Mixing in Stellar Explosions

Ke-Jung (Ken) Chen
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ASIAA(中研院天文所)

Seminar, Tokyo U., 11/06/2019

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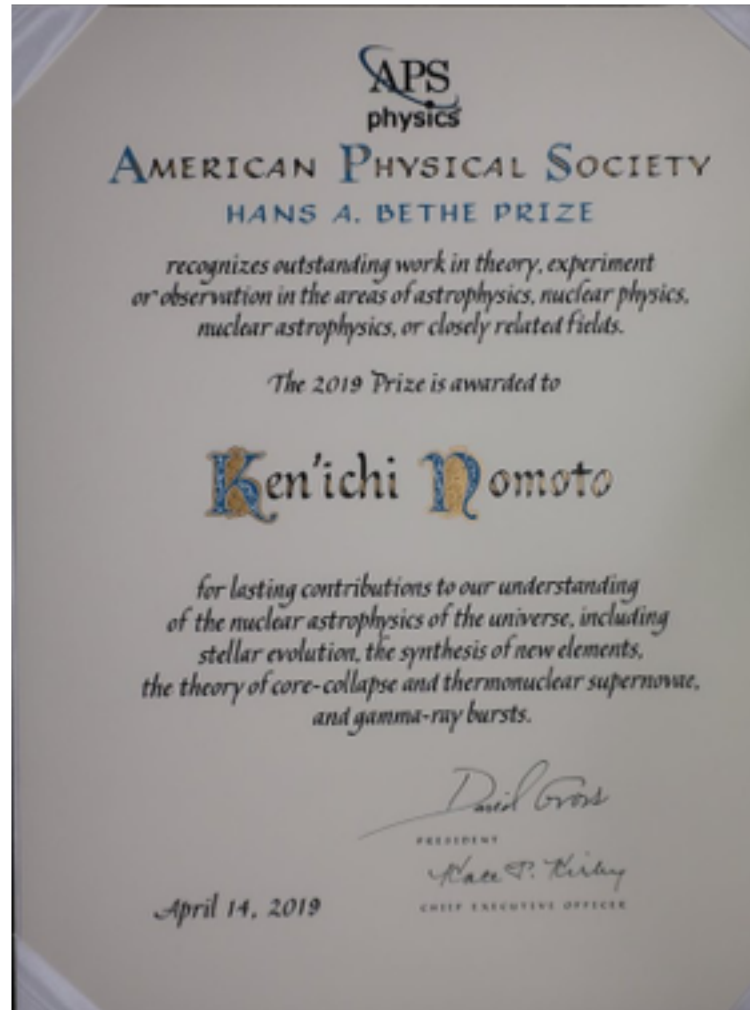

APS physics
American Physical Society
HANS A. BETHE PRIZE
recognizes outstanding work in theory, experiment or observation in the areas of astrophysics, nuclear physics, nuclear astrophysics, or closely related fields.
The 2019 Prize is awarded to
Ken'ichi Nomoto
for lasting contributions to our understanding of the nuclear astrophysics of the universe, including stellar evolution, the synthesis of new elements, the theory of core-collapse and thermonuclear supernovae, and gamma-ray bursts.
PRESIDENT
CHIEF EXECUTIVE OFFICER
April 14, 2019

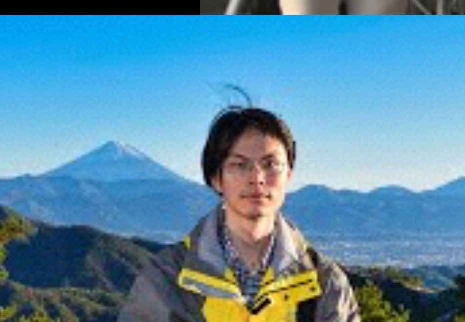
中央研究院
天文及天文物理研究所
ACADEMIA SINICA
Institute of Astronomy and Astrophysics

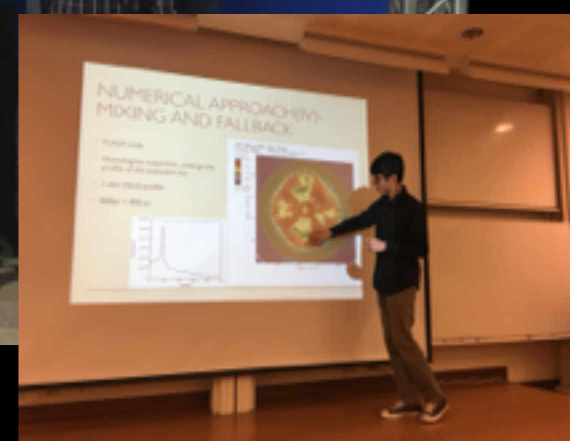
ASIAA has approximately **200 staff, including 30 faculty members.** ASIAA has access to forefront observing facilities including ALMA, SMA, JCMT, CFHT, and Subaru Telescope. We are partners in the Subaru Hyper Suprime-Cam (HSC) and Prime Focus Spectrograph (PFS) projects, and are an associate member of the SDSS-IV and LSST Surveys.

Theoretical and computational astrophysics is pursued in our theoretical division, TIARA. We aim to develop numerical simulators to bridge observations and theories in fluid dynamics, astrochemistry, and radiative transfer.

The Explosion Group at ASIAA

Since Sep. 2017 ~





Spherical Cow and Stars???

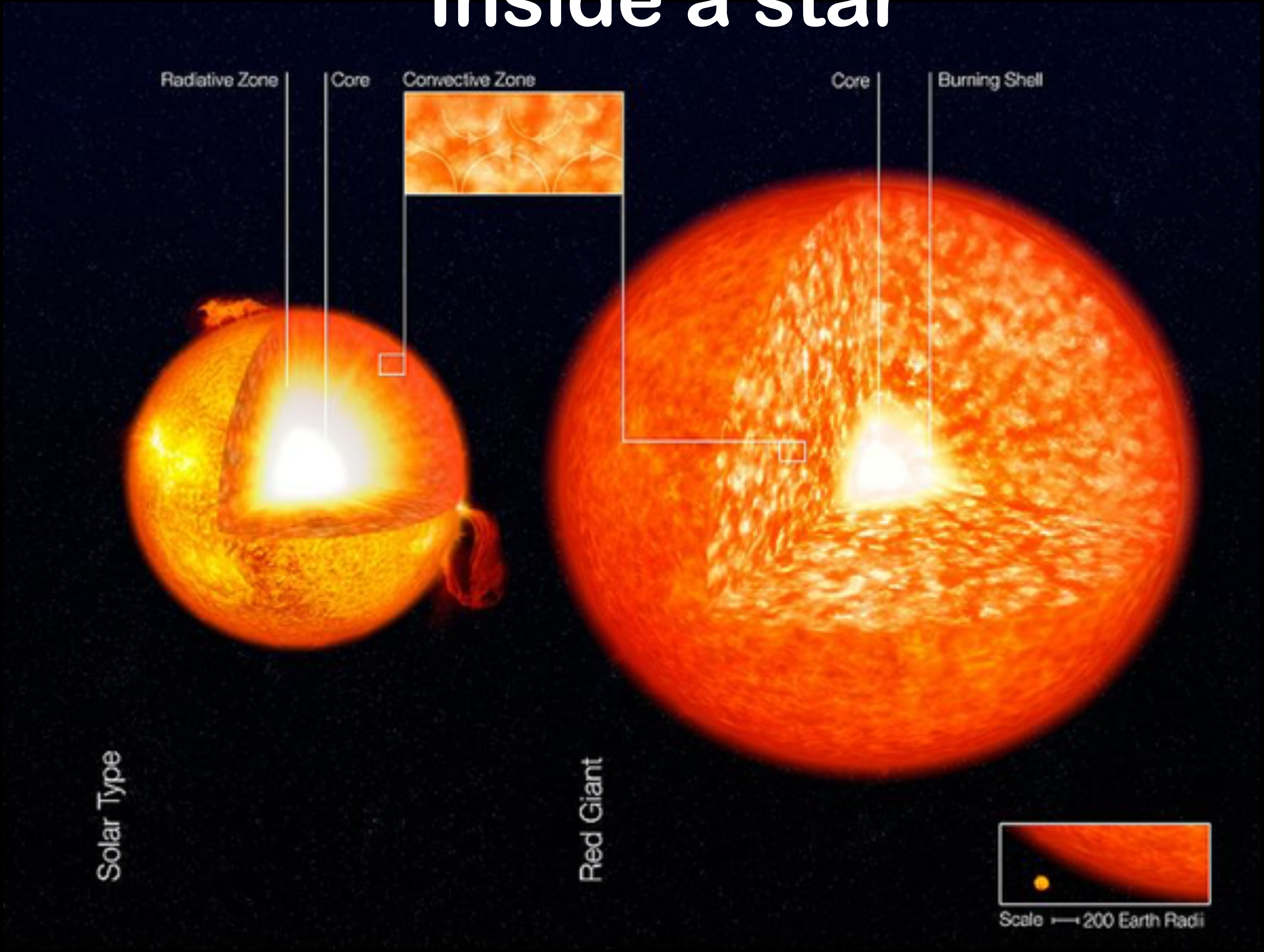
Spherical Cow and Stars???

Spherical Cow and Stars???

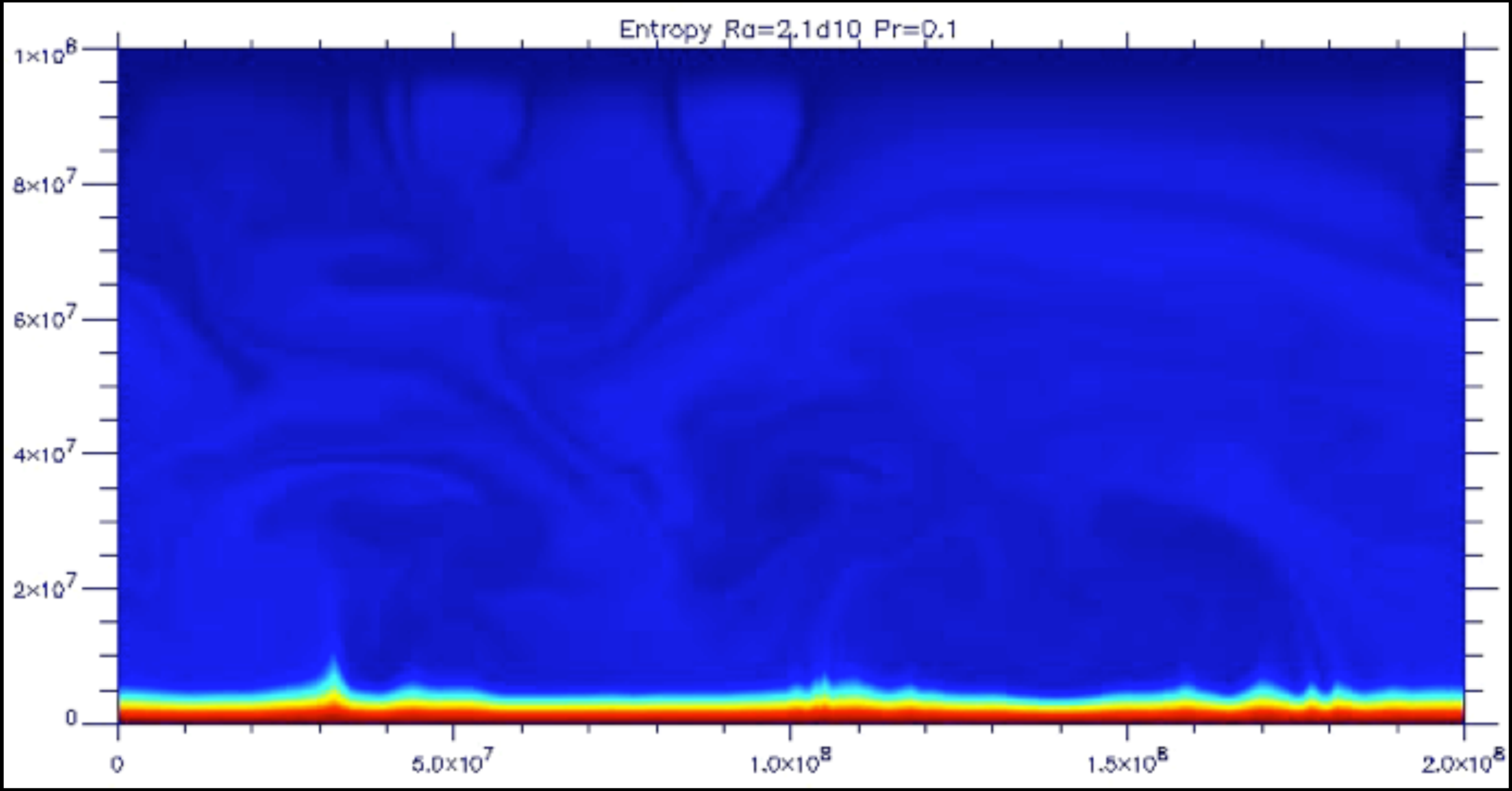
Spherical Cow and Stars???

Spherical Cow and Stars???

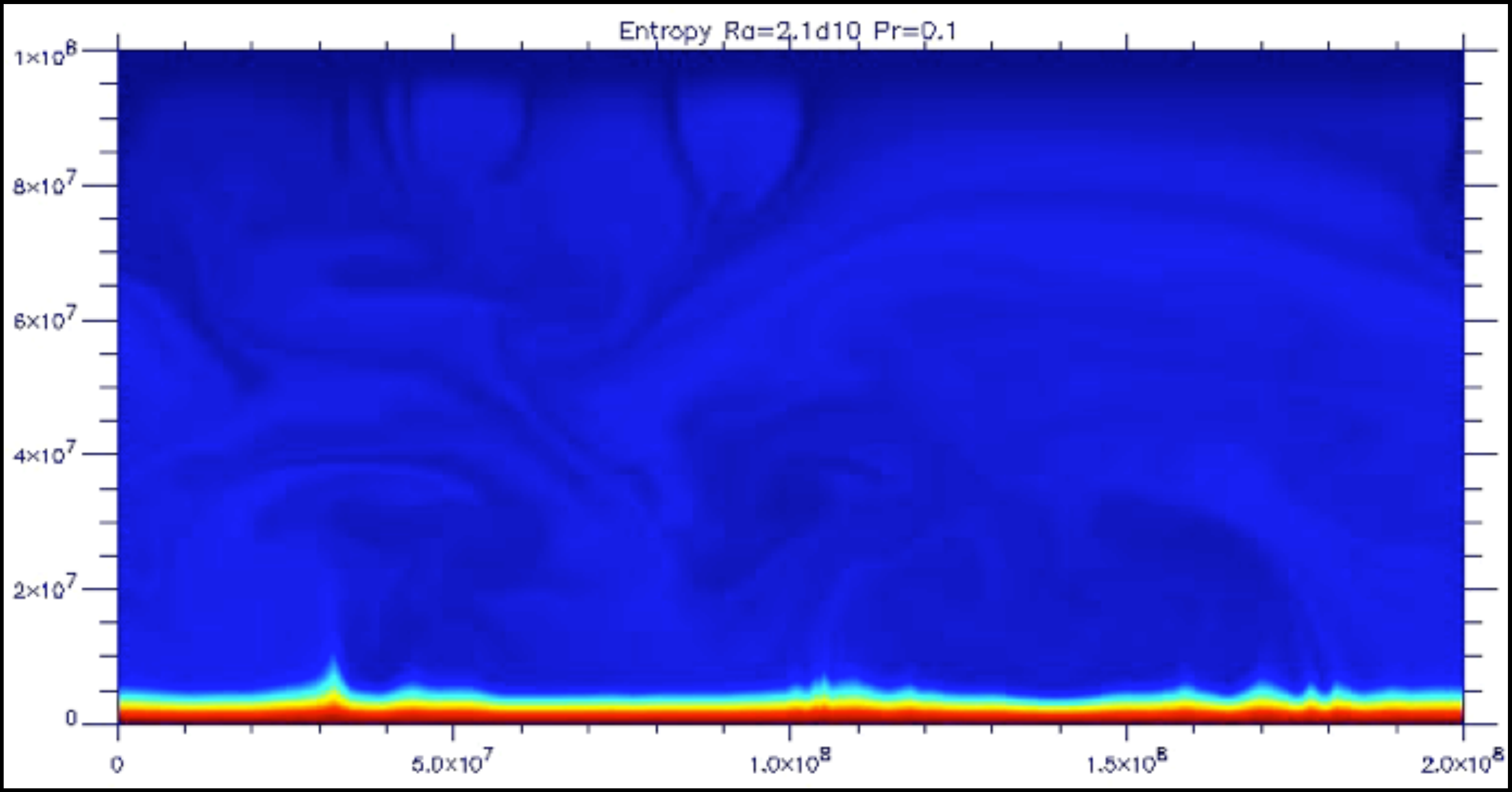
Inside a star



Physics of Convection



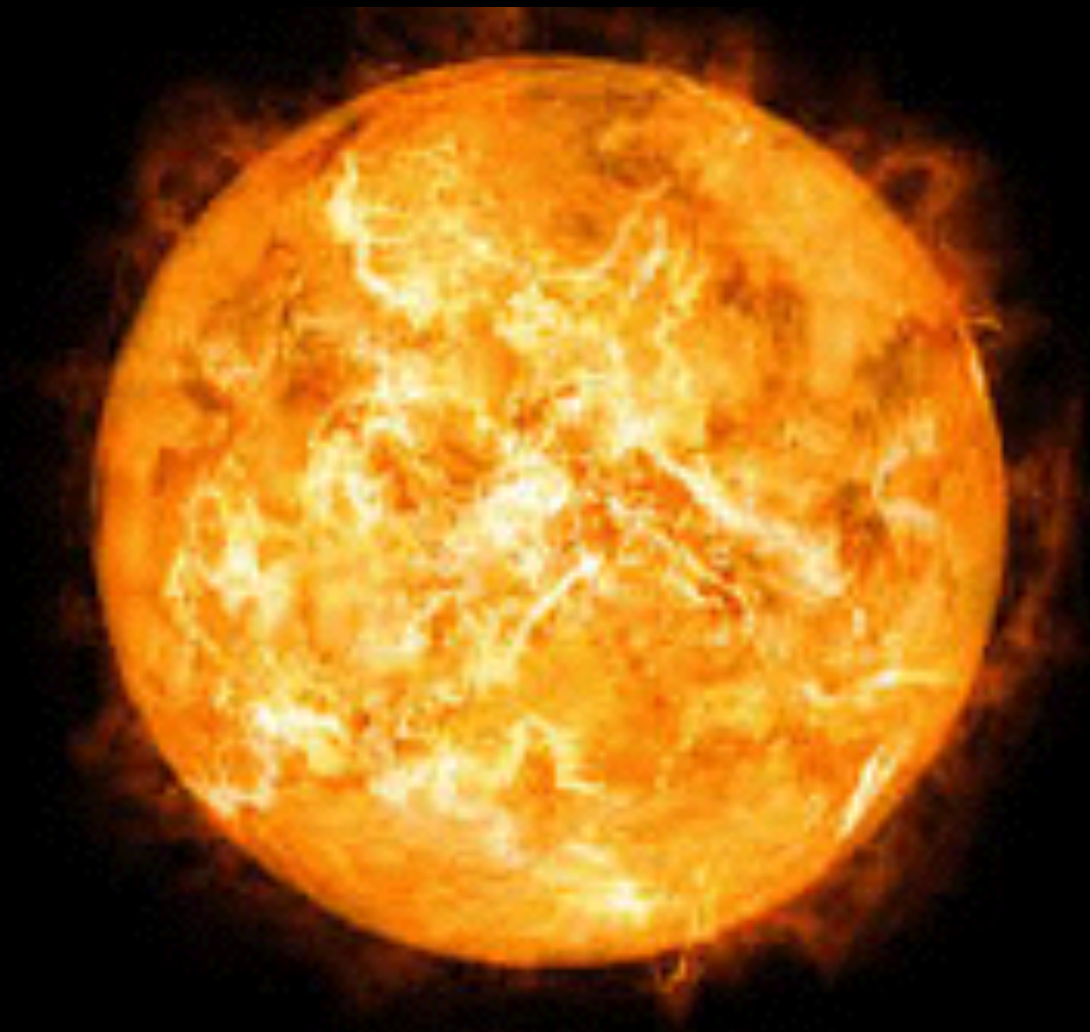
Physics of Convection



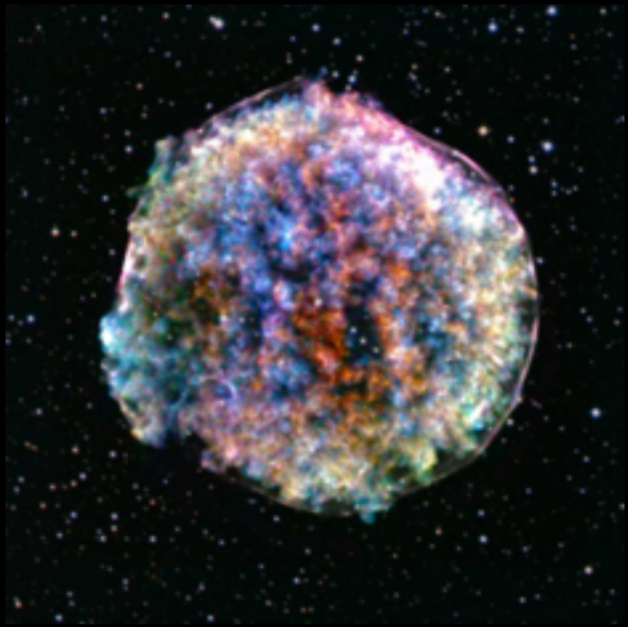
Physics of Convection

Physics of Convection

When a star blows up!



When a star blows up!



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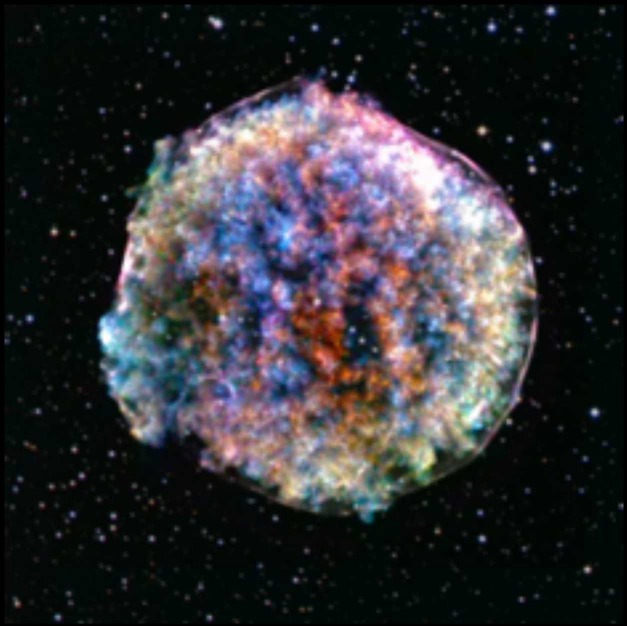

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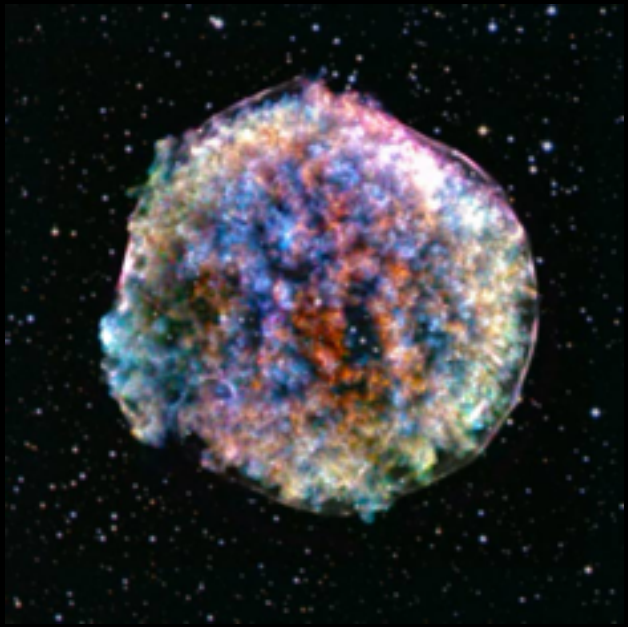
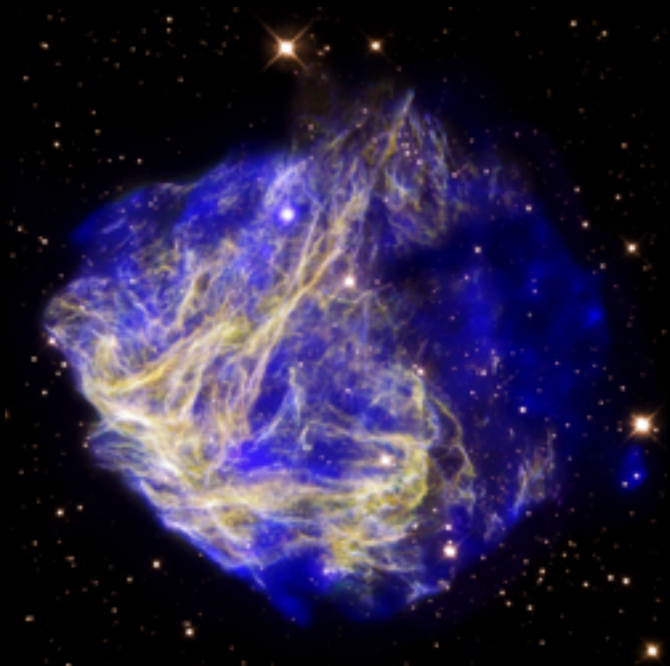
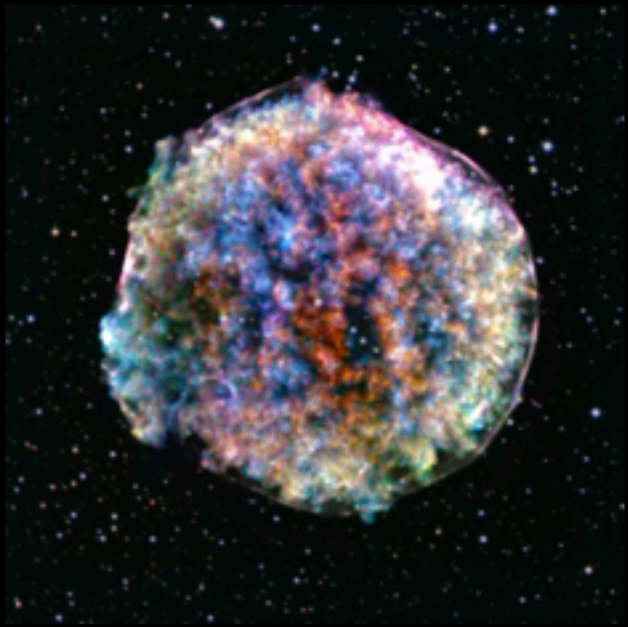
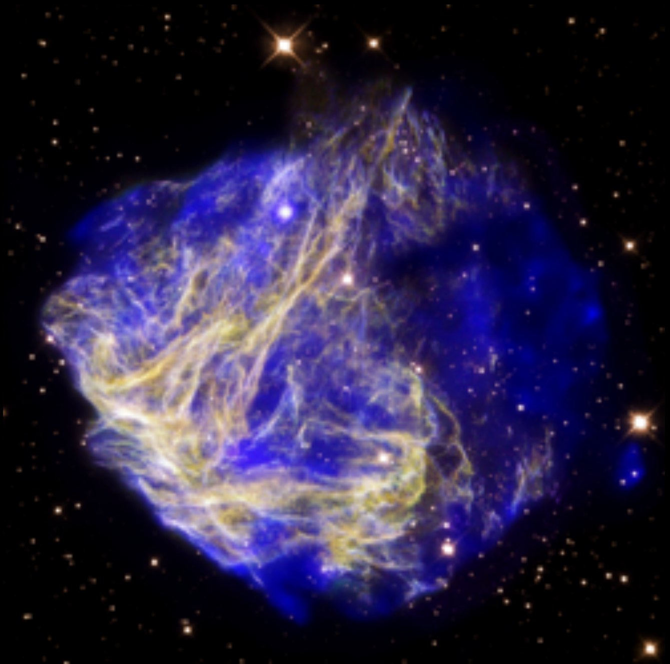




When a star blows up!





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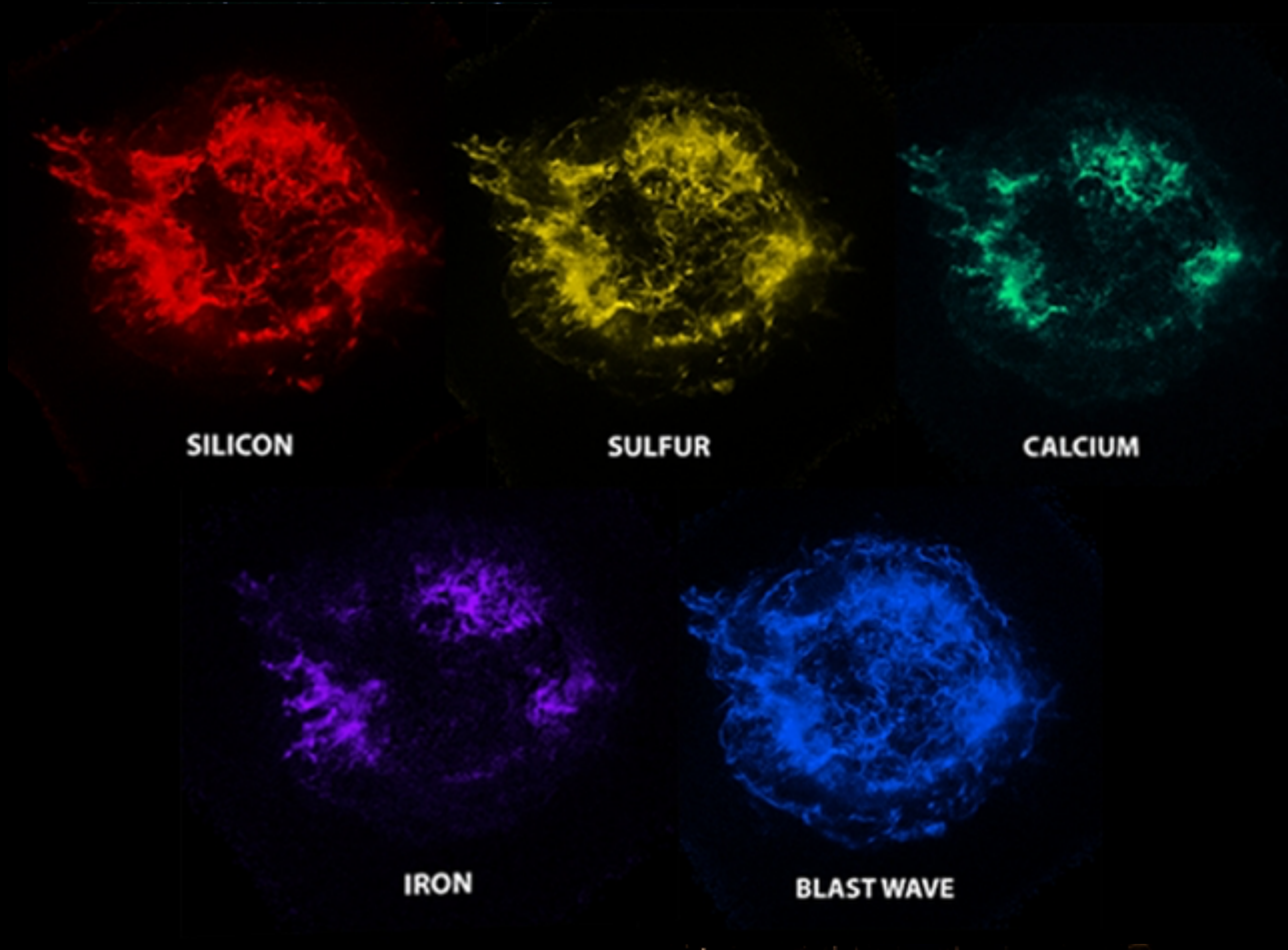
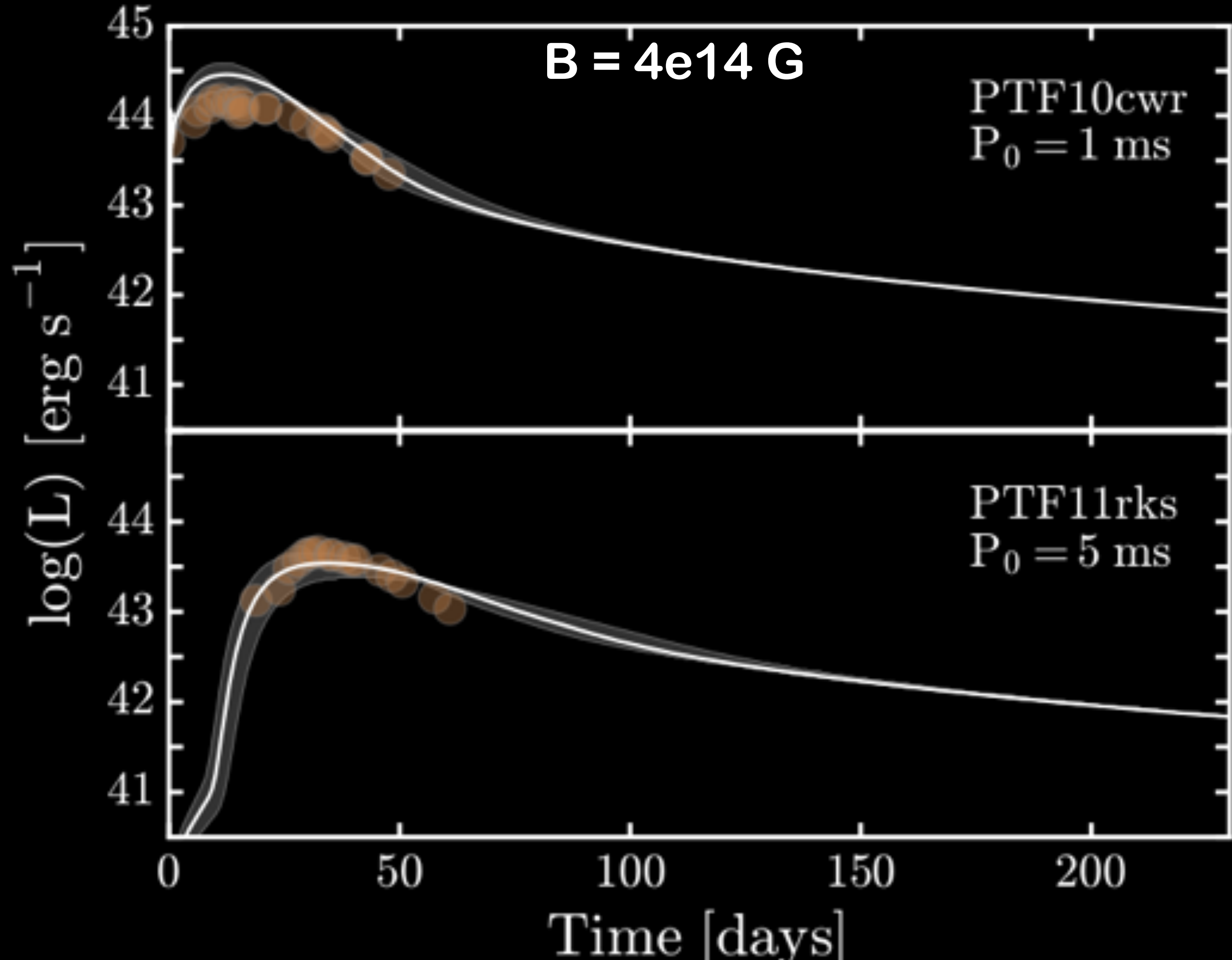


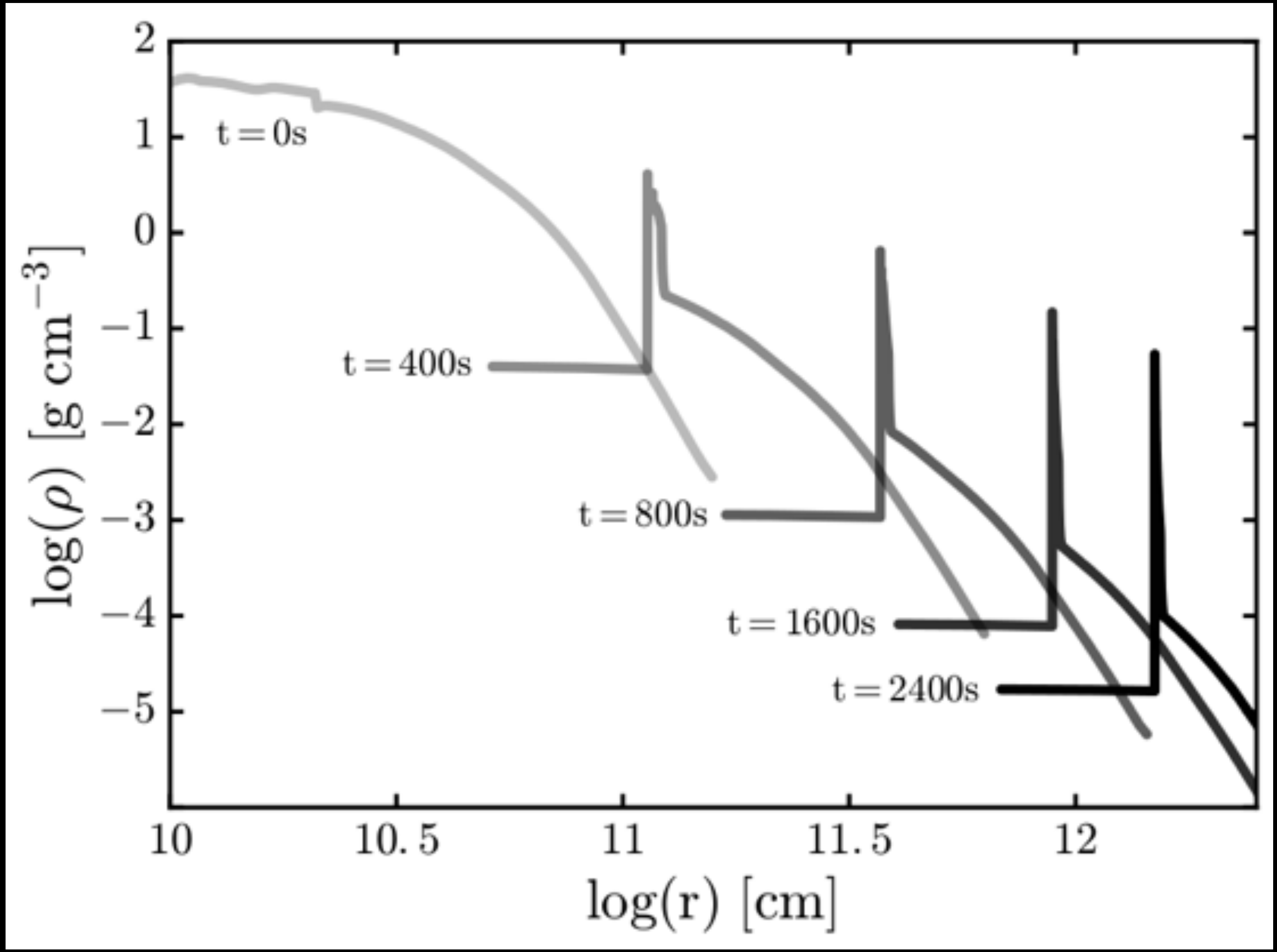
1D Models are Great but ..

Original ideas from Maeda, Kasen, Bildsten, Woosley



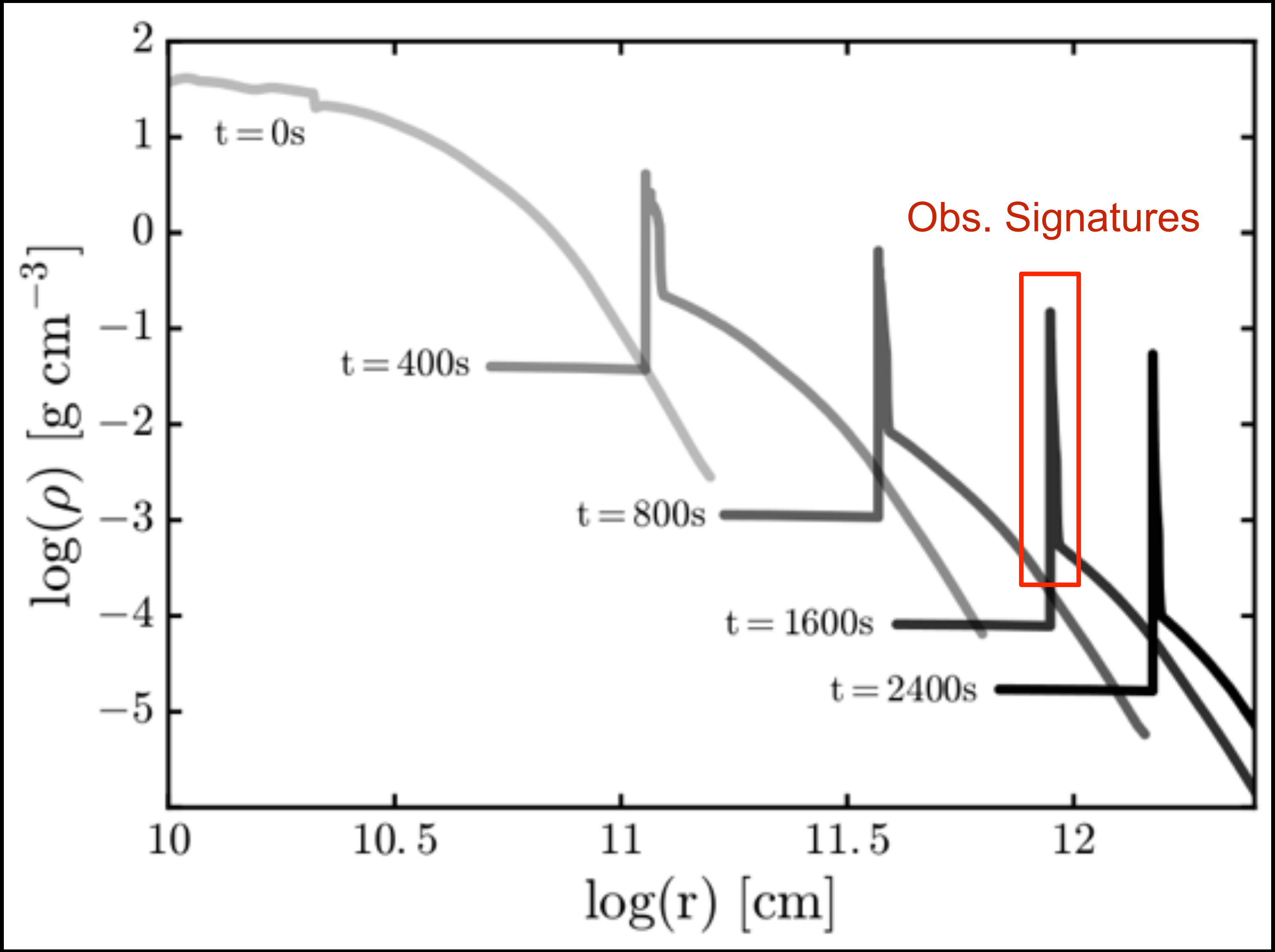
Chen+ (ApJ 2016)

The shortcoming of 1D SN Models



Density spike in 1D magnetar (Chen+ 16)

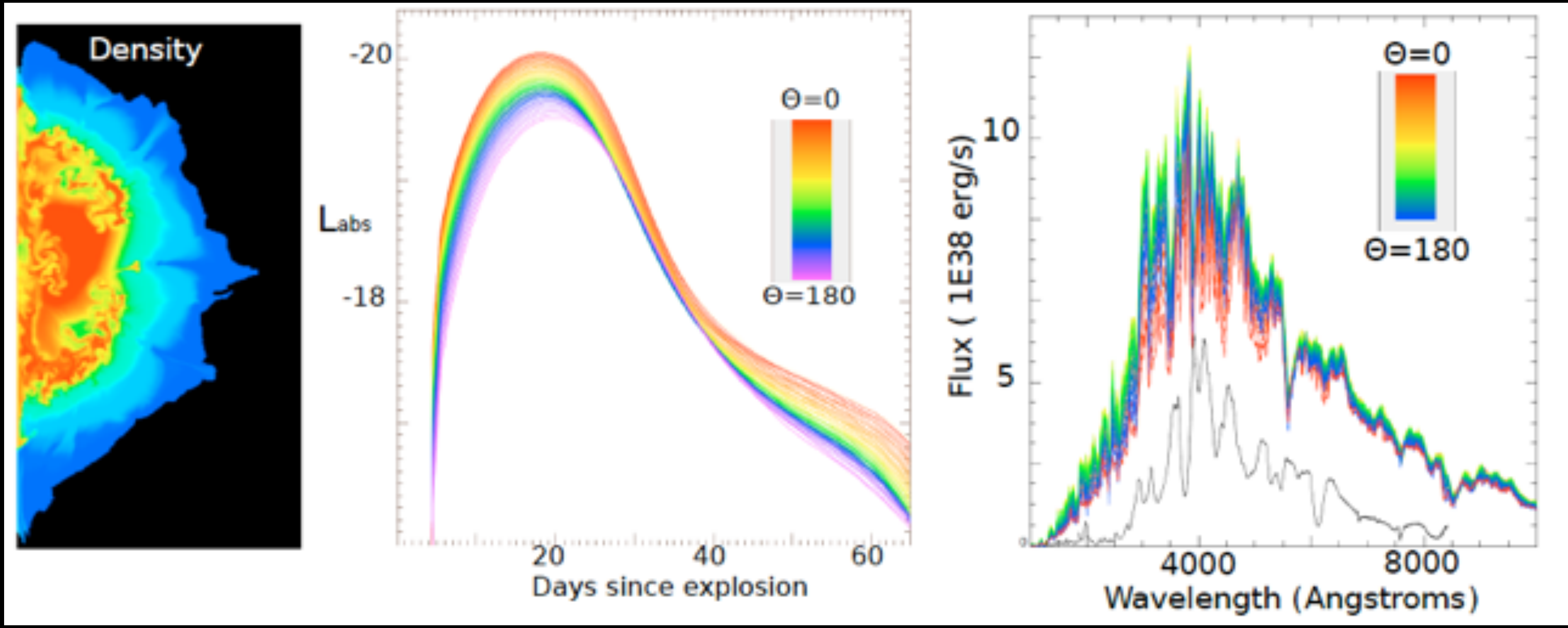
The shortcoming of 1D SN Models



Density spike in 1D magnetar (Chen+ 16)

The shortcoming of 1D SN Models

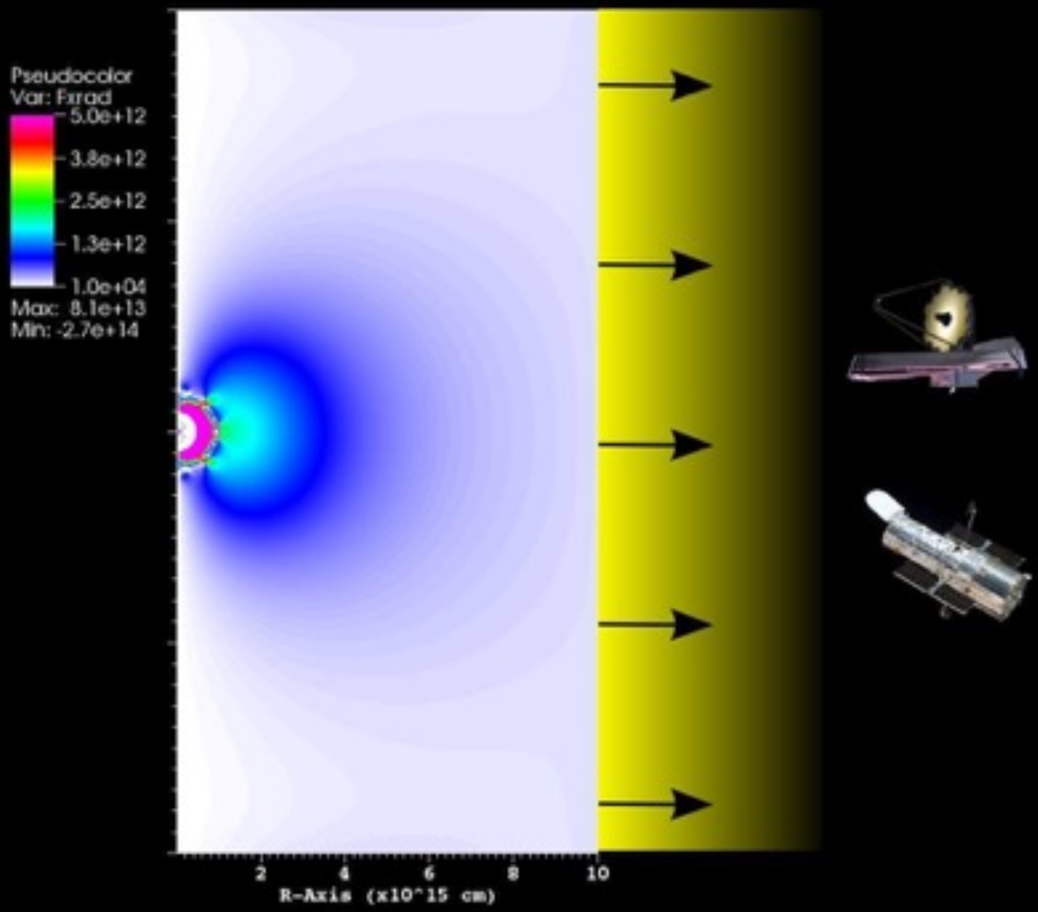
Why do we care mixing?



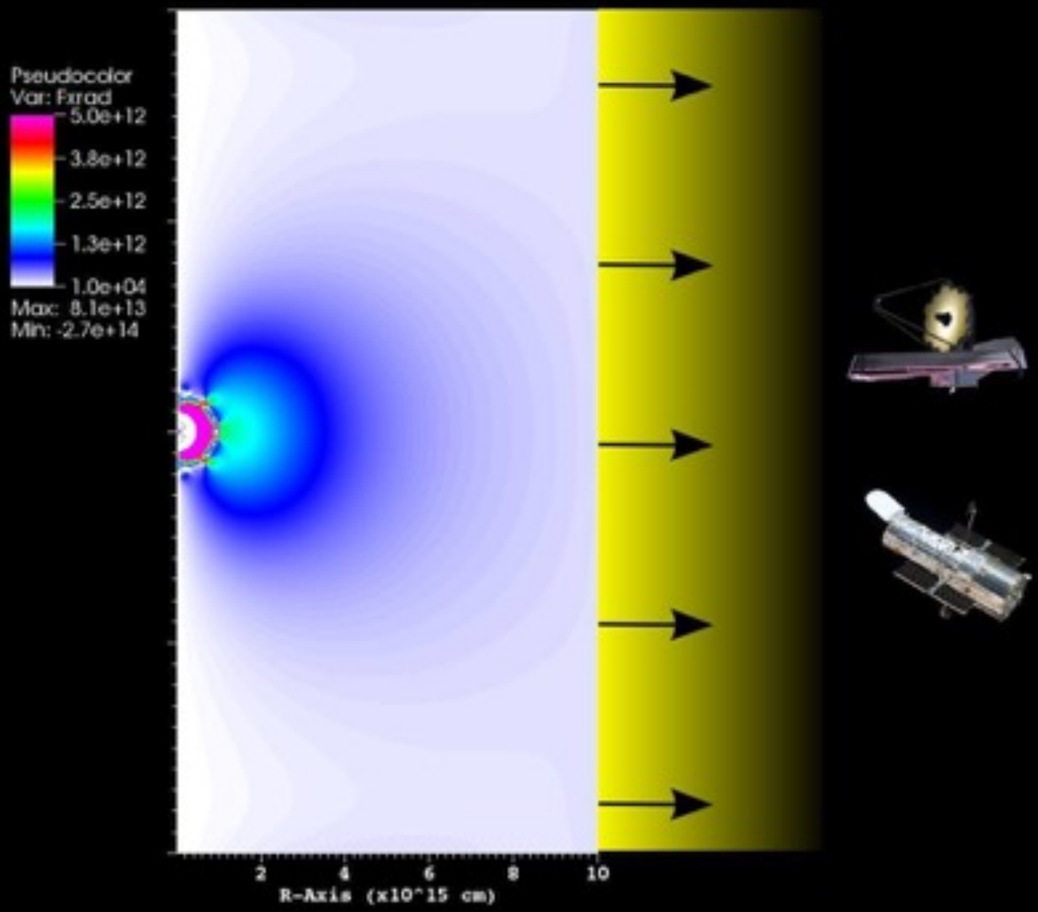
A Type Ia Example from Kasen+ 2008

Multidimensional Radiation Transport Simulations are needed !!

Supernovae light



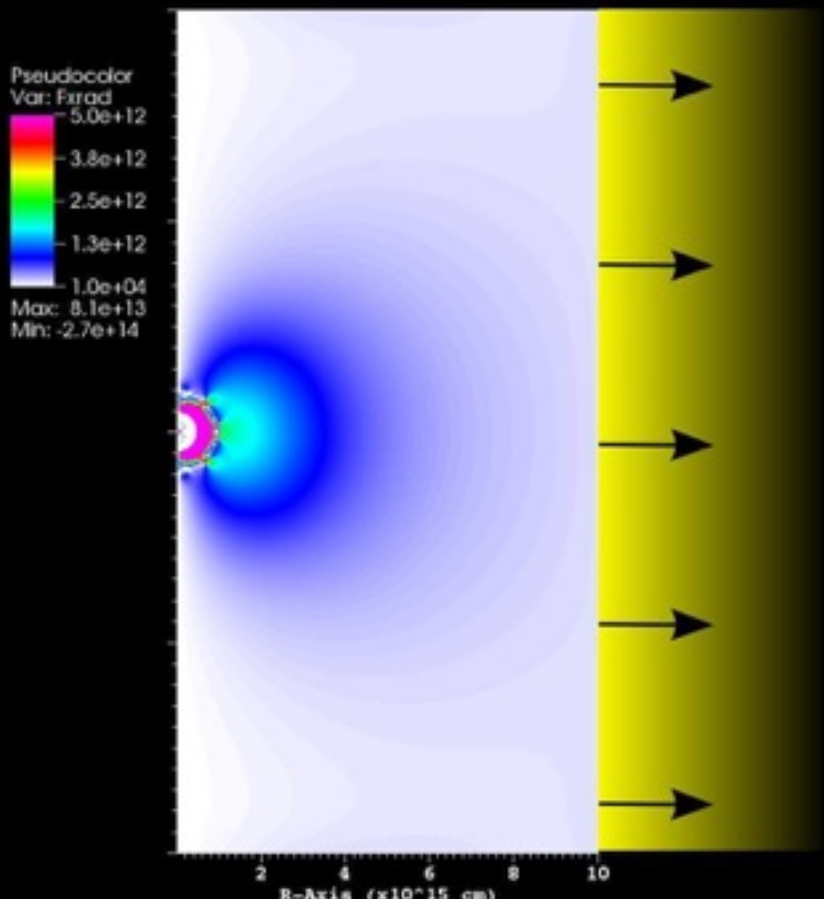
Supernovae light



1D models

Stellar Evolution > Explosions > lights > yields

Supernovae light



1D models

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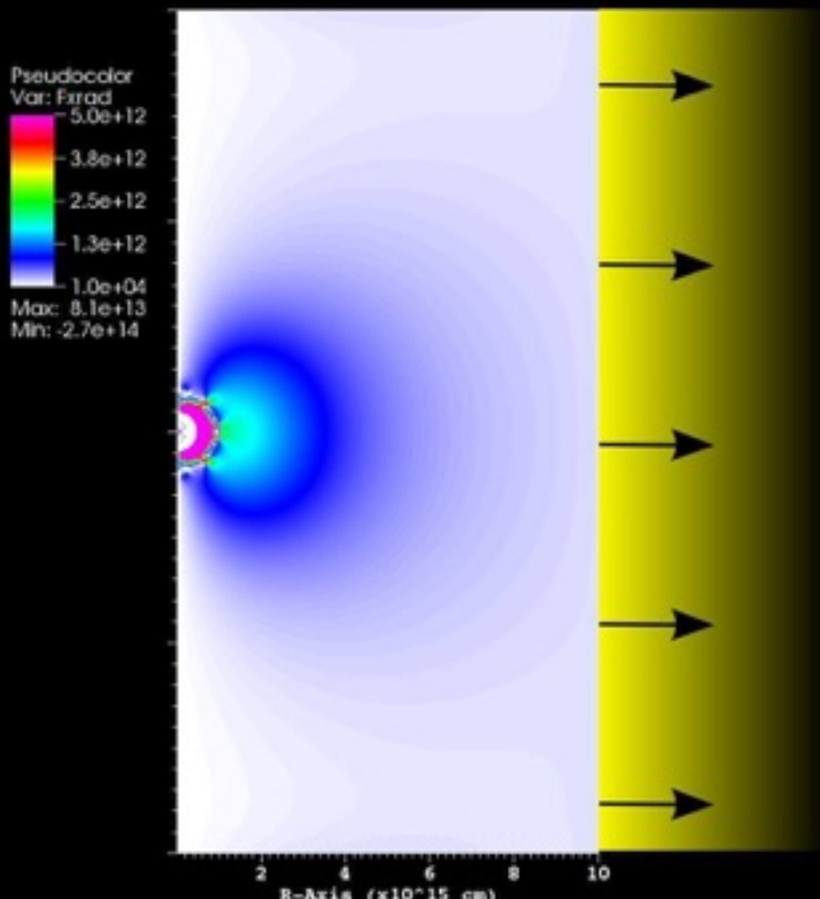
Supernovae light



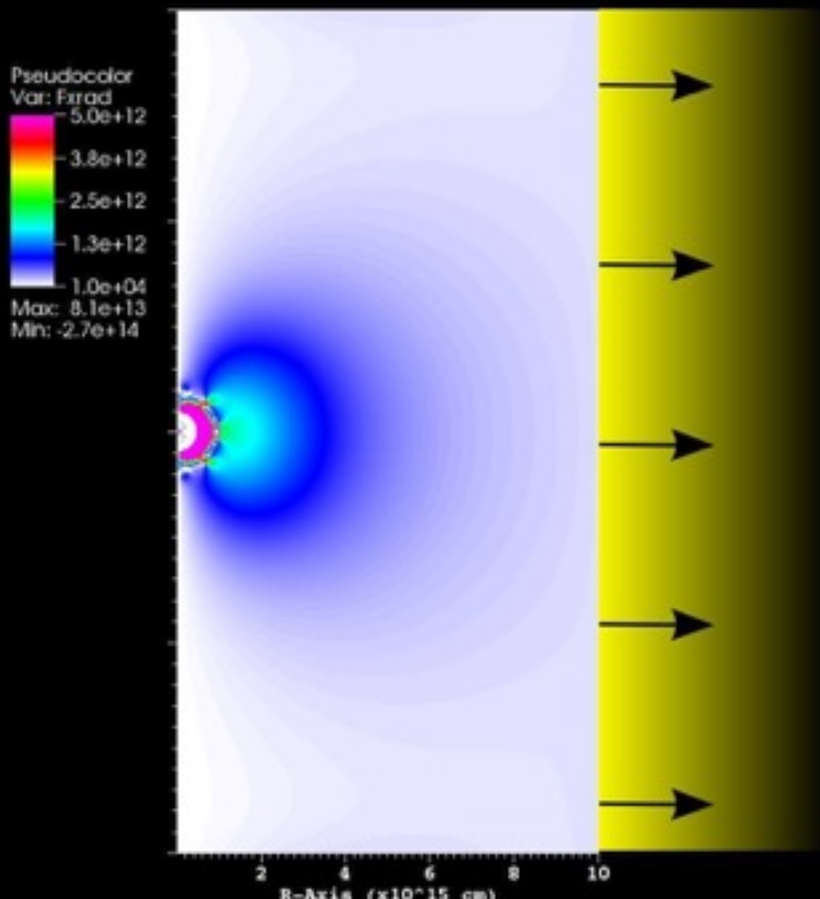
1D models

Stellar Evolution > Explosions > lights > yields

Crazy Multi-D models

Stellar Evolution > Explosions > lights > yields

Supernovae light



1D models

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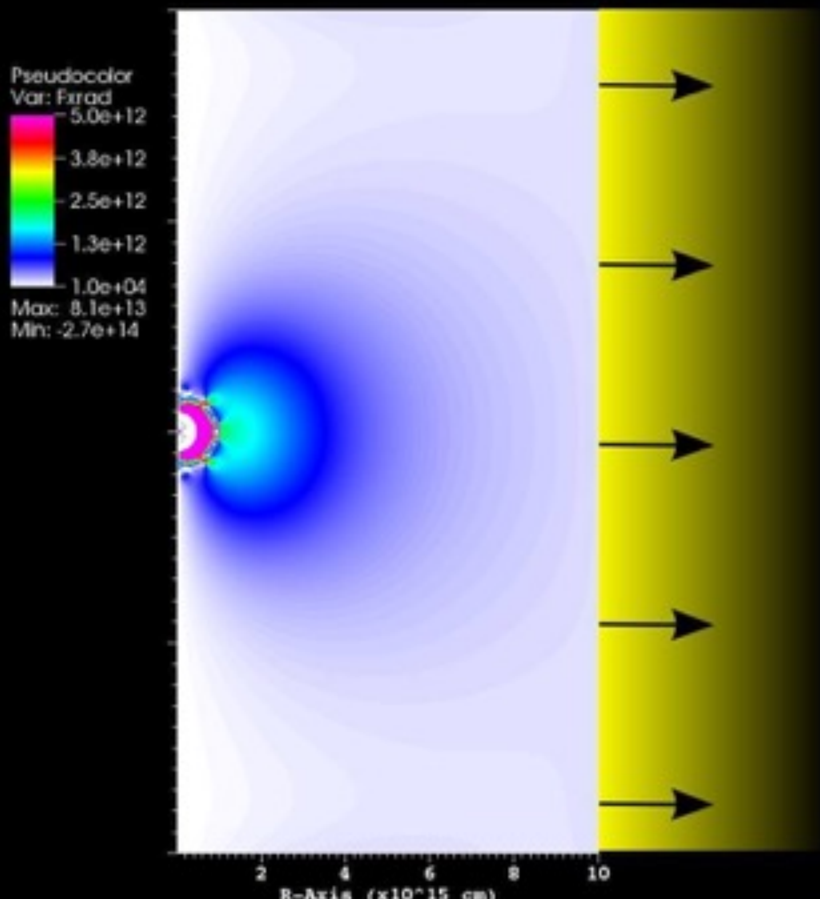
Supernovae light



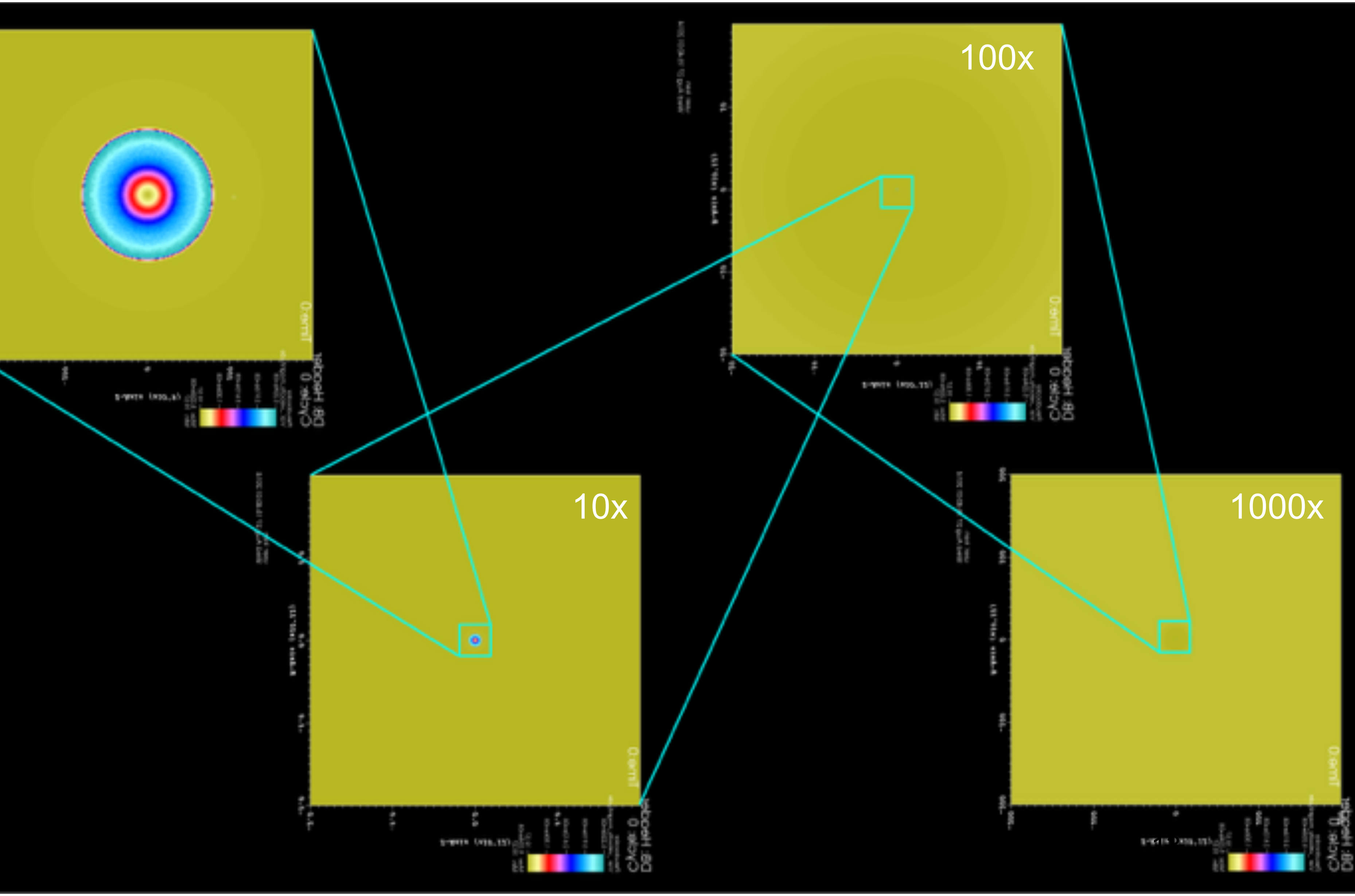
1D models

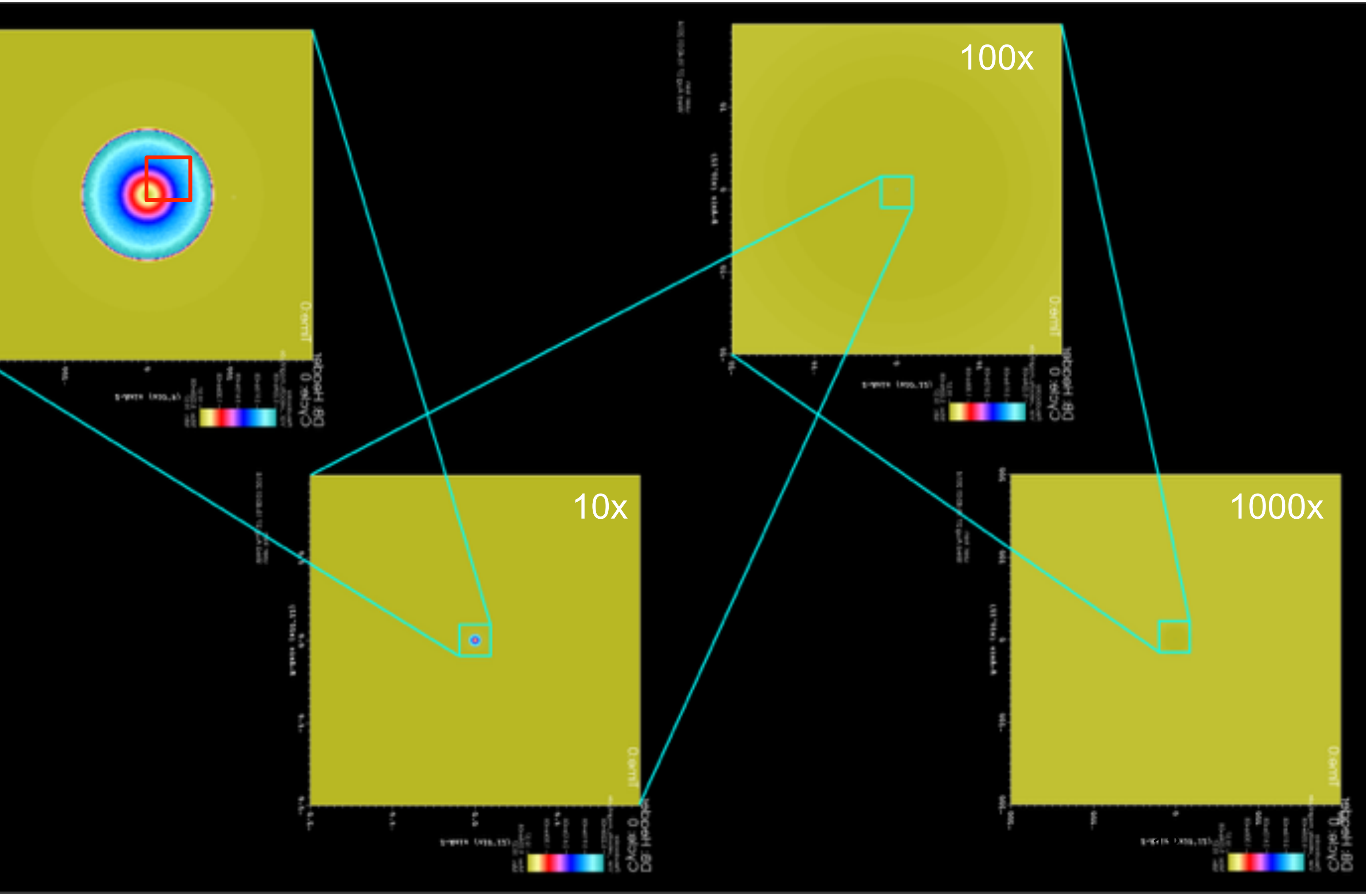
Stellar Evolution > Explosions > lights > yields

Crazy Multi-D models

Stellar Evolution > Explosions > lights > yields

Observations !!!


100x
10x
1000x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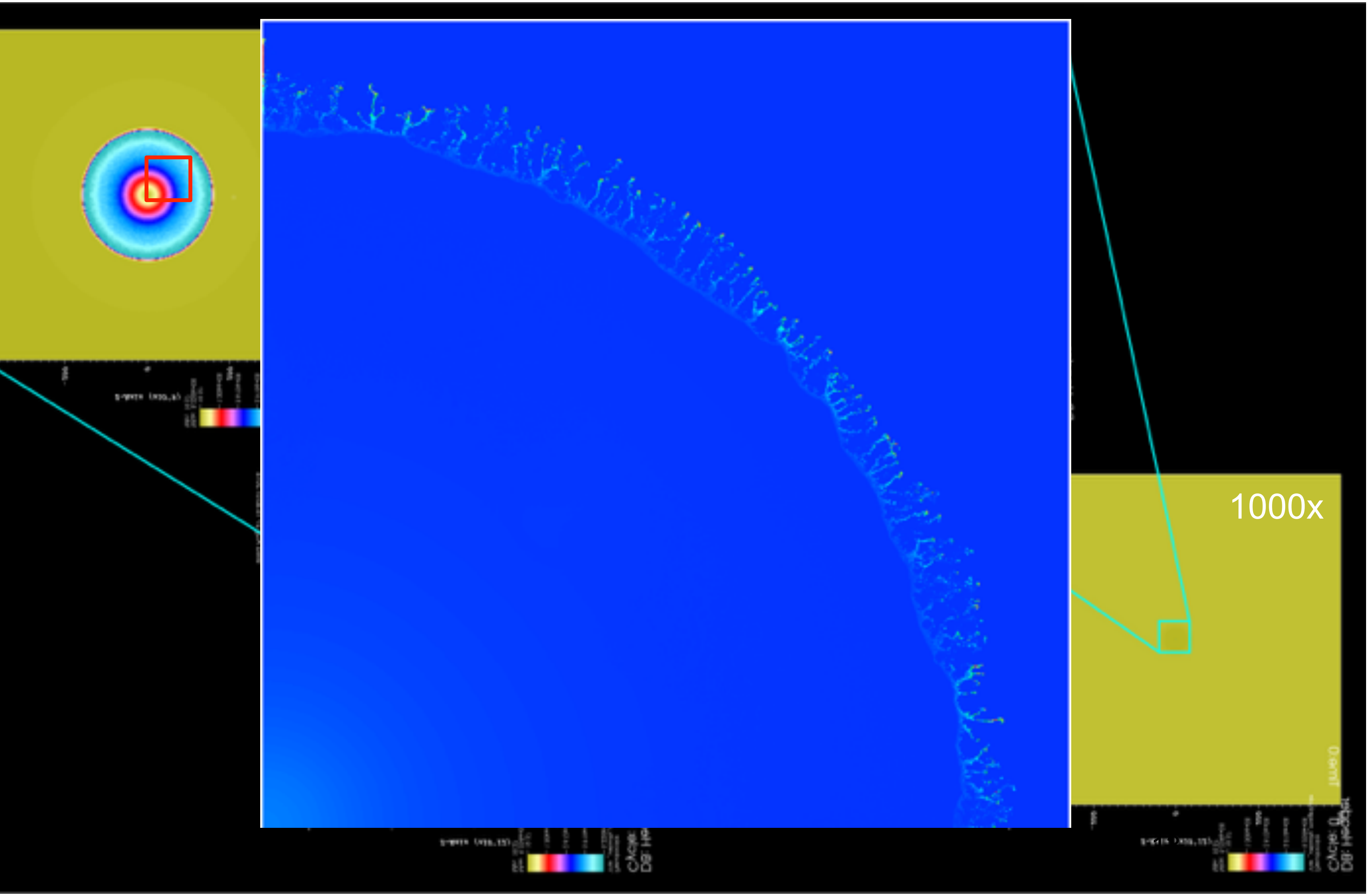
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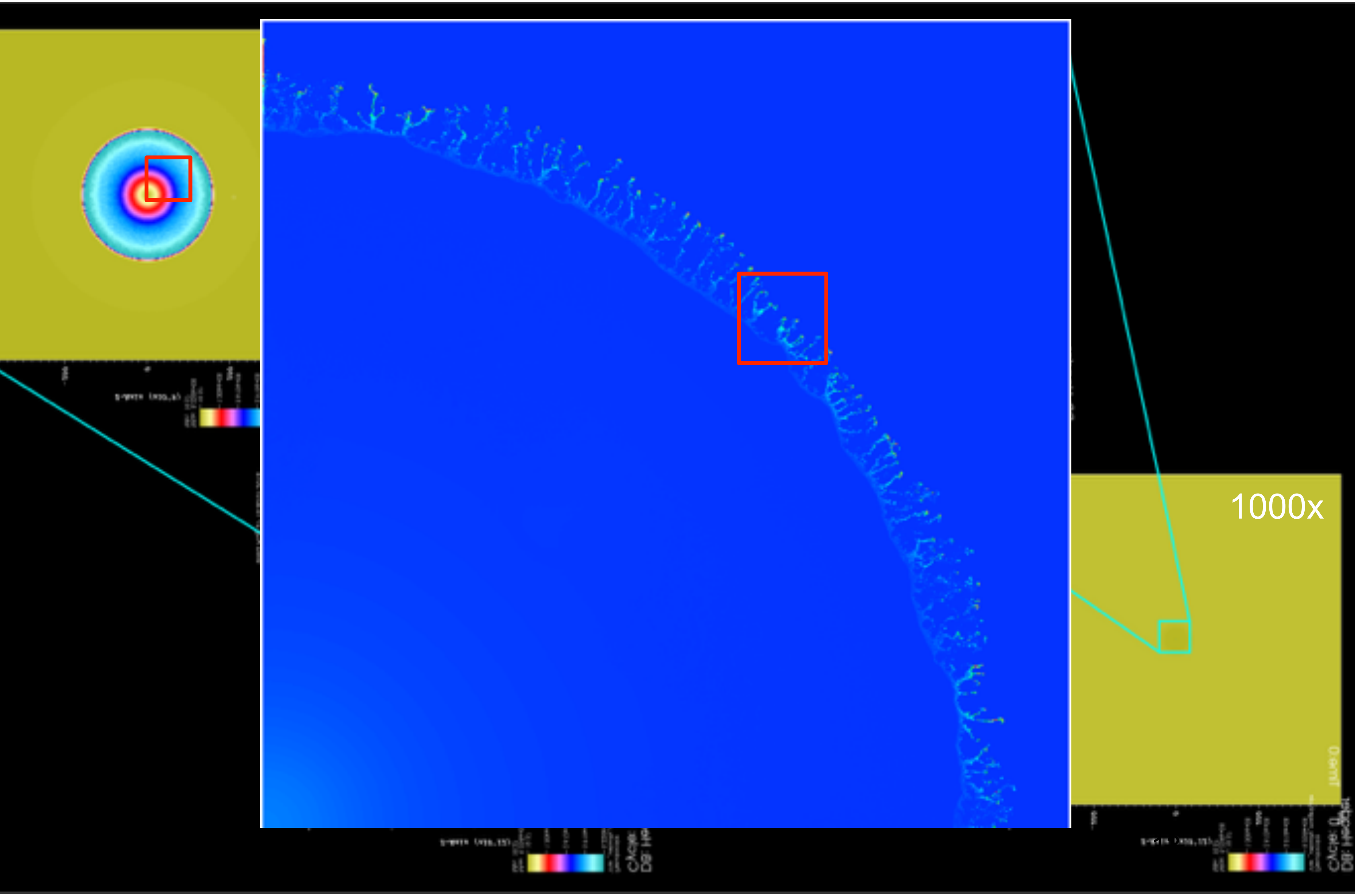
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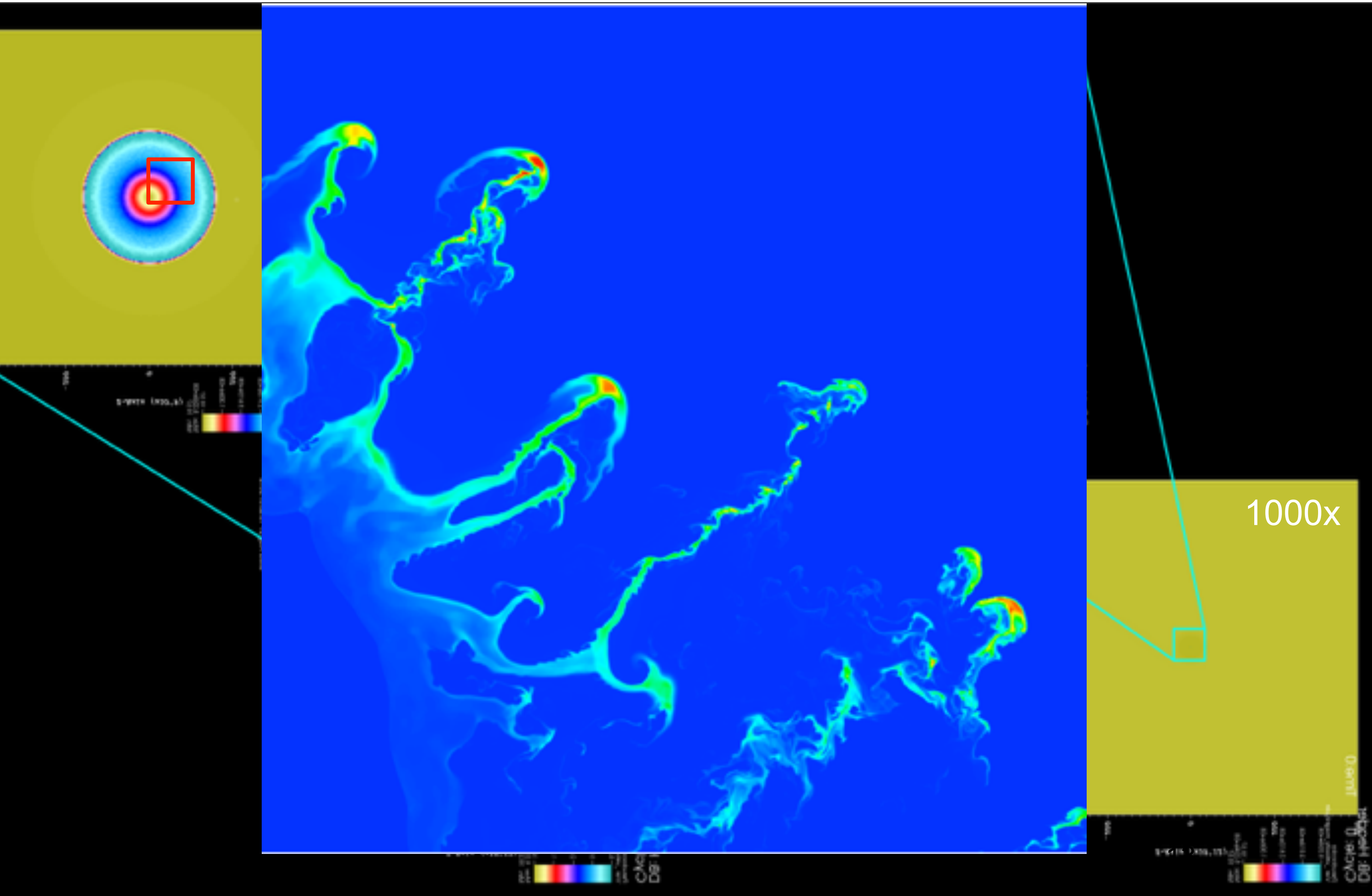
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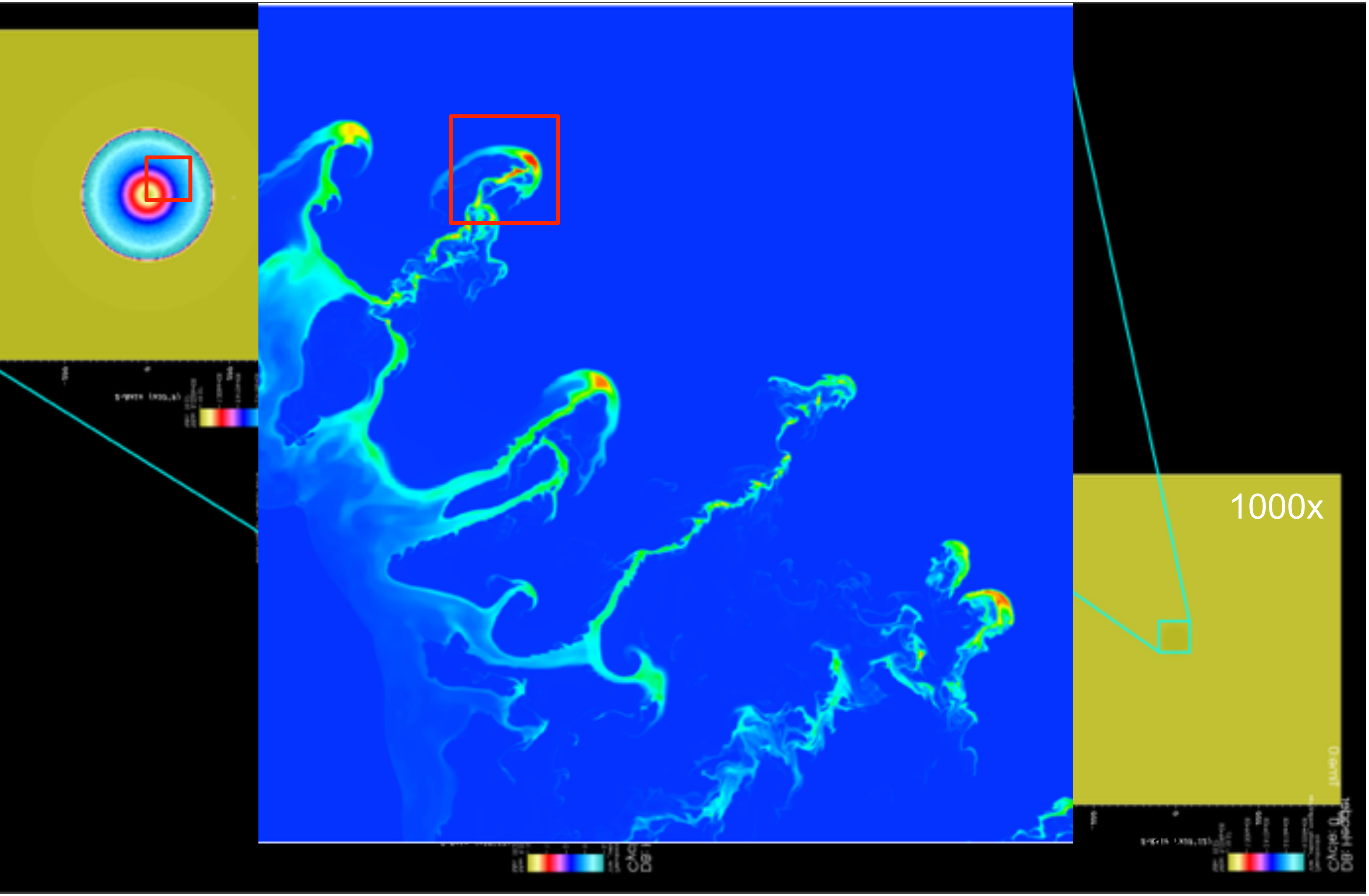
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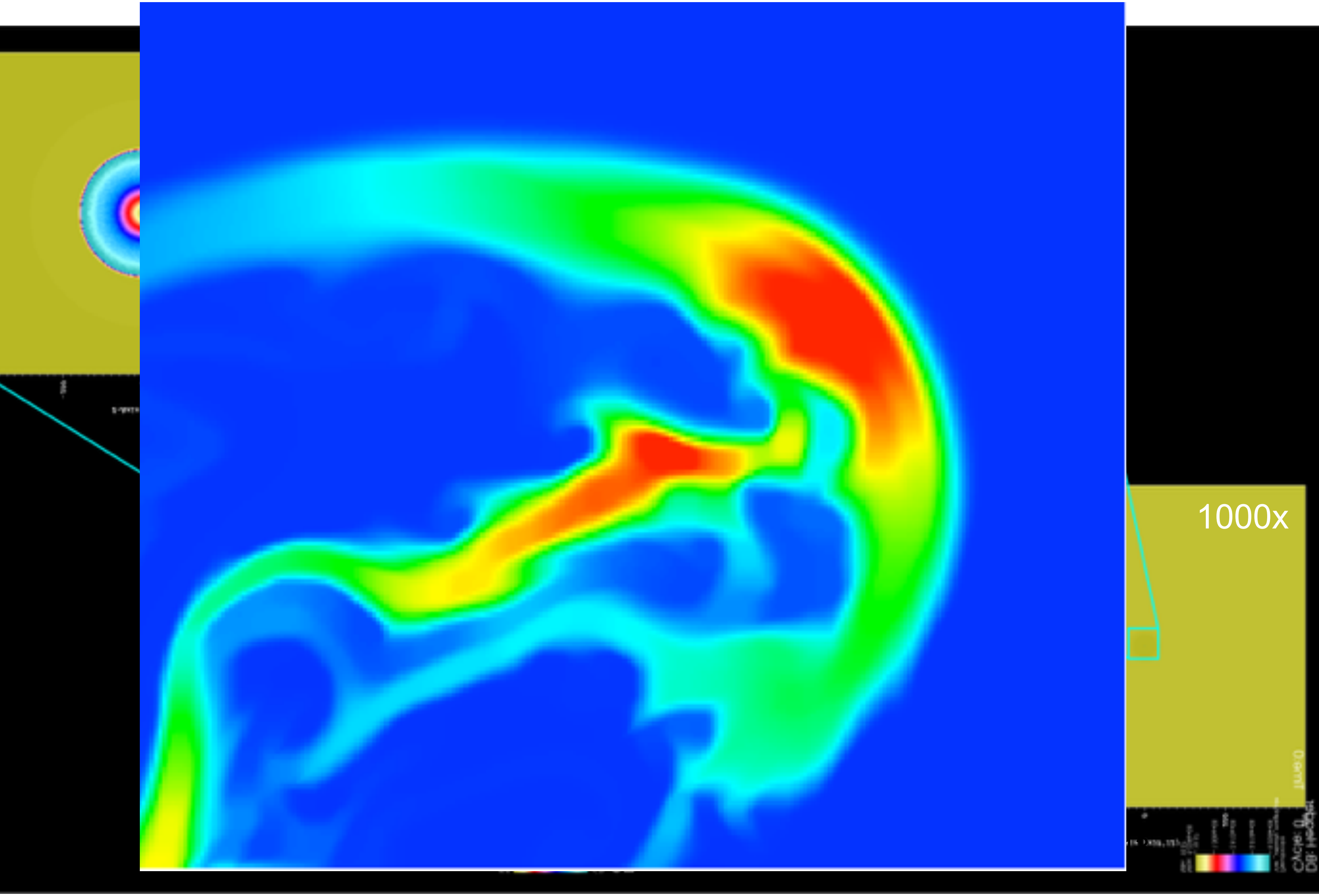
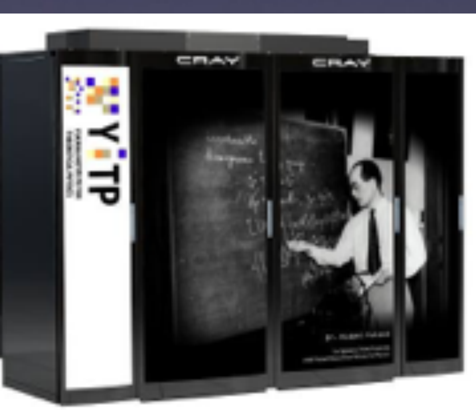

1000x

Telescopes for Simulators (faster is better)

Franklin

NAOJ ATERUI

Hopper



YITP

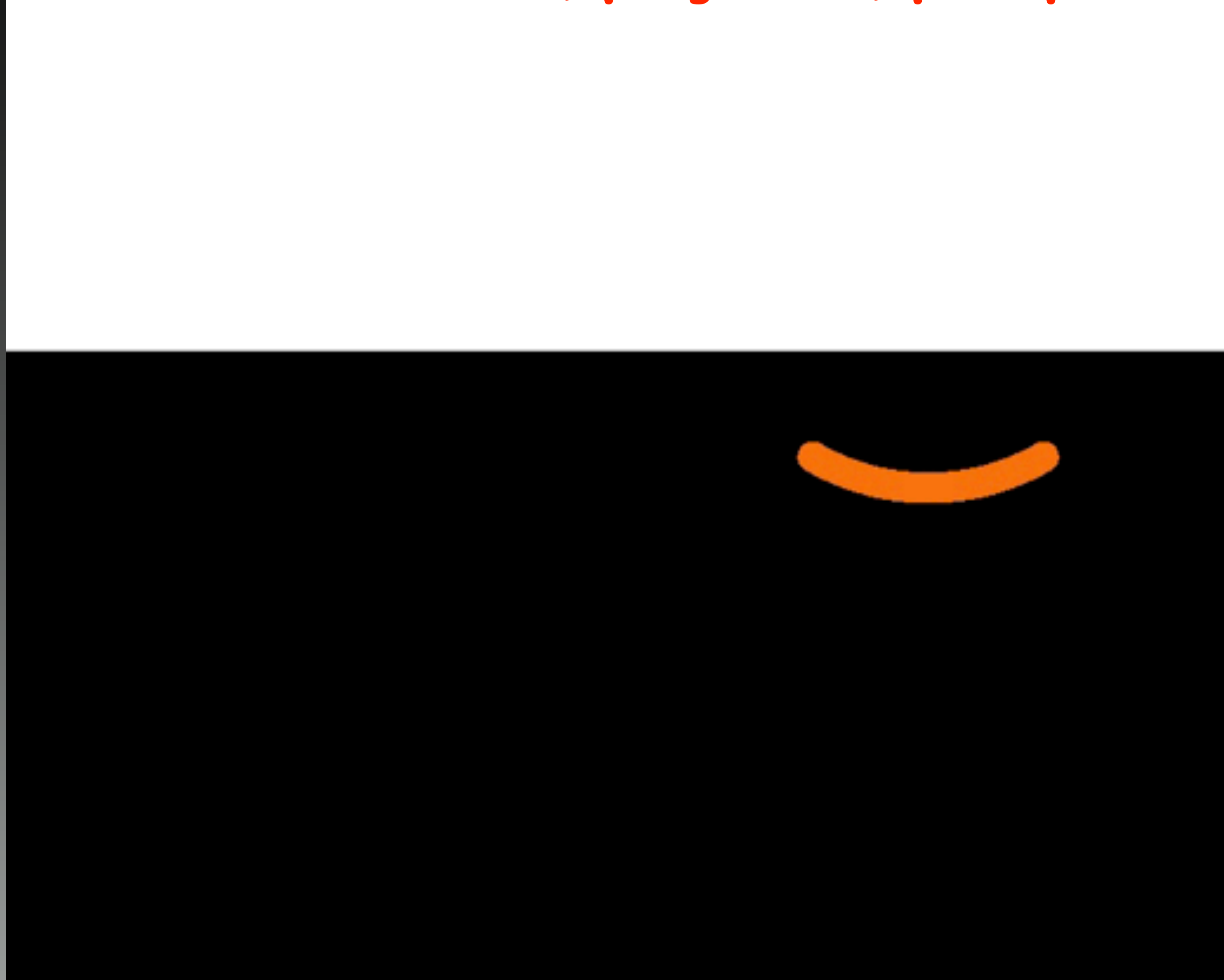
Edison

Cori


Future Machine
CRAY
CRAY XC50

NCHC

Why can we believe simulations?
(because of math, physics, people!?)



Courtesy of Volker Springel (AREPO code, 2009)

Why can we believe simulations?
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Why can we believe simulations?
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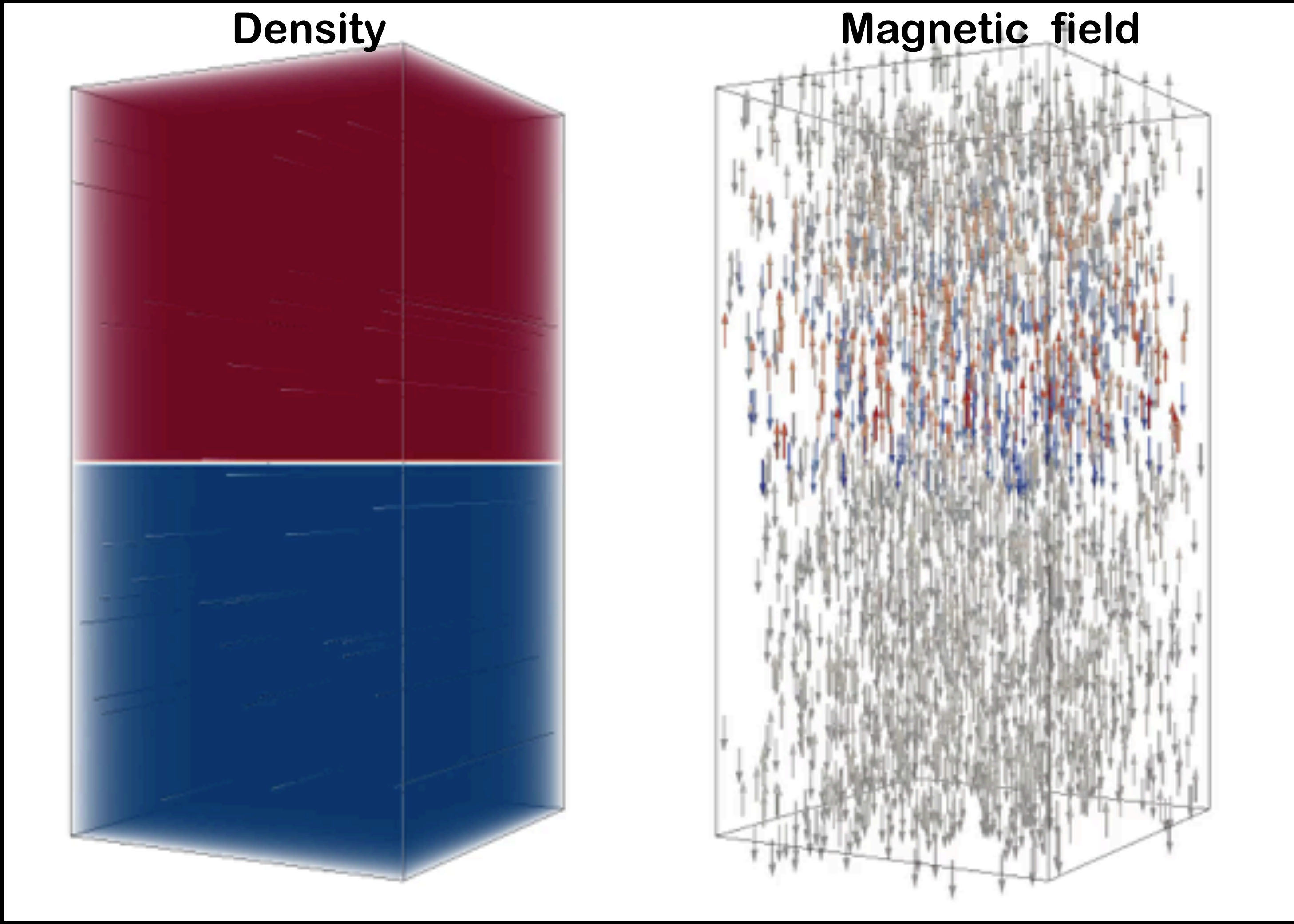
Rayleigh–Taylor instability

$$\frac{dP}{dr}\frac{d\rho}{dr} < 0$$



3D MHD RTI by I-Ta Hish

Rayleigh–Taylor instability

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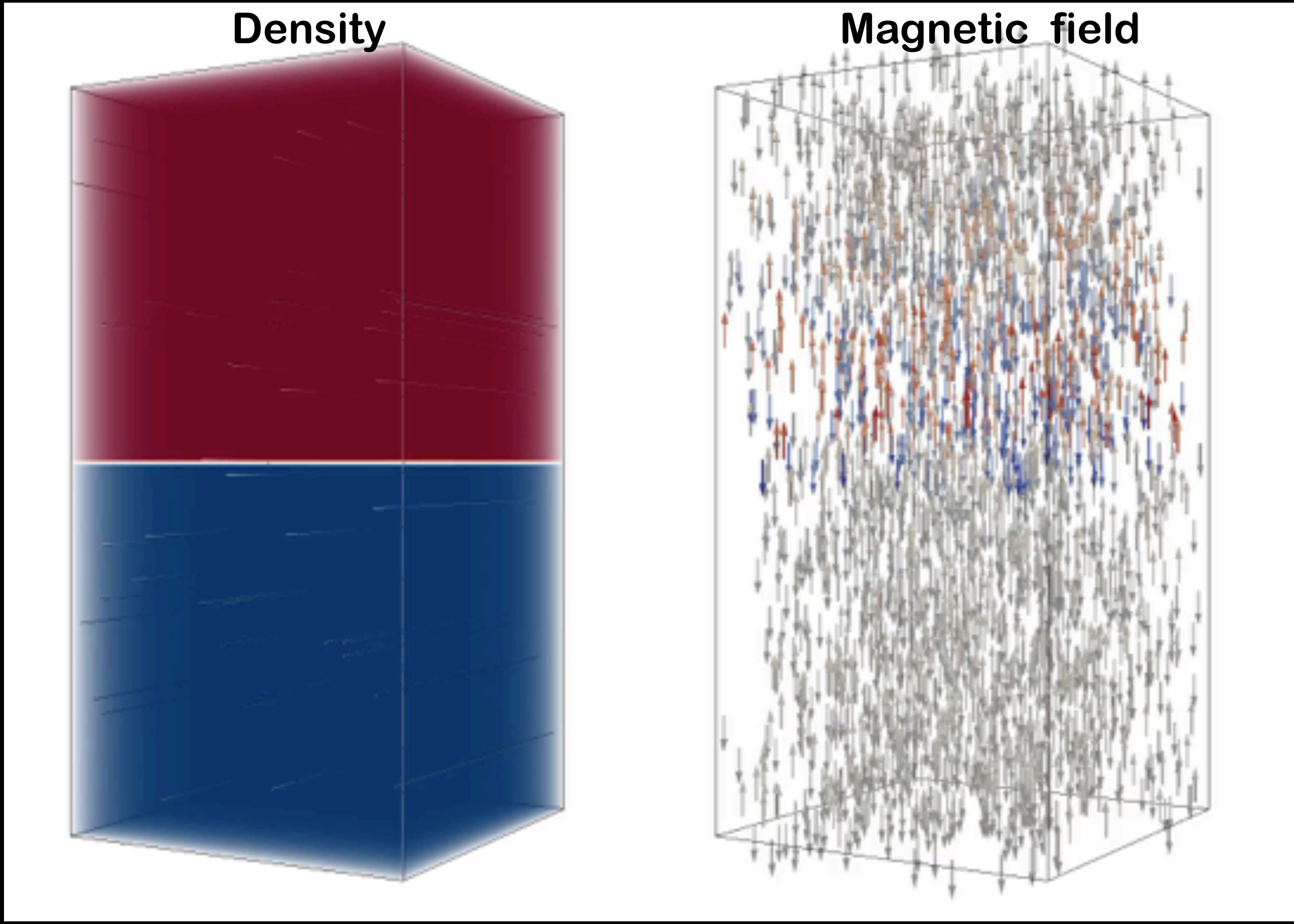

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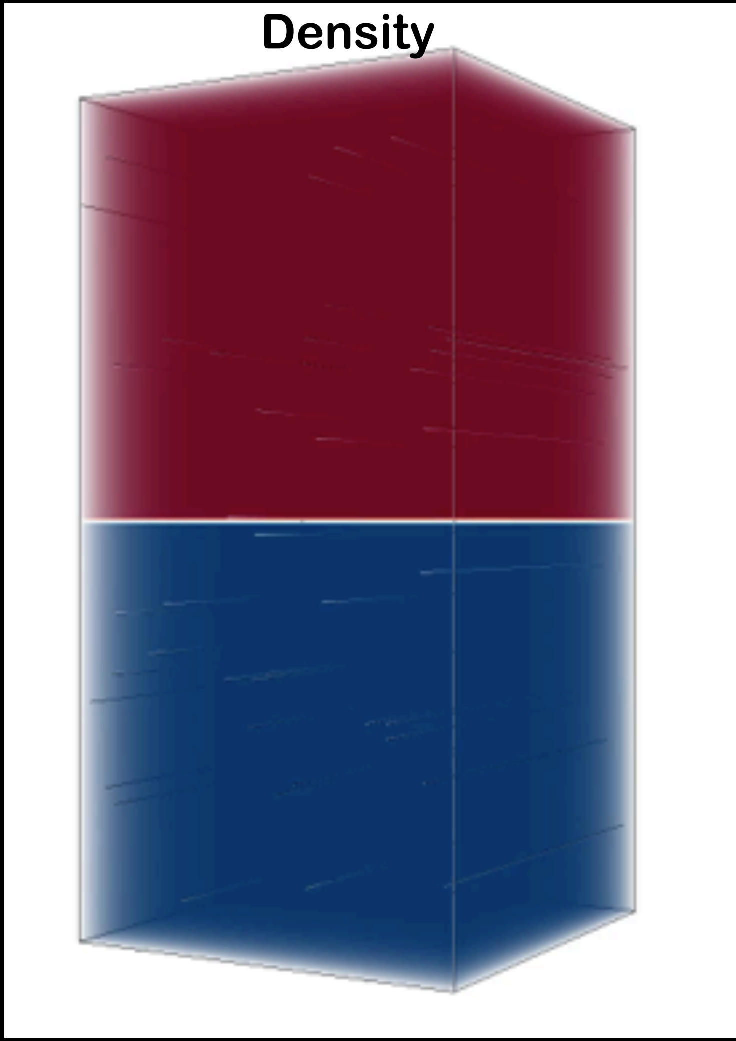
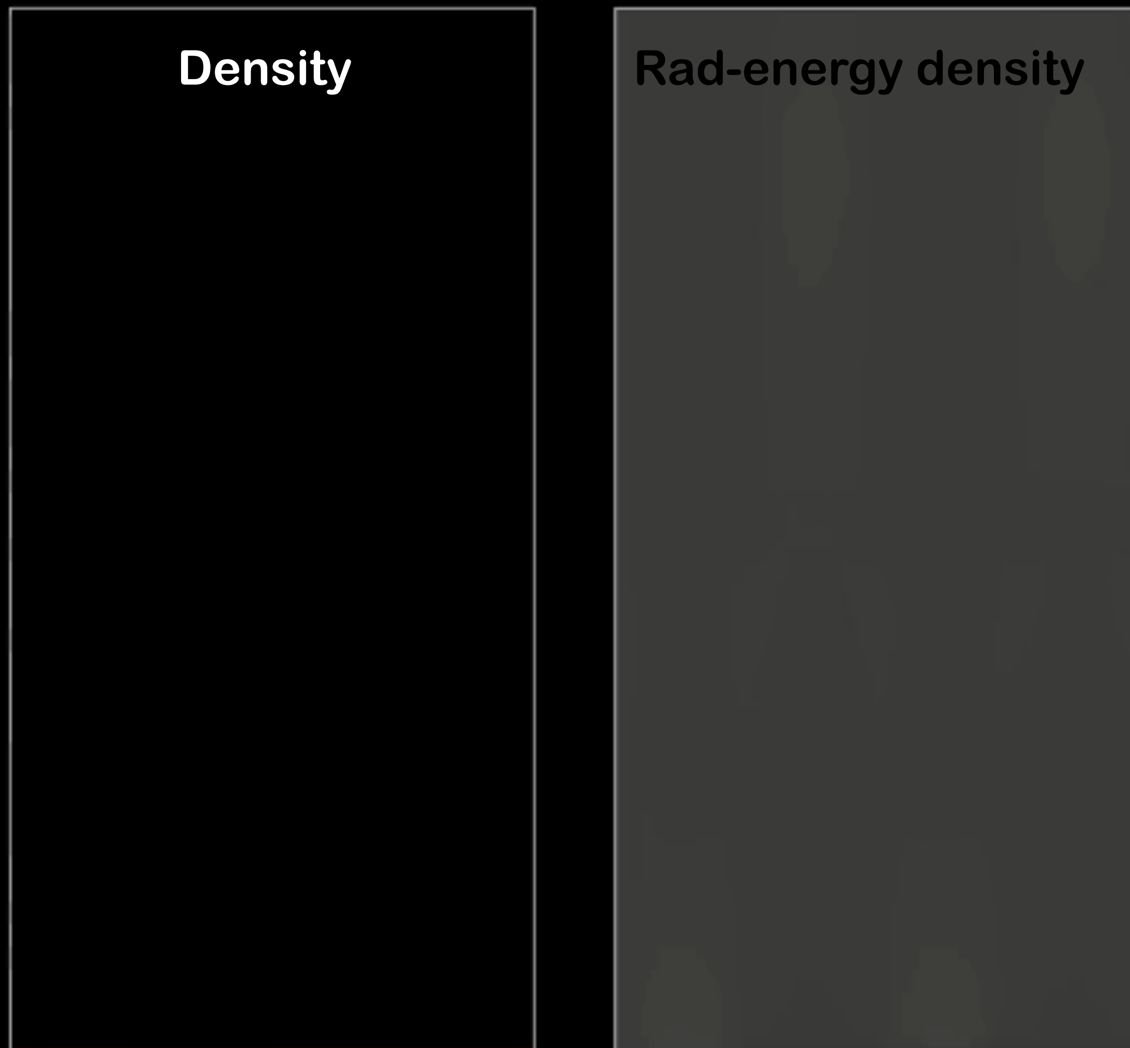


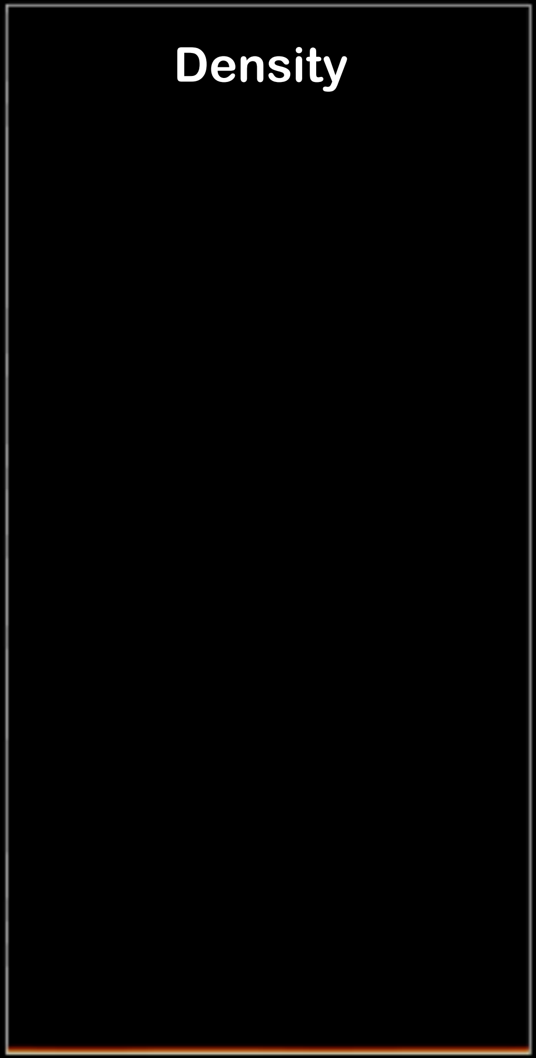
3D MHD RTI by I-Ta Hish

Radiation-driven Rayleigh–Taylor instability (Athen++ with VET method)



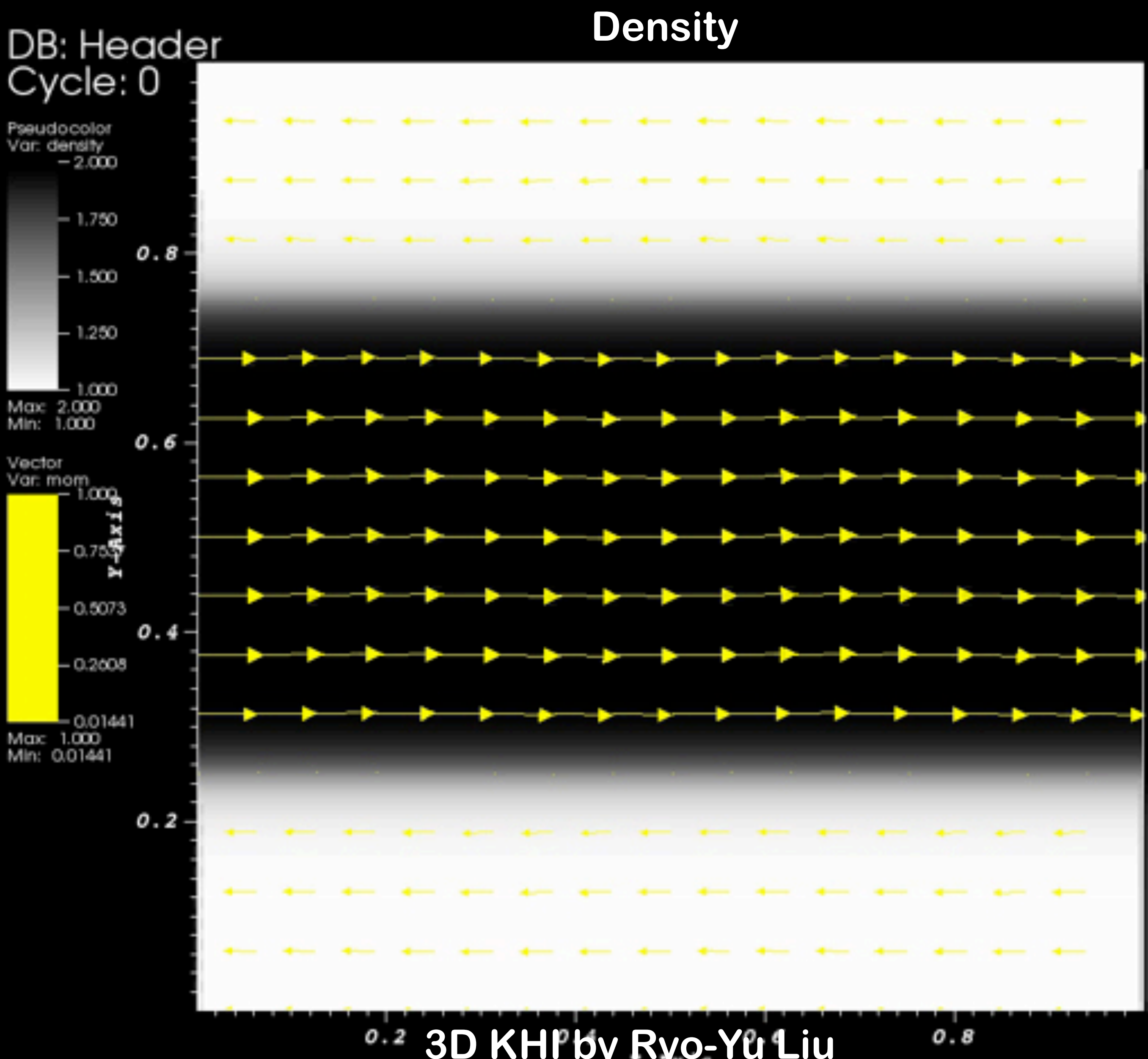
by Wun-Yi Chen

Radiation-driven Rayleigh–Taylor instability (Athen++ with VET method)



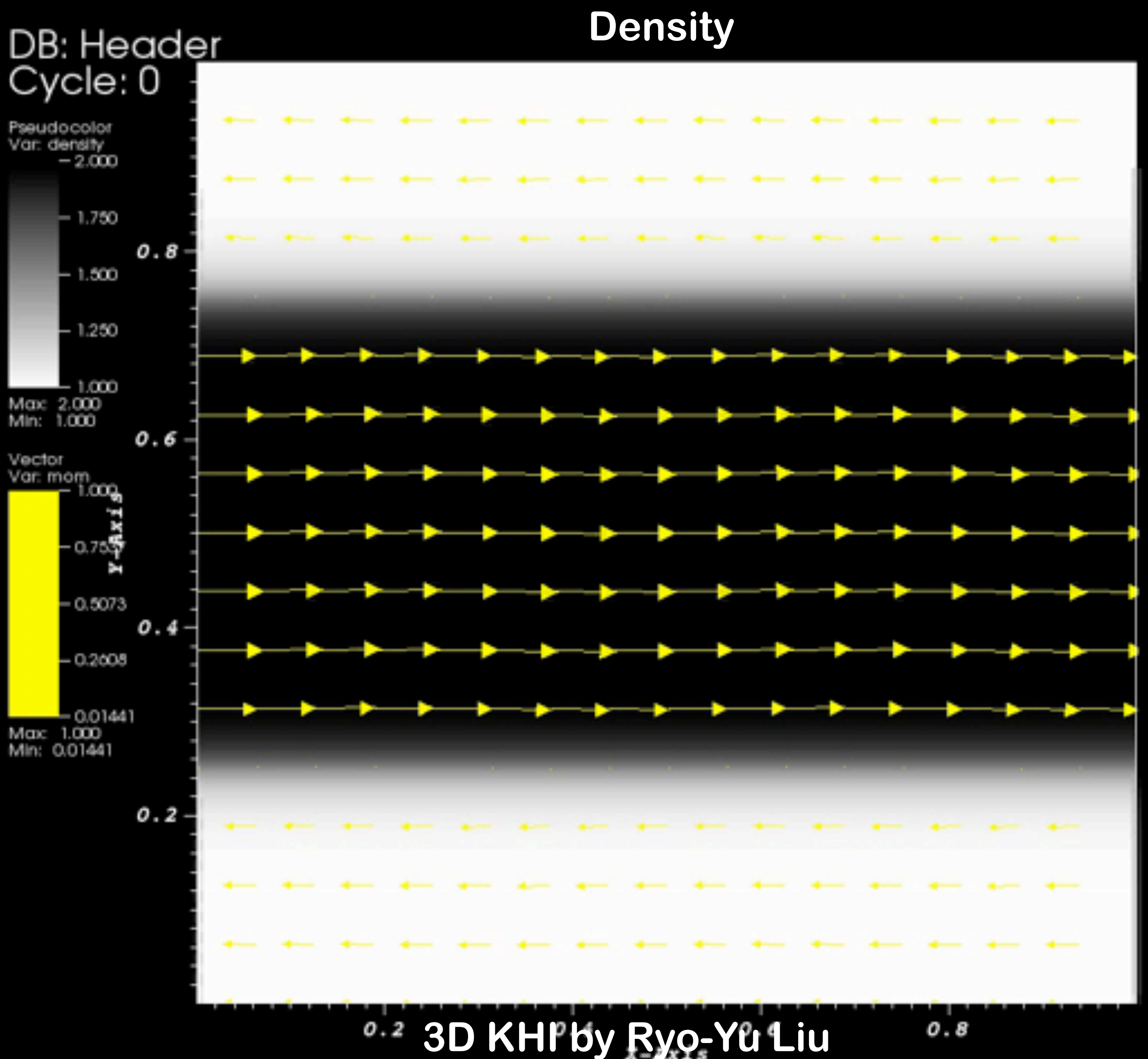
by Wun-Yi Chen

Kelvin-Helmholtz (Shear) instability,



3D KHI by Ryo-Yu Liu

Kelvin-Helmholtz (Shear) instability,



3D KHI by Ryo-Yu Liu

Kelvin-Helmholtz (Shear) instability,

The Death of Massive Stars

Woosley, Heger, & Weaver (2002)

MS Mass	He Core	Supernova Mechanism
$10 \leq M \leq 80$	$2 \leq M \leq 32$	Fe core collapse to a neutron star or black hole
$80 \leq M \leq 150$	$35 \leq M \leq 60$	Pulsational pair instability followed by core (PPSN)
$150 \leq M \leq 250$	$60 \leq M \leq 133$	Pair instability supernova (PSN)
$250 \leq M$	$133 \leq M$	All BH or any Bang??

Mass Unit: solar mass $\odot$

When Massive Stars Die, How Do They Explode?

Neutron Star + Neutrinos

Colgate and White (1966)
Arnett
Wilson
Bethe
Janka
Herant
Burrows
Fryer
Mezzacappa
etc.

10

Neutron Star + Rotation

Hoyle (1946)
Fowler and Hoyle (1964)
LeBlanc and Wilson (1970)
Ostriker and Gunn (1971)
Bisnovatyi-Kogan (1971)
Meier
Wheeler
Usov
Thompson
etc

20

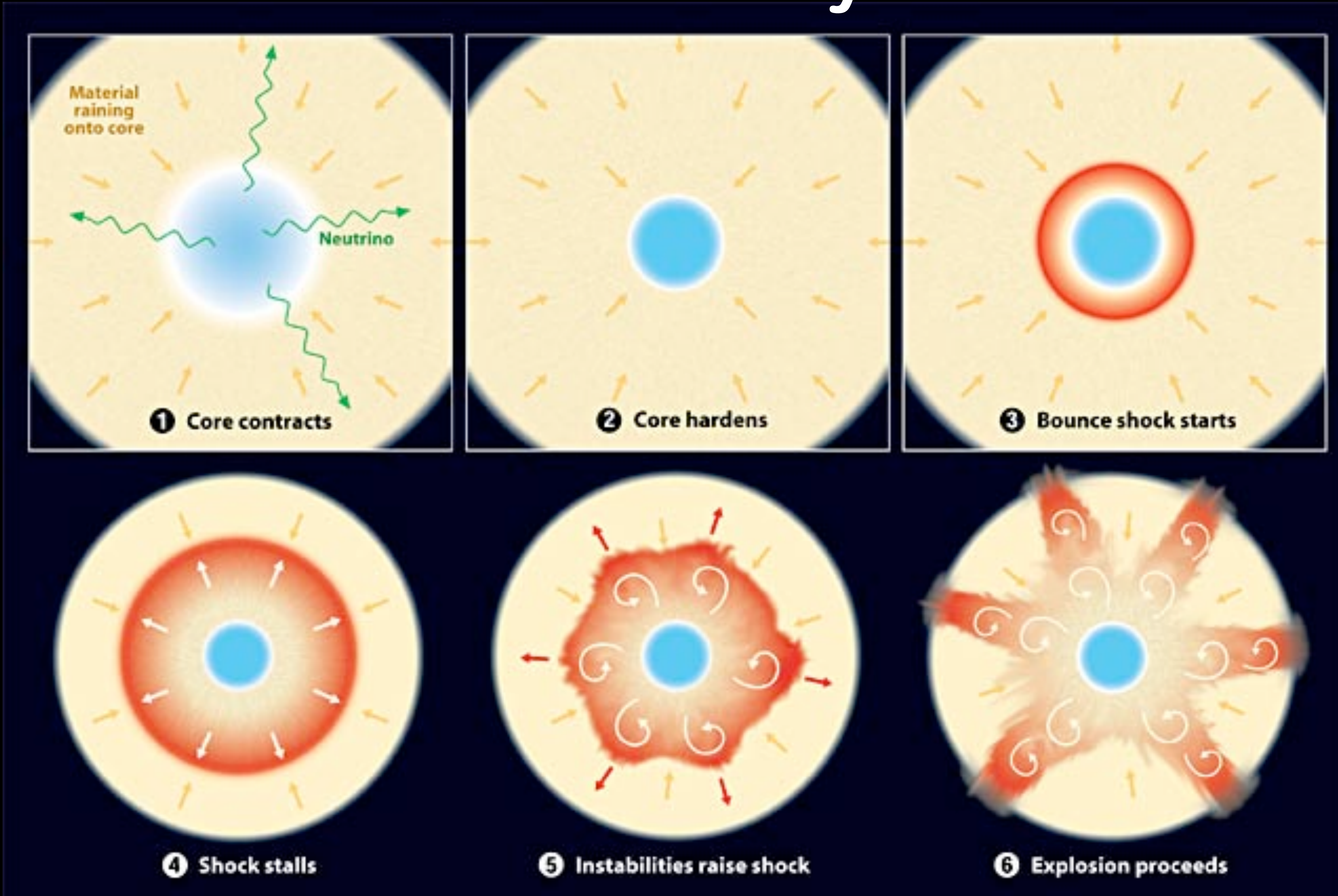
Black Hole + Rotation

Bodenheimer and Woosley (1983)
Woosley (1993)
MacFadyen and Woosley (1999)
Narayan (2004)

All of the above?

35 $M_{\odot}$

Neutrino as a Dynamite



Neutrino-Powered SN Explosions?

Nordhaus+ 2010

Neutrino-Powered SN Explosions?

Nordhaus+ 2010

Neutrino-Powered SN Explosions?

Neutrino Burst Properties:

$E_{tot} \sim \frac{3}{5}\frac{GM^2}{R}$ $\quad$ $M = 1.5\ M_\odot$

$\boxed{\sim 3\times10^{53}\ \text{erg}}$ $\quad$ $R = 10$ km

emitted roughly equally in ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$, ν_τ, and $\bar{\nu}_\tau$

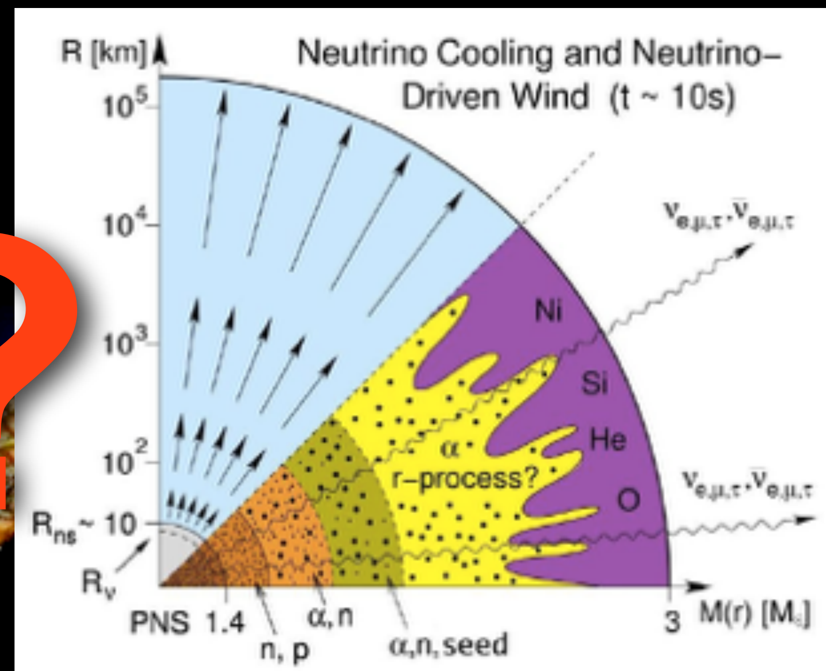
Time scale

$\tau_{Diff} \sim \left(\frac{R^2}{l\ c}\right)$ $\quad$ $l = \frac{1}{\kappa_\nu \rho}$

$\kappa_\nu \sim 10^{-16}\ \text{cm}^2\ \text{gm}^{-1}$ for $\varepsilon_\nu = 50$ MeV (next page)

$\rho \sim 3\times10^{14}\ \text{gm cm}^{-3} \Rightarrow l \sim 30$ cm $\quad$ $R \sim 20$ km

$\tau_{Diff} \sim \left(\frac{(2\times10^6)^2}{30\cdot 3\times10^{10}}\right) \sim \boxed{5\ \text{sec}}$ *Very approximate*

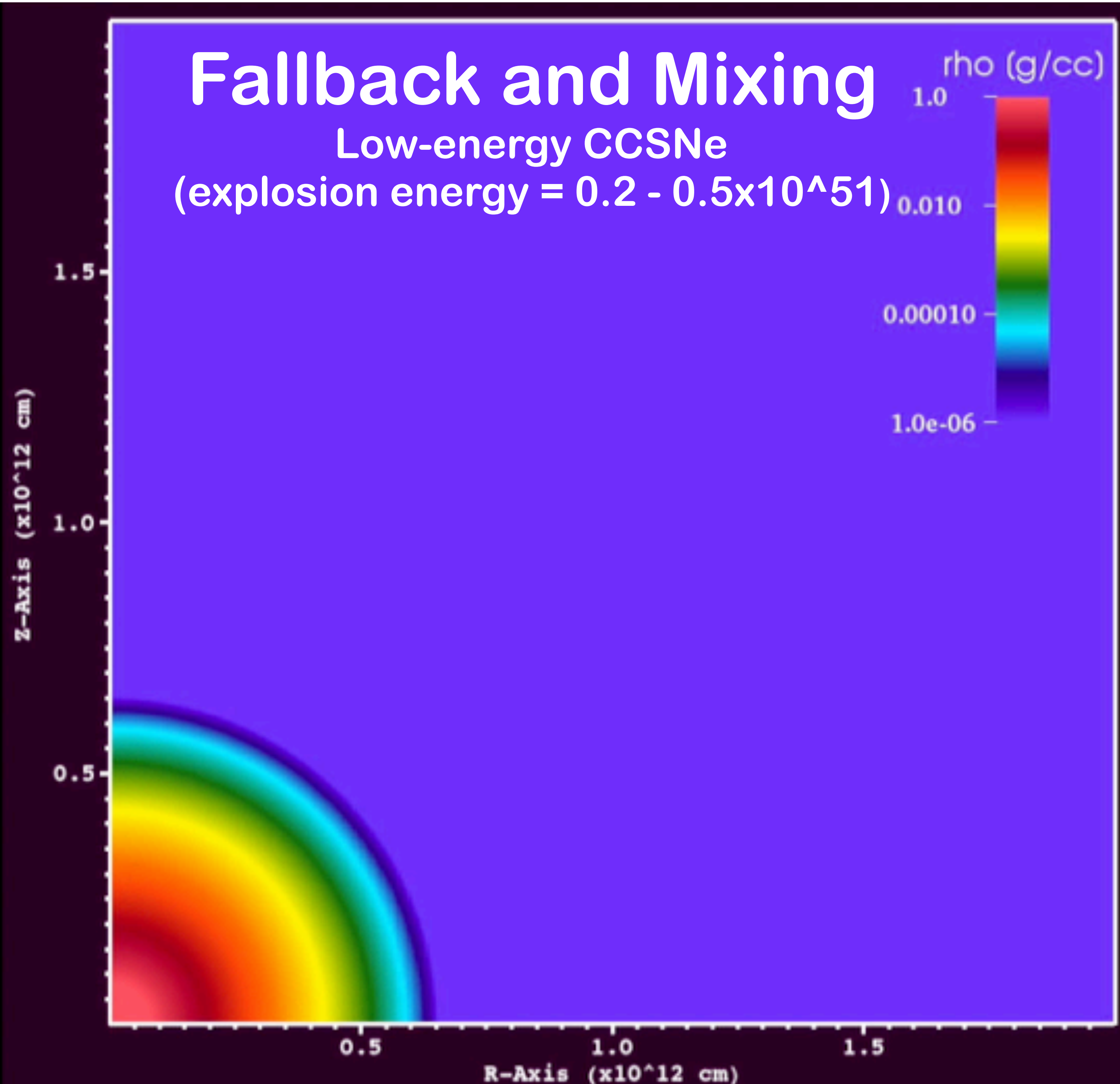


Nordhaus+ 2010

Fallback and Mixing

Low-energy CCSNe

(explosion energy = 0.2 - 0.5x10^51)



Fallback and Mixing

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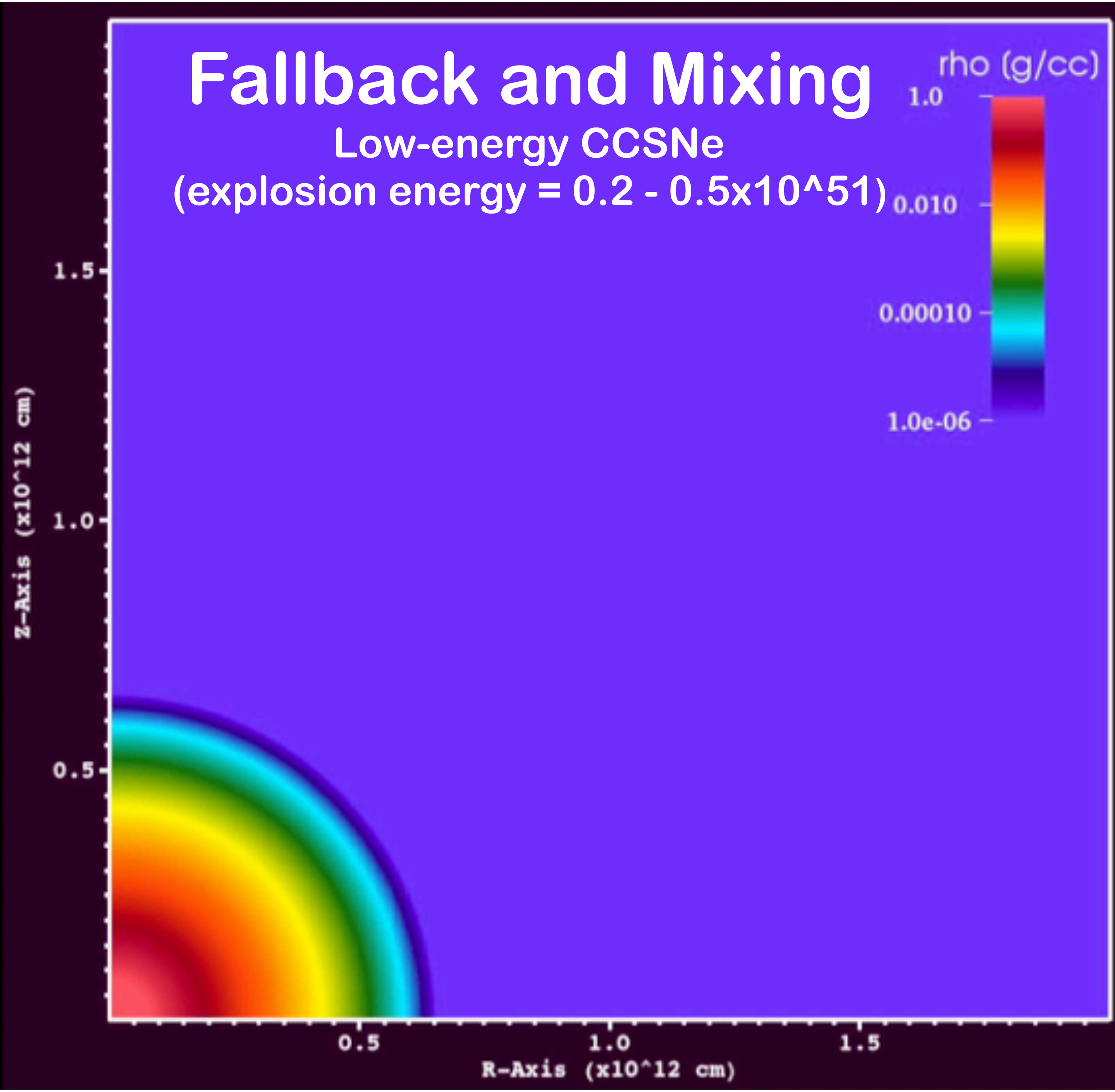
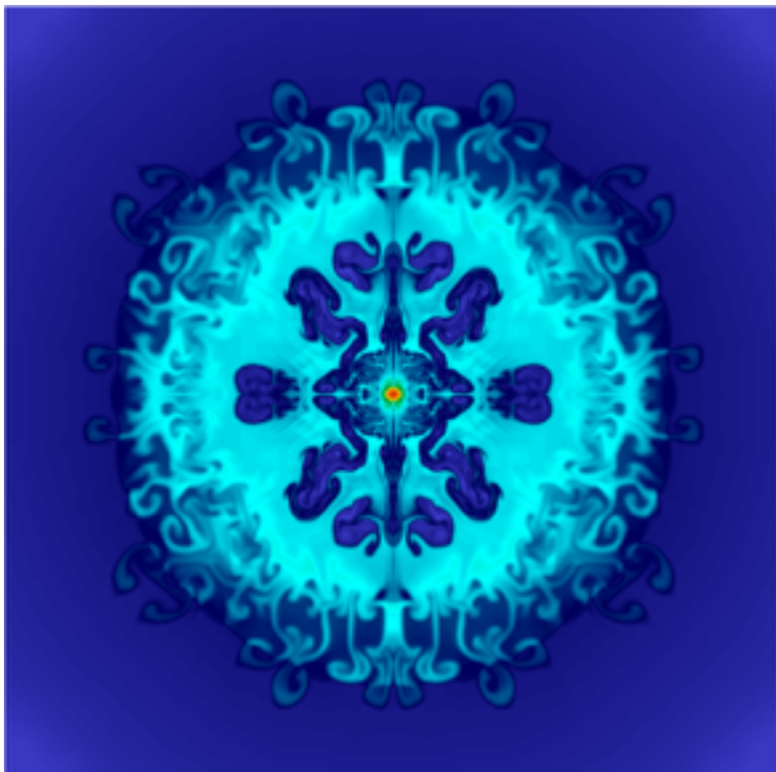
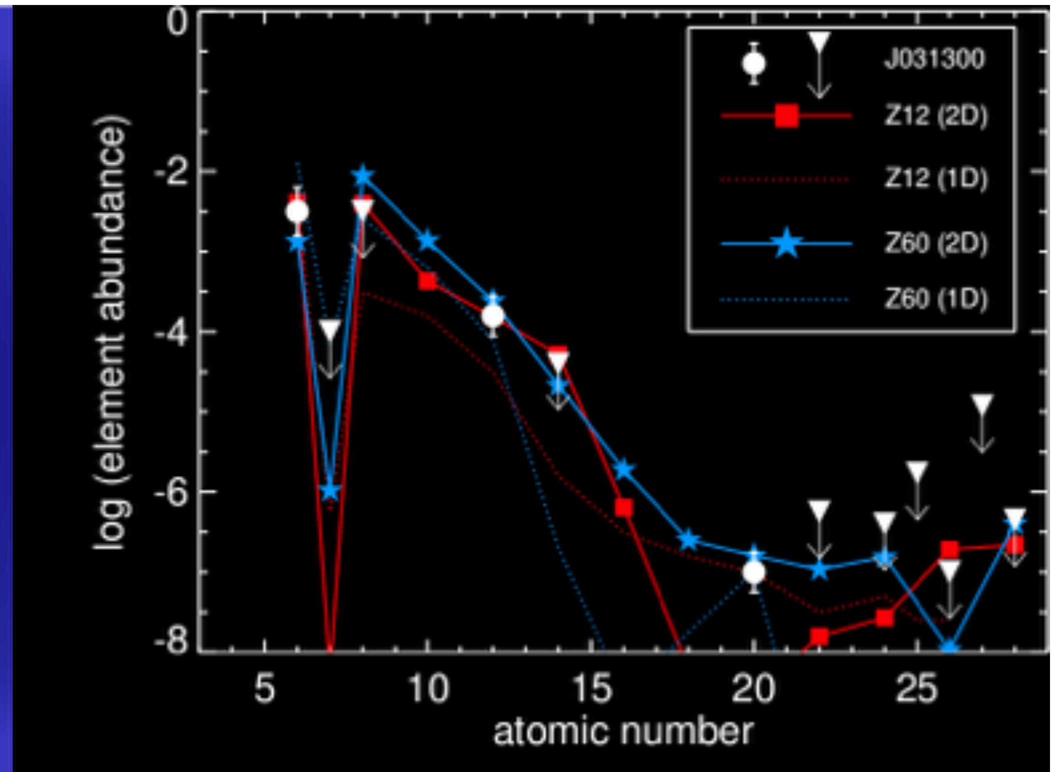


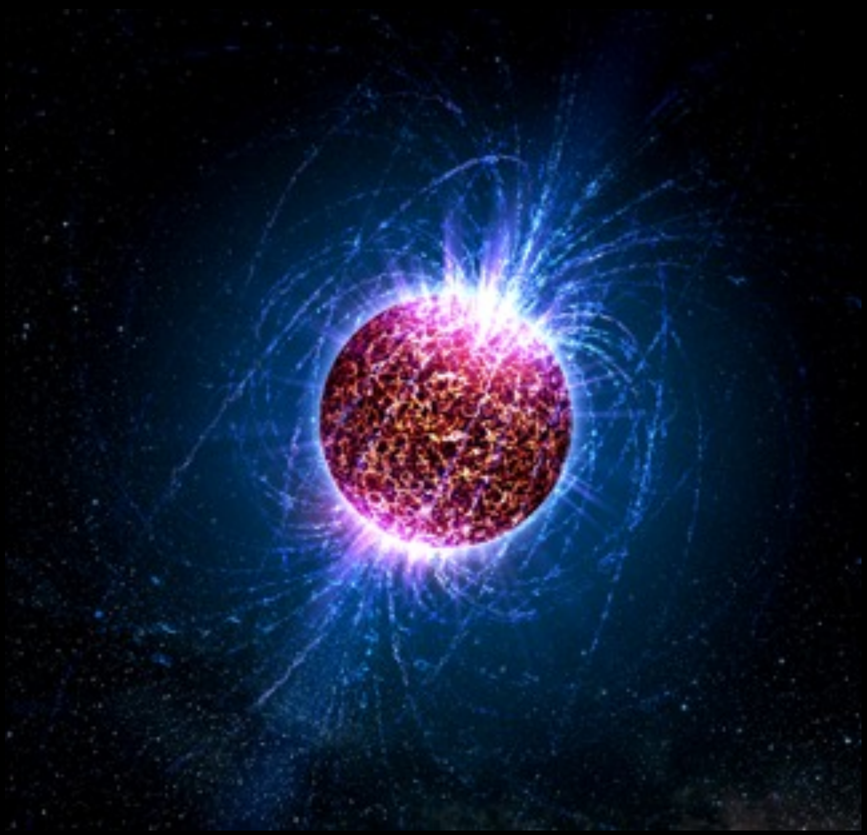




J031300
Z12 (2D)
Z12 (1D)
Z60 (2D)
Z60 (1D)
log (element abundance)
atomic number
0
-2
-4
-6
-8
5
10
15
20
25

If Magnetar formation

30 M⊙ > M* > 20 M⊙



$$E = \frac{1}{2} I\omega^2 \approx 2 \times 10^{52} P_{ms}^{-2} \quad \text{erg.}$$

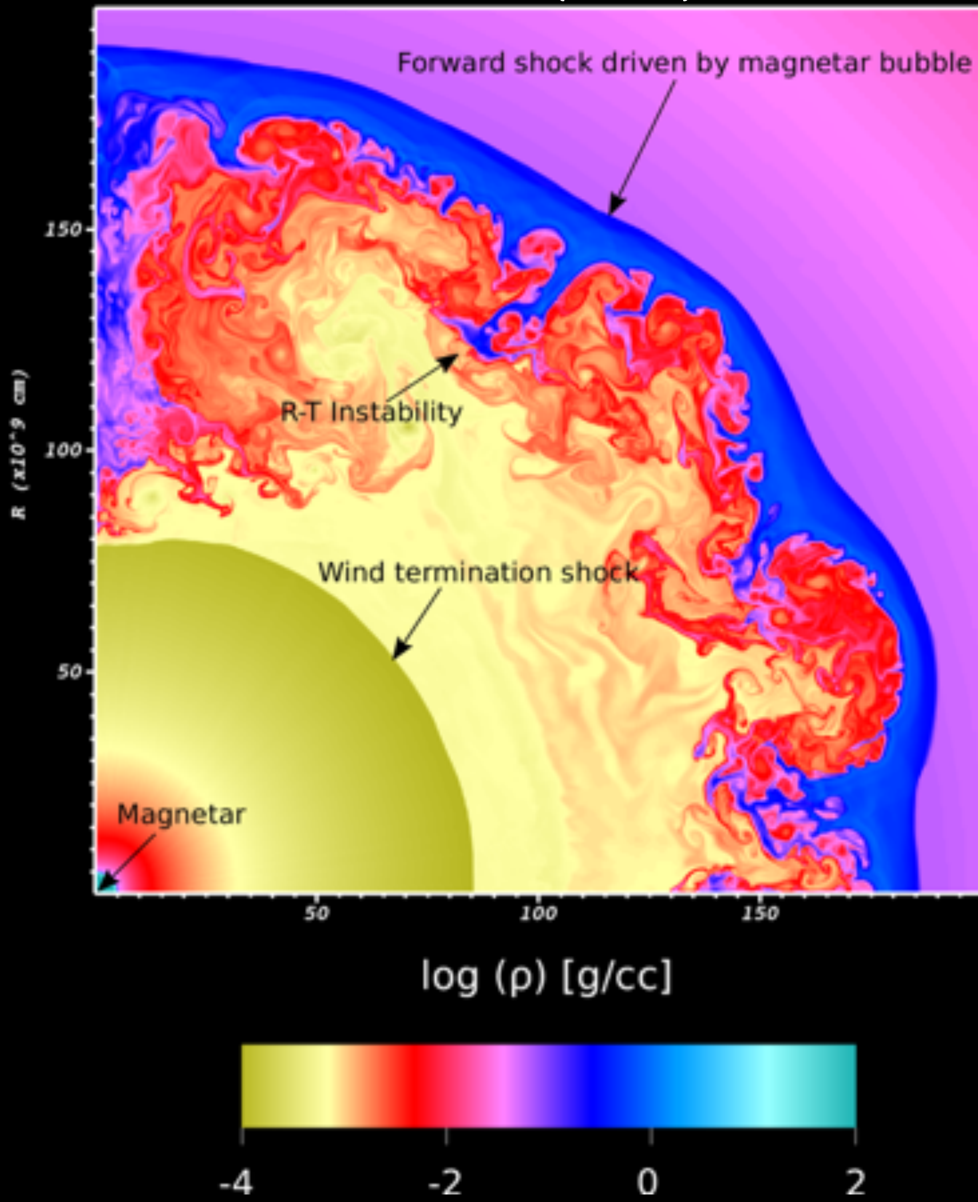
$$L_m = -\frac{32\pi^4}{3c^2}(BR_{ns}^3 \sin\alpha)^2 P^{-4}$$
$$\approx -1.0 \times 10^{49} B_{15}^2 P_{ms}^{-4} \quad \text{erg s}^{-1}$$

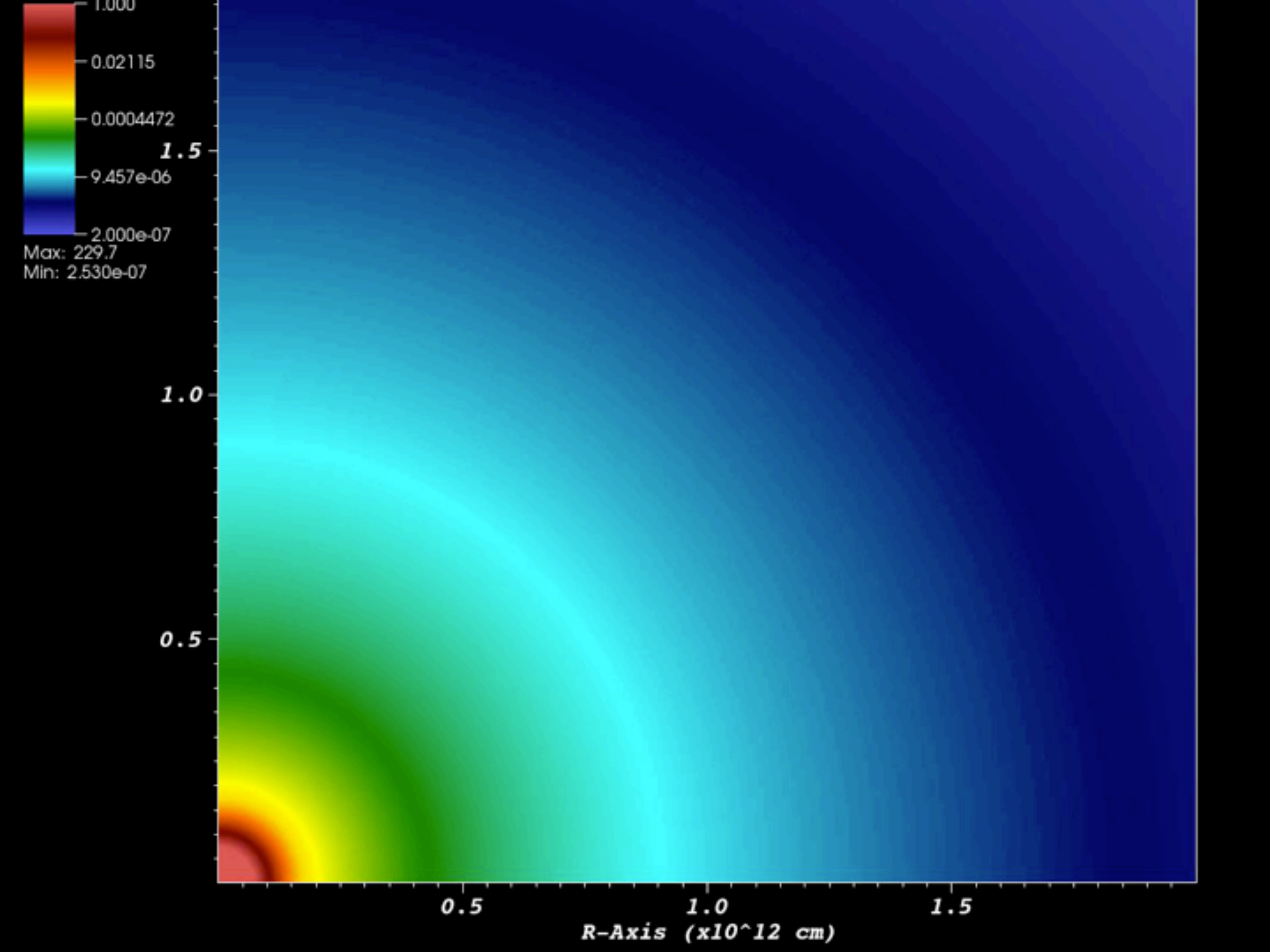
$$P(t) \approx (1 + t/t_m)^{1/2} P_0 \ \text{ms},$$
$$L(t) \approx (1 + t/t_m)^{-2} E_0 t_m^{-1} \ \text{erg s}^{-1},$$
$$E(t) \approx (1 + t/t_m)^{-1} E_0 \ \text{erg},$$

where $P_0 = P_{ms}(0)$, $E_0 = E(P_0)$ and $t_m \approx 2\times10^3 P_{ms}^2 B_{15}^{-2}$

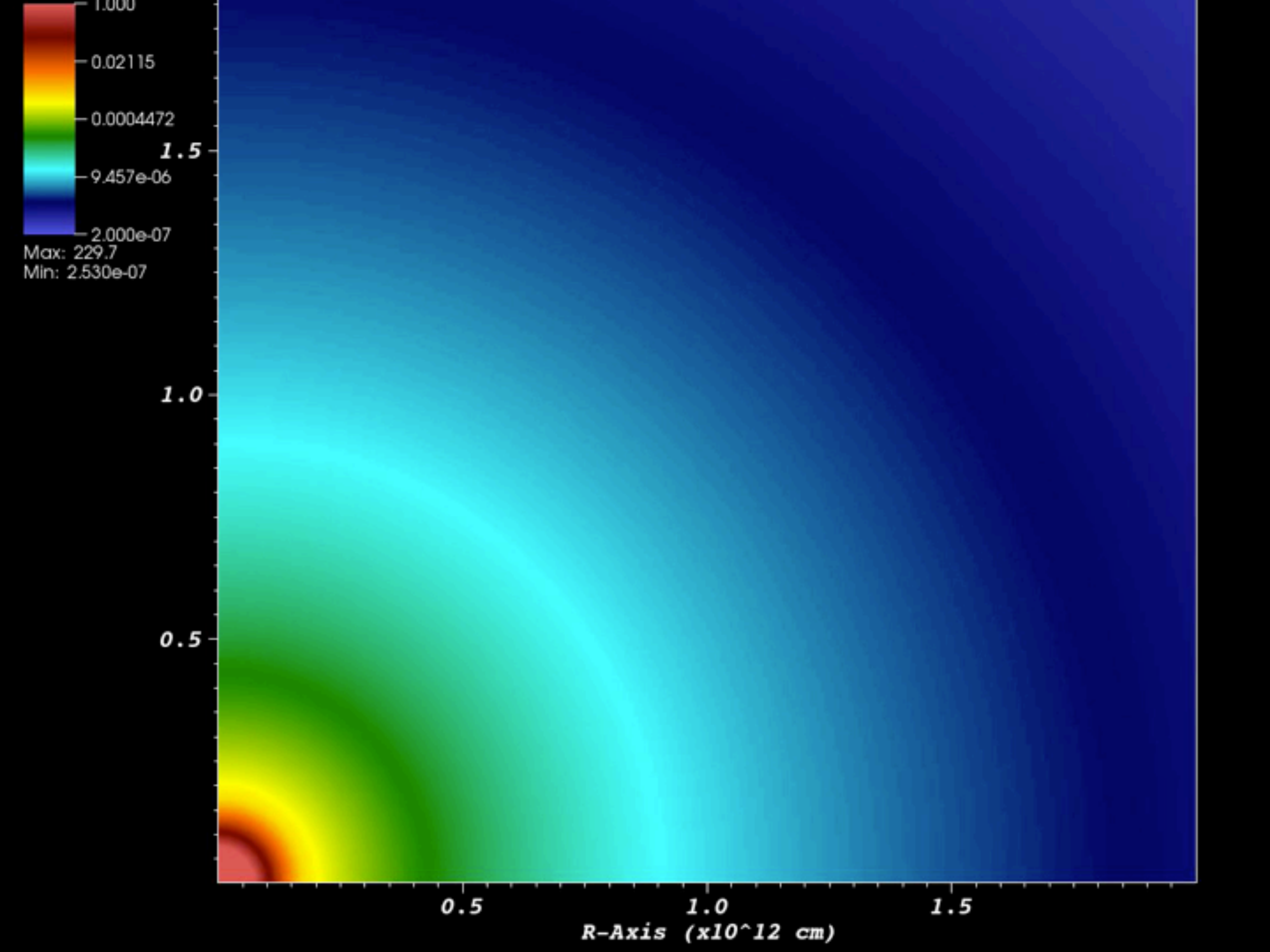
Fluid Instabilities

Chen+ (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)


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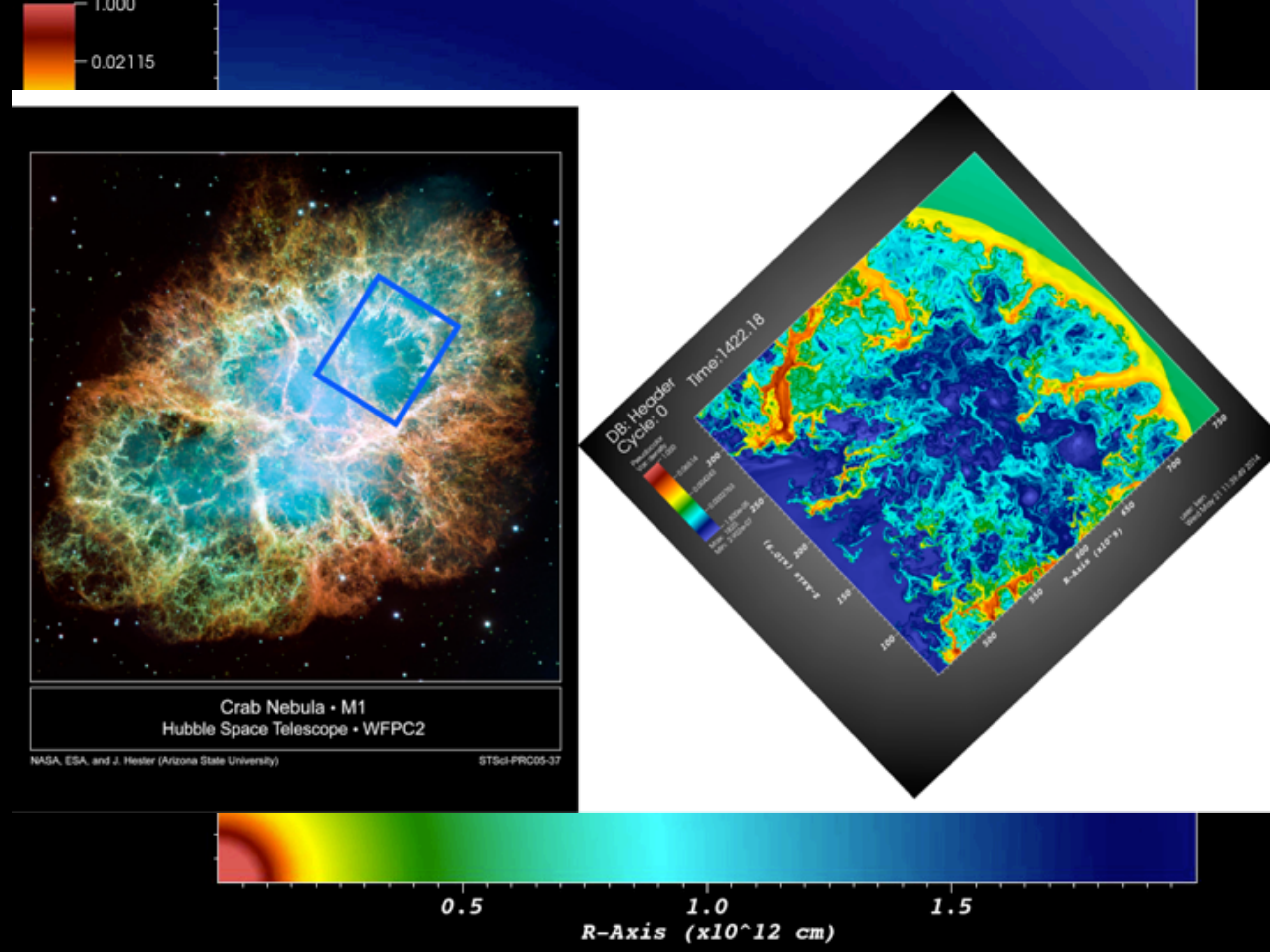
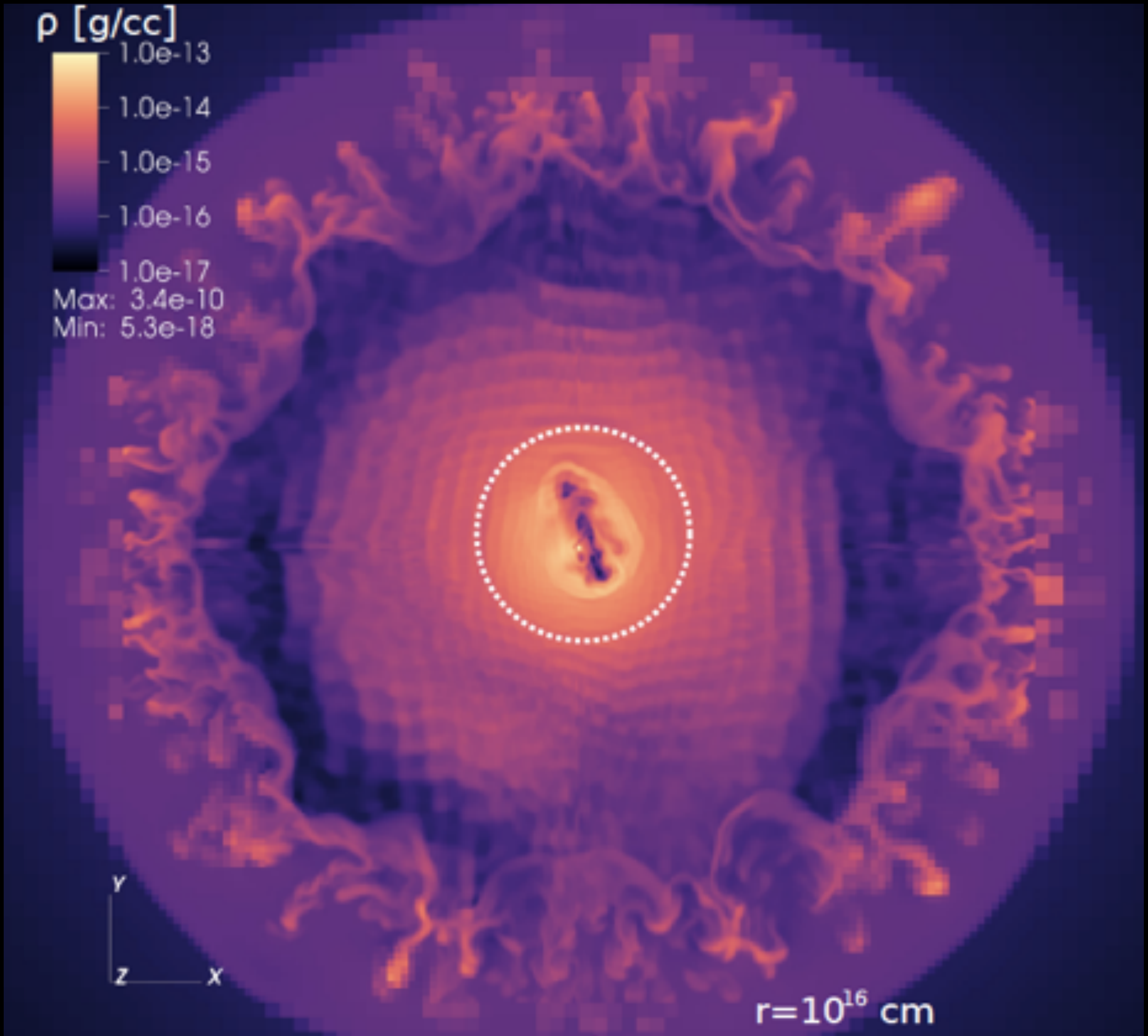
Max: 229.7
Min: 2.530e-07
0.5
1.0
1.5
R-Axis (x10^12 cm)



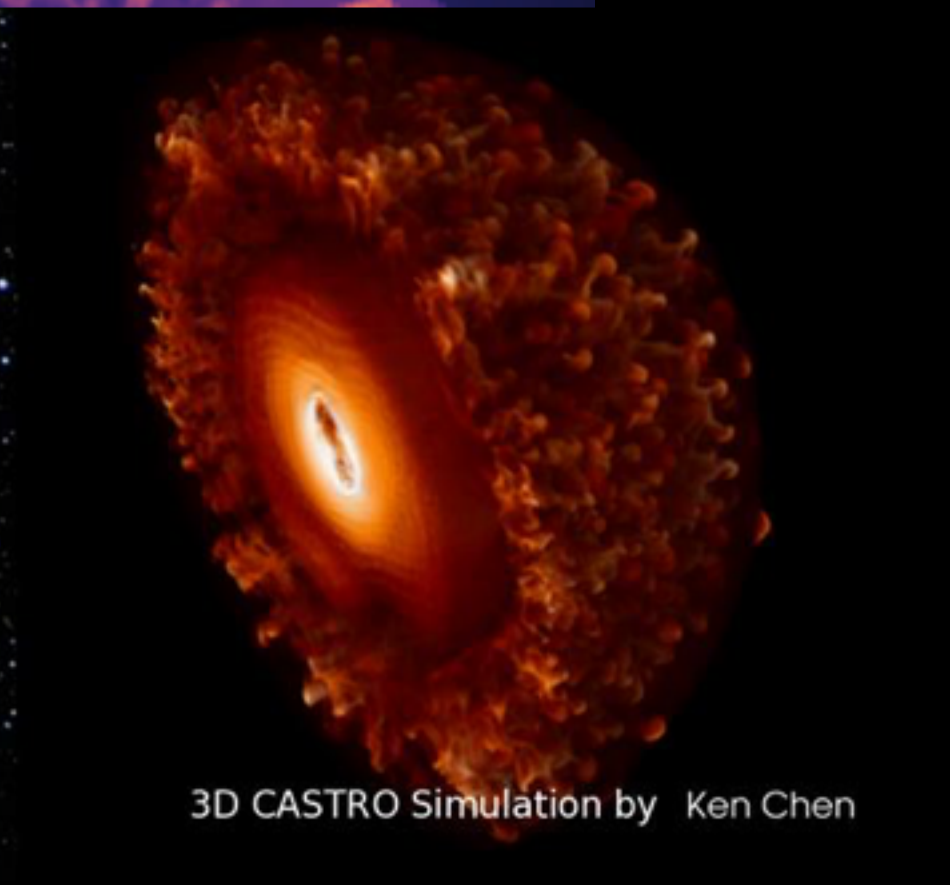
1.000
0.02115
Crab Nebula • M1
Hubble Space Telescope • WFPC2
NASA, ESA, and J. Hester (Arizona State University)
STScI-PRC05-37
DB: Header
Cycle: 0
Time:1422.18
0.5
1.0
1.5
R-Axis (x10^12 cm)

From SN to SNR (Mixing grows)



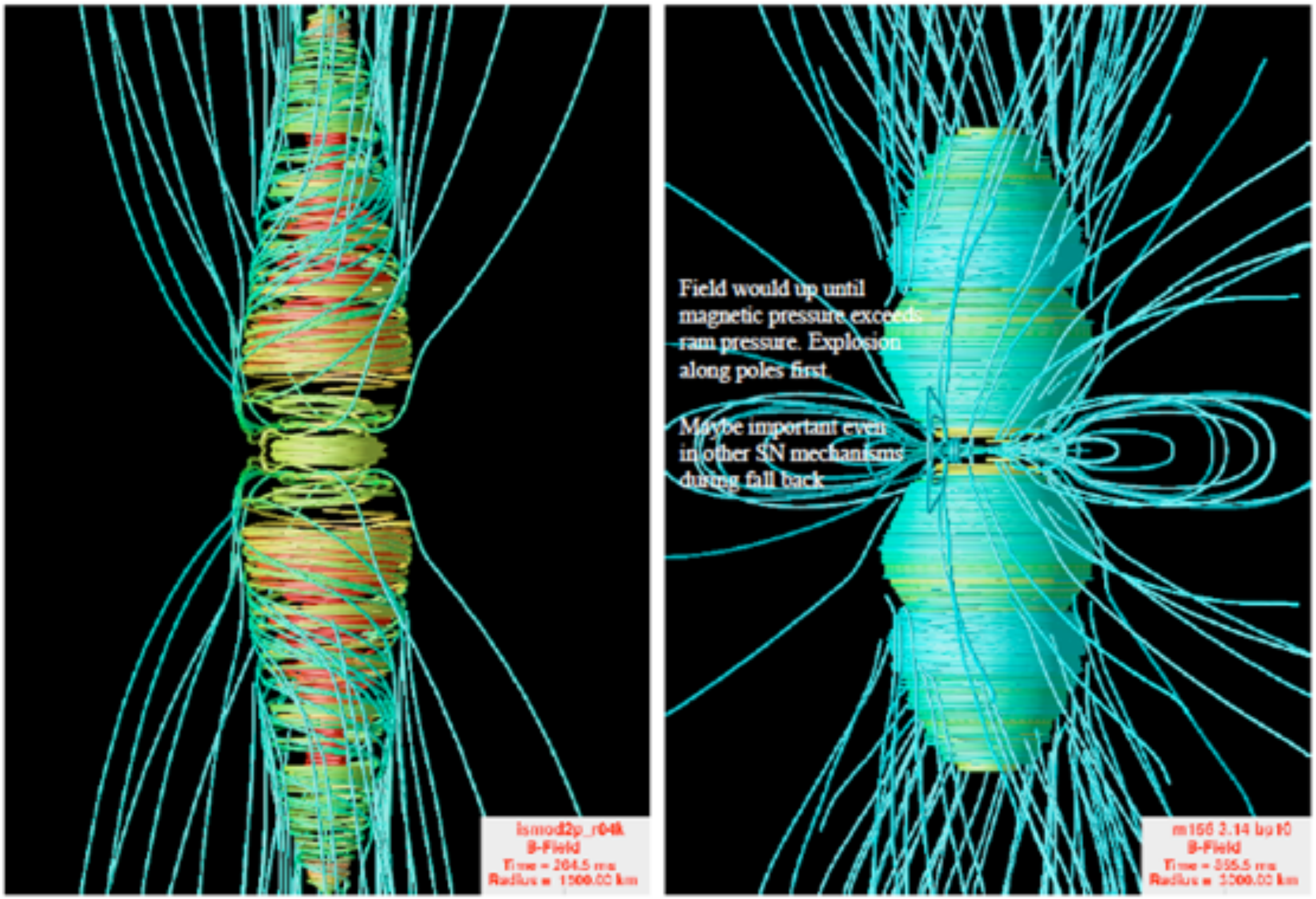
Chen+ (2019)

From SN to SNR (Mixing grows)



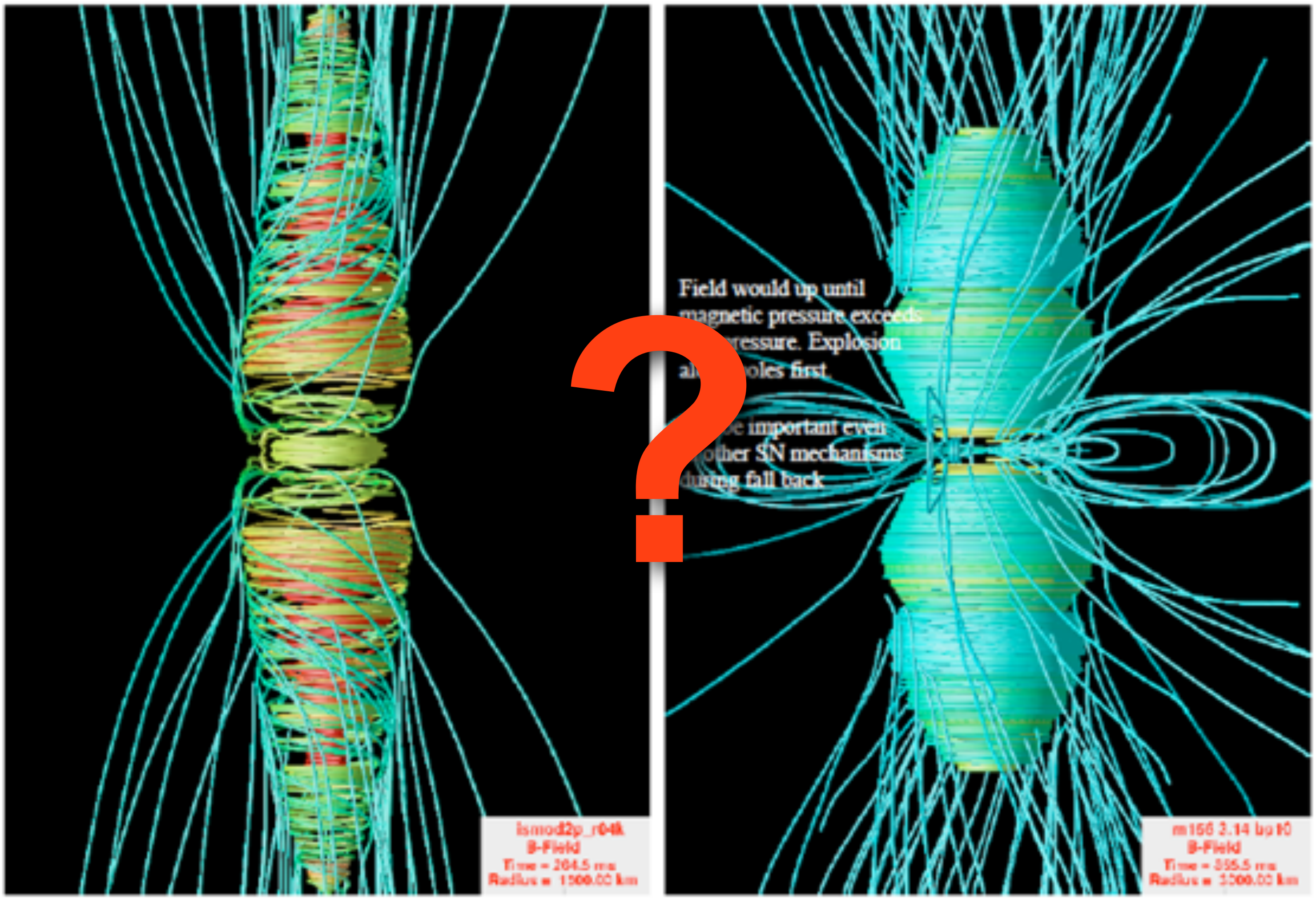
Chen+ (2019)

Jet powered Supernovae



Burrows et al 2007, *ApJ*, **664**, 416

Jet powered Supernovae

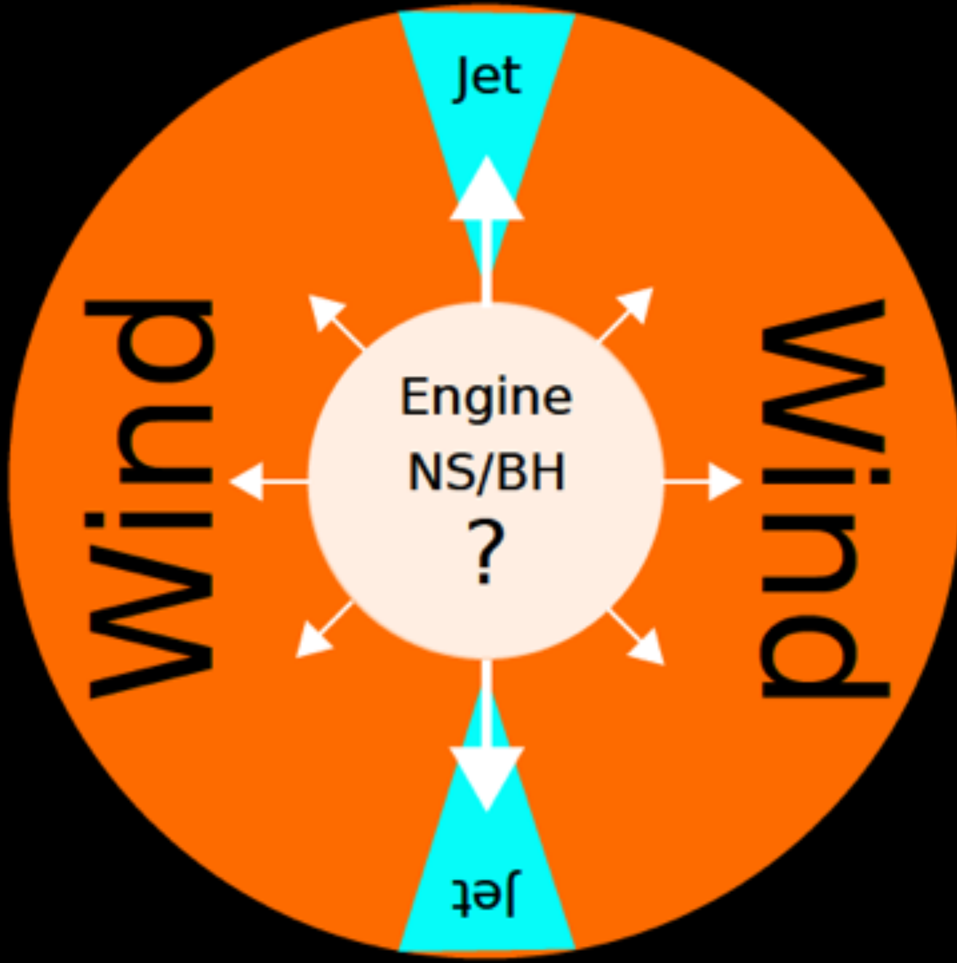


Burrows et al 2007, *ApJ*, **664**, 416

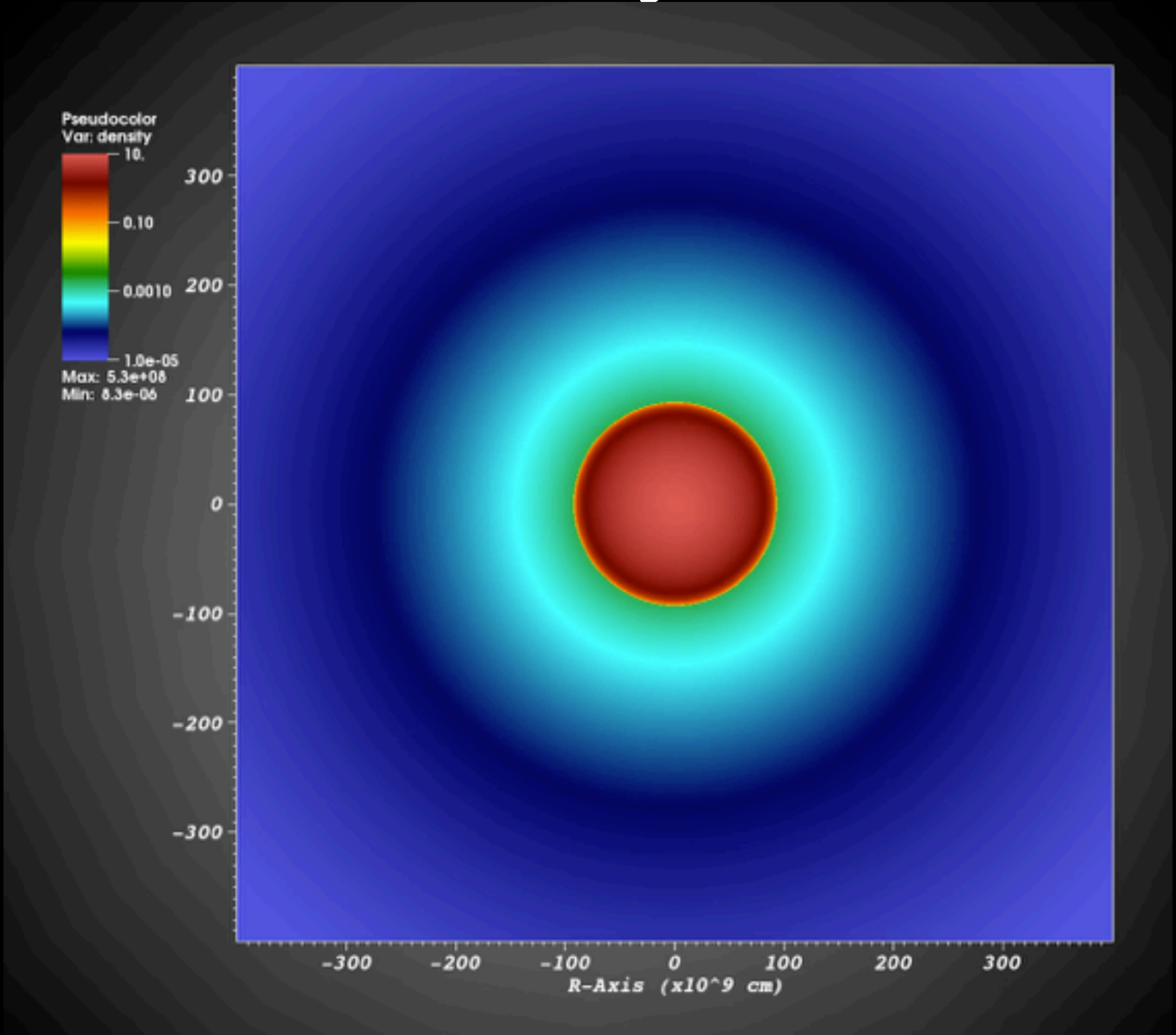
Very Energetic SNe - Hypernovae

60 M☉ > M* > 30 M☉

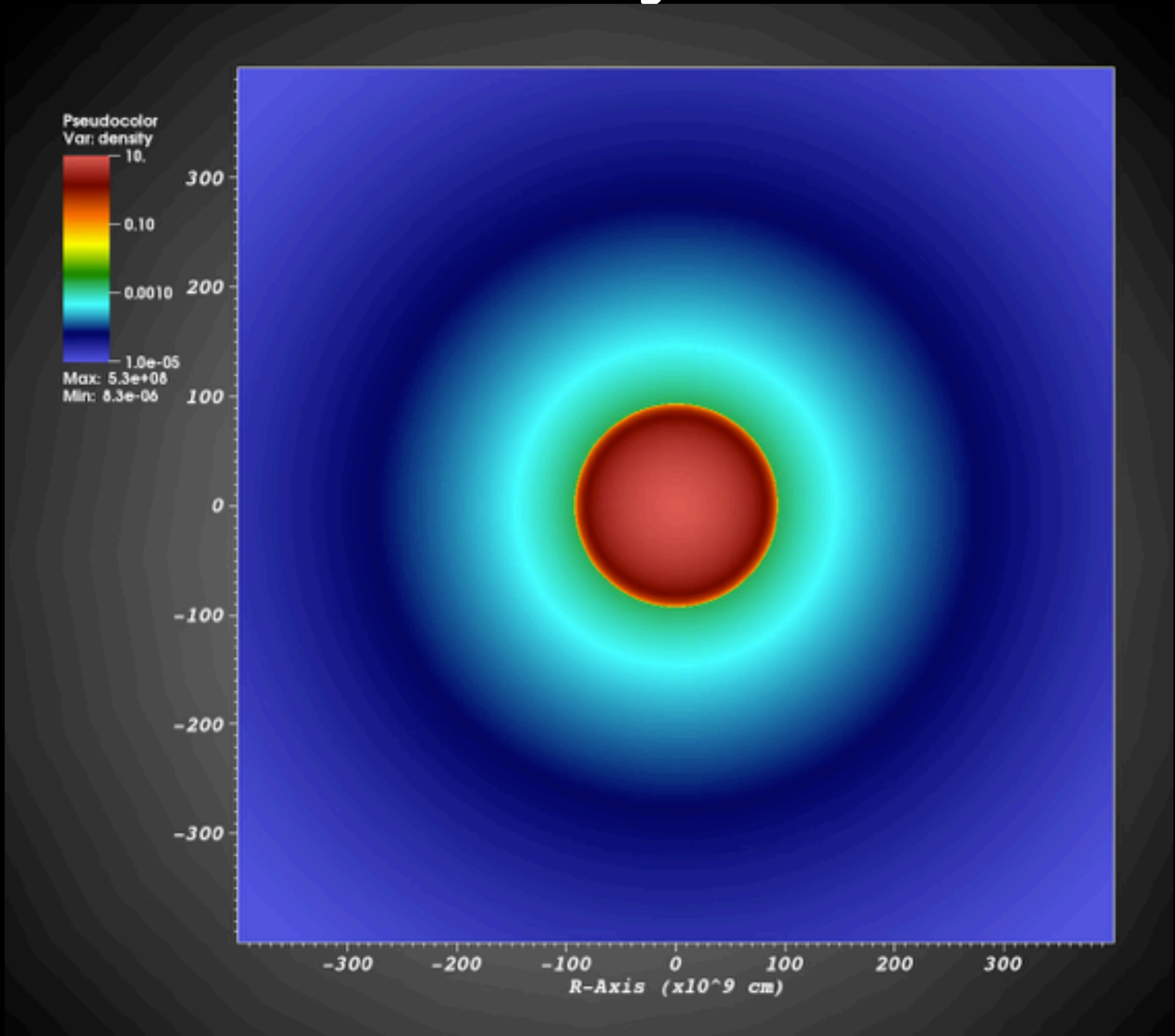
B > 1e16 G, P < 1 ms



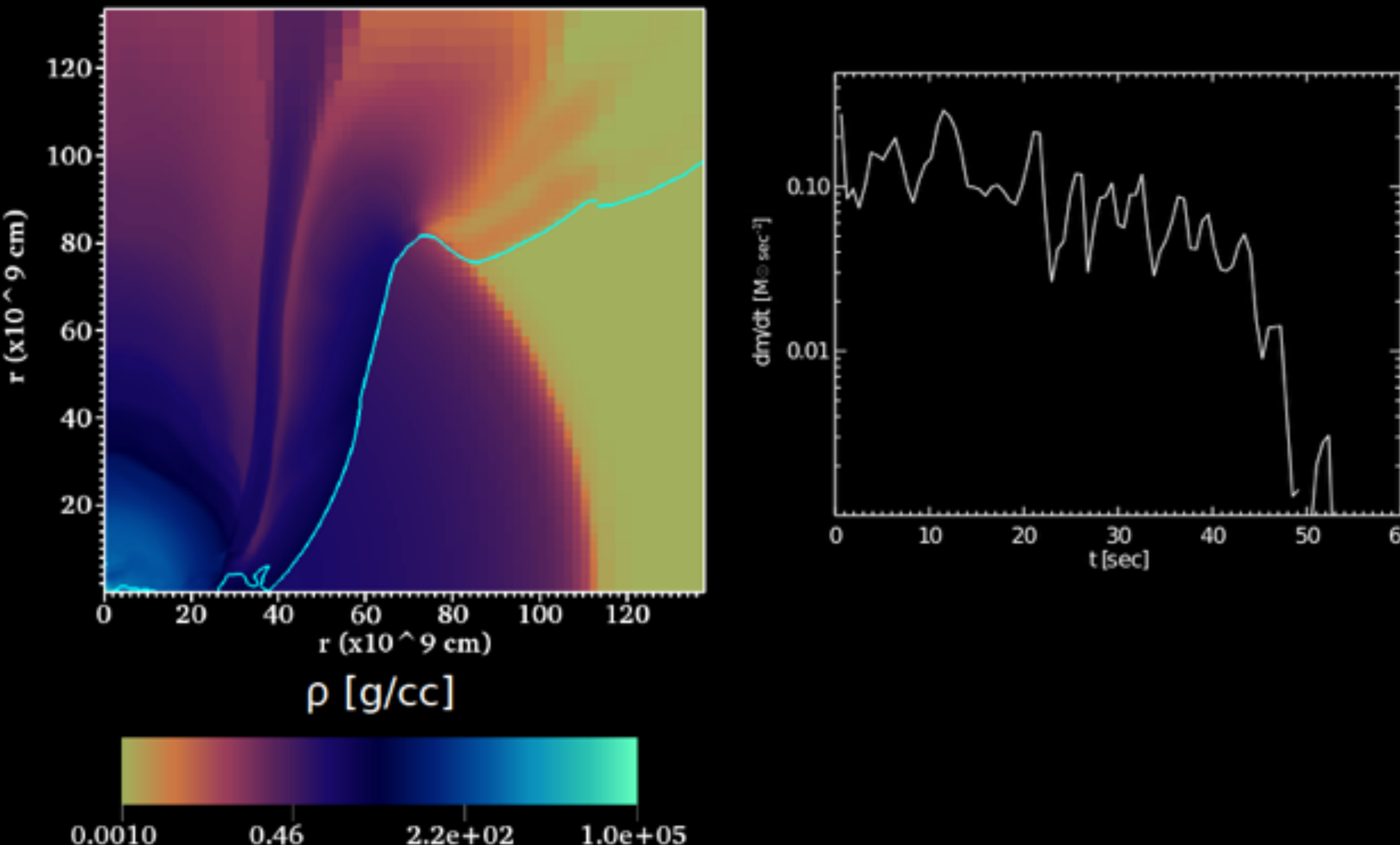
But there may be a GRB !



But there may be a GRB !

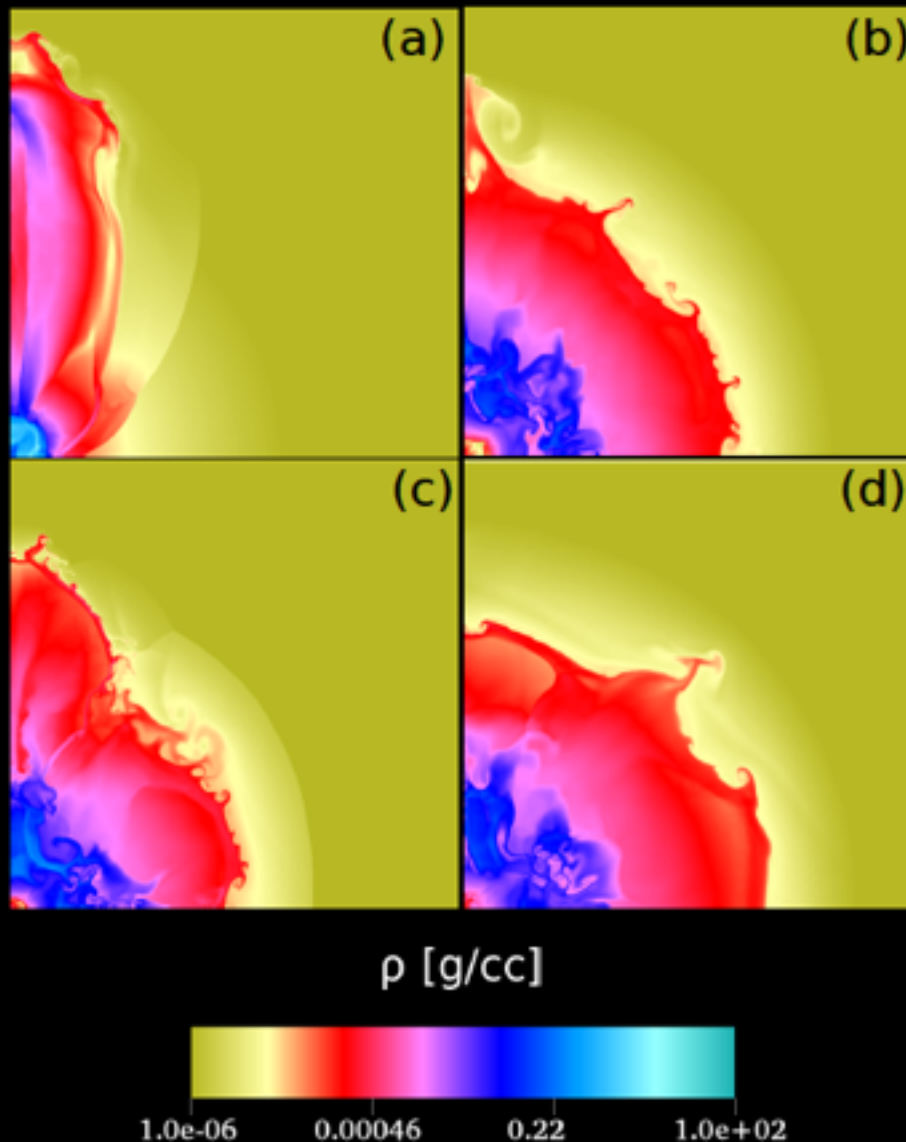


Jet only Model



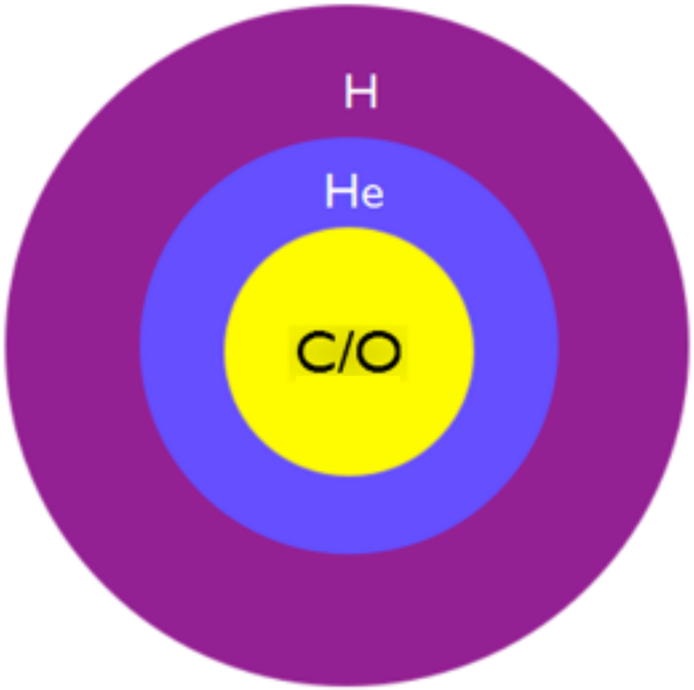
Chen+ ApJ 2017

HNe Explosions



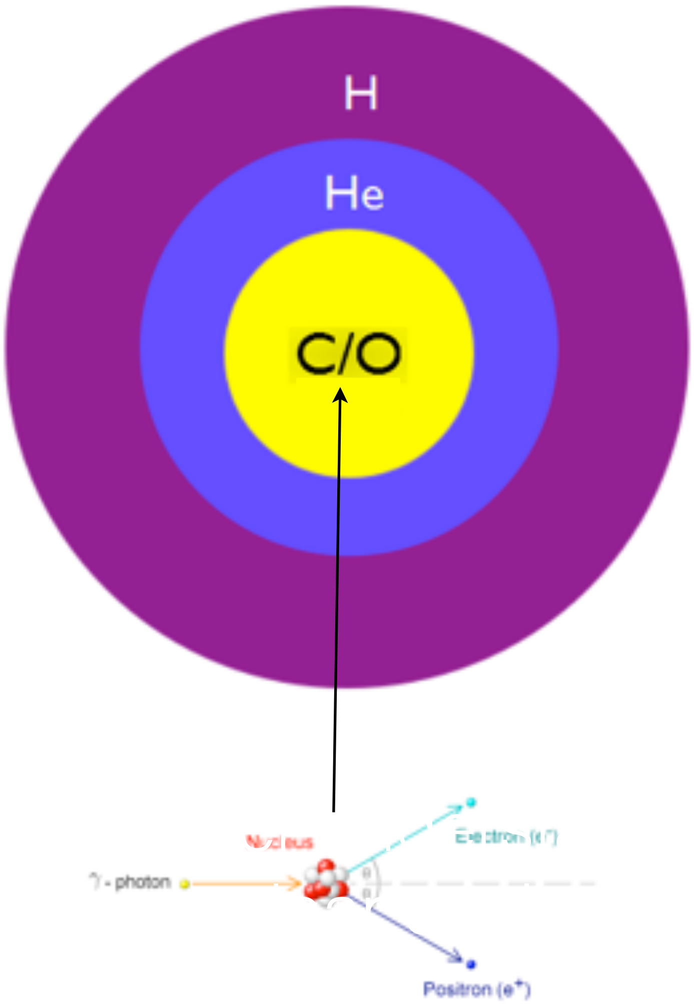
Fate of Very Massive Stars

Star > 80 M☉



Fate of Very Massive Stars

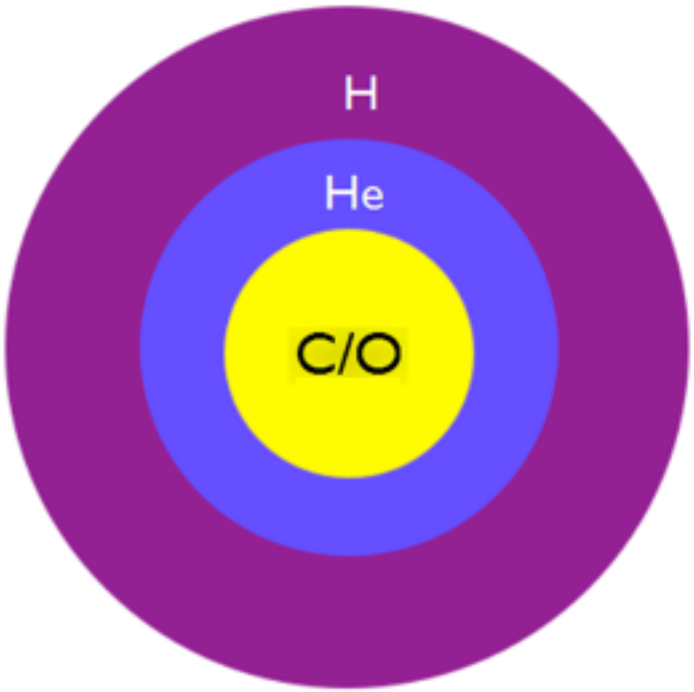
Star > 80 M☉



$E_o > 2m_0c^2$, where m_0 is the electron rest mass

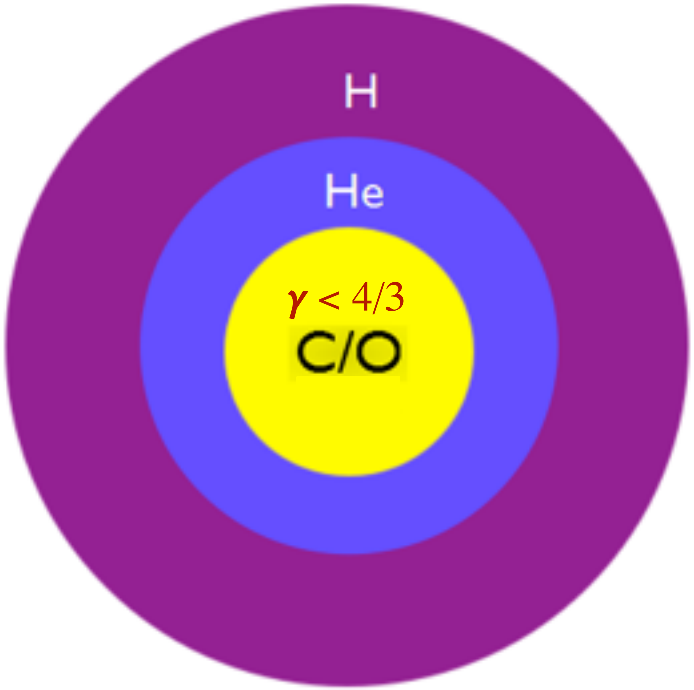
Fate of Very Massive Stars

Star > 80 M☉



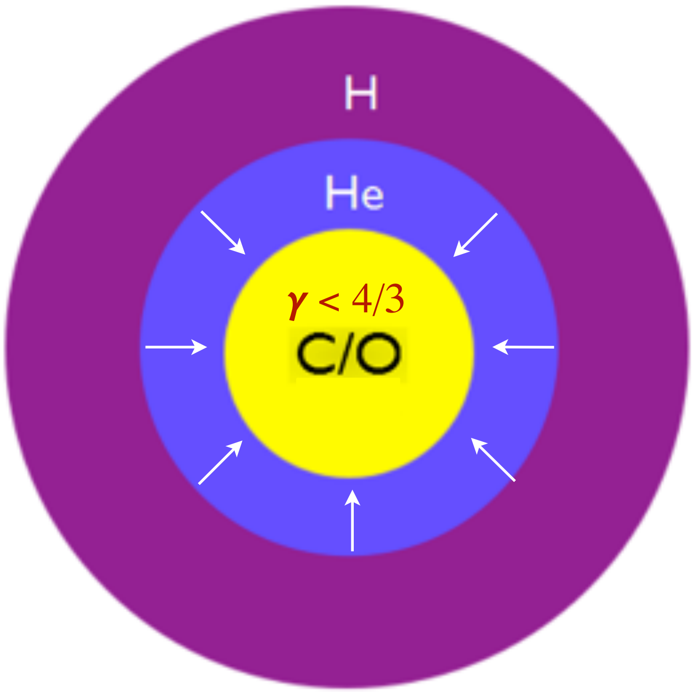
Fate of Very Massive Stars

Star > 80 M☉



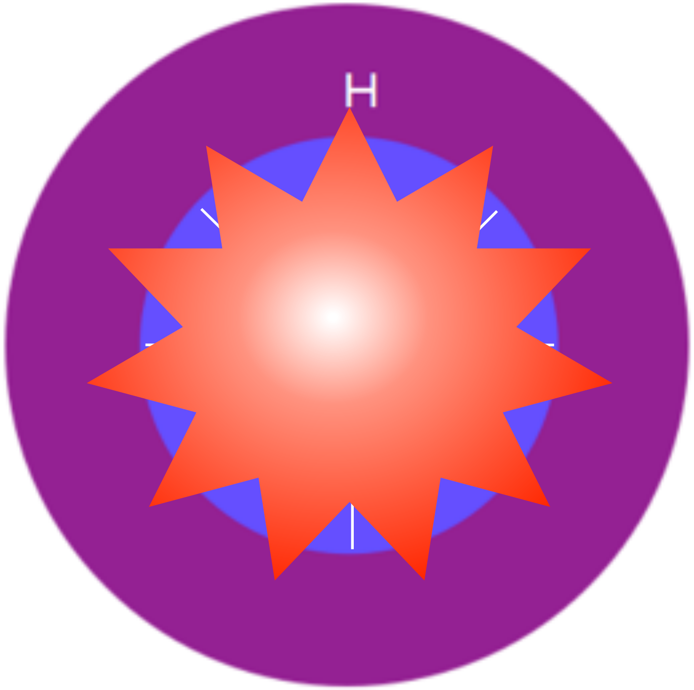
Fate of Very Massive Stars

Star > 80 M☉



Fate of Very Massive Stars

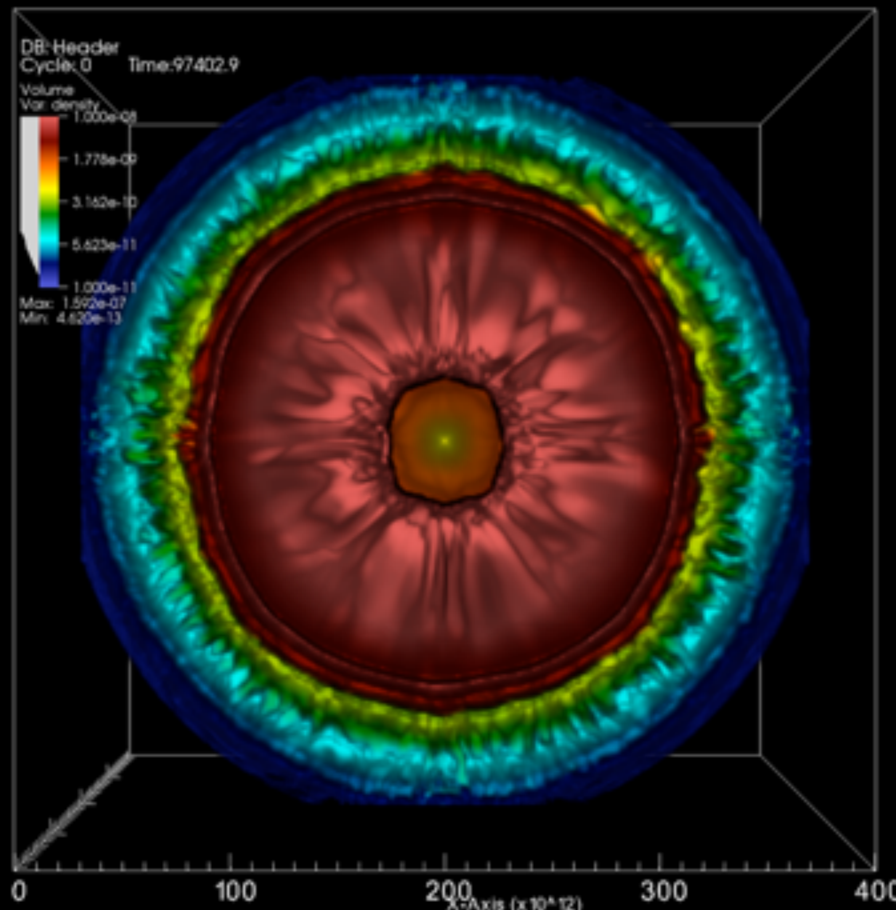
Star > 80 M☉




We have a better understanding of
Thermonuclear explosion

Pulsational Pair-Instability Supernovae (PPSNe)

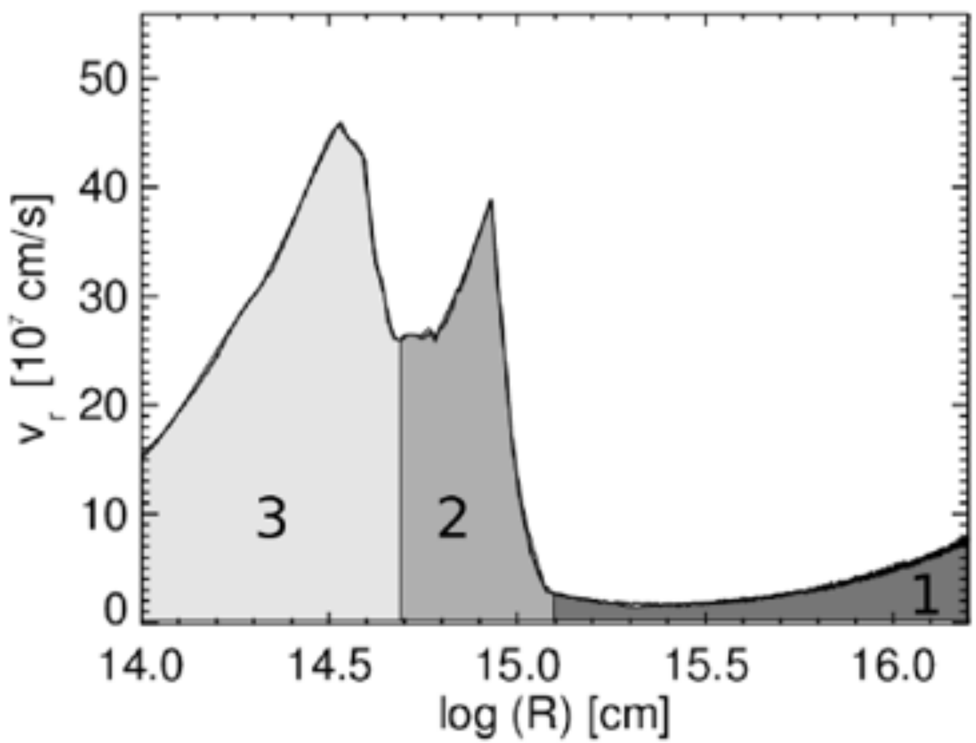
$150\ M_\odot > M^* > 80\ M_\odot$



Chen+ ApJ 792 28 (2014)

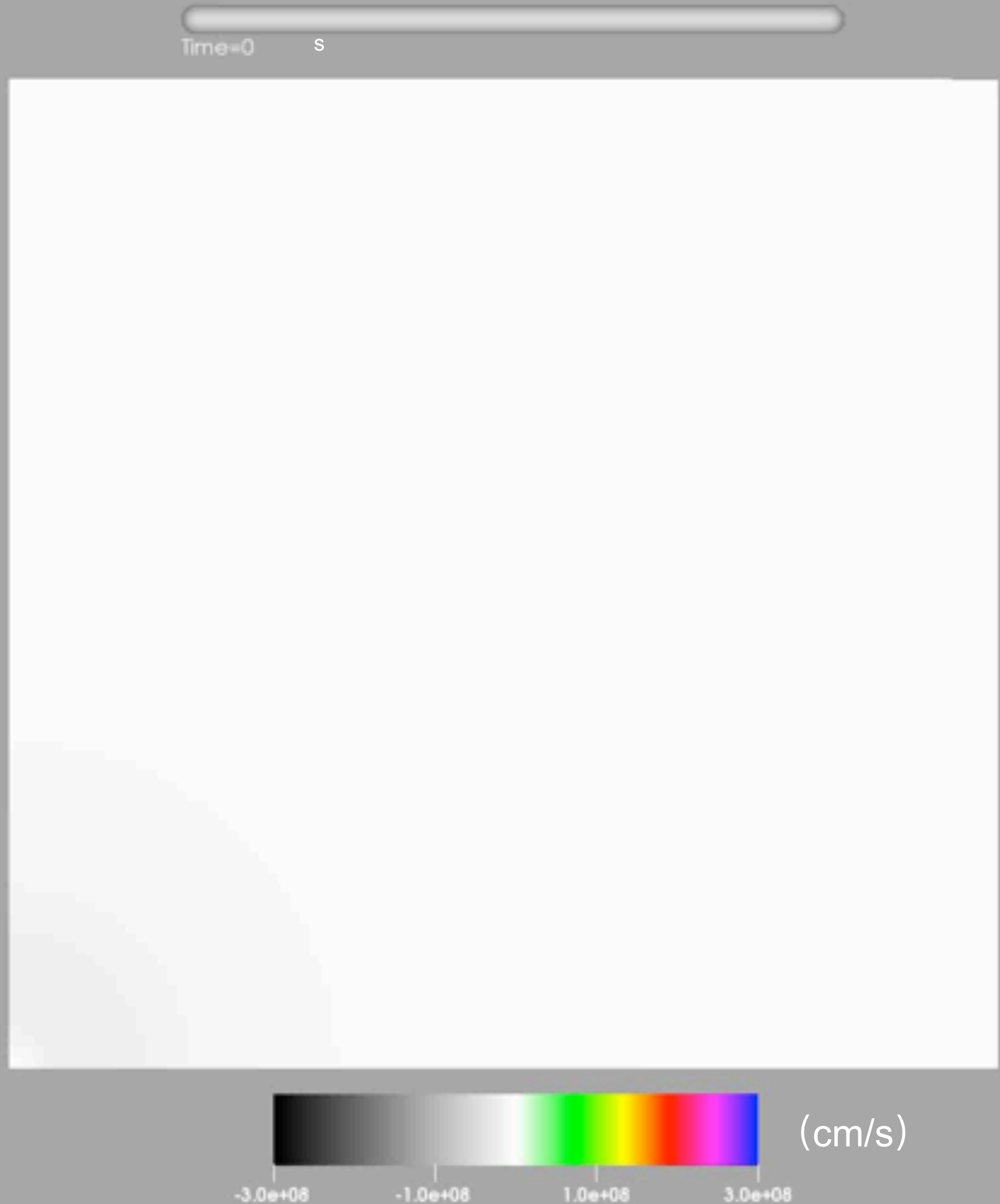
Eruption History

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.



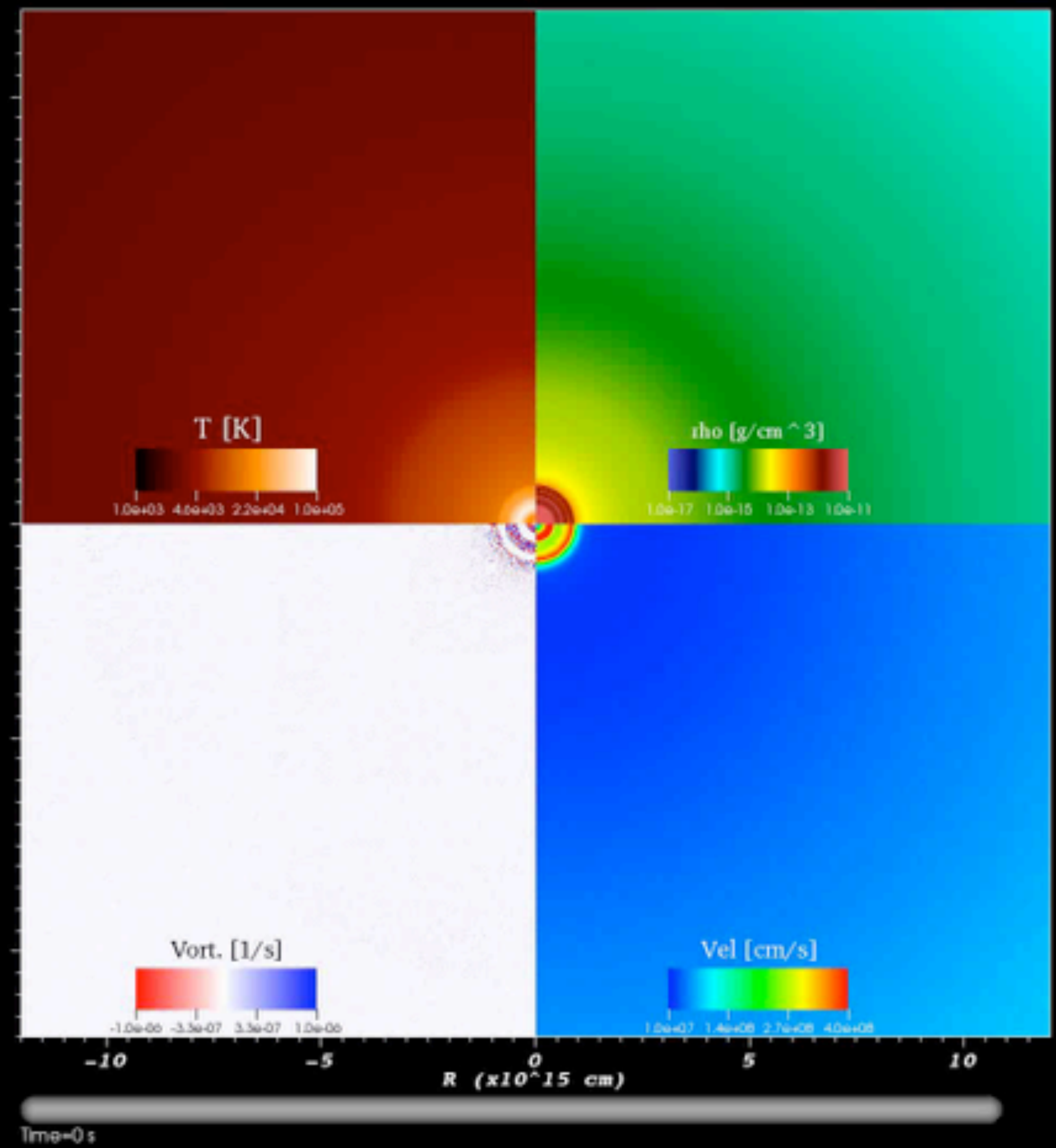
Core of 110 M☉ star

Core of 110 M☉ star

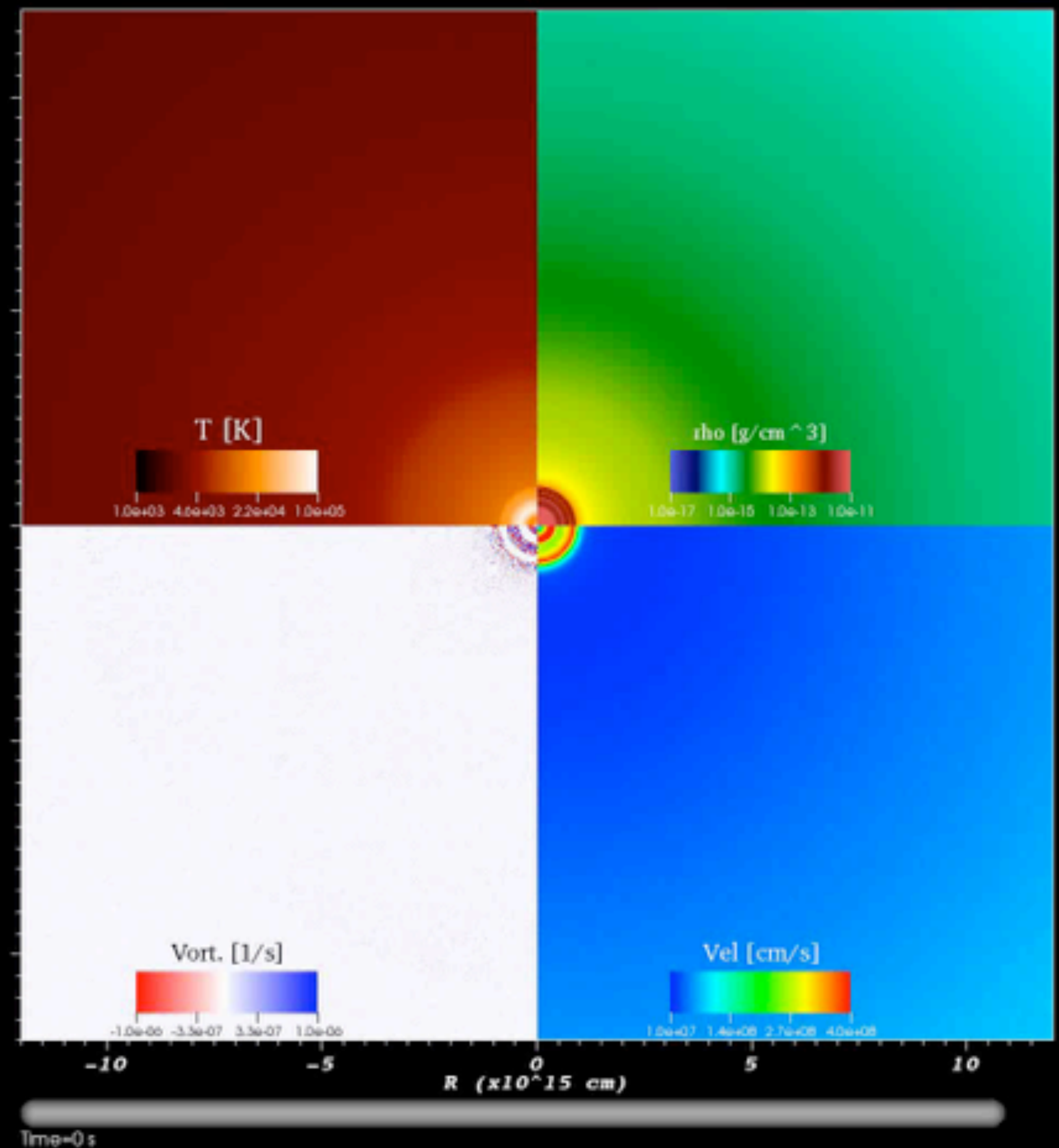


Core of 110 $M_\odot$ star

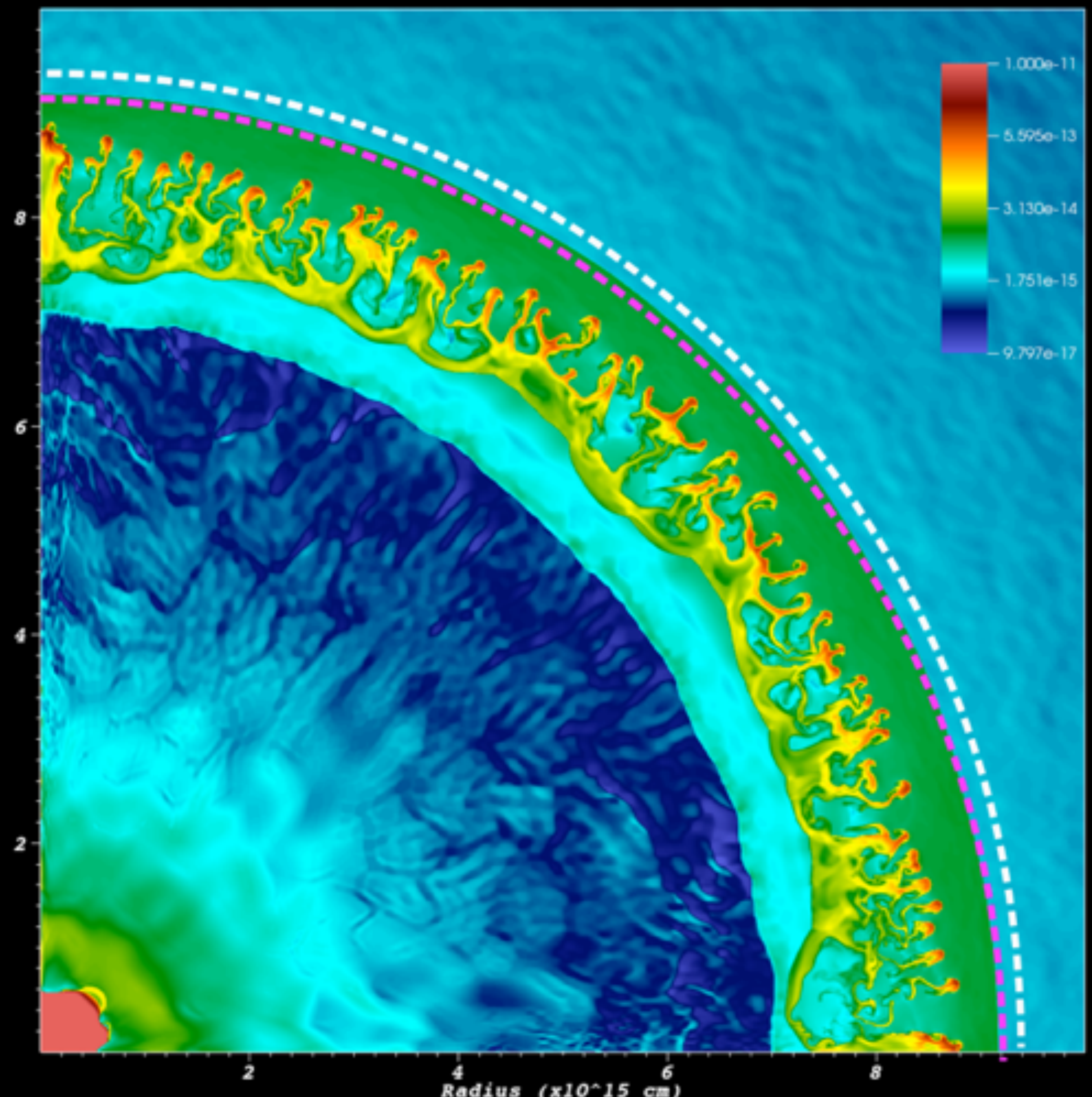
Physical Properties of Colliding Shells



Physical Properties of Colliding Shells



Physical Properties of Colliding Shells



Zombie Supernovae
(iPTF14hls, 2017)

Les dossiers Astrophysique

Supernova iPTF14hls

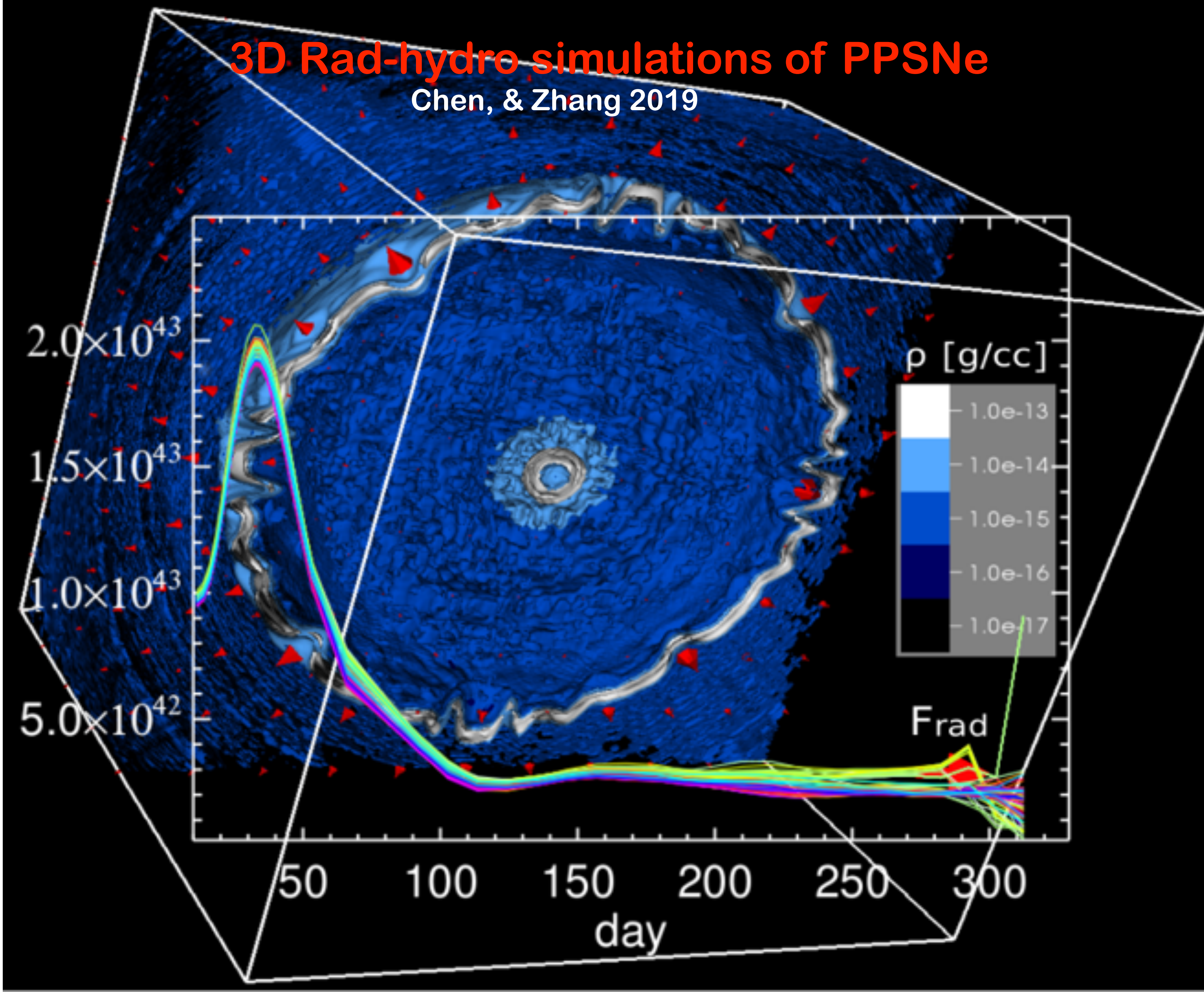
L'étoile qui défie la mort

Du jamais-vu ! Dans la Grande Ourse, une supernova n'en finit pas de mourir et de ressuciter depuis... 1954. Une véritable énigme, que nul ne parvient à élucider, comme l'a constaté Benoît Rey.

Repères

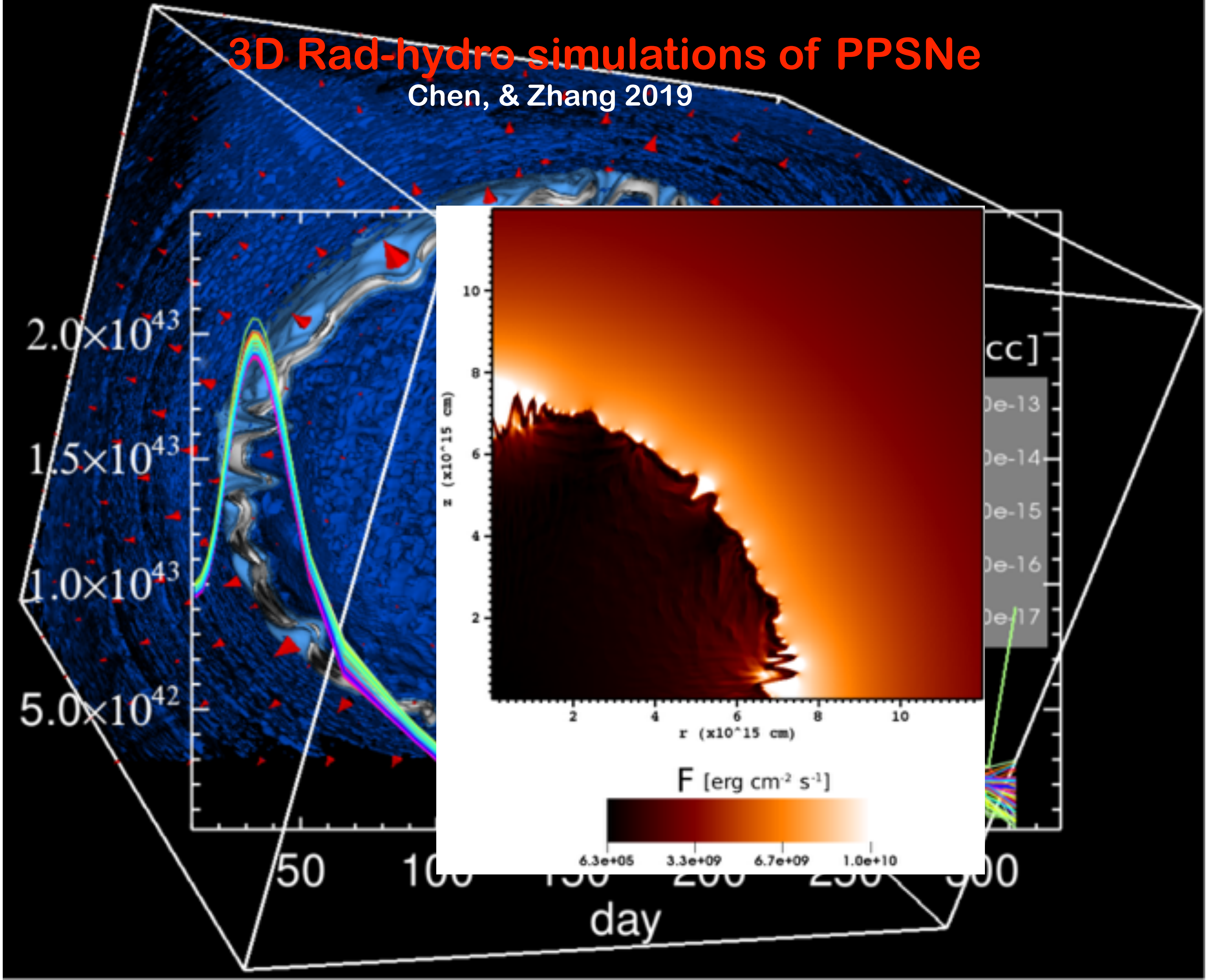
60 ANS POUR MOURIR AU LIEU DE 100 JOURS

UNE ÉTOILE MORTE-VIVANTE

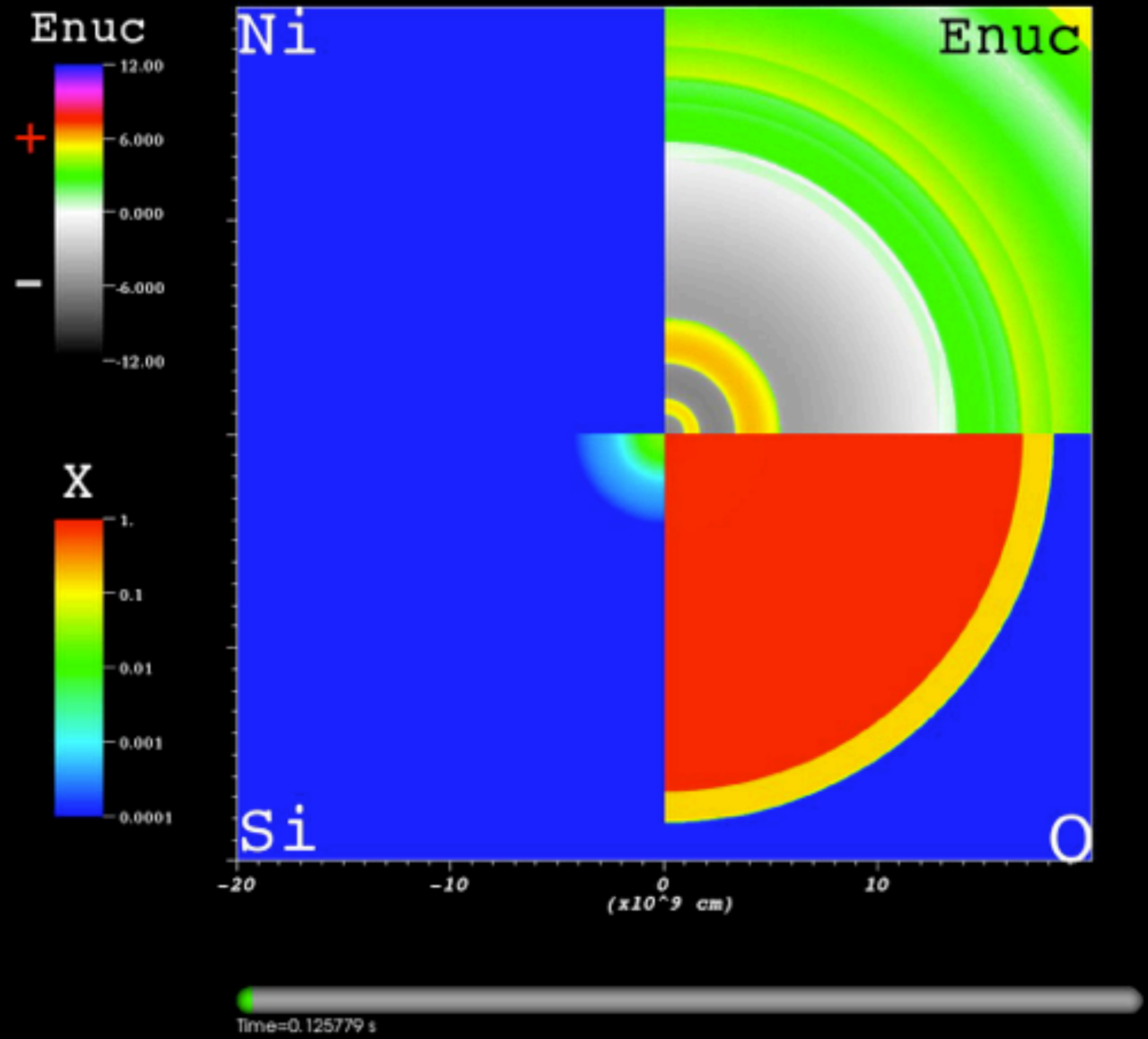

3D Rad-hydro simulations of PPSNe
Chen, & Zhang 2019
2.0×10^43
1.5×10^43
1.0×10^43
5.0×10^42
50
100
150
200
250
300
day
ρ [g/cc]
1.0e-13
1.0e-14
1.0e-15
1.0e-16
1.0e-17
Frad

3D Rad-hydro simulations of PPSNe

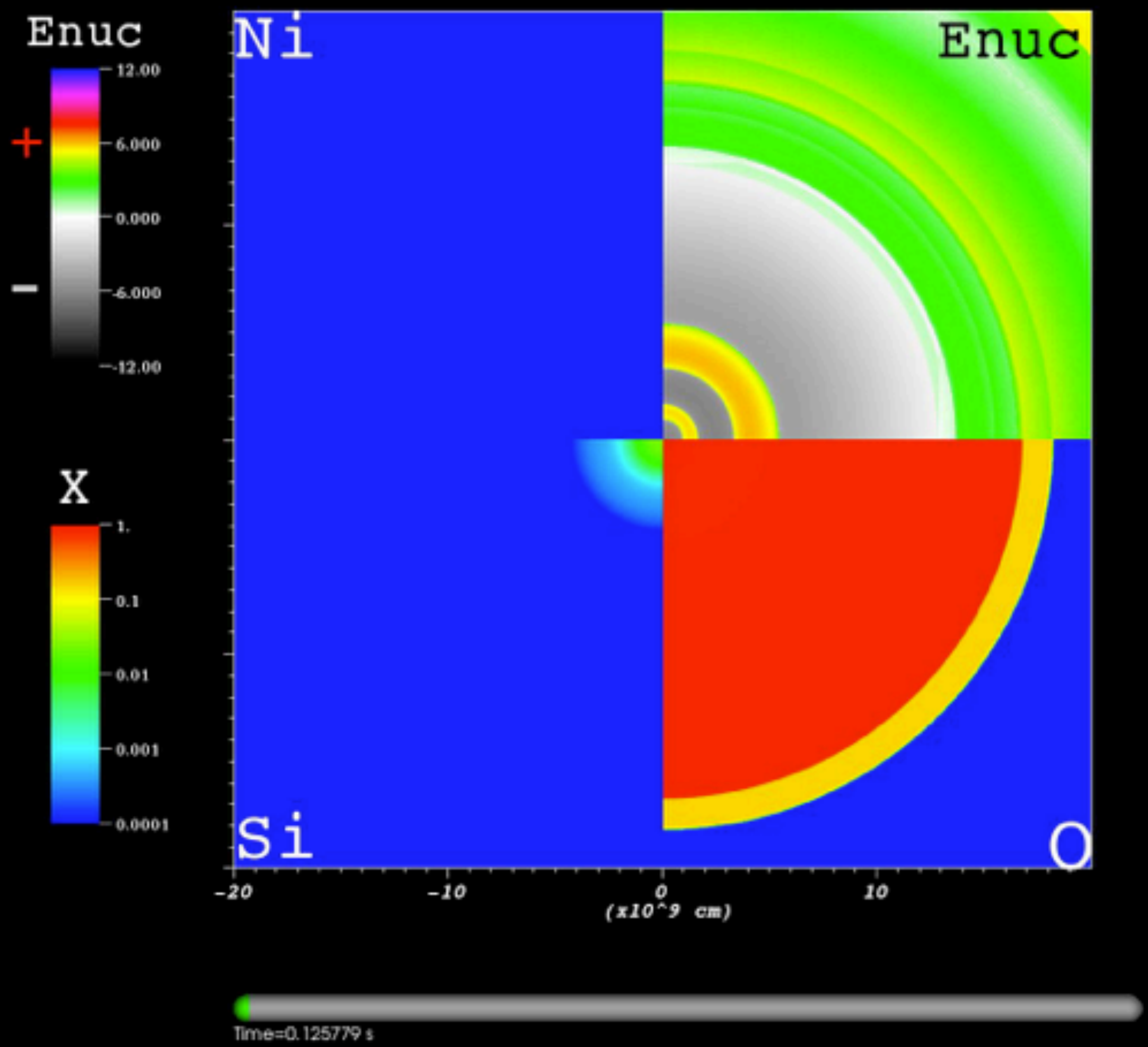
Chen, & Zhang 2019



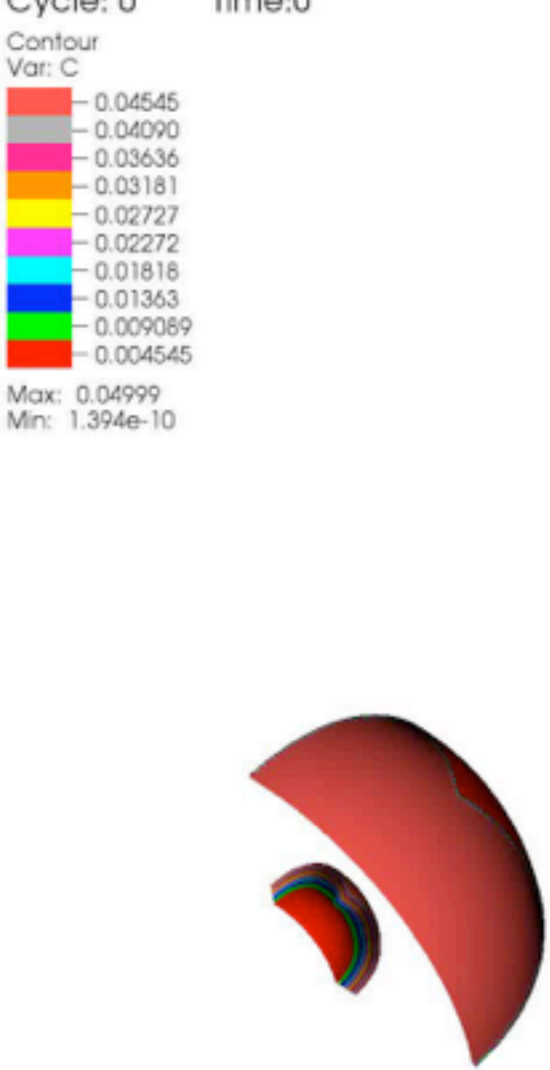
Explosive Burning of 150 M☉ Star



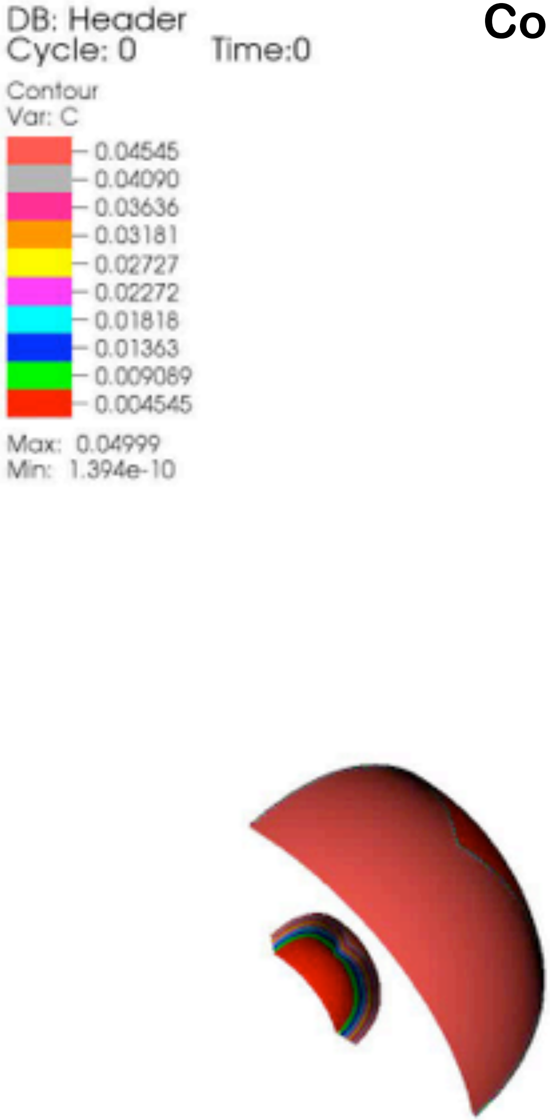
Explosive Burning of 150 M⊙ Star



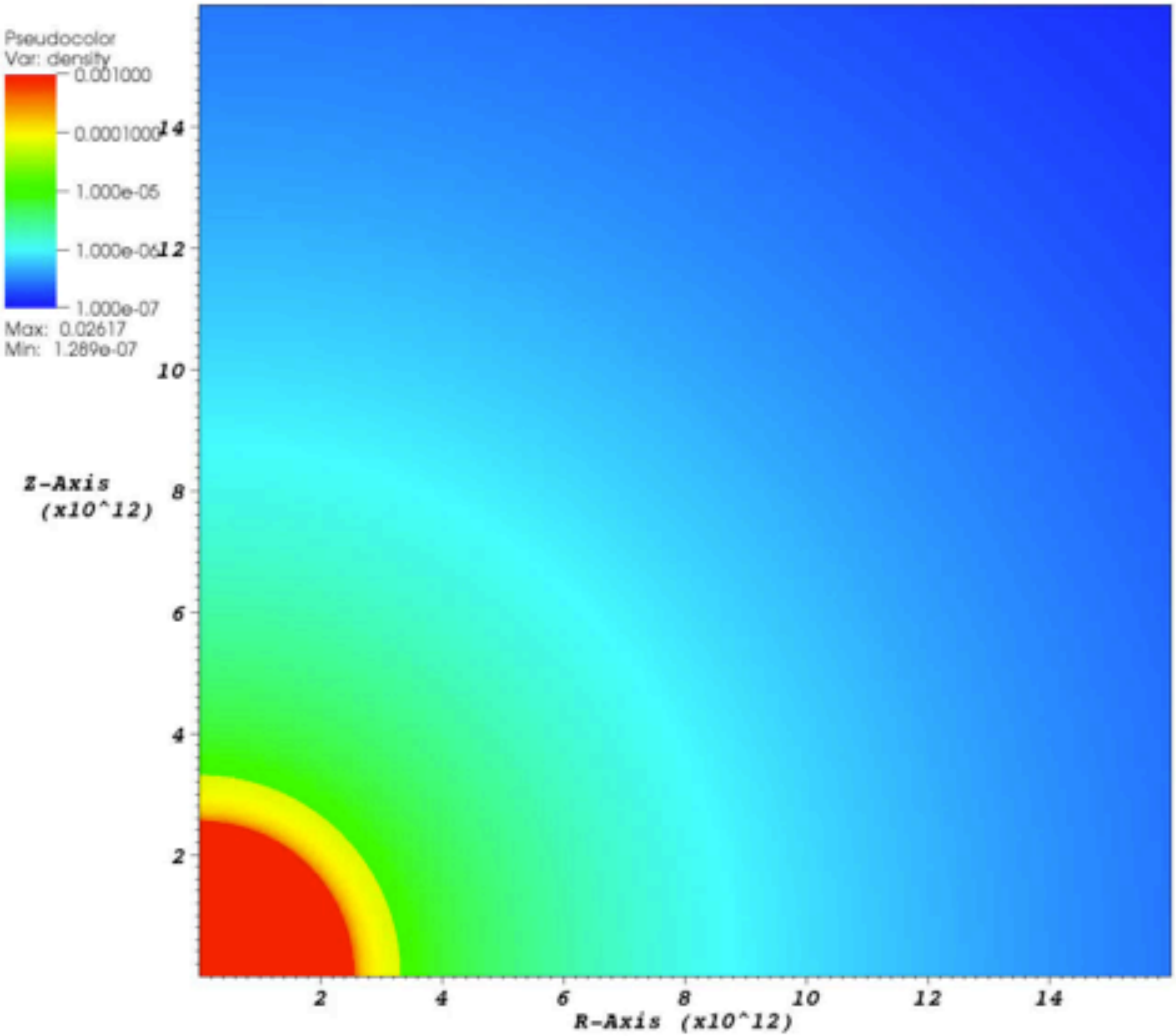
Core of 150 M☉ Star



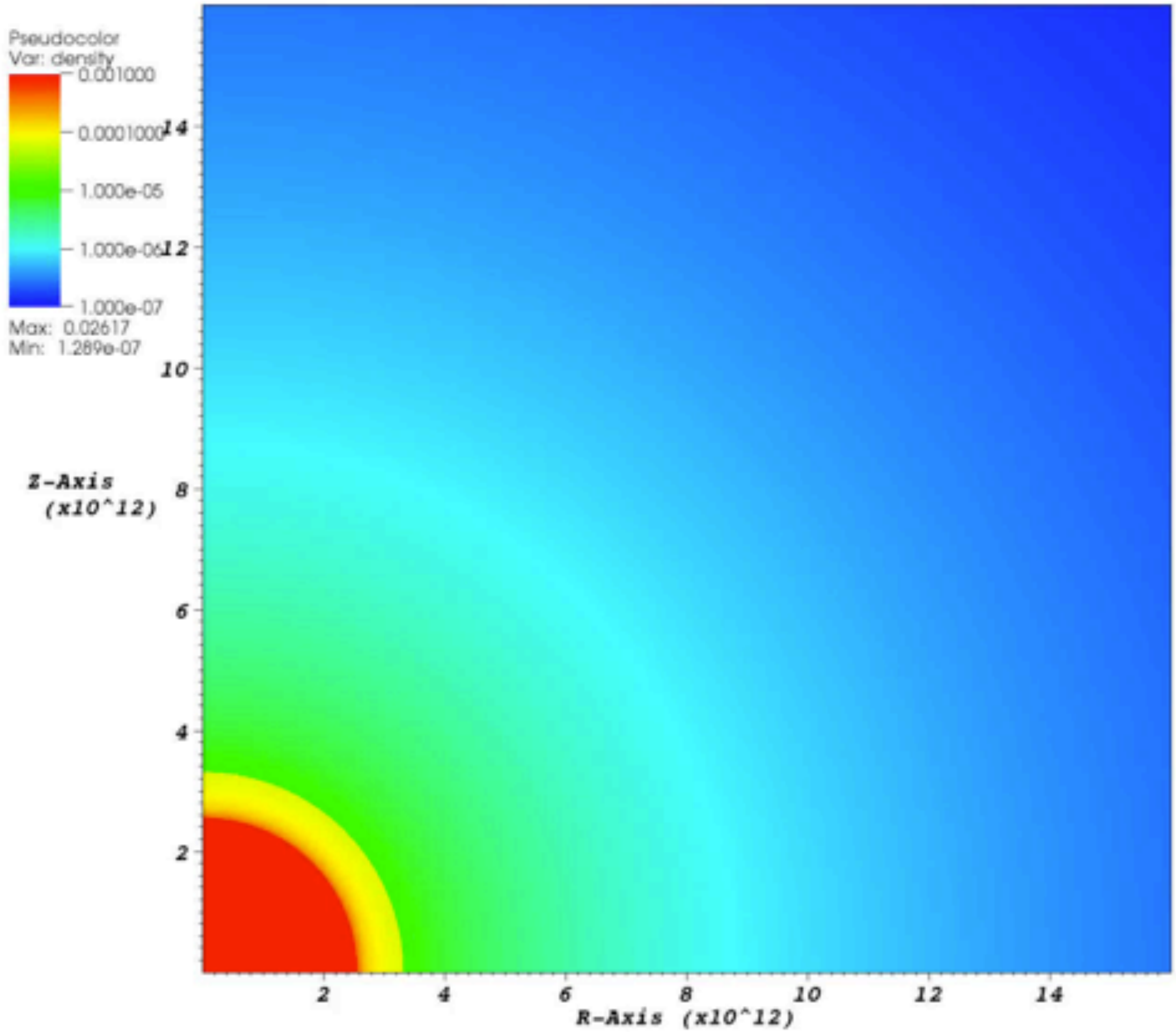
Core of 150 M☉ Star



Exploding 200 M☉ Star (2007 bi)



Exploding 200 M☉ Star (2007 bi)



Take Home Message

Take Home Message

- Mixing occurs at different stages of SNe.
- They are likely to break down the spherical symmetry of star as shown in SNRs.
- Strong mixing shows in Multi-D hydro/rad-hydro SNe models (smaller stars do mixing).
- Mixing definitely affect the observational signatures of SNe and future multi-D rad hydro models can give more quantitive answers.

Many thanks for your attention

My work has been kindly supported by:

中央研究院

天文及天文物理研究所

MOST 科技部

Ministry of Science and Technology

GRUBER FOUNDATION

IAU

Office of Science

U.S. Department of Energy

NSF

NERSC

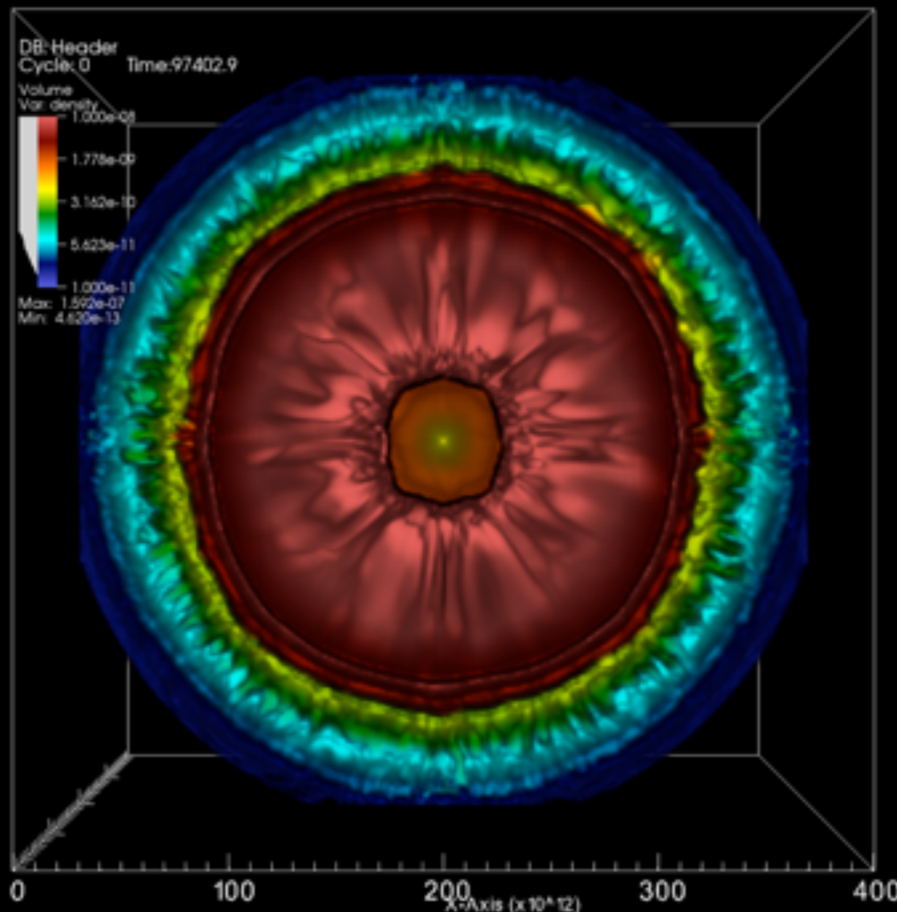
CFCA

Center for Computational Astrophysics

The Kavli Institute for Theoretical Physics

University of California, Santa Barbara

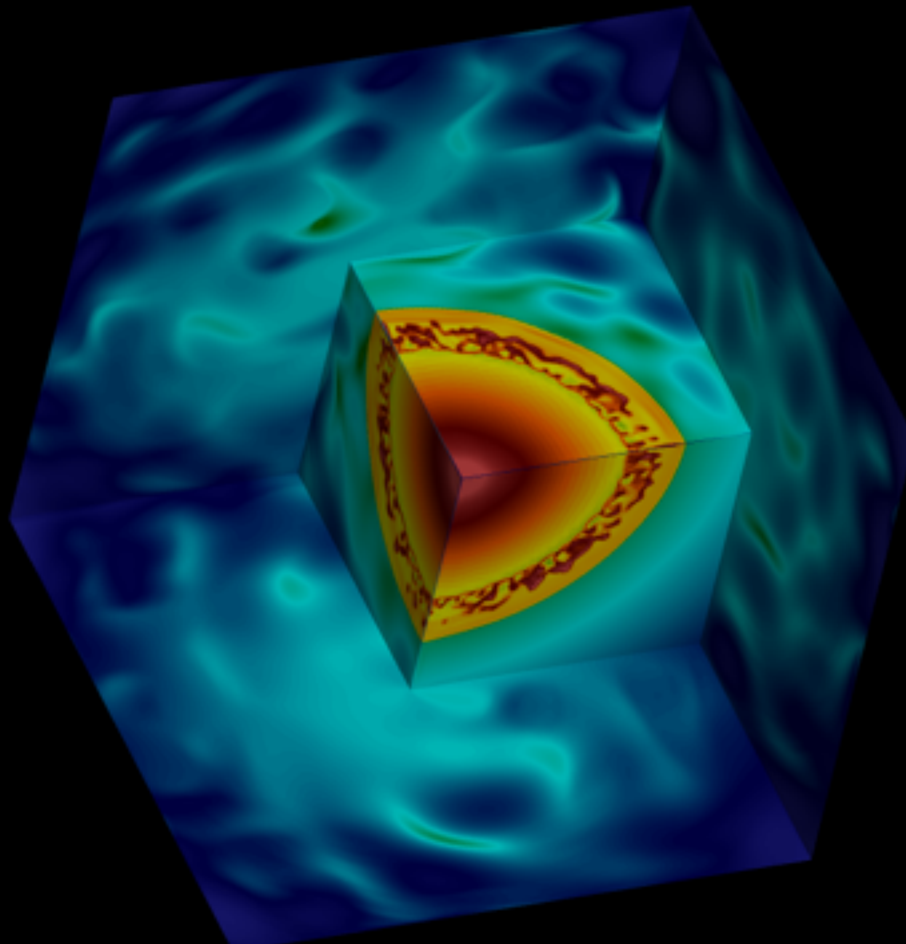
Mulit-D Simulations of PPSNe



Chen+ ApJ 792 28 (2014)

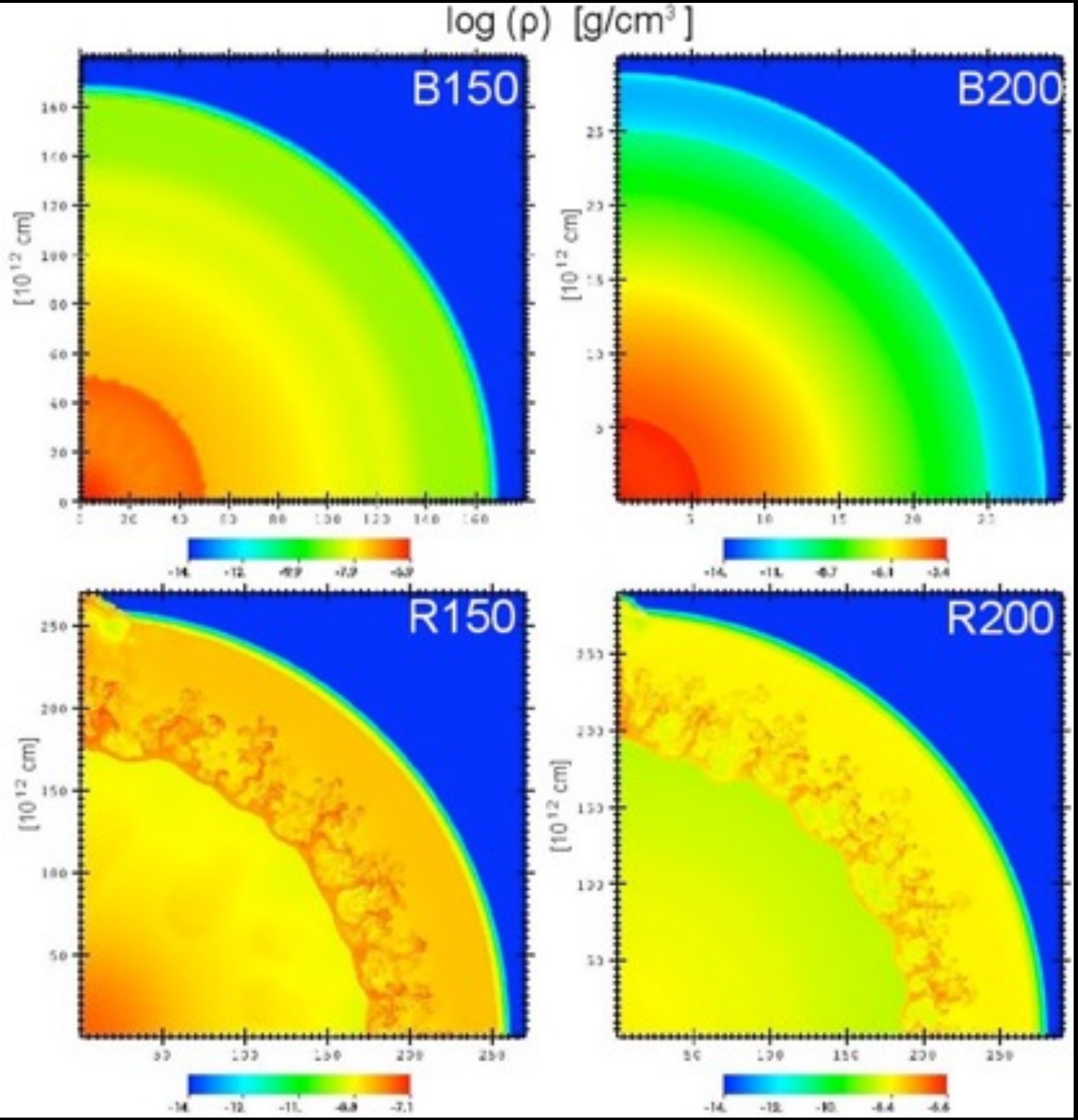
Pair-Instability Supernovae (PSNe)

260 M⊙ > M* > 150 M⊙

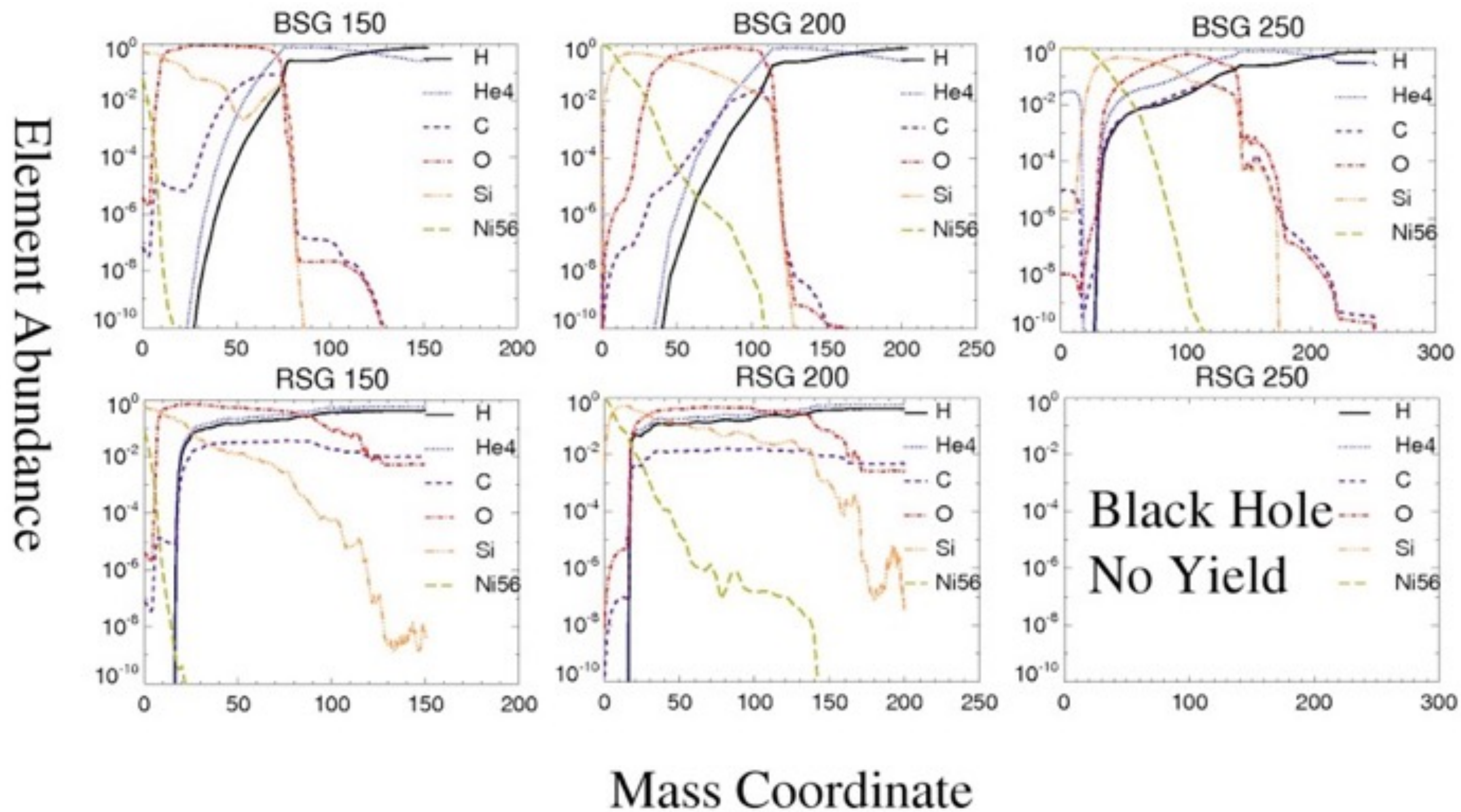


Chen+ ApJ 792 44 (2014)

Mixing of PSNe



Mixing of Elements



Results

Model	Mass [M⊙]	Core [M⊙]	E [10 ^{52} erg]	Ni [M⊙]	Instab.	Mixing
B150	150	67	1.29	0.07	Burning	weak
B200	200	95	4.14	6.57	Burning	weak
B250	250	109	7.23	28.05	Burning	weak
R150	150	59	1.19	0.1	Rev.	Strong
R200	200	86	3.43	4.66	Rev.	Strong
R250	250	156	...	...	...	...

Results

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R200	200	86	3.43	4.66	Rev.	Strong
R250	250	156	...	...	...	...

Ni is only slightly mixed out .
The Gamma-Ray emission for PSNe is unlikely.