Supernovae From Very Massive Stars

Ke-Jung (Ken) Chen

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Massive Stars Meeting, Saint Paul, MN

Team Members

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UC Santa Cruz

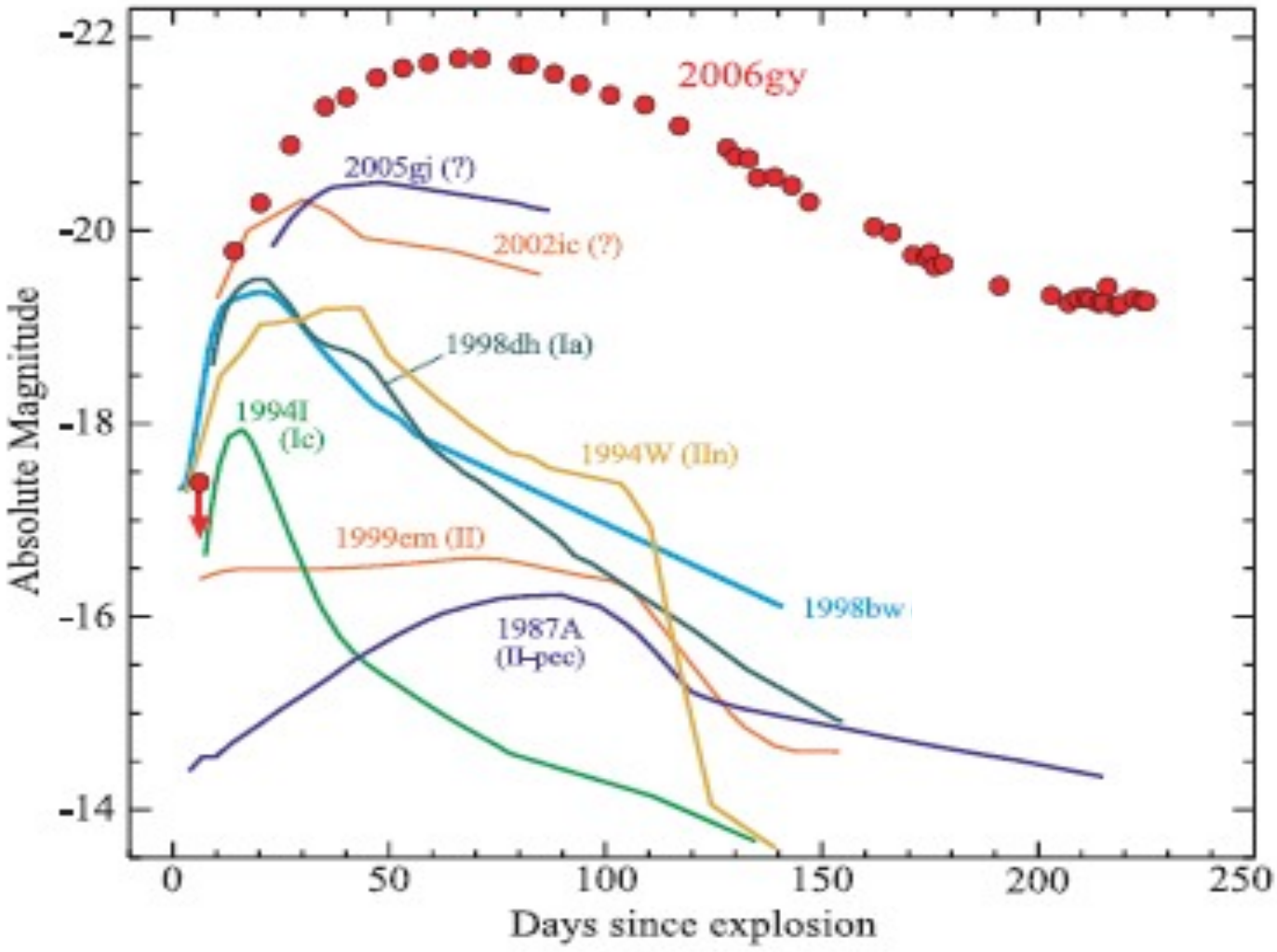
Volker Bromm
University of Texas

Ann Almgren
Lawrence Berkeley National Lab

Daniel Kasen
UC Berkeley

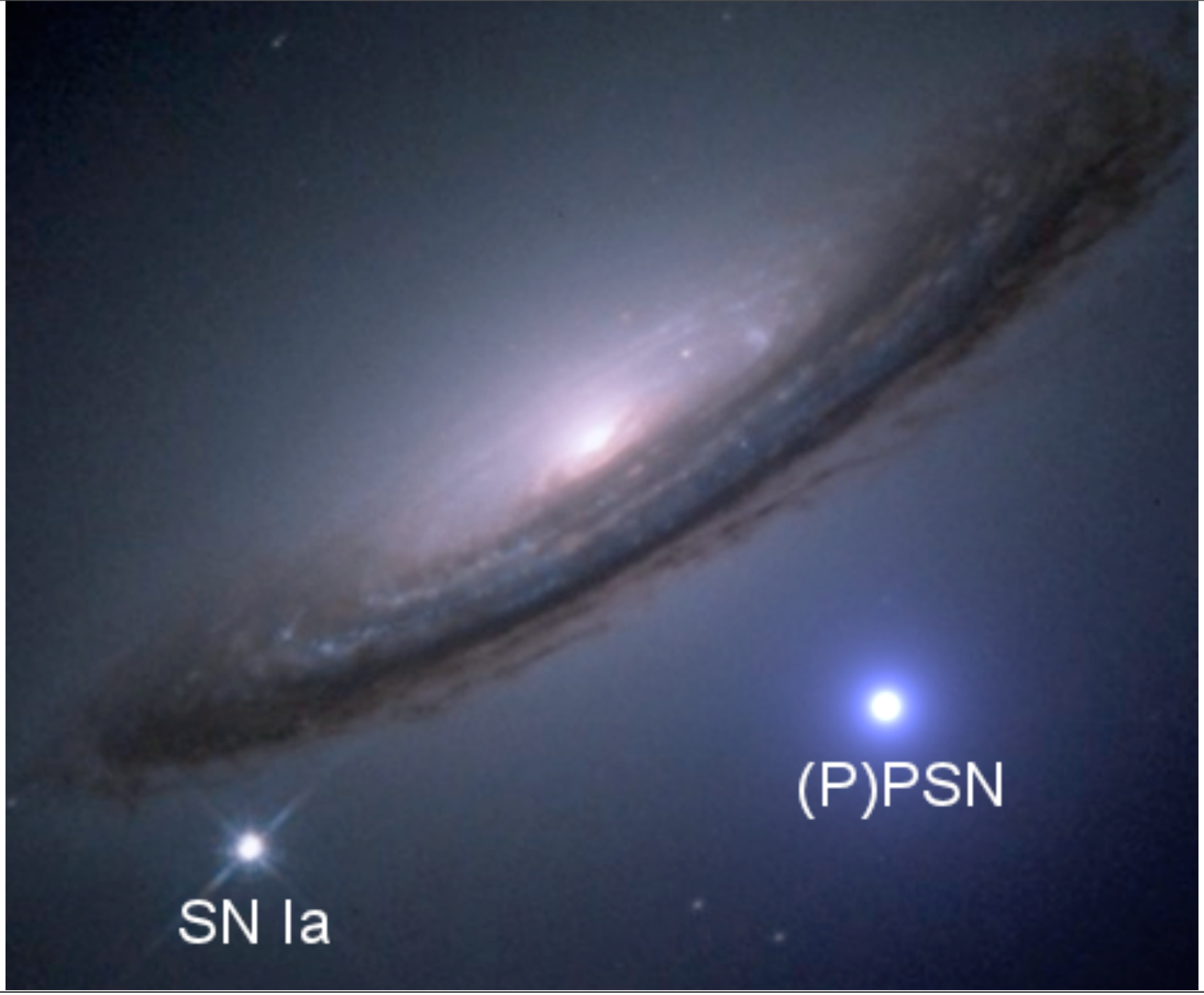
Weiqun Zhang
Lawrence Berkeley National Lab

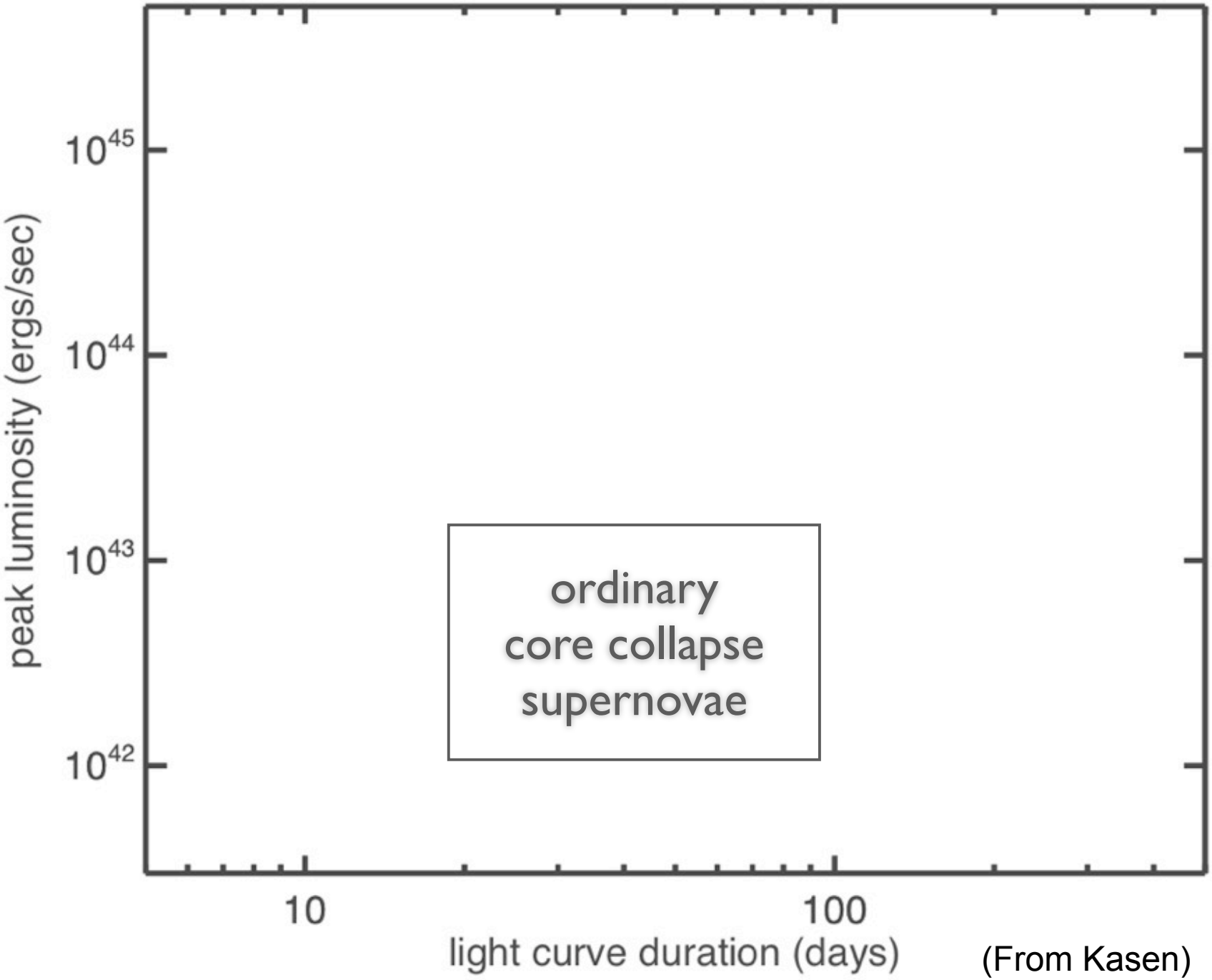
Super Luminous SNe



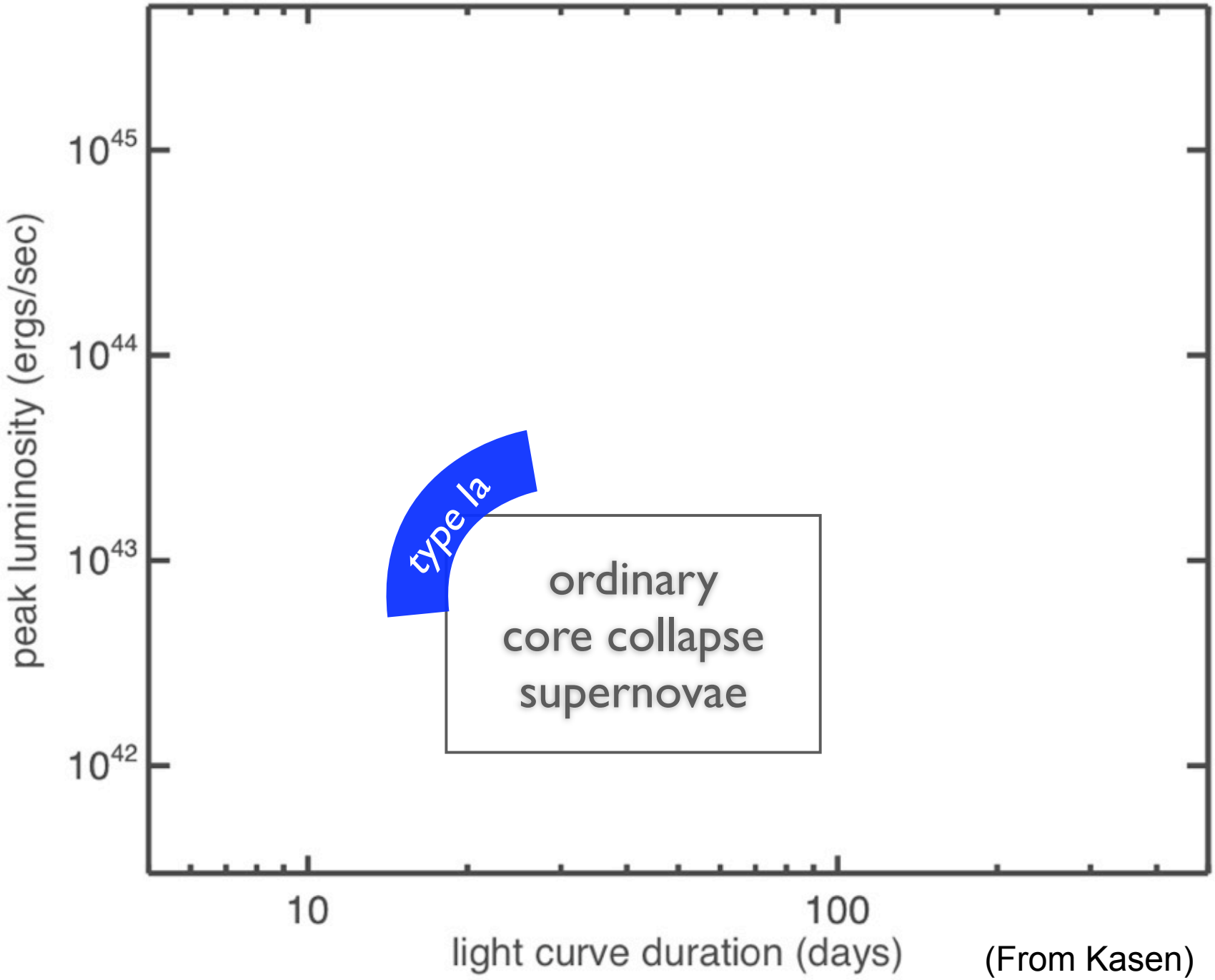
Smith+ 2007

Talk : Smith Posters : Quimby, Moriya


(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)

(From Kasen)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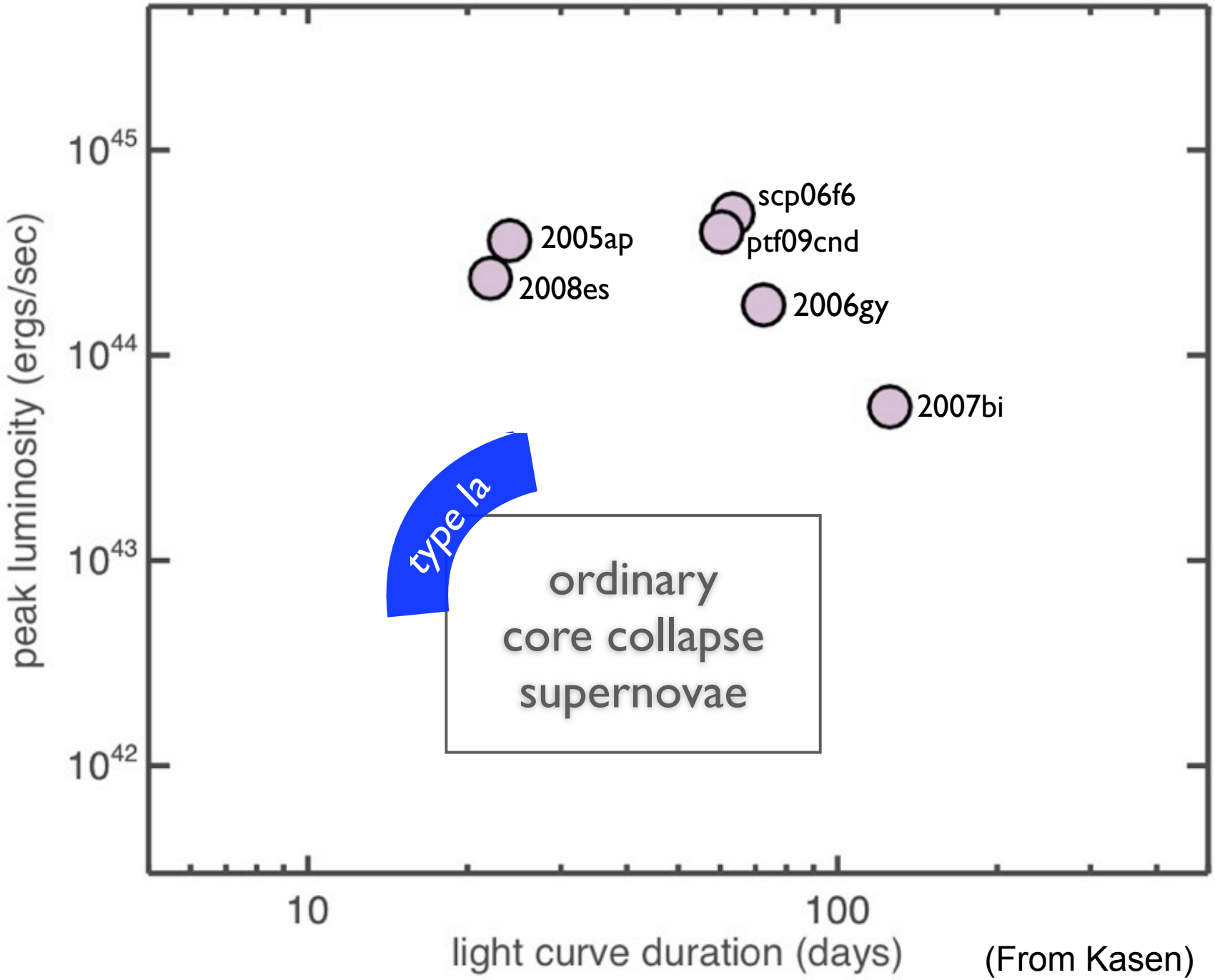
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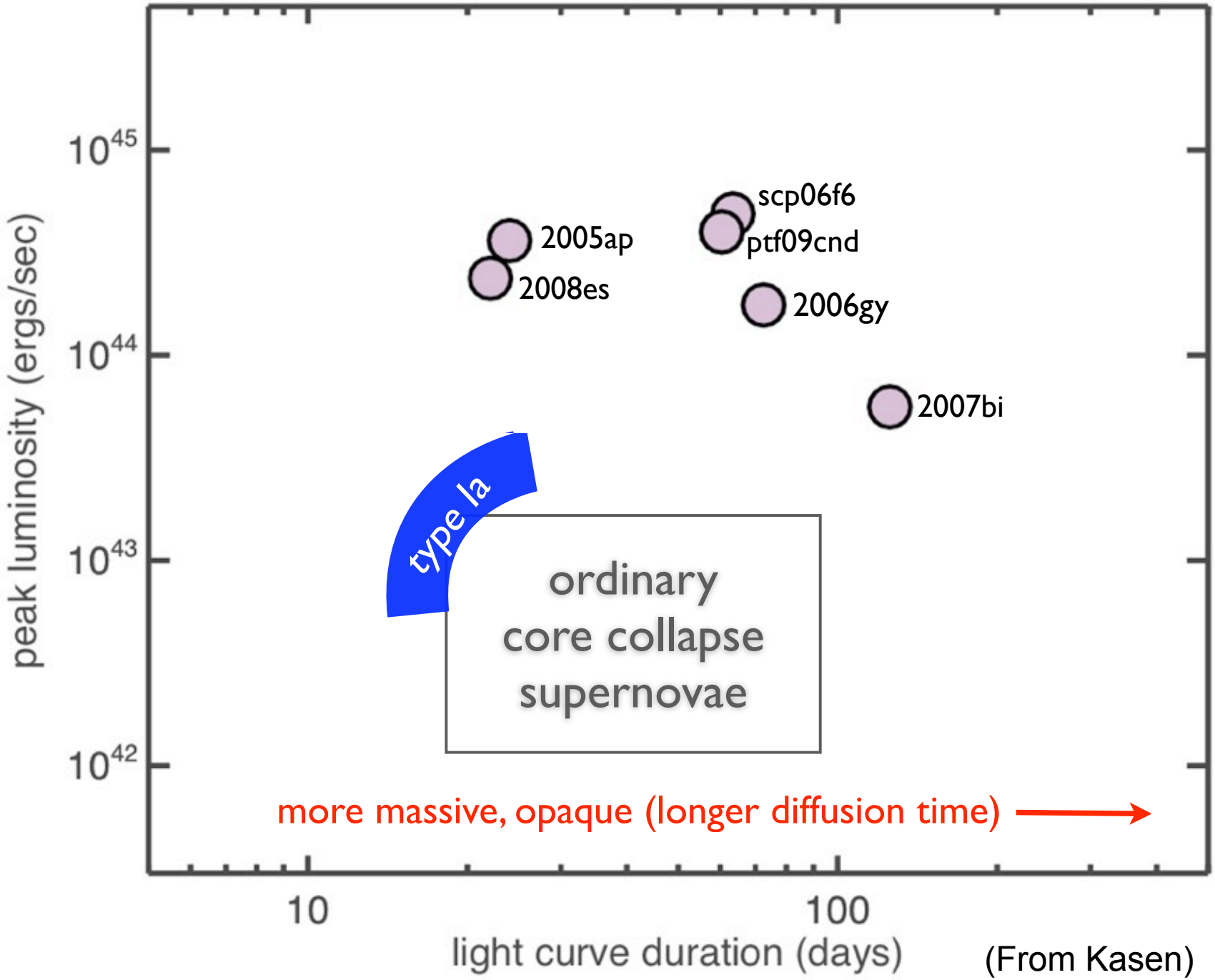
scp06f6
ptf09cnd
2005ap
2008es
2006gy
2007bi
type Ia
ordinary
core collapse
supernovae

(From Kasen)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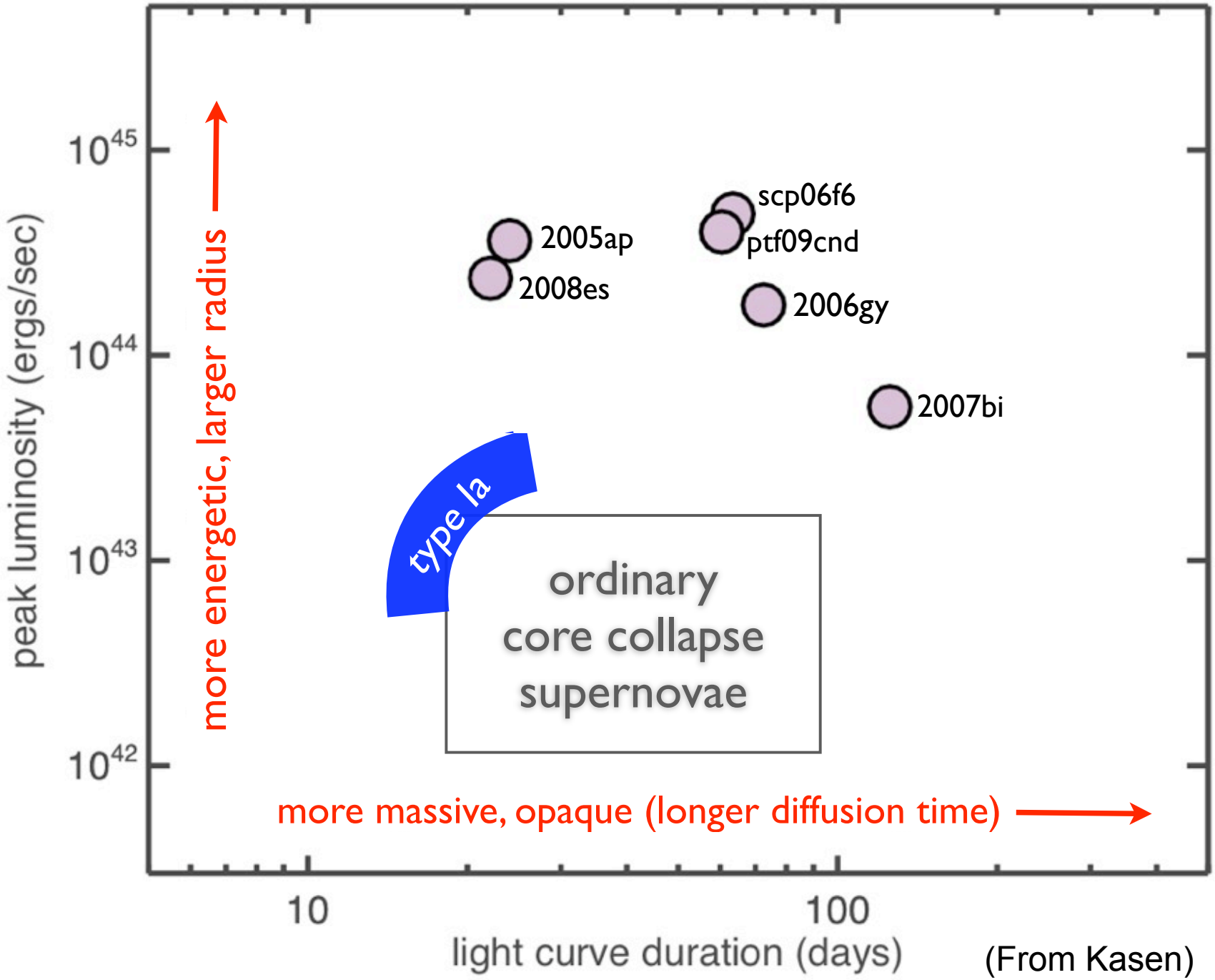
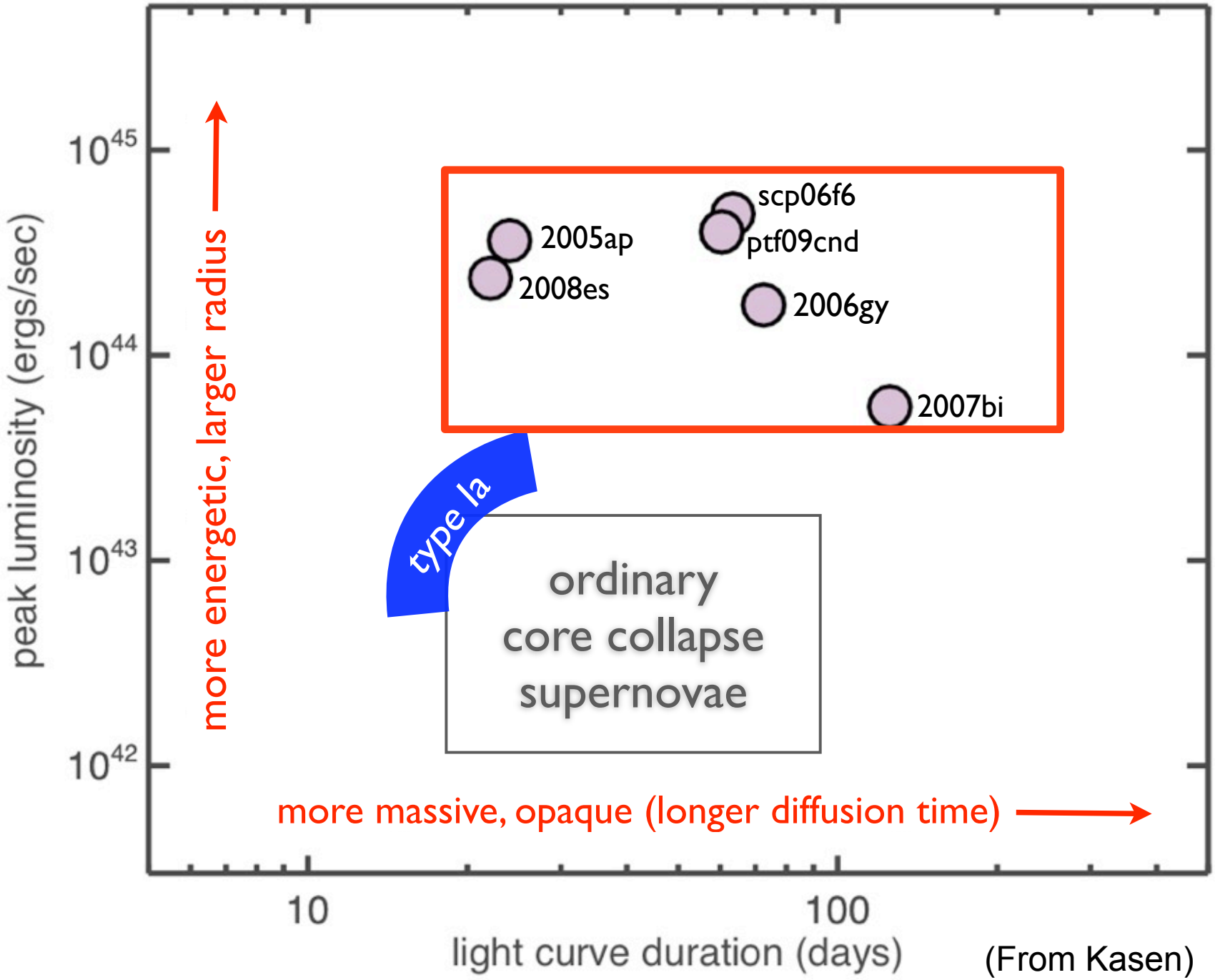
more massive, opaque (longer diffusion time)

(From 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)

(From Kasen)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(From Kasen)

The Death of Massive Stars

Woosley, Heger, & Weaver (2002)

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
$80 \leq M \leq 150$	$35 \leq M \leq 60$	Pulsational pair instability followed by core (PPSN)
$150 \leq M \leq 250$	$60 \leq M \leq 133$	Pair instability supernova (PSN)
$250 \leq M$	$133 \leq M$	Black holes

(CCSNe Talks: Janka, Mueller, Murphy, O'Connor)

Mass Unit: solar mass $\odot$

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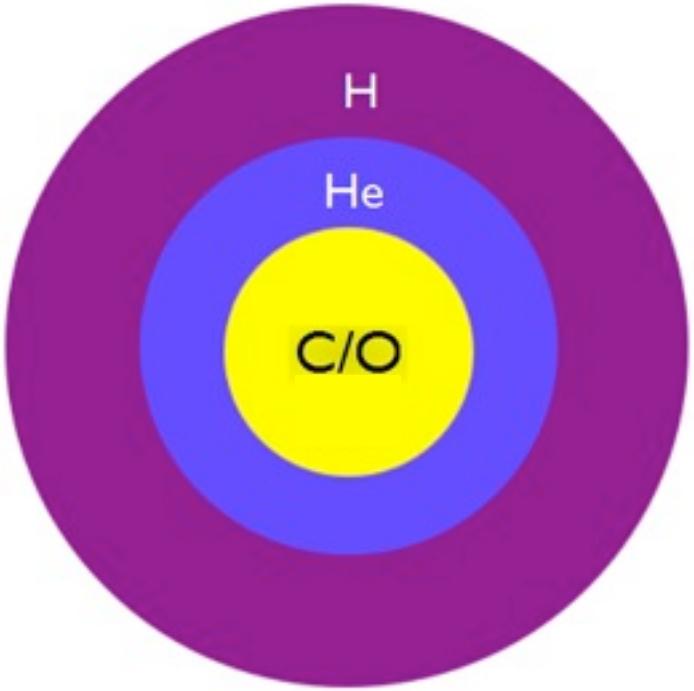
Mass Unit: solar mass $\odot$

Physics of PPSN & PSN

(Talk: Woosley)

Star > 80 M⊙



Physics of PPSN & PSN

(Talk: Woosley)

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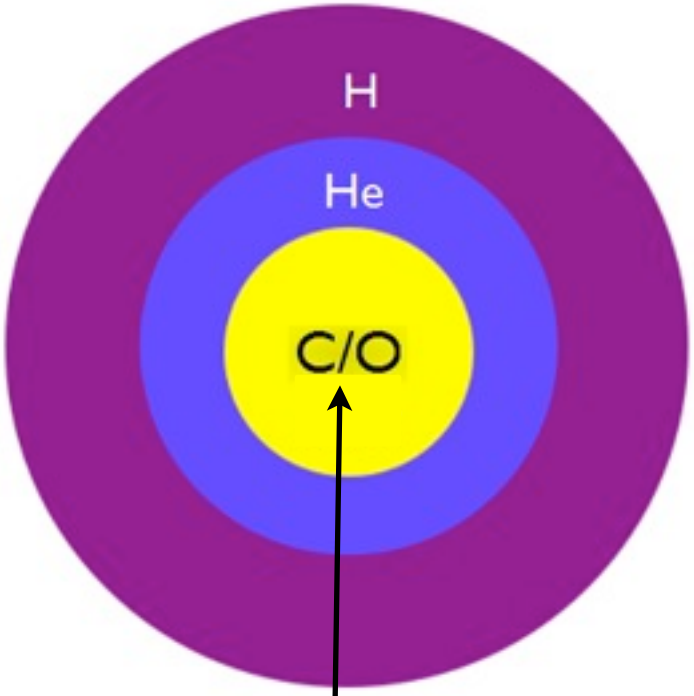
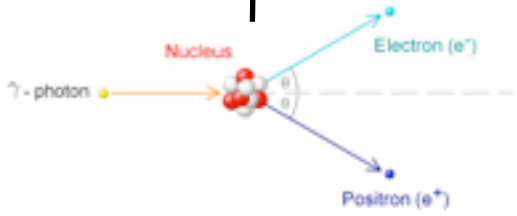


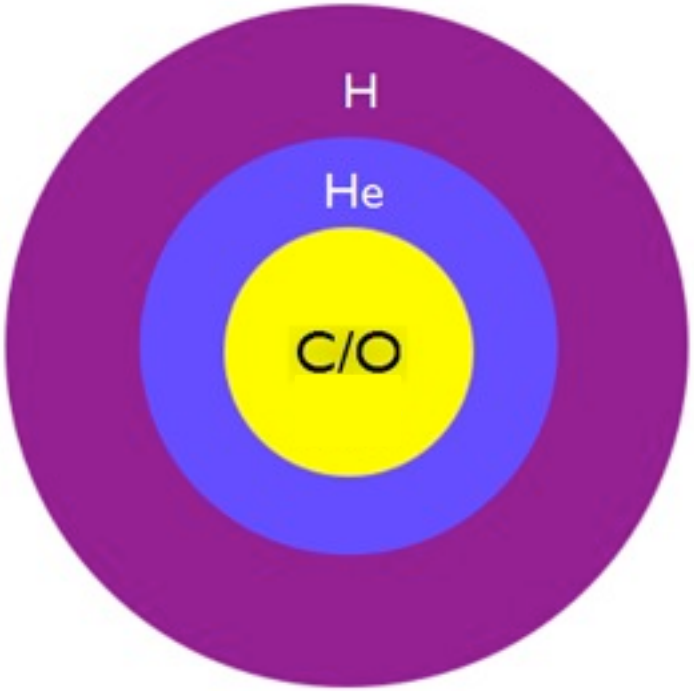


$E_o > 2m_0c^2$, where m_0 is the electron rest mass

Physics of PPSN & PSN

(Talk: Woosley)

Star > 80 M⊙



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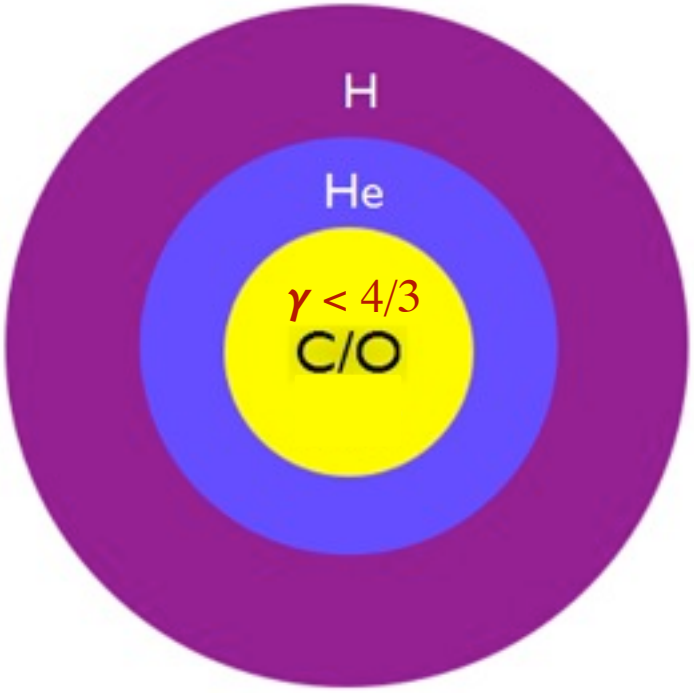

Physics of PPSN & PSN

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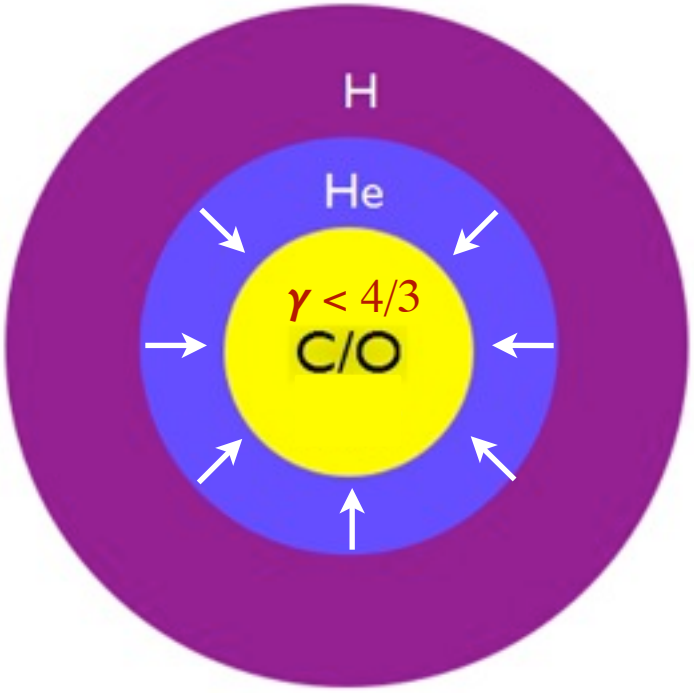

Physics of PPSN & PSN

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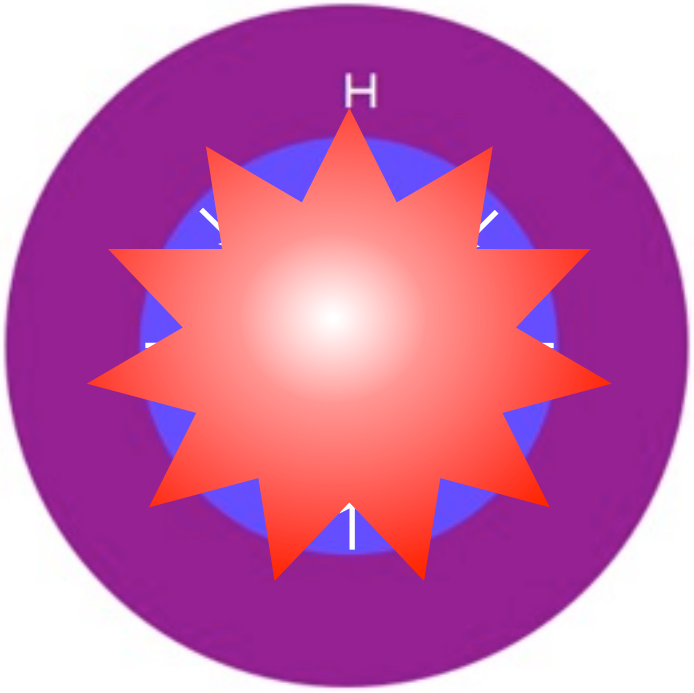
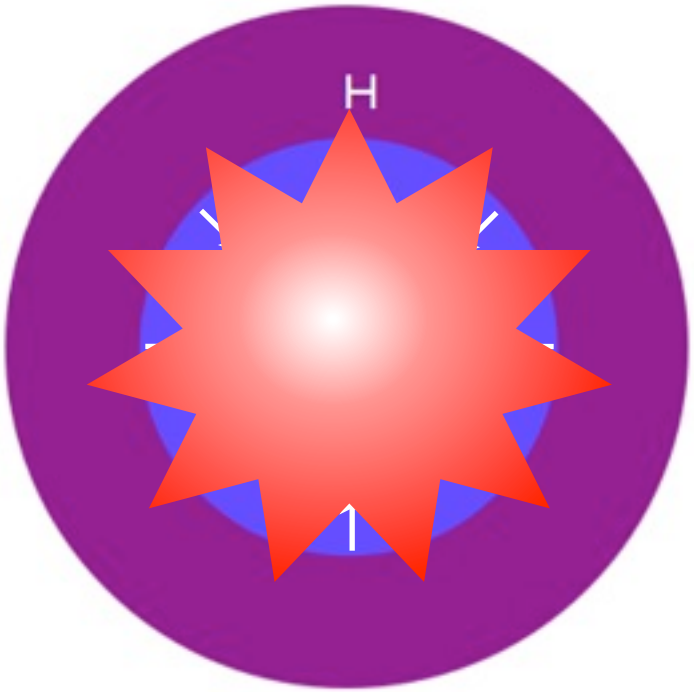


Physics of PPSN & PSN

(Talk: Woosley)

Star > 80 M⊙

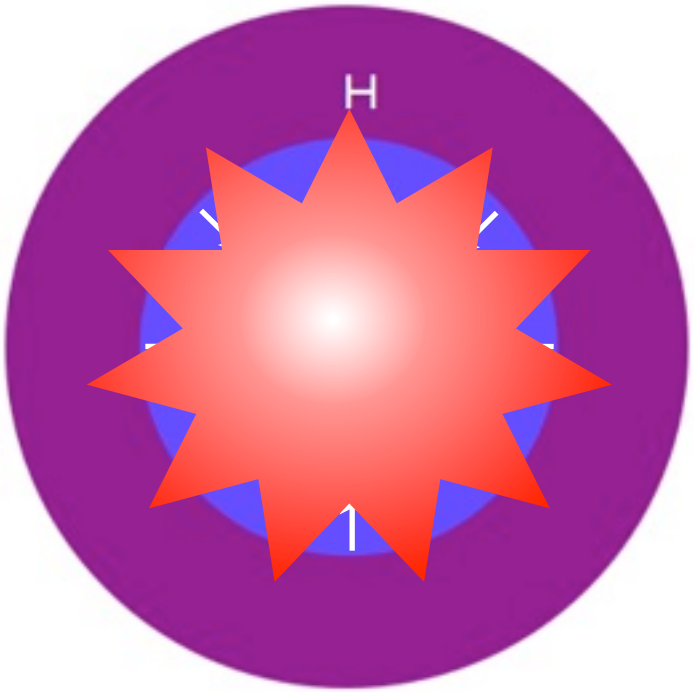


?

Physics of PPSN & PSN

(Talk: Woosley)

Star > 80 M⊙



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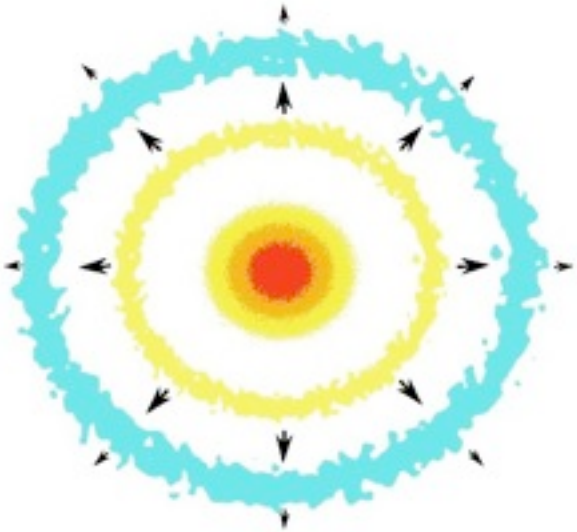
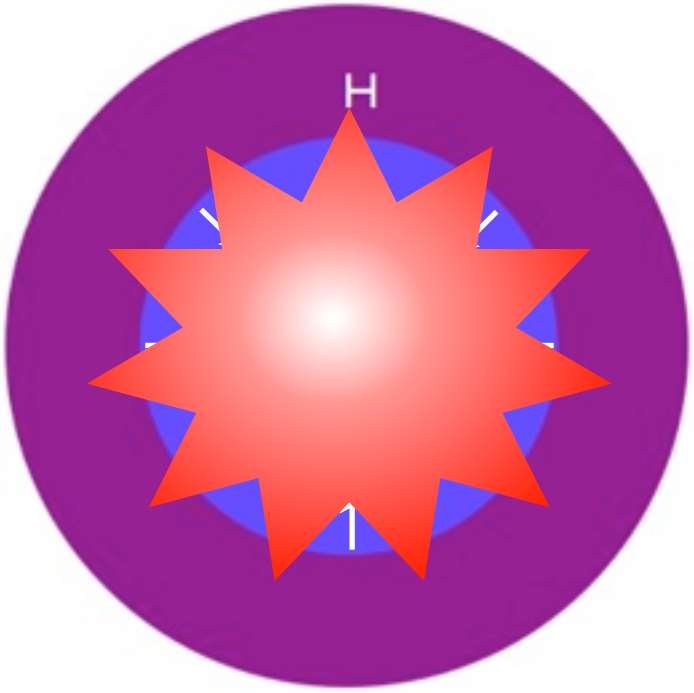


150 M⊙ > Star > 80 M⊙

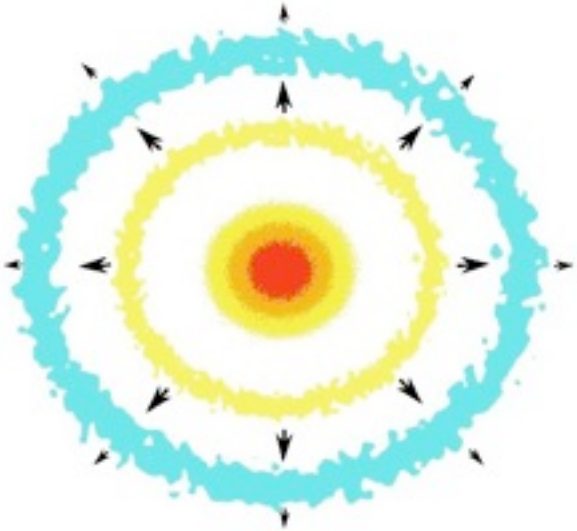
Physics of PPSN & PSN

(Talk: Woosley)

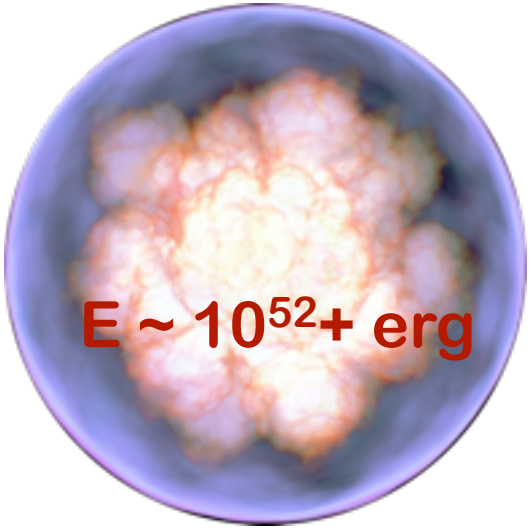
Star > 80 M⊙



?



150 M⊙ > Star > 80 M⊙



250 M⊙ > Star > 150 M⊙

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 (SciDAC CAC PI: Woosley)

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

Supercomputers

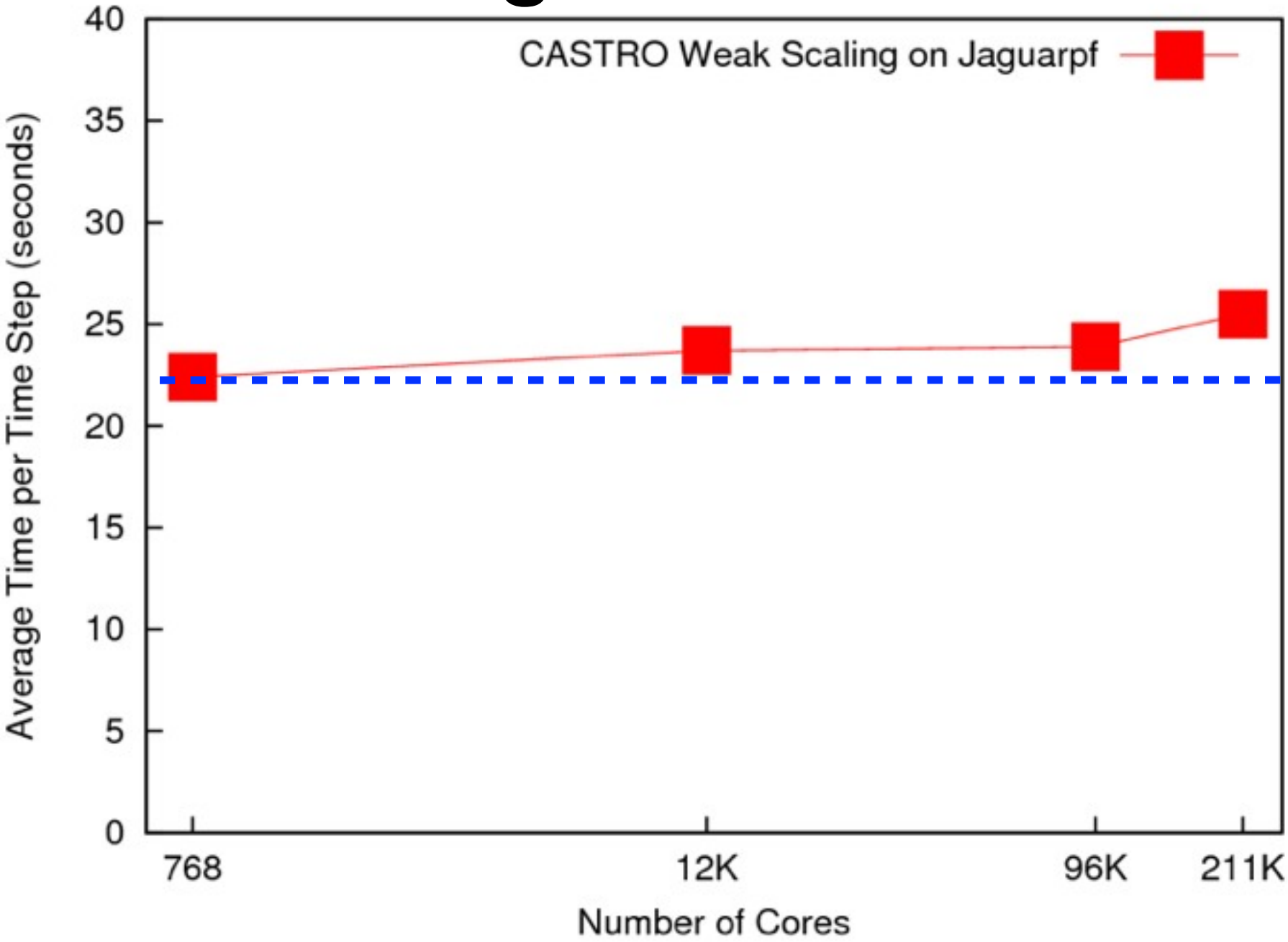
Itasca

Franklin

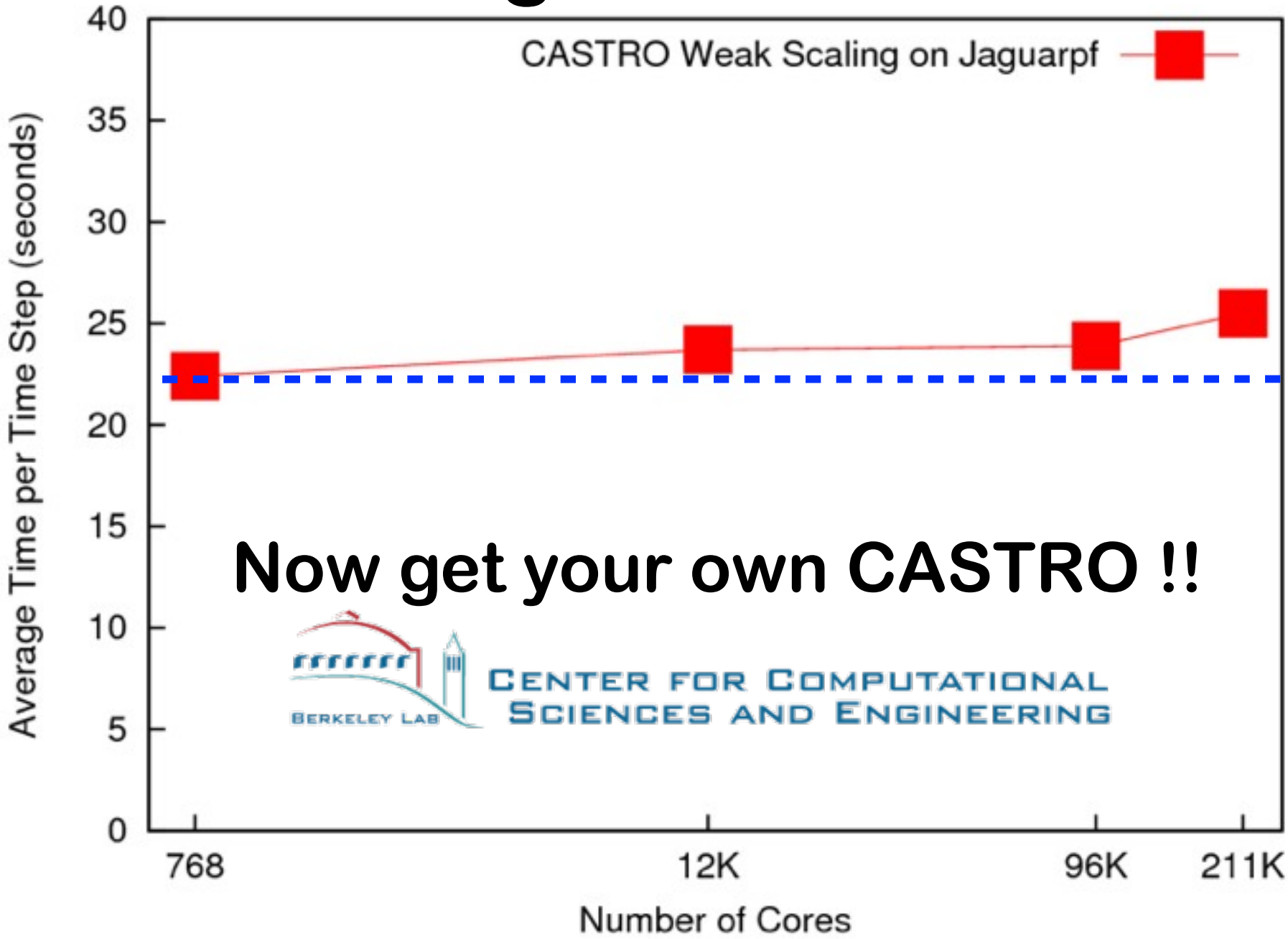
Hopper

Jaguar

Scaling Performance



Scaling Performance



Now get your own CASTRO !!

BERKELEY LAB

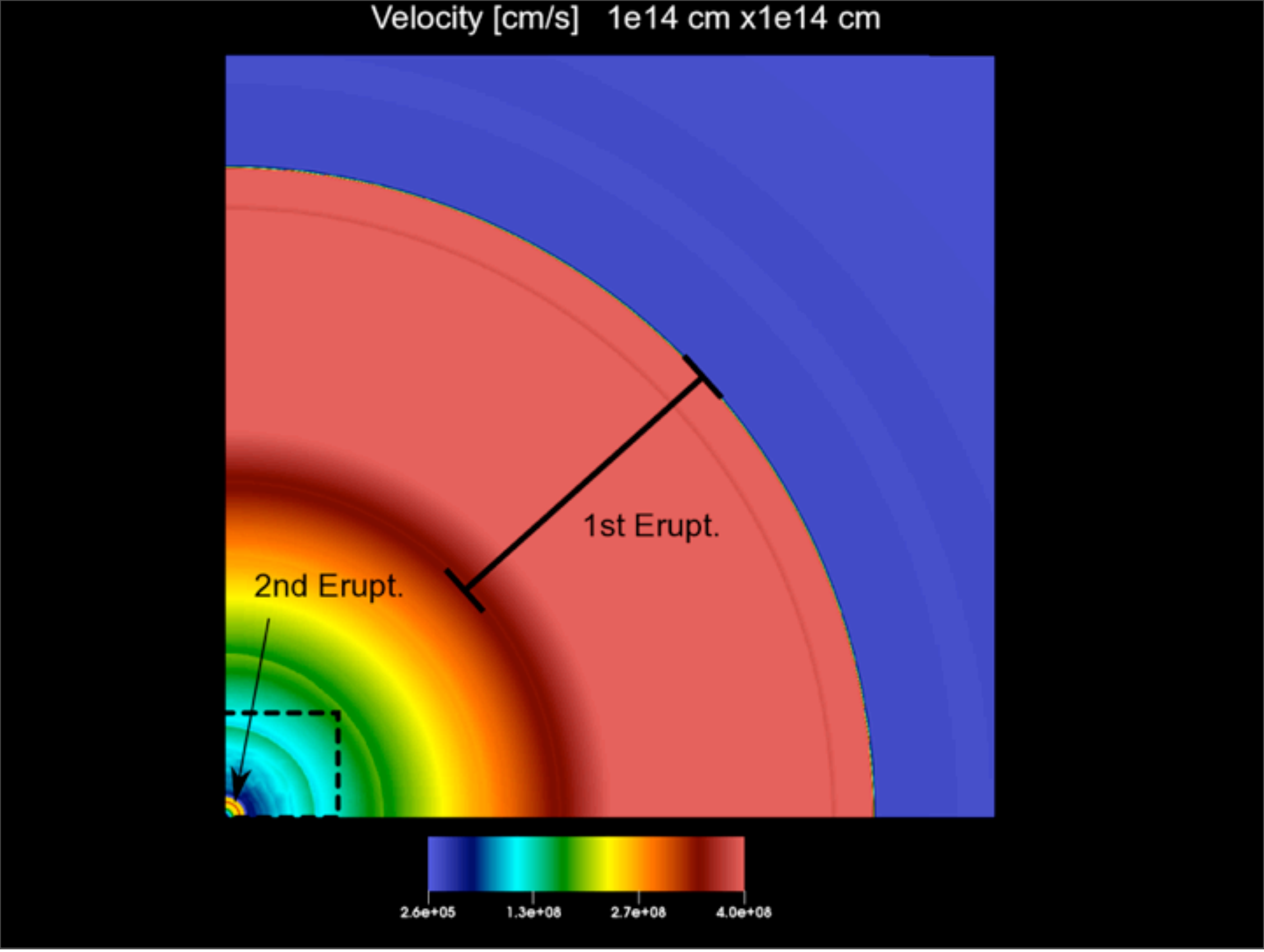
CENTER FOR COMPUTATIONAL SCIENCES AND ENGINEERING

Core of 110 M⊙ star

s

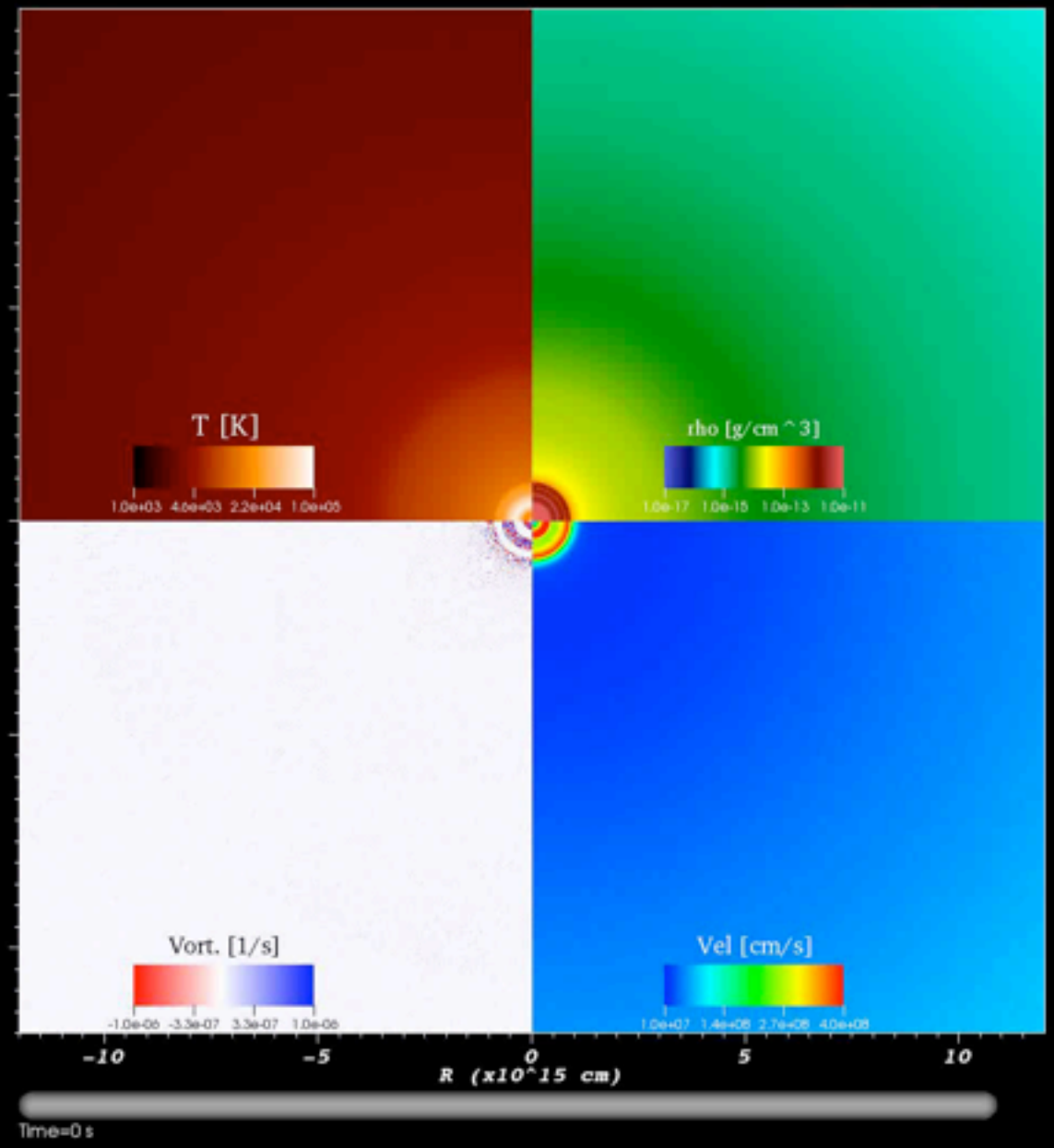
(cm/s)

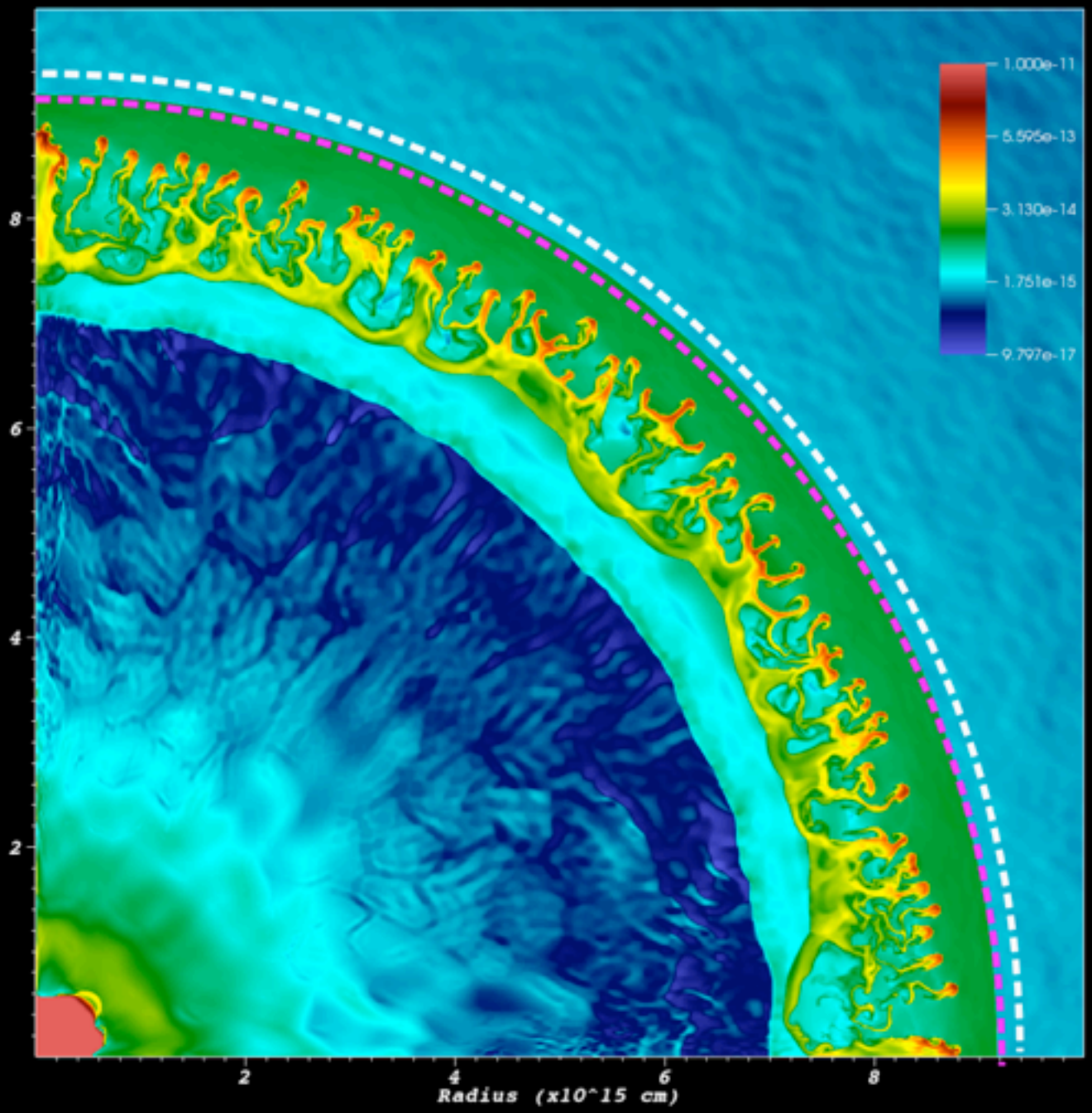
Core of 110 M⊙ star


Velocity [cm/s] 1e14 cm x1e14 cm
1st Erupt.
2nd Erupt.
2.6e+05
1.3e+08
2.7e+08
4.0e+08

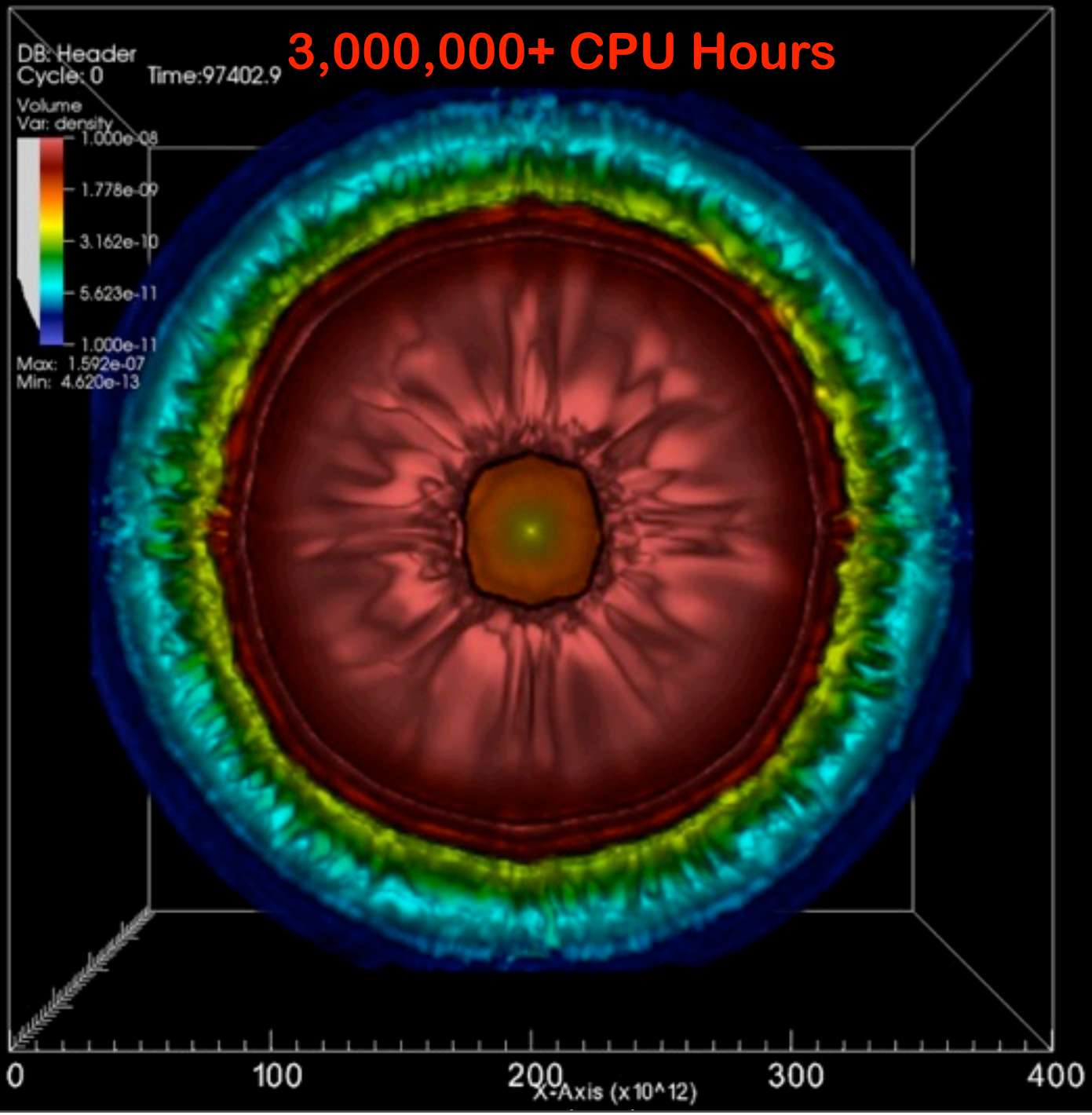
Physical Properties of Colliding Shells

Physical Properties of Colliding Shells



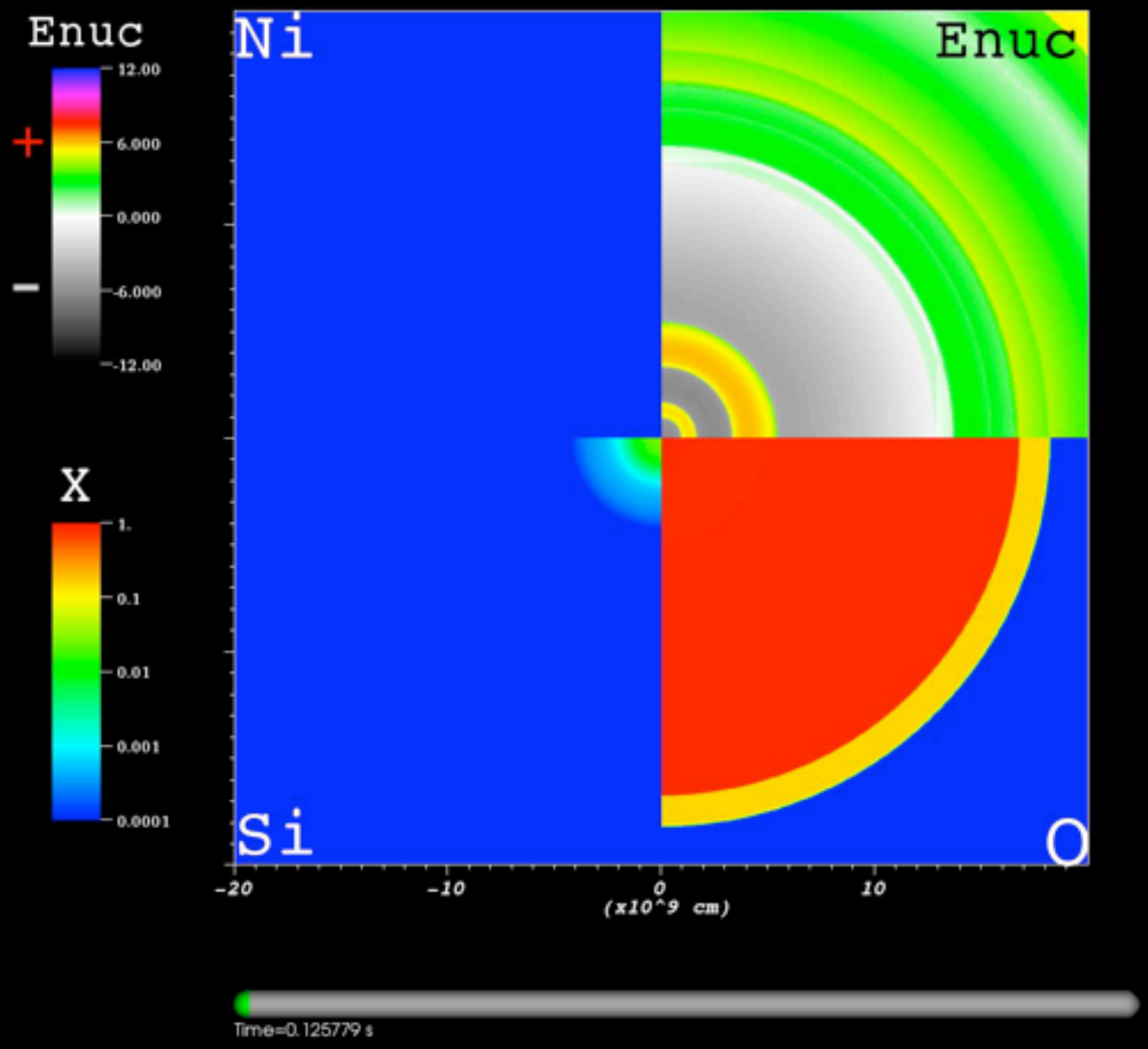

1.000e-11
5.595e-13
3.130e-14
1.751e-15
9.797e-17
8
6
4
2
2
4
6
8
Radius (x10^15 cm)

Chen + in prep


3,000,000+ CPU Hours
DB: Header
Cycle: 0
Time:97402.9
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)

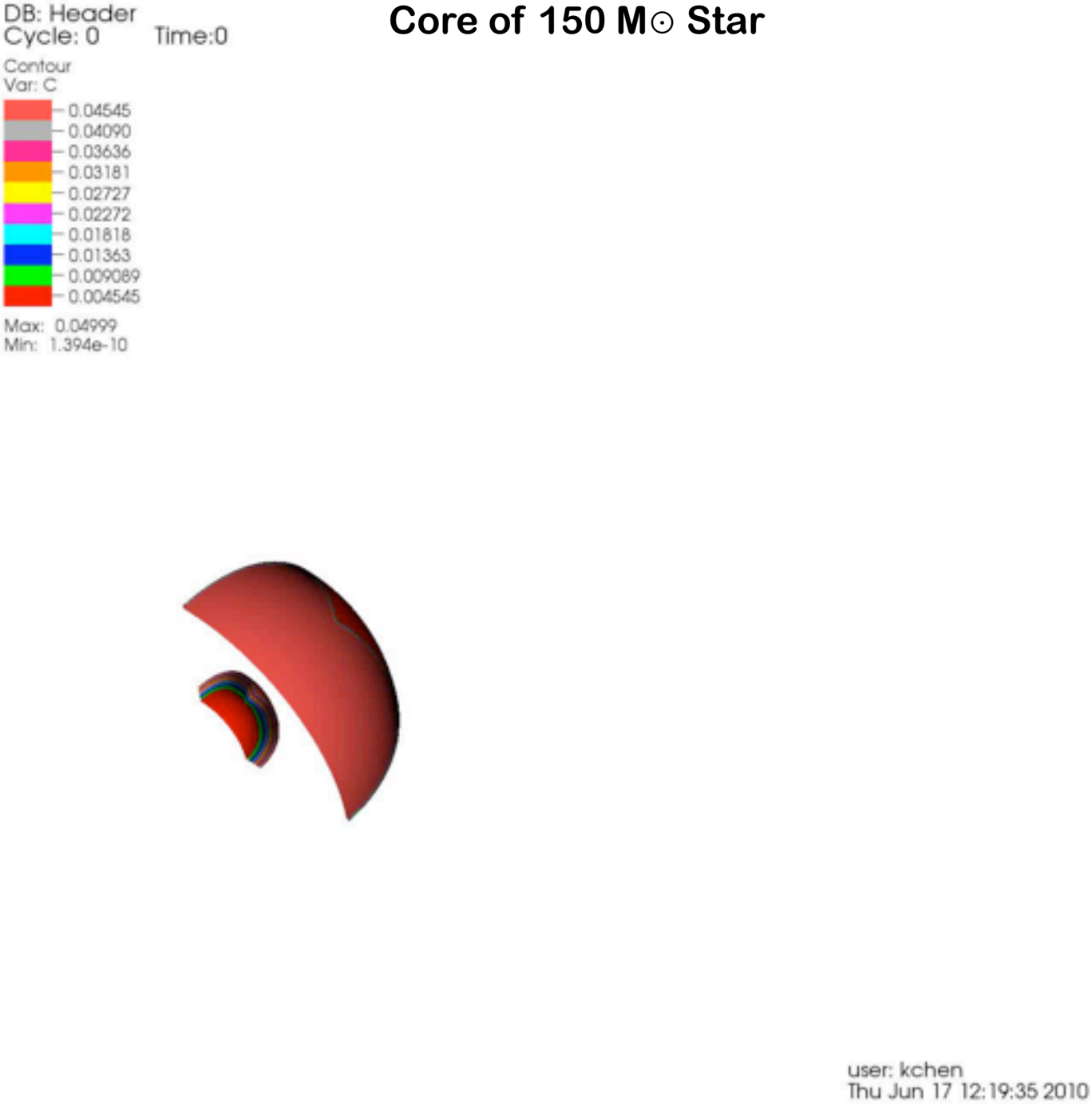
Explosive Burning of 150 M⊙ Star

Explosive Burning of 150 M⊙ Star



Core of 150 M⊙ Star

Core of 150 M⊙ Star



Exploding 200 M⊙ Star (2007 bi)

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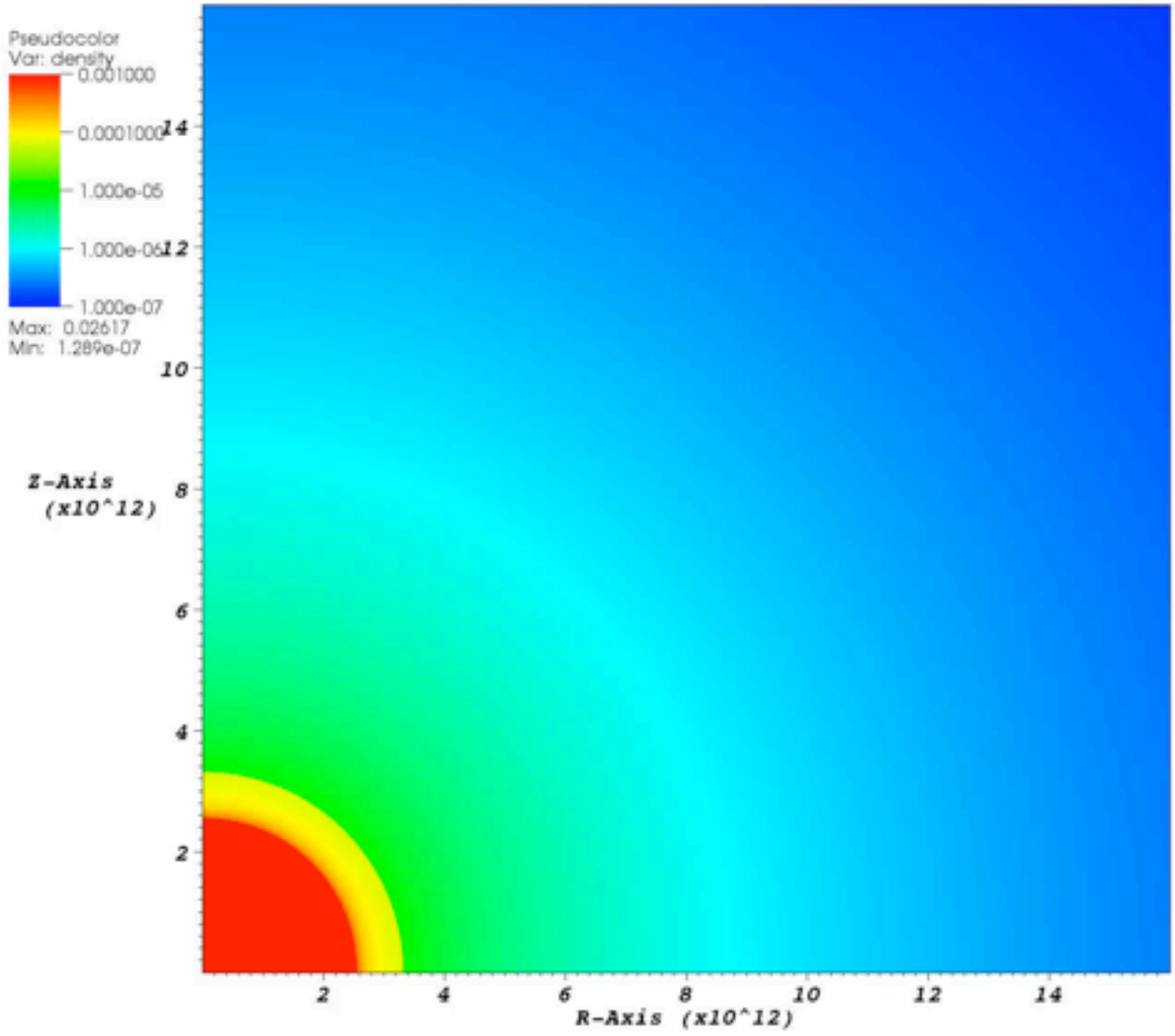
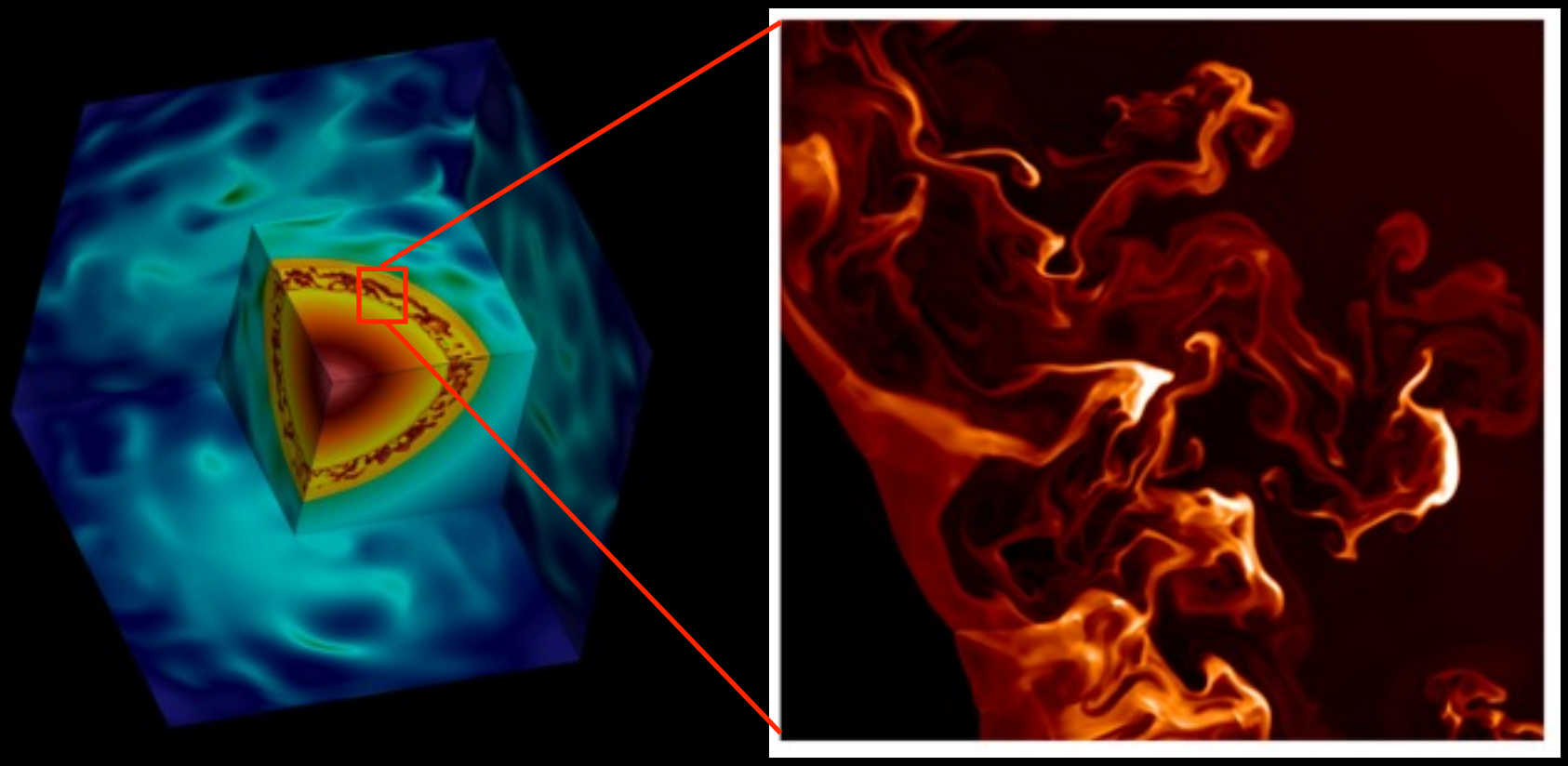
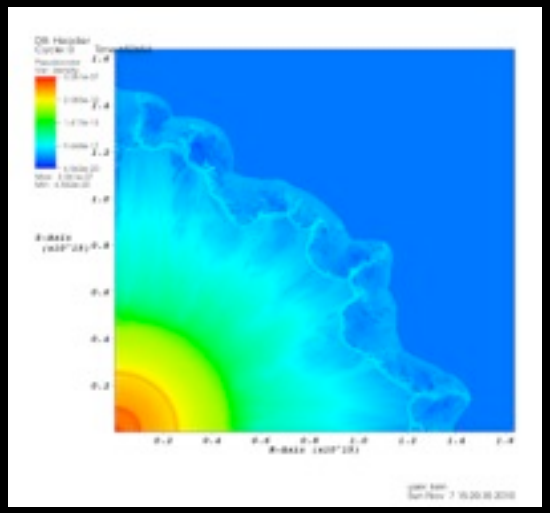


Mixing

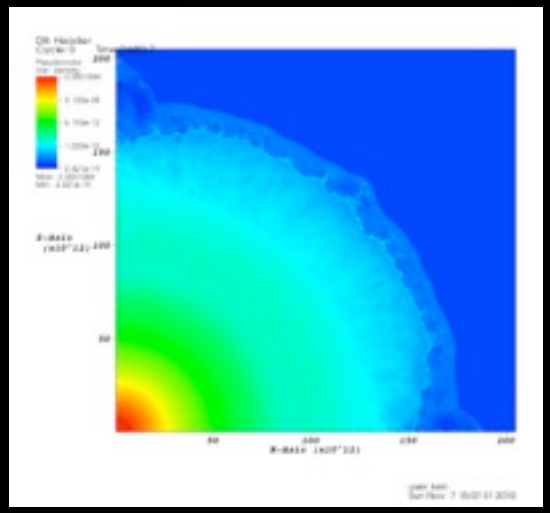


More Explosions !

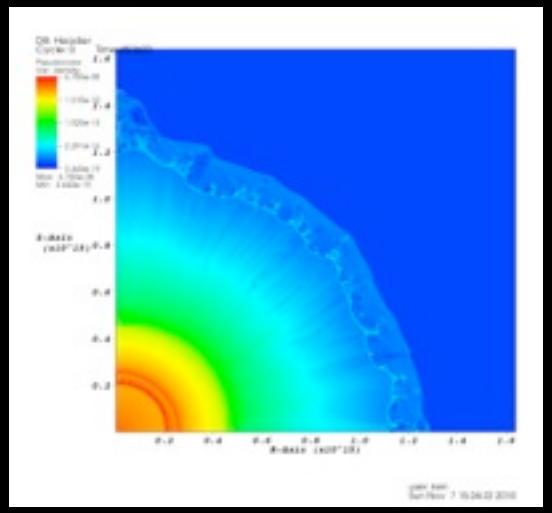
(Chen+ in prep)



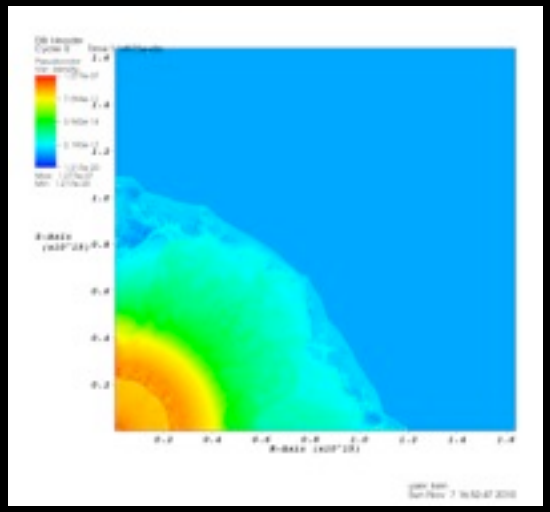
BSG 150



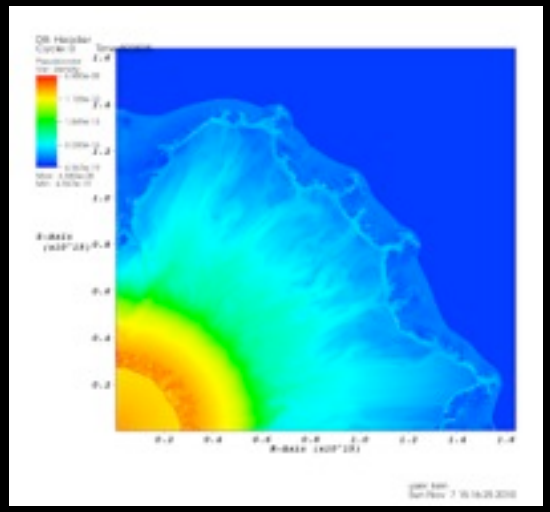
BSG 200



BSG 250



RSG 150

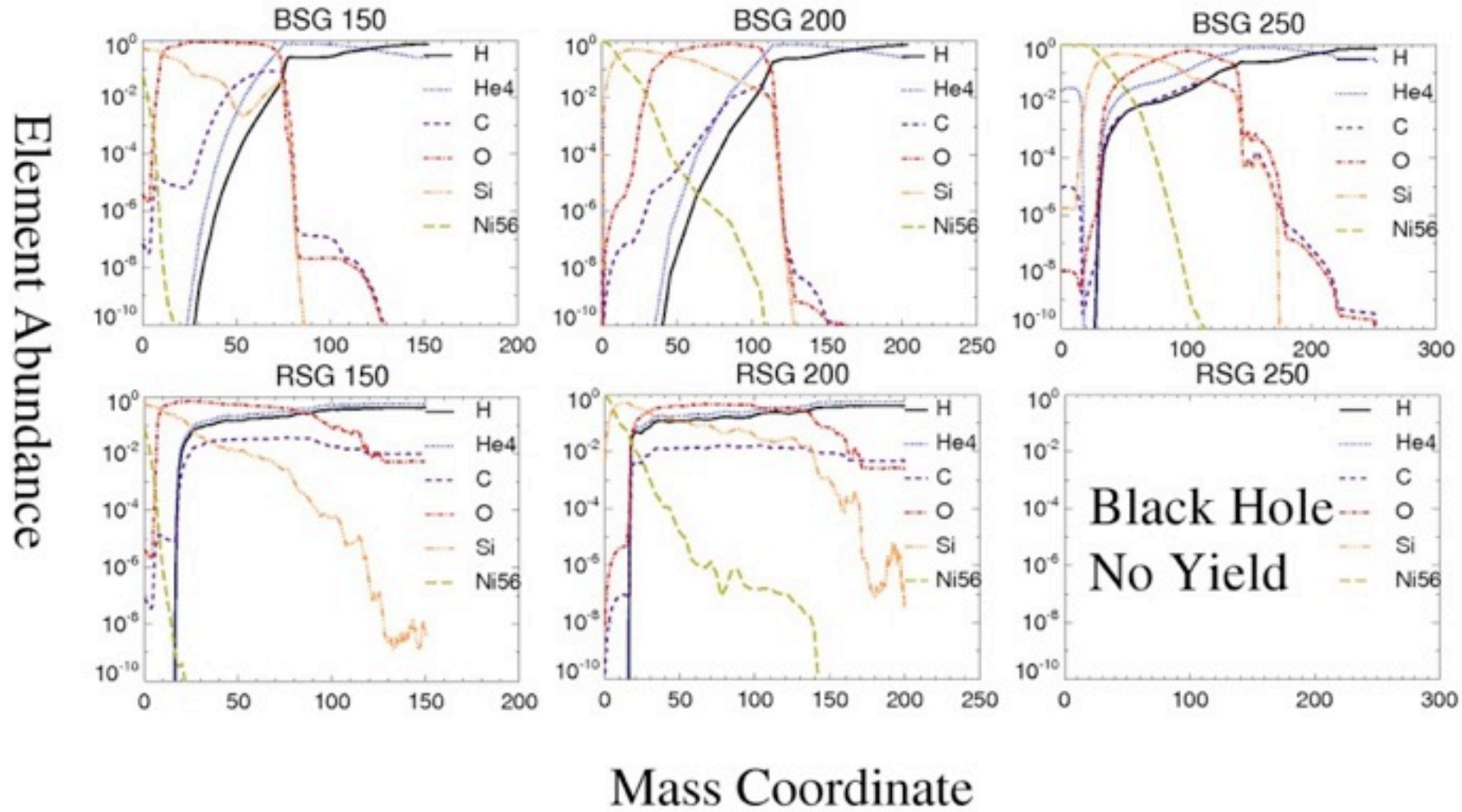


RSG 200

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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R250	250	156	...	...	...	...

Ni is only slightly mixed out .
The Gamma-Ray emission for PSNe is unlikely.
(Talk: Fruchter)

Conclusion

	Fate	Very Bright	Sources	observation
80 ~ 150 $M_\odot$				
150 ~ 250 $M_\odot$				
250+ $M_\odot$				

Conclusion

	Fate	Very Bright	Sources	observation
80 ~ 150 **M**⊙	PPSN			
150 ~ 250 **M**⊙	PSN			
250+ **M**⊙	BH			

Conclusion

	Fate	Very Bright	Sources	observation
80 ~ 150 **M**⊙	PPSN	YES		
150 ~ 250 **M**⊙	PSN	YES		
250+ **M**⊙	BH	No		

Conclusion

	Fate	Very Bright	Sources	observation
			(Talk: Smartt)	
80 ~ 150 **M**⊙	PPSN	YES	Pop I, II, III	
150 ~ 250 **M**⊙	PSN	YES	Pop I(?), II, III Mass loss rate (Talks: Arnett, Vink, Guzik, Fox, Shiode)	
250+ **M**⊙	BH	No	No	

Conclusion

	Fate	Very Bright	Sources	observation
			(Talk: Smartt)	
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250+ **M**⊙	BH	No	No	GW Talk: O'Shaughnessy

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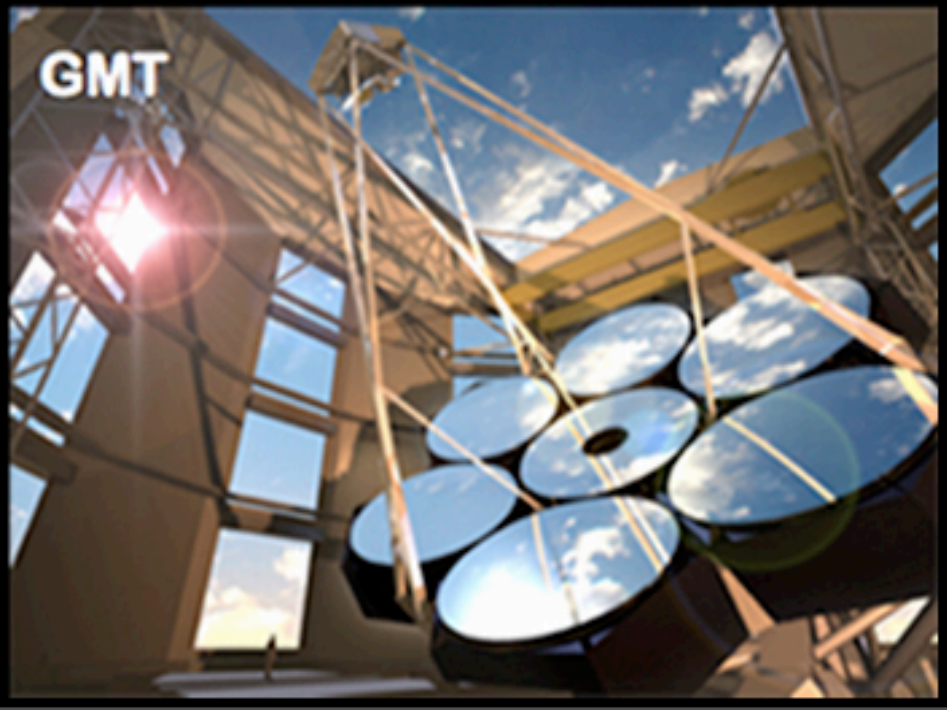
250+ **M**⊙	BH	No	No	GW Talk: O'Shaughnessy

Mixing can alter the observational signature

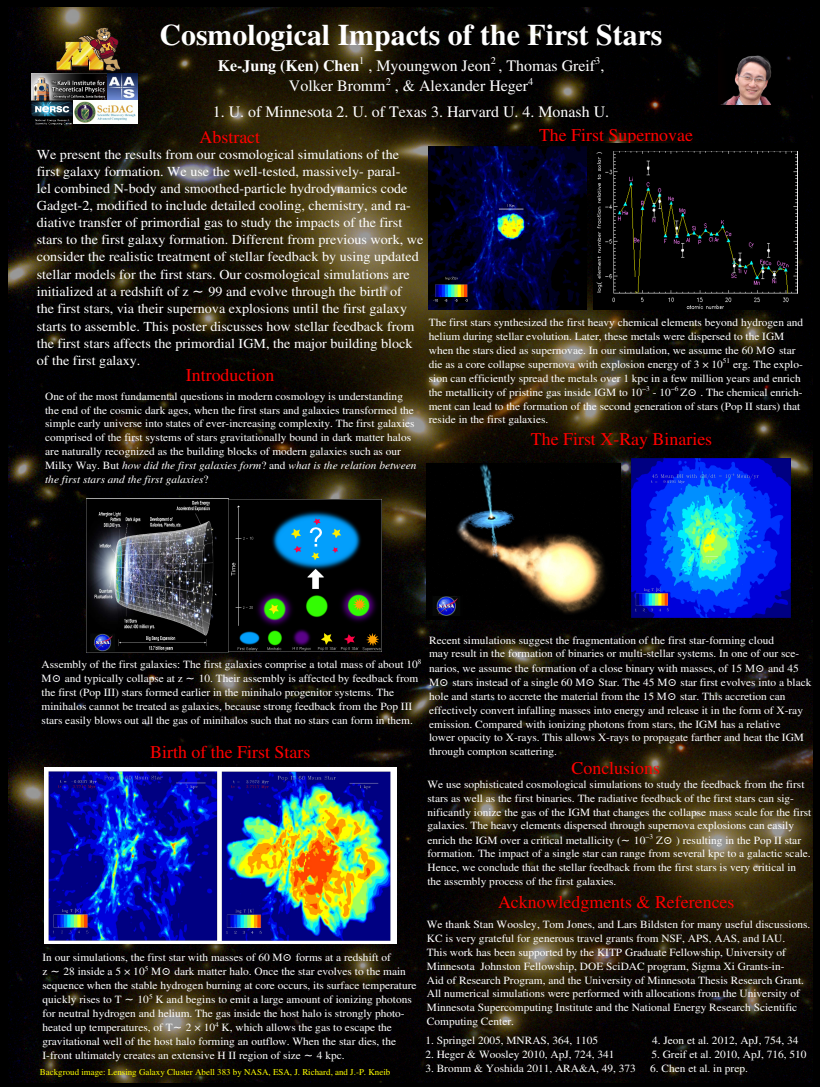

TMT


LSST


GMT


JWST

Impact of the First Stars



Cosmological Impacts of the First Stars

Ke-Jung (Ken) Chen[1] , Myoungwon Jeon[2] , Thomas Greif[3], Volker Bromm[2] , & Alexander Heger[4]

1. U. of Minnesota 2. U. of Texas 3. Harvard U. 4. Monash U.

Abstract

We present the results from our cosmological simulations of the first galaxy formation. We use the well-tested, massively- parallel combined N-body and smoothed-particle hydrodynamics code Gadget-2, modified to include detailed cooling, chemistry, and radiative transfer of primordial gas to study the impacts of the first stars to the first galaxy formation. Different from previous work, we consider the realistic treatment of stellar feedback by using updated stellar models for the first stars. Our cosmological simulations are initialized at a redshift of $z \sim 99$ and evolve through the birth of the first stars, via their supernova explosions until the first galaxy starts to assemble. This poster discusses how stellar feedback from the first stars affects the primordial IGM, the major building block of the first galaxy.

Introduction

One of the most fundamental questions in modern cosmology is understanding the end of the cosmic dark ages, when the first stars and galaxies transformed the simple early universe into states of ever-increasing complexity. The first galaxies comprised of the first systems of stars gravitationally bound in dark matter halos are naturally recognized as the building blocks of modern galaxies such as our Milky Way. But *how did the first galaxies form*? and *what is the relation between the first stars and the first galaxies*?

Assembly of the first galaxies: The first galaxies comprise a total mass of about 10^8 M⊙ and typically collapse at $z \sim 10$. Their assembly is affected by feedback from the first (Pop III) stars formed earlier in the minihalo progenitor systems. The minihalos cannot be treated as galaxies, because strong feedback from the Pop III stars easily blows out all the gas of minihalos such that no stars can form in them.

Birth of the First Stars

In our simulations, the first star with masses of 60 M⊙ forms at a redshift of $z \sim 28$ inside a 5×10^5 M⊙ dark matter halo. Once the star evolves to the main sequence when the stable hydrogen burning at core occurs, its surface temperature quickly rises to $T \sim 10^5$ K and begins to emit a large amount of ionizing photons for neutral hydrogen and helium. The gas inside the host halo is strongly photo-heated up temperatures, of $T \sim 2 \times 10^4$ K, which allows the gas to escape the gravitational well of the host halo forming an outflow. When the star dies, the I-front ultimately creates an extensive H II region of size ~ 4 kpc.

Background image: Lensing Galaxy Cluster Abell 383 by NASA, ESA, J. Richard, and J.-P. Kneib

The First Supernovae

The first stars synthesized the first heavy chemical elements beyond hydrogen and helium during stellar evolution. Later, these metals were dispersed to the IGM when the stars died as supernovae. In our simulation, we assume the 60 M⊙ star die as a core collapse supernova with explosion energy of 3×10^{51} erg. The explosion can efficiently spread the metals over 1 kpc in a few million years and enrich the metallicity of pristine gas inside IGM to 10^{-3} - 10^{-4} Z⊙ . The chemical enrichment can lead to the formation of the second generation of stars (Pop II stars) that reside in the first galaxies.

The First X-Ray Binaries

Recent simulations suggest the fragmentation of the first star-forming cloud may result in the formation of binaries or multi-stellar systems. In one of our scenarios, we assume the formation of a close binary with masses, of 15 M⊙ and 45 M⊙ stars instead of a single 60 M⊙ Star. The 45 M⊙ star first evolves into a black hole and starts to accrete the material from the 15 M⊙ star. This accretion can effectively convert infalling masses into energy and release it in the form of X-ray emission. Compared with ionizing photons from stars, the IGM has a relative lower opacity to X-rays. This allows X-rays to propagate farther and heat the IGM through compton scattering.

Conclusions

We use sophisticated cosmological simulations to study the feedback from the first stars as well as the first binaries. The radiative feedback of the first stars can significantly ionize the gas of the IGM that changes the collapse mass scale for the first galaxies. The heavy elements dispersed through supernova explosions can easily enrich the IGM over a critical metallicity ($\sim 10^{-3}$ Z⊙) resulting in the Pop II star formation. The impact of a single star can range from several kpc to a galactic scale. Hence, we conclude that the stellar feedback from the first stars is very critical in the assembly process of the first galaxies.

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Cosmological Simulations including

1 Star Formation
2 Stellar Evolution
3 Radiative Transfer
4 Supernovae
5 Chemical Enrichment
6 Chemical Cooling
7 Binary Scenario

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