Supernovae of Very Massive Stars

Ke-Jung (Ken) Chen
ASIAA, Taiwan

RIKEN Big Bang Workshop, 19th Feburary 2025

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The Explosion Group at ASIAA

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Realistic 1D Stellar and SN Models ?

Physicists' view of everything

Massive Stars

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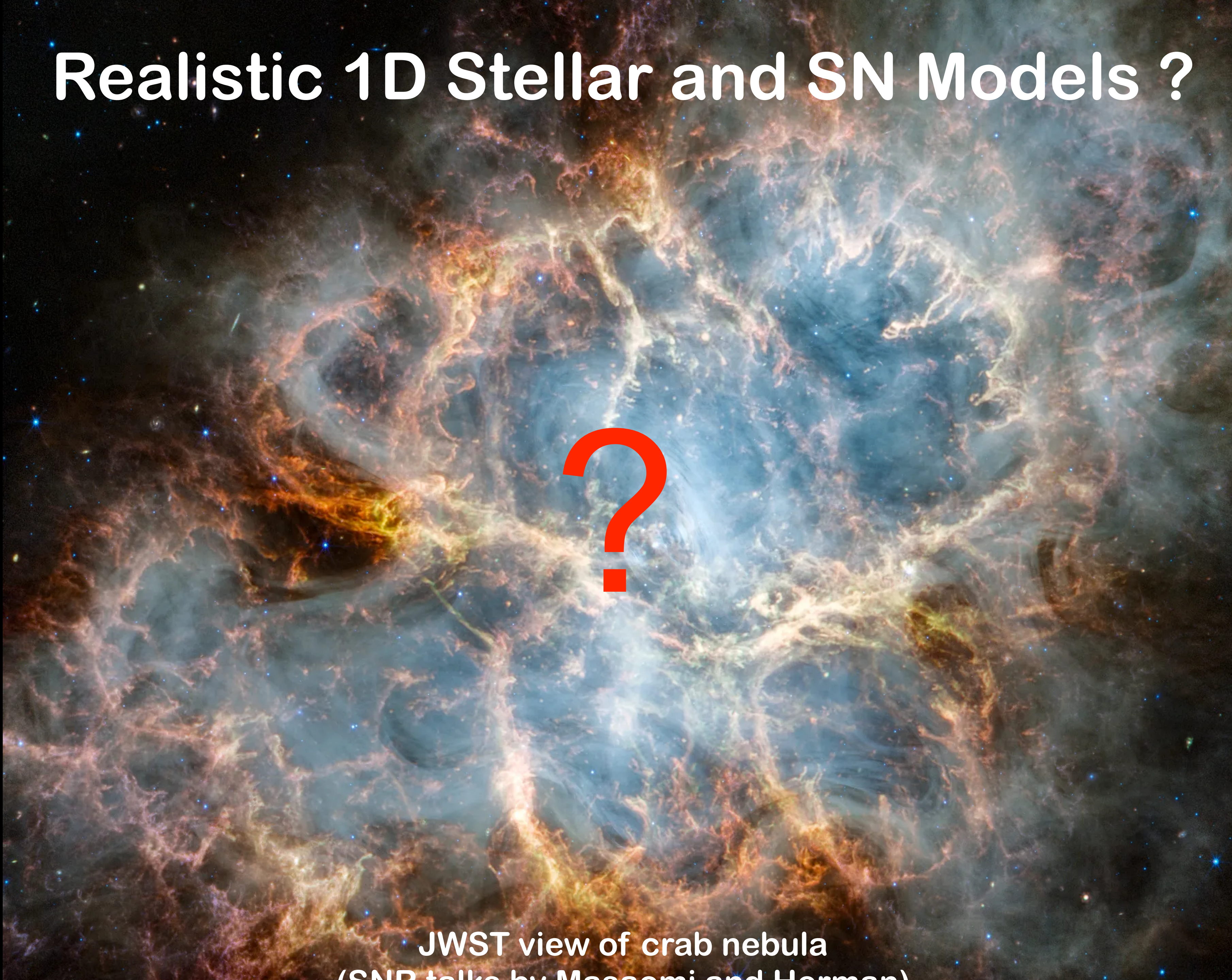

JWST view of crab nebula
(SNR talks by Masaomi and Herman)

Physics of Mixing in SNe and SNRs

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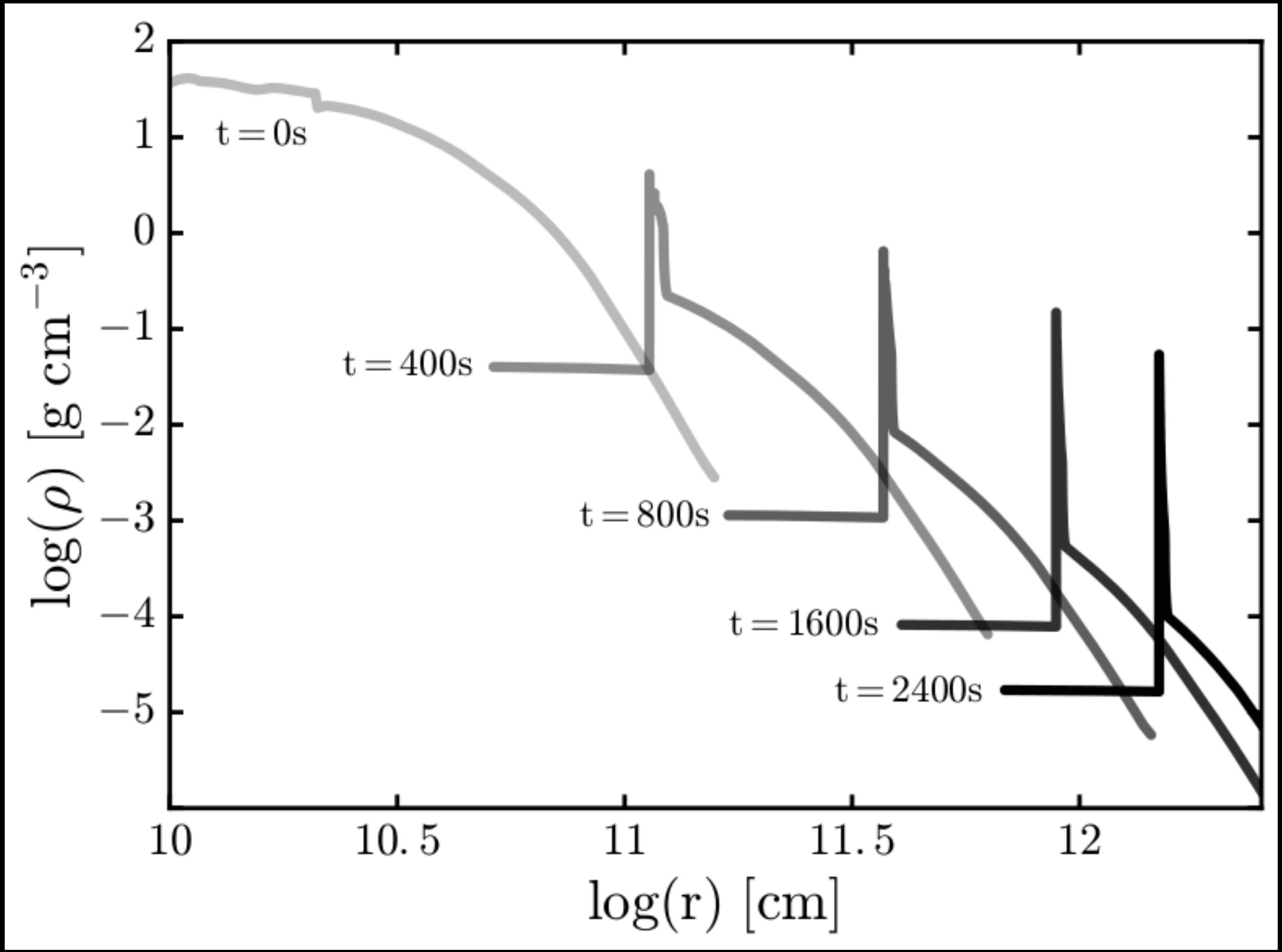
- Plasma and Radiative instabilities
- Colliding with CSM and ISM

Issues on 1D Models for SNe Observables



Density spike in 1D magnetar (KC+ 16)

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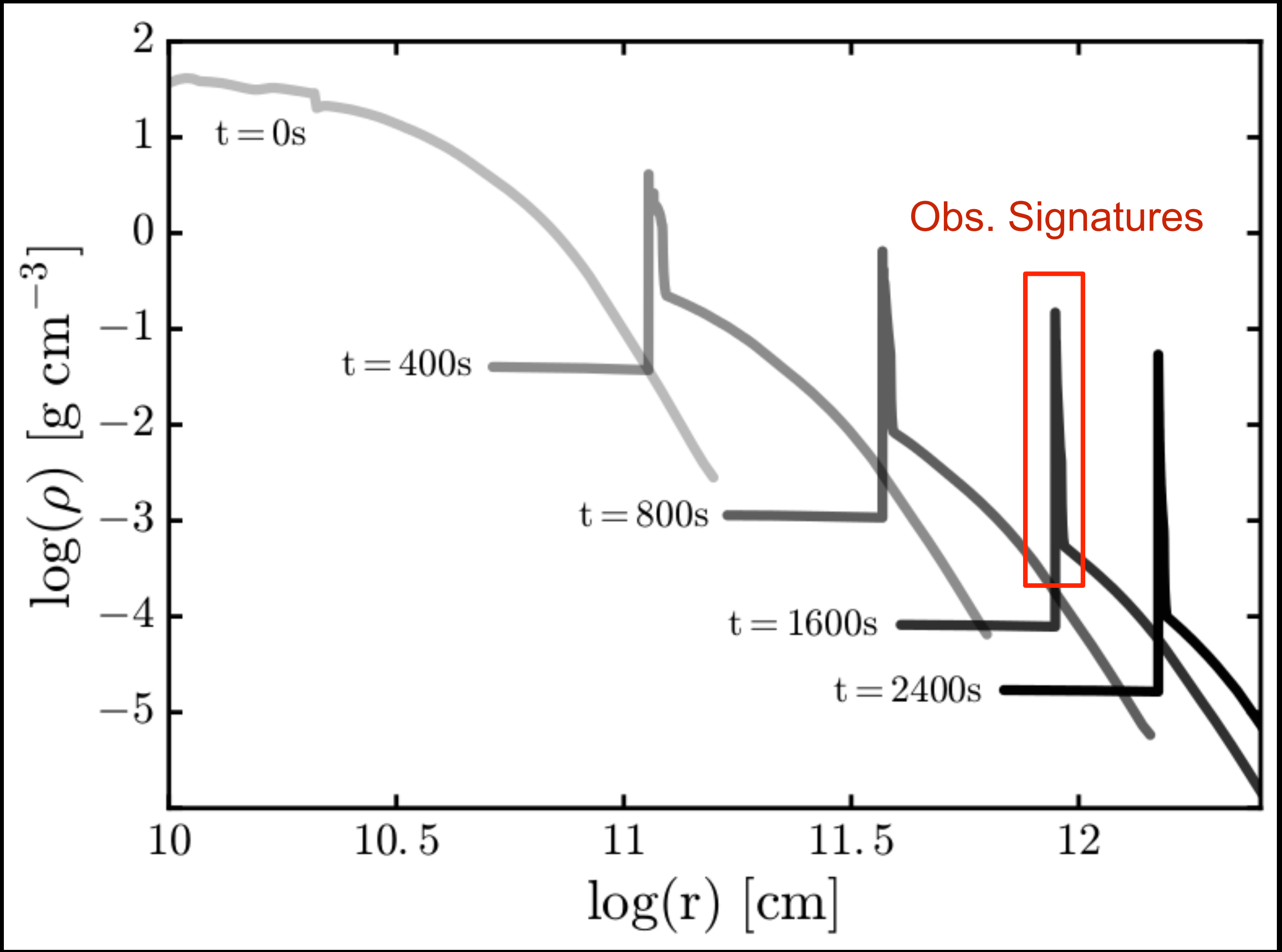

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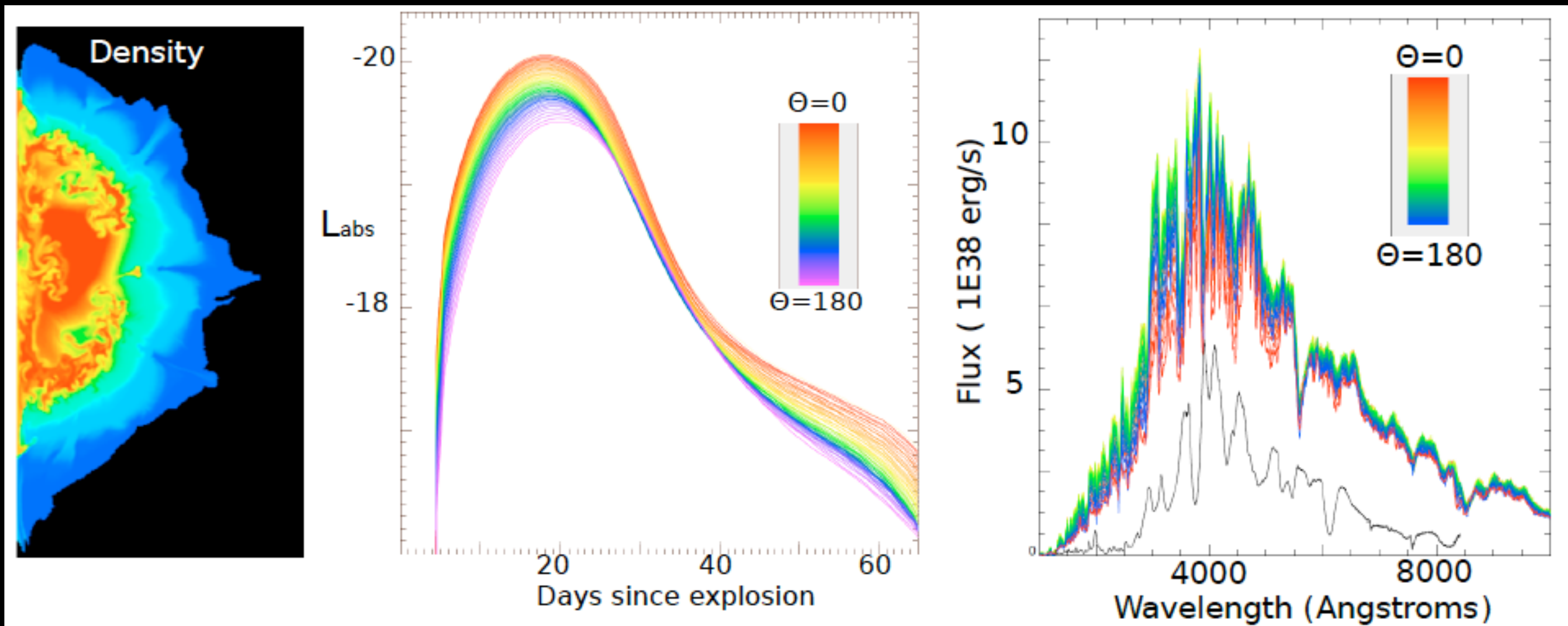
Impact of Mixing on SN Observational Signatures



A Type Ia Example from Kasen+ 2008

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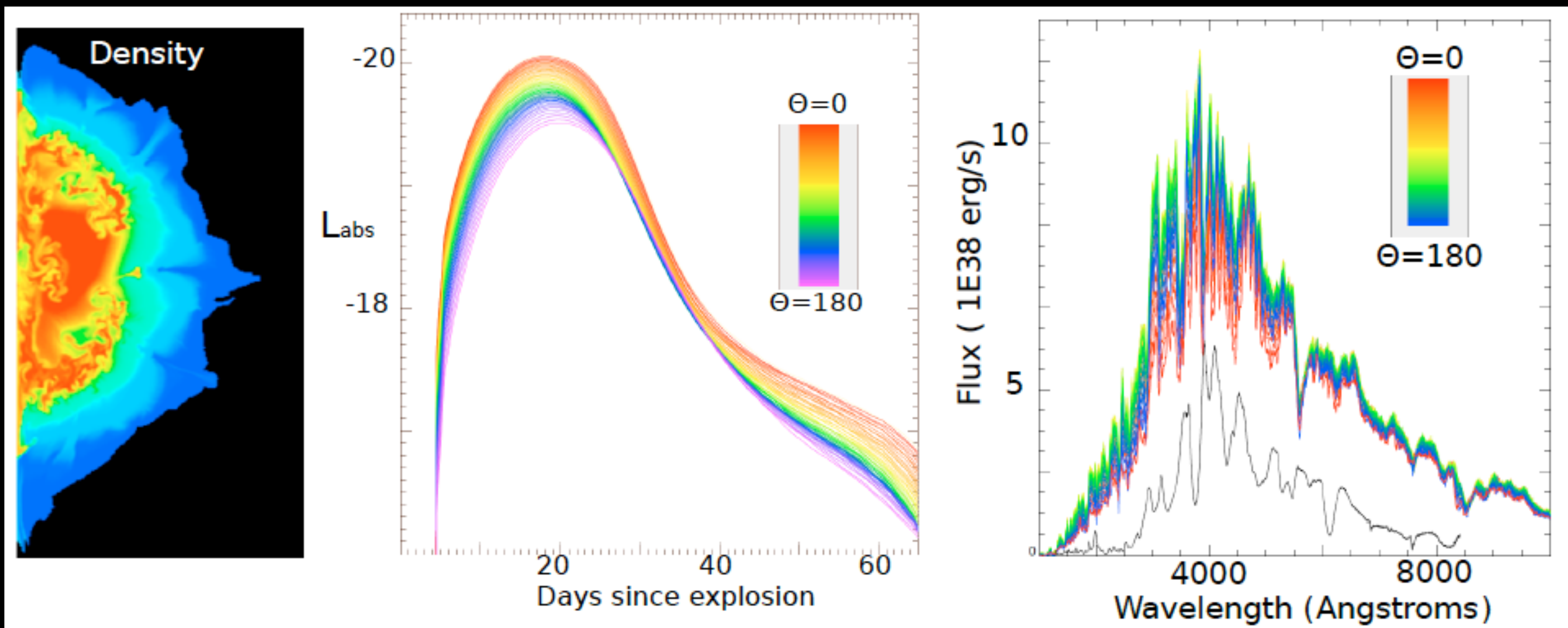
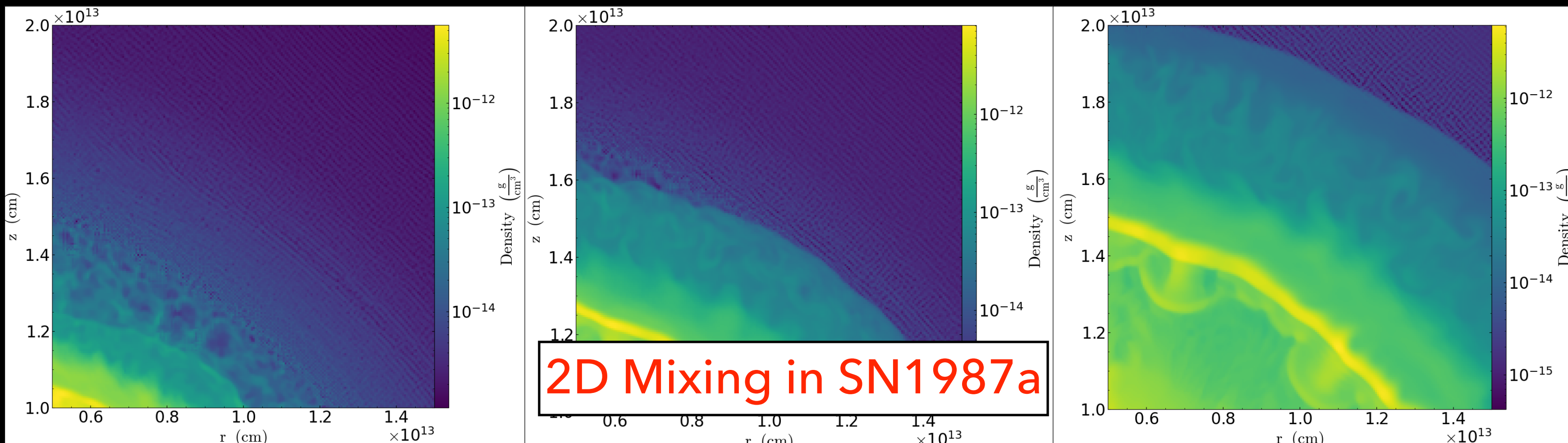


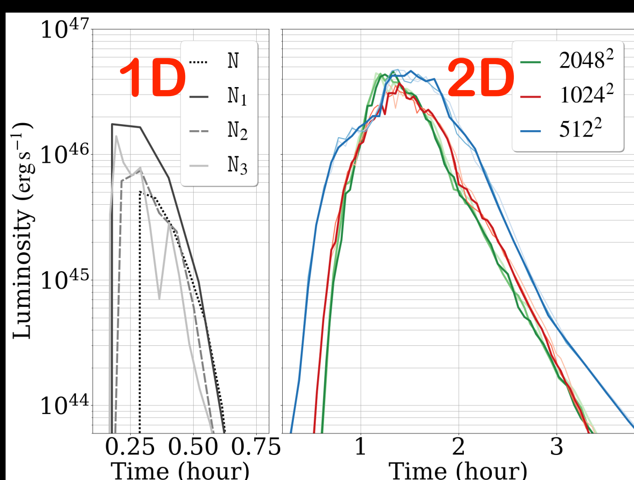
A Type Ia Example from Kasen+ 2008

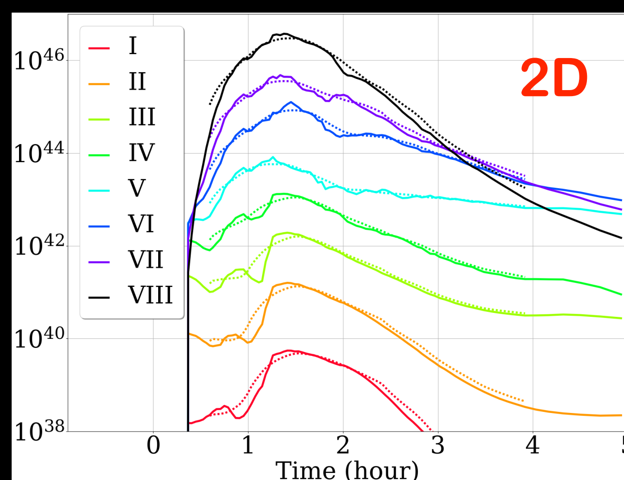
Multidimensional Radiation Transport Simulations will be ideal !!

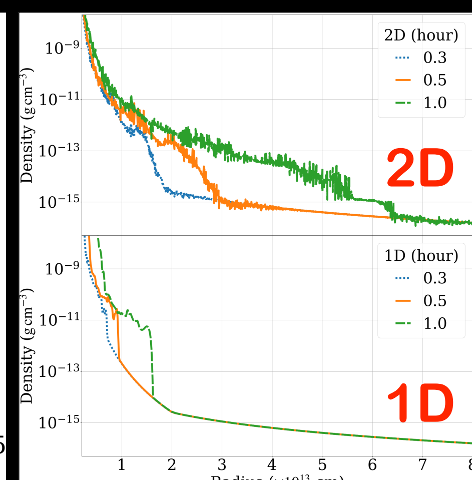
Mixing on Breakout Signatures

New 2D radiation transport simulations with CASTRO









Chen W.-Y., KC, Ono, 2024, ApJ, 976, 147.

Ken's SN Simulations

1D Models

30-60, 80 - 250 $M_\odot$ Stars (Heger & Woosley)

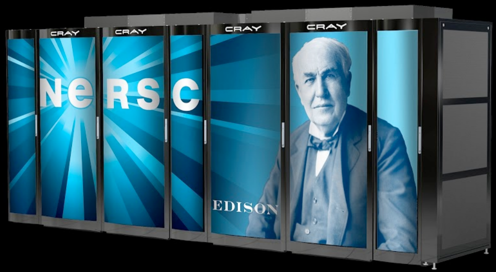
CASTRO

Massive Parallel, Adaptive Mesh Refinement (AMR), Multi-D,
Radiation, Hydro+(Burning, Rotation, GR …)
(Almgren+ 2010, Zheng+ 2011 2012, KC+ 2013)

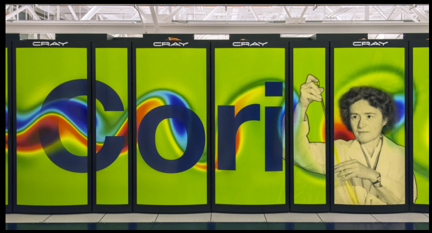
Supercomputers

XC30

Hopper

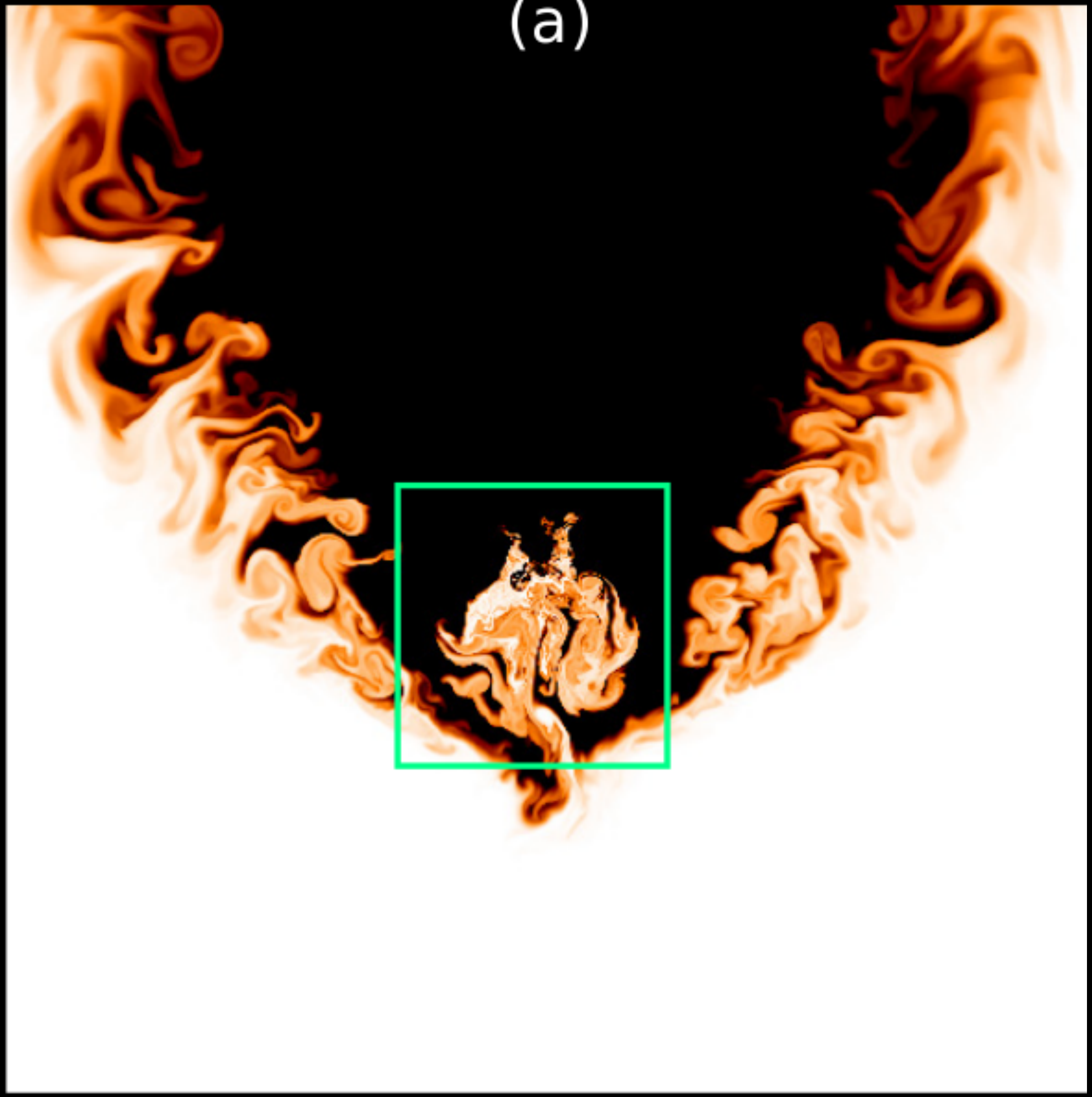


Edison

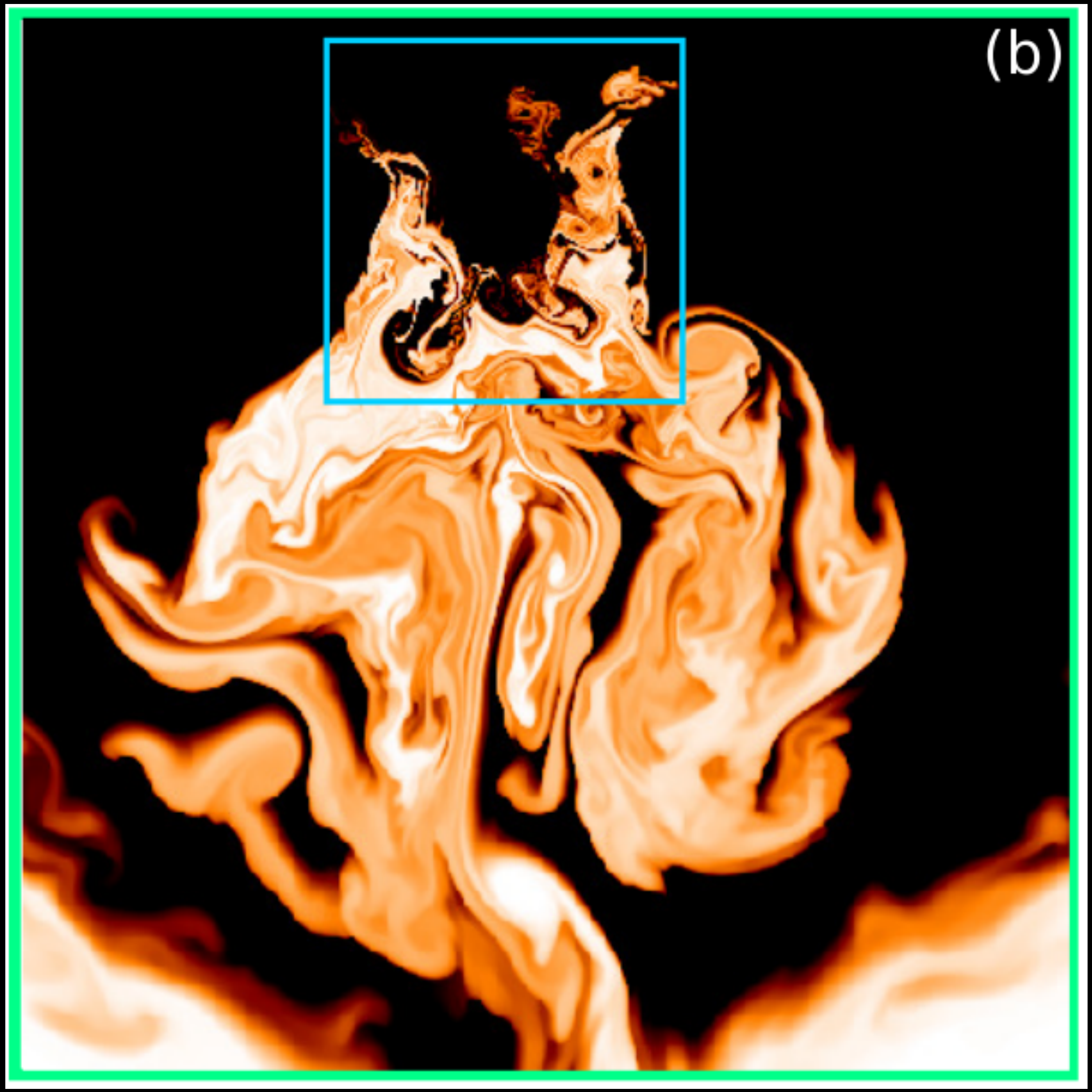


Cori

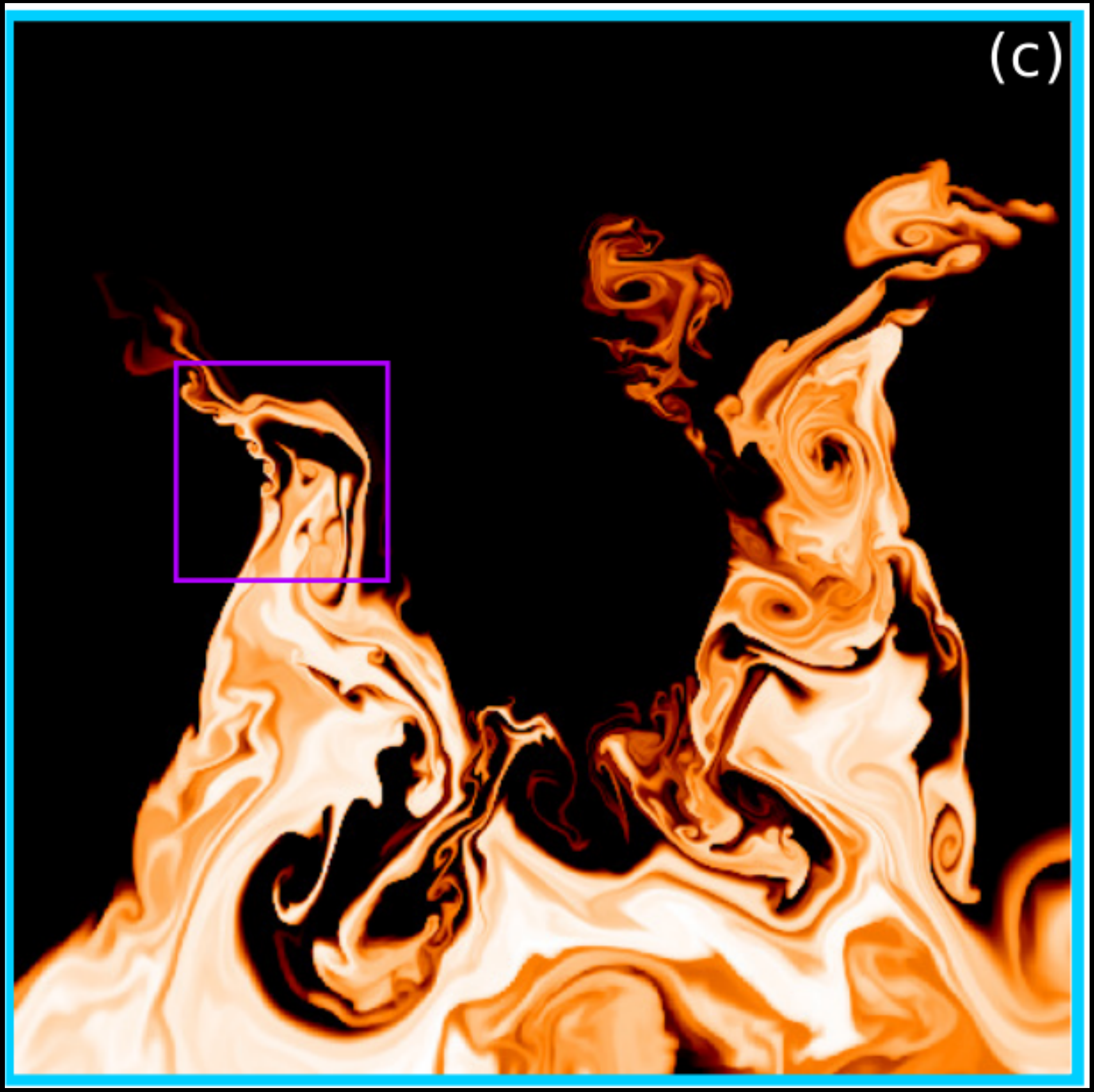
Resolving Scales of Mixing



Resolving Scales of Mixing



Resolving Scales of Mixing



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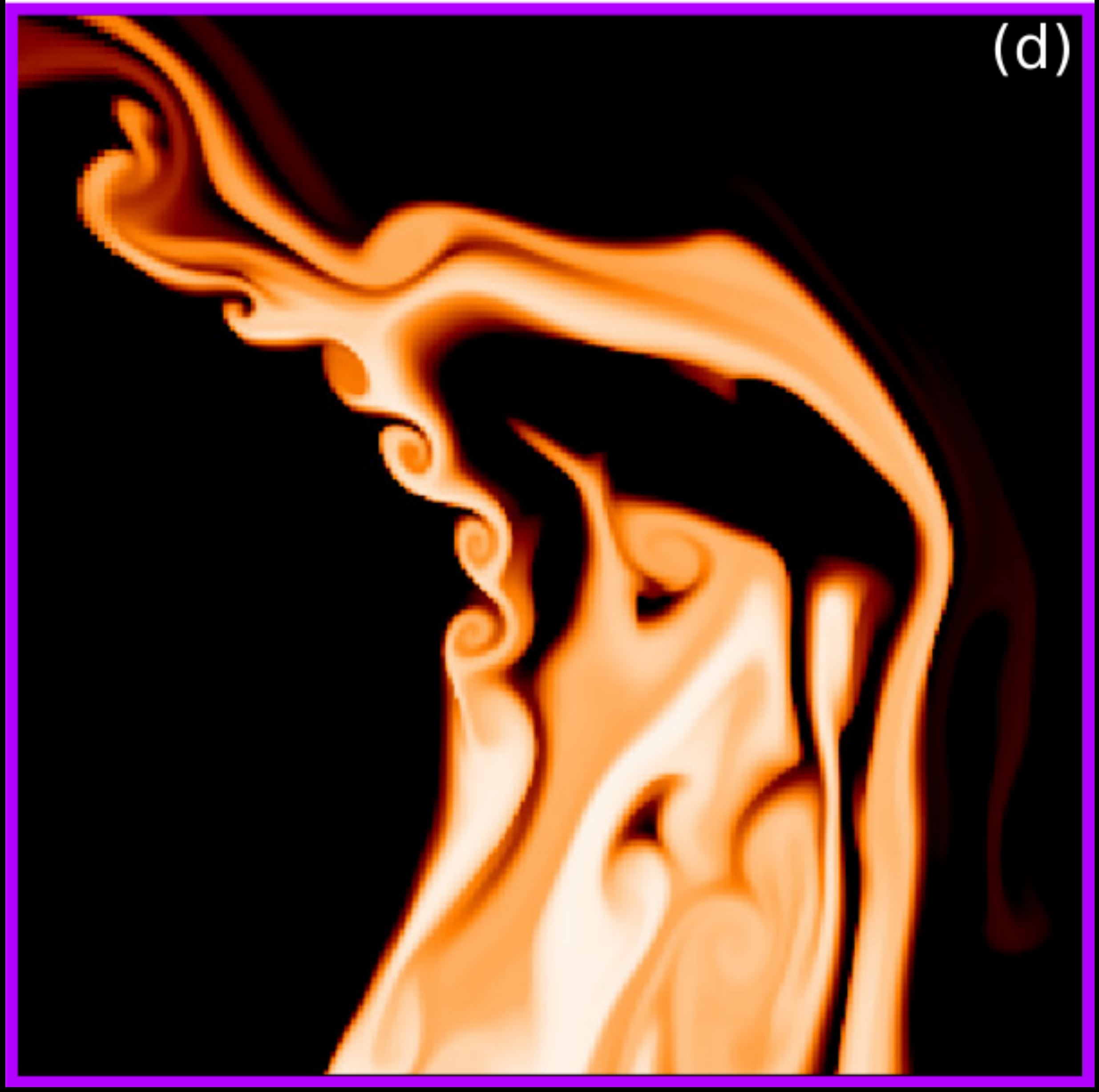

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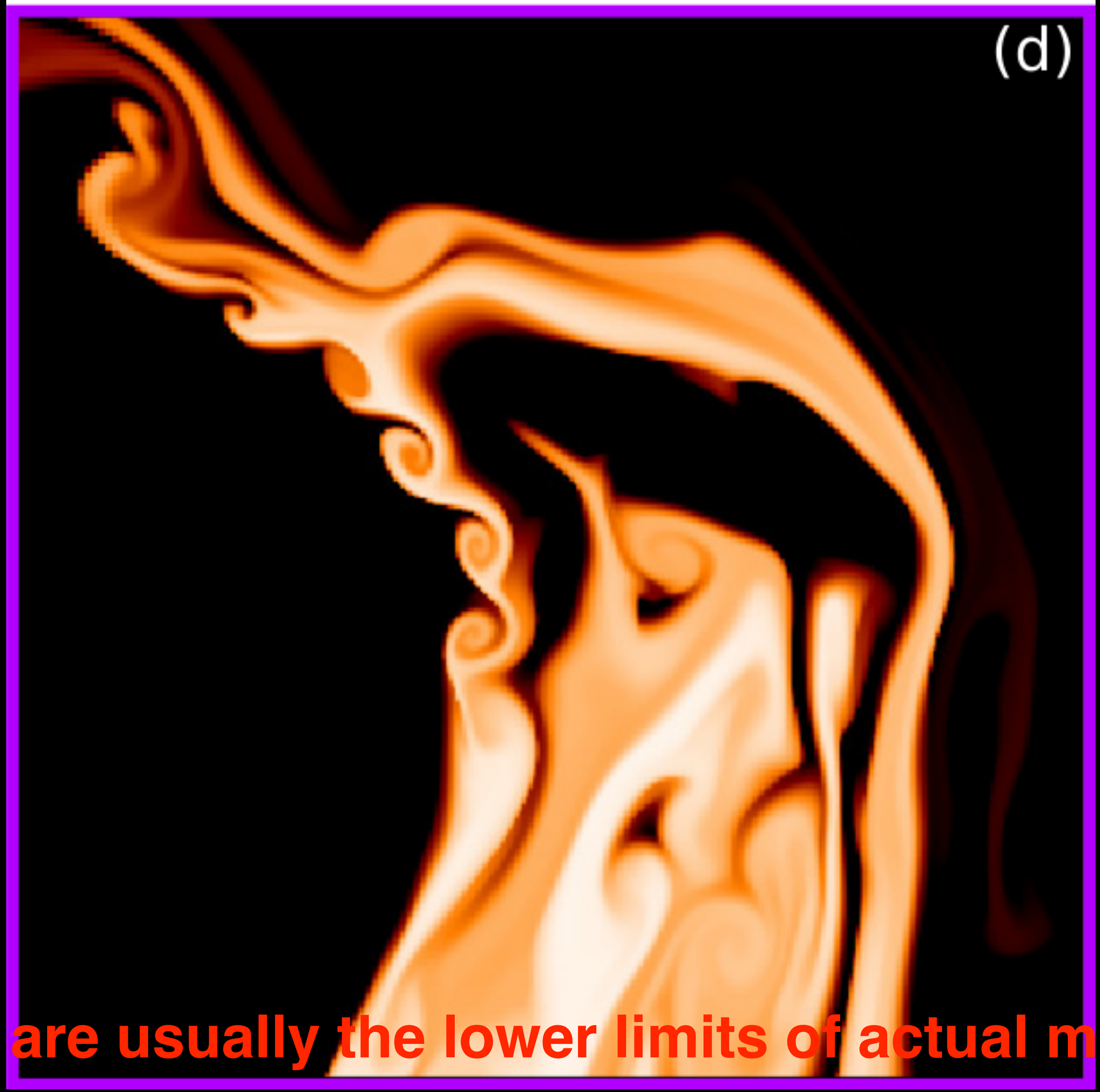
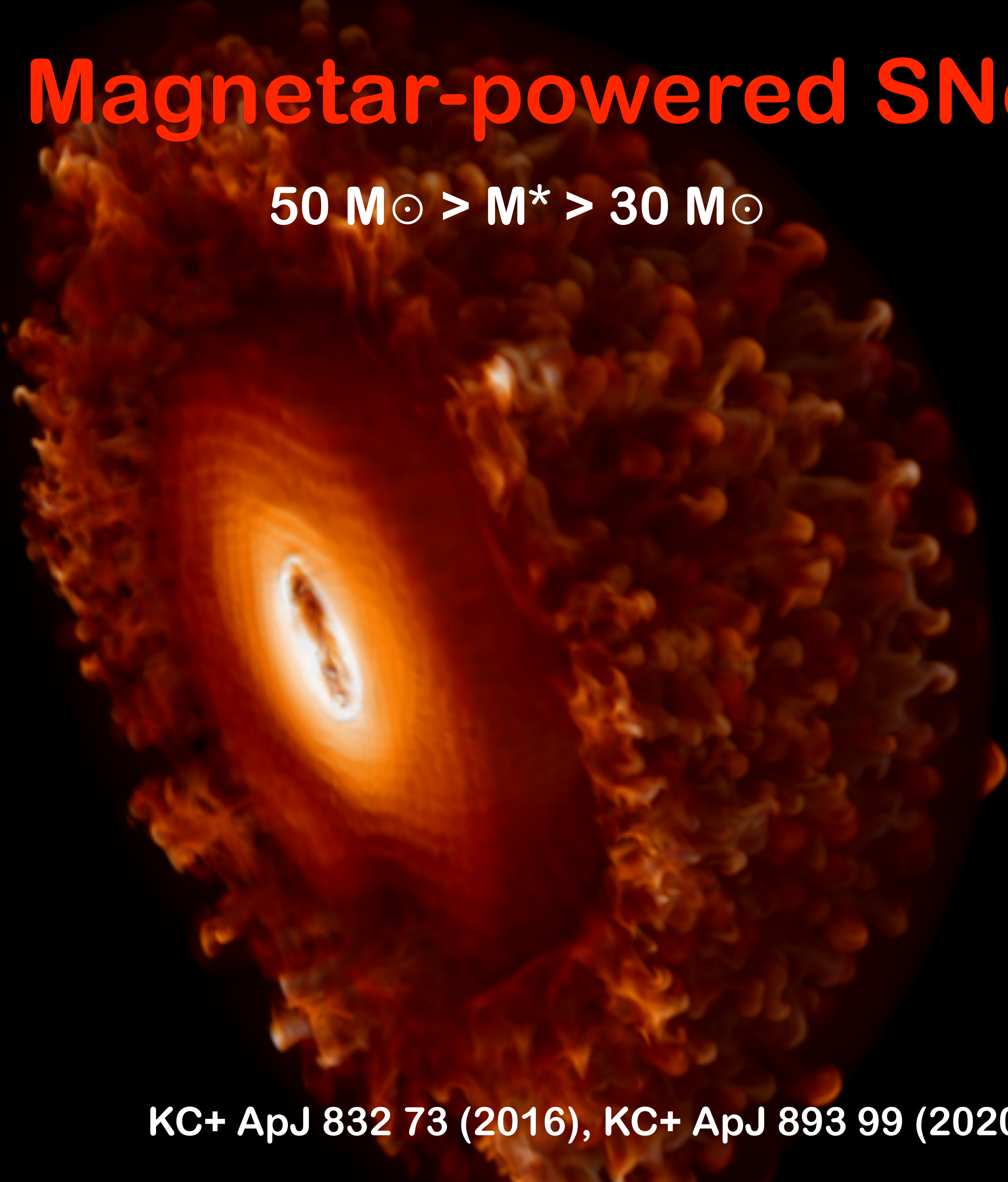


Results are usually the lower limits of actual mixing !

Magnetar-powered SNe

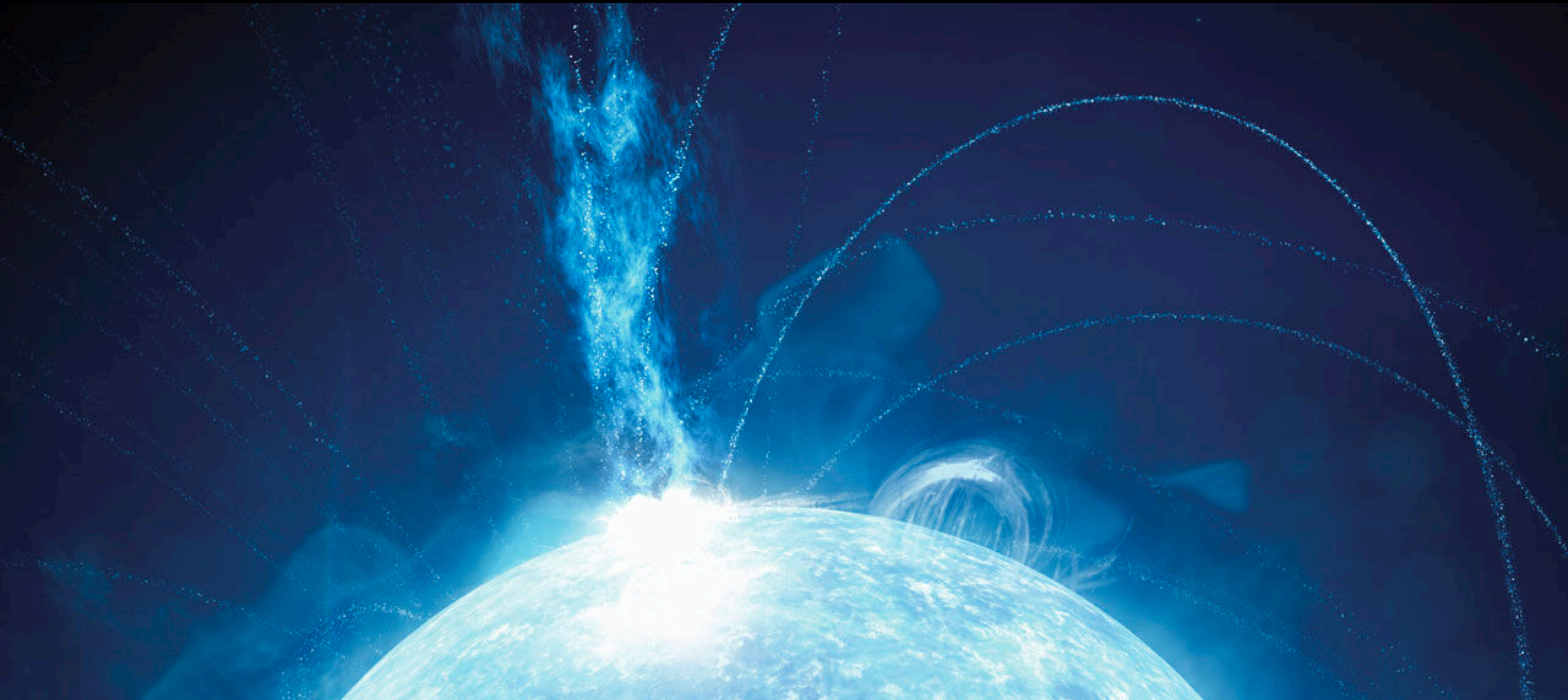
$50\ M_\odot > M^* > 30\ M_\odot$



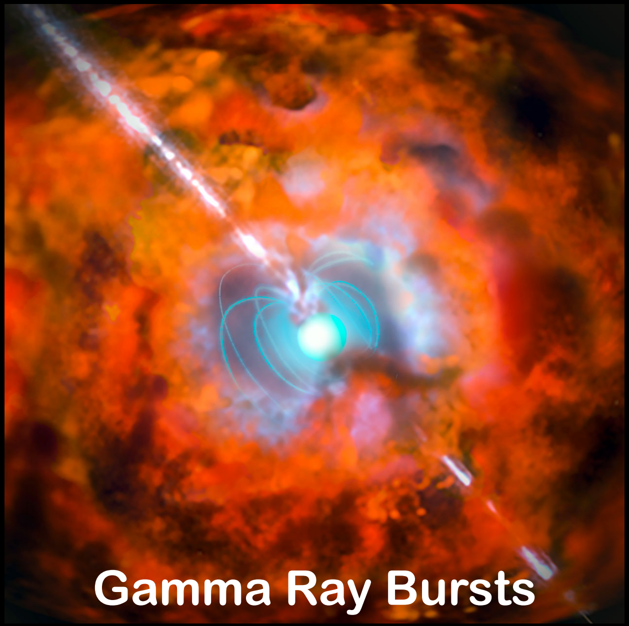
KC+ ApJ 832 73 (2016), KC+ ApJ 893 99 (2020)

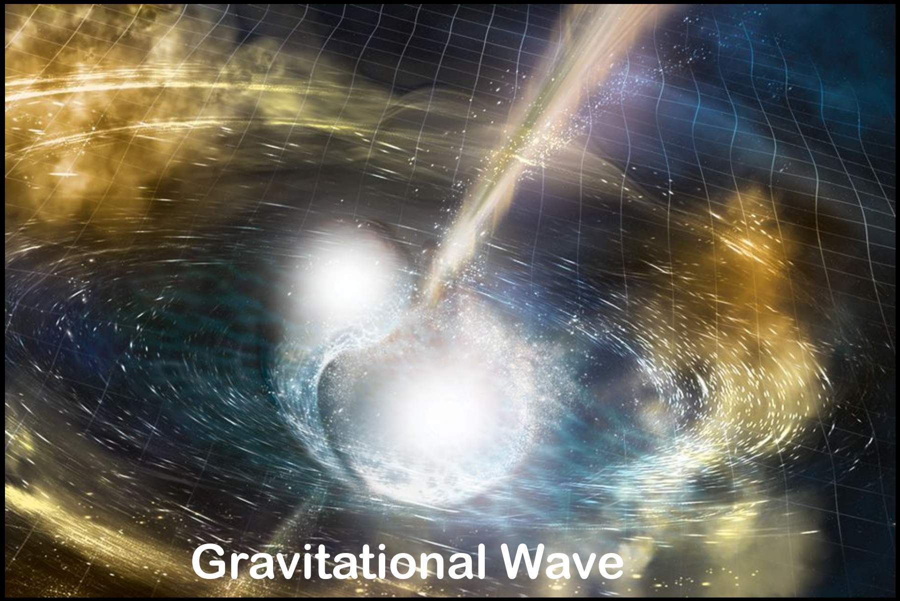
What is a Magnetar?

A magnetar is an exotic type of neutron star, its defining feature that it has an ultra-powerful magnetic field. The field is about 1,000 times stronger than a normal neutron star and **about a trillion times stronger than the Earth's**. Magnetars are, by far, the most magnetic stars in the universe.



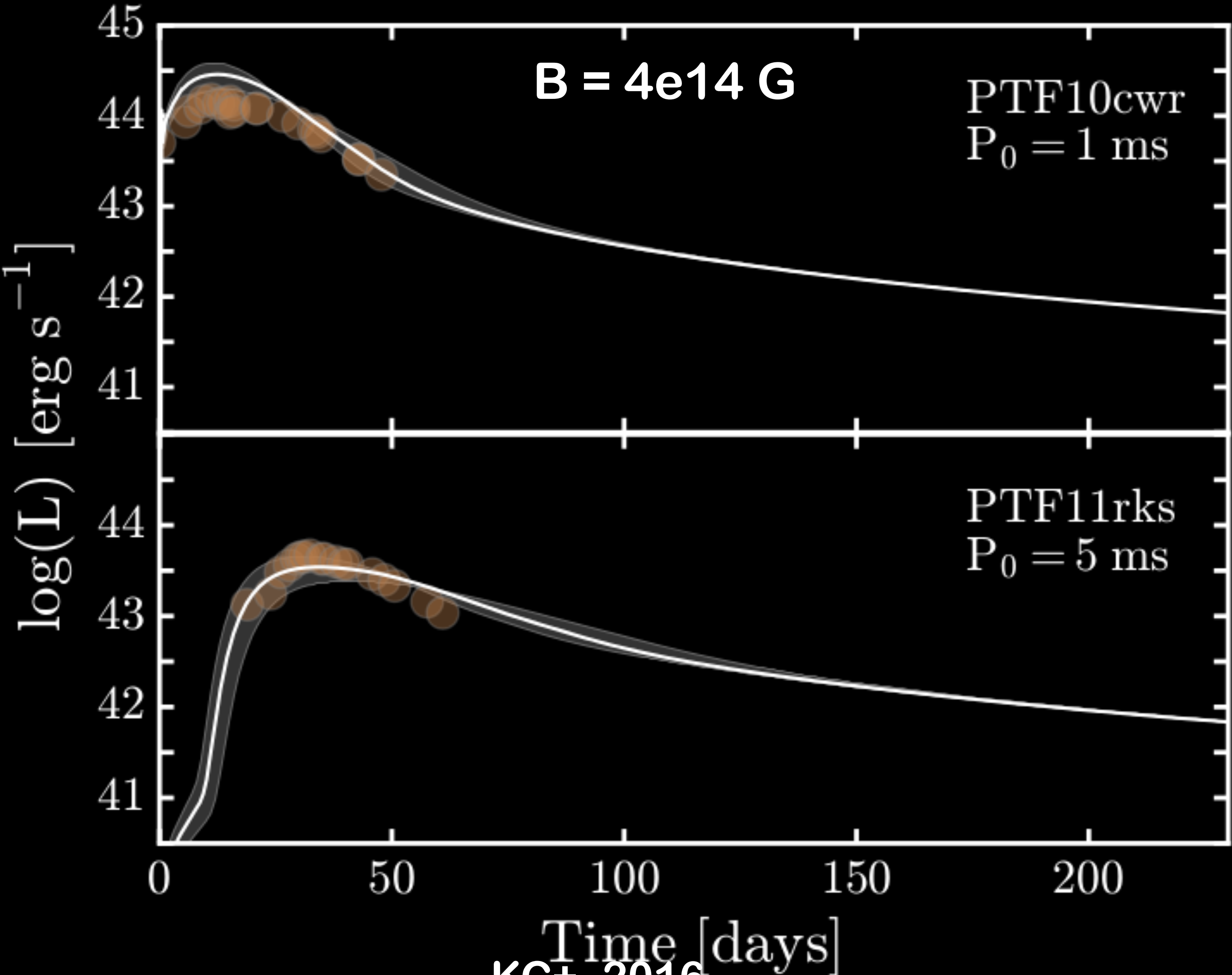
Mighty Magnetar!



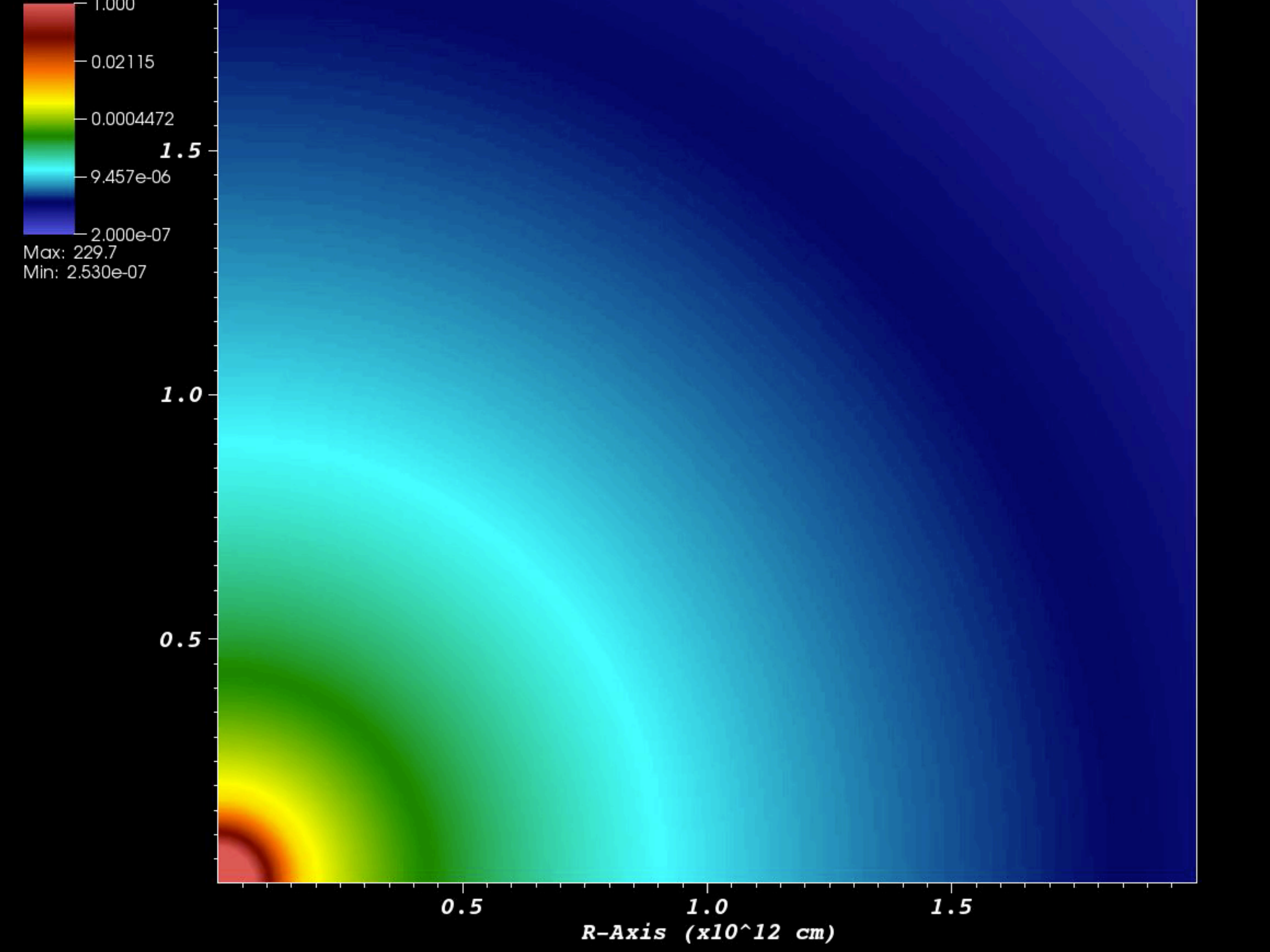


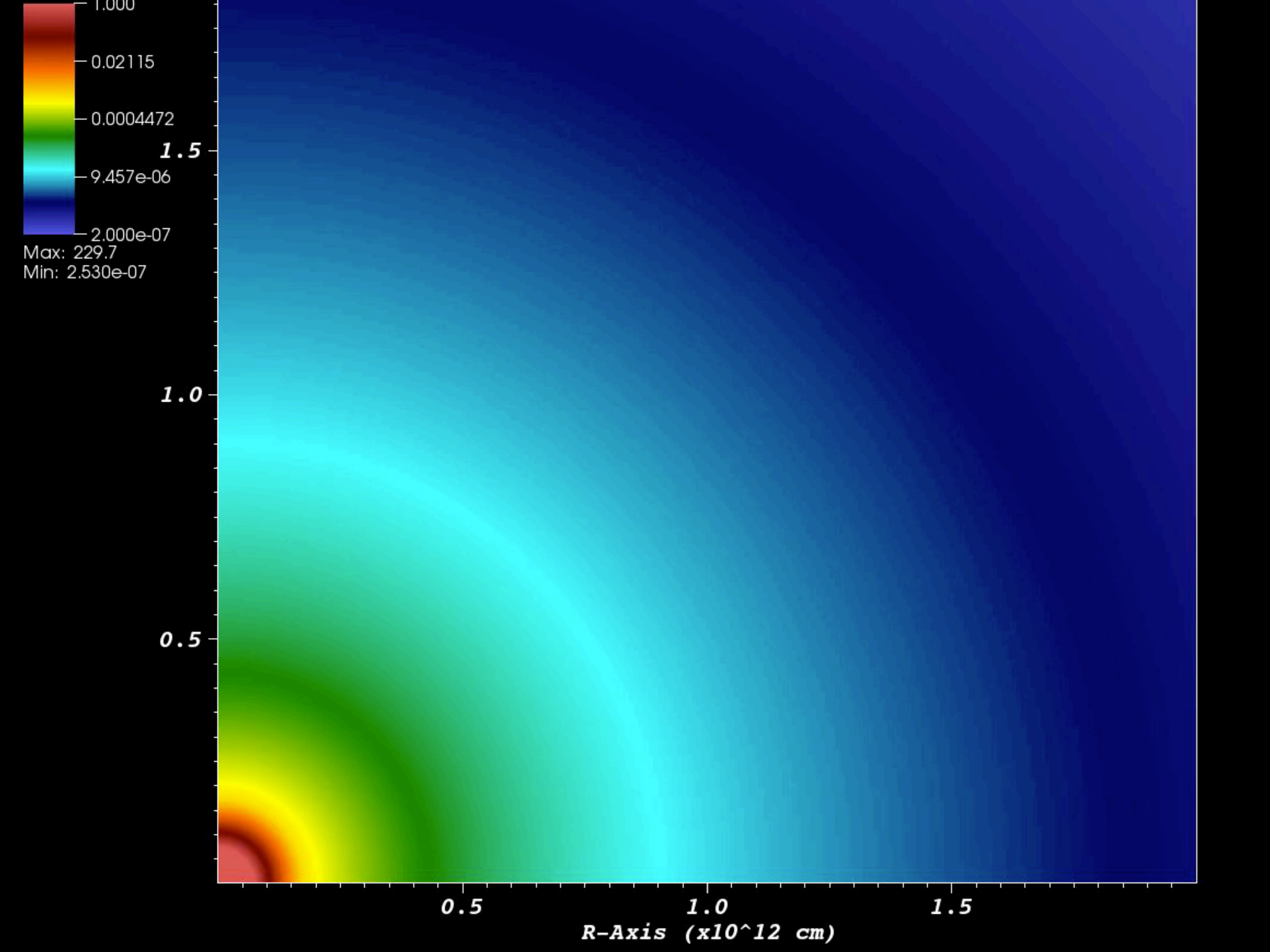
Superluminous SNe by Magnetar

Original Ideas from Maeda, Kasen, Bildsten, Woosley



KC+, 2016


1.000
0.02115
0.0004472
9.457e-06
2.000e-07
Max: 229.7
Min: 2.530e-07
1.5
1.0
0.5
0.5
1.0
1.5
R-Axis (x10^12 cm)



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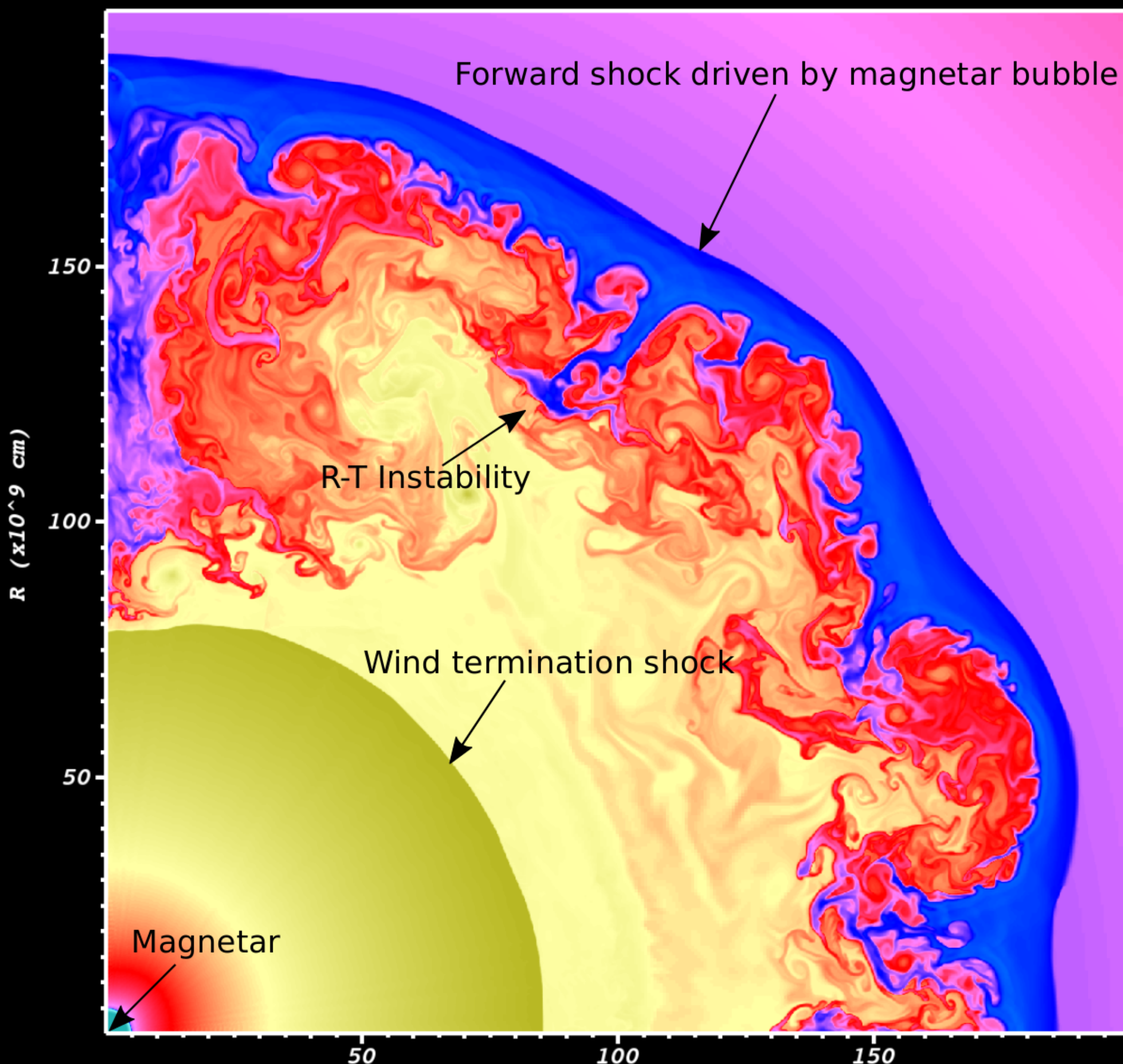
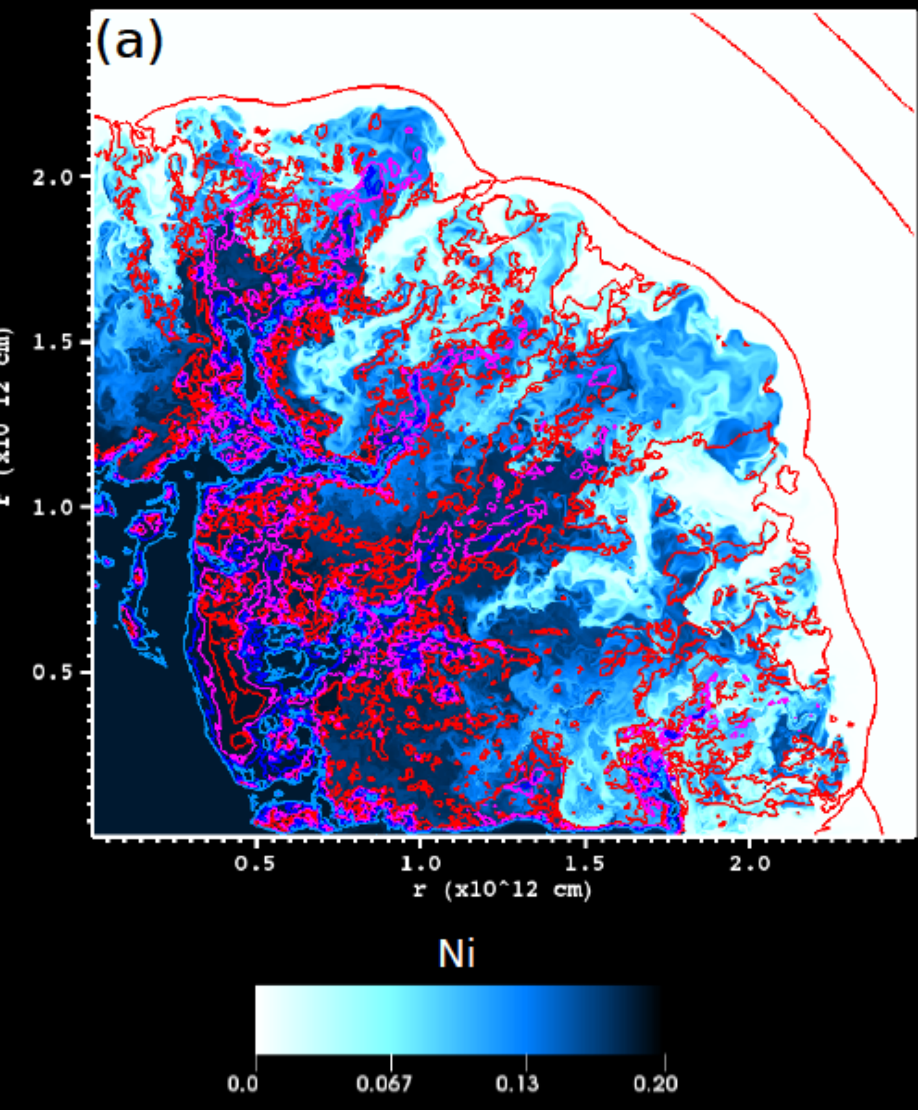
1.5
1.0
0.5
0.5
1.0
1.5
R-Axis (x10^12 cm)

Ejecta Structure

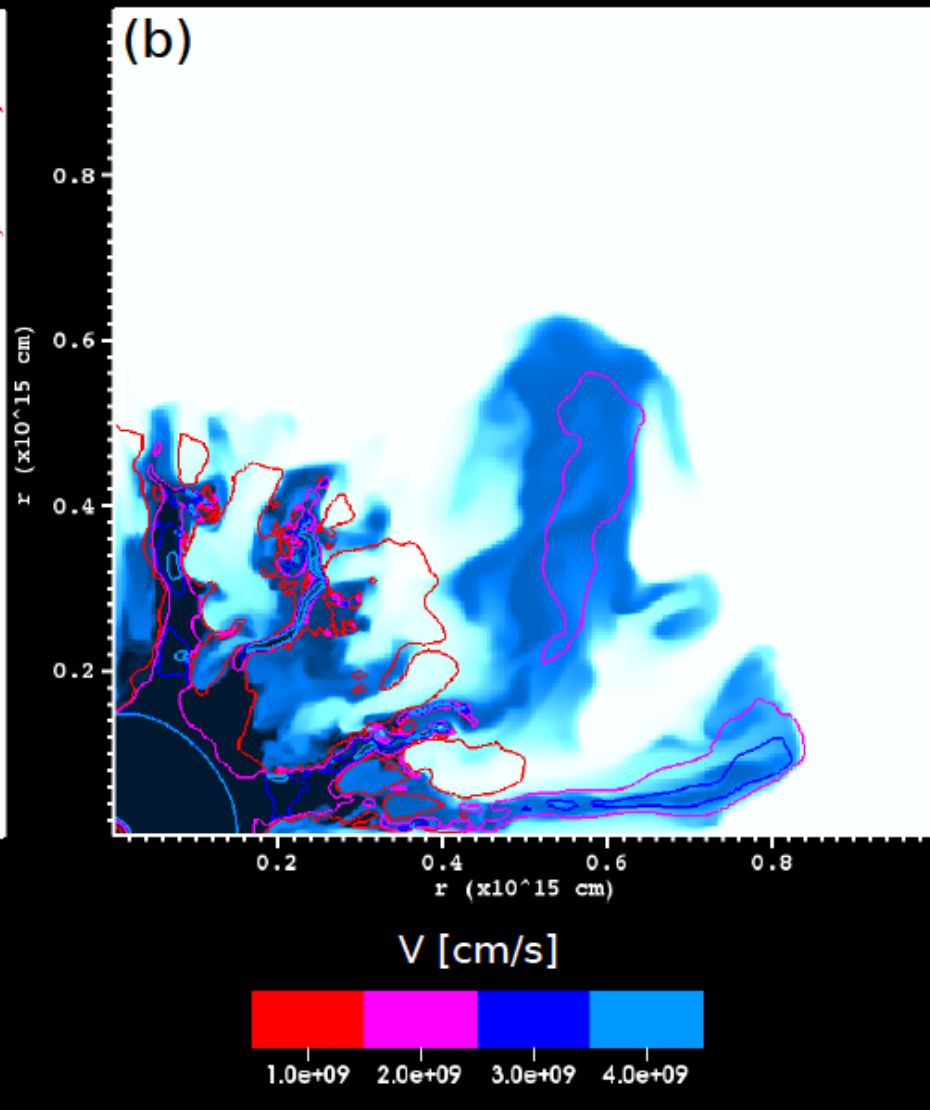


Radiation Breakout

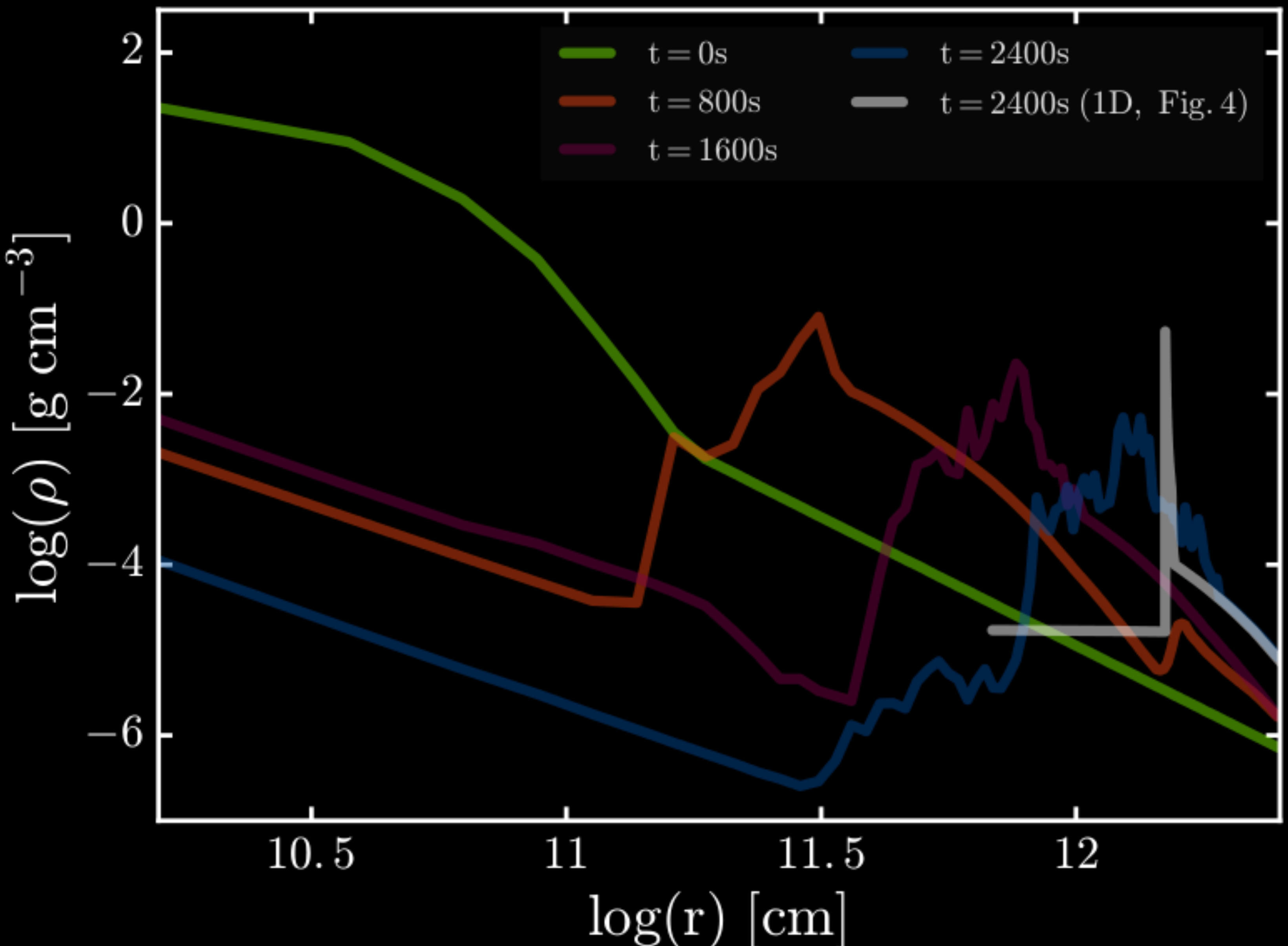
P = 1 ms, B = 4e14 G



P = 5 ms, B = 4e14 G

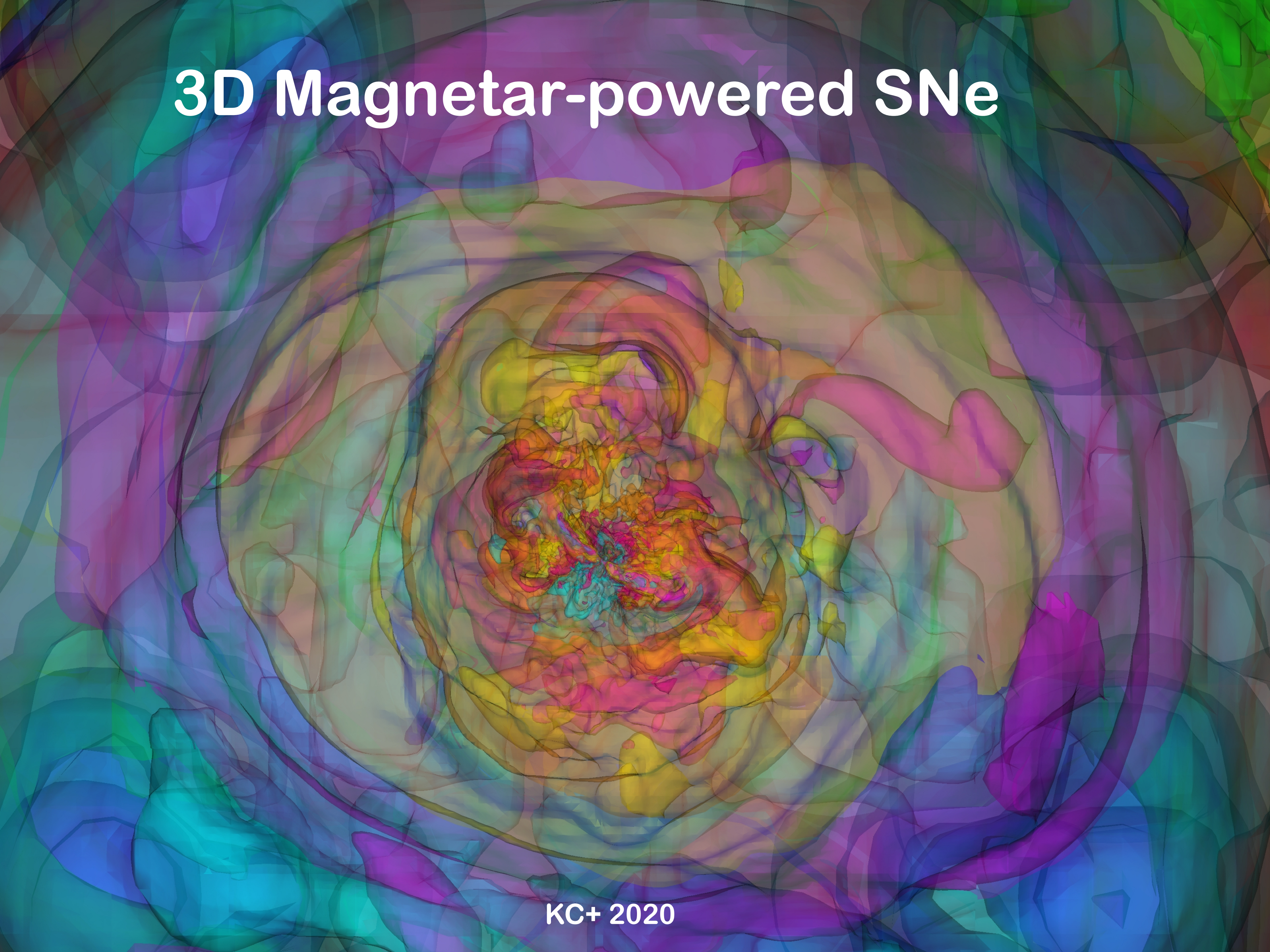


1D vs 2D



t = 0s
t = 800s
t = 1600s
t = 2400s
t = 2400s (1D, Fig. 4)
log(ρ) [g cm^−3]
2
0
−2
−4
−6
10.5
11
11.5
12
log(r) [cm]

3D Magnetar-powered SNe



KC+ 2020

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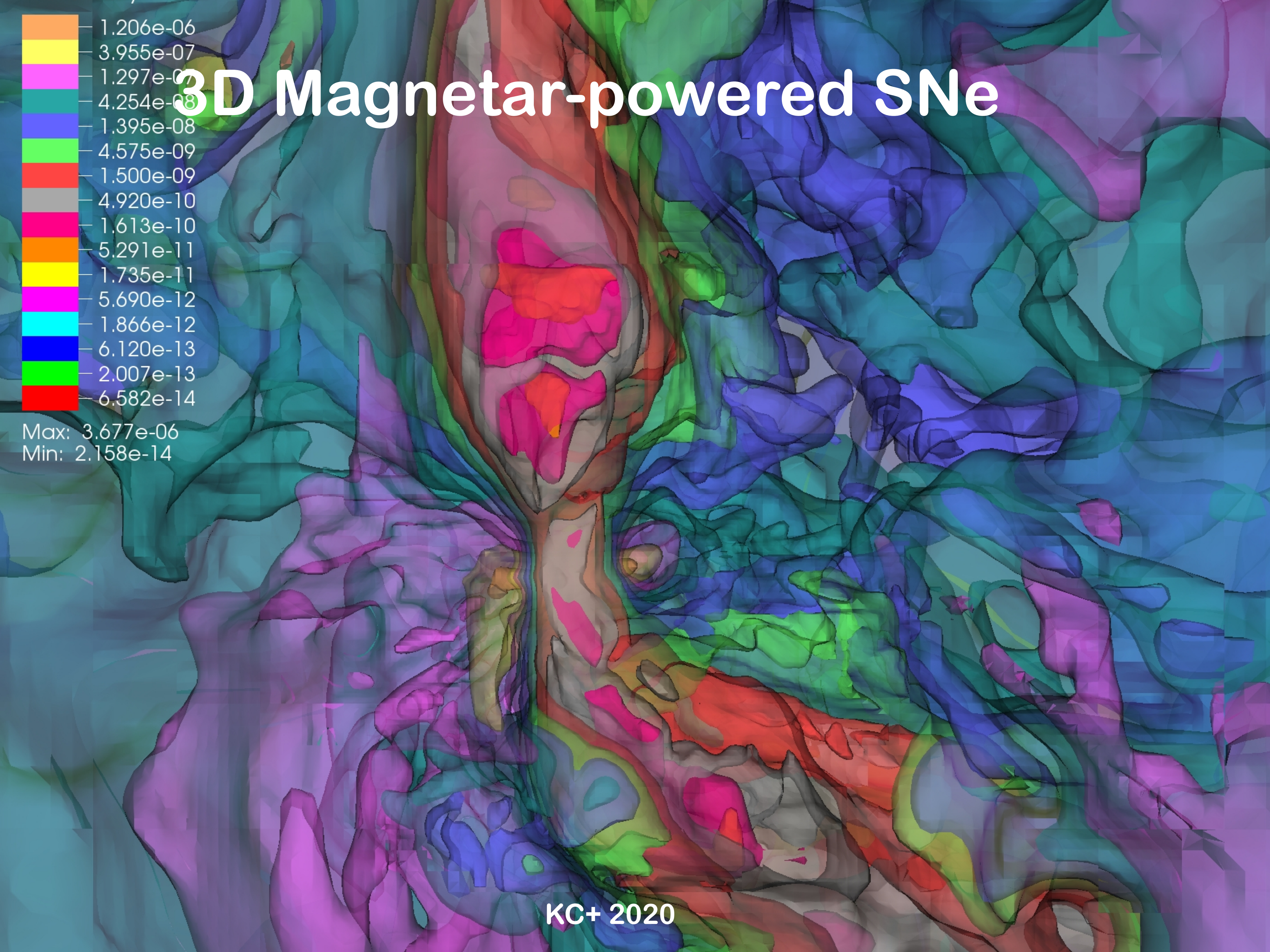

KC+ 2020

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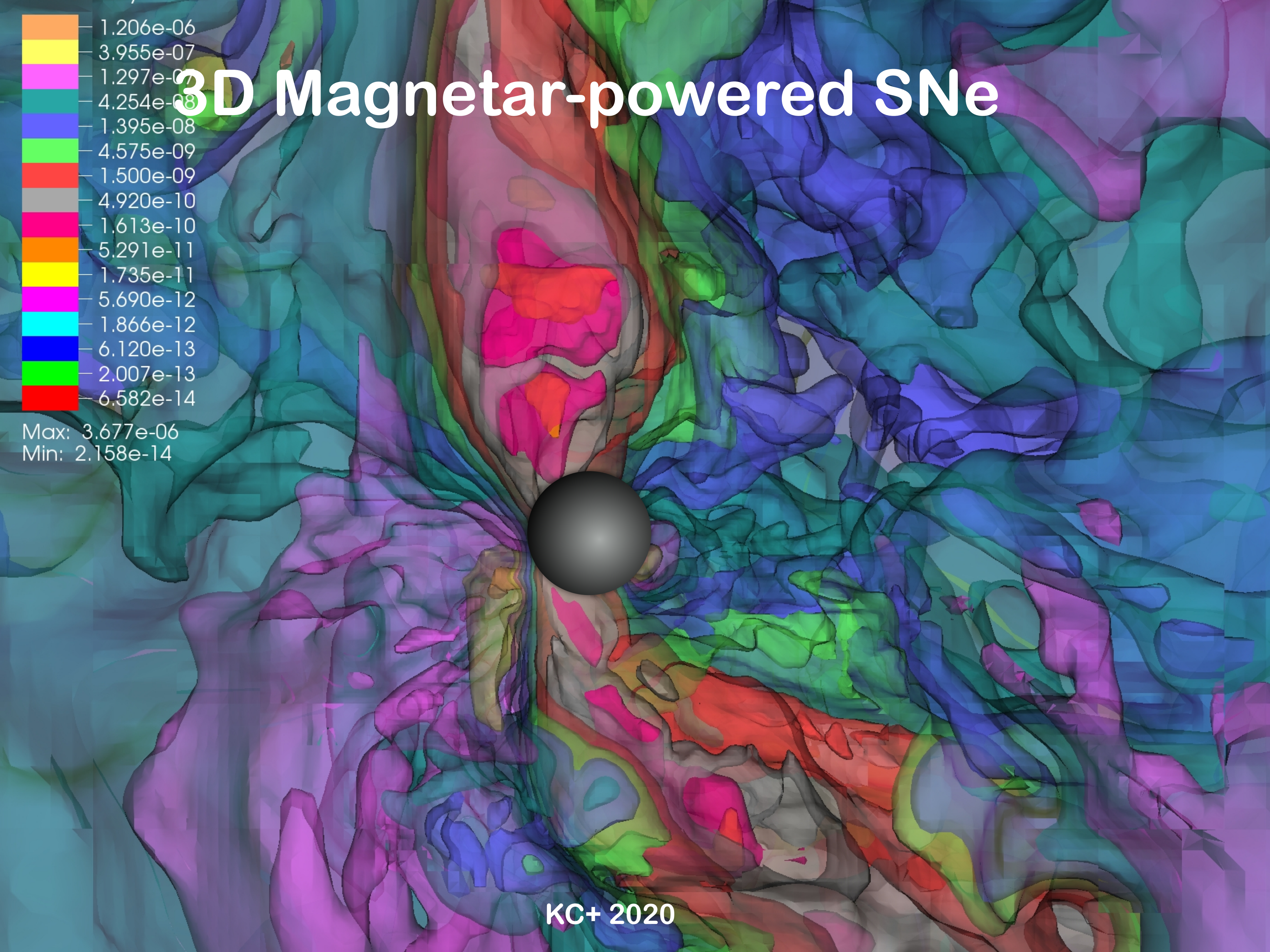
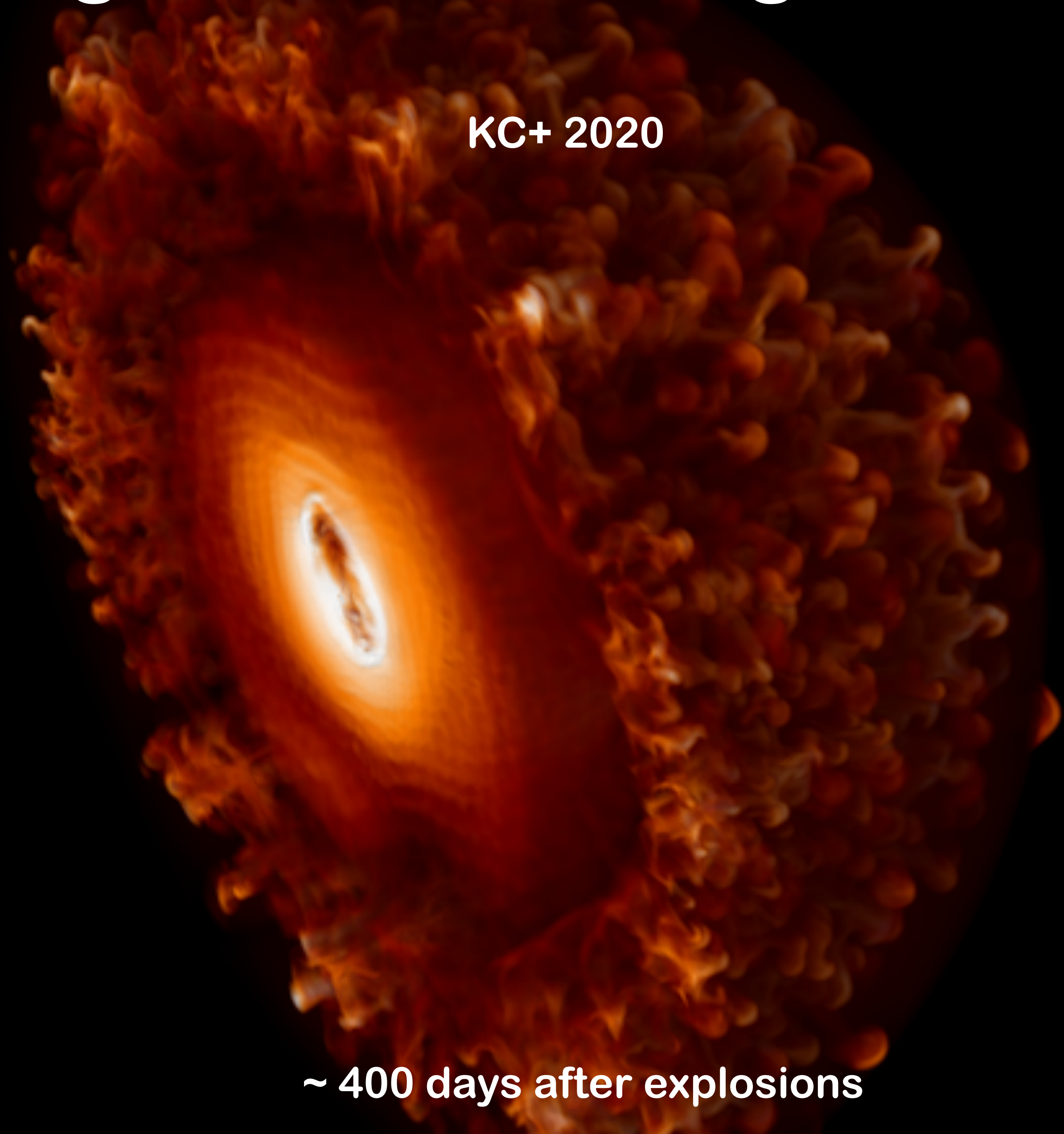


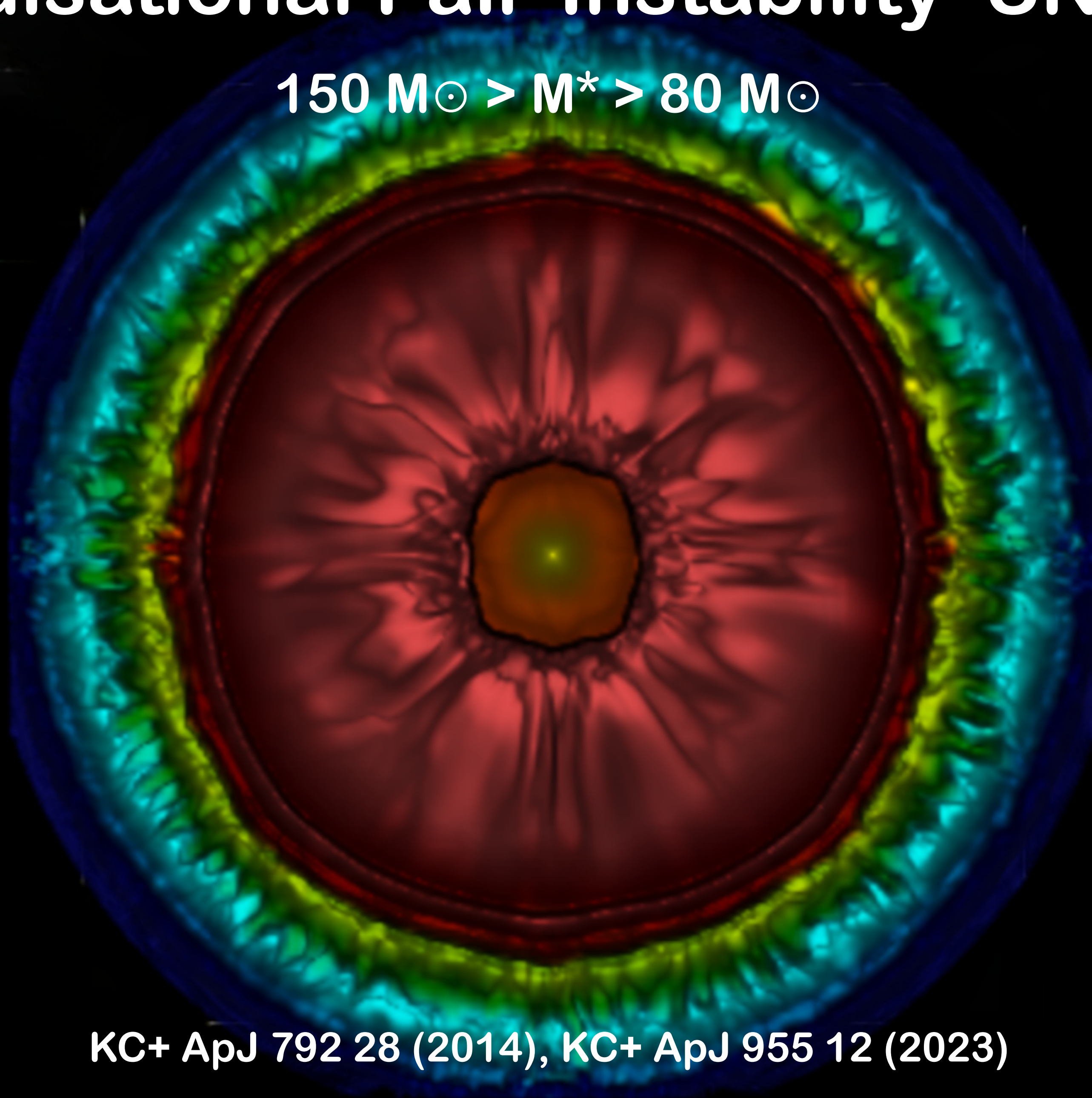
KC+ 2020

Bridging the Central Magnetar to its SNR

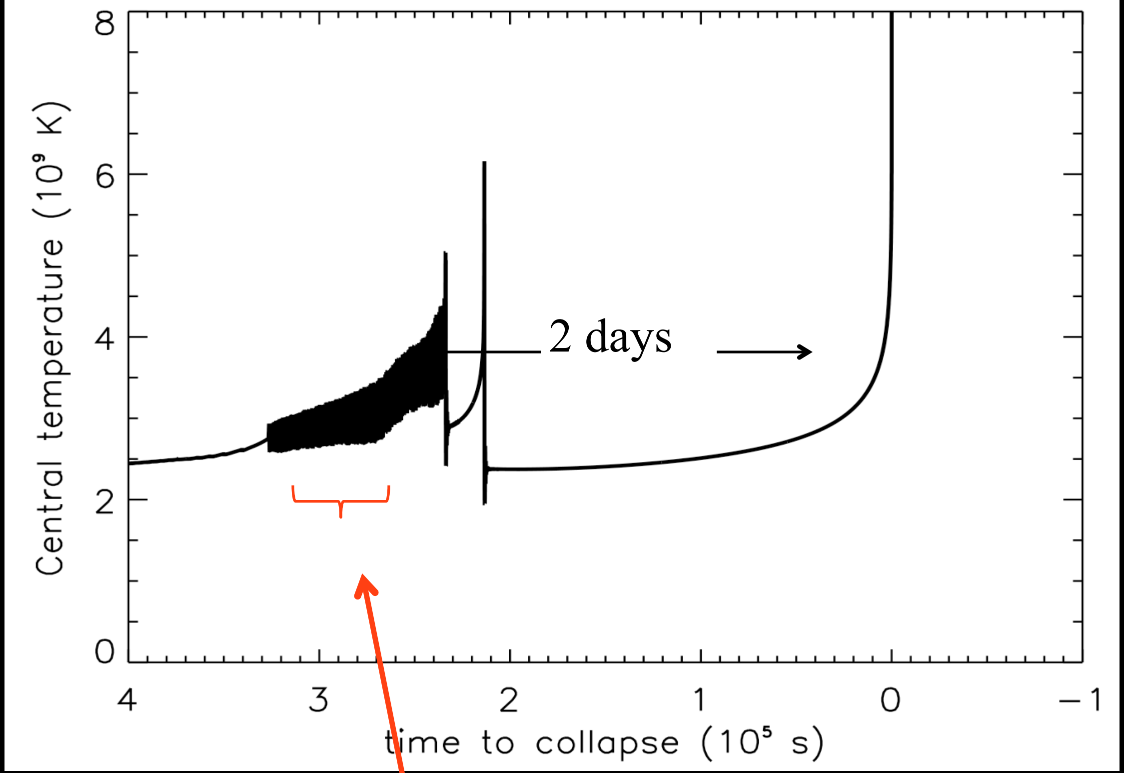


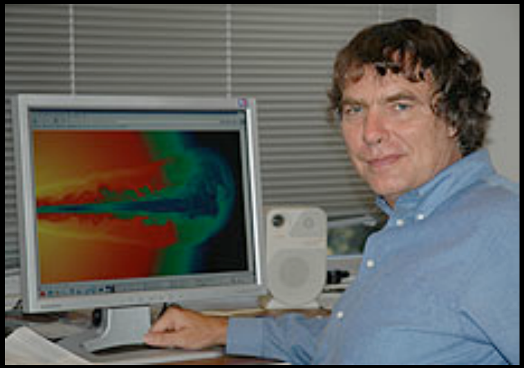
Pulsational Pair-Instability SNe

150 M⊙ > M* > 80 M⊙



KC+ ApJ 792 28 (2014), KC+ ApJ 955 12 (2023)

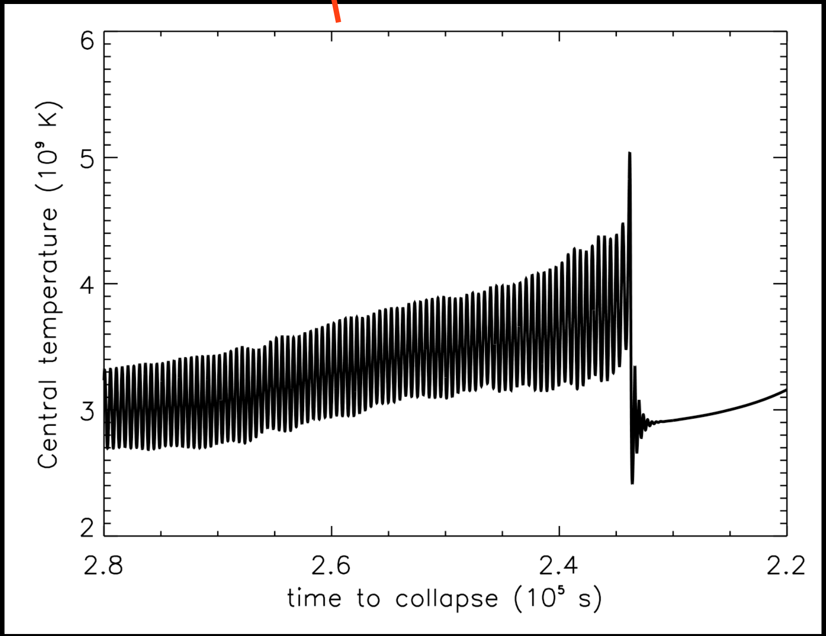




Based on Stan's Model

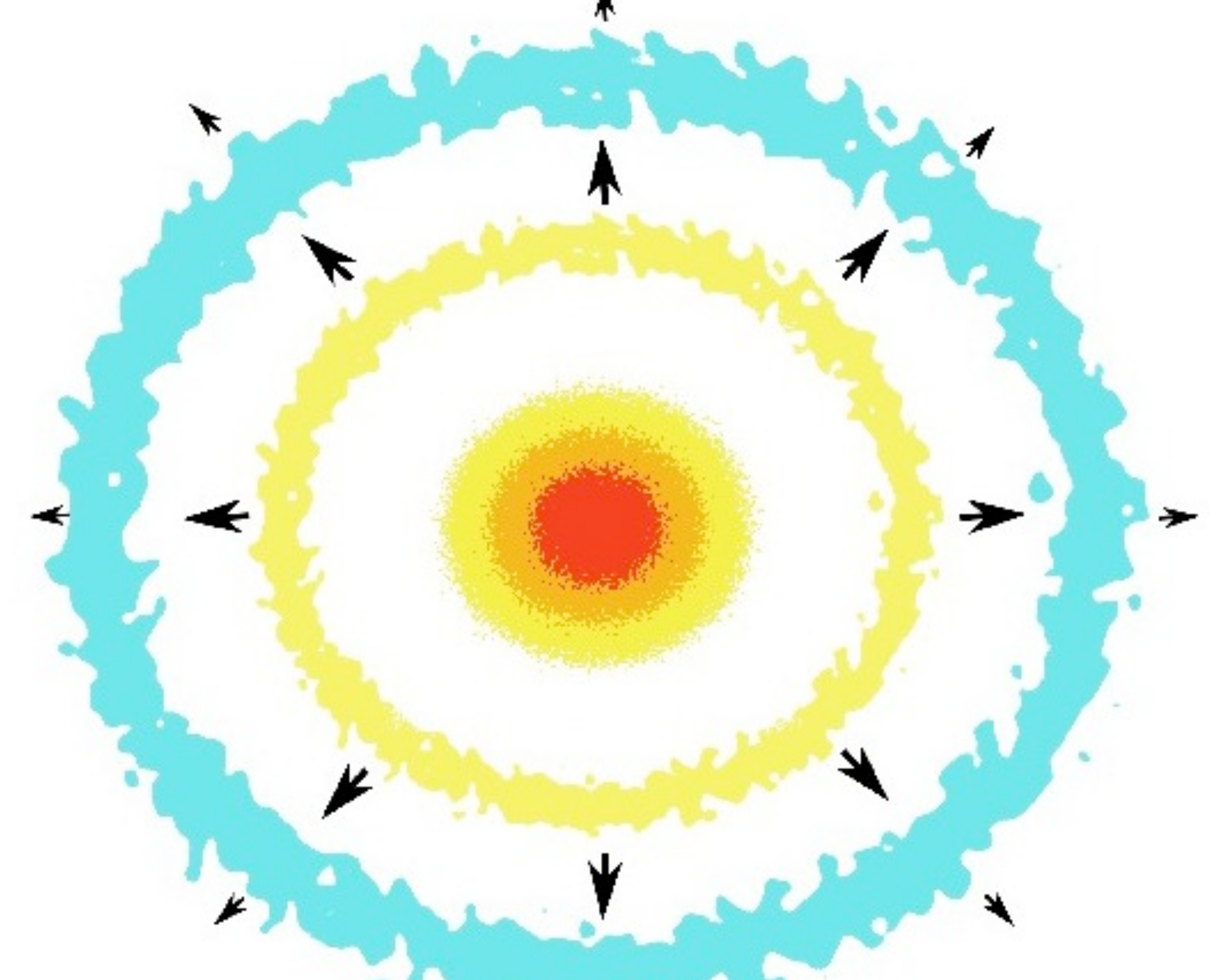
Woosley+ 2007, Woosley 2017

Woosley Priv. Comm.

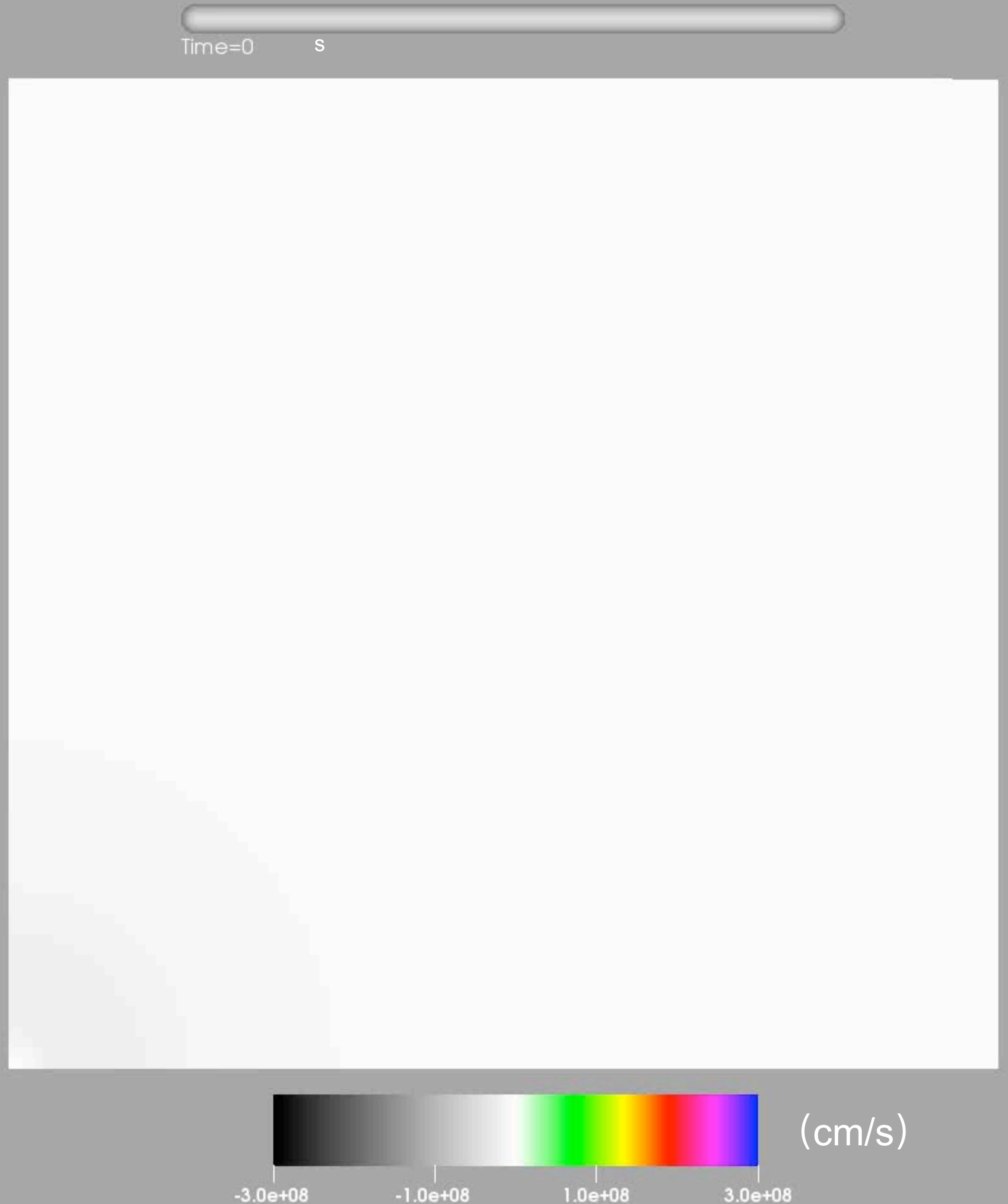


90 M⊙
Helium core 41.3 M⊙

For still larger helium cores, the pulses become more violent and the intervals between them longer. Multiple supernovae occur but usually just one of them is very bright.



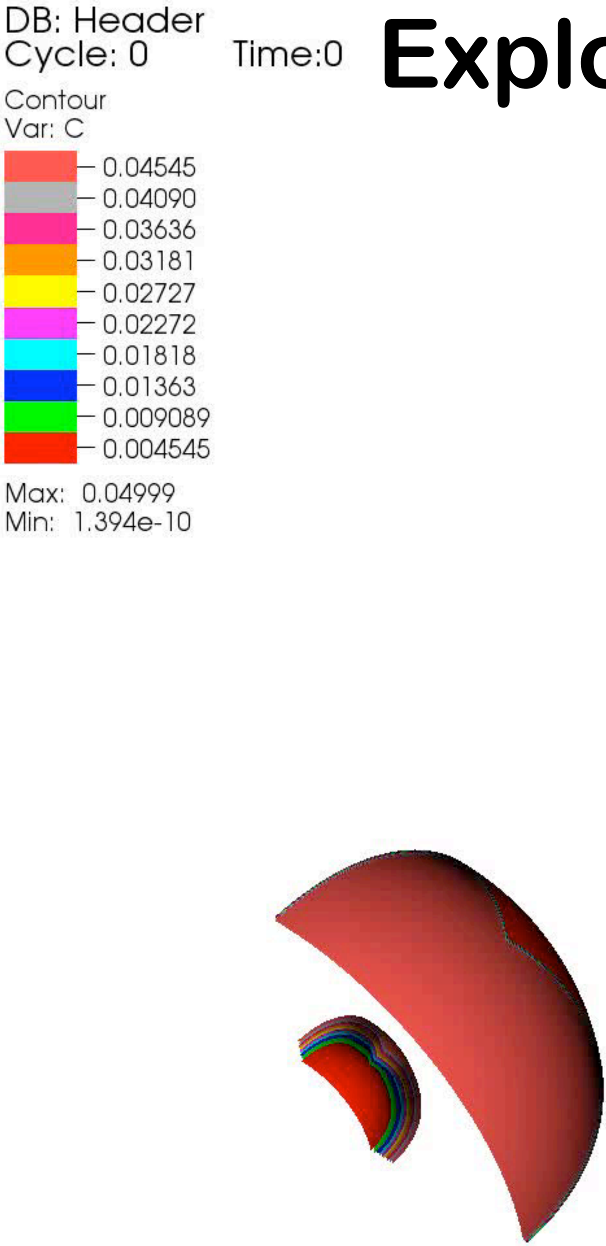
Core of 110 M⊙ star



Core of 110 $M_\odot$ star

Explosive Burning of (P)PSNe

KC+ 2011, KC+ 2014



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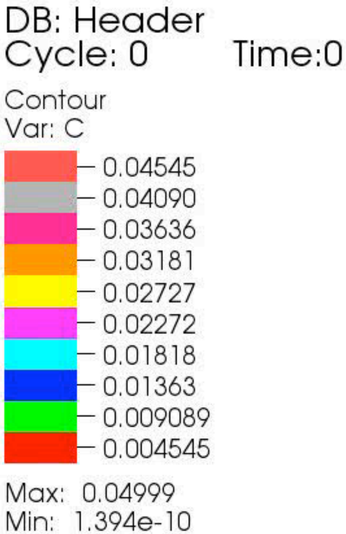
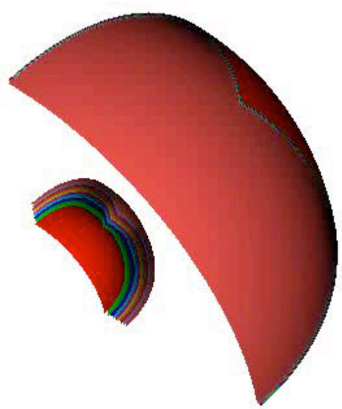
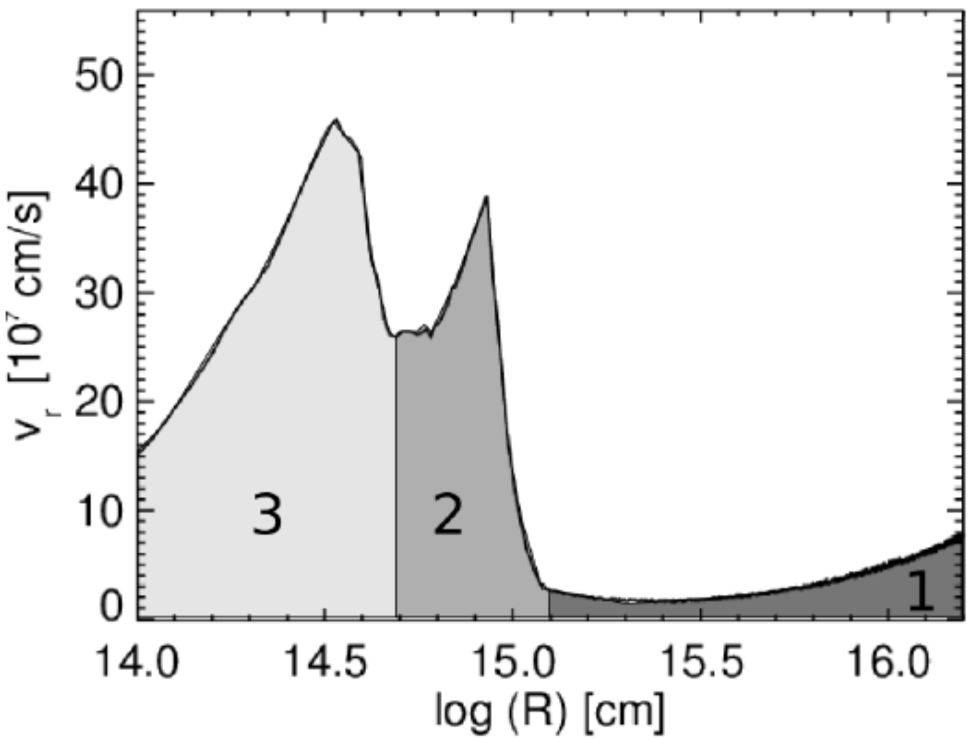


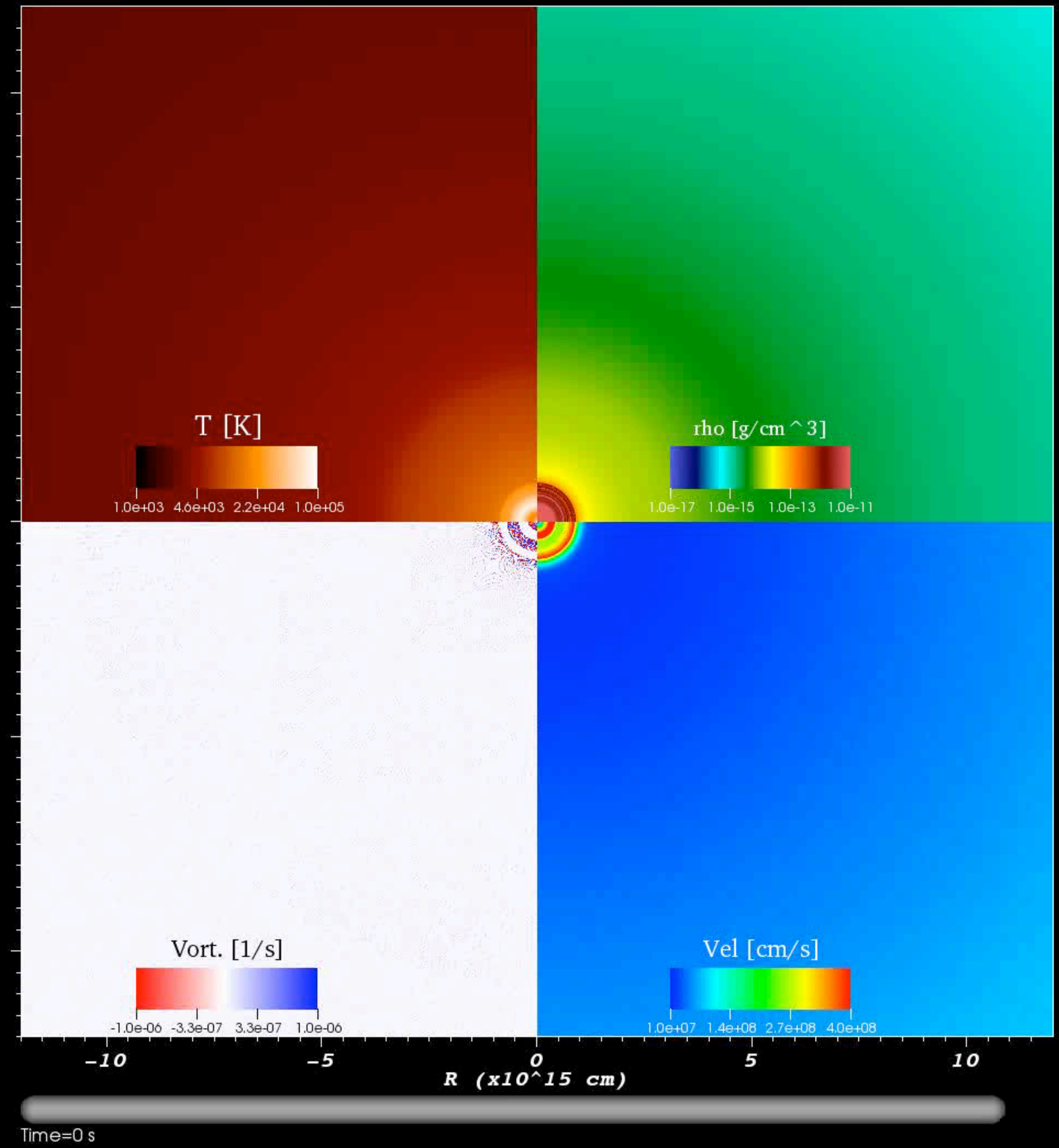


Eruption History

The star produces three violent outbursts.The first, P1, ejects most of the hydrogen envelope, making a faint Type II supernova and leaving a residual of 50.7 Msun, just a bit more than the helium core itself. After 6.8 yr, the core again contracts and encounters the pair instability, twice in rapid succession. The total mass of the second and third pulses (P2 and P3) is 5.1 Msun and their kinetic energy is 6e50 erg. P3 collides with P2 at large optical depths that are not visible to an external observer. These combined shells then overtake P1 at 1e15 cm and speeds of a few 1000 km/s.



Physical Properties of Colliding Shells



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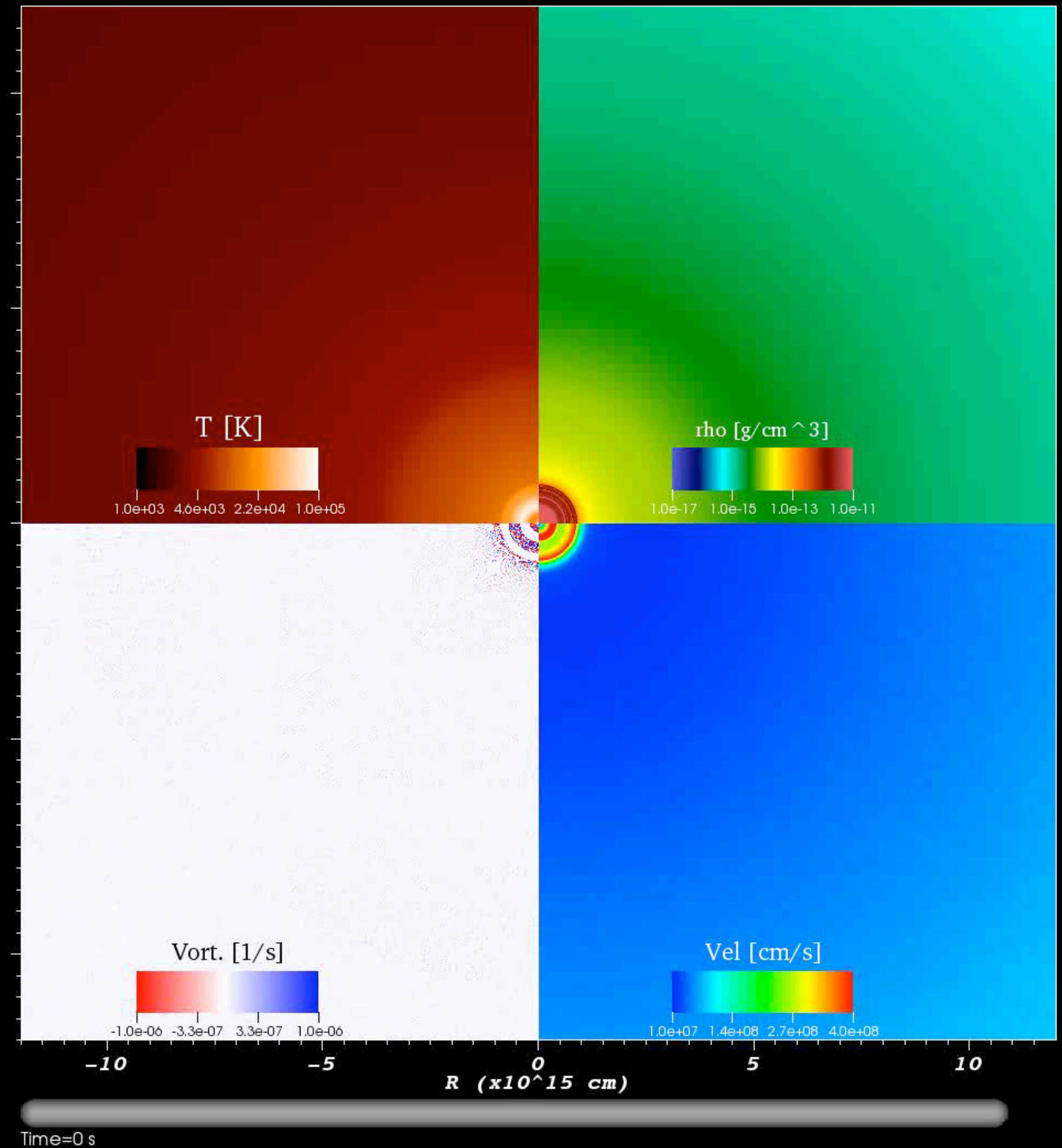

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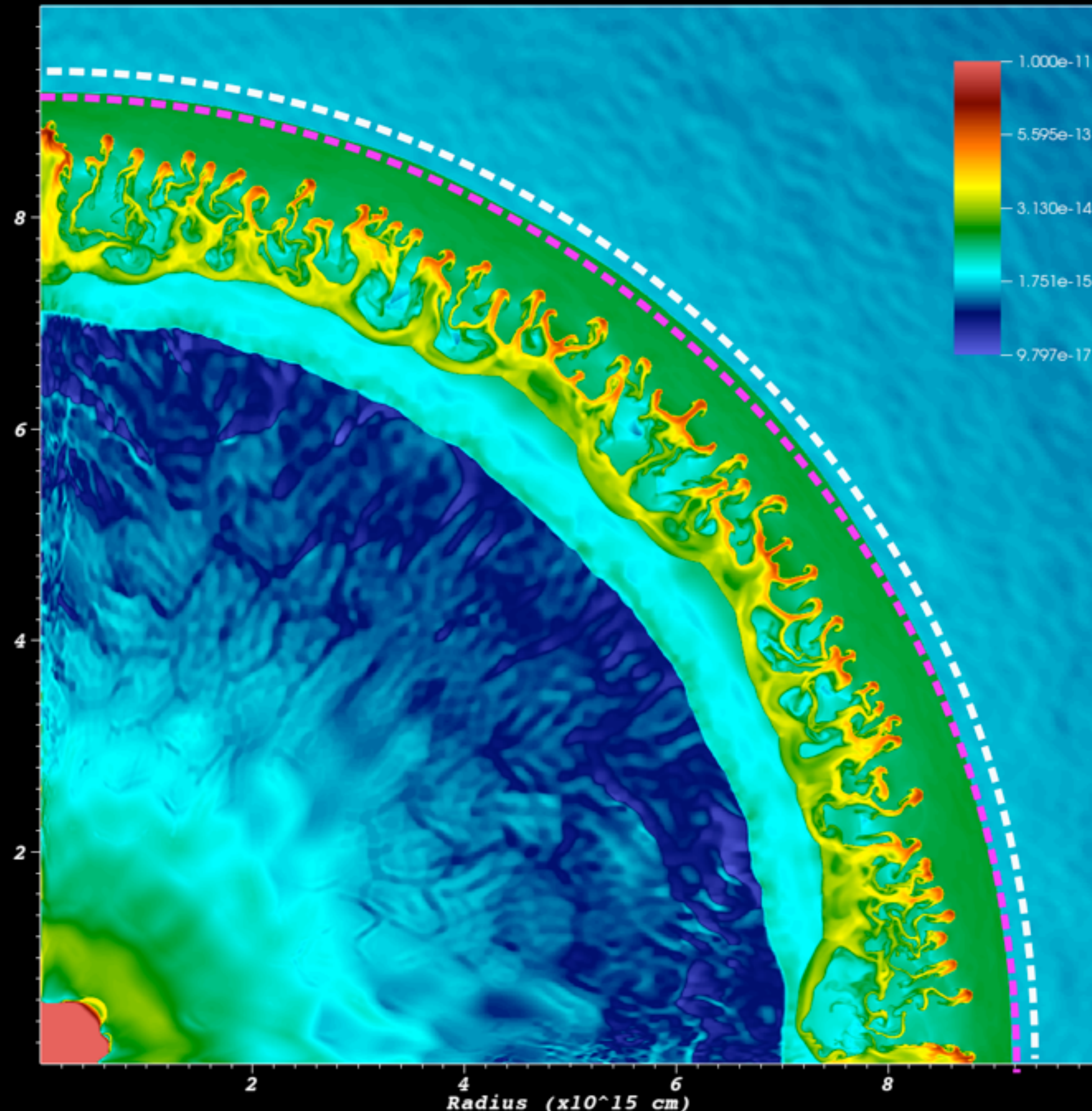
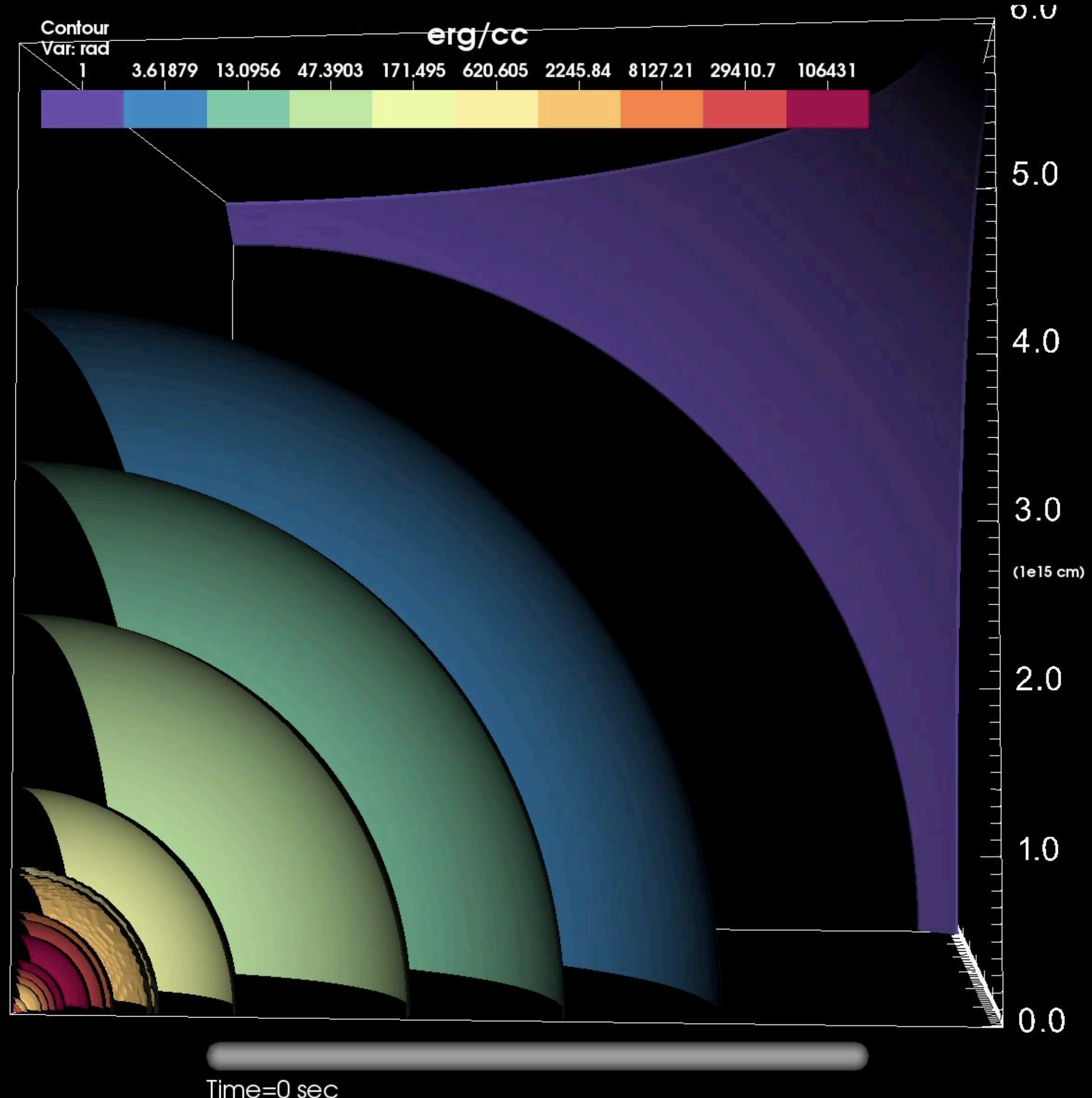


1D+2D+3D Radiation Transport Simulations of PPSNe

KC+ 2023



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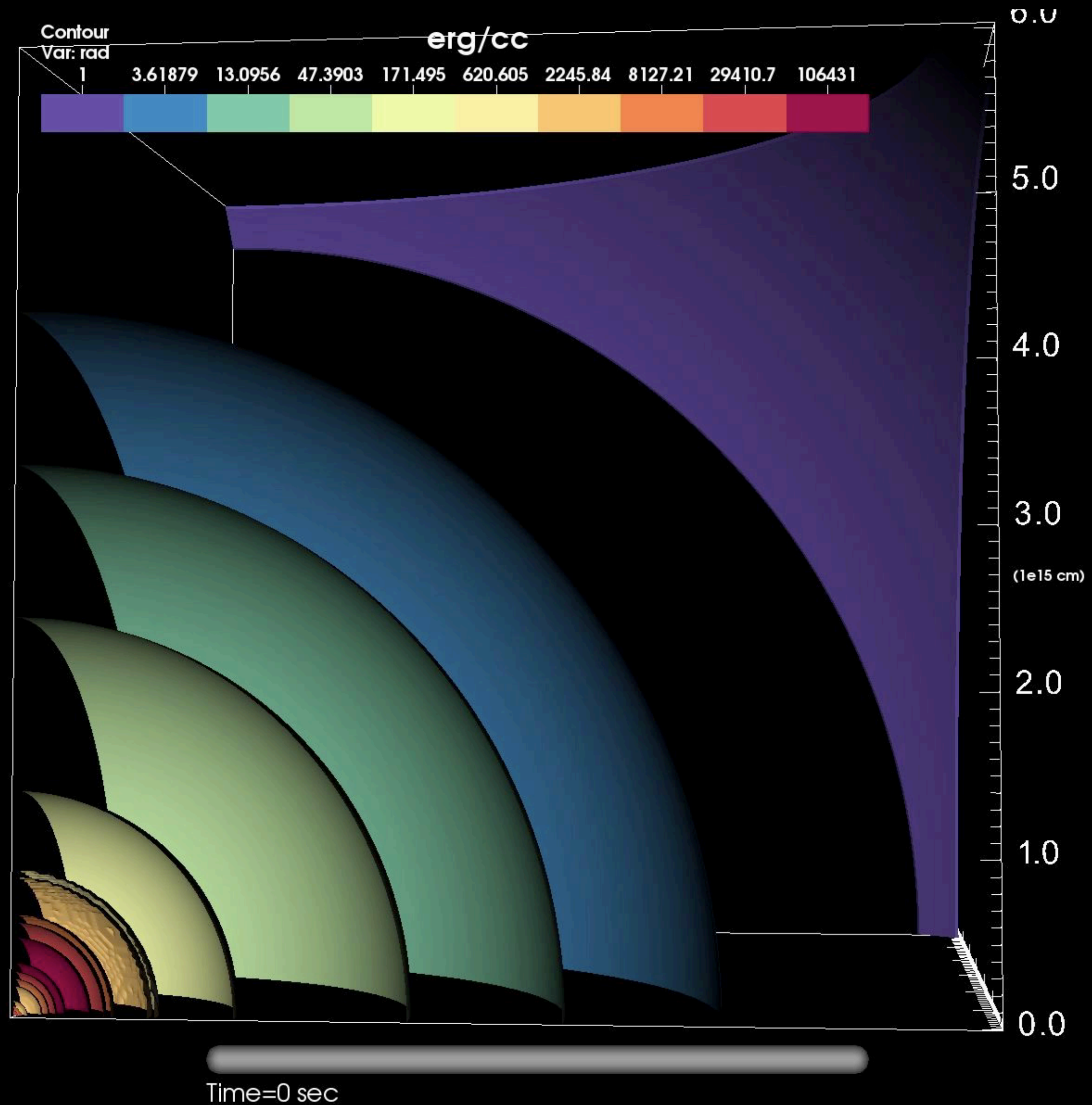
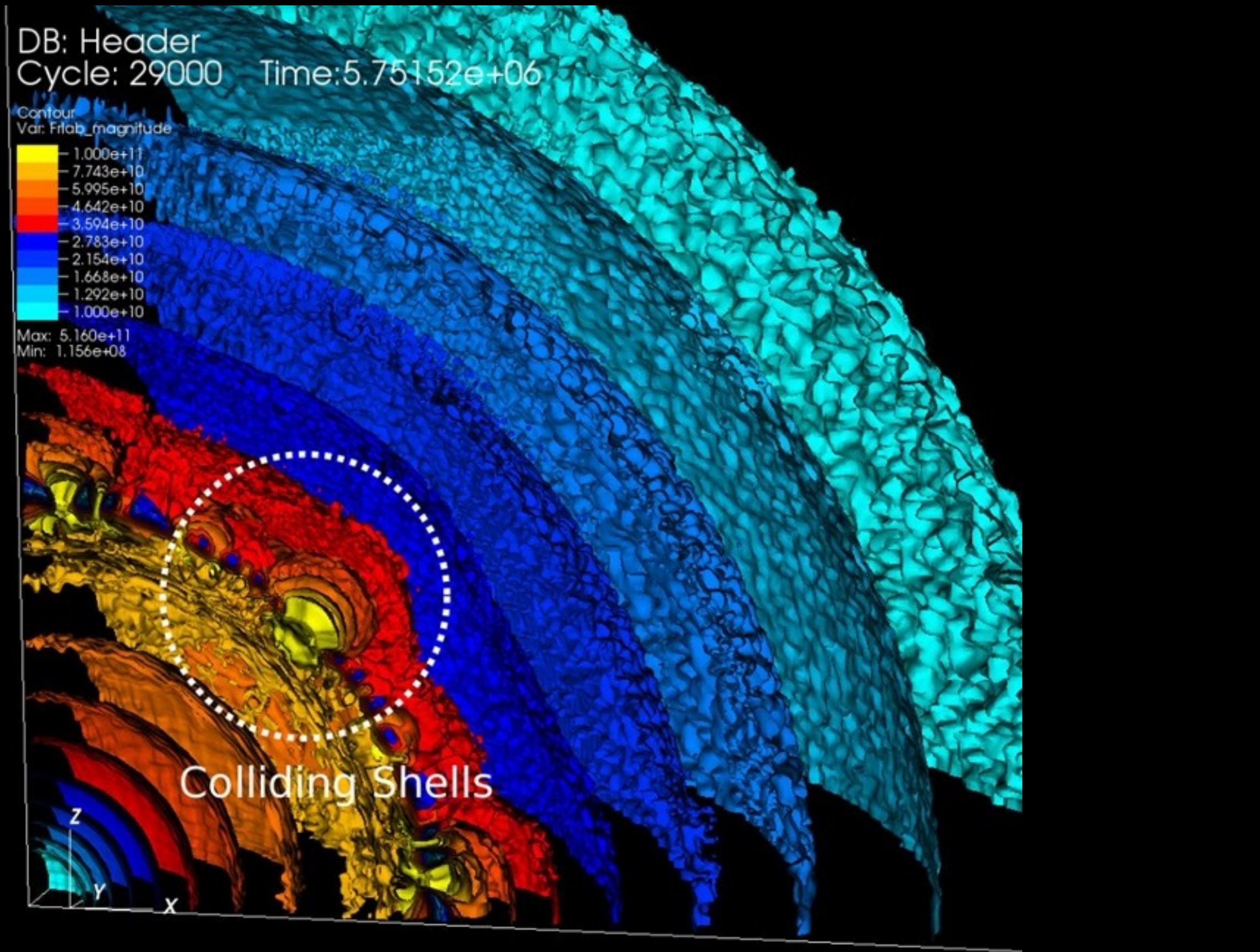
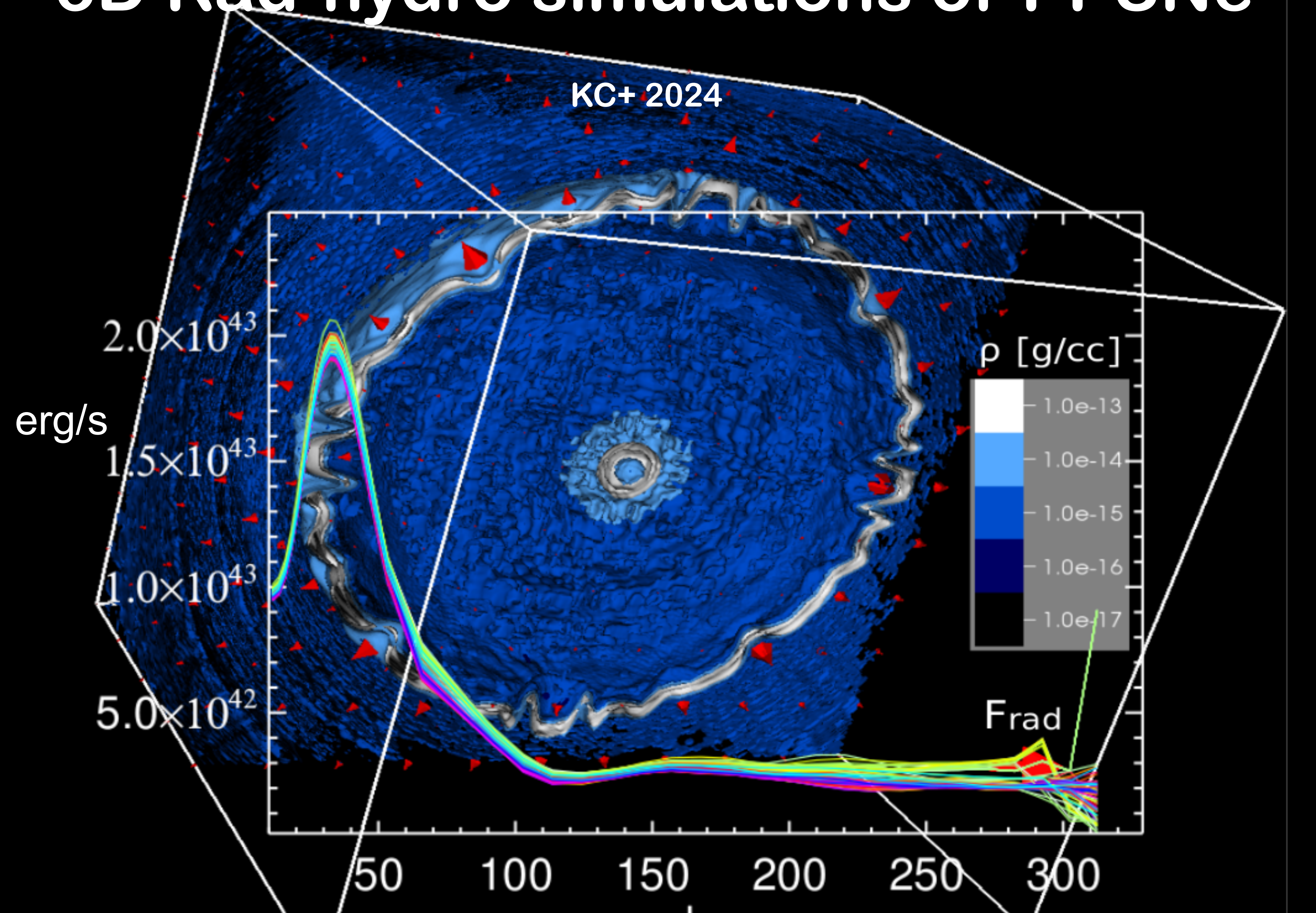


1D+2D+3D Radiation Transport Simulations of PPSNe

KC+ 2023



3D Rad-hydro simulations of PPSNe



Take Home Message

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- Violent mixing occurs at phases of explosions
- Drivers of mixing contain rich physics
- Mixing physics in 1D SN light curves and spectra is completely missing
- Multi-D rad-hydro simulations are powerful tools to model the mixing and signatures properly.