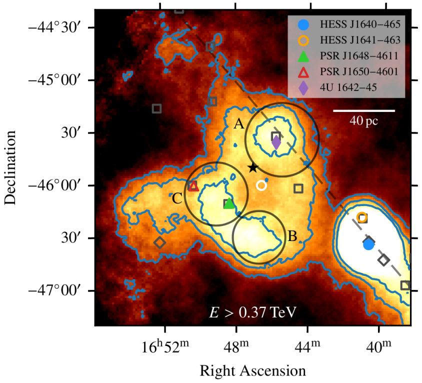
Stellar wind interaction around young star clusters: 3D MHD simulations

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

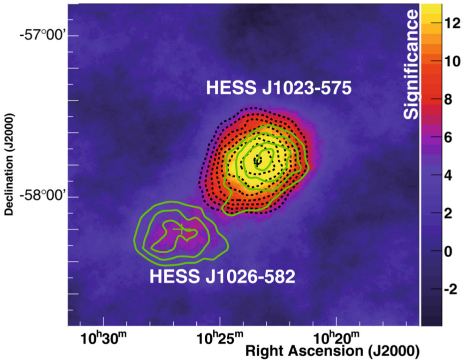
October 29, 2024
TOSCA, Siena

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

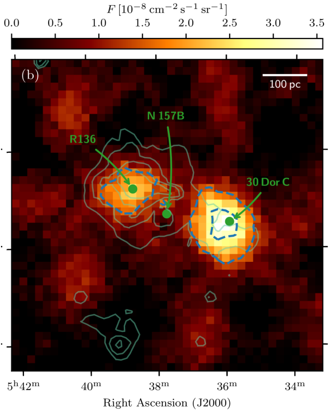
Young star clusters are gamma-ray sources!



Westerlund 1
H.E.S.S. 2023

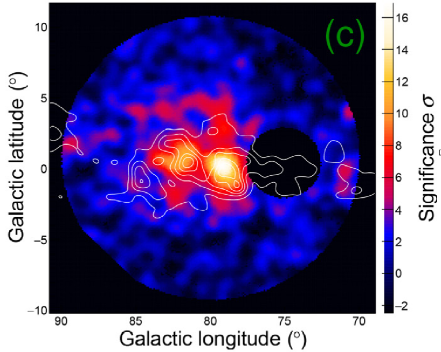


Westerlund 2
H.E.S.S. 2011

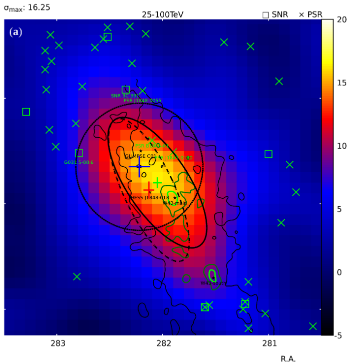


R136, 30 Dor C
H.E.S.S. 2024

>100 TeV



Cygnus SFR
LHAASO 2024

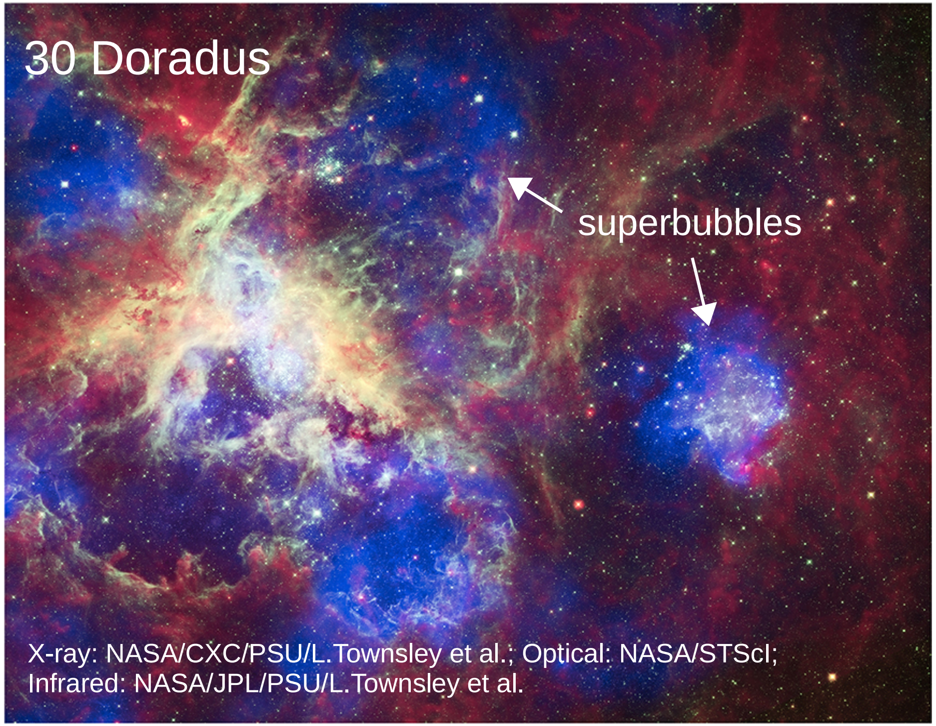


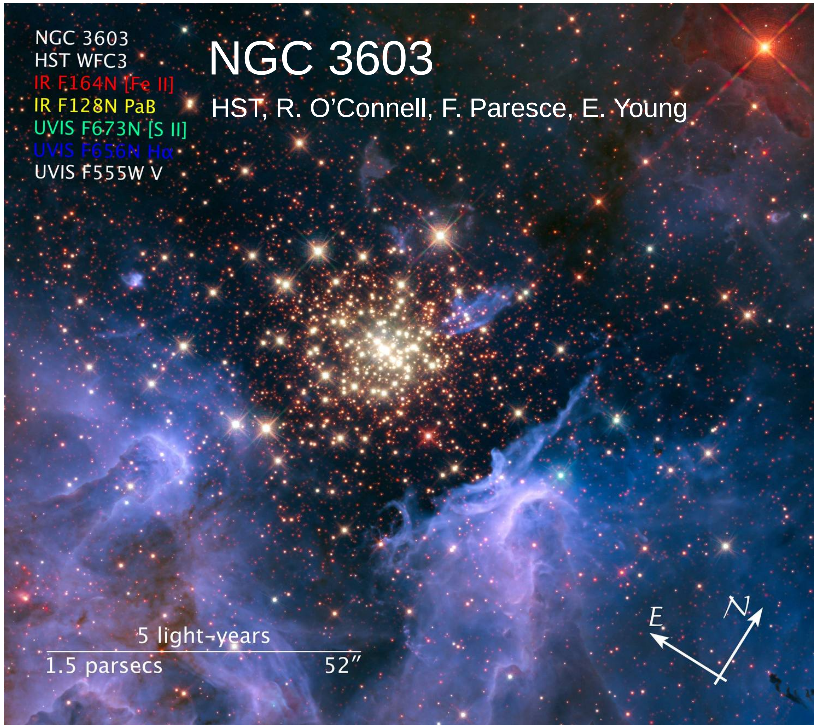
W43
LHAASO 2024

How are particles accelerated? How do they propagate?

Emission extends over *<u>~10-100 pc!</u>* ⟶ Comes from *<u>surroundings</u>* of star clusters.

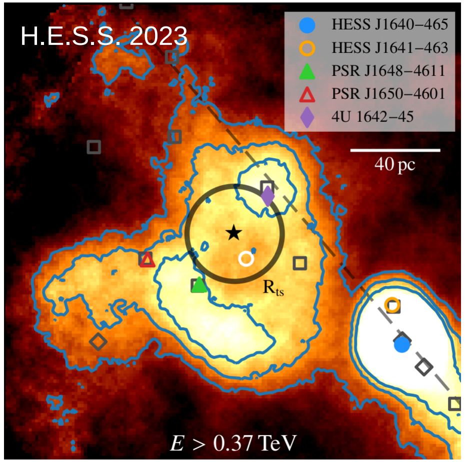
Star Cluster Environments





- *<u>Complicated regions</u>*, shaped by *<u>stellar wind feedback</u>*.
- Highly *<u>diverse</u>*: ambient medium, cluster age, compactness, stellar content etc.

Westerlund 1



cluster wind
termination
shock

compact cluster

⟶ *cluster* wind termination shock (WTS)

Härer+23: preferred model:
leptonic (IC), acceleration at WTS

> *Hadronic model fails to predict morphology.*
> *Emission comes from **low density** region.*

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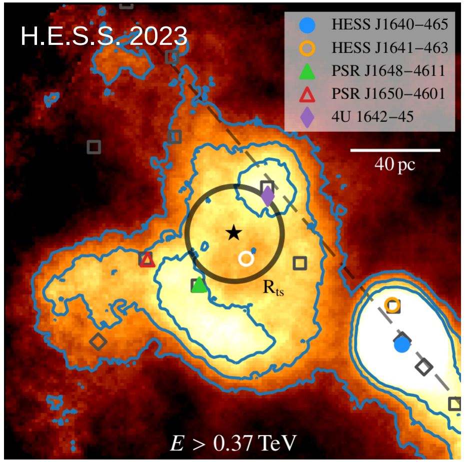

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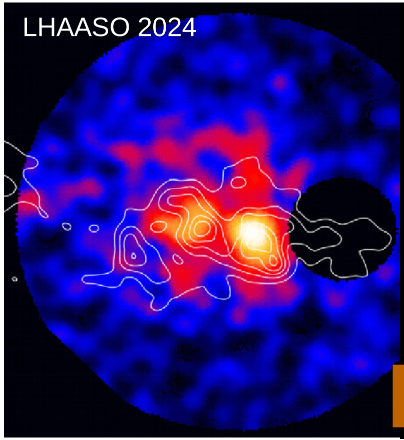
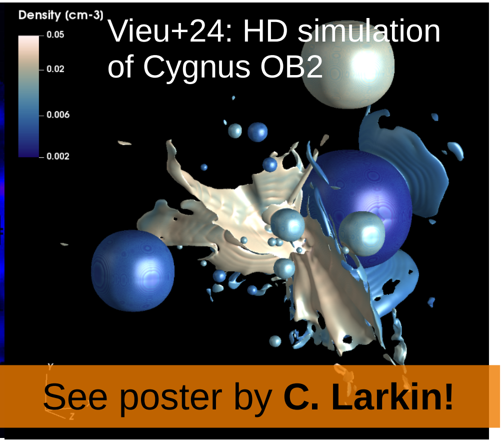
Cygnus OB2





loose cluster/association
⟶ *<u>individual</u>* termination shocks

photons >1 PeV!
⟶ hadronic (at UHE)

Particle Acceleration and Propagation

How to model these complicated and highly diverse regions?
Are criteria for efficient particle acceleration met?

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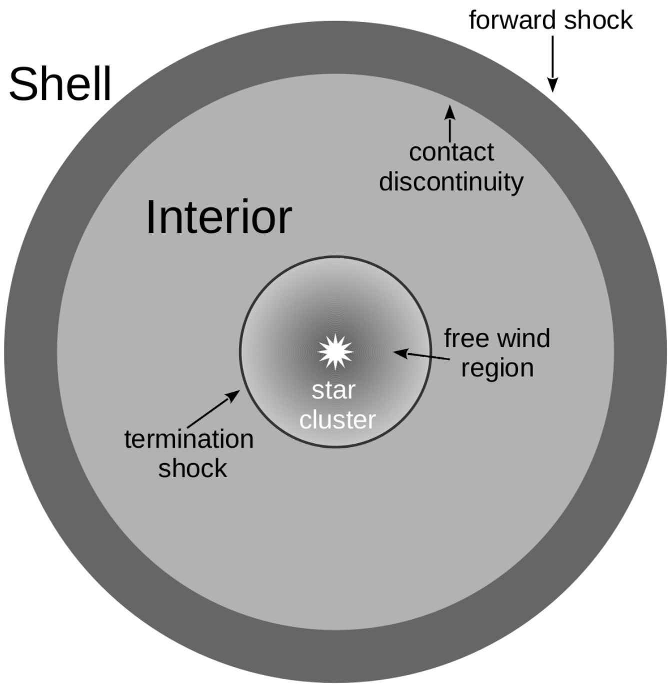
1D theory: single star



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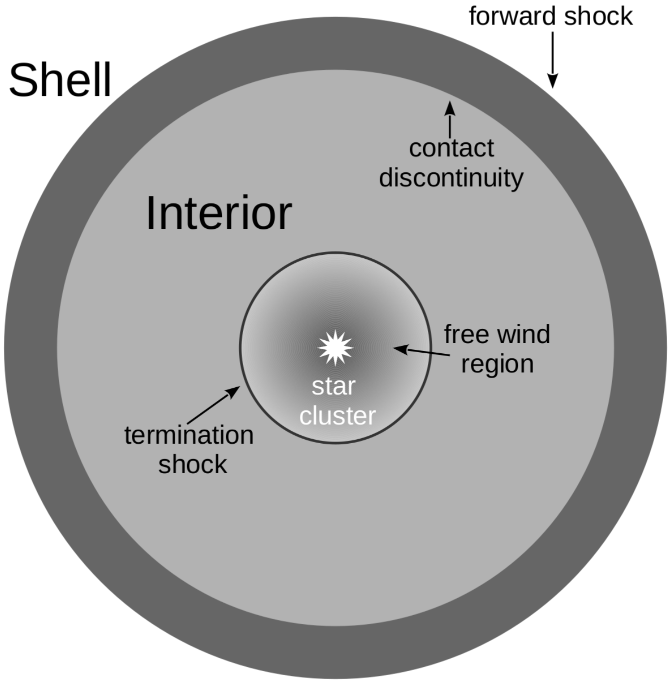
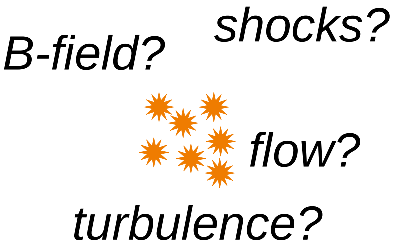


star cluster?



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

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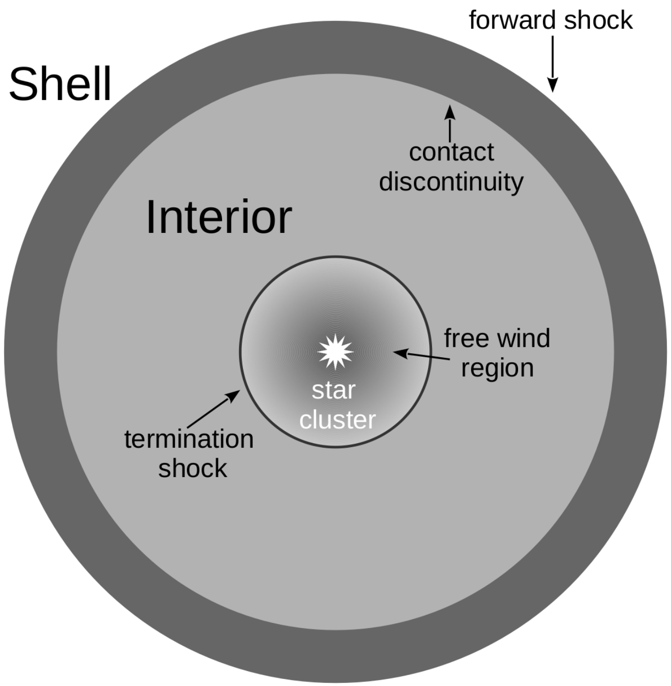

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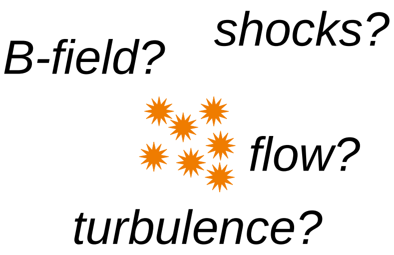


Perform 3D MHD simulations!

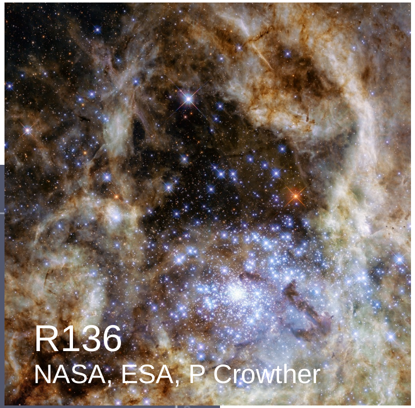
3D MHD Simulations of Young **Compact** Clusters

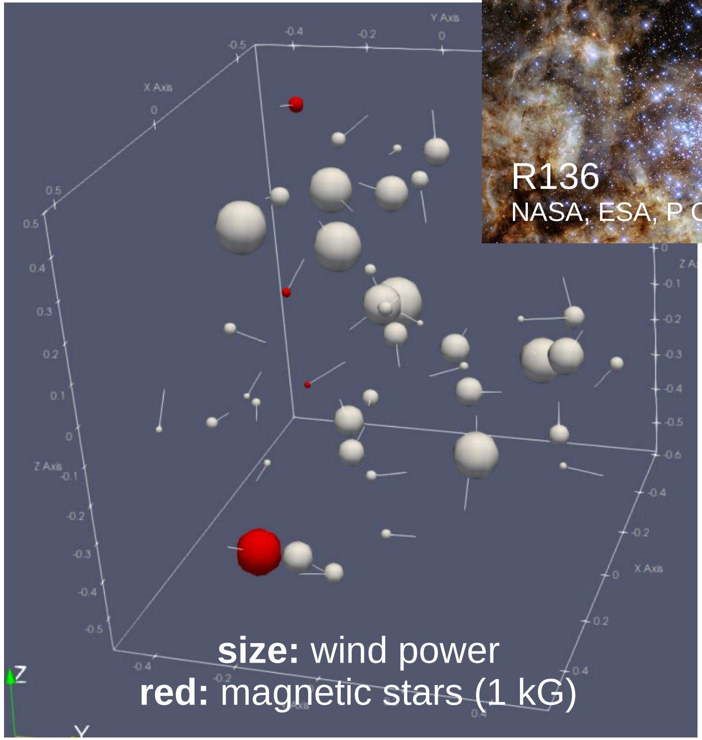
PLUTO code, ideal MHD module

radius < 2-3 pc

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

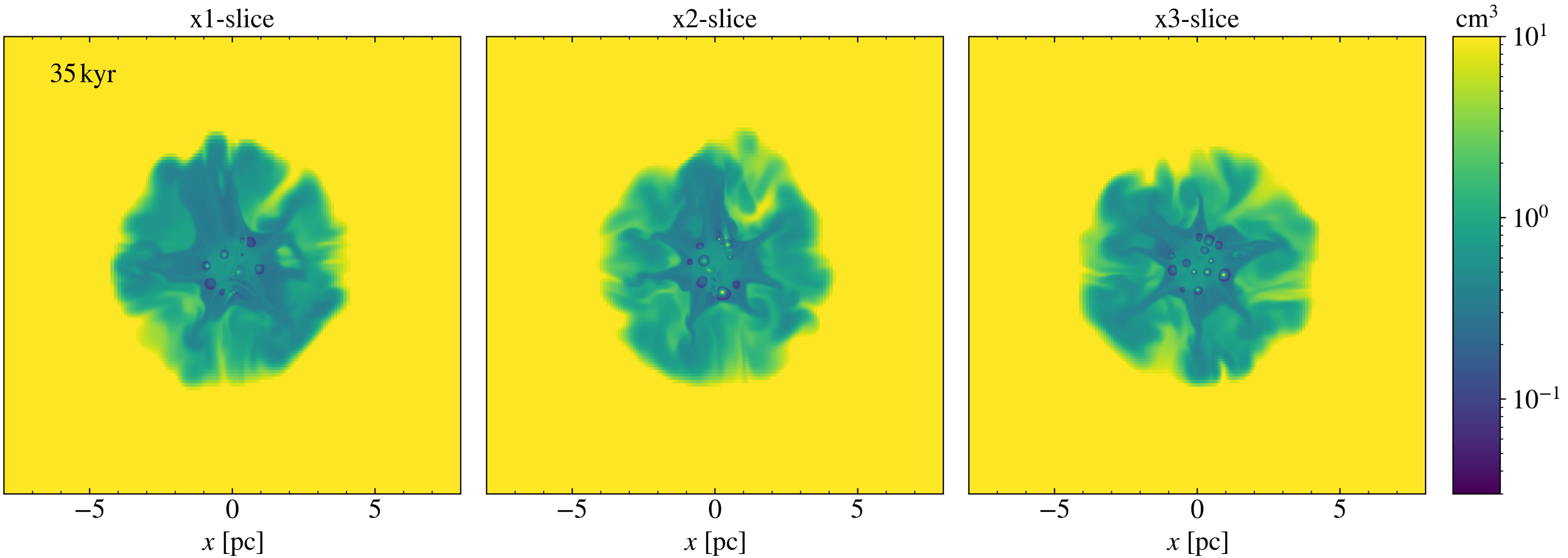
See also HD simulations by **T. Vieu!**



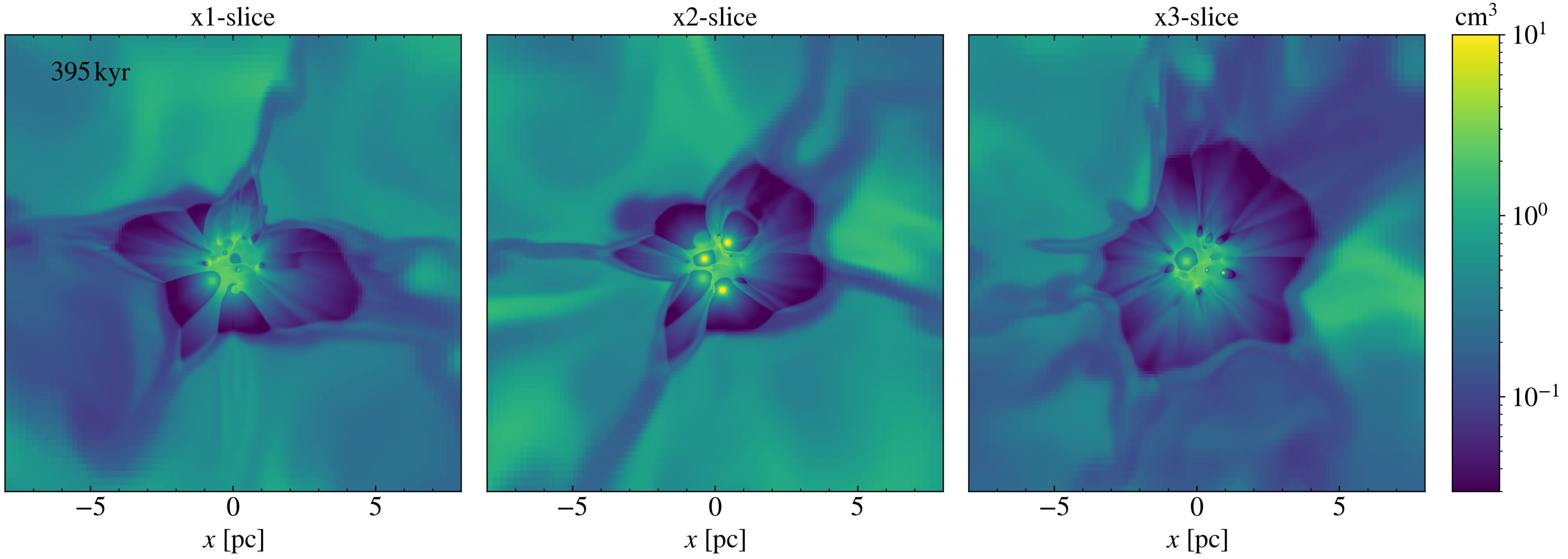


Density Slices

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



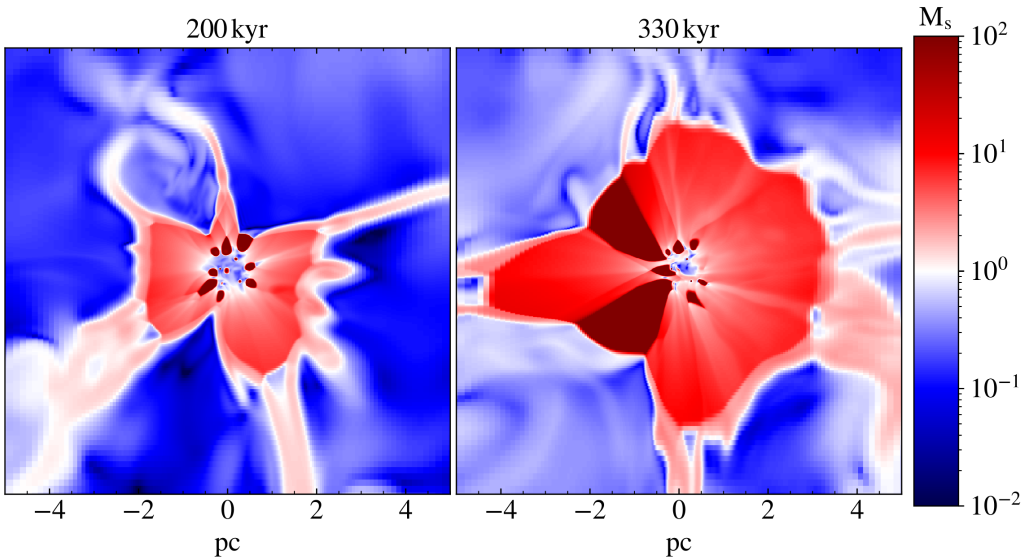
Wind Termination Shock



1. non-spherical,
non-uniform strength

2. sometimes dominated
by individual stellar WTS

Wind Termination Shock



3. WTS is strong ($M_S > 10$)
and super-Alfvénic

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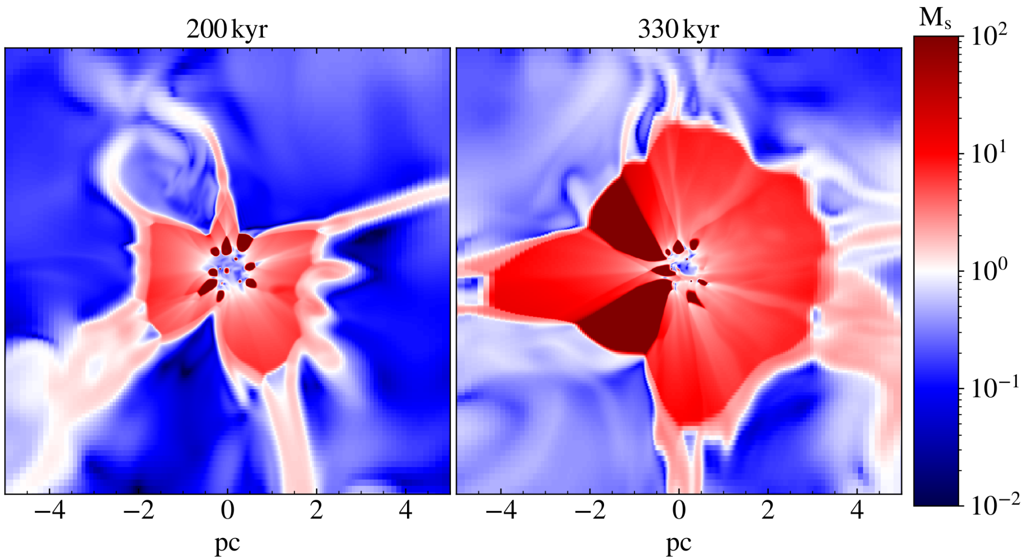

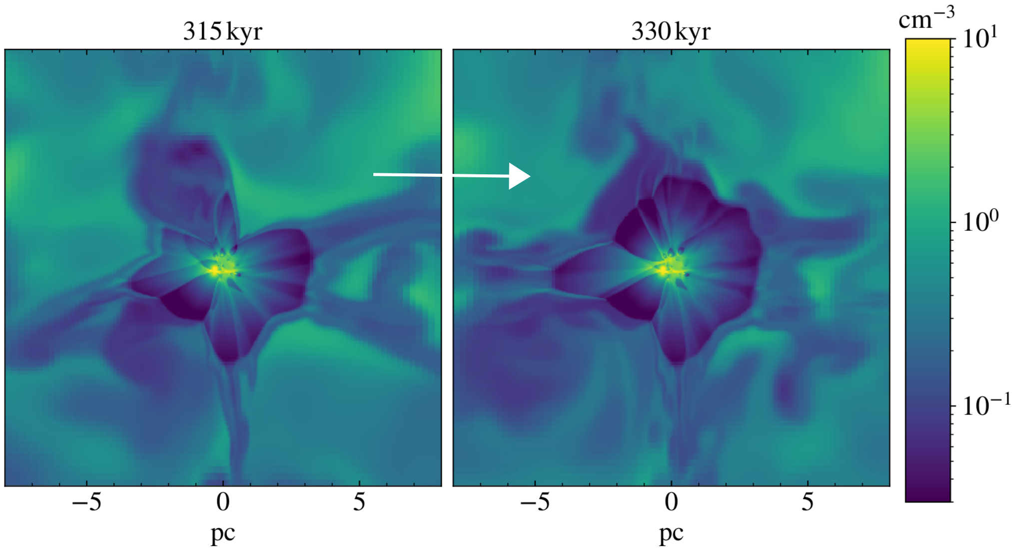

3. WTS is strong (M_S > 10)
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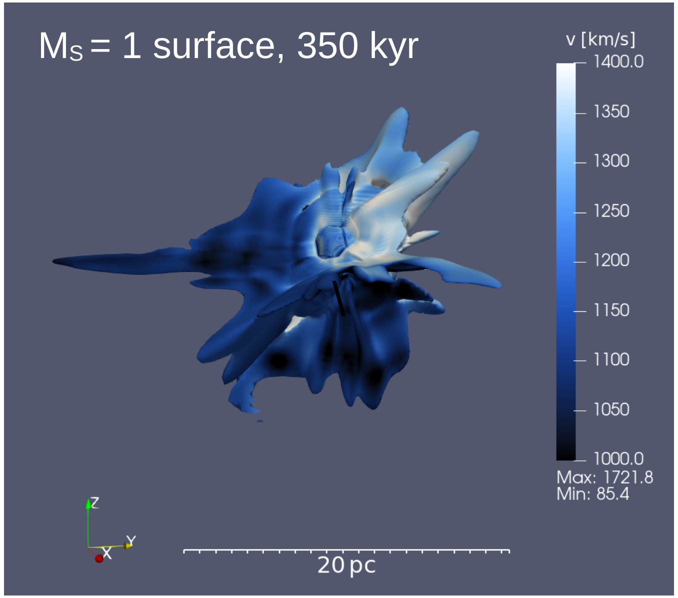
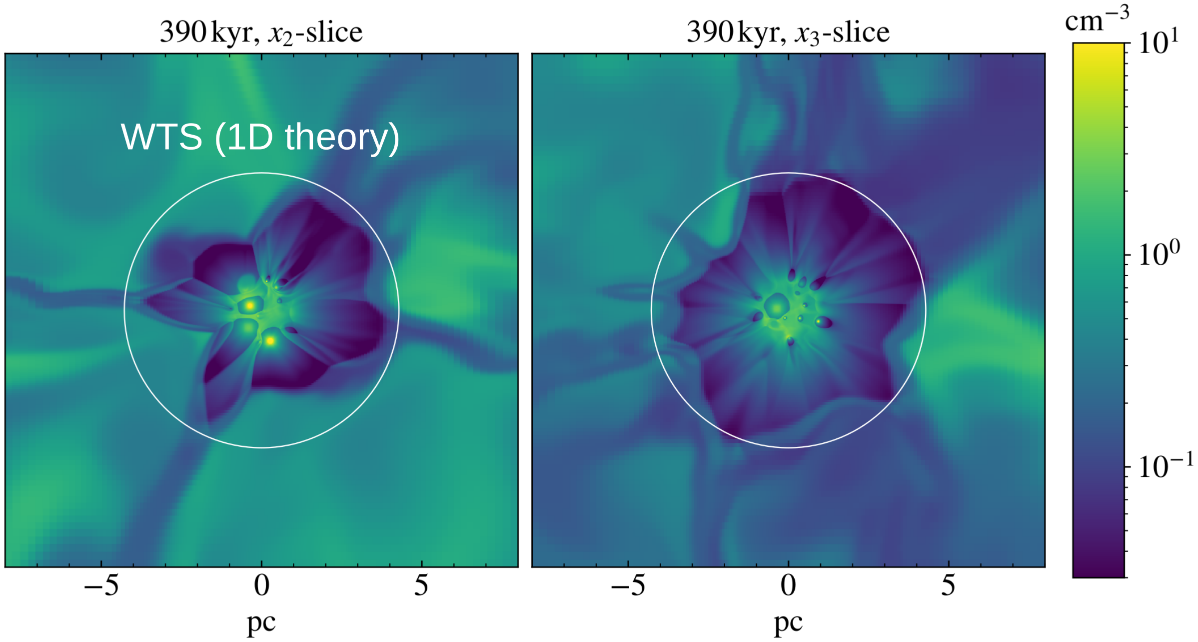
4. "decoupling" of individual winds:
WTS becomes more spherical

but: time-scales for decoupling can be long,
very strong winds might never decouple (WRs!)

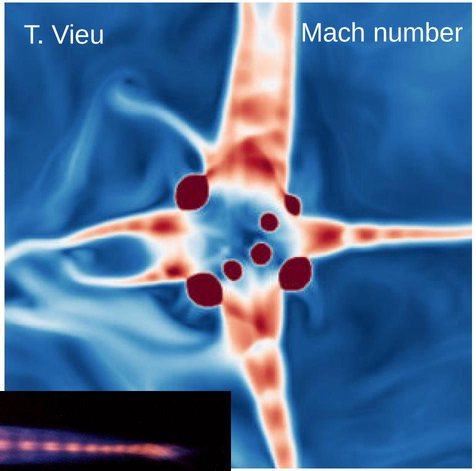
Wind Termination Shock

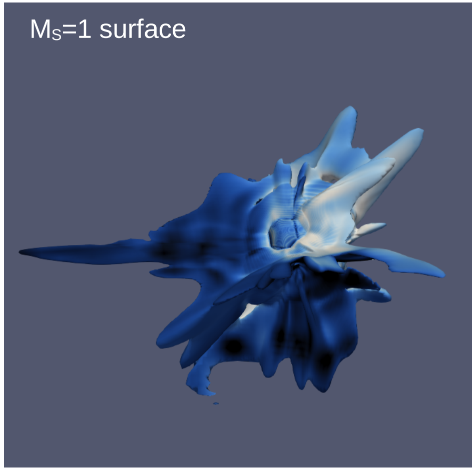


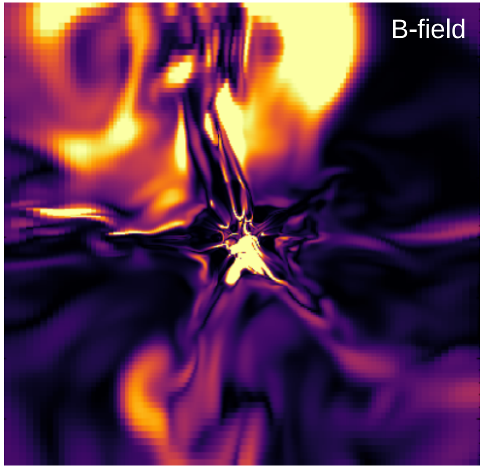


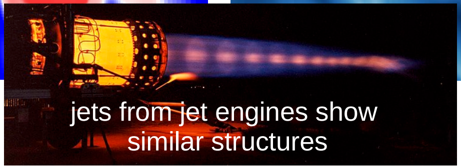
5. WTS volume smaller than predicted by 1D theory: *transonic streams*

Transonic Streams



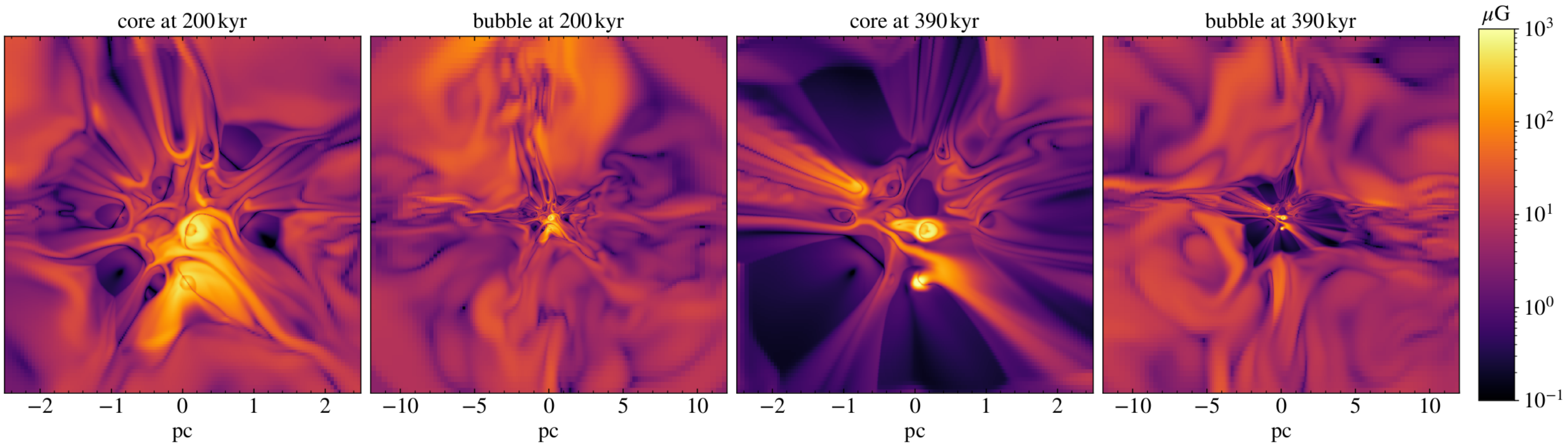






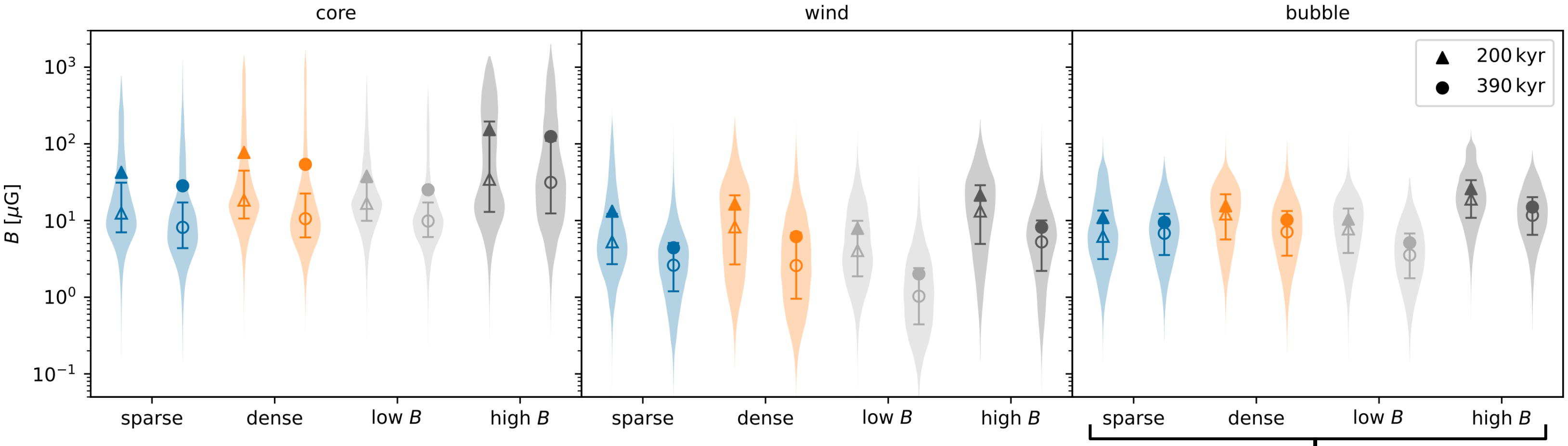
- collimated outflows with M_S~1-3, up to 10 pc long
- can have a strong shock at their base (WTS), consecutively weaker internal shocks
- get unstable at “tip” and mix with downstream medium
- B-field can be increased in vicinity

B-field Maps

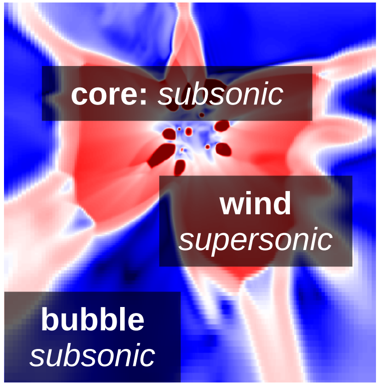


- highly non-uniform (is expected – 10% of stars with 1 kG, 90% with 10 G)
- |**B**| strongly depends on proximity to magnetic stars
- mixing of winds in WTS downstream leads to fewer extreme B-field values

B-field Average Values



3 regions



4 clusters

- sparse: radius 1 pc, 1 kG for 10% of stars
- dense: same stars as sparse but different spatial distribution and radius 0.6 pc
- low B: same as dense, but 100 G for 10% of stars
- high B: same again, 20% with 1 kG

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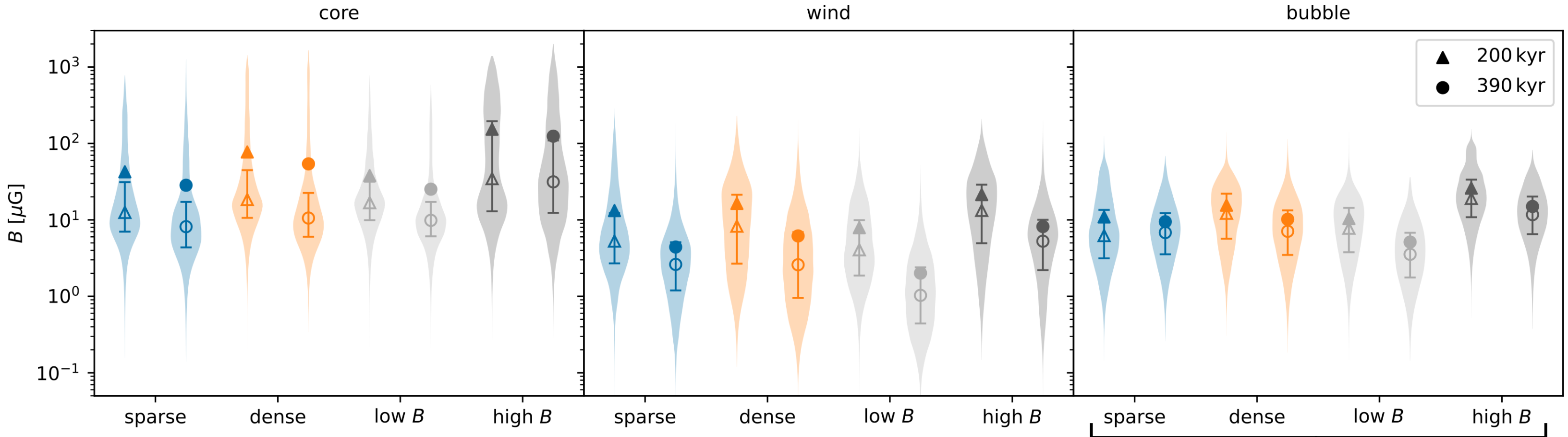

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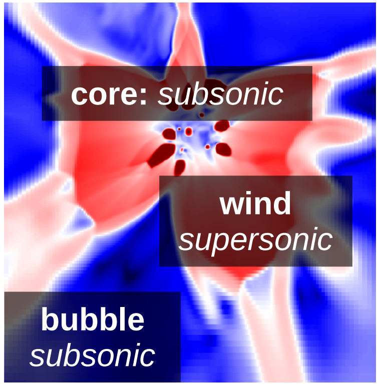

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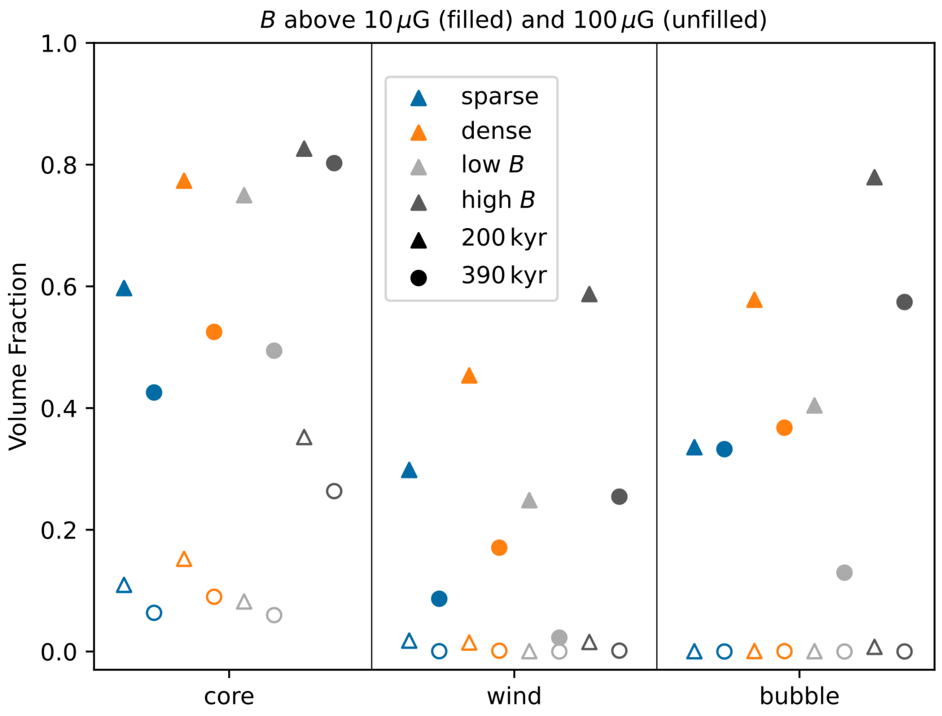
- large spread, dependence on compactness and stellar content
- on average: core 30-200 µG, wind 2-20 µG, bubble 5-20 µG
- but: superbubble not stationary ⟶ averages slowly drop

⟶ *difficult to constrain, 1 µG to a few 10s of µG are plausible in wind and bubble*

B-field Average Values



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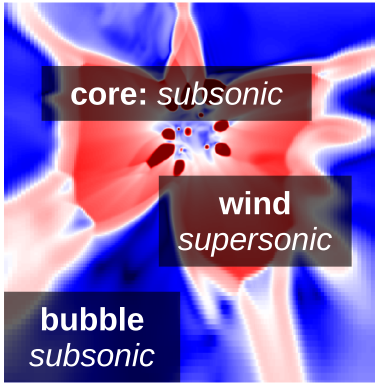

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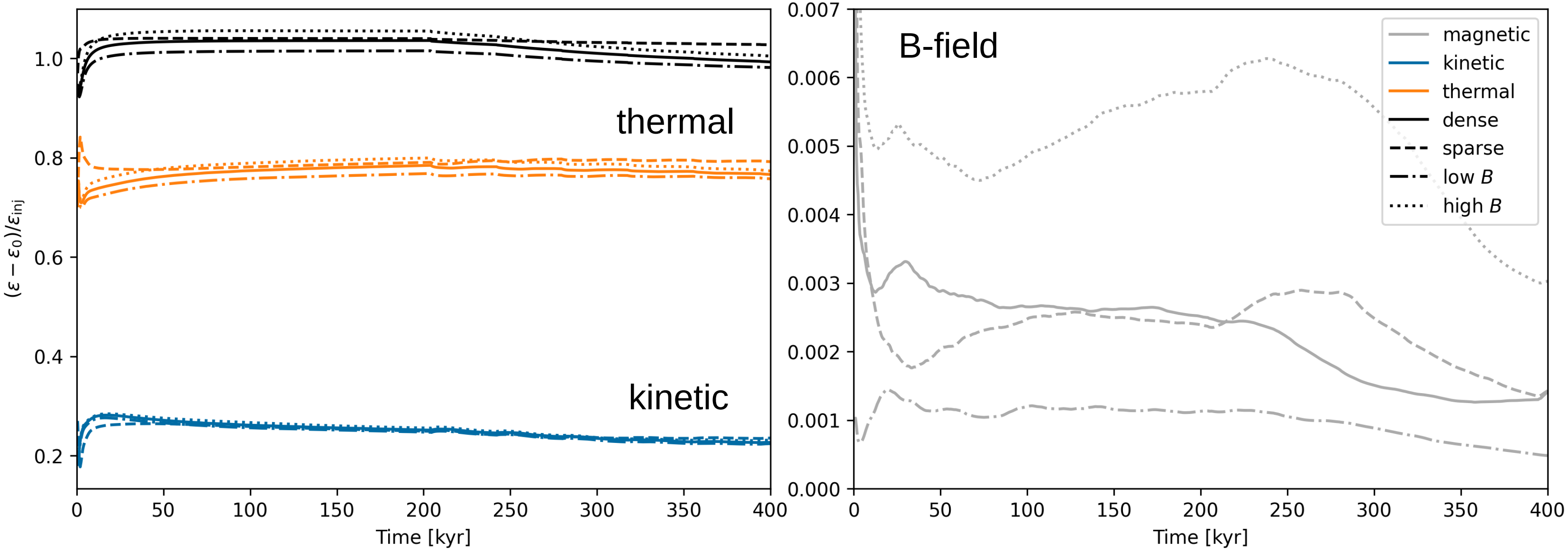
- B > 10 μG in up to ~50% of volume for standard stellar B-fields
- Negligible fraction with B > 100 μG in wind and bubble

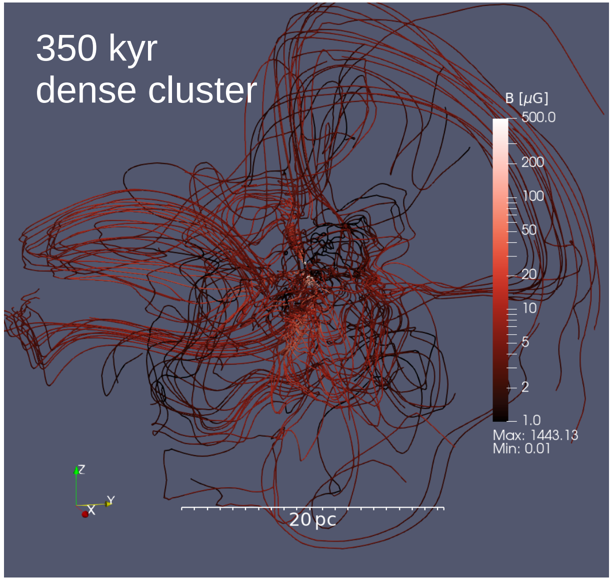
B-field Amplification

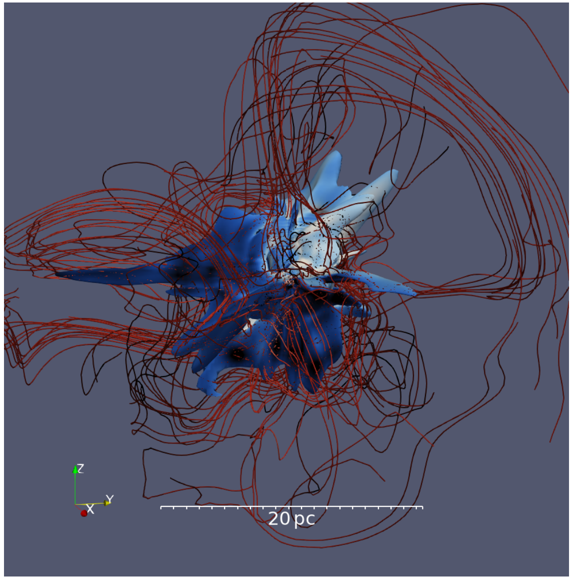
energy increase over injected energy in the full domain

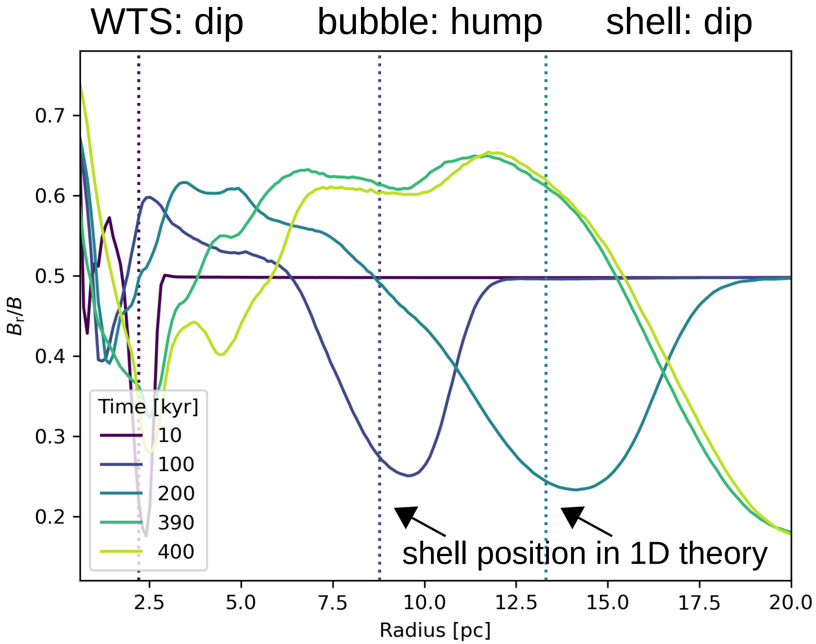


- power converted to kinetic and thermal energy is consistent with 1D theory
- *0.1-1% of power goes into B-field*,
  amounts to *total increase by factor ~2-8 over 400 kyr* (default case: ~4)

B-field Morphology



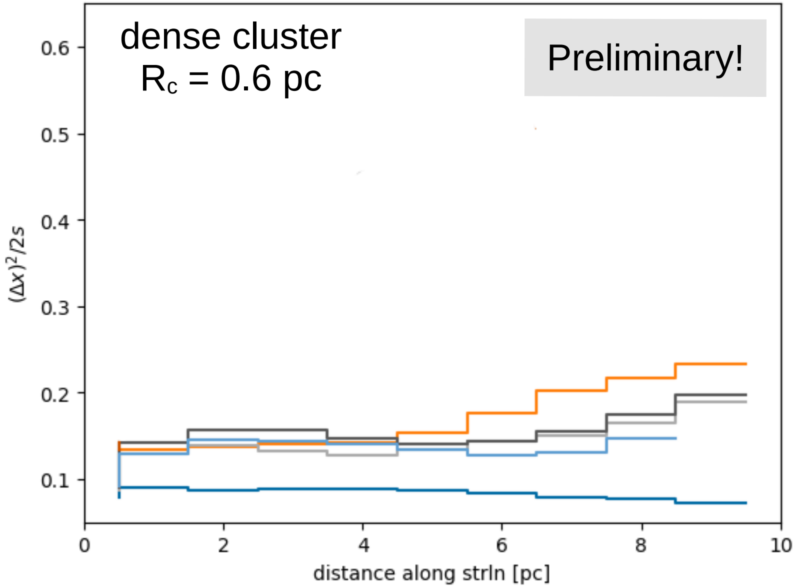


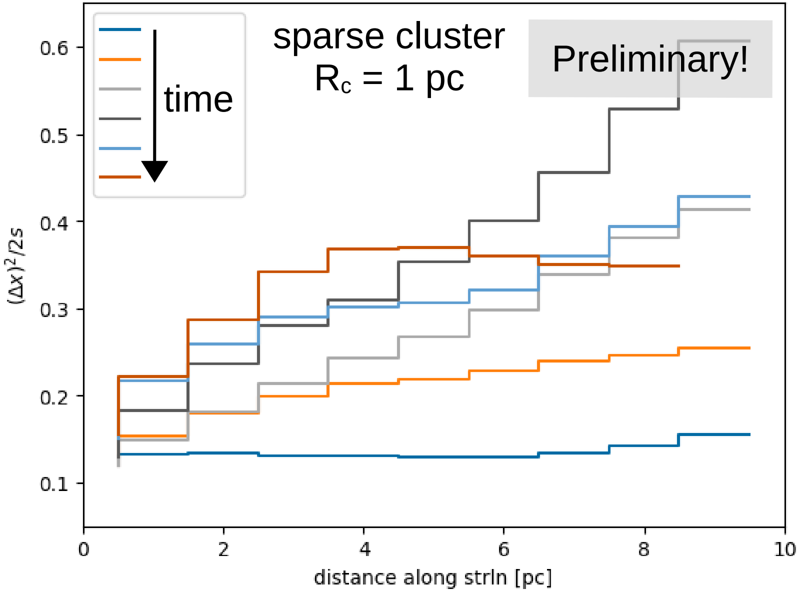


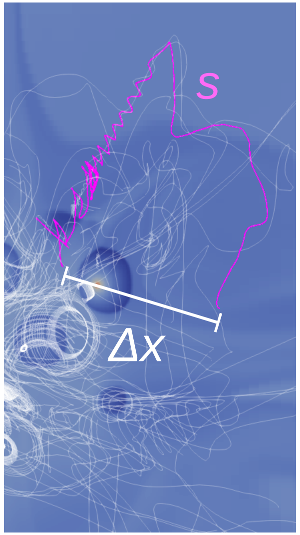
- tangled field lines and spiral structures in the core
- bundles of field lines following radial coherent flows
- radial component higher than for isotropic B-field: ~0.6 in bubble

Field Line Diffusivity

Compares distance along the field line to straight distance







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

(Magnetic) Wolf-Rayet Stars

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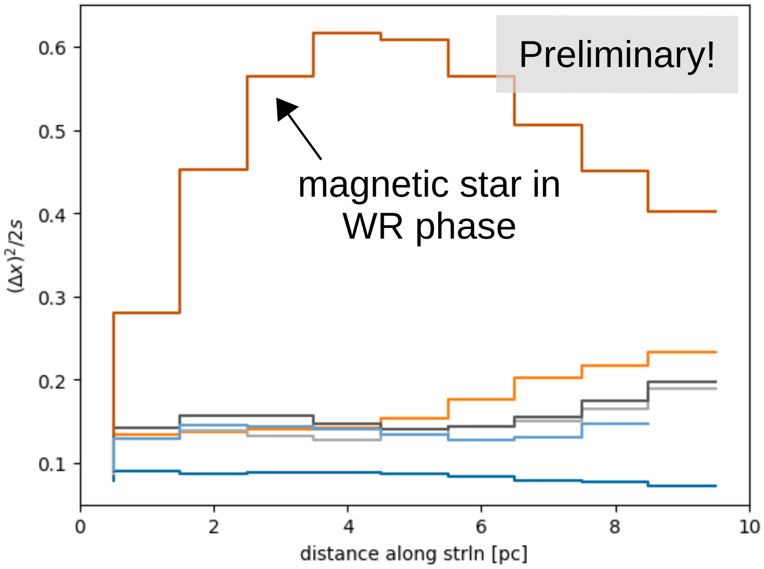
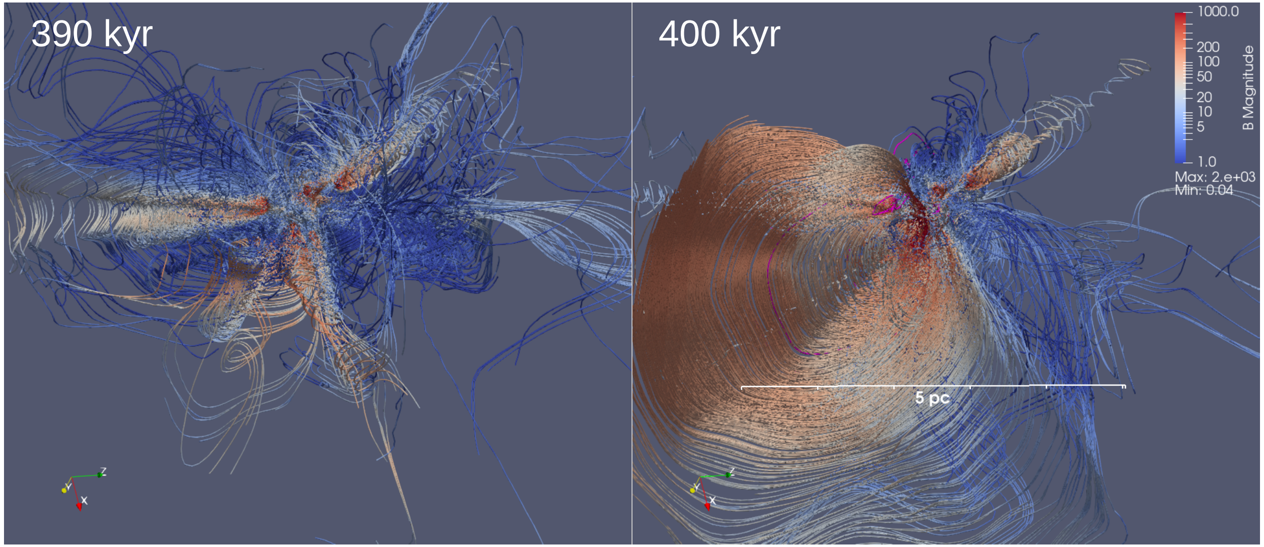
- Wolf-Rayet stars with high B-fields can produce *large coherent structures.*





Considerations on Particle Acceleration

*(in **compact** clusters: radius < 2-3 pc)*

- ✓ Simulations show a strong, super-Alfvénic WTS and a turbulent superbubble interior.

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Maximum Energy: $E_{\max} = 0.5 \times Z \left(\frac{B}{5\,\mu\mathrm{G}} \right) \left(\frac{R}{10\,\mathrm{pc}} \right) \left(\frac{u_\mathrm{w}}{3000\ \mathrm{km\,s^{-1}}} \right) \mathrm{PeV}$

(parameters measured in upstream)

→ Particles *could reach 1 PeV* at WTS in an optimistic scenario.
However: fitting CRs beyond the knee *requires 10s of PeV*.

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However: fitting CRs beyond the knee *requires 10s of PeV*.

- Spectra might show multiple components due to non-uniform WTS and contributions from other sources.
- SNe in compact clusters could be powerful accelerators (Vieu & Reville 23).

Conclusions

- Strong, large-scale wind termination shock.
  but: *non-uniform, smaller than in 1D theory*

  ⟶ Acceleration to 100s of TeV.

- Flow and B-field show *complex morphology.*
  e.g. supersonic streams

  ⟶ Challenging to account for in 1D acceleration and transport models.

- Strong dependence on *individual* wind-wind interactions.

  ⟶ **Care should be taken when using average values!**
  Instead: understand stellar population, its history, and the cluster environment.

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

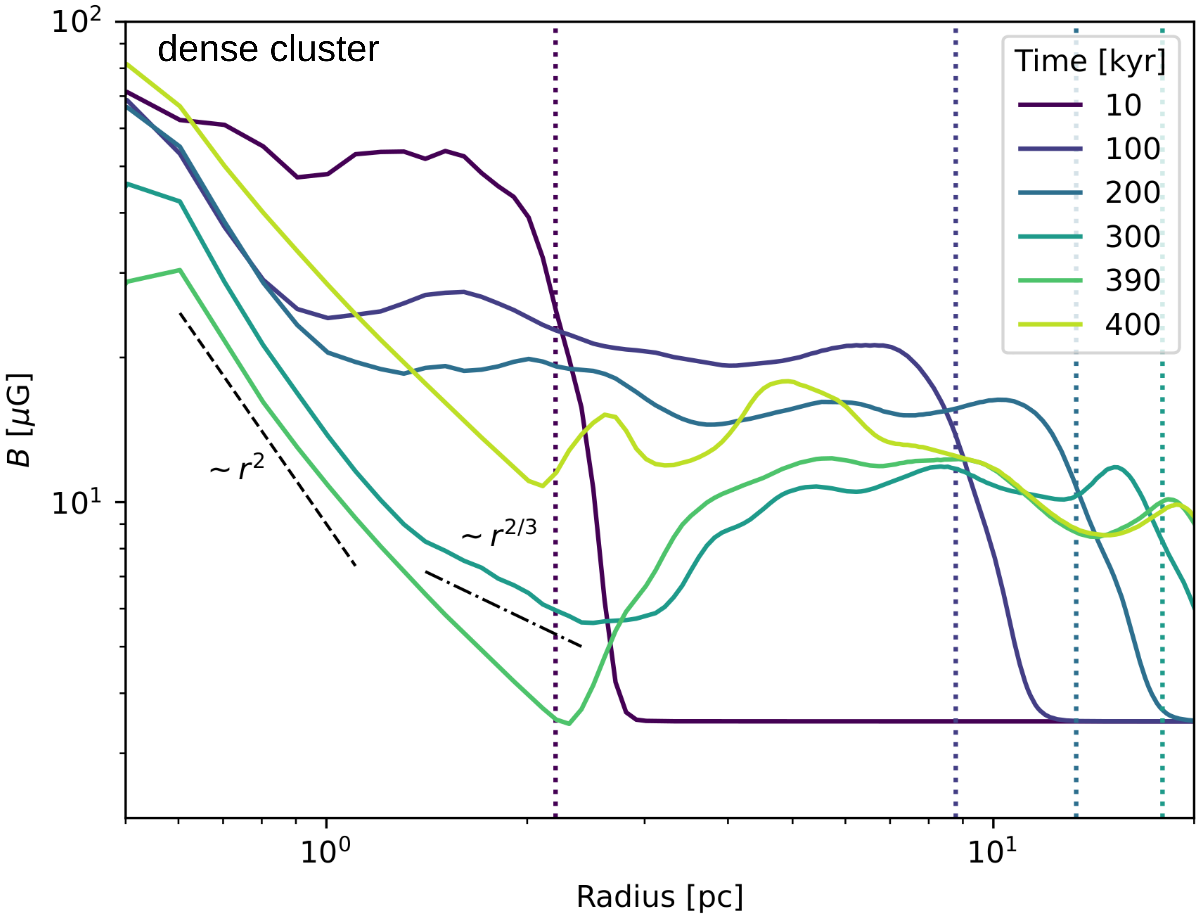
Paper in prep.!

BACKUP

Nr.	M	T_{eff}	R	t_{MS}	$\dot{M}$	v_∞	L_w
	$M_\odot$	K	$R_\odot$	kyr	$10^{-6}\,M_\odot\,yr^{-1}$	km/s	10^{36} erg s^{-1}
1[a,b]	40.2	45,519	11.4	4591	0.74	2632	1.61
2	40.7	45,708	11.5	4548	0.77	2635	1.69
3	41.2	45,899	11.6	4506	0.81	2637	1.77
4	41.7	46,094	11.7	4463	0.85	2640	1.86
5[b]	42.3	46,291	11.8	4421	0.89	2643	1.95
6	42.8	46,491	12.0	4379	0.93	2647	2.05
7	43.4	46,694	12.1	4337	0.97	2650	2.15
8	44.0	46,901	12.2	4295	1.02	2653	2.26
9	44.6	47,111	12.3	4254	1.07	2656	2.38
10[b]	45.2	47,324	12.5	4212	1.12	2659	2.50
11[a]	45.9	47,541	12.6	4170	1.17	2663	2.62
12	46.5	47,761	12.8	4129	1.23	2666	2.76
13	47.2	47,984	12.9	4088	1.29	2670	2.90
14[b]	47.9	48,212	13.1	4047	1.36	2673	3.06
15	48.6	48,443	13.2	4006	1.43	2677	3.22
16	49.4	48,679	13.4	3965	1.50	2681	3.39
17	50.2	48,919	13.6	3924	1.57	2685	3.57
18	51.0	49,163	13.7	3883	1.65	2688	3.76
19[b]	51.8	49,411	13.9	3843	1.74	2692	3.96
20	52.7	49,664	14.1	3803	1.83	2696	4.18
21[a]	53.6	49,921	14.3	3762	1.92	2701	4.41
22	54.6	50,184	14.5	3722	2.02	2705	4.65
23	55.6	50,451	14.8	3682	2.12	2709	4.91
24[b]	56.6	50,724	15.0	3642	2.23	2714	5.18
25	57.7	51,003	15.2	3602	2.35	2718	5.47
26	58.8	51,286	15.5	3563	2.48	2723	5.78
27	60.0	51,576	15.7	3523	2.61	2728	6.11
28[b]	61.2	51,872	16.0	3484	2.74	2733	6.46
29	62.5	52,174	16.3	3445	2.89	2738	6.82
30	63.8	52,482	16.6	3406	3.04	2743	7.21
31[a]	65.3	52,798	17.0	3367	3.20	2749	7.63
32[b]	66.8	53,120	17.3	3328	3.37	2754	8.06
33	68.3	53,450	17.7	3289	3.55	2760	8.53
34	70.0	53,787	18.1	3250	3.74	2766	9.02
35	71.7	54,133	18.5	3212	3.94	2772	9.54
36	73.6	54,487	18.9	3174	4.15	2779	10.08
37	75.6	54,849	19.4	3135	4.36	2785	10.66
38	77.7	55,220	19.9	3097	4.59	2792	11.27
39[b]	79.9	55,601	20.4	3059	4.82	2799	11.91
40	82.3	55,992	21.0	3022	5.07	2807	12.58
41[a,b]	84.8	56,393	21.6	2984	5.32	2814	13.28
42	87.5	56,805	22.3	2947	5.58	2822	14.00
43	90.4	57,227	23.0	2909	5.85	2831	14.76
44	93.6	57,662	23.8	2872	6.12	2839	15.54
45	97.0	58,109	24.7	2835	6.39	2849	16.33
46	100.7	58,568	25.7	2798	6.66	2858	17.14

Table A1. Parameters of the stars in our model cluster. Stars with superscript a have $B_s = 1$ kG in the dense and compact case and 100 G in low-field case. In the high-field case, the number of magnetic stars is doubled, but individual stars still have $B_s = 1$ kG (superscript b).

B-field Radial Profile



Comparison between simulation runs