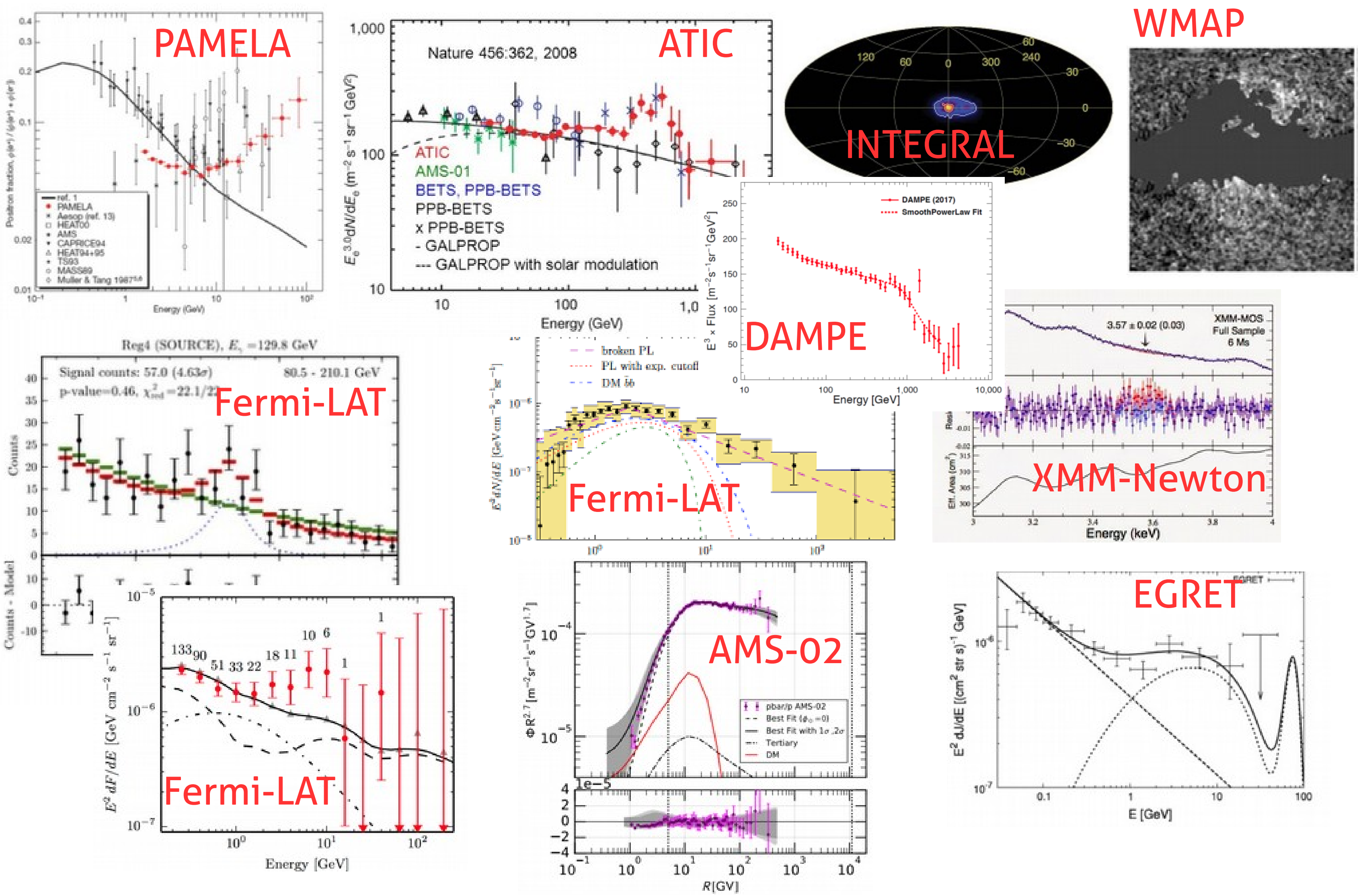
Can we trust an excess in indirect DM searches?

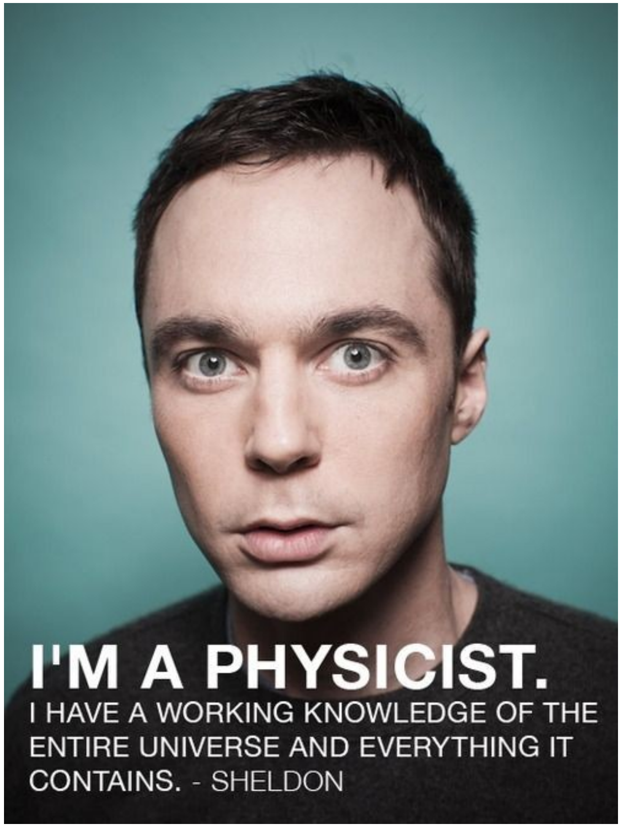


DM at the dawn of discovery?
11th April 2018

Christoph Weniger
University of Amsterdam

Indirect searches are never background free

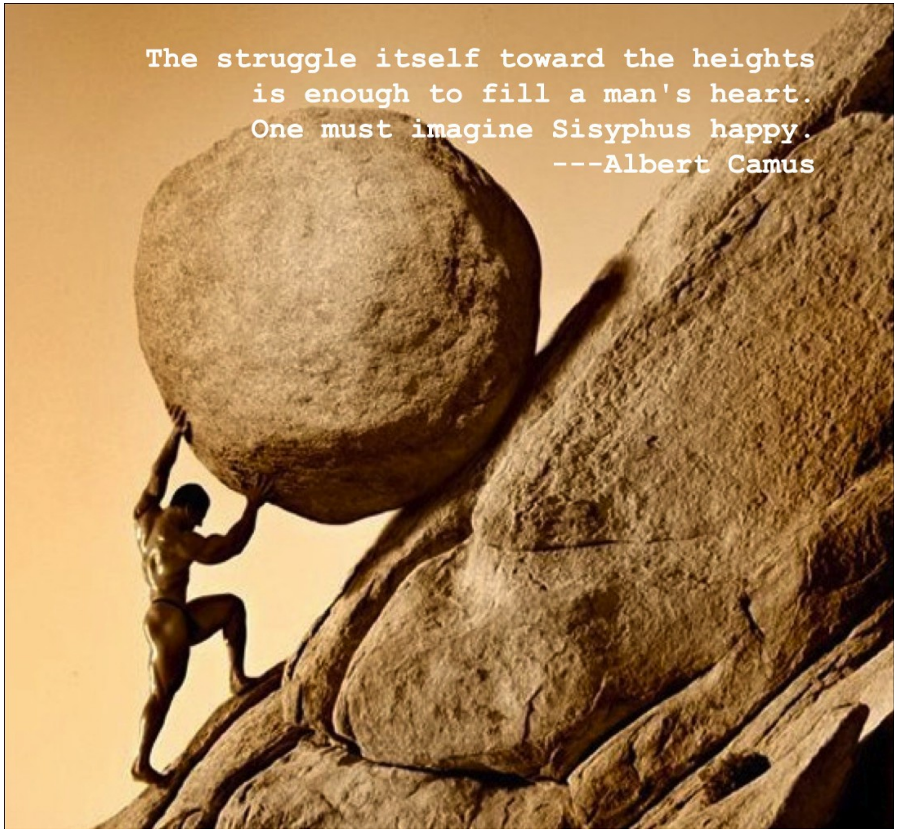
Fiction



Signal discovery strategy

- Predict SM contribution
- Subtract from data
- What is left is DM

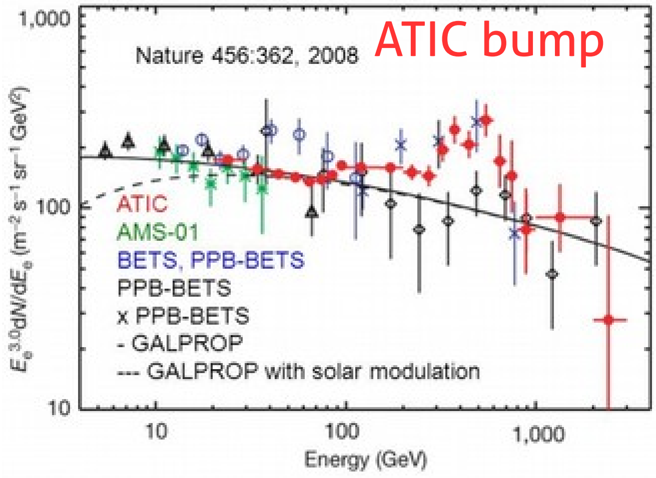
Reality



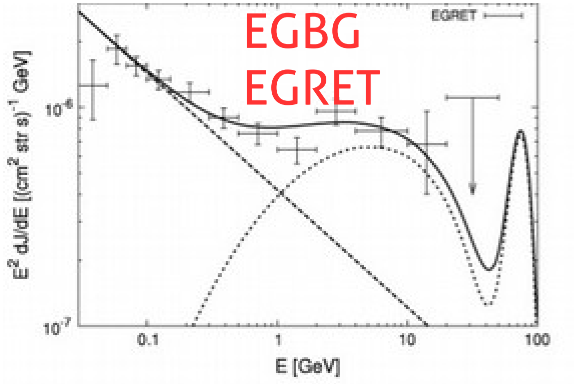
Signal discovery strategy

- Find DM-like excess above naive astro background
- Search for corroborating evidence
- Better understand astro backgrounds
- Converge against DM as only viable solution

Some excesses that went away

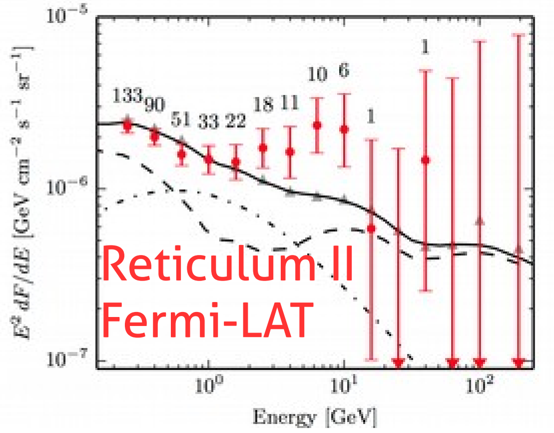


Electrons
ATIC bump



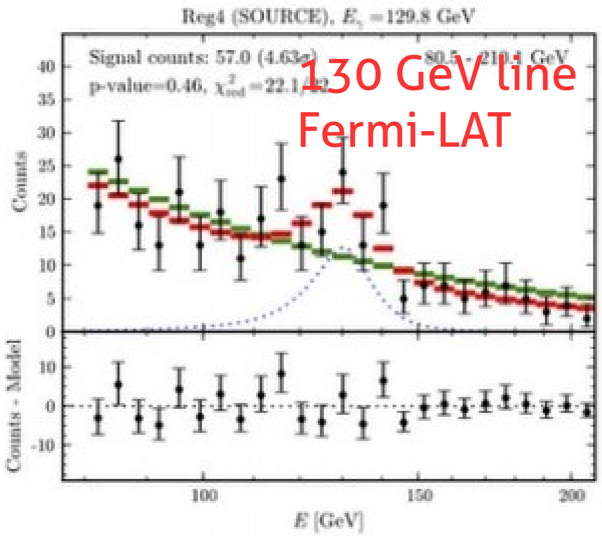
EGBG
EGRET

Strong+ 04; Ibarra & Tran 08; ...



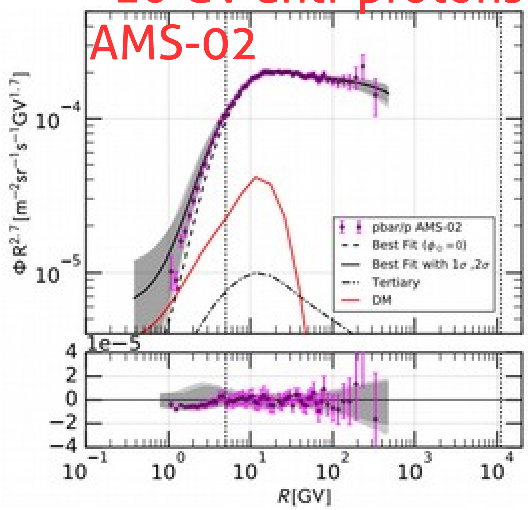
Reticulum II
Fermi-LAT

Geringer-Sameth+ 15; Zhao+ 17; ...



130 GeV line
Fermi-LAT

Bringmann+ 12, CW 12, Finkbeiner+ 12, ...



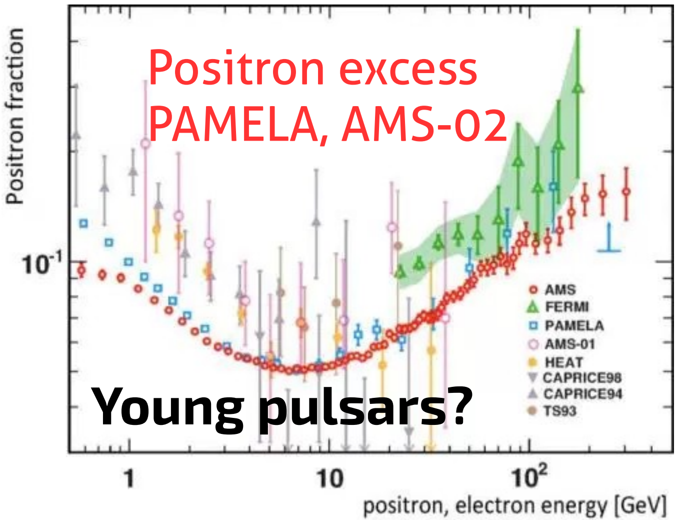
~10 GV anti-protons
AMS-02

Cuoco+ 16, Cui+ 16

Reinart & Winkler 17

Some excesses that stayed (as of today)

Positron excess
PAMELA, AMS-02



Young pulsars?

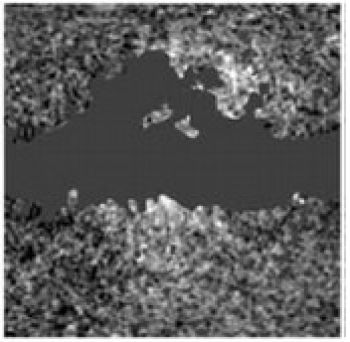
HAWC Geminga; Hooper & Linden 17; …

511 keV line
INTEGRAL

??

Knodelseder+ 05; Siegert+ 16; Beacom & Yuksel 06;

WMAP haze



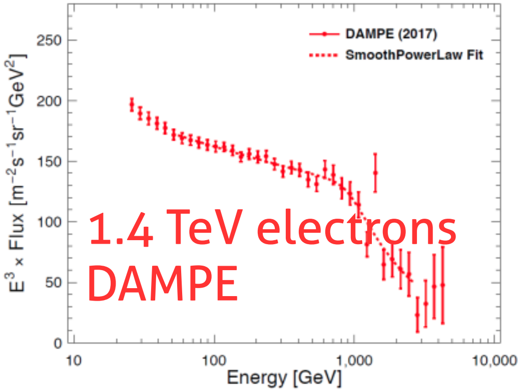
Dobler+; Slatyer, Su, Finkbeiner 10; …

Fermi bubbles?

NS/BH-UCXB?
Bartels+ 18

Stat. Fluke?

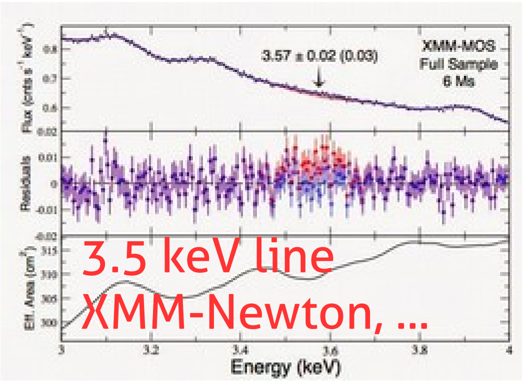
1.4 TeV electrons
DAMPE



DAMPE 17; Fowlie 17 (2.3 sigma, not seen by other experiments)

Charge exchange?

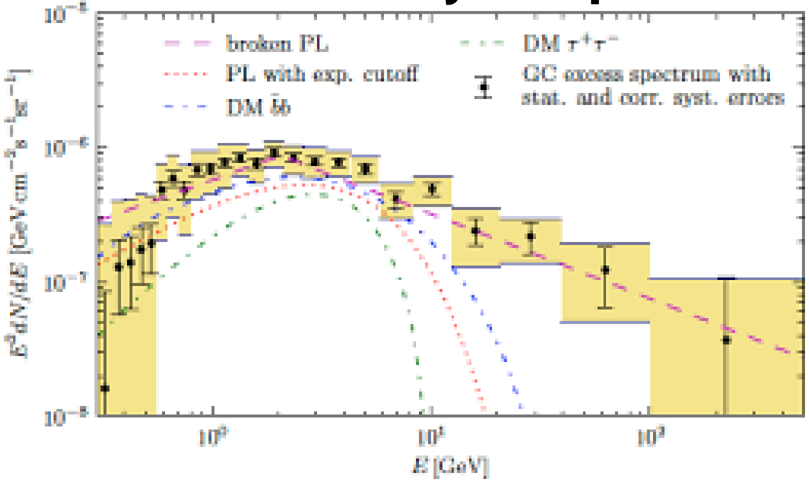
3.5 keV line
XMM-Newton, …



Bulbul+ 14; Boyarsky+ 14; Hitomi coll 16; …

Galactic center excess
Fermi-LAT

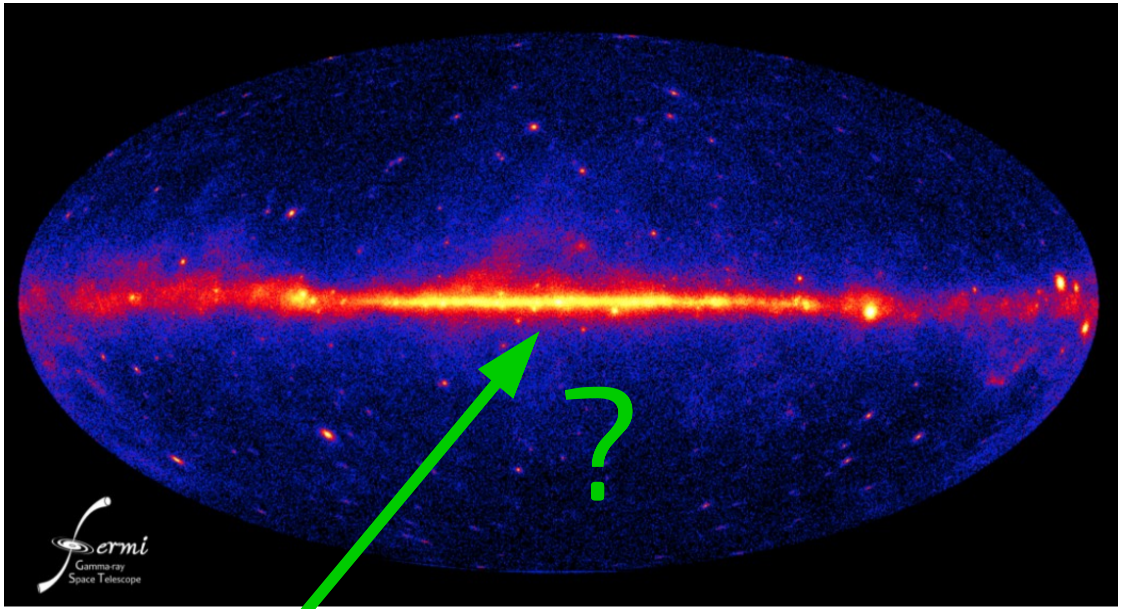
Recycled pulsars?

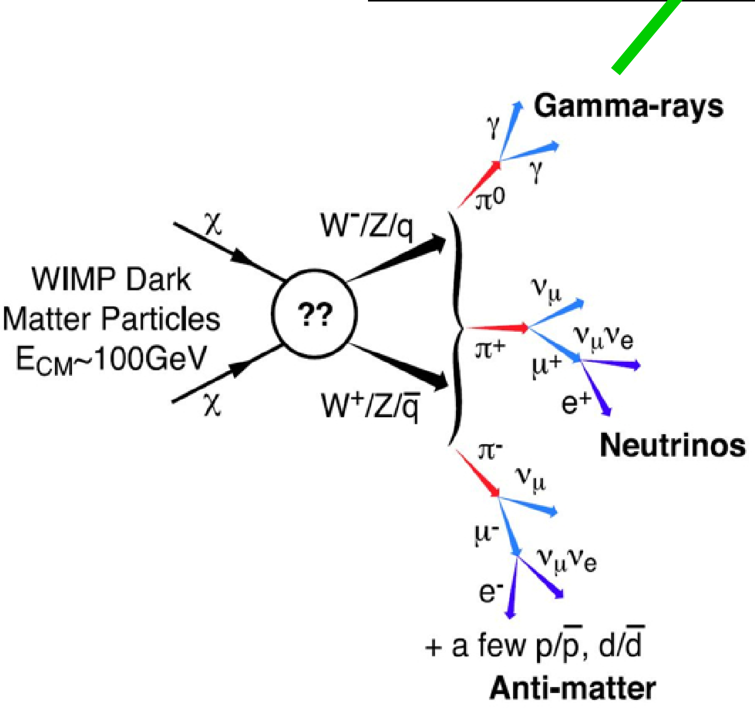


The Fermi GeV excess

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 from 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

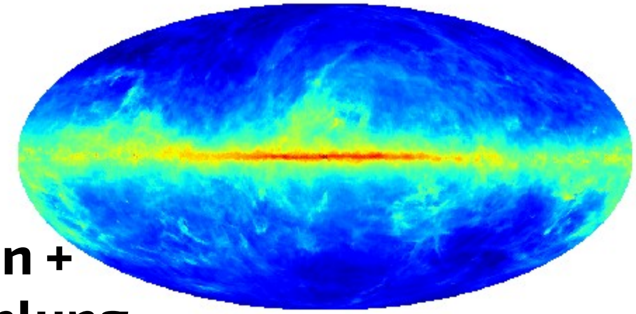
- **Papers that looked at data**
- Goodenough & Hooper, arXiv:0910.2998
- Vitale & Morselli, 2009
- Hooper & Goodenough, Phys. Lett. B697 (2011) 412
- Hooper & Linden, Phys. Rev. D84 (2011) 123005
- Boyarsky, Malyshev & Ruchayskiy, Phys. Lett. B705 (2011) 165
- Abazajian & Kaplinghat, PRD 86 (2012) 083511
- 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

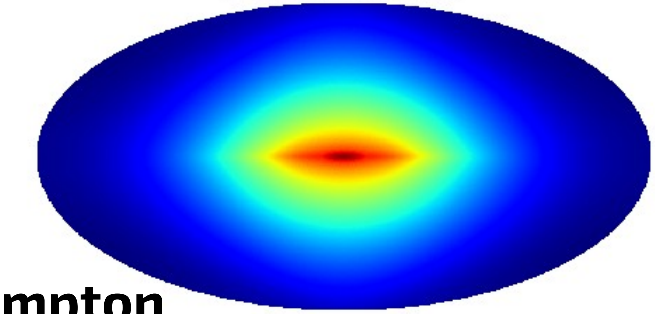
+ hundreds of DM theory papers

Method 1) Template regression



Neutral pion + Bremsstrahlung

+

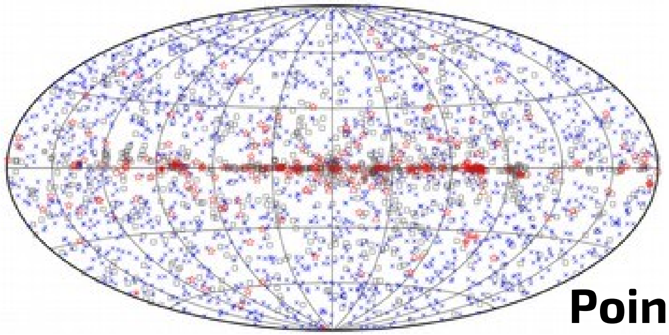


Inverse Compton

+

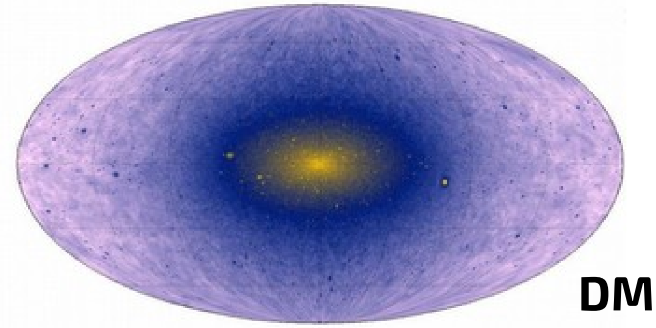
Fermi bubbles, isotropic background, Loop I, Earth limb, Sun, …

+



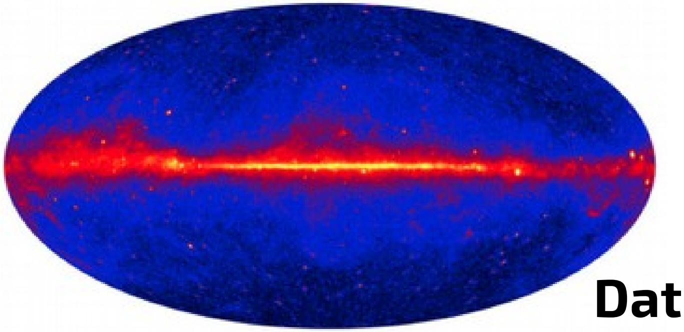
Point sources

+



DM signal

=



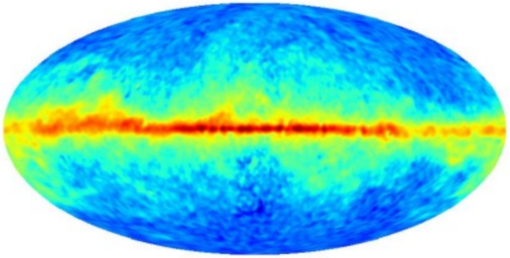
Data

Free parameters: $N_{\text{params}} = N_{\text{ebins}} \times N_{\text{comp}}$

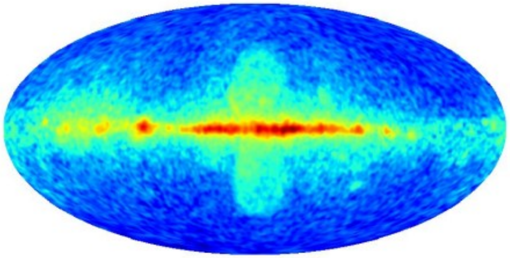
Method 2) Spectral decomposition

Huang+ 2015 (using D3PO)

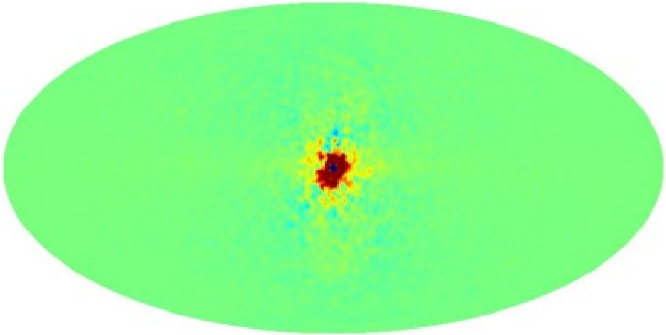
“Cloud-like” component



“Bubble-like” component



“DM-like” component

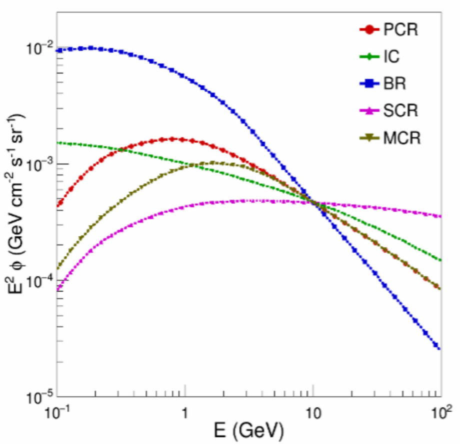


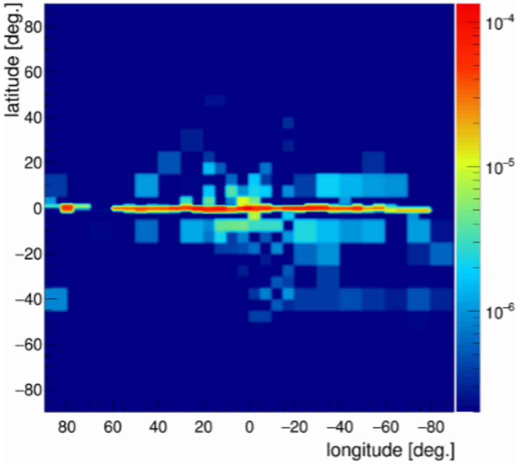
Pixel-by-pixel spectral decomposition:

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

But: other spectra lead to different results

De Boer, Gebauer, et al. 2016





Accounting for systematics with SkyFACT

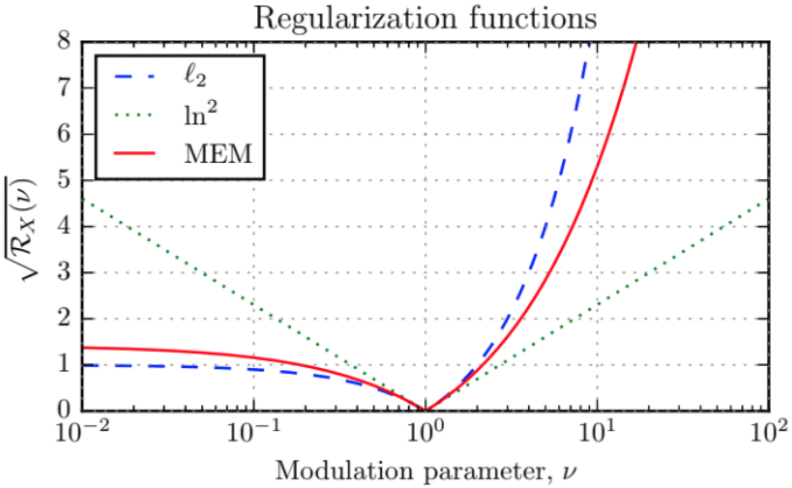
SkyFACT (**S**ky **F**actorization with **A**daptive **C**onstrained **T**emplates)

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

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

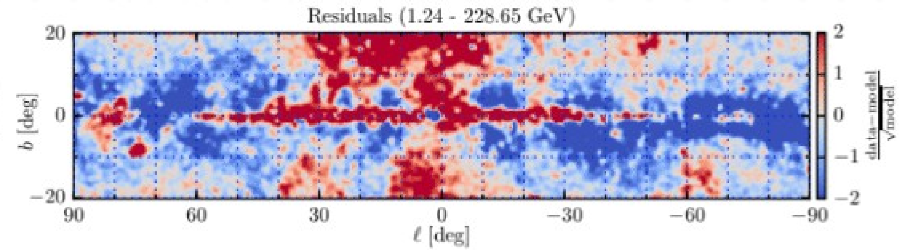
$$+ \sum_s \lambda'_s \mathcal{R}_X(\boldsymbol{\sigma}^{(s)}) + \lambda''_s \mathcal{R}_X(\nu^{(s)}) + \eta'_s \mathcal{S}_2(\boldsymbol{\sigma}^{(s)}) \ ,$$

Notes

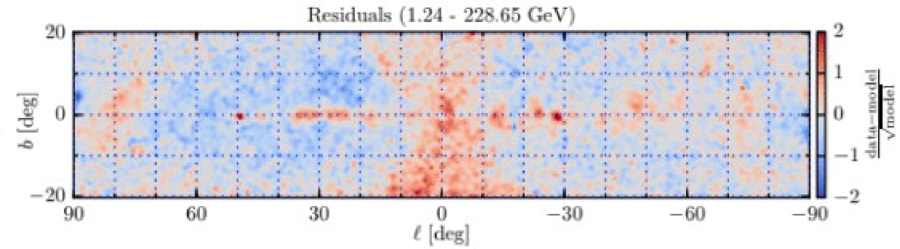
- Typically >10^5 parameters
- Problem typically convex → only one minimum

Storm, CW, Calore, 2017

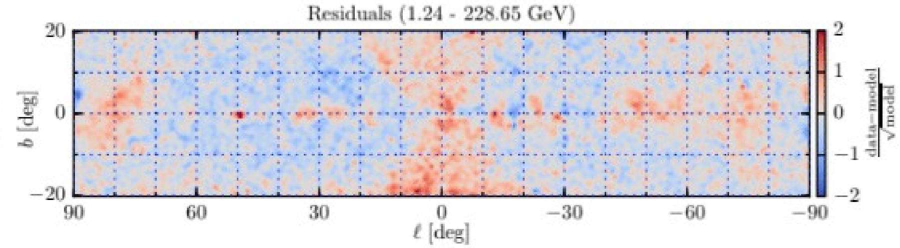
Residuals



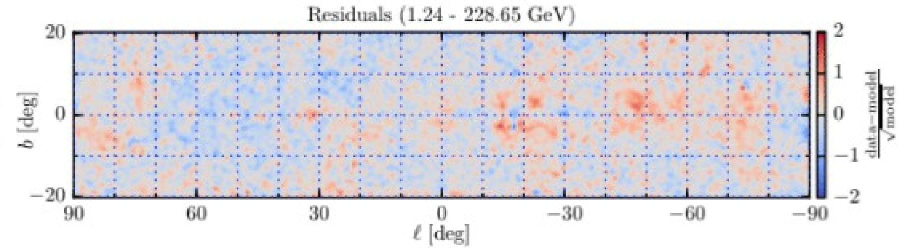
Baseline model



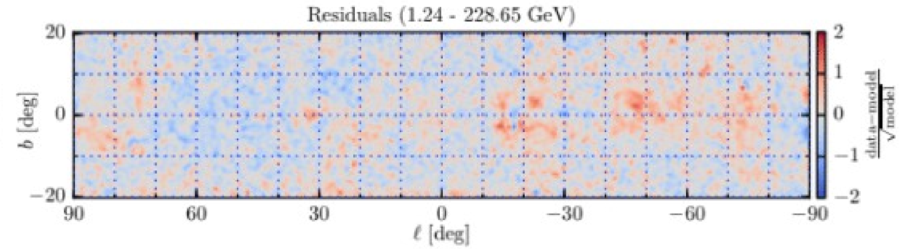
+ Nuisance parameters



+ Multiple rings



+ Fermi bubbles
+ Extended sources

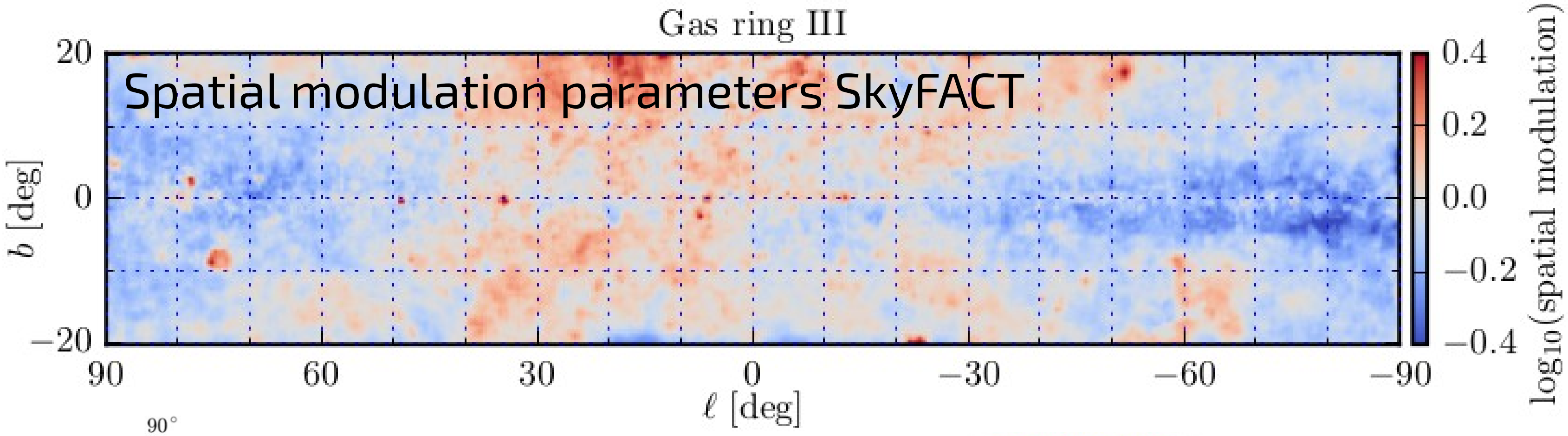


+ Galactic center excess

Nuisance parameters contain physics:
CR gradient, dark gas, extended sources, CMZ SF, ...

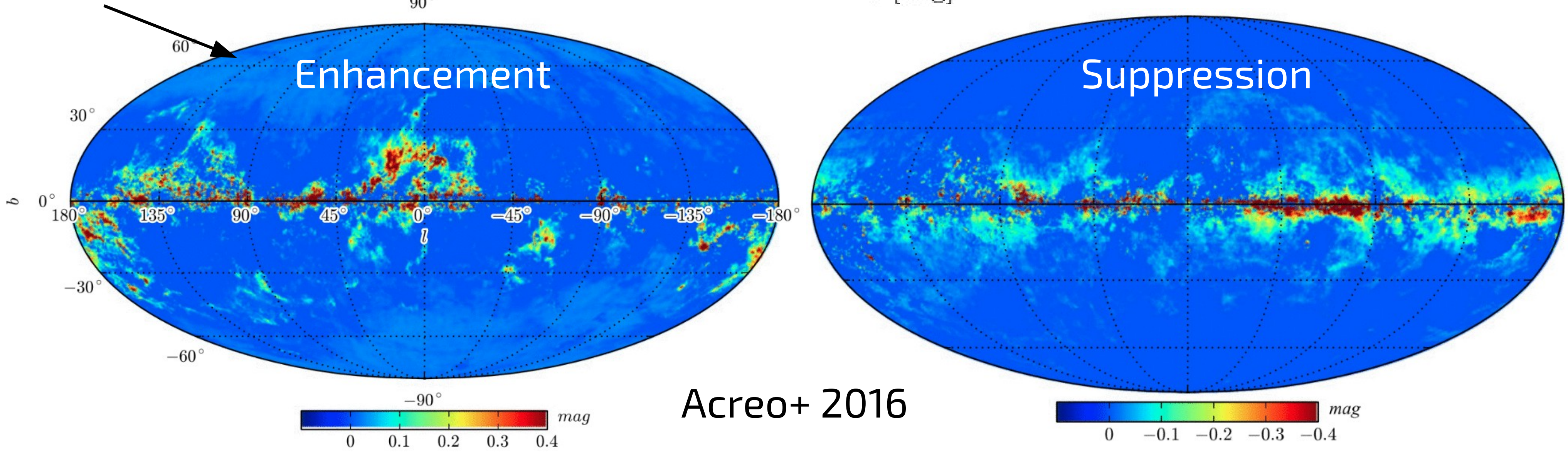
Dark gas corrections

- 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



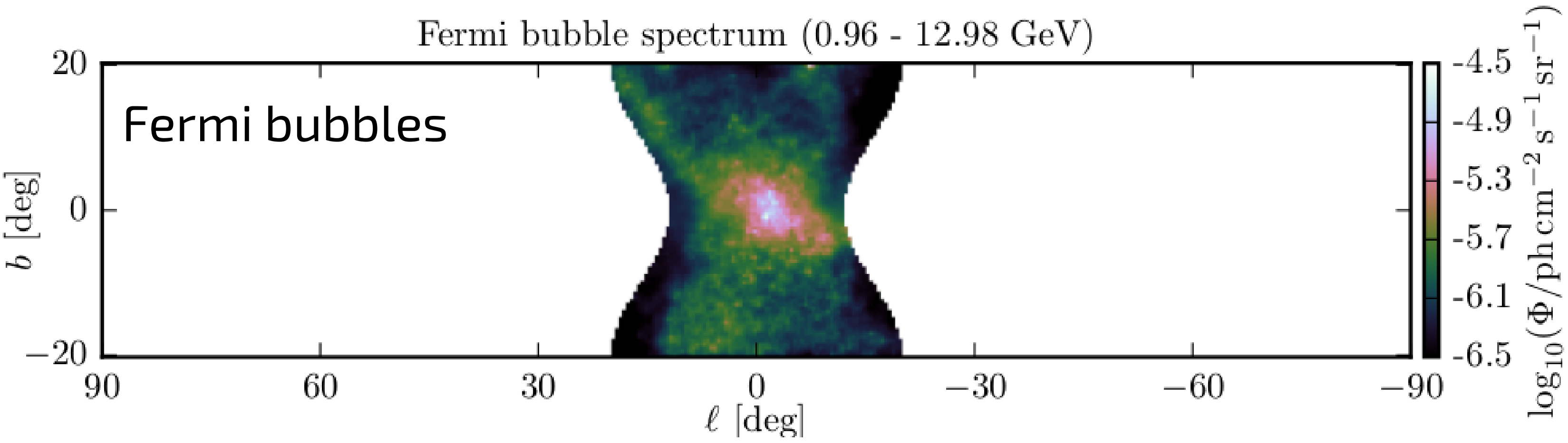
Enhancement

Suppression

Acreo+ 2016

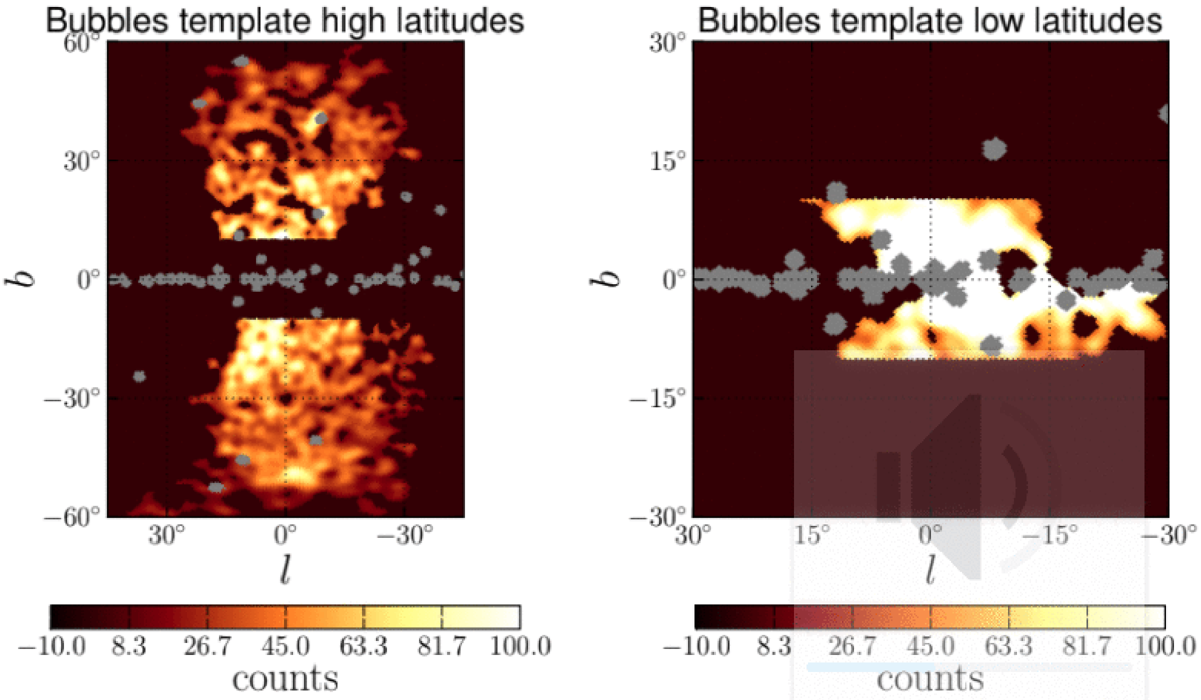
Low-latitude Fermi bubbles

Modulation parameters



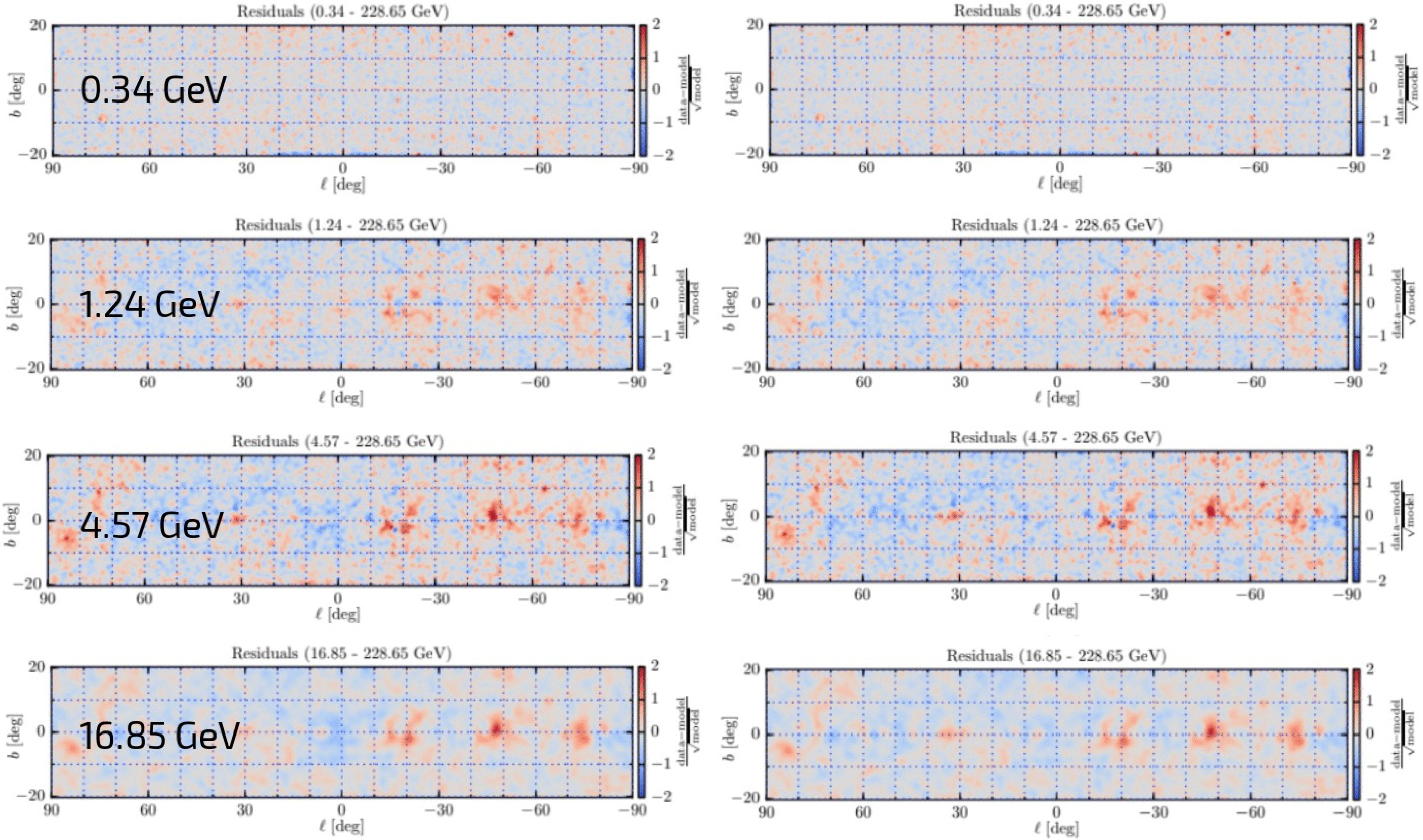
- Low-latitude part of Fermi bubbles is not well studied
- However, a MSP component + bubble component (hard spectrum) decomposition is possible
- Suggests strongly enhanced HE emission in the inner few degrees
- ICS from star formation?
- However, statistically not very significant, hard to study

Ackermann+ 17



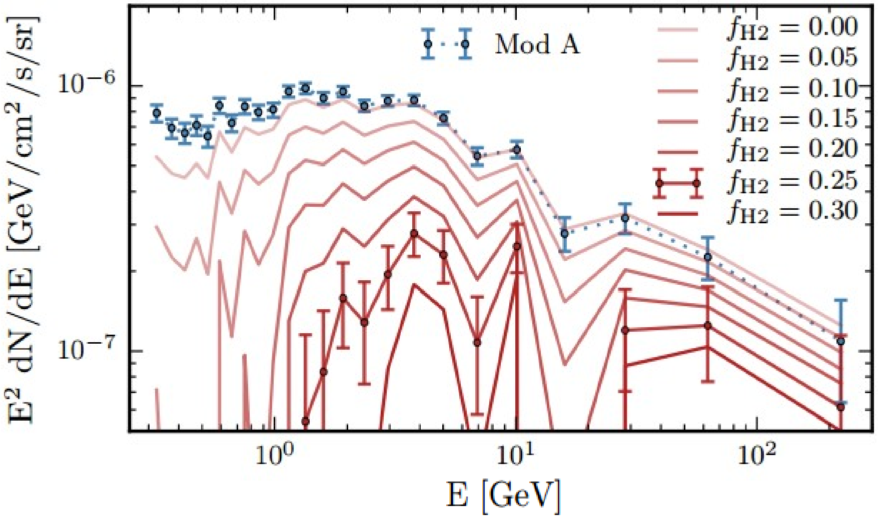
Residuals

→ add GCE →

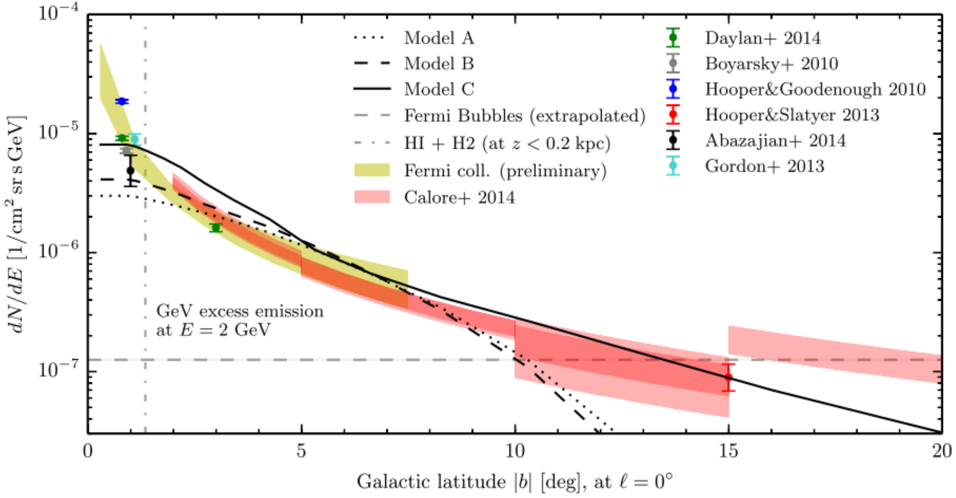


Possible contributions to bulge emission

Carlson+ '15



Cholis+ '15



Expected contributions

- Star formation (Gaggero+ '15, Carlson+ '15)
  - GeV excess: 1e37 erg/s
  - 1 SN (1e51 erg) per 100 yr, 10% in GC, 10% into CR, 1% into leptons

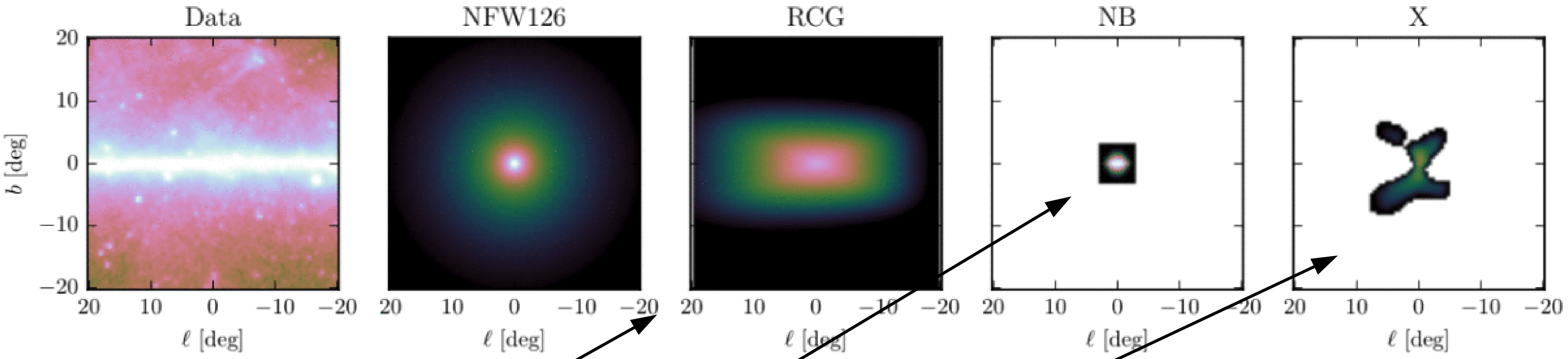
    → few 1e37 erg/s → enough to power GeV excess
- Bubble-related emission (very hard to model)
- Young pulsars (can be reasonably modeled, O'Leary+ '15)
- Millisecond pulsars* (spectrum expected to bump at GeV energies, but not clear how many, how distributed, etc; Abazajian 11; Brand & Kocsis 15)

Speculative contributions

- Dark matter annihilation* (spectrum not exactly known but can bump at ~GeV energies, not clear how strong signal, what shape)
- Past activity of central black hole (cooling effects might in principle explain the observed peaked spectrum; e.g. Cholis+15; Petrovic+13)

*predict extended quasi-diffuse uniform spectrum

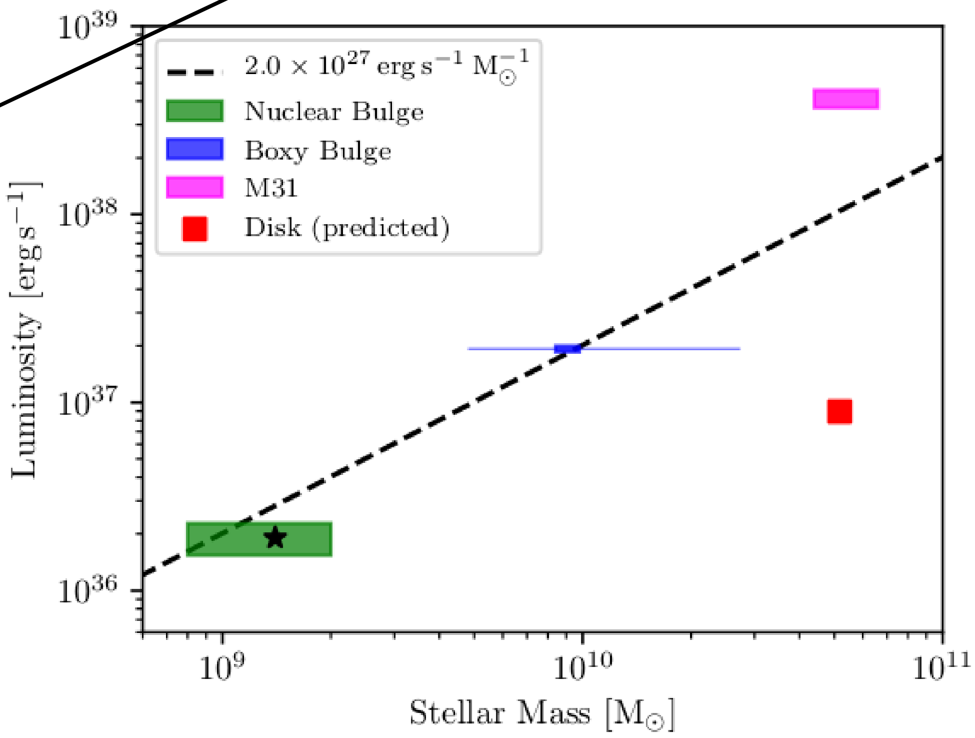
The morphology of the Fermi GeV excess



Red-clump giants

Nuclear bulge

WISE template (X-shape)
Wright+ 2010, Ness & Lang 2016
(following Macias+ 2016)



Richard Bartels, E. Storm, CW, F. Calore, 17

Radio searches for bulge MSPs

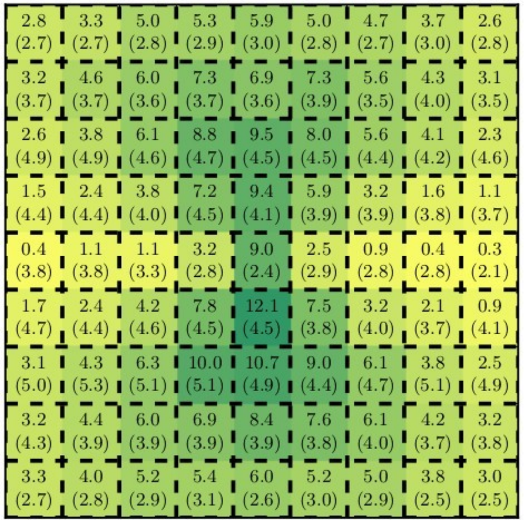
Radio detection prospects (CDDHW 16)

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

- GBT targeted searches ~100h: ~3 bulge MSPs
- MeerKAT mid-lat survey ~100h: ~10 bulge MSPs

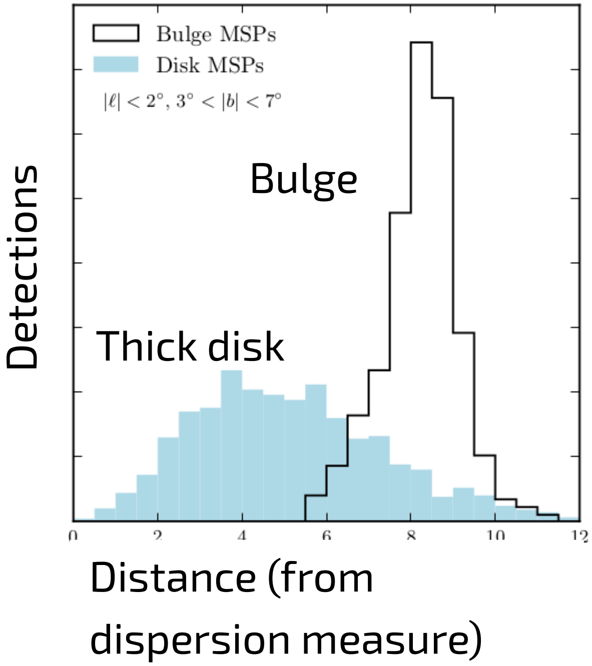
Our plans for the near future

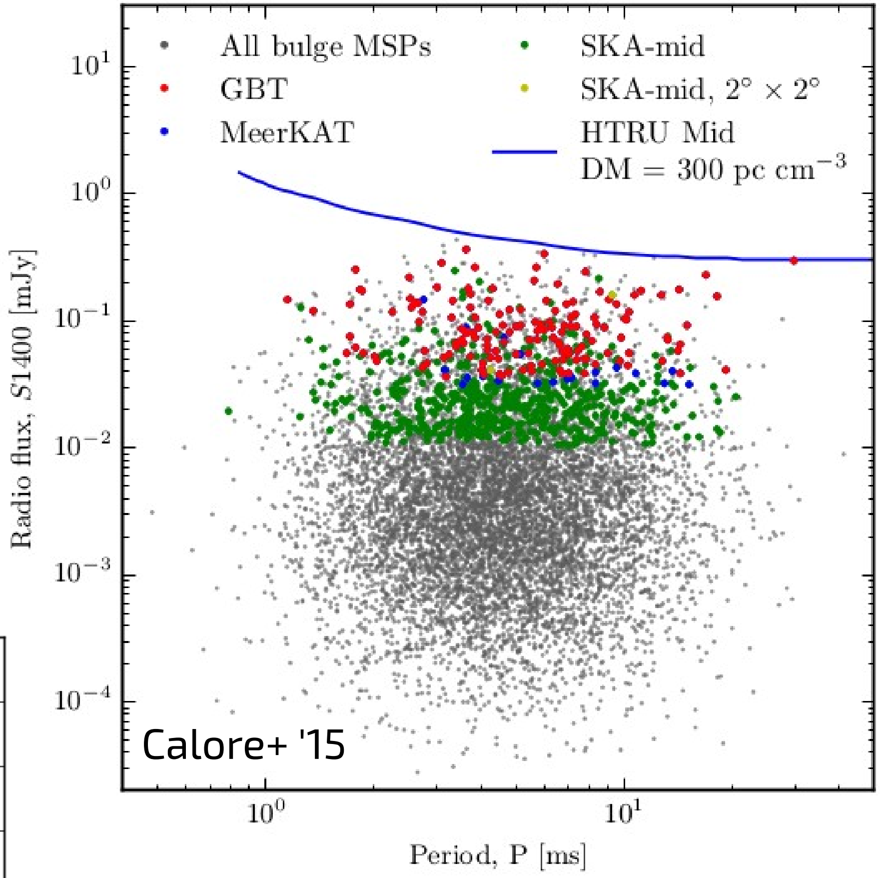
- We teamed up with MeerKAT TRAPUM → plans for a dedicated survey in 2019



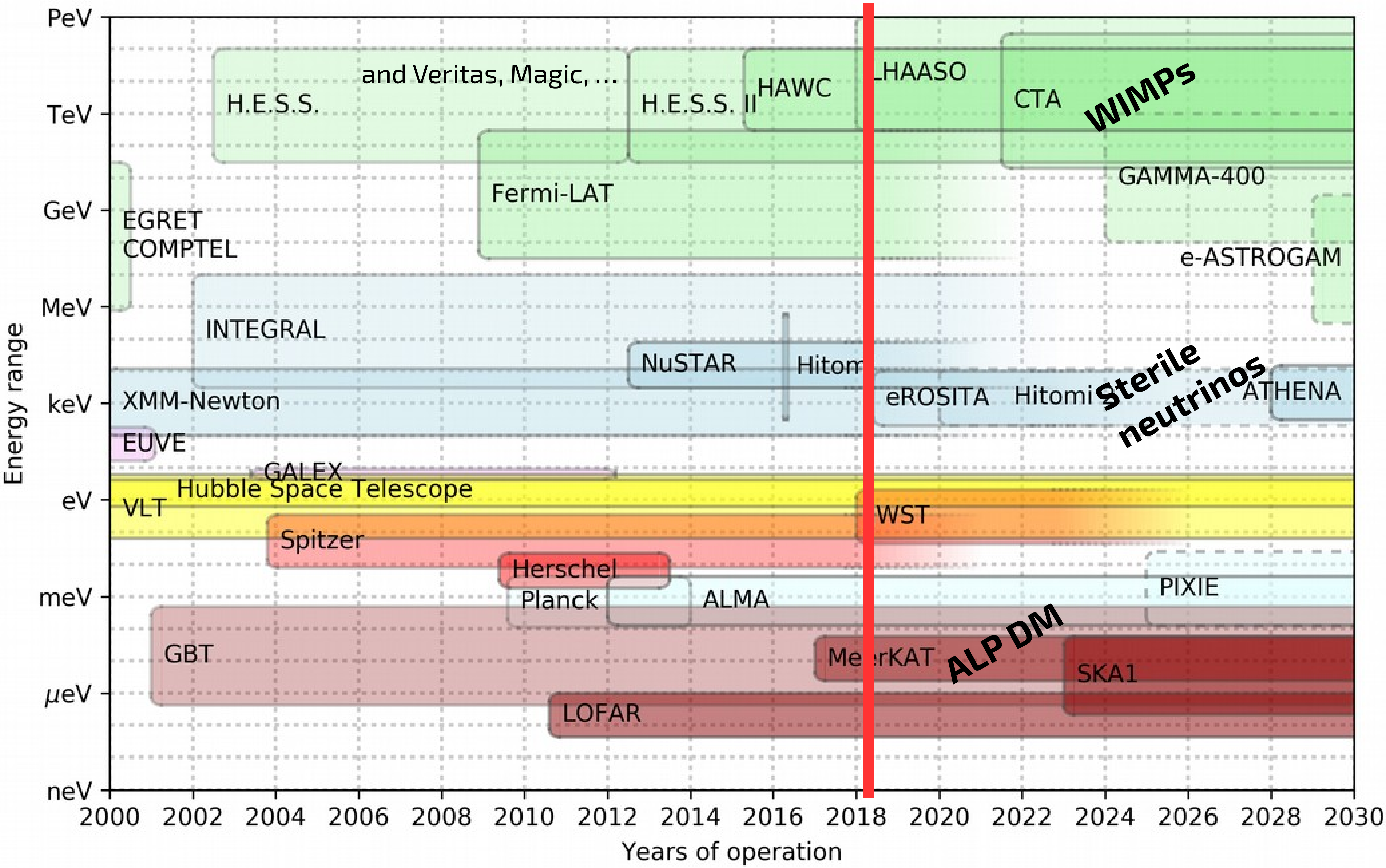
$18^\circ \times 18^\circ$

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)





Instrumental panorama – Photons



Some new statistical methods for

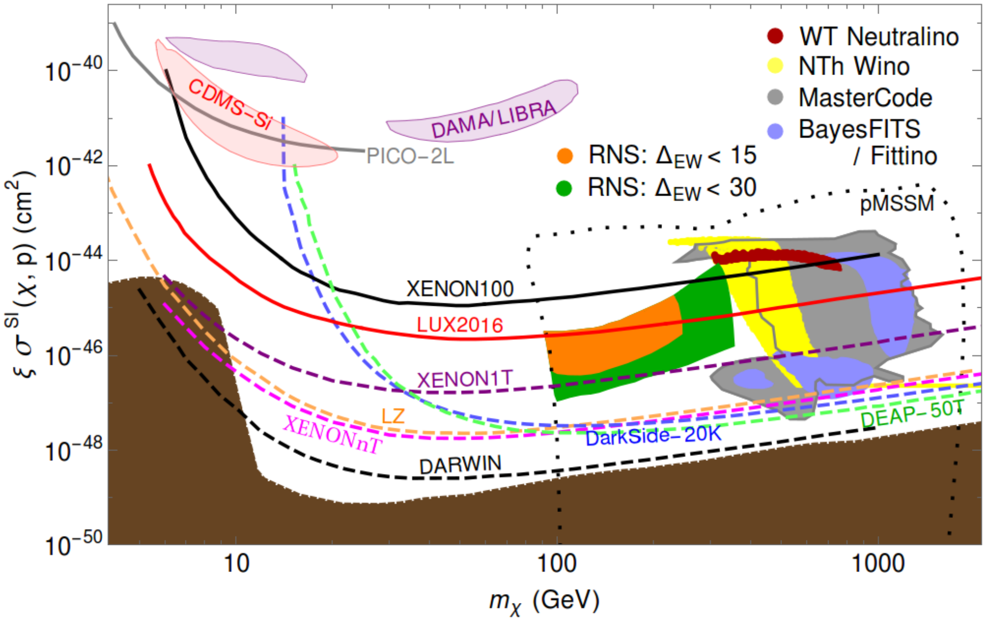
- Experimental design
- Benchmark-free forecasting

Motivation

Q: How to study and optimize the sensitivity of future instruments for your favourite dark matter model?

Standard approach

- **Upper limits**: Estimate what part of the parameter space can be killed.



Baer+ 2016

- **Confidence contours**: How well can benchmark points be reconstructed?

More interesting but hard to address

- Can one discriminate model A, B, C, …, Z? Where do models overlap?
- Where do additional experiments break model parameter degeneracies?
- What are the distinct phenomenological features of a model?

A general statistical model ("Cox process")

Rather general model structure, relevant for (astro-)particle physics

- Poisson likelihood
- Gaussian random field for modeling background uncertainties

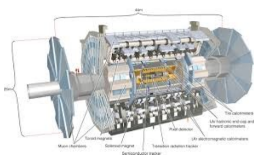
$$\ln \mathcal{L}_{\mathrm{prof}}(\mathbf{d}|\mathbf{S}) = \max_{\boldsymbol{\delta}\mathbf{B}} \left(\underbrace{\sum_{i=1}^{n_\mathrm{b}} \left(d_i \cdot \ln \mu_i(\mathbf{S}, \boldsymbol{\delta}\mathbf{B}) - \mu_i(\mathbf{S}, \boldsymbol{\delta}\mathbf{B})\right)}_{\text{Poisson likelihood}} - \underbrace{\frac{1}{2} \sum_{i,j=1}^{n_\mathrm{b}} \delta B_i \left(K^{-1}\right)_{ij} \delta B_j}_{\text{Bkg uncertainty}} \right)$$

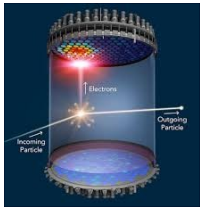
with

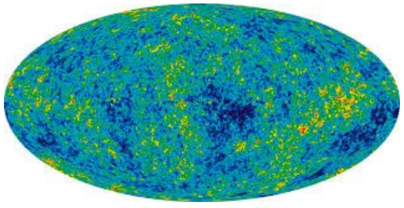
$$\mu_i(\mathbf{S}, \boldsymbol{\delta}\mathbf{B}) = \Big(\underbrace{S_i + B_i}_{\text{Signal + Bkg}} + \underbrace{\delta B_i}_{\uparrow\ \text{Bkg variations}} \Big) \cdot \underbrace{E_i}_{\text{Exposure}}$$

Fisher information matrix
for parametrized signal, $\mathbf{S} = \mathbf{S}(\theta)$

$$\mathcal{I}_{kl}(\boldsymbol{\theta}) \equiv - \left\langle \frac{\partial^2 \ln \max_{\boldsymbol{\delta}\mathbf{B}} \mathcal{L}(\mathcal{D}|\boldsymbol{\theta}, \boldsymbol{\delta}\mathbf{B})}{\partial\theta_k \partial\theta_k} \right\rangle_{\mathcal{D}(\boldsymbol{\theta})}$$

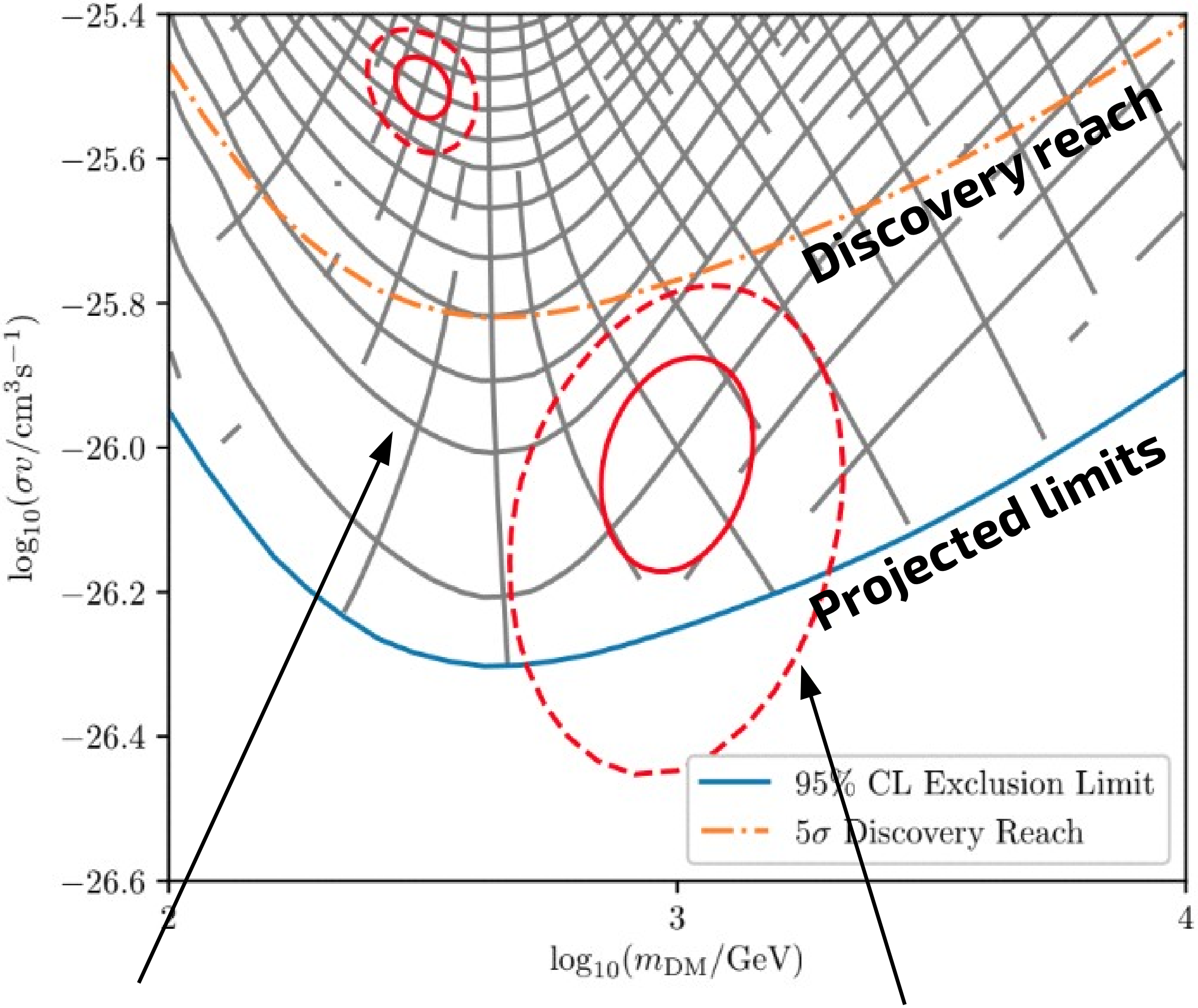






Fisher information → Geometry → Sensitivty

Upper limits for toy CTA, bb final states



Fisher information metric

Confidence contours from geodesic equation

The “Information flux” (effective S/N ratio)

Information flux

- Signal-to-noise ratio modulo bkg systematics
- Increase of Fisher information under infinitesimal exposure increase

$$\mathcal{F}_i \equiv \frac{\partial(1/\sigma^2)}{\partial E_i}$$

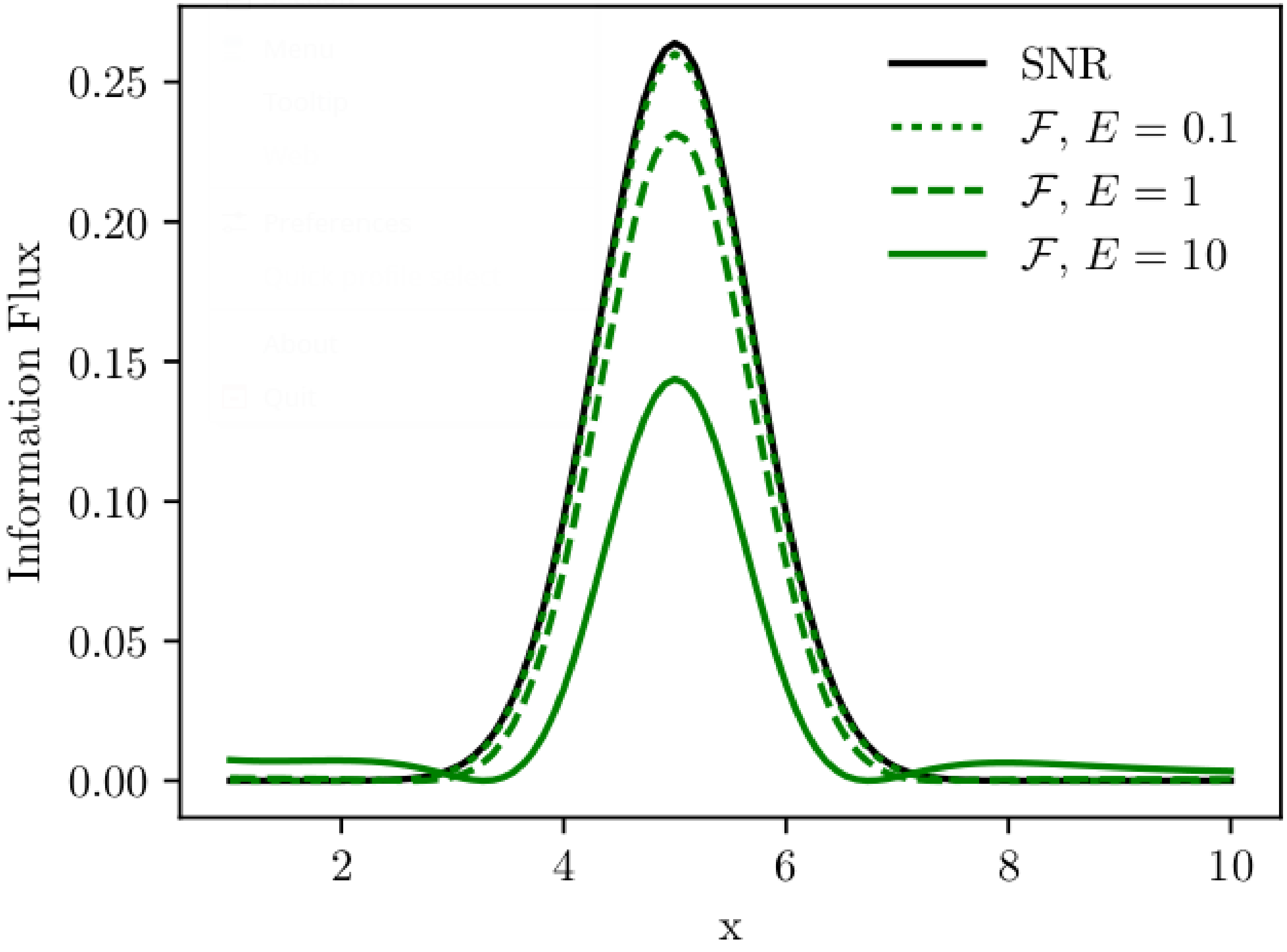
exposure

Statistics limited regime:

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

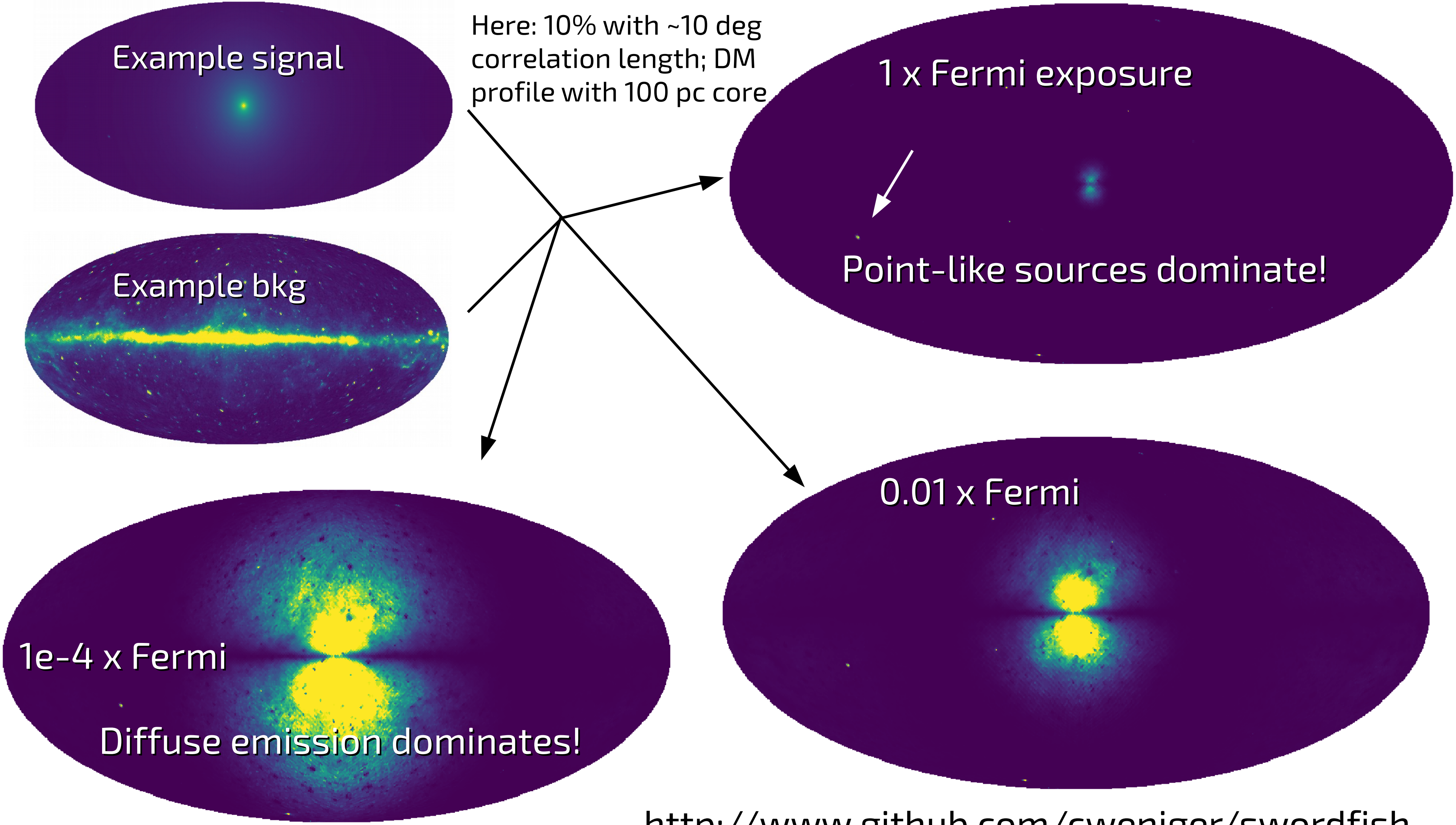
Background limited regime:

$\mathcal{F}_i \simeq$ ON/OFF regions



Dark information flux

Depending on the exposure and BG systematics, different aspects of the indirect DM signal can dominate.



Here: 10% with ~10 deg correlation length; DM profile with 100 pc core

Example signal

Example bkg

1 x Fermi exposure

Point-like sources dominate!

0.01 x Fermi

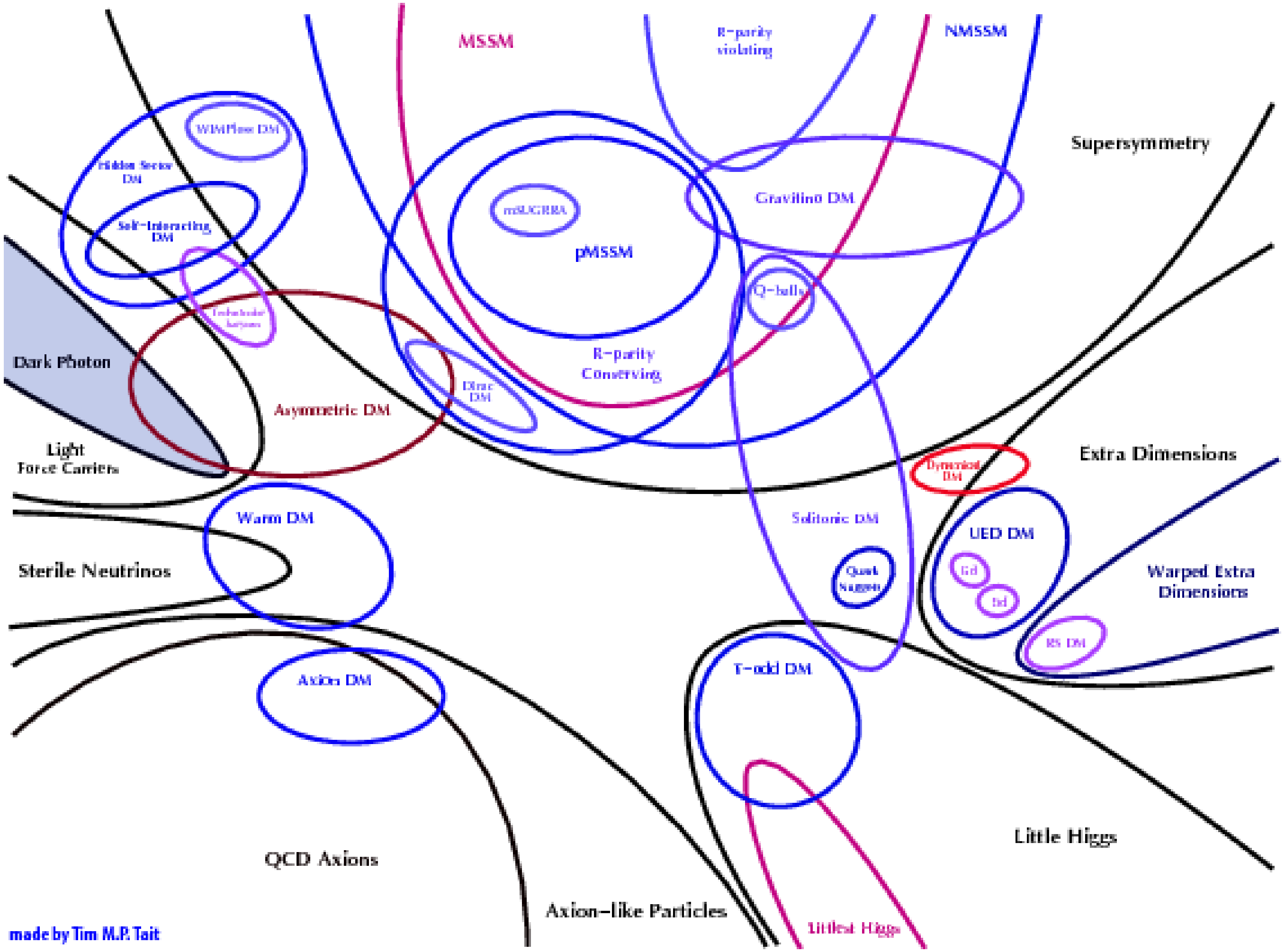
1e-4 x Fermi

Diffuse emission dominates!

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

Signal (& model) discrimination

Quantify Venn diagrams of dark matter models



How different/similar are models from the perspective of actual observations?

Complicated model parameters → Simple signals

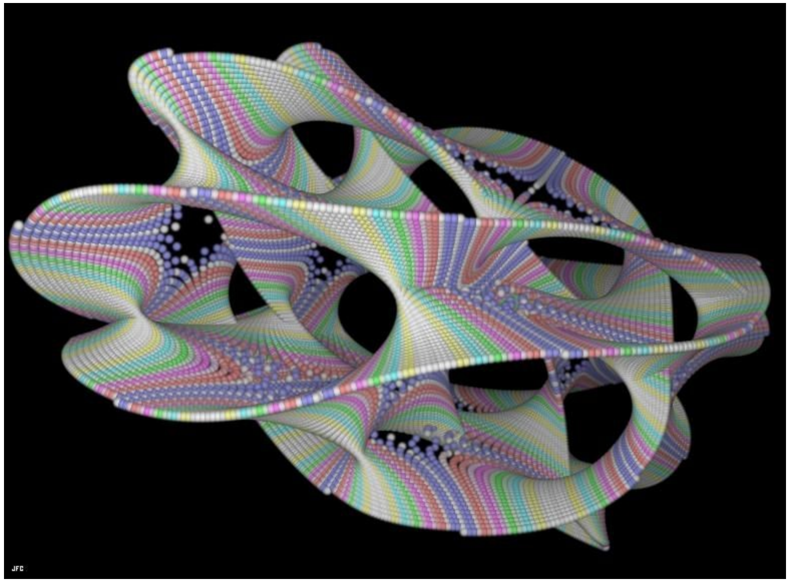
Model parameters

$$\vec{\theta} \in \Omega_{\mathcal{P}} \subset \mathbb{R}^d$$

Embedding in higher-dimensional space
with unit Fisher information matrix.

$$\vec{\theta} \mapsto \vec{x}(\vec{\theta})$$

$$\vec{x} \in \mathbb{R}^n \qquad \mathcal{I} = \mathbb{1}$$



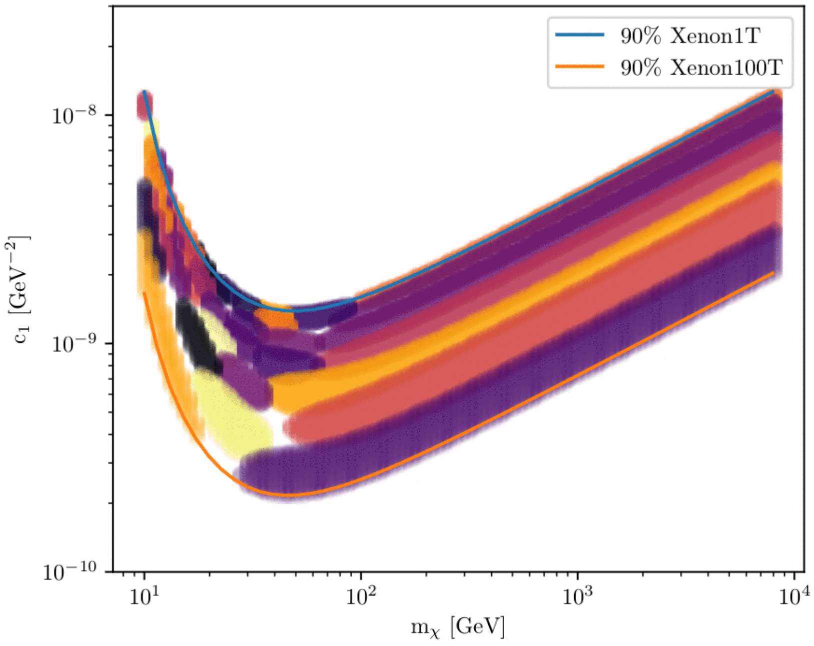
Likelihood ratios --> Euclidean distances

$$\mathrm{TS} = -2 \ln \frac{\mathcal{L}(\vec{\theta}_2 | \mathcal{D}(\vec{\theta}_1))}{\mathcal{L}(\vec{\theta}_1 | \mathcal{D}(\vec{\theta}_1))} \approx \|\vec{x}_1 - \vec{x}_2\|^2$$

Makes problem accessible to many Machine Learning tools:

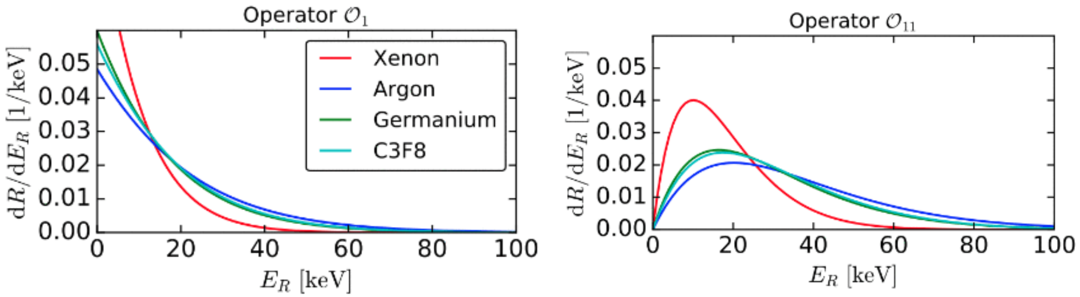
Dimensionality reduction, Clustering algorithms, Manifold learning, …

The “number of discriminatable signals”



Analysis

- Xenon1T S1-only analysis
- Toy DARWIN detector by multiplying exposure by 100x
- NRET: here O1 vs O11
- Fixed halo model



Our definition of “distinct signal”: *Signals can be discriminated at 95% CL.*

Method

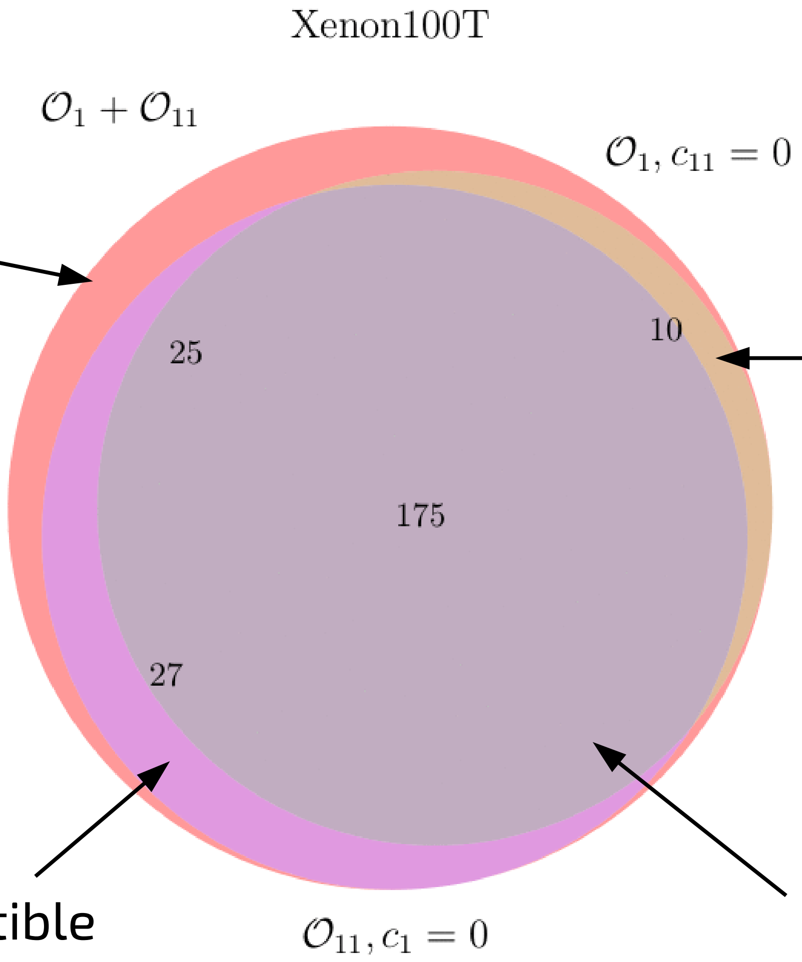
- Estimate effective model degrees of freedom, d_{eff}, from euclideanized signals
- Signals are distinct if euclideanized signals have distance of 2 (if d_{eff}=1)
- 68%CL contours can be calculated analogously

Volume(A) = maximum number of mutually distinct signals

Tom Edwards, B. Kavanagh, CW, in prep.

Compare also Baum+ 2018, **Talk R. Catena**

“Infometric Venn Diagram”



~240 distinct (at 95% CL) signals from O1 + O11 mixed model

~10 signals compatible (at 95% CL) with O11-only

~30 signals compatible (at 95% CL) with O1-only

~175 signals compatible (at 95% CL) with both O1-only *and* O11-only

Outlook:

Also works for combination of LHC + Fermi + DD, non-nested models, etc …

Tom Edwards, B. Kavanagh, CW, in prep.

Summary

- Can we find DM with indirect searches? Yes! Simple:
  - We have to be lucky
  - Exclude astrophysical backgrounds (not always possible)
  - Find corroborating signals in multiple targets, etc

- Most interesting candidate signal: Fermi Galactic center excess is by now well established. Properties consistent with either DM annihilation or MSPs in the Galactic bulge. Wavelet fluctuation / non-Poissonian analyses & morphology (with SkyFACT) point towards the latter
- Could be conclusively tested with upcoming radio surveys with MeerKAT, potentially in 2019.

- Some new statistical ideas building on information geometry can be helpful to optimize experimental design & astronomical DM searches (indirect searches, direct searches, cosmology, LHC)
- Information flux: Effective S/N ratio maps, including bkg modeling systematics
- Infometric Venn Diagrams: Quantify signal discrimination power of future instruments in a benchmark-free way.

Thank you