New techniques for Dark Matter and Bulge Pulsar Searches at sub-GeV energies

Christoph Weniger

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1) Point source studies → Wavelet fluctuation analyses (some updates)
2) Fast informative forecasting → Fisher information flux (ongoing work)
[3) SkyFACT (ongoing work)]

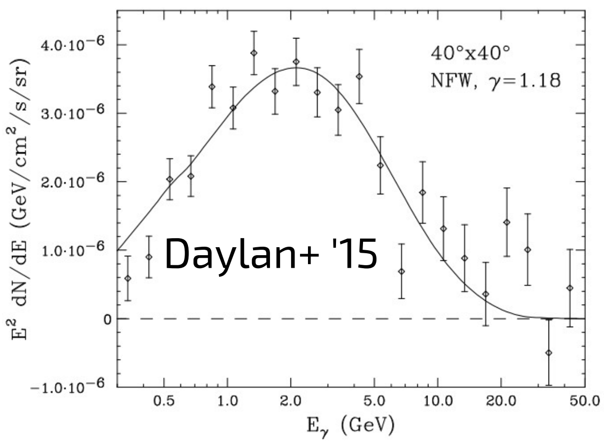
NWO Netherlands Organisation for Scientific Research
GRAPPA GRavitation AstroParticle Physics Amsterdam
Universiteit van Amsterdam

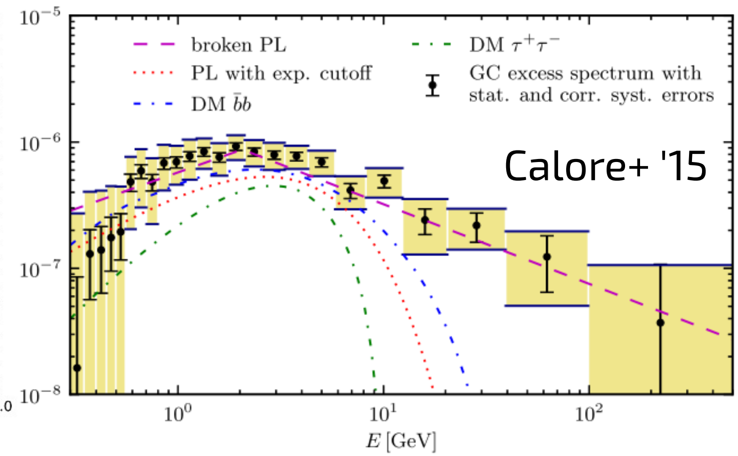
Padova, e-ASTROGAM workshop
1st March 2017

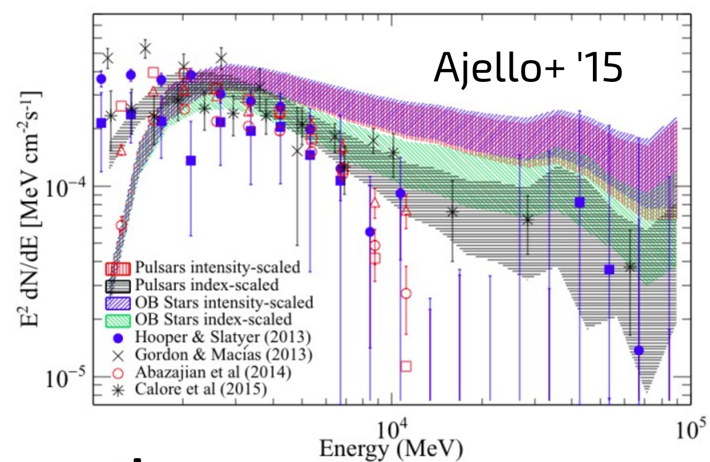
The Fermi GeV bulge emission

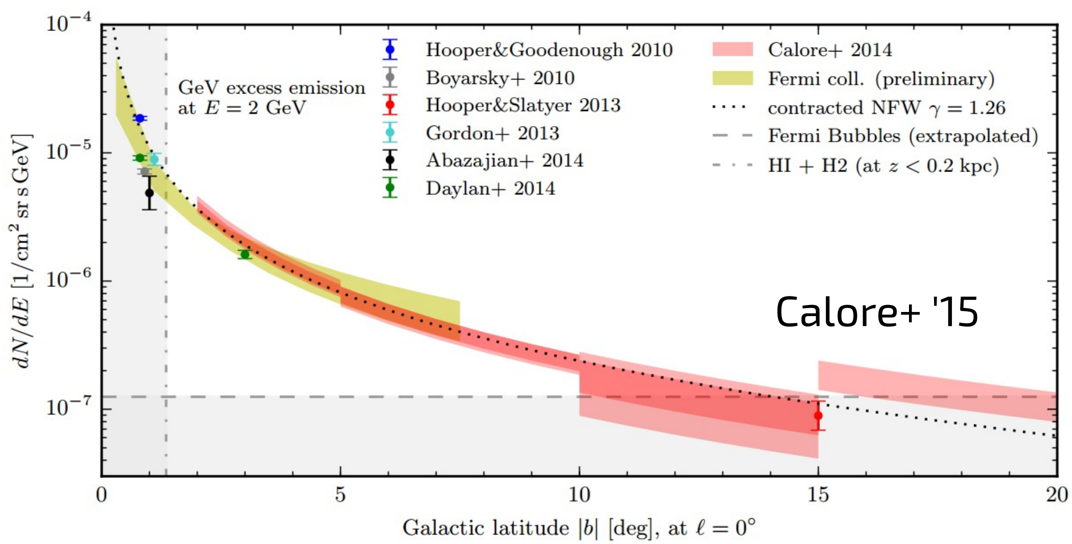
Various groups found an "excess of GeV photons" that extends from the Galactic center up to mid-latitudes. (Goodenough & Hooper 2009; Vitale & Morselli 2009, …

… 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, …)









Talk by D. Malyshev

Overall properties

- Extends up to 10-15 deg
- Probably spherically symmetric (but see e.g. Casandjian+'16)
- Spectrum peaks uniformly at ~2 GeV

Interpretation unclear – probably several components

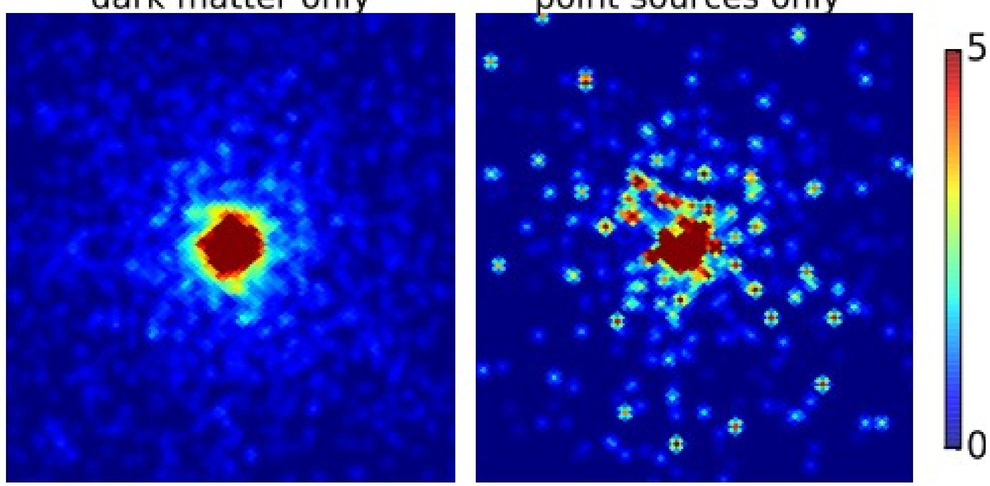
- Dark matter annihilation? [e.g. Calore+'15]
- Bulge millisecond pulsars? [e.g. Abazajian 11]
- Inverse Compton emission? [e.g. Petrovic+'15]

1) Millisecond pulsars

"Fermi GeV bulge emission could be due to combined flux from thousands of bulge MSPs" [Abazajian '11; Petrovic+ '13; Brand & Kocsis '15]

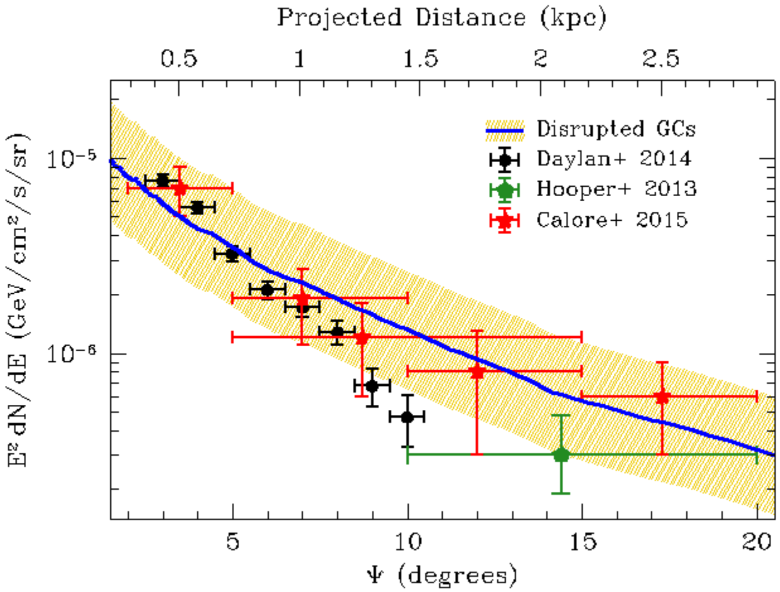
- MSP spectrum in agreement with bulge emission (peaks around ~1-3 GeV)
- No direct obs. constraints on MSP distribution in the bulge → They could be distributed like suggested by Fermi data

Challenge: Discriminate purely diffuse emission from unresolved PSCs:



Lee+14

Required number density and spherical distribution possibly created from disrupted globular clusters

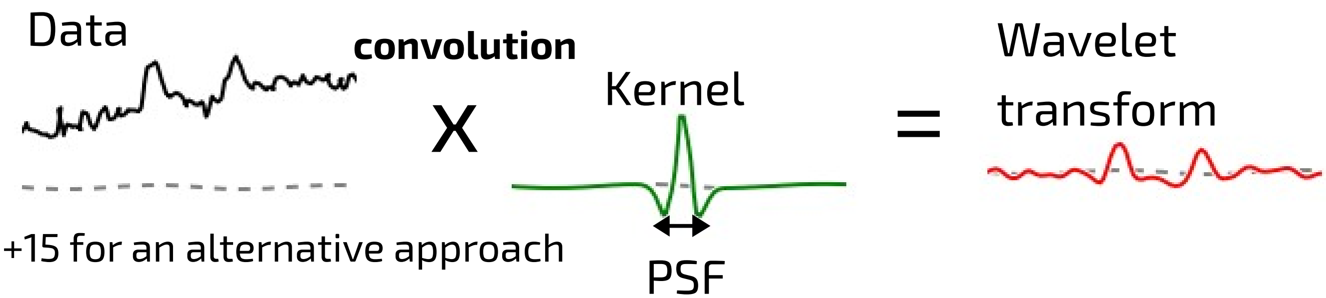


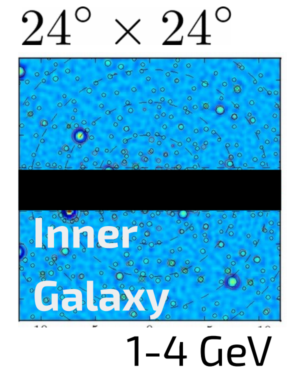
Brandt & Kocsis '15

For a list of possible caveats: see e.g. Hooper+'13, Cholis+'14, Linden & Hooper '16, ...

Wavelet Fluctuation analysis

Wavelet fluctuation analysis (Bartels+15 PRL)





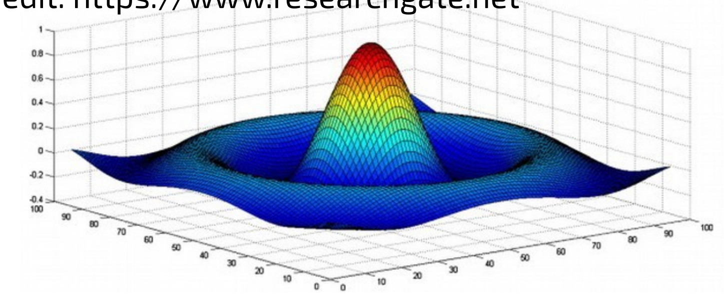
See also Lee+15 for an alternative approach

Signal-to-noise ratio of wavelet transform

$$\mathcal{S}(\mathbf{\Omega}) = \frac{\mathcal{F}_{\mathcal{W}}[\mathcal{C}](\mathbf{\Omega})}{\sqrt{\mathcal{F}_{\mathcal{W}^2}[\mathcal{C}](\mathbf{\Omega})}}$$

Looks complicated, but is just significance of peaks

Credit: https://www.researchgate.net



Our simple MSP model

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

Two free parameters

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

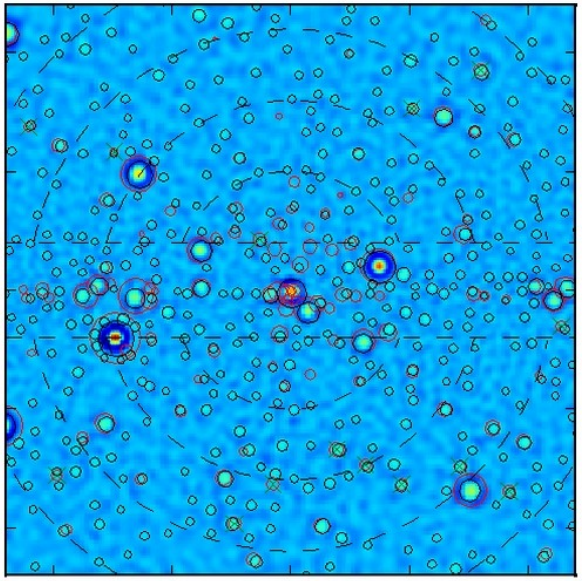
A bulge MSP population would lead to

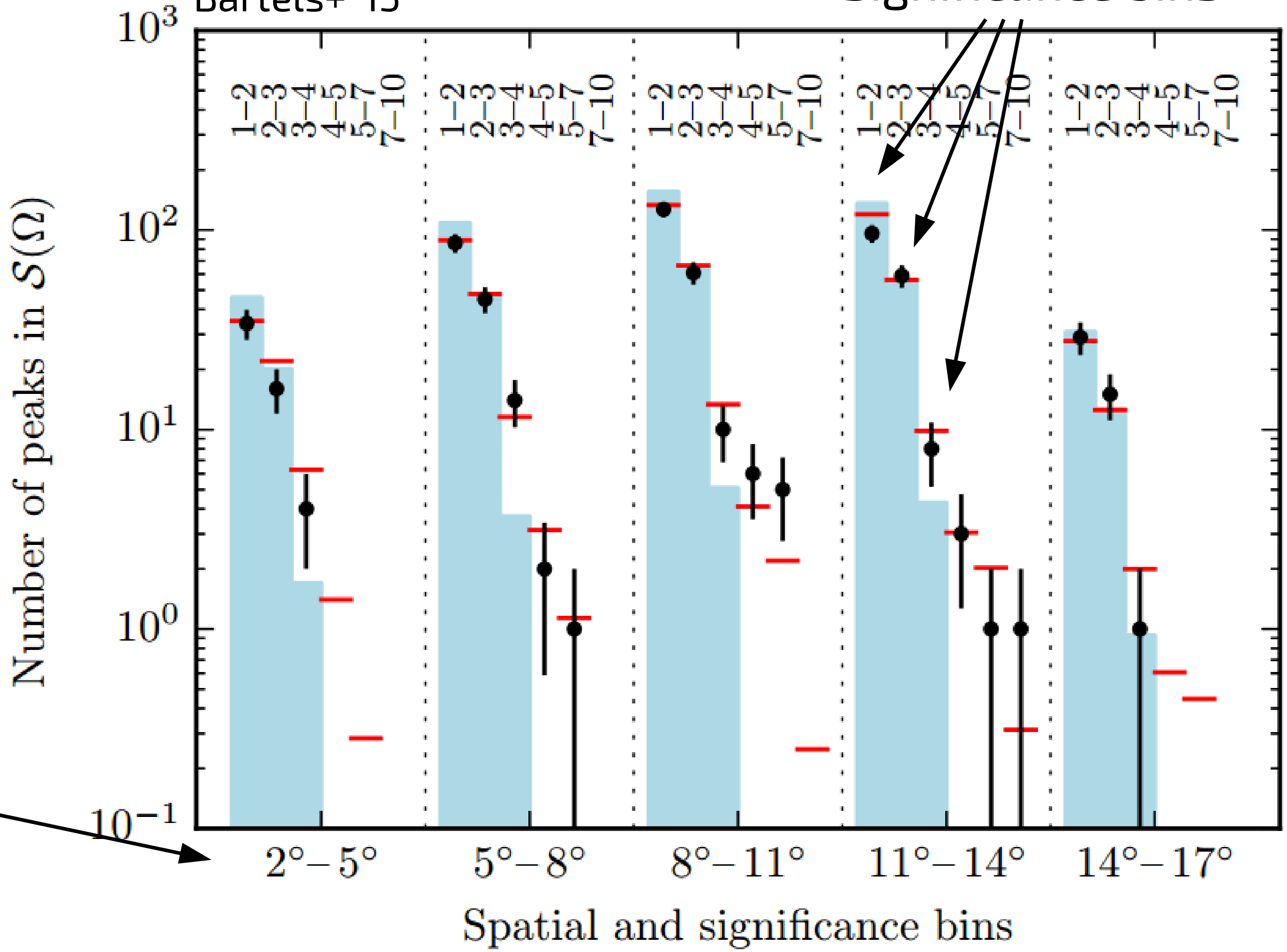
- suppression of 1-2 sigma peaks
- enhancement of 3-10 sigma peaks

→ This is exactly what we found in our analysis, at 10.0 sigma (1-4 GeV, 6yr pass 8 Fermi data)

Histogram of wavelet transform peaks

Bartels+ '15





We find

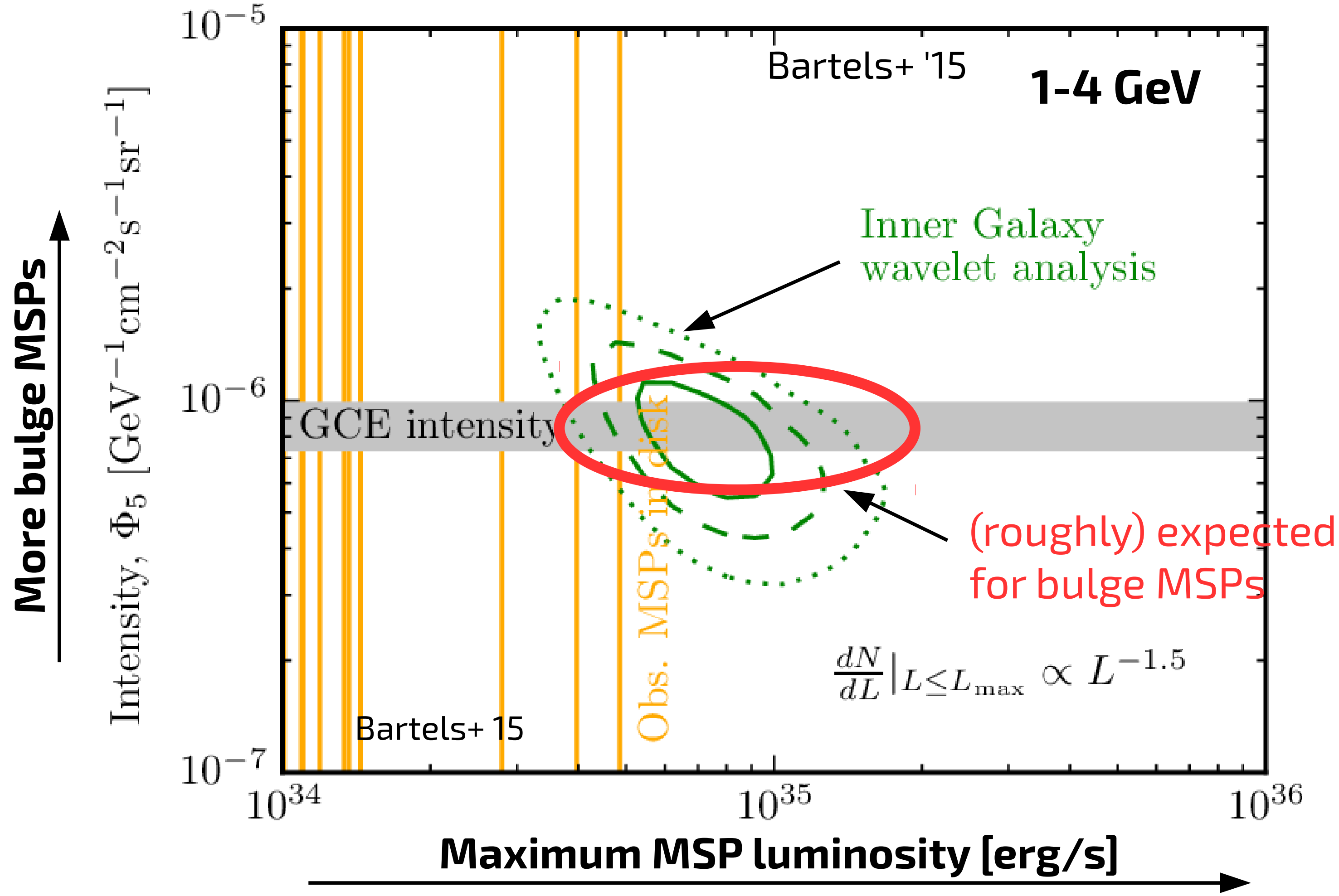
- Suppression at <2 sigma
- Excesses at >3 sigma

Blue bars: Null hypothesis (diffuse-only emission)

Black: Measured data

Red: best-fit model with MSP population in bulge

Results from six year Pass8 Fermi data



Why MSPs? Wavelet signal is unlikely to be caused by:

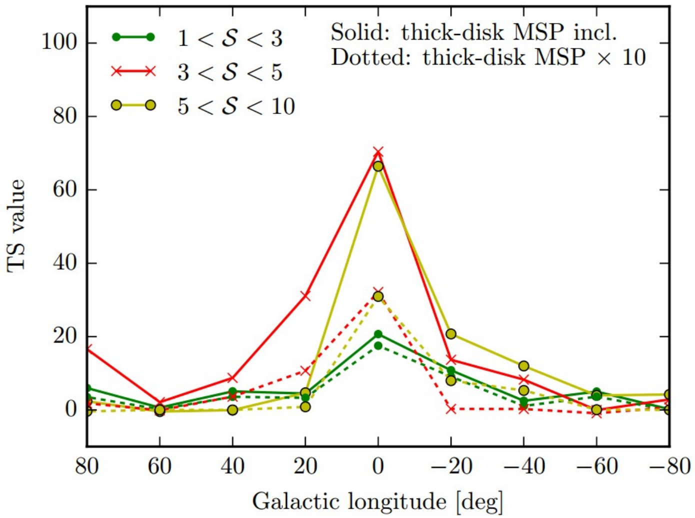
- gas structure (signal not correlated with SFD/Planck gas maps; see backup slides)
- extragalactic sources, SNR or PWN (too few); young pulsars (cutoff luminosity)

→ Leaves MSPs as arguably most plausible interpretation

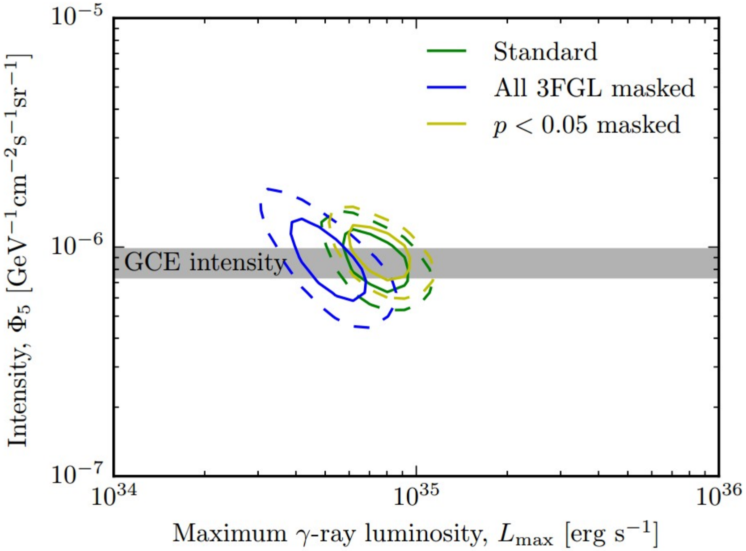
Robustness of result

Bartels+ '15

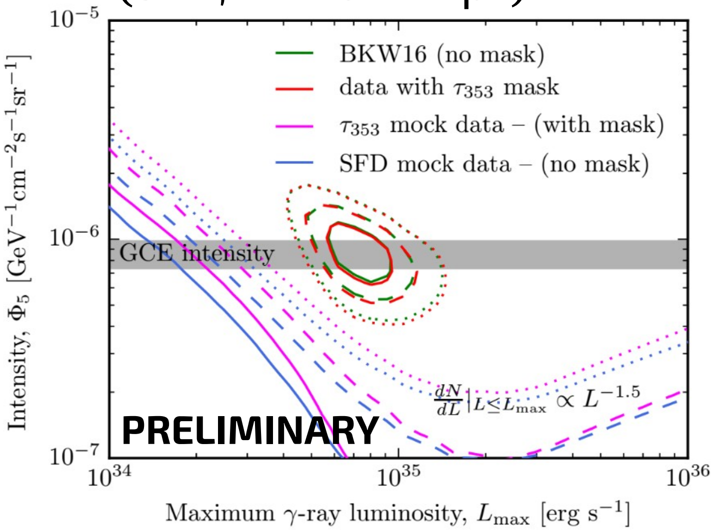
Only towards inner galaxy



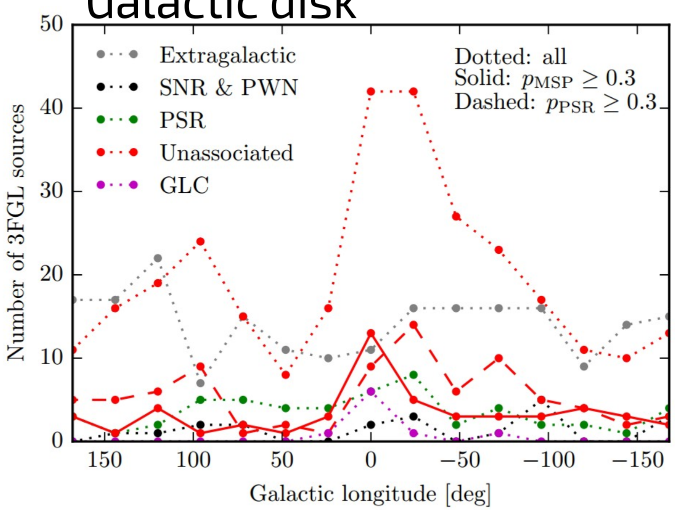
No strong dependence on masking of known PSCs



Signal not correlated with gas (SFD, Planck maps)



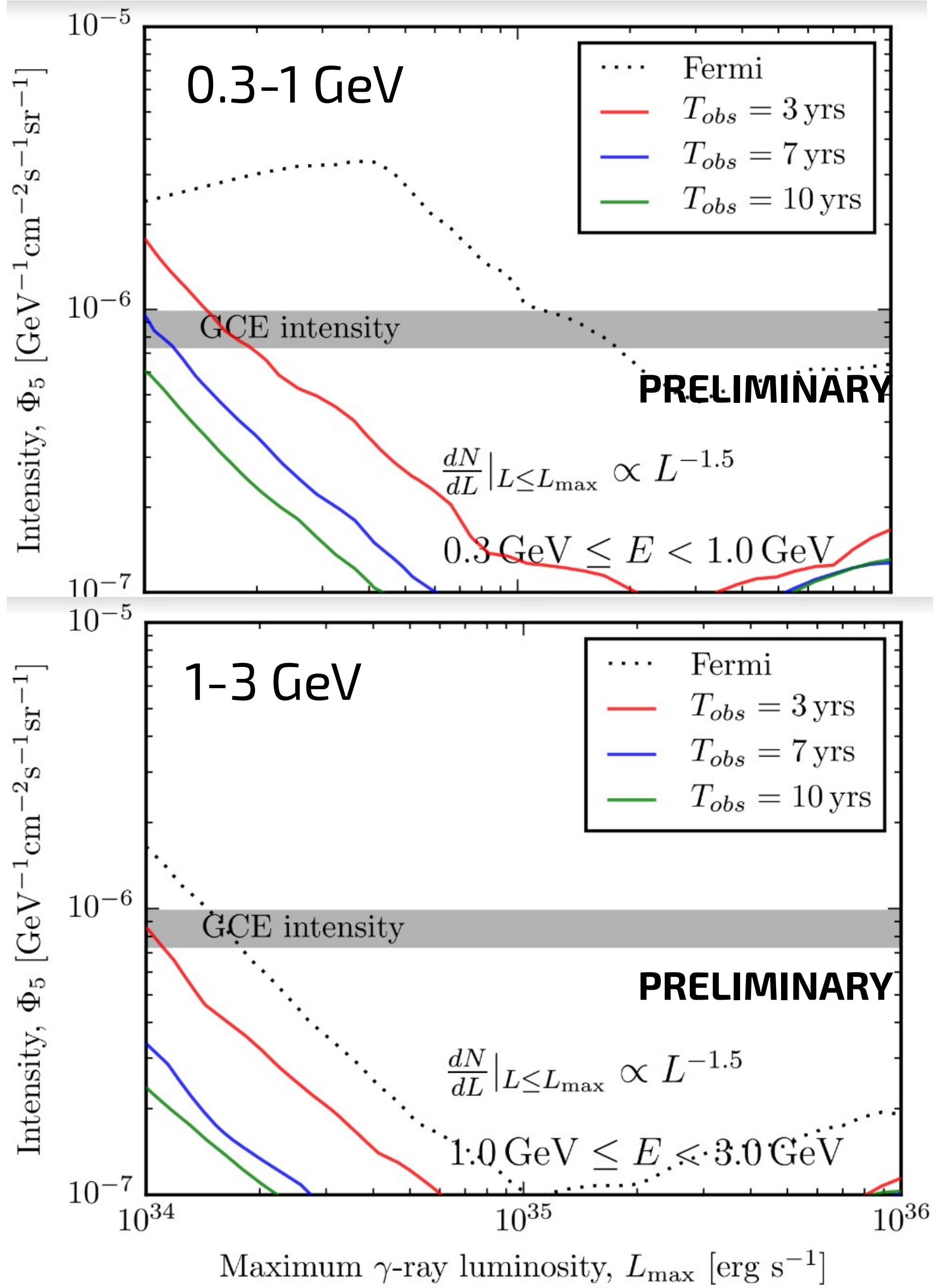
3FGL sources along Galactic disk



Projected improvements with e-ASTROGAM

e-ASTROGAM prospects

- The better angular resolution below 1 GeV greatly improves the sensitivity towards wavelet fluctuation signals, w.r.t. Fermi
- Even above 1 GeV, there is some improvement
- Larger number of photons per source → Better chance to identify pulsation in gamma-ray emission
- Additional information about spectra of bulge sources

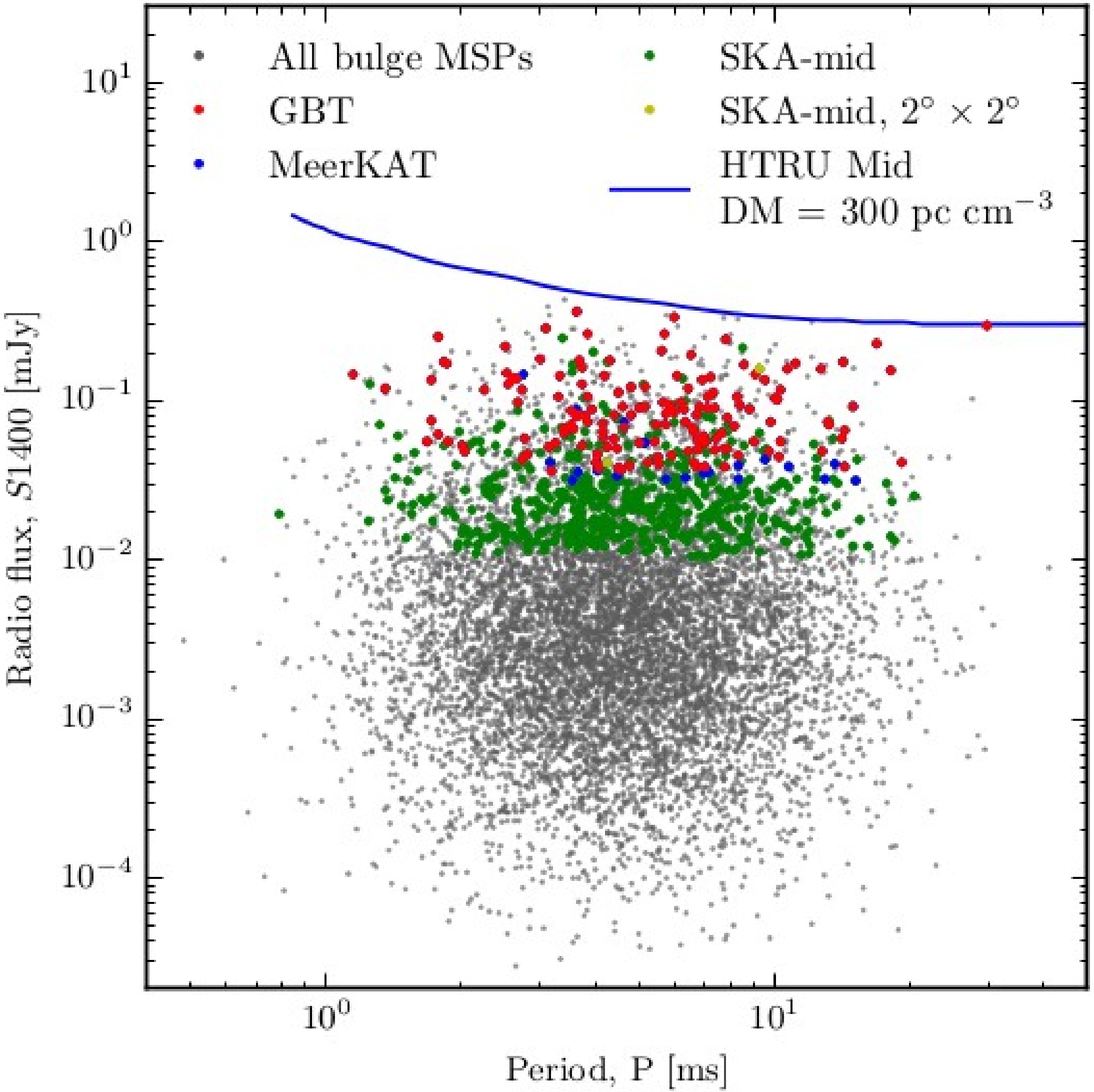


(Radio detection prospects)

Radio detection prospects (Calore+ '15)

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

- GBT targeted searches ~80h: ~6 bulge MSPs (updated)
- MeerKAT mid-lat survey ~300h: ~30 bulge MSPs



Our plans for the near future

- We teamed up with MeerKAT TRAPUM → dedicated survey planned for **2018** (~**300h**)
- Proposals for GBT and VLA submitted (PIs Paul Ray & Matthew Kerr)

2) No unified framework for forecasting

Searching for dark matter signals:

- A multitude of targets
  - Galactic center
  - Dwarf spheroidal galaxies
  - Local group members
  - Galaxy clusters
  - Subhalos
- A multitude of techniques
  - Line searches
  - Morphological searches
  - Cross-correlation
- A multitude of DM models
  - Annihilating DM
    - s-wave, p-wave, excited
  - Decaying DM
    - direct decays
    - Cascade decays

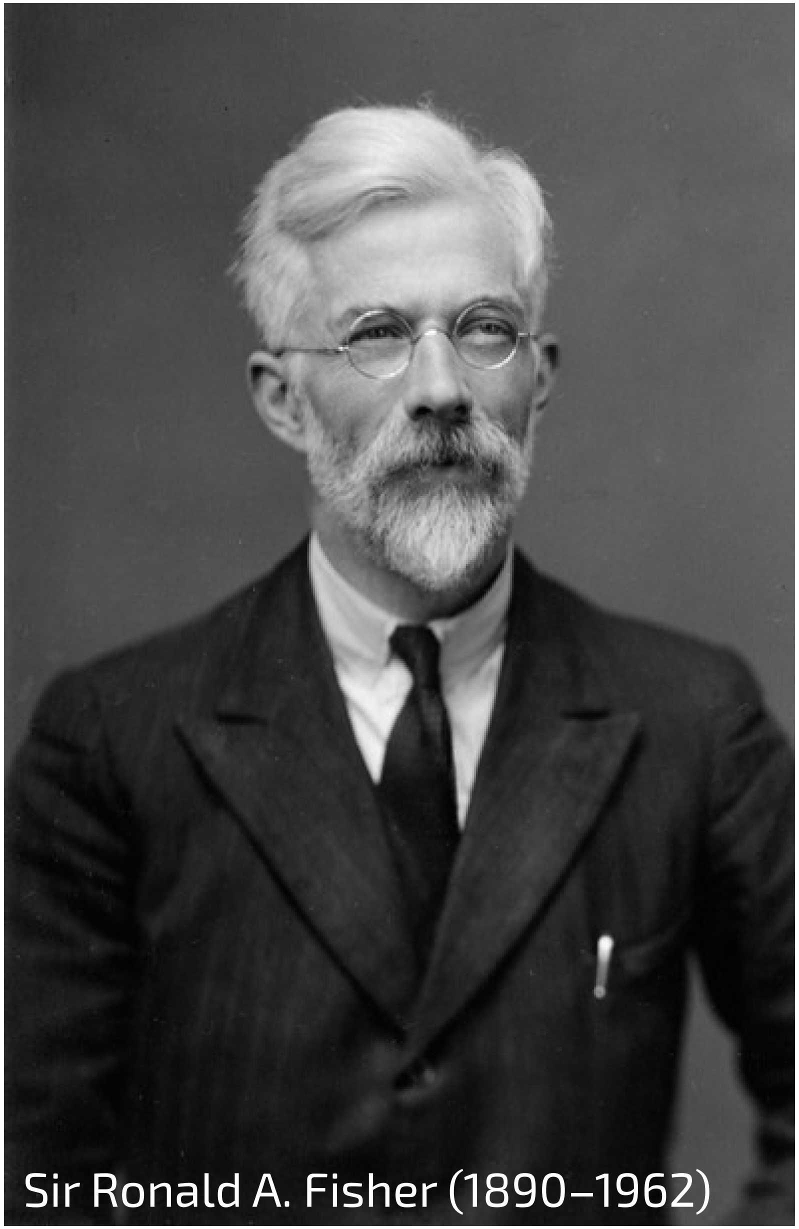
Analysis choices:

- Need MCs
- Choice of binning
- Choice of ROI and energy ranges
- Choice of source modeling
- Choice of background modeling
- Systematics

Questions?

- How to quickly check what method works best for what model?
- How to make forecasting fast and informative?

This guy has the answer



Fisher forecasting for astroparticle physicists

1) Unbinned Poisson likelihood

$$\ln \mathcal{L}_{\rm pois}(\boldsymbol{\theta}|\mathcal{D}) = \int dE \; \left[\mathcal{C}(E) \ln \Phi(E|\boldsymbol{\theta}) - \Phi(E|\boldsymbol{\theta})\right]$$

2) Concentrate on additive component models

$$\Phi(E|\boldsymbol{\theta}) = \sum_{i=1}^{n} \theta_i \Psi_i(E) \qquad \Psi_i(E) = \mathcal{E}(E)\, I_i(E)$$

3) Derive Fisher information matrix

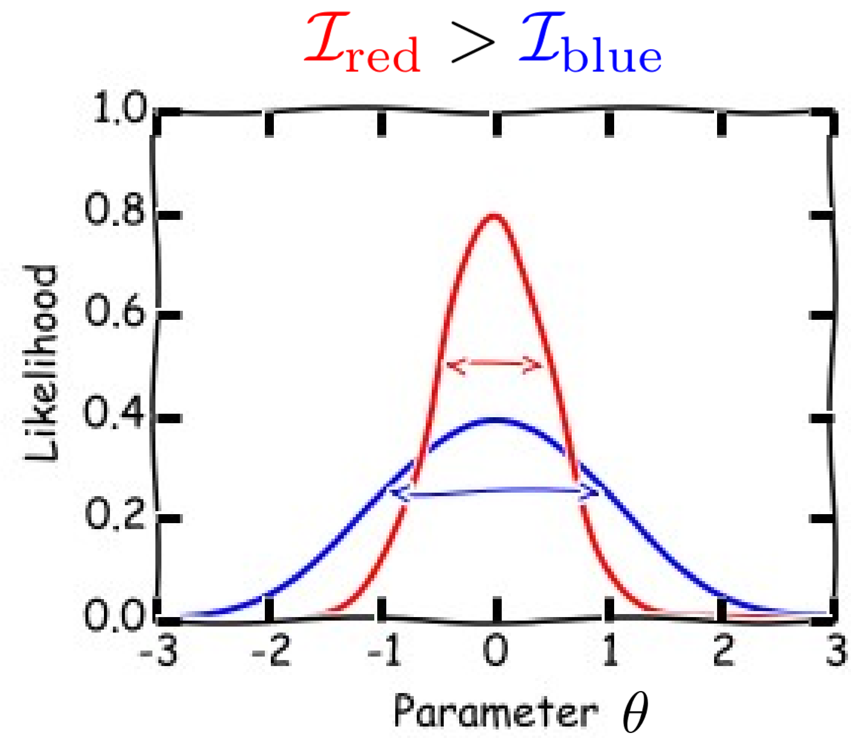
$$\mathcal{I}_{ij} \equiv -\left\langle \frac{\partial^2}{\partial\theta_i \partial\theta_j} \ln \mathcal{L}(\theta|\mathcal{D}) \right\rangle_{\mathcal{D}(\theta)}$$

$$(\mathcal{I}^{-1})_{ij} \approx \Sigma_{ij}$$

Very simple form:

$$\mathcal{I}_{ij}^{\rm pois}(\boldsymbol{\theta}) = \int dE \frac{\Psi_i(E)\Psi_j(E)}{\Phi(E|\boldsymbol{\theta})}$$

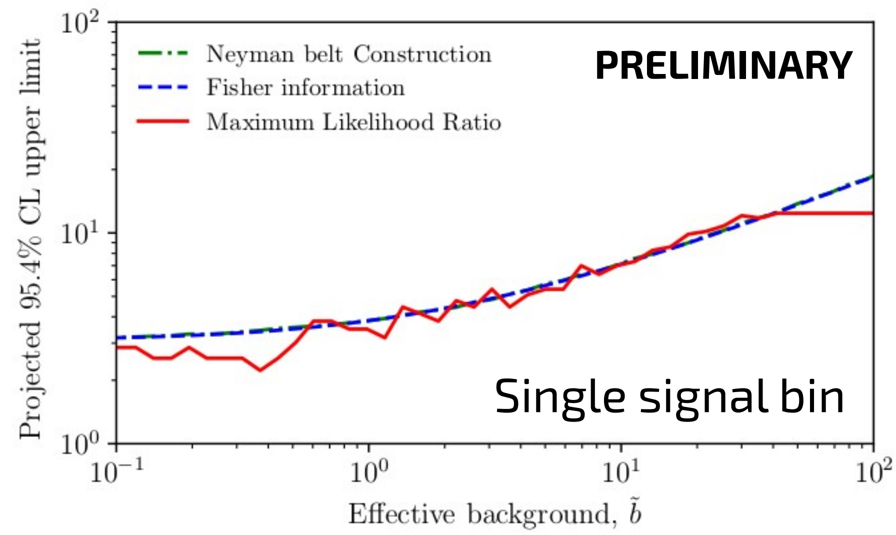
(SIG^2 / BG)



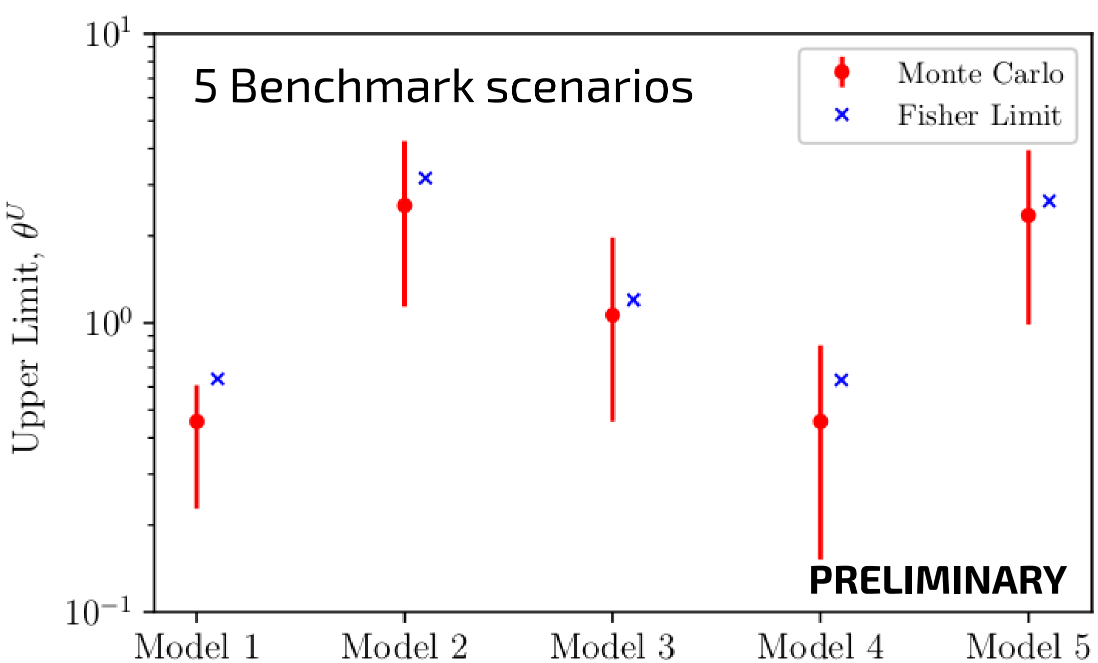
Fisher limits compared with full-blown MCs

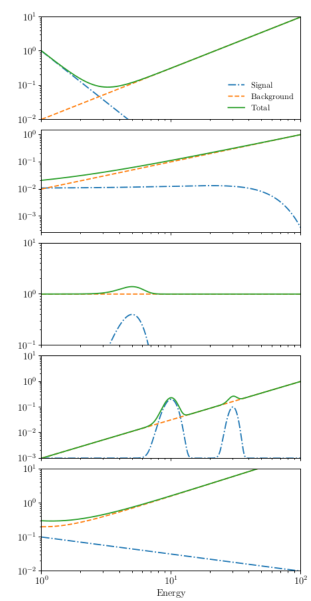
Can be used to quickly calculate projected upper limits, even **deeply in the Poisson regime.**

$$\theta_1^U(\boldsymbol{\theta}) = Z(\alpha) \cdot \sigma_i \left(\theta_1^U, \theta_2, \ldots, \theta_n\right)$$



Monte Carlo upper limits (MLR with coverage correction) compared to Fisher upper limits.





Flux and BG of benchmark scenarios

Information flux: Saturation and correlation

We found it very convenient to introduce the **flux of Fisher information** (not done before, to our knowledge)

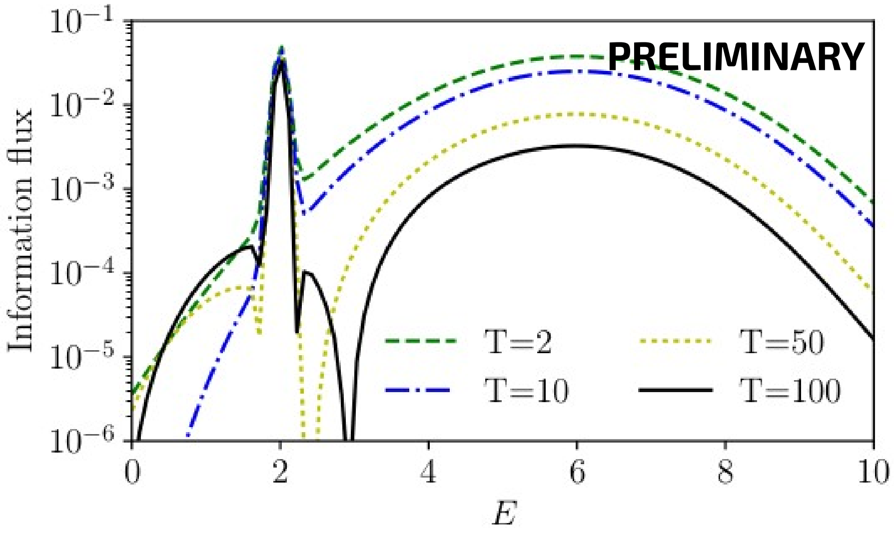
$$\frac{d\mathcal{F}_i}{d\Omega}(\boldsymbol{\theta}) \equiv \frac{\delta \mathcal{I}_{ii}(\boldsymbol{\theta}, \mathcal{E})}{\delta \mathcal{E}(\Omega)}$$

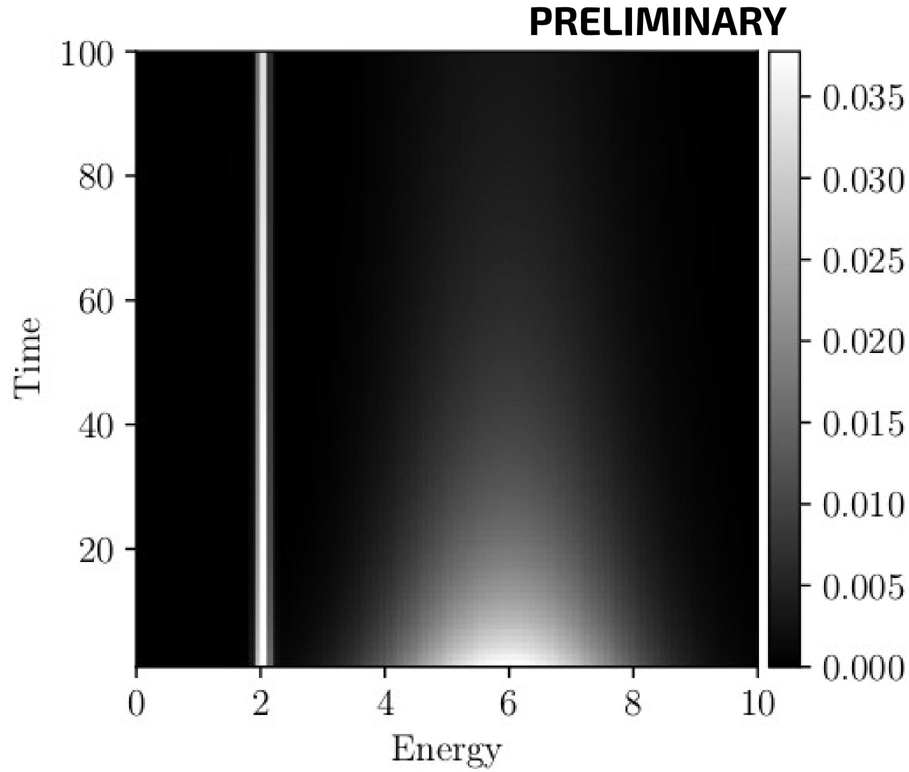
which generalizes the simple signal-to-noise ratio and naturally includes correlations and systematics.

Example:

- Signal with peaked and broad component
- Systematic background uncertainties correlated over large energy range

→ Saturation effects stronger for broad component than for peak





Exemplary applications

Annihilation of sub-GeV DM particles

- Most common final states
  [Boddy & Kumar 15]

$$\chi\chi \to \pi^0\pi^0 \qquad \chi\chi \to \gamma\gamma$$

$$\chi\chi \to \gamma\pi^0 \qquad \chi\chi \to e^+e^-$$

- At low energies, Bremsstrahlung and In-flight-annihilation starts playing a role
- The main antagonist of the signal are Galactic winds (here 250 km/s)

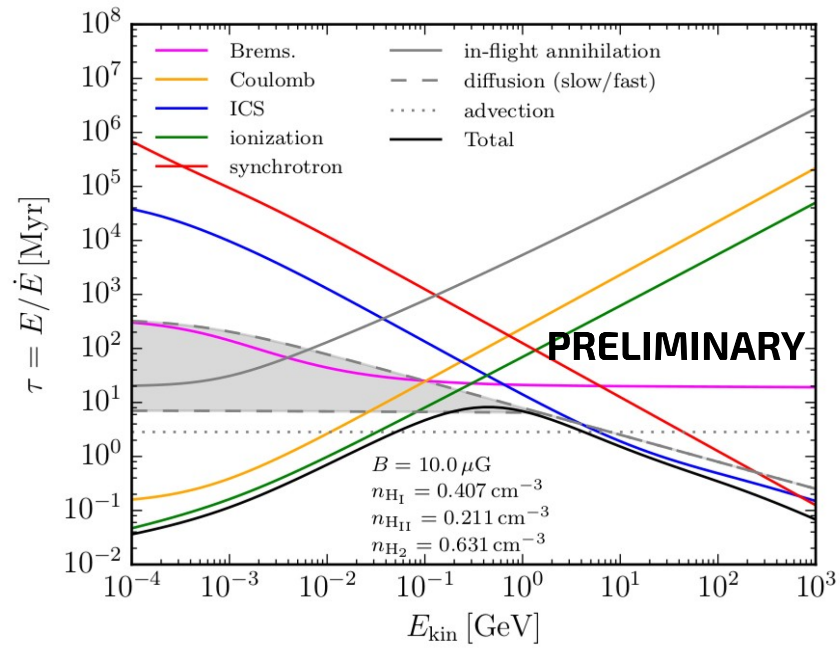
- Modeling of background: Matches COMPTEL data (flux from |b|,|l|<5deg)
- Modeling of uncertainties: Matches experience from Fermi LAT:

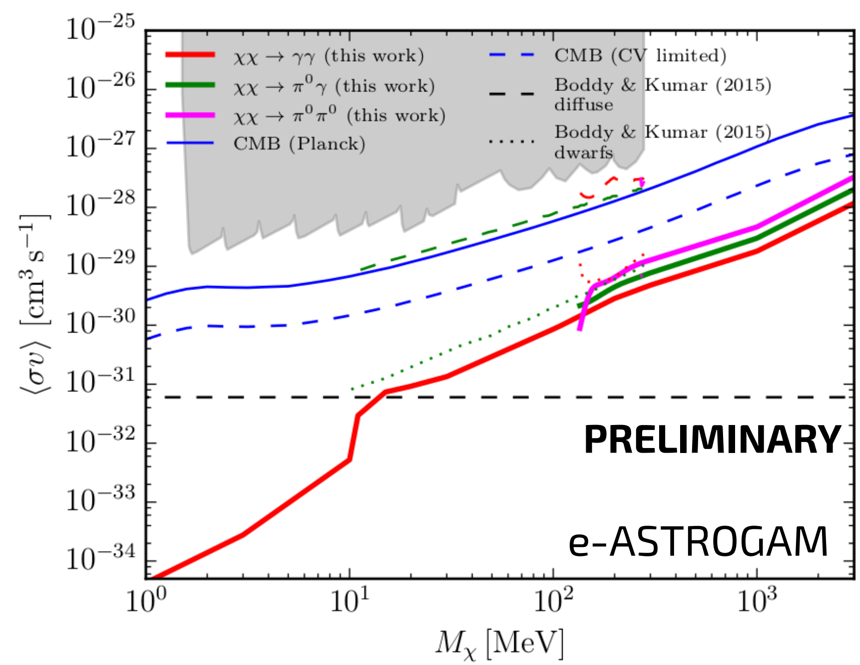
  BG uncertainties depend on correlation length in energy space

  1% @ 0.01dex

  15% @ 0.5dex

Talk by D. Gaggero tomorrow





Exemplary applications

Annihilation of >GeV particles

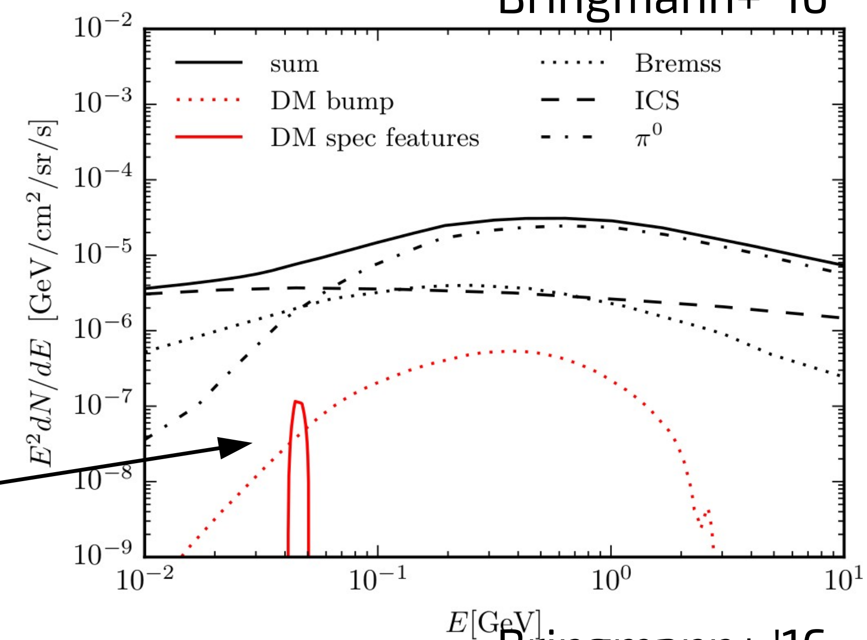
- Relevant channels

$$\chi\chi \rightarrow \bar{b}b \qquad \chi\chi \rightarrow \bar{c}c$$

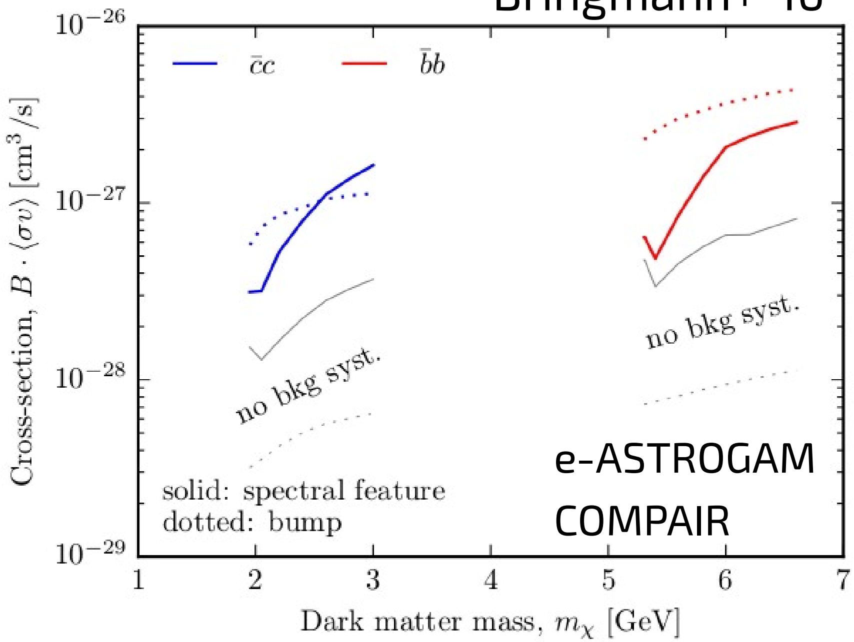
- If close to the kinematic threshold, exited meson states are produced almost at rest; their decay gives rise to box-like or line-like features

- Although these features are at lower energies than the main signal, they can be easier to detect, since backgrounds uncertainties are less problematic for spectral features.
- Modeling of uncertainties: normalization and slope of background components is left free

Bringmann+ '16



Bringmann+ '16

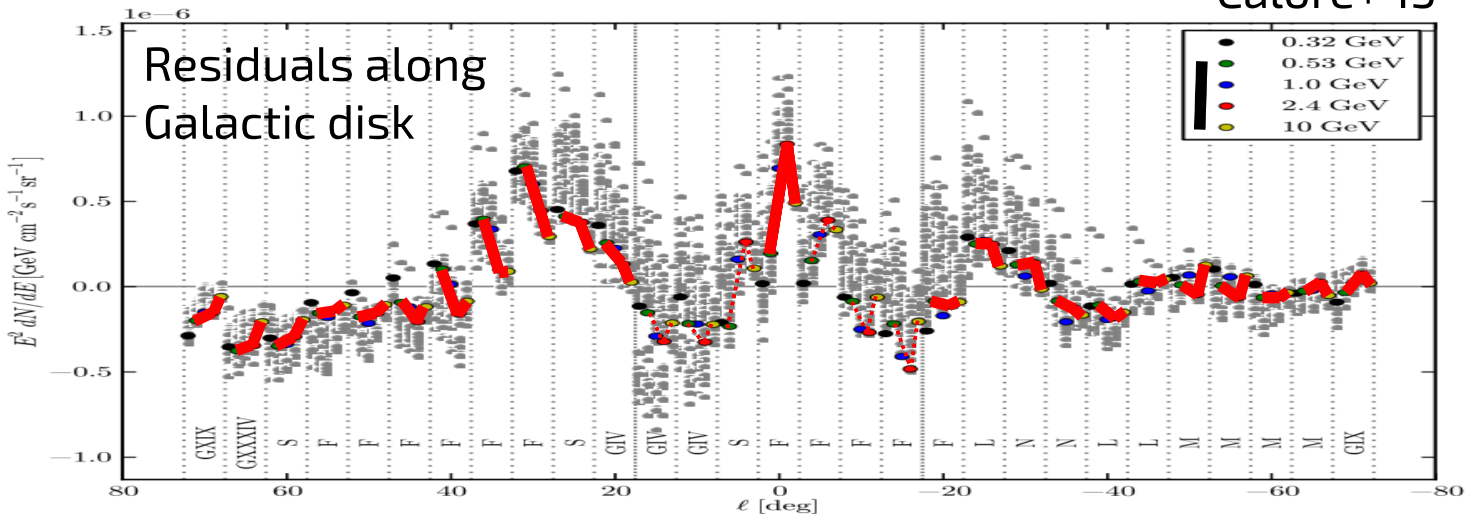


3) The Diffuse Analysis Statistics Nirvana

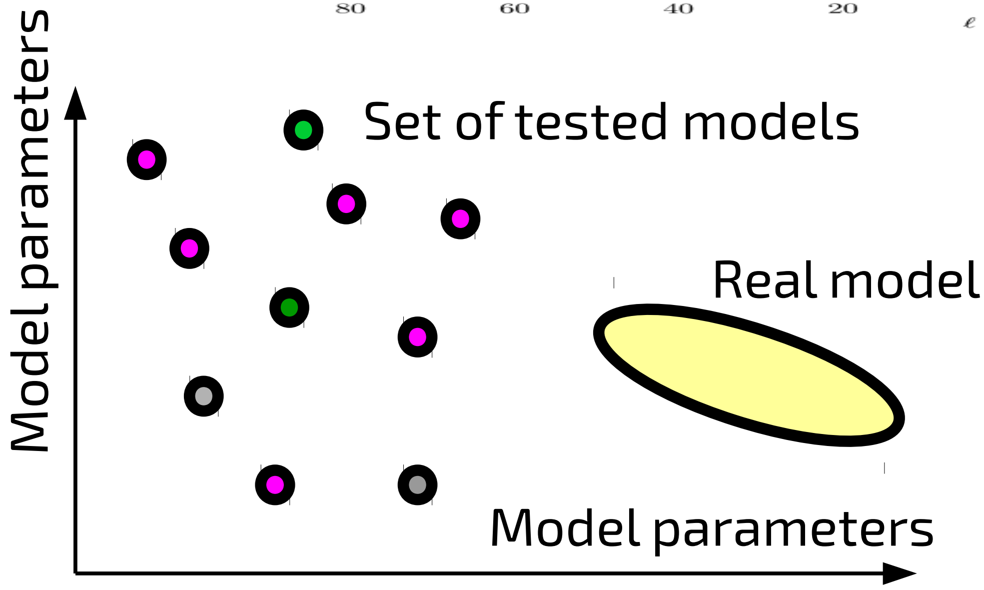
In studies of Galactic diffuse emission, even the best models are formally excluded by many hundred sigmas:

$$p \ll 10^{-300}$$

Calore+'15



Talk by D. Malyshev



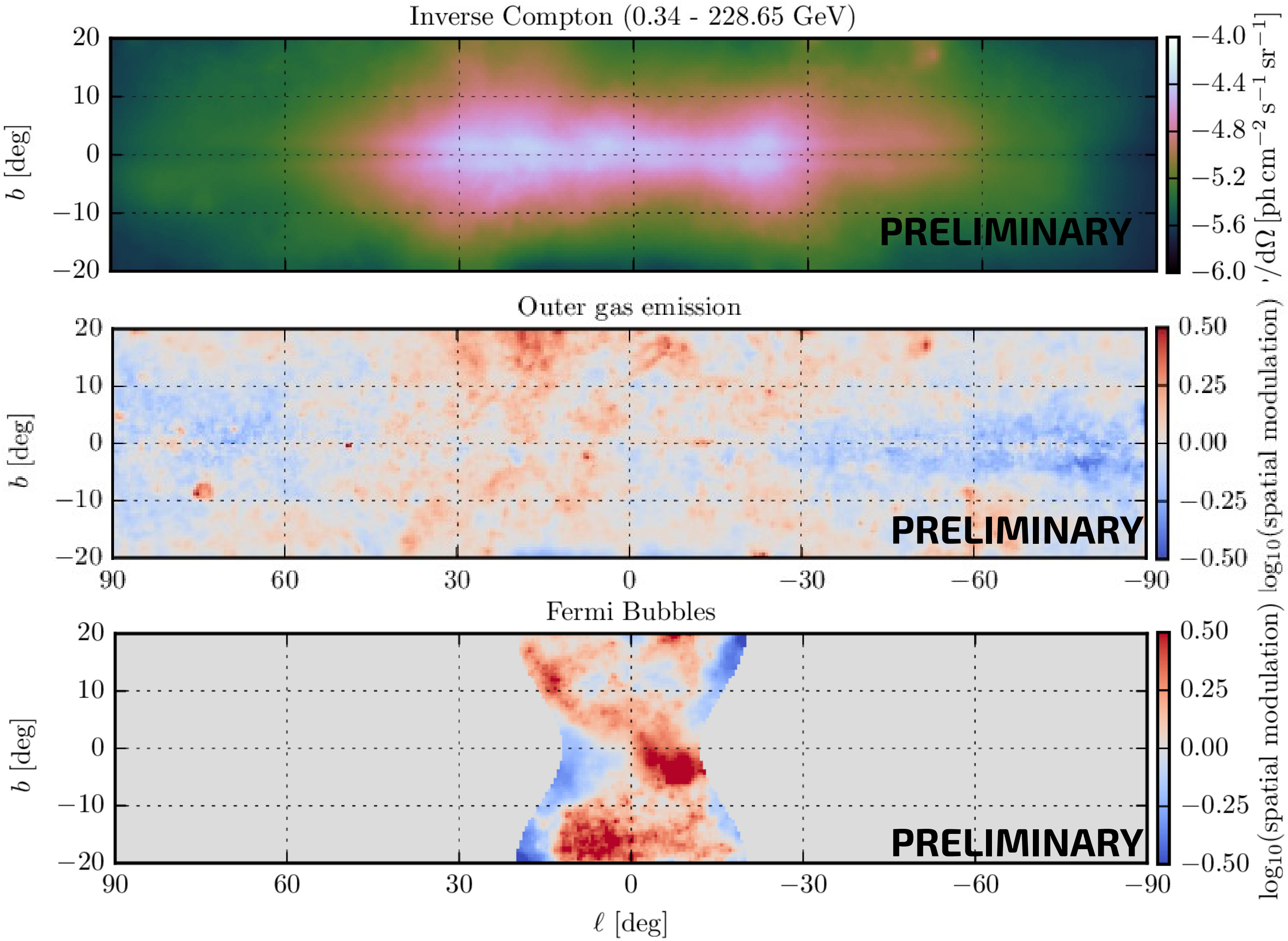
This is not just an aesthetic problem!

- Model comparison is meaningless
- No real estimate of systematic uncertainties (just “bracketing uncertainties”)
- No real treatment of covariances
- Ad hoc methods for extracting un-modeled components (Fermi bubbles)

SkyFACT: Some preliminary results

SkyFACT (Sky Factorization with Adaptive Constrained Templates). Uses panelized Poisson likelihood. Combines in one framework

- Traditional template regression [e.g. Finkbeiner '03; Su+'10; many others]
- Image reconstruction / spectral decomposition
  [maximum entropy methods, e.g. Skilling+'79; de Boer+'16; see also D3PO Selig+'15]



Bi-modal or ring structure of **ICS emission** (disk spectrum)
[see also Casandjian+ '16]

We start with gas HI+CO maps without dark gas correction. Modulation parameters pick up **dark gas** (similar to SFD/gas map).

Fermi bubbles at low latitudes

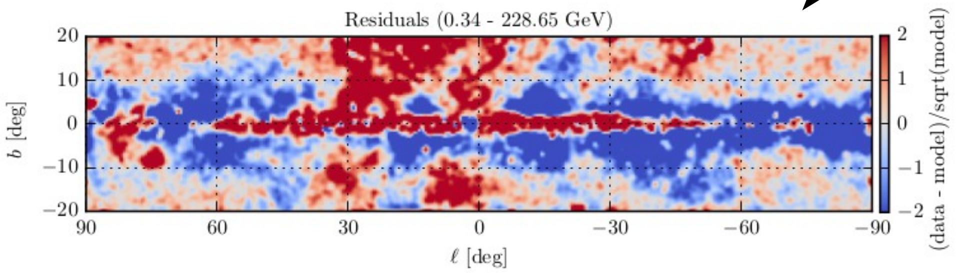
Note: Inner part strongly correlated with extended sources and GeV excess

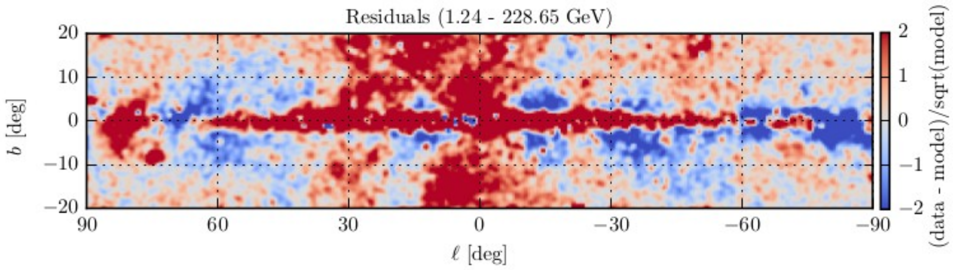
SkyFACT residual maps

Typical GALPROP/Dragon model
w/o nuisance parameters

>340 MeV

>1.24 GeV

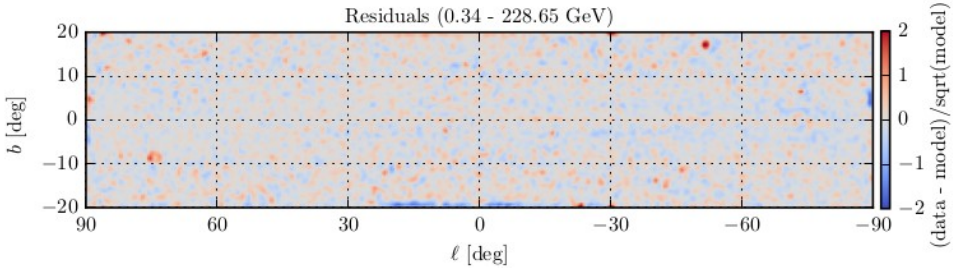


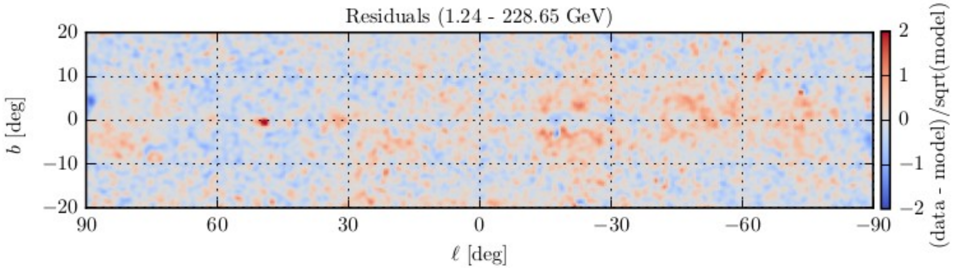


Typical GALPROP/Dragon model **with reasonable nuisance parameters**
(+Fermi bubbles, GC excess, extended sources)

>340 MeV

>1.24 GeV





Conclusions

- **Wavelet fluctuation analyses**
  - Excellent probe for putative bulge MSP population that could cause Fermi GeV bulge emission
  - Superior angular resolution of e-ASTROGAM at sub-GeV enegies will greatly help to characterize this component
- **Fisher information flux and forecasting**
  - Very powerful tool, but largely ignored in our community (very different in cosmology, GW, etc)
  - Fast, and can work well in Poissonian regime
  - Excellent tool to forecast e.g. DM search sensitivities
  - Ex: sub-GeV dark matter, excited meson features
  - e-ASTROGAM could improve existing limits significantly
- **SkyFACT (Image reconstruction + template regression)**
  - Does not replace modeling, but makes it possible to test models against data in a statistically sound way

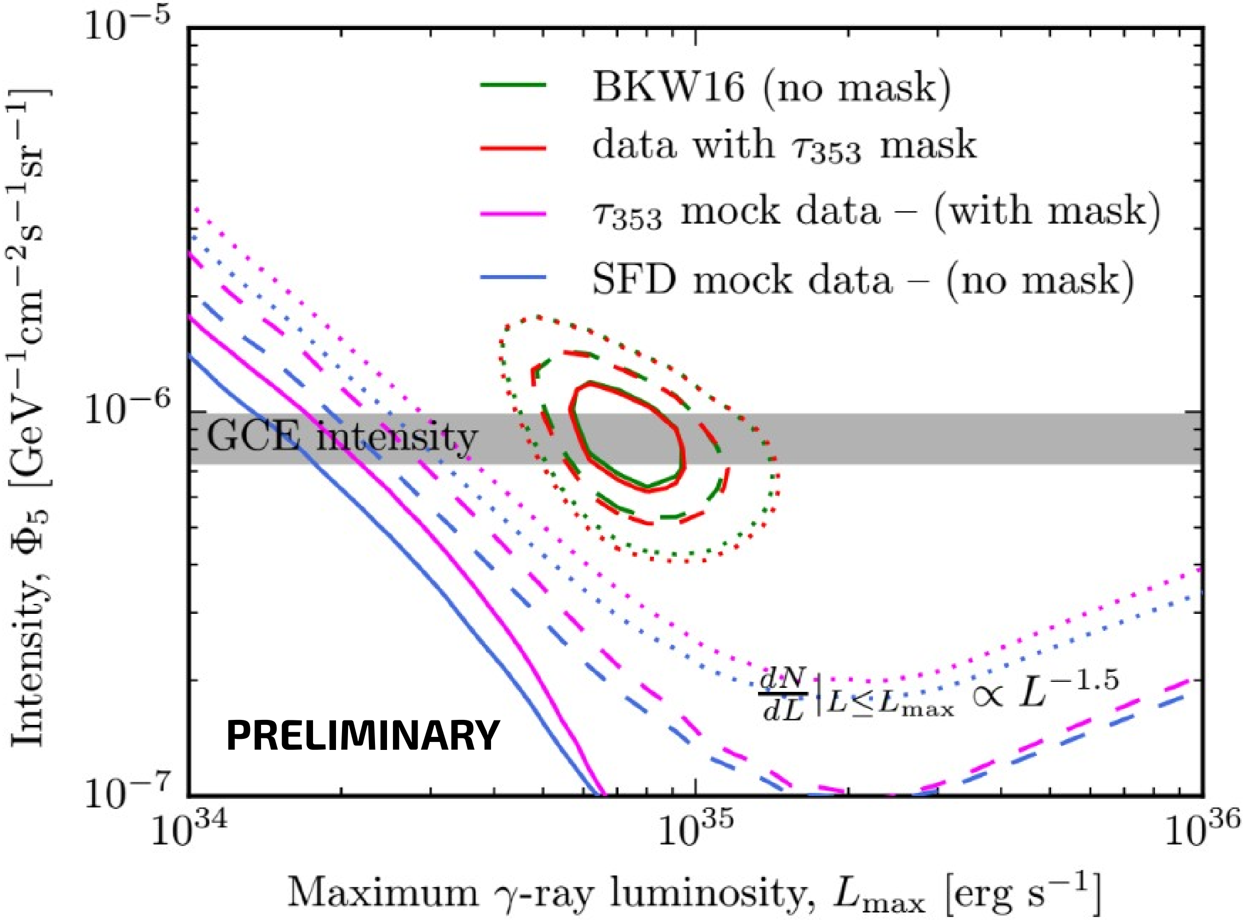
Thank you!

Gas fluctuations etc unlikely to cause signal

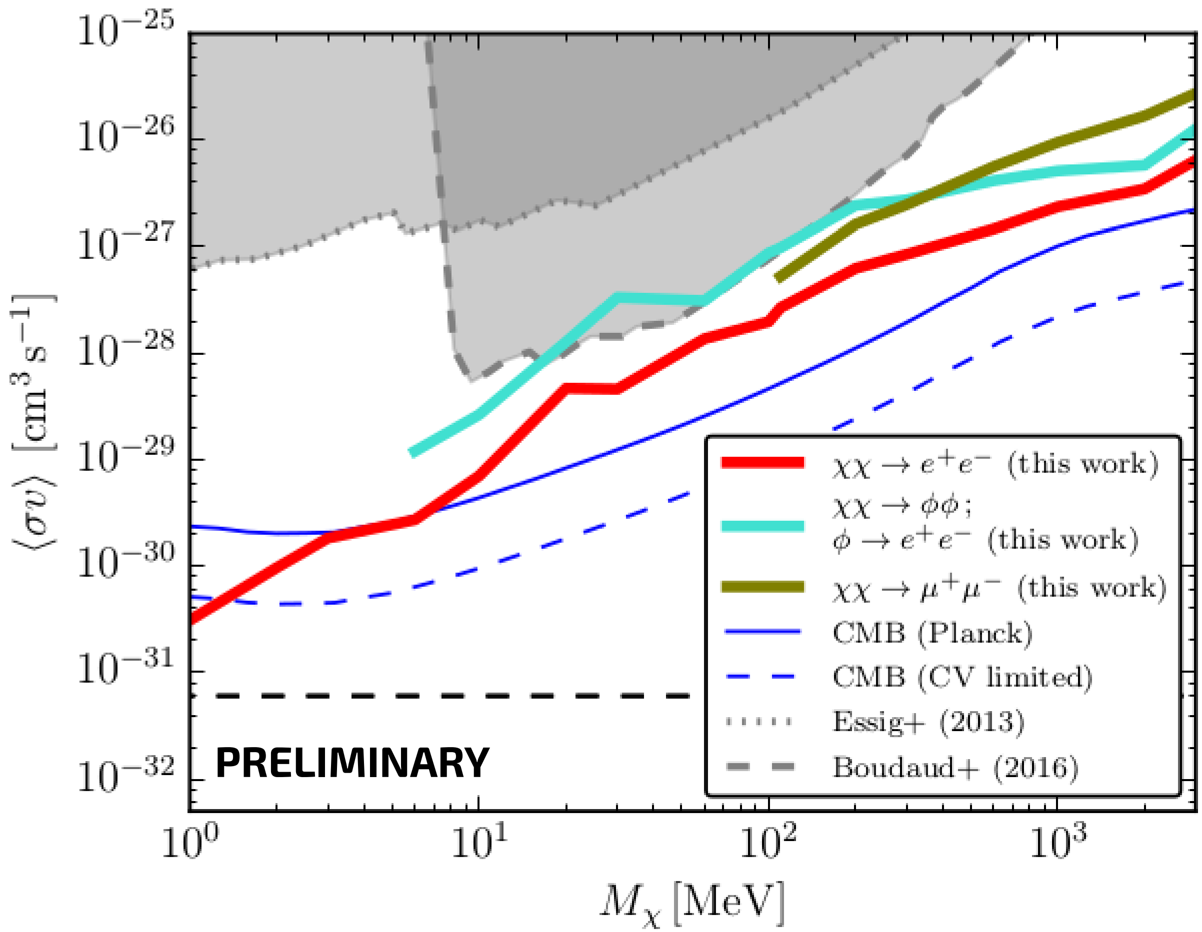
Small scale feature in gas

- Even assuming that *all* diffuse emission comes from gas, we predict a non-detection (Schlegel+97 with ~0.1 deg resolution; Planck optical depth map)

Check out extensive appendix of Bartels+16 for more details.



Limits on leptonic channels



→ Adaptive template regression (SkyFACT)

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

- **Externally predicted**
  - ***Spectral decomposition***
  - Local gas emission & ICS etc.
- **Inferred from data**
  - ***Traditional template regression***
  - Fermi bubbles etc

- **Externally predicted**
  - ***Traditional template regression***
  - Gas emission etc
- **Inferred from data**
  - ***Image reconstruction***
  - Fermi bubbles etc

$$\mu_{ij} = \sum_k T_i^{(k)} S_j^{(k)} \nu_j^{(k)} \tau_i^{(k)} \theta^{(k)}$$

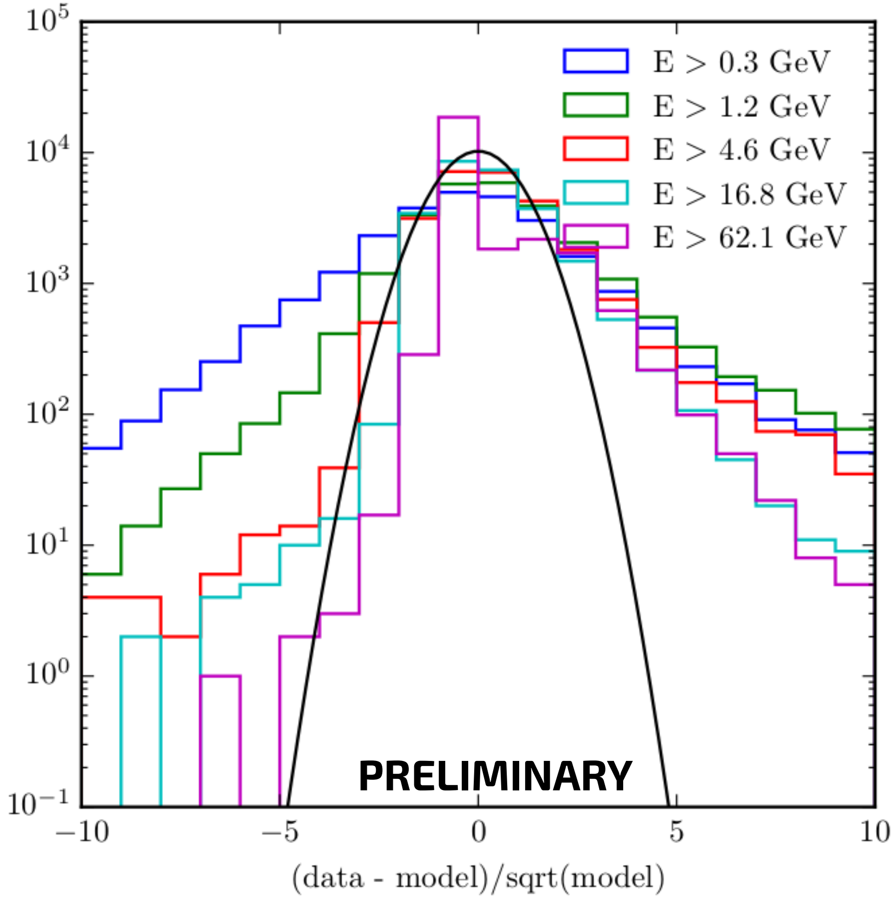
Spectral/spatial templates

Modulation parameters

For each component, the optimal method can be chosen by imposing constraints on the modulation parameters.

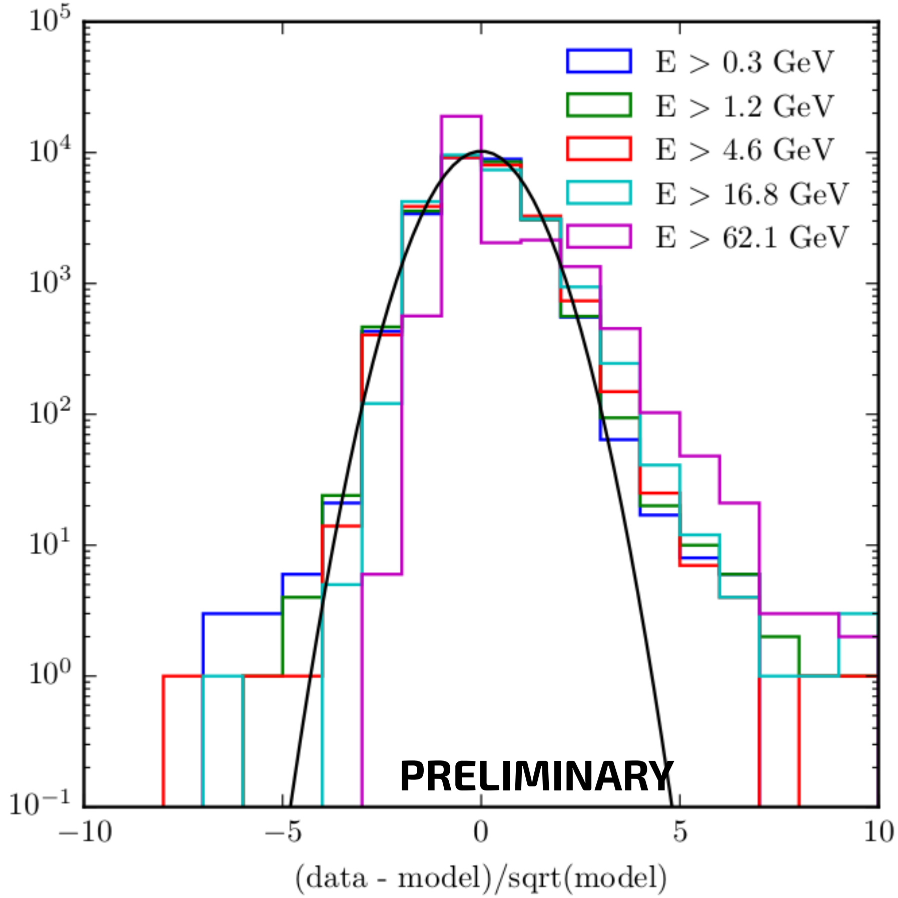
Residual histograms

Conventional template regression



Simple model with rigid gas and ICS templates, isotropic + 3FGL PSCs

Adaptive template regression



Complex model with adaptive gas and ICS templates, several rings, Fermi bubbles, GeV bulge emission, extended sources