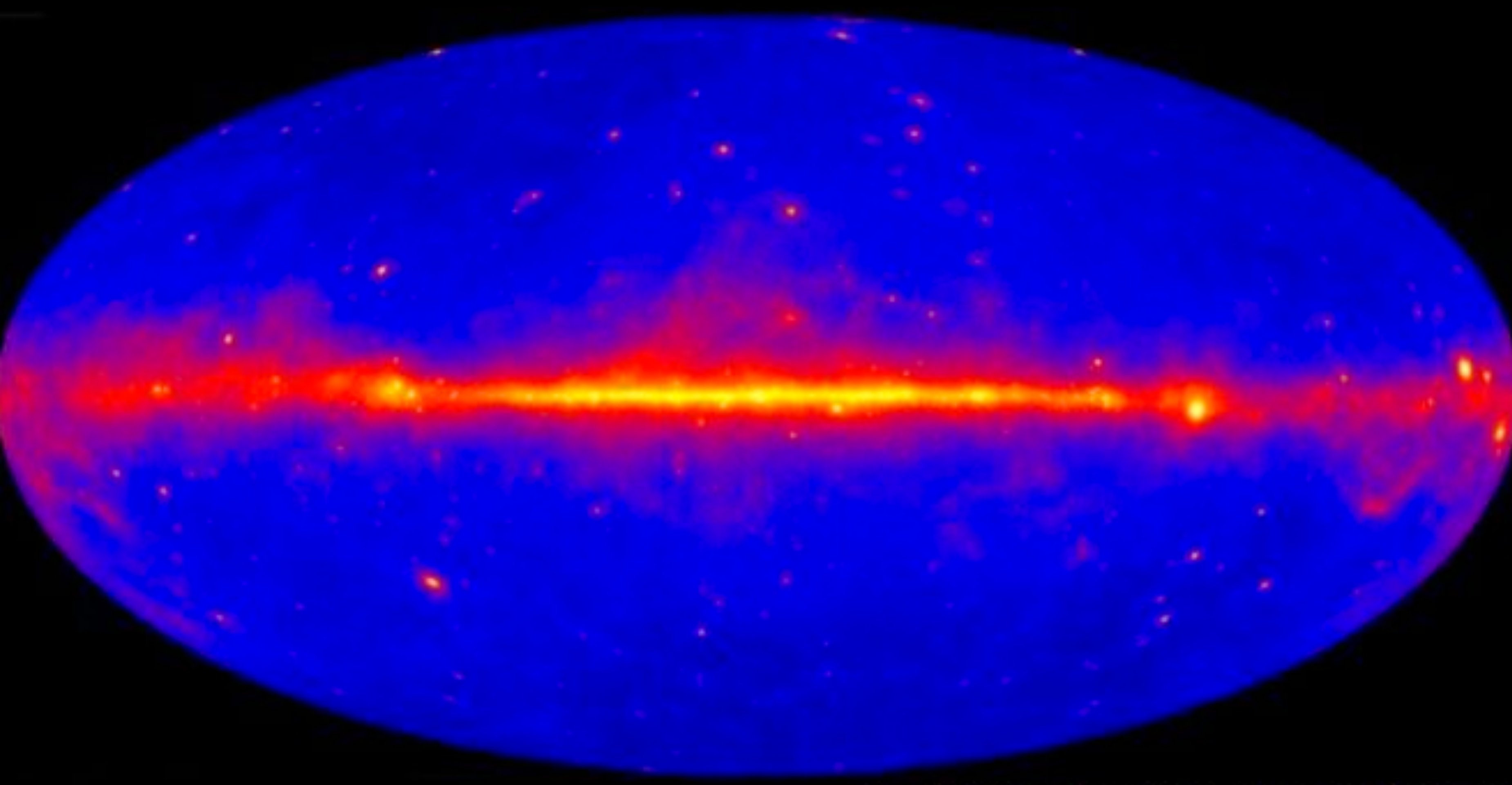
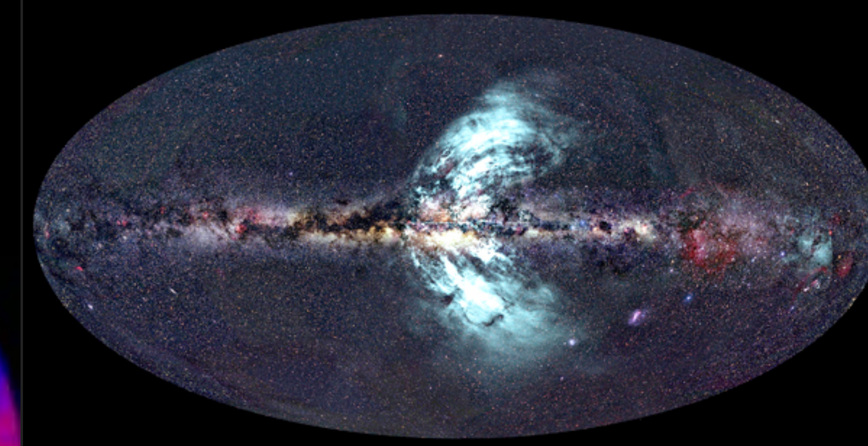
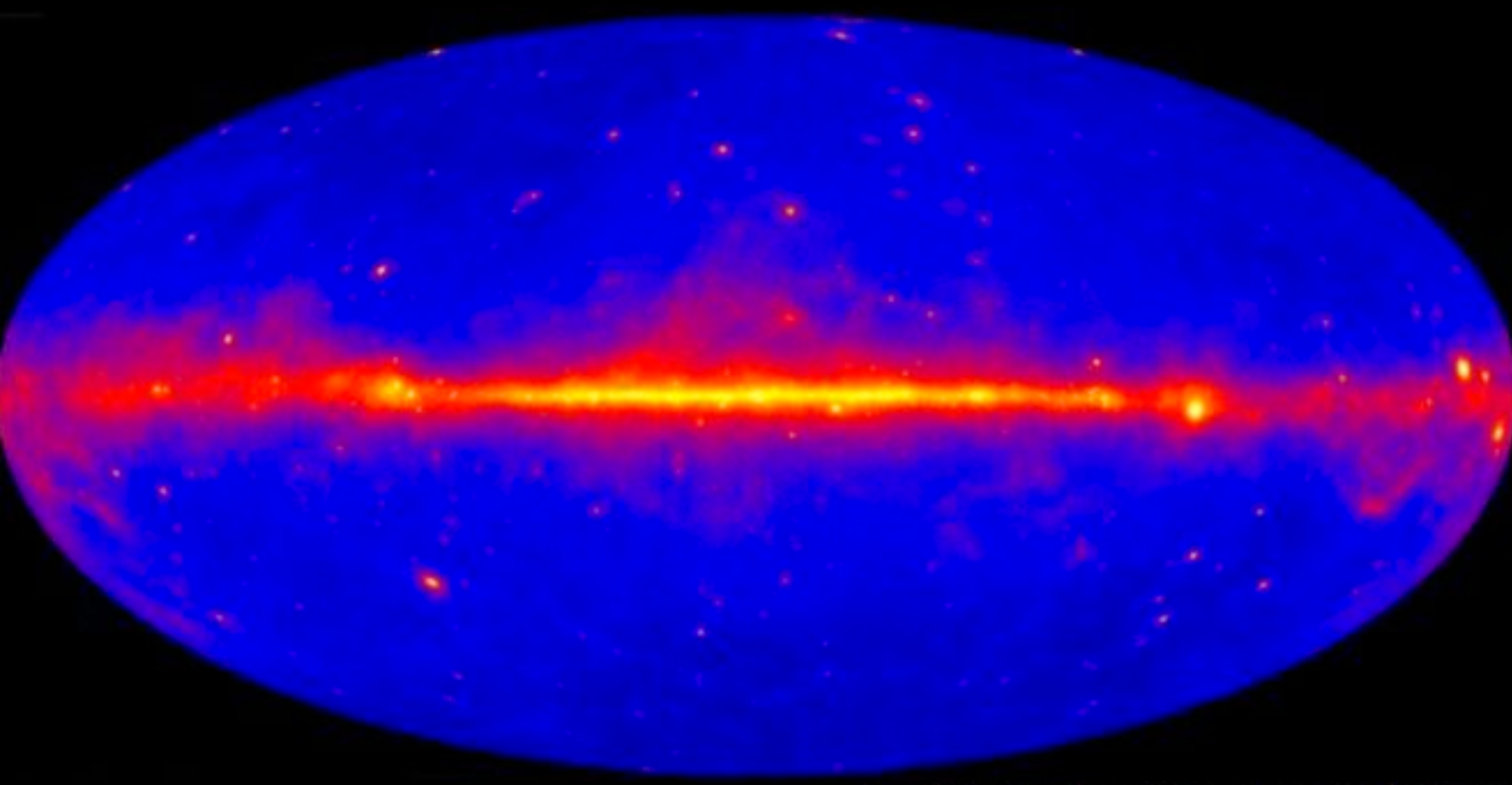


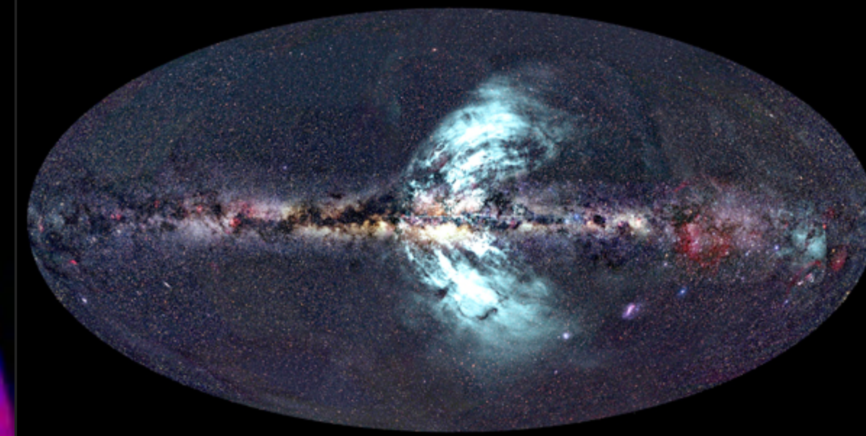


DARK MATTER IN THE MILKY WAY

THE INDIRECT DETECTION OF DARK MATTER

Francesca Calore and Tim Linden





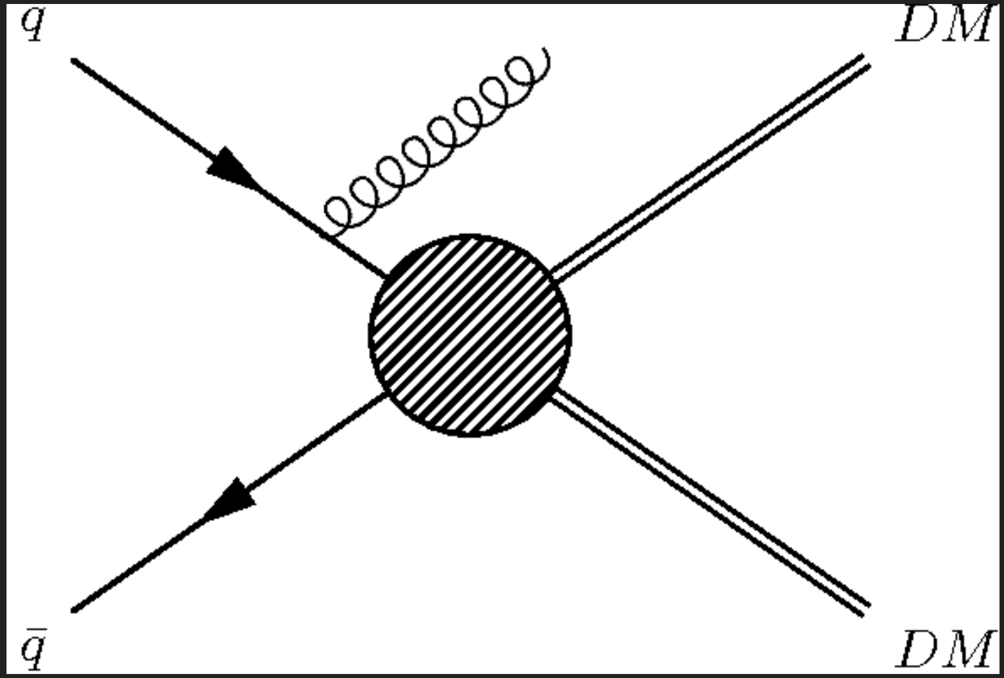
DARK MATTER IN THE MILKY WAY

THE INDIRECT DETECTION OF WIMP DARK MATTER

Francesca Calore and Tim Linden

- DARK MATTER PARTICLE PHYSICS
- DARK MATTER INDIRECT DETECTION
- SEARCHES WITH GAMMA RAYS
- SEARCHES WITH CHARGED COSMIC RAYS AND OTHER WAVELENGTHS

DARK MATTER INDIRECT DETECTION



We want to investigate an interaction where dark matter annihilates to produce final states containing standard model particles.

Will make one assumption at this point:

1.) Dark Matter is stable because it is protected by a conserved symmetry (e.g. r-parity). This only needs to be approximately true.

In this case, we can generically write down an interaction rate:

$$\Gamma_{\mathrm{SM,\ ann}} = \left(\int \frac{\rho_{\mathrm{DM}}^2}{m_\chi^2} \mathrm{d}V \right) \times (\sigma v) \times (N_{\mathrm{SM,\ ann}})$$

DARK MATTER INDIRECT DETECTION

Will make three more assumptions:

1.) This interaction is CP-symmetric, i.e. at high temperatures:

$$\Gamma_{\chi\chi->q\bar{q}} = \Gamma_{q\bar{q}->\chi\chi}$$

2.) The interaction rate is sufficiently large such that the number of dark matter and standard model particles equilibrates in the early universe (alternative is freeze-in dark matter).

$$\Gamma \gtrsim H \quad \Rightarrow \text{thermal equilibrium}$$
$$\Gamma \lesssim H \quad \Rightarrow \text{decoupled evolution}$$

This derivation closely follows 1301.0952

DARK MATTER INDIRECT DETECTION

Will make three more assumptions:

3.) Freeze out occurs when the dark matter particle is non-relativistic (alternative is hot dark matter).

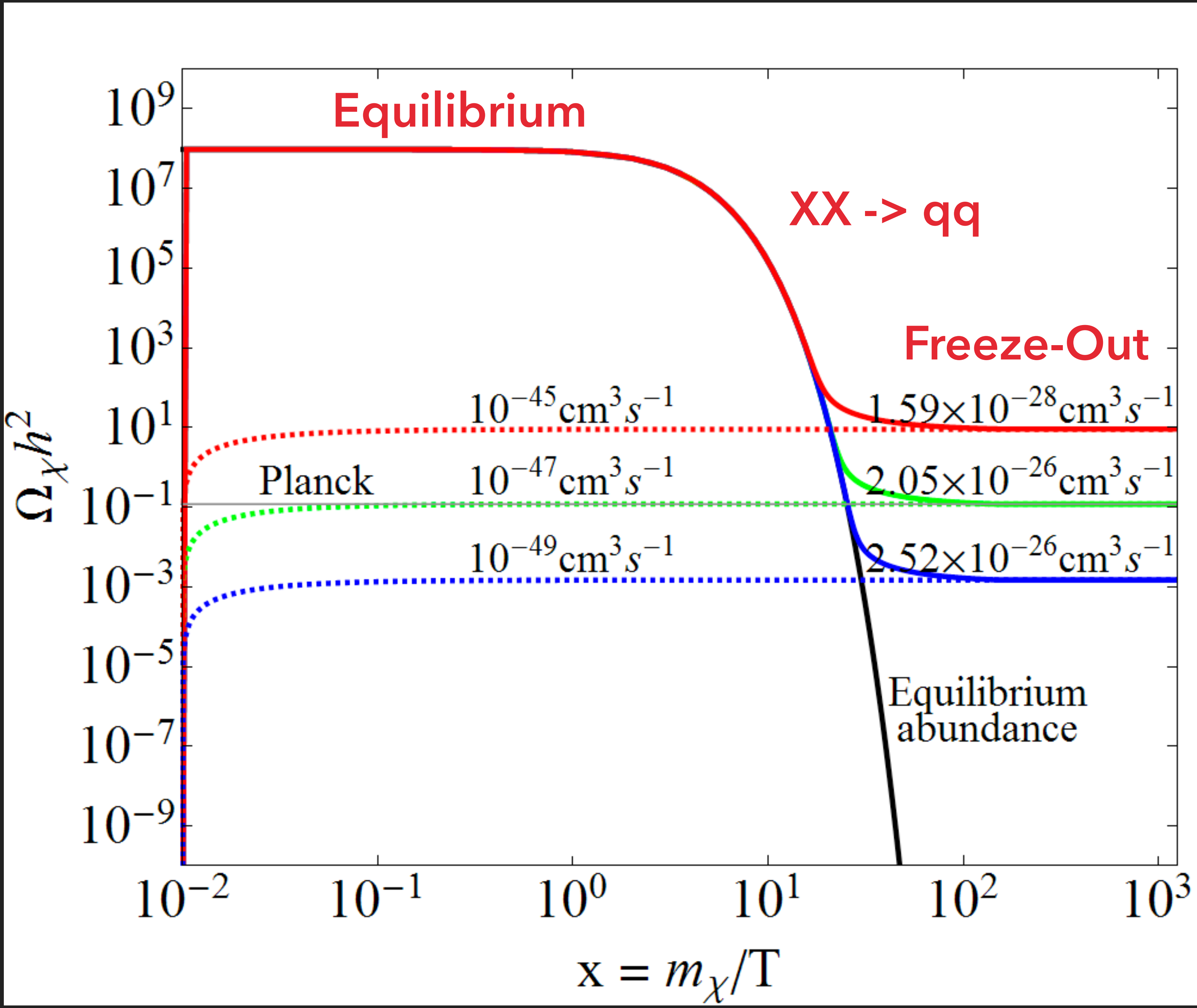
$$m \geq T$$

In that case, statistical mechanics tells us that the number density of dark matter is given by

$$n_{\mathrm{non-rel}} \sim (mT)^{3/2} \exp\left(-\frac{m}{T}\right) \quad \text{for} \quad m \gg T.$$

This derivation closely follows 1301.0952

DARK MATTER INDIRECT DETECTION



DARK MATTER INDIRECT DETECTION

We can set the interaction strength Γ = nσ, the number density of dark matter times its interaction cross-section. And we want to find the time of freeze-out by setting this to equal the Hubble Constant.

$$H^2 = \frac{8\pi G_N}{3}\rho$$

Assuming a radiation dominated universe, we get:

$$\rho \simeq \rho_{\text{rad}} = \frac{\pi^2}{30} \cdot g \cdot T^4$$

Setting nσ = H and noting that $H \cong T^2 / m^P$ we get that:

$$n_{\text{f.o.}} \sim \frac{T_{\text{f.o.}}^2}{M_P \cdot \sigma}$$

This derivation closely follows 1301.0952

DARK MATTER INDIRECT DETECTION

Intriguingly, we note that if we put in values for the weak nuclear force (i.e. $\sigma = G_F^2 m_X^2$) we get:

note $n_0 \sim 1/m_x$ at constant density of the universe!

$$\Omega_\chi = \frac{m_\chi \cdot n_\chi(T = T_0)}{\rho_c} = \frac{m_\chi\, T_0^3}{\rho_c} \frac{n_0}{T_0^3}$$

Noting that in an iso-entropic universe n_0 / T_0^3 is constant:

$$\Omega_\chi = \frac{m_\chi\, T_0^3}{\rho_c} \frac{n_{\text{f.o.}}}{T_{\text{f.o.}}^3} = \frac{T_0^3}{\rho_c} x_{\text{f.o.}} \left(\frac{n_{\text{f.o.}}}{T_{\text{f.o.}}^2} \right) = \left(\frac{T_0^3}{\rho_c\, M_P} \right) \frac{x_{\text{f.o.}}}{\sigma}$$

And simplifying (by substituting in known constants) we obtain:

$$\left(\frac{\Omega_\chi}{0.2} \right) \simeq \frac{x_{\text{f.o.}}}{20} \left(\frac{10^{-8}\ \text{GeV}^{-2}}{\sigma} \right)$$

This derivation closely follows 1301.0952

DARK MATTER INDIRECT DETECTION

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$$\left(\frac{\Omega_\chi}{0.2}\right) \simeq \frac{x_{\mathrm{f.o.}}}{20}\left(\frac{10^{-8}\ \mathrm{GeV}^{-2}}{\sigma}\right)$$

Which can be written in more familiar units as:

$$\langle\sigma v\rangle \sim 10^{-8}\ \mathrm{GeV}^{-2}\left(3\times 10^{-28}\ \mathrm{GeV}^2\ \mathrm{cm}^2\right)\ 10^{10}\ \frac{\mathrm{cm}}{\mathrm{s}} = 3\times 10^{-26}\ \frac{\mathrm{cm}^3}{\mathrm{s}}$$

This derivation closely follows 1301.0952

DARK MATTER INDIRECT DETECTION

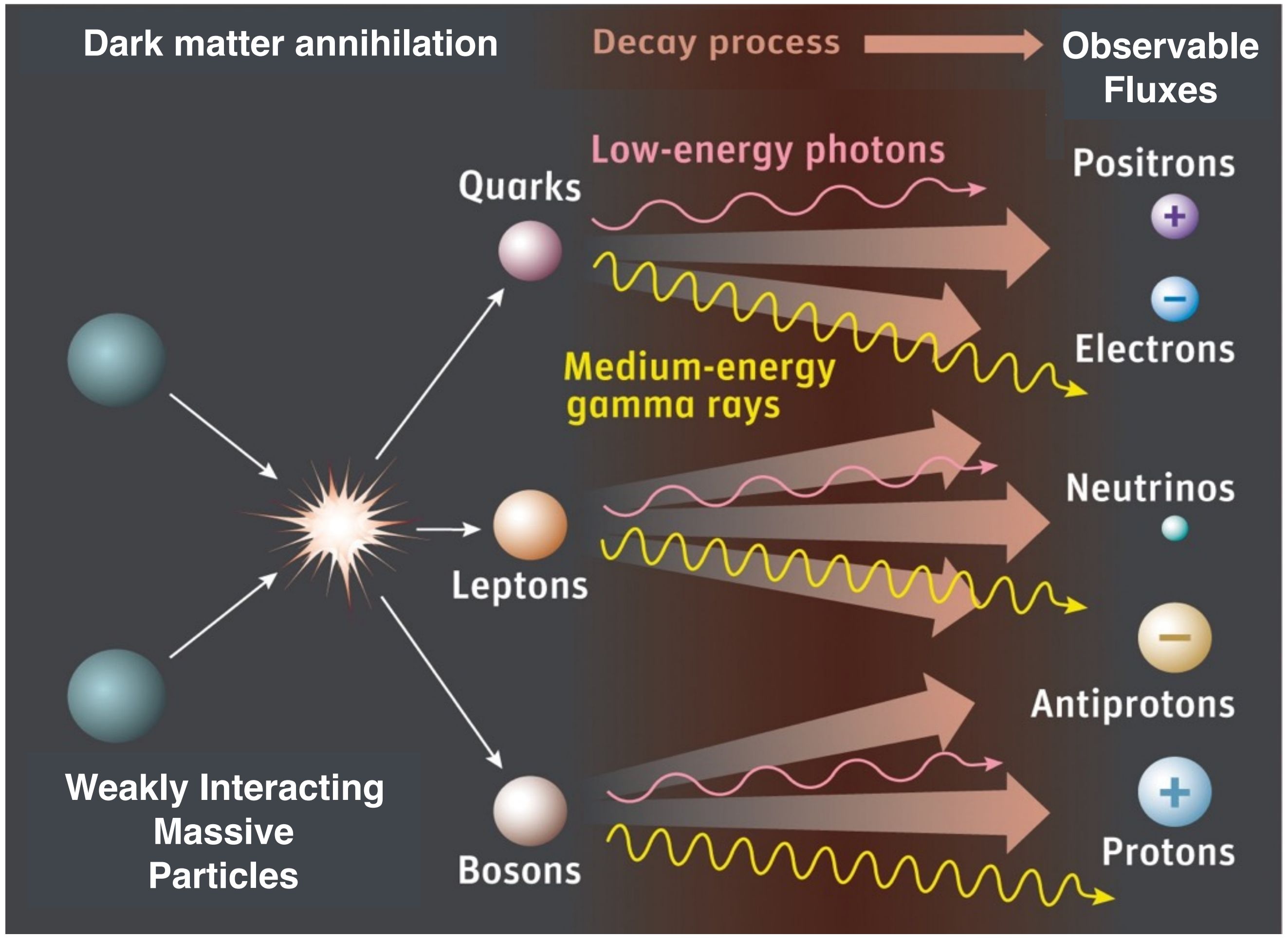
So besides very quickly going over some math, what do we learn?

1.) Dark Matter annihilations at the present day are directly linked to annihilations in the early universe.

2.) The Weak nuclear force provides the correct interaction strength to produce the observed dark matter density.

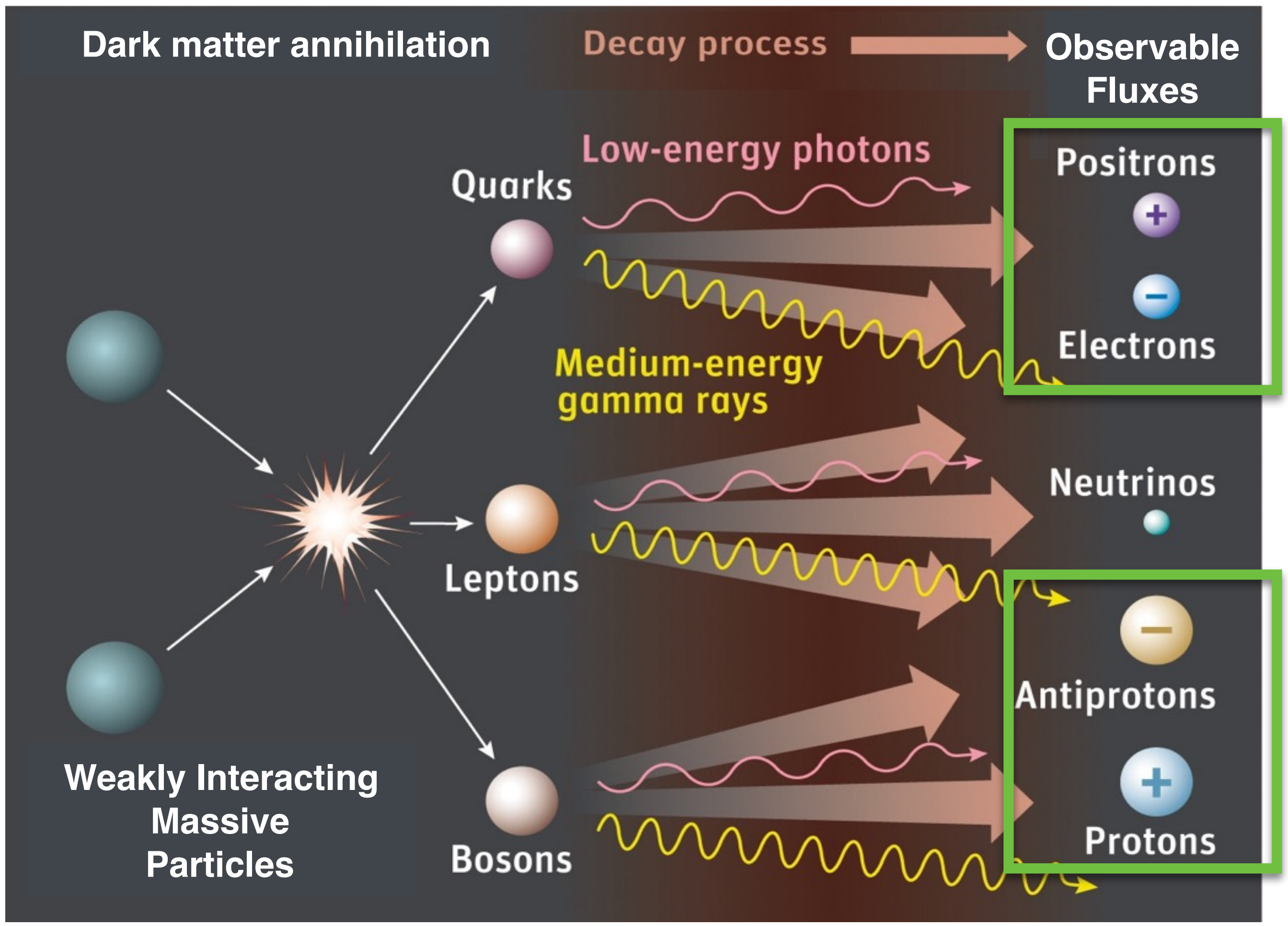
2.) Under a very reasonable (though not certain) set of assumptions, the annihilation cross-section is fixed by the observed relic density. This is unique among WIMP detection strategies (direct/collider detection)

Indirect dark matter detection



Indirect searches
for stable dark matter annihilation
(or decay) products.

Indirect dark matter detection



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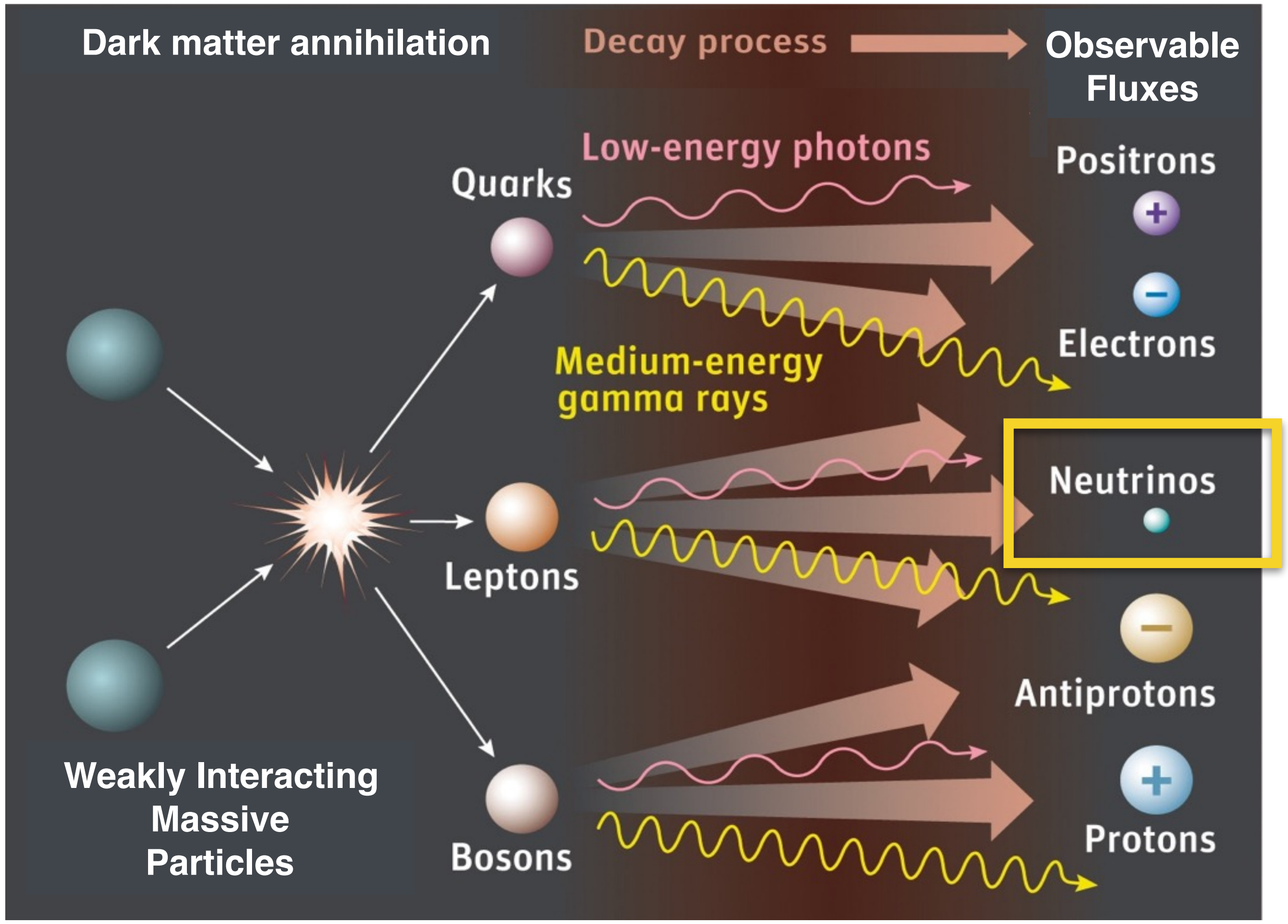

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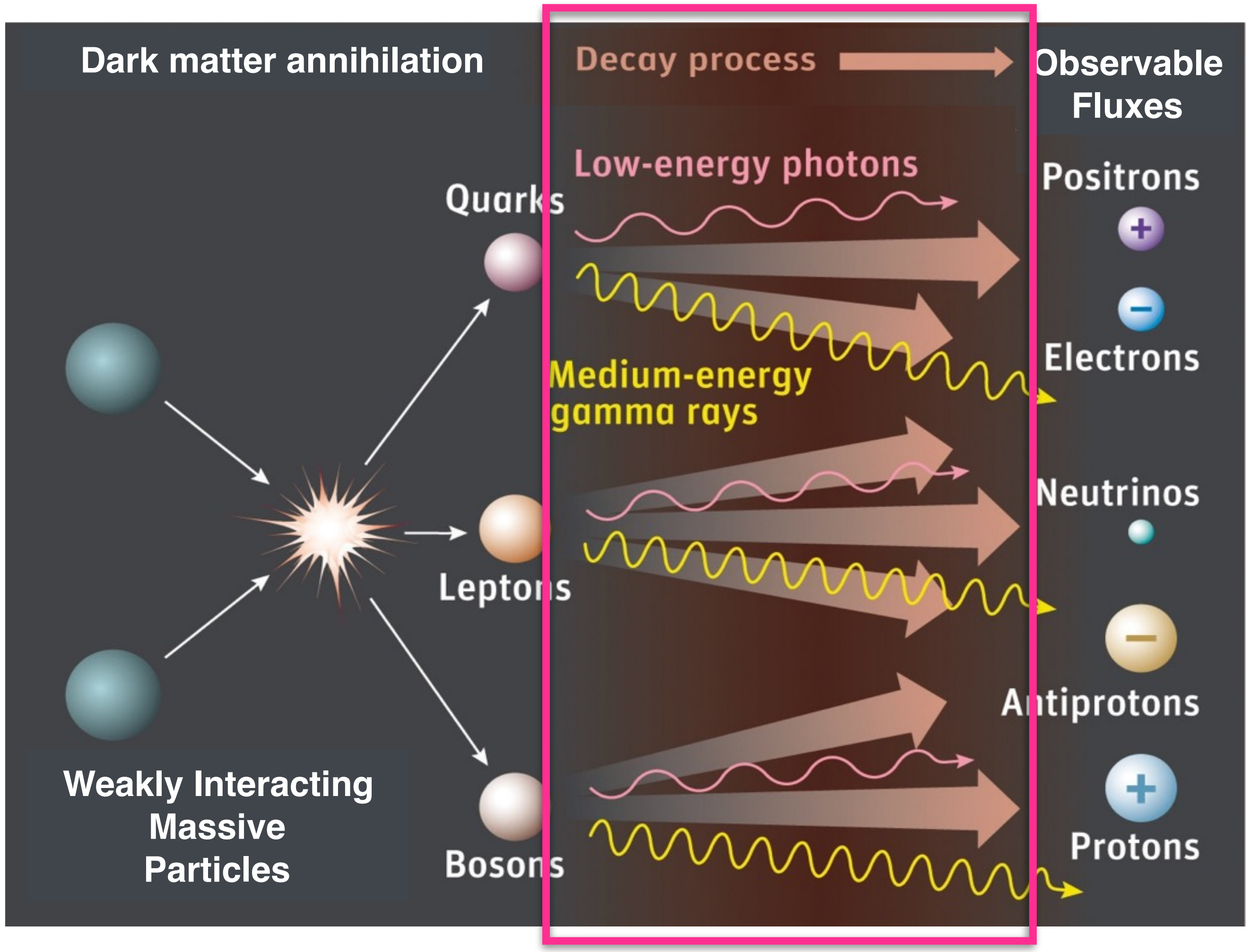
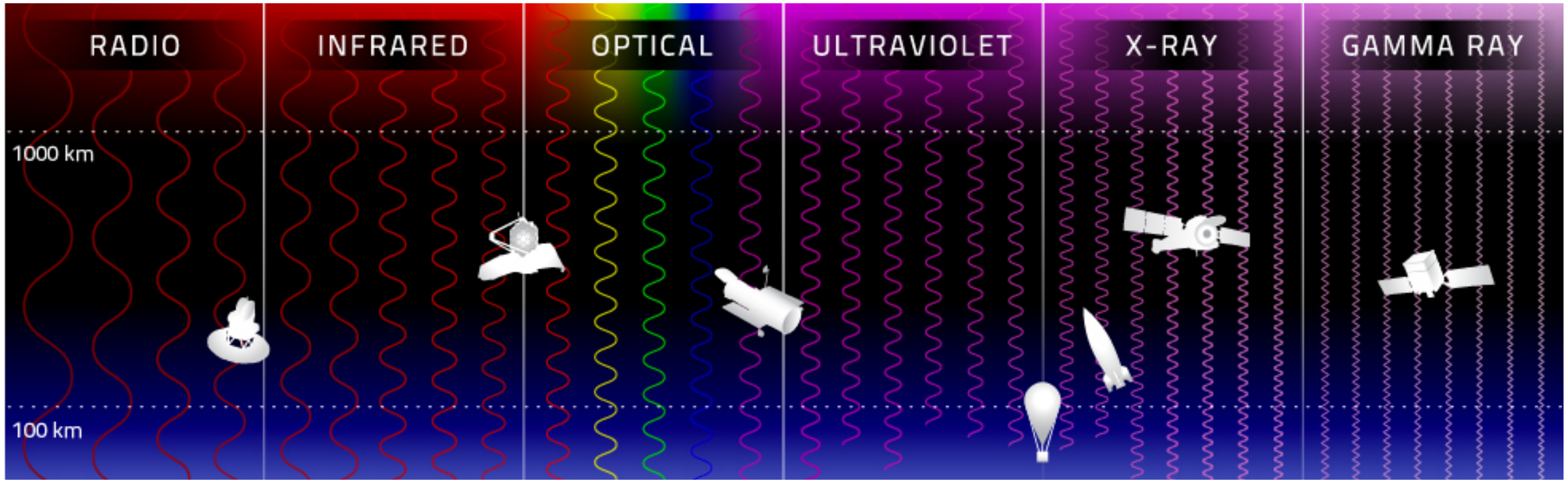
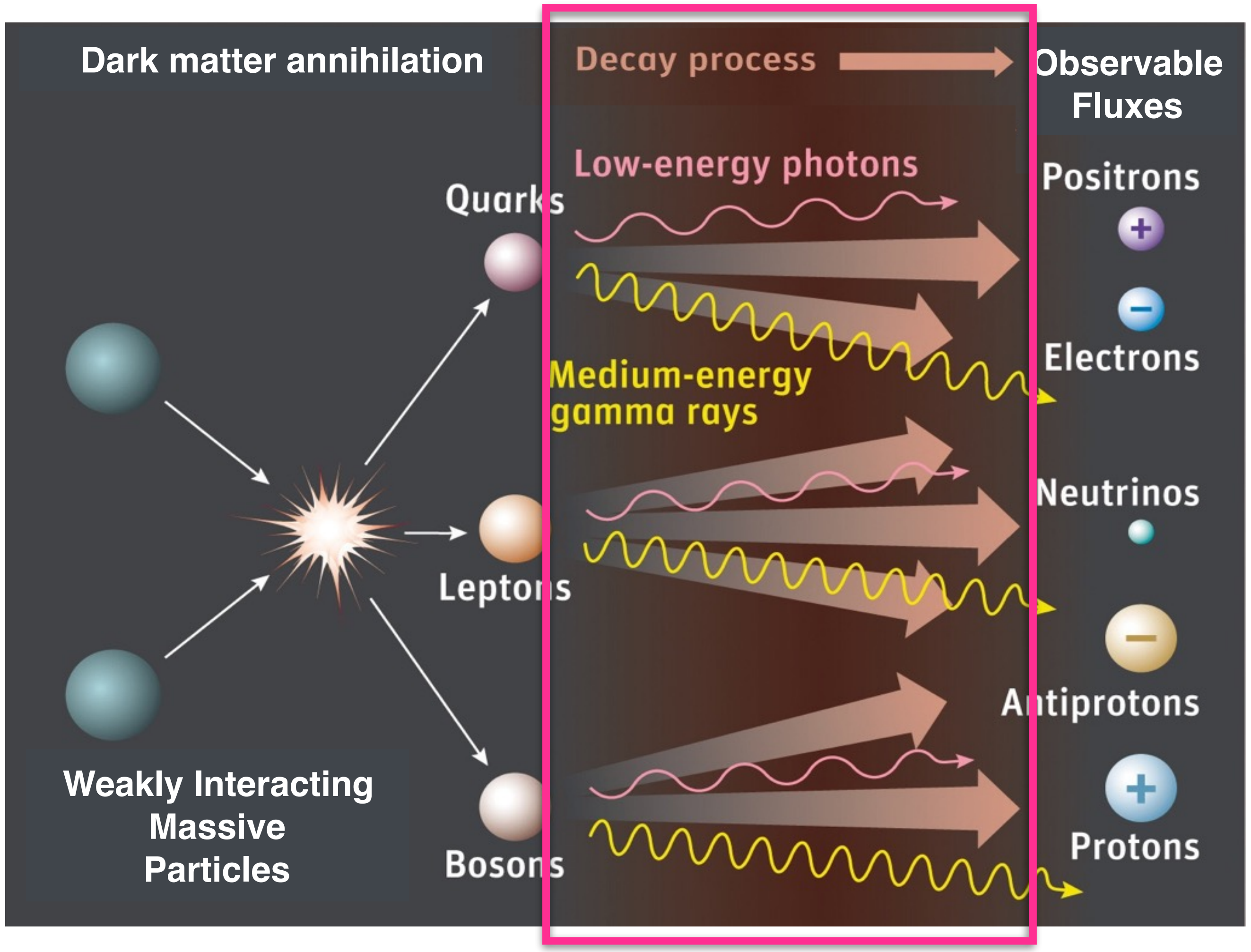
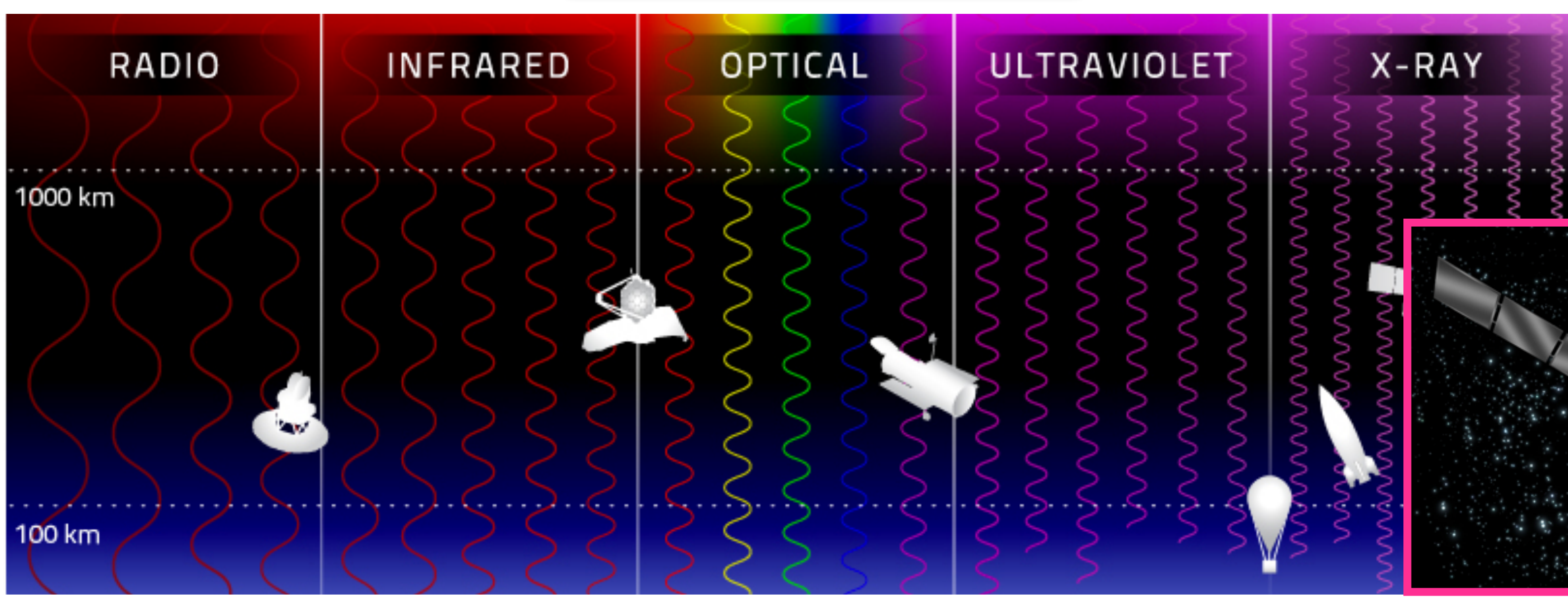


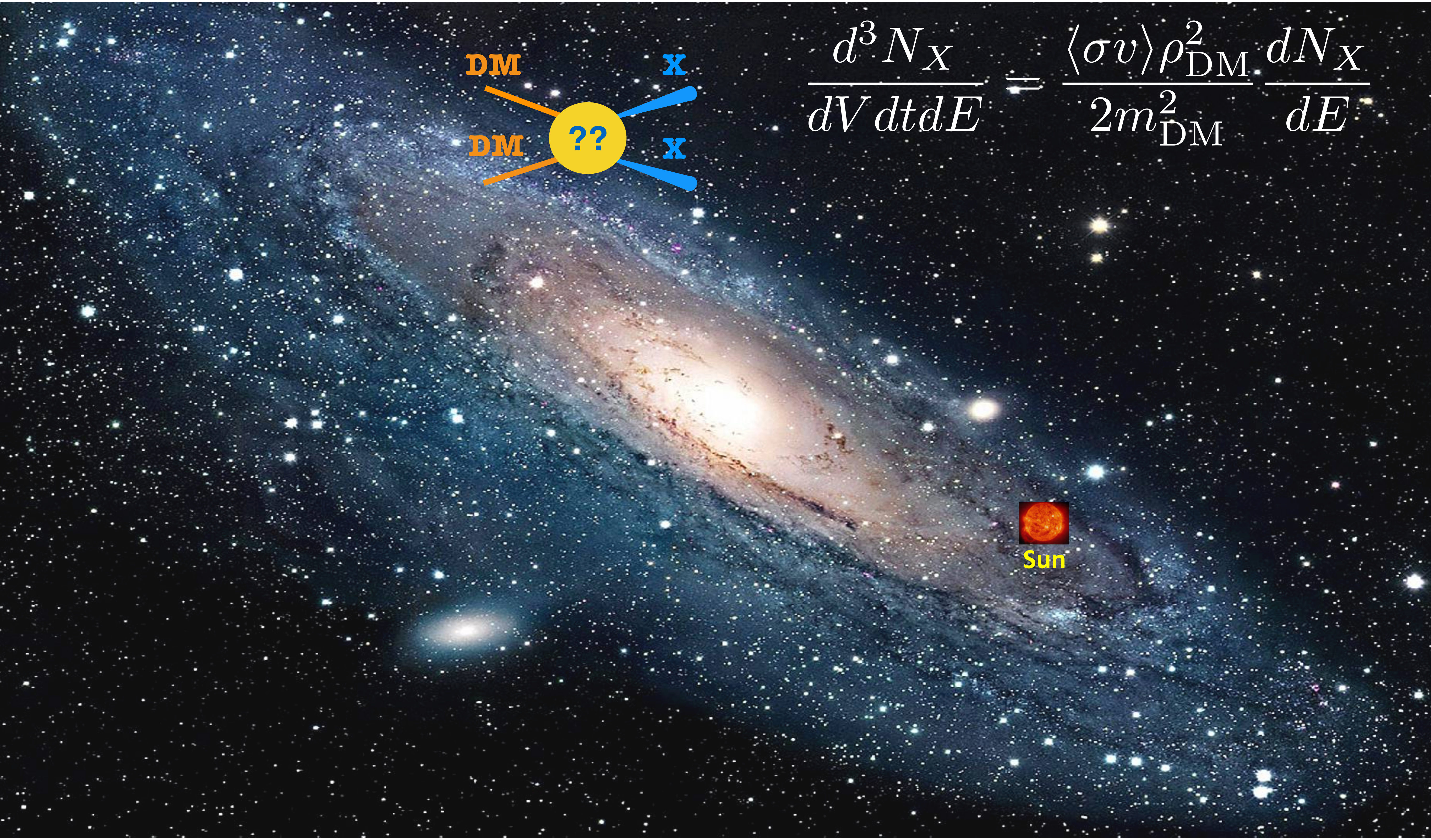


Indirect dark matter detection





Indirect dark matter detection messengers in the Galaxy



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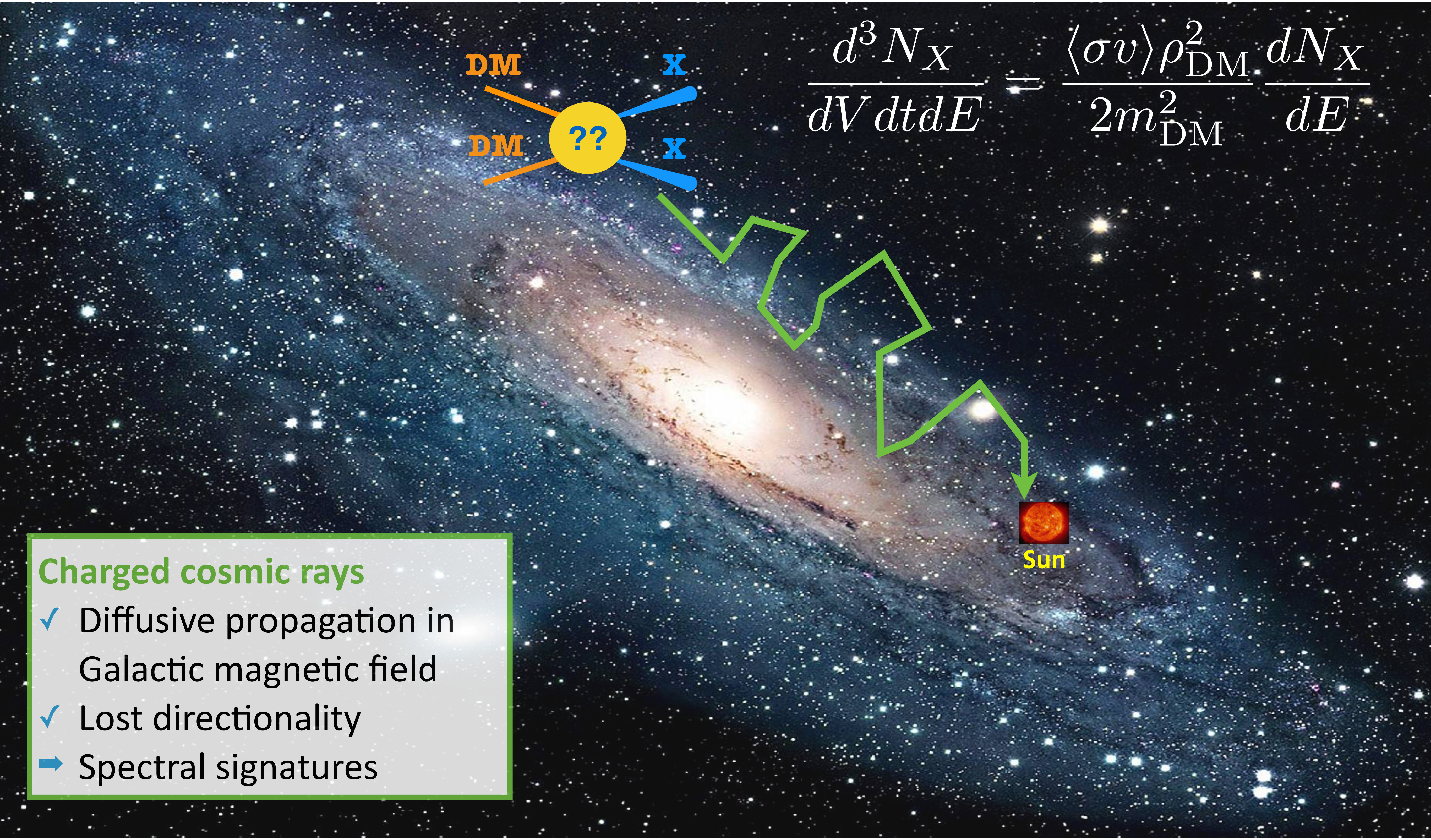
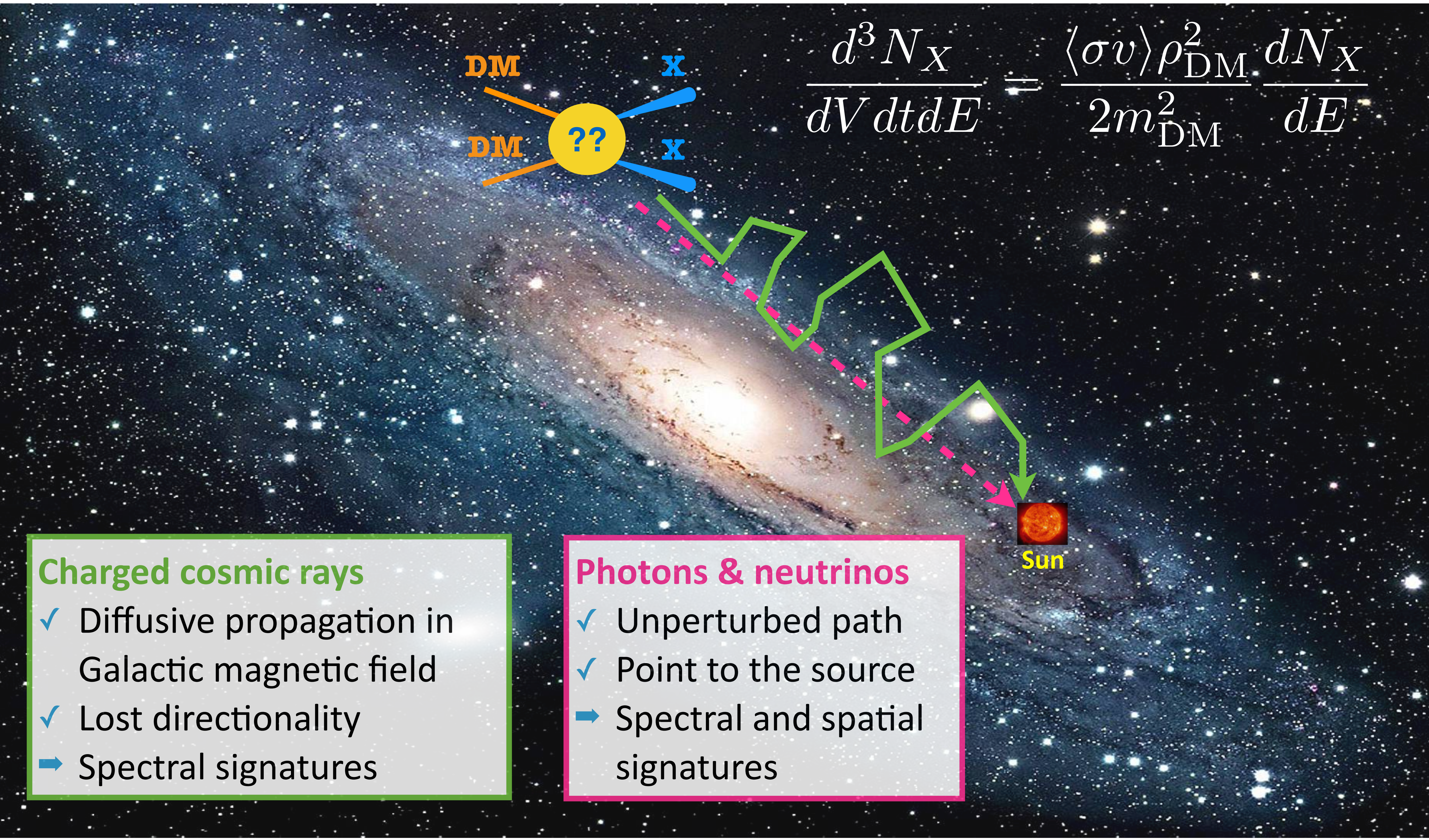


$$\frac{d^3 N_X}{dV\,dt\,dE} = \frac{\langle \sigma v \rangle \rho^2_{\rm DM}}{2 m^2_{\rm DM}} \frac{dN_X}{dE}$$

Charged cosmic rays

- ✓ Diffusive propagation in Galactic magnetic field
- ✓ Lost directionality
- ➡ Spectral signatures

Indirect dark matter detection messengers in the Galaxy



$$\frac{d^3 N_X}{dV\,dt\,dE} = \frac{\langle\sigma v\rangle \rho^2_{\mathrm{DM}}}{2 m^2_{\mathrm{DM}}} \frac{dN_X}{dE}$$

Charged cosmic rays

- ✓ Diffusive propagation in Galactic magnetic field
- ✓ Lost directionality
- ➡ Spectral signatures

Photons & neutrinos

- ✓ Unperturbed path
- ✓ Point to the source
- ➡ Spectral and spatial signatures

Gamma rays from dark matter annihilation

Gamma-ray differential flux from dark matter annihilation with spatial distribution ρ_{DM}

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, s, \Delta\Omega) = \frac{\langle\sigma v\rangle}{2m_{\mathrm{DM}}^2} \sum_i B_i \frac{dN_\gamma^i}{dE_\gamma} \frac{1}{4\pi} \int_0^{\Delta\Omega} d\Omega \int_{\mathrm{l.o.s}} \rho_{\mathrm{DM}}^2(s) ds$$

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Particle Physics factor

➡ Spectral information

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Particle Physics factor

➡ Spectral information

Astrophysics factor

➡ Spatial information

The particle physics factor

Gamma-ray differential flux from dark matter annihilation with spatial distribution ρ_{DM}

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The particle physics factor

Gamma-ray differential flux from dark matter annihilation with spatial distribution ρ_{DM}

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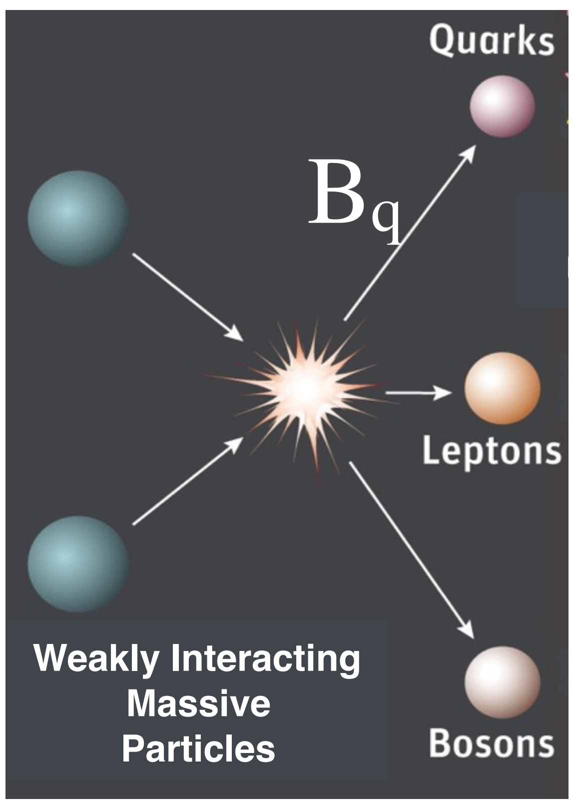
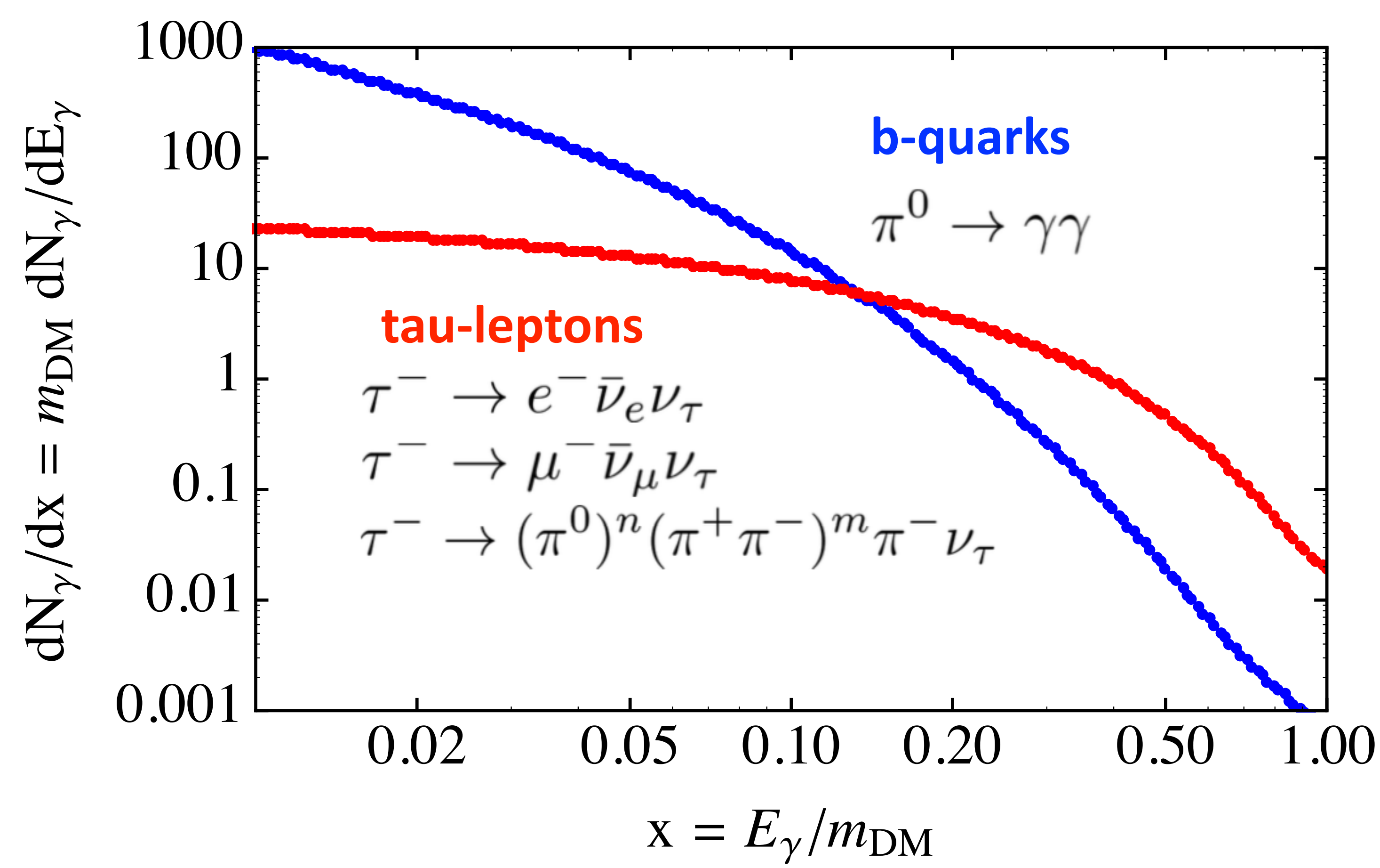
$\mathrm{DM}\,\mathrm{DM} \to \mathrm{SM}\,\mathrm{SM}$



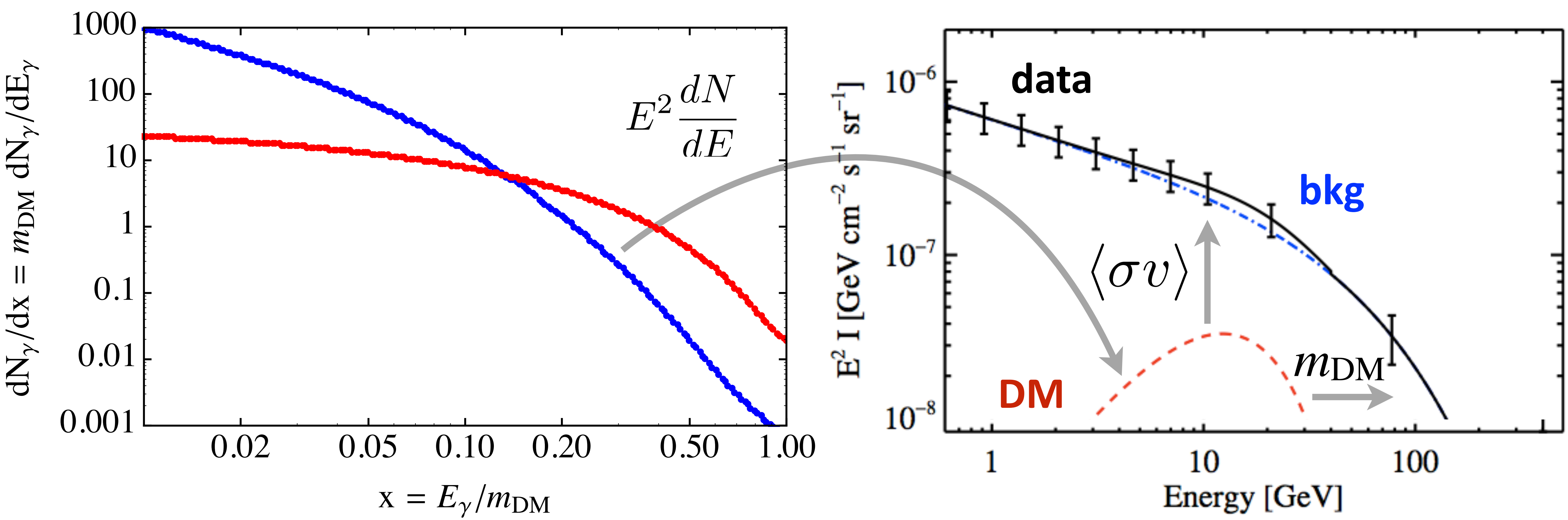


Typical gamma-ray emission from hadronic decays and cascades

The particle physics factor

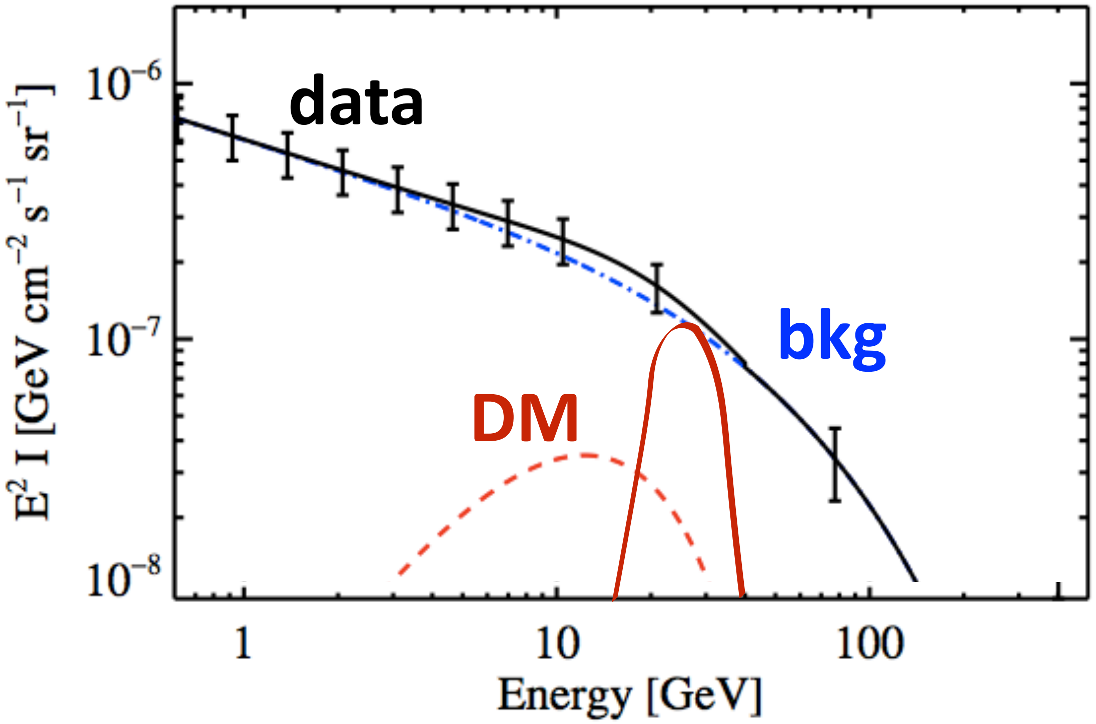
Gamma-ray differential flux from dark matter annihilation with spatial distribution $\rho_{\rm DM}$

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, s, \Delta\Omega) = \boxed{\frac{\langle\sigma v\rangle}{2m_{\rm DM}^2}\sum_i B_i \frac{dN_\gamma^i}{dE_\gamma}} \frac{1}{4\pi}\int_0^{\Delta\Omega} d\Omega \int_{\rm l.o.s} \rho_{\rm DM}^2(s)ds$$



Typical gamma-ray emission from hadronic decays and cascades

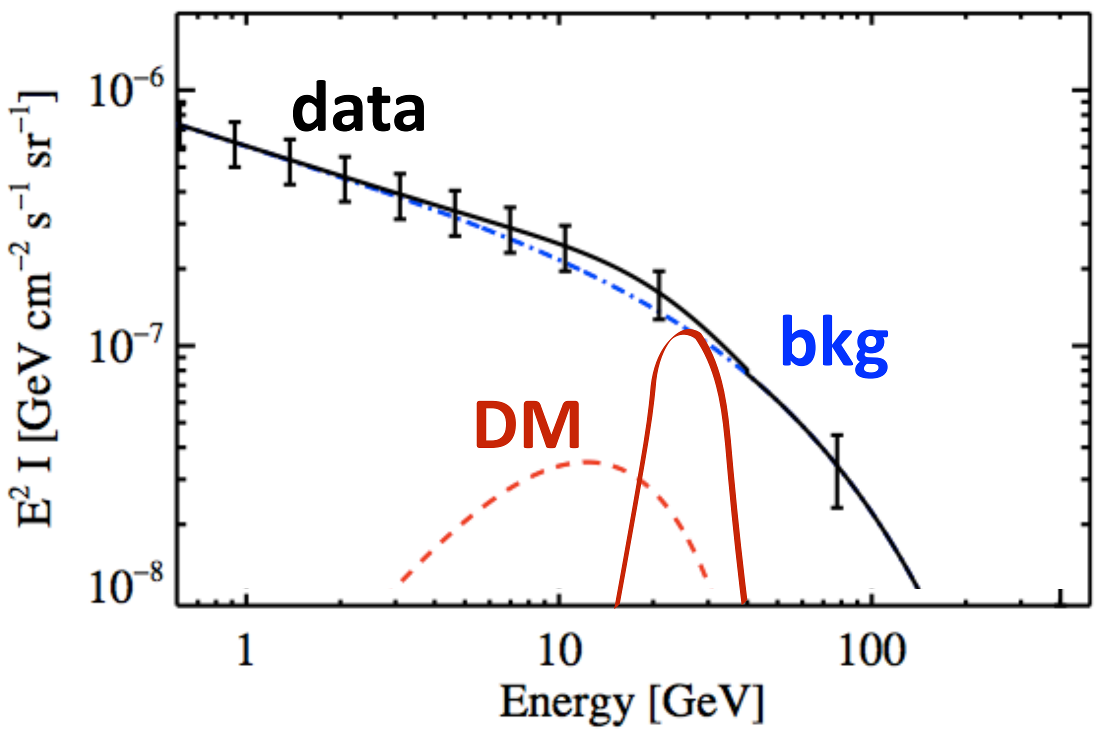
Spectral features in annihilation spectrum



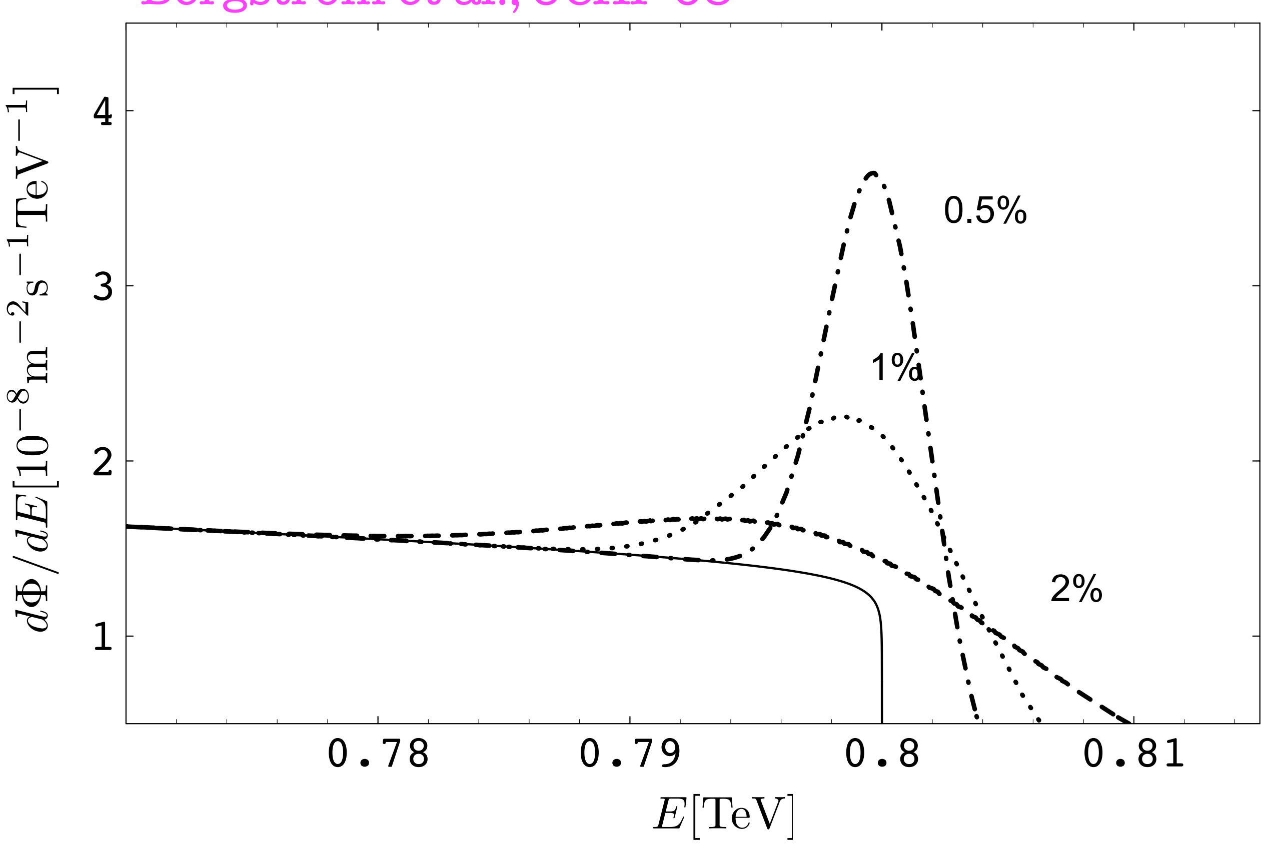
Spectral features

Smoking-gun dark matter signatures

Spectral features in annihilation spectrum



Bergström et al., JCAP'05



SPECTRAL FEATURES

Smoking-gun dark matter signatures

Gamma-ray line from loop suppressed direct annihilation into

$$\gamma\gamma, Z\gamma, H\gamma$$

Looking for dark matter **spectral features** in gamma rays requires optimised search strategies.

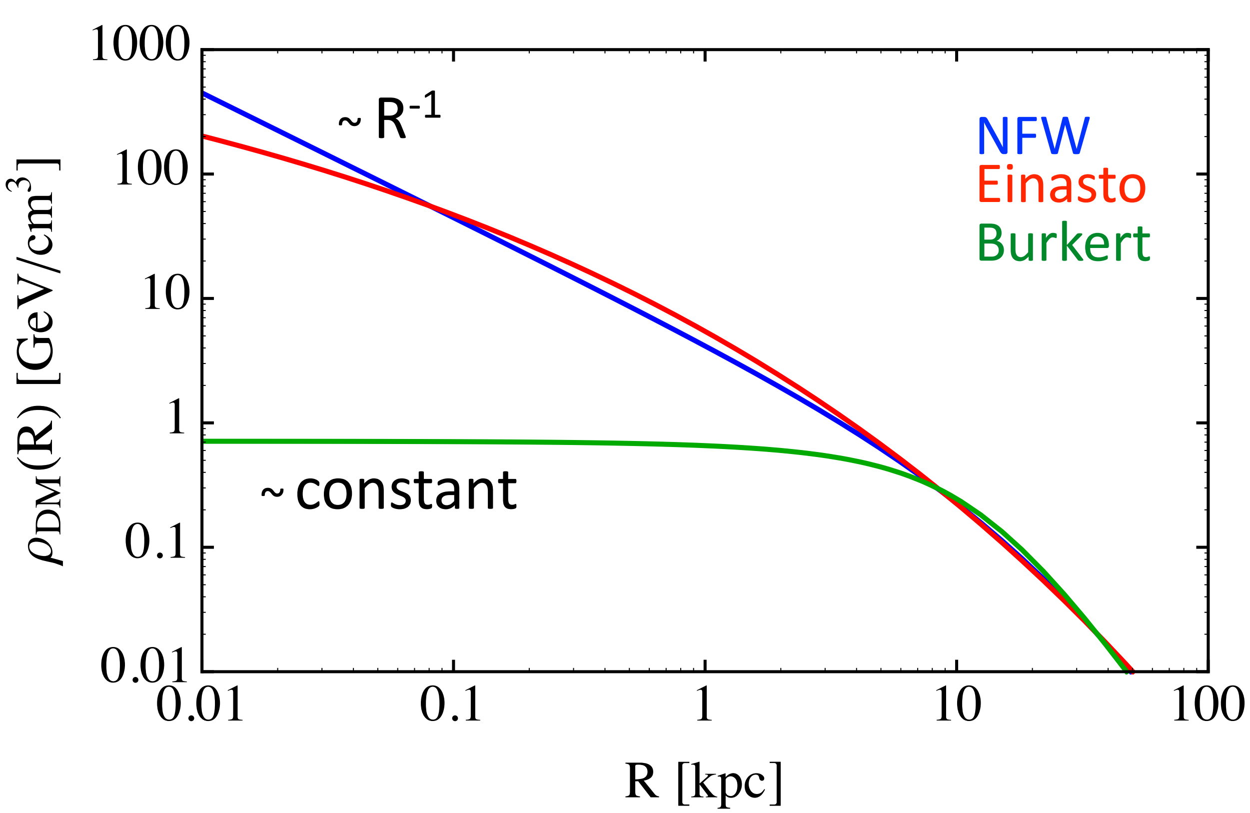
Bringmann,Calore+ PRD'11

The astrophysics factor

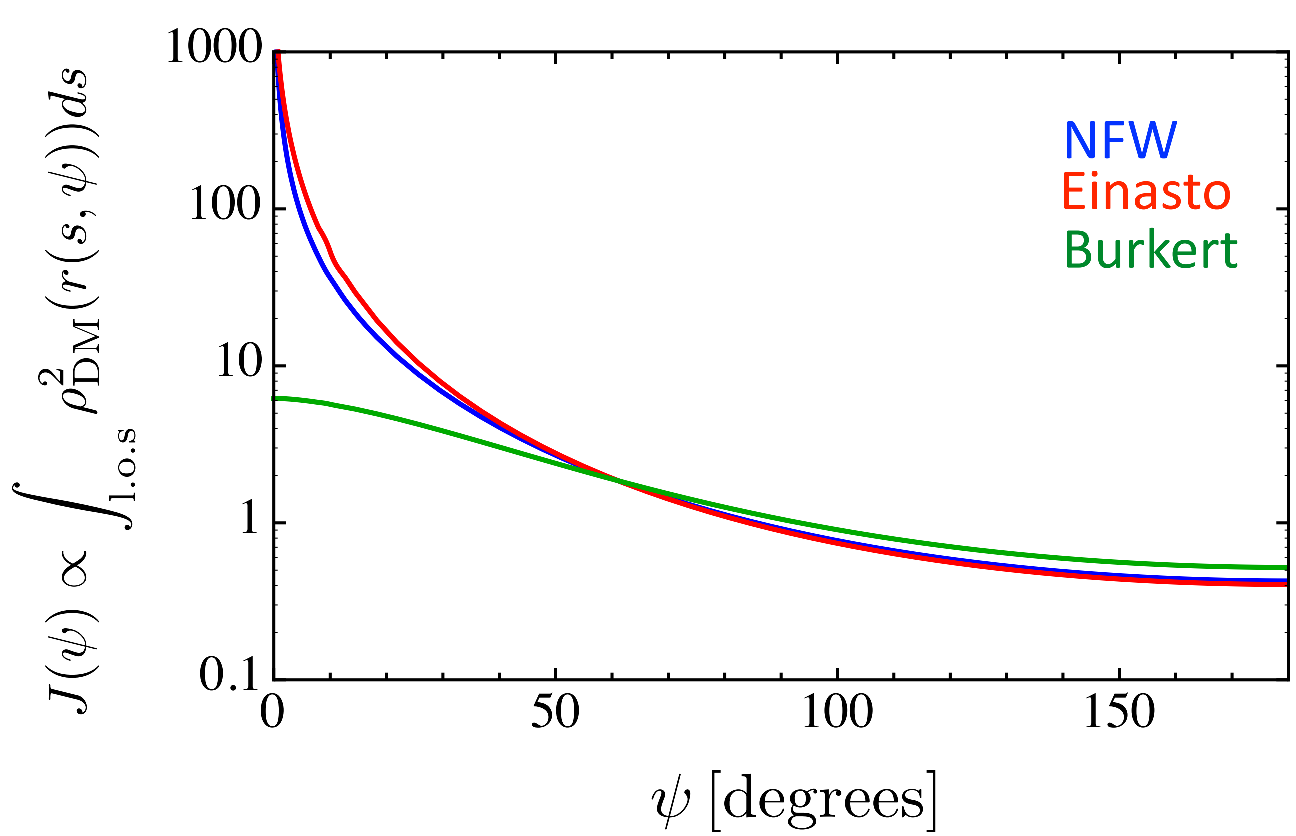
Gamma-ray differential flux from dark matter annihilation with spatial distribution $\rho_{\rm DM}$

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, s, \Delta\Omega) = \frac{\langle\sigma v\rangle}{2m_{\rm DM}^2}\sum_i B_i \frac{dN_\gamma^i}{dE_\gamma}\boxed{\frac{1}{4\pi}\int_0^{\Delta\Omega} d\Omega \int_{\rm l.o.s} \rho_{\rm DM}^2(s)ds}$$

Dark matter density profiles:



Spatial distribution of the signal:

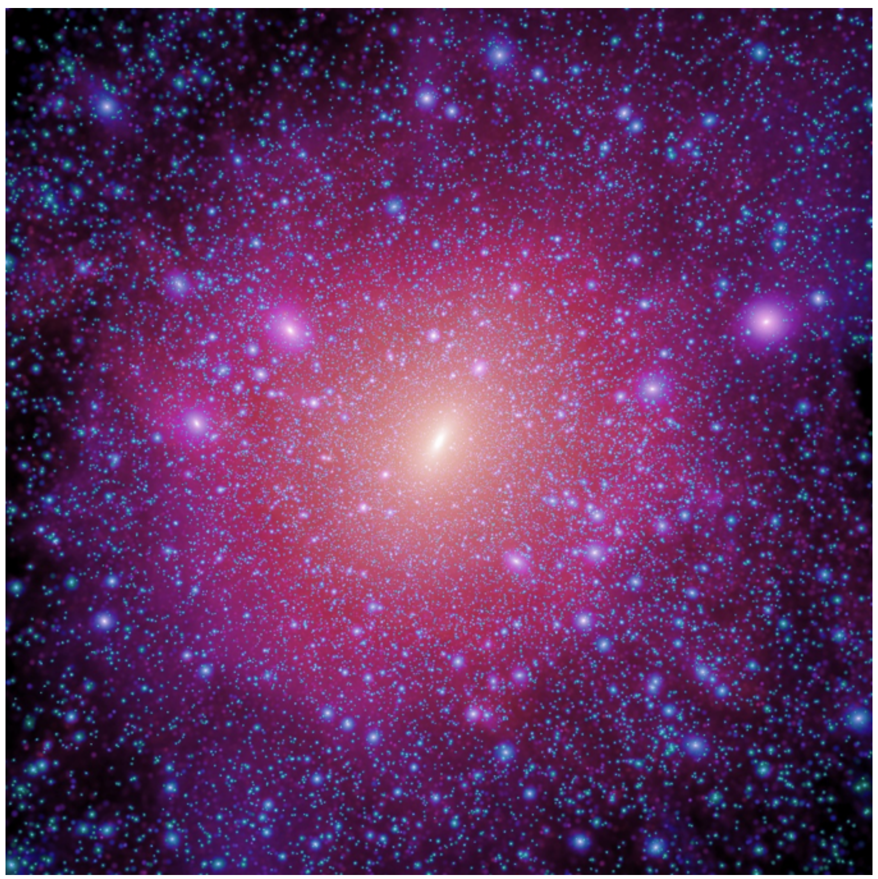


The dark matter spatial distribution

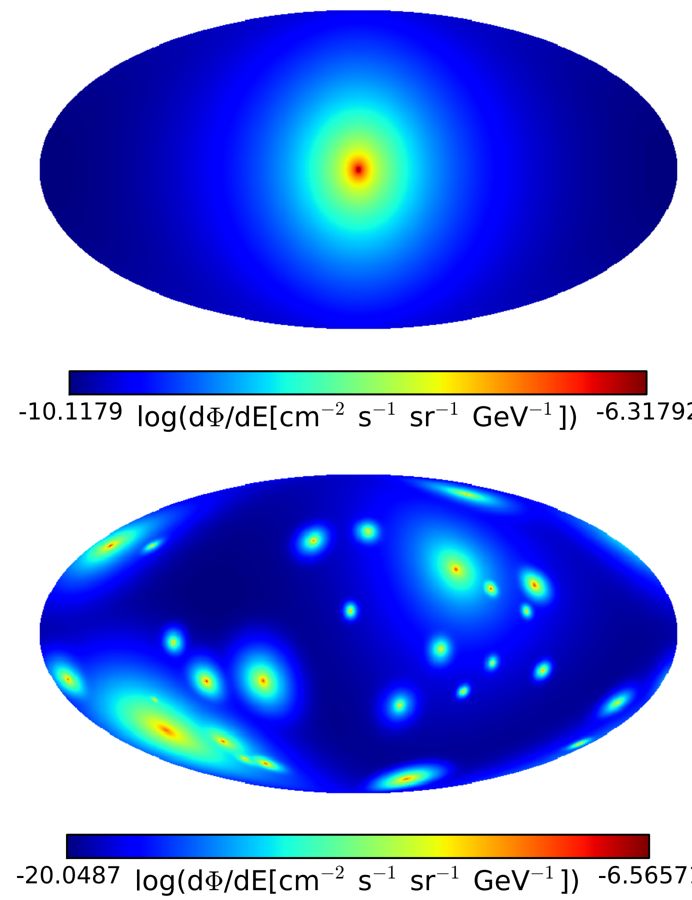
Simulations of structure formation allow to predict the distribution and size of haloes in cosmological volumes

Aquarius DM N-body simulation

Expected gamma-ray flux



Springel+ MNRAS'08



Main halo

Sub-haloes

Calore, Donato, Macciò, Stinson+ MNRAS'14

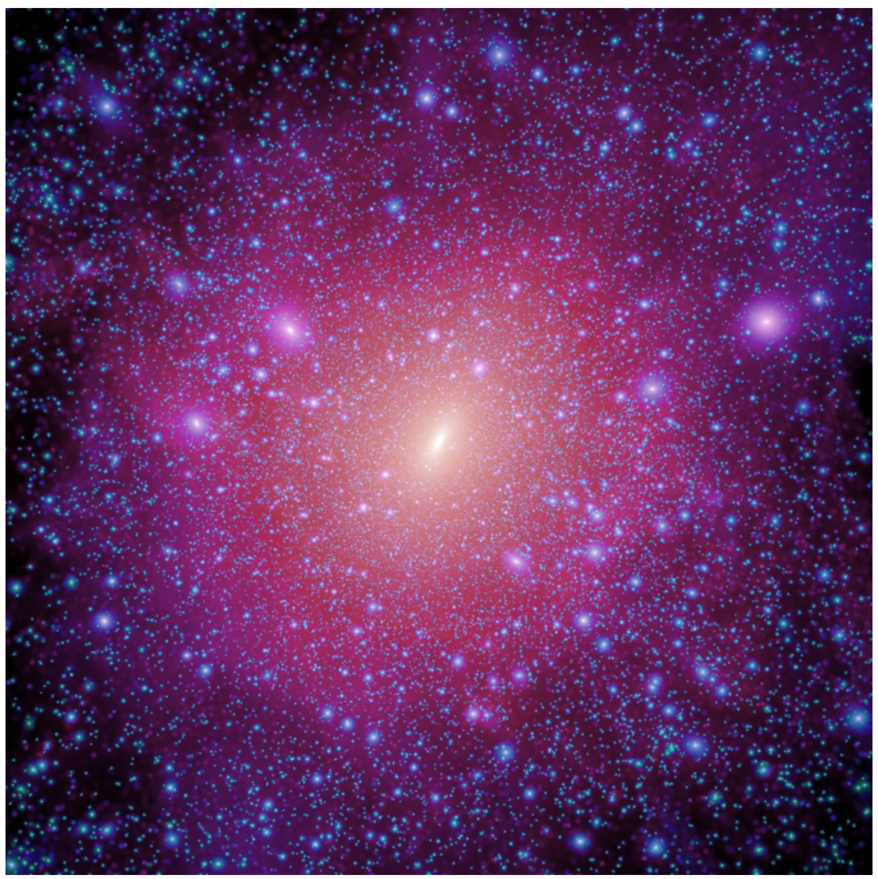
SPATIAL (ANGULAR) FEATURES

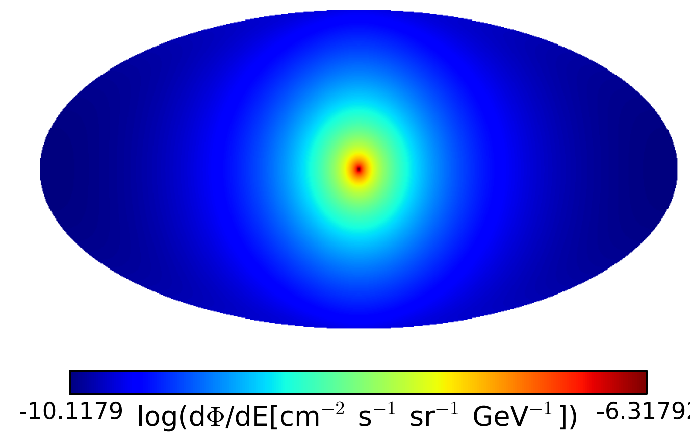
The dark matter spatial distribution

Simulations of structure formation allow to predict the distribution and size of haloes in cosmological volumes

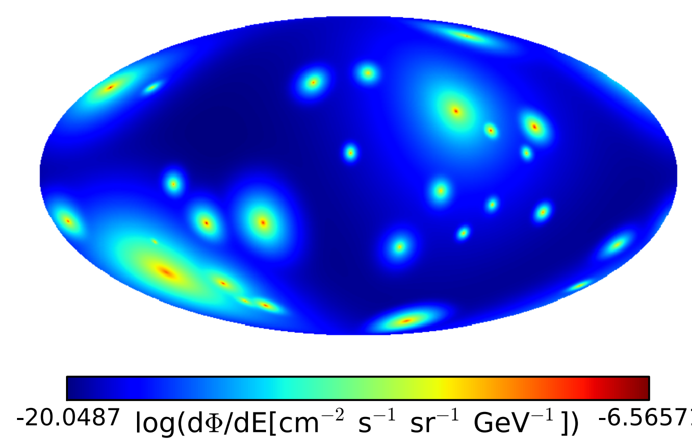
Aquarius DM N-body simulation

Expected gamma-ray flux





Main halo



Sub-haloes

Springel+ MNRAS'08

Calore, Donato, Macciò, Stinson+ MNRAS'14

SPATIAL (ANGULAR) FEATURES

Important effect of baryons during galaxy formation (highly debated)

Current gamma-ray telescopes

Space based:
(Pair conversion detector)

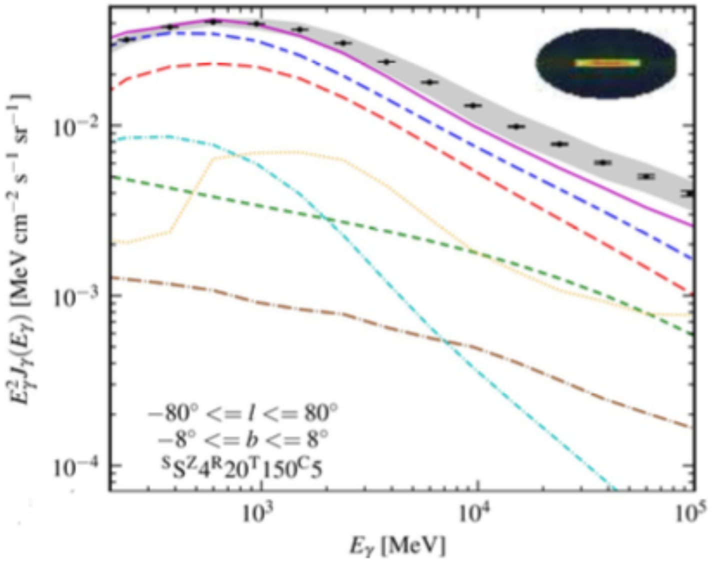
A_{eff}~1m^2
T~<10yr
20 MeV – 300 GeV

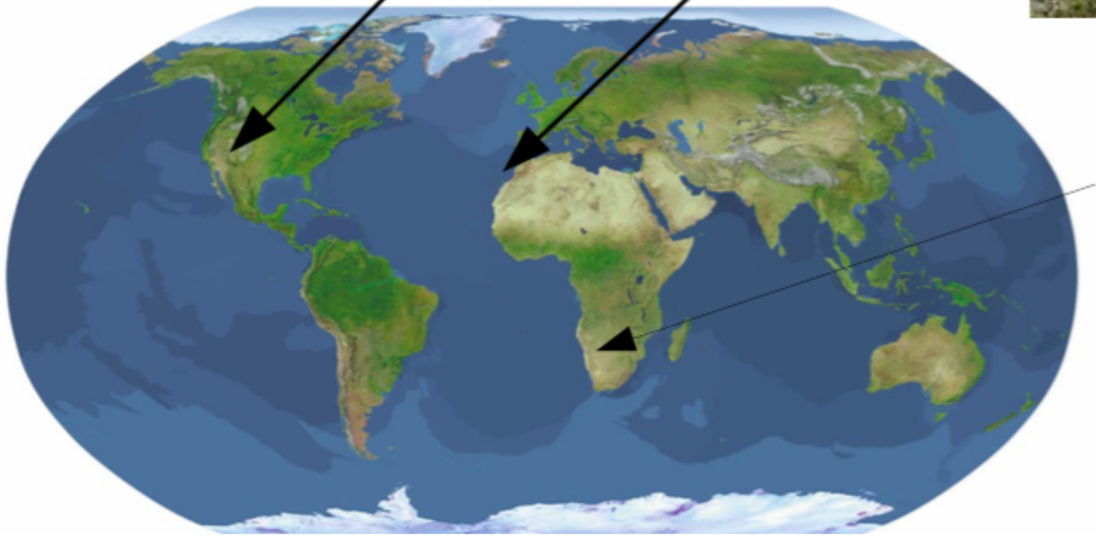
Fermi LAT
since 2008

Ground based:
(Atmospheric Cherenkov Telescopes)

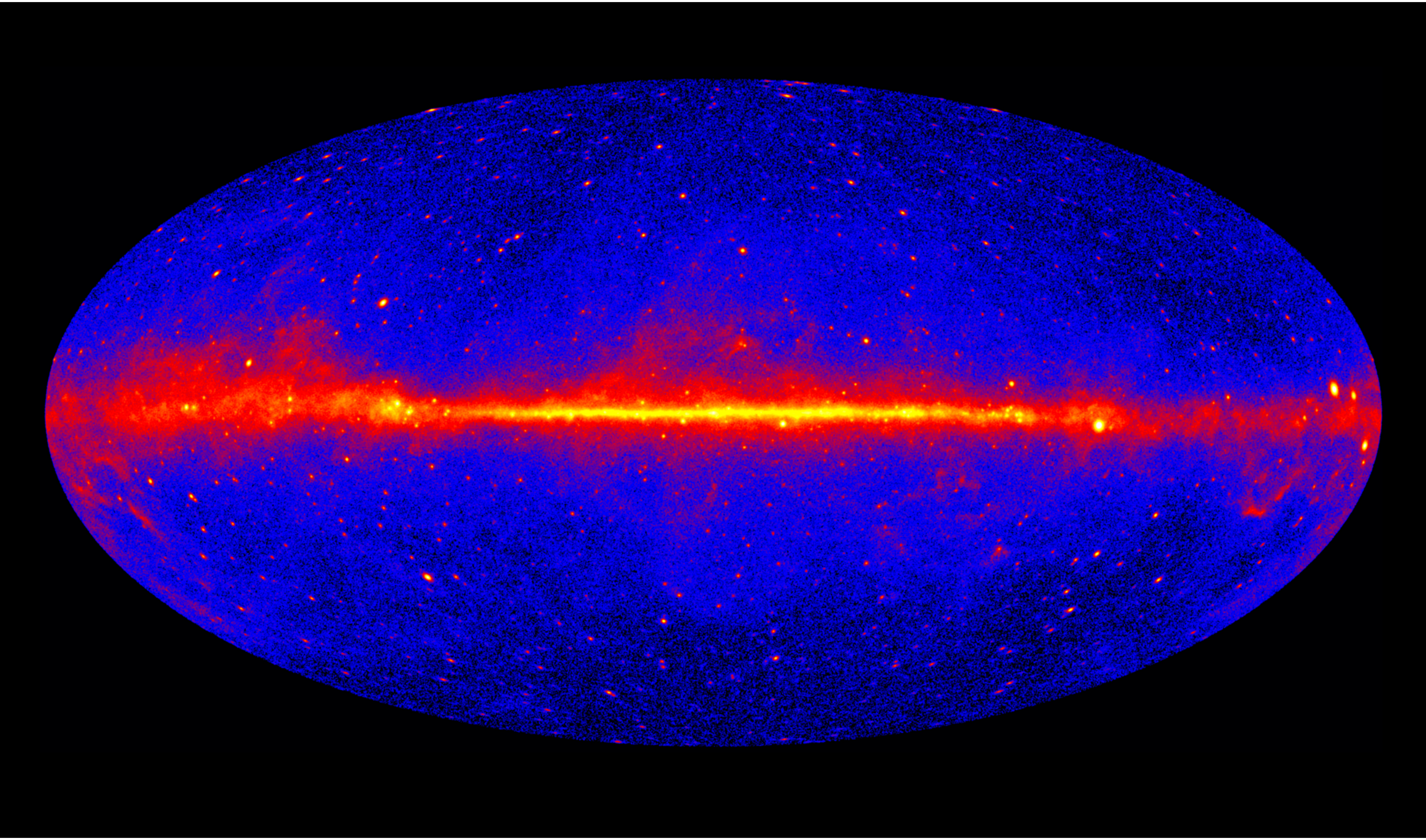
A_{eff}~1km^2
T~<100h
>10 GeV

Fluxes are falling <u>rapidly</u> with increasing energy
High energy measurements require huge collection areas

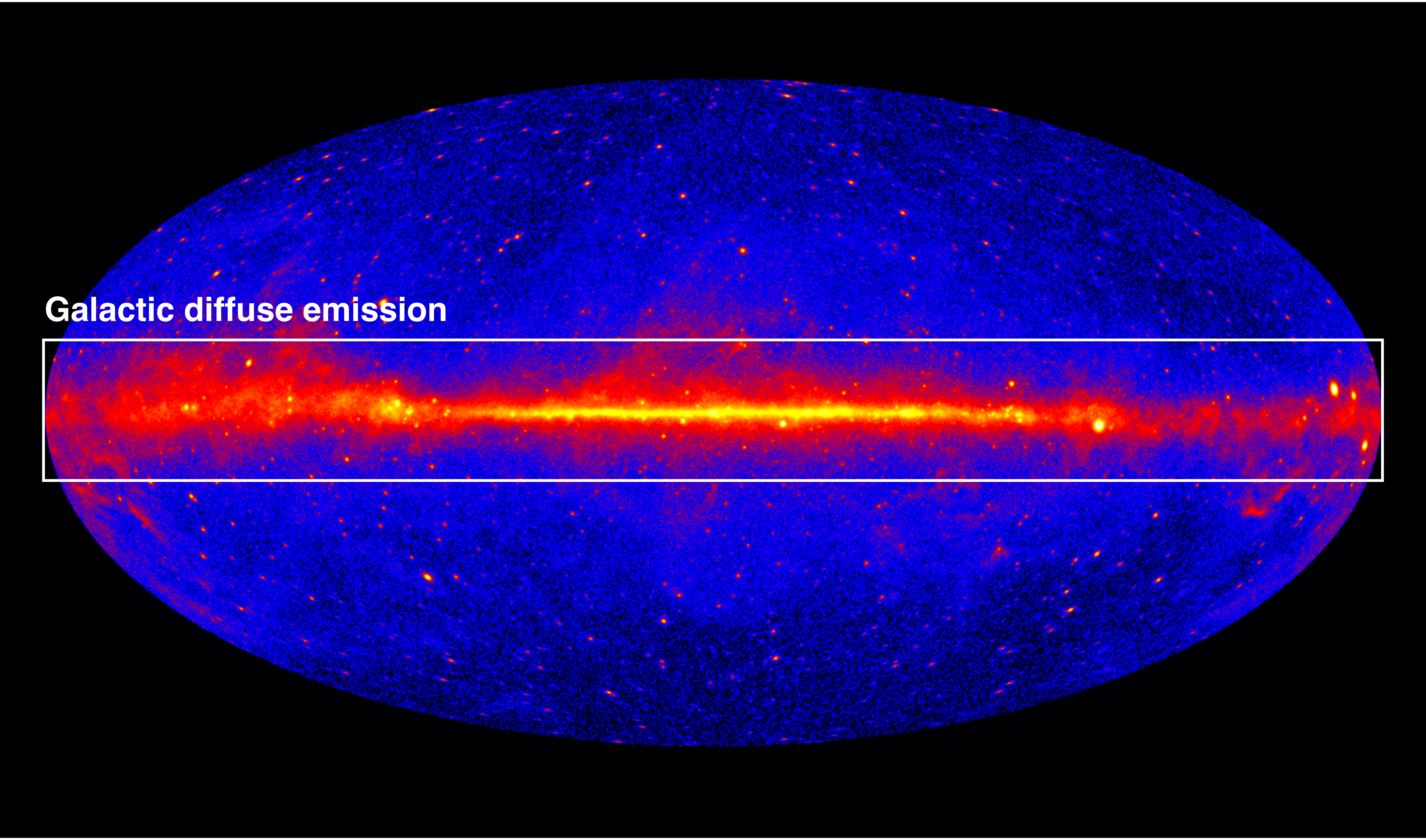




The Fermi-LAT gamma-ray sky



Astrophysical components:
The Galactic diffuse emission



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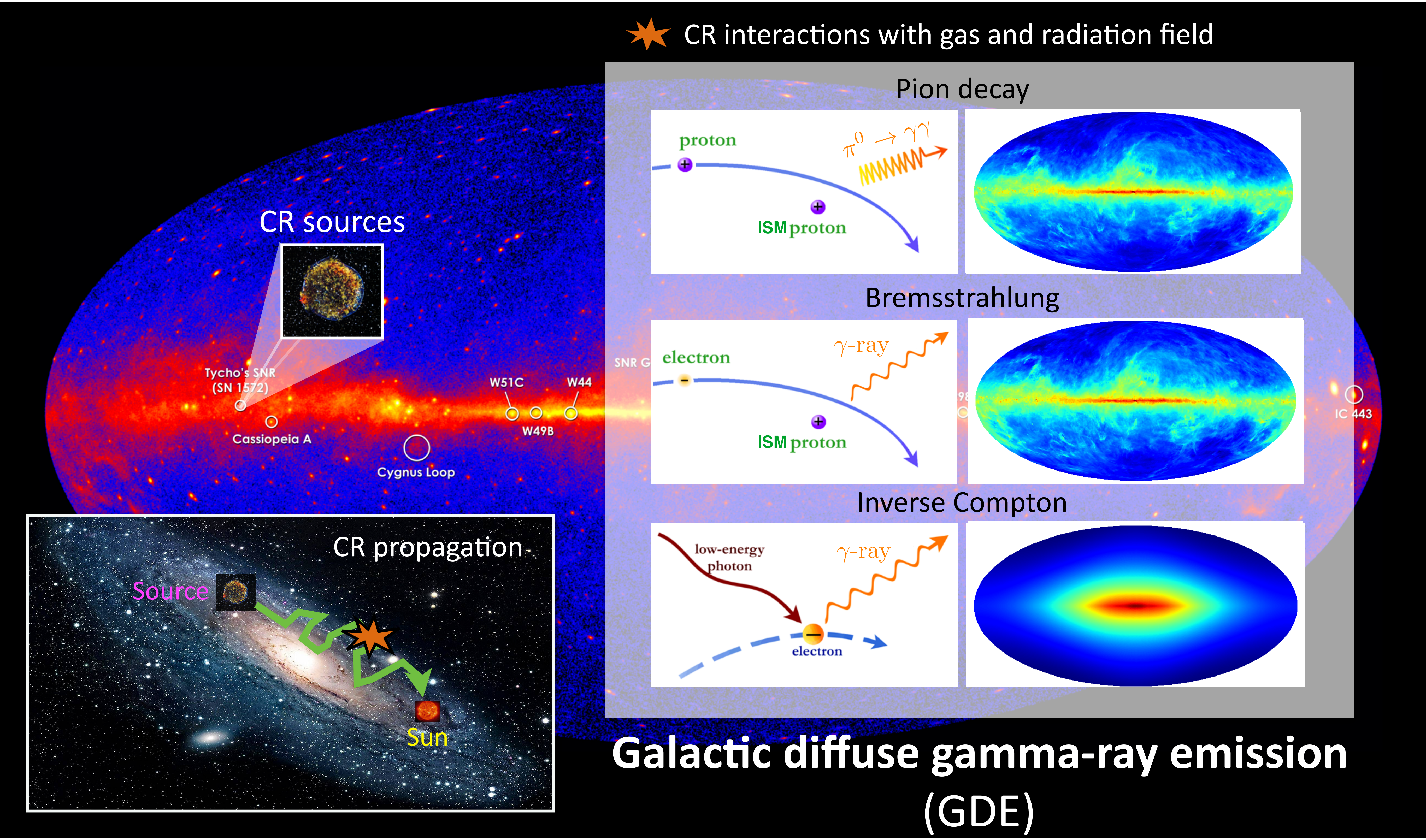
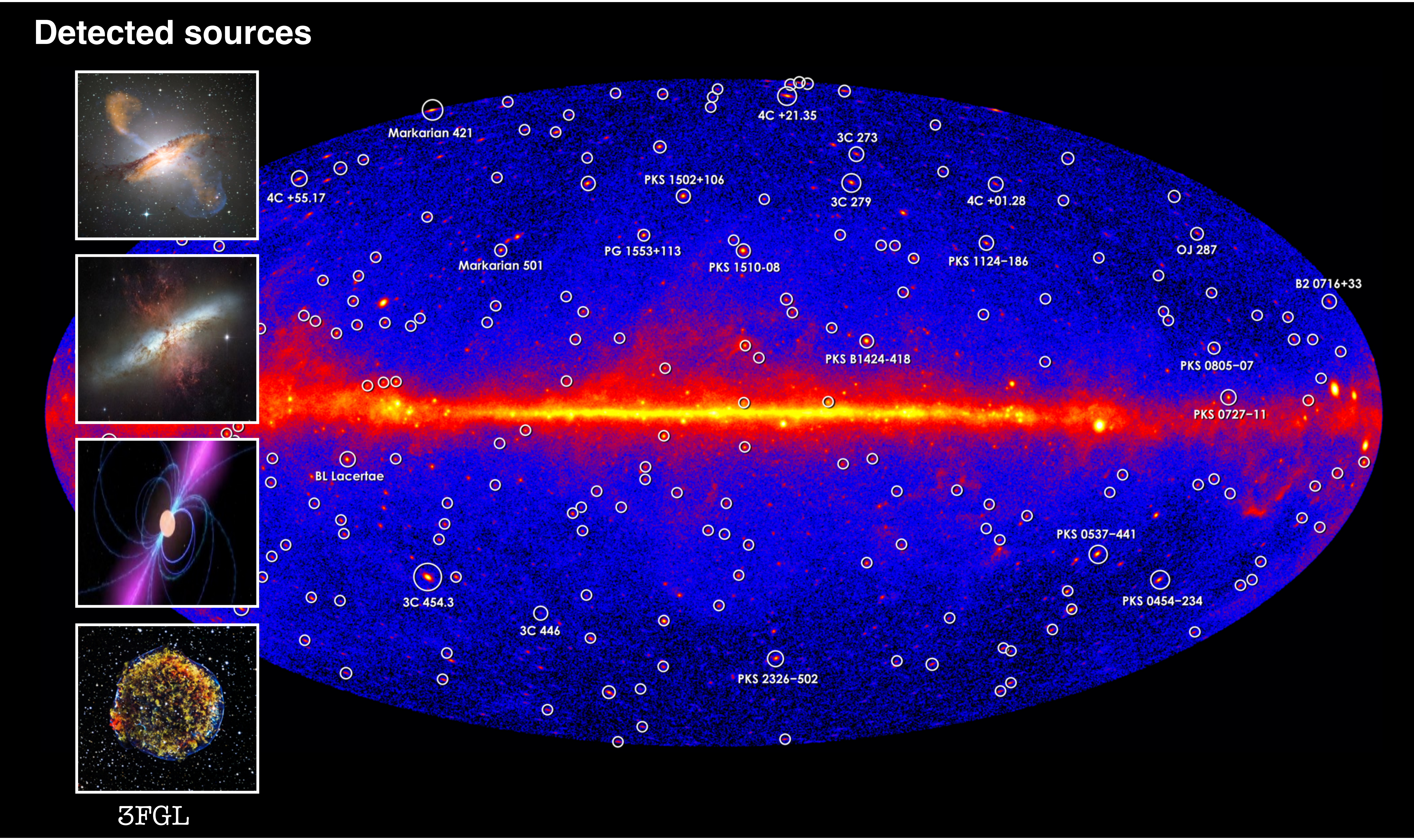


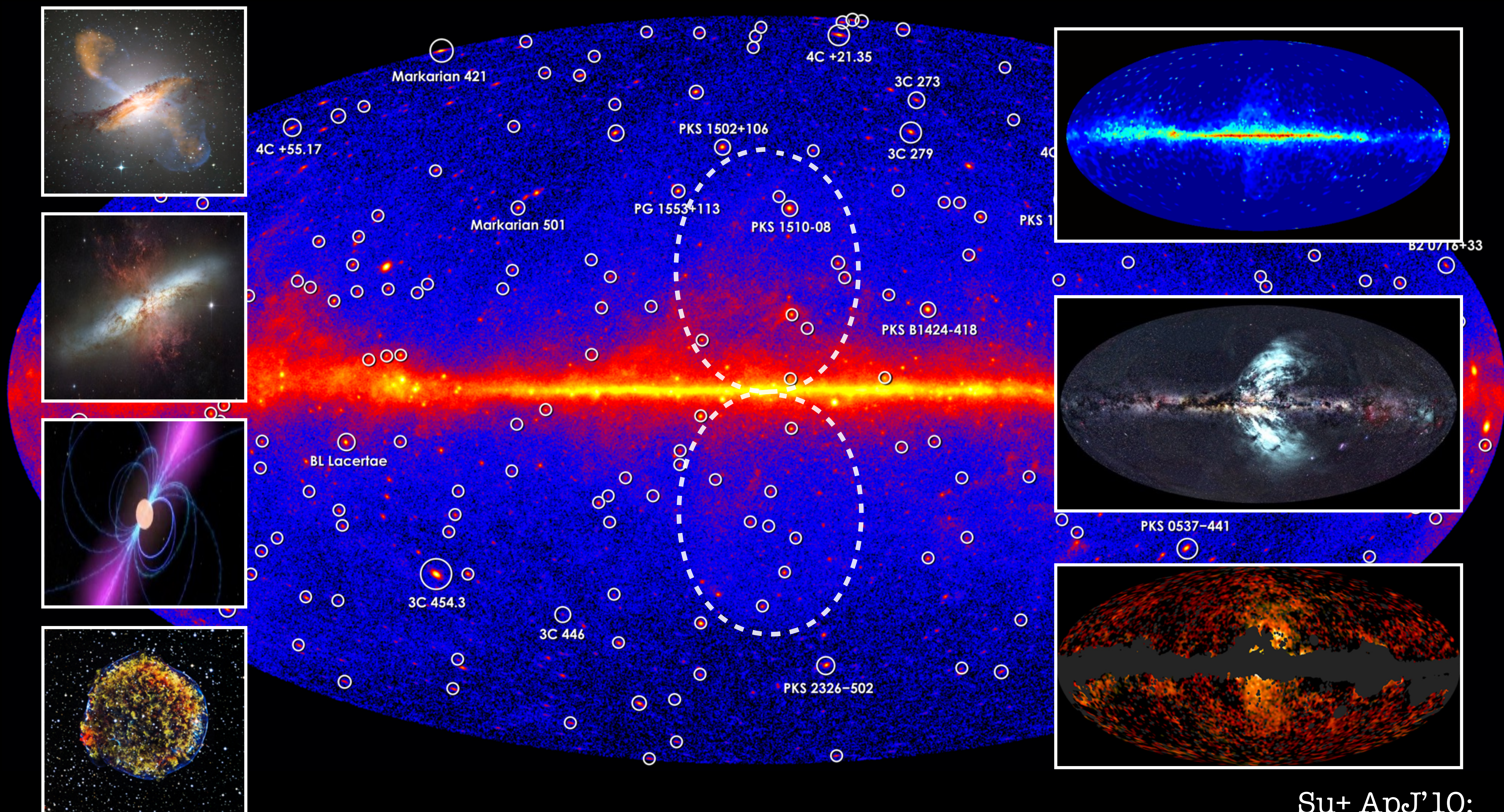
Astrophysical components:
Detected sources and Fermi bubbles



Astrophysical components: Detected sources and Fermi bubbles

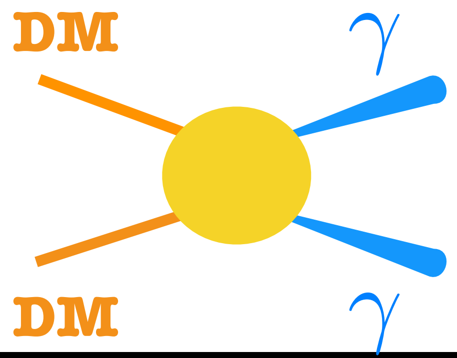
Detected sources

Fermi bubbles

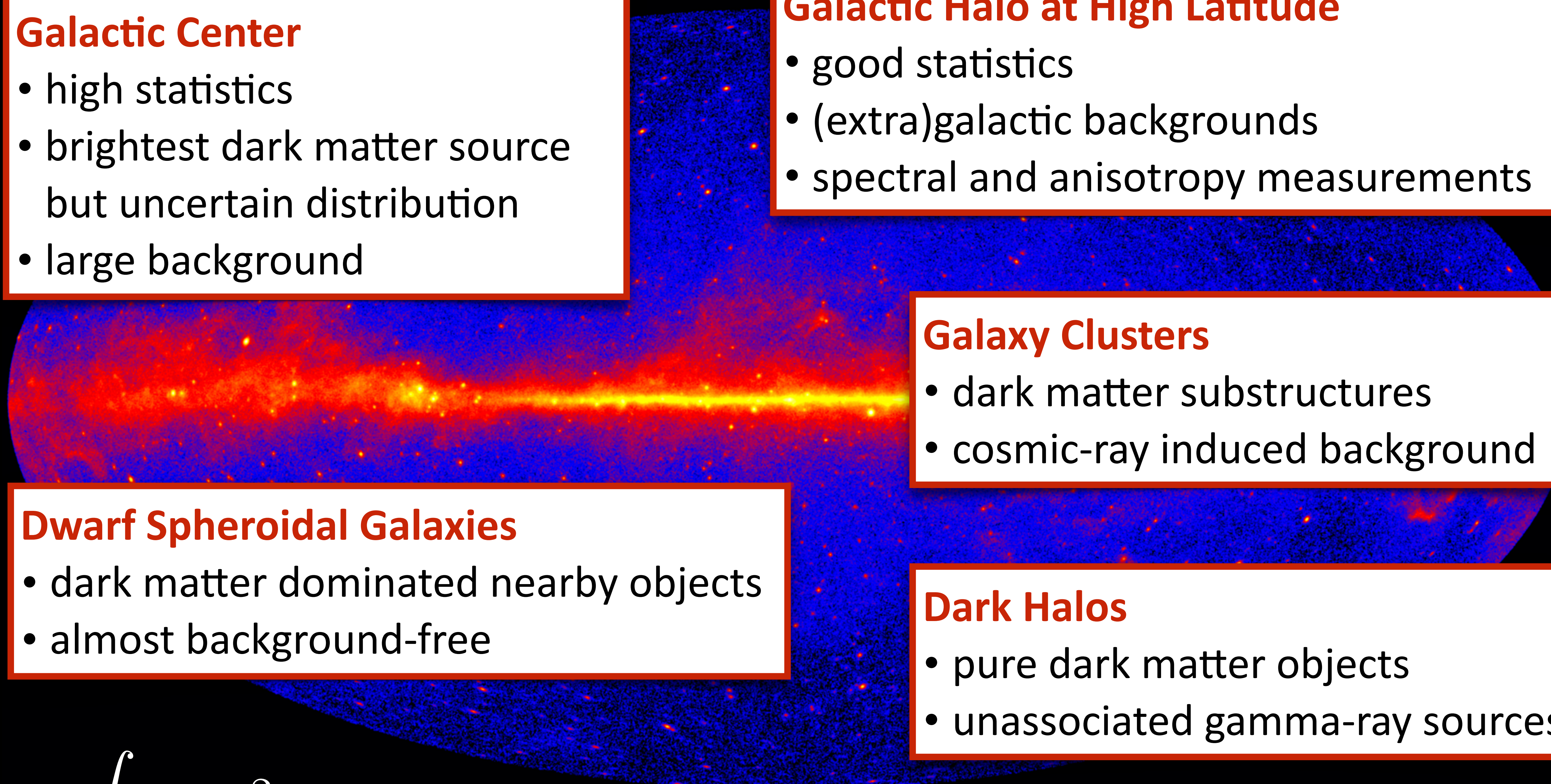


3FGL

Su+ ApJ'10;
Fermi-LAT Coll. ApJ'14



Targets for dark matter searches



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

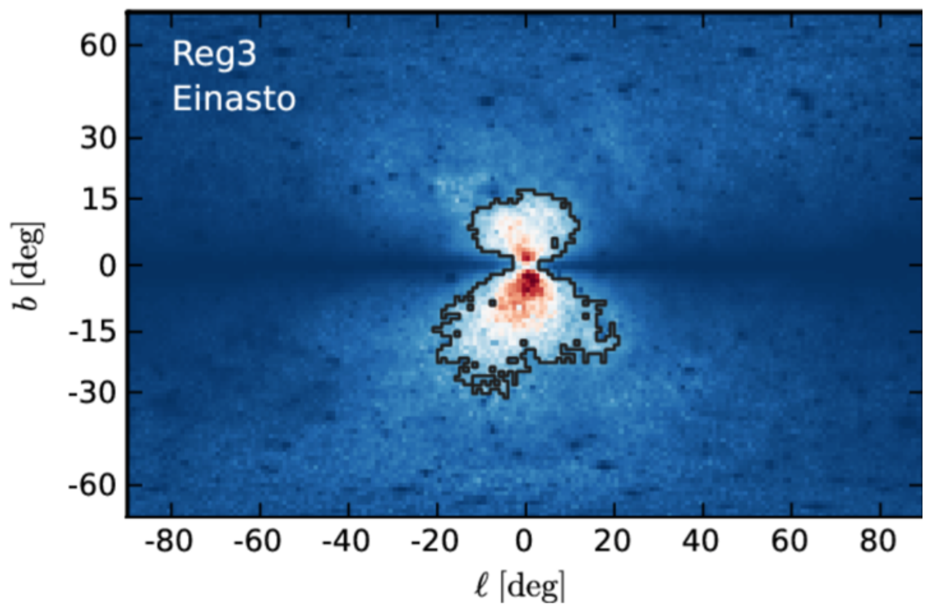
Dark Halos
- pure dark matter objects
- unassociated gamma-ray sources

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

+ dedicated searches for gamma-ray lines

Searching for gamma-ray lines

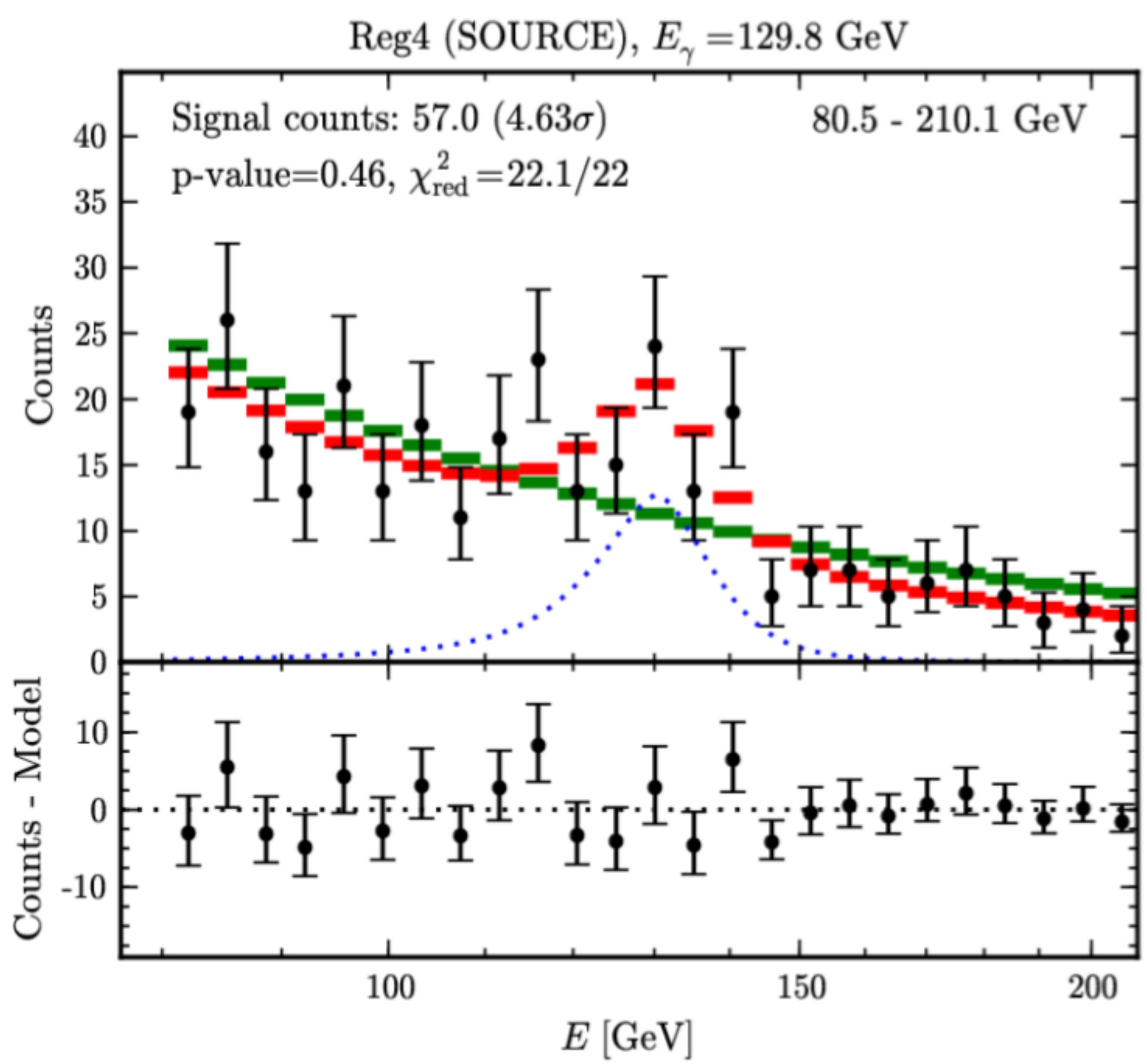
Gamma-ray line searches



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

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

Signal/Noise ratio



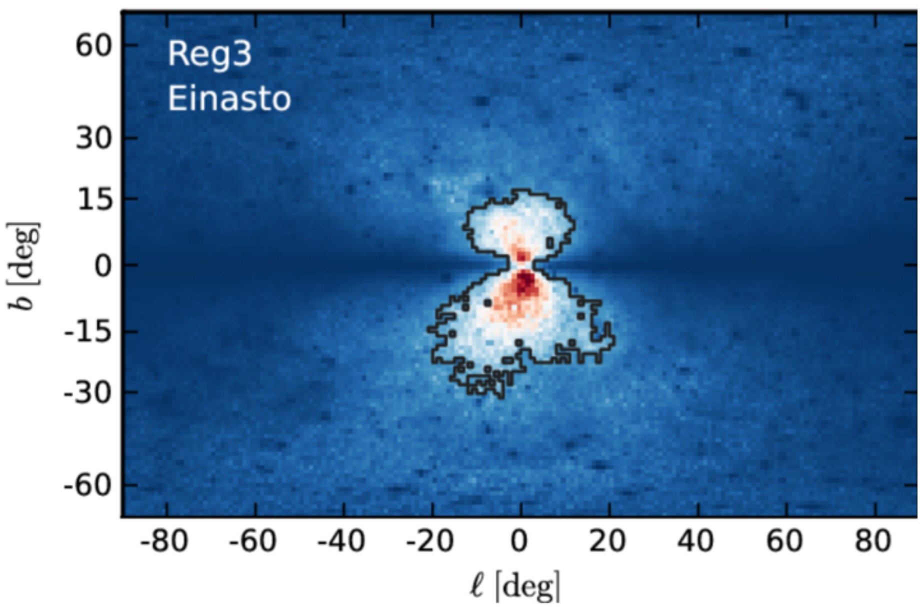
A gamma-ray line signal at 130 GeV?

Bringmann+ JCAP'12
Weniger JCAP'12

43 months of SOURCE data (P7V6)
Local significance: 4.6 sigma
Global significance: 3.2 sigma

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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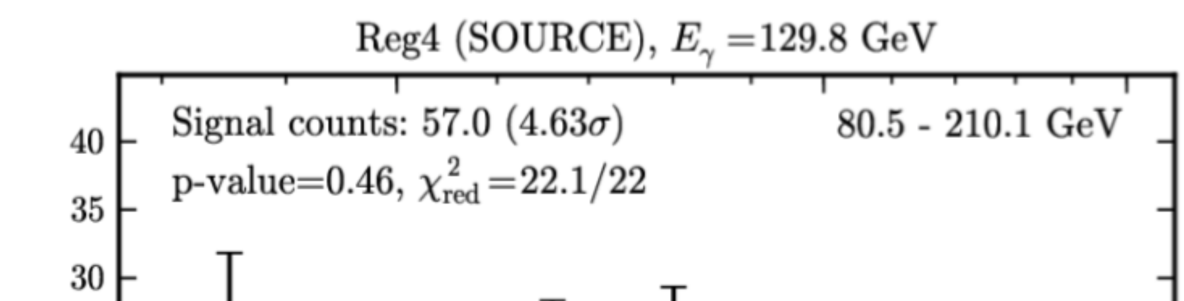

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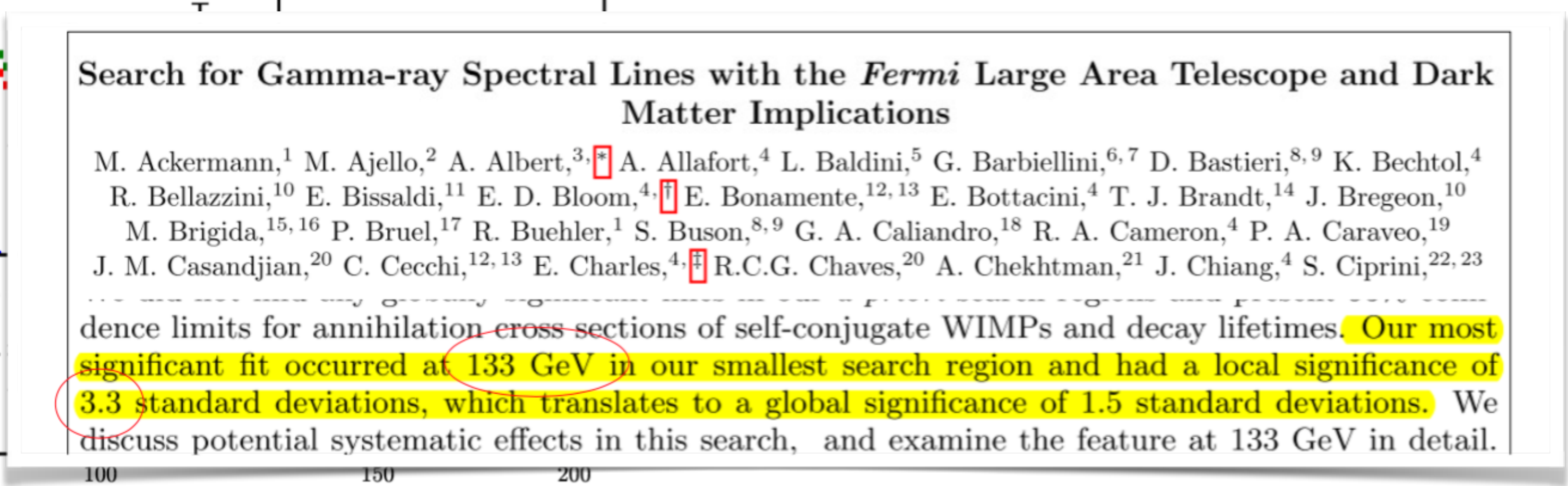
Bringmann+ JCAP'12
Weniger JCAP'12

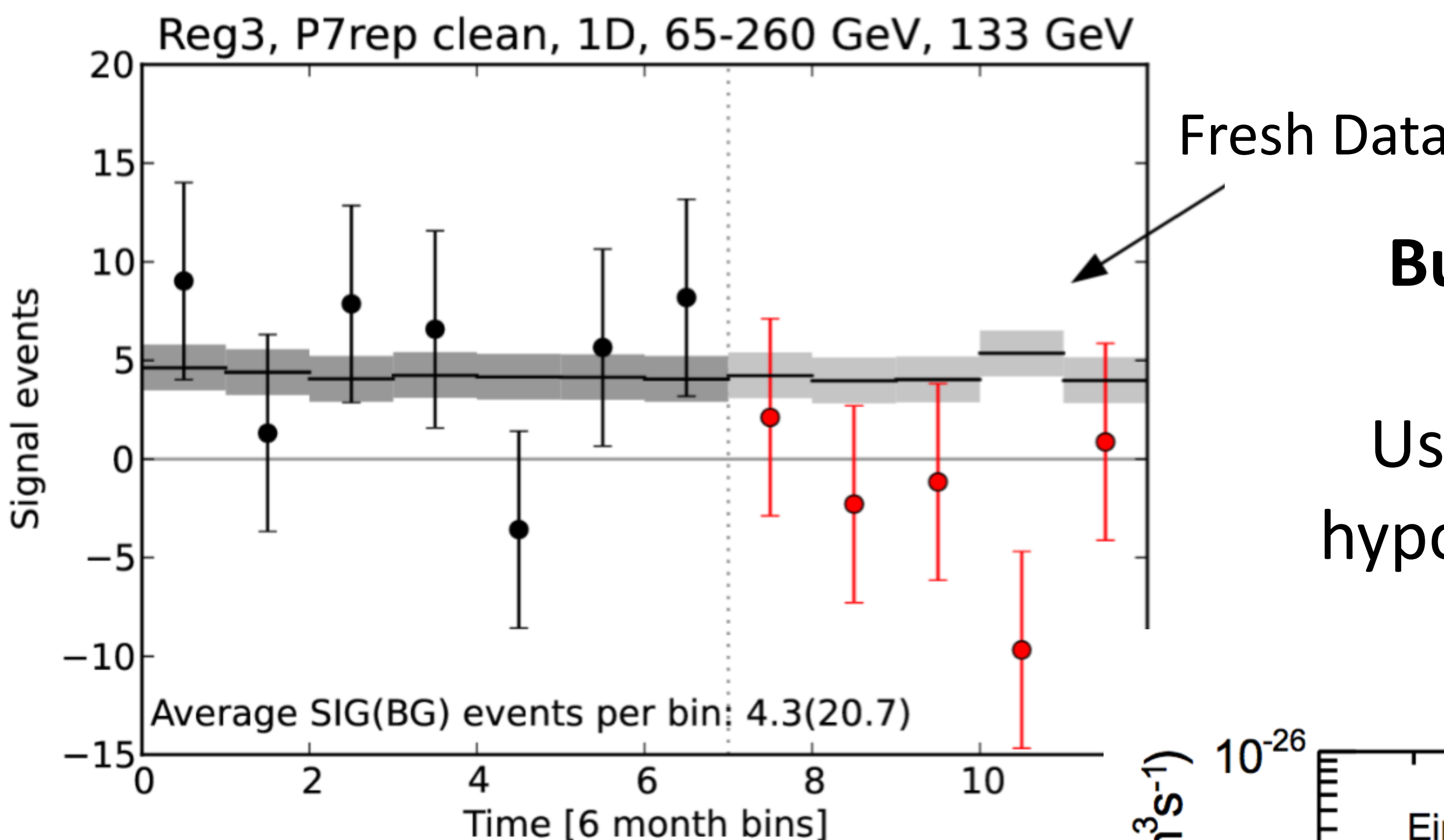


Search for Gamma-ray Spectral Lines with the *Fermi* Large Area Telescope and Dark Matter Implications

M. Ackermann,[1] M. Ajello,[2] A. Albert,[3,*] A. Allafort,[4] L. Baldini,[5] G. Barbiellini,[6,7] D. Bastieri,[8,9] K. Bechtol,[4] R. Bellazzini,[10] E. Bissaldi,[11] E. D. Bloom,[4,†] E. Bonamente,[12,13] E. Bottacini,[4] T. J. Brandt,[14] J. Bregeon,[10] M. Brigida,[15,16] P. Bruel,[17] R. Buehler,[1] S. Buson,[8,9] G. A. Caliandro,[18] R. A. Cameron,[4] P. A. Caraveo,[19] J. M. Casandjian,[20] C. Cecchi,[12,13] E. Charles,[4,‡] R.C.G. Chaves,[20] A. Chekhtman,[21] J. Chiang,[4] S. Ciprini,[22,23]

dence limits for annihilation cross sections of self-conjugate WIMPs and decay lifetimes. Our most significant fit occurred at 133 GeV in our smallest search region and had a local significance of 3.3 standard deviations, which translates to a global significance of 1.5 standard deviations. We discuss potential systematic effects in this search, and examine the feature at 133 GeV in detail.

Gamma-ray line searches

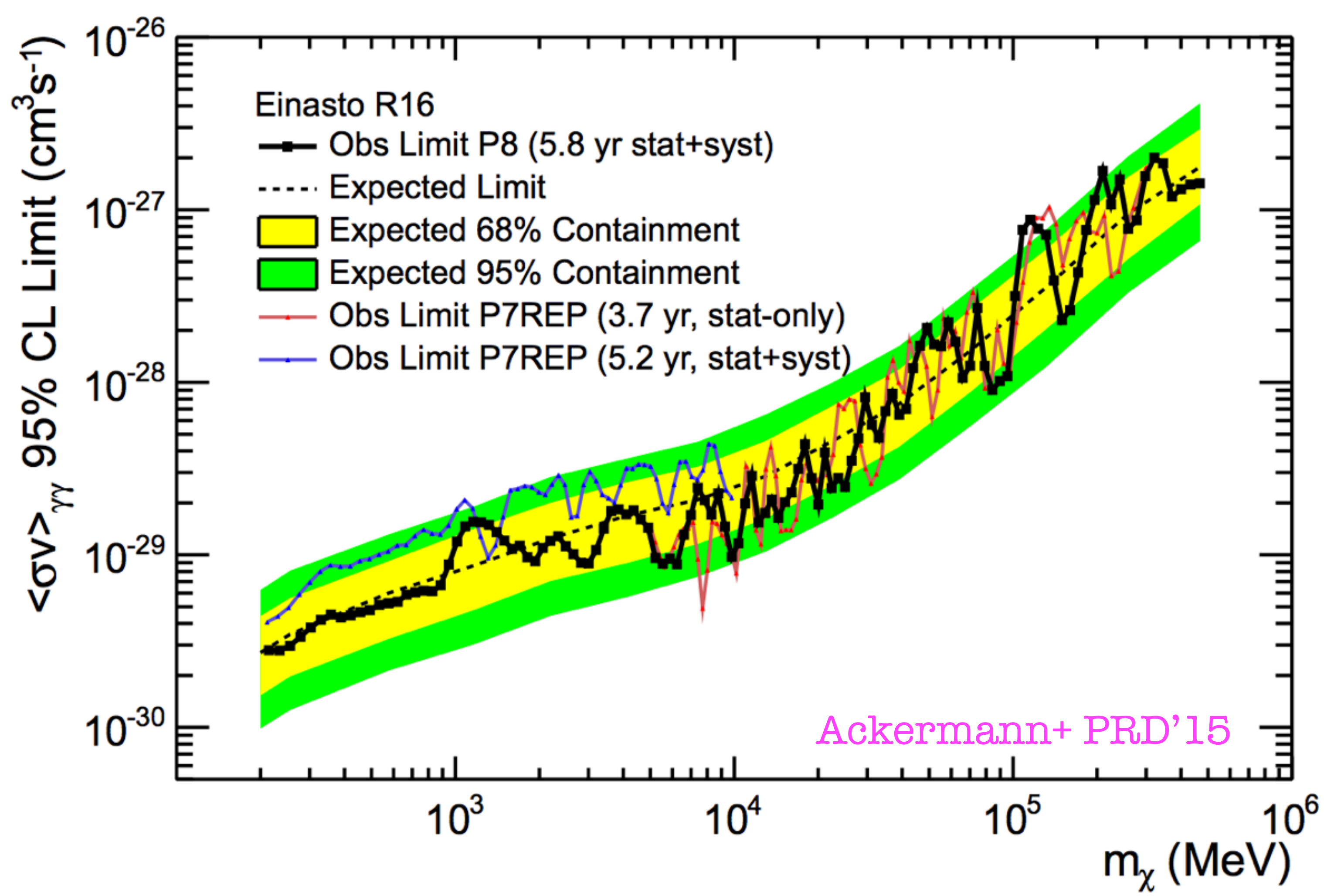


But no signal since Summer 2012!

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

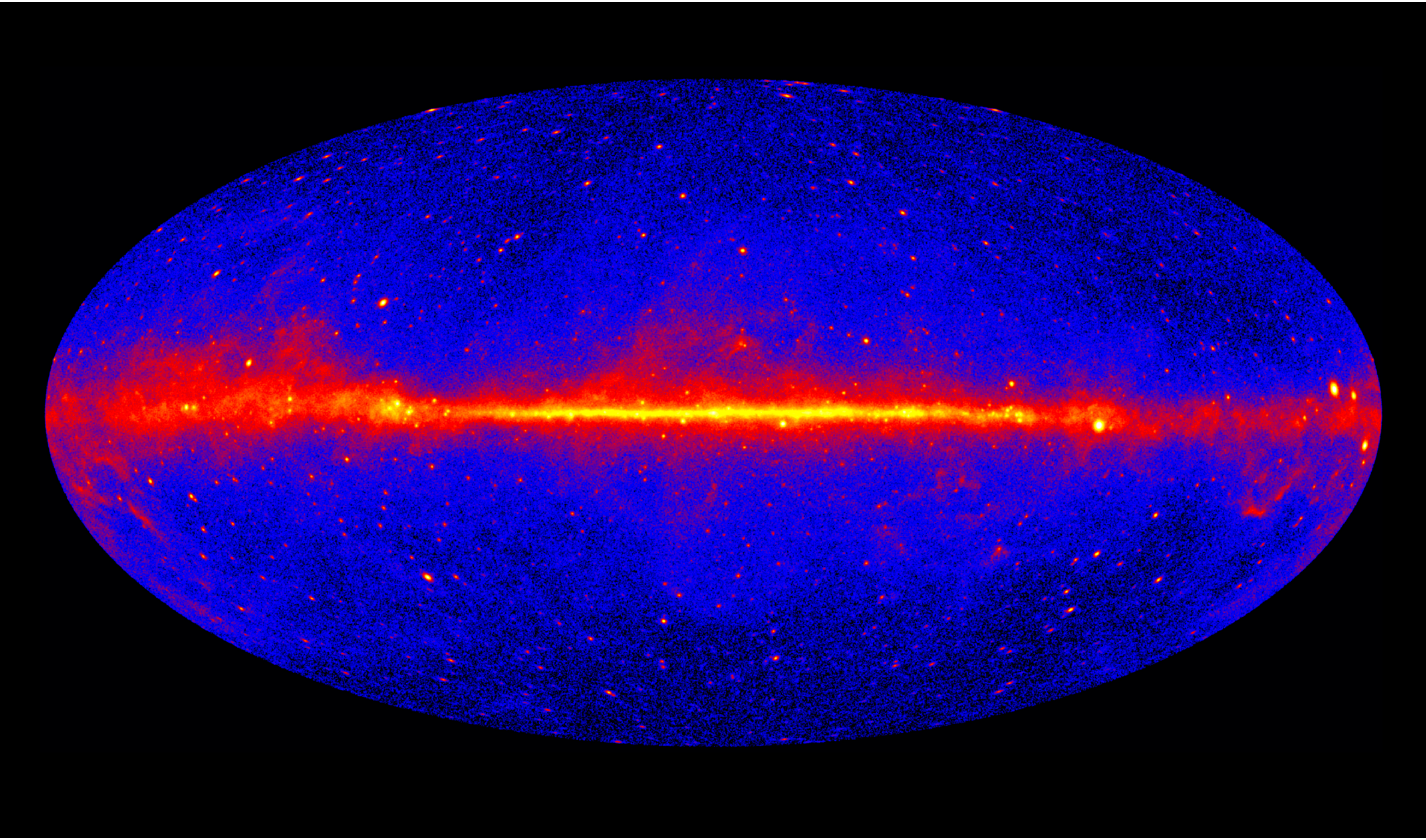
- 200MeV - 500 GeV
- 5.8 years of data
- 5 optimised sky regions

—> Local significance: 0.72 sigma



Searching for dark matter in the inner Galaxy

The low-latitude Fermi-LAT gamma-ray sky



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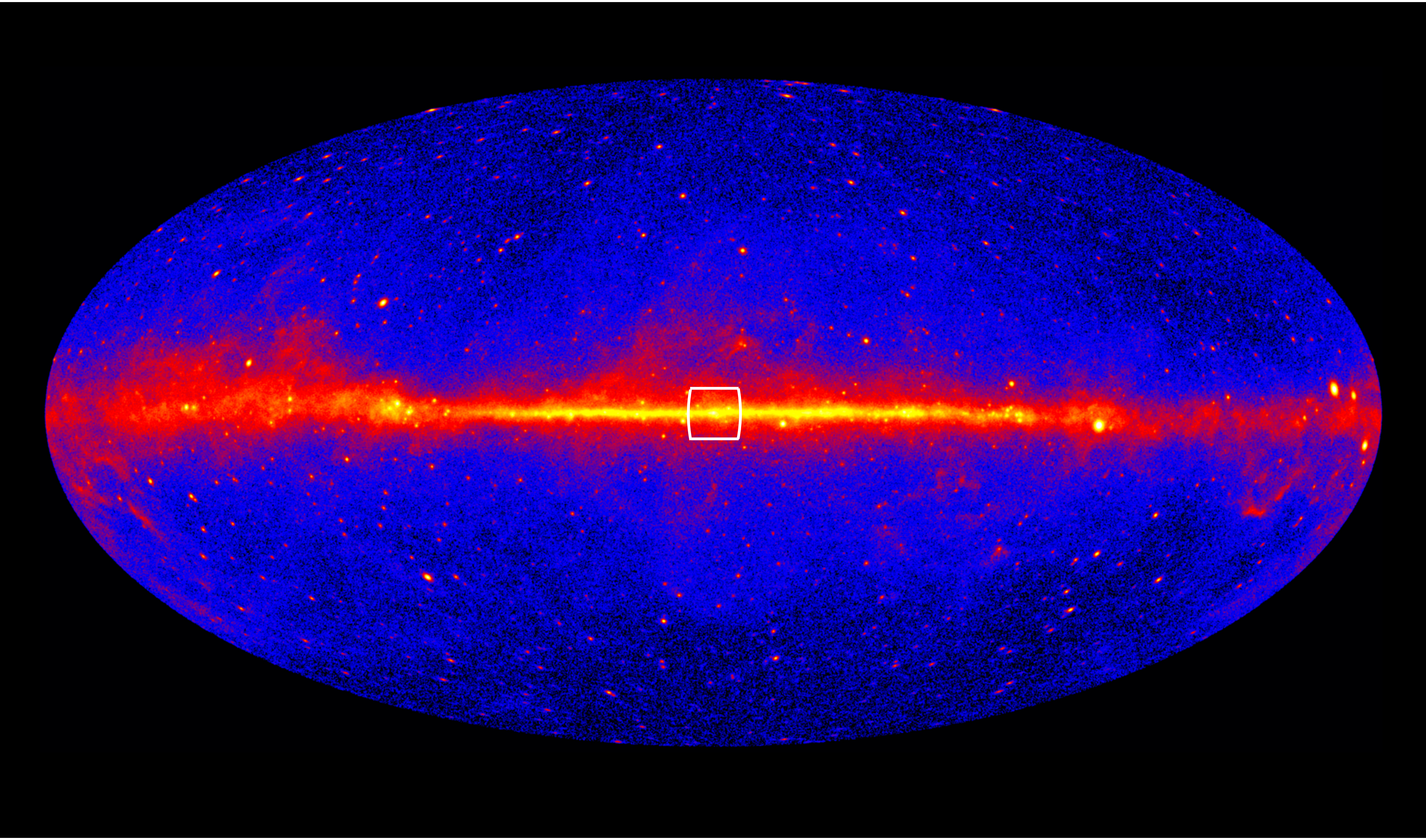
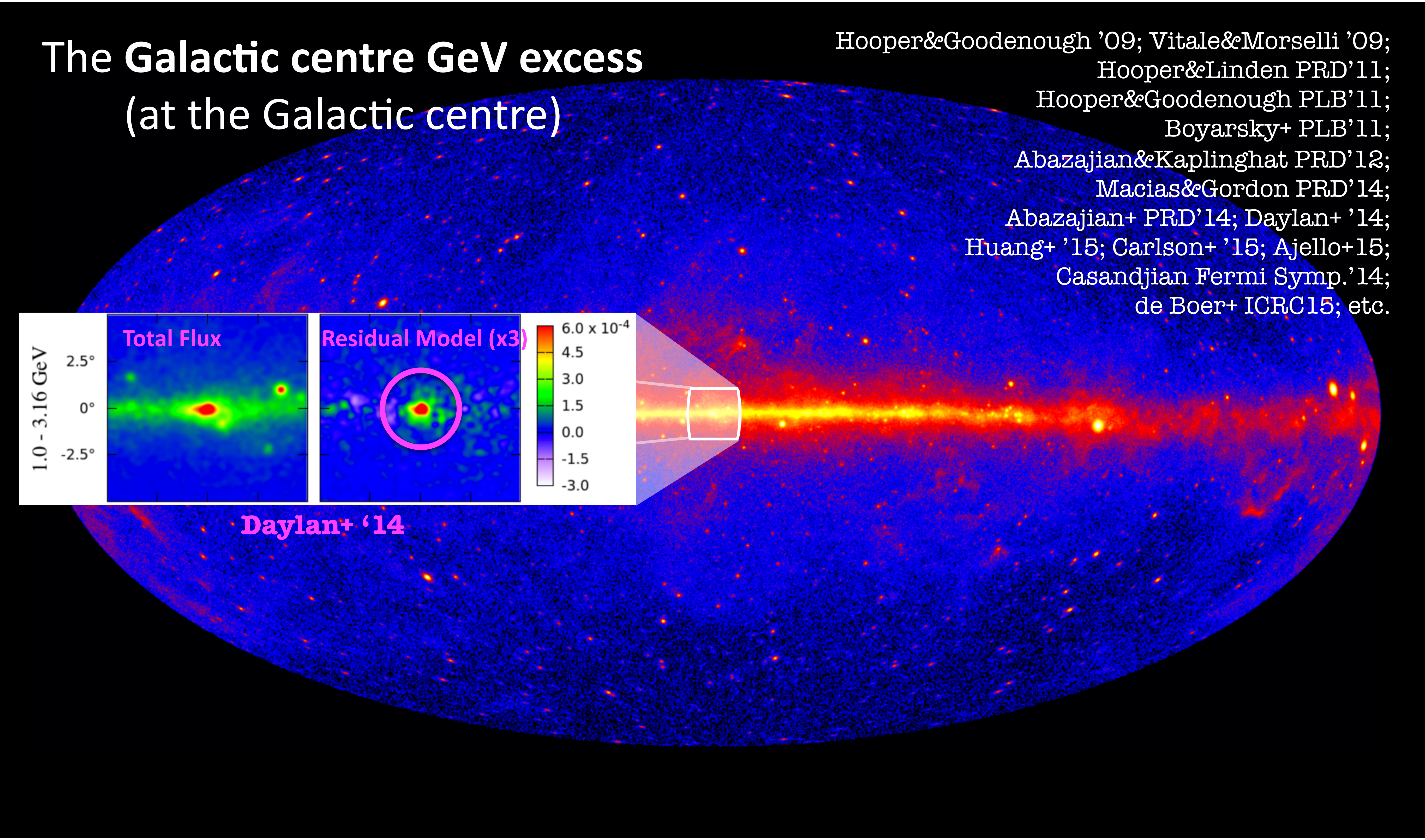
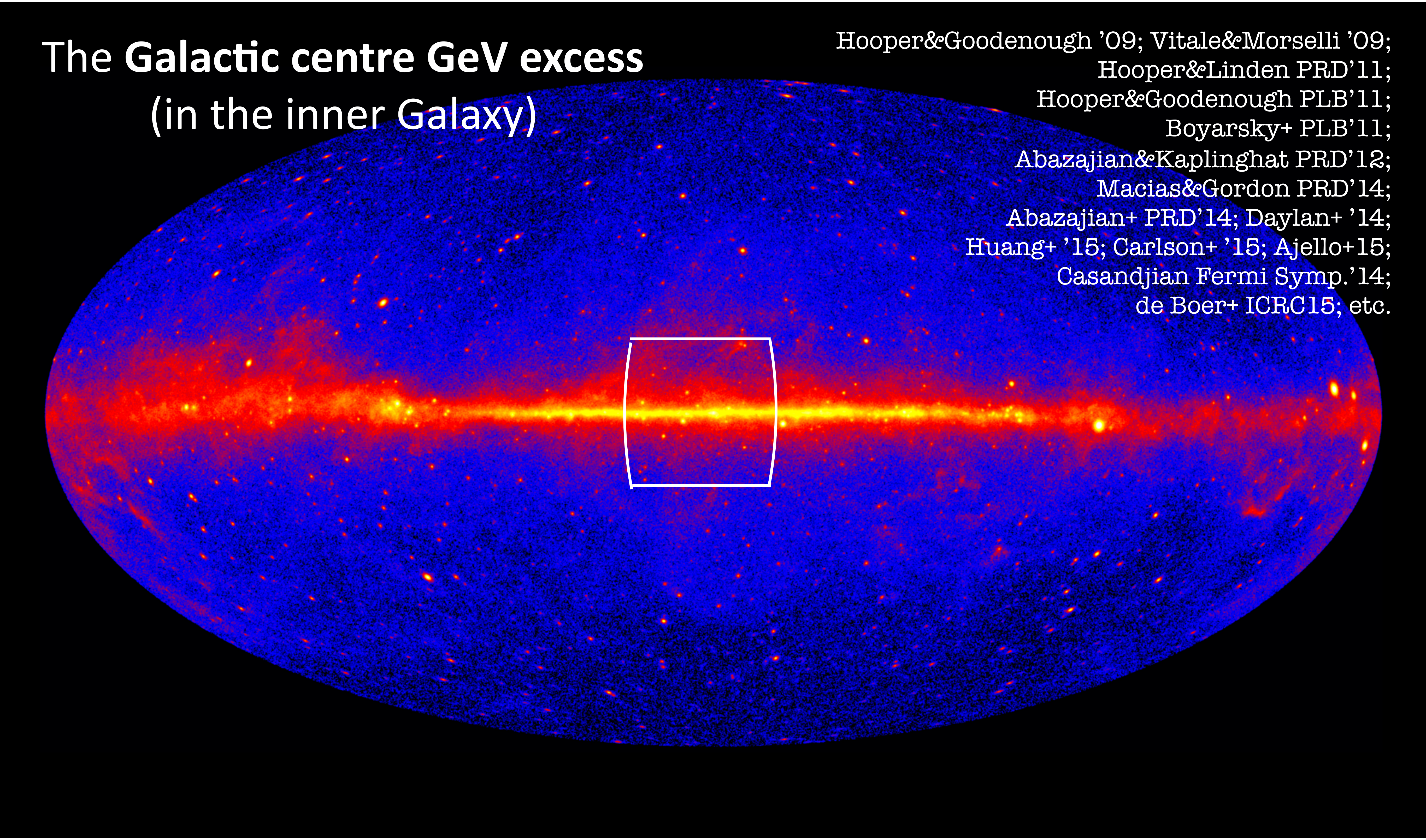


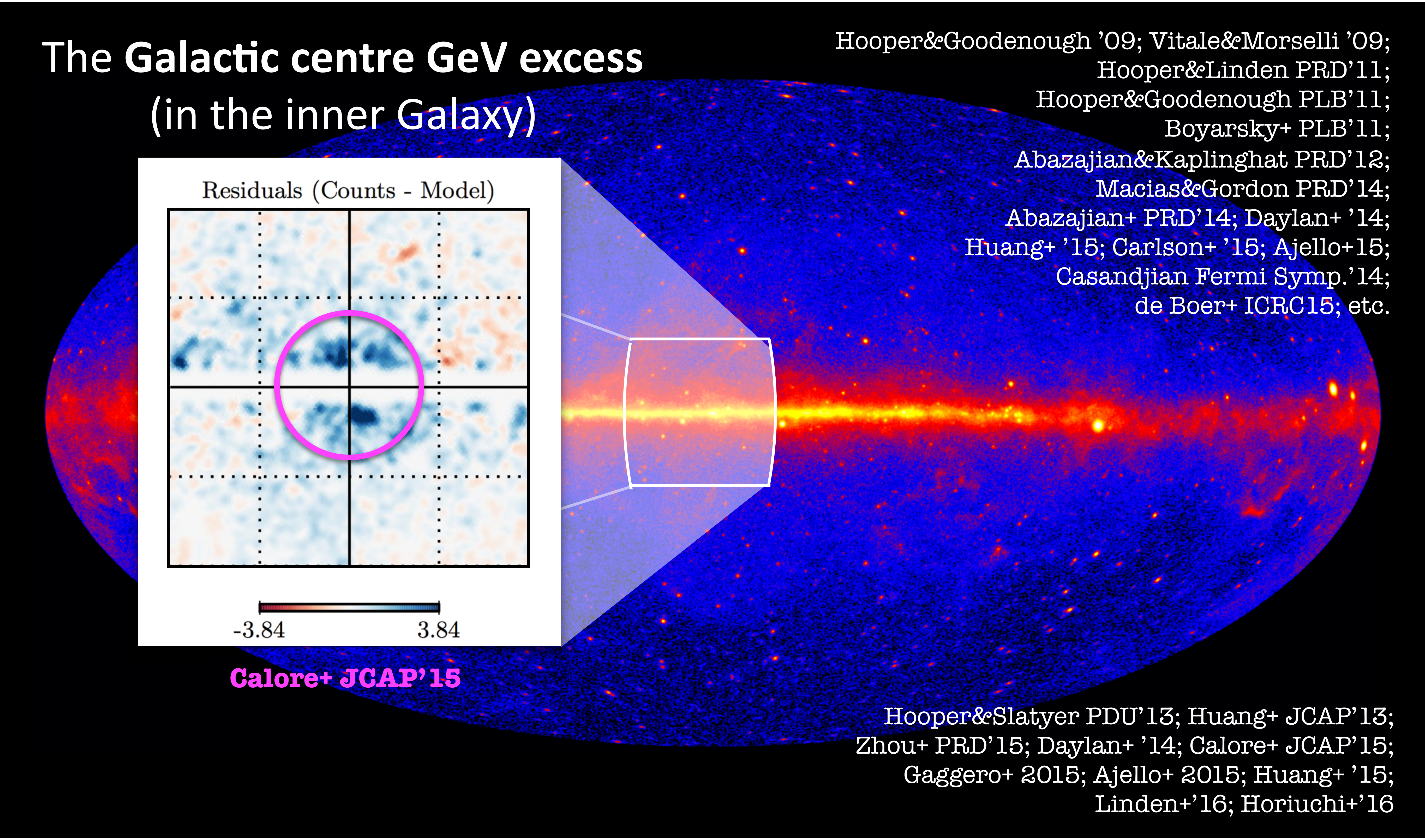
The low-latitude Fermi-LAT gamma-ray sky



The low-latitude Fermi-LAT gamma-ray sky

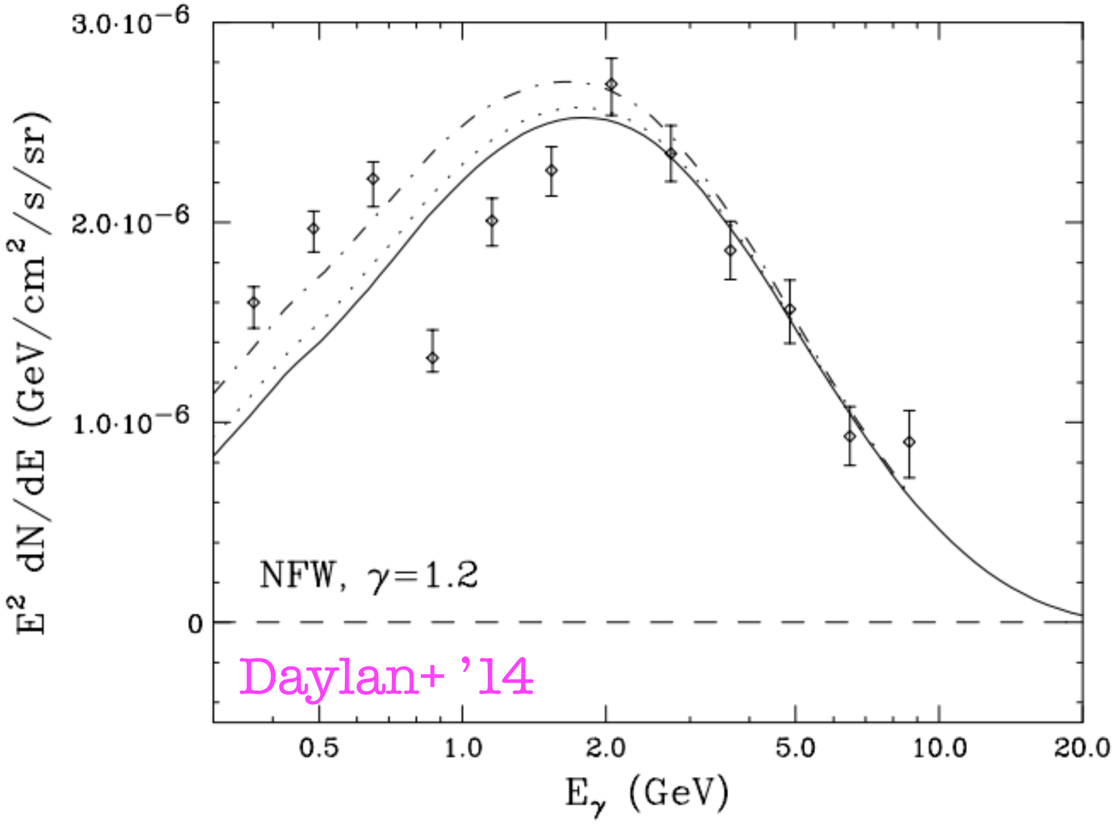


The low-latitude Fermi-LAT gamma-ray sky

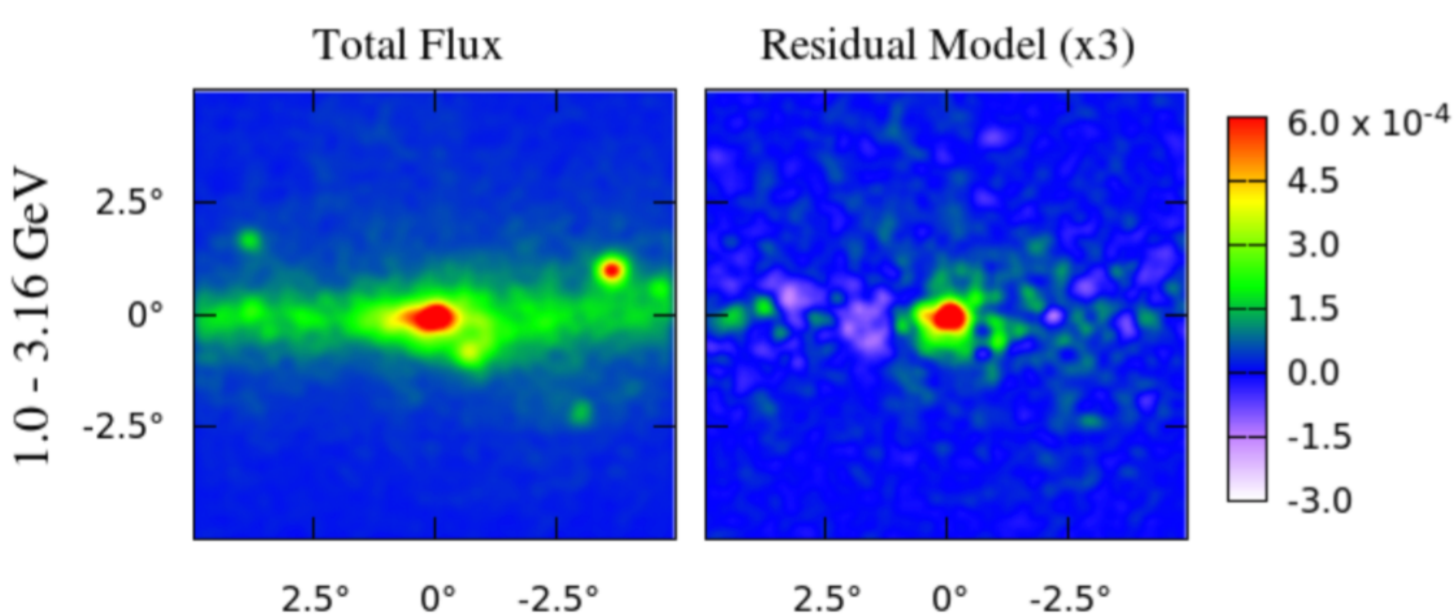


The GeV excess at the Galactic centre

Spectrum



Morphology



$$|\ell|, |b| \lesssim 2^\circ$$

- ✓ **Extended excess emission** above: model for diffuse emission, Sgr A* and other point sources.
- ✓ The **spectrum** might strongly suffer from **background modeling**.

Abazjian+ PRD'14

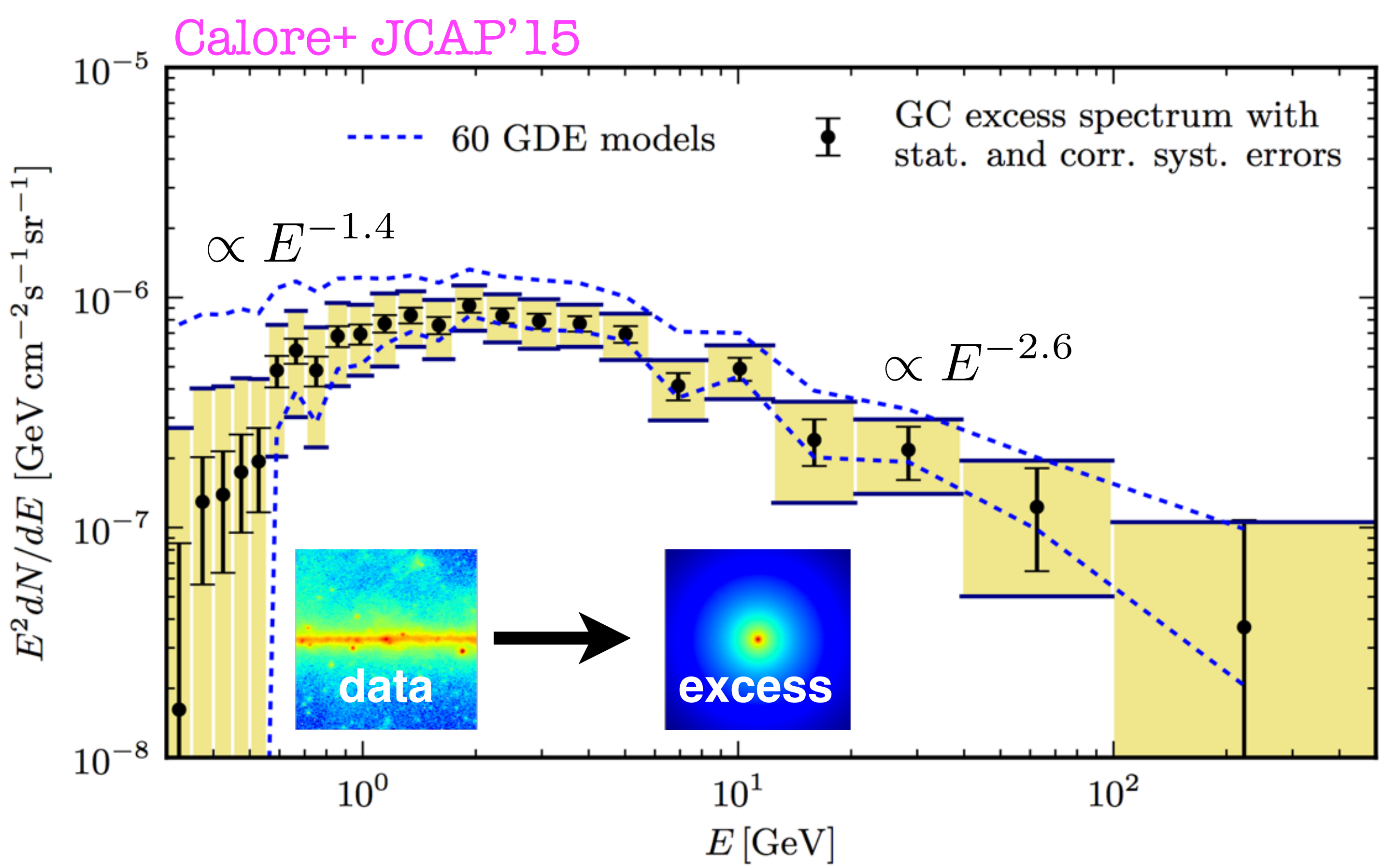
- ✓ Compatible to be **spherically symmetric** about the Galactic centre.
- ✓ Emission profile:

$$\frac{dn}{dV} \sim r^{-\Gamma} \qquad \Gamma \sim 2.6$$

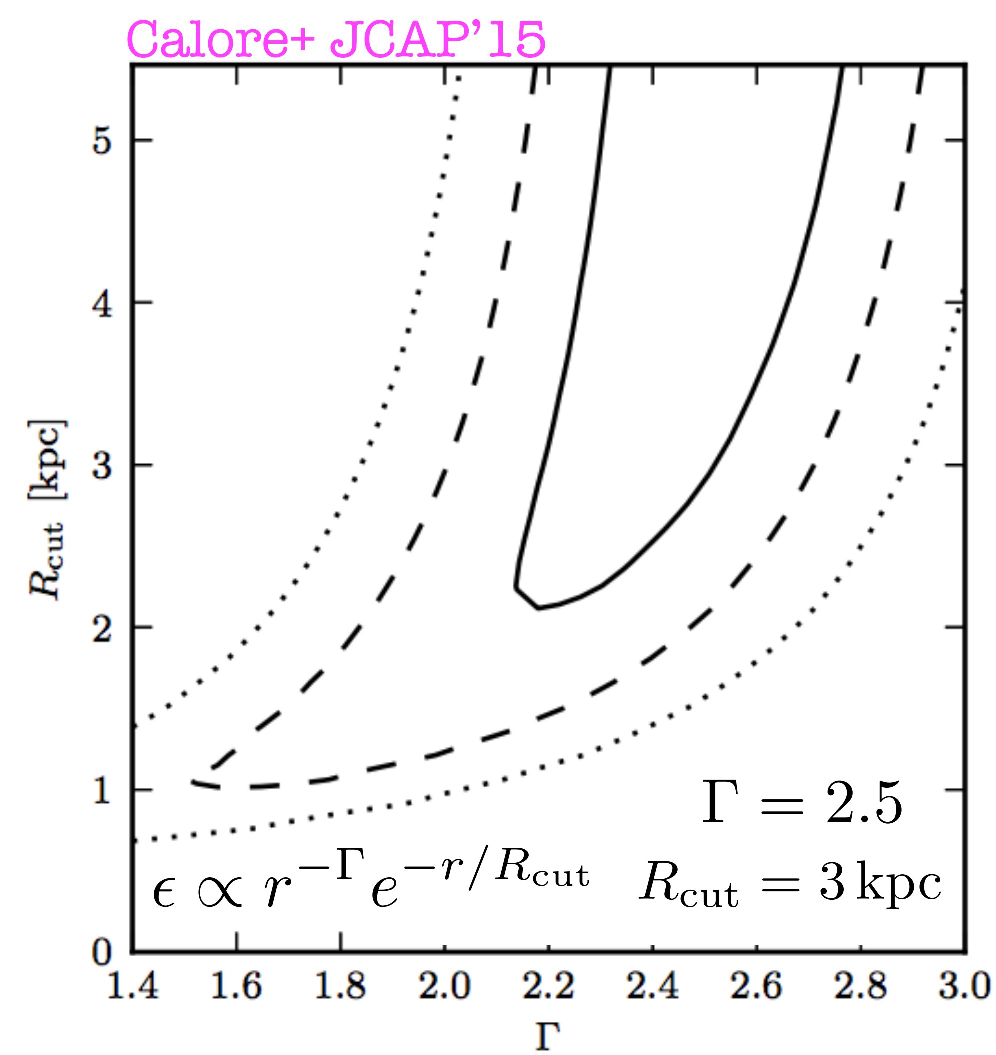
The GeV excess in the inner Galaxy

$$|\ell| \lesssim 20^\circ, \quad 2^\circ \lesssim |b| \lesssim 20^\circ$$

Spectrum



Morphology



- ✓ **Stable spectrum** against background model systematics.
- ✓ Specific spectrum, **peak @ few GeV**.

- ✓ Compatible with a spherically symmetric unique component.
- ✓ **Extended** *at least* up to **10 degrees**, 1.5 kpc

The Fermi-LAT Collaboration analysis

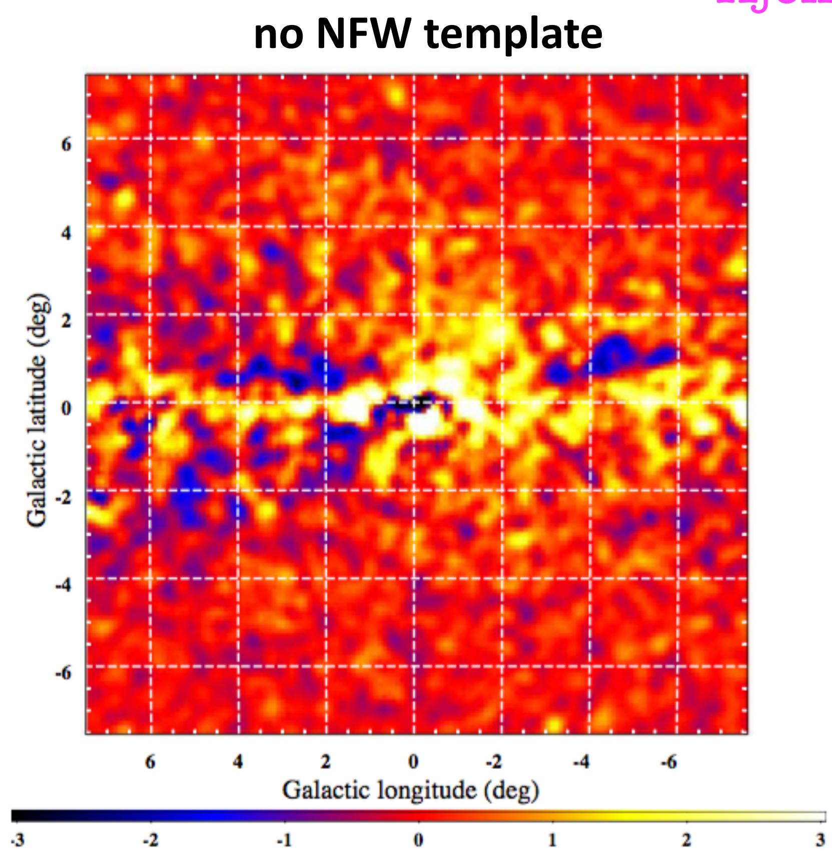
Ajello+ ’15

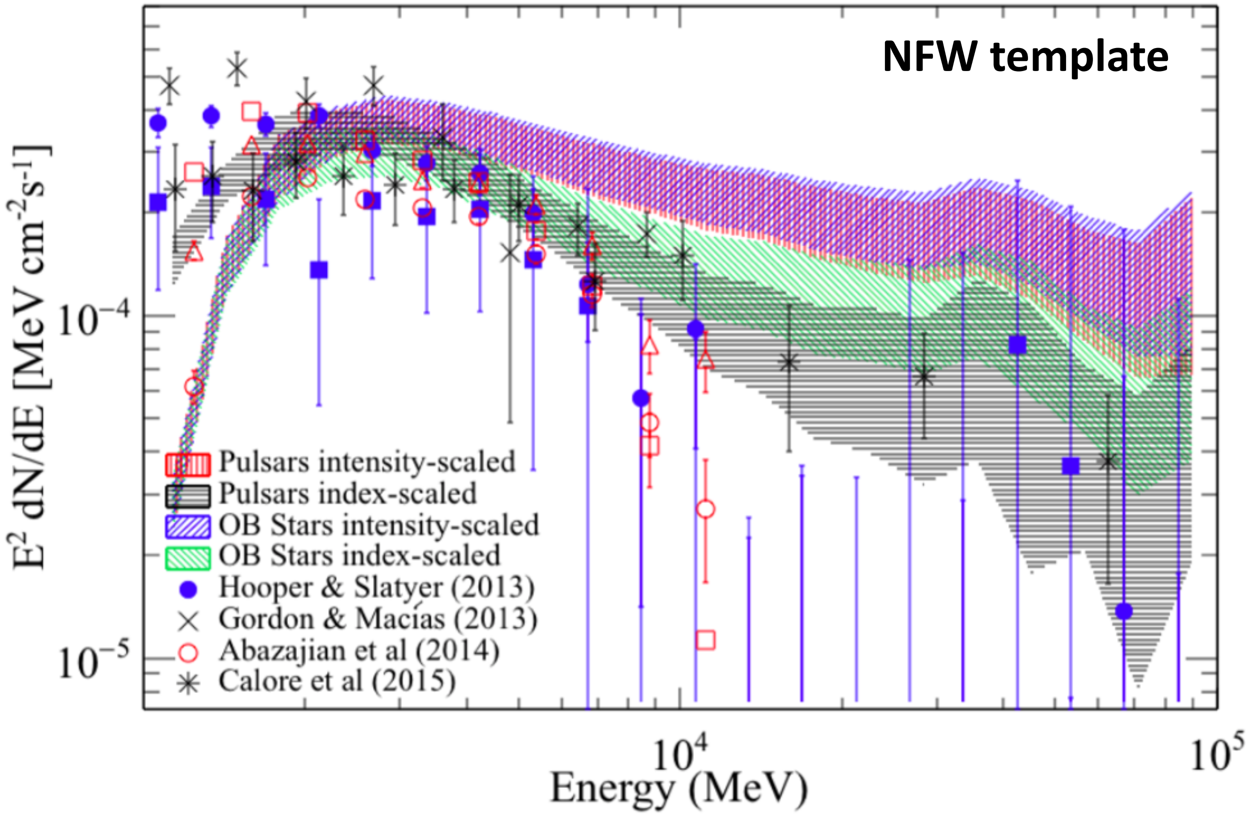
- 15° x 15° ROI; tuning of GDE outside → specialised interstellar emission models.
- Wavelet transform for source identification (1FIG catalog).

✓ **IC emission in inner 1 kpc enhanced** w.r.to baseline prediction (20% of the total GDE emission).

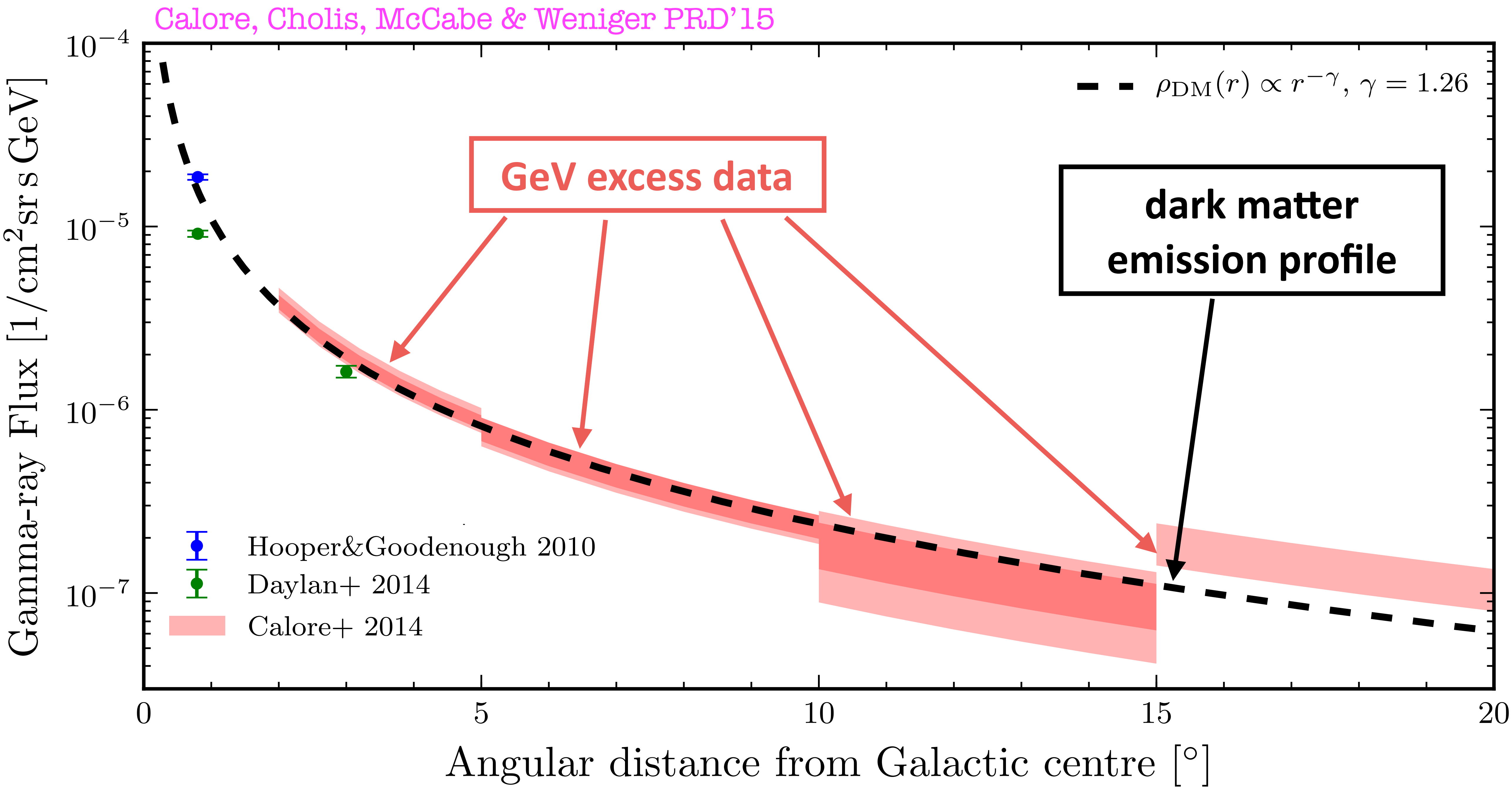
✓ Positive residuals are left and can be partially absorbed by an **additional centrally peaked spatial template**.

✓ **Not all positive residuals** are **accounted for** by such a model.





Why is the GeV excess so exciting?



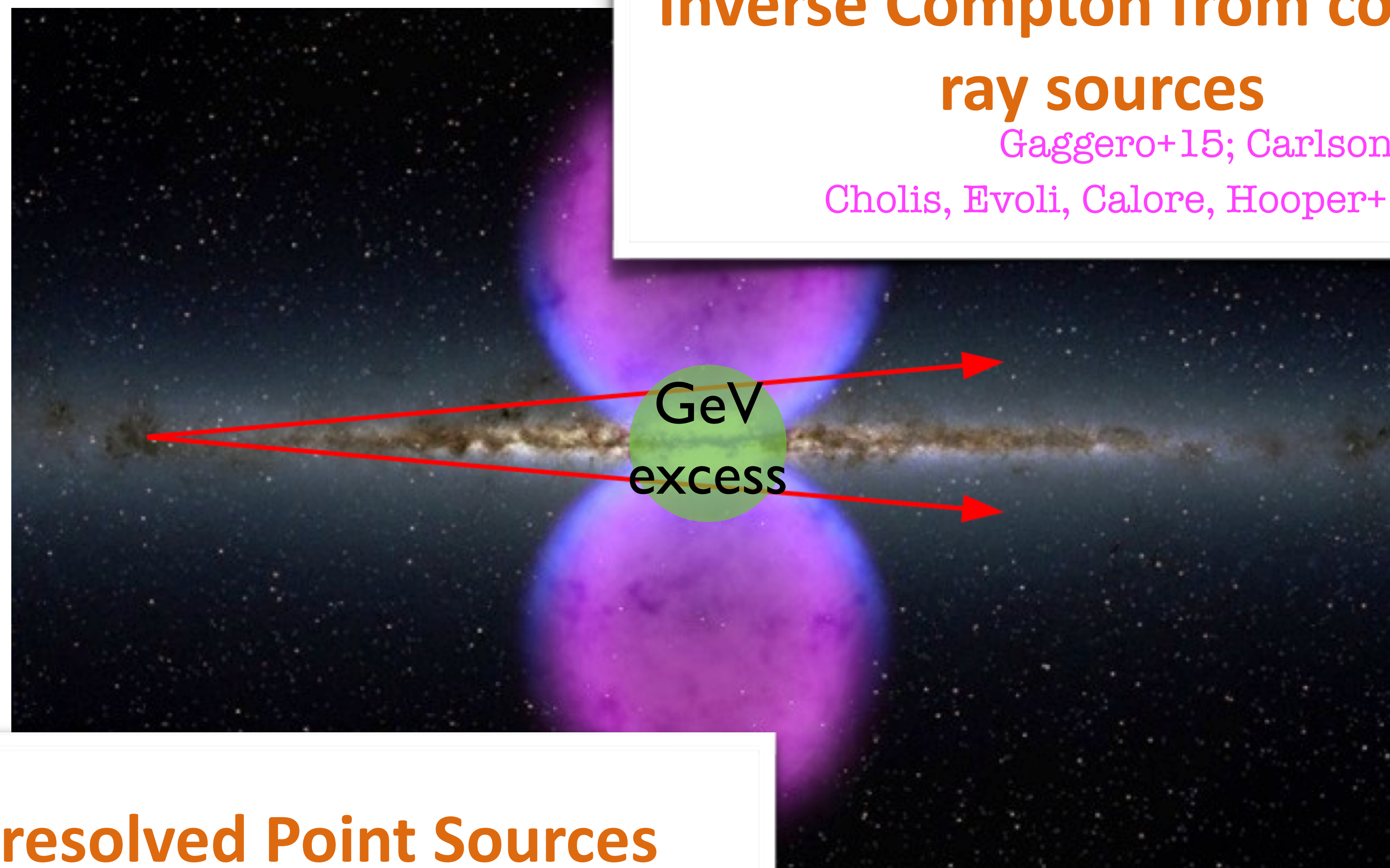
+ O(100) papers about DM interpretation

Possible astrophysical interpretations

Inverse Compton from cosmic-ray sources

Gaggero+15; Carlson+ '15; etc

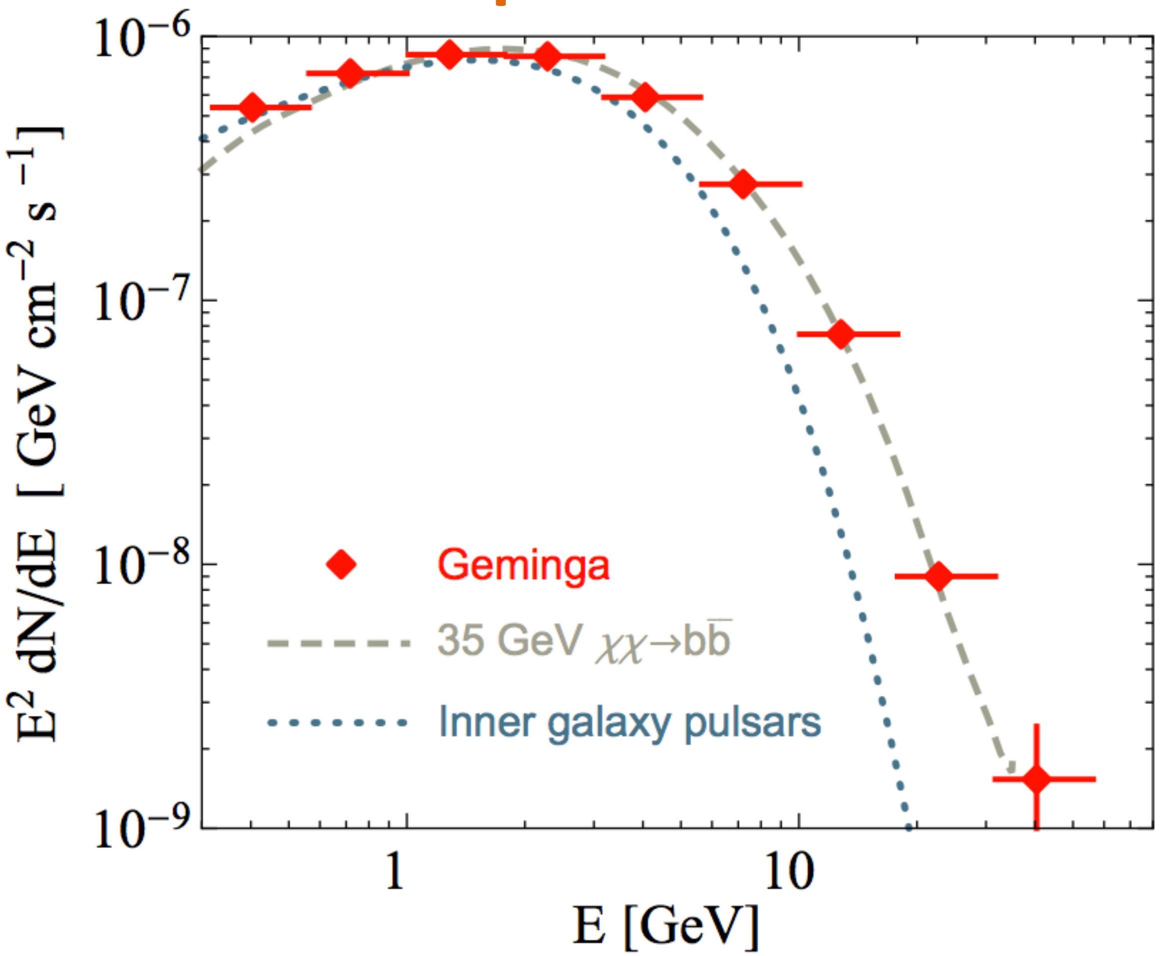
Cholis, Evoli, Calore, Hooper+ JCAP'15



Unresolved Point Sources

Unresolved pulsars and millisecond pulsars

Spectrum



- ✓ Spectrum compatible with Fermi-LAT observed **millisecond pulsars** (MSPs), and marginally **young pulsars**.

Morphology

$$\epsilon \propto r^{-\Gamma} e^{-r/R_{\rm cut}}$$

$$\Gamma = 2.5 \quad R_{\rm cut} = 3\,\rm kpc$$

- ✓ Proposed population of MSPs in the bulge (vs disk).

  Cholis+'14; Petrovic+ JCAP'15; Yuang+ MNRAS'14;

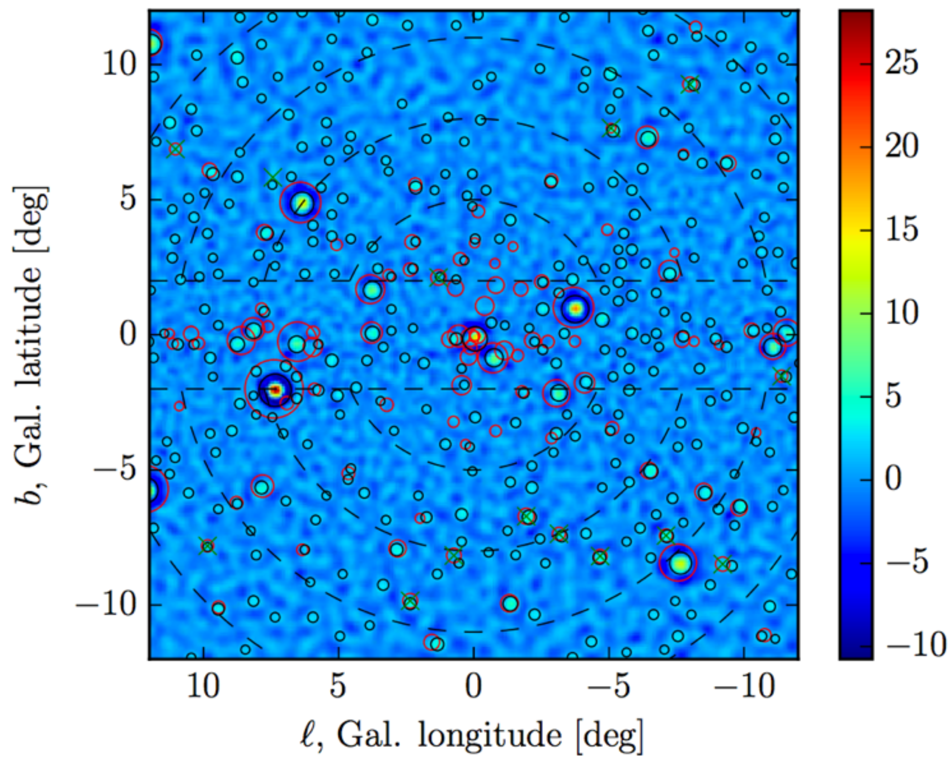
- ✓ Young pulsars from SF in the CMZ.

  O'Leary+ '15

- ✓ Bulge MSPs: from tidally disrupted globular clusters. Brandt&Kocsis'15

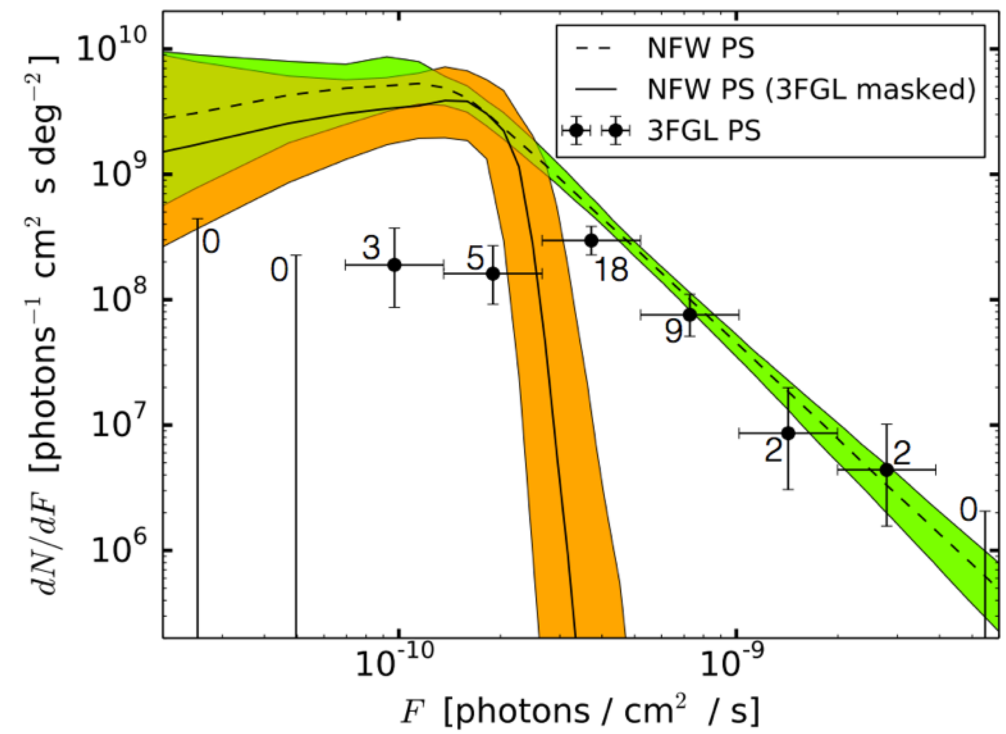
Support for MSPs interpretation

Bartels+ 15



Local maxima of normalised wavelet transform

Lee+'15



Non-Poissonian template fitting

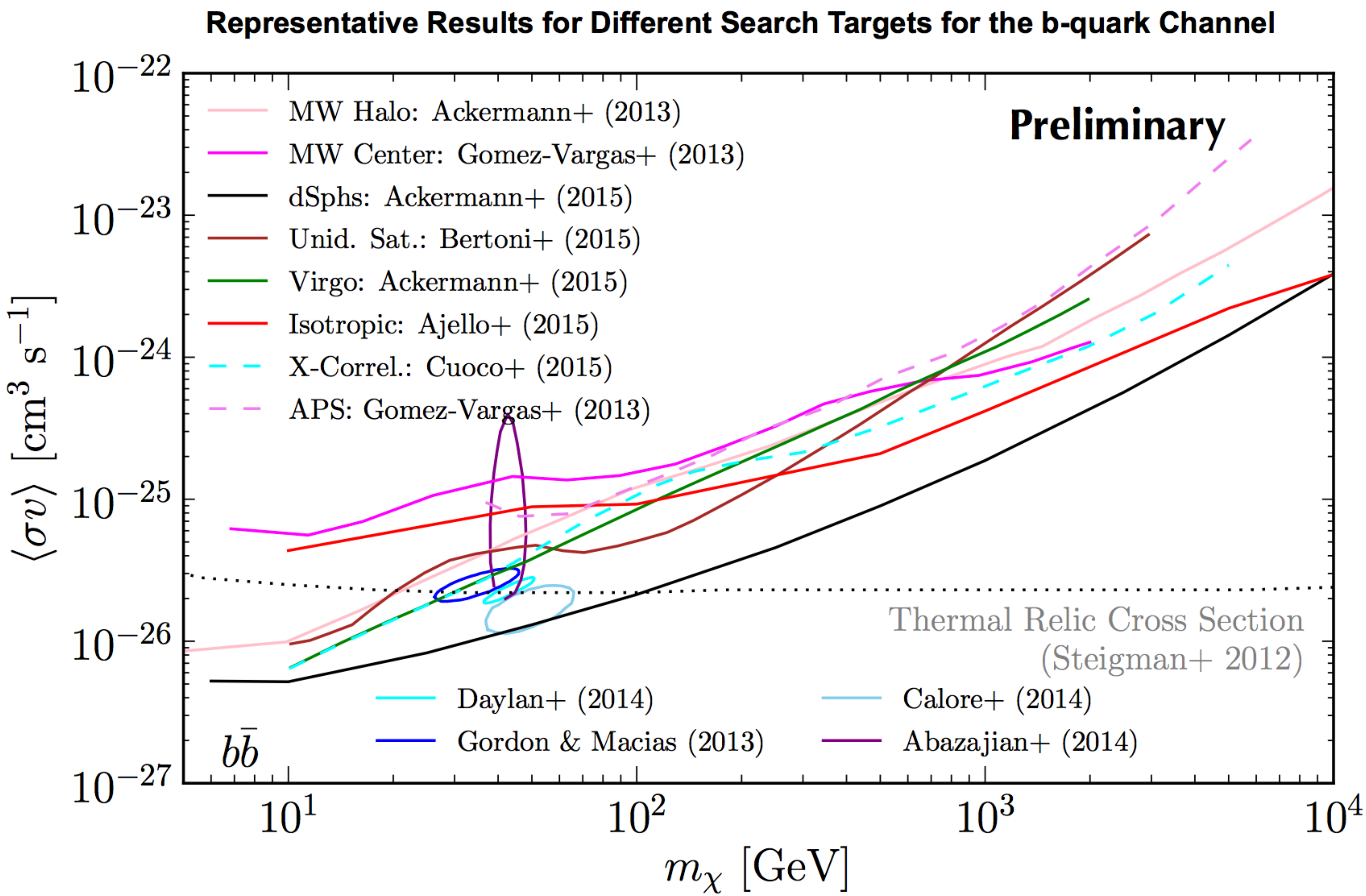
Linden+'16

Sensitivity of future radio surveys (long-term)

Future dedicated observations can allow us to **discover the bulge MSP population**.

Calore, Di Mauro, Donato, Hessels & Weniger+'15
Fermi-LAT GI Proposal 2016

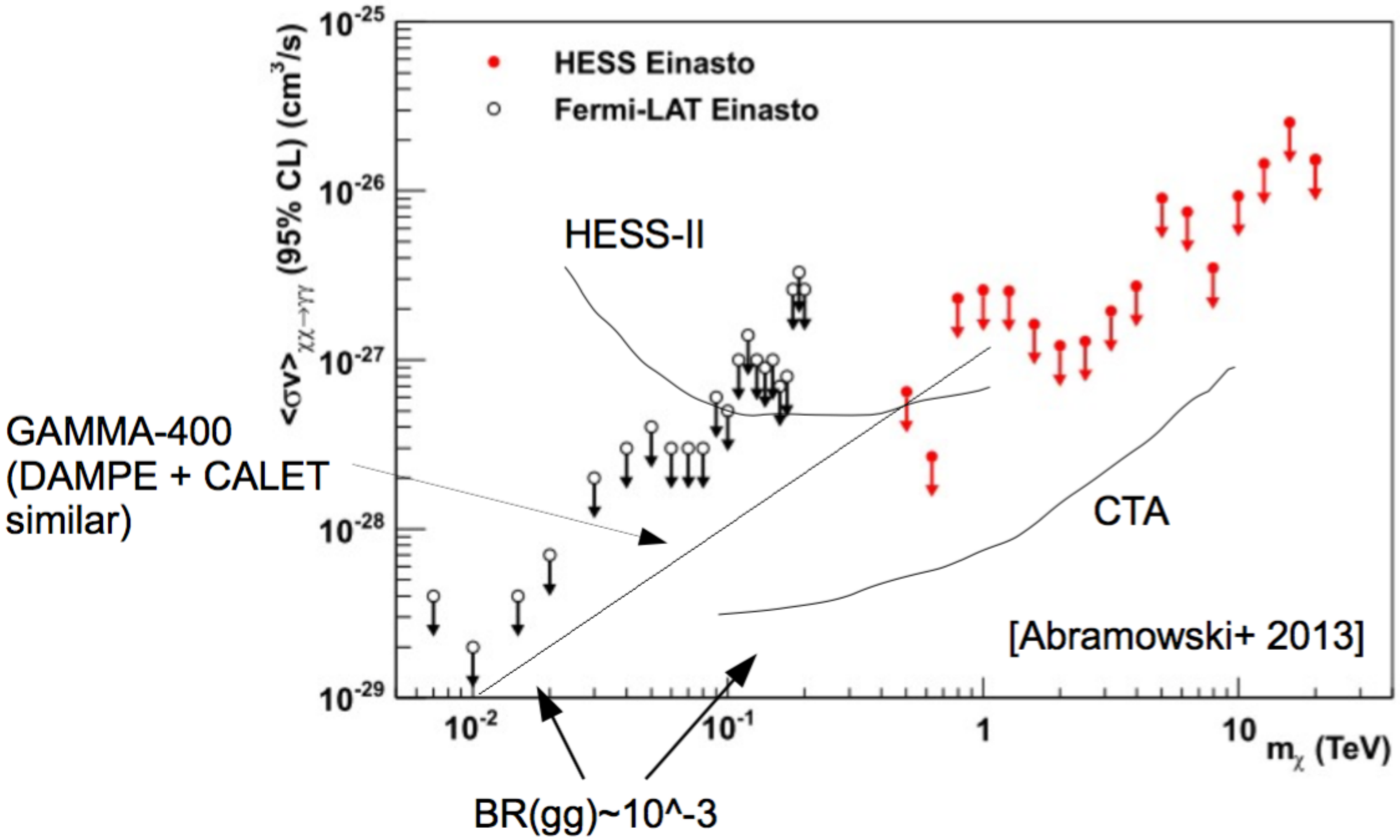
Other constraints from Fermi-LAT searches



from G. Zaharijas II Anisotropic Universe Workshop

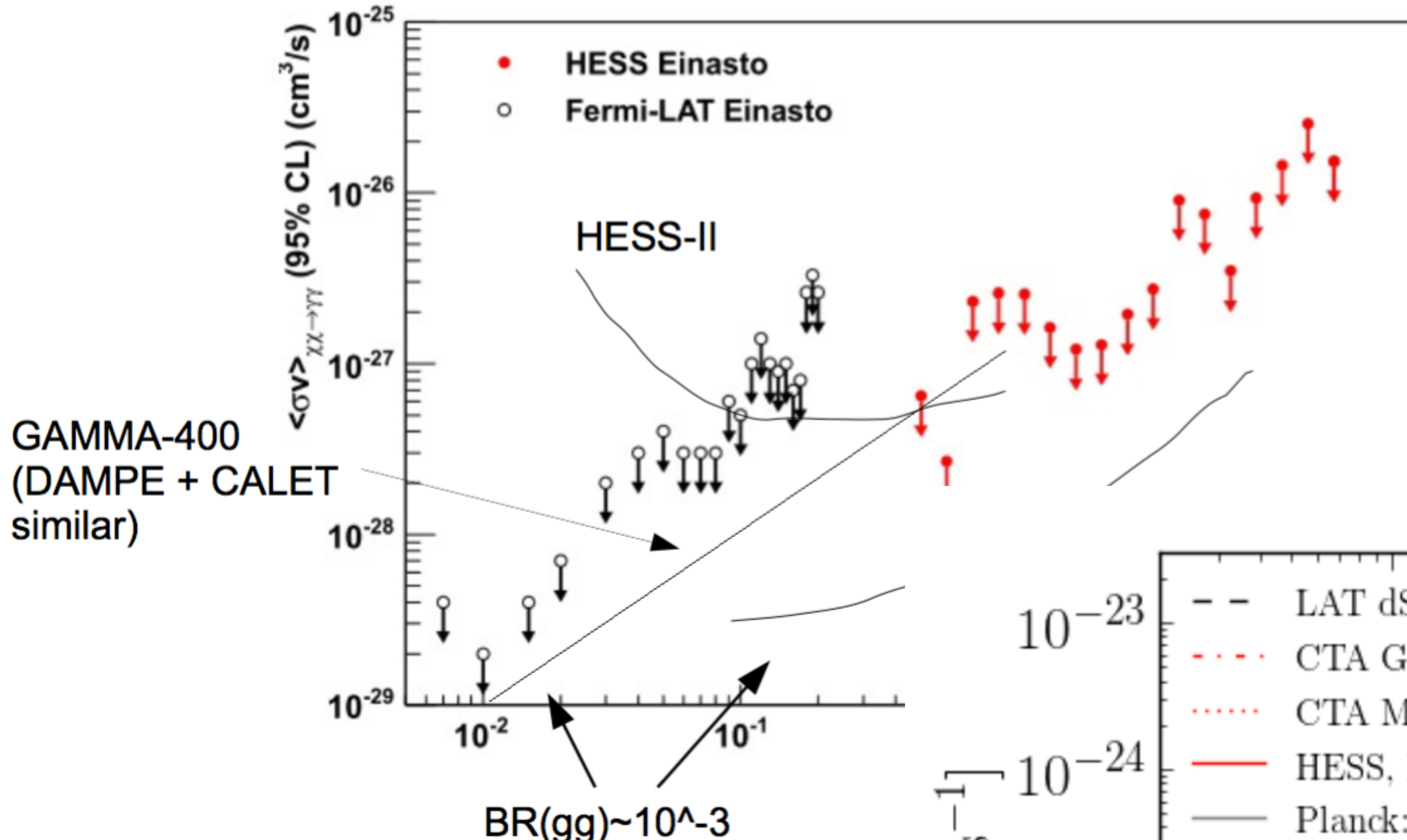
[Charles+, submitted to Physics Reports]

Future prospects



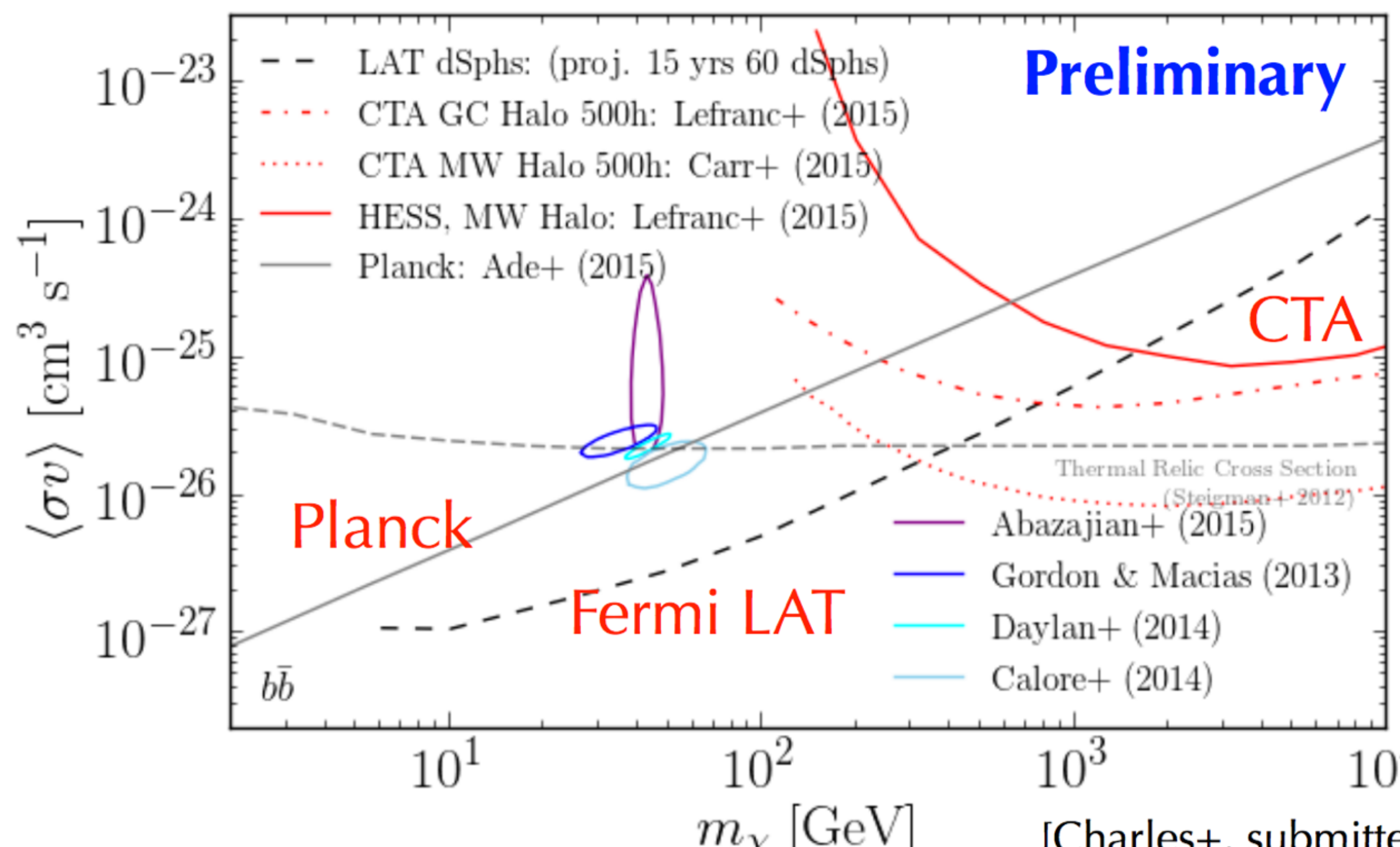
Line (spectral features) searches

Future prospects



Line (spectral features) searches

Continuum gamma-ray targets

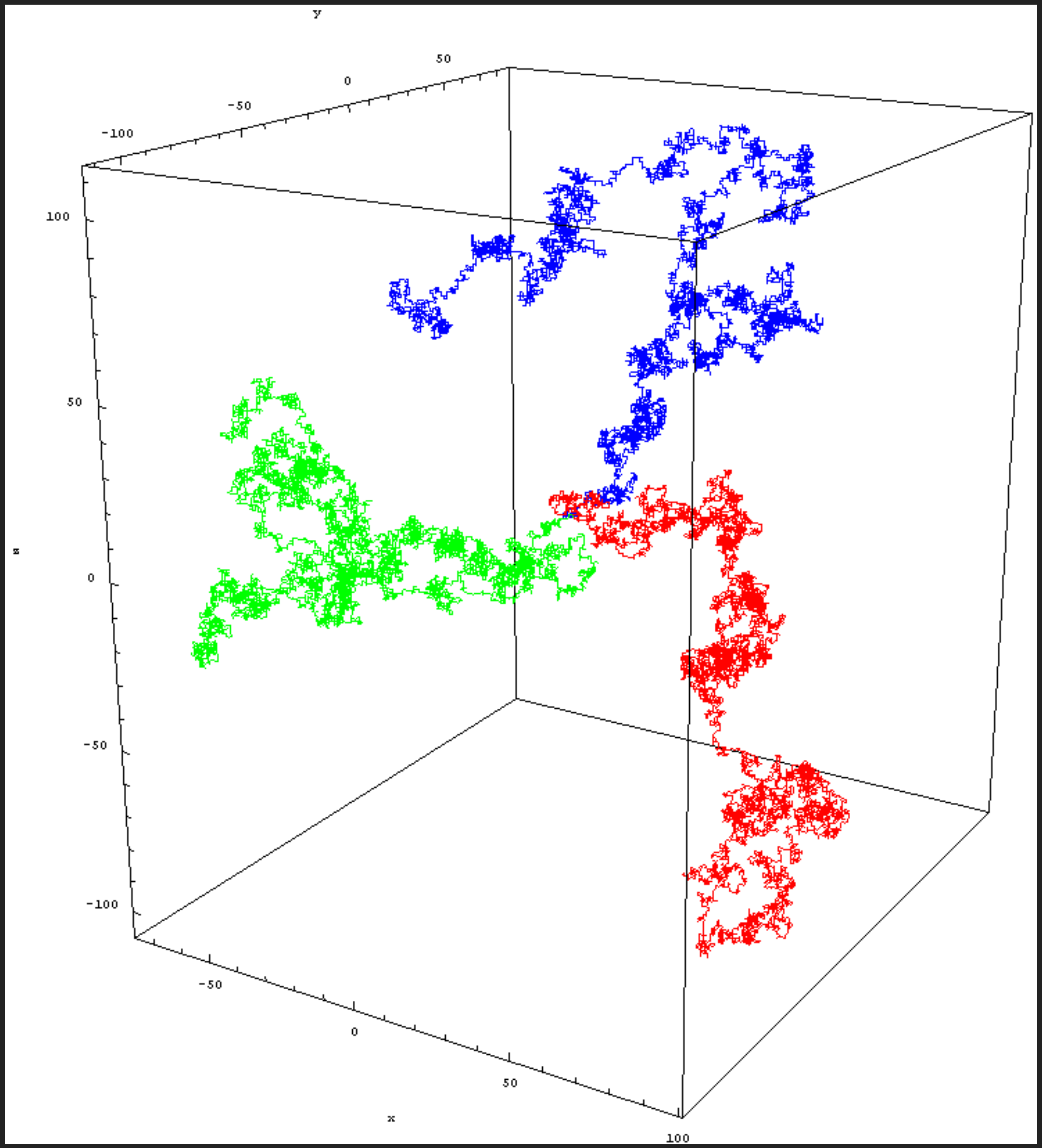


[Charles+, submitted to Physics Reports]

Searching for dark matter:
Other messengers

DOUBLY INDIRECT DETECTION

We can also think about the detection of electromagnetically interacting particles besides gamma-rays.



However these are either:

1.) Themselves charged

2.) Not promptly produced in the dark matter annihilation event.

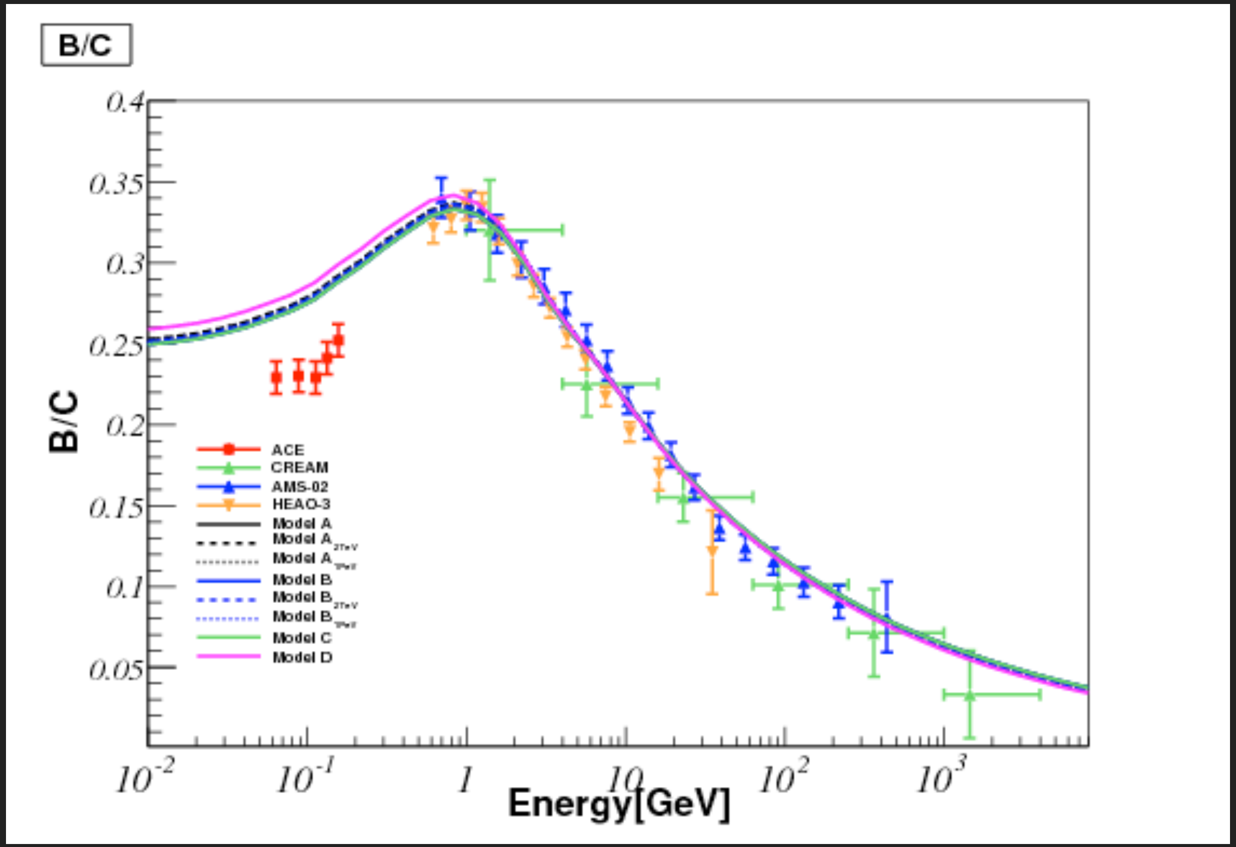
In either case, we have to worry about the diffusion of energy from the dark matter annihilation event.

DOUBLY INDIRECT DETECTION

$$\frac{\partial f}{\partial t} = \underbrace{-V_{w,i}\frac{\partial f}{\partial x_i}}_{\textit{advection}} + \underbrace{\frac{\partial}{\partial x_i}\kappa_{ij}\frac{\partial f}{\partial x_j}}_{\textit{diffusion}} \underbrace{-V_{D,i}\frac{\partial f}{\partial x_i}}_{\textit{drift}} + \underbrace{\frac{1}{3}\frac{\partial V_{w,i}}{\partial x_i}\frac{\partial f}{\partial \ln p}}_{\textit{energy change}} + Q$$

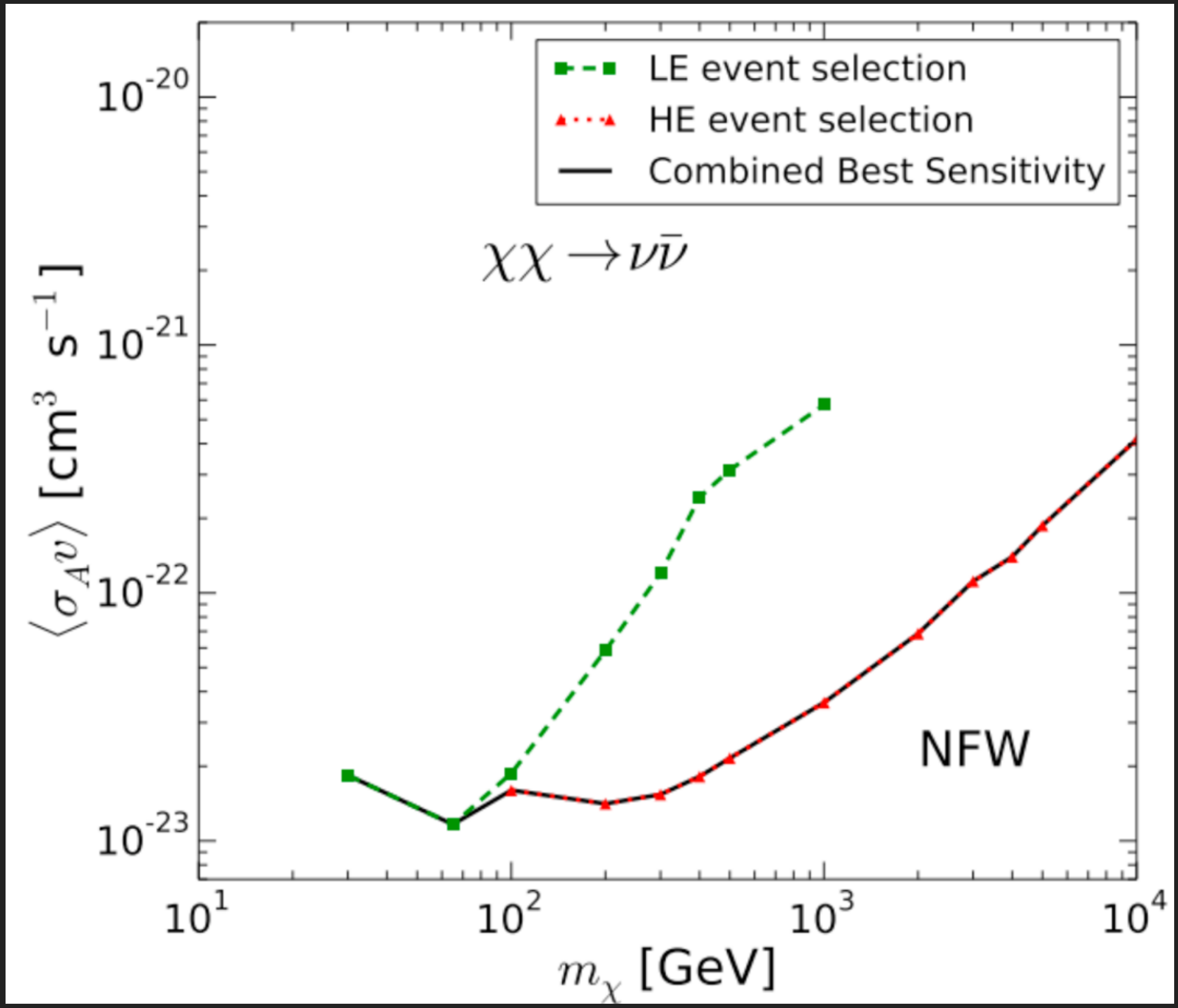
Thus, we need to solve a diffusion equation in our galaxy. This is typically done with codes such as *Galprop*, or *Dragon*.

There are many free parameters in these codes, and we fix them by trying to solve for the ratio of cosmic-ray primary to secondary species in the Milky Way.



DOUBLY INDIRECT DETECTION

The mechanics of dark matter indirect detection with neutrinos are similar to those with gamma-rays.

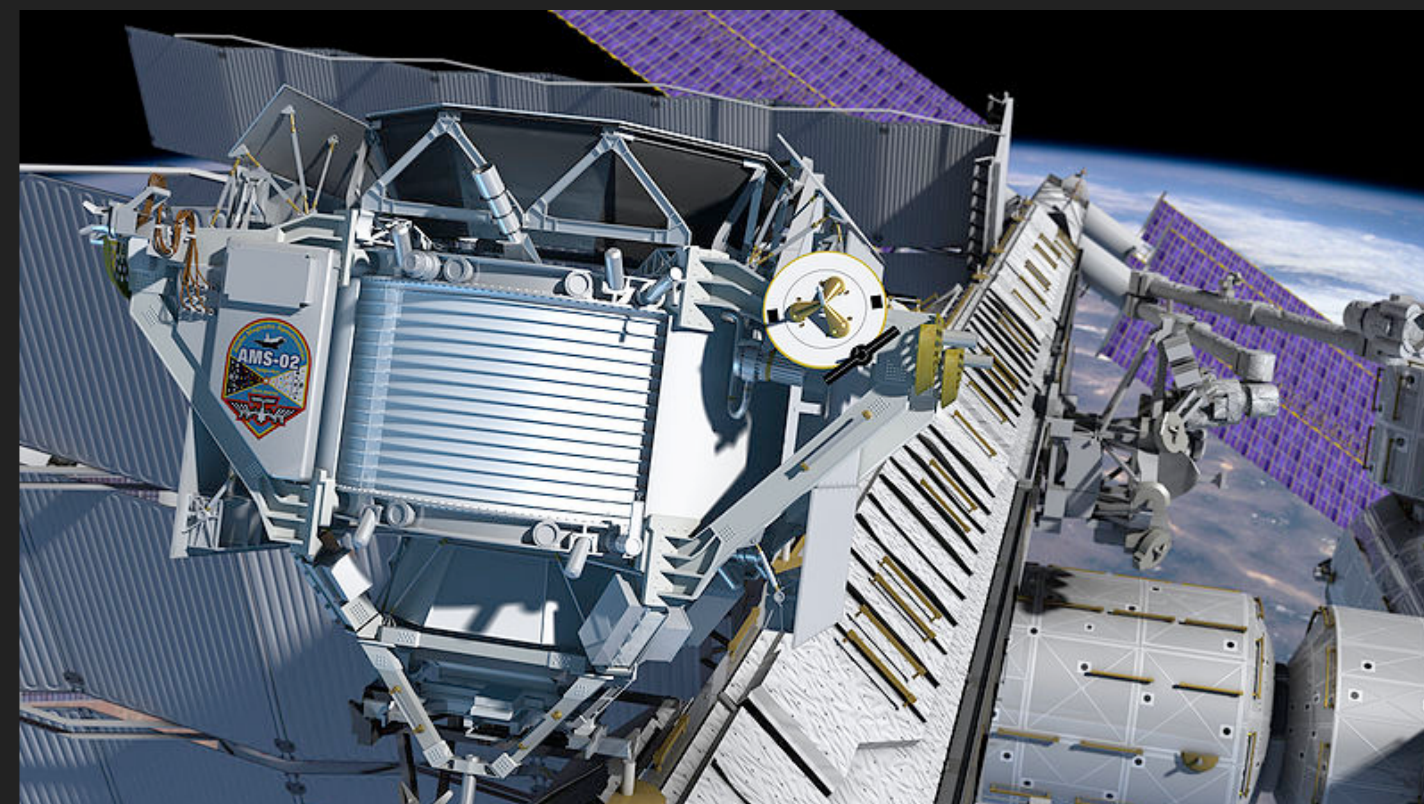


IceCube observations take place at a much higher energy, and with a similar size instrument as Fermi (~1m^2 effective area). Thus the constraints are significantly worse (compared to thermal).

IceCube does provide competitive limits in the XX -> vv channel.

CHARGED COSMIC-RAYS

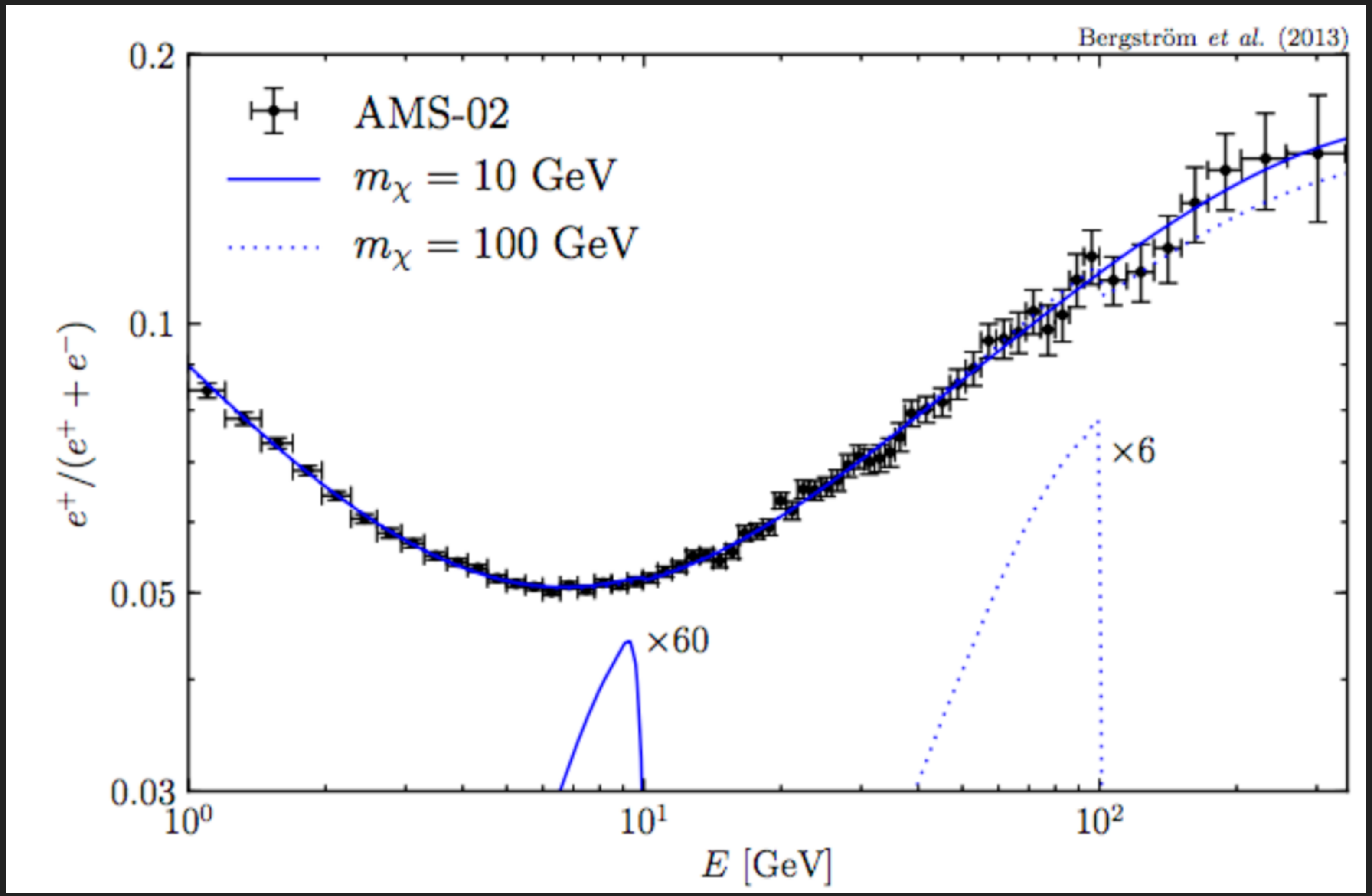
PAMELA
June 2006 –



AMS-02
May 2011 –

COSMIC-RAY TARGETS

A particularly effective method is to look for bumps in the cosmic-ray particle/anti-particle ratio.



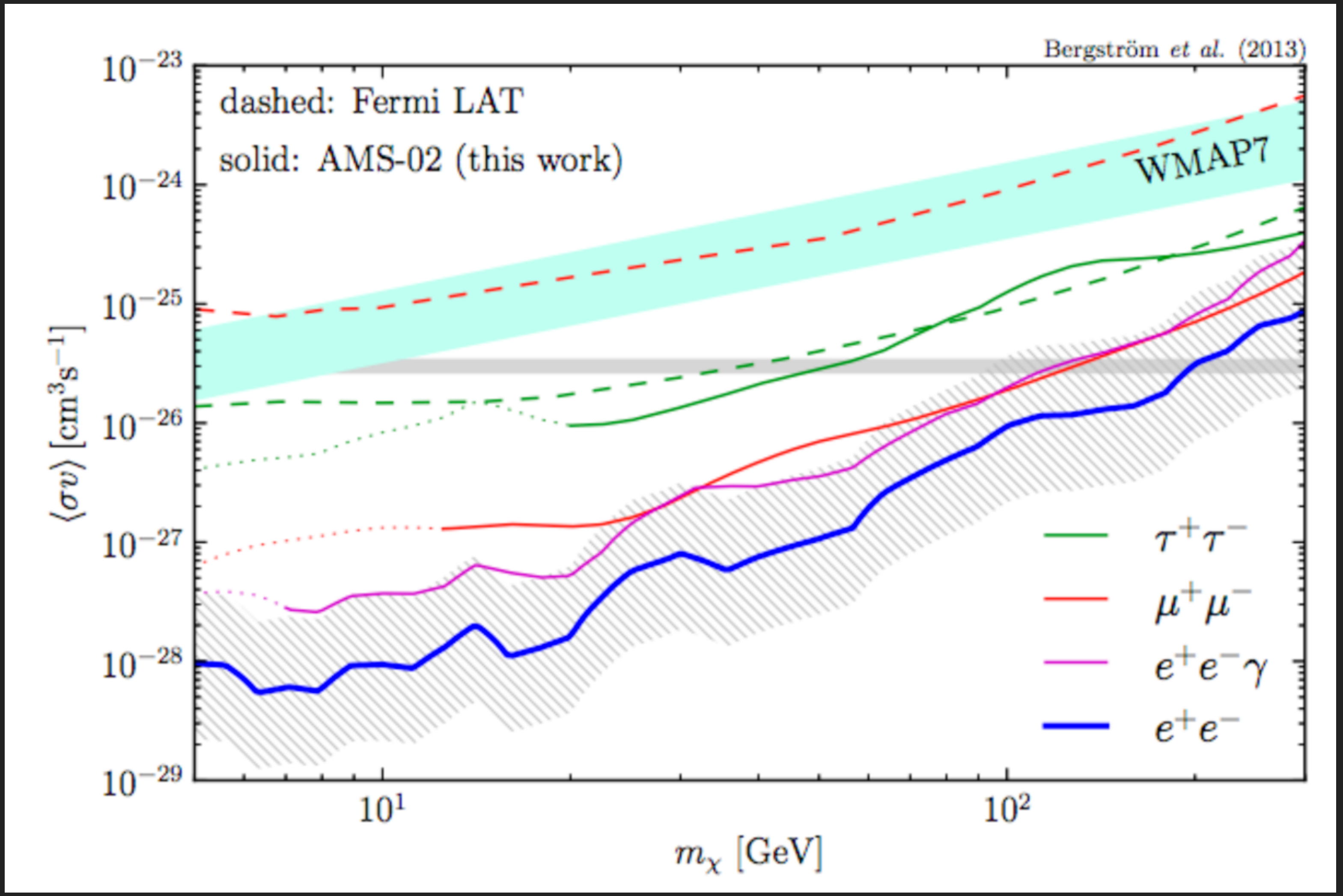
Bergstrom et al. (2013)

Astrophysical uncertainties can be constrained by using information from the energy sidebands.

This is particularly effective for leptophilic dark matter candidates, since the electron energy is highly peaked. Also, results are most sensitive to electrons formed locally.

COSMIC-RAY TARGETS

For annihilation directly to electron/positron pairs, these constraints rule out dark matter at the thermal annihilation cross-section to masses ~200 GeV.

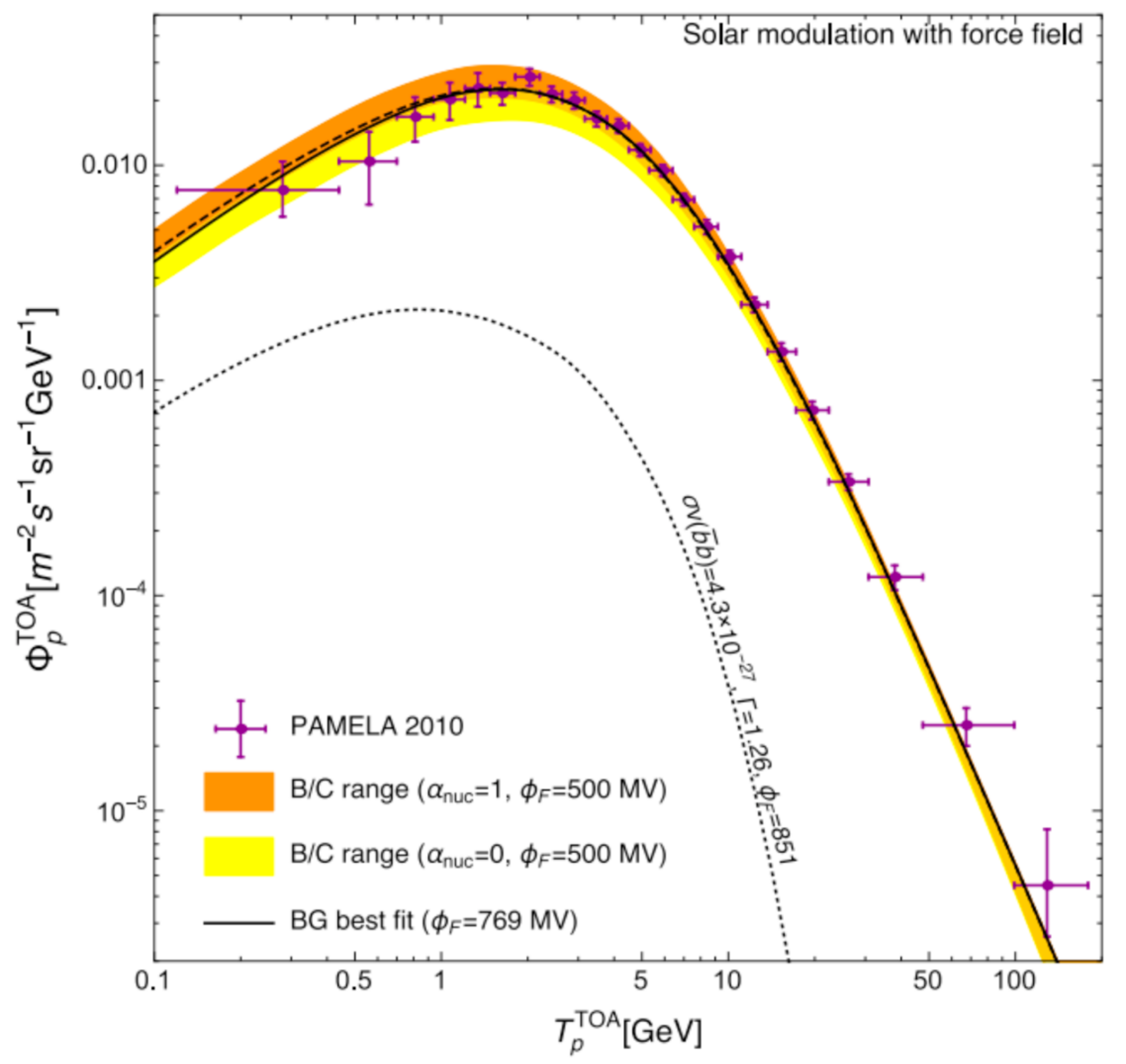


Bergstrom et al. (2013)

Constraints will continue to improve as AMS-02 data is collected (models hide in the statistical uncertainties in the positron fraction.)

COSMIC-RAY TARGETS

In the case of the antiproton flux, the bump is significantly wider, making the astrophysical background determination more important.



Bringmann, Vollman, Weniger (2014)

Moreover, because protons do not cool rapidly, models are sensitive to proton production and diffusion across the entire Galaxy.

Hooper, TL, Mertsch (2015)

COSMIC-RAY TARGETS

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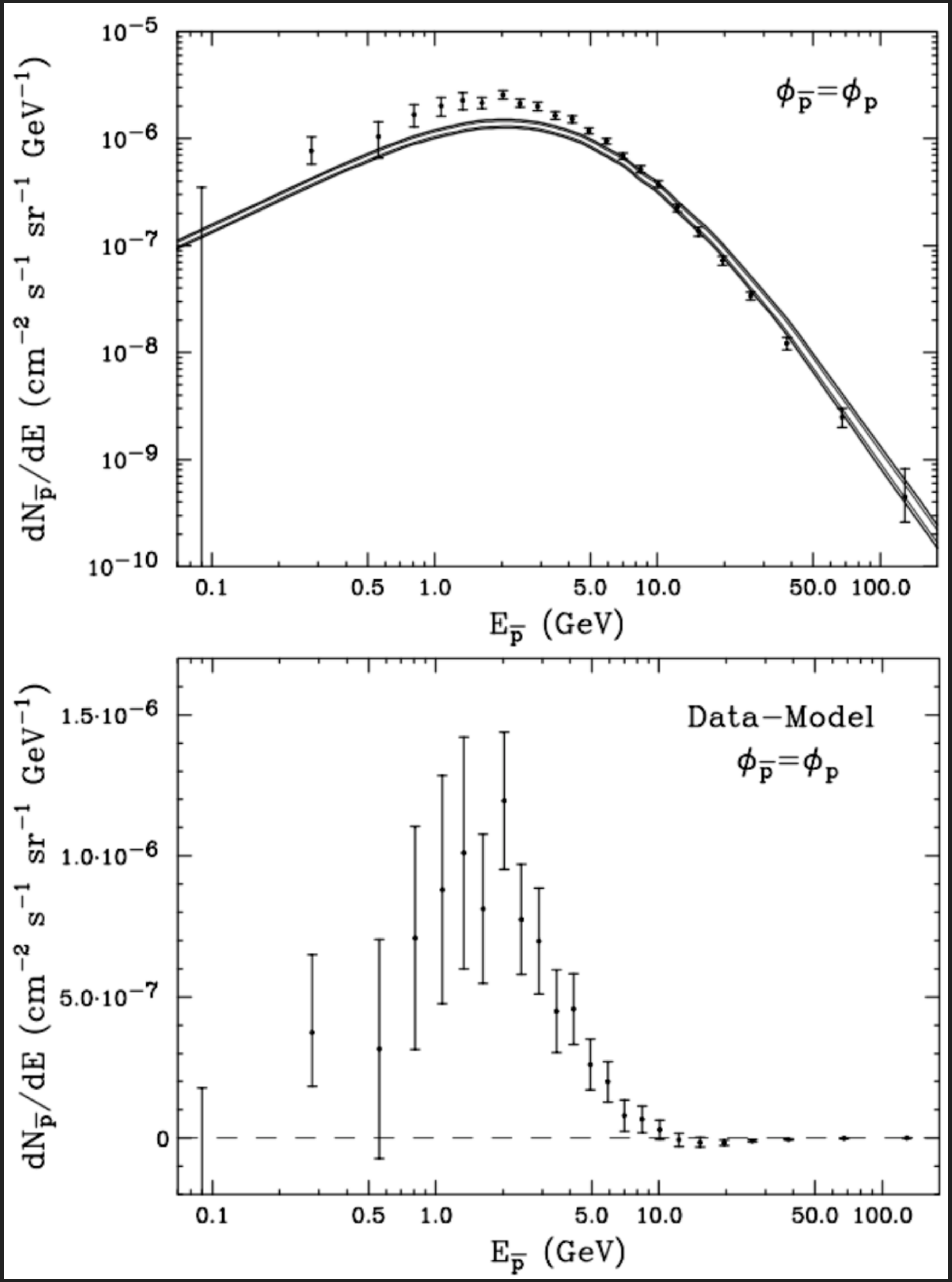
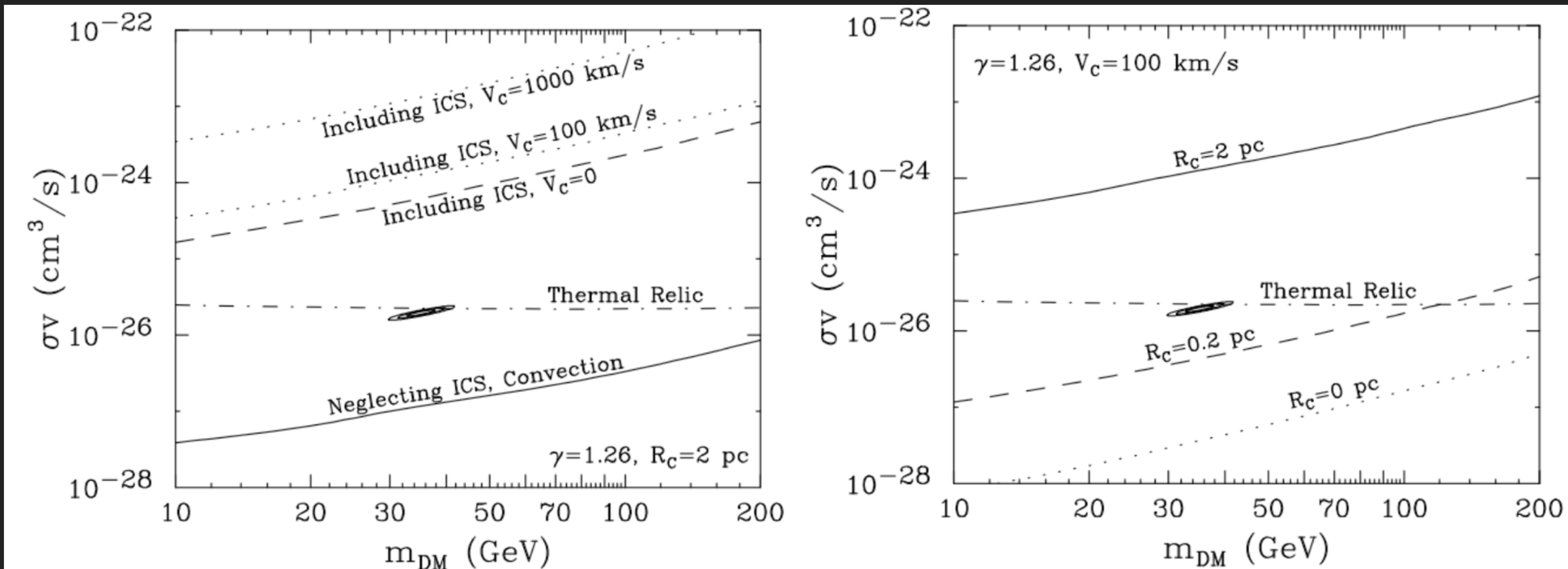
Moreover, because protons do not cool rapidly, models are sensitive to proton production and diffusion across the entire Galaxy.



RADIO TARGETS

Galactic Center - Impressive Angular Resolution in Radio

RADIO TARGETS



Cholis, Hooper, TL (2015)

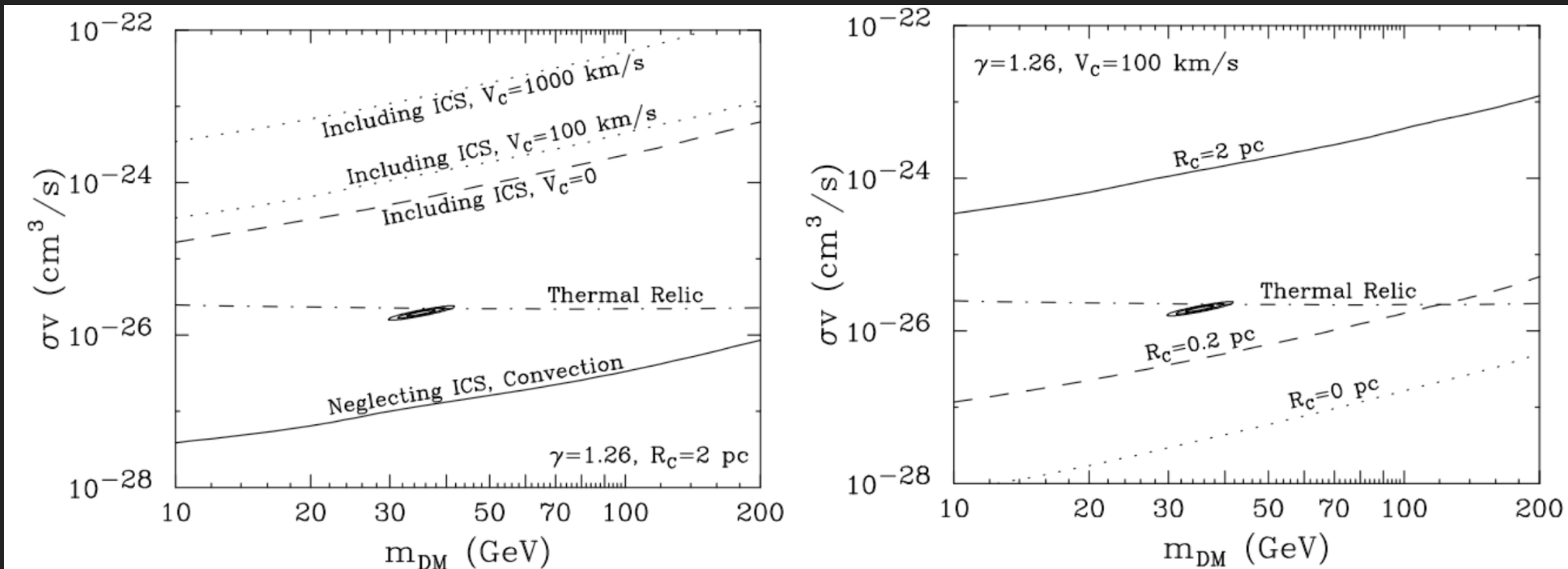
Three Major Uncertainties:

1.) The ratio of the magnetic field and ISRF energy densities.

2.) The strength of the convective wind.

3.) The dark matter density profile.

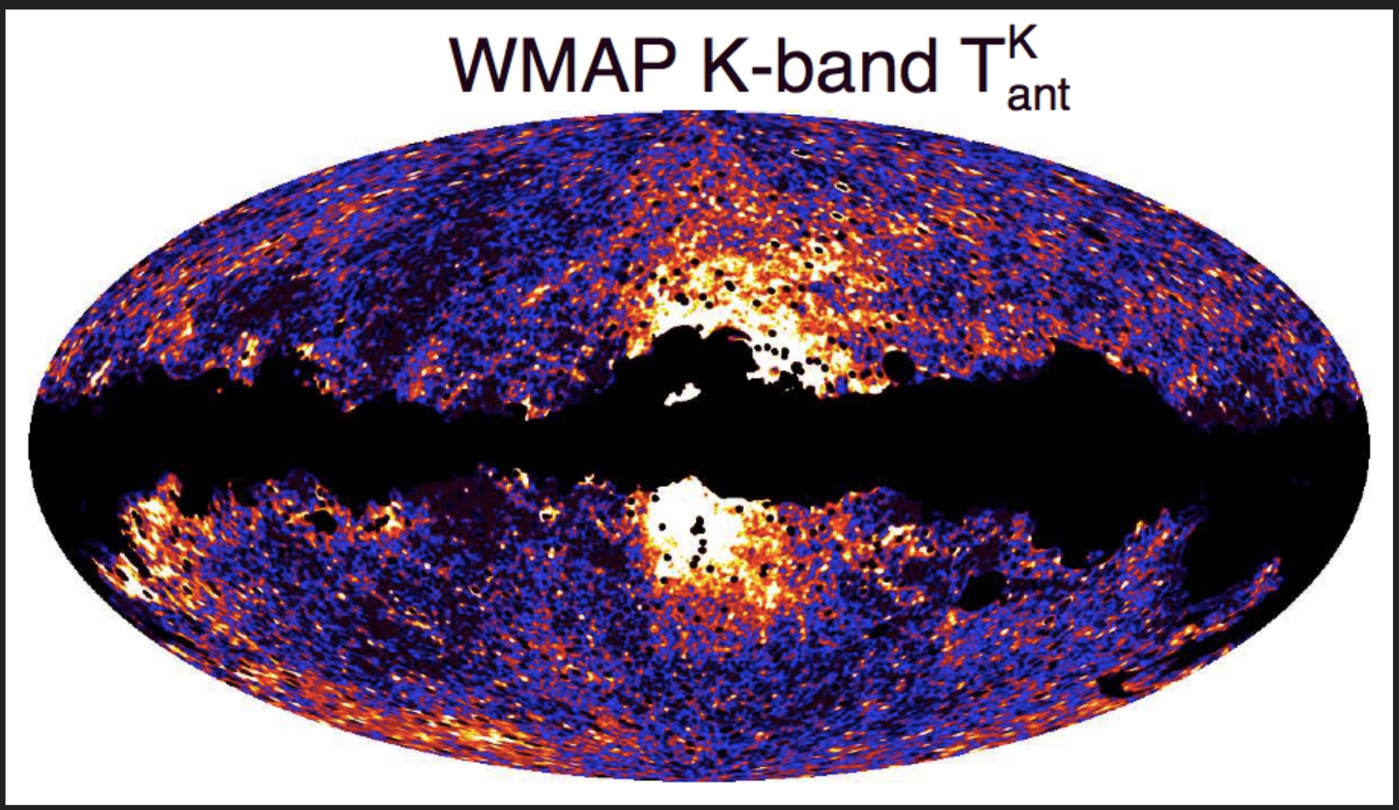
RADIO TARGETS



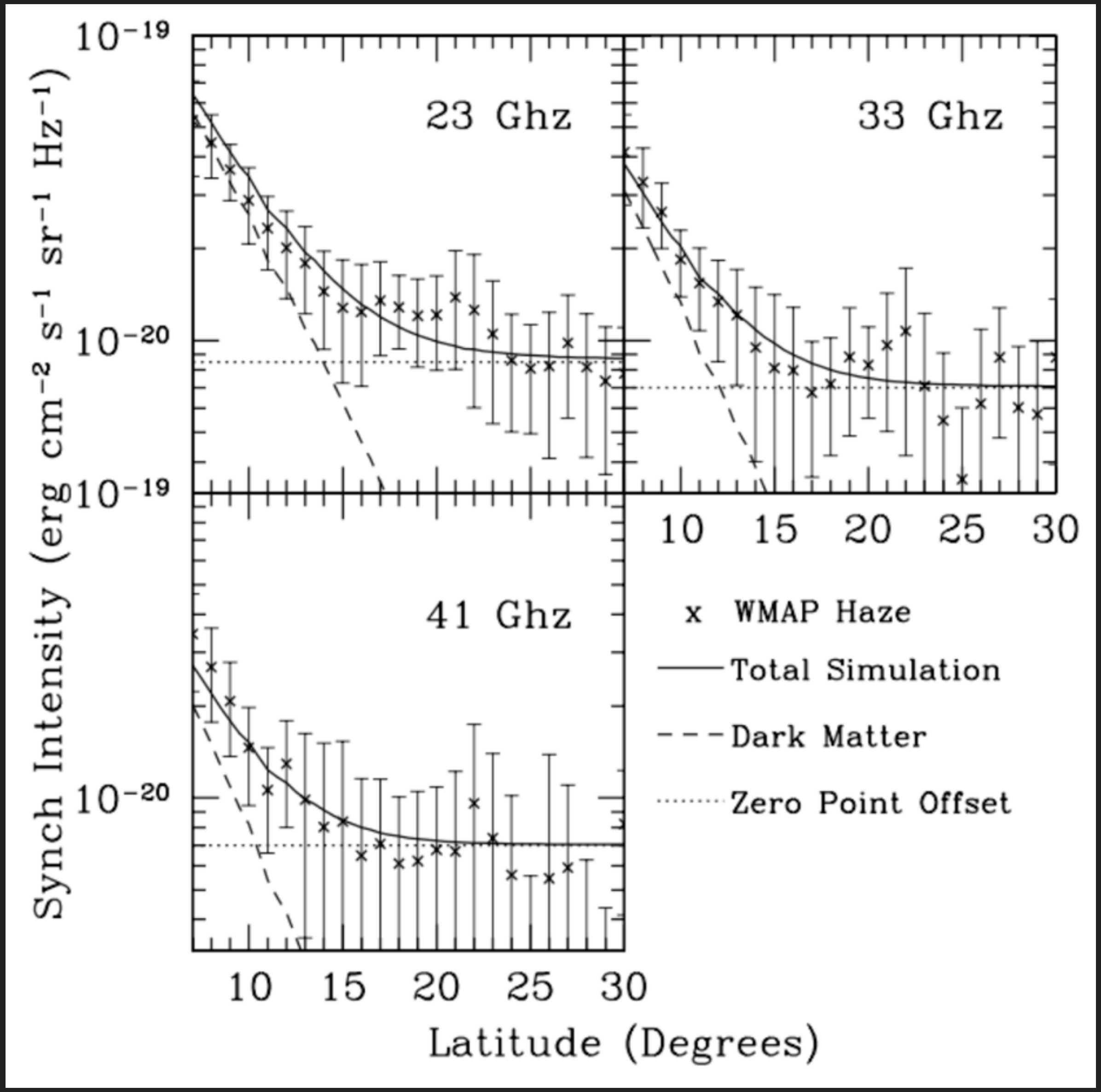
Cholis, Hooper, TL (2015)

It is difficult to imagine that all of these uncertainties will be suitably controlled in the near future, to the extent that limits from dark matter induced synchrotron emission near the Galactic center will provide the most stringent limits.

RADIO TARGETS



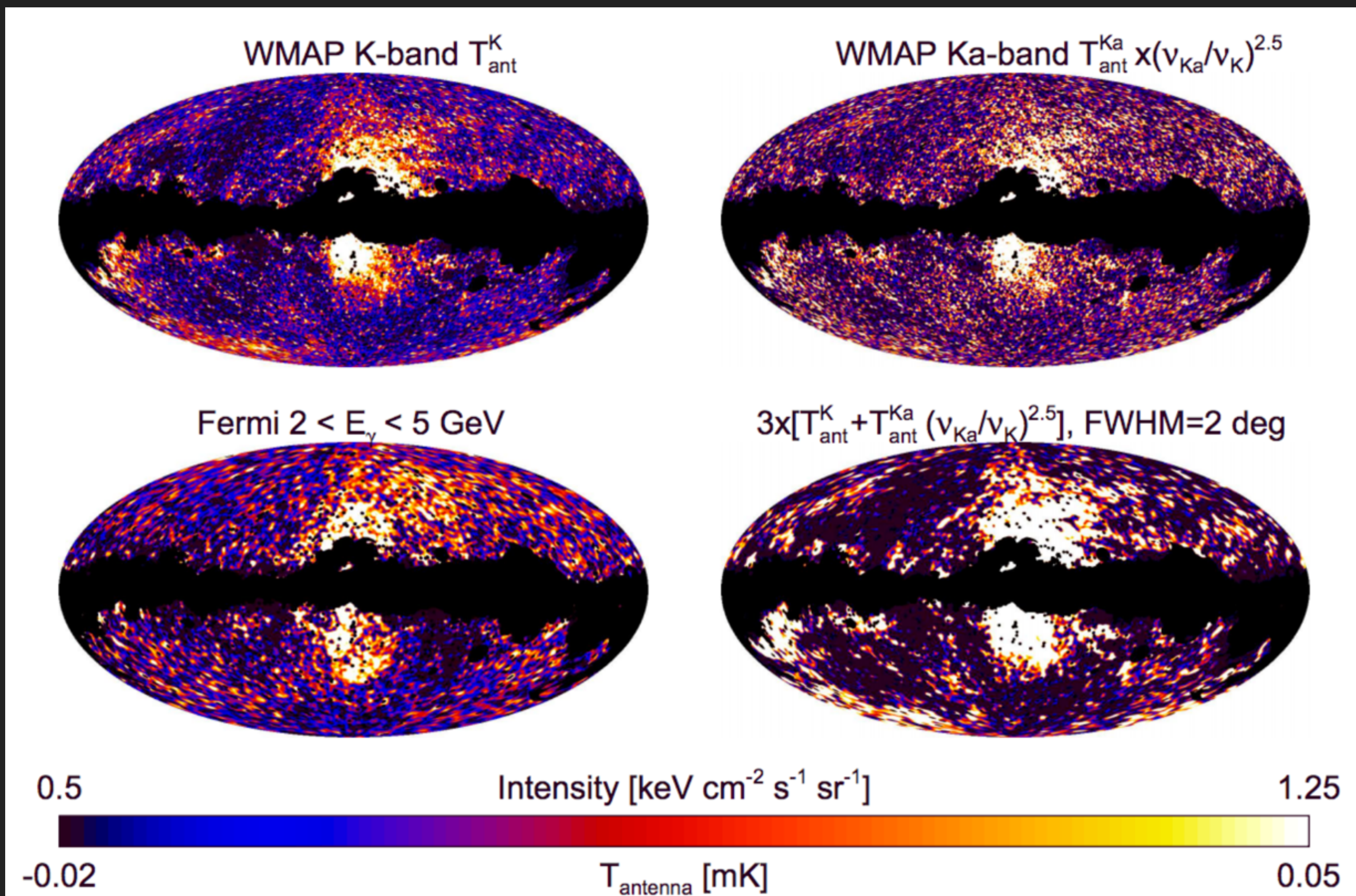
courtesy: Doug Finkbeiner

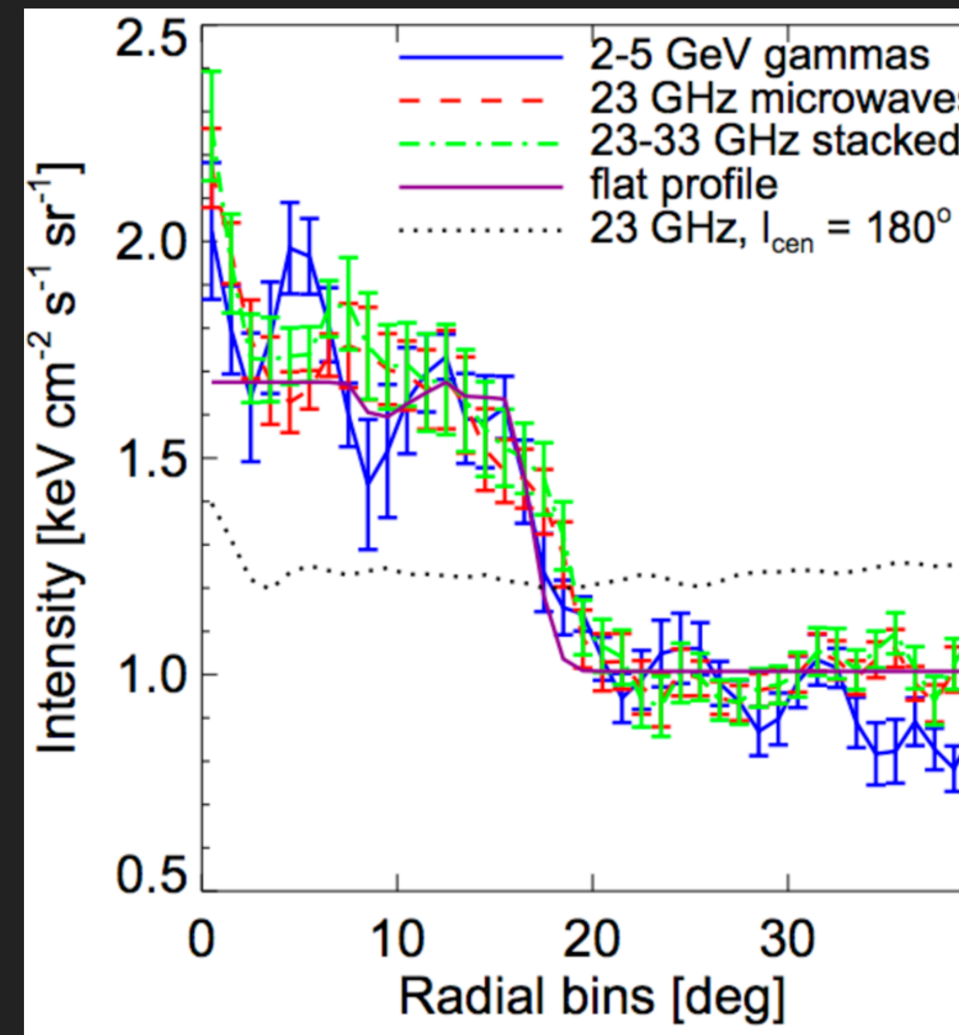


Hooper & Linden (2010)

About 10 years ago, there was significant excitement that the synchrotron excess observed by WMAP (and later PLANCK) could be a sign of dark matter annihilation.

RADIO TARGETS

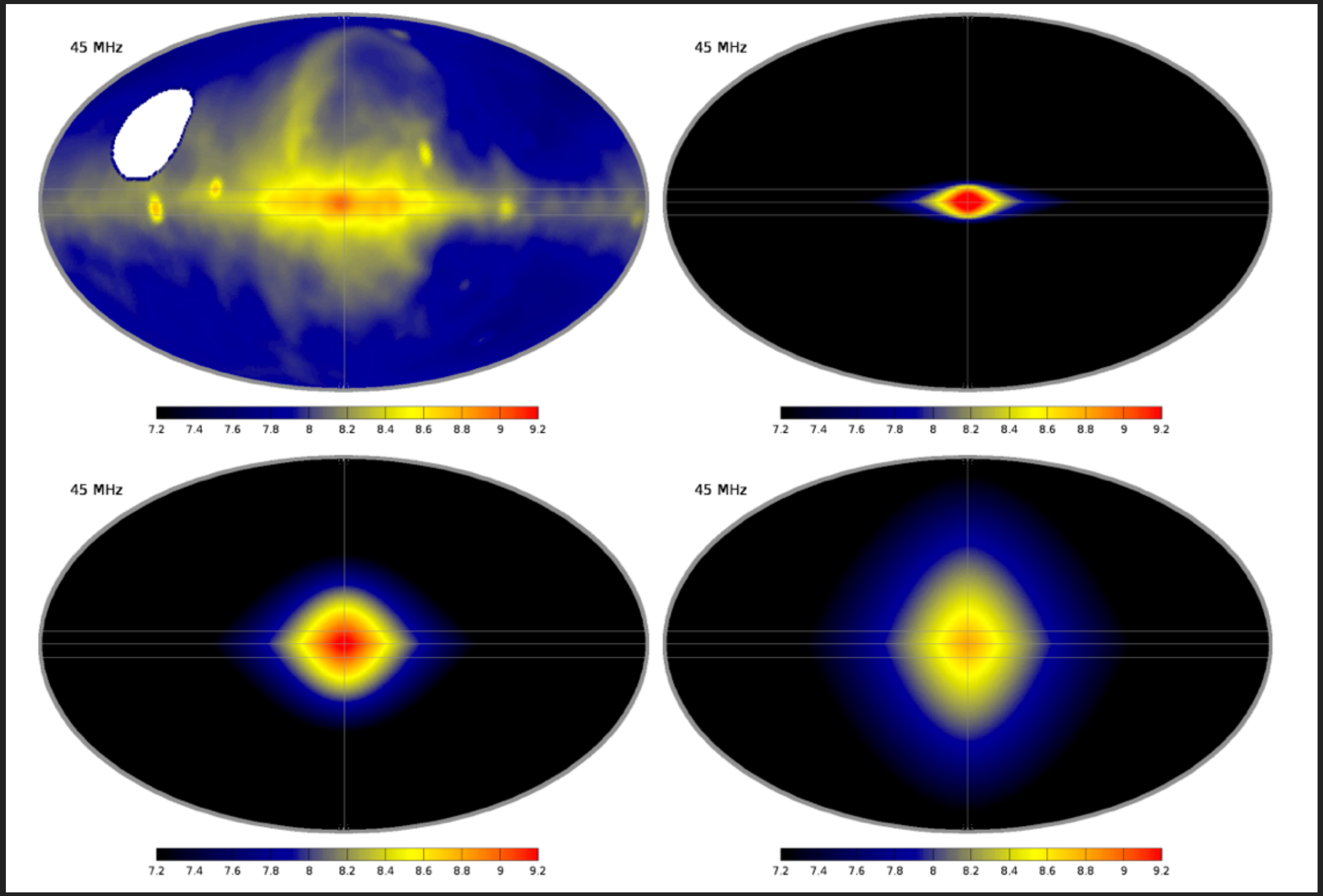


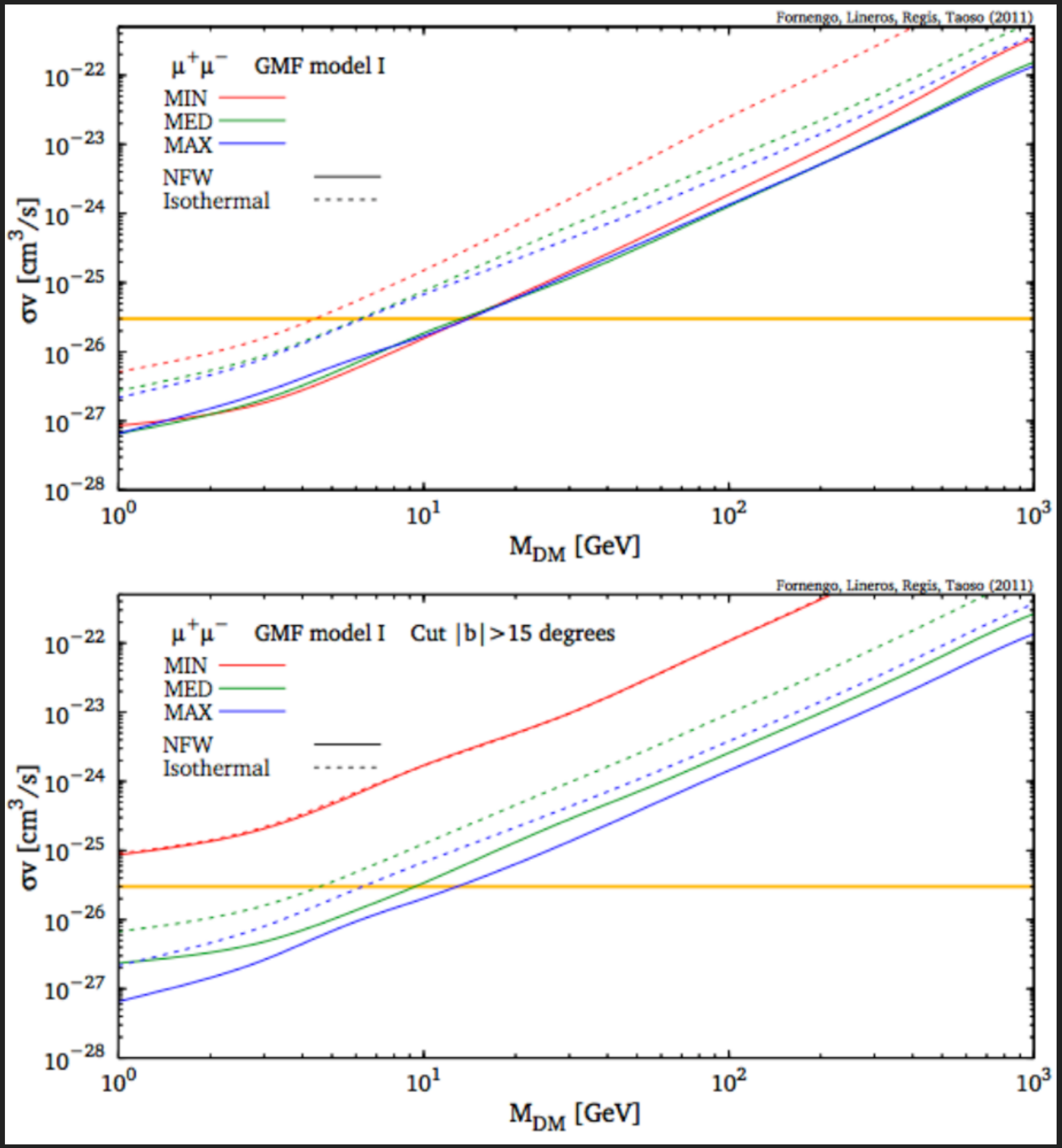


However, the WMAP residual has since been correlated with the Fermi bubbles. The sharp edges observed in both disfavors a dark matter interpretation.

Dobler (2012)

RADIO TARGETS





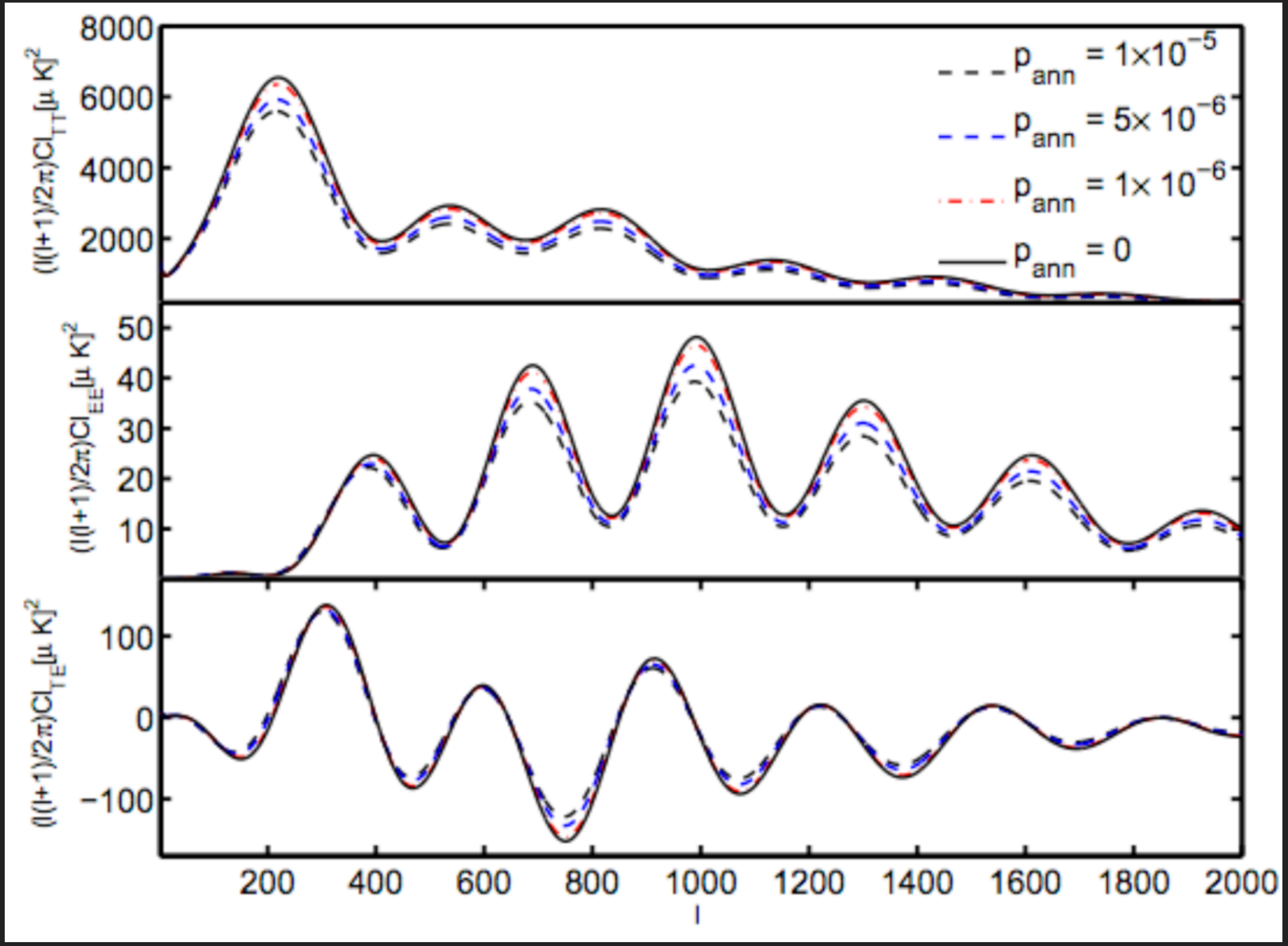
Can look for excesses above the level of the WMAP/PLANCK bubbles, setting constraints on dark matter signals.

Fornengo, Lineros, Regis, Taoso (2011)

CMB TARGETS

Going back to the beginning, remember that dark matter annihilations in the present day require dark matter annihilation in the Early universe.

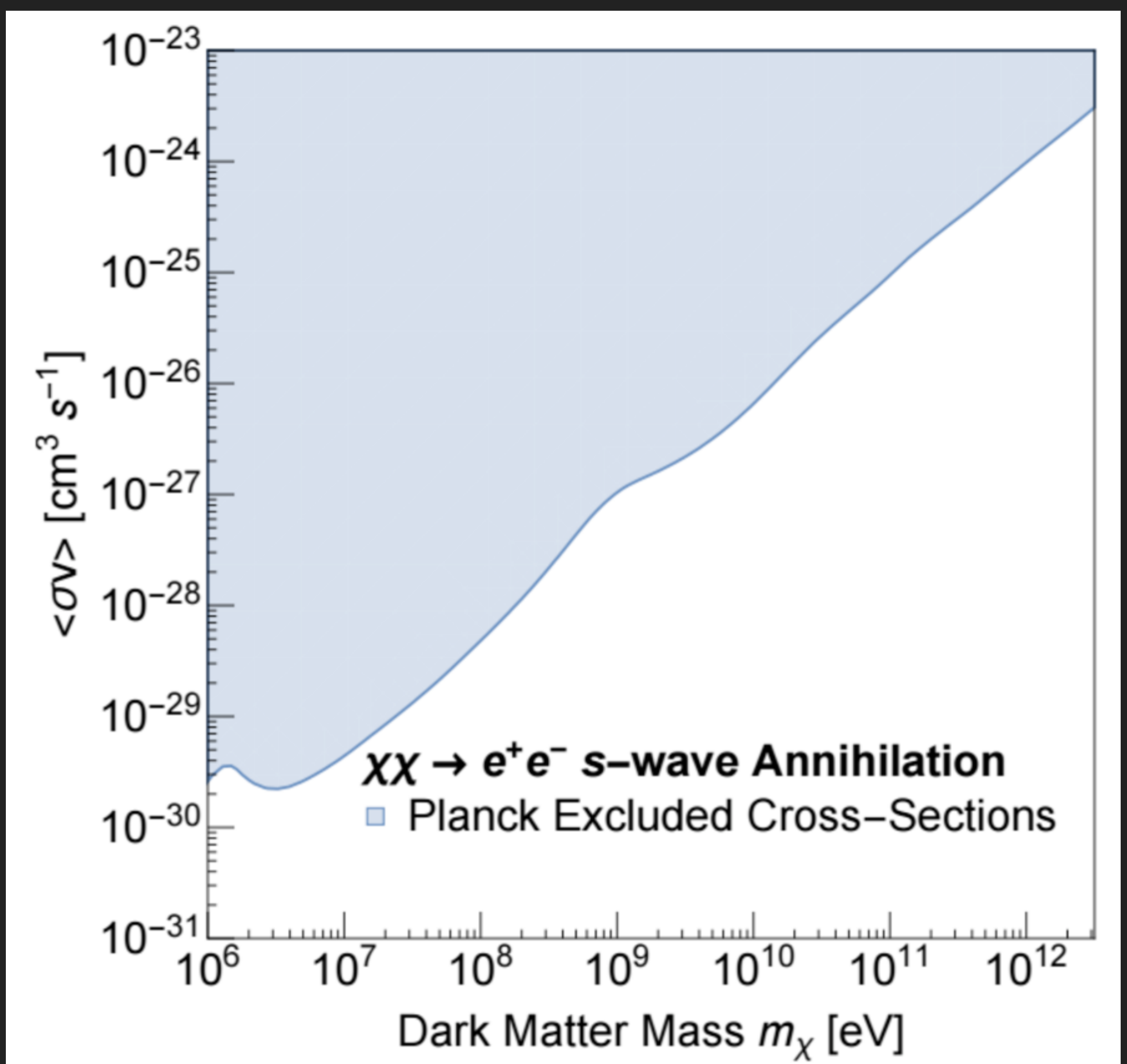
Can study the fluctuations in the CMB imposed by the energy deposition of dark matter during the epoch of recombination.



Galli et al. (0905.0003)

CMB TARGETS

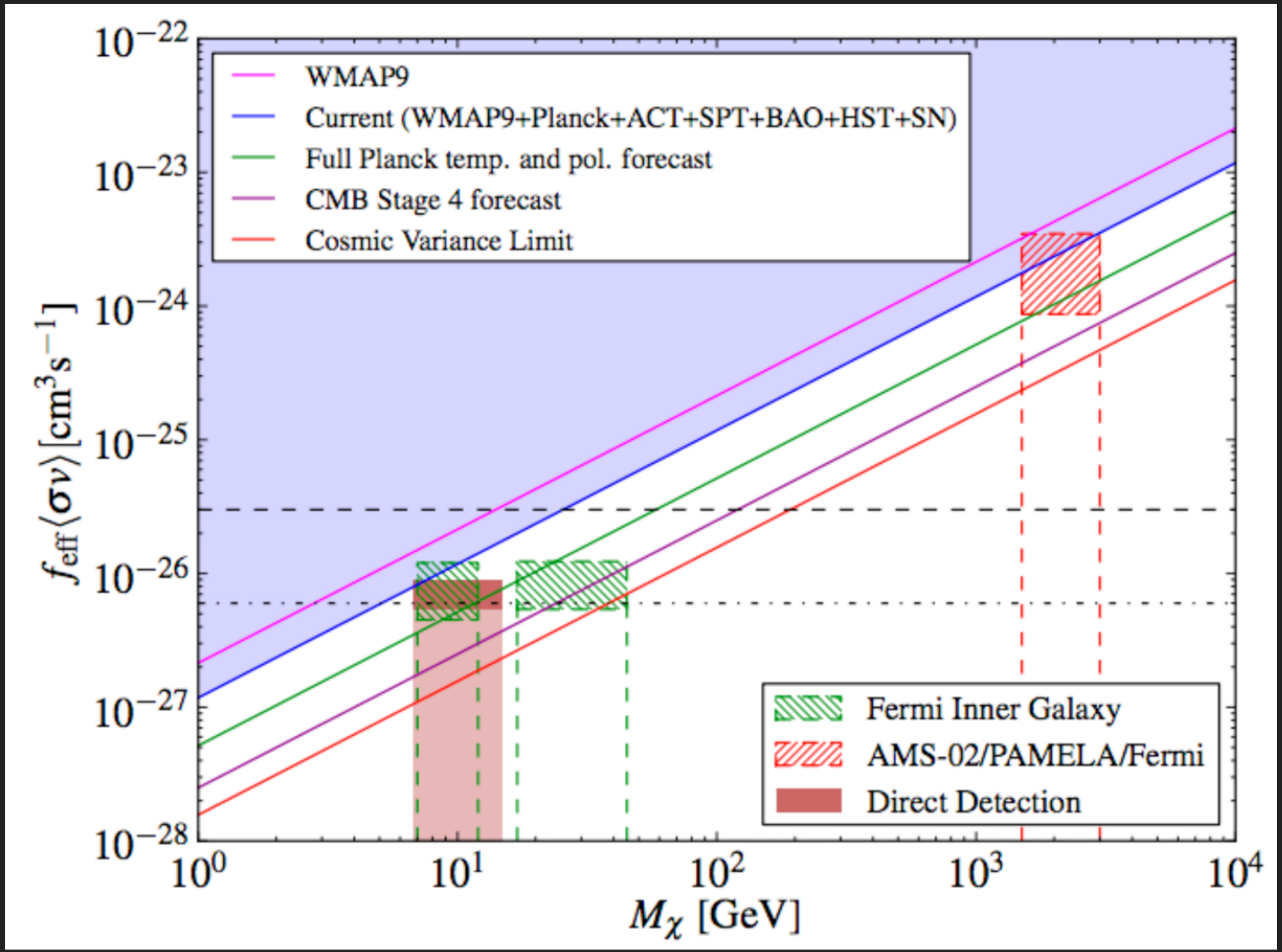
For annihilation directly to electron/positron pairs, these constraints rule out dark matter at the thermal annihilation cross-section to masses ~200 GeV.



Channel	DM Mass (GeV)	$f_{\rm eff}$	$f_{\rm eff,new}$
Electrons	1	0.85	0.45
$\chi\chi \rightarrow e^+e^-$	10	0.77	0.67
	100	0.60	0.46
	700	0.58	0.45
	1000	0.58	0.45
Muons	1	0.30	0.21
$\chi\chi \rightarrow \mu^+\mu^-$	10	0.29	0.23
	100	0.23	0.18
	250	0.21	0.16
	1000	0.20	0.16
	1500	0.20	0.16
Taus	200	0.19	0.15
$\chi\chi \rightarrow \tau^+\tau^-$	1000	0.19	0.15
XDM electrons	1	0.85	0.52
$\chi\chi \rightarrow \phi\phi$	10	0.81	0.67
followed by	100	0.64	0.49
$\phi \rightarrow e^+e^-$	150	0.61	0.47
	1000	0.58	0.45
XDM muons	10	0.30	0.21
$\chi\chi \rightarrow \phi\phi$	100	0.24	0.19
followed by	400	0.21	0.17
$\phi \rightarrow \mu^+\mu^-$	1000	0.20	0.16
	2500	0.20	0.16
XDM taus	200	0.19	0.15
$\chi\chi \rightarrow \phi\phi, \phi \rightarrow \tau^+\tau^-$	1000	0.18	0.14
XDM pions	100	0.20	0.16
$\chi\chi \rightarrow \phi\phi$	200	0.18	0.14
followed by	1000	0.16	0.13
$\phi \rightarrow \pi^+\pi^-$	1500	0.16	0.13
	2500	0.16	0.13
W bosons	200	0.26	0.19
$\chi\chi \rightarrow W^+W^-$	300	0.25	0.19
	1000	0.24	0.19
Z bosons	200	0.24	0.18
$\chi\chi \rightarrow ZZ$	1000	0.23	0.18
Higgs bosons	200	0.30	0.22
$\chi\chi \rightarrow h\bar{h}$	1000	0.28	0.22
b quarks	200	0.31	0.23
$\chi\chi \rightarrow b\bar{b}$	1000	0.28	0.22
Light quarks	200	0.29	0.22
$\chi\chi \rightarrow u\bar{u}, d\bar{d}$ (50% each)	1000	0.28	0.21

CMB TARGETS

Unfortunately, we are fast approaching the cosmic-variance limit of CMB observations (for an instrument with PLANCK-like angular resolution).



Currently, several observed excesses lie right at the threshold of the best possible CMB constraints.