Magnetar-Powered Supernova Explosions

Ke-Jung (Ken) Chen
EACOA Fellow, NAOJ and ASIAA
IAU Gruber Fellow, UC Santa Cruz
Seminar, YITP Workshop, 11/11/2016

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Acknowledgement

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Stan Woosley (UCSC)
Alex Heger (Monash)
Masaomi Tanaka (NAOJ)
Weiqun Zhang (LBNL)
Tuguldur Sukhbold (UCSC)
Takashi Moriya (NAOJ)
Yudai Suwa (Kyoto)

Special Thanks to:
YITP
Kyoto University
NPCSM Workshop organizers

East Asian Core Observatories Association (EACOA)

Japan   Taiwan

China   Korea

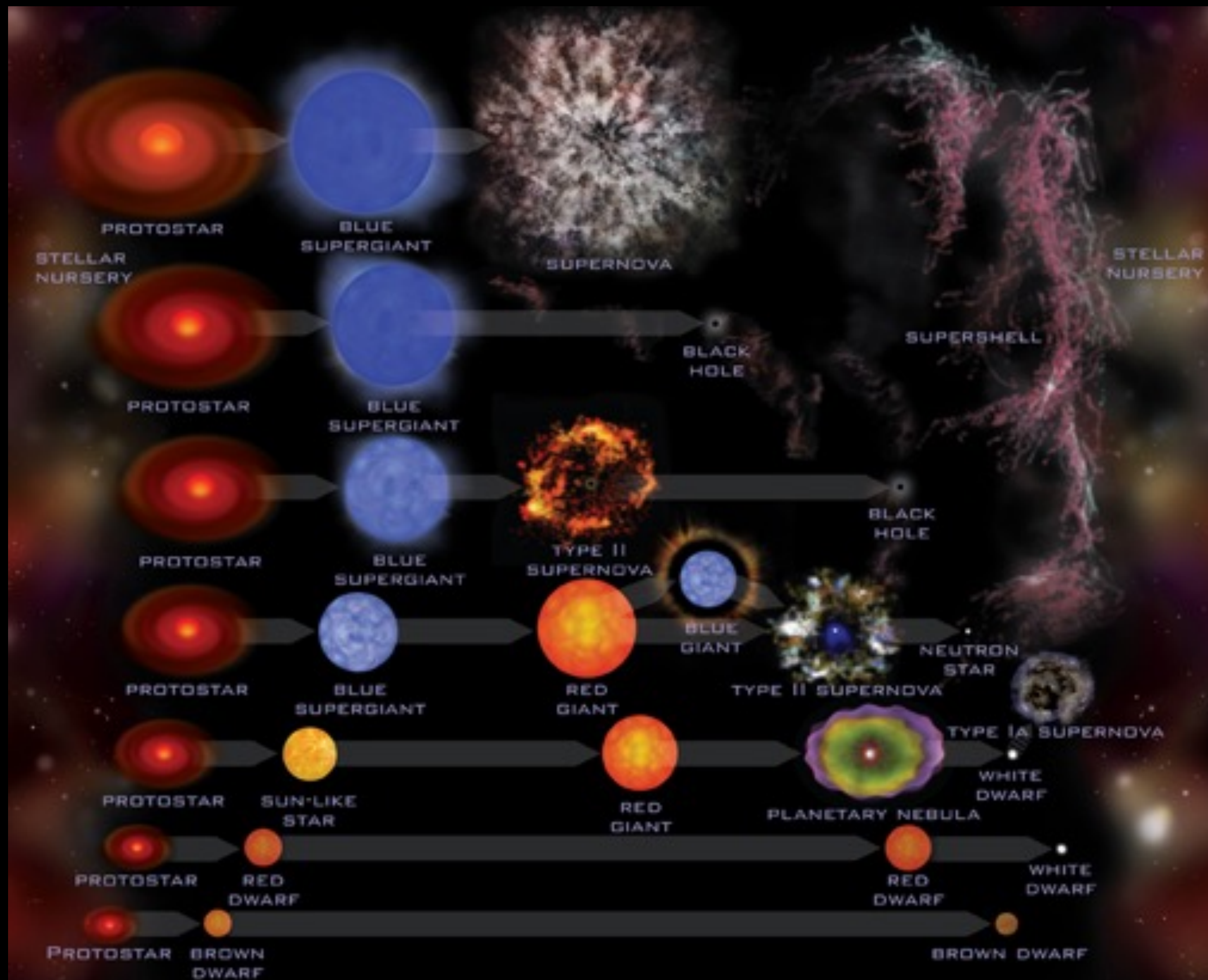
Call for 2017 EACOA Postdoctoral Fellowship application now !!

(Deadline : Nov. 15 2016)

- up to 5 year duration
- $20,000+ annual research fund
- $60,000 annual stipend (tax-free)
- $4,000 relocation
- Fellows are free to select at least two host institutions from the EACOA member institutions and have the opportunity to access all research facilities run by the EACOA member institutes, including the LAMOST, Subaru Telescope, CFCA, ALMA, etc.

Deaths of Stars

MASS



MASS

Why do We Care about SNe ?

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- Exceptional explosion and brightness

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- Metal

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- Fundamental physics (GR, HEP)

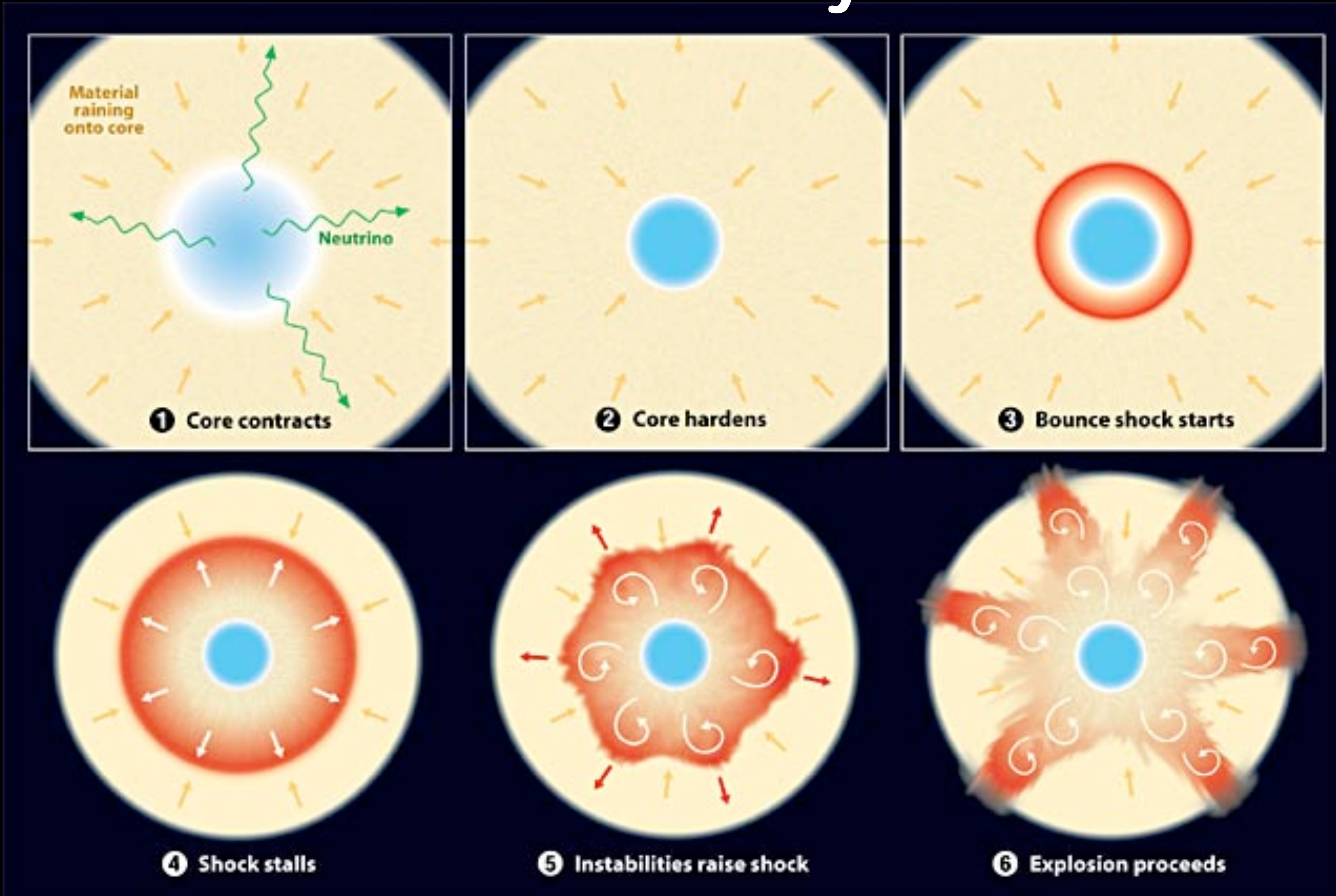
Why do We Care about SNe ?

- Exceptional explosion and brightness
- Metal
- Fundamental physics (GR, HEP)
- Accessibility in Research (models and observations)

When Massive Stars Die, How Do They Explode?

Neutron Star + Neutrinos	Neutron Star + Rotation	Black Hole + Rotation
Colgate and White (1966) Arnett Wilson Bethe Janka Herant Burrows Fryer Mezzacappa etc.	Hoyle (1946) Fowler and Hoyle (1964) LeBlanc and Wilson (1970) Ostriker and Gunn (1971) Bisnovatyi-Kogan (1971) Meier Wheeler Usov Thompson etc	Bodenheimer and Woosley (1983) Woosley (1993) MacFadyen and Woosley (1999) Narayan (2004) *All of the above?*
10	20	35 $M_\odot$

Neutrino as a Dynamite



Neutrino-Powered SN Explosions

Nordhaus+ 2010

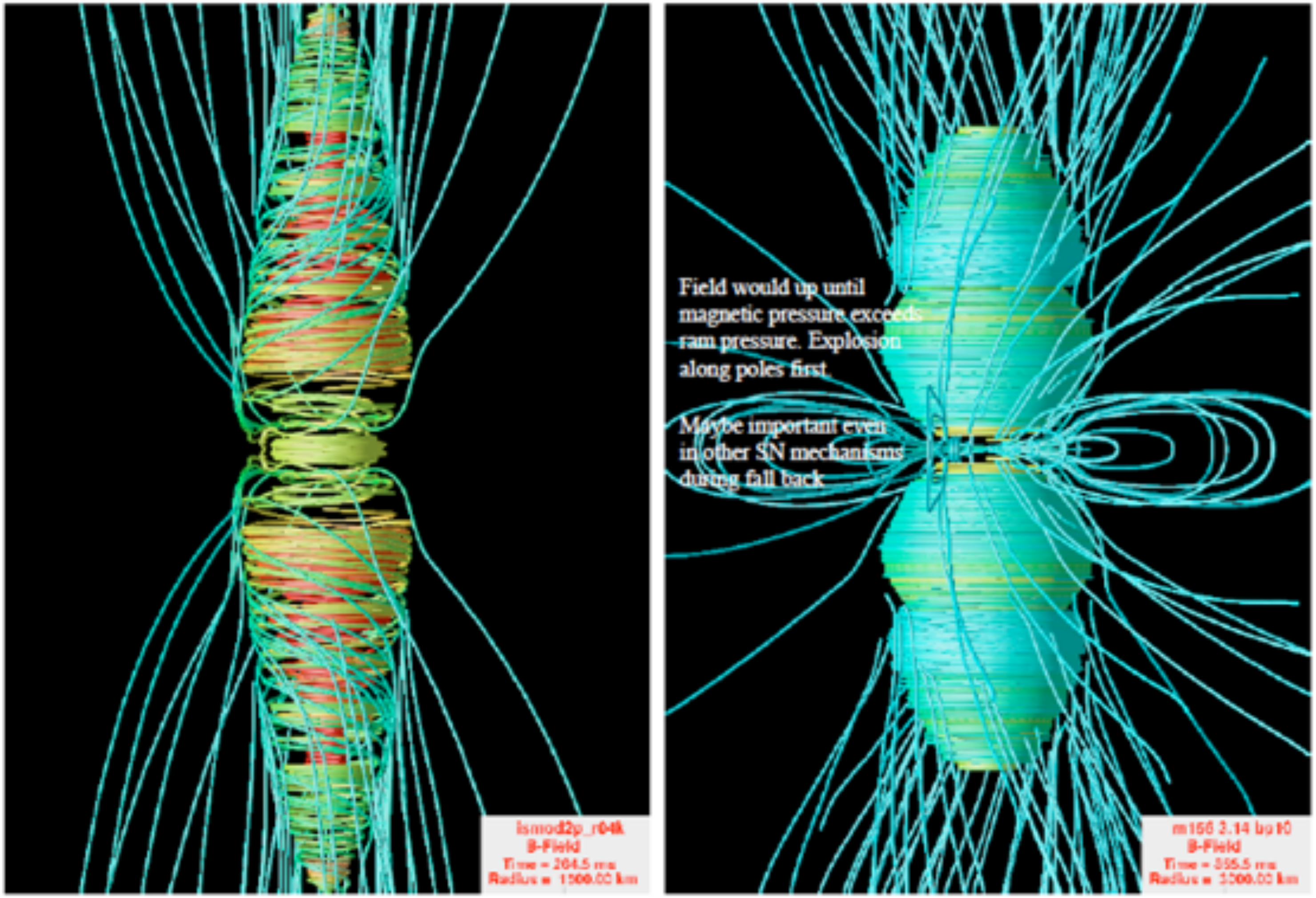
Neutrino-Powered SN Explosions

Nordhaus+ 2010

Neutrino-Powered SN Explosions

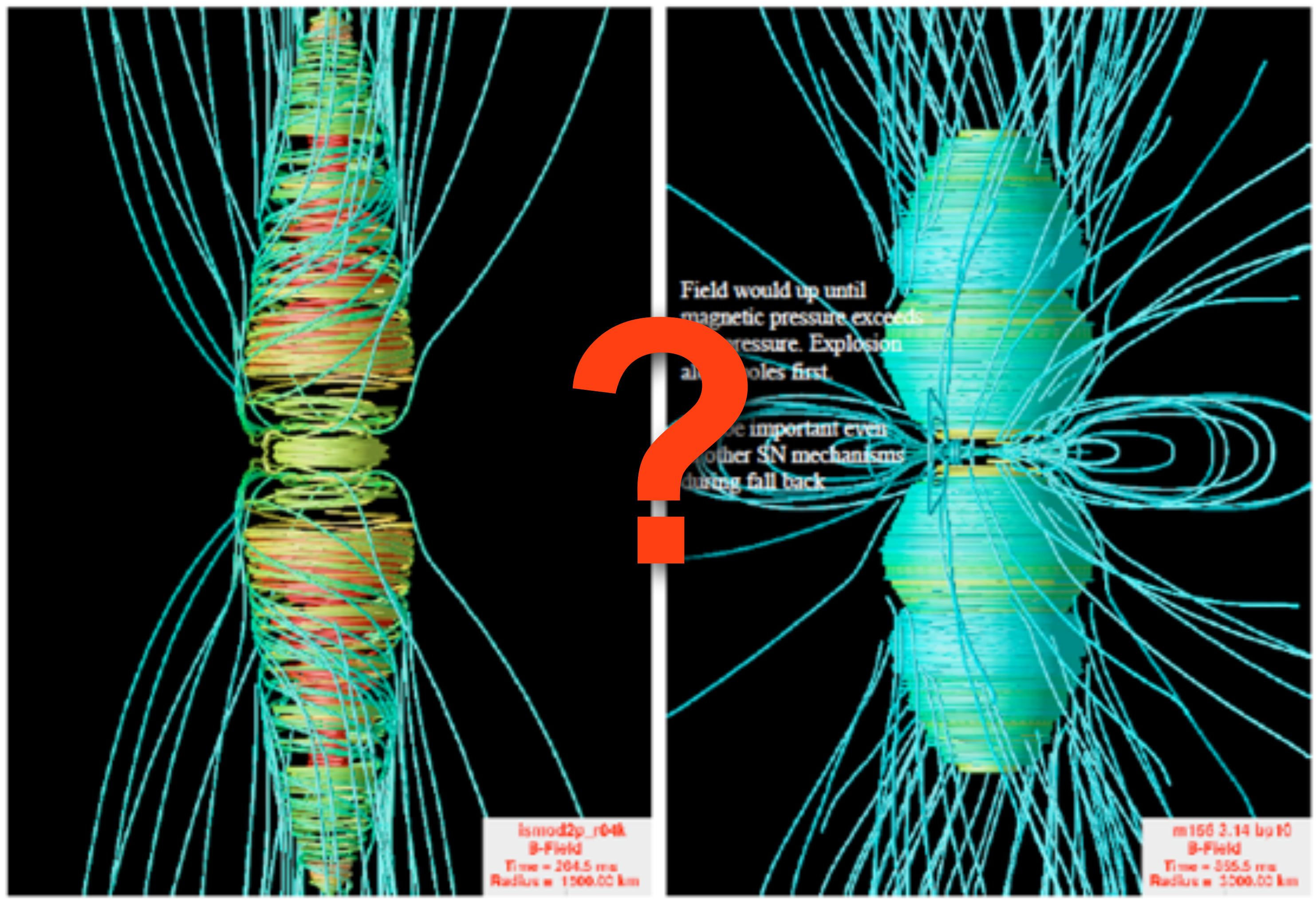
Nordhaus+ 2010

Jet as a Dynamite



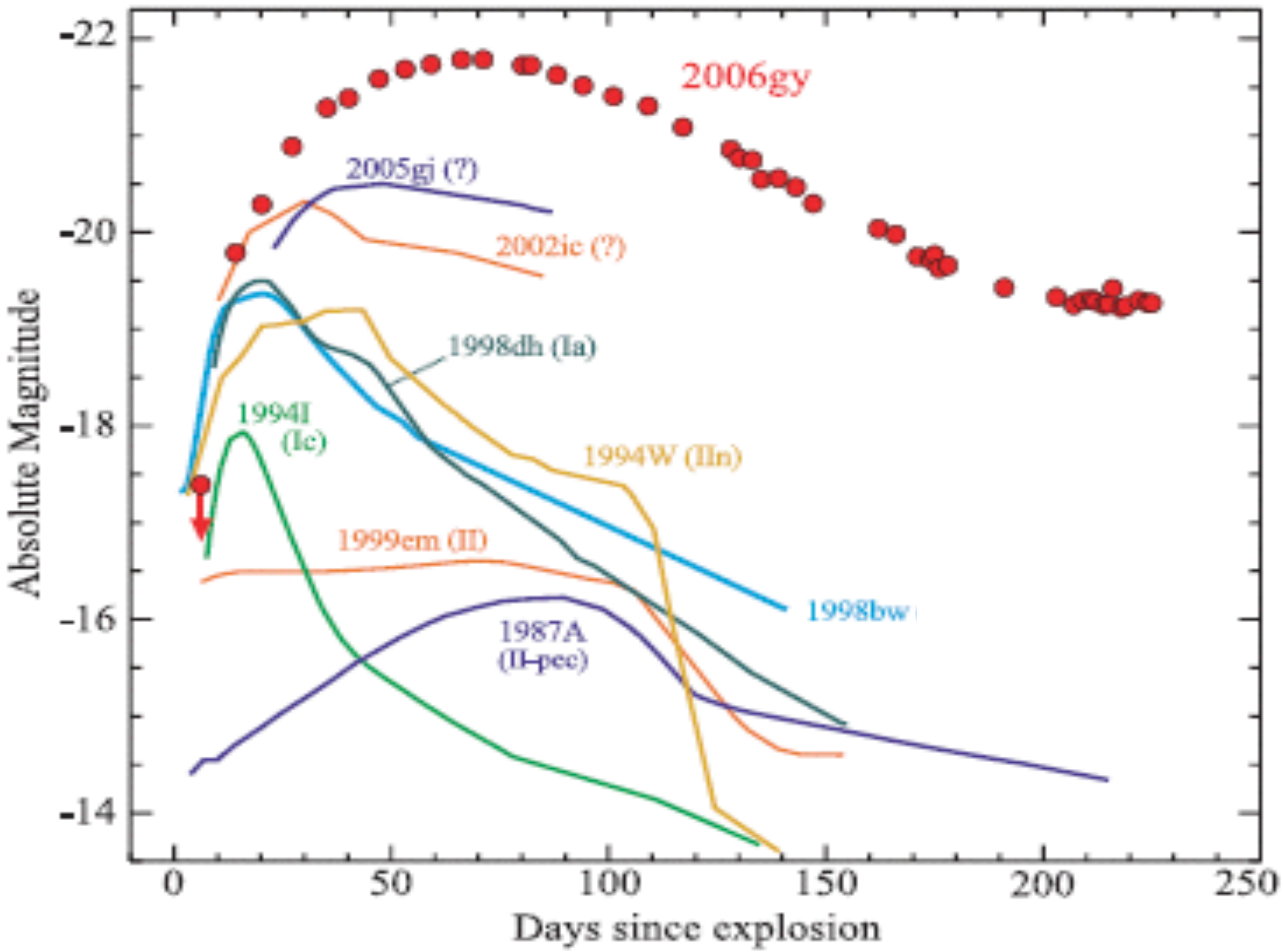
Burrows et al 2007, *ApJ*, **664**, 416

Jet as a Dynamite

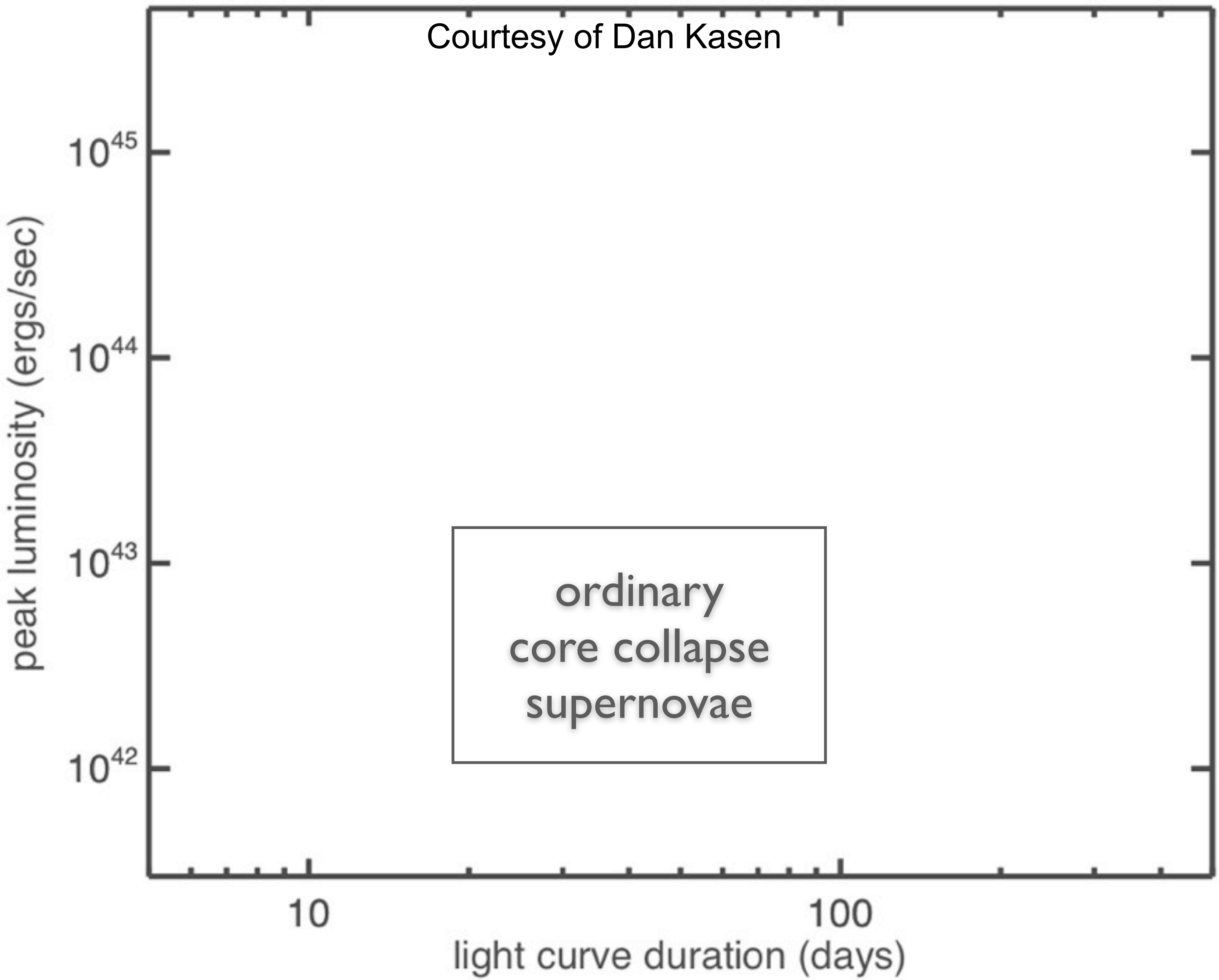


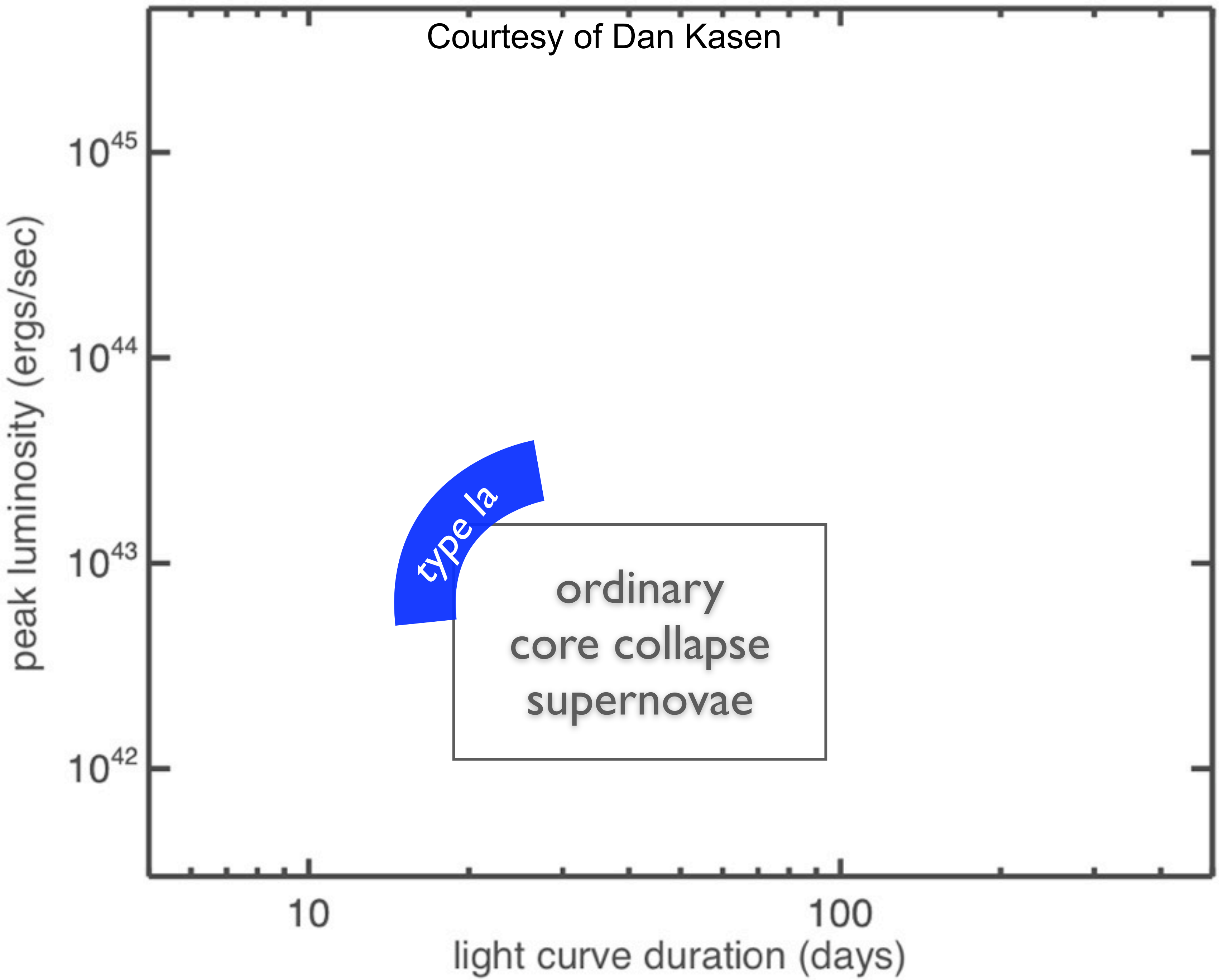
Burrows et al 2007, *ApJ*, **664**, 416

Super Luminous SNe (SLSNe)

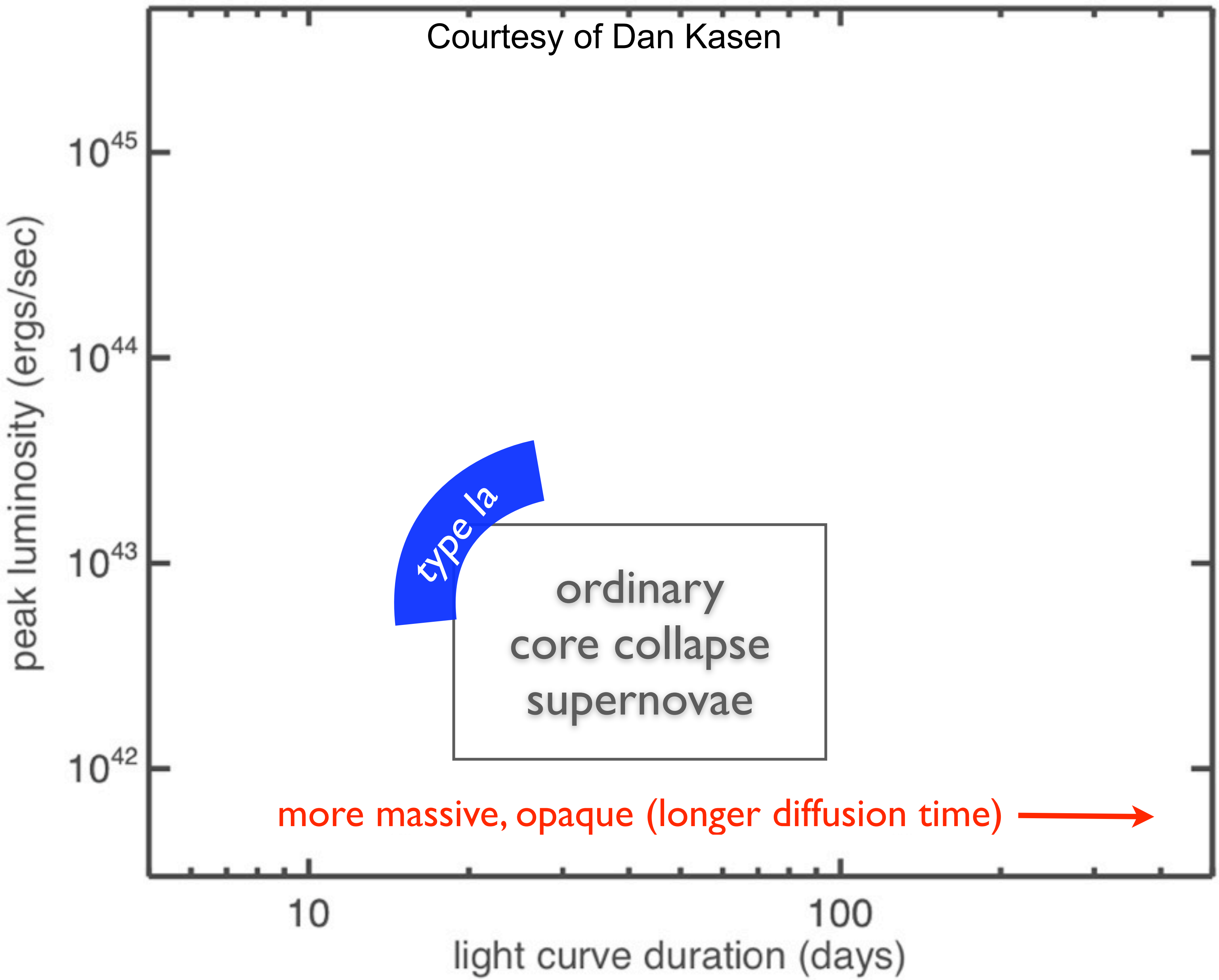


Smith+ 2007

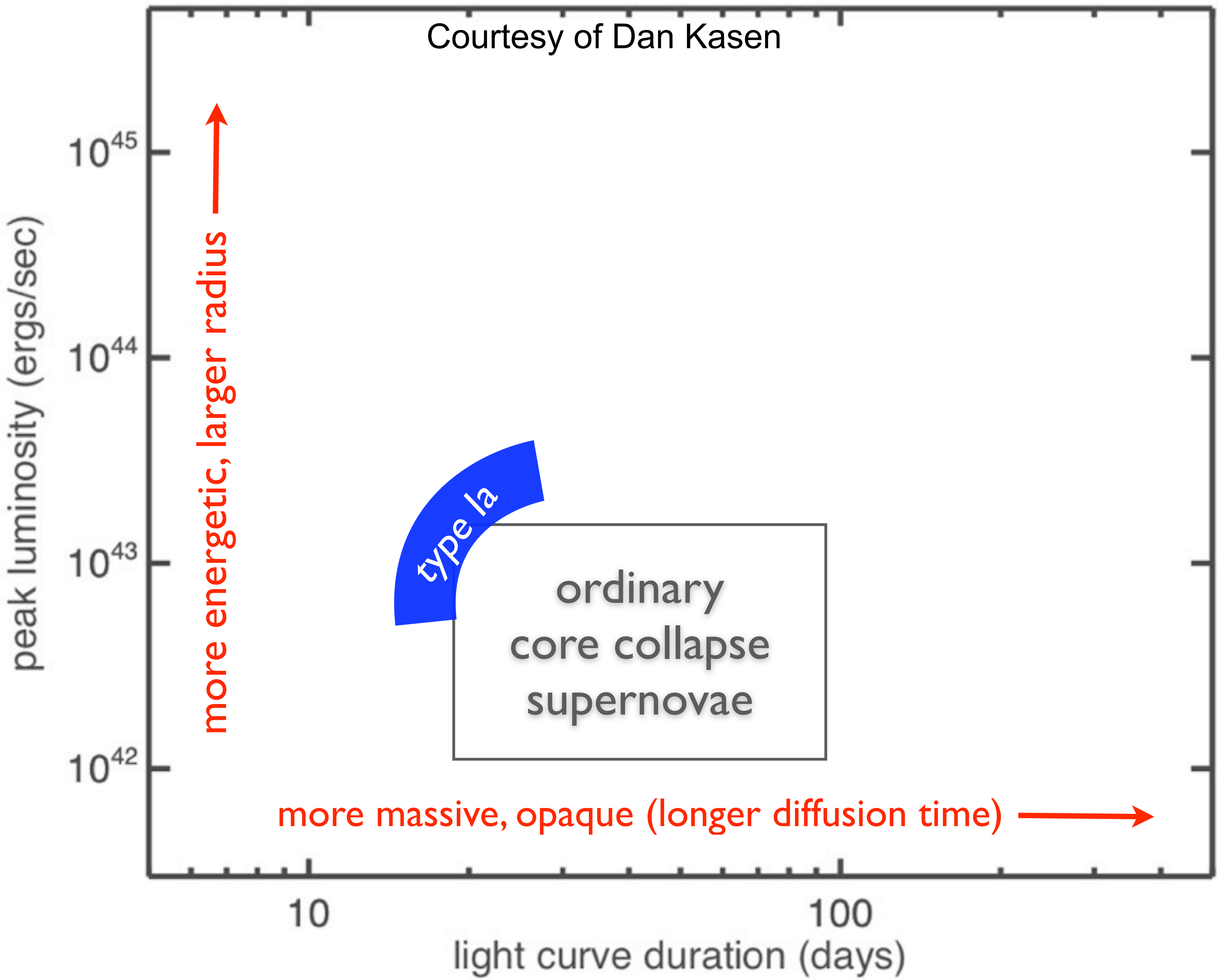

Courtesy of Dan Kasen
10^{45}
10^{44}
10^{43}
10^{42}
peak luminosity (ergs/sec)
ordinary
core collapse
supernovae
10
100
light curve duration (days)

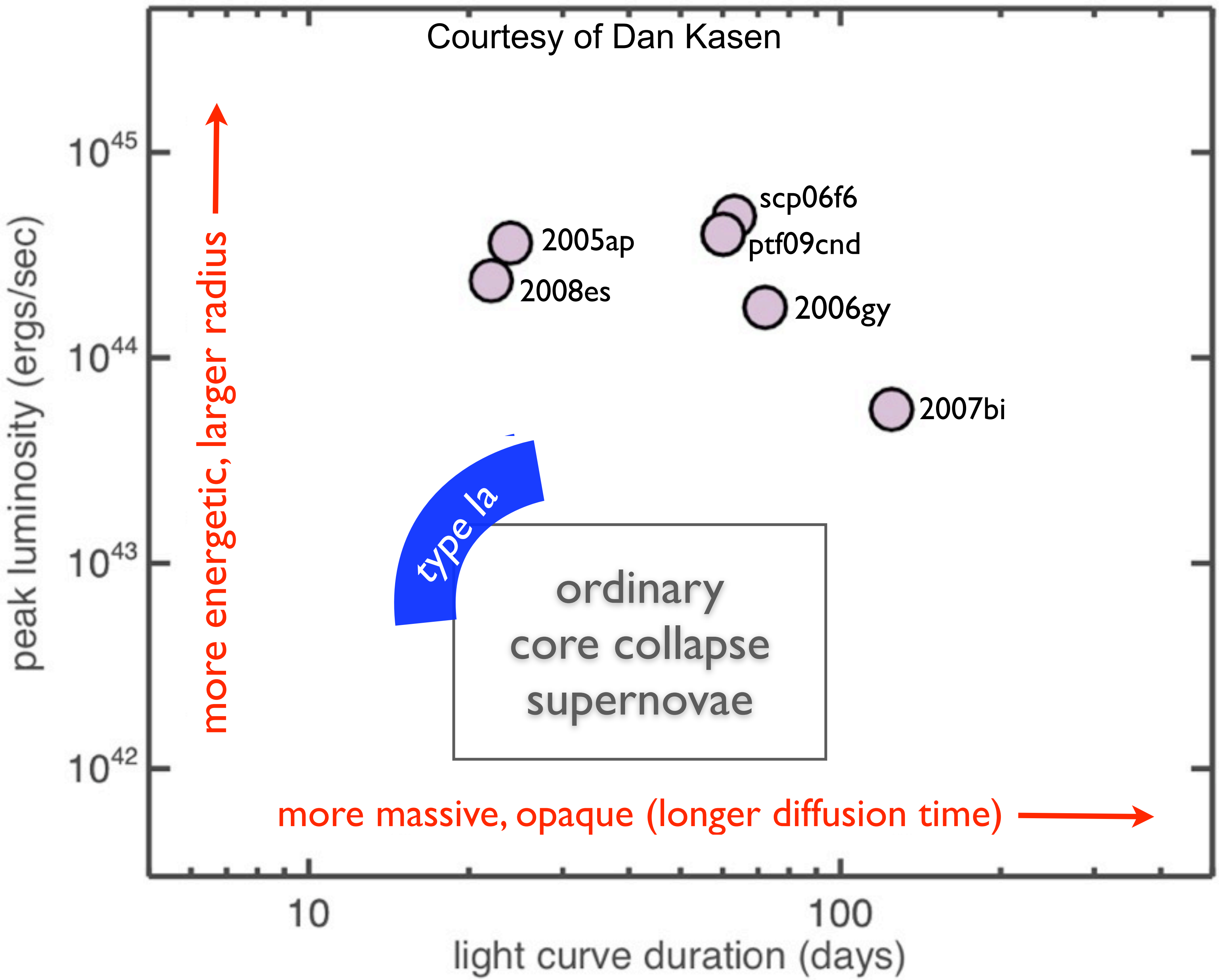


Courtesy of Dan Kasen
10^45
10^44
10^43
10^42
peak luminosity (ergs/sec)
type Ia
ordinary
core collapse
supernovae
10
100
light curve duration (days)



Courtesy of Dan Kasen
peak luminosity (ergs/sec)
10^45
10^44
10^43
10^42
type Ia
ordinary
core collapse
supernovae
more massive, opaque (longer diffusion time)
10
100
light curve duration (days)


Courtesy of Dan Kasen
peak luminosity (ergs/sec)
10^{45}
10^{44}
10^{43}
10^{42}
more energetic, larger radius
type Ia
ordinary
core collapse
supernovae
more massive, opaque (longer diffusion time)
10
100
light curve duration (days)



Courtesy of Dan Kasen
peak luminosity (ergs/sec)
10^{45}
10^{44}
10^{43}
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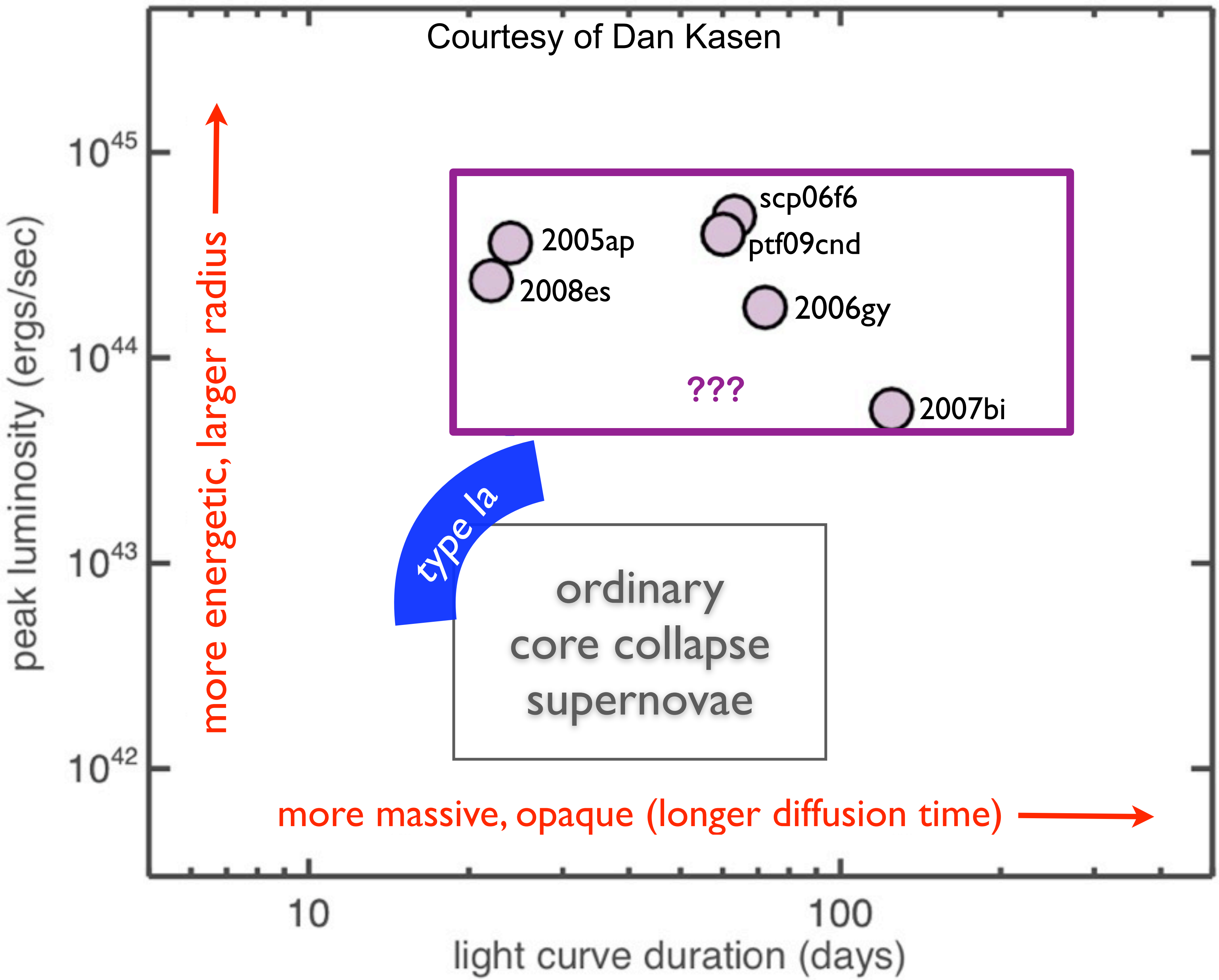
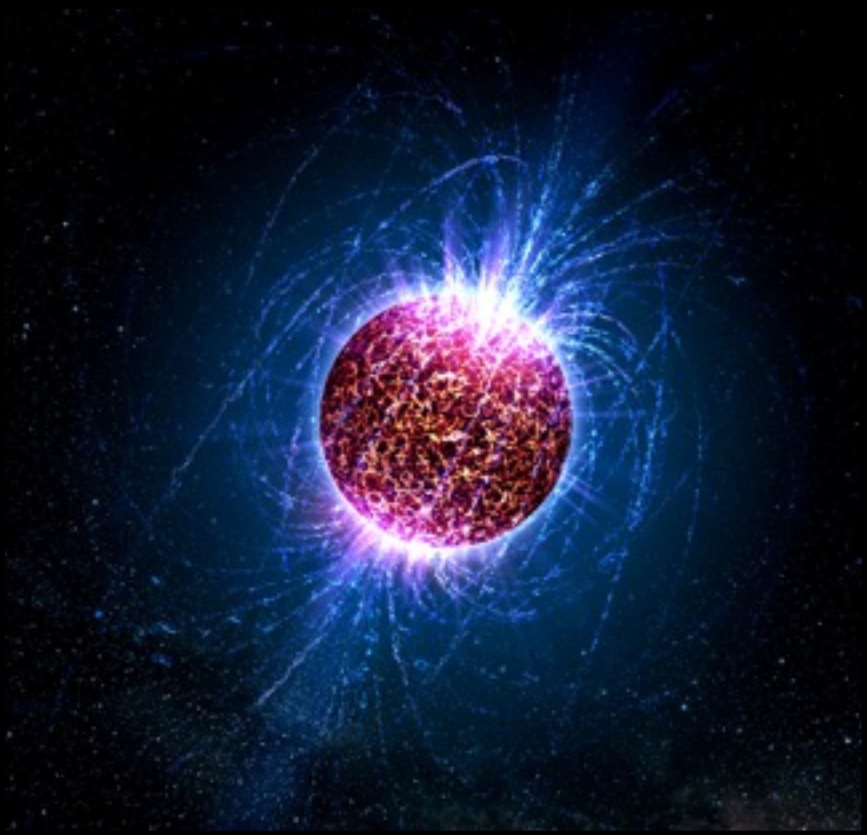
more energetic, larger radius
2005ap
2008es
scp06f6
ptf09cnd
2006gy
2007bi
type Ia
ordinary core collapse supernovae
more massive, opaque (longer diffusion time)
10
100
light curve duration (days)



Courtesy of Dan Kasen
peak luminosity (ergs/sec)
10^{45}
10^{44}
10^{43}
10^{42}
more energetic, larger radius
2005ap
2008es
scp06f6
ptf09cnd
2006gy
???
2007bi
type Ia
ordinary
core collapse
supernovae
more massive, opaque (longer diffusion time)
10
100
light curve duration (days)

Energy Input from NS

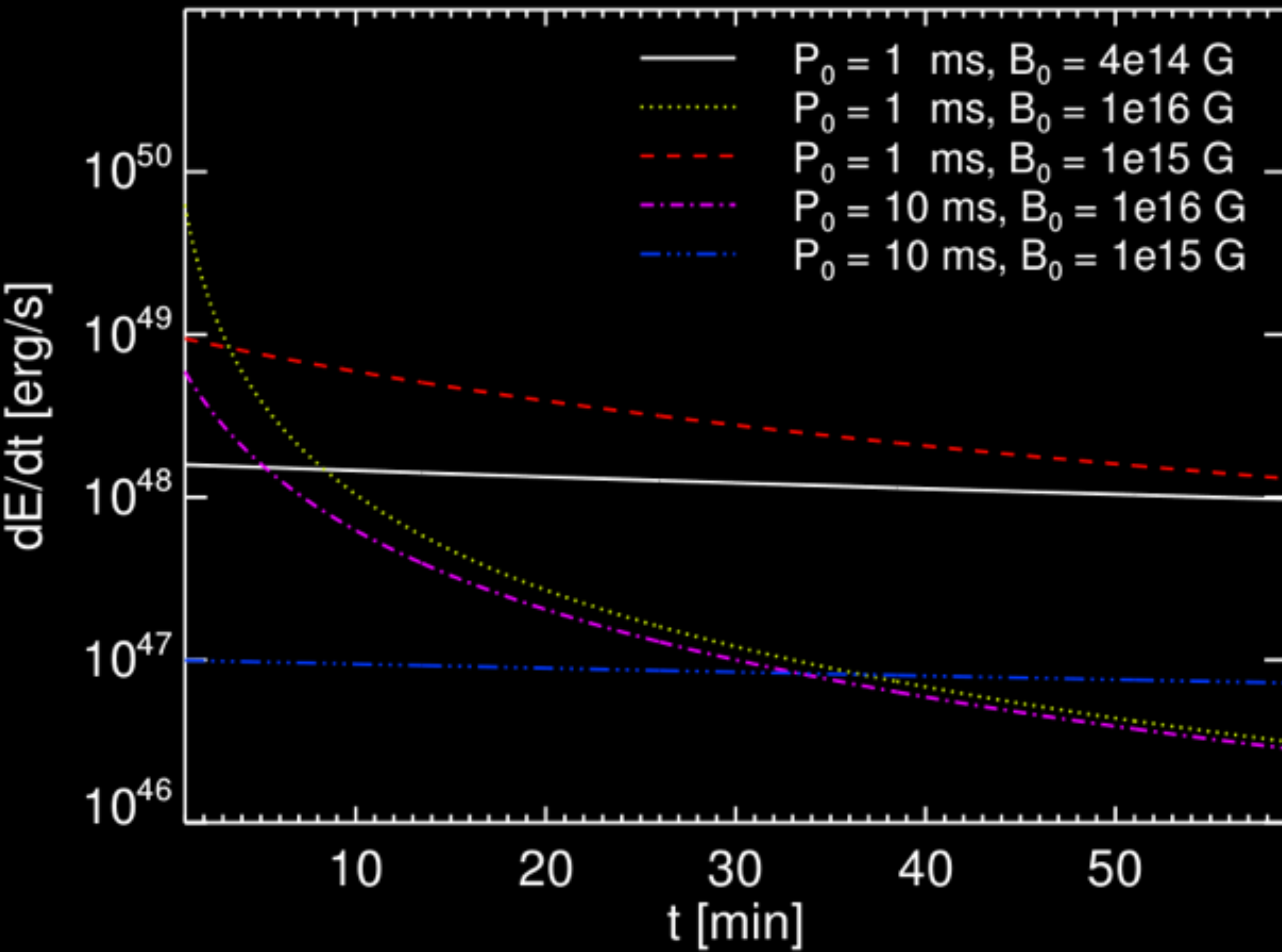


$$E = \frac{1}{2} I\omega^2 \approx 2 \times 10^{52} P_{ms}^{-2} \quad \text{erg.}$$

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

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

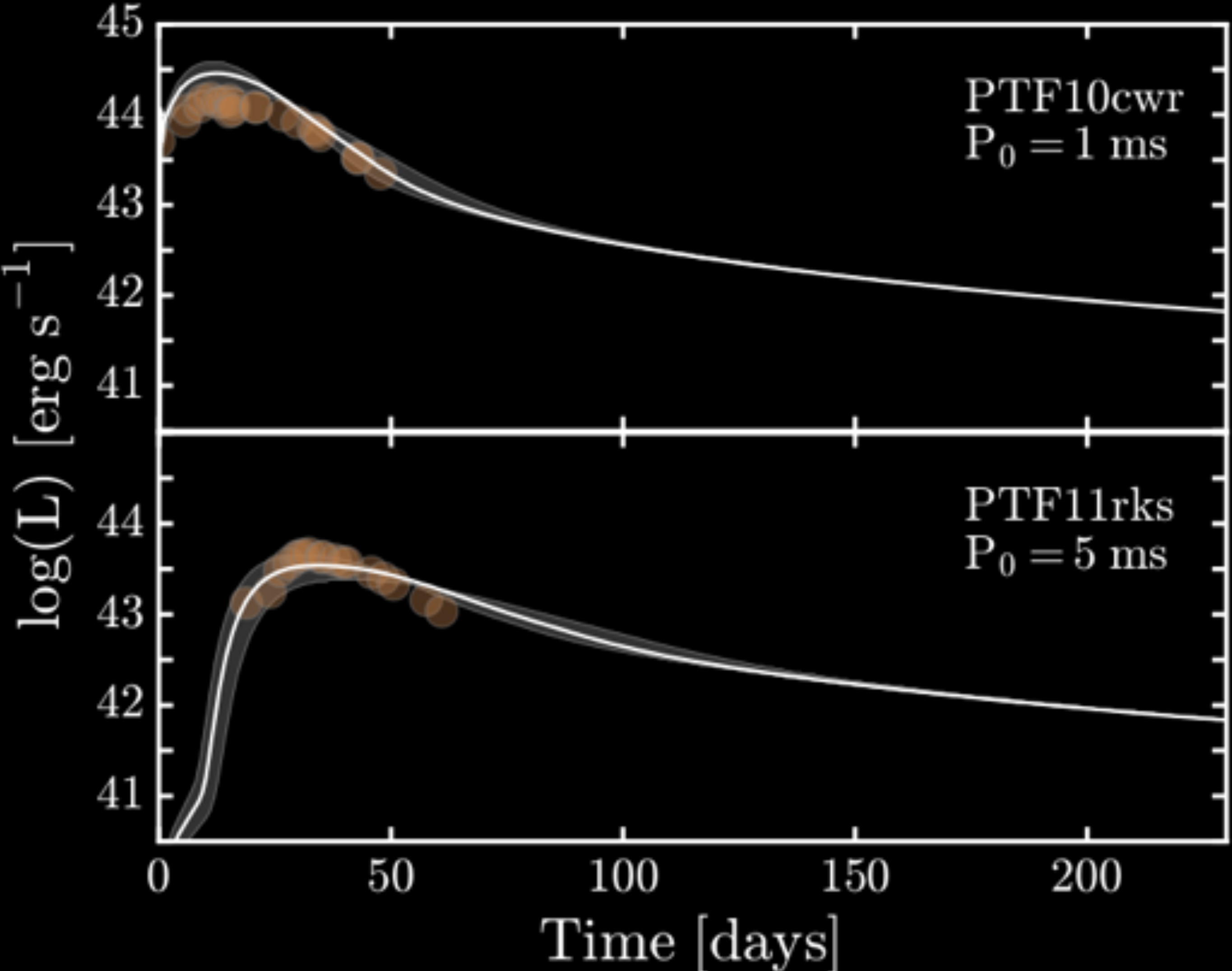
where $P_0 = P_{ms}(0)$, $E_0 = E(P_0)$ and $t_m \approx 2 \times 10^3 P_{ms}^2 B_{15}^{-2}$



P_0 = 1 ms, B_0 = 4e14 G
P_0 = 1 ms, B_0 = 1e16 G
P_0 = 1 ms, B_0 = 1e15 G
P_0 = 10 ms, B_0 = 1e16 G
P_0 = 10 ms, B_0 = 1e15 G
dE/dt [erg/s]
10^{50}
10^{49}
10^{48}
10^{47}
10^{46}
10
20
30
40
50
t [min]

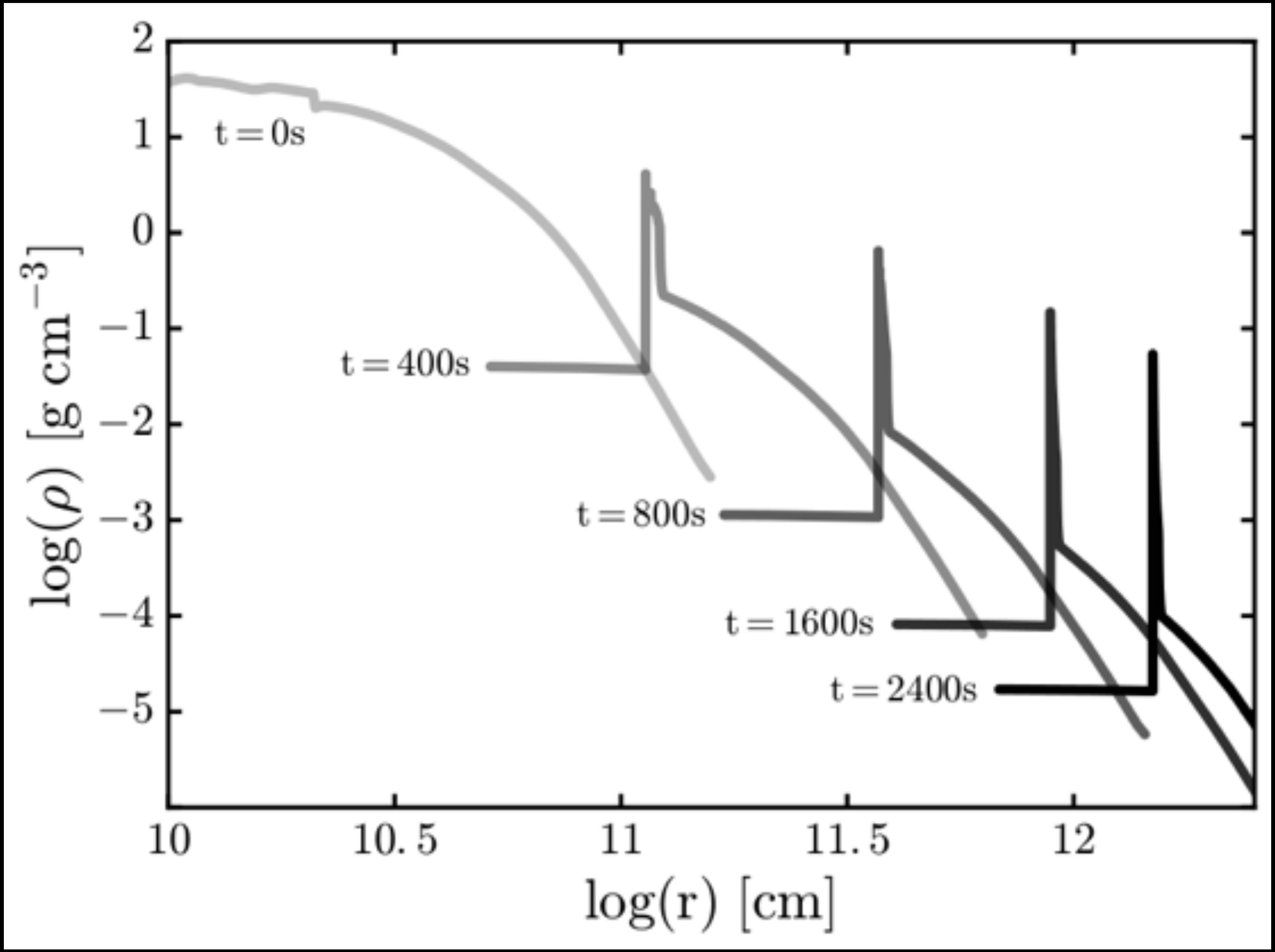
SLSNe by magnetar

B = 4e14 G



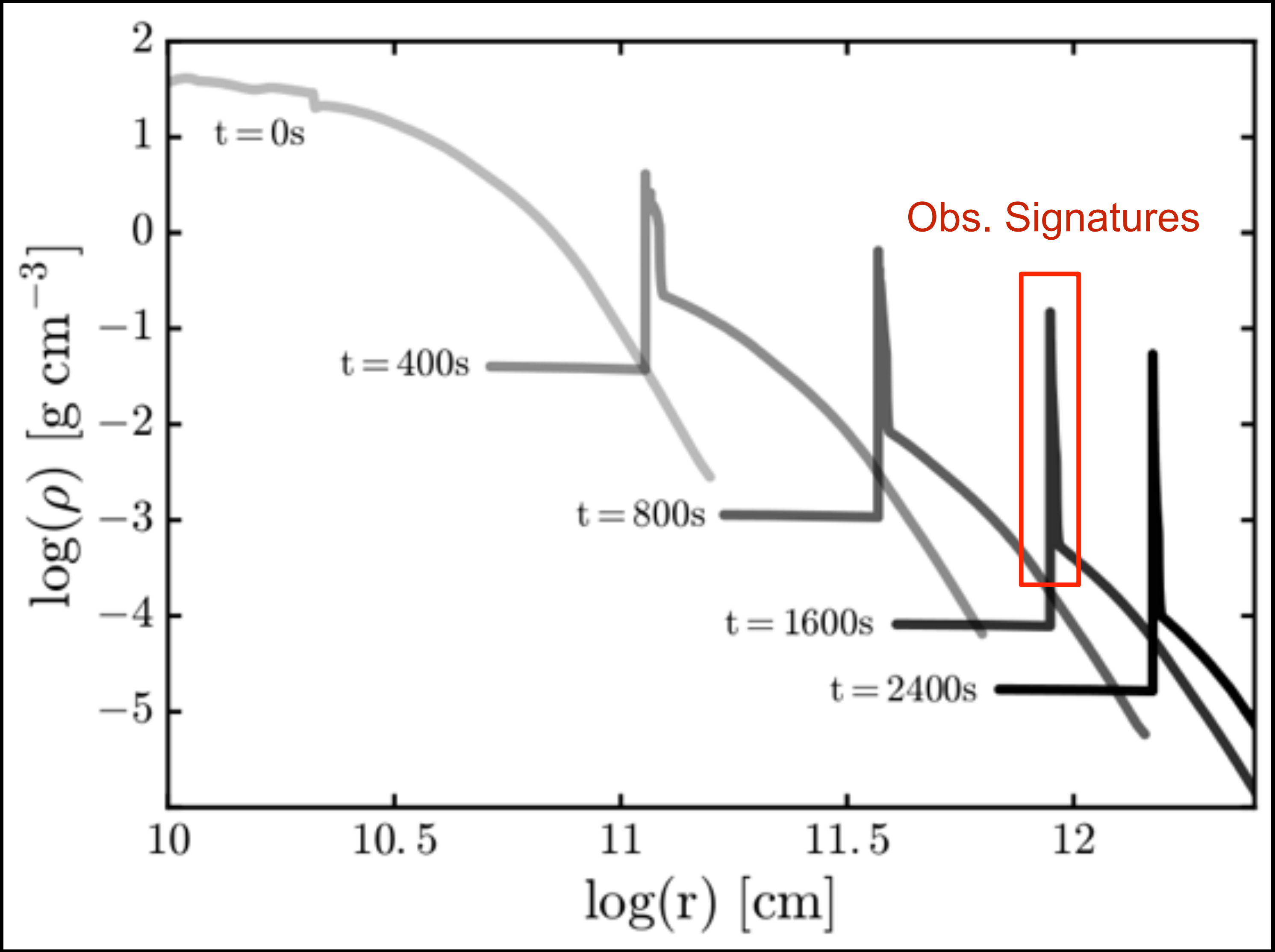
Chen, Woosley, Sukhbold (ApJ in pres; arXiv:1604.07989)

The shortcoming of 1D SLSN Models



Density spike in 1D magnetar

The shortcoming of 1D SLSN Models



Density spike in 1D magnetar

The shortcoming of 1D SLSN Models

Multi-D SN Simulations

1D Models

30 - 45 $M_\odot$ Stars (Sukhbold & Woosley)

CASTRO

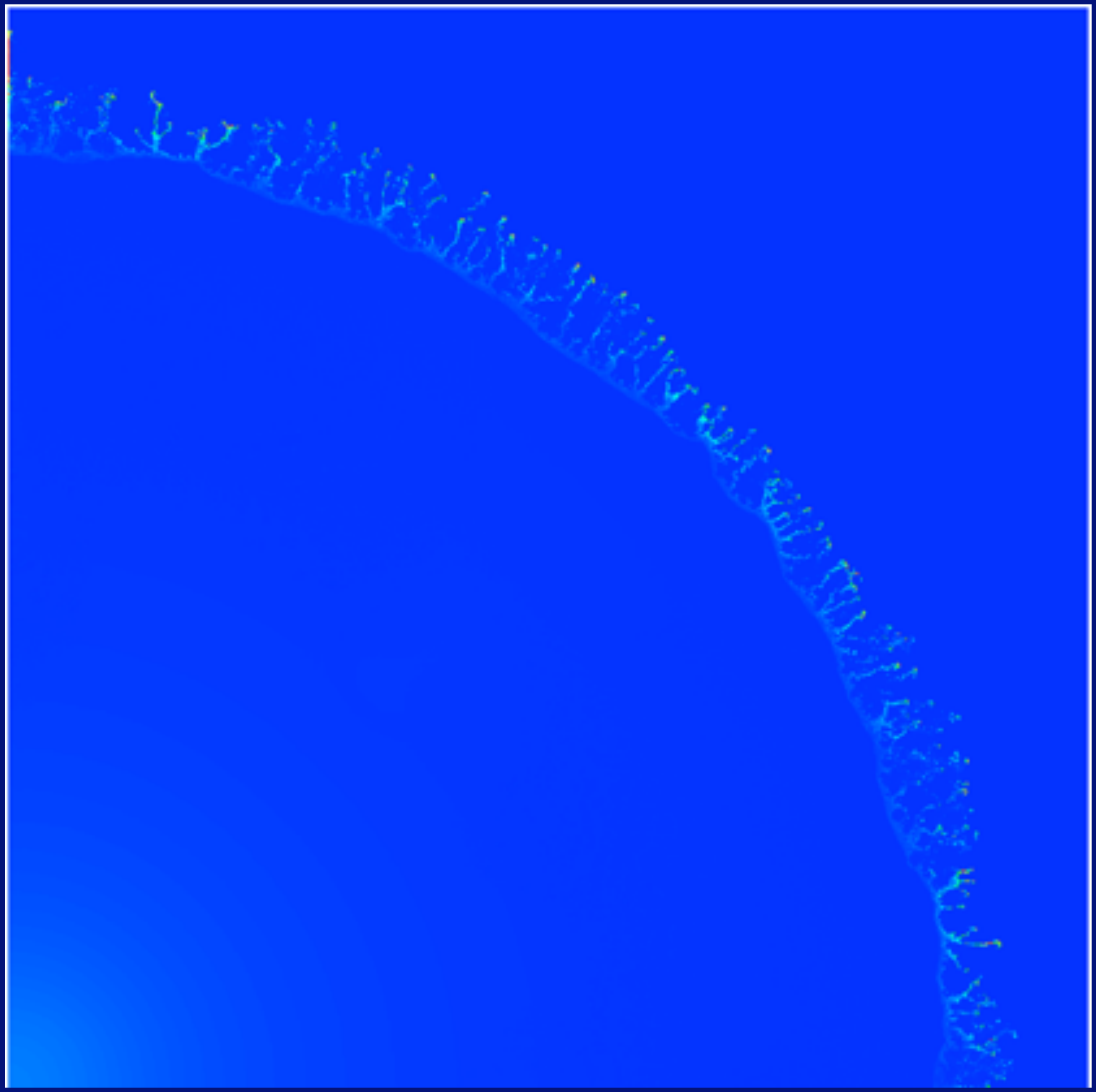
Massive Parallel, Adaptive Mesh Refinement (AMR), Multi-D, Radiation, Hydro+(Burning, Rotation, GR ...)
(Almgren+ 2010, Zheng+ 2011 2012, Chen+ 2011 2012)

Supercomputers:

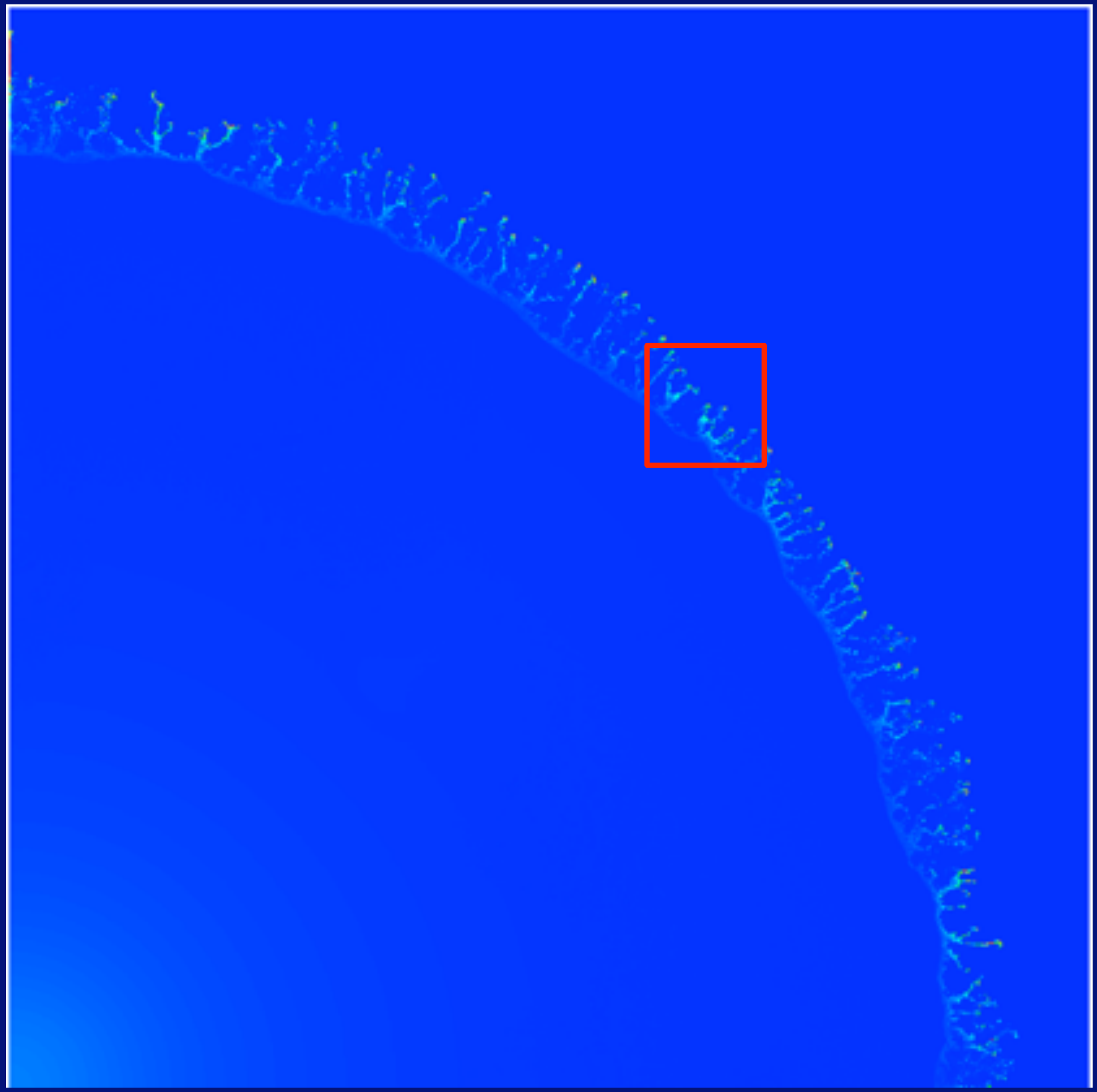
ATERUI

Edison

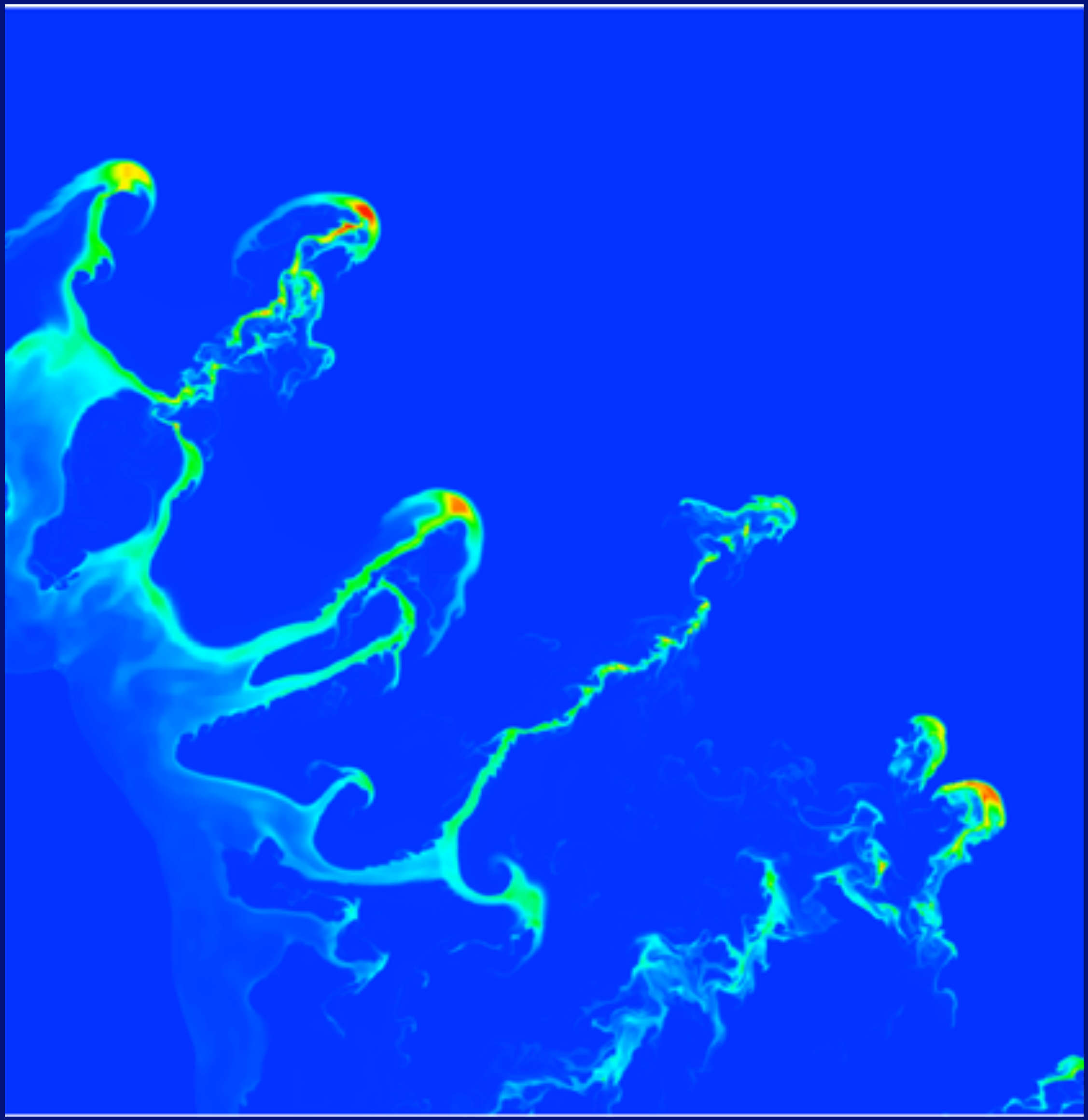
Resolution of CASTRO



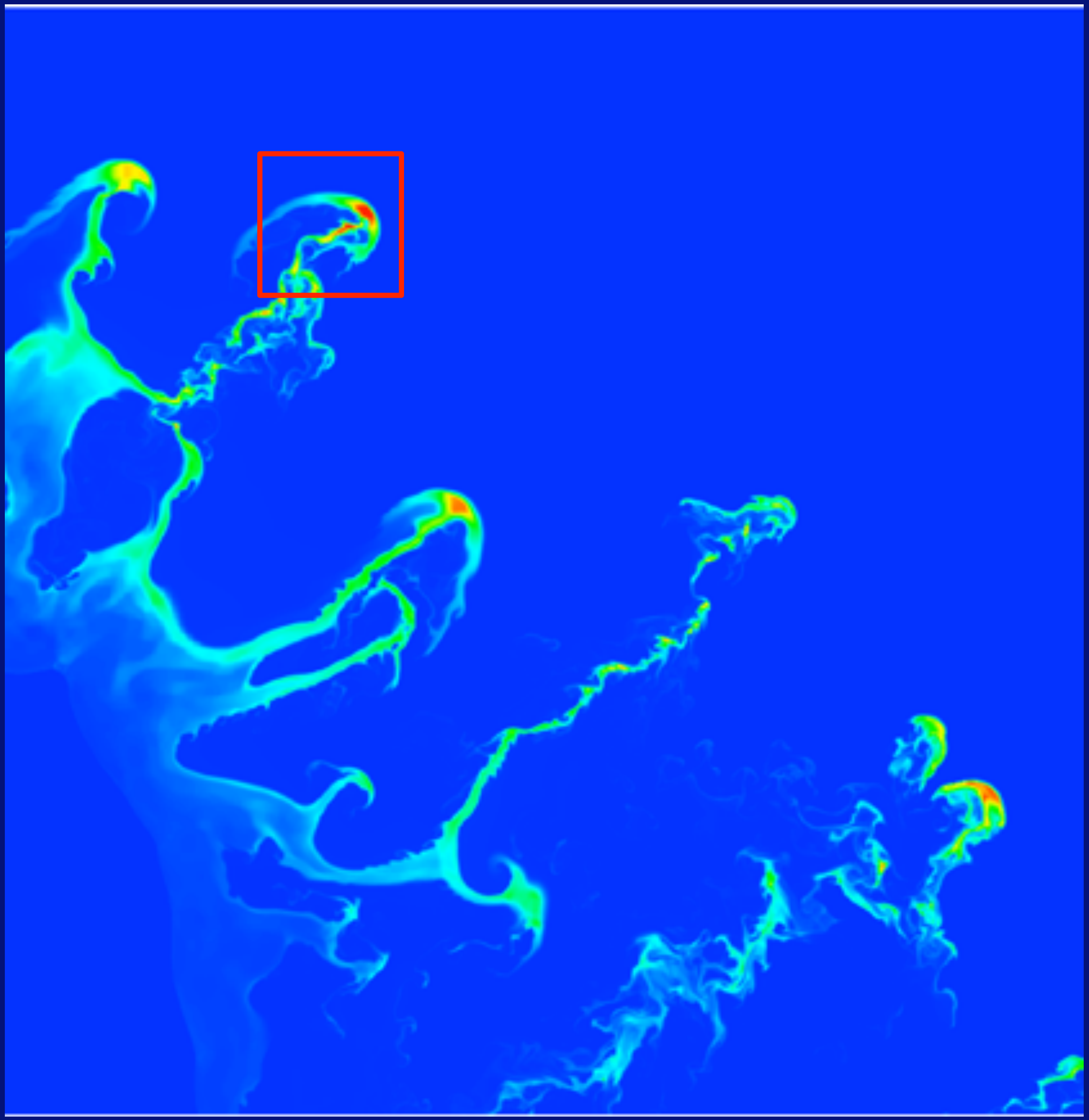
Resolution of CASTRO



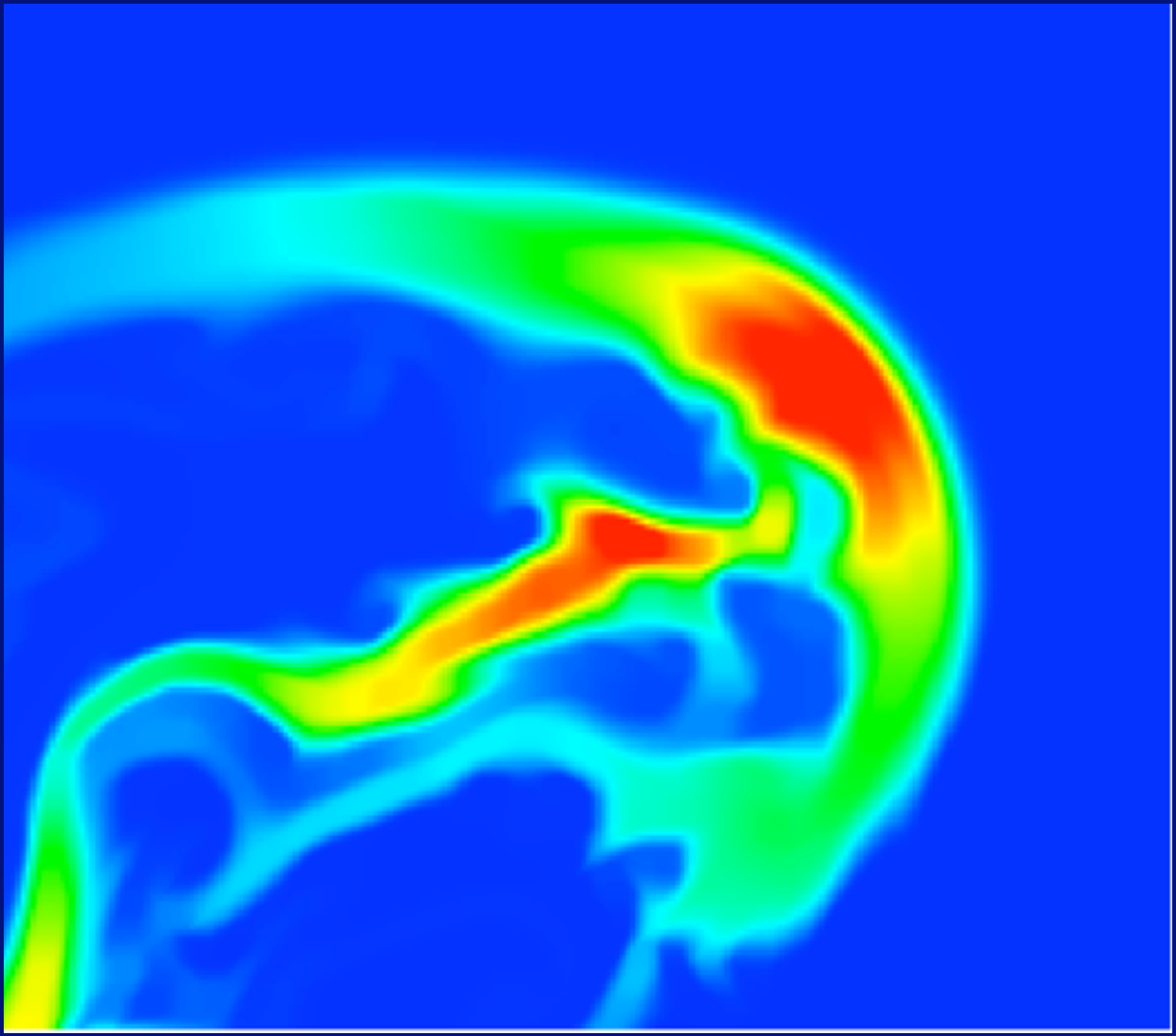
Resolution of CASTRO



Resolution of CASTRO

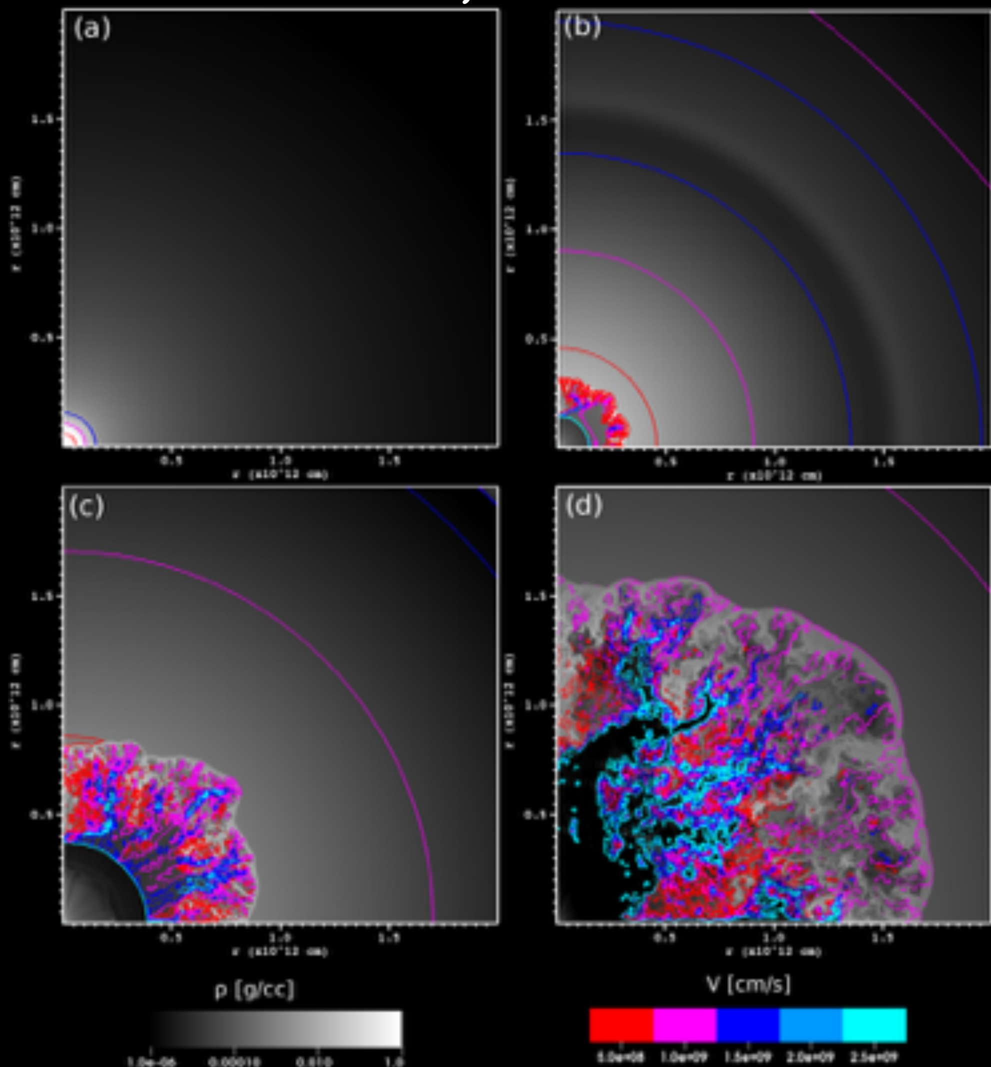


Resolution of CASTRO



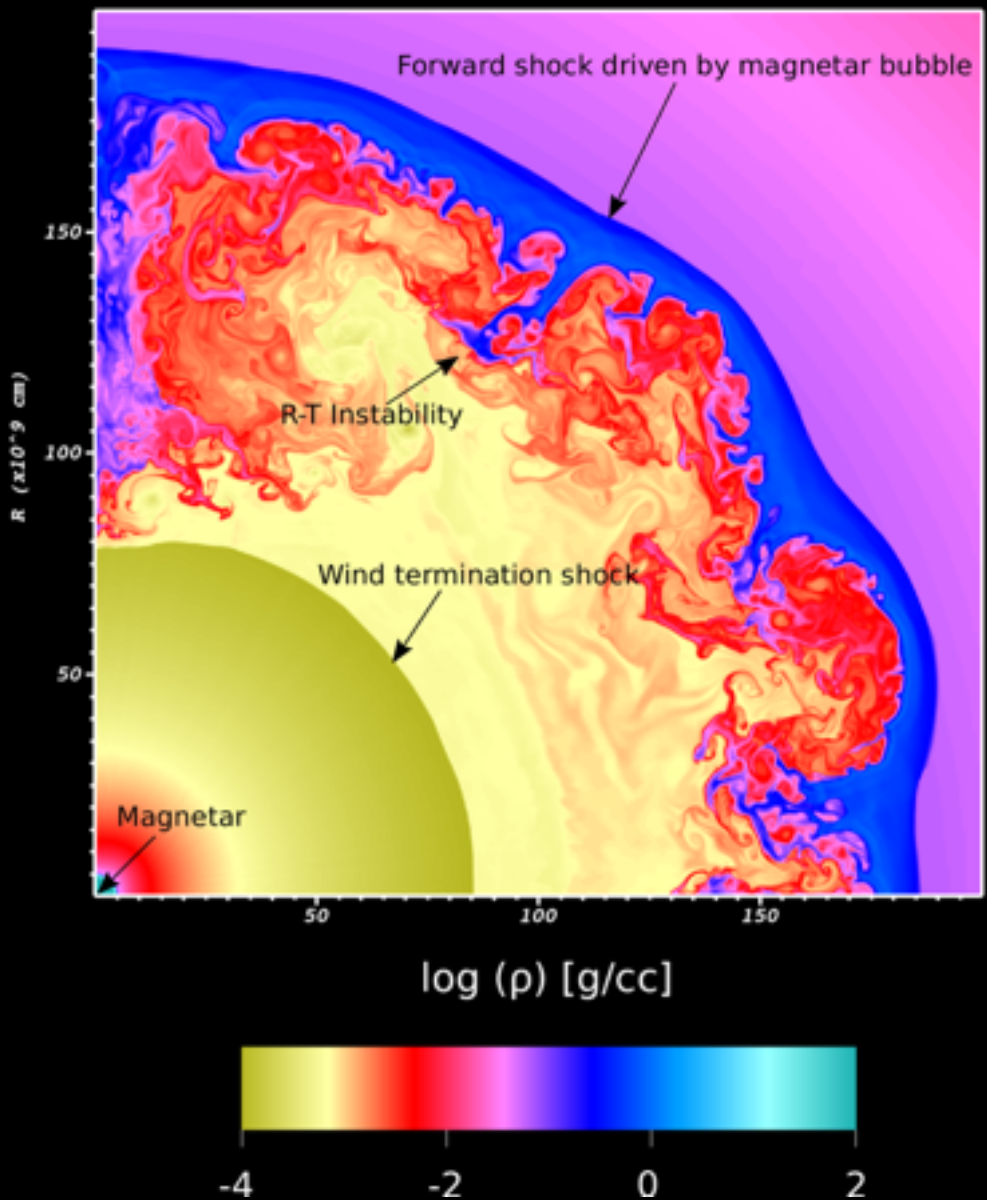
SLSNe in 2D

P = 1 ms, B = 4e14 G

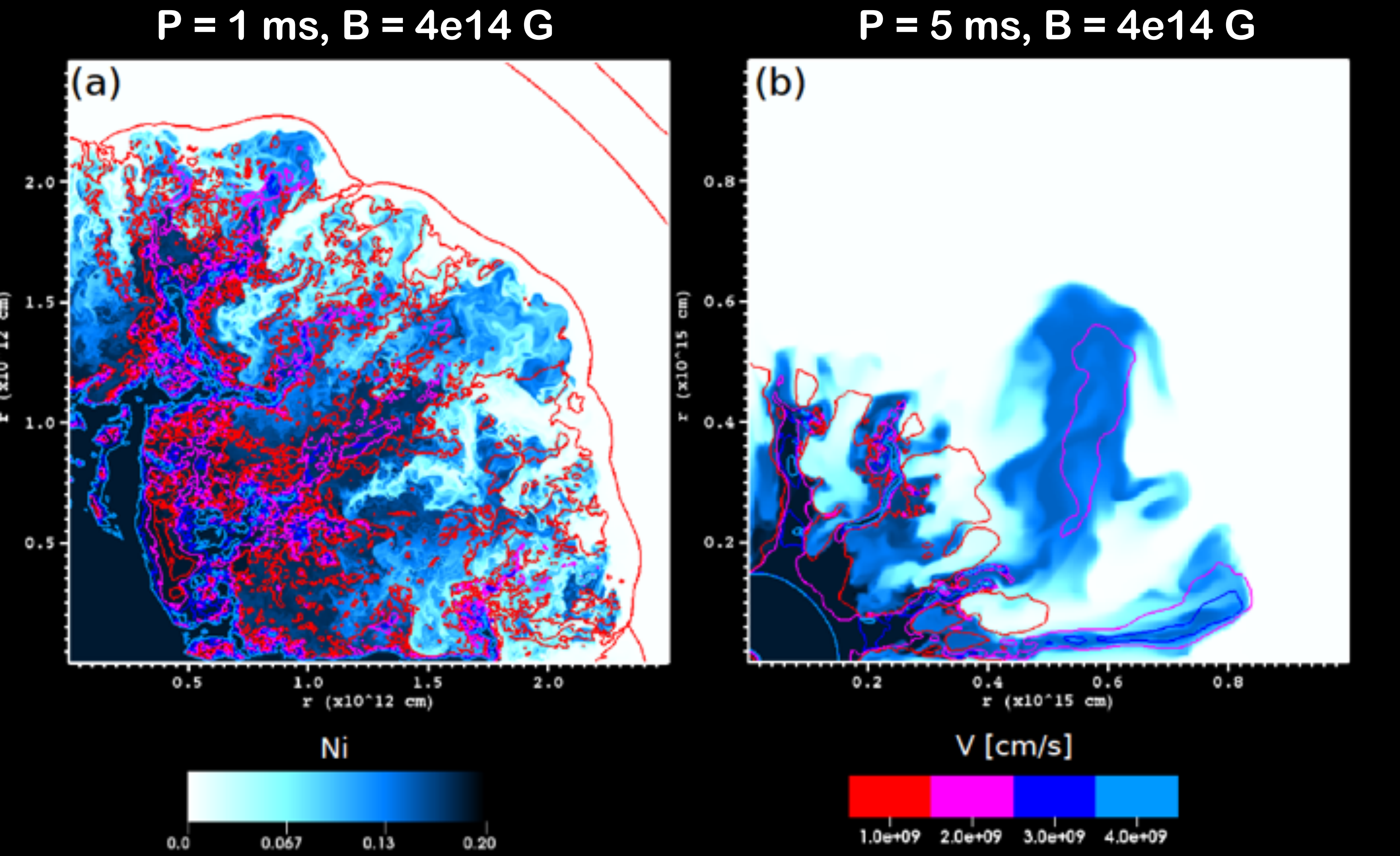


Chen, Woosley, Sukhbold (ApJ in press)

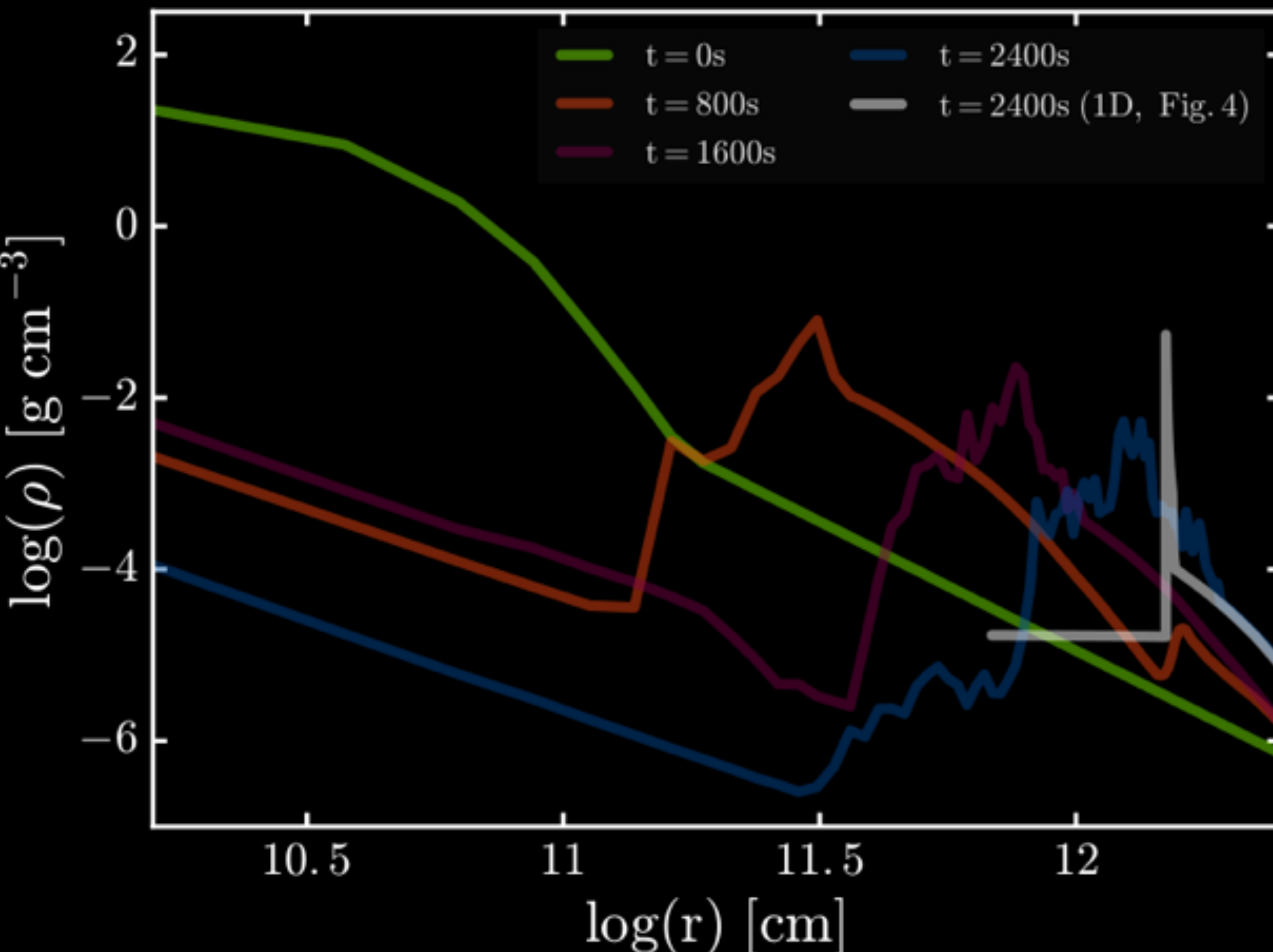
Fluid Instabilities

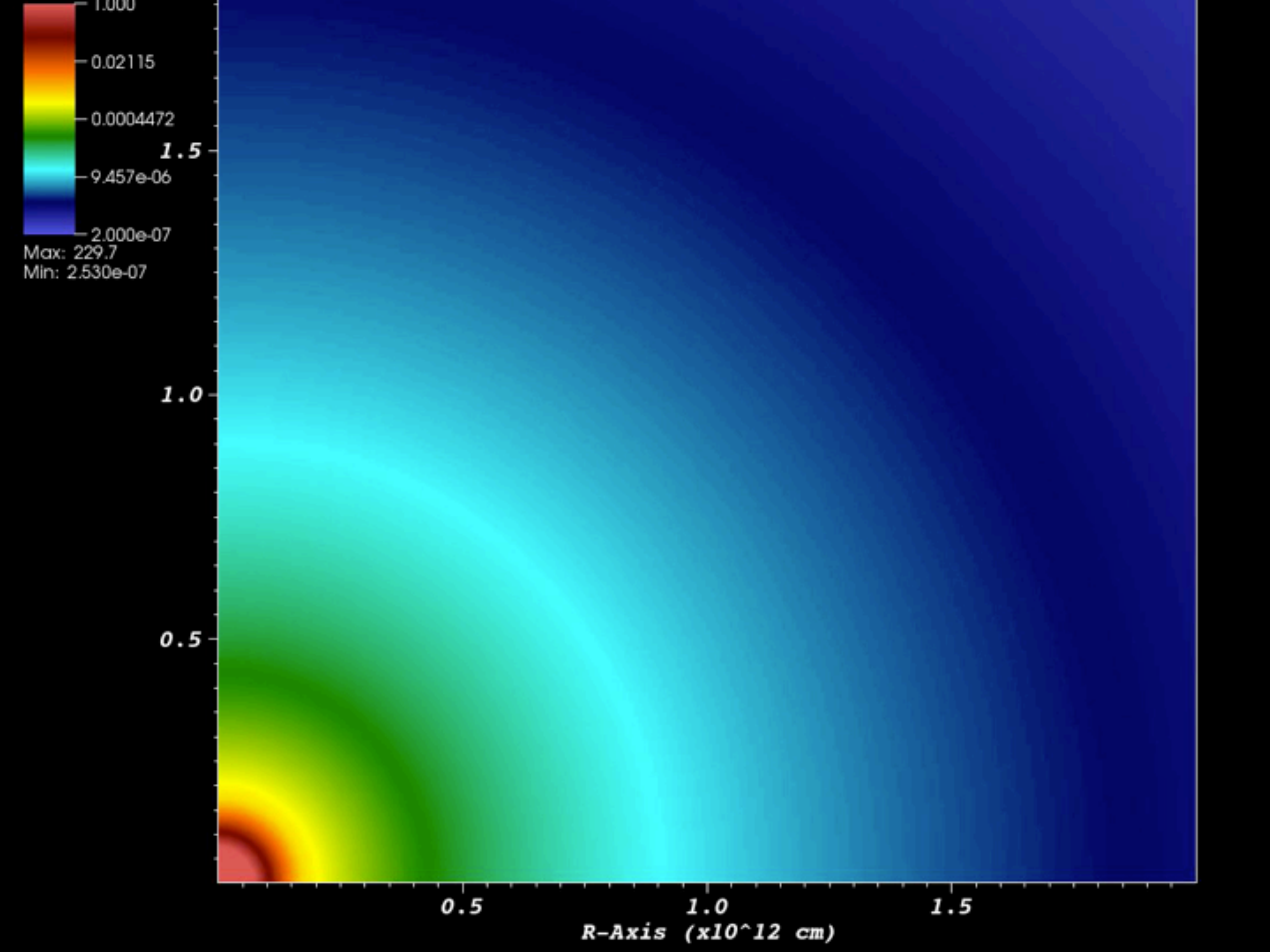


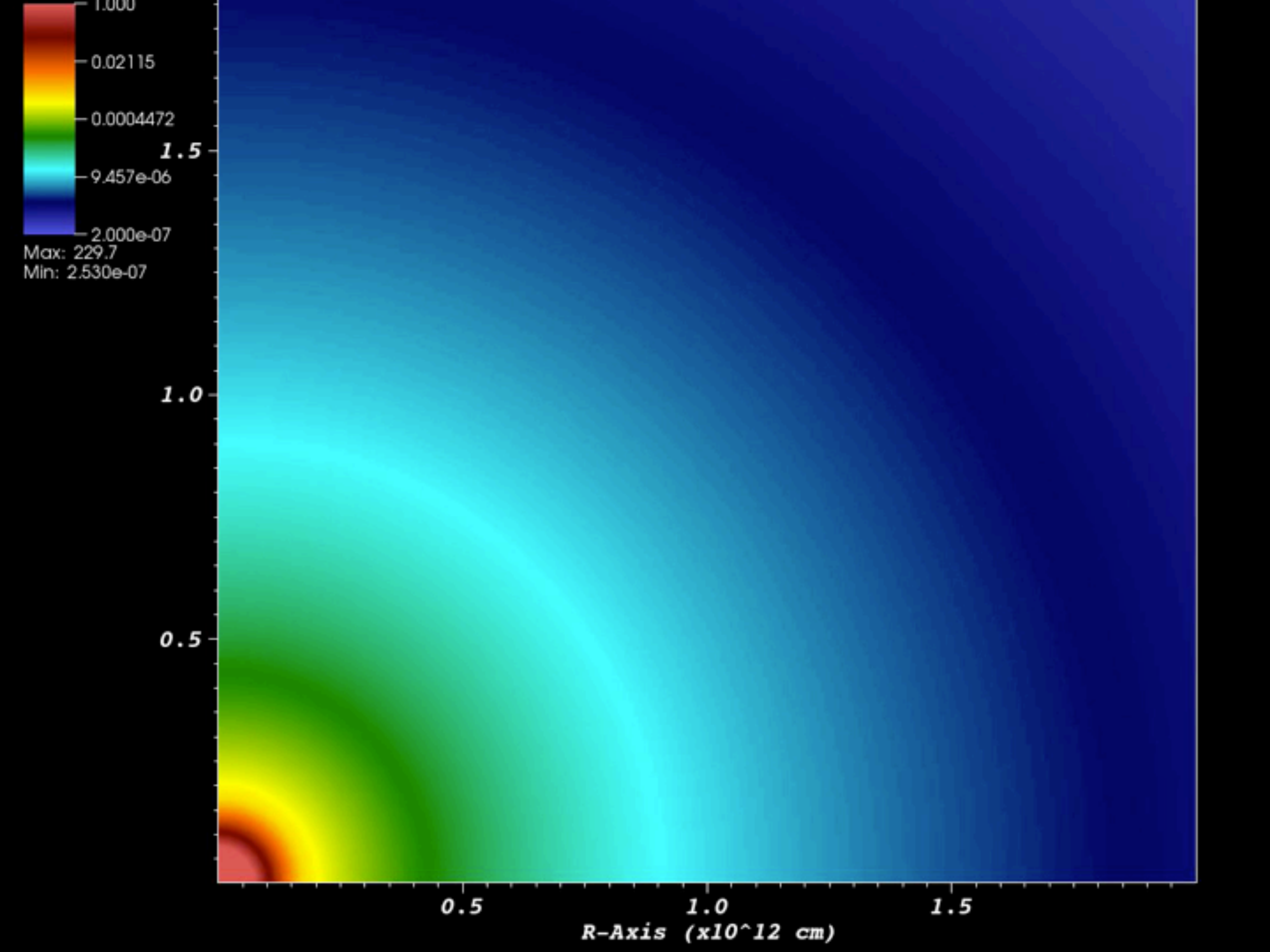
Radiation Breakout



Density Profiles



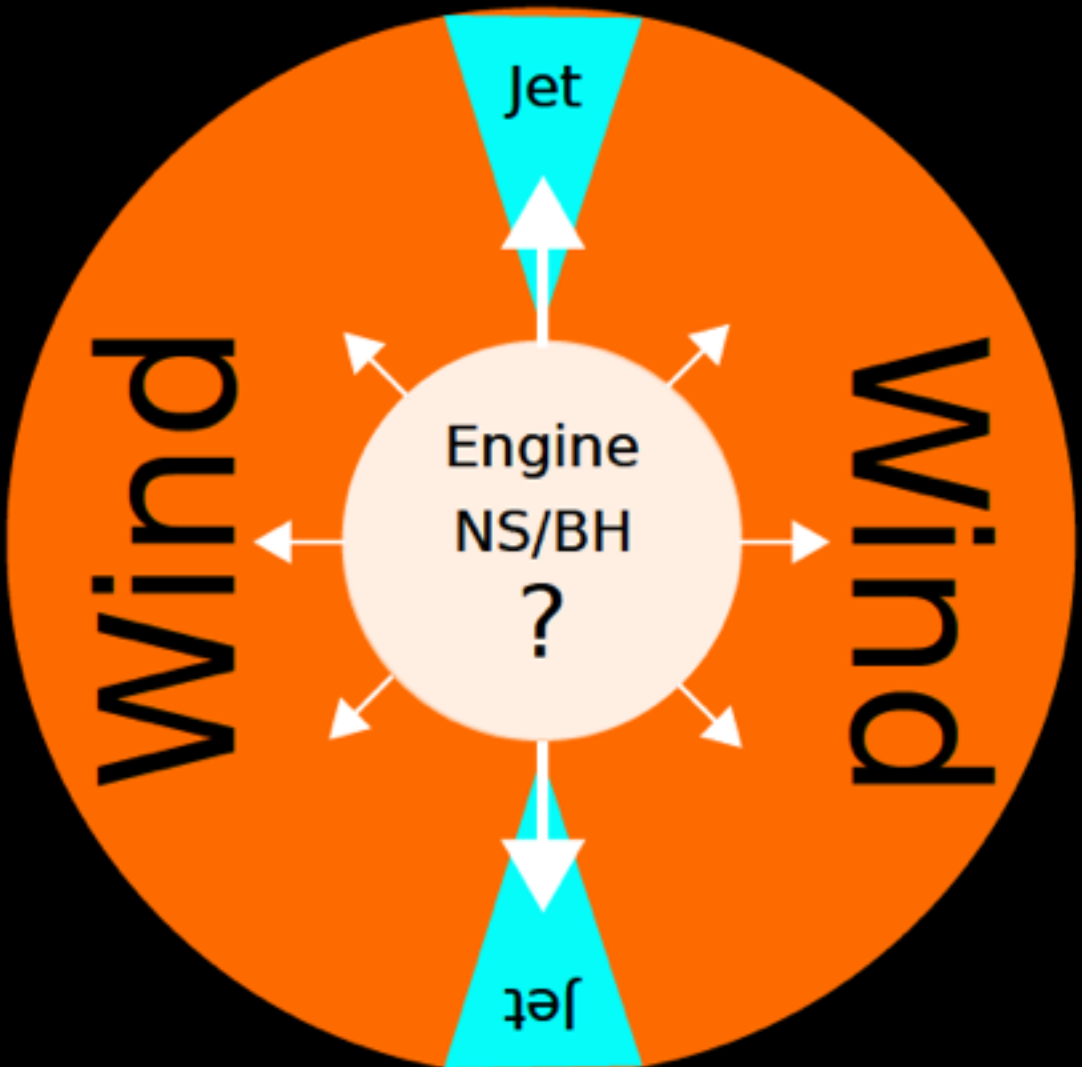

1.000
0.02115
0.0004472
9.457e-06
2.000e-07
Max: 229.7
Min: 2.530e-07
1.5
1.0
0.5
0.5
1.0
1.5
R-Axis (x10^12 cm)



1.000
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)

Hypernovae

B > 1e16 G, P < 1 ms

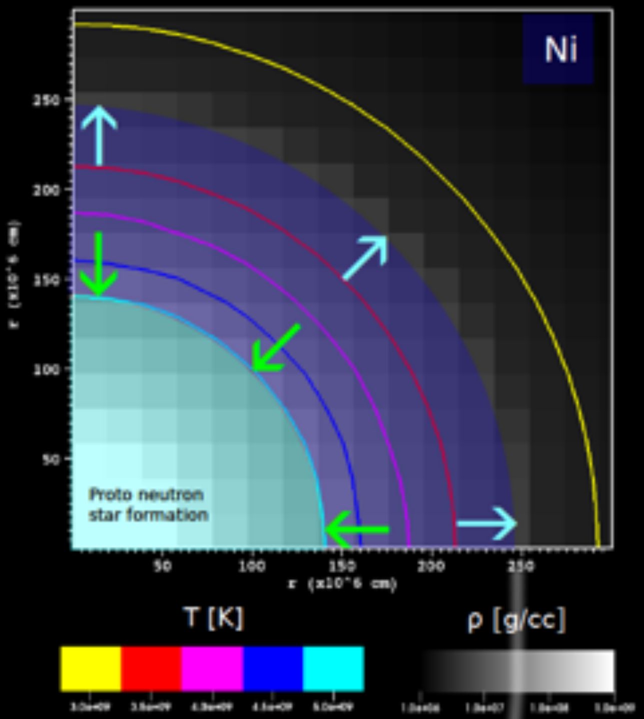


Ni Production

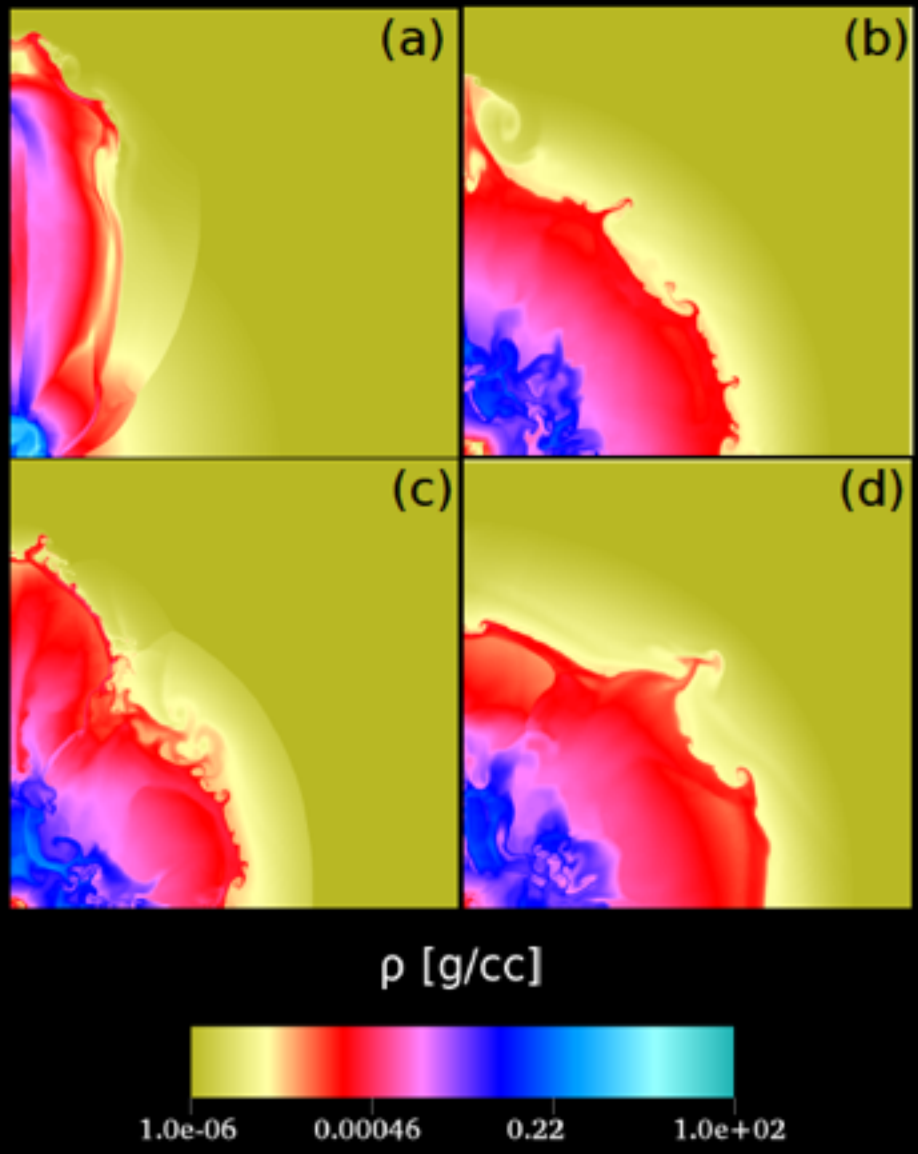
TABLE 1
Magnetar-powered Explosions

Model	Type	Engine Type	^{56}Ni Mass $M_\odot$	Remnant	M_{ej} $M_\odot$	E_{ej} 10^{51} erg
A	J	J(2.5°, ϵ)	0.016	4.54$M_\odot$ BH	5.46	9.84
B	W	W(90°, ϵ)	0.038	1.66$M_\odot$ NS	8.34	11.34
C	J+W	J(2.5°, 0.1ϵ), W(0.9ϵ)	0.036	1.66$M_\odot$ NS	8.34	11.19
D	J+W	J(10°, 0.1ϵ), W(0.9ϵ)	0.037	1.66$M_\odot$ NS	8.34	10.35

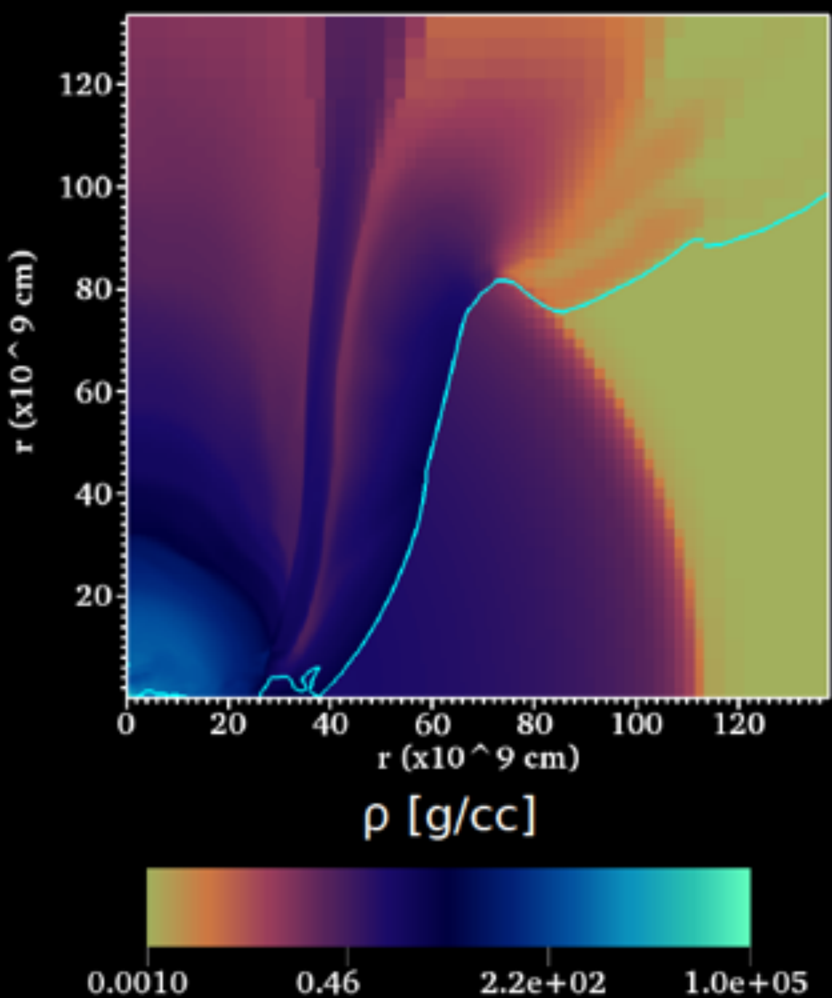
Note. — The rate of energy deposition is $\epsilon = 10^{51}$ erg s^{-1} and its duration is 20 sec

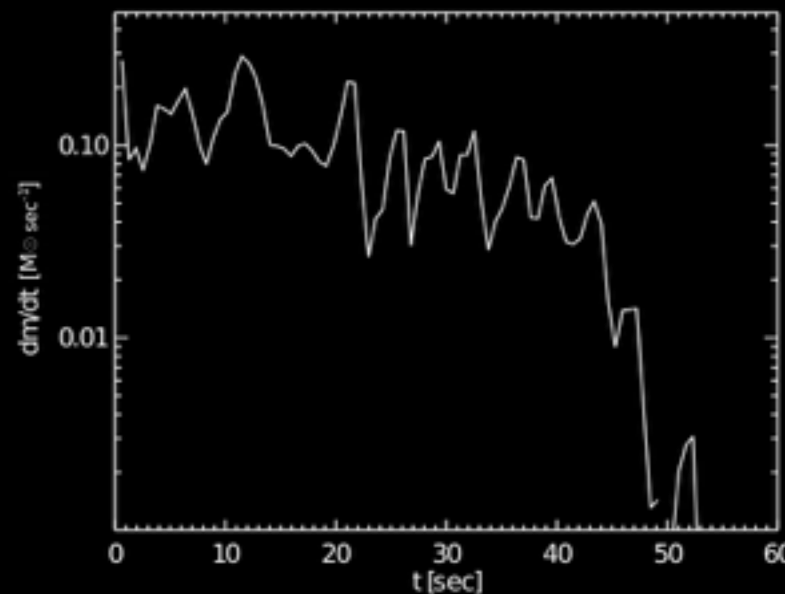


Explosions

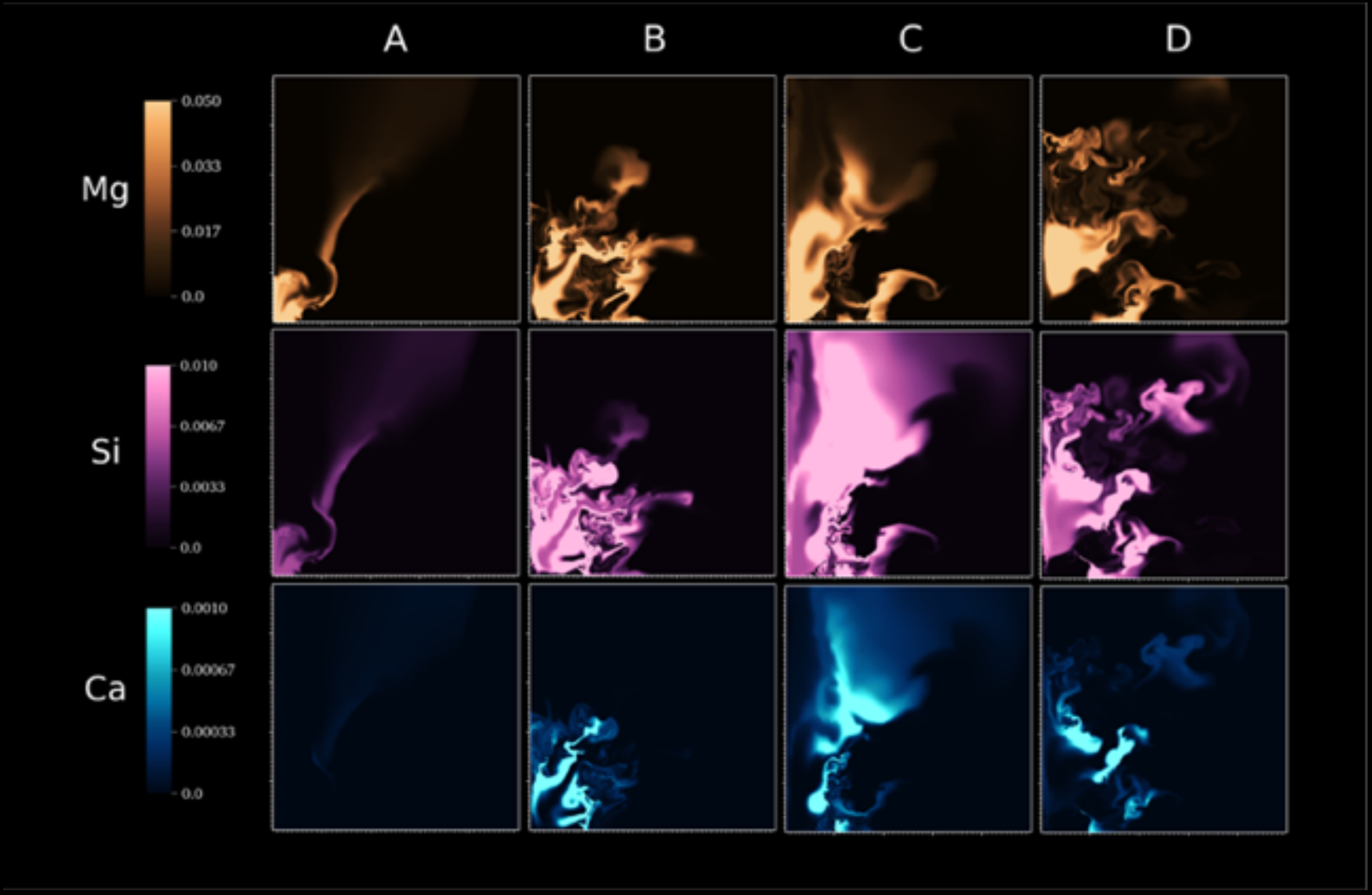


Jet only Model

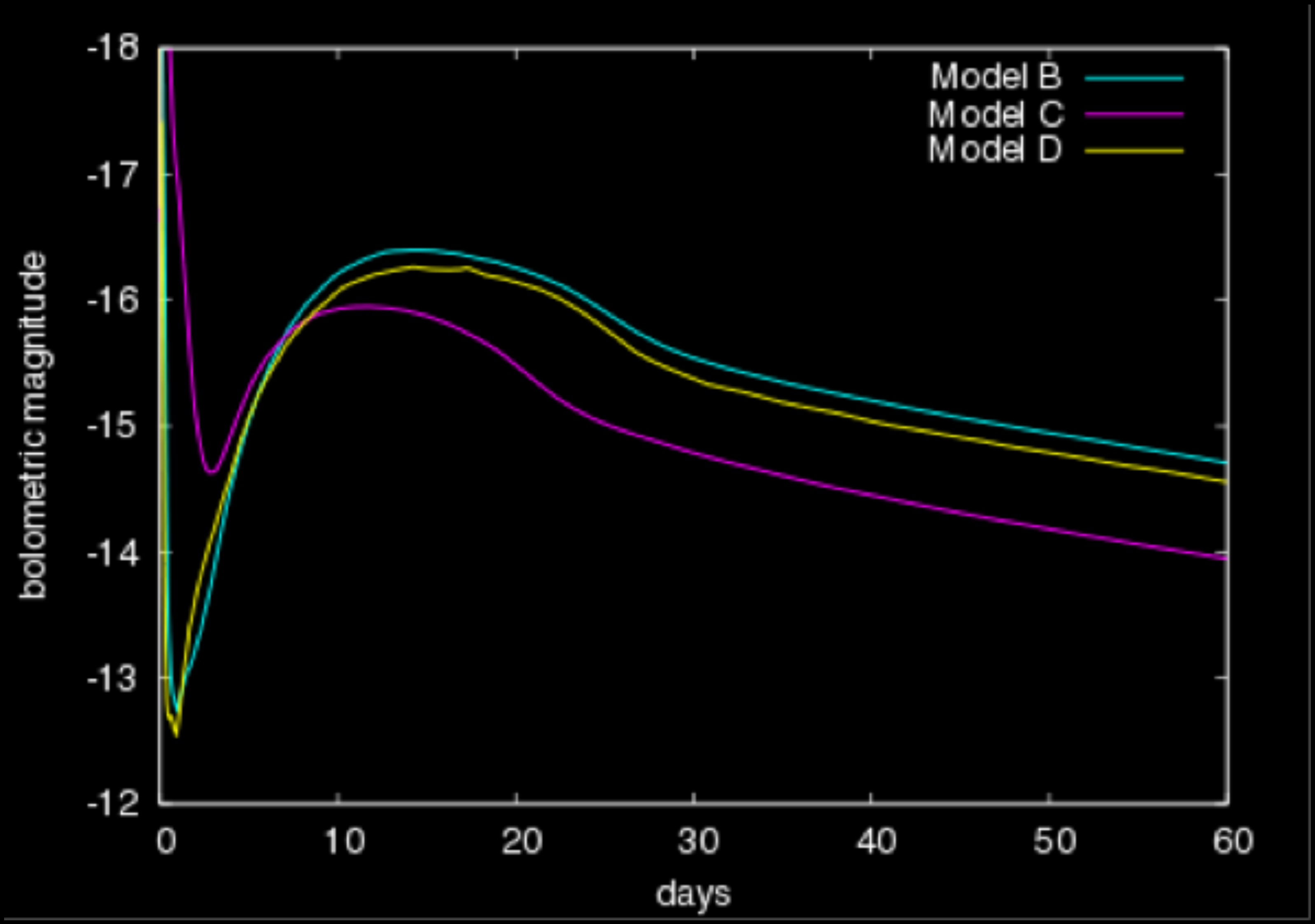




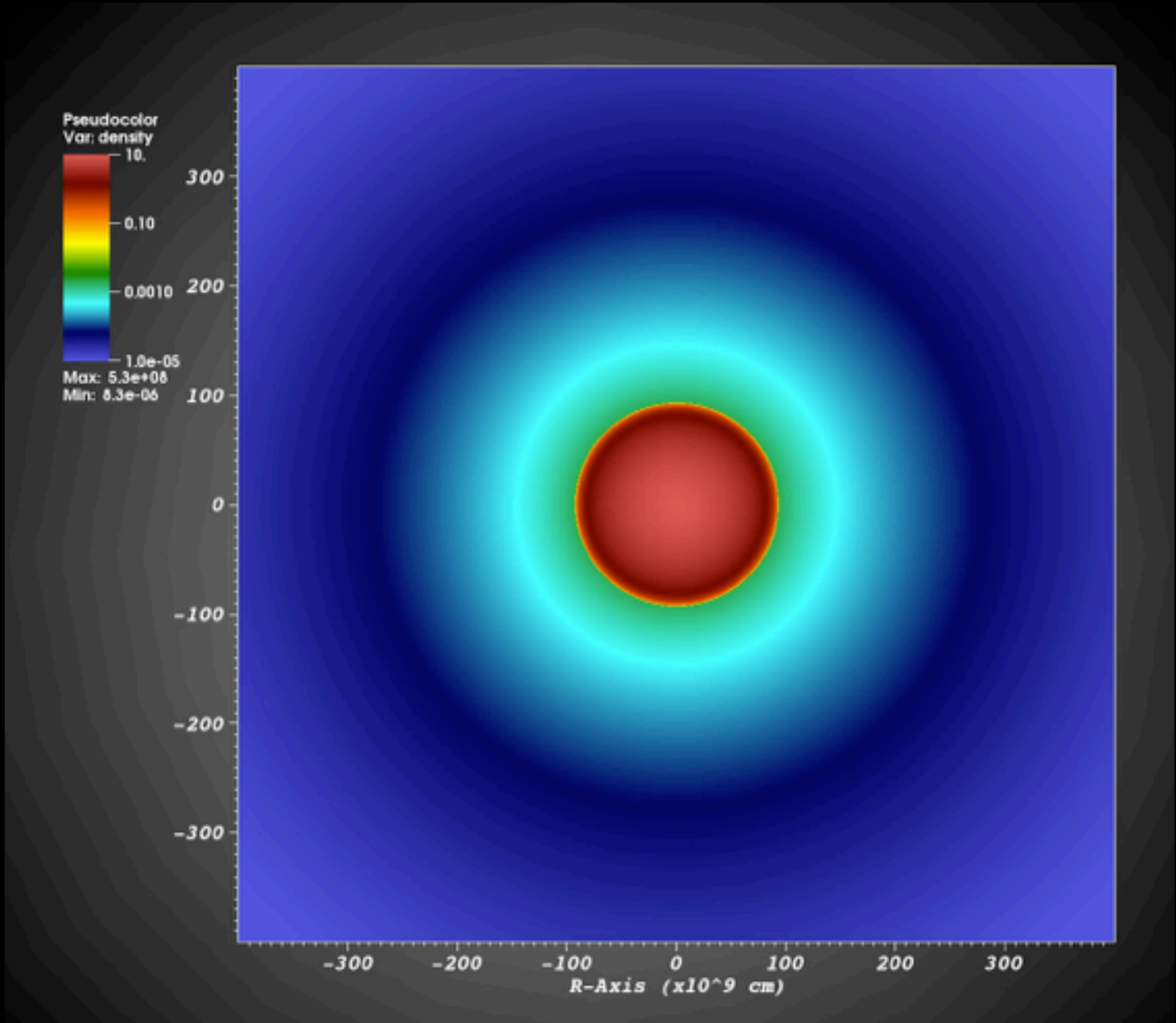
Yields and Mixing



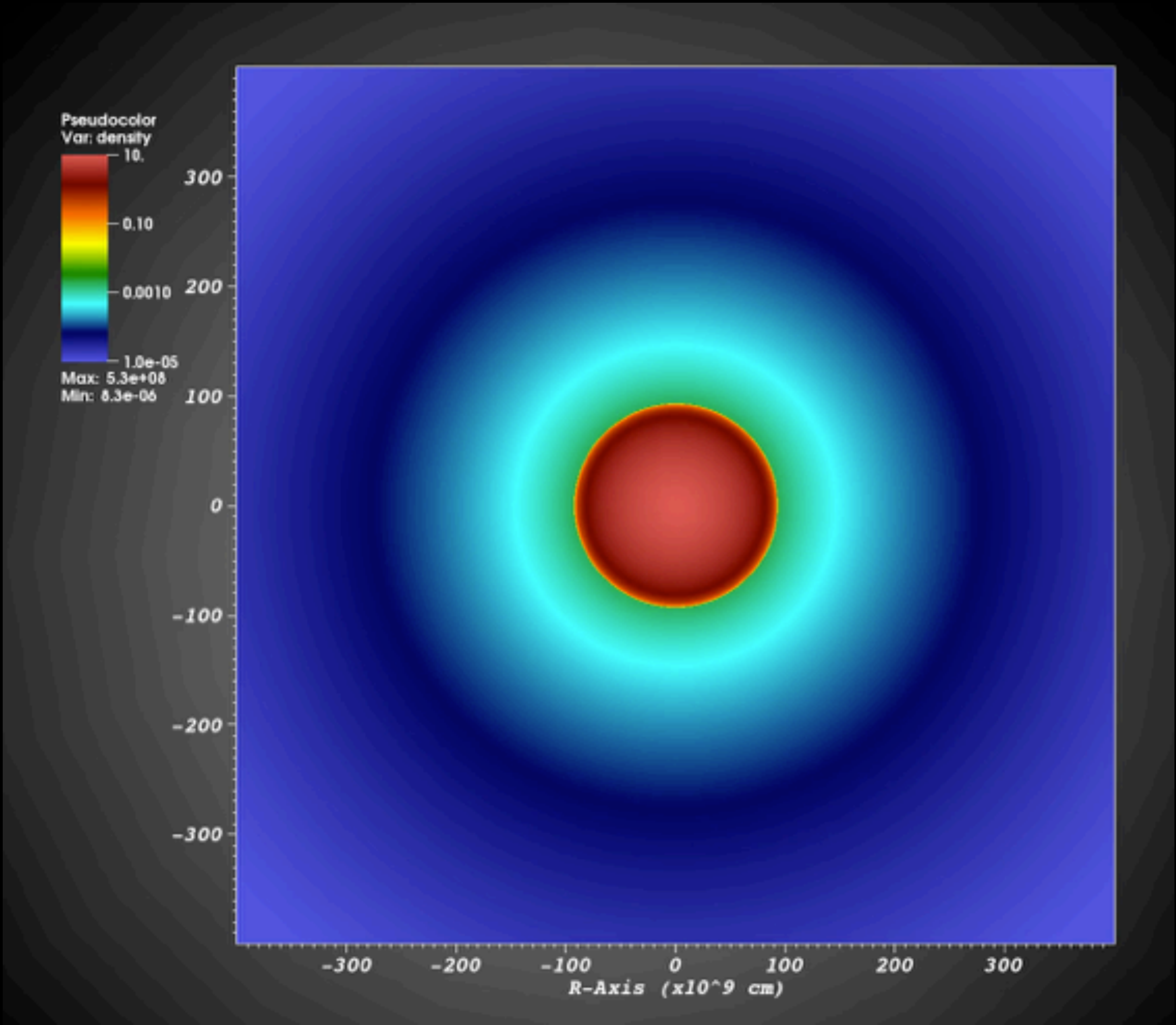
Light Curves



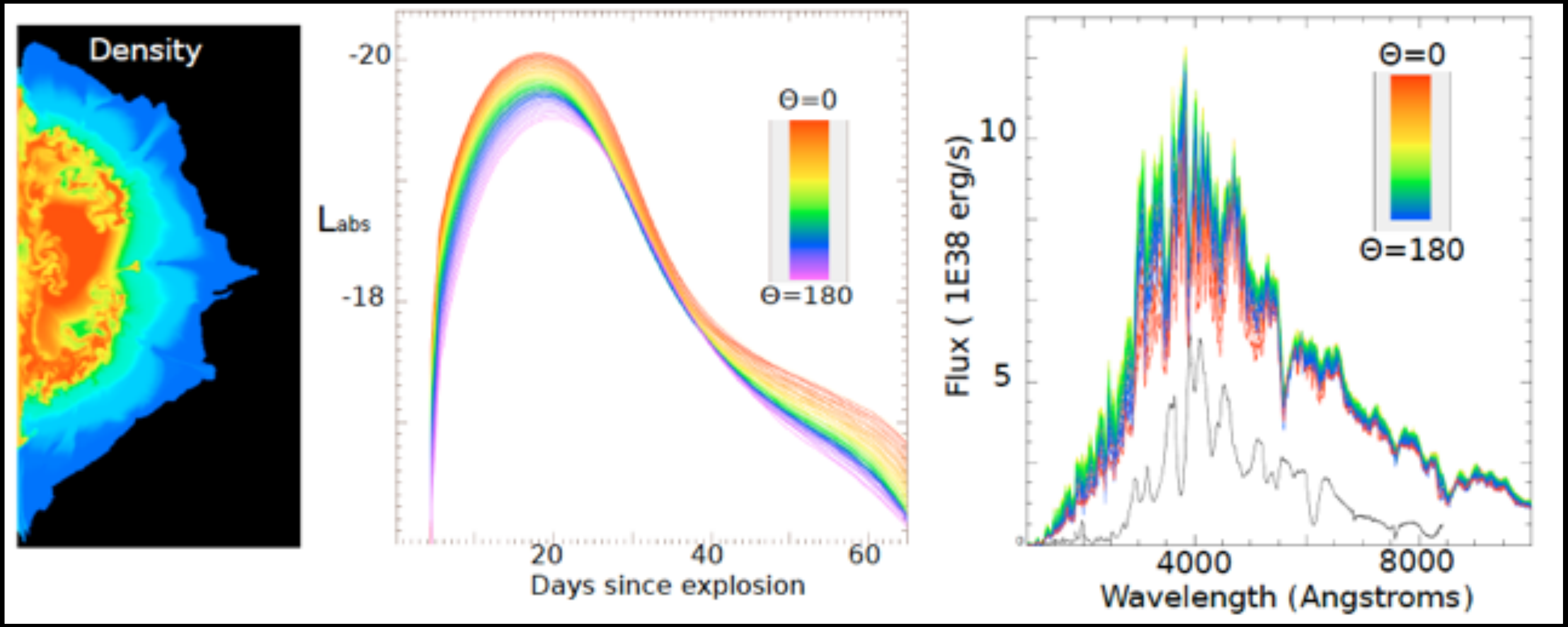
But there may be a GRB !



But there may be a GRB !

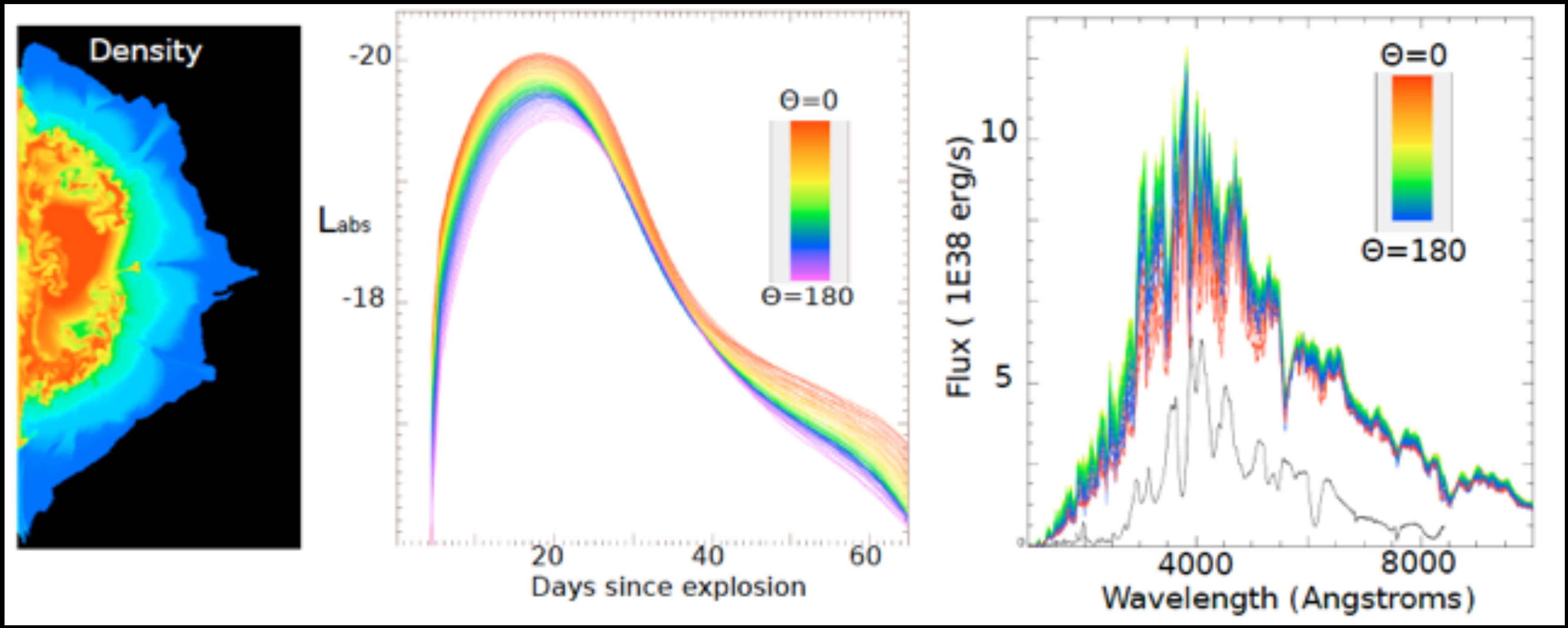


Toward Realistic SN observational Signatures



A Type Ia Example from Kasen+ 2008

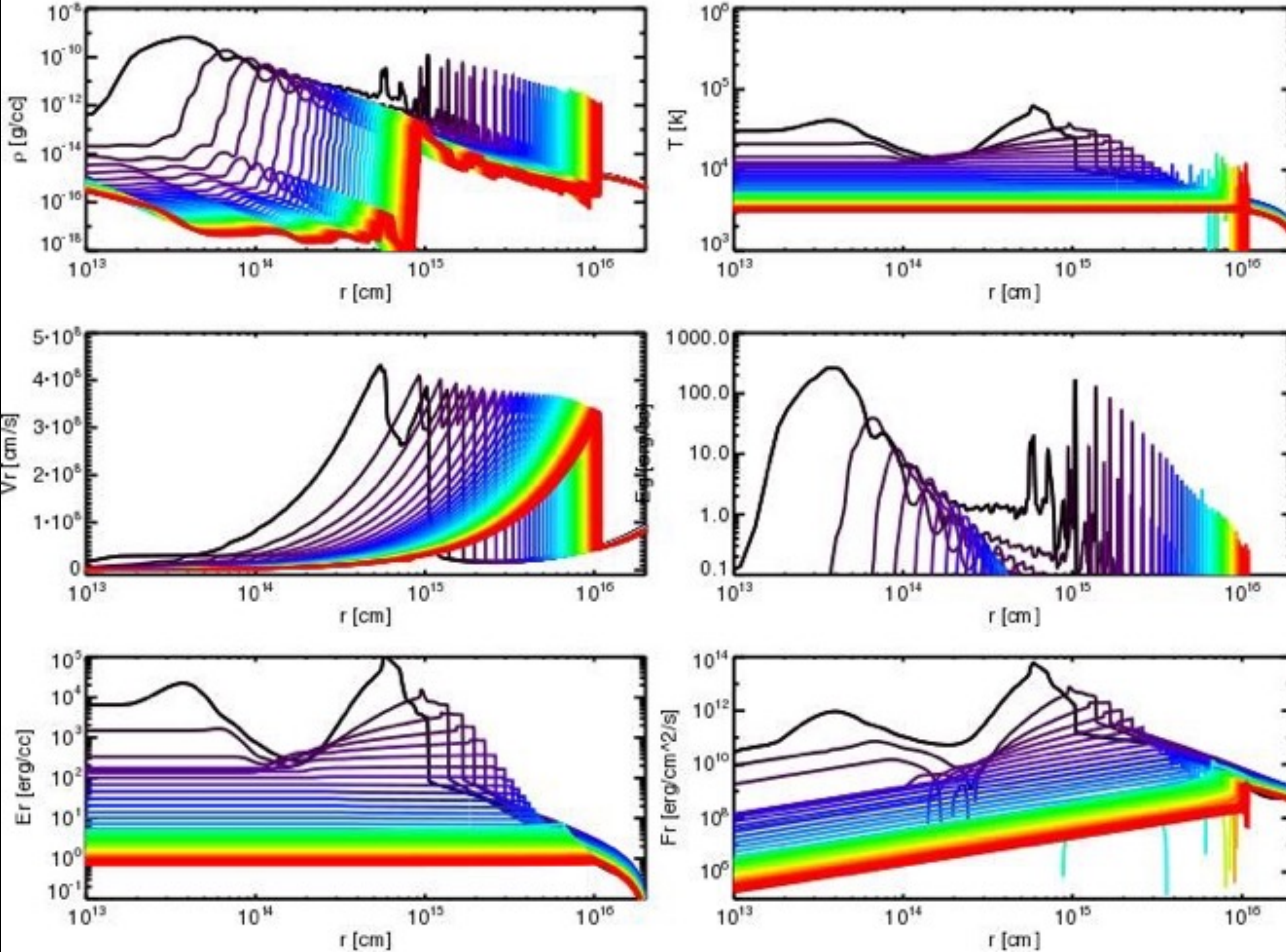
Toward Realistic SN observational Signatures

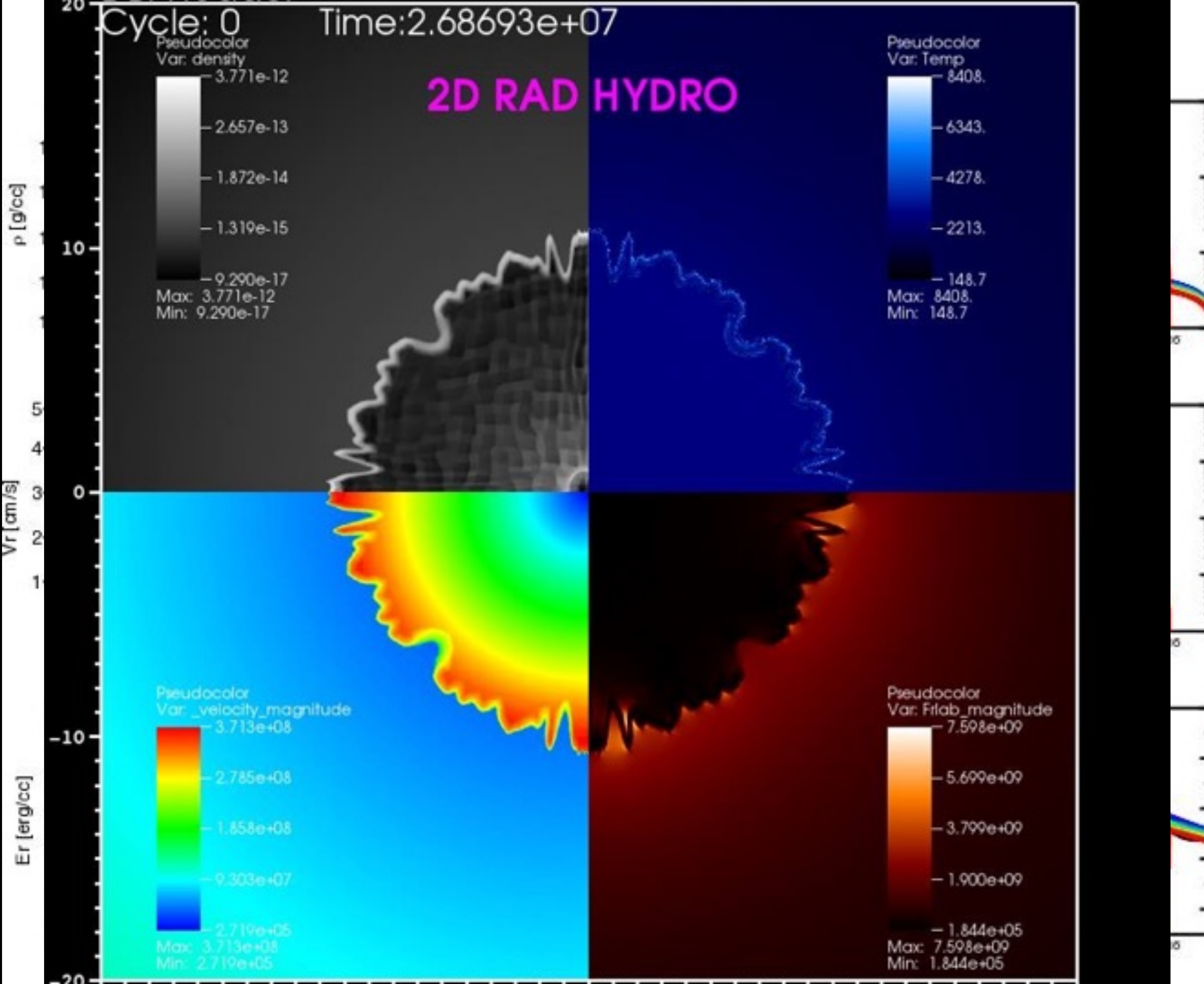


A Type Ia Example from Kasen+ 2008

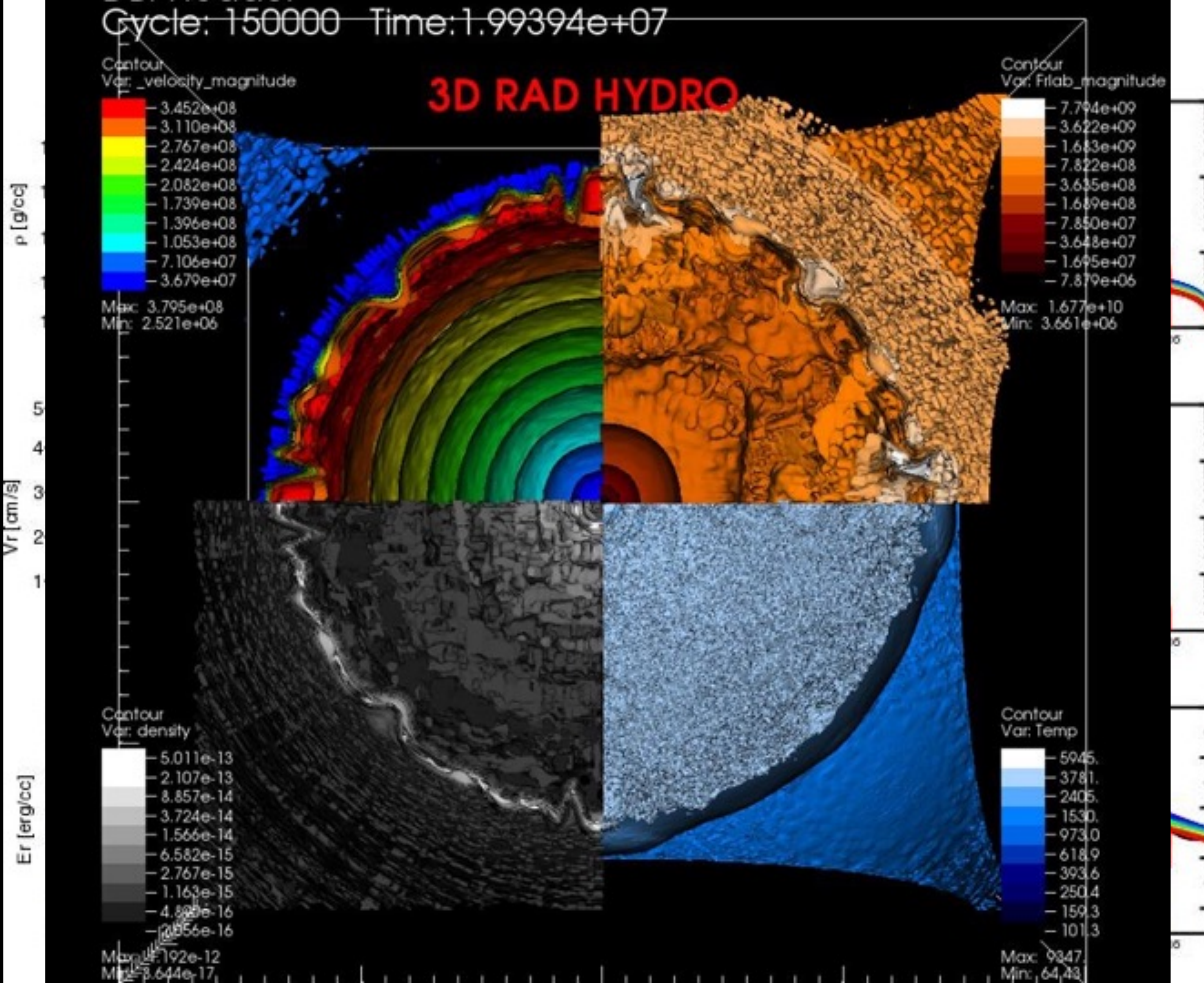
Multidimensional Radiation Transport Simulations of Exotic SNe !!

RAD HYDRO

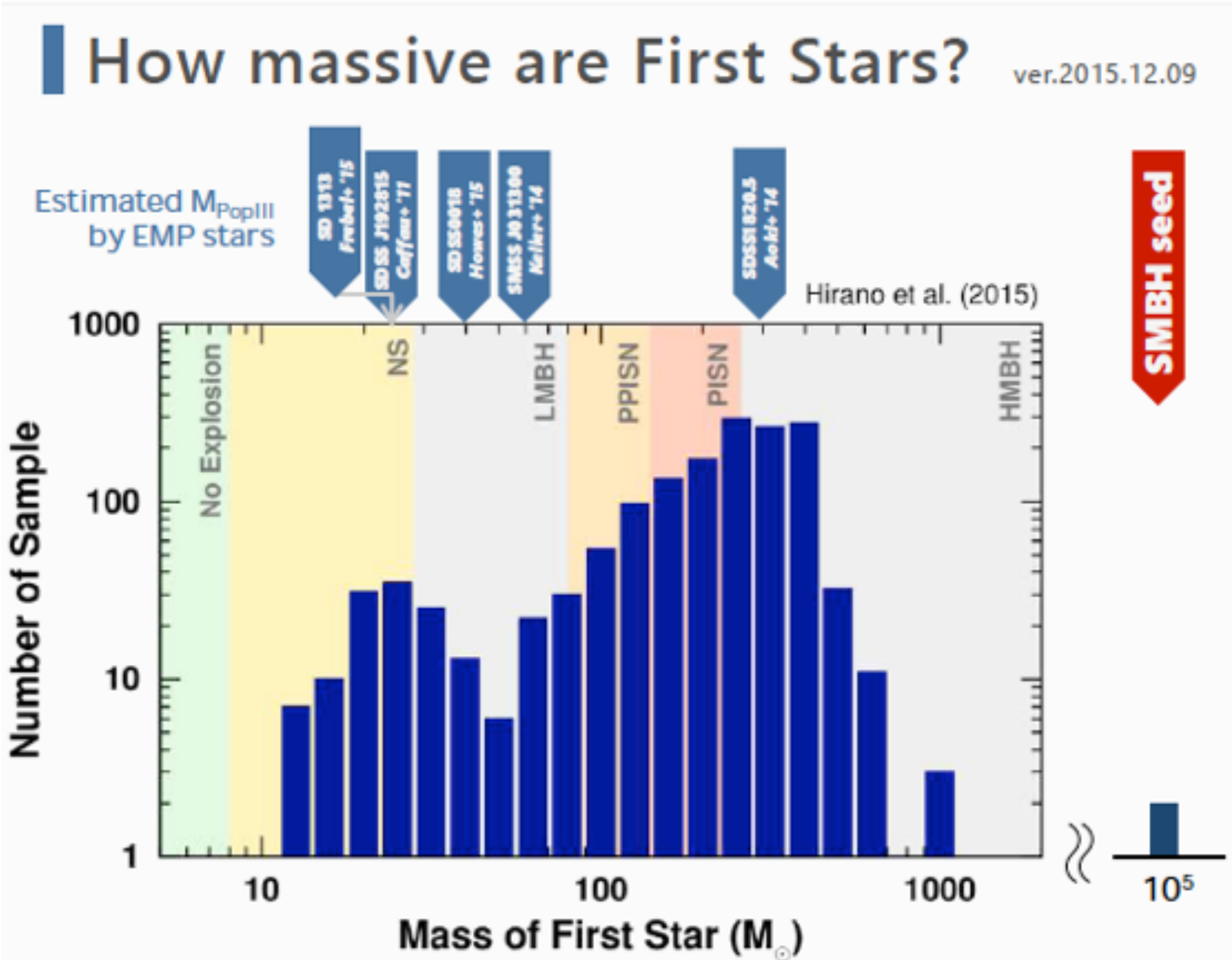




Cycle: 0
Time:2.68693e+07
2D RAD HYDRO
Pseudocolor
Var: density
3.771e-12
2.657e-13
1.872e-14
1.319e-15
9.290e-17
Max: 3.771e-12
Min: 9.290e-17
Pseudocolor
Var: Temp
8408.
6343.
4278.
2213.
148.7
Max: 8408.
Min: 148.7
Pseudocolor
Var: _velocity_magnitude
3.713e+08
2.785e+08
1.858e+08
9.303e+07
2.719e+05
Max: 3.713e+08
Min: 2.719e+05
Pseudocolor
Var: Frlab_magnitude
7.598e+09
5.699e+09
3.799e+09
1.900e+09
1.844e+05
Max: 7.598e+09
Min: 1.844e+05
20
10
0
-10
-20
ρ [g/cc]
Vr [cm/s]
Er [erg/cc]


Cycle: 150000 Time:1.99394e+07
3D RAD HYDRO
Contour
Var: _velocity_magnitude
3.452e+08
3.110e+08
2.767e+08
2.424e+08
2.082e+08
1.739e+08
1.396e+08
1.053e+08
7.106e+07
3.679e+07
Max: 3.795e+08
Min: 2.521e+06
Contour
Var: Frlab_magnitude
7.794e+09
3.622e+09
1.683e+09
7.822e+08
3.635e+08
1.689e+08
7.850e+07
3.648e+07
1.695e+07
7.879e+06
Max: 1.677e+10
Min: 3.661e+06
Contour
Var: density
5.011e-13
2.107e-13
8.857e-14
3.724e-14
1.566e-14
6.582e-15
2.767e-15
1.163e-15
Contour
Var: Temp
5945.
3781.
2405.
1530.
973.0
618.9
393.6
250.4
159.3
101.3
Max: 9347.
Min: 64.43
ρ [g/cc]
Vr [cm/s]
Er [erg/cc]

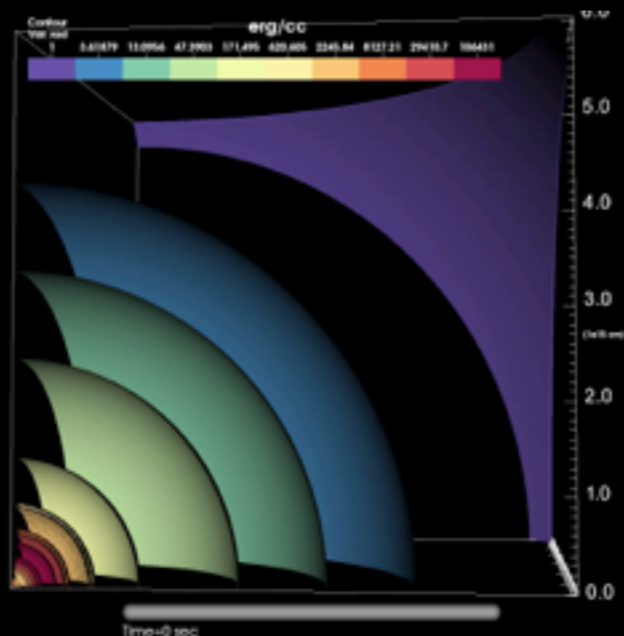
Hunting for the First Cosmic Explosions ?

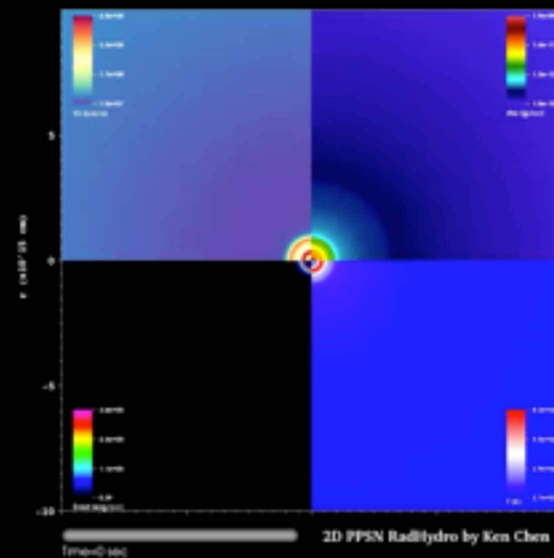


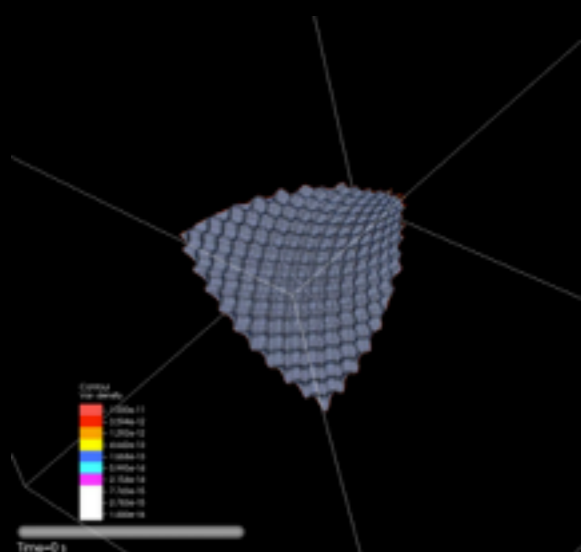
Courtesy of Shingo Hirano

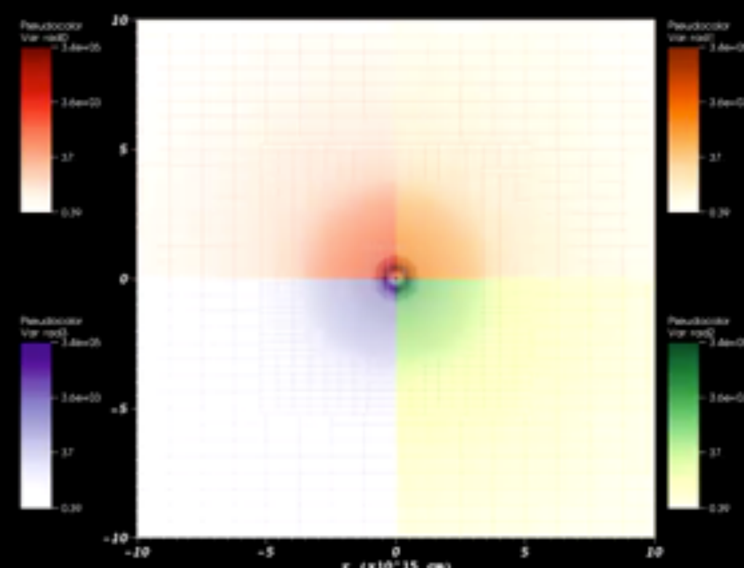
Multidimensional Radiation Transport Simulations of Extreme SNe

Chen, Woosley, & Zhang in prep.



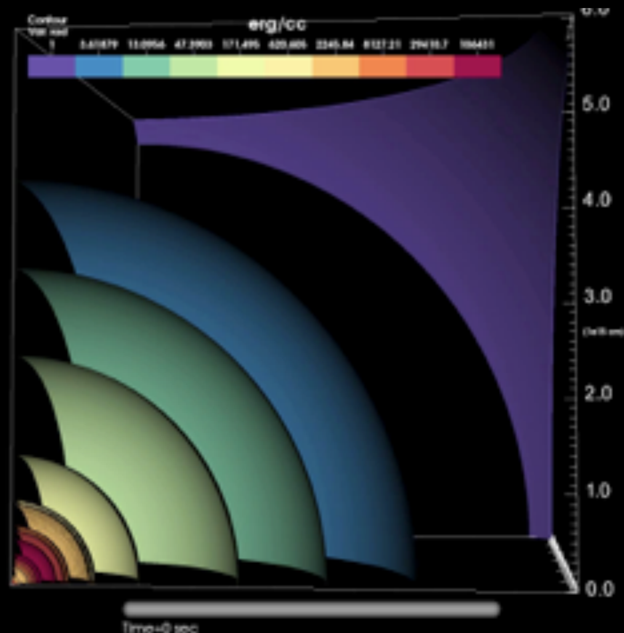


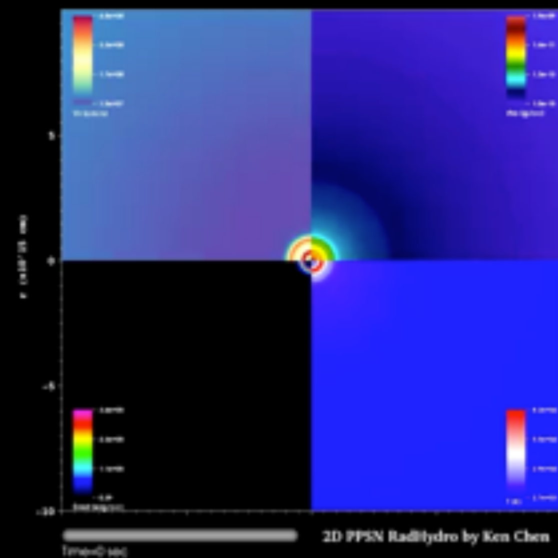


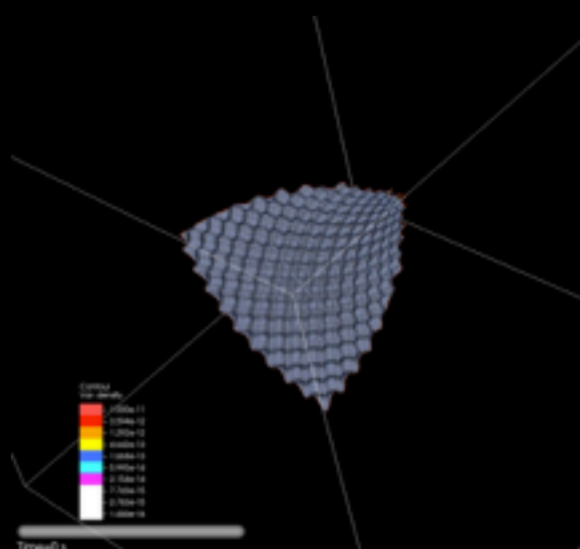


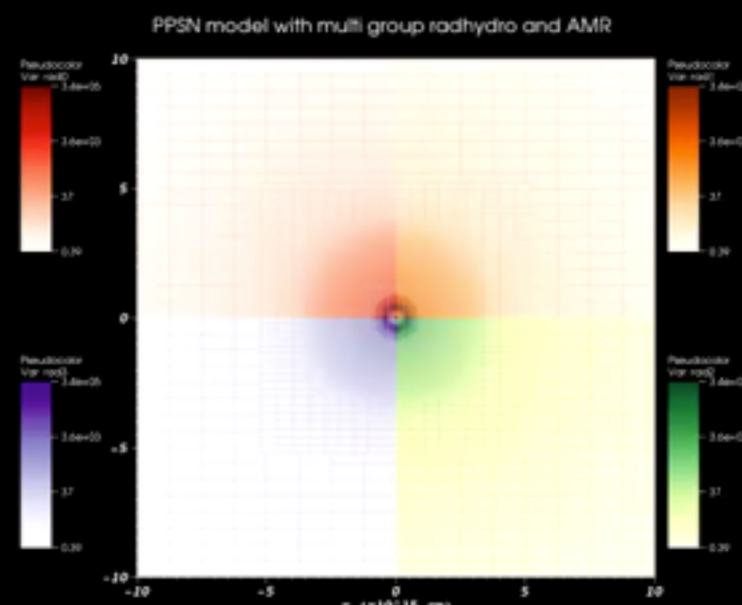
Multidimensional Radiation Transport Simulations of Extreme SNe

Chen, Woosley, & Zhang in prep.









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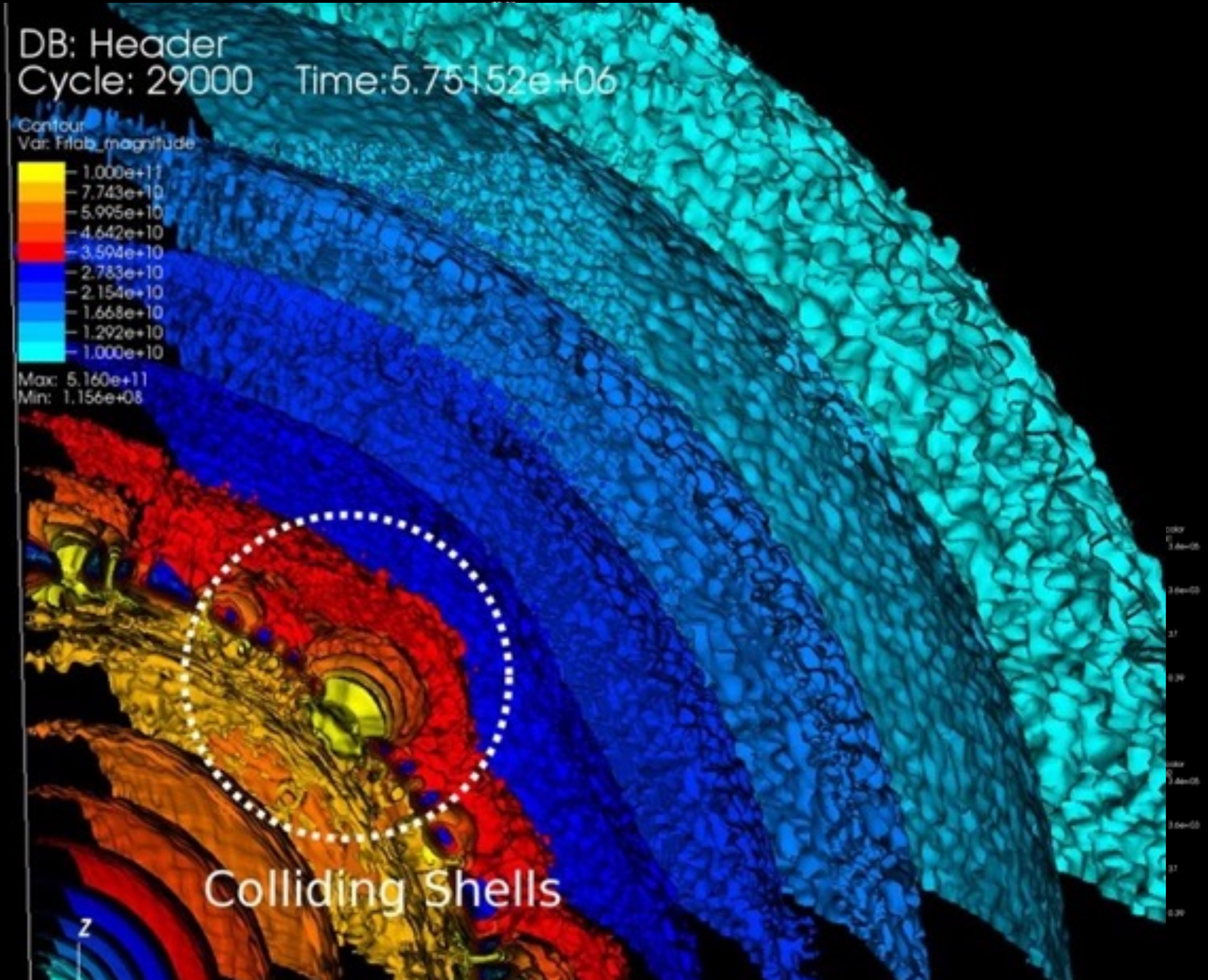

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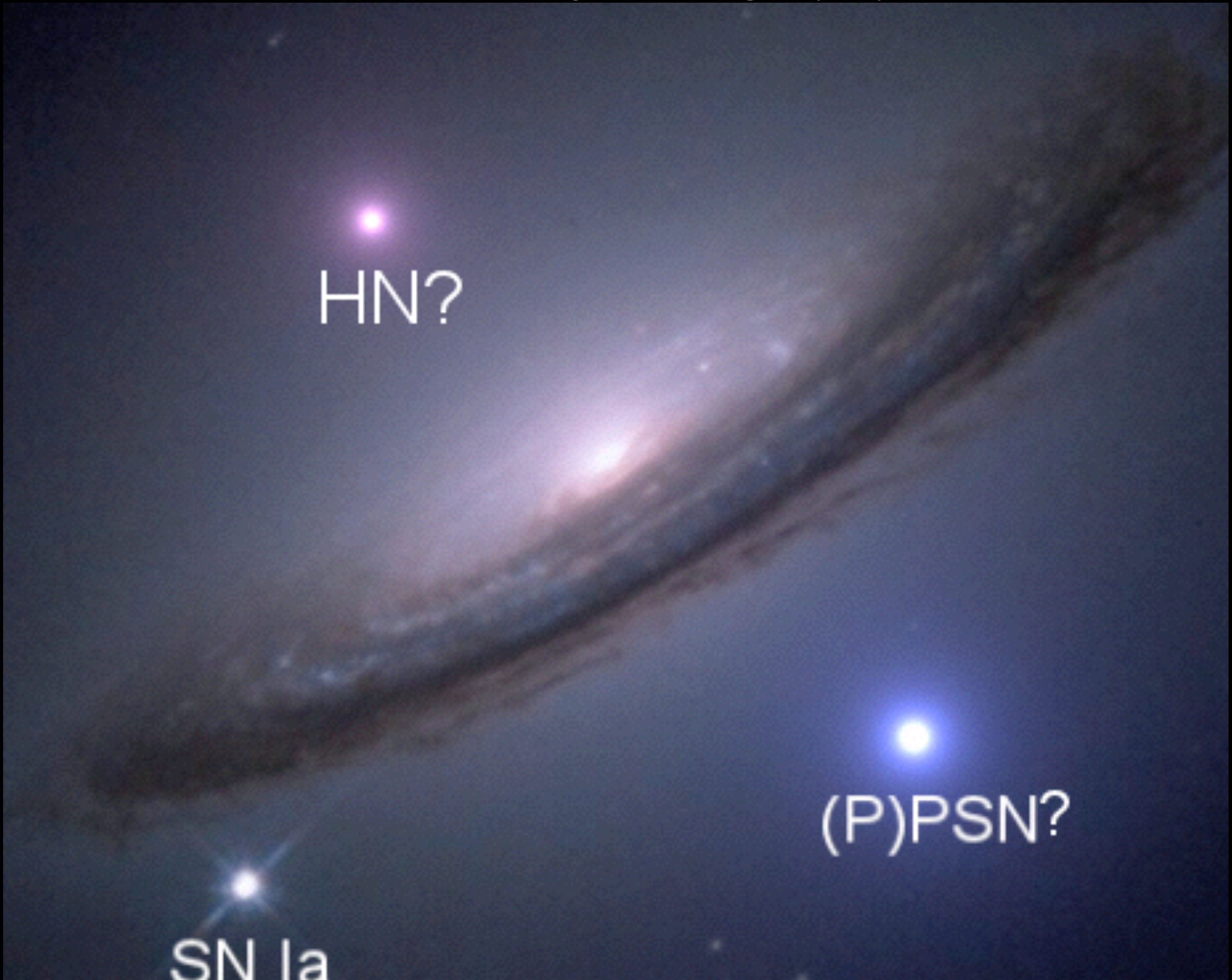

Multidimensional Radiation Transport Simulations of Extreme SNe

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