



Applying SBI to Spectral and Spatial Information from the GCE

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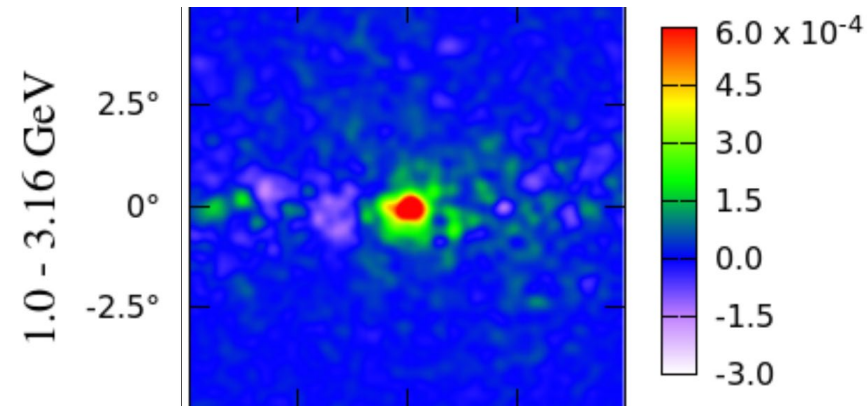
w/ Eric J. Baxter, Katharena Christy

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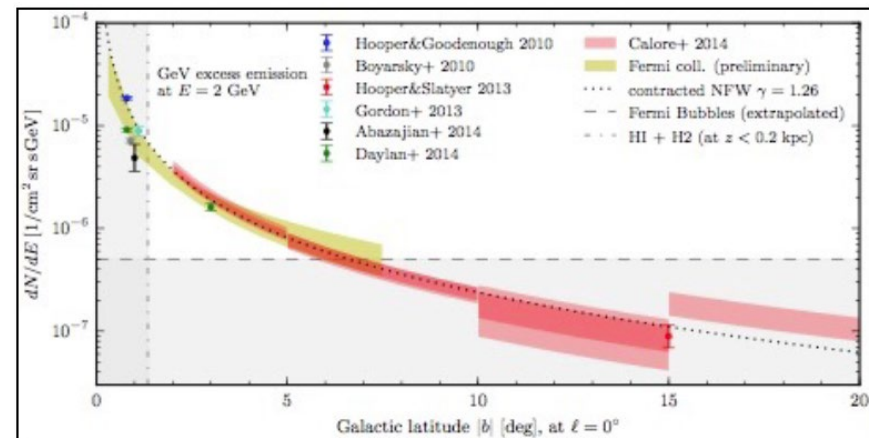


Galactic Center excess

- excess of GeV-range photons from **GC** seen by **Fermi** (Goodenough, Hooper 0910.2998, 1010.2752; Abazajian, Kaplinghat 1207.6047; Fermi 1511.02938)
 - long-standing excess ...
- ... but **origin is still a puzzle**
 - **dark matter** annihilation?
 - $XX \rightarrow \bar{b}b$ ($m_X \sim 50$ GeV)
 - unresolved **millisecond pulsars**?
 - see Hooper and Calore's talks
- good to find **new ways** to shed light on this question



Hooper, PPC 2022





some approaches ...

- **morphology**
 - does **angular distribution** follow **squared density of DM** (gNFW)?
 - or does it follow the **stellar distribution** (boxy bulge)?
 - see Dan Hooper and Chris Gordon's talks
- **counts-in-pixels distribution (CPD)**
 - if GCE arises from bright unresolved MSPs, will be **clumpy**
 - **non-Poisson probability distrib.**
 - but difficult to disentangle from **mismodelling of background**
- Di Mauro 2101.04694; Cholis, et al. 2112.09706; McDermott, et al. 2209.0006; Zhong, et al. 2401.02481
- Macias, et al. 1601.06644; Storm, et al. 1705.04065; Bartels, et al. 1711.04778; Macias, et al 1901.03822; Ploeg, et al. 2105.13034; Pohl, et al. 2203.11626; Song, et al. 2402.05449
- Lee, et al. 1506.05124; Zechlin, et al. 1512.07190; Leane, et al. 1904.08430; Leane, et al. 2002.12370; Buschmann, et al. 2002.12373; Dinsmore, et al. 2112.09699
- ... for example



spatial and spectral information

- many approaches “factorize” spatial and spectral information
 - spatially-averaged spectrum for the excess
 - angular distribution
- even using both, you lose correlations between spatial and spectral data
- for example, if GCE arises from bright (but unresolved) MSPs
 - a single pulsar produces several observed photons
- but each pulsar’s spectrum is different
- so photon energy distribution will exhibit non-Poisson behavior, and vary from pixel to pixel
- our goal → see if we can gain from jointly using spatial and spectral info



simulation-based inference

- with joint spatial and spectral information, and non-Poisson distributions, computing exact **likelihood** is **computationally intractable**
- instead use **simulation-based inference** (**likelihood-free inference**)
- basic reason
 - it's **hard** to compute the likelihood of getting particular data because of the **combinatoric** sums over which sources produce which photons
 - but **easy** to **generate mock data** from source distributions
- goal is to use simulated data to **estimate posterior**



NPE

- we use **neural posterior estimation** (NPE)
- essentially, train a neural network to **learn the posterior** from simulated data
- we use **sbi** package (Tejero-Cantero, et al. JOSS 5(52):2505, 2020)
 - default parameters
 - trained on **10^5 simulations**
 - 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 $\rho_{\text{DM}}^2(r)$
 - also use disk pulsars, but **not important** after masking galactic plane
- mock analysis **doesn't tell about mismodelling effects** ...
- ... or if our models **match Fermi data**
- that's a **next step**



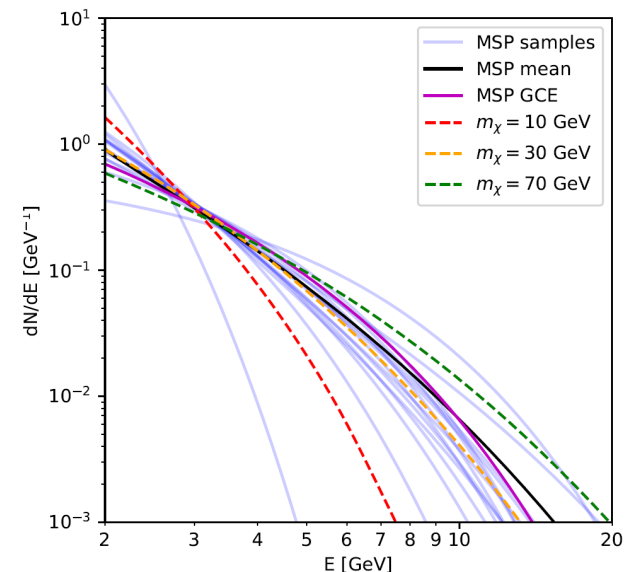
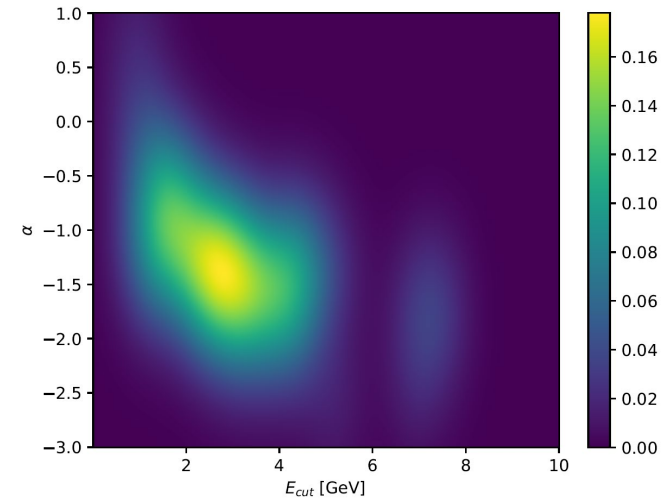
photon generation

- analysis begins with generating **individual photons**
- photon generation steps
 - generate photons from **DM annihilation and diffuse bgds** from a high-resolution **pixelized flux map**
 - generate **MSPs** from **density/luminosity function**, draw **spectral parameters** from distribution
 - draw **number of photons** from each MSP, draw **energies** from spectrum
 - vary photon energies and directions by **instrument response function (IRF)**
 - produced lower-resolution **pixelized count map for each energy bin**
- generating individual photons allows us to **correctly** treat the **energy dependence of the PSF**



MSP spectra and luminosity

- use fit of 61 pulsars to **power law**
× exp. (Cholis, et al., 1407.5583)
- **estimate parameter distribution**
from fits using **Gaussian KDE**
- main point → **significant variation** in spectrum from pulsar to pulsar
- **luminosity fcn.** → broken power law (Lee, et al., 1506.05124)
- GCE produced by **~ 650 pulsars**



$$\frac{1}{N_\gamma} \frac{dN_\gamma}{dE} \propto \frac{E^\alpha}{E_{\text{cut}}^{1+\alpha}} e^{-E/E_{\text{cut}}}$$



DM and backgrounds

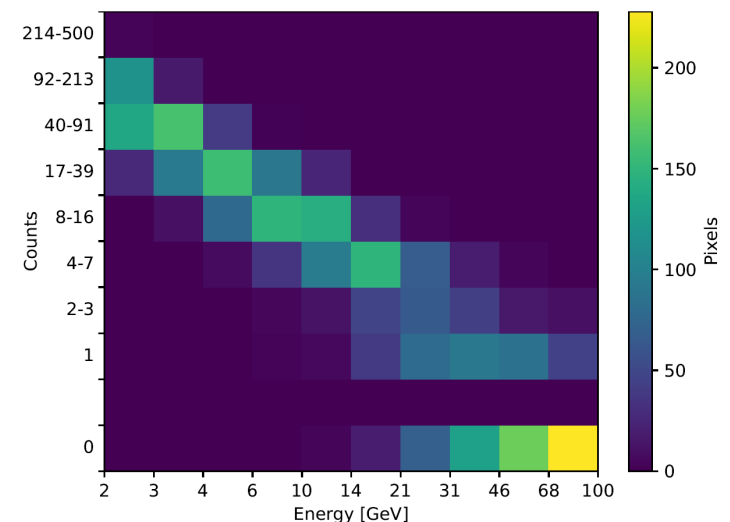
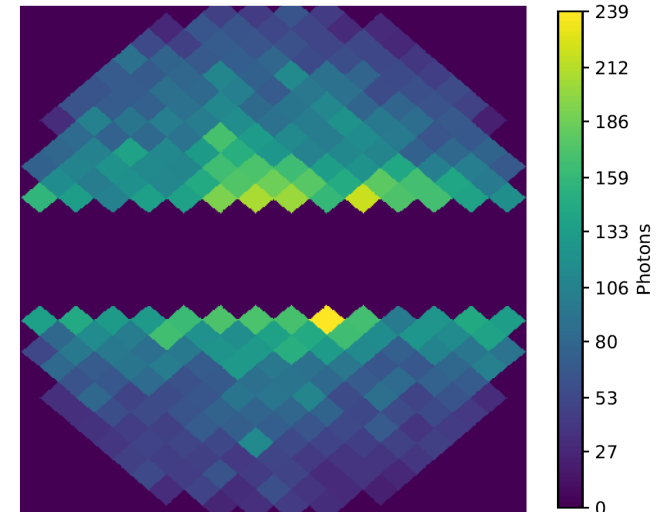
- take **DM annih. spectrum** to be same as **average MSP spectrum**
 - **minimal** spectral information without spatial correlation
- distributed according to **gNFW** profile
 - $\rho_{\text{DM}}(r) \propto r^{-\gamma}$ near GC
 - $\gamma = 1.2$
 - DM signal distributed as $\rho_{\text{DM}}^2(r)$
 - MSP distributed as $\rho_{\text{DM}}^2(r)$
- also include **galactic diffuse**, **isotropic**, and **Fermi bubbles**
- **diffuse anisotropic** = model O of 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



data and summary statistic

- ROI: within 10° of GC, $|b| > 2^\circ$
- energy: $2 - 100$ GeV
- 280 pixels, 10 log-spaced energy bins
- compress data to summary statistic
 - **energy+direction**: energy-dependent histogram of photon counts per pixel
 - **direction**: histogram of photon counts per pixel
 - **energy**: counts per energy bin

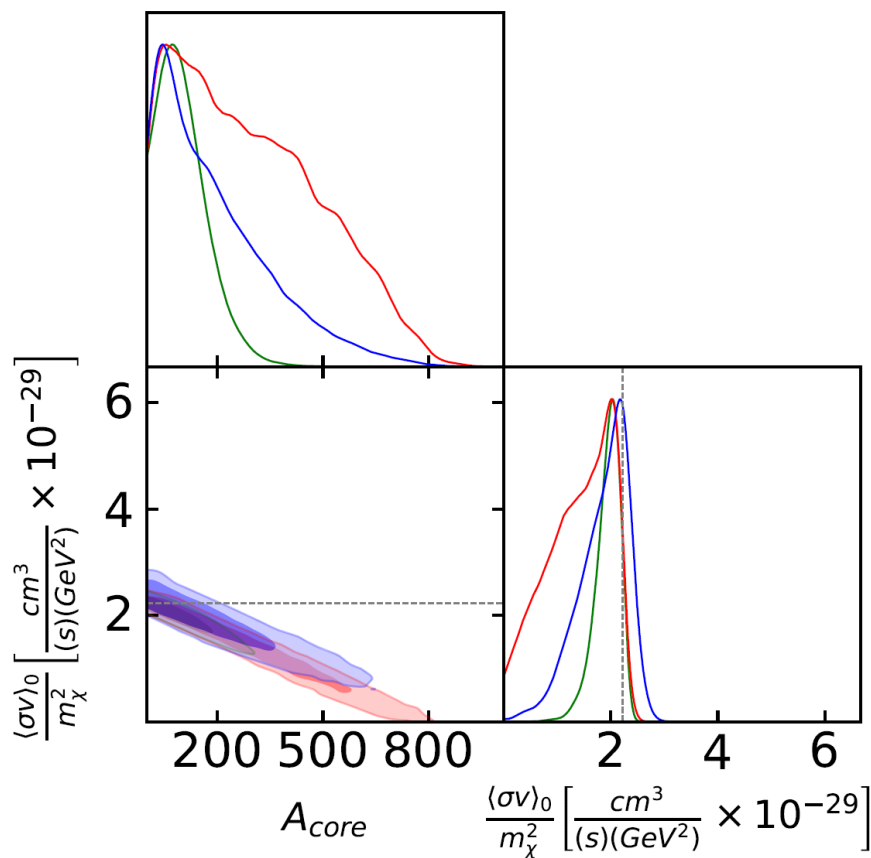
2 - 2.96 GeV



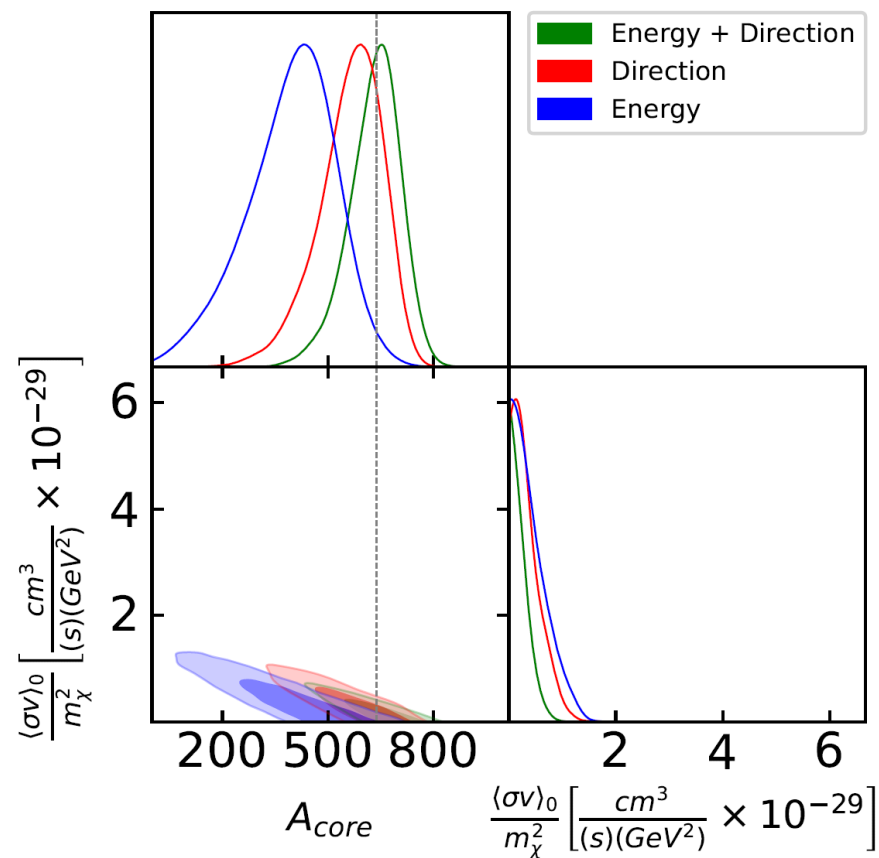


results

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(?)





Backup Slides

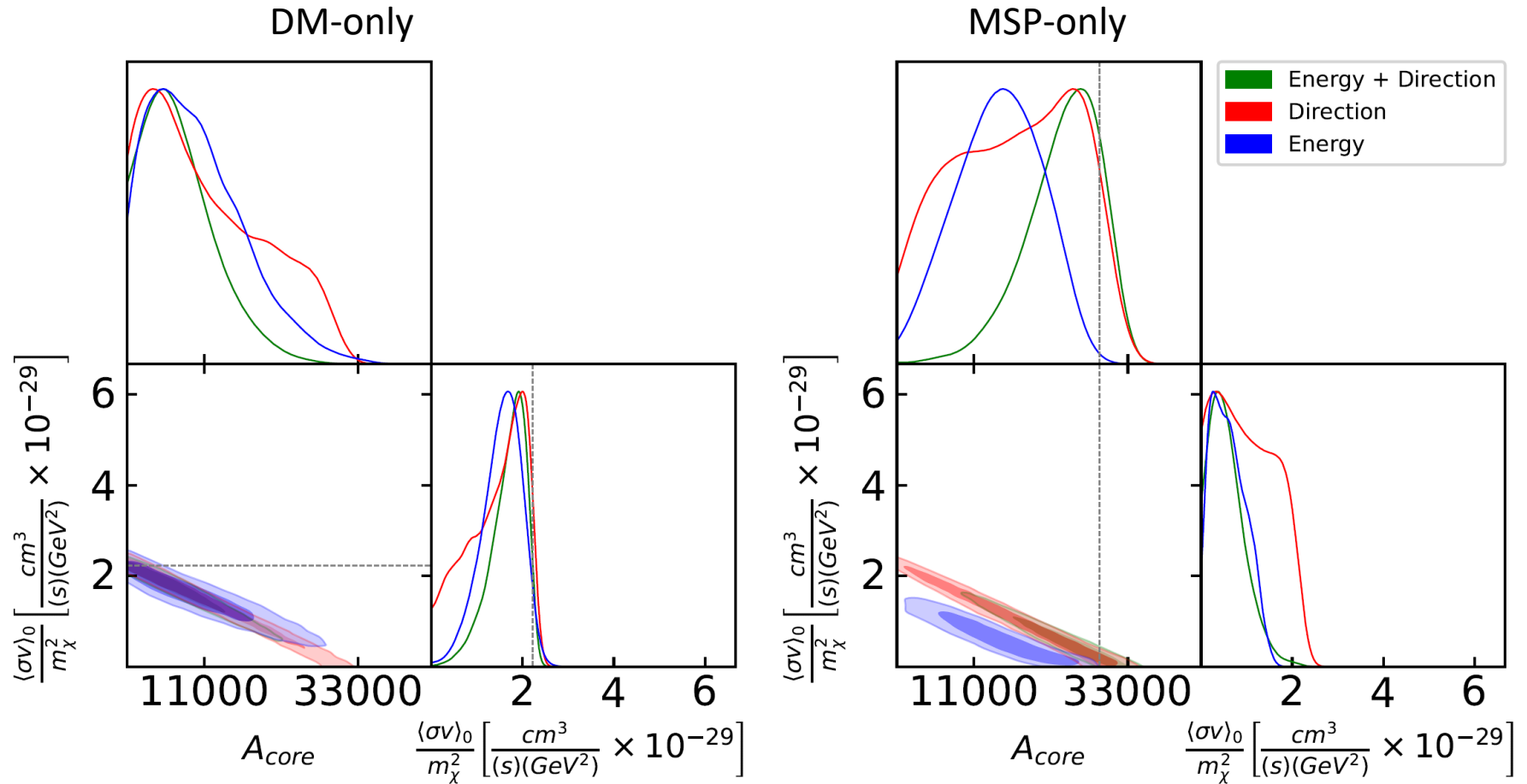
conclusion

- the origin of the **Galactic Center excess** is still an interesting **puzzle**
- want to utilize as much **information** as possible
- we use **SBI** to **correlate spatial** and **spectral** information
- takes advantage of the **variation** of the spectra of **bright MSPs**

- combined information **improves ability to reconstruct GCE origin**



alternative pulsar model



GCE from 30000 pulsars, much more Poisson