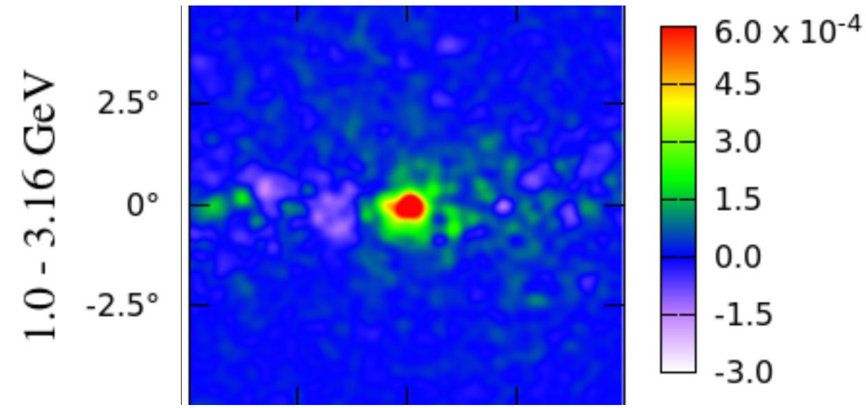
Applying SBI to Spectral and Spatial Information from the GCE

Jason Kumar
University of Hawaii
w/ Eric J. Baxter, Katharena Christy

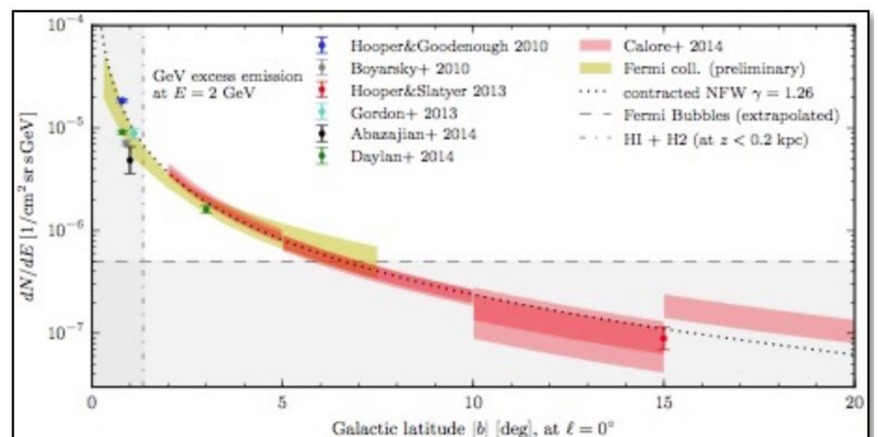
2402.04549

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 → $\bar{b}b$ ($m_X \sim 50$ GeV)
  - unresolved millisecond pulsars?
- 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)?
- 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 $\rho_{DM}^2(r)$
  - also use disk pulsars, but not important after masking galactic plane

- mock analysis doesn’t tells about mismodelling effects …
- … or if our models match Fermi data
- that’s a next step

photon generation

- analysis begins with generating individual photons

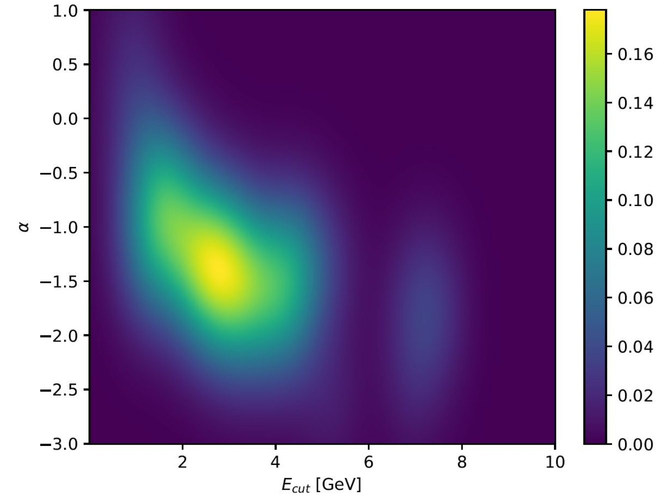
- photon generation steps
  - generate photons from DM annihilation and diffuse bgds from a high-resolution pixelized flux map
  - generate MSPs from density/luminosity function, draw spectral parameters from distribution
  - draw number of photons from each MSP, draw energies from spectrum
  - vary photon energies and directions by instrument response function (IRF)
  - produced lower-resolution pixelized count map for each energy bin

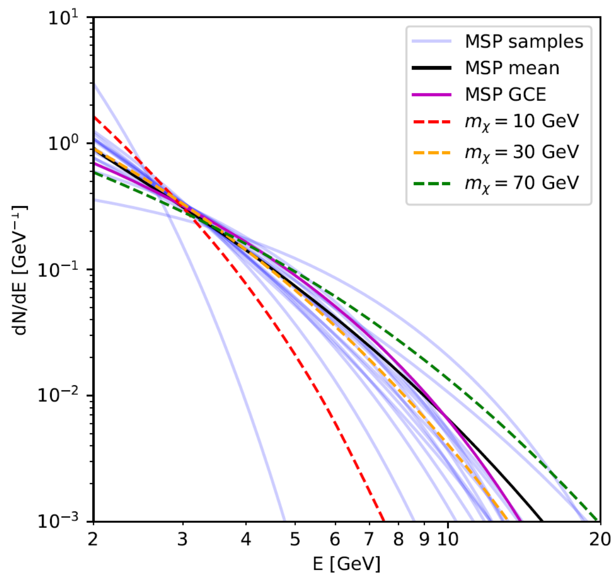
- generating individual photons allows us to correctly treat the energy dependence of the PSF

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

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





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
  - $\rho_{DM}(r) \propto r^{-\gamma}$ near GC
  - $\gamma = 1.2$
  - DM signal distributed as $\rho_{DM}^2(r)$
  - MSP distributed as $\rho_{DM}^2(r)$

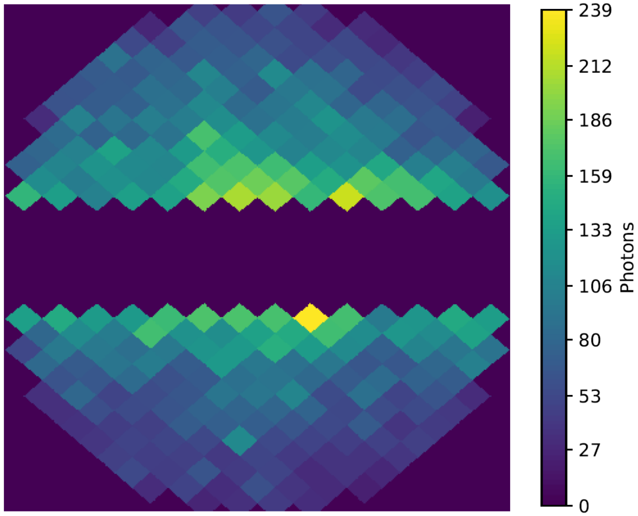
- also include galactic diffuse, isotropic, and Fermi bubbles
- diffuse anisotropic = model O of Buschmann, et al. 2002.12373
- isotropic = Fermi-LAT model (https://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html)
- Fermi bubbles
  - spatial distribution = NPTFit
  - spectrum = Su, et al.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

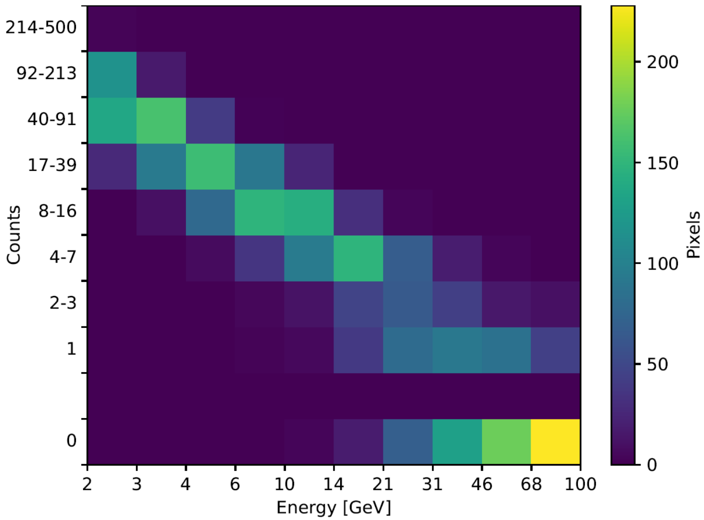
data and summary statistic

- ROI: within 10° of GC, |b|> 2°
- energy: 2 – 100 GeV
- 280 pixels, 10 log-spaced energy bins

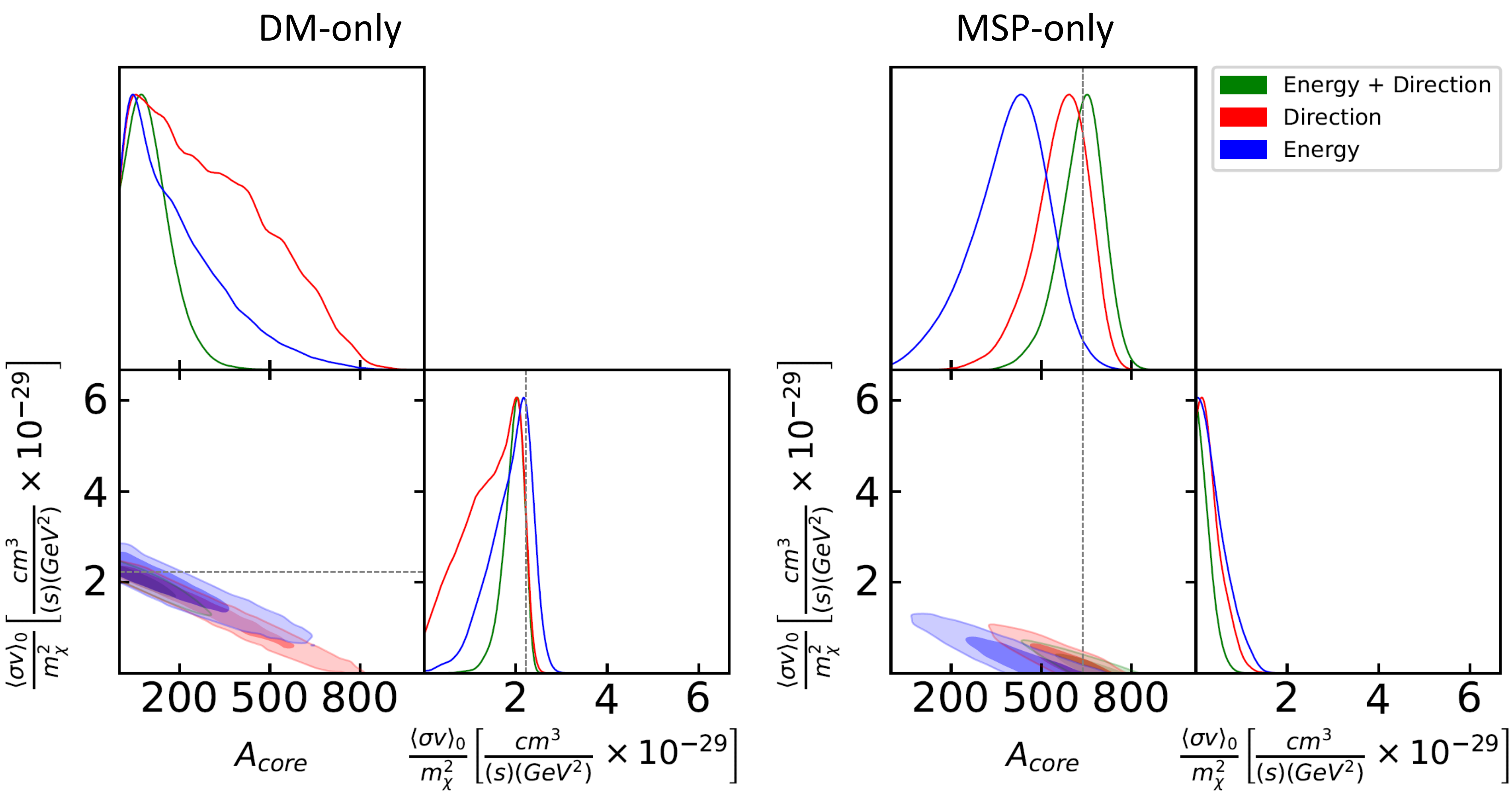
- compress data to summary statistic
  - energy+direction: energy-dependent histogram of photon counts per pixel
  - direction: histogram of photon counts per pixel
  - energy: counts per energy bin

2 - 2.96 GeV





results



DM-only
MSP-only
Energy + Direction
Direction
Energy
200 500 800
2 4 6
A_{core}
$\frac{\langle\sigma v\rangle_0}{m_\chi^2}\left[\frac{cm^3}{(s)(GeV^2)}\times 10^{-29}\right]$

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(?)

UNIVERSITY OF HAWAI'I
MĀLAMALAMA
1907
UA MAU KE EA O KA 'ĀINA I KA PONO

Backup Slides

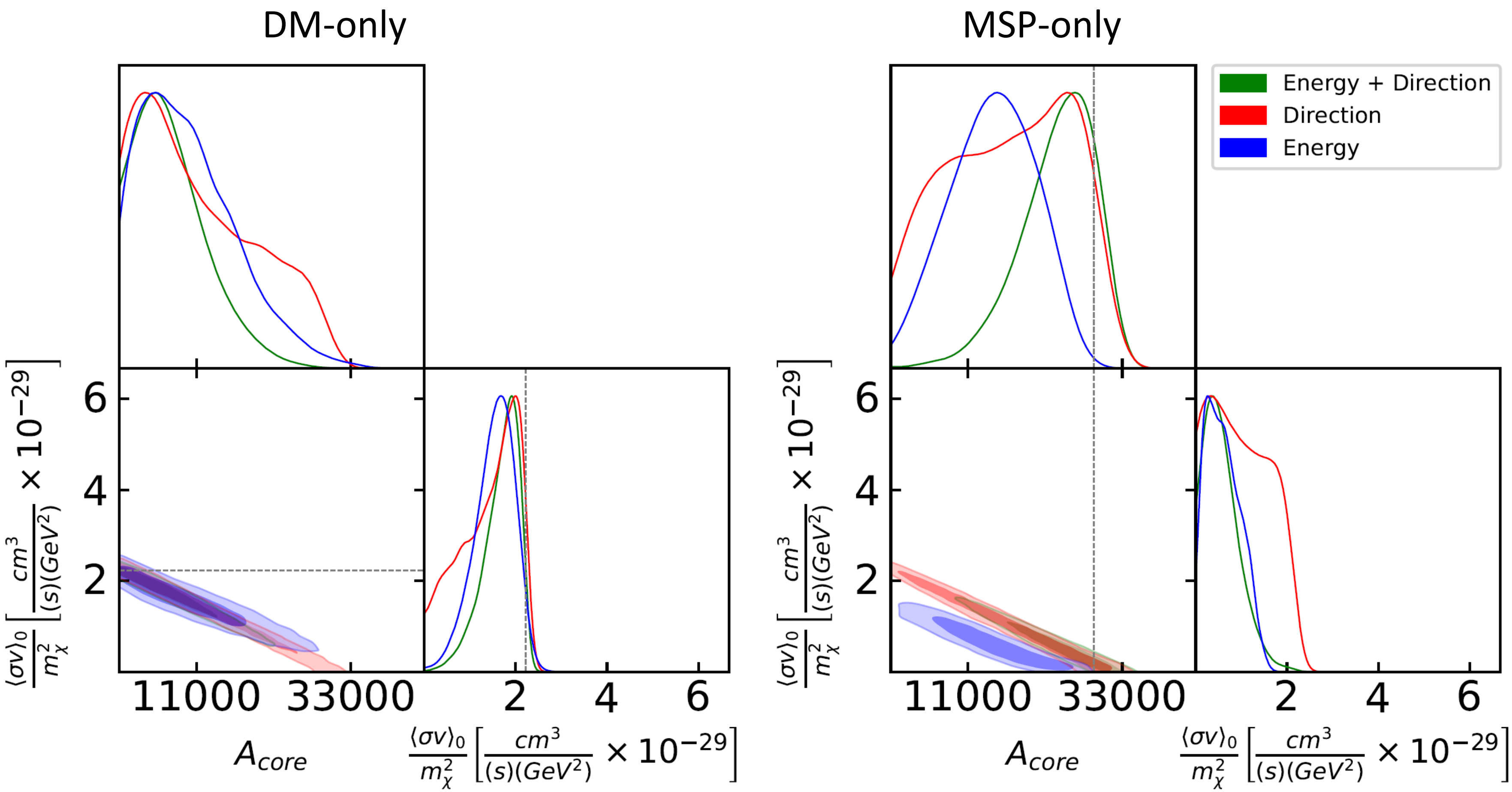
conclusion

- 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

Mahalo!

alternative pulsar model



GCE from 30000 pulsars, much more Poisson