Improving astrophysical γ-ray modeling with Gaussian processes and variational inference

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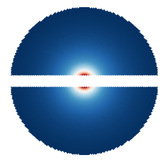
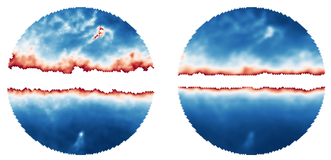
Motivation

- Signals of dark matter (DM) may be hiding in γ-ray observations of the Galactic Center
- Galactic backgrounds of astrophysical origin make up a large fraction ($\gtrsim 80\%$) of the data in this region
- The poorly-understood spatial morphology of these backgrounds makes it difficult to characterize DM signals [1-2]
- Motivates analysis techniques that can account for uncertainty in knowledge of Galactic background contribution (e.g., Refs. [3,5])

Dark matter signal model



Two different Galactic background models



Summary

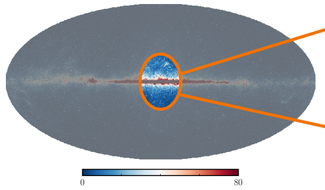
- Traditional γ-ray analyses model data as a sum of rigid spatial templates, each corresponding to a specific astrophysical component [4]
- We modulate the poorly-understood Galactic background templates by a Gaussian process (GP) in order to give them more freedom and account for uncertainty in their spatial variation
- The GP is included as part of a larger probabilistic model that includes parameters describing other modeled components, including a dark matter signal. Variational inference is used for tractable analysis.

Traditional template fitting

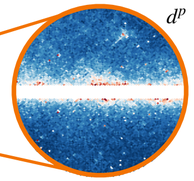
- Spatially-binned (pixelized) data d^p is modeled as a Poisson realization of sum of templates T_i^p ← Pixel index ← Template index
- Spatial profile of each template is rigidly fixed
- Normalizations A_i of templates are floated as free parameters of the model

$$d^p \sim \text{Pois}\left(\sum_i A_i T_i^p\right)$$

Full-sky γ-ray data from *Fermi* satellite

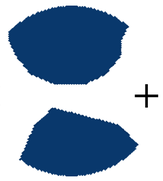


Galactic Center region (4234 pixels)



$$= \text{Pois}\Big(A_{\text{bub}} \times$$

"Bubbles" template T_{bub}

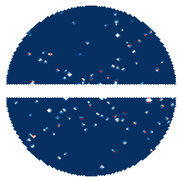


$$+ A_{\text{iso}} \times$$

Isotropic template T_{iso}

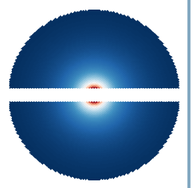
$$+ A_{\text{PS}} \times$$

Point sources template T_{PS}



$$+ A_{\text{DM}} \times$$

Dark matter template T_{DM}



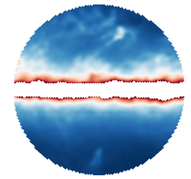
$$\Big)$$

(poorly-understood)

Augmenting Galactic background template with a GP

- Modulate Galactic background template with GP
- Exponential link function to ensure positivity

$$+ \exp(\text{GP}) \times$$

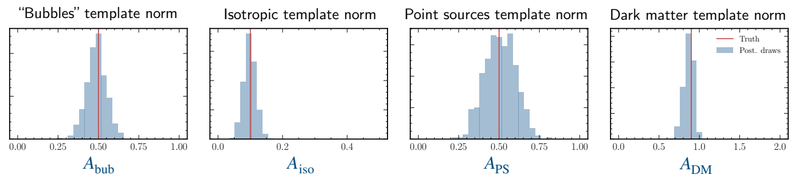


$$\Big)$$

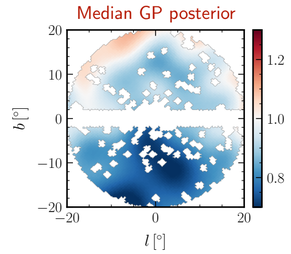
Proof-of-principle analysis on simulated data

- Create simulated data using one Galactic background model (Model 1), analyze using other model (Model 2) (templates from Refs. [5-6])
- GP used for variational posterior defined using GPyTorch [7] and Pyro [8]
- Variational distributions of non-GP parameters (template normalizations) $q(A_i \,|\, \text{GP})$ defined using inverse autoregressive flows conditioned on GP summary statistics in order to capture correlations between GP and non-GP parameters

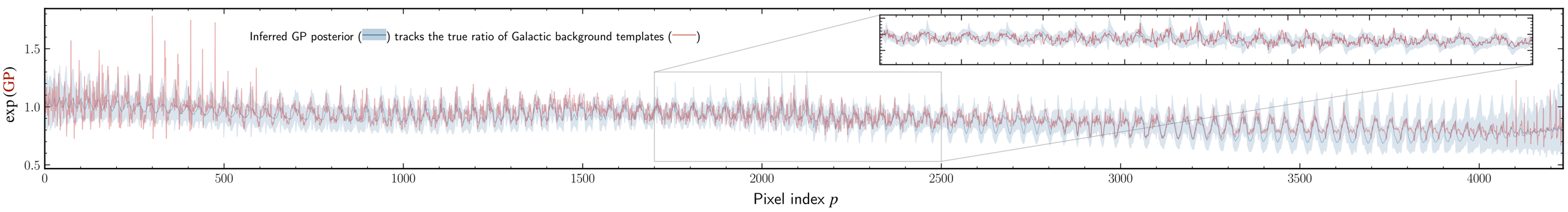
Posteriors of non-GP parameters (template normalizations)



Median GP posterior



Ratio of Galactic background templates Model 1 (in simulation) and Model 2 (in analysis), inferred via GP (▭) vs truth (—)



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References

[1] Leane & Slatyer [1904.08430]
[2] Leane & Slatyer [2002.12370]
[3] Storm et al [1705.04065]
[4] Lee et al [1506.05124]
[5] Buschmann et al [2002.12373]
[6] Mishra-Sharma et al [1612.03173]
[7] Gardner et al [1809.11165]
[8] Bingham et al [1810.09538]

Siddharth Mishra-Sharma and Kyle Cranmer
Semi-parametric γ-ray modeling with Gaussian processes and variational inference [2010.10450]
https://github.com/smsharma/gamma-gp