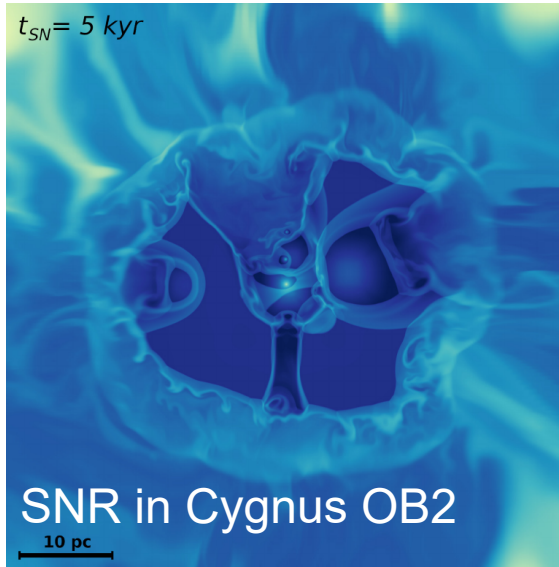
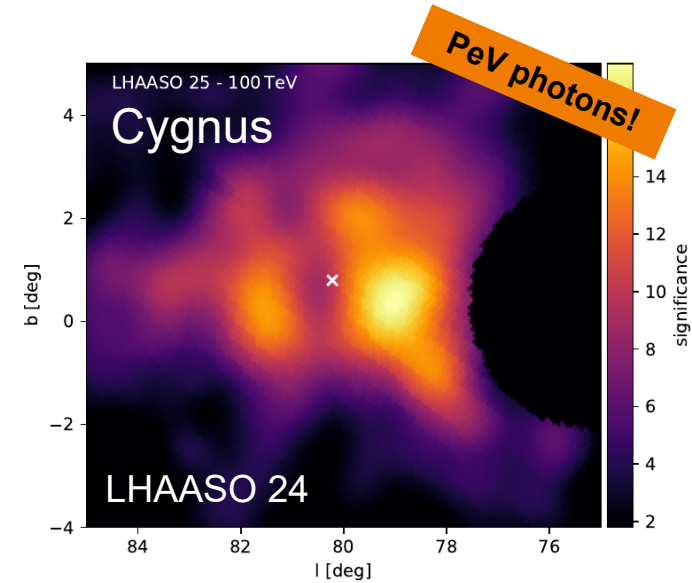


Deciphering the γ -ray emission in the Cygnus region



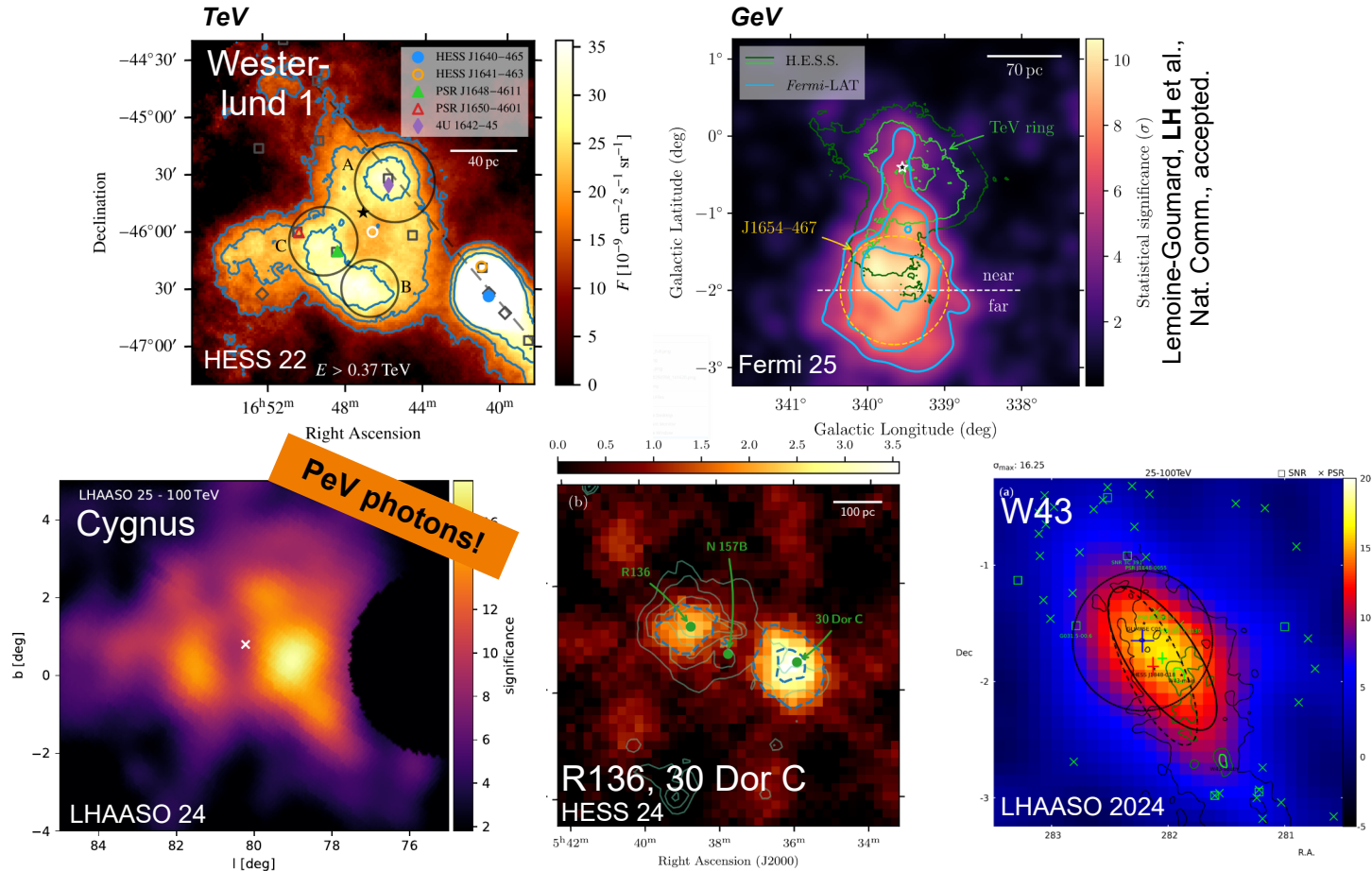
Lucia Härer
with Thibault Vieu, Brian Reville,
Cormac Larkin, Florian Schulze

Oct 10, 2025



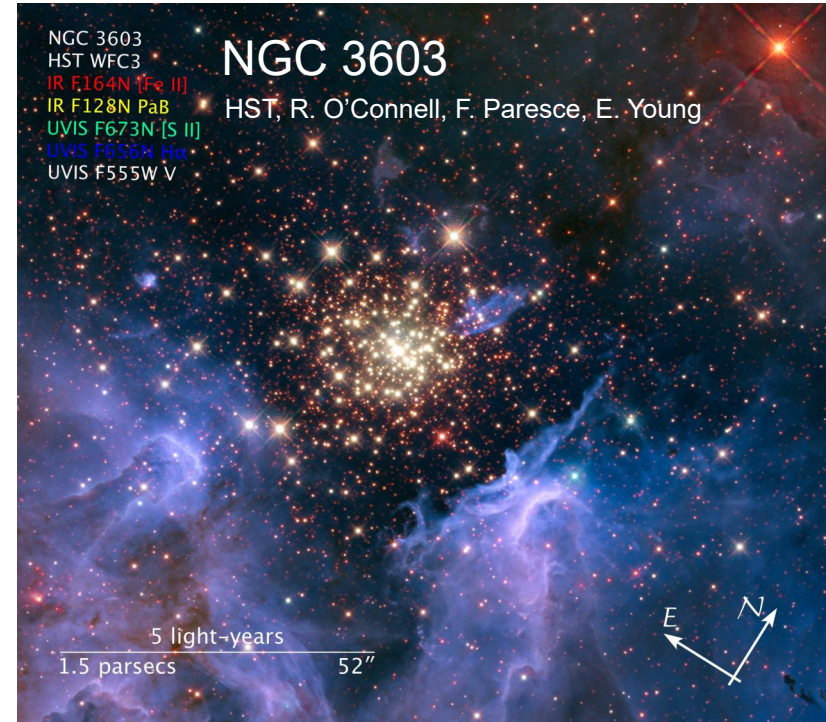
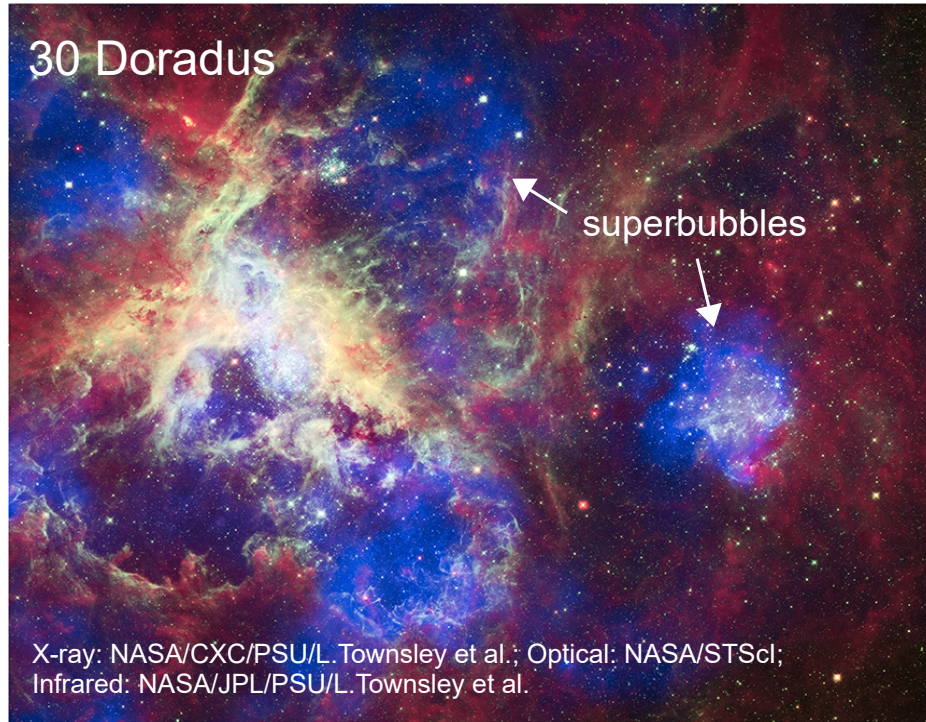
Young star clusters produce γ -rays!

10-100 pc scale diffuse emission



Massive-star environments

are shaped by stellar feedback.

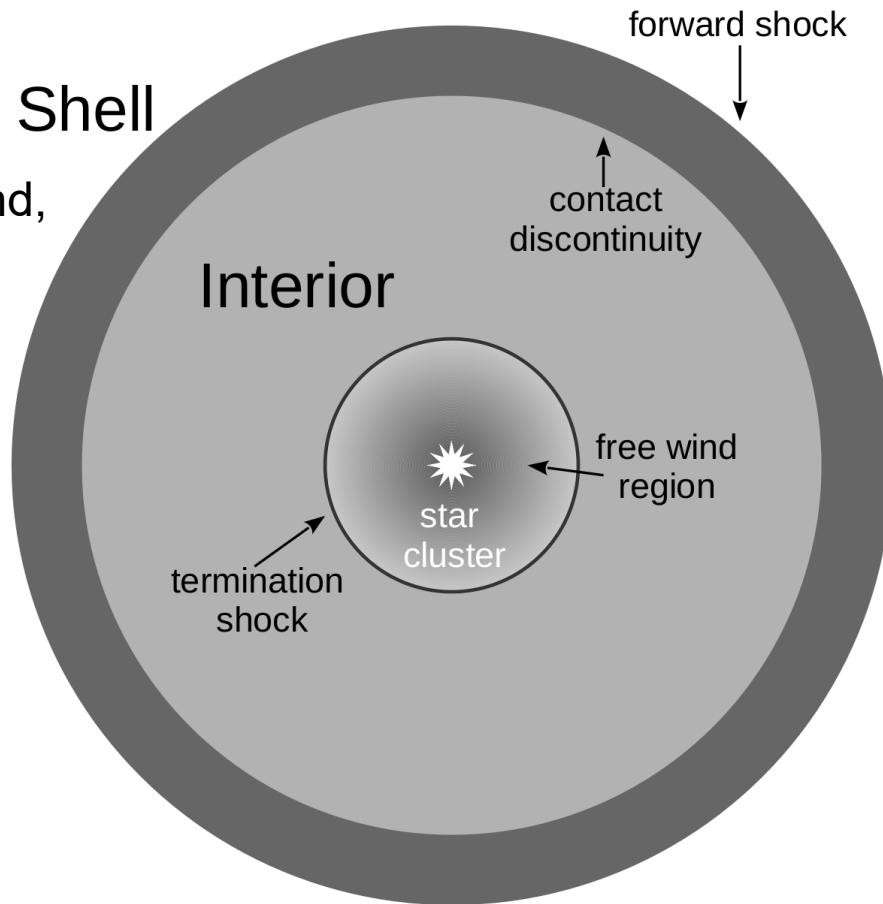


Massive-star environments

Stellar winds and SNe blow superbubbles.

Idealised 1D model:
(Weaver+ 77)

single star, continuous wind,
homogeneous medium



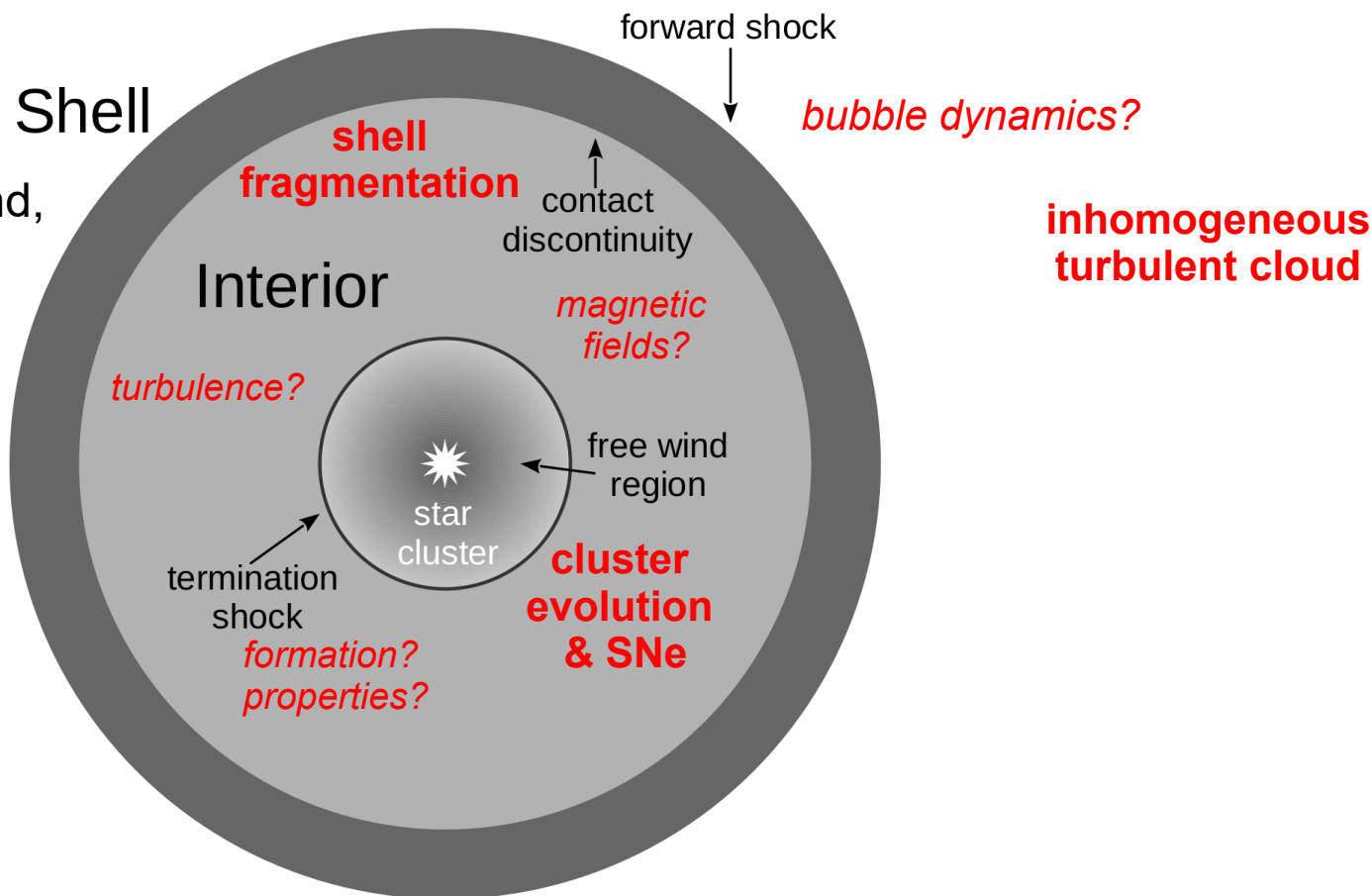
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Many **complications**
and *unknowns* ...



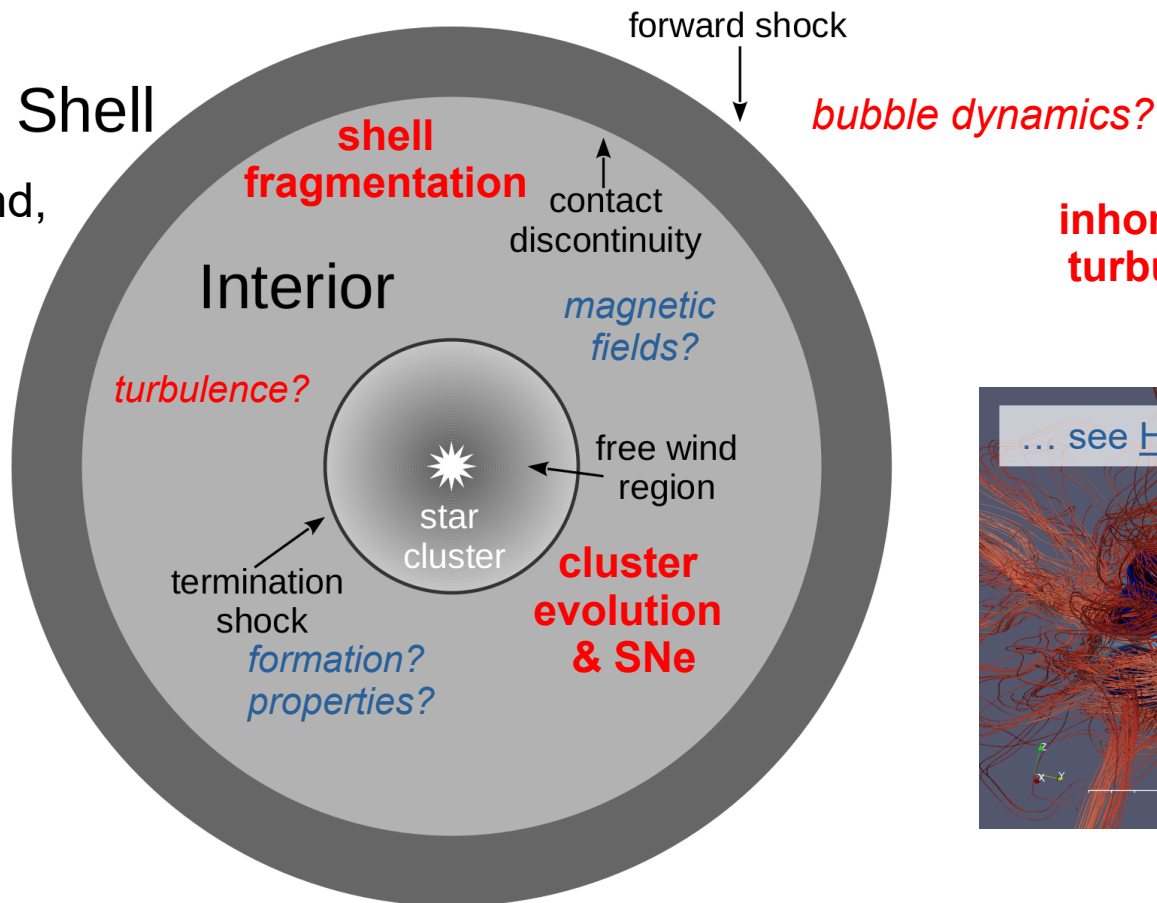
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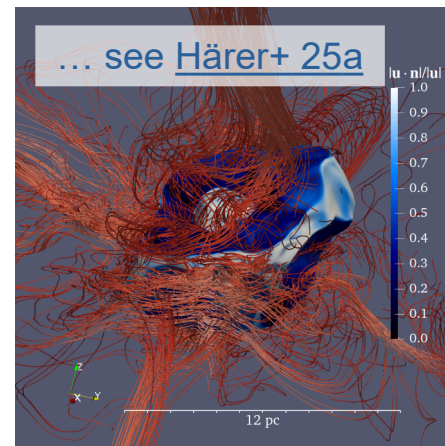
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**inhomogeneous
turbulent cloud**



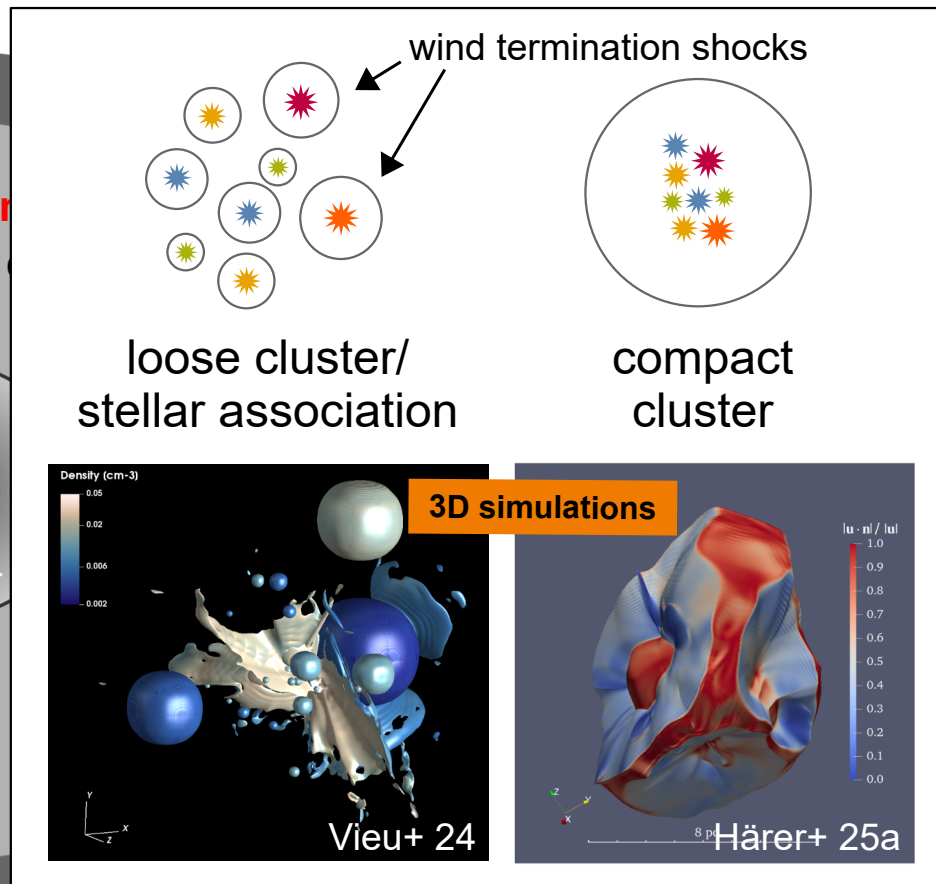
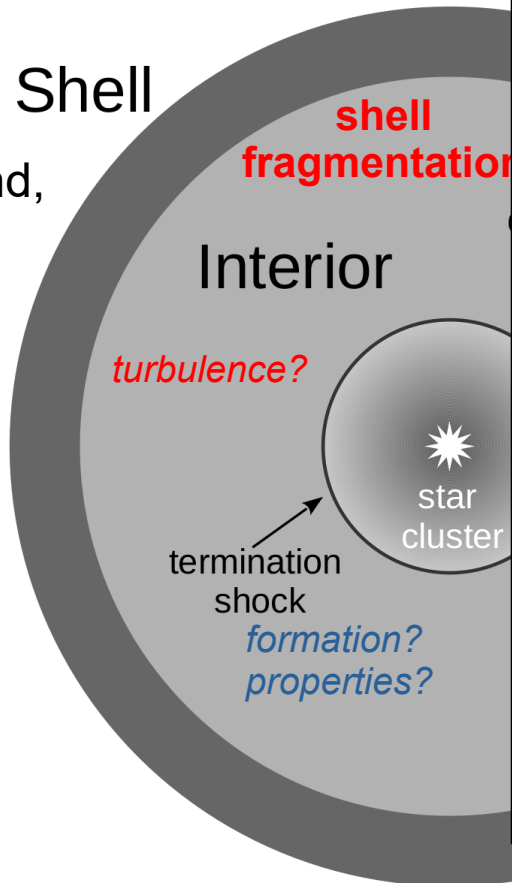
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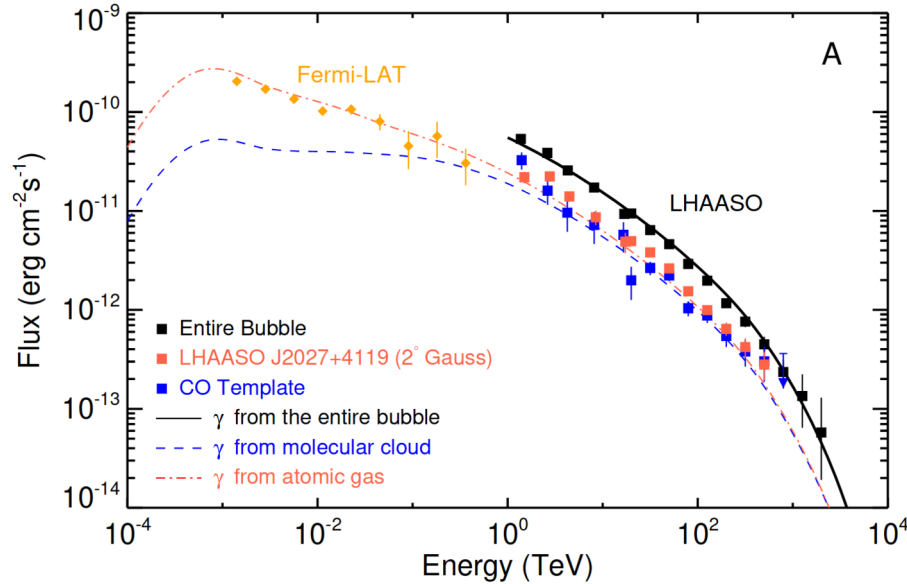


Acceleration around star clusters – What we know

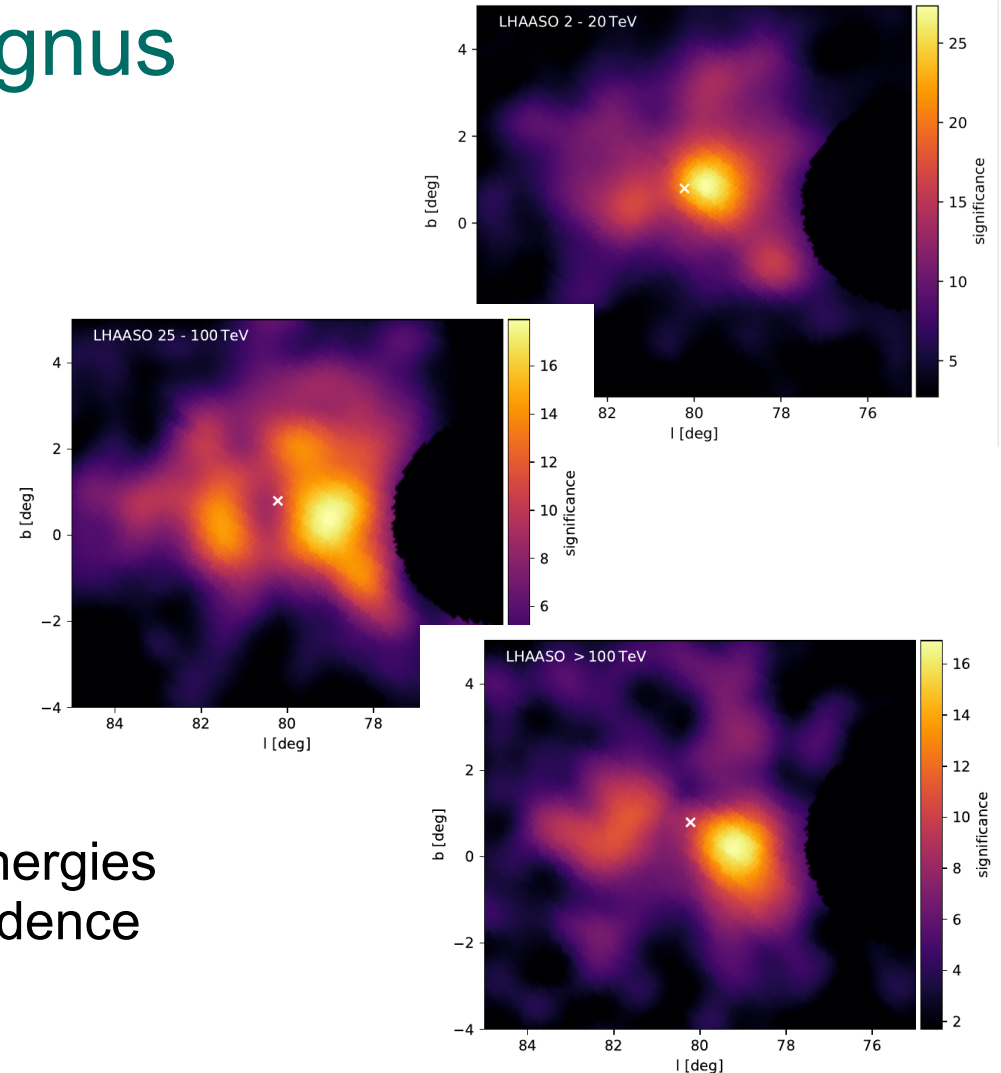
- Low-density, turbulent bubbles are **ubiquitous** around star clusters.
(see Chu 08)
- Continuous injection at winds shocks + high radiation fields + low-density bubble
→ **leptonic** scenarios naturally favoured! (e.g. Westerlund 1: Härer+ 23)
... except in very young (< 1 Myr) embedded clusters. (Peron+24)
- Cluster wind shocks are **unlikely** to reach PeV, but **SNRs in clusters** can.
(Hillas' limit; e.g. Morlino+ 21, Vieu & Reville 23, Härer+ 25)
 - Most SNe explode in clusters! (Higdon & Lingenfelter 05)
 - SNe in clusters can explain CRs to ~ 100 PeV. (Vieu & Reville 23)
- Colliding winds: ~~PeV~~, **no** spectral signatures in realistic scenarios.
(Upstream adiabatic losses, Vieu+ 24)
- Superbubble turbulent reacceleration: ~~PeV~~, might produce **bump** at $\sim$ GeV.
(Ferrand & Marcowith 10, Vieu+ 22)

PeV γ -rays from Cygnus

LHAASO (2024)

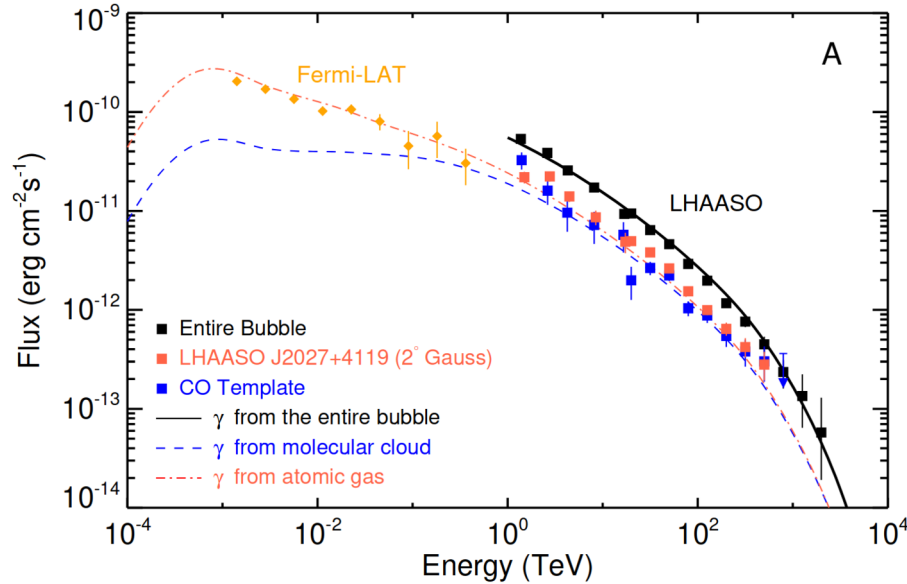


- Steep, curved spectrum up to PeV energies
- Emission over ~ 5 deg, energy dependence

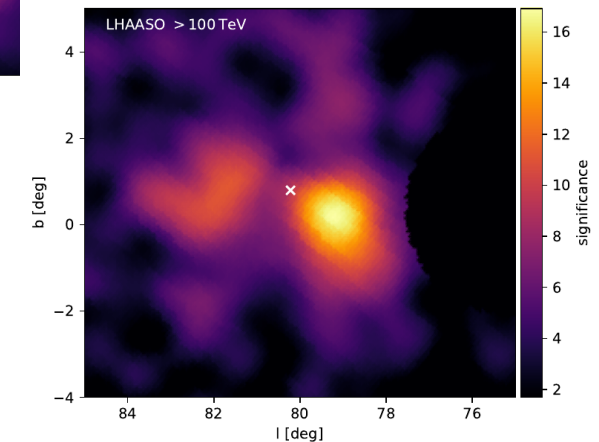
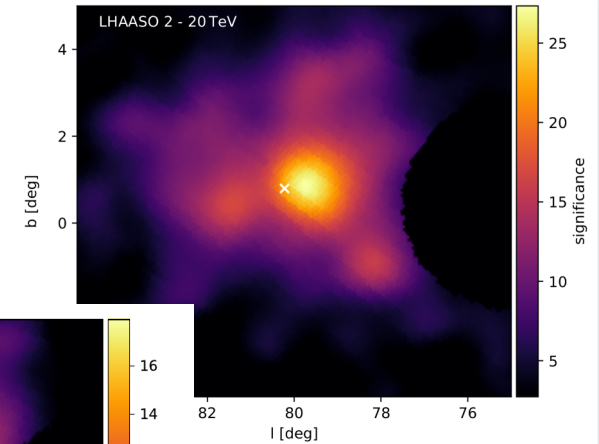
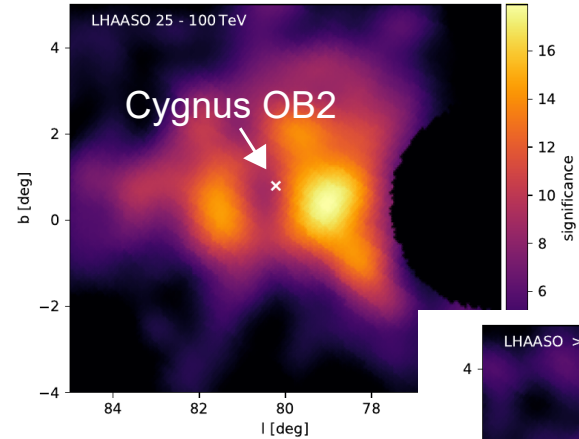


PeV γ -rays from Cygnus

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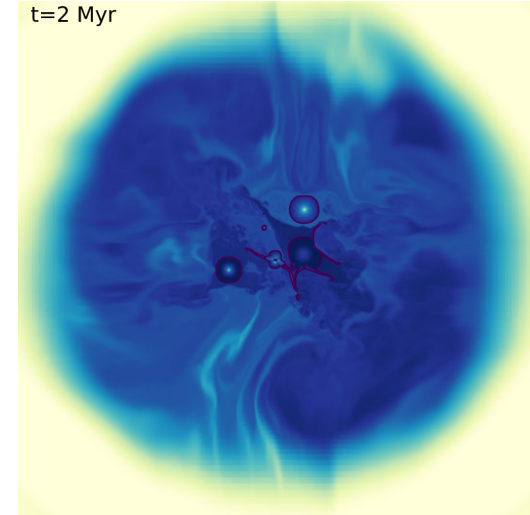
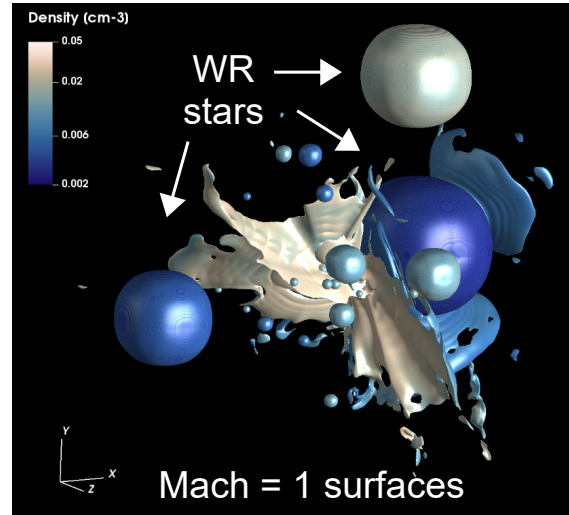
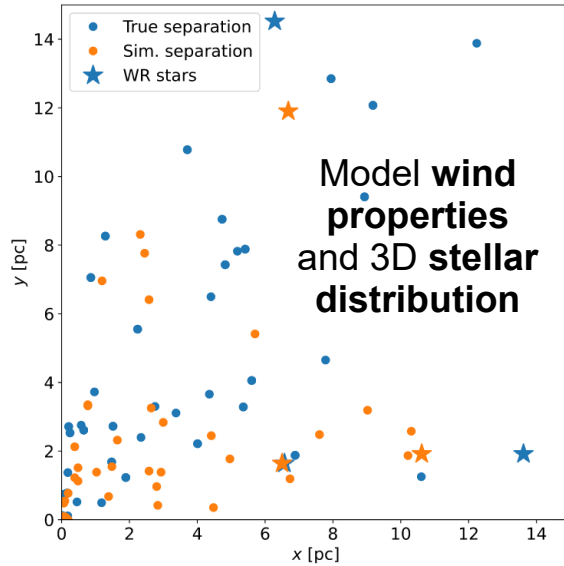


- Steep, curved spectrum up to PeV energies
- Emission over ~ 5 deg, energy dependence



Simulating Cygnus OB2

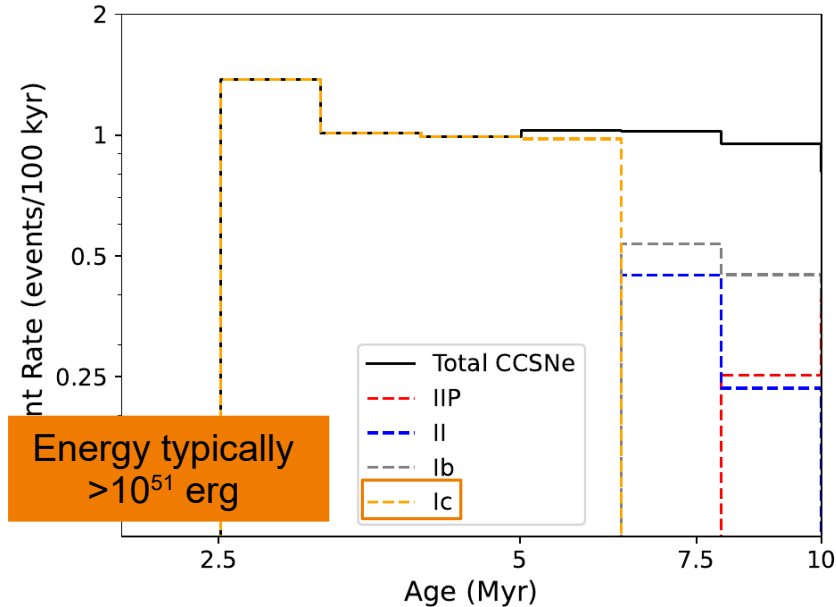
A loose cluster (stellar association)



- 3D HD simulation wind-wind interaction in Cygnus OB2 (Vieu, Larkin, Härer +24)
- **No cluster WTS**, even after several Myr $\rightarrow$ cut-off at $\sim 10\text{s}$ of TeV (Hillas' limit)

A “recent” supernova in Cygnus OB2

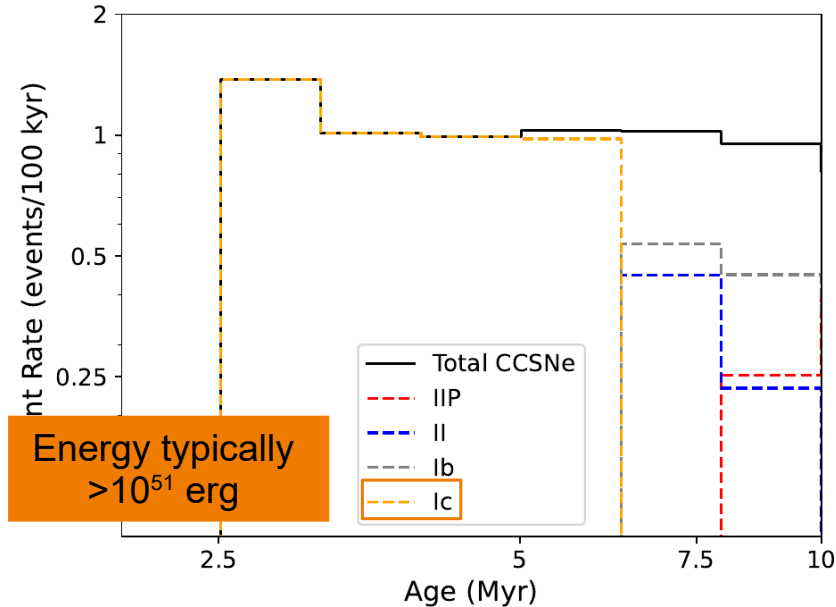
Energetic SN has probably occurred in
Cyg OB2 in the last ~100 kyr



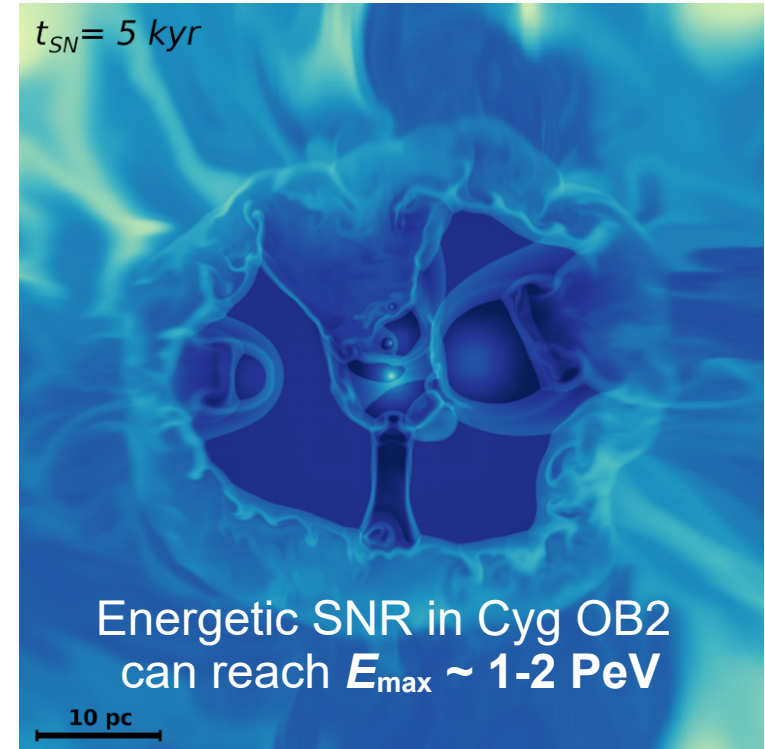
Estimate for SN event rates for Cyg OB2
[Hoki/BPASS]

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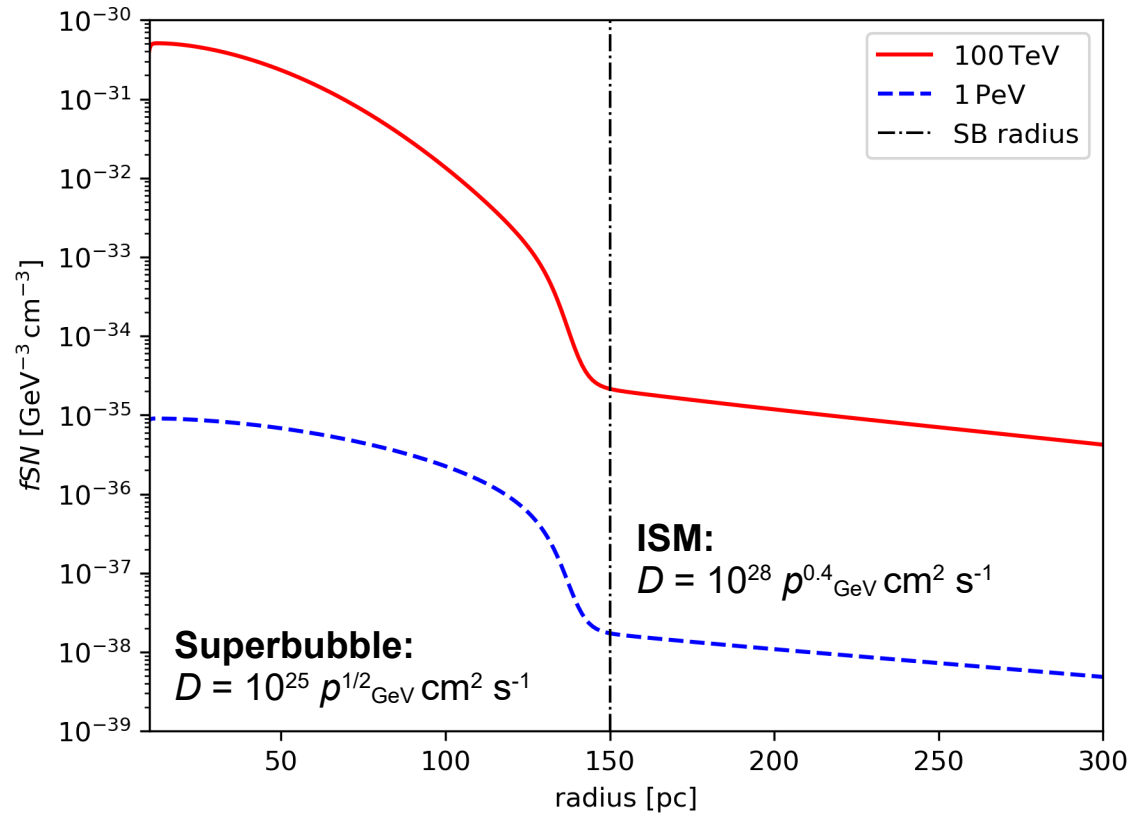


3D HD simulation
B-field energy: 10% downstream flow

γ -rays from Cygnus – a “recent” supernova?

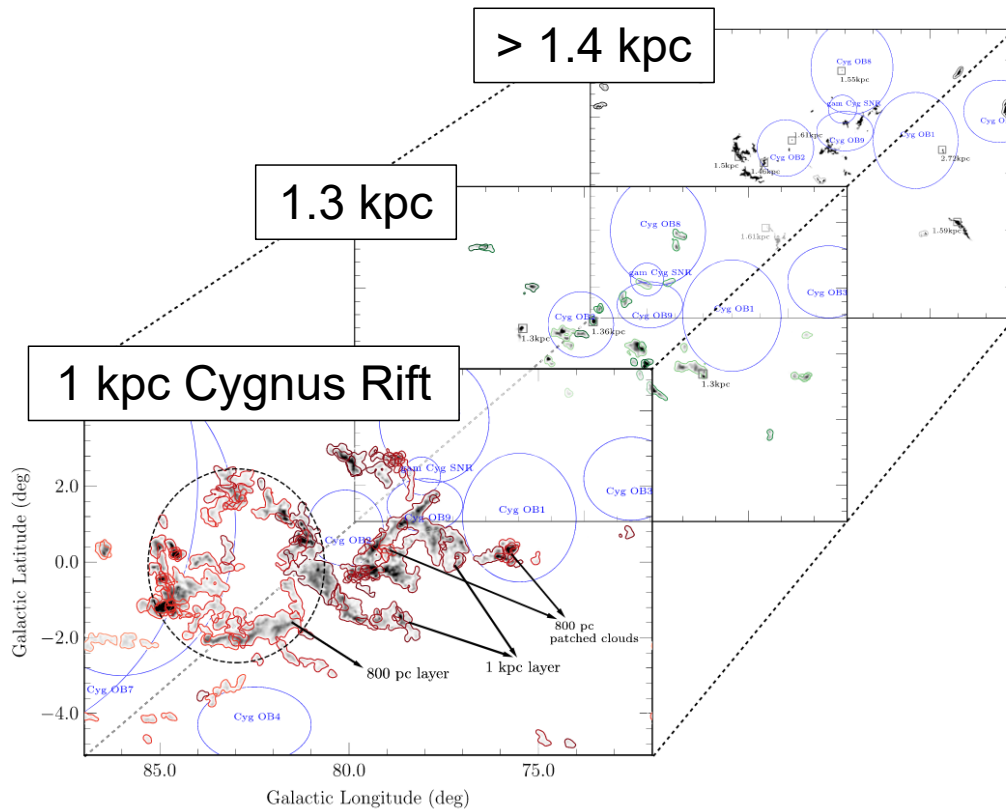
- No SNR observed $\rightarrow$ SN several 10 kyr old
 - ~ 150 pc superbubble (low density, slow diffusion)
 - Within several 10 kyr, PeV protons are expected to pass 150 pc
 $\rightarrow$ require two-zone diffusion model
- $\rightarrow$ *solve transport equation numerically (1D spherical), convolve with target material and fields, compute γ -ray emission (GAMERA)*

Radial proton distribution for a 50 kyr SNR



Clouds and neutral medium – 3D model

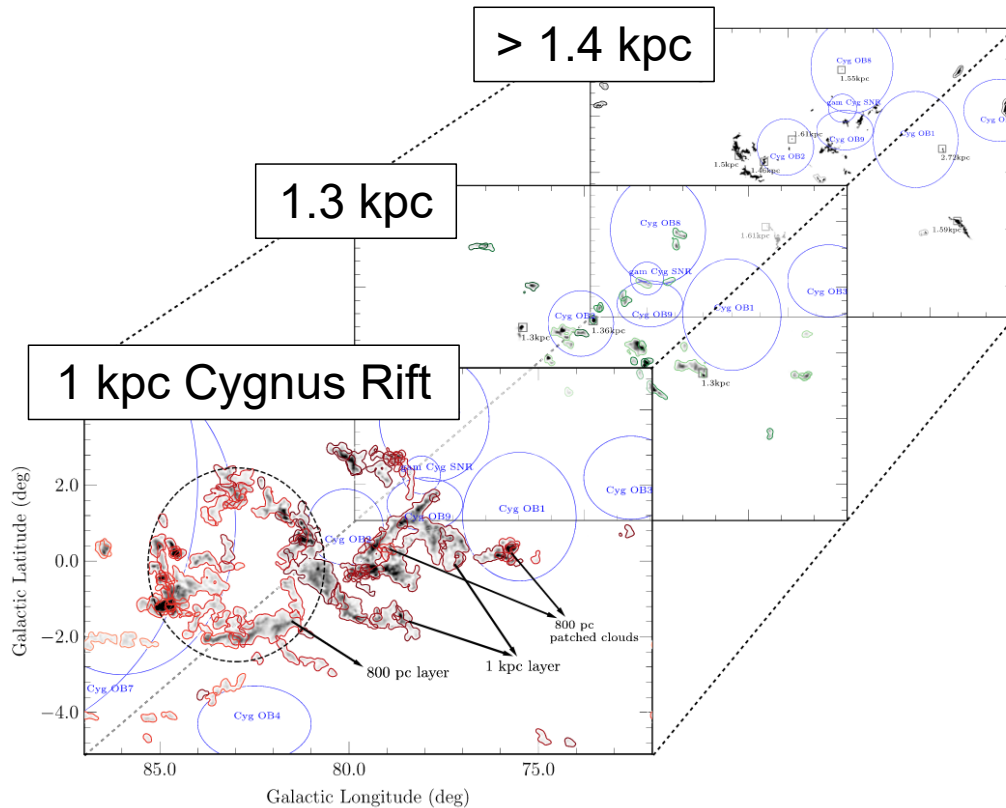
Complex, multi-layered structure – challenging to disentangle



Zhang+ 24

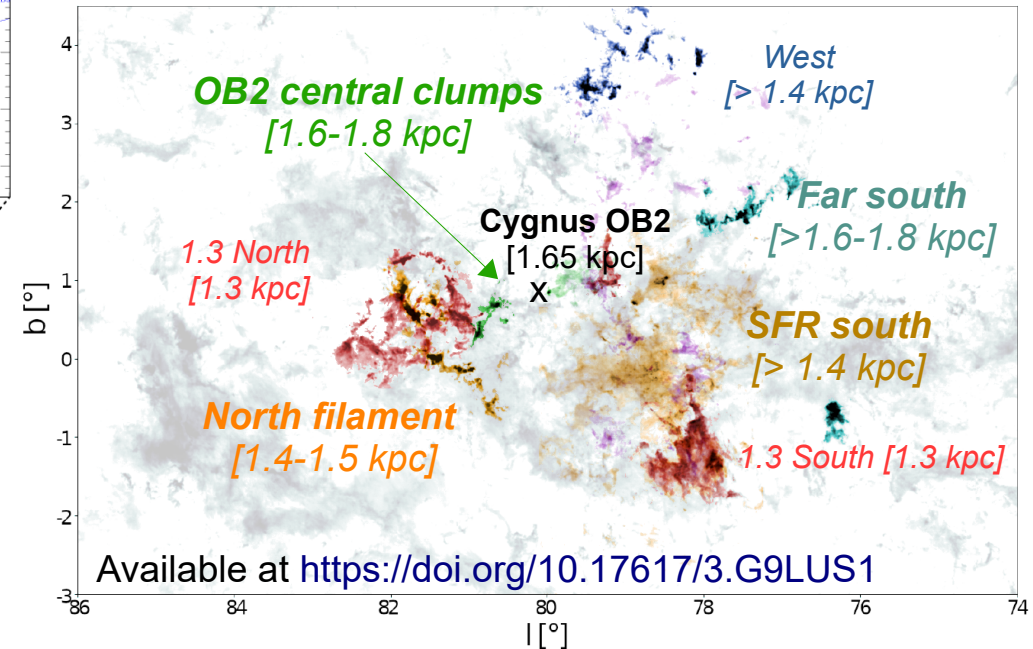
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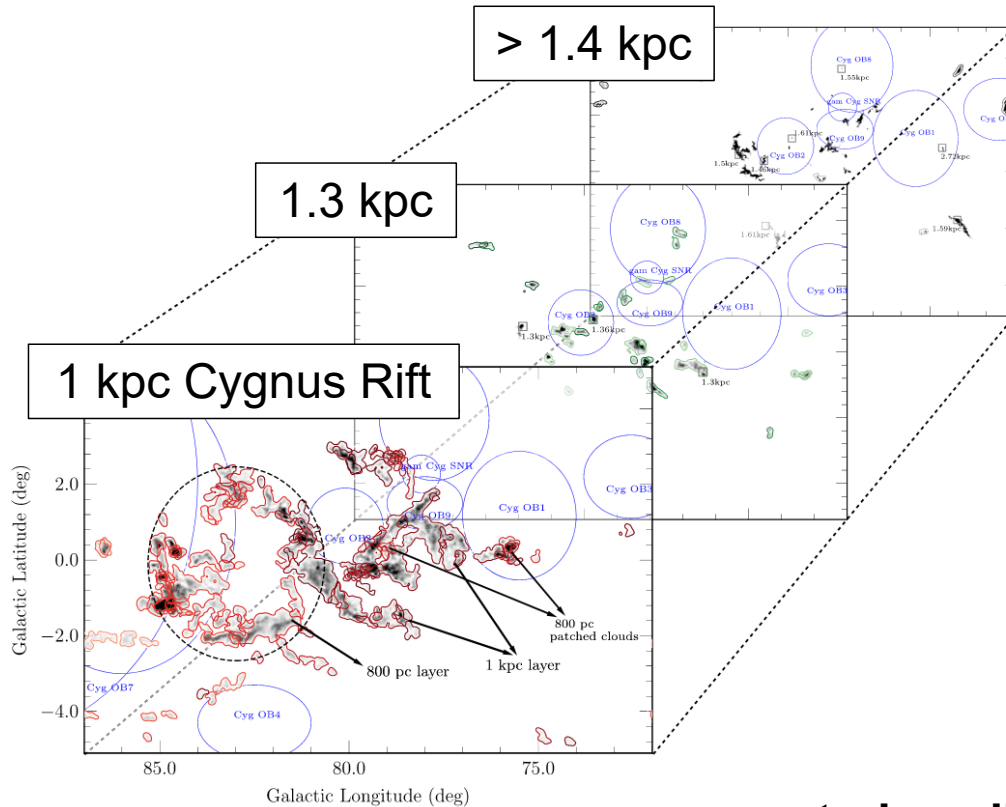
Clouds > 1.3 kpc
based mainly on Schneider+ 06 & 07, Zhang+ 24



Available at <https://doi.org/10.17617/3.G9LUS1>

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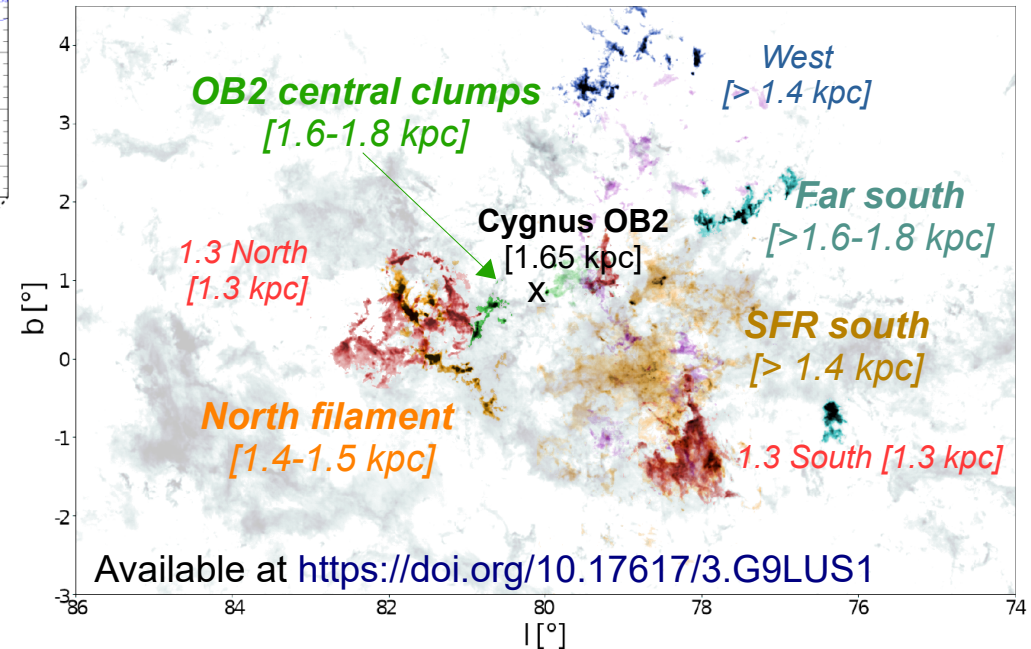
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Lucia Härer, lucia.haerer@mpi-hd.mpg.de

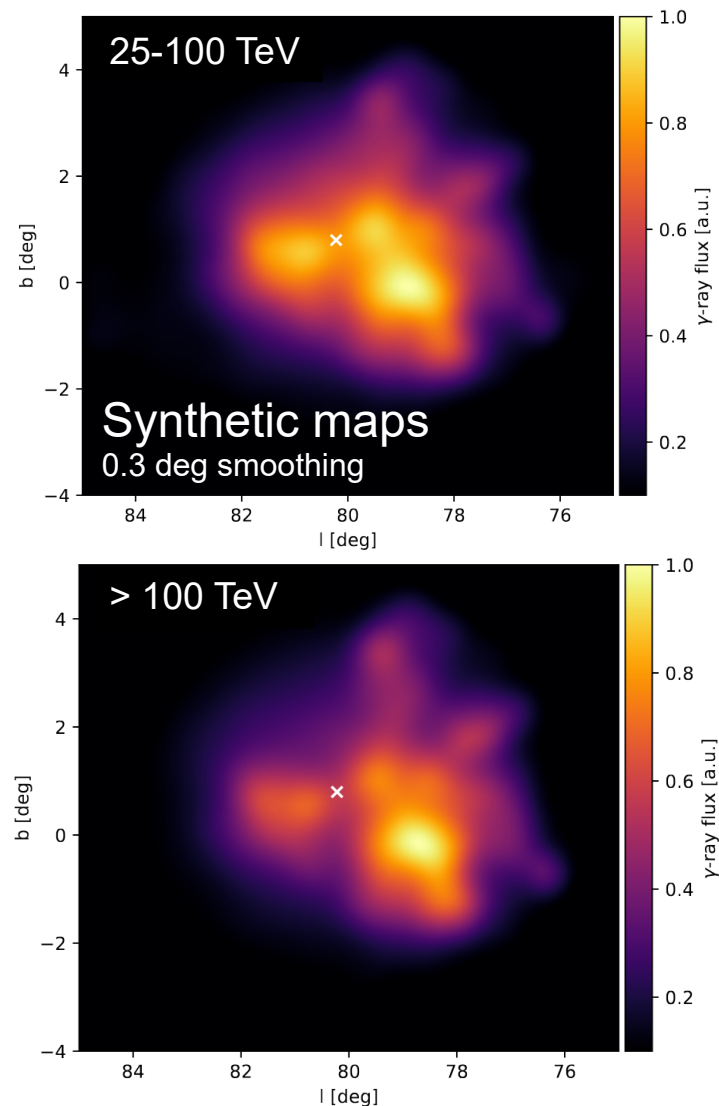
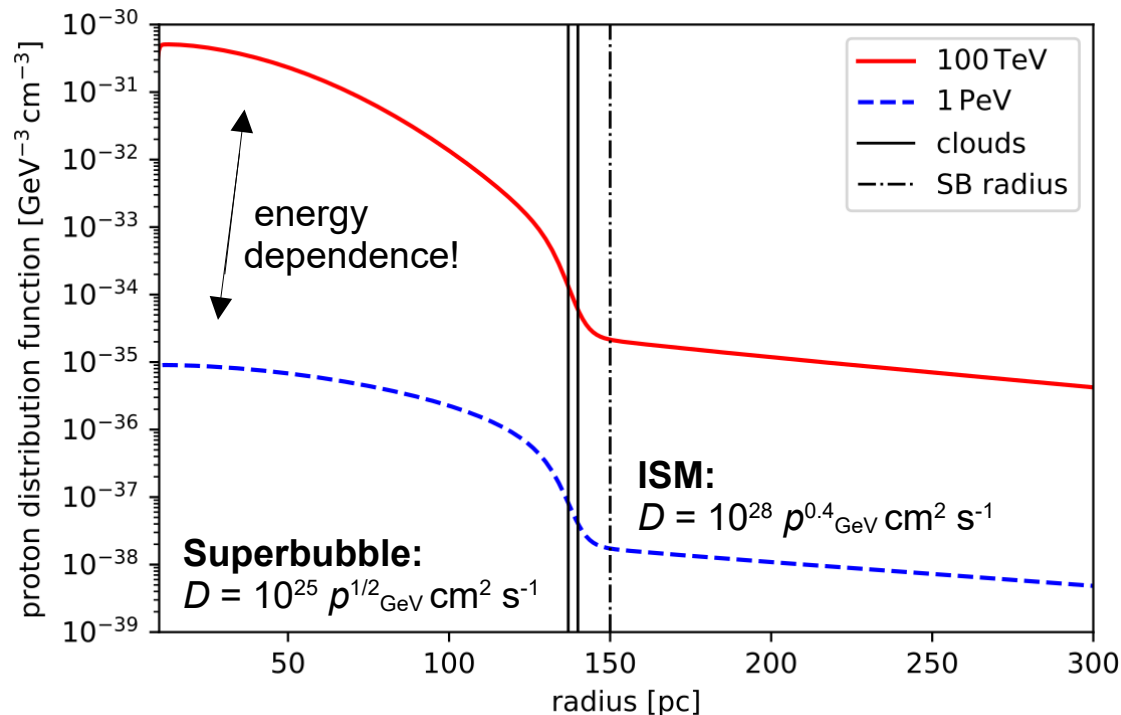
Clouds > 1.3 kpc
based mainly on Schneider+ 06 & 07, Zhang+ 24



+ **neutral medium**: Rift (1 kpc) and SFR (1.7 kpc) incl.
150 pc cavity around Cygnus OB2

Morphology

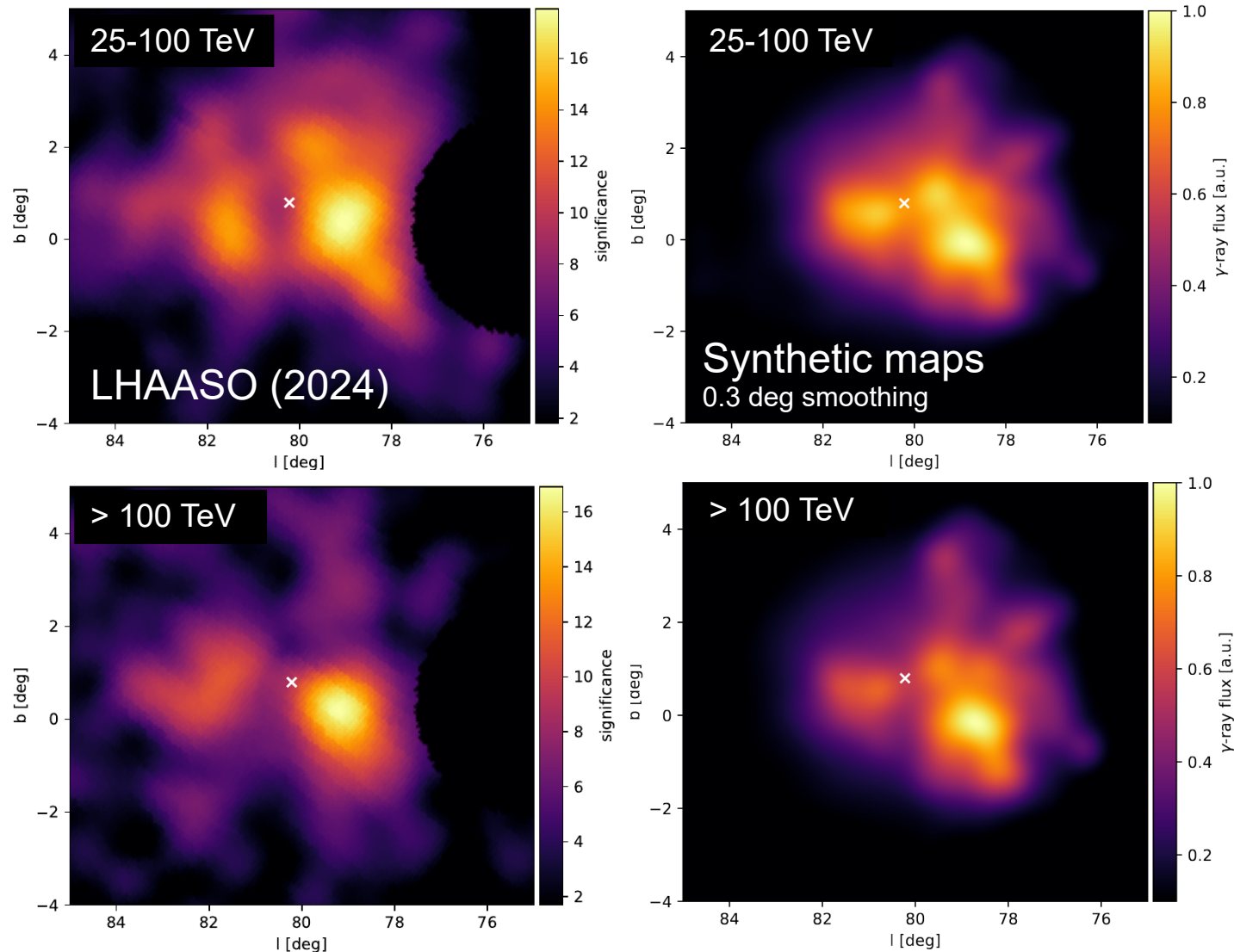
Radial proton distribution (50 kyr SNR):



Morphology

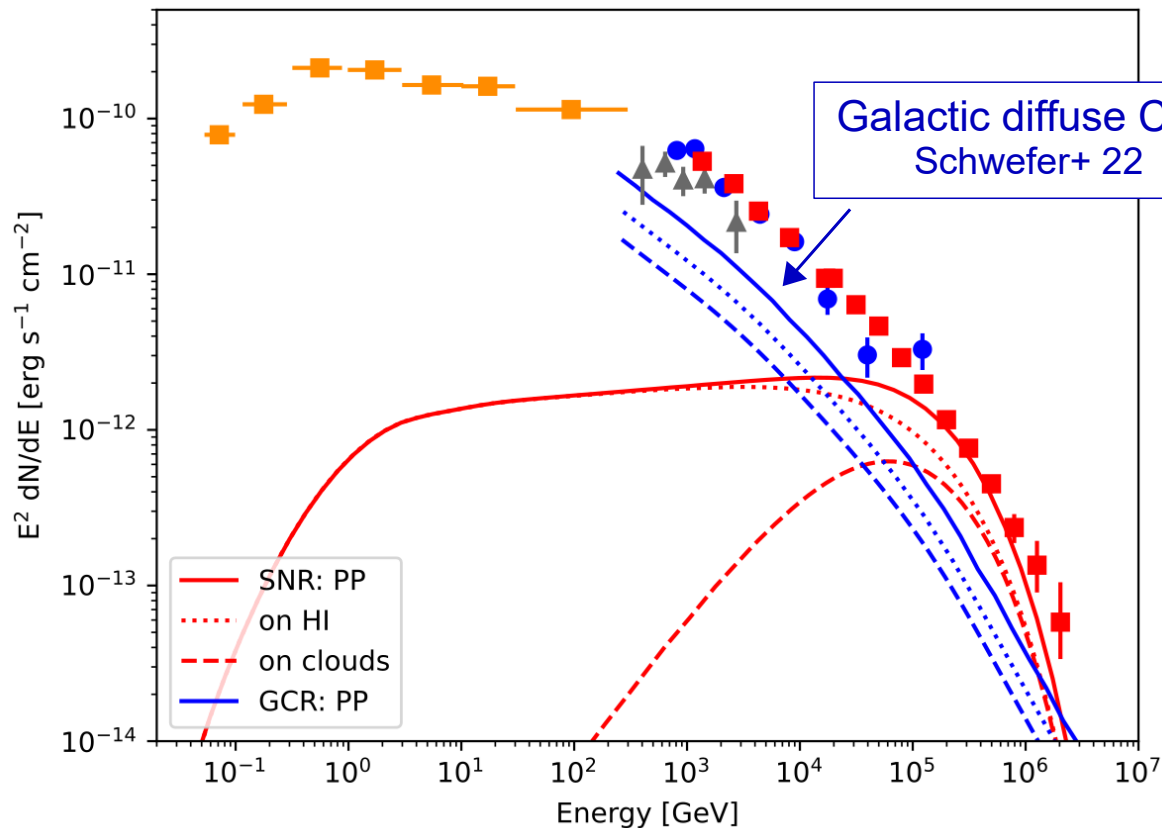
Energy
dependence
reproduced!

50 kyr SNR, clouds
at superbubble edge
(as expected!)



SNR model: spectrum

E^{-2} protons, cut-off 2 PeV, 3×10^{51} erg (10% in protons), SNR age 50 kyr

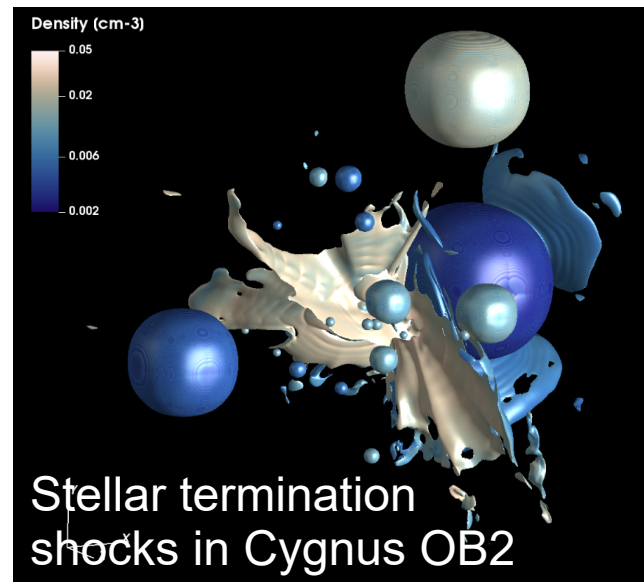
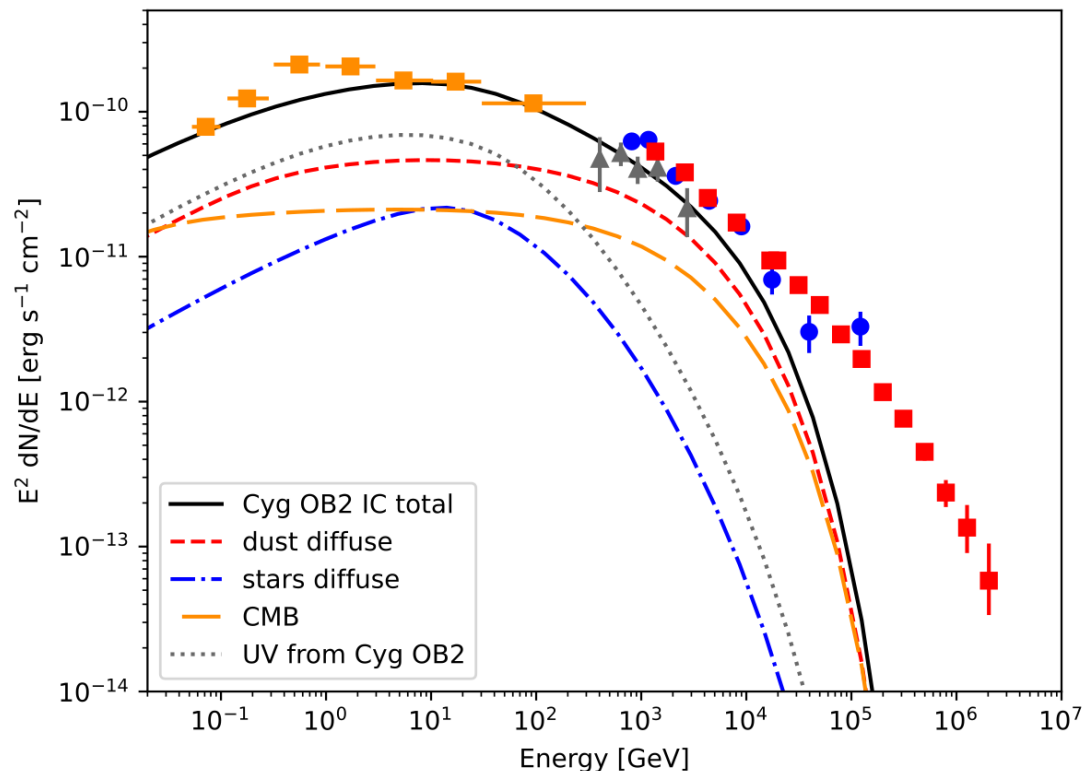


GCR substantially contribute to flux above PeV!

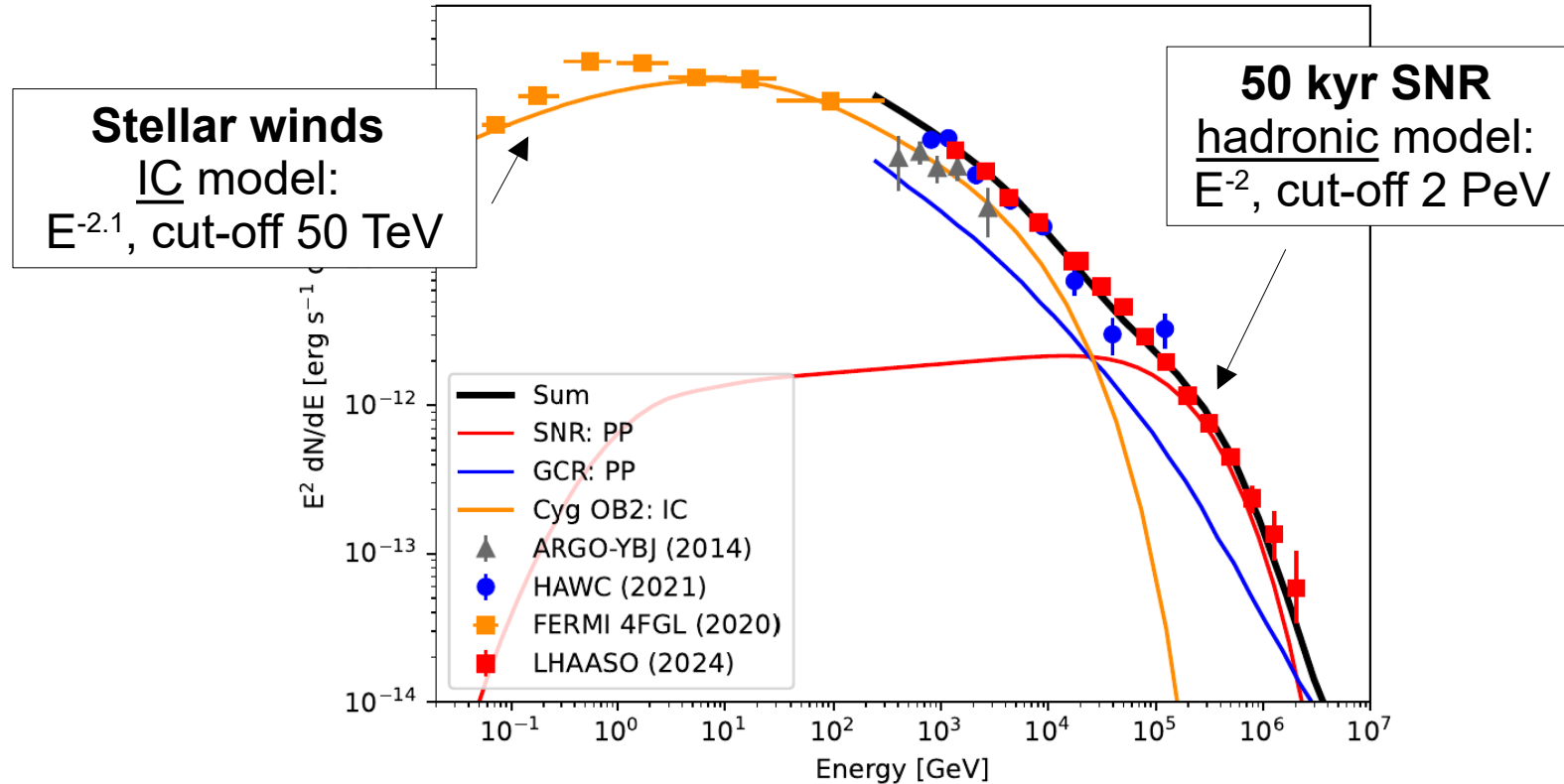
Inverse Compton from stellar termination shocks

from solving transport in two-zone diffusion model (as before) incl. electron losses

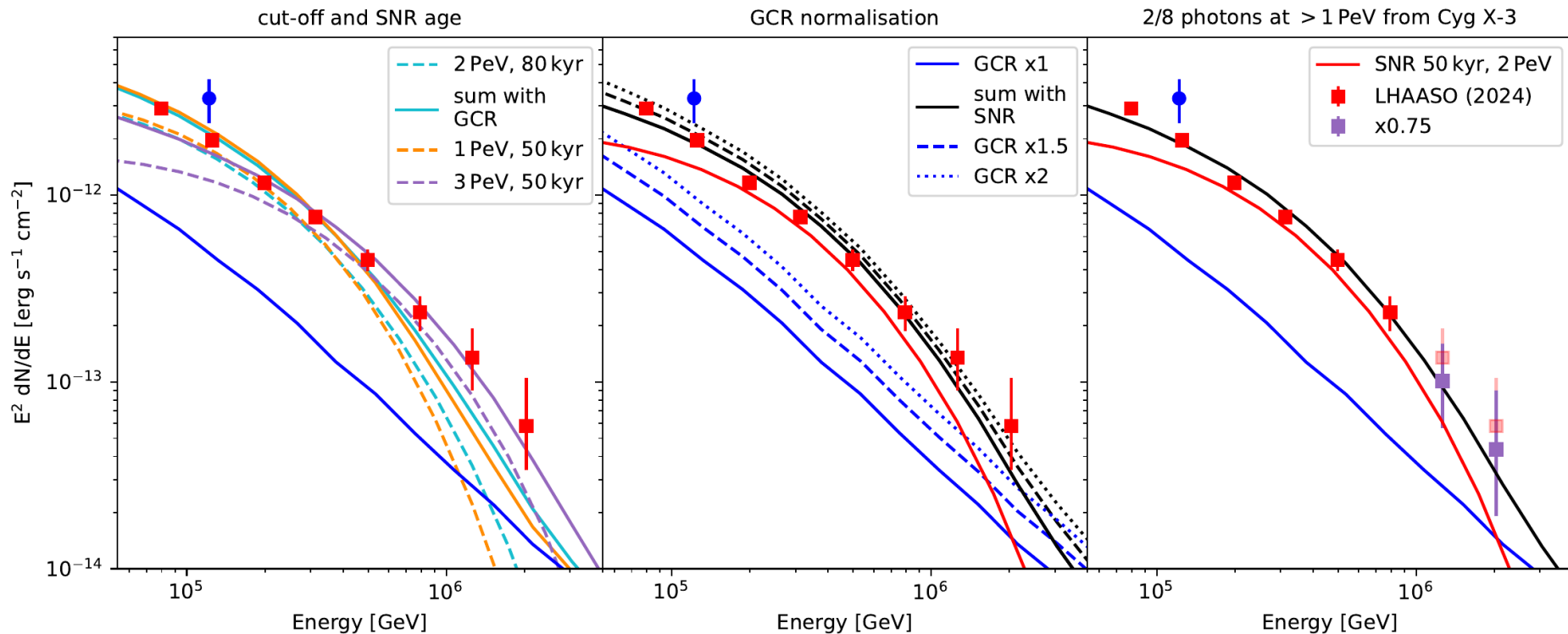
$E^{-2.1}$ **electrons**, cut-off 50 TeV, injection over 3 Myr, 3×10^{38} erg/s ($\sim 1\%$ in electrons)



Combined spectral model



Origin of the PeV γ -rays



Diffuse Galactic CRs and microquasar Cyg X-3 can contribute significantly at PeV

—► Cut-off $> \text{PeV}$ in SNR model not strictly necessary

Takeaways

- γ -rays in Cygnus can be modelled with a SNR (age: ~ 10 s of kyr).



~ 10 s of **TeV-PeV spectrum** + energy-dependent **morphology**



Härer+ 25b
accepted to A&A
[arXiv:2508.21644](https://arxiv.org/abs/2508.21644)

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But: Direct observation of SNR unlikely in hot, low-density bubble.
- Observed objects cannot account for source size and power. No cluster WTS.



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- GeV – 10s of TeV emission: Inverse Compton, stellar wind shocks.



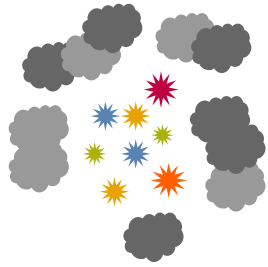
Like in Westerlund 1: low density **bubble**, strong **radiation** fields, winds **continuously** inject energy (see [Härer+ 23](#)).



Härer+ 25b
accepted to A&A
[arXiv:2508.21644](#)

BACKUP

γ -ray bright clusters are highly diverse



ambient medium



stellar content
age/formation history, mass,
massive-star population ...



compactness
compact clusters vs. loose
clusters/associations

All these factors can impact acceleration, transport, and γ -ray emission.

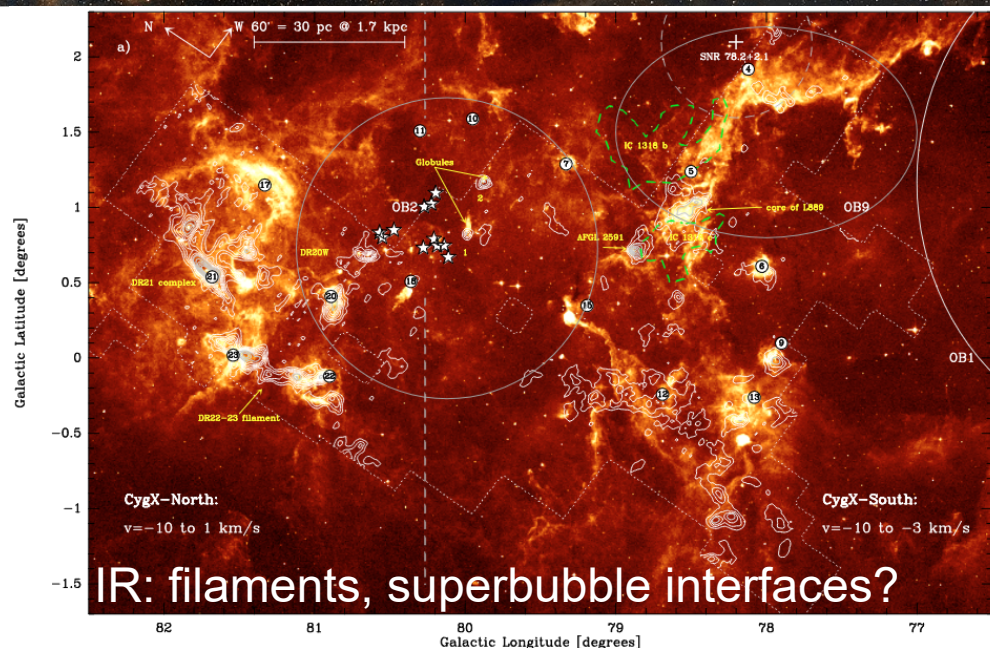
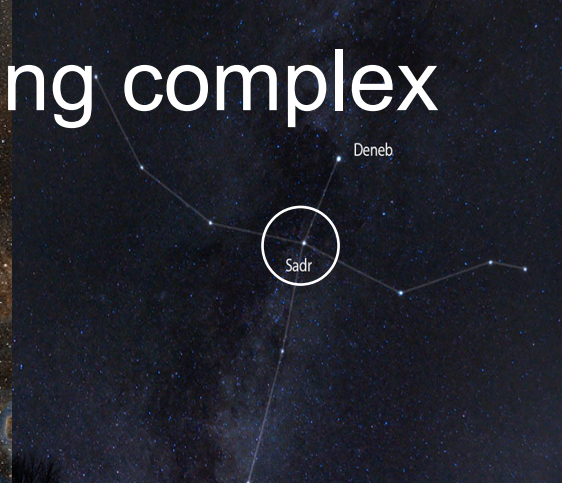
Cygnus – A massive nearby star-forming complex



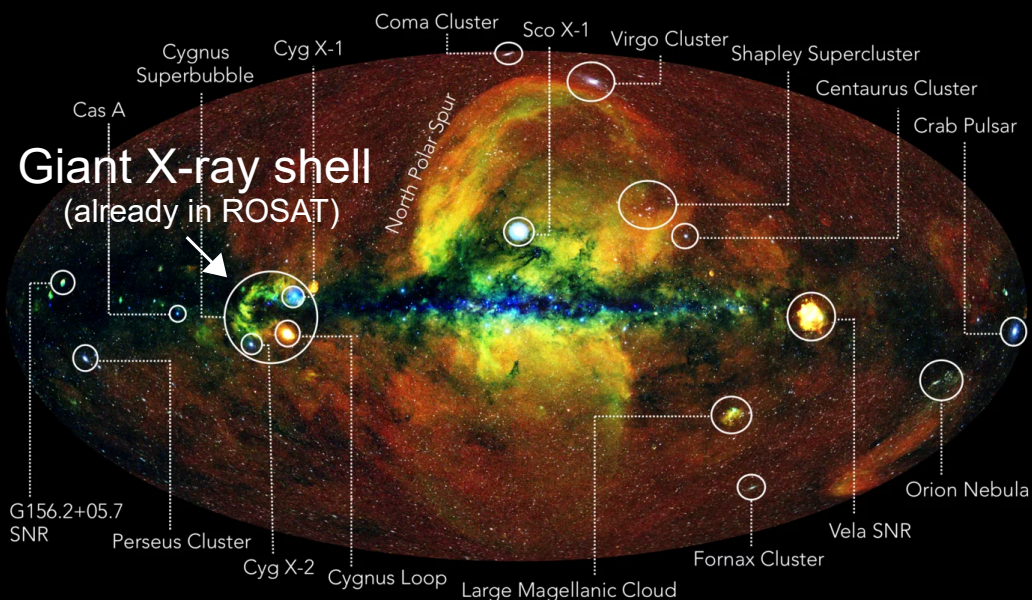
NAP Nebula

Cygnus X
heavily obscured
(Cygnus Rift, end of
Great Galactic Rift)

Sadr Nebula



Navigating the eROSITA X-ray sky



Cygnus – A massive nearby star-forming complex

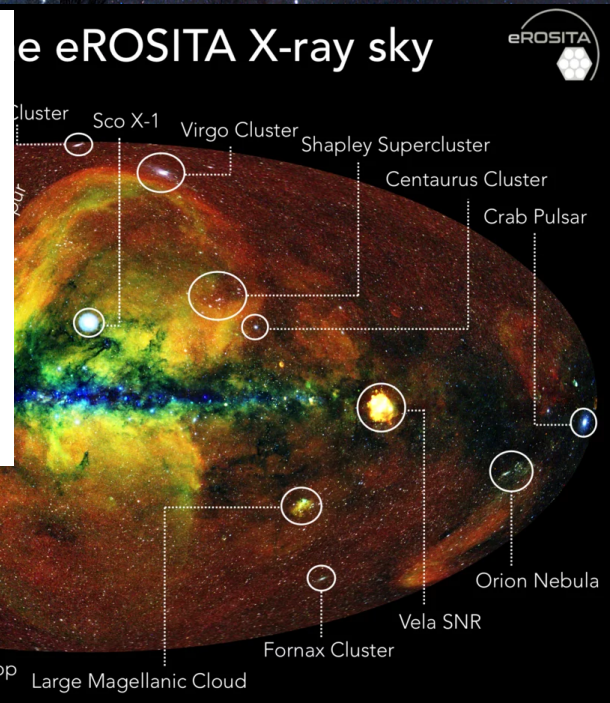
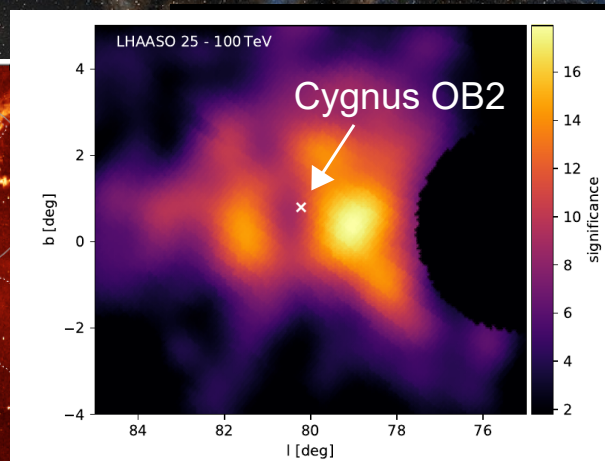
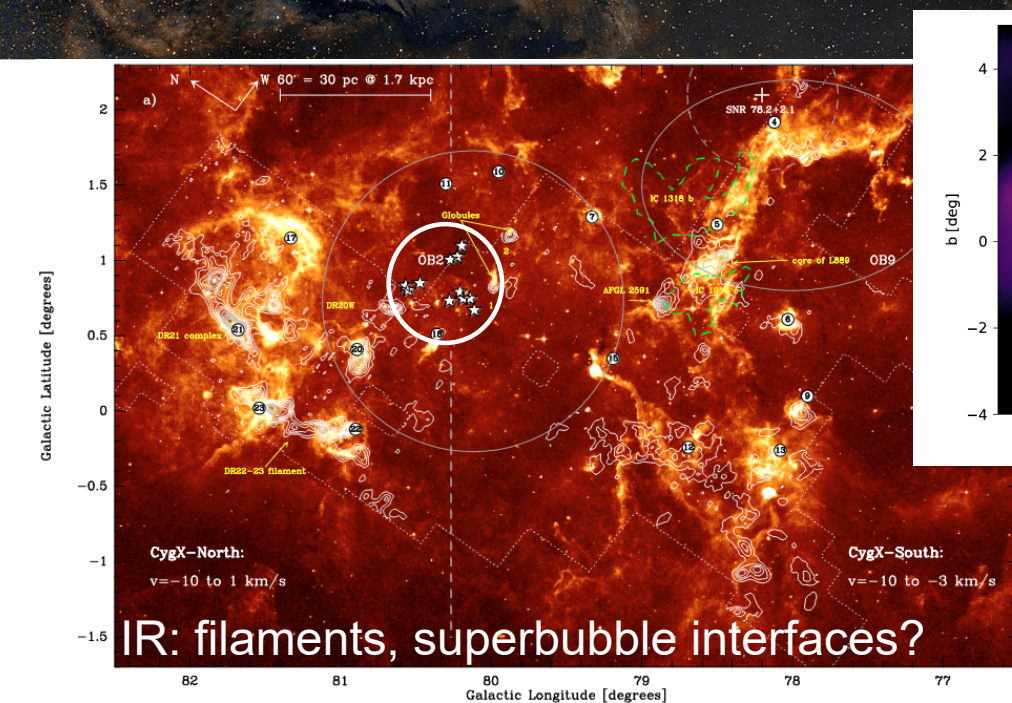
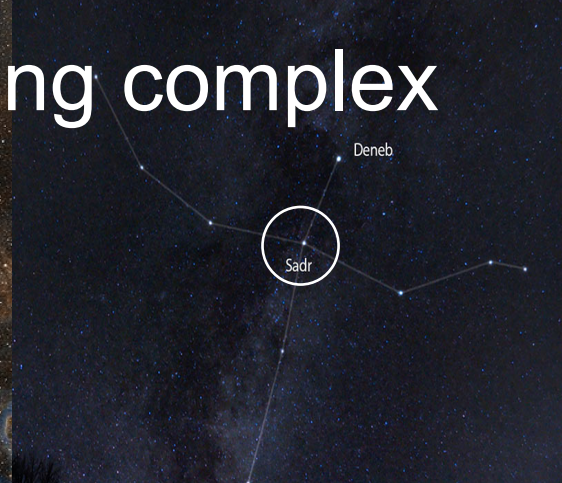


SADr Nebula

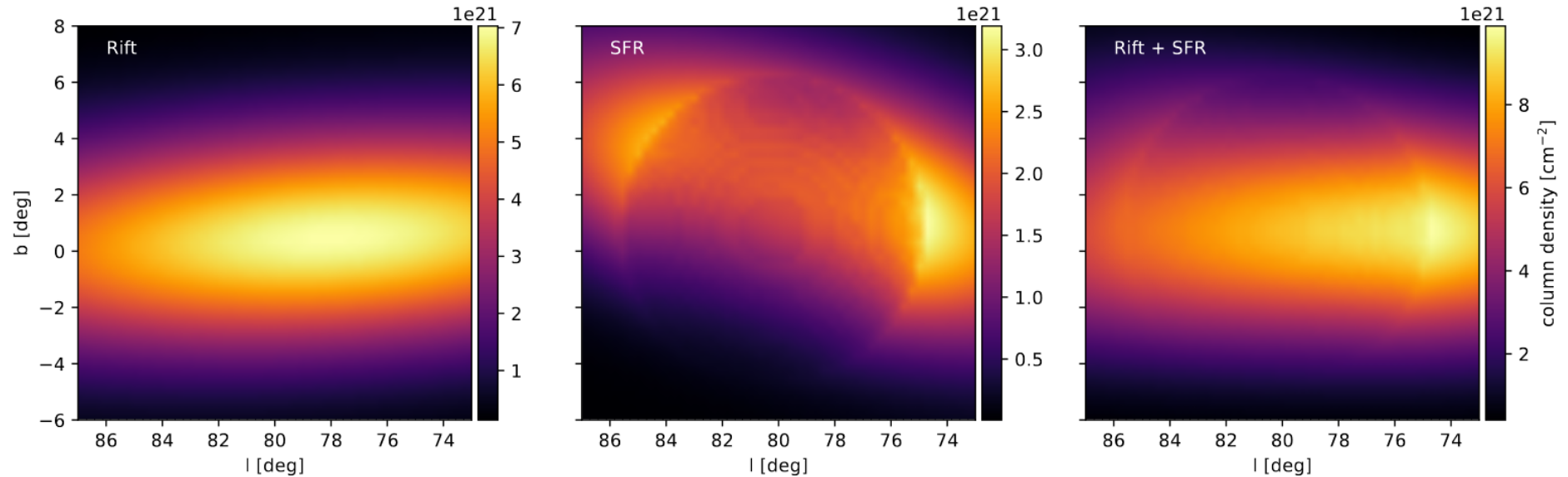
Cygnus X
heavily obscured

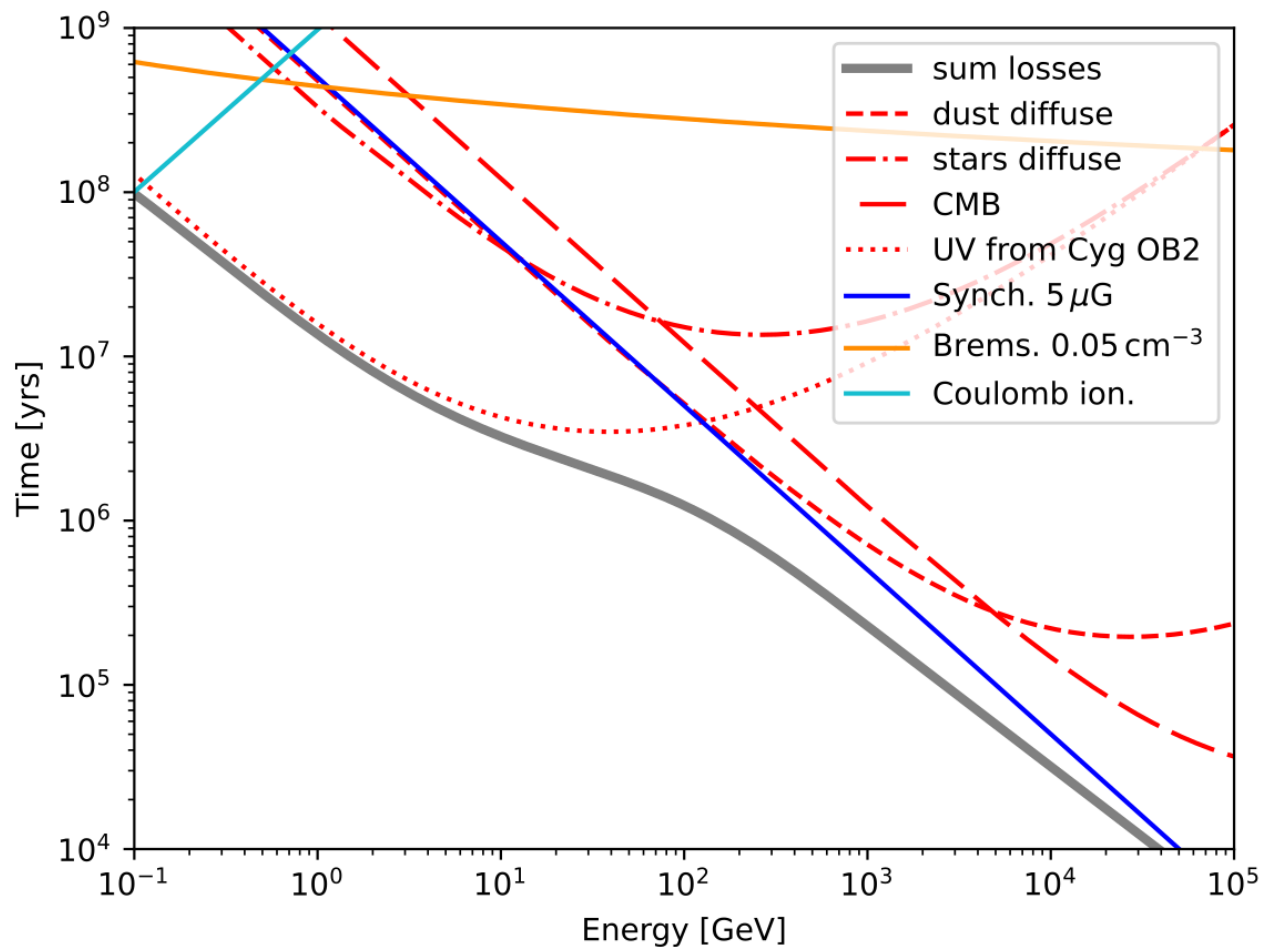
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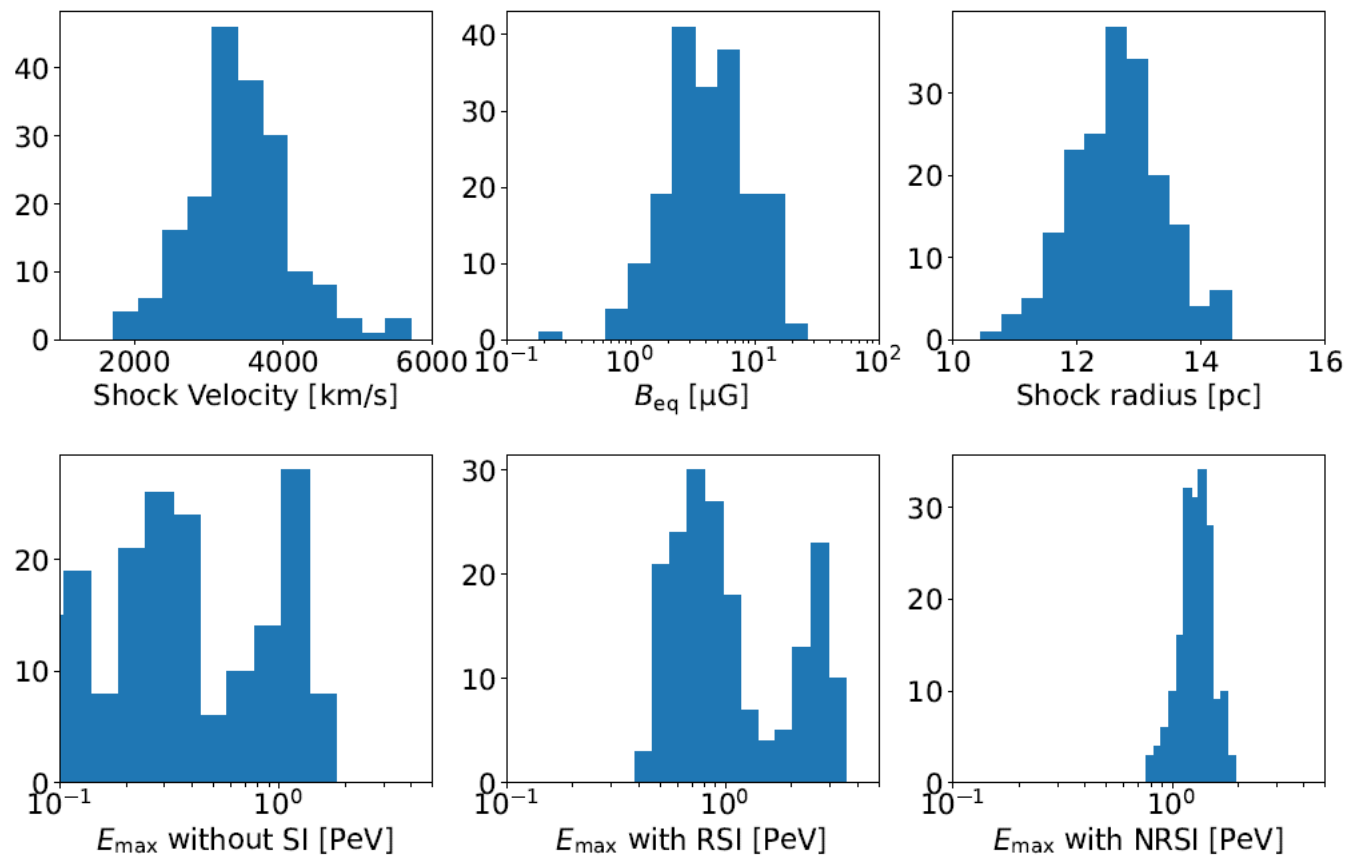
NAP Nebula

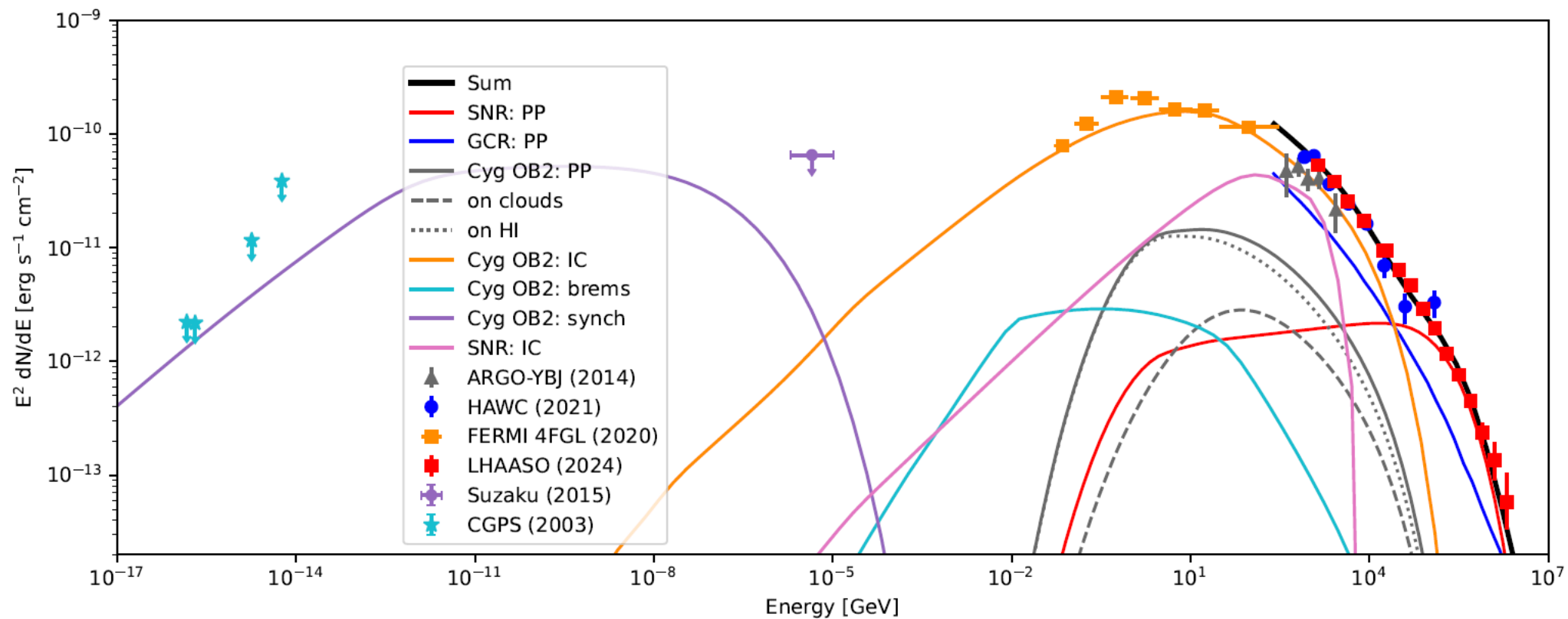


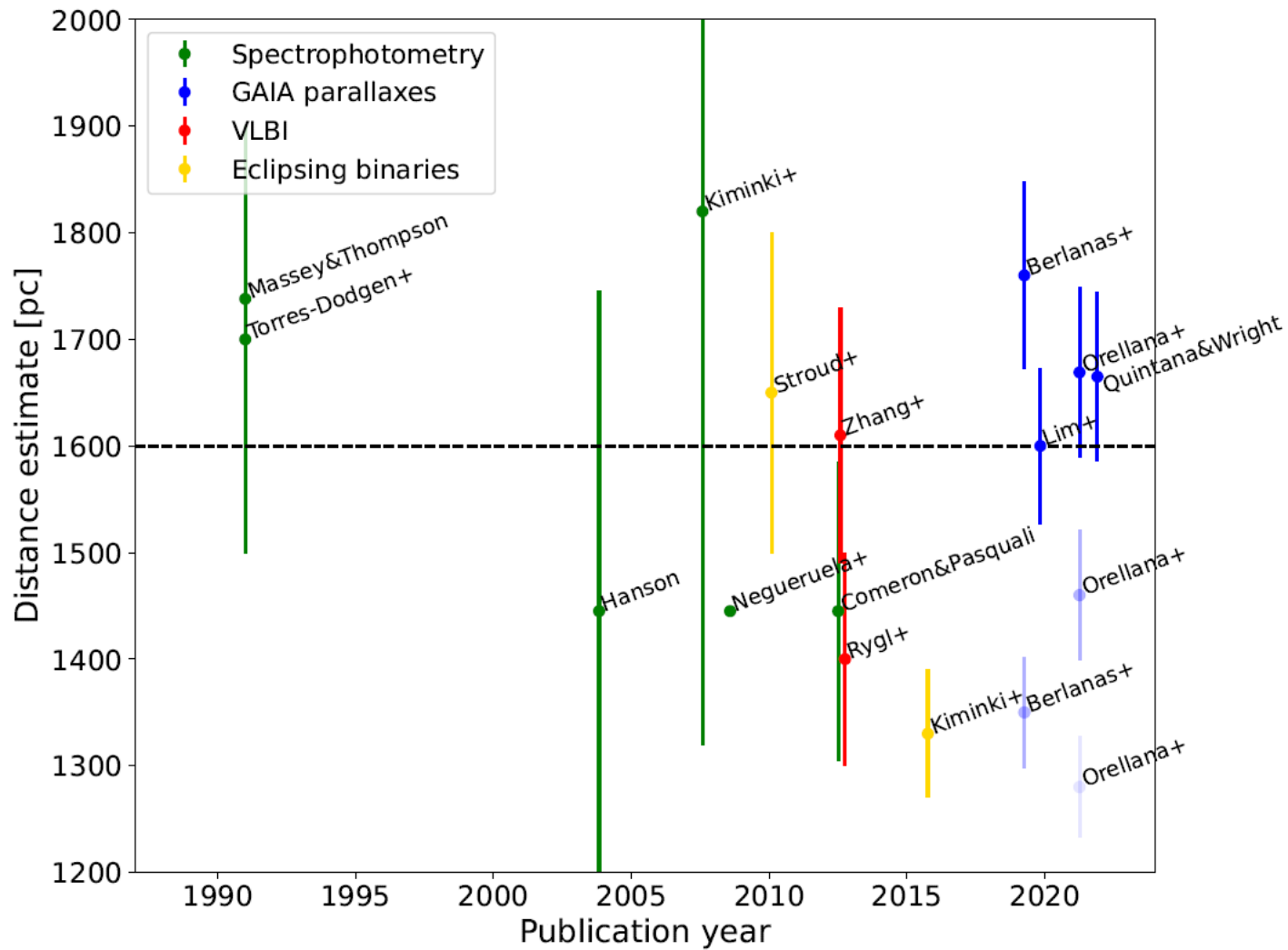
Neutral medium – 3D model

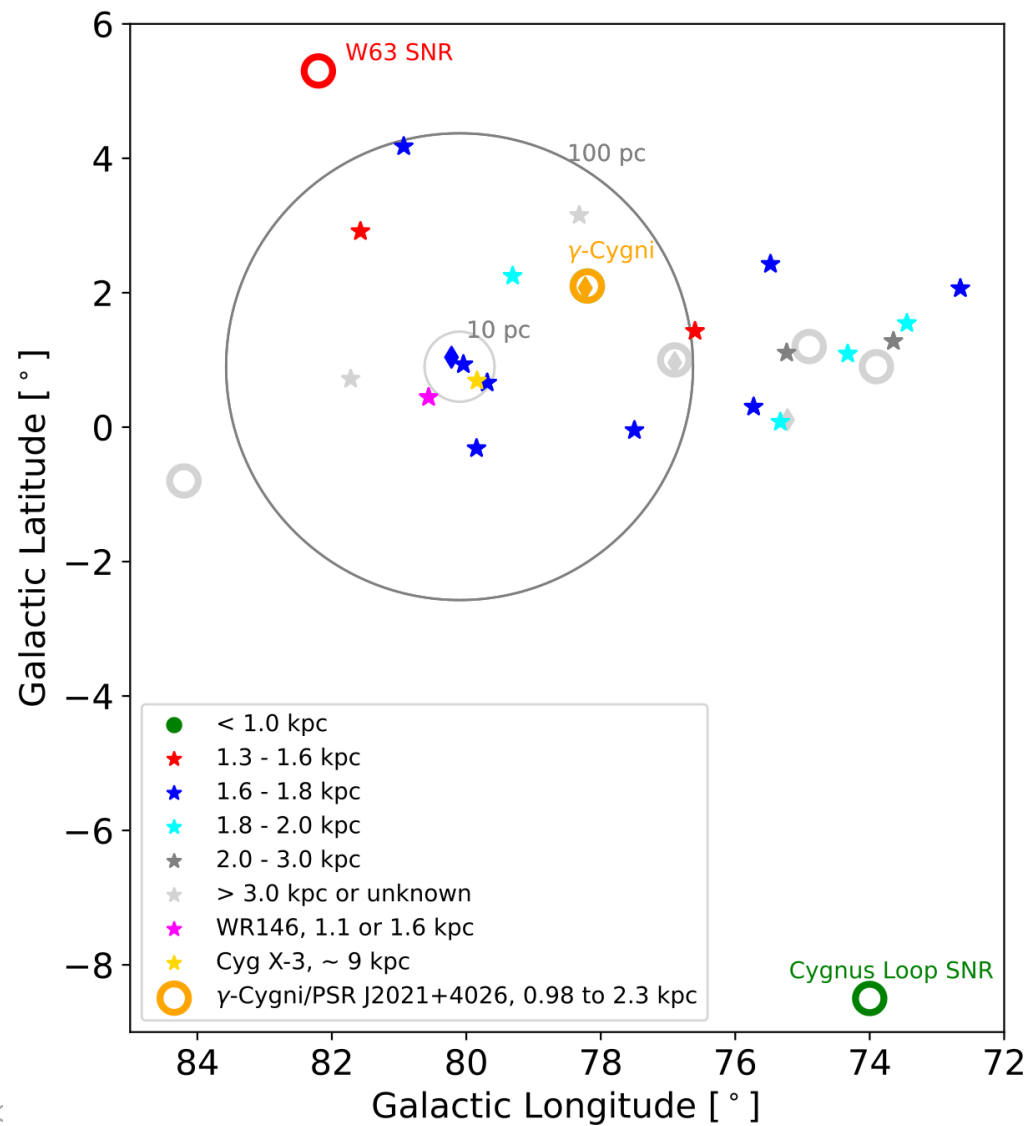








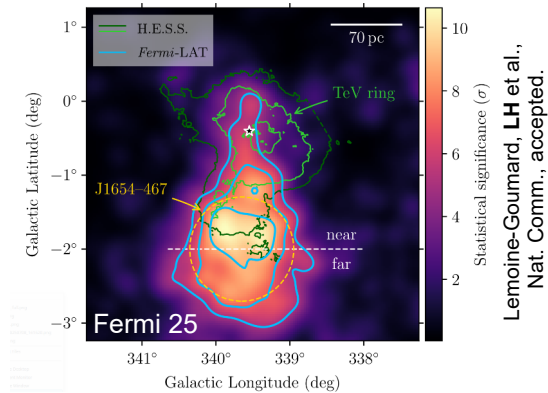
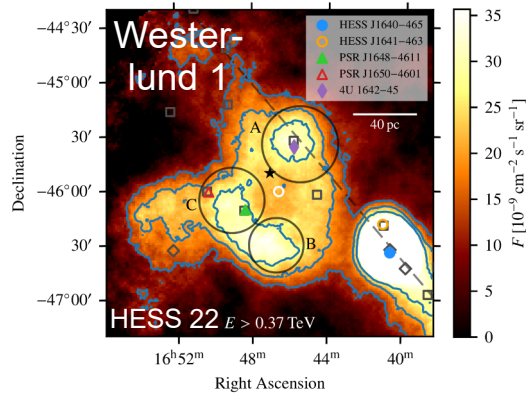




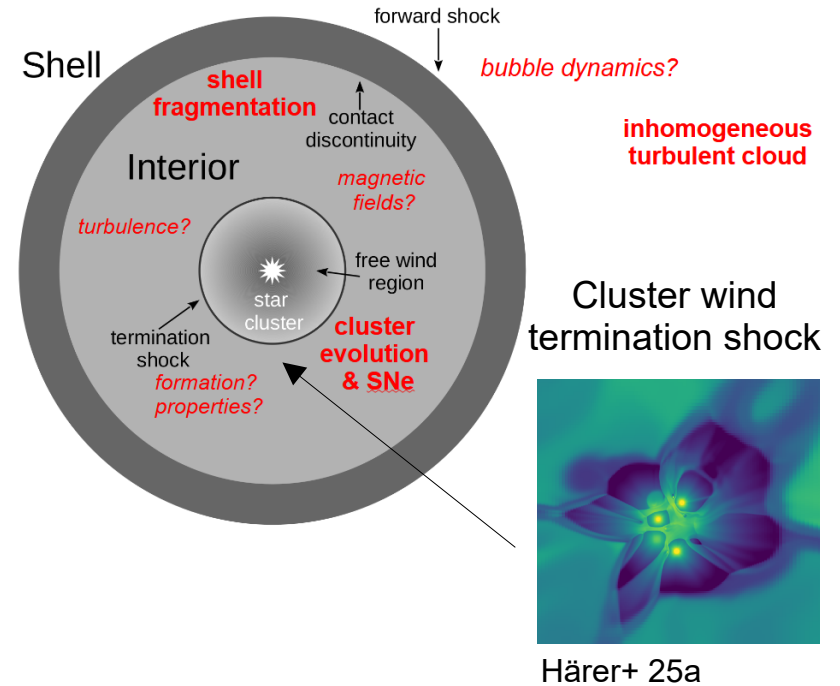
Conclusions

1. Young star clusters accelerate cosmic rays – diffuse degree-scale γ -ray emission.

- Large scales: environments are critical!
- Low-density, hot, turbulent bubbles blown by stellar winds & SNe.



Lemoine-Goumard, LH et al.,
Nat. Comm., accepted.



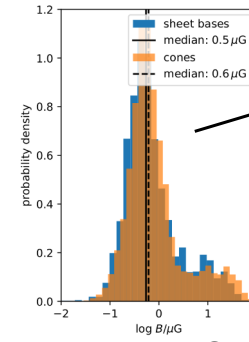
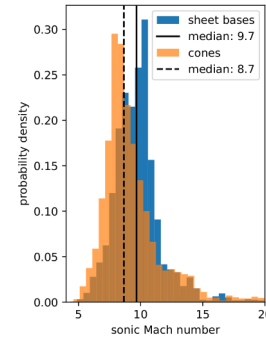
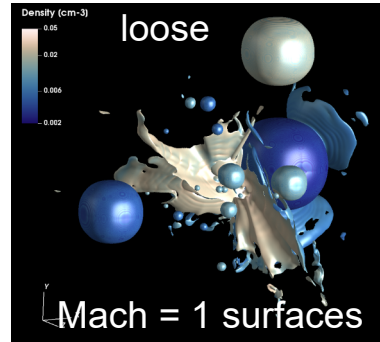
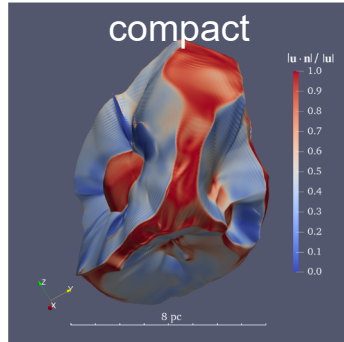
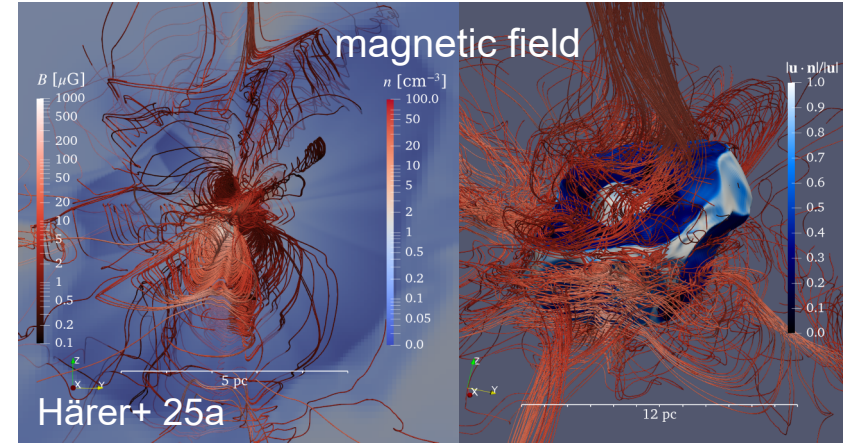
Conclusions

2. Wind-wind interactions form intricate 3D structures.

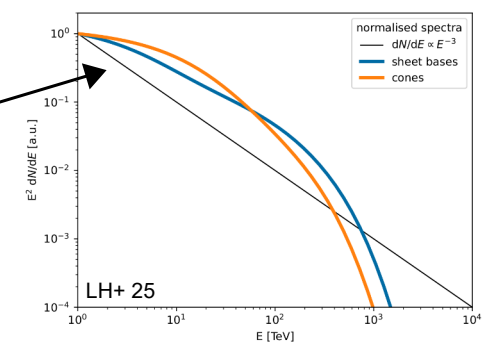
- Depend on properties and positions of individual stars.

3. Cluster wind termination shock:

- Compact clusters only ($r < 2\text{-}3\text{ pc}$), highly non-uniform.
- Consequence: steep, curved particle spectra.



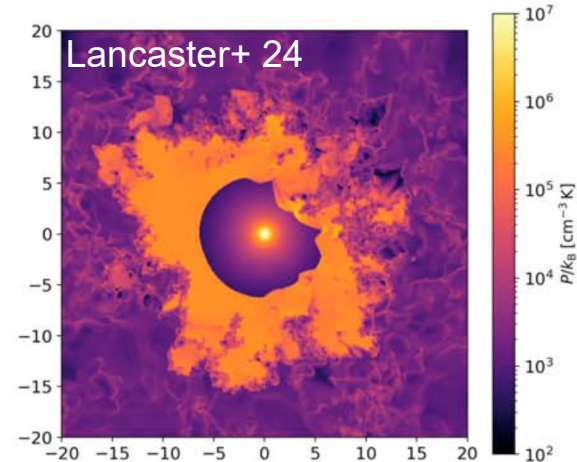
M_s and B at cluster WTS



toy particle spectrum

What's next?

- CR transport across superbubble shell?
- Superbubble: Diffusion vs. advection? Turbulence?
- Stellar and cluster wind shocks (non-parallel!): acceleration and transport?
- B-field: dynamo effects in cluster core? Observational constraints?
- ...



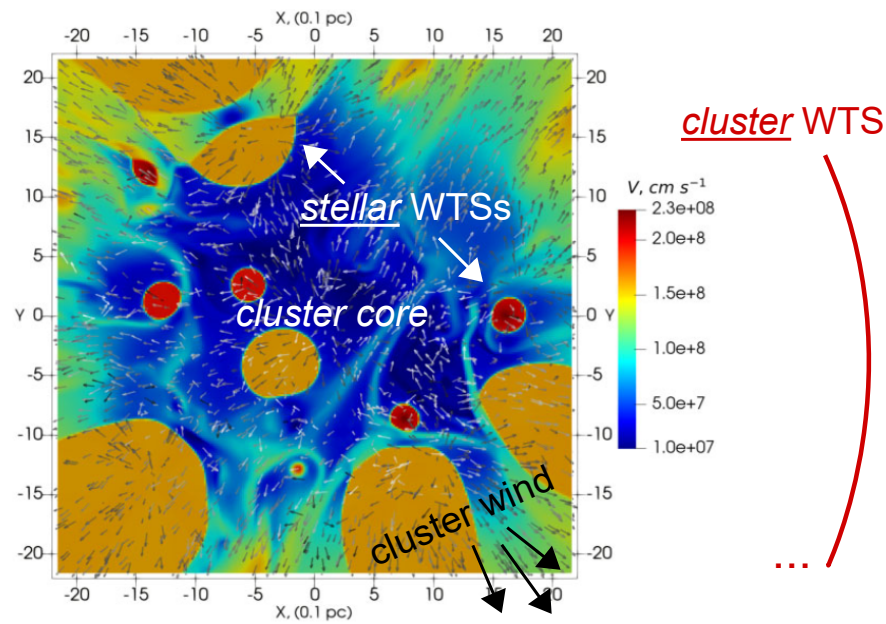
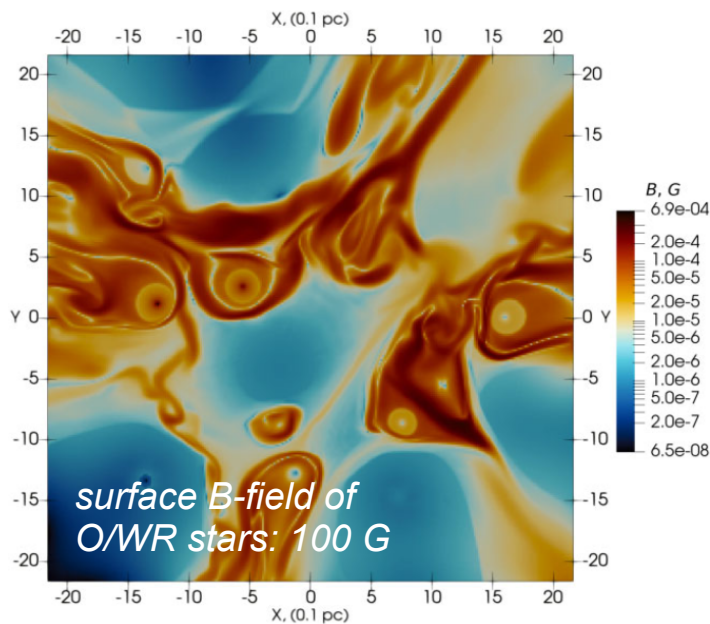
Simulations: several extensions in progress!
e.g. cooling, longer time-evolution, SNe, inhom. ambient medium etc.

Simulating wind-wind interactions

to constrain flow and B-field morphology in 3D

In the cluster core: Badmaev+ 23

- “Westerlund 1-like” cluster with O-stars, Wolf-Rayet stars, supergiants
- Find strong shocks, highly asymmetric B-field reaching up to 1 mG

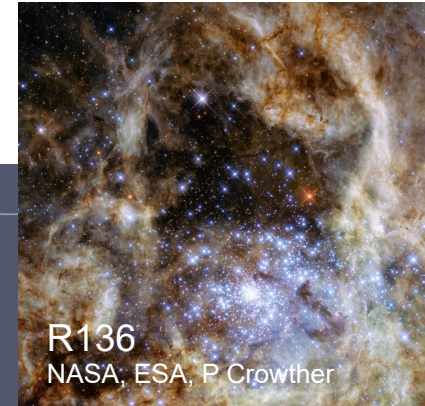
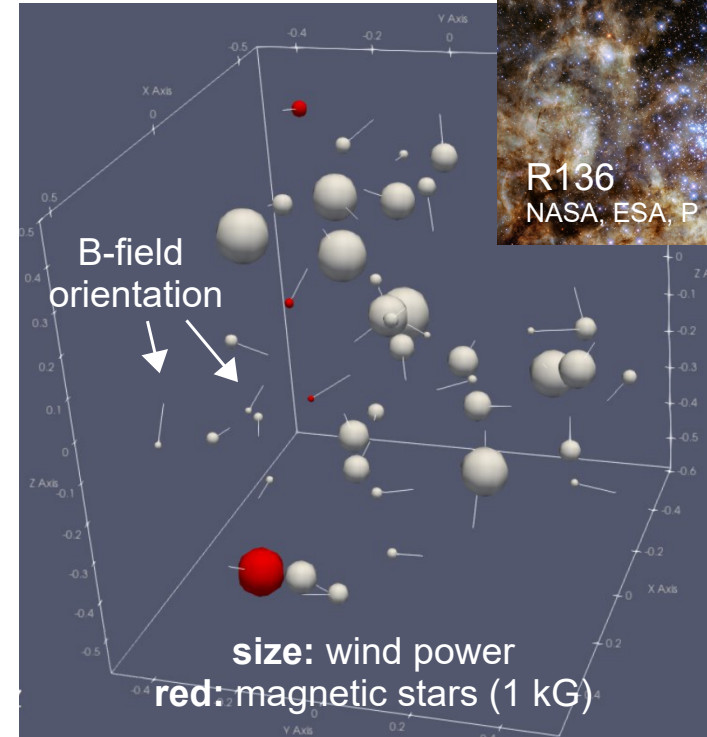


3D MHD simulations of Young Compact Clusters

PLUTO code, ideal MHD

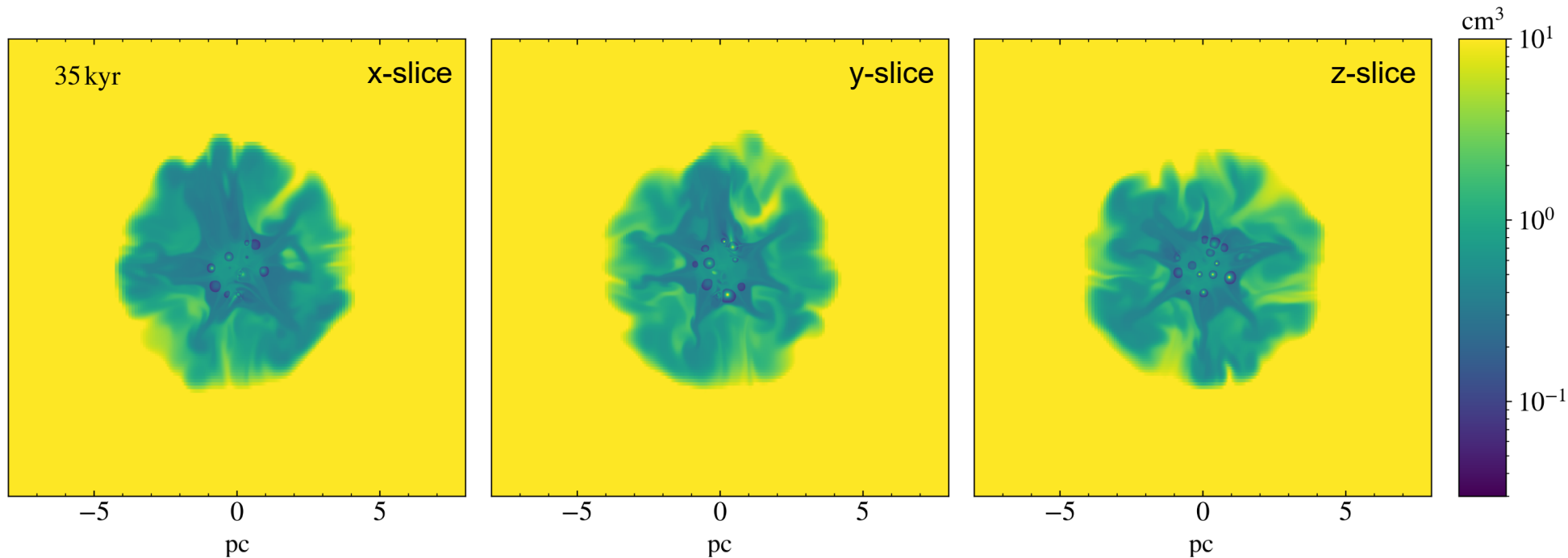
radius < 2-3 pc

- ✓ Resolve winds of 10-100 most massive stars ($> 10s M_{\odot}$ $v_{\text{wind}} \sim 1000s \text{ km/s}$) within $\sim 1 \text{ pc}$
- ✓ Simulate evolution of full superbubble over 400 kyr $\rightarrow$ requires box size $> 50 \text{ pc}$
- ✓ Evolution: Wolf-Rayet phase
mass-loss increase 10x (see Seo+ 18)
- ✓ Parker spiral B-fields
10% magnetic stars: 1 kG (see Grunhut+ 17)

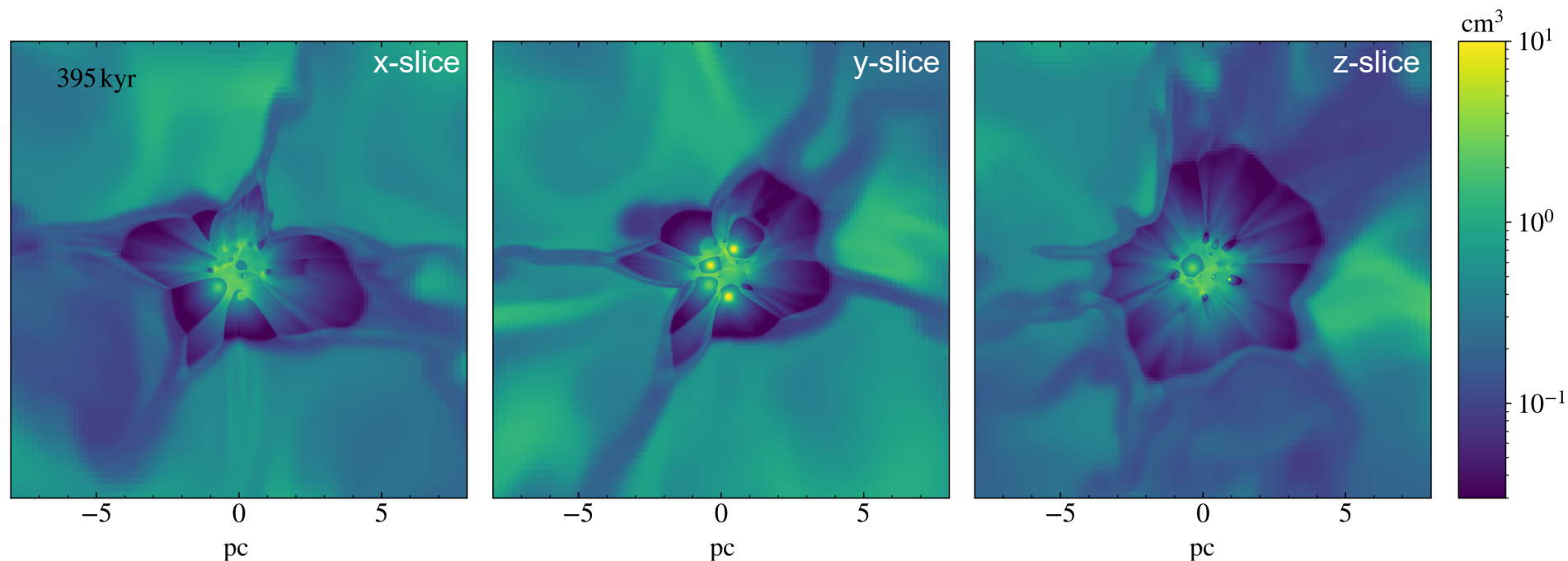


Density slices

cluster setup: mass: $3.5 \times 10^4 M_{\odot}$,
46 stars $> 40 M_{\odot}$, radius 1 pc



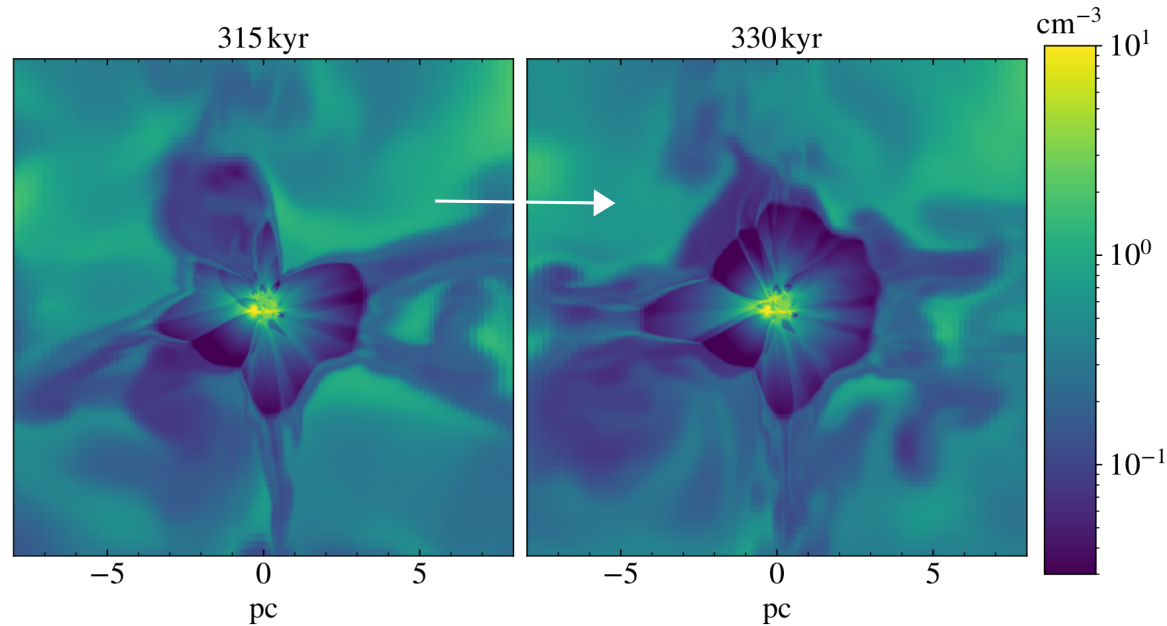
Cluster Wind Termination Shock



1. non-spherical,
non-uniform strength

2. sometimes dominated
by individual stellar WTS

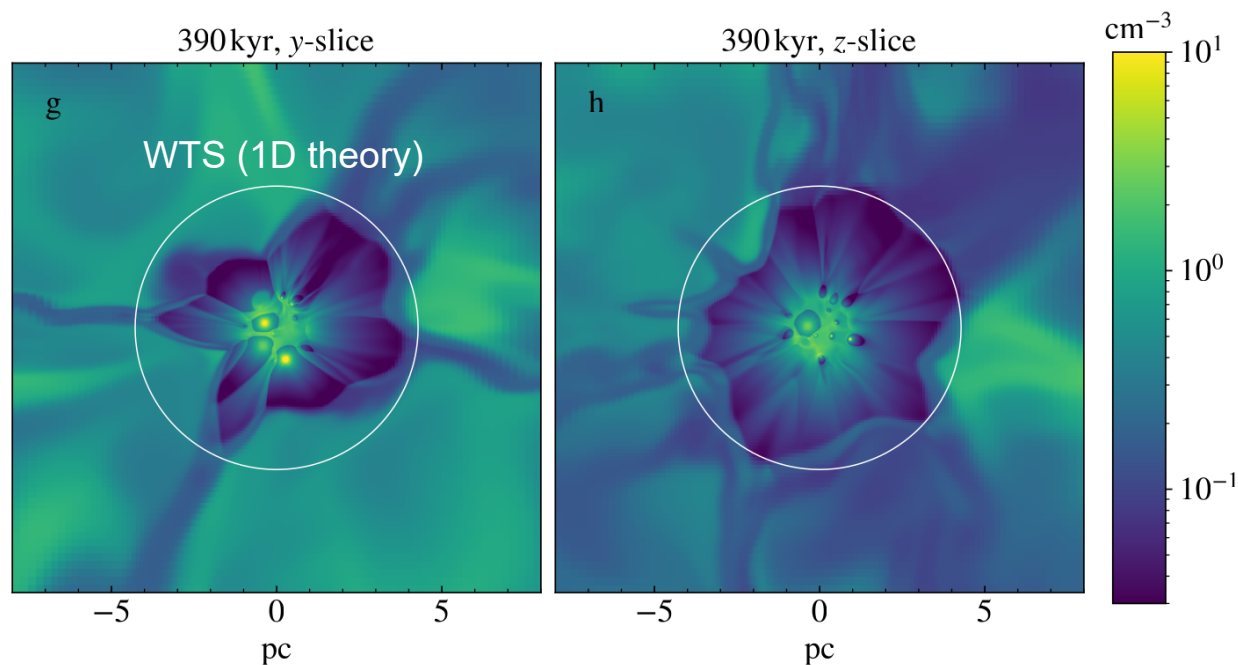
Cluster Wind Termination Shock



3. “decoupling” of individual winds: WTS becomes more spherical

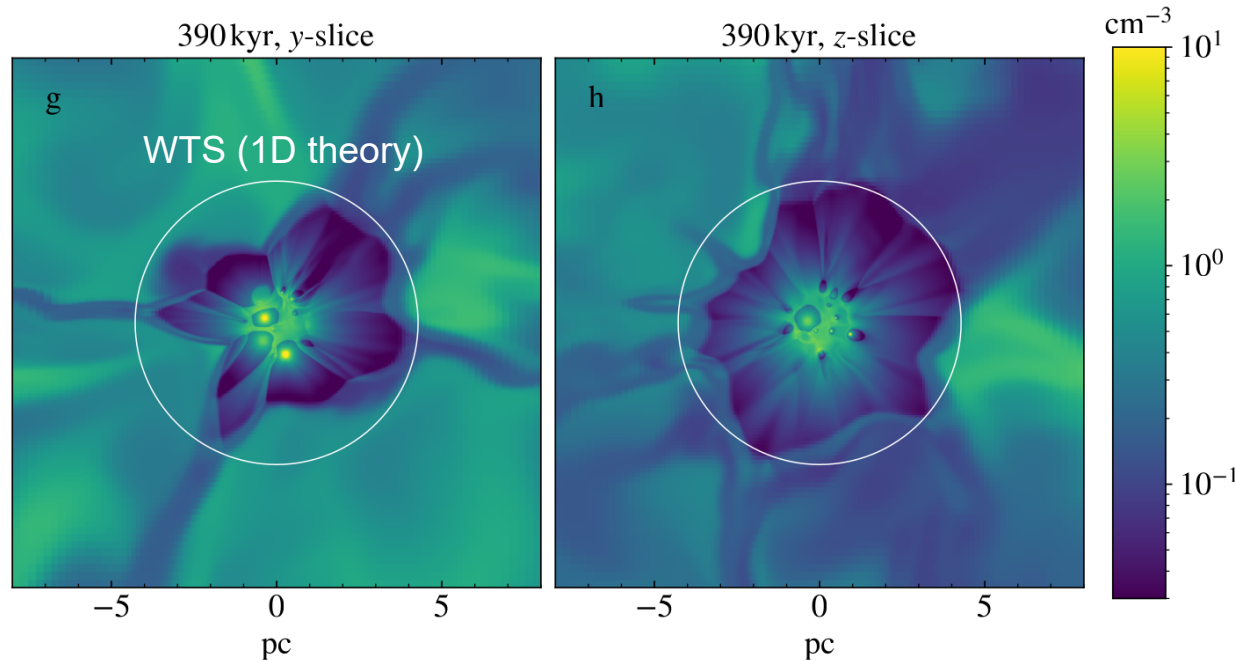
but: time-scales for decoupling *can be long*,
extreme winds might never decouple (e.g. Wolf-Rayet stars)

Cluster Wind Termination Shock

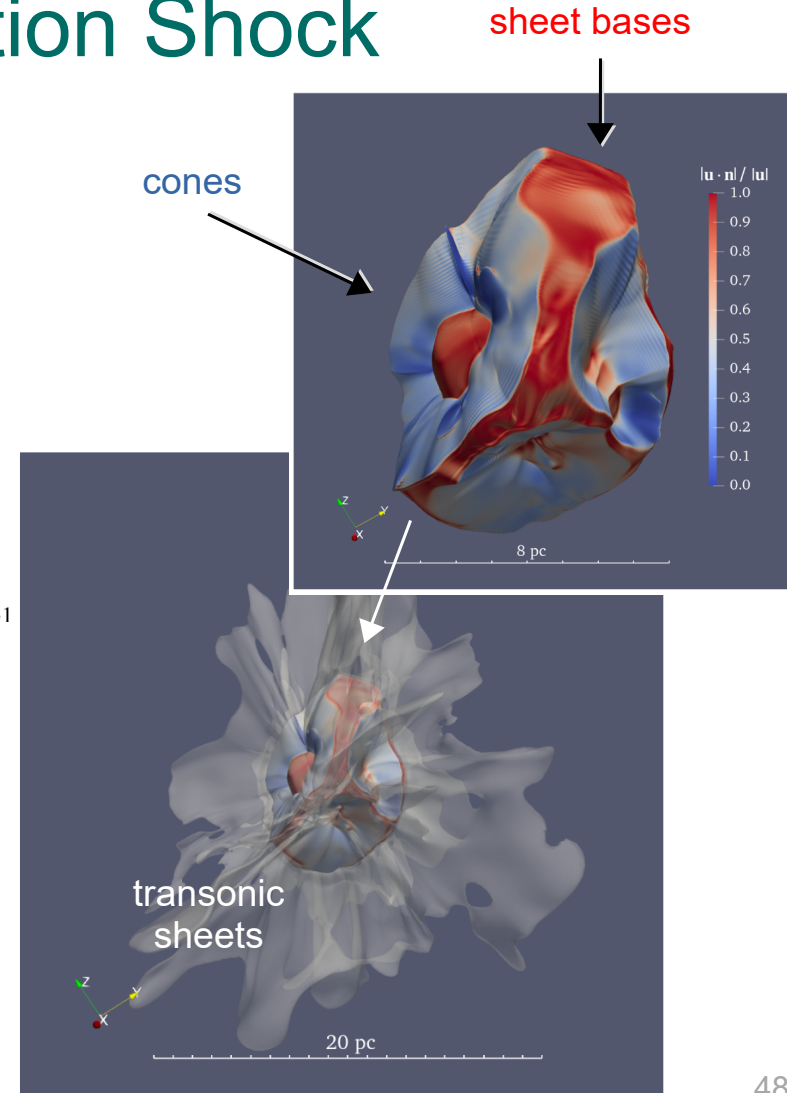


4. smaller volume (transonic sheets!)

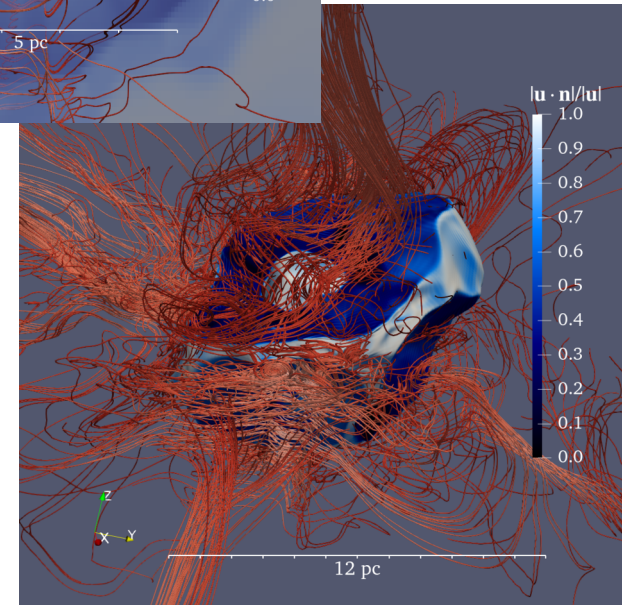
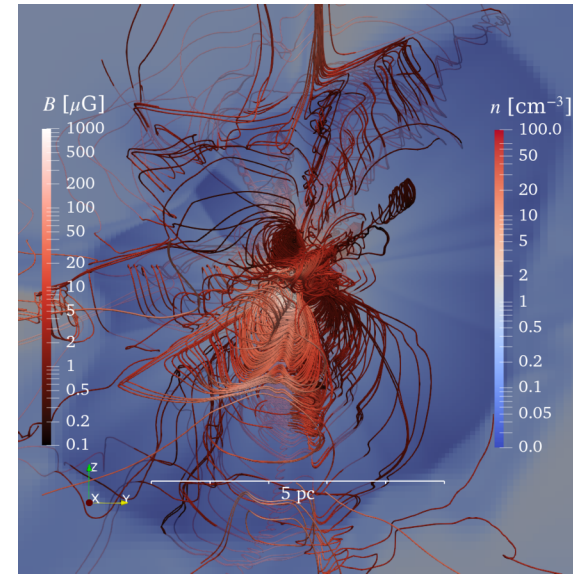
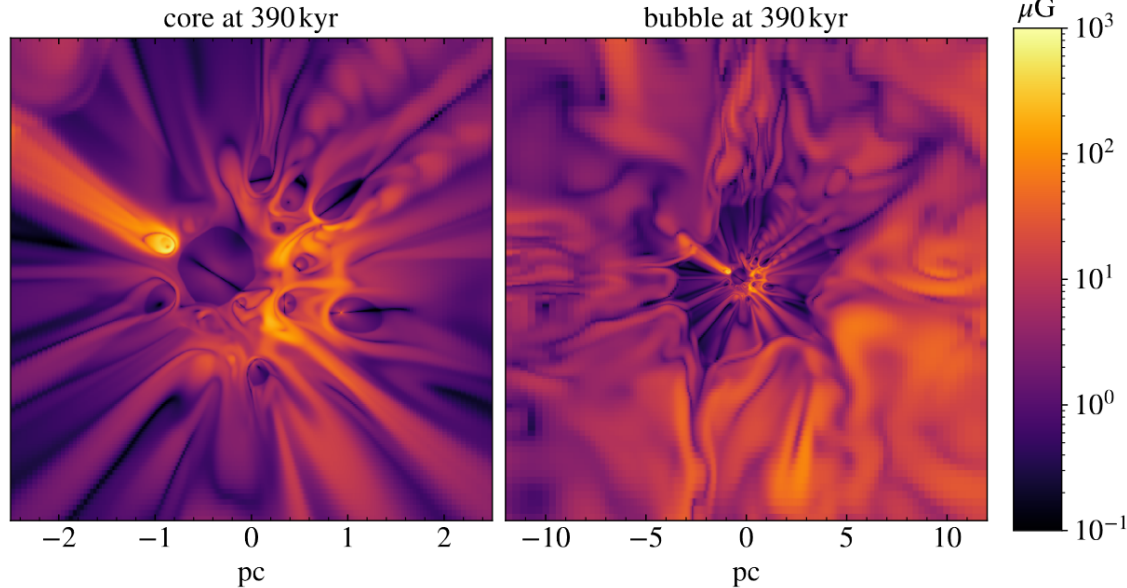
Cluster Wind Termination Shock



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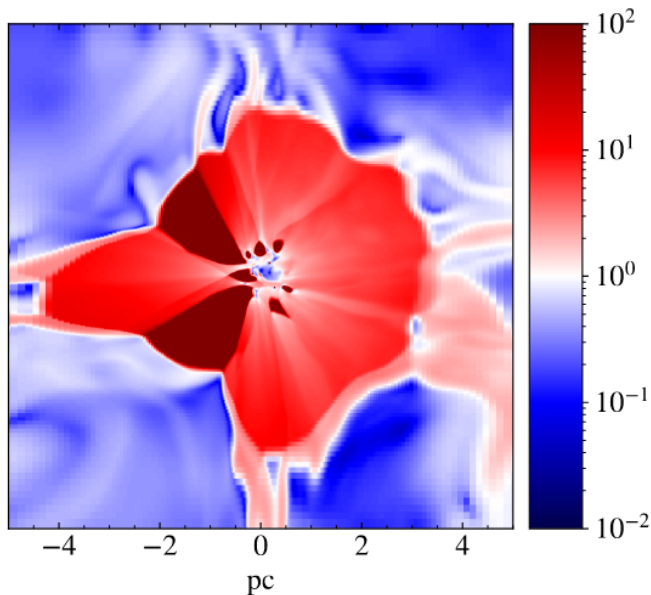


Magnetic field

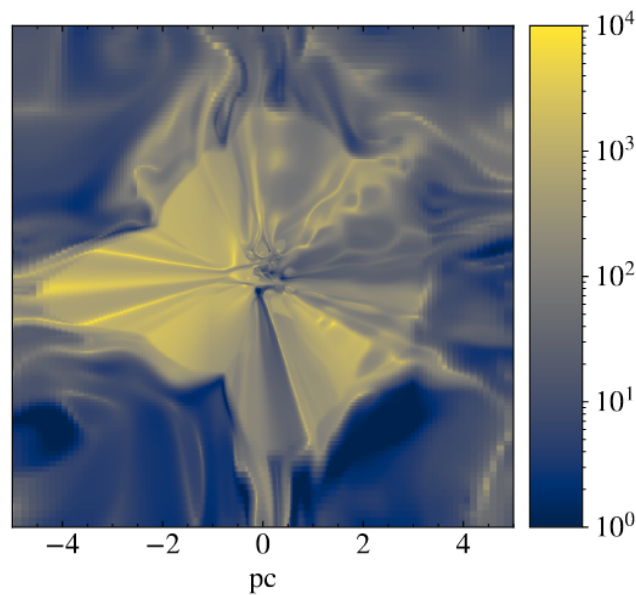


- non-uniform
is expected – 10% of stars with 1 kG, 90% with 10 G
- tangled in the core, coherent field-line bundles dragged outwards by flows
- median value: 8–35 μG (core), 4–20 μG (bubble)
across runs with different cluster radius and stellar distribution

Cluster WTS acceleration

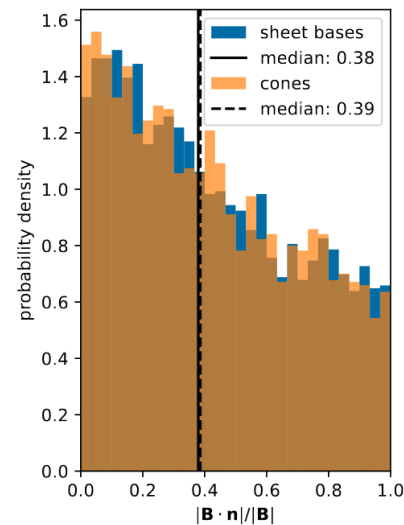
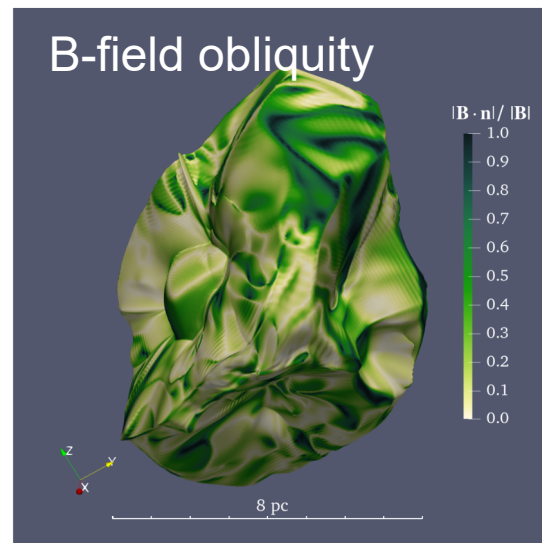


(a) Sonic Mach number.



(b) Alfvénic Mach number.

Cluster WTS is strong ($M_s > 10$),
super-Alfvénic, but not quasi-parallel

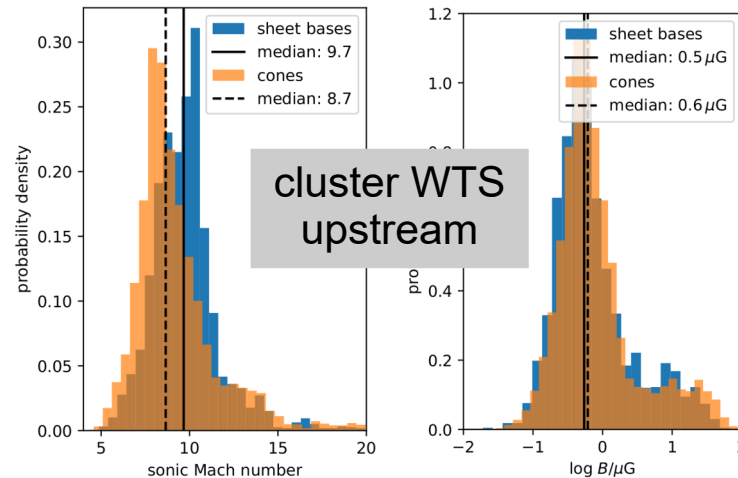
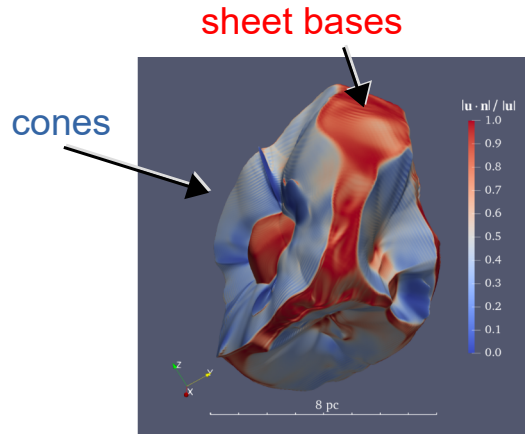


Cluster WTS acceleration: steep, curved spectra

Maximum energy (Hillas' limit):

$$E_{\text{max}}^{\text{sheetbase}} = 4.0 \times Z \left(\frac{B}{0.5 \mu\text{G}} \right) \left(\frac{d}{1 \text{ pc}} \right) \left(\frac{u}{2600 \text{ km s}^{-1}} \right) \text{ TeV}$$

$$E_{\text{max}}^{\text{cones}} = 11 \times Z \left(\frac{B}{0.5 \mu\text{G}} \right) \left(\frac{d}{5 \text{ pc}} \right) \left(\frac{u}{1400 \text{ km s}^{-1}} \right) \text{ TeV}$$

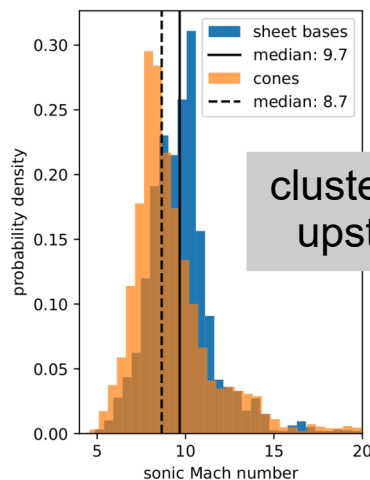
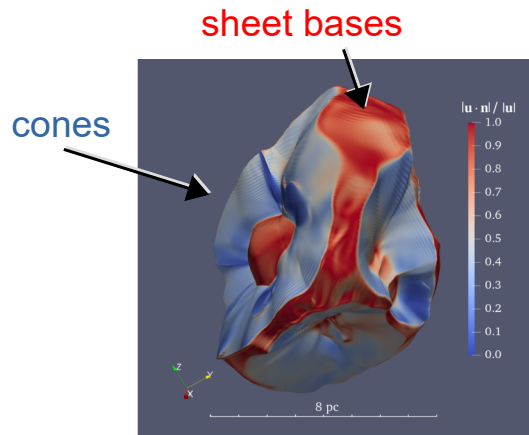


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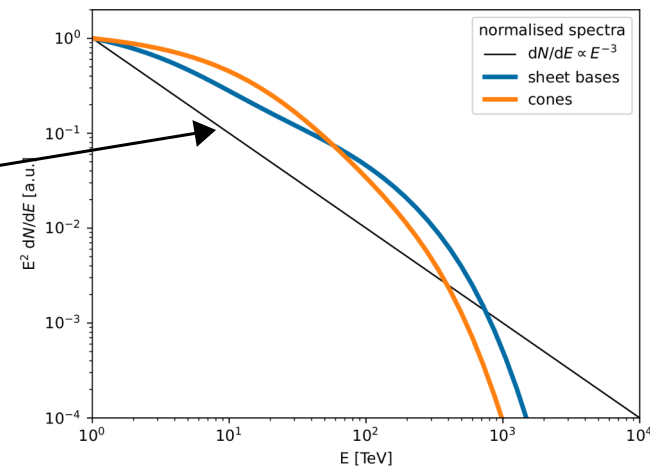
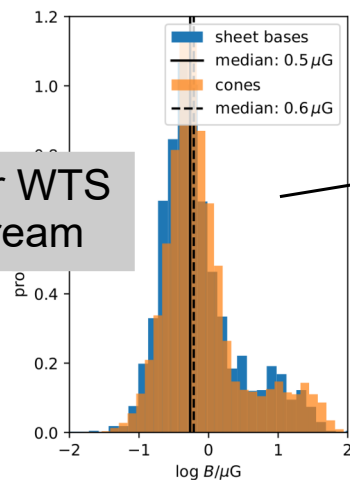
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cluster WTS upstream



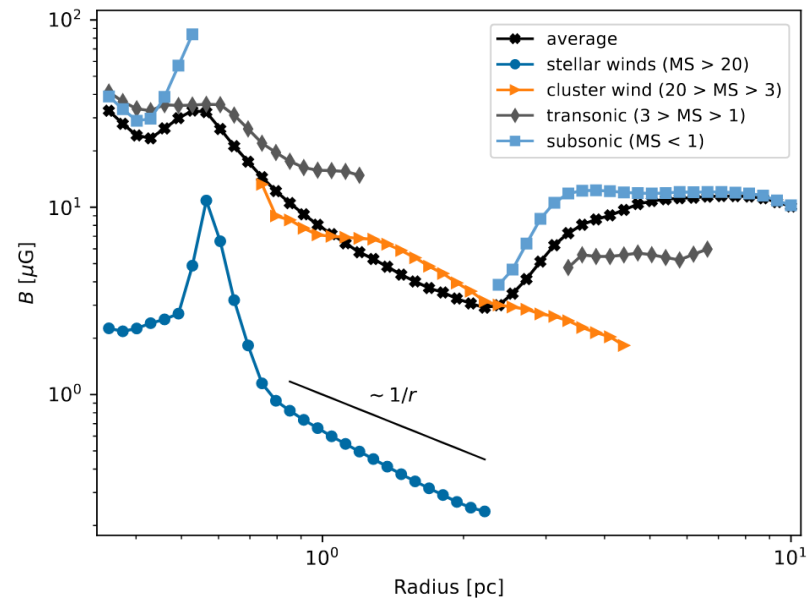
toy model spectrum: sum of cut-off powerlaws for different lineouts

- Steep, curved spectra are expected due to non-uniform magnetic field
- Such spectra are observed in γ-rays!

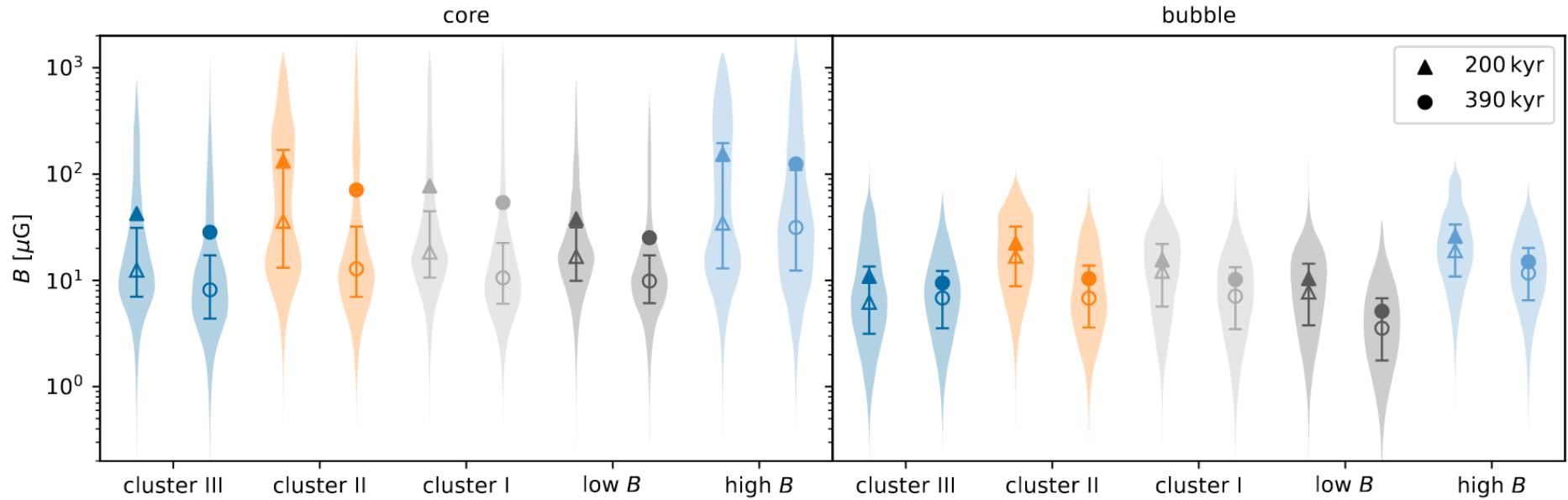
Cluster WTS maximum energy

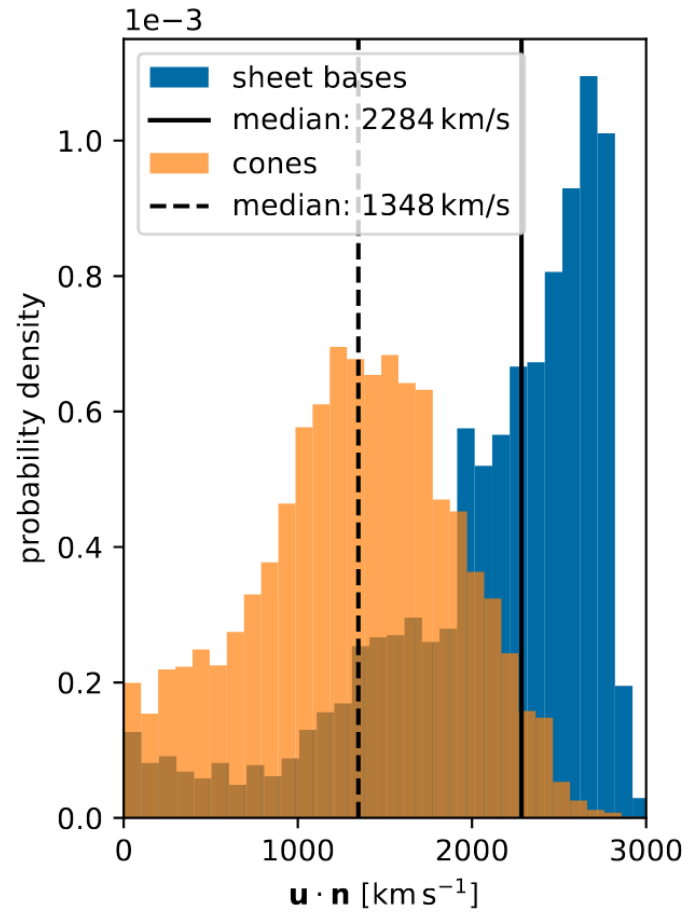
- Neither streaming instabilities nor sub-grid dynamos are likely to increase limits into the PeV range (factor 100!)
 - **Streaming instabilities** give factor ~ 10
for typical parameters at saturation, assuming Bohm scaling (= optimistic scenario)
 - **Sub-grid dynamos**: most energy would need to be in fields on scales ~ 0.1 pc
- Magnetic field is found to scale $\sim 1/r$
→ $E_{\max}$ stays constant as cluster WTS radius increases

Note: same as for a single star!

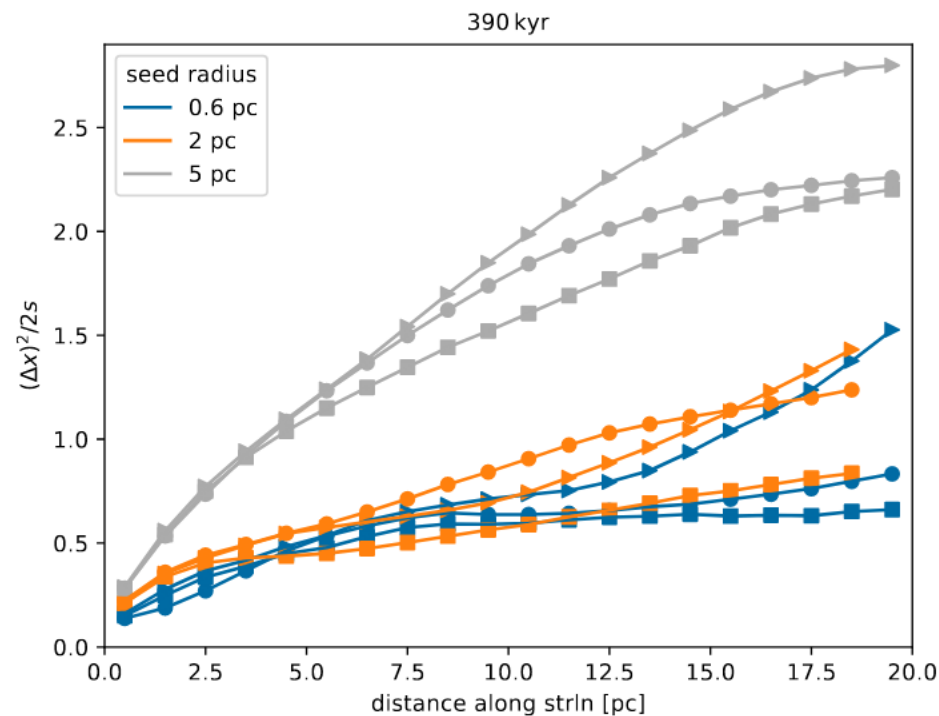
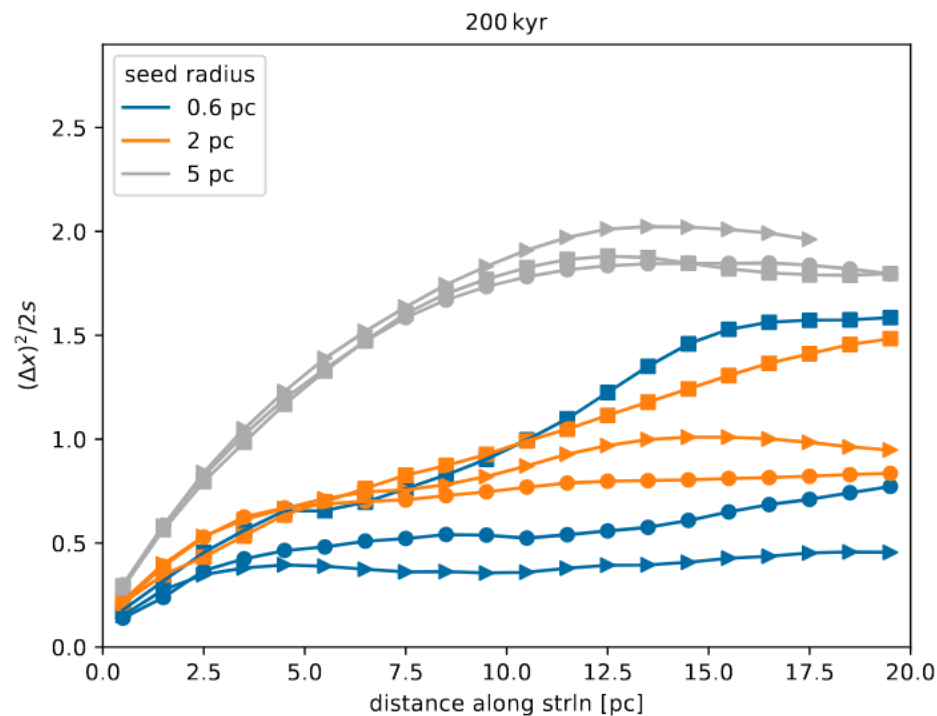


Magnetic field averages





Streamline Diffusivity



Magnetic field radial scaling

