MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

MHD simulations of termination shocks in massive star clusters

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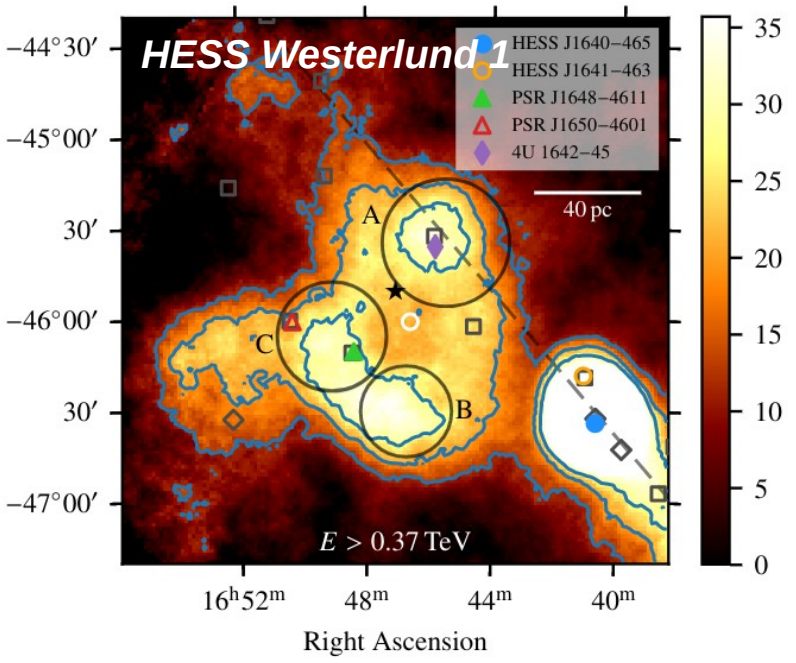
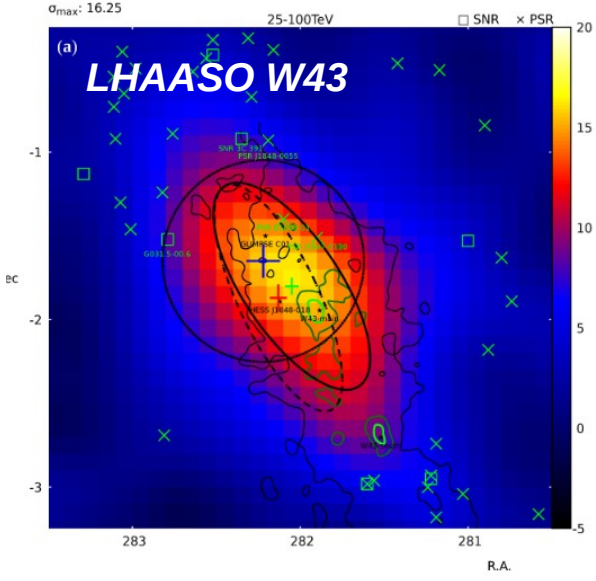
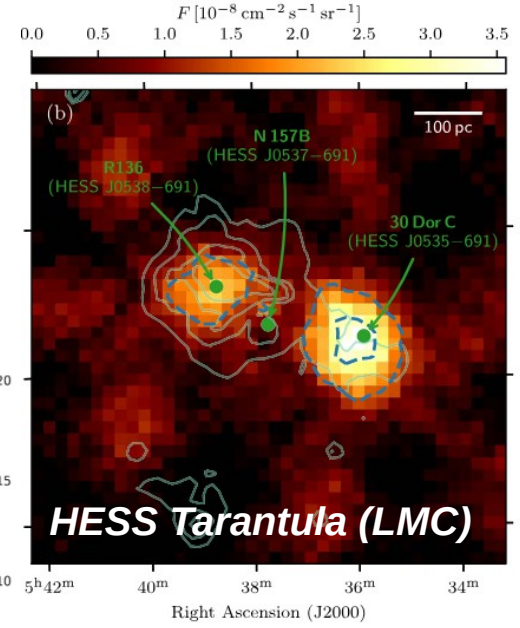
Star-forming regions as TeV γ-ray sources

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

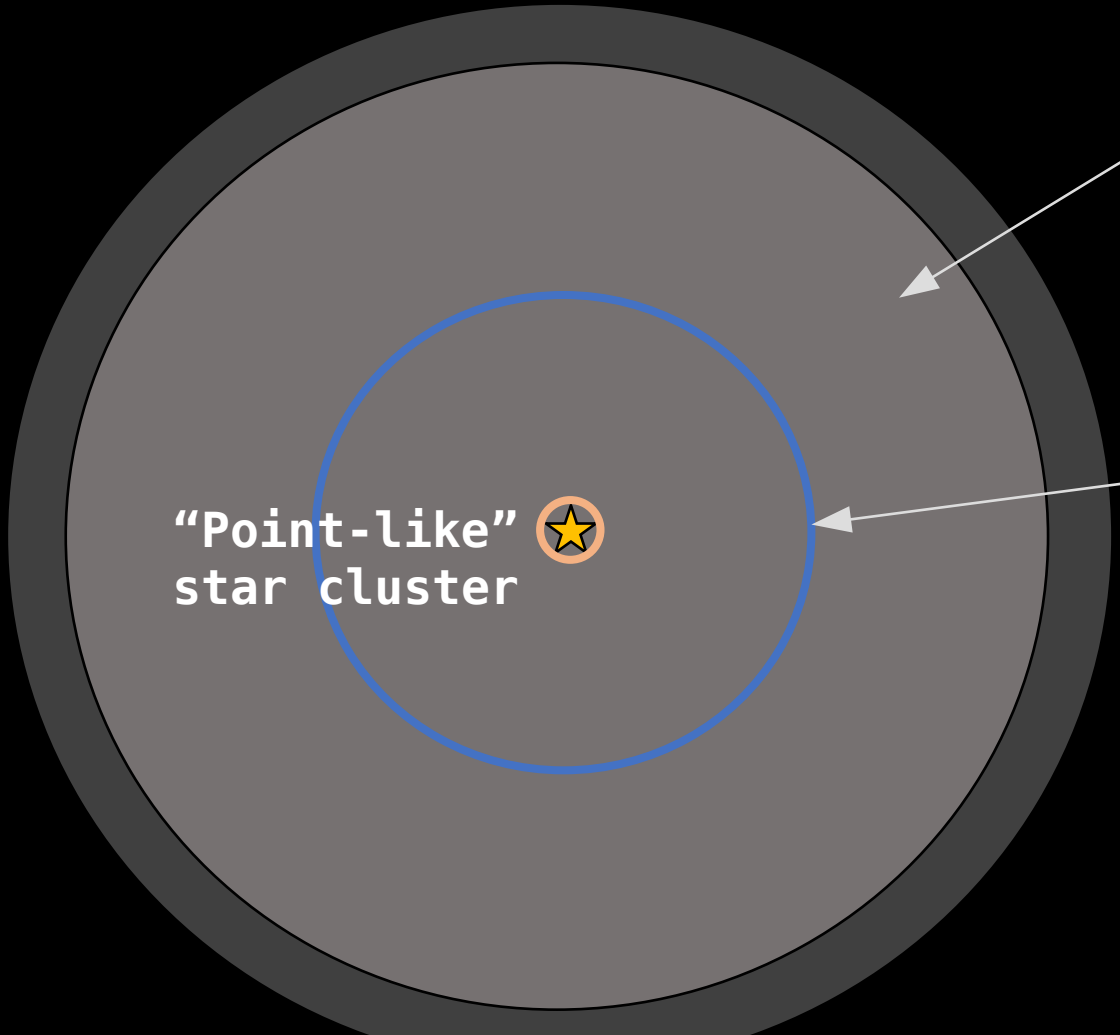
Key question: what kind of shocks are produced by interacting stellar winds?







Superbubble and wind termination shock: textbook



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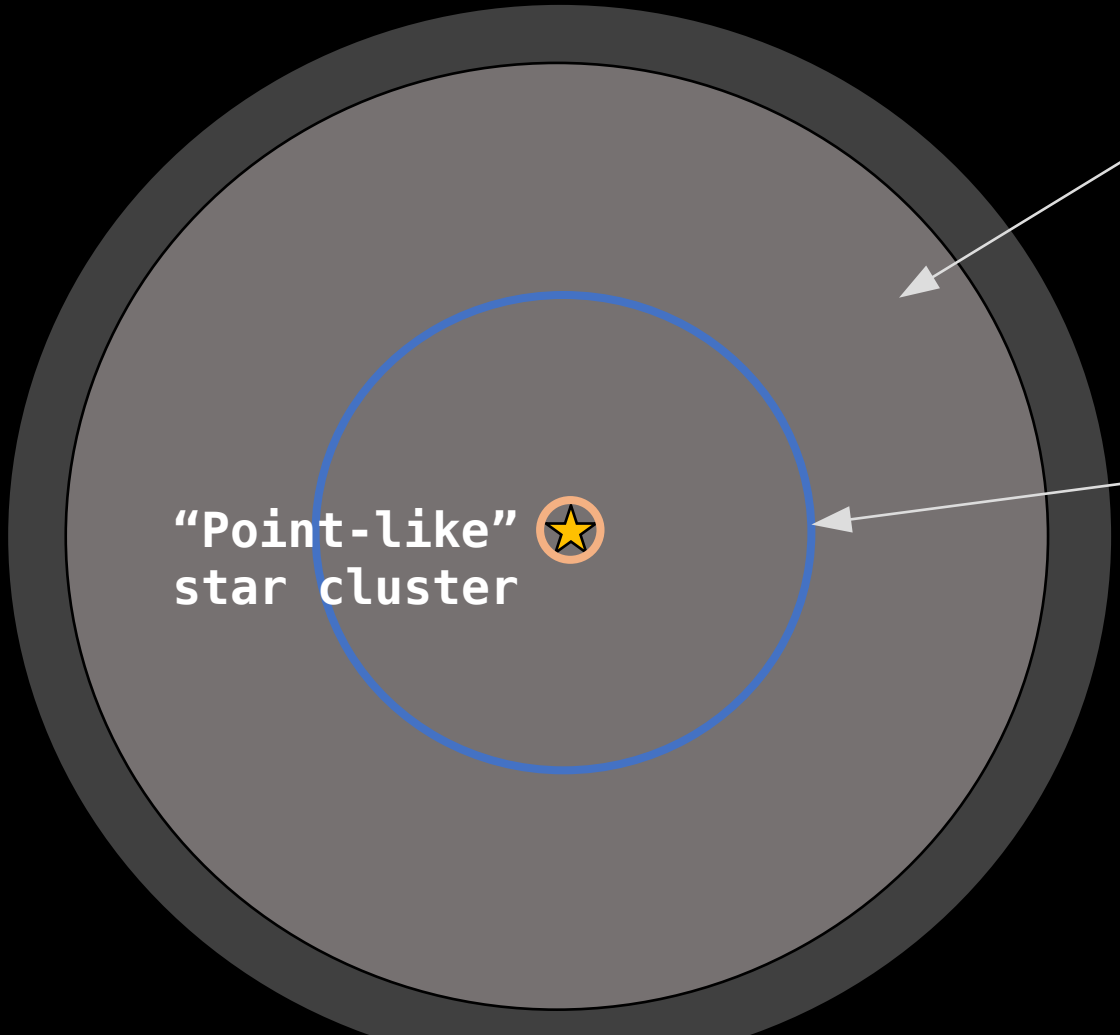
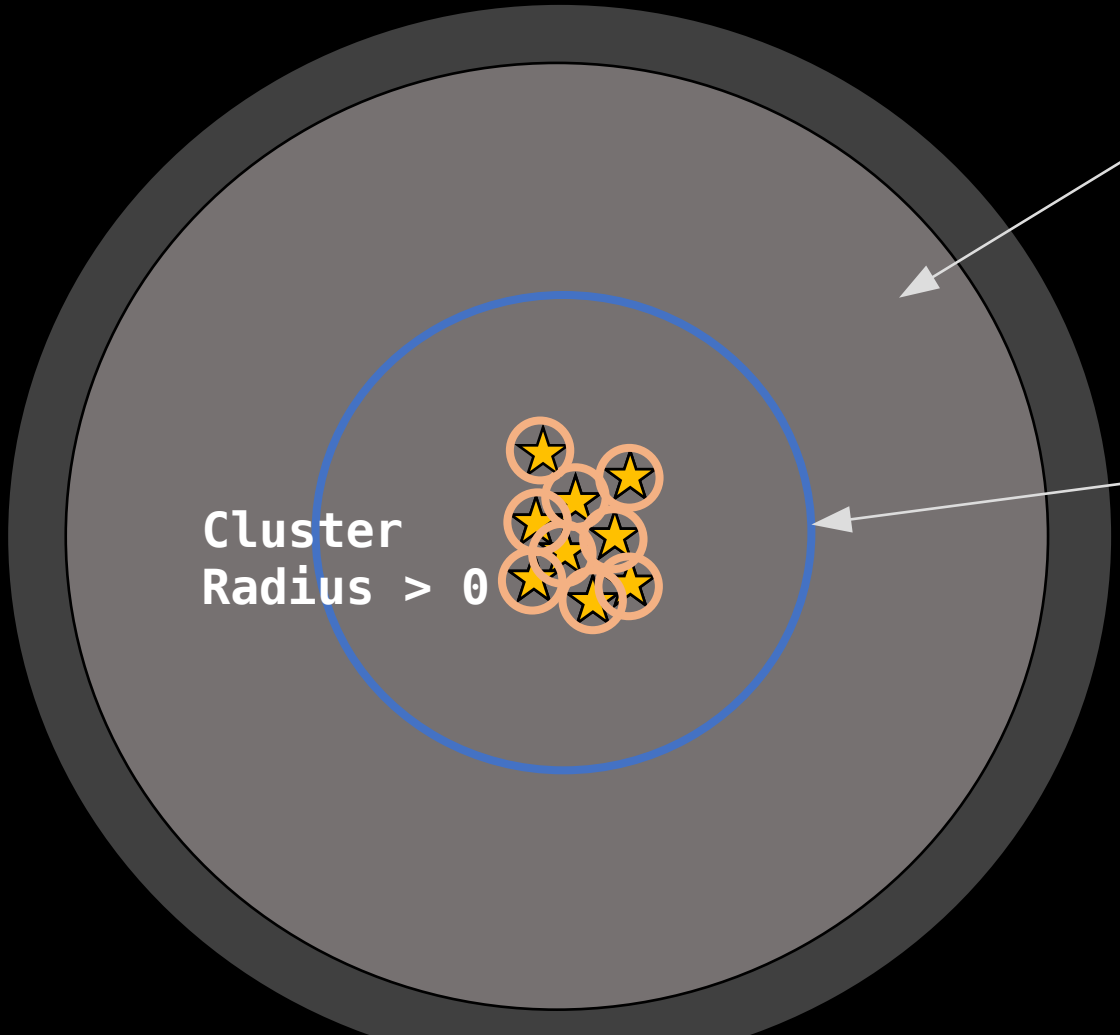


Expanding superbubble heated by the cluster

Wind termination shock (reverse shock)

Spherical cows are nice and simple...

Superbubble and wind termination shock: textbook



Expanding superbubble heated by the cluster

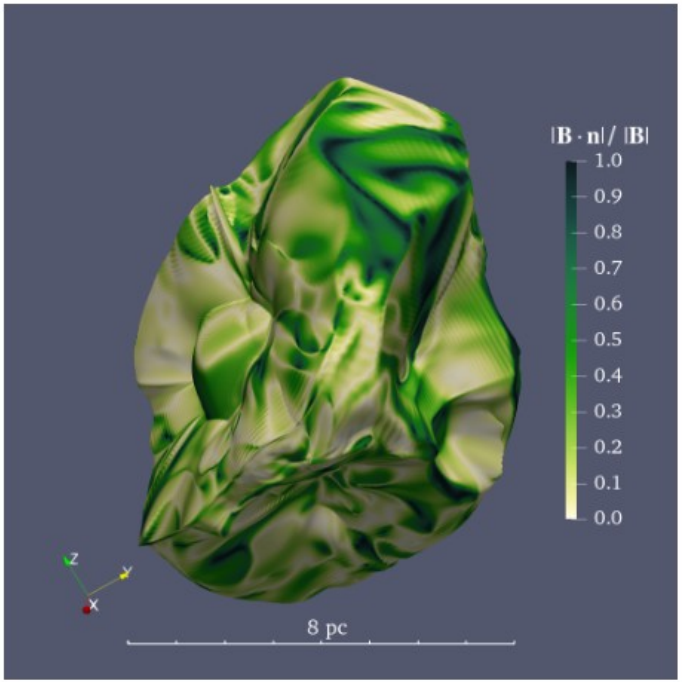
Wind termination shock (reverse shock)

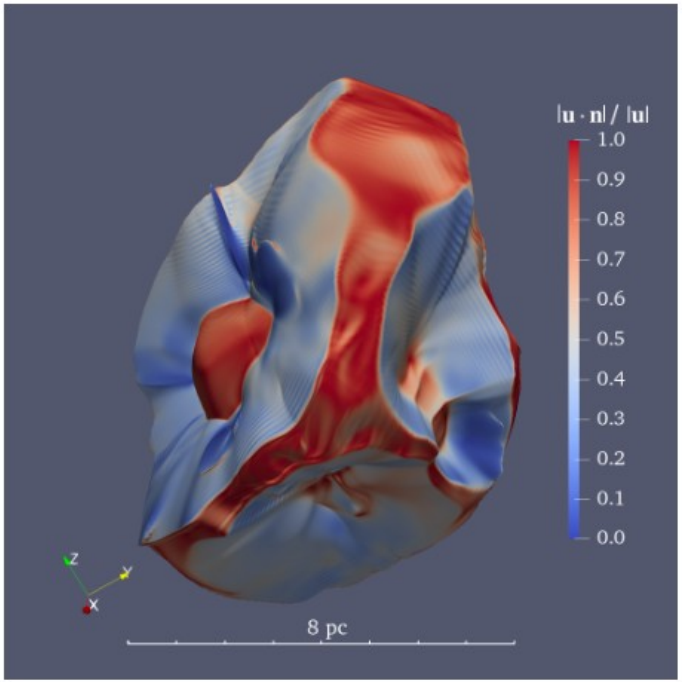
Spherical cows are nice and simple…

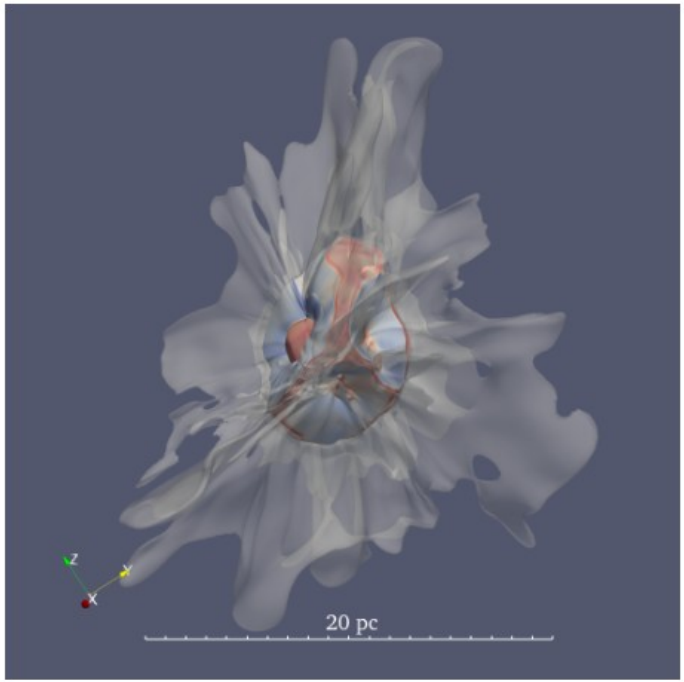
… but reality is more complex.

Superbubble and cluster wind termination shock: simulations

Härer, Vieu, Reville, A&A, 2025
Core radius = 0.6 pc







(a) $M_S = 3$, visualising the cluster-wind termination shock.

(b) $M_S = 1$, visualising transonic sheets.

Very asymmetric termination shock after 400 kyr of evolution!

Superbubble and cluster wind termination shock: simulations

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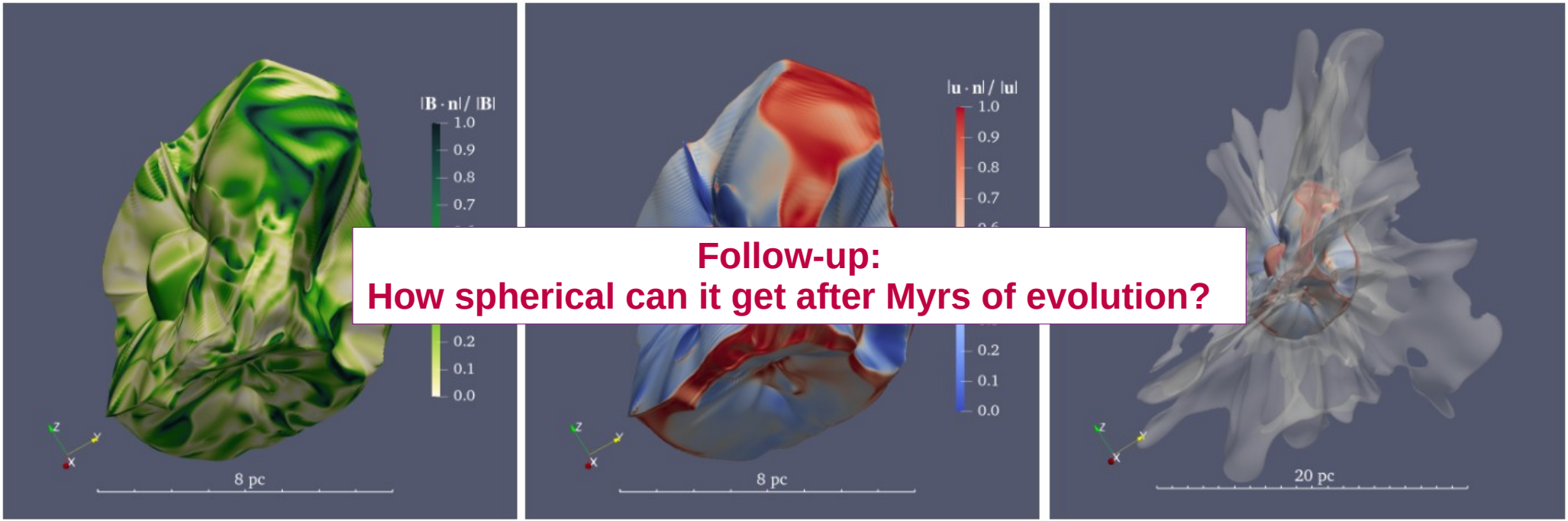


Follow-up:
How spherical can it get after Myrs of evolution?

(a) $M_S = 3$, visualising the cluster-wind termination shock.

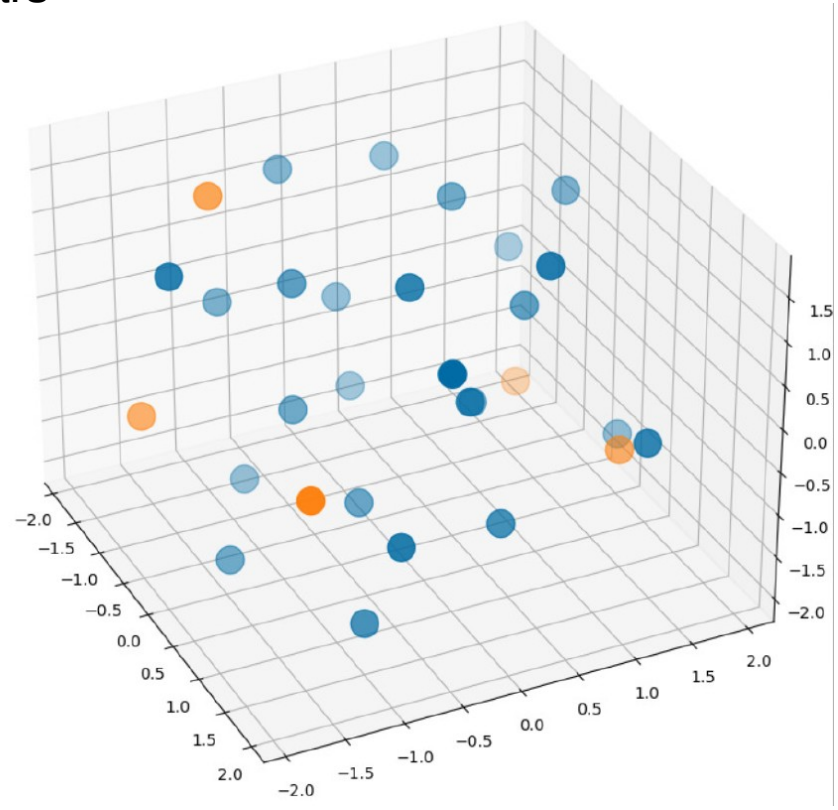
(b) $M_S = 1$, visualising transonic sheets.

Very asymmetric termination shock after 400 kyr of evolution!

MHD Simulations: setup

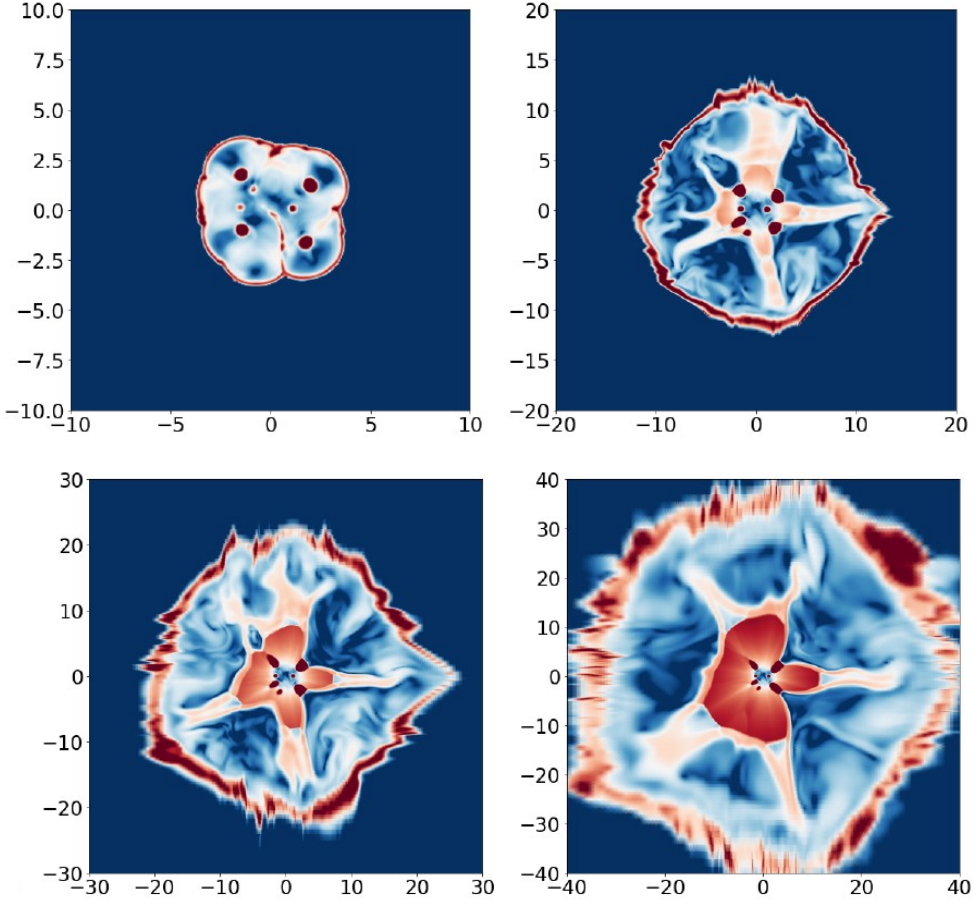
Ideal MHD + cooling with PLUTO code

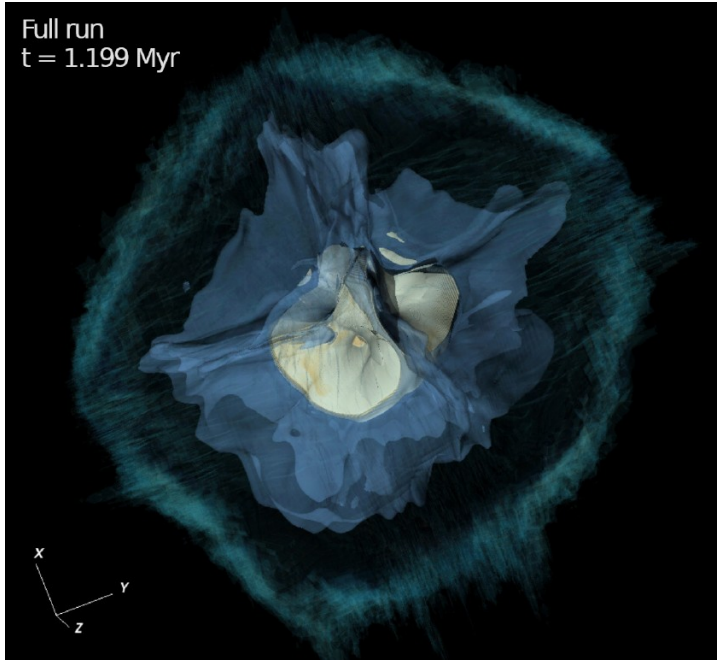
- Resolve individual stellar winds of 30 identical stars
  Mdot = 3e-6 $M_\odot$/yr, V_{wind} = 2500 km/s
- Homogeneous distribution in the cluster core
  core radius = 2.5 pc
- Parker spiral B-fields
  surface field: 100 G
- Toy cluster: no stellar evolution
  see Härer, Vieu, Reville, A&A, 2025 for a more realistic cluster



MHD Simulations: early evolution (< 1 Myr)

Mach number slices showing the development of stellar wind interactions
Dark red = strongly supersonic, **light red = transsonic**, **blue = subsonic**





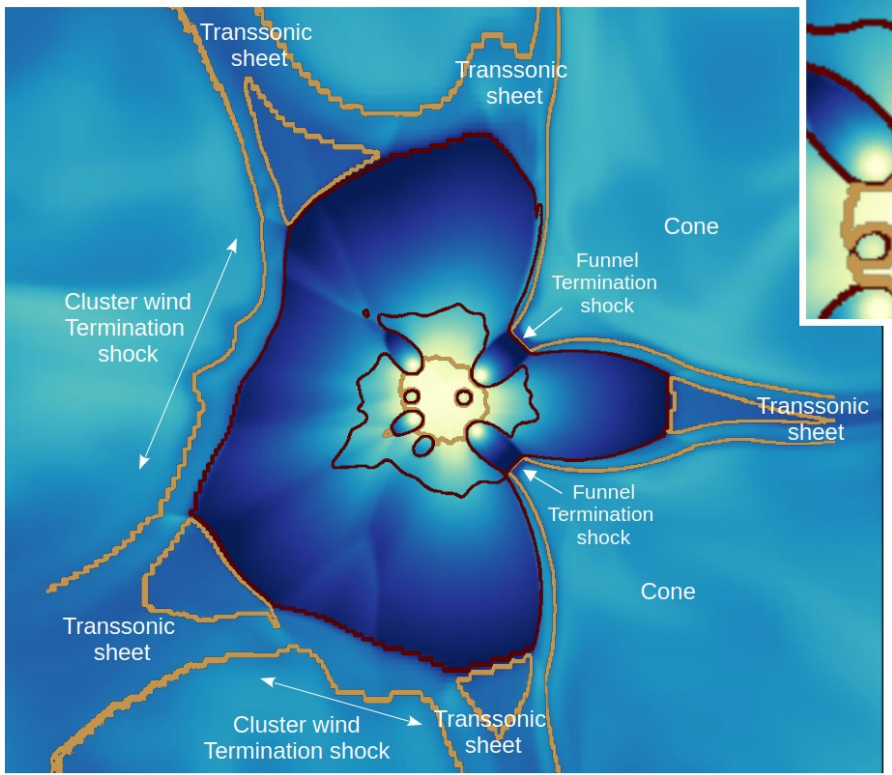
Edge stars block the expansion of the cluster wind and hinder the development of the spherical solution
=> very aspherical termination front at 1 Myr!

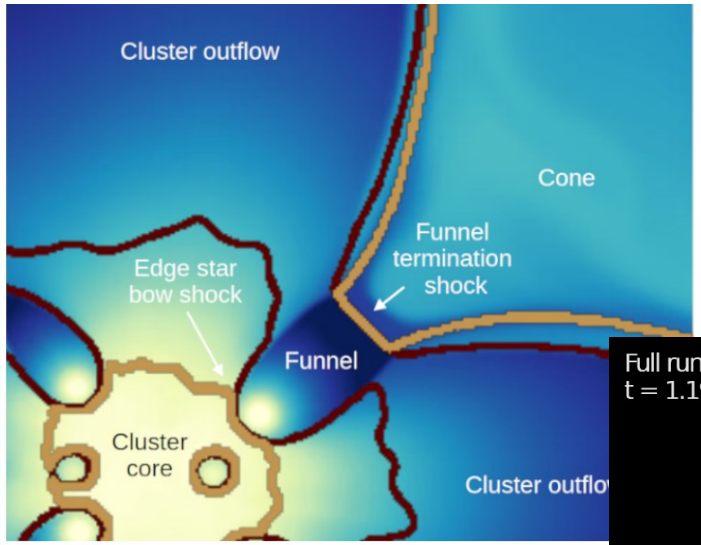
MHD Simulations: solution at 1 Myr

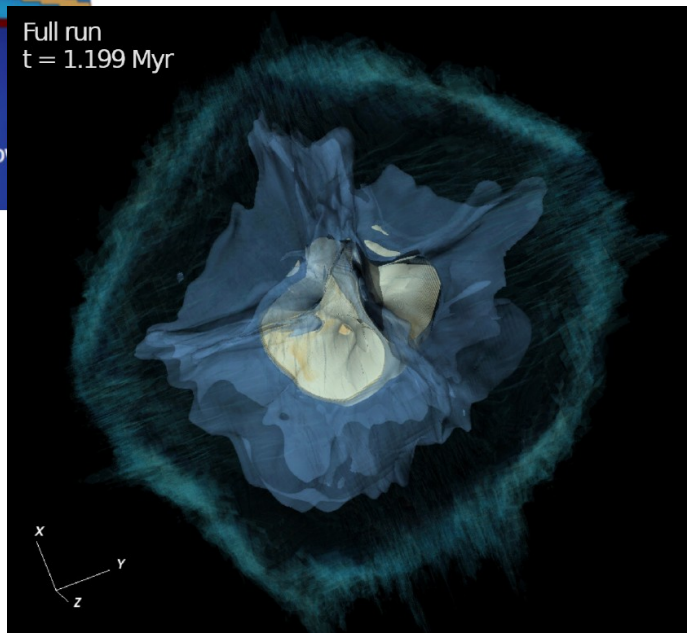
Structure of the cluster outflow and cluster termination front

Strong supersonic contour (Ms = 3)

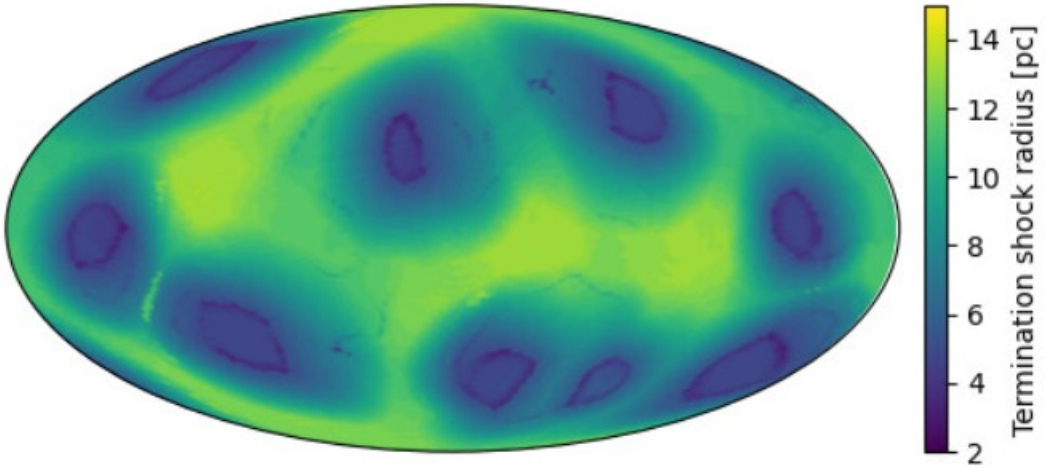
Transsonic contour (Ms = 1)

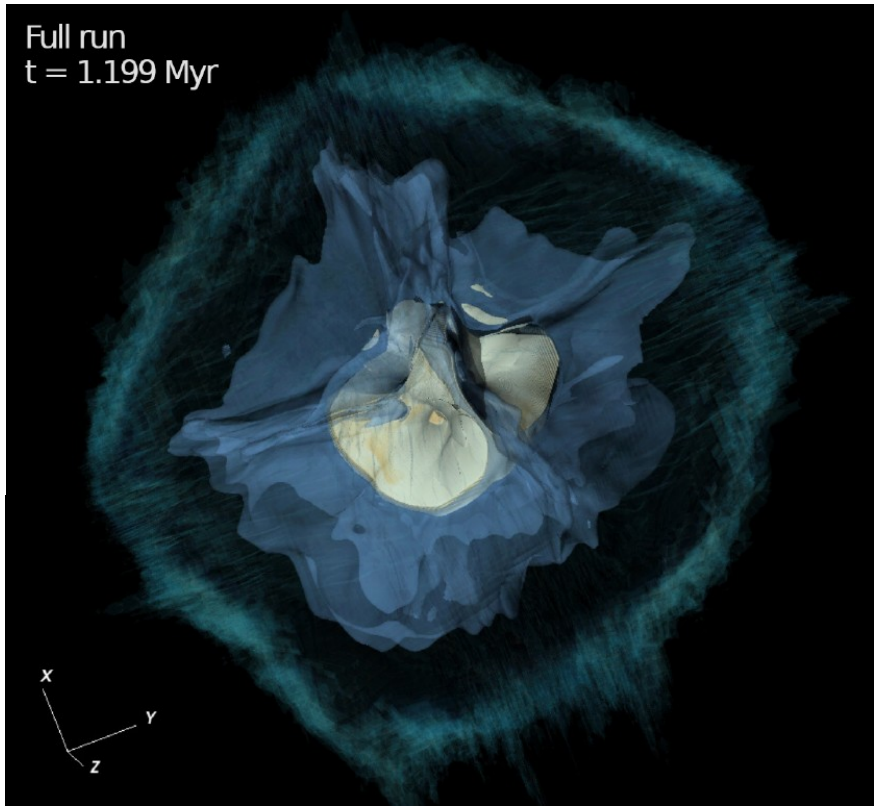






MHD Simulations: cluster wind termination shock at 1 Myr





=> very inhomogeneous

=> not spherical at all

=> edge star winds are still coupled to the flow

MHD Simulations across Myr timescales: superbubble ansatz

Question:

can we obtain a fully decoupled, reasonably spherical, cluster termination front if we increase the simulation time or setup a more compact core?

Issue:

would take weeks to obtain the solution at Myrs

MHD Simulations across Myr timescales: superbubble ansatz

Question:

can we obtain a fully decoupled, reasonably spherical, cluster termination front if we increase the simulation time or setup a more compact core?

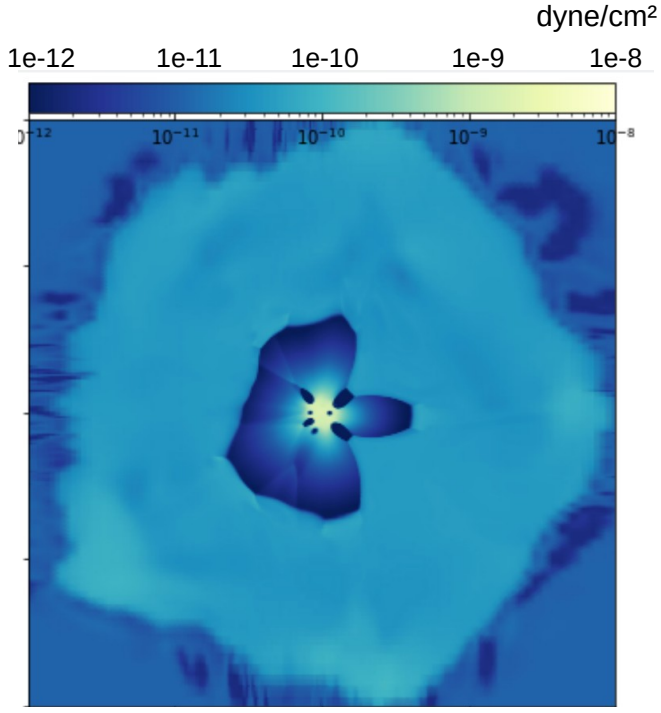
Issue:

would take weeks to obtain the solution at Myrs

Solution: start with a “superbubble ansatz”!

=> the expansion of the termination front should only depend on the superbubble pressure

=> the superbubble pressure is very uniform



The pressure is always very uniform inside the superbubble

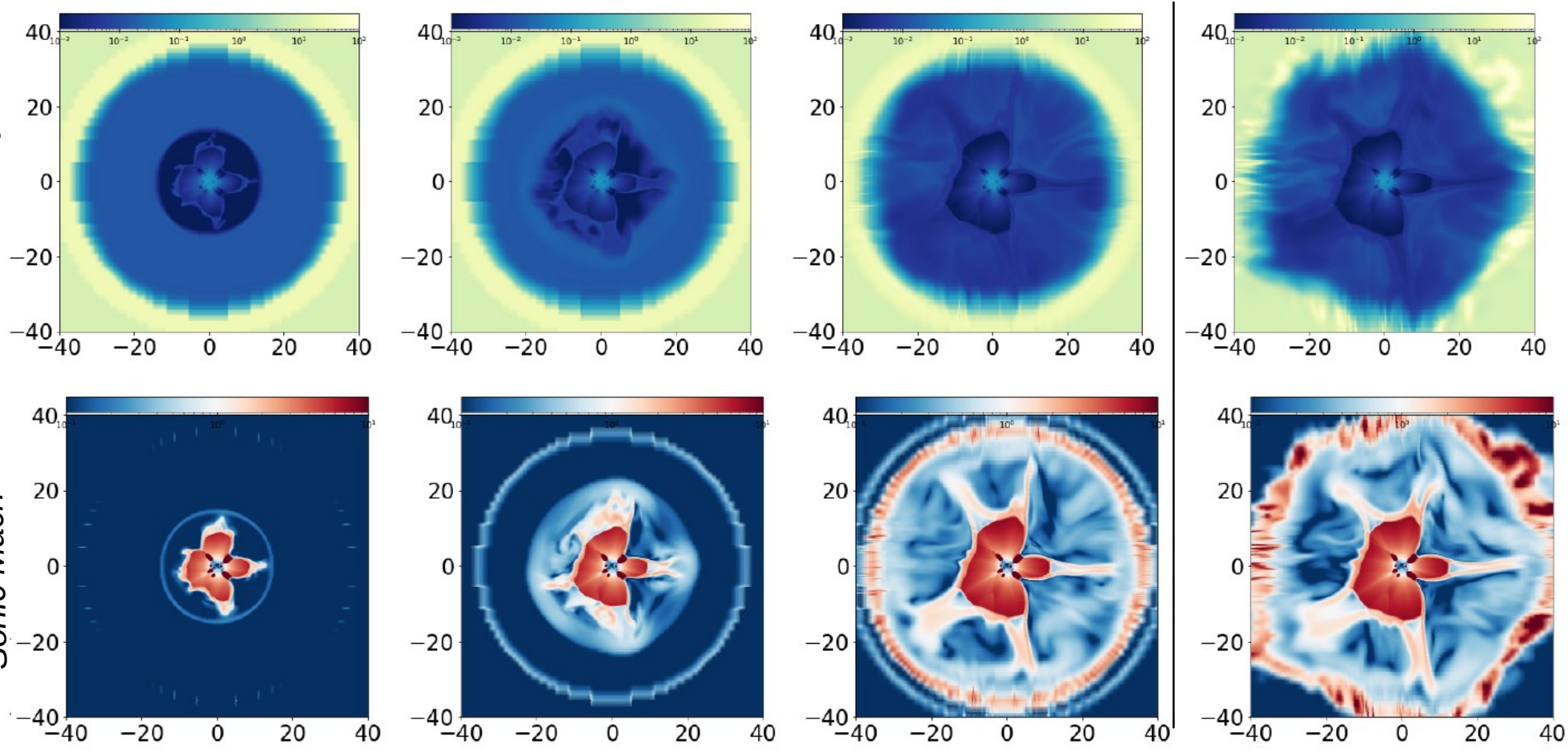
MHD Simulations across Myr timescales: superbubble ansatz

Starting from ansatz, evolve over 100 kyr…

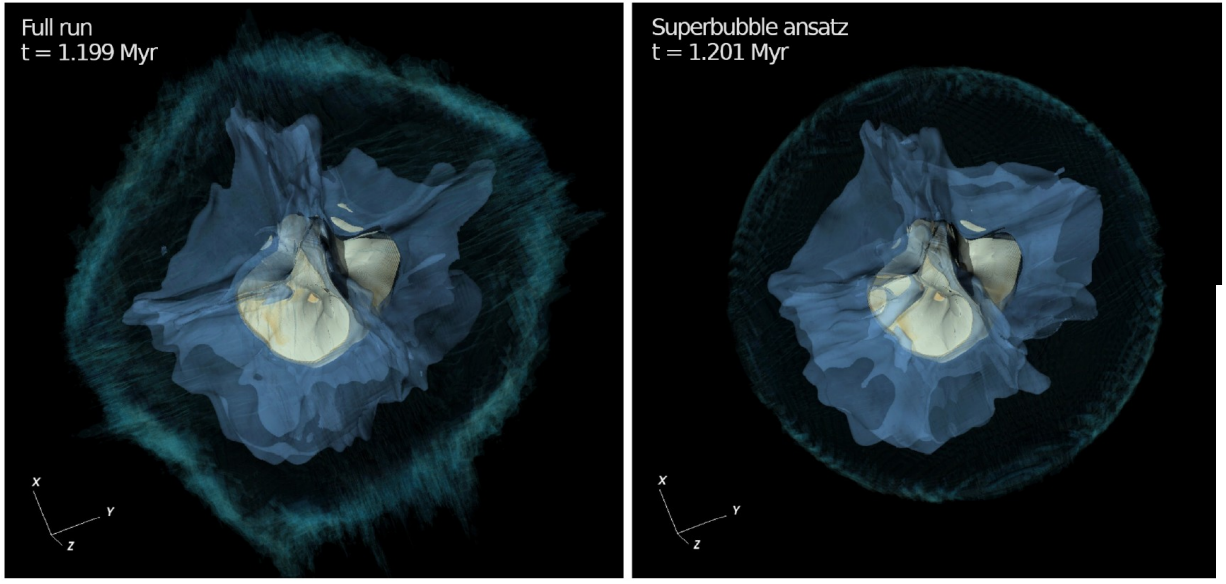
… and compare with full run

Density

Sonic Mach

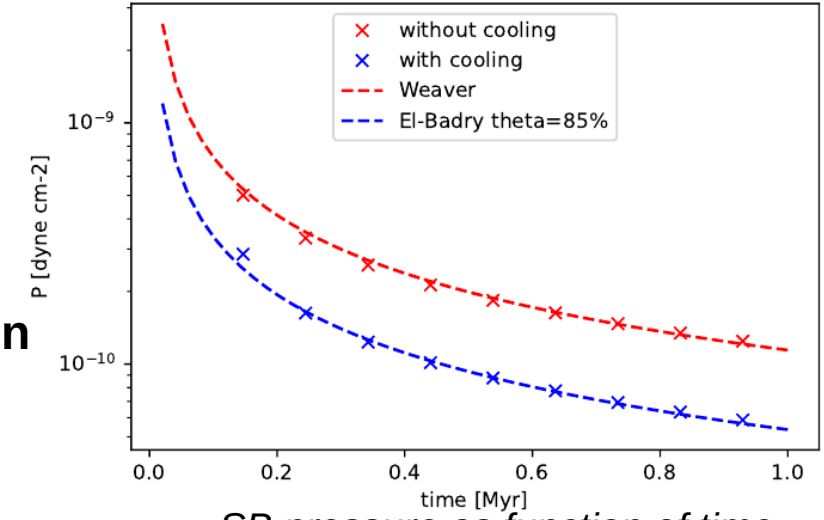


MHD Simulations across Myr timescales: superbubble ansatz



=> we can compute the shape of a cluster termination front for an arbitrary SB pressure

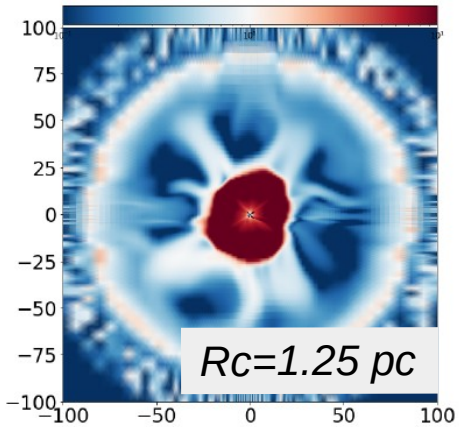
→ about 10x less expensive
→ shows that the past activity of the cluster is irrelevant
→ no need to include prior stellar evolution

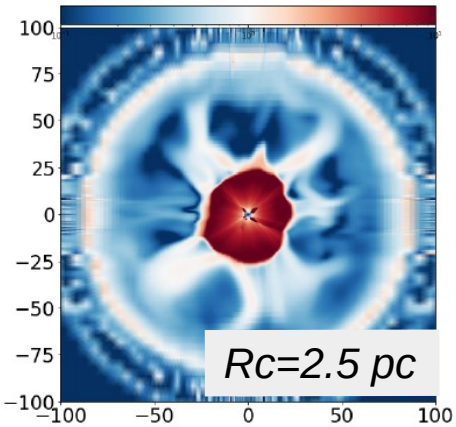


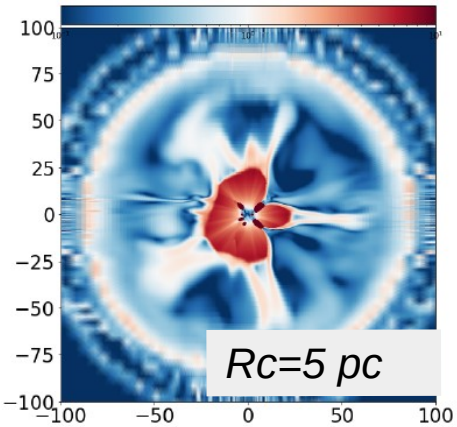
SB pressure as function of time

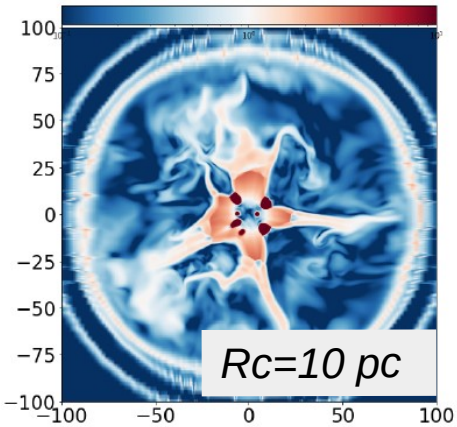
MHD Simulations at 5 Myr varying cluster compactness

30 stars

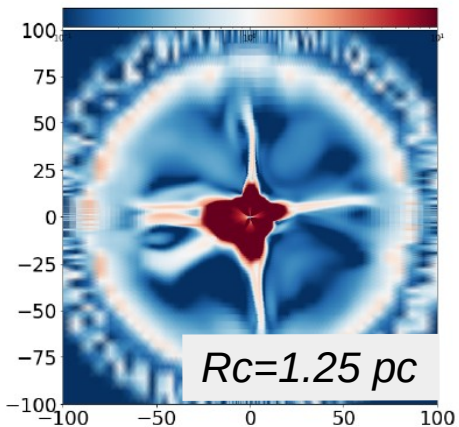


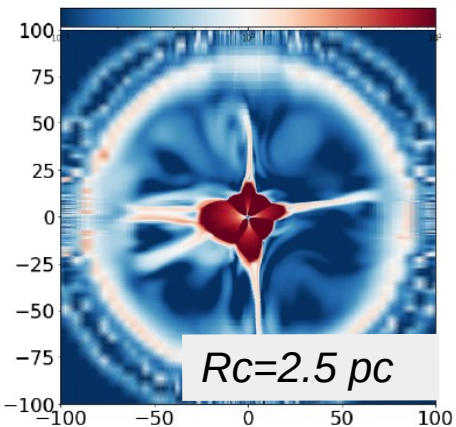


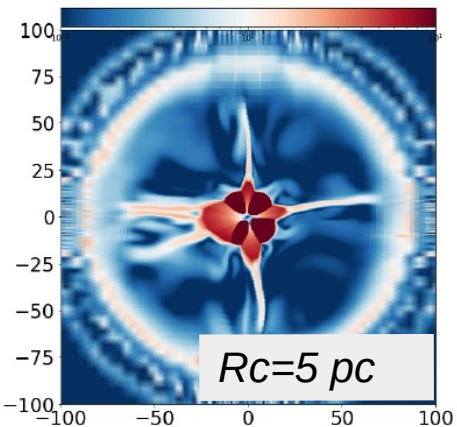


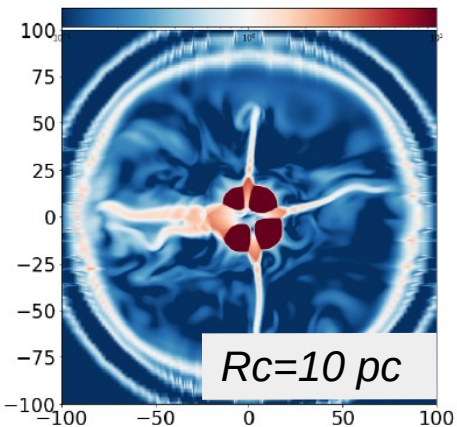


5 stars

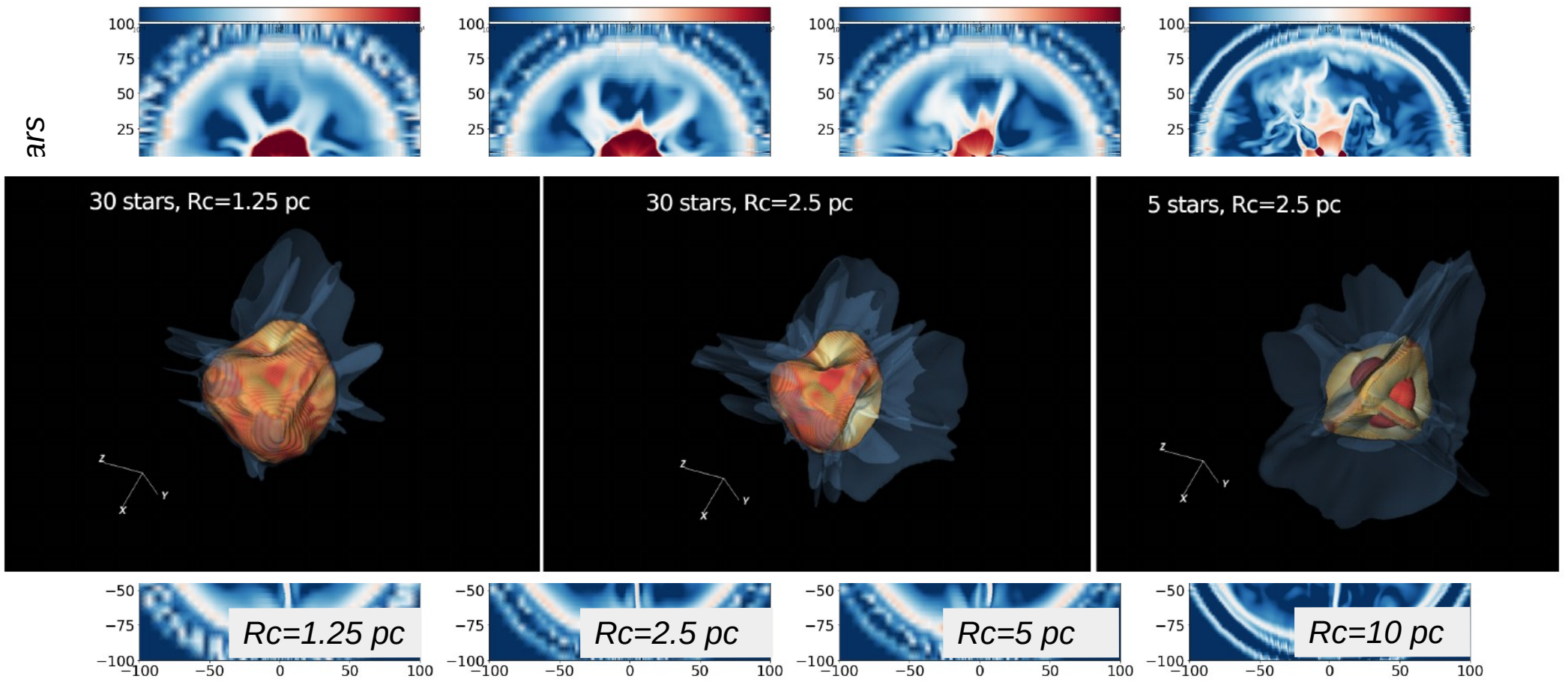








MHD Simulations at 5 Myr varying cluster compactness



Summary

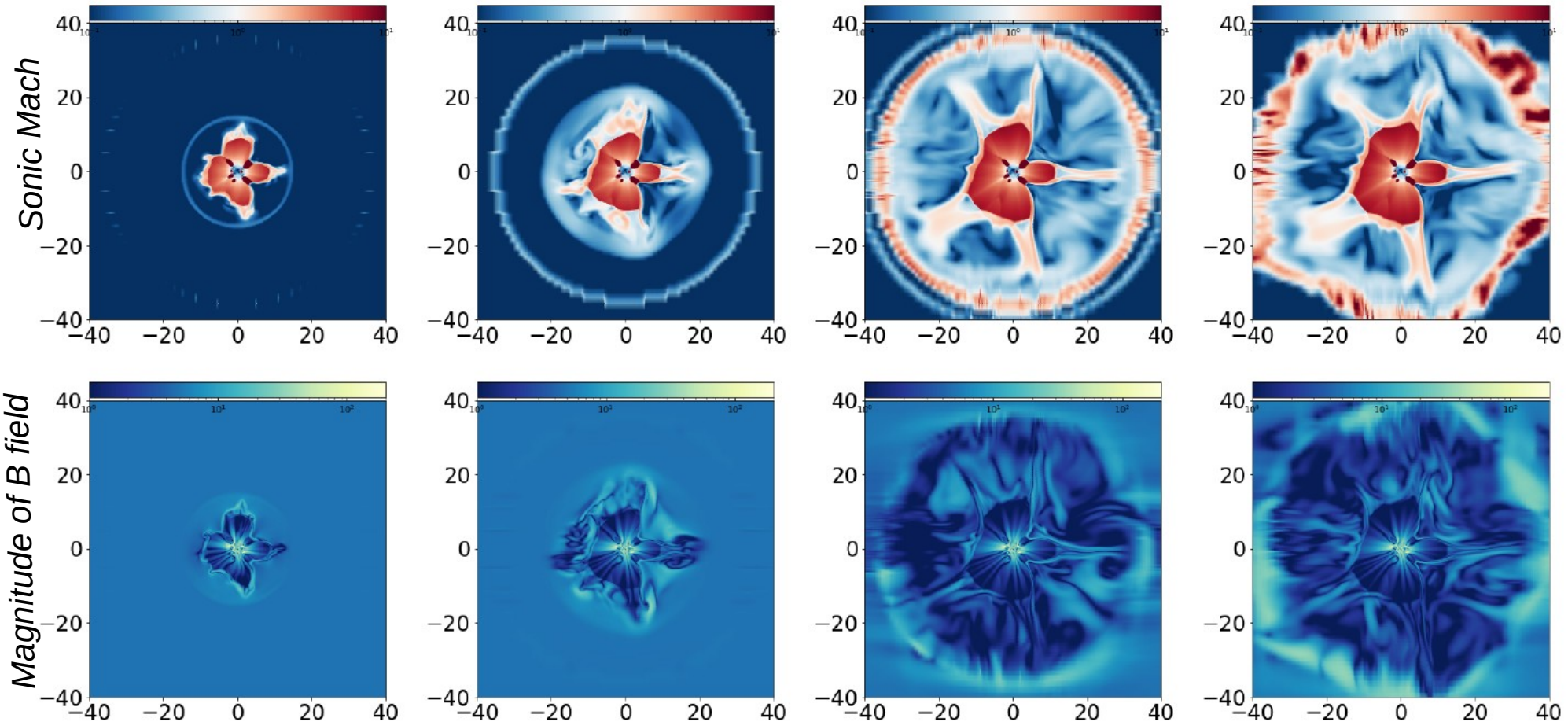
- A cluster cannot be modelled as a continuous deposition of thermal energy: **kinetics of individual wind-wind interactions is key!**
- These interactions generically produce **highly asymmetric outflows**
- Important consequences for DSA at the cluster wind termination shock: **reduced acceleration efficiency & maximum energy.**
- Non spherical => **morphology of extended gamma-ray emission** is key!

Back-up

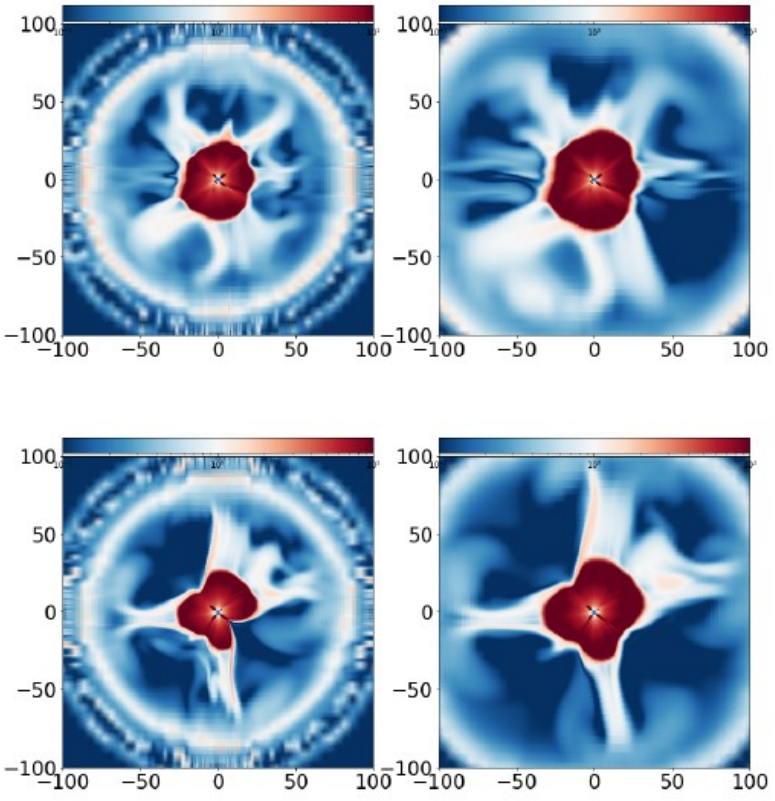
MHD Simulations across Myr timescales: superbubble ansatz

Starting from ansatz, evolve over 100 kyr…

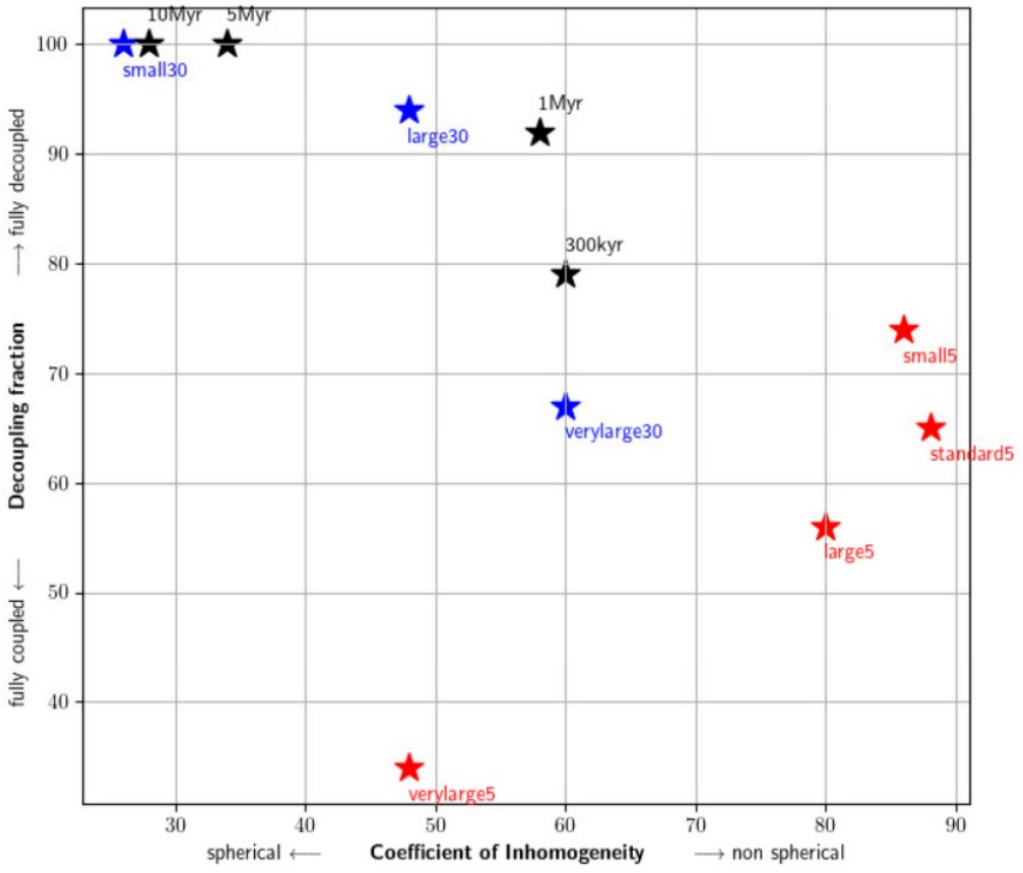
… and compare with full run

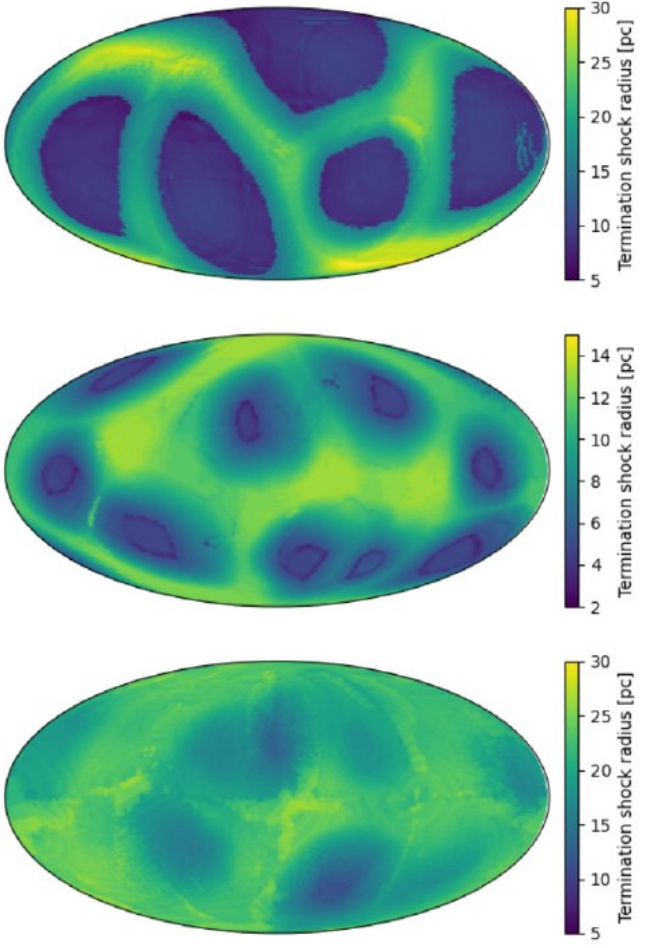


MHD Simulations across Myr timescales: older clusters

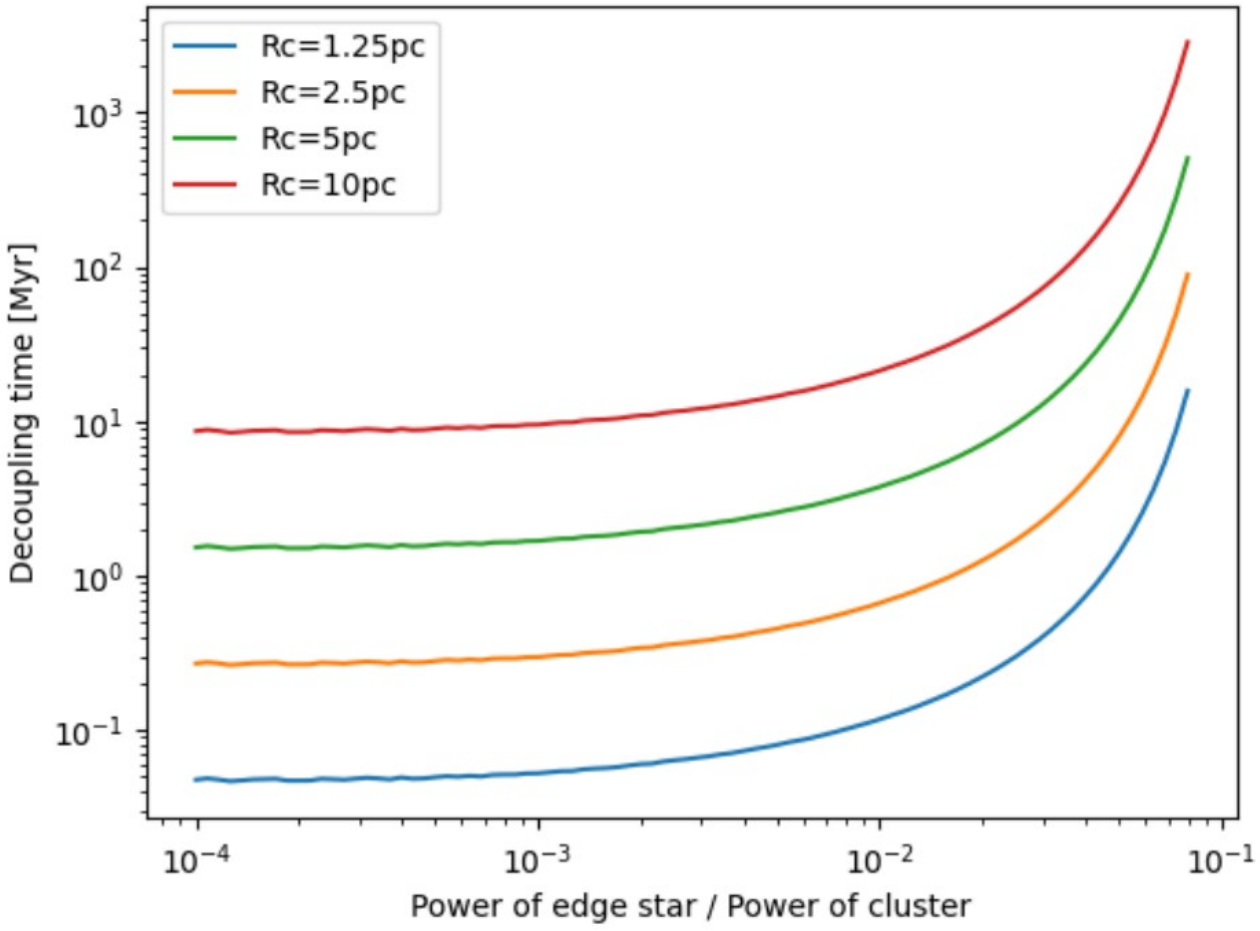


MHD Simulations across Myr timescales





Semi-analytic solution for the decoupling time



This model also applies to a cluster with an IMF.

=> even for very compact clusters, if the edge star is too powerful, it will never decouple within any reasonable time