Indirect dark matter searches

Jennifer Siegal-Gaskins

Caltech

Outline

TODAY

- Motivation and methods of indirect detection
- Calculating indirect signals
- Spectra from DM annihilation and decay
- The dark matter distribution — see also Tom Abel's and Louie Strigari's talks
- Gamma-ray searches — see also Miguel Sánchez-Conde's and Dan Hooper's talks

TOMORROW

- Neutrino searches — see also Justin Vandenbroucke's talk
- Cosmic-ray searches — see also the AMS talk
- Secondary emission
- Anomalies! — see also Dan Hooper's talk

Early evidence for dark matter:

Fritz Zwicky, 1933
The Coma Galaxy Cluster

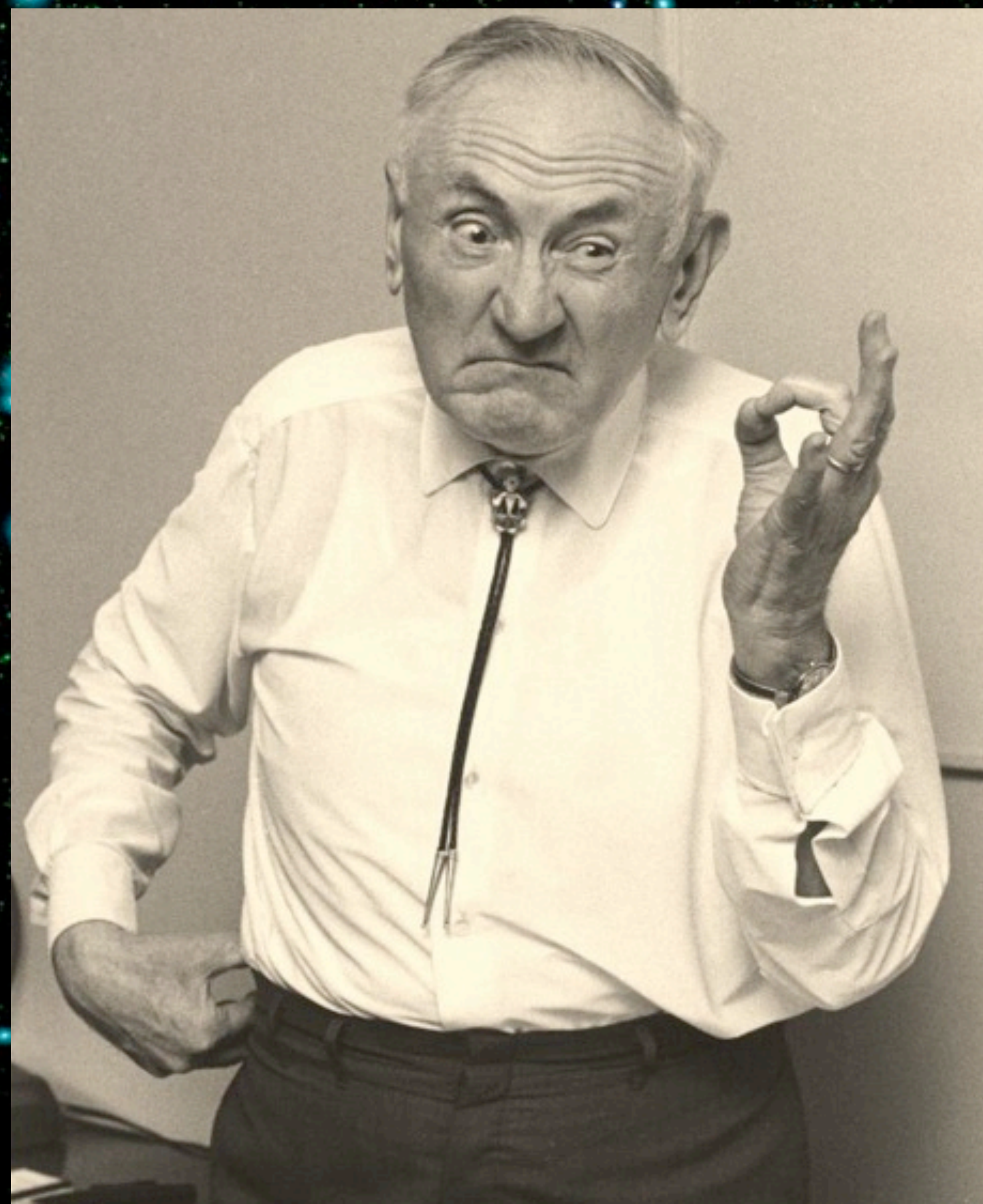

Image Credit: NASA/JPL-Caltech/GSFC/SDSS

Dark matter: evidence

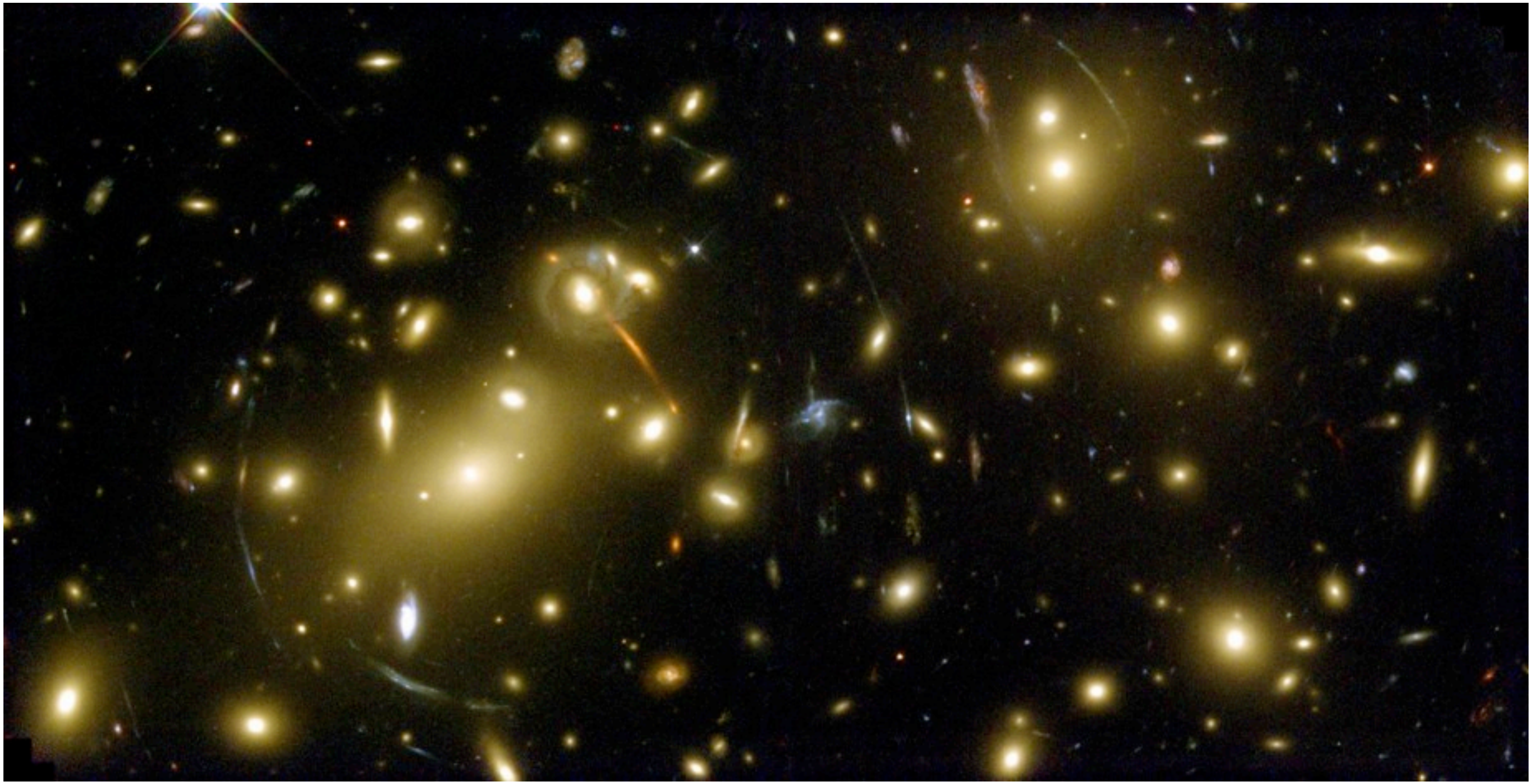

Image: NASA/ESA

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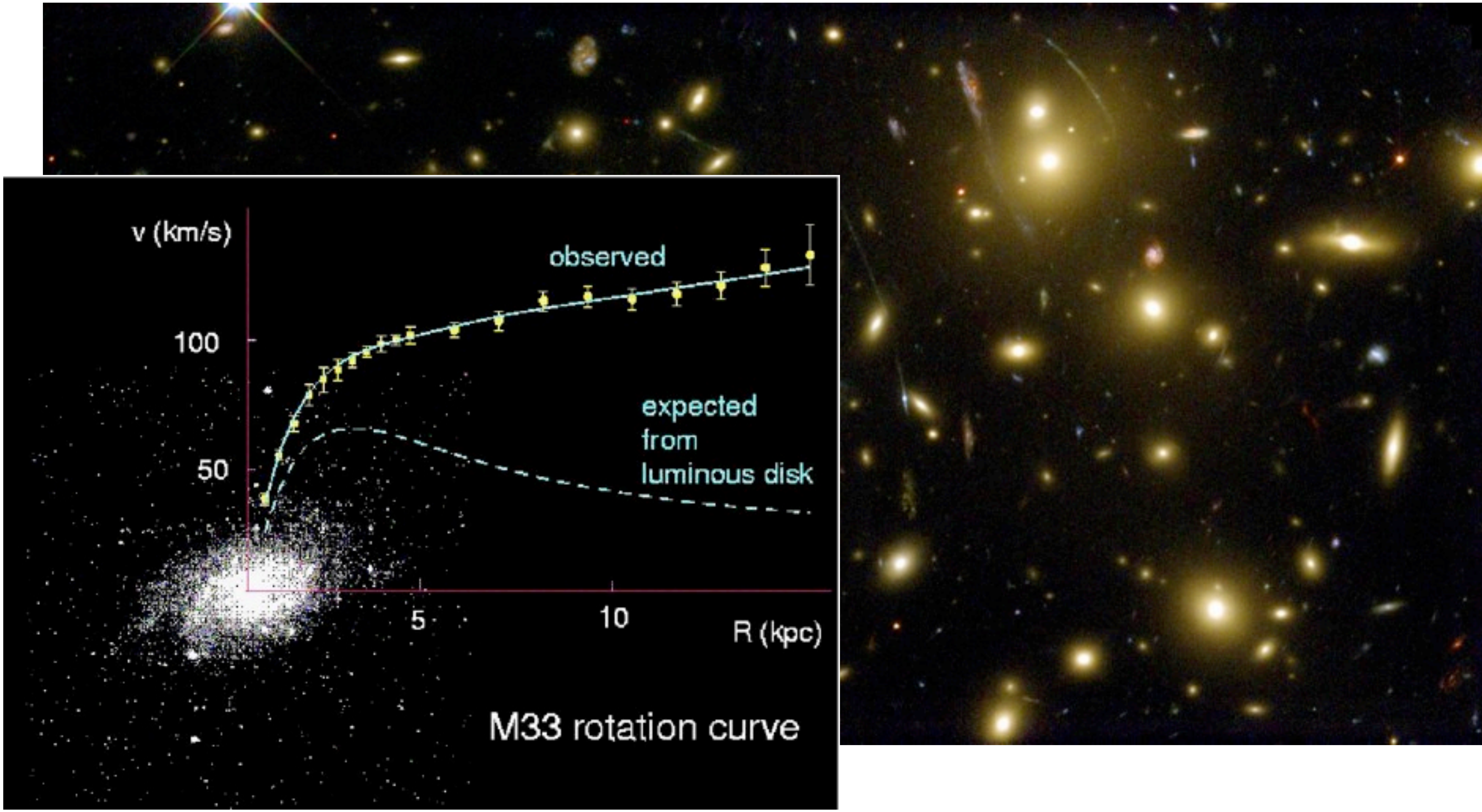

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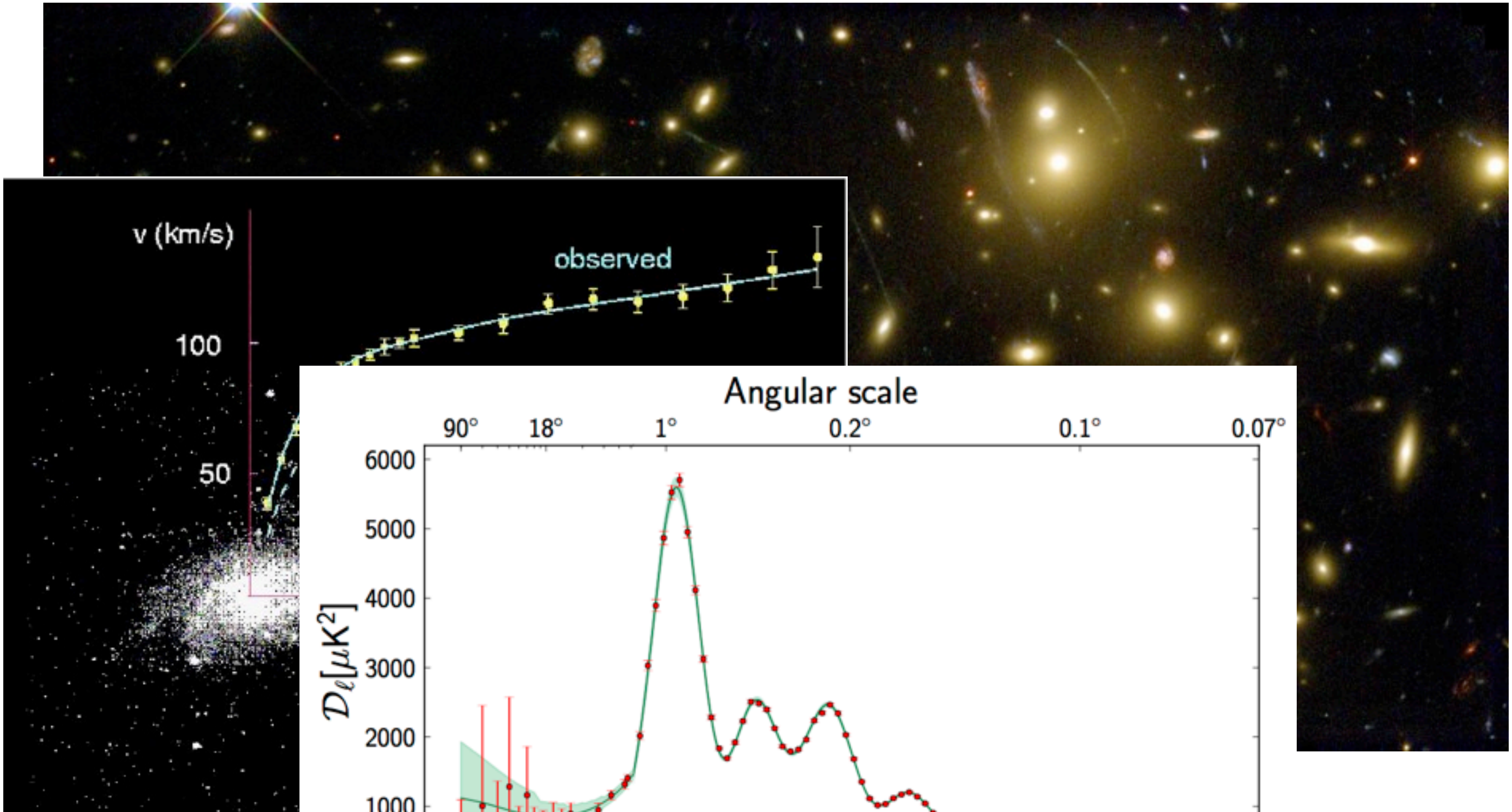
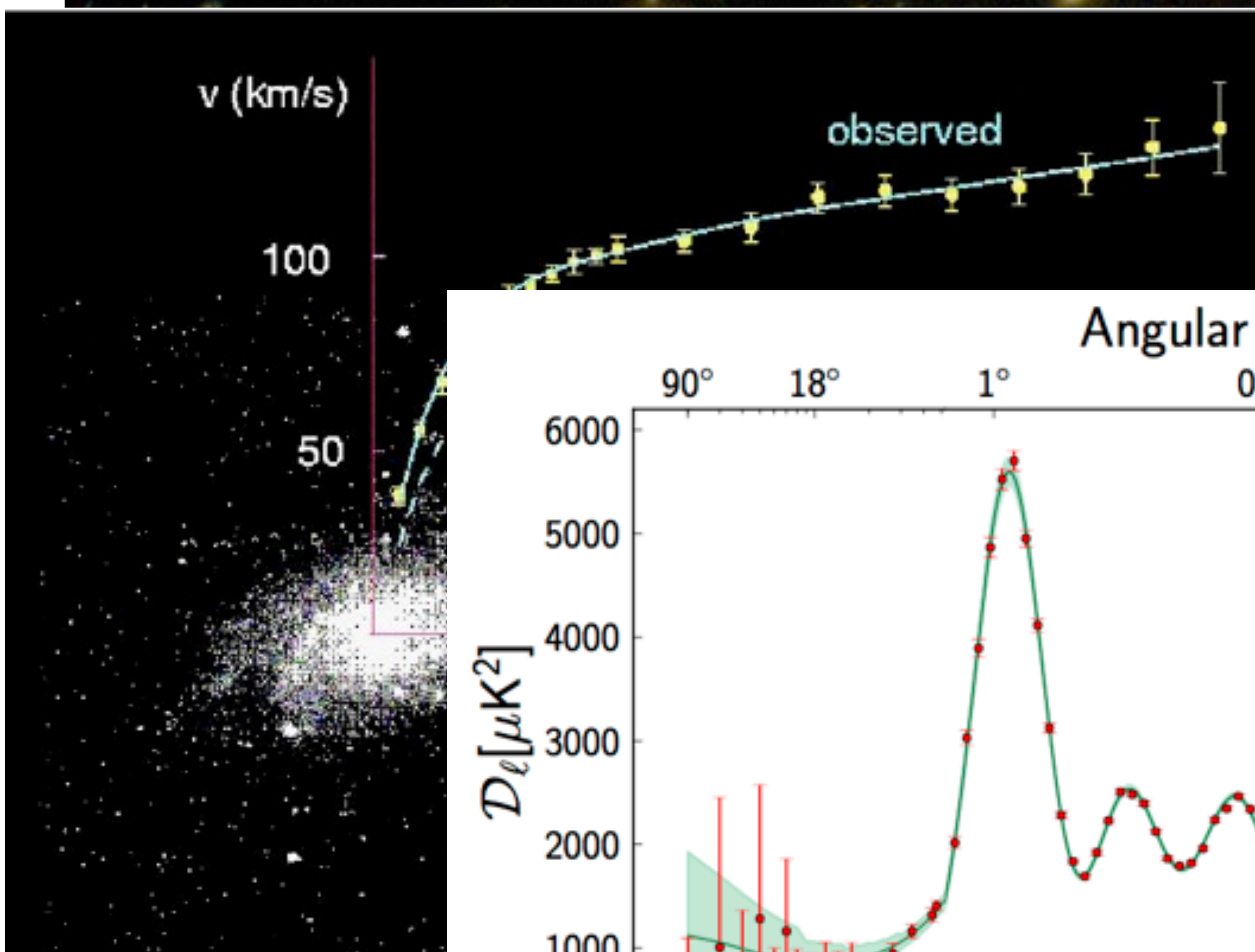
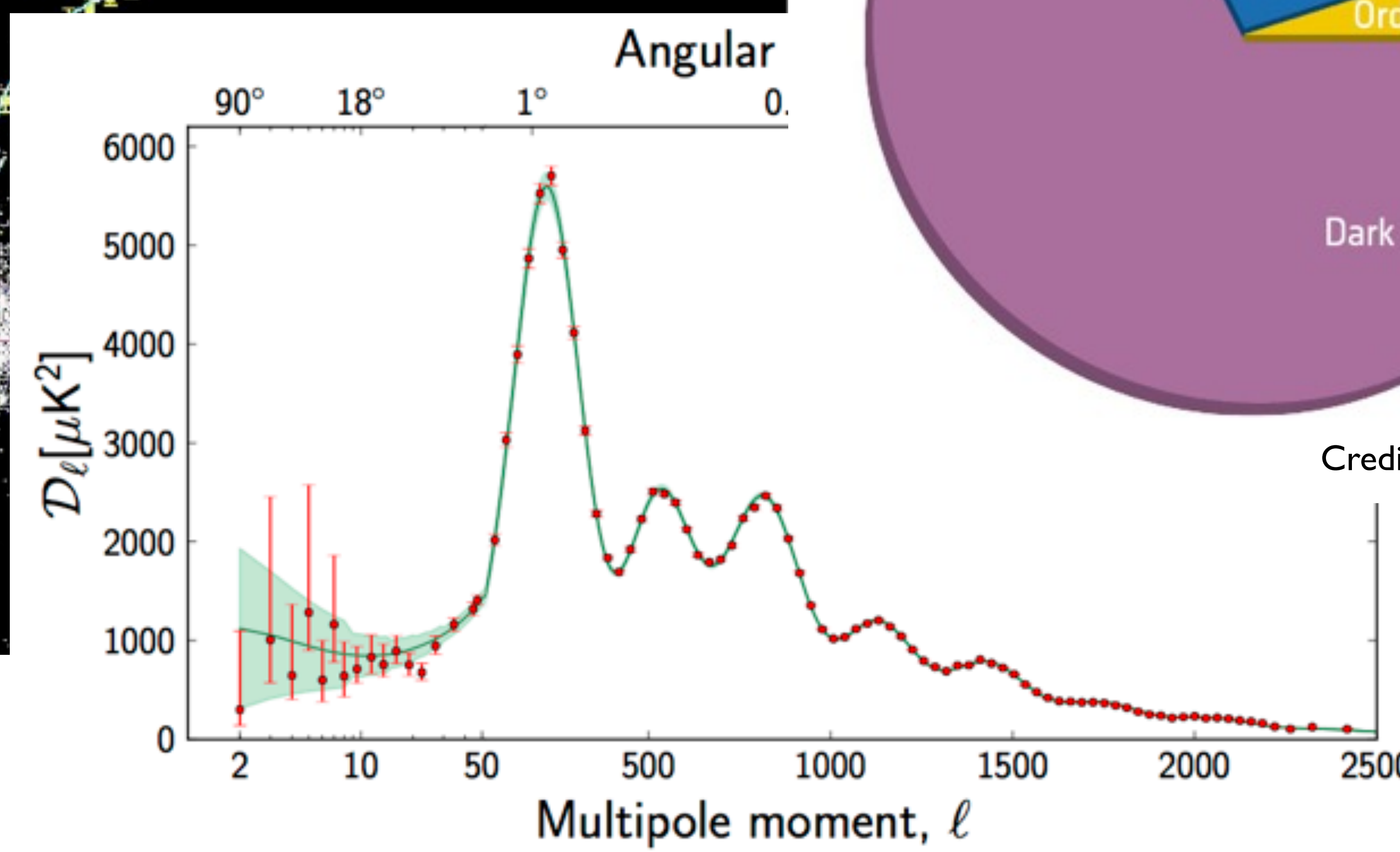
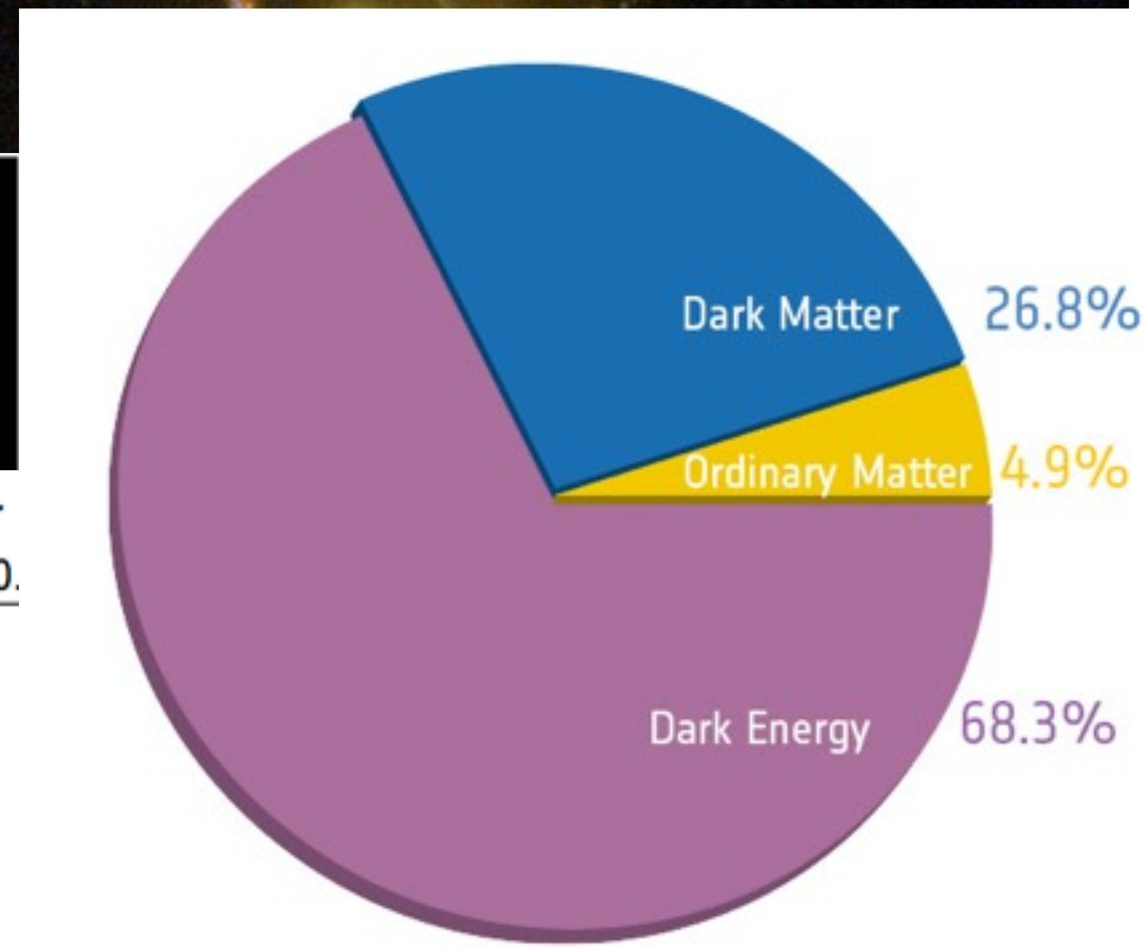


Planck Collaboration, 2013

Dark matter: evidence







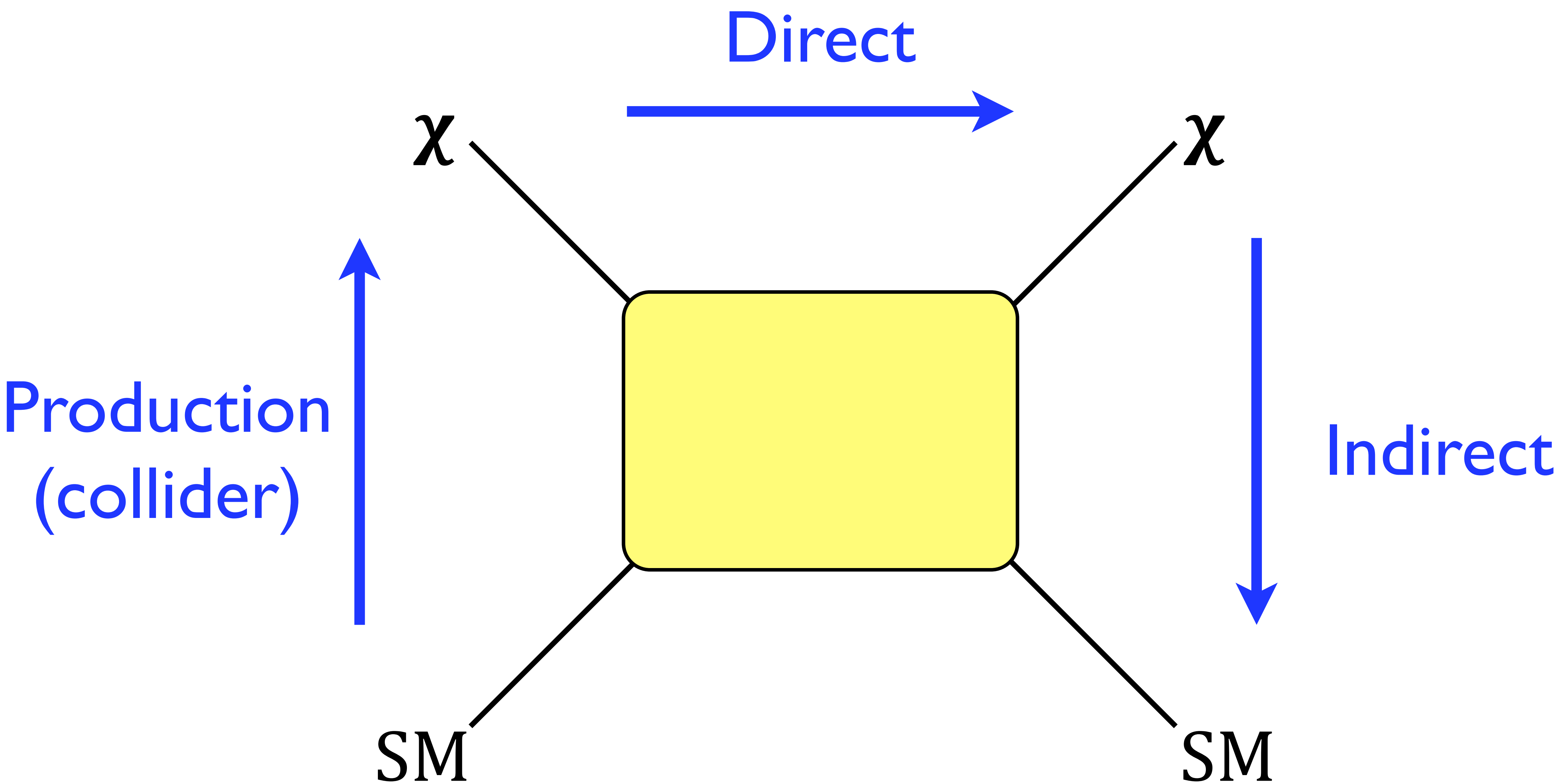
Credit: Planck Collaboration

Planck Collaboration, 2013

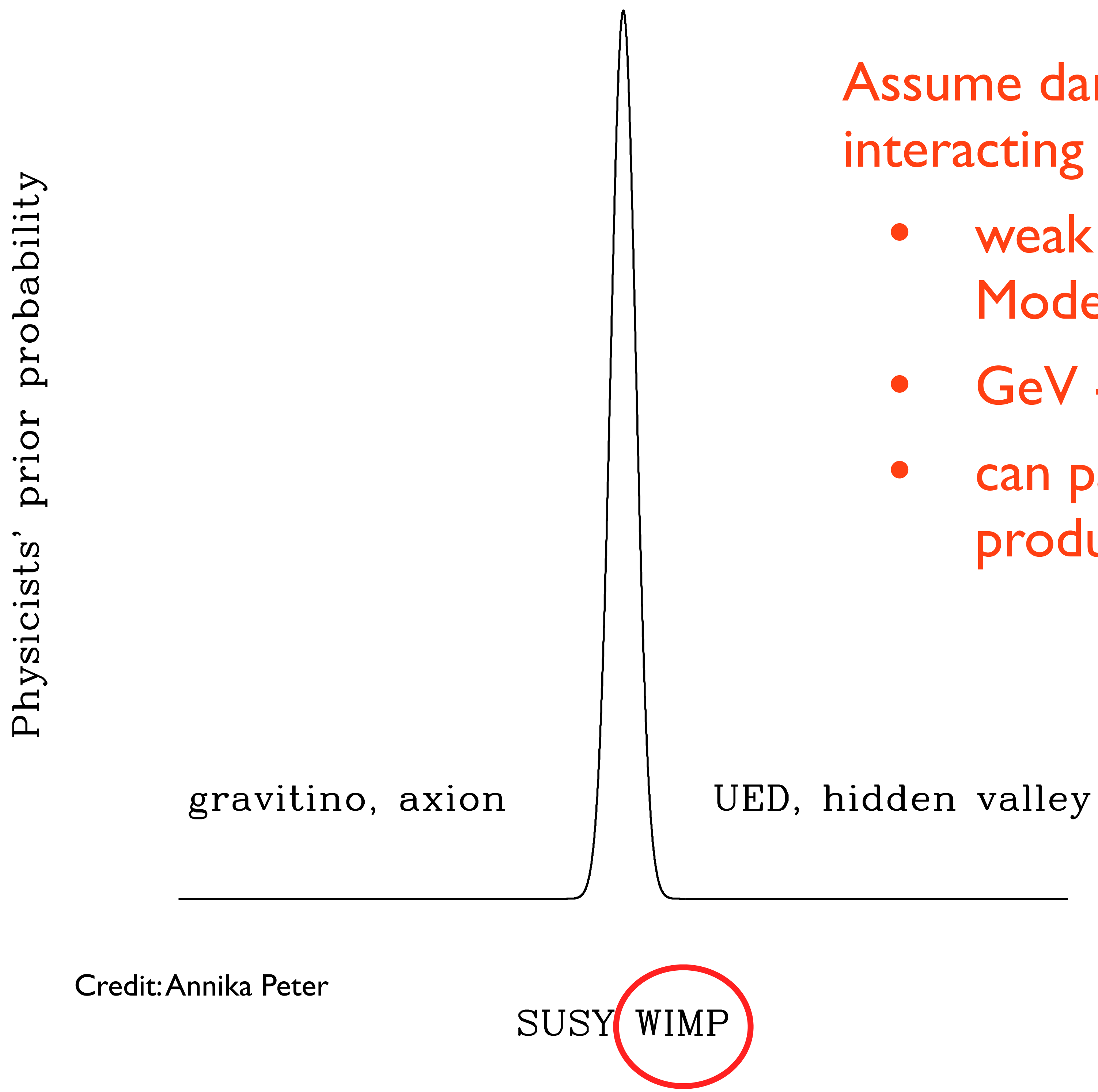
Indirect detection: key questions

- What kind of particle is dark matter?
- How does it interact with Standard Model particles?
- How is it distributed in the Universe? (And can this tell us about its particle properties?)

How to detect particle dark matter?



Particle dark matter candidates



Credit: Annika Peter

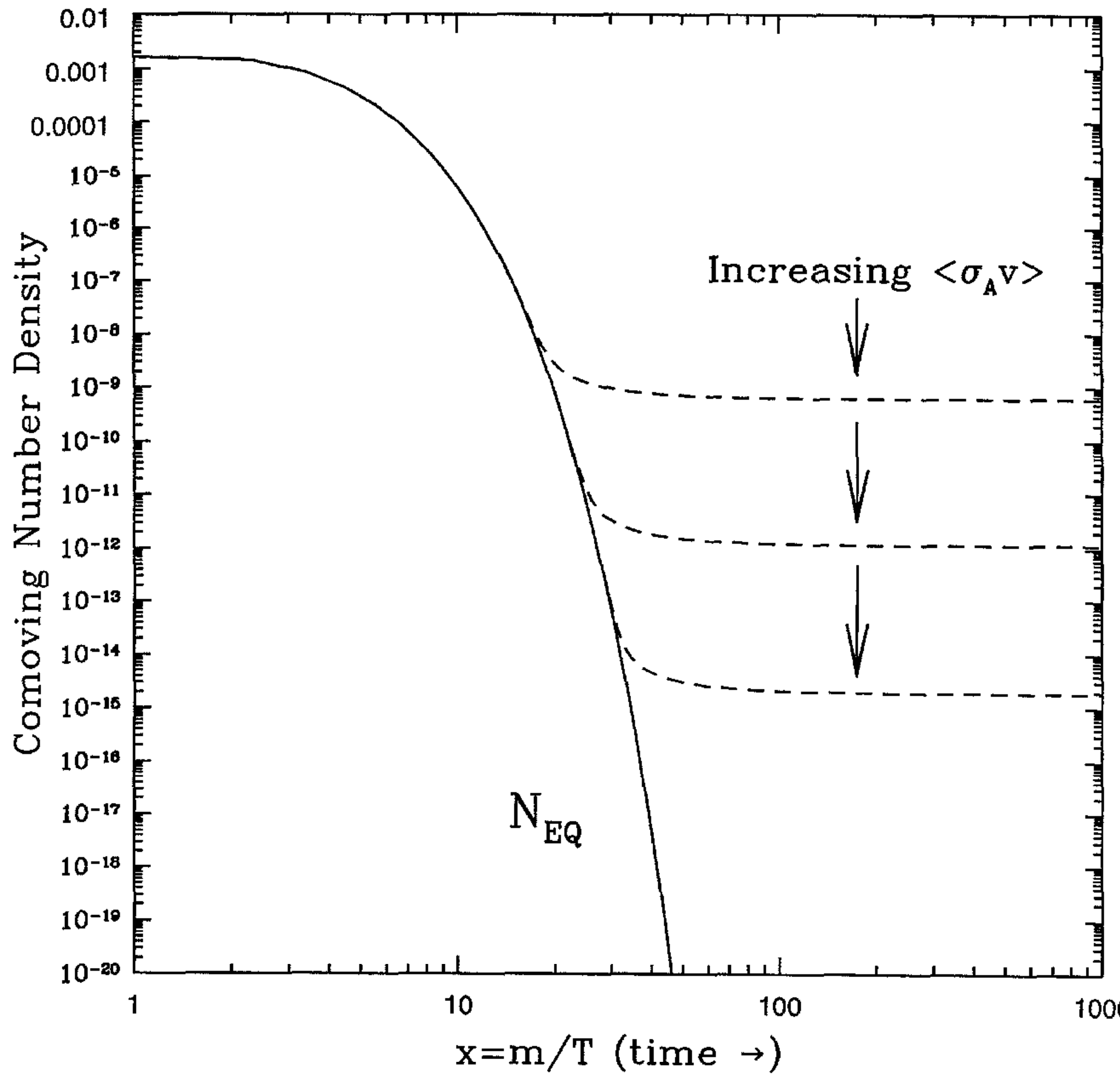
Assume dark matter is a WIMP (weakly-interacting massive particle):

- weak interactions with Standard Model
- GeV - TeV mass scale
- can pair annihilate or decay to produce Standard Model particles

Thermal relic dark matter

- if DM is a WIMP produced thermally in the early universe, its pair annihilation cross-section is related to the relic abundance today
- measured DM abundance gives prediction for the annihilation cross-section: $\langle\sigma v\rangle \sim 3 \times 10^{-26}$ cm^3 s^{-1}

Evolution of comoving density of DM particles



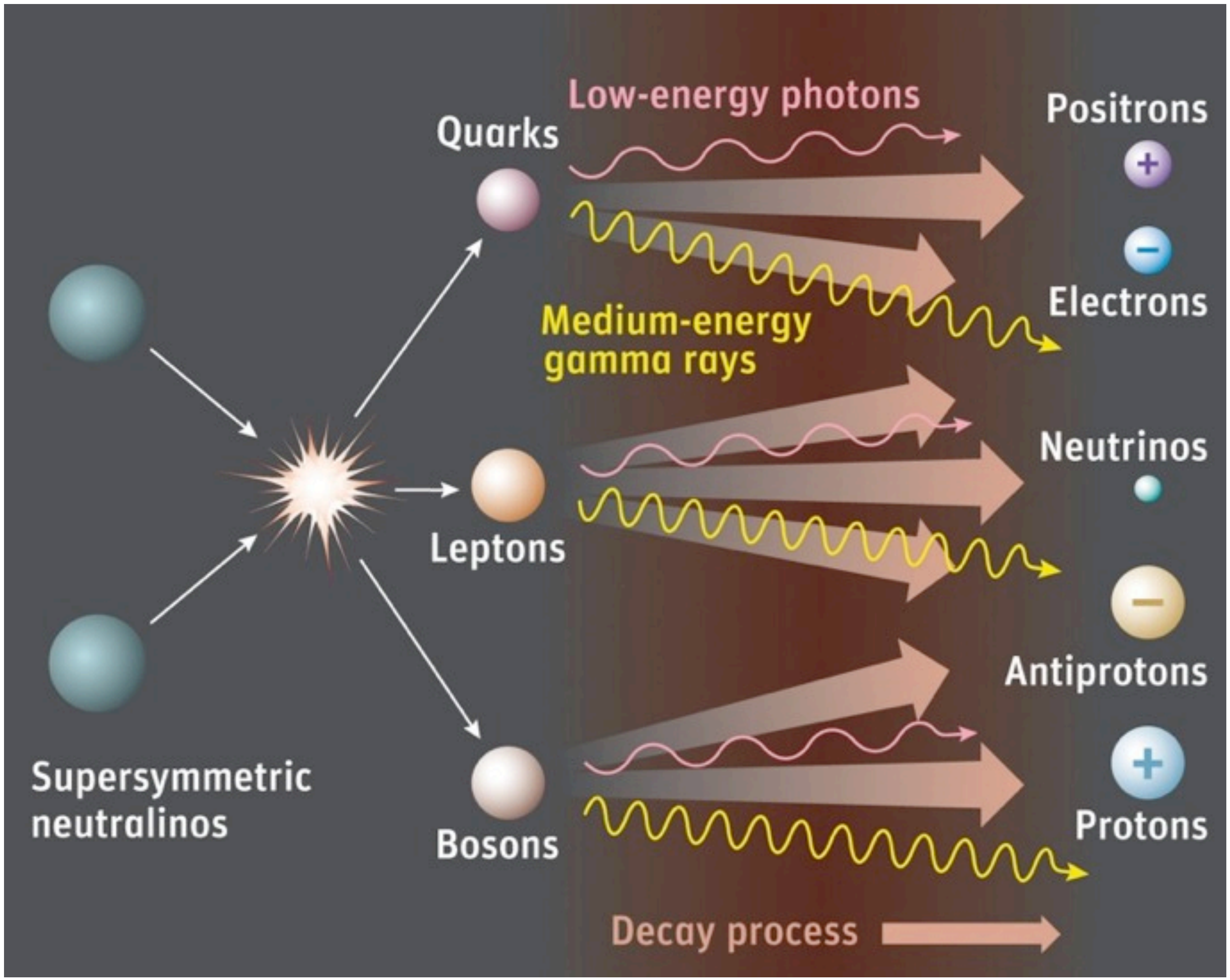
Jungman, Kamionkowski, and Griest 1996

Other candidates for indirect searches

- Sterile neutrinos
  - viable warm or cold DM candidate depending on production mechanism
  - radiatively decay to active neutrinos producing a photon line at half the sterile neutrino mass
  - most currently viable parameter space is for 1-100 keV mass (X-ray energies)
  - responsible for claimed 3.5 keV line?

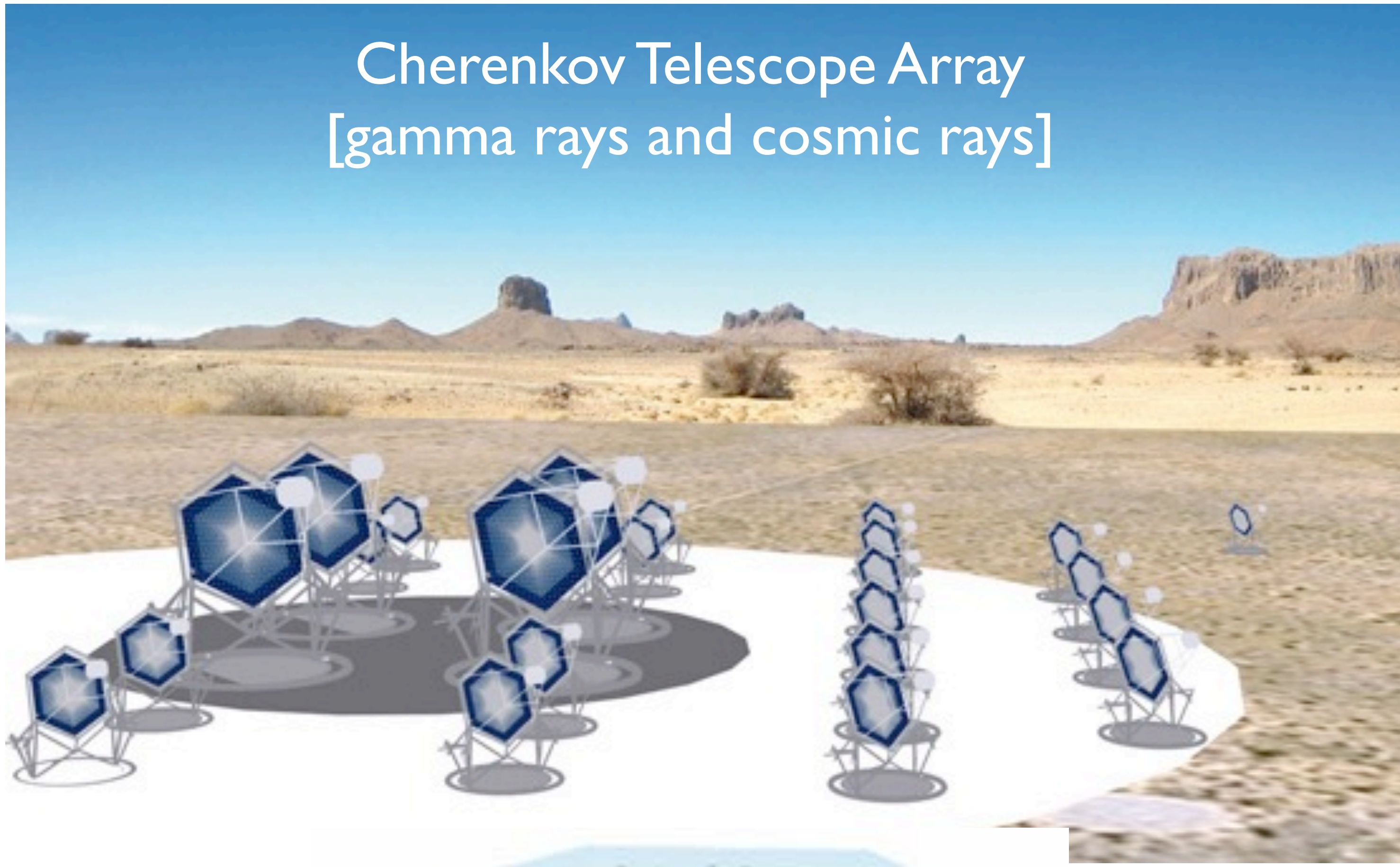
- Superheavy dark matter (mass > 10^{12} GeV)
  - non-thermal relic
  - can annihilate or decay to SM particles, such as ultra-high-energy cosmic rays or neutrinos

Indirect dark matter signals

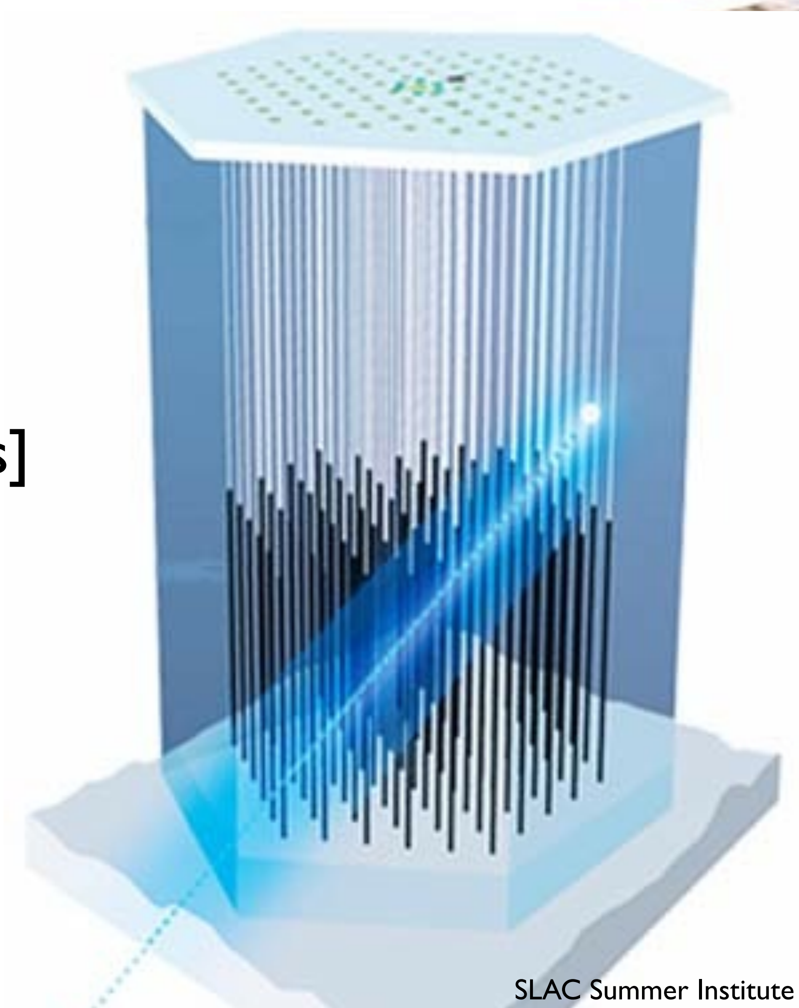


Credit: Sky & Telescope / Gregg Dinderman

Indirect detection

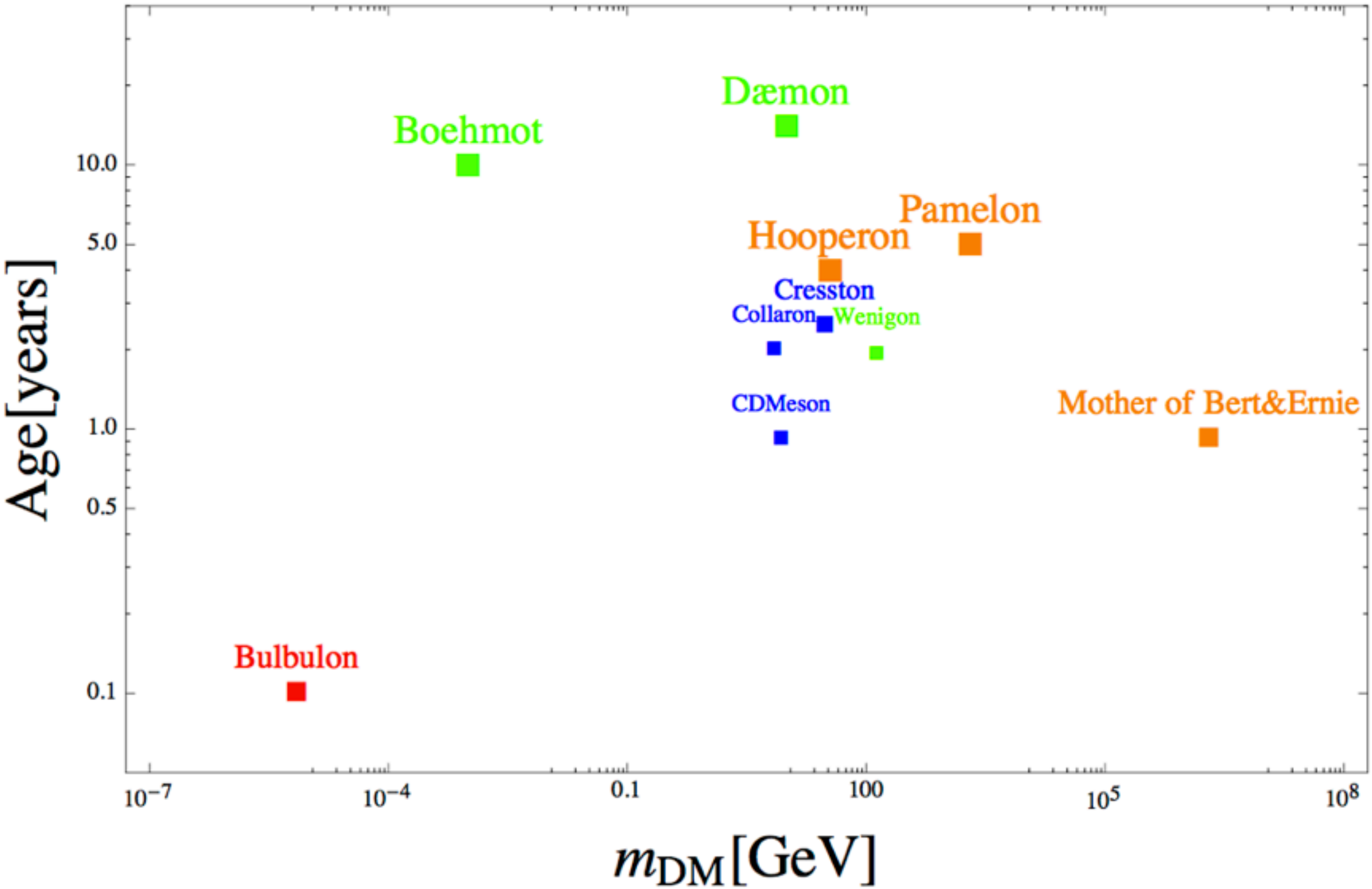


IceCube
[neutrinos]



Anomalies!

Credit: Jester @ http://resonaances.blogspot.com



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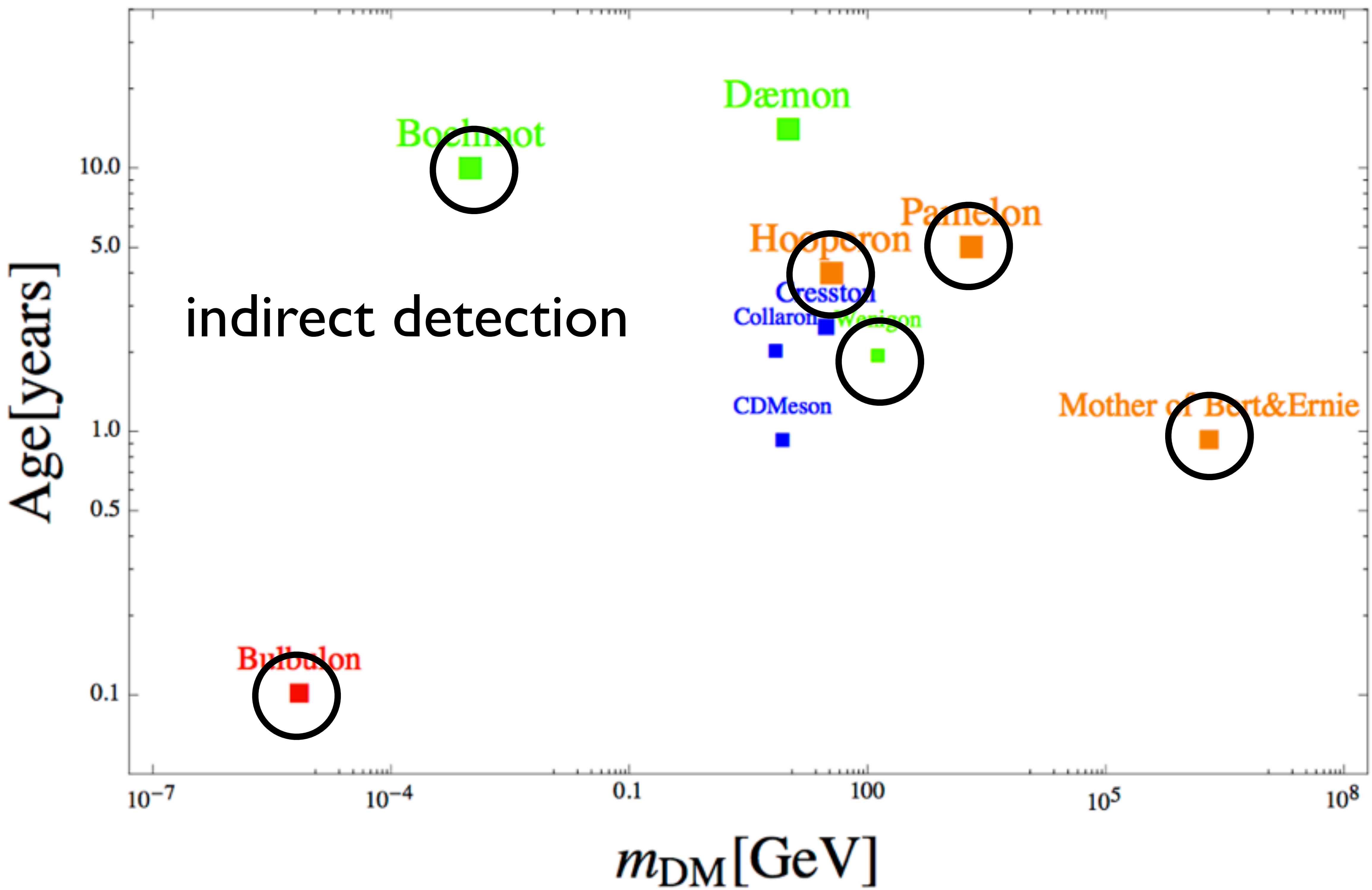

Indirect detection: selling points

- only way to identify *particle* DM in an astrophysical context

- needed to show that a DM candidate detected at a collider or in a lab indeed is the cosmological DM and is stable on cosmological timescales

- for WIMPs, there is a theoretical prediction for the total annihilation cross section

- anomalies! see also Dan Hooper's talk

Indirect messengers

	Instruments	Advantages	Challenges
Gamma-ray photons	Fermi, ACTs (HESS, VERITAS, MAGIC, CTA, GAMMA-400)	point back to source, spectral signatures	backgrounds, attenuation
Neutrinos	IceCube/DeepCore/PINGU, ANTARES, KM3NET, Super-K, Hyper-K	point back to source, spectral signatures	low statistics, backgrounds
Charged particles	PAMELA, AMS(-02), ATIC, ACTs, Fermi, CTA, CALET, GAPS	antimatter hard to produce astrophysically	diffusion, propagation uncertainties, don't point back to sources
Multiwavelength emission	[radio to X-ray telescopes!]	often better angular resolution, more statistics, different backgrounds	depends on assumptions about environment for secondary processes

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Predicting indirect signals

- particle physics factor x astrophysics factor
- several packages publicly-available to perform these calculations and more

Calculating indirect signals

(for particles that propagate directly to the observer without deflection, attenuation, or secondary production)

differential intensity = particle physics term “K” • astrophysics term “J”

$$[\text{differential intensity}] = \frac{\text{particles}}{\text{time} \cdot \text{area} \cdot \text{solid angle} \cdot \text{energy}}$$

Caution: definition of “J” is not standardized! Watch for factors of 2, 4π, $r_\odot$, $\rho_\odot$, and integration over solid angles!

ANNIHILATION:

$$K_{\rm ann} = \frac{\mathrm{d}N}{\mathrm{d}E}\frac{\langle\sigma v\rangle}{2m_\chi^2}$$

$$J_{\rm ann}(\psi) = \frac{1}{4\pi}\int_{los} \mathrm{d}s\ \rho^2(s,\psi)$$

DECAY:

$$K_{\rm decay} = \frac{\mathrm{d}N}{\mathrm{d}E}\frac{1}{m_\chi \tau_\chi}$$

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spectrum of particles produced

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dark matter particle mass

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pair annihilation cross section times average relative velocity

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dark matter particle lifetime (τ_χ)

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dark matter density

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Tools to calculate indirect signals

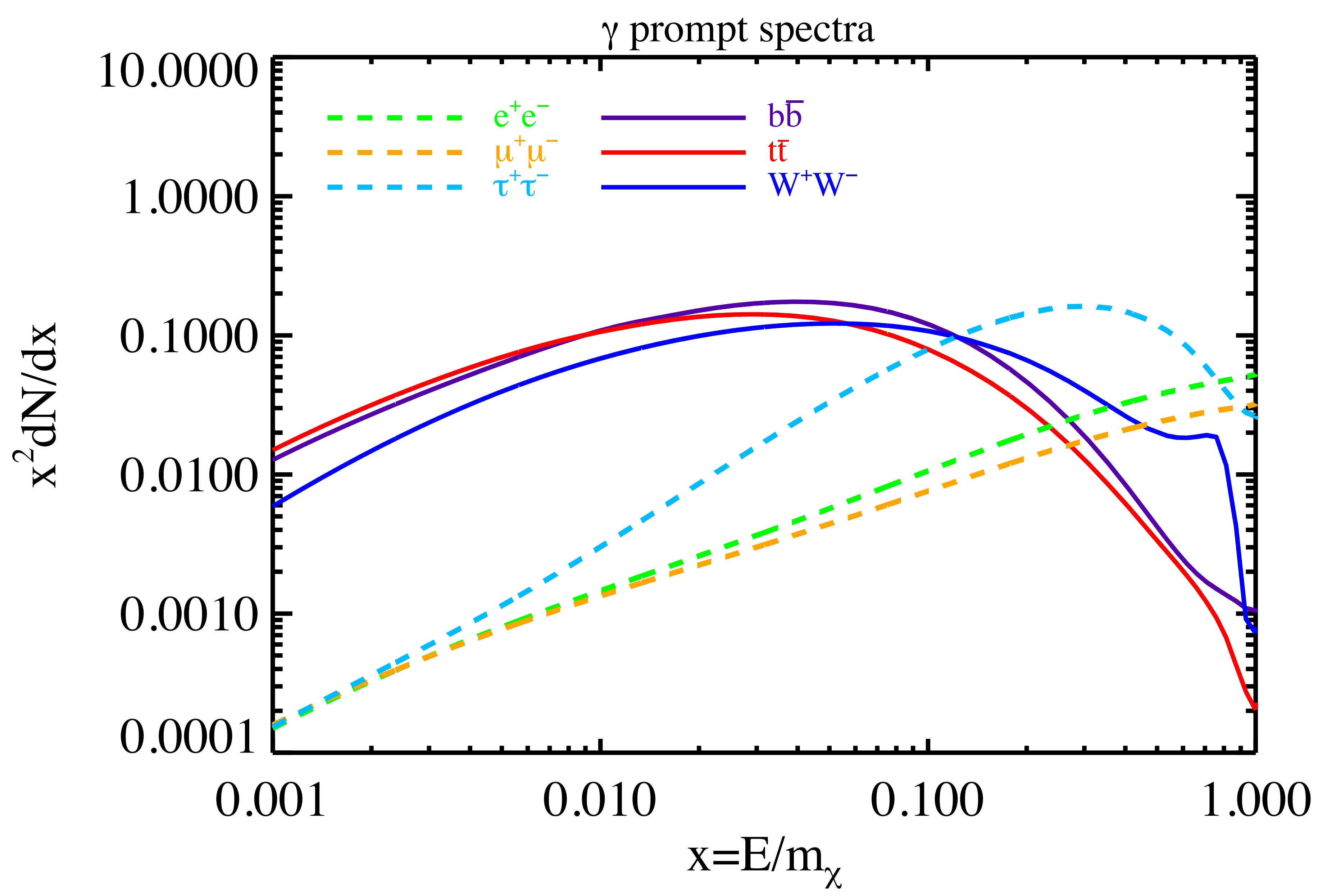
- DarkSUSY: http://www.fysik.su.se/~edsjo/darksusy/
- PPPC4DMID: http://www.marcocirelli.net/PPPC4DMID.html

Annihilation and decay spectra

- particles produced at energies up to the dark matter mass for annihilation (half the mass for decay)
- spectral shape encodes info about particle properties
- spectra shown are source spectra in vacuum -- secondary processes can modify observed spectra

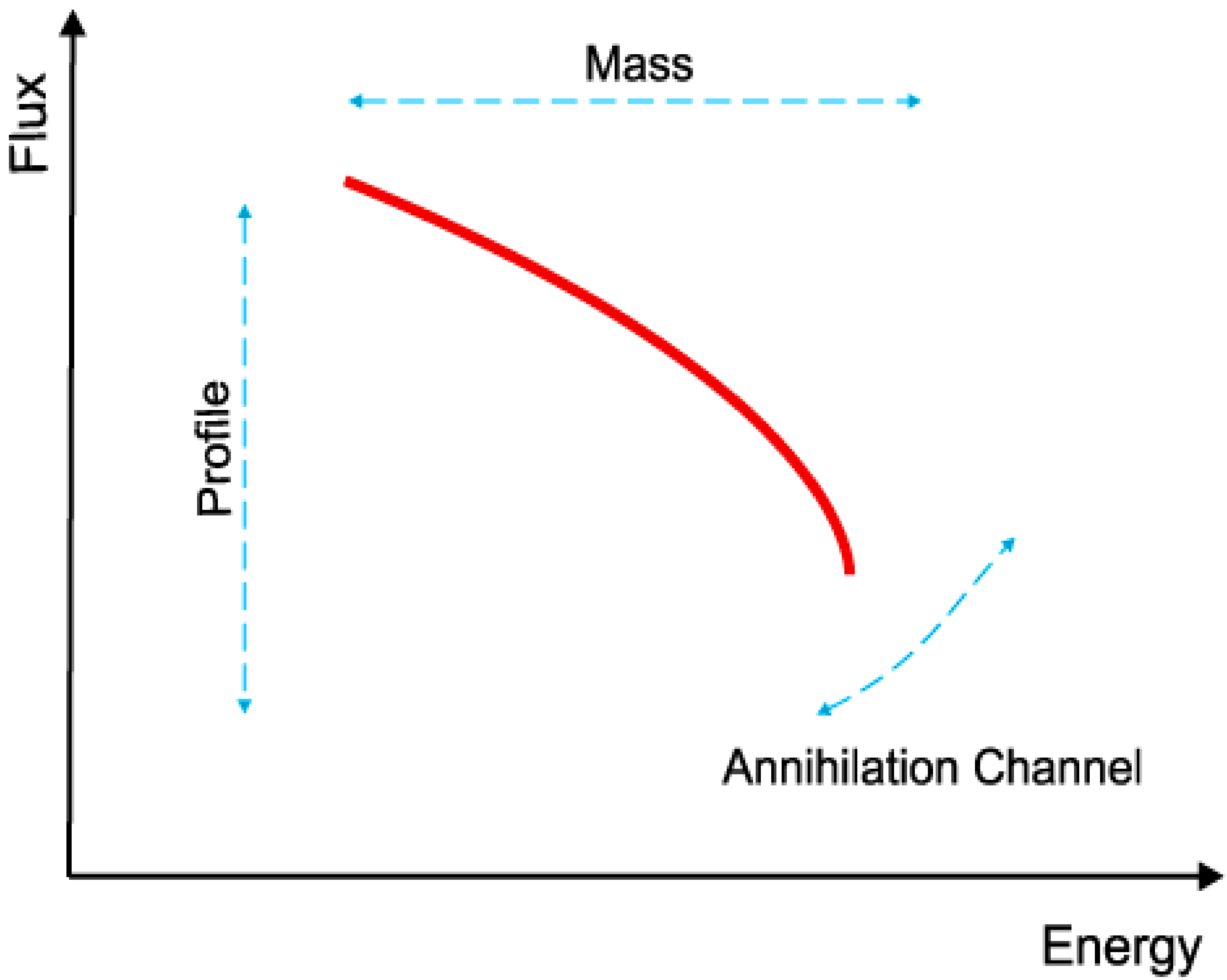
Dark matter photon spectra

- "soft" channels: produce a continuum gamma-ray spectrum primarily from decay of neutral pions
- "hard channels": include final state radiation (FSR) associated with charged leptons in the final states
- line emission: γγ, Zγ, hγ (not shown), loop-suppressed



Spectra calculated with PPPC 4 DM ID [Cirelli et al. 2010]

Indirect dark matter signals

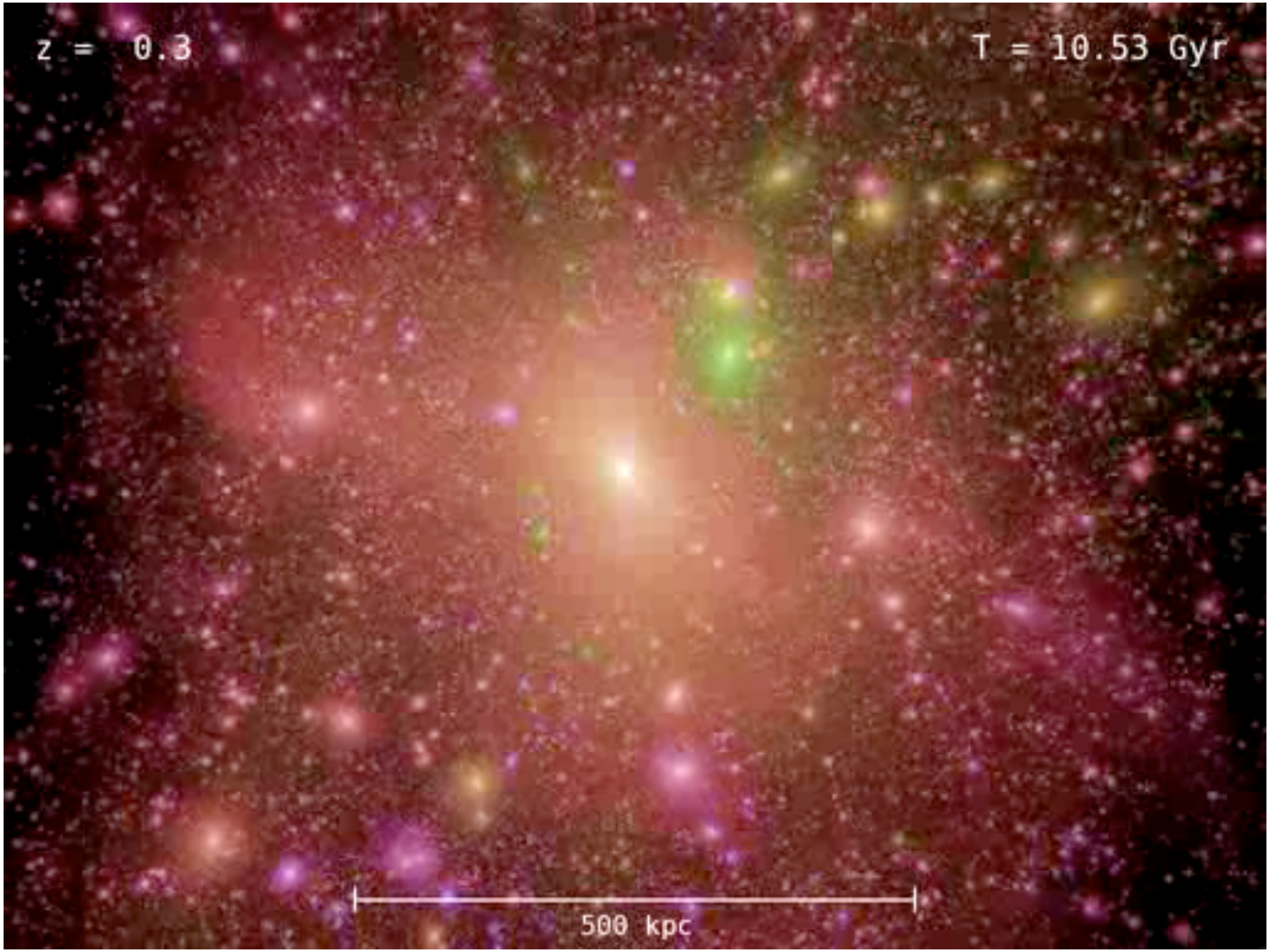


Bertone 2007

The DM distribution

- motivated by numerical simulation results, constrained by observations
- DM density in inner part of halo goes as roughly $r^{-\Gamma}$ with $\Gamma \approx 1$, but there is likely large variation between halos, and this is only weakly constrained for individual objects
- presence of baryons can significantly modify the DM density

The dark matter spatial distribution



Credit: Springel et al. (Virgo Consortium)

Dark matter annihilation signal

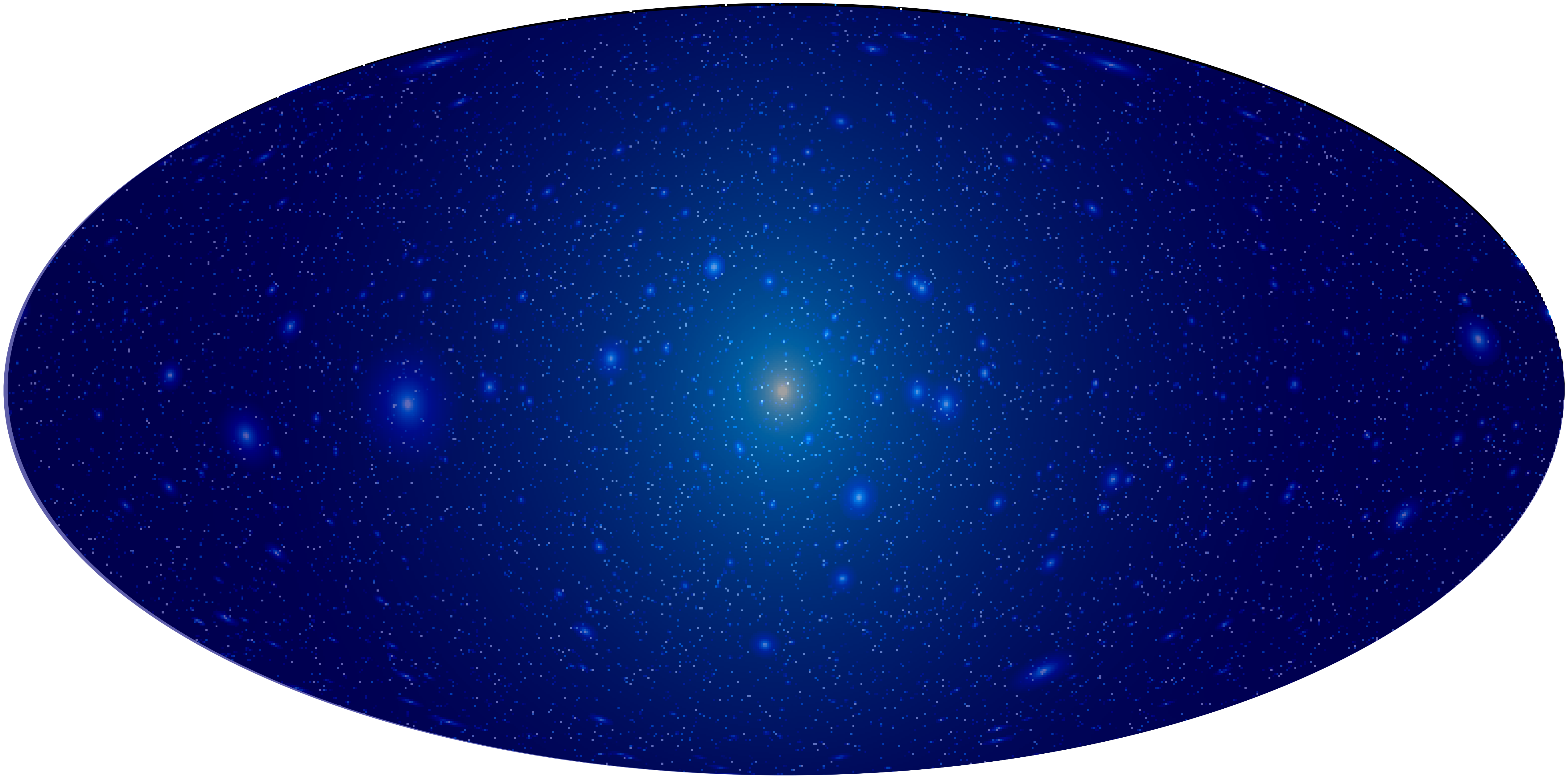


Image credit: JSG 2008

Density profiles

Navarro-Frenk-White (NFW):

$$\rho_{\rm NFW}(r) \propto \frac{1}{\left(\frac{r}{r_s}\right)\left[1+\left(\frac{r}{r_s}\right)\right]^2}$$

Generalized NFW (GNFW):

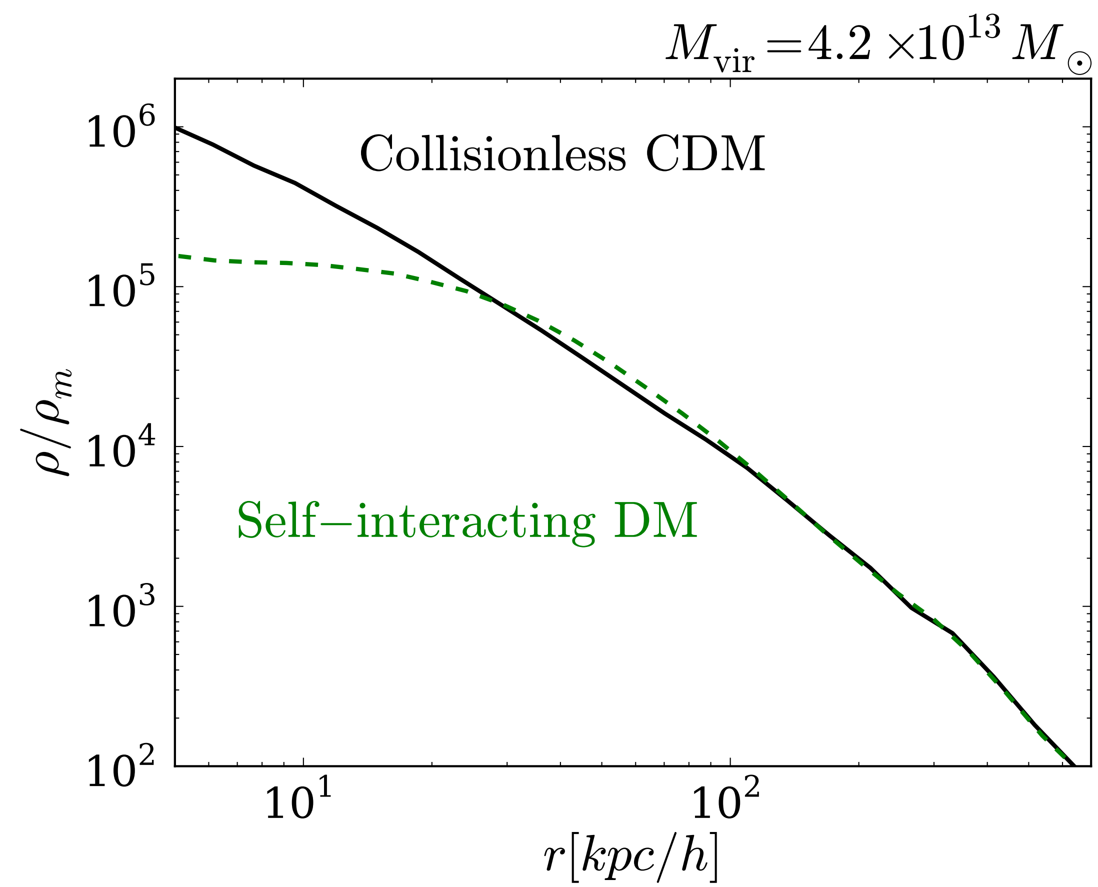
$$\rho_{\gamma}(r) \propto \frac{1}{\left(\frac{r}{r_s}\right)^{\gamma}\left[1+\left(\frac{r}{r_s}\right)\right]^{3-\gamma}}$$

Einasto:

$$\rho_{\rm Ein}(r) \propto e^{-\left(\frac{2}{a}\right)\left[\left(\frac{r}{r_s}\right)^{a}-1\right]}$$

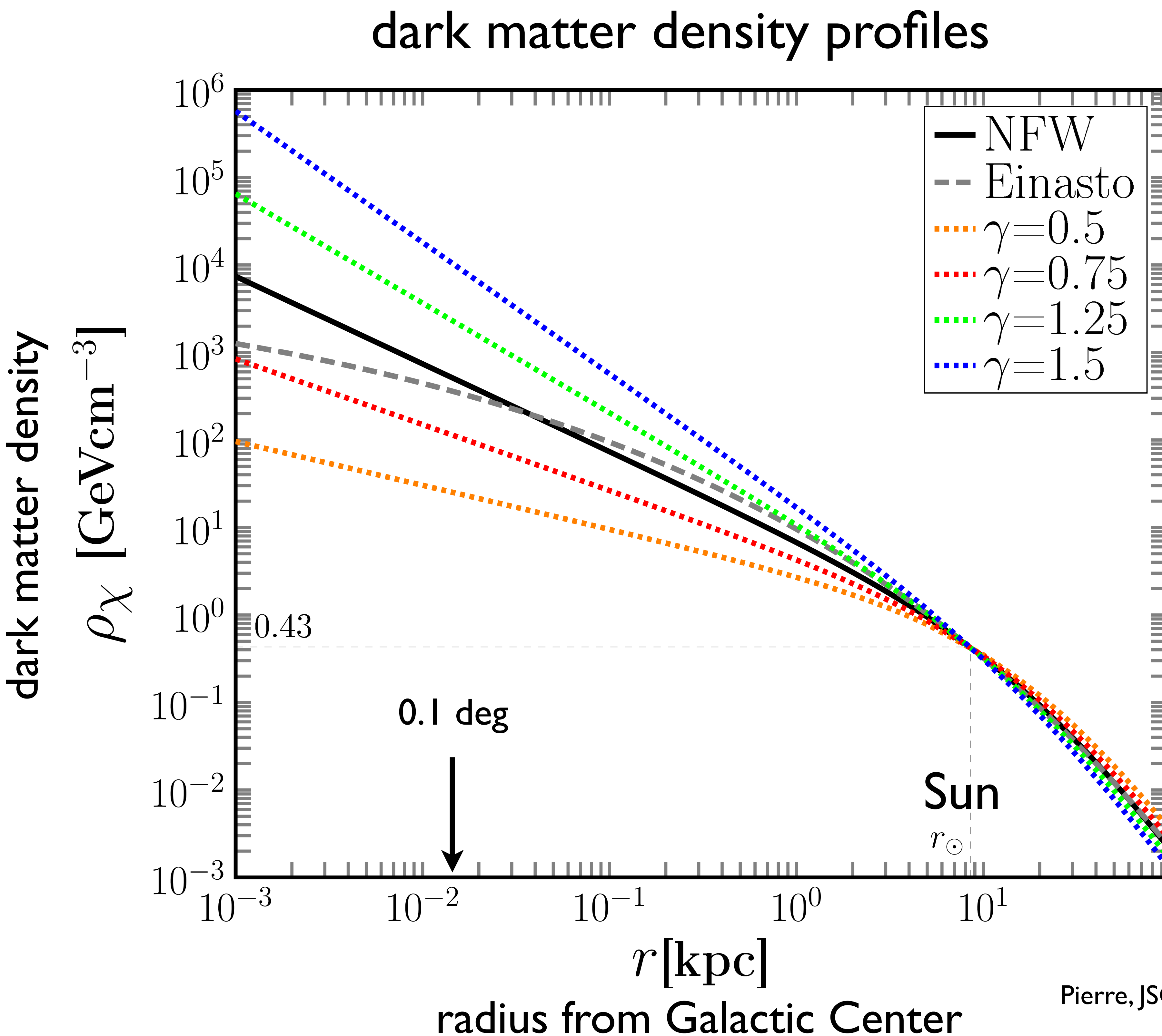
Modifying the density profile

- adiabatic contraction: baryons pull in the DM, steepening the profile
- feedback: supernovae blow out gas, rapidly changing the potential and disrupting cuspy DM profiles
- self-interacting DM: allowing DM to exchange energy leads to a flattening of the DM profile



Weinberg et al. 2013

Dark matter signals from the Inner Galaxy



inner regions:

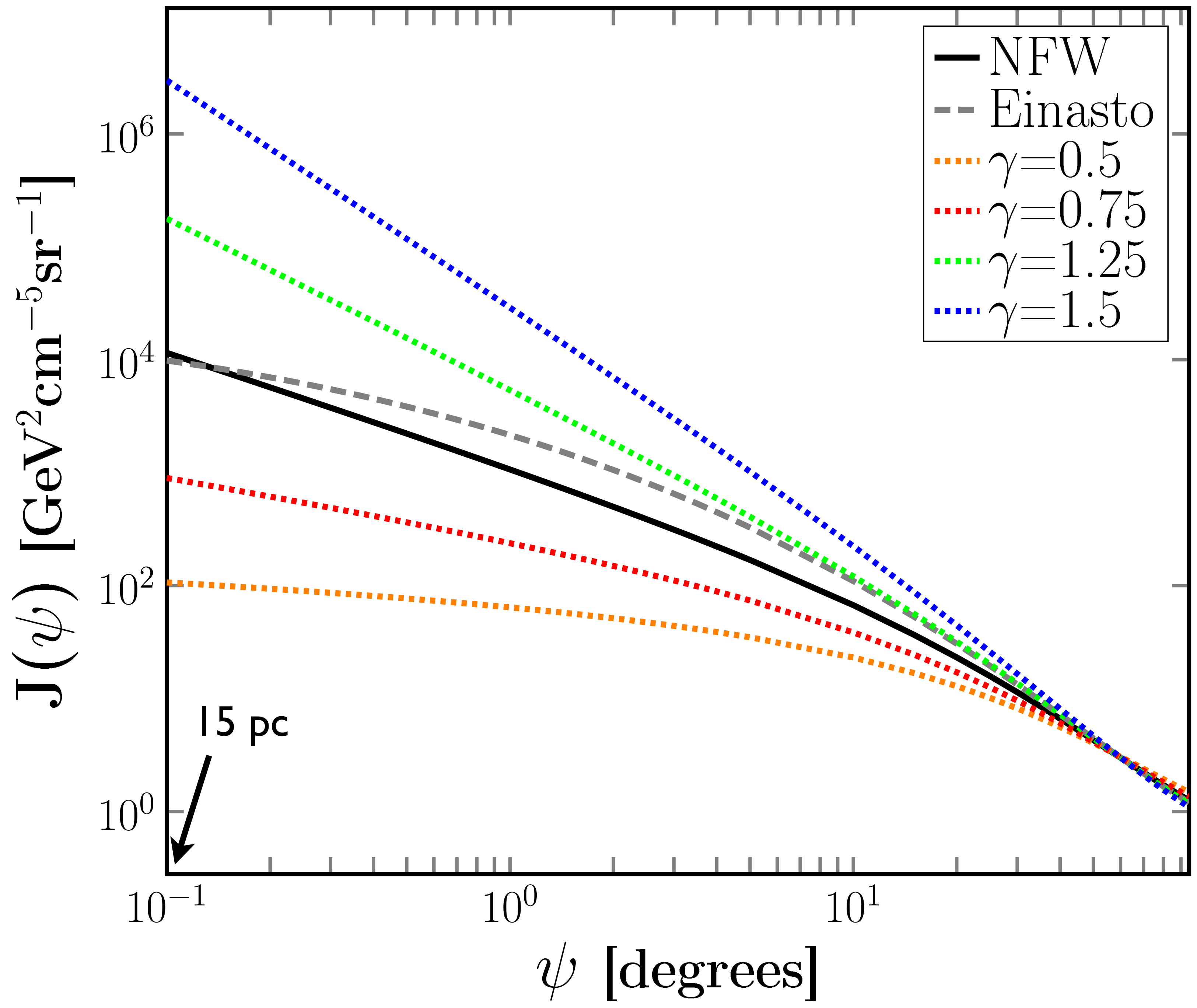
$$\rho(r) \propto r^{-\gamma}$$

Pierre, JSG, & Scott, 2014

Dark matter signals from the Inner Galaxy

angular dependence of dark matter intensity

(proportional to intensity)



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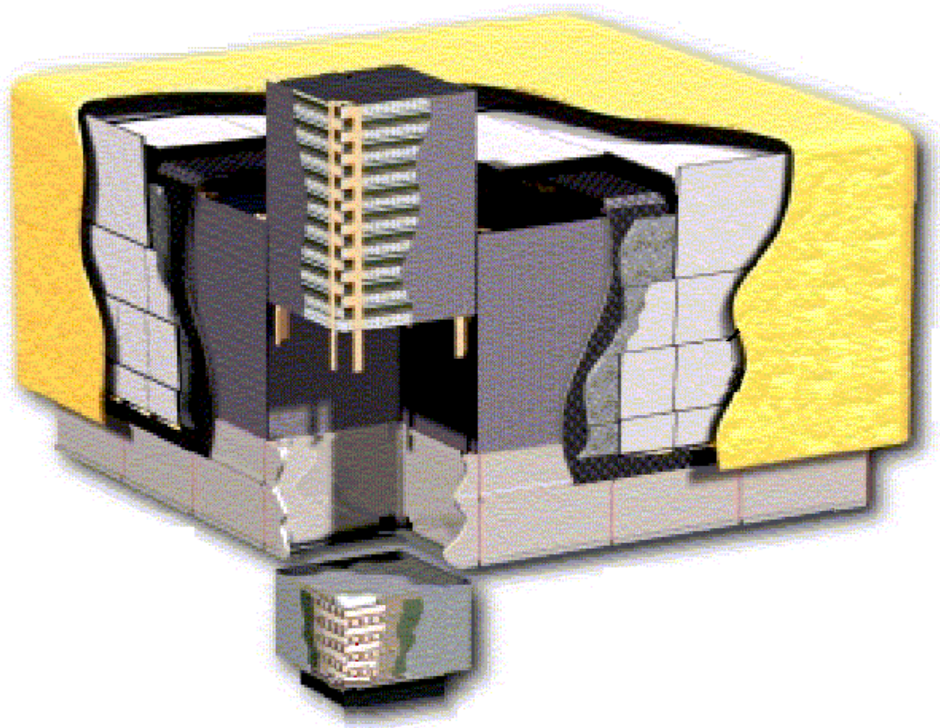
angle from Galactic Center

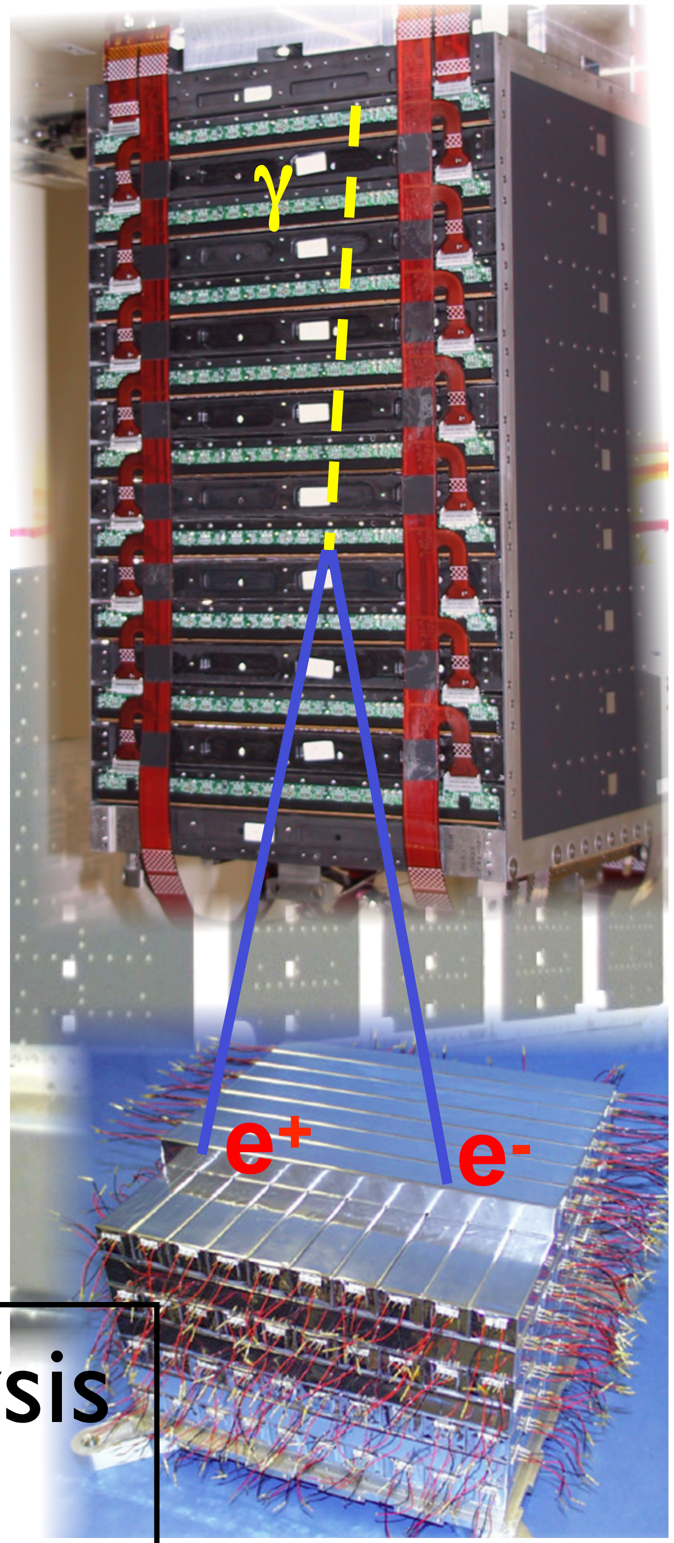
Pierre, JSG, & Scott, 2014

Gamma-ray searches

- look for prompt and sometimes also secondary emission from WIMP annihilation/decay; sift through large, uncertain backgrounds
- to observe gamma rays below about 10 GeV MUST GO TO SPACE: Fermi Large Area Telescope (LAT)
- for high energies, need large effective area: ground-based imaging atmospheric Cherenkov telescopes (IACTs), e.g., H.E.S.S., MAGIC, VERITAS, and CTA

The Fermi Large Area Telescope (LAT)





- pair-production detector: detects charged particles as well as gamma rays
- excellent charged particle event identification and background rejection
- 20 MeV to > 300 GeV
- angular resolution ~ 0.1 deg above 10 GeV
- large FOV ~ 2.4 sr

Fermi data and analysis tools are public!

The Fermi LAT gamma-ray sky

3-year all-sky map, E > 1 GeV

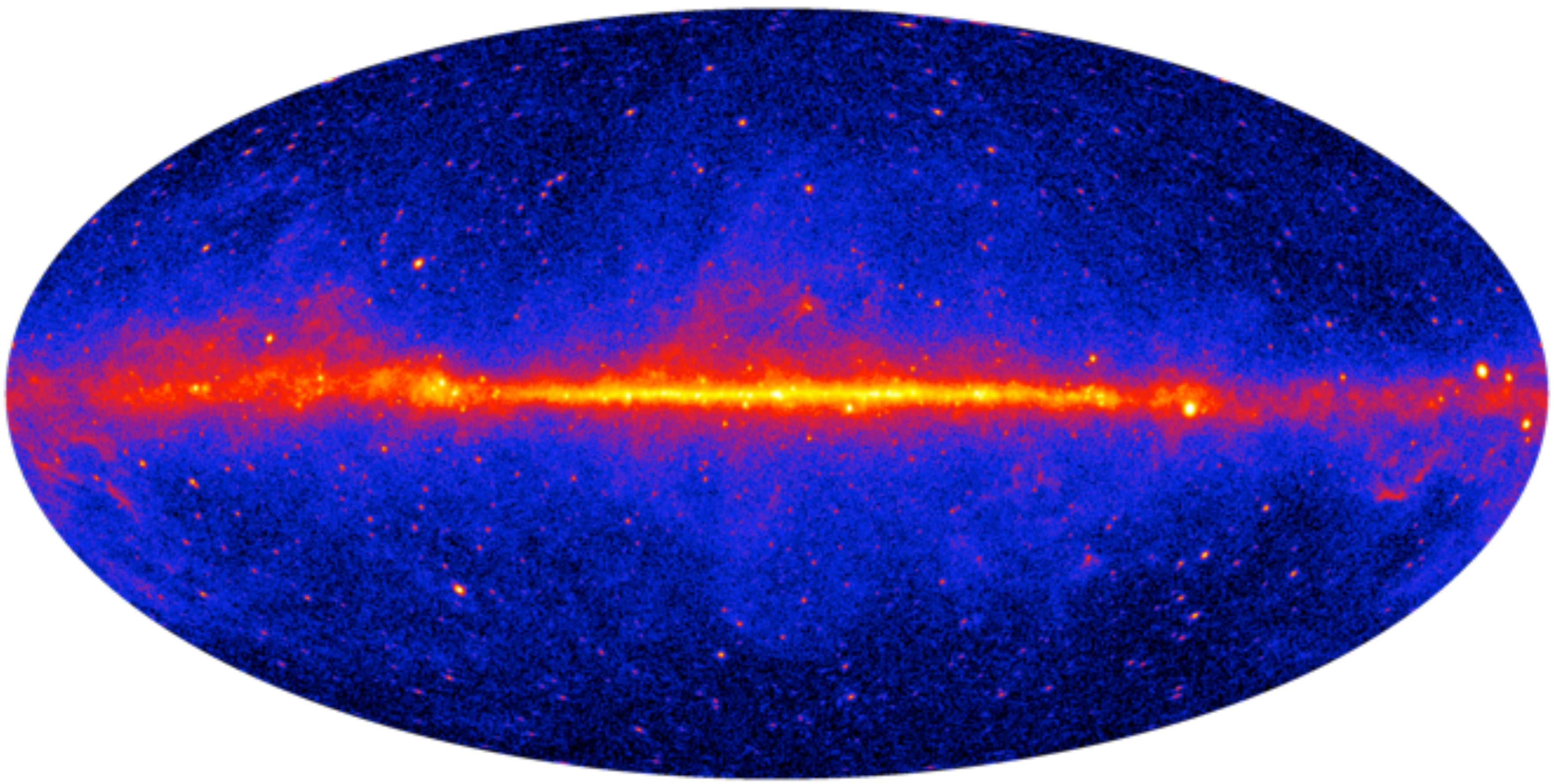
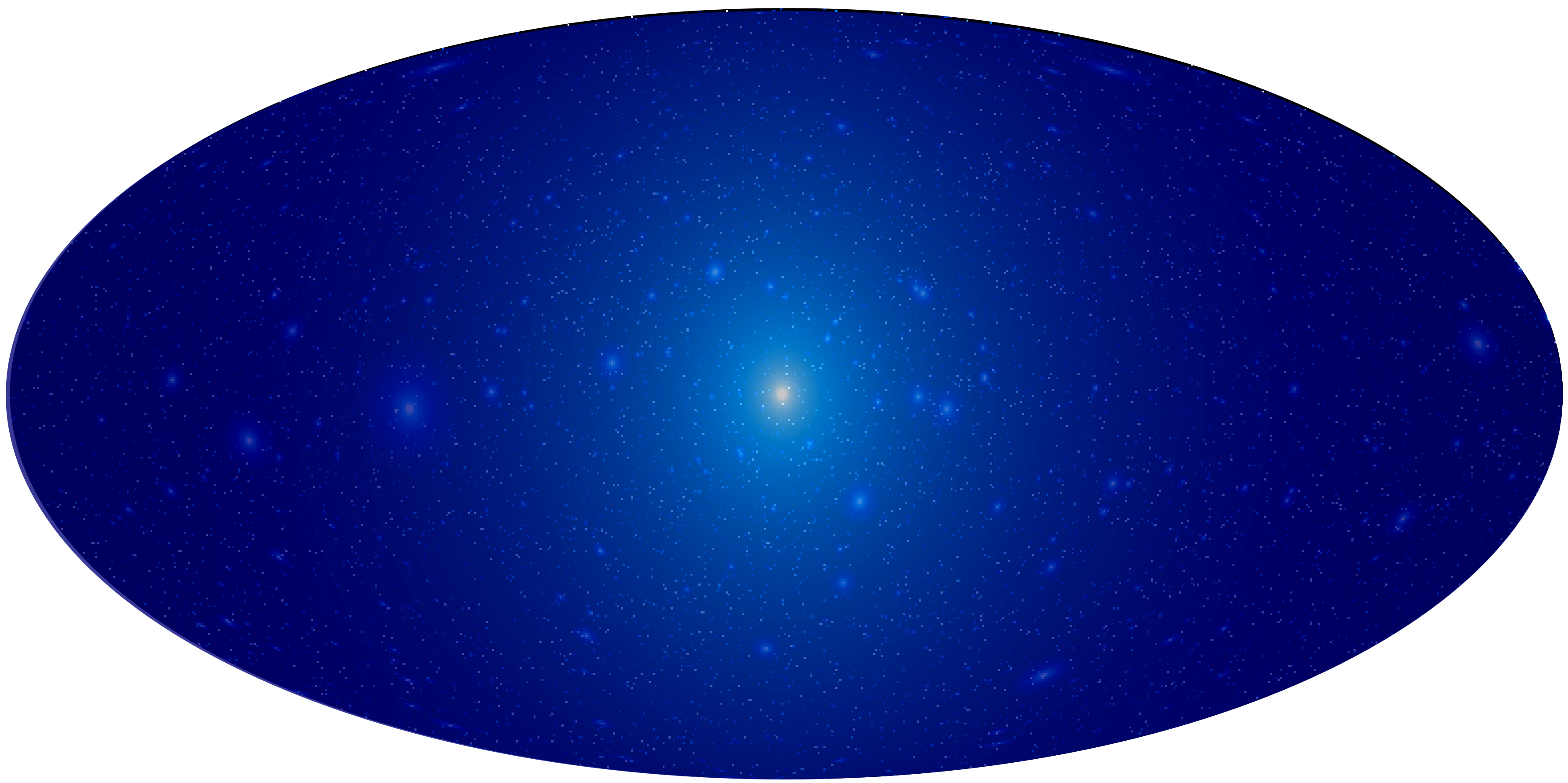


Image Credit: NASA/DOE/International LAT Team



Gamma rays from dark matter annihilation

Image credit: JSG 2008

Fermi LAT dark matter search targets

The Milky Way halo

The inner galaxy

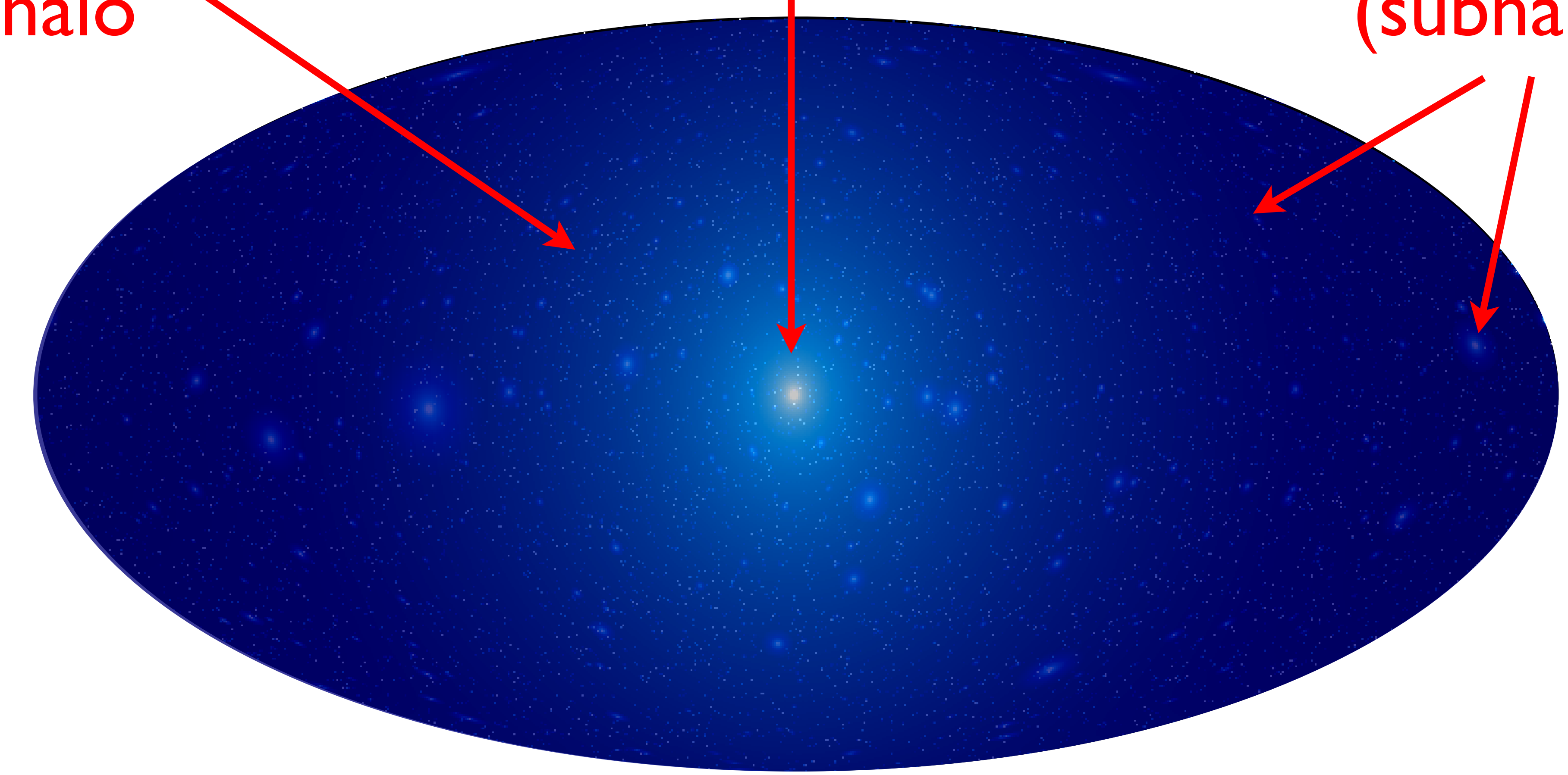
Unassociated sources (subhalos?)

Galaxy clusters

Dwarf galaxies

The Sun

Spectral lines



Gamma rays from dark matter annihilation

Cosmic-ray electrons and positrons

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The isotropic gamma-ray background

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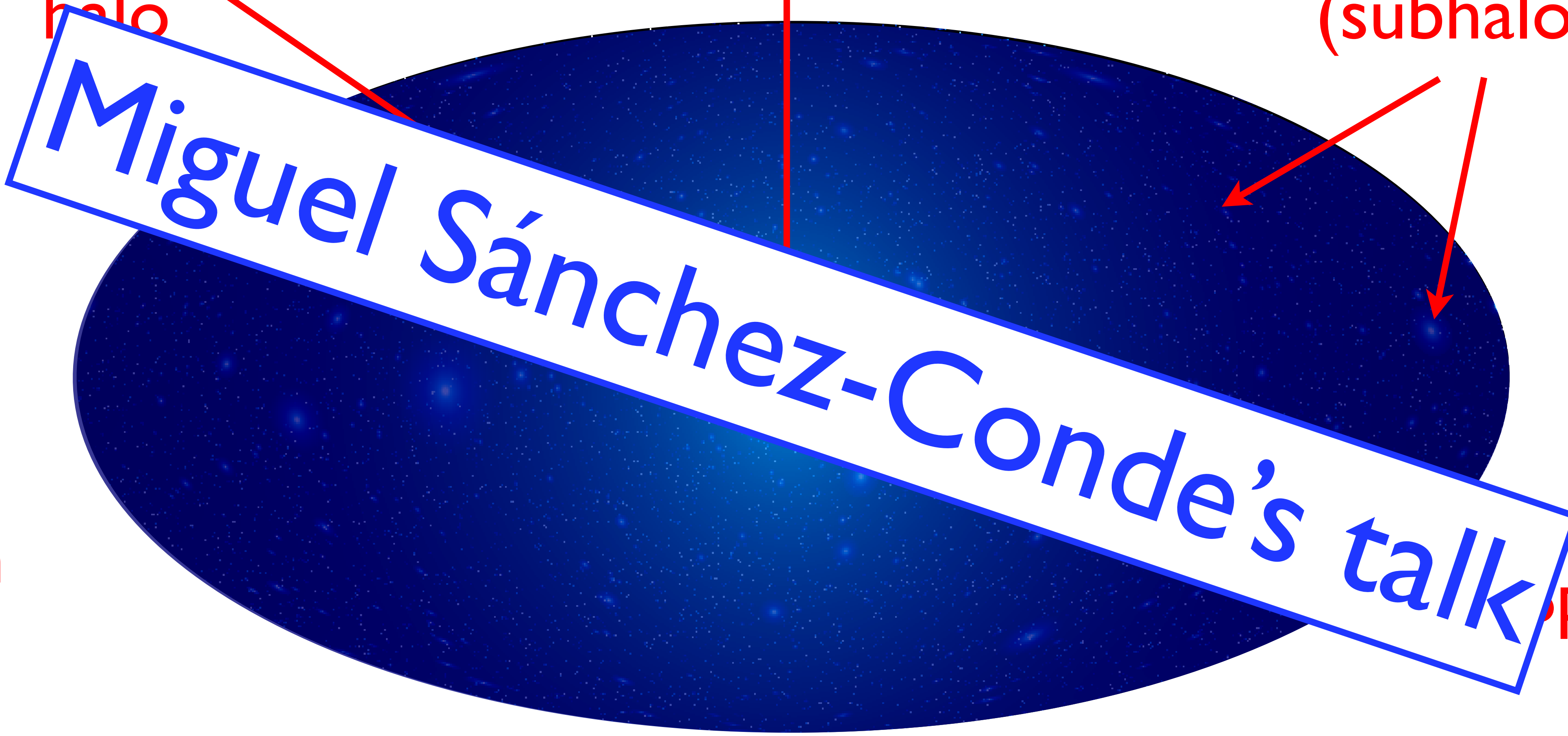

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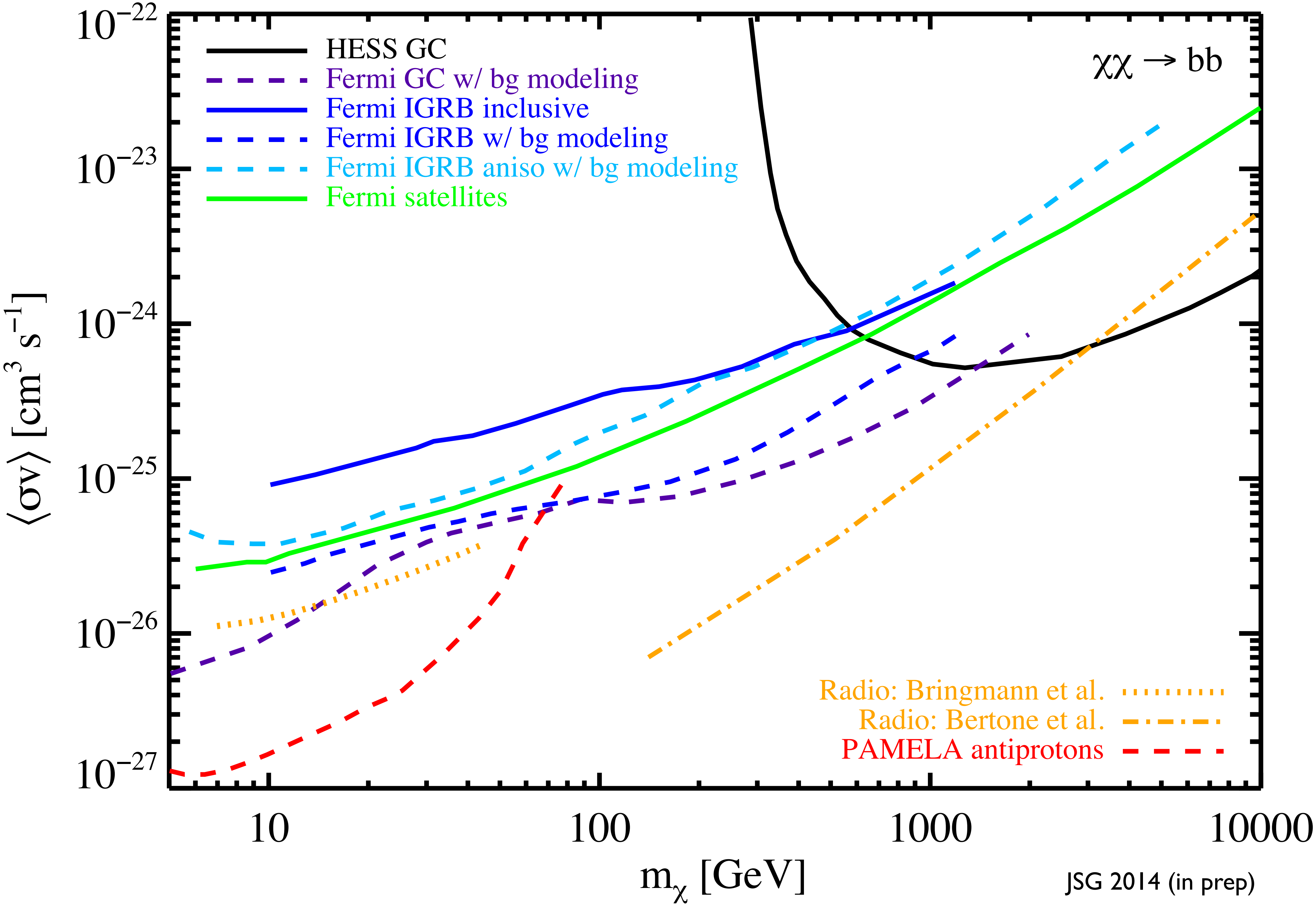
Current constraints

95% CL upper limits on annihilation cross section to bb



JSG 2014 (in prep)

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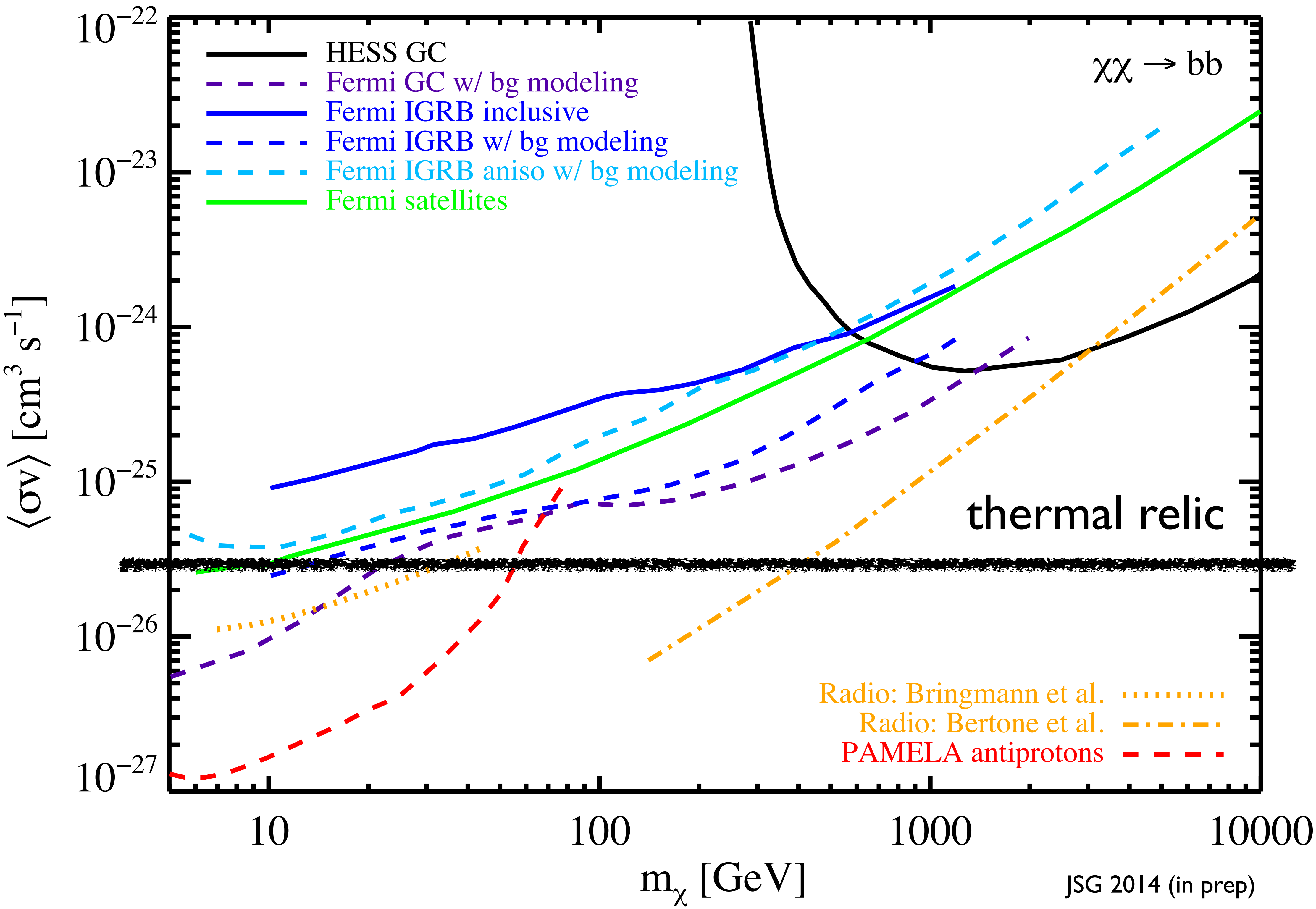


JSG 2014 (in prep)

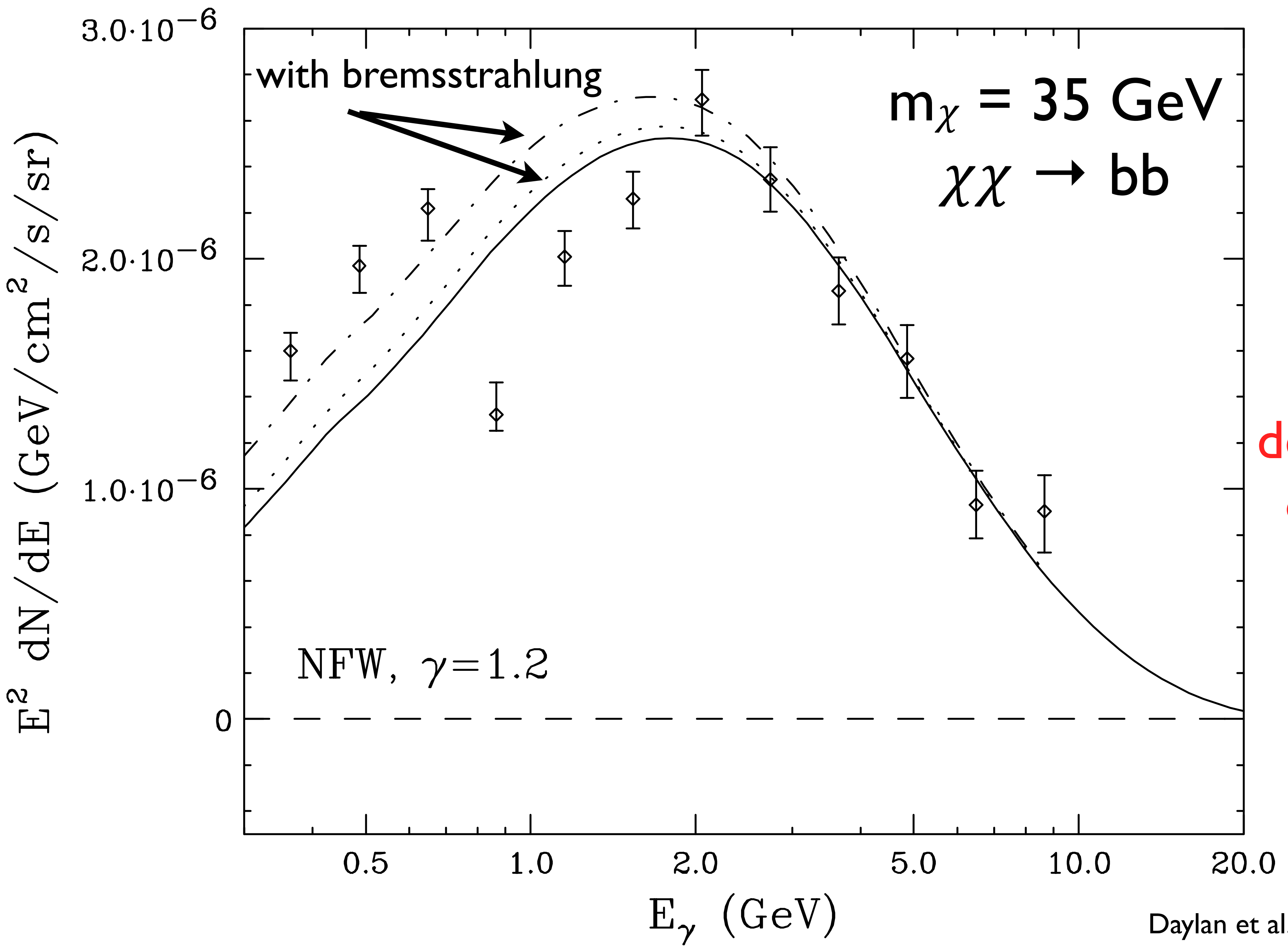
Anomaly: the Galactic Center GeV excess

- Using Fermi LAT data, multiple groups have claimed an excess at a few GeV from the Galactic Center and higher Galactic latitudes. The excess has been interpreted as emission from DM annihilation and/or unresolved millisecond pulsars (MSPs).
- Energy spectrum of the excess:
  - can be fit by DM with mass of ~10-40 GeV, depending on channel
  - uncomfortably similar to MSPs
- Excess is spatially extended:
  - if from annihilation, need steep DM density profile $r^{-\gamma}$ with γ = 1.2-1.4
  - uncertain if MSPs could explain large extension and steep profile
- To generate amplitude of the excess:
  - requires roughly thermal relic DM annihilation cross section
  - would require a few thousand MSPs, which seems plausible

see: Hooper & Goodenough 2011, Abazajian & Kaplinghat 2012, Hooper & Slatyer 2013, Gordon & Macías 2013, Abazajian et al. 2014, Daylan et al. 2014, and others

A dark matter signal in the Inner Galaxy?

Energy spectrum of excess in Galactic Center

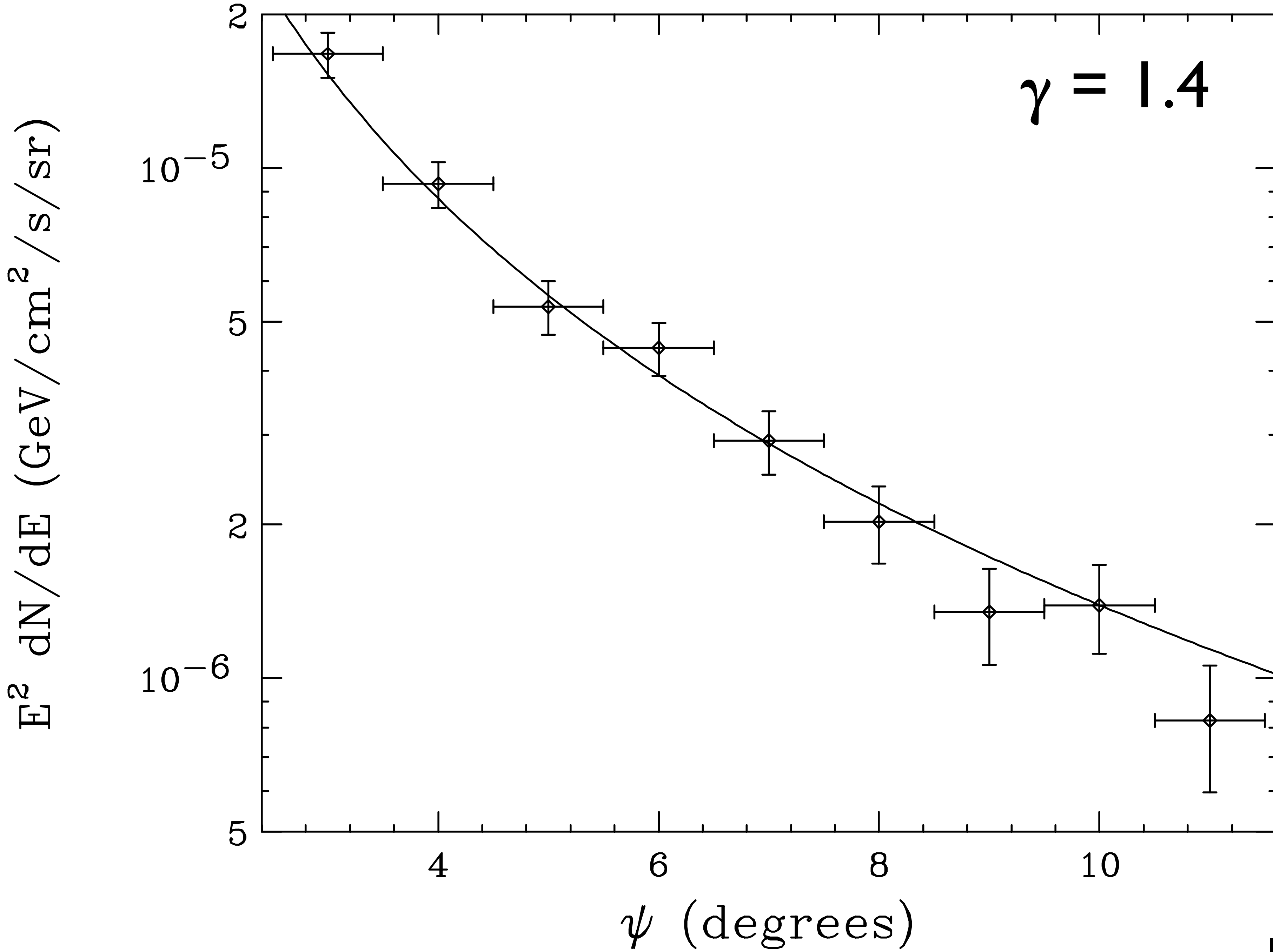


Daylan et al. 2014

NB: Abazajian et al (2014) find strong dependence of spectrum of excess on details of background model

A dark matter signal in the Inner Galaxy?

Excess is spatially extended

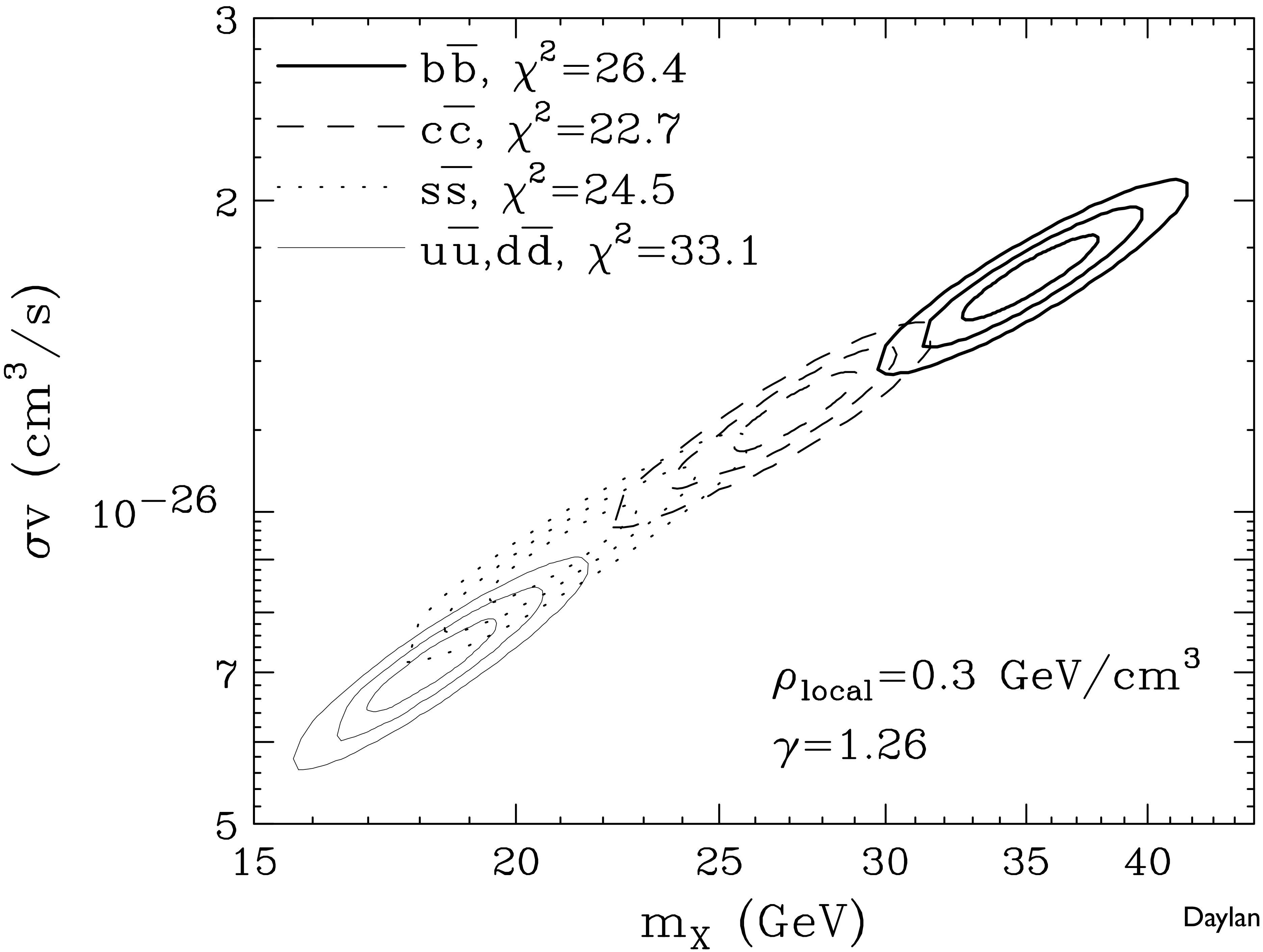


also detected out to at least |b| ~ 20 deg (Hooper & Slatyer 2013)

Daylan et al. 2014

A dark matter signal in the Inner Galaxy?

Needed cross section is close to thermal relic value



Daylan et al. 2014

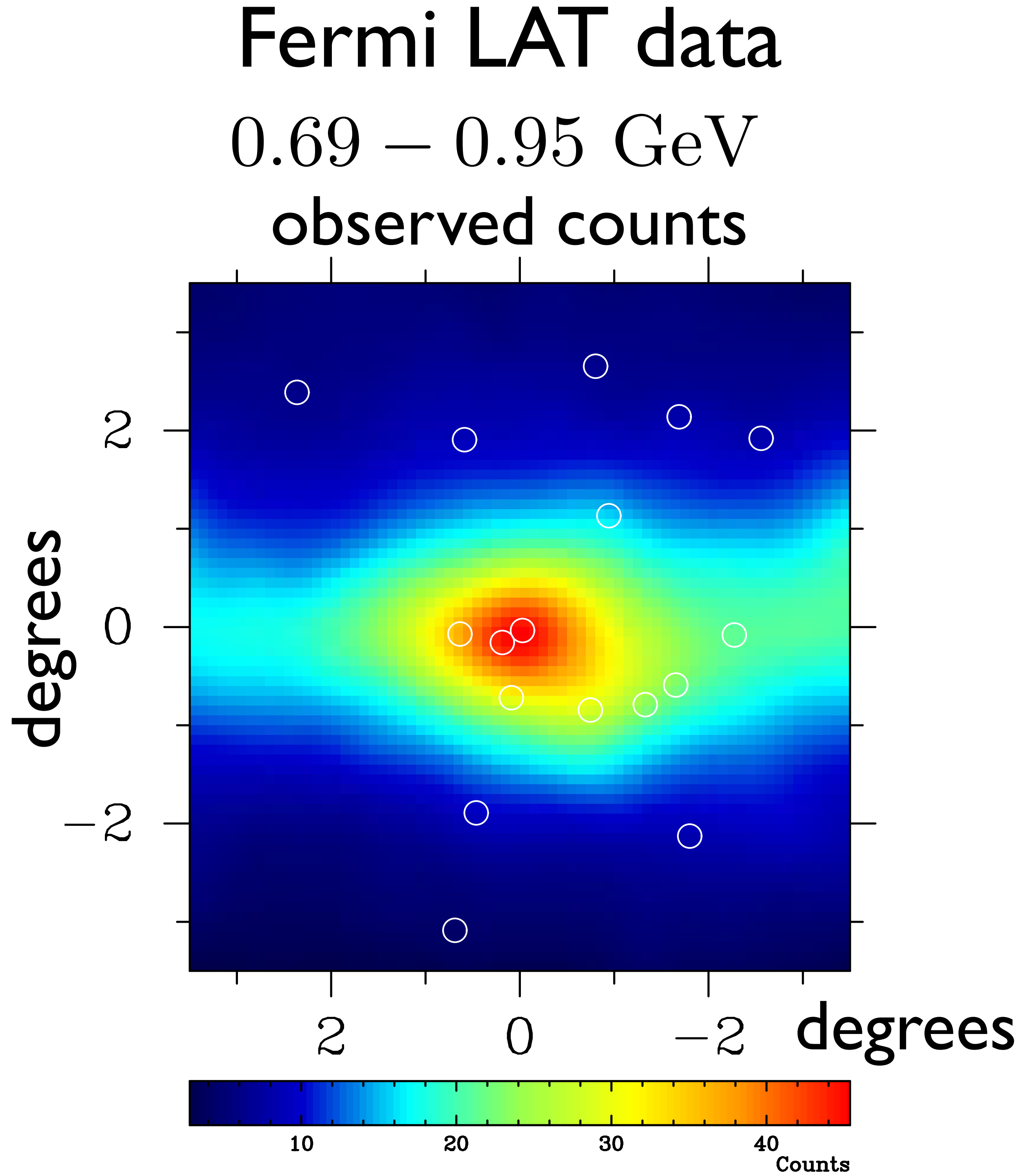
Excess over what?

What's in the model:

- Galactic diffuse emission associated with cosmic-ray interactions (sum of many processes)
- isotropic gamma-ray background (measured)
- detected gamma-ray sources (e.g., pulsars, supernova remnants)

What's not in the model:

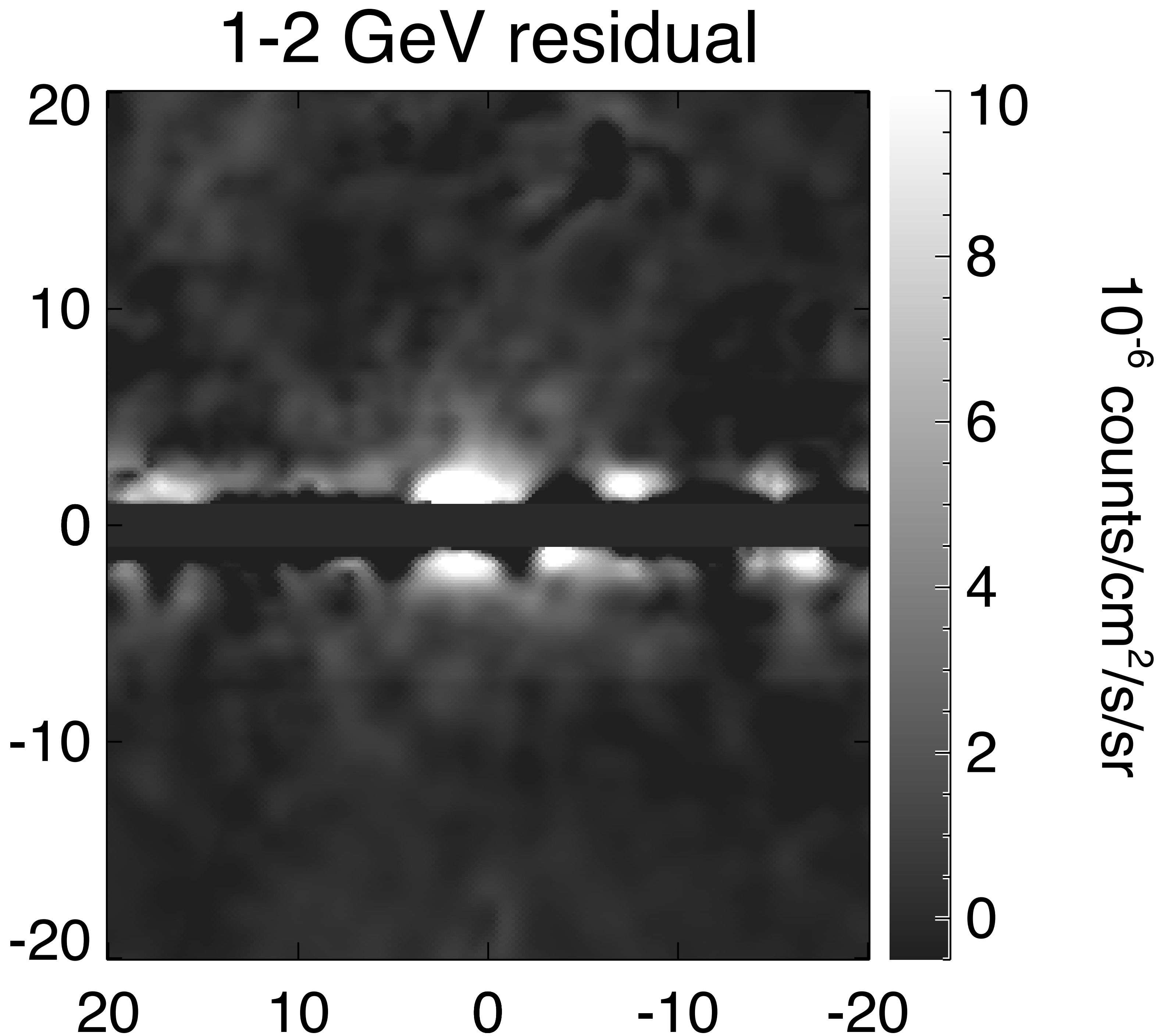
- unresolved gamma-ray sources
- dark matter



Abazajian & Kaplinghat 2012

Residuals

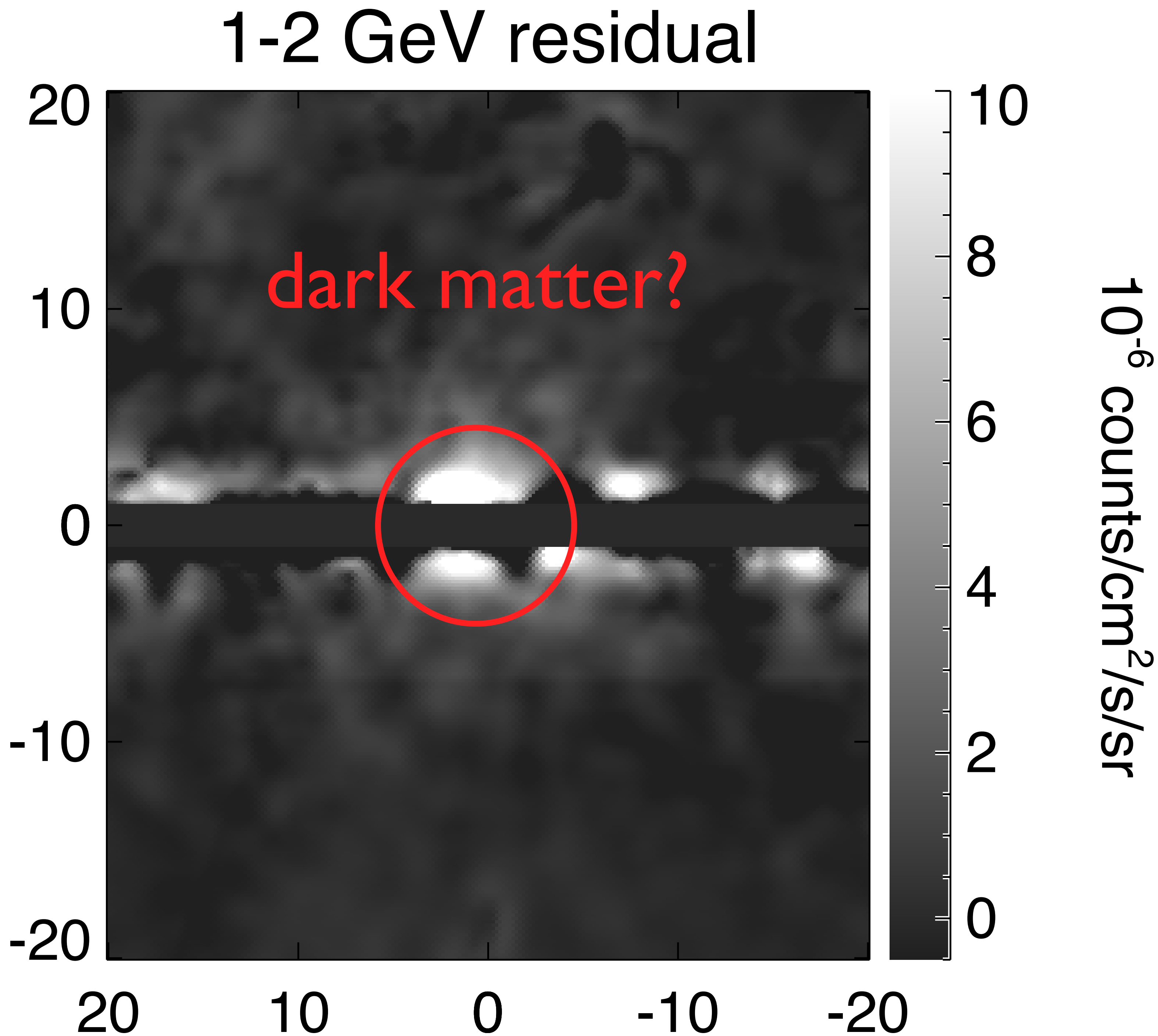
(for best-fit model w/o dark matter component)



Daylan et al. 2014

Residuals

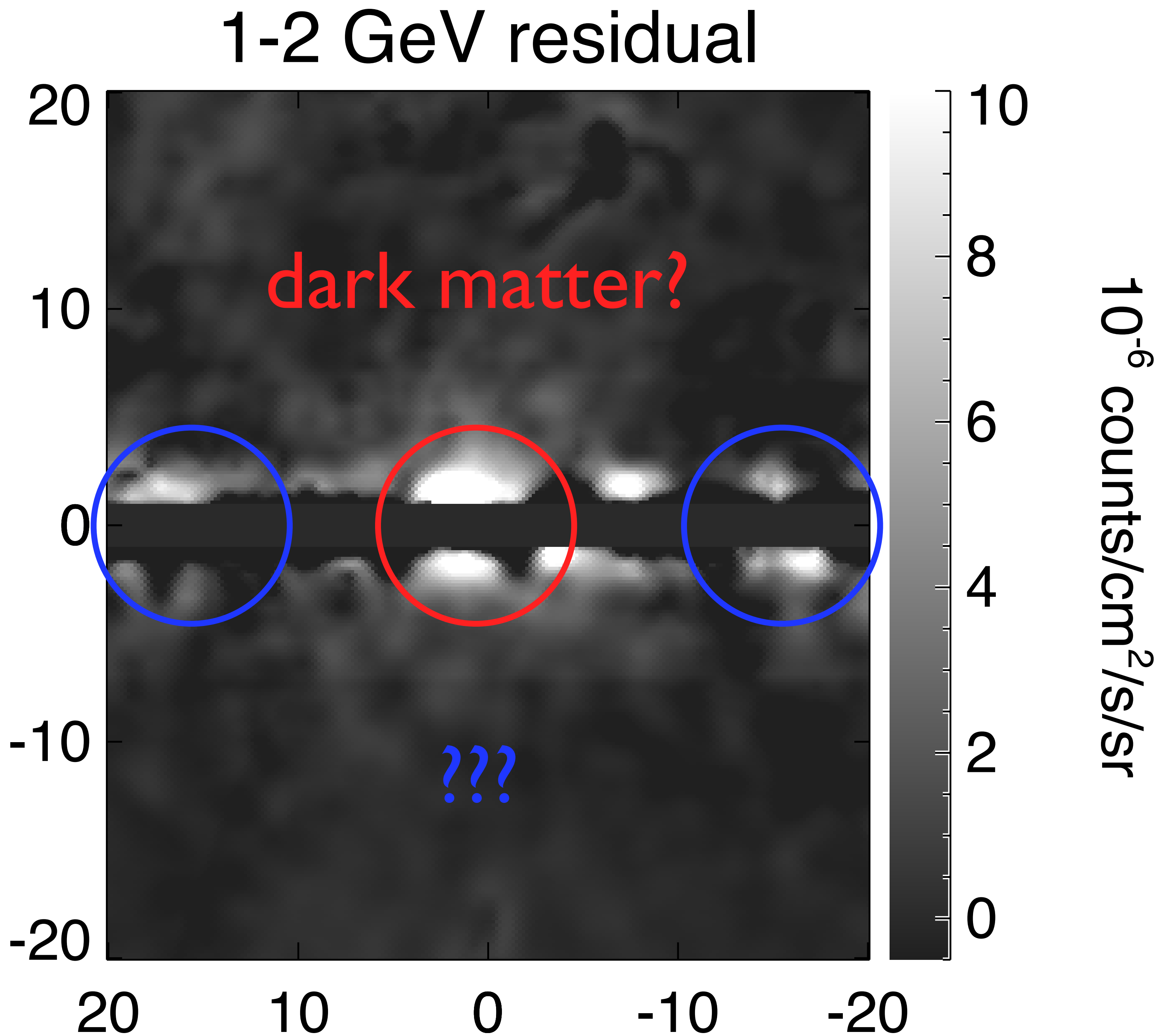
(for best-fit model w/o dark matter component)



Daylan et al. 2014

Residuals

(for best-fit model w/o dark matter component)



Daylan et al. 2014

Does DM uniquely improve the fit?

Does DM uniquely improve the fit?

No.

Does DM uniquely improve the fit?

models adding an additional component with an extended spatial distribution

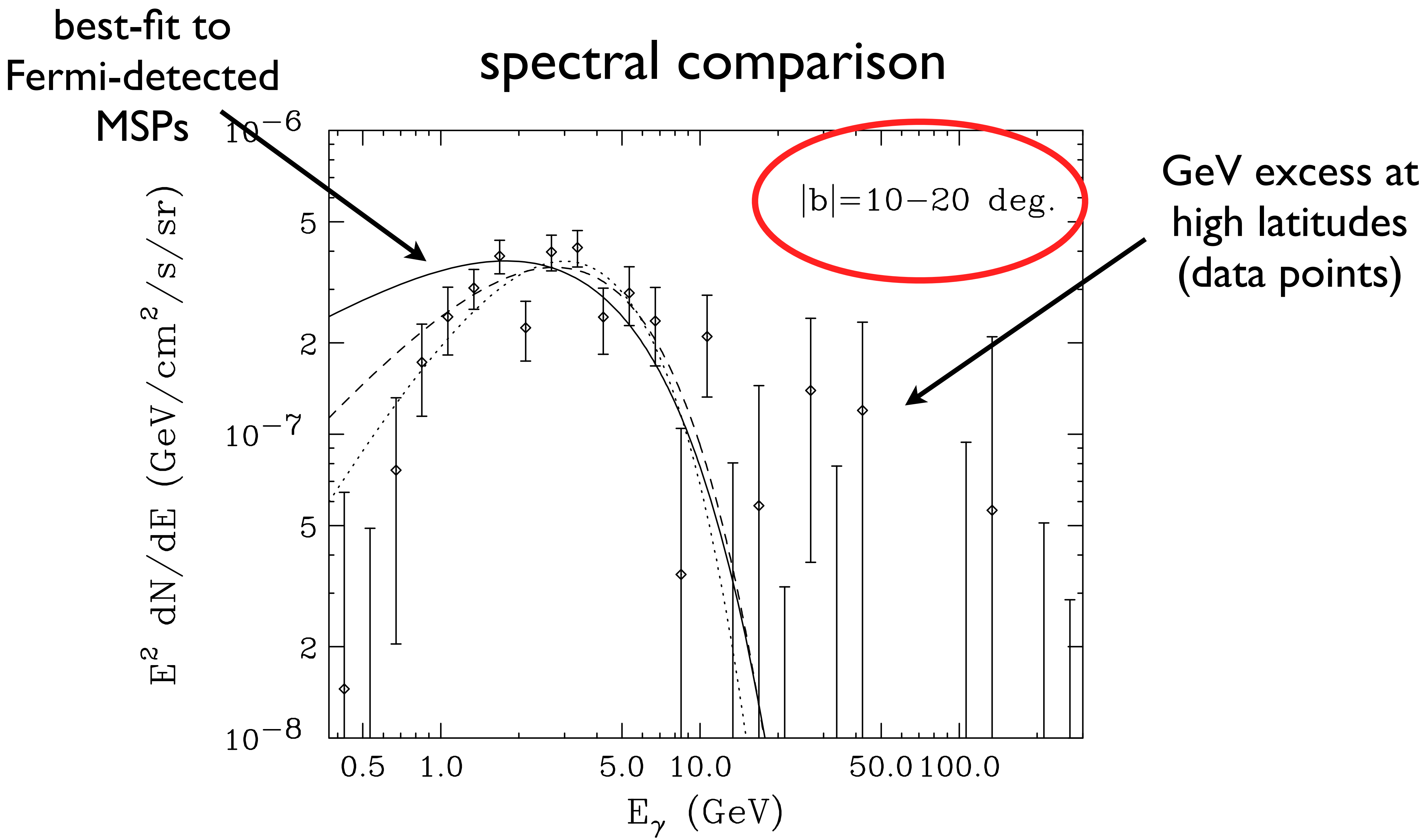
TABLE I. The best-fit $TS_{\approx}$, negative log-likelihoods, and $\Delta \ln\mathcal{L}$ from the baseline for general models in the 200 MeV–100 GeV analysis.

Spatial model	Spectrum	$TS_{\approx}$	$-\ln\mathcal{L}$	$\triangle \ln\mathcal{L}$
Baseline	⋯	⋯	140 070.2	⋯
Density $\Gamma = 0.7$	LogPar	1725.5	139 755.5	314.7
Density^2 $\gamma = 0.9$	LogPar	1212.8	139 740.0	330.2
Density^2 $\gamma = 1.0$	LogPar	1441.8	139 673.3	396.9
Density^2 $\gamma = 1.1$	LogPar	2060.5	139 651.8	418.3
Density^2 $\gamma = 1.2$	LogPar	4044.9	139 650.9	419.2
Density^2 $\gamma = 1.3$	LogPar	7614.2	139 686.8	383.4
Density^2 Einasto	LogPar	1301.3	139 695.7	374.4
Density^2 $\gamma = 1.2$	PLCut	3452.5	139 663.2	407.0

improvement in fit ($2\Delta\ln\mathcal{L} > 25$ is highly significant)

Abazajian & Kaplinghat 2012

Can the GeV excess be millisecond pulsars?

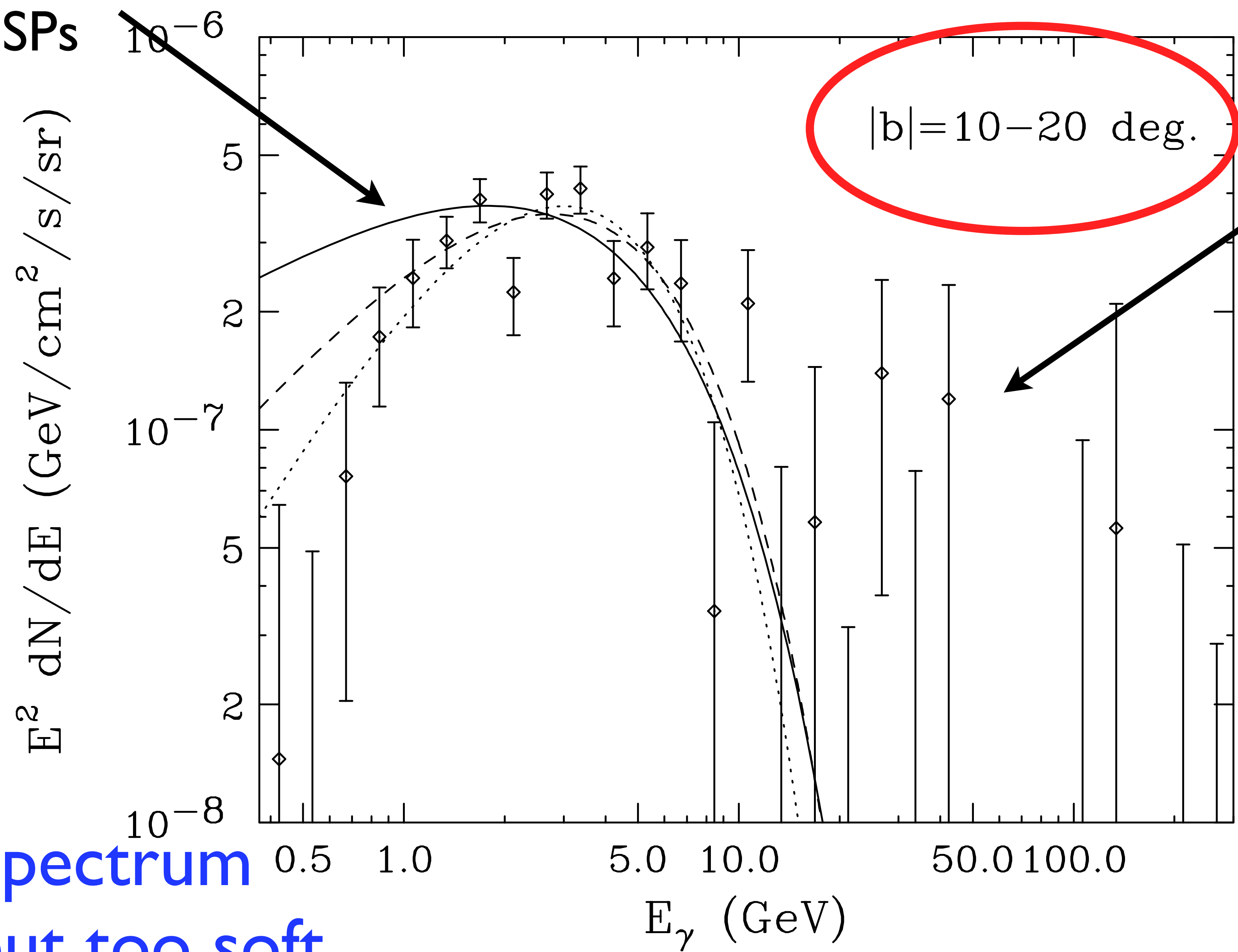


Hooper, Cholis, Linden, JSG, Slatyer 2013

Can the GeV excess be millisecond pulsars?

best-fit to Fermi-detected MSPs

spectral comparison



GeV excess at high latitudes (data points)

MSP spectrum similar but too soft at low energies

Hooper, Cholis, Linden, JSG, Slatyer 2013

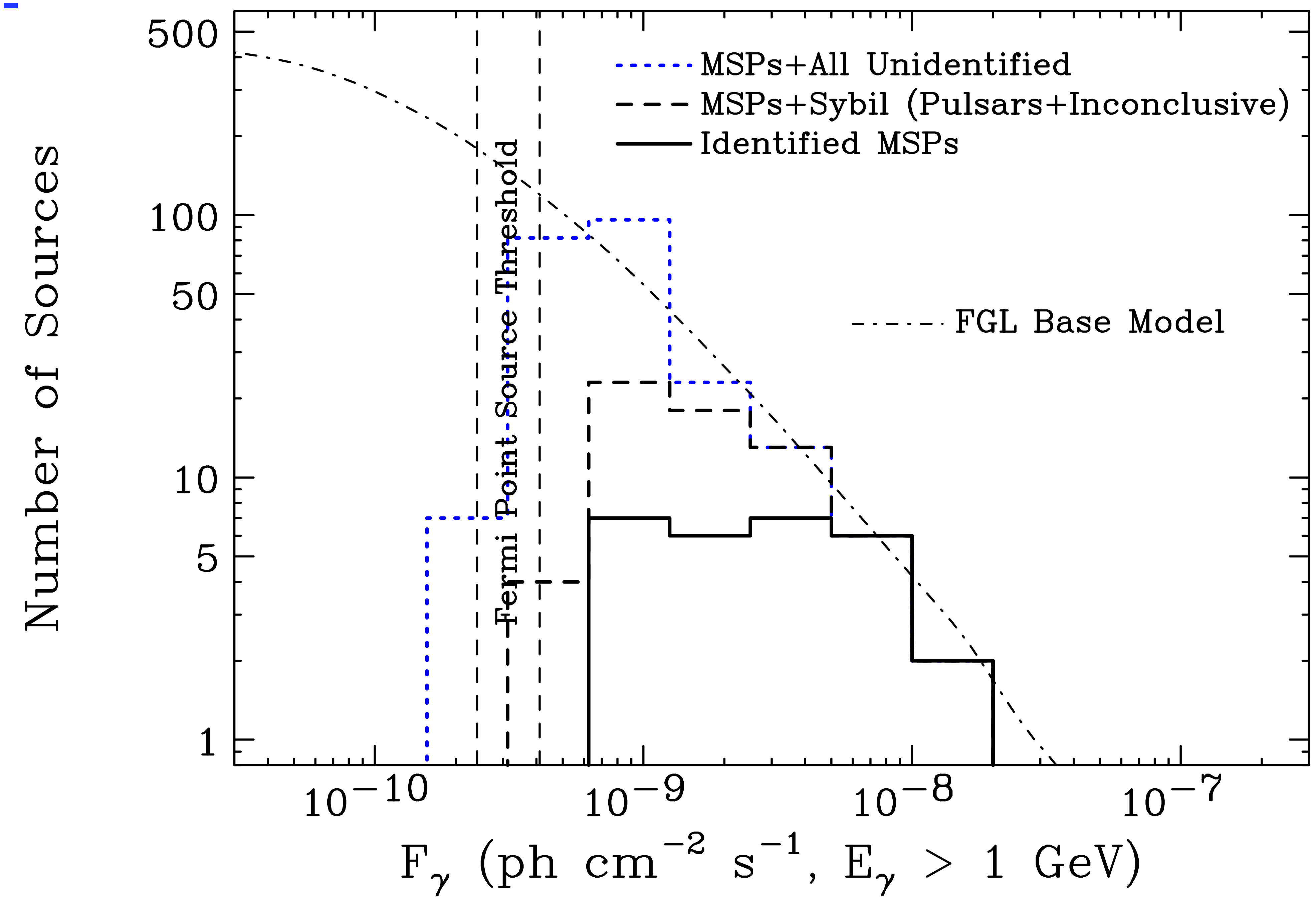
Can the GeV excess be millisecond pulsars?

Can unresolved MSPs produce the high-latitude excess?

- adopt a spatial model and luminosity function for the MSPs, calibrated to detections in radio
- base model can roughly account for the amplitude of Inner Galaxy excess, but strongly overpredicts number of Fermi-detected MSPs

Unresolved sources (contribute to diffuse) | Resolved sources

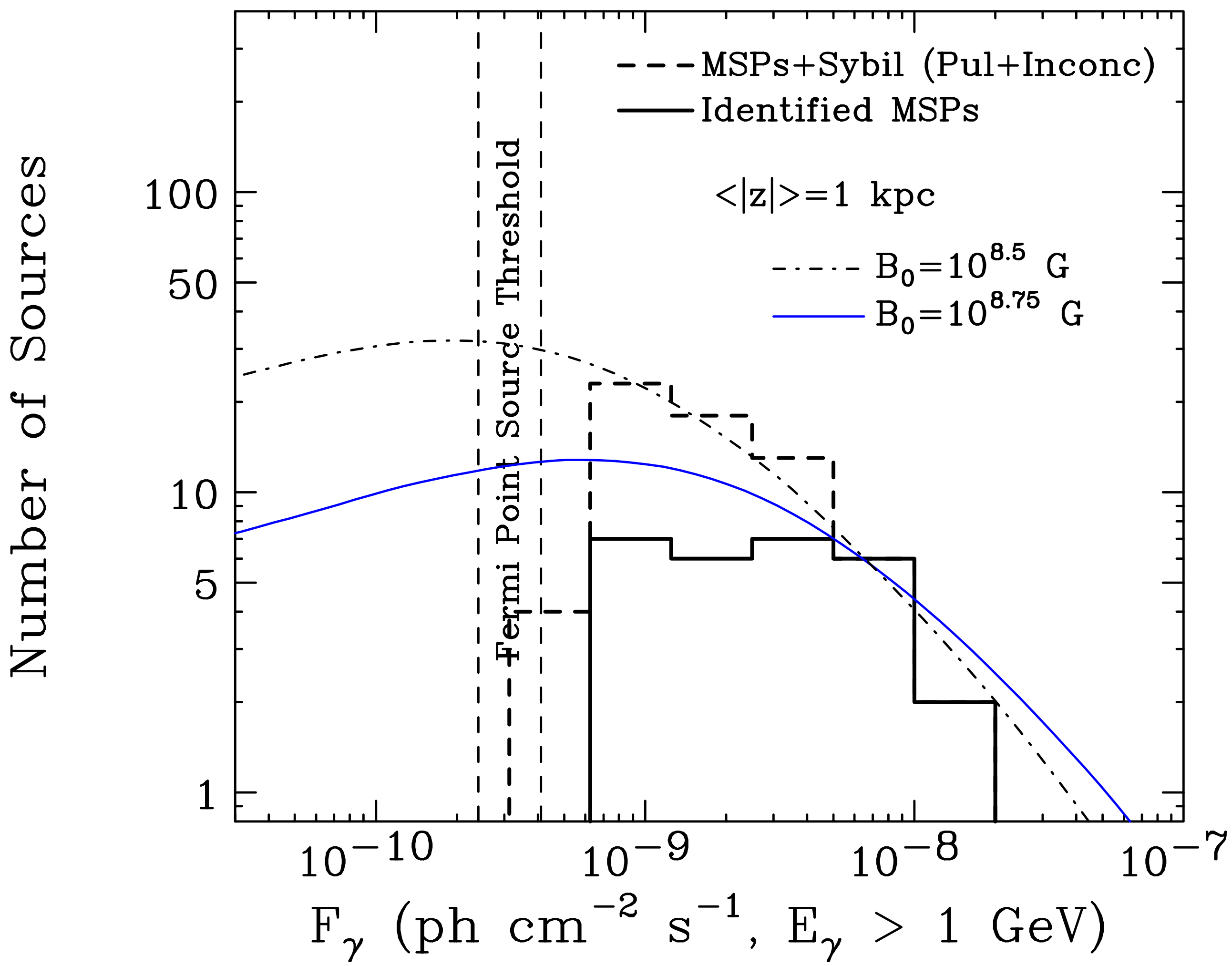
source count distribution (|b|>10 deg)



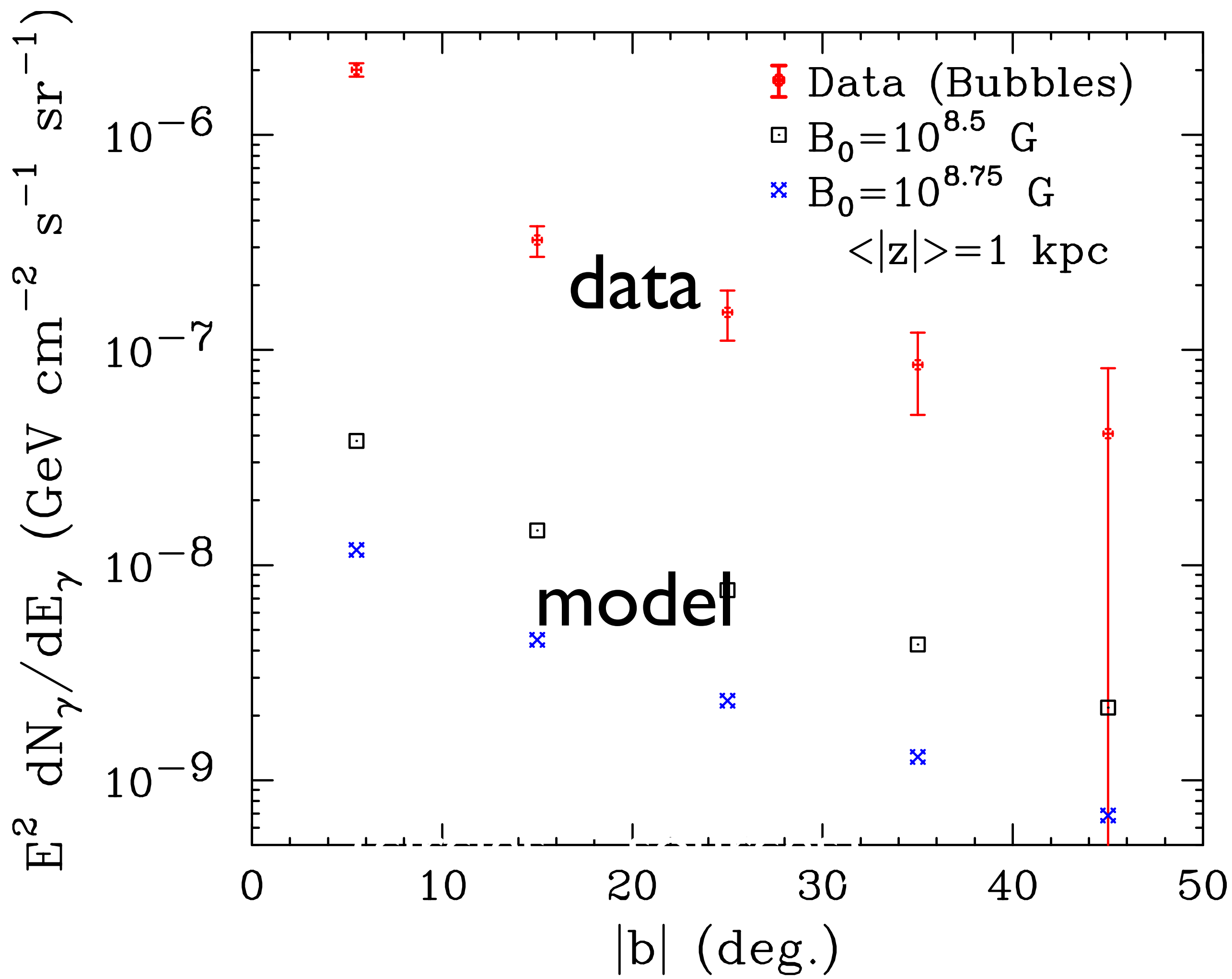
Hooper, Cholis, Linden, JSG, Slatyer 2013

Can the GeV excess be millisecond pulsars?

Source count distribution



Latitude dependence of excess



adjusting MSP model parameters to better reproduce the observed source counts leads to models that cannot explain the *amplitude* of the observed excess

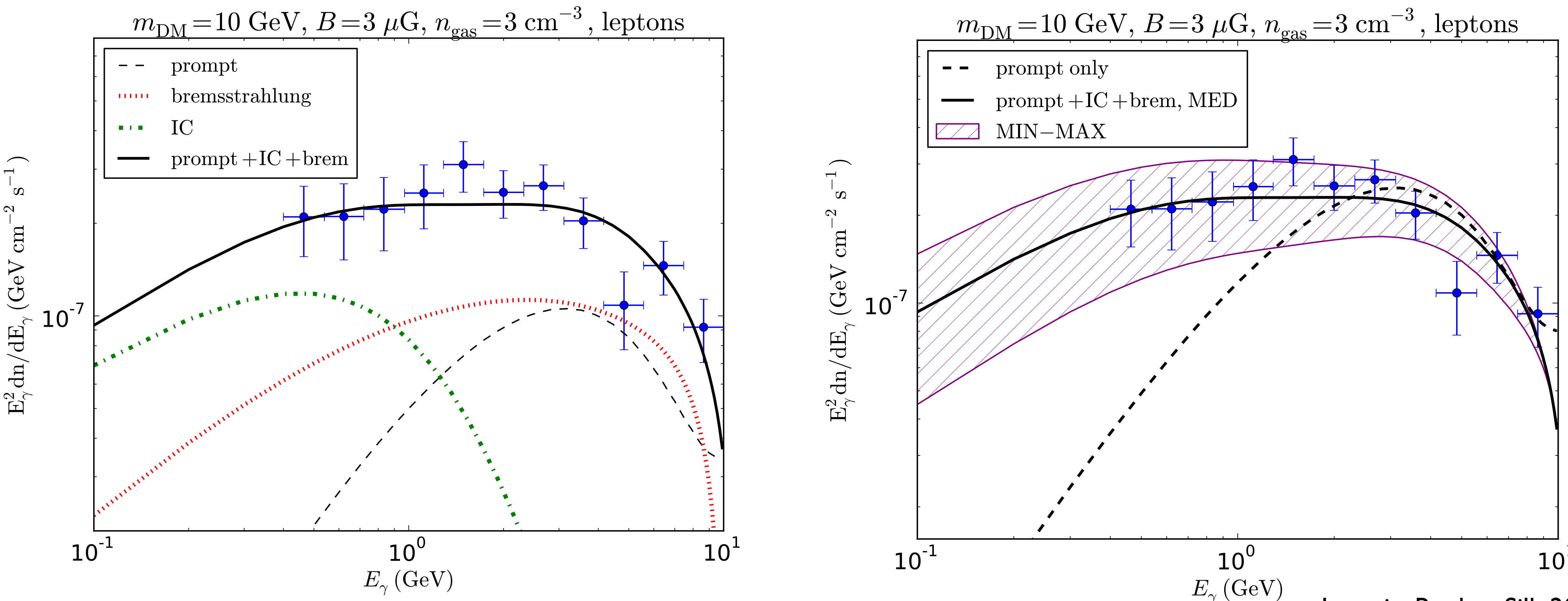
Hooper, Cholis, Linden, JSG, Slatyer 2013

Is the GeV excess dark matter?

- Hard to explain with gamma-ray millisecond pulsars. Other source populations? (NB: Yuan & Zhang 2014 claim MSPs ok with softer luminosity function.)
- Attributable to uncertainties in modeling of Galactic diffuse emission?
  - Sum of several processes with not-strongly-constrained inputs:
    - cosmic-ray spectra and distribution
    - gas distribution
    - interstellar radiation field
    - magnetic fields
  - Galactic diffuse model tuned to fit all-sky data
- Systematics? (Not statistics-limited!)

Bed of Procrustes

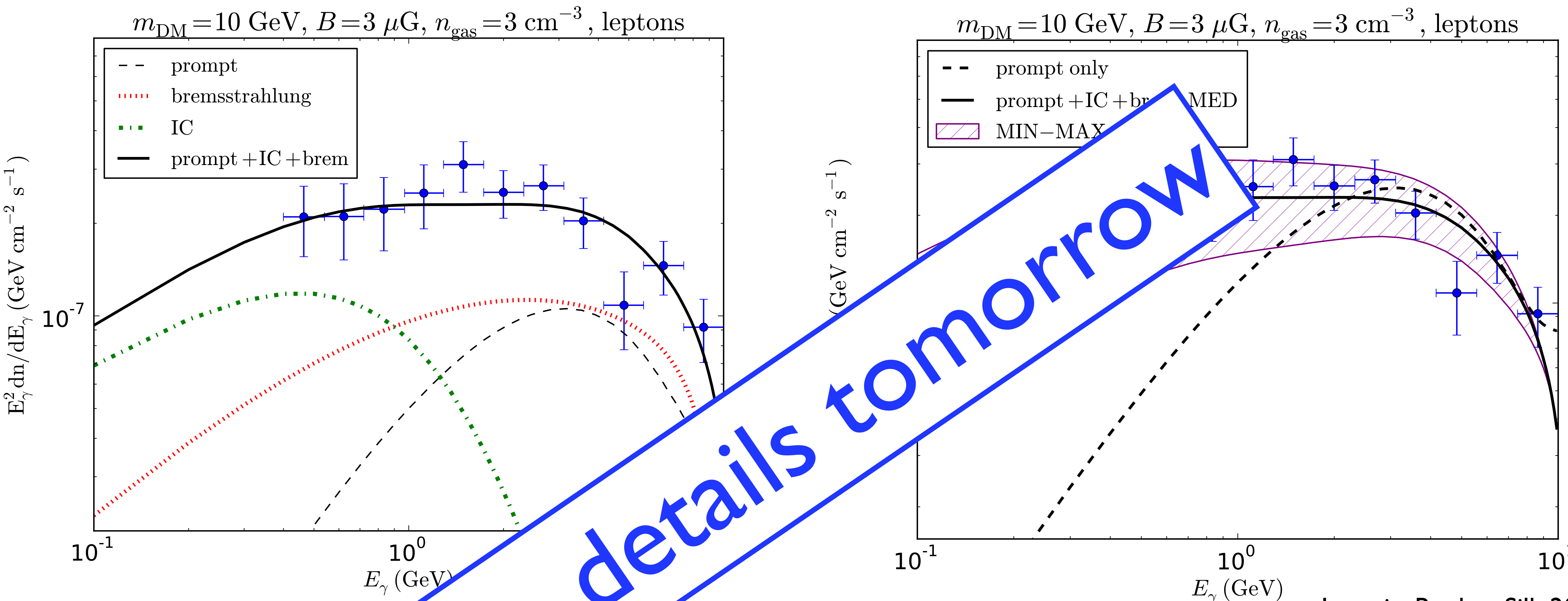
Bed of Procrustes



Lacroix, Boehm, Silk 2014

- Lacroix et al. point out importance of:
  - inverse Compton
  - propagation model
  - diffusion (and latitude dependence of secondary emission)

Bed of Procrustes



Lacroix, Boehm, Silk 2014

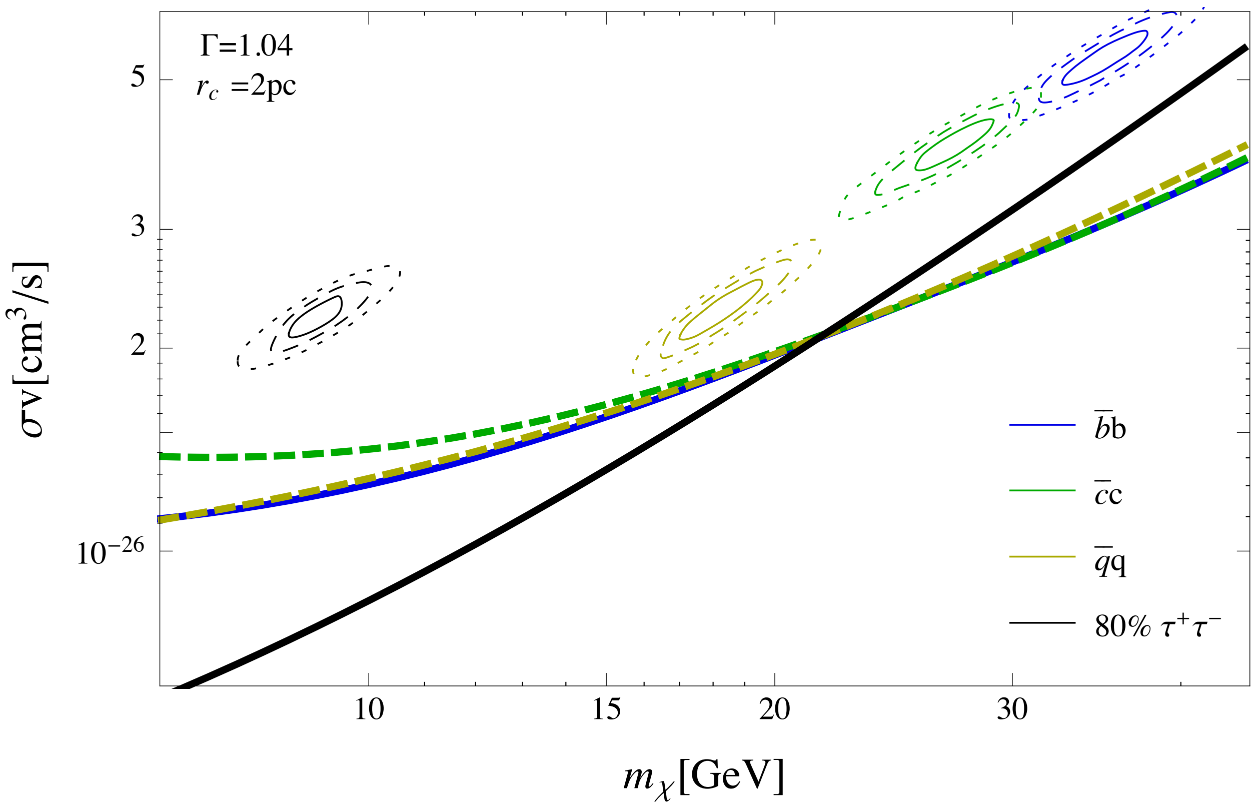
more details tomorrow

... et al. point out importance of:

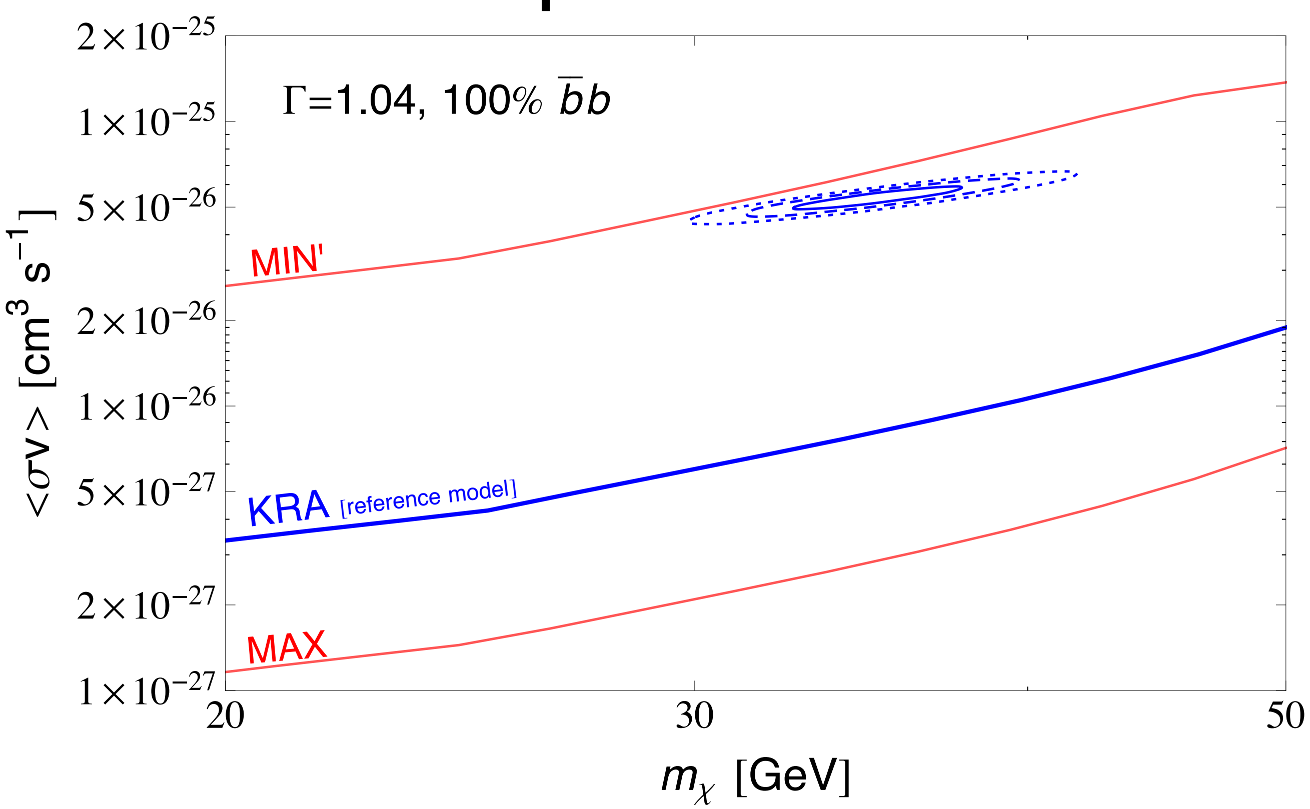
- inverse Compton
- propagation model
- diffusion (and latitude dependence of secondary emission)

Multiwavelength / multi-messenger constraints

Radio constraints



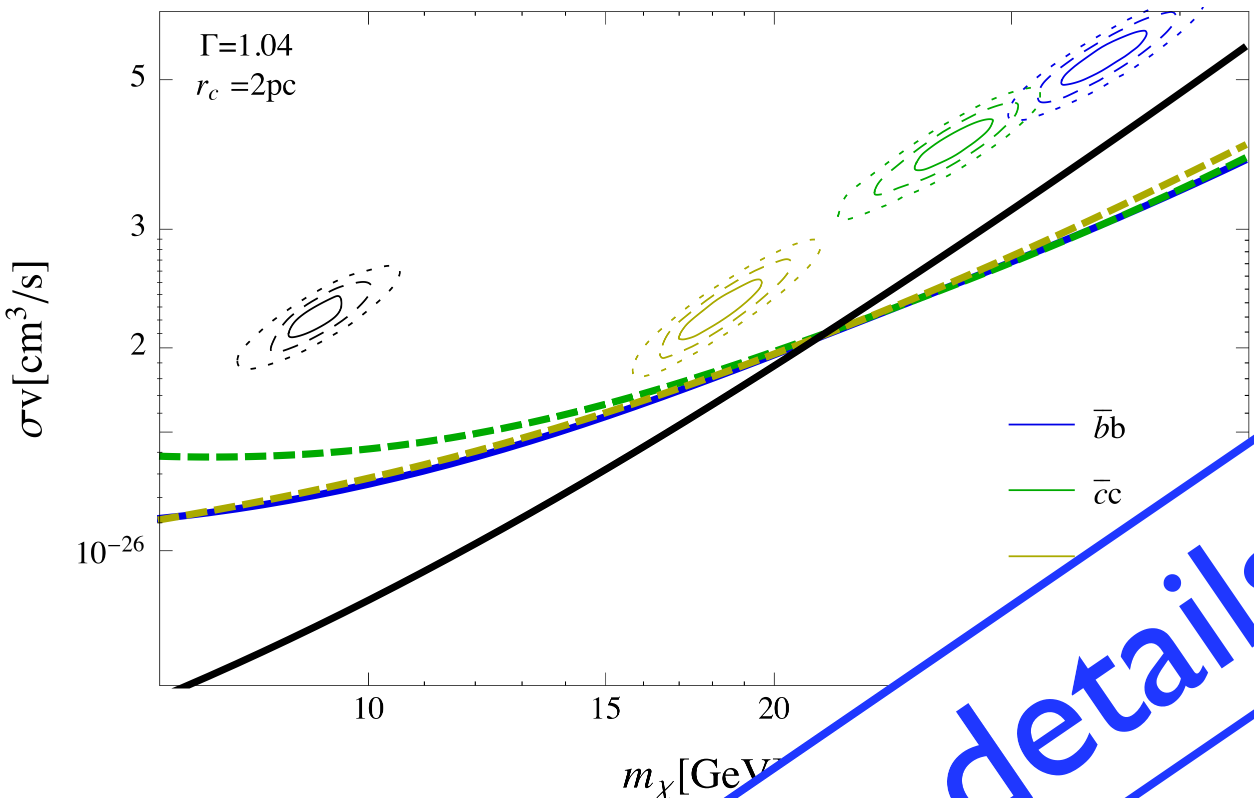
Anti-proton constraints



Bringmann et al. 2014

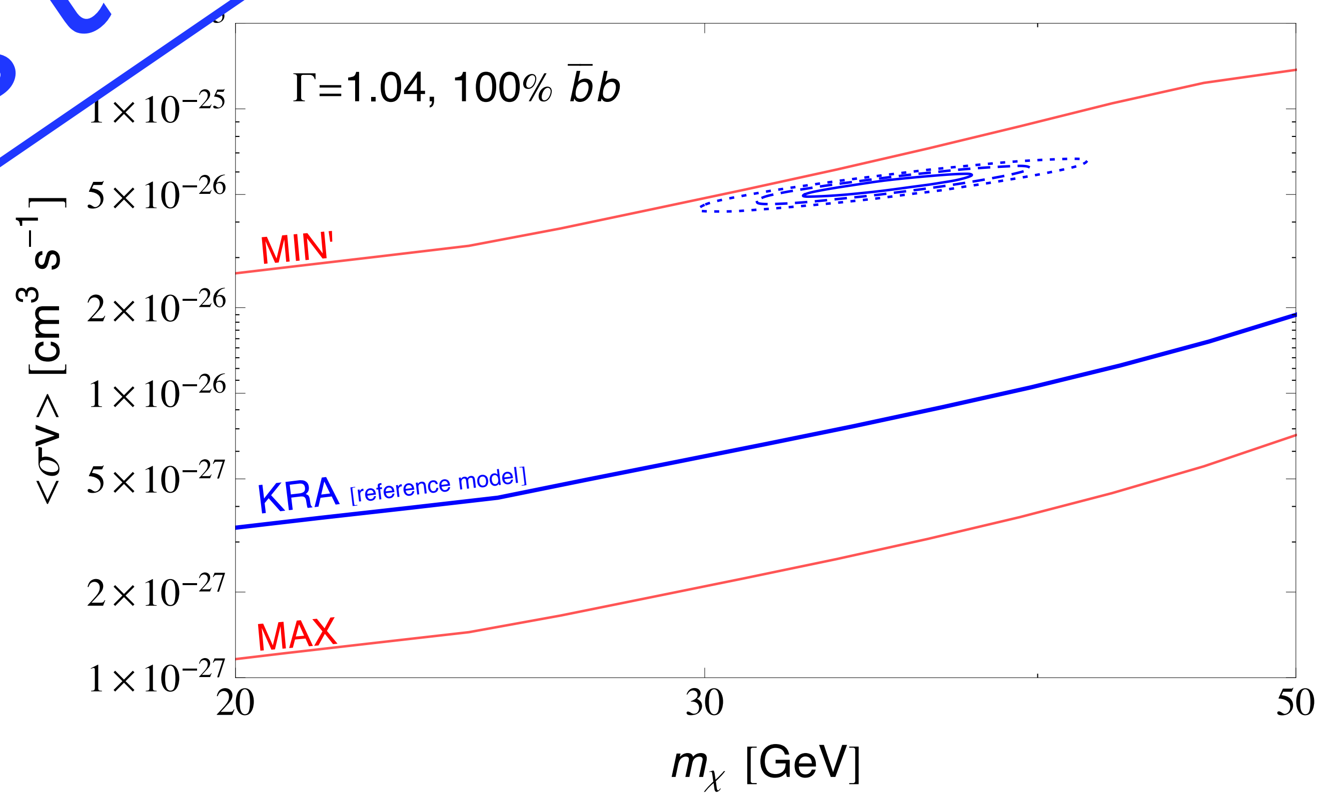
Multiwavelength / multi-messenger constraints

Radio constraints



more details tomorrow

Anti-proton constraints



Bringmann et al. 2014

Summary: Part I

- indirect detection tests particle nature of DM with astrophysical observations
- we are beginning to probe favored models of dark matter with gamma-ray searches
- hints of possible dark matter signals have been uncovered in gamma-ray data!