Applying SBI to the Spectral and Spatial Information from the GCE

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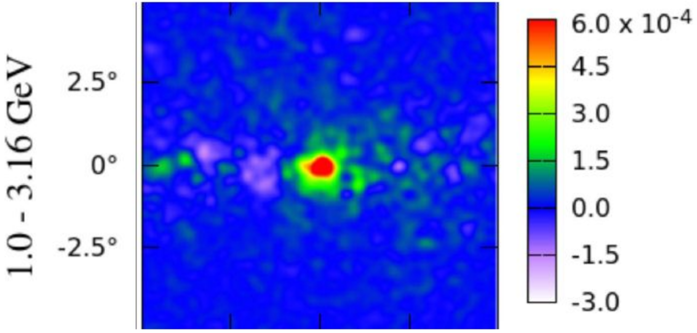
[2402.04549]

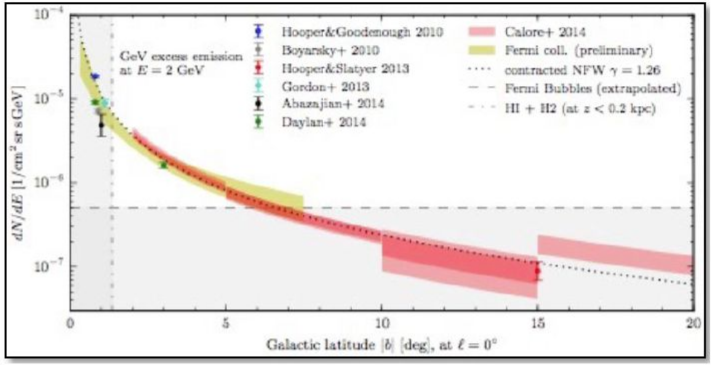
Galactic Center Excess

- excess of photons O(GeV) from Galactic Center seen by Fermi LAT
  - (Goodenough, Hooper [0910.2998], [1010.2752]; Abazajian, Kaplinghat [1207.6047]; Fermi [1511.02938])

- 15 year mystery
  - $\chi\chi \rightarrow$ SM SM ($m_{DM} \sim O(50\ \mathrm{GeV})$)?
  - unresolved millisecond pulsars?



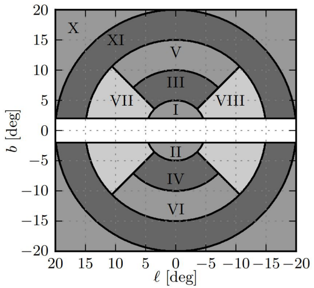
Hooper, LCTP SASDM (2023)

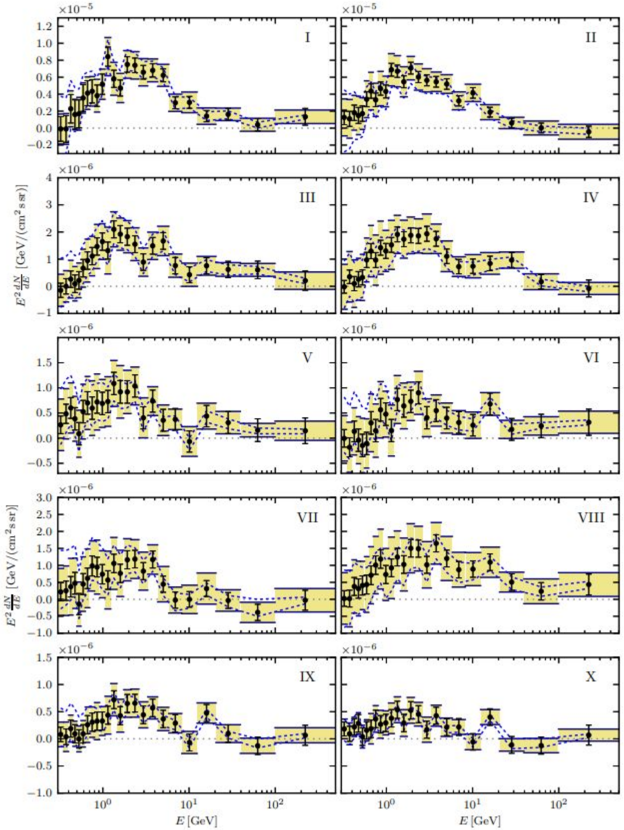


morphology & spectrum

- approximately spherically symmetric about GC
  - may more closely follow galactic bulge

- spectrum consistent with DM and MSPs
  - uniform in ~20° radius





Calore et al. [1409.0042]

spatial and spectral information

- many approaches “factorize” spatial and spectral information, losing correlations between them
  - NPTFit Mishra-Sharma, et al. [1612.03173]
- others employ template fitting that does fit both in tandem
  - SkyFACT Storm, et al. [1705.04065]
  - many template parameters O(10^5)
  - Poisson likelihoods
- GCE may arise from few bright (but unresolved) MSPs
  - spectrum varies from pulsar to pulsar → non-Poisson energy fluctuations between pixels
  - difficult to fit
- goal: to see if joint spatial and spectral analysis improves posteriors

simulation based inference

- energy dependent likelihood becomes computationally intractable with non-Poisson sources
  - probability of observing photons involves many combinatoric sums over sources
  - easy to generate mock data from a model
- important for MSPs
  - a single pulsar produces several observed photons
  - results in non-Poisson counts fluctuations from pixel to pixel
- estimate the likelihood/posterior by simulating data over parameter space
  - rejection algorithms: ABC
  - neural algorithms: normalizing flows, SNPE, SNLE, SNRE
- goal: use a neural algorithm on non-Poisson data

Neural Posterior Estimation (NPE)

- trained a neural network to learn the posterior from simulated data
    - sbi python package (Tejero-Cantero, et al. [2007.09114]): algorithm based on (Greenberg, et al. [1905.07488])
- amortized analysis
    - non-amortized (SNPE): multiple rounds of training based on observed data
- Processing
    - ~10^5 simulations per network, requiring ~50 CPU hours
    - ~5 CPU hours to train (more for SNPE)
- results robust to varying training sample size

mock data analysis

- our source distribution models are exact, by definition
    - isotropic, galactic diffuse, Fermi bubbles, DM annihilation, MSPs
- clarifies how much the joint use of spatial and spectral information helps
- focus on case where spatial and spectral information alone from DM vs. MSPs are nearly degenerate
    - DM annihilation spectrum is average pulsar spectrum
    - pulsar spatial distribution goes as $\rho_{DM}^2(r)$
    - also use disk pulsars, but not important after masking galactic plane
- mock analysis doesn't tell us about mismodelling effects, or if our models match Fermi data

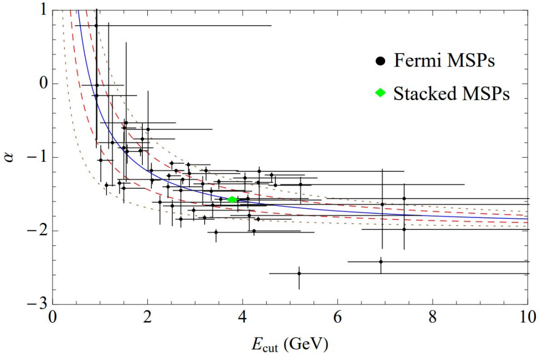
simulating data

- individual photon directions and energies are generated
- Steps
  - stochastically draw photons from high-resolution (N_{side} 2^9, 10^3 E bins) pixelated flux maps (DM annihilation, diffuse and isotropic backgrounds)
  - place MSPs in 3d space from density function
  - assign luminosities from luminosity function
  - draw number of photons and spectral parameters for each MSP
  - draw corresponding photon energies from each MSP spectrum
  - perturb photon energies and directions by the Fermi IRF
  - compress data to a lower resolution pixelated counts map
- having individual photons makes applying energy dependant PSF trivial

millisecond pulsar model

- use fit of 61 Fermi pulsars to power law ×exp. (Cholis, et al., [1407.5583])

$$\frac{dN}{dE} \propto \frac{E^{\alpha}}{E_{cut}^{\alpha+1}} e^{E/E_{cut}}$$



Cholis et al. (2014) [1407.5583]

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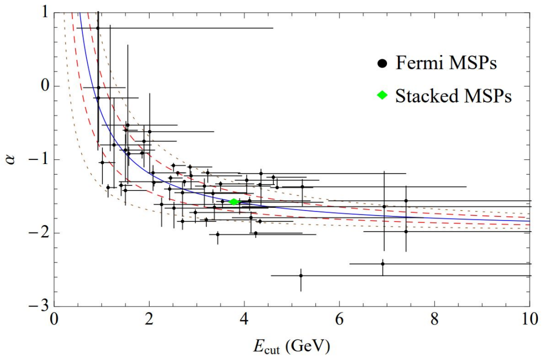

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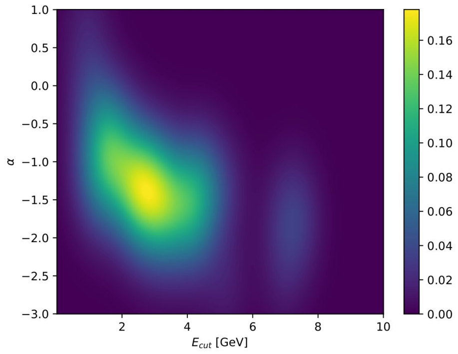

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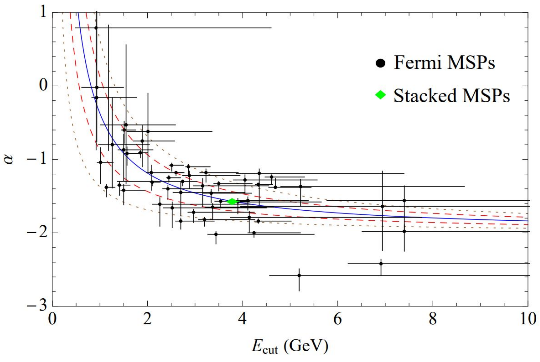

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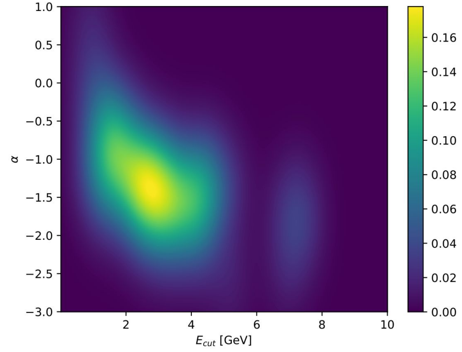
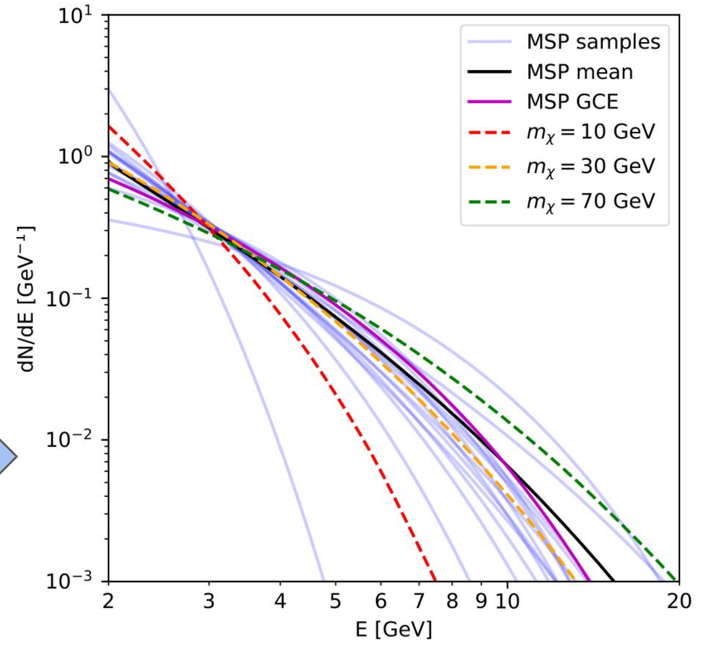


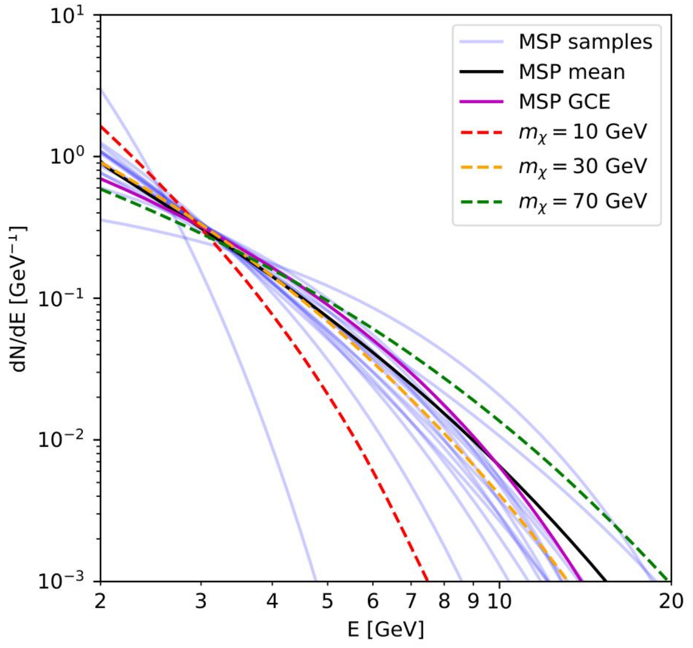


$\chi\chi \to b\bar{b}$

millisecond pulsar model

- use fit of 61 Fermi pulsars to power law ×exp. (Cholis, et al., [1407.5583])
- estimate parameter distribution from fits using Gaussian KDE
- luminosity function: broken power law (Lee, et al. [1506.05124])
- distribution: gNFW^2 (**γ** = 1.2)
- GCE produced by ~650 pulsars

$$\frac{dN}{dE} \propto \frac{E^{\alpha}}{E_{cut}^{\alpha+1}} e^{E/E_{cut}}$$

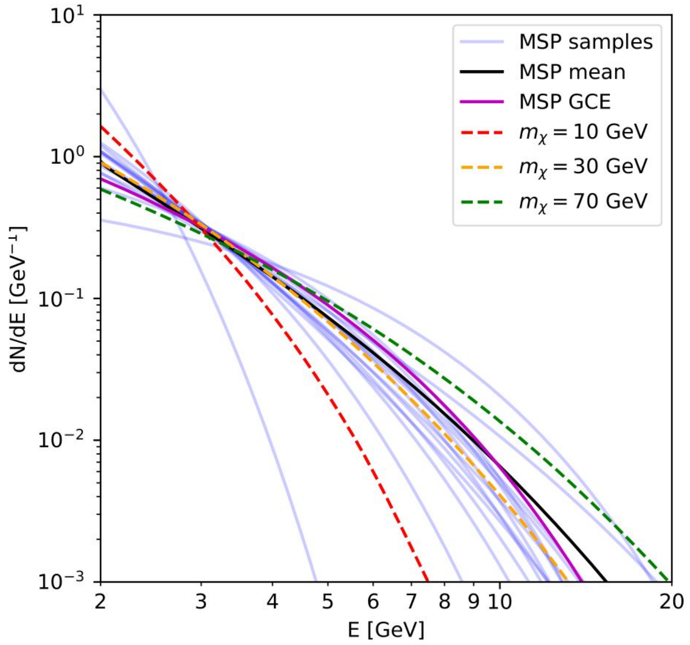


$$\chi\chi \to b\bar{b}$$

dark matter model

- spectrum
  - equal to MSP mean (minimum spectral info)

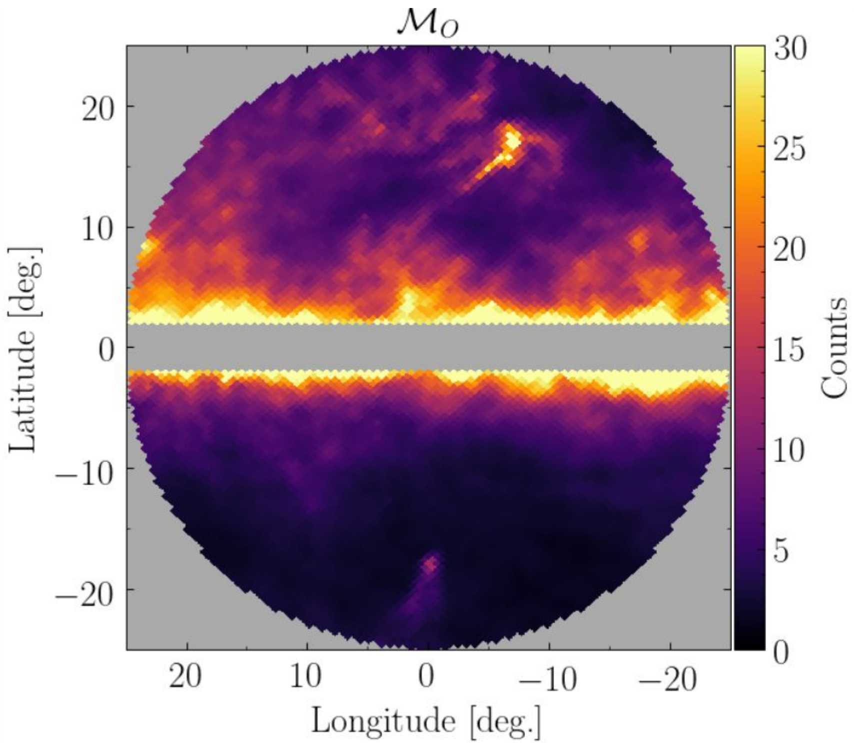
- distribution: gNFW^2 (**γ** = 1.2)



$$\chi\chi \to b\bar{b}$$

back/foreground models

- galactic diffuse, isotropic, and Fermi bubbles
- diffuse anisotropic: Model O (Buschmann, et al. [2002.12373])
- isotropic: Fermi-LAT model
    - (https://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html)
- Fermi bubbles
    - spatial distribution = NPTFit
    - spectrum: Su, et al. [1005.5480]

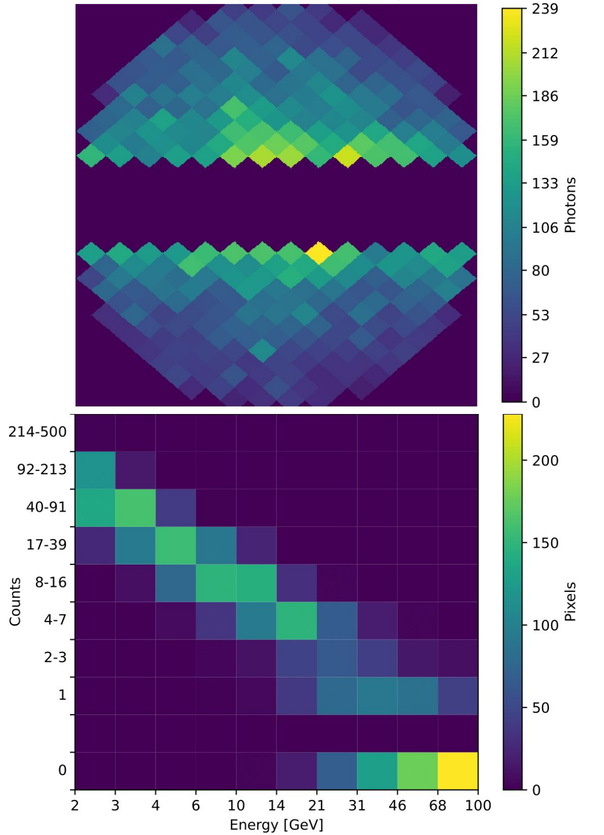


Buschmann, et al. [2002.12373]

summary statistic

- ROI
  - within 10° of GC, |b|> 2°
  - energy: 2 –100 GeV
- photons binned into 280 pixels, 10 log-spaced energy bins
- data compressed to 3 summary statistics
  - energy+direction: energy-dependent histogram of photon counts per pixel
  - direction: histogram of photon counts per pixel
  - energy: counts per energy bin

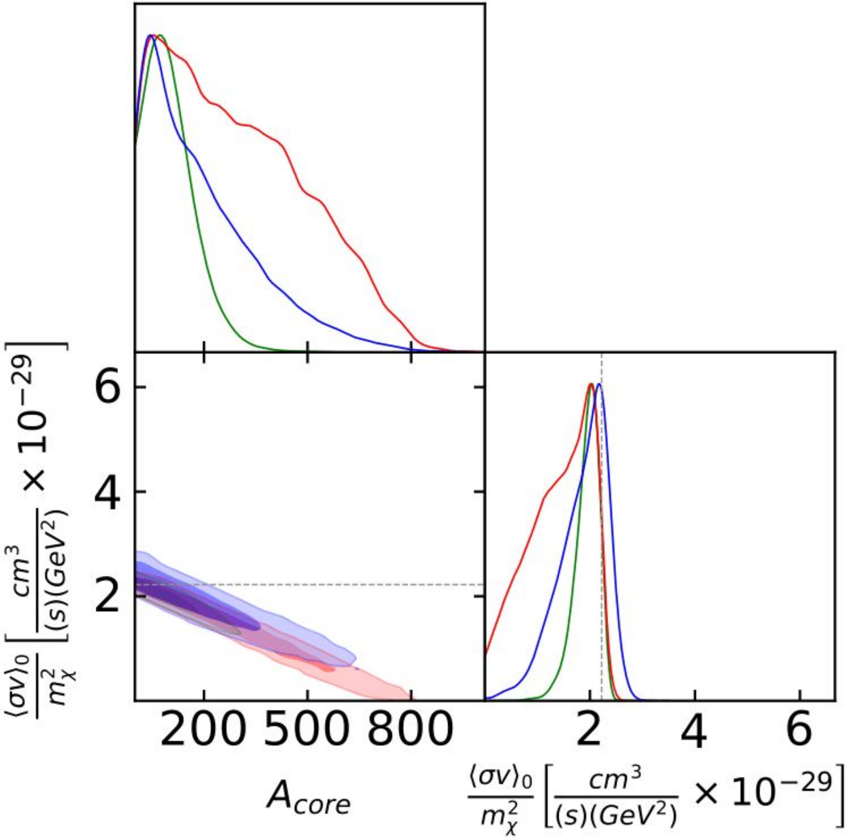
counts (2 - 2.96 GeV)



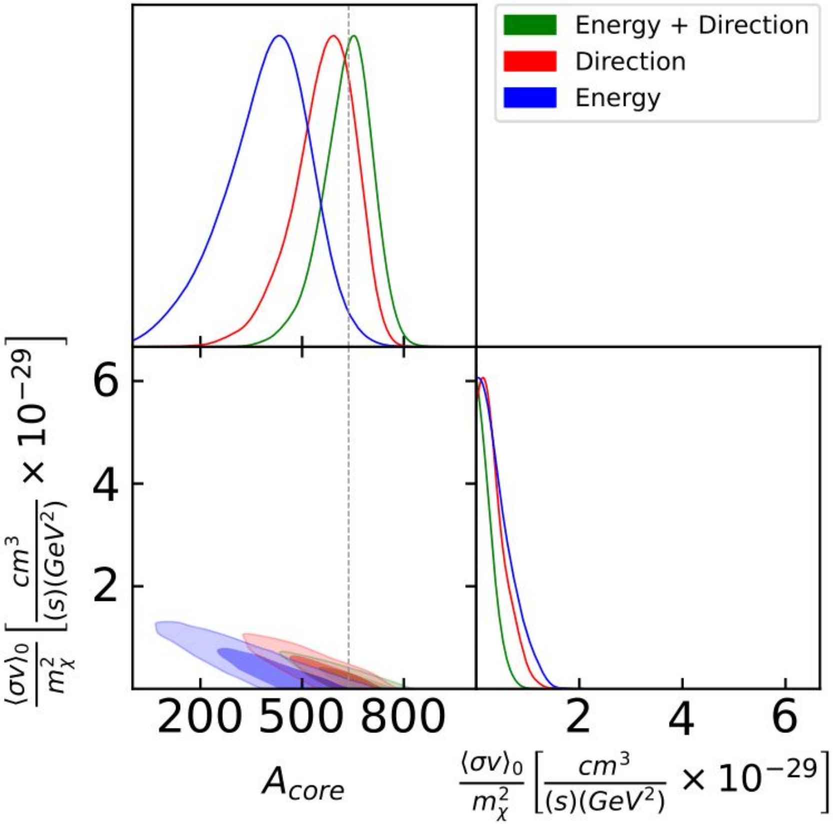
Energy+direction summary

results

DM-only



MSP-only



discussion

- can discriminate origin of GCE using energy information only, even though DM spectrum is the same as average MSP spectrum
  - varying MSP spectrum → NP fluctuations in photon count per energy bin
- directional information alone (clumpiness of CPD) also provides discriminating power, consistent with previous work
- but using energy+direction jointly provides significant improvement in parameter constraints
- we analyzed 100 mock data samples from same true model
  - 50% DM, 50% MSP
  - mean reconstructed parameters biased, but bias small compared to 68% credible interval of single 1D posterior

future work

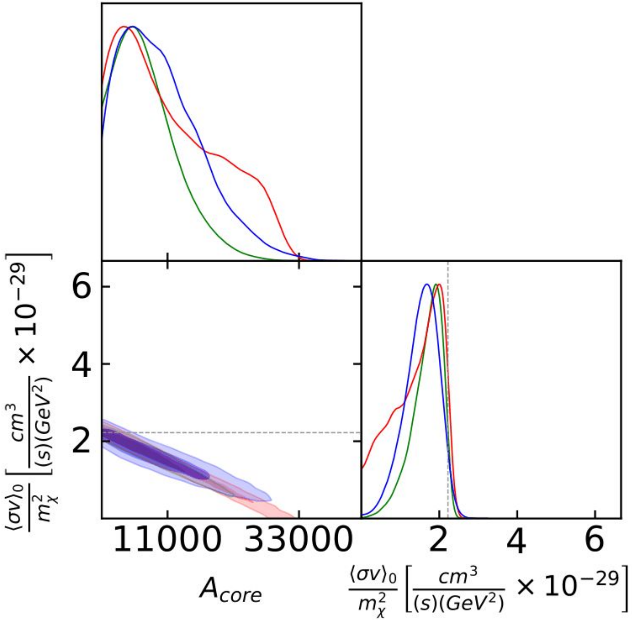
- mock analysis assumes correctly modelled source distributions
  - NP CPD analysis more complicated if sources are mismodelled
  - difficult to distinguish NP fluctuation of a correctly modelled source from a Poisson fluctuation of an incorrectly modelled source
  - use of joint spatial and spectral information can potentially be more robust
- next step is to do a mock analysis with mismodelled background
- after that, analysis of actual Fermi-LAT data
- general-purpose photon generation tool/ SBI analysis
- apply methodology to diffuse gamma ray background(DGRB)
  - sources are diffuse galactic emission, SFG, blazars, mAGN, dark matter(?)

mahalo!

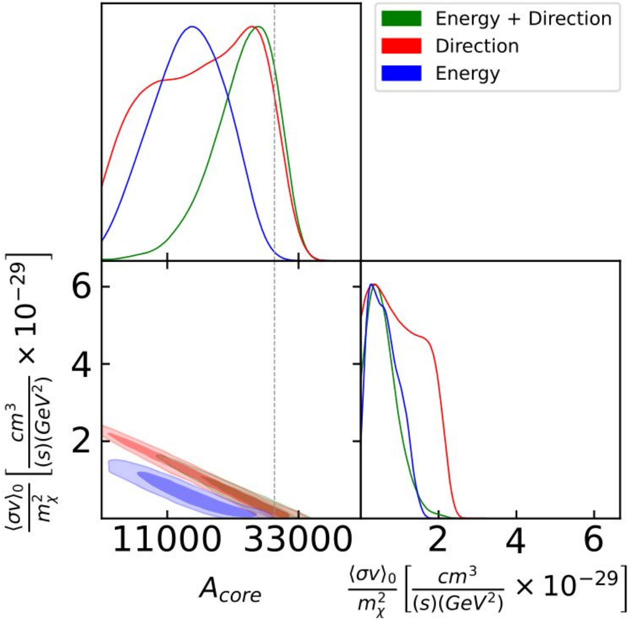
backup slides

alternative pulsar model

DM-only



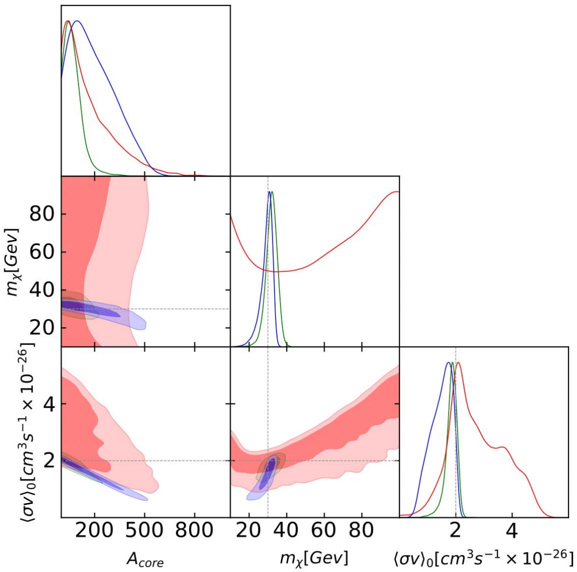
MSP-only



- **alternative MSP luminosity model**
  - **GCE produced from 30000 pulsars**
  - **much more Poisson (degenerate with DM)**

DM spectrum from $b\bar{b}$

DM-only



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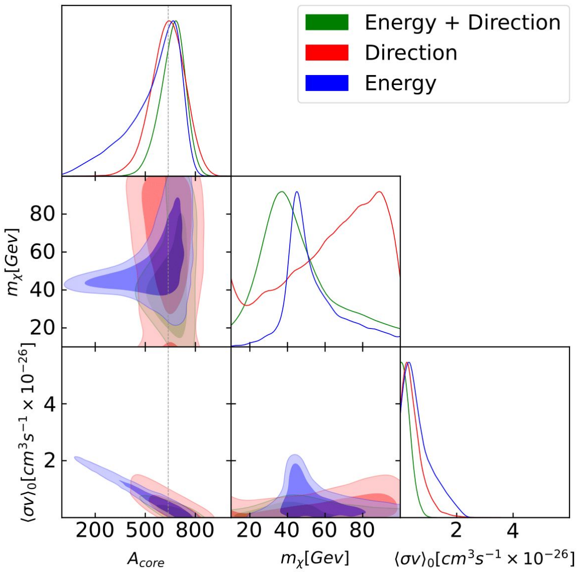
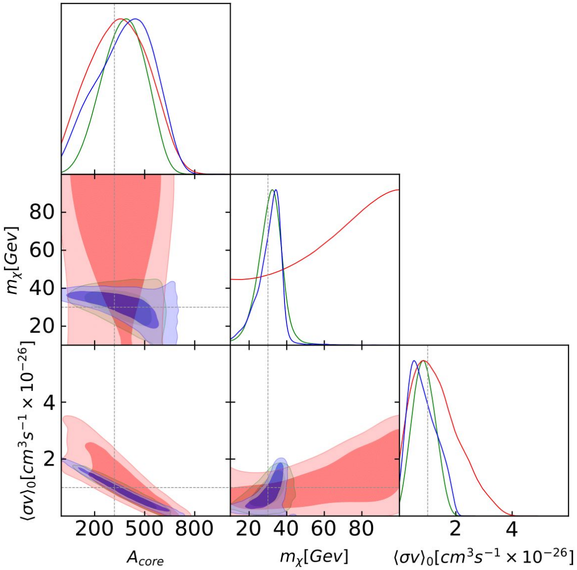


50% DM - 50% MSP



- DM mass allowed to vary
  - able to reconstruct all three parameters
  - pulsar spectrum most similar to 30-50 GeV DM