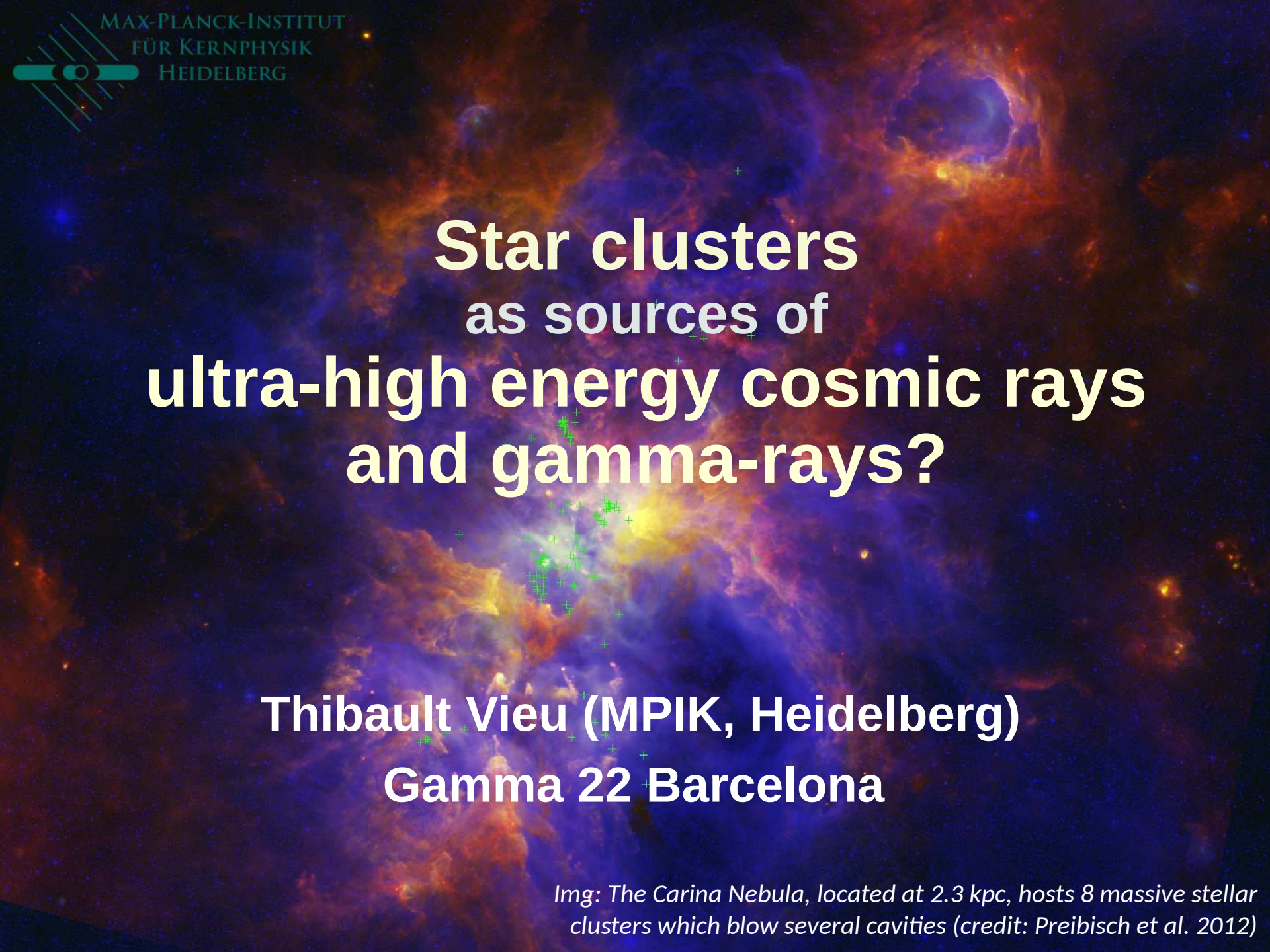


Star clusters
as sources of
ultra-high energy cosmic rays and gamma-rays?

Thibault Vieu (MPIK, Heidelberg)

Gamma 22 Barcelona

Img: The Carina Nebula, located at 2.3 kpc, hosts 8 massive stellar clusters which blow several cavities (credit: Preibisch et al. 2012)

UHE photons : where do they come from ?

→ > 100s TeV

Article | Published: 17 May 2021

Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

Zhen Cao, F. A. Aharonian, ... X. Zuo + Show authors

Nature **594**, 33–36 (2021) | Cite this article

From Cygnus-X star forming region / OB2 association of massive stars

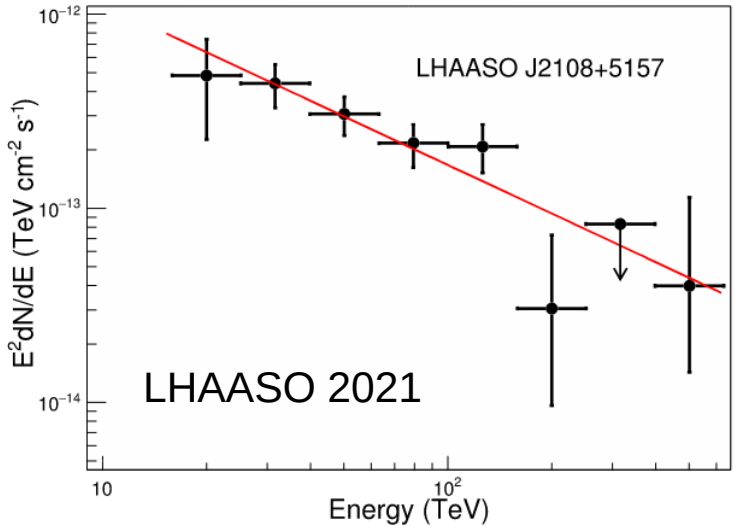
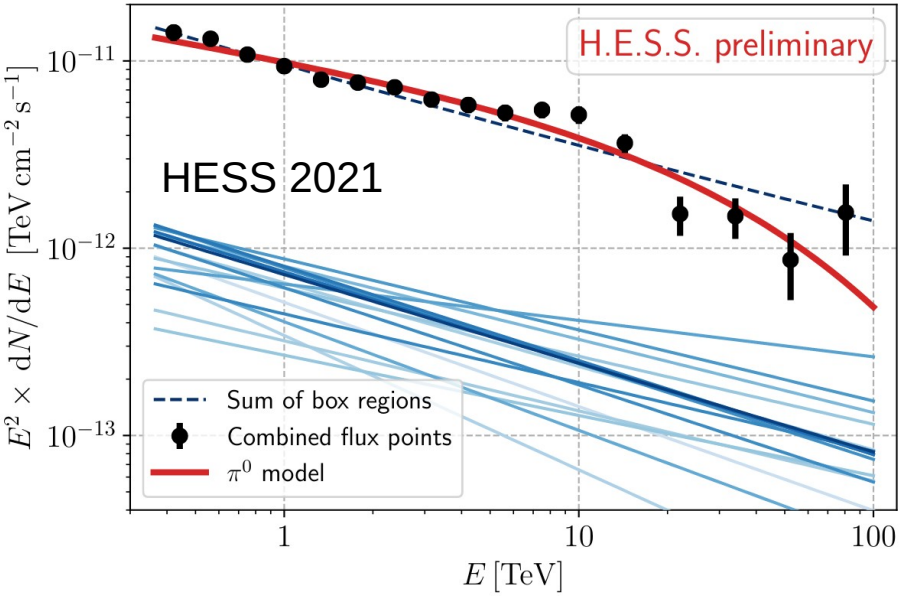


Figure 3. The SED of LHAASO J2108+5157. The solid red line shows the best-fit power-law function.

Unknown source, but correlated with a giant MC



From Westerlund 1, one of the most powerful young compact massive star cluster

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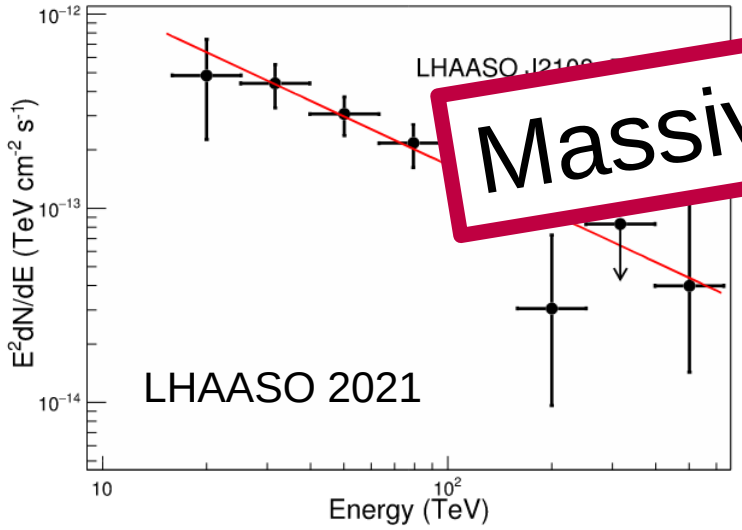
Massive star clusters?



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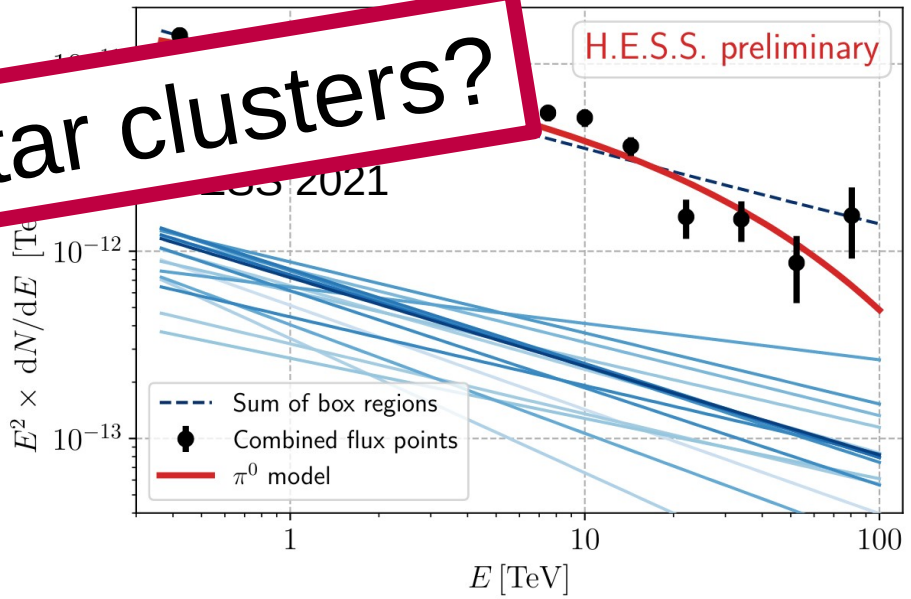

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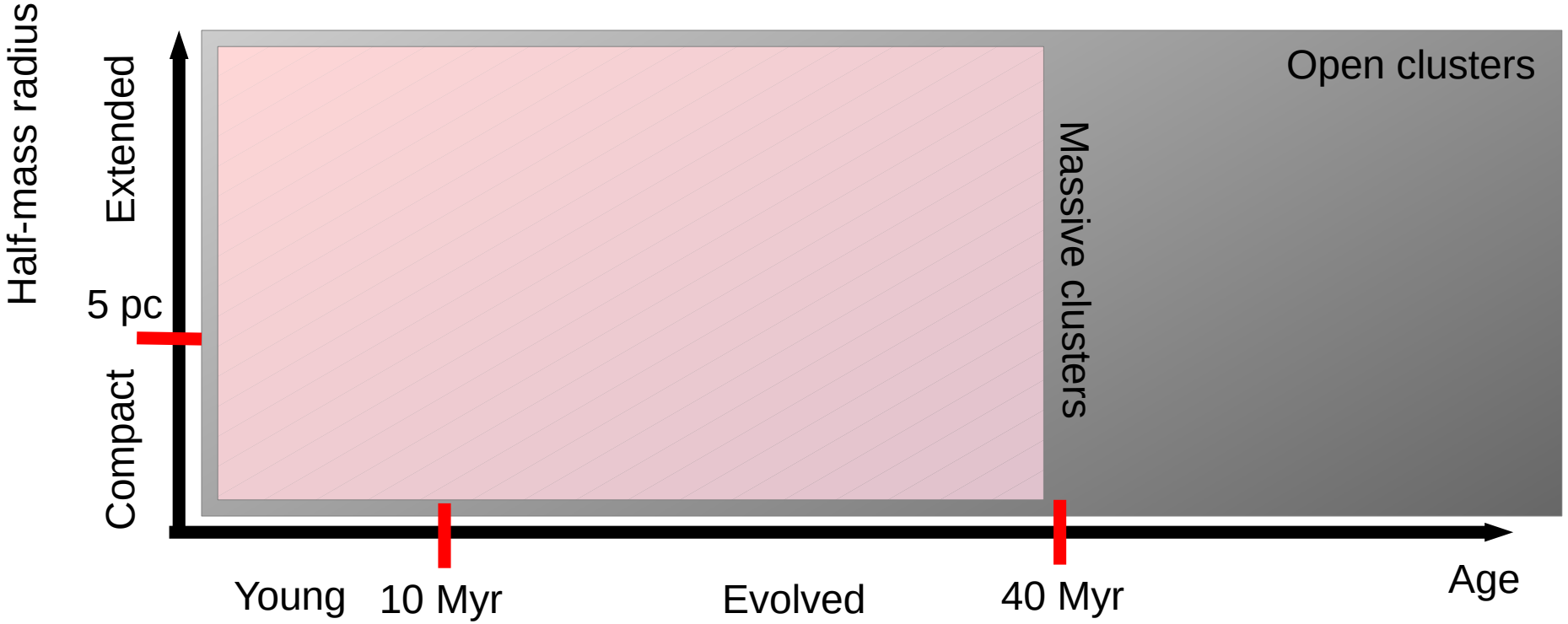
Massive star clusters?

- Terminology:

  Massive star cluster = a bounded group of stars which contains SN progenitors (ZAMS >~ 8 Msol).



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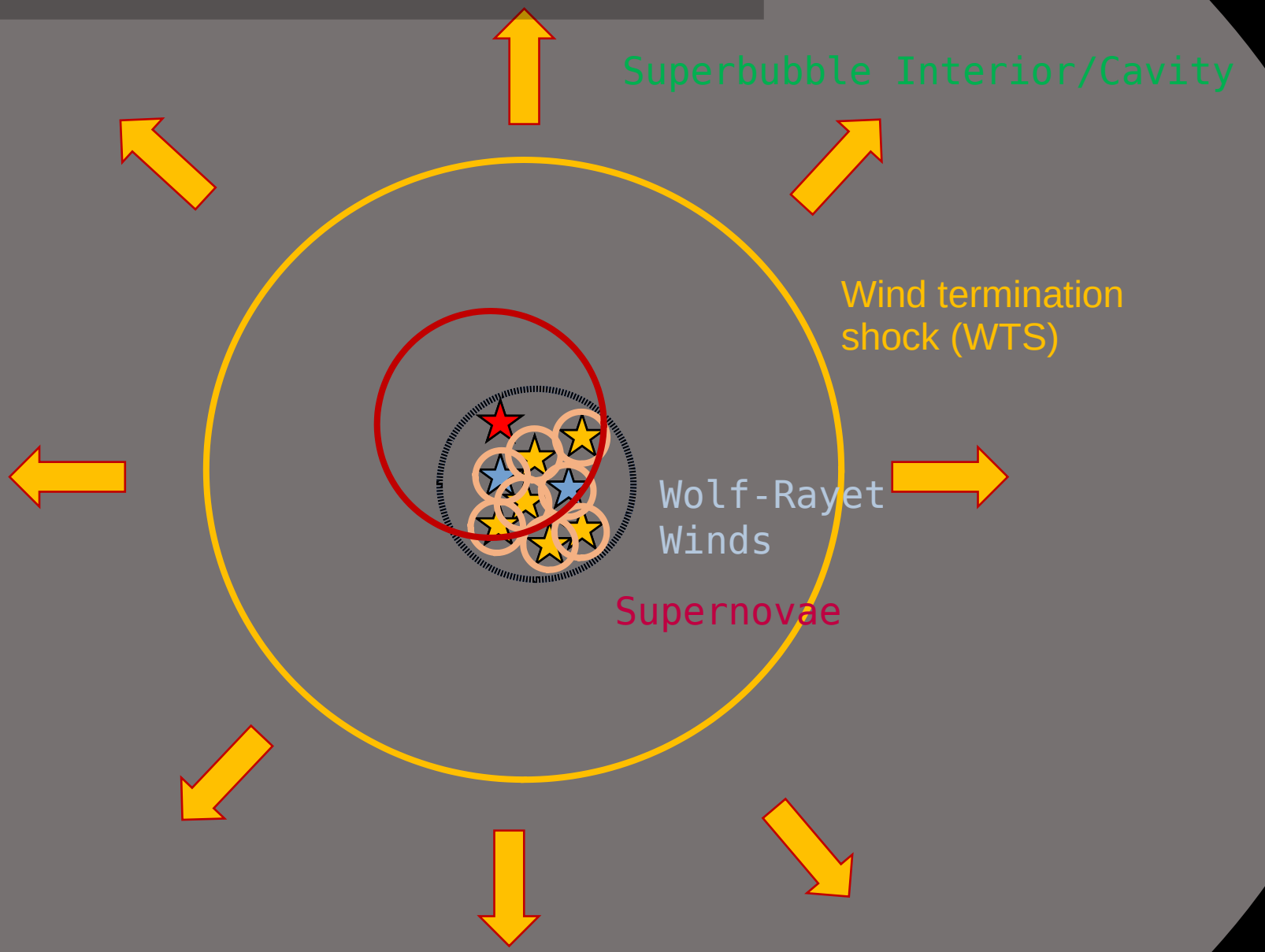
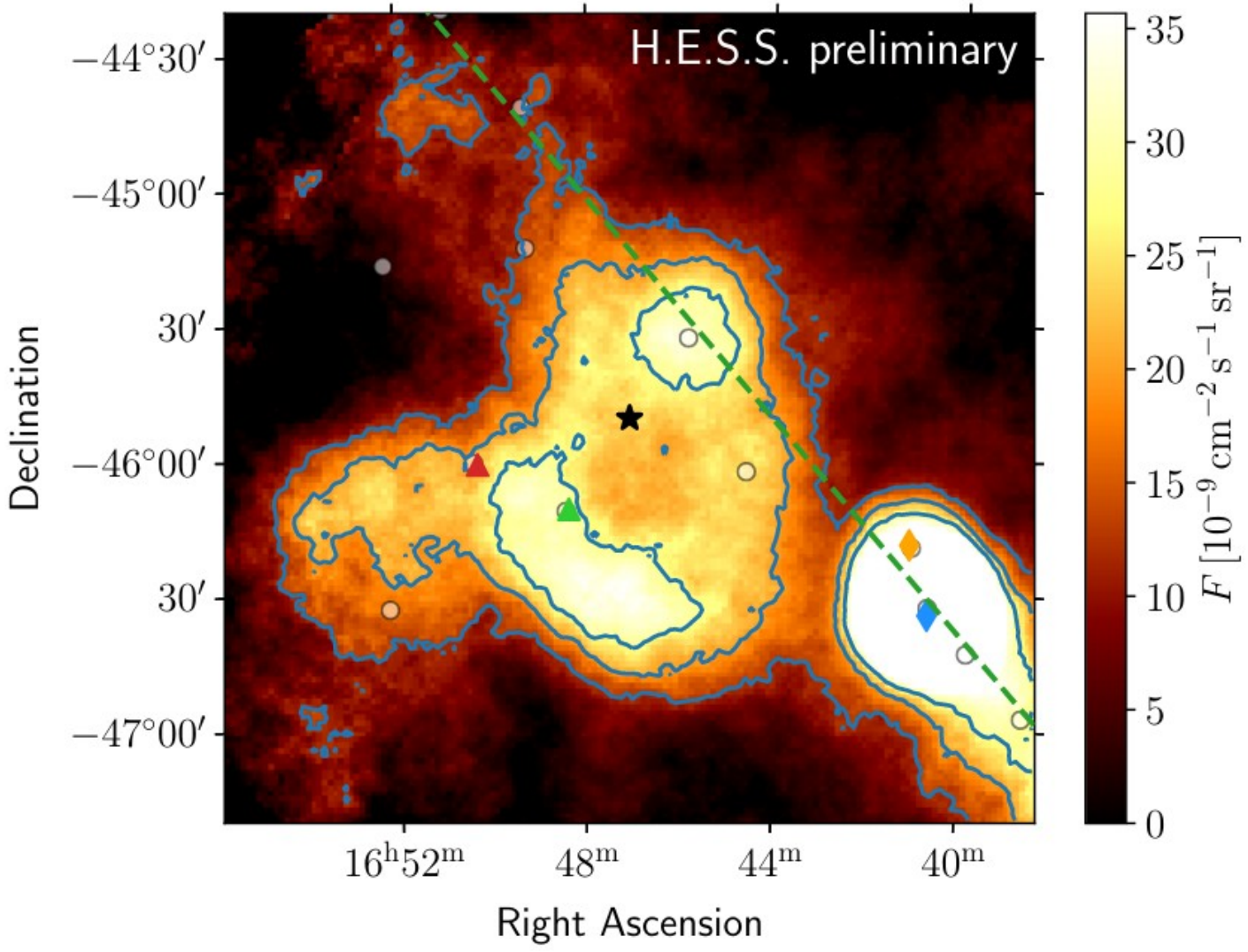
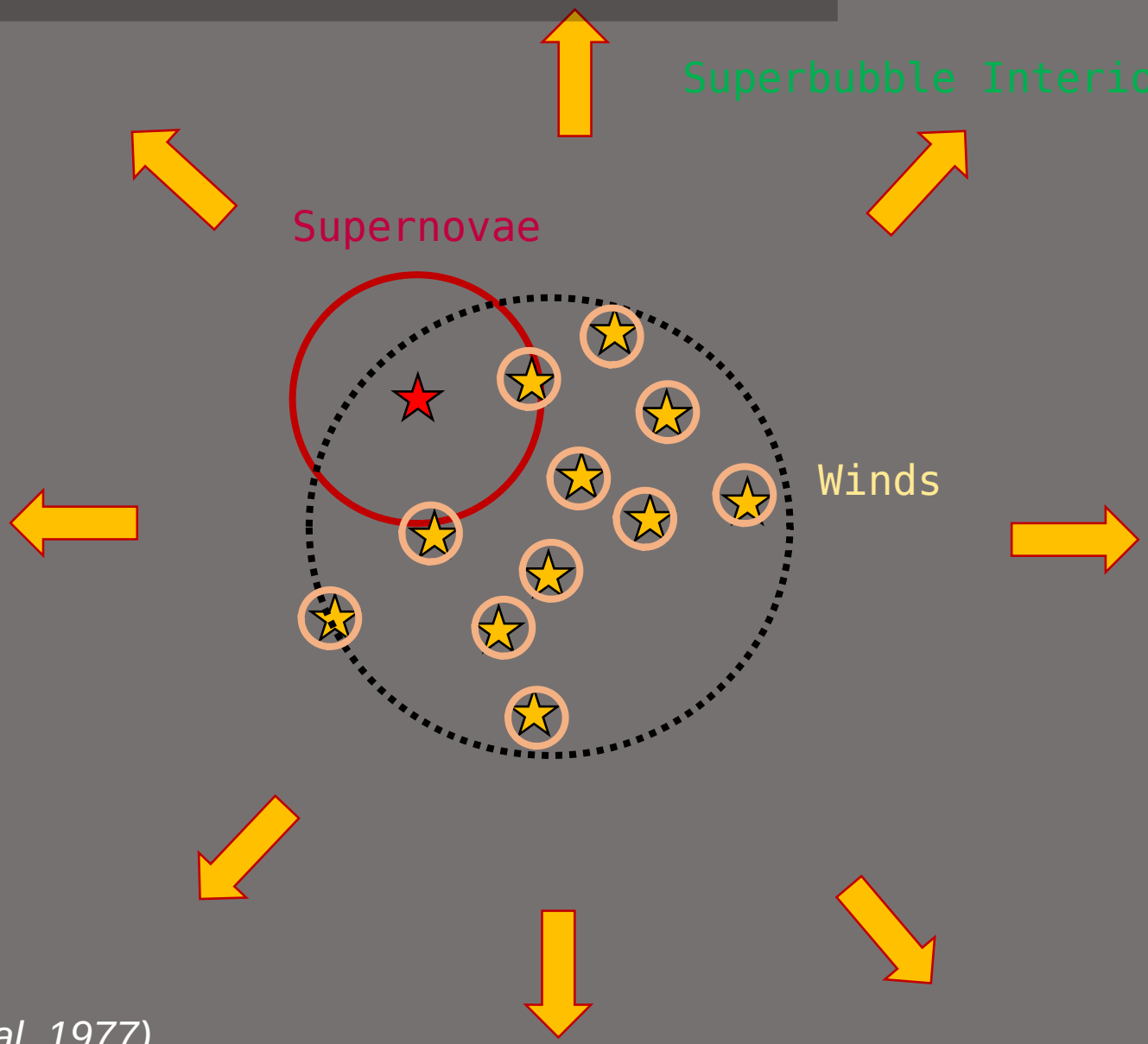


Young compact MSC

Famous example: Westerlund 1
Map from HESS collab. ICRC 2021



Loose MSC



(Weaver et al. 1977)

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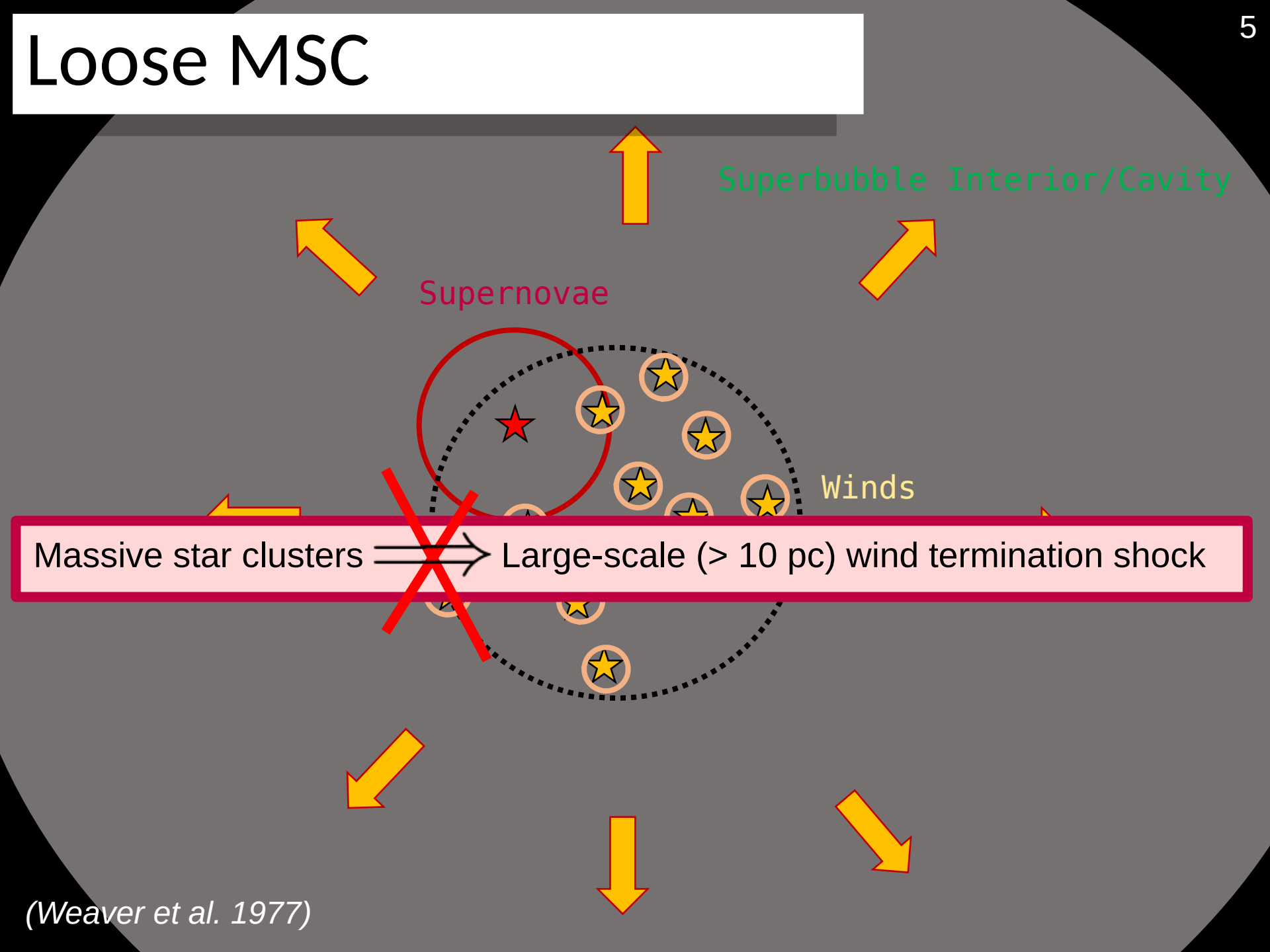

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Can massive star clusters accelerate CRs up to PeV ?

The Maximum Energy of an Astrophysical Accelerator

[Hillas 1984]

$$E_{max} \lesssim ZER \lesssim ZUBR$$

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Fast SNR shock expanding in the wind close to the cluster:

$$U \sim 30\,000\ \mathrm{km/s}\,,\ \mathrm{B} \sim 100\ \mu\mathrm{G}\,,\ \mathrm{R} \sim 1\ \mathrm{pc} \implies \mathrm{E_{max}} \sim 10\ \mathrm{PeV}$$

Computation details in [Vieu, Reville, Aharonian 2022 (2207.01432)]

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The only way to produce PeV γ

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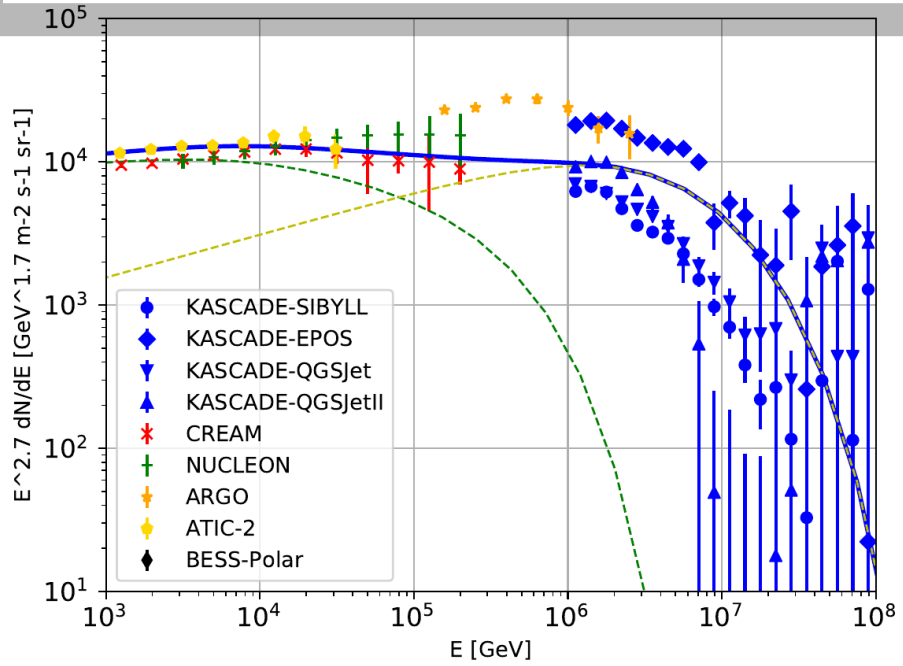
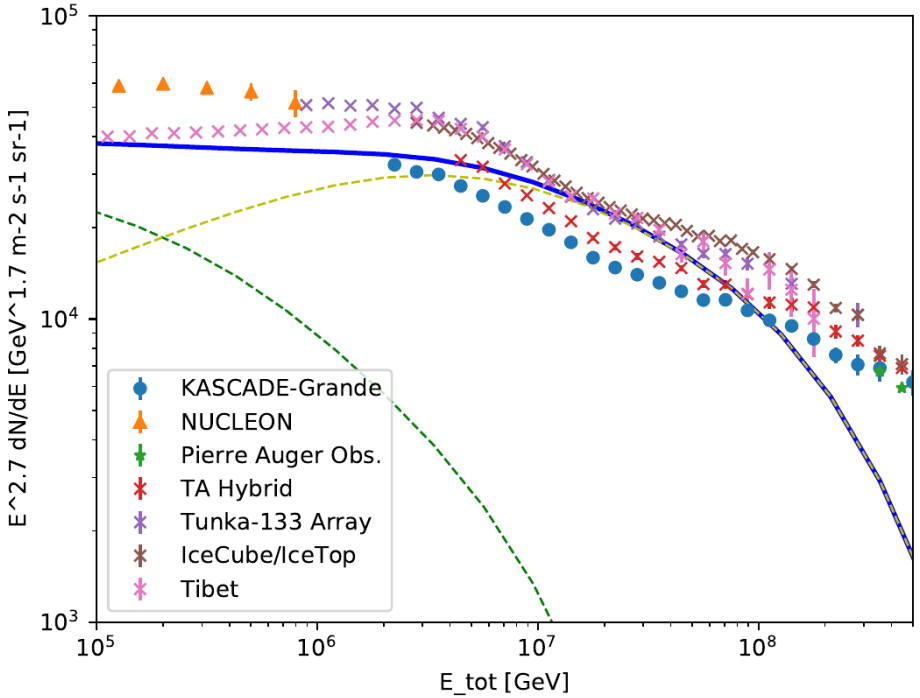
Star clusters as the sources of galactic cosmic rays

PRELIMINARY
[in prep]



Fitting the UHE GCR
with loose and young/compact clusters



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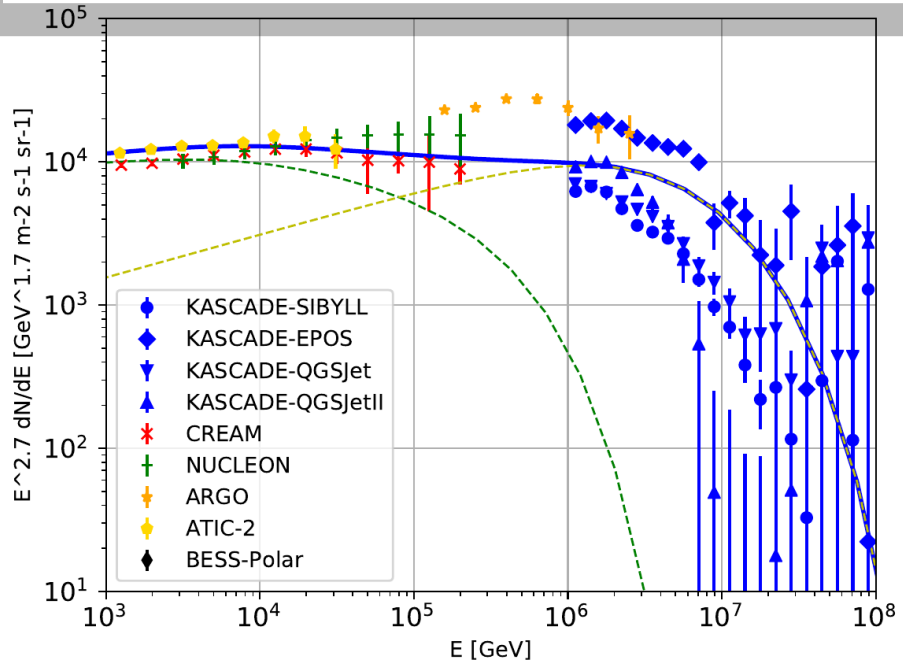

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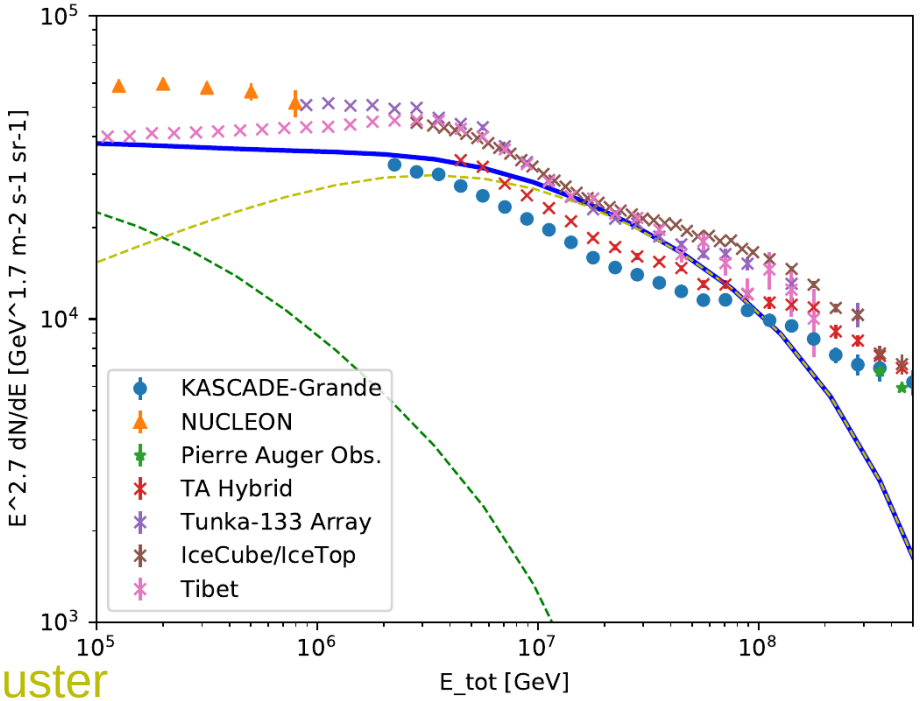


Normalisation requires:
1 SN every ~100 yr from a loose cluster
1 SN every ~2 kyr from a young compact cluster

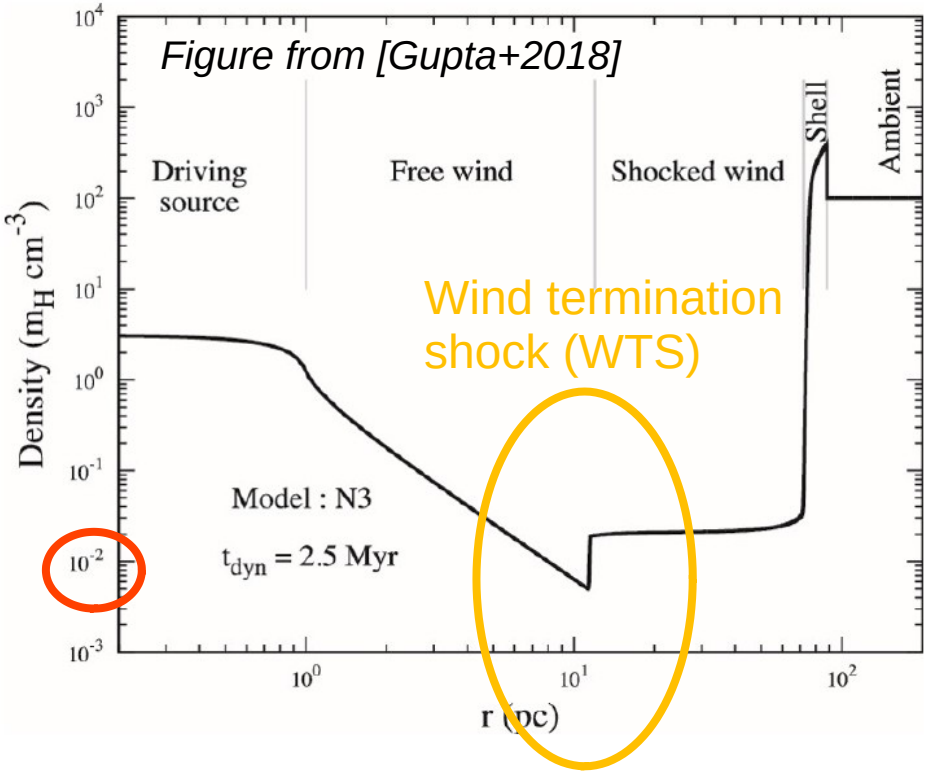
=> about 1000 MSCs including about 100 young compact MSCs.

Diffusion time of PeV particles from source to Earth: ~ 20 kyr
=> less than 10 sources contribute at UHE

Star clusters as sources of γ-rays?

The wind termination shocks are generically expected to accelerate CRs up to PeV.

Hadronic gamma-ray emission?



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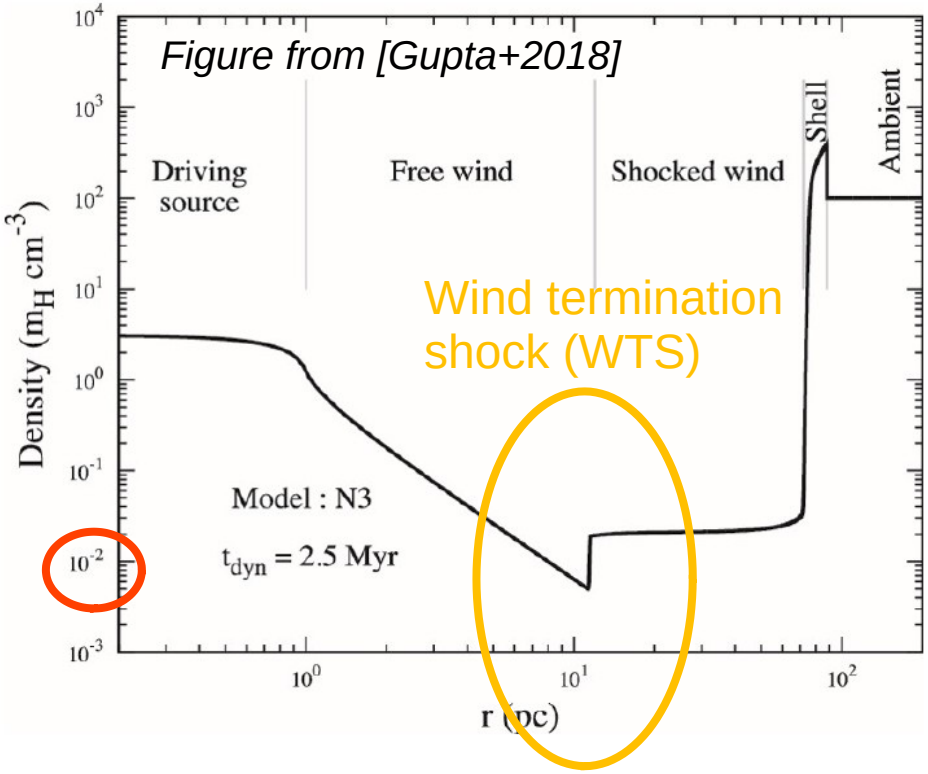

$$\frac{\text{CR flux at shell}}{\text{CR flux at WTS}} \sim \left(\frac{\text{Shell width}}{\text{Cavity radius}}\right)^2 \frac{D_{\text{cavity}}}{D_{\text{shell}}}$$

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"Confinement parameter"

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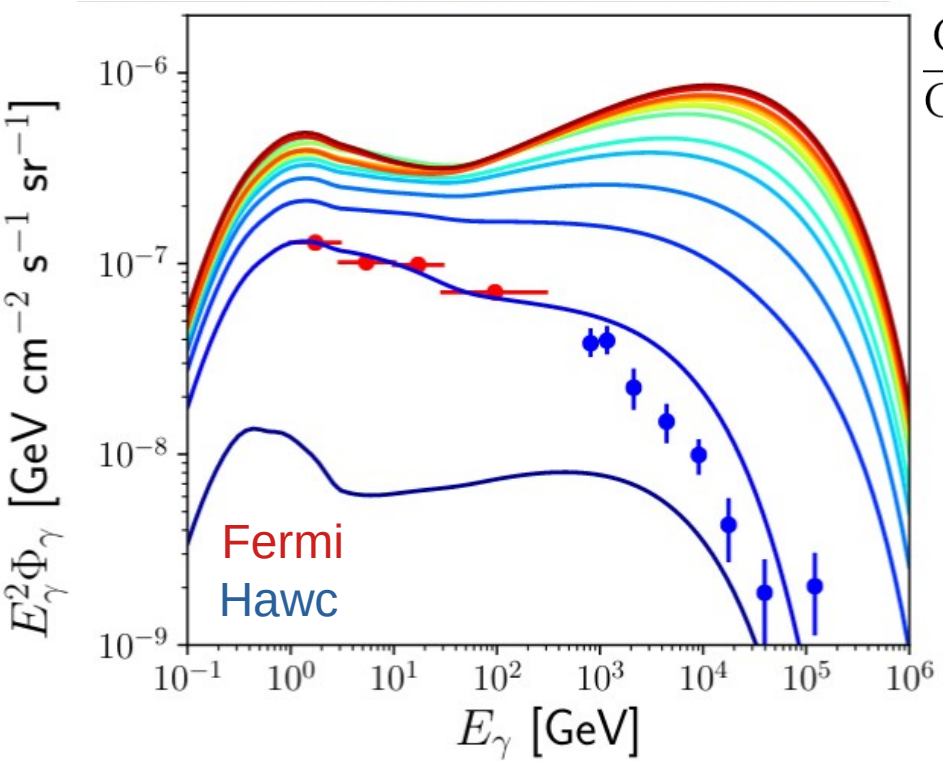

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"Confinement parameter"

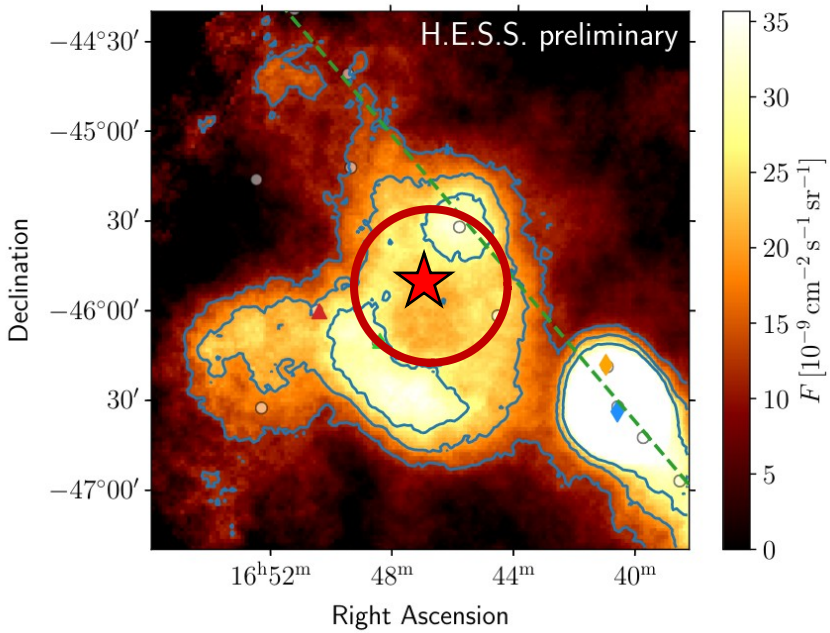
e.g. Cygnus OB2 with mildly enhanced confinement

Hadronic signature of CRs accelerated near the cluster or WTS only if enhanced confinement (e.g. peculiar turbulence configuration in the shell).

(Leptonic signature expected from ICS around the WTS => Lucia Härer's poster)

Star clusters as sources of PeV γ-rays?

Only fast SNR shocks expanding in the collective wind can accelerate CRs well beyond PeV to produce UHE photons



To account for UHE GCR,
we only need **1 such event per ~10 kyr.**
=> very few sources contribute to
10-100 PeV CRs observed locally

How many of these events still produce gamma-rays (by ICS from e^- around the cluster or p-p in the dense shell of the SB)?

Diffusion time of 10 PeV CRs in the cavity: **~ 1 kyr** (without enhanced confinement)
[Vieu, Gabici, Tatischeff, Ravikularaman 2022]

Conclusion: **very few sources** might have produced 10 PeV CRs about 10 kyr ago, which now reach the Earth, but **there are no UHE particles anymore around the sources** (unless enhanced confinement).

Conclusions

> Can massive star clusters produce PeV photons?

Fast SN exploding within young compact massive star clusters **can account for the UHE GCR up to 100 PeV.**

Very few of these events are required (~ 1/10 000 yr) and UHE particles escape within 1kyr => **O(1), or possibly O(0) gamma-ray counterpart**!

> Can massive star clusters produce γ-rays up to 100 TeV?

Young compact clusters can accelerate particles at the WTS up to 1 PeV and produce detectable photons up to 100s TeV.