Statistics in Indirect Dark Matter Searches

Banff
28th Feb 2018

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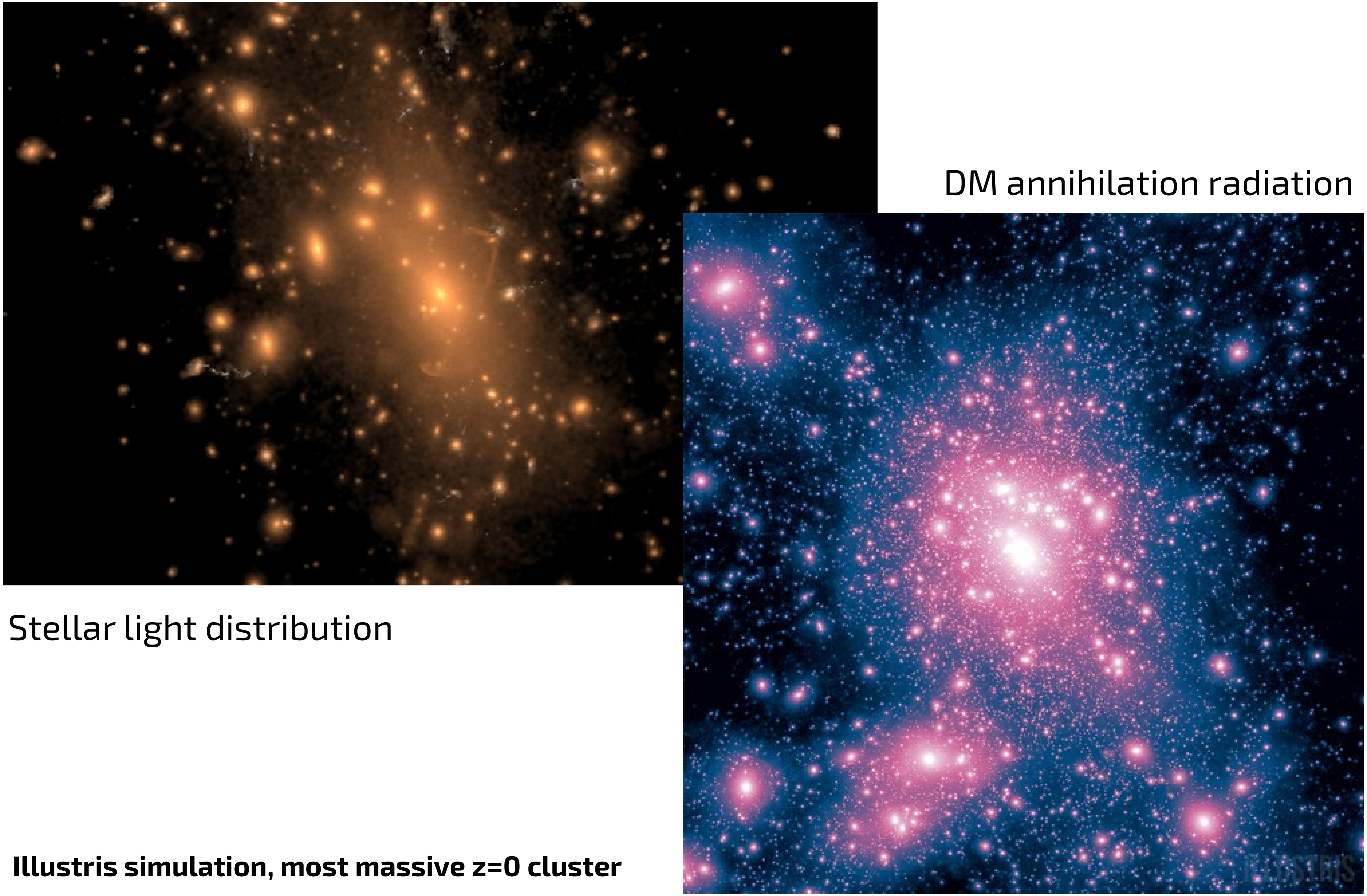
Introduction

Is dark matter dark?



DM annihilation radiation

Stellar light distribution

Illustris simulation, most massive z=0 cluster

http://www.illustris-project.org/media/

Dark matter annihilation/decay and cosmic rays

DM self-annihilation into gamma rays

Gunn+ 1978; Stecker 1978, ...

Proposal to search for anti-protons from MSSM neutralinos

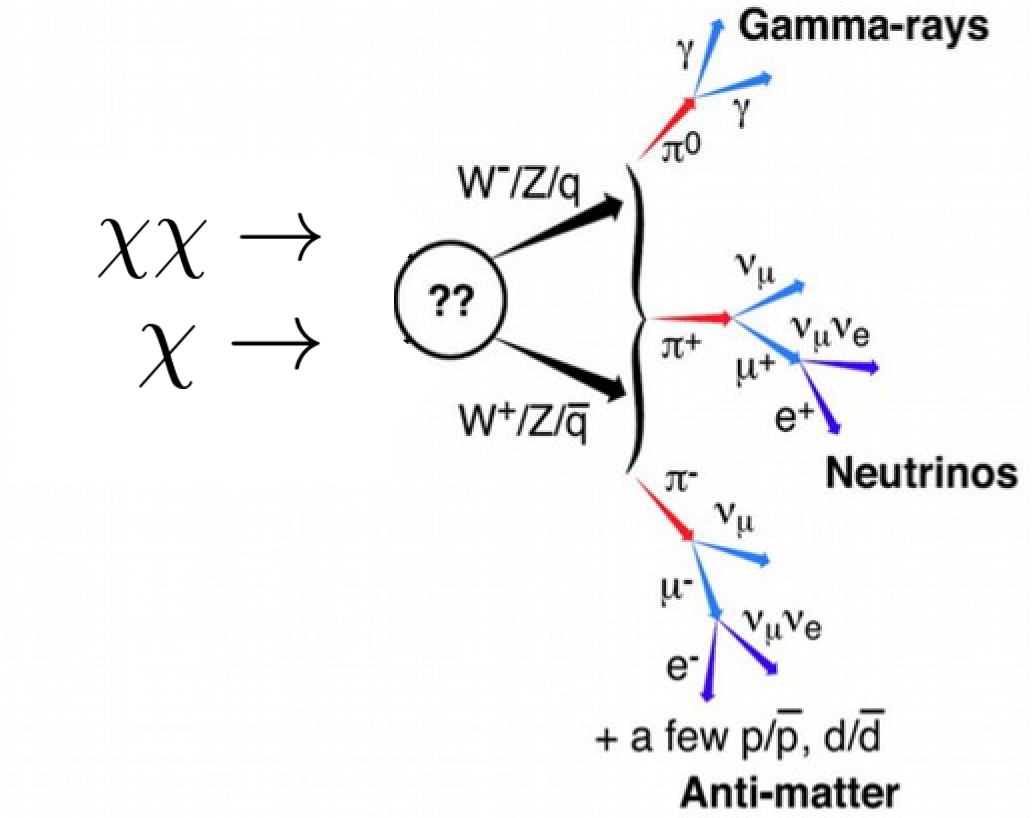
Silk & Srednicki 1984; ...

Searching for neutrinos from the Sun

Silk, Olive & Srednicki 1985; Press & Spergel 1985; ...

Searches for gamma-ray lines

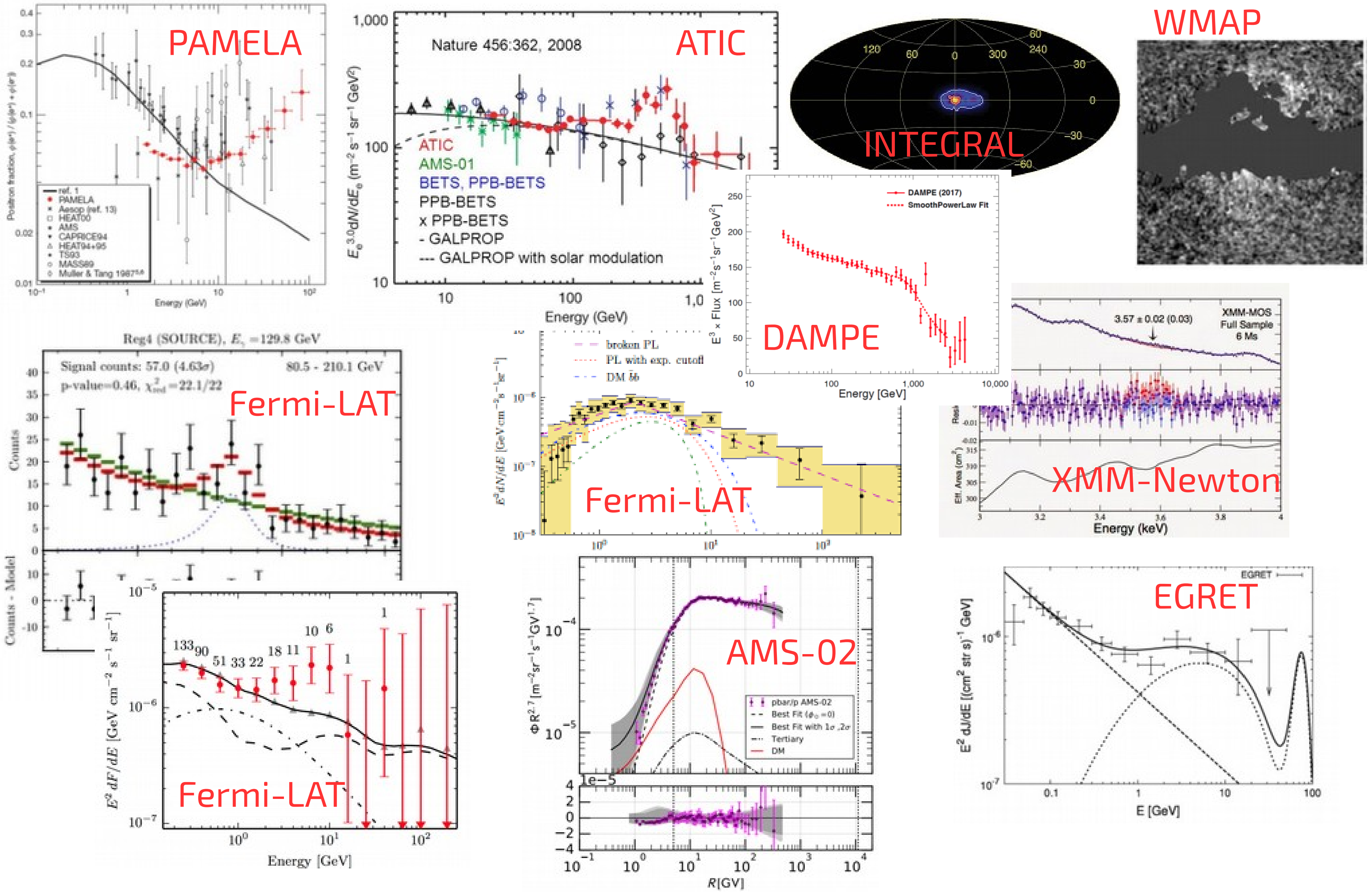
Bergström & Snellmann 1988; Rudaz 1989; ...



Decay

Very model dependent (sterile neutrinos, R-partiy violating gravitino DM, axions, ...)

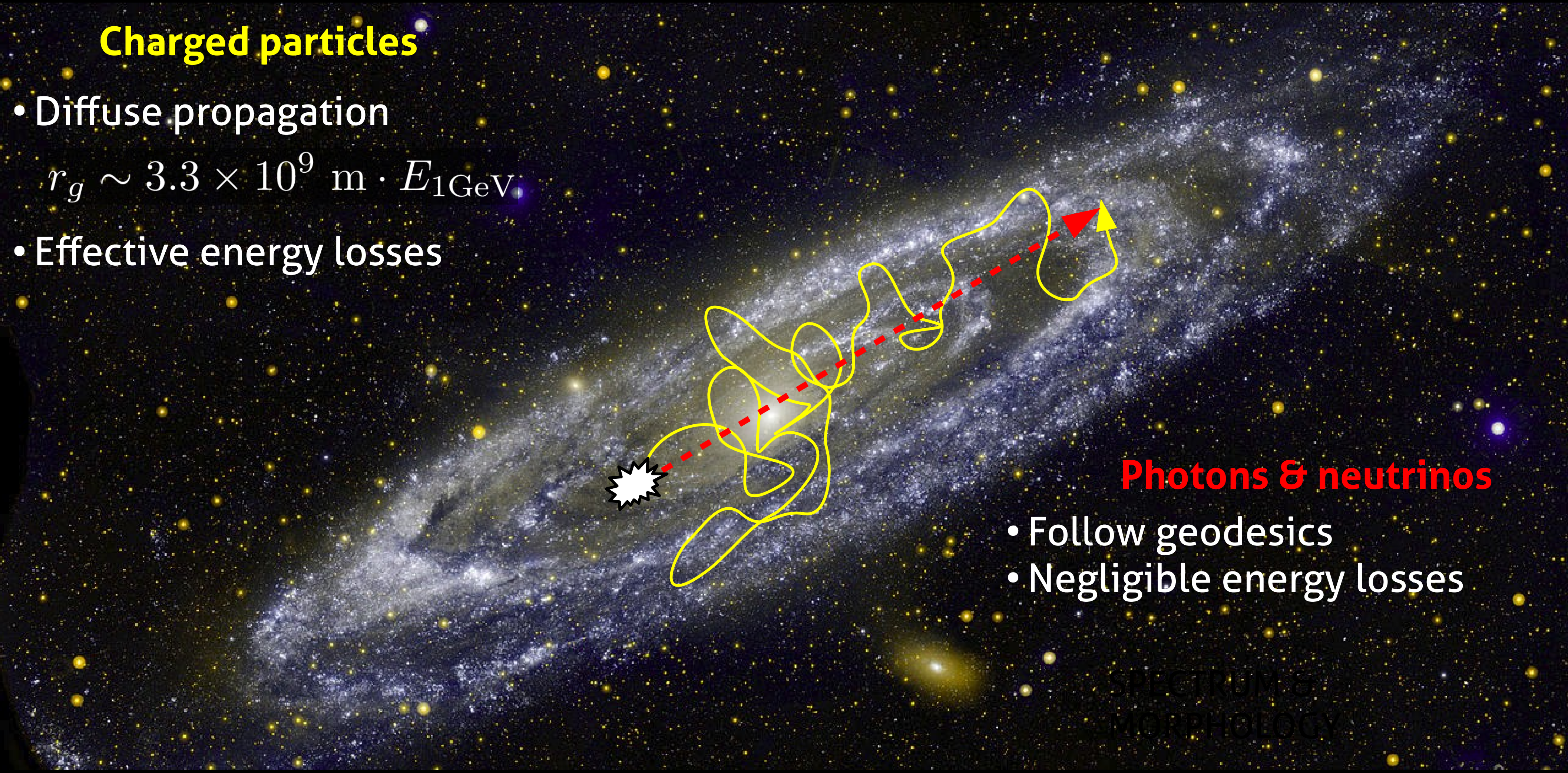
Some of the signal claims of recent years



Propagation of messengers from DM

Differential emissivity of DM annihilation products

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



Charged particles

- Diffuse propagation

  $r_g \sim 3.3\times 10^9~{\rm m}\cdot E_{\rm 1GeV}$

- Effective energy losses

Photons & neutrinos

- Follow geodesics
- Negligible energy losses

SPECTRUM &
MORPHOLOGY

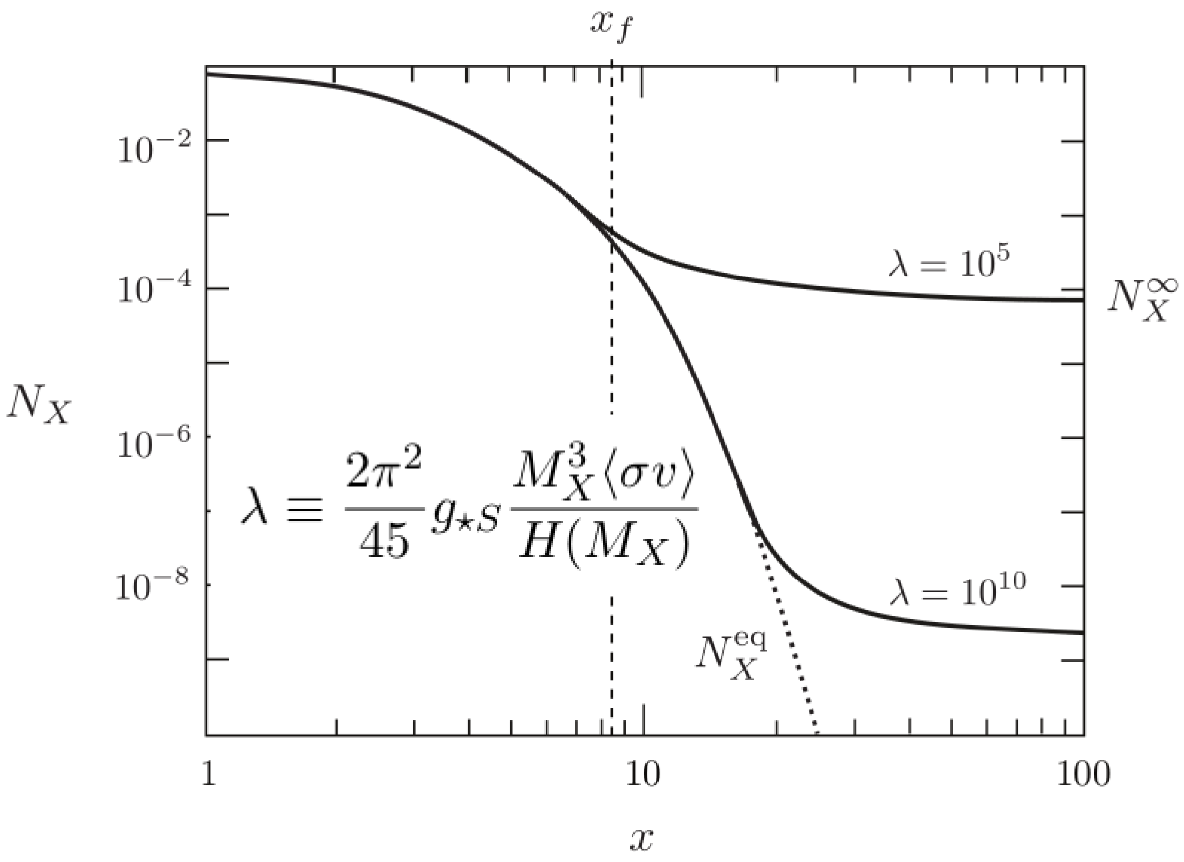
Dark matter freeze-out

Boltzmann equation for particles in comoving volume

$$\frac{dN_X}{dt} = -s\langle\sigma v\rangle\left[N_X^2 - (N_X^{\rm eq})^2\right]$$

$$N_X \equiv n_X/s \qquad x \equiv \frac{M_X}{T}$$

$$X + \bar{X} \ \leftrightarrow \ \ell + \bar{\ell}$$



$$\lambda \equiv \frac{2\pi^2}{45} g_{\star S} \frac{M_X^3\langle\sigma v\rangle}{H(M_X)}$$

Relic density today

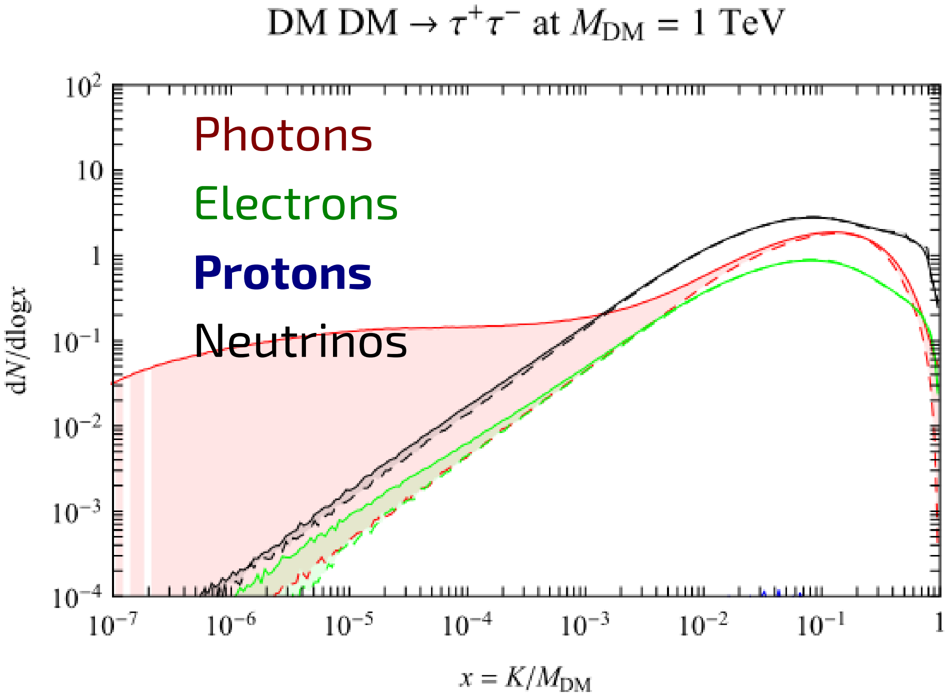
$$\Omega_X = \frac{\rho_{X,0}}{\rho_{\rm crit,0}} = \frac{M_X N_X^\infty s_0}{\rho_{\rm crit,0}}$$

Annihilation cross-section

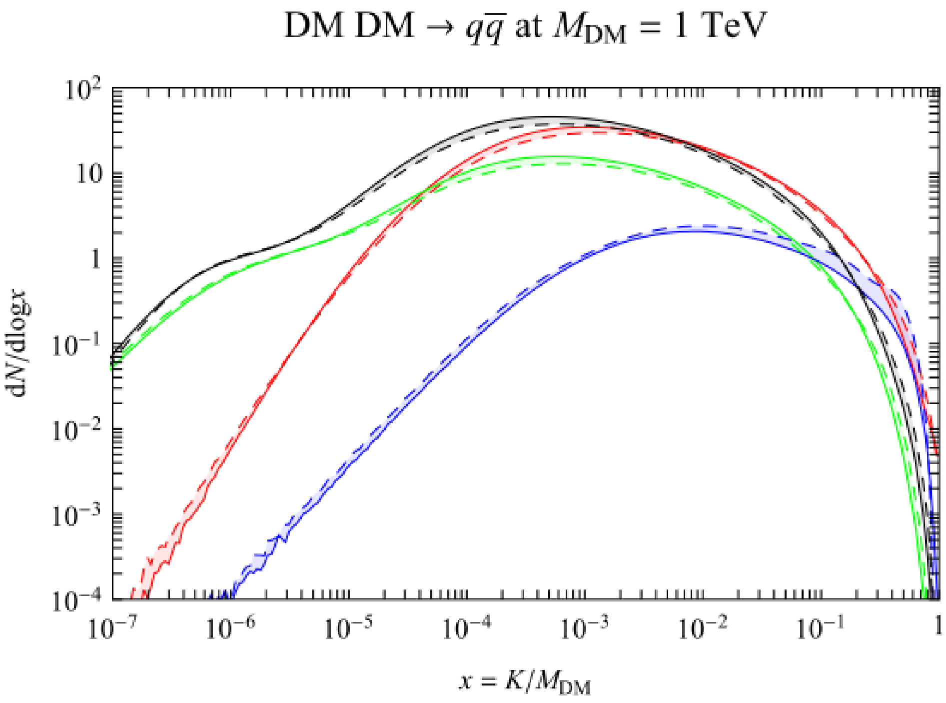
$$\Omega_X h^2 \sim 0.1 \frac{3\times 10^{-26}{\rm cm}^3{\rm s}^{-1}}{\langle\sigma v\rangle} \sim \frac{10^{-3}G_F}{\langle\sigma v\rangle}$$

Final state energy spectra

Annihilation into tau leptons

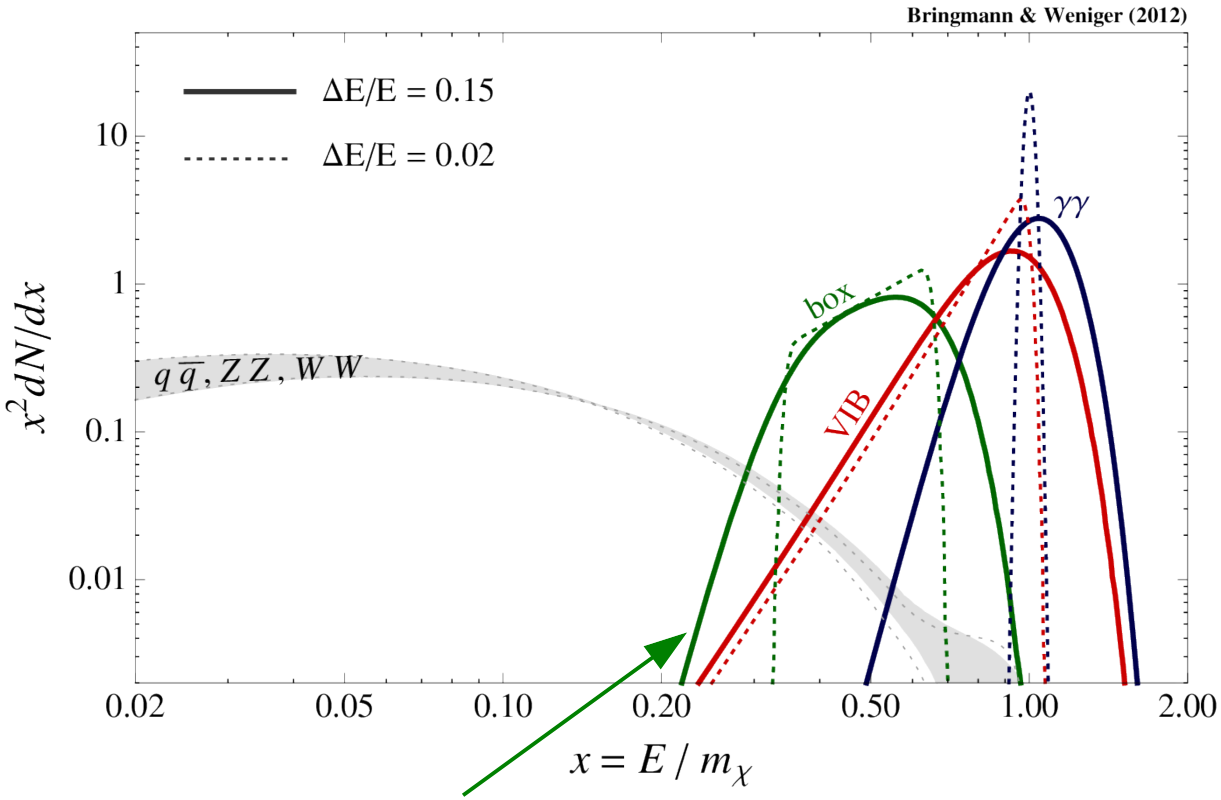


Annihilation into quarks



Cirelli et al. (2010)

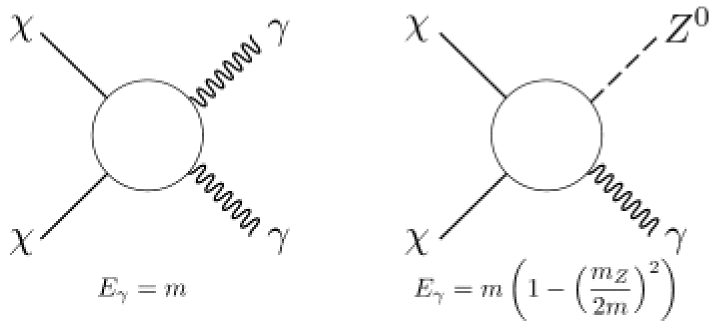
Gamma-ray spectral features



Bringmann & Weniger (2012)

Gamma-ray lines

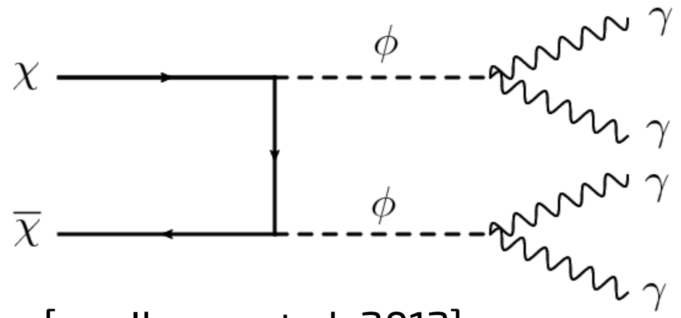
$$\chi\chi \to \gamma\gamma, \gamma Z^0$$



[Bergström & Snellman (1988)]

Cascade decays

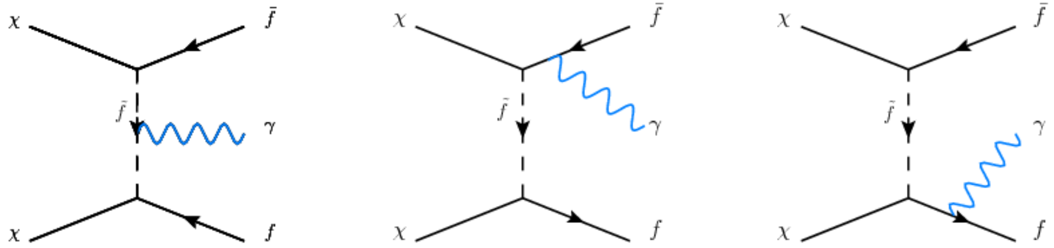
$$\chi\chi \to \phi\phi \to \gamma\gamma\gamma\gamma$$



[e.g. Ibarra et al. 2012]

Internal Bremsstrahlung (IB)

$$\chi\chi \to \bar{f} f \gamma$$



[e.g. Bringmann, Bergström & Edsjö (2008)]

Spatial characteristics

Signal is approx. proportional to column square density of DM:

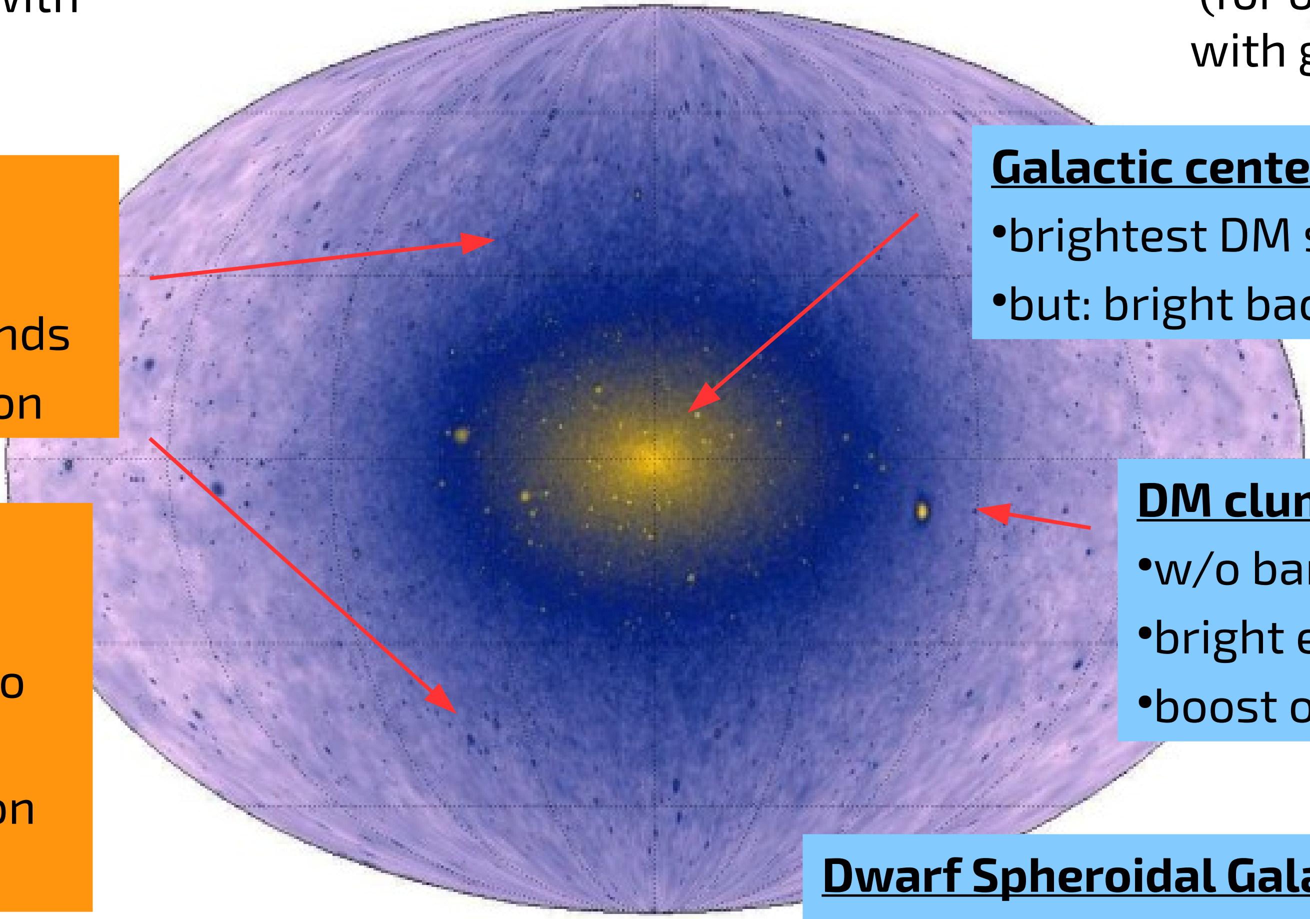
$$\propto \int_{\mathrm{l.o.s.}} ds\, \rho_{\mathrm{DM}}^2$$

Extended or diffuse:

(for observations with gamma rays)

Point-like:

(for observations with gamma rays)



Galactic DM halo

- good S/N
- difficult backgrounds
- angular information

Extragalactic

- nearly isotropic
- only visible close to Galactic poles
- angular information
- Galaxy clusters?

Galactic center (~8.5 kpc)

- brightest DM source in sky
- but: bright backgrounds

DM clumps

- w/o baryons
- bright enough?
- boost overall signal

Dwarf Spheroidal Galaxies

- harbor small number of stars
- otherwise dark (no gamma-ray emission)

review on N-body simulations: Kuhlen, Vogelsberger & Angulo (2012)

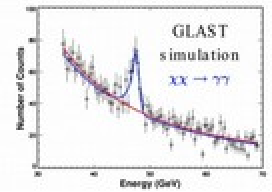
Different searches, different challenges

Number of 'control regions'

dwarf spheroidals

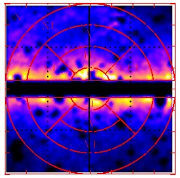
dark matter subhalos

gamma-ray lines, etc



HARD

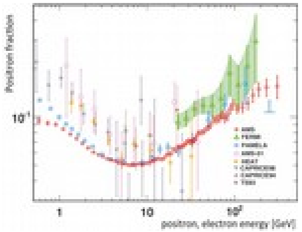
extragalactic background



Galactic bulge/center

galactic neutrinos

anti-proton cosmic rays



positron cosmic rays

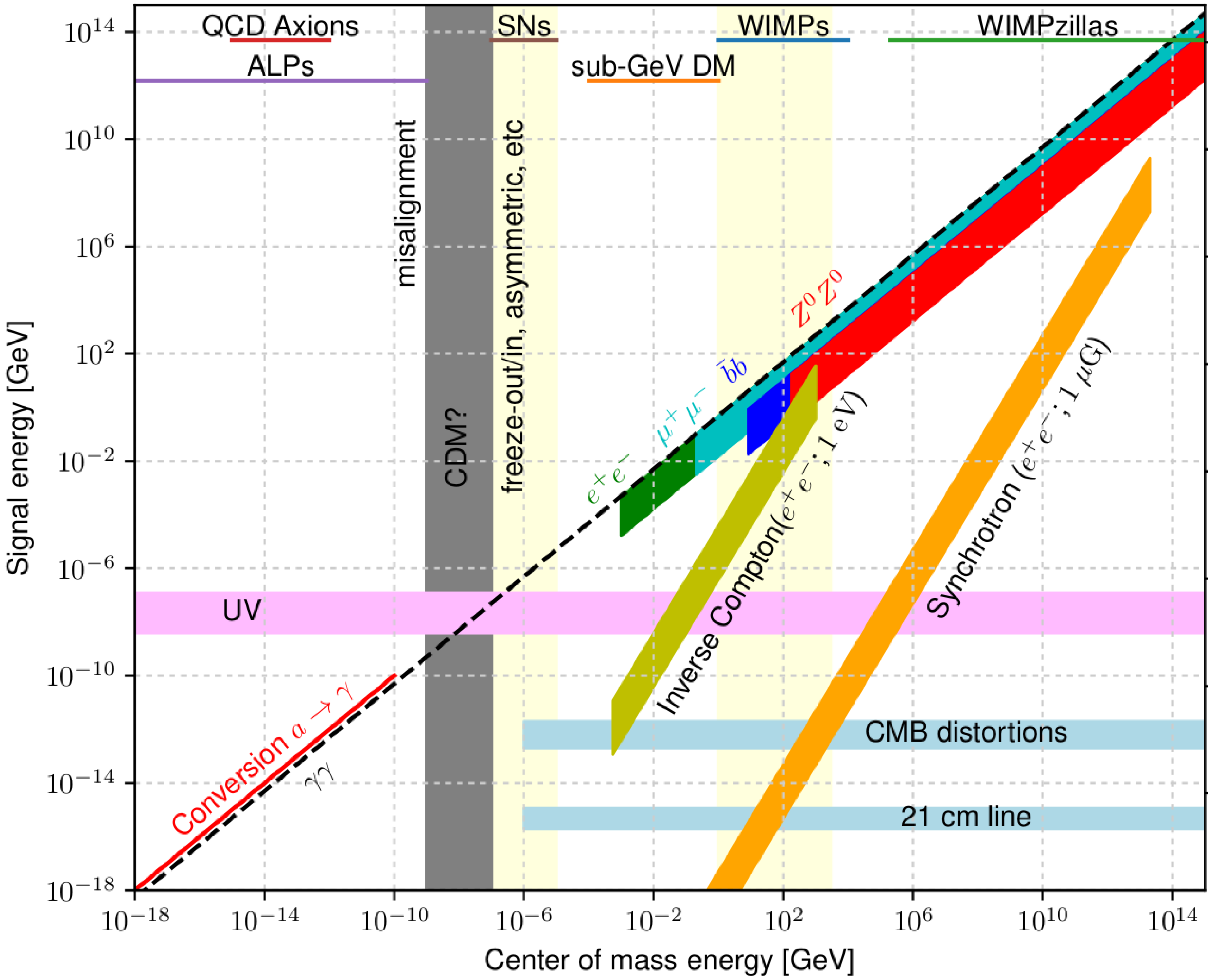
anti-deuteron cosmic rays

solar HE neutrinos

Background modeling complexity

Relevant radiation mechanisms

CSW, in prep



UHECRs

Gamma rays & Cosmic rays

X rays

UV

Optical/IR

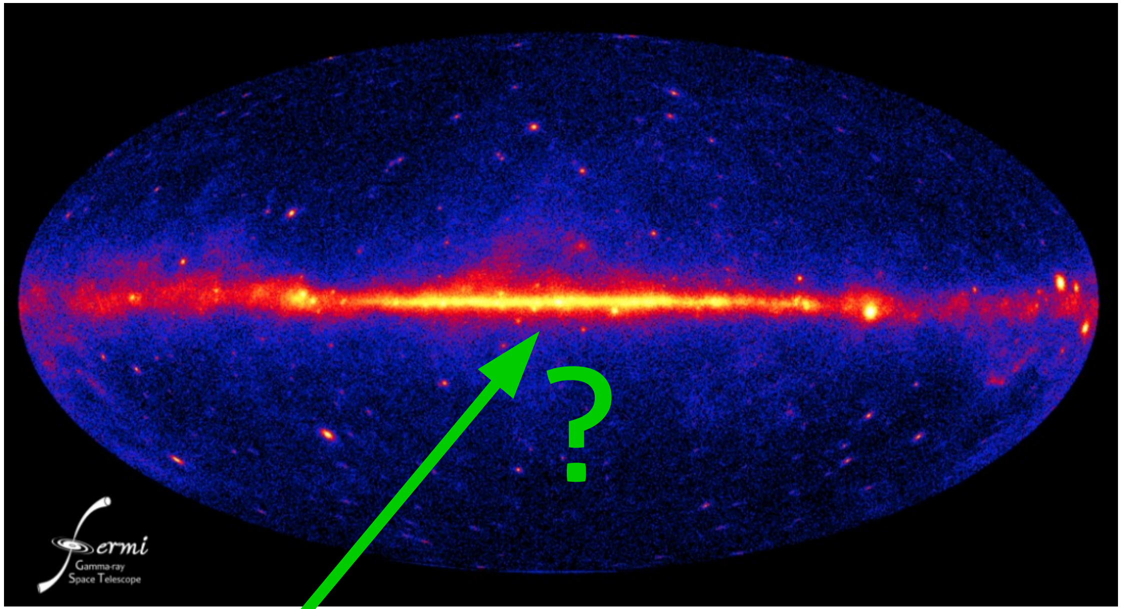
CMB

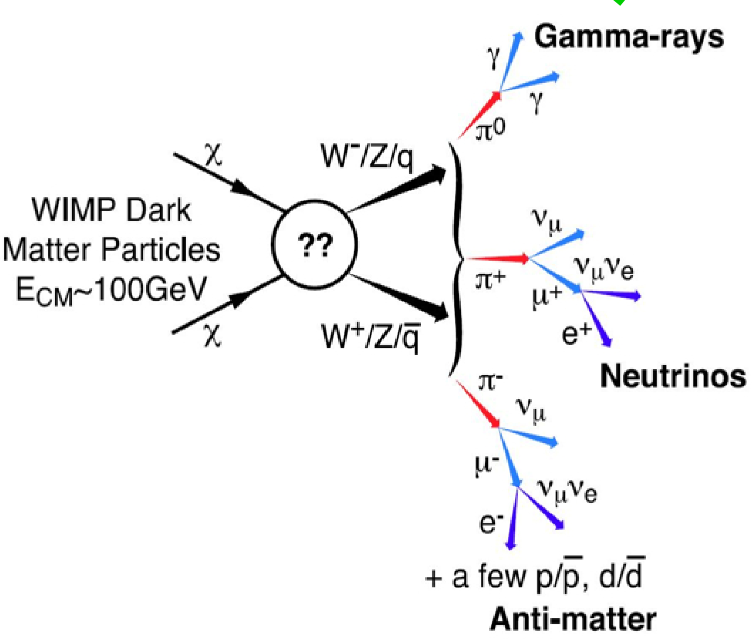
Radio

Spatial analyses

Galactic center searches & the Fermi GeV excess

Five years of
Fermi LAT data
> 1 GeV





The Fermi GeV bulge emission

- Initial claims by Goodenough&Hooper (2009) [see also Vitale&Morselli (2009)]
- Controversial discussion in the community for six years
- In 2015, existence of “GeV excess” finally got the blessing of the Fermi LAT collaboration
- **Is it a DM signal?**

… Hooper & Linden 11; Boyarsky+ 11; Abazajian & Kalpinghat 12; Hooper & Slatyer 13; Gorden & Macias 13; Macias & Gorden 13; Huang+ 13; Abazajian+ 14; Daylan+ 14; Zhou+ 14; Calore+ 14; Huang+15; Cholis+ 15; Bartels+ 15; Lee+ 15, …)

Literature overview

Papers that looked at data

- Goodenough & Hooper, arXiv:0910.2998
- Vitale & Morselli, 2009
- Hooper & Goodenough, Phys. Lett. B697 (2011) 412
- Hooper & Linden, Phys. Rev. D84 (2011) 123005
- Boyarsky, Malyshev & Ruchayskiy, Phys. Lett. B705 (2011) 165
- Abazajian & Kaplinghat, PRD 86 (2012) 083511
- Hooper & Slatyer, Phys. Dark Univ. 2 (2013) 118
- Gordon & Macias, Phys. ReV. D88 (2013) 083521
- Macias & Gordon, PRD 89 (2014) 063515
- Abazajian, Canac, Horiuchi, Kaplinghat, Phys. Rev. D90 (2014) 023526
- Cholis, Evoli, Calore, Linden, Weniger, Hooper, JCAP 1512 (2015) 12
- Calore, Cholis & Weniger, JCAP 1503 (2015) 038
- Zhou, Liang, Huang, Li, Fan, Chang, Phys. Rev. D91 (2015) 123010
- Gaggero, Taoso, Urbano, Valli & Ullio, JCAP 1512 (2015) 056
- Daylan, Finkbeiner, Hooper, Linden, Portillo et al., Physics of Dark Universe 12 (2016) 1
- De Boer, Gebauer, Neumann, Biermann, arXiv:1610.08926 (ICRC 2016 proceedings)
- Huang, Ensslin & Selig, JCAP 1604 (2016) 030
- Carlson, Linden, Profumo, Phys. Rev. D94 (2016) 063504
- Bartels, Krishnamurthy, Weniger, Phys. Rev. Lett. 116 (2016) 5
- Macis, Gordon, Crocker, Coleman, Paterson, arXiv:1611.06644
- Lee, Lisanti, Safdi, Slatyer, Xue, Phys. Rev. Lett. 116 (2016) 5
- Ajello et al. 2016, Astrophys. J. 819, 44
- Ackermann et al., 2017, Astrophys. J. 840, 43
- Ajello et al., 2017, arXiv:1705.00009

(+ a few that I must have missed)

Excess is likely DM

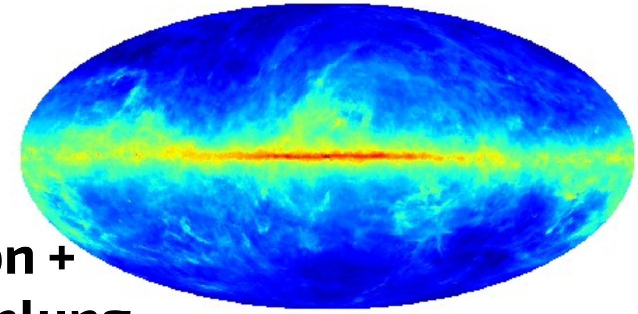
Excess is there

Excess is likely not DM

Excess is not there

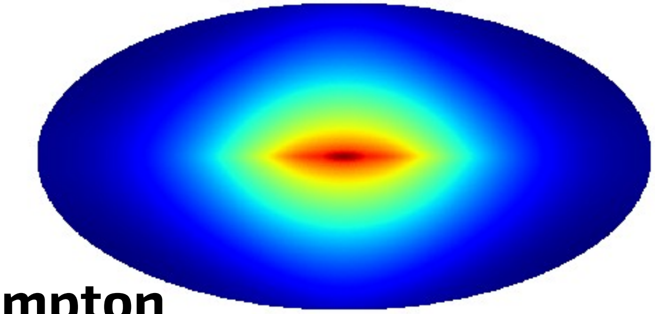
+ hundreds of DM theory papers

Template regression



Neutral pion + Bremsstrahlung

+

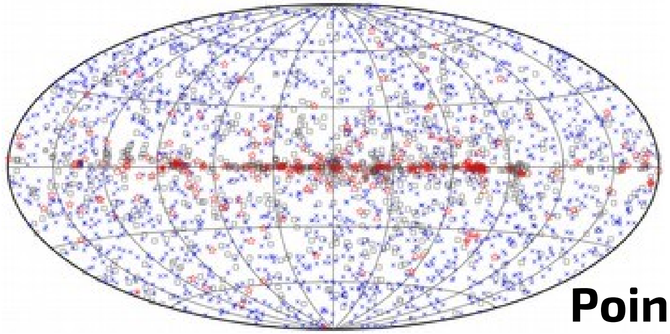


Inverse Compton

+

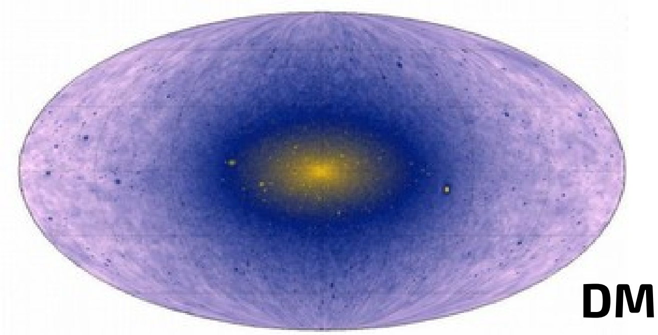
Fermi bubbles, isotropic background, Loop I, Earth limb, Sun, …

+



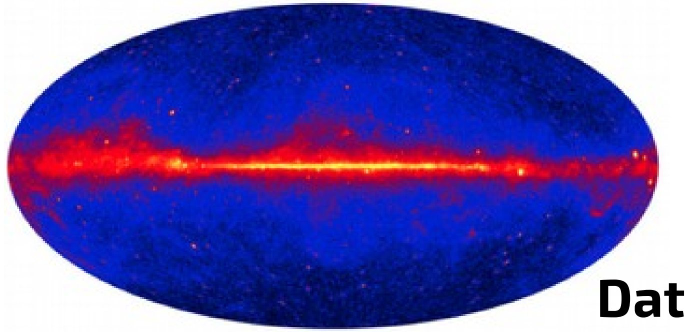
Point sources

+



DM signal

=

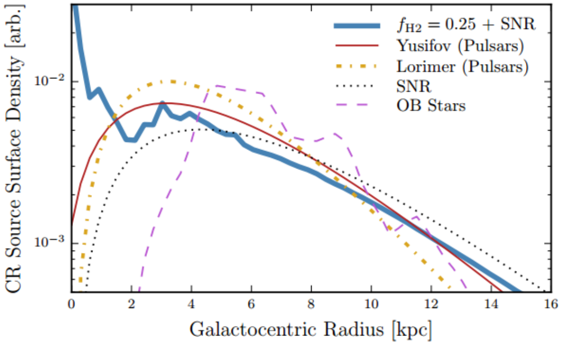


Data

How to get the templates

1) Inject primary CR at sources

Carlson+ 2015



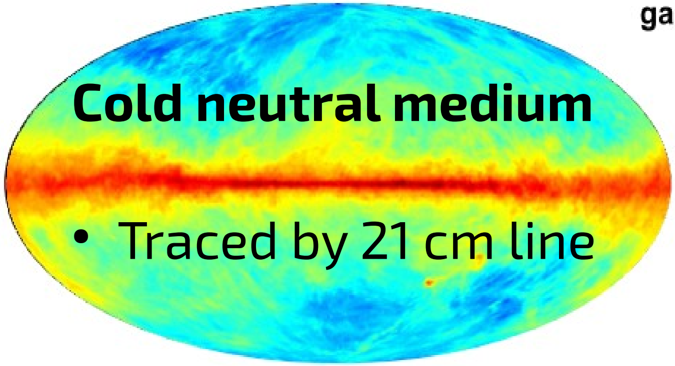
2) Propagate them with the code of your choice

GALPROP

DRAGON

3) Interaction with gas & ISRF

HI (LAB) Kalberla '05



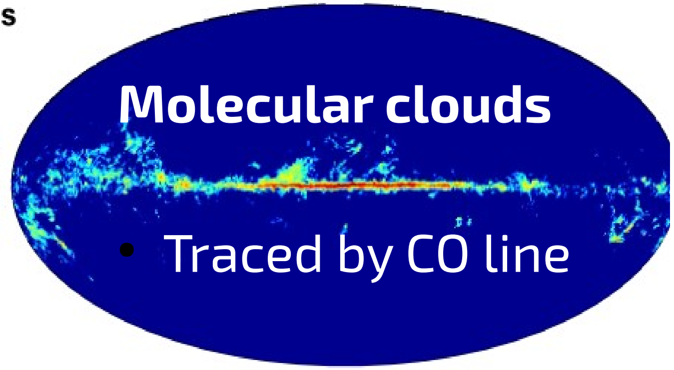
Cold neutral medium

- Traced by 21 cm line

HII <<

gas

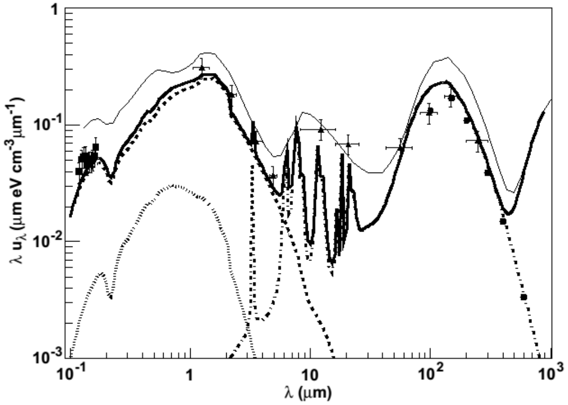
CO (CfA) Dame '01



Molecular clouds

- Traced by CO line

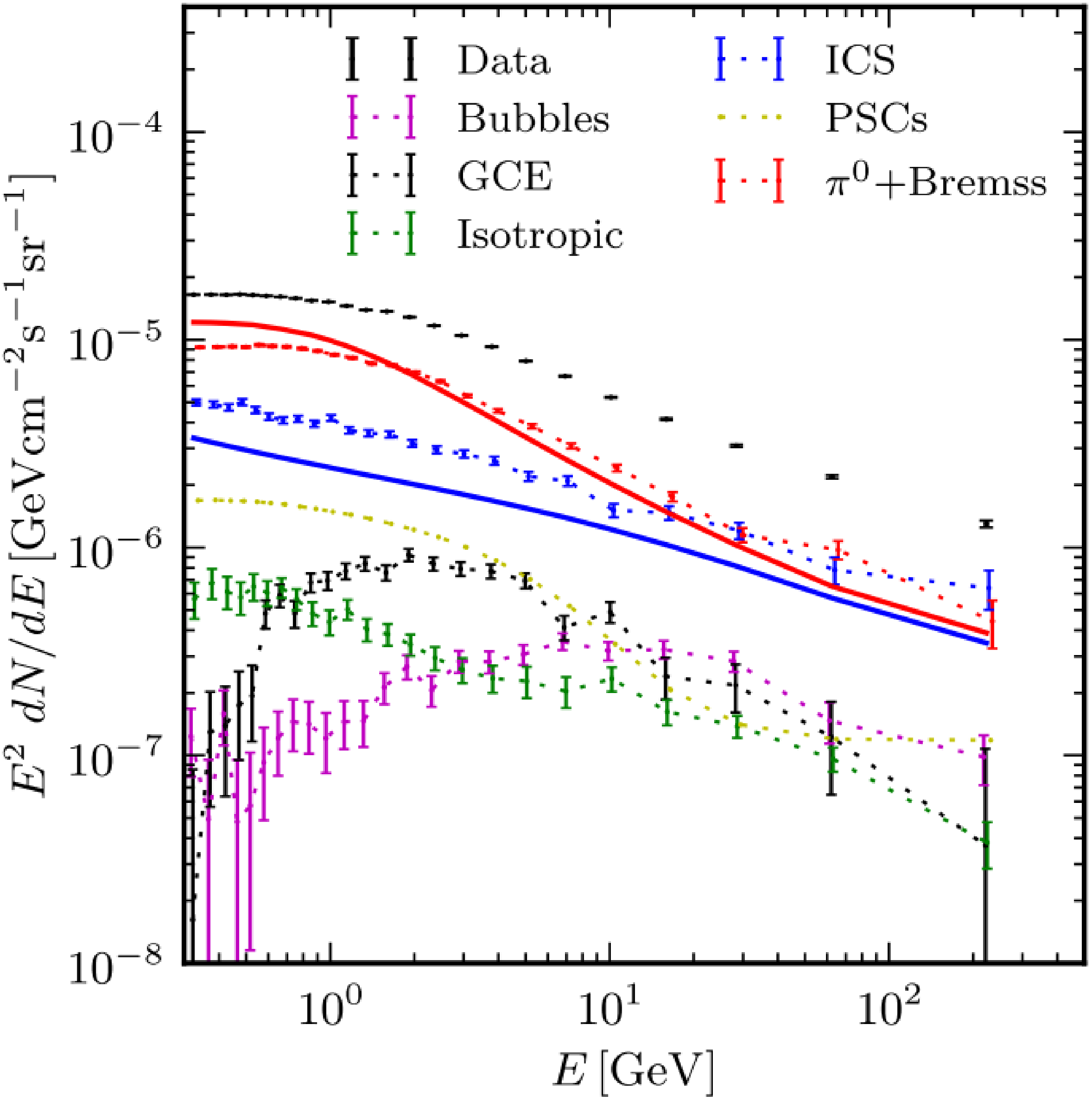
Strong+ 2000; Porter & Strong 2005; Moskalenko+ 2006; Porter+ 2008



$$\begin{tikzcd}
 & & & \gamma \\
 & & \pi^0 \arrow[ur] \arrow[dr] & \\
p_{\rm CR} \arrow[r] & p_{\rm ISM} \arrow[ur] \arrow[dr] & & \gamma \\
 & & \ldots &
\end{tikzcd}$$

$$\begin{tikzcd}
 & & \gamma \\
e^{\pm}_{\rm CR} \arrow[r] & \gamma_{\rm ISRF} \arrow[ur] \arrow[dr] & \\
 & & e^{\pm}_{\rm CR}
\end{tikzcd}$$

Spectra from template fits



Calore+ 2015

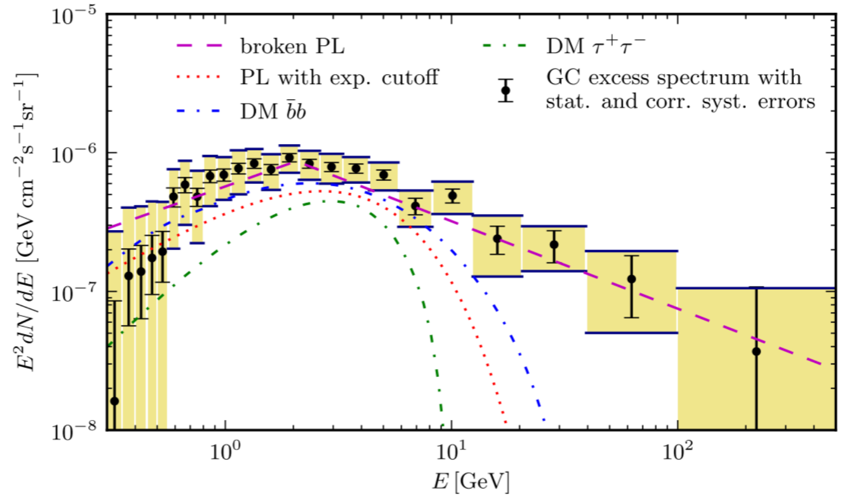
Free parameters:

$$N_{\mathrm{params}} = N_{\mathrm{ebins}} \times N_{\mathrm{comp}}$$

$$F_{ij} = \sum_{k=1}^{N_{\mathrm{comp}}} \theta_{k,j} F_i^{(k)}$$

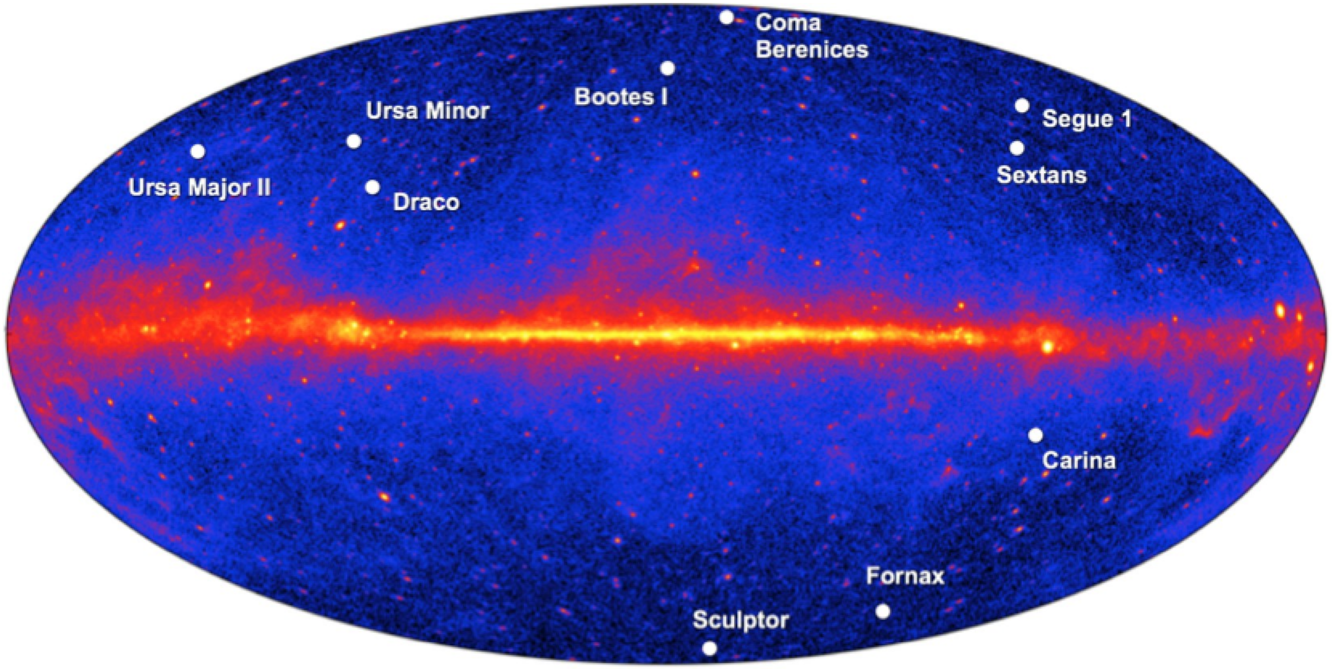
$$j = 1, \ldots, N_{\mathrm{ebins}}$$

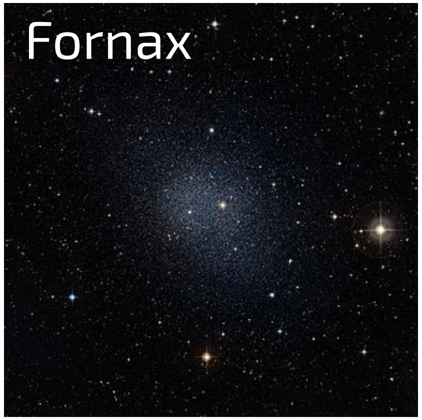
$$\mathcal{L} = P_{\mathrm{pois}}(c_{ij}|\mu_{ij}) \qquad c_{ij} \propto F_{ij}$$

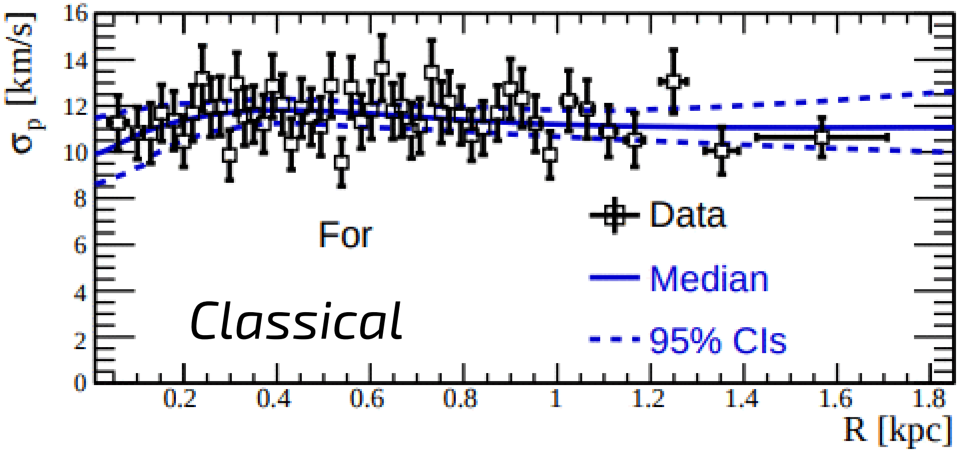


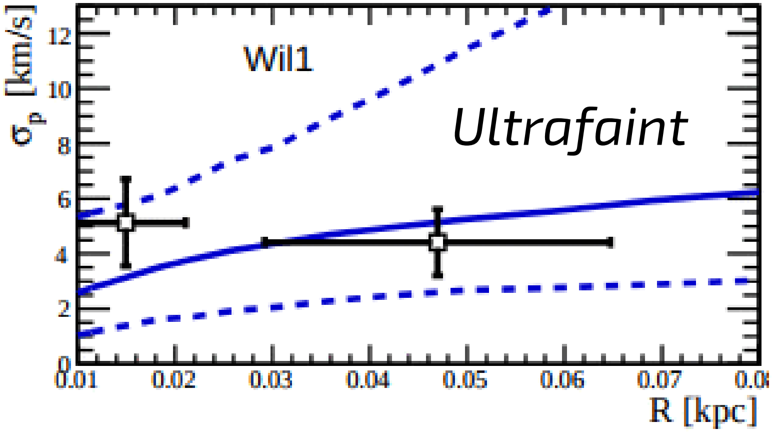
more later…

Searches in dwarf spheroidal galaxies







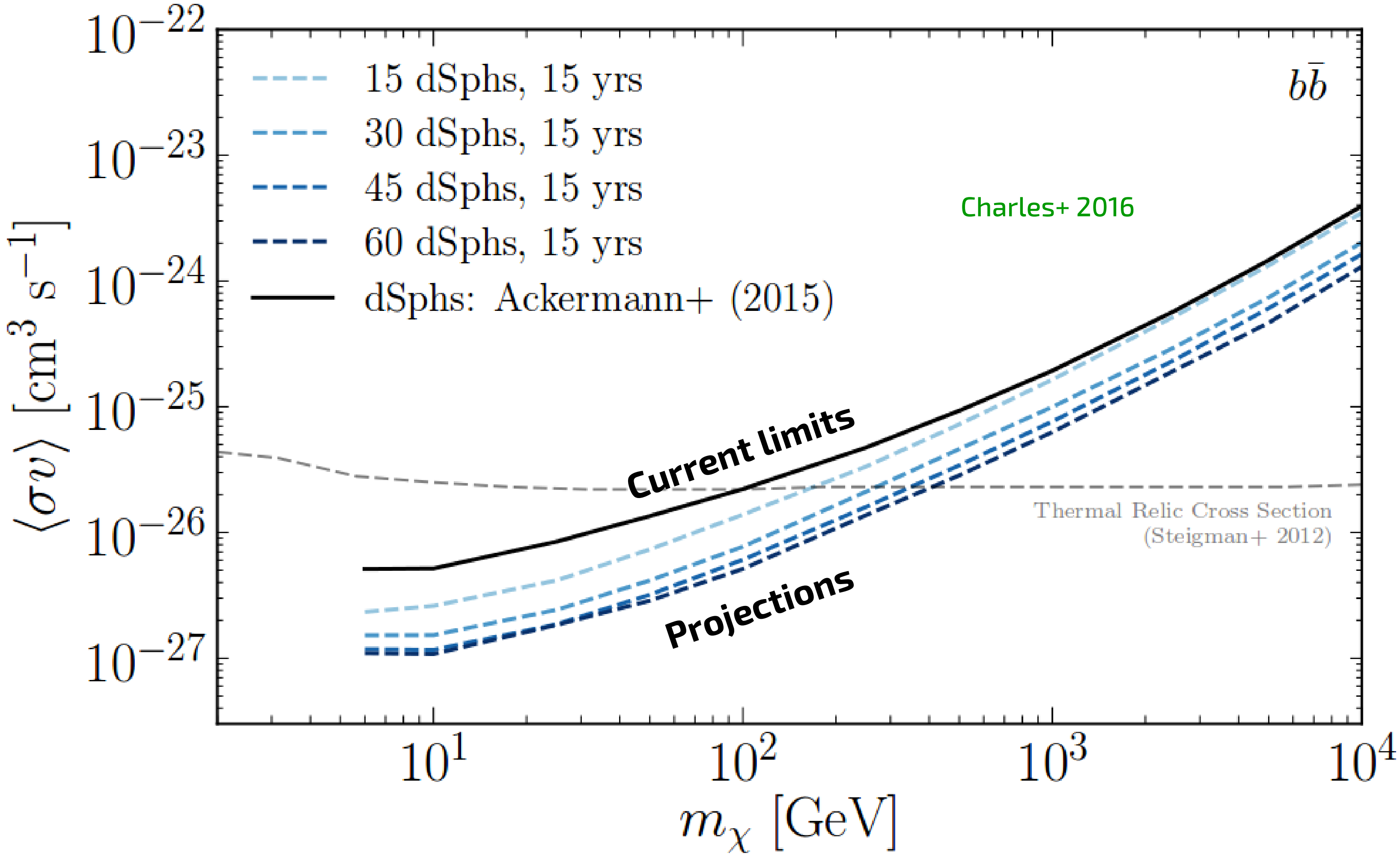


$$\frac{1}{\nu}\frac{d}{dr}(\nu\bar{v_r^2}) + 2\frac{\beta_{\rm ani}(r)\bar{v_r^2}}{r} = -\frac{GM(r)}{r^2}$$

e.g. Bonnivard+ 15

Fermi LAT limits from dwarf spheroidal galaxies

Combined likelihood limits using data from the Fermi Large LAT, ~0.5 – 300 GeV



$$\mathcal{L}(\sigma v) \propto \prod_{i=\mathrm{dwarfs}} \mathcal{L}_i(\mathcal{D}_i|\sigma v, J_i) P_i(J_i)$$

Spectral analyses

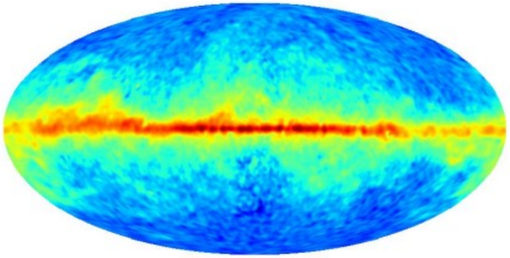
Spectral decomposition

Pixel-by-pixel spectral decomposition:

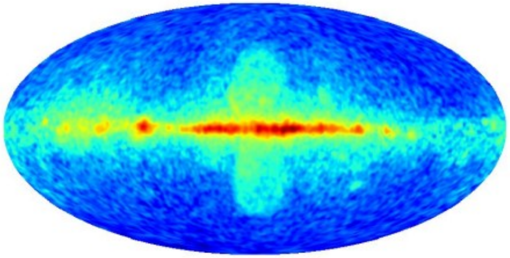
$$\frac{dN}{dE} = \alpha_1 \left.\frac{dN}{dE}\right|_{\mathrm{Bu}} + \alpha_2 \left.\frac{dN}{dE}\right|_{\mathrm{Cl}} + \alpha_3 \left.\frac{dN}{dE}\right|_{b\bar{b}} + \mathrm{PSC}$$

Huang+ 2015 (using D3PO)

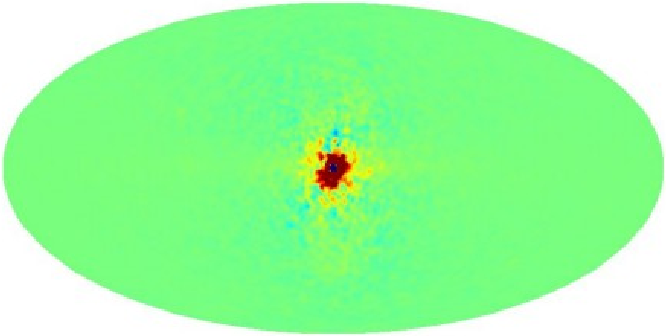
“Cloud-like” component



“Bubble-like” component

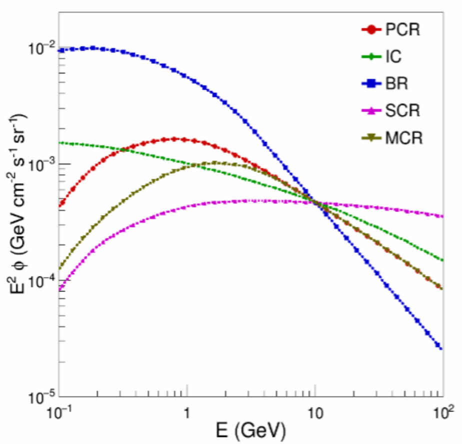


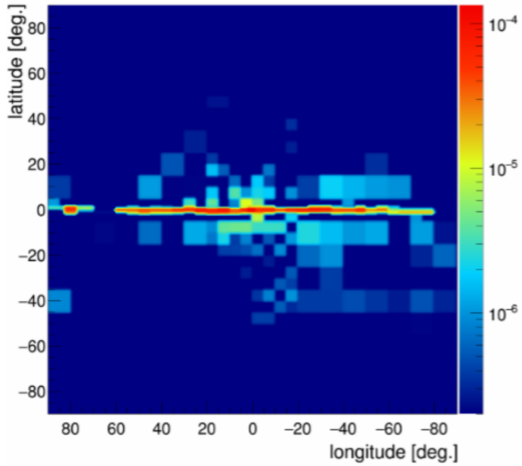
“DM-like” component



But: different spectra
lead to different results

De Boer, Gebauer, et al. 2016

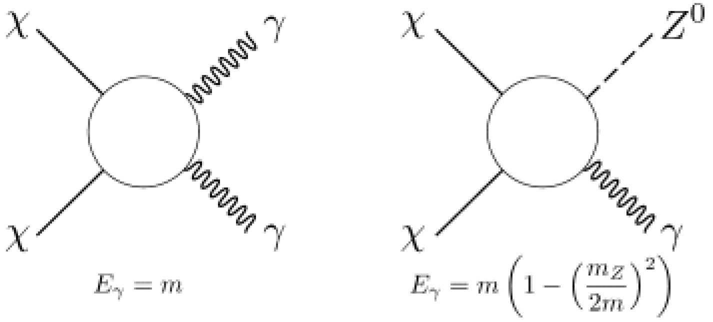




Simple: X-ray & gamma-ray lines

WIMP annihilation

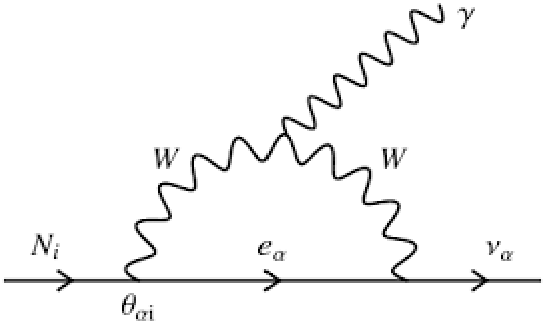
$$\chi\chi \to \gamma\gamma, \gamma Z^0$$



[Bergström & Snellman (1988)]

Sterile neutrino decay

$$\chi \to \gamma\nu$$



Likelihood analysis

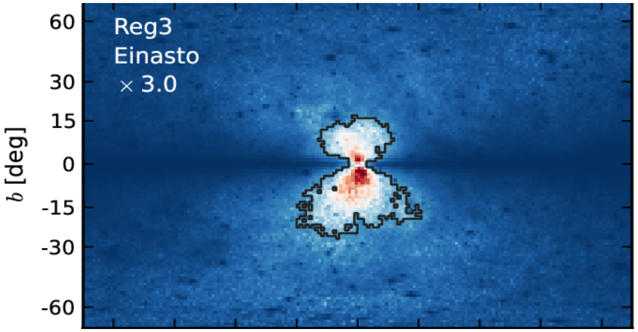
Typical strategy

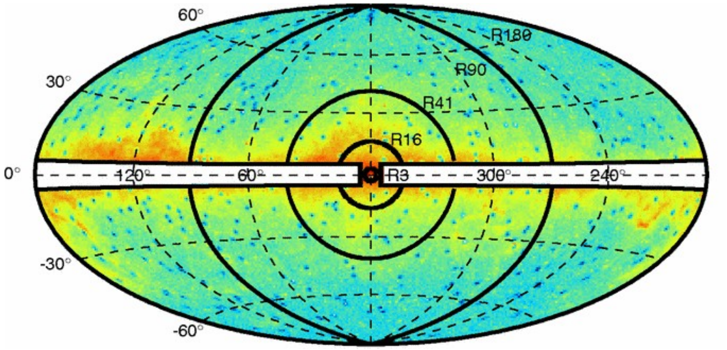
- Select some region of interest (ROI)
- Derive integrated energy spectrum inside region
- Perform fit with (simplistic) background model and line signal

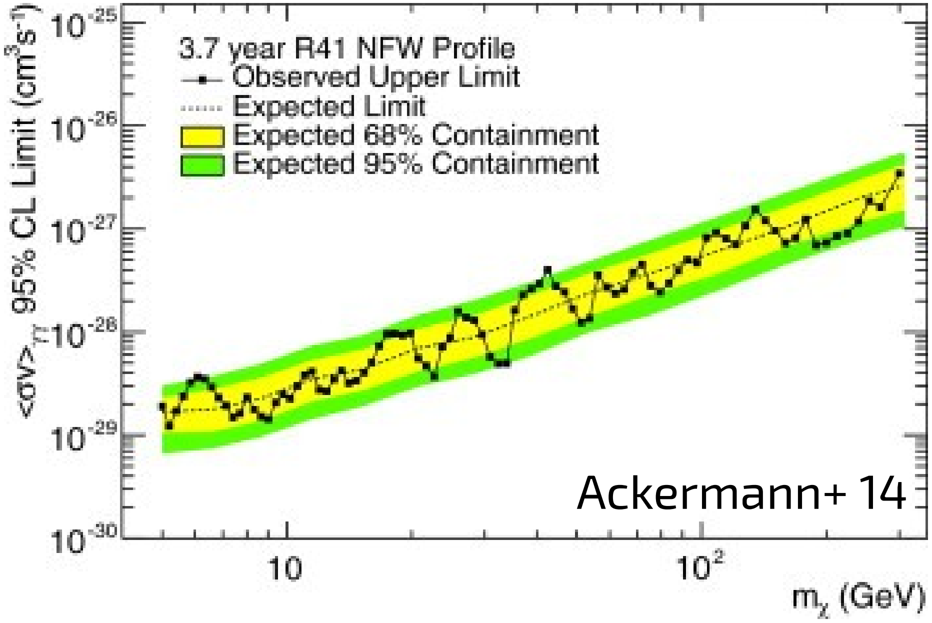
$$\frac{dJ}{dE} = S\;\delta(E - E_\gamma) + \beta E^{-\gamma}$$

How to select optimal ROI?

- Depends on backgrounds and signal morphology
- Can cover various cases by taking multiple representative ROIs
- Weighting of events w.r.t. expected S/N (e.g., Anderson+ 16)

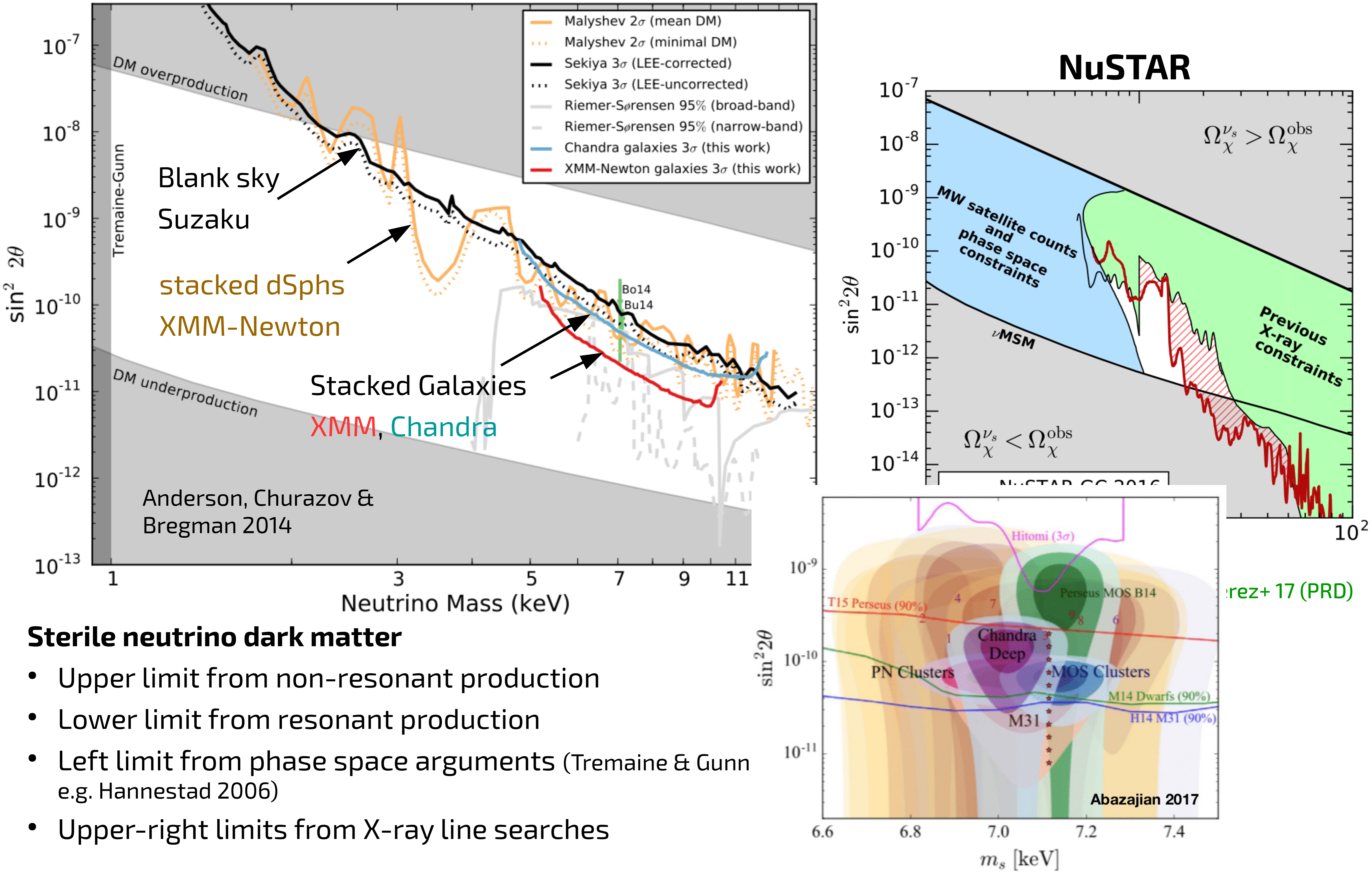






Ackermann+ 14

Sterile neutrino Dark Matter

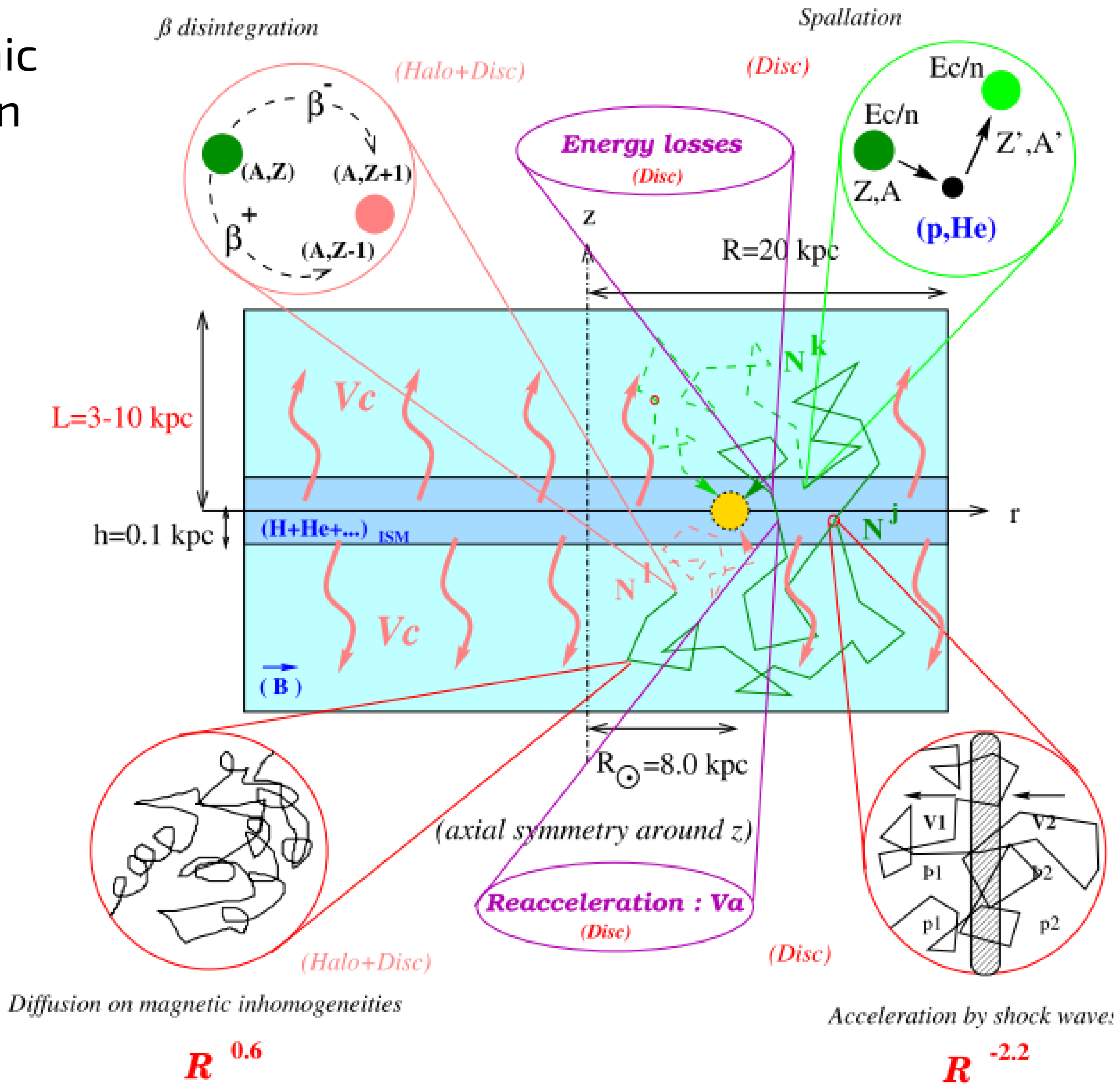


Sterile neutrino dark matter

- Upper limit from non-resonant production
- Lower limit from resonant production
- Left limit from phase space arguments (Tremaine & Gunn e.g. Hannestad 2006)
- Upper-right limits from X-ray line searches

Anti-proton searches for dark matter

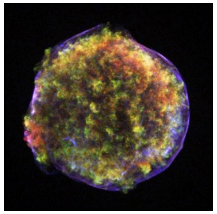
Sketch of cosmic ray propagation



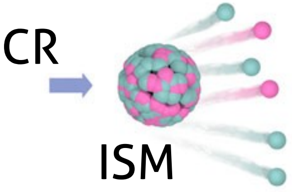
[see e.g. Evoli et al. (2012) and refs therein; Lavalle & Salati (2012); Strong, Moskalenko and Ptuskin (2007)]

Grammage to the rescue

Two sources for cosmic rays

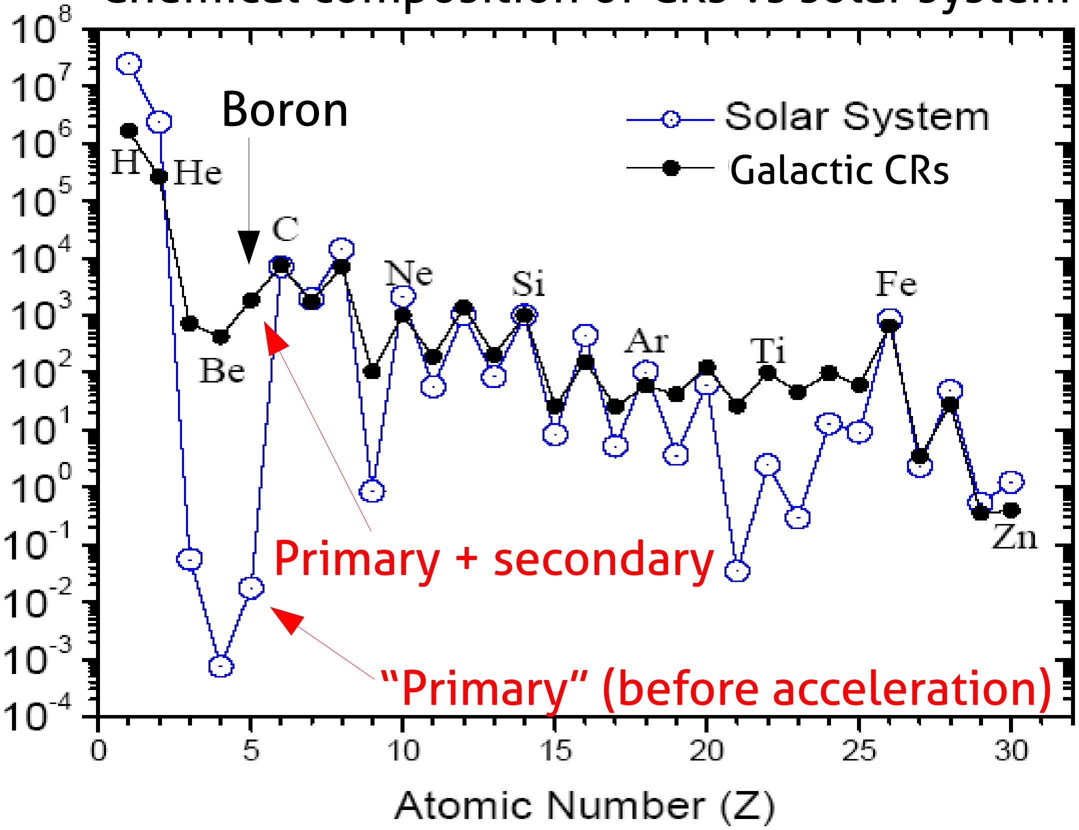


Primary cosmic rays from supernova remnants (likely)

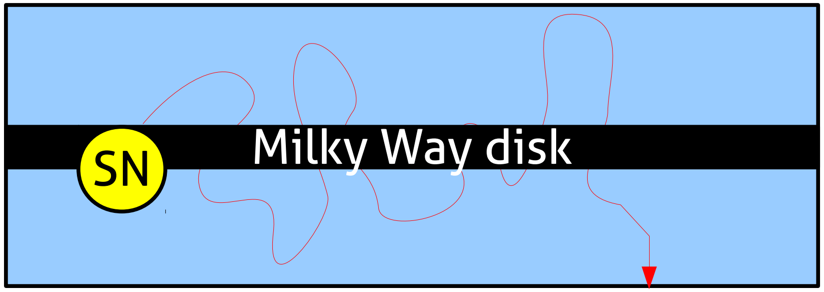


Secondary cosmic rays from spallation etc

Chemical composition of CRs vs solar system



Diffusion in a box



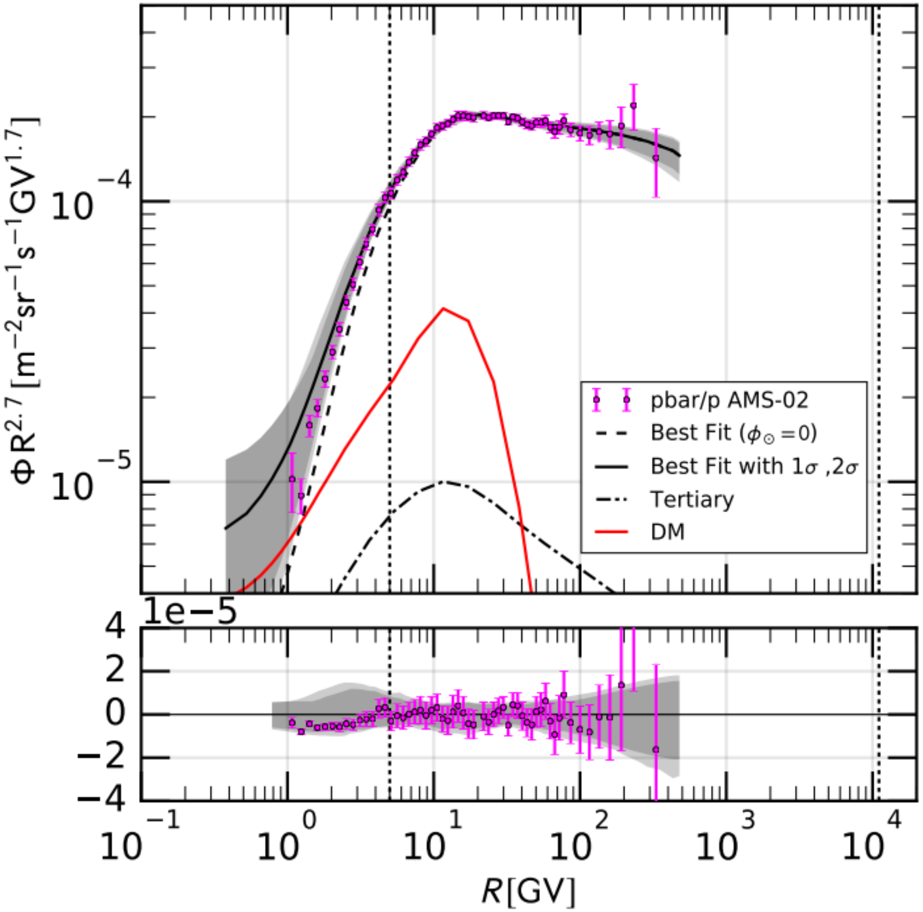
Total grammage (column density along propagation path)

$$G_{\text{total}} = n_{\text{crossings}} G_{\text{disk}} \sim \mathcal{O}(10\ \text{g cm}^{-2})$$

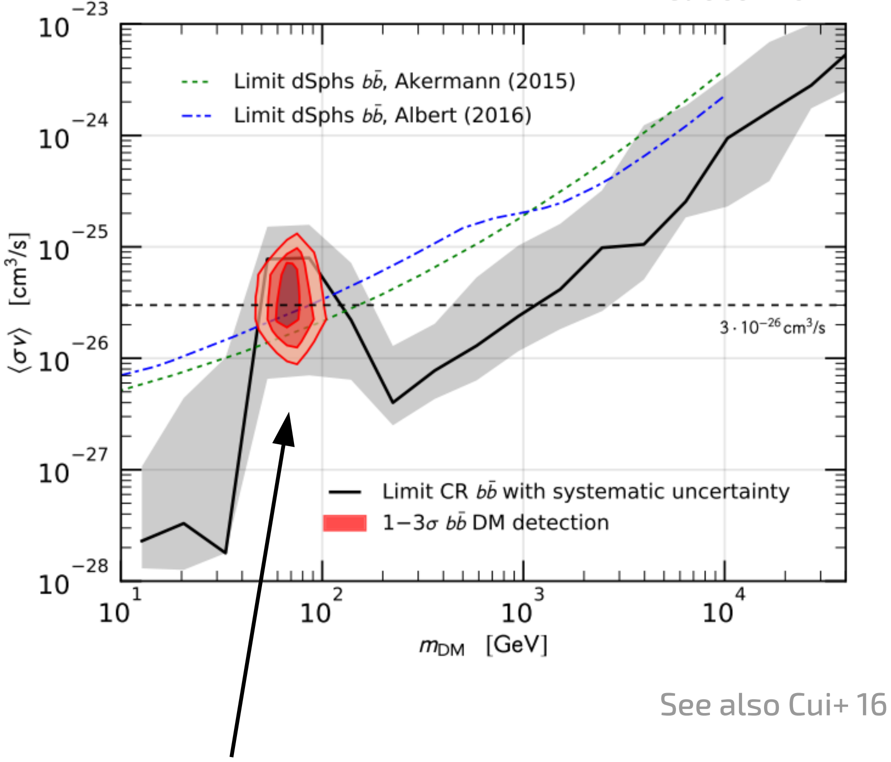
Secondary Boron: $n_B \sim n_C \sigma(C \to B) \cdot G_{\text{total}} \Rightarrow G_{\text{total}}$

Secondary antiprotons: $n_{\bar{p}} \sim n_p \sigma(p \to \bar{p}) \cdot G_{\text{total}} \Rightarrow n_{\bar{p}}$

AMS-02 anti-protons - ~ 10 GeV



Cuoco+ 16



See also Cui+ 16

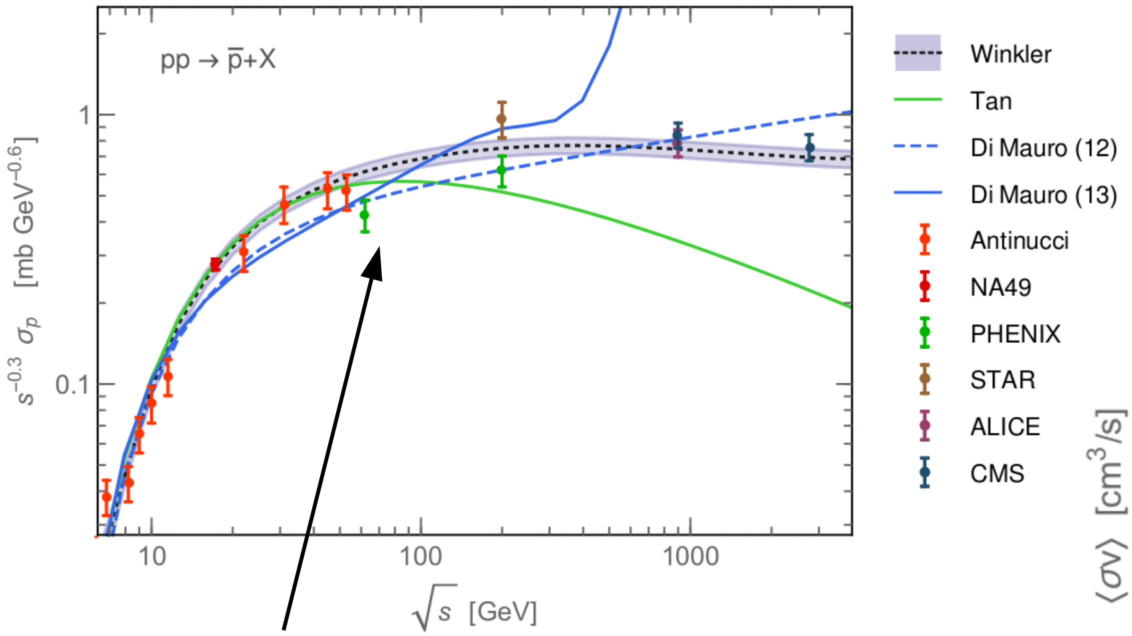
Agrees with Fermi GeV excess…

Indications for an excess around 10 GeV (Cuoco+16, see also Cui+ 16)

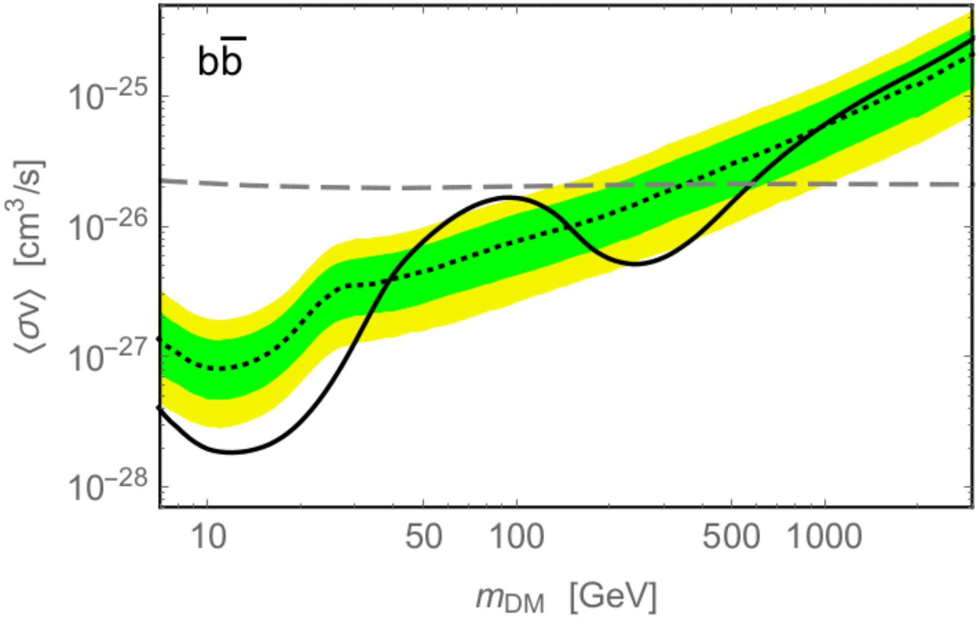
- Formally ~5 sigma preference for DM contribution, mass & flux compatible with GCE
- But: Simple propagation scenarios are insufficient to explain *all* CR data (and DM does not help) → Extraction of reliable limits or signal becomes a huge challenge

See also: Winkler+ 17; Carlson+14; Cirelli+14; Jin+15; Ibe+15; Hamaguchi+15; Lin+15; Kohri+15; Balazs&Li15; Doetinchem+15; Fornengo+13

Accounting for modeling uncertainties



Derive covariance of production cross-section from parameteric model



Accounting for covariances of various systematics (Reinart & Winkler 2017)

- Refitting nuclear spallation data for Boron production from Carbon, Oxygen, Nitrogen, etc
- Charge-dependent solar modulation
- Refitting primary cosmic ray measurements
- → Reasonable fit to B/C and pbar data with universal diffusion-reacceleration model
  → Significance for ~80 GeV DM contribution drops to below 2 sigma
  → Very strong limits on DM annihilation at low and higher DM masses

Hybrid techniques

Problems with gamma-ray template anlayses

NONE of the diffuse emission models gives an acceptable fit to the data

1. Even the best models are excluded by many hundred sigmas

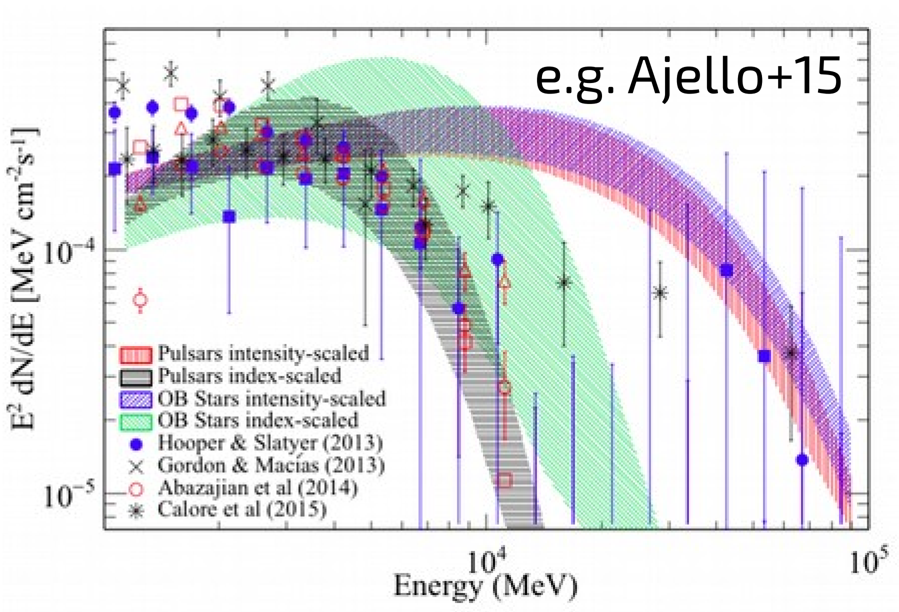
Goodness-of-fit tests typically return **p-value < 10^{-300}**

2. Many excess along the Galactic disk

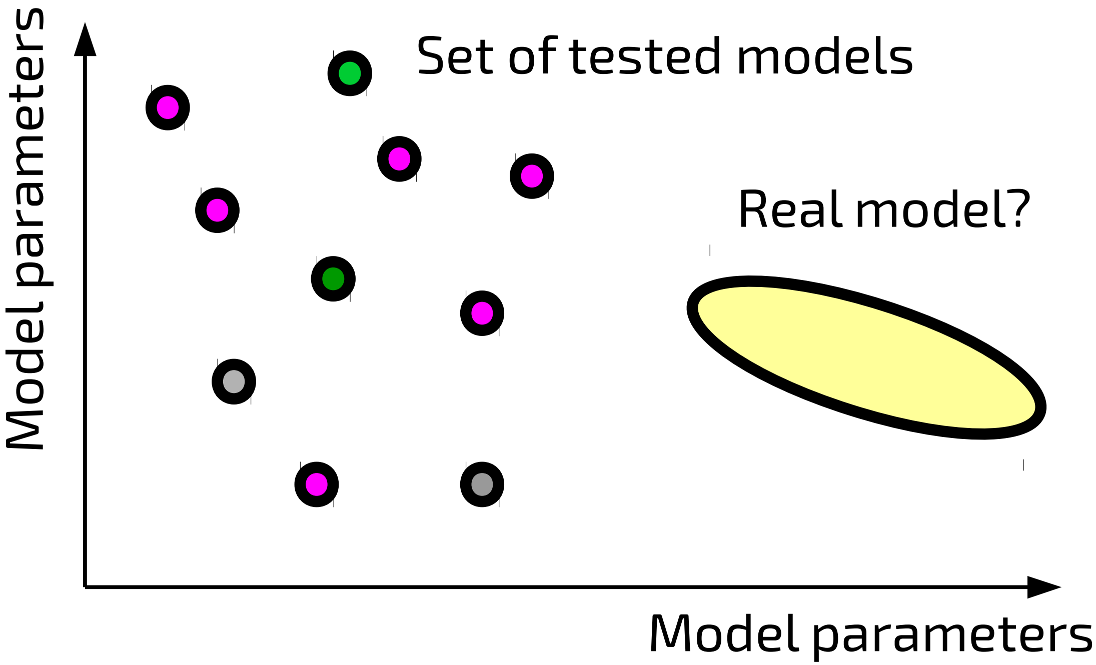
Some of the excesses have same size as Galactic center excess (Calore+15)

3. "Bracketing uncertainties" by looking at many wrong models does not give the right answer

But everybody is doing it.



e.g. Ajello+15



We need better models and/or massively enlarge the parameter space.

Accounting for systematics with SkyFACT

SkyFACT (**S**ky **F**actorization with **A**daptive **C**onstrained **T**emplates)

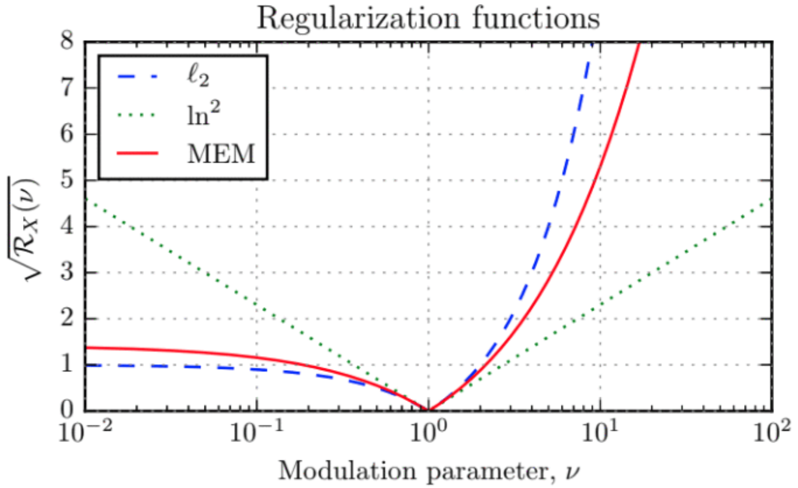
Hybrid between template fitting & image reconstruction

Spatial template

Spectral template

$$\phi_{pb} = \sum_k T_p^{(k)} \tau_p^{(k)} \cdot S_b^{(k)} \sigma_b^{(k)} \cdot \nu^{(k)}$$

Nuisance parameters



Poisson likelihood

$$\ln \mathcal{L} = \ln \mathcal{L}_\mathrm{P} + \ln \mathcal{L}_\mathrm{R}$$

Regularization of nuisance parameters

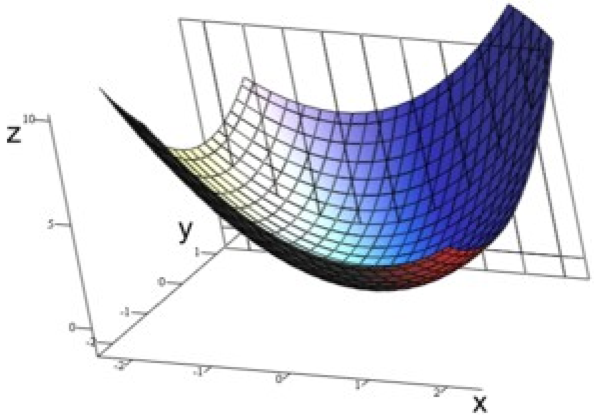
$$\begin{aligned} -2\ln \mathcal{L}_R = \sum_k \lambda_k \mathcal{R}_X(\boldsymbol{\tau}^{(k)}) + \lambda'_k \mathcal{R}_X(\boldsymbol{\sigma}^{(k)}) + \lambda''_k \mathcal{R}_X(\nu^{(k)}) + \eta_k \mathcal{S}_1(\boldsymbol{\tau}^{(k)}) + \eta'_k \mathcal{S}_2(\boldsymbol{\sigma}^{(k)}) \\ + \sum_s \lambda'_s \mathcal{R}_X(\boldsymbol{\sigma}^{(s)}) + \lambda''_s \mathcal{R}_X(\nu^{(s)}) + \eta'_s \mathcal{S}_2(\boldsymbol{\sigma}^{(s)}) \ , \end{aligned}$$

Notes

- Typically >10^5 parameters
- Problem typically convex → only one minimum

Storm, CW, Calore, 2017

Fit stability & potential bias



If the likelihood function is convex, any minimum is the global minimum.
→ We have to make sure that this is the case for the problem at hand.

One can show that these problems are convex

- Pure template analysis (templates fixes, spectra free or constrained)
- Pure spectral analysis (spectra fixed, templates free or constrained)
- Mixed analysis (pure template + pure spectral analysis components)

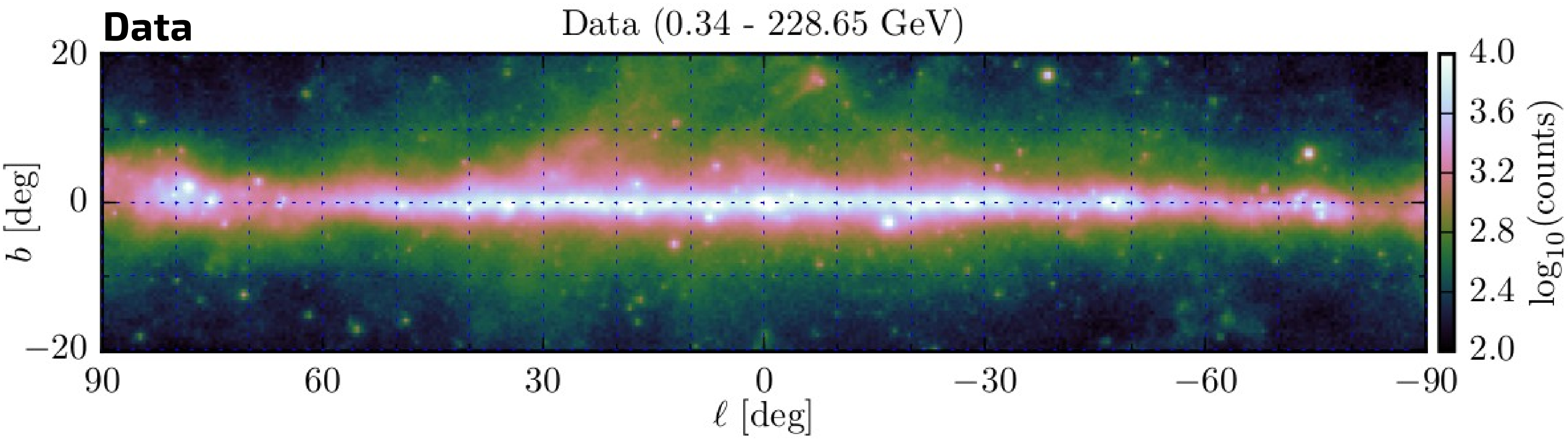
Potentiall problematic (but present in our analysis)

- Components with *both* spectral and spatial freedom
- Smoothing

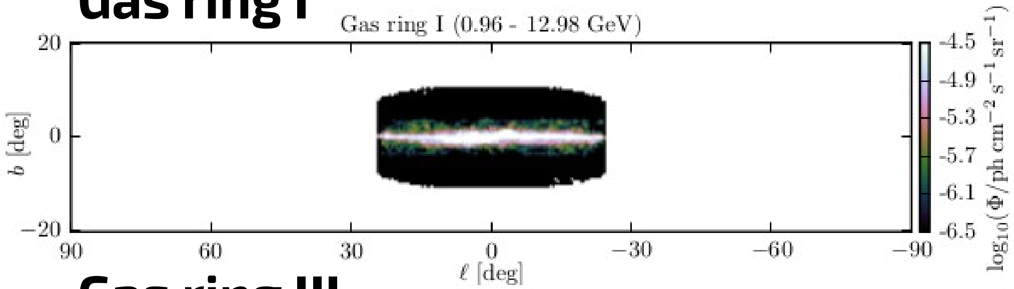
→ Problems can be avoided if spectral *or* spatial freedom remains small.
→ We test for potential biases etc by refitting best-fit models to mock data.

Data and templates

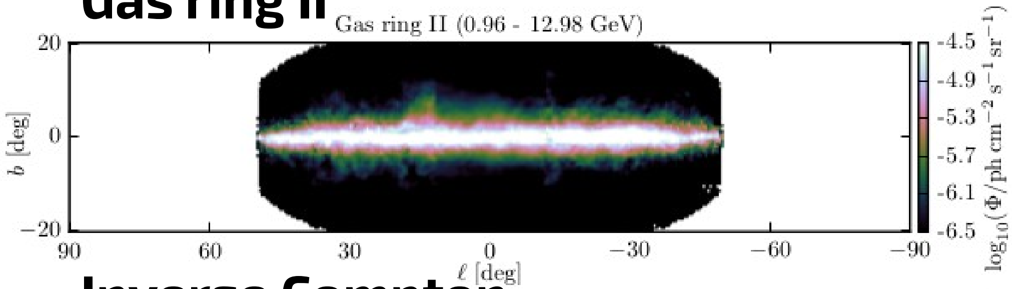
Data



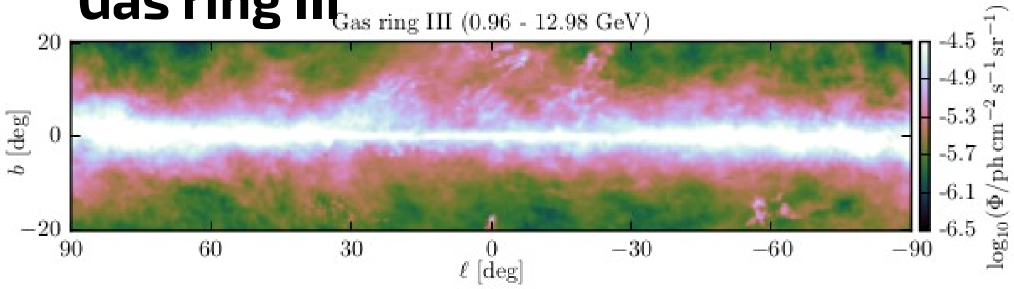
Gas ring I



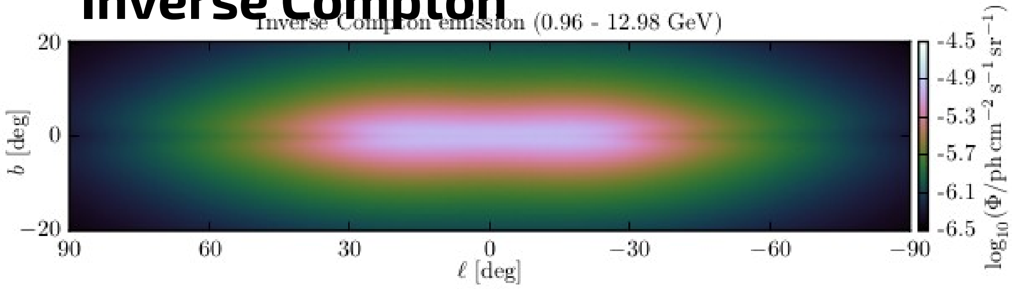
Gas ring II



Gas ring III

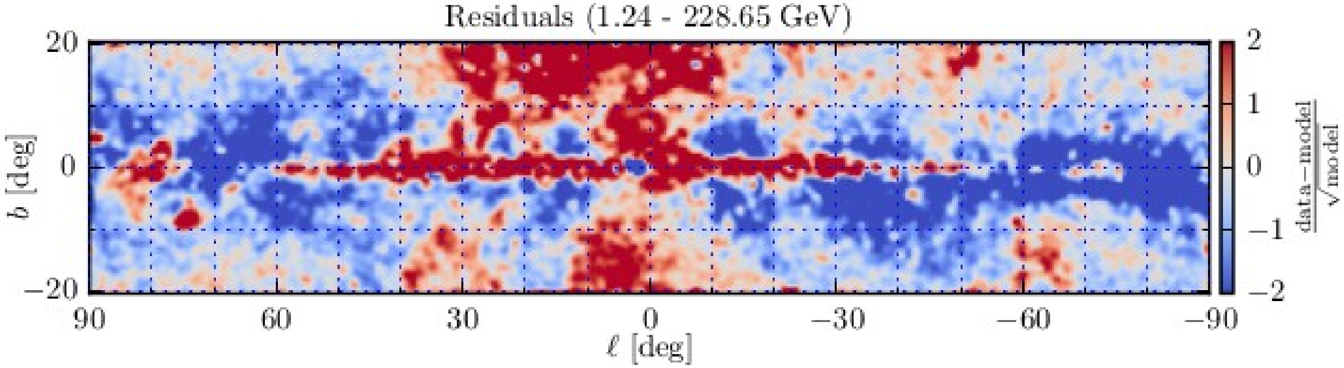


Inverse Compton

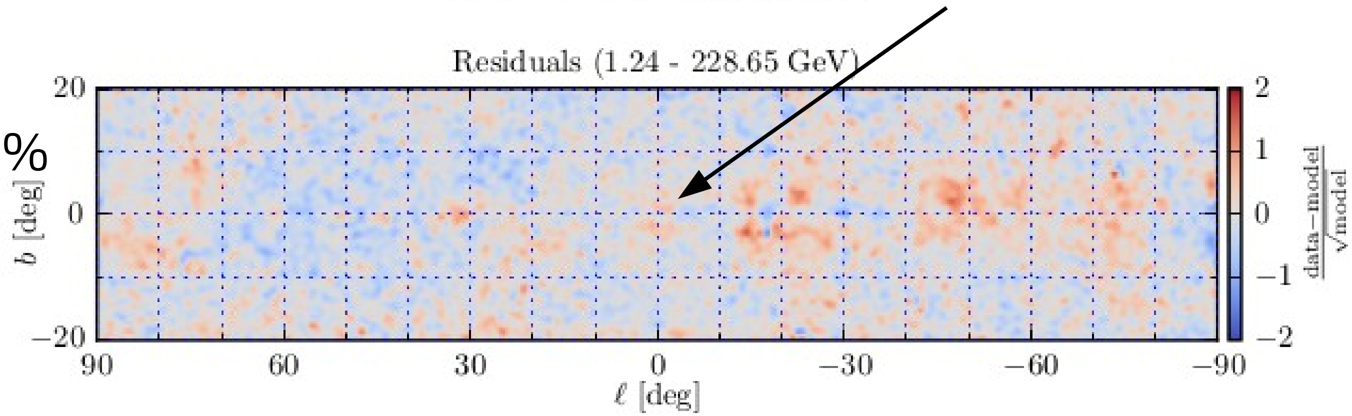


Residuals ~2 GeV

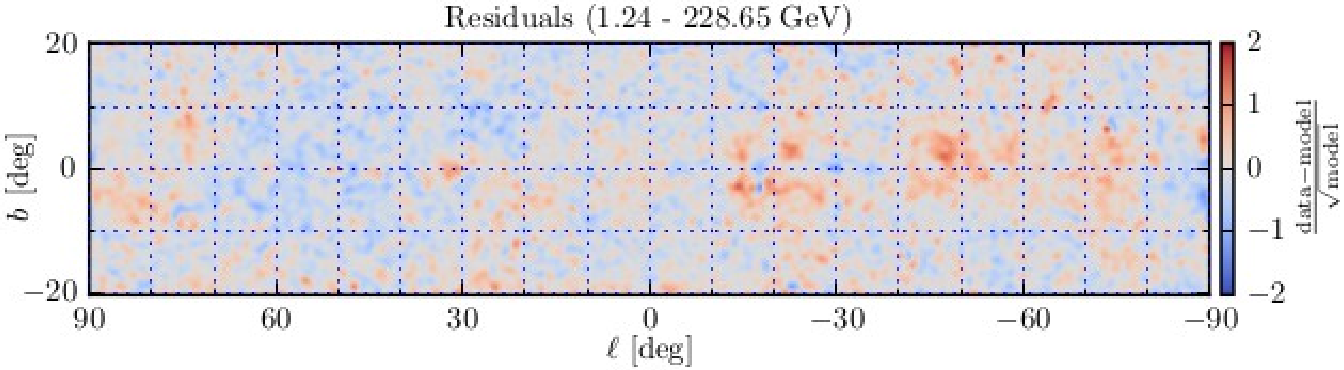
Regular template fit



Templates with 10%-30% uncertainty

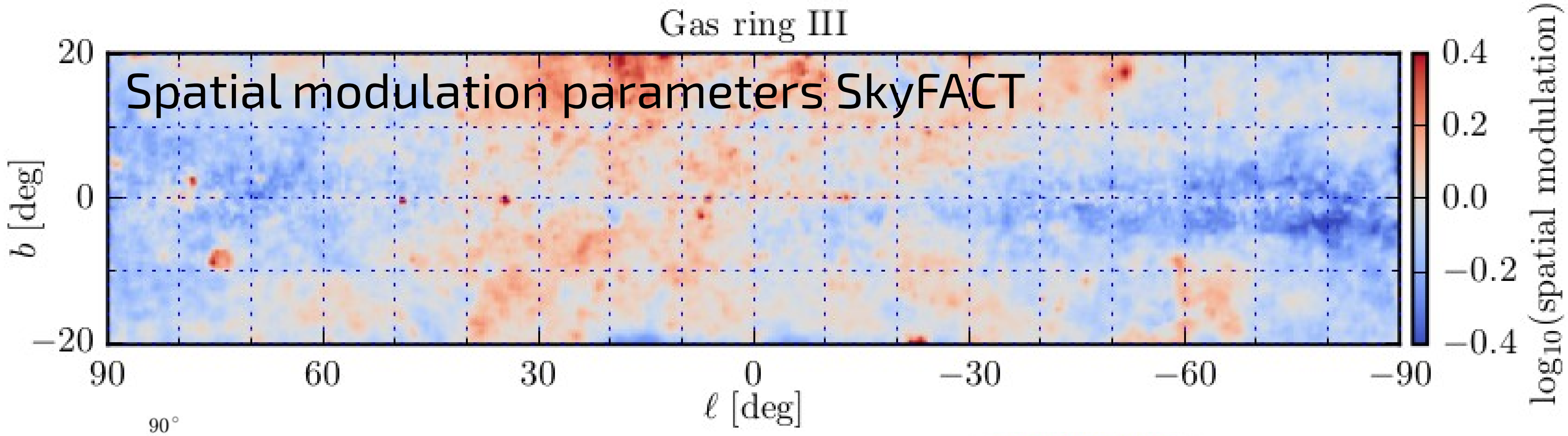


+ GeV excess



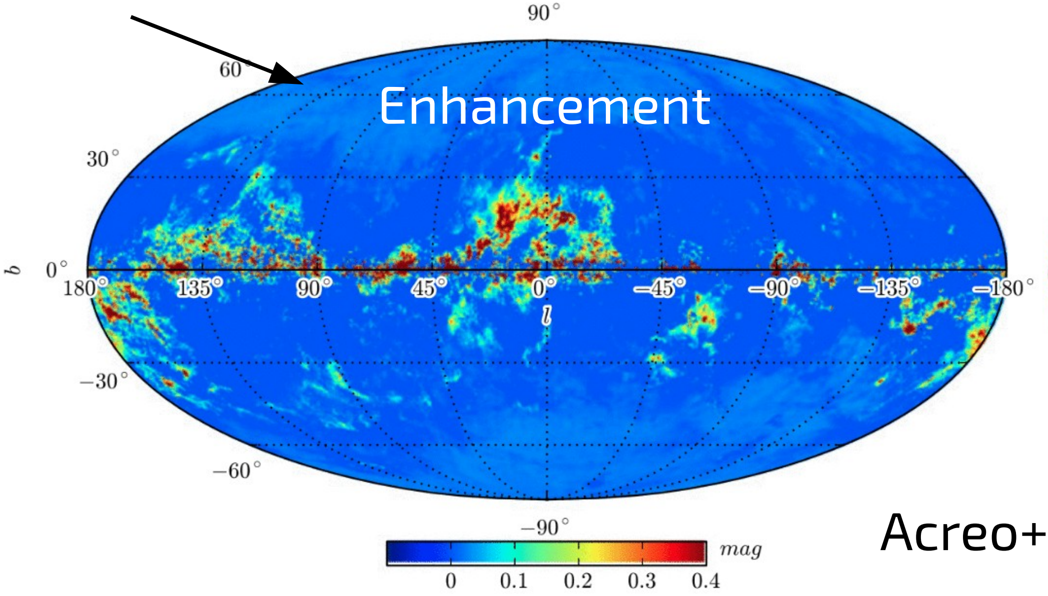
Dark gas corrections

- Fraction of gas neither emits CO (molecular gas) nor 21 cm line (atomic gas) → Not included in gas maps
- Correction factors are usually derived by considering dust reddening maps (assuming that dust is well mixed with ISM)

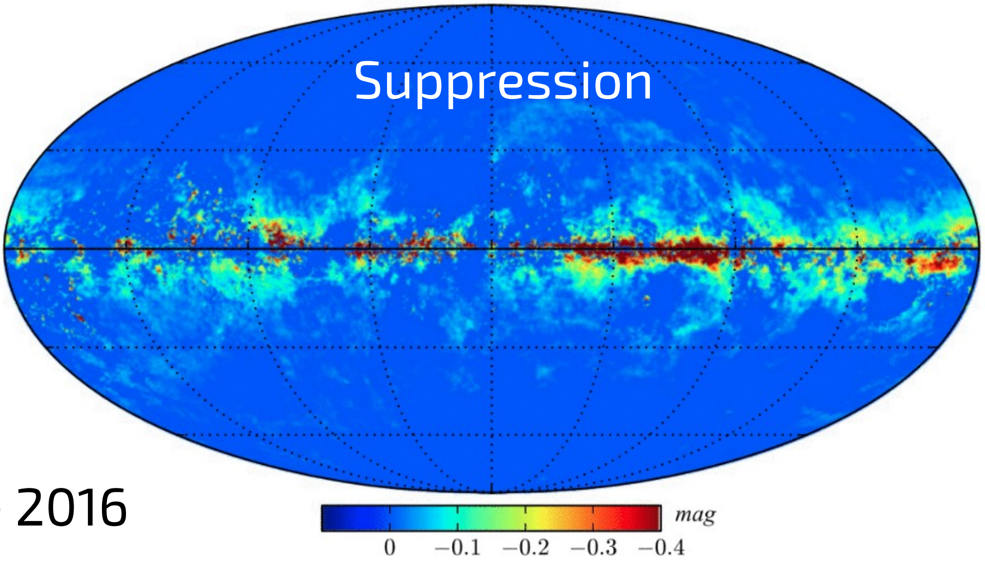


Spatial modulation parameters SkyFACT

Dust corrections



Enhancement

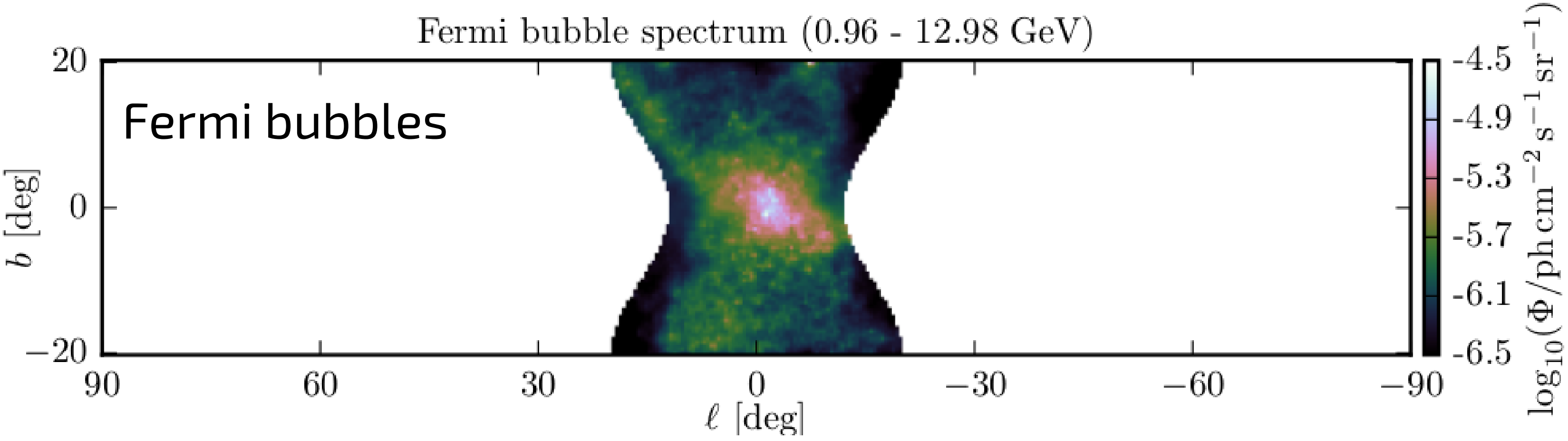


Suppression

Acreo+ 2016

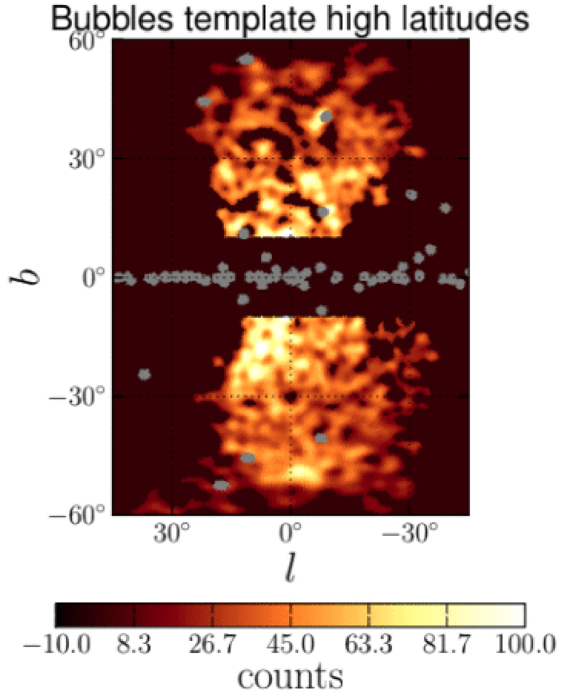
Low-latitude Fermi bubbles

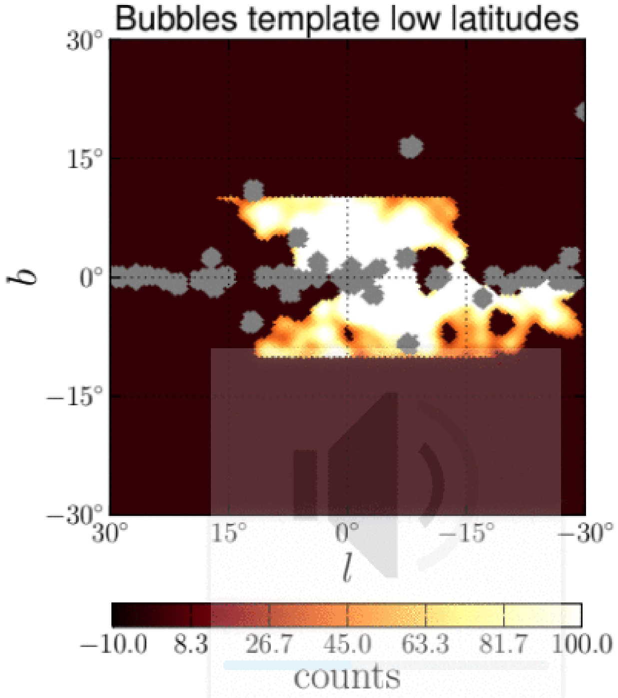
Modulation parameters



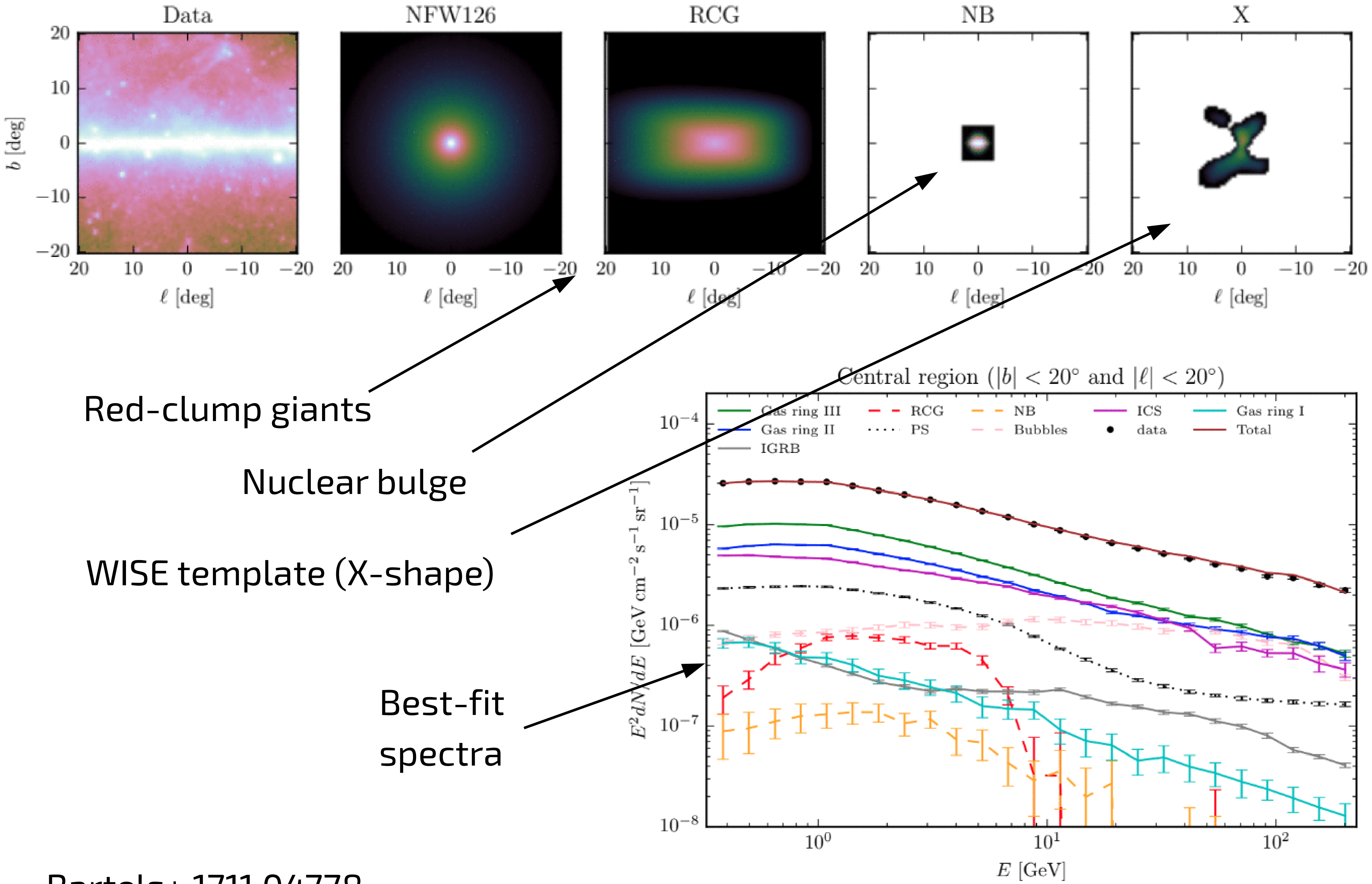
Ackermann+ 17

- Low-latitude part of Fermi bubbles is not well studied
- However, a MSP component + bubble component (hard spectrum) decomposition is possible
- Suggests strongly enhanced HE emission in the inner few degrees
- ICS from star formation?
- However, statistically not very significant, hard to study





The morphology of the GeV excess



Red-clump giants

Nuclear bulge

WISE template (X-shape)

Best-fit spectra

Bartels+ 1711.04778

Beyond Poissonian noise

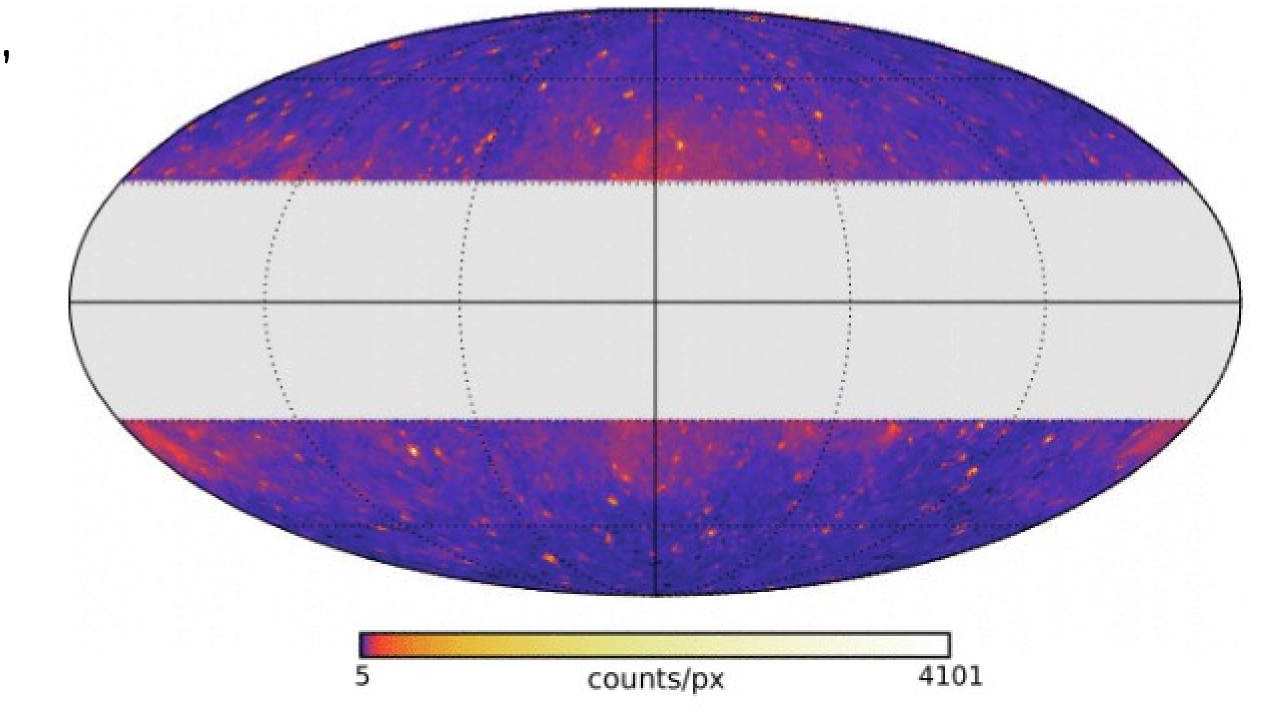
1-point statistics: Extragalactic background

Discrete probability distribution, given by generating function.

$$p_k^{(p)} = \frac{1}{k!} \frac{d^k \mathcal{P}^{(p)}(t)}{dt^k} \bigg|_{t=0}$$

Can be expressed in terms of source probabilities

$$\mathcal{P}^{(p)}(t) = \exp\left[\sum_{m=1}^{\infty} x_m^{(p)} (t^m - 1)\right]$$



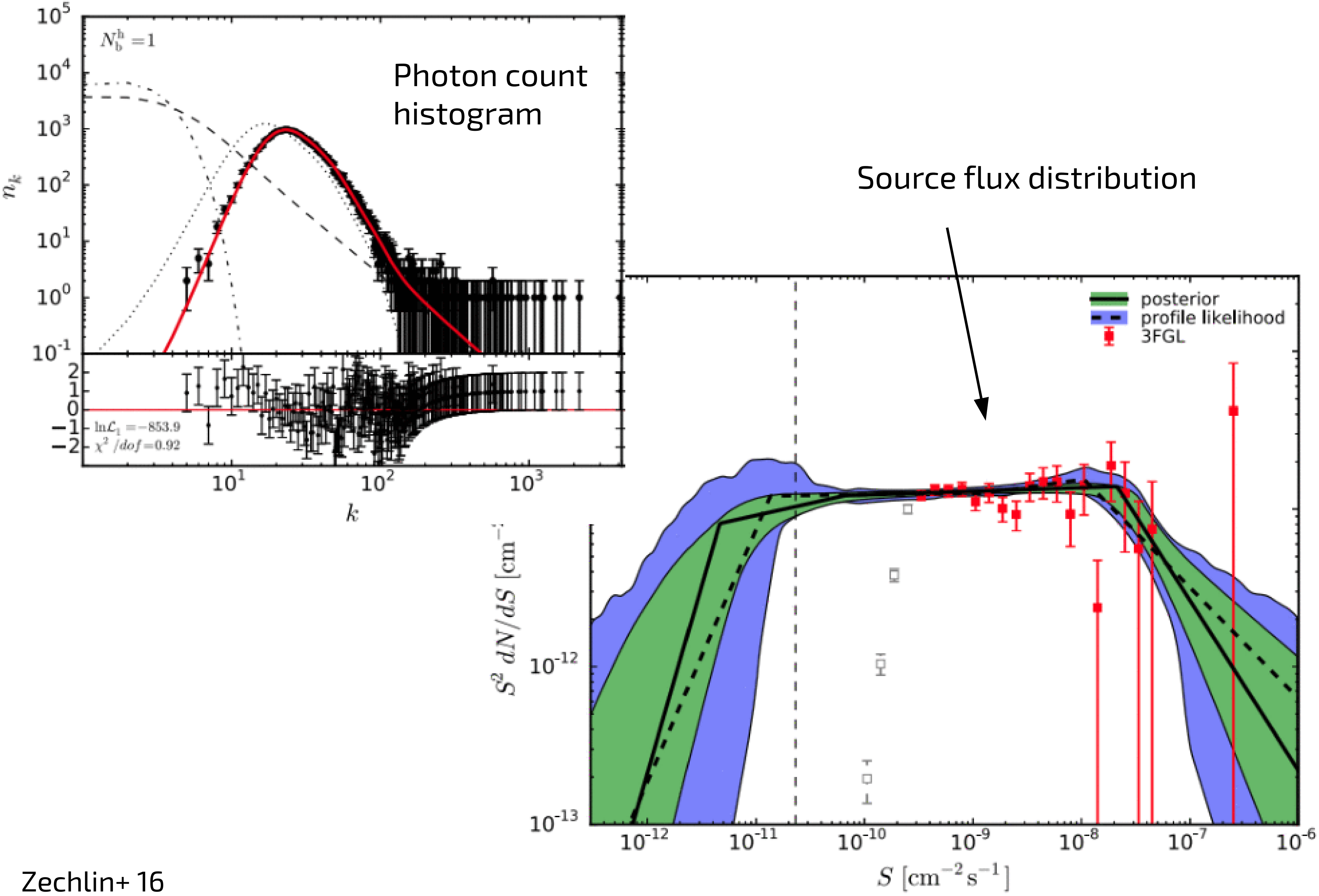
Flux distribution of extragalactic sources

$$\frac{dN}{dS} \propto \begin{cases} \left(\frac{S}{S_0}\right)^{-n_1}, & S > S_{\mathrm{b1}} \\ \left(\frac{S_{\mathrm{b1}}}{S_0}\right)^{-n_1+n_2} \left(\frac{S}{S_0}\right)^{-n_2}, & S_{\mathrm{b2}} < S \leqslant S_{\mathrm{b1}} \\ \vdots & \vdots \\ \left(\frac{S_{\mathrm{b1}}}{S_0}\right)^{-n_1+n_2} \left(\frac{S_{\mathrm{b2}}}{S_0}\right)^{-n_2+n_3} \cdots \left(\frac{S}{S_0}\right)^{-n_{N_{\mathrm{b}}+1}}, & S \leqslant S_{\mathrm{bN_b}} \end{cases}$$

$$\mathcal{L}_2(\Theta) = \prod_{p=1}^{N_{\mathrm{pix}}} P(k_p)$$

Zechlin+ 16

1-point statistics: Extragalactic background

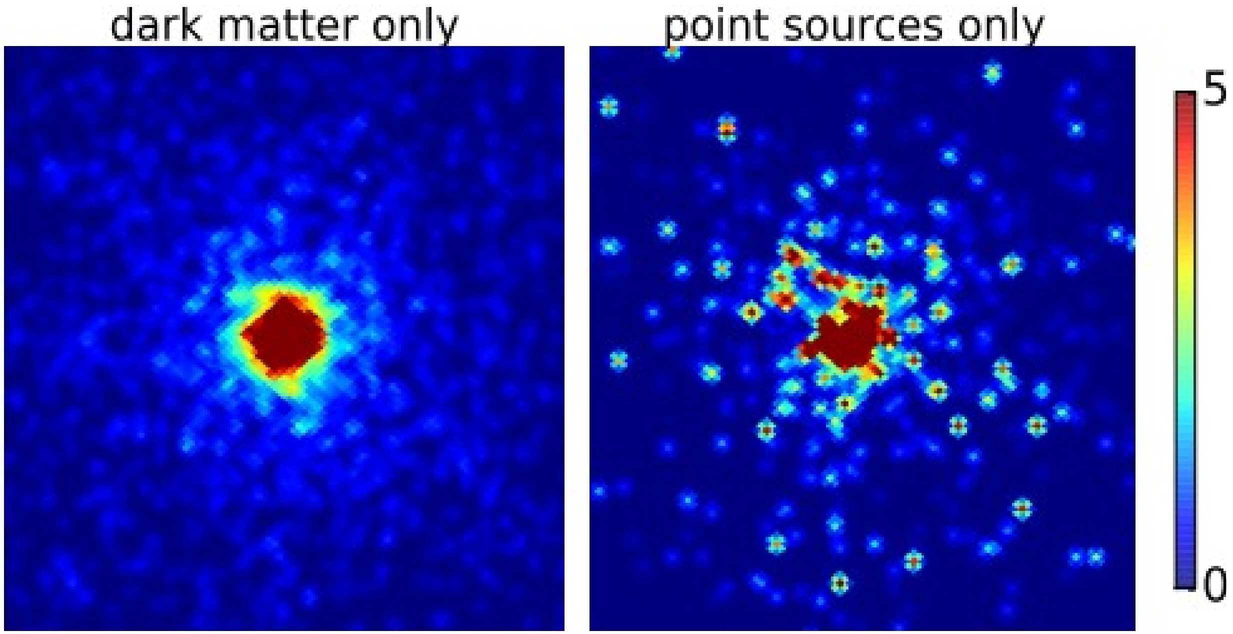

Photon count histogram

Source flux distribution

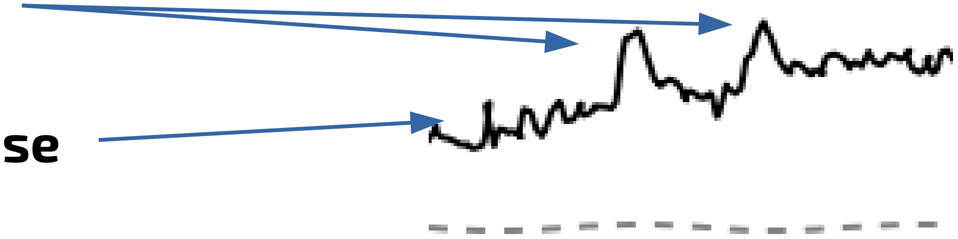
Zechlin+ 16

Fluctuation analyses: Fermi GeV excess

A signal composed of point sources would appear more “speckled” than a purely diffuse signal (like from DM annihilation)



(Credit: Lee+ 2014)



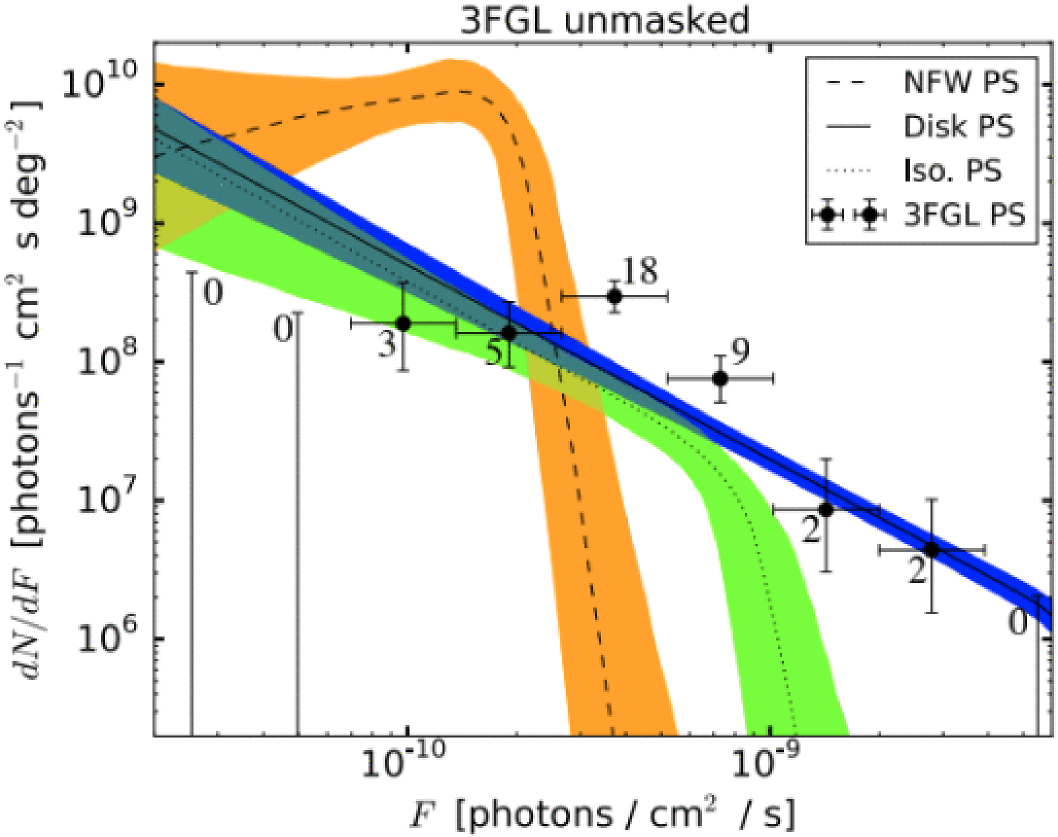
Find **peaks**

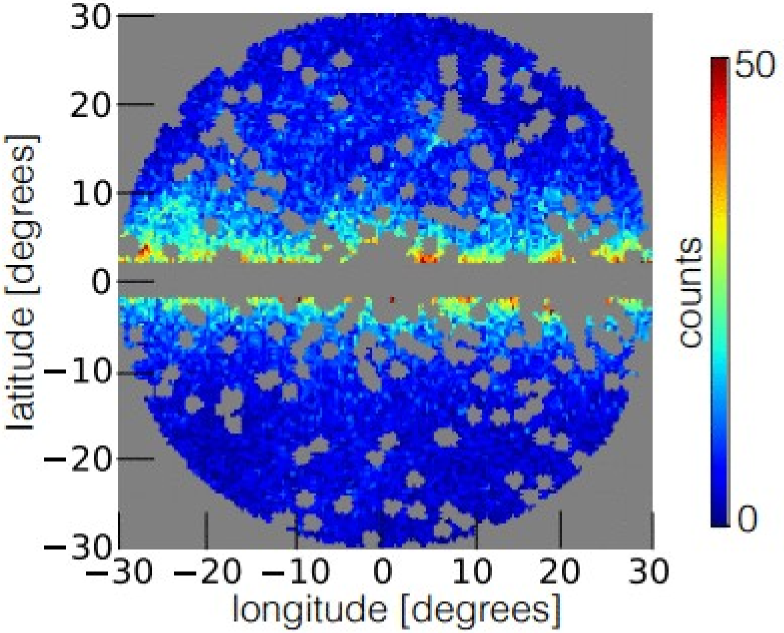
on top of

Poisson noise

See Lee+16 for an analysis using non-Poissonian noise

Non-Poissonian template fit analysis



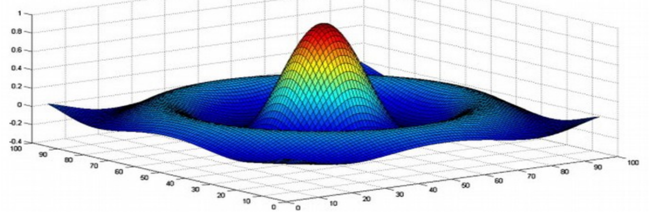


→ Strong indications for sub-threshold source distribution in the inner Galaxy, compatible with morphology of the Fermi GeV excess

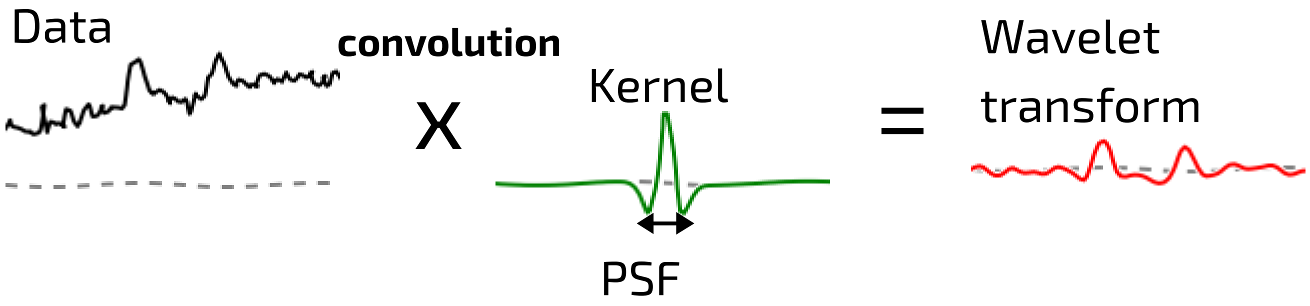
Lee+ 16

Wavelet transform to filter out point sources

Mexican hat wavelet



Credit:
https://www.researchgate.net



Data

convolution

X

Kernel

PSF

=

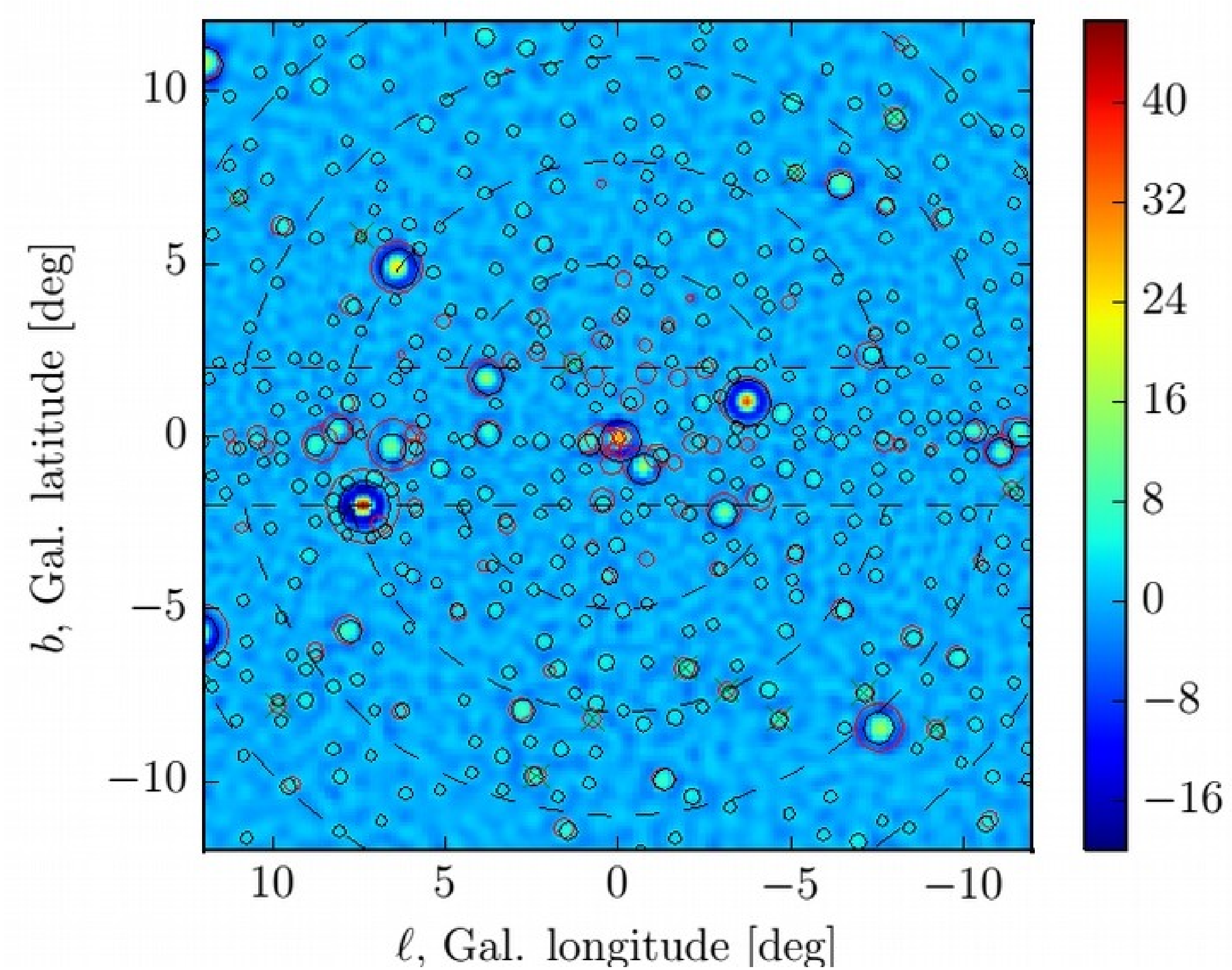
Wavelet
transform

Wavelet approach is robust and simple

- No background modeling required for wavelet analysis (separation of scales!!!)
- Build-in source localization
- Extremely fast (allowed careful Monte Carlo tests of the results)

Bartels+ 15

Wavelet transform of inner Galaxy data



MSP model used in Monte Carlo

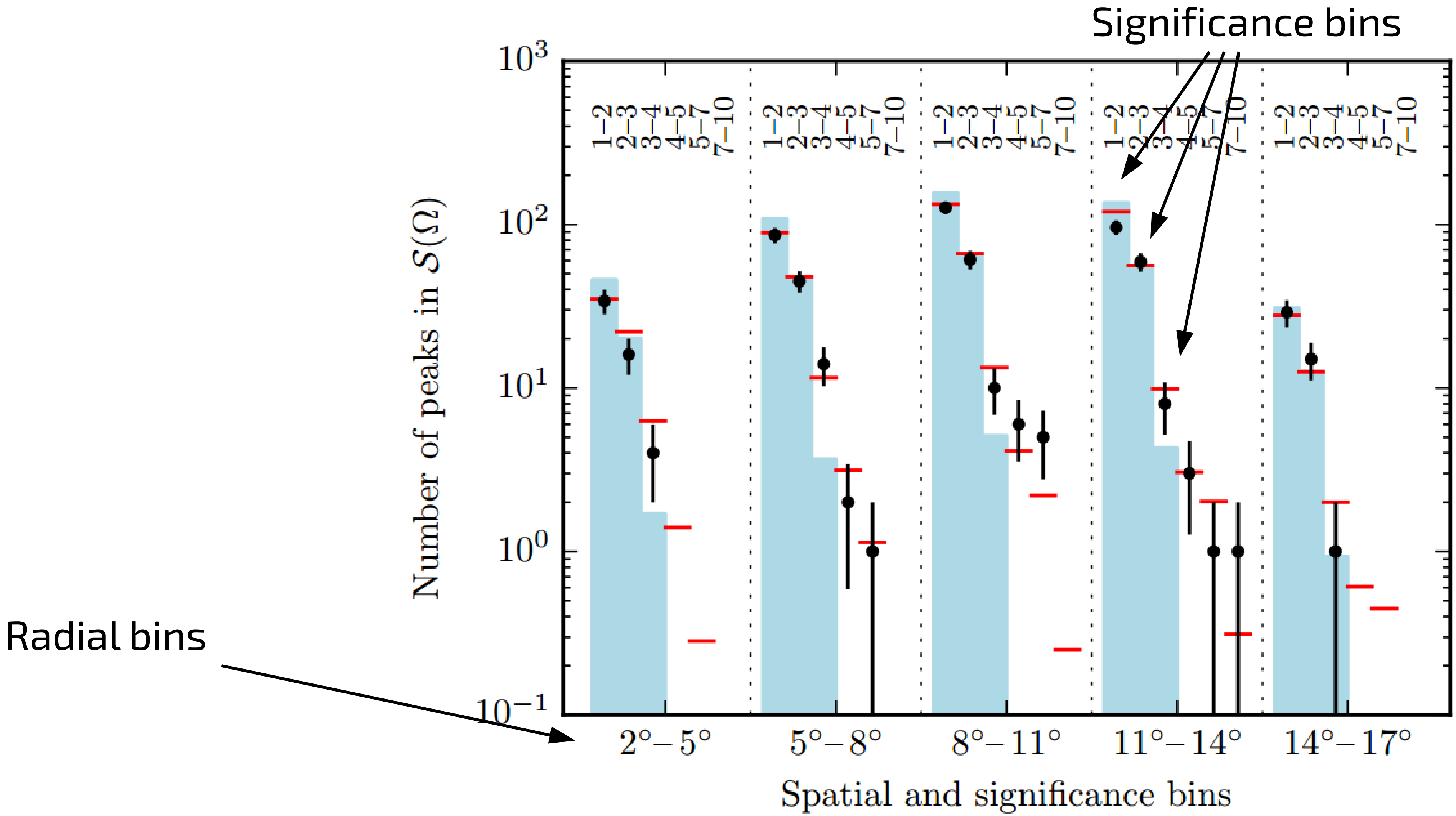
$$\frac{dN_{\rm MSP}}{dV\,dL} \propto \frac{\mathcal{N}}{r^{2.5}}\frac{\theta(L_{\rm max}-L)}{L^{1.5}}$$

Free parameters

- Total number of sources *N*
- Cutoff luminosity L_{max}

1) Count peaks in different sky regions and bin them according to significance
2) Run MCs for different bulge population configurations
3) Compare using a Poisson likelihood
4) Study all kinds of systematics (foreground sources, gas fluctuations etc)

Histogram of wavelet transform peaks



We find

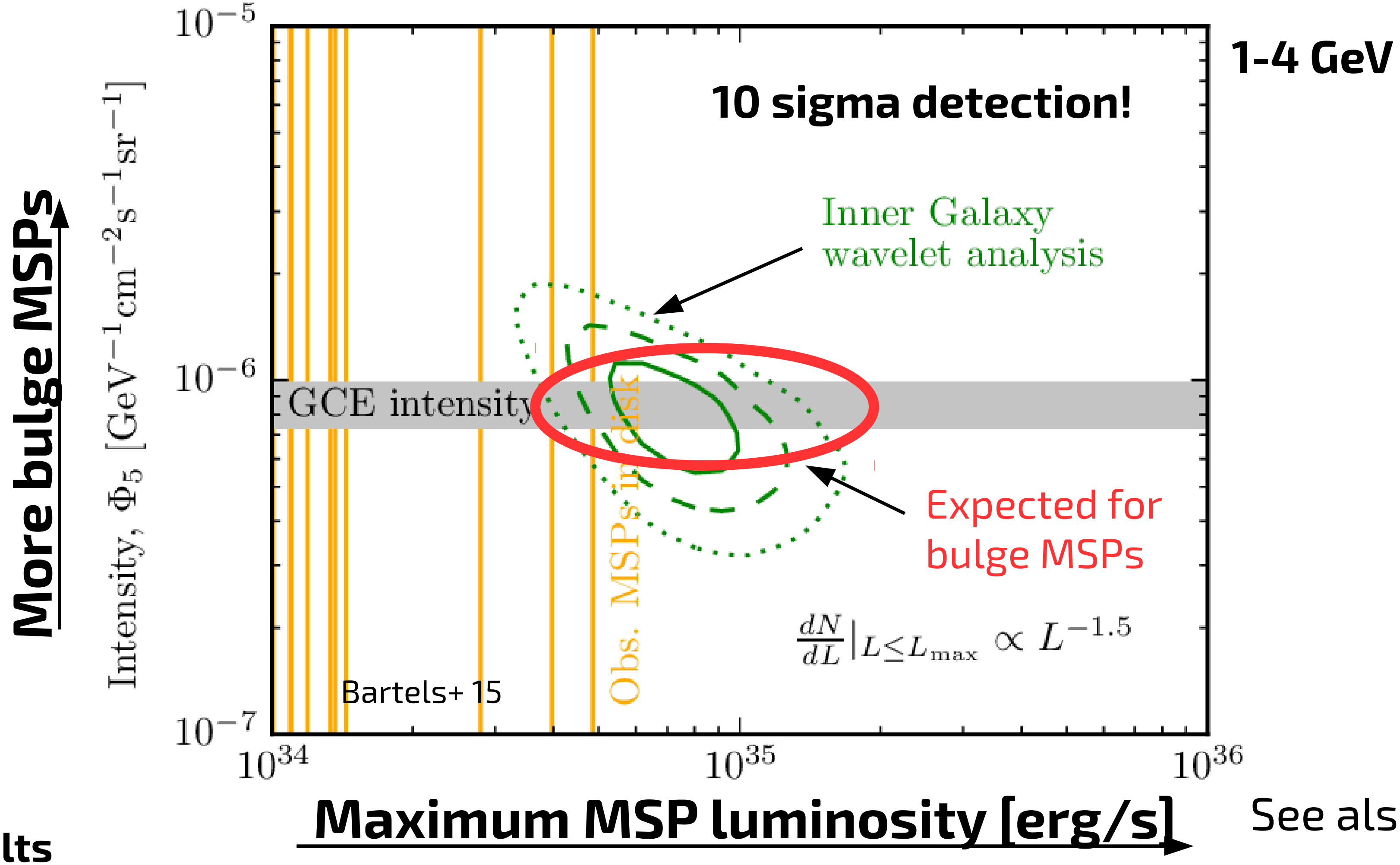
- Suppression at <2 sigma
- Excesses at >3 sigma

Blue bars: Null hypothesis (diffuse only emission)

Black: Measured data

Red: best fit model with PSC population in bulge

Strong support for MSP hypothesis



See also Lee+15

Results

- For a luminosity function index around 1.5, a MSP population with the best-fit normalization would reproduce 100% of the excess emission
- The best-fit cutoff luminosity is compatible with gamma-ray emission from detected nearby MSPs (beware of large uncertainties due to uncertainties in the distance measure, Petrovic+ 2014, Brandt & Kocsis 2015)

Planned radio searches for bulge MSPs

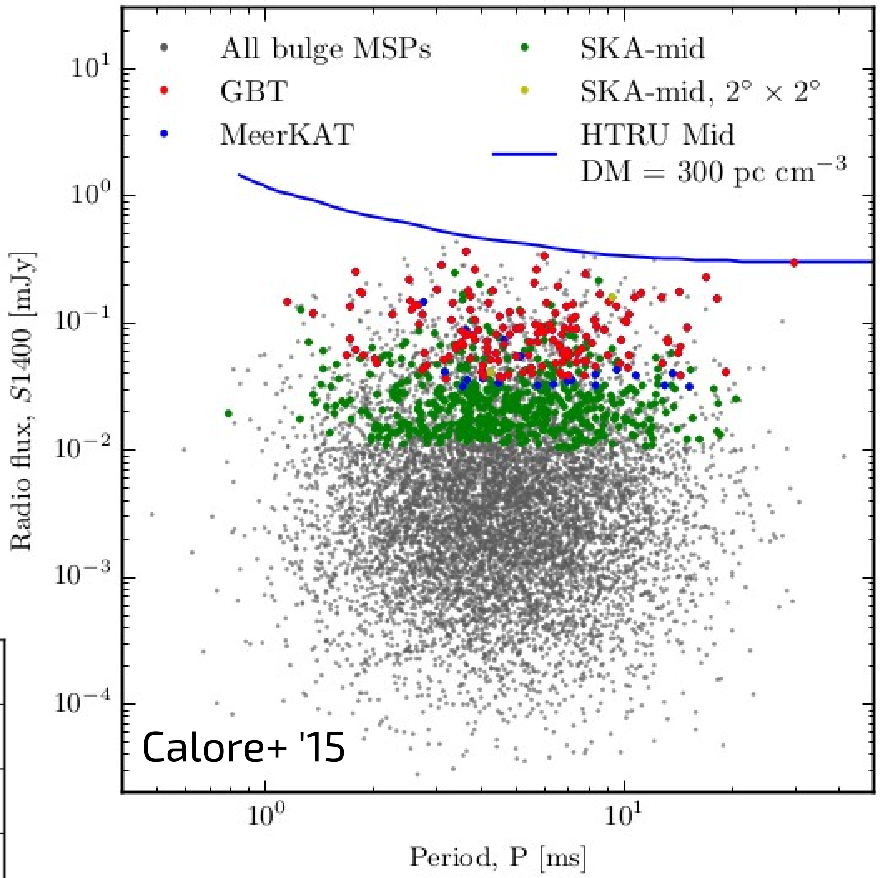
Radio detection prospects (Calore+ '15)

(Bulge population is just below sensitivity of Parkes HTRU mid-lat survey)

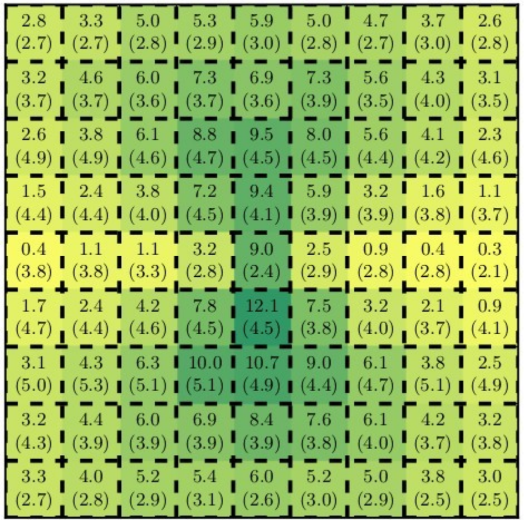
- GBT targeted searches ~100h: ~3 bulge MSPs
- MeerKAT mid-lat survey ~300h: ~30 bulge MSPs

Our plans for the near future

- We teamed up with MeerKAT TRAPUM → plans for dedicated survey in ~2019!

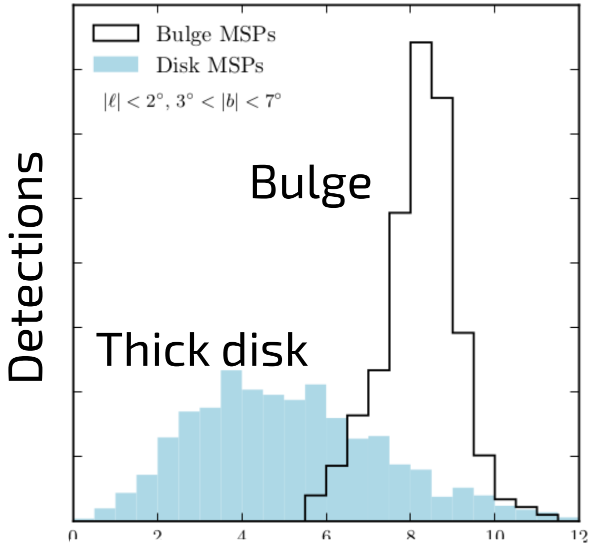


$18^\circ \times 18^\circ$



2.8 (2.7)	3.3 (2.7)	5.0 (2.8)	5.3 (2.9)	5.9 (3.0)	5.0 (2.8)	4.7 (2.7)	3.7 (3.0)	2.6 (2.8)
3.2 (3.7)	4.6 (3.7)	6.0 (3.6)	7.3 (3.7)	6.9 (3.6)	7.3 (3.9)	5.6 (3.5)	4.3 (4.0)	3.1 (3.5)
2.6 (4.9)	3.8 (4.9)	6.1 (4.6)	8.8 (4.7)	9.5 (4.5)	8.0 (4.5)	5.6 (4.4)	4.1 (4.2)	2.3 (4.6)
1.5 (4.4)	2.4 (4.4)	3.8 (4.0)	7.2 (4.5)	9.4 (4.1)	5.9 (3.9)	3.2 (3.9)	1.6 (3.8)	1.1 (3.7)
0.4 (3.8)	1.1 (3.8)	1.1 (3.3)	3.2 (2.8)	9.0 (2.4)	2.5 (2.9)	0.9 (2.8)	0.4 (2.8)	0.3 (2.1)
1.7 (4.7)	2.4 (4.4)	4.2 (4.6)	7.8 (4.5)	12.1 (4.5)	7.5 (3.8)	3.2 (4.0)	2.1 (3.7)	0.9 (4.1)
3.1 (5.0)	4.3 (5.3)	6.3 (5.1)	10.0 (5.1)	10.7 (4.9)	9.0 (4.4)	6.1 (4.7)	3.8 (5.1)	2.5 (4.9)
3.2 (4.3)	4.4 (3.9)	6.0 (3.9)	6.9 (3.9)	8.4 (3.9)	7.6 (3.8)	6.1 (4.0)	4.2 (3.7)	3.2 (3.8)
3.3 (2.7)	4.0 (2.8)	5.2 (2.9)	5.4 (3.1)	6.0 (2.6)	5.2 (3.0)	5.0 (2.9)	3.8 (2.5)	3.0 (2.5)

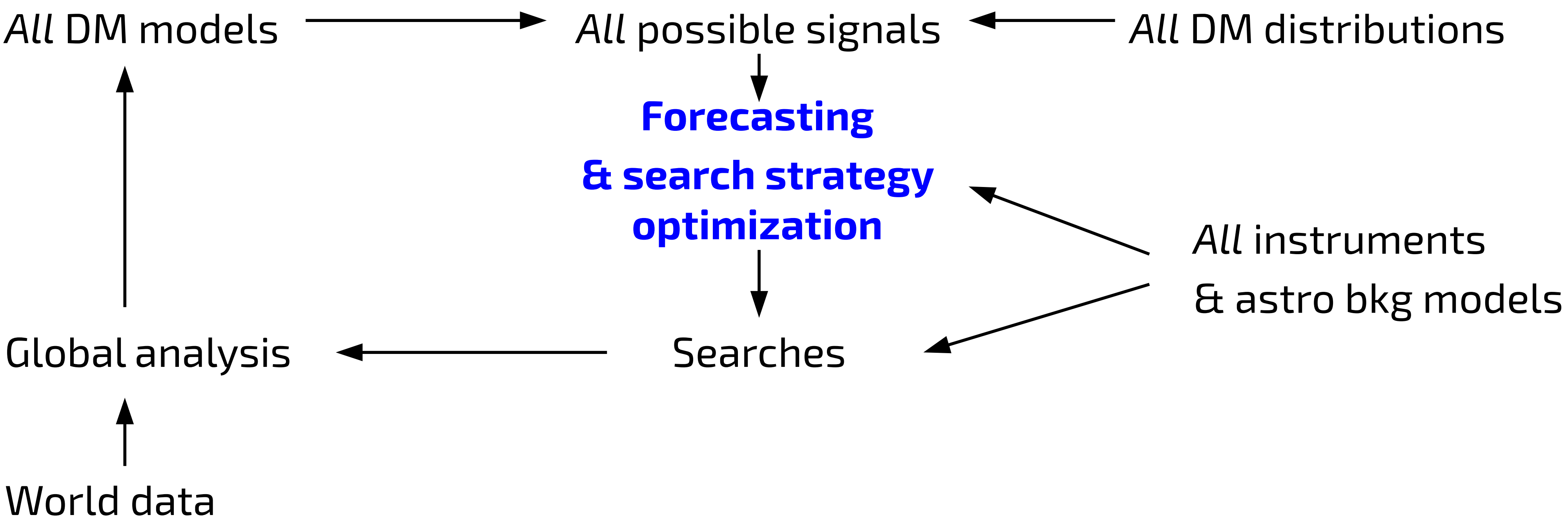
(SKA)



Distance (from dispersion measure)

Outlook

The forecasting bottle beck



All DM models

All possible signals

All DM distributions

Forecasting

& search strategy optimization

All instruments

& astro bkg models

Global analysis

Searches

World data

Problem:

- How to identify minimum set of necessary searches to cover *all* possible DM models?
- How to make forecasting easy and informative?

Solution:

- Fisher forecasting on the rocks

S/N + systematics = Information flux

Poisson model with background uncertainties

(uncertainties described by Gaussian random field)

Edwards & CW
1704.05458

$$\mu_i(\boldsymbol{\theta}) = (S_i(\boldsymbol{\theta}) + B_i + \delta B_i) \cdot E_i$$

Fisher information

(accounts for background uncertainties)

$$\mathcal{I} \sim \frac{1}{\sigma^2}$$

Information flux

(derivative w.r.t. exposure per bin)

$$\mathcal{F}_i \equiv \frac{\partial \mathcal{I}}{\partial E_i}$$

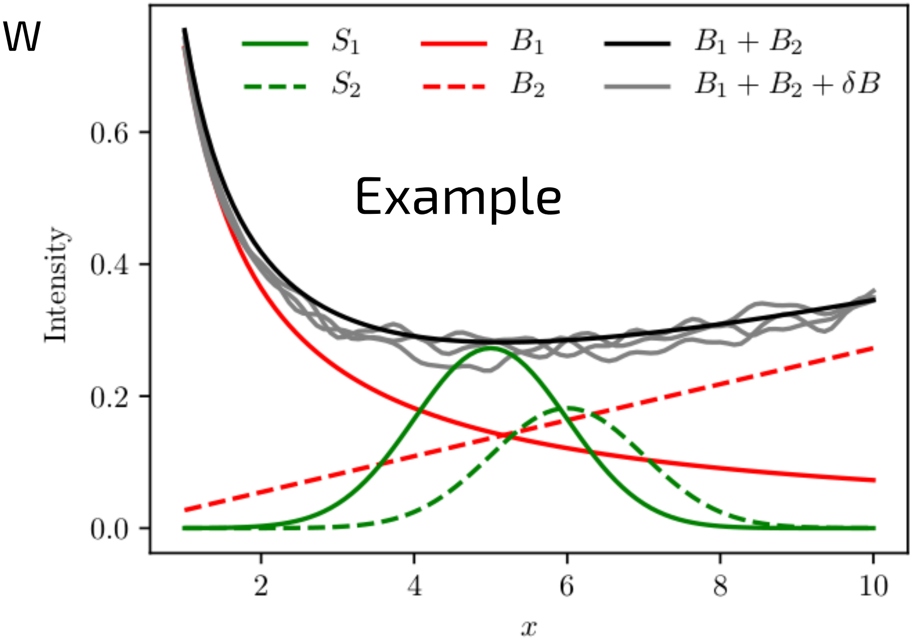
Stats. only

In general

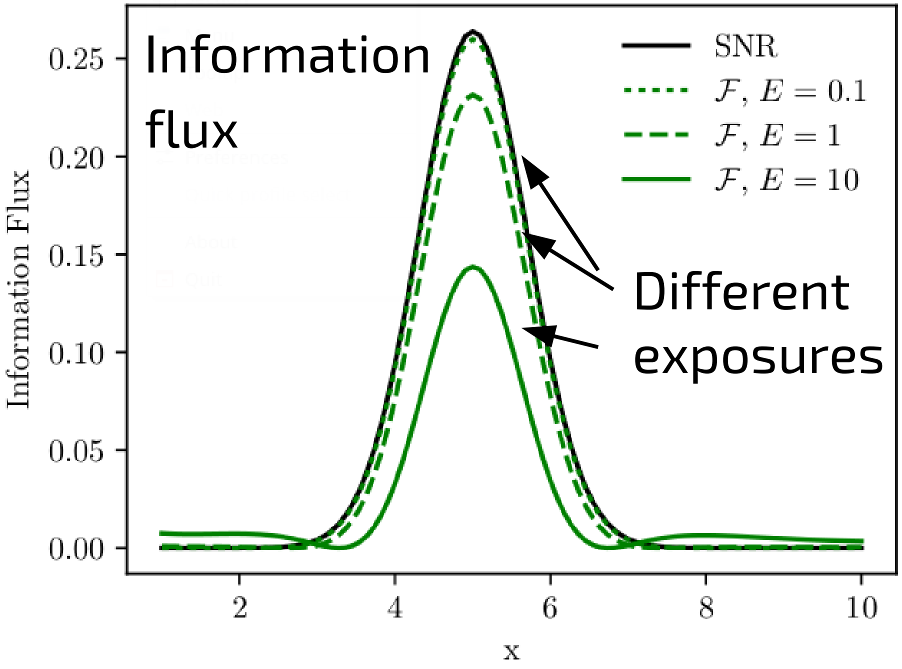
$$\mathcal{F}_i = \frac{S_i^2}{B_i}$$

(common **signal-to-noise** ratio)

$$\mathcal{F}_i = \mathcal{F}_i(\mathbf{S}, \mathbf{B}, K)$$



Example



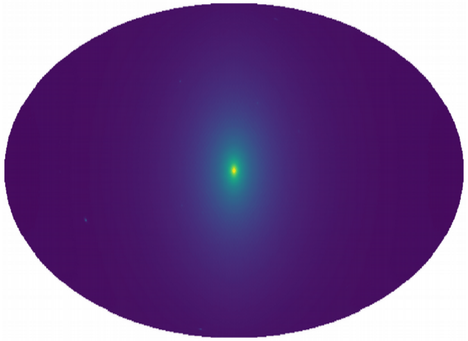
Information flux

Different exposures

Dark information flux – DM annihilation

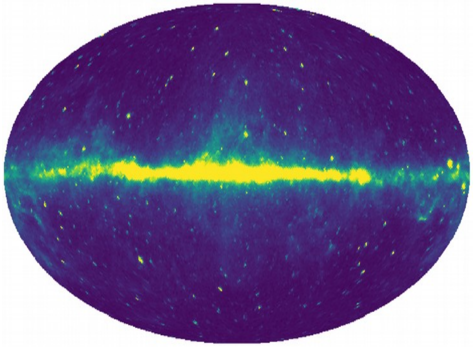
A toy example: Galactic halo vs nearby galaxies

DM signal



Galactic halo dominates

Background



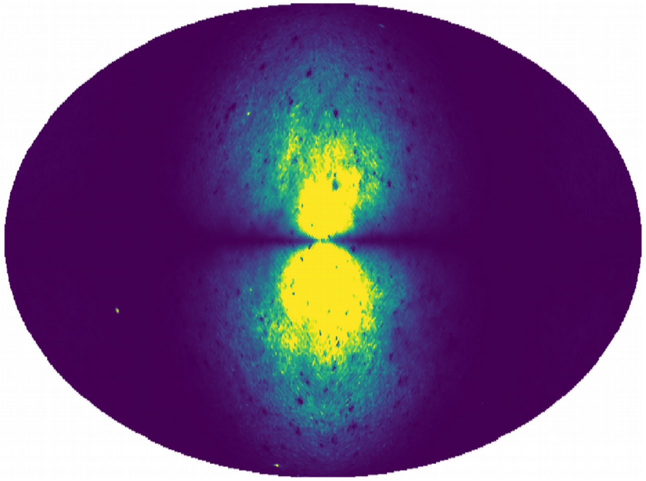
Here: 10% with ~10 deg correlation length

Can be used to calculate

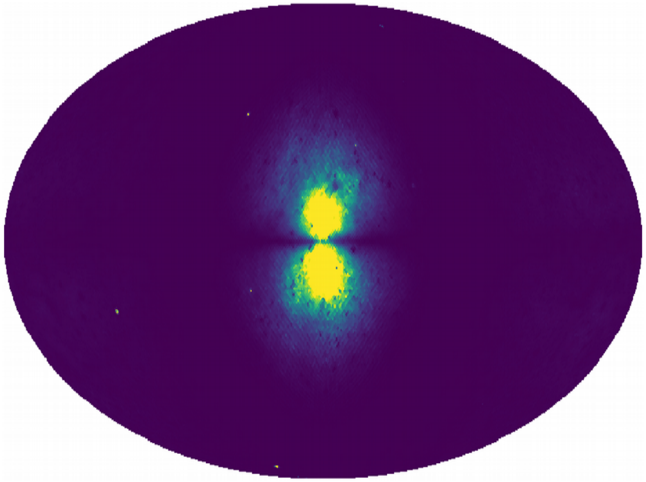
- projected upper limits
- discovery thresholds
- reconstruction contours
- in the Poissonian regime
- no Monte Carlos

M31 as relevant as GC

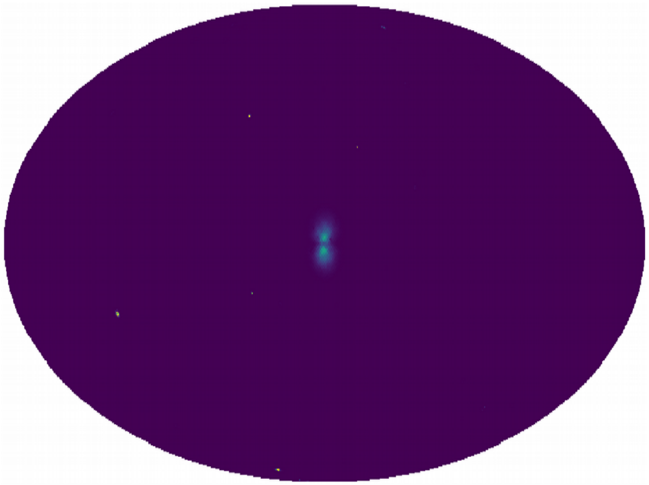
Statistics only



1/100 x Fermi LAT exposure



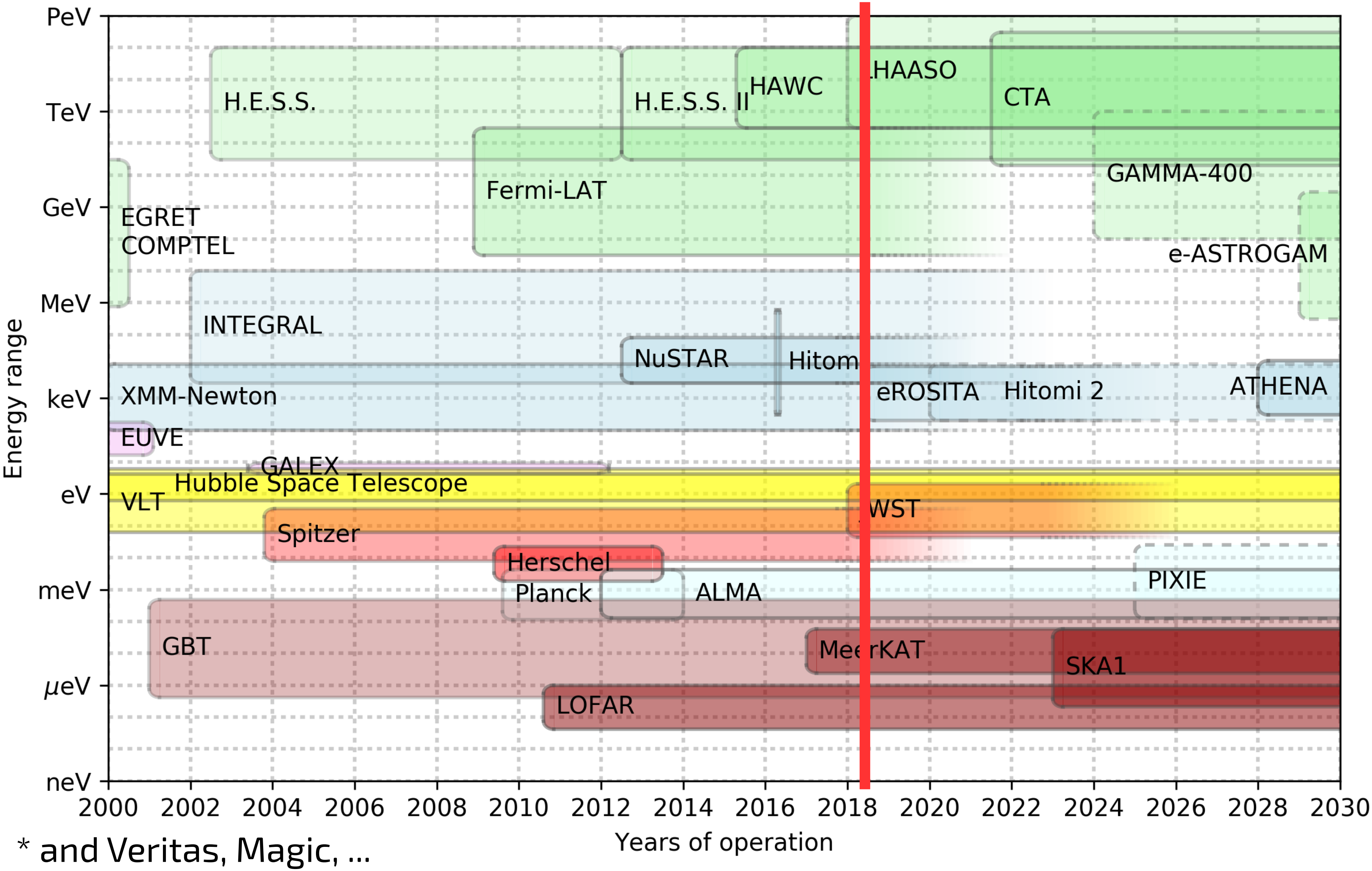
Fermi LAT exposure



Edwards & Weniger, 1712.05401

http://www.github.com/cweniger/swordfish

Conclusions



* and Veritas, Magic, …