The potential role of second order Fermi acceleration in Galactic PeVatron candidates

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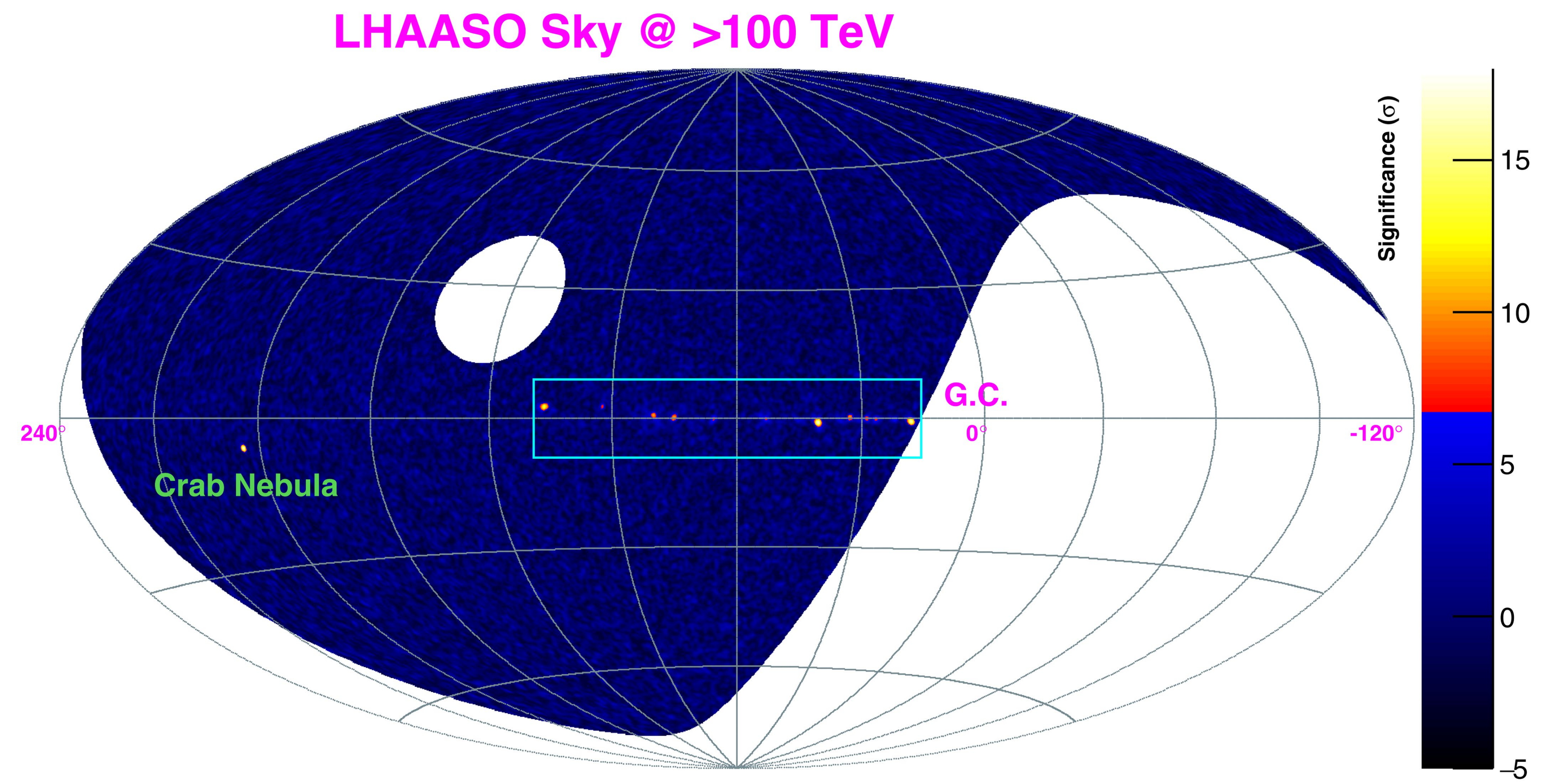
LHAASO PeVatrons: 100-1400 TeV sources



LHAASO coll, Nat. '21

- Since LHAASO (2021)—but see also HAWC— PeVatrons have been discovered!
- But the situation is still complicated:
  - Many sources are pulsars → do not (?) accelerate protons, but leptons!
  - LHAASO PSF is poor: multiple source within PSF → which (if any) is the true PeVatron?
- One source may provide a hint: the Cygnus OB2 association/Cygnus Bubble
  - Combined effects SNe & Stellar winds? (Bykov & Toptygin '92, Parizot+ '04, Vieu+ '22)

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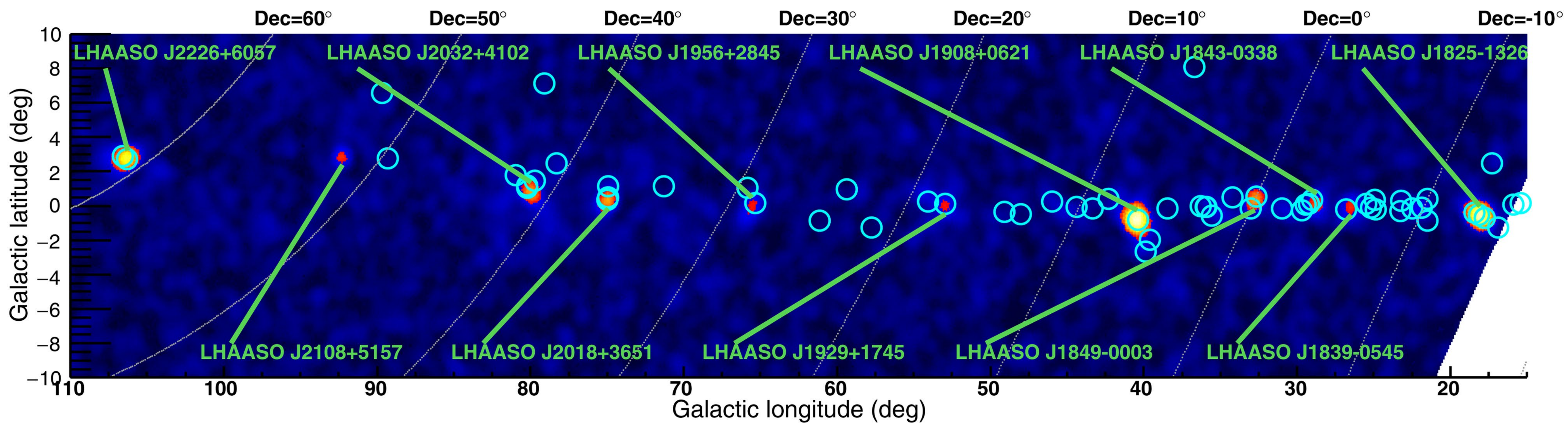

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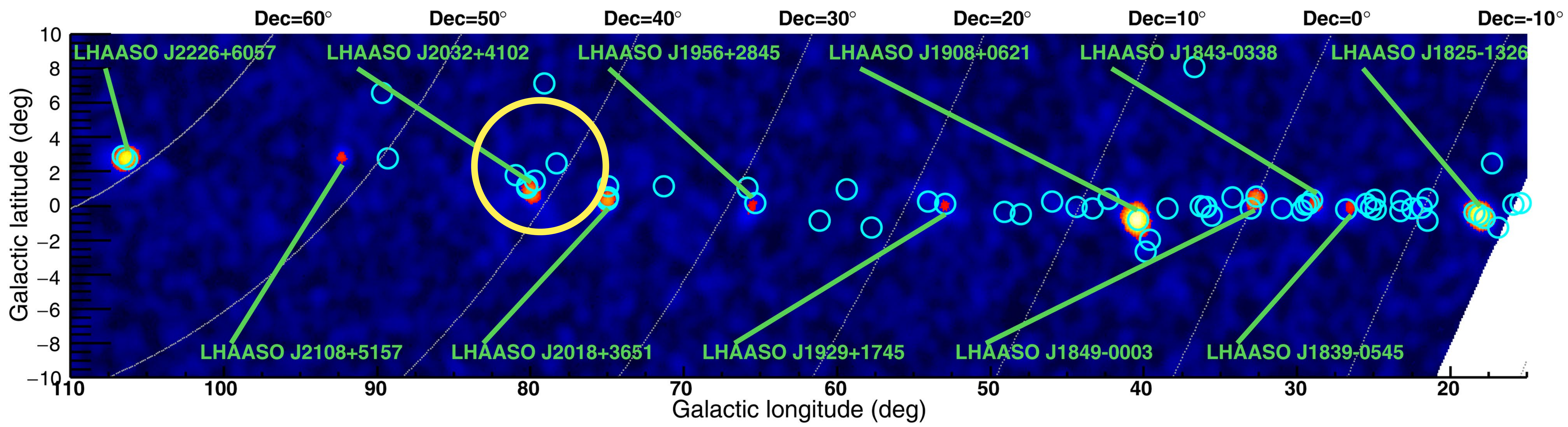

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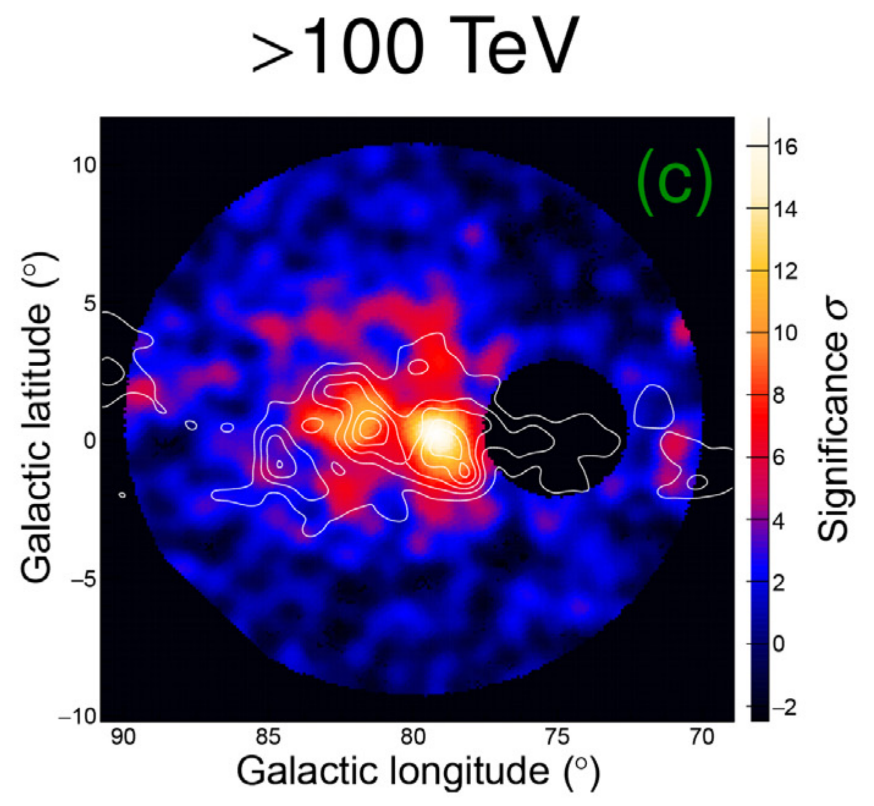

Cygnus Bubble: LHAASO coll, Sc. Bull. '24

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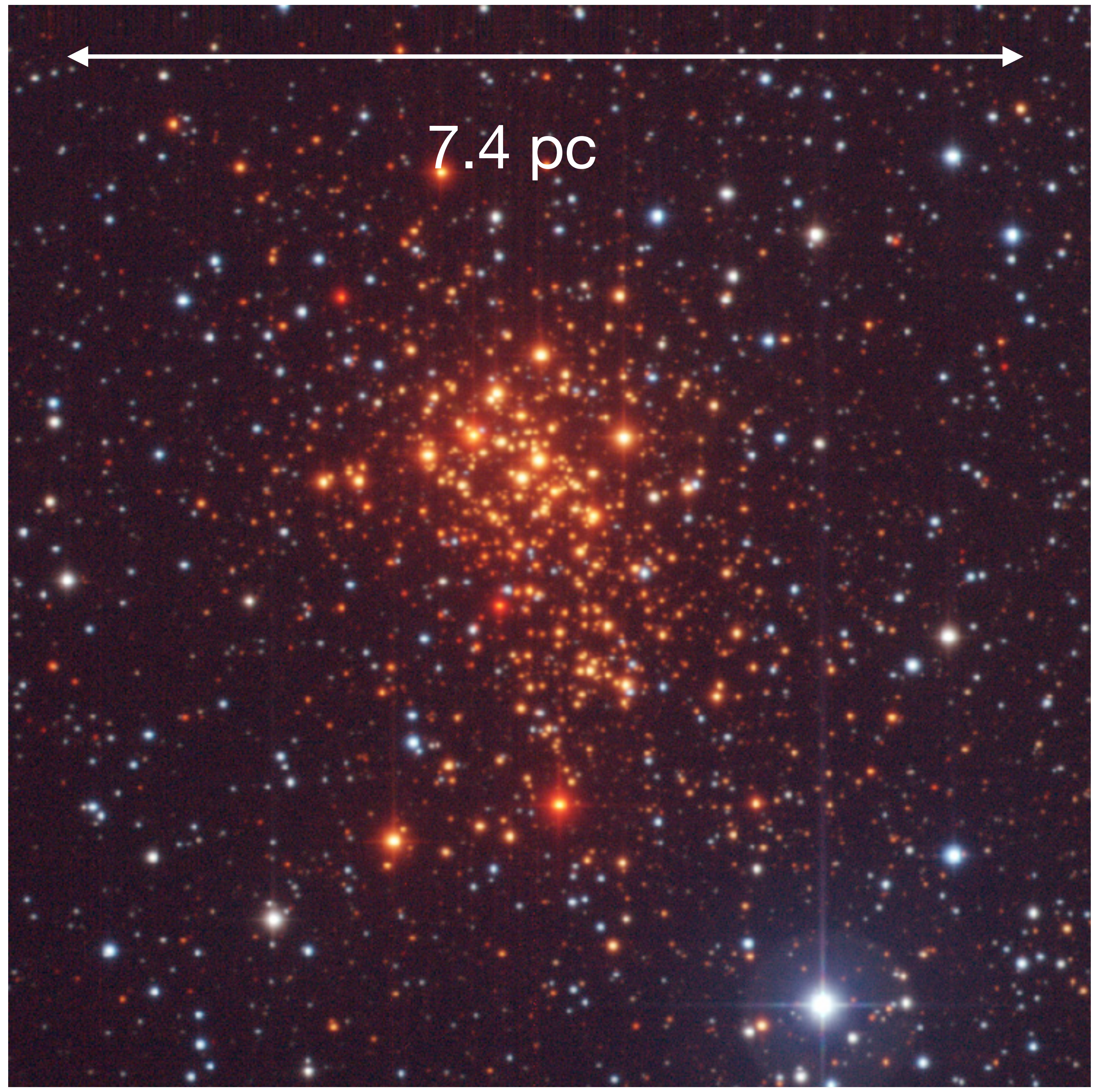
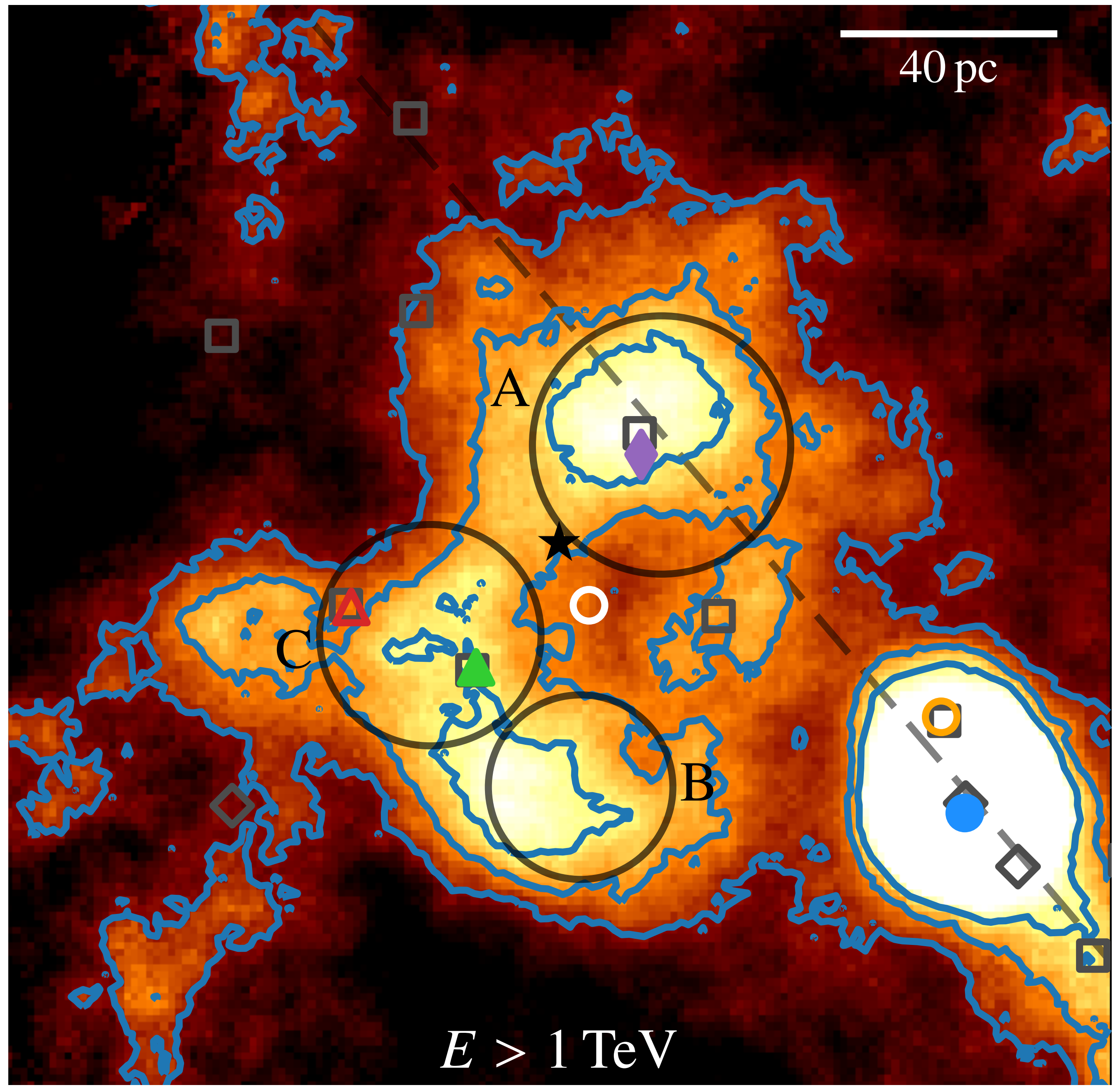
Starforming region Westerlund 1



Clark+ '08

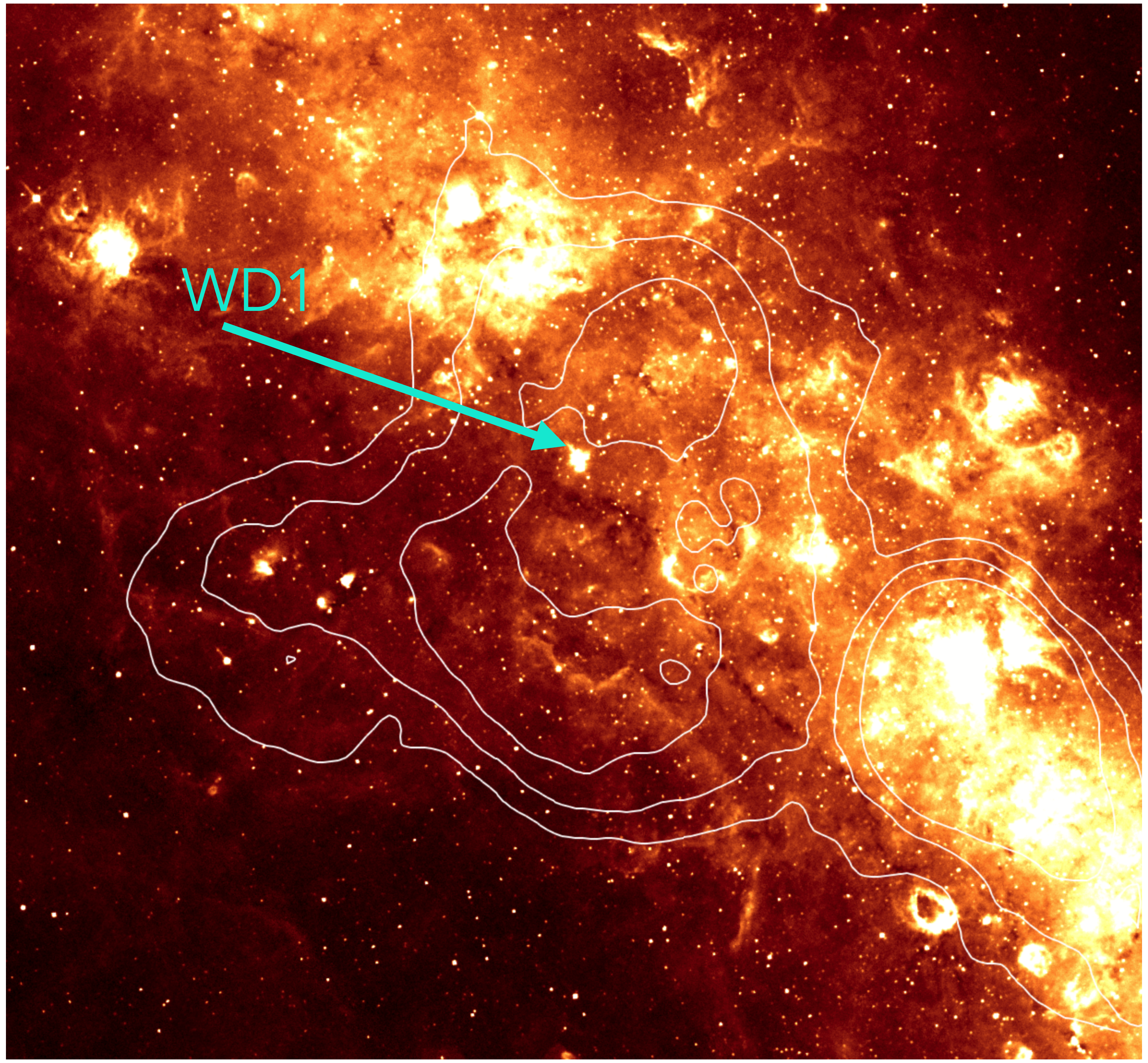


H.E.S.S. collab. 2022

- Very rich massive cluster (27 Wolf-Rayet stars!): $L_w \approx 10^{39}$ erg/s
- About 4 Myr old
- Associated with TeV gamma-ray source: HESS J1646−458
- Total CR energy: $W_p \approx 6 \times 10^{51} d_{4.9kpc}^2 n_H$ erg (~20% of $E_w = L_w t$)

Starforming region Westerlund 1

- The H.E.S.S. is located inside a low luminosity IR part
- No associated molecular clouds
- The H.E.S.S. source has shell-type shape:
  - R~ 50 pc (c.f. cluster: 7.5 pc)
- Several possible CR acceleration sites
  - stellar cluster itself
  - supernova(e) remnants
  - cluster wind termination shock
  - second-order shock acceleration inside superbubble



IR map (8micron) with H.E.S.S. contours

Superbubbles

A. Cluster itself: colliding stellar winds

- Gives rise to X-ray emission
- Possible CR acceleration site (1st order Fermi)

B. Hot gas expands: collective cluster wind

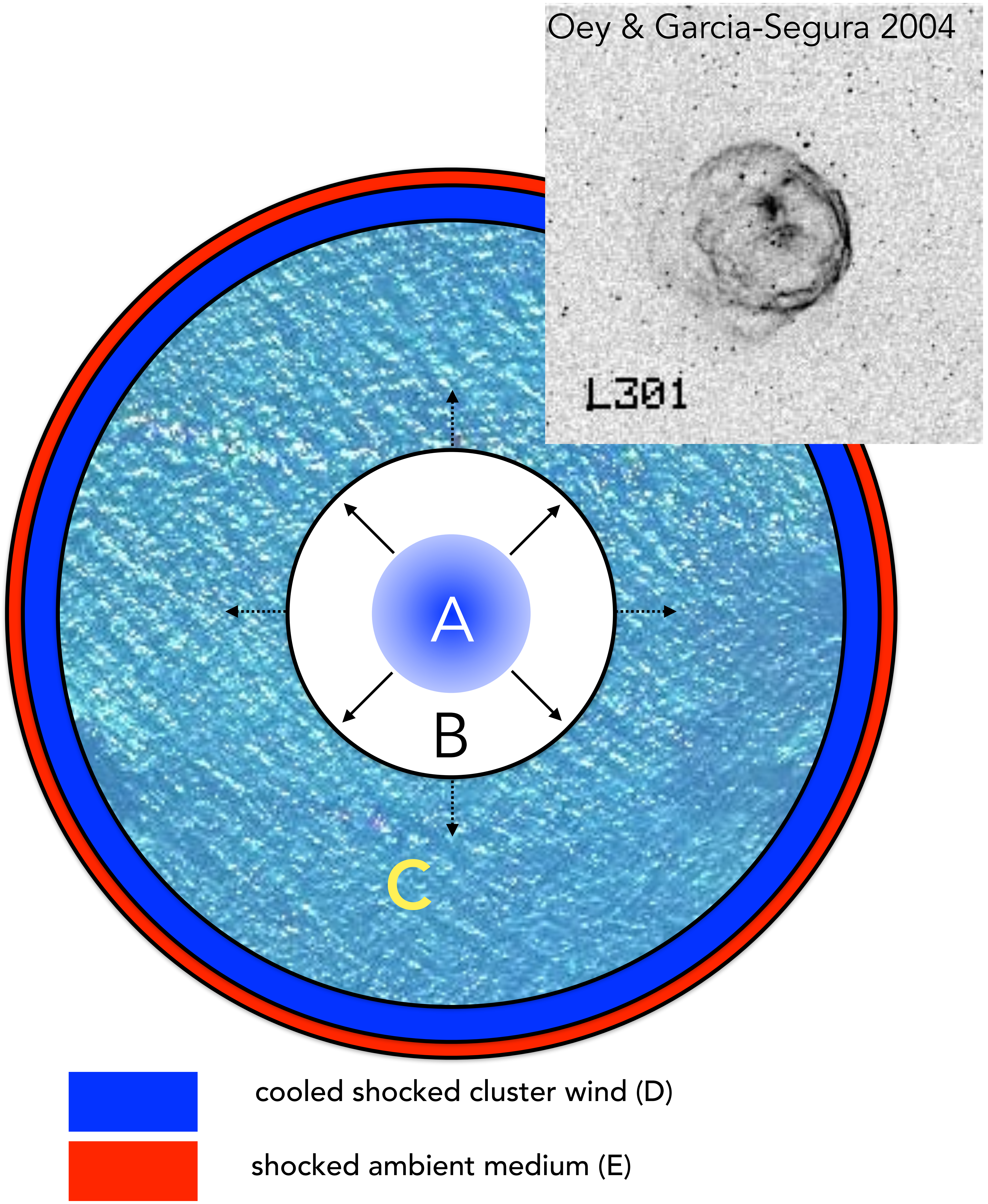
- Ends in termination shock of ~1000-3000 km/s
- Possible CR acceleration site (1st order Fermi)
  - See Morlino+ ’22, Vieu+ ’22,’23

C. Low density shocked wind bubble (~50—200 pc)

- *Second order Fermi acceleration?*
- Occasional SNR (Fermi 1)

D. and E. Dense slowly expanding shell (20-50 km/s)

- Could be location of gamma ray production



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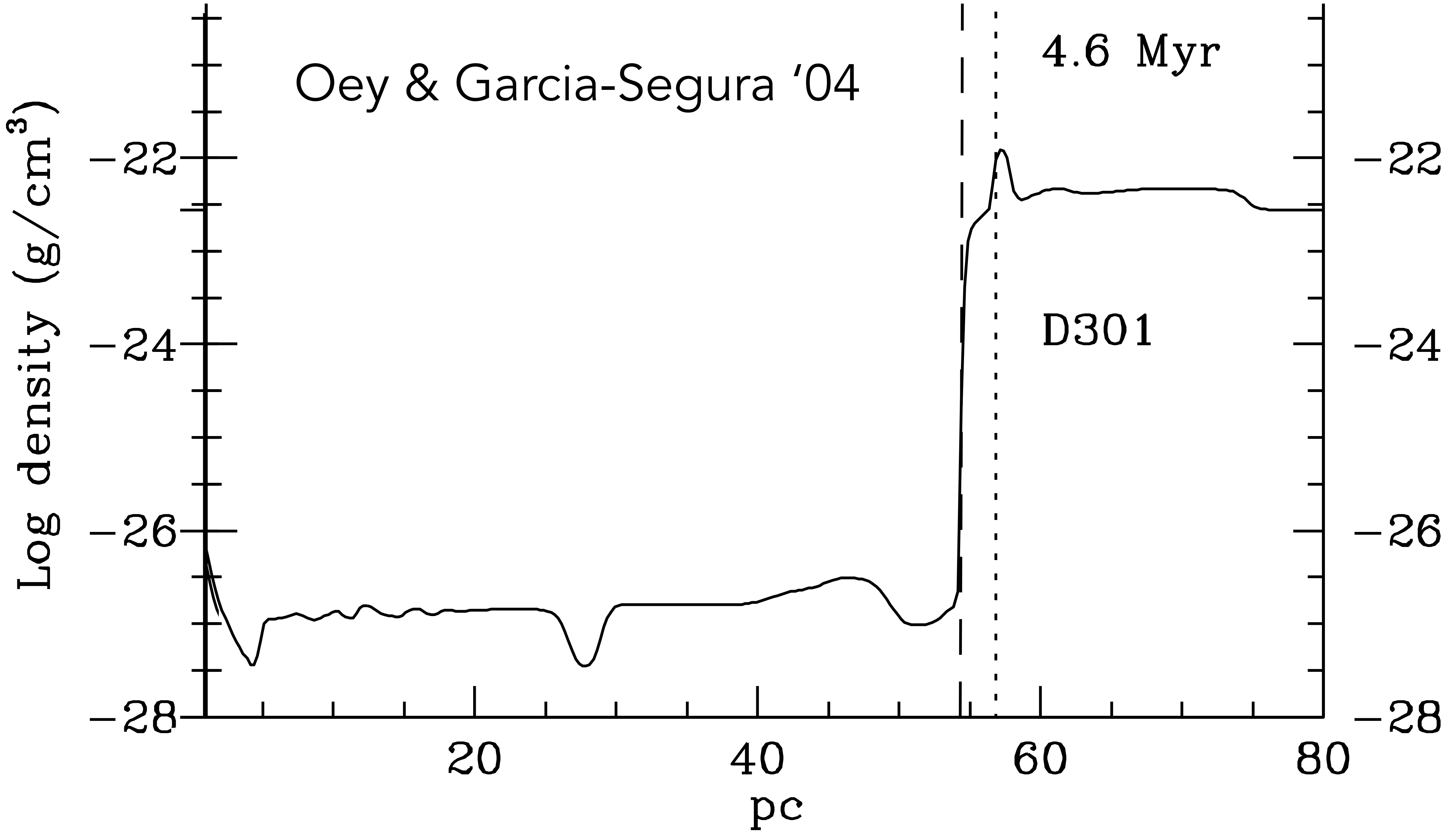

- Sizes controversial: models predict 100-200 pc (Weaver+ '77)
- But typical sizes LMC: 50 pc
  - Cause: interstellar pressure locally high (Oey & Garcia Segura '04)
- Superbubble itself: could be very low density!
  - $\rho \approx 10^{-27} - 10^{-26}$ g cm^{-3} (~0.001—0.01 cm^{-3})

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- Maximum energy: $E_\mathrm{max} = \left[E_\mathrm{inj}^\delta + \frac{\delta \xi}{3D_0} V_\mathrm{A}^2 E_0^\delta t \right]^{1/\delta}$

Remarkable: Fermi-2 as efficient as Fermi-1?

- 1st order Fermi acceleration time scale: $\tau_{\mathrm{acc,1st}} \approx \frac{8D_0}{\delta V_s^2}\left(\frac{E_{\max}}{E_0}\right)^{\delta} = \frac{8D(E_{\mathrm{emax}})}{\delta V_s^2}$
- 2nd order Fermi acceleration time scale: $\tau_{\mathrm{acc,2nd}} \approx \frac{3D_0}{\delta \xi V_A^2}\left(\frac{E_{\max}}{E_0}\right)^{\delta} = \frac{3D(E_{\max})}{\delta \xi V_A^2}$

- So for relevant velocity both are similar!
- In reality: SNRs can have V~ 5000 km/s, Alfvén speed is rarely that high!

Maximum energy taking into account escape

- Emax given is only valid if the particles stay in the accelerator region
- In reality at large energies particles leak away due to diffusion:
  - $R = \sqrt{6Dt} \;\; \rightarrow \;\; \tau_{\rm esc} = \dfrac{R^2}{2D}$
  - Equation with $\tau_{\rm acc}$ and $D = \dfrac{1}{3}\lambda_{\rm mfp}c = \dfrac{1}{3}\eta\dfrac{cE}{eB}$ gives

$$E_{\rm max} = 5.5 \times 10^{14}\eta^{-1}\sqrt{\delta\xi}\left(\frac{B}{10\ \mu{\rm G}}\right)\left(\frac{R}{50\ {\rm pc}}\right)\left(\frac{V_{\rm A}}{500\ {\rm km\ s^{-1}}}\right)\ {\rm eV}$$

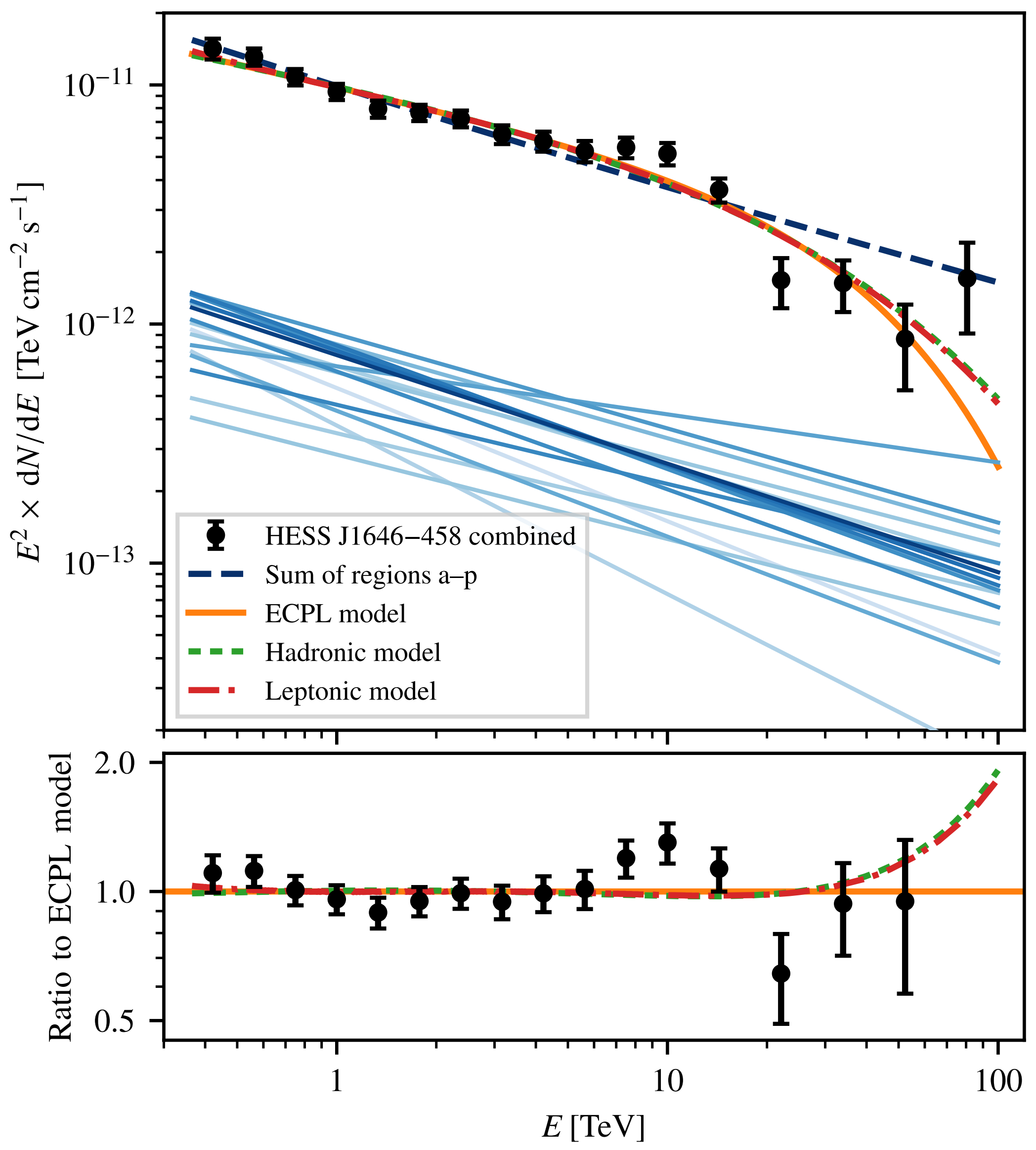
  - or using $V_{\rm A} = \dfrac{B}{\sqrt{4\pi\rho}}$:

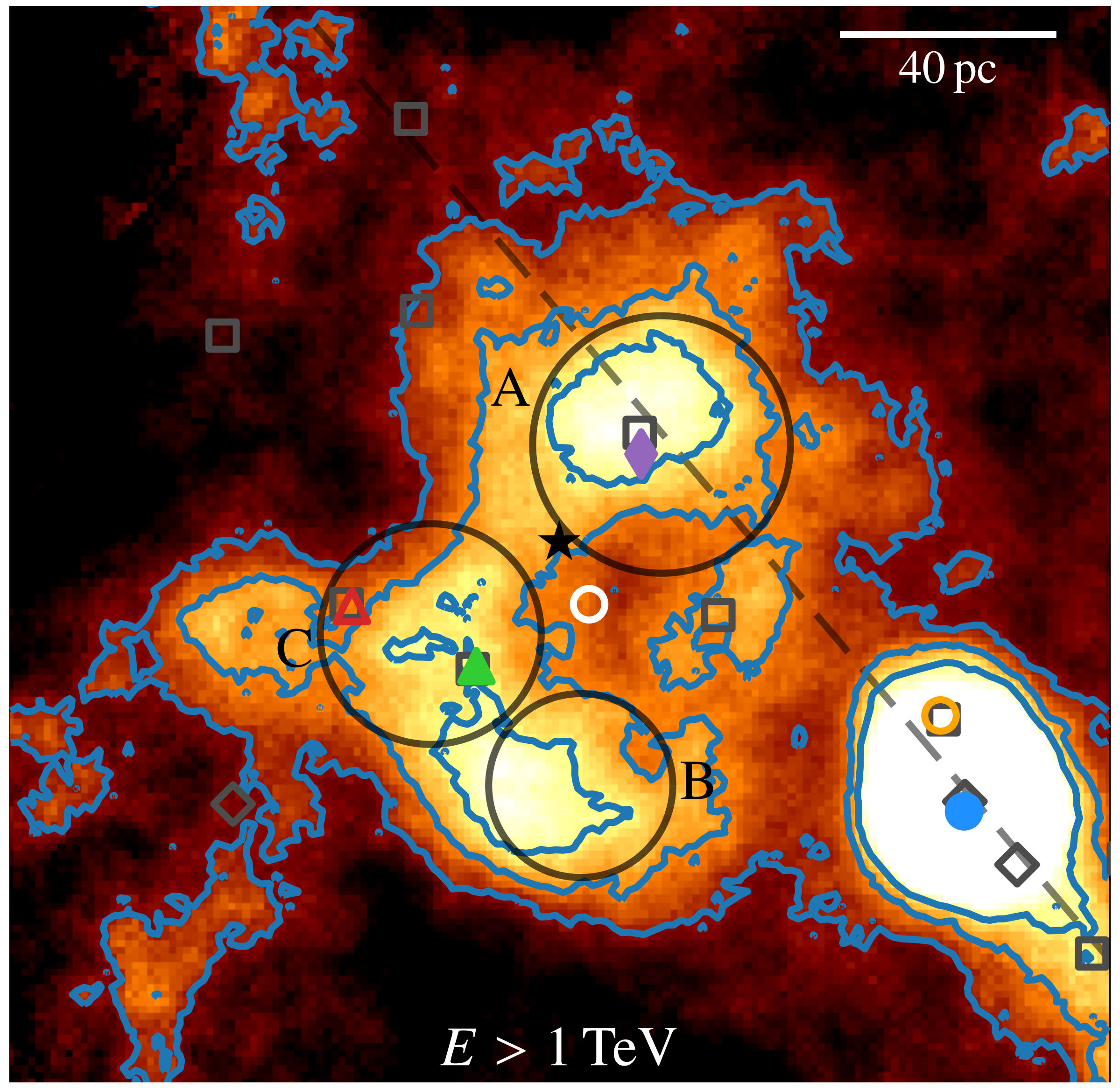
$$E_{\rm max} = 7.5 \times 10^{14}\eta^{-1}\sqrt{\delta\xi}\left(\frac{B}{10\ \mu{\rm G}}\right)^2\left(\frac{R}{50\ {\rm pc}}\right)\left(\frac{n_{\rm H}}{0.001\ {\rm cm^{-3}}}\right)^{-1/2}\ {\rm eV}$$

  - Needed for multi-PeV protons: $B \gtrsim 30\ \mu$G and η~1 (Bohm diffusion)

What are the conditions in Westerlund 1

- Total energy in CRs: $W_p \sim 6 \times 10^{51}$ erg
- Total energy from winds: $L_w t \approx 3 \times 10^{52} t_6$ erg
  - So high efficiency!
  - Requires low/no escape of CRs!





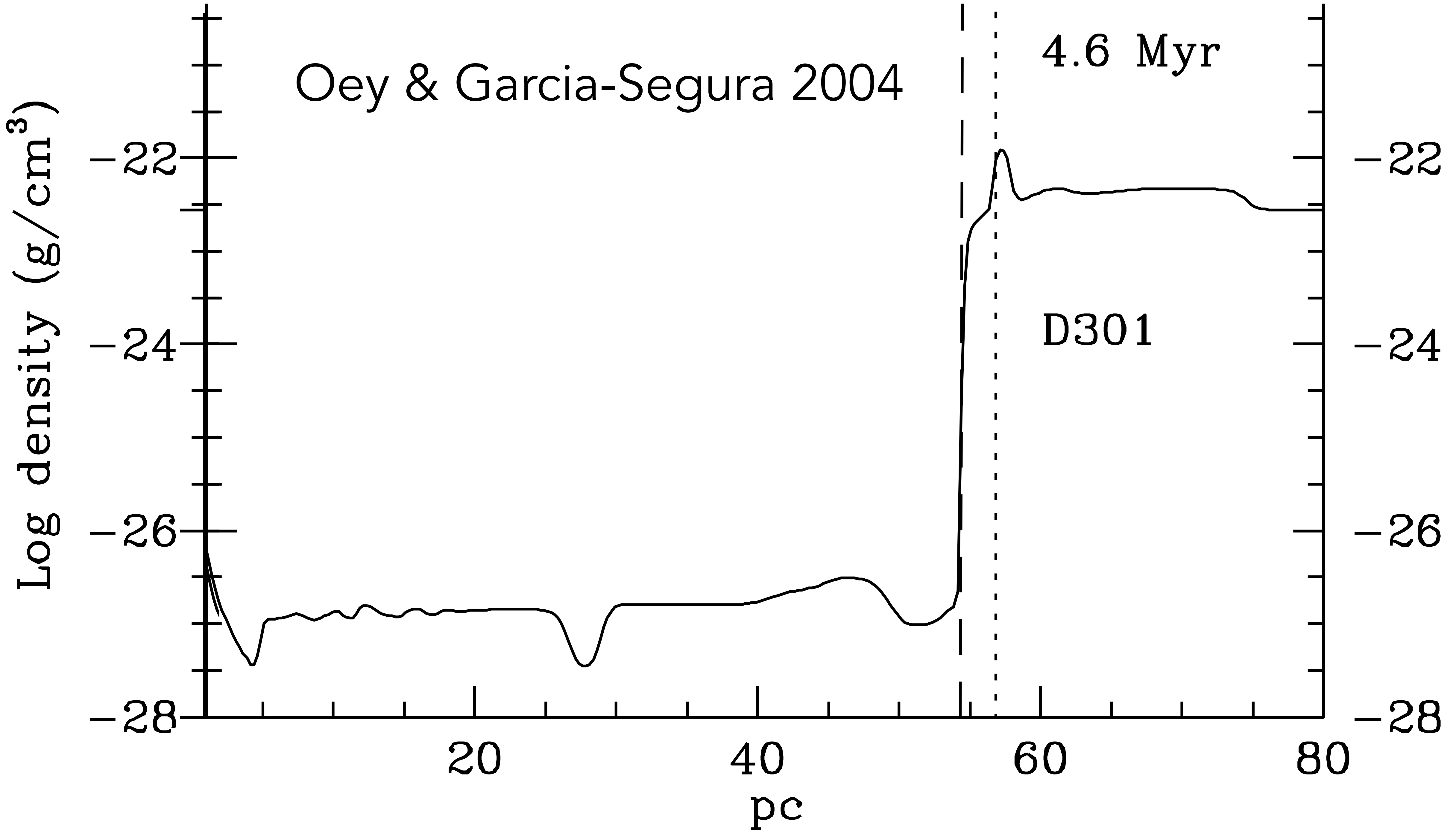
H.E.S.S. collab. 2022

- Implications for diffusion coefficient?
  - Particles producing gamma rays up to 200 TeV
  - No escape: D(200 TeV)$D(200 \text{ TeV}) \lesssim \frac{R}{6t} \approx 10^{26} t_6^{-1} (R/50 \text{ pc})$!
  - Requires B~30 μG and η~1
  - If $V_A \sim 500$ km/s Westerlund 1 could be a PeVatron powered by 2nd order Fermi acceleration!

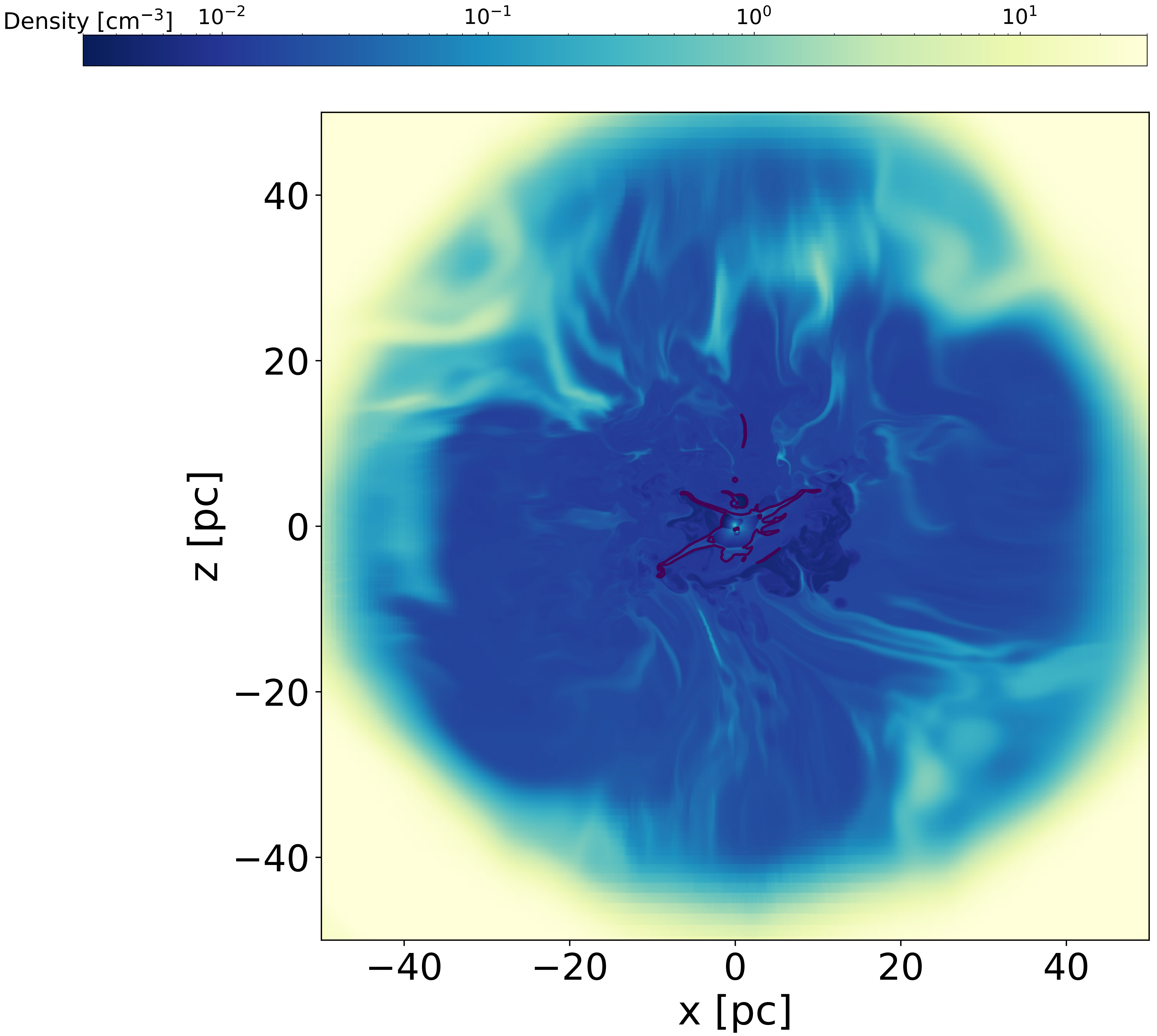
Conclusions

- The source of Galactic >PeV cosmic rays is still a puzzle
- LHAASO provides a few hints, but no clear smoking guns!
- Promising sources: Galactic superubbles (Bykov & Toptygin 90,…)
  - Combine the power of winds and supernovae
  - Many potential acceleration sites (cluster, cluster shock, superbubble itself)
- This talk: potential of second order shock acceleration in low density bubble:
  - Second order acceleration as efficient as first order!
  - Requires small diffusion coefficient (Westerlund 1/HESS provides observational evidence)
  - Alfvén speed needs to be high: for n~0.001 cm^{-3}, B~30 μG → V_A~ 600 km/s
  - $E_{max} > 10^{15}$ eV possible!

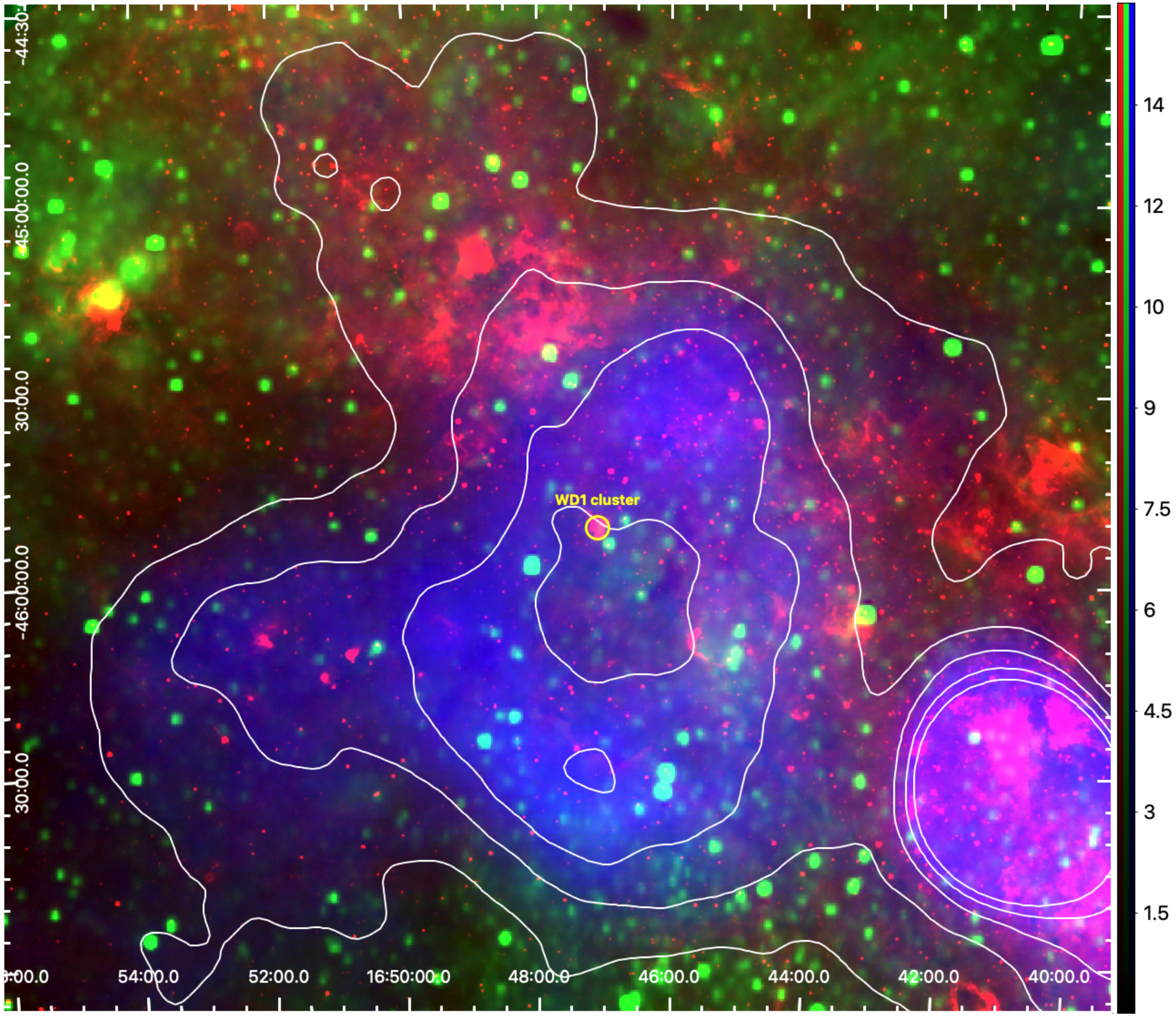
Superbubble



- Driven by strong stellar winds and SNe: $L_{\rm w} \gtrsim \frac{1}{2}\dot{M}v_{\rm w}^2 \approx 10^{37} - 10^{39}$ erg/s
- Self-similar wind models (Weaver+ '77, Koo&McKee '92): R_{sb}~150 pc
- Taking into account high pressure ambient medium (Oey & Garcia-Segura '04): R_{sb}~50 pc
- Densities $\rho \approx 10^{-27} - 10^{-26}$ g cm^{-3} (~0.001—0.01 cm^{-3})



Density [cm^{-3}]
10^{-2}
10^{-1}
10^{0}
10^{1}
z [pc]
40
20
0
−20
−40
x [pc]
−40
−20
0
20
40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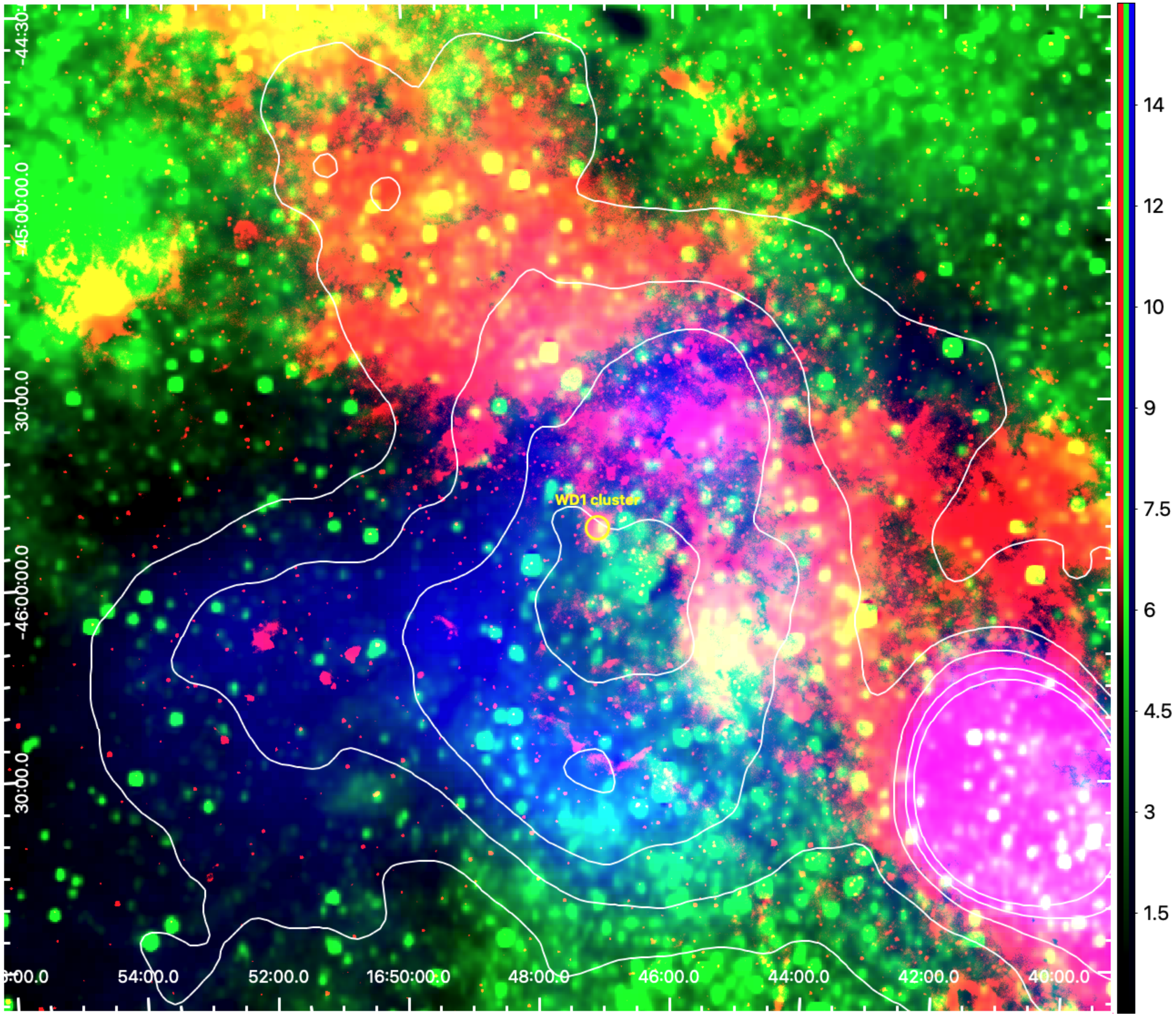
WD1 cluster
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