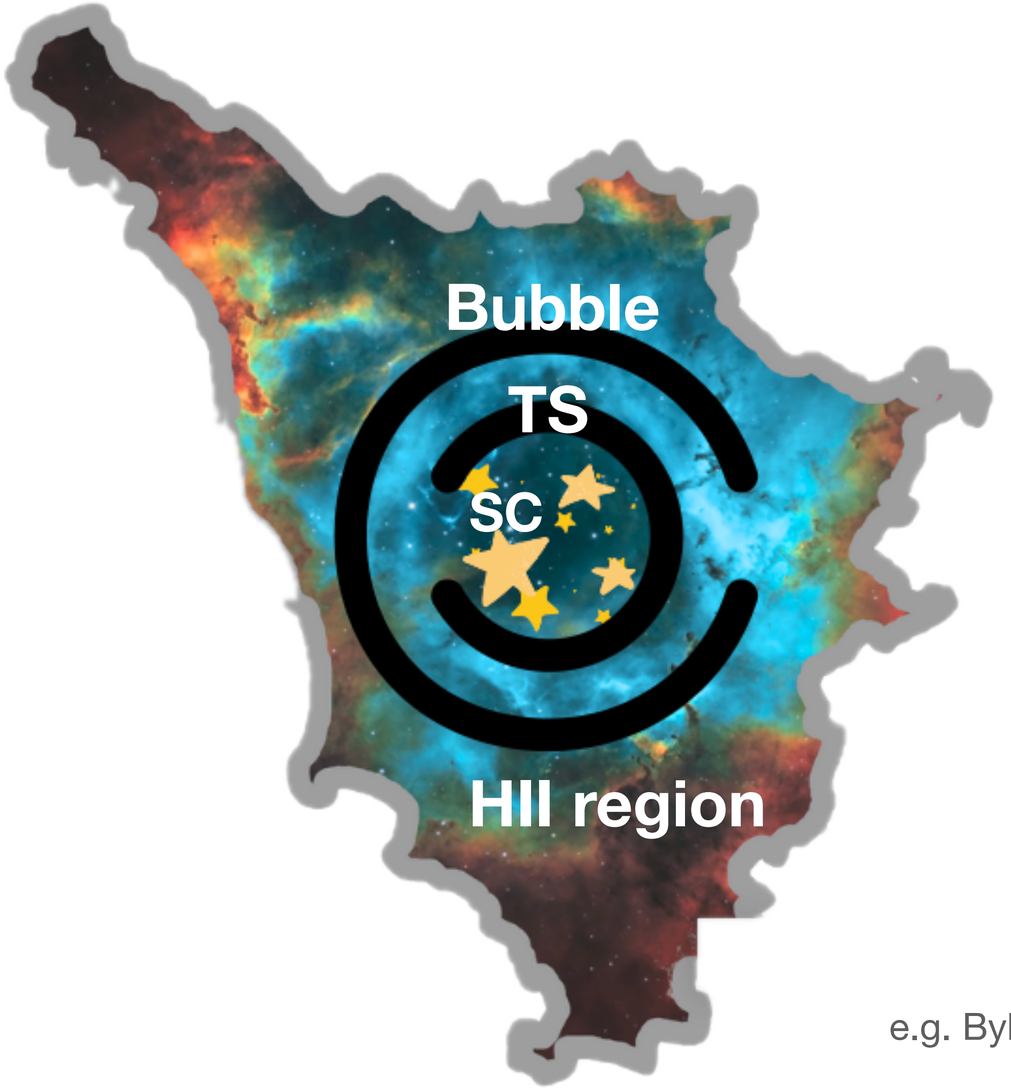

Topical Overview on Star Clusters Astrophysics

Siena 28.10.2024 - 31.10.2024

# Young star clusters as seen by Fermi-LAT

Giada Peron — 28.10.2024

# Why star clusters?




- **Star clusters/associations/forming regions are detected in gamma rays up to the highest energies** [See Luigi+Lars+Rui-Zhi's Talks]
- Gamma-rays prove the presence of high energy particles $F_\gamma \propto n_{target} F_{CR}$
- Collective or single winds of stars are powerful enough to accelerate particles that emit then gamma-rays $\mathscr{P}_w \approx 0.1 \mathscr{P}_{SN}$

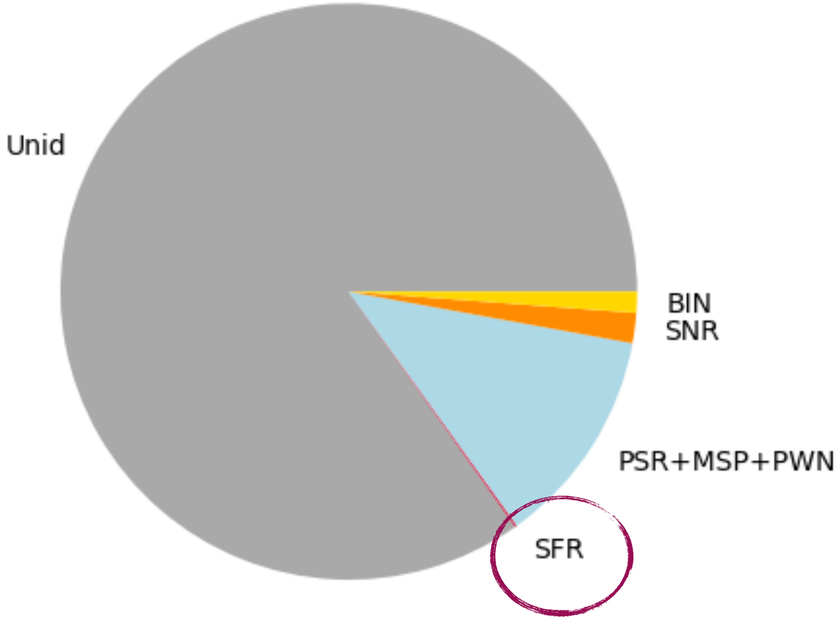
e.g. Bykov et al. 2020, Morlino et al. 2021, Vieu et al. 2022, Gabici et al. 2023,

# How many star clusters?

## In the Fermi-LAT sky only a handful

### Why no star clusters?

- Too few?
- Too faint?
- Too extended?
- Confused for/obscured by other sources?

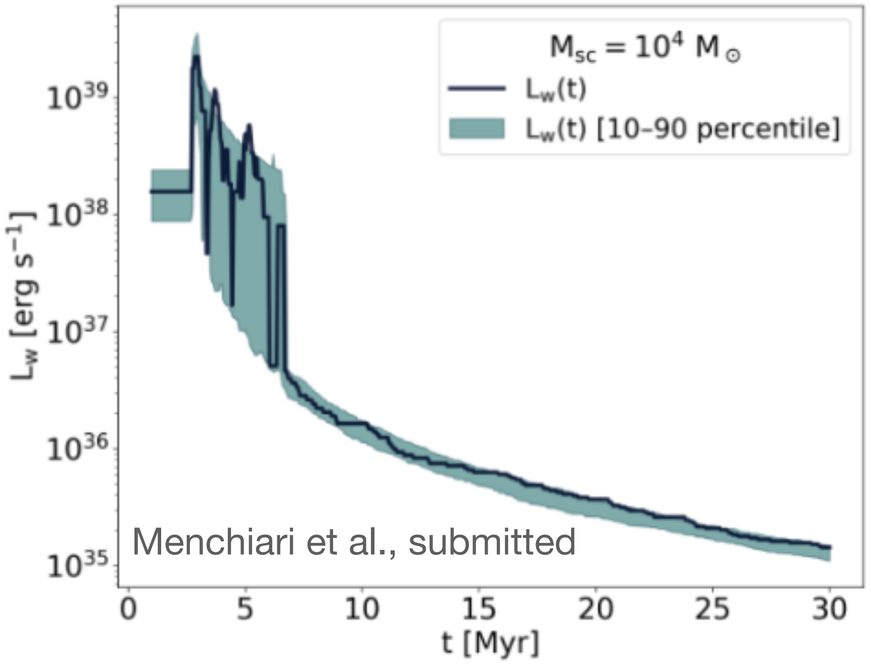



Fermi-4FGL [DR3]

500 MeV-1 TeV

# Star clusters

## In the Milky Way  Where to look?

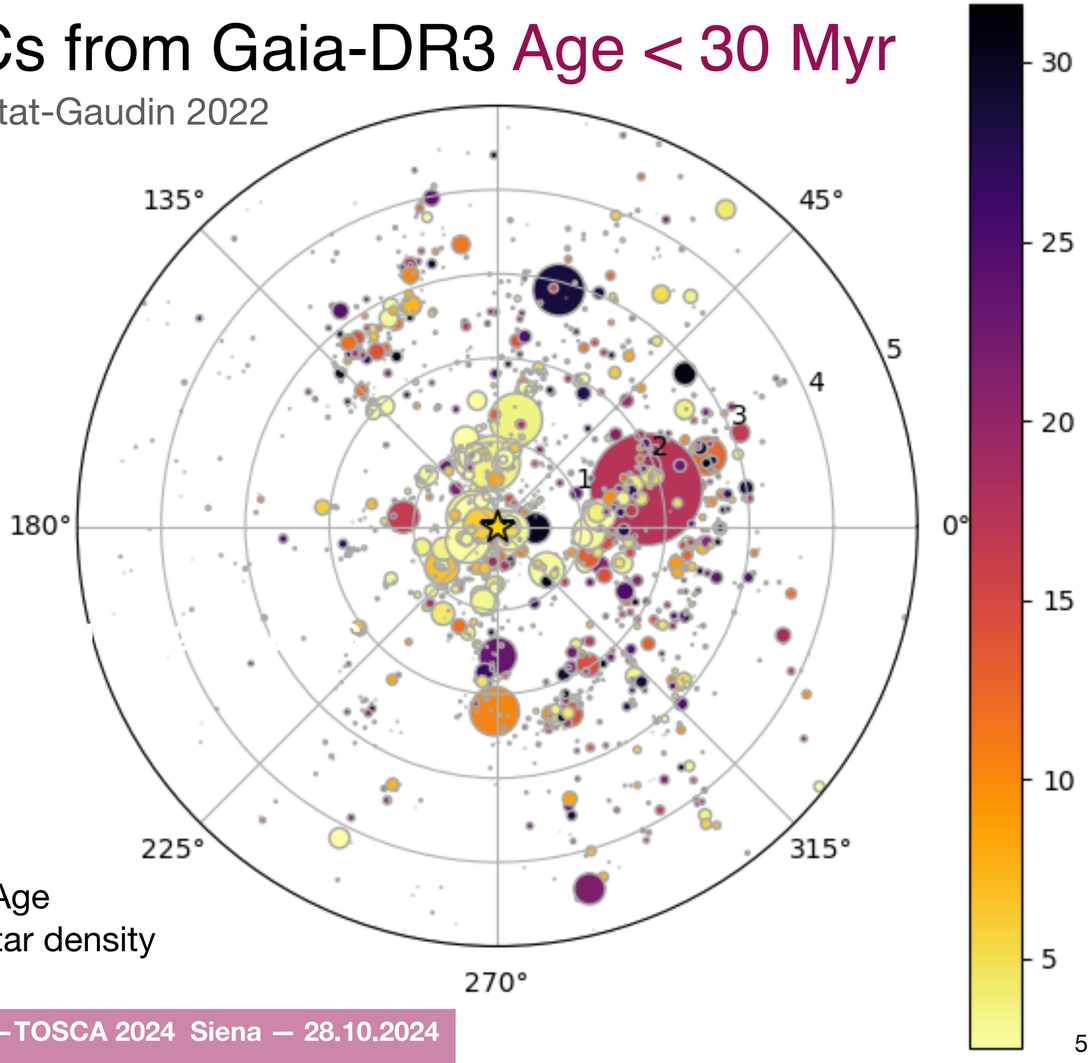


# Star clusters

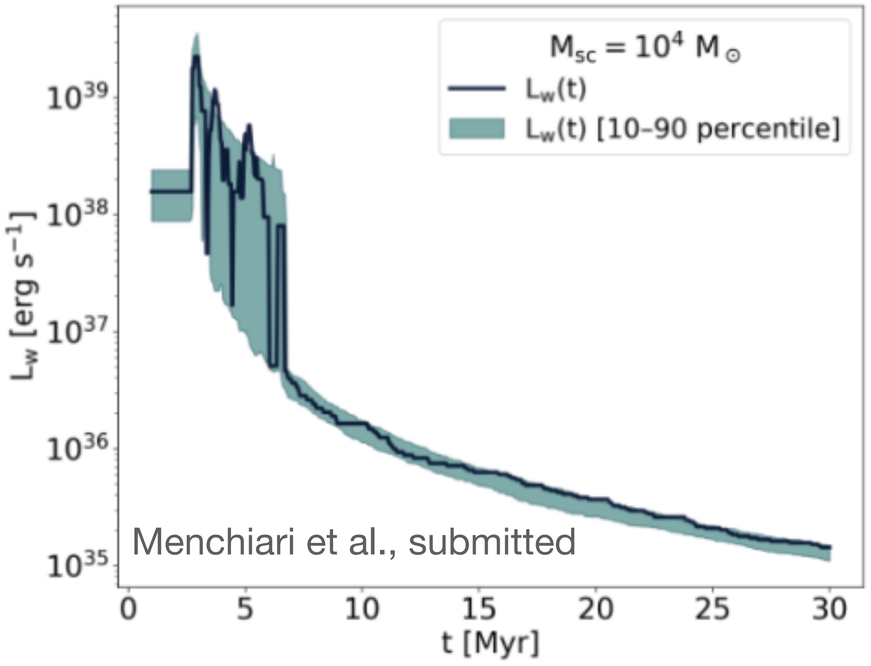
## In the Milky Way  Where to look?

SCs from Gaia-DR3 Age < 30 Myr

Cantat-Gaudin 2022




Color = Age
Size = Star density

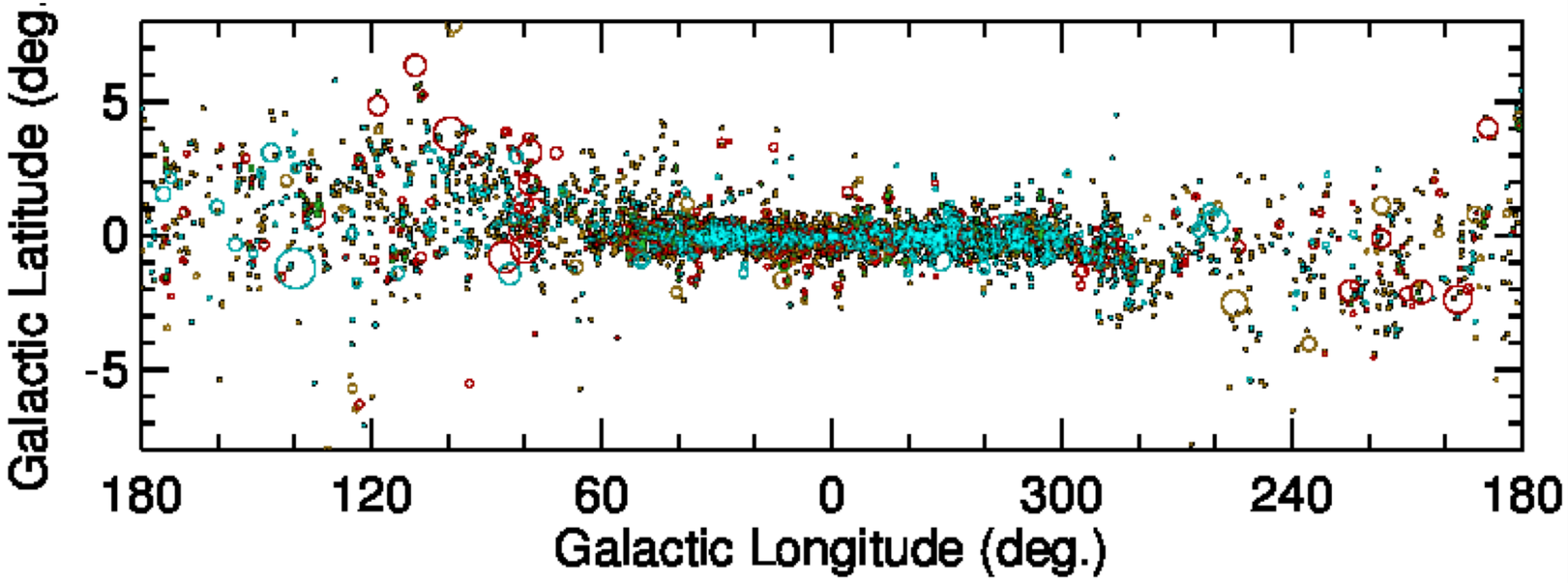


# Star clusters

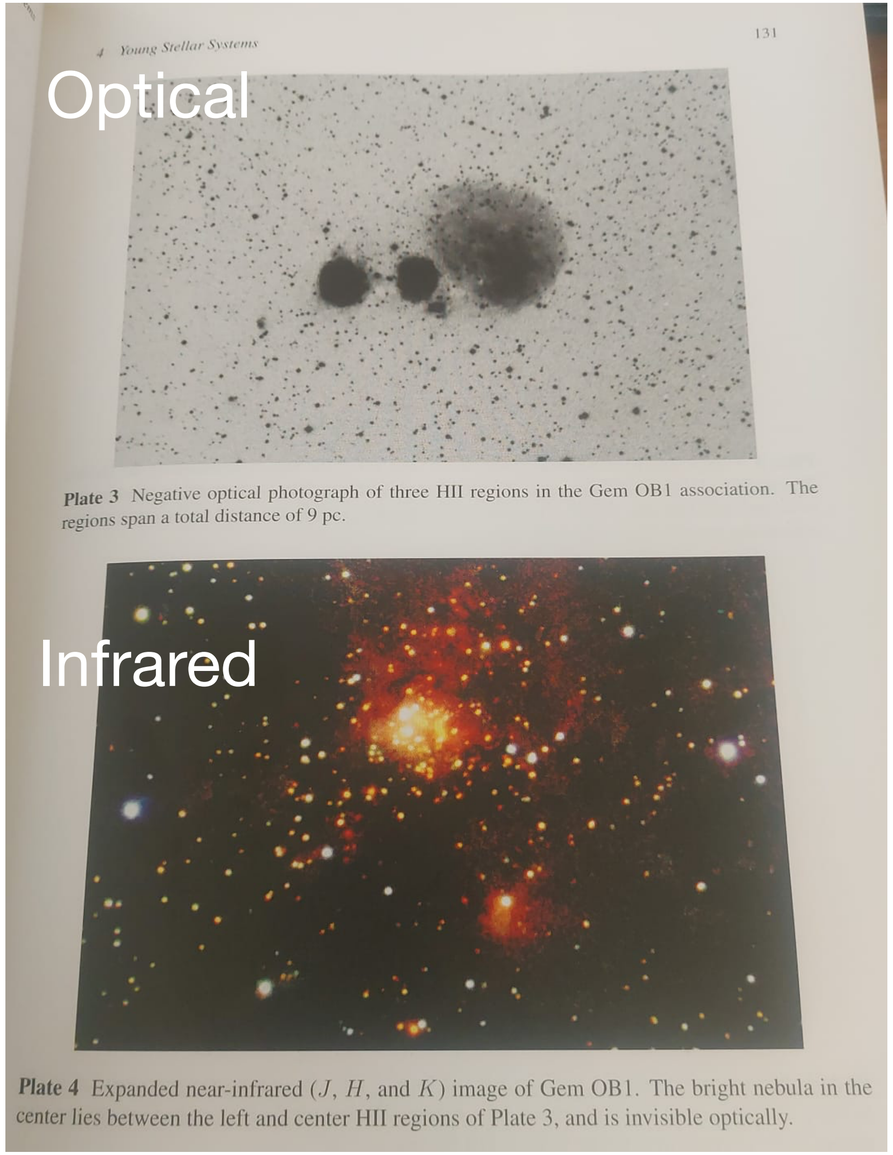
## In the Milky Way  Where to look?

SCs embedded in HII regions Age $\lesssim$ 3 Myr

Anderson et al. 2013



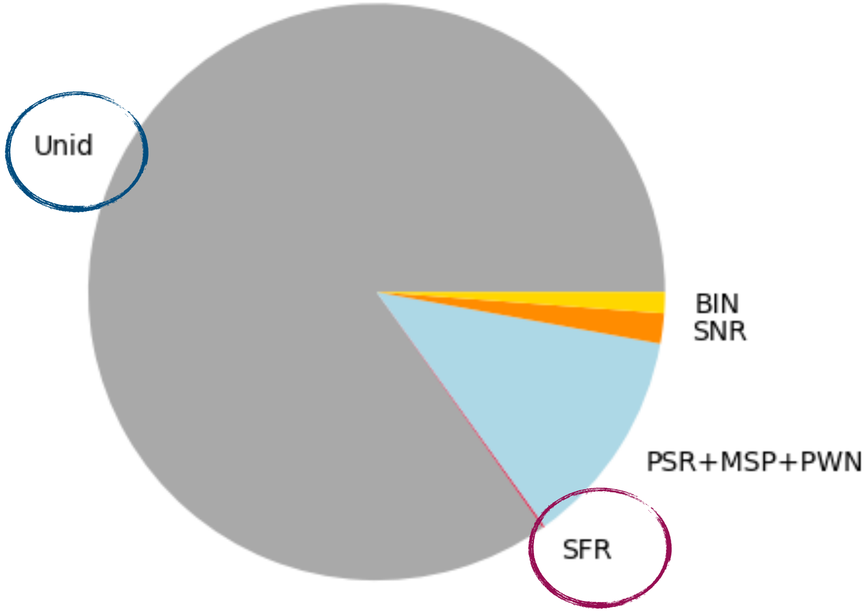

Stahler & Palla 2005

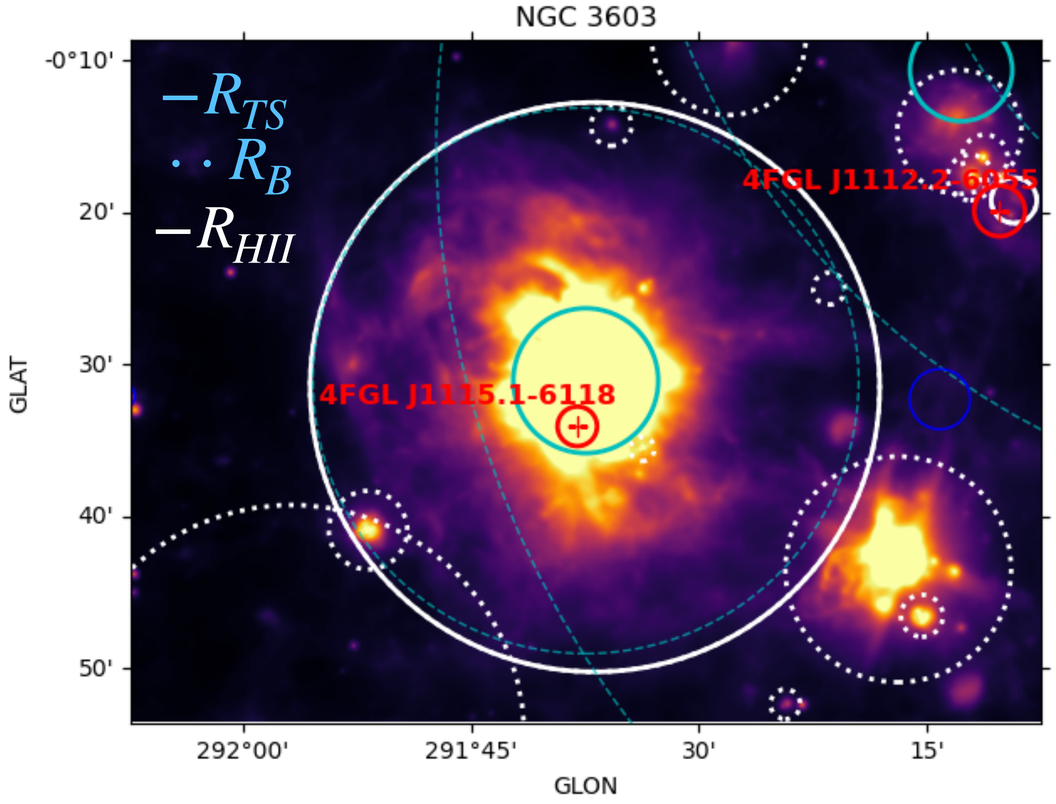


Peron et al. 2024, ApJL, 972, 2, L22

# Are there
# Star clusters
## Matching with gamma-ray sources ?

**How many SCs are hidden within unidentified sources?**



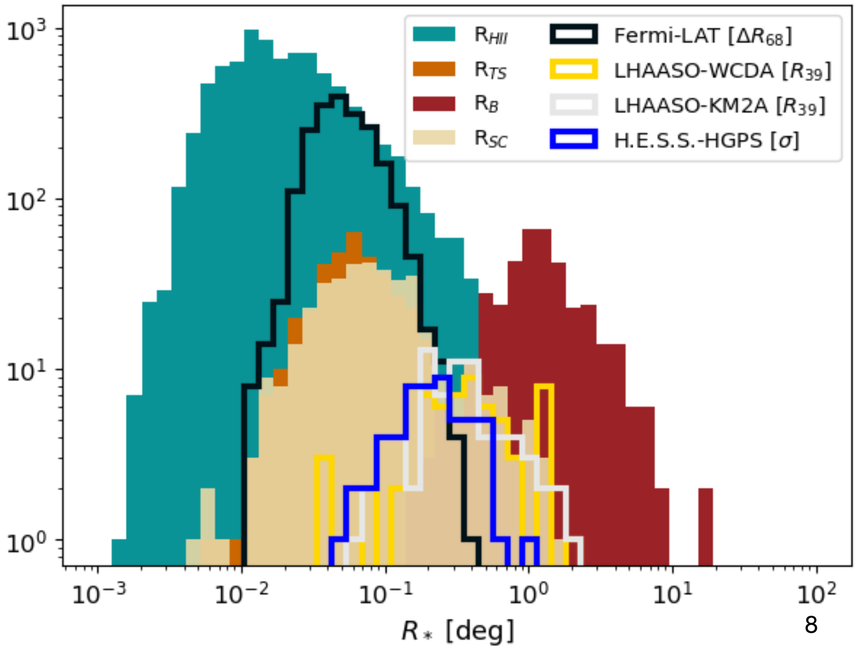



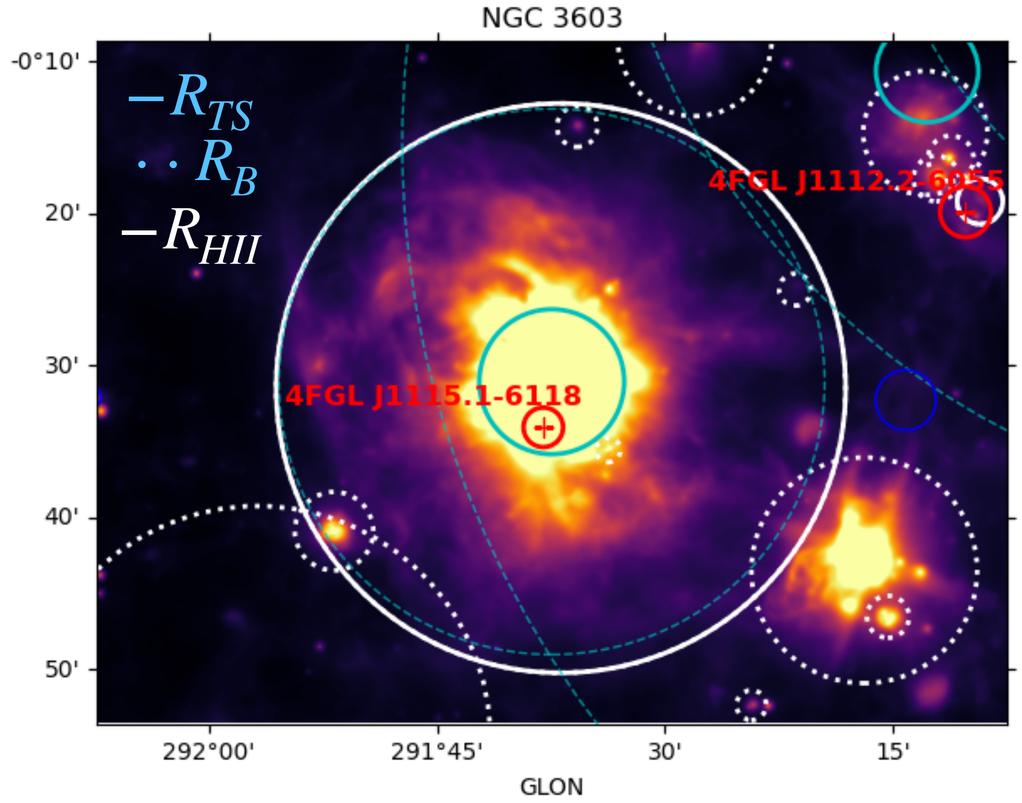
# Star clusters

## Matching with gamma-ray sources

The match is defined on a geometrical basis:
match if their distance < R*

*R of the HII region*
*R of the SCs (50% of stars)*
*R of the termination shock*
*R of the bubble*



# Star clusters

## Matching significance

i. Calculate the number of matches with SC catalogs;
ii. Calculate the number and distribution of matches with 1000 randomly generated catalogs;
iii. Evaluate matching significance as:

$$\Sigma = \frac{N_{match}^{real} - < N_{match}^{sim} >}{\sigma(N_{match}^{sim})}$$

Peron et al. 2024, ApJL, 972, 2, L22

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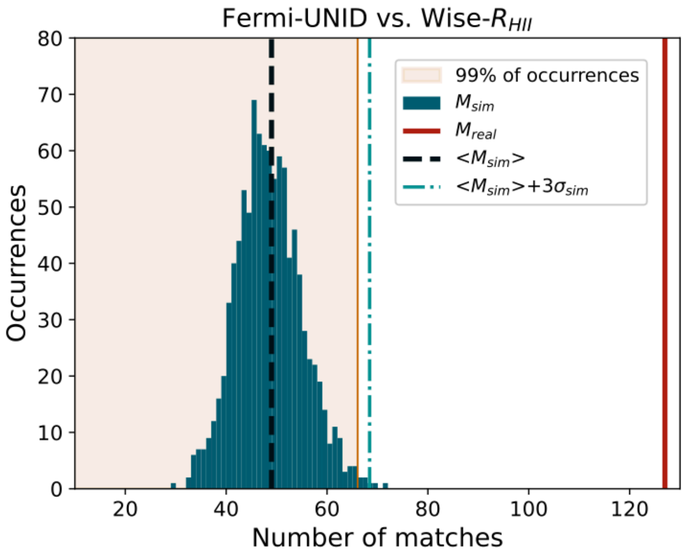
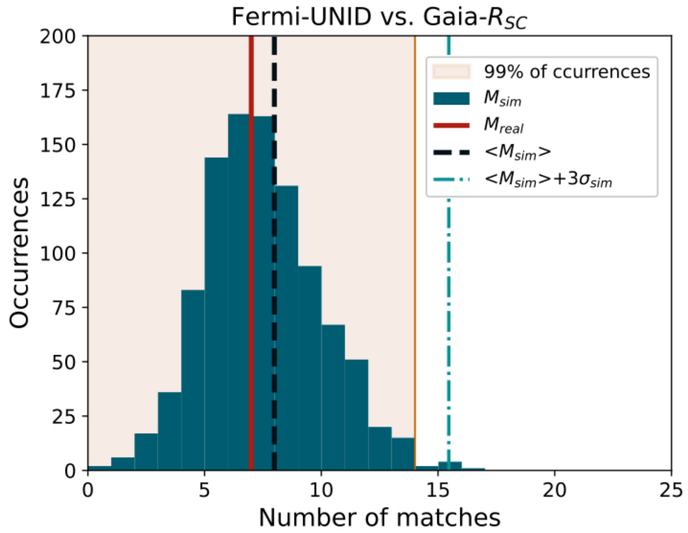
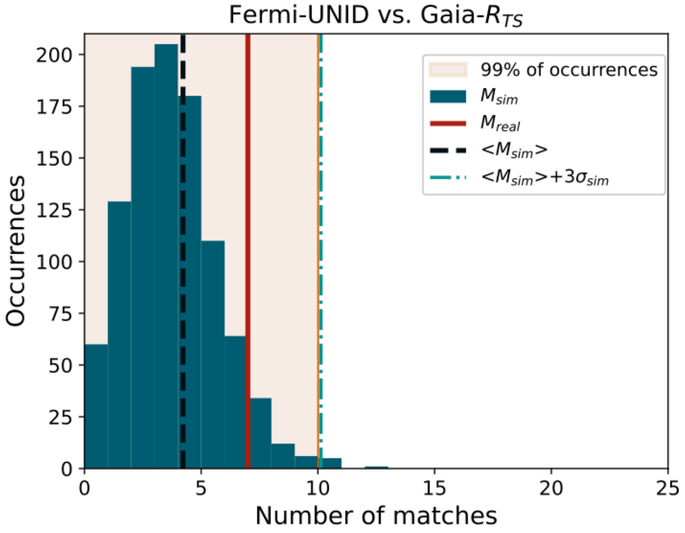
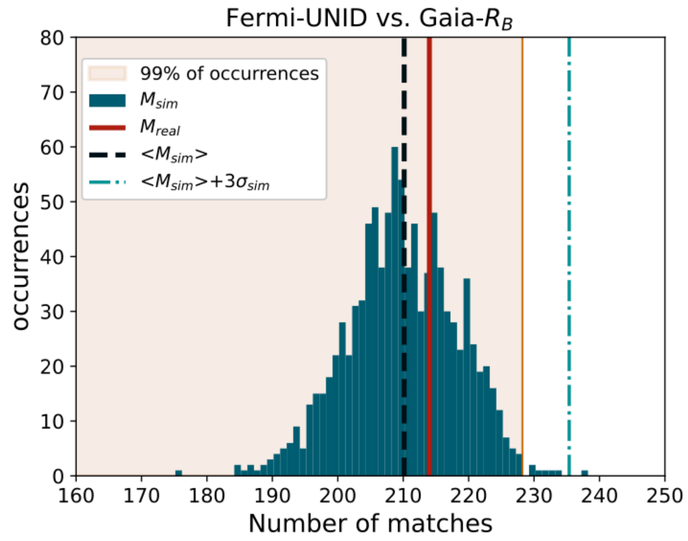
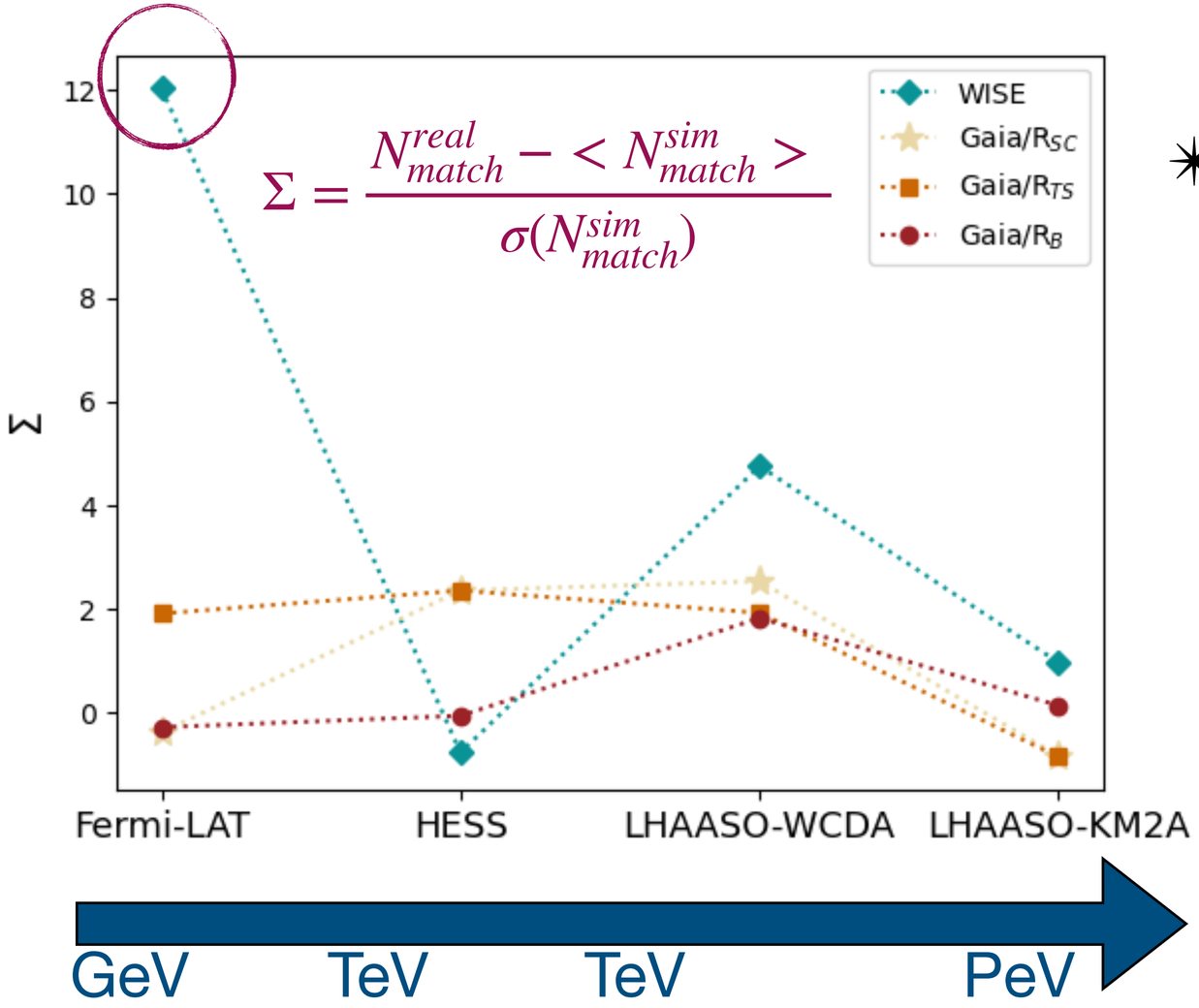


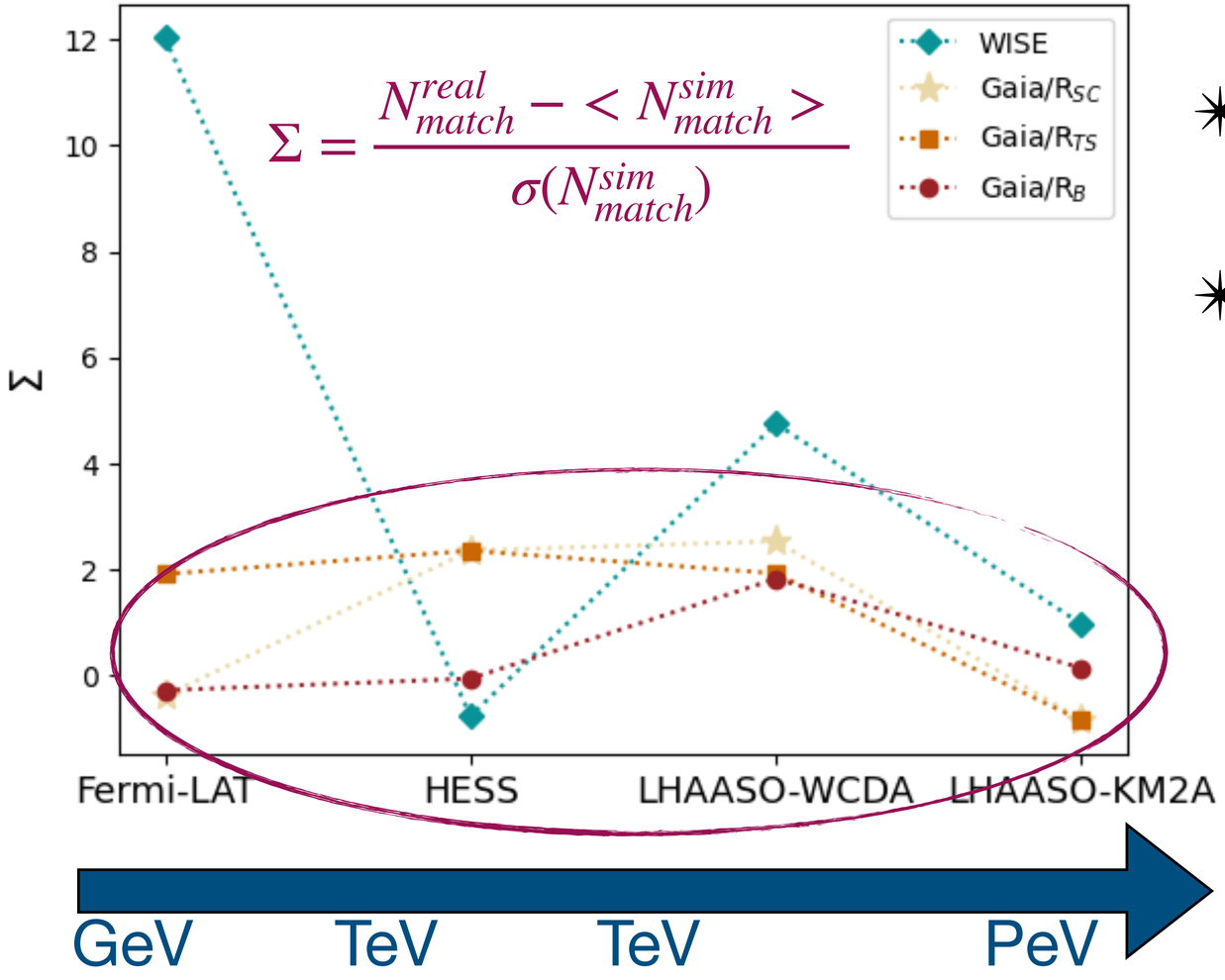



# Star clusters Matching with gamma-ray sources

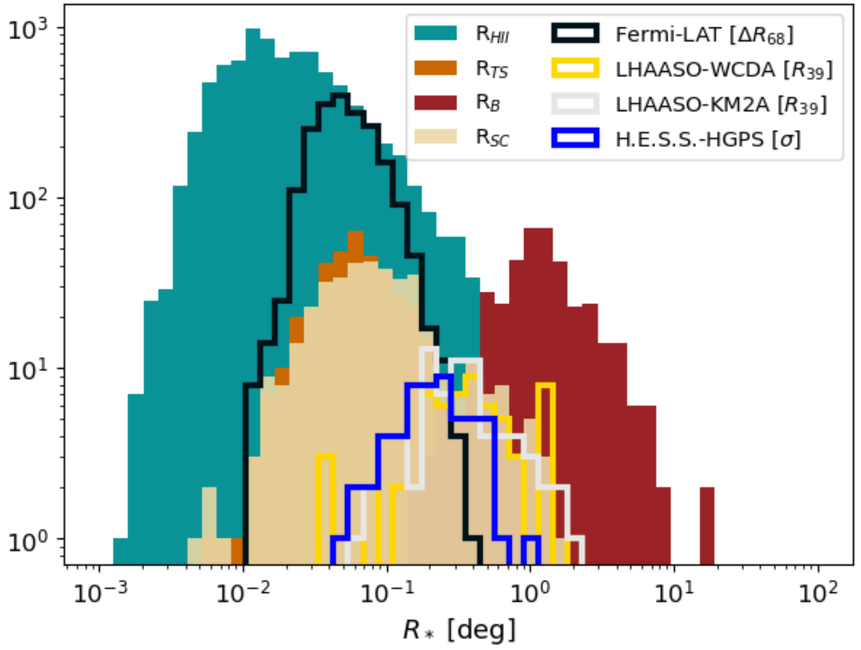



✳ Very good correspondence between **WISE** and **Fermi-LAT** sources

# Star clusters Matching with gamma-ray sources




- Very good correspondence between **WISE** and **Fermi-LAT** sources
- The significance decreases for Gaia SCs: maybe due to **larger areas** or larger ages?



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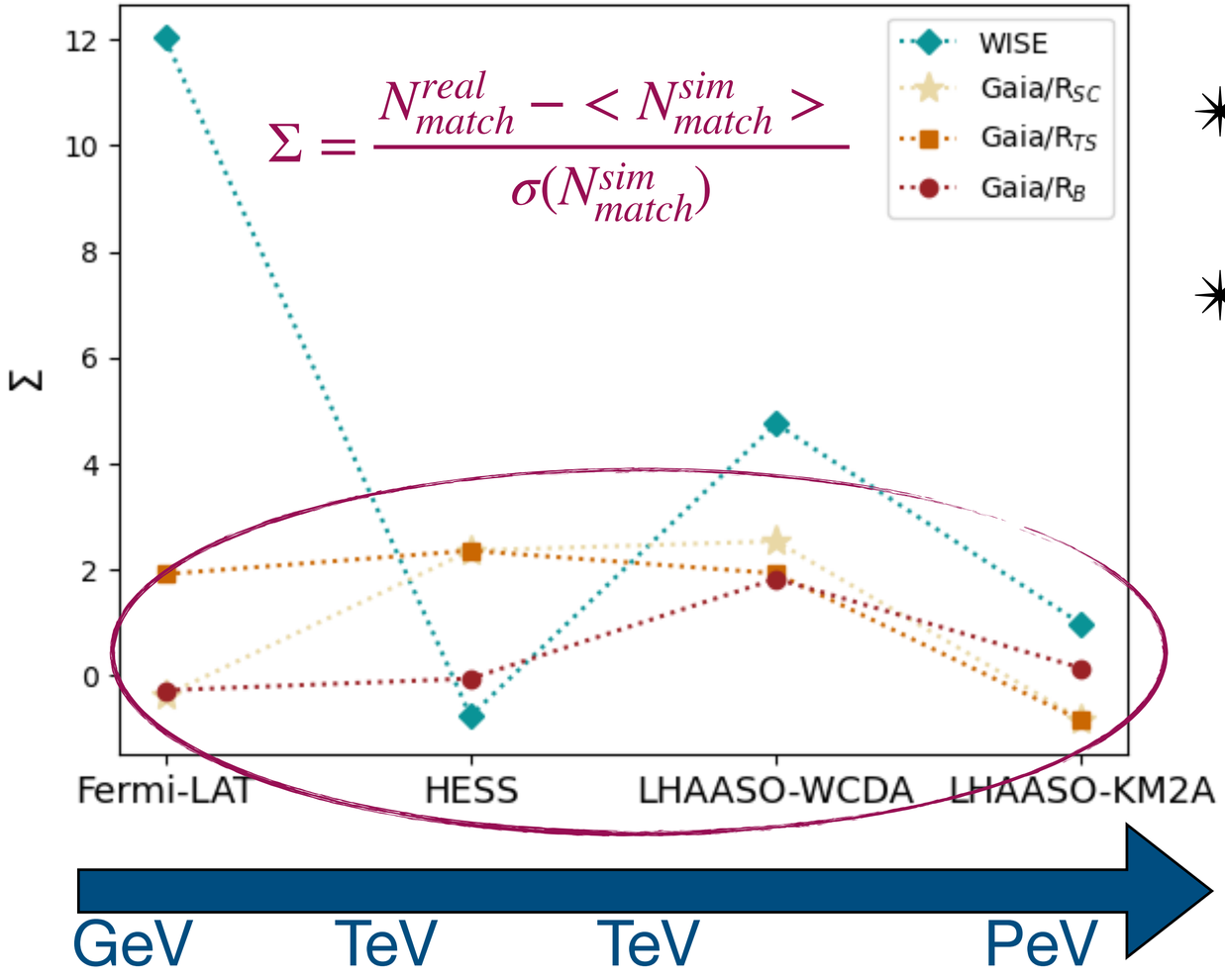
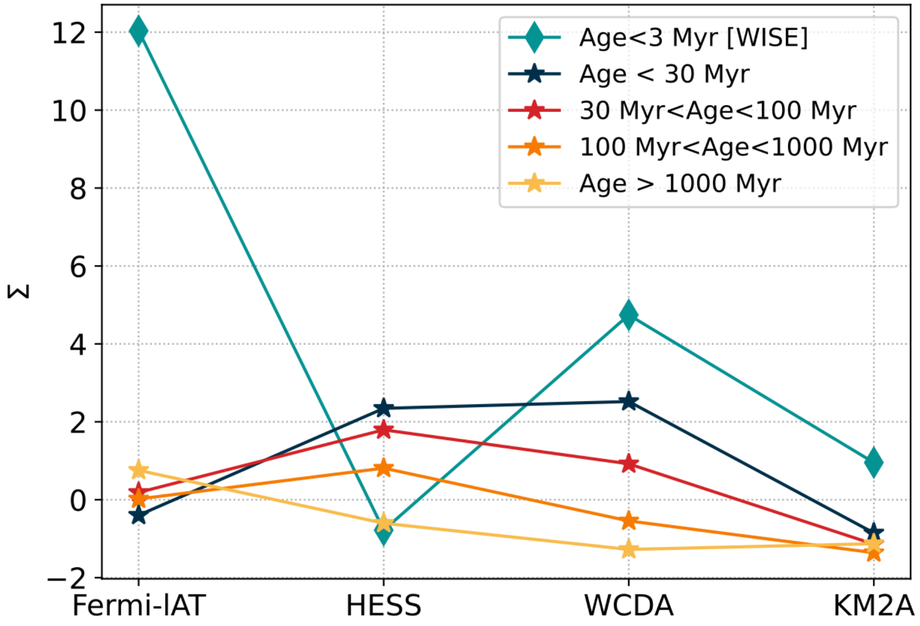
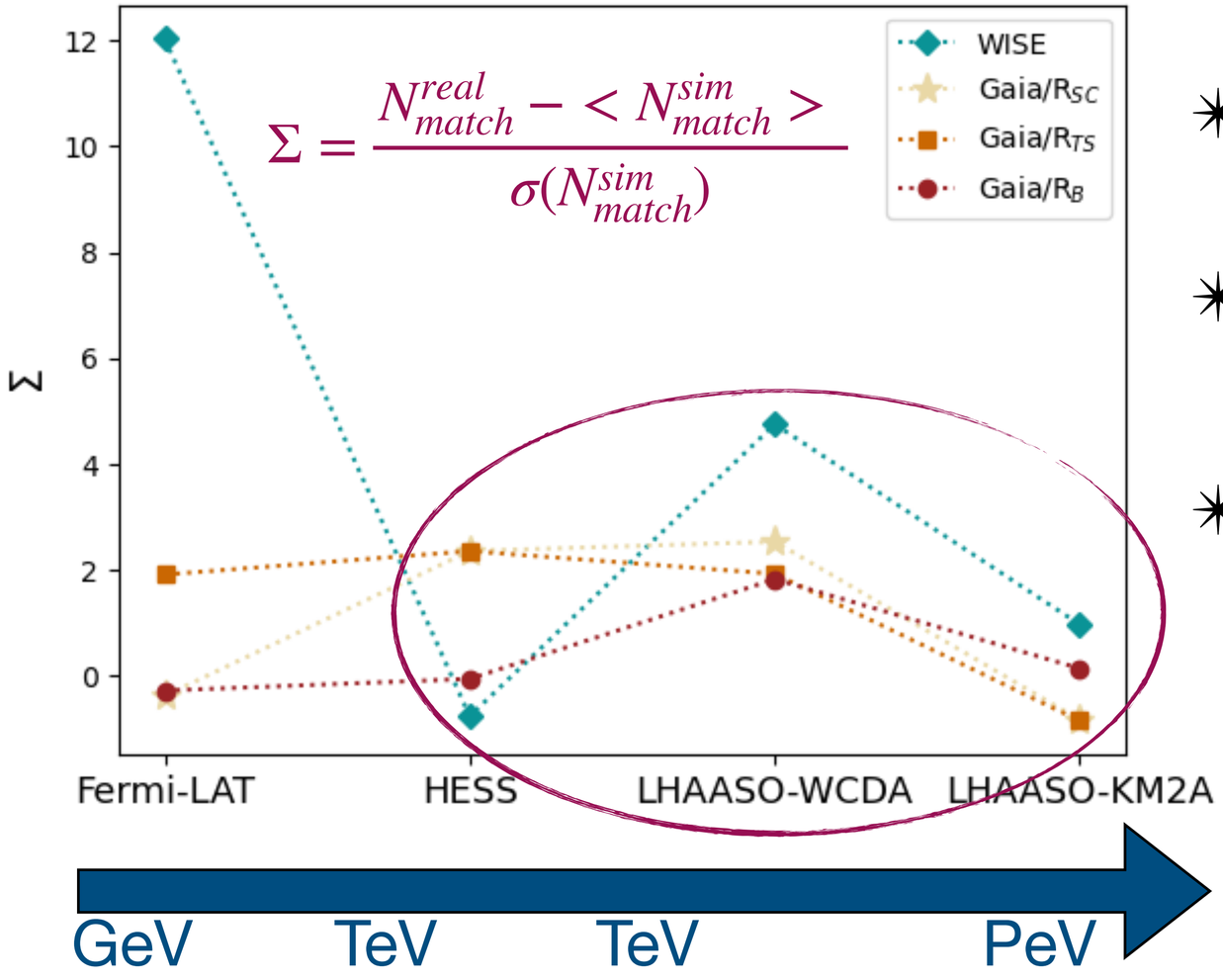



- Very good correspondence between **WISE** and **Fermi-LAT** sources
- The significance decreases for Gaia SCs: maybe due to larger areas or to **larger ages**?



# Star clusters Matching with gamma-ray sources



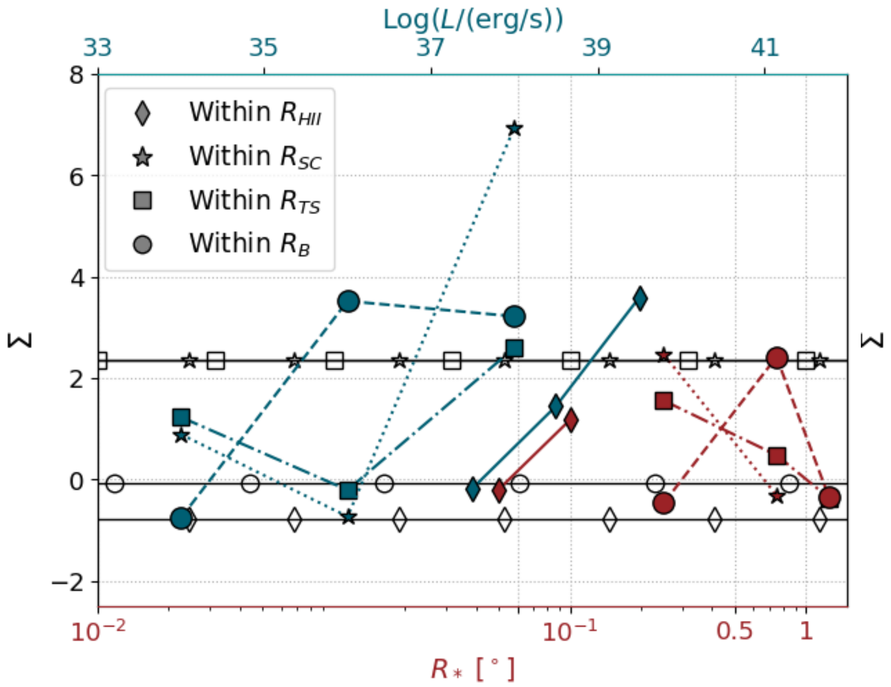

- Very good correspondence between **WISE** and **Fermi-LAT** sources
- The significance decreases for Gaia SCs: maybe due to larger areas?
- No convincing matching with VHE sources

# Star clusters

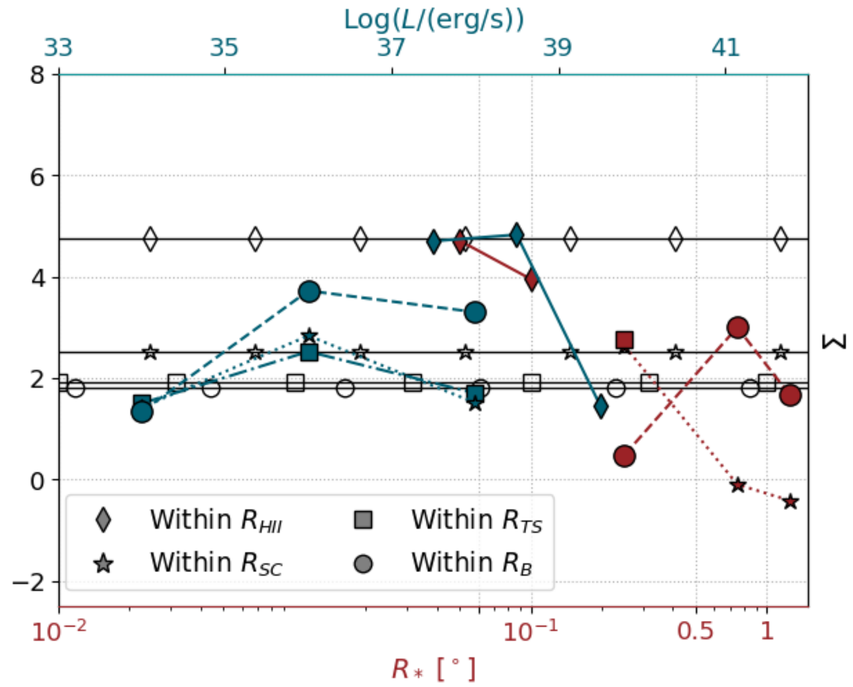
## Matching with gamma-ray sources

Peron et al. 2024, ApJL, 972, 2, L22

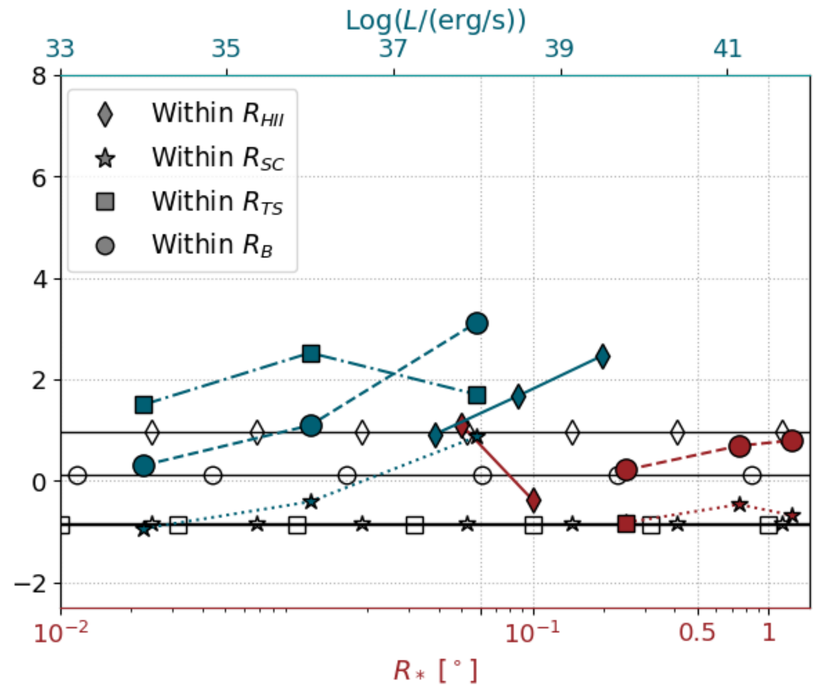
### H.E.S.S.




### LHAASO-WCDA




### LHAASO-KM2A

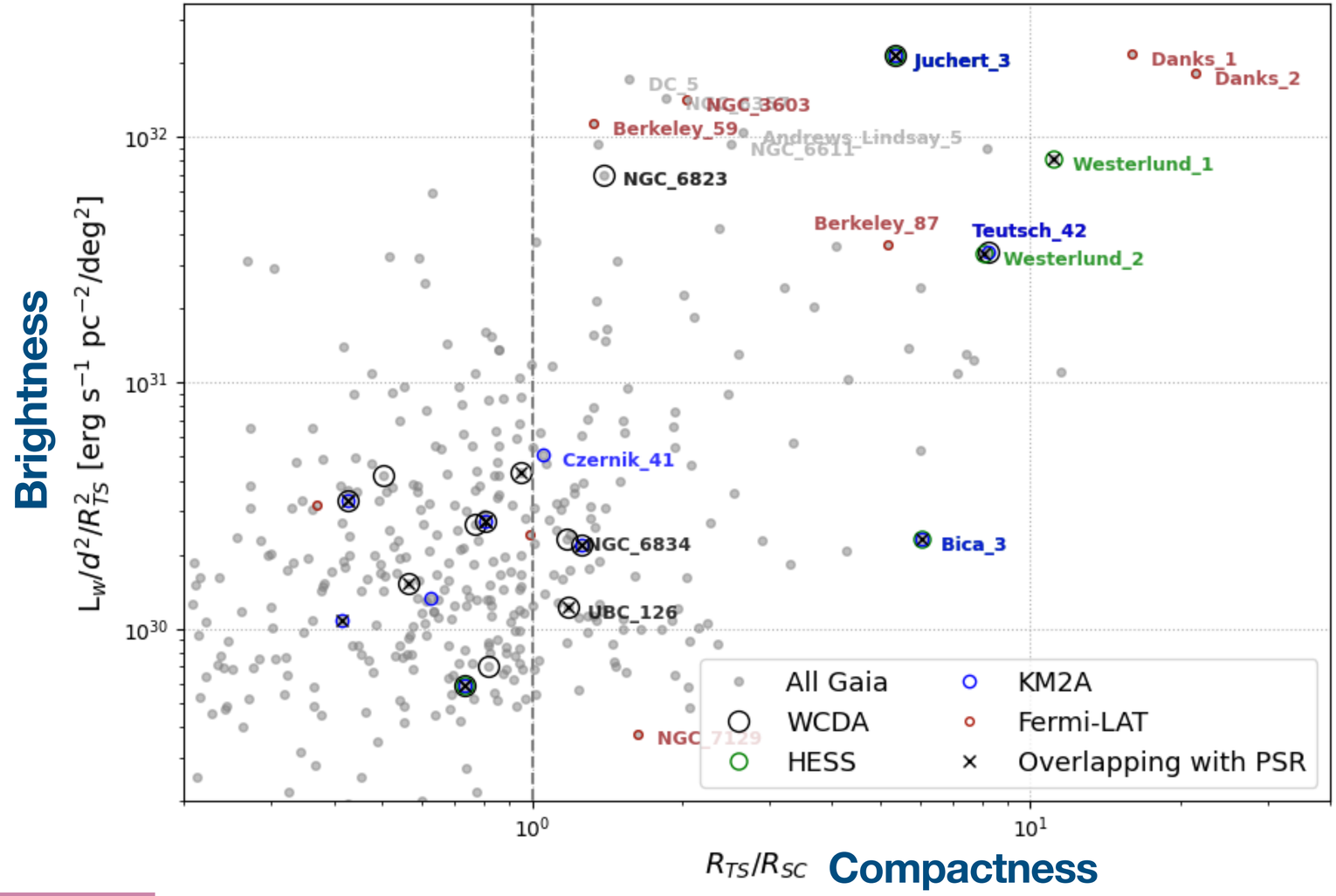



TeV TeV PeV

Peron et al. 2024, ApJL, 972, 2, L22

# Star clusters from Gaia

## where are they?



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+ Peron et al., in prep.

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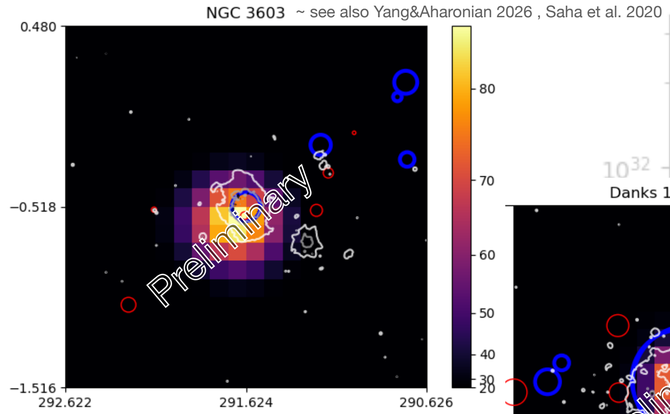
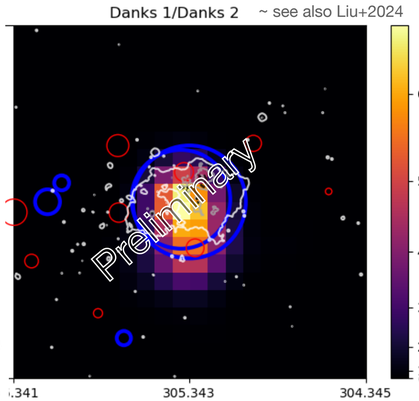
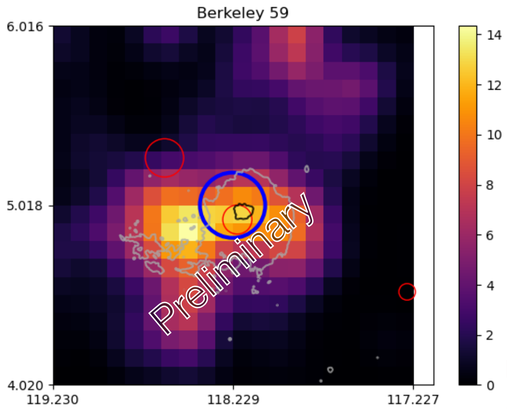
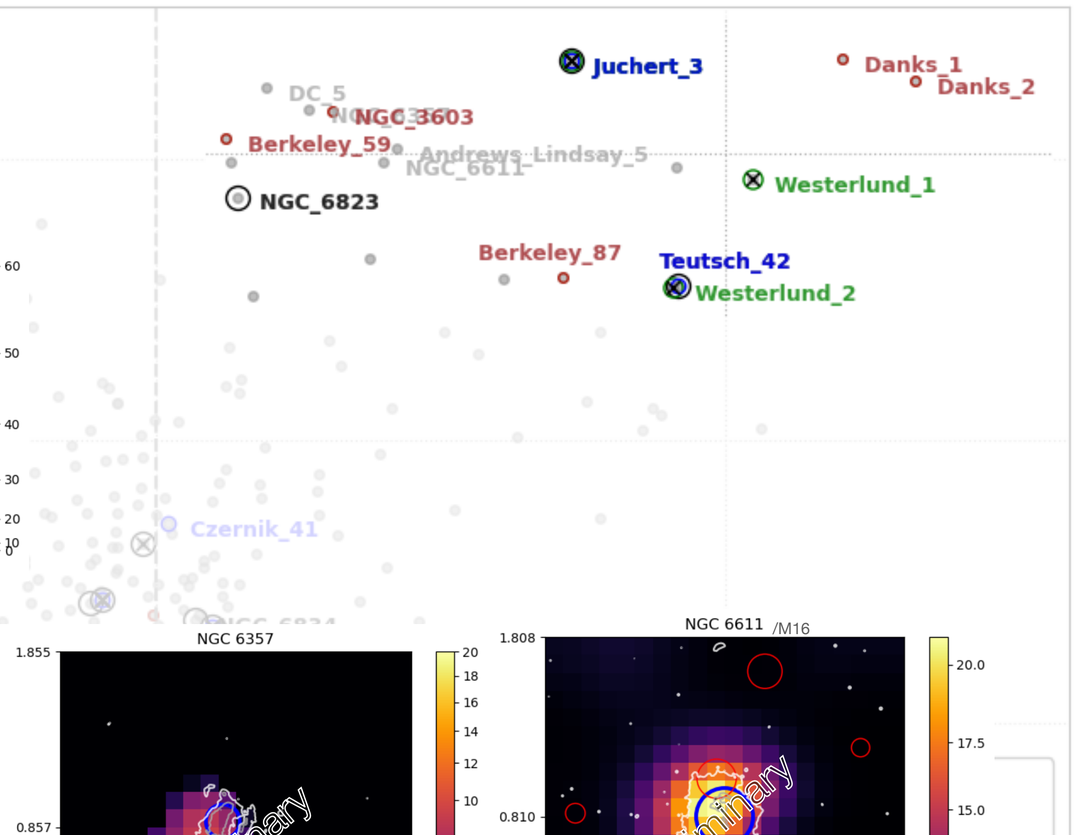



Map: Fermi-LAT TS (>1 GeV)

Regions: Fermi-LAT 4FGL sources

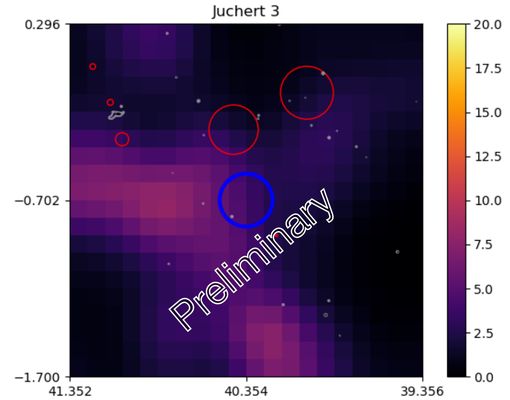
Region: Gaia RTS

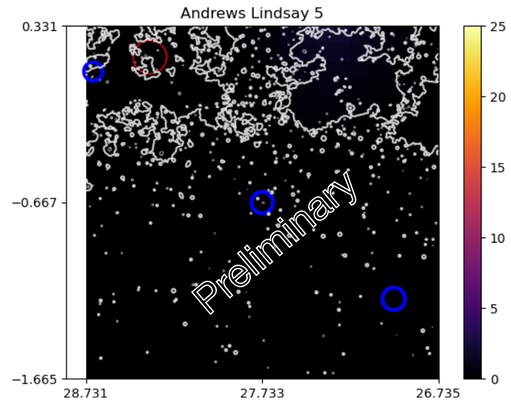
Contours: WISE (22 micron) emission

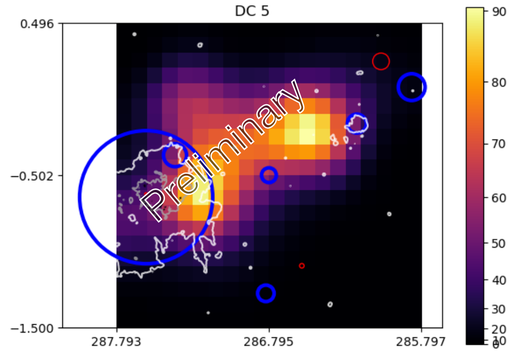








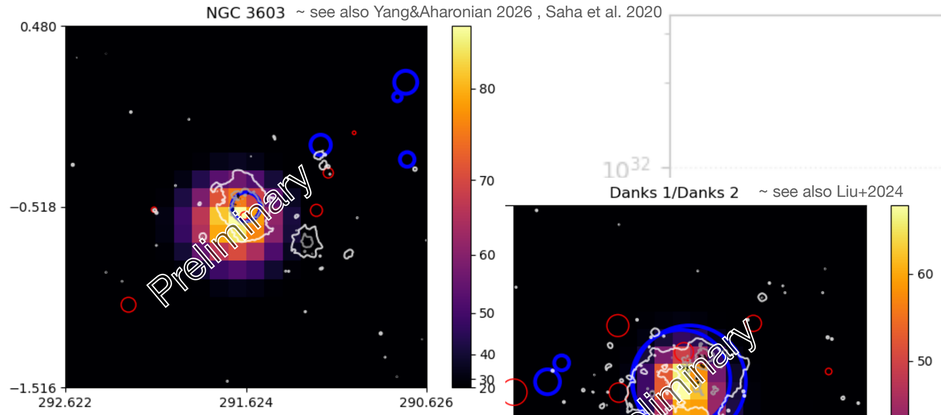



Peron et al. 2024, ApJL, 972, 2, L22
+ Peron et al., in prep.

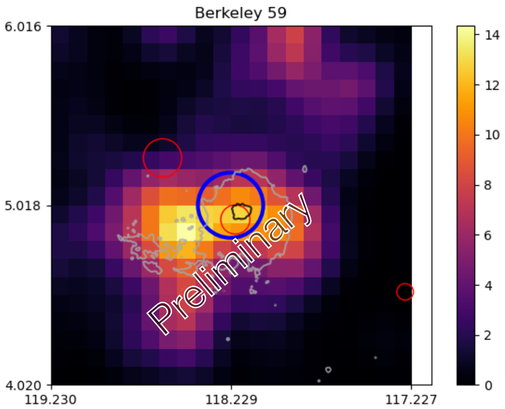
# Star clusters from Gaia
## where are they?

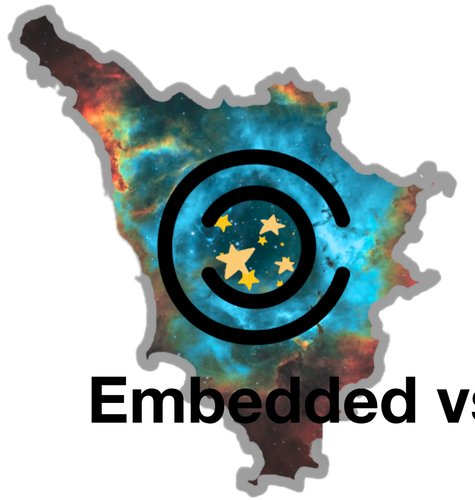
## Unid Fermi source + HII gas





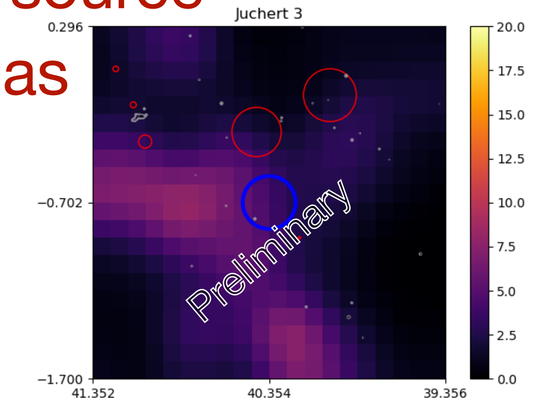


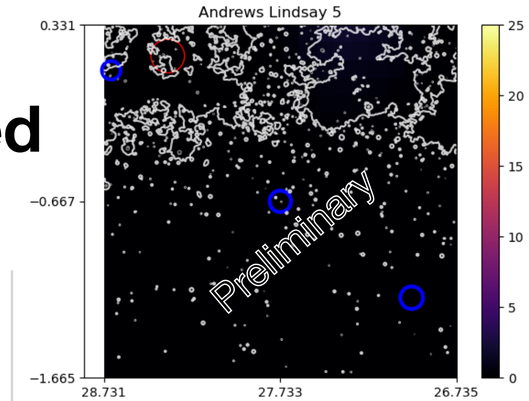


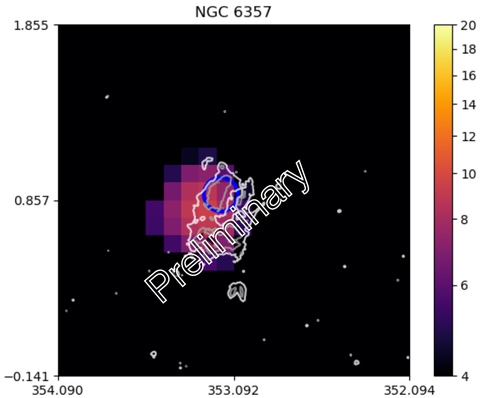
**Embedded vs. Non-embedded**

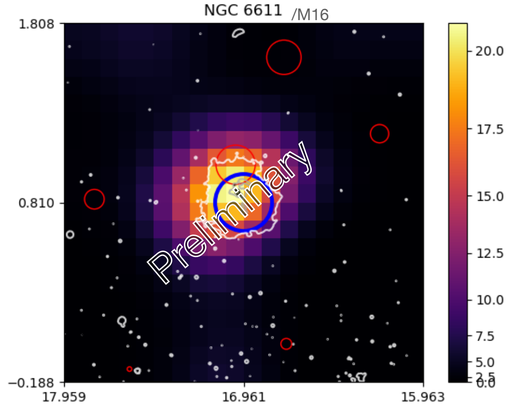
## No unid source
## No HII gas

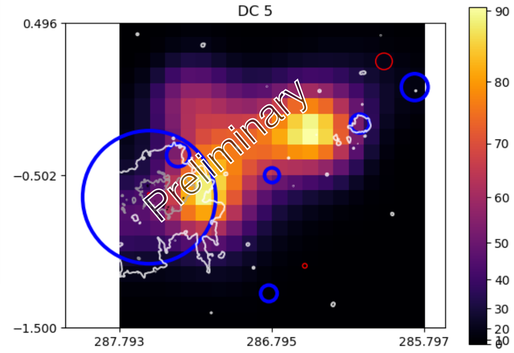



## No Unid Fermi source but HII gas




Map: Fermi-LAT TS (>1 GeV)

Regions: Fermi-LAT 4FGL sources

Region: Gaia RTS

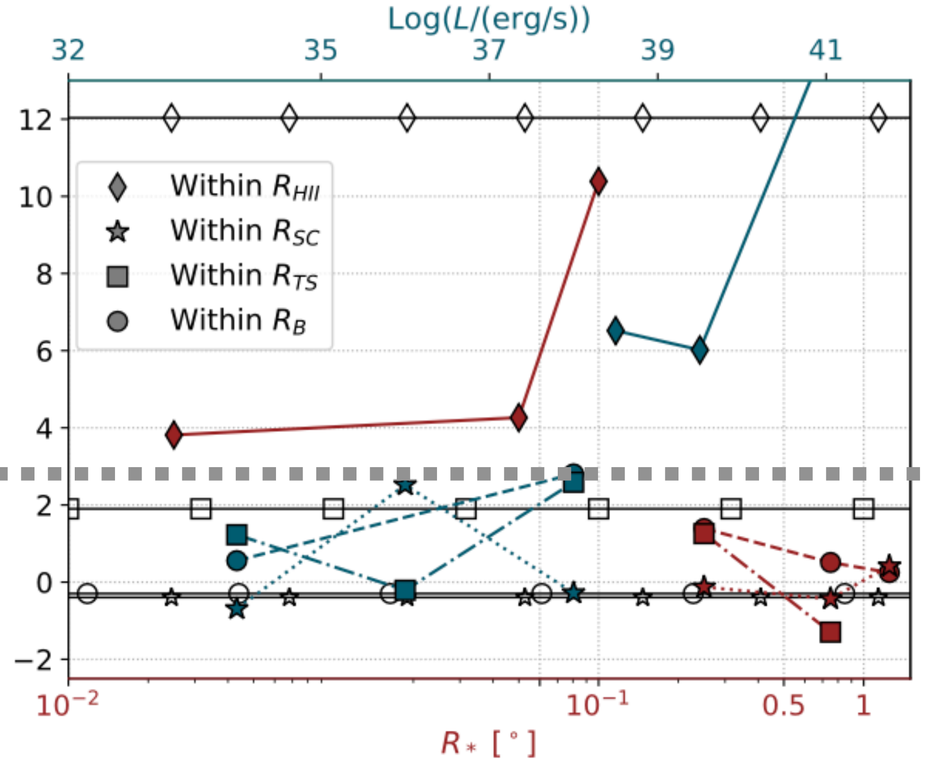
Contours: WISE (22 micron) emission

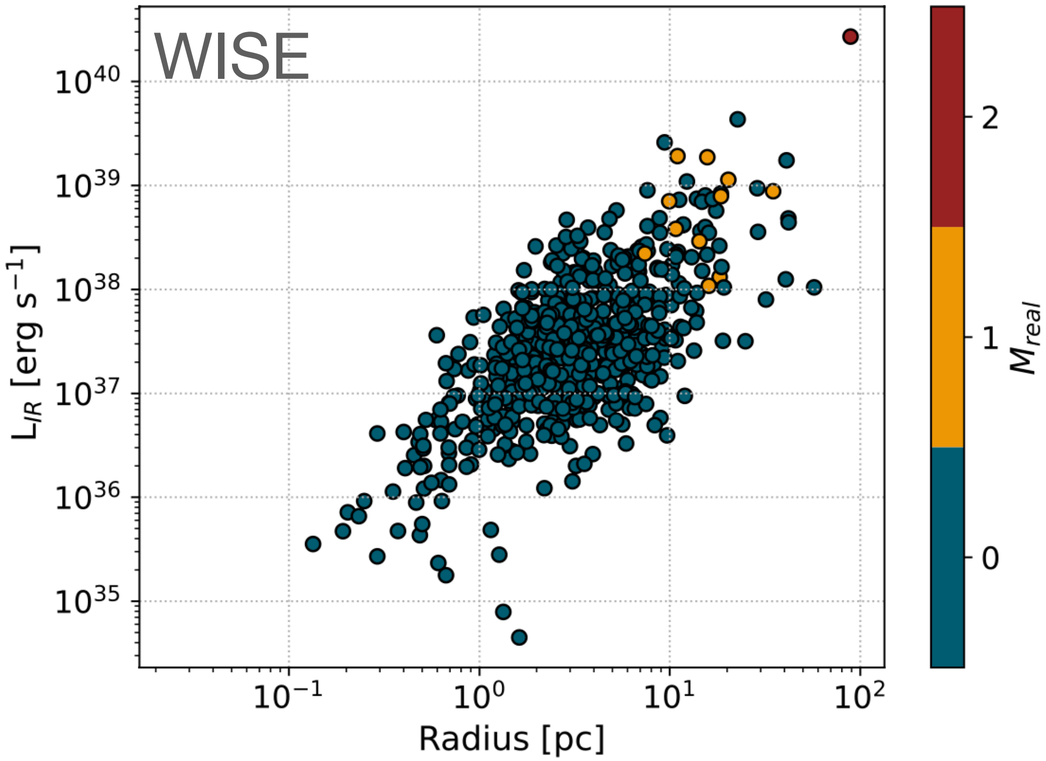
# Star clusters from WISE

## Matching with Fermi-LAT (50 MeV — 1 TeV)

WISE

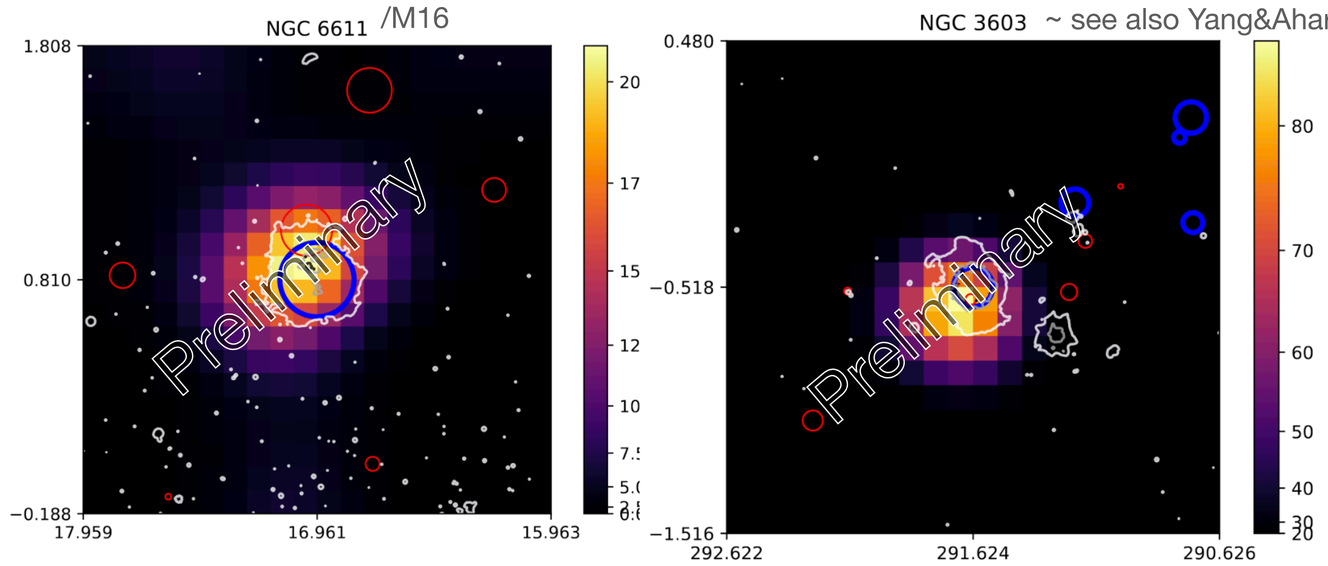
Gaia



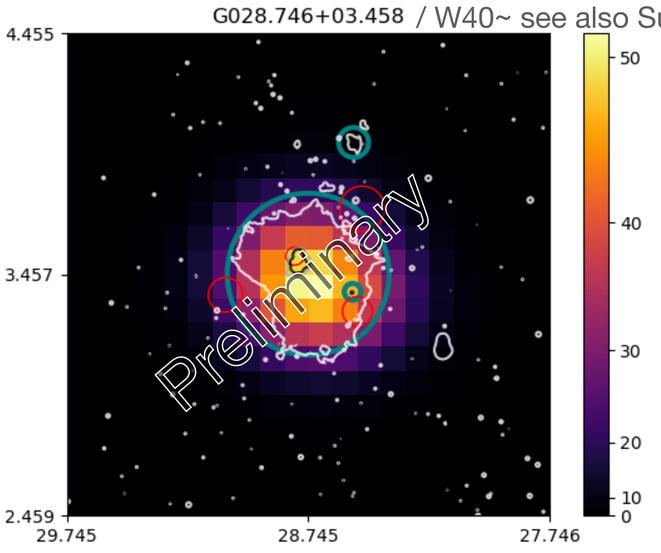

Matching significance and number of matching sources **increase** with **luminosity** and **radius**

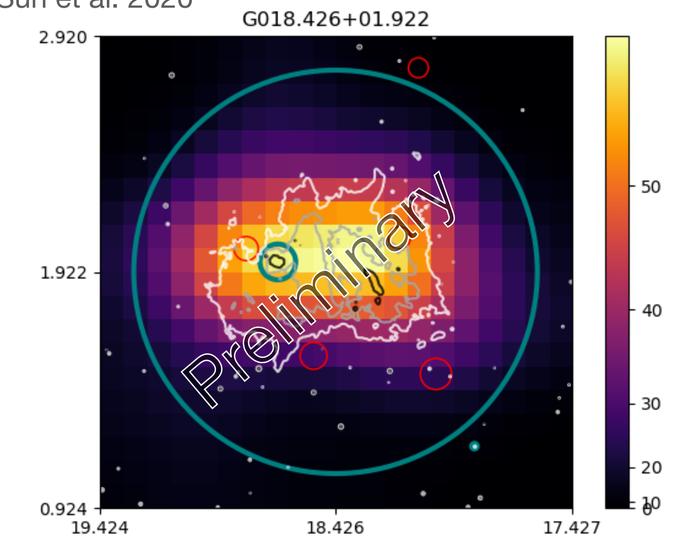
# Star clusters seen by Fermi-LAT










## Gaia identified SCs + HII region

Map: Fermi-LAT TS (>1 GeV)

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Region: Gaia RTS

Region : WISE (22 micron) HII regions

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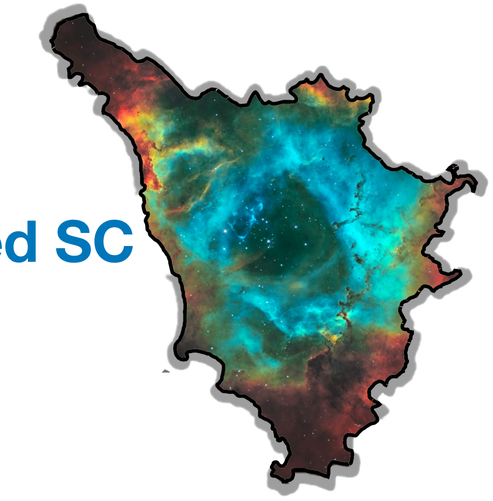
## HII region without Gaia identified SC



..and more examples

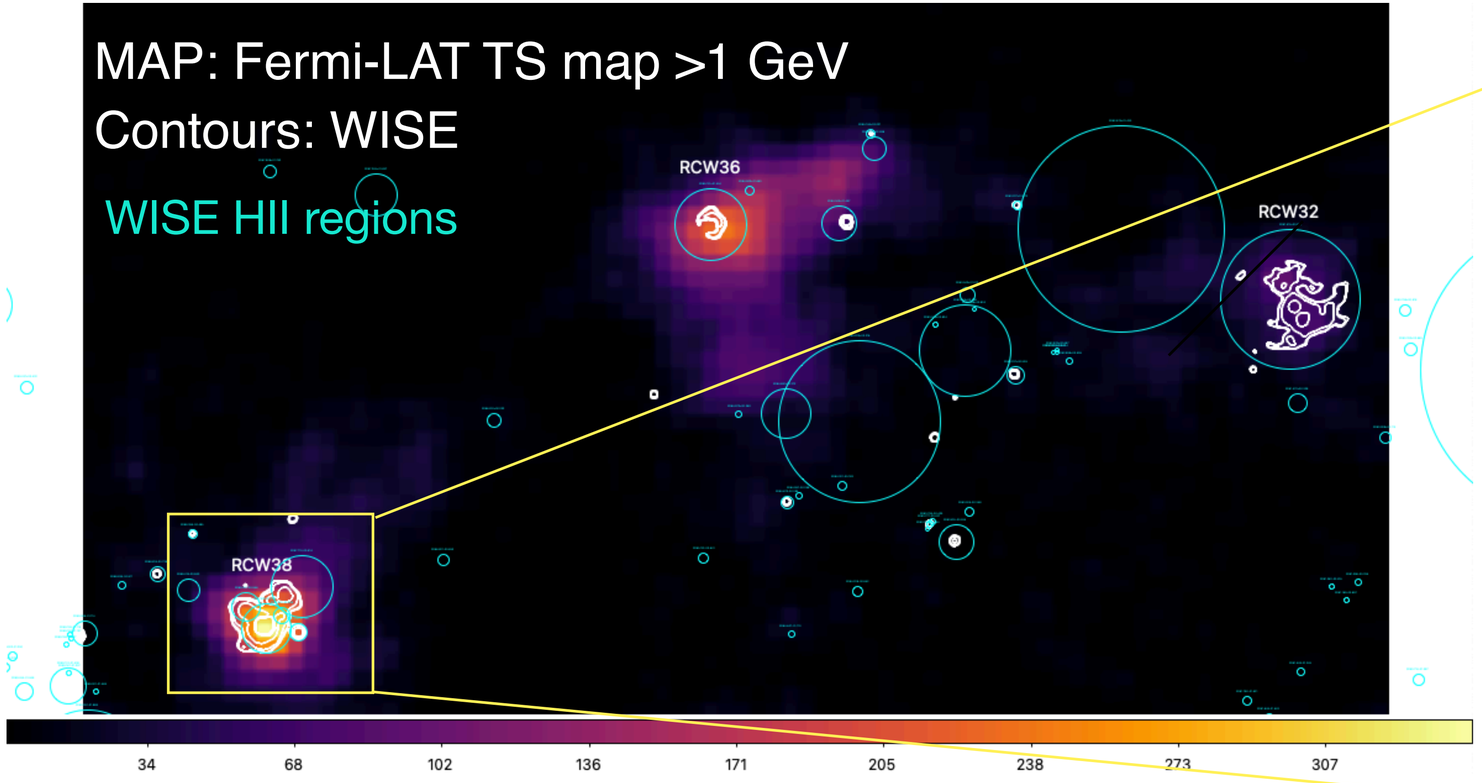
**Peron et al. 2024, in prep**

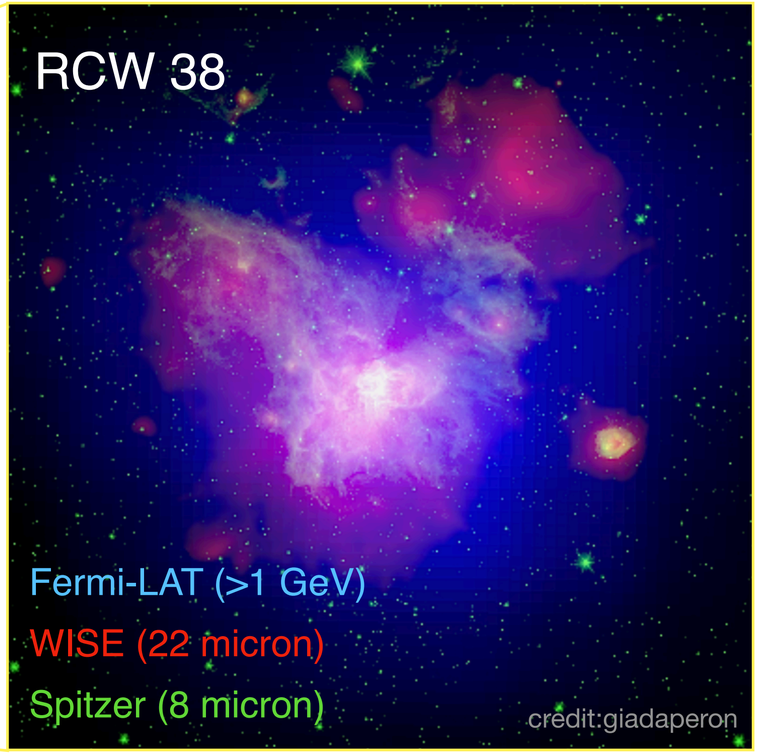
# Star clusters from WISE

## In the Vela Molecular cloud Ridge

Star forming complex at ~1-2 kpc

- Evidence of **gamma-ray** excess in 3 HII regions
- SC of Age ~ 1 Myr —> No Supernovae
- Embedded in dense medium ~ 1000 $\mathrm{cm}^{-3}$



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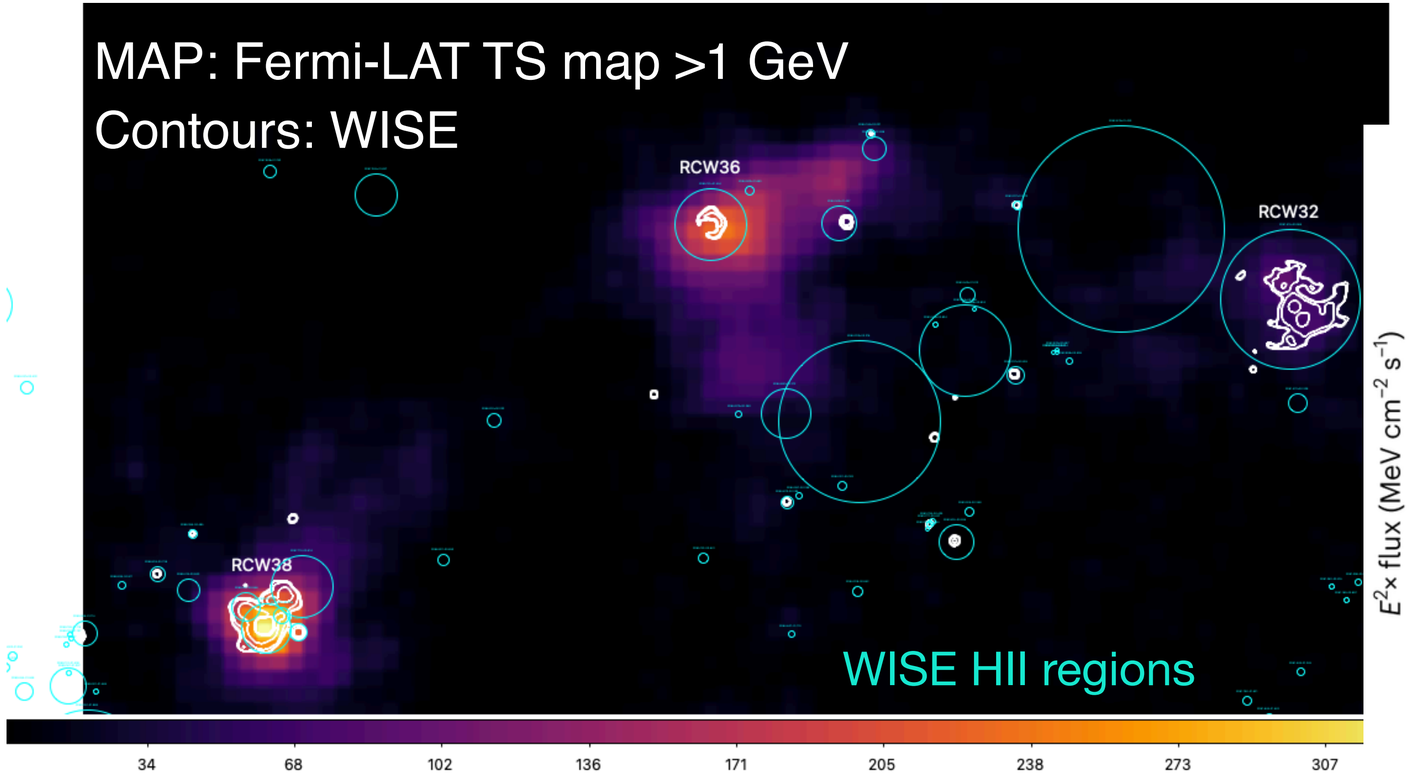
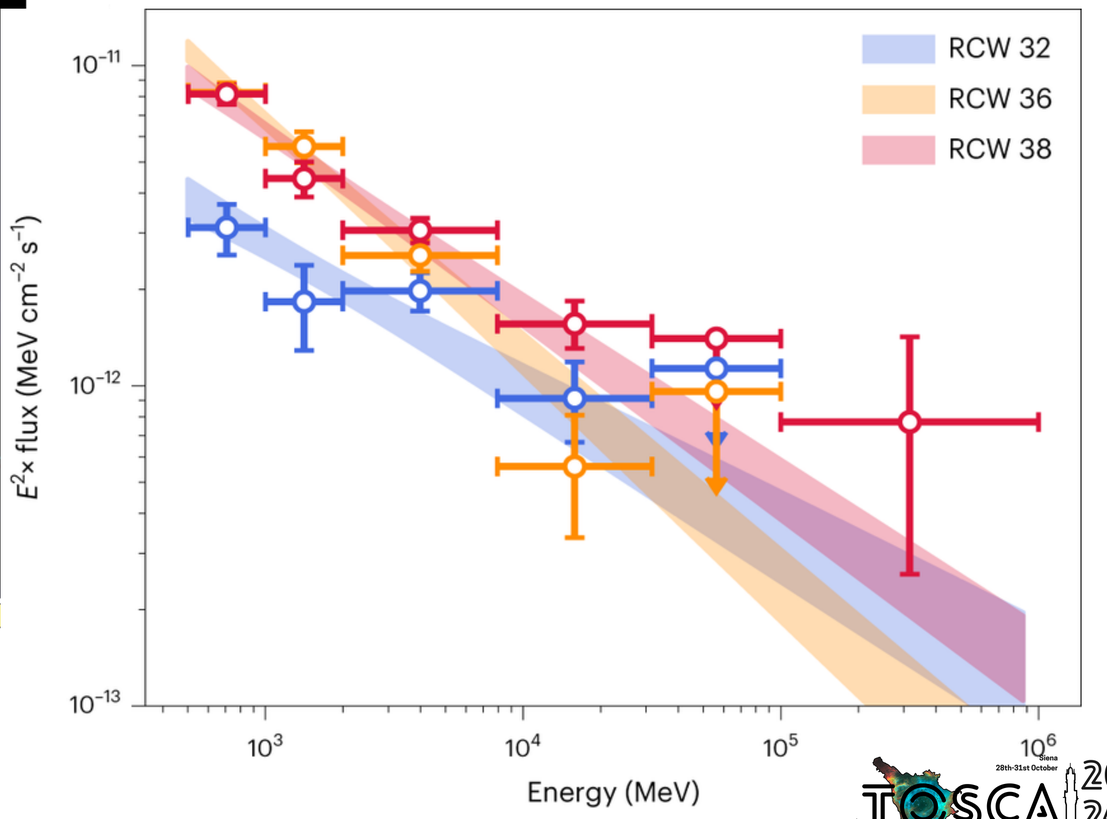
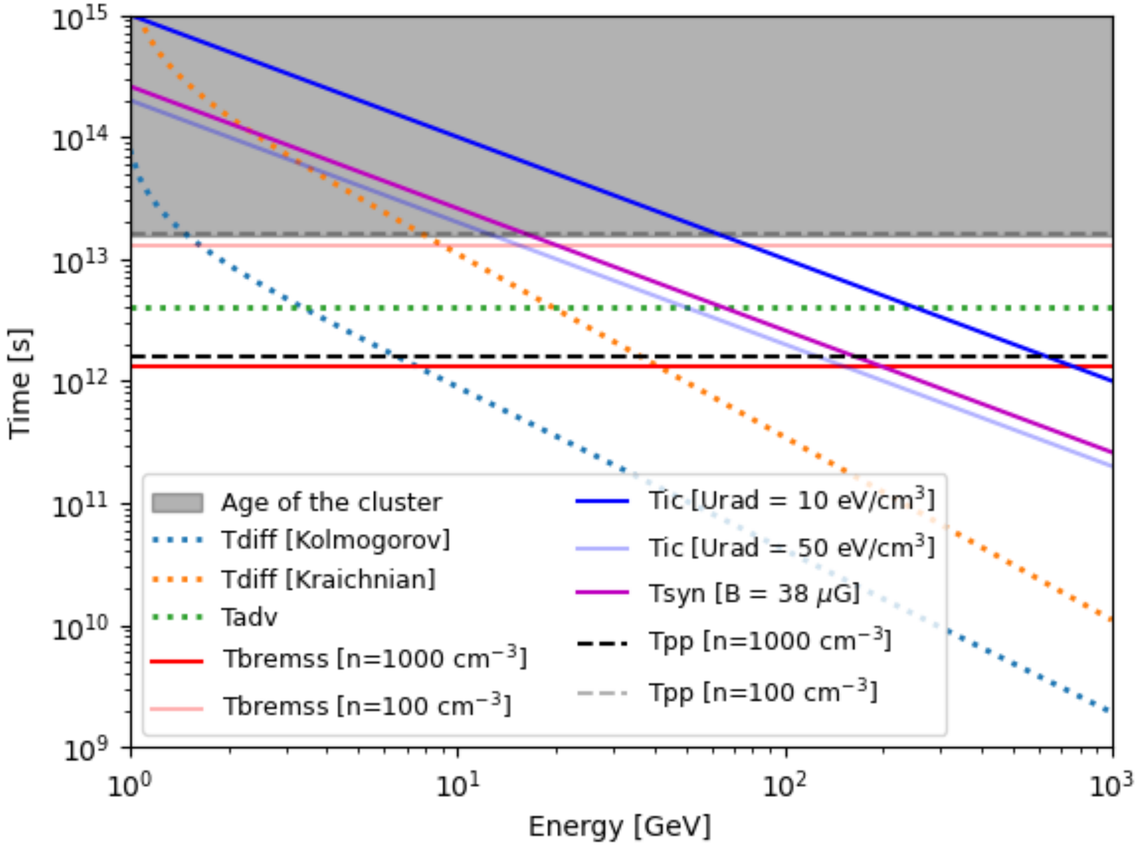
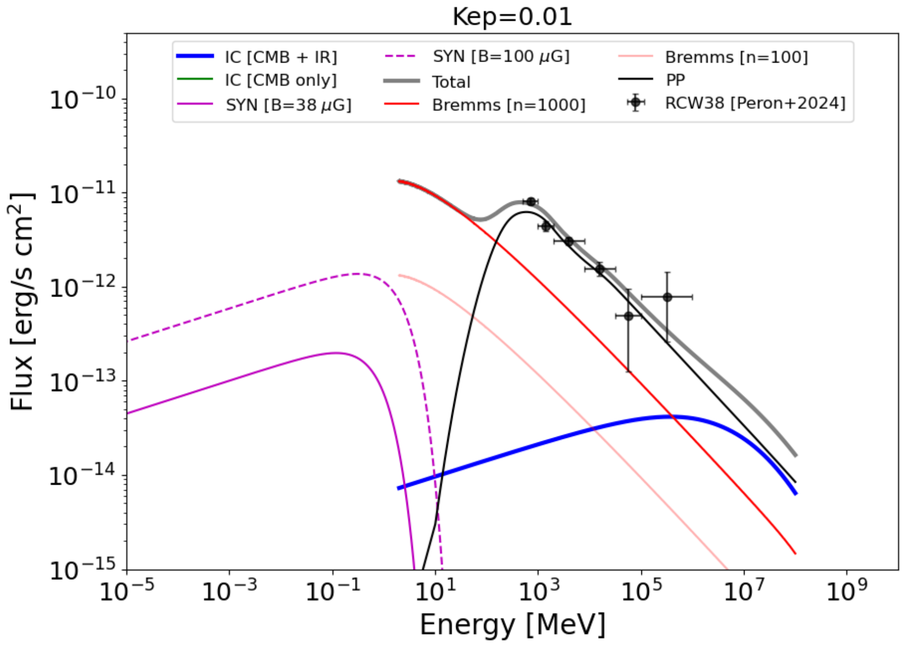


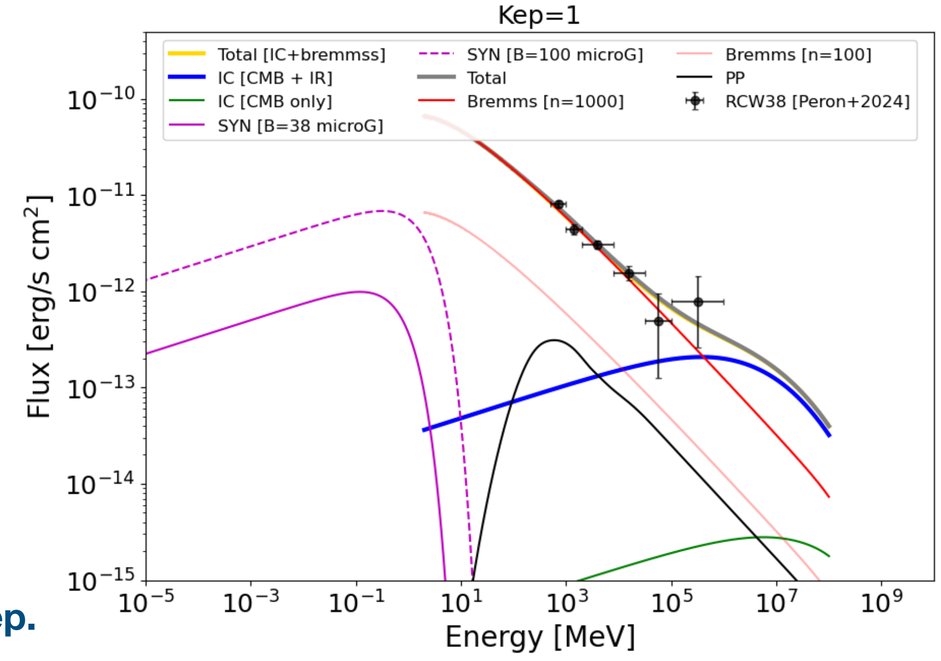



# Star clusters from WISE

## Hadronic or leptonic?




Peron et al., in prep.

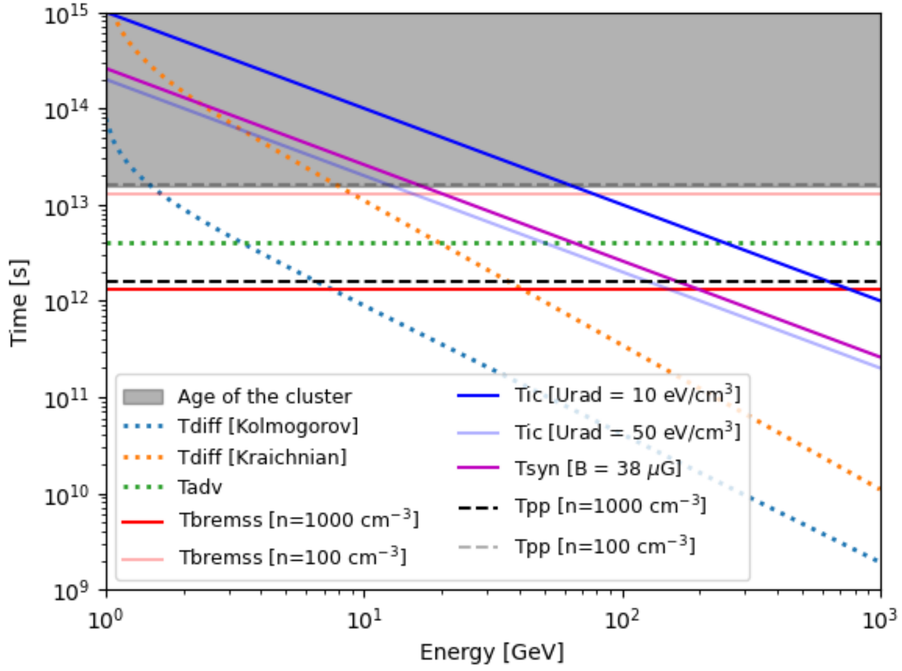
# Star clusters

## Acceleration efficiency

$$\eta = \frac{L_{CR}}{L_w}$$

We derive $L_{CR}$ from $L_\gamma$ assuming **full confinement** in a pion-decay scenario

$$L_{CR}[measured] << L_{CR}[real]$$



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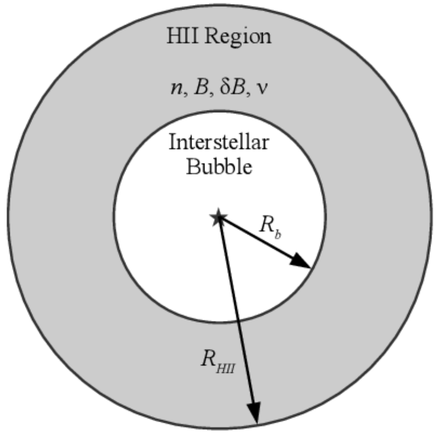
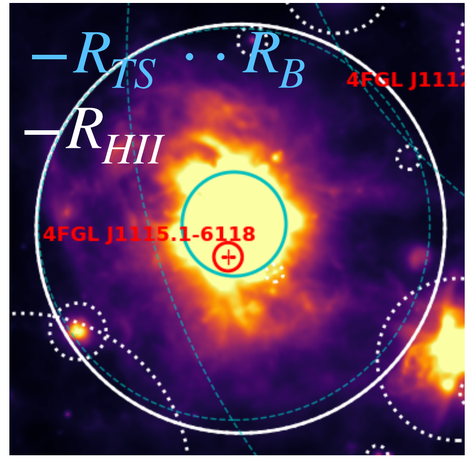
Maurin et al. 2016




A fraction, $\xi$ , of $L_w$ goes to blown the bubble of radius R

$$R \simeq R_{HII} = \left(\frac{\xi L_w}{n}\right)^{\frac{1}{5}} t^{\frac{3}{5}}$$

Weaver et al. 1977

**Peron et al. Nature Astronomy 2024**

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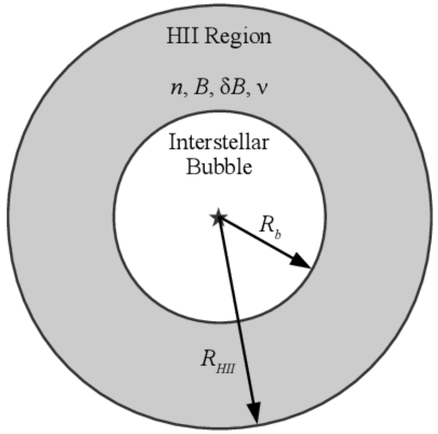


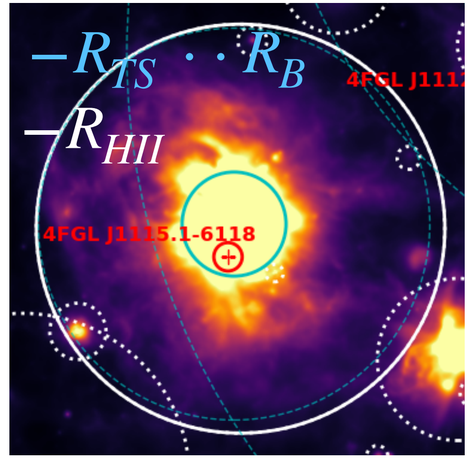


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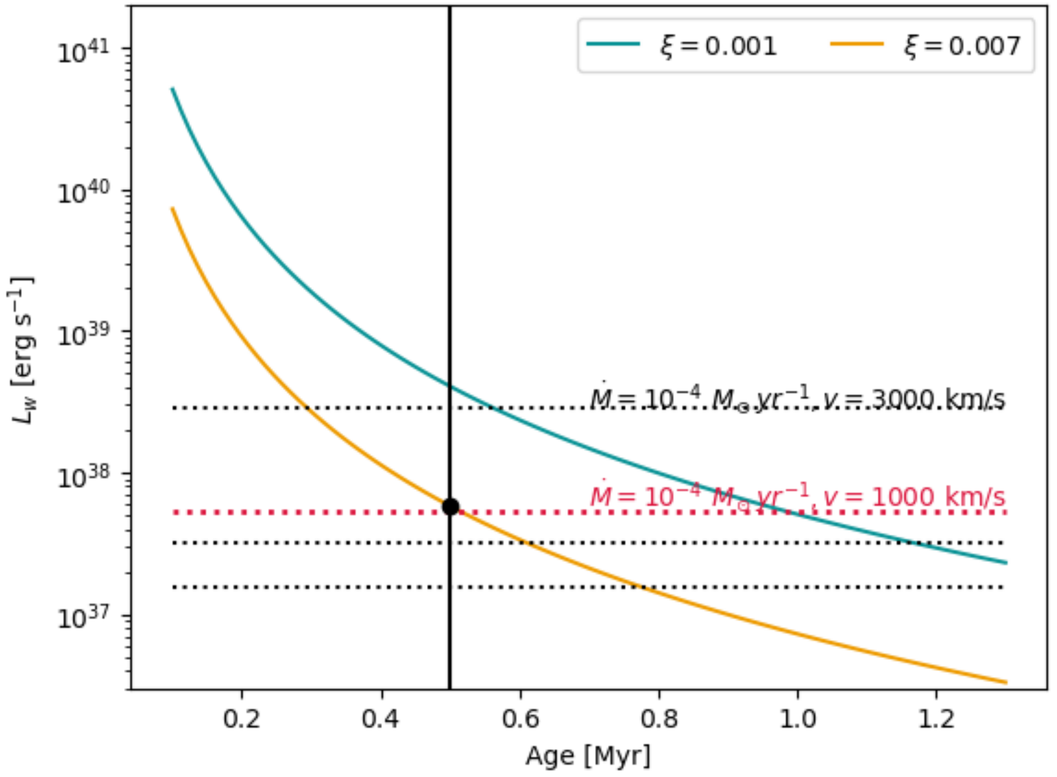



$$\dot{M} \sim 10^{-4} M_\odot yr^{-1}$$

$$v \sim 1000 \text{ km s}^{-1}$$

$$R \sim R_{HII} \sim R_\gamma$$

Canto' et al. 2000 [Simulations]

**Peron et al. Nature Astronomy 2024**

# Star clusters

## Acceleration efficiency

$$\eta = \frac{L_{CR}}{L_w}$$

$$L_{CR}[measured] << L_{CR}[real]$$

$$< \eta > \sim 0.5\,\% << \eta[real]$$

| Source | Age [Myr] | N [1E3 cm-3] | Efficiency [%] |
|---|---|---|---|
| RCW 32 | 2 | 1.9 | 0.85 |
| RCW 36 | 1.1 | 2.6 | 0.79 |
| RCW 38 | 0.5 | 2.1 | 4E-03 |

$$\epsilon_w = \frac{\mathscr{P}^w_{CR}}{\mathscr{P}^{tot}_{CR}} = \frac{0.0005 \times 10^{41} \mathrm{erg\ s^{-1}}}{7 \times 10^{40} \mathrm{erg\ s^{-1}}} \simeq 1\,\% << \epsilon_w[real]$$

From isotopic ratio:

$$\epsilon_{winds} X_{winds} + (1 - \epsilon_{winds}) X_{ISM} = X_{CR} \rightarrow \epsilon_{winds} \simeq 16\,\%$$

# Conclusions

✴ We detected **GeV gamma-ray** emission in correspondence of several **embedded star clusters**;

✴ We showed that the coincidence is **statistically significant** and is interpreted as a consequence of the enhanced target around these regions and their compactness; Conversely, no significant emission with Gaia SCs.

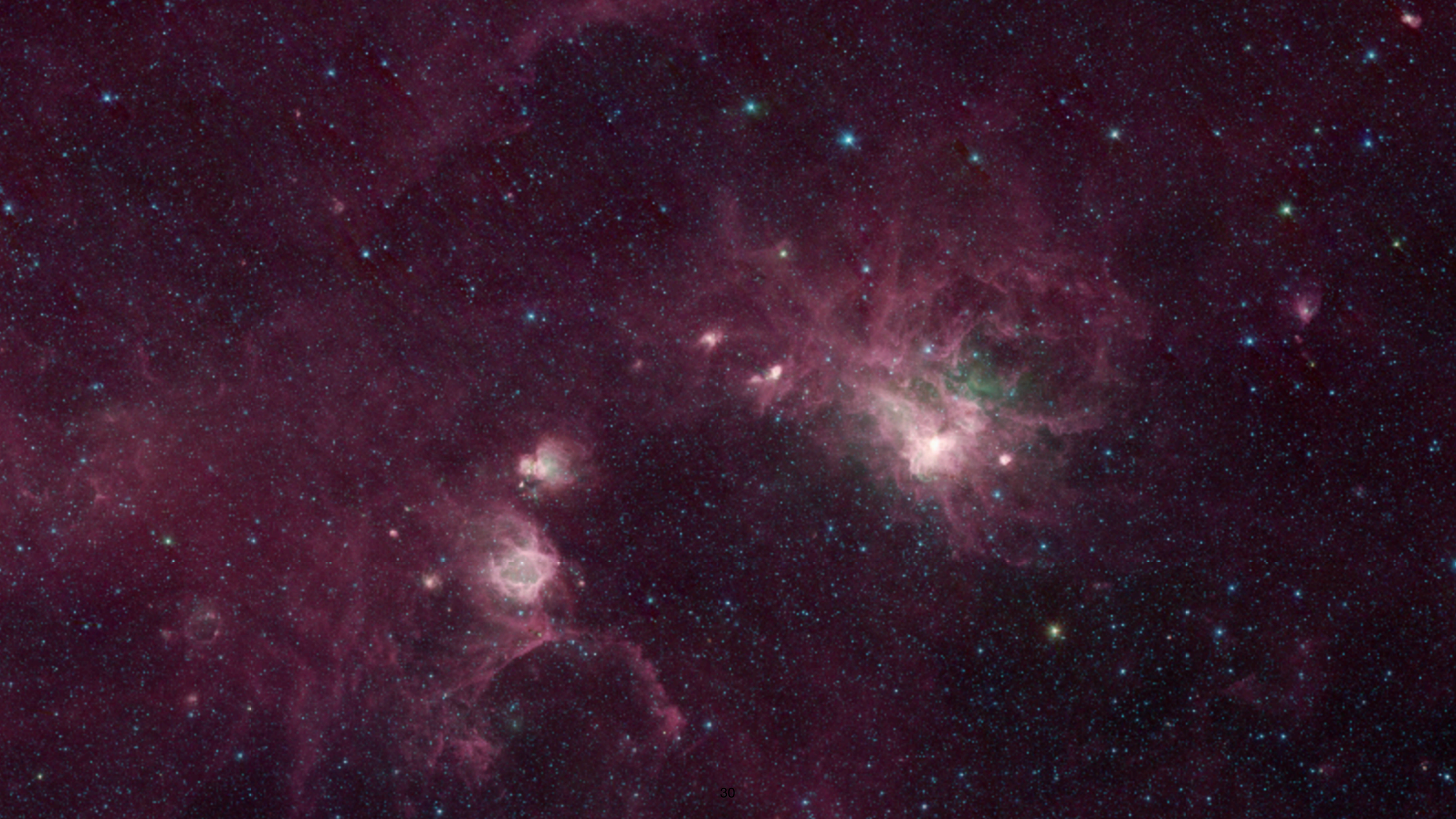
✴ Embedded clusters are **young** therefore they are not influenced by SN explosions -> their power should arise from the winds;

✴ The derived efficiency suggests that a small **part of galactic cosmic rays could be contributed by stellar winds**

✴ The real **efficiency is larger** than what we measured as it should account also for escaped particles;

✴ More observations will come to help constraining these values and to shed light on  Star Clusters As Cosmic ray Accelerators.

# THANK YOU



# Star clusters

## Acceleration efficiency

$$\eta = \frac{L_{CR}}{L_w}$$

We derive $L_{CR}$ from $L_\gamma$ assuming **full confinement** in a pion-decay scenario

➡ Are particle confined? $L_{CR} = \int dE\ E\ \frac{dN}{dE} = \int dE\ E\ q(E) \frac{R^2}{D_0 \left(\frac{E}{E_0}\right) \delta} < L_w = \frac{1}{2}\dot{M}v^2$

From gamma-ray observations

$\sim E^{-\alpha_{CR}+2}$ $\sim E^{-\alpha_{inj}-\delta+2}$

$\dot{M} \sim 10^{-4} \mathrm{M}_\odot \mathrm{yr}^{-1}$

$v \sim 1000\ \mathrm{km\ s}^{-1}$

$R \sim R_{HII} \sim R_\gamma$

$\delta = 0.3$

$D_0(E_0 = 1GeV) < 1.7 \times 10^{28}\ \mathrm{cm}^2\mathrm{s}^{-1}$

➡ Diffusion is suppressed but not enough to retain particles

$t_{esc} \sim 7.6 \times 10^{11}\mathrm{s} < t_{pp} \sim 1.6 \times 10^{12} (n/1000\ \mathrm{cm}^{-3})^{-1}\ \mathrm{s}$

$L_{CR}[measured] << L_{CR}[real]$