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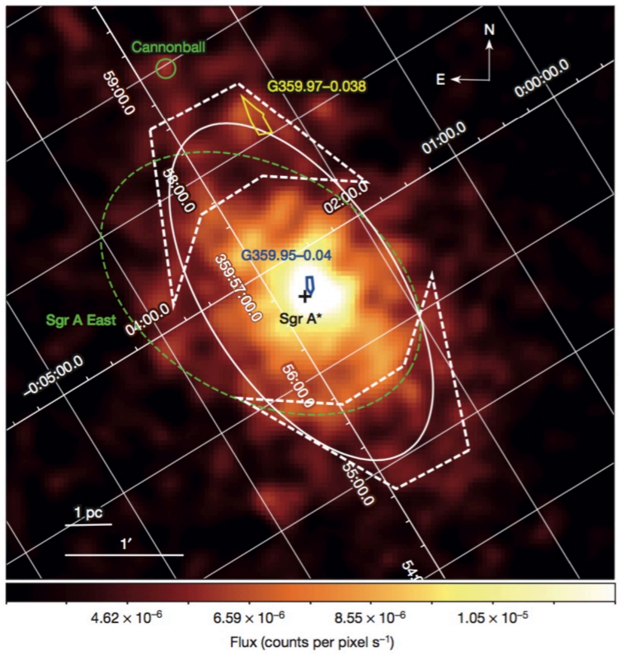
Gamma rays from the Inner Galaxy: summary report

08/07/2019, LAPTh, Annecy

Illustration by Sandbox Studio, Chicag

Anomalies in the gamma-ray sky

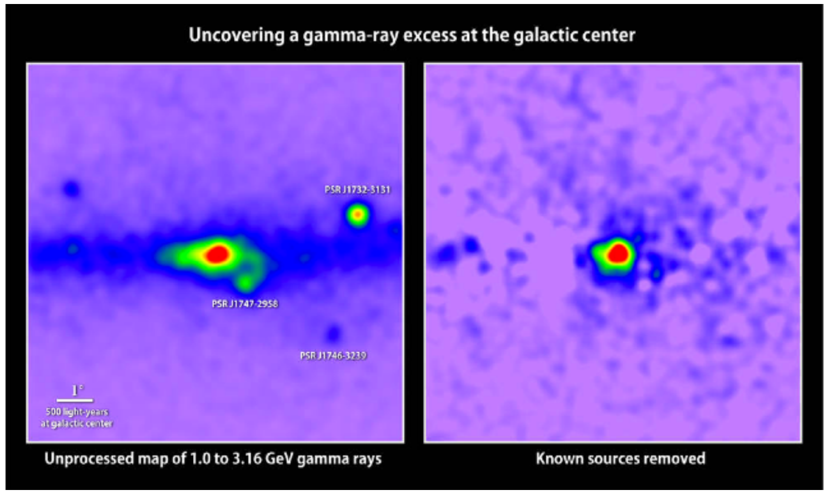
Perez+Nature'15

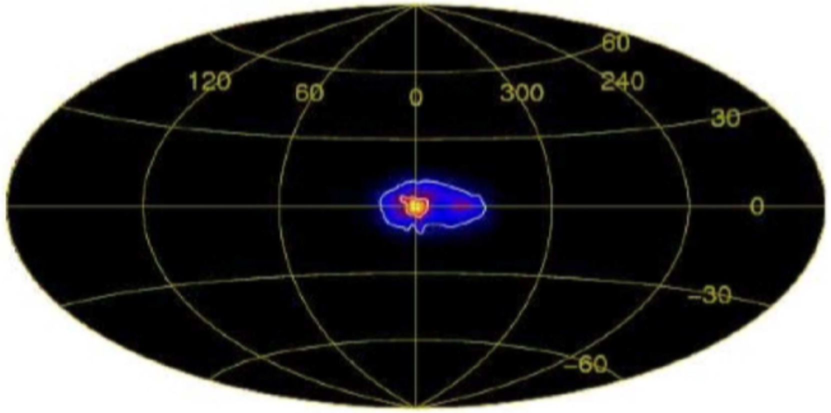


X-ray @ 20-40 keV
NuSTAR
hard diffuse excess emission

Gamma-ray @ few GeV
Fermi-LAT
Fermi GeV excess

Daylan+PRD'16

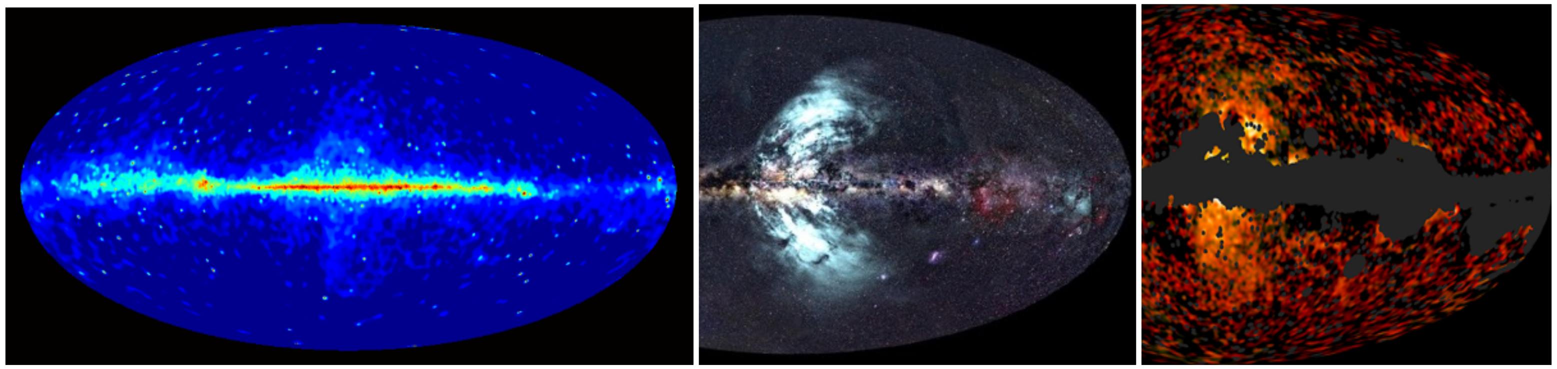




Gamma-ray @ 511 keV
INTEGRAL/SPI
Positron annihilation line

Purcell+'93,'97; Knödlseder+'03,'05

Su+'10; Fermi-LAT Collab'14; Carretti+'13; Planck Collab.'13



Gamma-ray @ hundreds GeV
Fermi-LAT
Fermi bubbles, and their radio/ microwave conterparts

Excesses extended far well beyond central CMZ and nuclear bulge

The Galactic centre GeV excess

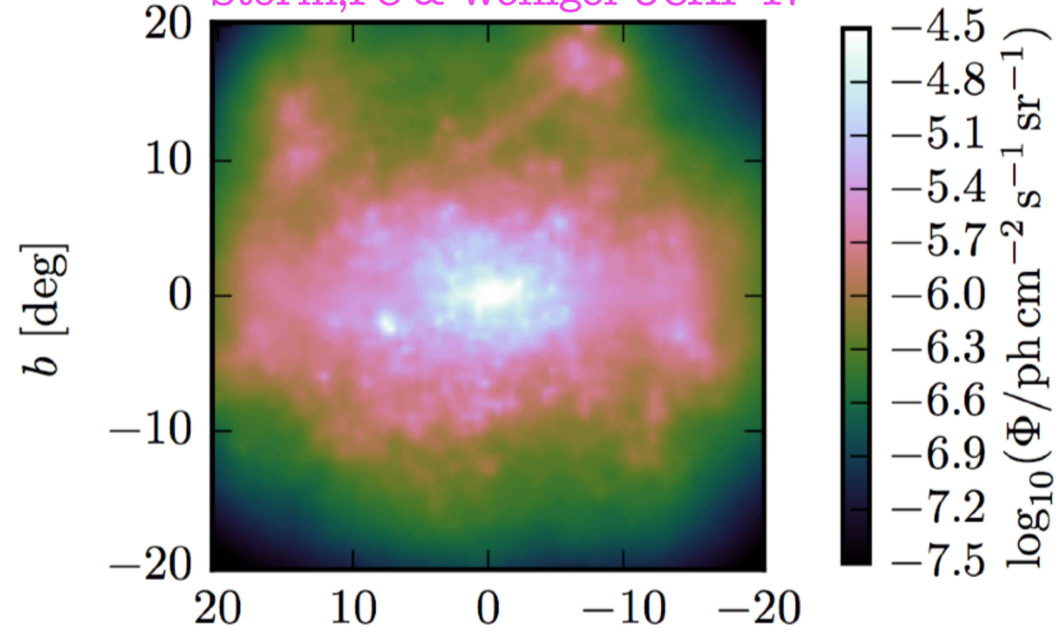
Signal:

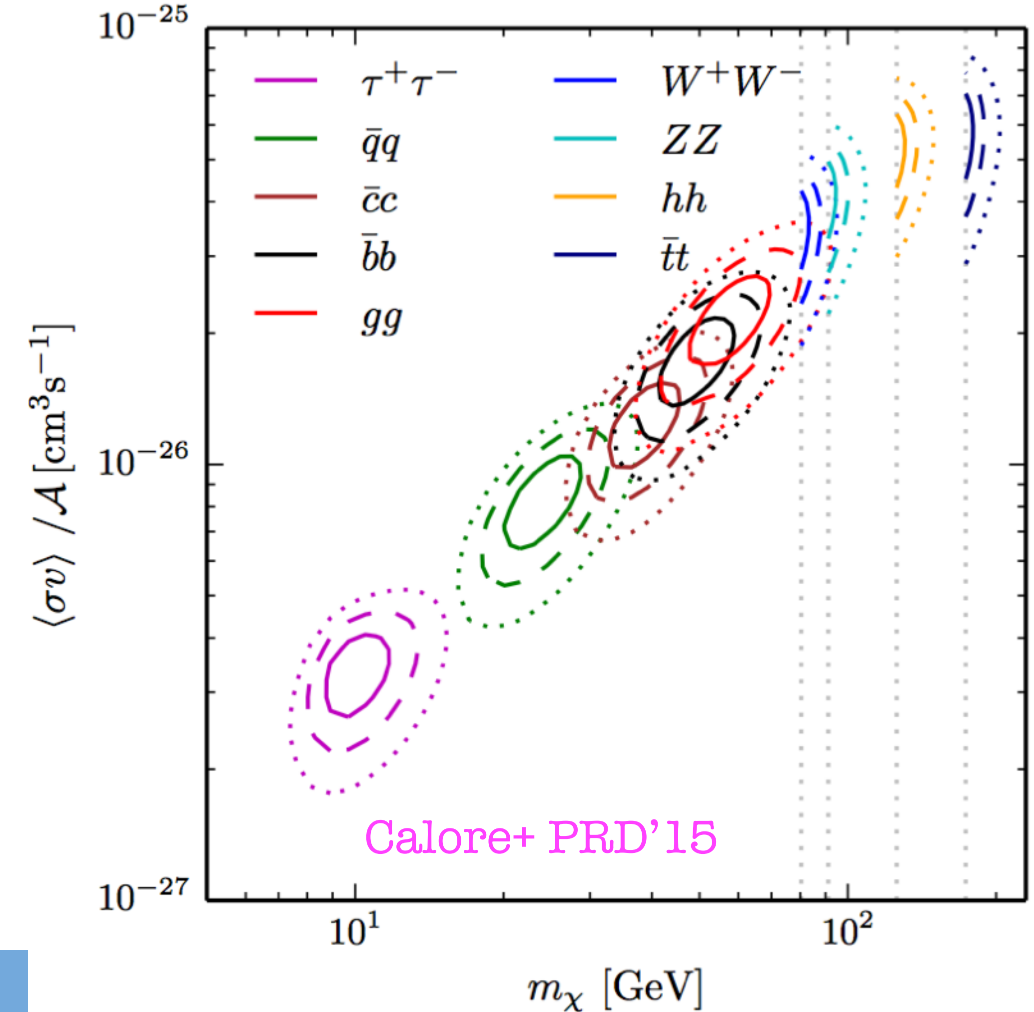
- Well-established excess of Fermi-LAT GeV photons from the inner Galaxy**
- Peculiar spectrum peaked at a few GeV
- Extended emission up to ~10 degrees (~1.5 kpc), almost spherically symmetric (but not quite so)

Interpretations:

- Diffuse emission from electrons/positrons at the Galactic centre (enhanced SF or activity GC) Gaggero+ JCAP'15; Carlson+PRD'15; Petrovic+ JCAP'14; Cholis,FC+JCAP'15
- Sub-threshold millisecond pulsar-like point sources Bartels+PRL'16; Lee+PRL'16; Ackermann+'17
- Dark matter annihilation: large freedom in channel/masses thanks to syst uncertainties Calore+ PRD'15; Agrawal+JCAP'15

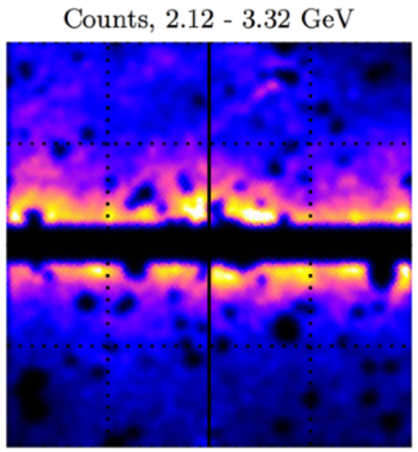
Storm,FC & Weniger JCAP'17





**Some Refs. since 2009: Hooper&Goodenough '09; Vitale&Morselli '09; Abazajian&Kaplinghat PRD'12; de Boer+'16; Macias+'16; Hooper&Slatyer PDU'13; Huang+ JCAP'13; Zhou+ PRD'15; Daylan+ '14; Calore+ JCAP'15; Gaggero+ 2015; Ajello+ 2015; Huang+JCAP '15; Linden+PRD'16; Horiuchi+'16; Ackermann+ApJ'17; Ackermann+2017; Leane & Slatyer'19

General: Fit to gamma-ray data

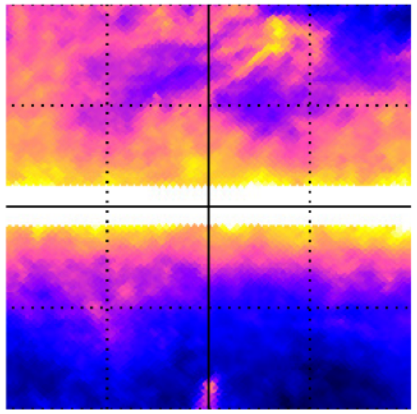


Data counts

$$k_{i,j}$$

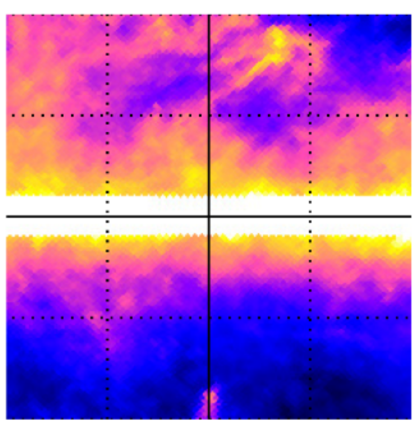
Model counts

$$\mu_{i,j} = \sum_k \theta_{i,k} \mu_{i,j}^{(k)}$$

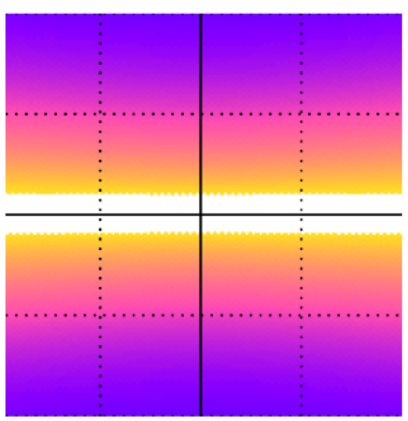


Challenge 1: Templates choice & modelling

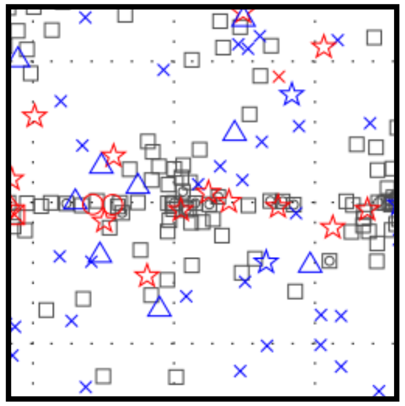
"Bkg" only



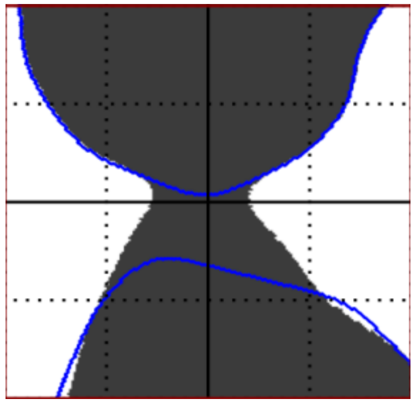
1. π^0 + Brems



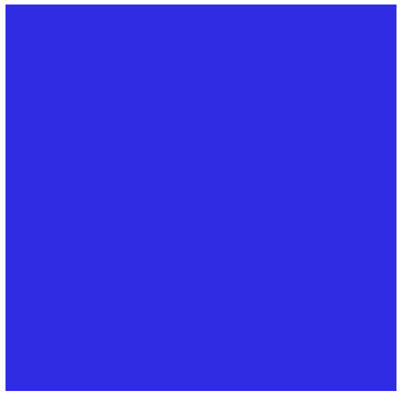
2. ICS



3. Point sources

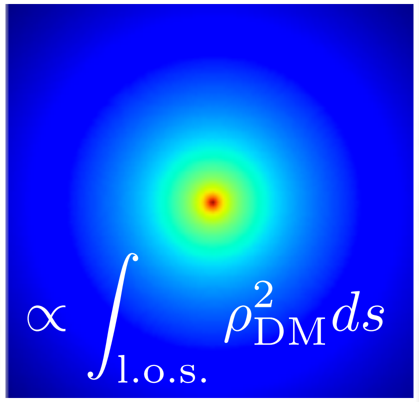


4. Fermi bubbles



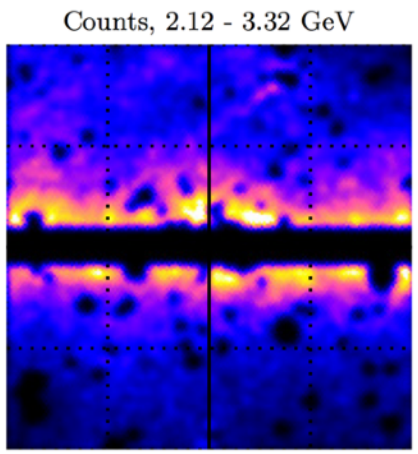
5. Isotropic diffuse bkg

"Signal"



6. GeV excess template

General: Fit to gamma-ray data



Data counts

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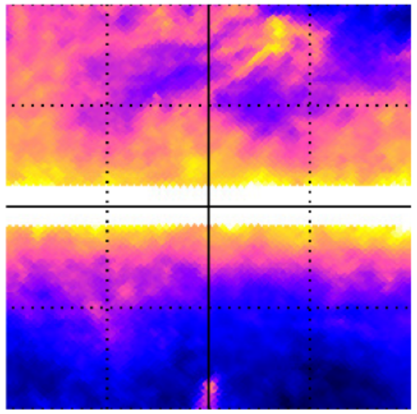
$$\mu_{i,j} = \sum_k \theta_{i,k} \mu_{i,j}^{(k)}$$



Challenge 2: Fitting techniques

$$\text{Model} = \sum_k \text{Morphology}^{(k)} \times \text{Spectrum}^{(k)}$$

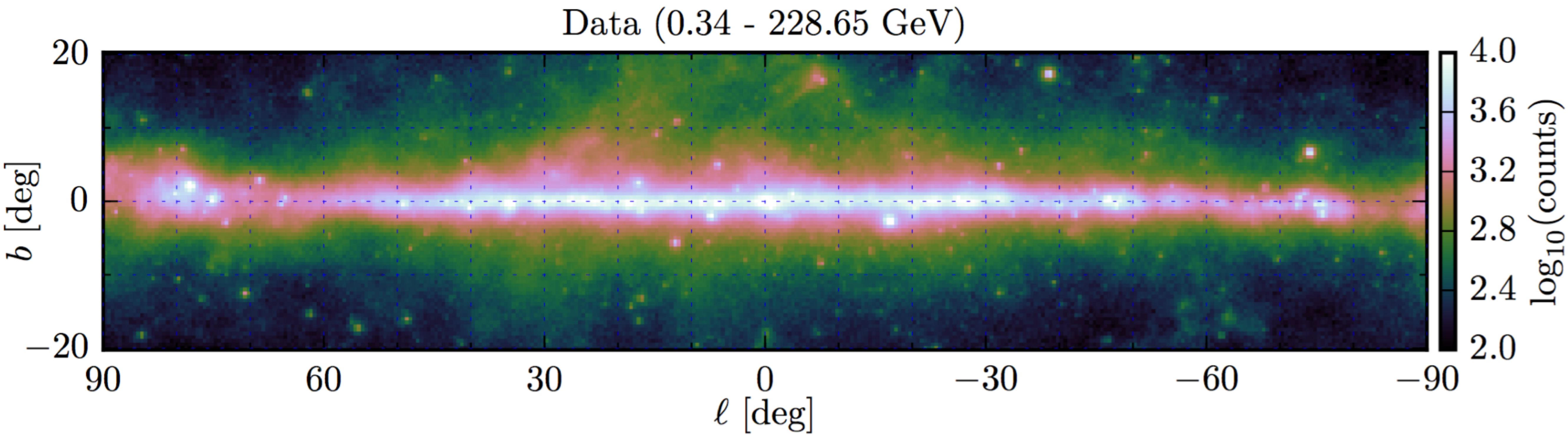
The (spatial) template-fitting method (maximum likelihood) → $\theta_{i,k}$ i^th energy

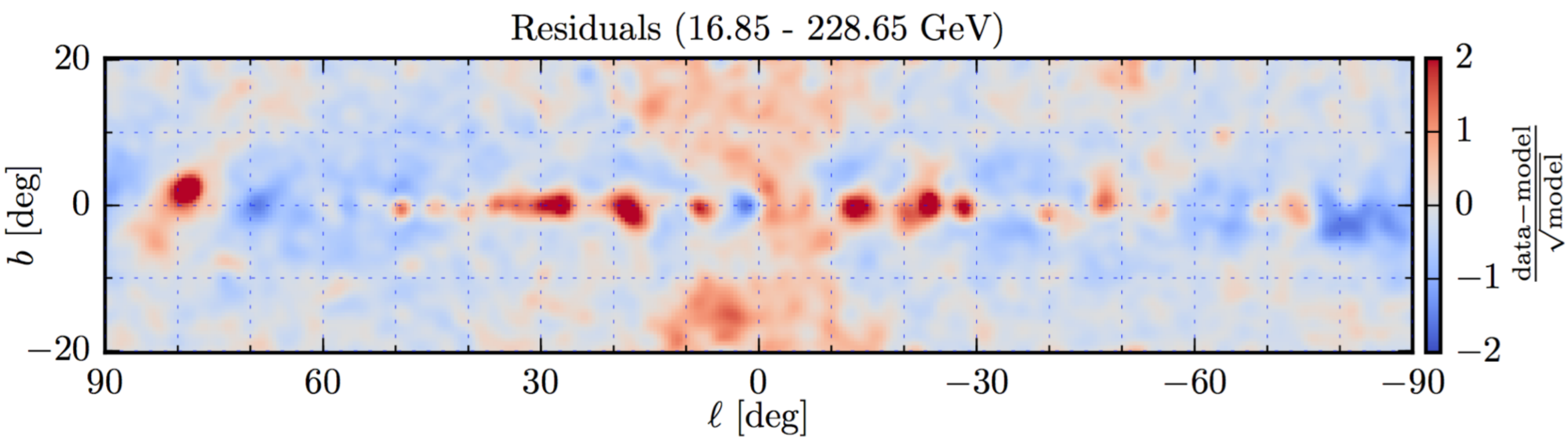
Hooper+ PDU'13; Huang+ JCAP'13; Daylan+ '14; Calore+ JCAP'15; Gaggero+ JCAP'15

Pixel-wise maximum likelihood decomposition → $\theta_{i,k}$ i^th pixel

D3PO – Selig+ A&A'14; Huang+ '15

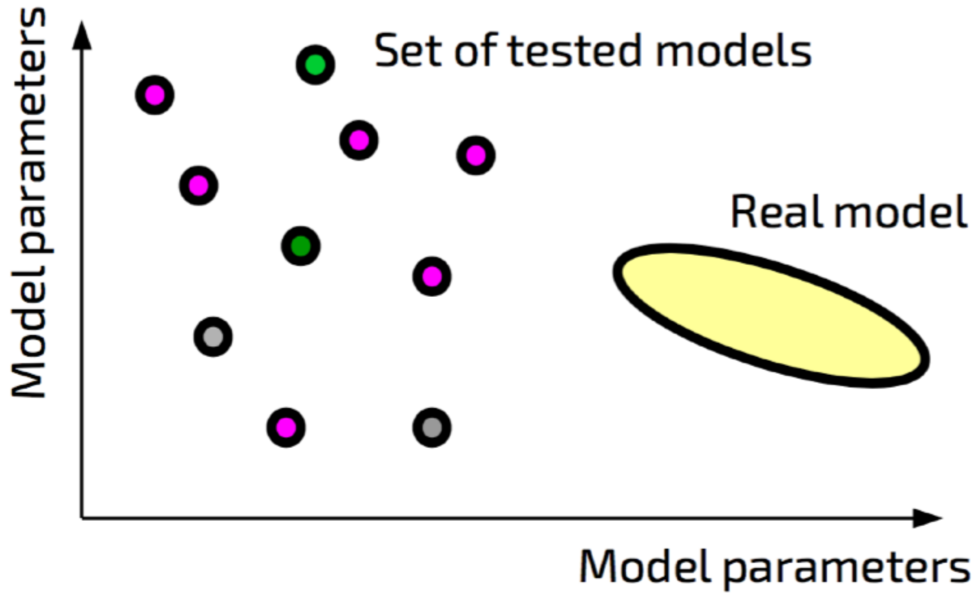
Fitting the gamma-ray sky





Large residuals (~30%) remain in the sky with this simple model, but clear structures emerge (extended sources, Fermi bubbles)

A way forward



Imperfect modelling might lead to severely biased estimators, above all for extended emission features.

How to fully account for intrinsic uncertainties in spectral/spatial predictions?

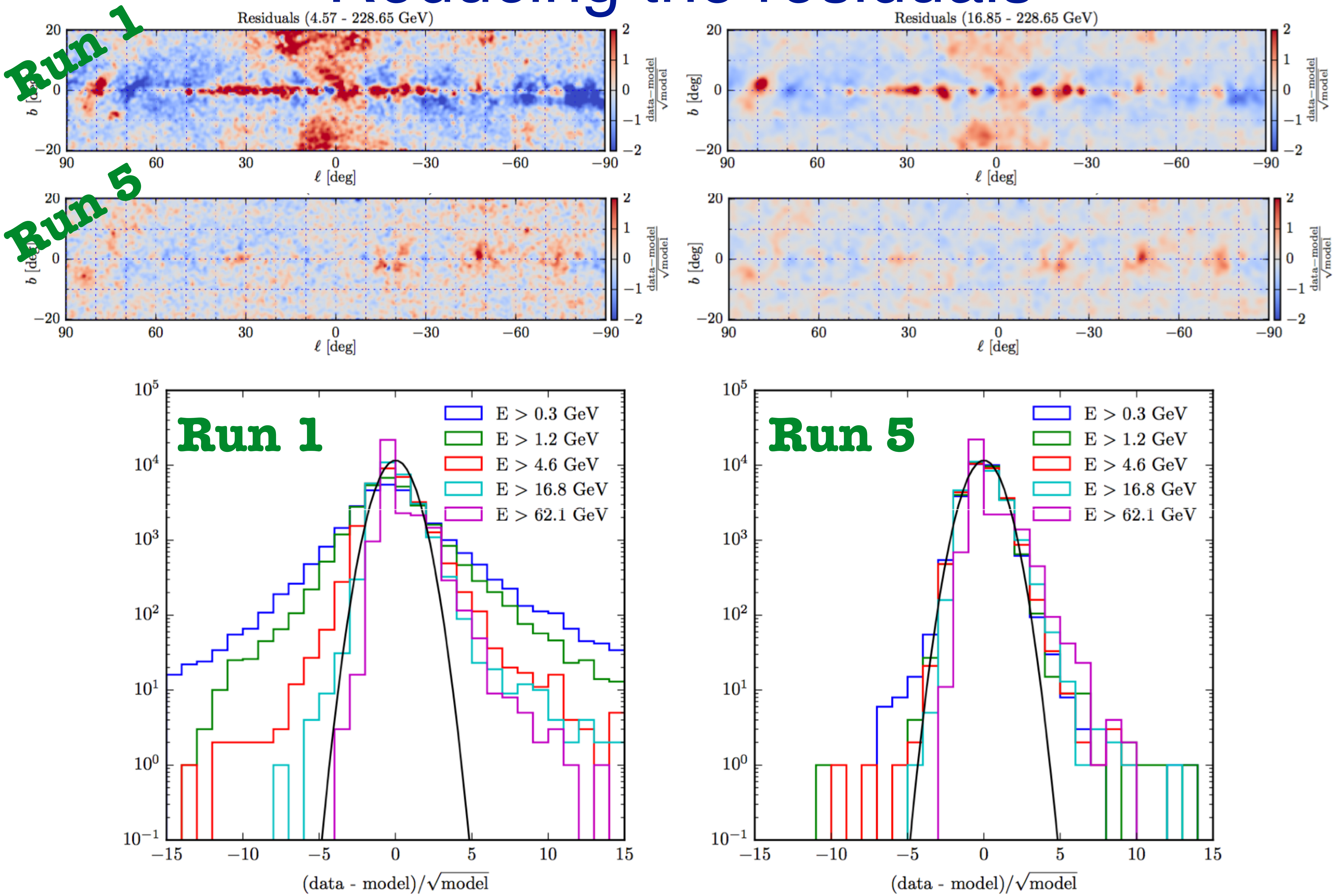
=> Introduce a very large number of parameters w/ regularisation conditions for the likelihood:

$$\mu_{i,j} = \sum_k \eta_{j,k} \tau_j^{(k)} \times \theta_{i,k} \sigma_i^{(k)}$$

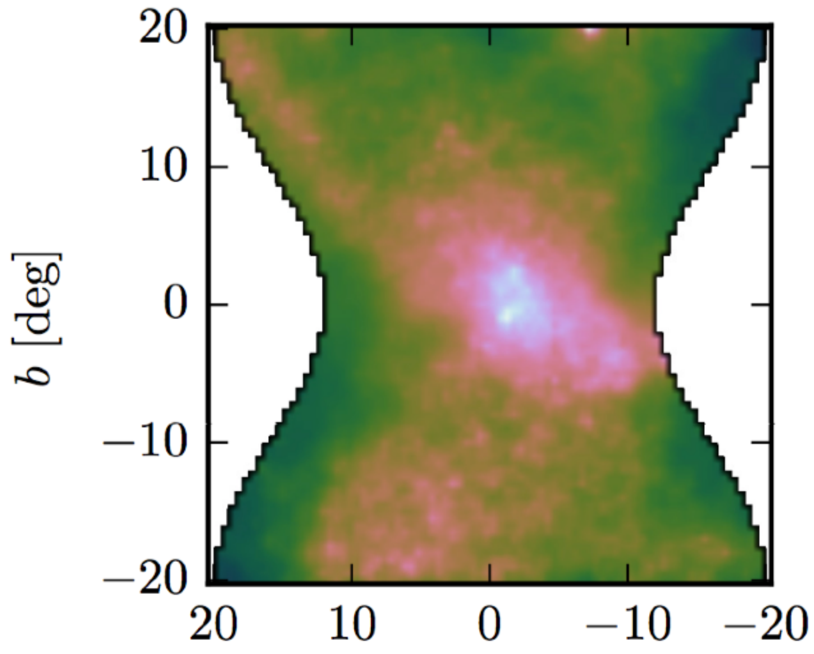
Sky Factorisation with Adaptive Constraining Templates (SkyFACT)

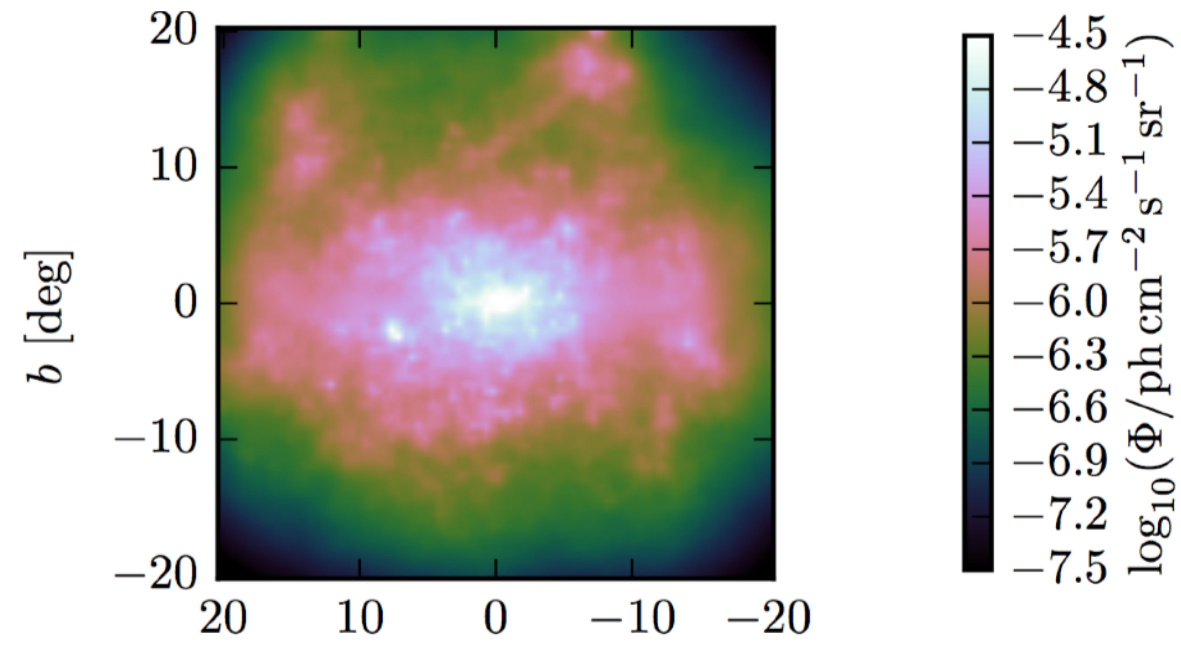
Storm, Weniger & Calore JCAP'17 [arXiv:1705.04065]

Reducing the residuals



The bulge emission morphology





McCann, ApJ'15

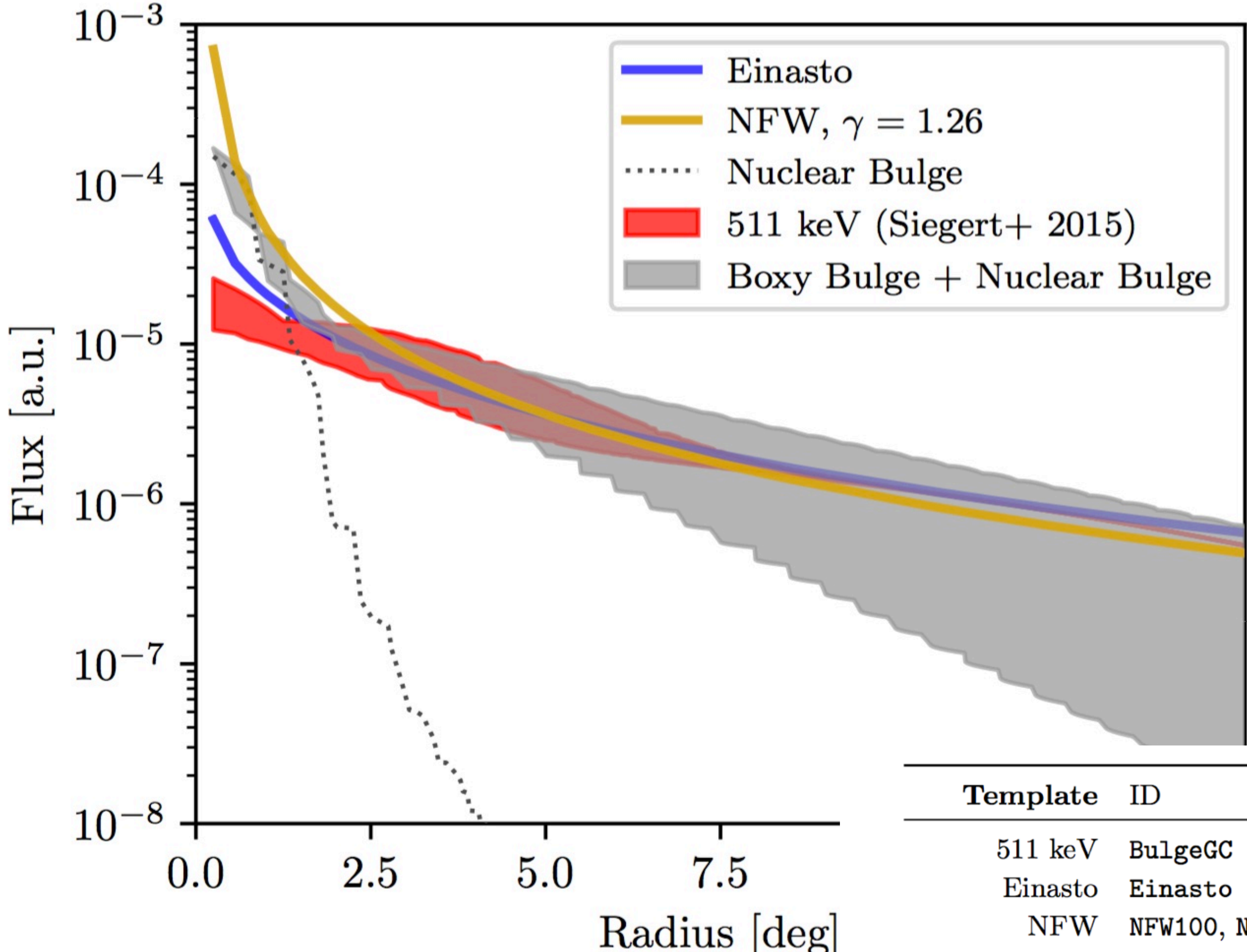
Fermi bubble spectrum
Free morphology

Fixed MSP-like spectrum
Reconstructed morphology
~12σ significance

- ✓ Strong degeneracy between Fermi bubbles and bulge emission (aka GeV excess)
- ✓ Residuals reduced significantly when (realistic) nuisance parameters are included in the fit (SKYFACT).
- ✓ Once again, strong evidence for GeV excess (> 10σ significance), although more oblate morphology than previous studies.

Storm, Weniger & Calore JCAP'17 [arXiv:1705.04065]

Going beyond DM-motivated templates



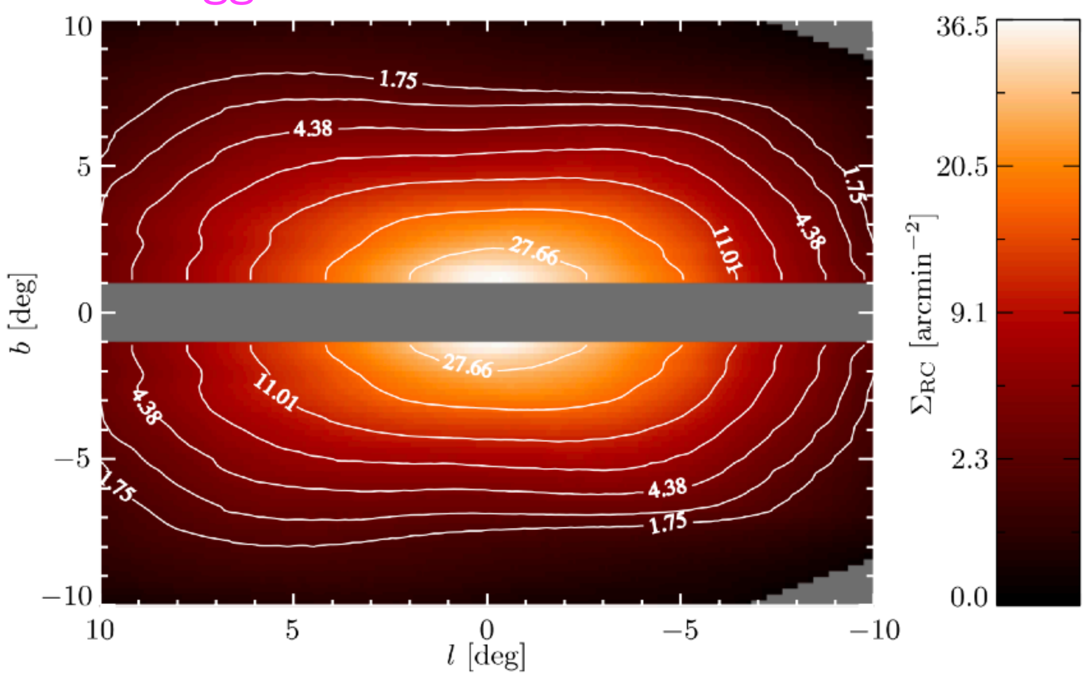
Template	ID	Reference
511 keV	BulgeGC	Siegert et al. (2016)
Einasto	Einasto	Vincent et al. (2012)
NFW	NFW100, NFW126	Navarro et al. (1997)
Boxy Bulge	RCG	Cao et al. (2013)
Nuclear Bulge	NB	Launhardt et al. (2002)
X-shape	X	Ness & Lang (2016)

Stellar distribution in the bulge

Boxy bulge

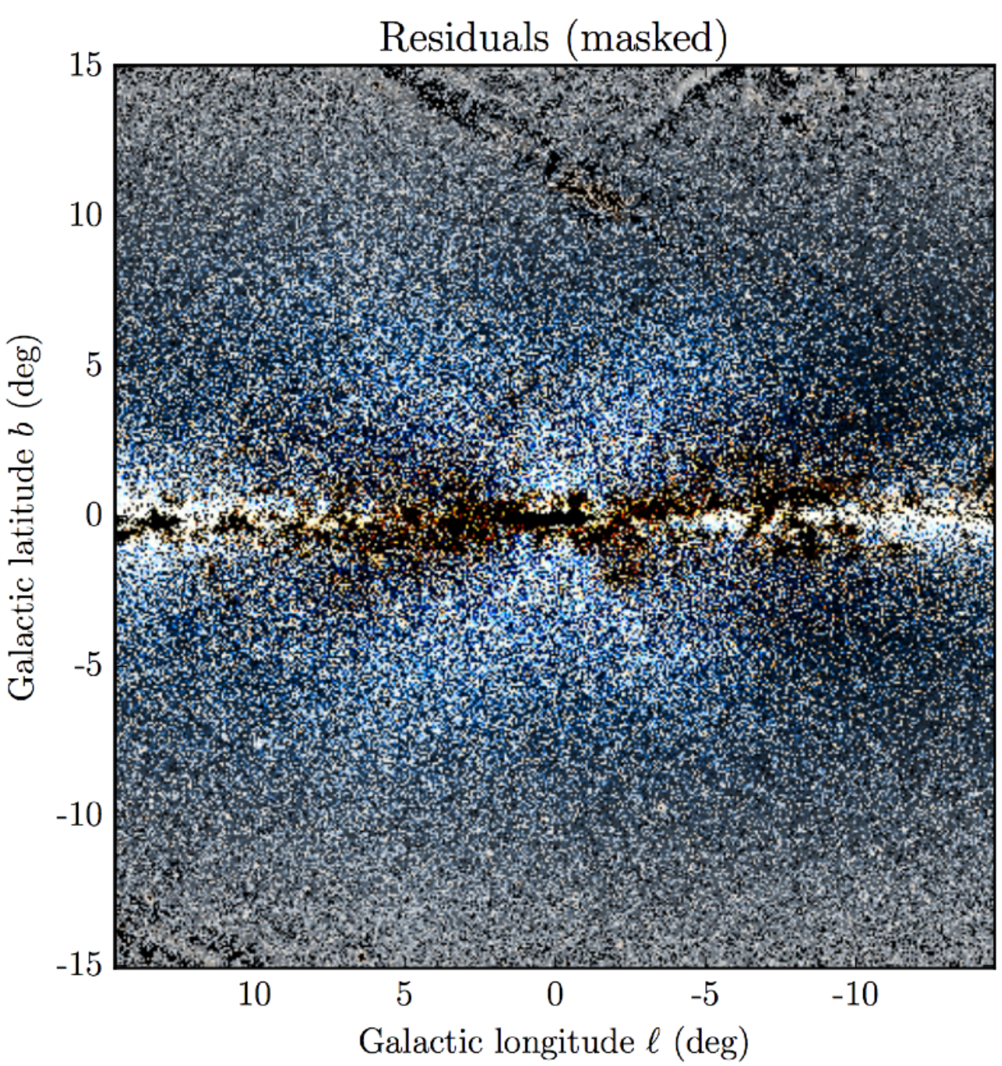
$0.9 \times 10^{10}\ M_\odot$

Wegg & Gerhard MNRAS'12



X-shaped bulge

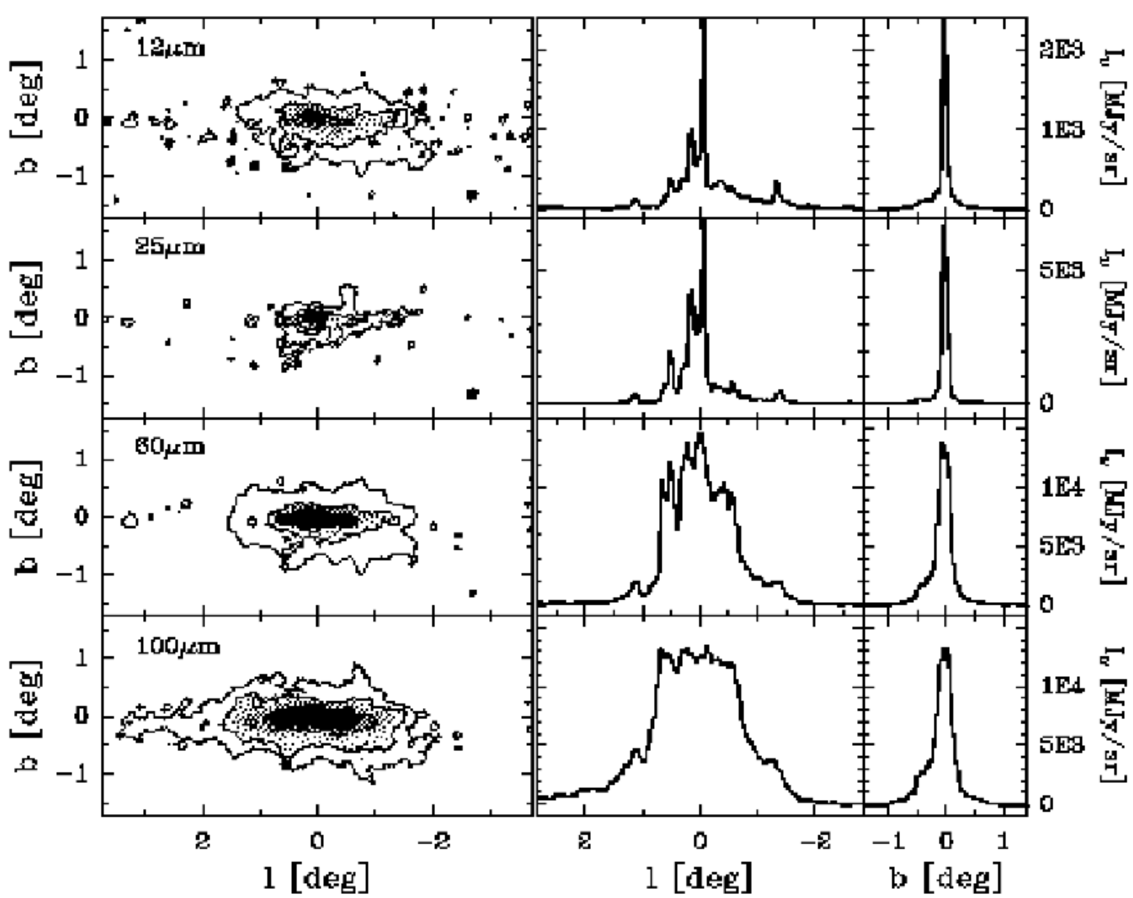
Ness&Lang AJ'16



Nuclear bulge

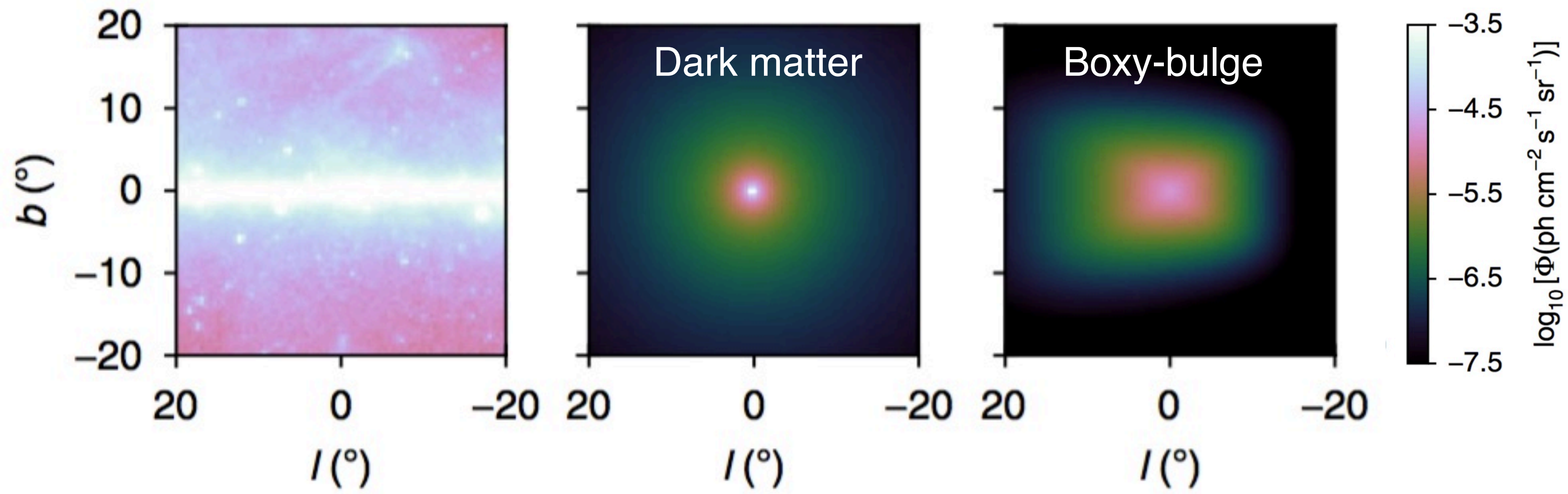
Launhardt+A&A'02

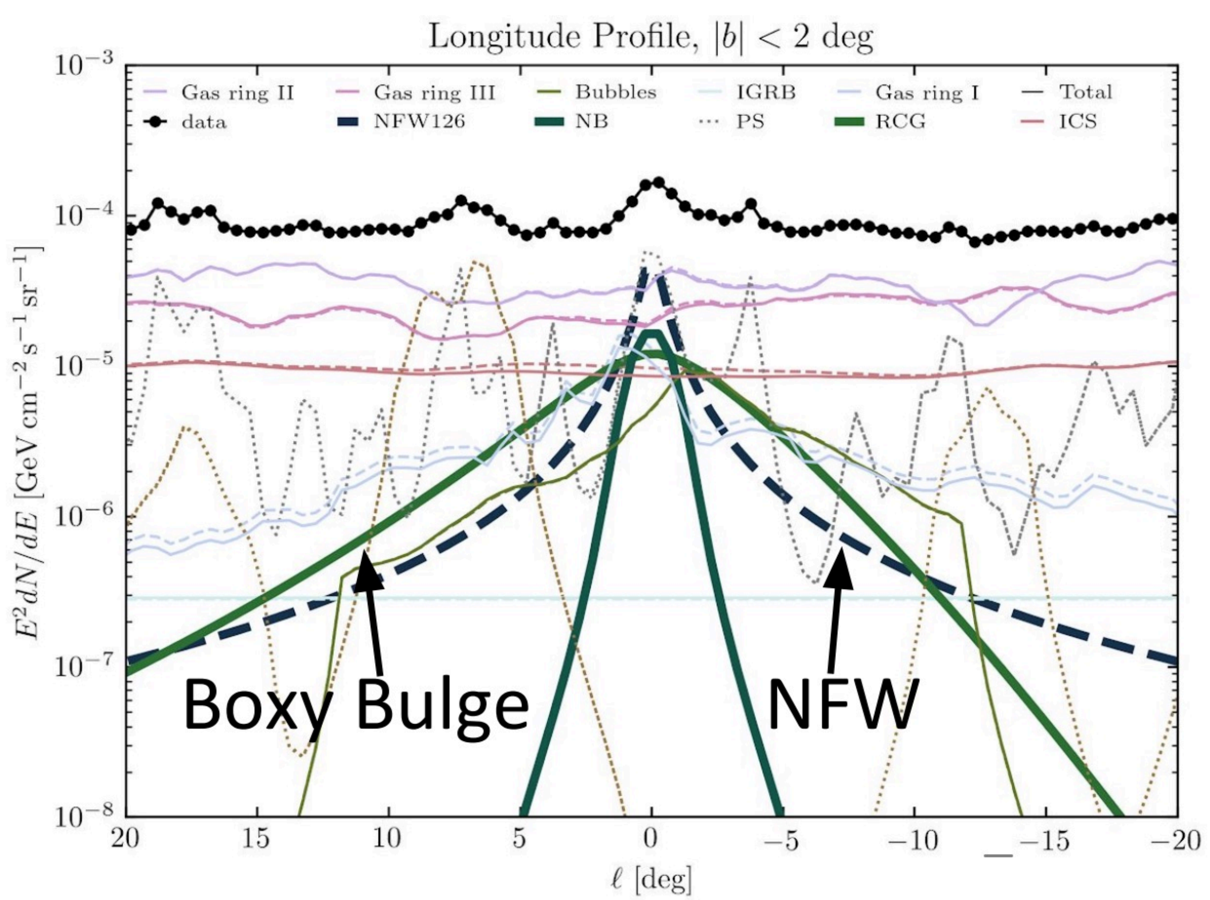
$1.4 \times 10^{9}\ M_\odot$



Evidence for stellar bulge emission

Bartels,FC+ Nature Astronomy'18

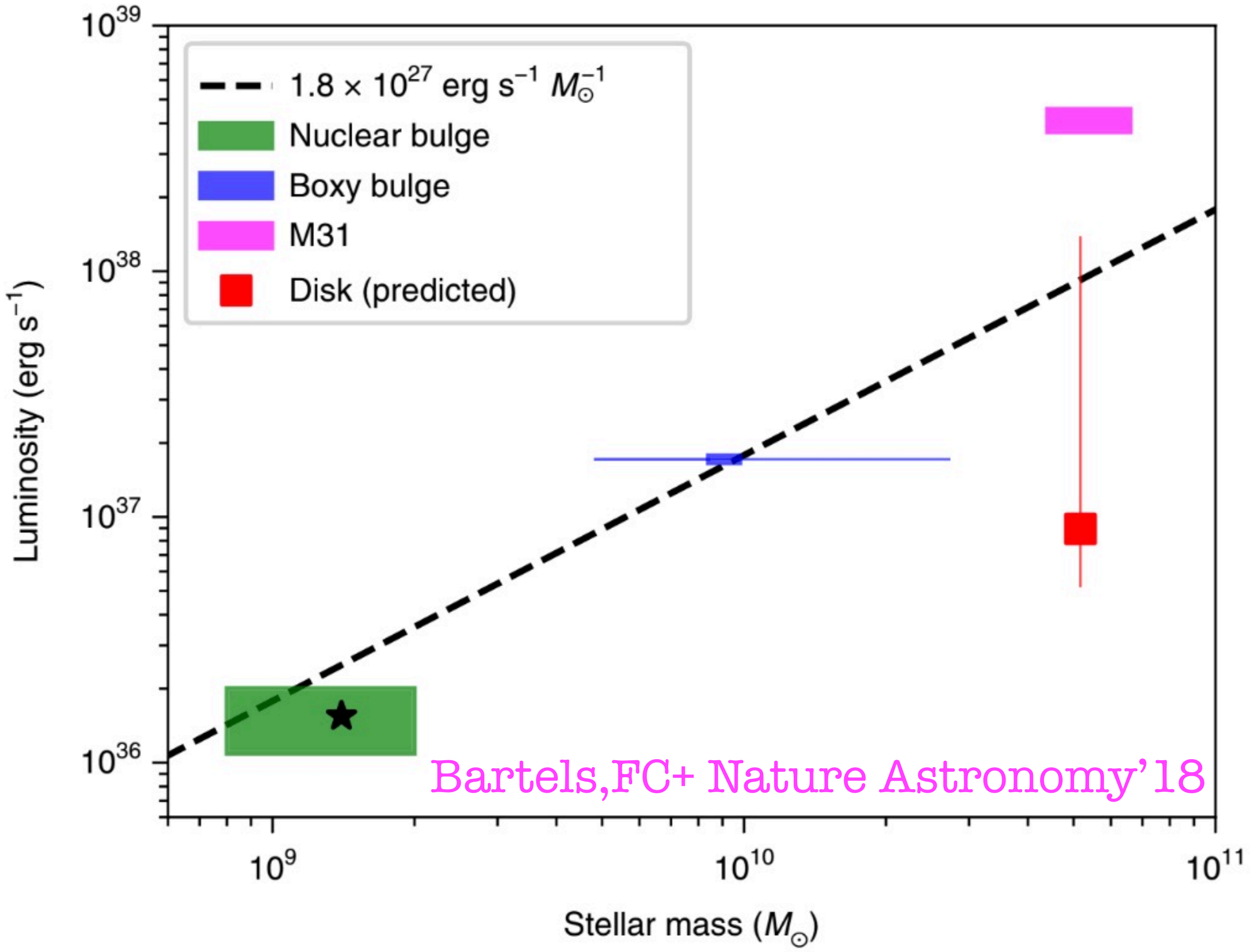




- ✓ Stellar bulge model (boxy + nuclear bulge) is preferred over (spherically symmetric) DM models with high statistical significance (16σ)
- ✓ Morphology of the GCE is more oblate than what found before
- ✓ Large enough ROI to discriminate foreground components (stable results)

[See also Macias+ Nature Astronomy'18]

Gamma-ray to stellar mass ratios



- ✓ Gamma-ray luminosity shows correlation with stellar mass in the Galactic bulge
- ✓ If from MSP: bulge and disk component consistent with each other

Bartels+ MNRAS'18; Eckner+ ApJ'18

- ✓ Debate: In-situ formation of MSP (+ dynamical formation) or from disrupted globular clusters

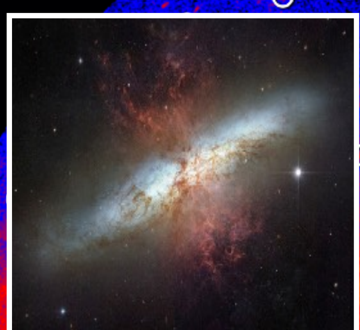
Fragione+1808.02497, MNRAS'18; Eckner+ ApJ'18
Macias+ 1901.03822

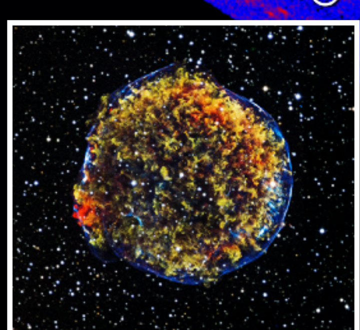
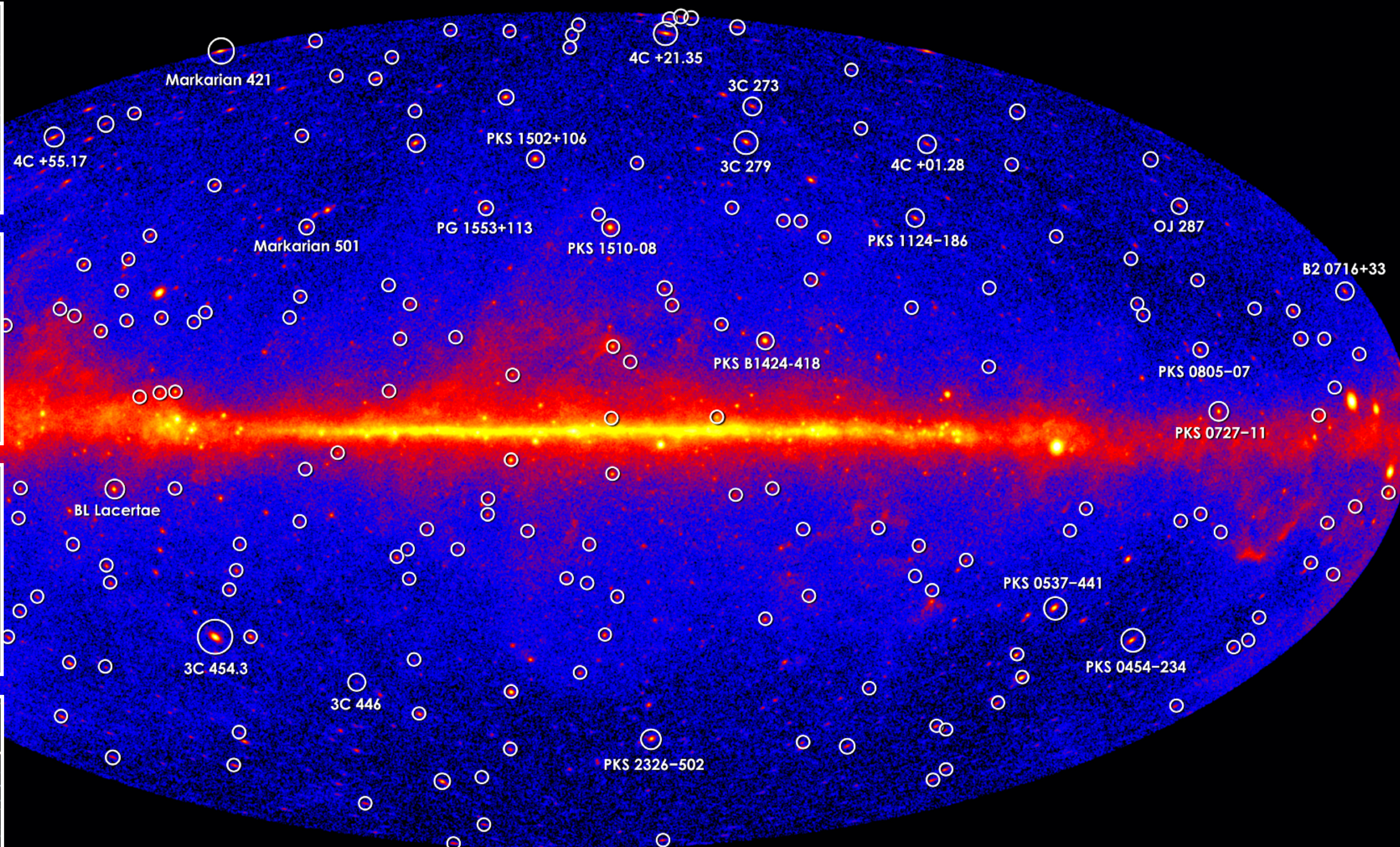
Evidence for gamma-ray emission from old stellar population

=> Should exist a large population of faint gamma-ray emitters dominating to the GeV excess signal

Detected vs unresolved point-like sources

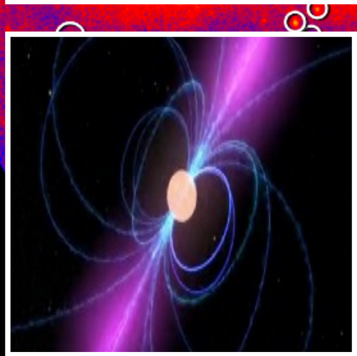
Detected sources

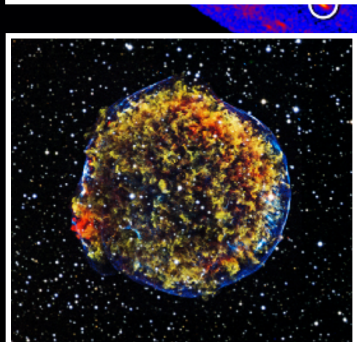



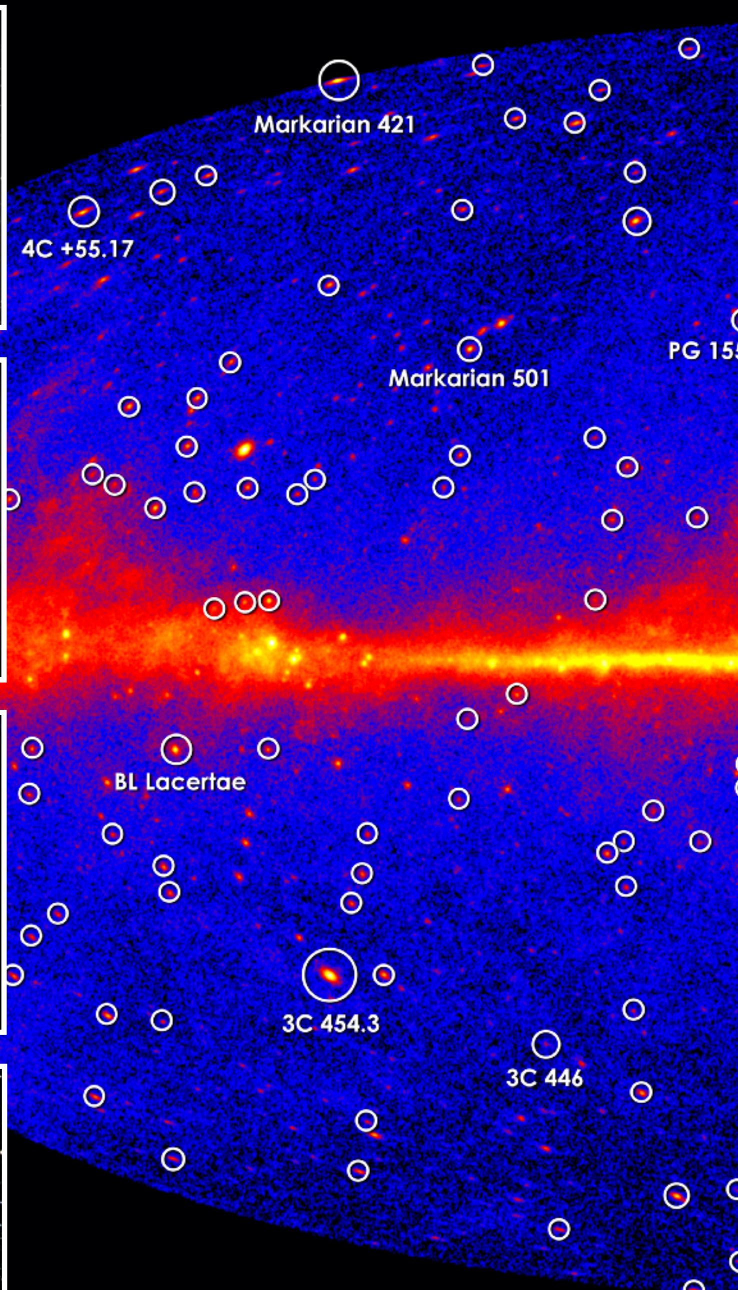



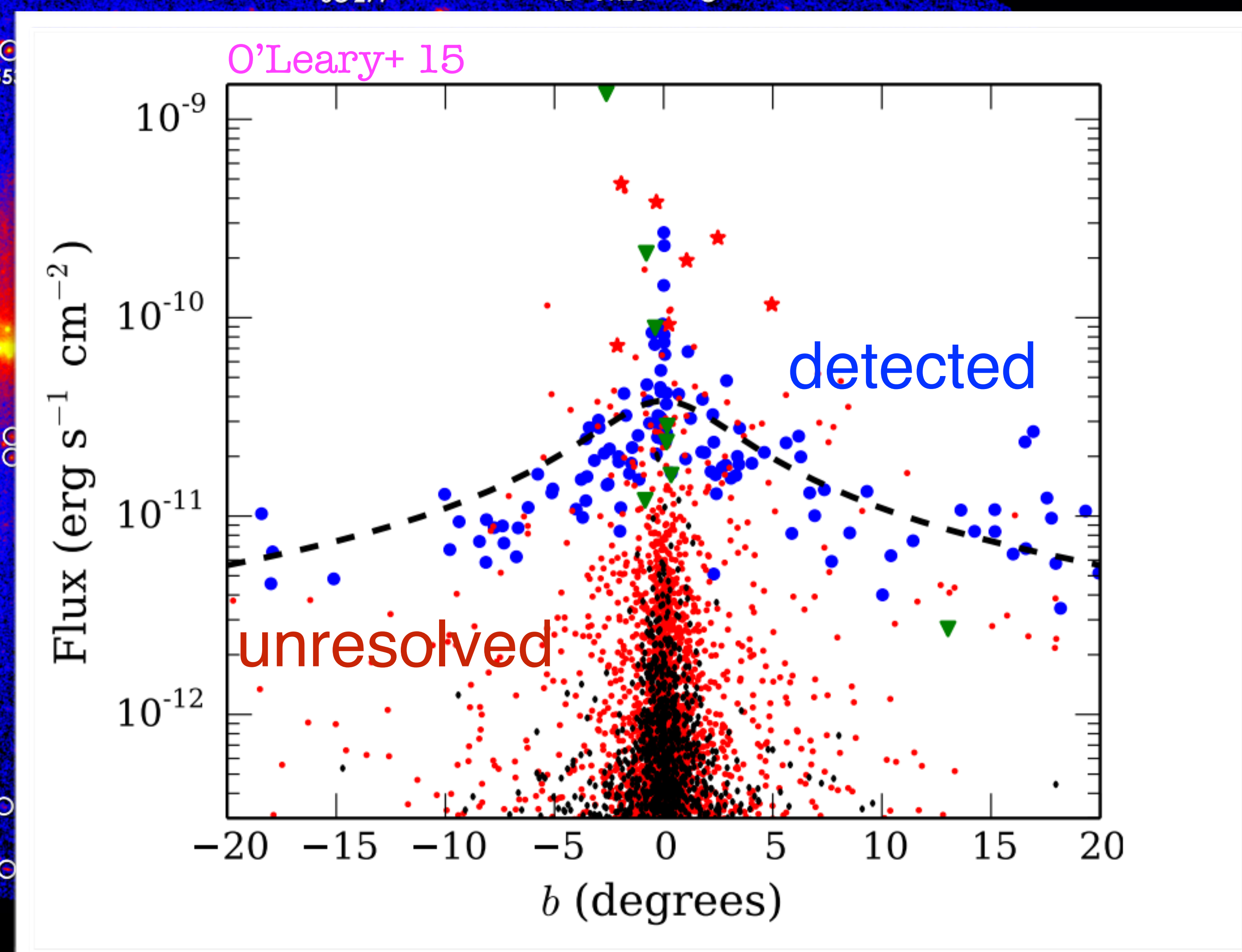
Detected vs unresolved point-like sources

Detected sources



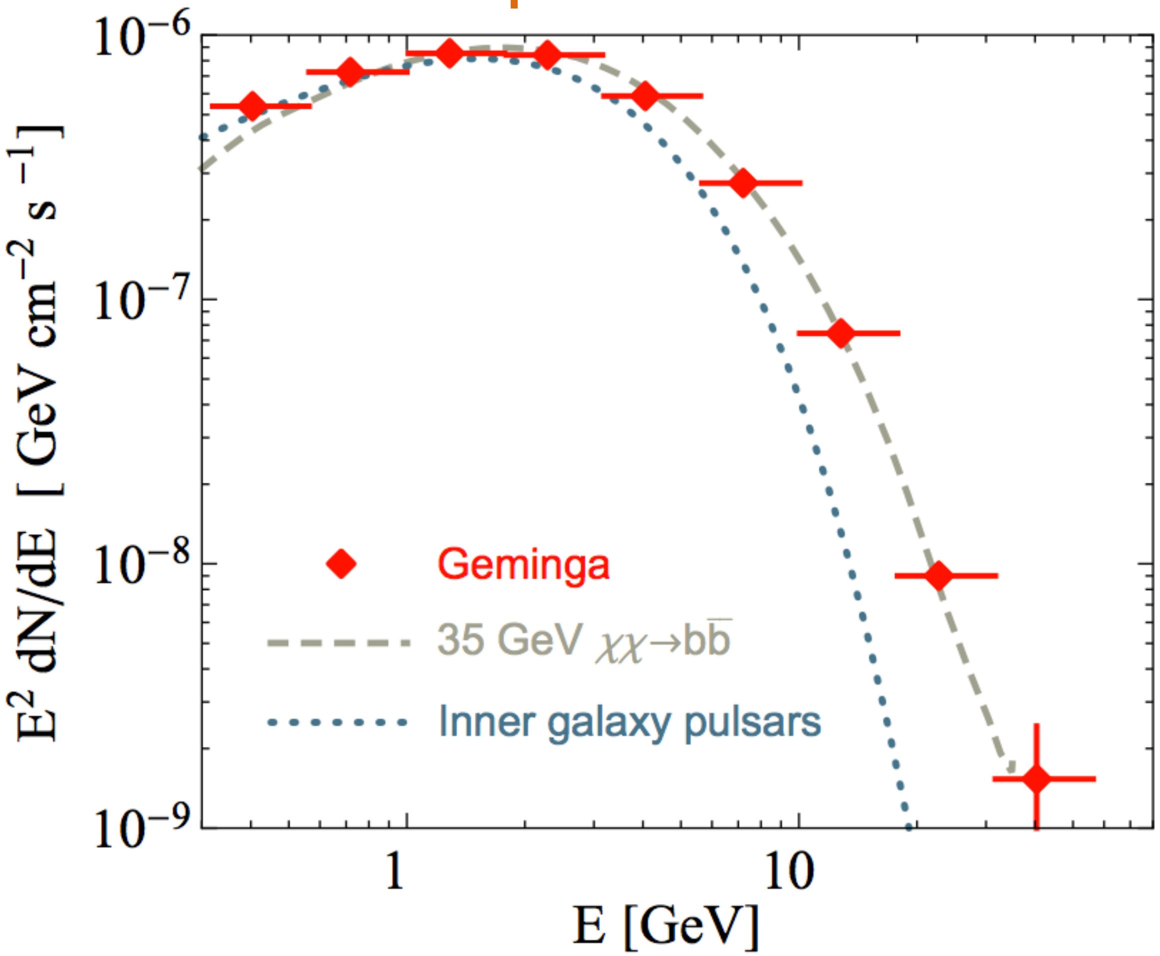






Unresolved pulsars and millisecond pulsars

Spectrum



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

Abazaijan&Kaplinghat'12

Morphology

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

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

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

  Hooper+PRD'14; Petrovic+ JCAP'15; Yuang+ MNRAS'14;

- ✓ Young pulsars from SF in the CMZ, but difficult to explain spatial extent and observed bright ones.

  O'Leary+ '15; Linden PRD'16

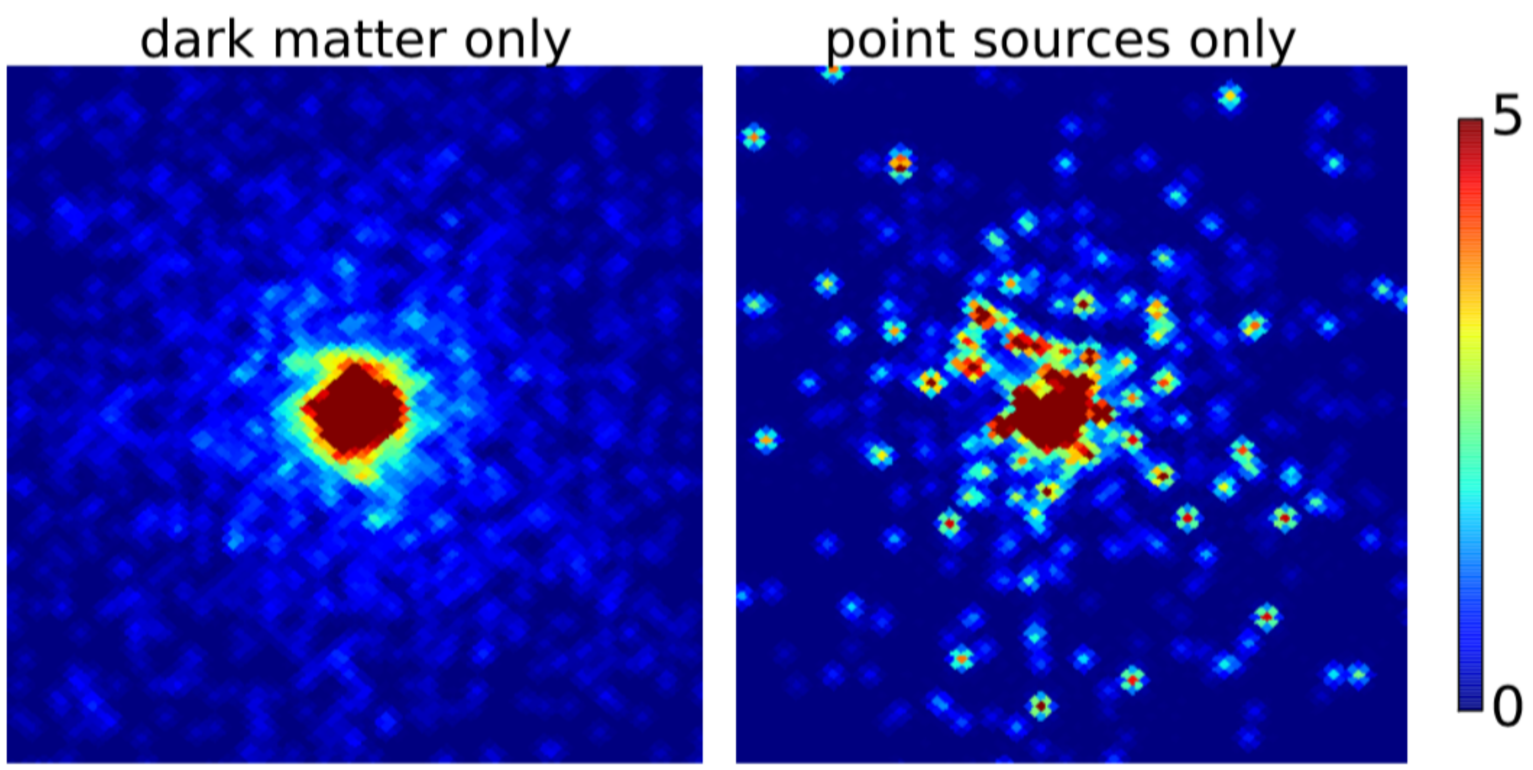
- ✓ Bulge MSPs: from tidally disrupted globular clusters.

  Brandt&Kocsis ApJ'15; Abbate et al. 2017; Fragione et al. 2017; Arca-Sedda et al. 2017

- ✓ Issues in luminosity function of observed MSP and LMXB-to-MSP ratio

  Cholis+'14; Hooper+'15; Hooper&Linden JCAP'16; Haggard+ JCAP'17; Ploeg+ JCAP'17

How to discriminate point sources from diffuse emission?



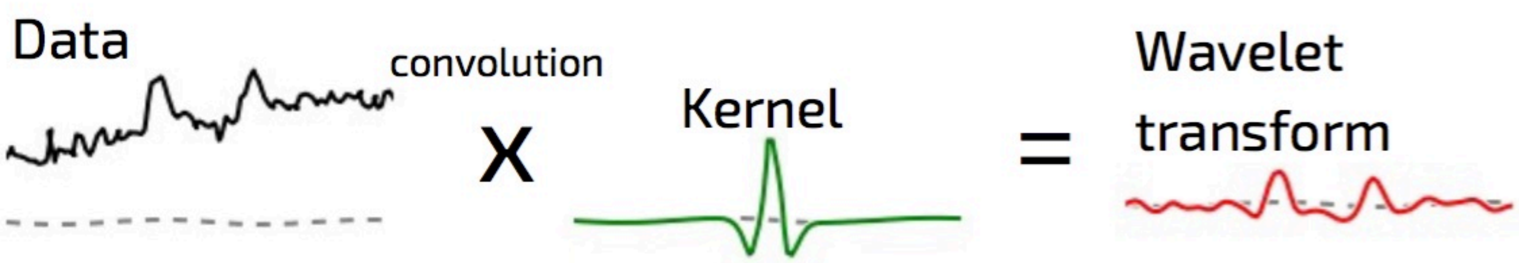
Lee+ JCAP'15

Differences in the statistics of the photon counts can be quantified and used for model comparison.

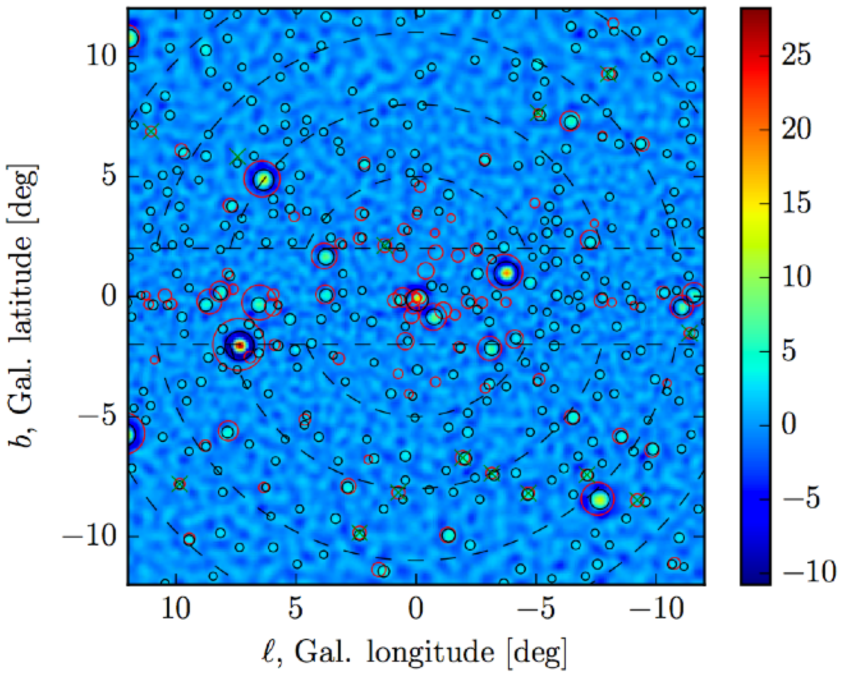
Caveat: Contamination from Galactic diffuse emission.

Support for unresolved point sources

Local maxima of normalised wavelet transform



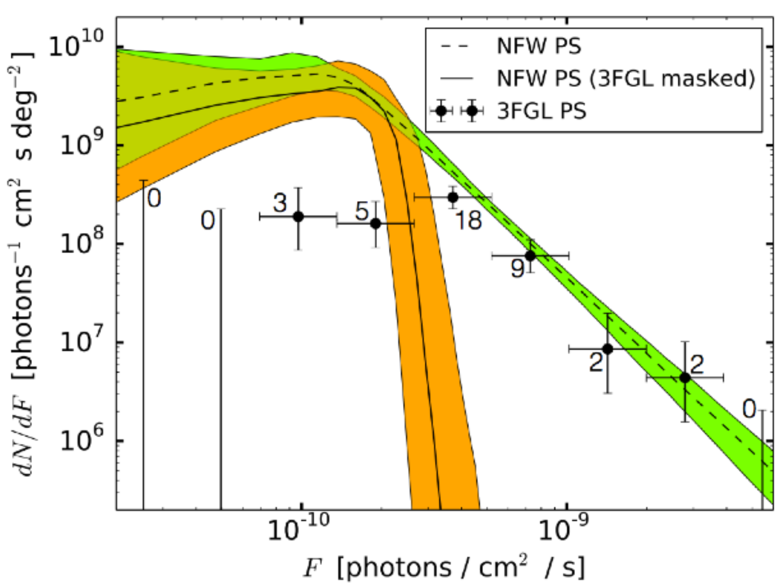
Bartels+ PRL'16

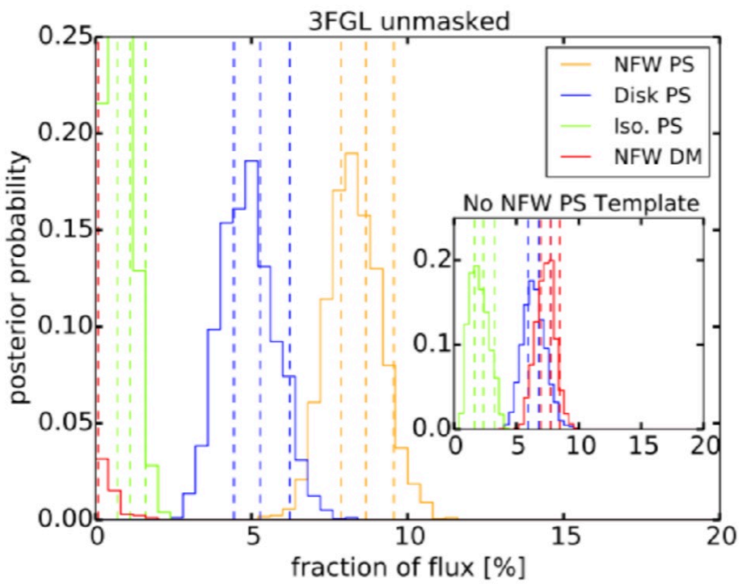


- No background modelling
- Evidence for MSP-like population in the bulge
- Constraints on luminosity function

Non-Poissonian template fitting

Lee+ PRL'16

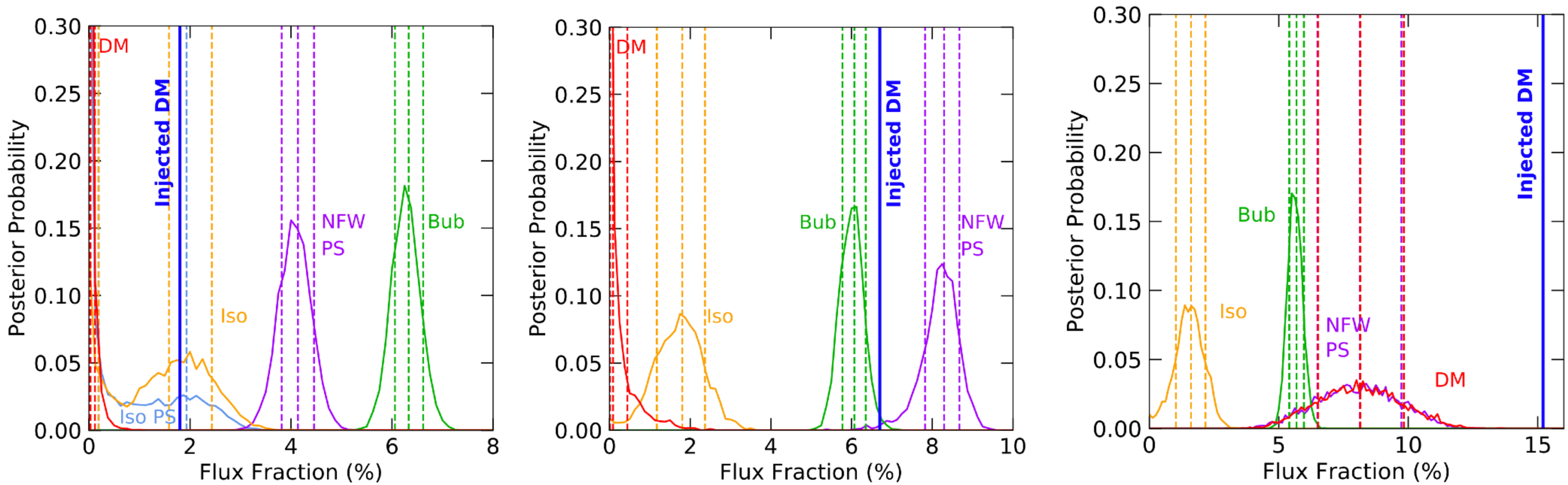




- The statistics of PS is non-Poissonian
- PS NPT NFW distribution absorbs the most of the excess
- A priori, it suffers more form contamination of background modelling

<u>Caveat</u>: Do we model the small scale gas correctly?

NPTF and mis-modelling



Leane & Slatyer 1904.08430

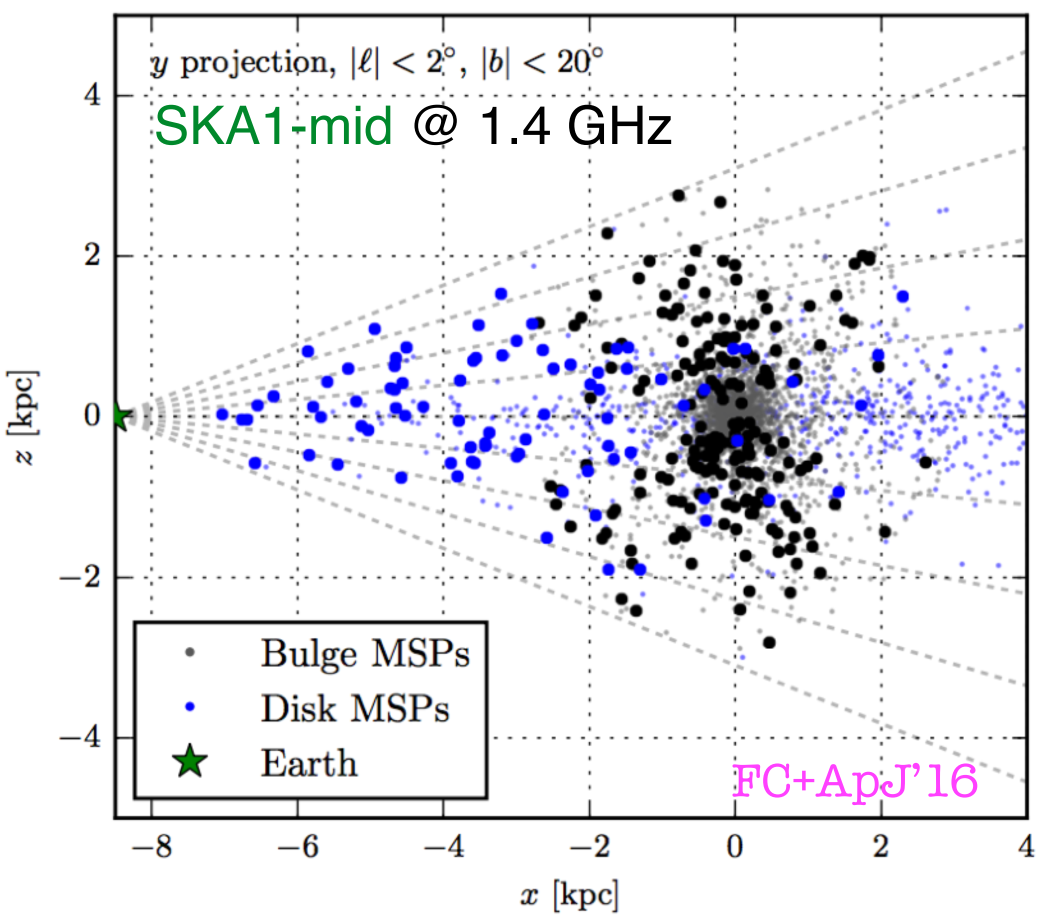
" Dark Matter Strikes Back at the Galactic Center"?

Wavelets methods should be less affected by these issues: evidence for power @ small scales

How to test conclusively PS interpretation of the GeV excess?

Multi-messenger tests of the GeV excess nature

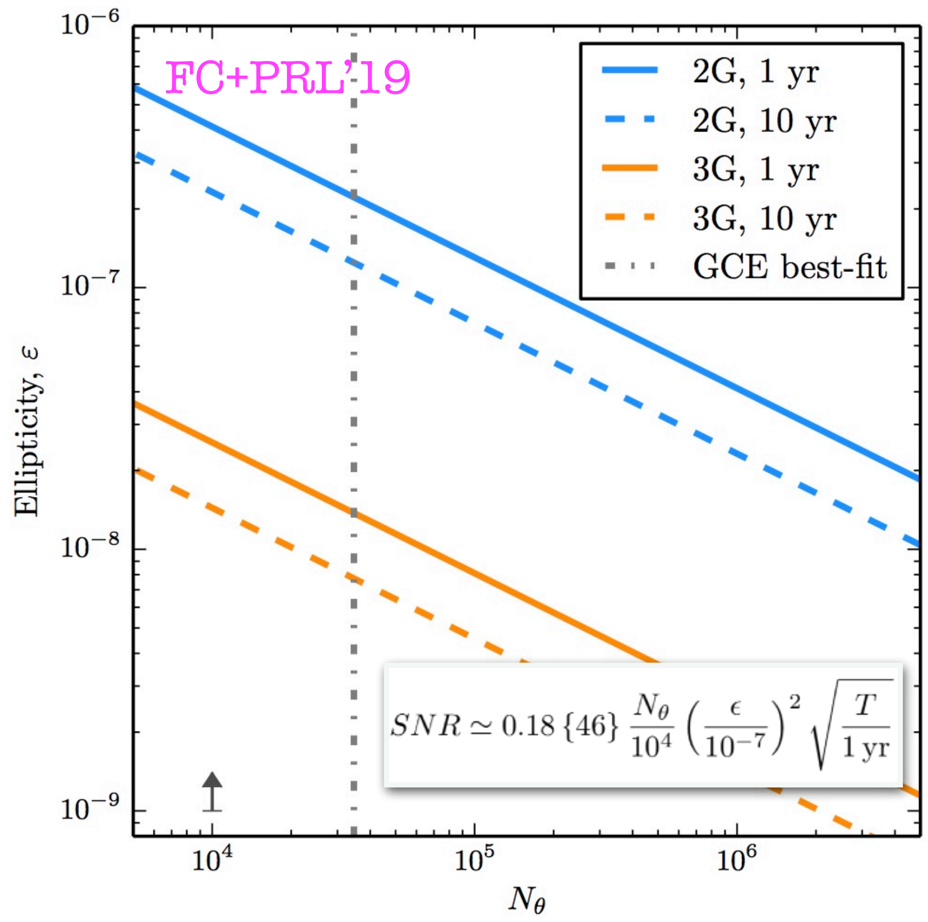
Testing a faint population of millisecond pulsars in the Galactic bulge



- ✓ Current radio telescopes are simply not sensitive to an MSPs population in the Galactic bulge
- ✓ Future radio telescopes can discover this population with a few hundreds hours of observations
- ✓ MeerKAT mid-lat survey ~300h: ~30 bulge MSPs => Enough to discriminate it from the foreground MSP disk population

Multi-messenger tests of the GeV excess nature

Testing a faint population of millisecond pulsars in the Galactic bulge



- ✓ Neutron stars high rotation velocities make any irregularity (ellipticity) in their shape a quadrupolar source of GWs
- ✓ A population of MSPs in the bulge represents the dominant contribution to the stochastic GW background in the LIGO/Virgo sensitivity range
- ✓ This search can provide crucial diagnostics for the GeV excess nature

Conclusions & Outlook

✓ Many questions have been answered thanks to the development of new advanced statistical tools for data analysis

✓ Improved characterisation the GeV excess (spectrum and morphology) but not conclusive determination of its origin

✓ The dark matter origin of the excess becomes less and less likely

- Degeneracy with Fermi bubbles hard emission, i.e. high-energy tail?

  Linden+ PRD'16; Horiuchi+ JCAP'16

- Contribution of molecular clouds in the CMZ?

  Dogiel+ ApJ'18

- Connection with TeV diffuse emission from the GC?

  Hooper&Linden PRD'18; Guepin+ JCAP'18

- Connection with 511 keV positron annihilation line?

  Crocker+ Nature Astronomy'17; Bartels,FC+ MNRAS'18

✓ However, the study of gamma rays from the inner Galaxy has the potential to lead new insights on the population of high-energy compact objects at the Galactic center, and on the formation of the bulge

Galactic binaries: 511 keV line and GC excess

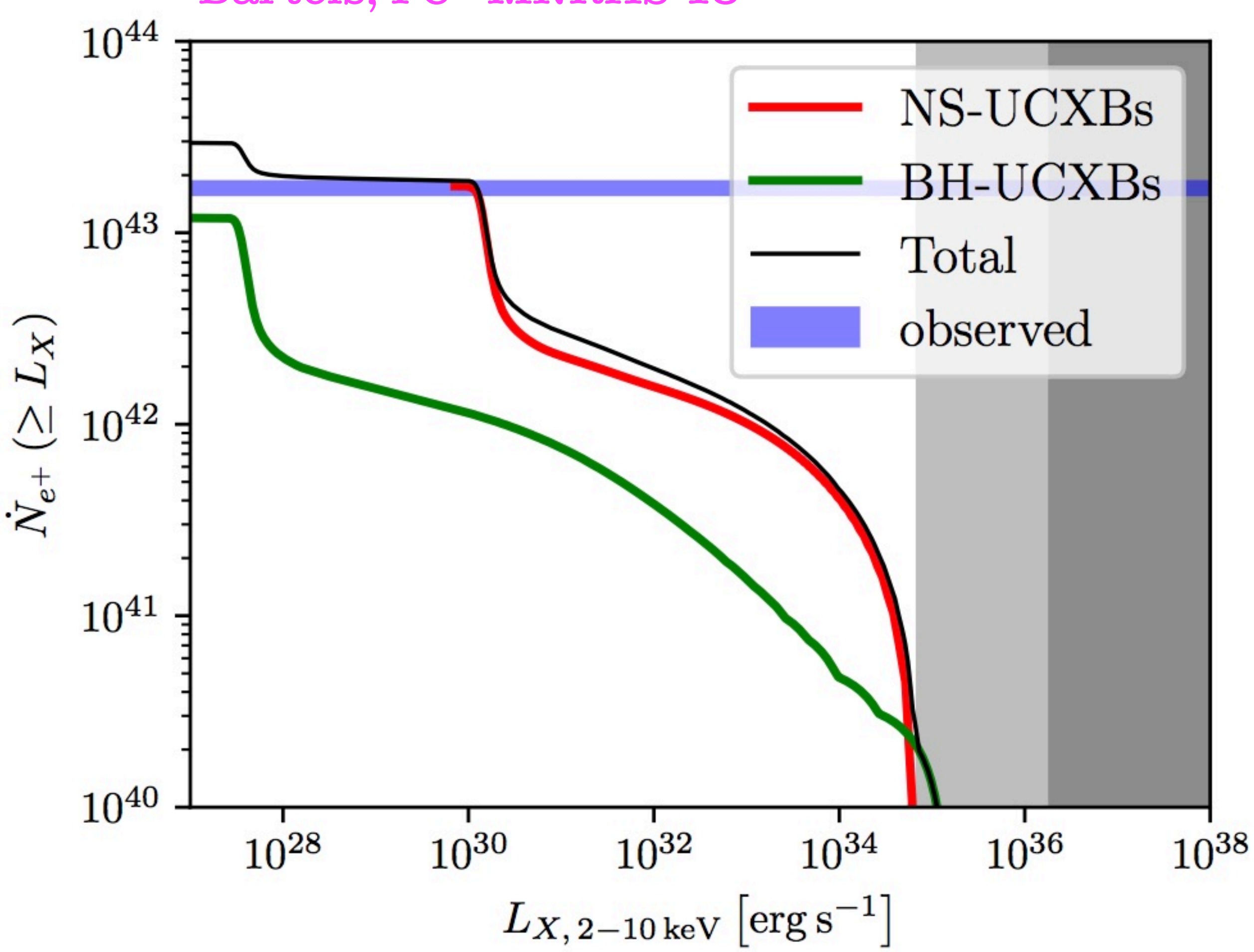
Bartels, FC+ MNRAS'18

Scenario:

- Population synthesis of ultra-compact X-ray binaries predicts about 2×10^5 NS-UCXB in the bulge, which leads also to $\sim 10^5$ MSPs van Haaften+ A&A'13,'15
- NS-UCXB progenitors of "recycled" MSPs that explain the GeV excess
- NS(BH)-UCXB in hard state with low accretion rates are jet dominated Deller+ ApJ'15; Fender+MNRAS'03
- Positron from cold, mildly relativistic, leptonic jets

Guessoum+ A&A'06; Bandyopadhyay+ MNRAS'09; Siegert+ A&A'16

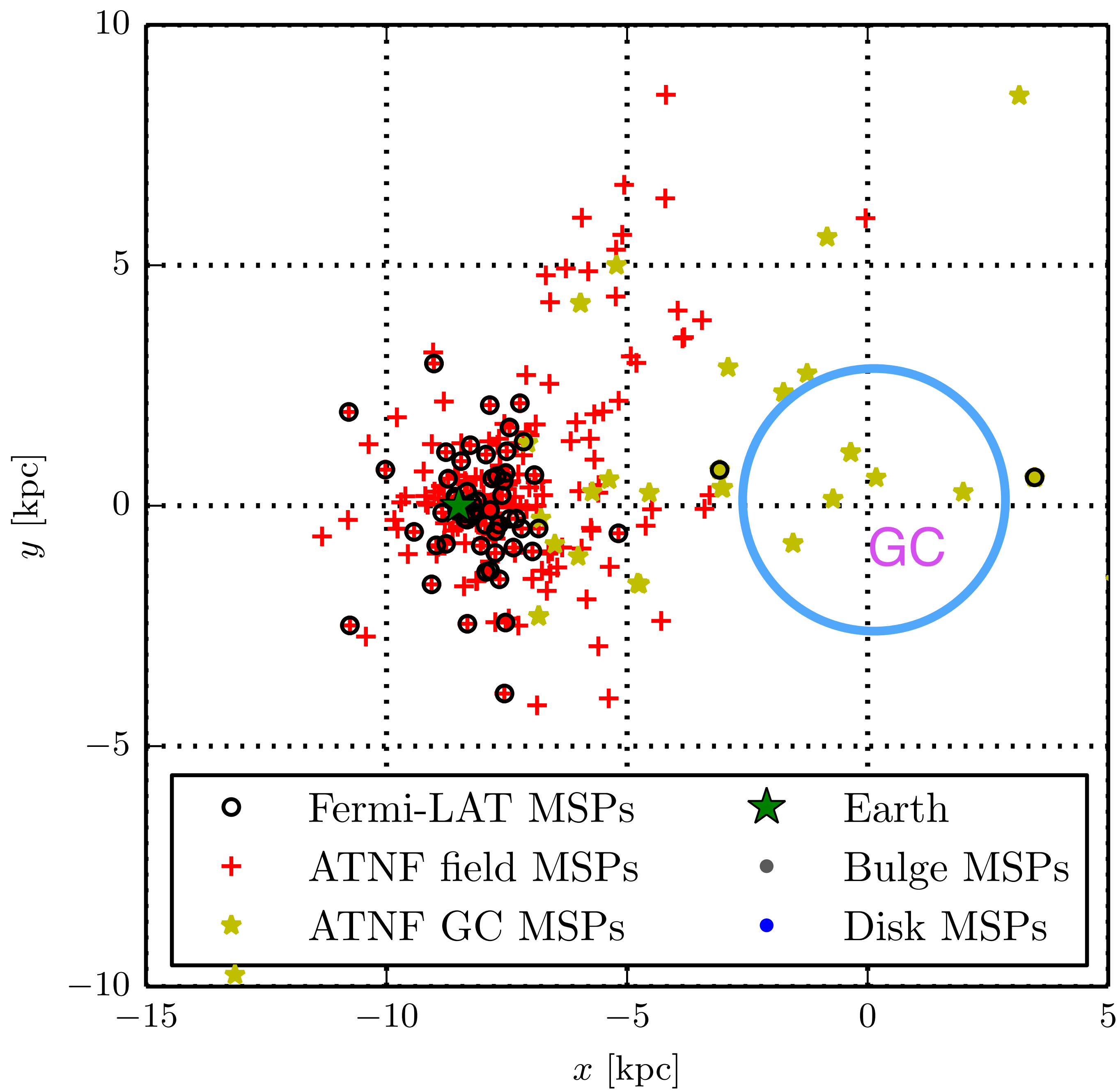
Bartels, FC+ MNRAS'18



Results:

- ✓ Can supply the required positron/ electron yield
- ✓ Can be tested with future observations of Milky Way globular clusters

Known MSPs in the radio sky



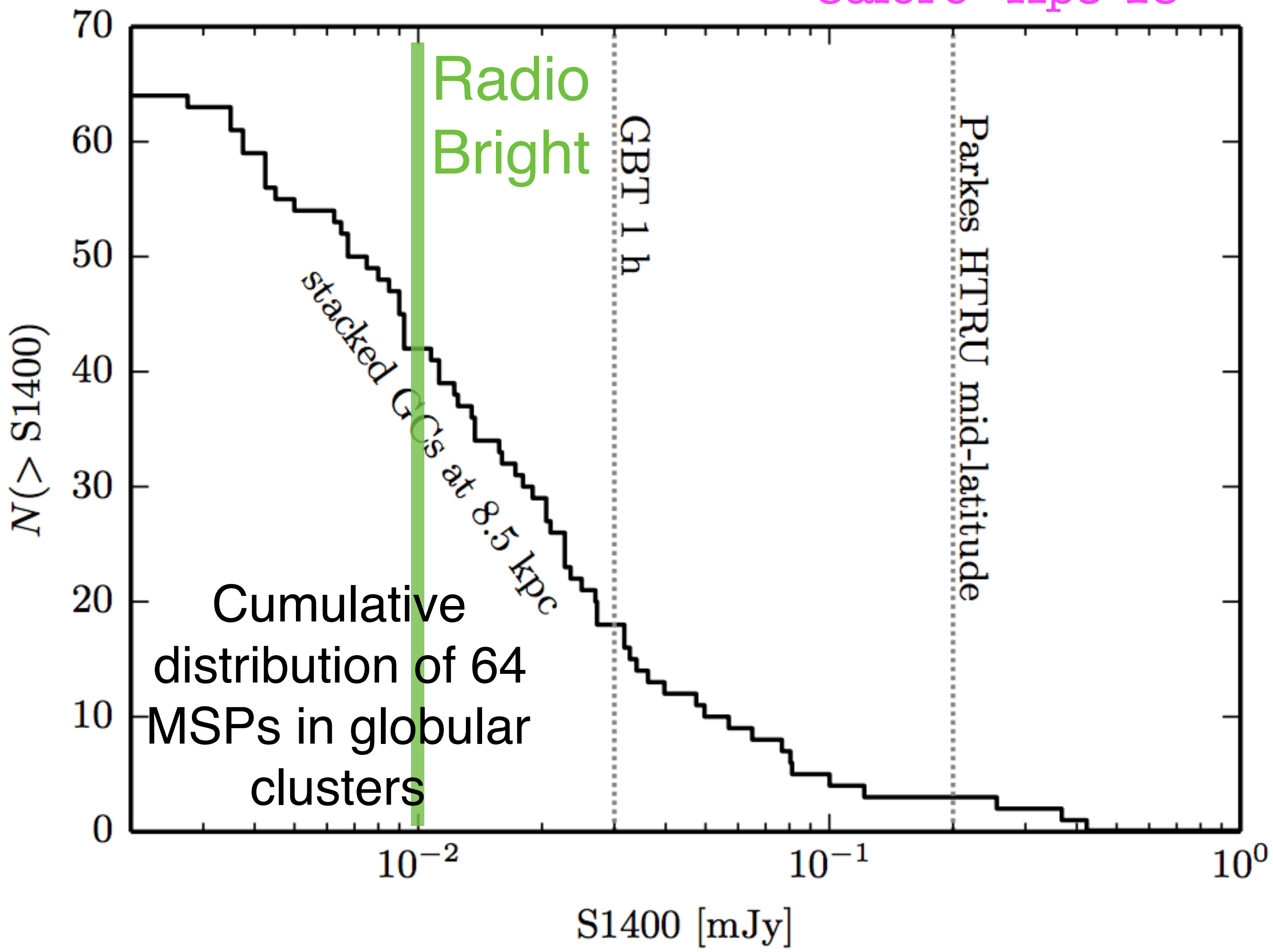
- About 370 MSPs in radio, P < 30 ms.
- Most sources are local, within 3-4 kpc from Earth.
- Among the sources in the GC l.o.s (lbl < 10º & lll < 10º), only a few in the inner 2 kpc.
- Only 5 globular clusters in the inner 2 kpc.
- Young pulsars more abundant.
- Clear selection effects.

Modelling the bulge MSP population

Assumptions:

- MSPs responsible of the Fermi GeV excess (dominant part) — total intensity, spectrum and morphology.
- Bulge MSPs have similar properties to MSPs in globular clusters.
- The whole gamma-ray emission from globular clusters comes from MSPs.
- We are interested in average emission properties.

Calore+ ApJ'16



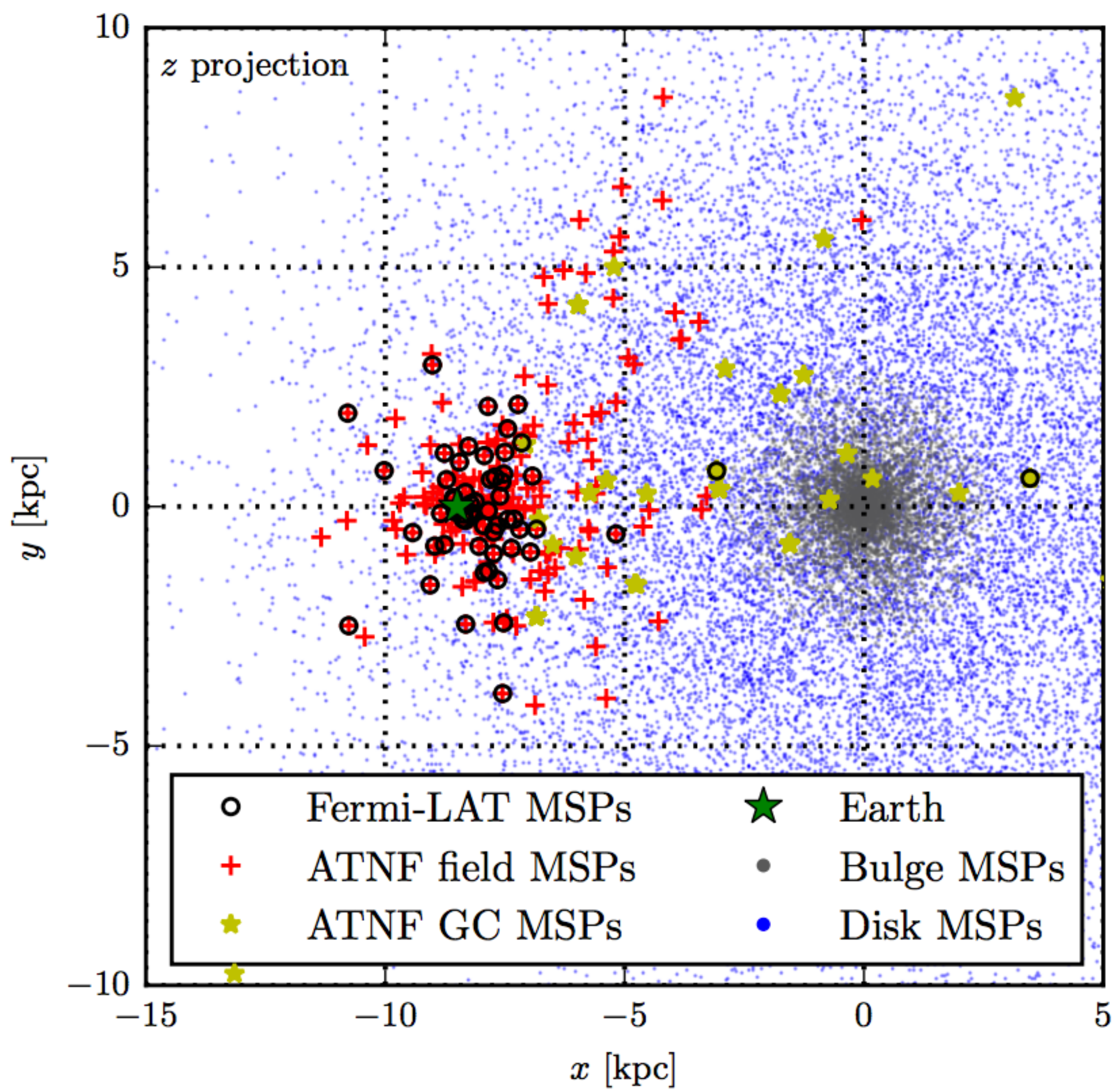
Bagchi+MNRAS'11

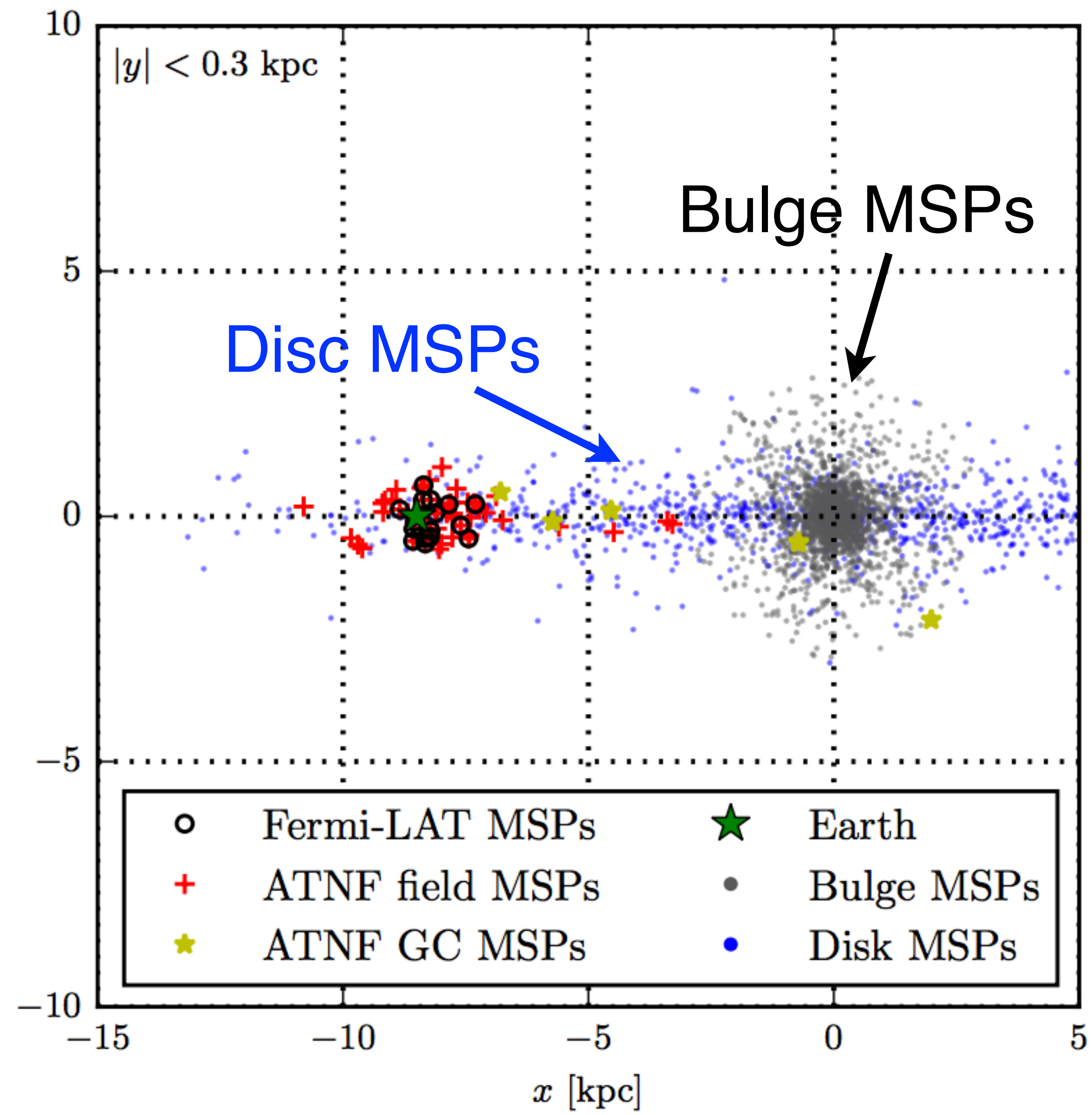
Luminosity function (μ, σ)	$N_{\rm rad}^{\rm stacked}$	$N_{\rm rb}^{\rm stacked}(d \simeq 8.5\,{\rm kpc})$
Model 1 $(-1.1, 0.9)$	514 ± 71	74 ± 10
Model 2 $(-0.61, 0.65)$	339 ± 49	80 ± 12
Model 3 $(-0.52, 0.68)$	264 ± 37	76 ± 11

$$N_{\rm rb}^{\rm bulge} = (2.7 \pm 0.9) \times 10^3$$

$$N_{\rm rad}^{\rm bulge} = (9.2 \pm 3.1) \times 10^3$$

Modelling the bulge MSP population





- O(10000) MSPs in the bulge, such to account for gamma-ray observations.

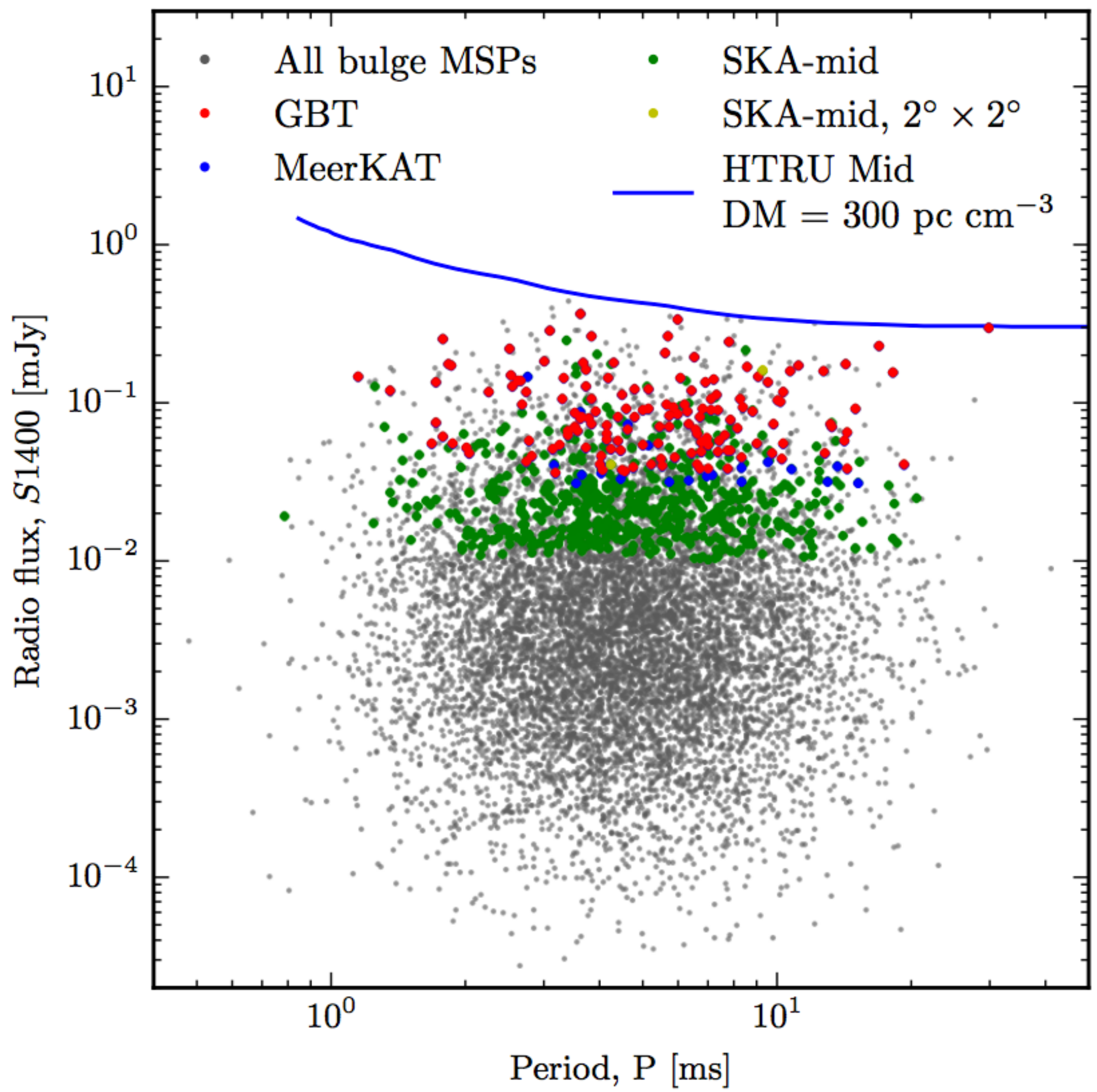
$$\epsilon \propto r^{-\Gamma} e^{-r/R_{\rm cut}} \qquad \Gamma = 2.5 \qquad R_{\rm cut} = 3\,{\rm kpc}$$

- O(20000) MSPs in the disc, radio luminosity of observed local radio sources.

Sensitivity of radio telescopes

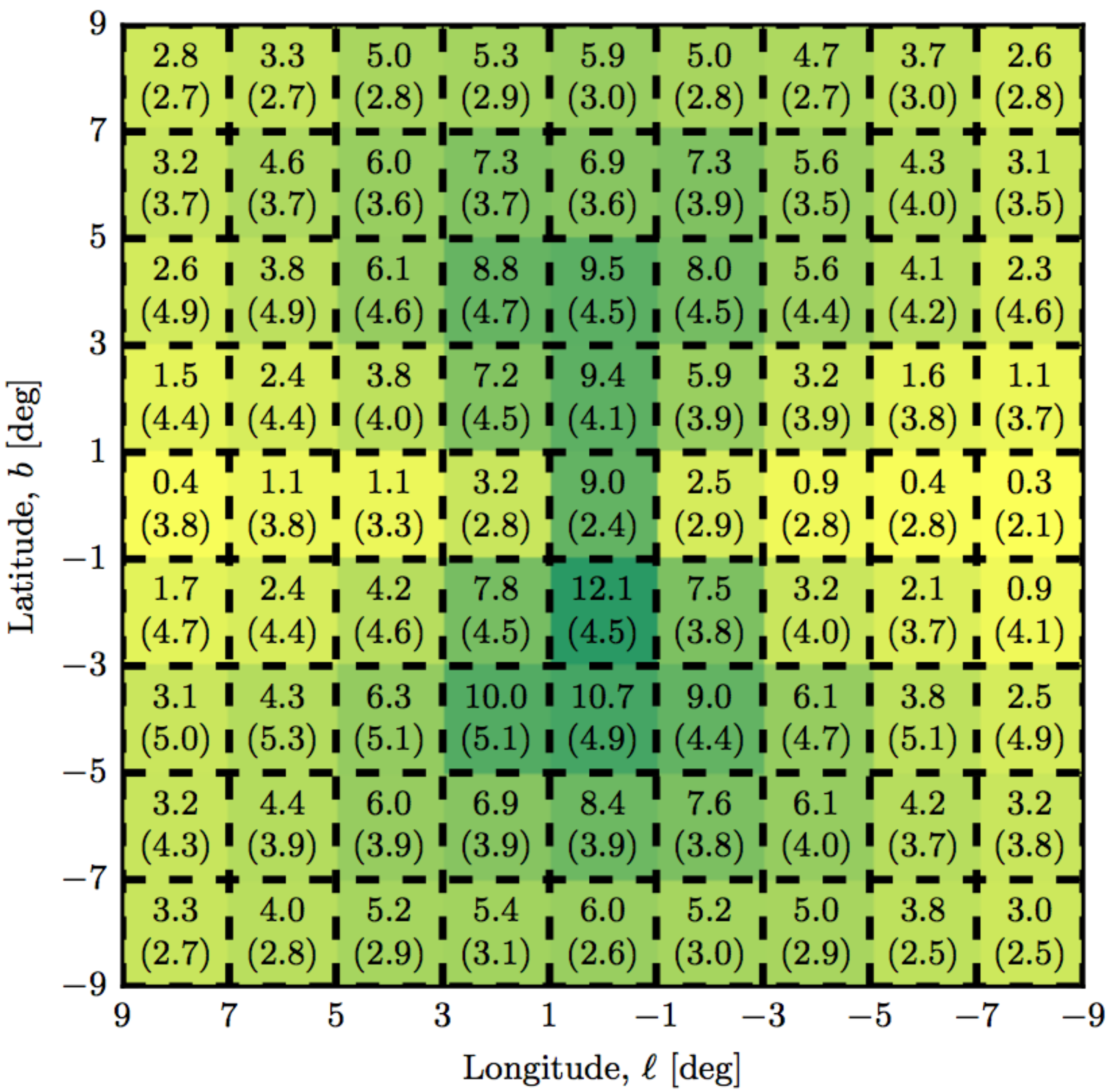
$$S_{\nu,\mathrm{rms}} = \frac{T_{\mathrm{sys}}}{G\sqrt{t_{\mathrm{obs}}\,\Delta\nu\, n_p}}\left(\frac{W_{\mathrm{obs}}}{P - W_{\mathrm{obs}}}\right)^{1/2} \qquad W_{\mathrm{obs}} = \sqrt{(w_{\mathrm{int}}P)^2 + \tau_{\mathrm{DM}}^2 + \tau_{\mathrm{scatt}}^2 + \tau_{\mathrm{samp}}^2 + \tau_{\Delta\mathrm{DM}}^2}$$

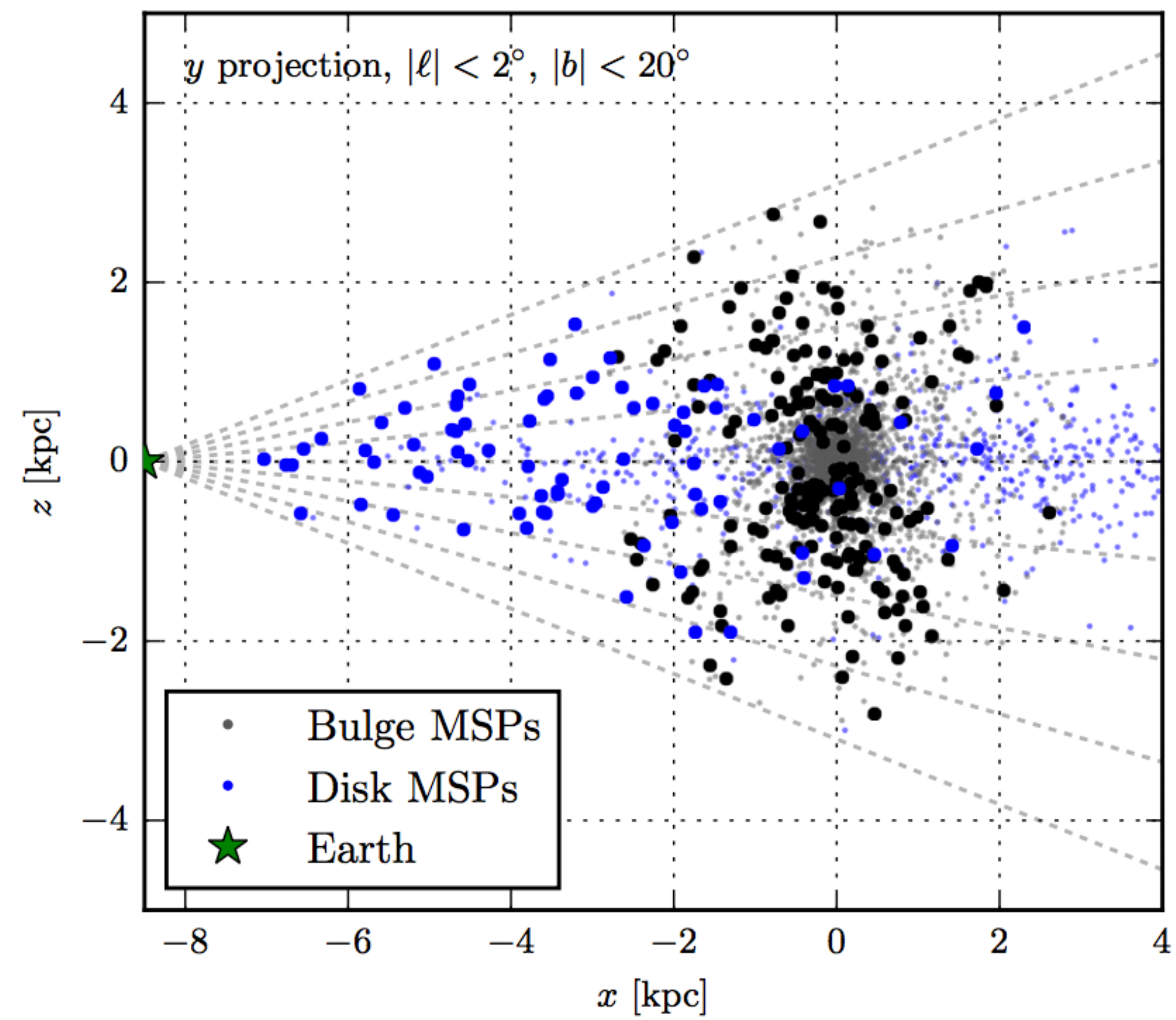
- Mid-latitude past surveys (|b| > 5°) not optimal for MSPs searches at the GC (too shallow, ca 200 sec).
- 3 observational scenarios: GBT, MeerKAT, SKA1-mid (T = 20 min, 1.4 GHz).
- Already with current instruments it is possible to achieve good sensitivities.



Detection prospects with radio surveys

SKA1-mid @ 1.4 GHz (T_{4deg^2} = 3.5 hr)





- ✓ Deep (100 hrs) surveys of deg² regions in the inner Galaxy with O(100) detections.
- ✓ Most promising strategy for future radio telescopes, like MeerKAT and SKA.
- ✓ Not feasible with GBT or VLA.

GW from MSPs (and pulsar)

- Quadrupolar emission of GW from a triaxial, non precessing, rapidly rotating star (period P)

$$f = 2/P$$

$$L_{\rm GW} = \frac{2048\pi^6 G}{5c^5}\frac{I^2\varepsilon^2}{P^6}$$

$$\varepsilon \equiv \frac{I_{xx} - I_{yy}}{I_{zz}} \propto Q$$

$$|\varepsilon| \ll 1$$

$$I_{xx} \simeq I_{yy} \simeq I_{zz} = I$$

- **Ellipticity**: Asymmetry can originate from elastic strains in the crust or strong internal, toroidal B fields. Not universal value.

$$\epsilon \approx 4.5 \times 10^{-7} \left(\frac{B_{\rm p}}{10^{14}\,{\rm G}}\right)^2 \left(1 - \frac{0.389}{\Lambda}\right)$$

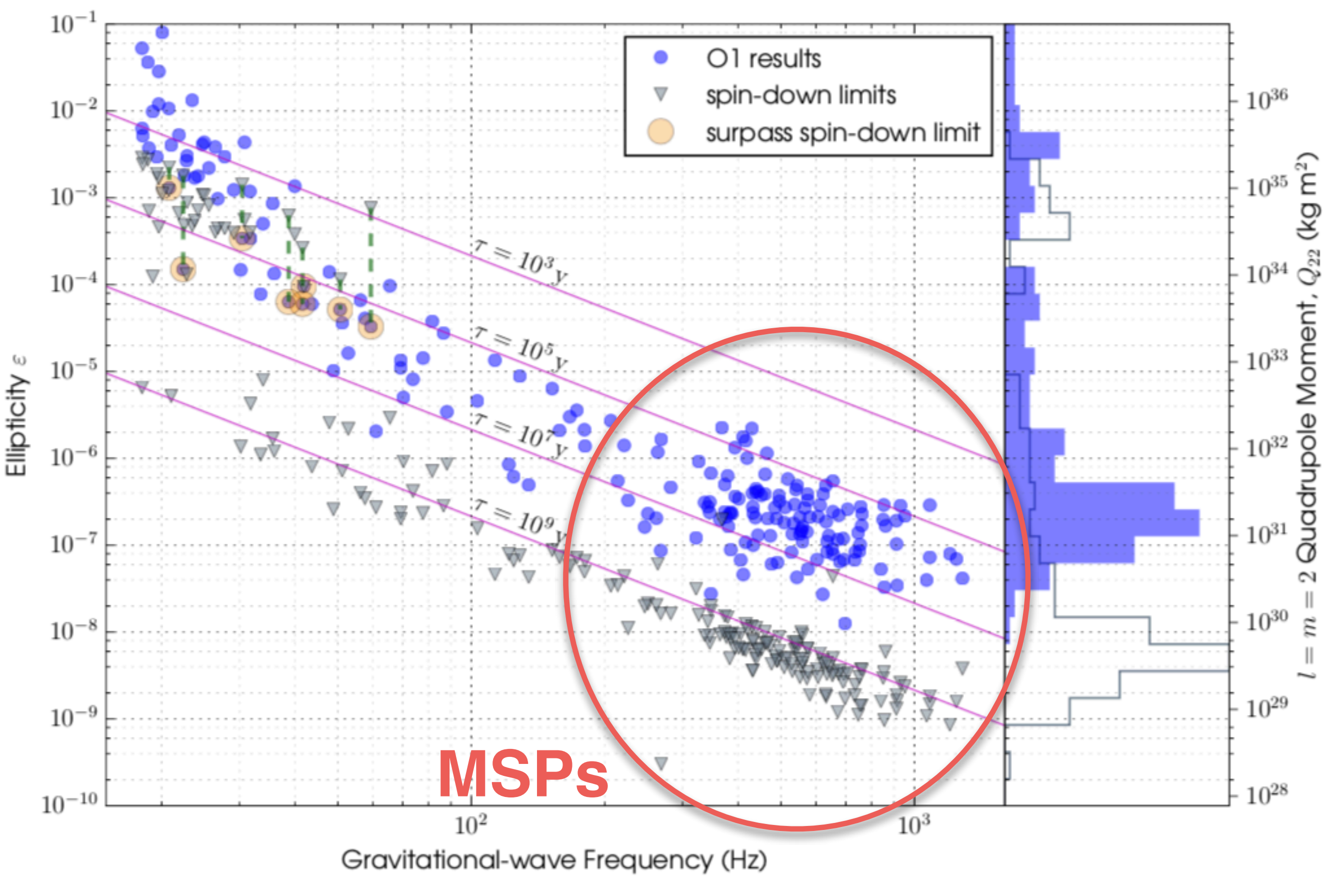
Mastrano+MNRAS'11

- Other mechanisms can induce GW, e.g. instability in the r-modes of the rotating star [not considered here]

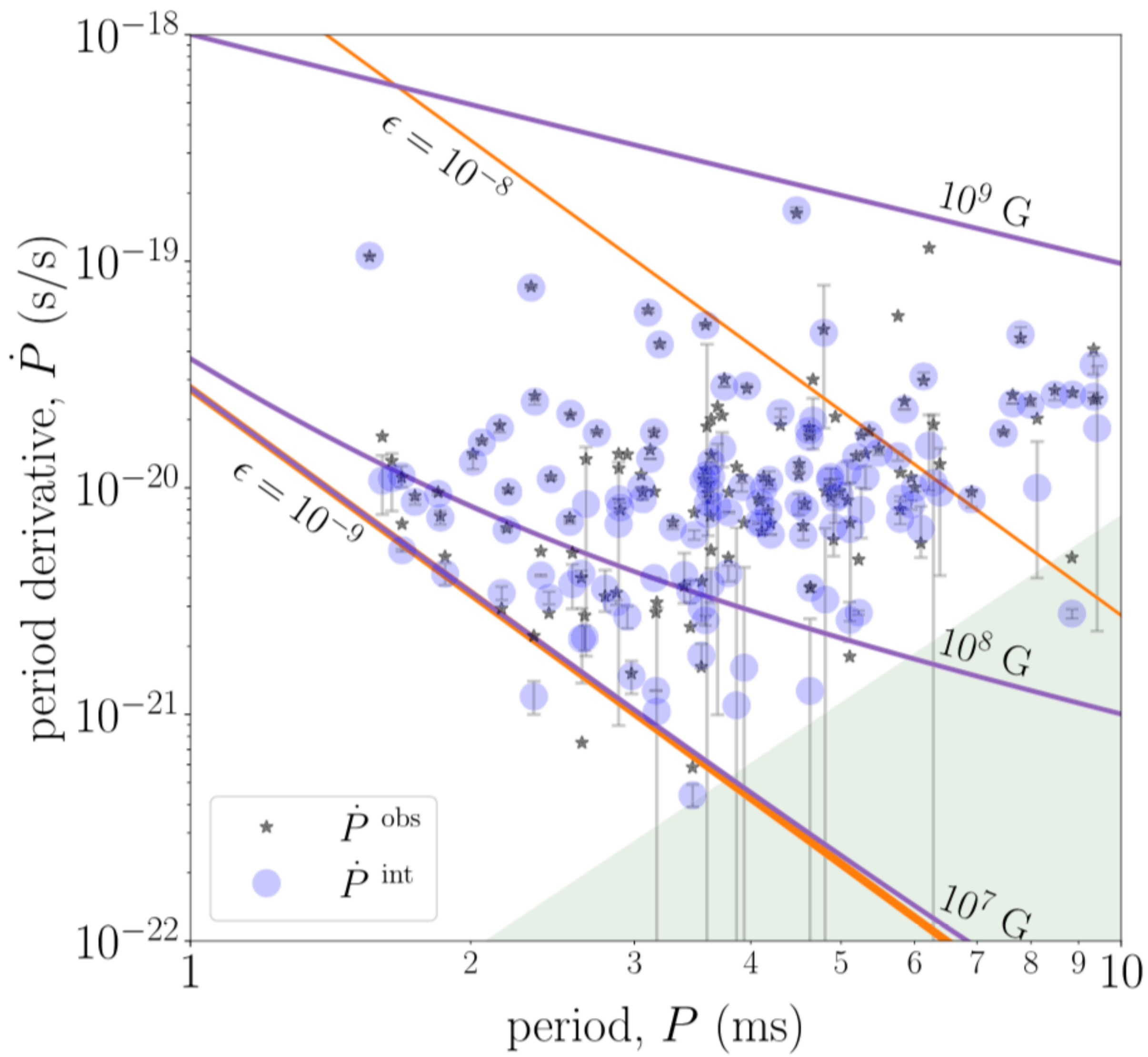
Andersson+ApJ'98; Owen+PRD'98

Under the hypothesis that the GCE is due to MSPs, what is the expected signal in GWs?

Current bounds on ellipticity



Abbott+ ApJ'17



Woan+ ApJL'18

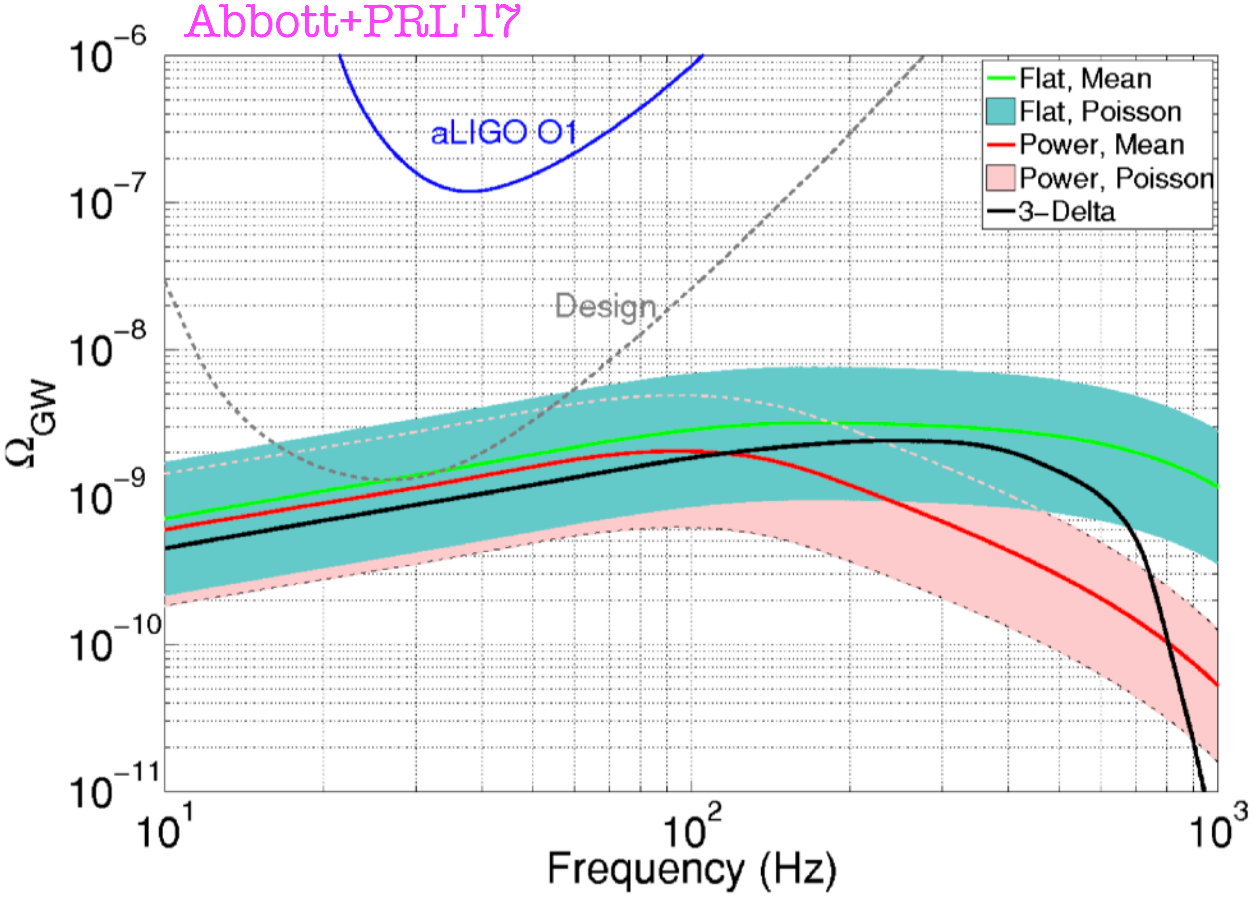
Searches towards *known* pulsars

Lower limit on MSPs ellipticity

The Stochastic GW bkg

- Arises mostly from the superposition of GWs from a large number of unresolved sources: unresolved compact binary coalescences, rotating neutron stars, supernovae, etc.
- Dominated by compact binary coalescences.
- Current searches and sensitivities to the SGWB (isotropic and directional, O1 run) sets upper limits on the energy density of the SGWB assuming a specific frequency spectrum.

Abbott+PRL'17



Galactic Pulsars/MSPs can contribute to the SGWB

Giazzotto+PRD'97

We expect the MSP population in the Galactic bulge to be the **strongest Galactic SGWB** component in the LIGO/ Virgo sensitivity band.

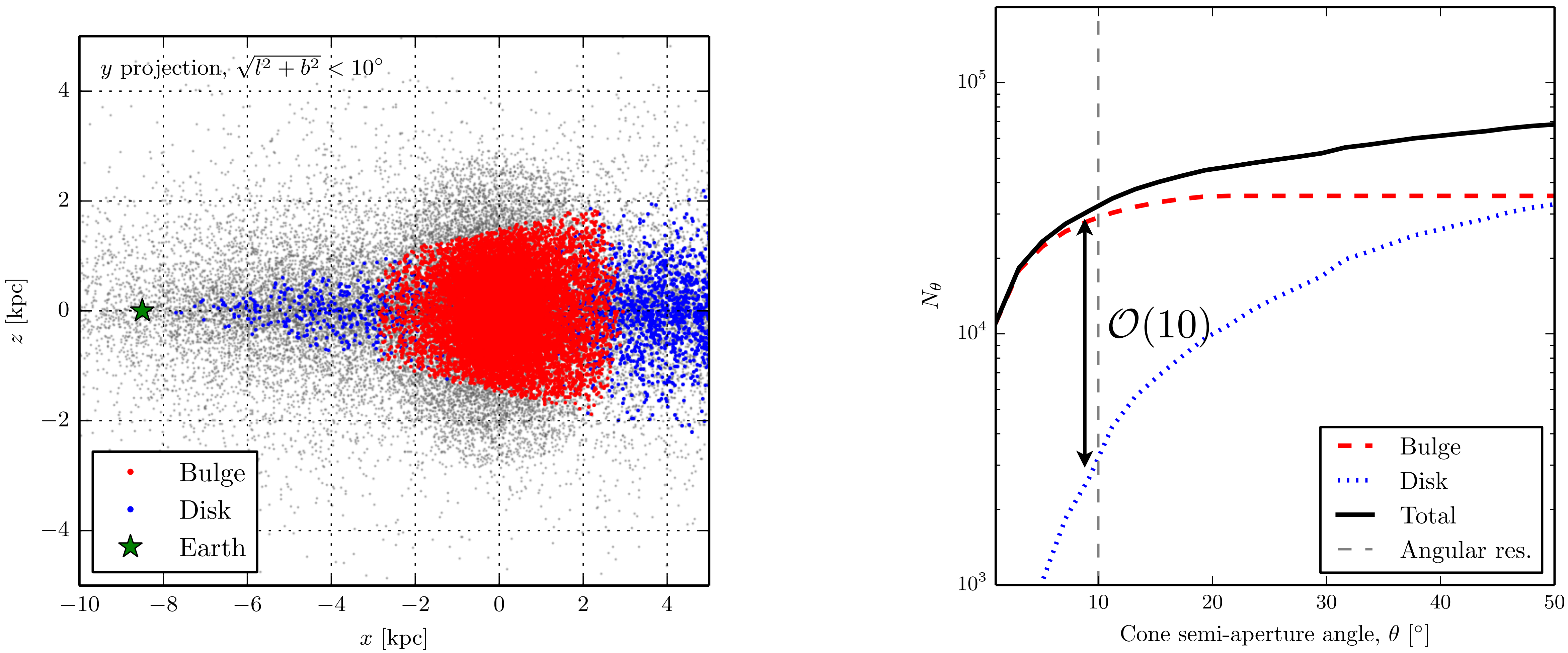
SWGB from MSPs in the bulge

- Modelling of the MSP population in the Galactic bulge based on gamma-ray results from analyses of the MSP source population and GeV excess
- Spatial distribution matches the spatial properties of the GeV excess
- Total number of sources is set by the GCE intensity and the MSP luminosity function.

Bartels+MNRAS'18

- Hypothesis: 1. GCE emission all due to bulge MSPs; 2. gamma-ray luminosity function of bulge MSPs is the same as the one of disk MSPs

-

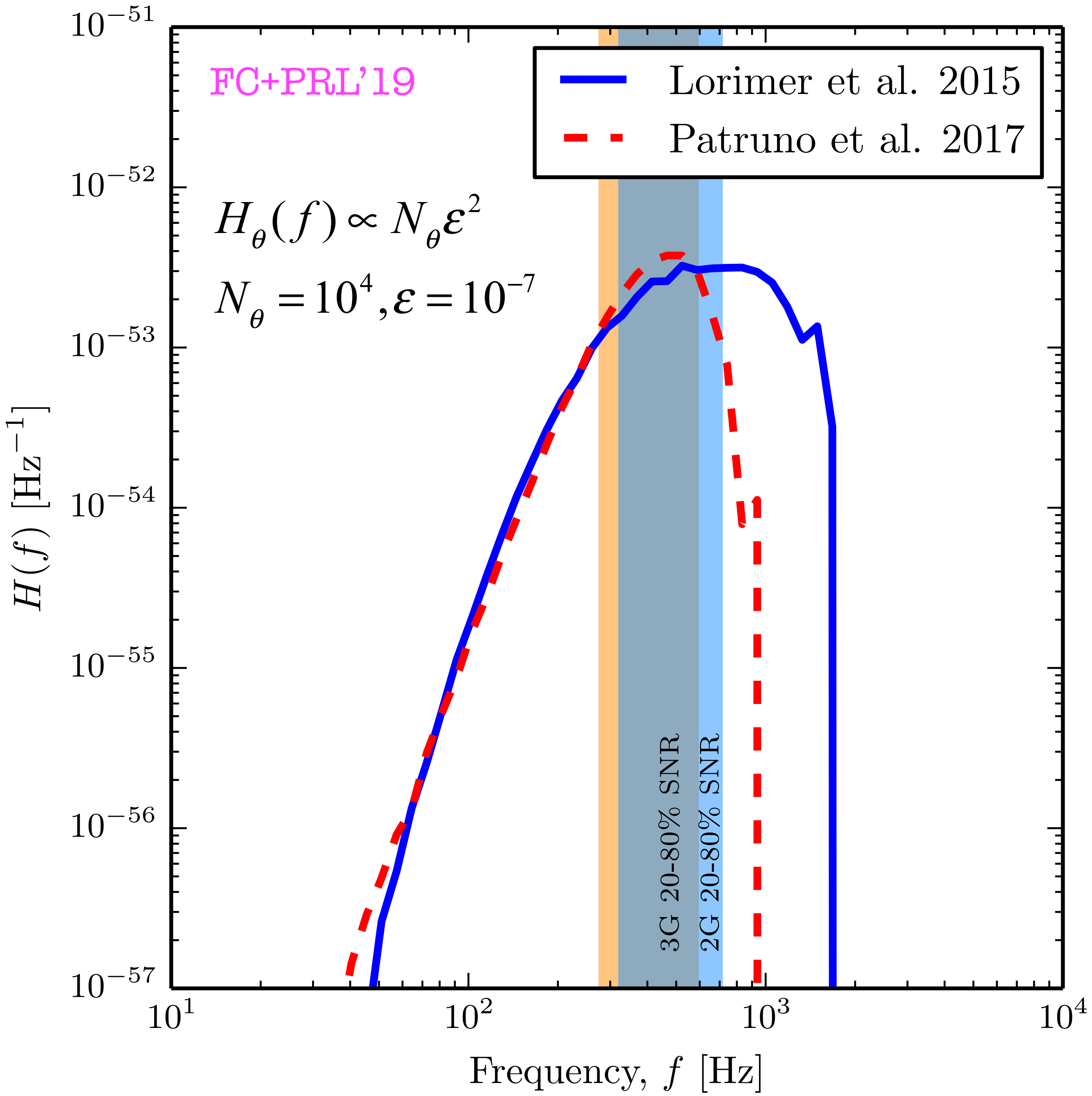


Bulge MSPs dominate over disk MSPs => Leading contribution to the Galactic SGWB

SWGB from MSPs in the bulge (con't)

GW power spectral density

$$H_\theta(f) = \frac{32\pi^4 G^2}{5\,c^8}\varepsilon^2 I^2 f^4 \mathcal{P}(f) \int_{\rm l.o.s.} \frac{\mathcal{N}_\theta(s)}{s^2} ds$$



$$N_\theta \equiv d_{\rm GC}^2 \int_{\rm l.o.s.} \frac{\mathcal{N}_\theta(s)}{s^2} ds$$

$$\mathcal{N}_\theta(s) = N_\theta \delta(s - d_{\rm GC})$$

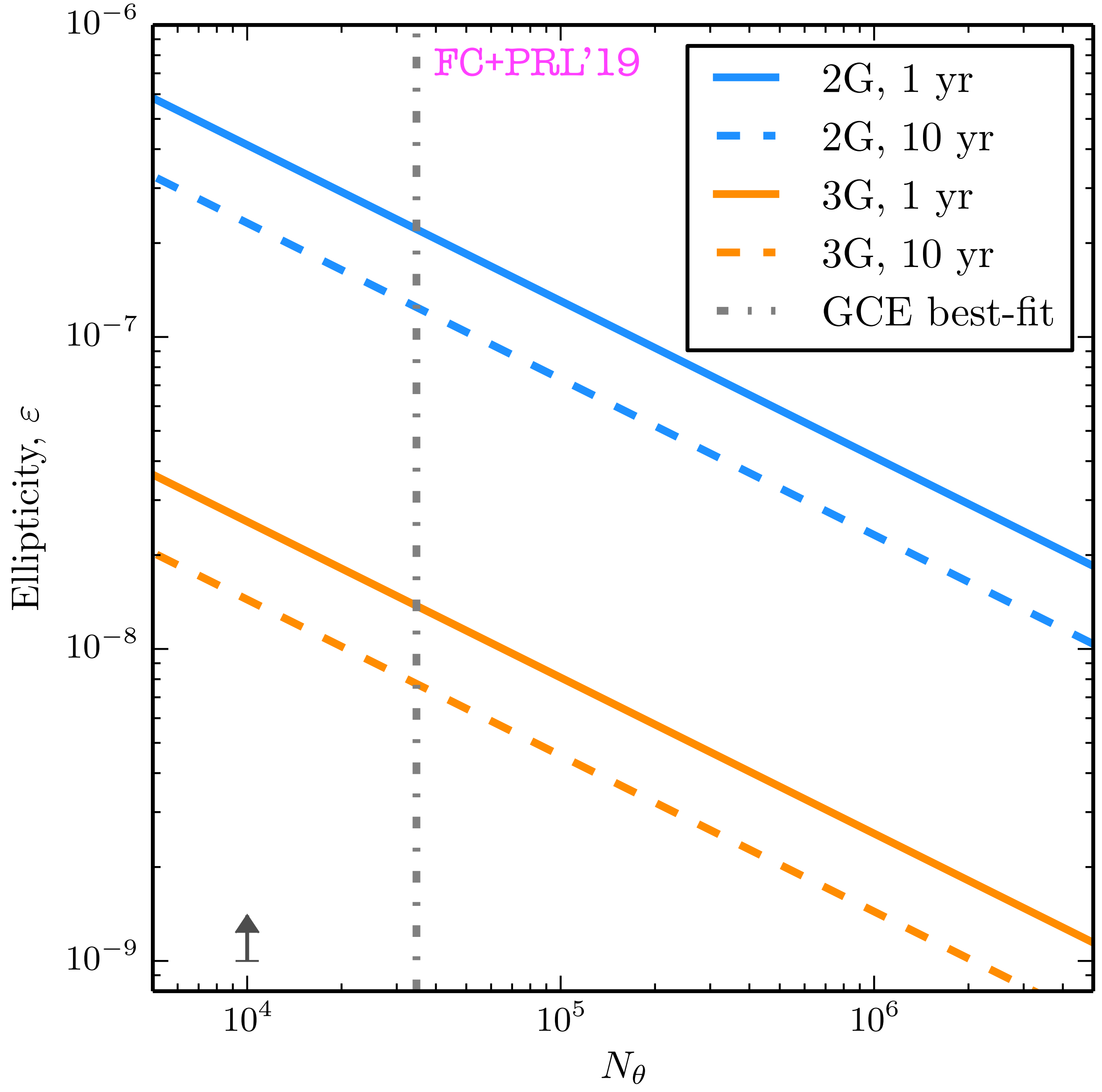
Detectability with radiometer search

- Search relies on excess coherence in the cross-correlated data streams from multiple detectors
- Method: GW radiometer — by applying appropriate time-varying delays between detectors it is possible to follow a specific direction, directional sensitivity (direction of GC)

$$SNR \simeq 0.18\,\{46\}\,\frac{N_\theta}{10^4}\left(\frac{\epsilon}{10^{-7}}\right)^2\sqrt{\frac{T}{1\,\mathrm{yr}}}$$

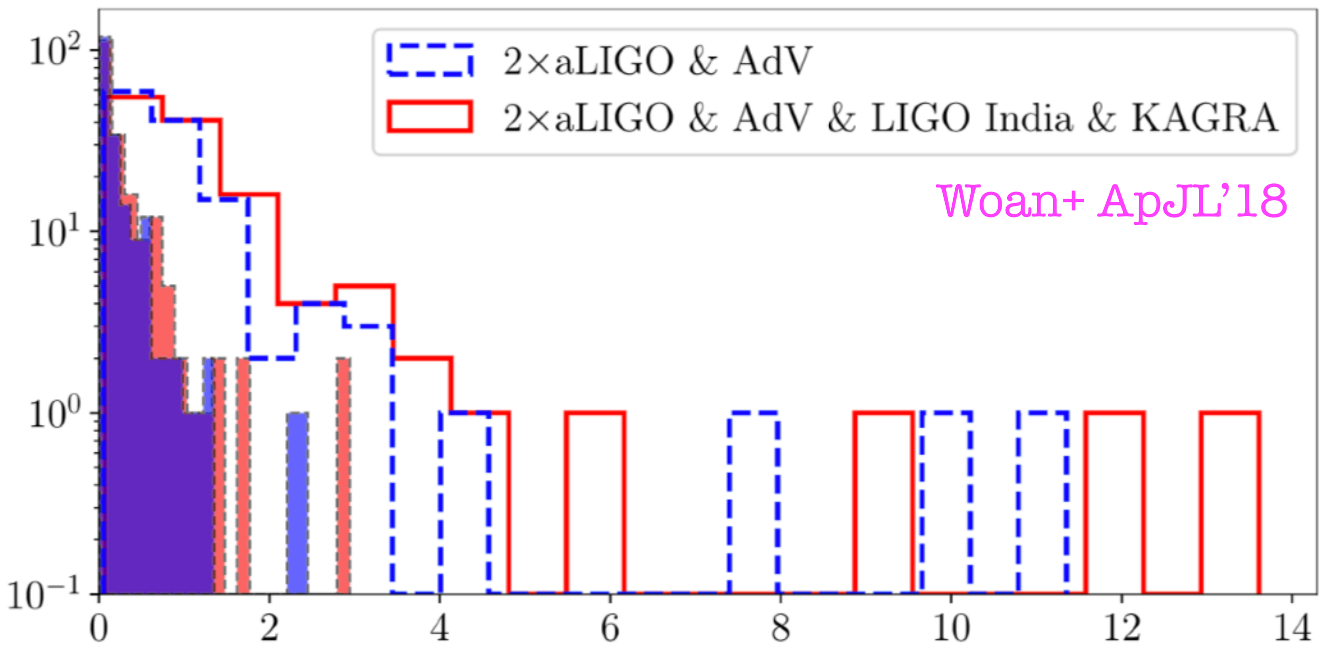
2G: two LIGO detectors at Hanford and Livingston and Virgo at design sensitivity

3G: two Cosmic Explorer detectors at the actual LIGO sites and one Einstein Telescope at the actual Virgo site



Perspectives

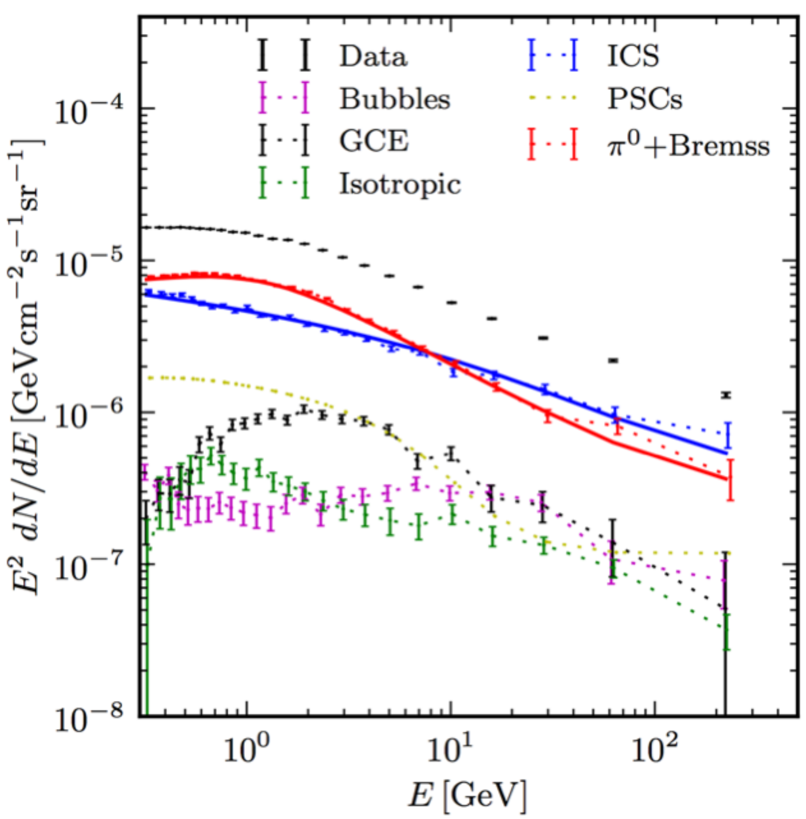
- If the ellipticity comparable to current bounds from spin-down => We expect a GW discovery in 3G detectors
- Interplay with targeted studies towards nearby MSPs (such as PSR J1643-1224 and PSR J0711-6830):
  - ✳ At least a few detection expected already in 2G => good perspectives that the 3G may detect the unresolved bulge contribution as well.
  - ✳ If the latter is not detected this will challenge the MSPs interpretation of the GeV excess
  - ✳ If no GW detection of single nearby MSP will be announced in the 2G run => no detection of the bulge population will take place at 3G either
  - ✳ A detection of the SGWB signal would profoundly shake the foundation of the current MSP interpretation of the GCE (young pulsars? Other compact objects?)



This search can provide crucial diagnostics for the GeV excess nature

General: Fit to gamma-ray data

$$\text{Model} = \sum_k \text{Spectrum} \times \text{Morphology}$$



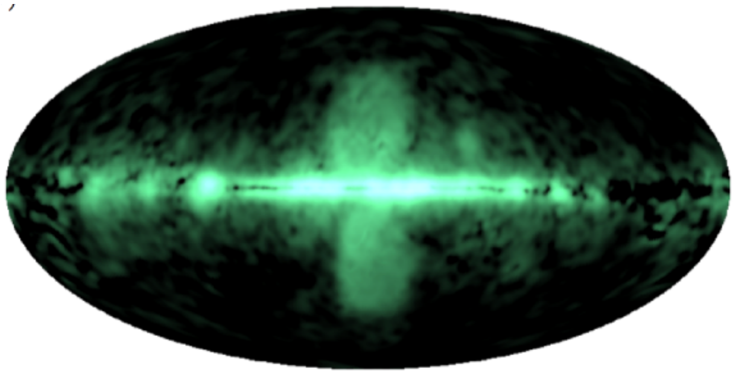
$$\phi_{pb} = \sum_k T_p^{(k)} \sigma_b^{(k)}$$

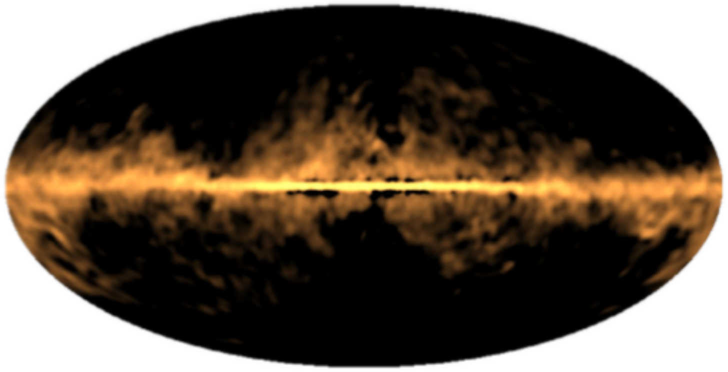
k: model component
p: spatial pixel
b: energy bin

Hooper+ PDU'13; Huang+ JCAP'13; Daylan+ '14; Calore+ JCAP'15; Ajello+ ApJ'15; Gaggero+ JCAP'15

$$\phi_{pb} = \sum_k S_b^{(k)} \tau_p^{(k)}$$

k: model component
p: spatial pixel
b: energy bin

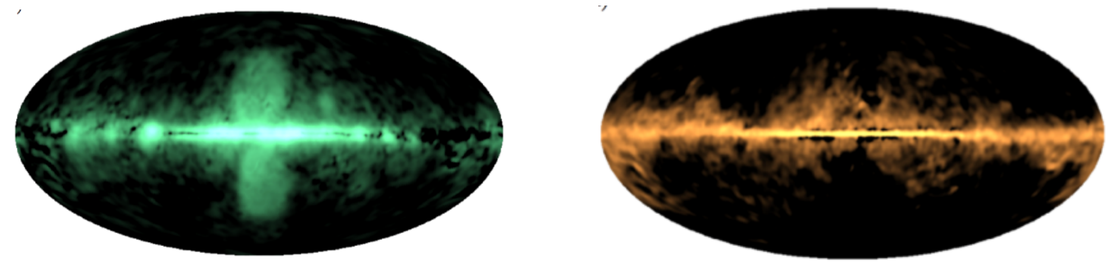




Selig+ A&A'14; Huang+ JCAP'16; de Boer+'16

Spectral decomposition

- GDE phenomenologically constructed 2-component model: bubble-like & cloud-like (90% emission).
- Faint point-sources accounted for.



D3PO – Selig+ A&A'14

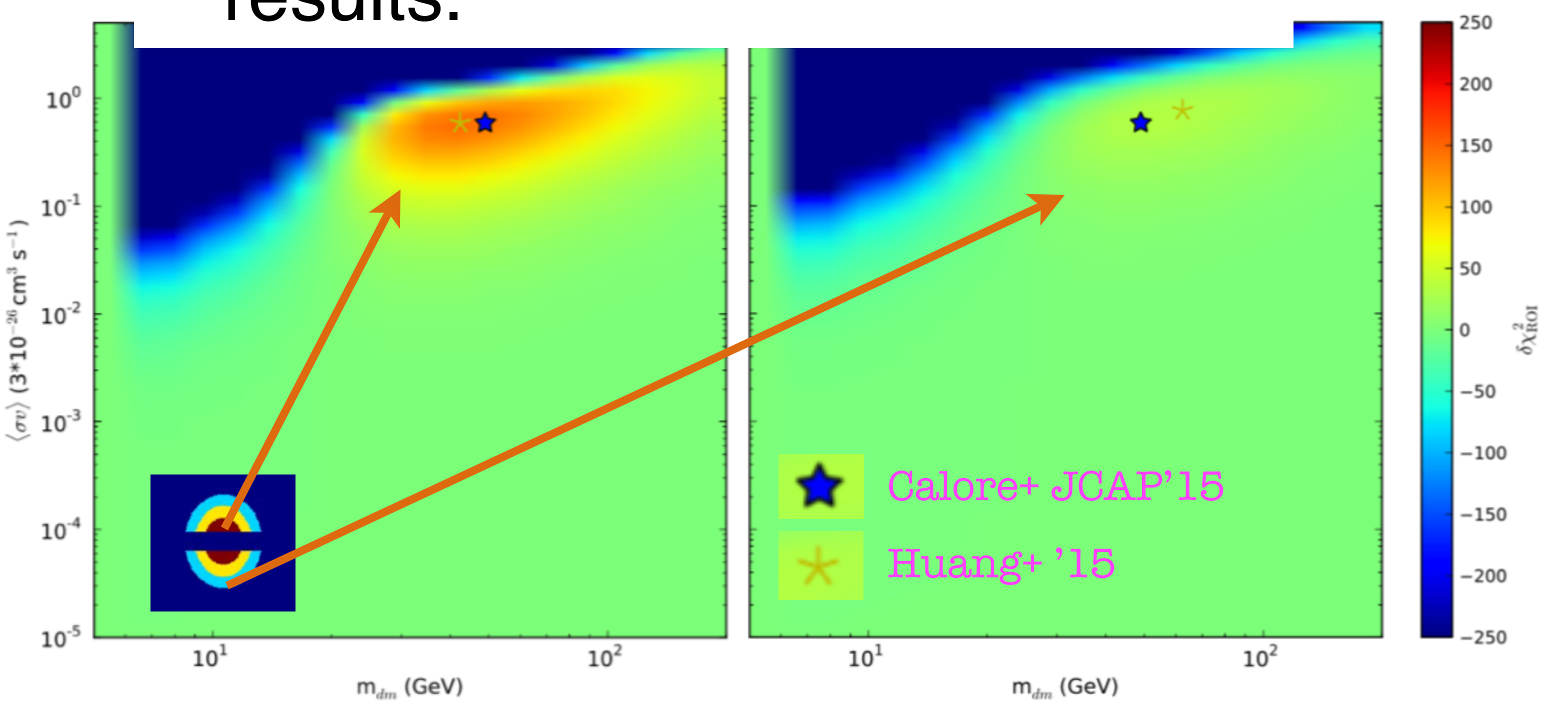
Pixel-wise maximum likelihood decomposition → $\theta_{i,k}$

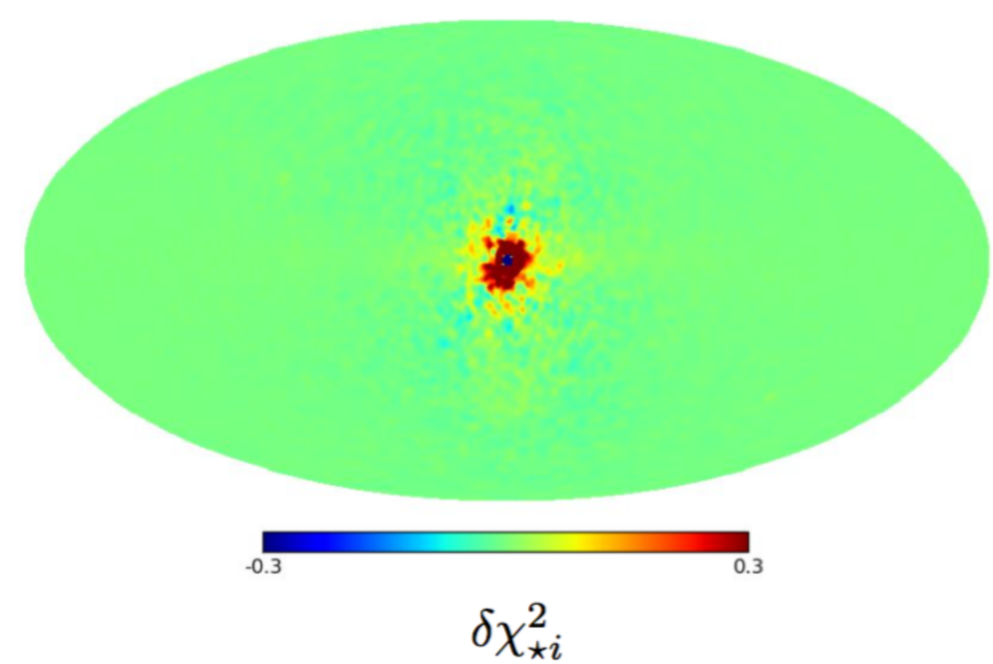
i[th] pixel

✓ Uniform and extended spectrum. Huang+ '15

✓ Compatible with previous results.

✓ Spherically symmetric about the Galactic centre.





See also de Boer+'16

SkyFACT

$$\text{Model} = \sum_k \text{Spectrum} \times \text{Morphology}$$

Spectrum → Uncertain spectral modelling

Morphology → Pixel-by-pixel correlated uncertainties

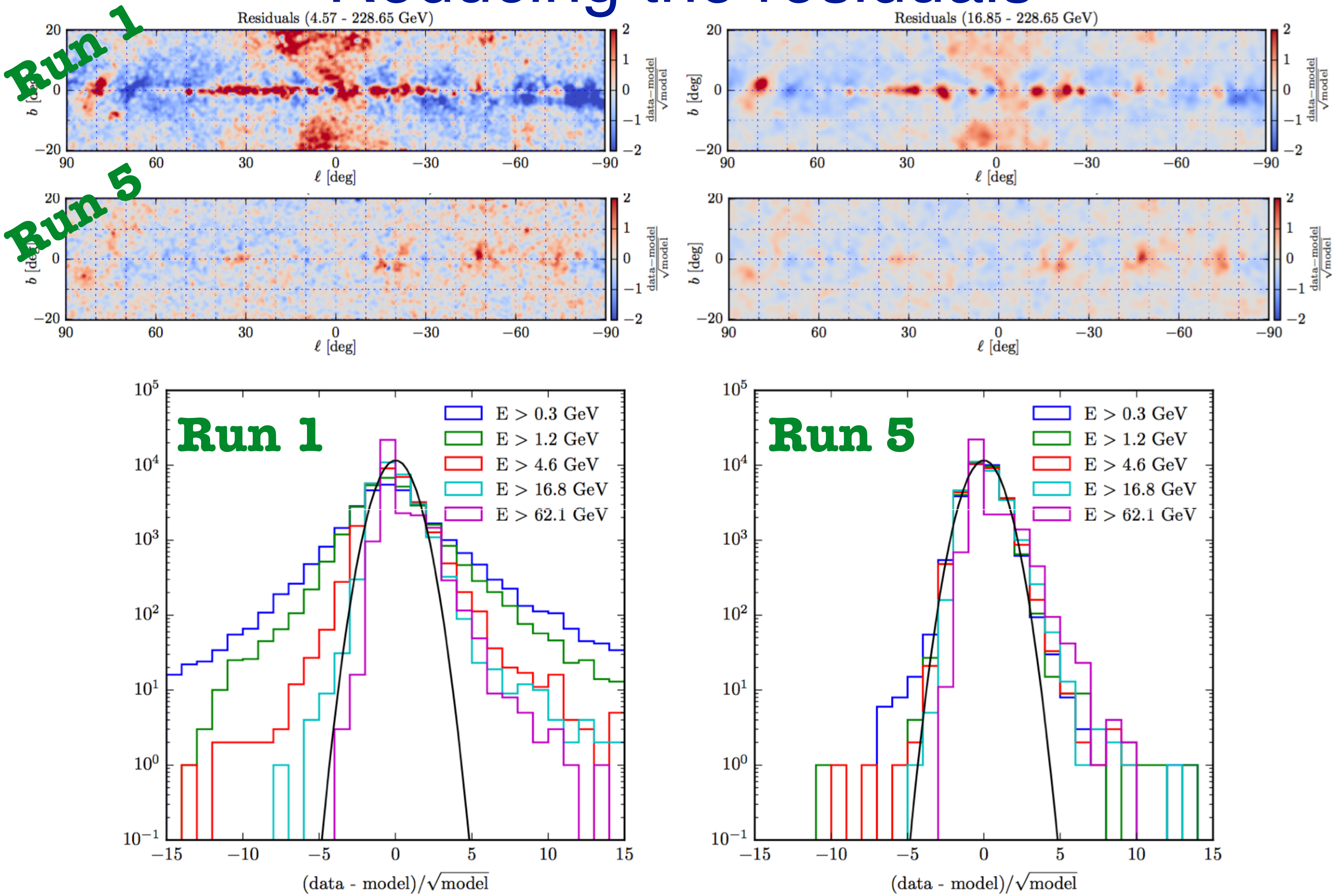
$$\phi_{pb} = \sum_k T_p^{(k)} \tau_p^{(k)} \cdot S_b^{(k)} \sigma_b^{(k)} \cdot \nu^{(k)}$$

$$\ln \mathcal{L} = \ln \mathcal{L}_{\rm P} + \ln \mathcal{L}_{\rm R}(\lambda, \lambda', \lambda'', \eta, \eta')$$

Penalized maximum likelihood regression with regularisation conditions

- Additional nuisance degrees of freedom in spatial/spectral templates
- Penalisation terms as priors on nuisance parameters
- Errors estimated by sampling from the inverse of Fisher information matrix of the best fit po

Reducing the residuals



Degrees of freedom

Naively:

$$N_{\rm data} = N_{\rm pix} \times N_{\rm ebin} = 360 \times 81 \times 25 = 7290000$$

$$N_{\rm param}$$

$$N_{\rm DOF} = N_{\rm ebin} \times N_{\rm pix} - N_{\rm param}$$

But:
No Gaussian regime, degeneracies in model parameters, and penalisation constraints

What is the real number of effective free model parameters?

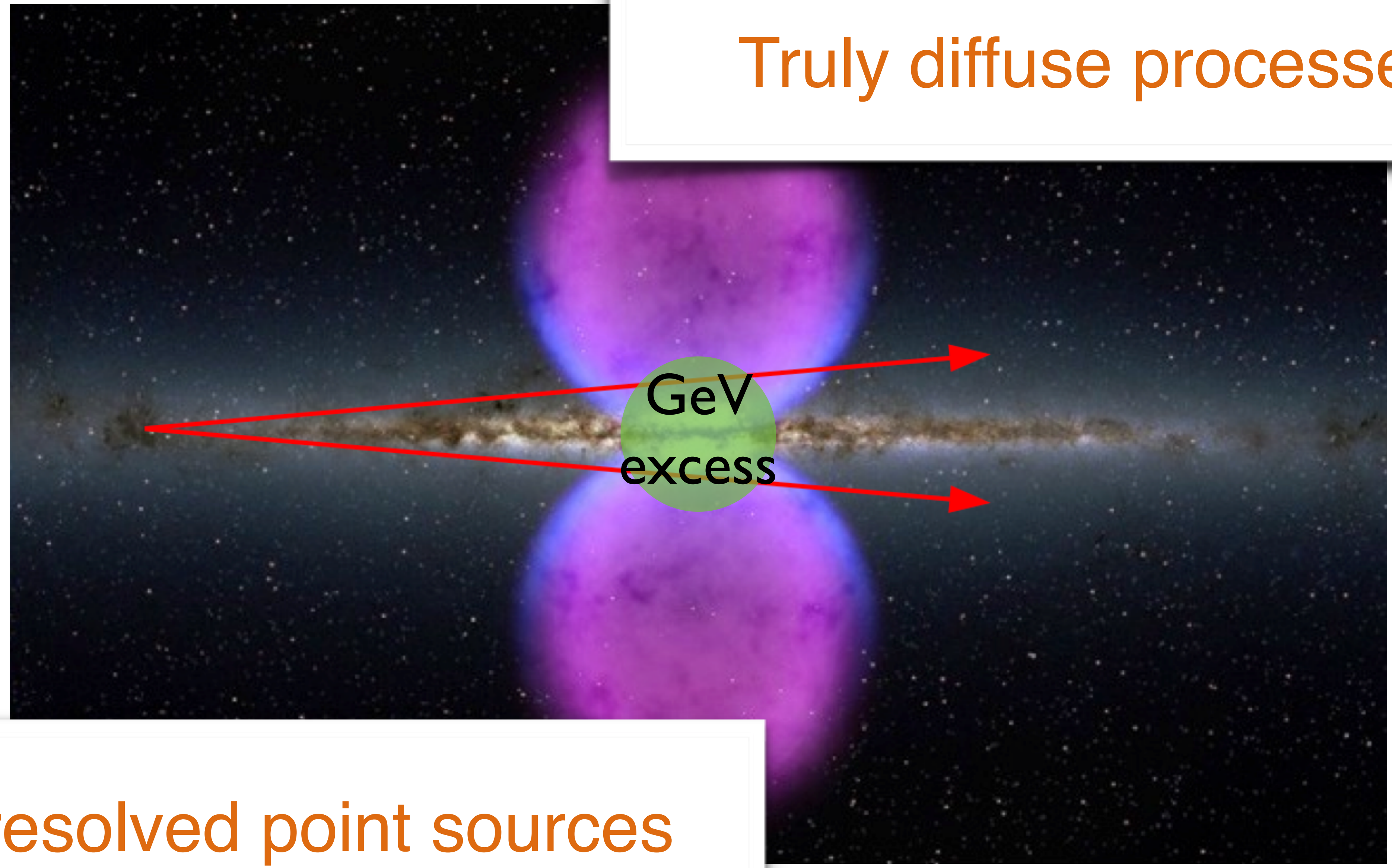
$$N_{\rm DOF}^{\rm eff} \sim \langle -2 \ln \mathcal{L}_P \rangle_{\rm mock}$$

$$N_{\rm data}^{\rm eff} \equiv \langle -2 \ln \mathcal{L}_P(\boldsymbol{\theta}) \rangle_{\mathcal{D}(\boldsymbol{\theta})}$$

Run 5

Naive model parameters, $N_{\rm param}$	107639
Naive DOF	621361
Eff. model parameters, $N_{\rm param}^{\rm eff}$	12800
Eff. data bins, $N_{\rm data}^{\rm eff}$	619000
Eff. DOF, k	606200

Possible interpretations



Truly diffuse processes

Unresolved point sources

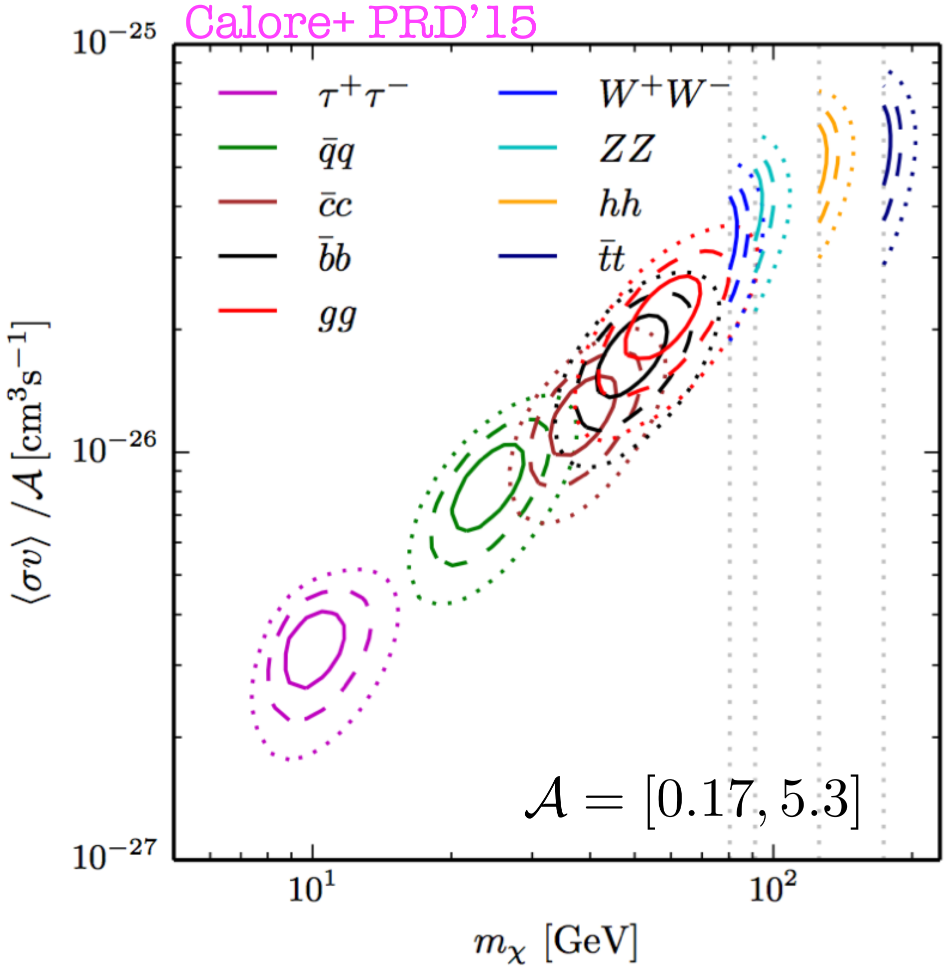
(a) Spectrum & Morphology of the excess?
(b) Emission in other wavelengths?

Dark matter annihilation

Spectrum

$$\frac{dN}{dE} = \sum_f \frac{\langle \sigma v \rangle_f}{8\pi\, m_\chi^2} \frac{dN_\gamma^f}{dE} \int_{\mathrm{l.o.s}} ds\, \rho^2(r(s,\psi))$$

Calore+ PRD'15

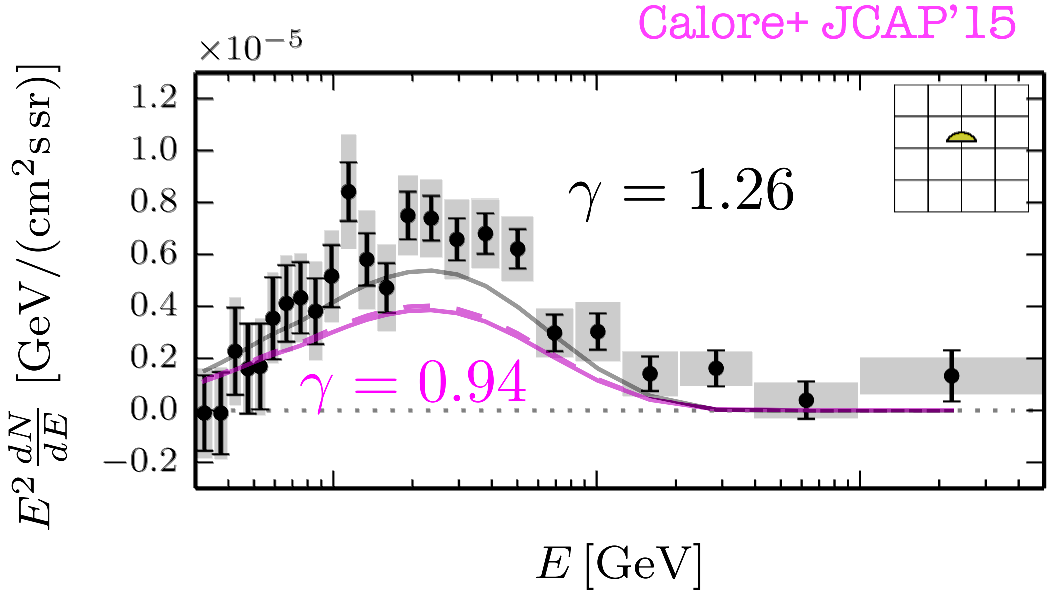


Agrawal+JCAP'15; Achterberg+JCAP'15;
Bertone, FC+ JCAP'15;
Liem, FC+ JCAP'16; etc.

Morphology

For EAGLE simulation: typically shallower profiles for Milky Way analogues, under conservative assumptions on resolution.

Calore+ JCAP'15



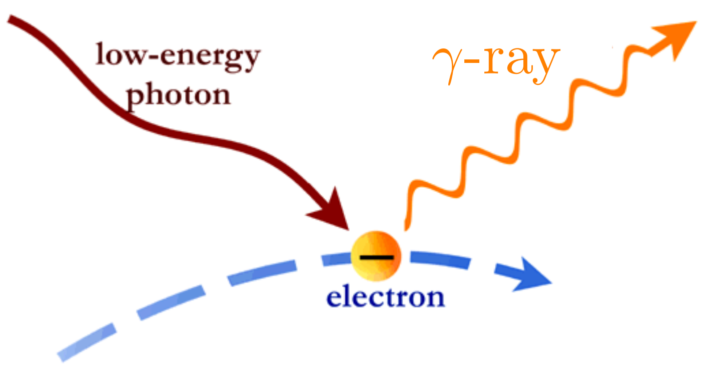
+ non-sphericity of the high-E excess?

Linden+'16

+ disk component?

Huang+JCAP'16, de Boer+'16

Inverse Compton scattering from GC CRs



Additional population of leptonic cosmic rays required at the Galactic centre:

a. Steady-state source term (from star forming CMZ)

Gaggero+JCAP'15; Carlson+ PRD'16, PRL'16

b. Time-dependent source term (from outburst event)

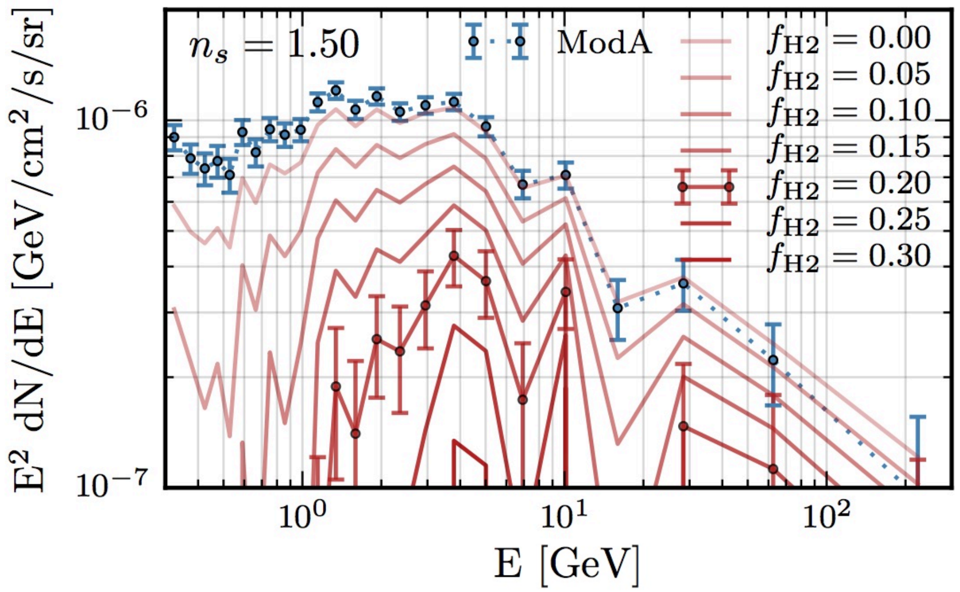
Petrovic+ JCAP'14; Cholis,FC+ JCAP'15

- Luminosity from SNe in the CMZ (with ~5% SF) enough to sustain energetics of Fermi GeV excess, ~3x10^{37} erg/s.

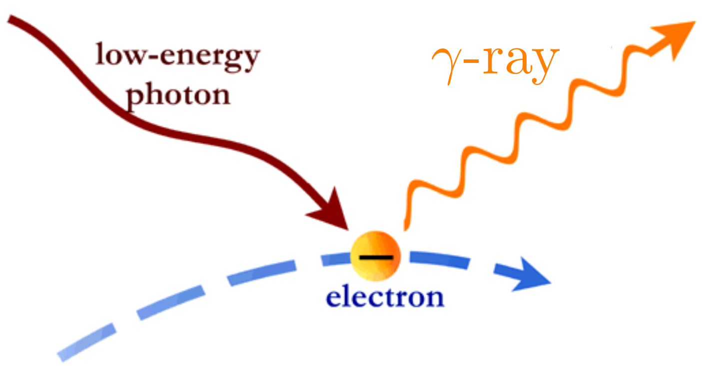
- Updated SN models for CR injection at the GC, accounting for enhaced SFR at the GC traced by H2 regions, 5-10% of total SFR.

- Better fit to the data and reduced intensity of the excess but some over-subtraction at low energies => Role of advective winds.

Carlson+ PRD'16



Inverse Compton scattering from GC CRs



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- Injection of high-energy CR in the past, at the GC (central black hole or starburst activity) ⟶ Tuning of burst(s) parameters.

- At least two bursts are required to fit the extended highly uniform spectrum, with somewhat hard injection indices (<2).

Cholis,FC+ JCAP'15