MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

Deciphering the γ-ray emission from Cygnus

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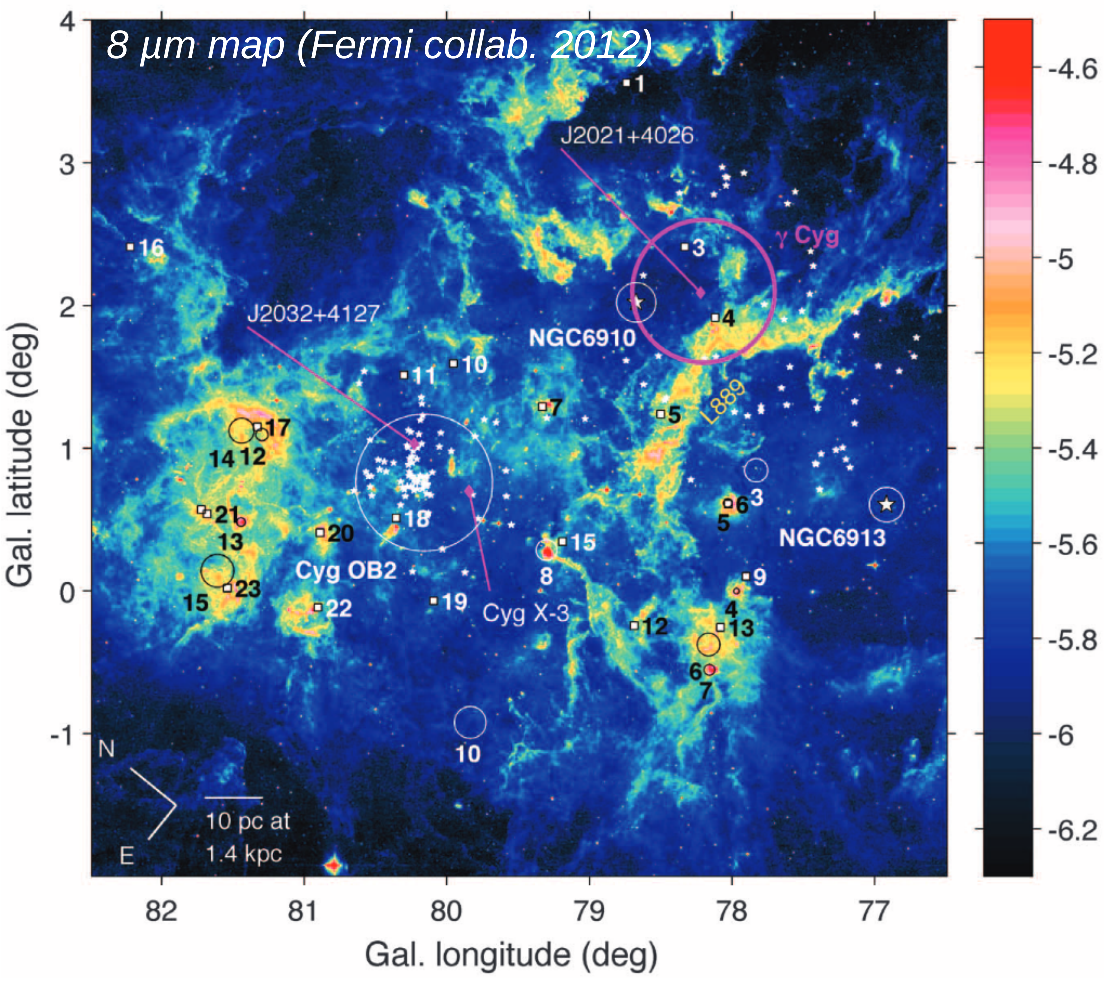
Background: Simulation of Cygnus OB2 after 2 Myr
T.Vieu/MPIK

Introducing the Cygnus X region



Very complex region

Diffuse clouds, HII regions, CO clumps, rims, cavities

Diffuse radio, radio hotspots

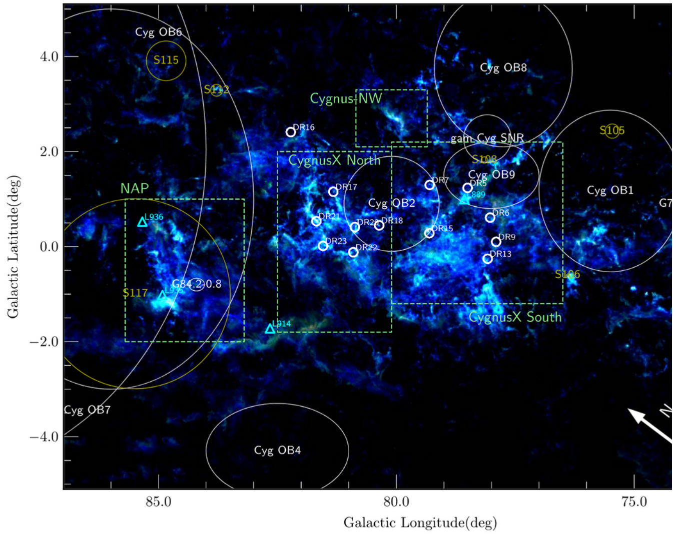
Diffuse X-rays

Several VHE sources

Several compact star clusters
Cygnus OB2 association
Cyg X-3 microquasar
PSR J2032+4127 pulsar
ɣ-Cyg SNR
10s WR stars

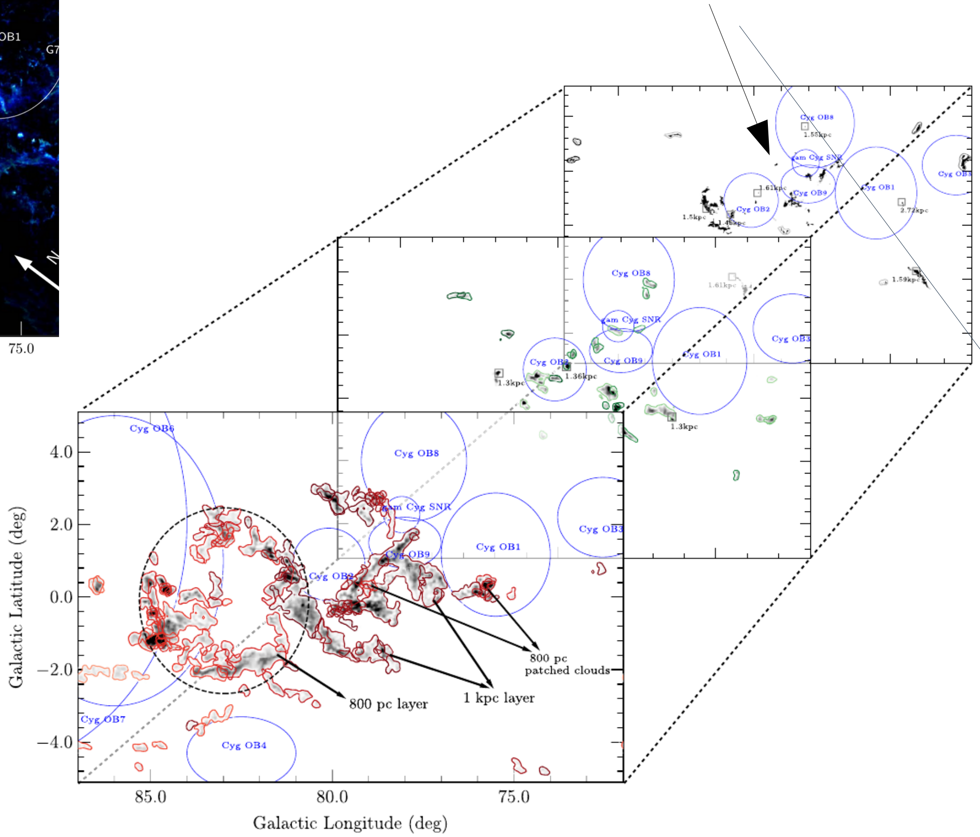
...

Multilayer structure: complex foreground

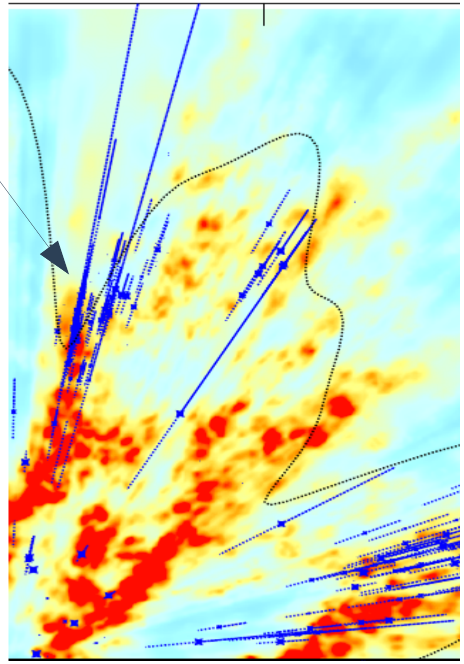


CO clouds from Zhang+2024

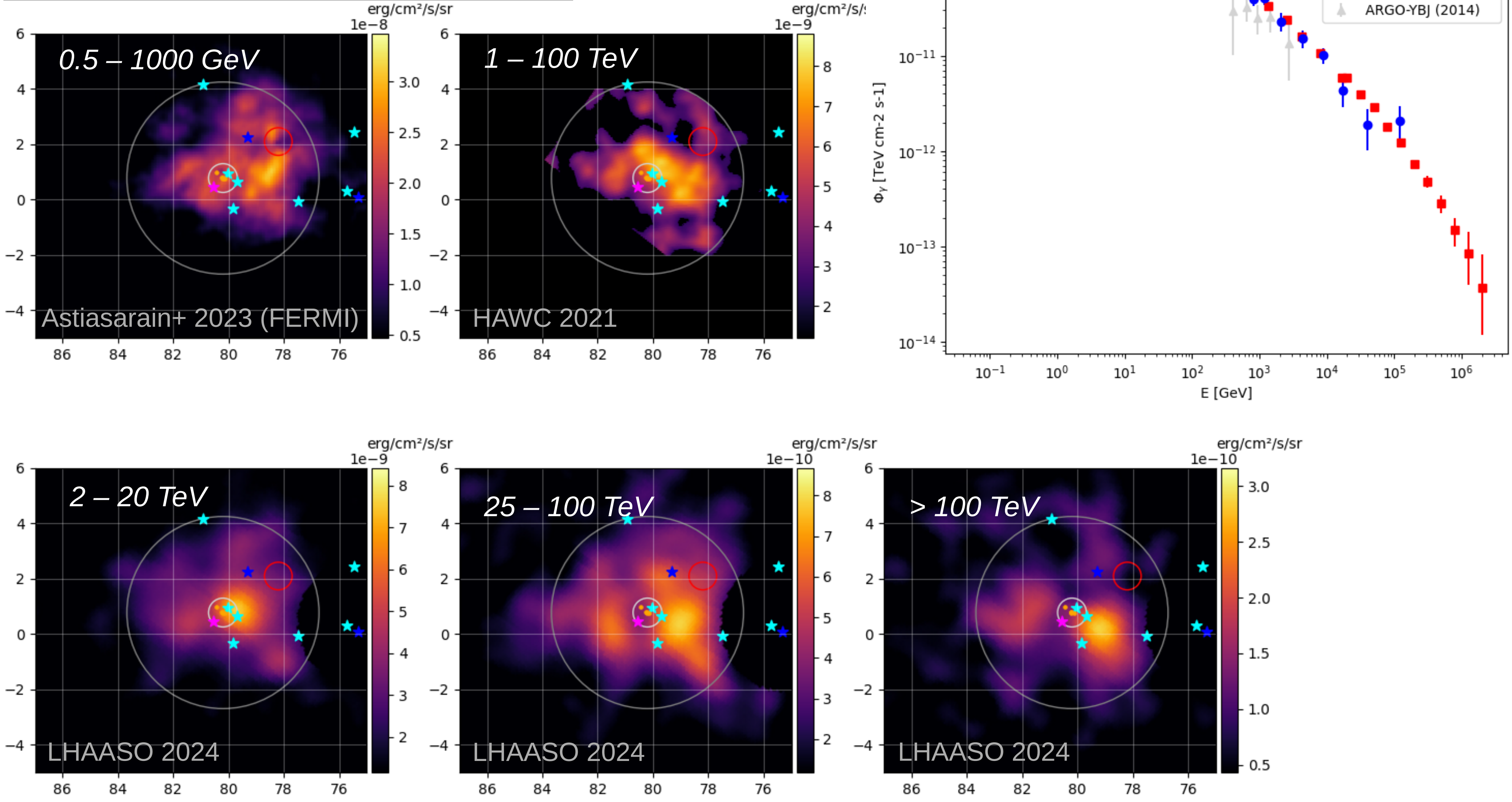
Star-forming region @ ~ 1.7 kpc
(1.4 kpc estimate is outdated)
Cygnus OB2, NGC6910, NGC6913...



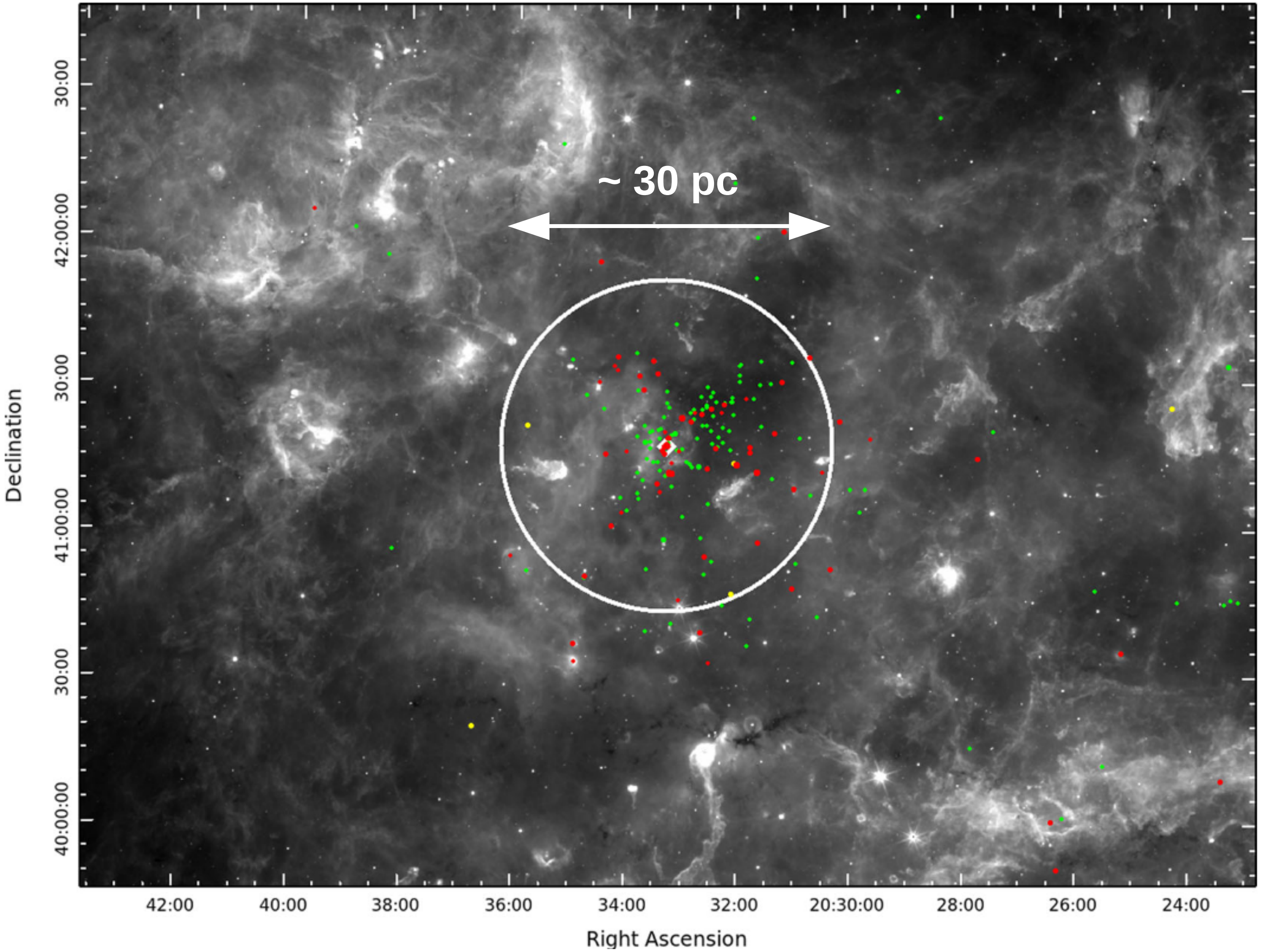
Dust map (differential extinction) from Lallement+2019



Cygnus in γ-rays



The Cygnus OB2 stellar ~~cluster~~ association



Wright+2015

Distance ~ ~~1.4 kpc~~ 1.65 kpc
Age ~ 3-5 Myr
Core extension ~ 15 pc

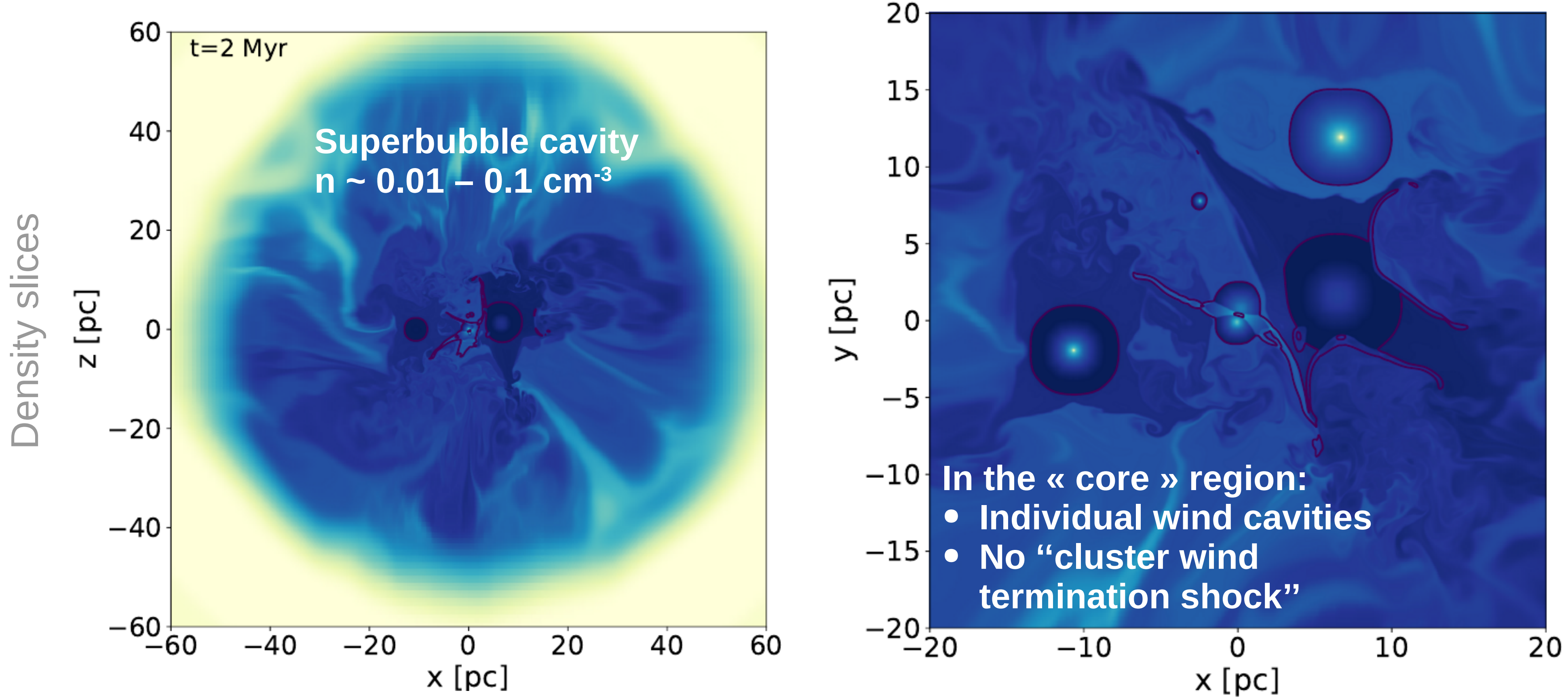
78 O stars
3 off-centred WR stars

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

Gas dynamics around an extended association

<u>*Vieu et al. 2024*</u>

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...)



Simulation over 2 Myr, including 400 kyr of WR phase

Gas dynamics around an extended association

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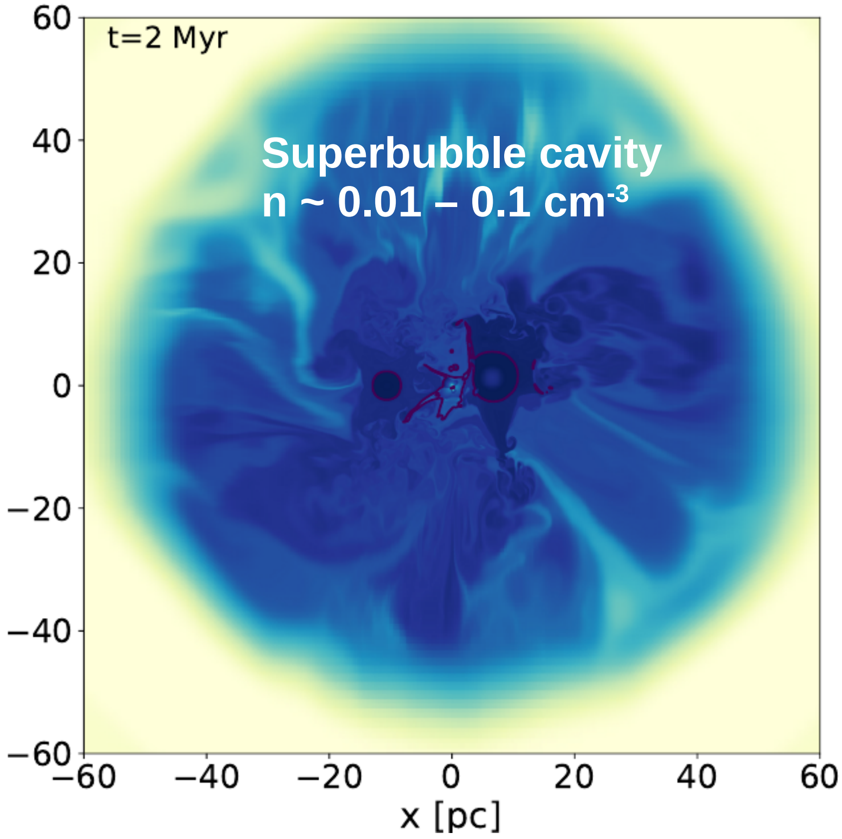
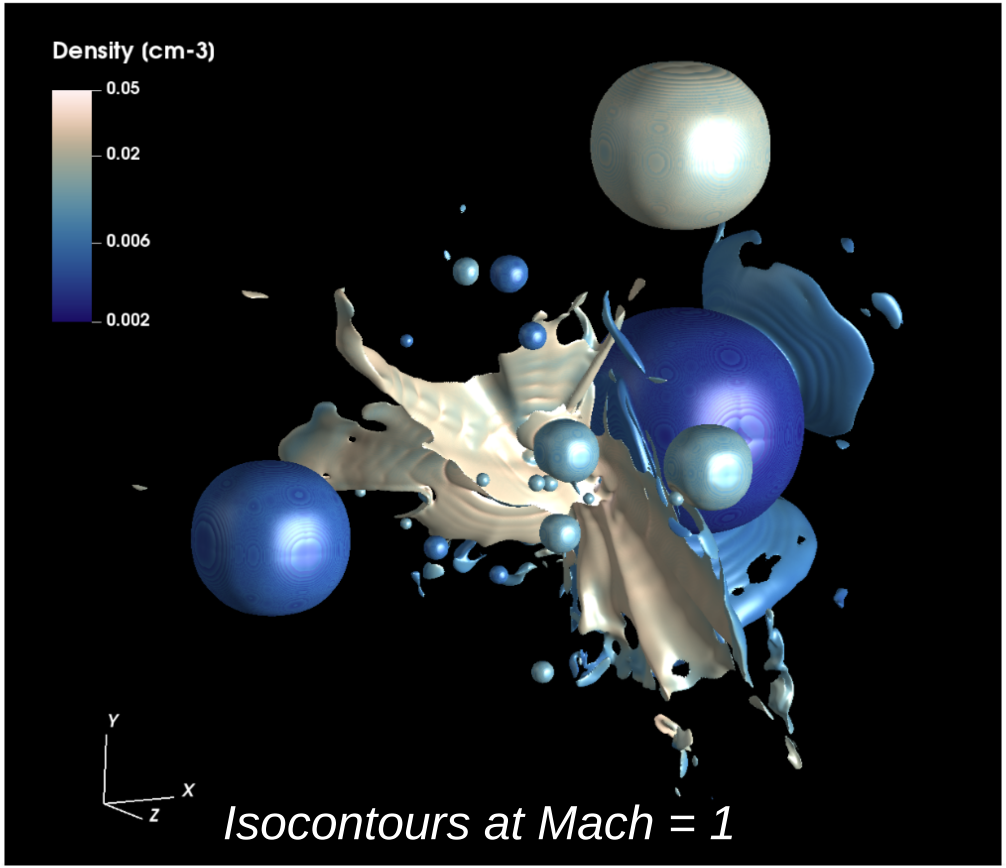
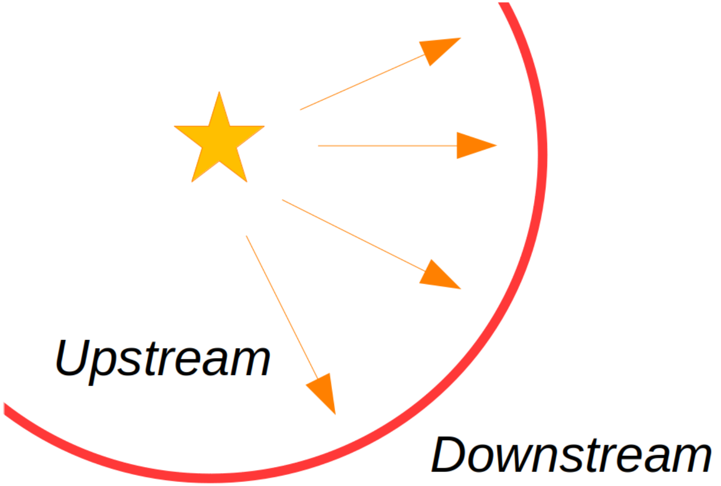
Density slices





Simulation over 2 Myr, including 400 kyr of WR phase

Maximum energy in stellar wind cavities



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

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

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

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

Absolute upper limit **independent of conditions downstream**

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

A past supernova in Cygnus?

Cygnus OB2 is not so young (3-5 Myr)

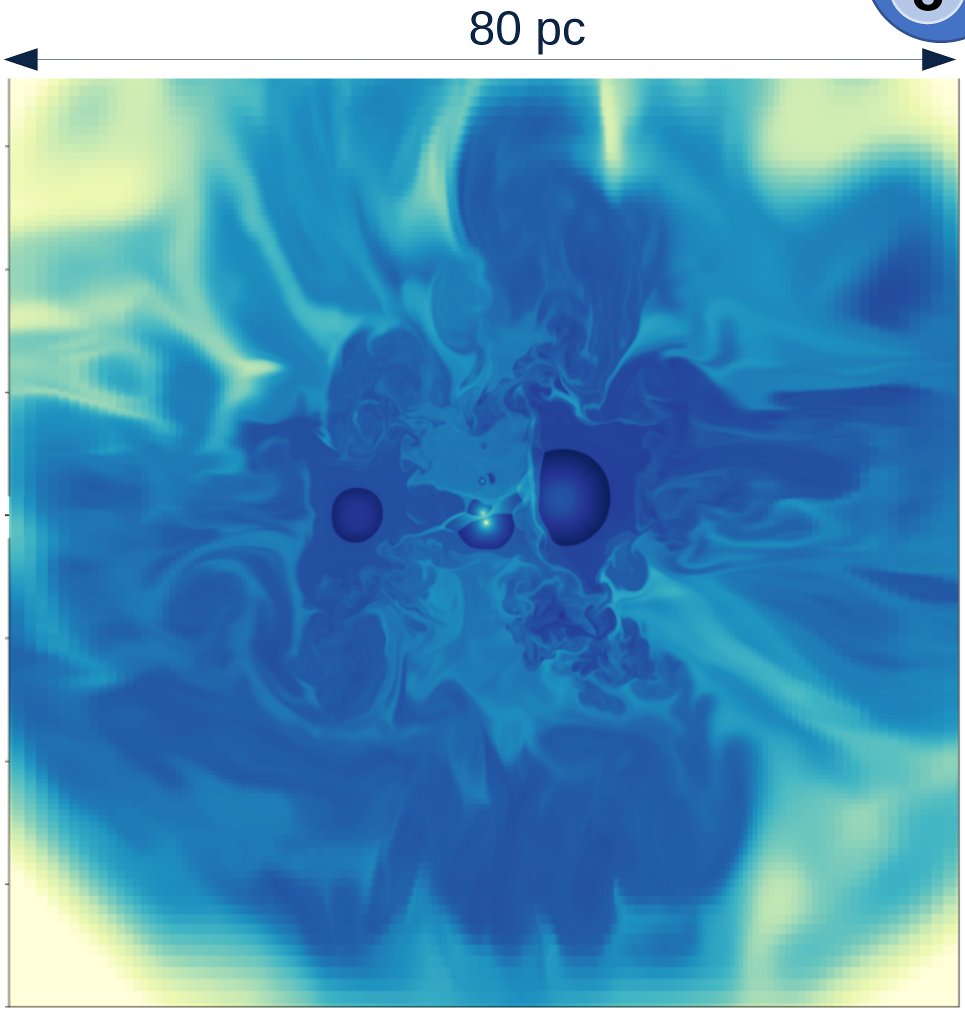
It contains 3 WR stars
and a pulsar (PSR J2032+4127, 200 kyrs old)

which suggests that **some stars already died.**

With 78 O stars, we expect **about 6 – 8 SN /Myr**
In the HIM, a SNR fades after ~ 100 – 200 kyr.

Let's blow a powerful SN in the simulation.

Initial velocity = 15 000 km/s
Explosion energy = 5e51 ergs



Density slice before the explosion

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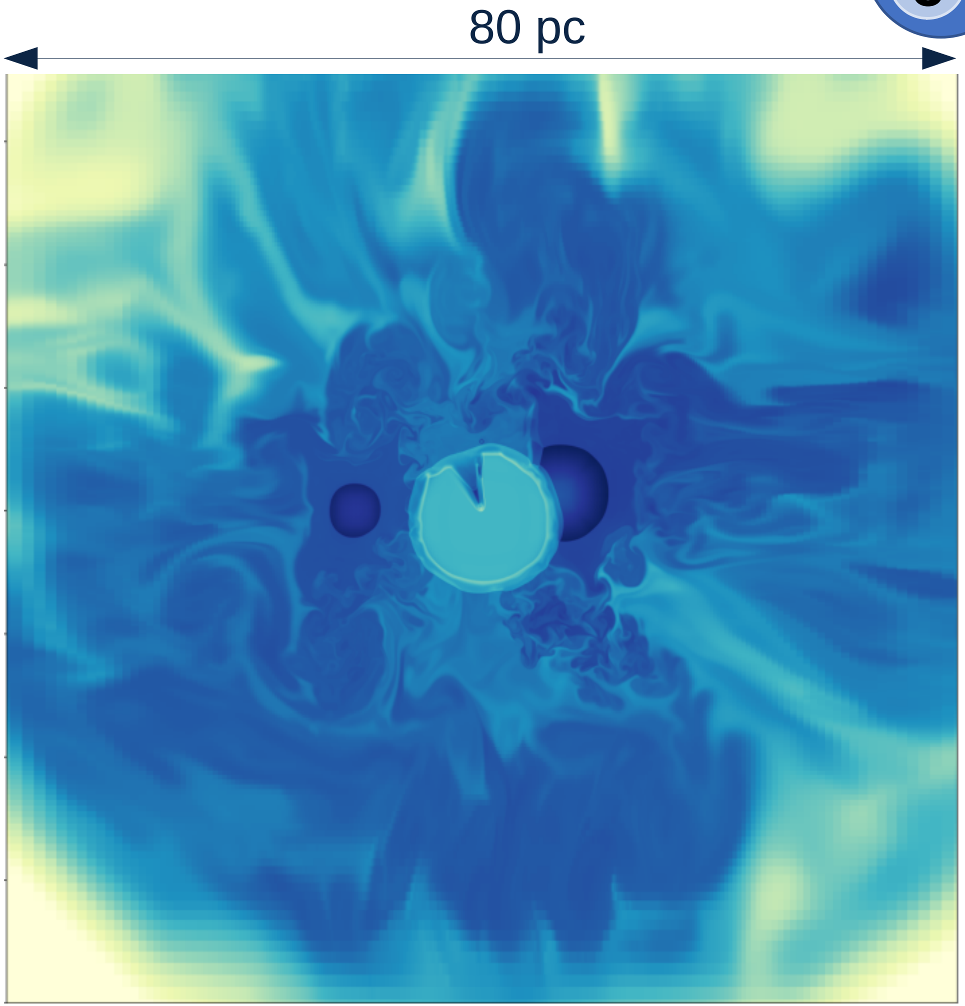

Density slice 300 yr after explosion

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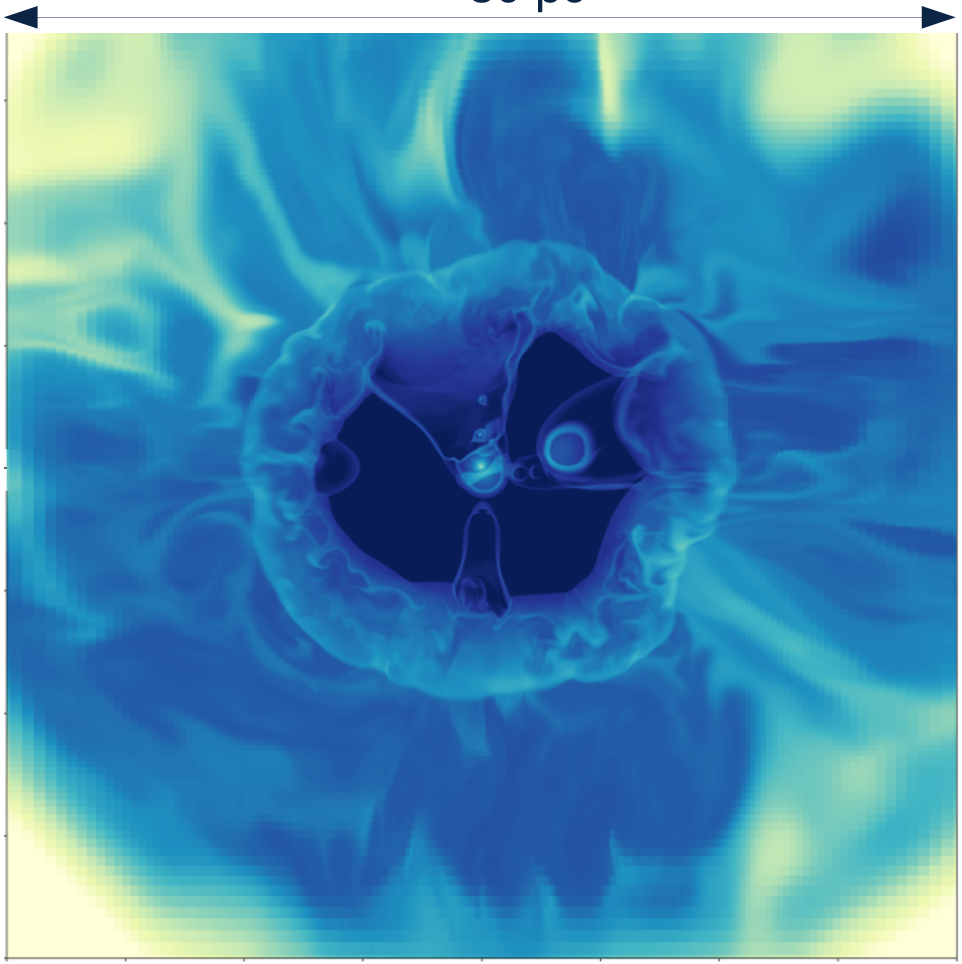
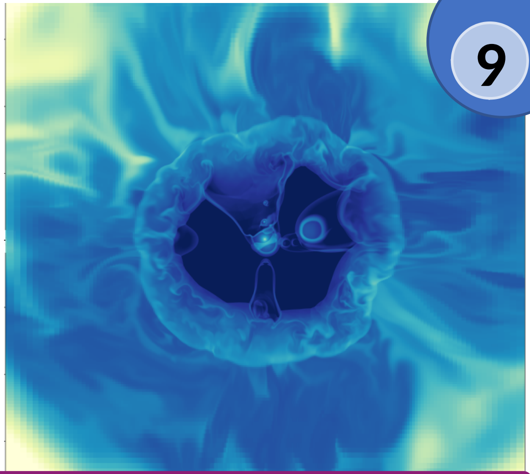


Density slice 1.5 kyr after explosion

A past supernova in Cygnus?

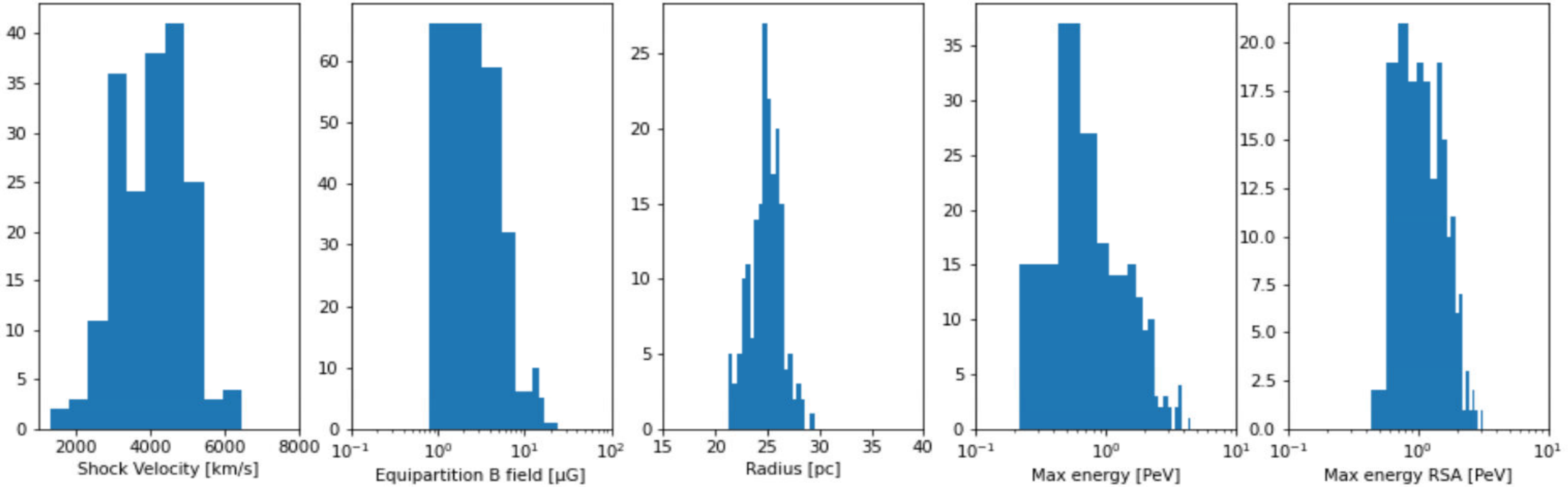


Powerful SNR in low density medium near powerful stars

✔ Longer phase of fast expansion

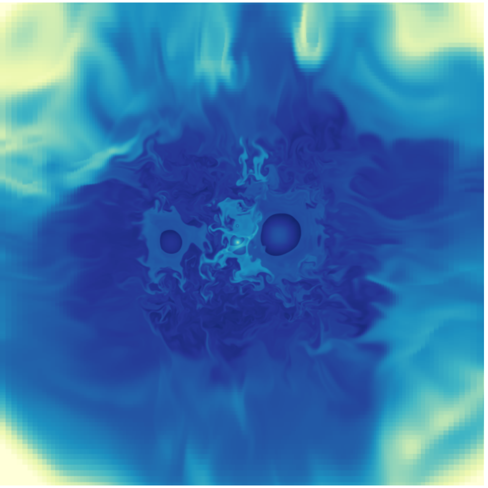
✔ Enhanced magnetic fields (~ 10 µG) from the stellar winds

=> E_{max} < 2 PeV



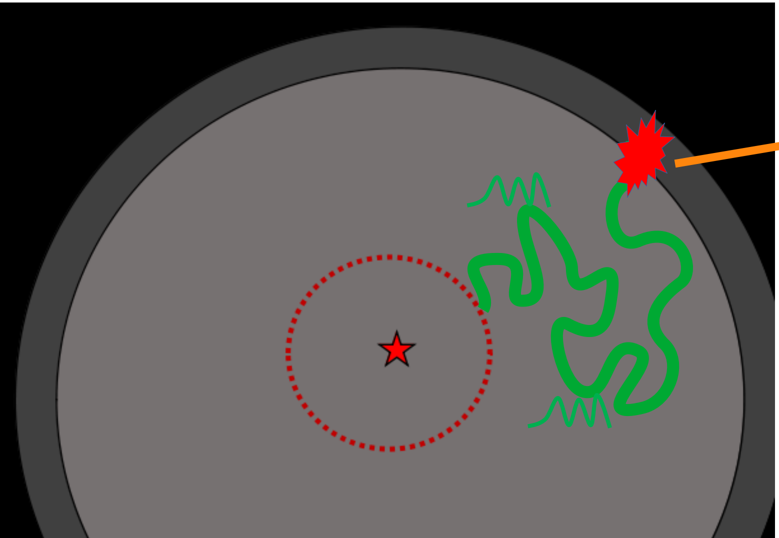
Relic ɣ-rays?

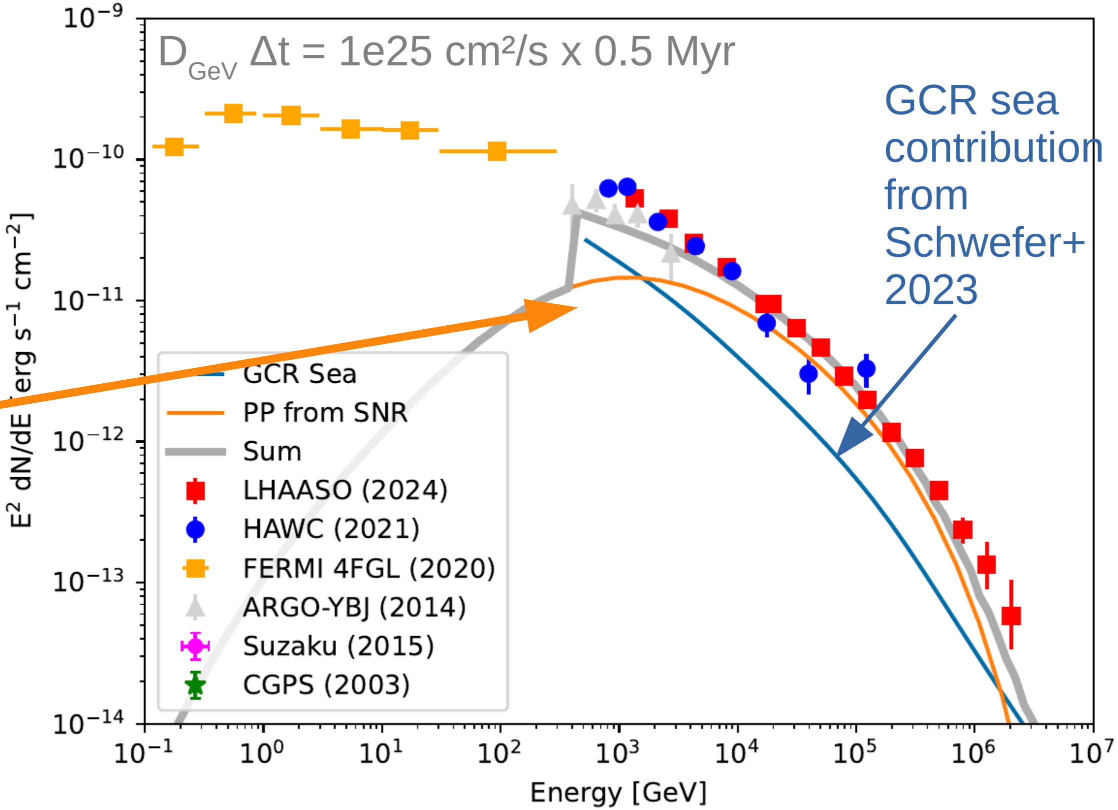
Härer+ in prep.



200 kyr after the explosion, the SNR signature should vanish.

VHE particles still continue to propagate for 100s kyr after their acceleration, reaching the high density clouds beyond the excavated region.

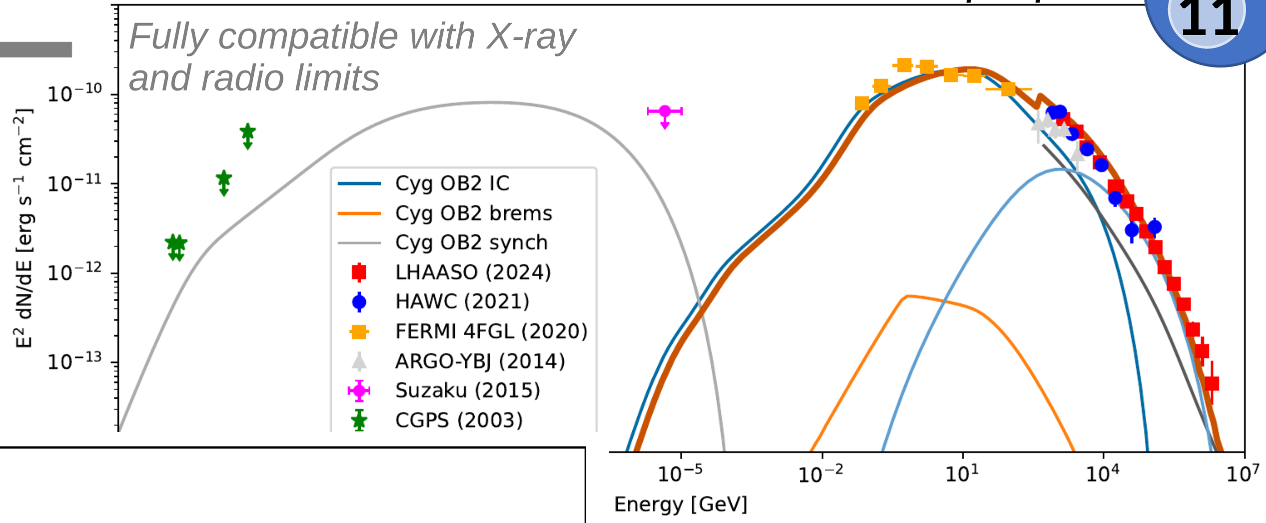


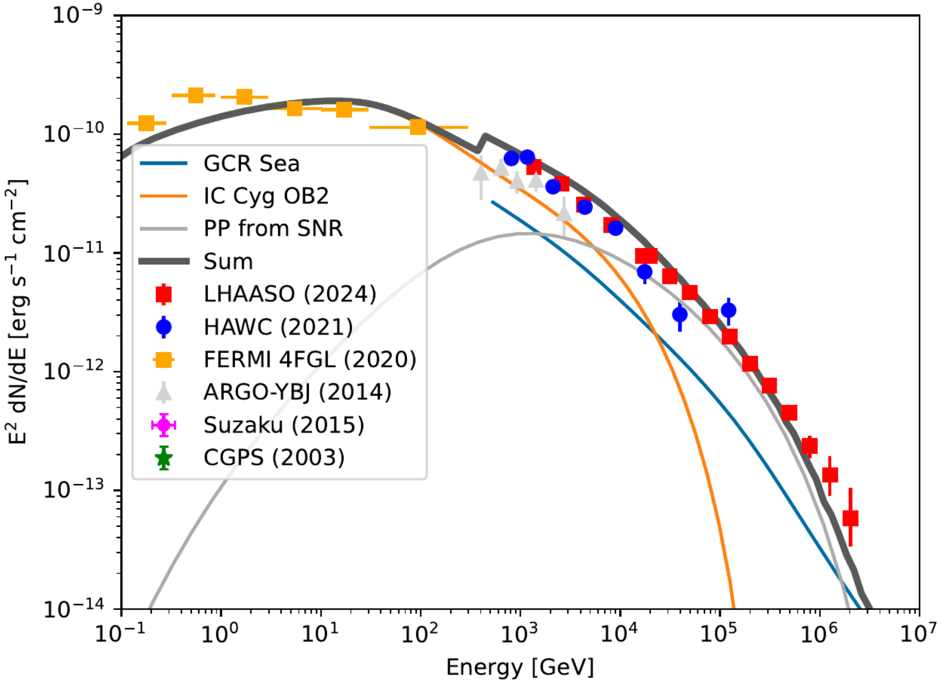


A leptonic model at GeV

Härer+ in prep.

- ✔ IC on cluster FUV field
- ✔ $n = 0.05\ cm^{-3}$
- ✔ B ~ 10 μG
- ✔ $P_{e-} = 0.005 \times P_{OB2}$





PRELIMINARY

We did not try yet to obtain the best fit...

… just input reasonable guess parameters.

Take-home

- **The Cygnus region is a very intricate environment**

  multiple gas / dust layers over > 1 kpc
  superposition of γ-ray sources, a complete bestiary of extreme objects

- **A past powerful supernova could account for the UHE photons**

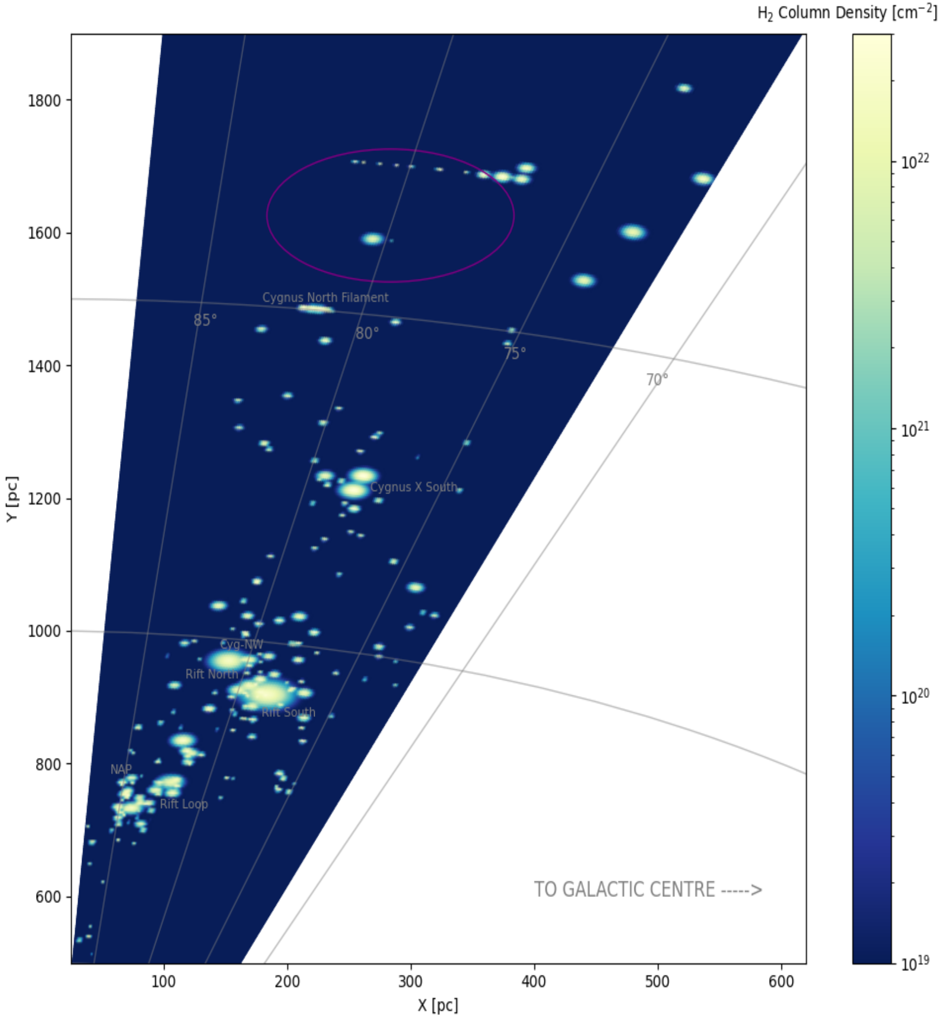
  other scenarios (stellar winds, cluster wind, wind-wind interactions…) are excluded

- **At GeV, a leptonic origin is favored**
  – in contrast with long-standing belief

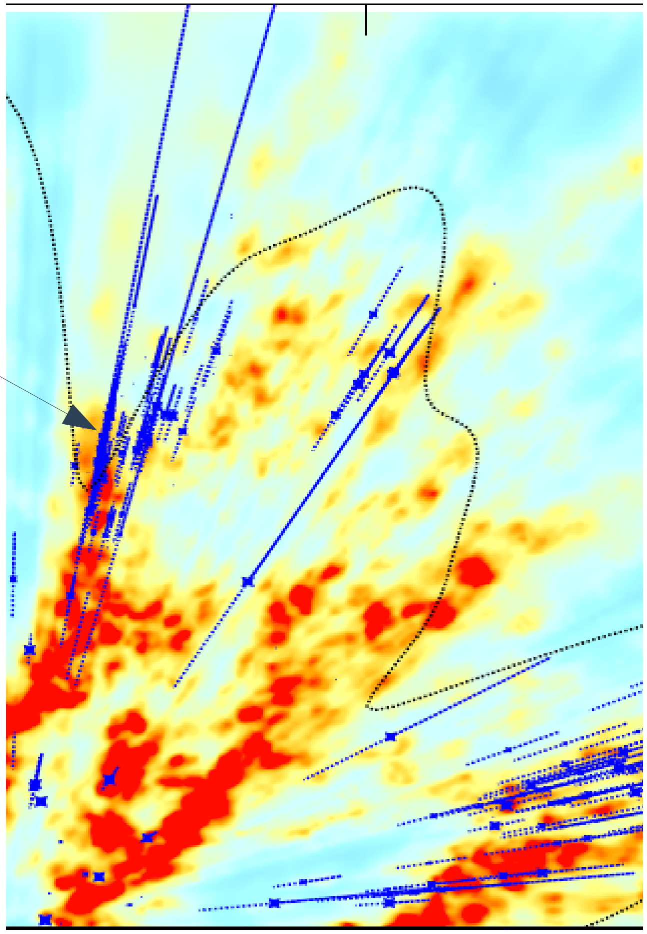
  there is no target gas in the vicinity of powerful stars

- BACK-UP

3D reconstruction of CO clouds with distance estimates from Zhang+2024

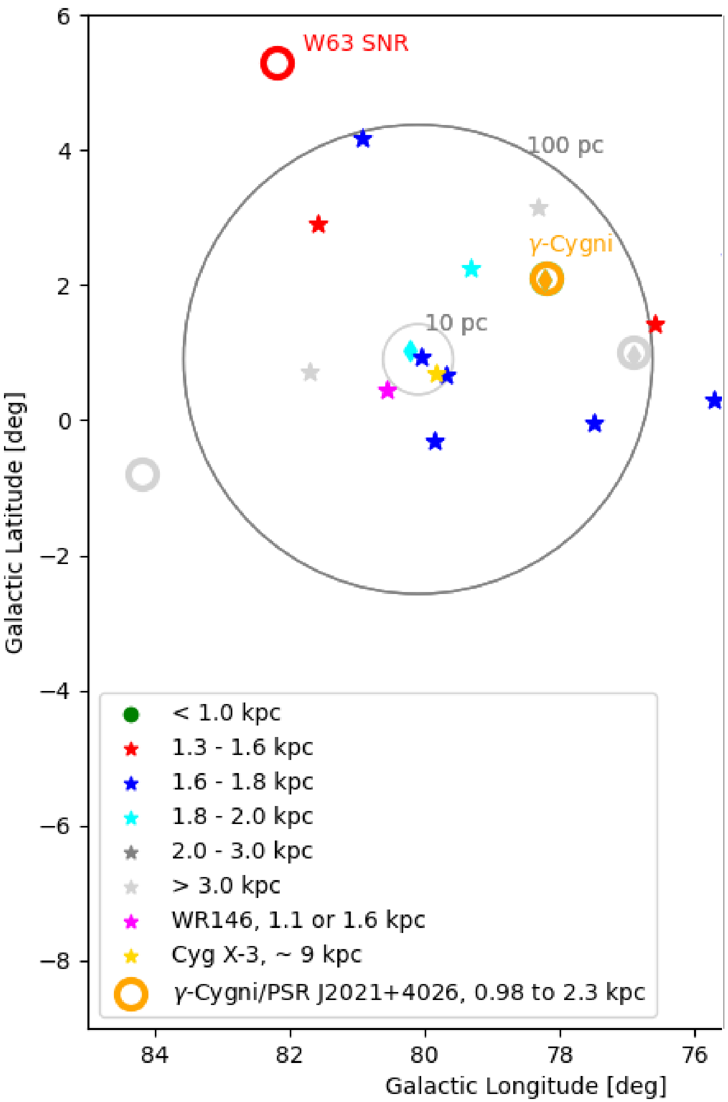


Dust map (differential extinction) from Lallement+2019

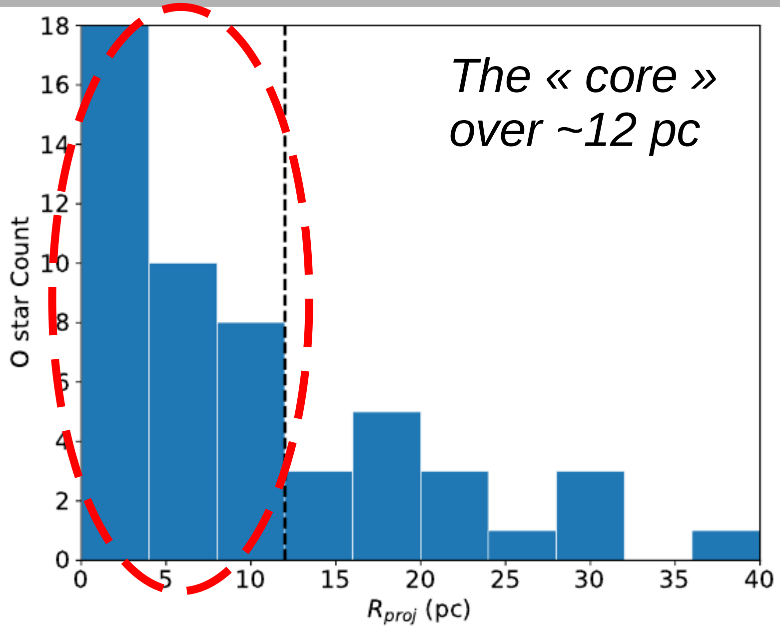


Concentration of O stars in the SFR at ~ 1.7 kpc

Extreme objects in Cygnus-X



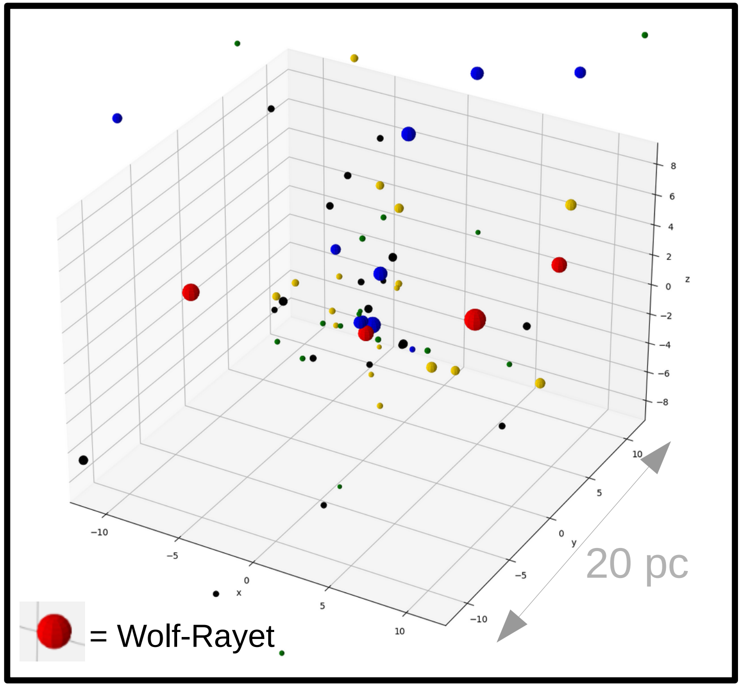
Cygnus OB2: a stellar ~~cluster~~ *association*



O stars	WR144	WR145	WR146
1e38 erg/s	9.3e37 erg/s !!	2e37 erg/s	3.4e37 erg/s

Work by C. Larkin

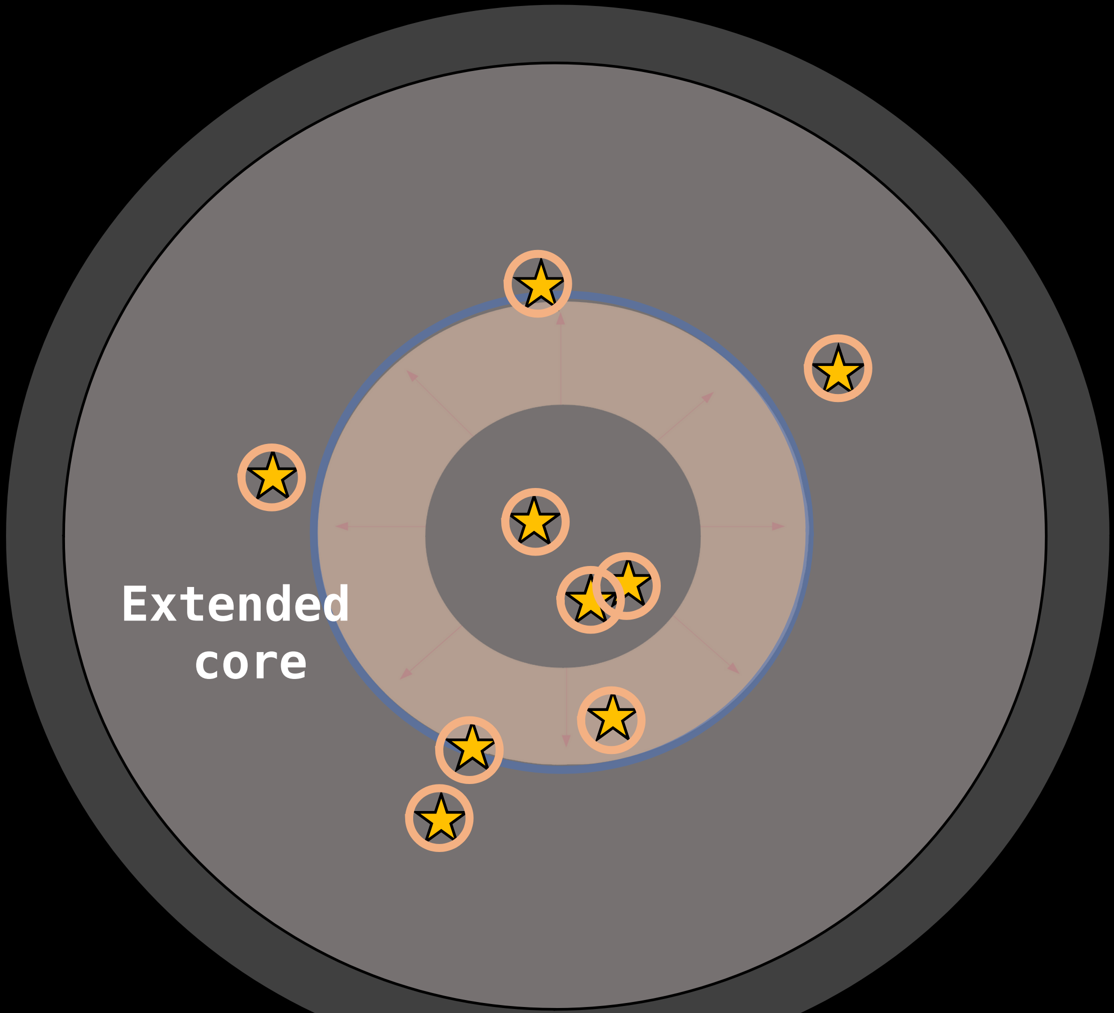
3D reconstruction



Note the large extension of the core!
Cygnus OB2 is definitively not a “compact” cluster!

Note that the O stars contribute only 40%!

Why Cygnus OB2 cannot expand a cluster WTS?



The stellar winds don't work together but against each other.

Low level of collective interactions

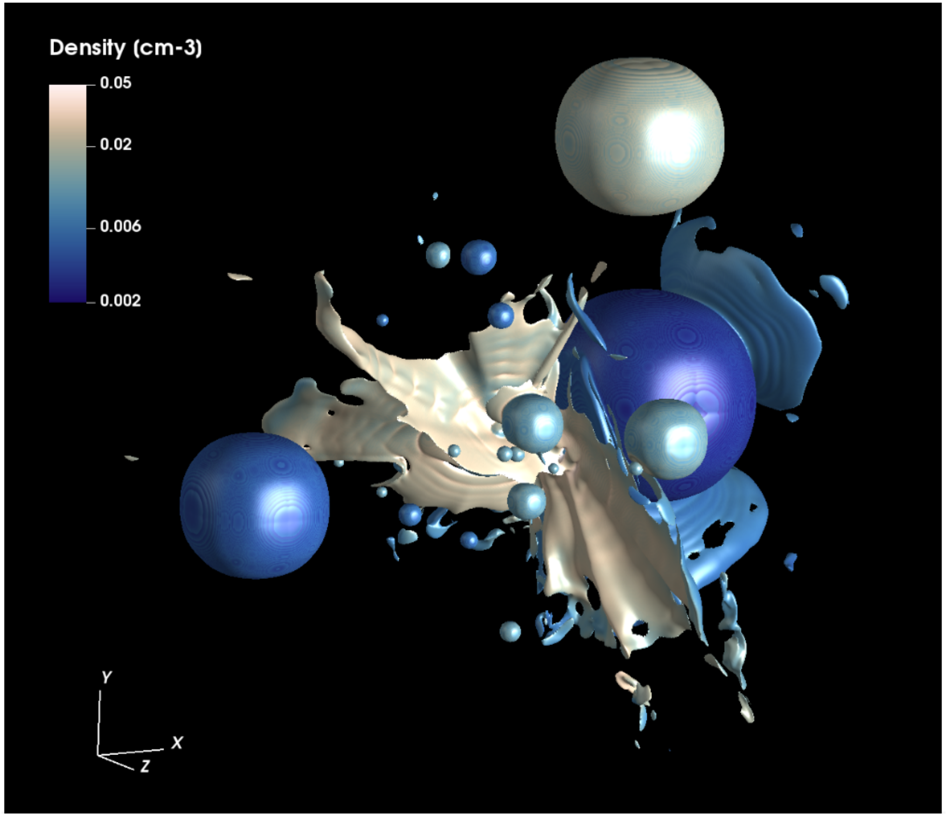
=> A collection of small individual stellar wind termination shocks

Gas dynamics around an extended association

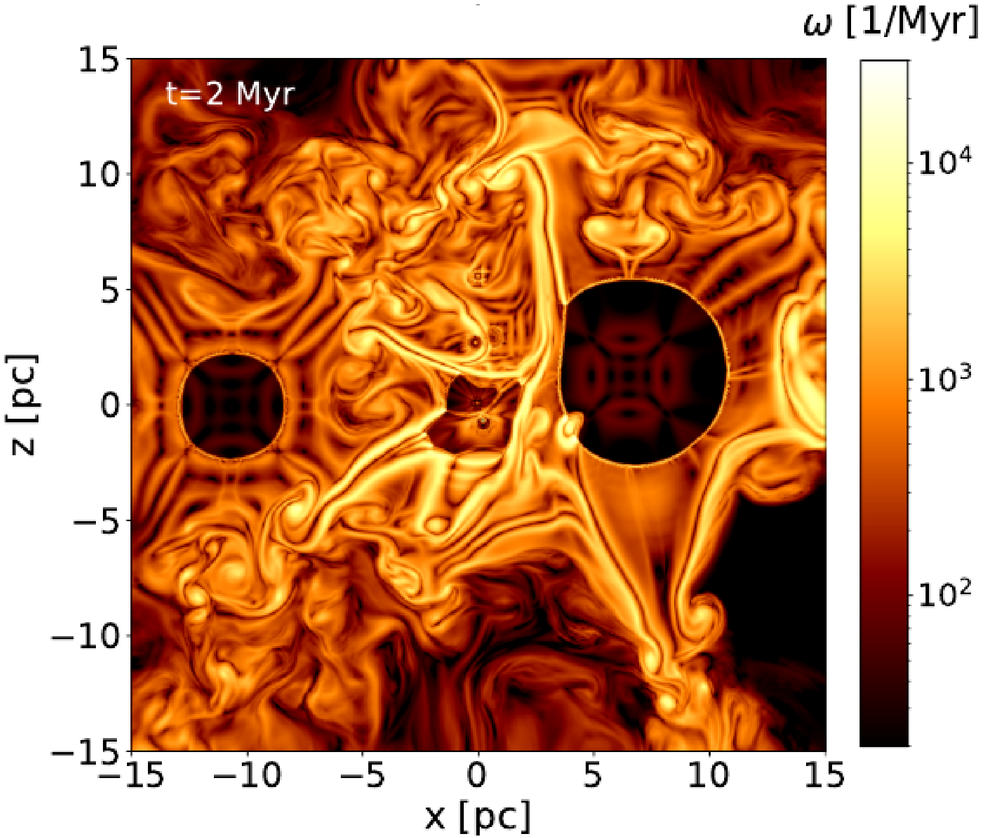
Vieu et al. 2024

Simulation over 2 Myr, including 400 kyr of WR phase

Isocontours at Mach = 1



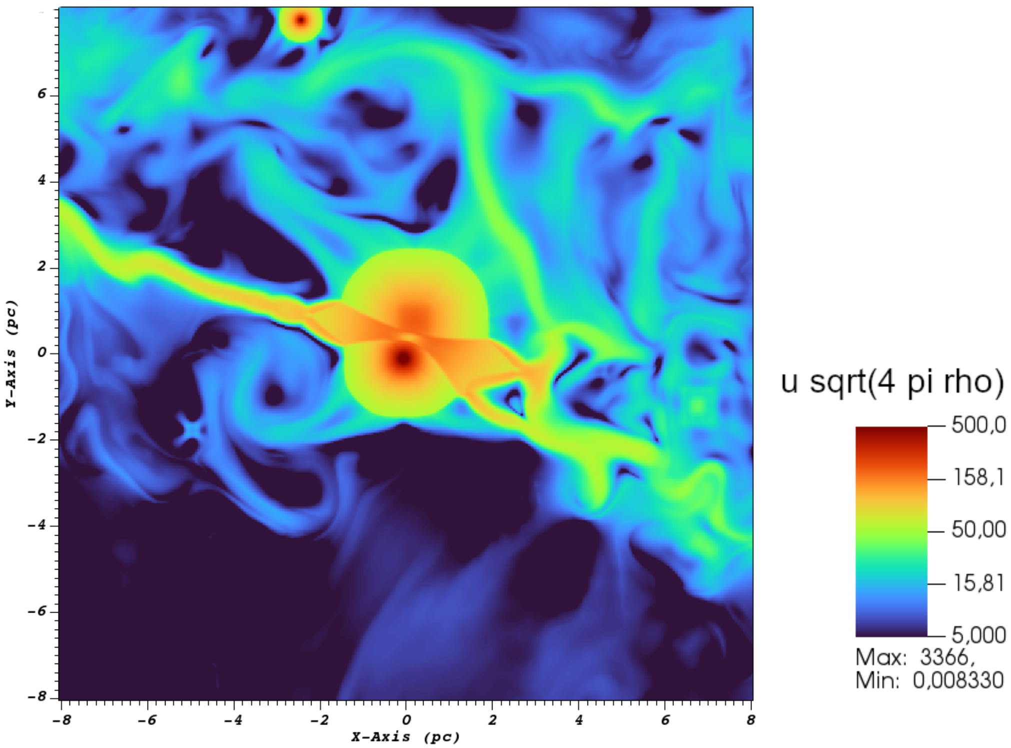
Vorticity in the inner region

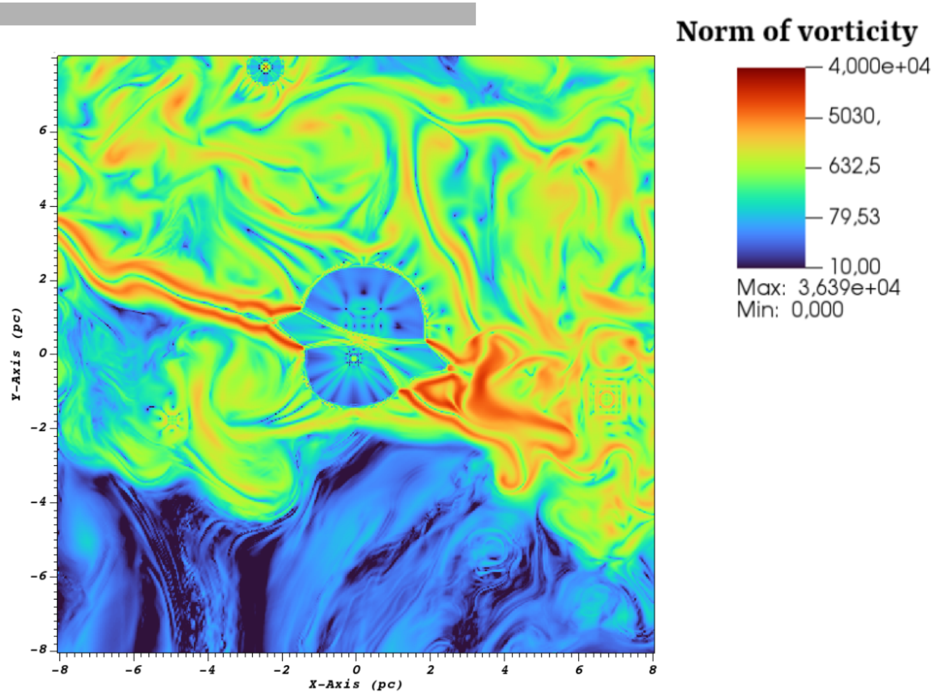


Wind interactions in the inner parsecs

A young powerful cluster…
… but extended

Much less efficient wind-wind interactions
than for compact clusters

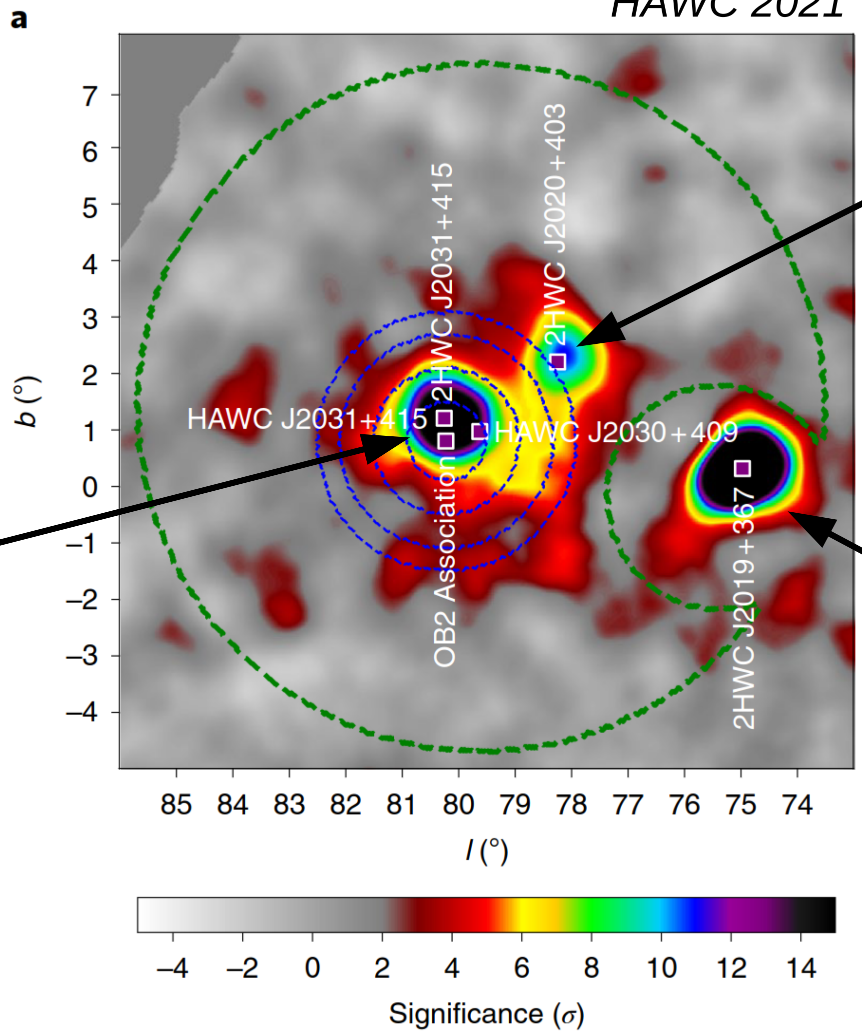




Nevertheless, assuming equipartition (u~vA),
the B_{eq} field could be fairly high in the inner region

Cygnus in VHE ɣ-rays

HAWC 2021



ɣ-Cygni (SNR)
up to > 300 TeV

PSR
J2032+4127
up to 30 TeV

Dragonfly
nebula
(PWN)

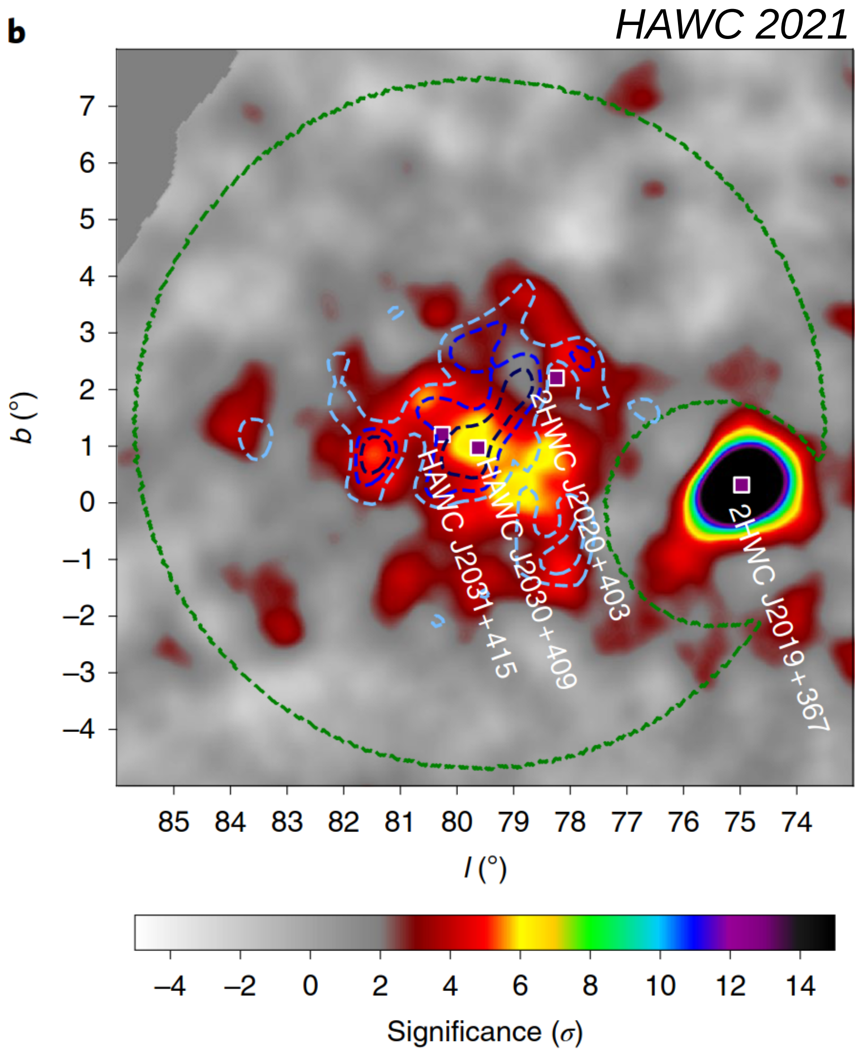
Cygnus in VHE ɣ-rays

The « Cygnus bubble » is revealed after masking/removing several sources

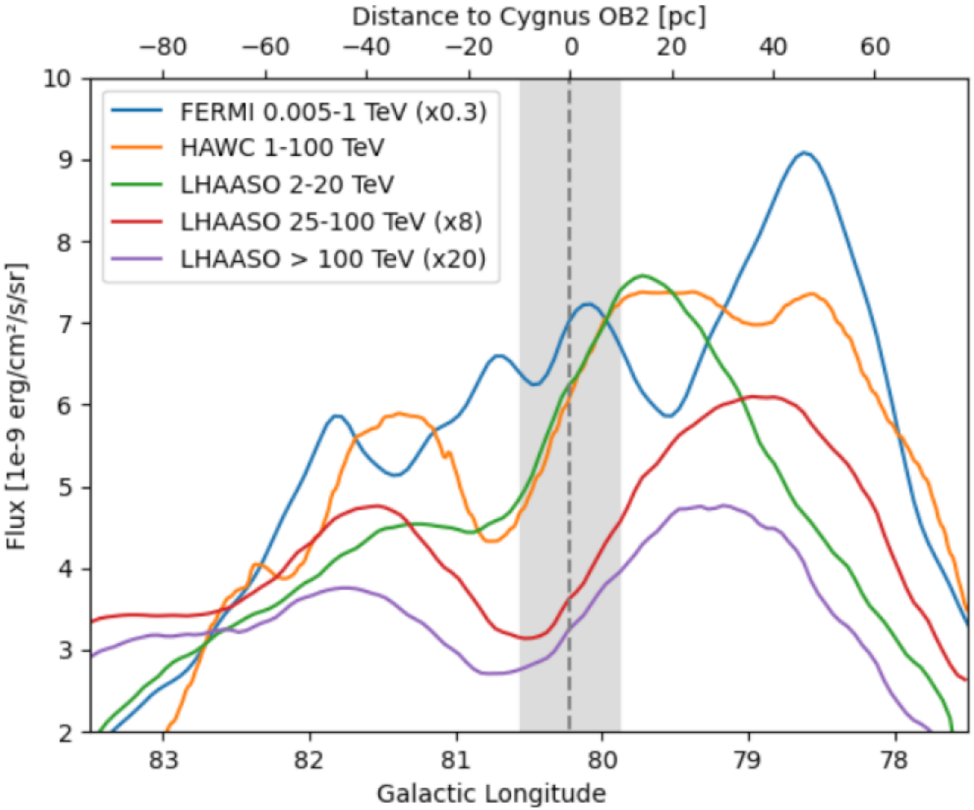
→ not straightforward to disentangle overlapping extended sources

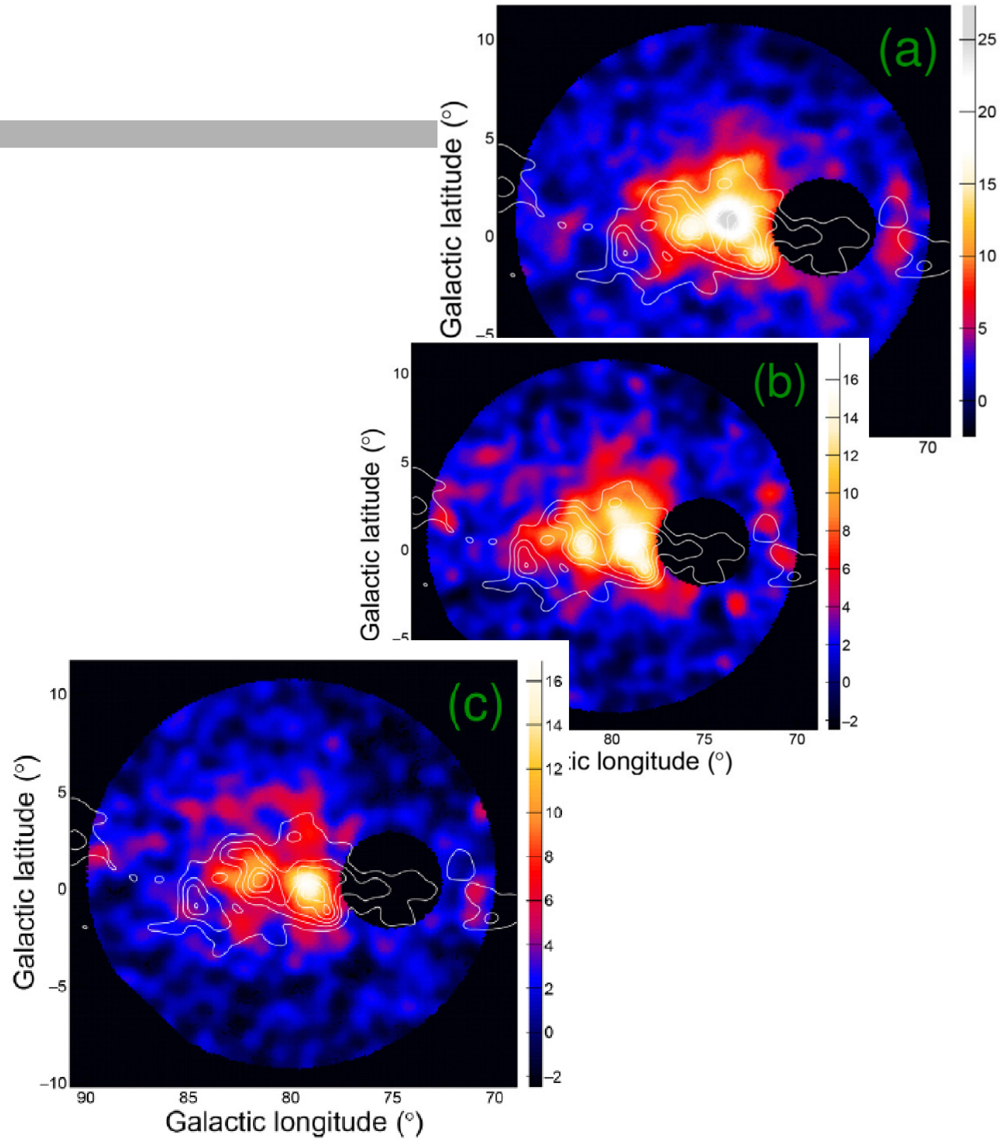
→ introduces uncertainties in the final « Cygnus bubble » ɣ-ray map

→ could still be contaminated by “tails” of pulsar / ɣ-Cygni hotspots



Morphology: the 1/r myth





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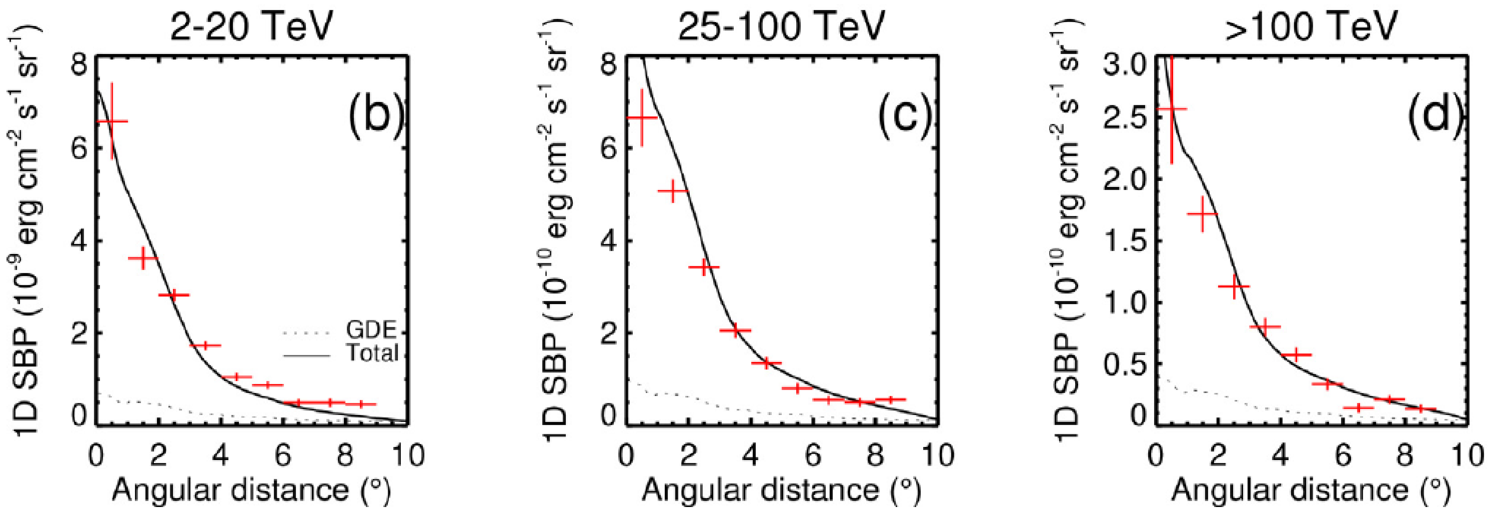

These “1/r” profiles are obtained by choosing the brightest point as the « centre », and then averaging over lineouts.

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 centre of these “1/r” is not Cygnus OB2 => doesn’t fit with a scenario of continuous injection by stellar winds.

Lower energies: the hadronic myth

“Cygnus gamma emission must be predominantly hadronic…”

✗ Because the emission correlates with gas → not really...

✗ Because Bremstrahlung component overshoots MeV and X-ray limits...
… assuming n ~ 30 cm^{-3}
… obviously unrealistic close to powerful O / WR stars
→ plausible range: 0.01 – 0.1

✗ Because synchrotron component overshoots radio limits...
… assuming B ~ 20 μG
→ high estimate for a loose association, even at its “heart”.