Superbubbles as Galactic PeVatrons: The Potential Role of Rapid Second-Order Fermi Acceleration

GRAPPA
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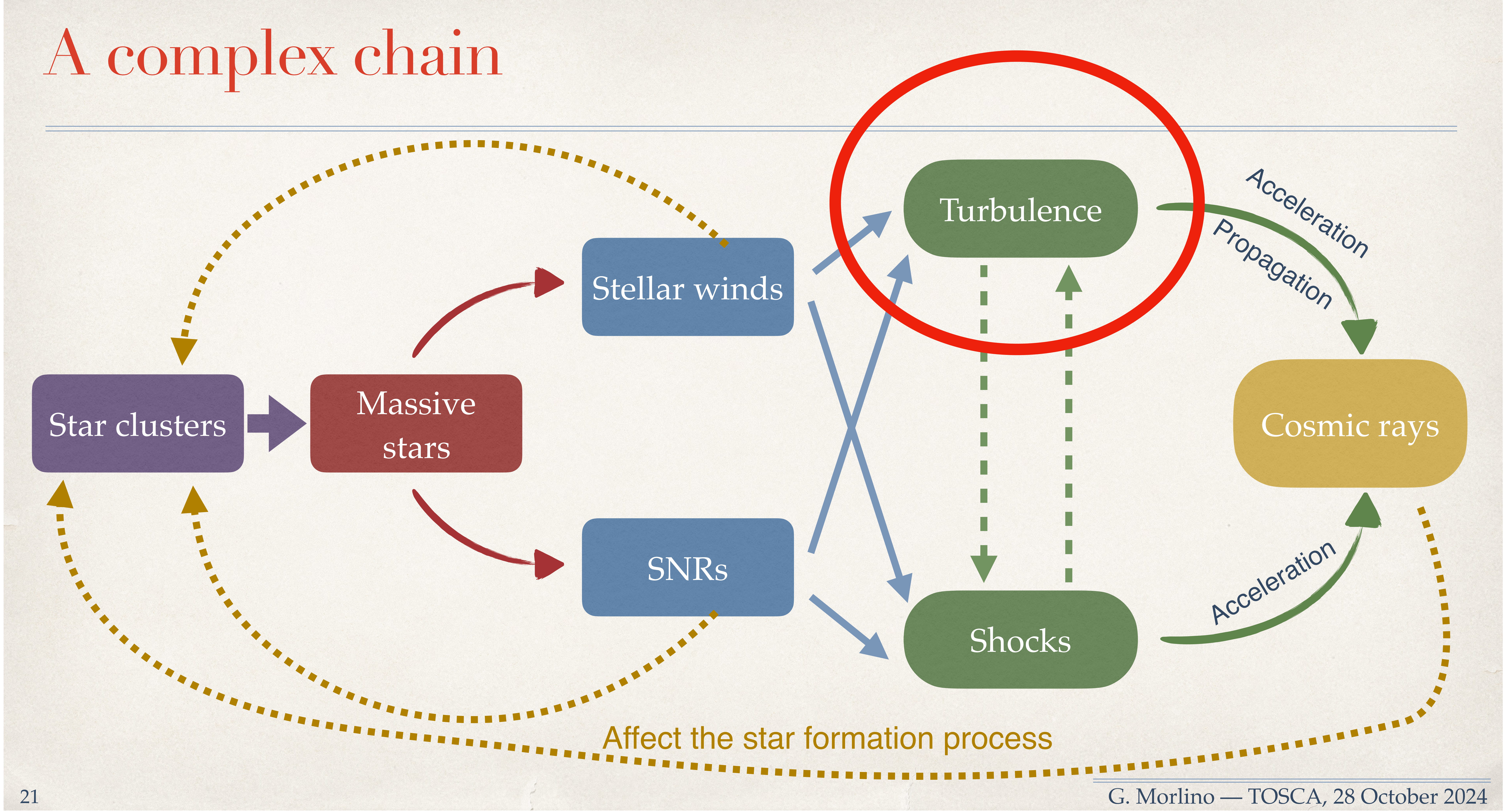
Jacco Vink

Topical Overview on Star Cluster Astrophysics, Siena, October 2024

This talk


A complex chain
Turbulence
Stellar winds
Acceleration
Propagation
Star clusters
Massive stars
Cosmic rays
SNRs
Shocks
Acceleration
Affect the star formation process
21
G. Morlino — TOSCA, 28 October 2024

Superbubbles as (PeV) sources of cosmic rays

- SNRs appear *not* to be PeVatrons
  - Observationally/theoretically $E_{\rm max} \lesssim 10^{14}$ eV
  - But: SNe/SNRs perhaps PeVatrons early on? (if dense winds)
  - Or in special environments (*superbubbles?!*)

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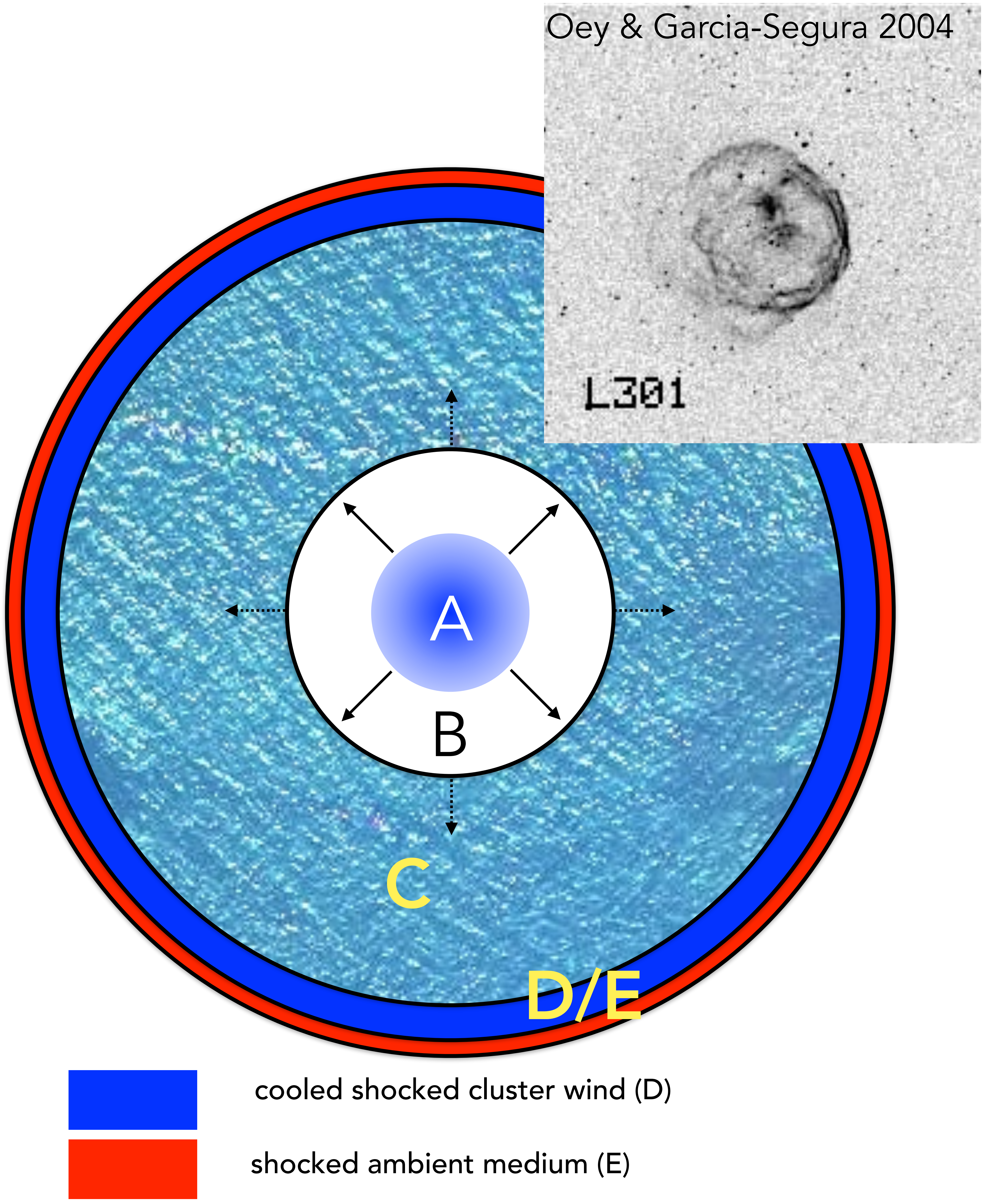
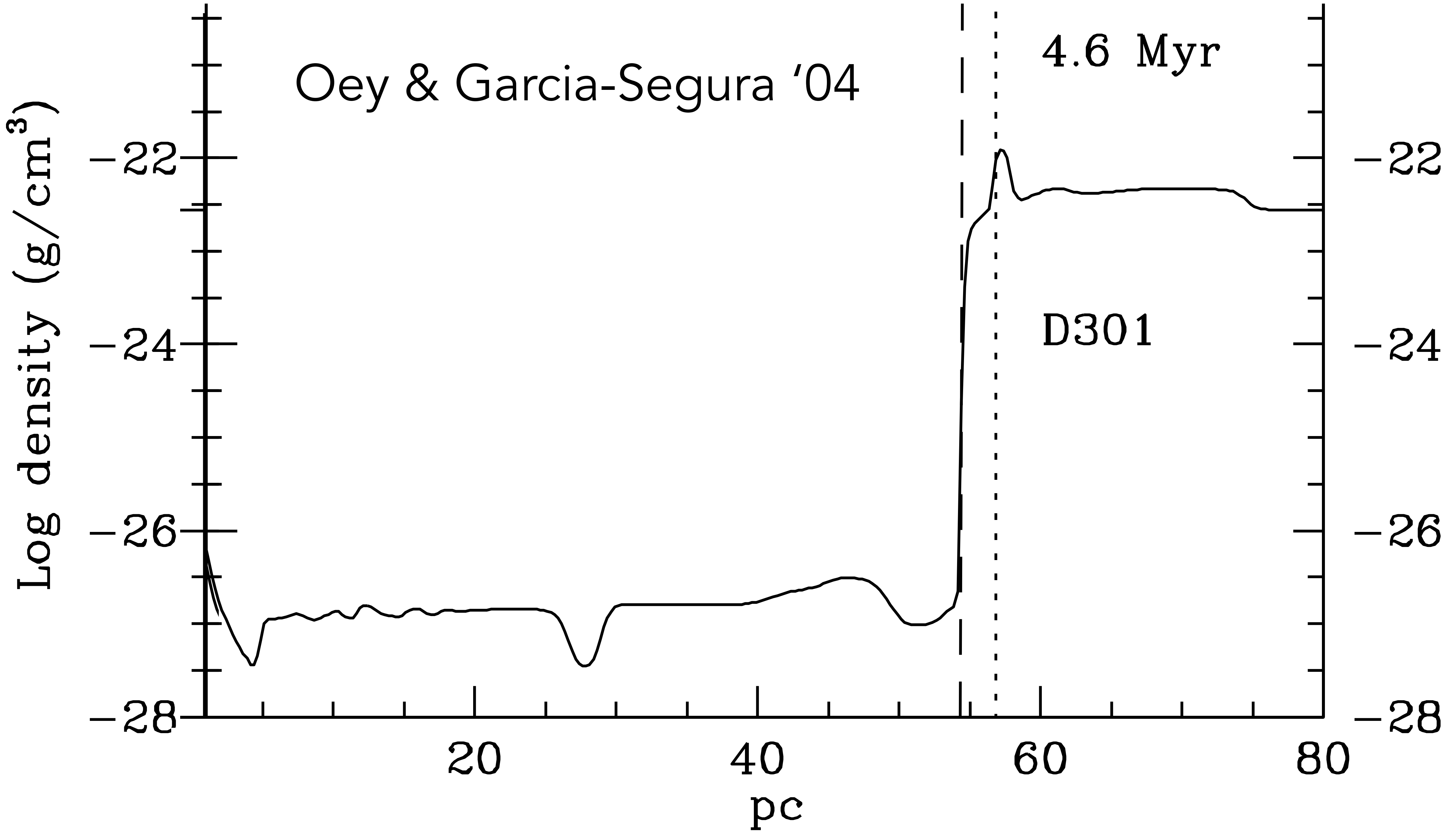
- Collective SB phenomena:
  - Multiple shocks (winds/snrs) keep interacting and accelerating particles (e.g. Bykov)
  - Long-lived and fast (2000 km/s) cluster wind termination shock
  - This talk: second order Fermi acceleration by magnetic field turbulence

Superbubbles

- Several options for CR acceleration:
  - Cluster itself: colliding winds (A)
    - DSA
  - Termination shock cluster wind (boundary B/C)
    - DSA
  - Inside tenuous superbubble ©
    - Stochastic/2nd order Fermi
  - Occasional supernova remnant in (mostly in C)
    - e.g. 30DorC (H.E.S.S. '15, Kavanagh+ '19)
- All may contribute!
  - But which is responsible for PeV CRs?
- Region D/E could be site of (hadronic) gamma-rays



Superbubble



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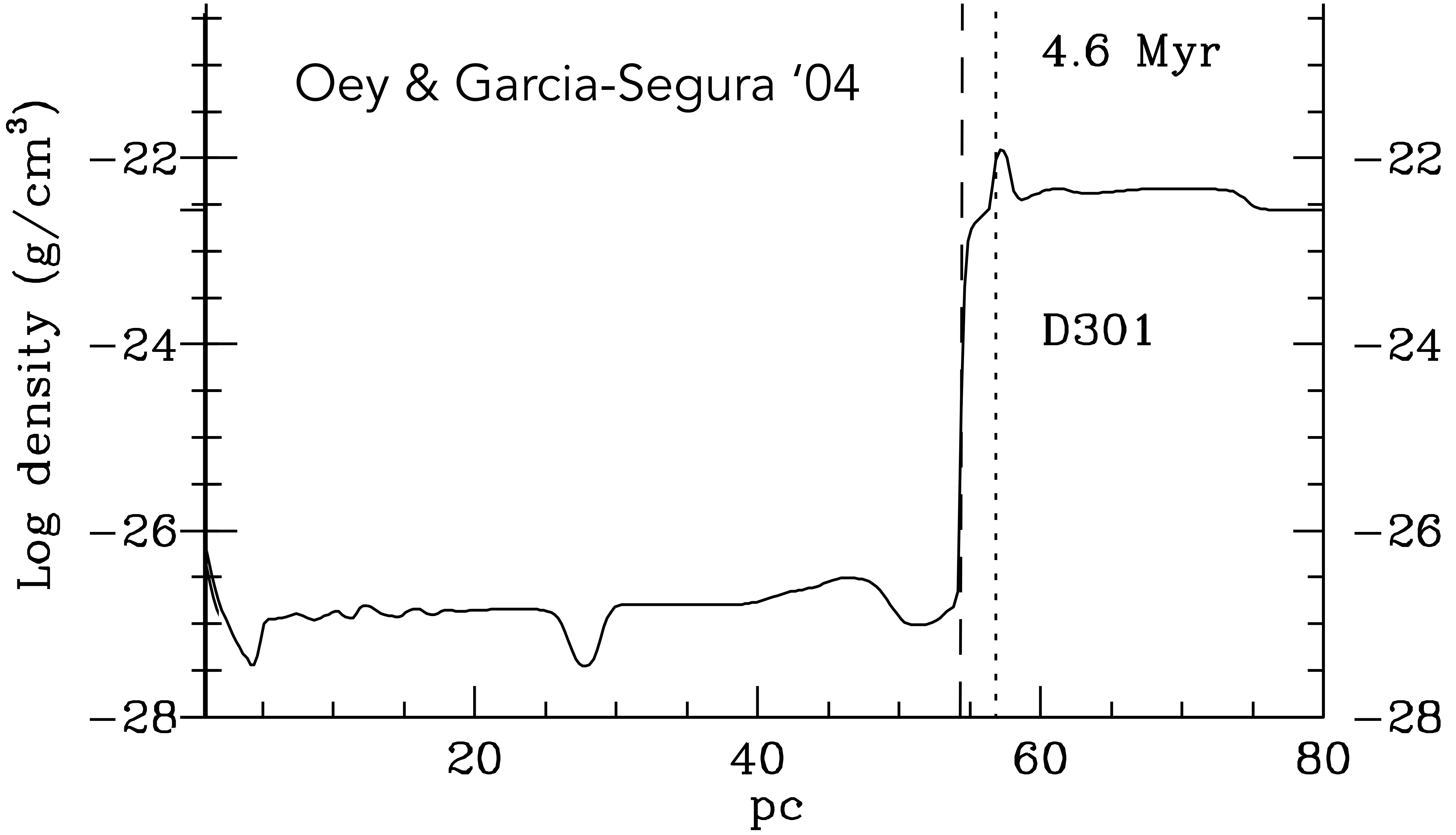

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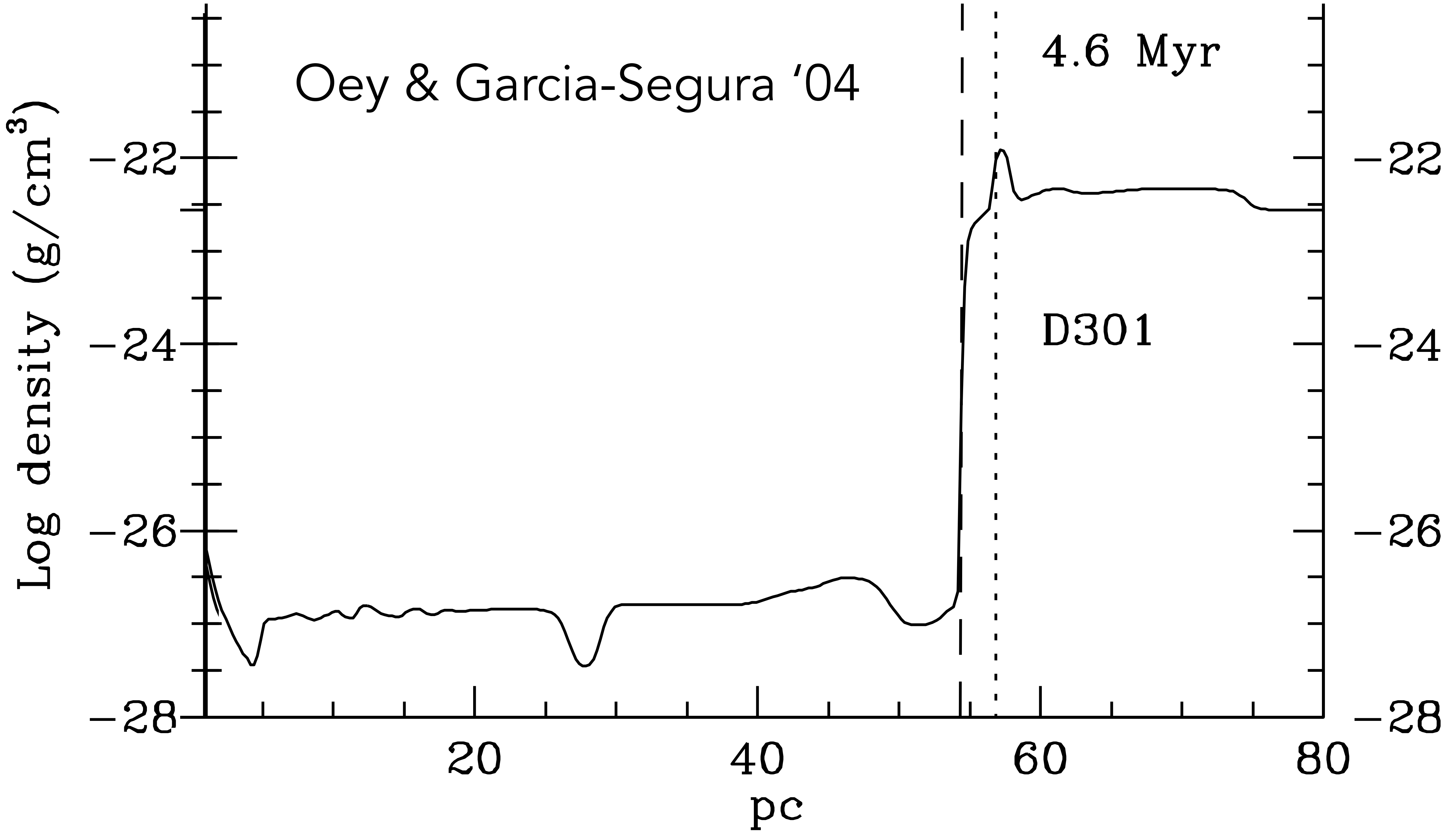

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- Superbubble itself: could be very low density!
  - $\rho \approx 10^{-27} - 10^{-26}$ g cm^{-3} ($n_\mathrm{H} \sim 0.0005 - 0.005$ cm^{-3})
  - expected Alfvén speed: $V_\mathrm{A} = \dfrac{B}{\sqrt{4\pi\rho}} \approx 585 \left(\dfrac{B}{10\ \mu\mathrm{G}}\right)\left(\dfrac{n_\mathrm{H}}{0.001\ \mathrm{cm}^{-3}}\right)^{-1/2}$ km/s

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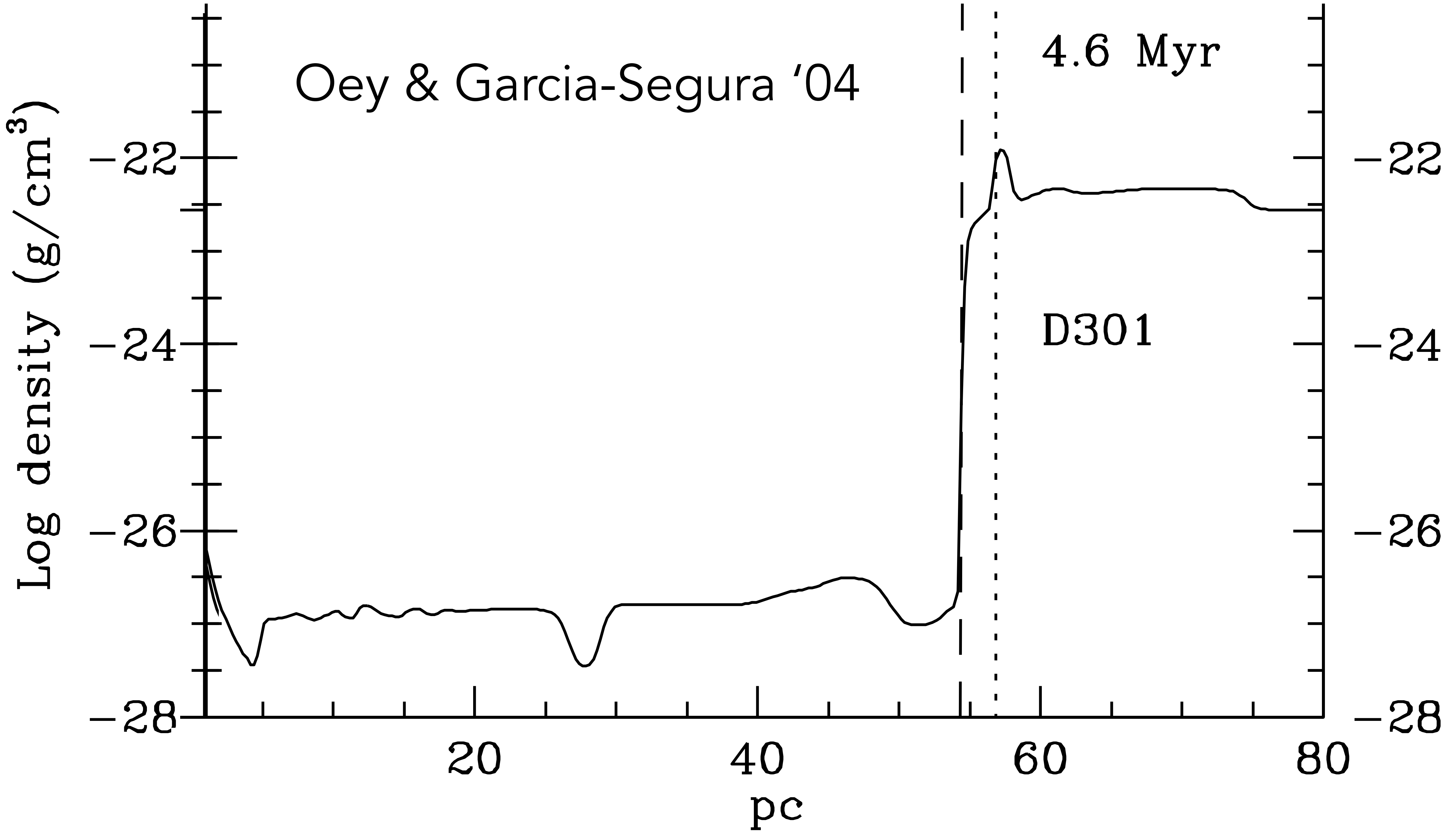

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- SB surrounding shell: $n_H \sim 1 - 100$ cm^{-3}

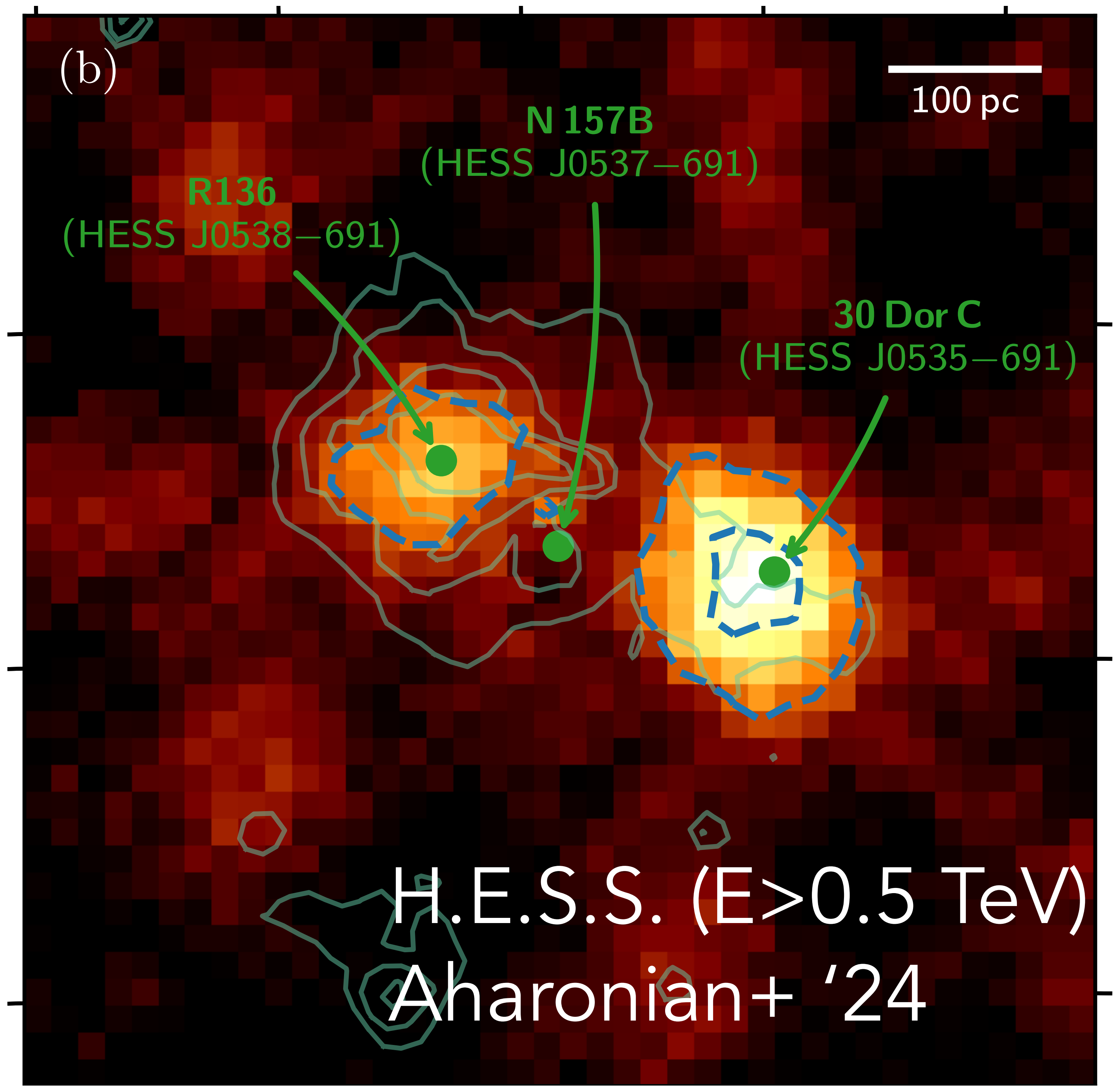
30 Dor C
(talk Lars Mohrman)

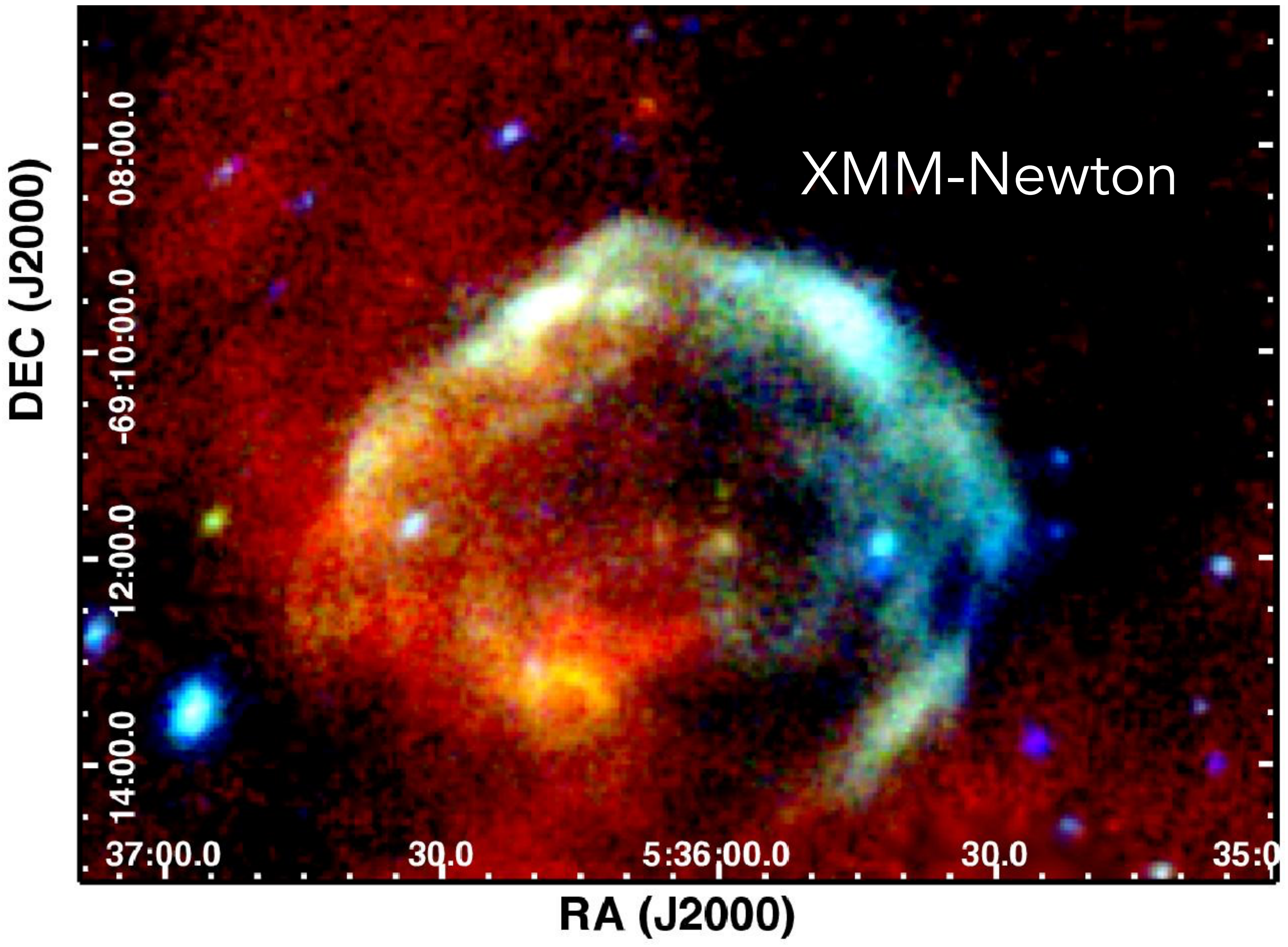
- Radius ~ 45-50 pc
- Non-thermal X-ray and VHE gamma-ray
- X-ray synchrotron: V_{sh} > 3000 km/s
- Optical HII: V<100 km/s (Kavanagh+ '19)
- Most likely explanation X-ray synchrotron:
    - Single SNR, t~6000 yr
    - X-ray width & leptonic model: B~10-20 μG
    - gamma-rays: leptonic

(Bamba+ '04, H.E.S.S. coll+ '15, Kavanagh+ '19, Aharonian+ '24)

•Single SNR, R~50 pc, V> 3000 km/s: n_H~0.0005 cm^{-3}

•$R \approx (Et^2/\rho)^{1/5},\ V_s = \frac{2}{5}\frac{R}{t}$





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NB connection acceleration-diffusion often expressed as

$$D_{xx}D_{pp} = \frac{1}{9}p^2V_A^2$$ **(e.g. Thornbury & Drury)**

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

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

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- NB: a similar equation was derived by Thornbury&Drury (2014)
- Their conclusion: Fermi-2 not important for ISM ($V_{\rm A} \sim 10-30$ km/s)

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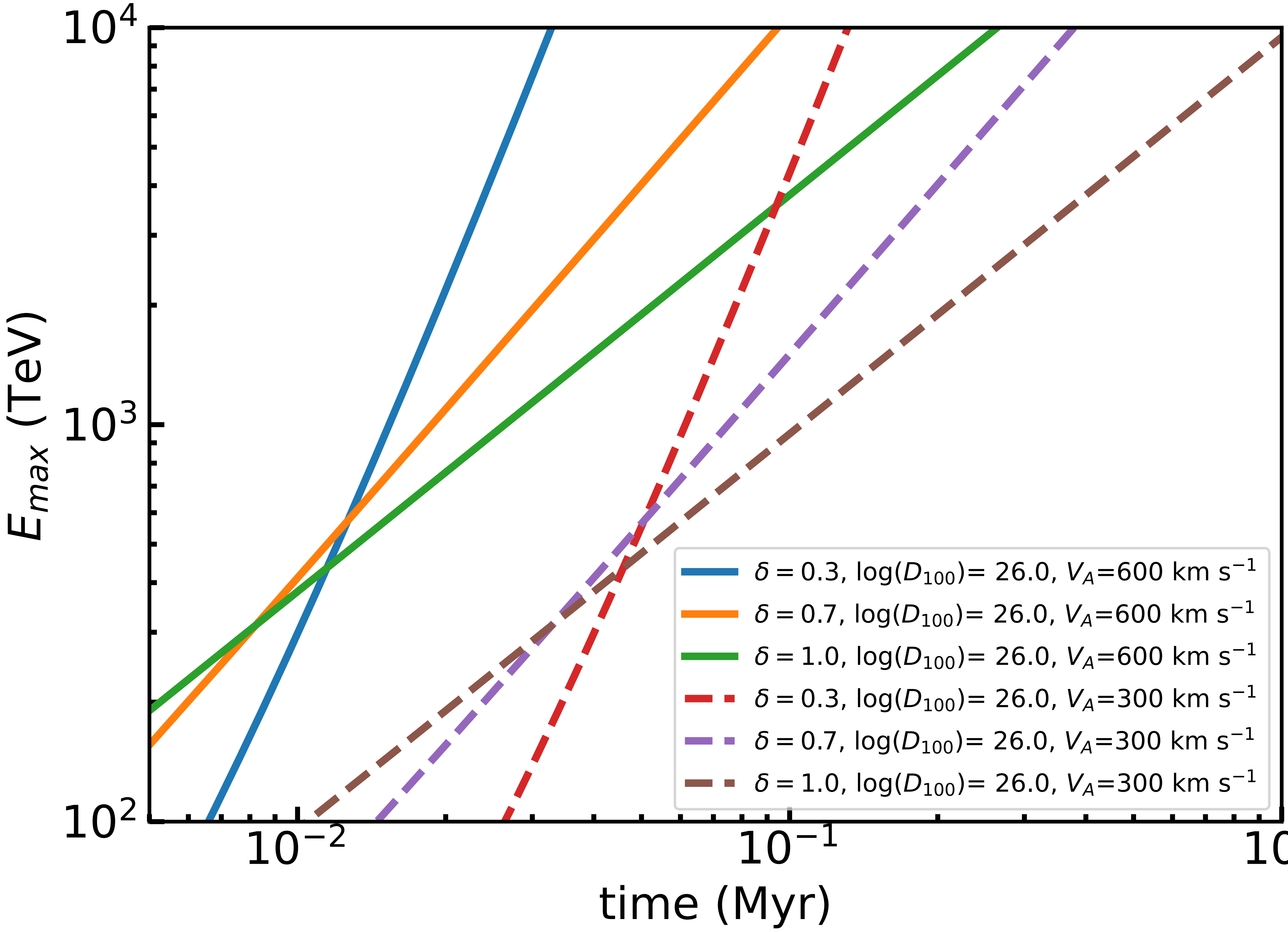
  - For multi-PeV protons: high B and η~1 (Bohm diffusion):
    - E.g. B=30 μG gives $E_{\rm max} \approx 6.8 \times 10^{15}$ eV

Conditions needed for Fermi-2 PeVatrons?



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    - i.e. $n_H \approx 0.001\ \mathrm{cm}^{-3}, B \approx 10 - 50 \mu\mathrm{G}$
  - Need very slow diffusion:
    - $D(100\ \mathrm{TeV}) \approx 10^{26}\ \mathrm{cm}^3\mathrm{s}^{-1}$
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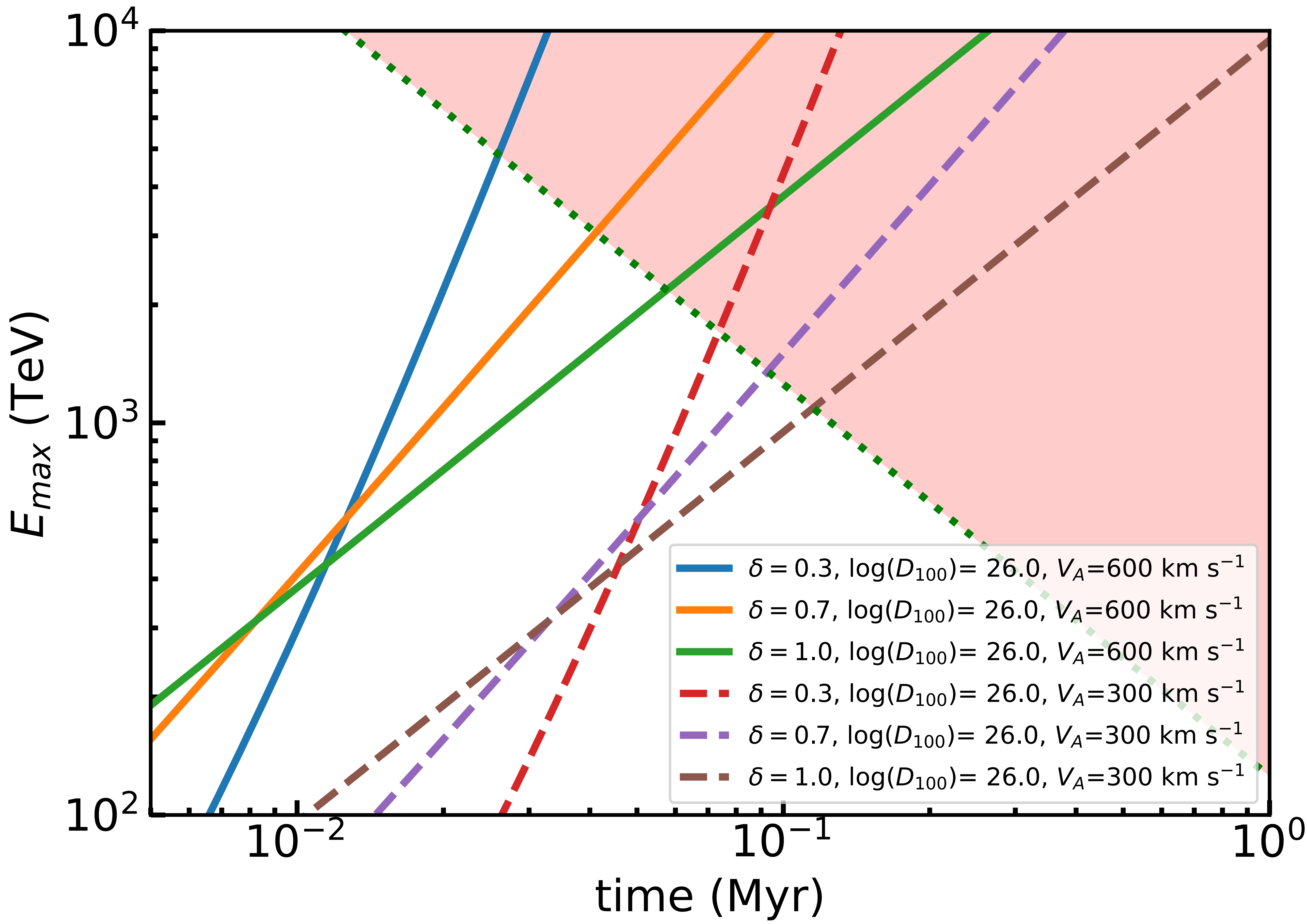

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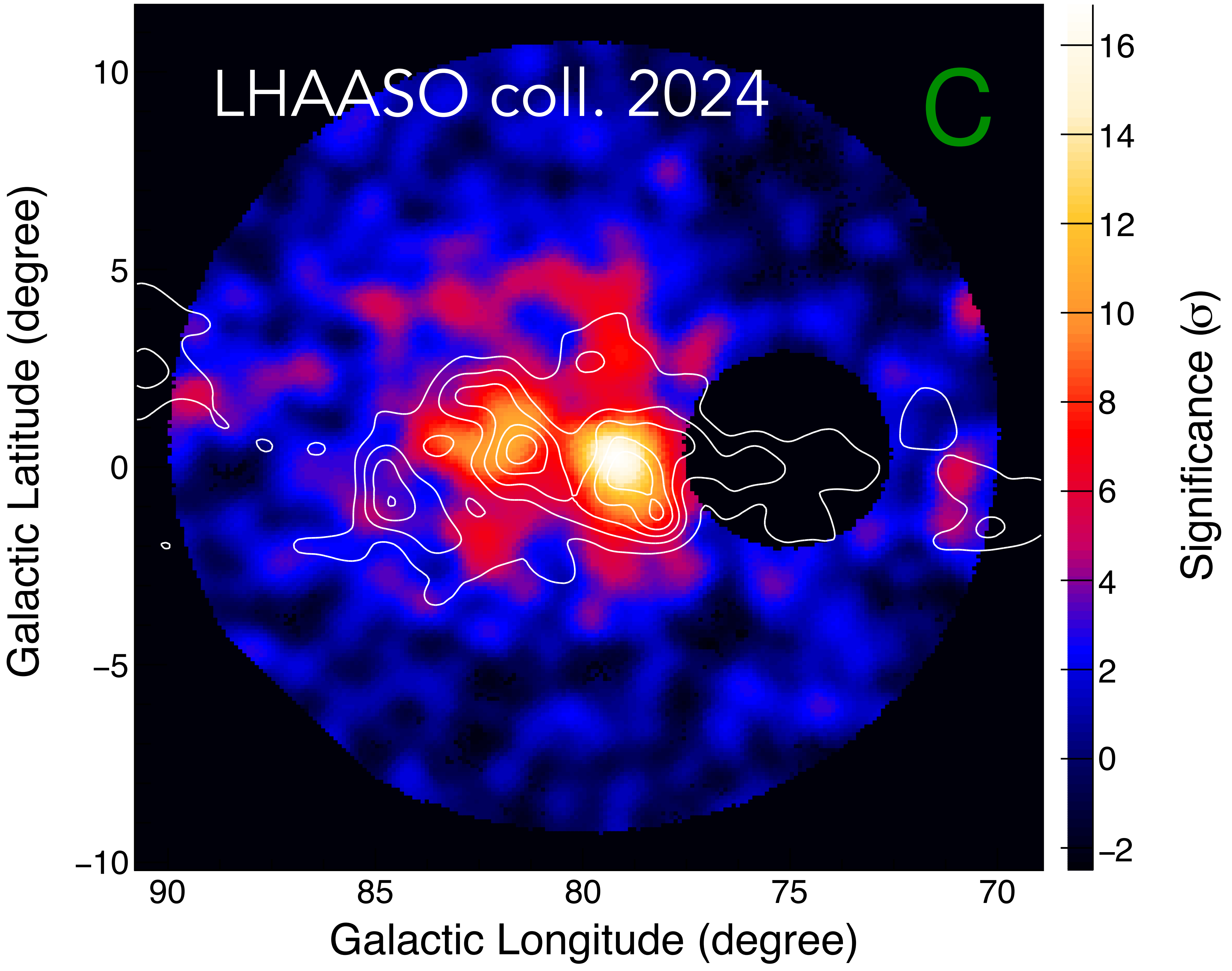
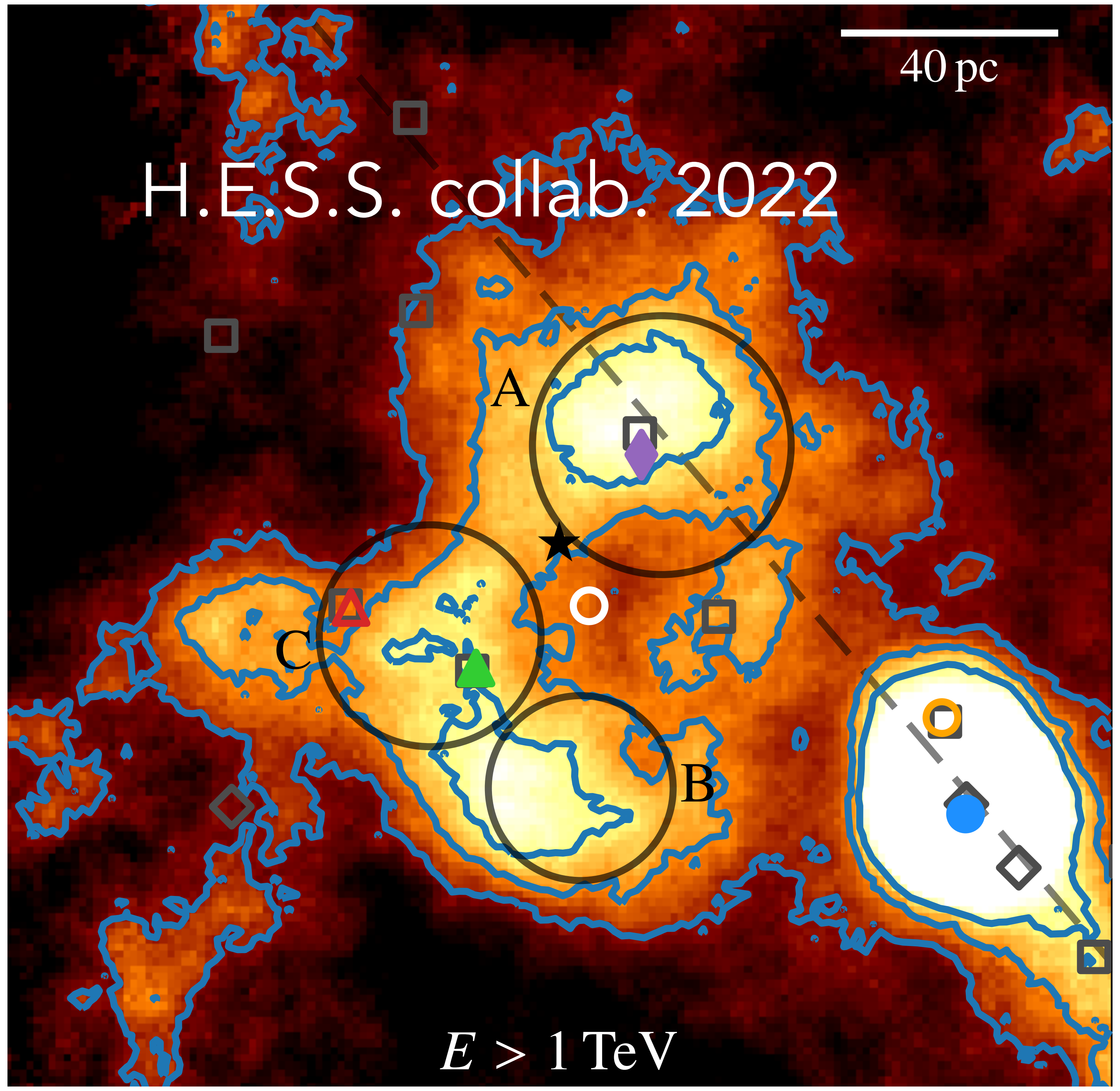
Cygnus Cocoon & Westerlund 1



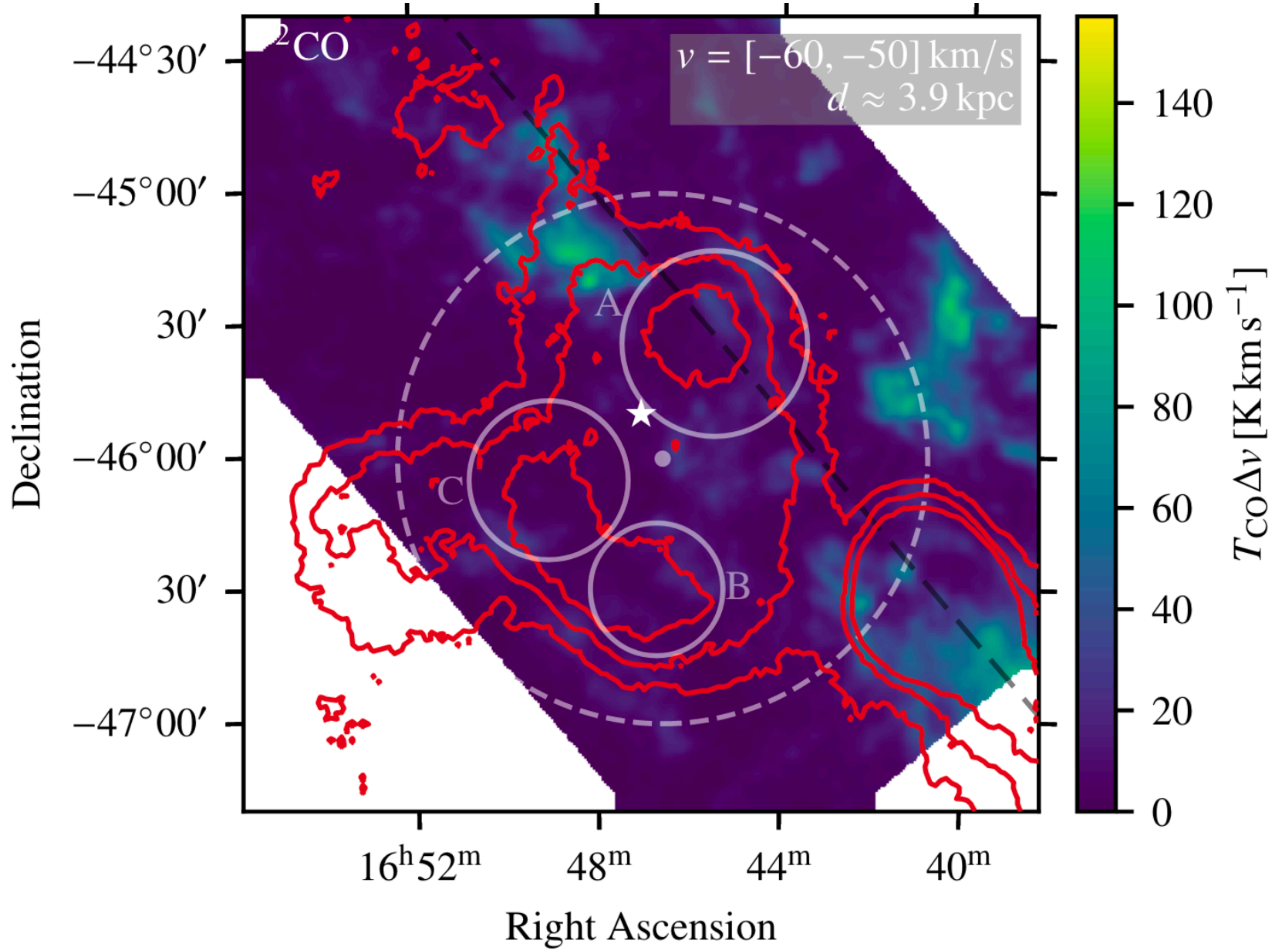


- >0.6 PeV photons
- R~55 pc
- $D(100\ \text{TeV}) \approx \frac{R^2}{6t} \approx 1.4 \times 10^{26} \left(\frac{t}{\text{Myr}}\right)^{-1}$
- Absence of termination shock? (Vieu+ '24)

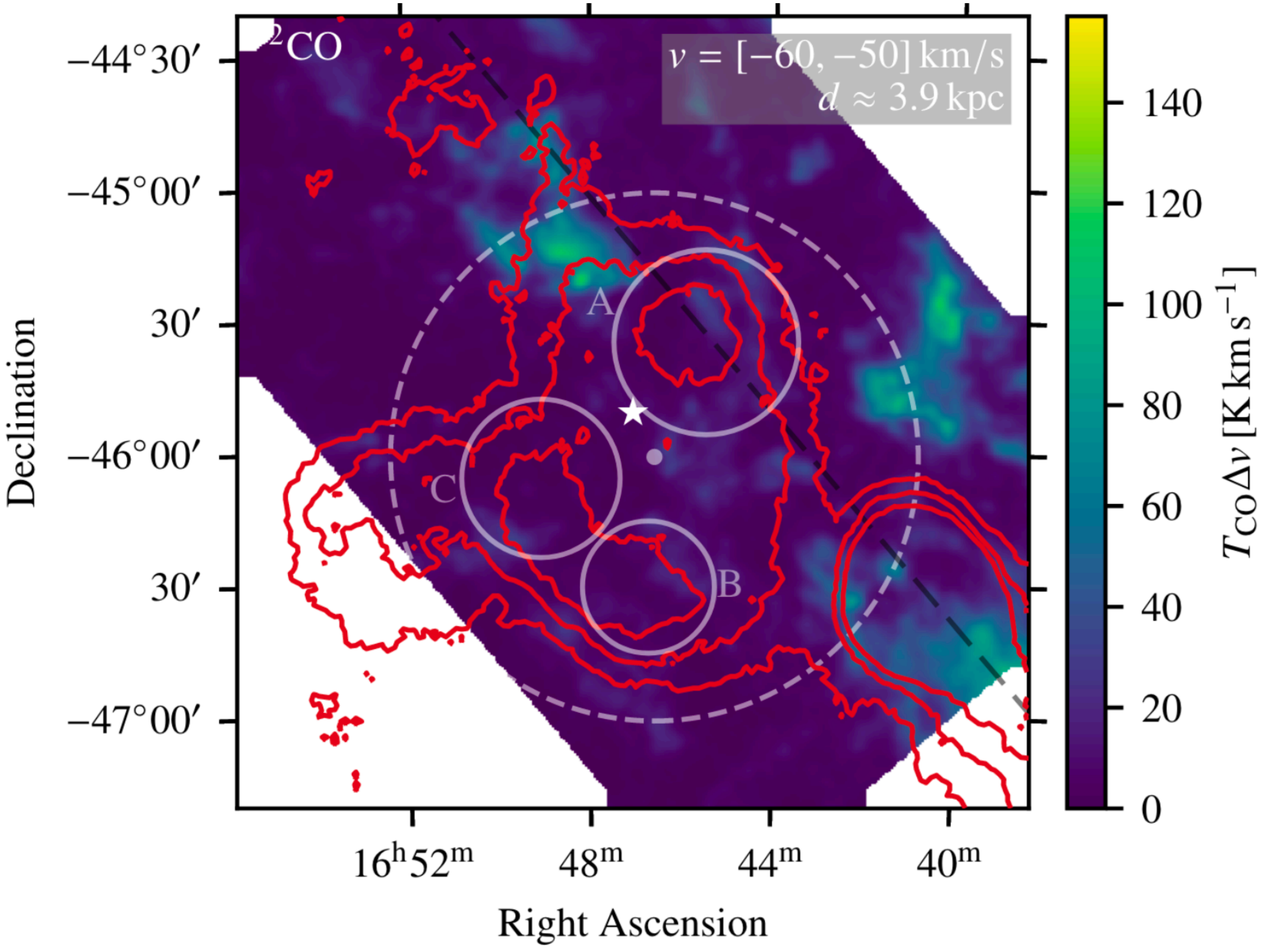
- proton break > 200 TeV
- R~50 pc
- $D(100\ \text{TeV}) \approx \frac{R^2}{6t} \approx 1.2 \times 10^{26} \left(\frac{t}{\text{Myr}}\right)^{-1}$
- H.E.S.S. coll. '24: $B \gtrsim 50\ \mu G$

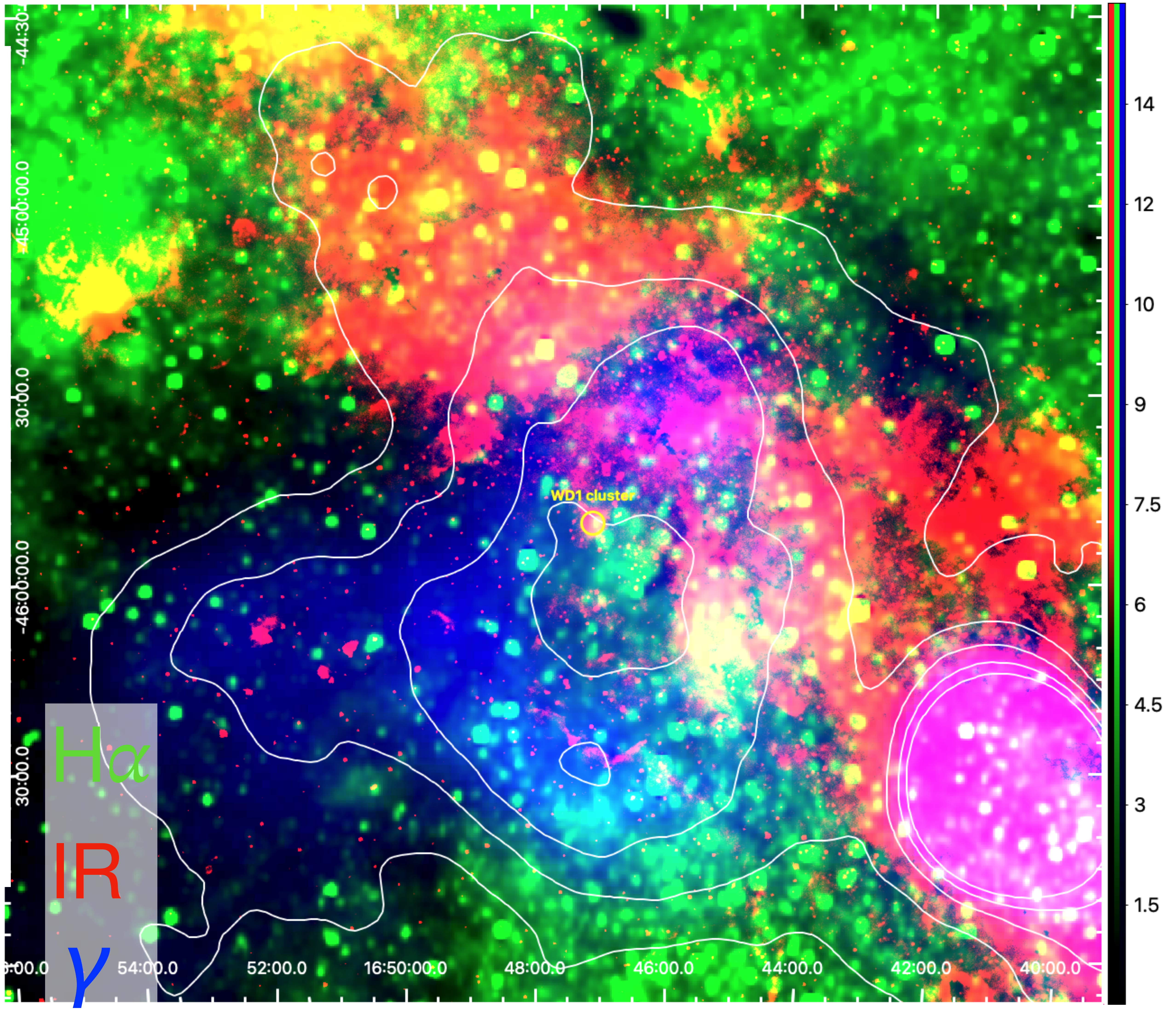
(Bohm diffusion, 200 TeV particles and t=1 Myr)

Westerlund 1 multiwavelength picture: an ISM hole



Westerlund 1 multiwavelength picture: an ISM hole





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- Very rich massive cluster: $L_\mathrm{w} \approx 10^{39}$ erg/s
- Age: 5~Myr (but active for ~Myr?)
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- What about CR energy in bubble vs shell?
  - $< n > = \dfrac{V_{\rm shell} n_{\rm shell} + V_{\rm bubble} n_{\rm bubble}}{V_{\rm tot}}$
  - $\Delta R/R \approx 10\,\% : \ < n > \approx 30\,\%\, n_{\rm shell} \approx 0.3 - 3\ {\rm cm}^{-3}$
  - So $W_{\rm p}$ estimate H.E.S.S. approximately valid, but may be off by factor ~3

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    - Works even if termination shock is weak/absent, provided enough turbulence
  - Cons: Fermi-2 spectrum intrinsically hard (no built-in escape mechanism)
    - Need additional, transport effects to explain spectrum
    - Feeds off turbulent field: needs continuous generation of Alfvén waves

2nd order Fermi acceleration in other environments

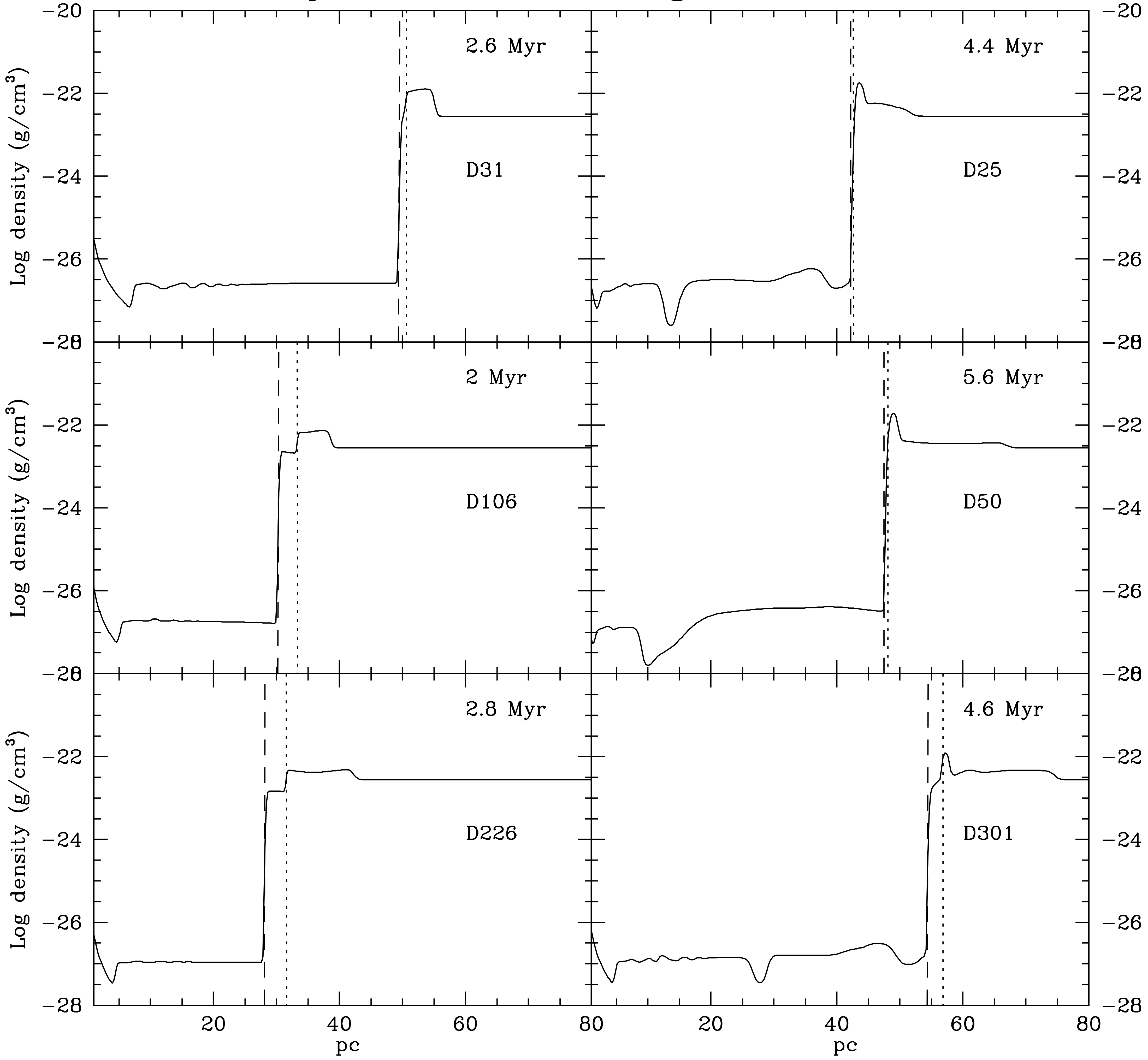
- Fermi-2 often invoked to explain cluster of galaxies' radio "haloes" (Brunnetti & Lazarian '07)
  - haloes require a leptonic origin (instead of secondary leptons from hadronic CRs)
  - prevelant in interacting clusters: source of turbulence
  - haloes are very smooth: not associated with shocks
- It may also explain the (leptonic?) emission from the Fermi bubbles:
  - One needs continuous acceleration
  - Surface brightness flat: filled center rather than shell/shock
  - See Mertsch & Petrosian 2019
- Could it operate efficiently in ISM of starburst galaxies?
  - CR could encounter multiple SBs before escaping galaxy
  - NB UHE CRs seem to require a very hard injection spectrum

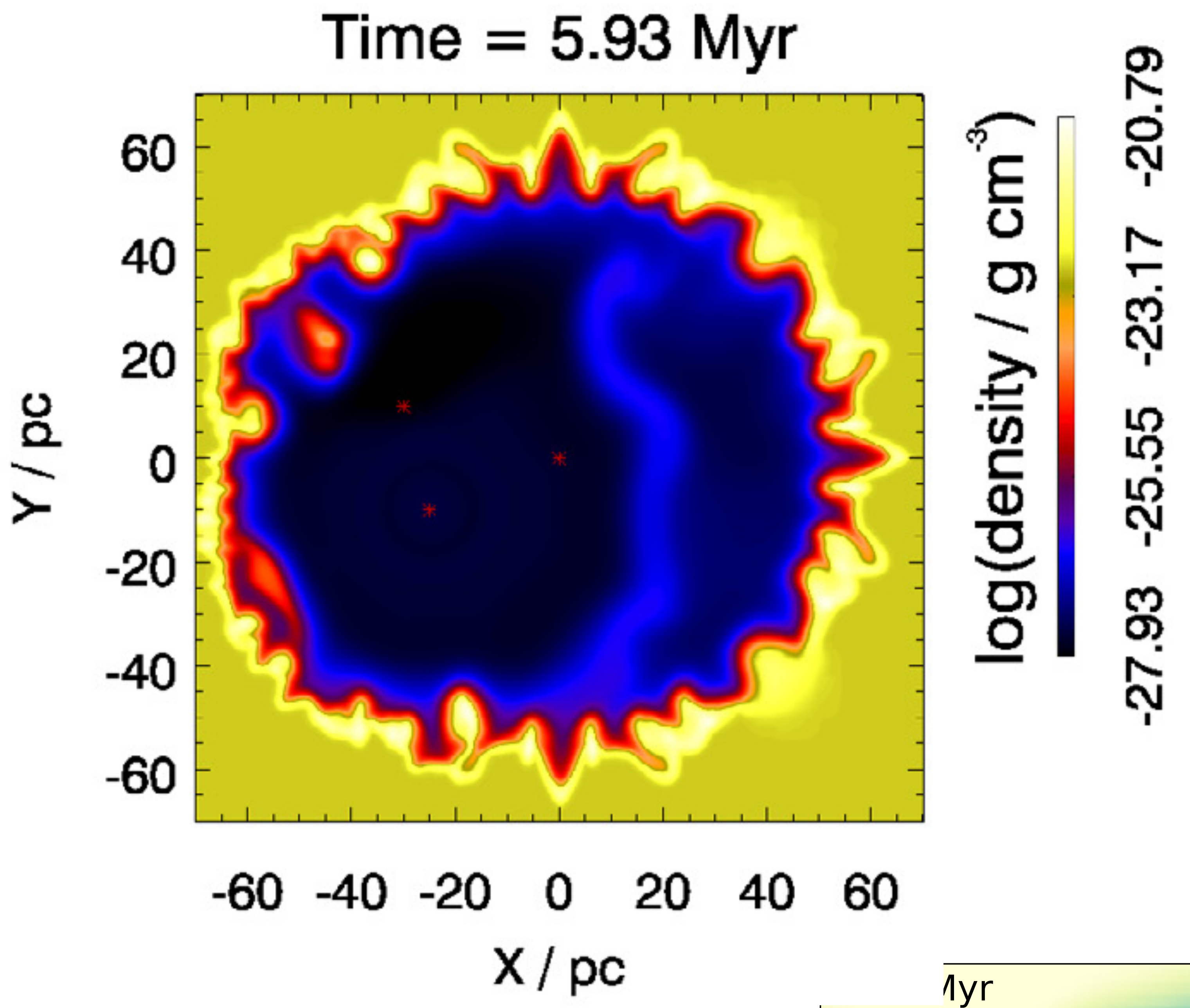
Summary

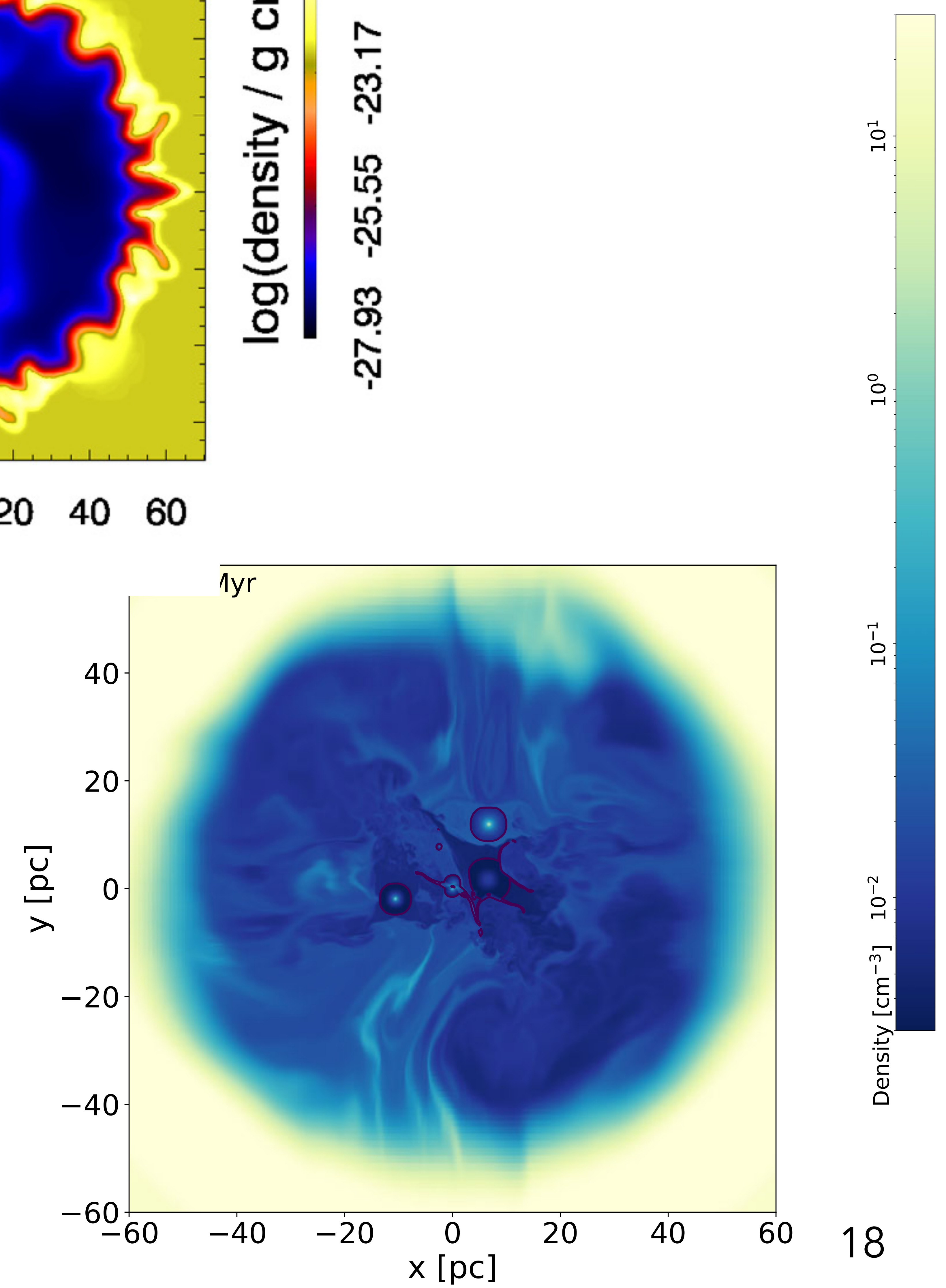
- Despite textbook case: Fermi-2 can be very efficient provided V_A is high and D is small
  - Physics: 2nd order in (V/c), but boost per scattering
  - DSA: multiple scatterings needed before boost
- In superbubbles environment for Fermi-2 potentially ideal:
  - If n~0.001 cm^{-3}: V_A>500 km/s
  - Observational evidence for D(100 TeV)~ 10^{26} $cm^{-3}s$
  - PeV energies cn be reached in those circumstances!
- What needs to be done:
  - realistic calculations of spectrum
  - does Fermi2 predict too hard spectra or will it be softened by transport?
  - does it drain the magnetic-field turbulence too quickly?
    - and if so: what will happen? quenching acceleration? are we sometimes lucky?

Superbubbles sizes and densities

Oey & Garcia-Segura ‘04

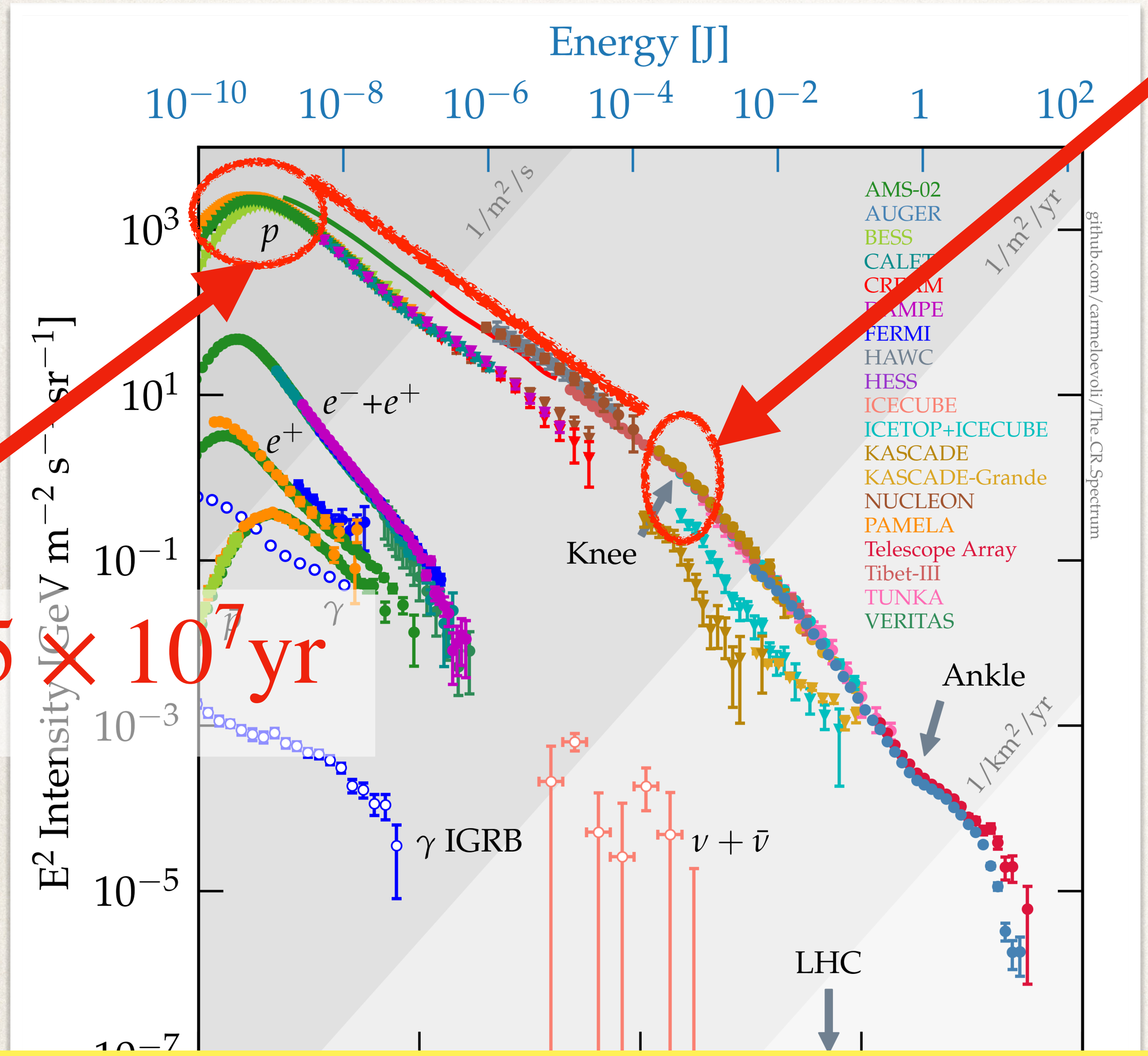






The intermittency of VHE cosmic rays a word of caution

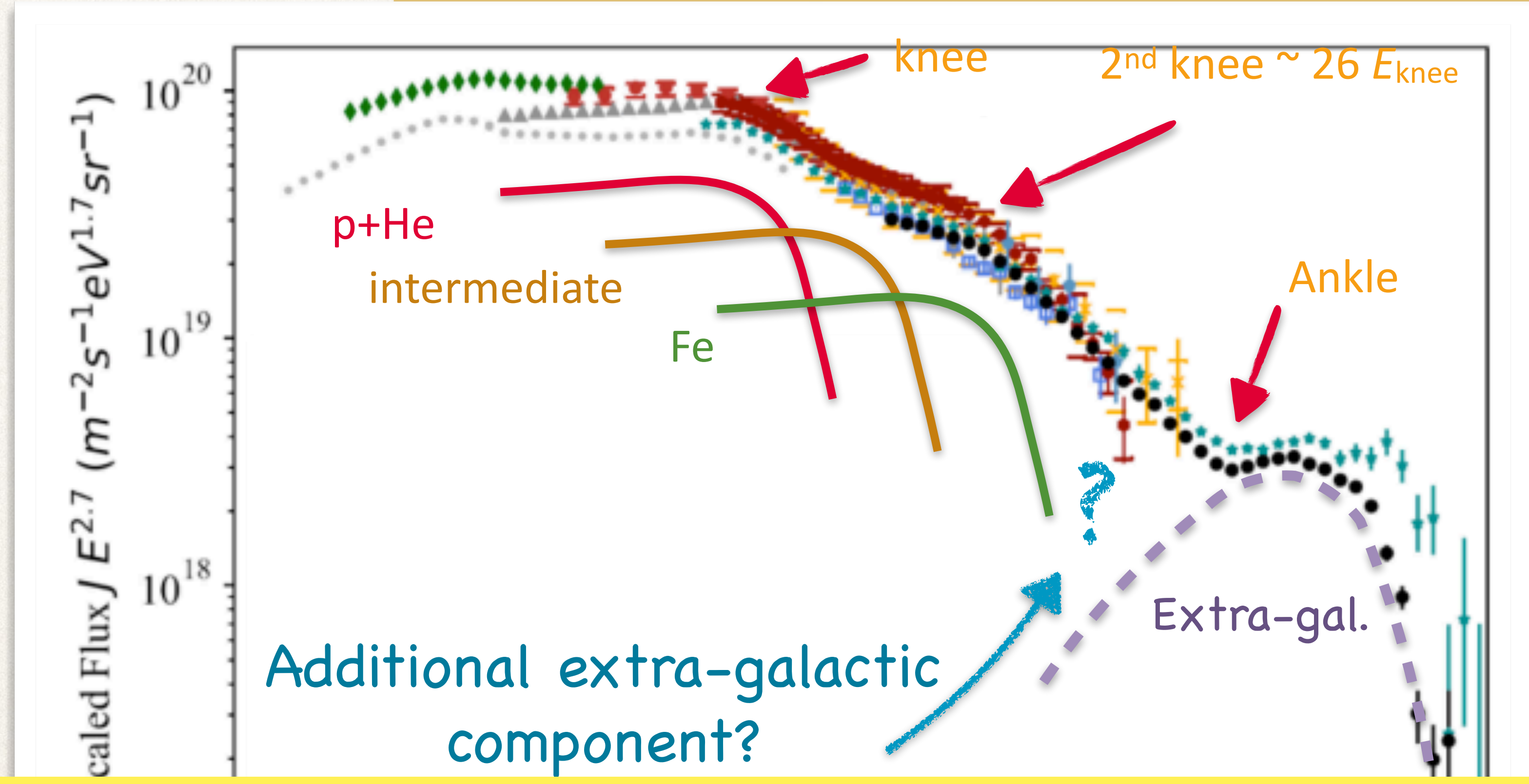
$\tau_{esc} \approx 10^4 - 10^5$yr



$\tau_{esc} \approx 1.5 \times 10^7$yr

Requirements

- **Luminosity:** $\sim 10^{40}$ erg/s
- **Spectrum:** $Q_{\mathrm{inj,Gal}} \propto E^{-2.3}$
- **Maximum energy:** $E_{\max,p} \gtrsim 10^{15}$ eV



At PeV energies the "CR sea" is likely not uniform
Don't try to explain all the details with one type of population