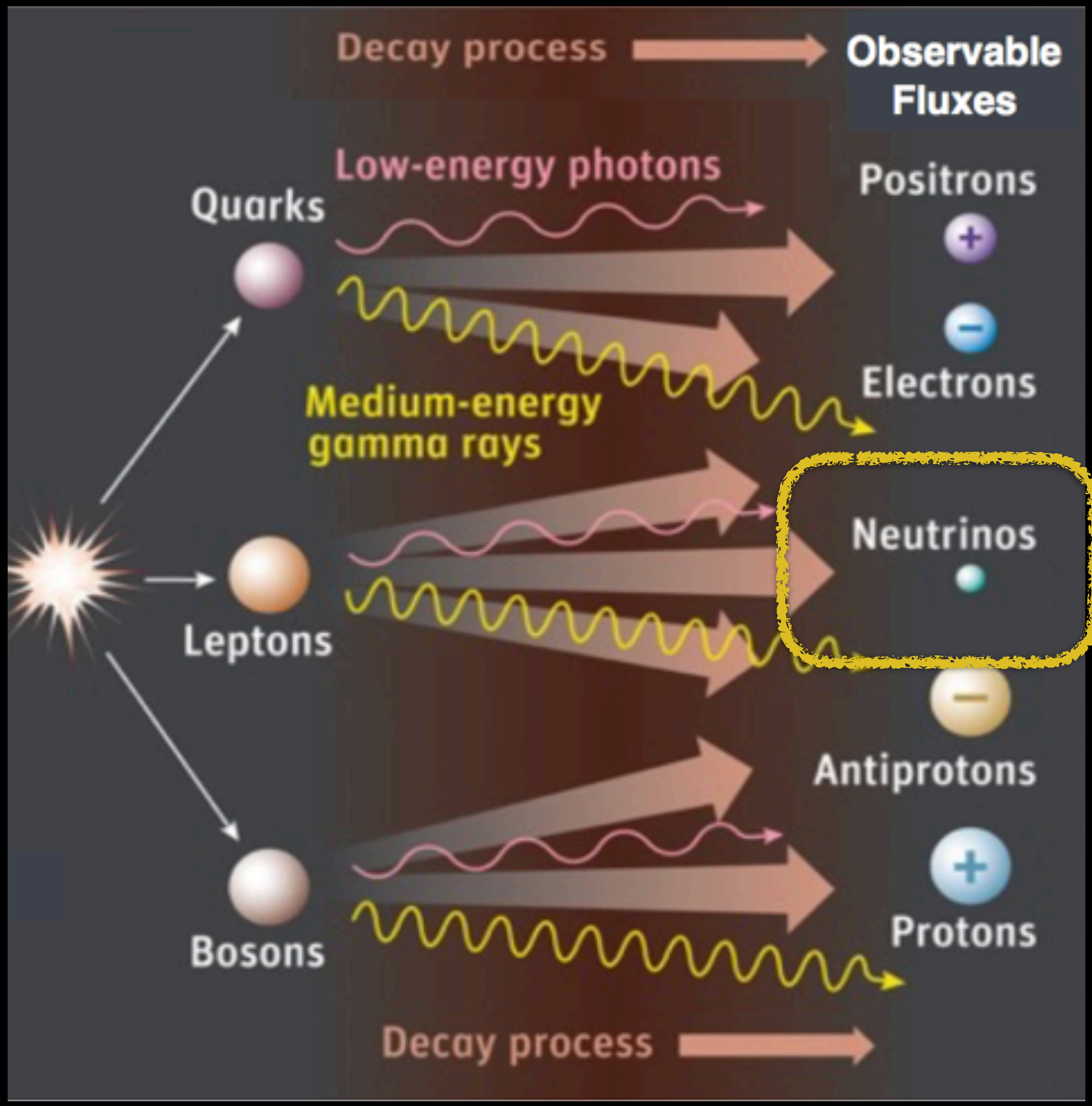


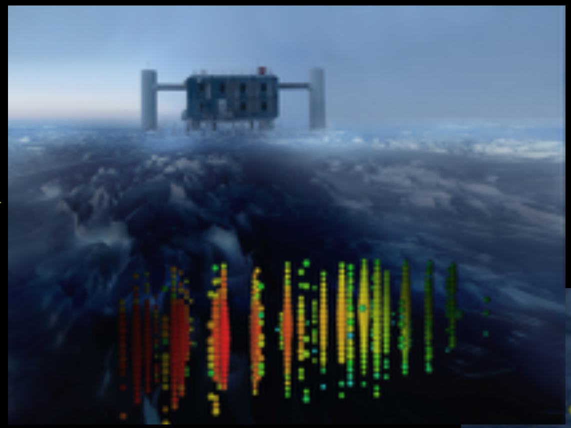
- Annihilation into leptons produces always an Inverse Compton emission, not seen in gamma rays → Gamma-ray constraints
- Tension with current constraints from CMB

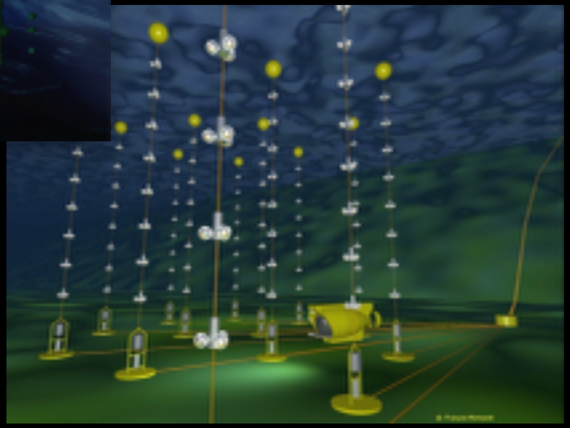
- Possibly positrons from pair production in pulsar magnetosphere
- How to discriminate DM from astrophysics?
    - Shape of the spectrum (challenging)
    - Anisotropy (directional signal)

Searches with Neutrinos

Neutrino Searches

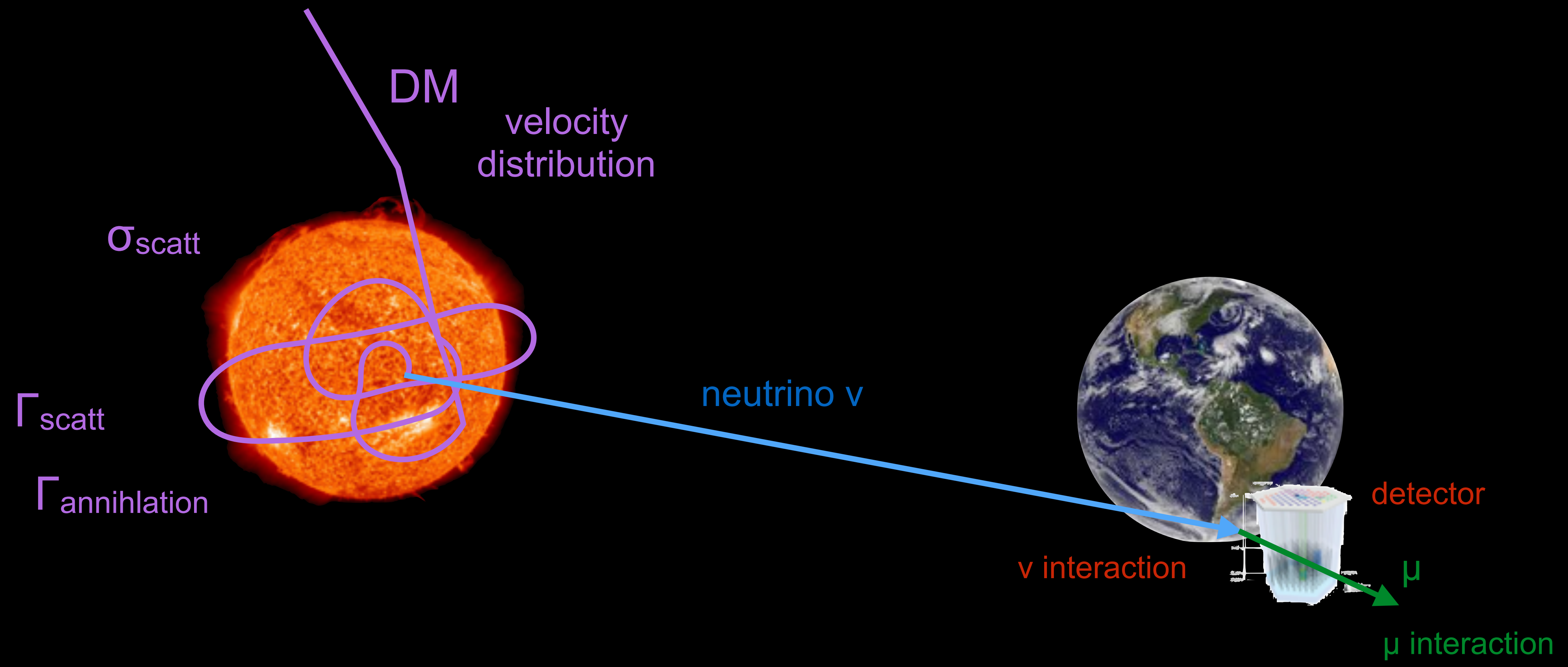






- Search for an excess of high-energy neutrinos from the Sun and the Earth, indicating the presence of dark matter annihilation
- Unperturbed propagation, like for photons
- Signal generally suppressed with respect to gamma rays

WIMPs in the Sun



In the Sun:

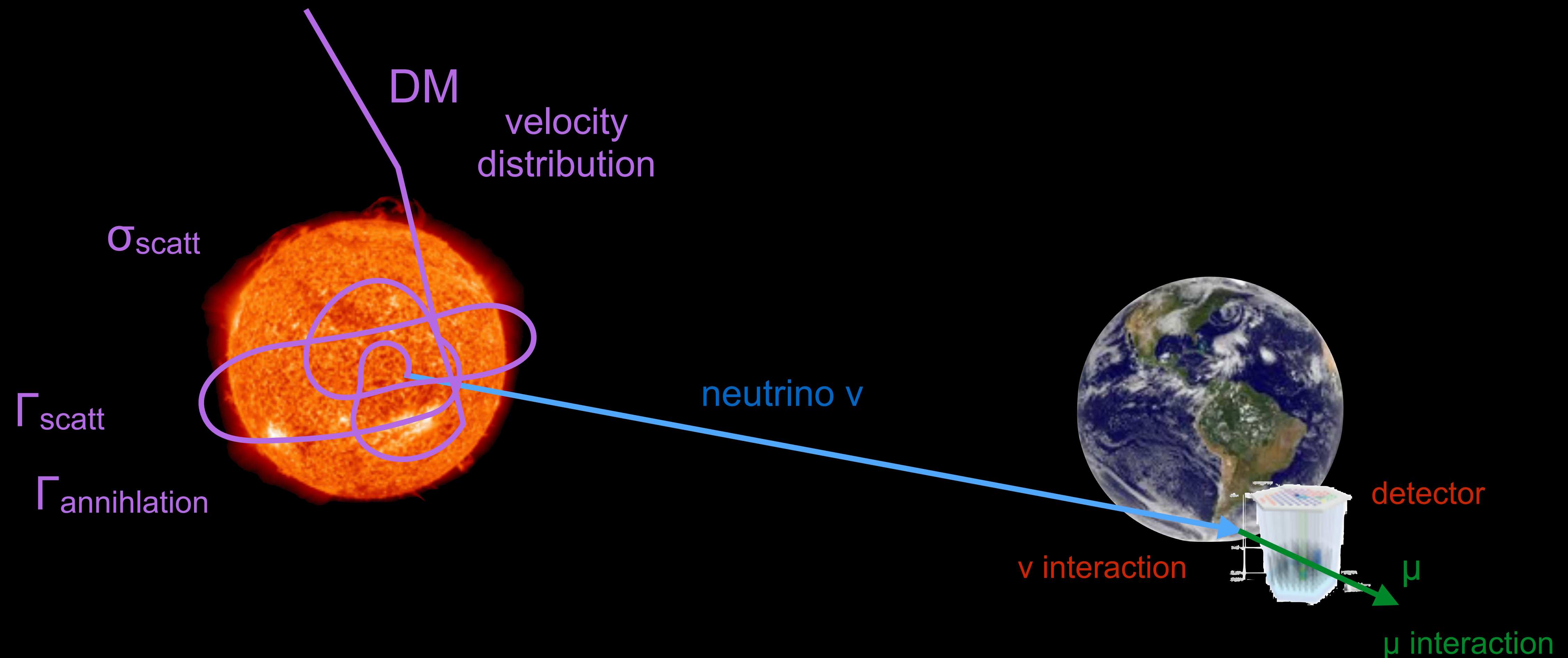
- Capture of DM
- Annihilation of DM
- High energy ν escape

oscillation/propagation

On Earth:

- Detection by e.g. IceCube

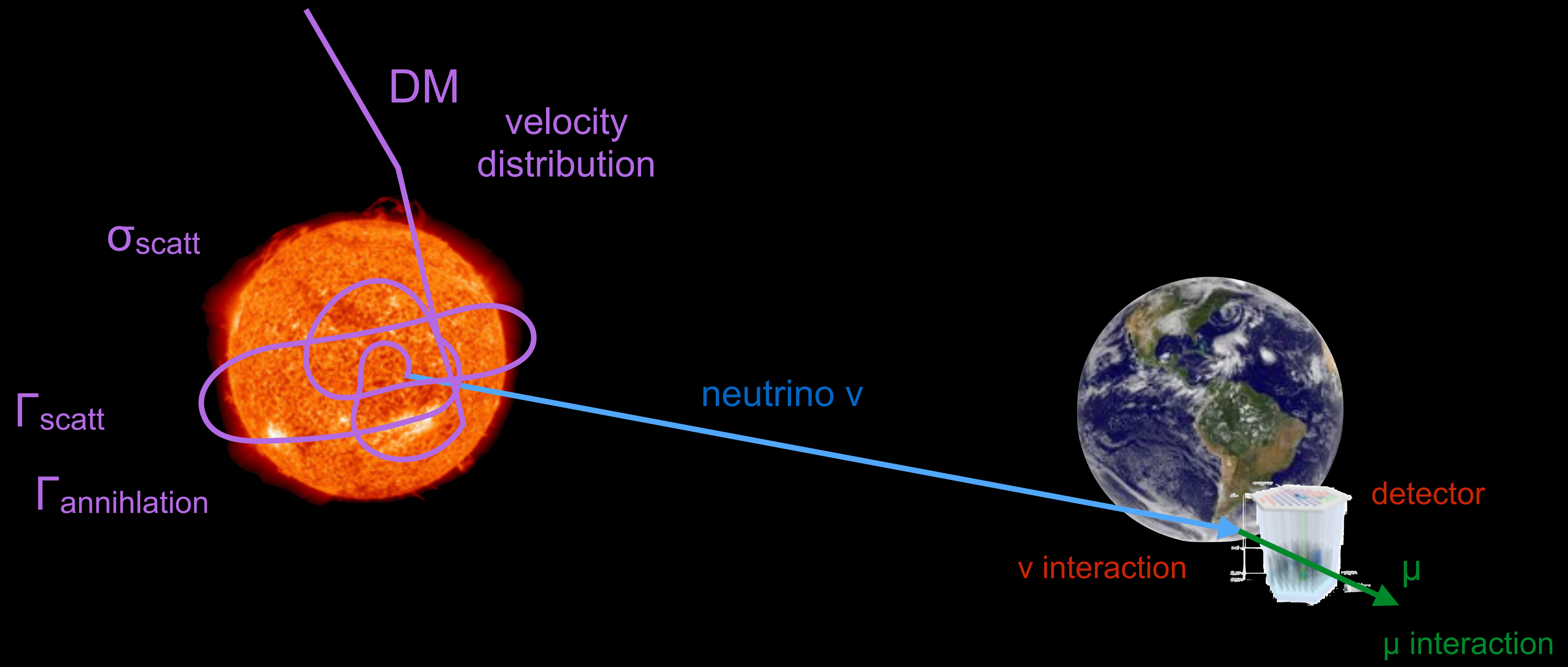
WIMPs in the Sun



Solar DM capture:

- DM going through the Sun interact with particles
- Elastic scattering with protons in the Sun (as in direct detection)
- DM looses energy and velocity decreases, once $v_{DM} < v_{escape}$, then DM becomes trapped
- After multiple scatterings, DM thermalizes in the core of the sun
- Dependencies: Local DM velocity and density, scattering cross section, Sun's element composition

WIMPs in the Sun



Solar DM annihilation:

- DM in the Sun might annihilate
  - only neutrinos can escape from the Sun because of low absorption
  - the dark matter annihilation competes with the capture rate
- Very slowly DM annihilation/capture reaches equilibrium

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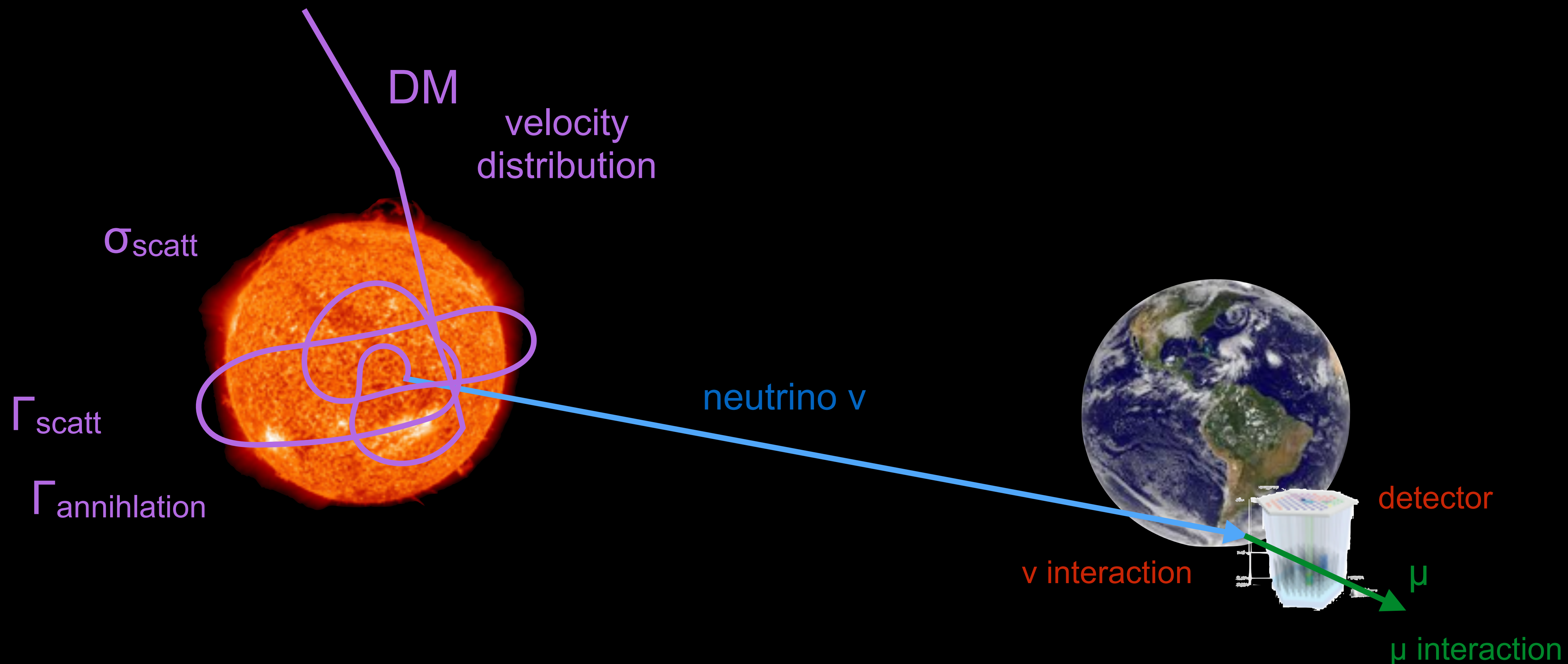
WIMPs in the Sun



- At equilibrium, dependence only on the scattering x-section (as direct detection)
- Less affected by DM halo uncertainties because average out over time

Equilibrium

$$\sigma_{\mathrm{SD}} = 10^{-41}\mathrm{cm}^2 \longrightarrow \tau_{\mathrm{eq}} = 0.28 \cdot 10^9 \mathrm{yr} \ll t_\odot$$

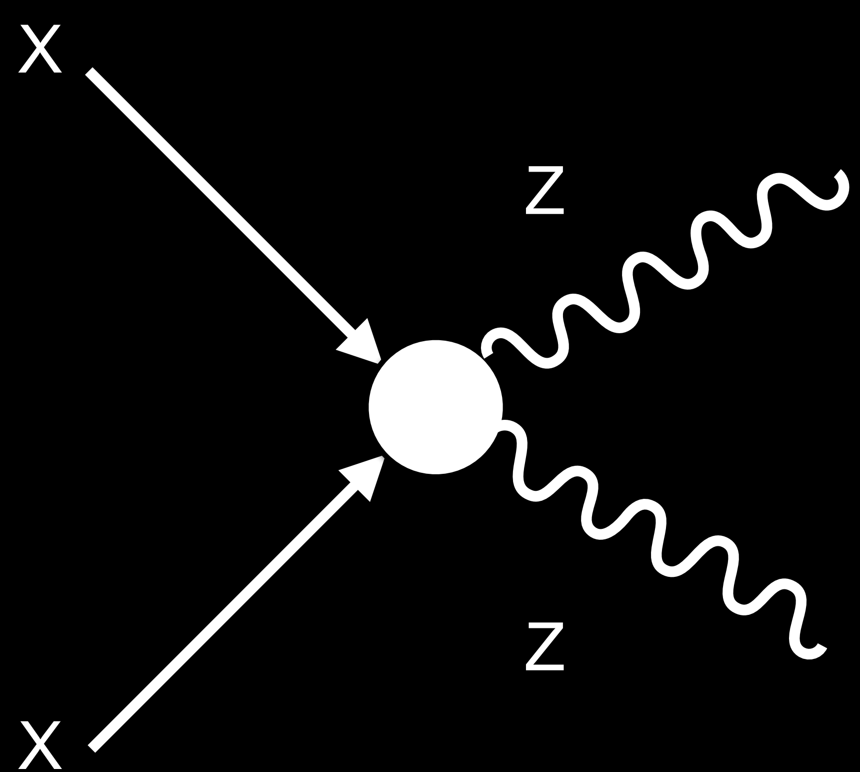
Out of Equilibrium

$$\sigma_{\mathrm{SD}} = 10^{-45}\mathrm{cm}^2 \longrightarrow \tau_{\mathrm{eq}} = 28 \cdot 10^9 \mathrm{yr} \gg t_\odot$$

Solar Neutrino Energys

$$\chi\chi \rightarrow \left\{ \begin{array}{c} \mathrm{ZZ},\ \mathrm{W}^+\ \mathrm{W}^-,\ \gamma\gamma \\ q\bar{q},\ \ell^+\ell^-,\ \nu\bar{\nu} \end{array} \right\} \xrightarrow{\text{had./decay}} \gamma, e^\pm, \mu^\pm, p/\bar{p}, \pi^\pm, \nu/\bar{\nu} \ldots$$

$\mathcal{O}$(GeV) - $\mathcal{O}$(TeV) from dark matter
$E_\nu \sim \mathcal{O}$(MeV) from sun



- Monochromatic neutrinos from Sun from e.g. ZZ decay

Solar Neutrino Energys

$$\chi\chi \to \left\{ \begin{array}{c} ZZ,\ W^+\ W^-,\ \gamma\gamma \\ q\bar{q},\ \ell^+\ell^-,\ \nu\bar{\nu} \end{array} \right\} \xrightarrow{\text{had./decay}} \gamma, e^\pm, \mu^\pm, p/\bar{p}, \pi^\pm, \nu/\bar{\nu} \ldots$$

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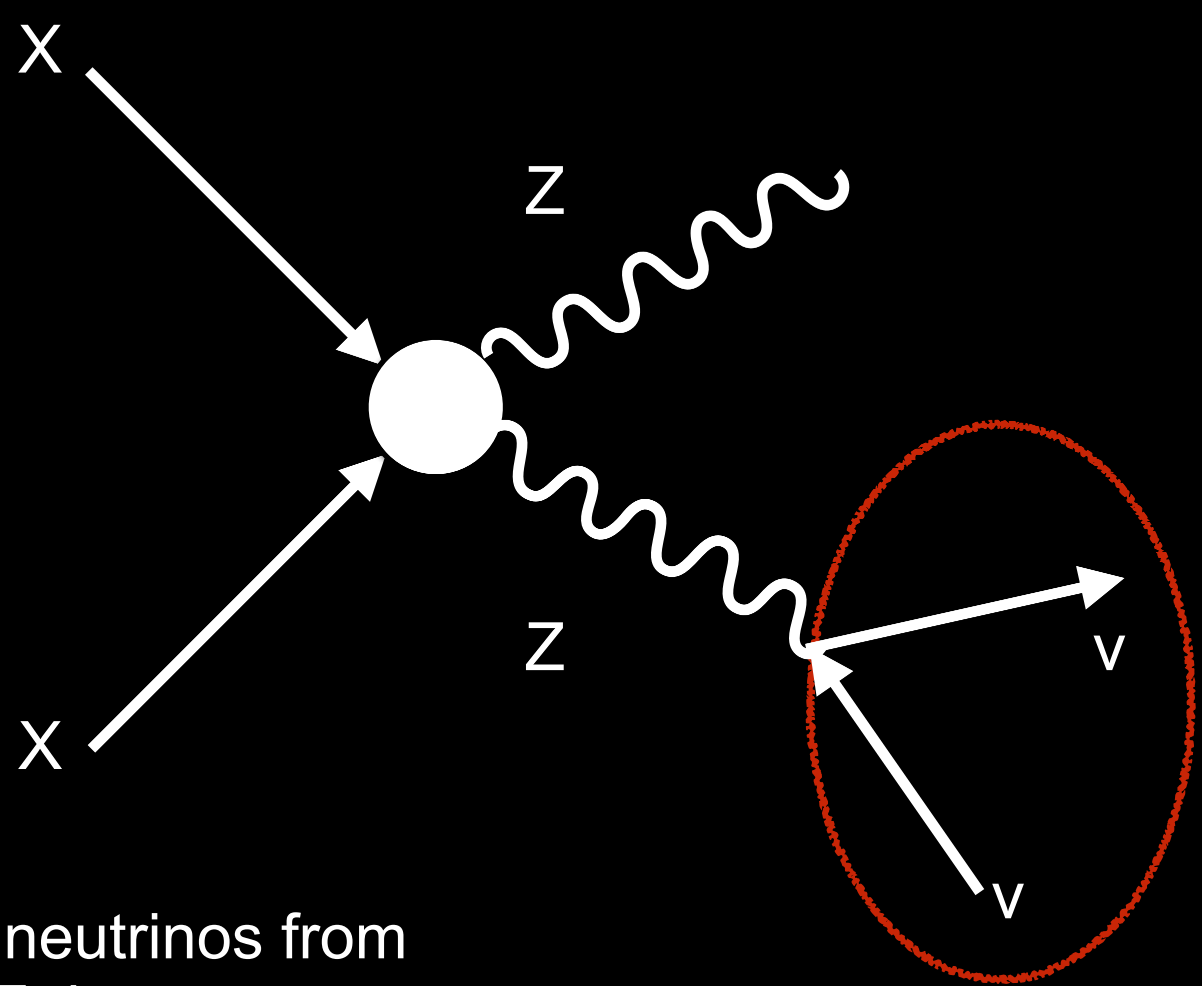

- Monochromatic neutrinos from Sun from e.g. ZZ decay
- In case of boosted neutrinos: $E_\nu \sim m_{DM}$

Solar Neutrino Energys

$$\chi\chi \to \left\{ \begin{array}{c} \mathrm{ZZ},\ \mathrm{W}^+\ \mathrm{W}^-,\ \gamma\gamma \\ q\bar{q},\ \ell^+\ell^-,\ \nu\bar{\nu} \end{array} \right\} \xrightarrow{\text{had./decay}} \gamma, e^\pm, \mu^\pm, p/\bar{p}, \pi^\pm, \nu/\bar{\nu}...$$

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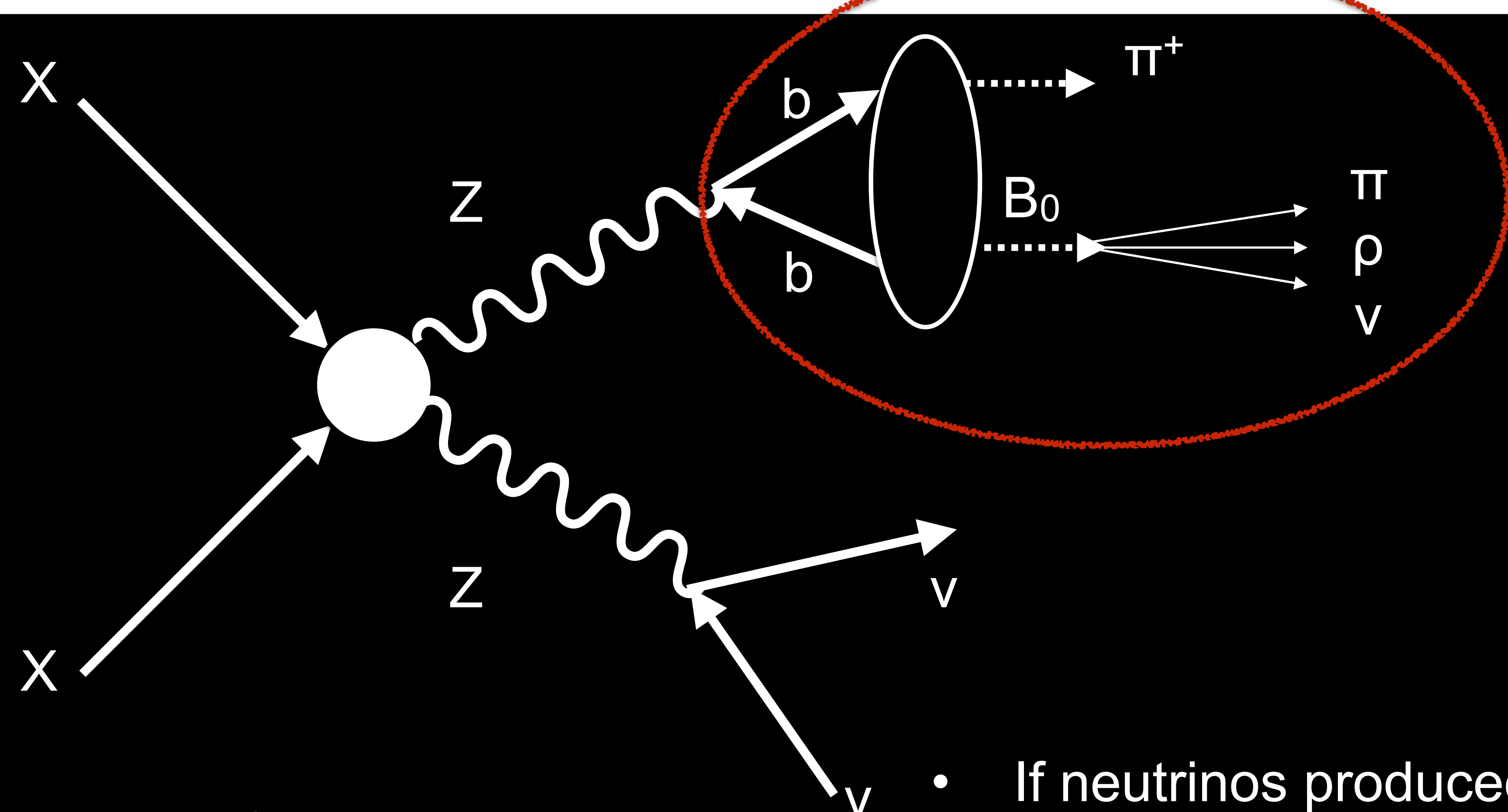
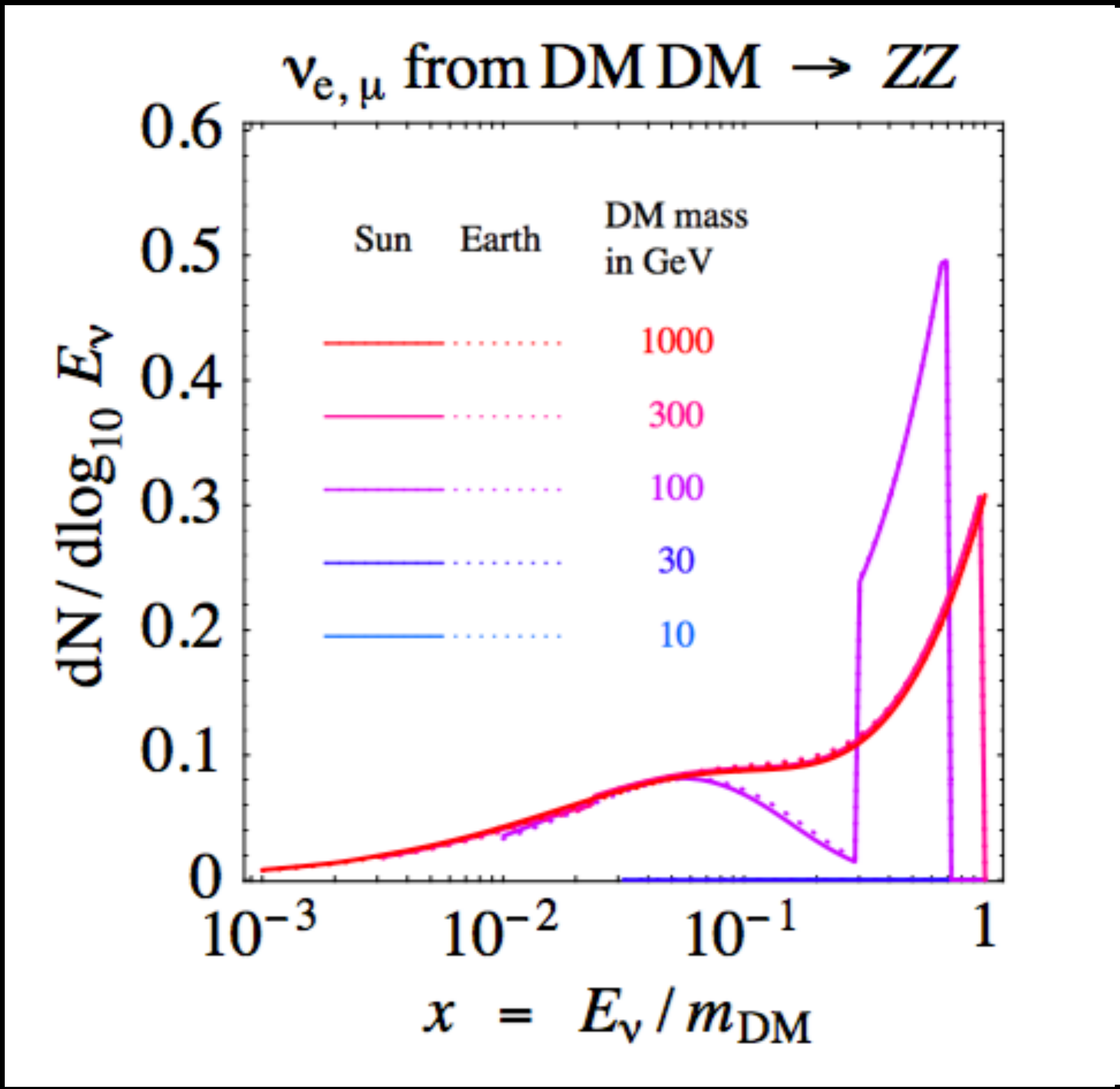


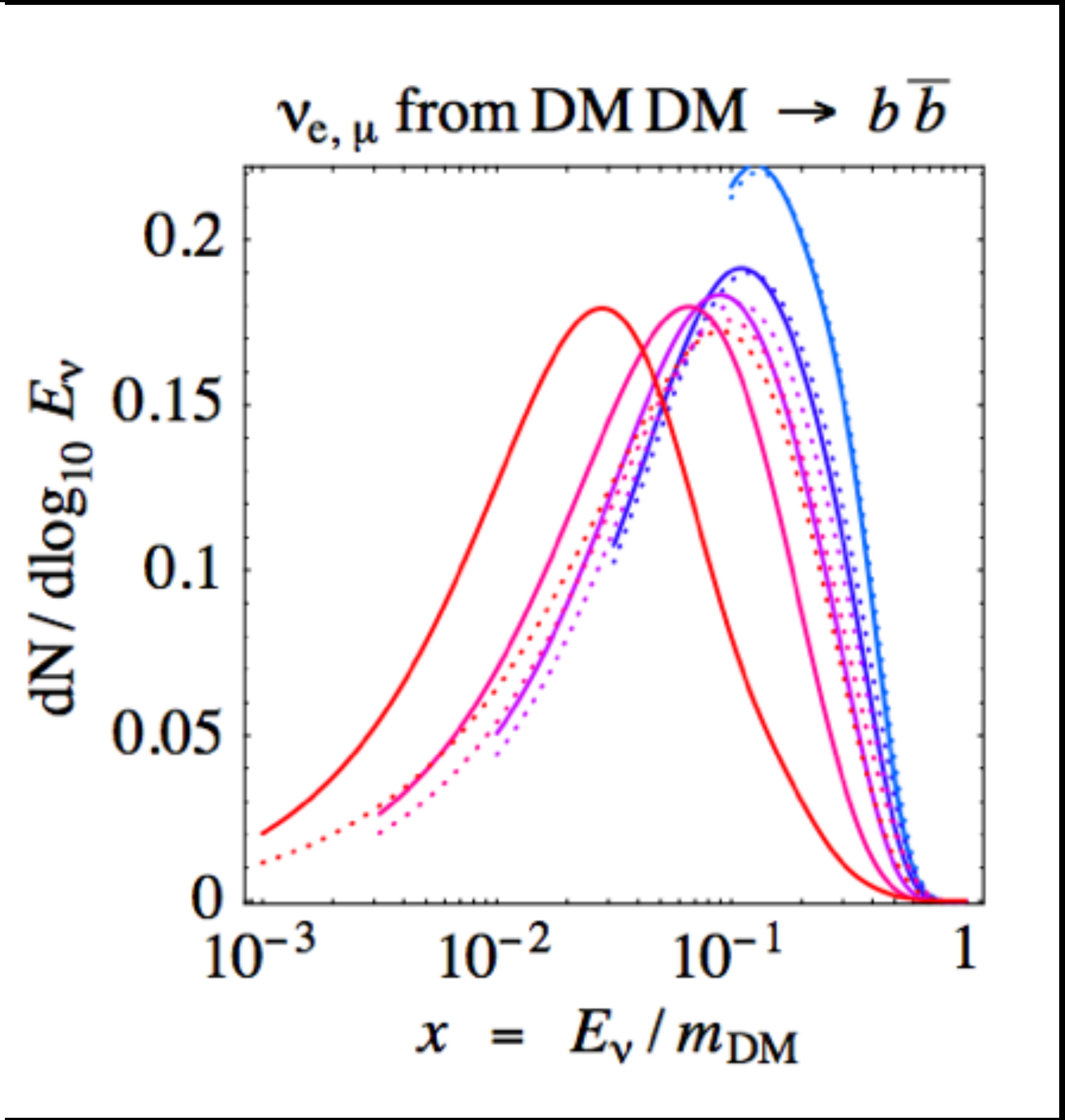
- Monochromatic neutrinos from Sun from e.g. ZZ decay
- In case of boosted neutrinos: $E_\nu \sim m_{DM}$

- If neutrinos produced via intermediate states
  - $E_\nu \ll m_{DM}$
  - ‘Soft neutrinos’

Neutrino Flux

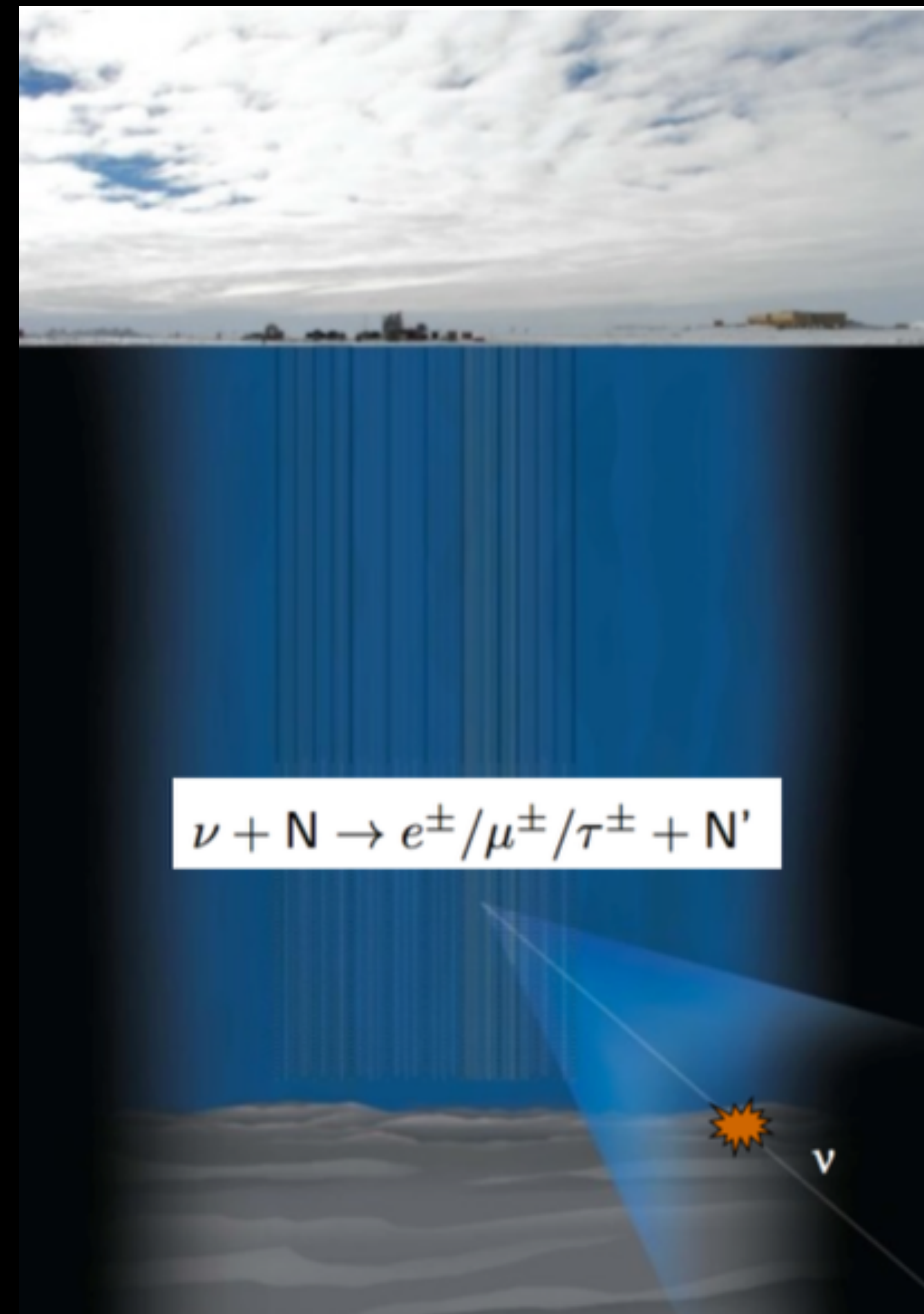
arXiv:0506298v5





Neutrino flux allows to constrain - or determine - DM properties.

Neutrino Telescopes



- Large volumes because of small cross-sections and fluxes
- Optical modules in a transparent medium to detect the Cherenkov light emitted in charged-current neutrino-nucleon interactions.

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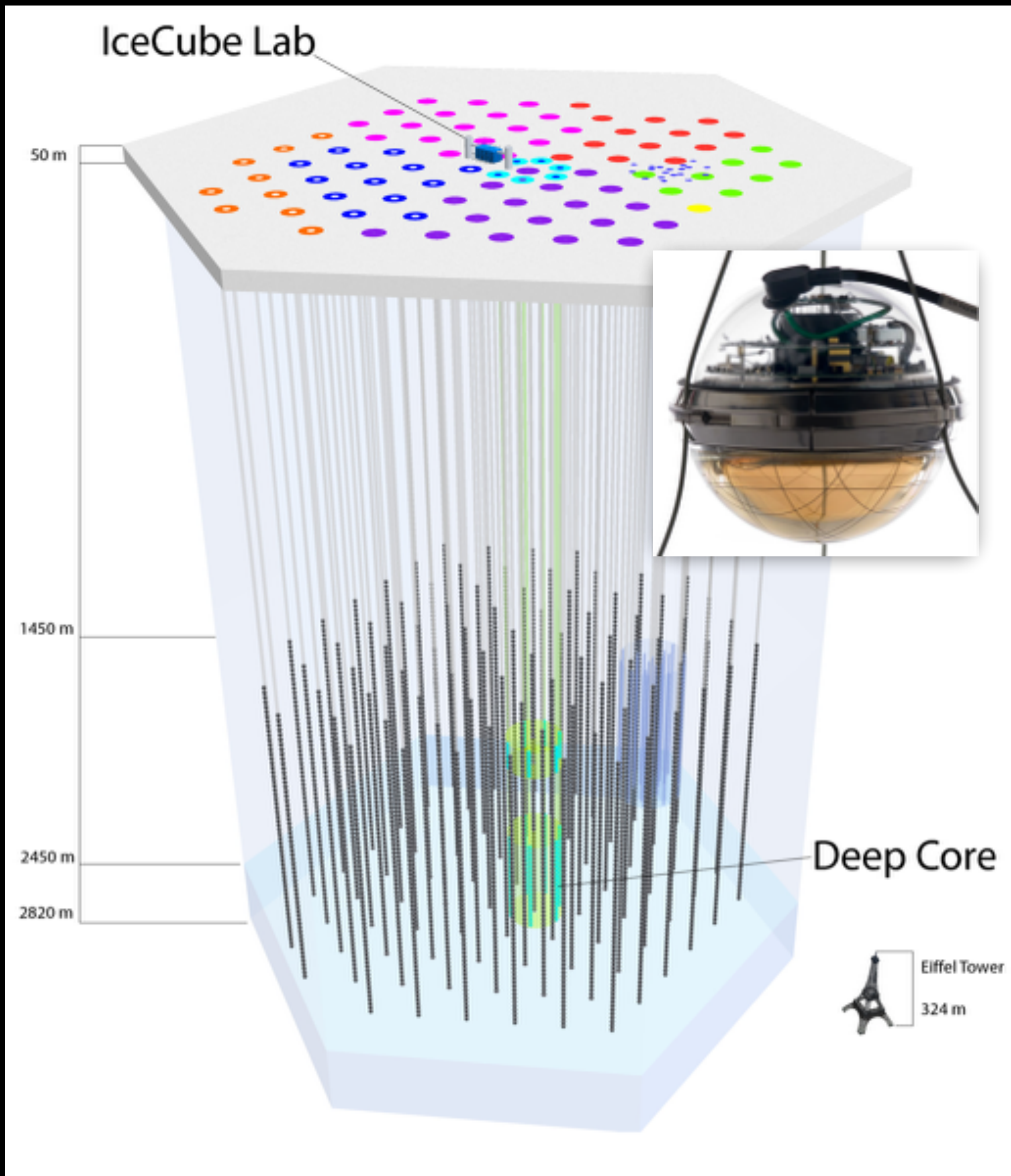
IceCube

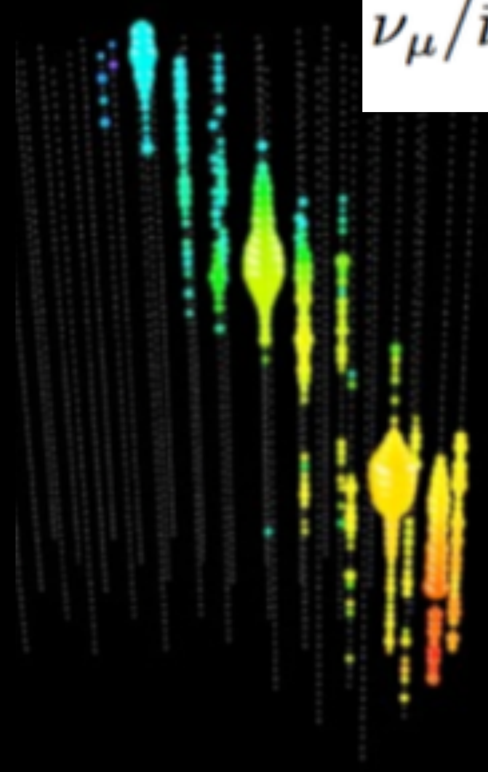


- Detector completion in 2010-2011
- Cubic km scale, 86 strings
- 1450 m – 2450 m
- IceCube
  - 125 string spacing
  - 17 sensor spacing
- DeepCore
  - 70 string spacing
  - 7 sensor spacing
  - Higher QE sensors

IceCube

arXiv:0902.2460

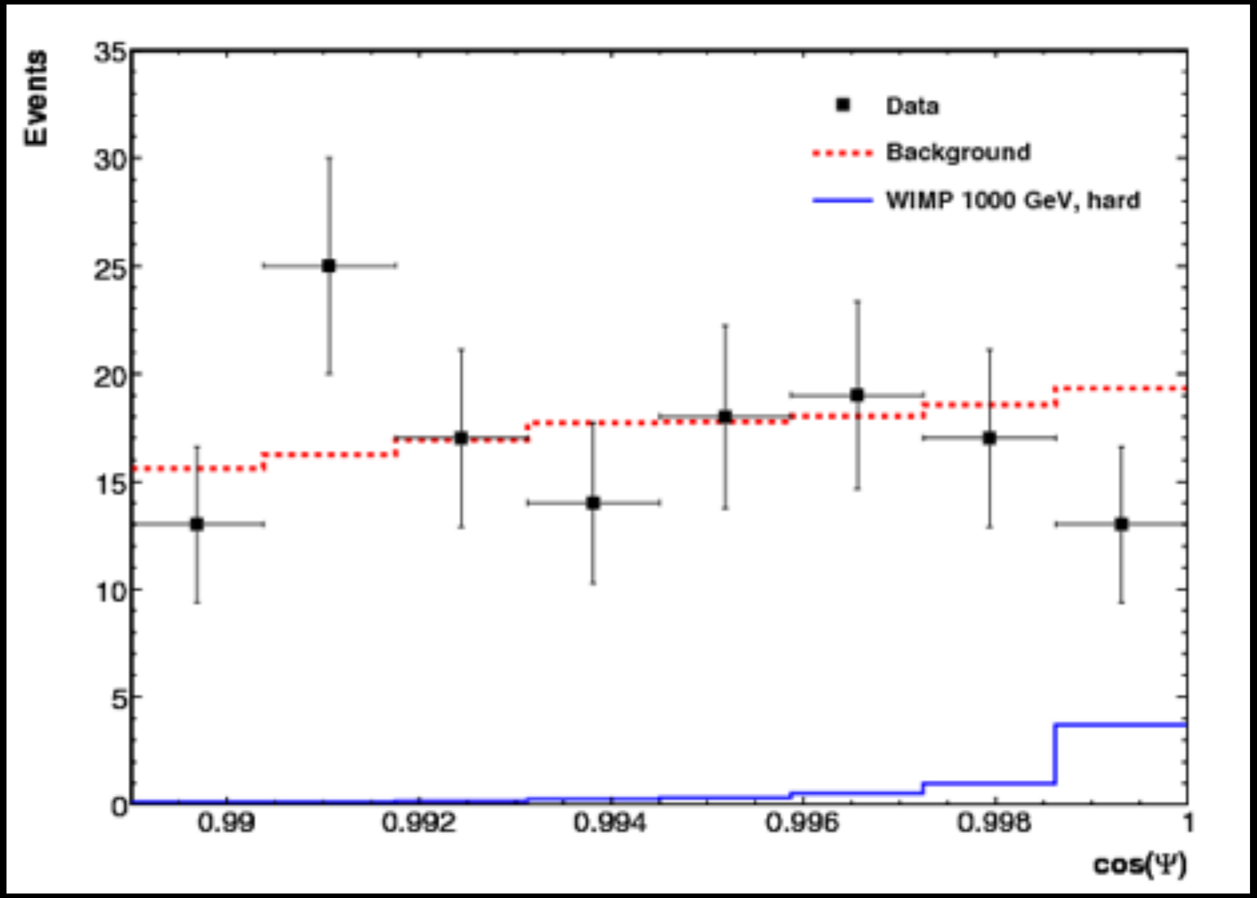
$$\nu_\mu/\bar{\nu}_\mu + \mathrm{N} \rightarrow \mu^\pm + \mathrm{N'}$$



- $\nu_{e,\tau}$ produce short track (O(10m))
- ν_μ interaction produces long muon tracks O(km)
  - Very good angular resolution, obtain arrival direction (from the Sun)
  - Bkgd: atmospheric neutrinos not correlated with the Sun

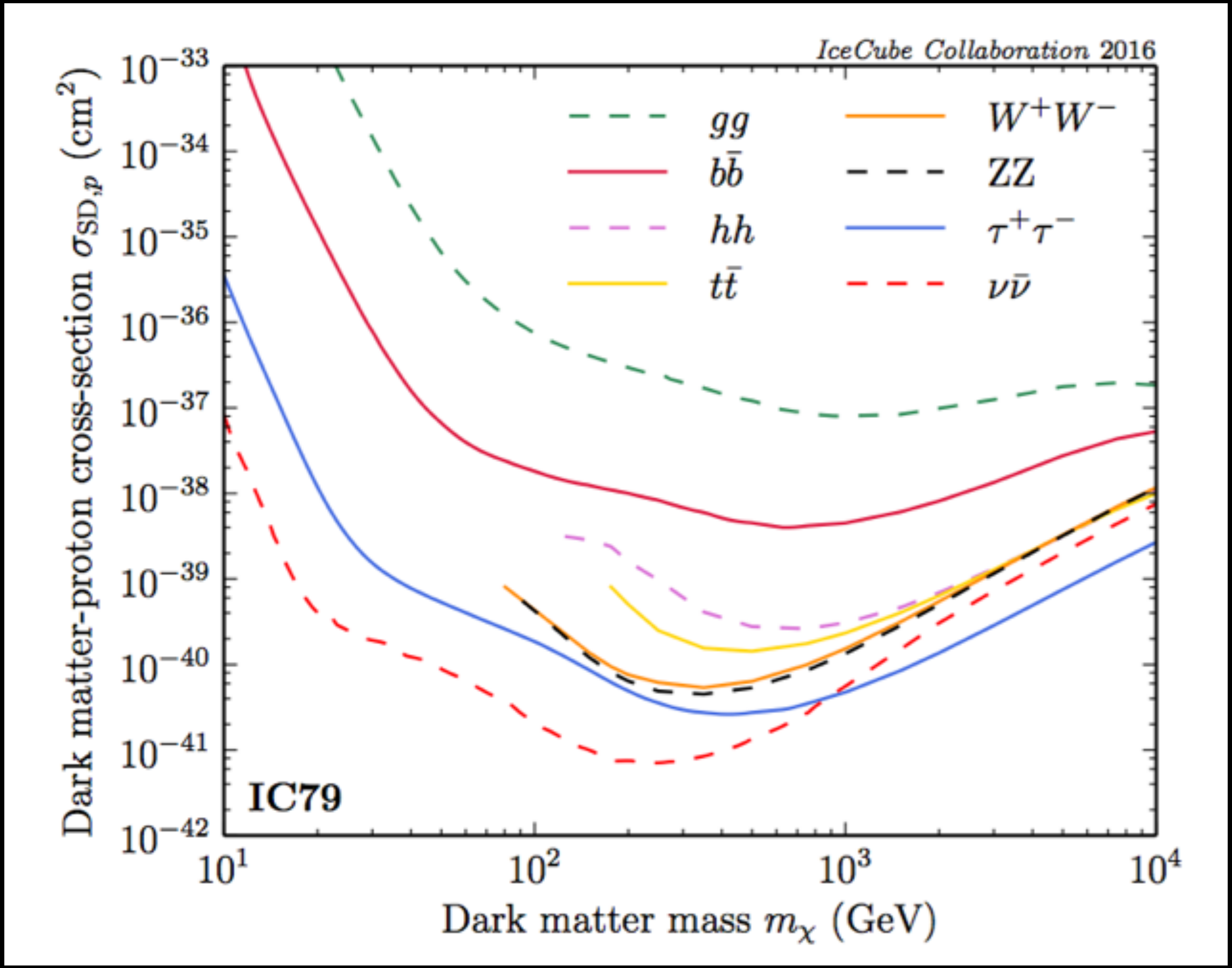
→ Signal signature: Excess towards the Sun?

- IceCube 79-strings results
- No significant excess
- Allows to set upper limits on capture rate, i.e. capture rate, i.e. elastic scattering cross section



Upper limits on WIMPs

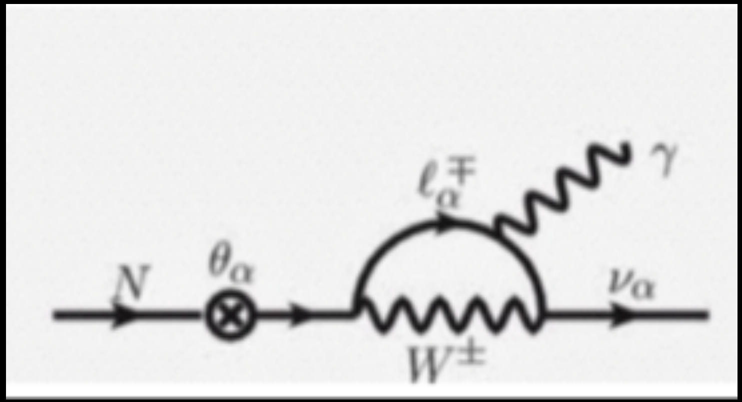
arXiv:1601.00653

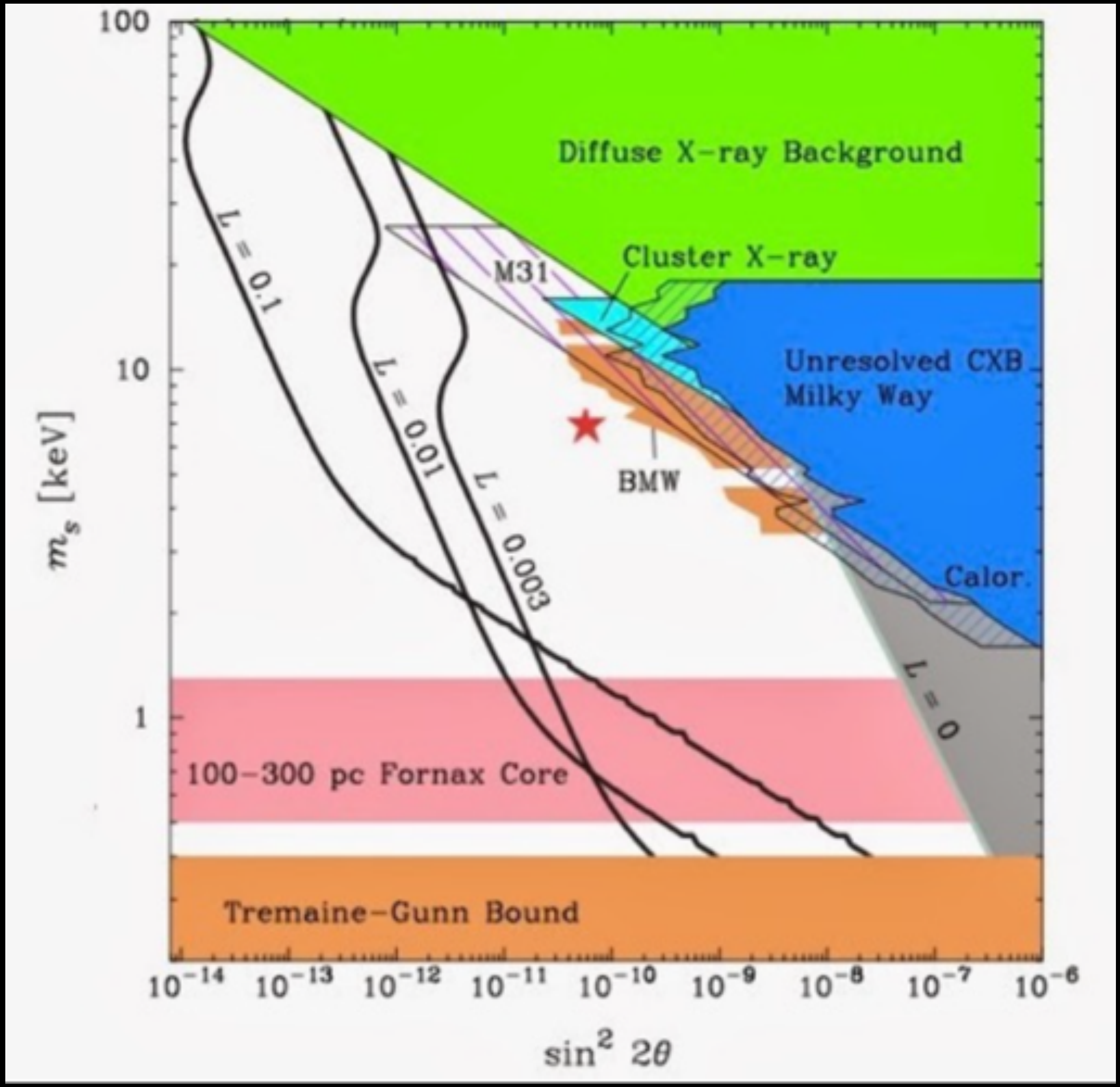


- Potential signal from the Sun leads to competitive constraints on the scattering cross section
- Same effect from the center of the Earth, but signal not competitive with direct detection (equilibrium typically not yet reached)

Sterile Neutrino

- Sterile Neutrinos can decay to photon+neutrino
- Can search for these photons: (X-rays)

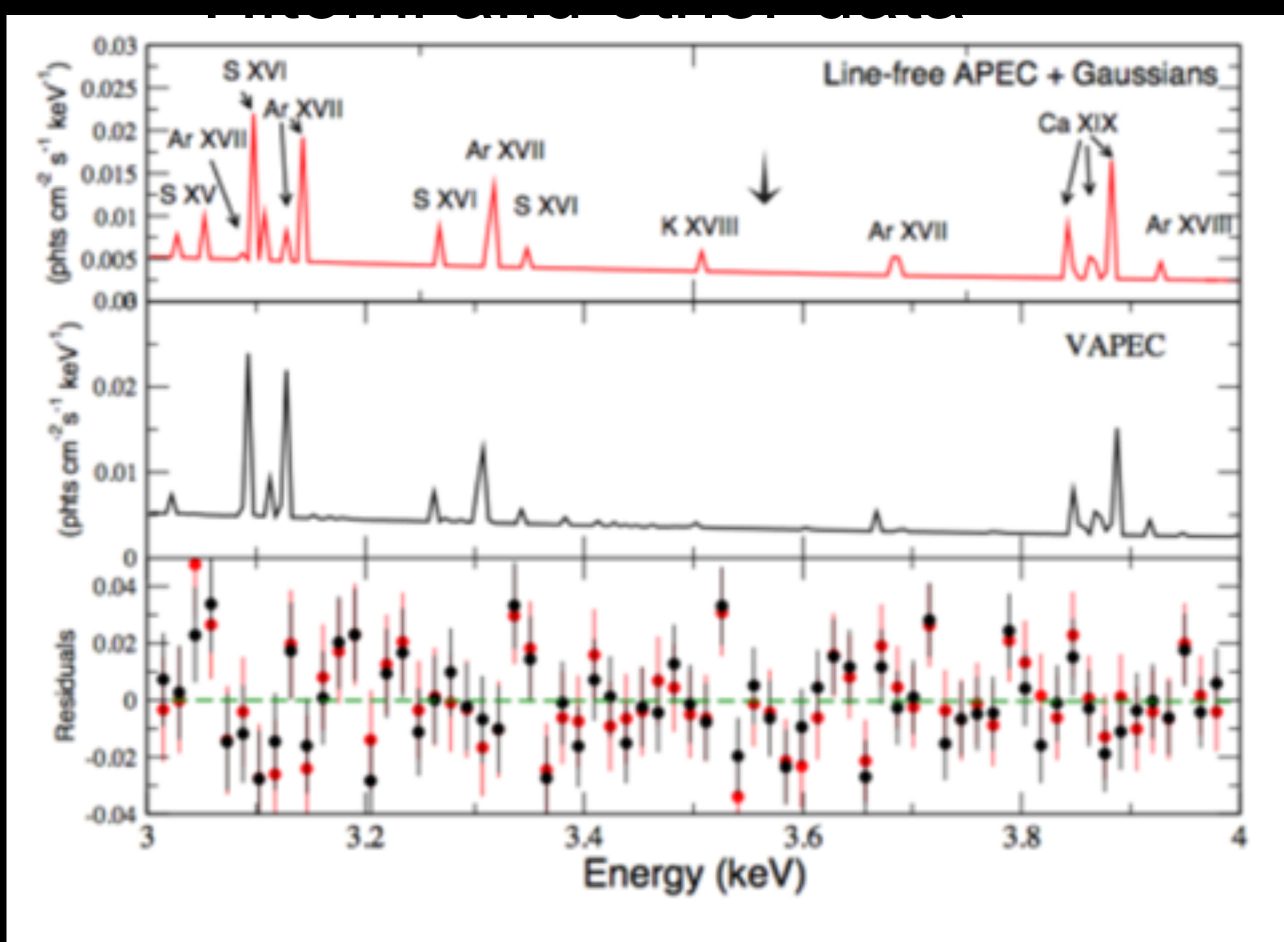


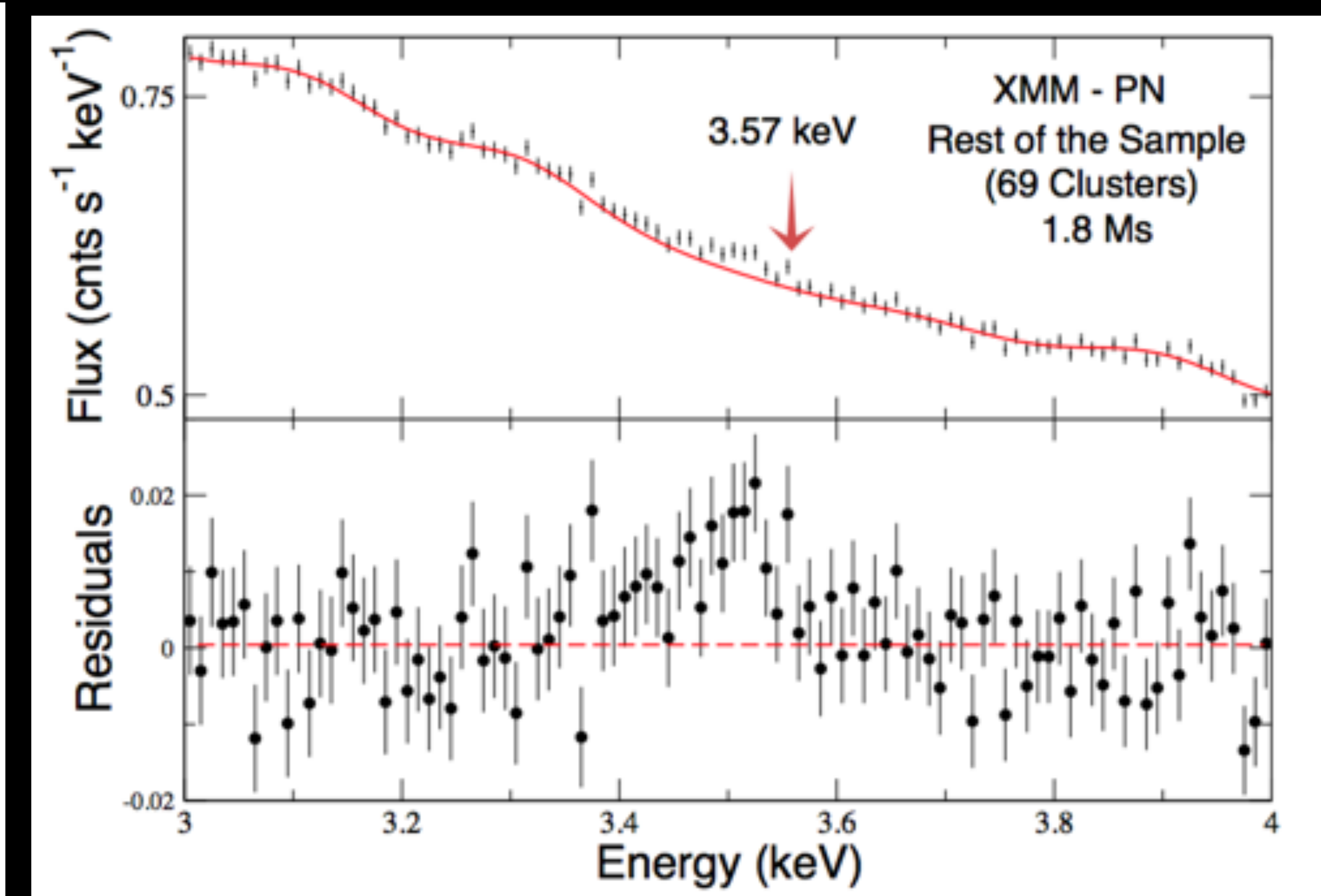


Sterile Neutrino

arXiv:1402.2301

- Telescope: XMM-Newton
  Target: Galaxy clusters (73)
- Analysis: look for non-atomic spectral lines





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Sterile Neutrino

arXiv:1607.07420

- Telescope: XMM-Newton
  Target: Galaxy clusters (73)
- Analysis: look for non-atomic spectral lines

arXiv.org > astro-ph > arXiv:1402.2301

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Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters

Esra Bulbul, Maxim Markevitch, Adam Foster, Randall K. Smith, Michael Loewenstein, Scott W. Randall

(Submitted on 10 Feb 2014 (v1), last revised 9 Jun 2014 (this version, v2))

We detect a weak unidentified emission line at E=(3.55-3.57)+/-0.03 keV in a stacked XMM spectrum of 73 galaxy clusters spanning a redshift range 0.01-0.35. MOS and PN observations independently show the presence of the line at consistent energies. When the full sample is divided into three subsamples (Perseus, Centaurus+Ophiuchus+Coma, and all others), the line is significantly detected in all three independent MOS spectra and the PN "all others" spectrum. It is also detected in the Chandra spectra of Perseus with the flux consistent with XMM (though it is not seen in Virgo). However, it is very weak and located within 50-110eV of several known faint lines, and so is subject to significant modeling uncertainties. On the origin of this line, we argue that there should be no atomic transitions in thermal

Sterile Neutrino

arXiv:1607.07420

- Telescope: XMM-Newton
  Target: Galaxy clusters (73)
- Analysis: look for non-atomic spectral lines
- Unfortunately now excluded by Hitomi and other data

arXiv.org > astro-ph > arXiv:1402.2301

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Summary

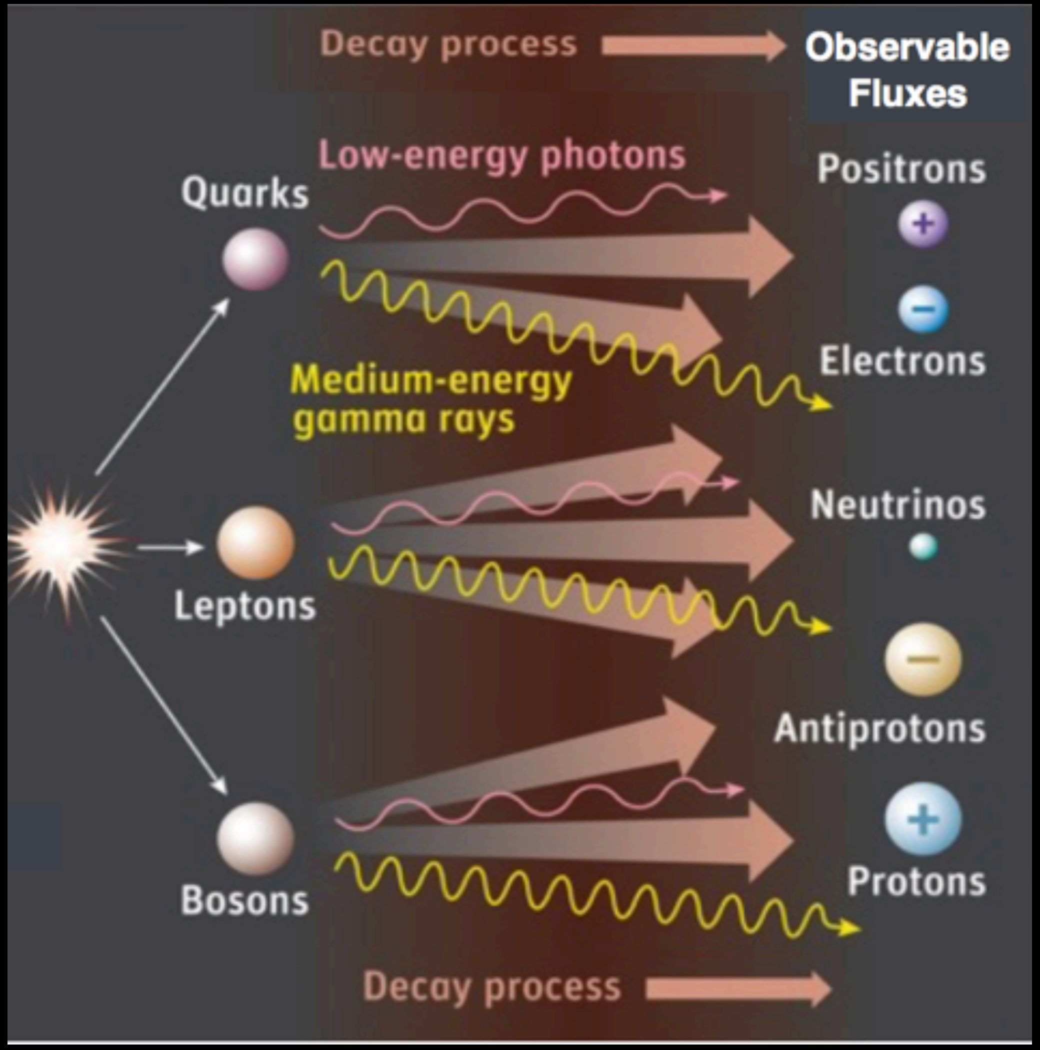
- Indirect searches cover a wide range of targets, messenger particles and energies
- Entering precision era, most recently thanks to Fermi-LAT and AMS-02
- Intriguing hints, but challenged by statistics and and alternative astrophysical interpretations
- Major effort is needed in the understanding of astrophysical processes
- Multi-wavelength and -channel approach needed for background understanding and DM discovery
- Planned future experiments will push the frontier in highly interesting regions where we expect signals to manifest

Backup

Indirect Dark Matter Detection

Key assumptions

- Dark matter exists and is the main responsible for the gravitational potential inferred in galaxies, clusters and cosmo.
- Dark matter is non-gravitationally coupled to standard matter.



DM Signals

Annihilation

Velocity averaged DM annihilation cross-section

$$\frac{dN_{\rm ann}}{dA\,dt\,d\Omega\,dE} = \frac{\langle\sigma v\rangle}{2m_\chi^2}\frac{dN_x}{dE}\frac{1}{4\pi}J_{\rm ann}(\psi)$$

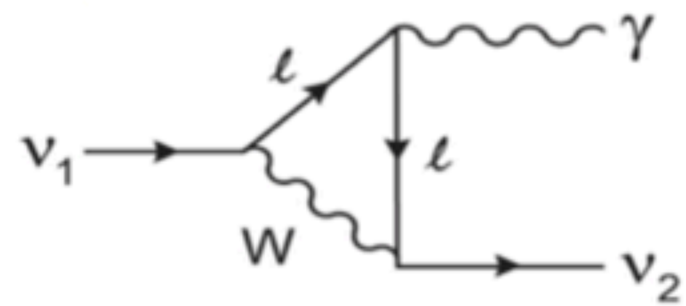
DM mass

DM spectrum

$$J_{\rm ann}(\psi) = \int_{\rm los}\rho^2(\psi,l)dl$$

DM spatial profile

Decay



$$\frac{dN_{\rm dec}}{dA\,dt\,d\Omega\,dE} = \frac{1}{m_\chi\,\tau}\frac{dN_x}{dE}\frac{1}{4\pi}J_{\rm dec}(\psi)$$

DM decay rate

$$J_{\rm dec}(\psi) = \int_{\rm los}\rho(\psi,l)dl$$

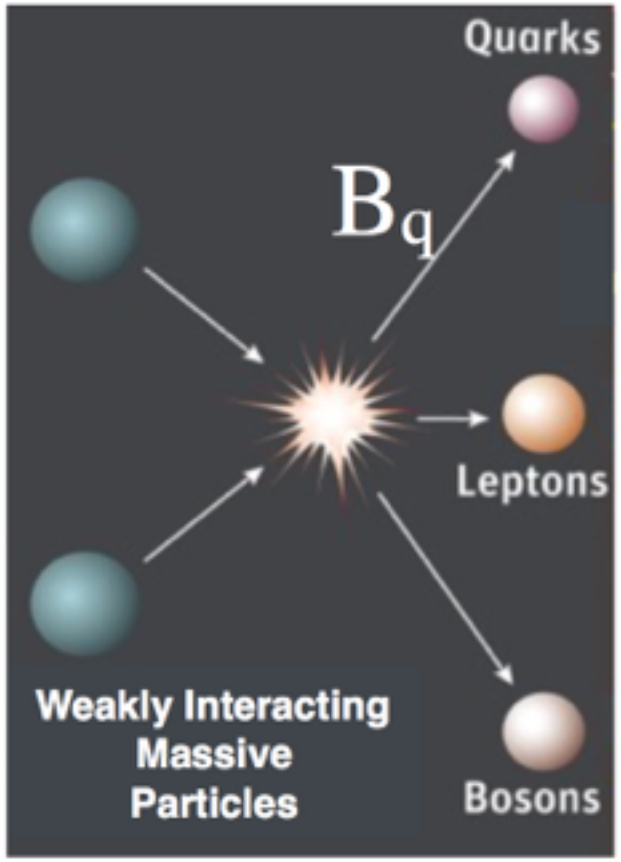
Reviews: Bringmann & Weniger, PDU’15; Ibarra+, Int. J. of Modern Physics A’13

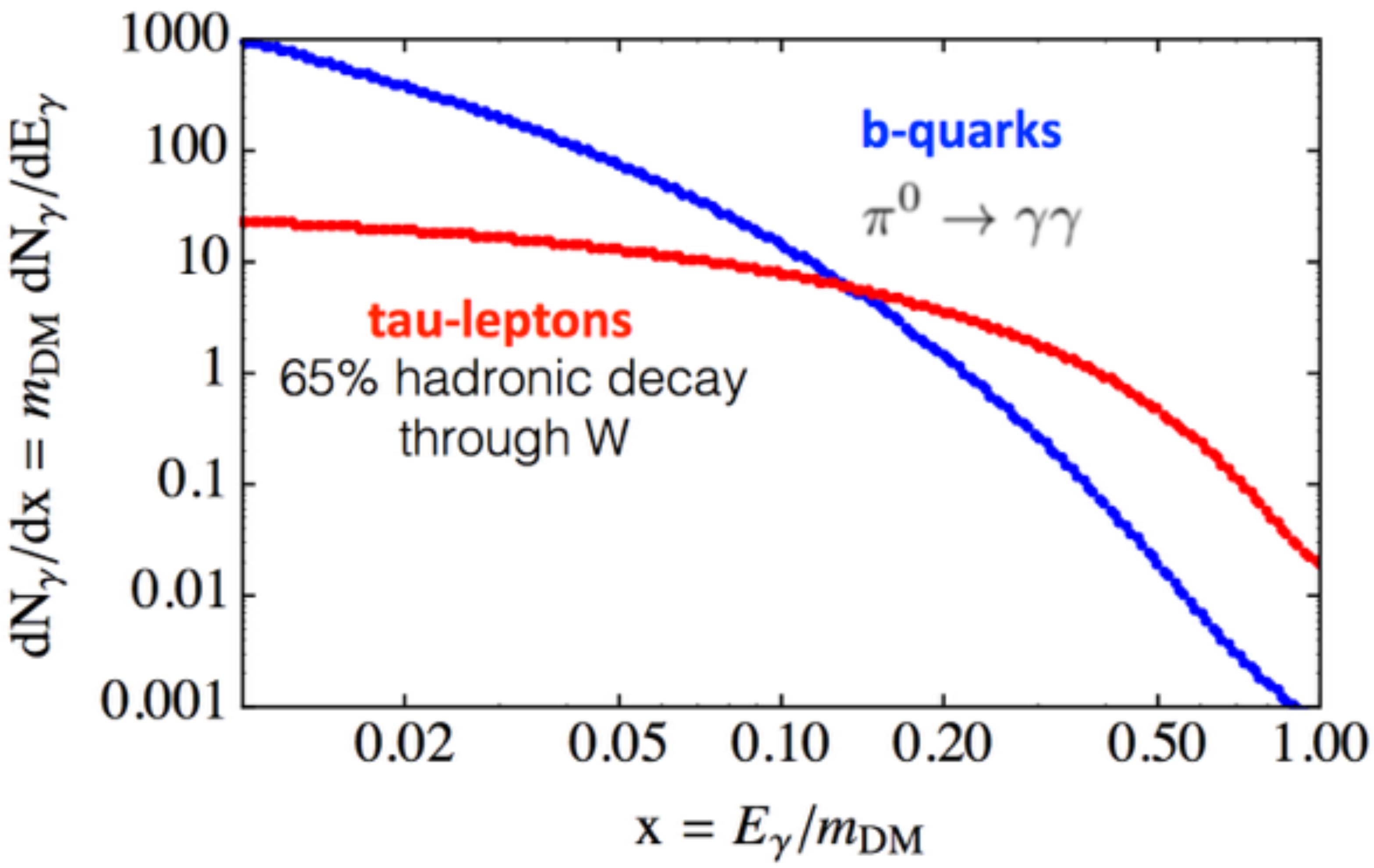
"Prompt" gamma-ray DM spectra

Number of photons per unit energy

$$x \equiv \frac{E_X}{m_\chi} \qquad \frac{dN_X}{dx} \equiv m_\chi \frac{dN_X}{dE}$$

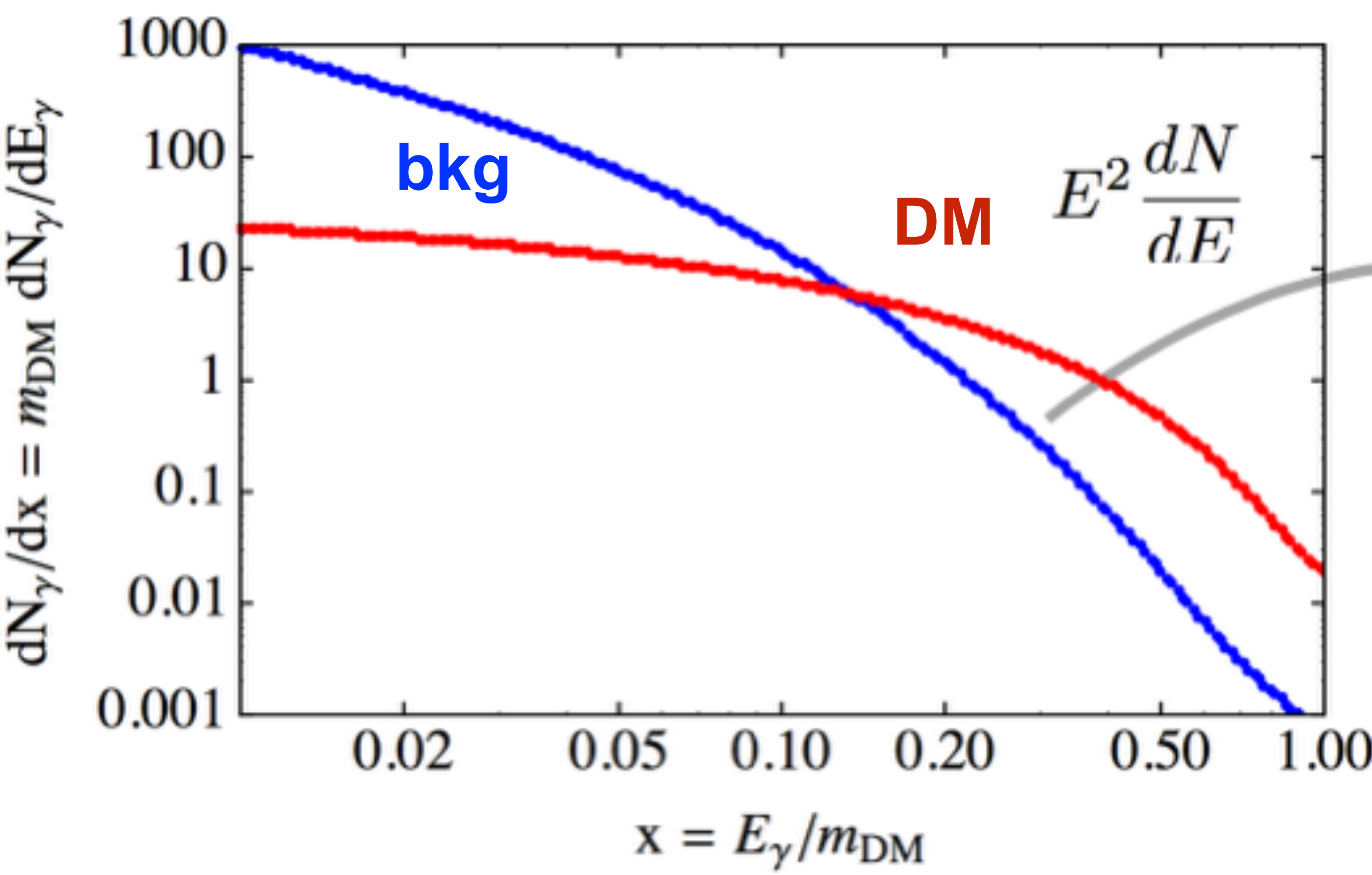
$$\mathrm{DM\,DM} \to \mathrm{SM\,SM}$$

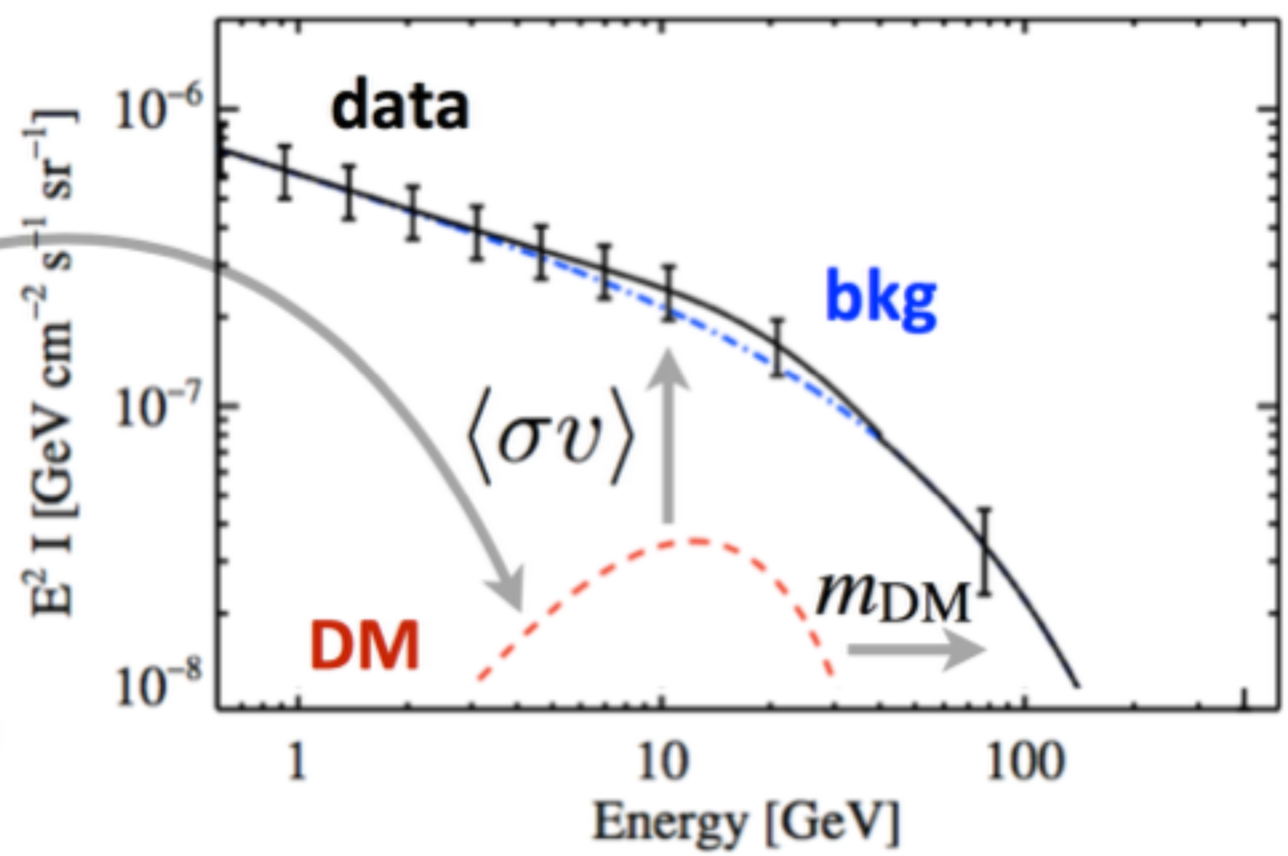




DM gamma-ray flux

$$\frac{dN_{\rm ann}}{dA\,dt\,d\Omega\,dE} = \frac{\langle\sigma v\rangle}{2m_\chi^2}\frac{dN_x}{dE}\frac{1}{4\pi}J_{\rm ann}(\psi) \qquad J_{\rm ann}(\psi) = \int_{\rm los}\rho^2(\psi,l)dl$$



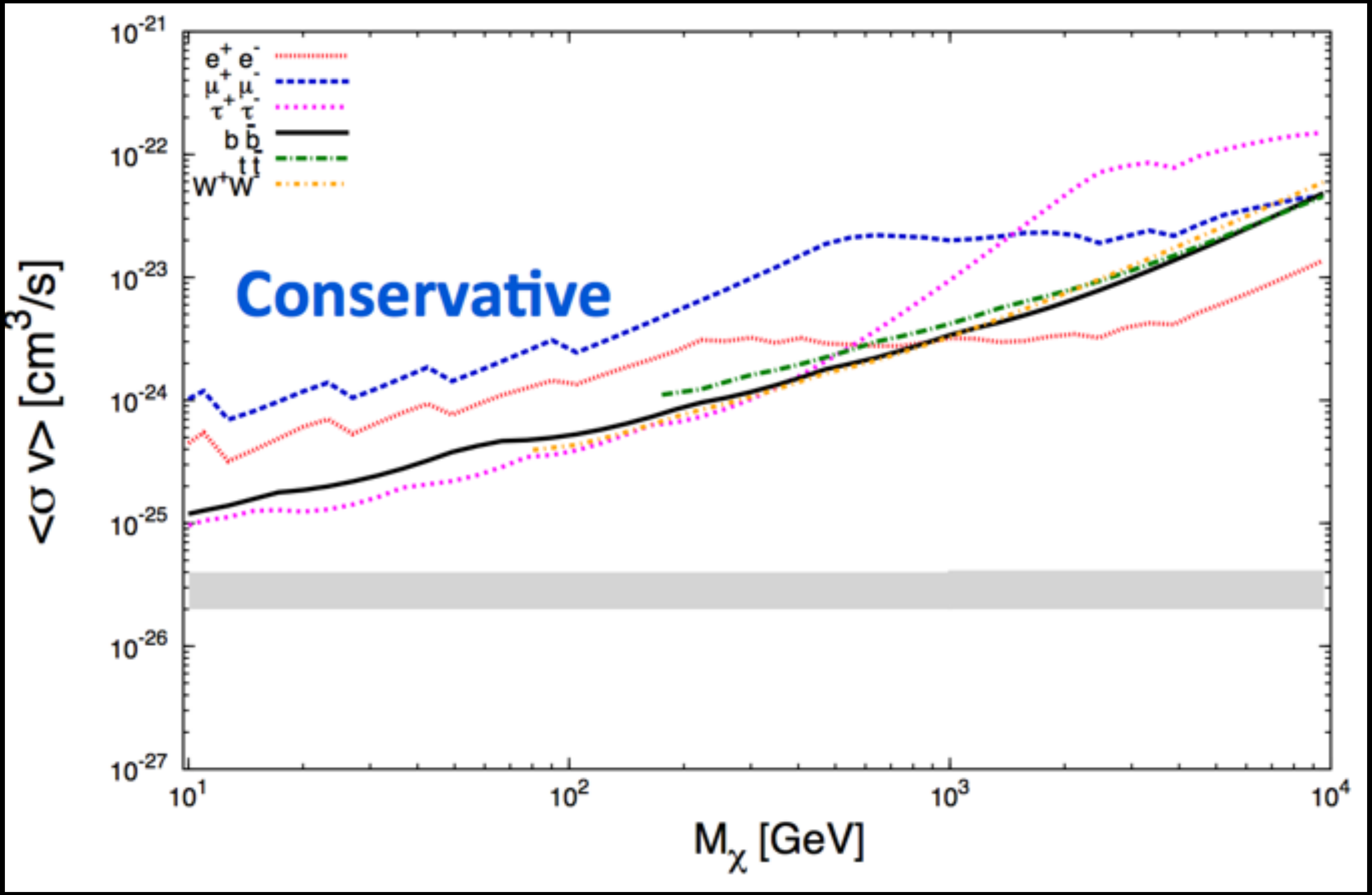


- The overall intensity of the signal also crucially depends on the distribution of dark matter.

Space-based: Fermi-LAT

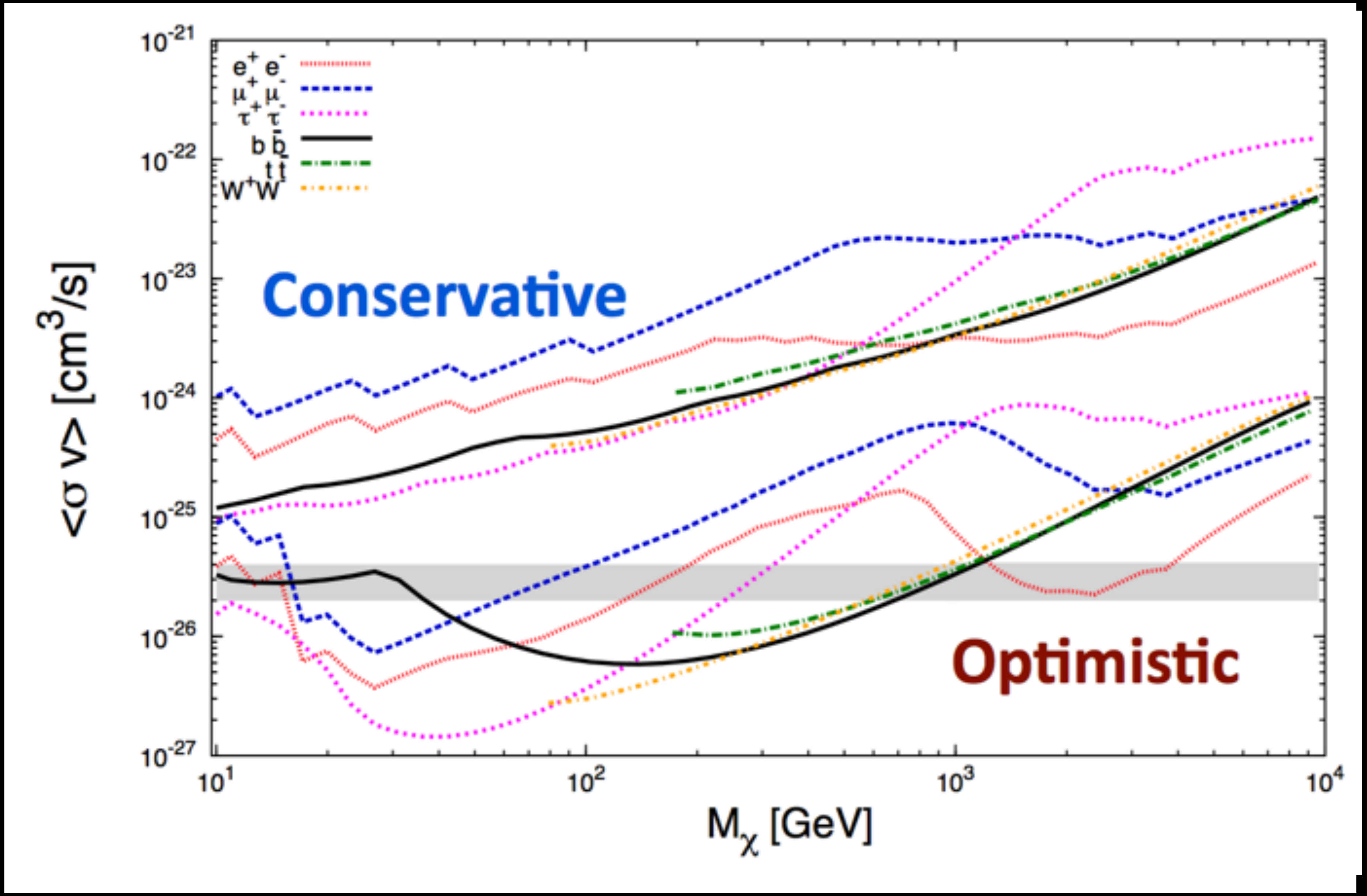
- Operation
  -
  -
- Performance
  -
  -
  -

Constrains on Dark Matter



- Conservative scenario:
  minimal blazars, millisecond psr, star-forming & MAGN

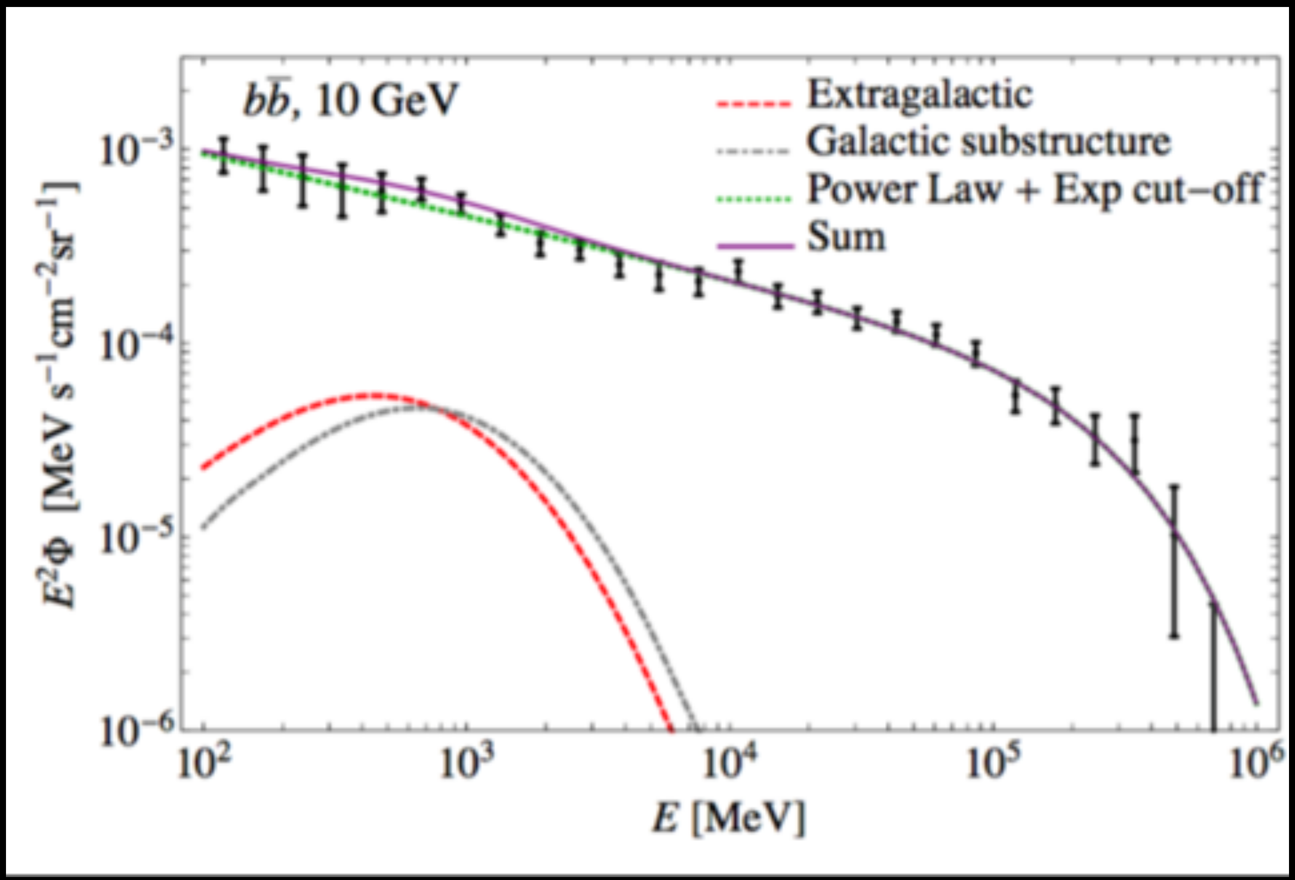
Constrains on Dark Matter

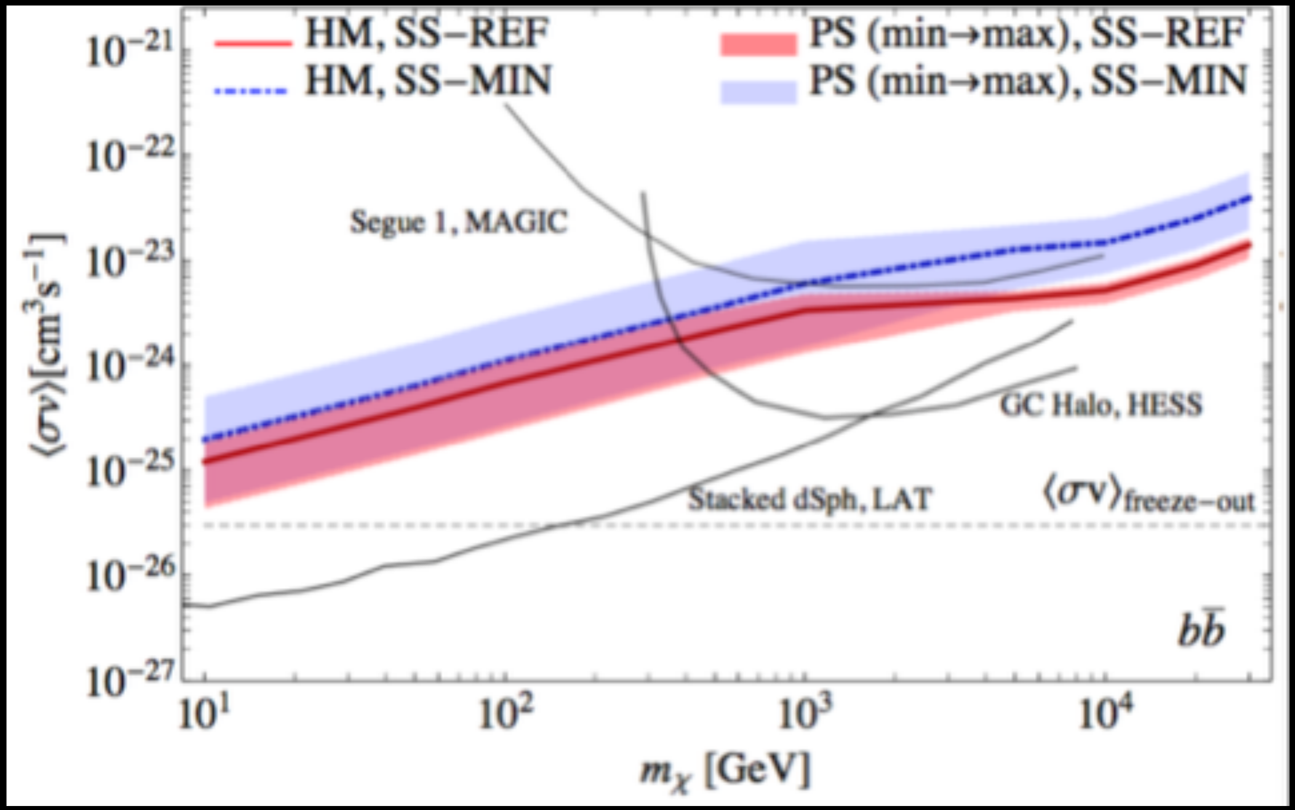


- Conservative scenario:
  minimal blazars, millisecond psr, star-forming & MAGN
- Optimistic scenario:

Limits on DM annihilation

Fermi-LAT Collaboration JCAP'15

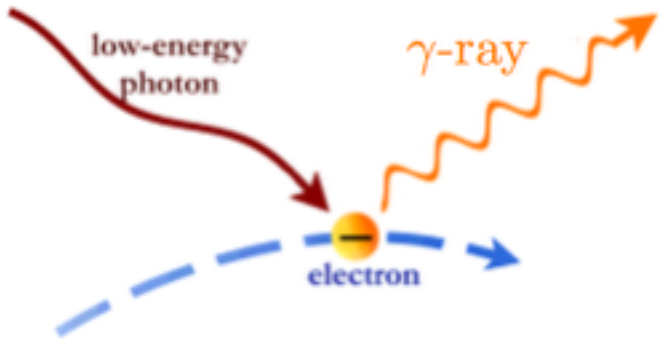




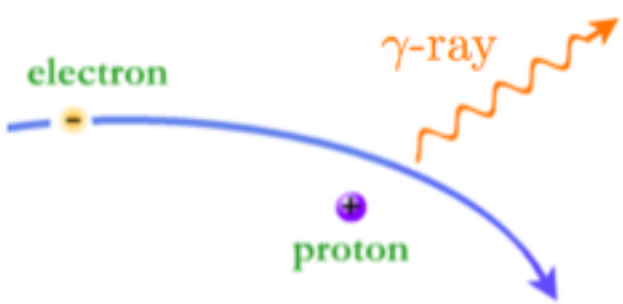
- Gamma-ray spectrum: galactic and extragalactic contributions
-

Secondary gamma-rays

$$\chi\chi \rightarrow \left\{ \begin{matrix} ZZ,\, W^+W^-,\, \gamma\gamma \\ q\bar{q},\, l^+l^-,\, \nu\bar{\nu} \end{matrix} \right\} \xrightarrow[\text{decays}]{\text{hadronization}} \gamma,\, e^\pm,\, \mu^\pm,\, p/\bar{p},\, \pi^\pm,\, \nu/\bar{\nu},\, \ldots$$



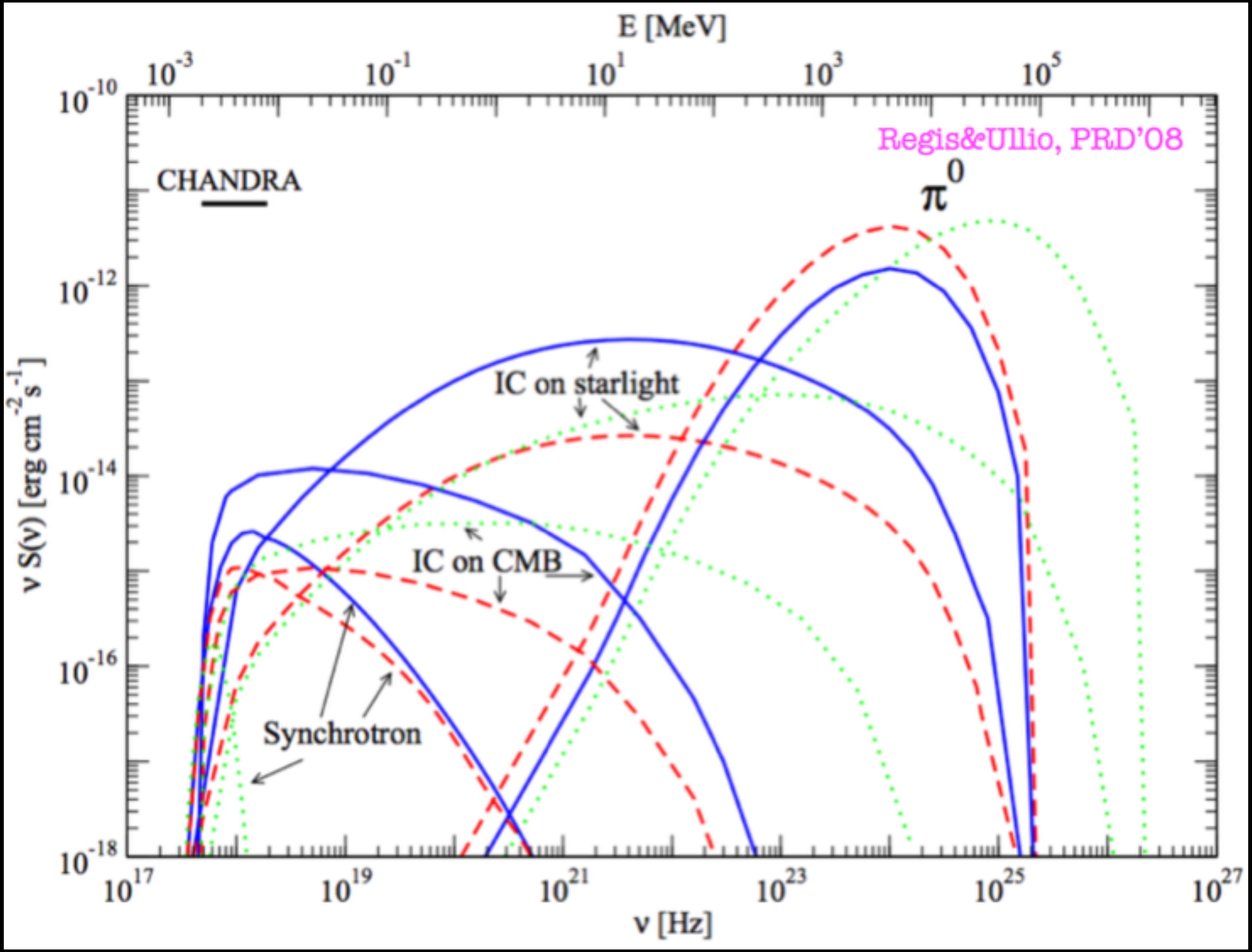
<u>Inverse Compton scattering</u>
on CMB, star-light, infrared-light



<u>Bremsstrahlung</u>
onto gas of interstellar medium

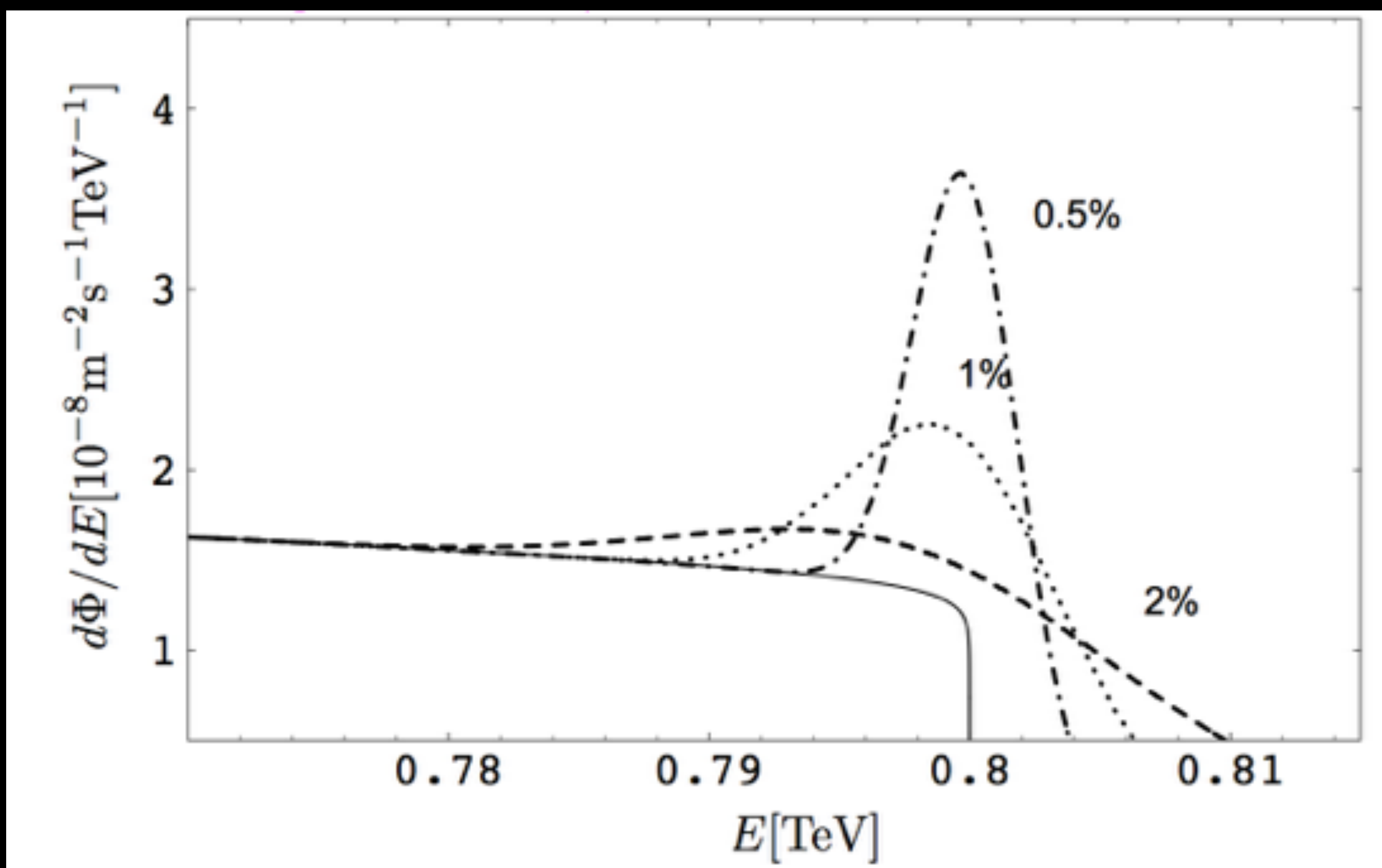
<u>Synchrotron radiation</u>
magnetic field $\mathcal{O}(\mu\text{Gauss})$
for $e^\pm$ of GeV-TeV
—> MHz-GHz radio signal

Multi-wavelength DM spectrum

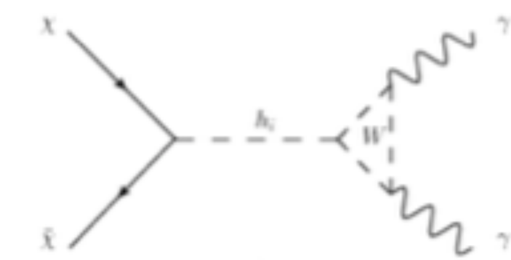


- Multi-wavelength spectrum from radio to gamma-ray given by the prompt and secondary DM-induced emissions.

gamma-ray spectral features

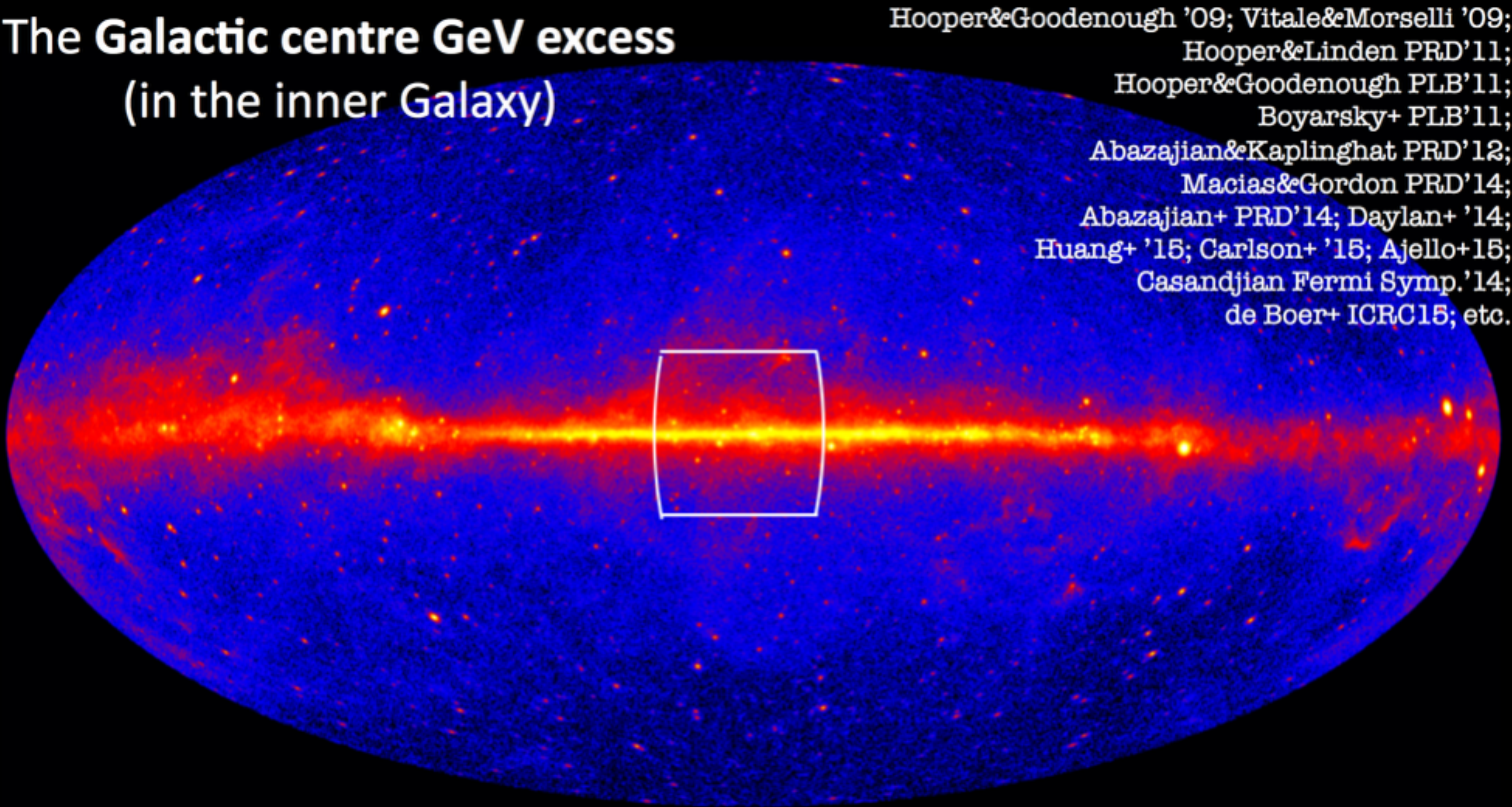


$$\gamma\gamma, Z\gamma, H\gamma \qquad E_\gamma = m_\chi\left(1 - \frac{m_P^2}{4m_\chi^2}\right)$$



- A spectral feature indicates an abrupt change of the gamma-ray flux as a function of energy, typically expected at the kinematic endpoint of the spectrum.

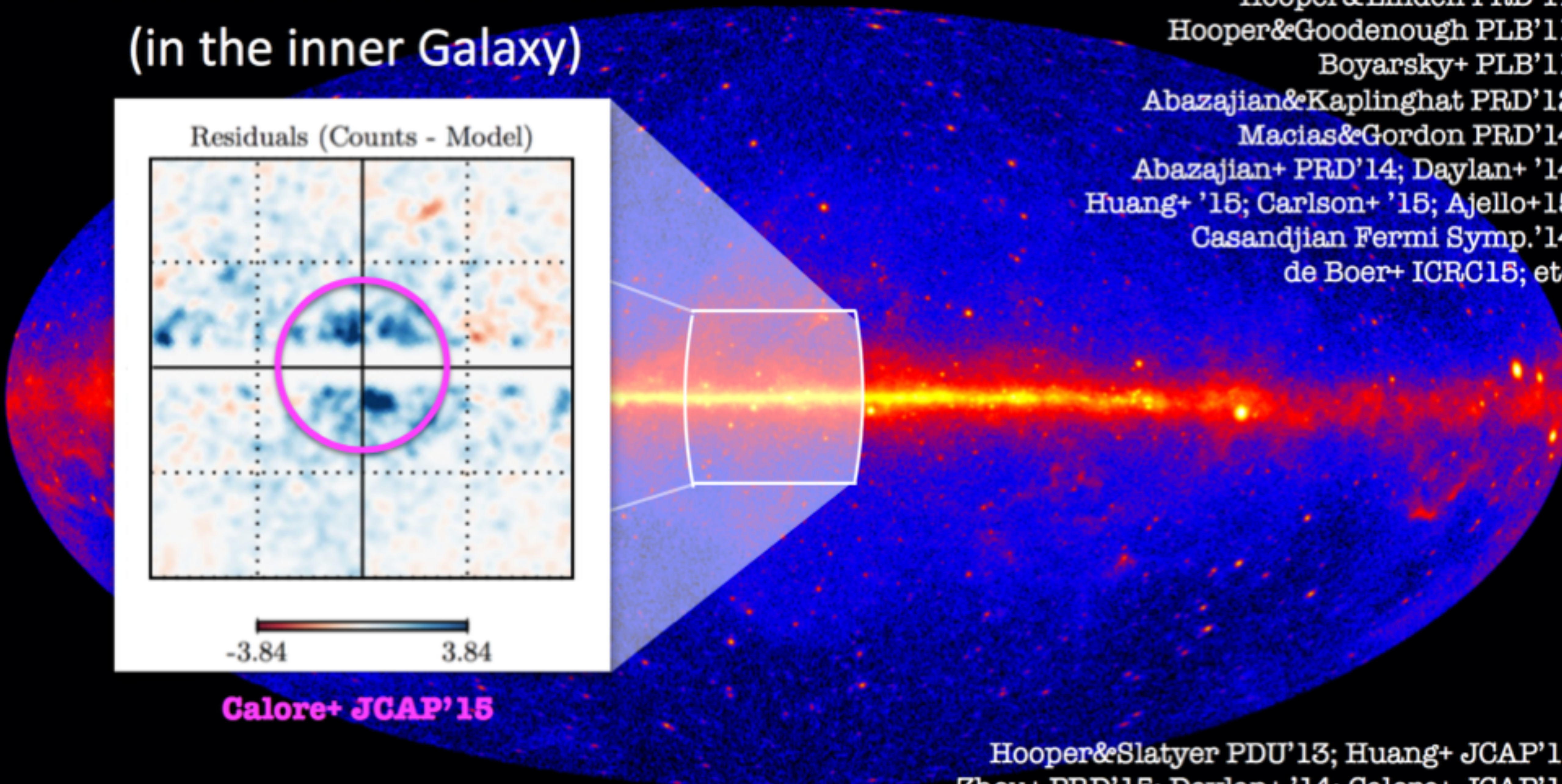
Low Latitude Fermi-LAT searches



Low Latitude Fermi-LAT searches

The **Galactic centre GeV excess** (in the inner Galaxy)

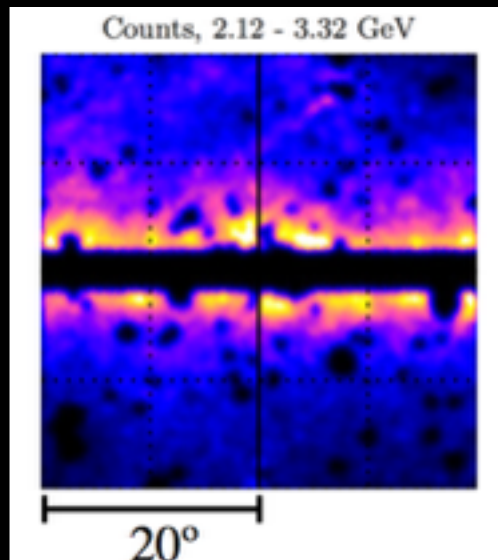
Hooper&Goodenough '09; Vitale&Morselli '09;
Hooper&Linden PRD'11;
Hooper&Goodenough PLB'11;
Boyarsky+ PLB'11;
Abazajian&Kaplinghat PRD'12;
Macias&Gordon PRD'14;
Abazajian+ PRD'14; Daylan+ '14;
Huang+ '15; Carlson+ '15; Ajello+15;
Casandjian Fermi Symp.'14;
de Boer+ ICRC15; etc.



Calore+ JCAP'15

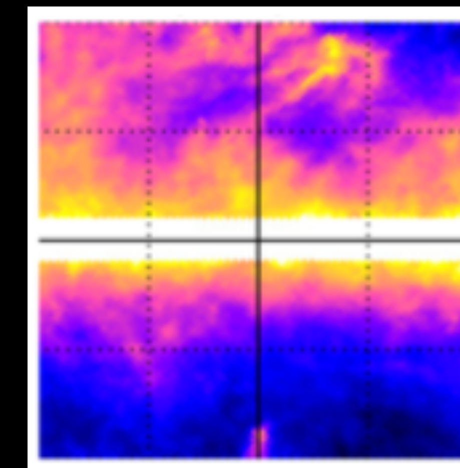
Hooper&Slatyer PDU'13; Huang+ JCAP'13;
Zhou+ PRD'15; Daylan+ '14; Calore+ JCAP'15;
Gaggero+ 2015; Ajello+ 2015; Huang+ '15;
Linden+'16; Horiuchi+'16

Inner Galaxy analysis setup



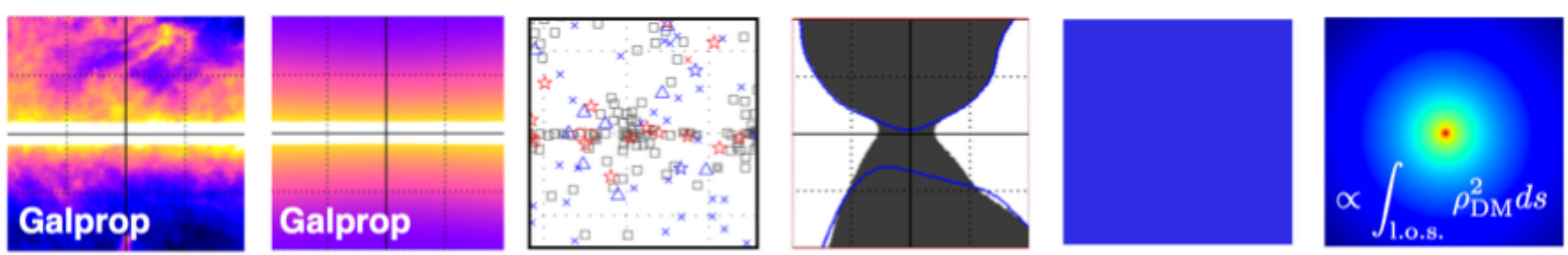
$k_{i,j}$

$$\mu_{i,j} = \sum_k \theta_{i,k} \mu_{i,j}^{(k)}$$



- The (spatial) template-fitting method (maximum likelihood) → $\theta_{i,k}$ i[th] energy

Hooper+PDU'13; Huang+JCAP'13; Daylan+'14; Calore+ JCAP'15; Gaggero+'15



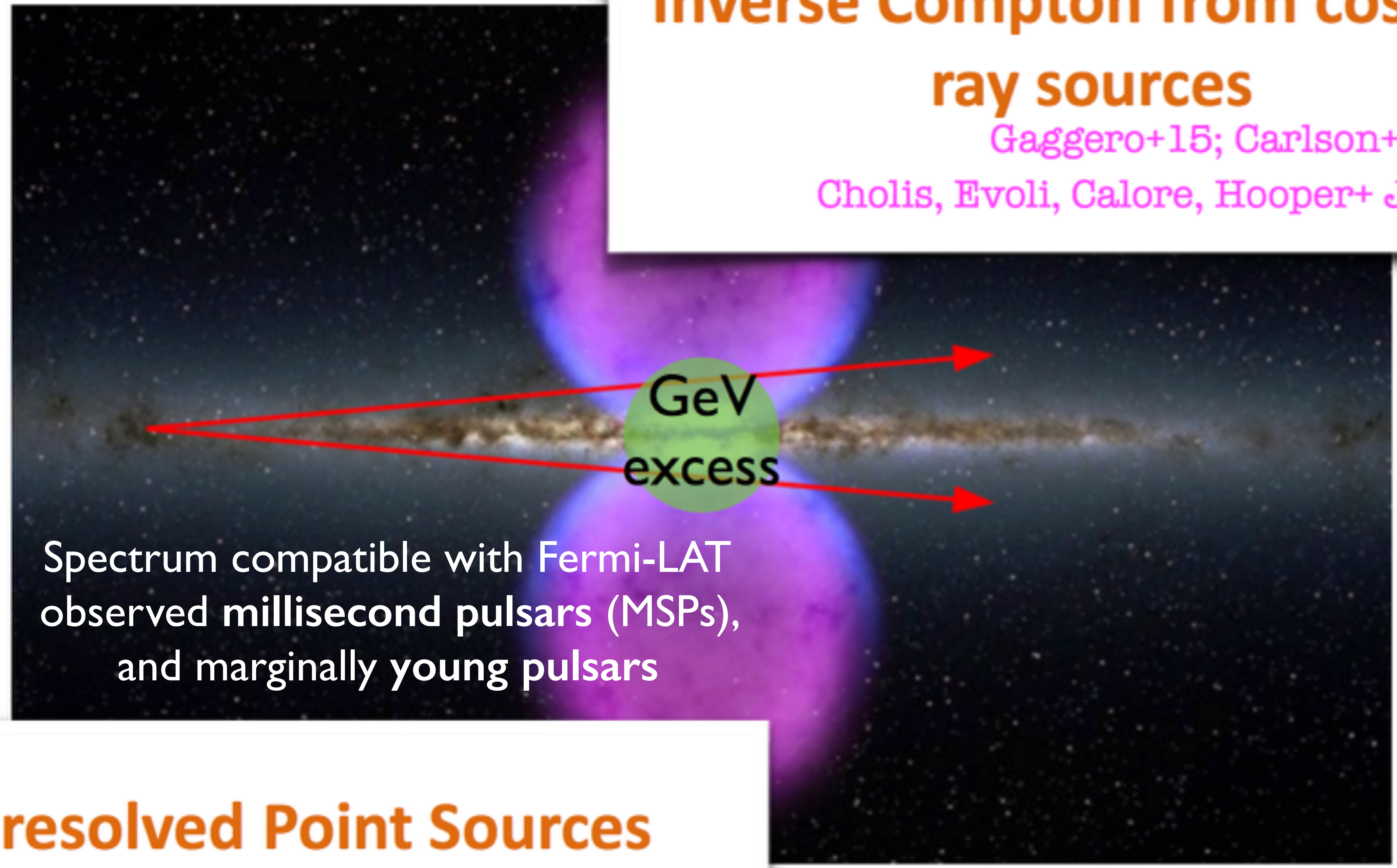
1. π^0 + Brems (free)
2. ICS (free)
3. 2FGL (fixed)
4. Fermi bubbles (constrained)
5. Isotropic diffuse bkg (constrained)
6. GeV excess template (free)

Astrophysical interpretations

Inverse Compton from cosmic-ray sources

Gaggero+15; Carlson+ '15; etc

Cholis, Evoli, Calore, Hooper+ JCAP'15



Unresolved Point Sources

Cherenkov Radtion

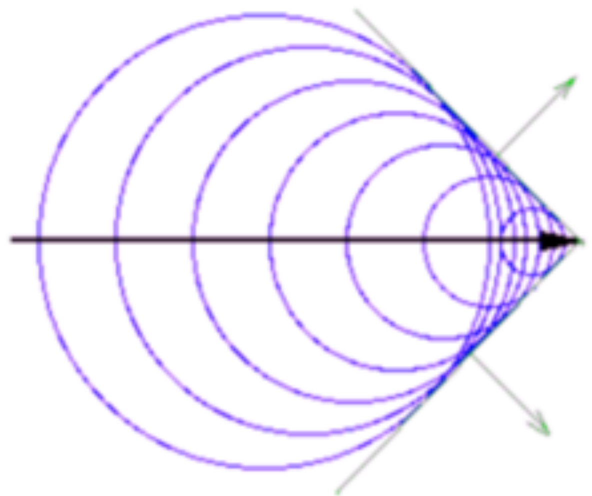
A relativistic particle travelling in a dielectric medium (air/water) faster than the speed of light in the medium polarises the medium that emits em radiation.

$$c/n < v_P < c$$

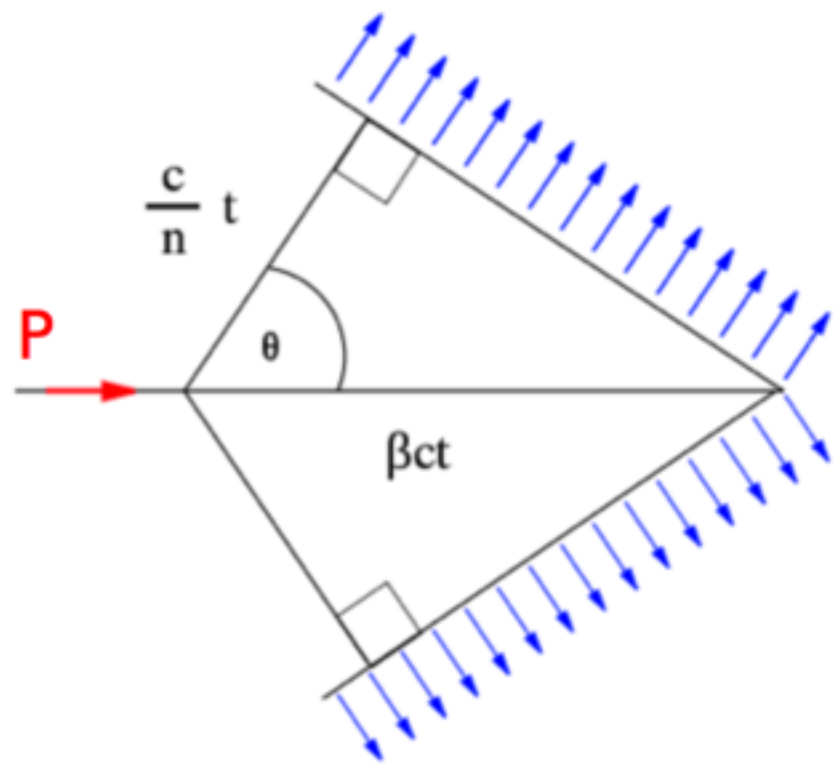
$$\cos\theta = \frac{ct}{n} \times \frac{1}{\beta ct} = \frac{1}{n\beta}$$

Number of photons emitted per unit length and wavelength

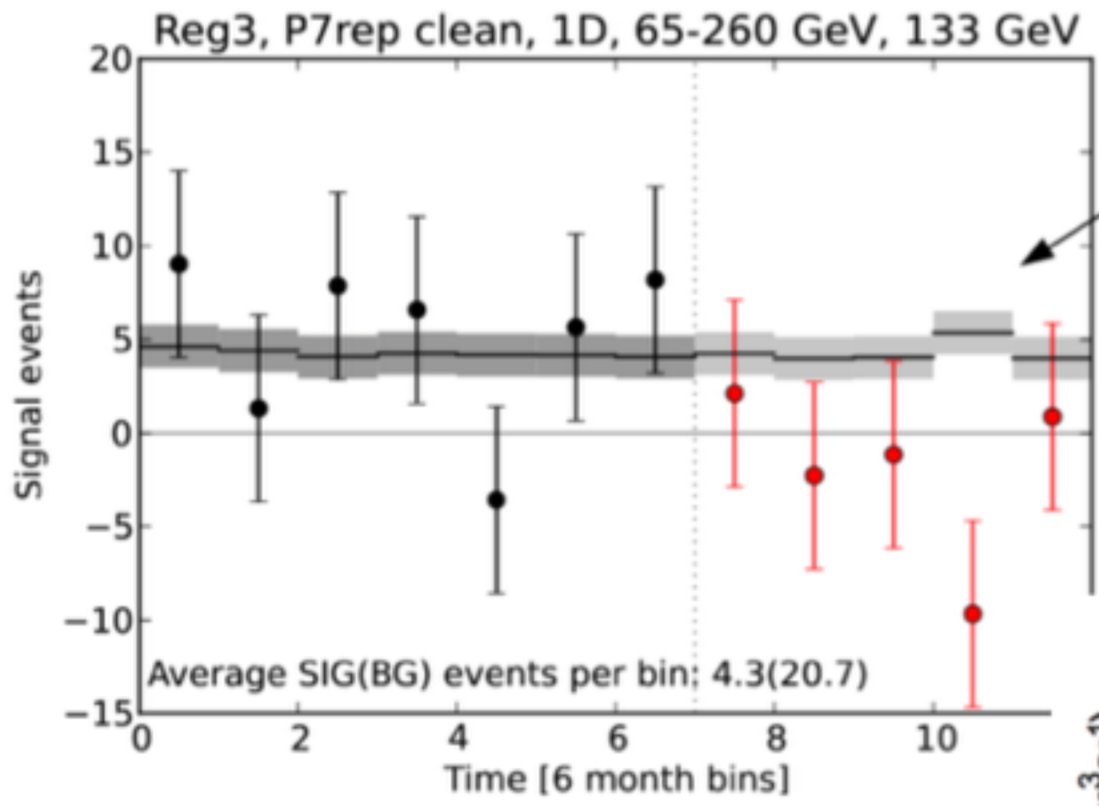
$$\frac{dN^2}{dx d\lambda} = \frac{2\pi\alpha}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2}\right)$$



v>c/n

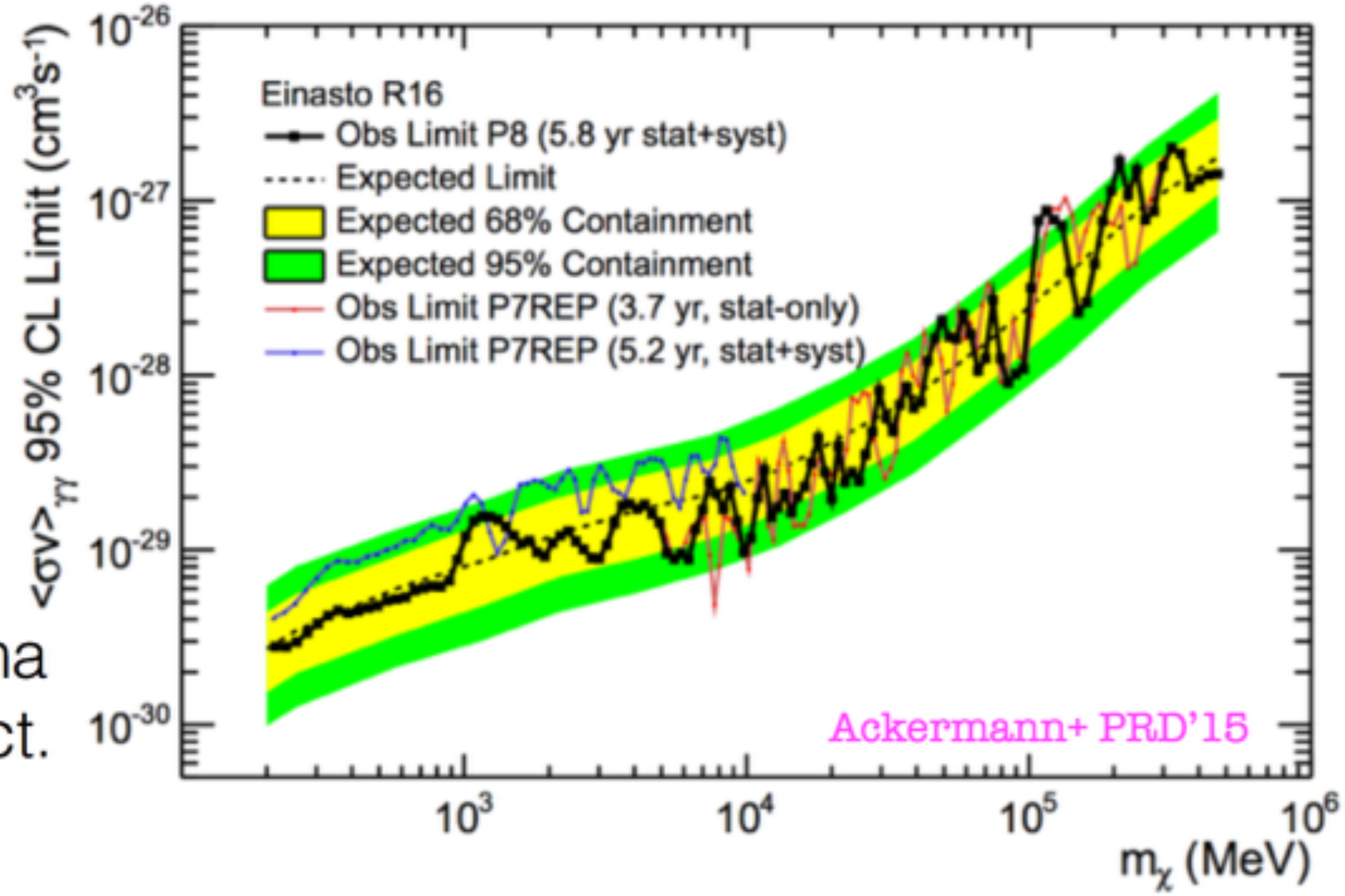


Gamma-ray line searches



But no signal since Summer 2012!

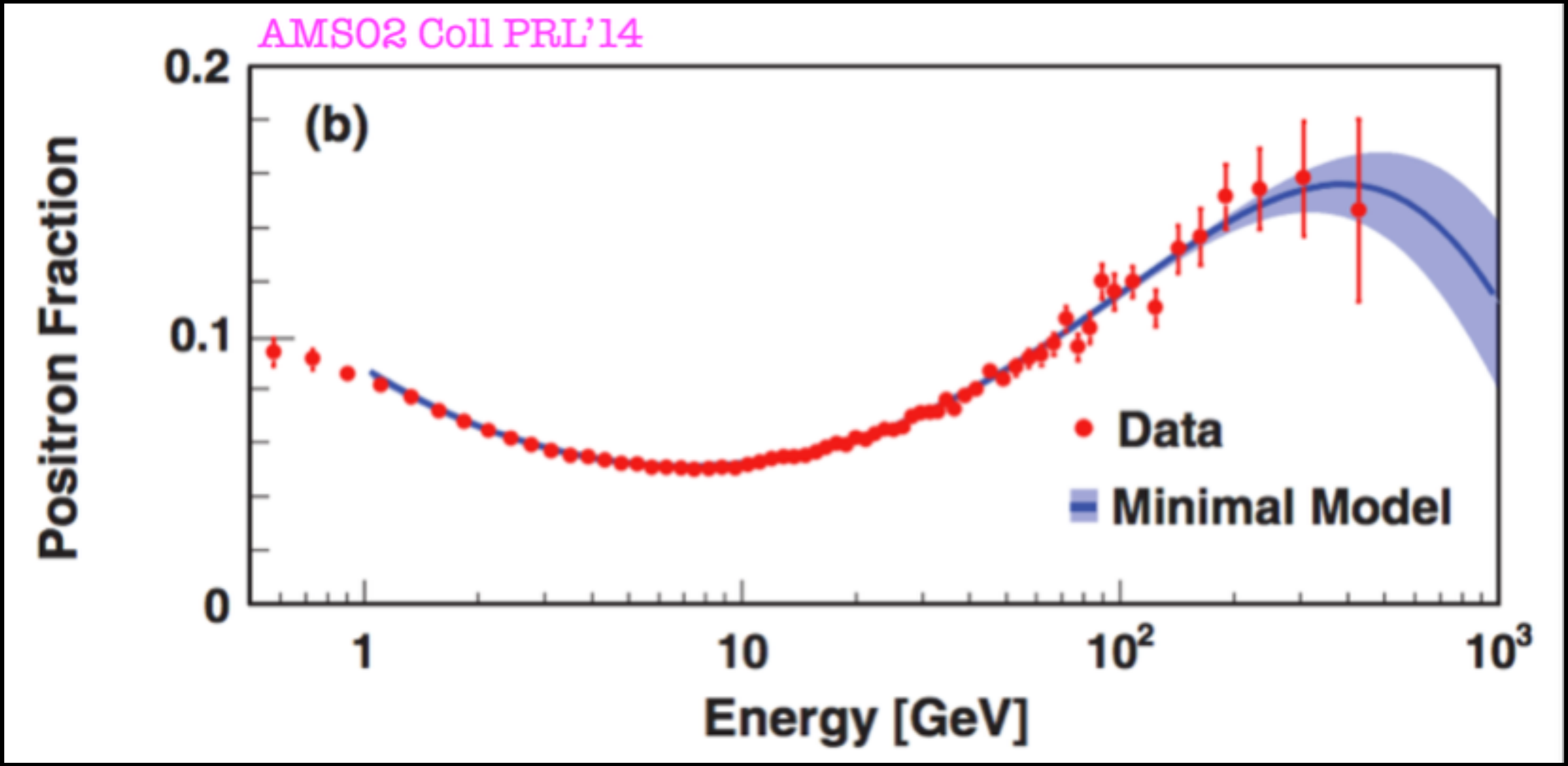
Using Fermi LAT data alone, the signal hypothesis can be excluded at more than 3 sigma.



- PASS 8 event selection
- 200MeV - 500 GeV
- 5.8 years of data
- 5 optimised sky regions

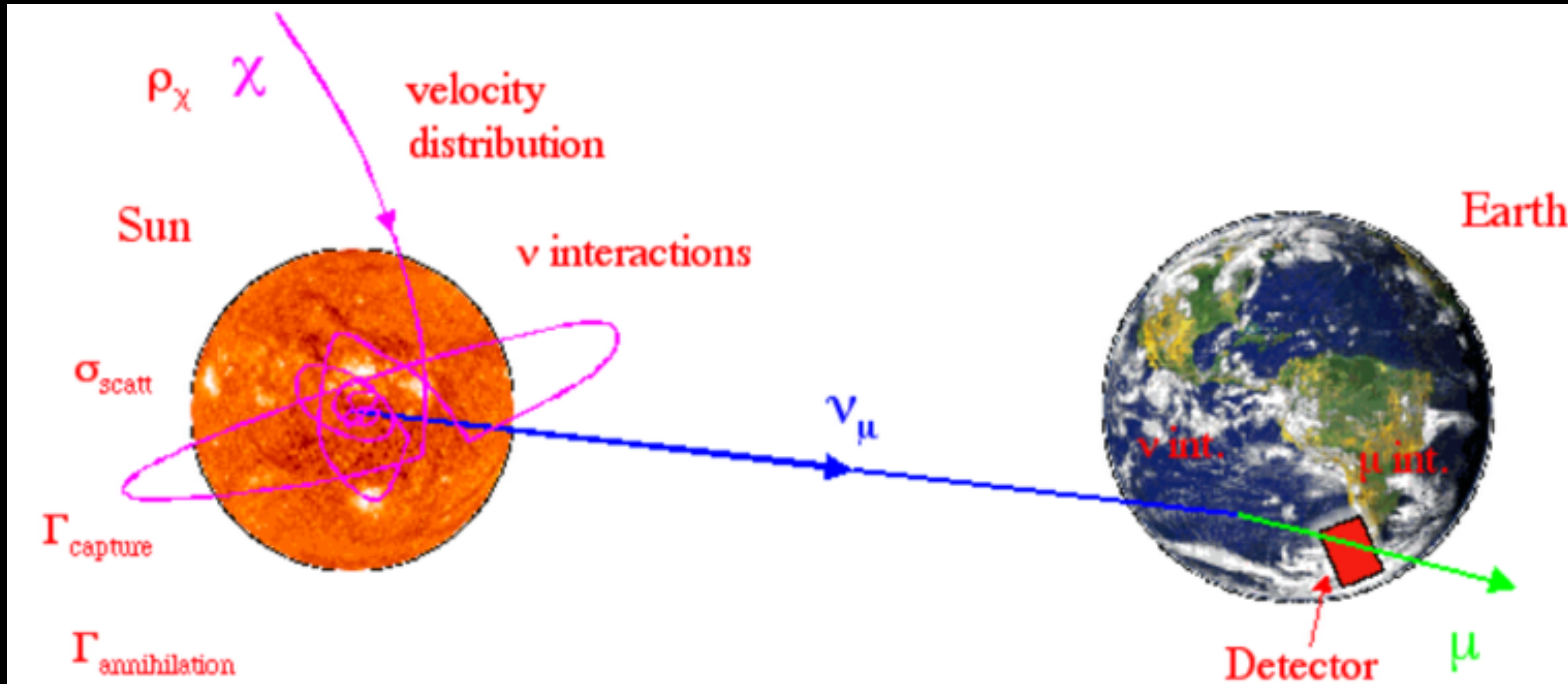
—> Local significance: 0.72 sigma
Consistent with statistical fluct.

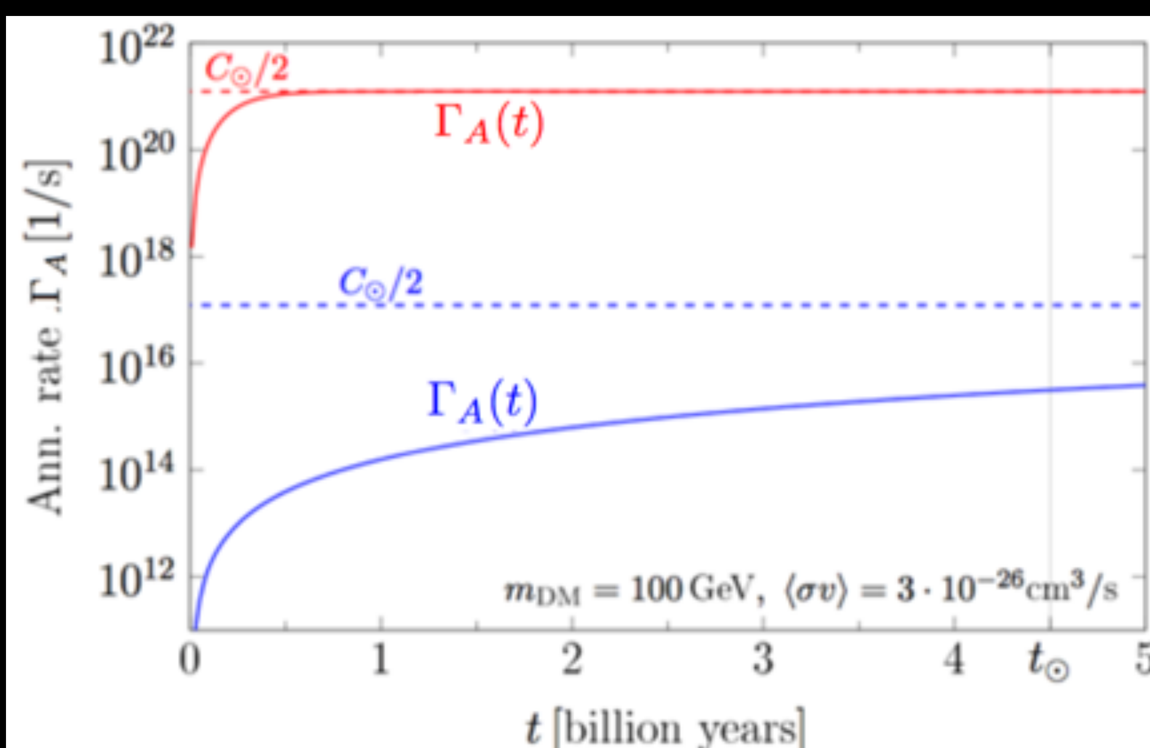
How to explain the data



- Minimal model requires an extra-component in the e- and e+ fluxes:
- New common source of e^-, e^+

WIMPs in the Sun





$\sigma_{SD} = 10^{-41}\,\text{cm}^2$ $\longrightarrow$ $t_\odot \gg \tau_{eq} \propto \frac{1}{\sqrt{\sigma_{SD}\cdot\langle\sigma v\rangle}}$

$\Downarrow$

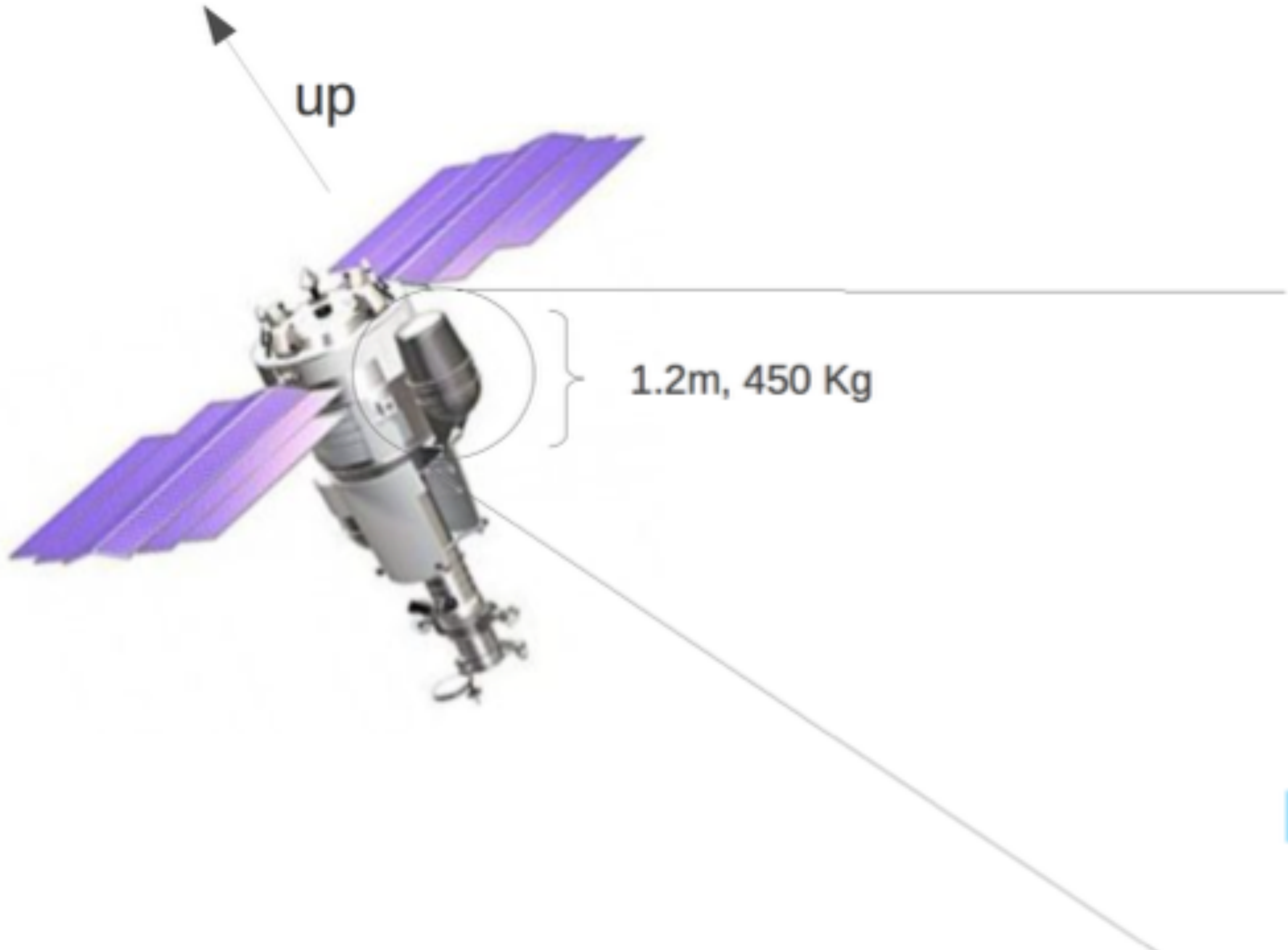
$\tau_{eq} = 0.28 \cdot 10^9\,\text{yr} \ll t_\odot$ Equilibrium

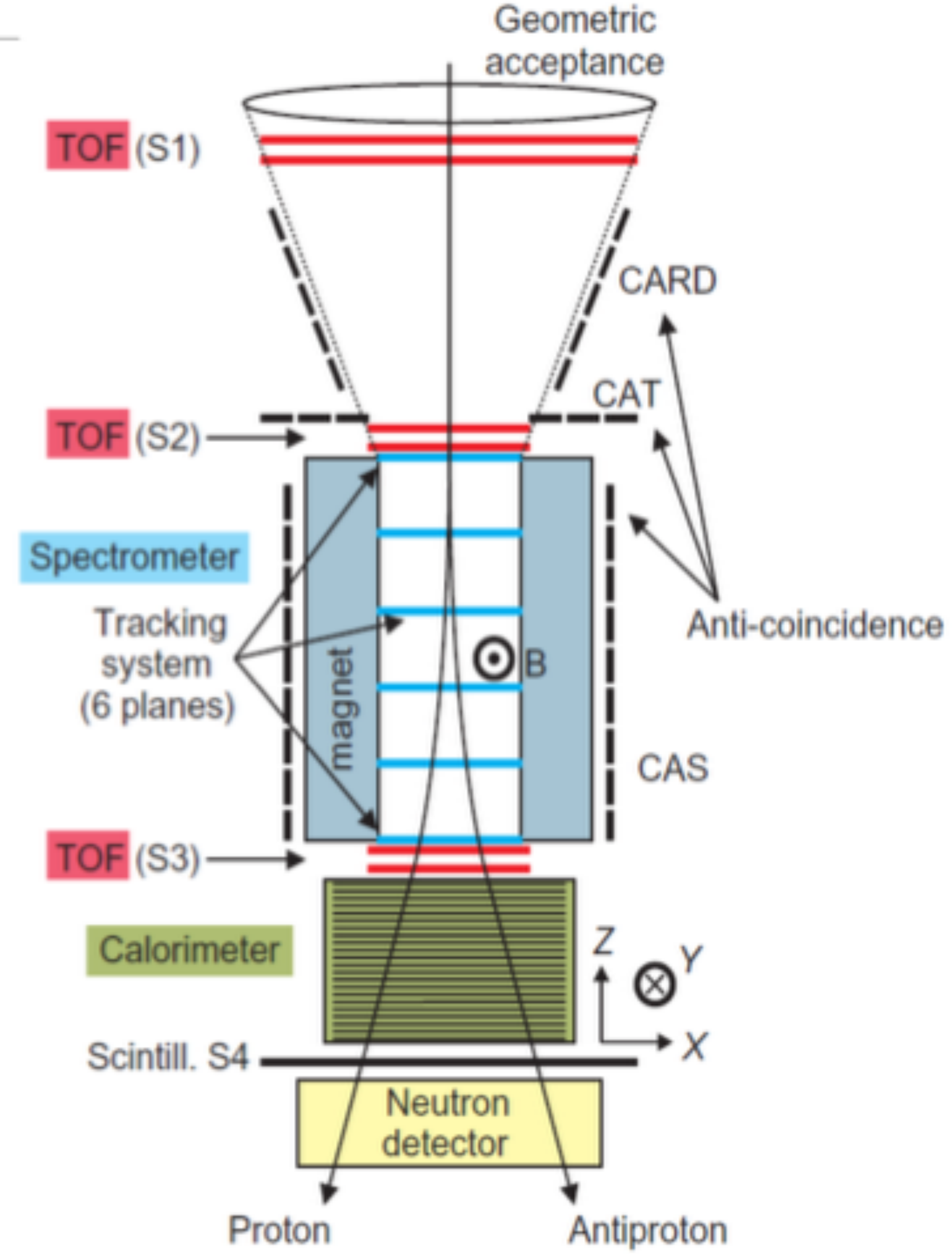
$\sigma_{SD} = 10^{-45}\,\text{cm}^2$ $\longrightarrow$ $t_\odot \lesssim \tau_{eq}$

$\Downarrow$

$\tau_{eq} = 28 \cdot 10^9\,\text{yr} \gg t_\odot$ Out of equilibrium

PAMELA satellite





Particle	Energy range
Antiprotons	80 MeV–190 GeV
Positrons	50 MeV–300 GeV
Electrons	up to 500 GeV
Protons	up to 700 GeV
Electrons + positrons	up to ~1 TeV (from calorimeter)
Light nuclei (He/Be/C)	up to 200 GeV nucleon $^{-1}$
Antinuclei search	sensitivity of 3×10^{-8} in anti-He/He