Max-Planck-Institut für Kernphysik Heidelberg

Particle acceleration in superbubbles: from dreams to reality

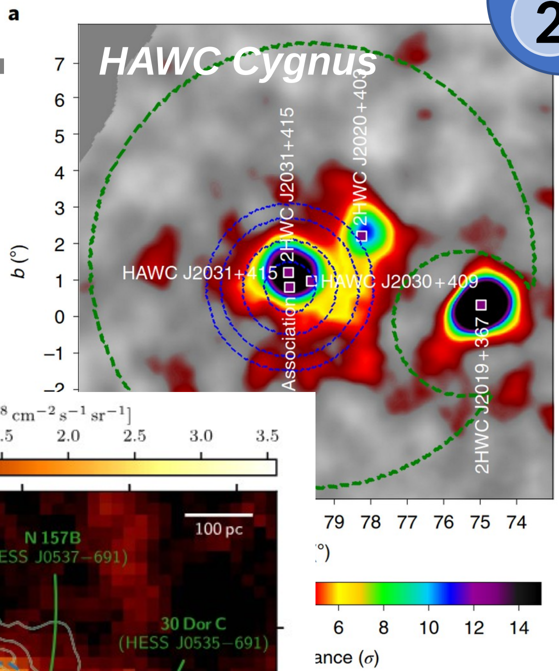
Thibault Vieu
w/ L. Härer, C. Larkin, B. Reville

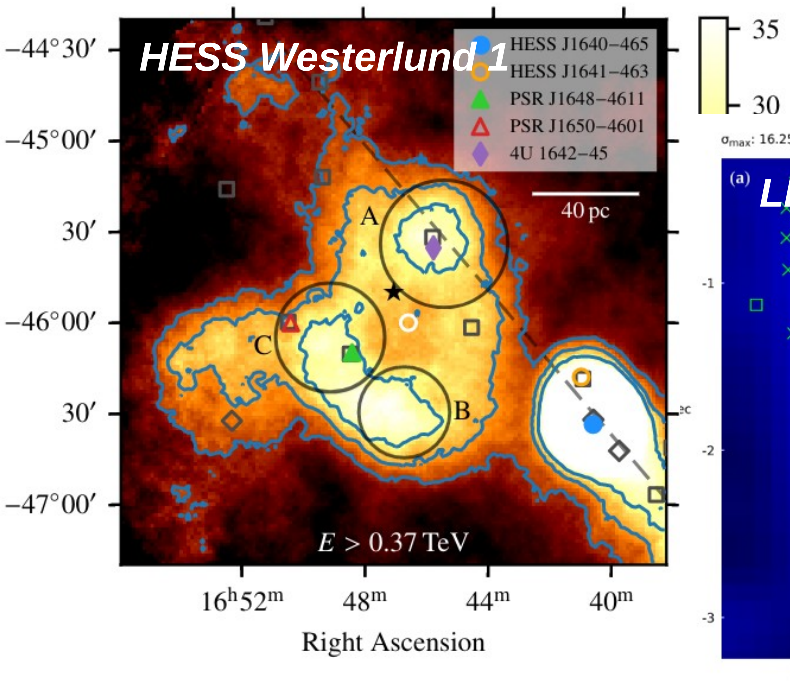
MPIK, Heidelberg

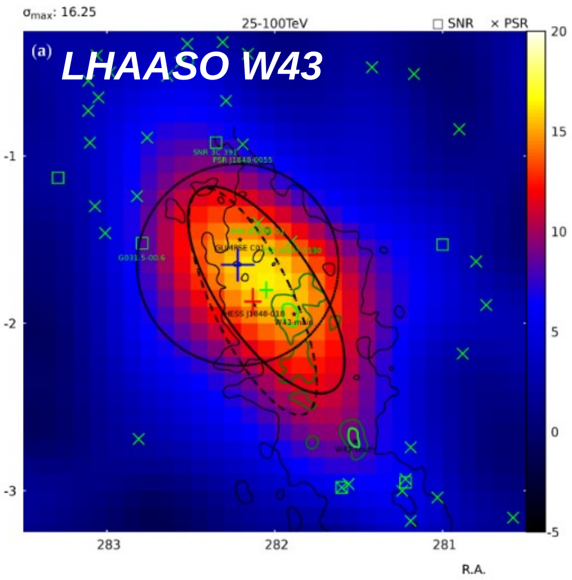
Star-forming regions as VHE γ-ray sources

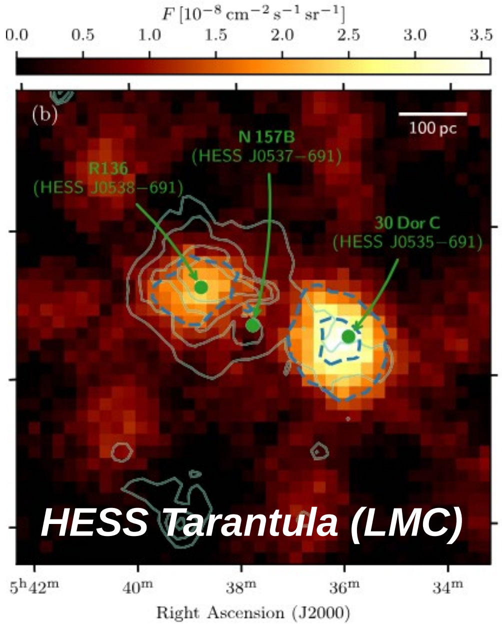
Most massive stars (supernova progenitors) are born in clusters or OB associations

Several massive star clusters are observed in gamma-rays up to 100s TeV





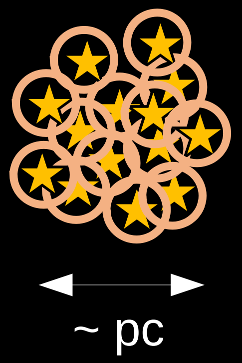




Compact star clusters: the core

~ 100 O stars crowded in a few pc^3
Stellar winds interact (collide) efficiently

The region is highly turbulent.
Thermal pressure builds up.



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Vieu, Härer, Reville 2024

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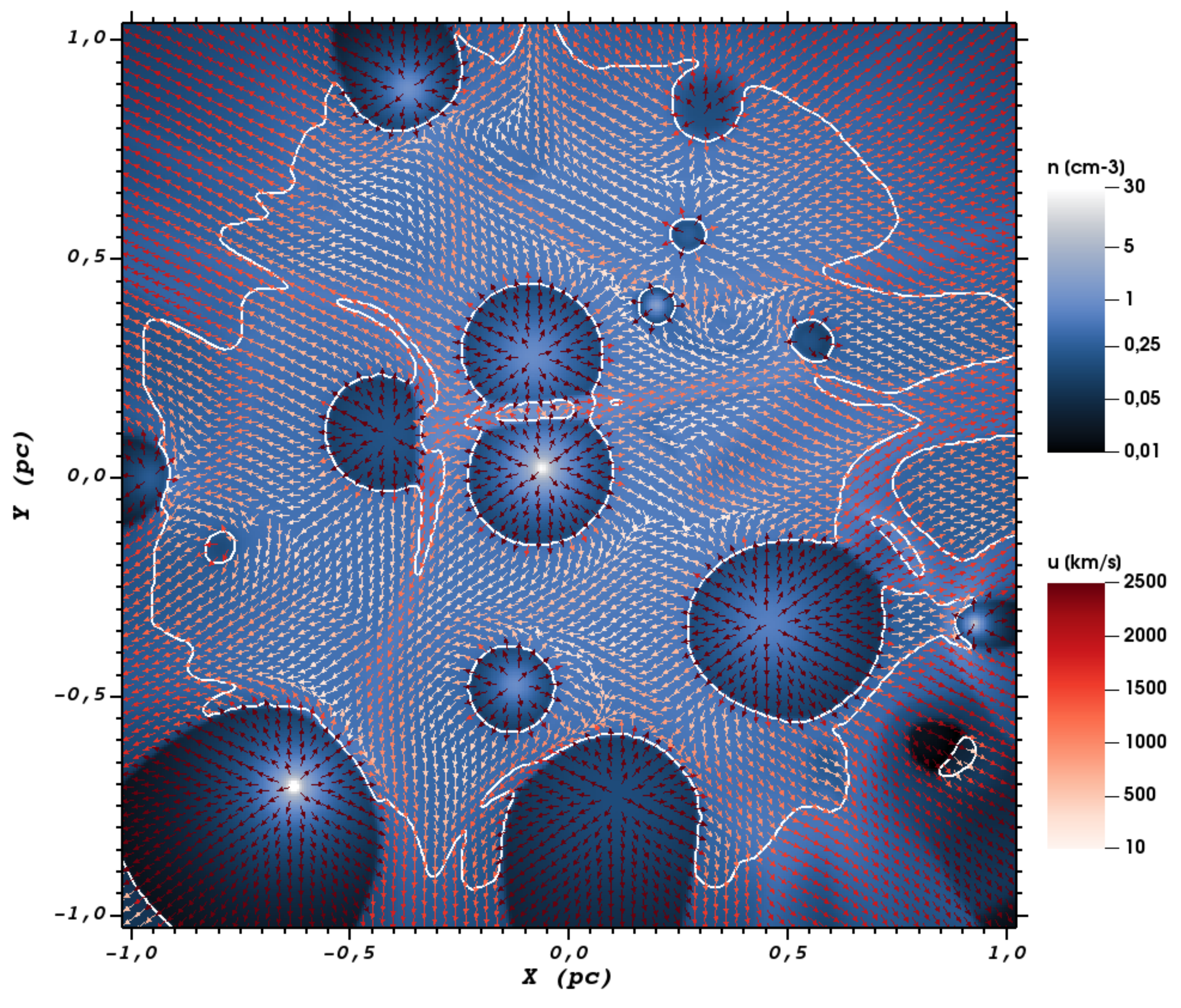
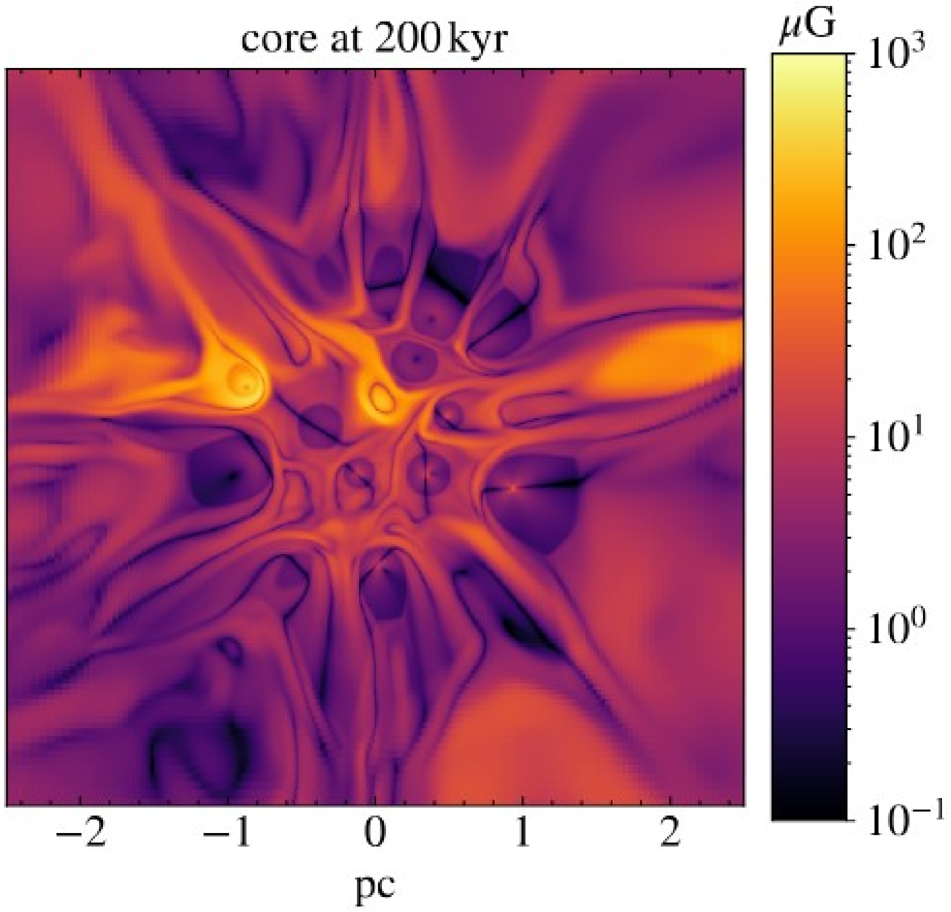
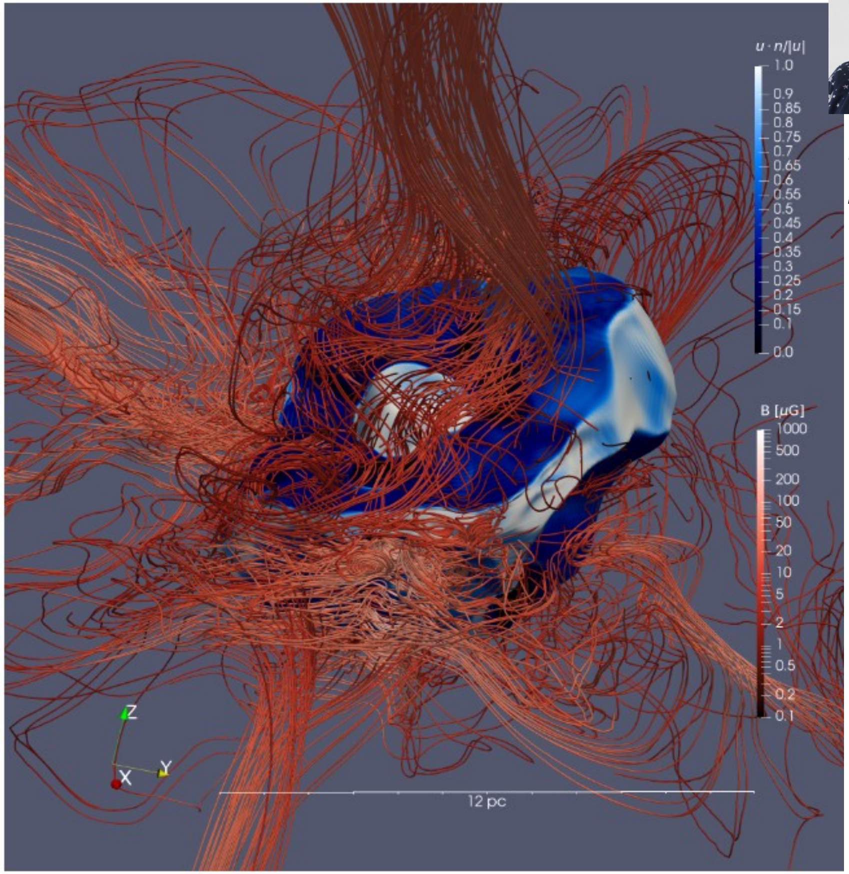


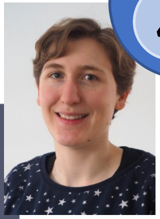
MHD simulations: unravelling the B field



B fields up to **100s μG in the core**

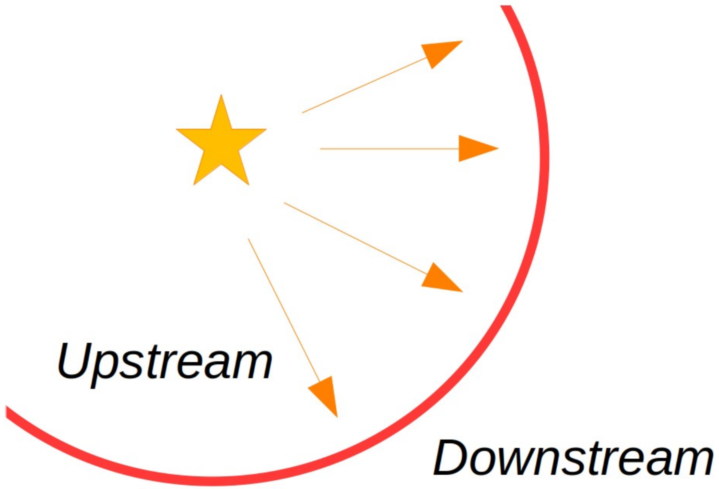


Stellar outflows colliding in the cluster core expand and mix the strong surface fields



Härer+, in prep

Maximum energy in stellar wind cavities



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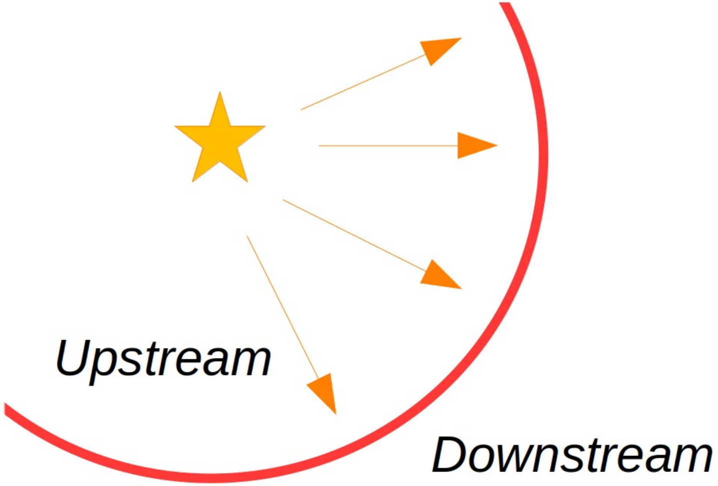

Adiabatic losses upstream => $E_{max} < V_w B R$

Super-Alfvénic stellar wind => $B << V_w \mathrm{sqrt}(4 \pi \varrho)$

=> $E_{max} << \mathrm{sqrt}(2 V_w L_w)/c \sim 100$ TeV

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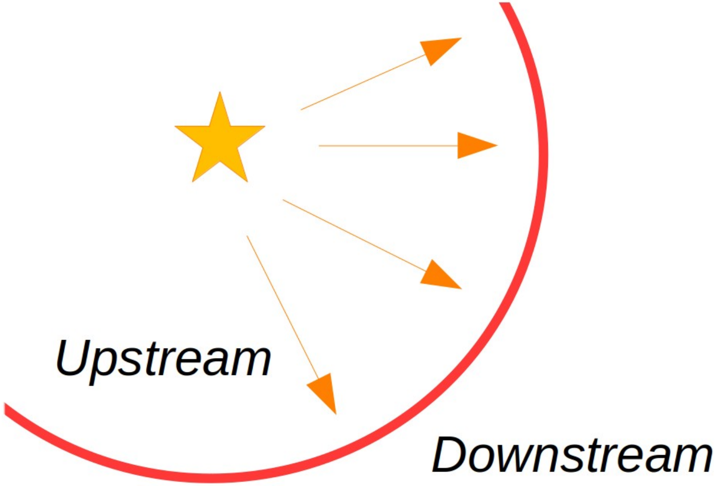

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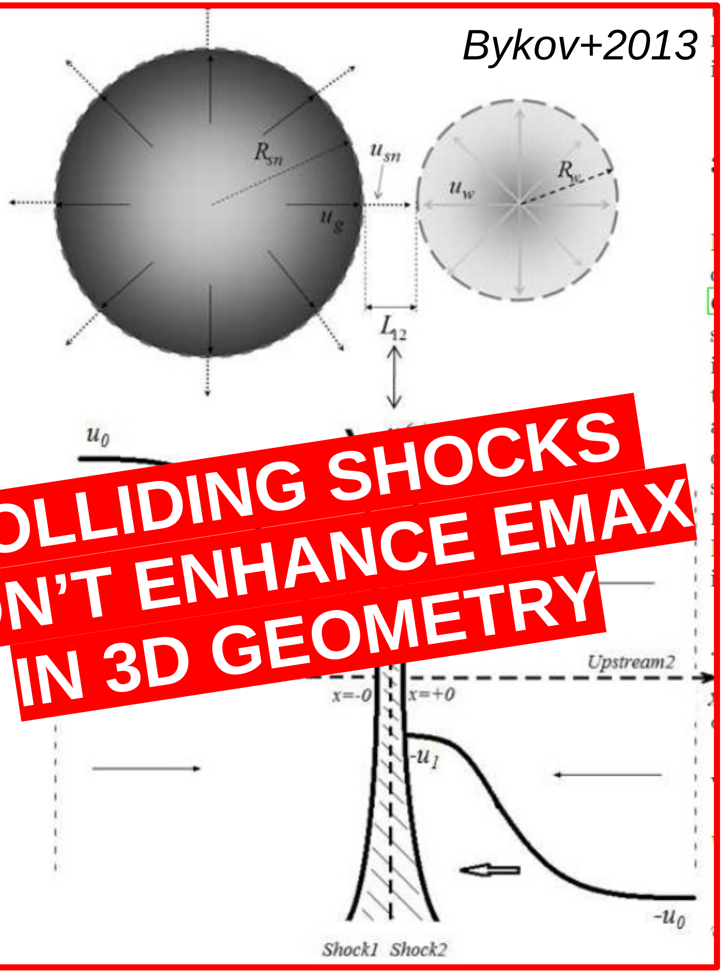
E_{max} < 100 TeV
absolute upper limit, would require very powerful stars, fast rotator, strongly magnetised (>> kG surface fields)

Absolute upper limit **independent of conditions downstream and independent of collective effects.**

- Same limitations in the case of wind-wind collisions.
- In general, particle advection downstream (escape) is more limiting: E_{max} << 100 TeV

The dream of collective effects...

Bykov+2013



COLLIDING SHOCKS DON'T ENHANCE EMAX IN 3D GEOMETRY

Bykov & Fleishman 1992
Klepach+2000
Bykov+2001

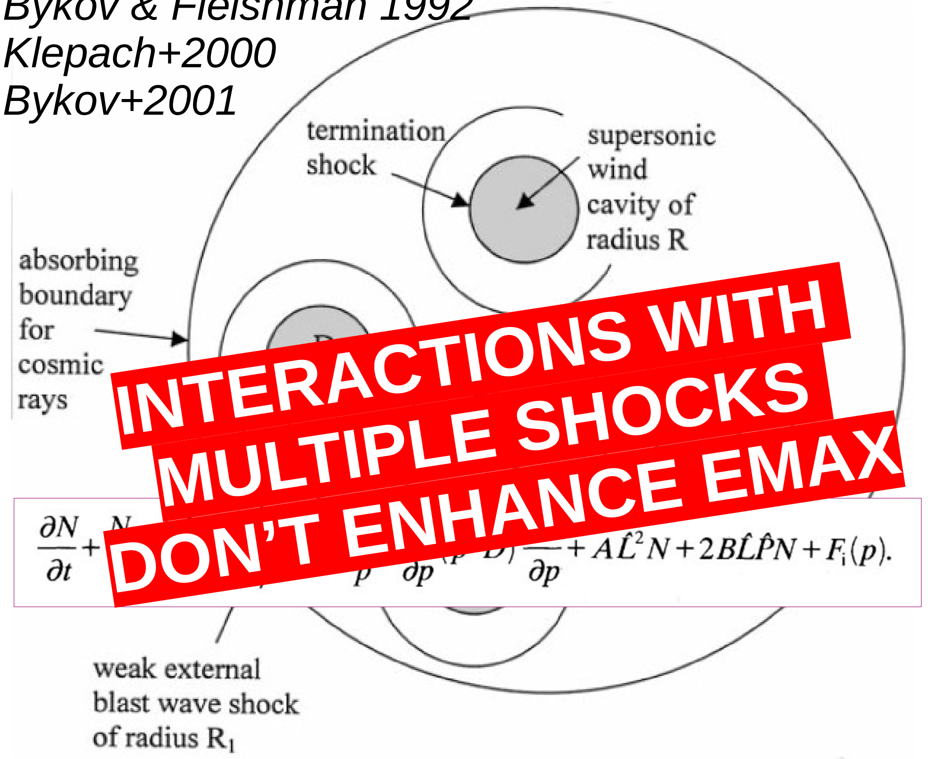
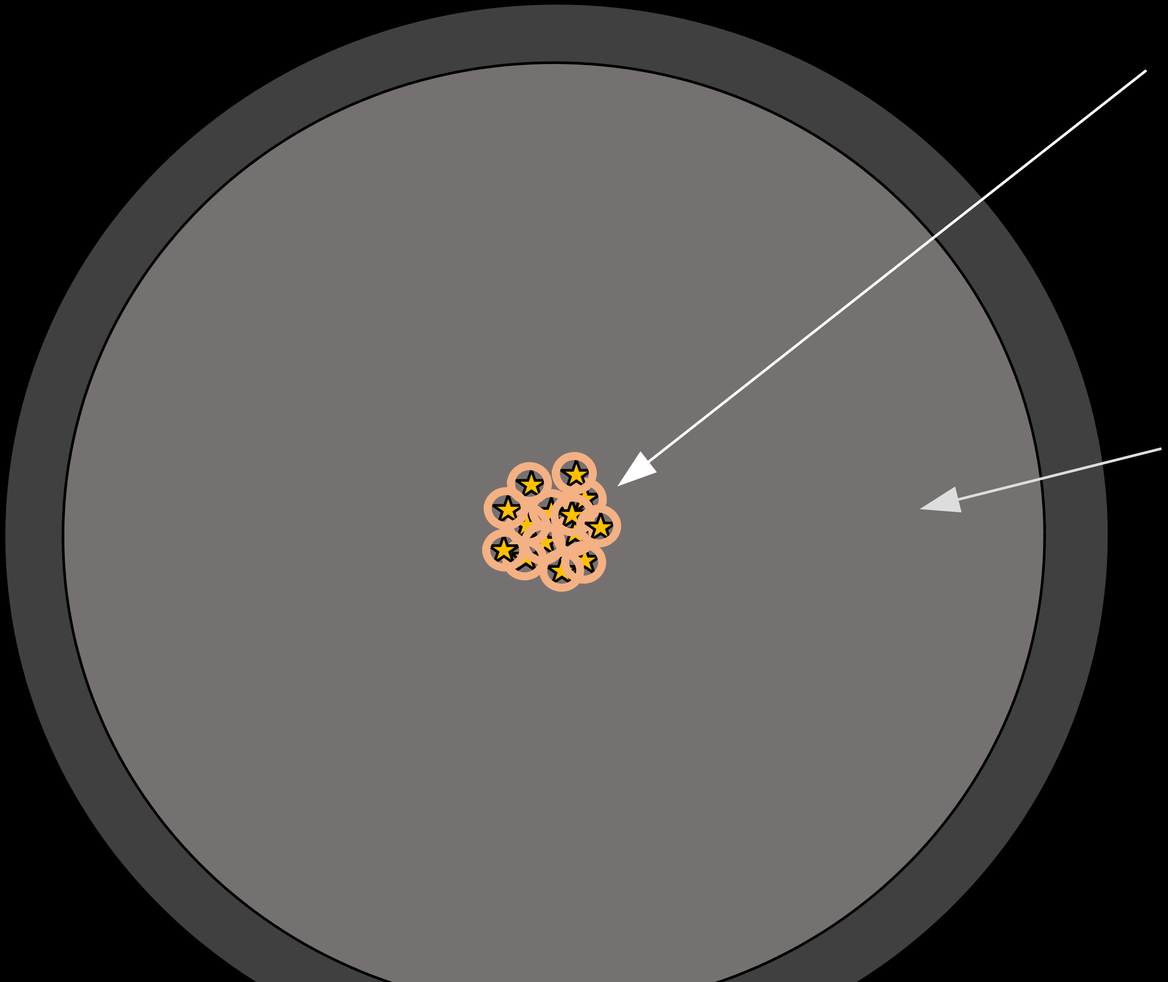


Fig. 3. The system of star winds in Model II.

INTERACTIONS WITH MULTIPLE SHOCKS DON'T ENHANCE EMAX

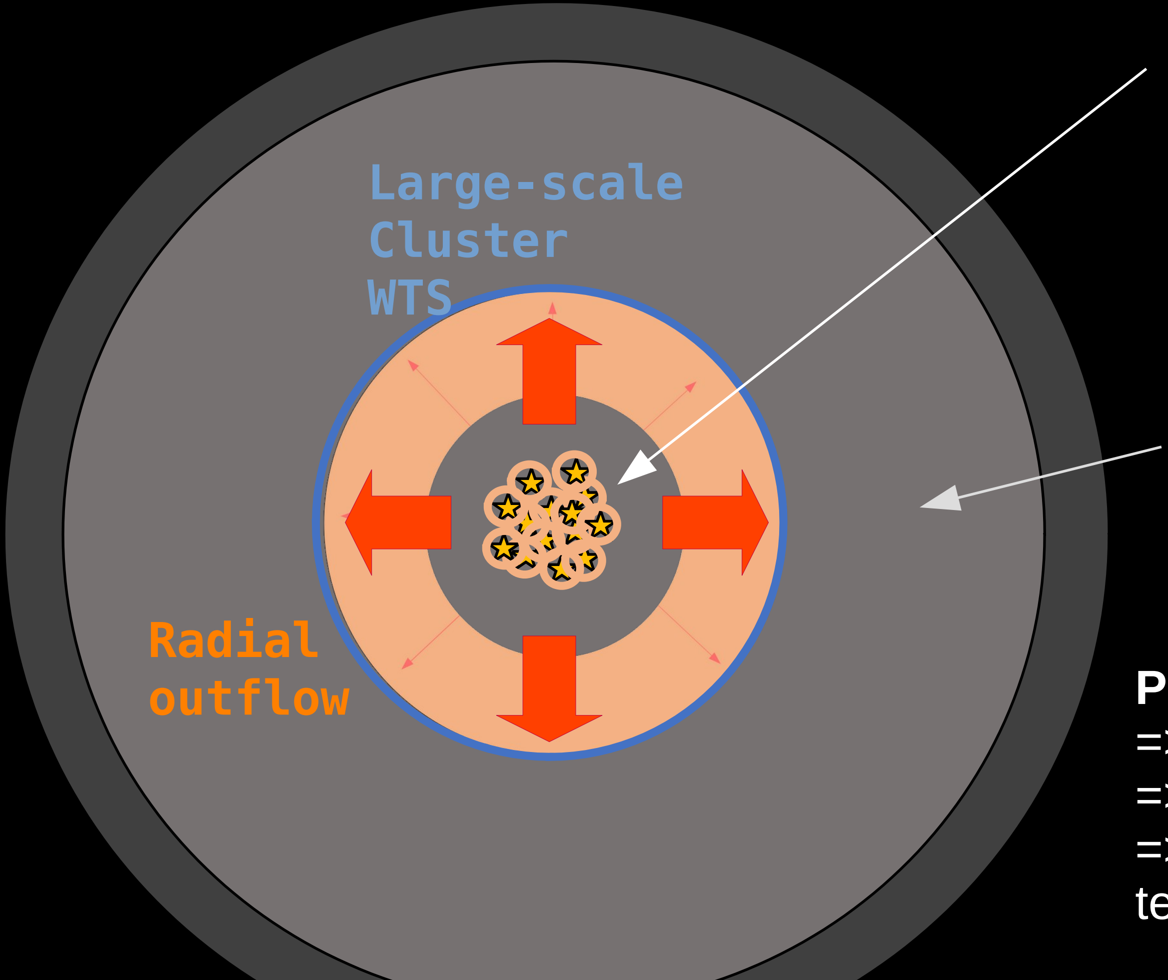
Beyond the core: cluster wind termination shock



Stellar wind interactions
=> pressure builds up in the core
=> heating of the ISM and superbubble expansion

Superbubble expansion
=> pressure drops outside of the core

Beyond the core: cluster wind termination shock



Stellar wind interactions
=> pressure builds up in the core
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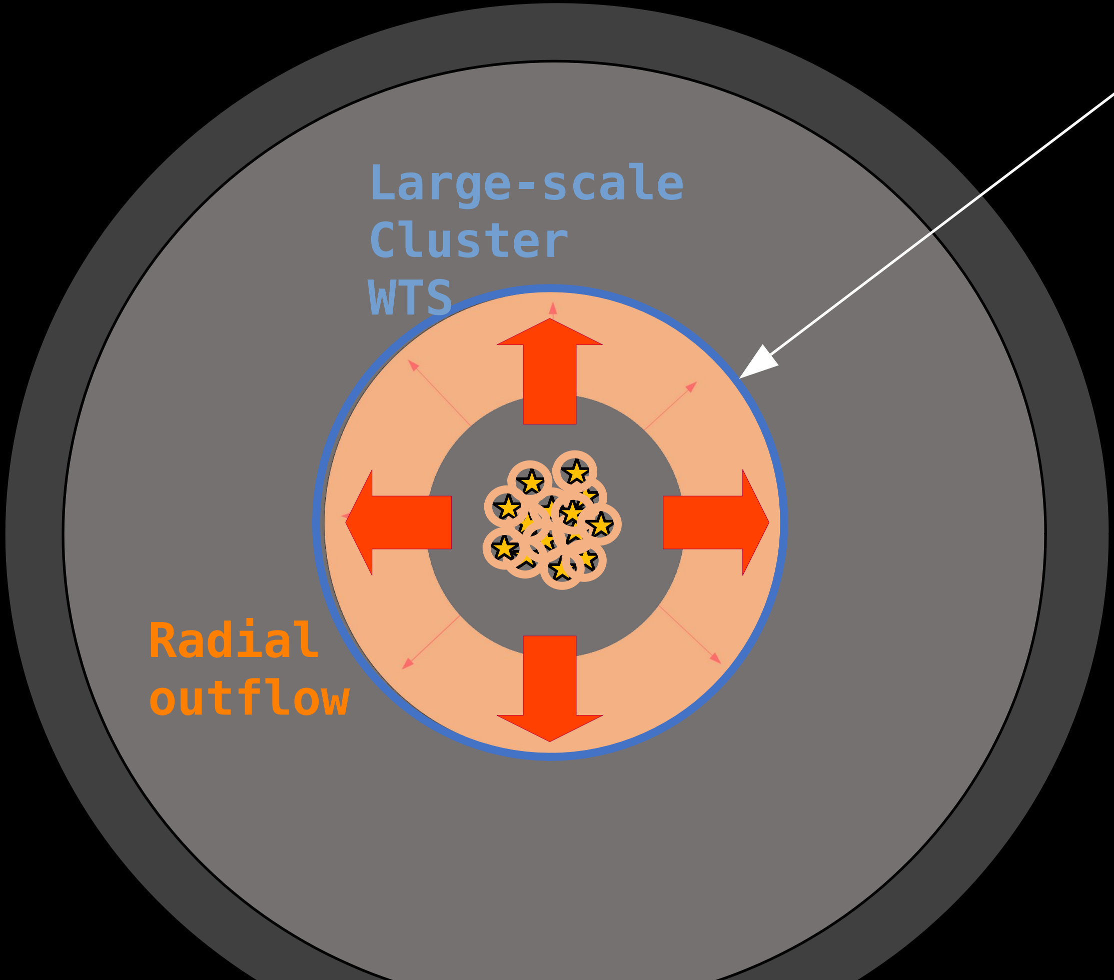
Superbubble expansion
=> pressure drops outside of the core

Pressure gradient
=> the flow accelerates outward
=> becomes supersonic
=> terminates at the “wind termination shock”

The dream of PeVatron



Emax at the WTS:
U ~ 2000 km/s
R ~ 10 pc
B ~ 10 μG (cannot be much more otherwise the shock is not super-Alfvénic)

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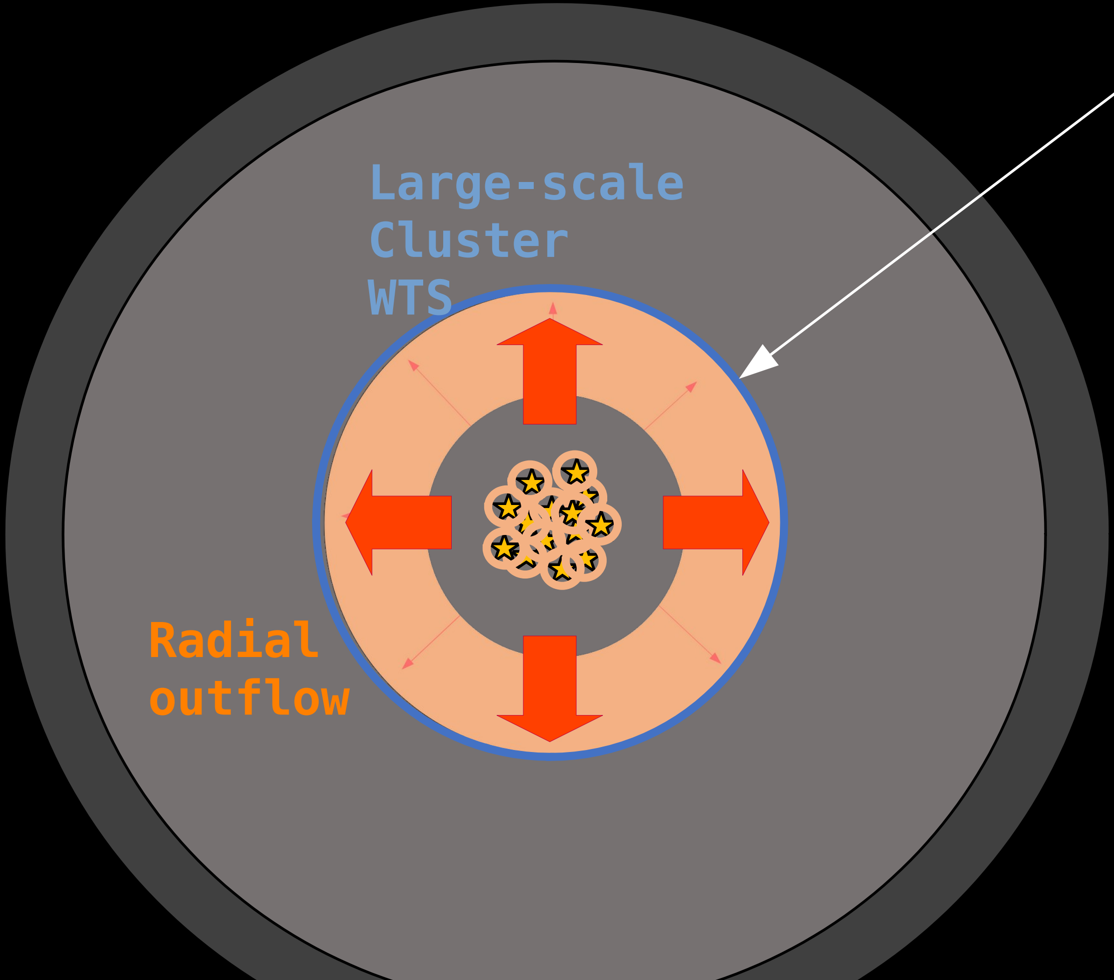

Emax at the WTS:
U ~ 2000 km/s
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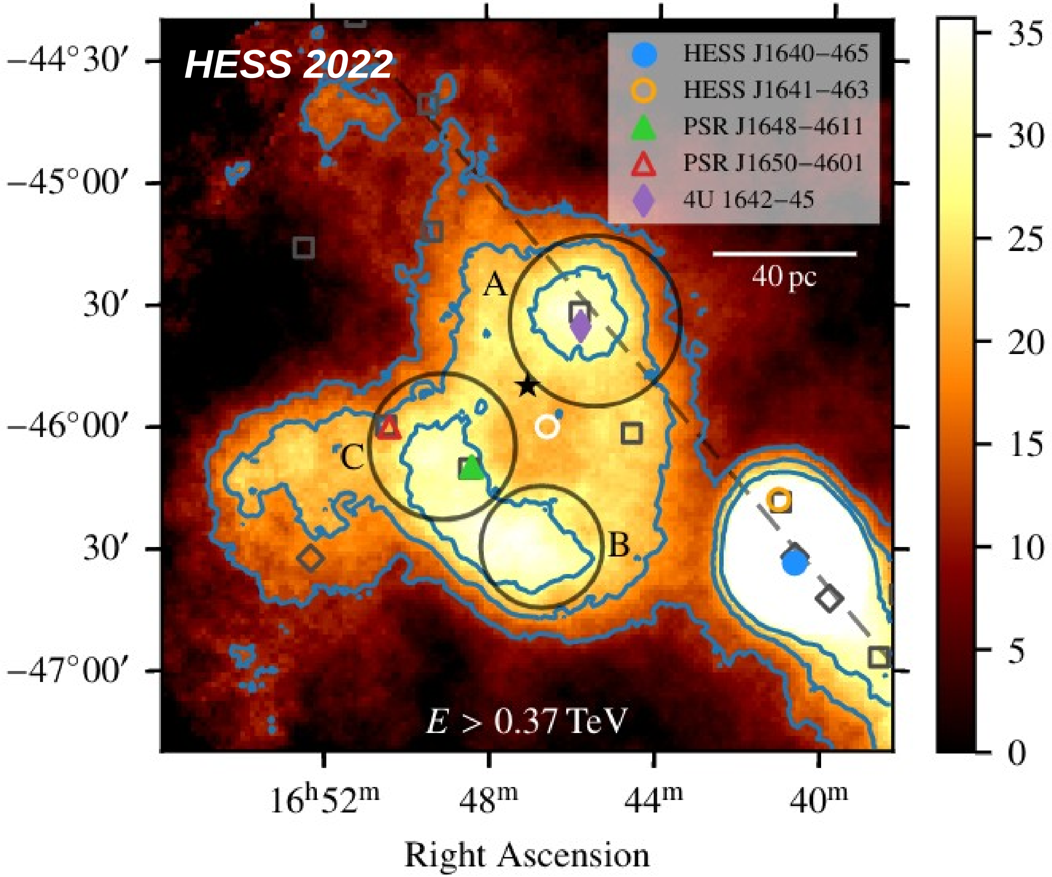
B ~ 10 µG (cannot be much more otherwise the shock is not super-Alfvénic)

=> E_{max} < 1 PeV

Cluster wind termination shock: Westerlund 1 example



Most powerful star cluster in the Galaxy
L_w ~ 10^{39} erg/s, $\dot{M}$ ~ 5e-4 Msol/yr

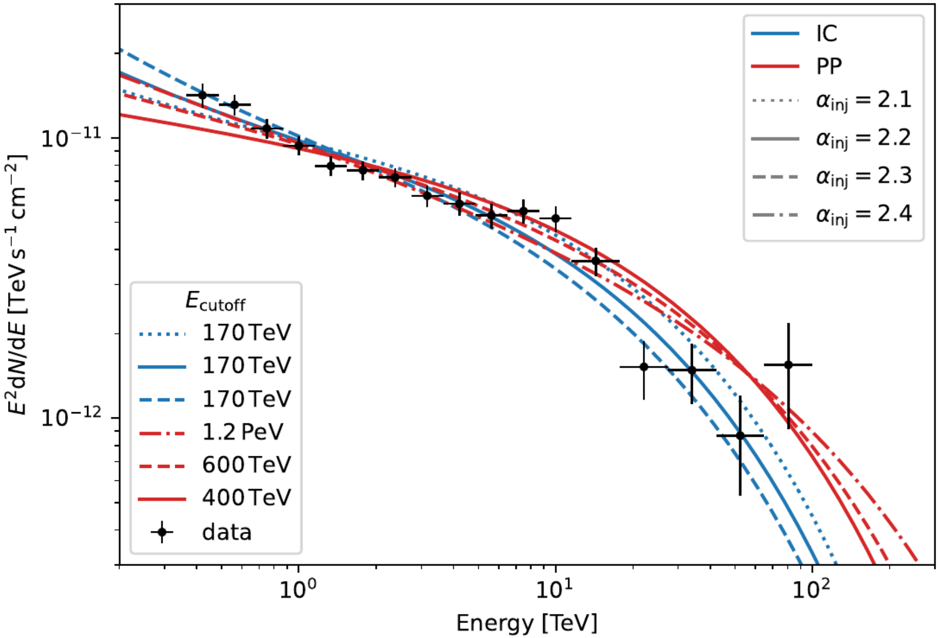
Very compact (hundreds of O stars and 24 WR stars within ~ 1 pc^3)

Ring-shape ɣ-ray emission up to 100 TeV

Cluster wind termination shock: Westerlund 1 example

Leptonic scenario
Standard photon fields (stars, CMB, dust)
D(10 TeV) ~ 1e27 cm²/s (constrained by morphology)
Acceleration efficiency ~ 0.1%
Emax = 170 TeV

Härer et al. 2023



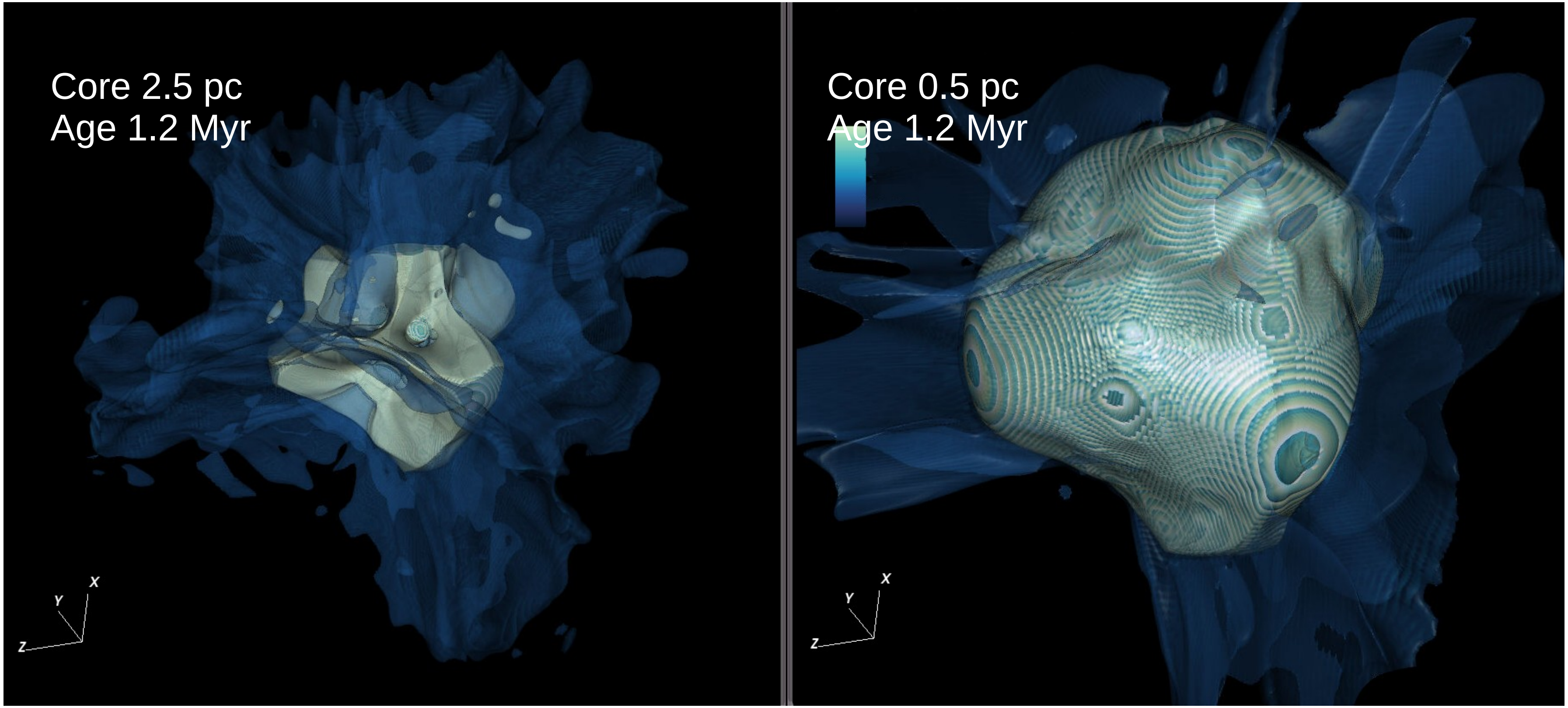
Note: Low density medium (n < 0.1 cm^{-3}) generically expected in the vicinity of star clusters

=> hadronic scenario usually disfavored, unless there are very dense molecular clouds nearby (not the case for Wd1 but see A. Inventar's poster for W43)

Intense UV field near the cluster => IC emission is hard to hide

The dream of spherical symmetry

Westerlund 1 is exceptionnally powerful and compact.
‘‘Standard’’ star clusters have an **asymmetric** distribution of powerful stars over a few parsecs.
This produces **highly asymmetric cluster outflows**.



Compact star clusters: let’s recap

- The core is a mess, yet small spherical shocks cannot accelerate beyond ~ 100 TeV (at very best and despite collective effects)

- Standard cluster winds are asymmetric, which is expected to reduce the acceleration efficiency and steepen the spectrum

- Bottom line: we expect somewhat steep gamma-ray spectra with cut-off around 10 TeV

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- Disappointing? … **Well, as of now, this is exactly what we observe!**

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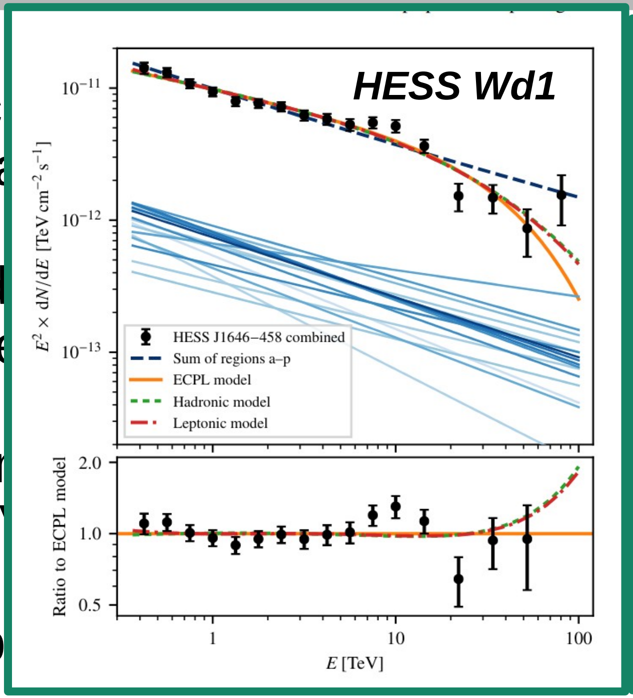

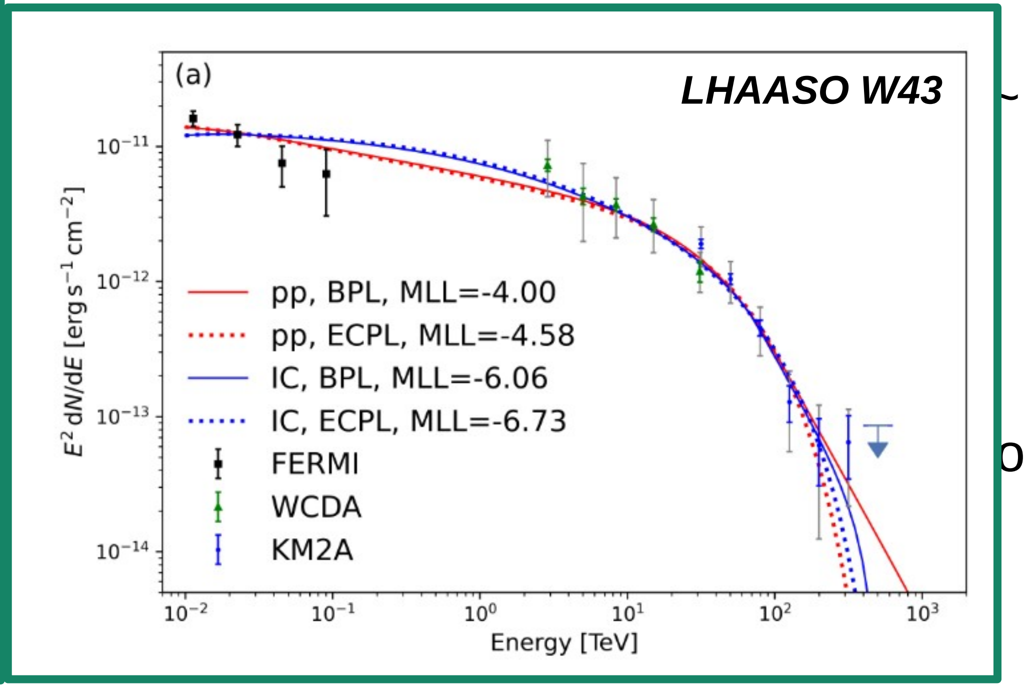

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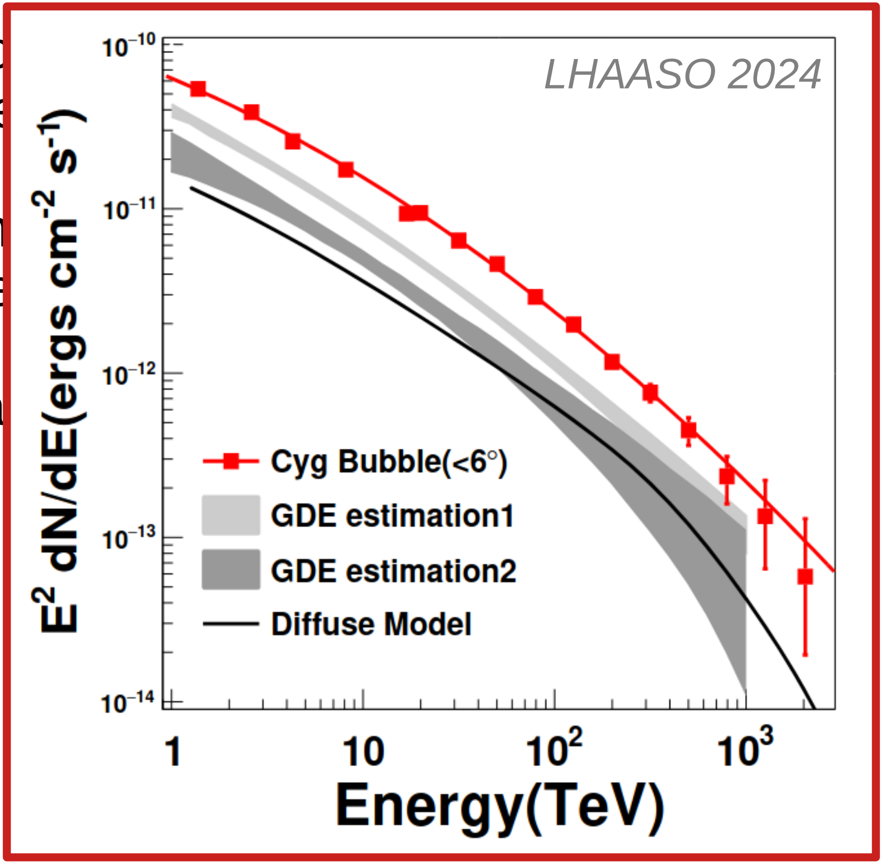
… with one exception: Cygnus.



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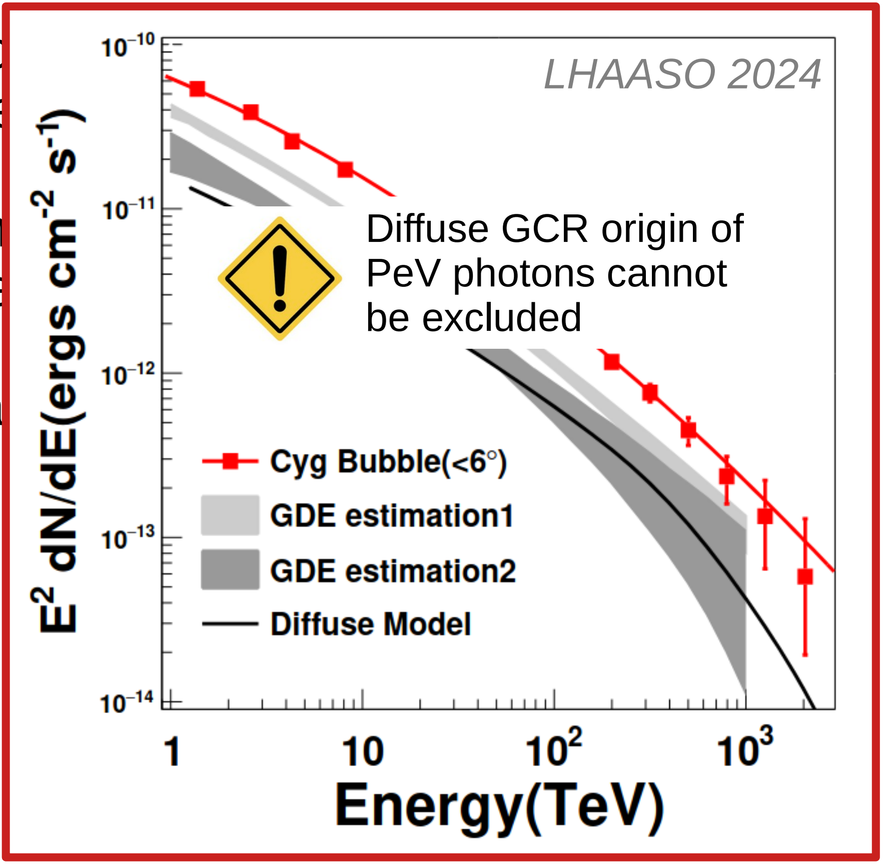
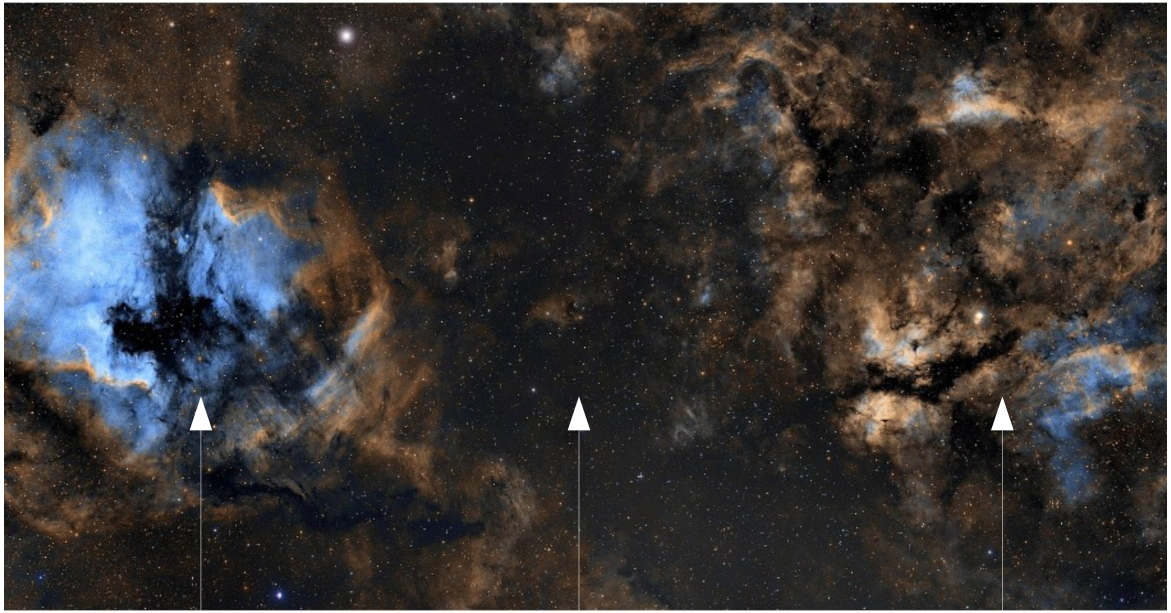


Introducing the Cygnus region

Highly extinct, very complex region

Optical (commons.wikimedia.org/Luka)



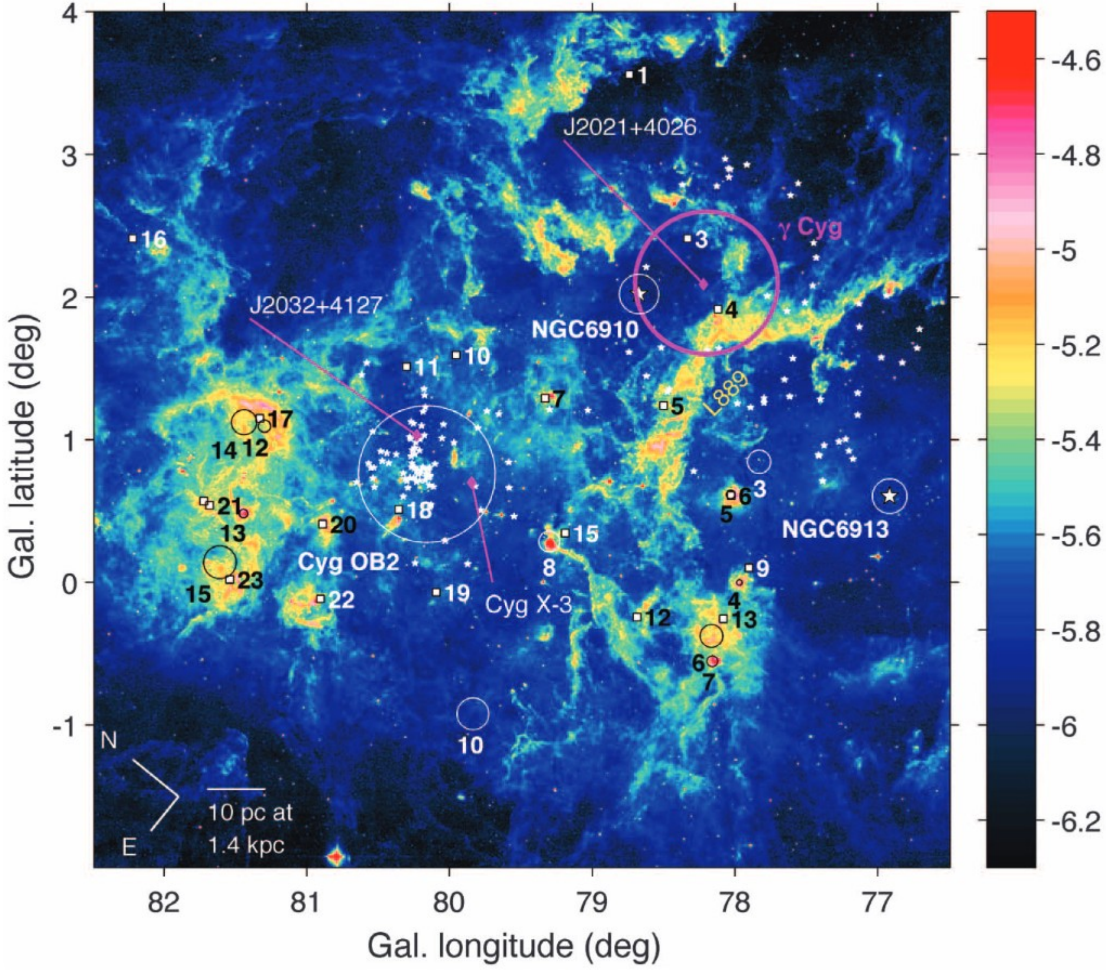
NAP nebula

Cygnus X

Sadr nebula (ɣ-Cygni)

Introducing the Cygnus region

8 µm map (Fermi collab. 2012)

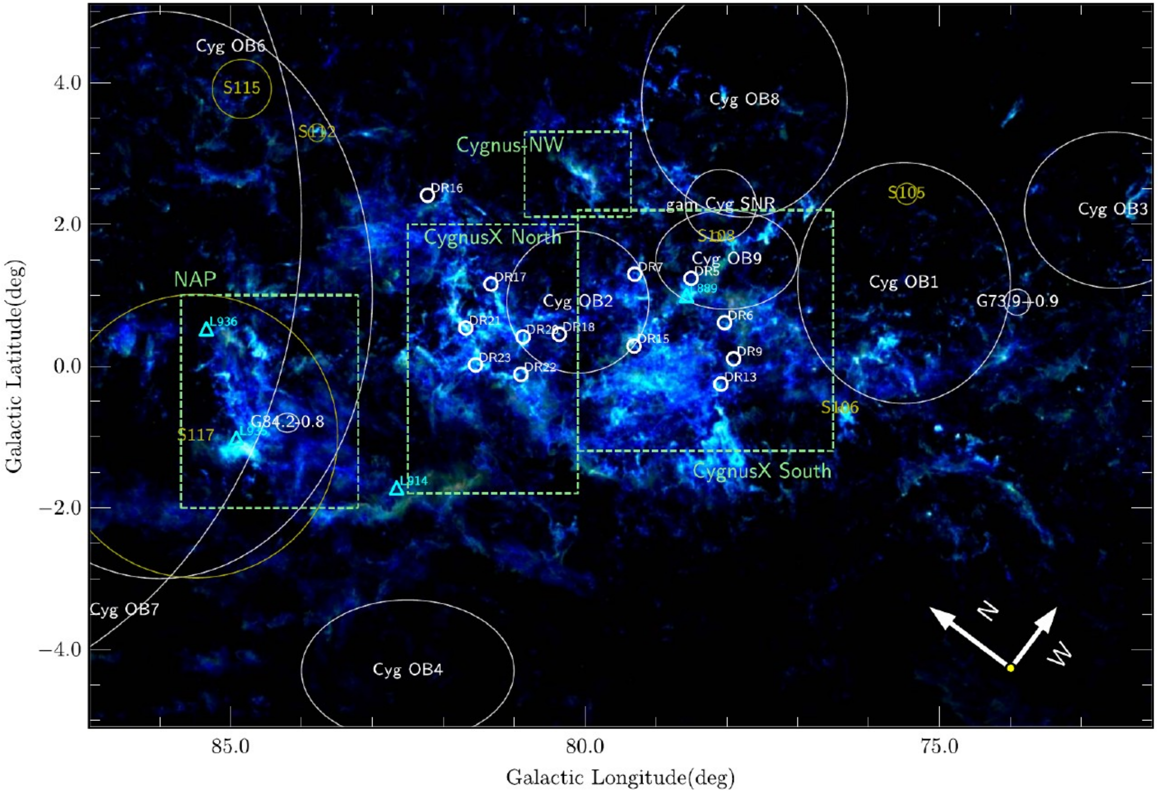


Highly extinct, very complex region

Diffuse clouds, HII regions, photodissociation rims, cavities

Introducing the Cygnus region

CO intensity (MWISP/Zhang+2024)



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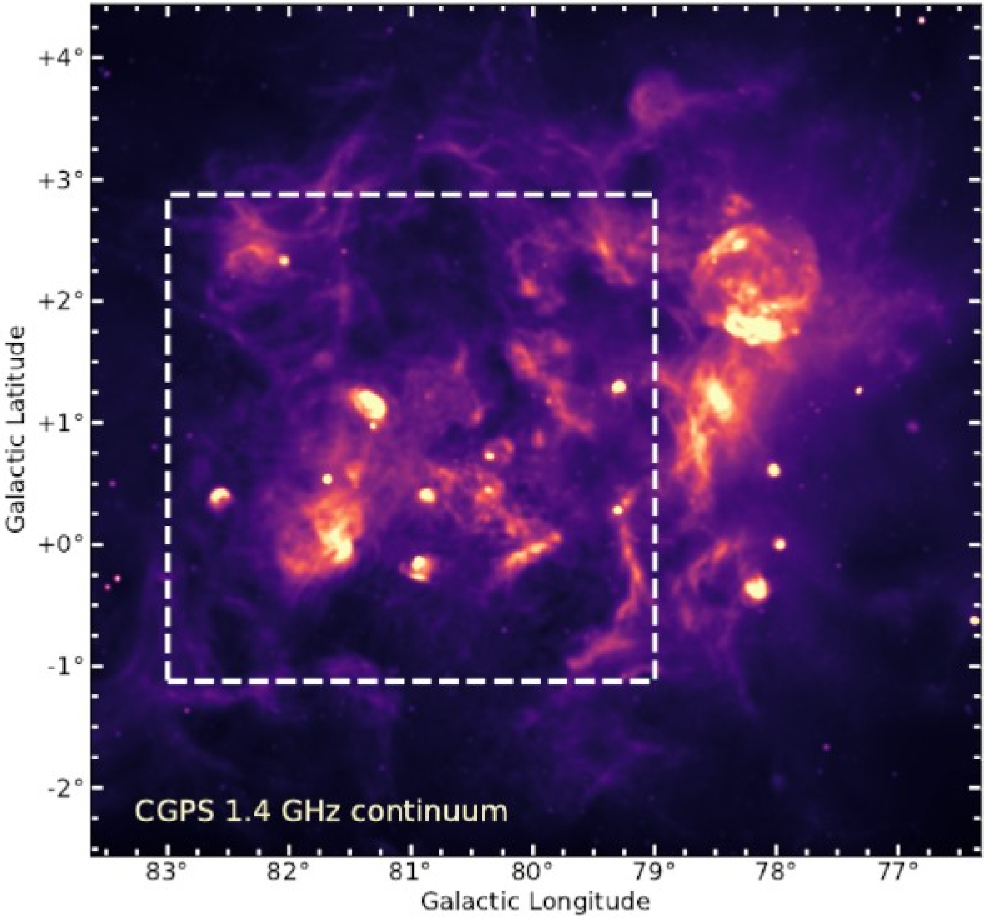
Diffuse clouds, HII regions, photodissociation rims, cavities

CO molecular clouds (> 1e6 Msol!)
Most massive molecular cloud within 2 kpc

Introducing the Cygnus region

Emig+2022 (CGPS data)



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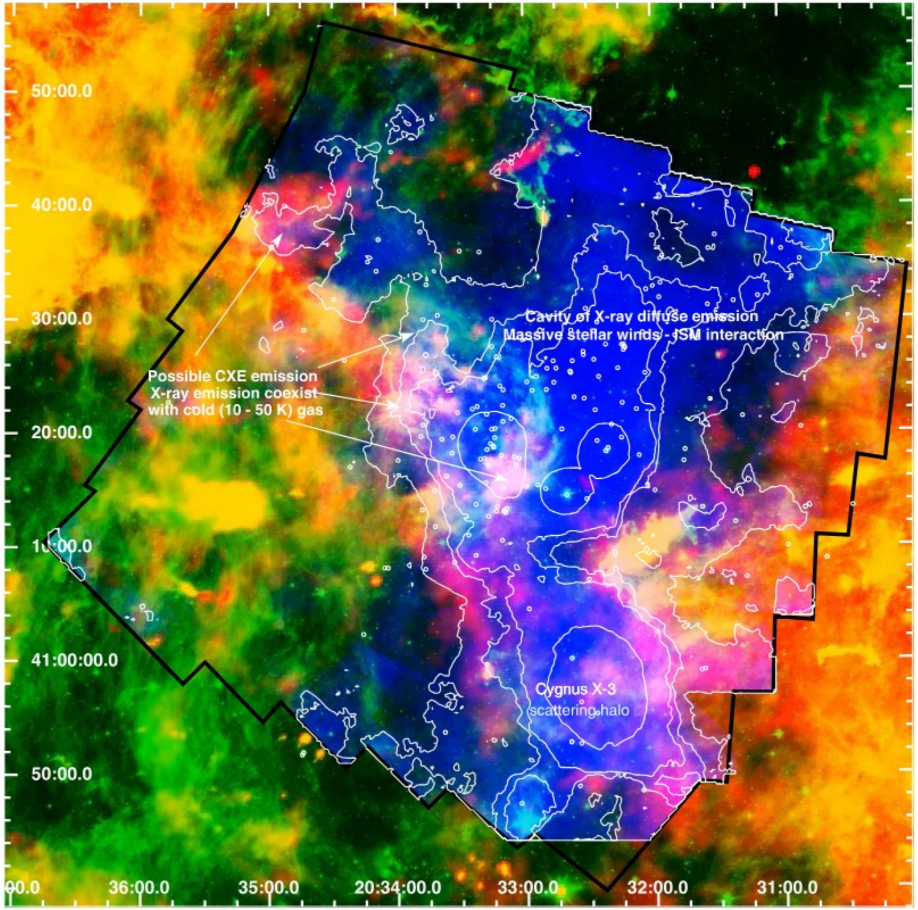
Diffuse radio, radio hotspots

Introducing the Cygnus region

Albacete-Colombo+2023 (Chandra)



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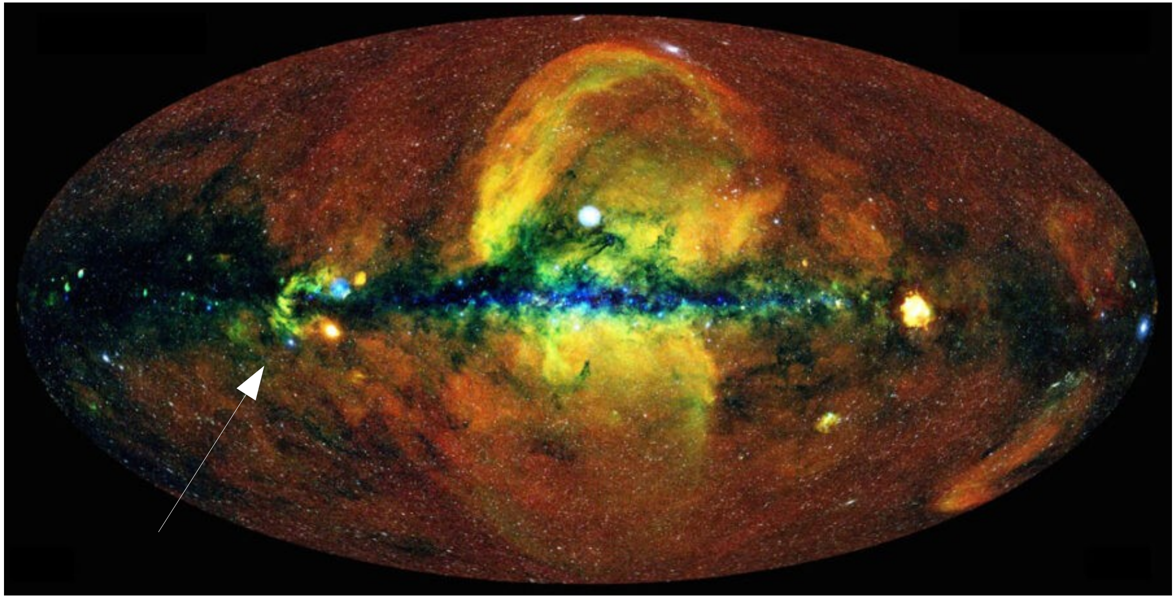
Diffuse X-rays

Introducing the Cygnus region

eROSITA



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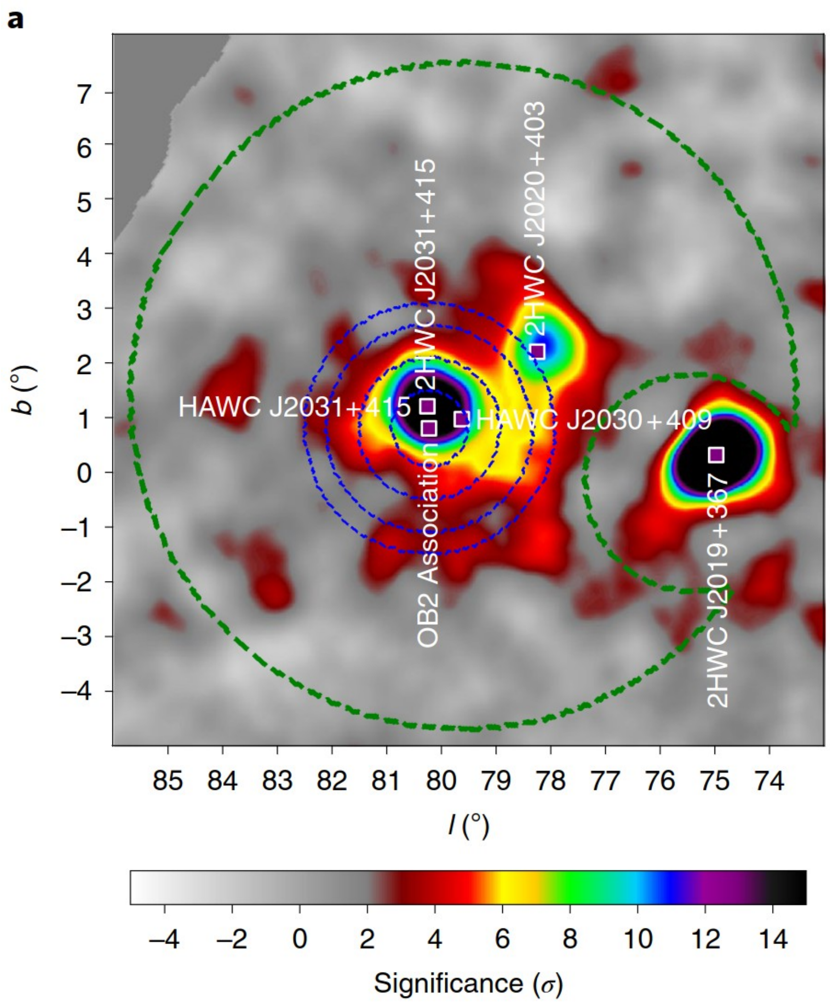
Gigantic X-ray shell / Hα filaments...

Introducing the Cygnus region

HAWC
2021



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Several VHE sources

Cygnus OB2 association
Cyg X-3 microquasar
PSR J2032+4127 pulsar
ɣ-Cyg SNR...

Introducing the Cygnus region

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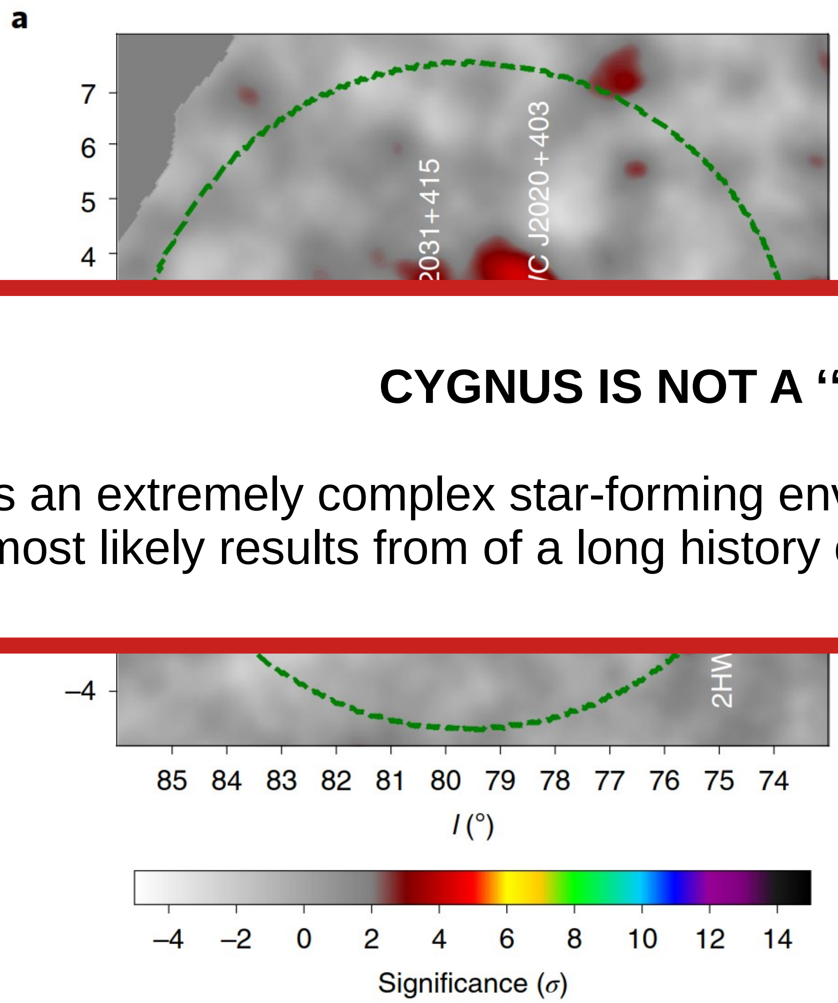


Highly extinct, very complex region

Diffuse clouds, HII regions, photodissociation rims, cavities

CO molecular clouds (> 1e6 Msol!)

kpc

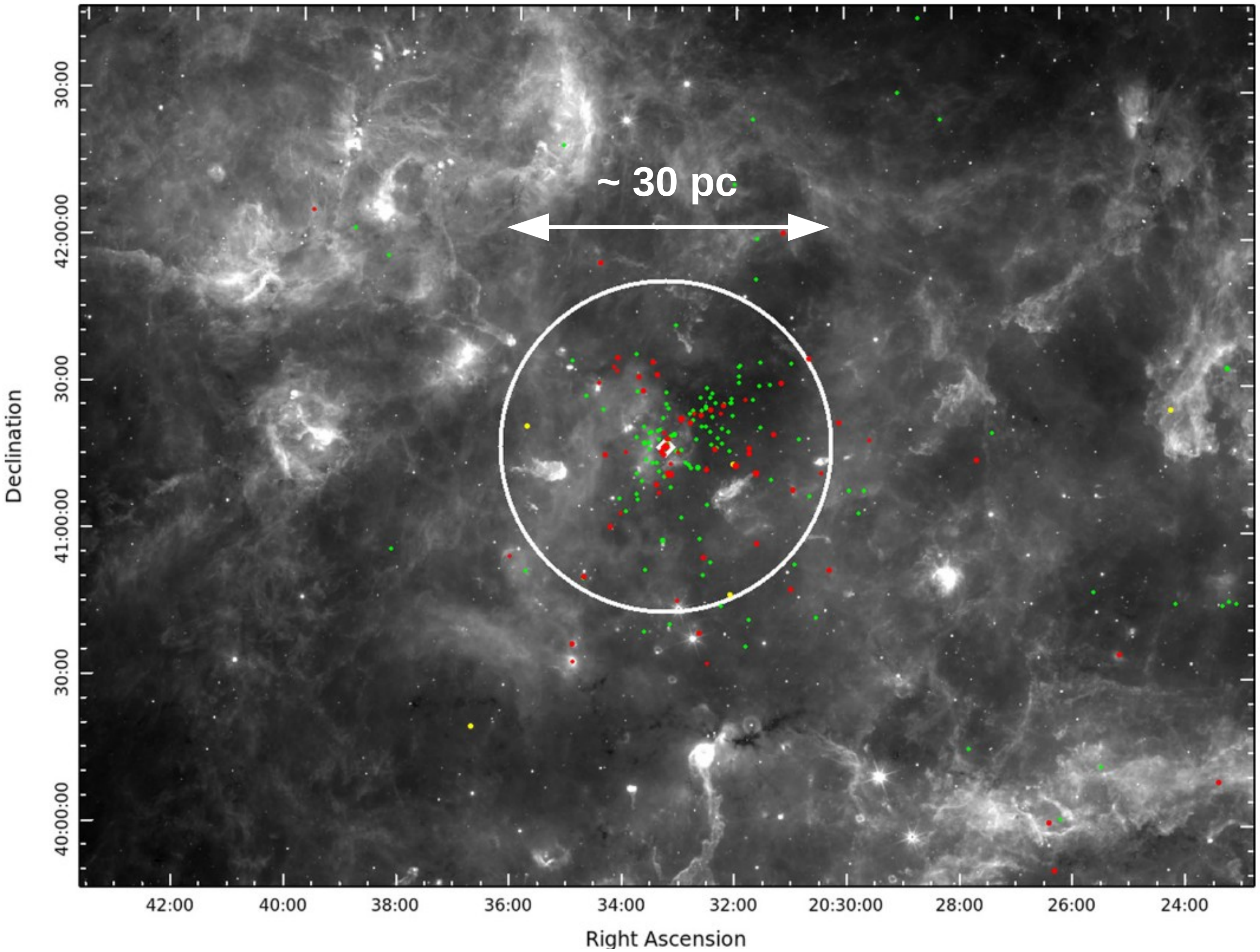
CYGNUS IS NOT A “STAR CLUSTER”

It is an extremely complex star-forming environment which nobody understands.
It most likely results from of a long history of starbirth events / SNe explosions.

Several VHE sources

Cygnus OB2 association
Cyg X-3 microquasar
PSR J2032+4127 pulsar
ɣ-Cyg SNR...

The Cygnus OB2 ~~star cluster~~ association



Wright+2015

Distance ~ ~~1.4 kpc~~ 1.65 kpc
Age ~ 3-5 Myr
Core diameter ~ 30 pc (!)

78 O stars
3 off-centred WR stars

L_w ~ 2 x 10^{38} erg/s

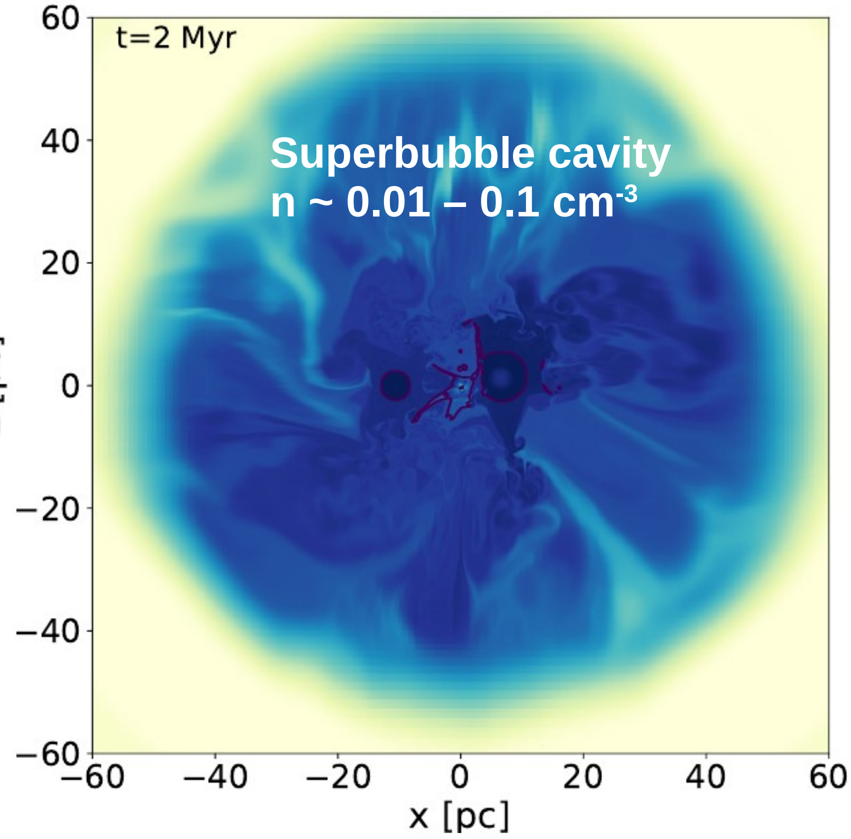
Simulating Cygnus OB2

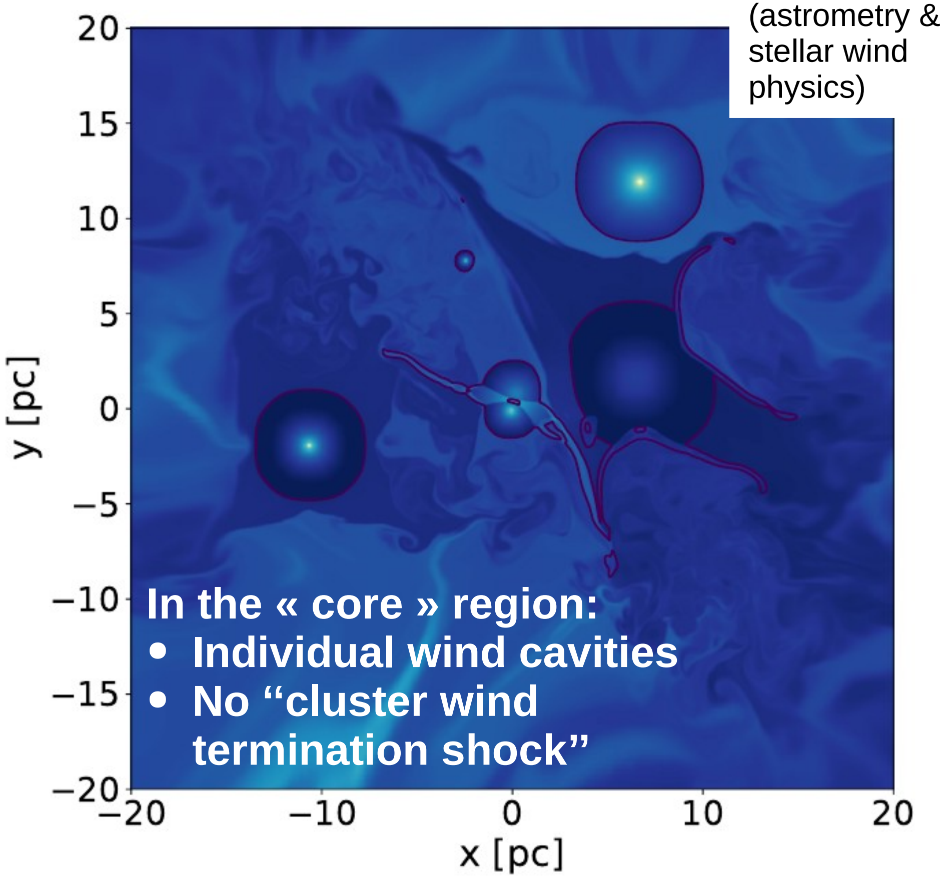
Vieu et al. 2024b

w/ C. Larkin (astrometry & stellar wind physics)

We put Cygnus OB2 in a (big) numerical box (1000^3 cells)
Solve with the PLUTO code on the Max-Planck HPC (~ 10^6 cpu-hour...)

Density slices





Simulation over 2 Myr, including 400 kyr of WR phase

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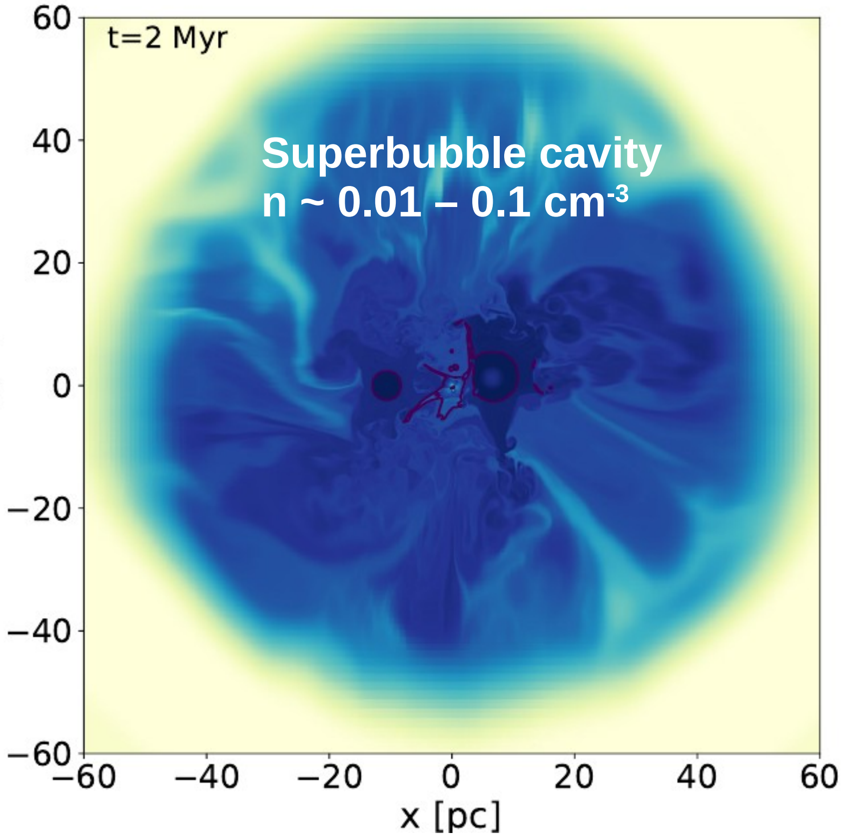

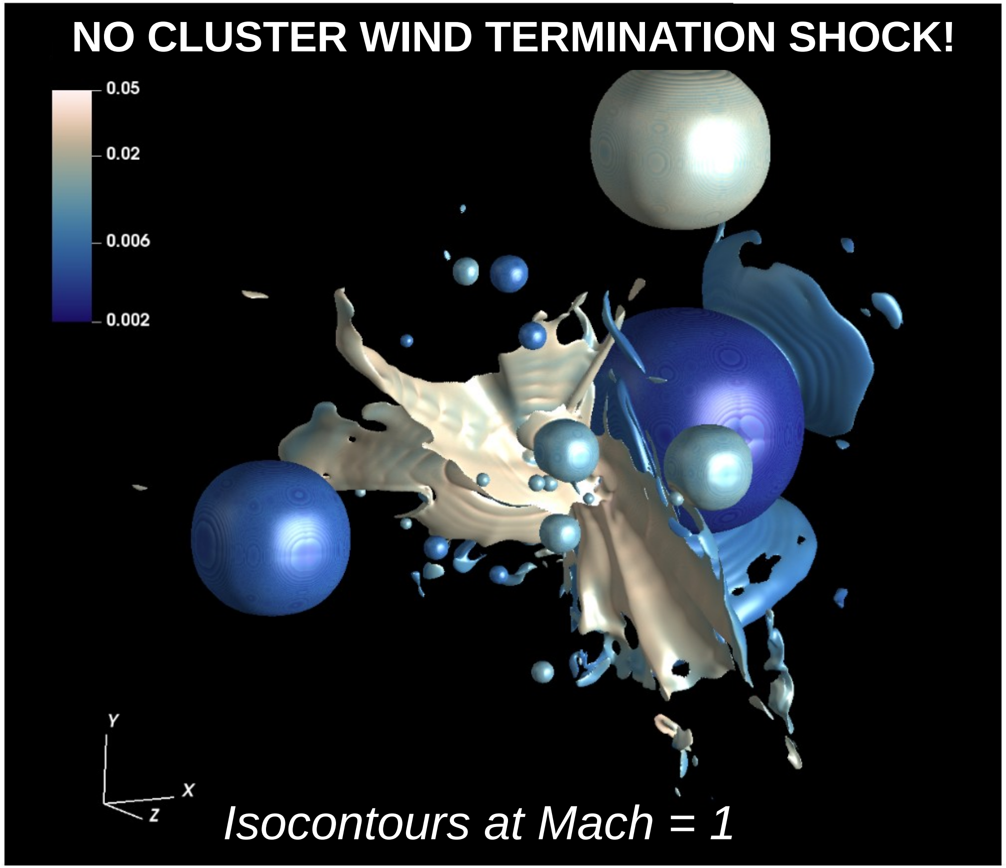

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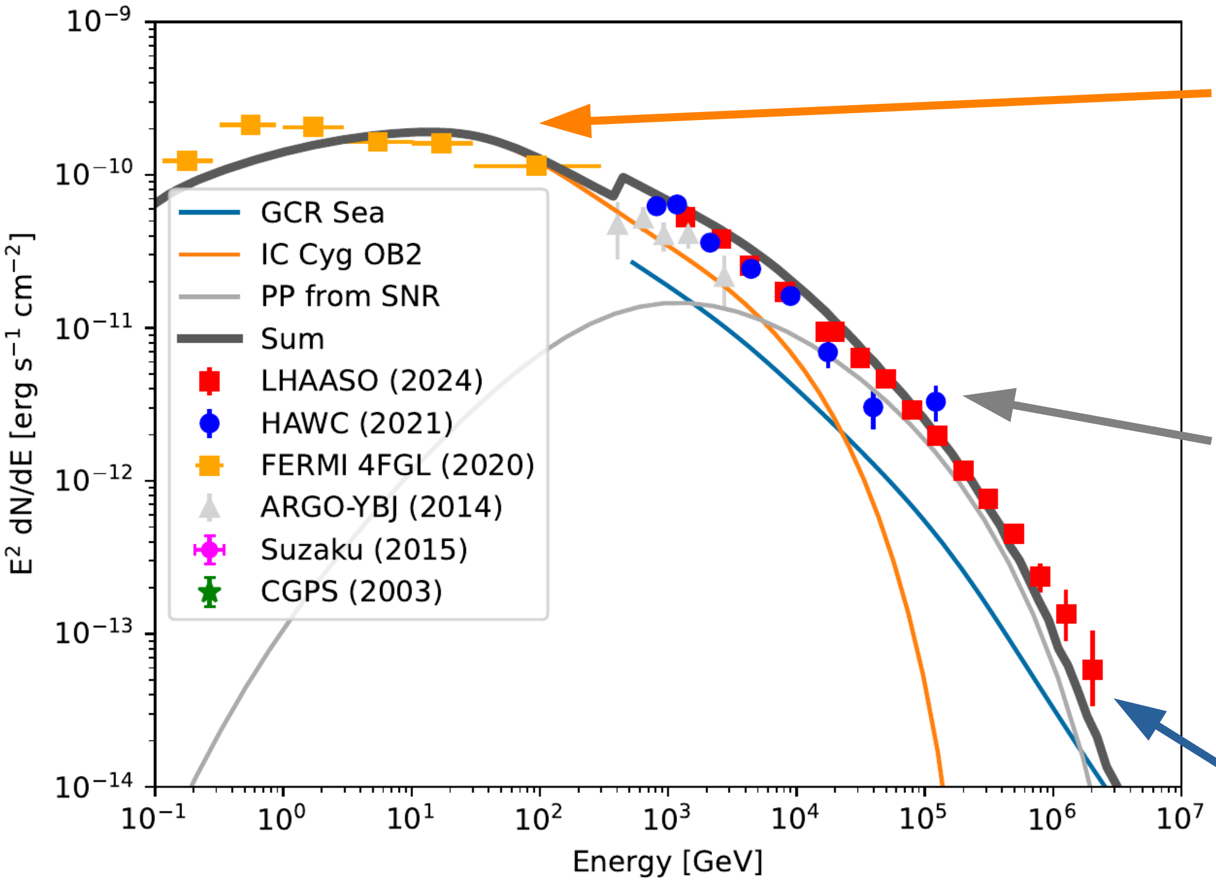
What's going on in Cygnus? - our interpretation

Härer+ in prep



e^- accelerated at individual WTS

IC on cluster FUV field

$n = 0.05$ cm^{-3}

B ~ 10 μG

$P_{e-} = 0.005 \times P_{OB2}$

Relic p from past clustered SN

Explosion 200 kyr ago

Energy ~ 5e51 ergs

γ-ray production on Cygnus Mcs

E_{max} protons = 2 PeV

UHE contamination

GCR sea (Schwefer+22)

Cygnus X-3

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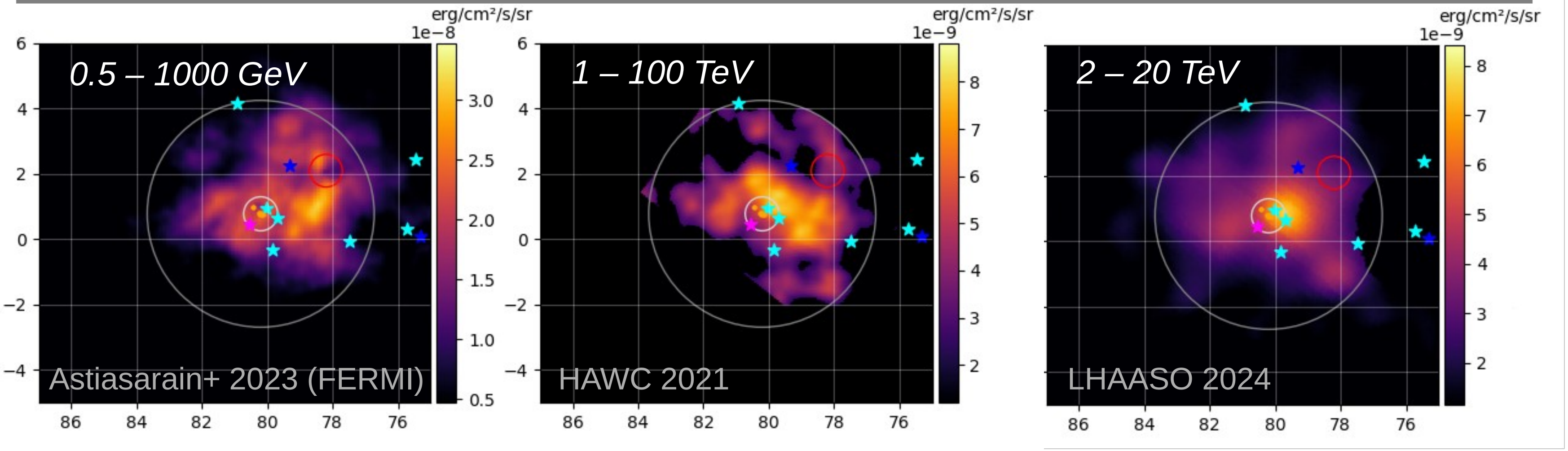

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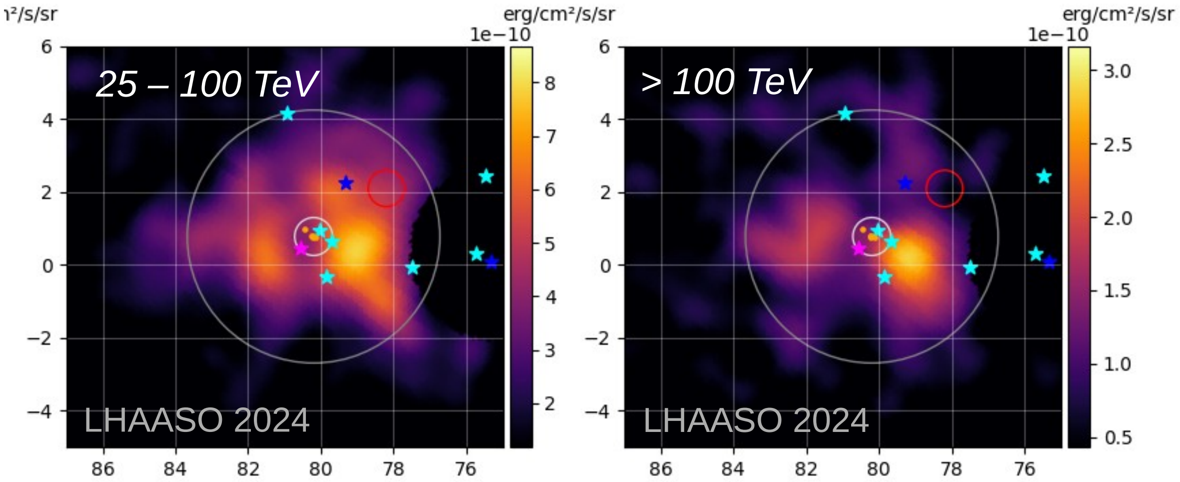


e^- accelerated at individual WTS => shrinking emission more and more correlated with the core

p-p on nearby clouds from past SNR => emission correlated with molecular clouds

Summary

- **Star clusters are intricate objects in complex regions**
  in most cases beyond the scope of spherical models
  asymmetric distribution of stars produce asymmetric outflows

- **Theories of collective effects (wind-wind, stochastic) fail on close inspection**
  adiabatic losses in spherical winds, low energy budget of turbulence…

- **Yet there is almost no tension with current observations**
  Wd 1, W43, Cygnus-X, 30 Doradus..., can be explained by acceleration in stellar winds

- **A component is missing for Cygnus between 100 TeV and 1 PeV**
  but this is a crowded region, difficult to observe at any wavelength.
  A past SN can fill the gap

- **Star clusters are not expected to be PeVatrons**
  in the sense that they can't contribute substantially to the CR spectrum beyond the knee

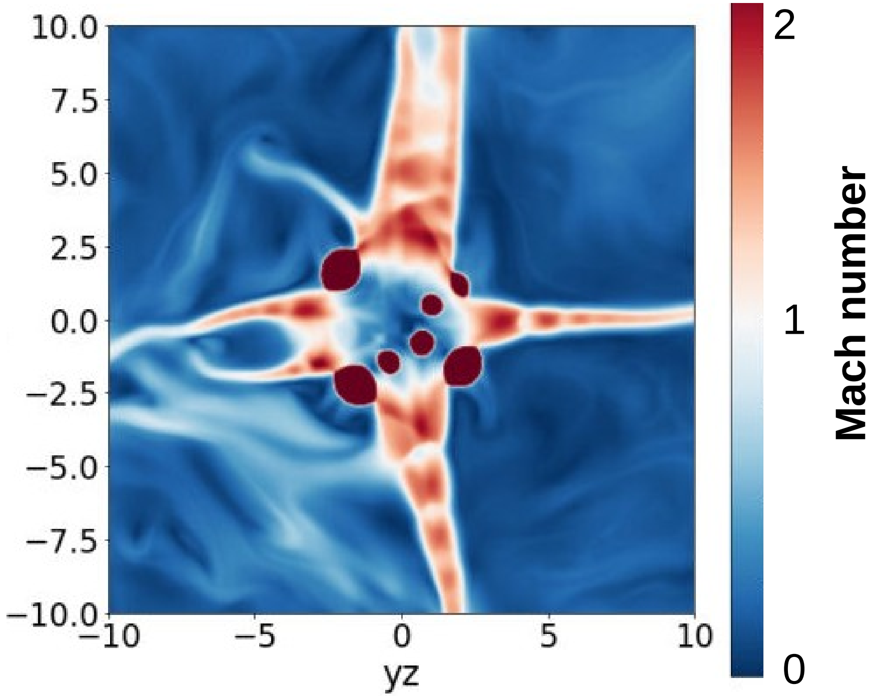
- Back up

Why asymmetric outflows

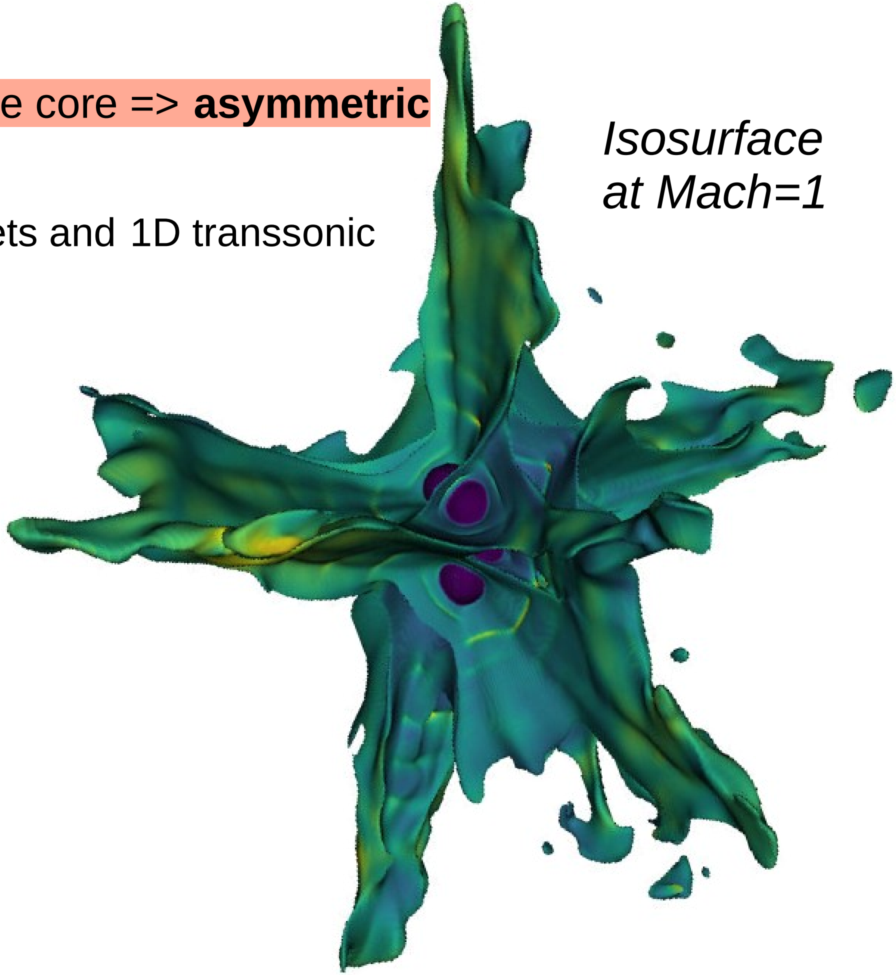
Pressure gradient between the core and the superbubble
=> the flow accelerates outward

But the flow is blocked by the individual winds at the edge of the core => **asymmetric launching**

Instead of a spherical strongly supersonic wind, we obtain 2D sheets and 1D transsonic streams



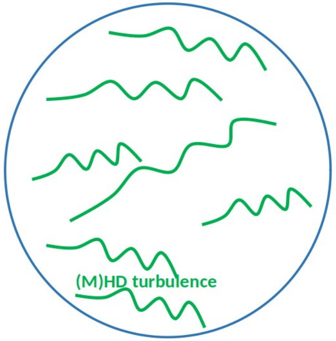
Isosurface at Mach=1



The dream of stochastic re-acceleration

No large-scale shock but a hot, turbulent(ish) cavity

MHD turbulence => Stochastic (re)acceleration / Fermi II
Emax = acceleration rate VS escape rate



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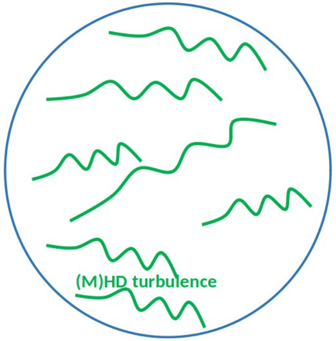

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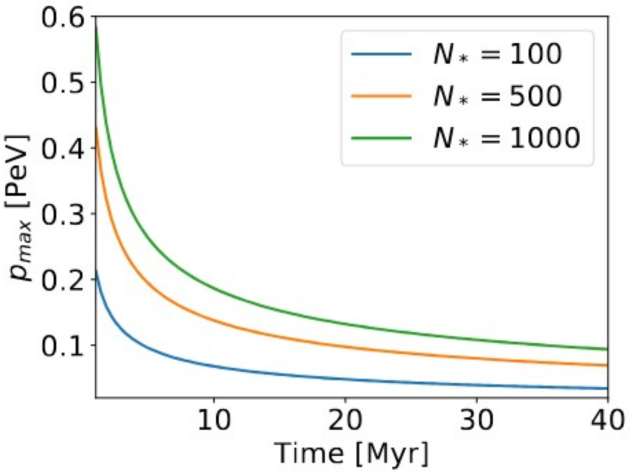

Vieu, Reville, Aharonian 2022:
Test-particle, Bohm, model for strong turbulence cascade *(Bykov's renormalisation theory)*
=> most optimistic!

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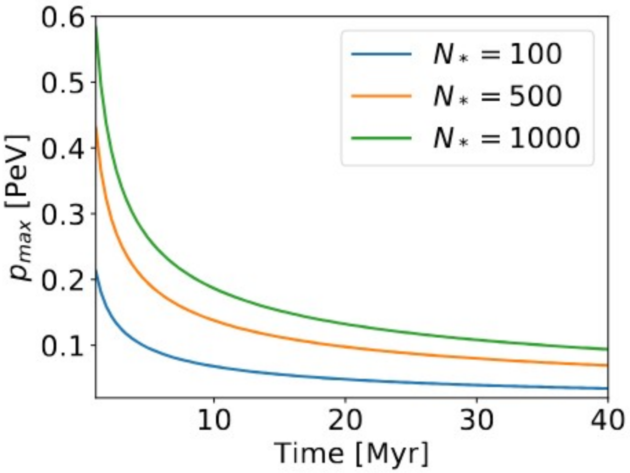

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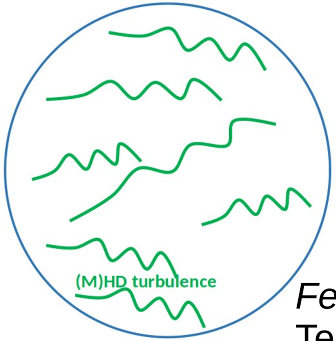
Test-particle, Bohm, model for strong turbulence cascade *(Bykov's renormalisation theory)*
=> most optimistic!



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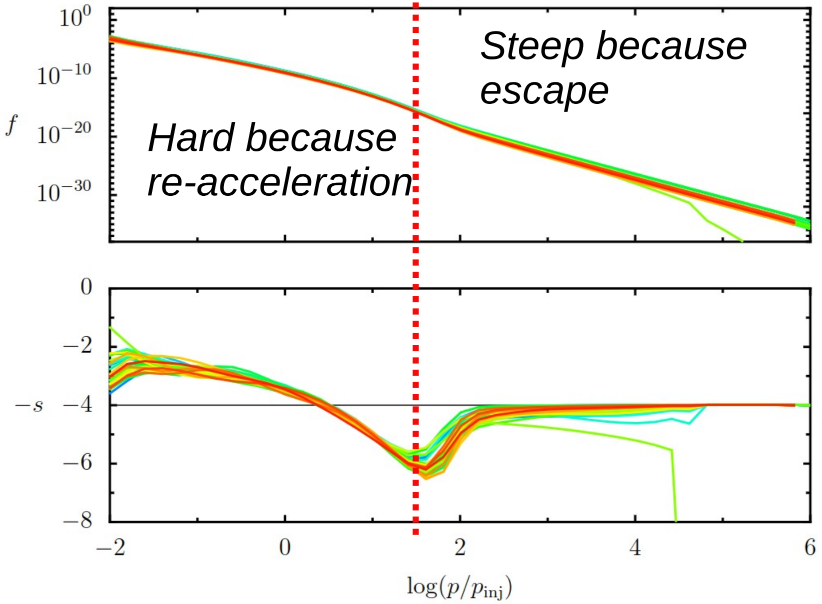

The dream of stochastic re-acceleration

No large-scale shock but a hot, turbulent(ish) cavity

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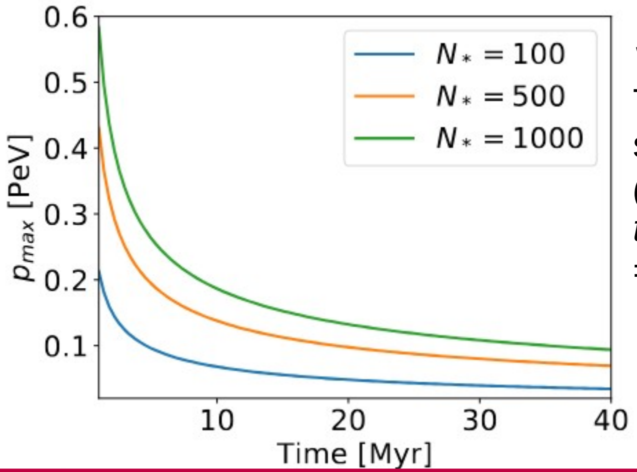

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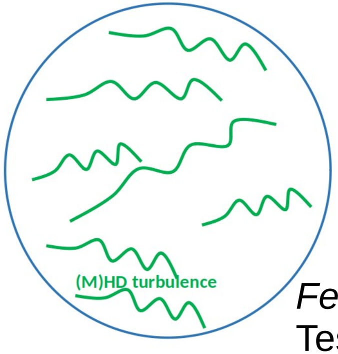

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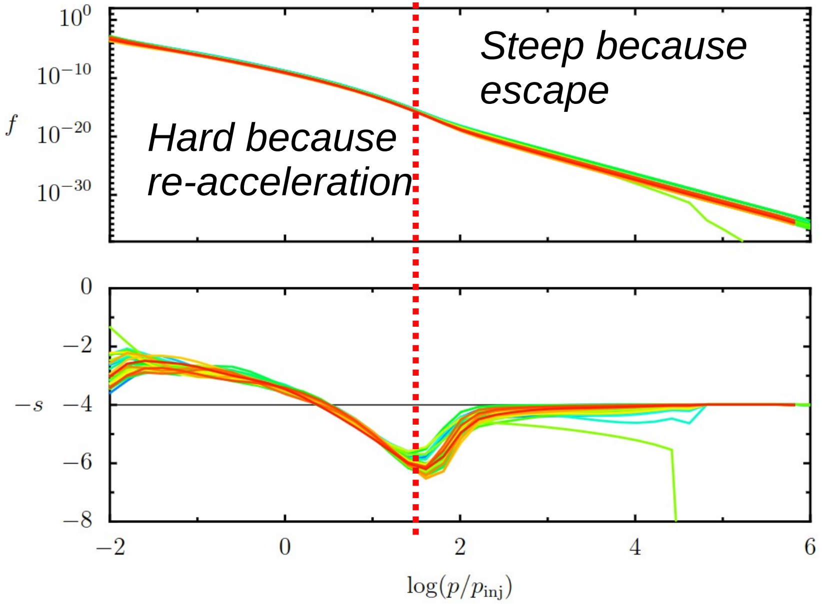

$e_{turbulence}$ = 1/2 rho u^2 ~ 0.1 eV/cm^3

e_{CR} ~ 10% L_w τ_e / V_{SB} >> 1 eV/cm^3

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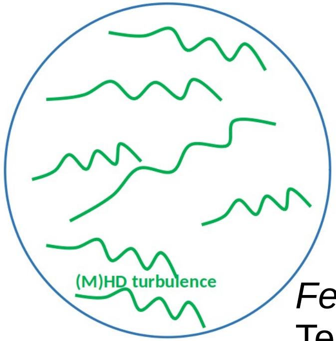

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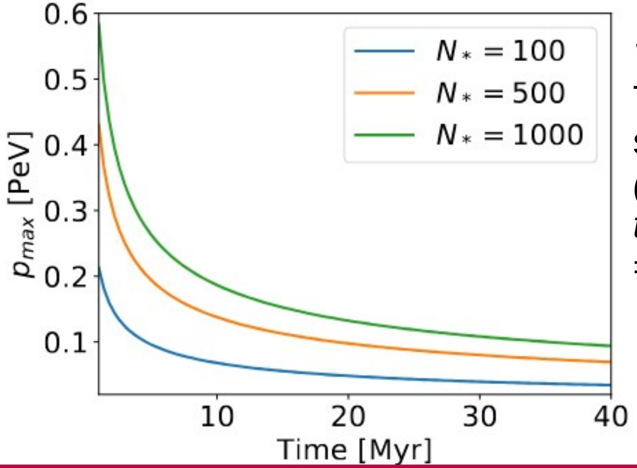

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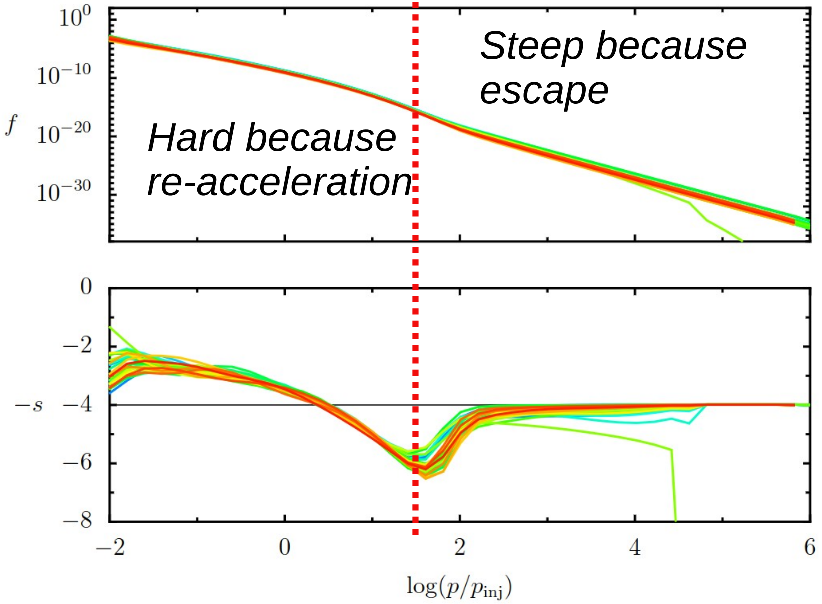

$e_{turbulence}$ = 1/2 rho u^2 ~ 0.1 eV/cm^3

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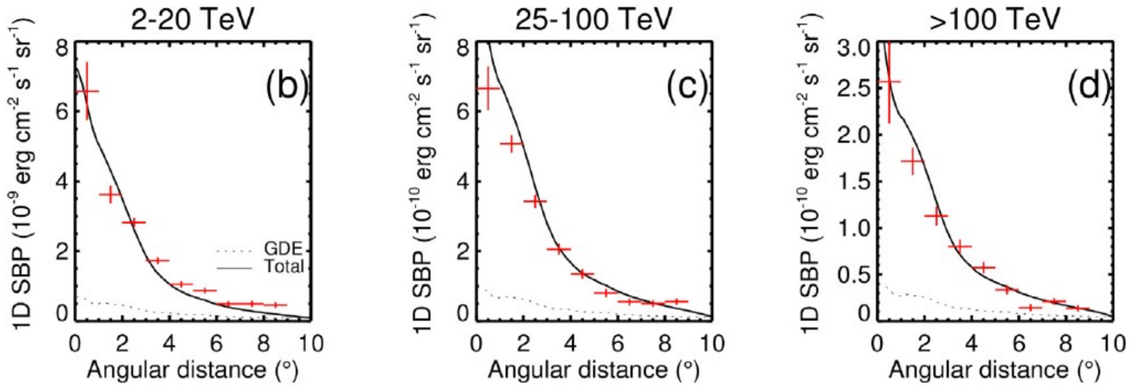
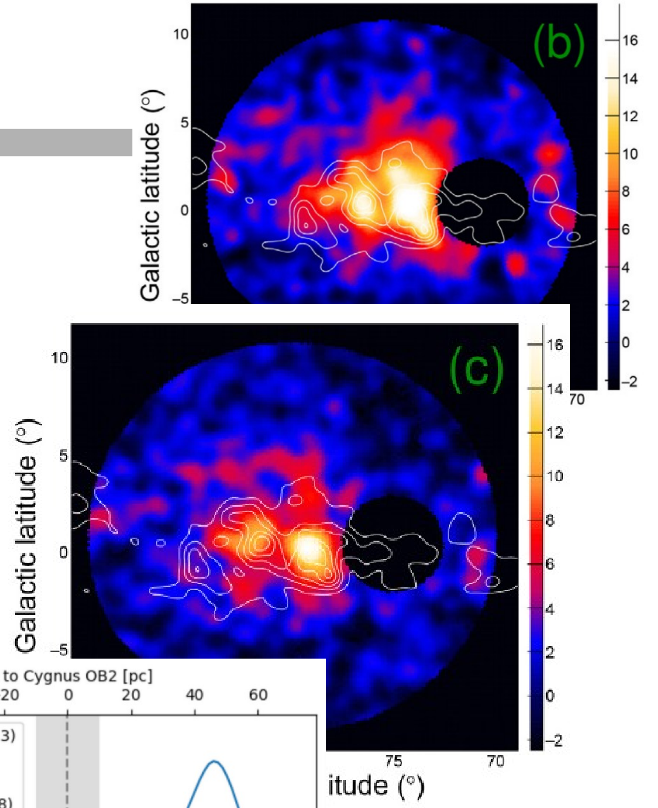
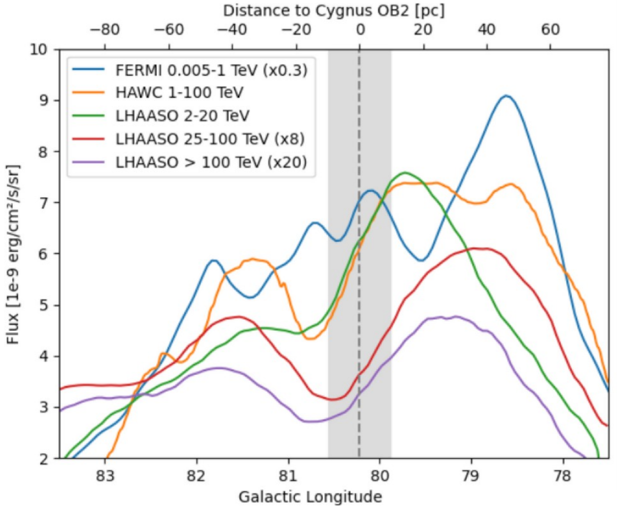
- Never reaches PeV
- Produces hard spectra
- Violates the energy balance

The 1/r dream

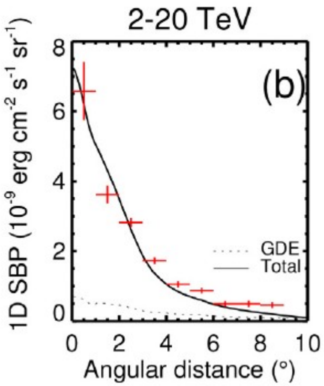


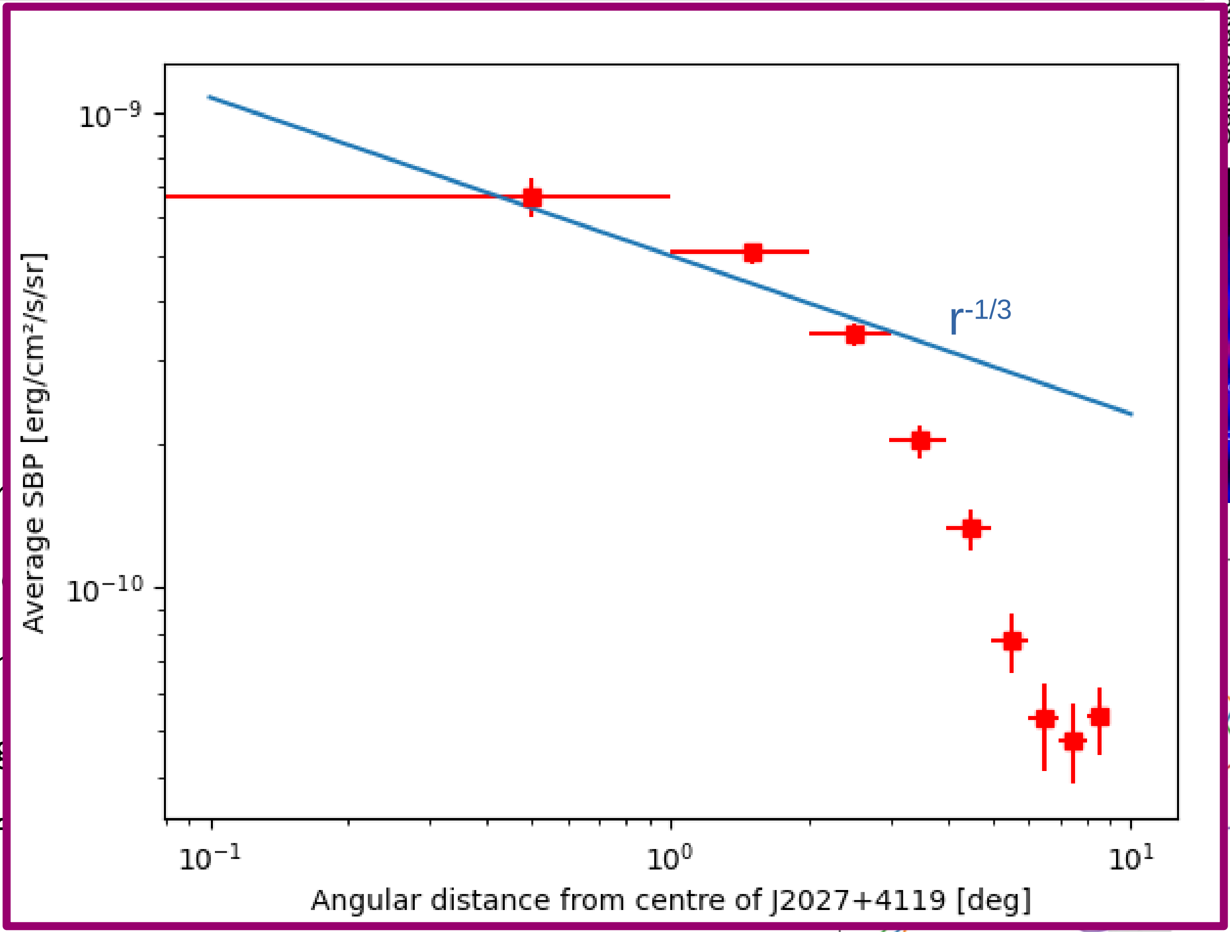


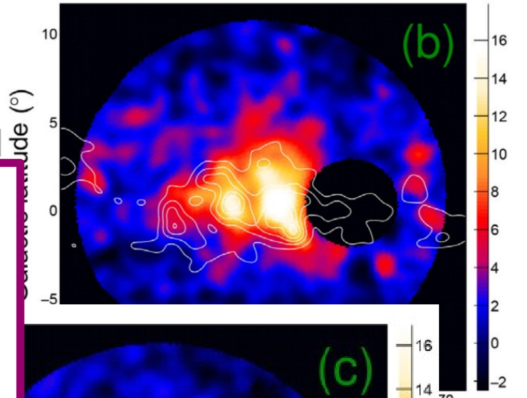


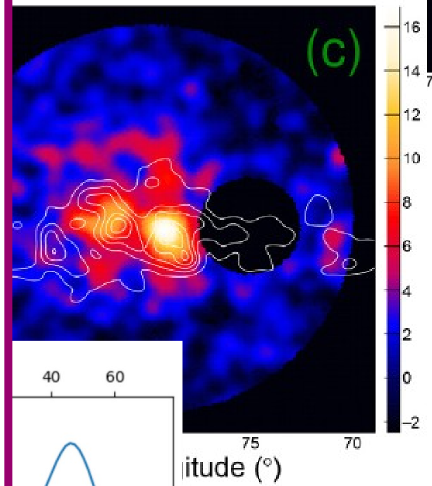
- These profiles are obtained by averaging over lineouts.
- This averaging does not make sense when the morphology is not symmetric. It will smear out any feature and give an overall decreasing function.
- The result strongly depends on the chosen “centre”
- Note: these profiles are not even close to $r^{-1/3}$!

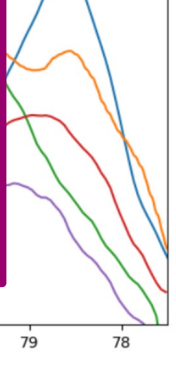
The 1/r dream











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