The contribution of Stellar Clusters to Galactic Cosmic Rays constrained by gamma-ray observations

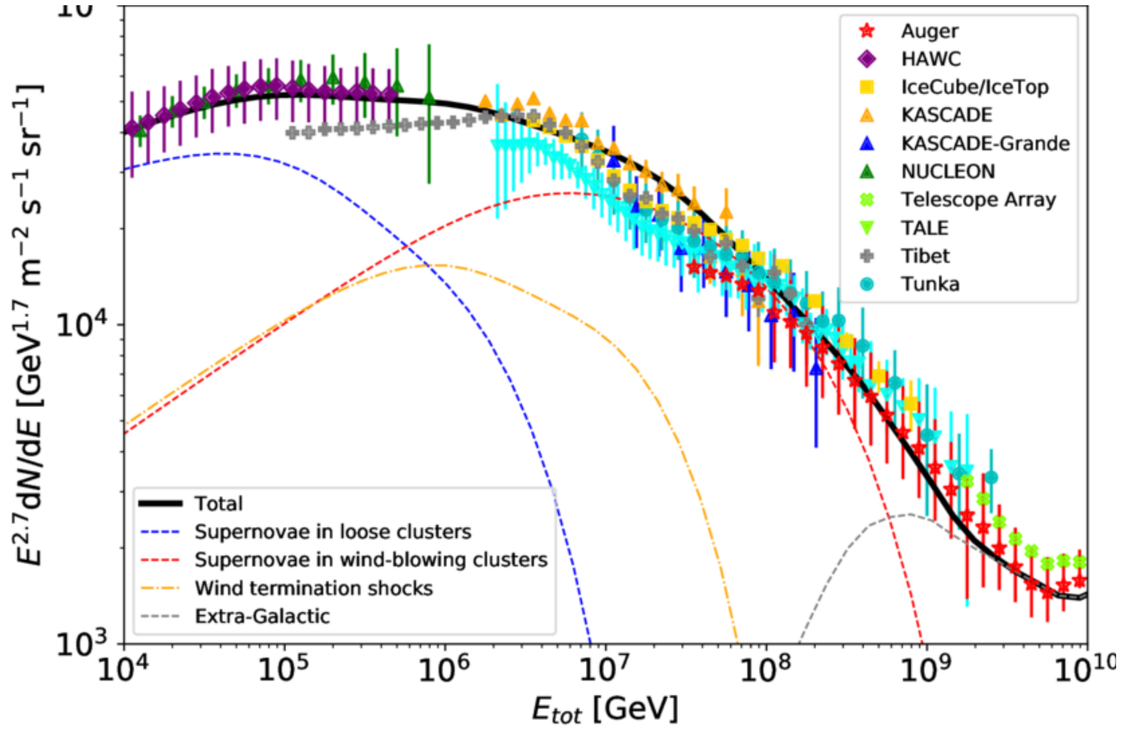
Giada Peron — CTA Symposium — 17.04.2024

Cosmic rays

challenges to the SNR paradigm

Spectrum

Vieu&Reville 2022

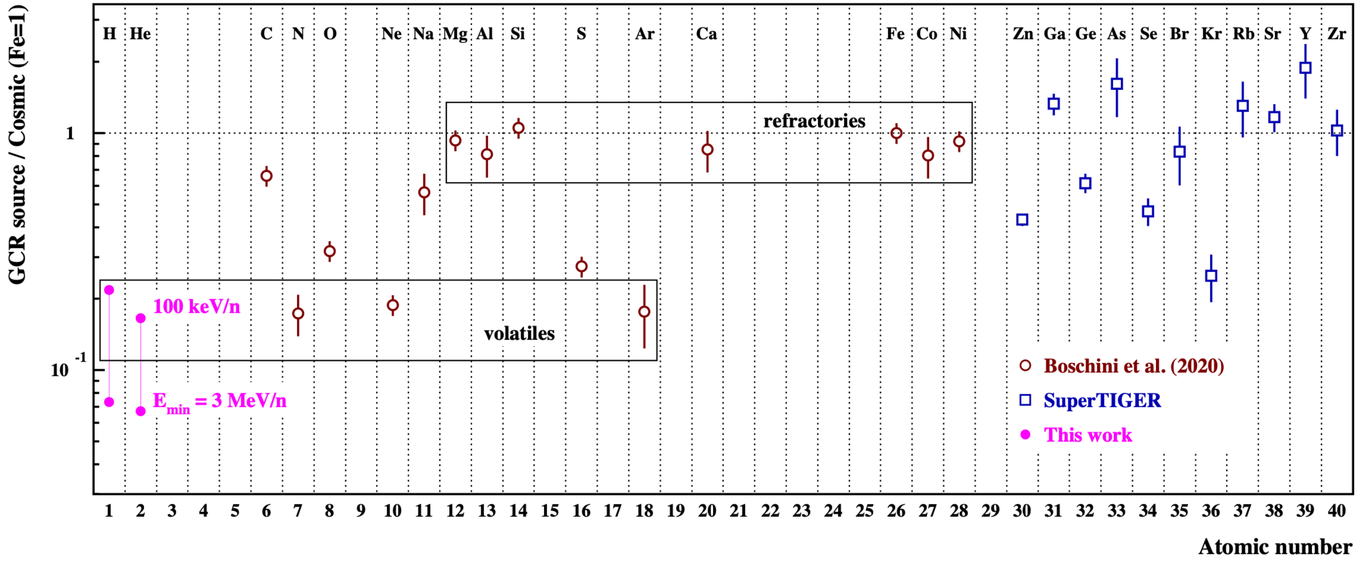


Isotopic ratio

$$X = \frac{^{22}Ne}{^{20}Ne} \qquad X_{CR} \simeq 0.317 \qquad X_{ISM} \simeq 0.0735$$

Composition

Tatischeff et al. 2021



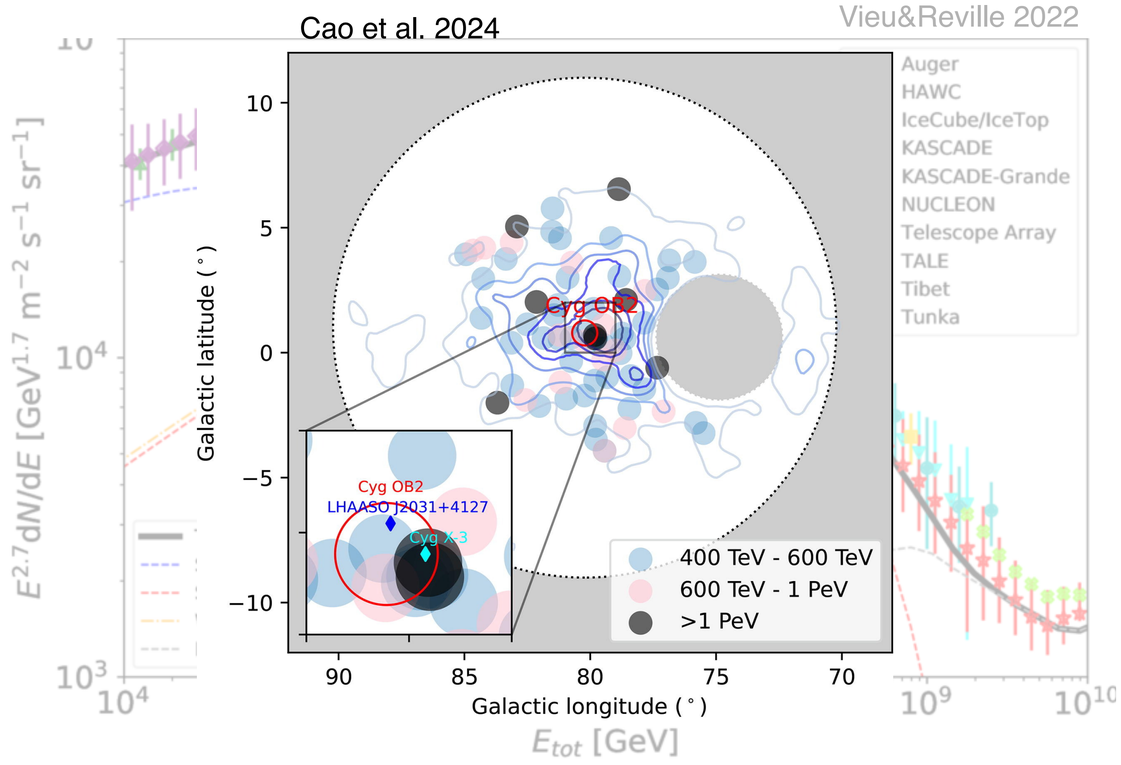
Cosmic rays

The role of Star Clusters

Spectrum

Cao et al. 2024

Vieu&Reville 2022

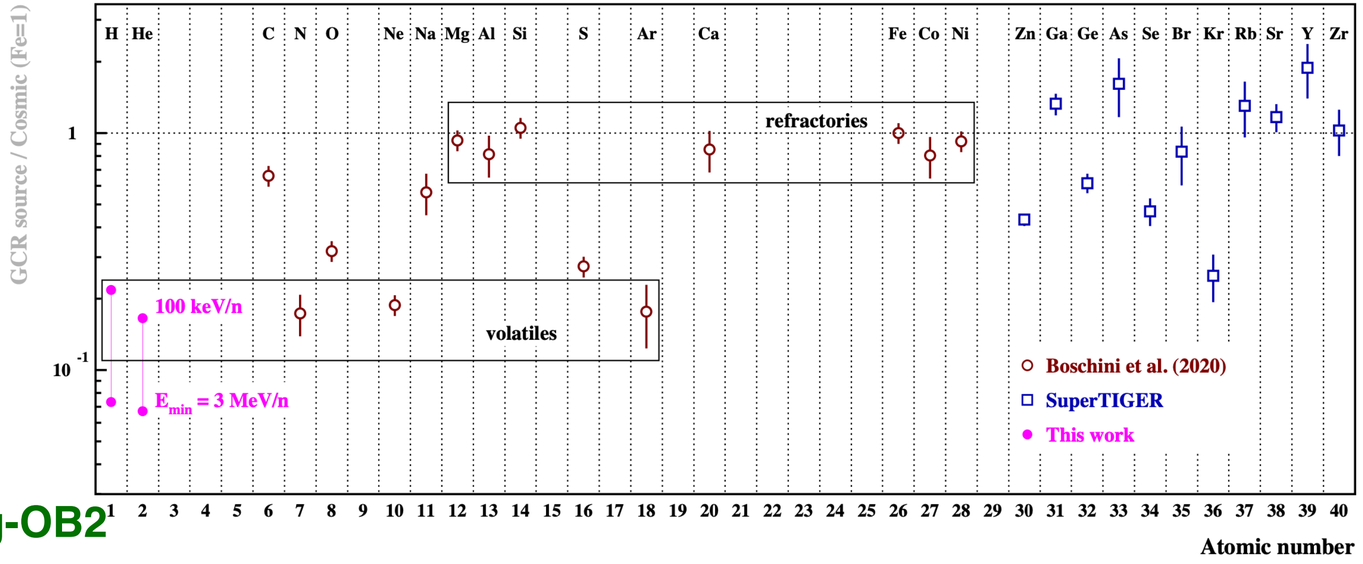


Isotopic ratio

$$X = \frac{^{22}Ne}{^{20}Ne} \qquad X_{CR} \simeq 0.317 \qquad X_{ISM} \simeq 0.0735$$

Composition

Tatischeff et al. 2021



Only convincing hadronic PeVatron in the region of Cyg-OB2

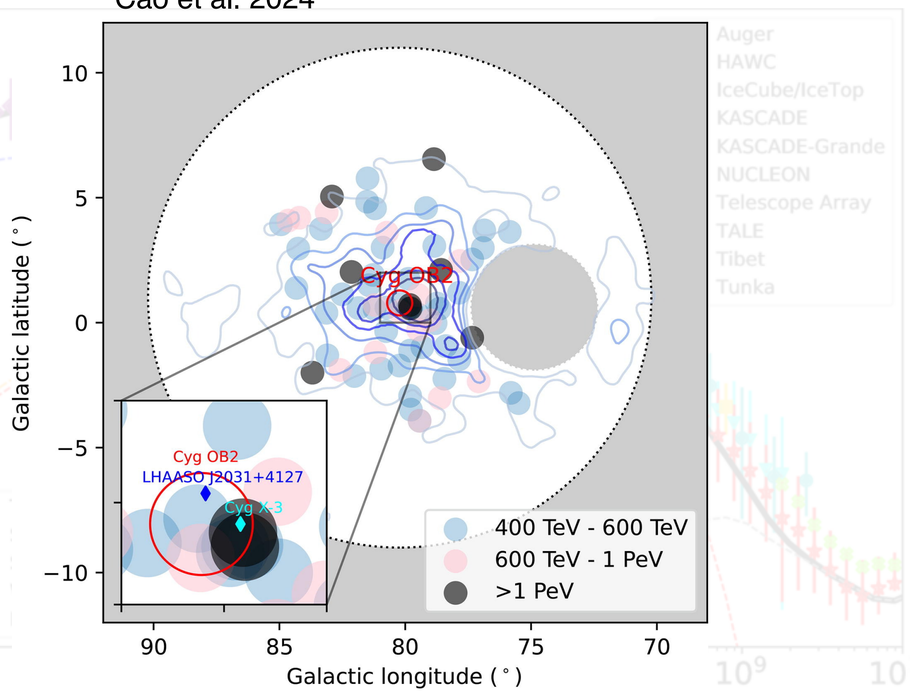
SCs are energetic enough to contribute to CRs ~ 10^{41} erg/s (in total)

Cosmic rays

The role of Star Clusters

Spectrum

Cao et al. 2024



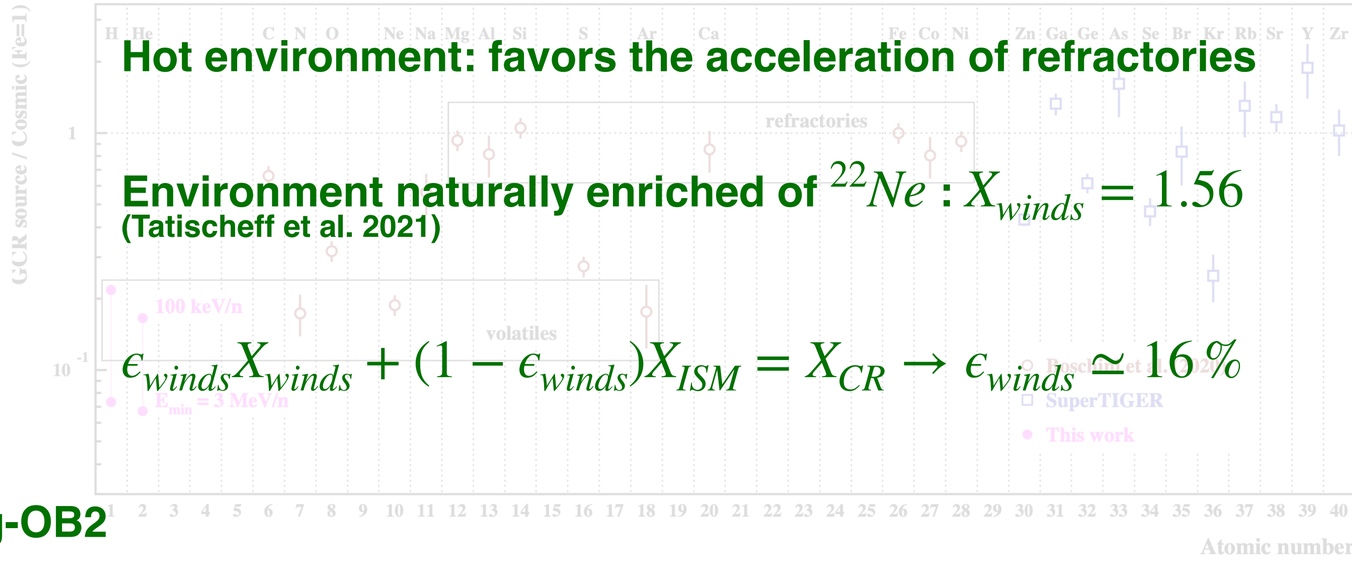
Vieu&Reville 2022

Isotopic ratio

$$X = \frac{^{22}Ne}{^{20}Ne} \qquad X_{CR} \simeq 0.317 \qquad X_{ISM} \simeq 0.0735$$

Composition

Tatischeff et al. 2021

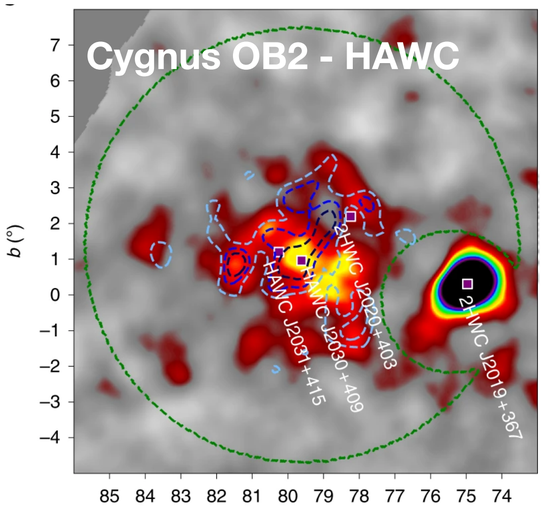


Only convincing hadronic PeVatron in the region of Cyg-OB2

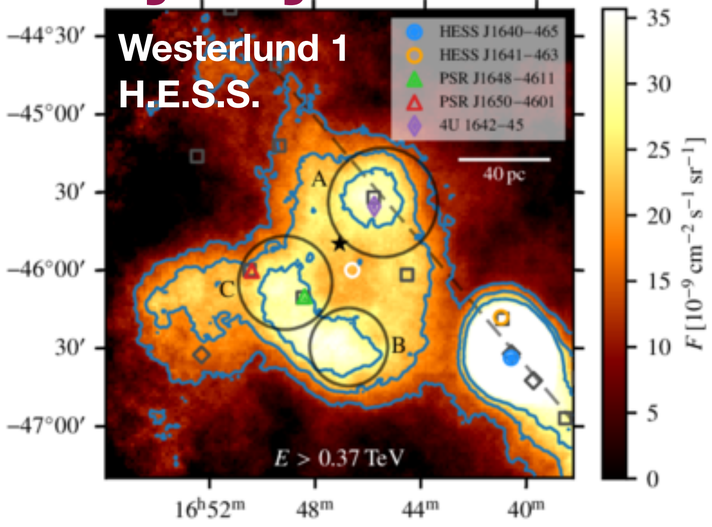
SCs are energetic enough to contribute to CRs ~ 10^{41} erg/s (in total)

Star clusters

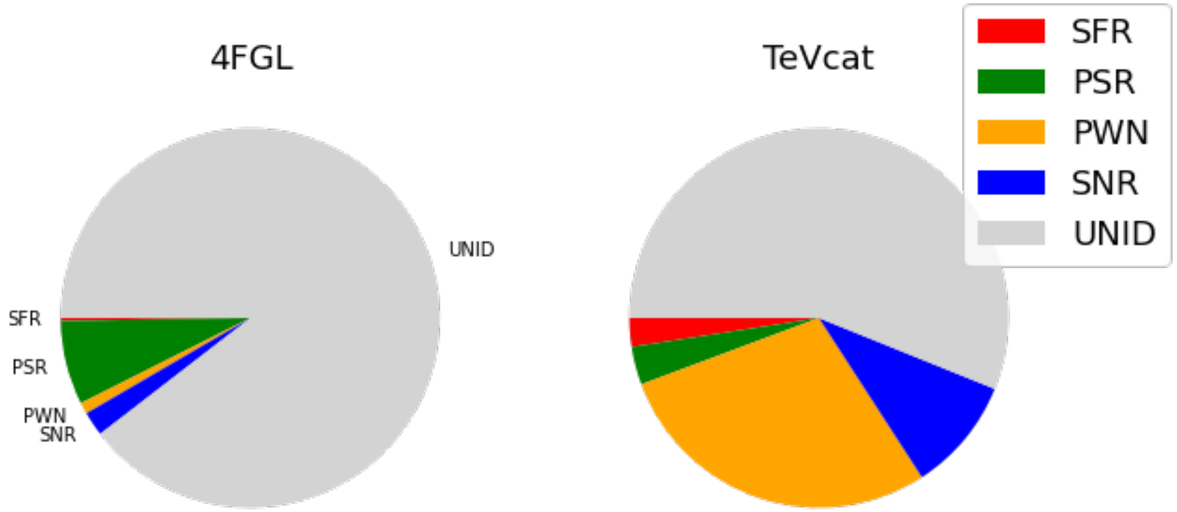
In the gamma-ray sky



Abeysekara et al. 2021

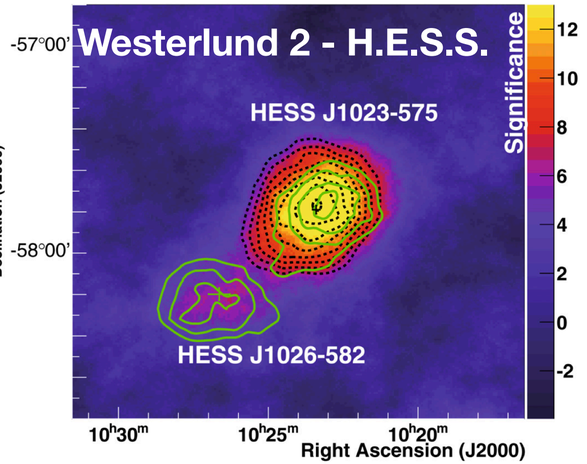


Aharonian et al. 2022

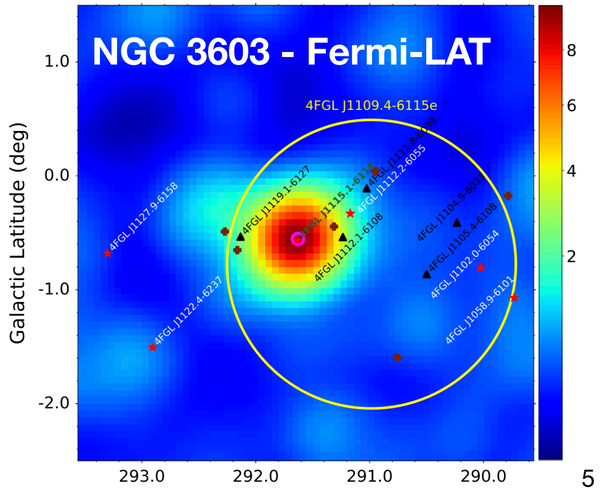


Only a handful of SCs identified in gamma rays

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



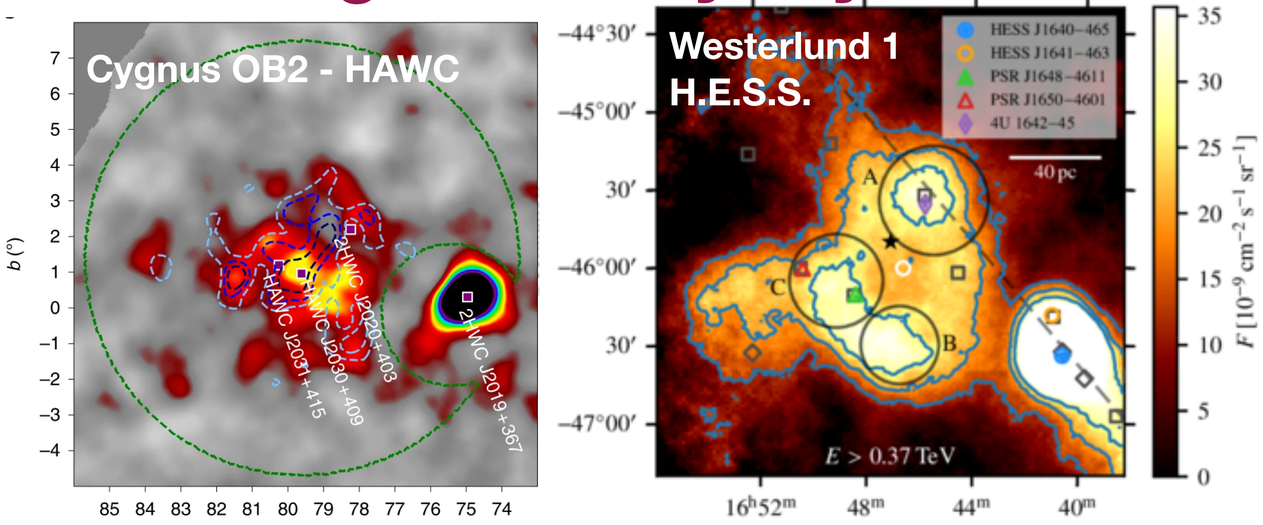
Abramowski et al. 2011



Saha et al. 2022

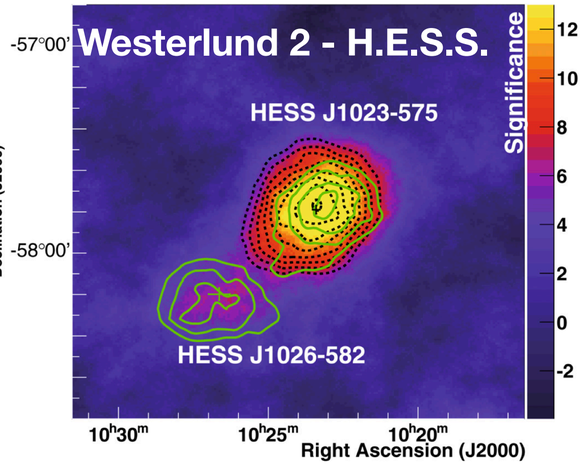
Star clusters

In the gamma-ray sky

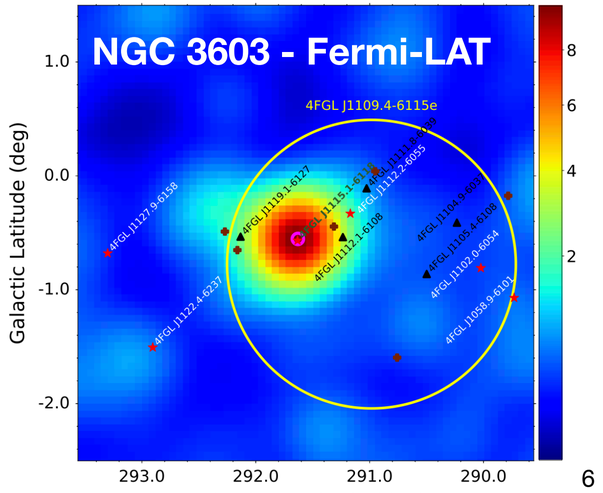


Abeysekara et al. 2021

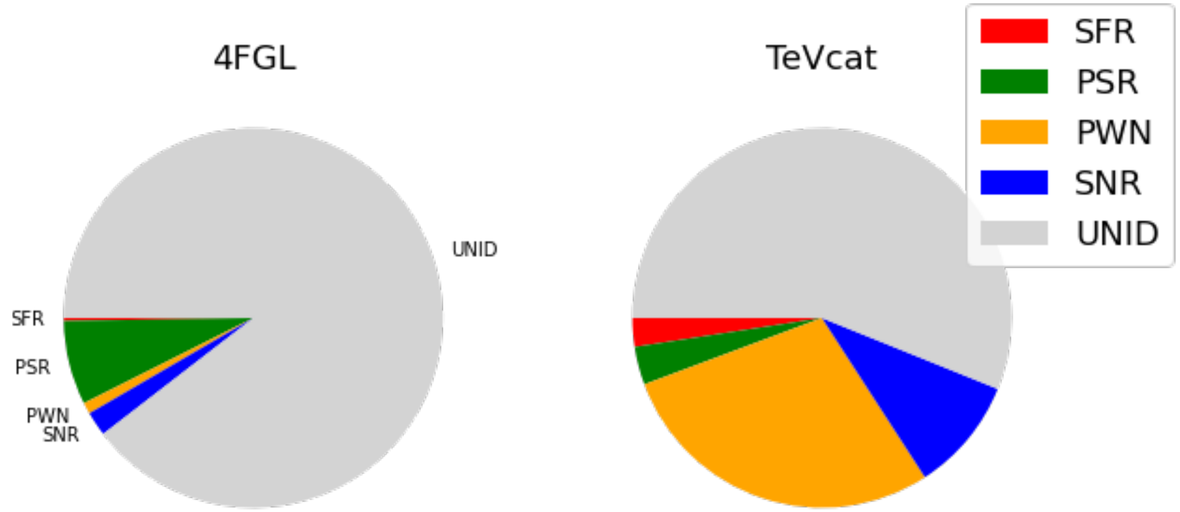
Aharonian et al. 2022



Abramowski et al. 2011



Saha et al. 2022



Only a handful of SCs identified in gamma rays

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

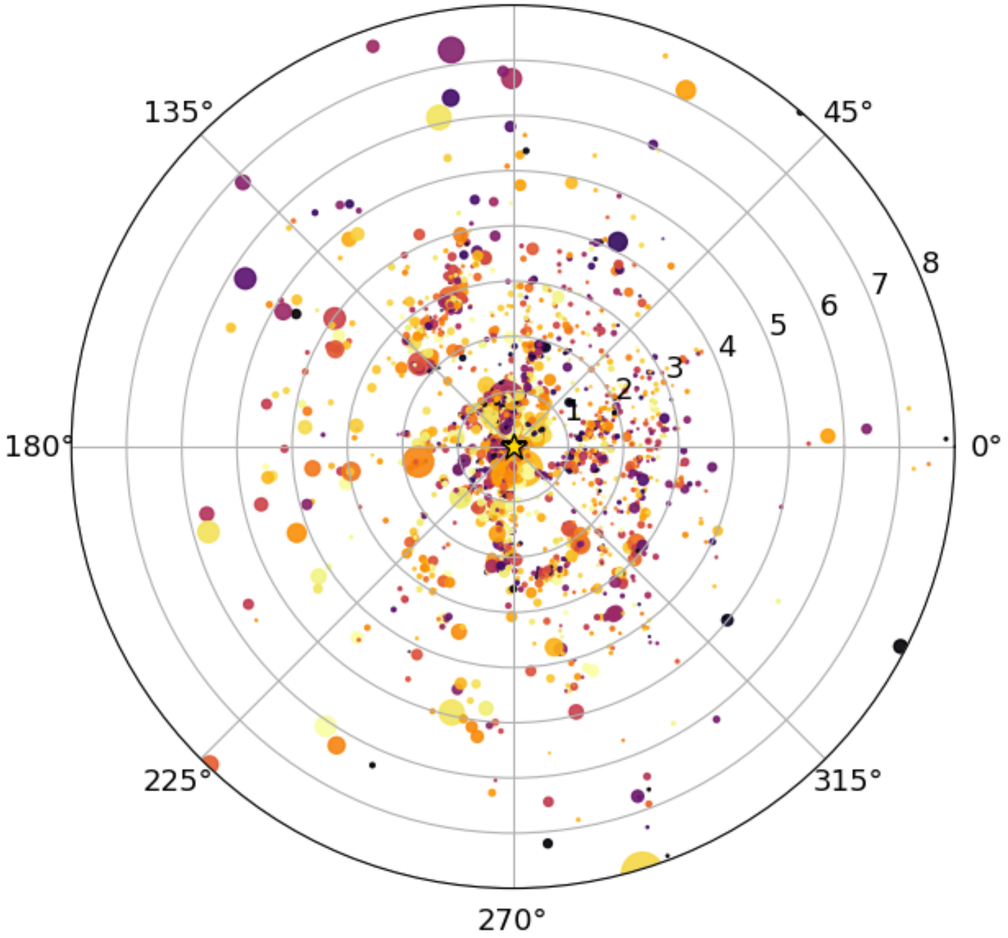
Contributing to the diffuse emission?

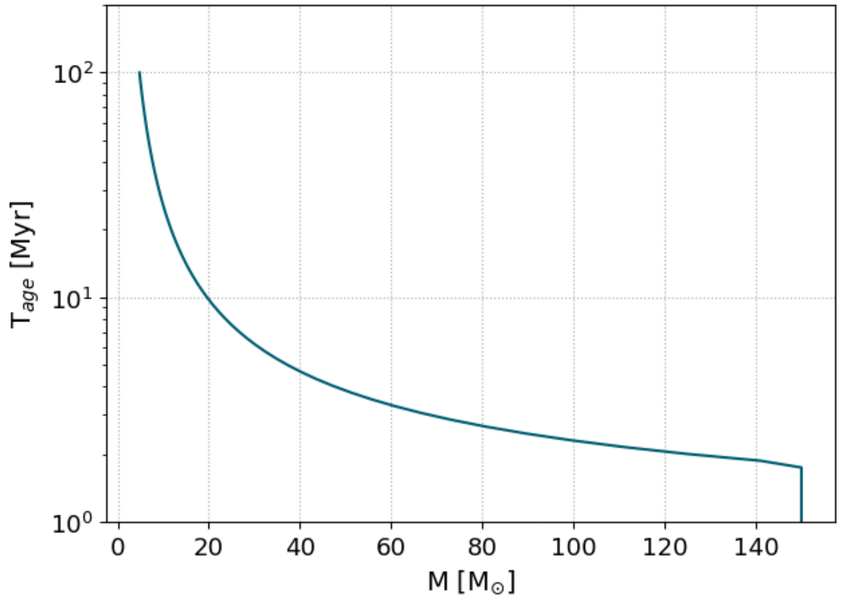
See Menchiari et al. PoS(ICRC2023)649

Star clusters

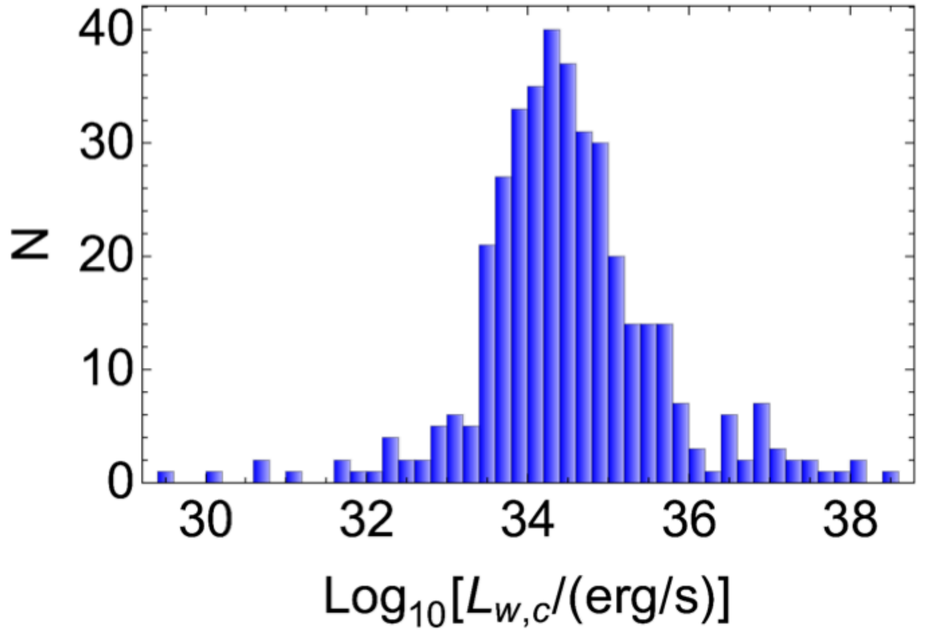
In the Milky Way

SCs from Gaia-DR3 Age < 30 Myr





Celli et al. 2023

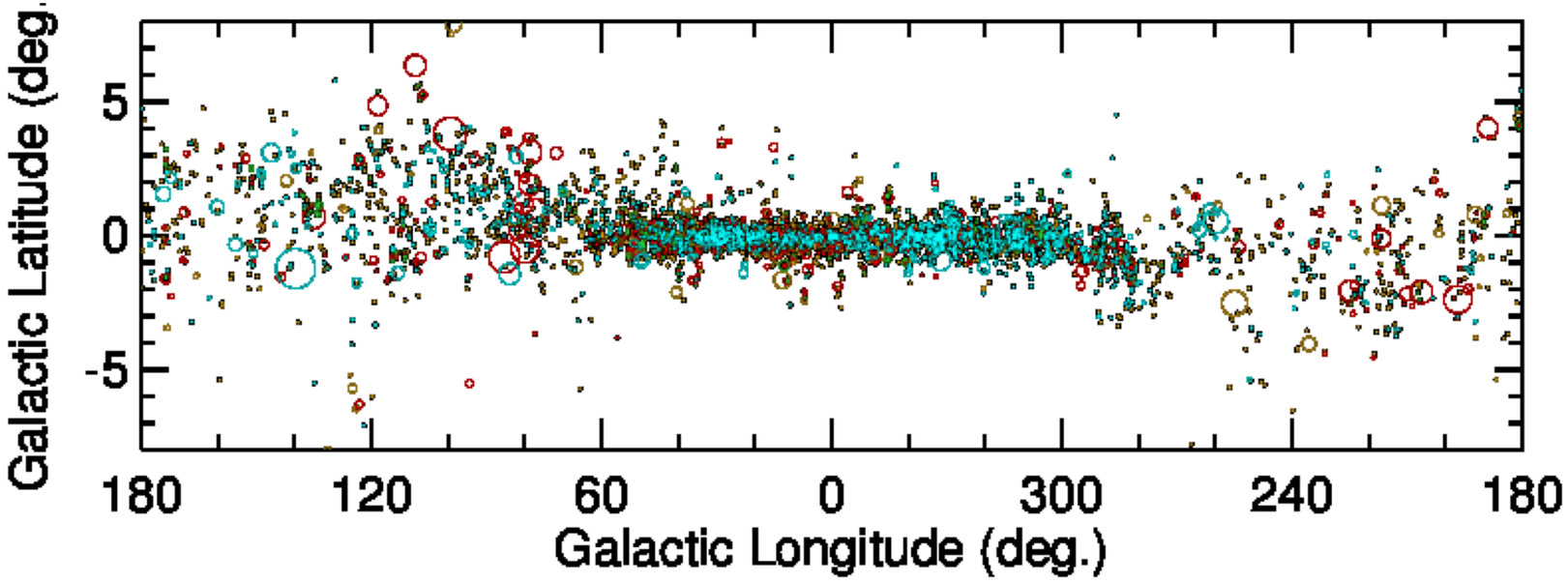


Star clusters

In the Milky Way

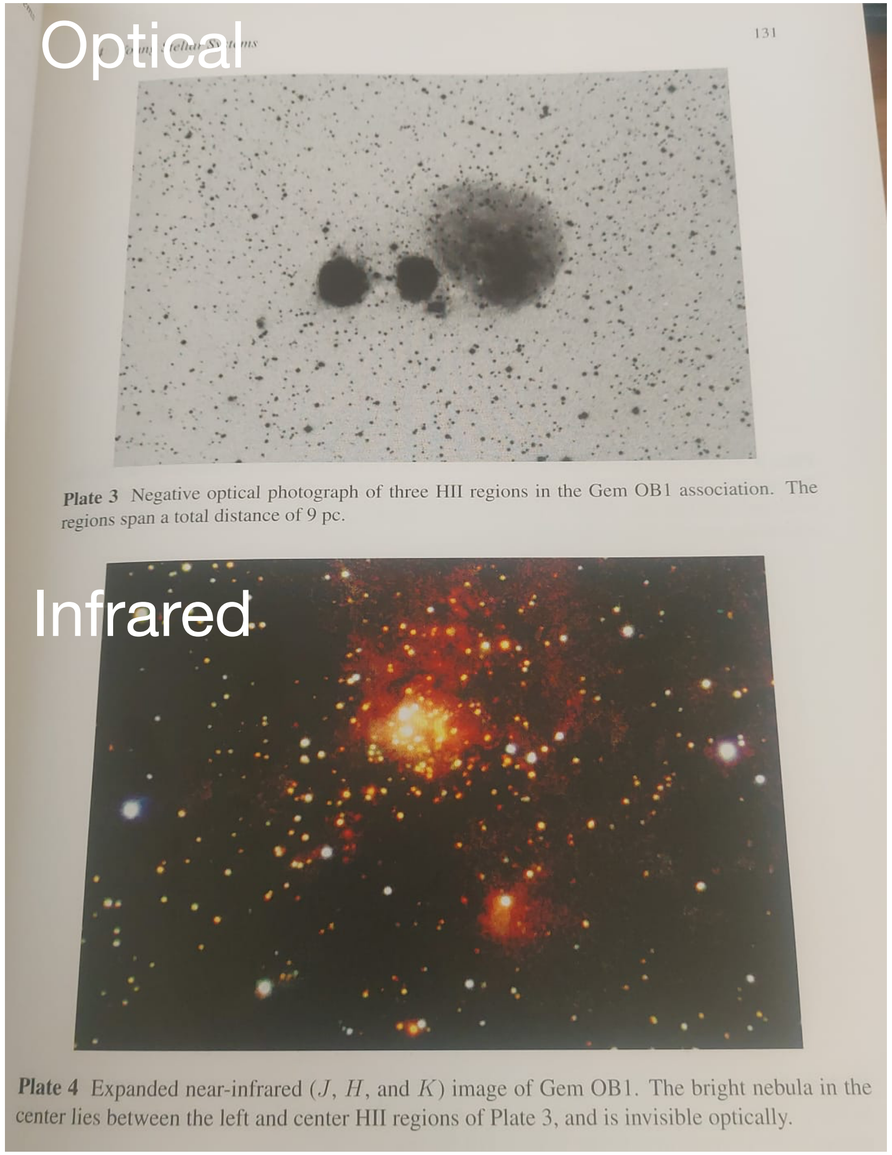
SCs embedded in HII regions Age $\lesssim$ 3 Myr

Anderson et al. 2013



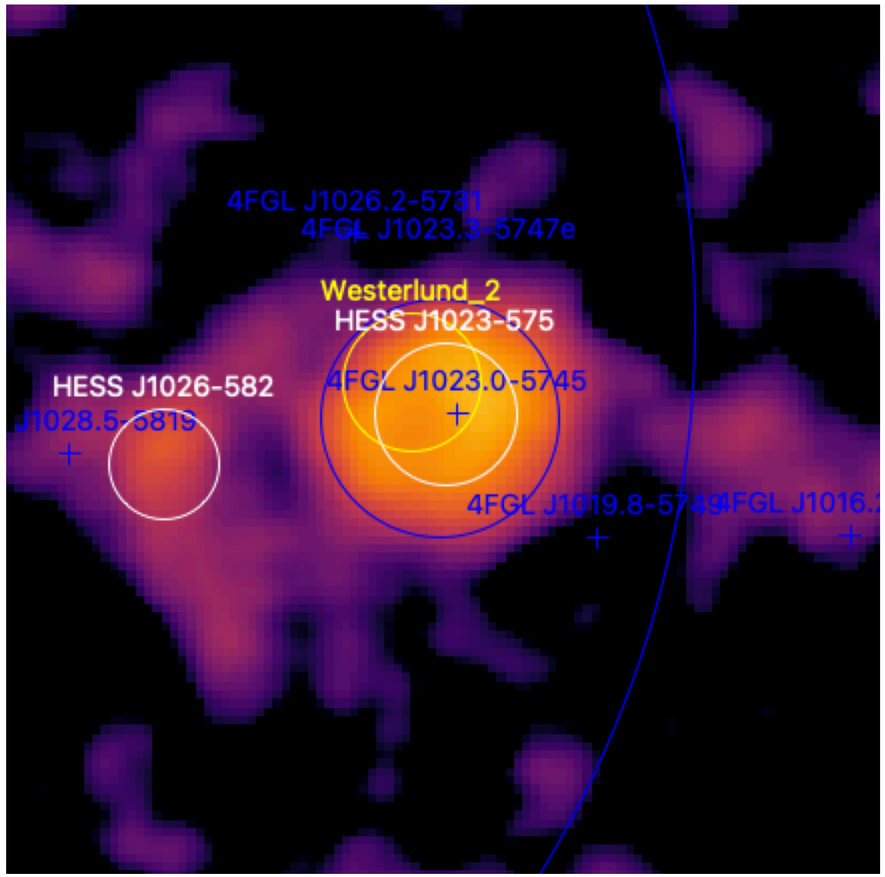
Stahler & Palla 2005

Optical



Star clusters

How many are gamma-ray emitters?



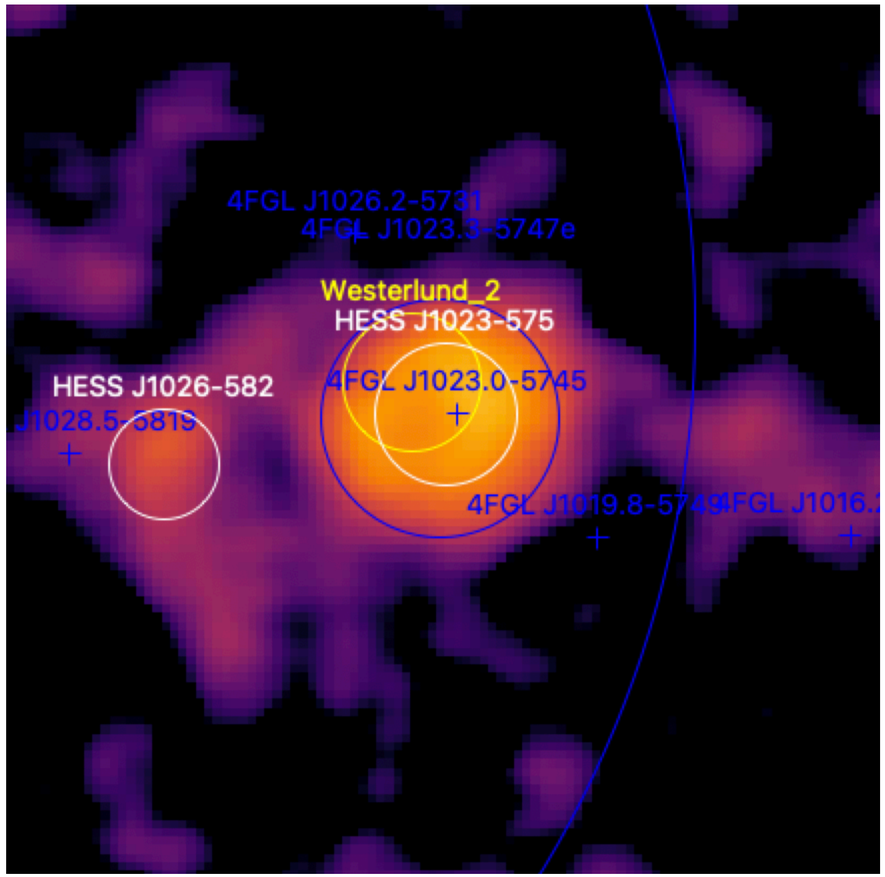
How many overlaps are there between SCs

and gamma-ray sources?

How significant is this overlap?

Star clusters

How many are gamma-ray emitters?



How many overlaps are there between SCs

and gamma-ray sources? —> we cross-match SC

(Gaia and WISE) catalogs to gamma-ray catalogs

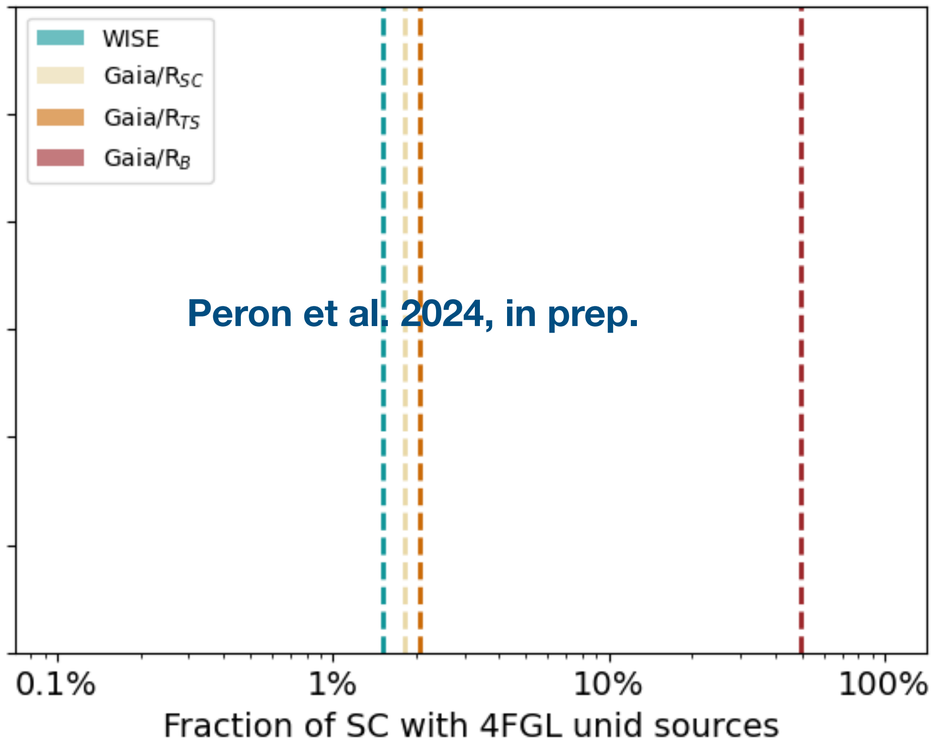
How significant is this overlap? —> we compare the results

with simulations to assess the matching significance

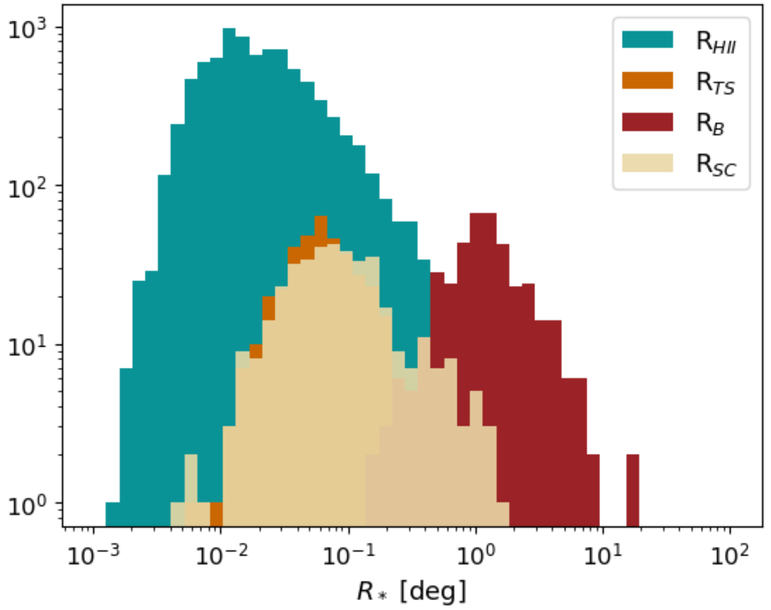
Star clusters

Matching with gamma-ray sources

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



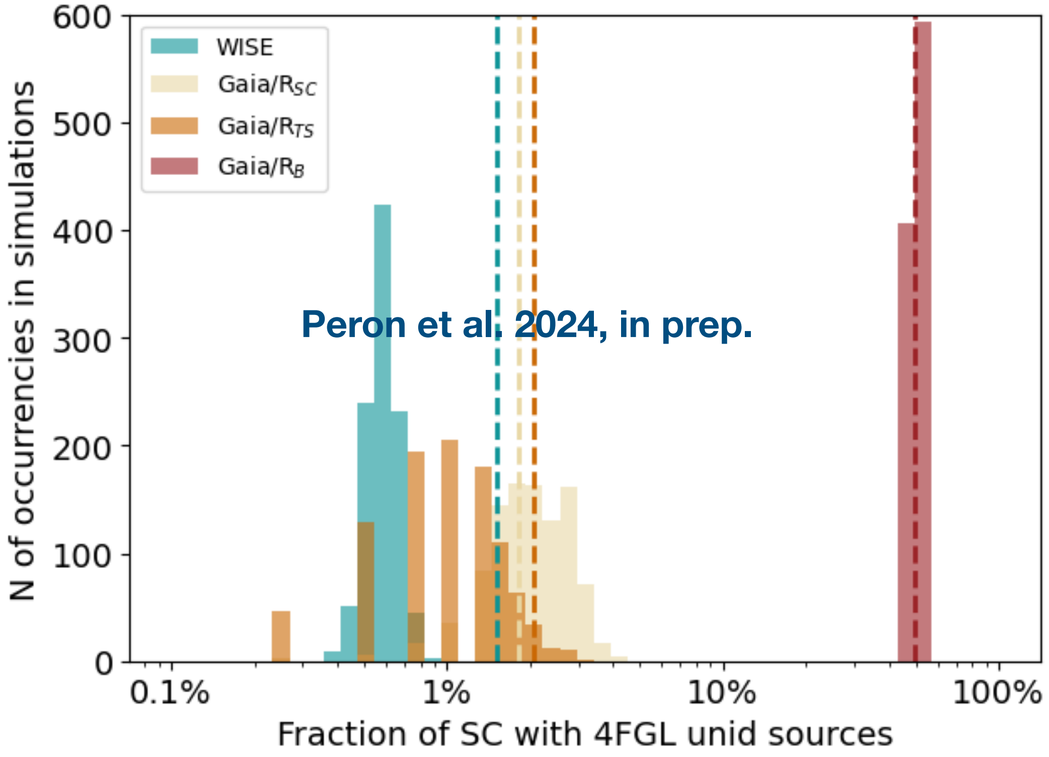
R of the HII region
R of the SCs (50% of stars)
R of the termination shock
R of the bubble



Star clusters

Matching with gamma-ray sources

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



Compared to simulations of 1000 synthetic catalogs (from MC simulations)

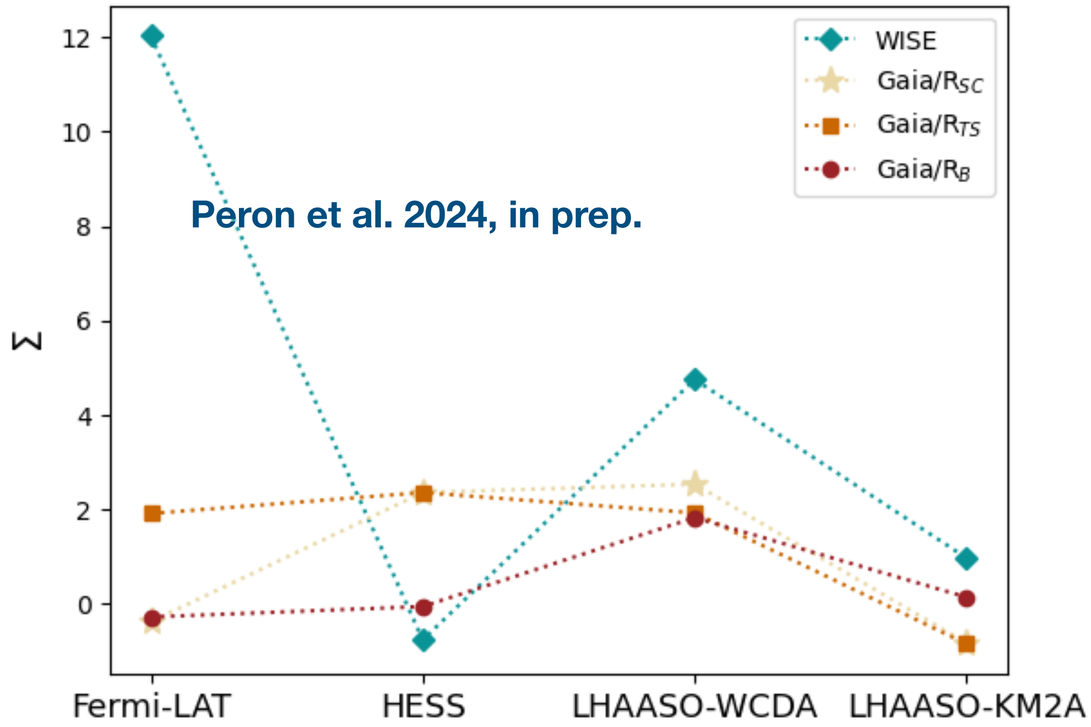
To evaluate matching significance:

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

Star clusters

Matching with gamma-ray sources

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



Compared to simulations of 1000 synthetic catalogs (from MC simulations)

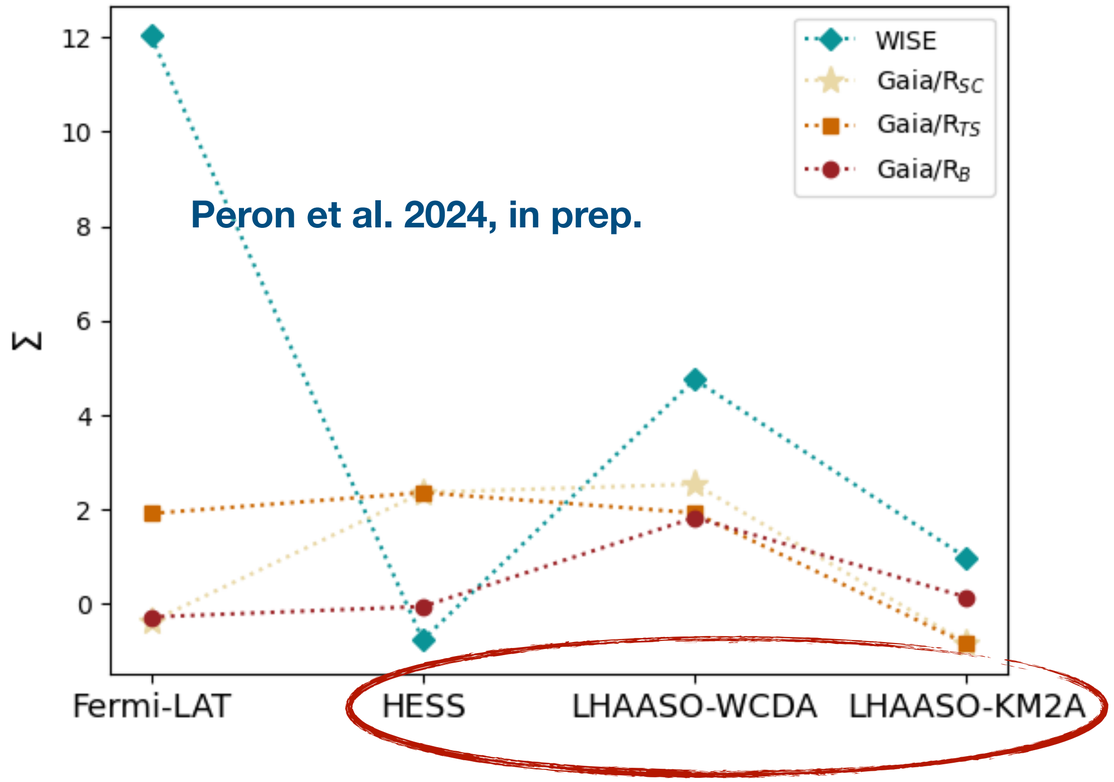
To evaluate matching significance:

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

Star clusters

Matching with gamma-ray sources

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



Compared to simulations of 1000 synthetic catalogs (from MC simulations)

To evaluate matching significance:

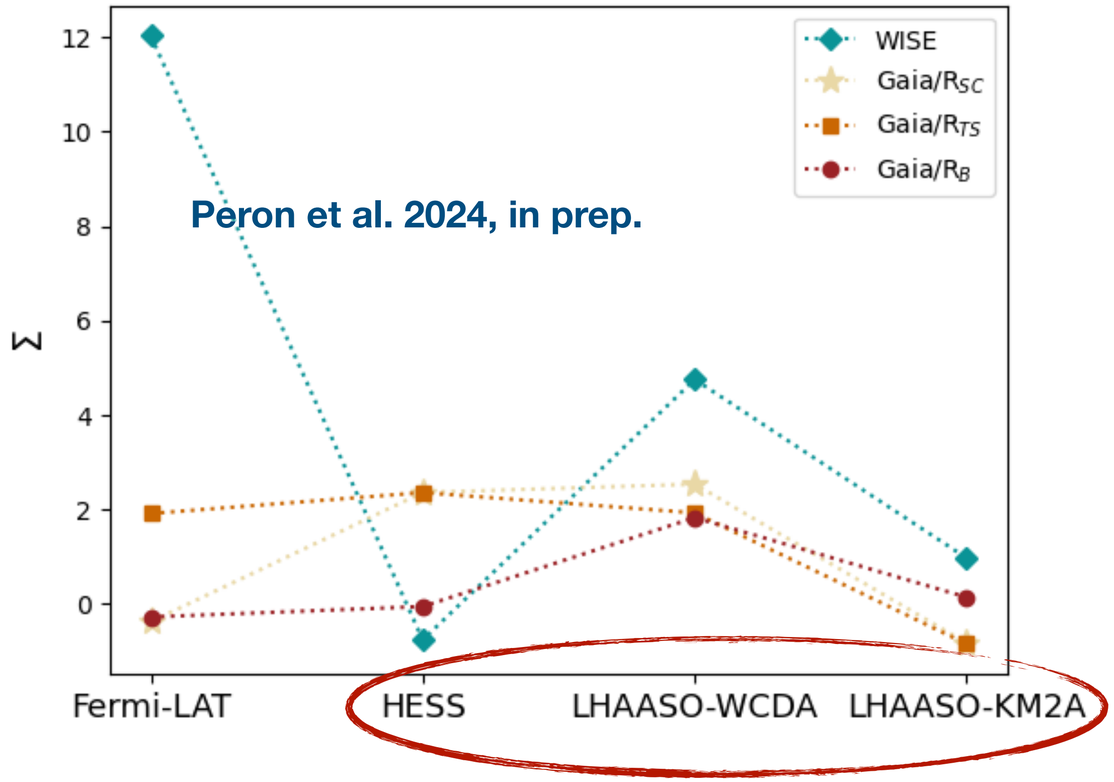
$$\Sigma = \frac{N_{match}^{real} - < N_{match}^{sim} >}{\sigma(N_{match}^{sim})}$$

> Extended and more concentrated on the Galactic Plane therefore more affected by chance coincidence

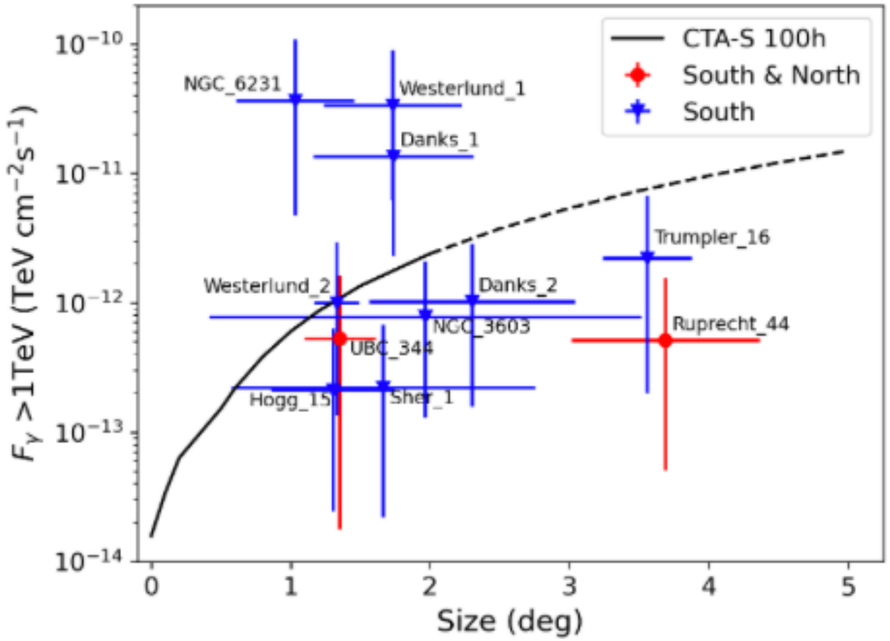
Star clusters

Matching with gamma-ray sources

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



Mitchell et al. 2024, arXiv:2403.16650v1

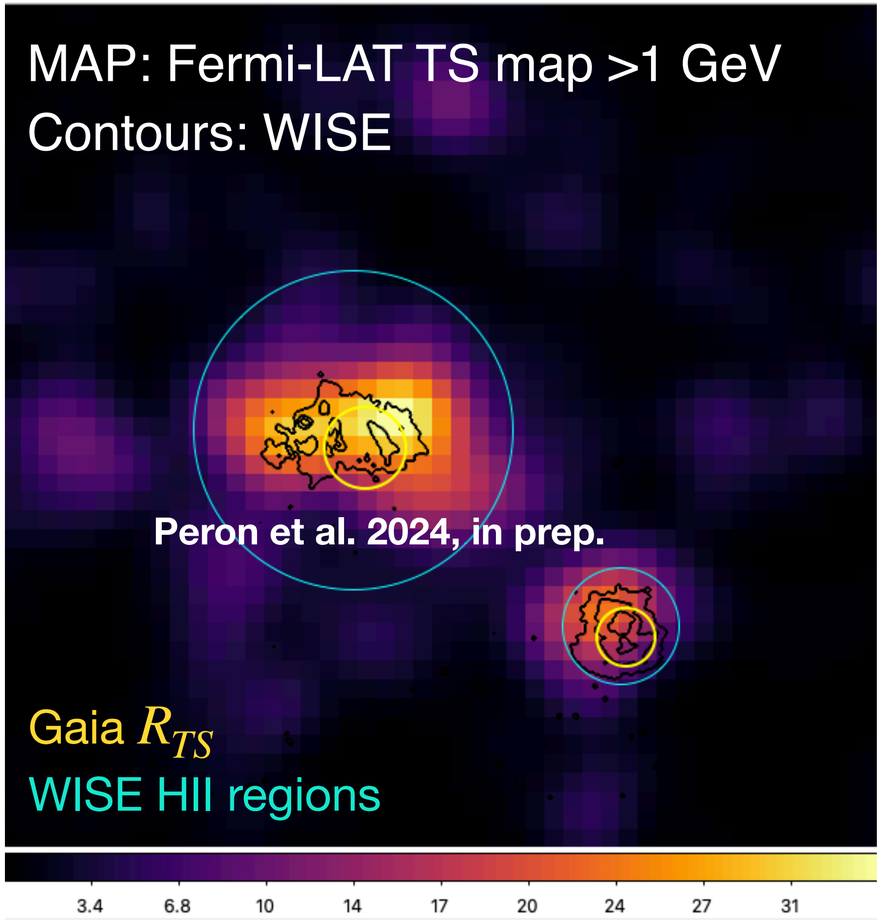


> Extended and more concentrated on the Galactic Plane therefore more affected by chance coincidence

> Harder to be detected [see Celli & Peron 2024 arXiv:2403.03731]

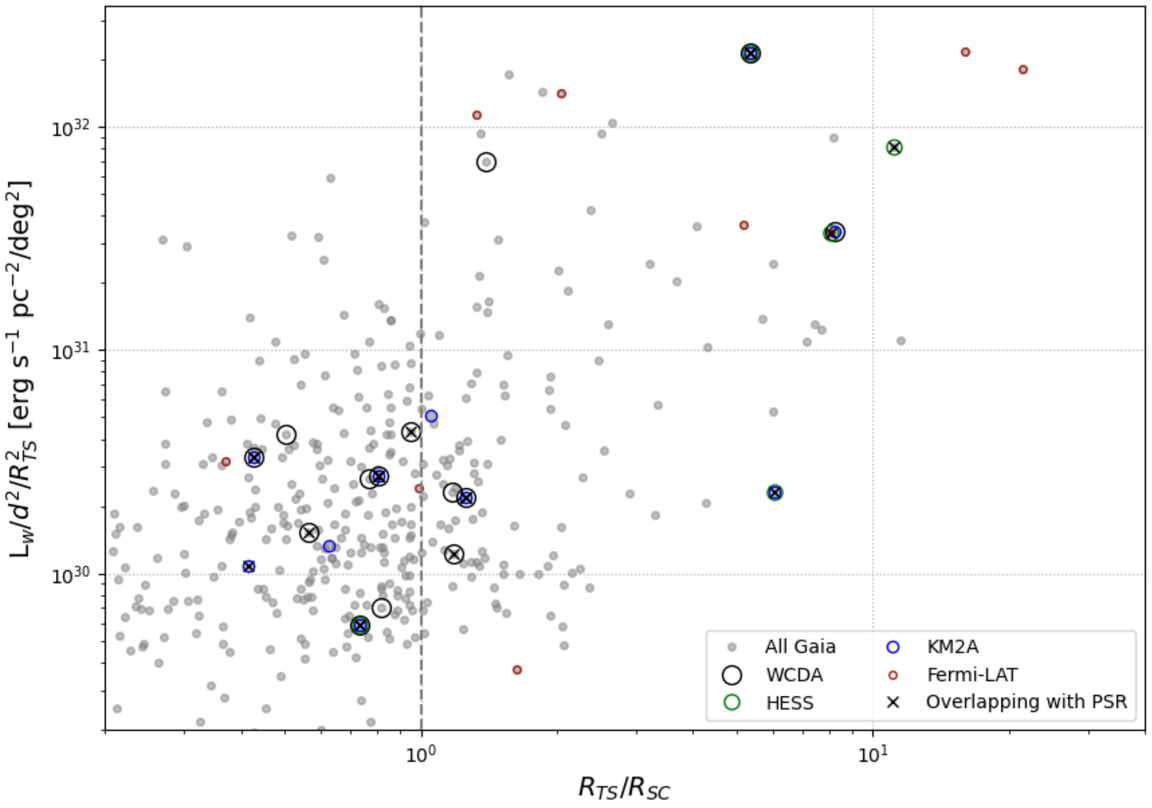
Star clusters

Detected in gamma rays



The brightest SCs have detectable Fermi-LAT emission coincident with the HII gas regions

At TeV-energies the situation is more complicated by large extensions and overlap with PSRs



Star clusters

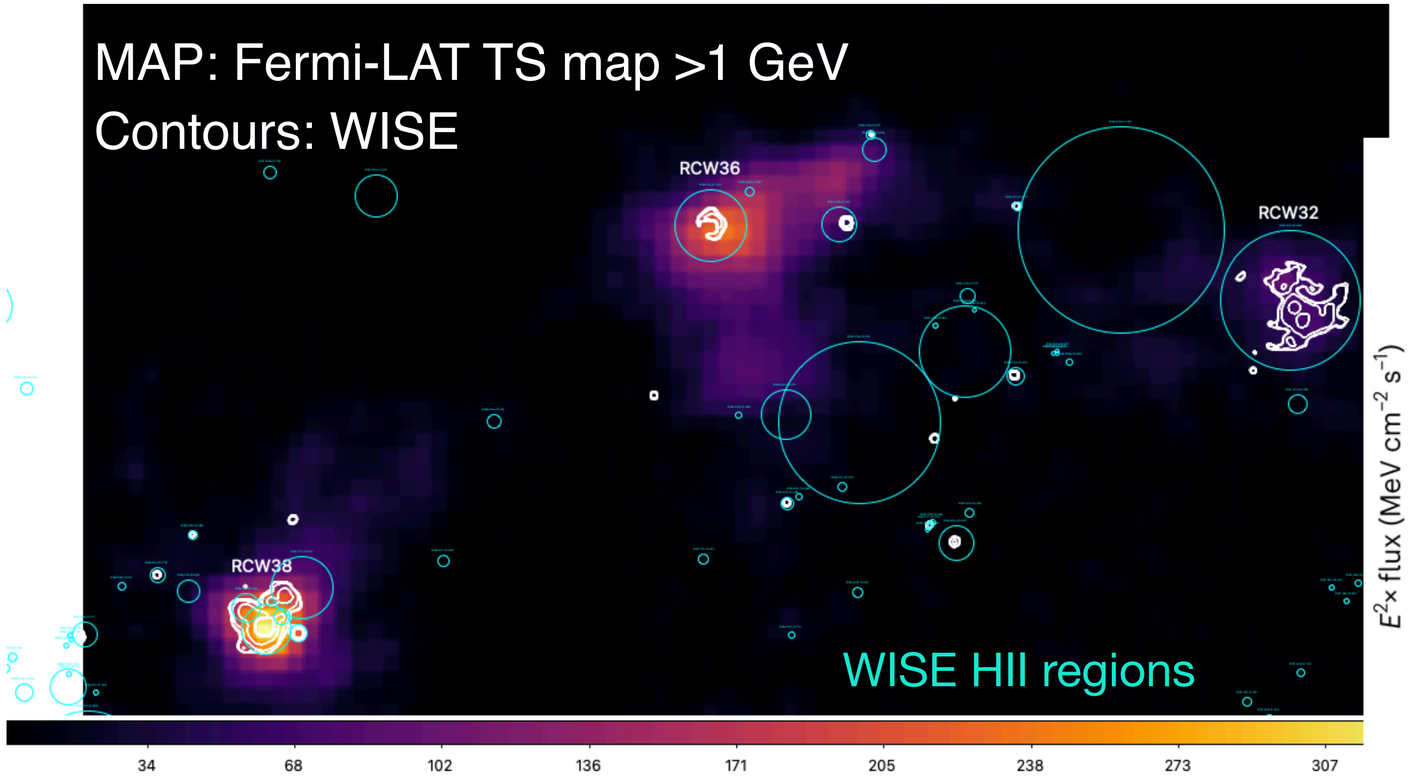
In the Vela Molecular cloud Ridge

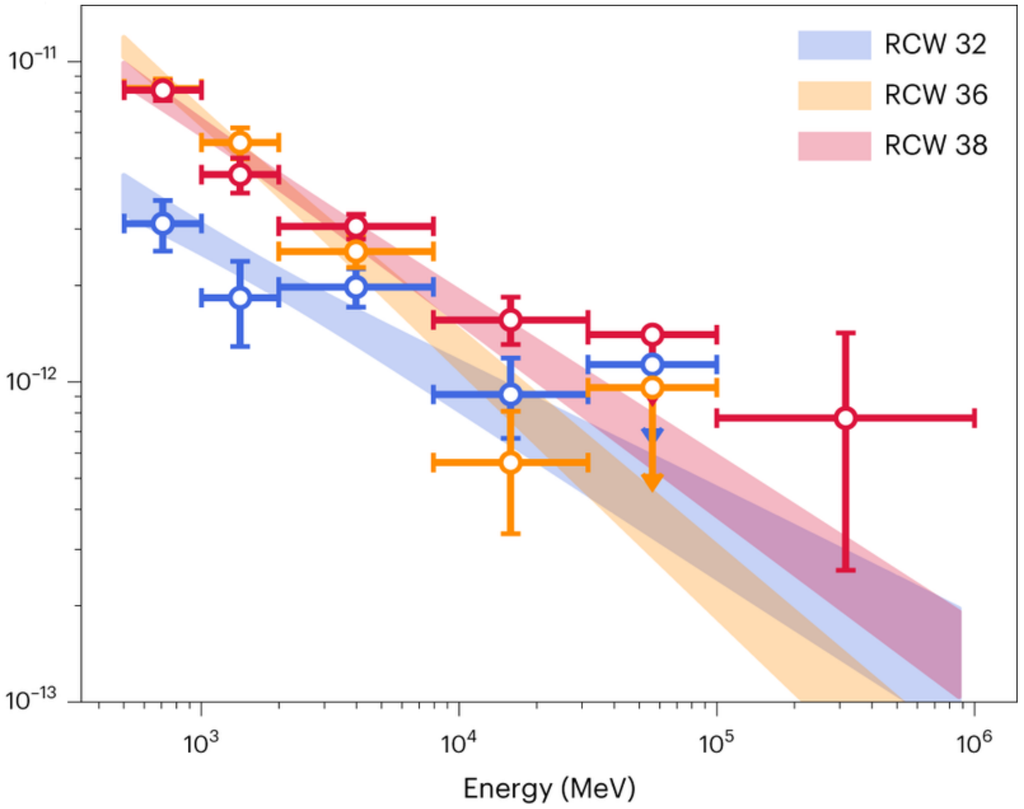
Star forming complex at ~1-2 kpc

Evidence of excess in 3 HII regions

SC of Age ~ 1 Myr —> No Supernovae

Embedded in dense medium ~ 1000 cm^{-3}



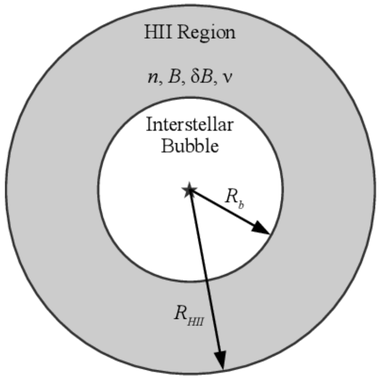


Stellar winds accelerate particles!

Star clusters

Acceleration efficiency

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



We derive L_{CR} from L_γ 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

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

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

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

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

$\delta = 0.3$

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

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

➡ Diffusion is suppressed but not enough to retain particles

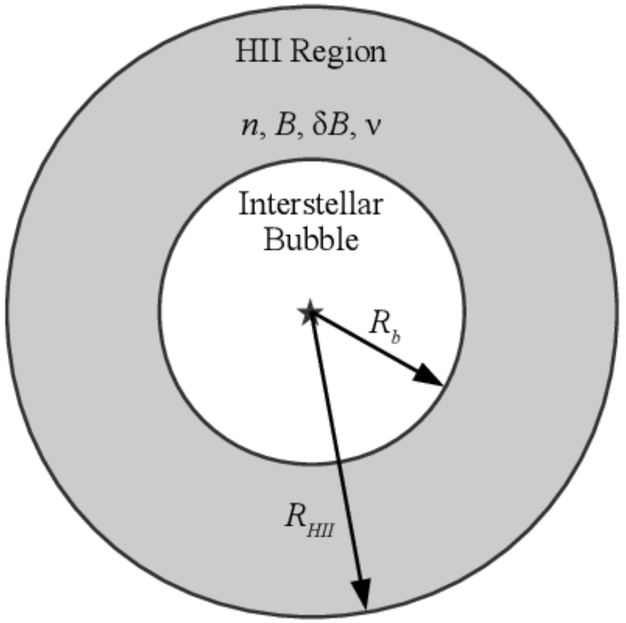
$L_{CR}[measured] << L_{CR}[real]$

Star clusters

Acceleration efficiency

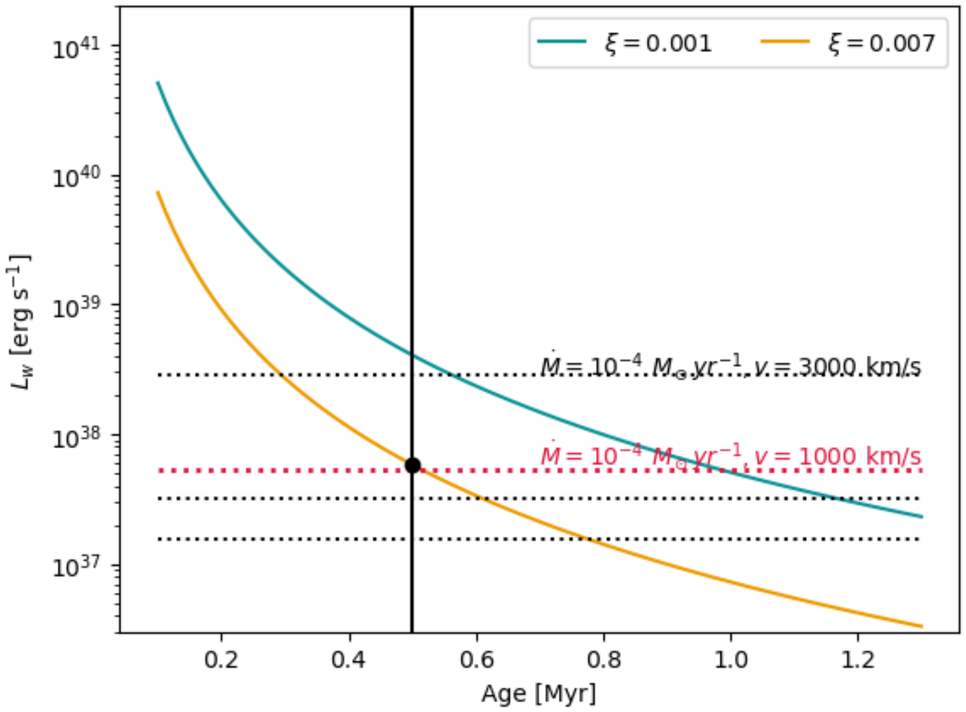
$$\eta = \frac{L_{CR}}{L_w}$$

Maurin et al. 2016



Weaver et al. 1977

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



Canto' et al. 2000 [Simulations]

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

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

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

Star clusters

Acceleration efficiency

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

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

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

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

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

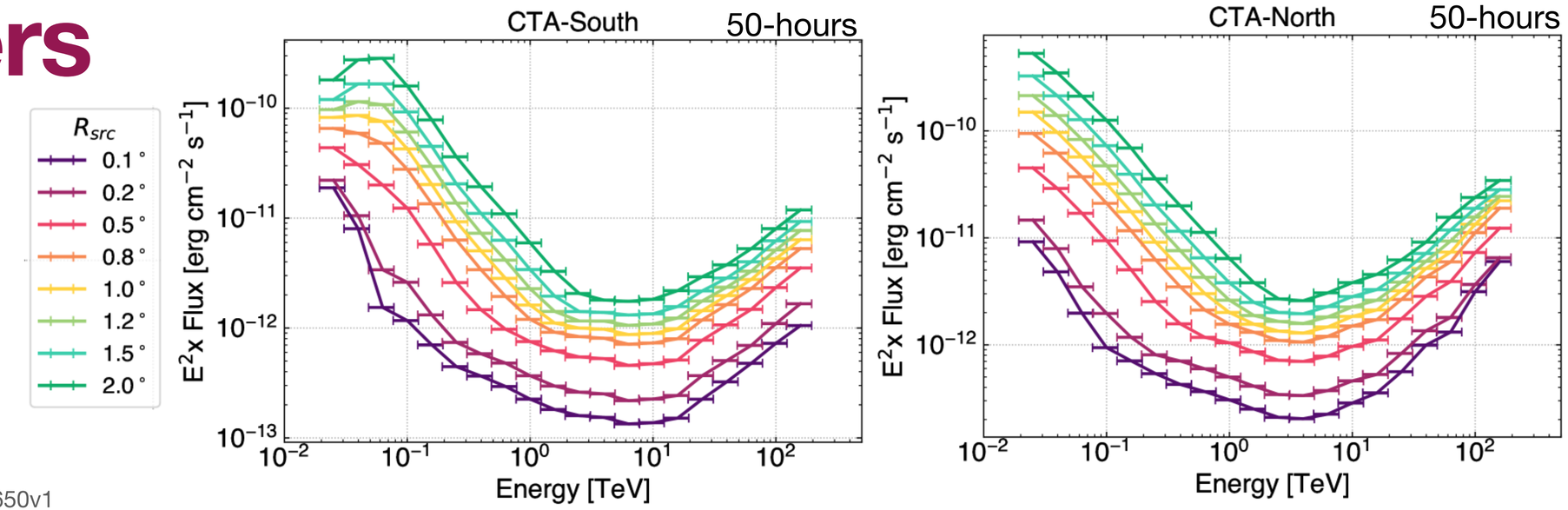
From isotopic ratio:

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

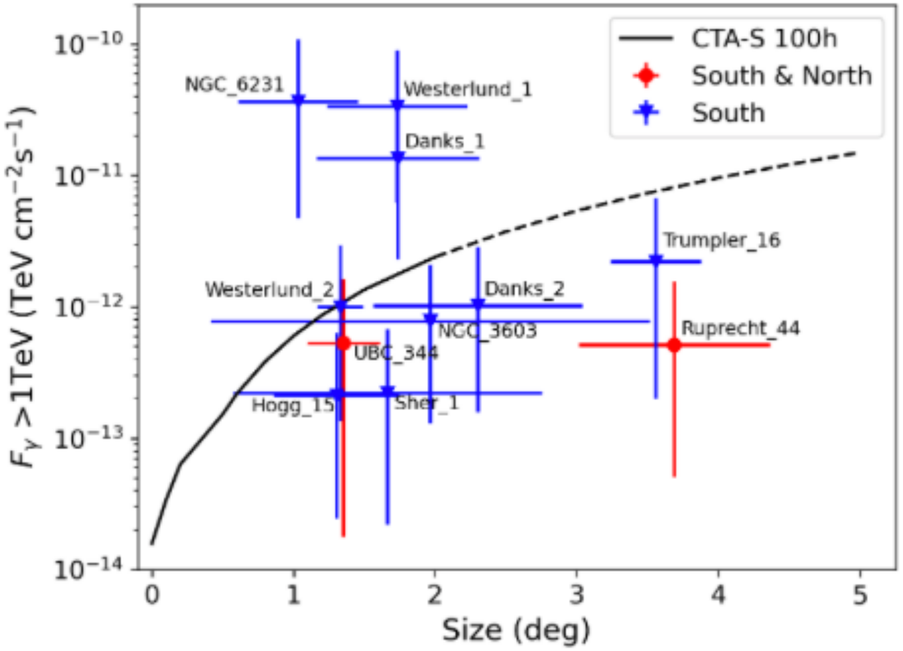
Star clusters

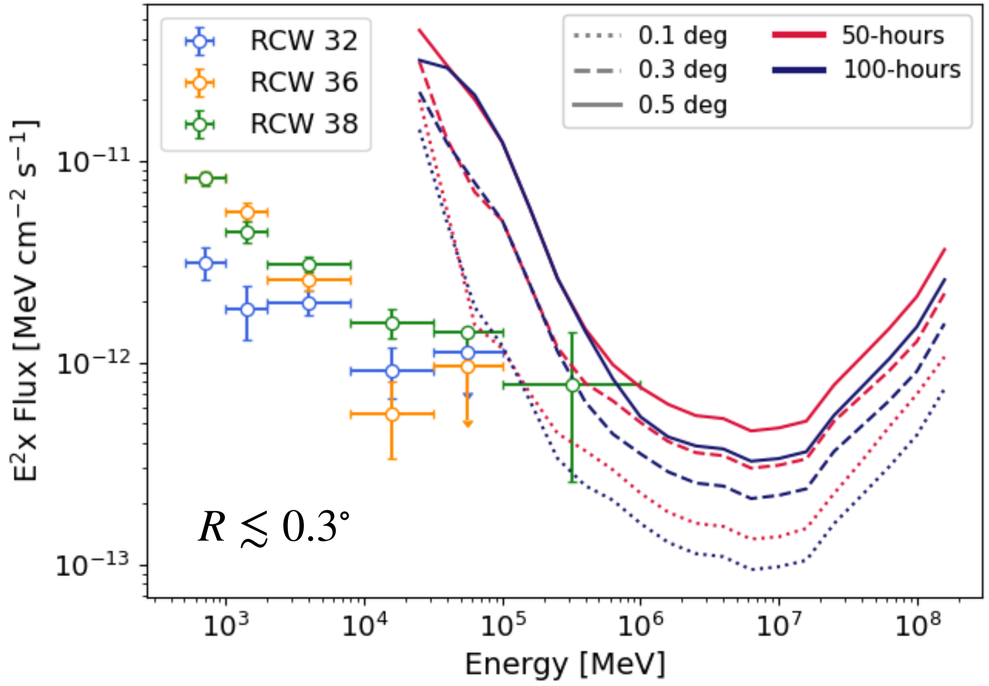
The role of CTA

Celli & Peron 2024 arXiv:2403.03731v1



Mitchell et al. 2024, arXiv:2403.16650v1





Conclusions

- We detected GeV gamma-ray emission in correspondence of a few **embedded star clusters**;
- We showed that the coincidence is statistically significant and is interpreted as a consequence of the enhanced target around these regions;
- Embedded clusters are **young** therefore they are not influenced by SN explosions;
- The derived efficiency suggests that a small **part of galactic cosmic rays is contributed by stellar winds**, consistently with the estimate based on composition;
- The real **efficiency is larger** as it should account also for escaped particles;
- More observations will come to help constraining these values and to shed light on the TeV energy band.

Conclusions

- We detected GeV gamma-ray emission in correspondence of a few **embedded star clusters**;
- We showed that the coincidence is statistically significant and is interpreted as a consequence of the enhanced target around these regions;
- Embedded clusters are **young** therefore they are not influenced by SN explosions;
- The derived efficiency suggests that a small **part of galactic cosmic rays is contributed by stellar winds**, consistently with the estimate based on composition;
- The real **efficiency is larger** as it should account also for escaped particles;
- More observations will come to help constraining these values and to shed light on the TeV energy band.

Grazie