3D MHD Simulations of Young Massive Stellar Clusters

Lucia Härer
with Thibault Vieu, Brian Reville, and Jieshuang Wang

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MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK

Diffuse γ-rays from Young Star Clusters

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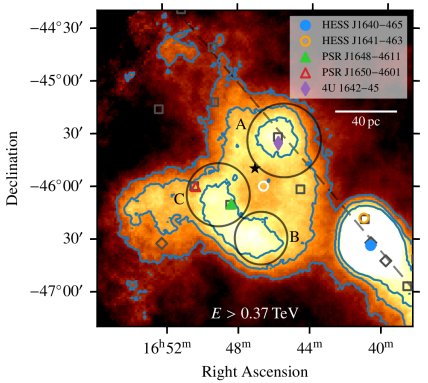
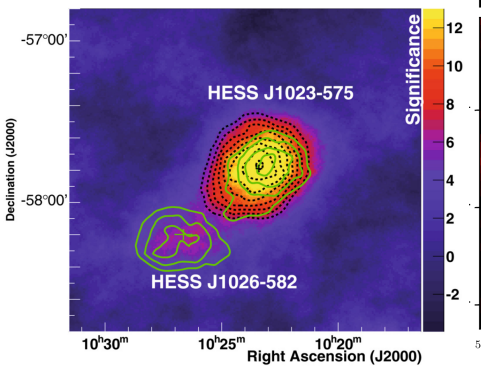
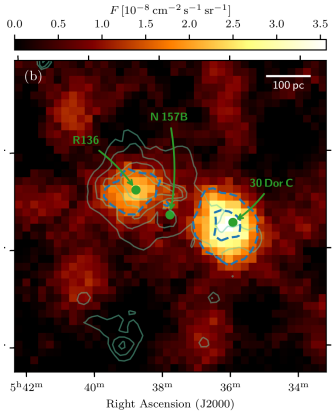


Westerlund 1
H.E.S.S. 2023



Westerlund 2
H.E.S.S. 2011



R136, 30 Dor C
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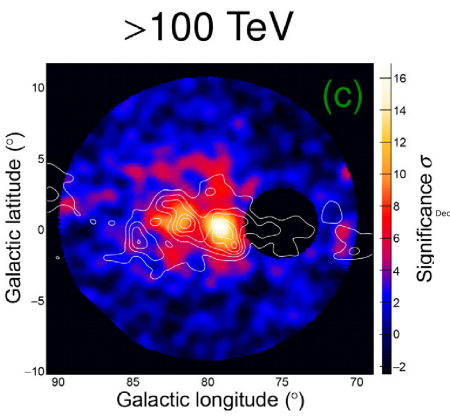
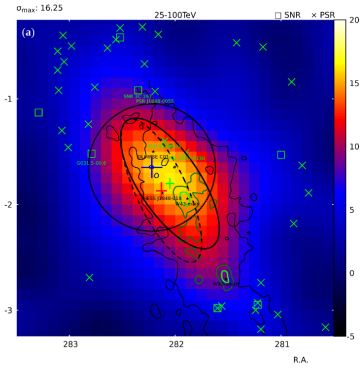


Cygnus X
LHAASO 2024



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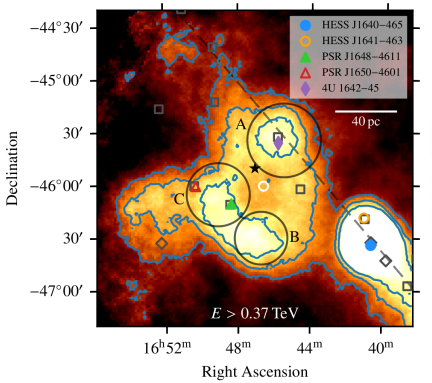

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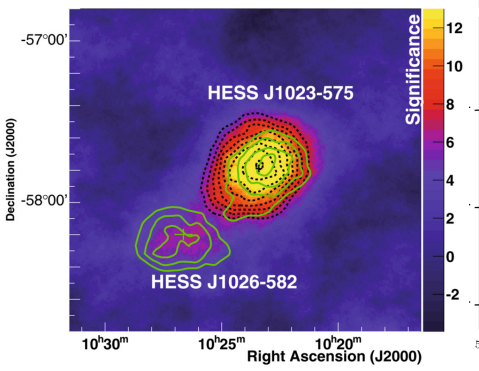

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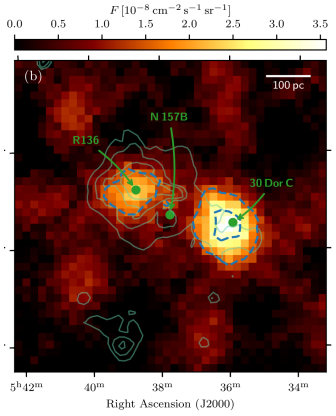

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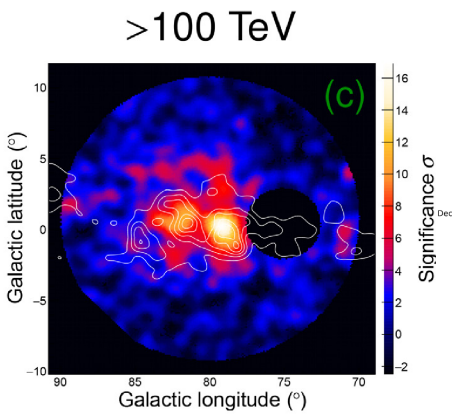

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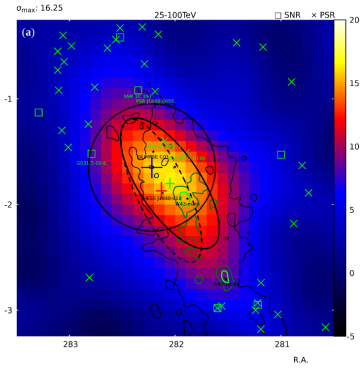

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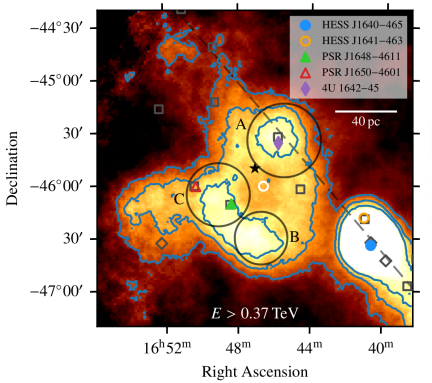

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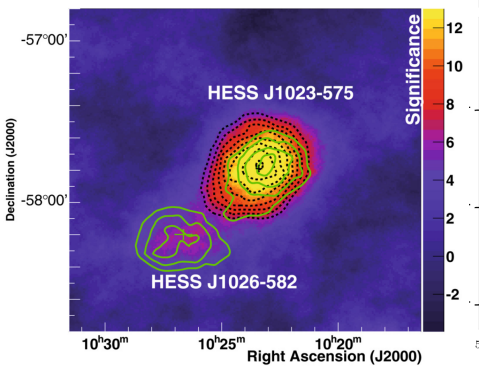

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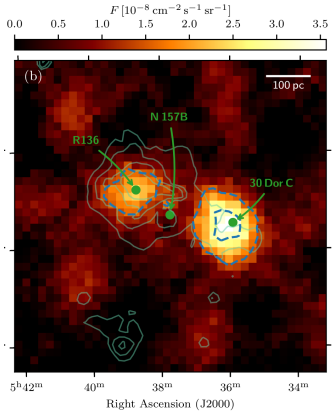

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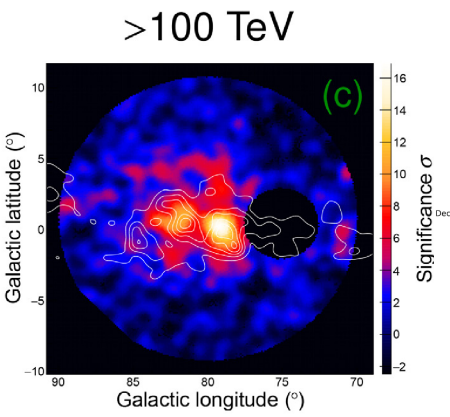

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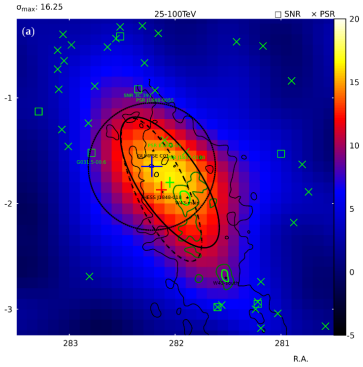

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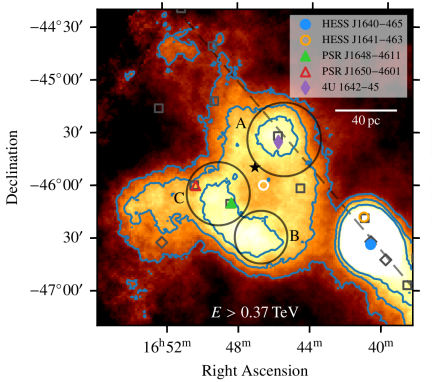

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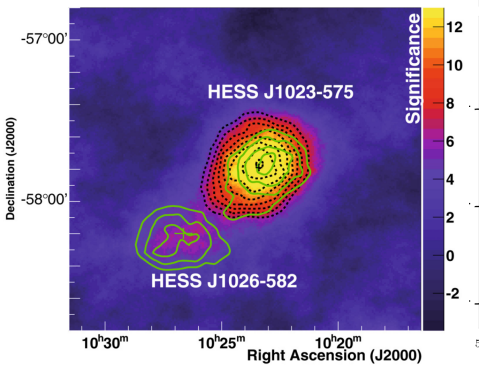

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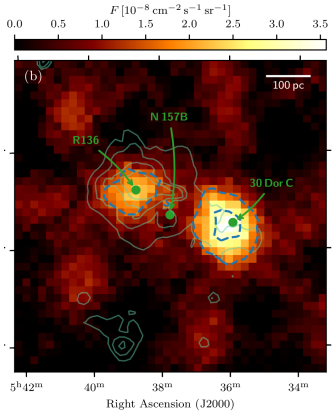

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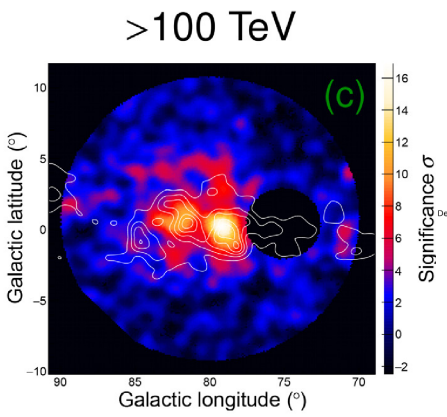

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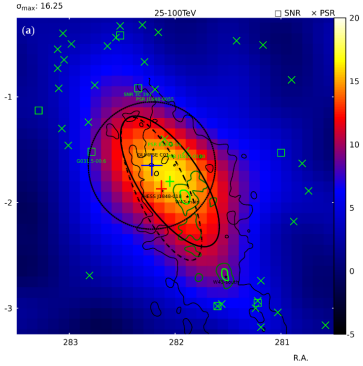

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- Stellar winds interact (⟶ shocks, turbulence) and blow cavities into the ambient medium: *superbubbles*.
- Highly *complex* and *diverse regions!* Acceleration and transport not well understood.
- Do young star clusters account for the *observed CR flux at ~1-100 PeV*?

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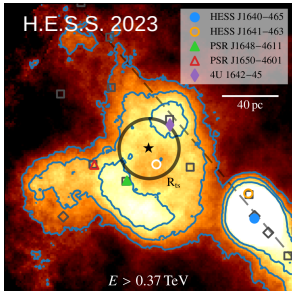
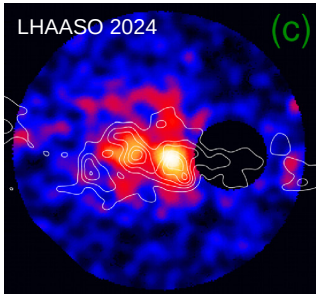


Cygnus OB2



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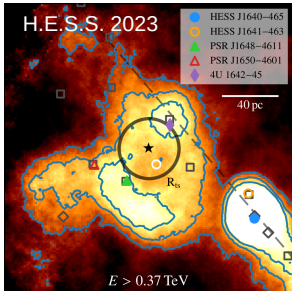

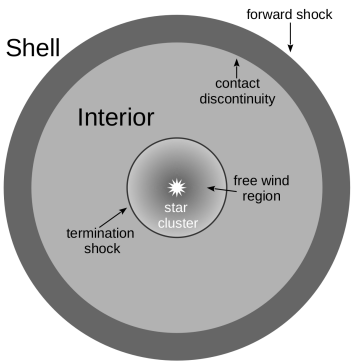

compact cluster

→ *has a cluster* wind termination shock

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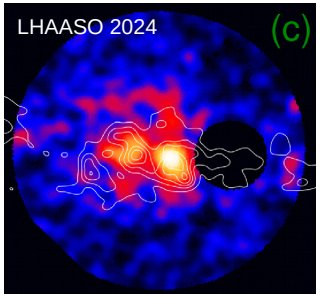

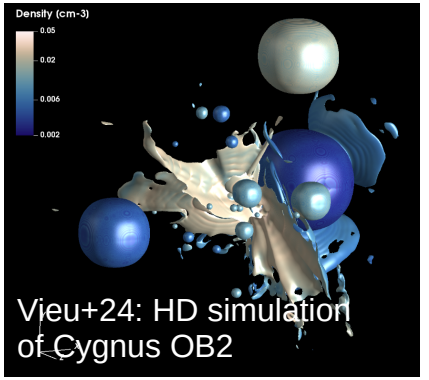

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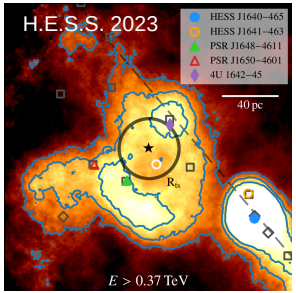

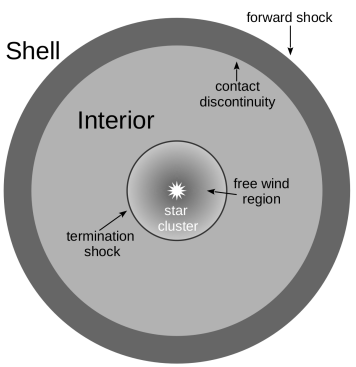

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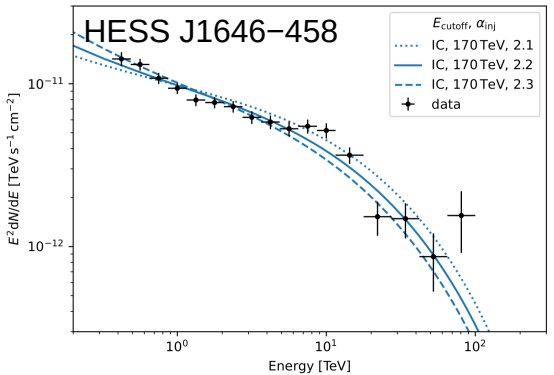

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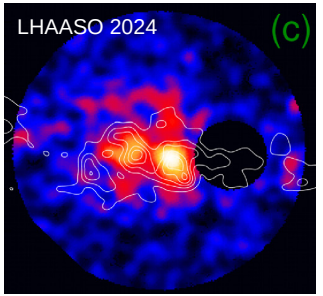

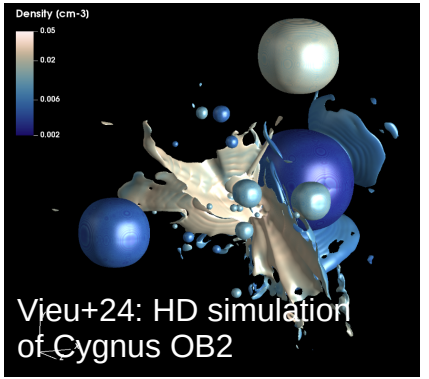

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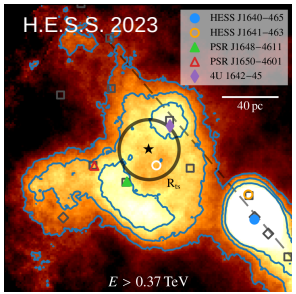

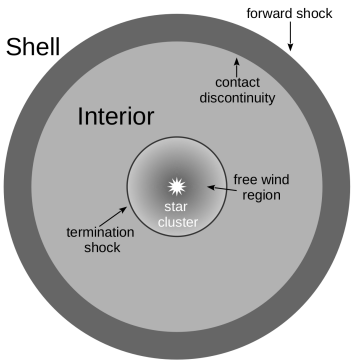

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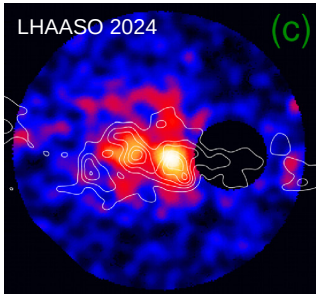

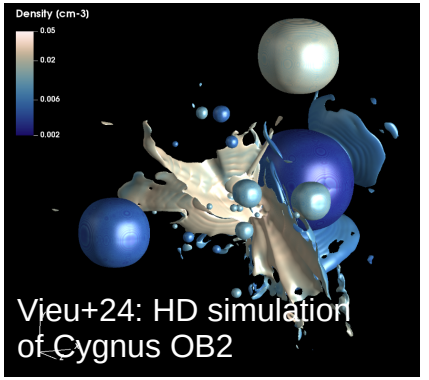

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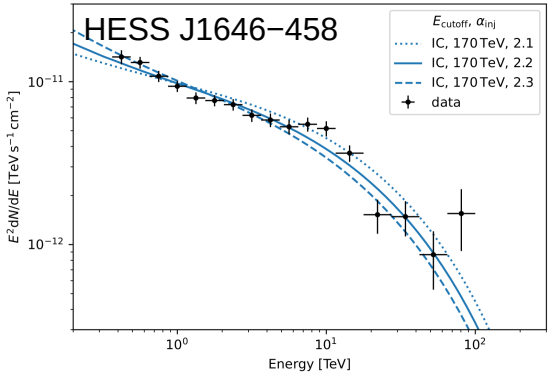

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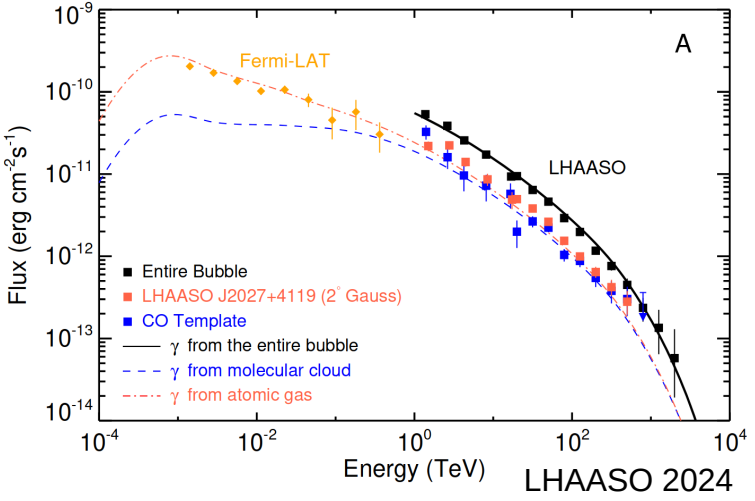

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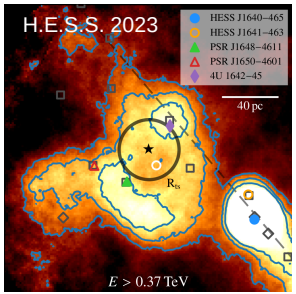

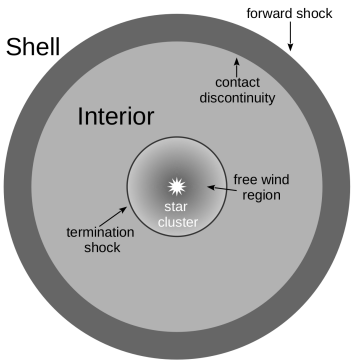

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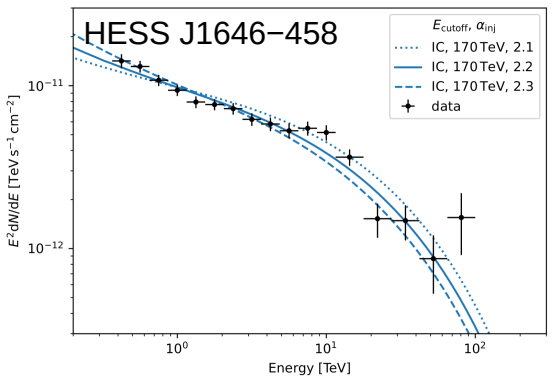

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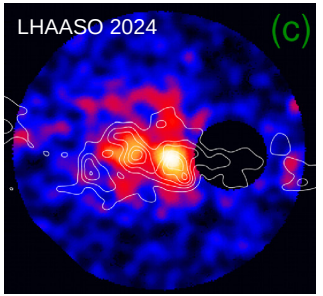

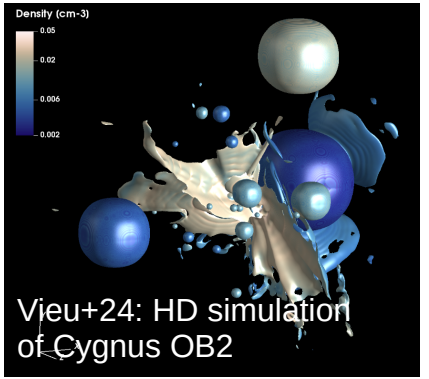

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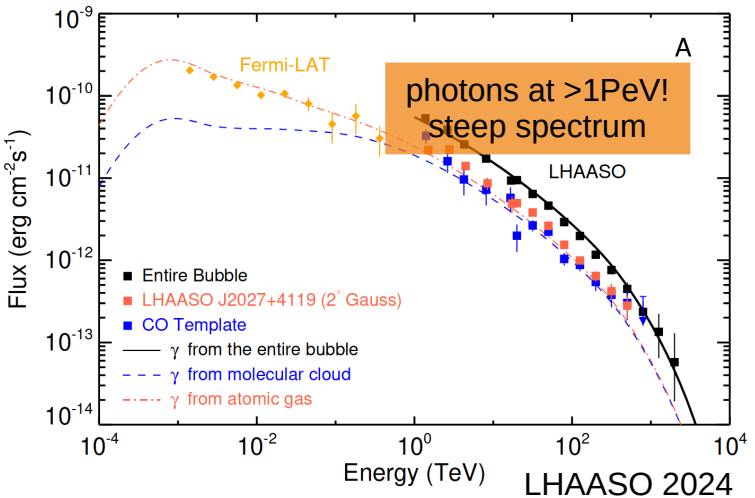

3D MHD Simulations of a Young Compact Cluster

resolving *individual stellar winds* to study wind interaction in 3D

3D ideal MHD, PLUTO code

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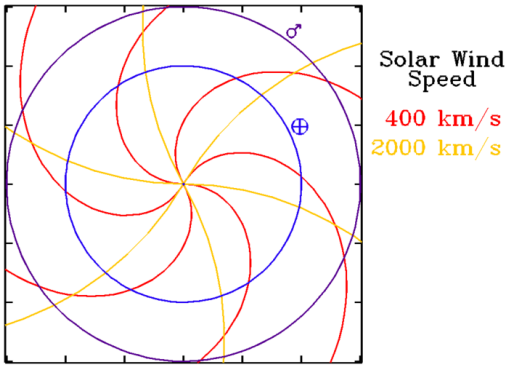
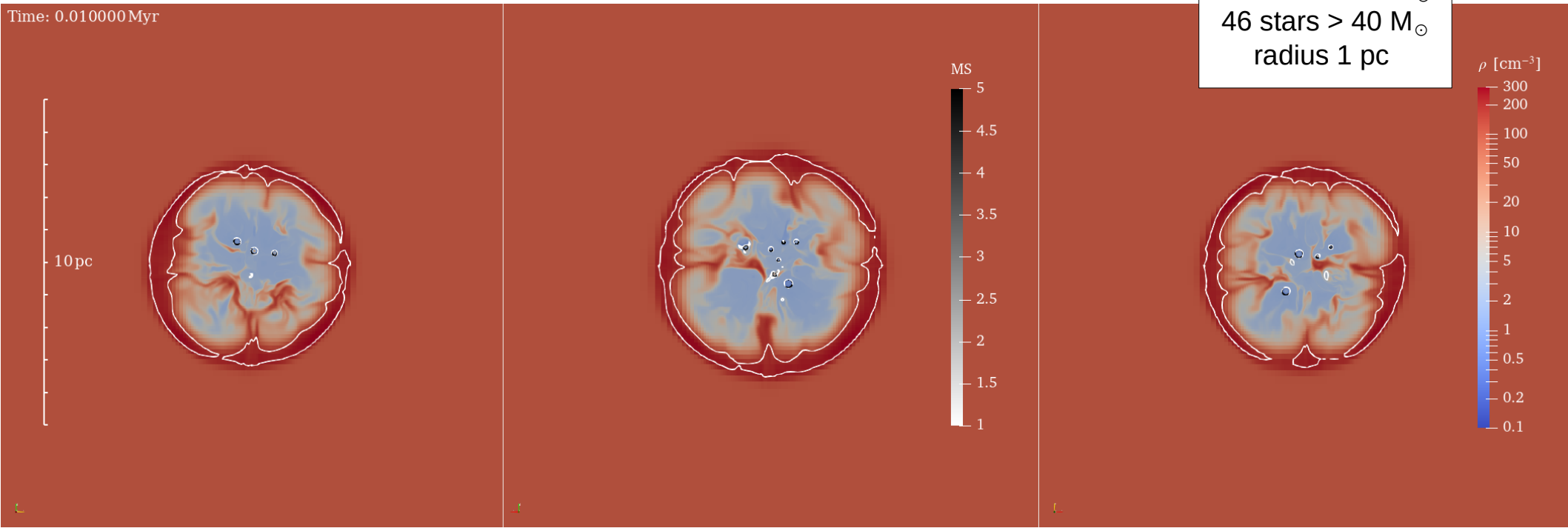
Cluster model

- IMF (distribution of stellar masses): $dN \sim M^{-2.3}\, dM$
  above 0.4 $M_\odot$, cf. Kroupa+ 02
- Simulate winds of stars > 40 $M_\odot$
  these contribute ~90% of total wind power for our IMF, cf. Seo+ 18
- Stars enter Wolf-Rayet phase one-by-one, Δt according to life-time
  Zakhozhay 13
- Wolf-Rayet phase: mass-loss increase 10x
  cf. Seo+ 18
- 10% magnetic massive stars: 1 kG
  at the stellar surface, for remaining stars choose fiducial value of 10 G, cf. Grunhut+ 17
- Parker spiral field structure (rotating dipole)
  cf. Grunhut+ 17



Bubble Structure and Evolution

cluster setup
mass: $3.5 \cdot 10^4$ $M_\odot$
46 stars > 40 $M_\odot$
radius 1 pc



cavity created

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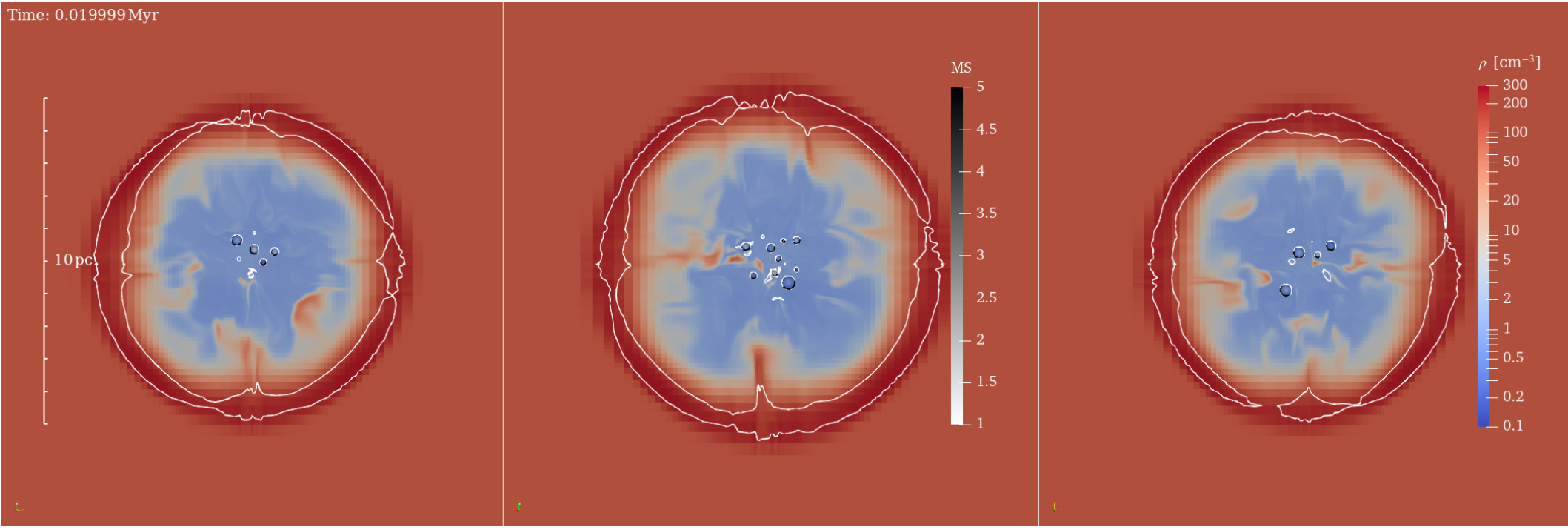

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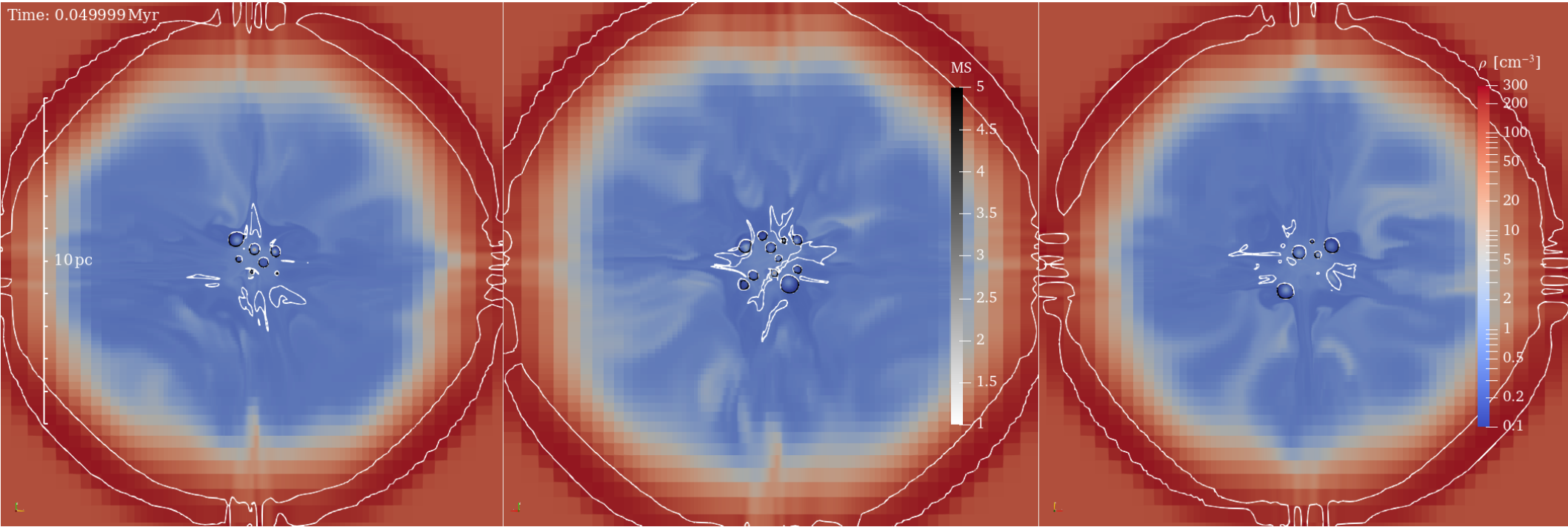
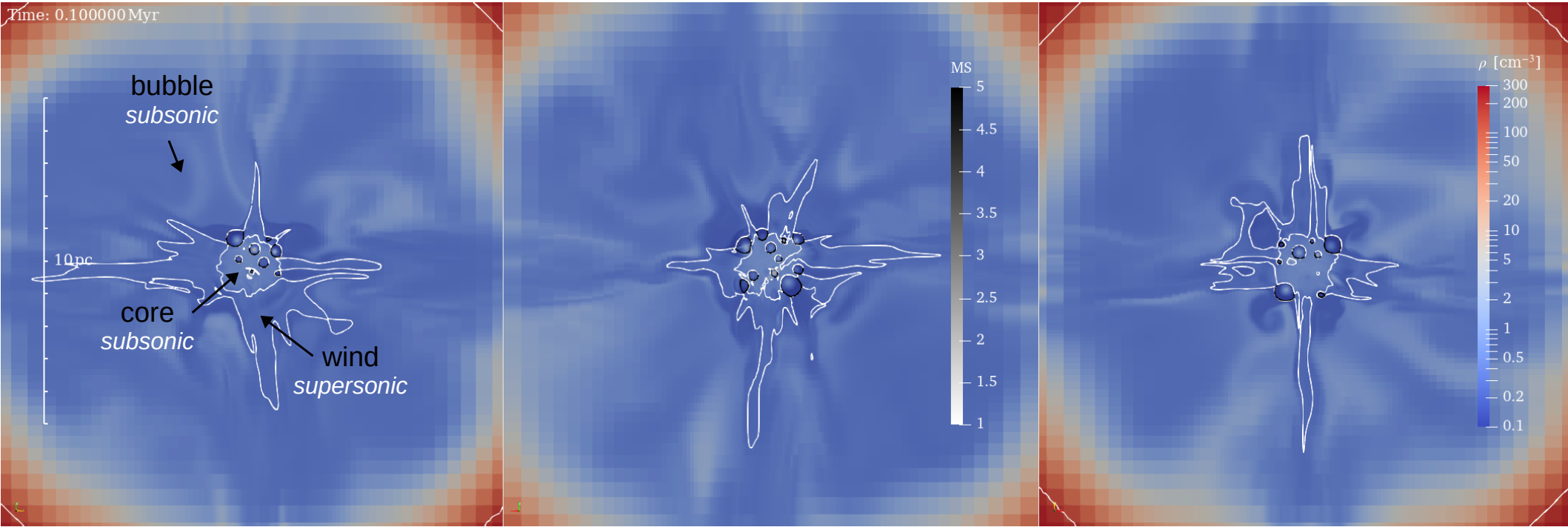


supersonic outflow starts to form

Bubble Structure and Evolution



subsonic core and supersonic wind

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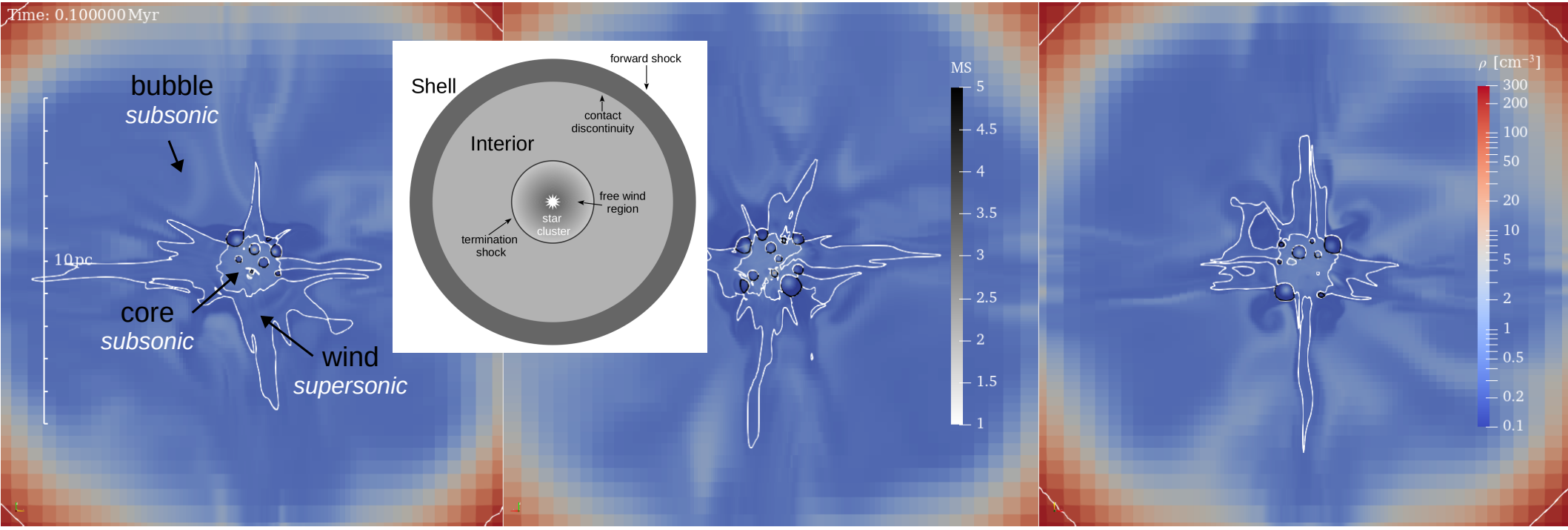

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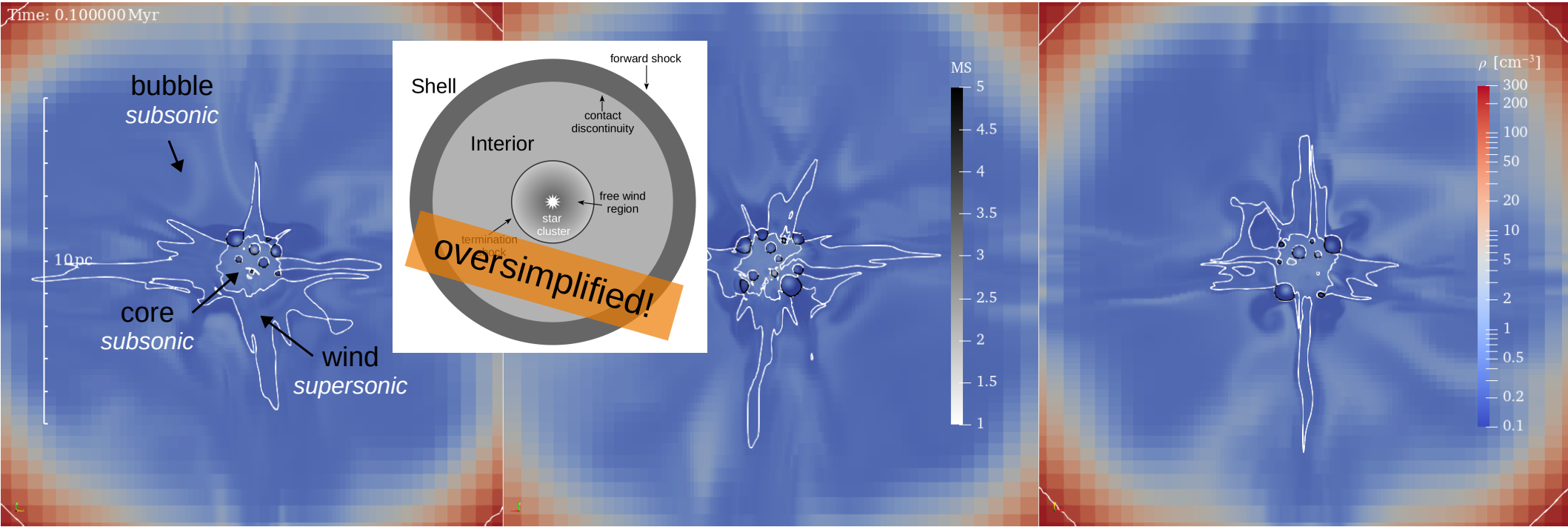
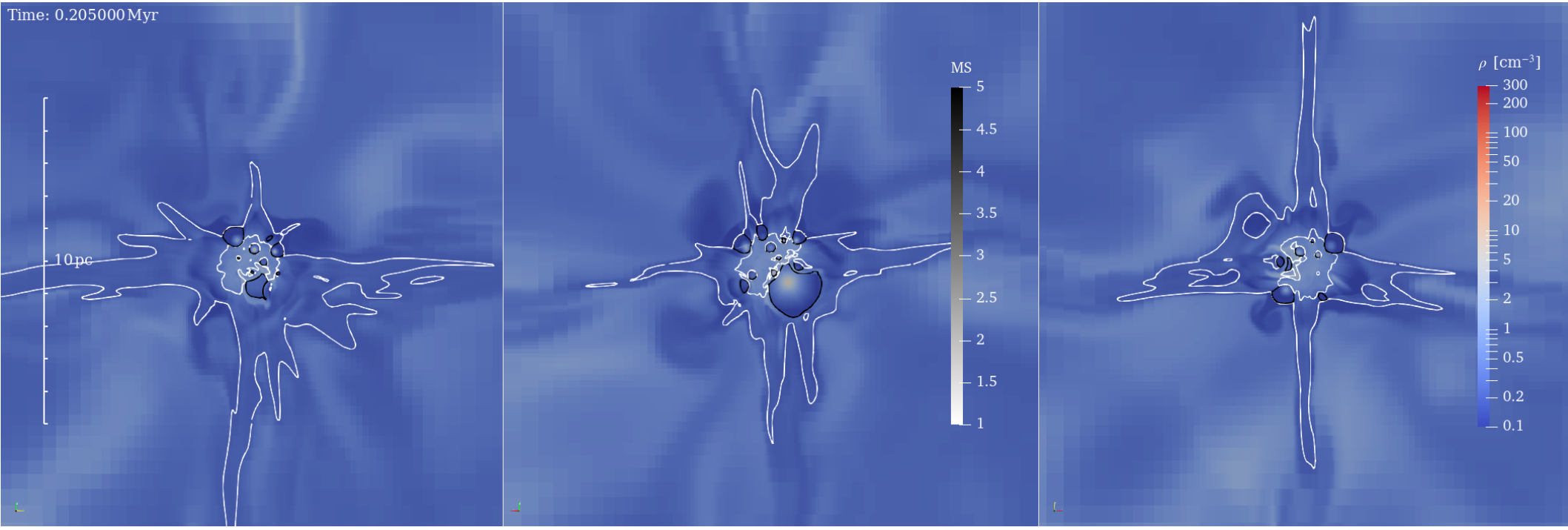


non-spherical termination shock

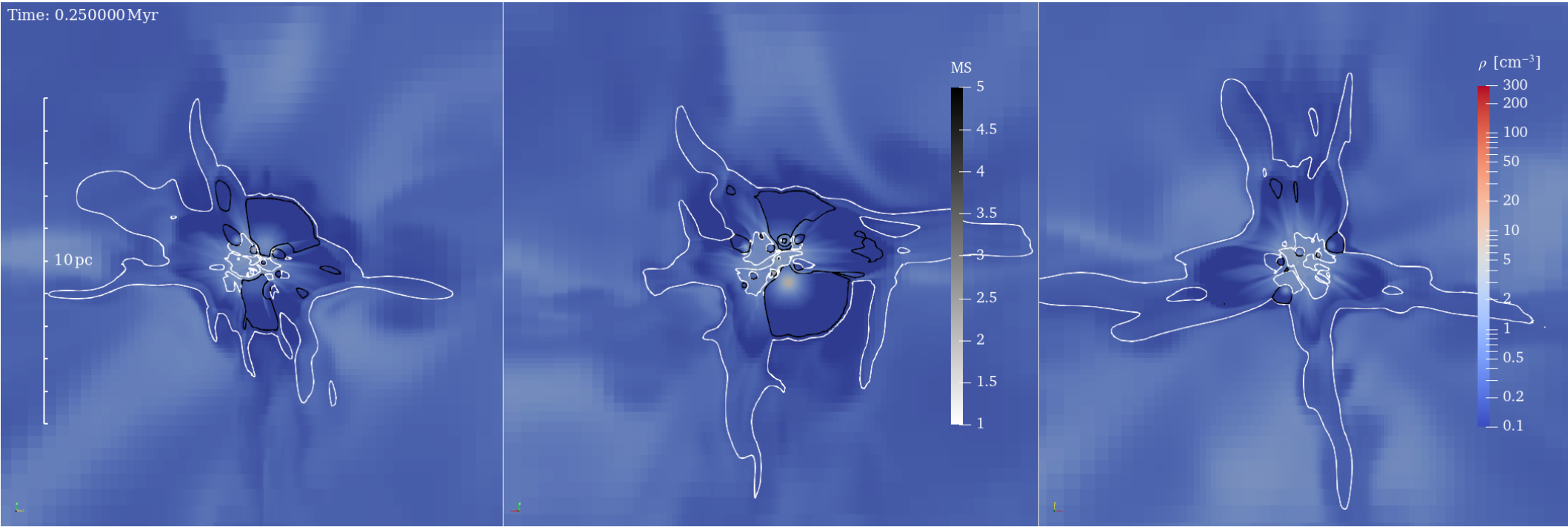
supersonic streams (‘tentacles’) created by wind-wind interaction

Bubble Structure and Evolution



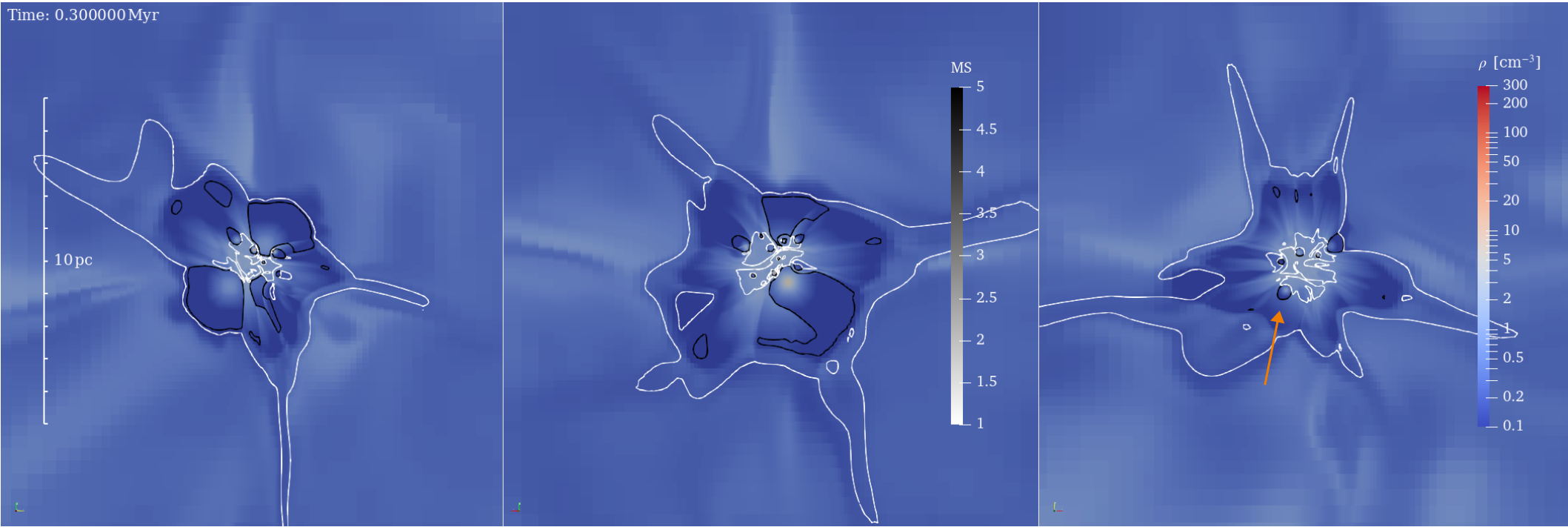
Wolf-Rayet phase begins

Bubble Structure and Evolution



Wolf-Rayet winds disturb established flow pattern

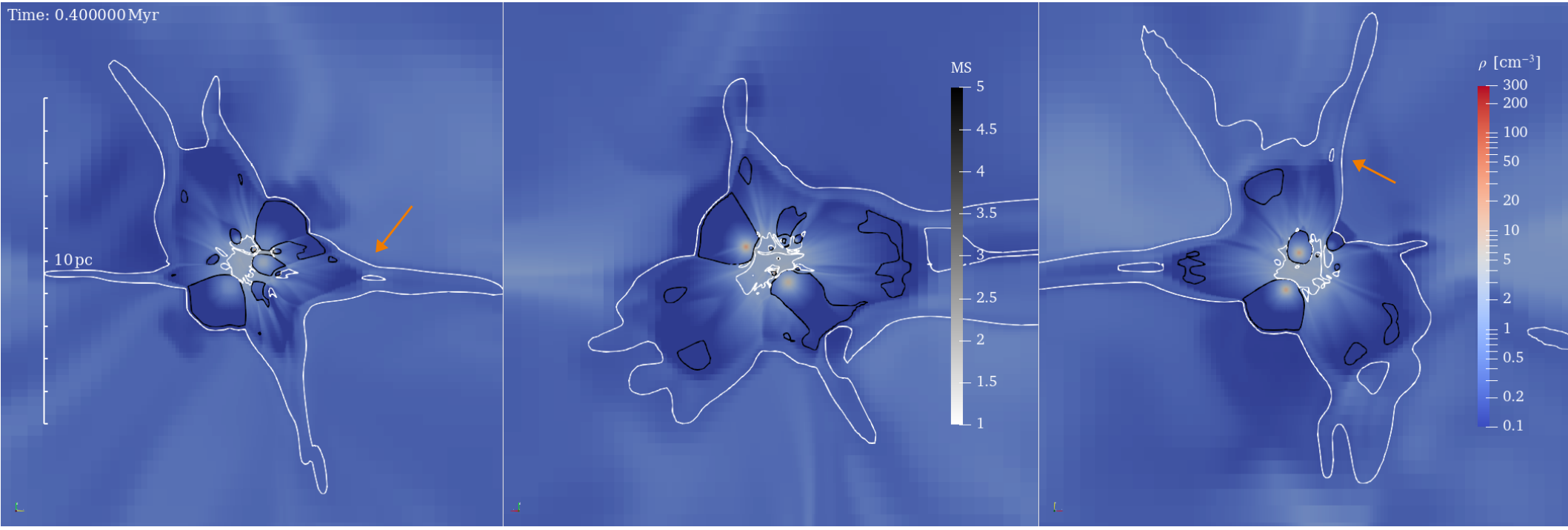
Bubble Structure and Evolution



shocks got stronger

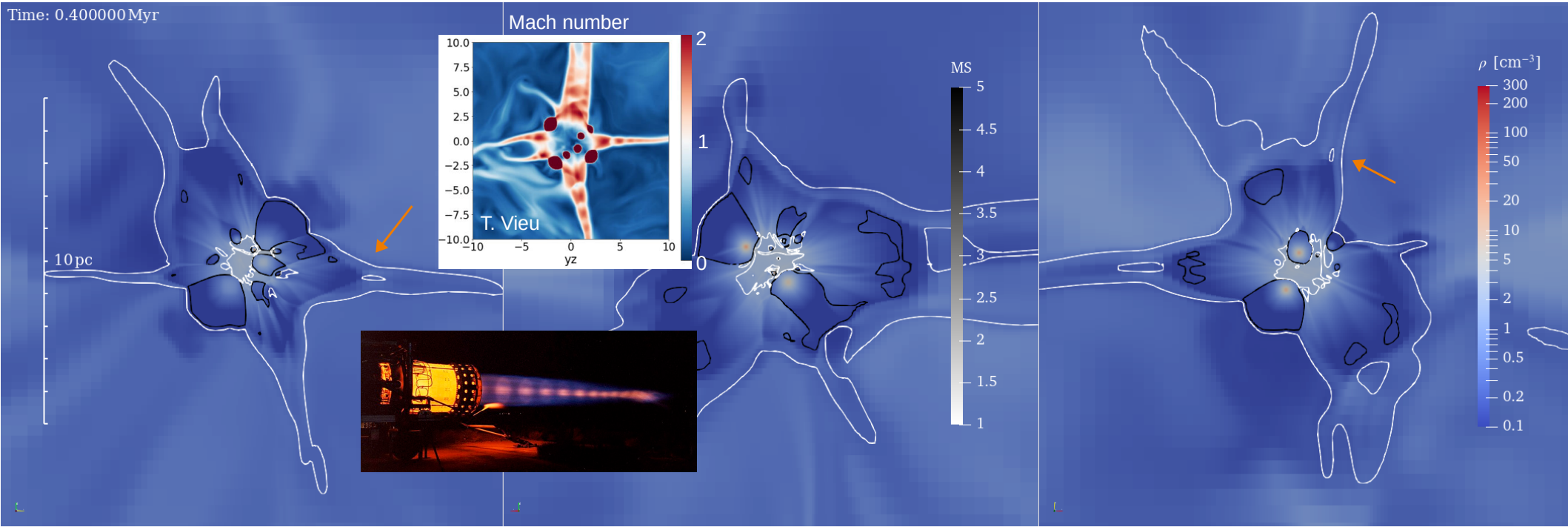
weak stellar termination shock decouples

Bubble Structure and Evolution



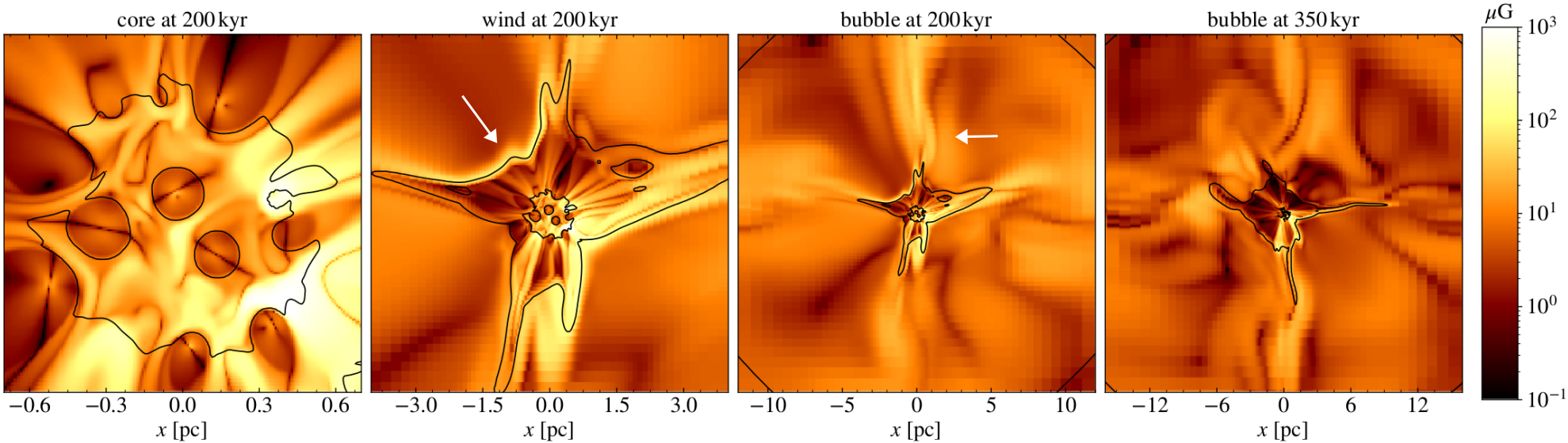
supersonic streams have *internal structure*

Bubble Structure and Evolution



supersonic streams have *internal structure*

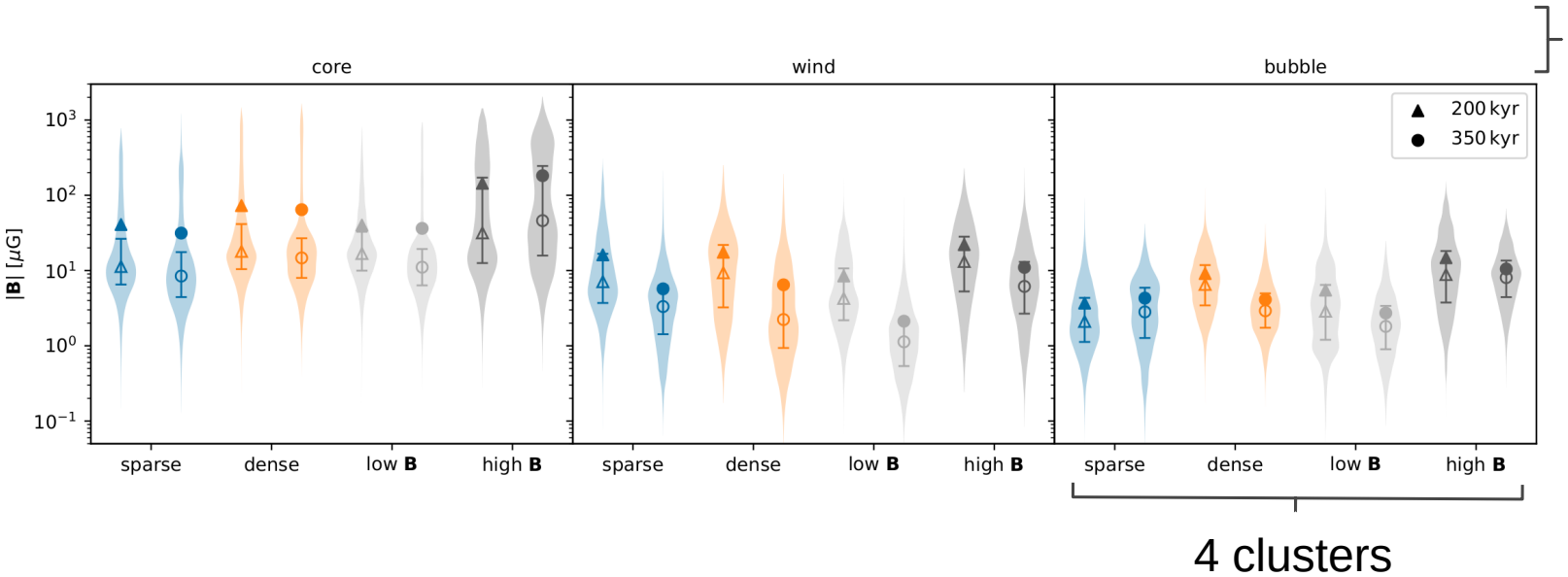
Magnetic Field by Region



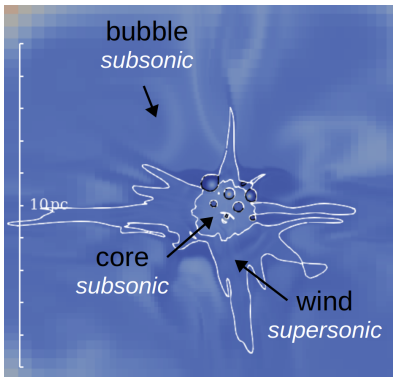
strong variation

Wolf-Rayet activity destroys established pattern

Magnetic Field by Region



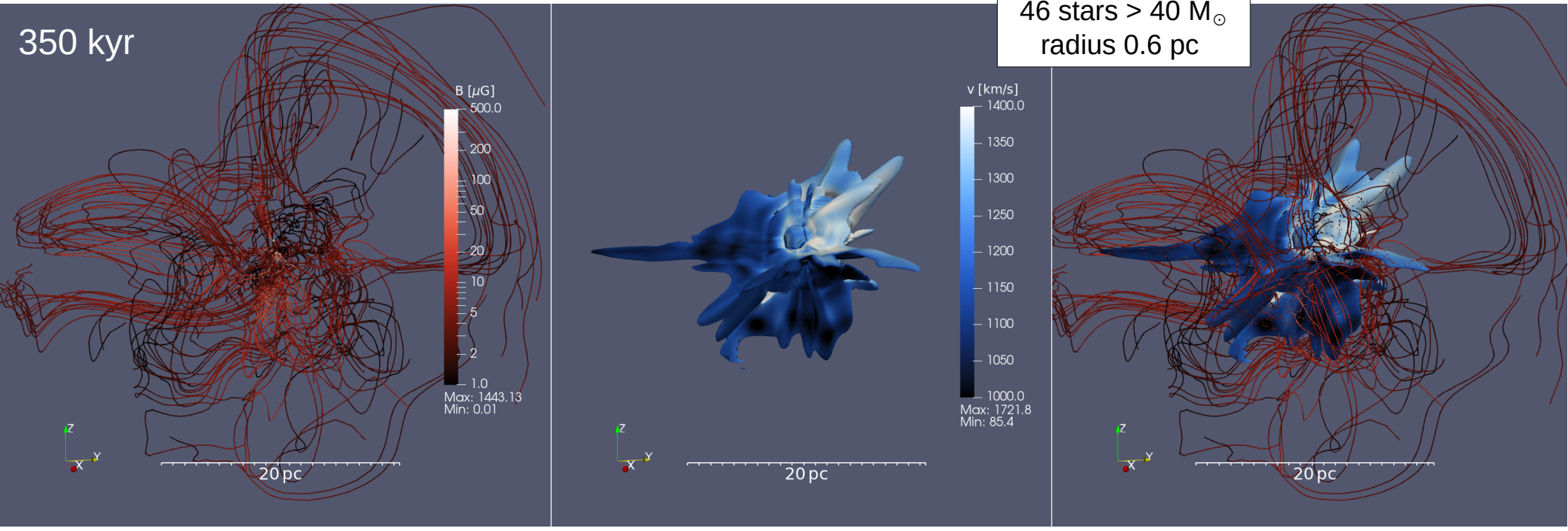
3 regions



→ on average: core 30-200 μG, wind 2-20 μG, bubble 3-15 μG

3D Structure

cluster setup
mass: $3.5 \cdot 10^4$ $M_\odot$
46 stars > 40 $M_\odot$
radius 0.6 pc



tangled field lines in the core and wind

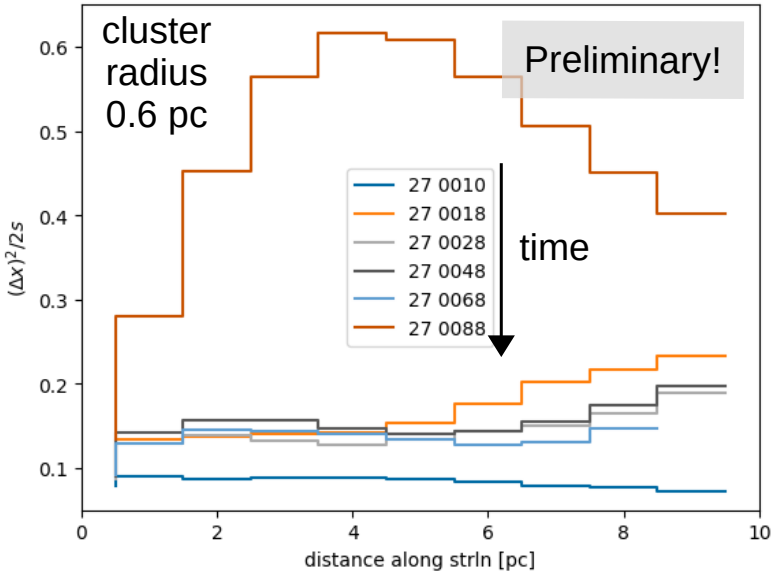
Mach 1 surface: 2D sheets and ‘tongues’

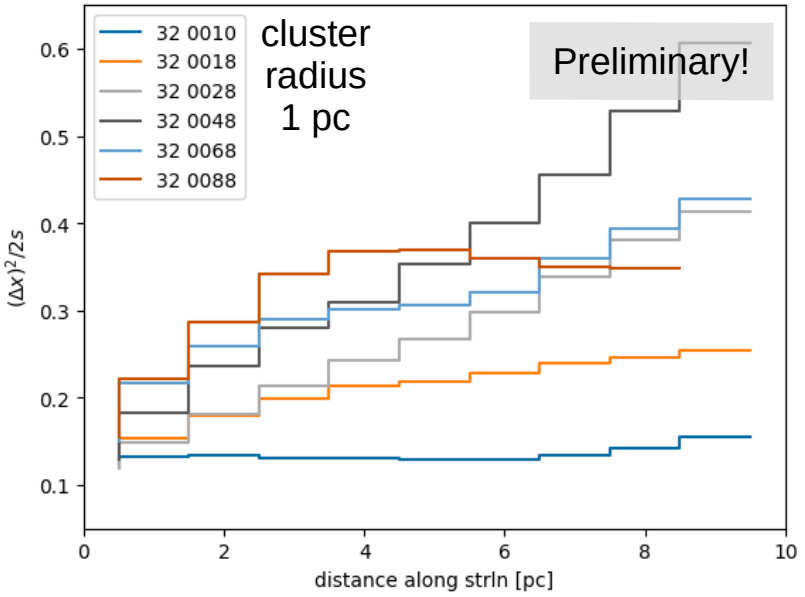
coherent flows carry out field → loops

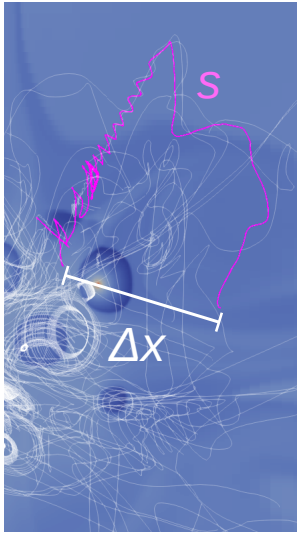
cluster setup
mass: $3.5 \cdot 10^4$ $M_\odot$
46 stars > 40 $M_\odot$
radius 0.6, 1 pc

Field Line Diffusivity

Compares distance along the field line to straight distance







Change of behaviour at ~5 pc (esp. for dense case)

Magnetic Wolf-Rayet star strongly impacts B-field morphology!

Conclusions

- Flow and B-field show *complex morphology*
  Non-spherical termination shock, supersonic streams etc.

  → limits applicability of 1D models.

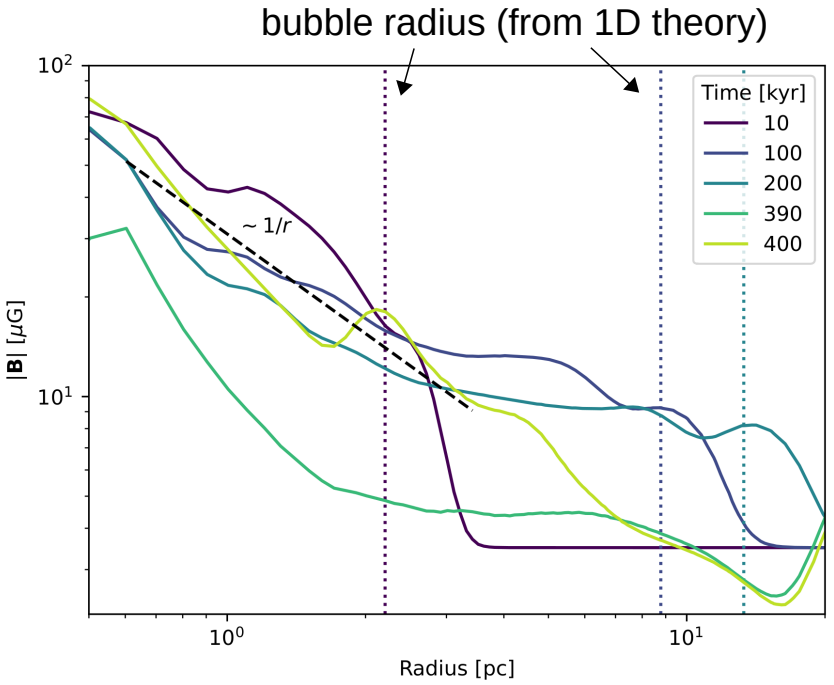
- Mean B-field: core 30-200 μG, wind 2-20 μG, bubble 3-15 μG

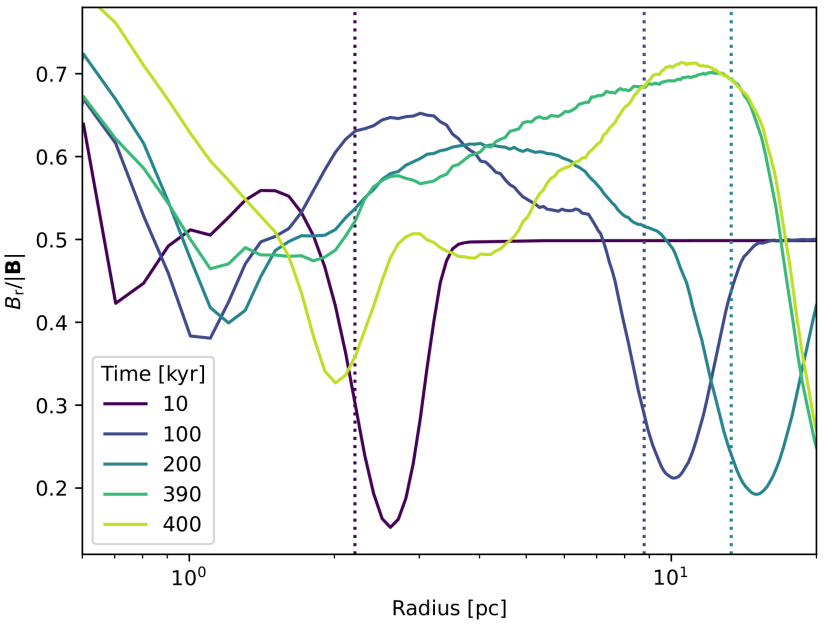
- *Individual* wind-wind interactions do matter!

MHD Simulations of Star Clusters
Härer et al.,
Proceedings ICRC 2023

Understanding the TeV γ-ray emission around Westerlund 1
Härer et al. 2023
A&A, 671, A4

Magnetic Field with Radius

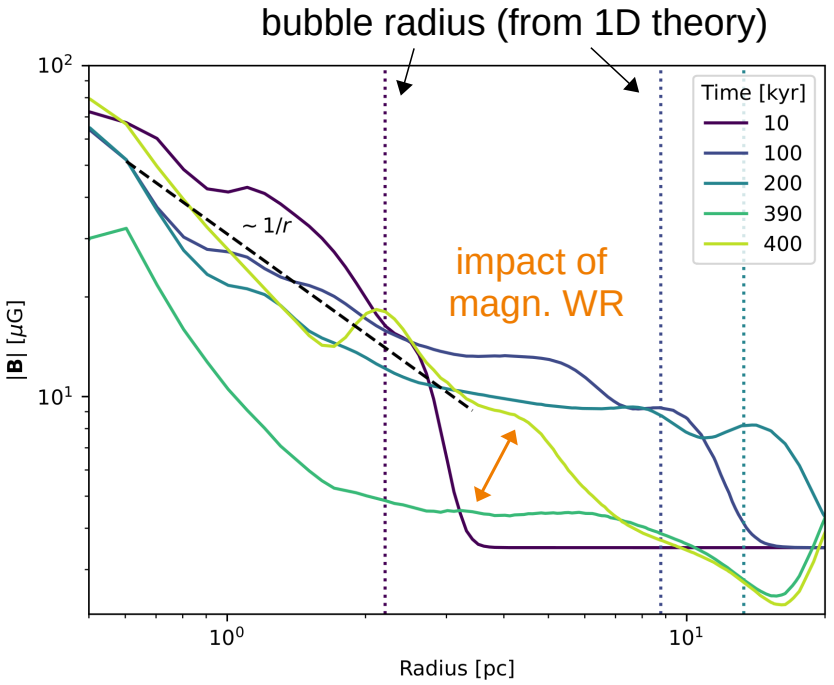


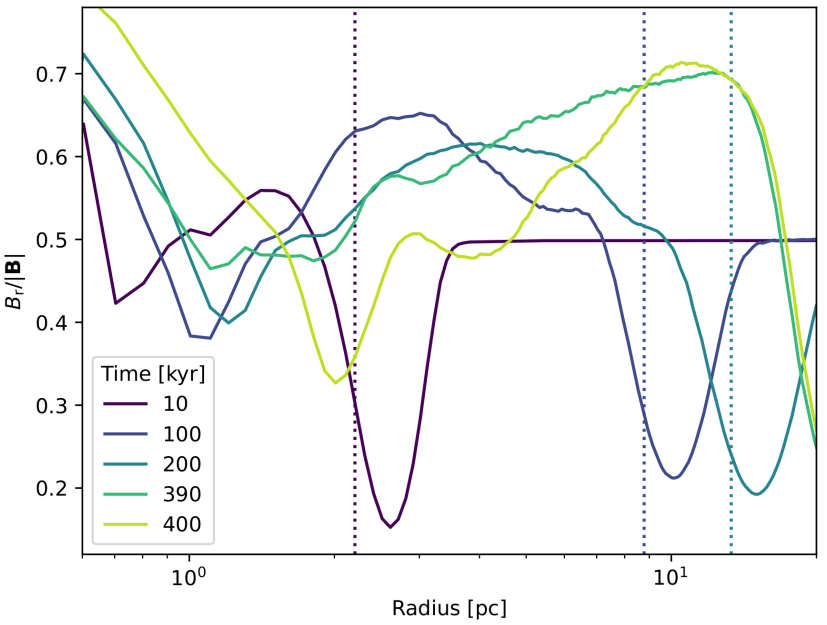


→ Slightly shallower than 1/*r* in MS phase

→ Amplification of $B_\perp$ behind shocks
B-field 50-70% radial in bubble

Magnetic Field with Radius





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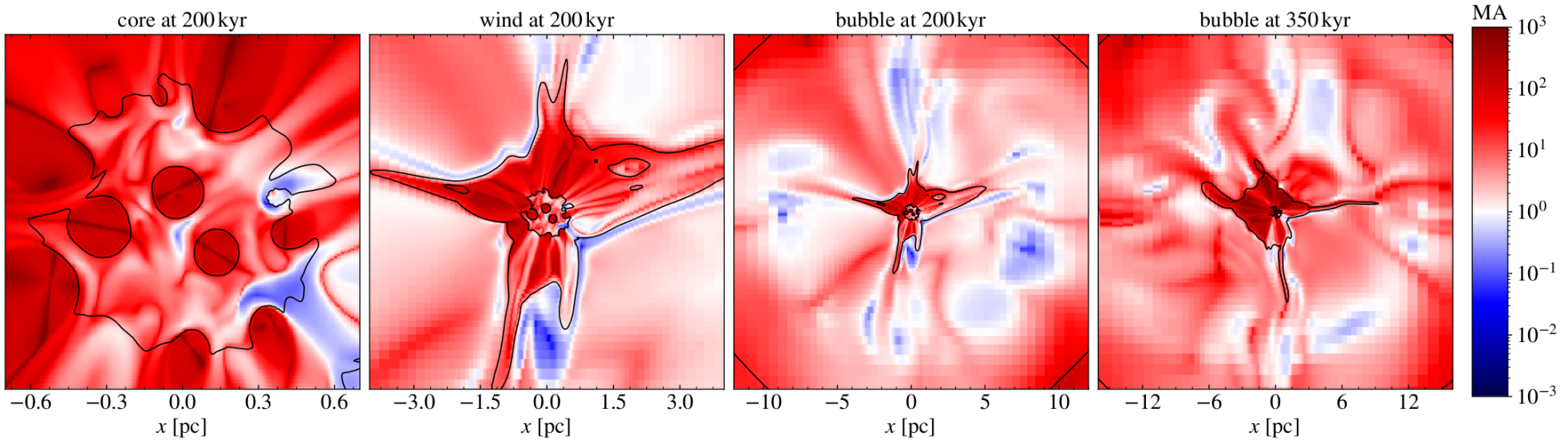
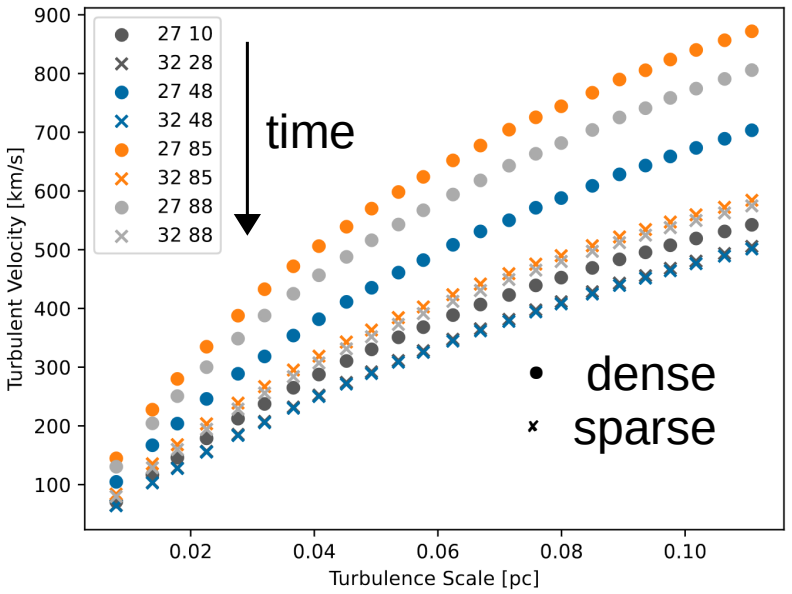
Alfvénic Mach Number



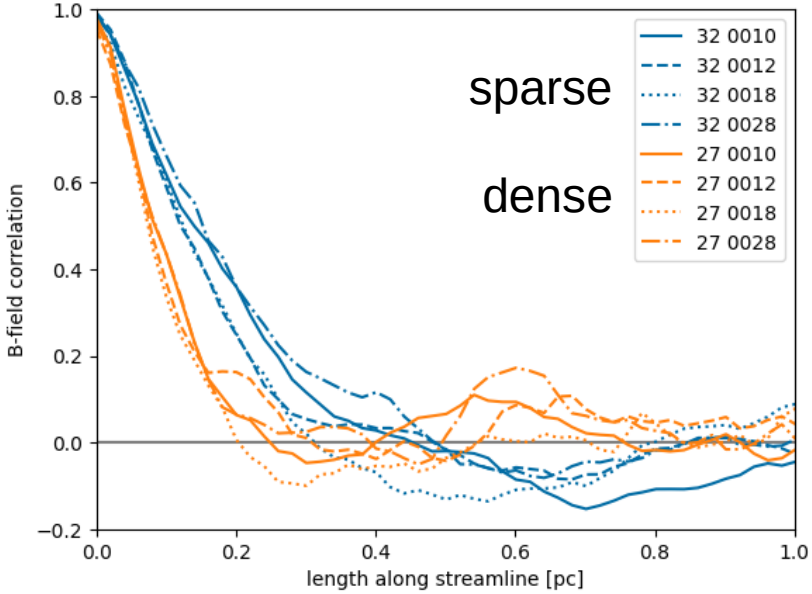
Turbulence



2nd order structure function

$$S_2(\lambda) = \left\langle |\boldsymbol{u}(\boldsymbol{r}) - \boldsymbol{u}(\boldsymbol{r}+\boldsymbol{\lambda})|^2 \right\rangle = \delta u^2(\lambda)$$

→ turbulent velocity at scale λ



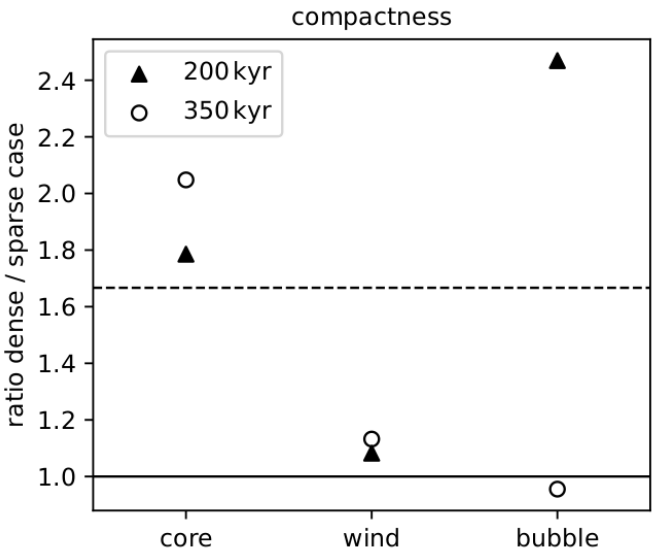
auto-correlation

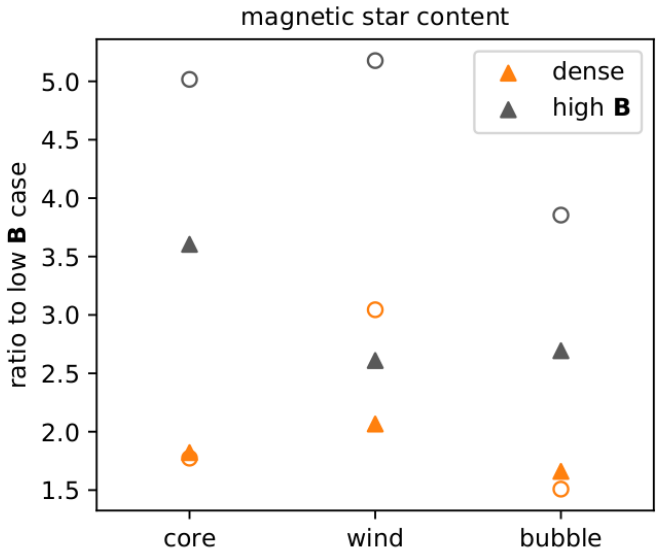
$$\sigma(\mathbf{B}) = \left\langle \frac{\mathbf{B}(\mathbf{x}) \cdot \mathbf{B}(\mathbf{x}+\mathbf{s})}{|\mathbf{B}(\mathbf{x})||\mathbf{B}(\mathbf{x}+\mathbf{s})|} \right\rangle$$

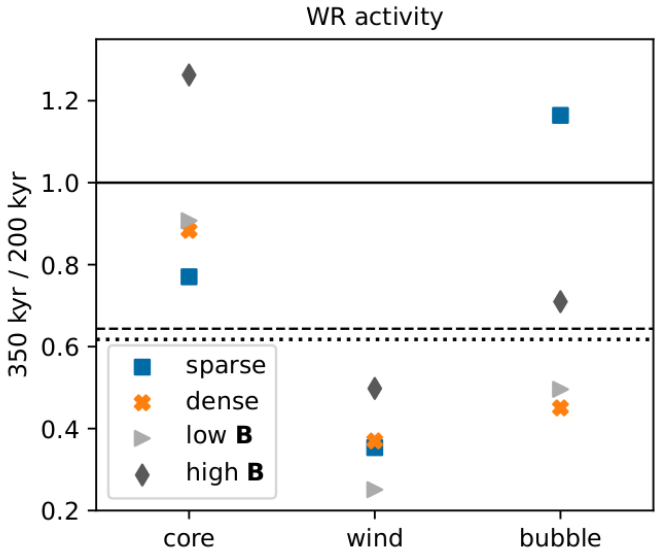
→ coherence length

Dense case shows a higher level of turbulence (except at 400 kyr → magn. WR star!) and shorter coherence length

Comparison between simulation runs







Shock diamonds