Supernovae from the Most Massive Stars

Ke-Jung (Ken) Chen

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East Asia Numerical Astrophysics Meeting, YITP Kyoto, Oct. 30 2012

Star Bombers

Alexander Heger
Monash University

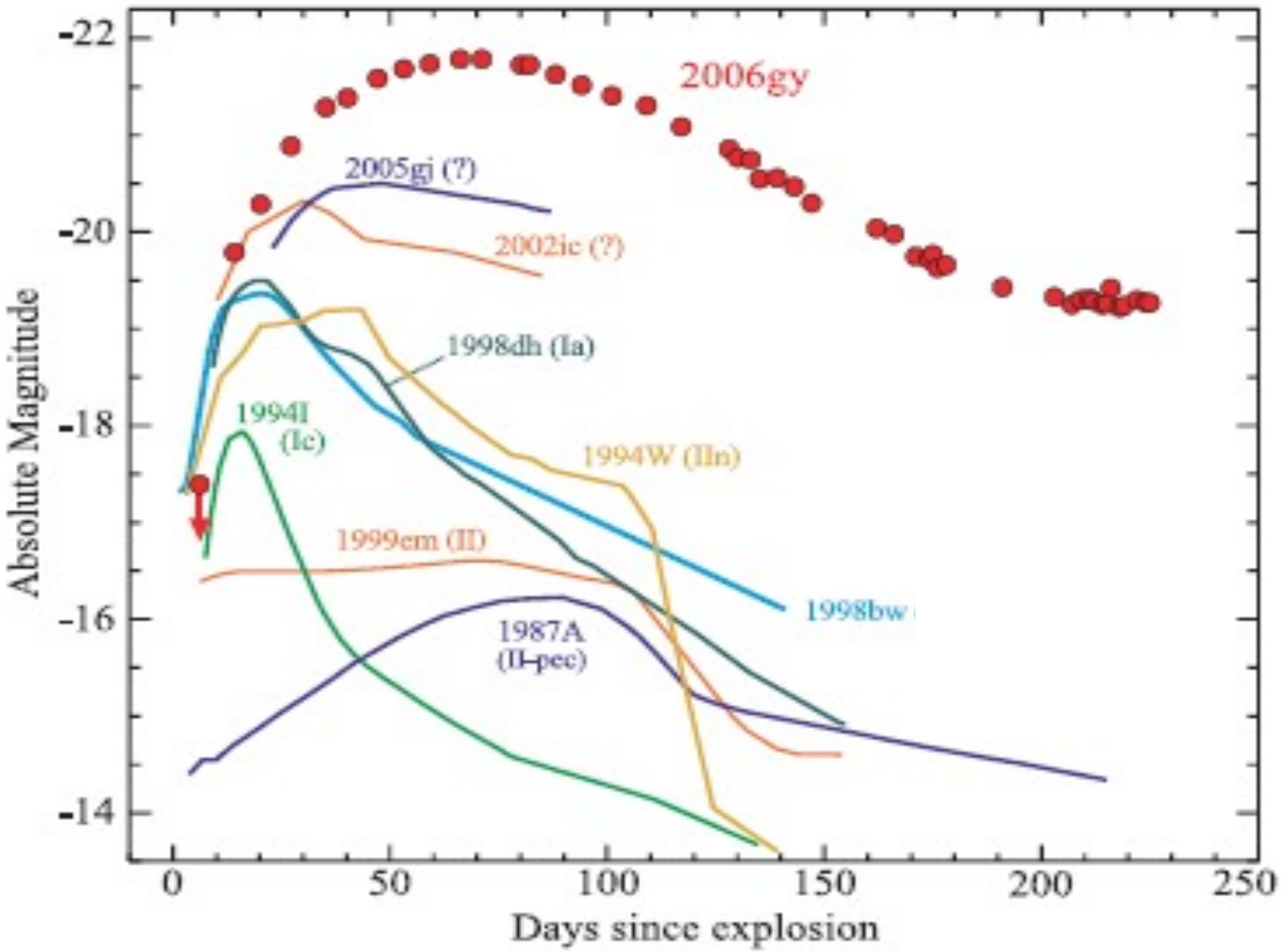
Stan Woosley
UC Santa Cruz

Ann Almgren
Lawrence Berkeley National Lab

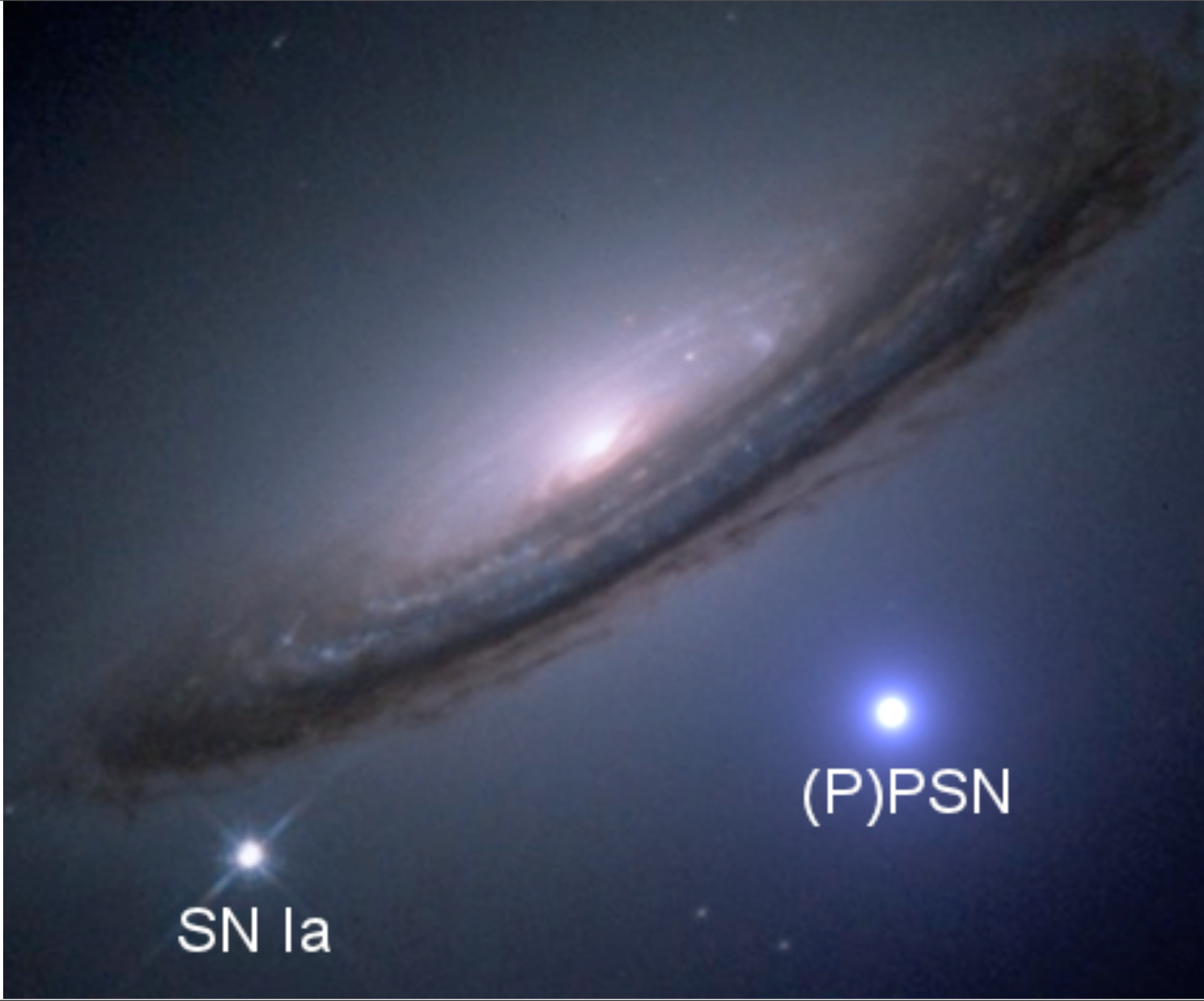
Daniel Kasen
UC Berkeley

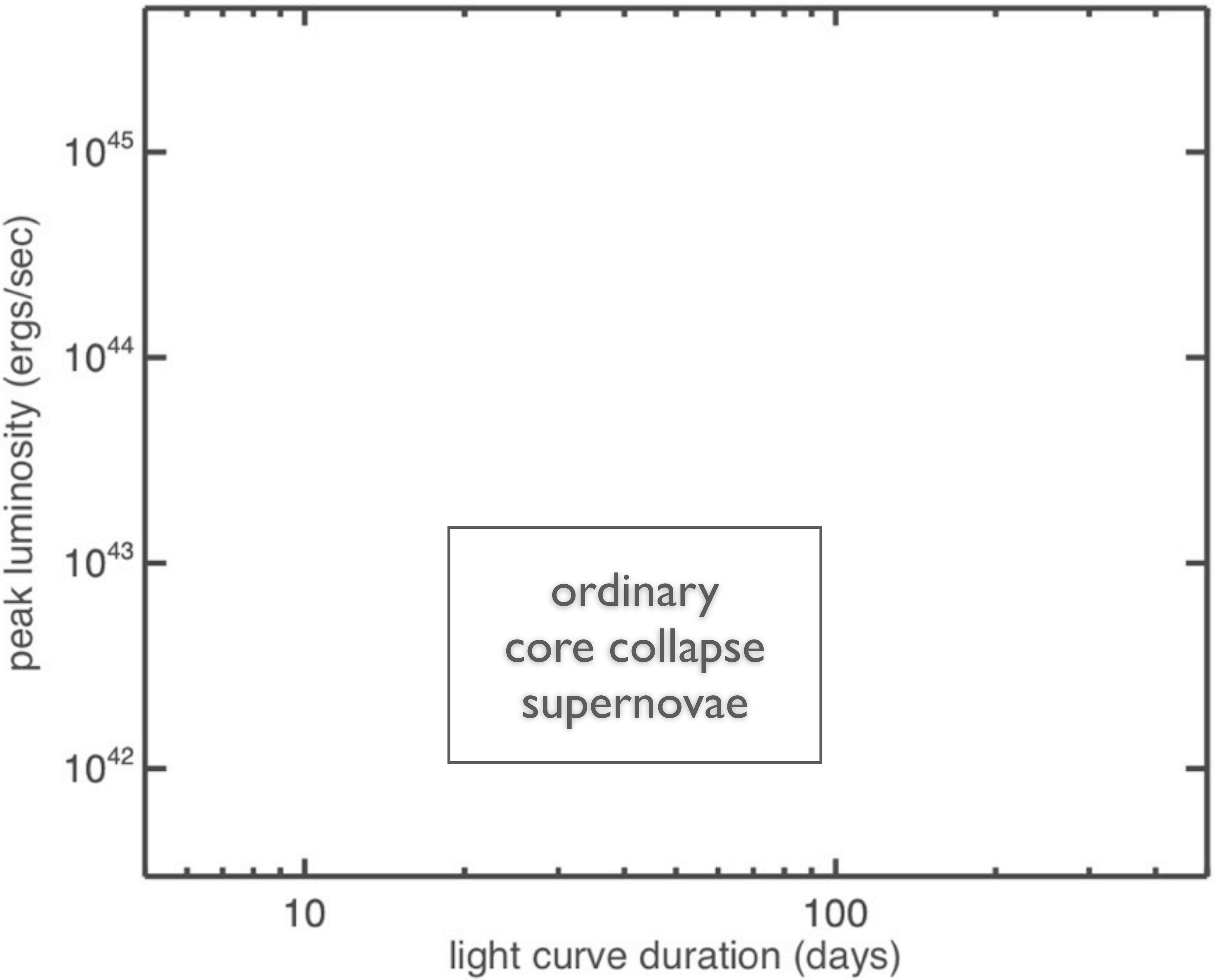
Weiqun Zhang
Lawrence Berkeley National Lab

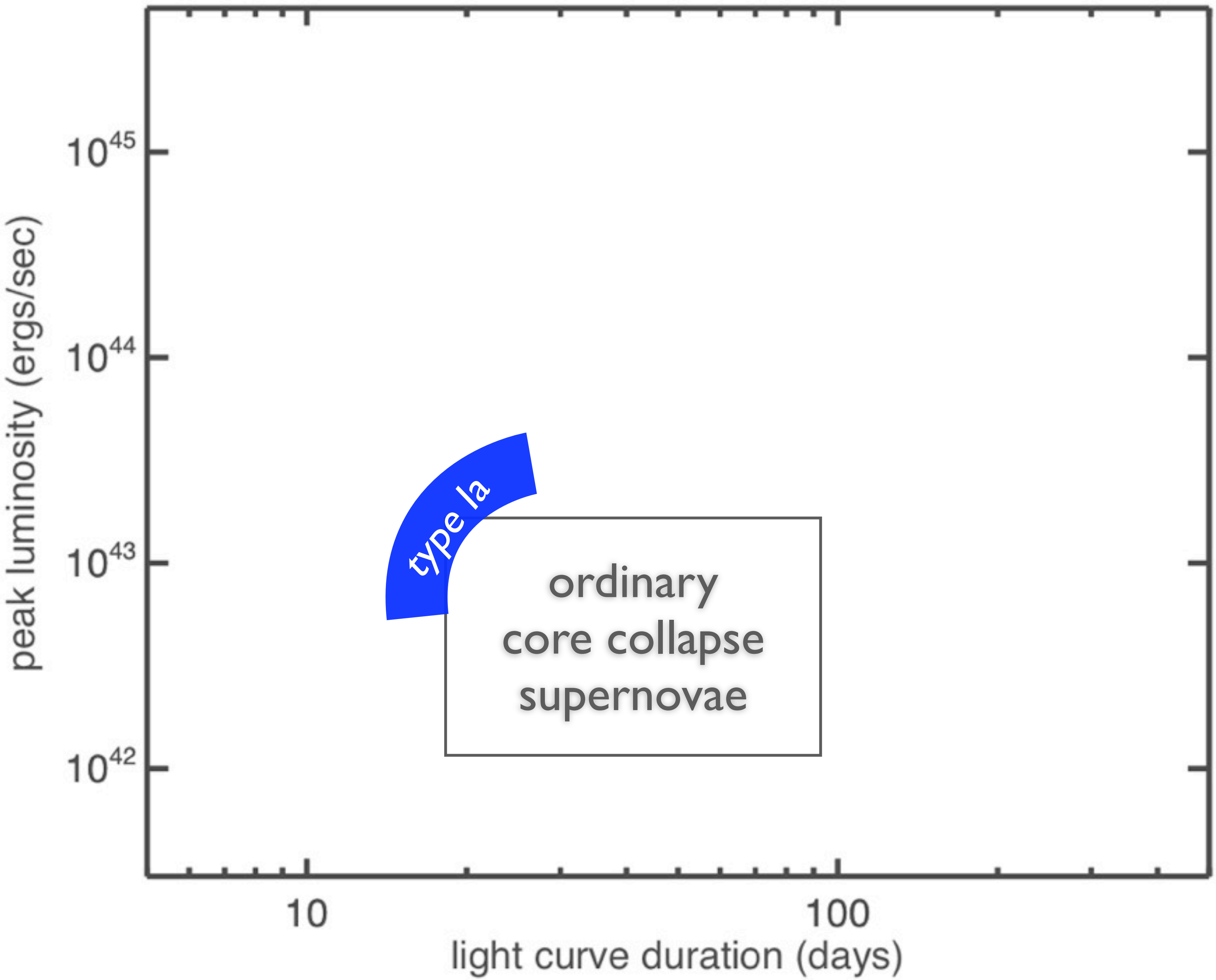
Super Luminous SNe



Smith+ 2007


(P)PSN
SN Ia


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



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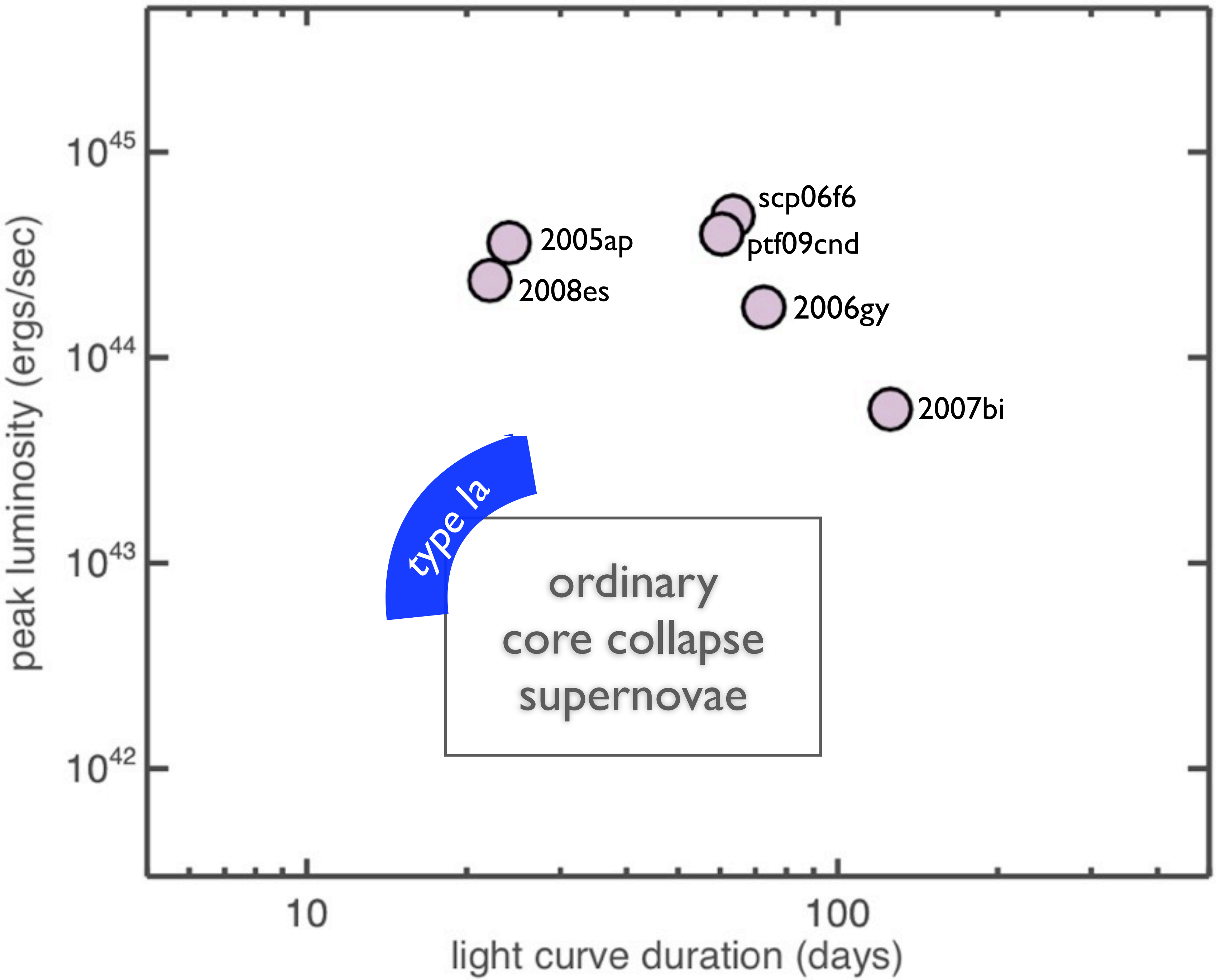

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scp06f6
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2006gy
2007bi
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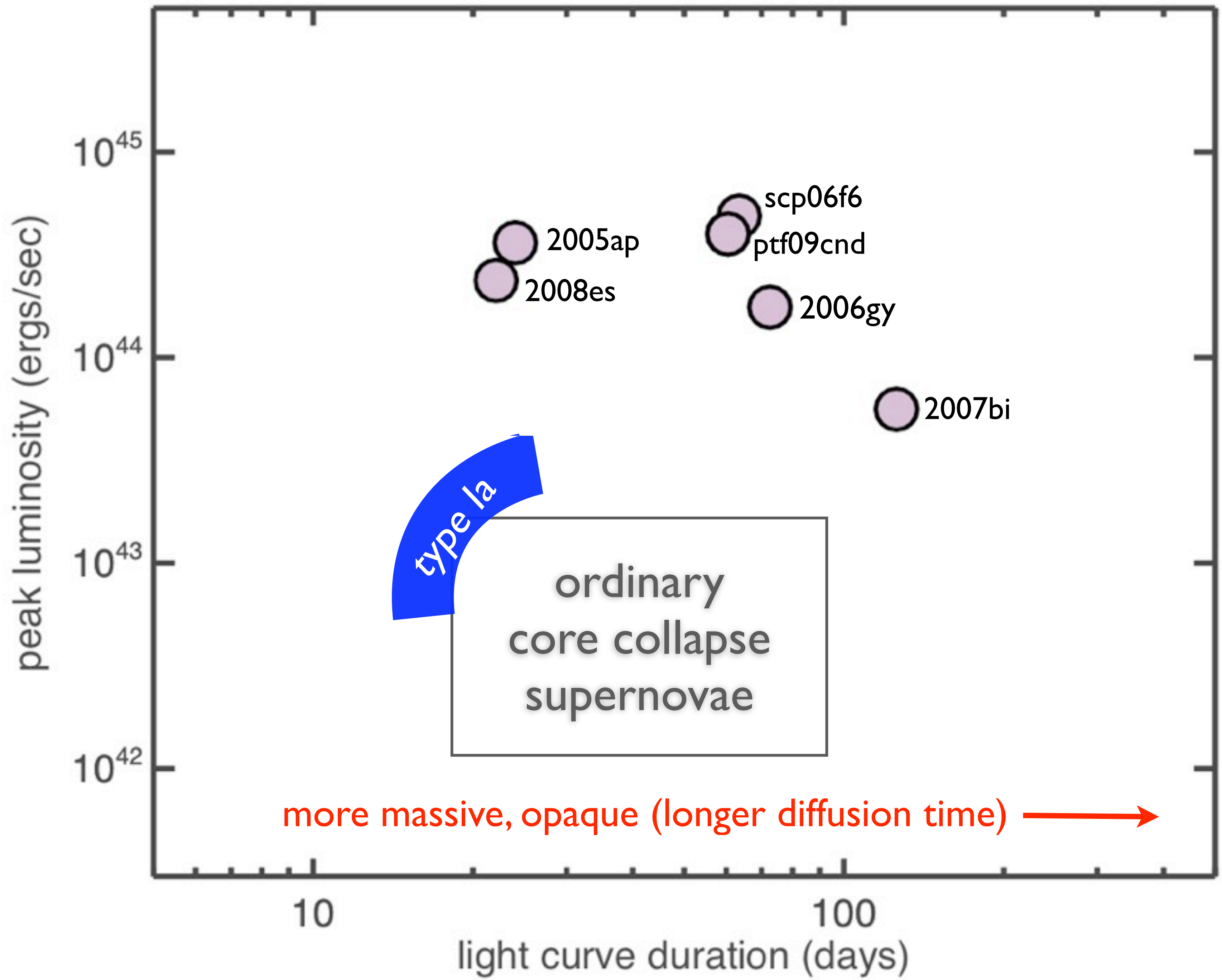

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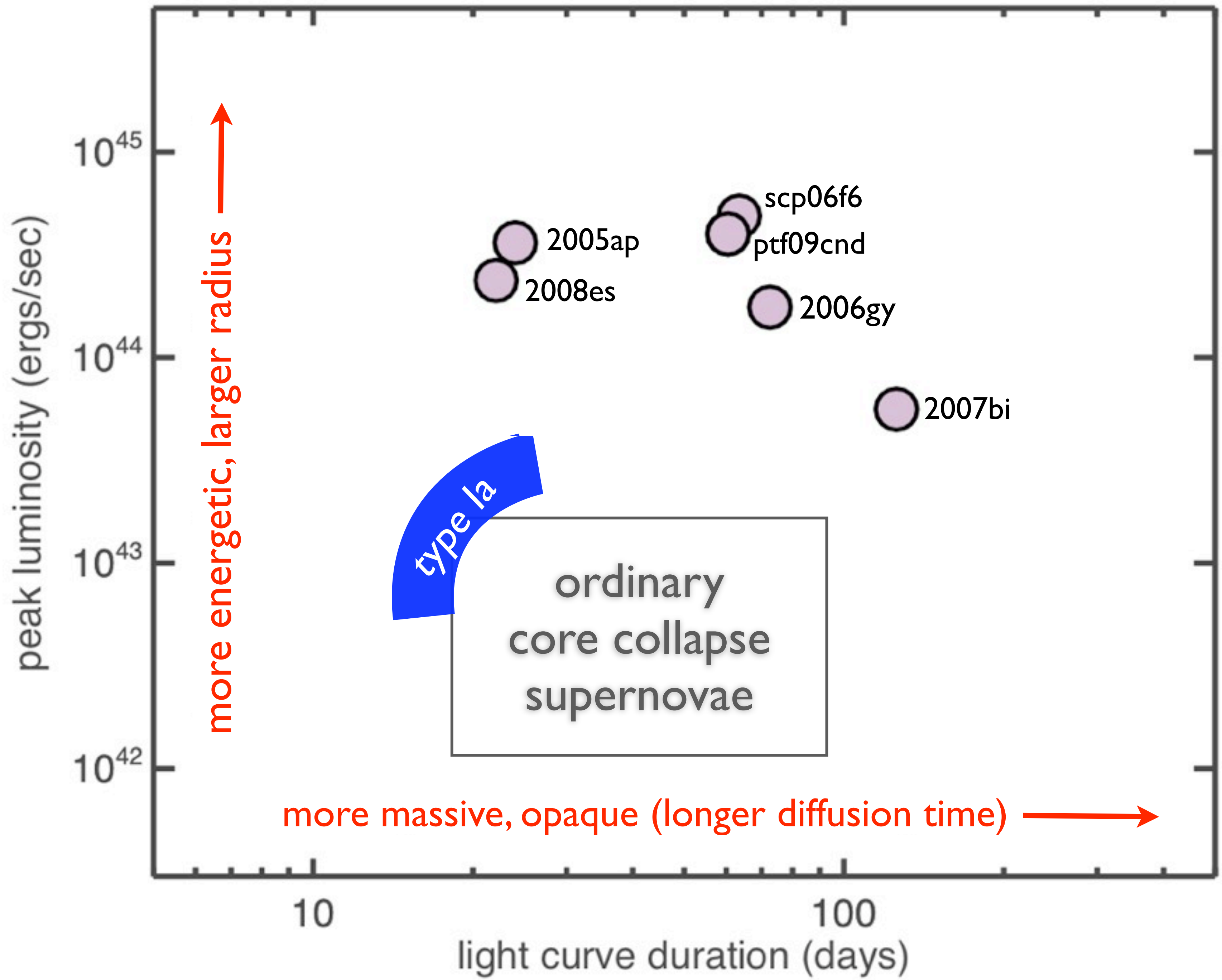

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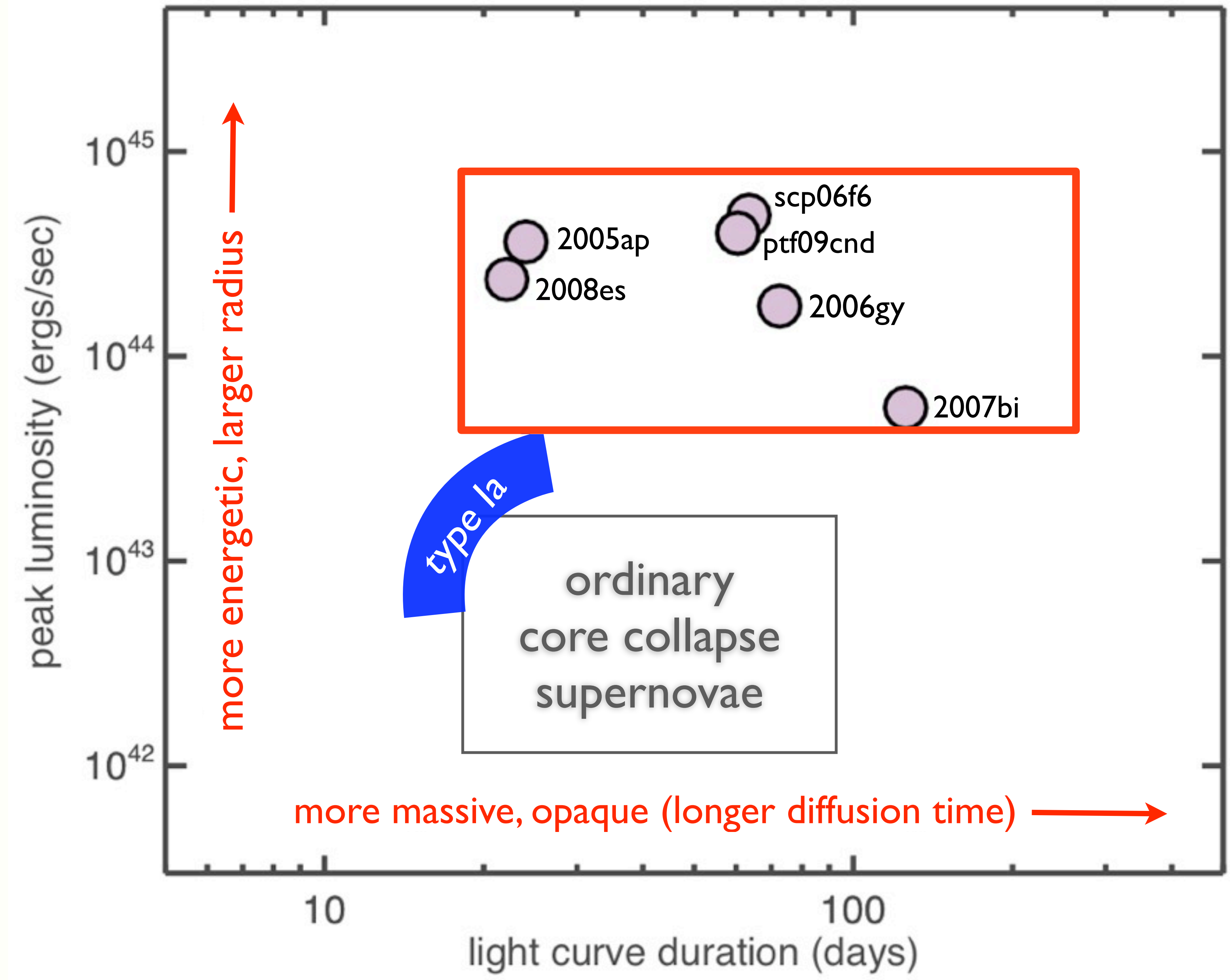

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The Death of Massive Stars

Woosley, Heger, & Weaver (2002)

(Talk by Wise)

MS Mass	He Core	Supernova Mechanism
$10 \leq M \leq 85$	$2 \leq M \leq 32$	Fe core collapse to a neutron star or black hole (GRB Talks: Aloy, Matsumoto, Mizuta) (CCSNe Talk by Suwa)
$80 \leq M \leq 150$	$35 \leq M \leq 60$	Pulsational pair instability followed by core (PPSN)
$150 \leq M \leq 250$	$60 \leq M \leq 133$	Pair instability supernova (PSN)
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Mass Unit: solar mass $\odot$

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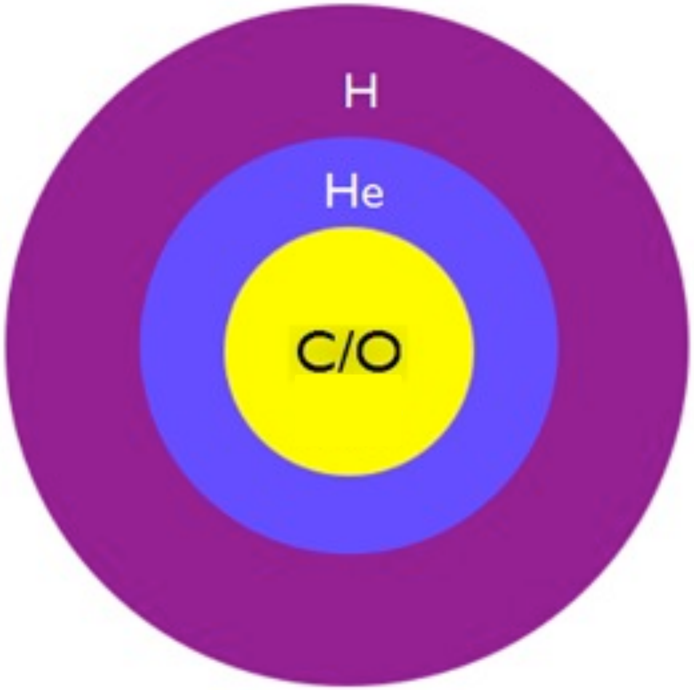
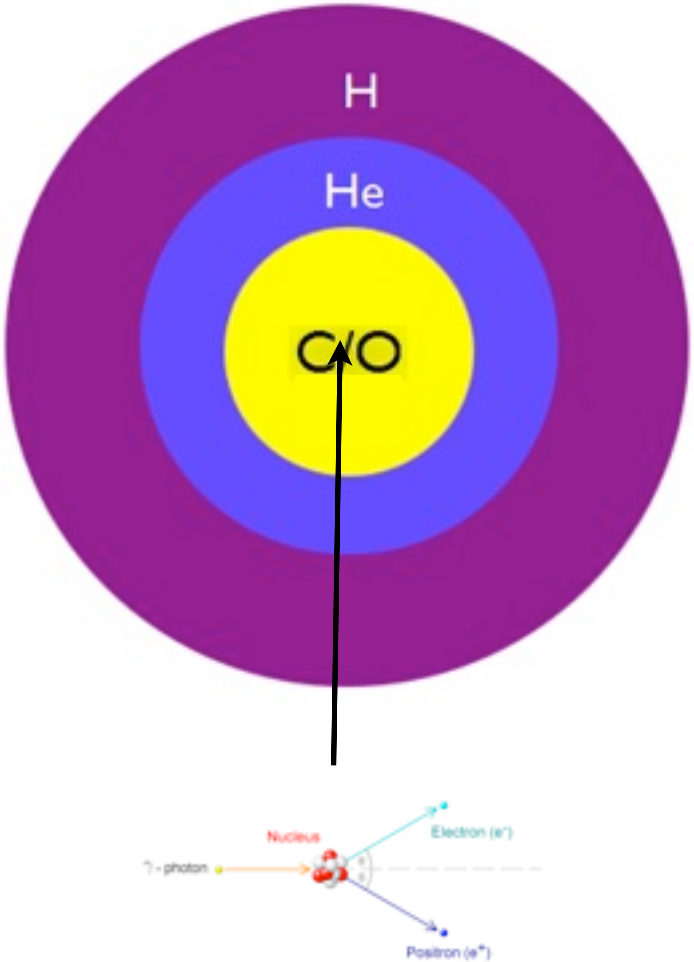
Physics of PPSN & PSN

Star > 80 M☉



Physics of PPSN & PSN

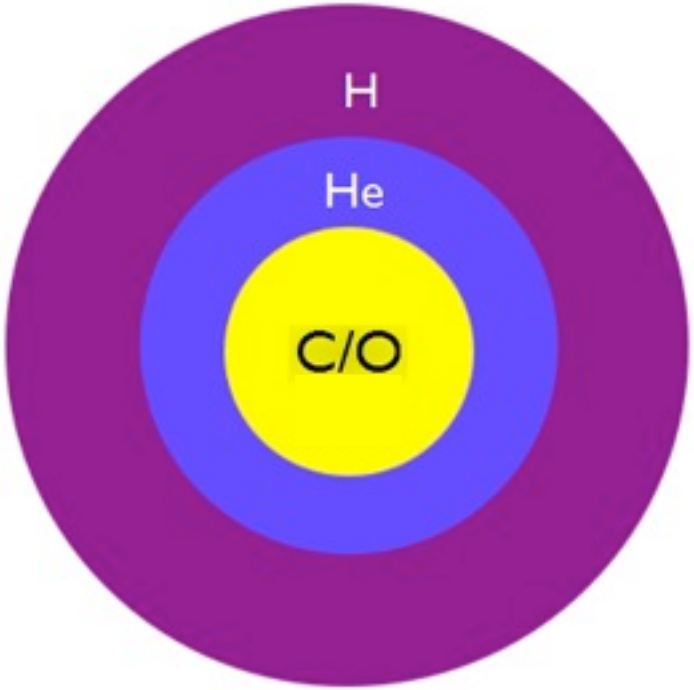
Star > 80 M☉



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

Physics of PPSN & PSN

Star > 80 M☉



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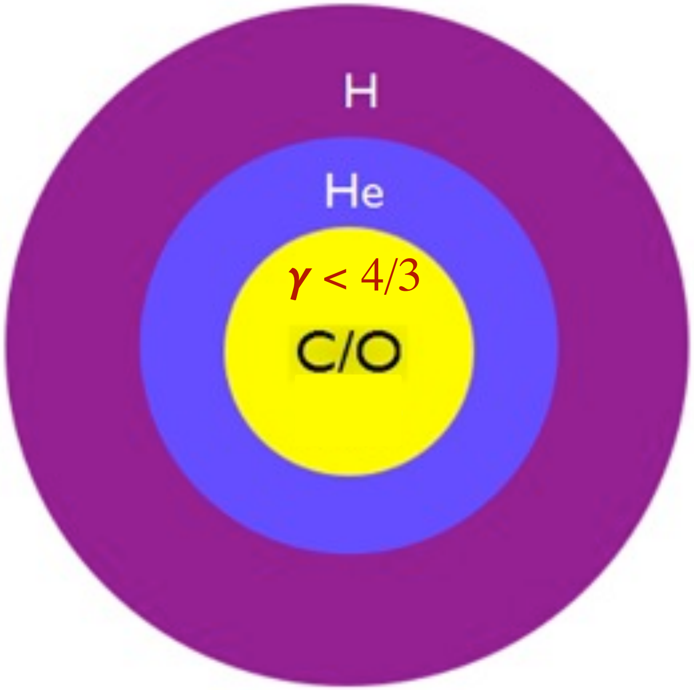

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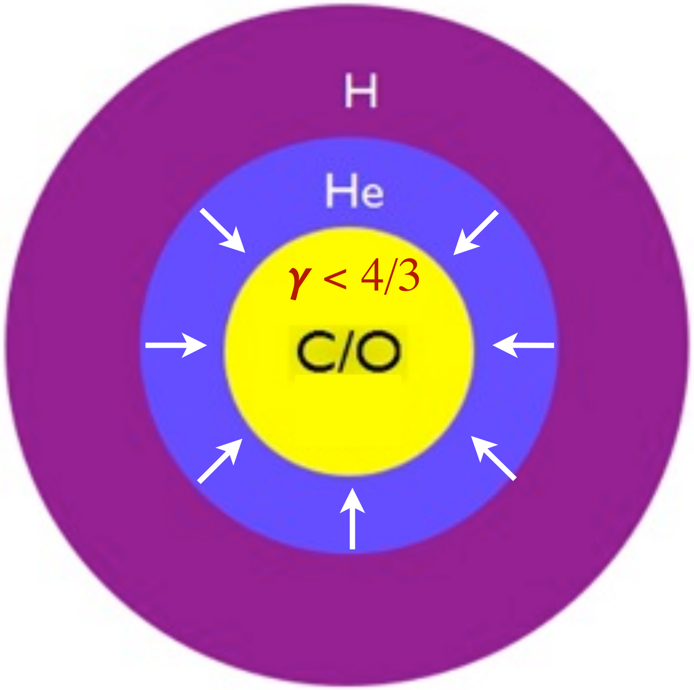
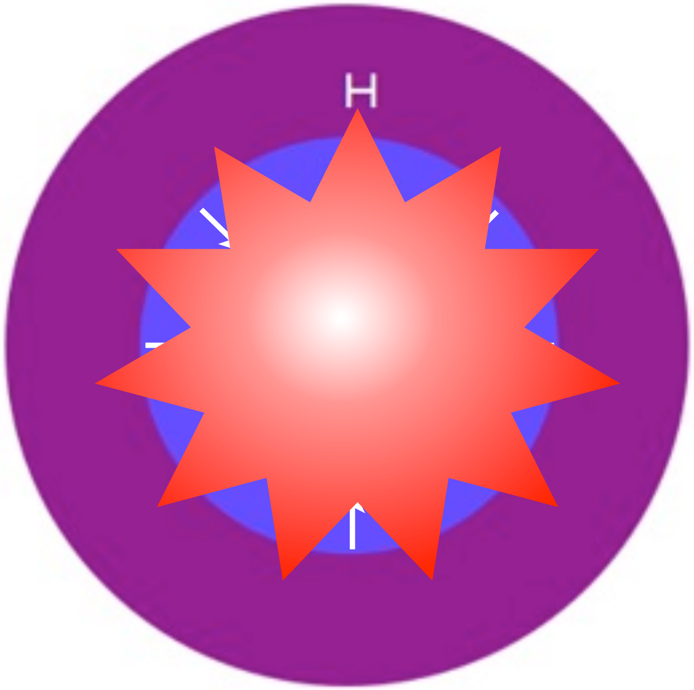


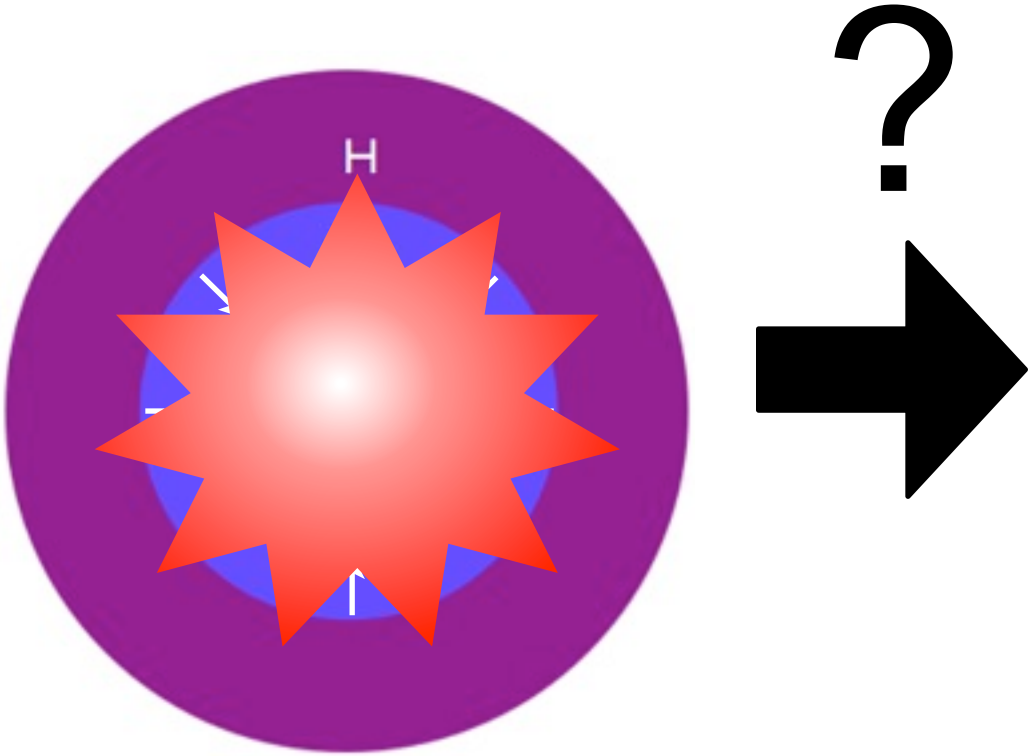
Physics of PPSN & PSN

Star > 80 M⊙



Physics of PPSN & PSN

Star > 80 M$_\odot$



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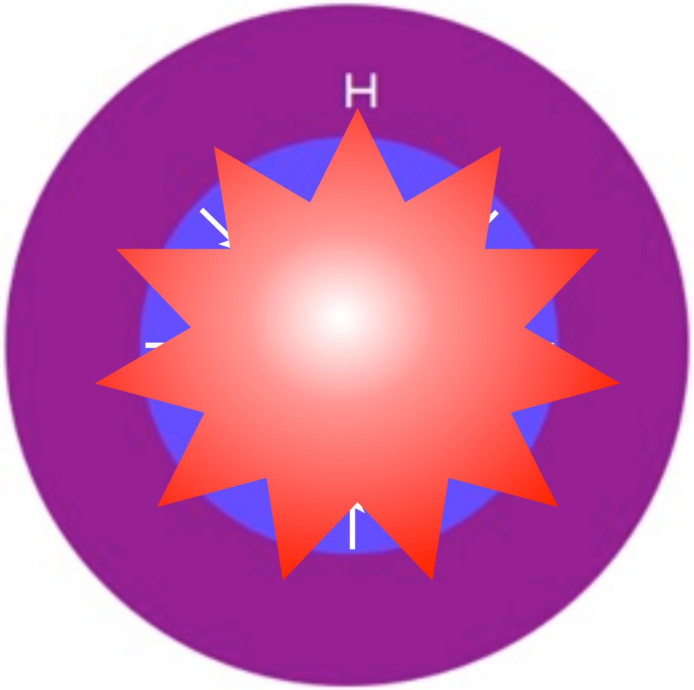
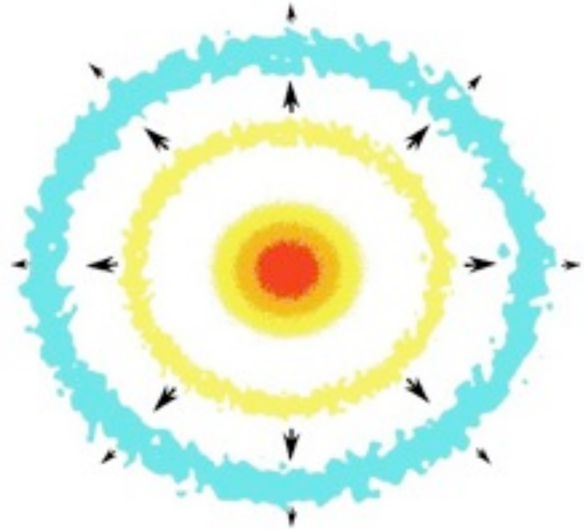


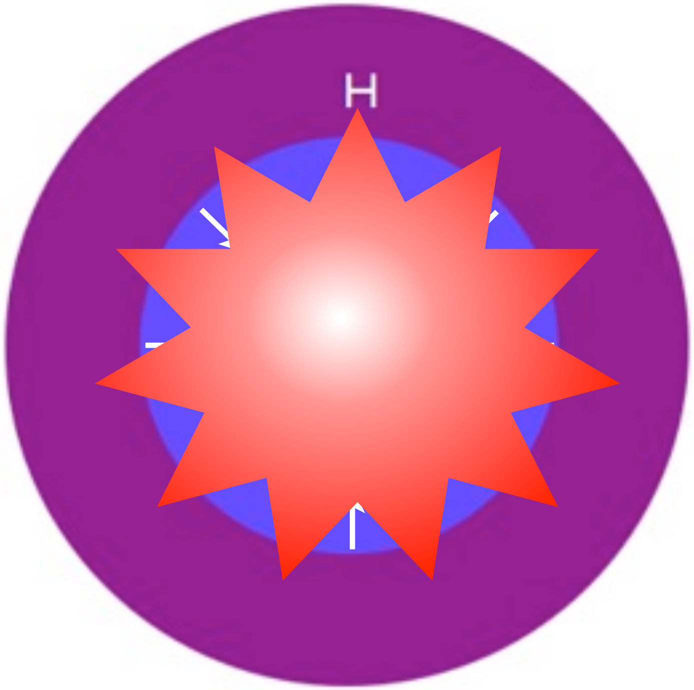
?



150 M⊙ > Star > 80 M⊙

Physics of PPSN & PSN

Star > 80 $M_\odot$



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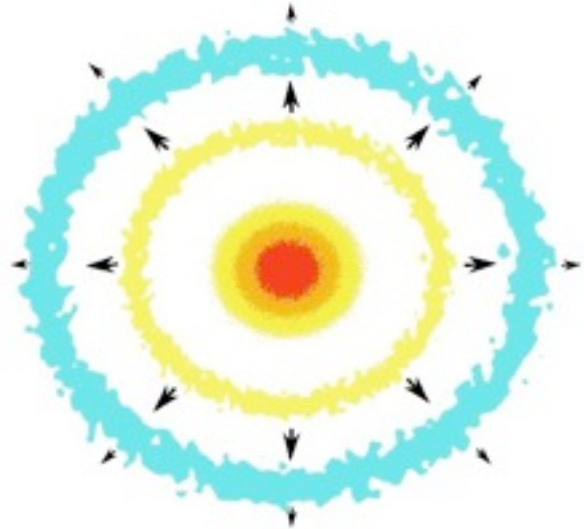
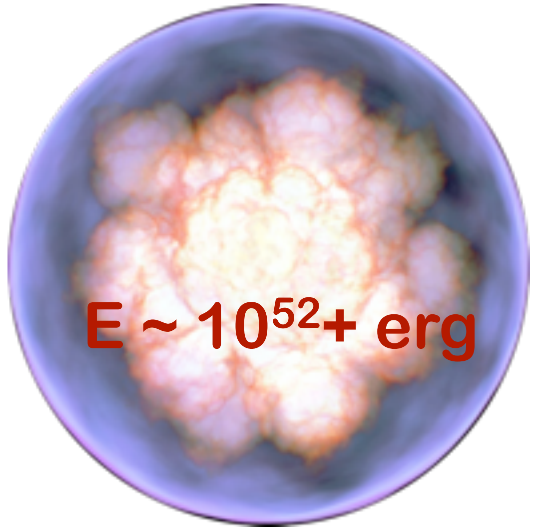


150 $M_\odot$ > Star > 80 $M_\odot$



250 $M_\odot$ > Star > 150 $M_\odot$

How to Blow Up Multi-D Stars ?

1D Models

80 - 150 M⊙ Stars (Woosley+ 2007, priv. comm.)
150 - 250 M⊙ Stars (Heger & Woosley 2002, 2010)

CASTRO (DOE SciDAC Computational Astrophysics Team)

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

Supercomputers

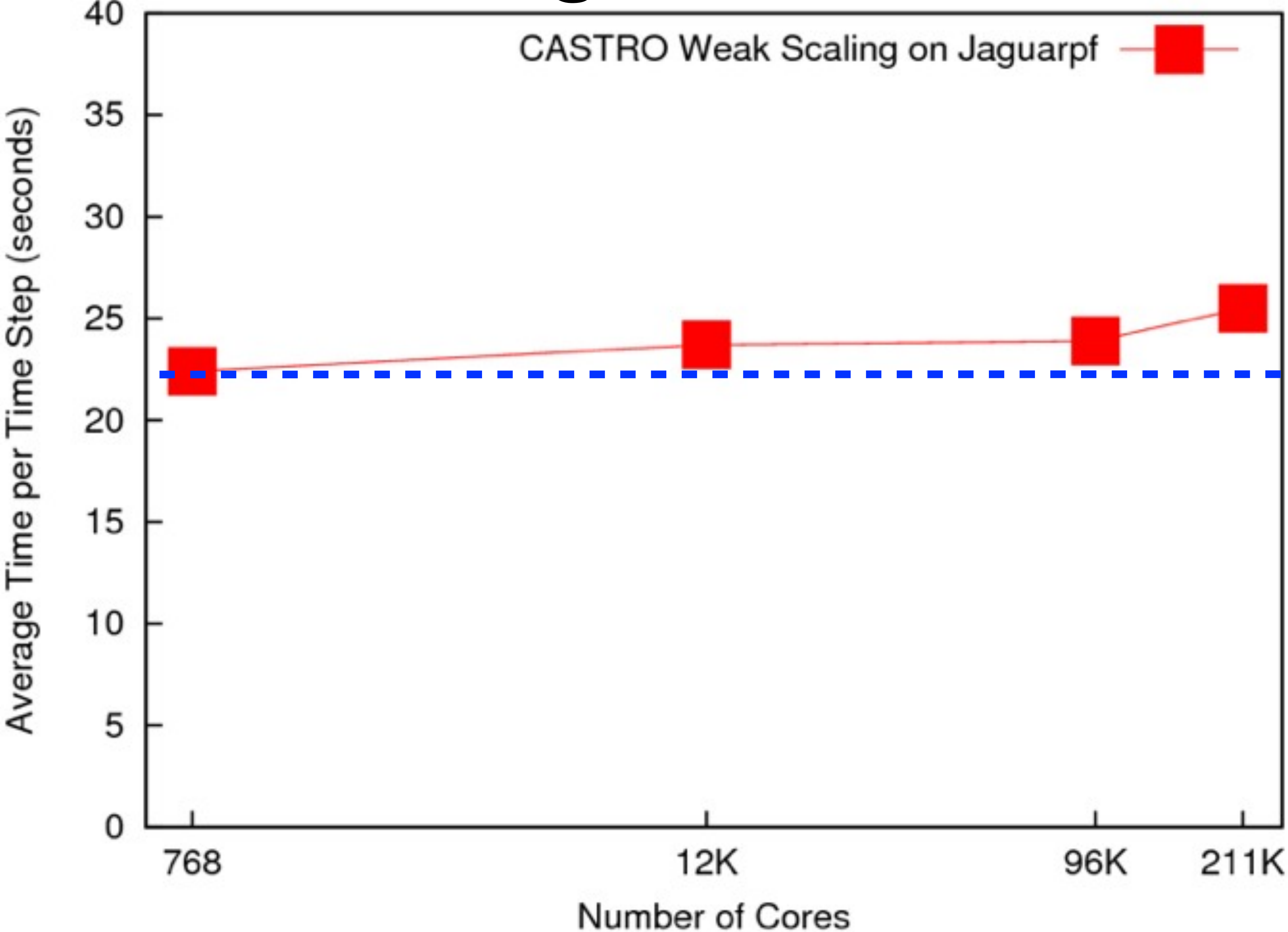
Itasca

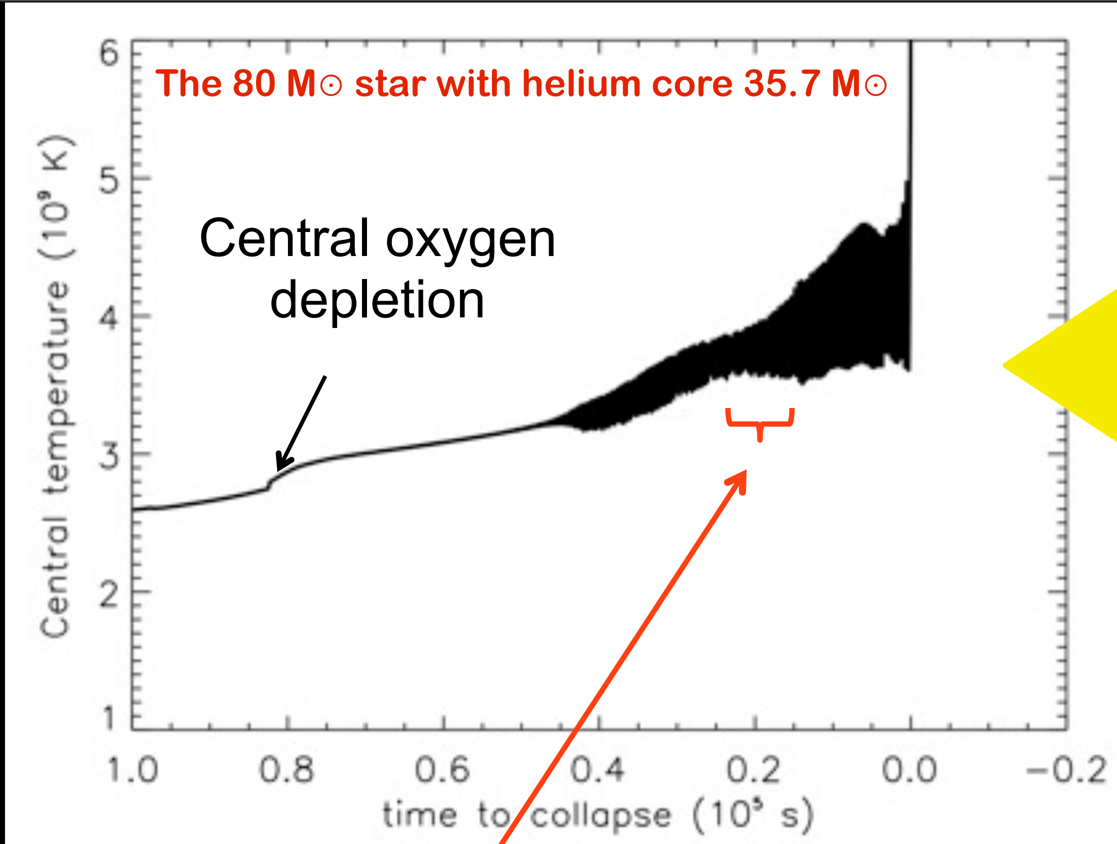
Franklin

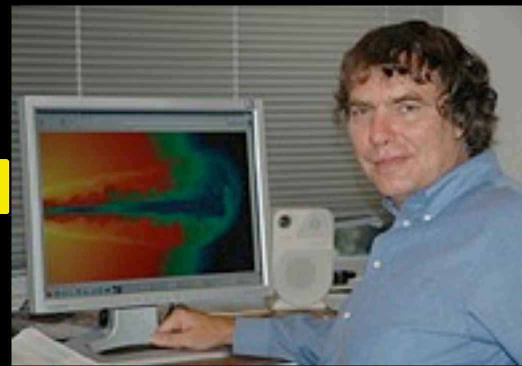
Hopper

Jaguar

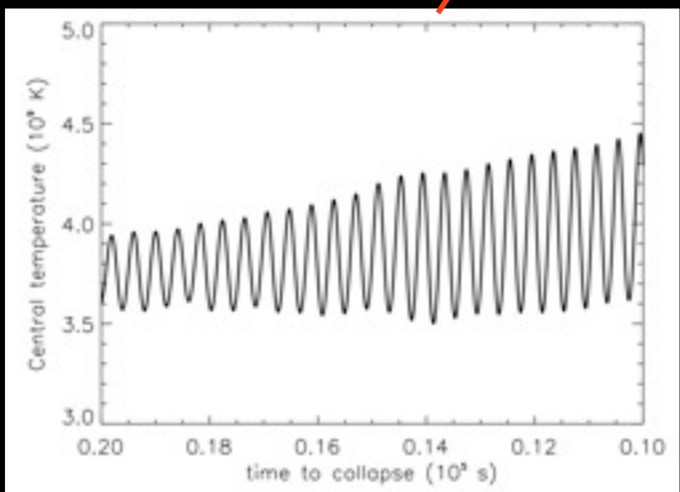
Scaling Performance





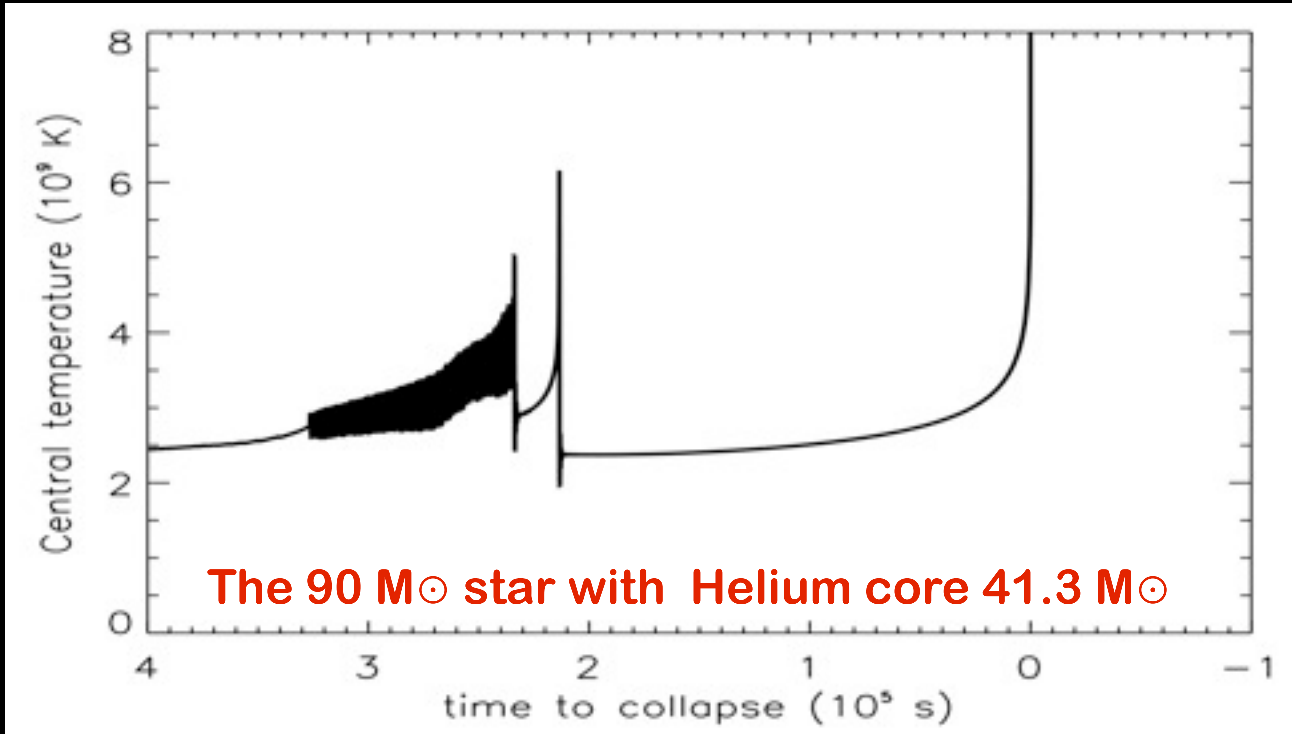


Based on Woosley's Models



Pulses occur on a hydrodynamic time scale for the helium and heavy element core (~500 s).

For this mass, there are no especially violent single pulses before the star collapses.



Pulses commence again after central oxygen depletion, but become more violent. Two strong pulses send shock waves into the envelope. Two days later the iron core collapses.

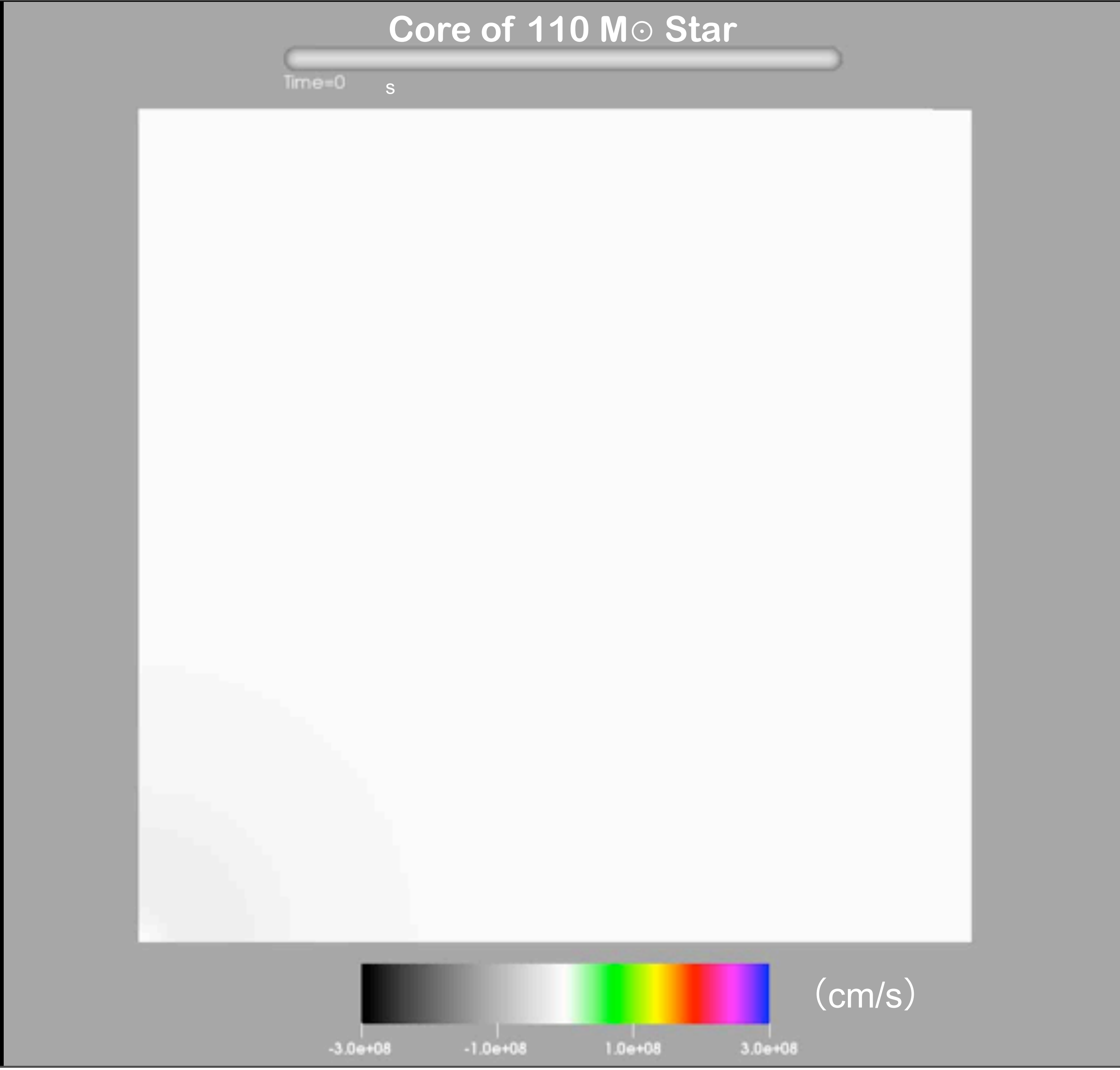
90+ M⊙

The pulses become more violent and the intervals between them longer. Multiple supernovae occur but usually just one of them is very bright.

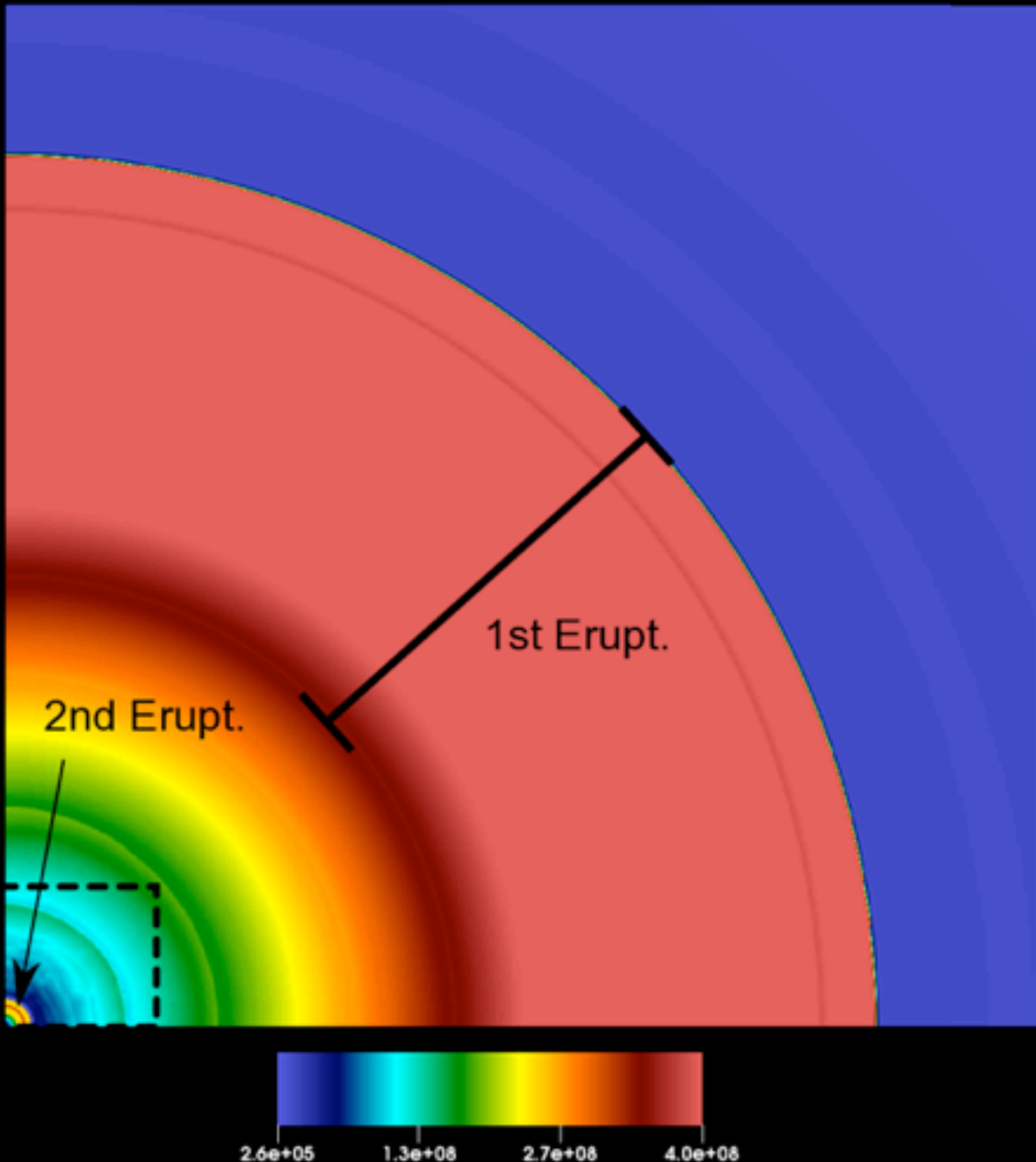
Core of 110 $M_{\odot}$ Star

s

(cm/s)


Core of 110 M⊙ Star
Time=0 s
-3.0e+08
-1.0e+08
1.0e+08
3.0e+08
(cm/s)

Velocity [cm/s]   1e14 cm x1e14 cm



Physical Properties of Colliding Shells

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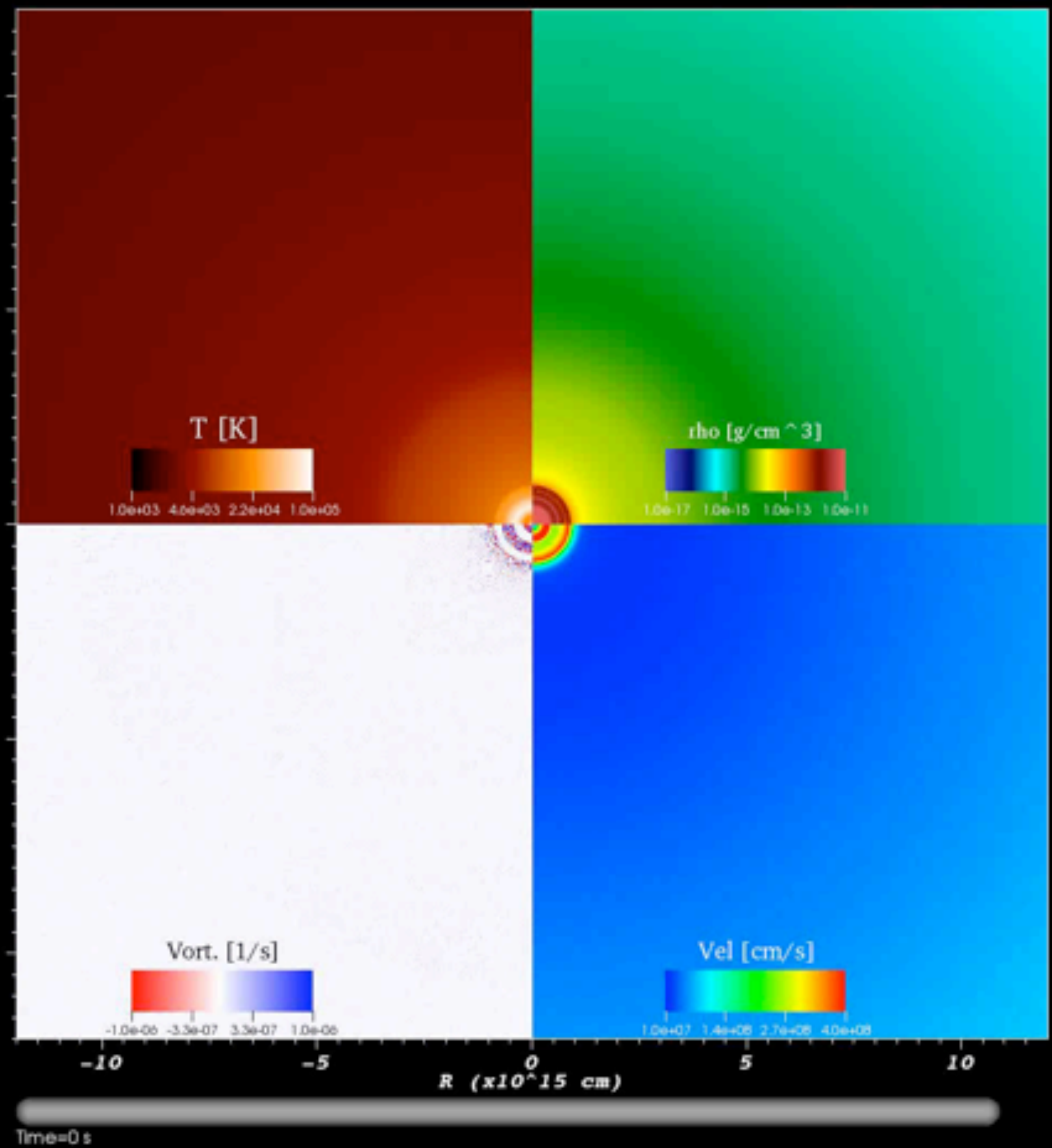
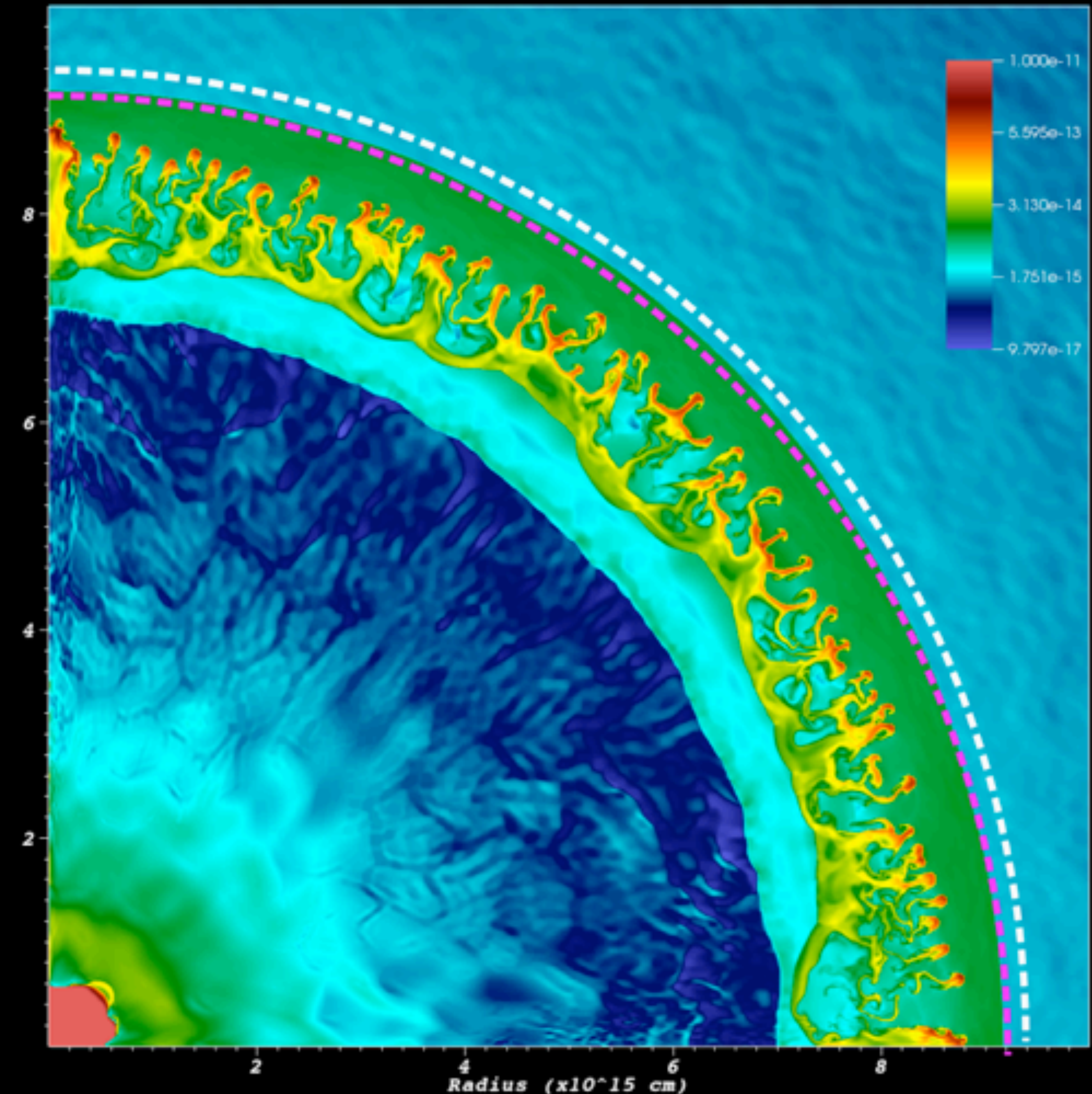
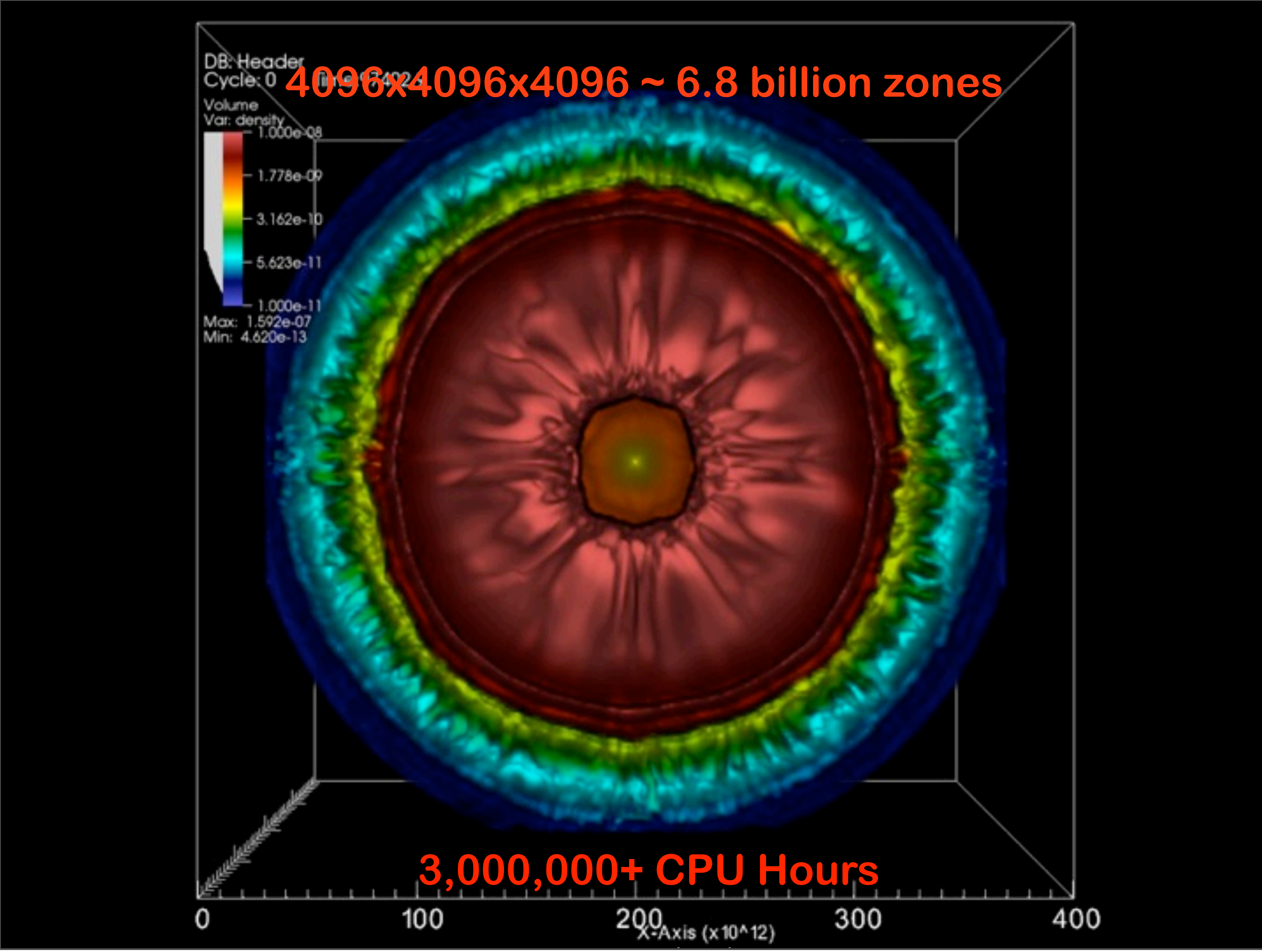




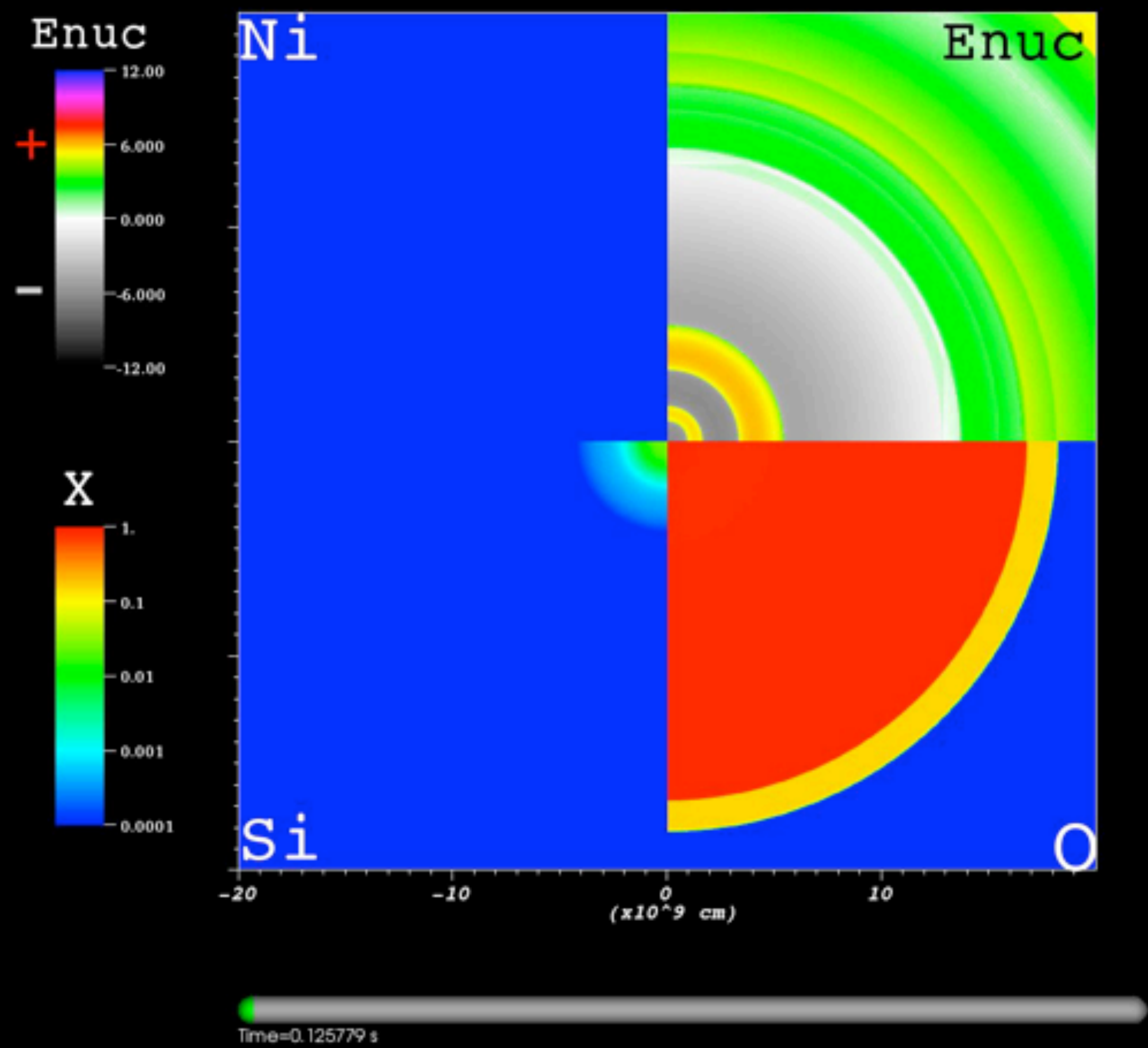
1.000e-11
5.595e-13
3.130e-14
1.751e-15
9.797e-17
8
6
4
2
2
4
6
8
Radius (x10^15 cm)

Chen + in prep


4096x4096x4096 ~ 6.8 billion zones
3,000,000+ CPU Hours
DB: Header
Cycle: 0
Volume
Var: density
1.000e-08
1.778e-09
3.162e-10
5.623e-11
1.000e-11
Max: 1.592e-07
Min: 4.620e-13
0
100
200
300
400
X-Axis (x10^12)

Explosive Burning of 150 M☉ Star

Explosive Burning of 150 M⊙ Star



Core of 150 M⊙ Star

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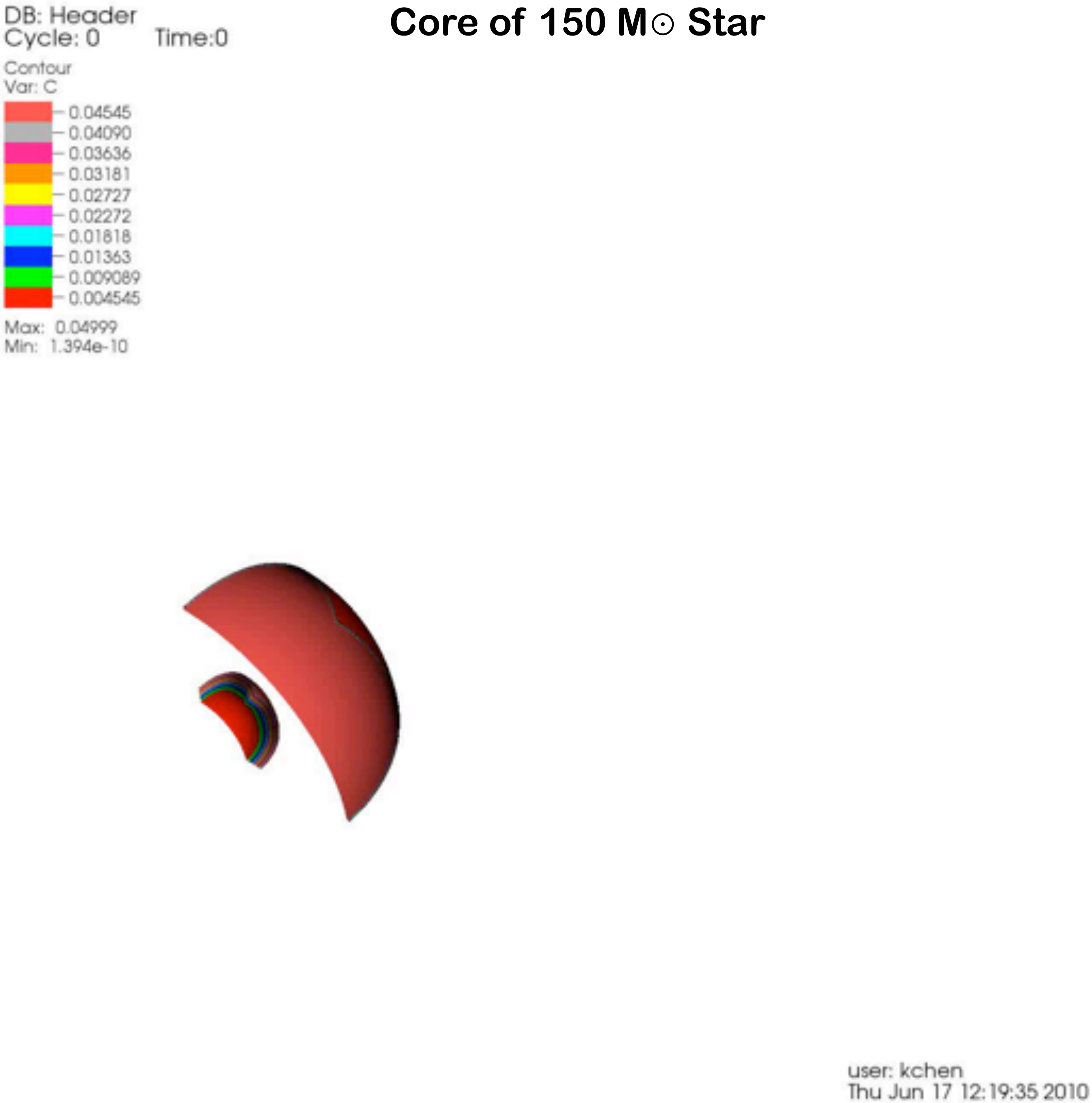

Exploding 200 M⊙ Star (2007 bi)

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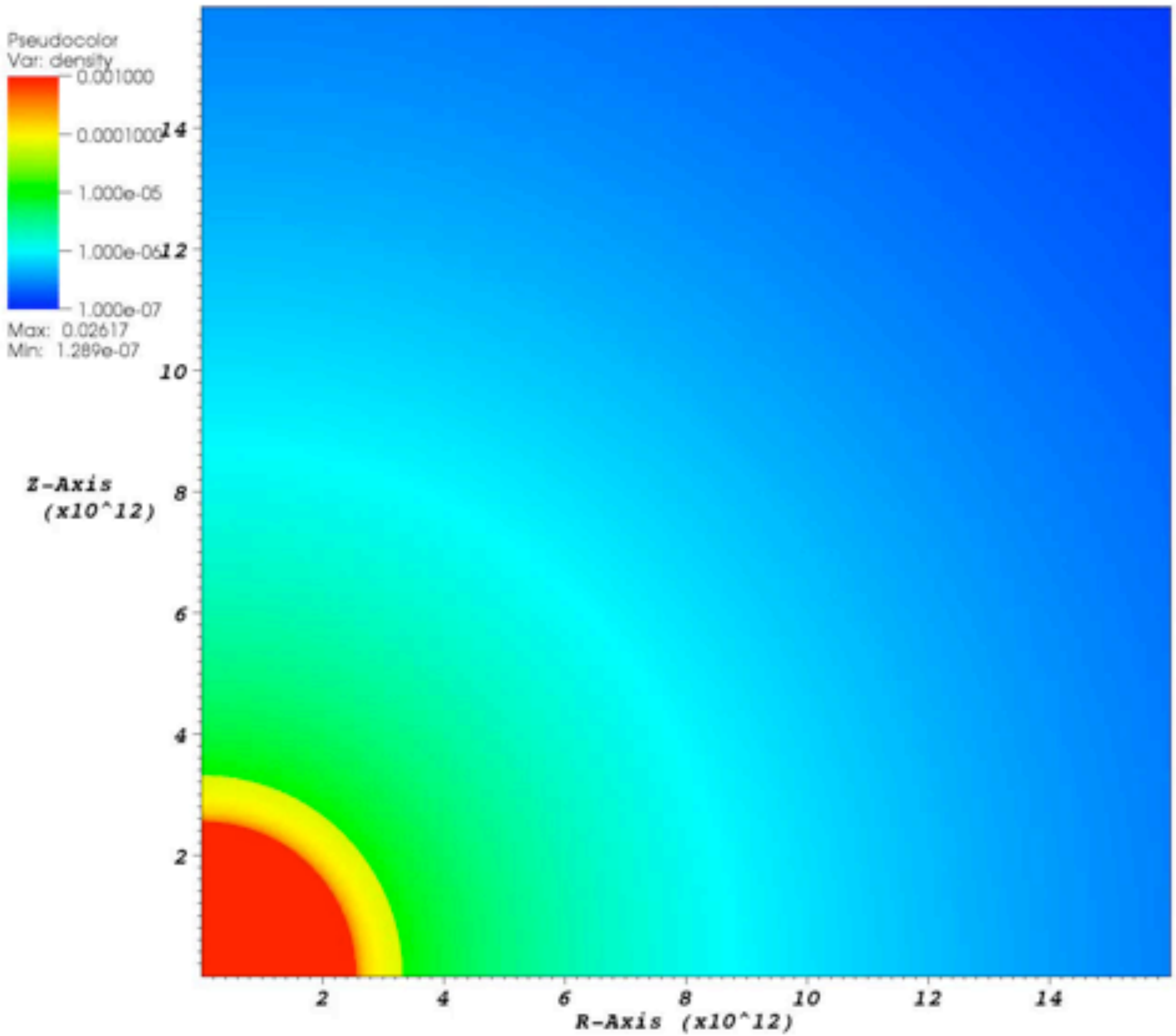
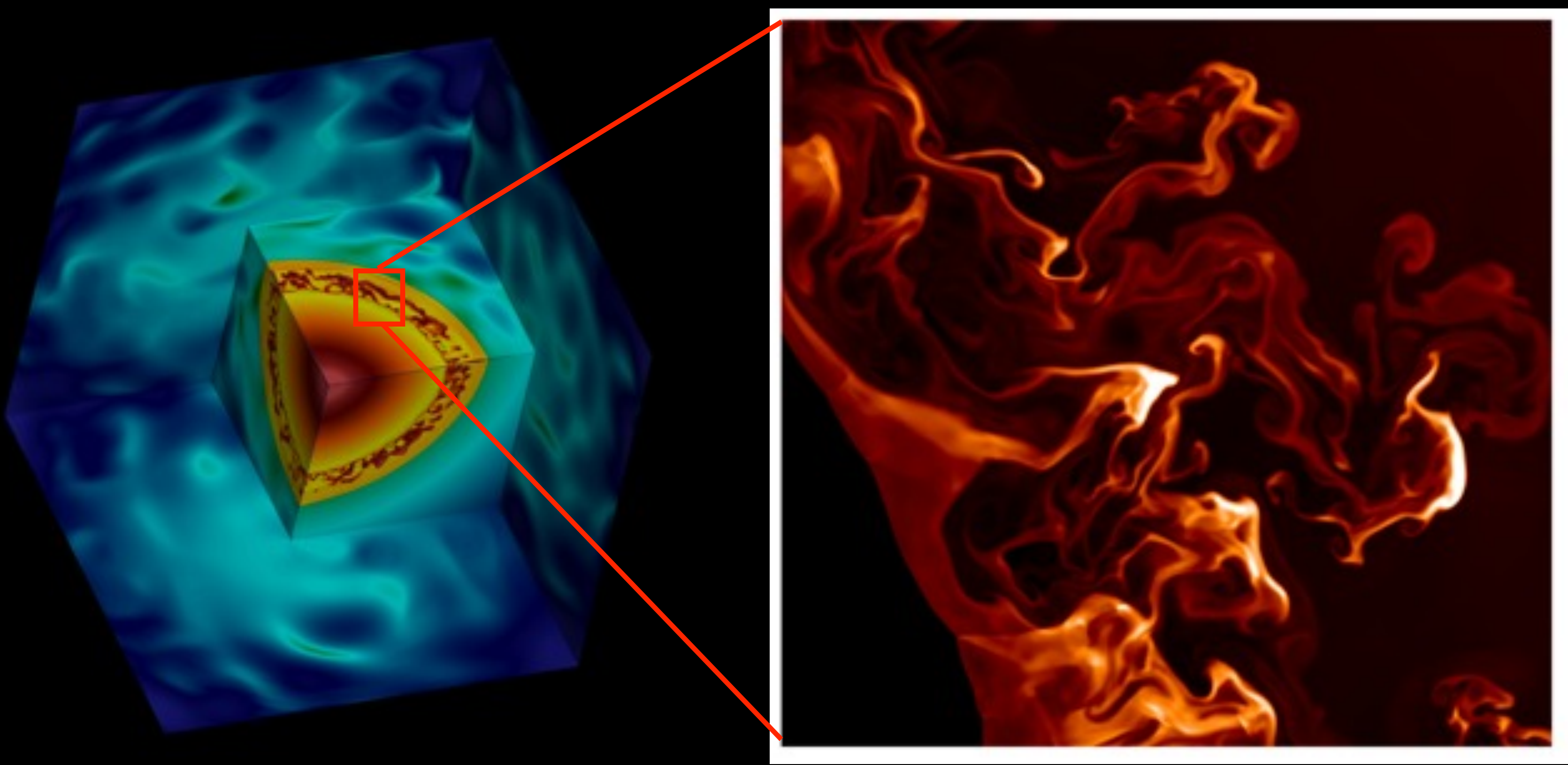
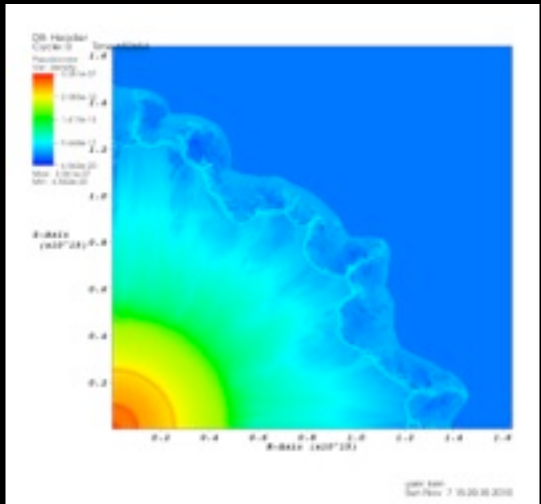


Mixing

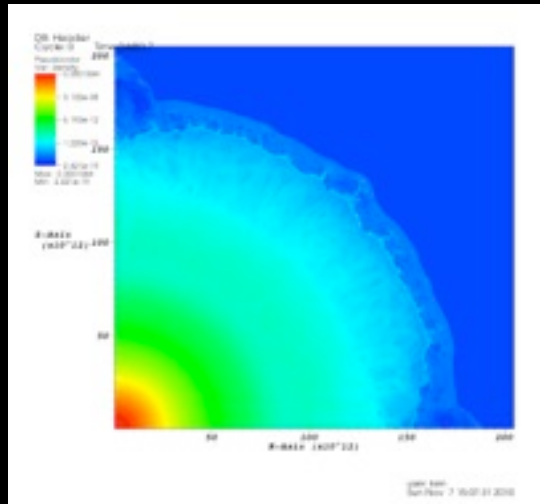


More Explosions !

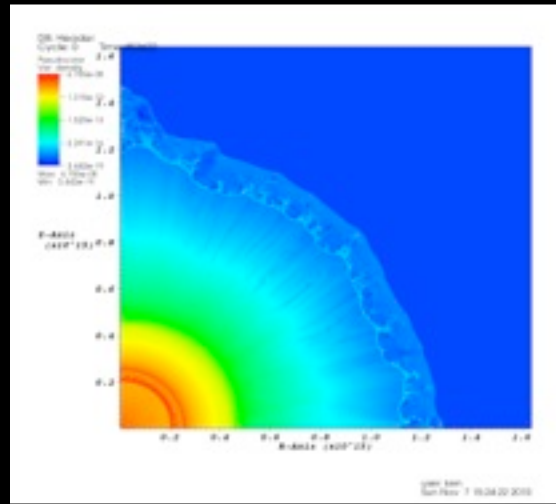
(Chen+ in prep)



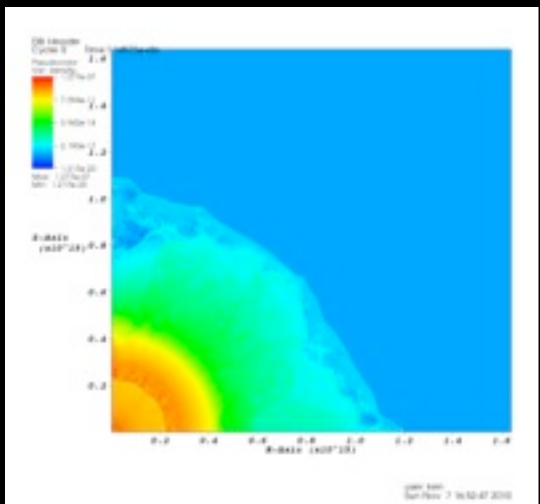
BSG 150



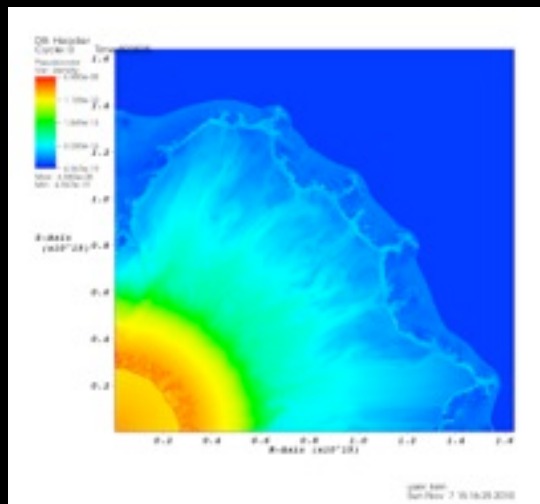
BSG 200



BSG 250



RSG 150

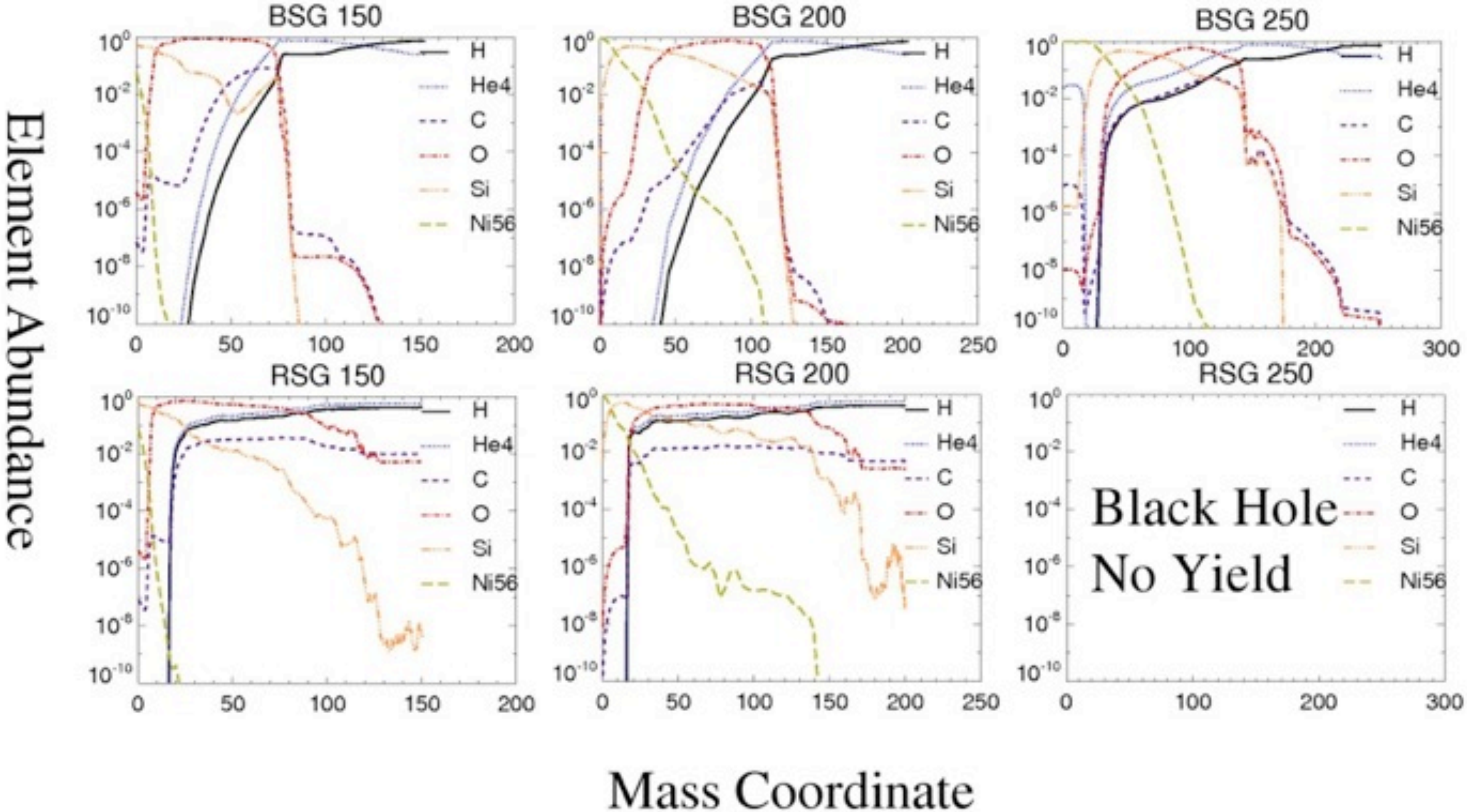


RSG 200

No Bang !!
form a black hole

RSG 250

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

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Ni is only slightly mixed out .

The Gamma-Ray emission for PSNe is unlikely.

Conclusion

	Fate	Very Bright	Sources	Observation
80 ~ 150 **M**☉				
150 ~ 250 **M**☉				
250+ **M**☉				

Conclusion

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80 ~ 150 $M_\odot$	PPSN			
150 ~ 250 $M_\odot$	PSN			
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80 ~ 150 **M**$\odot$	PPSN	YES	Pop I, II, III	Multi-SN
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The first stars are promising candidates
(Abel+ 2002, Bromm+ 2009)

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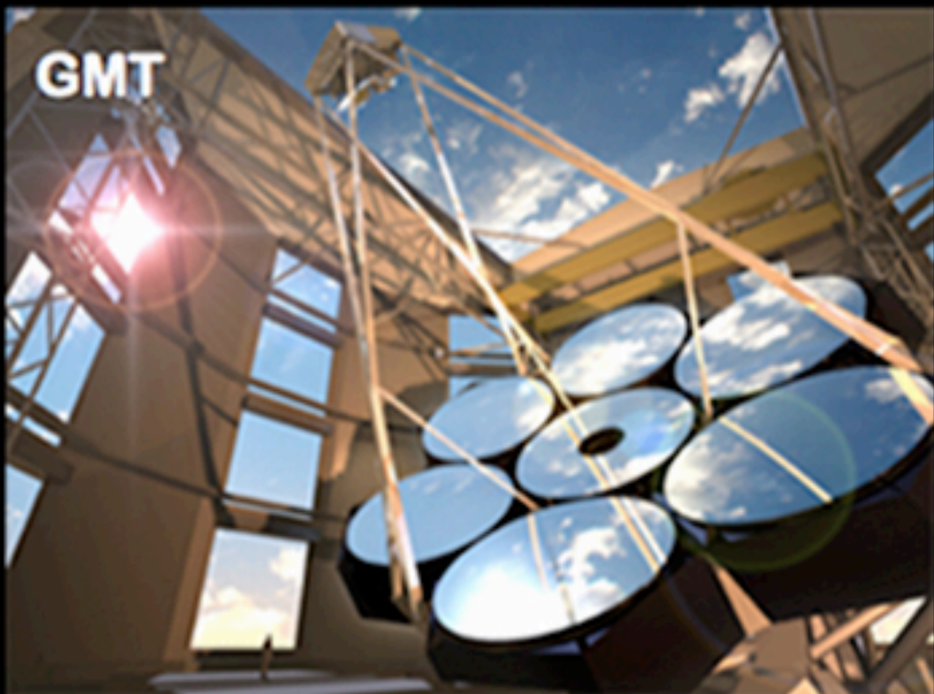
(Abel+ 2002, Bromm+ 2009)

Mixing can be important !


TMT

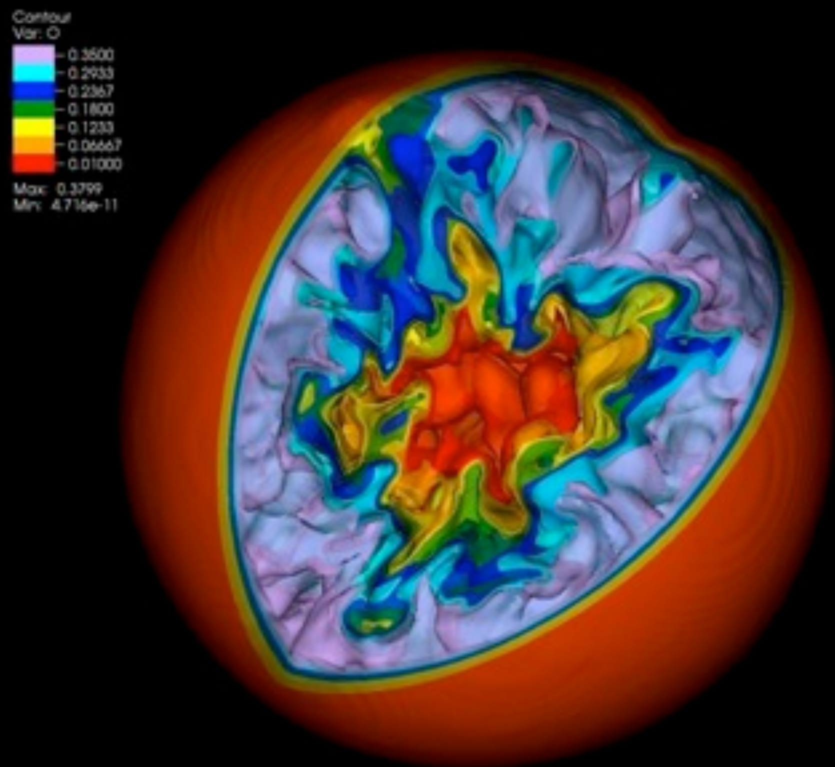

LSST


GMT


JWST

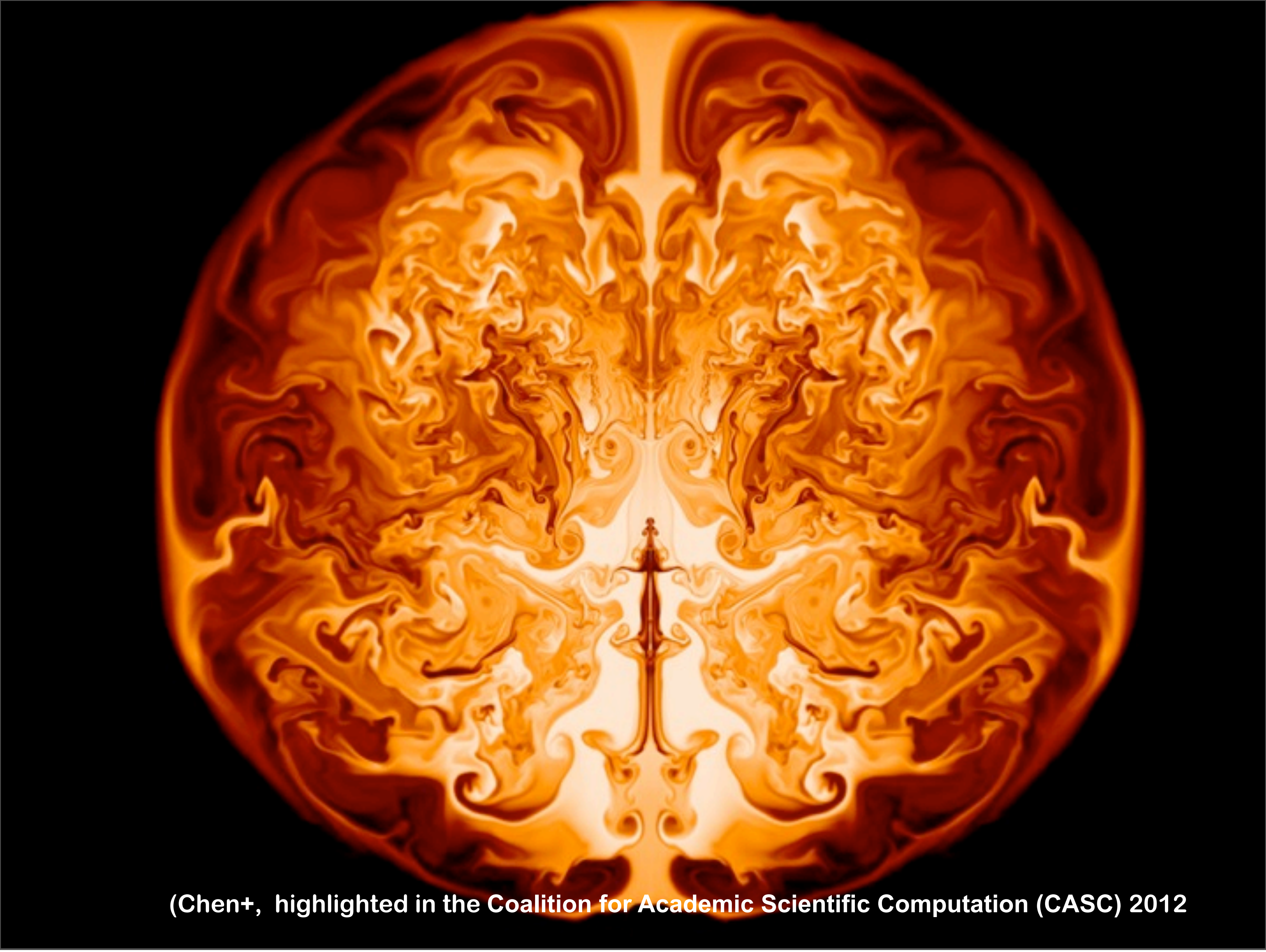
Super Explosions !!

Stars > 1,000M⊙ may not die as black holes



An Explosion of 55,000 M⊙ Star

(Heger, & Chen+ in prep., Whalen, Heger, & Chen+ to be submitted)


(Chen+, highlighted in the Coalition for Academic Scientific Computation (CASC) 2012

Many thanks for your attention

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The Kavli Institute for Theoretical Physics
University of California, Santa Barbara

M

NERSC
National Energy Research Scientific Computing Center

Department of Energy · United States of America
SciDAC
Scientific Discovery through Advanced Computing

Office of Science
U.S. Department of Energy

NSF

AAS

APS physics

SIGMA XI
THE SCIENTIFIC RESEARCH SOCIETY