Topical Overview on Star Cluster Astrophysics 2024

Siena
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Population study of Star Clusters derived from Fermi-LAT observations

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Star-Forming Regions

WHAT? These are Galactic objects. We are looking at young massive star clusters.

WHERE? In molecular clouds, mainly in the Galactic plane; opaque clumps of cold (~10K) dense (~100-1000 particles/cc) gas and dust.

WHEN? $M_{cloud} > M_{Jean's}$

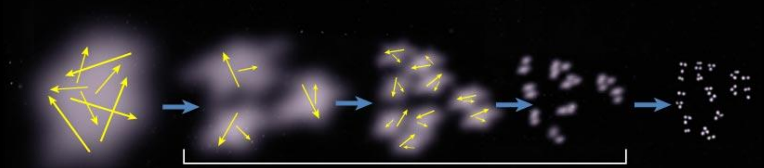


Image credit: Linda Huff

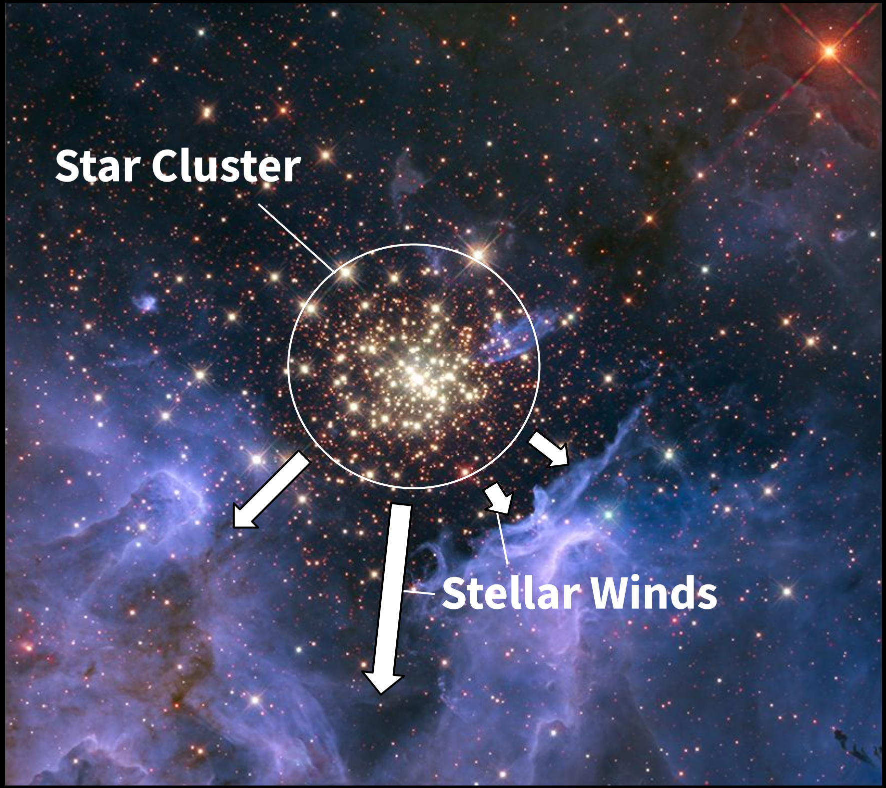
Research Motivations

★ Galactic star-forming regions (SFRs) are potential cosmic ray (CR) accelerators and sources of γ-ray emission

★ SFRs may play an important role in the diffuse galactic emission and CR acceleration in the Galaxy; the Galactic CR flux is not fully understood

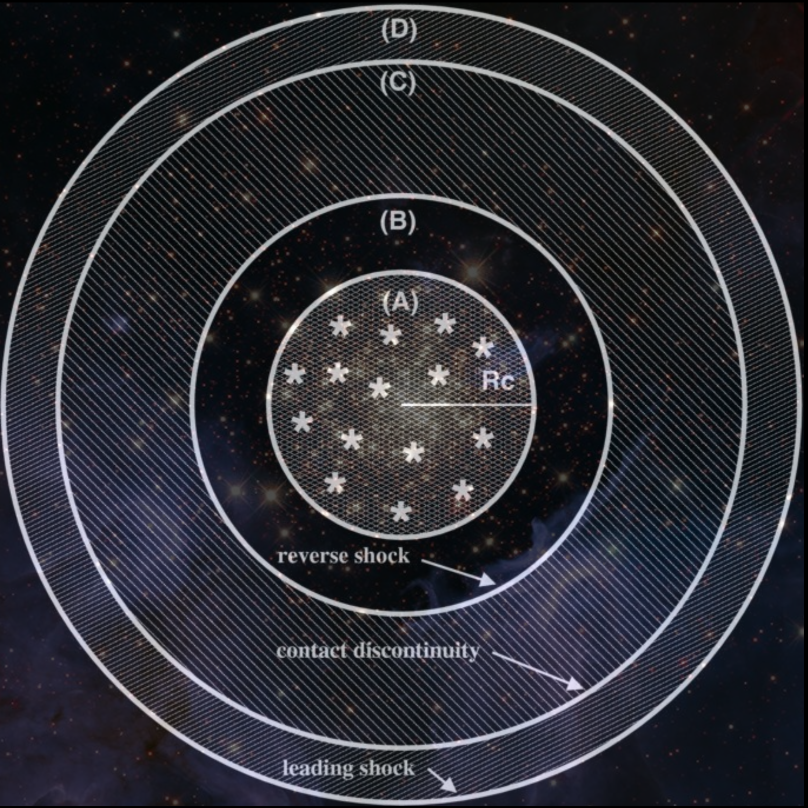
★ Only a few instances where γ-ray associations with SFRs have been realized, while many more SFRs have not yet been detected

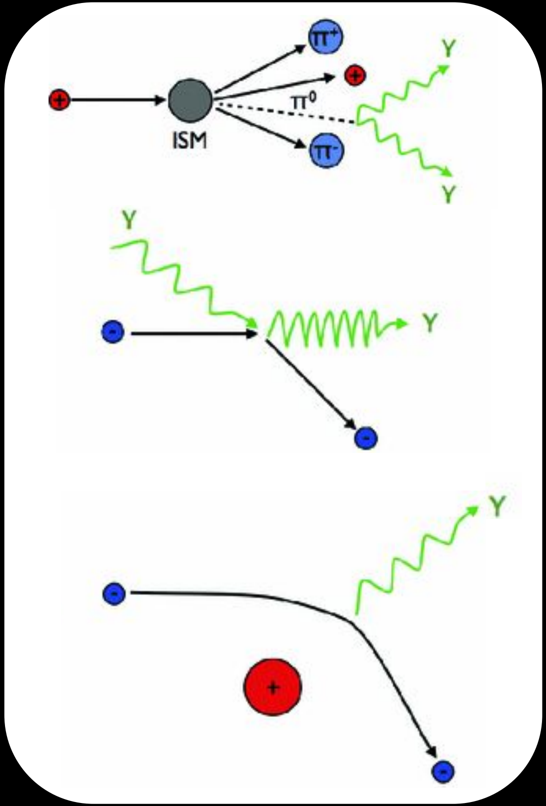
SFRs as CR Accelerators

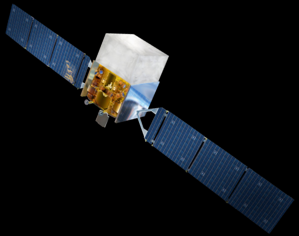


- Host known cosmic ray (CR) accelerators (pulsars & SNRs)
- Collective stellar winds
  - Expected CR accelerators are young massive clusters (O and B stars greatly contribute to collective winds)
  - High velocity winds interacting with ISM give rise to shocks and superbubble (SB) formation
  - Diffusive shock acceleration (DSA) effectively accelerates particles to CR energies

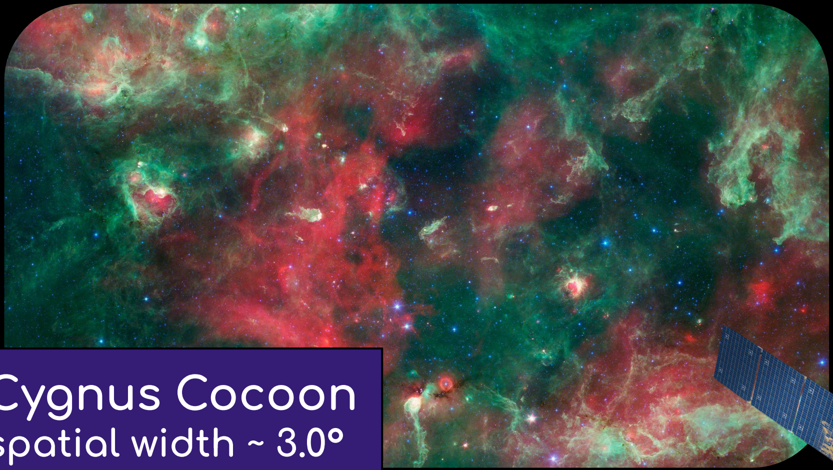
SFRs as γ-ray Emitters







P. Velazquez et. al 2013



Cygnus Cocoon
spatial width ~ 3.0°

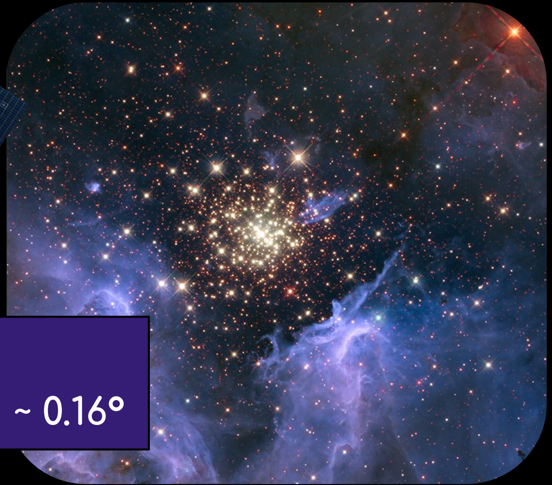
X. Astiasarain et al. 2022

Westerlund 2
spatial width ~ 0.24°

E. Mestre et al. 2021

Westerlund 1
spatial width ~ 2.0°

F. Aharonian et al. 2022



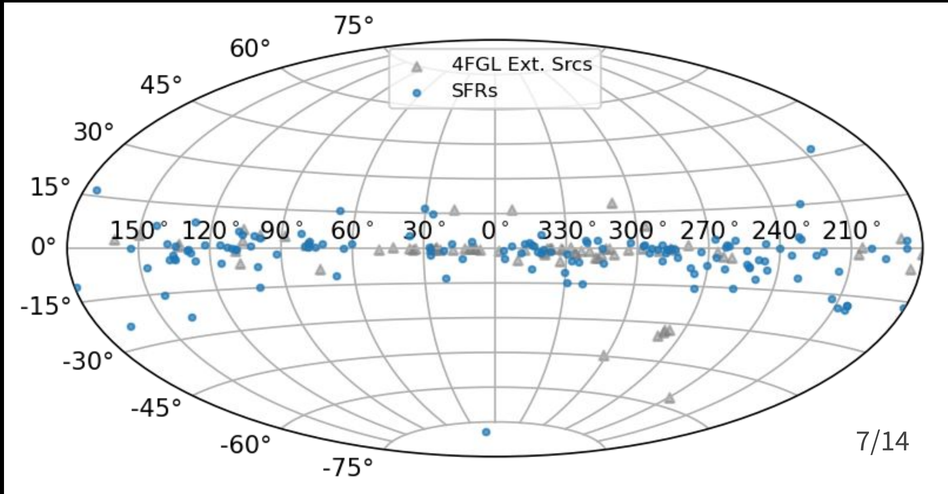
NGC 3603
spatial width ~ 0.16°

L. Saha et al. 2020

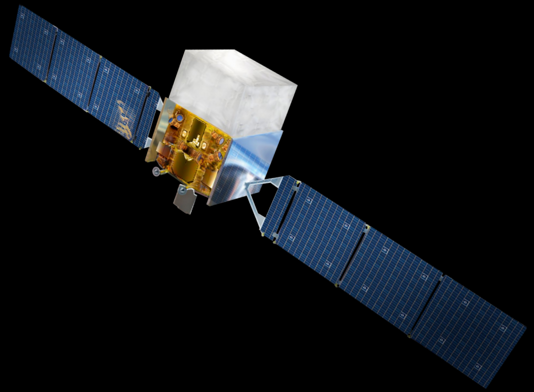
SFRs Sample Selection

- Majority from Cantat-Gaudin+2020 analysis of Gaia data
- Manageable sample: keep only optically bright (dereddened mG < 5.5) clusters
  - Diverse sampling of intrinsic properties (age, distances, stellar membership)
  - Majority of stellar clusters with O and B stars
  - All previously known γ-ray detections of SFRs
- Part of sample: Fermi γ-ray sources (e.g. Cyg-OB2, Westerlund 1, Westerlund 2, NGC 3603)

Total sample: 139 targets →

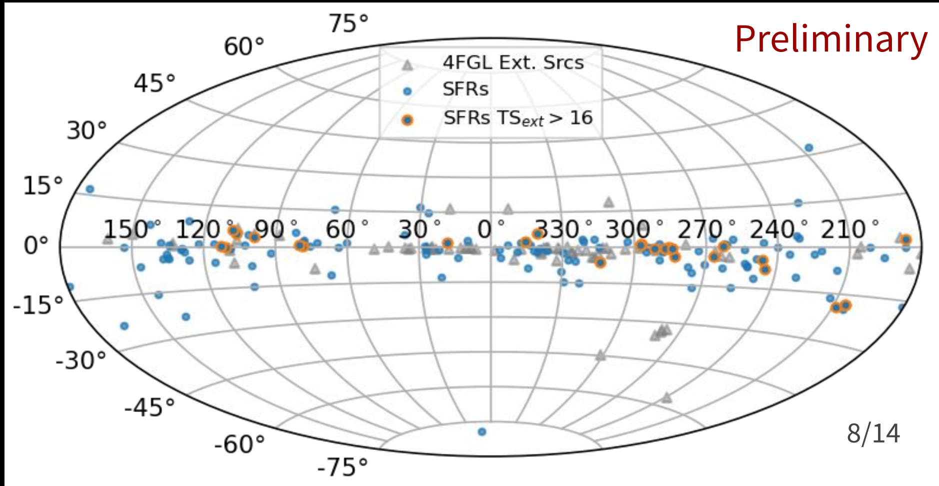


Fermi Data & Analysis

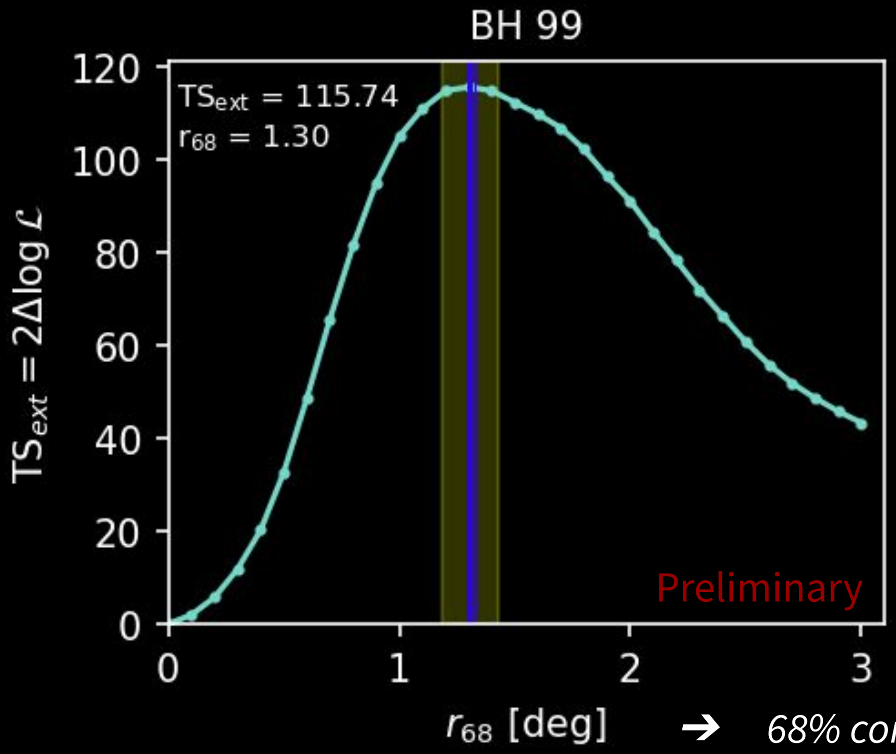


- ~15 years of data, 1 GeV - 1 TeV range, ROI 10x10 deg.
- Binned joint likelihood analysis
- Preprocessing steps
  - All targets modeled as point sources with TS = $2\ln(L_{ps}/L_{null})$
  - ***No*** SFRs detected as point sources (TS > 16)

- Extension fitting with Fermipy (Main Pipeline)
  - Perform likelihood scan in spatial extension with Fermipy's gta.extension( )
    - BG source parameters *fixed*
    - BG source normalizations *free* up to 3° from the center of ROI
  - 20 *new* targets detected showing significant (S ≥ 4σ) extension



Extension Fitting Results



- ➔ Radial Gaussian model
- ➔ BG source parameters fixed
- ➔ Source normalizations free within 3°
- ➔ Do not fit position

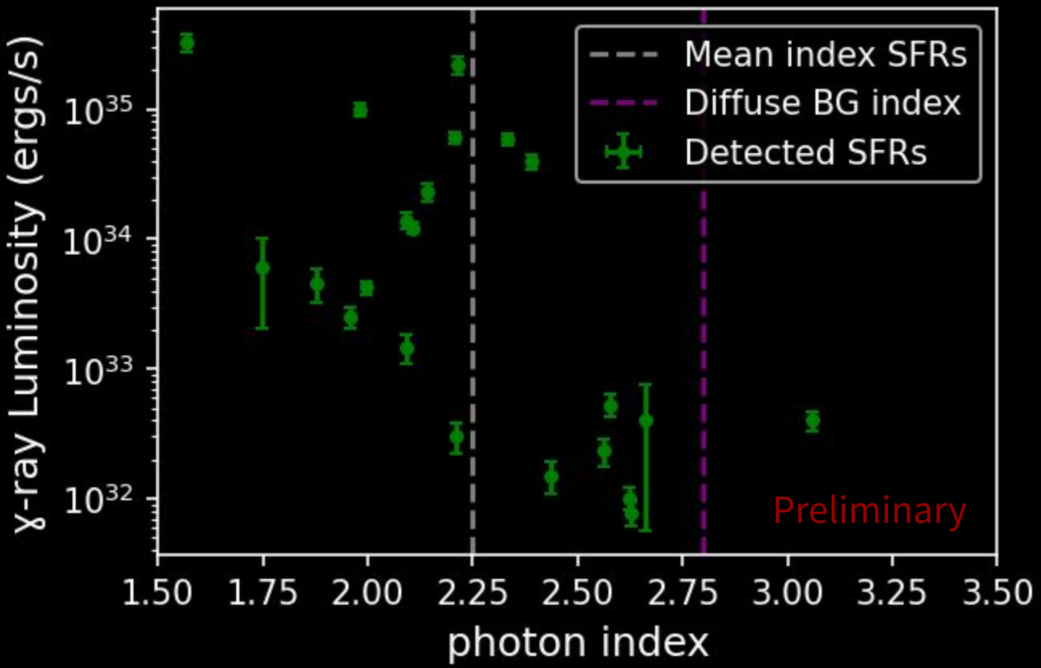
$$TS_{ext} = 2ln\left(\frac{L_{ext}}{L_{ps}}\right)$$

$$\sqrt{TS_{ext}}\,\sigma \sim S$$

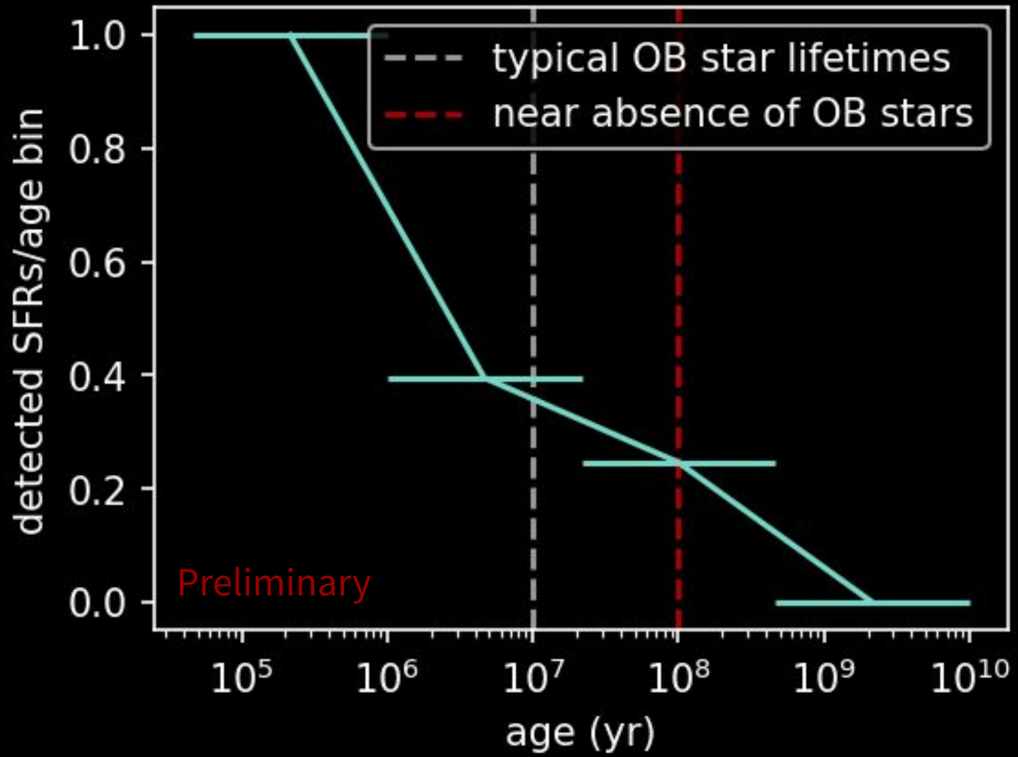
➔ $S \geq 4\sigma :\ 16\%\ or\ \frac{22}{139}$

➔ *68% containment radius (within 1σ of the mean value)*

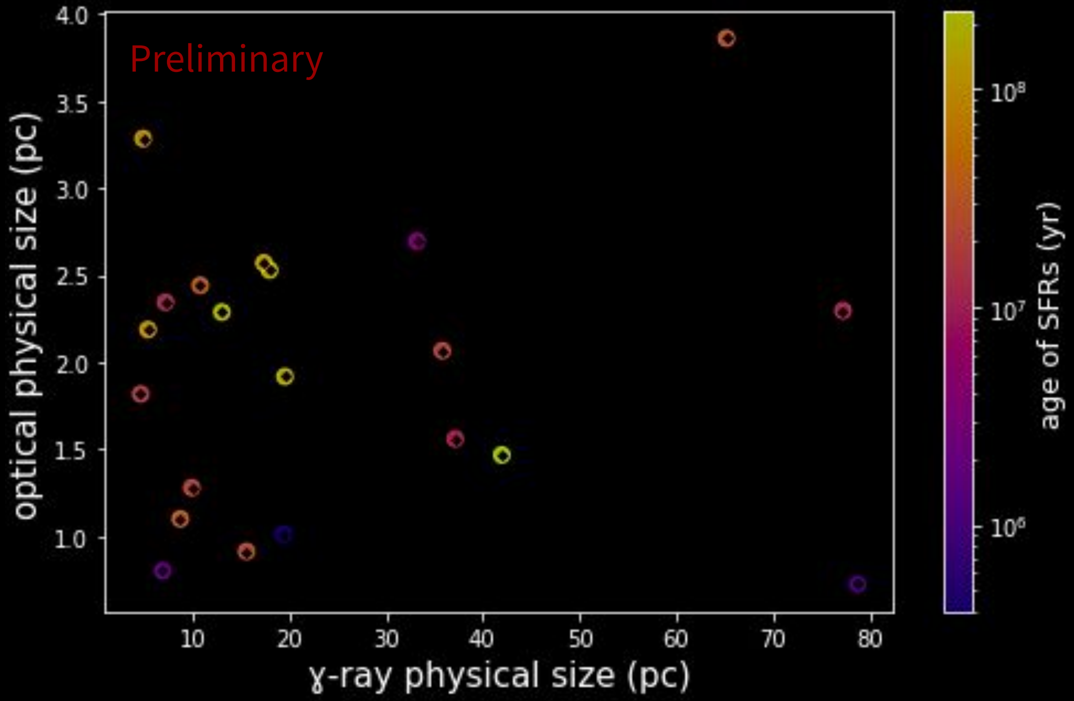
γ-ray Luminosity Dependence on Spectra



γ-ray Detectability Dependence on Age



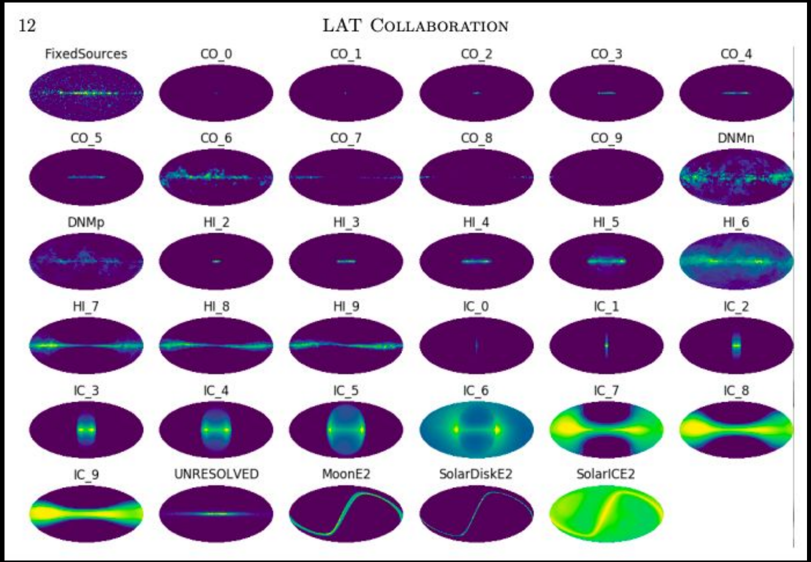
Size Comparison: optical & γ-ray



Robustness Tests of Analysis

Increase DOF in background model

- Multiple component modeling of Galactic diffuse emission



The *Fermi*-LAT Collaboration 2019

Extension Fitting Checks/Adjustments

- Refining our fits "recipe" for all 139 targets
- Ensure detections of extended sources are robust against changes of:
  - BG source parameters
  - Galactic diffuse modeling
  - Fitting for position

Main Takeaways

- ★ Through refining of our models we have Identified 22 significant candidates for newly detected γ-ray emitting SFRs
- ★ These preliminary detections are in support of the idea that star clusters are indeed CR factories
- ★ γ-ray luminosity and detection rate as a function of age is consistent with expectation: younger clusters brighter and easier to detect
- ★ **Future work:** multiwavelength studies of individual SFRs will be used to determine emission mechanisms from our brightest sources, revealing further the relation between physical features of Galactic SFRs and their emissions

THANK YOU

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- Lab Saha
- Marianne Lemoine
- Dr. Ajello's Clemson University HEA group →

Image Credits:

Velazquez, Pablo & Rodríguez-González, Ary & Esquivel, Alejandro & Rosado, Margarita & reyes-iturbide, Jorge. (2013). Modeling the thermal diffuse soft and hard x-ray emission in M17. The Astrophysical Journal. 767. 69. 10.1088/0004-637X/767/1/69.

Cygnus X (NASA/JPL-Caltech/Harvard-Smithsonian CfA)

Westerlund 1 (NASA/ESA/Hubble)

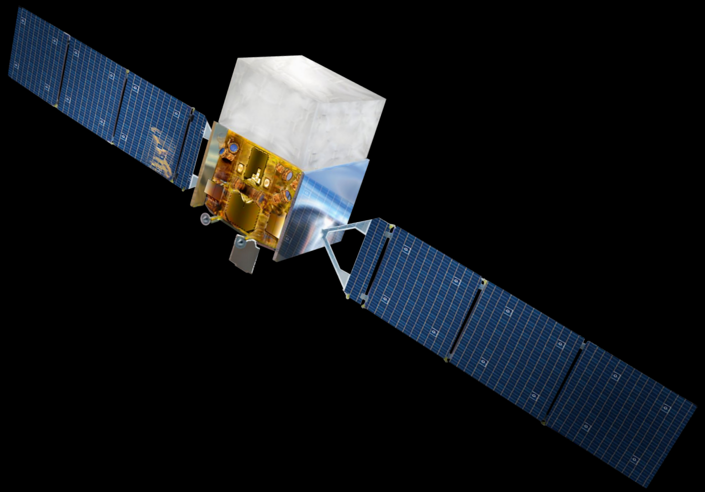
Westerlund 2 (NASA/ESA/Hubble)

NGC 3603 (NASA/ESA/Hubble)

The *Fermi*-LAT Collaboration. (2019). Galactic Interstellar Emission Model for the 4FGL Catalog Analysis.

Extra Slides

Fermi-LAT Data Details



- Joint-Likelihood Analysis using PSF 1,2,3
- ~15 years of data
- P8R3
- 1 GeV - 1 TeV
- z < 105
- 10 x 10 ROI (modeled as PS)
- 8 energy bins per decade
- Pix = 0.08 deg
- Point Source catalog: 4FGL-DR3
- Additional sources found with find_sources()

$$\mathcal{L} = \prod_i \frac{(m_i^{n_i} e^{-m_i})}{n_i!}$$

$$\mathcal{L}_{\text{joint}} = \prod_j \mathcal{L}_j$$

Extension Fitting Explained

- gta.extension( ) method executes a source extension analysis for a given source by computing a likelihood ratio test with respect to the no-extension (point-source) hypothesis and a best-fit model for extension.
- The best-fit extension is found by performing a likelihood profile scan over the source width (68% containment) and fitting for the extension that maximizes the model likelihood.
- We implement the 2D Gaussian (RadialGaussian) model.

TS & Map (target BH 99)