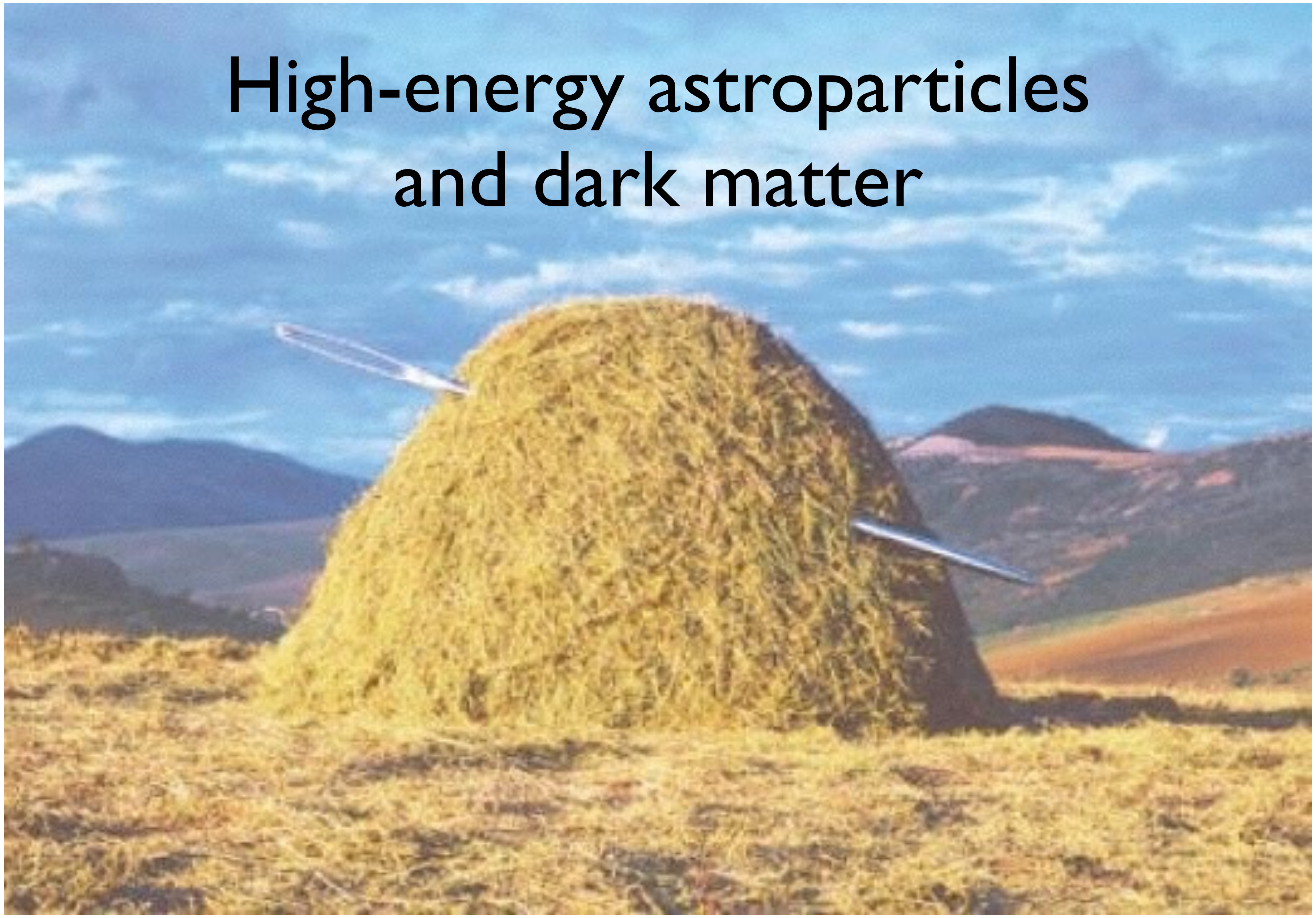
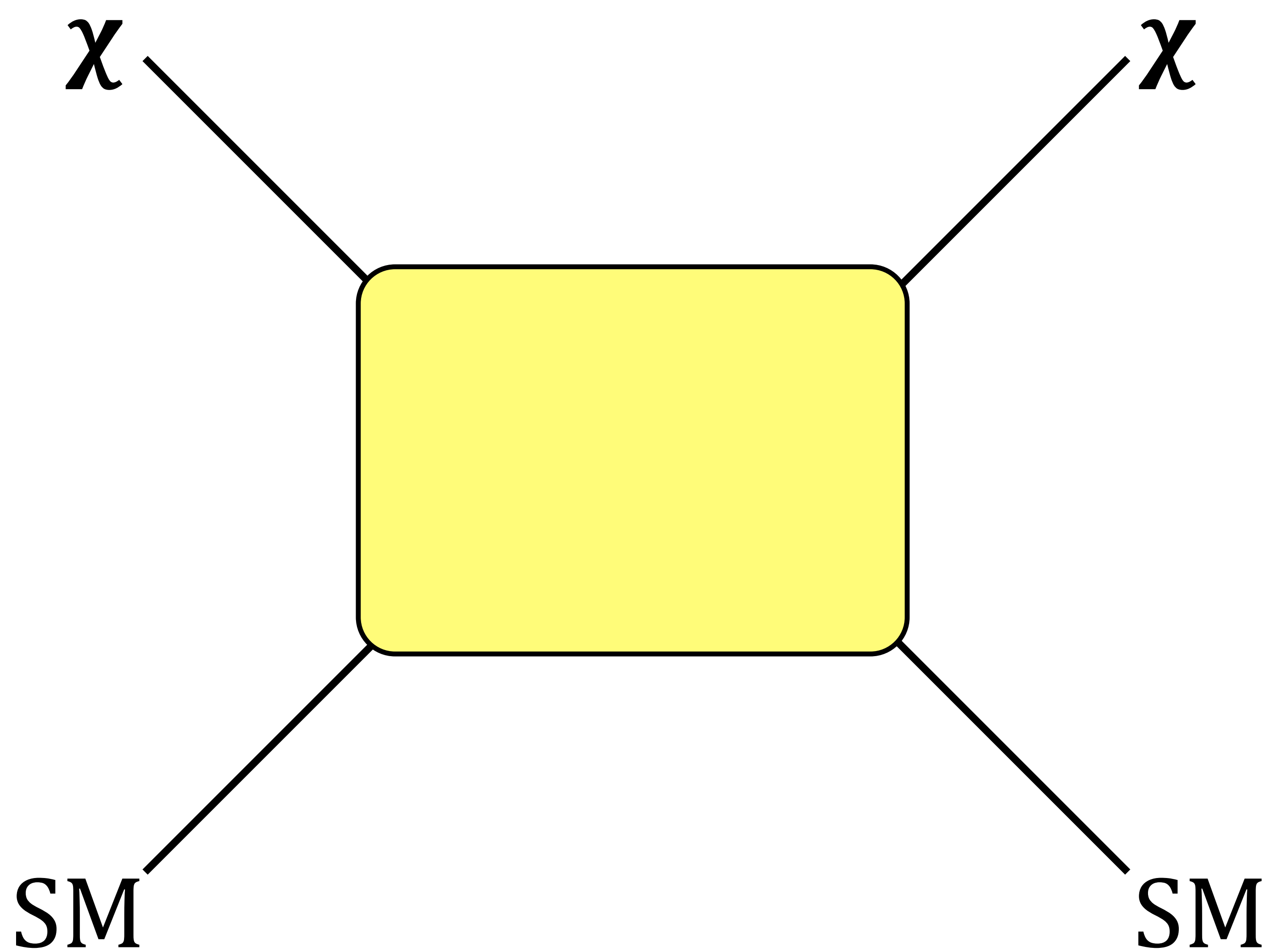
High-energy astroparticles and dark matter



Jennifer Gaskins
Marie Curie Fellow
GRAPPA, University of Amsterdam

How to detect particle dark matter?



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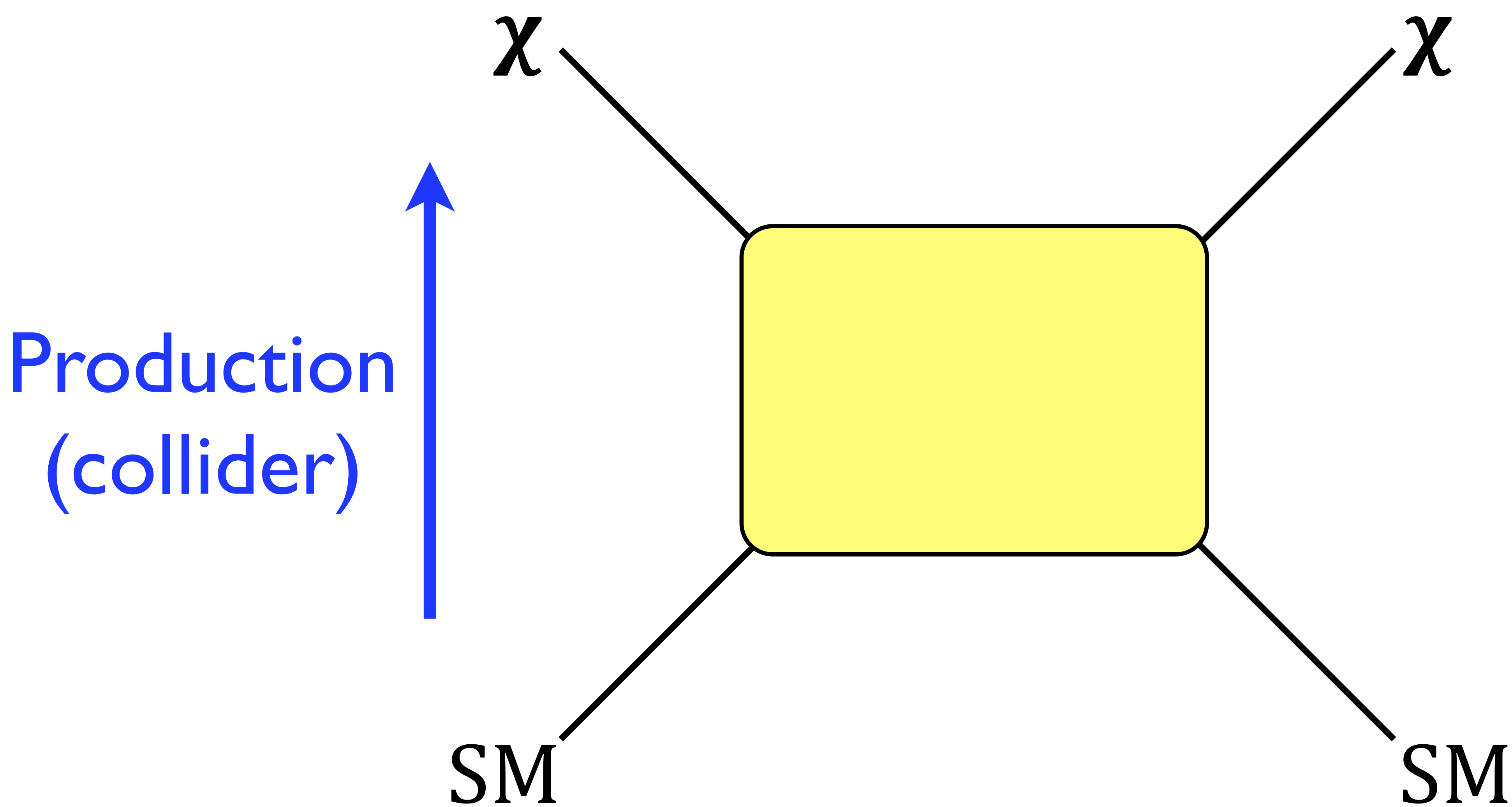
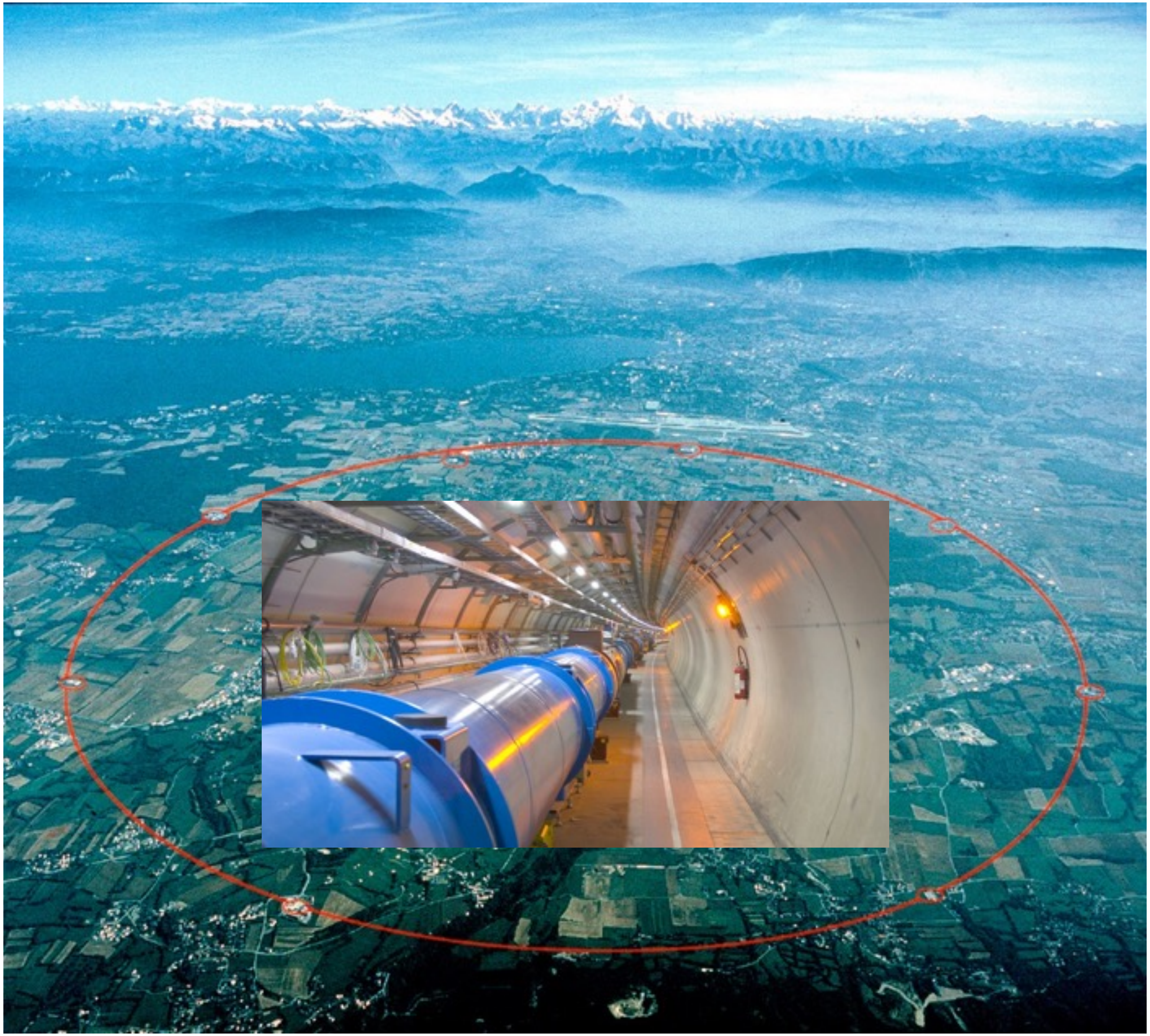


Production at a collider



(Large Hadron Collider)

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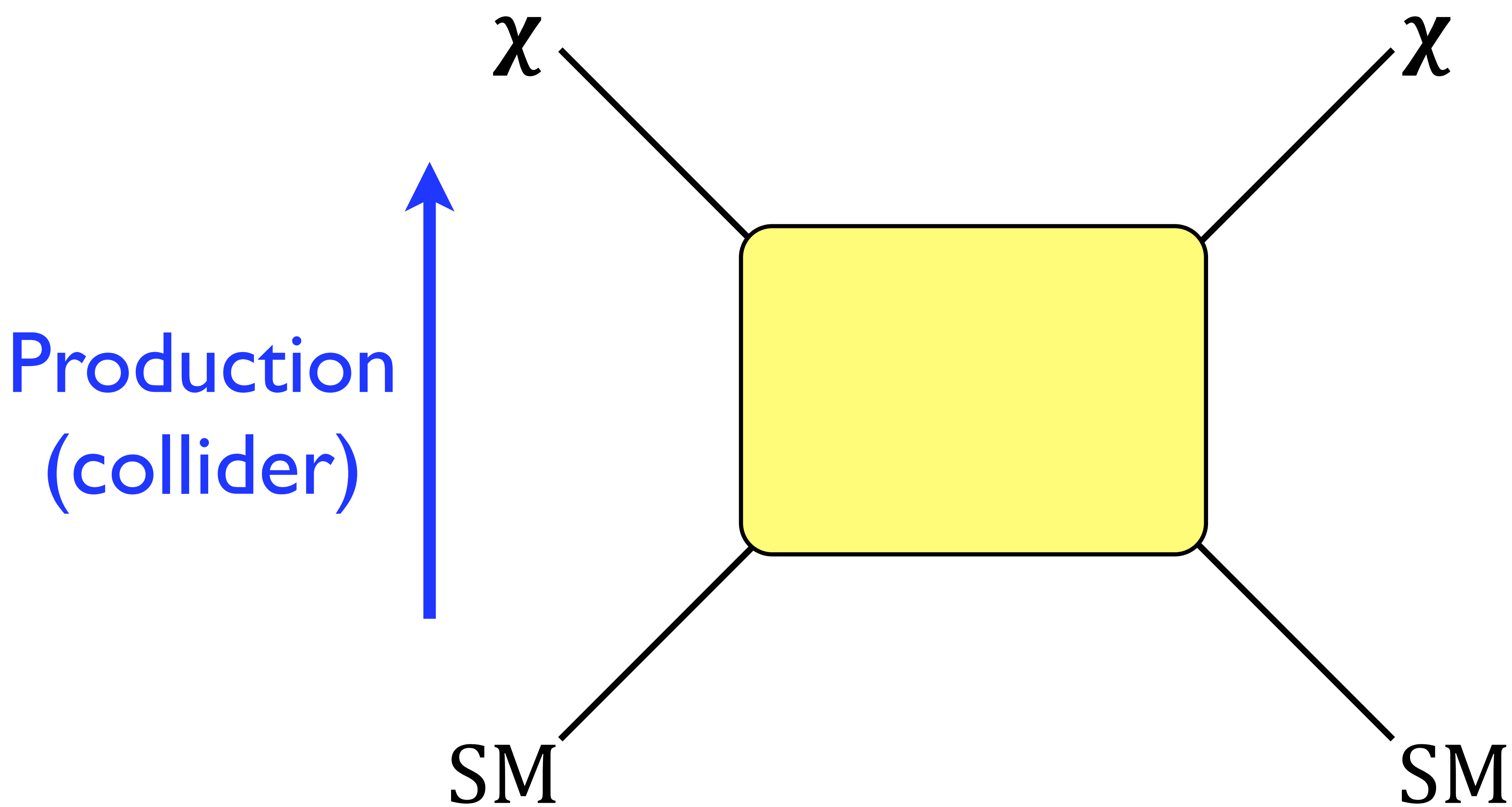

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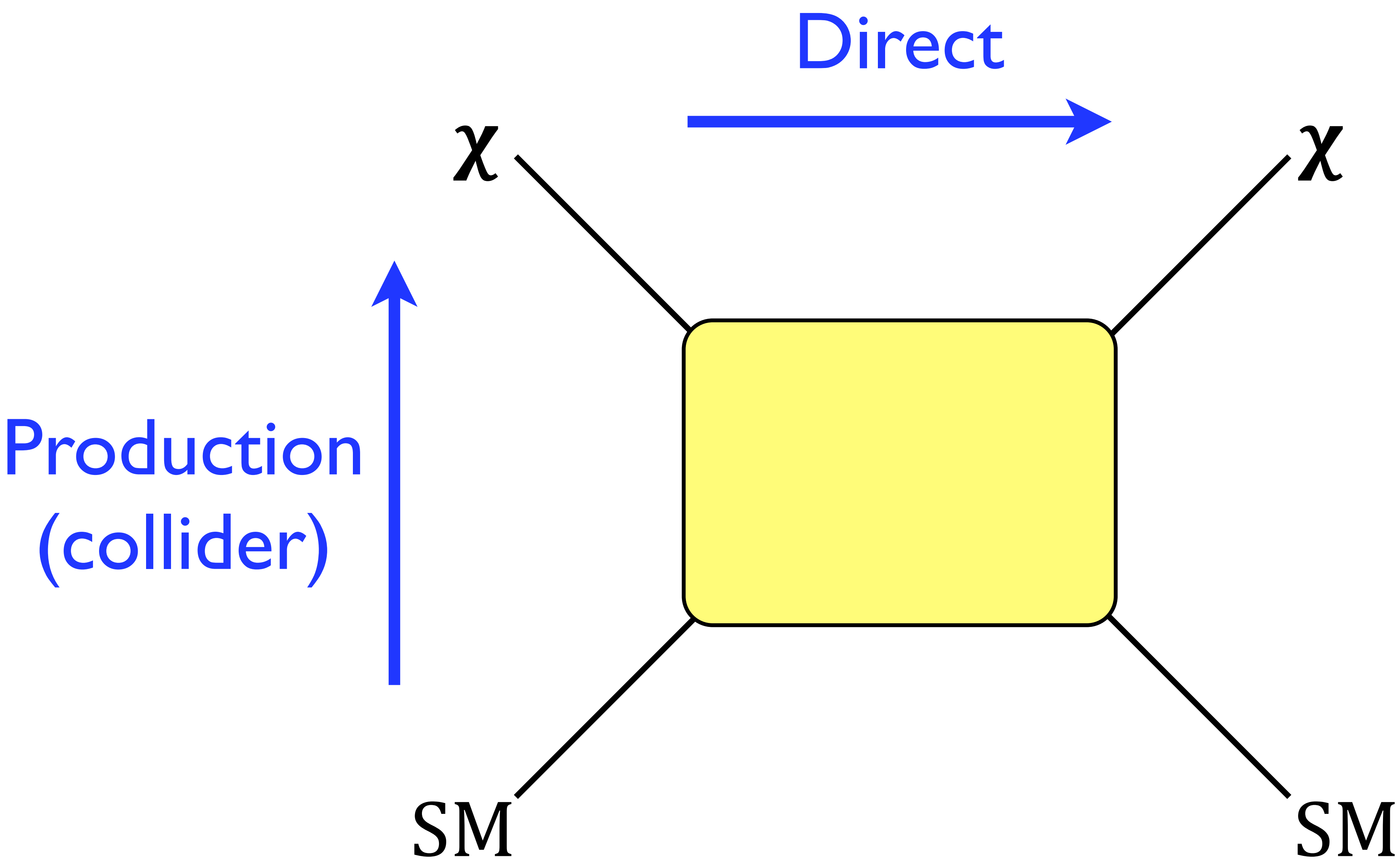
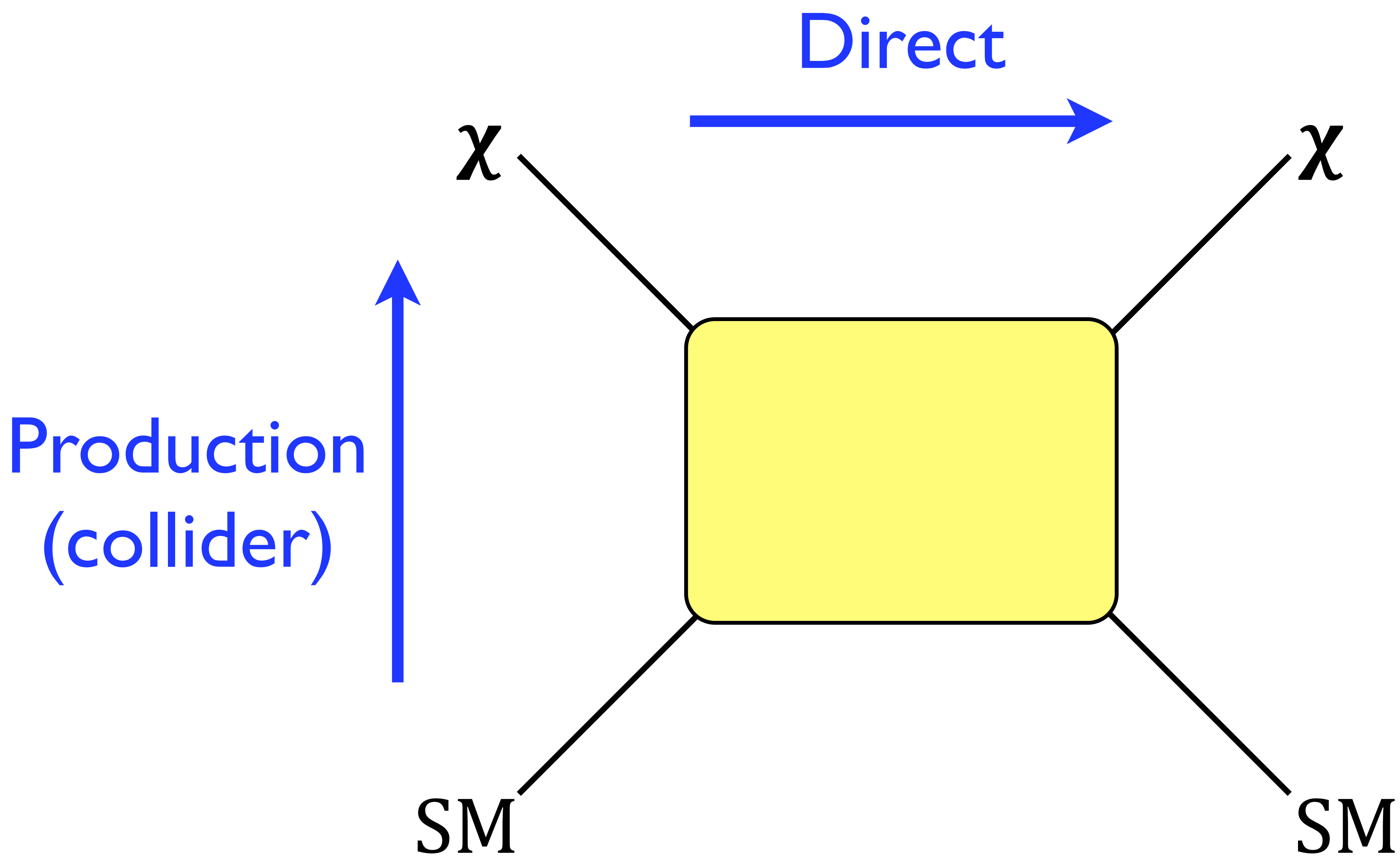


Direct detection

LUX experiment

How to detect particle dark matter?



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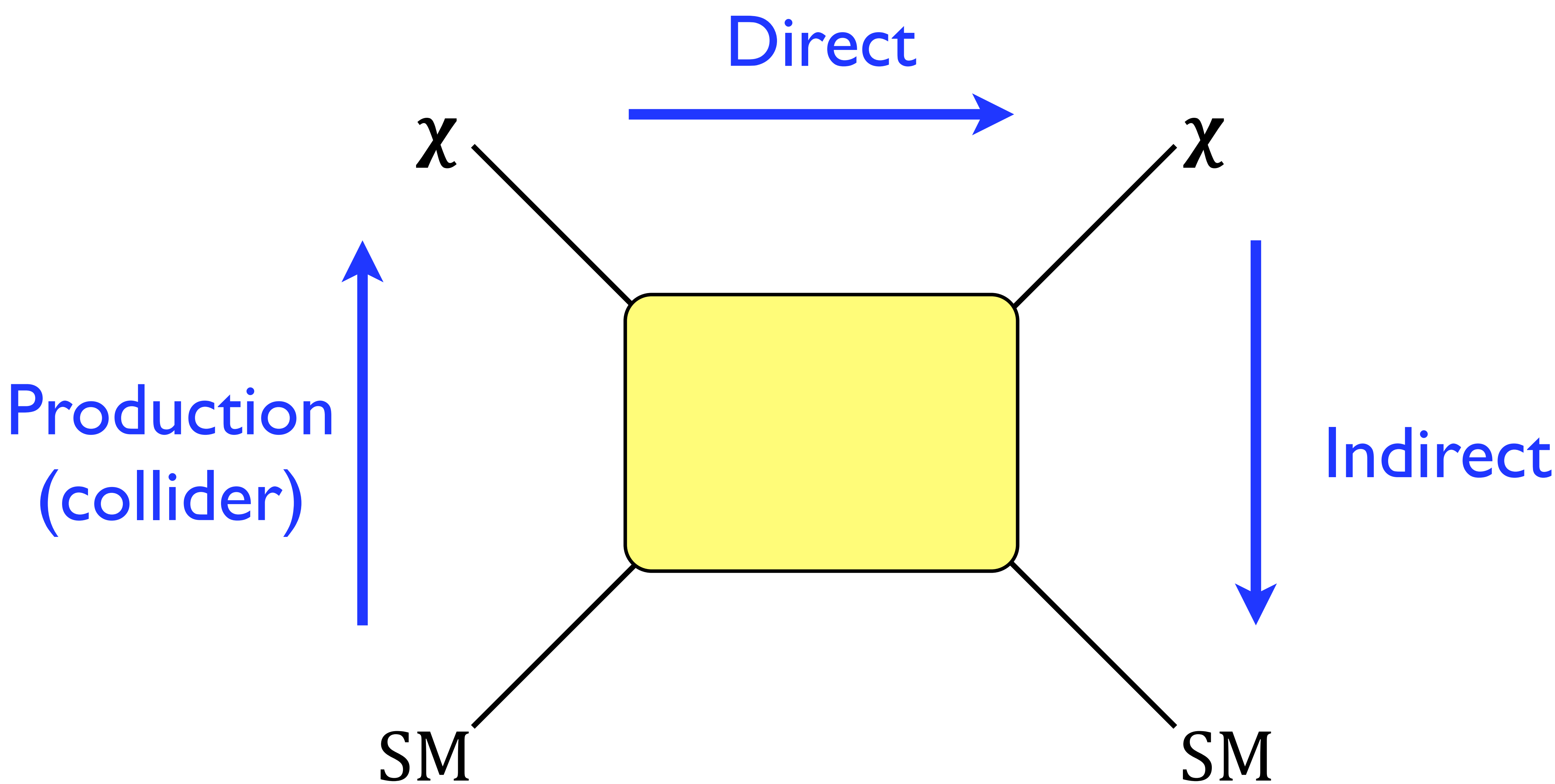

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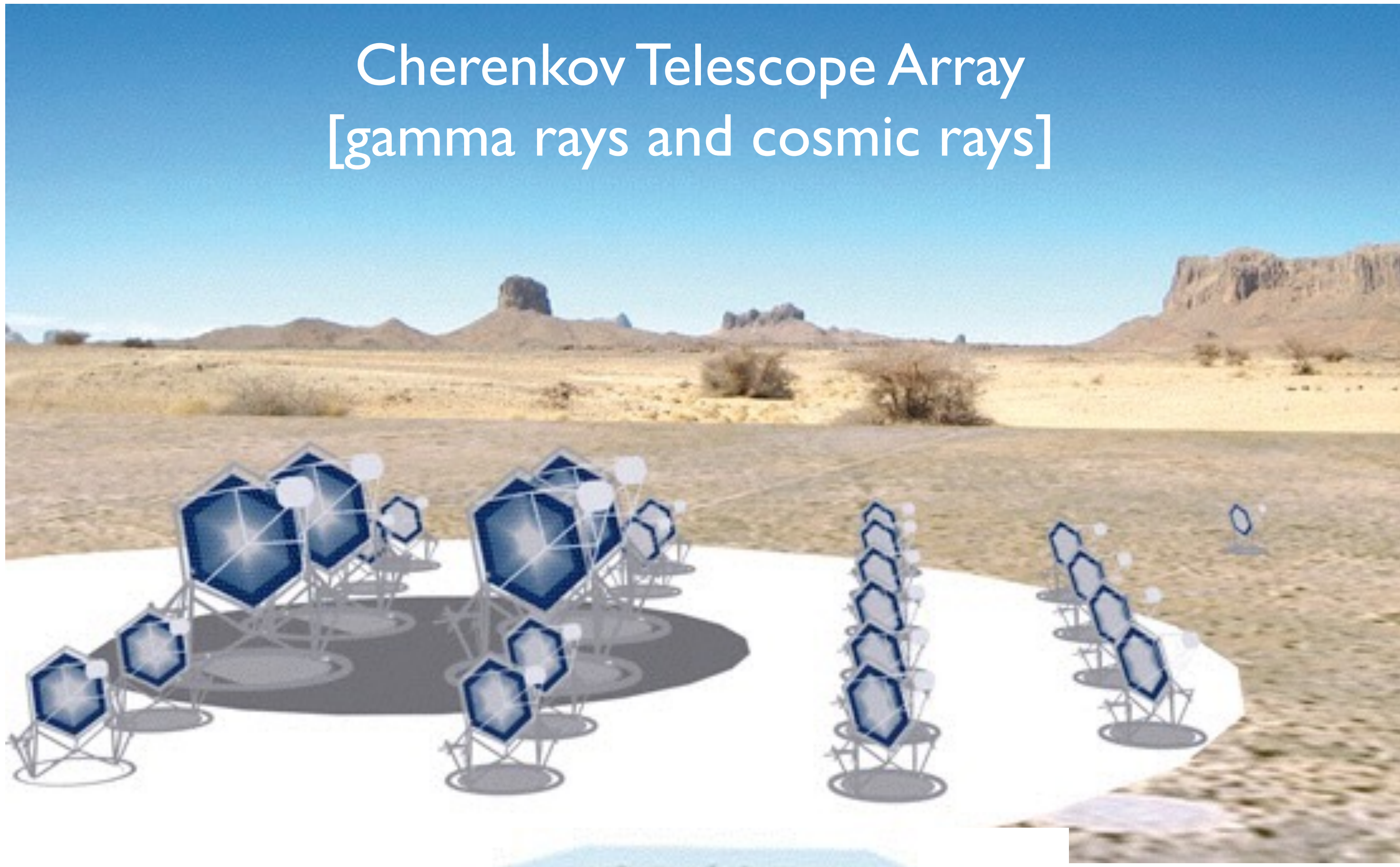
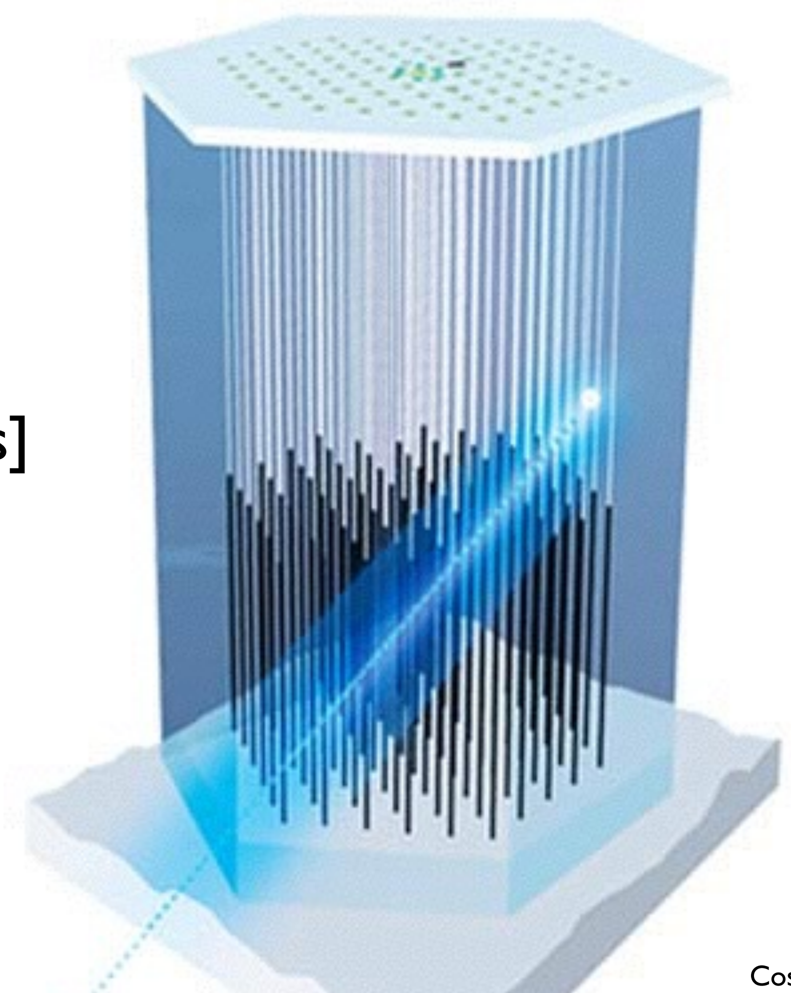
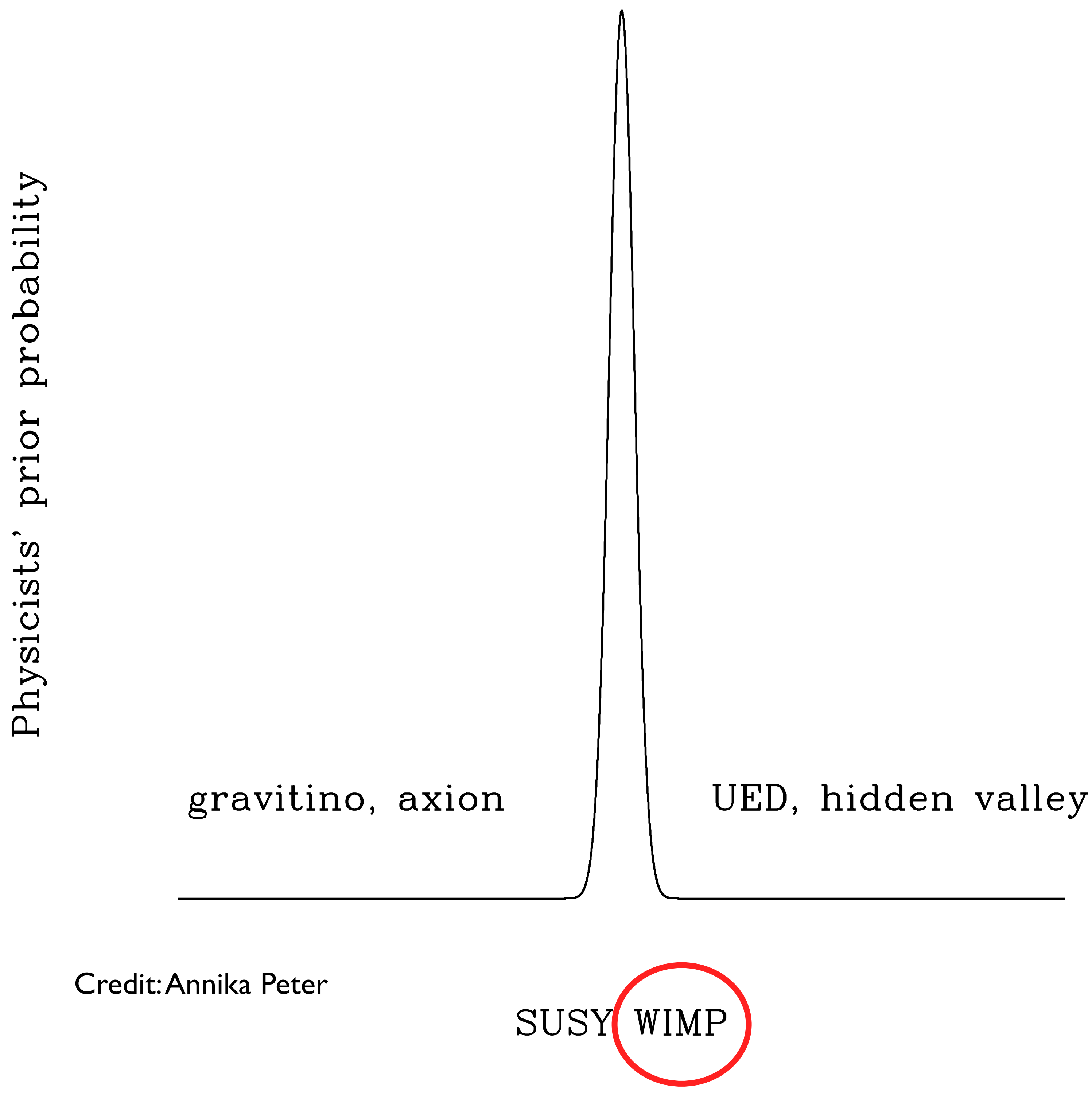


IceCube
[neutrinos]



Particle dark matter candidates



Credit: Annika Peter

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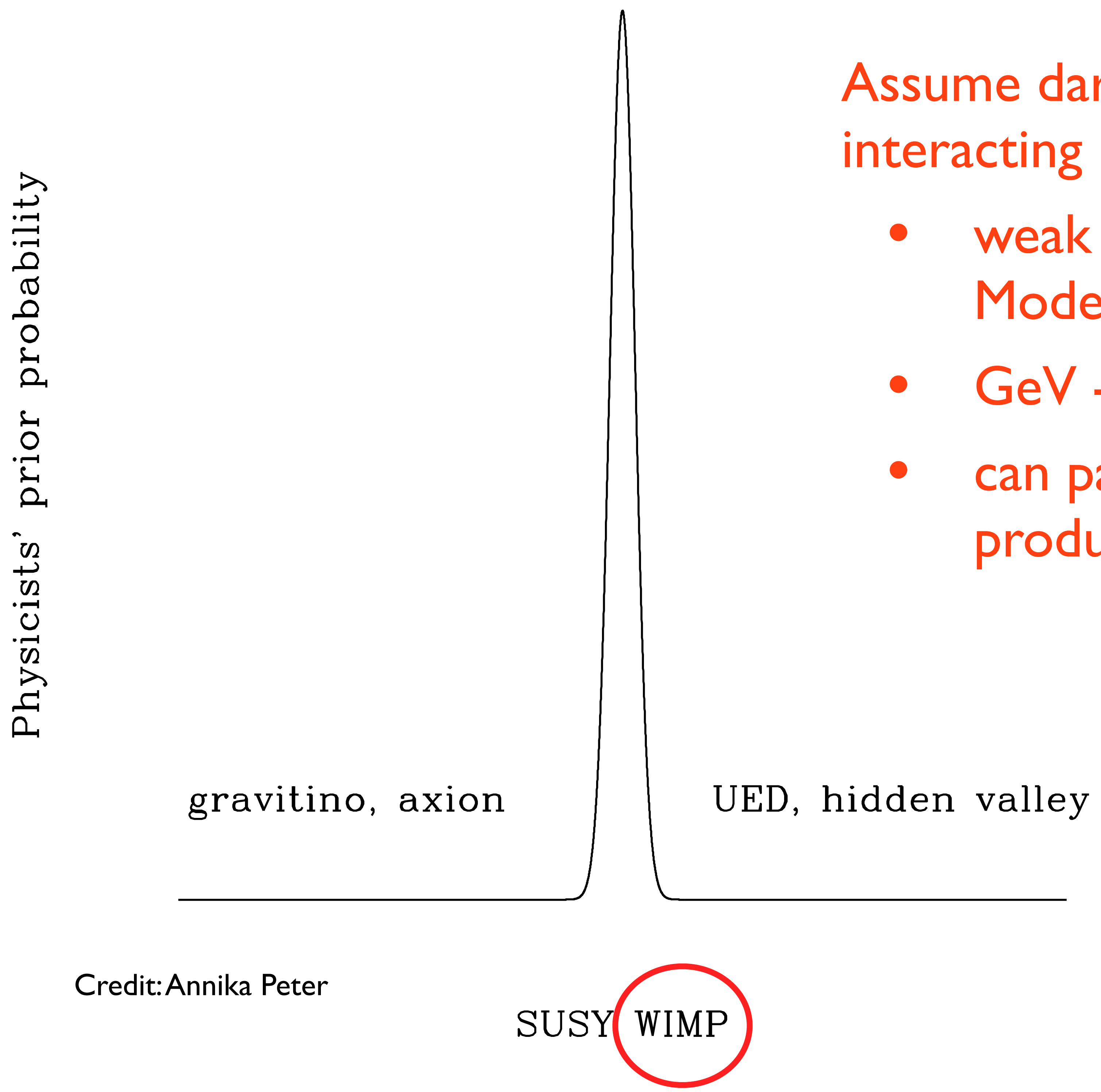


Credit: Annika Peter

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

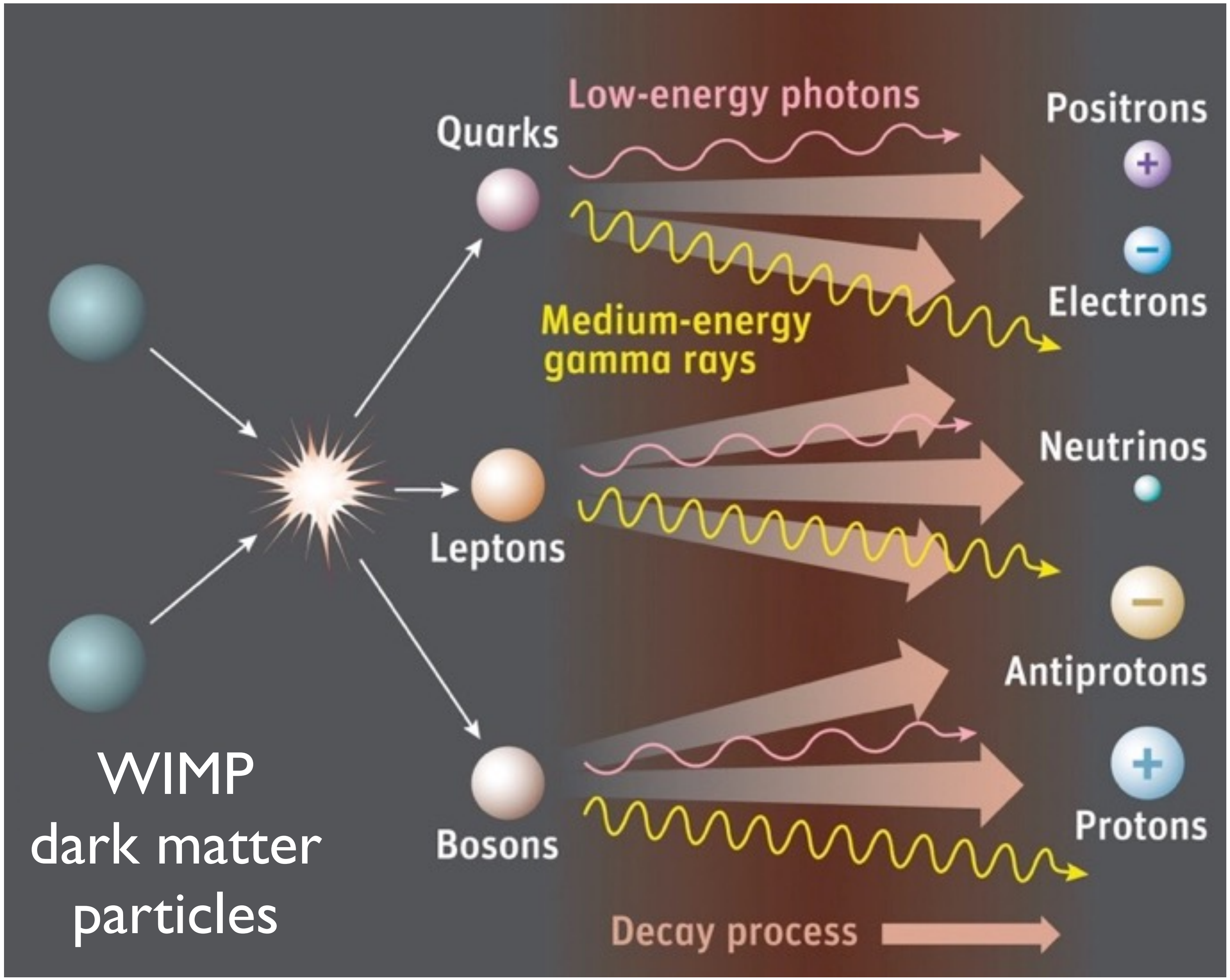
- weak interactions with Standard Model
- GeV - TeV mass scale
- can pair annihilate or decay to produce Standard Model particles

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?

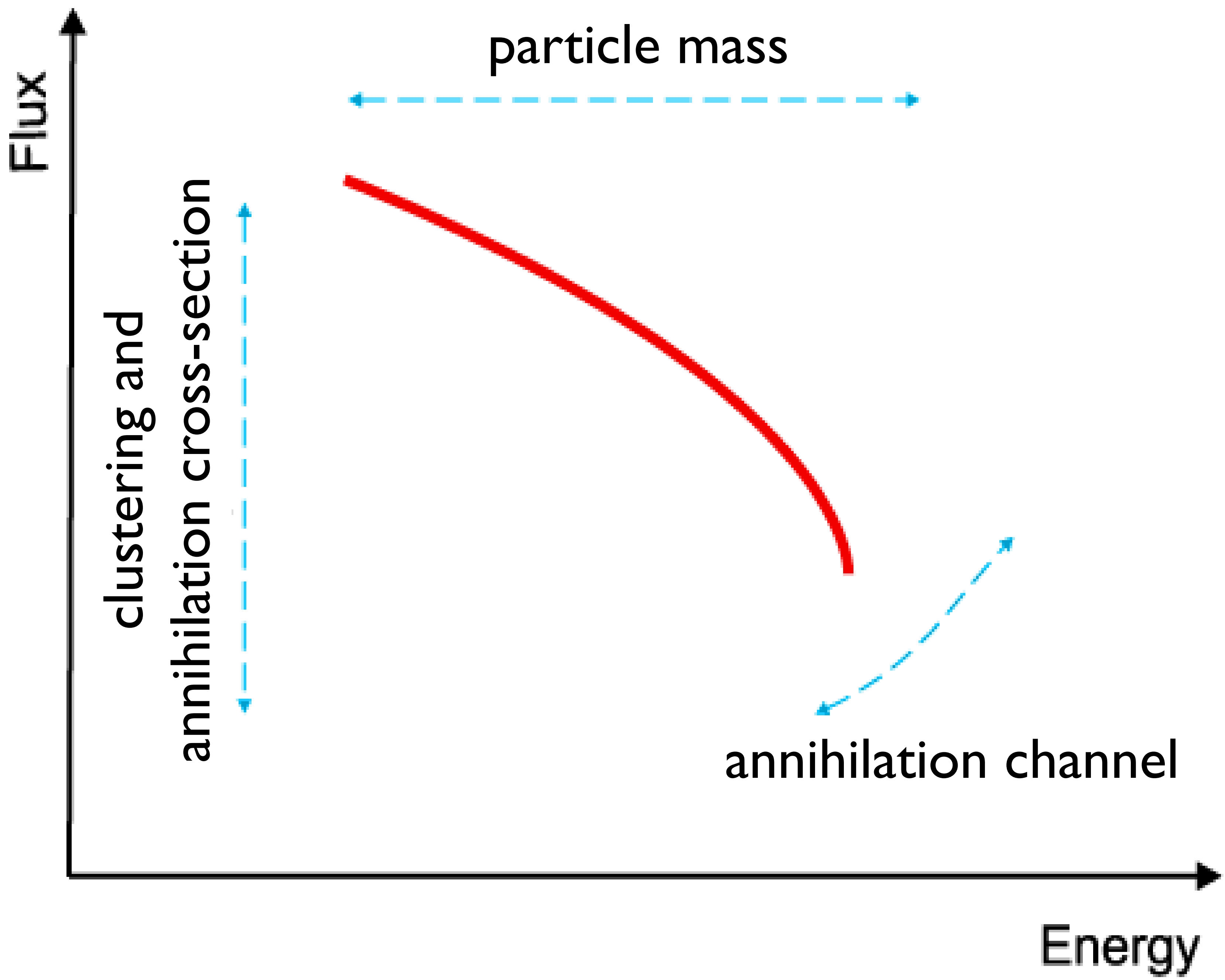
- Superheavy dark matter (mass > 10^{12} GeV)
  - non-thermal relic
  - can annihilate or decay to SM particles, such as ultra-high-energy cosmic rays or neutrinos

Indirect dark matter signals



Credit: Sky & Telescope / Gregg Dinderman

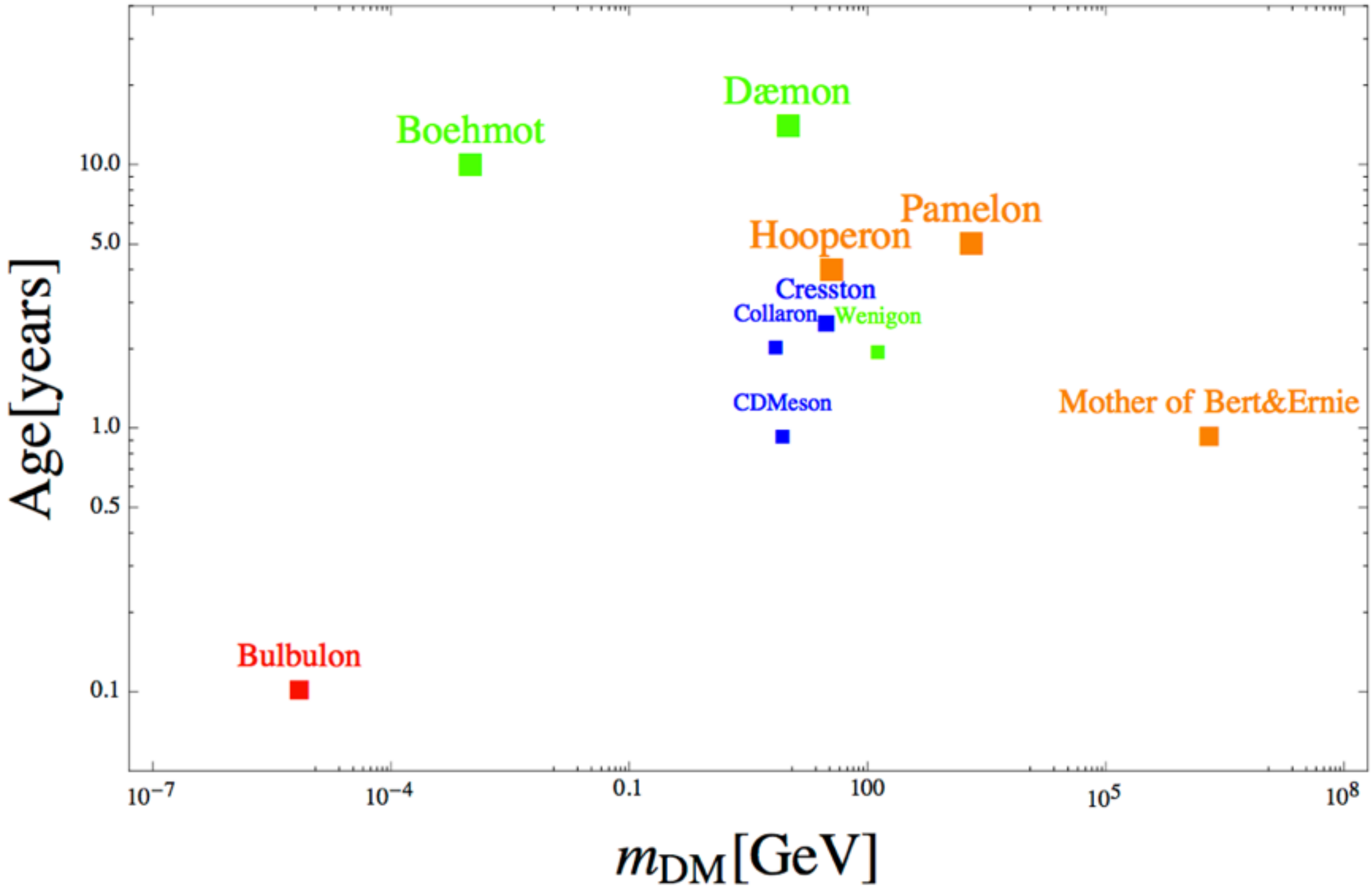
Indirect dark matter signals



adapted from Bertone 2007

Anomalies!

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



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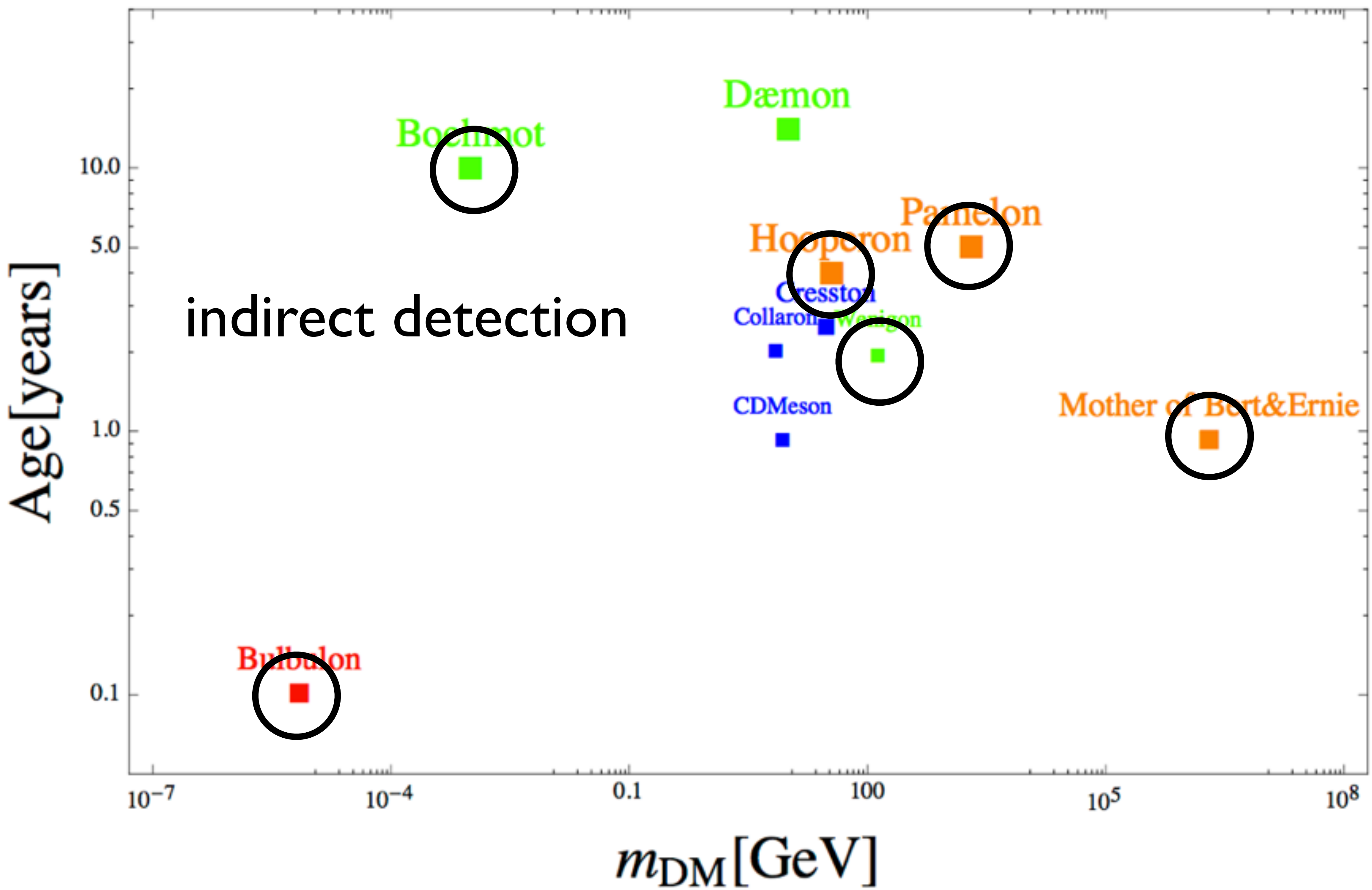

Indirect detection: selling points

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Indirect messengers

	Instruments	Advantages	Challenges
Gamma-ray photons	Fermi, HESS(-II), VERITAS, MAGIC, CTA, GAMMA-400, DAMPE, ASTROGAM	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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The Fermi Large Area Telescope (LAT)

- launched June 2008
- 20 MeV to > 300 GeV
- angular resolution:
  - ~ 0.1 deg above 10 GeV
  - ~ 1 deg at 1 GeV

Fermi data and analysis tools are public!

Credit: NASA/General Dynamics

Dark matter in the gamma-ray sky

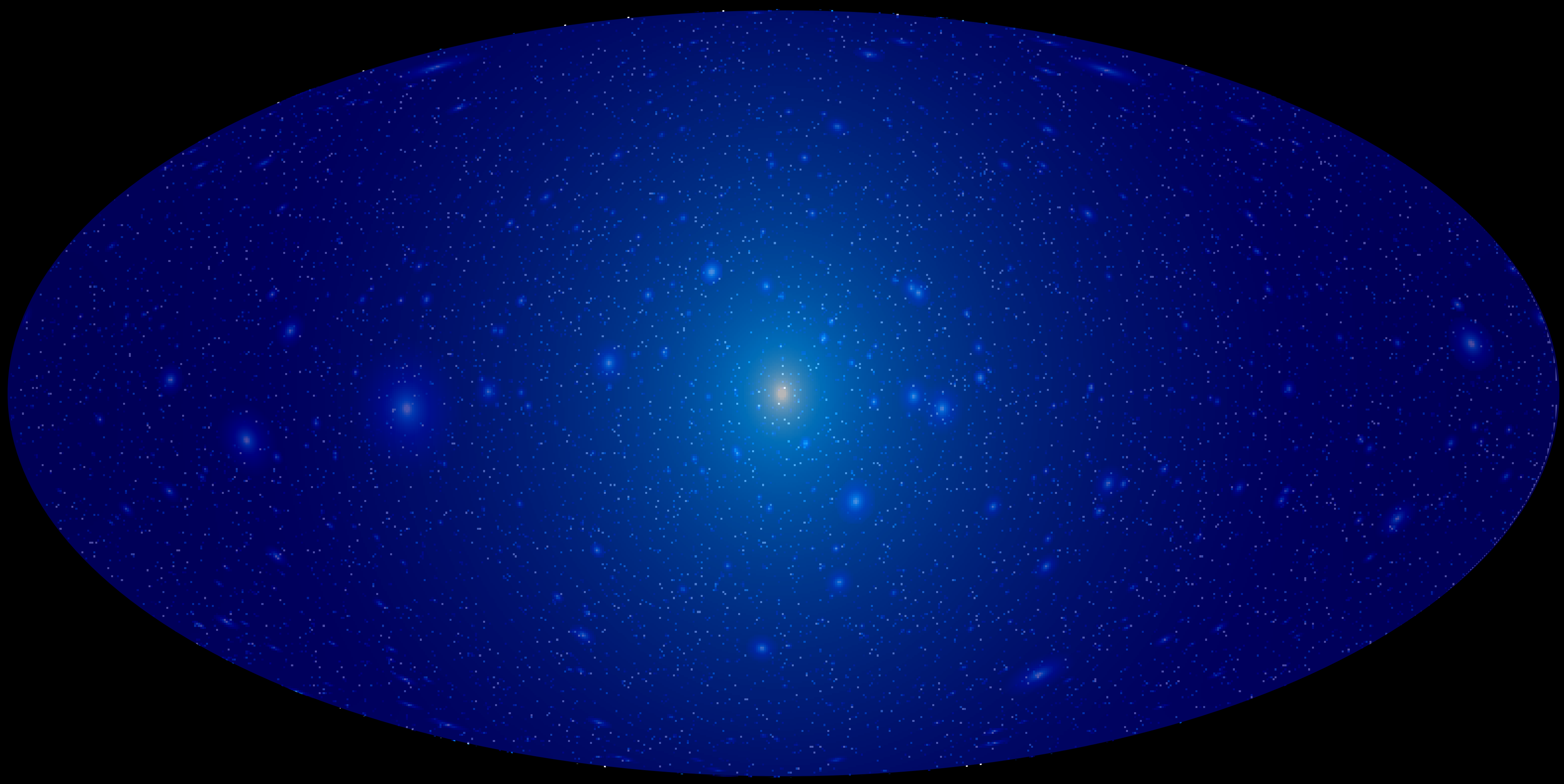

Image Credit: JG 2008

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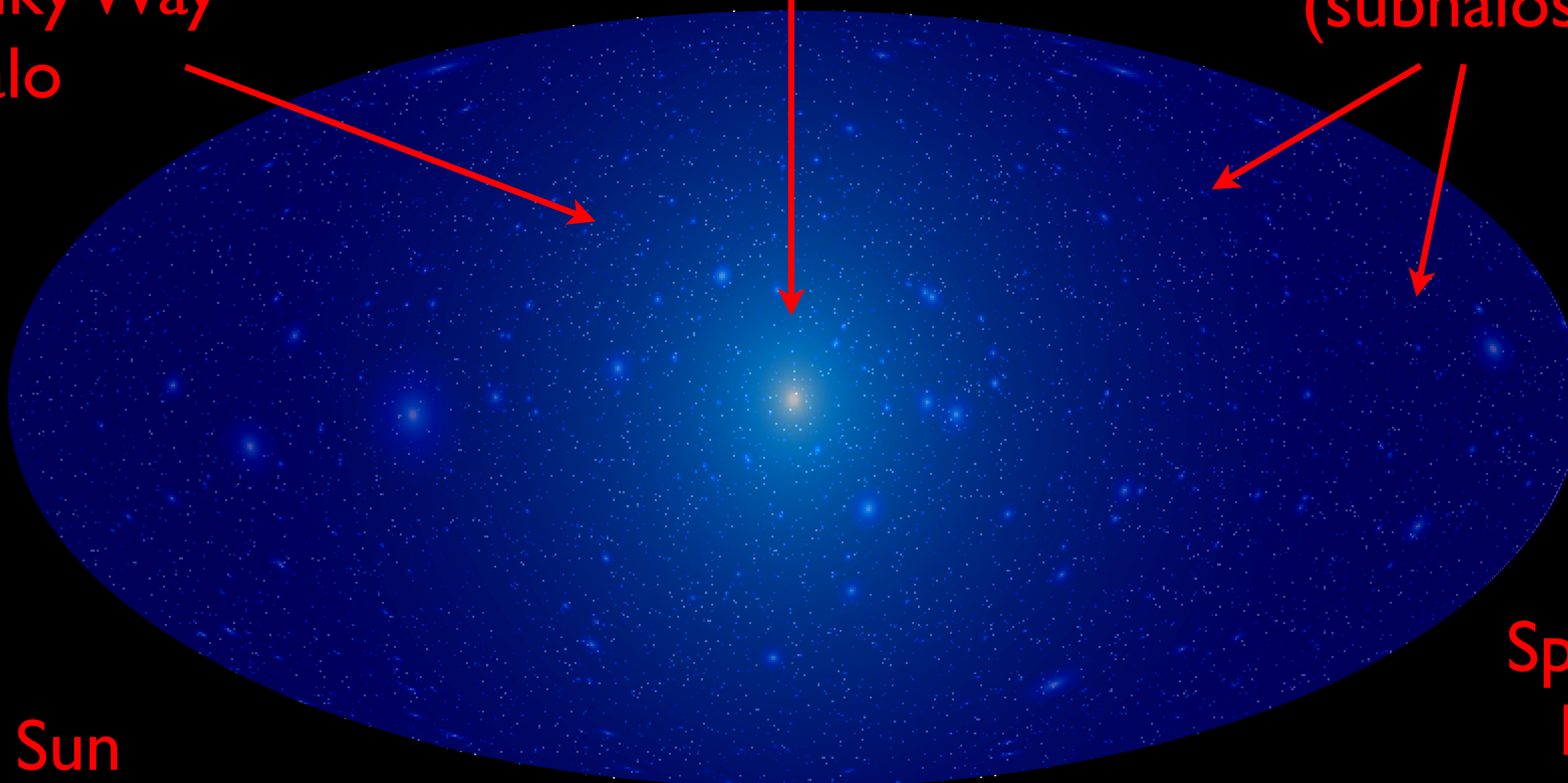

Image Credit: JG 2008

The Fermi LAT gamma-ray sky

5 years, E > 1 GeV

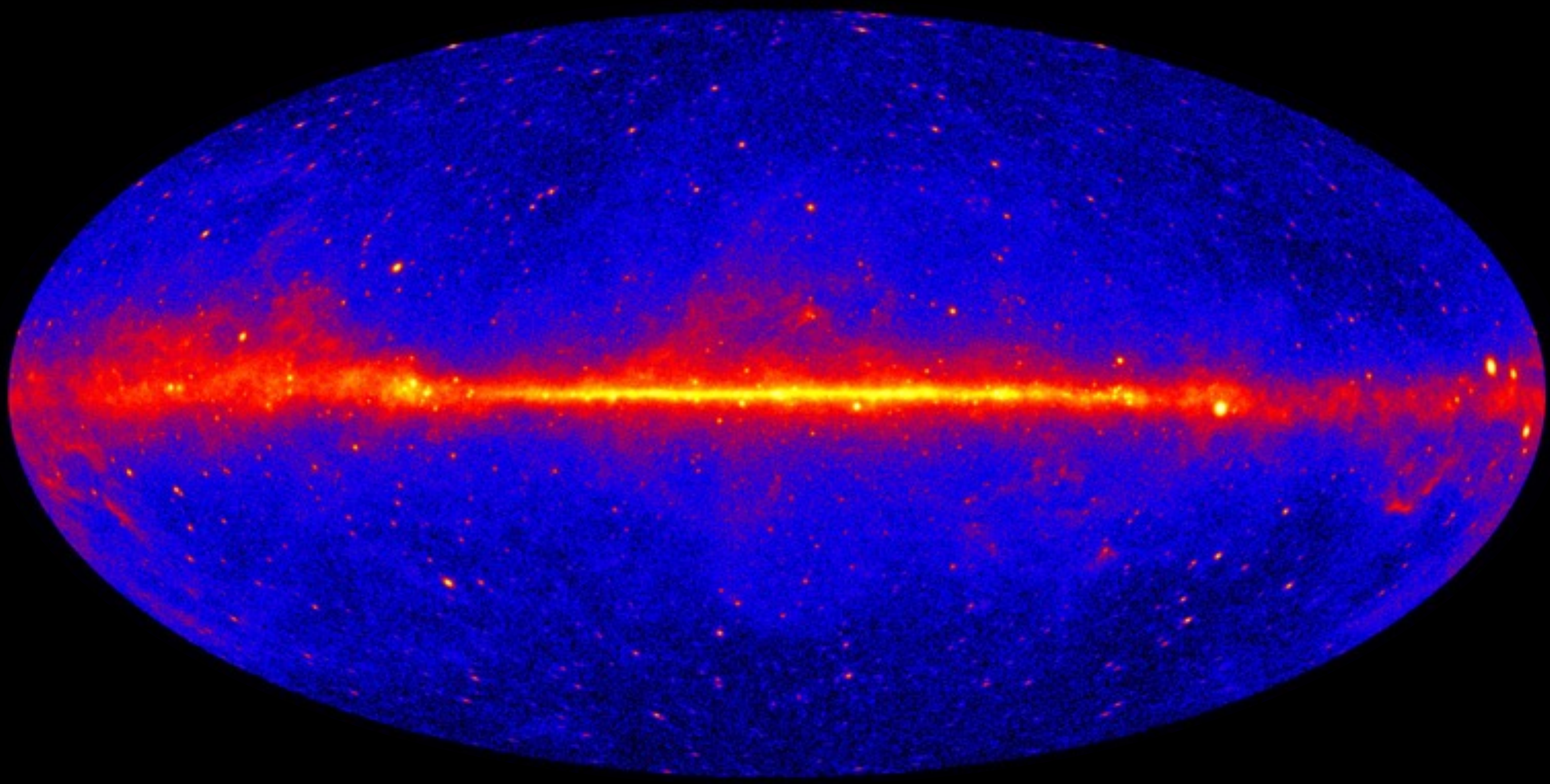

Image Credit: NASA/DOE/International LAT Team

A dark matter signal in the Inner Galaxy?

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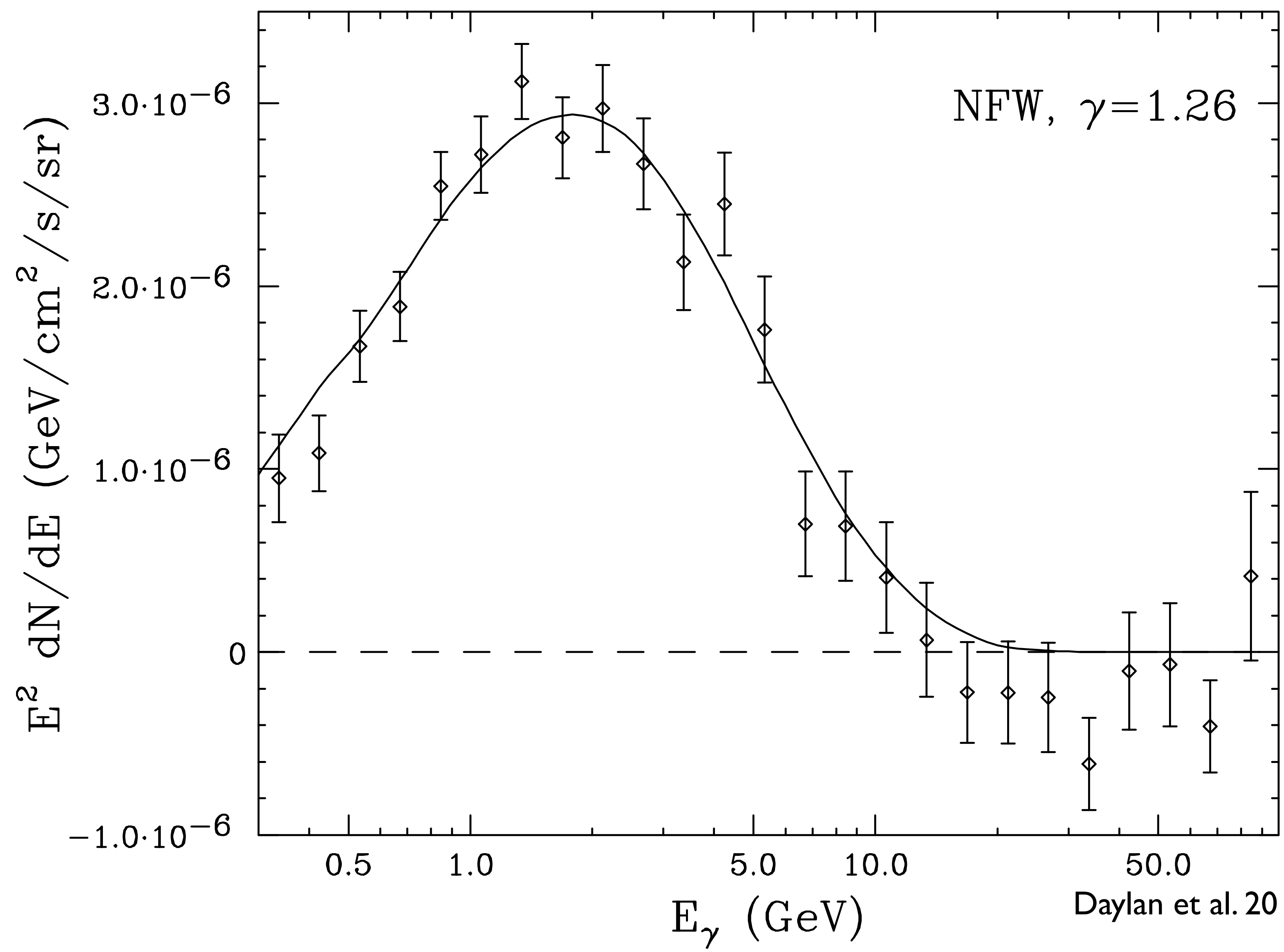

Daylan et al. 2014

see: Hooper & Goodenough 2011, Morselli, Cañadas, Vitale (Fermi LAT) 2011, Abazajian & Kaplinghat 2012, Hooper & Slatyer 2013, Gordon & Macías 2013, Abazajian et al. 2014, Daylan et al. 2014, Calore et al. 2014, and others

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- To generate amplitude of the excess:
  - requires roughly thermal relic DM annihilation cross section
  - for the Galactic Center would require a few thousand MSPs, which seems plausible
  - for higher Galactic latitudes (|b|>10 deg), hard to explain with MSP models

see: Hooper & Goodenough 2011, Morselli, Cañadas, Vitale (Fermi LAT) 2011, Abazajian & Kaplinghat 2012, Hooper & Slatyer 2013, Gordon & Macías 2013, Abazajian et al. 2014, Daylan et al. 2014, Calore et al. 2014, and others

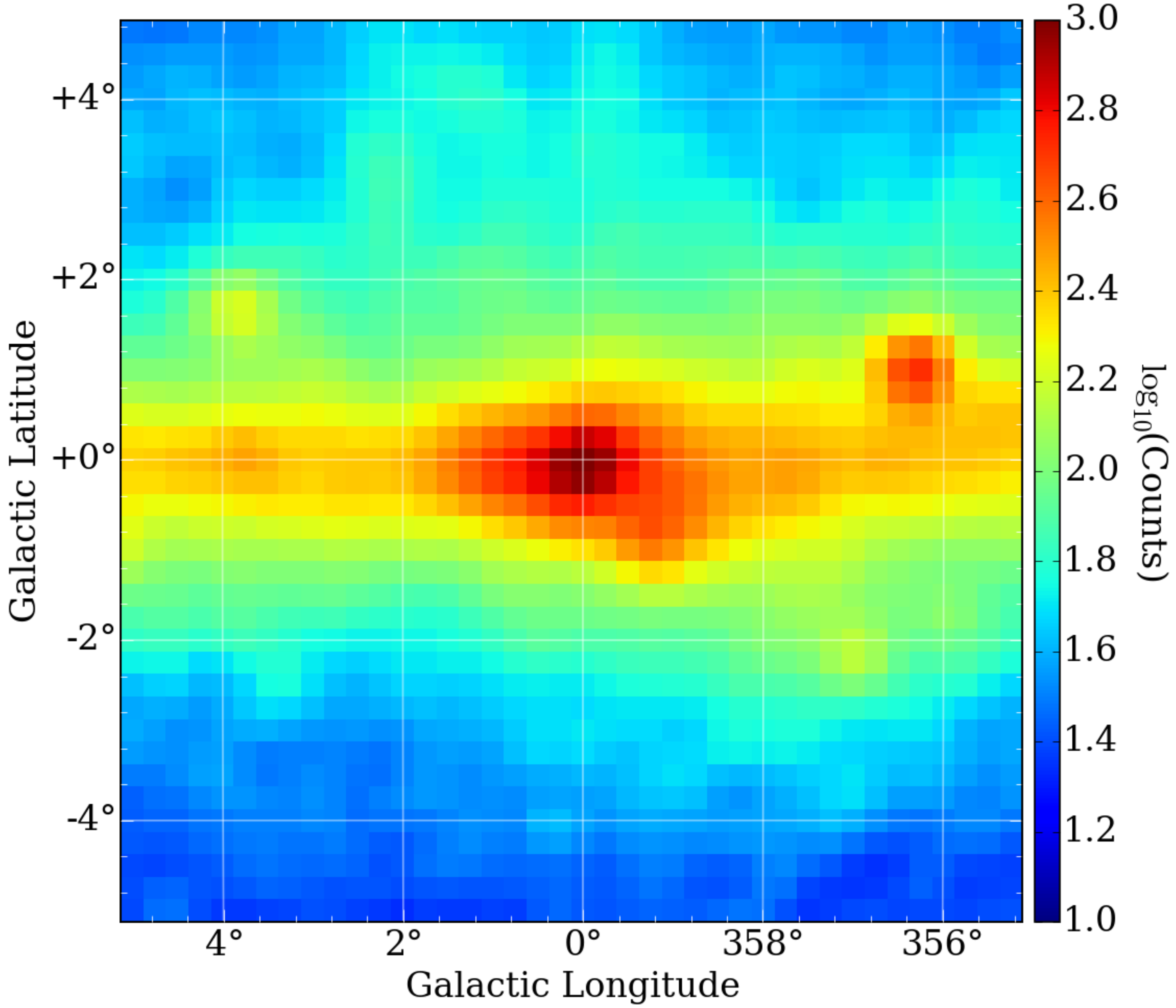
Excess over what?

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)

Fermi LAT data

observed counts (1-35 GeV)



JG 2015 (in prep)

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What's not in the model:

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- dark matter

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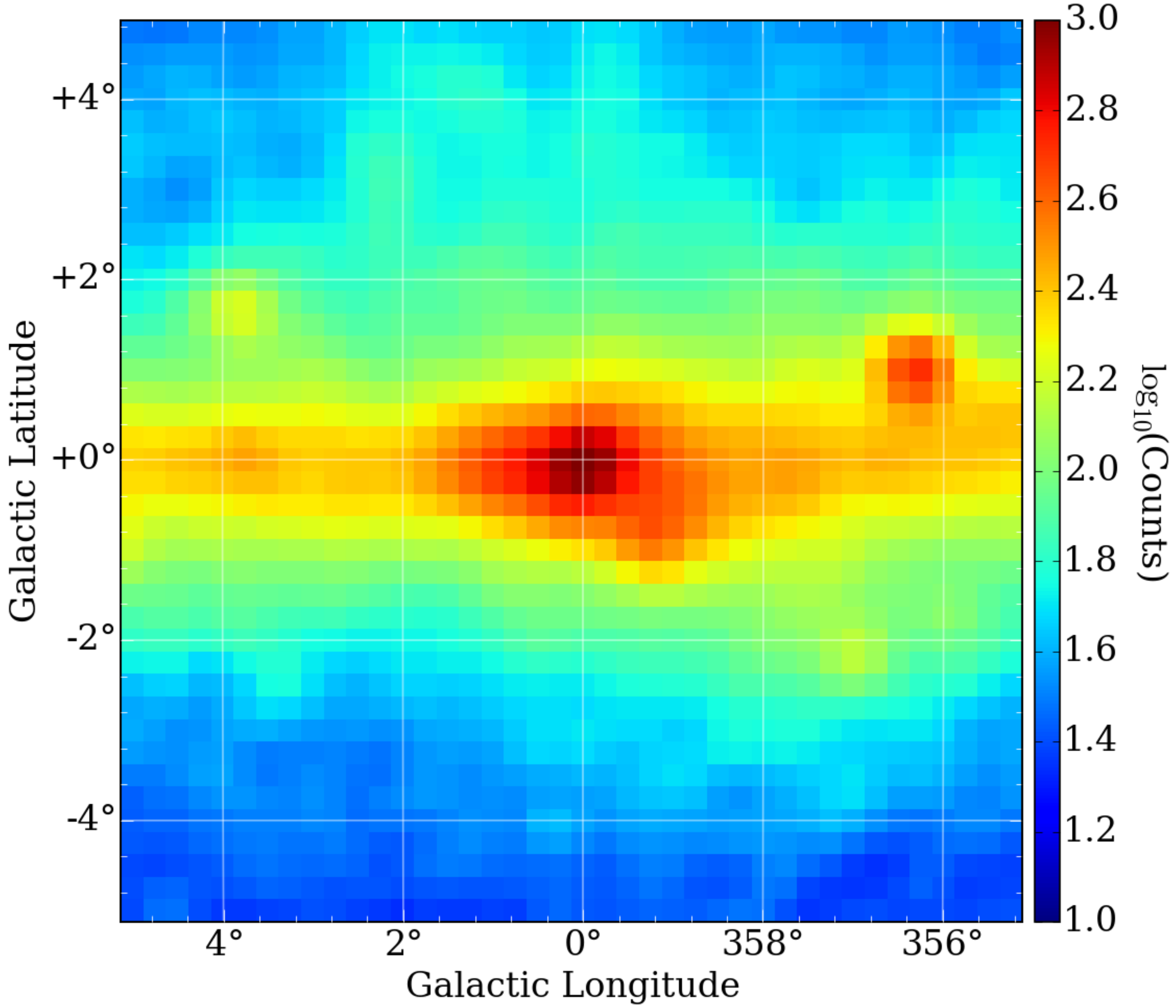

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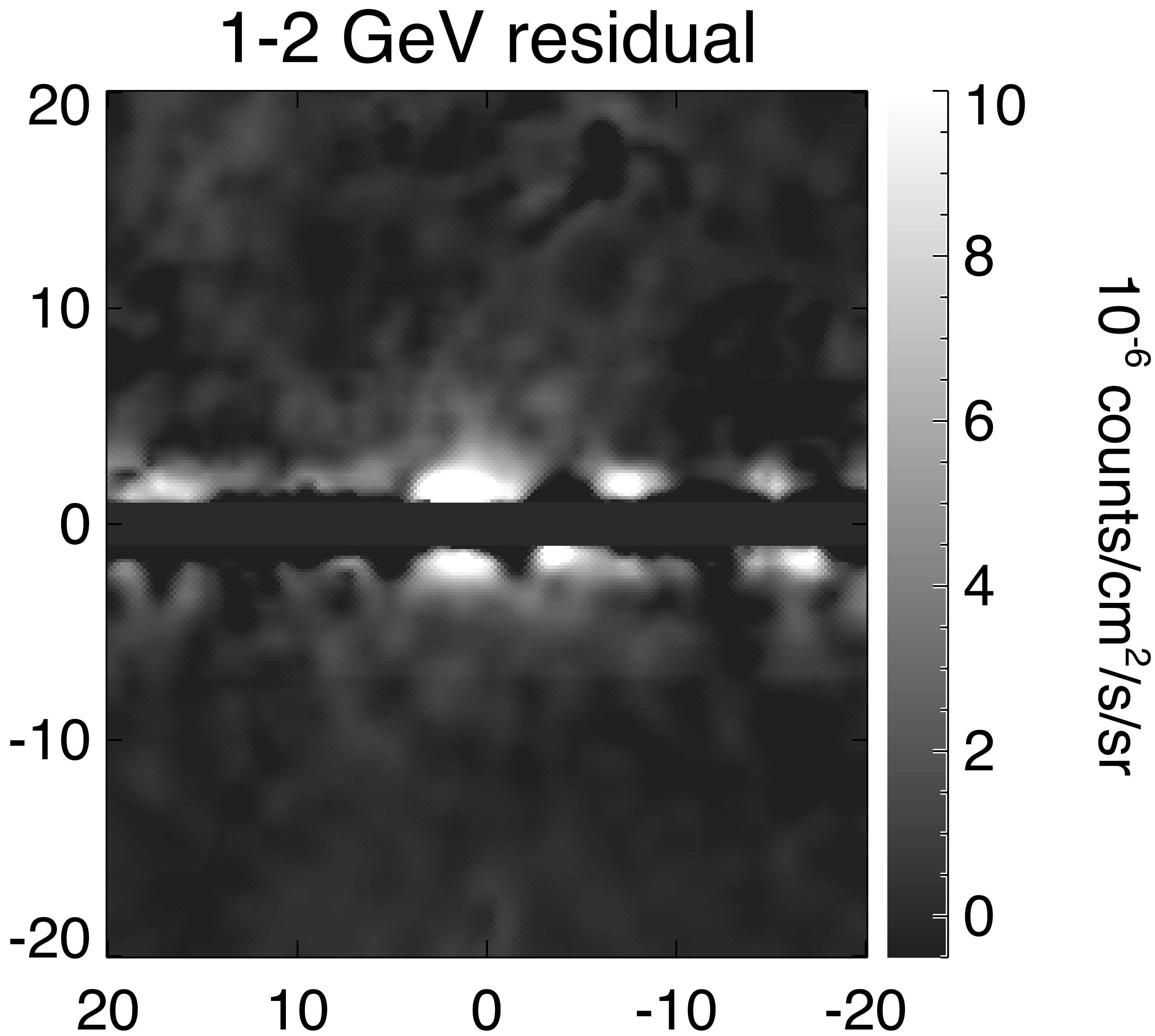
(for best-fit model w/o dark matter component)



Daylan et al. 2014

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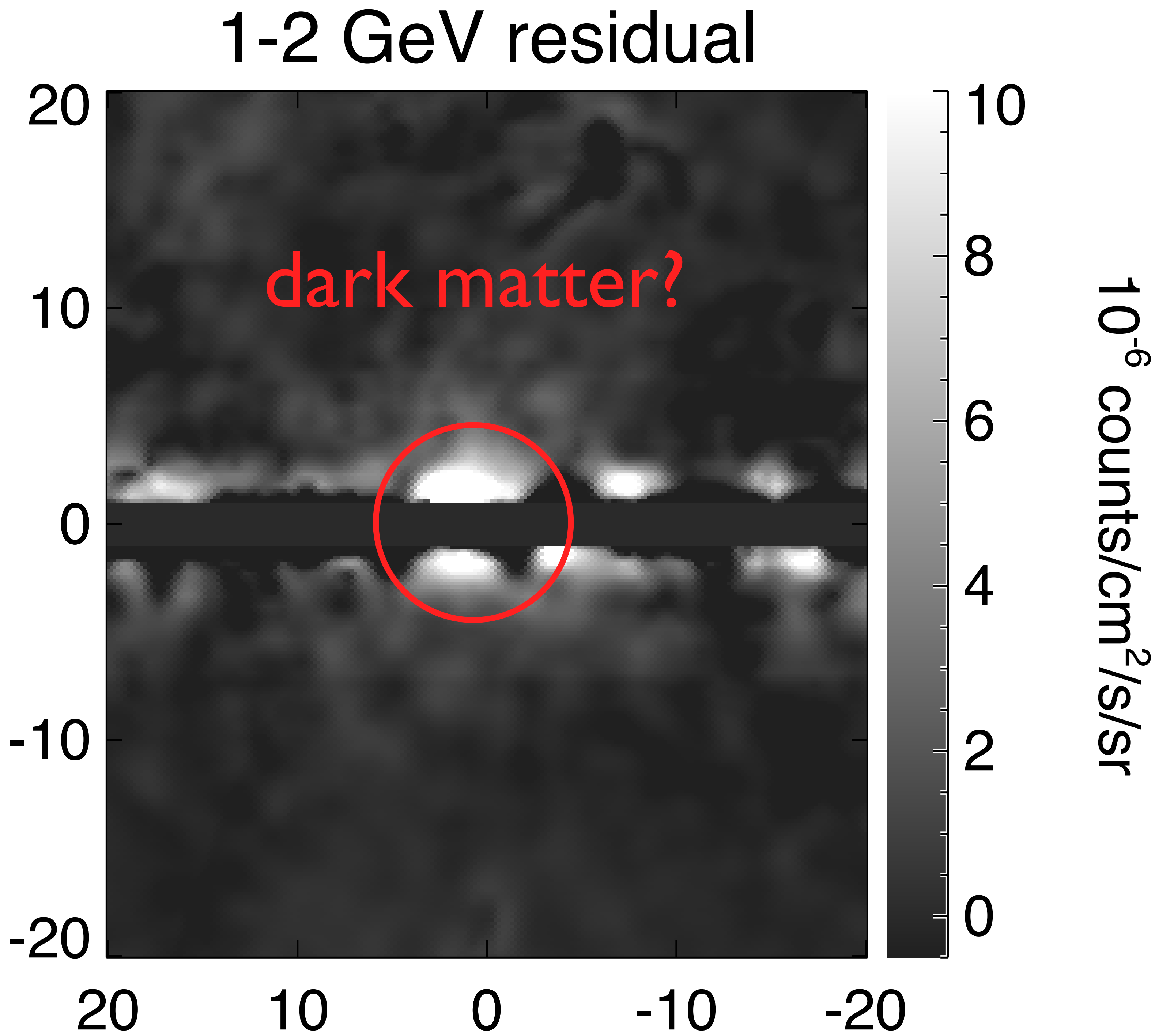

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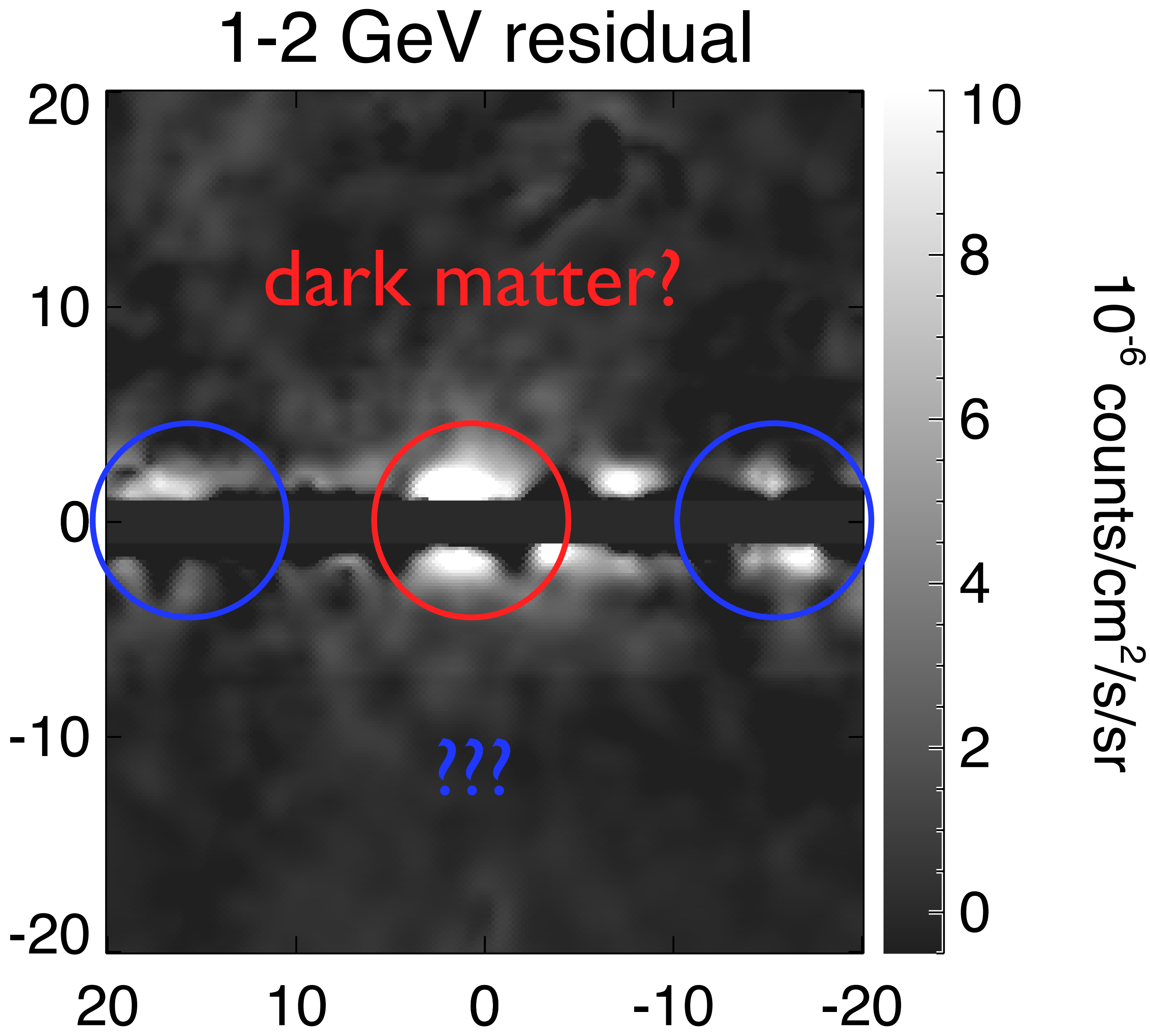


Daylan et al. 2014

Can the GeV excess be millisecond pulsars?

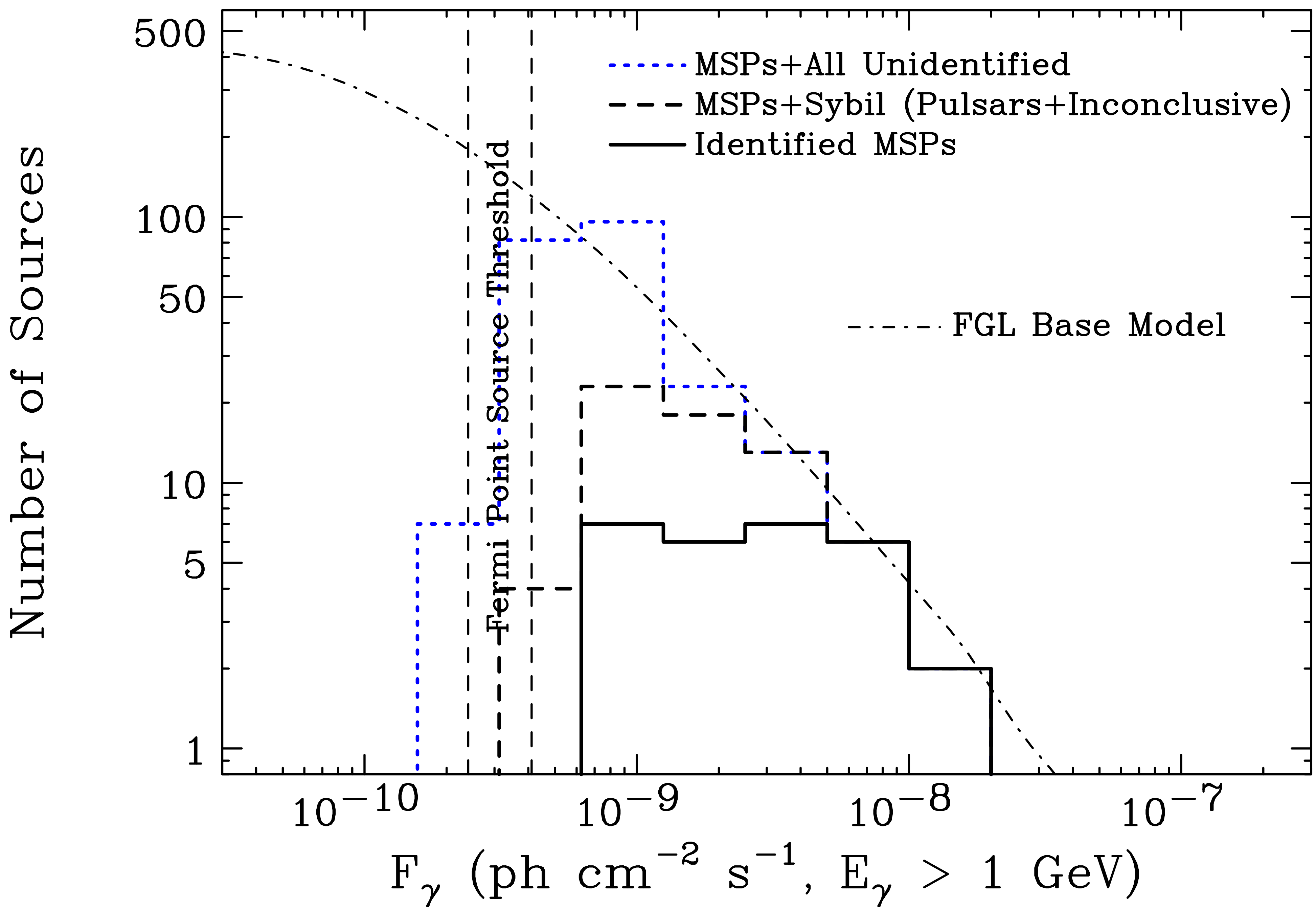
Can unresolved MSPs produce the high-latitude excess?

- first, note that only a few dozen MSPs have been detected in gamma rays; Galactic MSP population could be ~ 10k! We've only seen the tip of the iceberg.
- adopt a spatial model and luminosity function for the MSPs, calibrated to detections in radio (start with base model of Faucher-Giguere & Loeb 2010)
- from model, calculate flux distribution of MSPs for |b|>10 deg
- (at low Galactic latitudes, model and observational uncertainties are larger)

Can the GeV excess be millisecond pulsars?

Unresolved sources (contribute to diffuse) | Resolved sources

source count distribution (|b|>10 deg)



Hooper, Cholis, Linden, JG, Slatyer 2013

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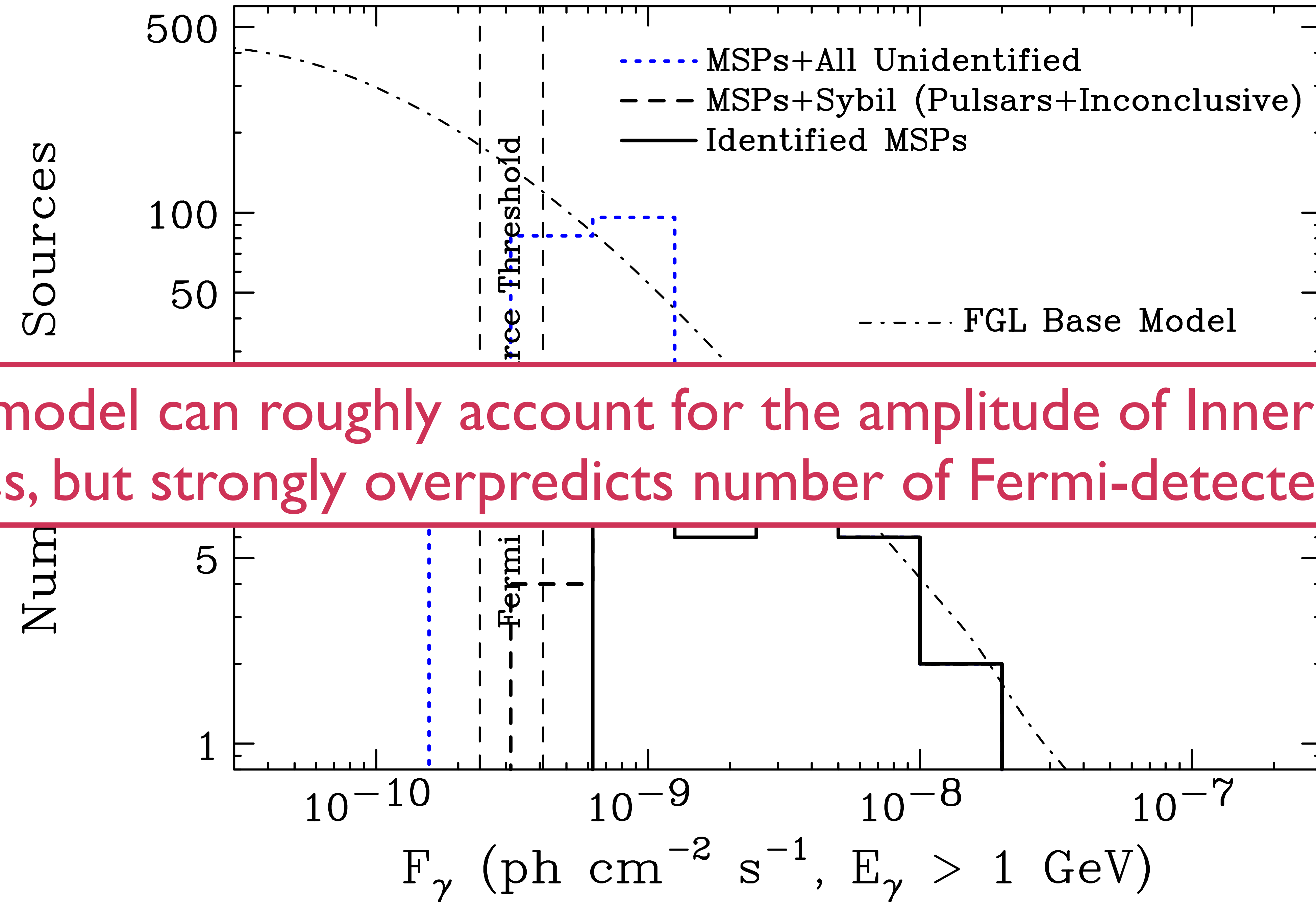

base model can roughly account for the amplitude of Inner Galaxy excess, but strongly overpredicts number of Fermi-detected MSPs

Hooper, Cholis, Linden, JG, Slatyer 2013

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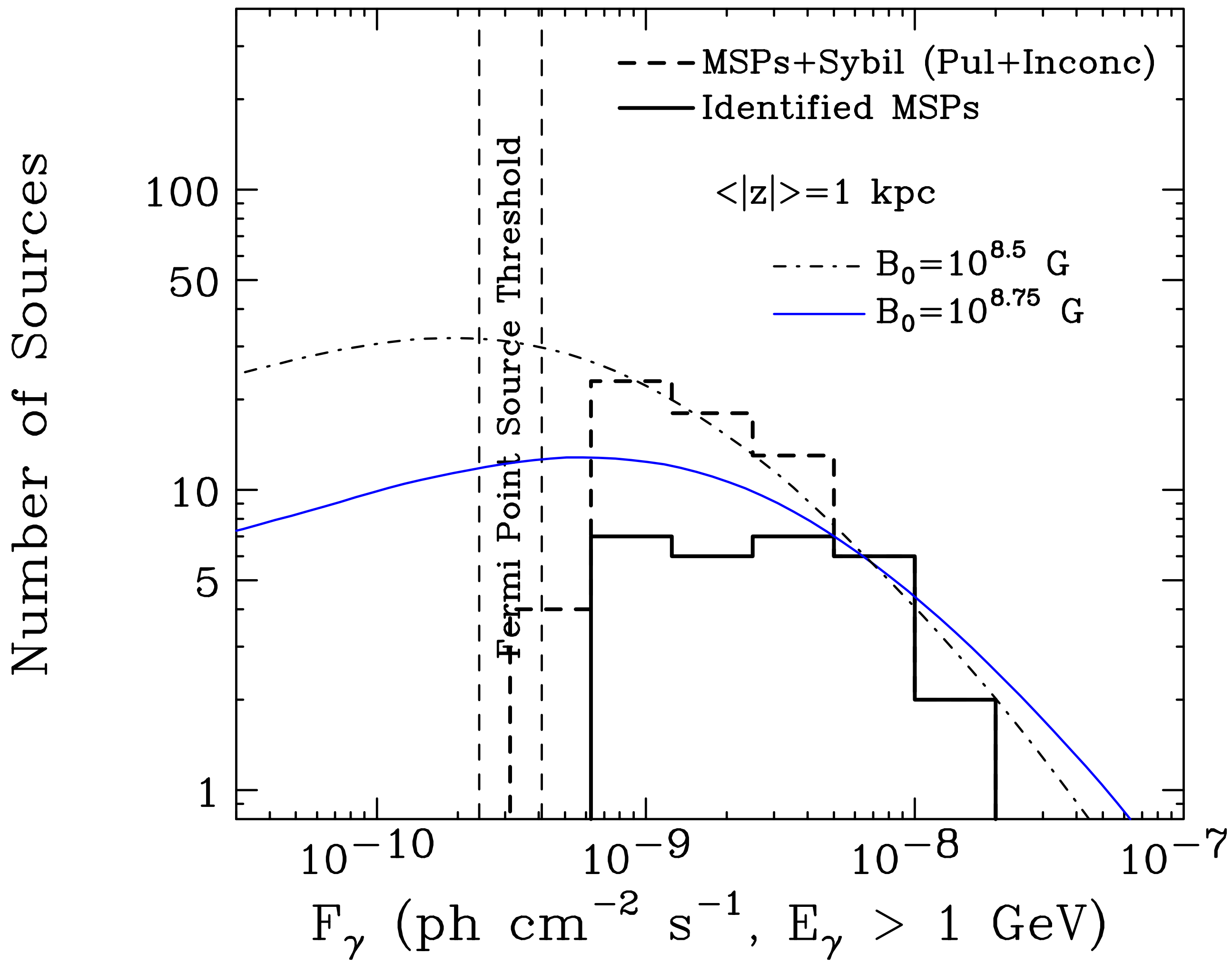
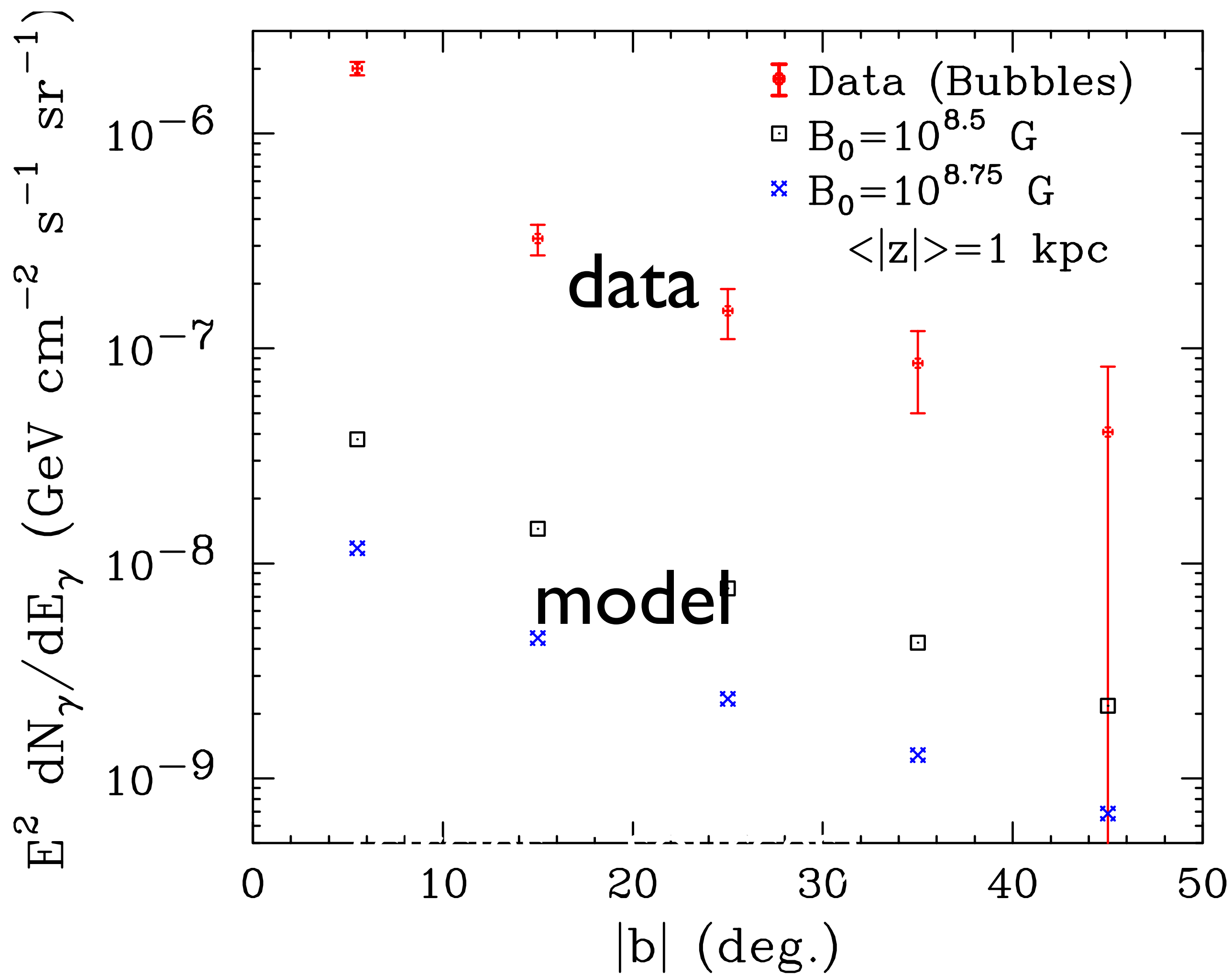


Latitude dependence of excess



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

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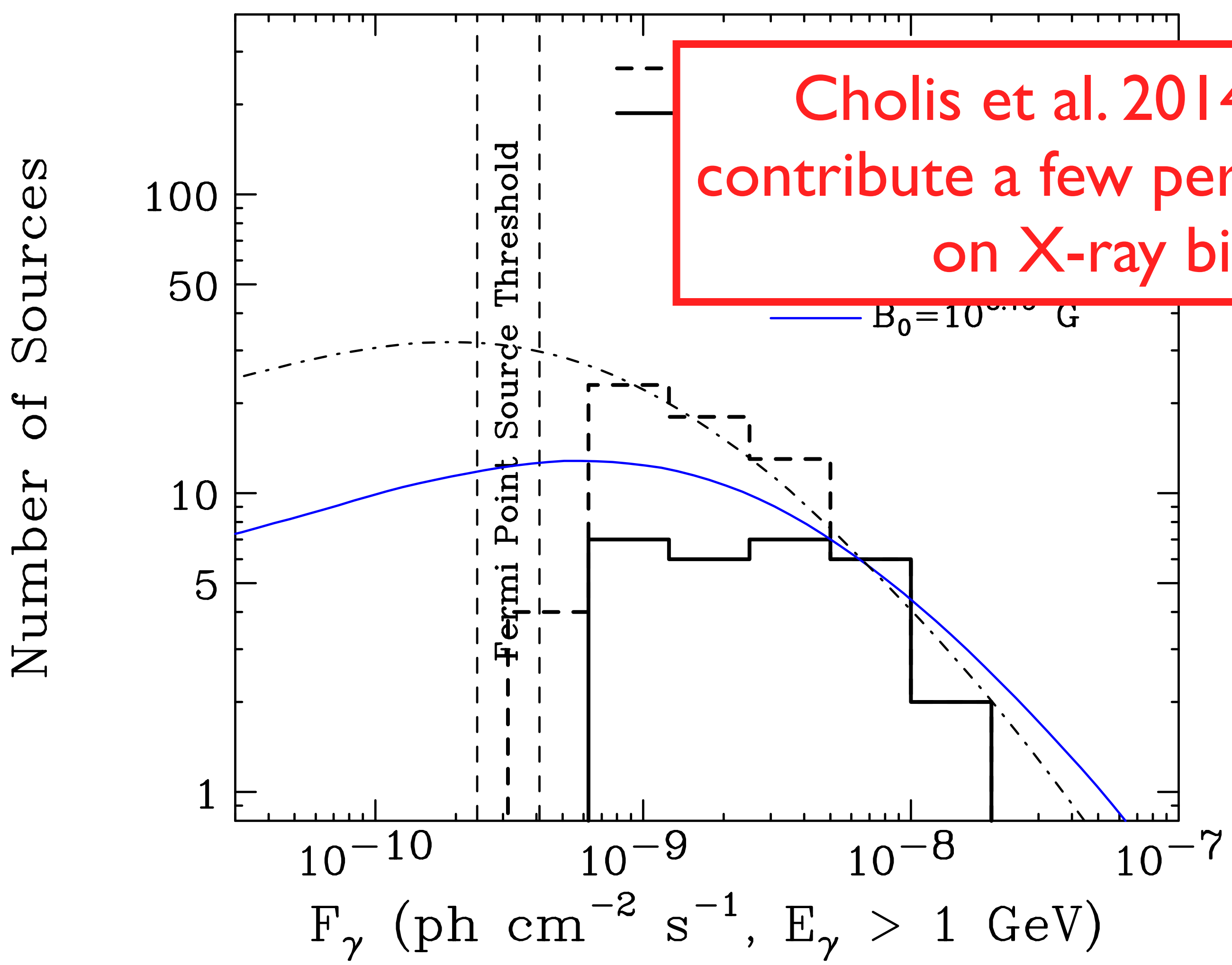

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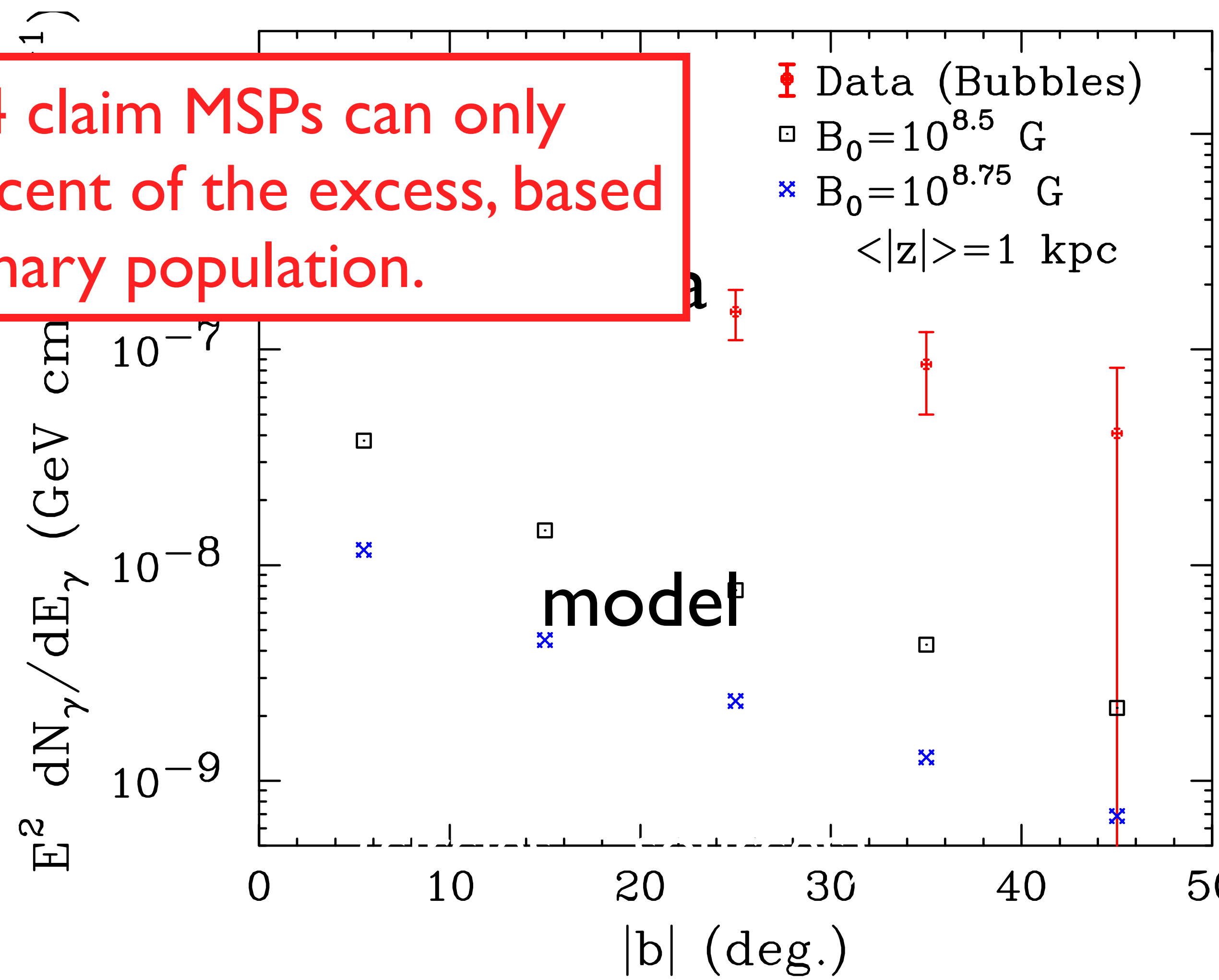

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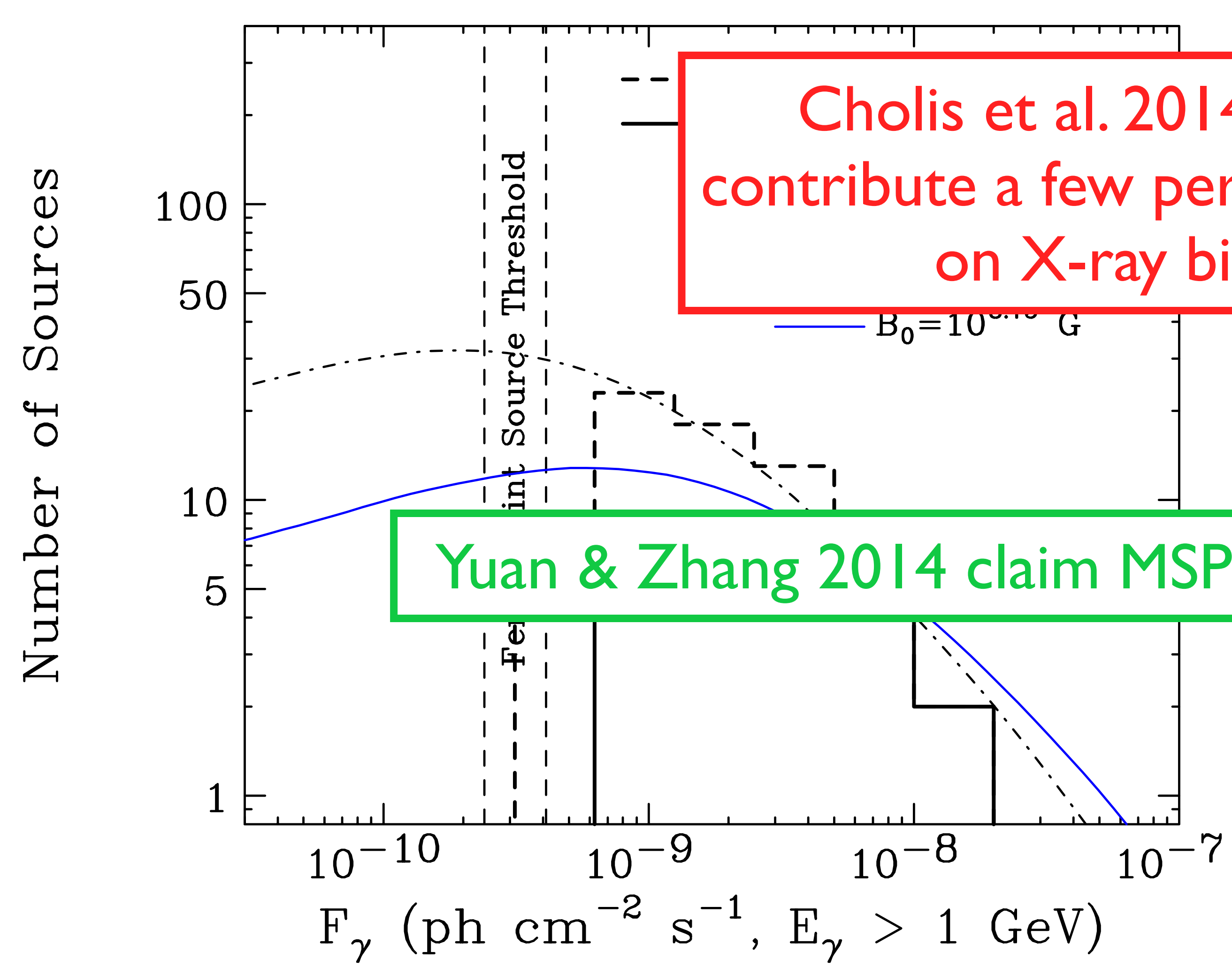

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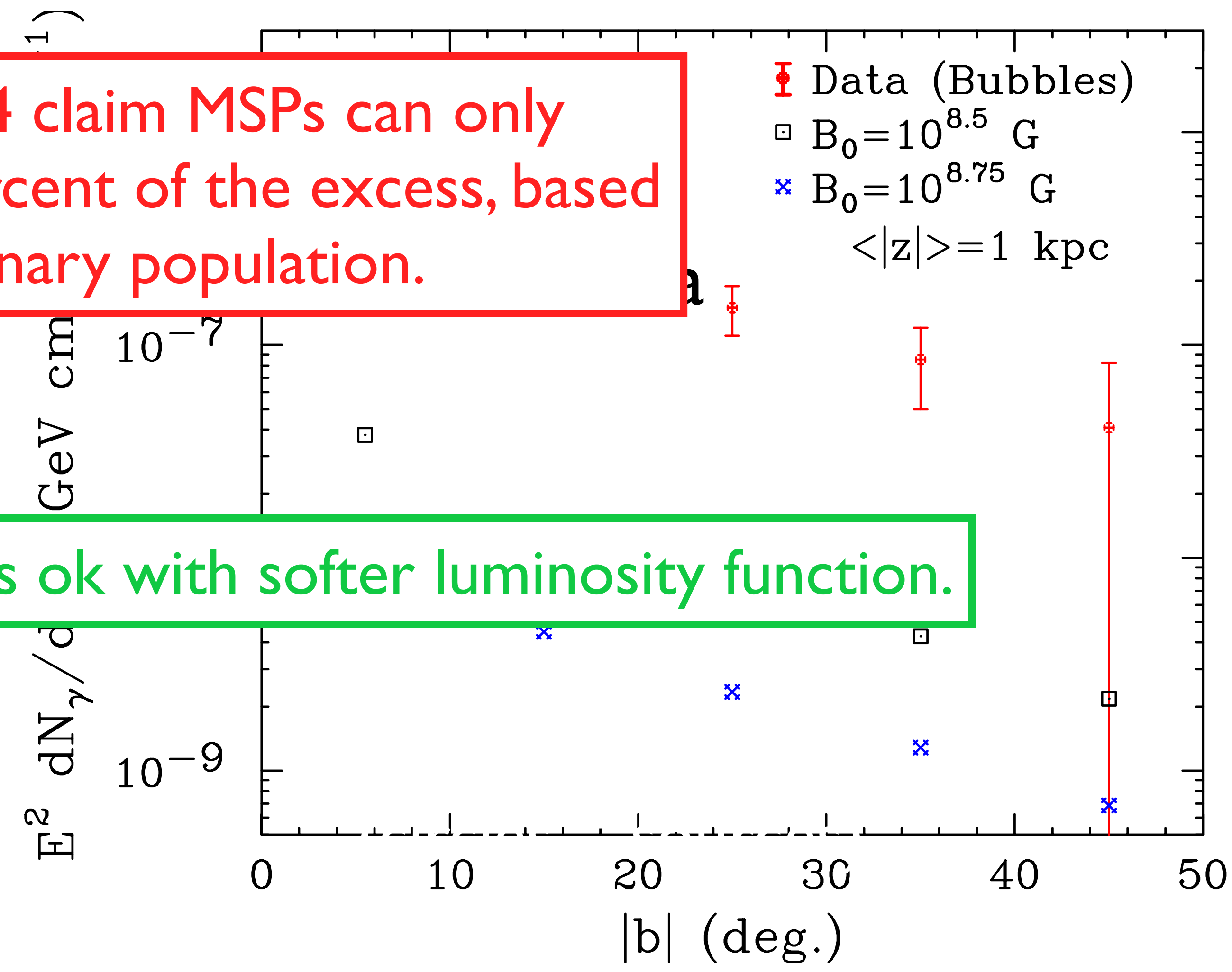

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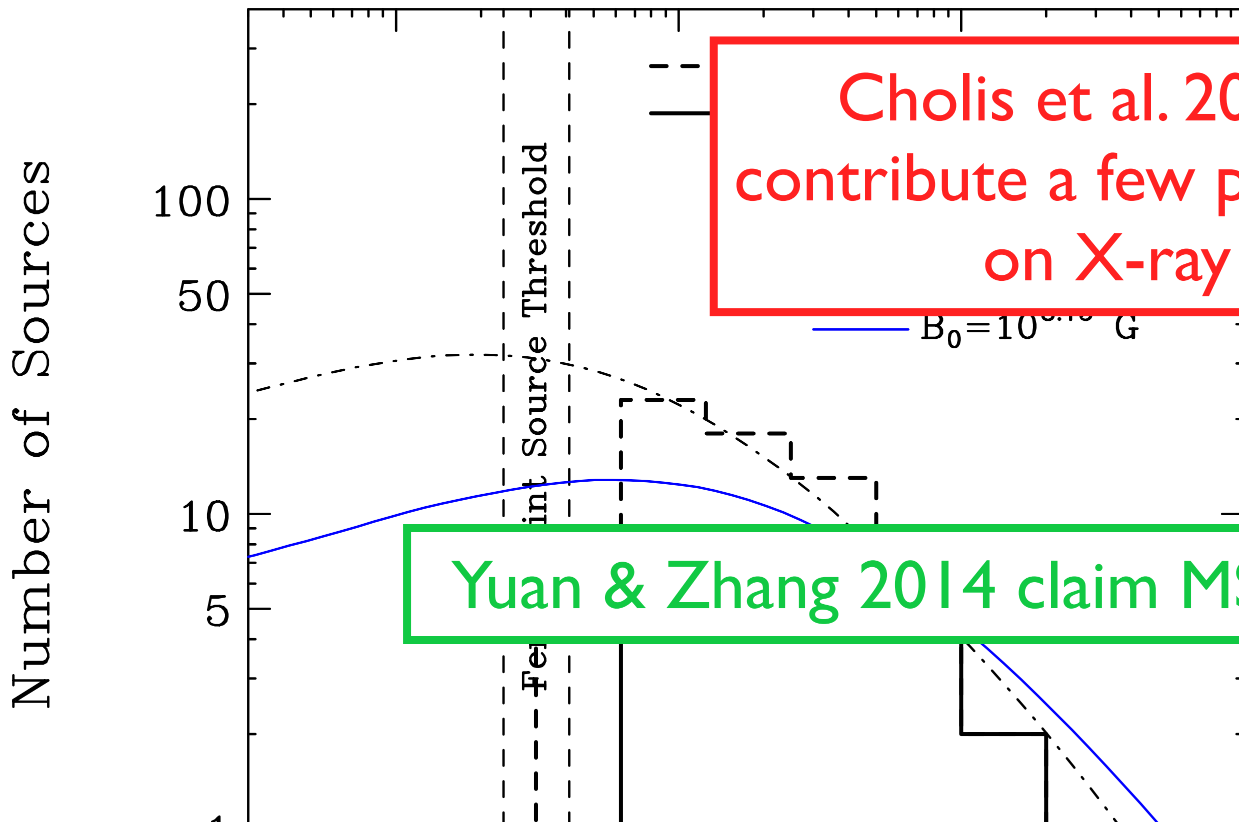

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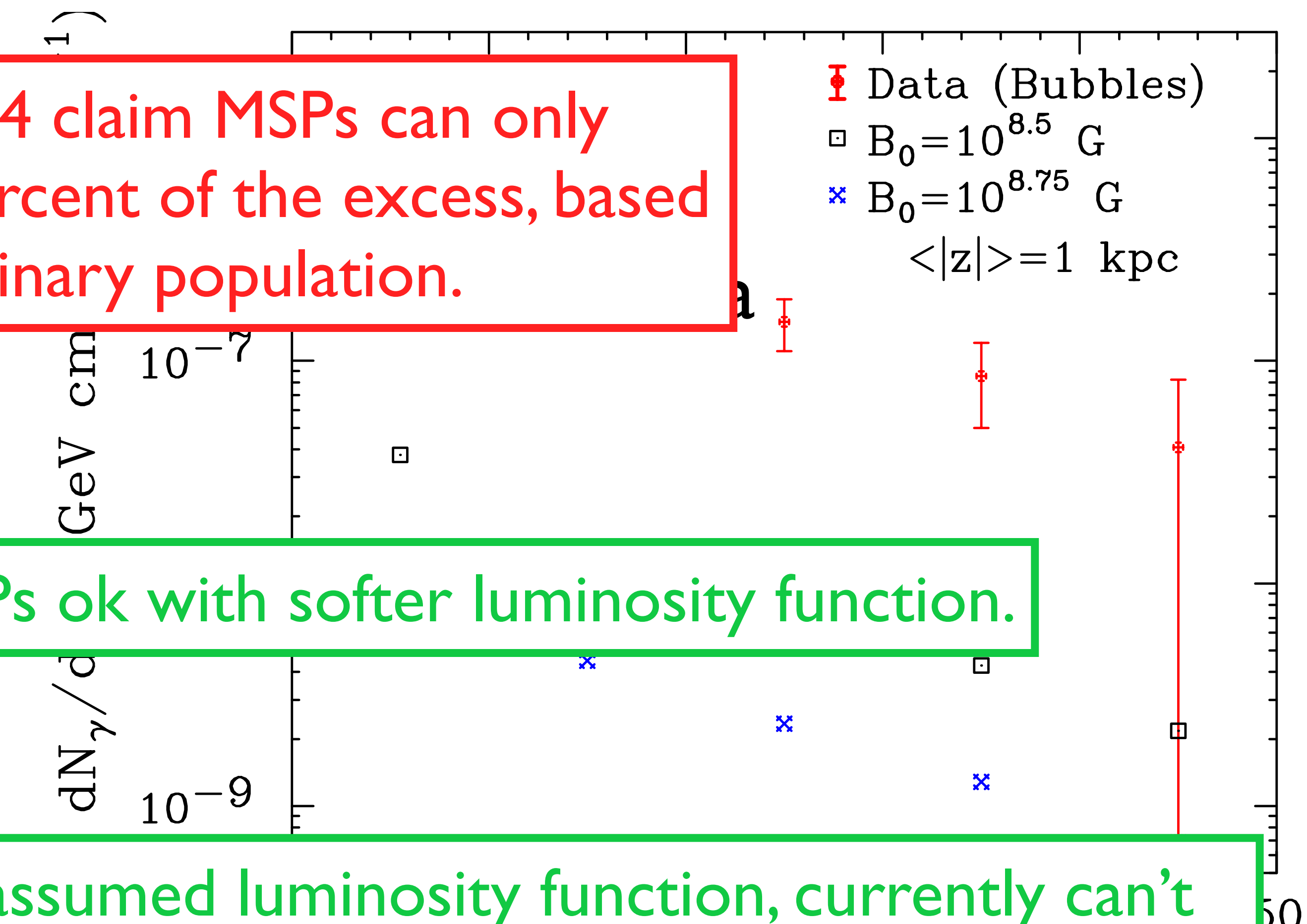

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Petrović et al. 2014 say depends on assumed luminosity function, currently can't exclude MSPs.

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, JG, Slatyer 2013

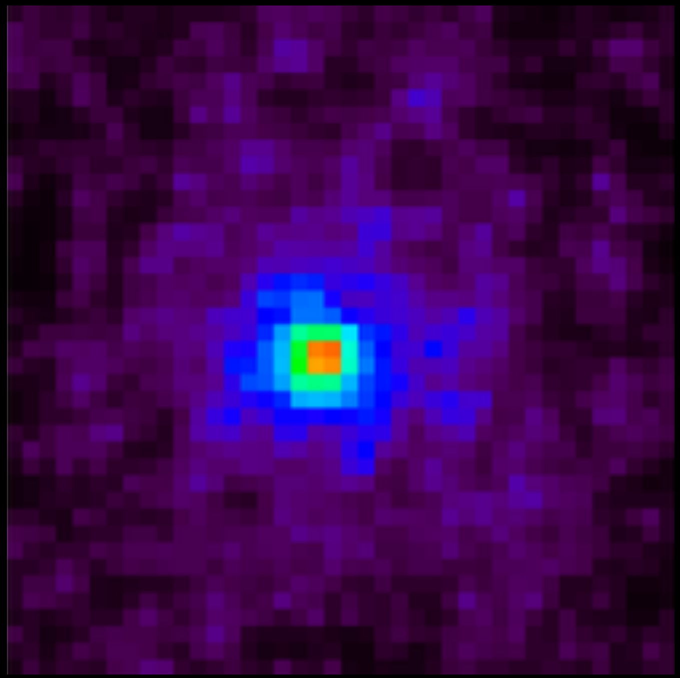
Bed of Procrustes

Statistics of the Inner Galaxy emission

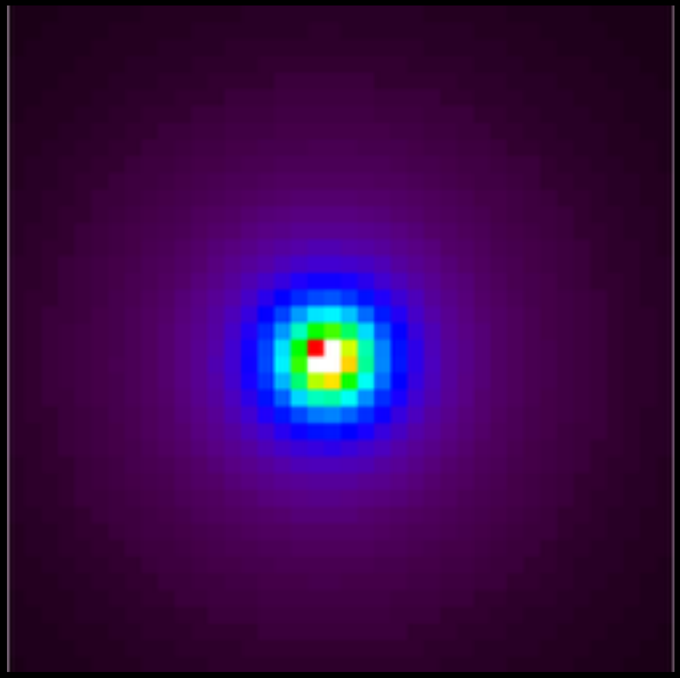
- GeV excess analyses to date have used spatial templates based on the *average* properties of the emission from DM or sources because we do not know the locations of unresolved sources
- real data contains information that is lost in spatial models which represent average source emission
- we will use *statistical information* in the emission to constrain the properties of its contributors

Statistical properties of diffuse emission

sources map



DM map

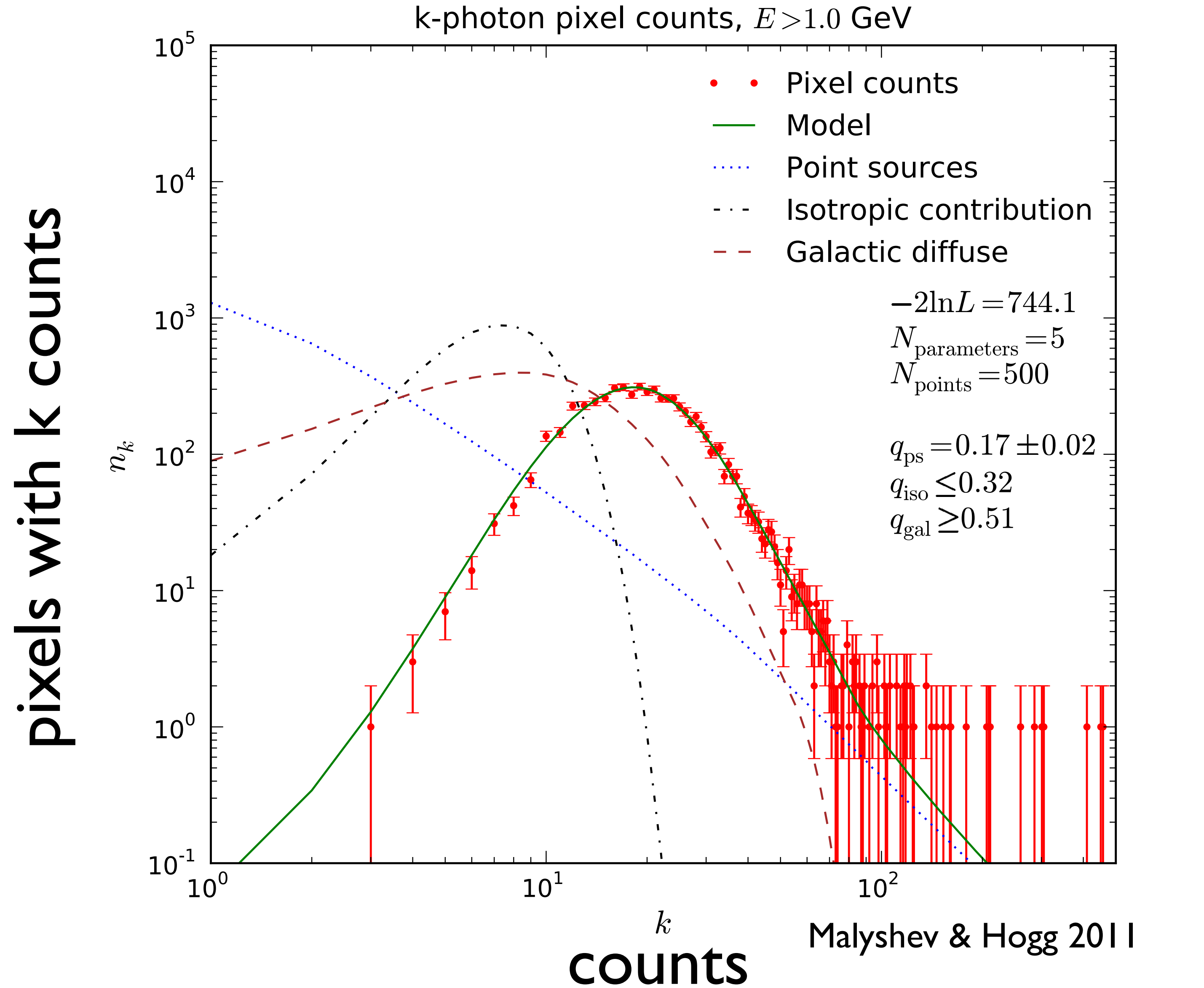


- diffuse emission arising from point sources has different clustering properties than emission from a smooth source (such as DM annihilation in the Inner Galaxy)
- can use the 1pt-PDF (# of pixels with k counts vs k counts) to characterize the clustering properties

The 1pt-PDF

- in the case of uniform exposure, the 1pt-PDF for a truly isotropic source will be Poisson-distributed
- sources feature a larger high-count tail and larger low count tail at the expense of the moderate-count regime

1pt-PDF of the Fermi gamma-ray background



Malyshev & Hogg 2011

NB: 1pt-PDFs are NOT additive

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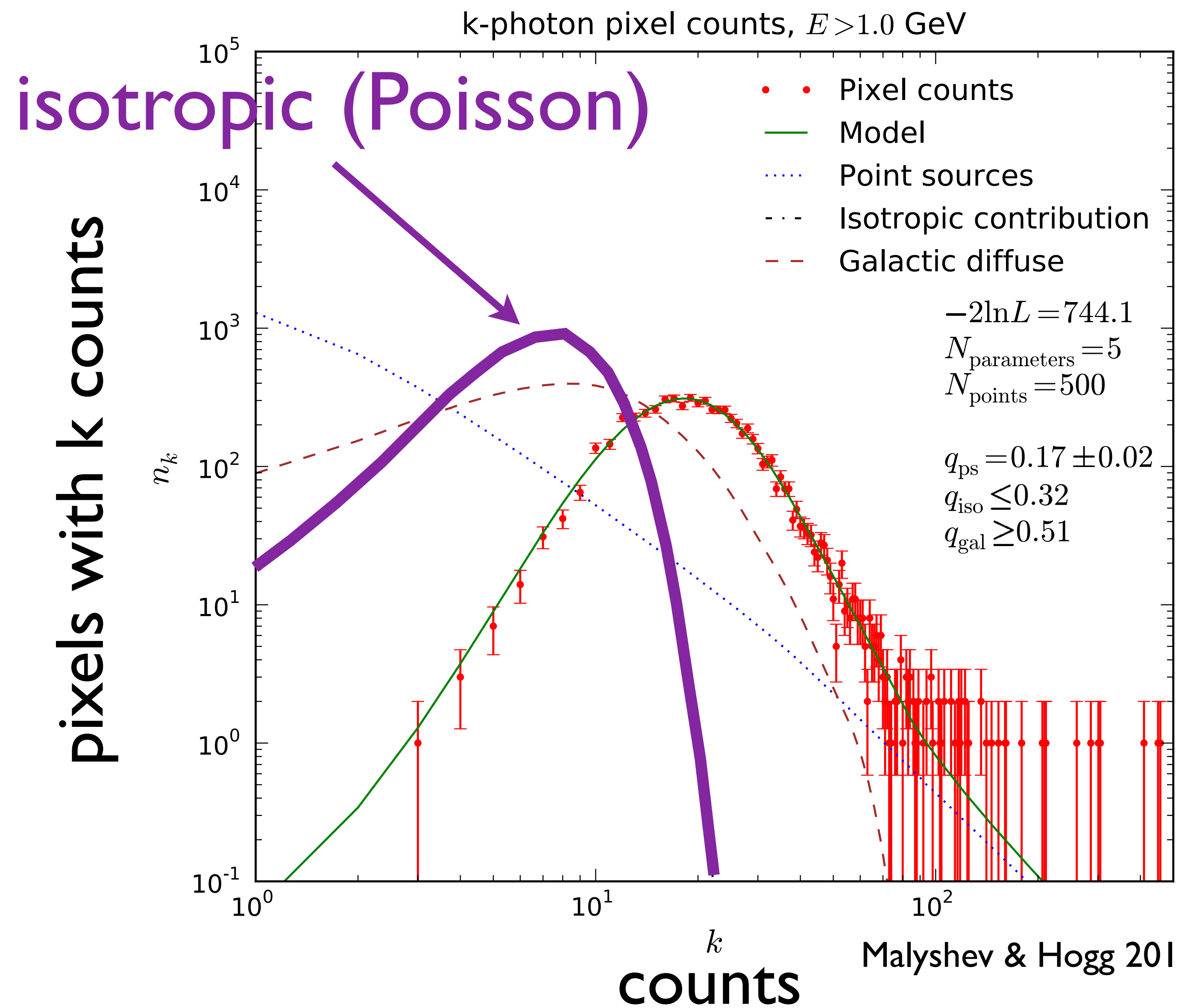
1pt-PDF of the Fermi gamma-ray background



Malyshev & Hogg 2011

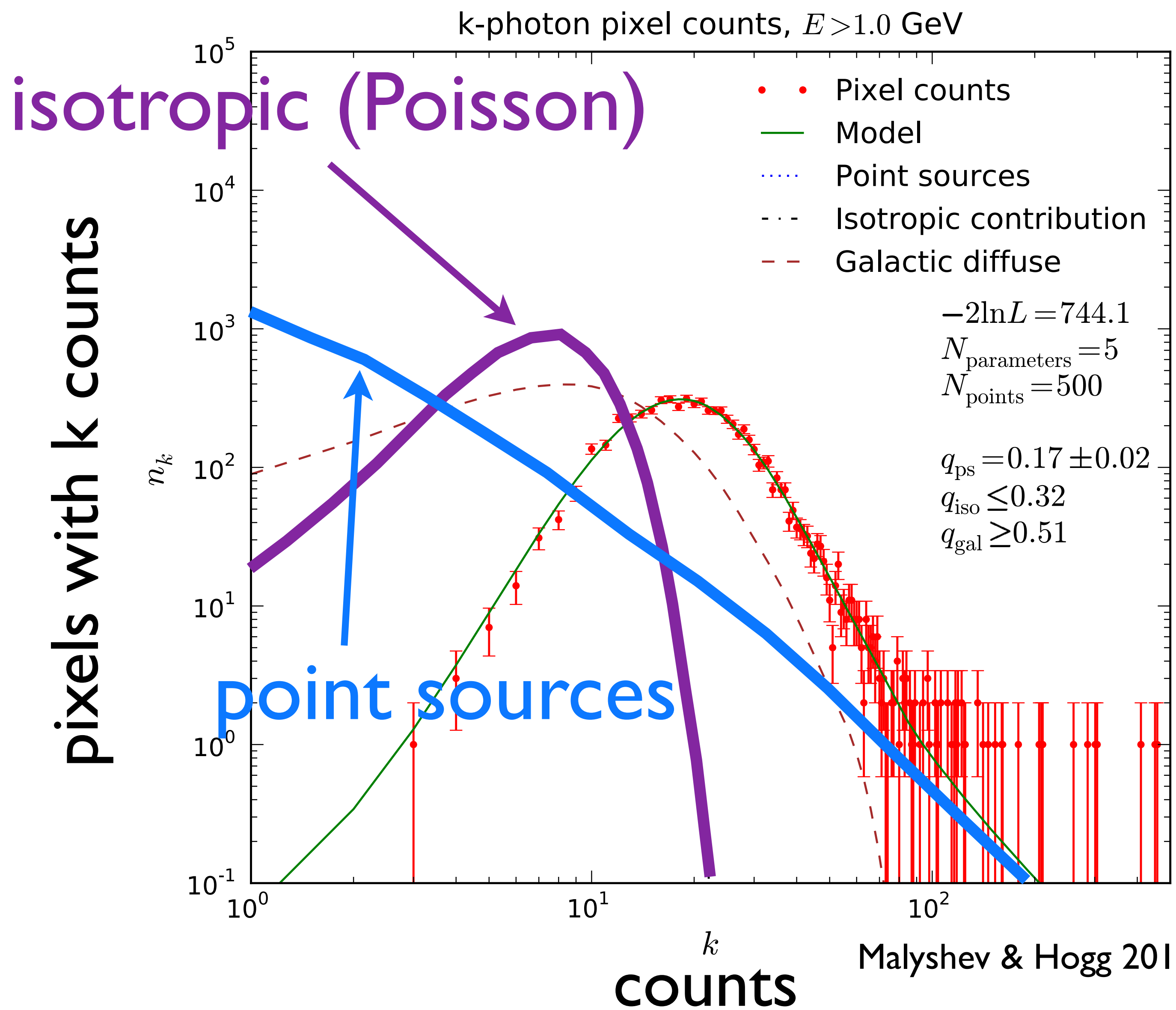
NB: 1pt-PDFs are NOT additive

The 1pt-PDF

- in the case of uniform exposure, the 1pt-PDF for a truly isotropic source will be Poisson-distributed

- sources feature a larger high-count tail and larger low count tail at the expense of the moderate-count regime

1pt-PDF of the Fermi gamma-ray background



Malyshev & Hogg 2011

NB: 1pt-PDFs are NOT additive

1pt-PDF analysis of the Inner Galaxy

- > 6 years of Fermi LAT data, Pass 8
- ROI: +/- 7.5 deg box centered on the Galactic Center
- energy range: 1-6 GeV (optimized to maximize GeV excess signal / Galactic diffuse background)
- today showing results of simulations only, NO DATA

Models to reproduce the GC excess

empirical models for DM and sources based on observed properties of excess:

- spatial distribution: DM annihilation profile
- energy spectrum to match the excess
- amplitude to match excess in ROI

(today showing results for standard NFW profile; steeper profiles easier to distinguish from Galactic diffuse)

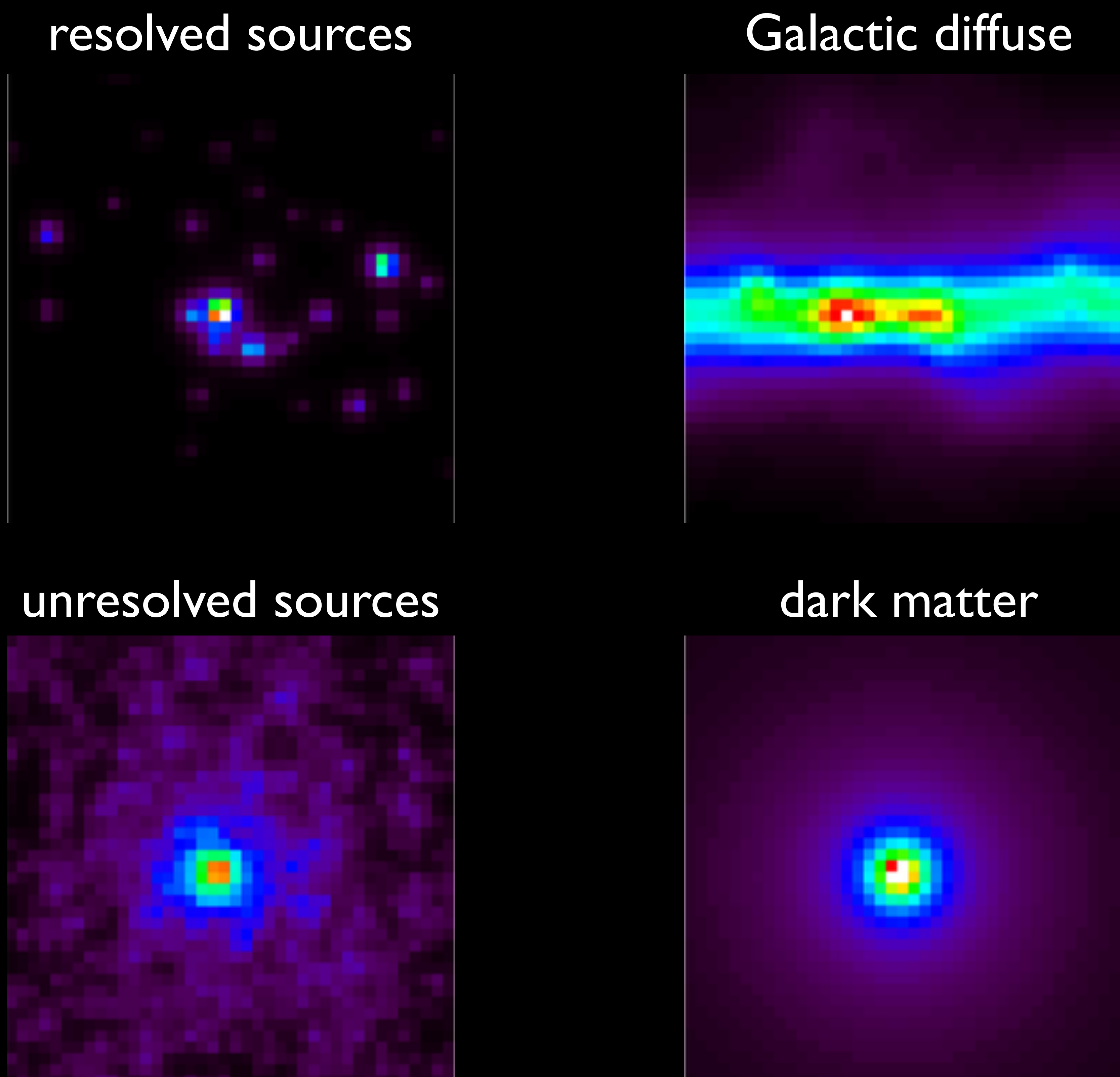
source flux distribution (dN/dS)

- $dN/dS \sim S^{-alpha}$
- distribute sources up to catalog threshold

(today showing results for alpha=-1)

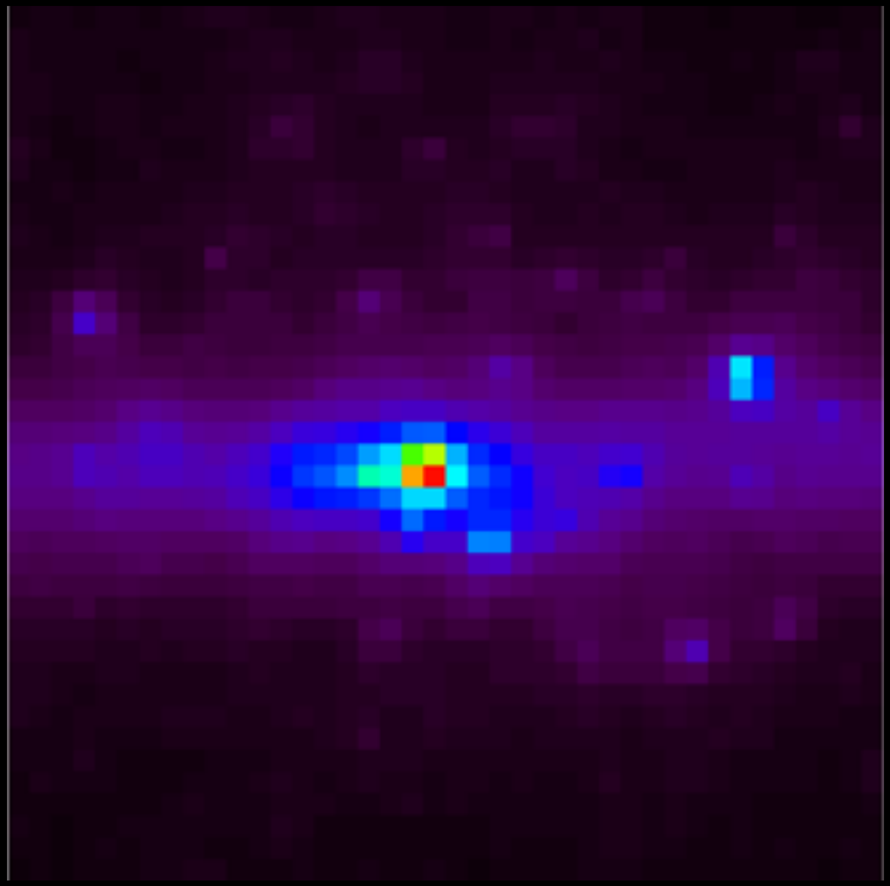
Inner Galaxy Components

- resolved sources (catalog)
- Galactic diffuse
- unresolved sources
- dark matter
- IGRB (included in model, but subdominant and not shown here)

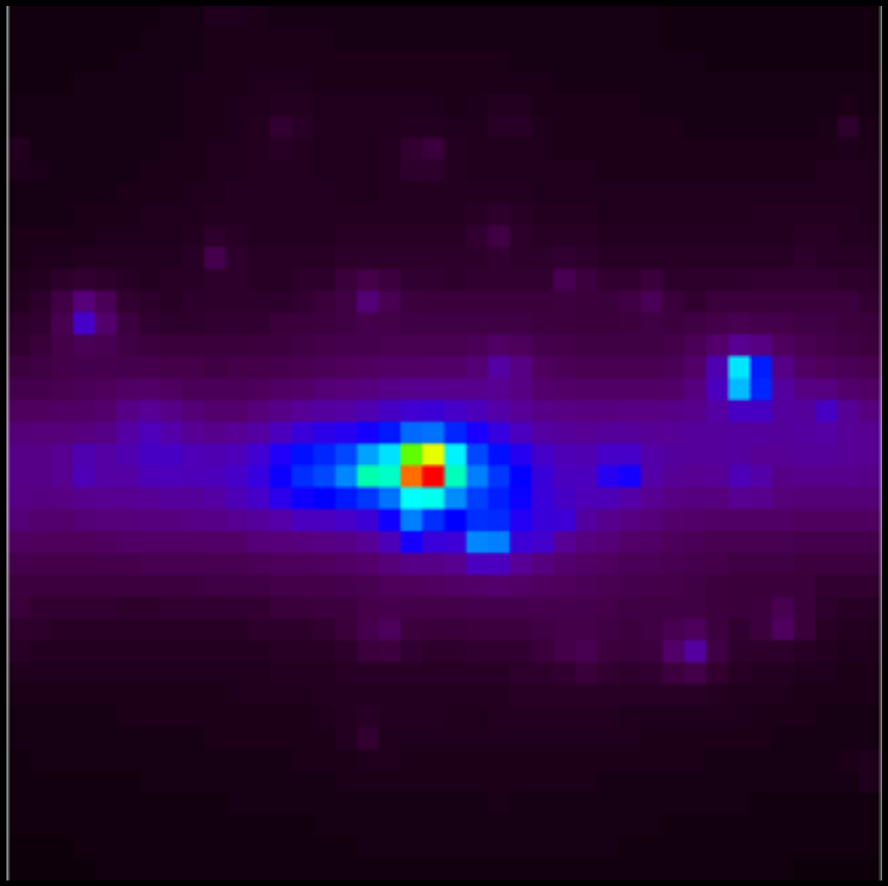


Total emission models

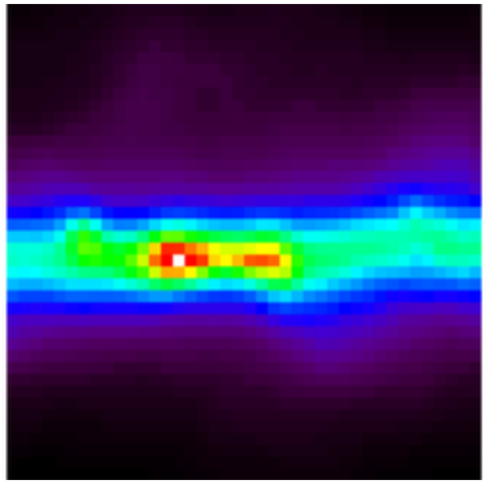
GAL+CAT+ISO+
unresolved sources

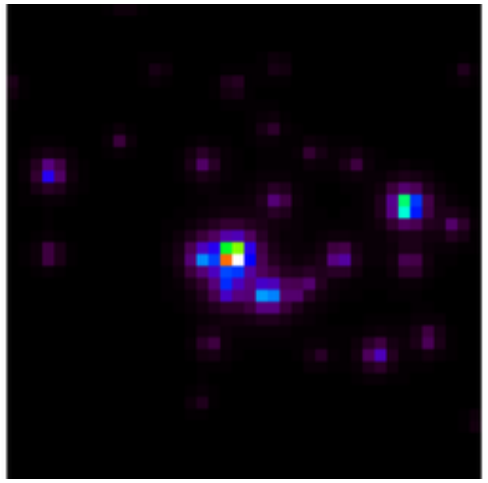


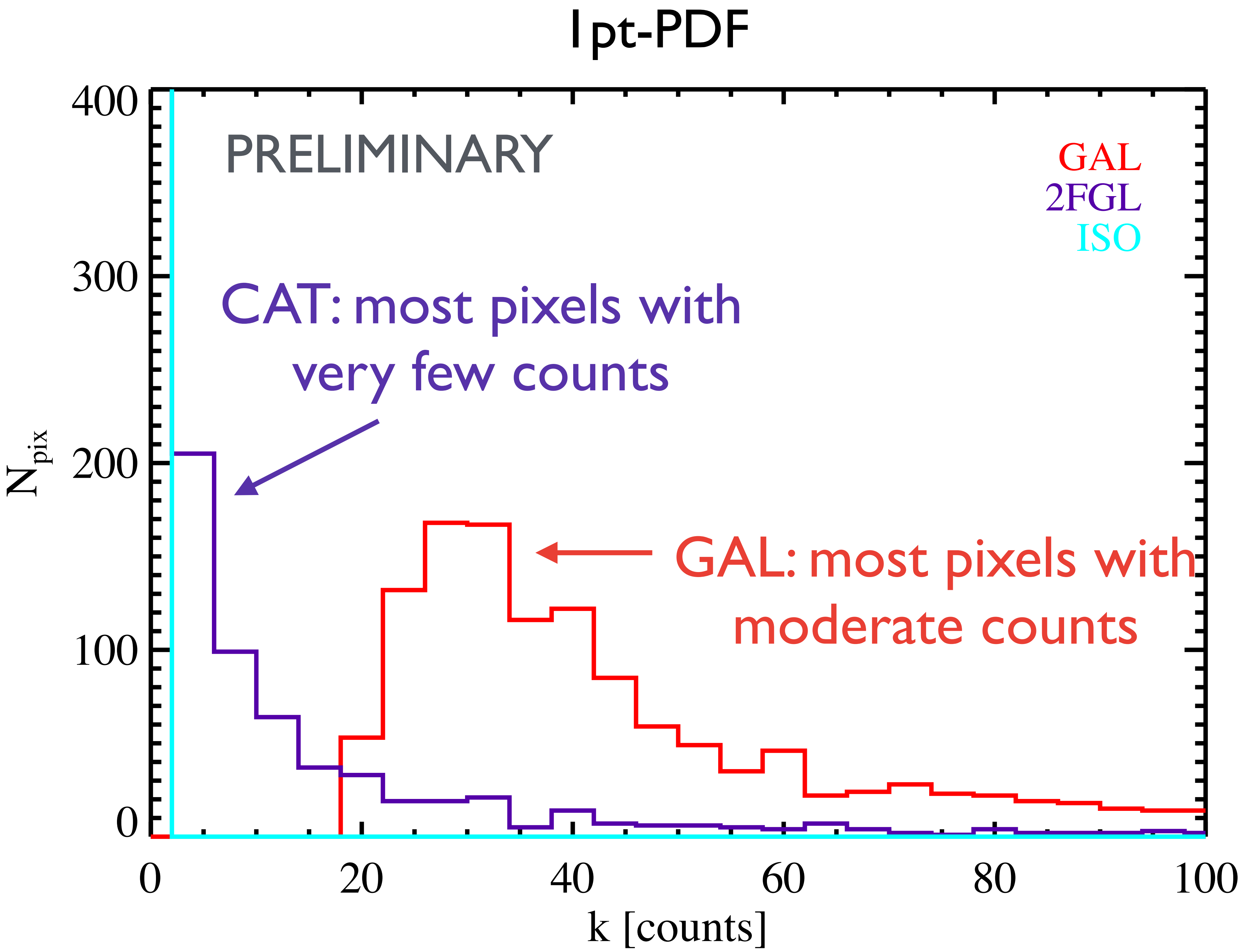
GAL+CAT+ISO+
dark matter



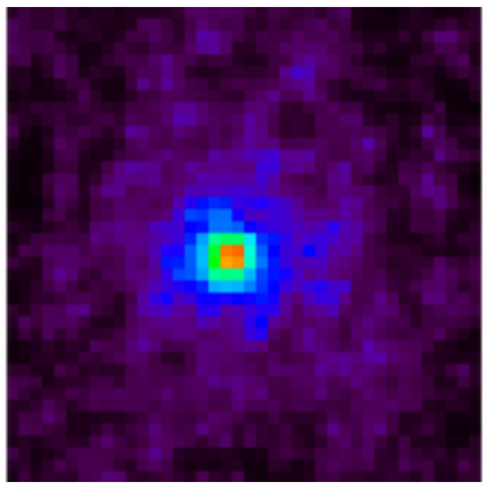
Inner Galaxy: components I

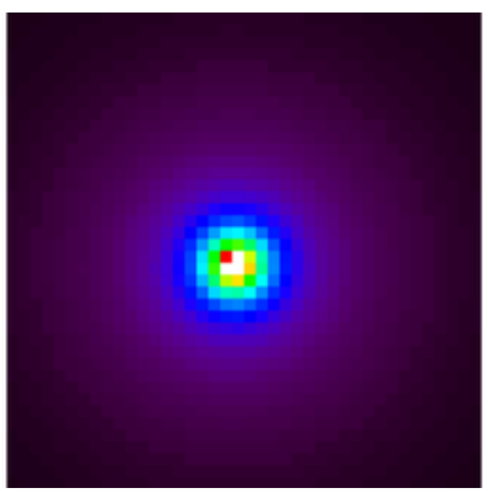




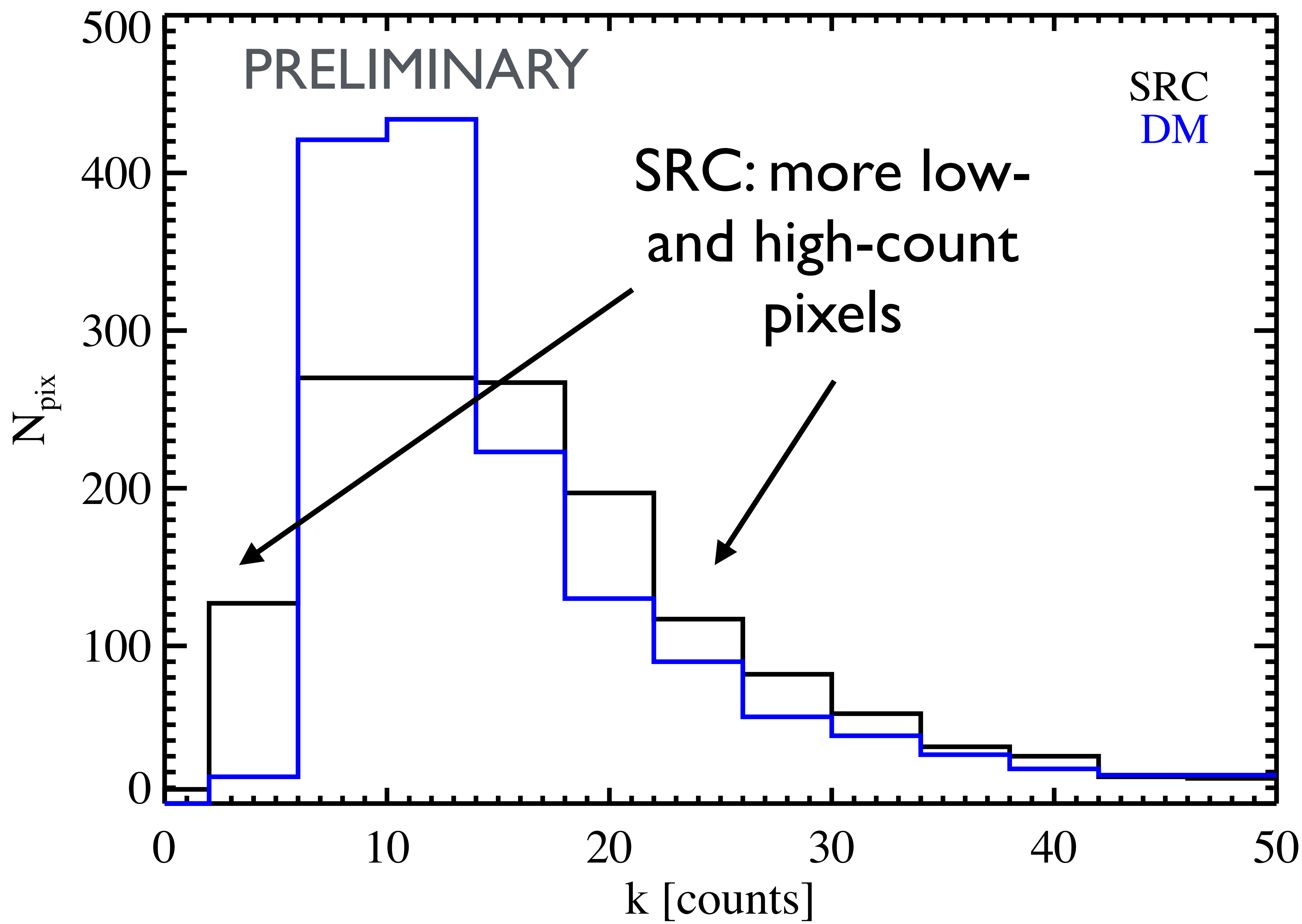


Inner Galaxy: components II



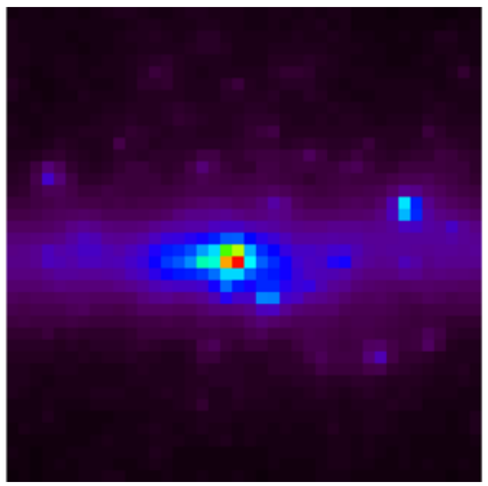


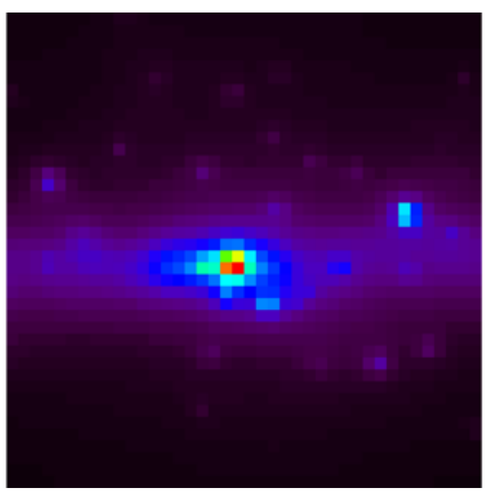
1pt-PDF



DM vs sources, with GAL+CAT+ISO

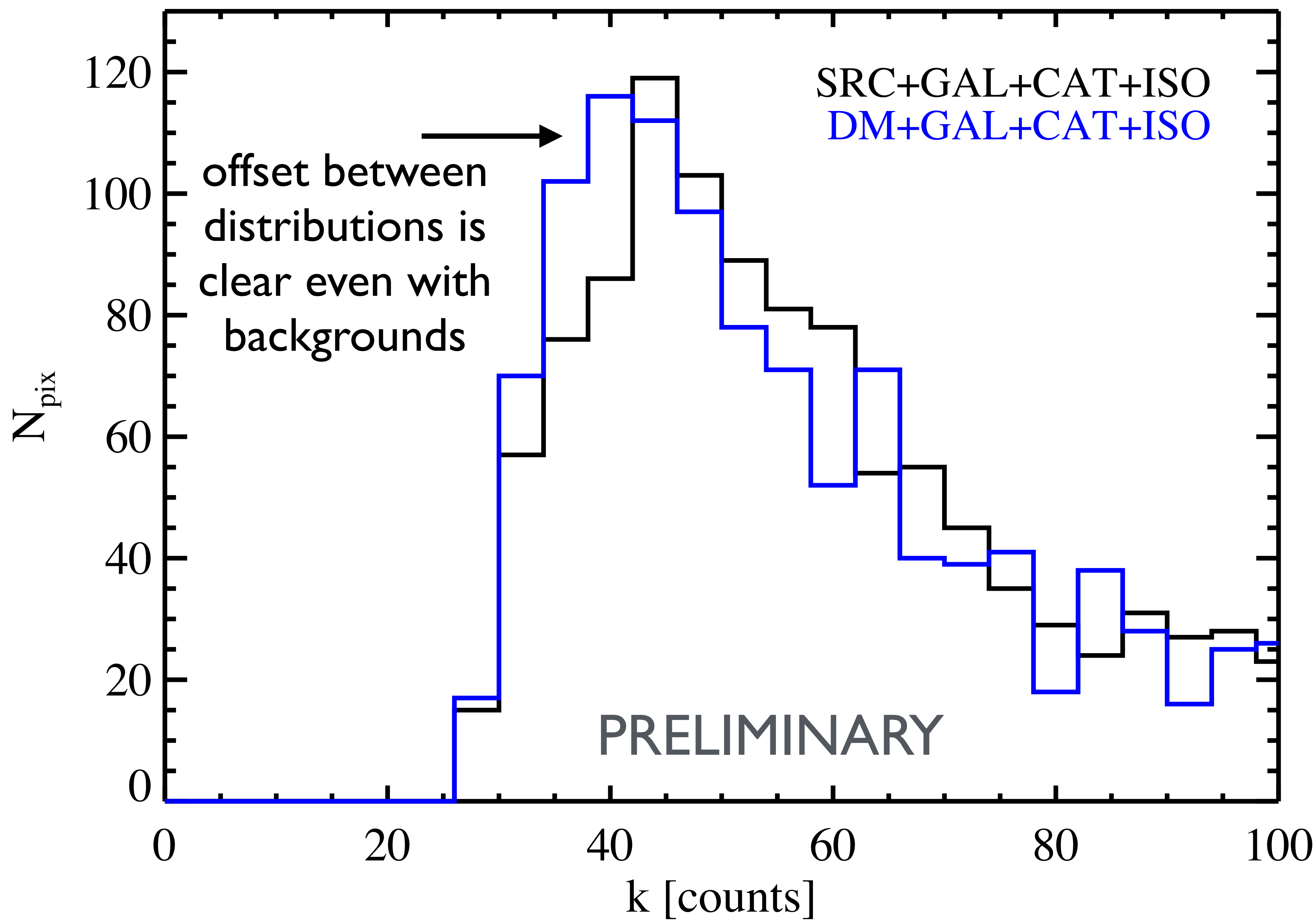
w/ sources





w/ DM

1pt-PDF (zoomed on low-count range)



Fitting multiple contributions to 1pt-PDF

(in progress)

- we take a simulation-based approach to predict the 1pt PDF from models
- models are convolved with Fermi instrument response, correctly accounting for nonuniform exposure, PSF
- best-fit model parameters are determined by likelihood analysis

See also recent work by:
Lee et al. 2015 (non-Poissonian template fit)
Bartels, Krishnamurthy, & Weniger 2015 (wavelet analysis)

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(stay tuned!)

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Imaging atmospheric Cherenkov telescopes (IACTs)

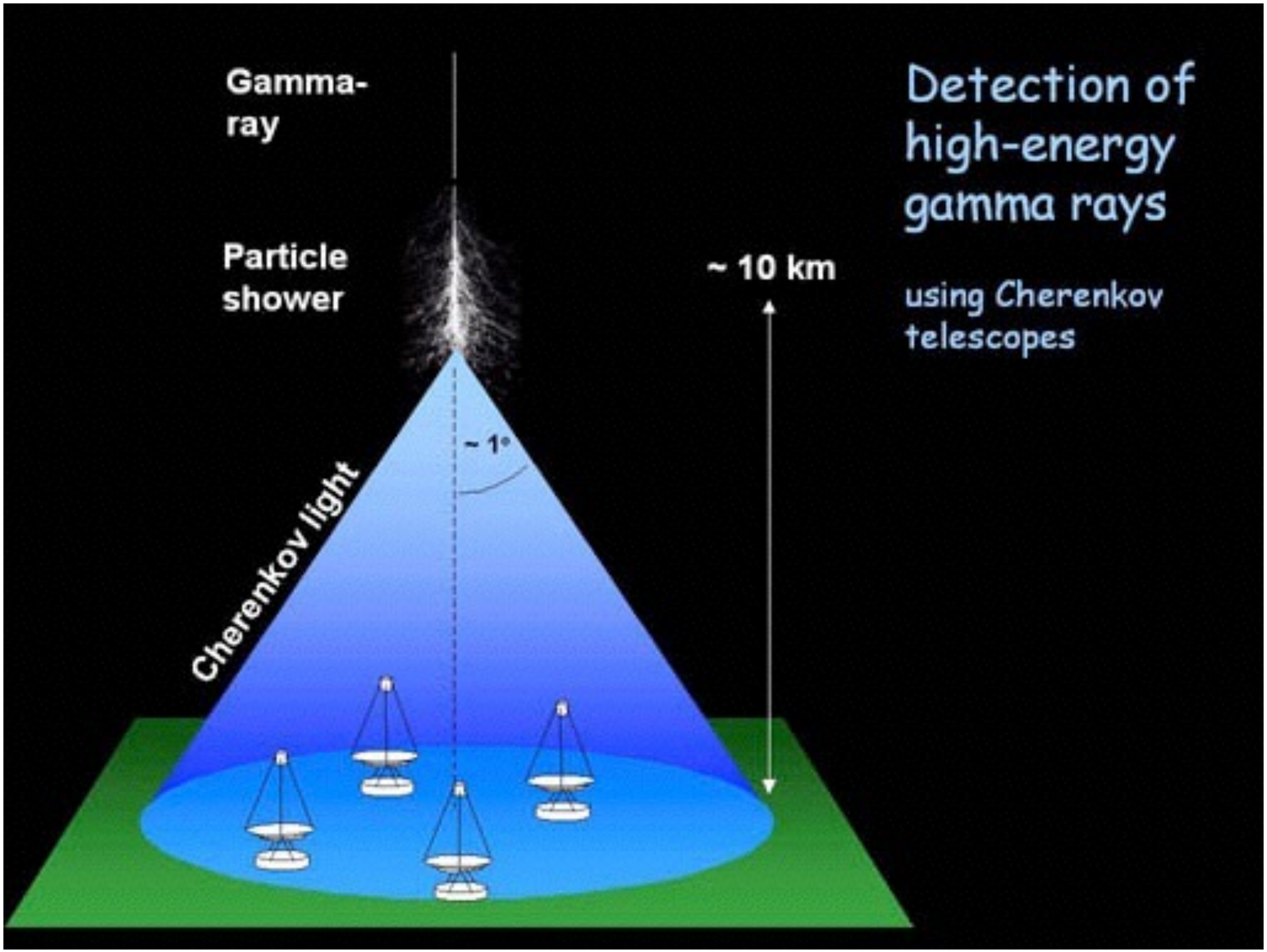
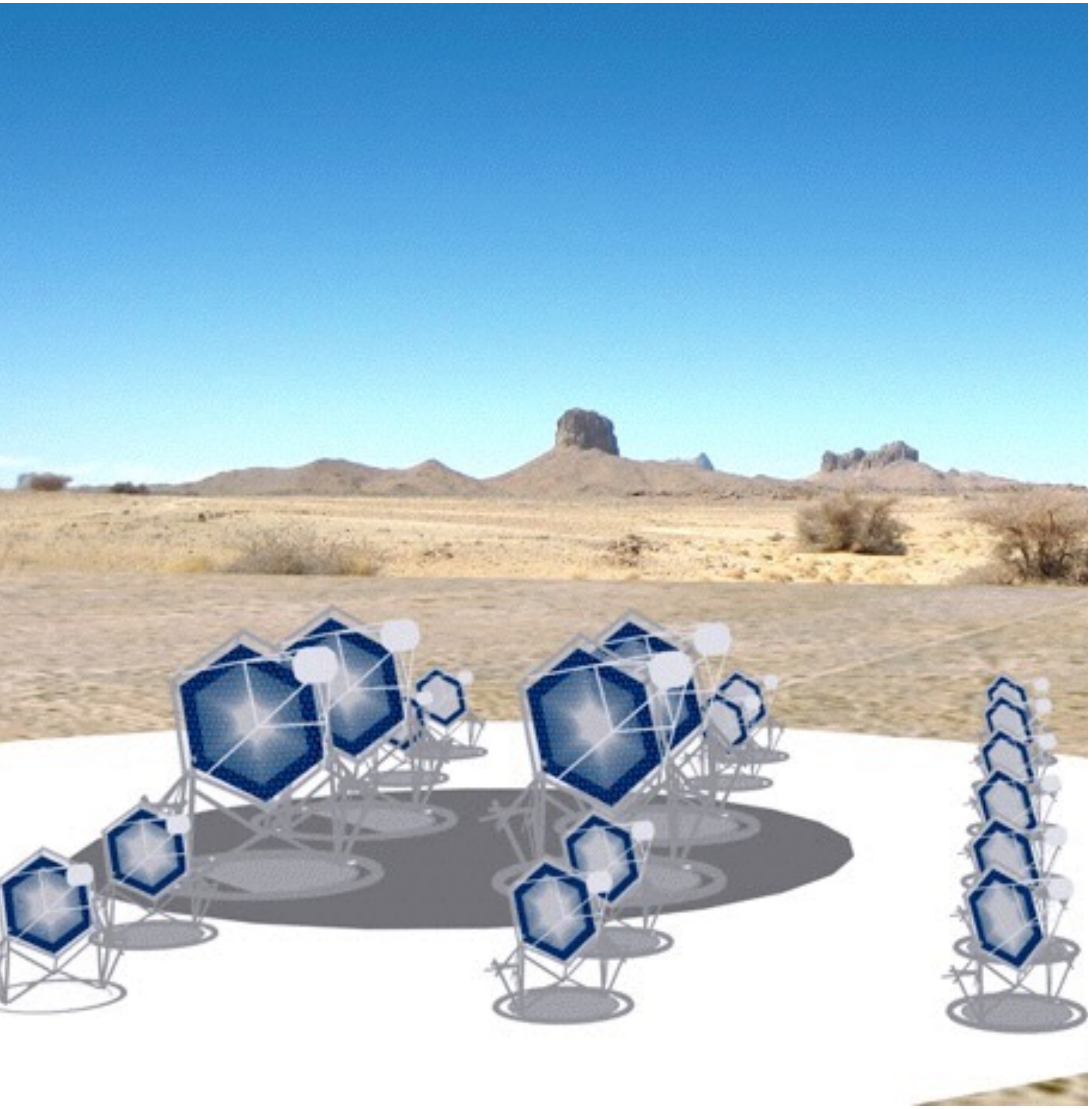


Image credit: H.E.S.S. Collaboration

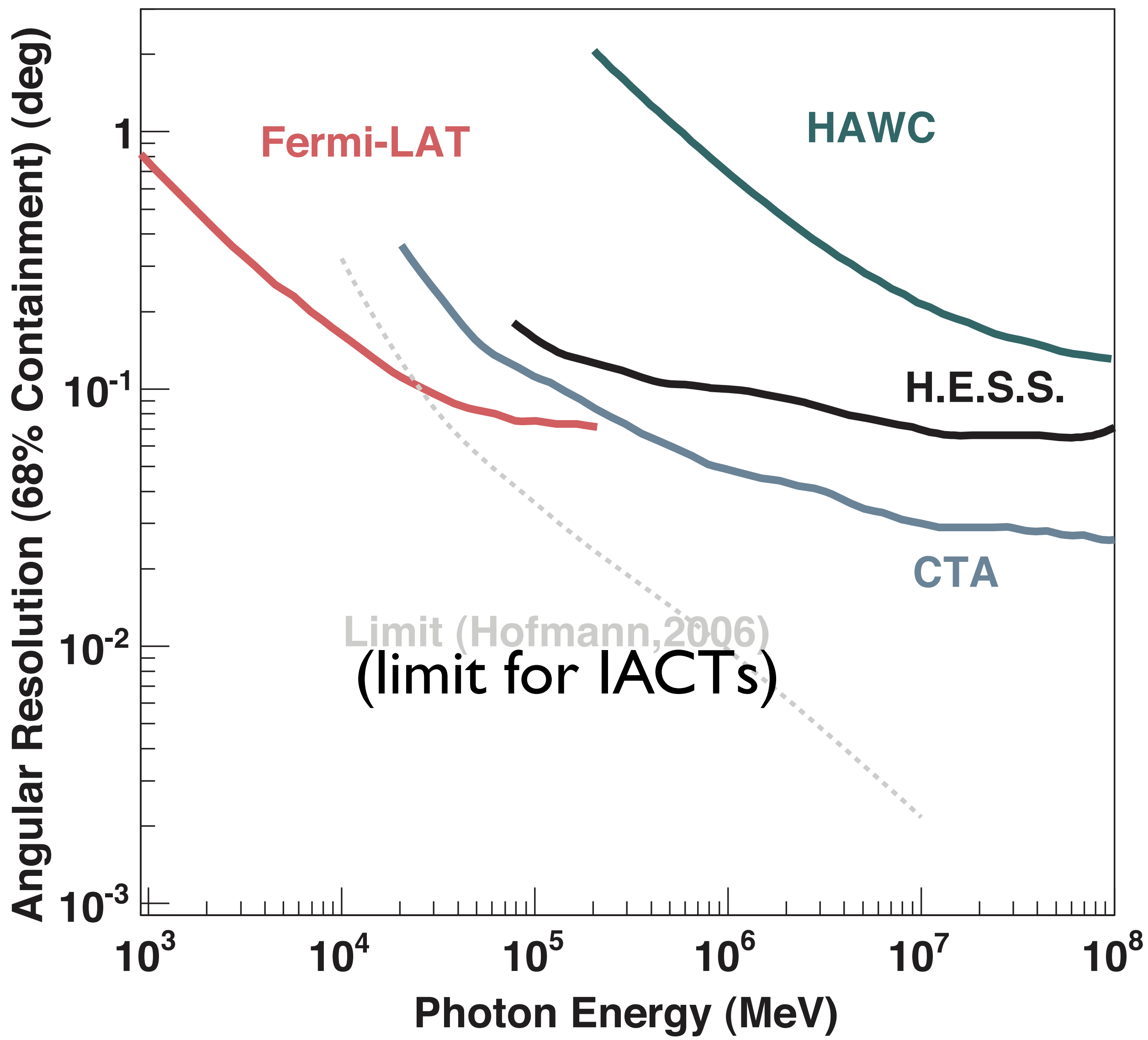
The Cherenkov Telescope Array

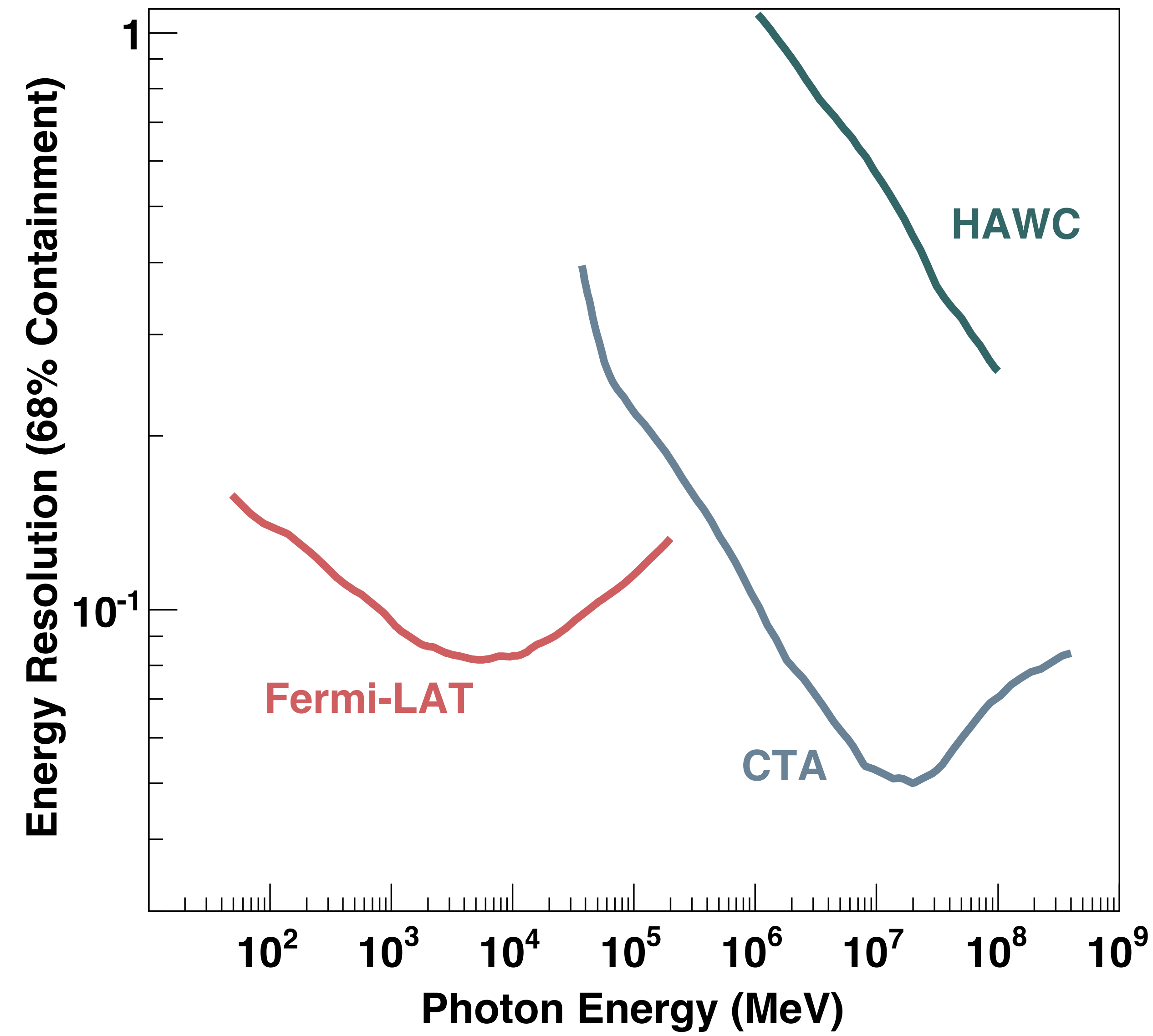


- next-generation gamma-ray observatory with > 100 telescopes
- will trigger as low as ~ few tens of GeV (compared to ~ 100 GeV for current IACTs)
- open observatory
- designed to operate for 30 years
- Northern and Southern sites
    - Southern: in Chile, near Paranal
    - Northern: La Palma, Canary Islands, Spain
- 27 nations, ~ €300M

Image credit: CTA Collaboration

Current and future capabilities





Funk et al. 2012

IACTs vs Fermi LAT

- IACTs have much larger effective area (Fermi LAT effective area ~ 0.8 m^2 vs ~ 10^6 m^2 for CTA), allowing sensitivity to smaller fluxes at higher energies
- IACTs have a large irreducible cosmic-ray background whereas the LAT can reject charged CRs at high efficiency

  ➡ this is a major challenge for searches for extended signals, such as dark matter annihilation in the Inner Galaxy

Comparison of targets

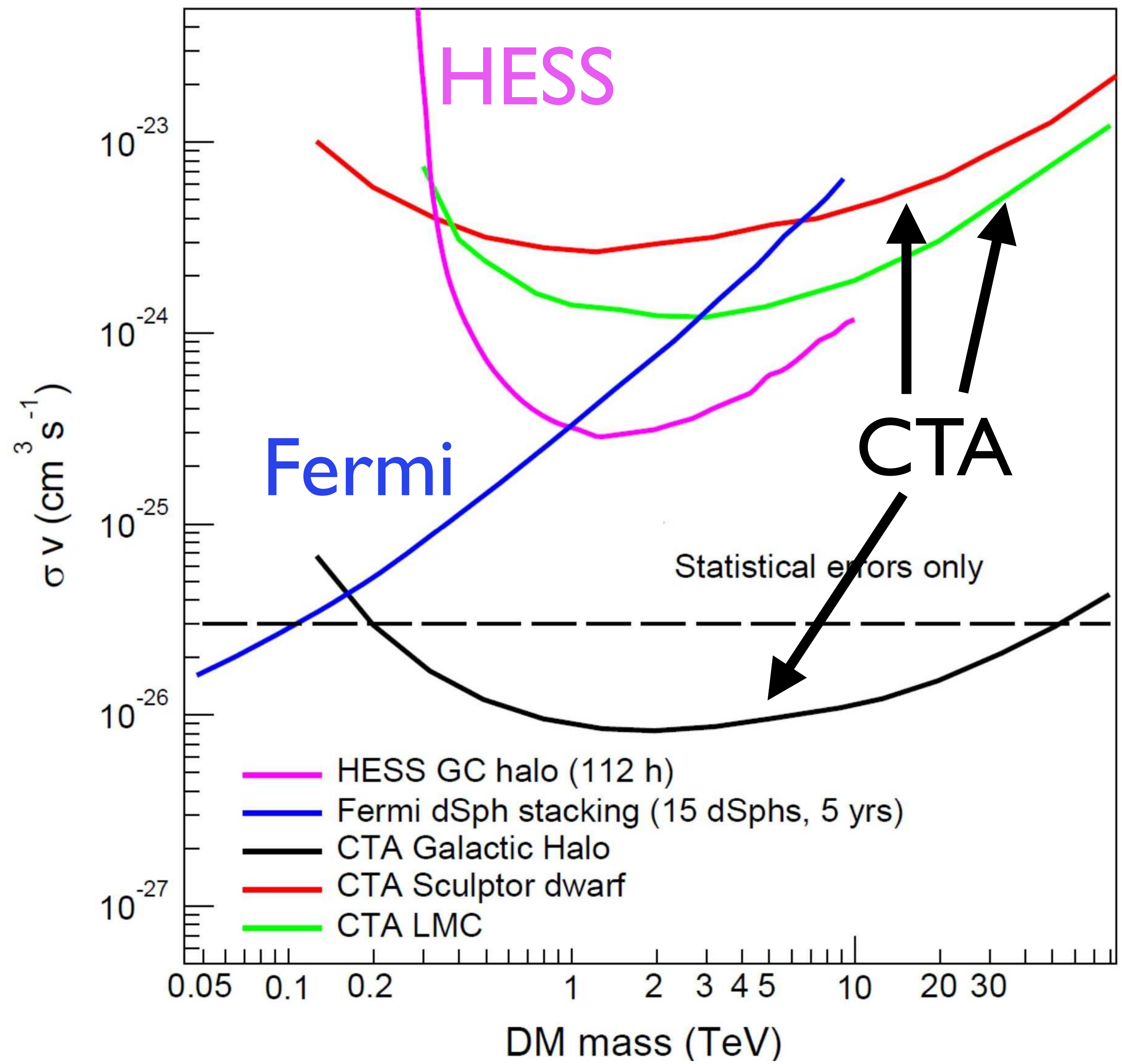
CTA Halo/Sculptor:
30 GeV threshold

CTA LMC: 200 GeV threshold

(statistical errors only)

SYSTEMATICS MUST BE CONTROLLED EXTREMELY WELL TO ACHIEVE STATISTICALLY-POSSIBLE SENSITIVITY

500h, WW, different targets



Carr et al. 2015 (CTA Consortium)

Summary

- this is an exciting time for indirect detection!
- the Galactic Center GeV excess is an intriguing possible dark matter signal, but it's important to rule out non-exotic explanations before claiming a dark matter origin
- the 1pt-PDF may offer a unique and robust means of distinguishing between sources and a smooth distribution; recent analyses point to a source origin for the excess
- CTA will probe a large region of favored WIMP parameter space — an excellent WIMP dark matter detector