The Cosmic Dawn

Physics of the First Luminous Objects

Ke-Jung (Ken) Chen
EACOA Fellow, NAOJ and ASIAA
IAU Gruber Fellow, UC Santa Cruz
Astrophysics Seminar, Fukuoka U., Nov. 27 2015

East Asian Core Observatories Association (EACOA)

Purpose of EACOA:

To promote researchers from all over the world to come and conduct joint research activities with colleagues at the EACOA member institutes.

Four Core Observatories in East Asian

- Academia Sinica Institute of Astronomy and Astrophysics (ASIAA)
- Korea Astronomy and Space Science Institute (KASI)
- National Astronomy Observatories, Chinese Academy of Sciences (NAOC)
- National Astronomical Observatory of Japan (NAOJ)

Four Missions of East Asian Core Observatories Association

I. East Asian Observatory
II. Fellowship Program
III. East Asian Meeting on Astronomy
IV. East Asian Young Astronomers Meeting

2016 EACOA Postdoctoral Fellowship Program - Now Recruiting!
Application Due Date: November 15. 2015

Fellowship Program:

- Initial appointment of three years, renewable for an additional two years.
- To work full-time on the research programs, and to be in residence in at least two EACOA member Institutions during the appointment period.
- The opportunity to access all research facilities run by the EACOA member institutes, including the LAMOST, Subaru Telescope, ALMA, etc.
- A monthly stipend of US$5,000, plus relocation expenses.
- Research funds and travel support by host institutes

Online Application at:
http://www.eacoa.net/job/

People

Alexander Heger
Monash University

Stan Woosley
UC Santa Cruz

Volker Bromm
UT-Austin

Ann Almgren
Lawrence Berkeley National Lab

Daniel Kasen
UC Berkeley

Weiqun Zhang
Lawrence Berkeley National Lab

People

YOU

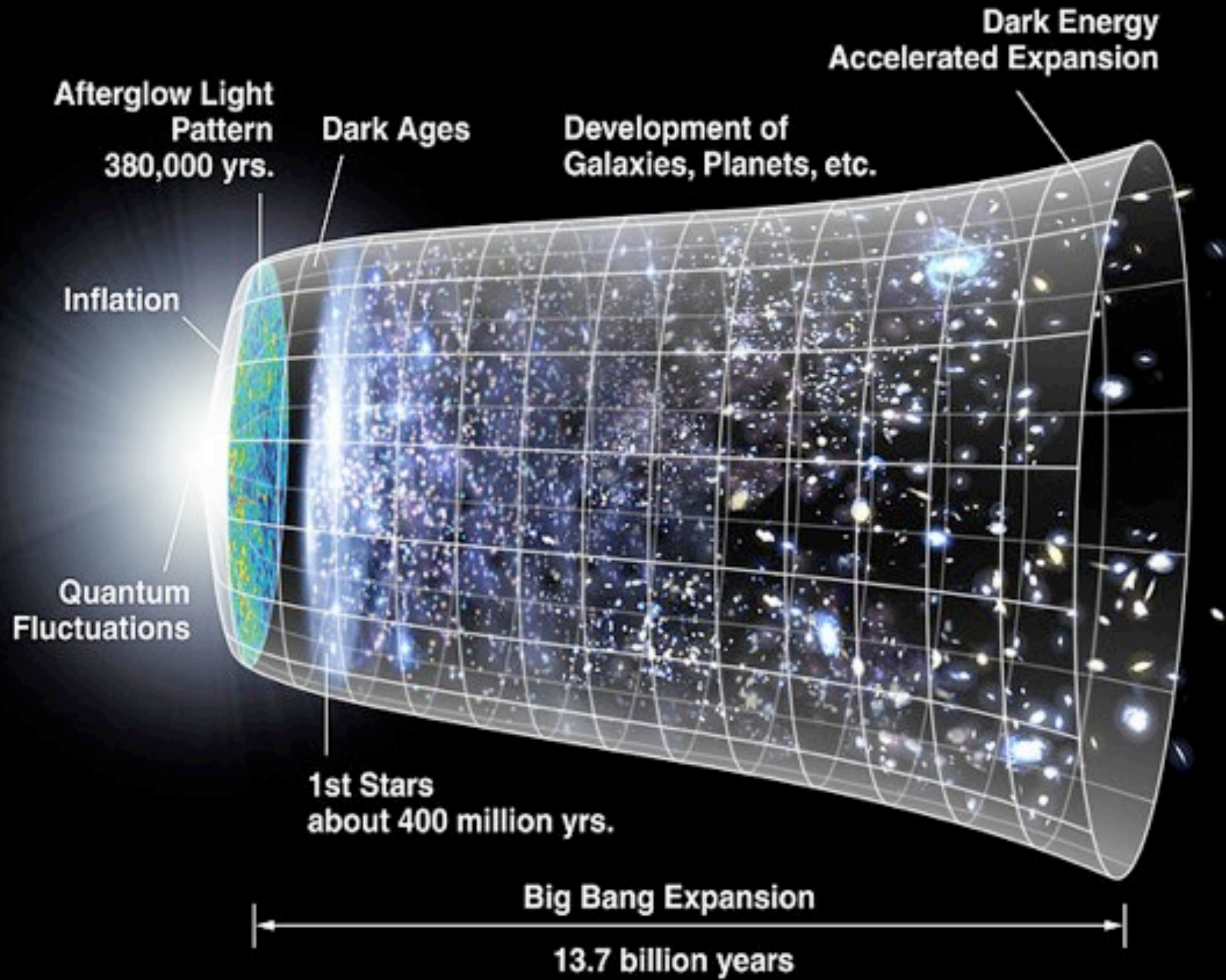
Kill Darkness?

Kill Darkness?

Light !!

Kill Darkness?

History of Universe



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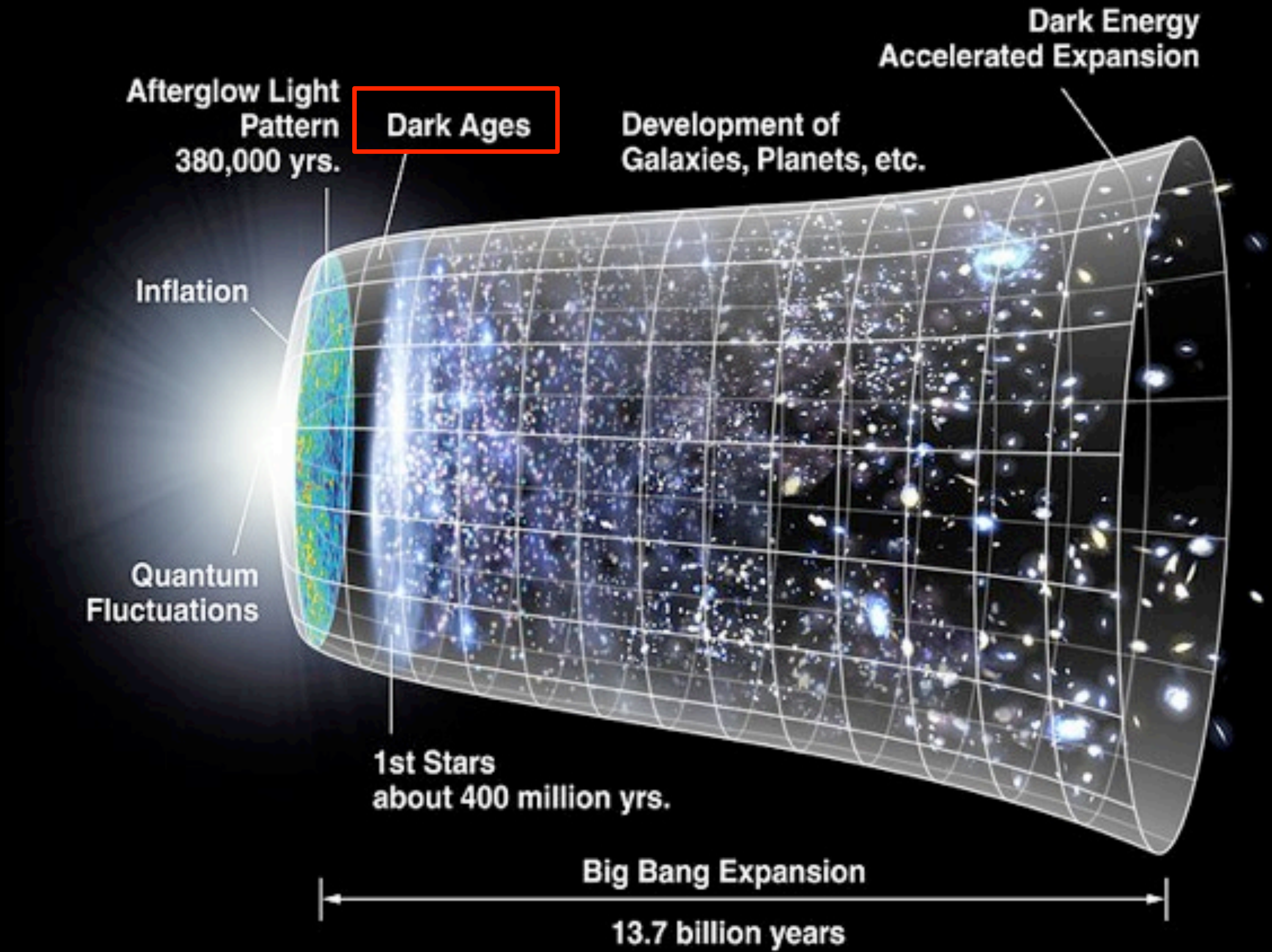

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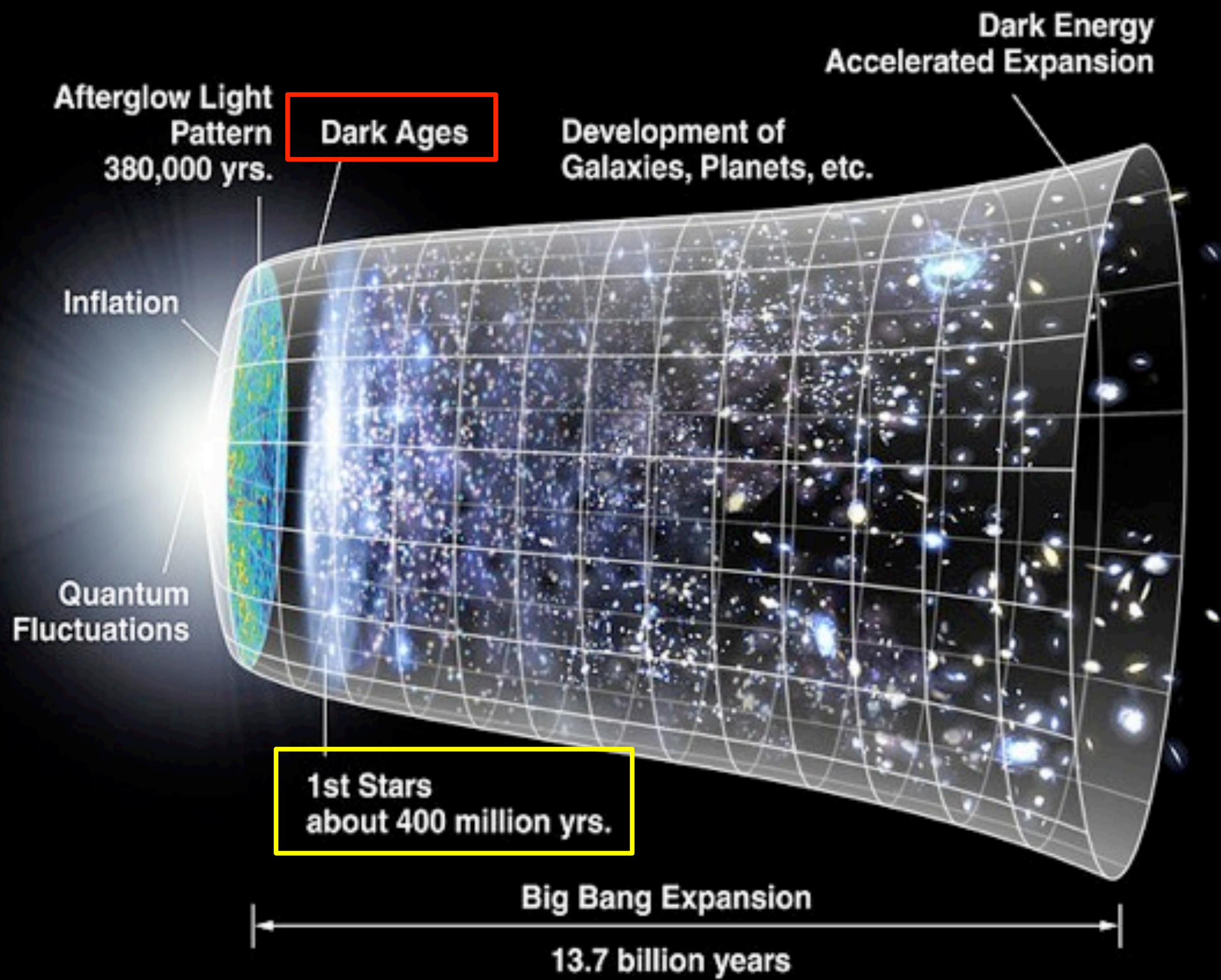

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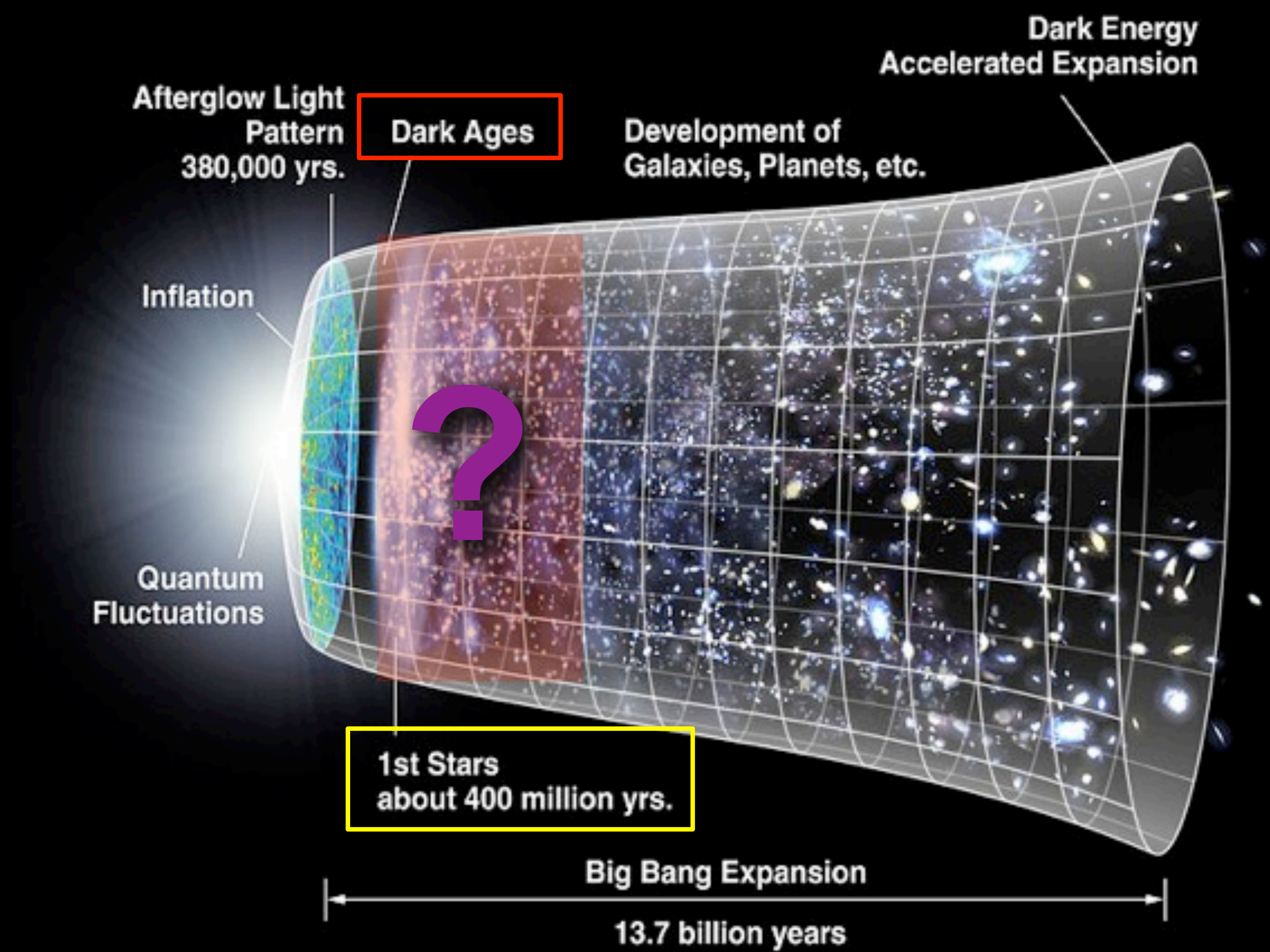

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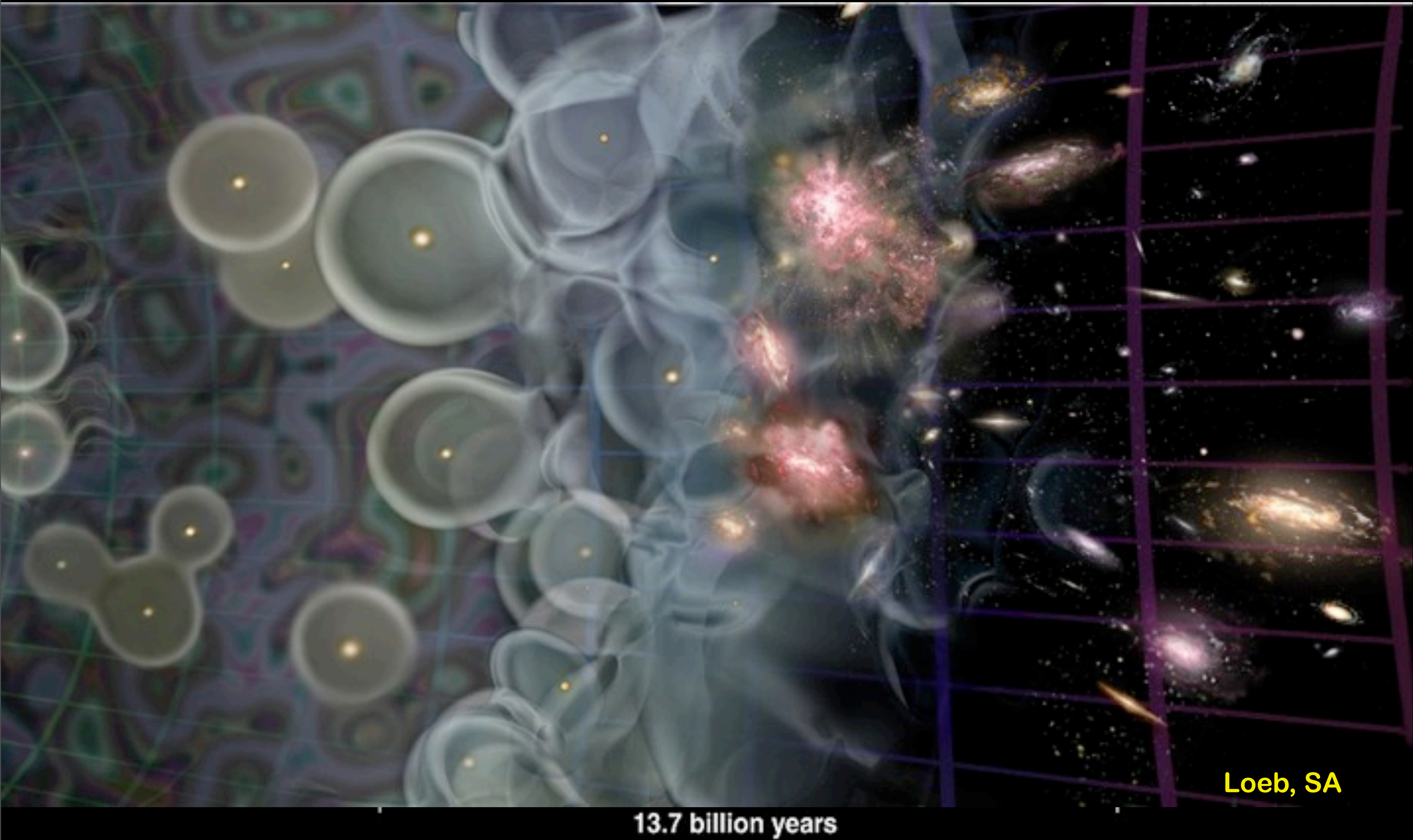

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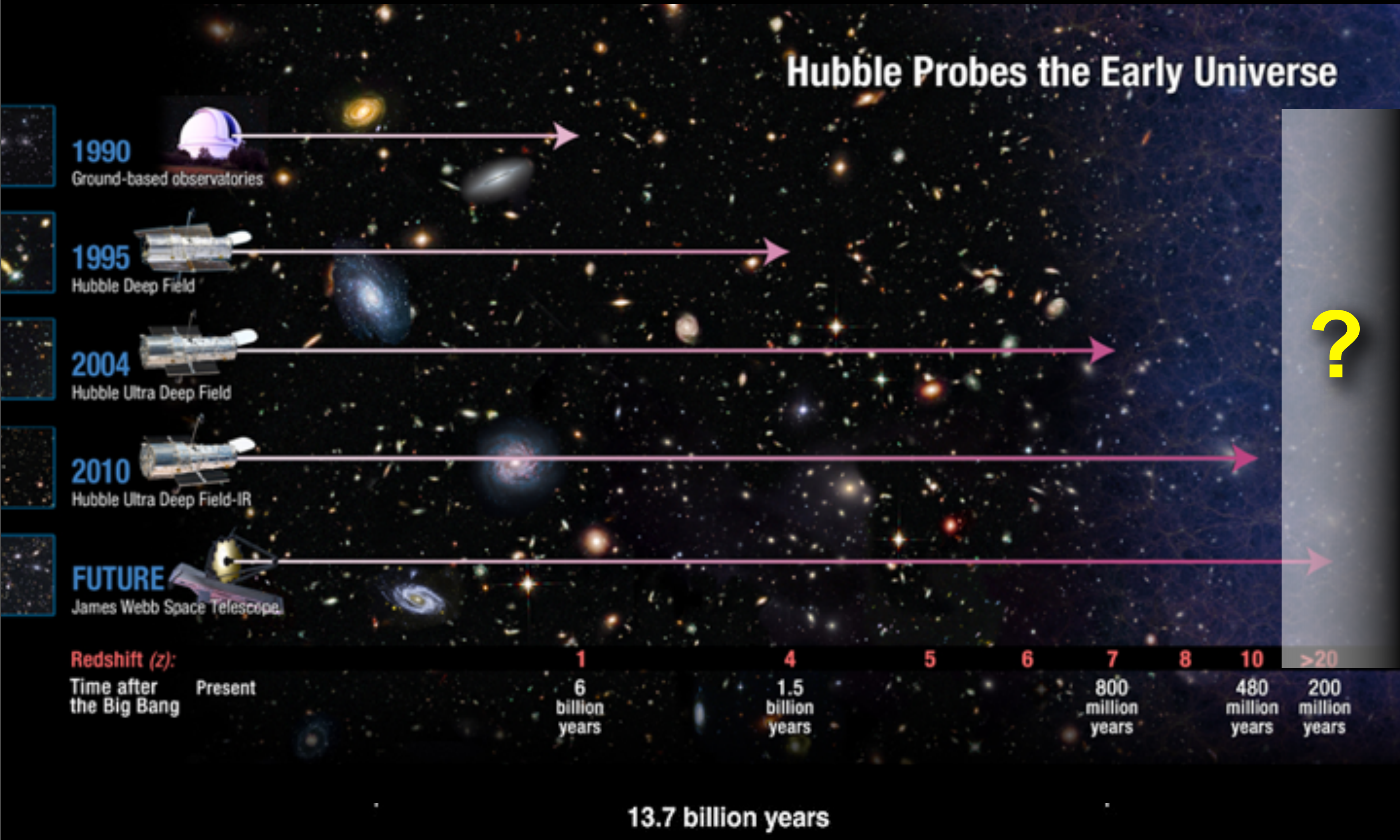
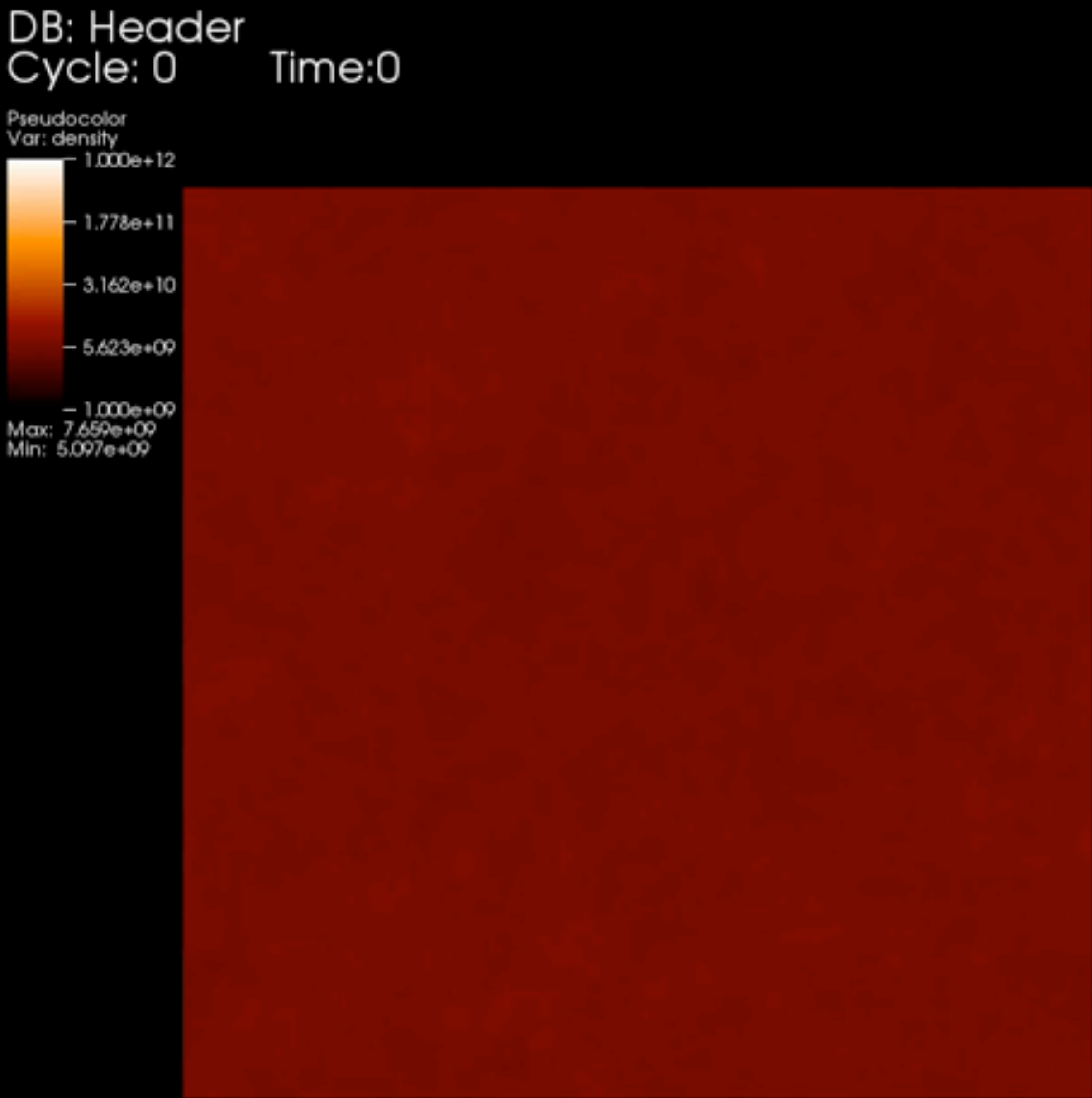


LCDM



NYX code (Almgren+ 2013)

The First Star Forming Cloud

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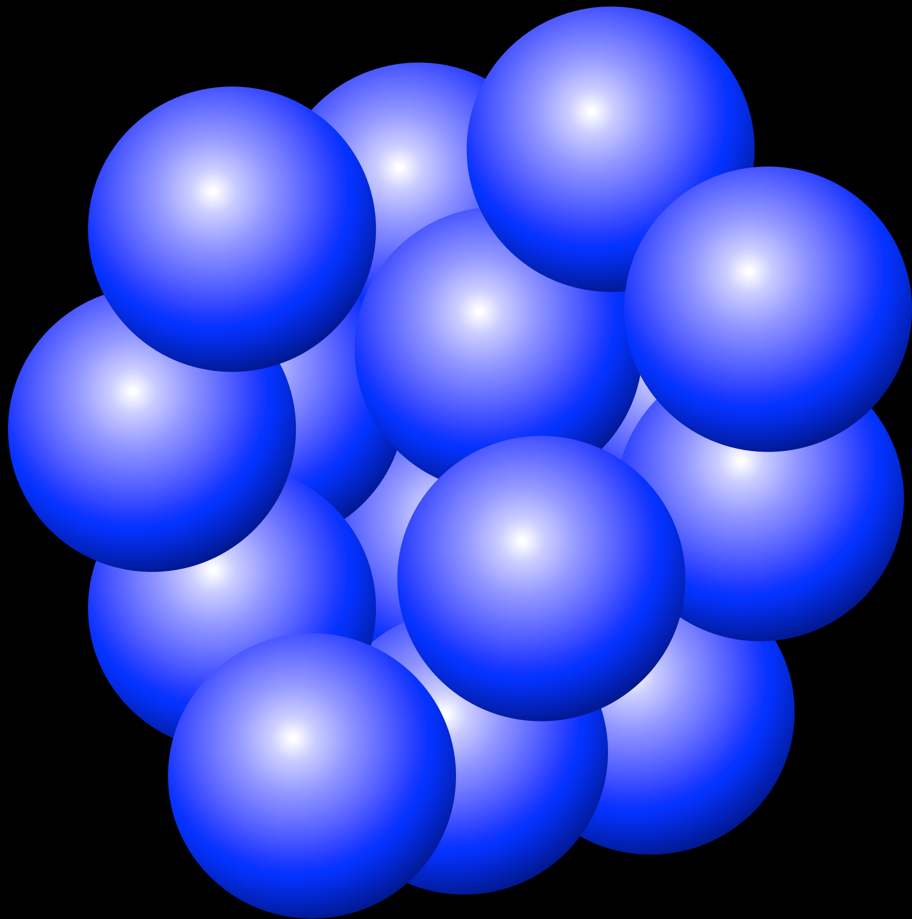

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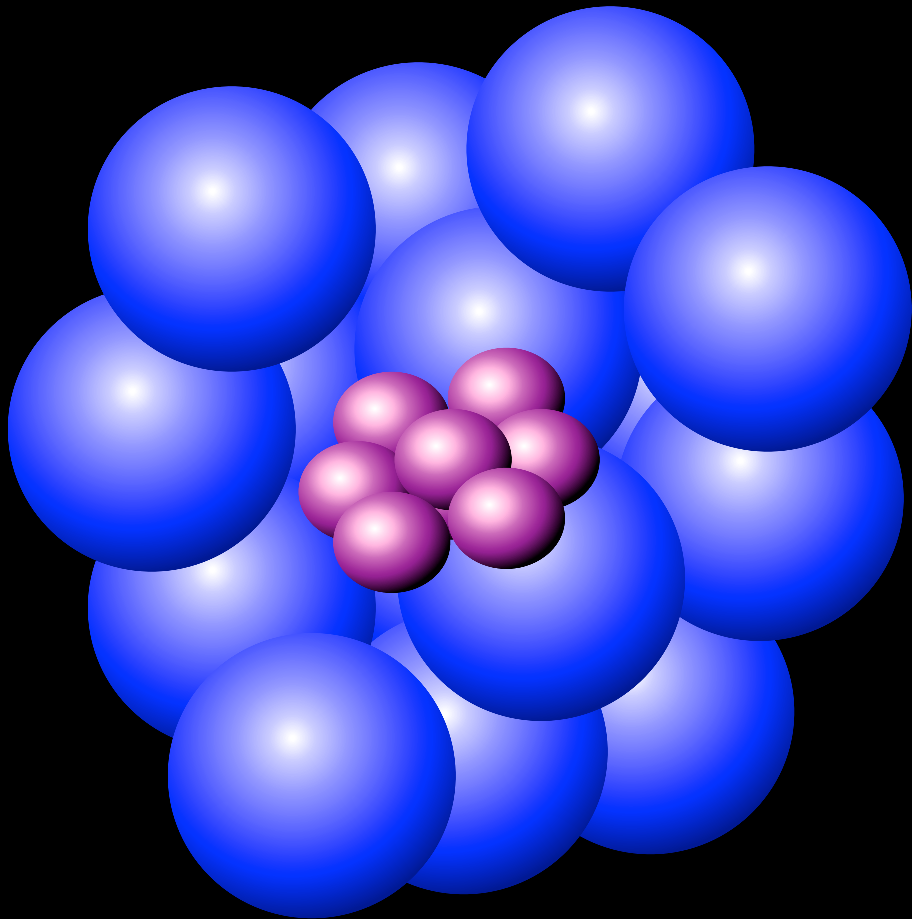
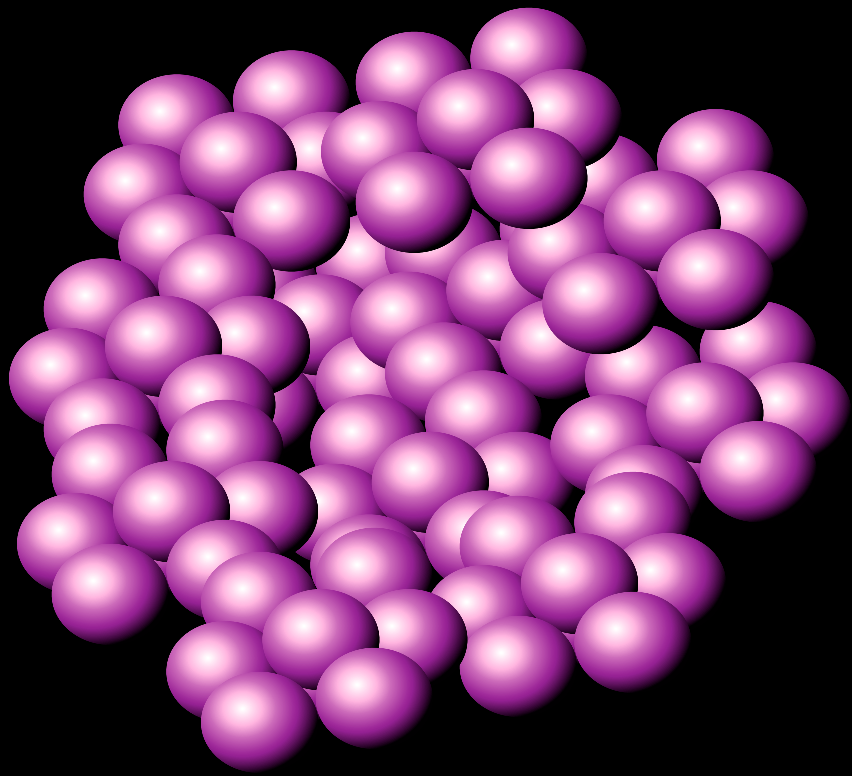


How did the First Stars Form?



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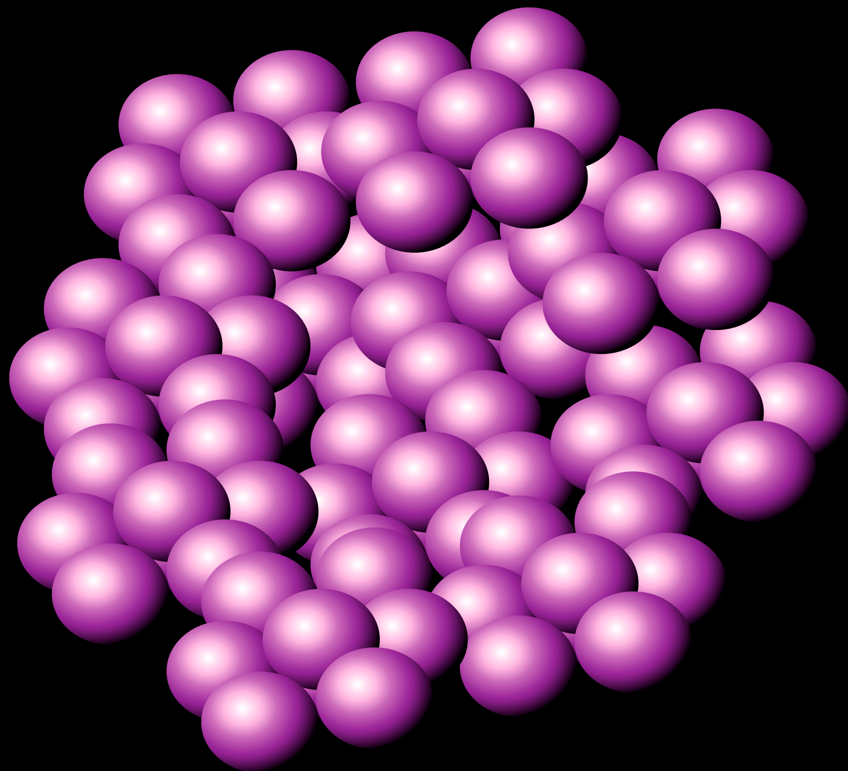

$$M_J = \left(\frac{5kT}{Gm}\right)^{3/2}\left(\frac{3}{4\pi\rho}\right)^{1/2}$$

$$\text{if } \mathrm{M}_{\text{cloud}} > M_J \quad \rightarrow \text{collapse!}$$

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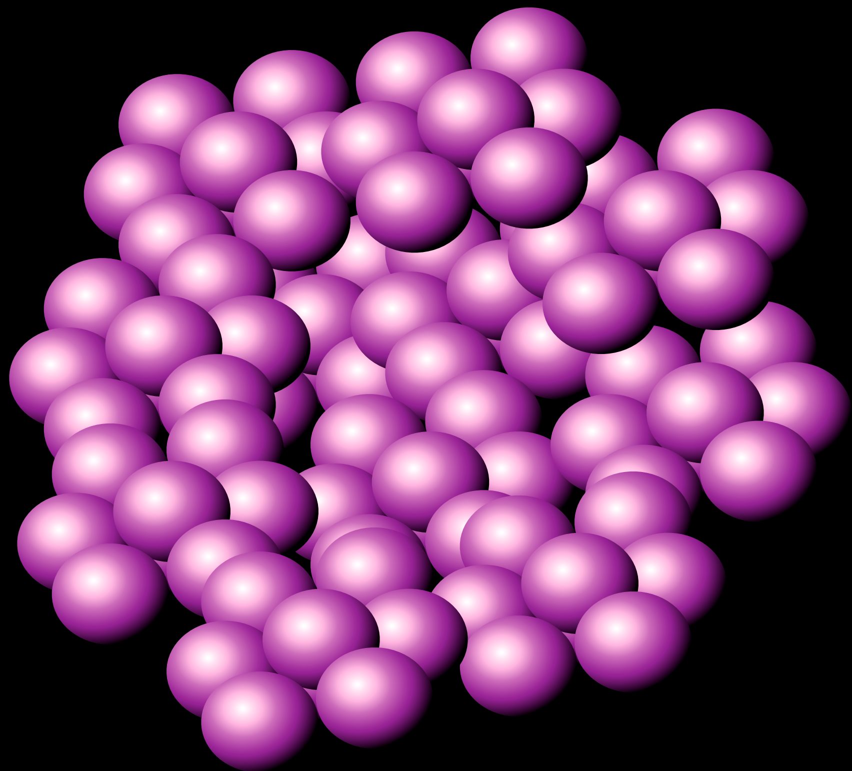

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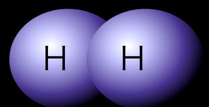

Cooling !!

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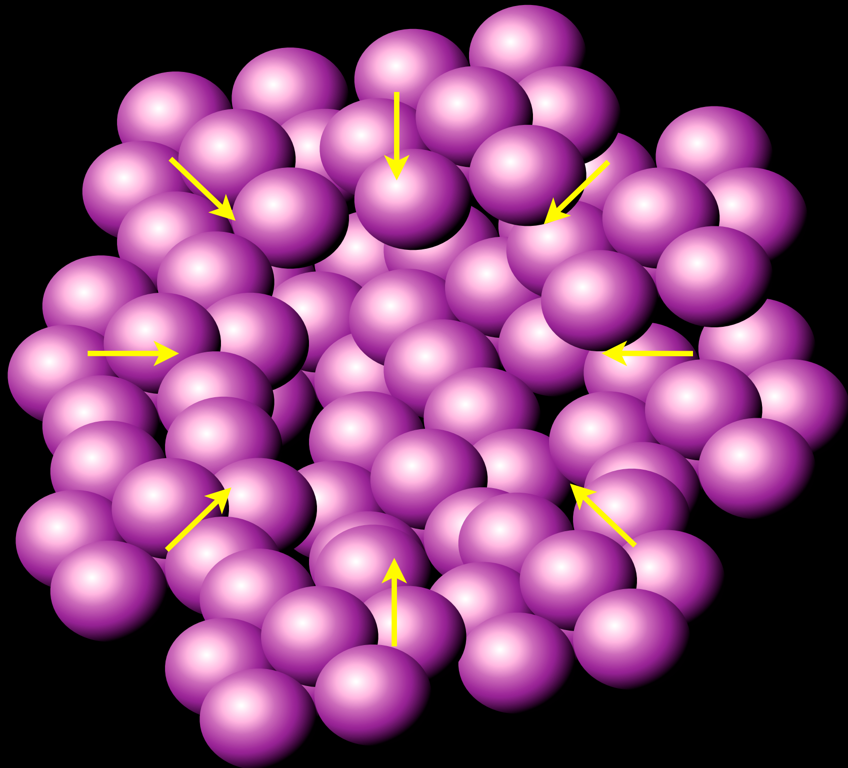

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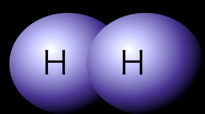

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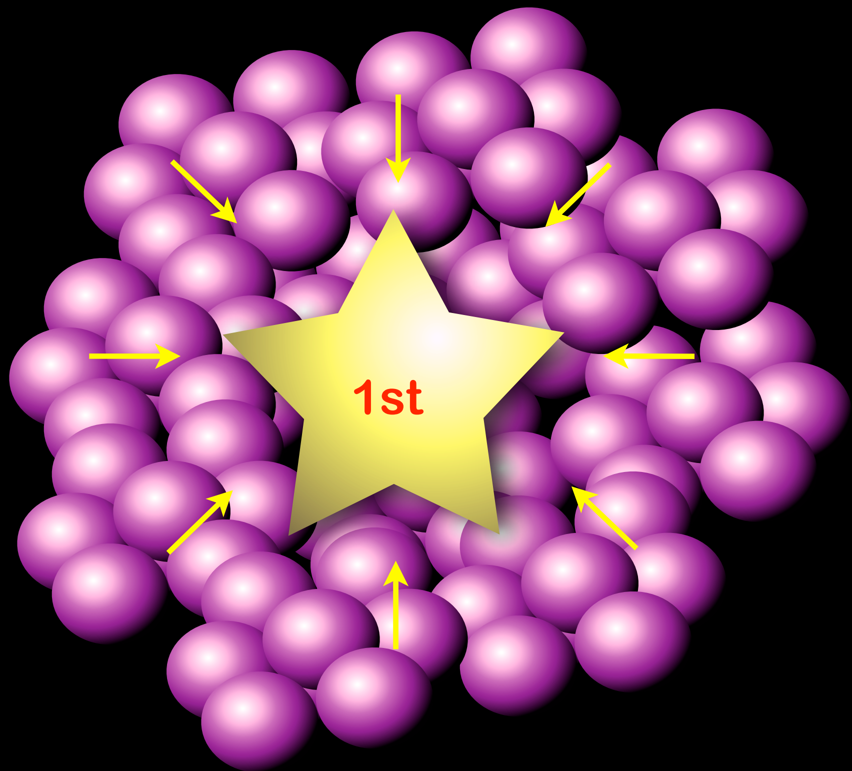

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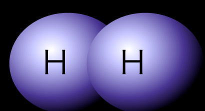

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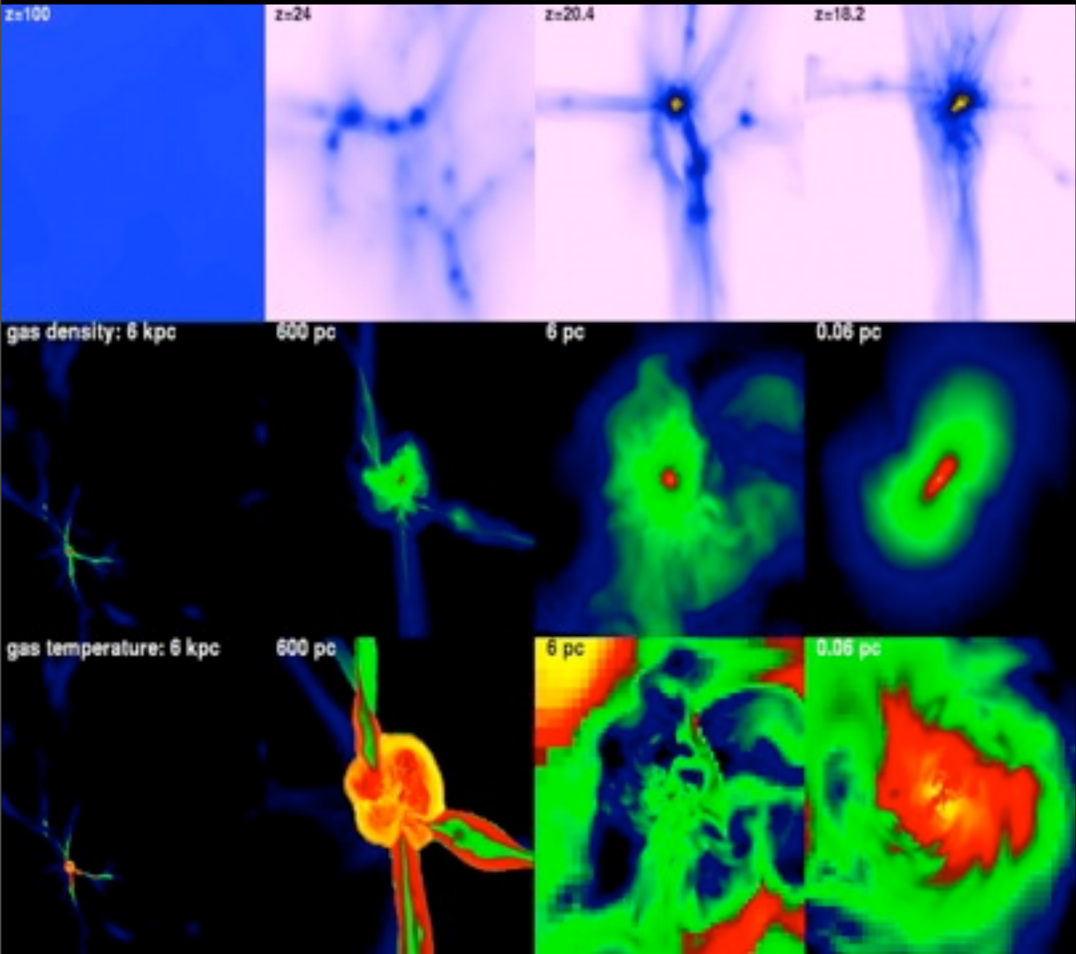
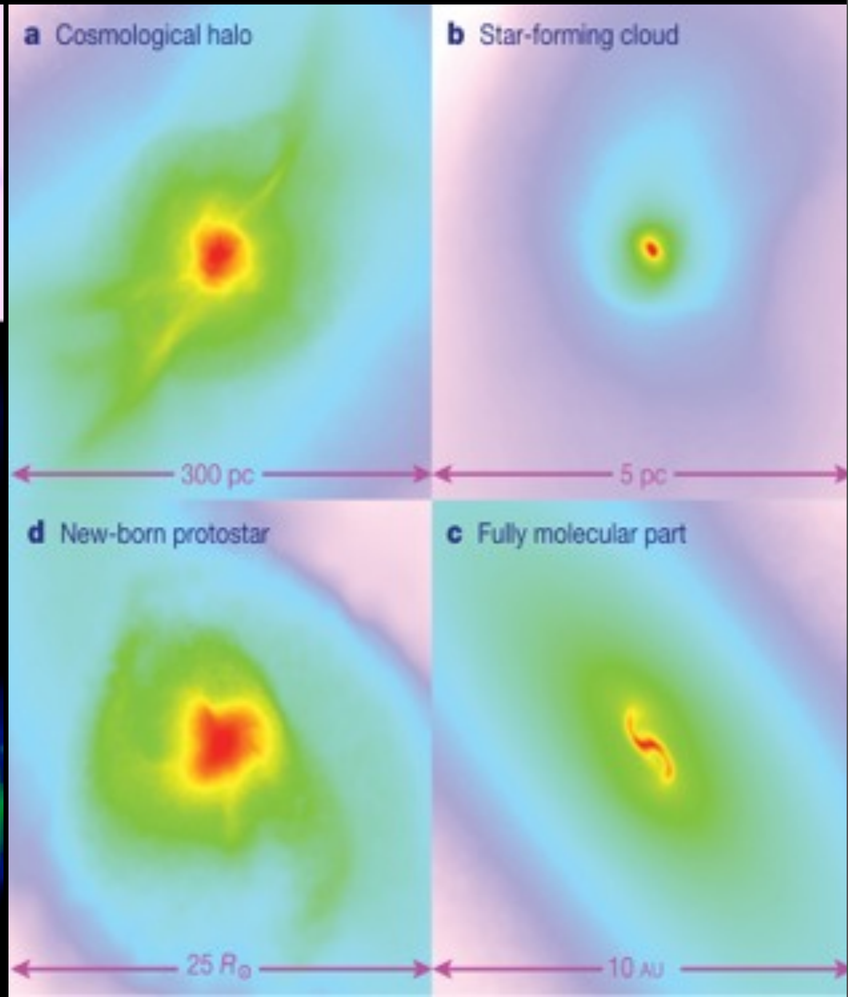
The First Stars



Abel, et al. Science (2002)



Yoshida+ Bromm+others

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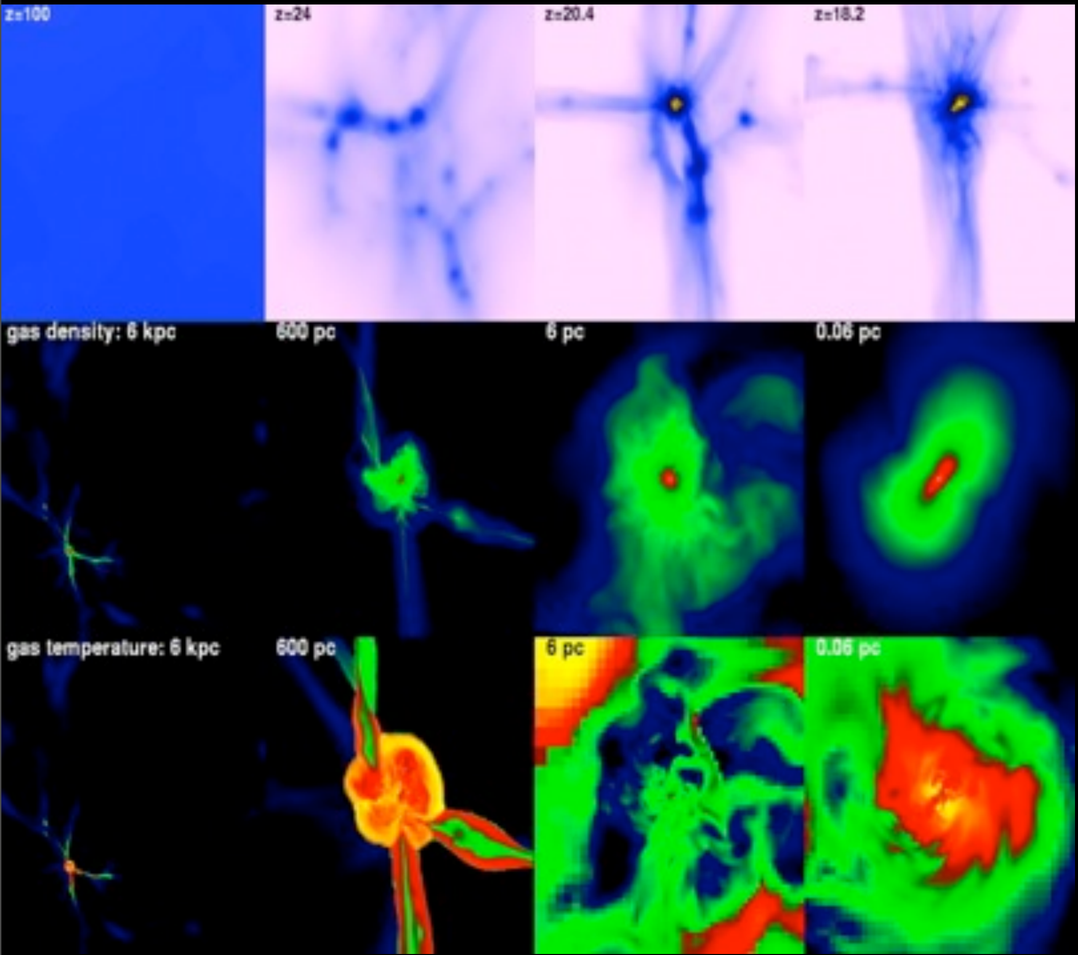

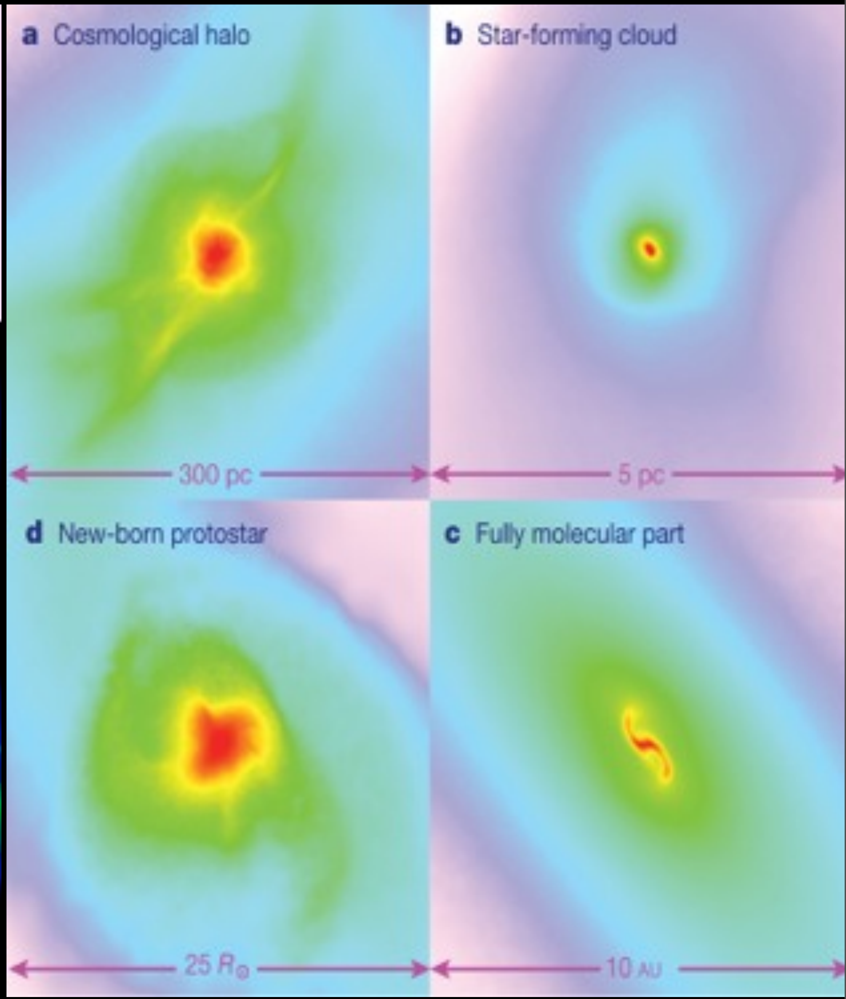

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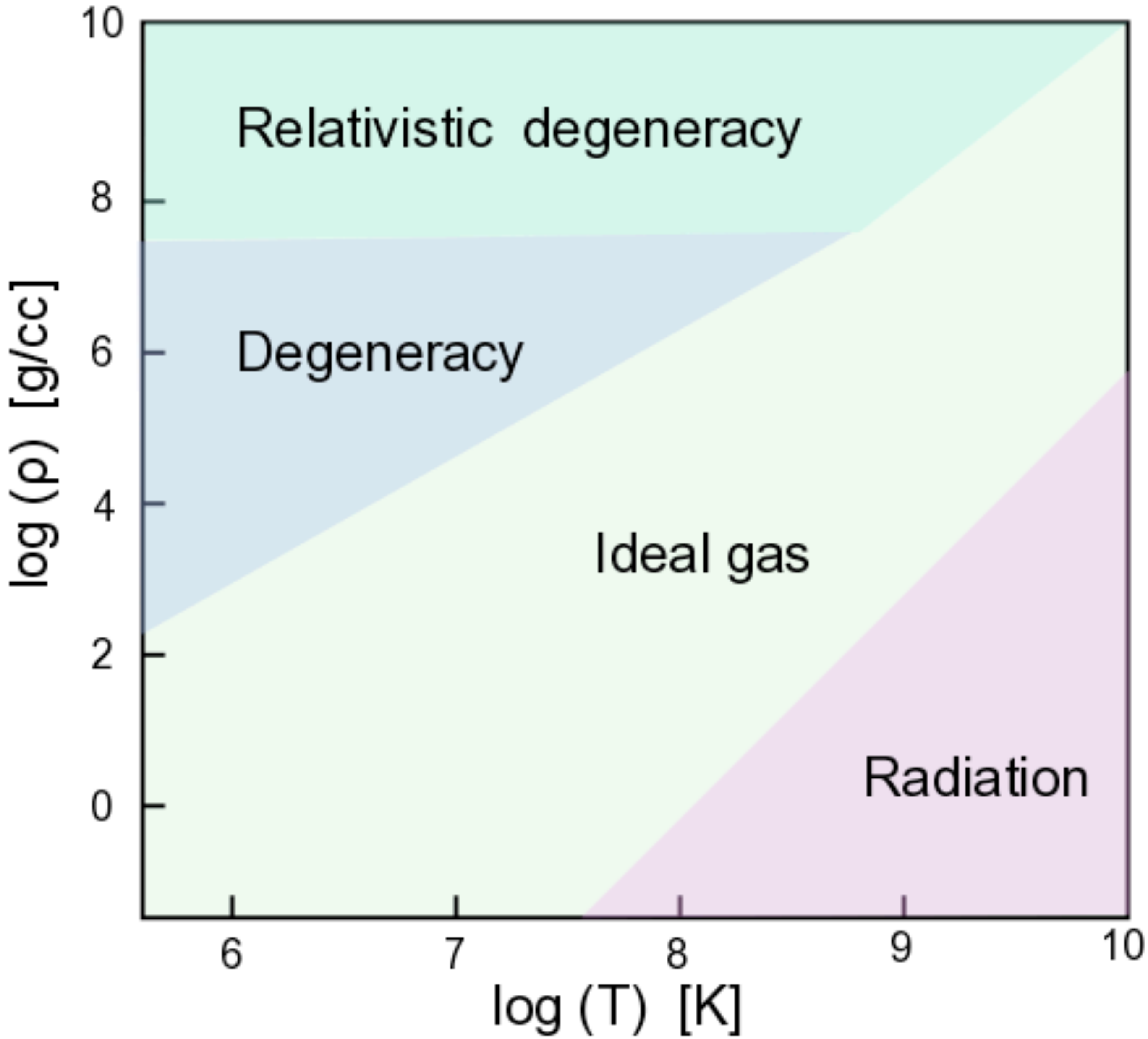
Yoshida+ Bromm+others

Mass Scale ~ 100 $M_\odot$

Temperature-Density Diagram of Stellar Evolution



Data from Prialnik 2000

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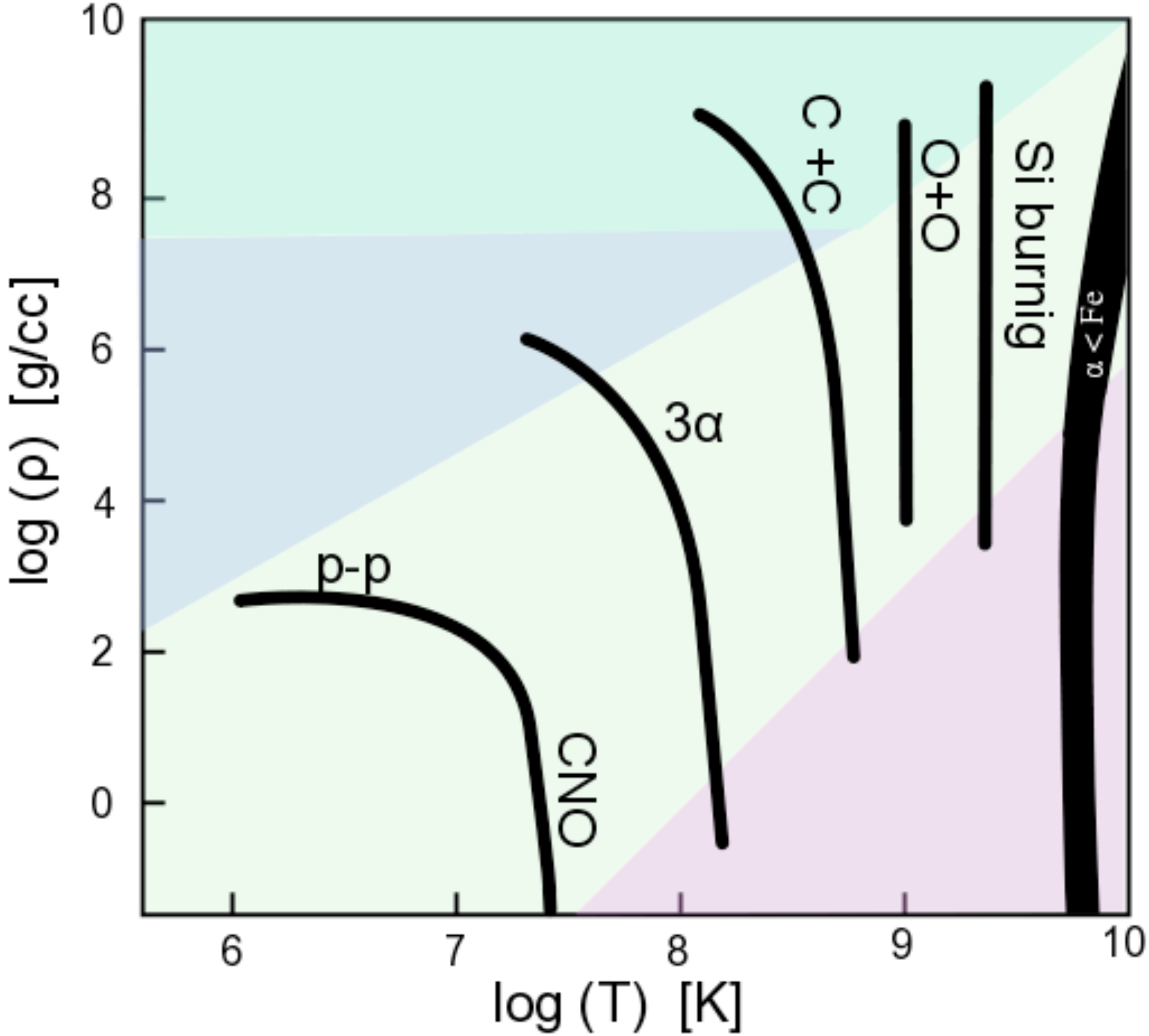

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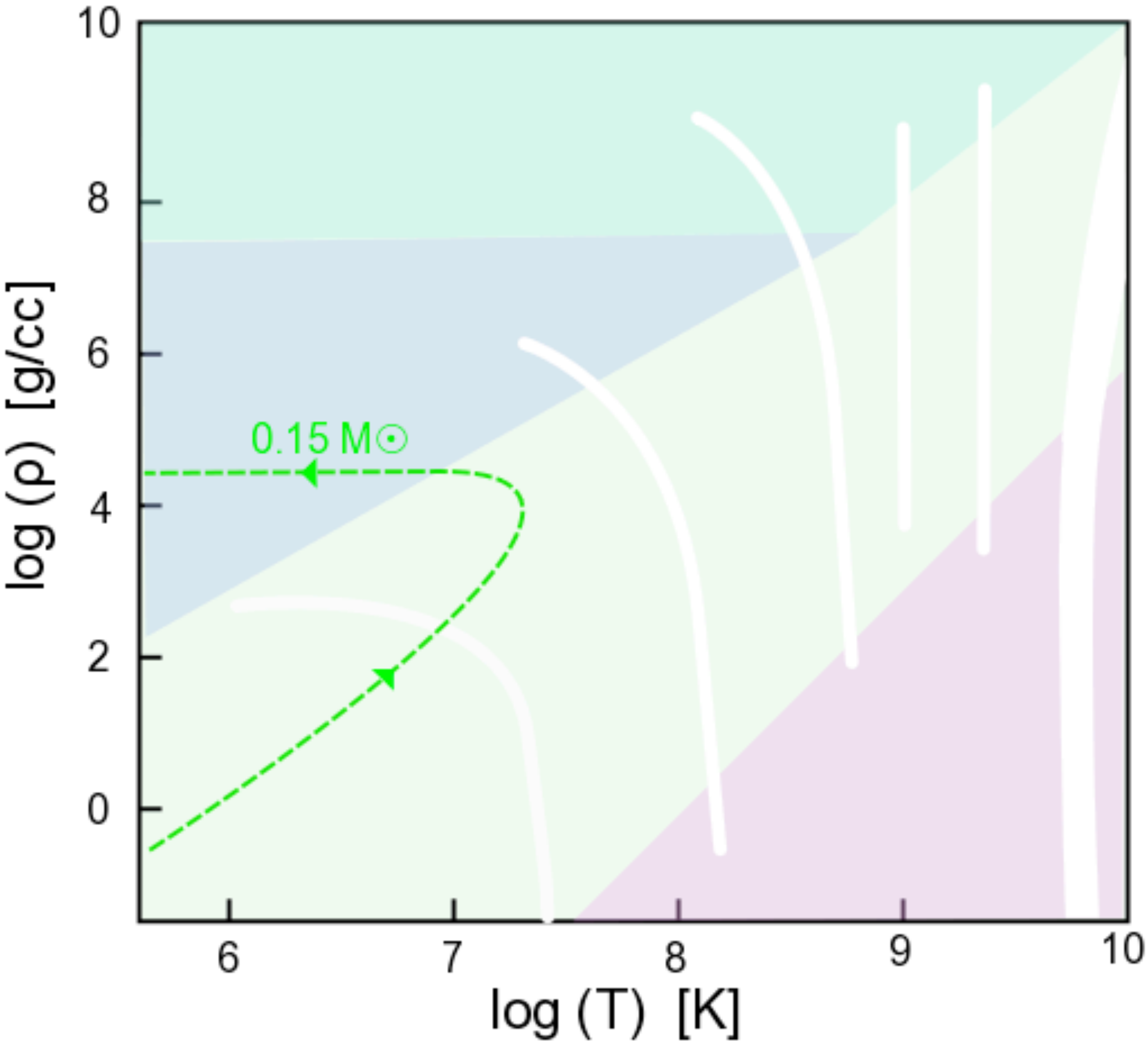

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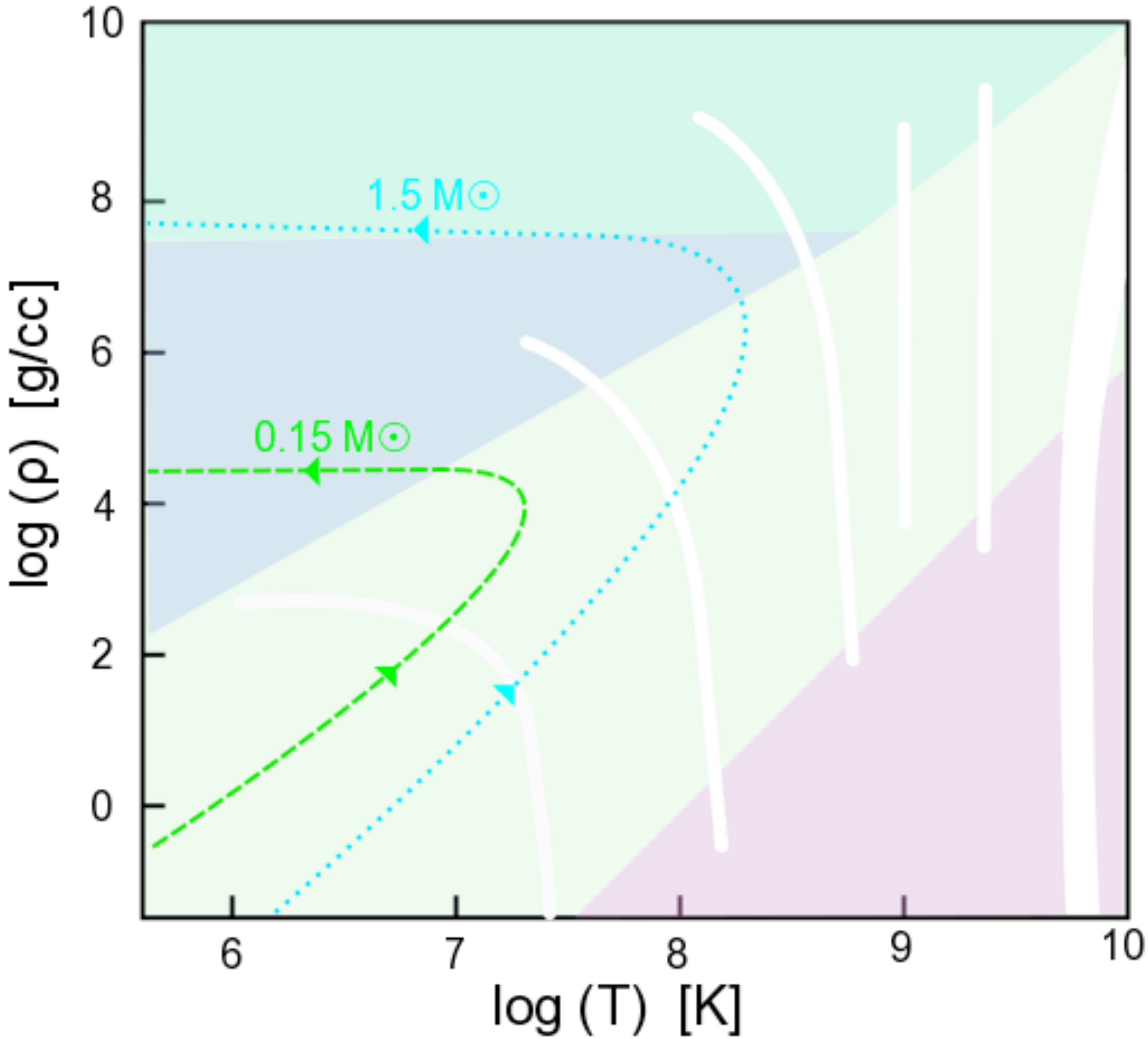

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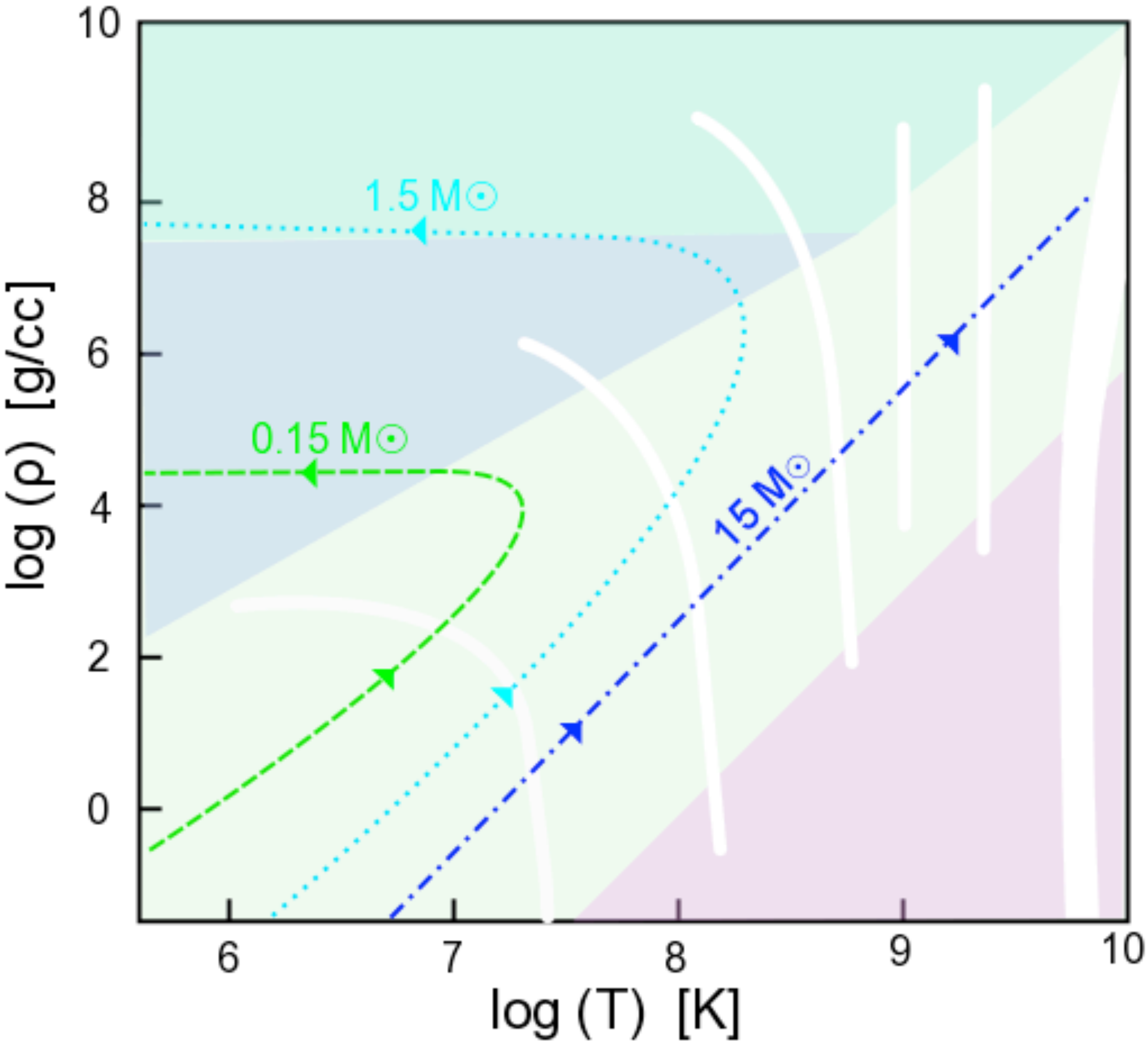

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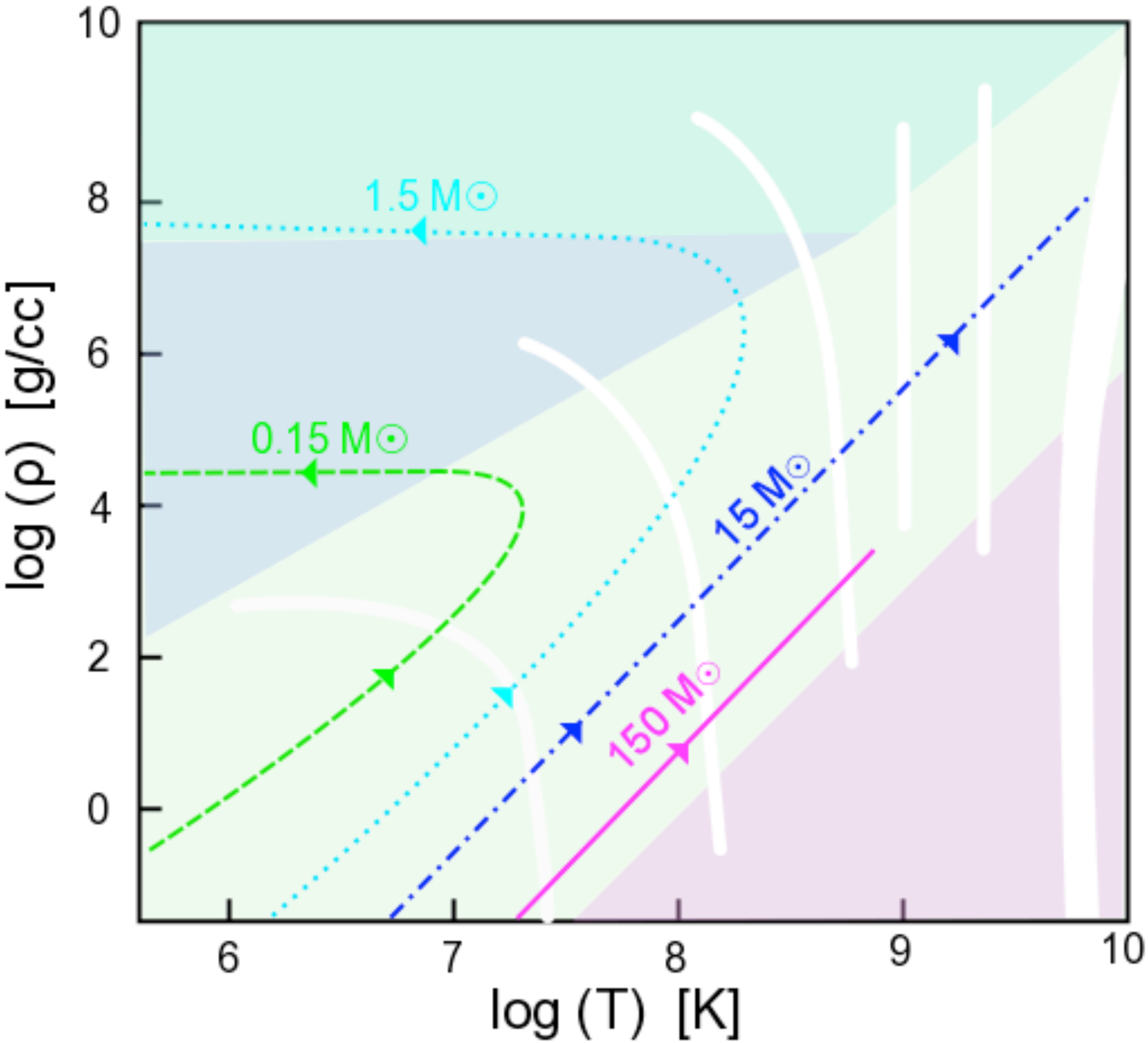

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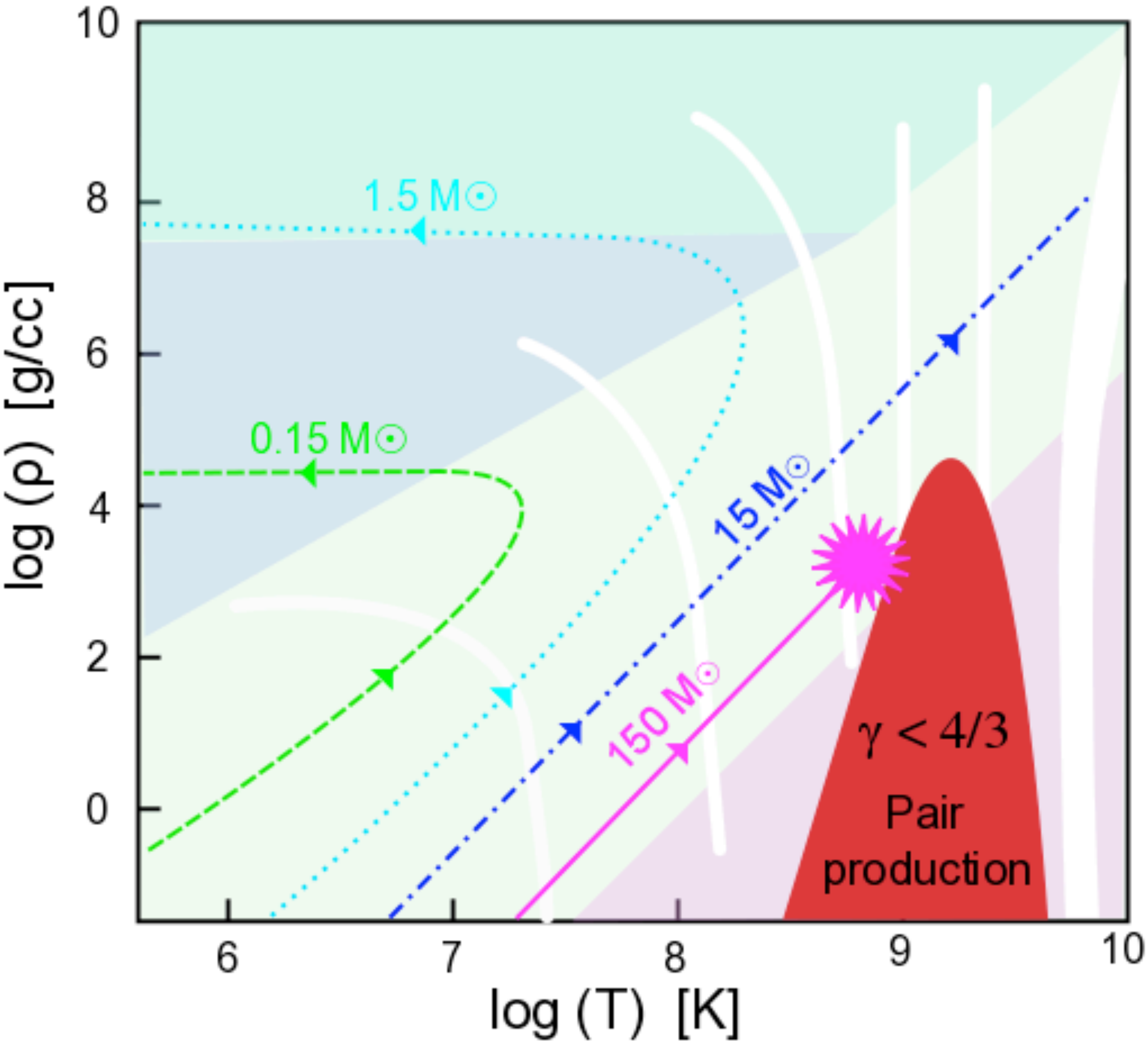

Data from Prialnik 2000

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 ??

Mass Unit: solar mass $\odot$

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Why do We Care about SNe ?

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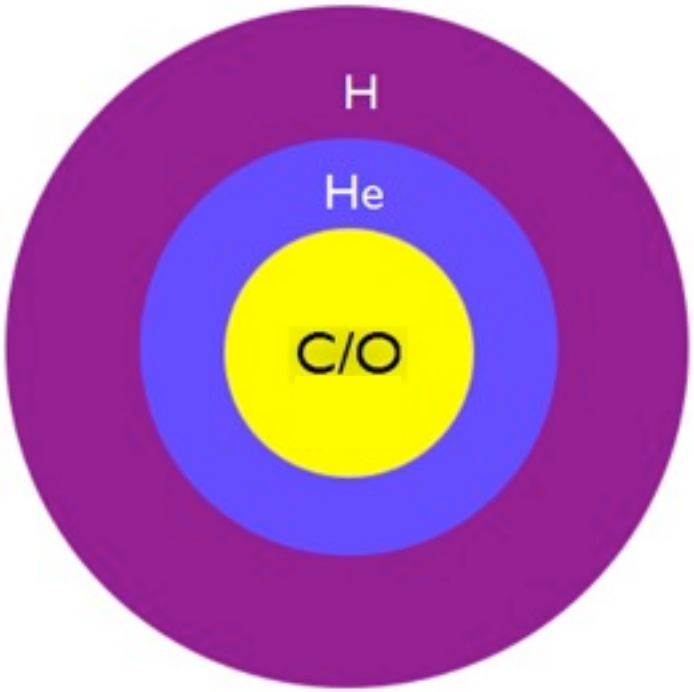
- Fundamental physics (GR, HEP)
- Accessibility in Research (models and observations)

Fate of Very Massive Stars

Star > 80 M☉



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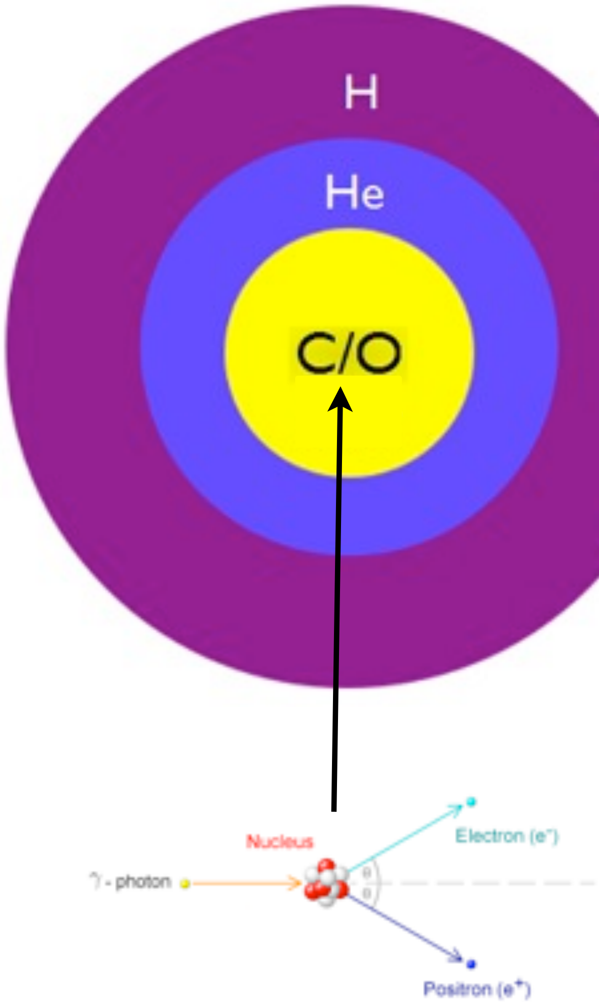

$E_o > 2m_0c^2$, where m_0 is the electron rest mass

Fate of Very Massive Stars

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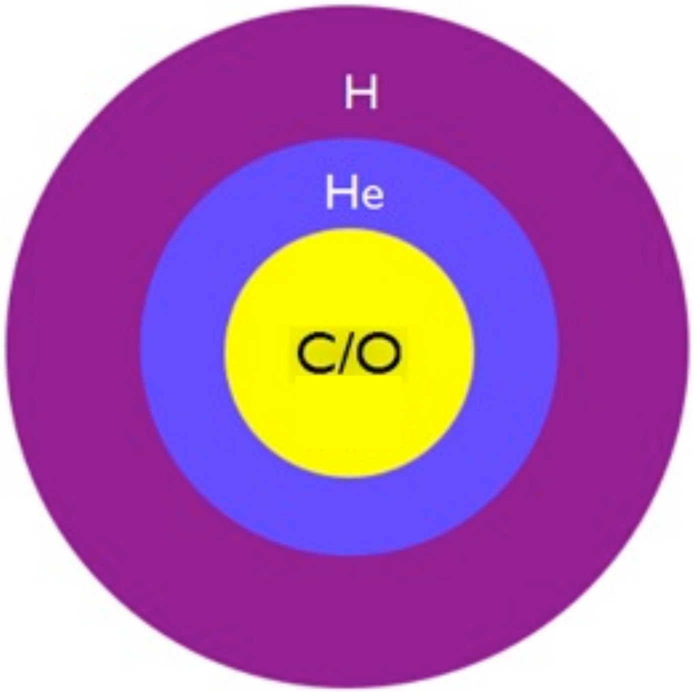

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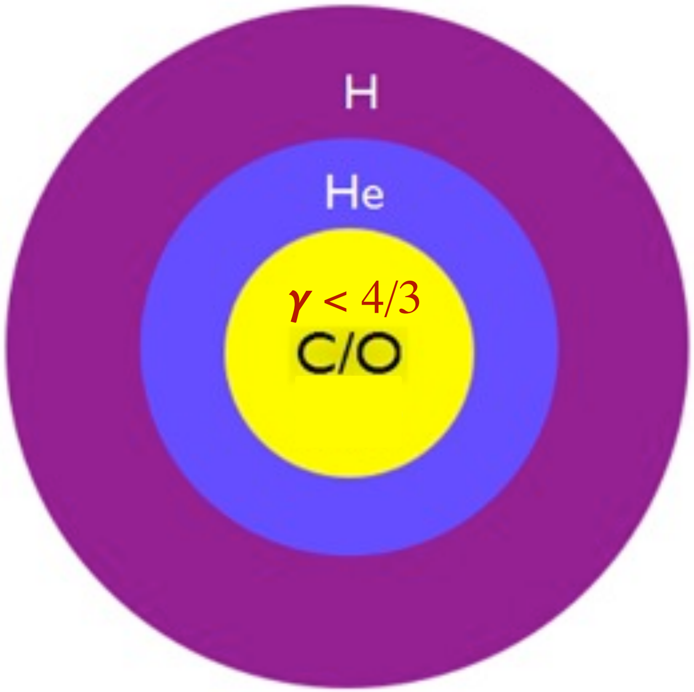

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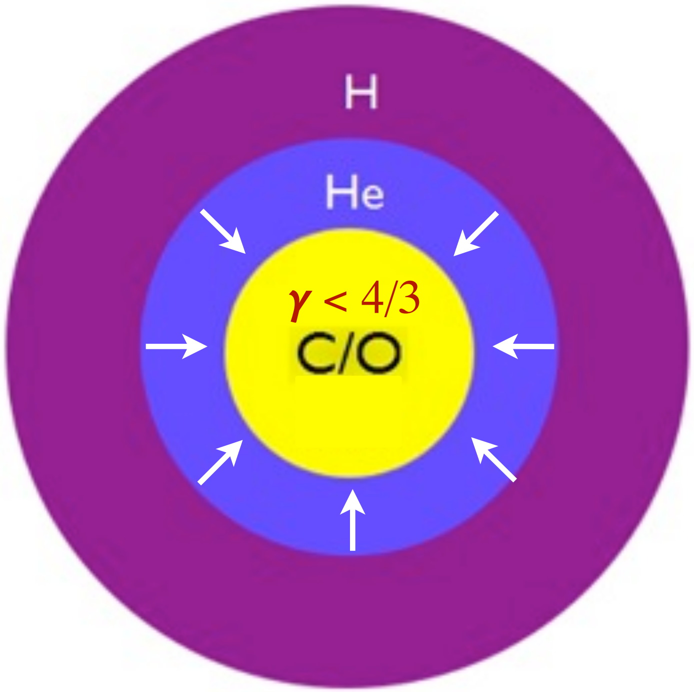

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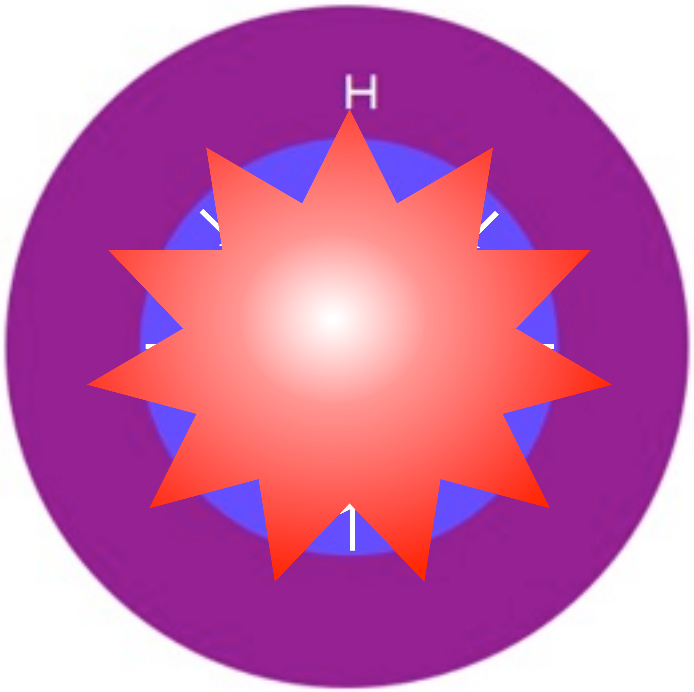


Multi-D SN Simulations

1D Models

80 - 55,000+ $M_\odot$ Stars (Heger & Woosley)

CASTRO

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

Supercomputers

Itasca

Franklin

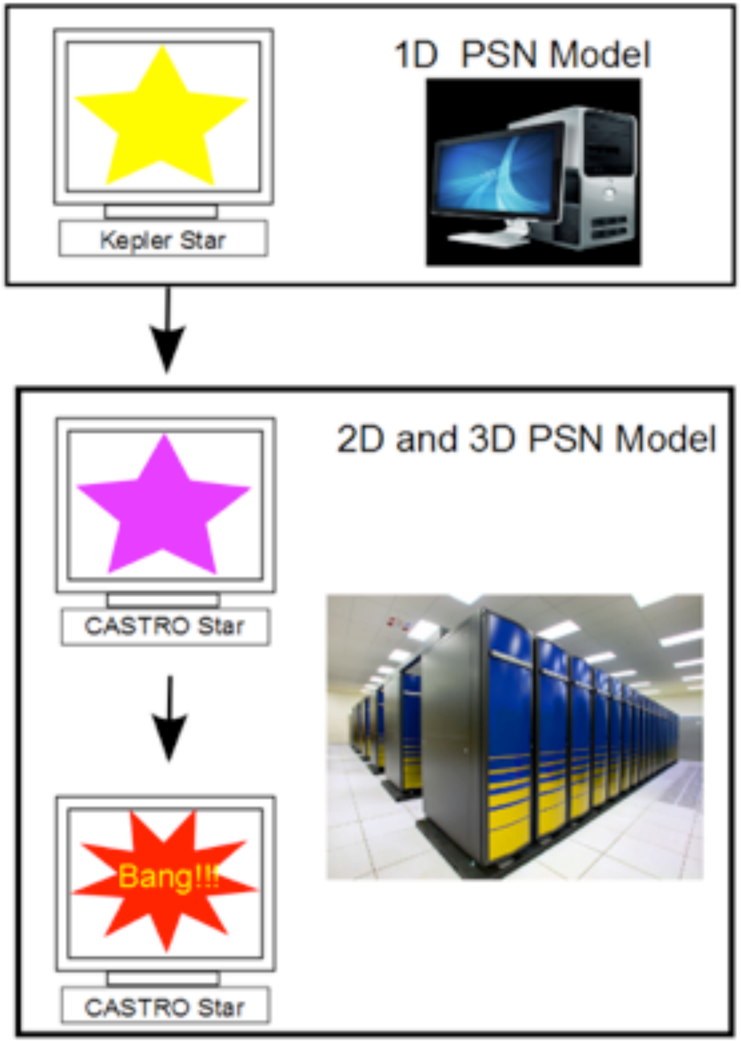
Hopper

Edison

CASTRO needs this big toy !!!

(CASTRO is massively running on XC30 now)

Numerical Setup



Why Using Multi-D Simulations ?

Rayleigh–Taylor instability

Courtesy of Volker Springel (AREPO code, 2009)

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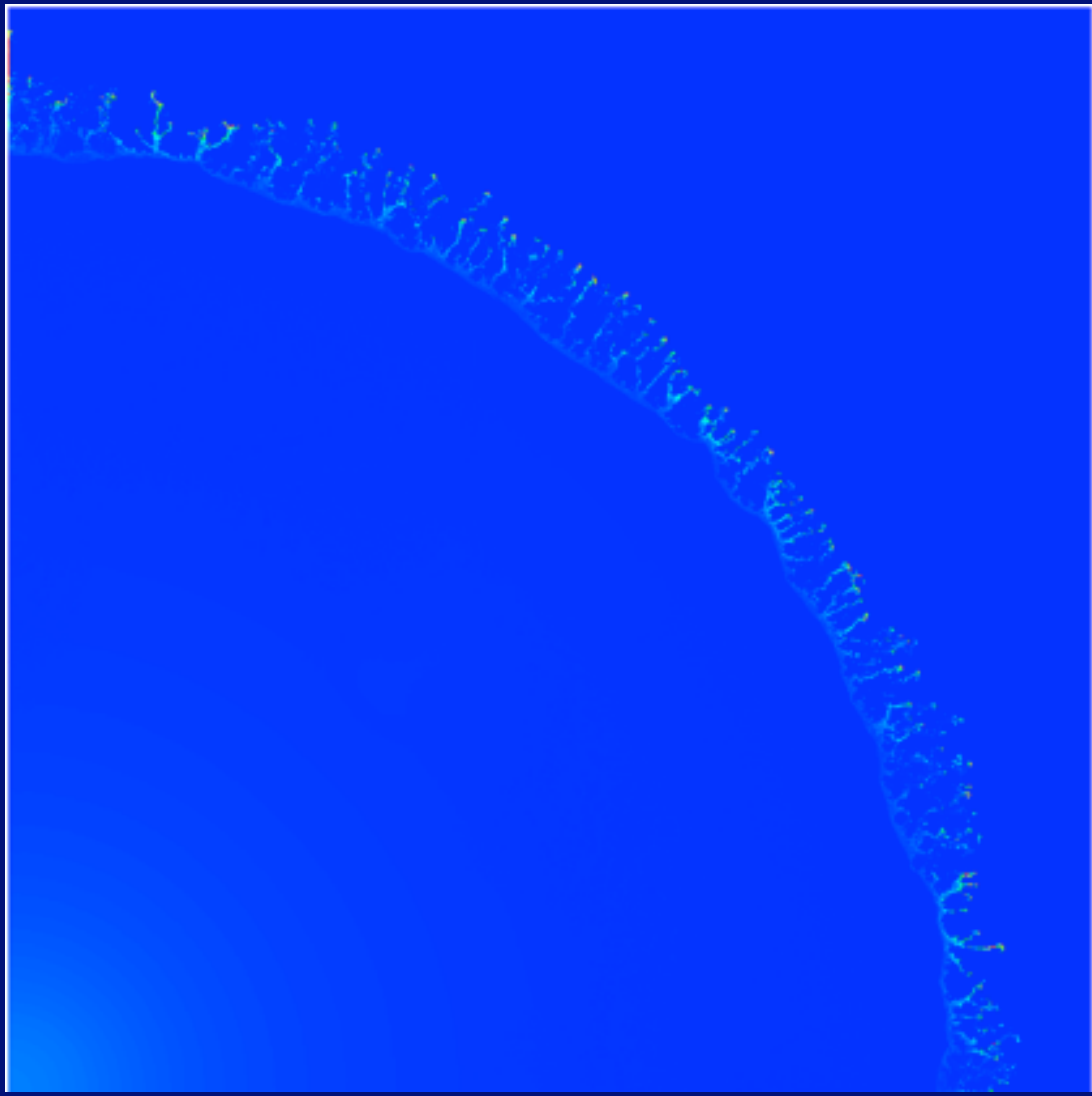
2D Resolution of CASTRO



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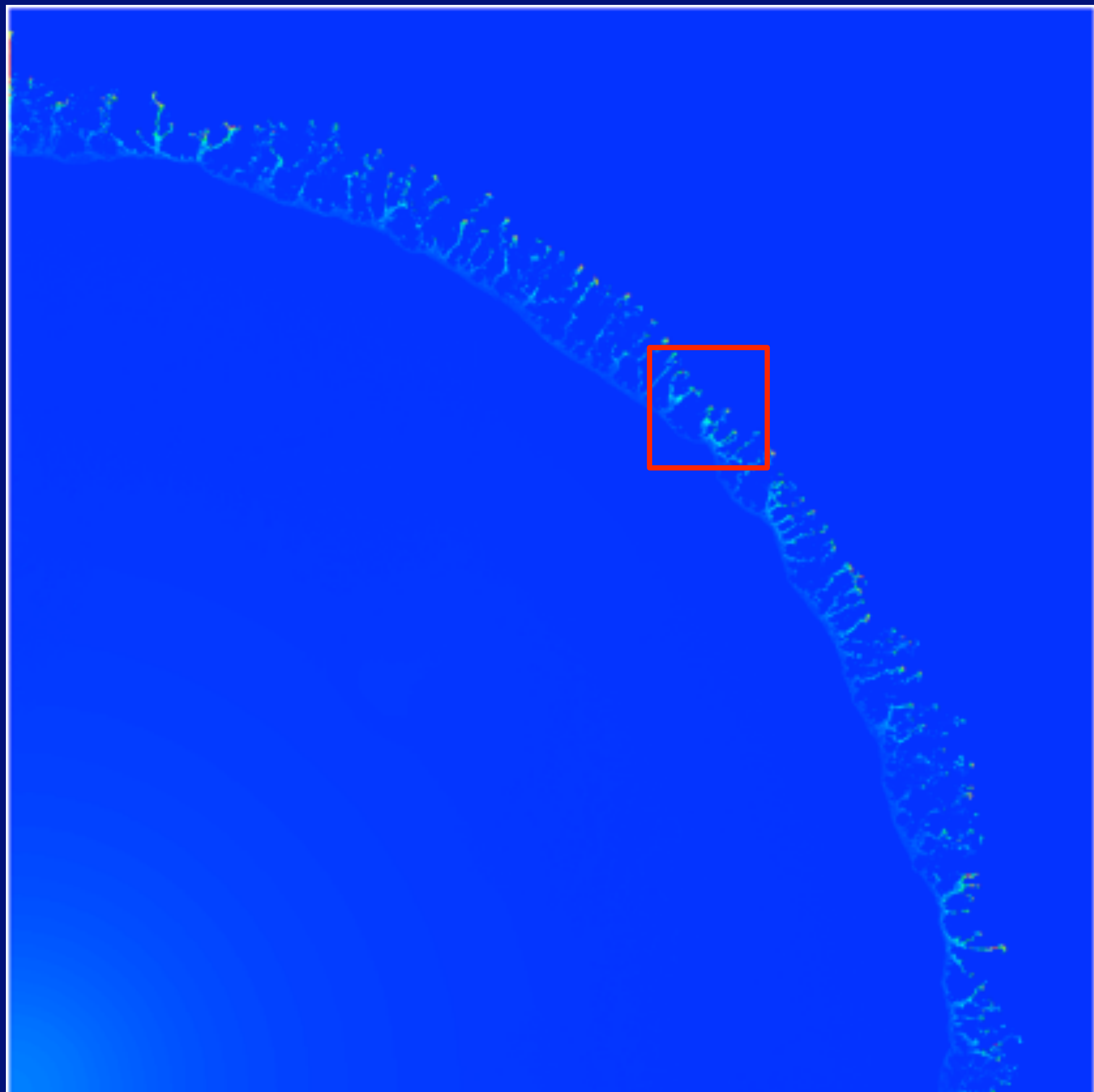

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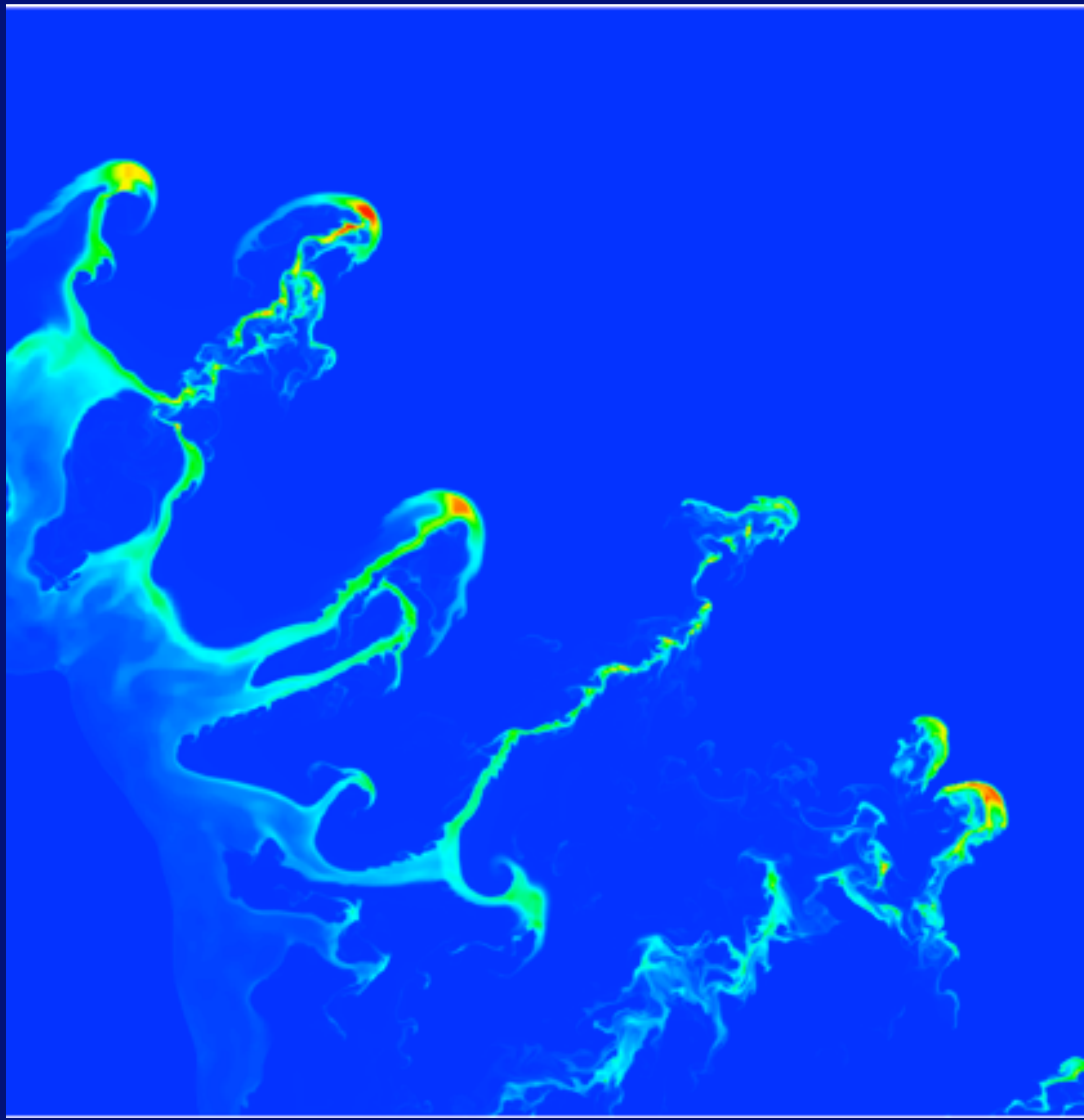

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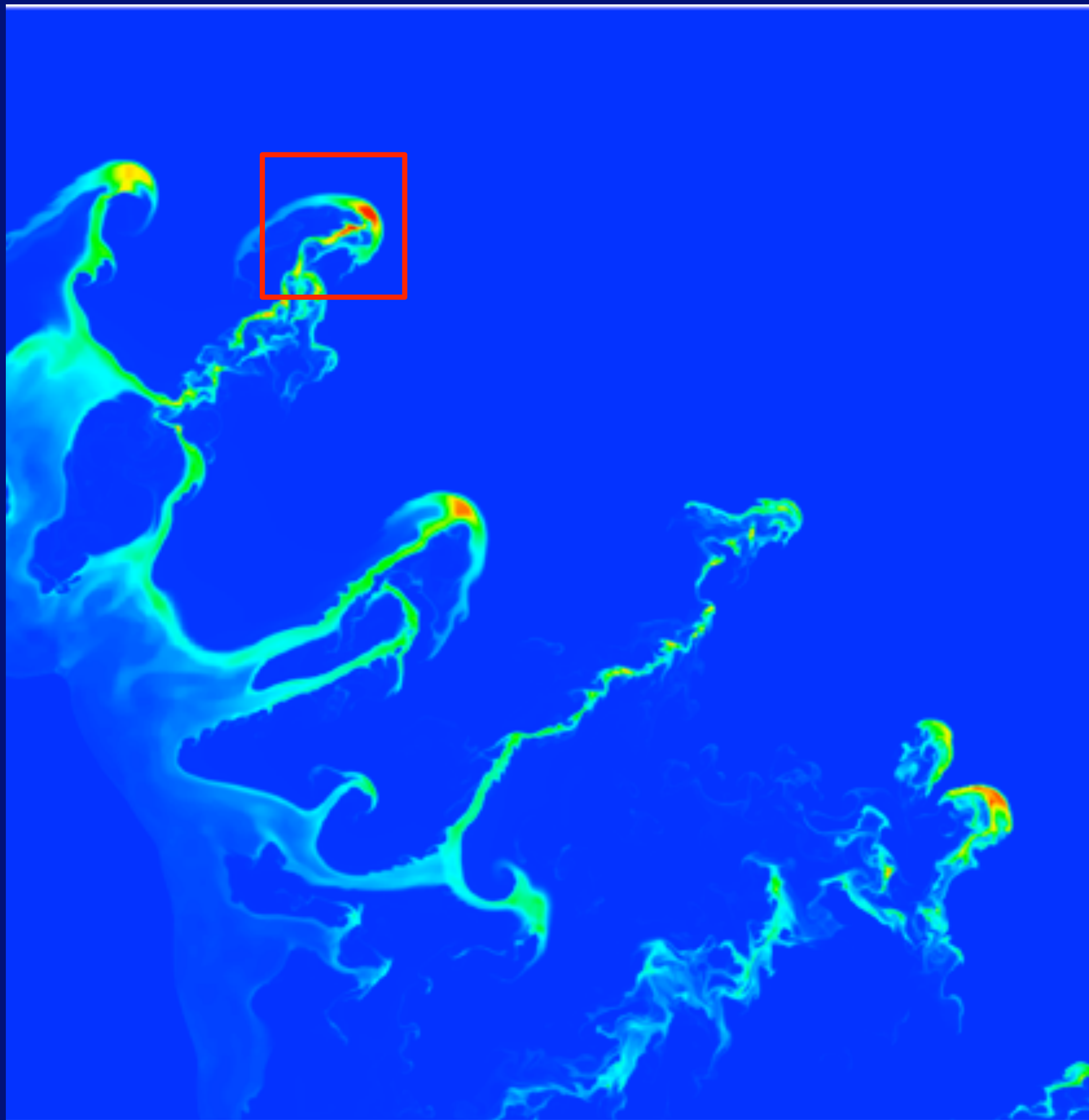

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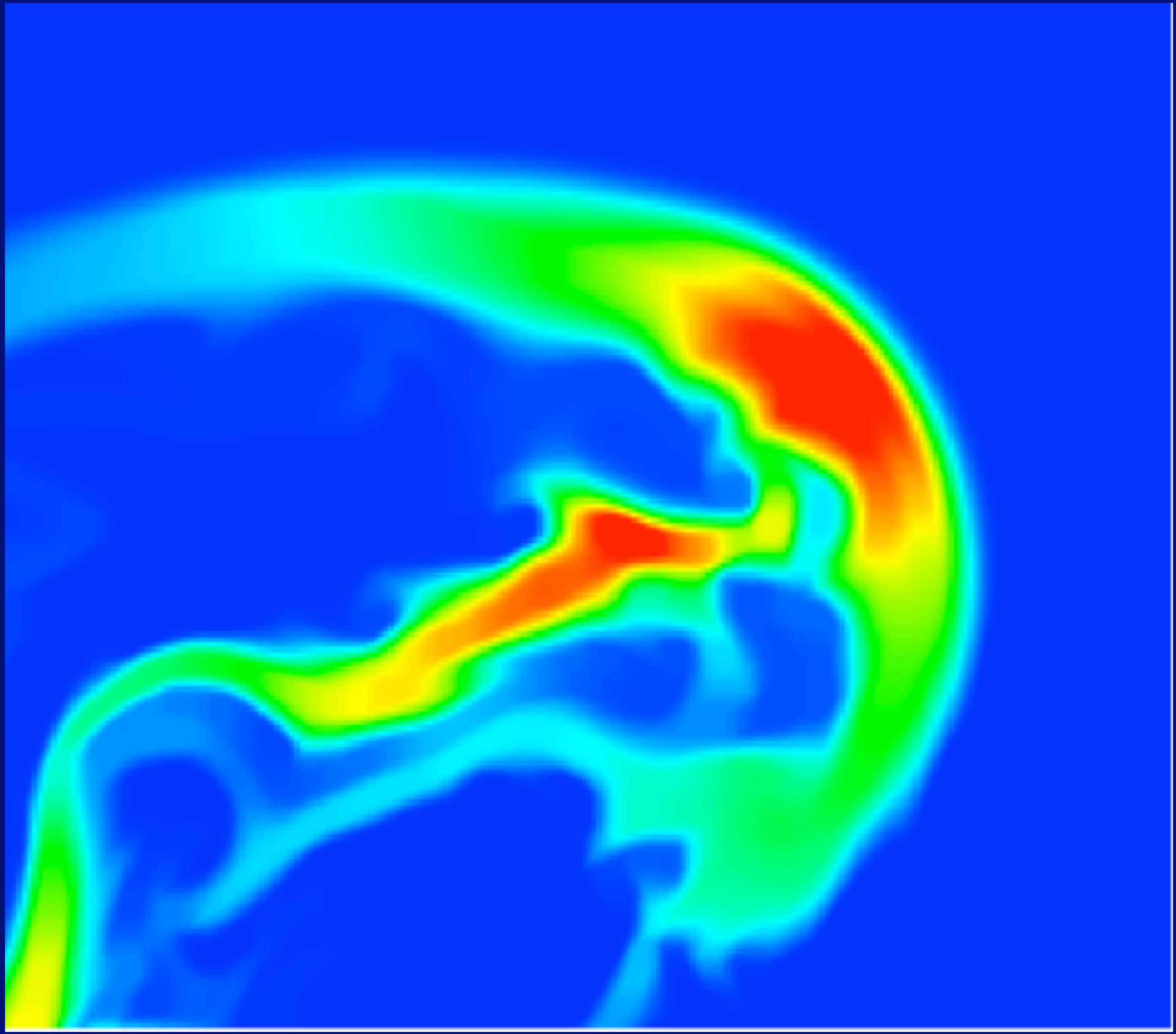
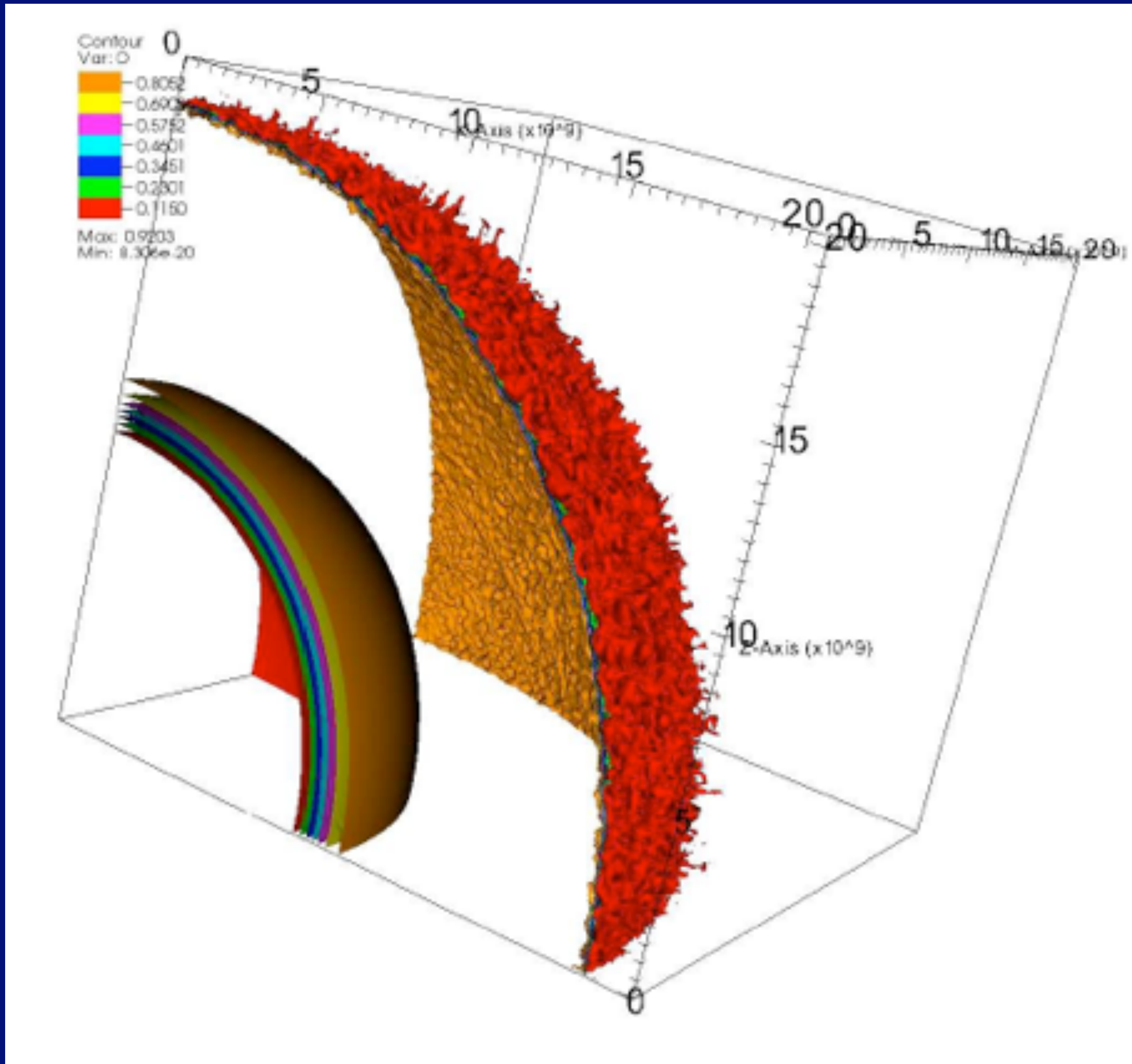


3D Resolution of CASTRO !



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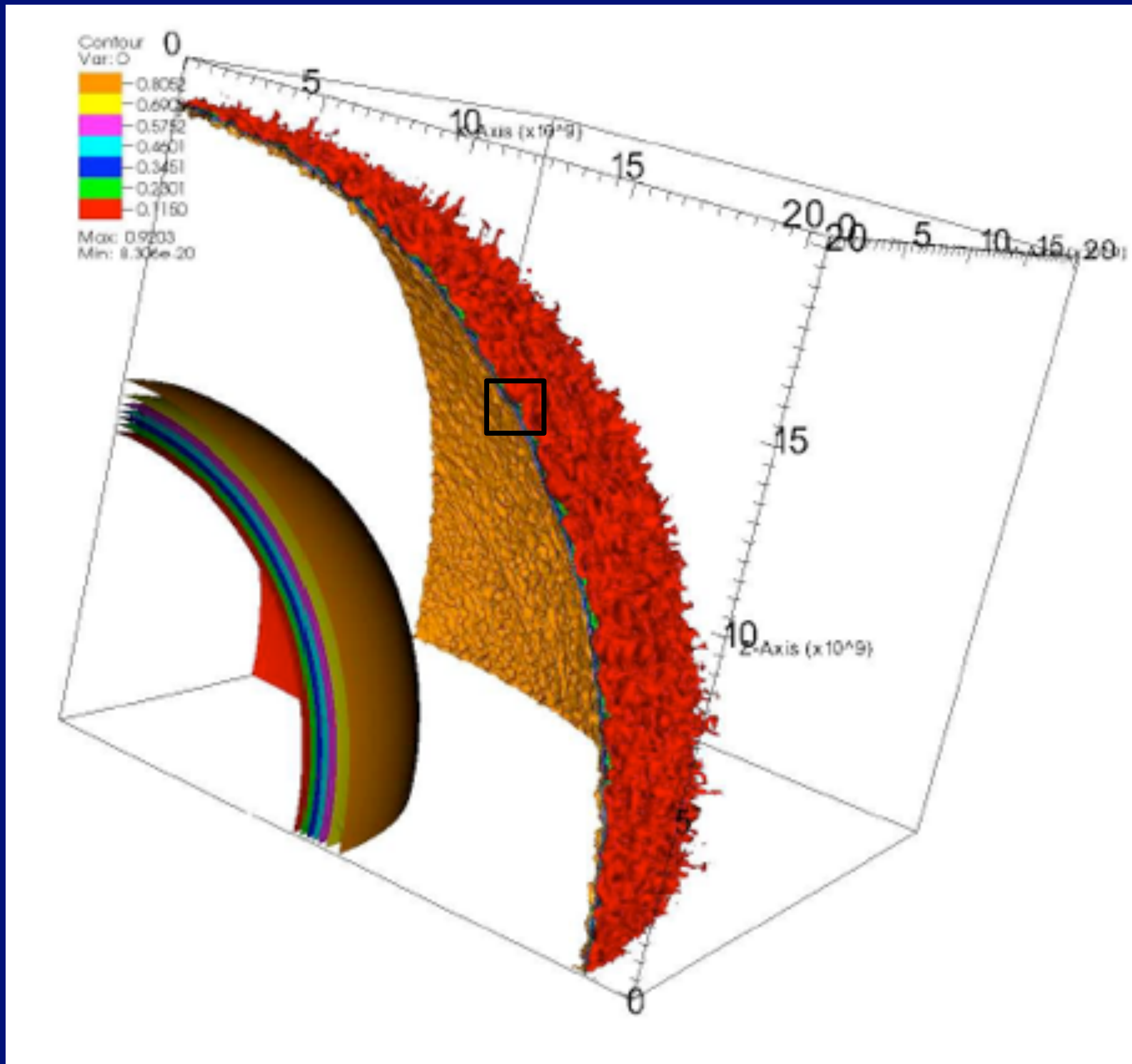

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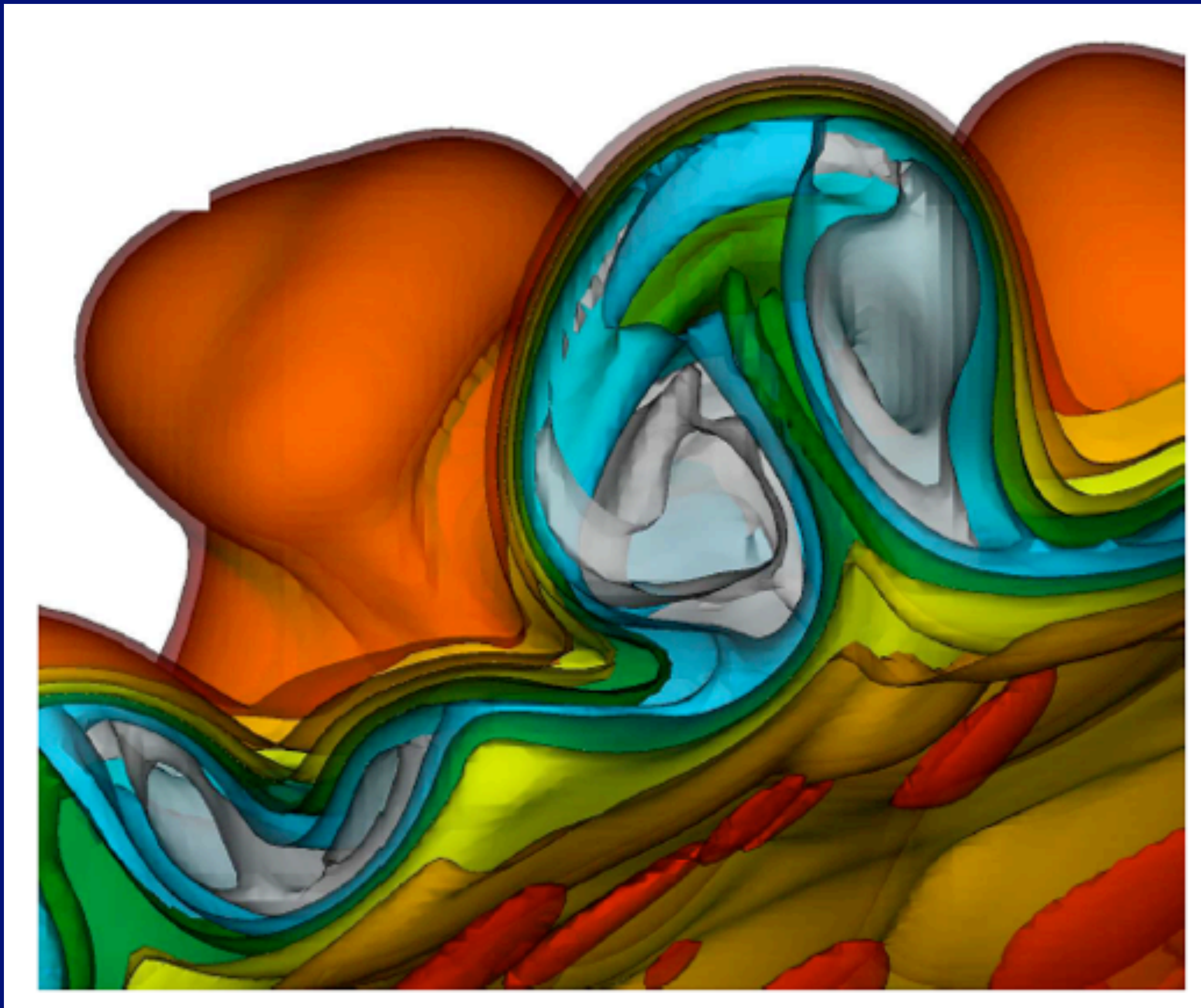
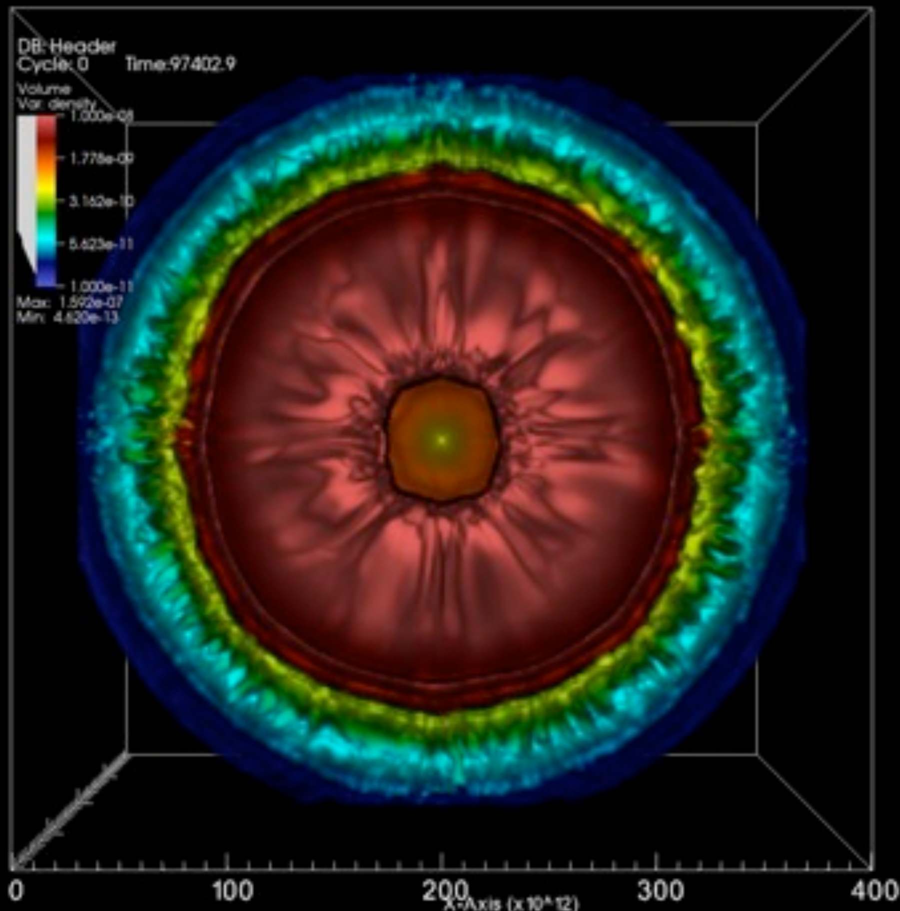
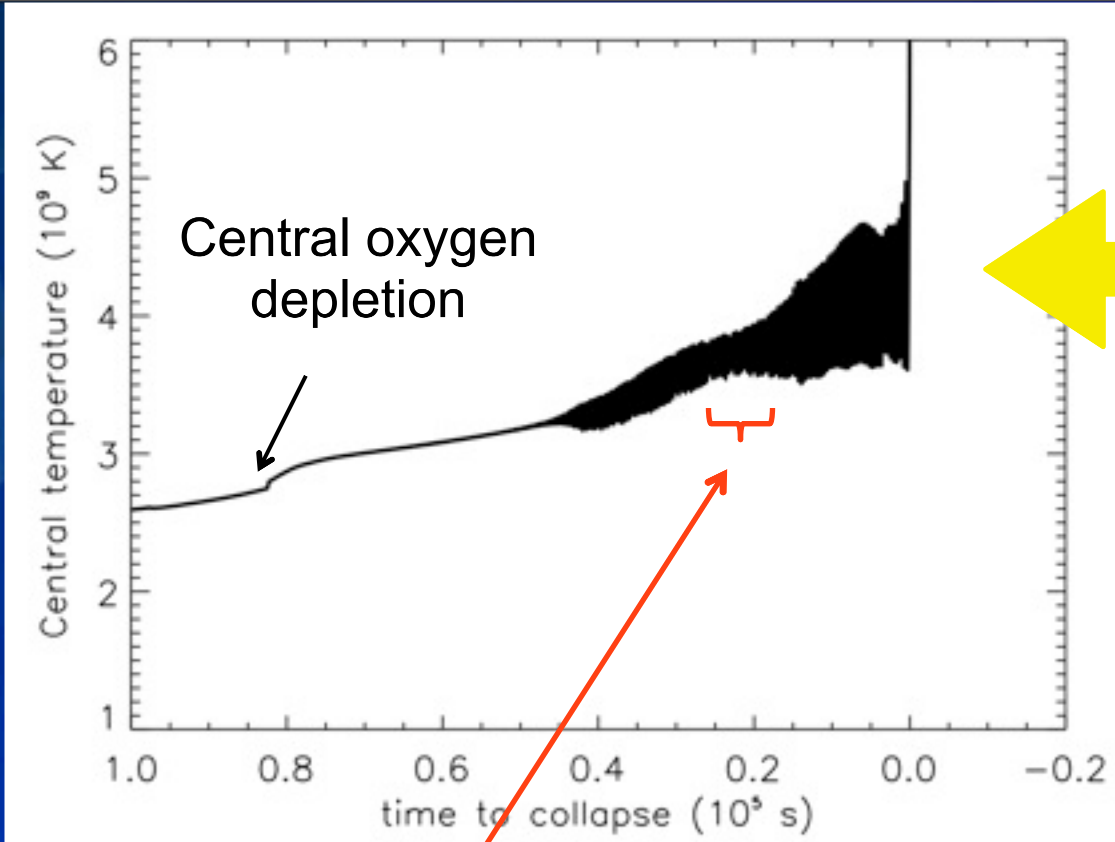


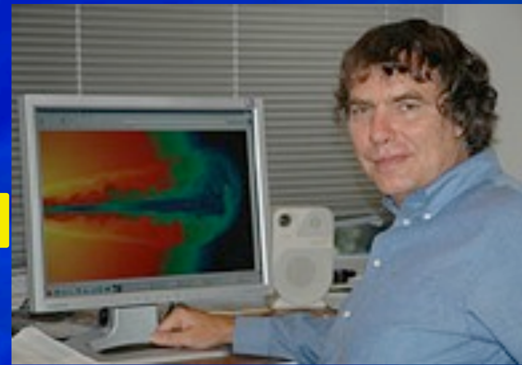
Pulsational Pair-Instability Supernovae (PPSNe)

150 M⊙ > M* > 80 M⊙

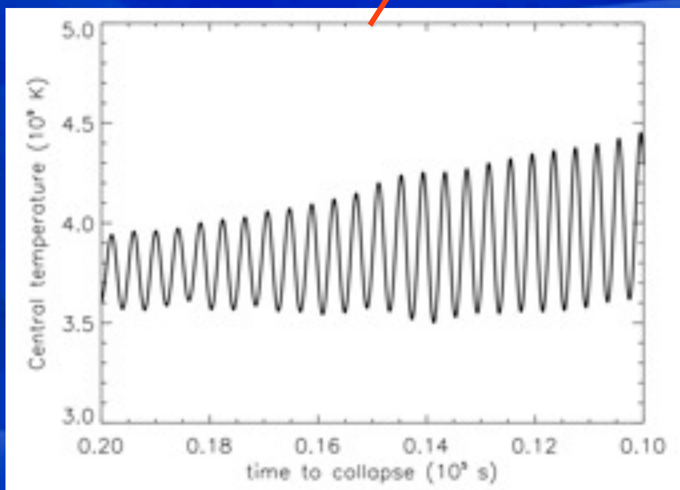


Chen+ ApJ 792 28 (2014)





Based on Stan’s Model

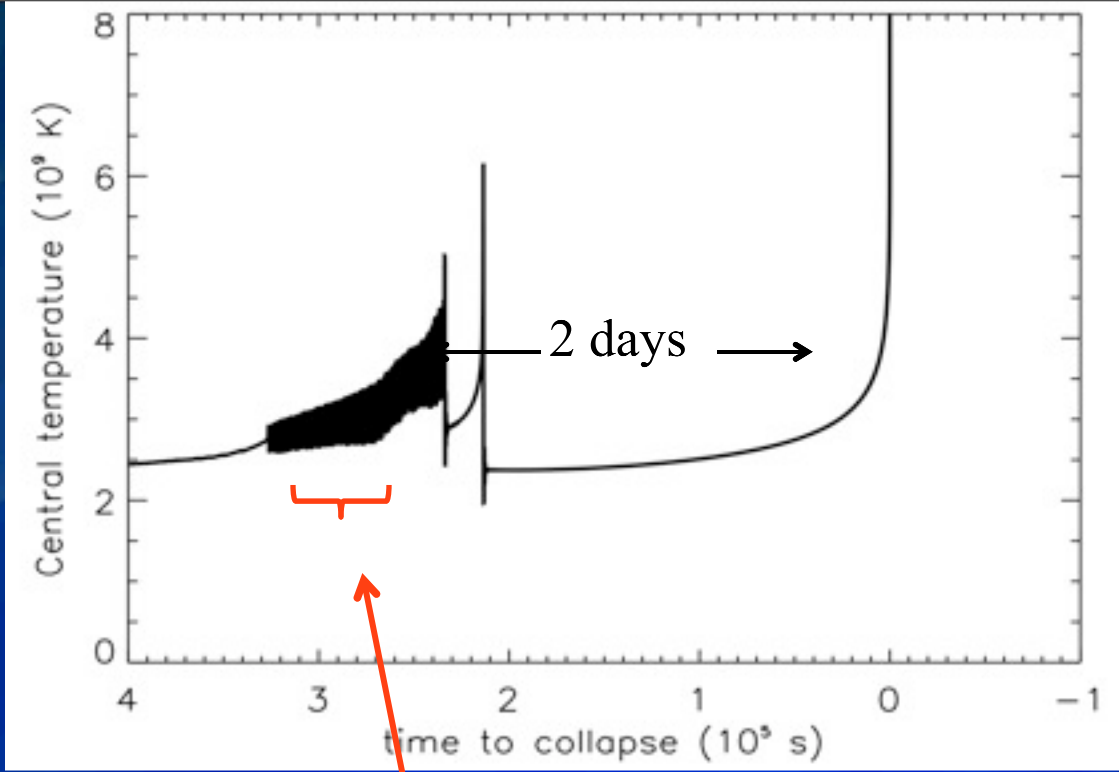


80 M⊙ Helium core 35.7 M⊙

Pulsational instability begins shortly after central oxygen depletion when the star has about one day left to live (t = 0 here is iron core collapse).

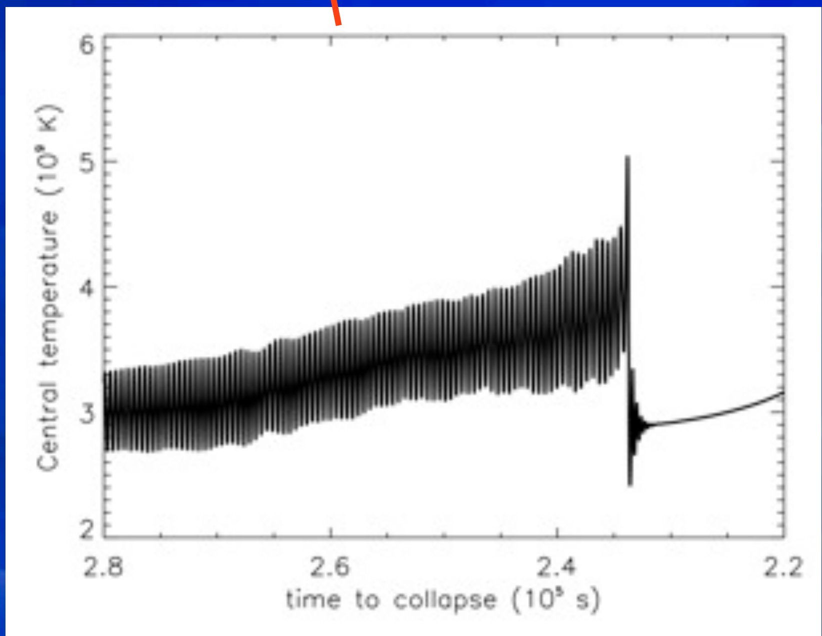
Pulses occur on a hydrodynamic time scale for the helium and heavy element core (~500 s).

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

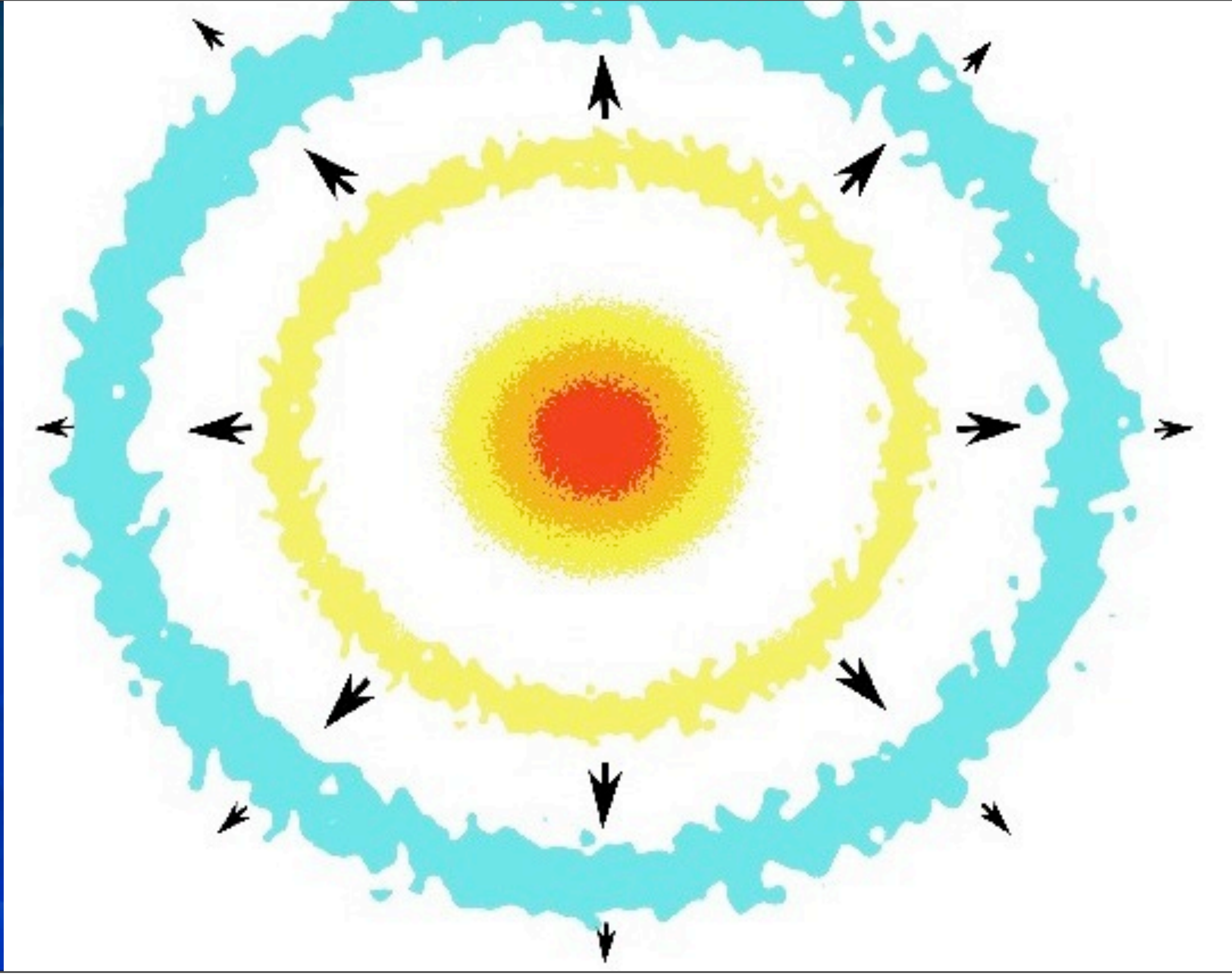


90 M⊙
Helium core 41.3 M⊙

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.



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

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)

Physical Properties of Colliding Shells

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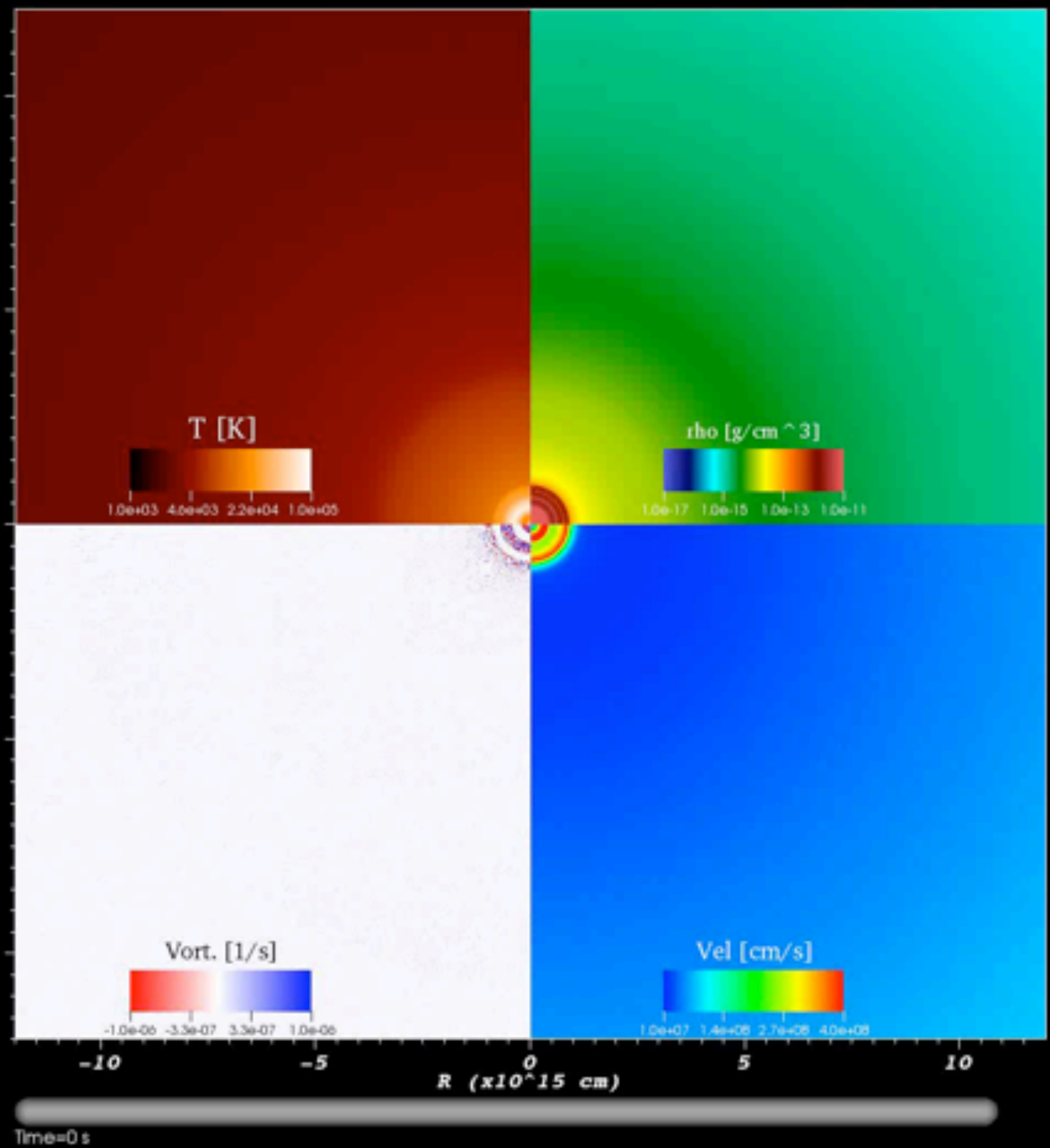

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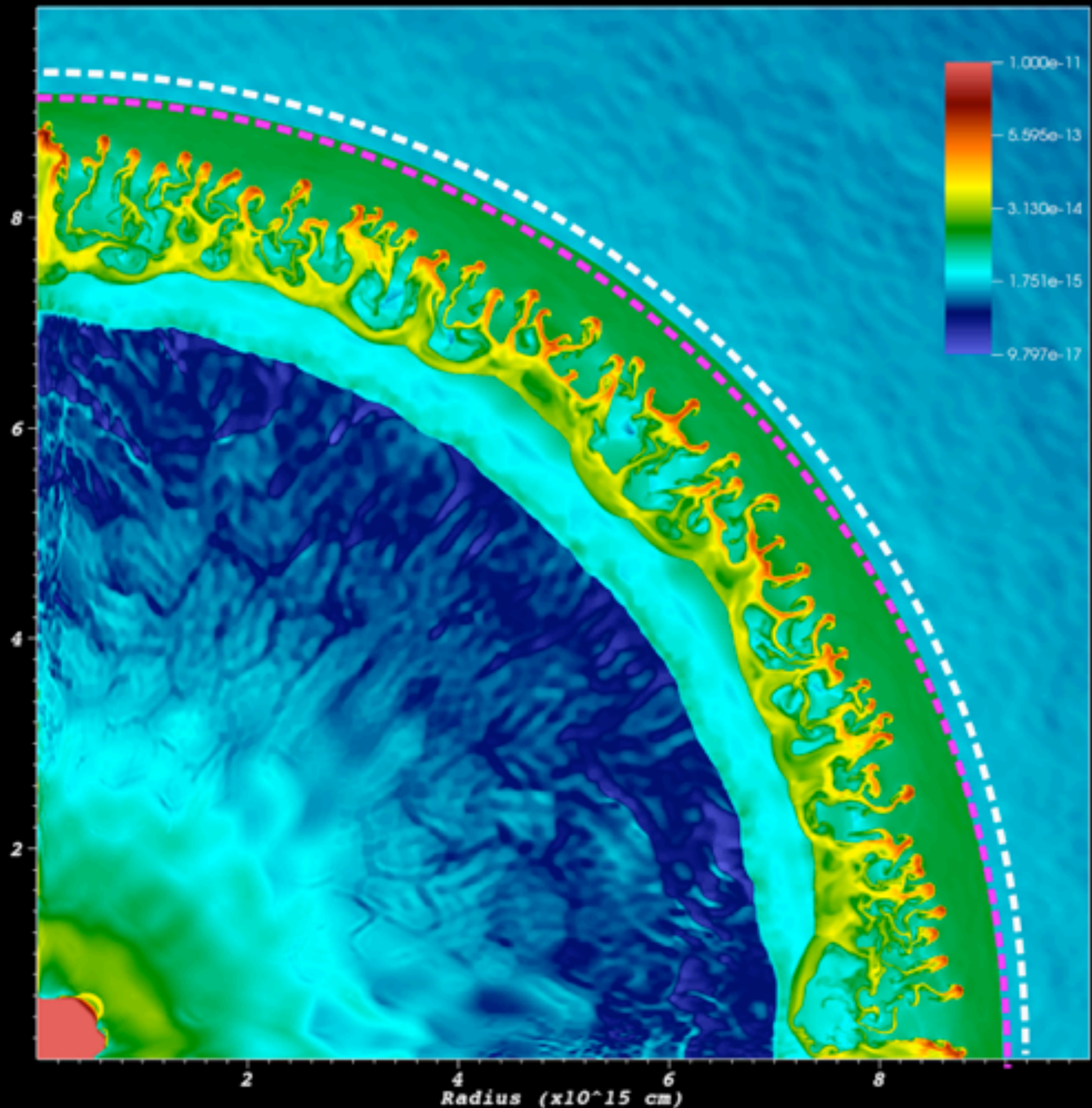
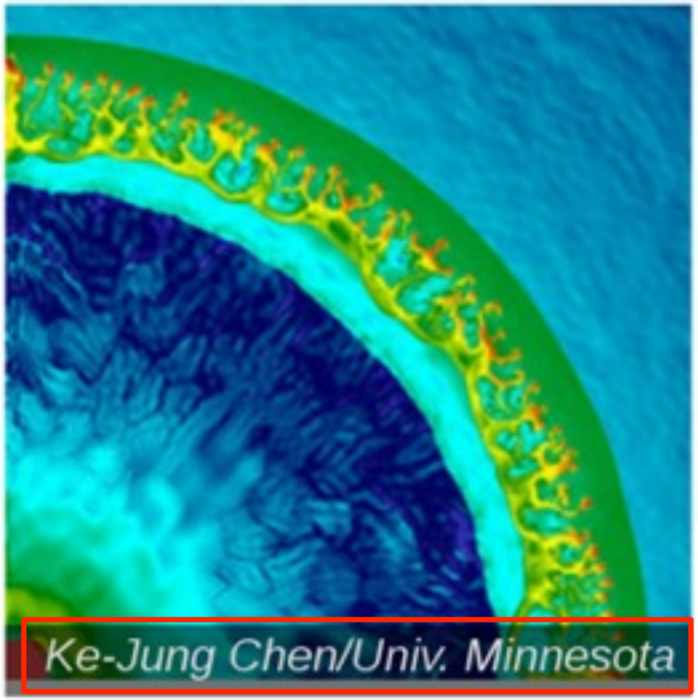


nature.com

Se

07 February 2013



Ofek, E. O., *et al. Nature* (2013)
Heger *Nature* (2013)

A dying star's massive outburst

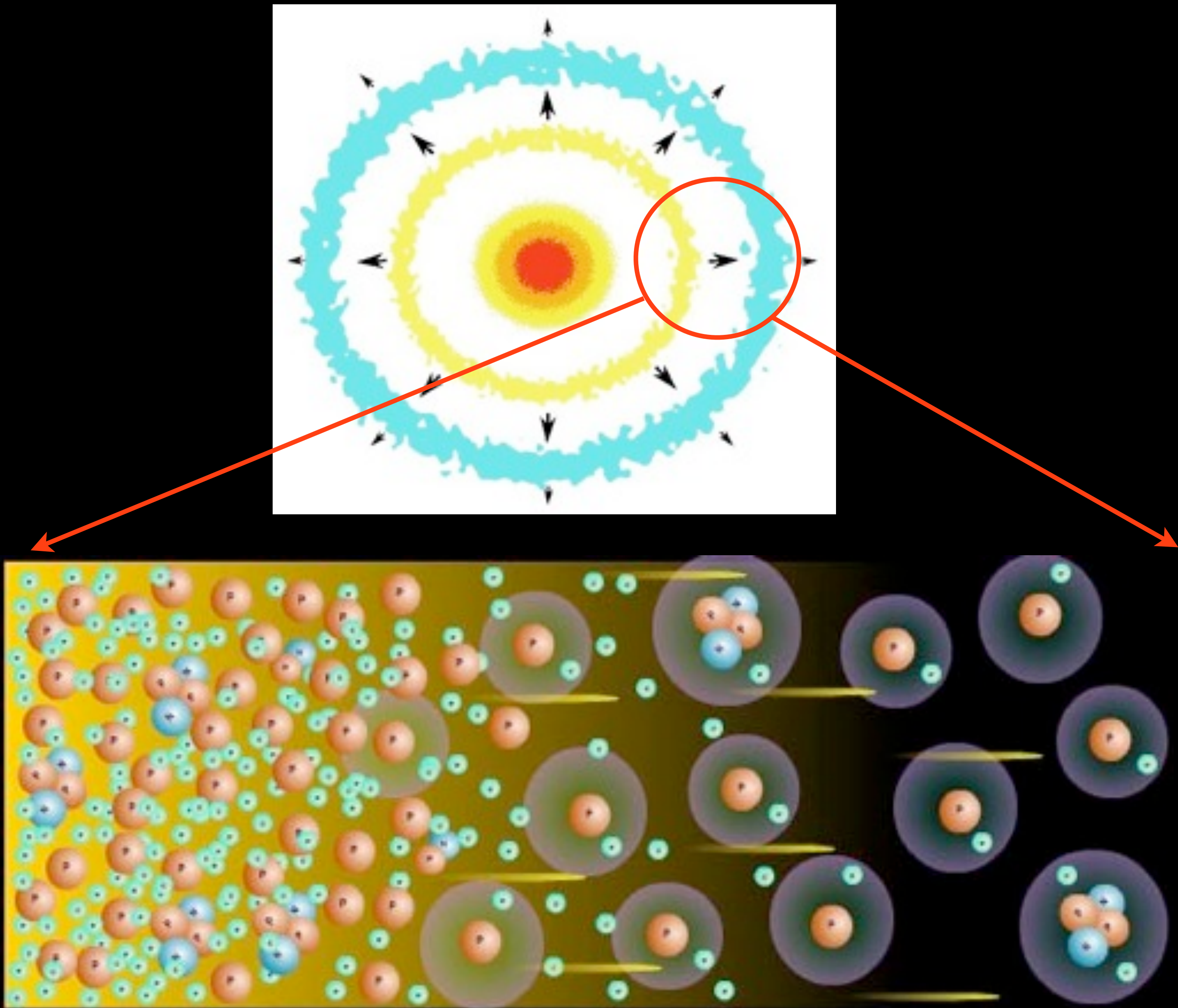
Observations of the final weeks of a massive star, just over a month before it exploded as a supernova, are reported in *Nature* this week.

Latest news

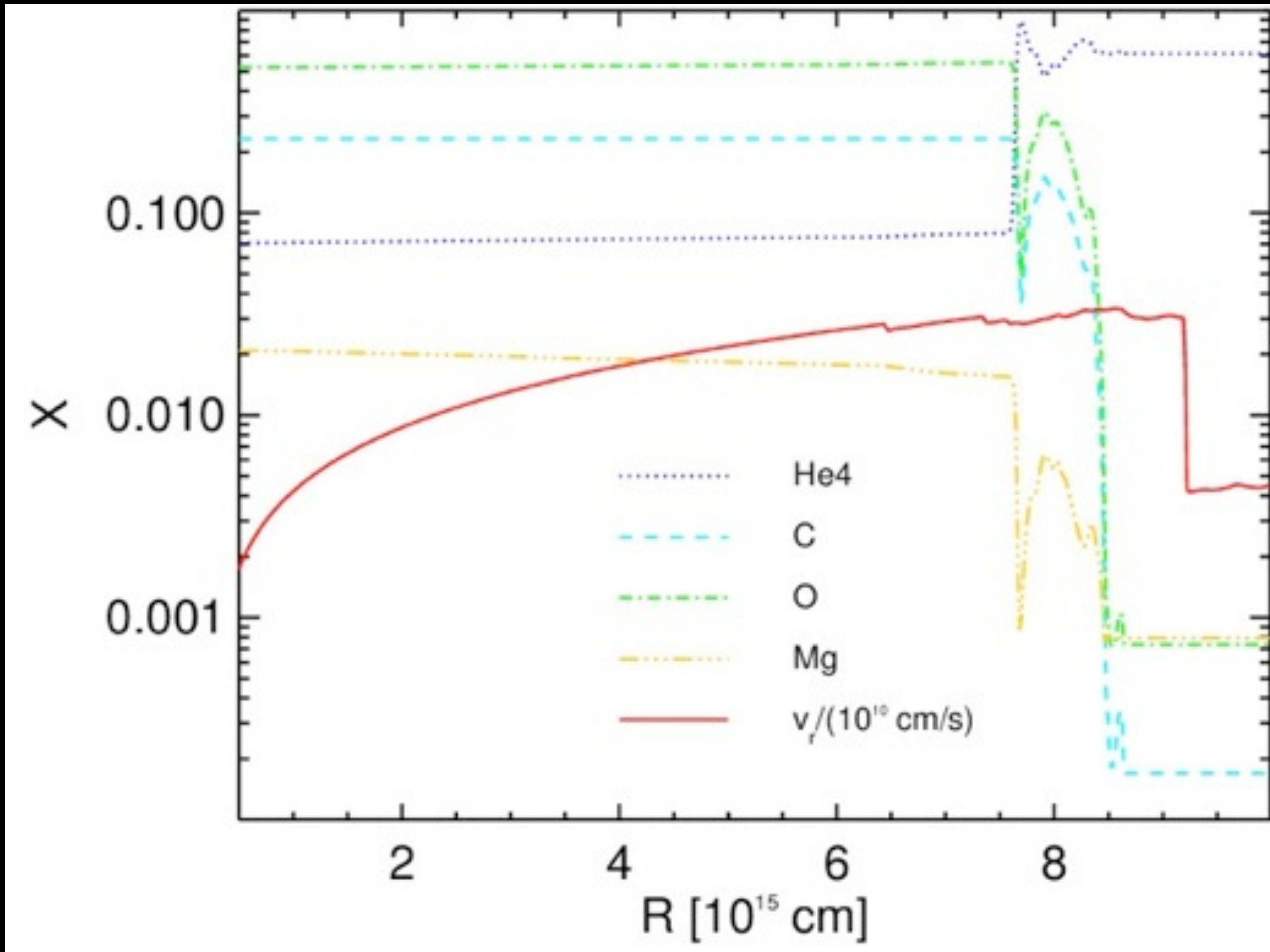
- Europe bets on drug discovery
- Seven days: 1–7 February 2013
- Landsat 8 to the rescue

More news from nature

Observational Signatures

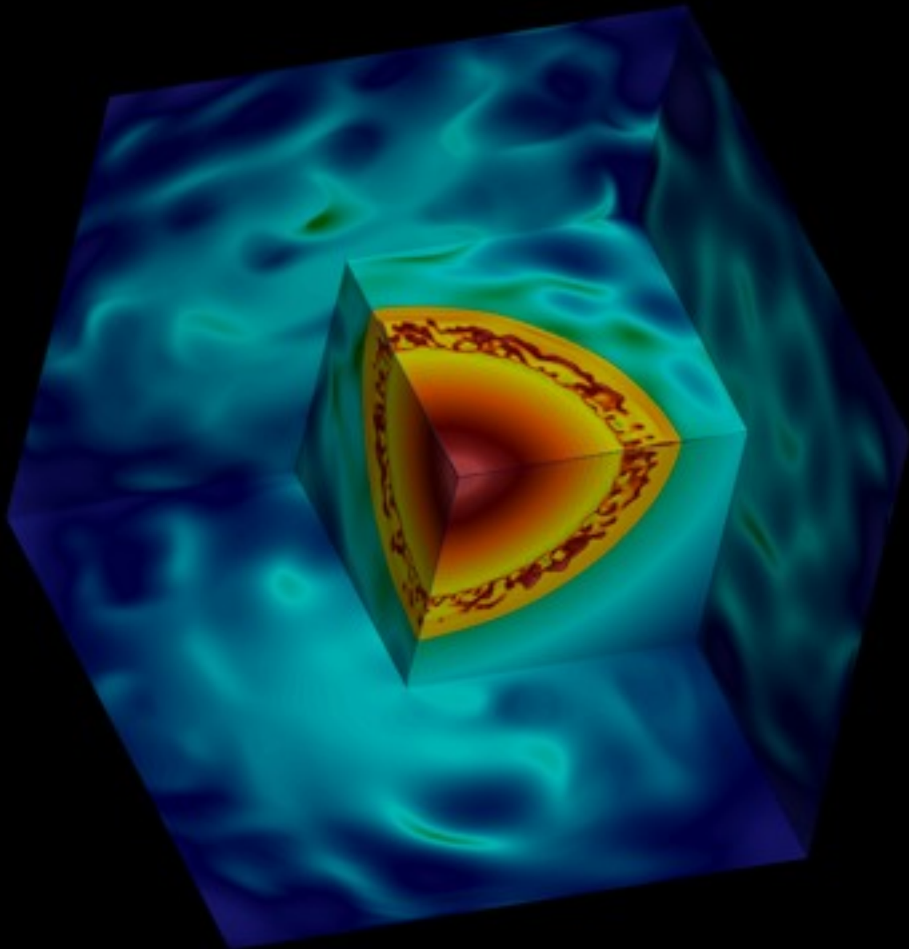


Mixing of PPSNe



Pair-Instability Supernovae (PSNe)

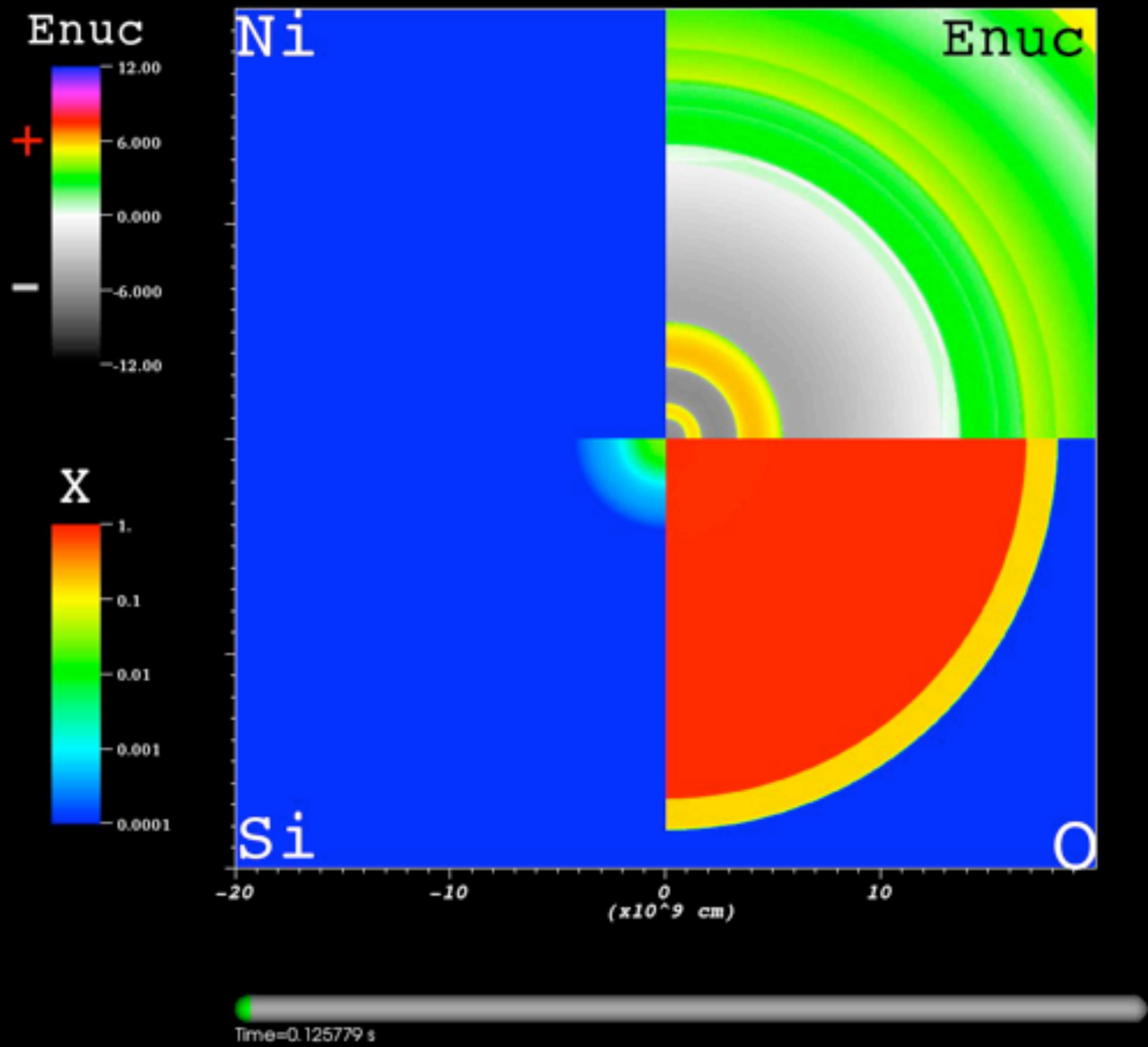
260 M⊙ > M* > 150 M⊙



Chen+ ApJ 792 44 (2014)

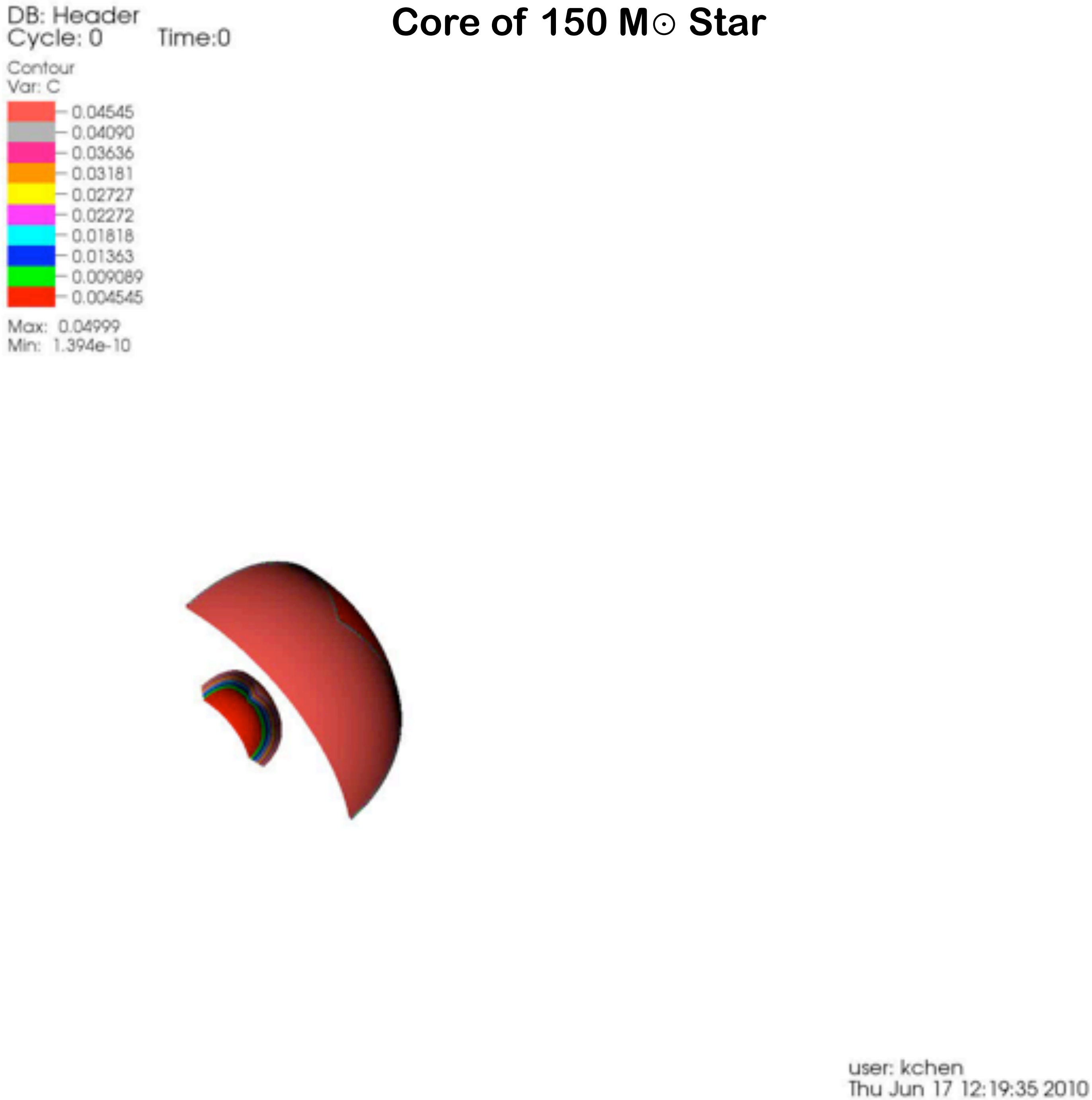
Explosive Burning of 150 $M_\odot$ Star

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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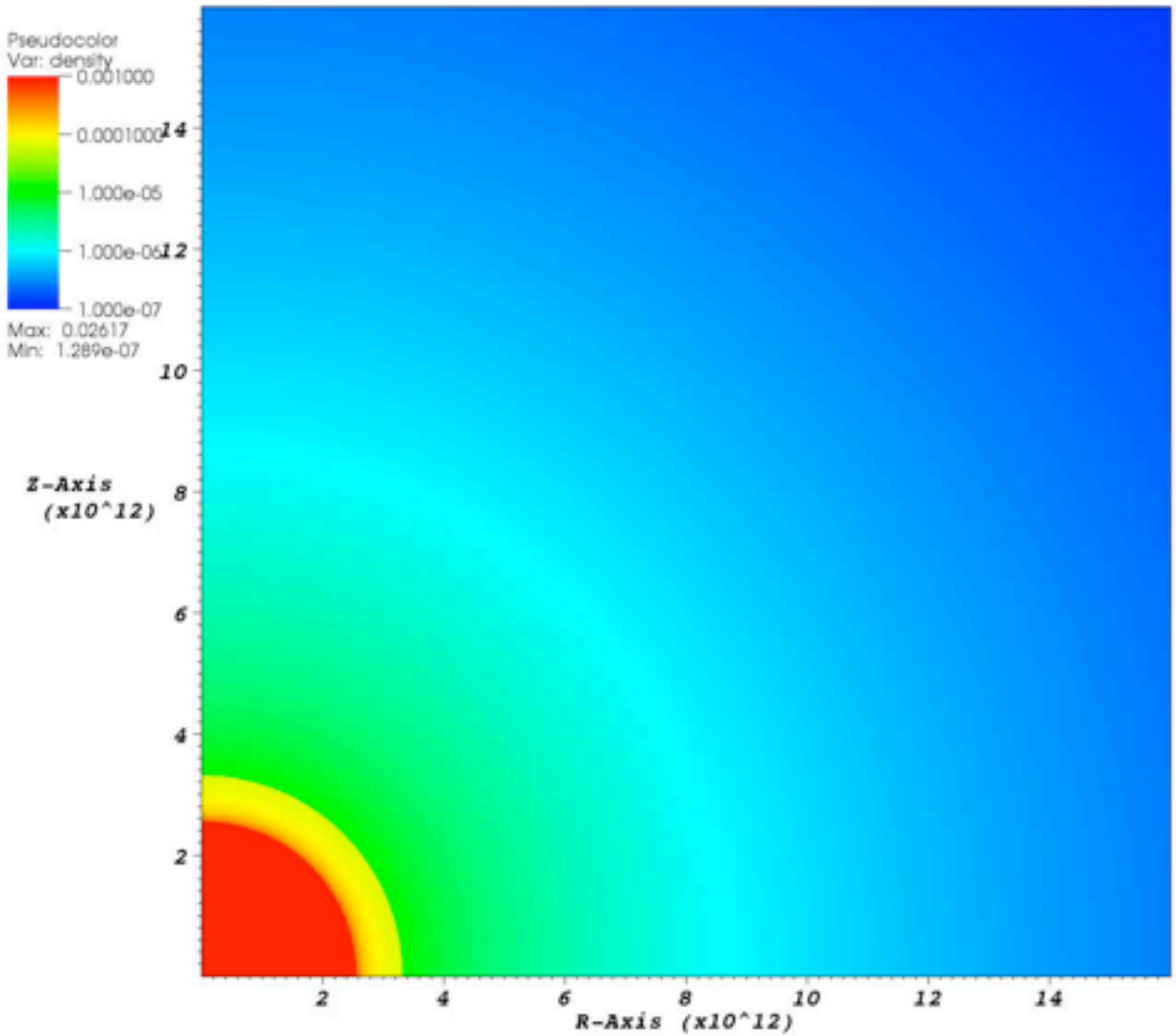
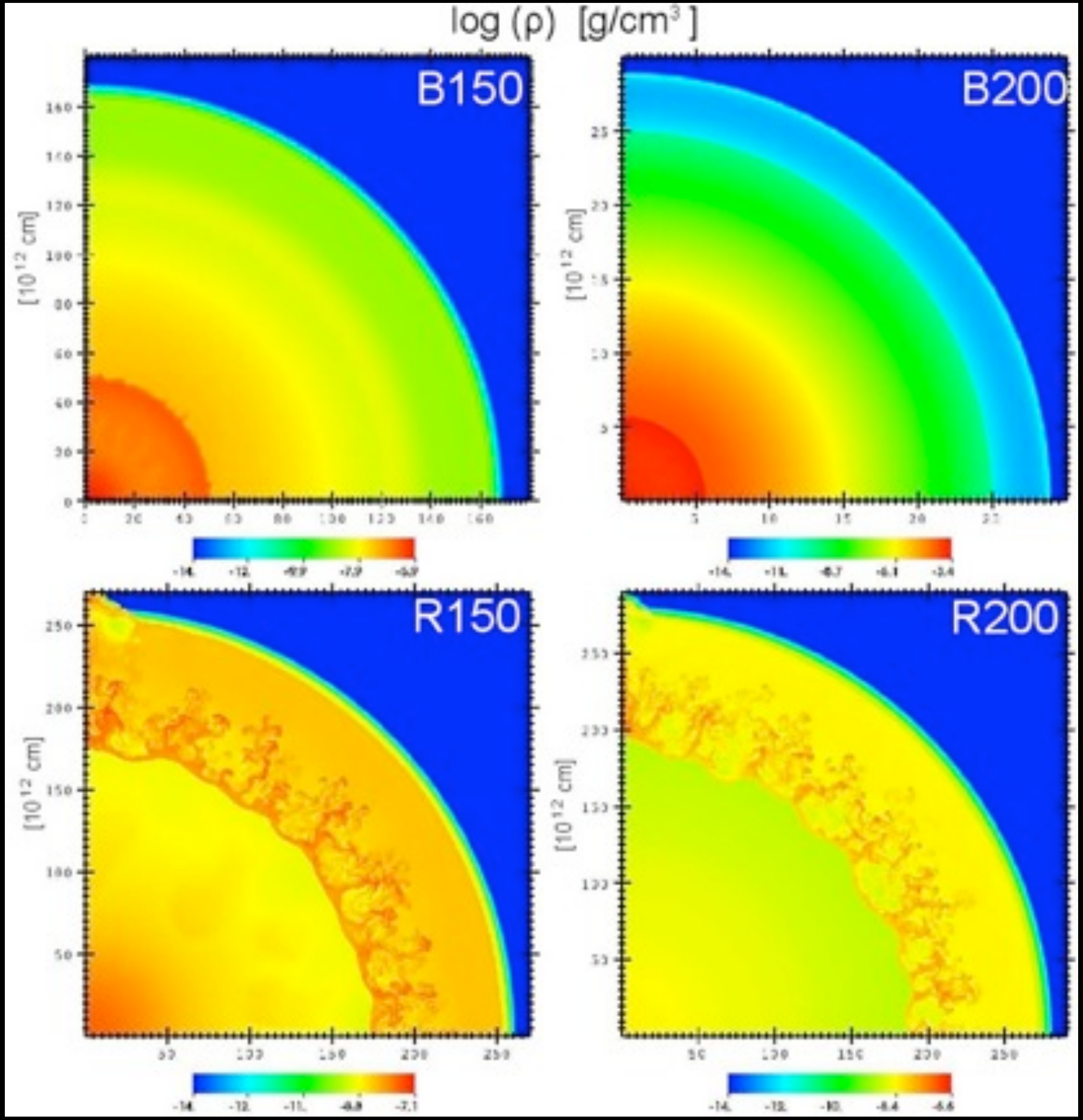


Mixing of PSNe

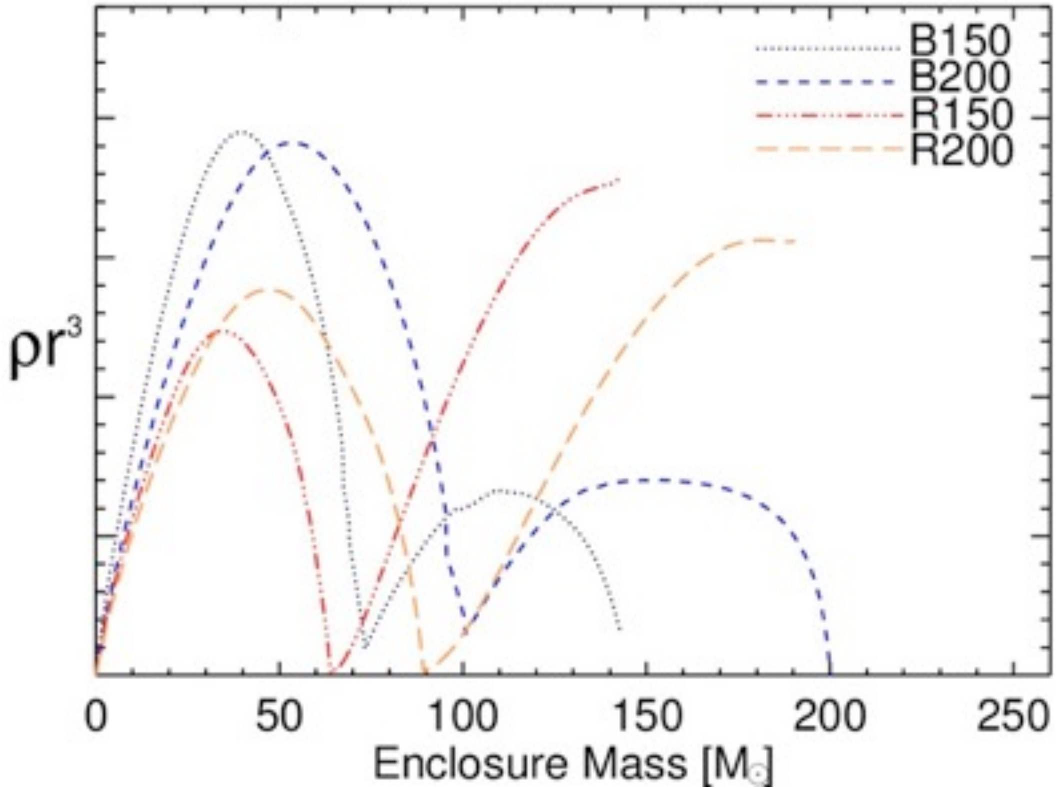


How does mixing occur?

$$\rho = Ar^w$$

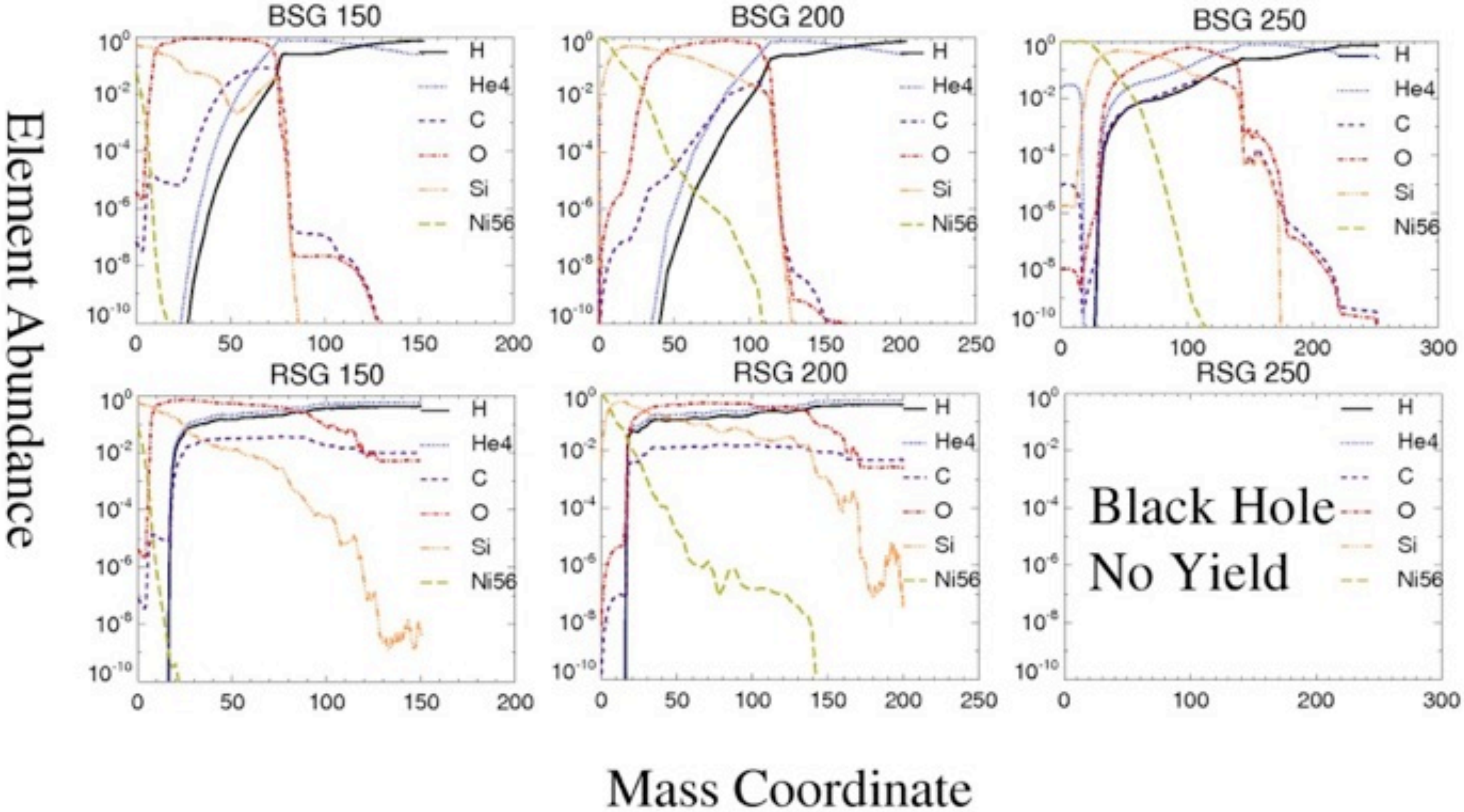
$$V_s = A^{\frac{-1}{(5+w)}} E^{\frac{1}{(w+5)}} t^{\frac{-(w+3)}{5+w}}$$

Sedov, 1959



$$\frac{dP}{dr}\frac{d\rho}{dr} < 0$$ **(Rayleigh–Taylor instability)**

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	...	...	...	...

Results

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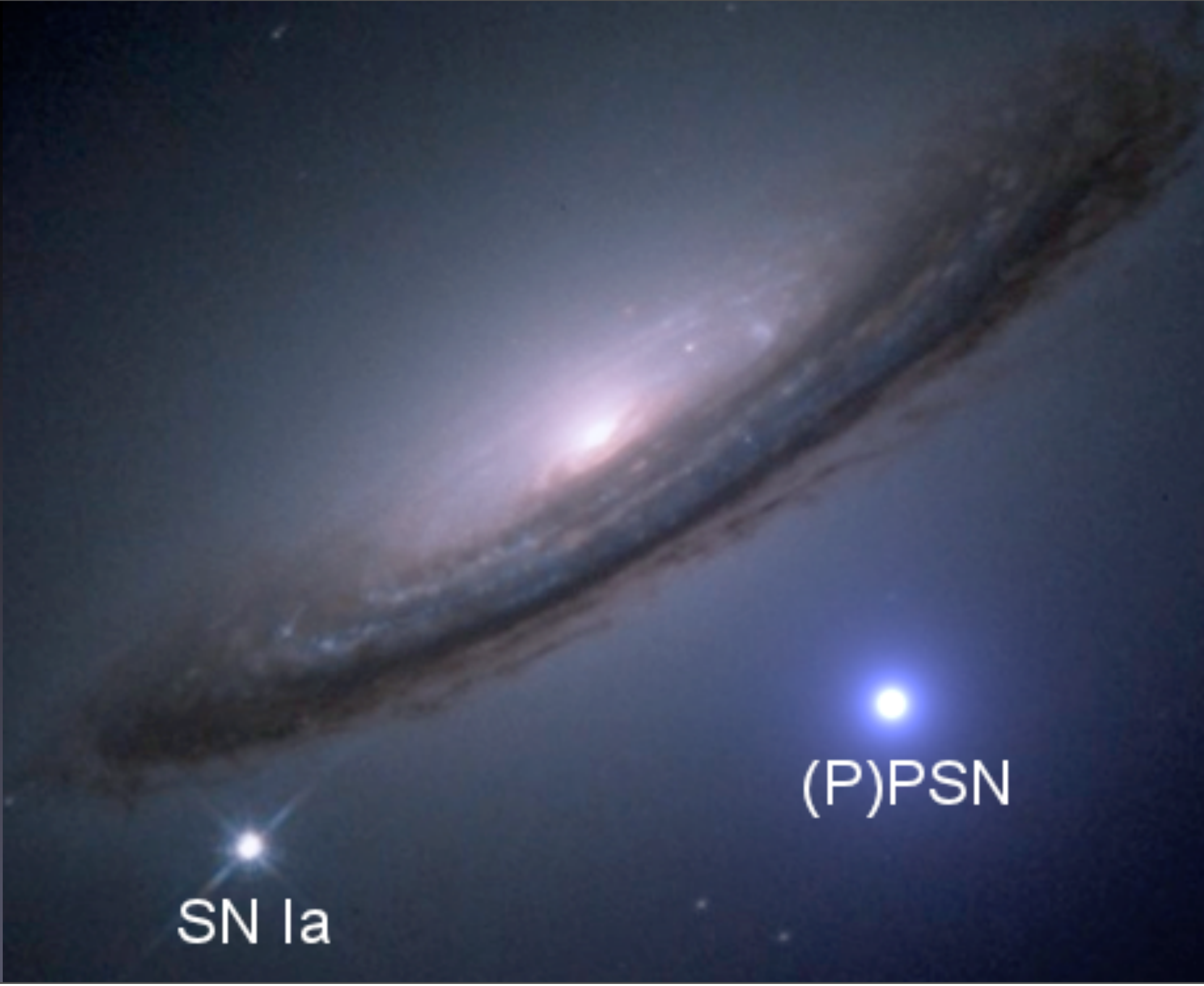
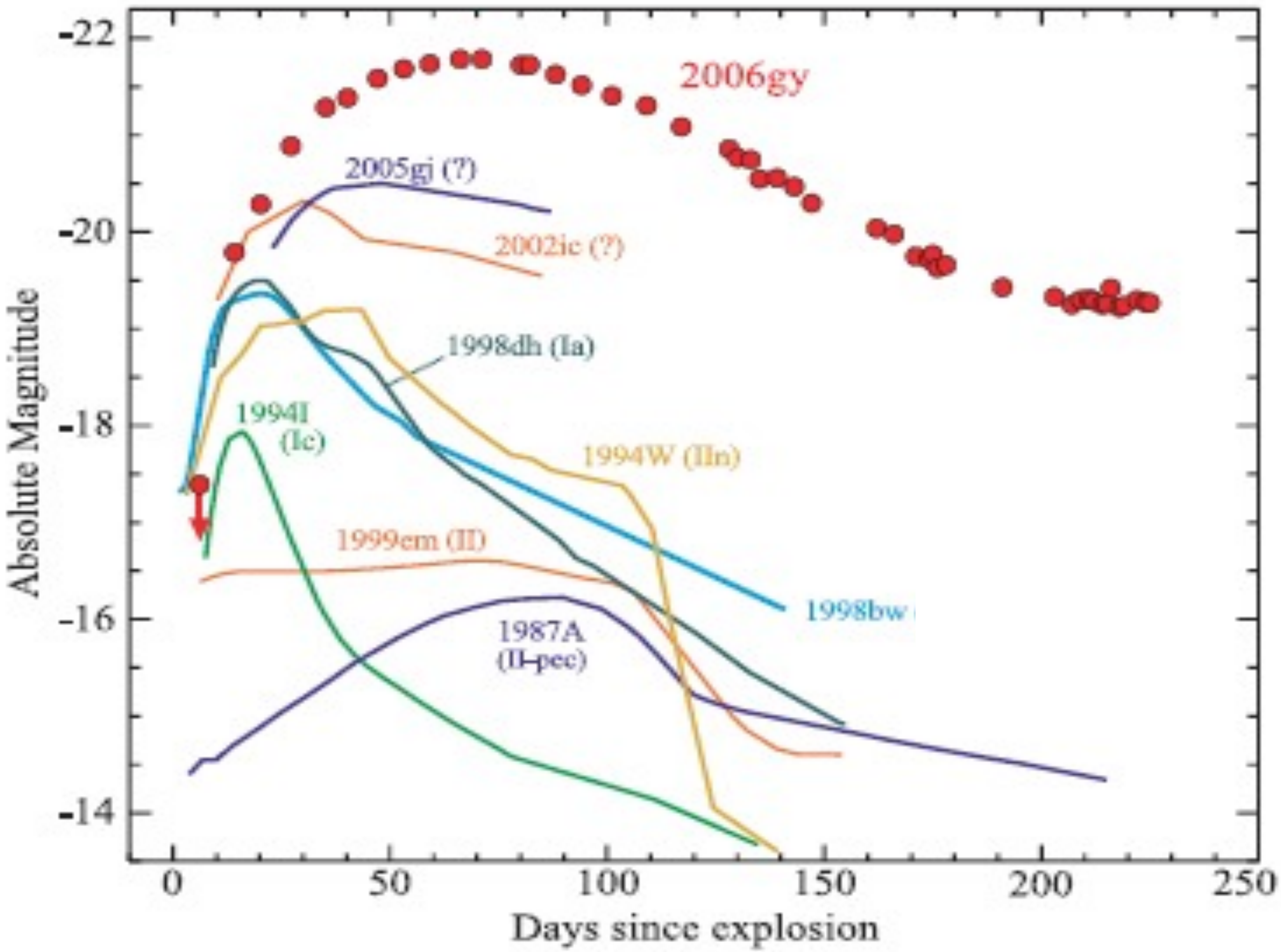
R250	250	156	...	...	...	...

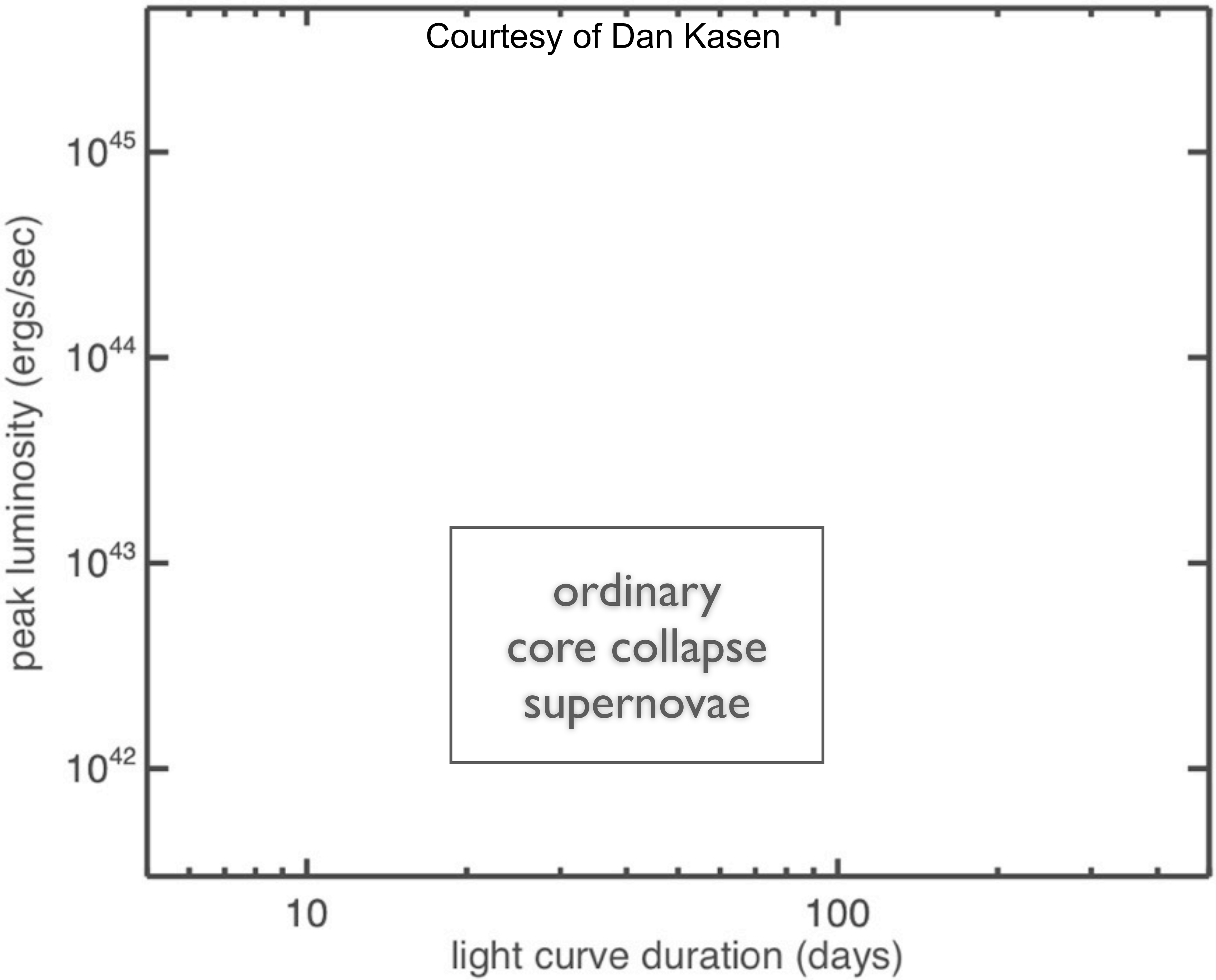
Ni is only slightly mixed out .
The Gamma-Ray emission for PSNe is unlikely.

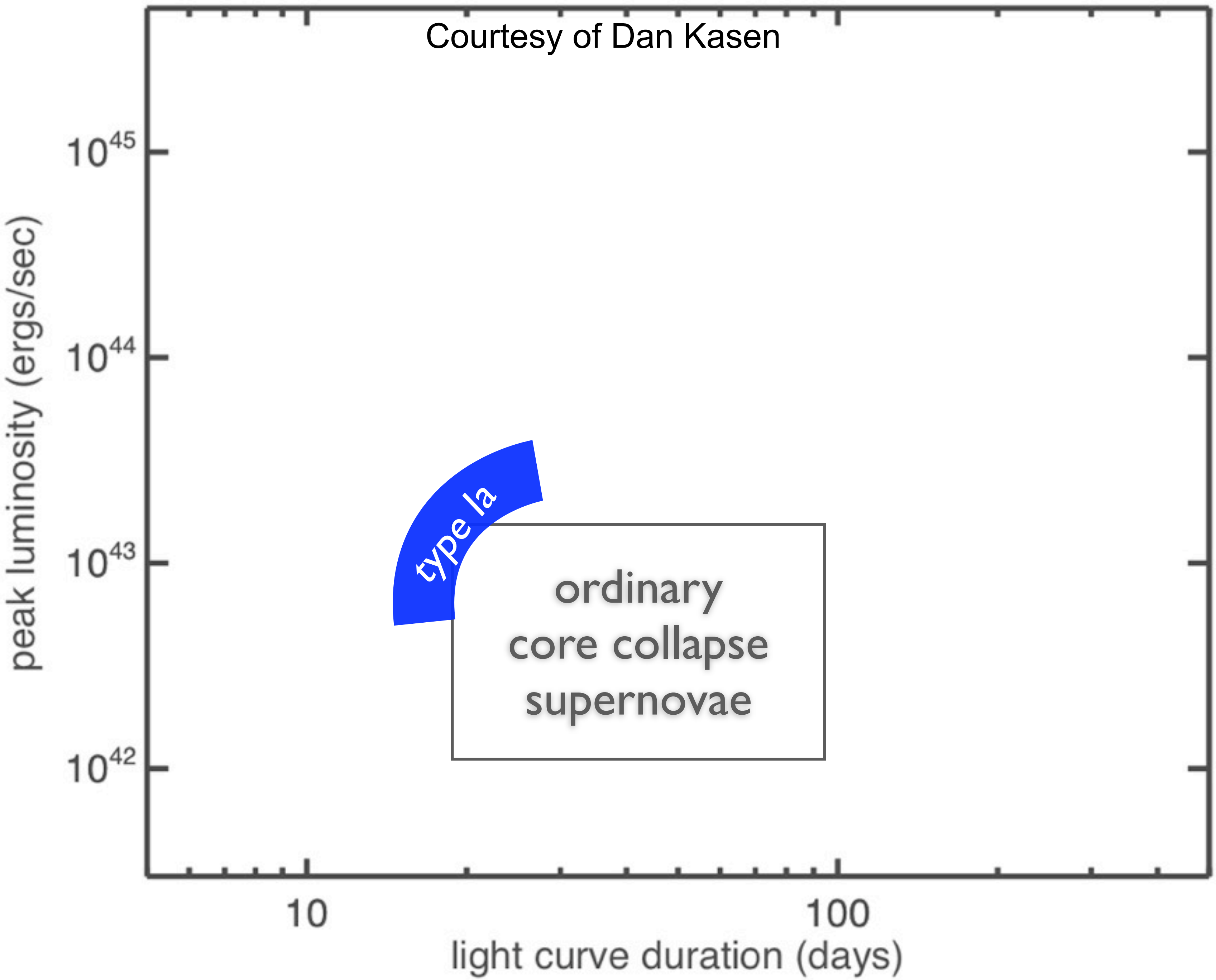

(P)PSN
SN Ia

Super Luminous SNe



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)



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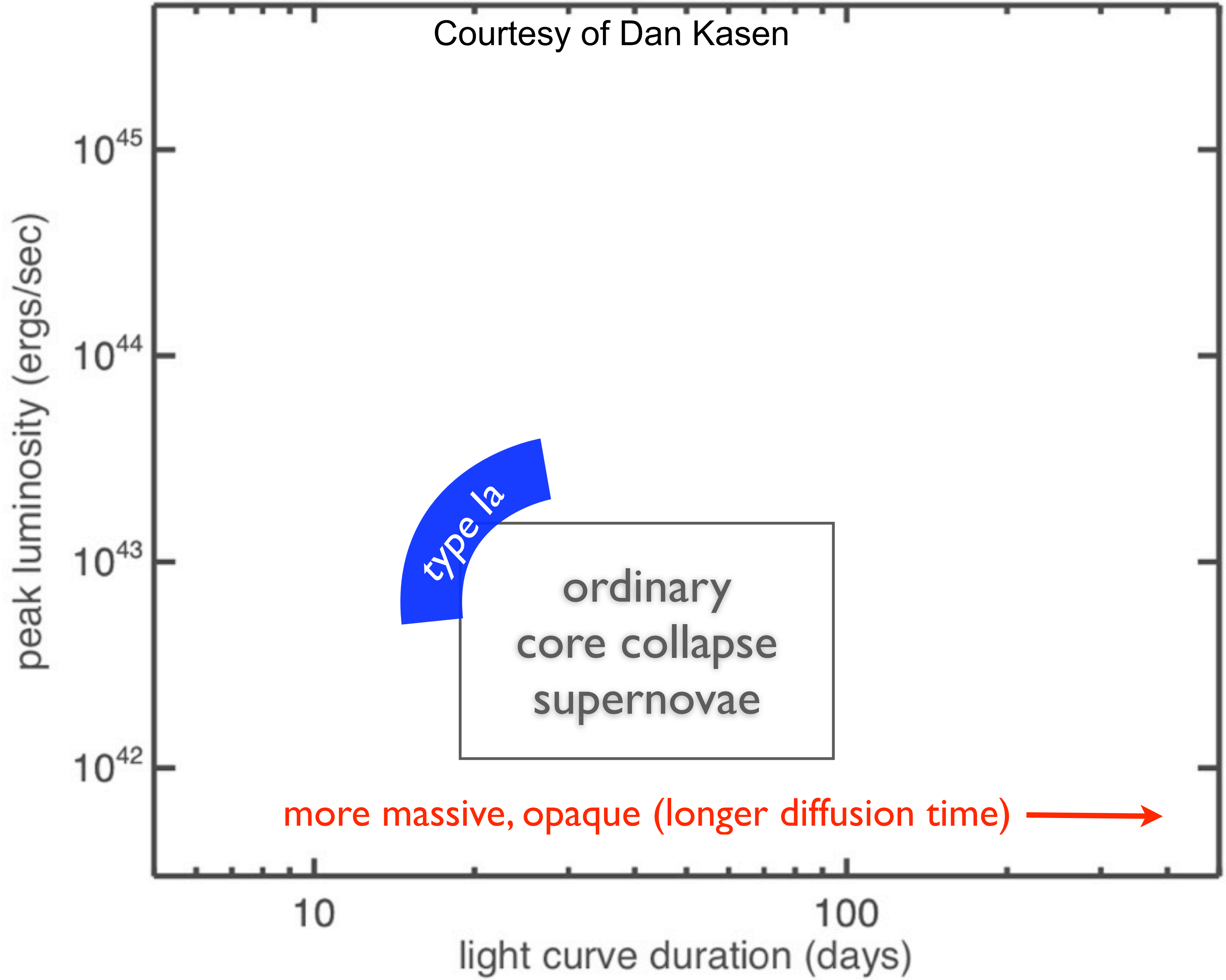
Courtesy of Dan Kasen
10^{45}
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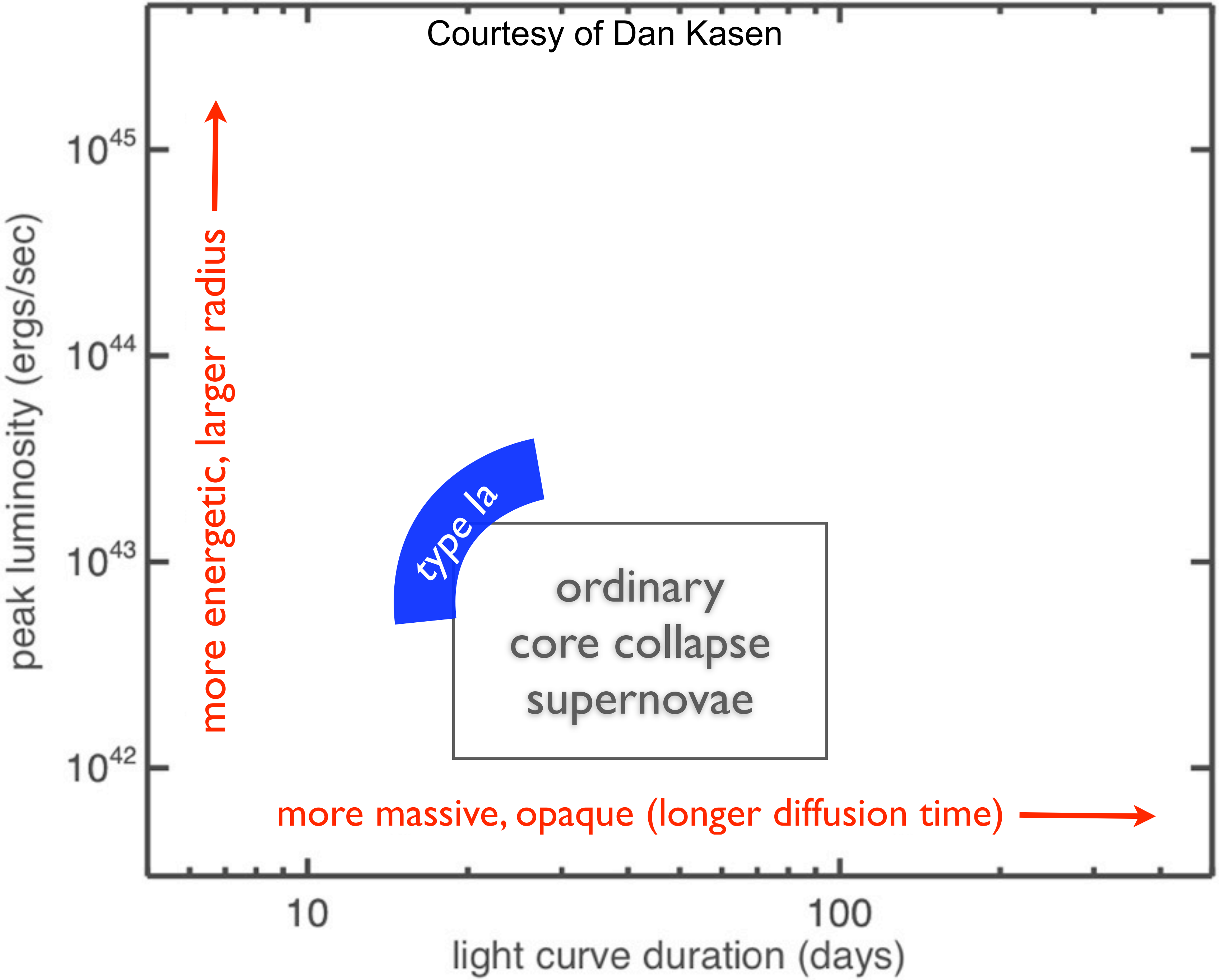
peak luminosity (ergs/sec)
type Ia
ordinary
core collapse
supernovae
more massive, opaque (longer diffusion time)
10
100
light curve duration (days)



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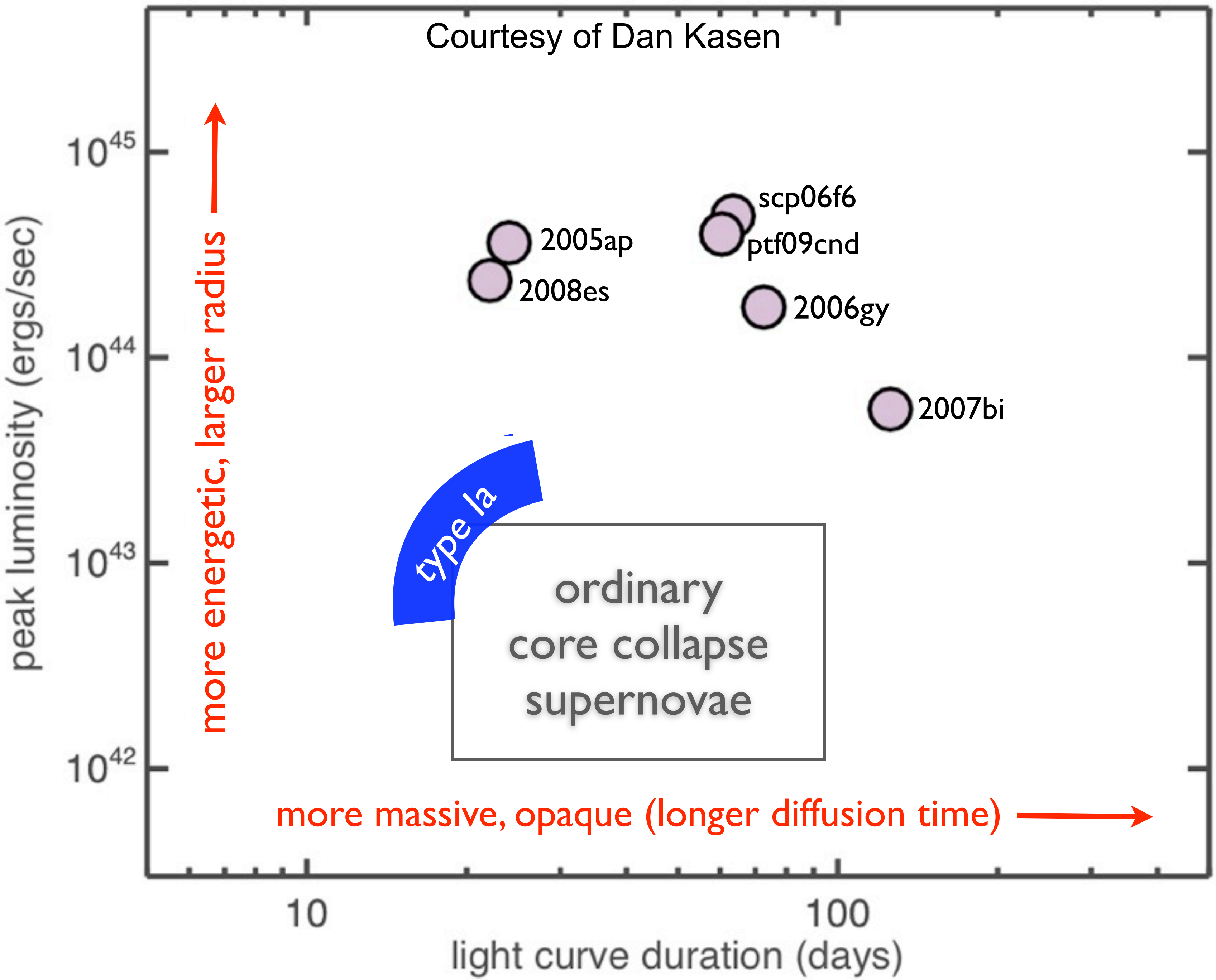

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10^45
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2005ap
2008es
scp06f6
ptf09cnd
2006gy
2007bi
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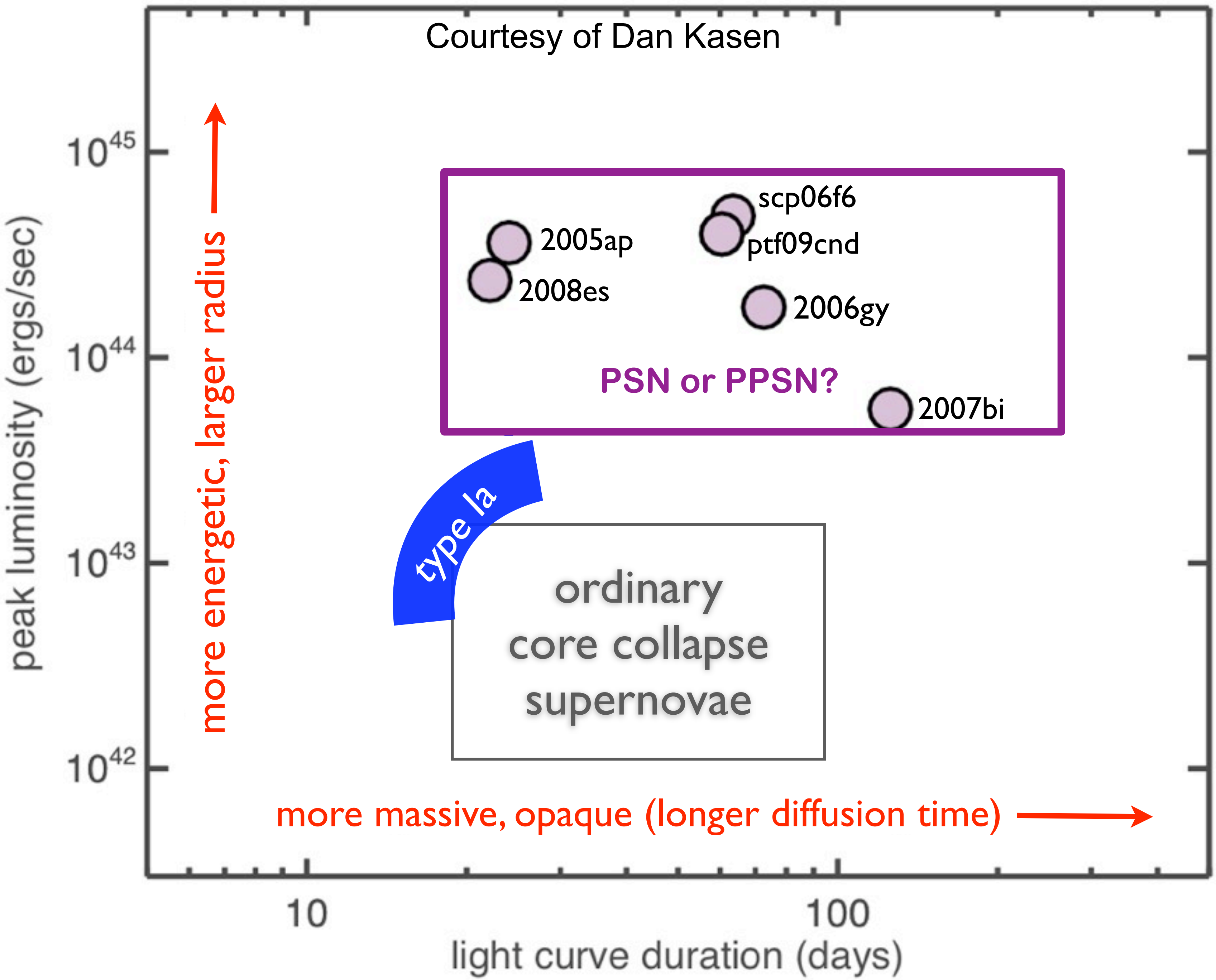

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10^{45}
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2005ap
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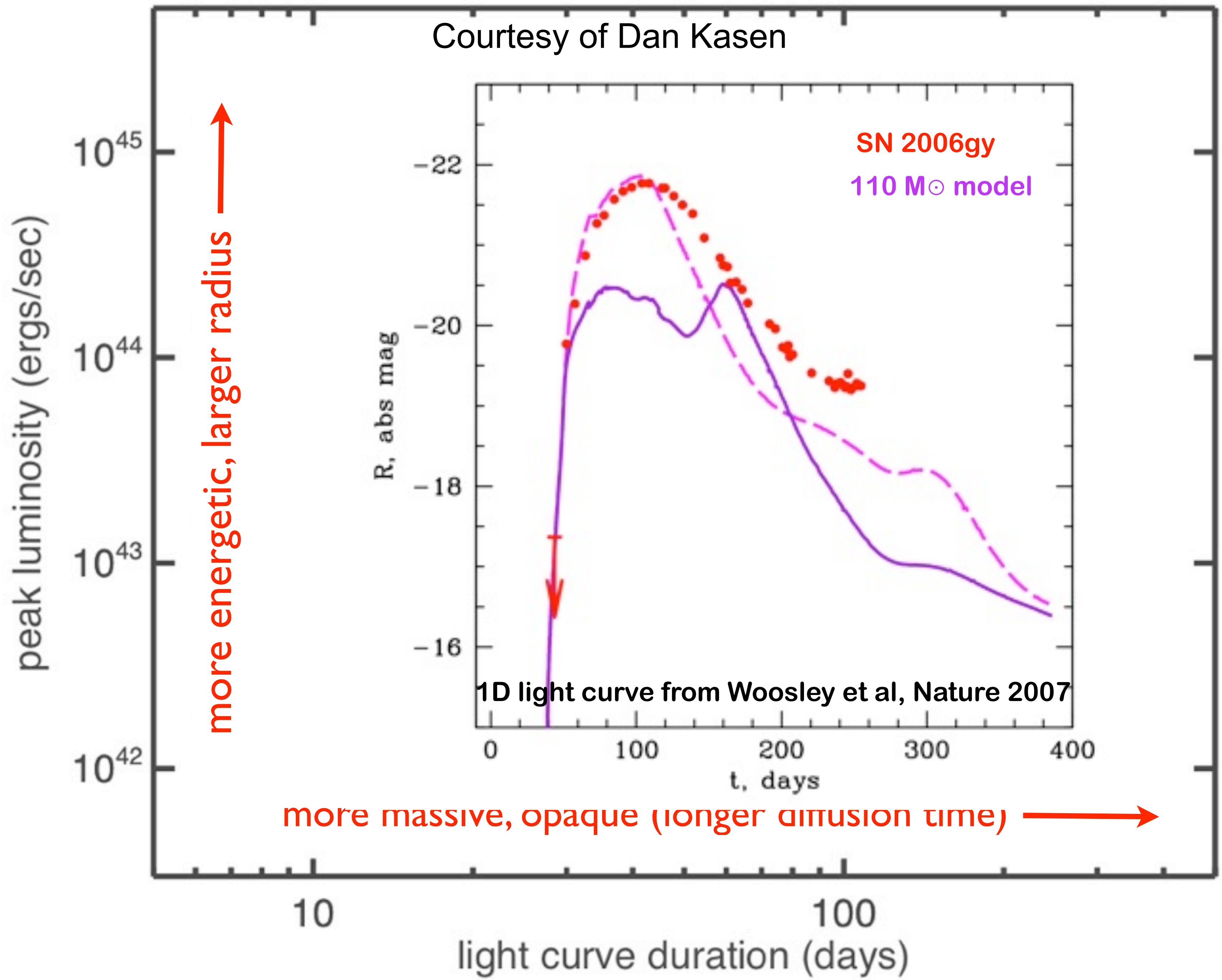
PSN or PPSN?
2007bi
type Ia
ordinary
core collapse
supernovae
more massive, opaque (longer diffusion time)
10
100
light curve duration (days)


Courtesy of Dan Kasen
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10^45
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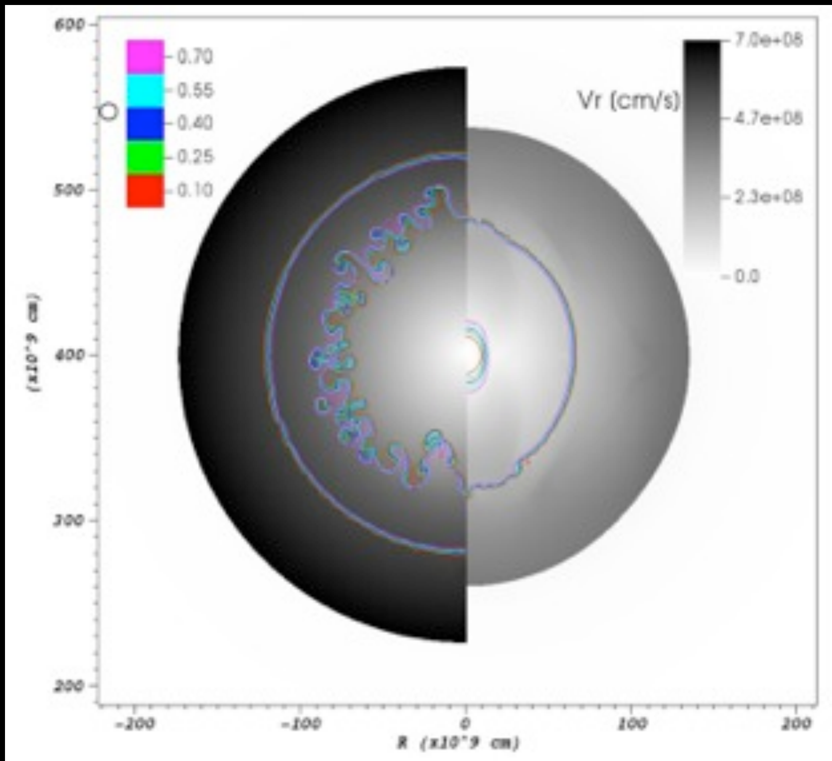
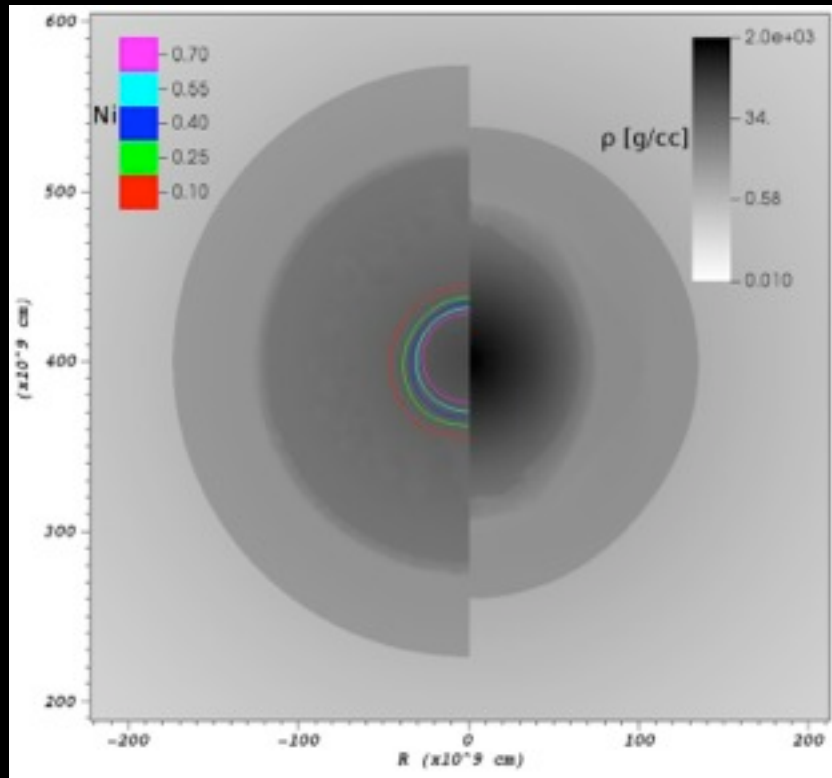
SN 2006gy
110 M☉ model
R, abs mag
−22
−20
−18
−16
1D light curve from Woosley et al, Nature 2007
0
100
200
300
400
t, days
more massive, opaque (longer diffusion time)
10
100
light curve duration (days)

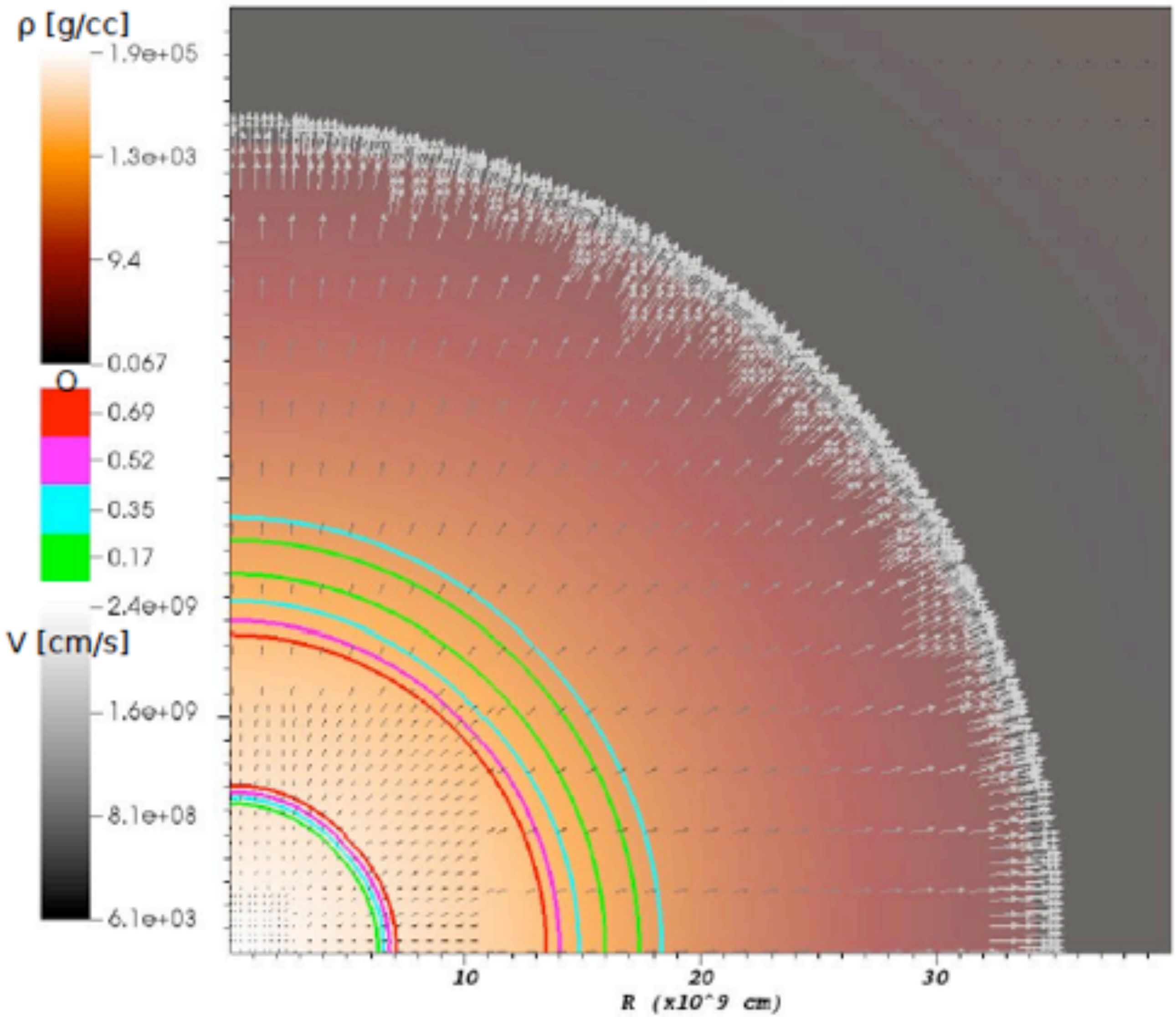
Pair-Instability Supernovae with Rotation





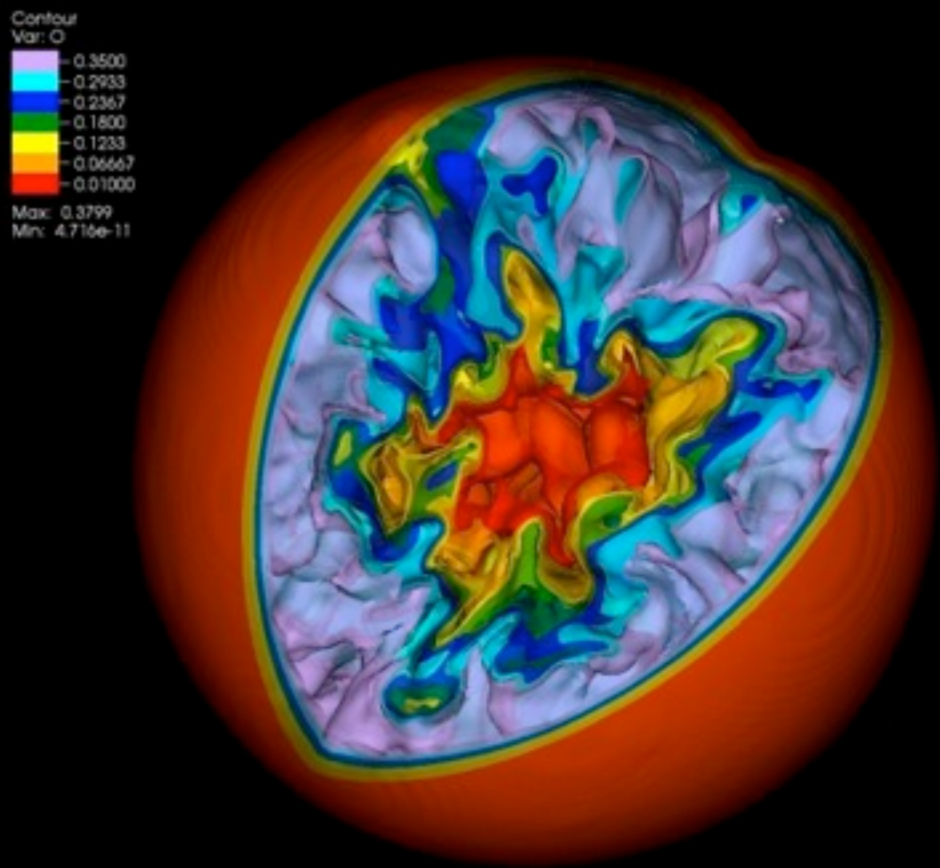
Asymmetry Explosion and Ni reduce !!

Solar Metallicity PSN



GR Instability Supernovae (GSNe)

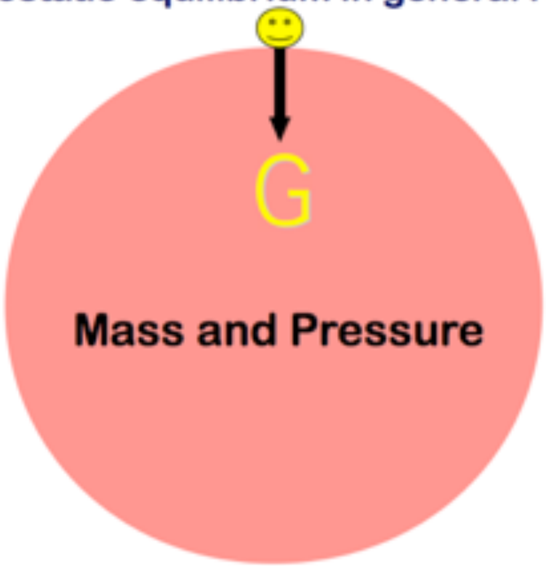
M*>> 100 M⊙



Chen+ ApJ 790 162 (2014)

GR correction for massive stars

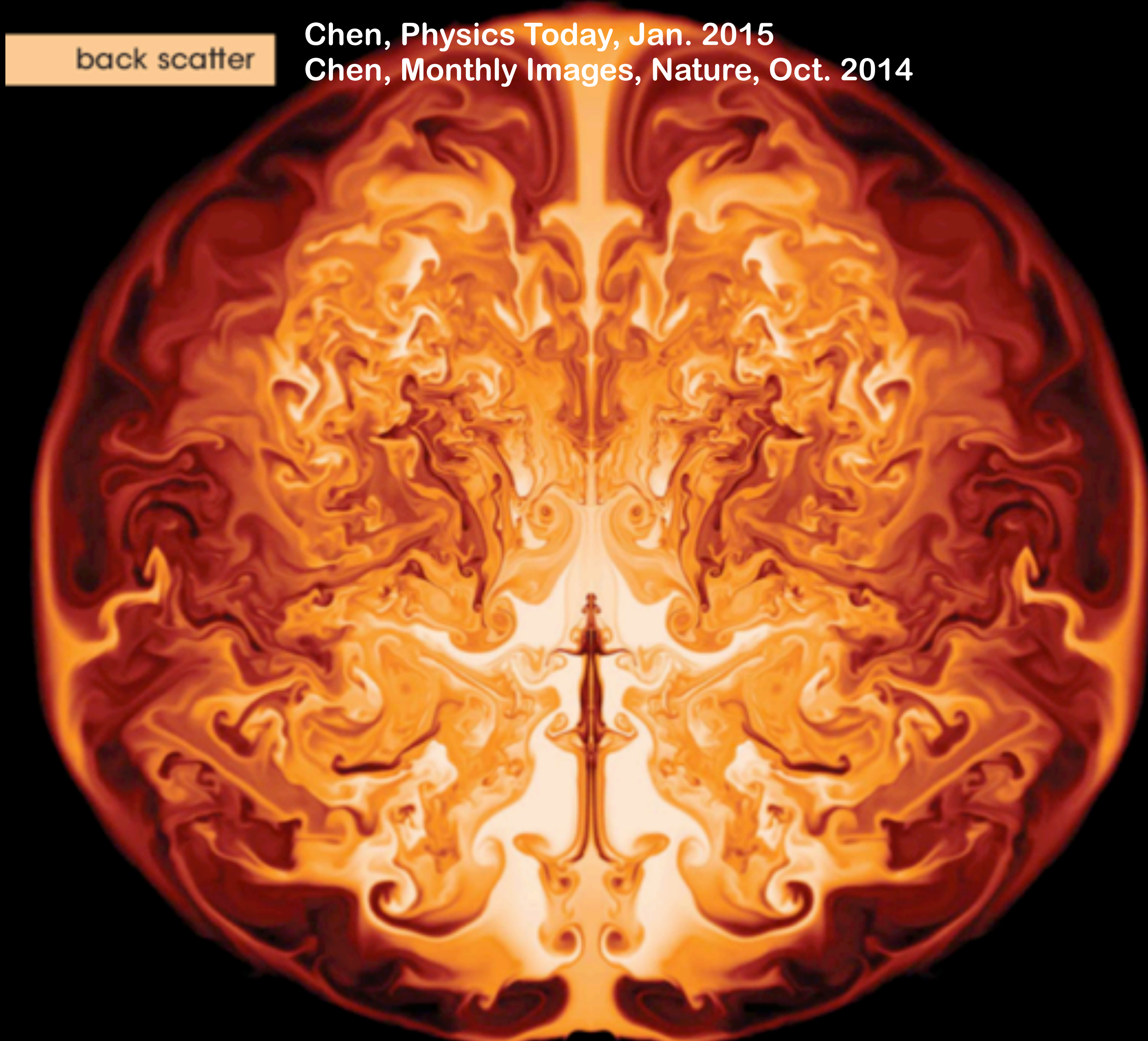
(Hydrostatic equilibrium in general relativity)



Tolman-Oppenheinmer-Volko equation

$$\frac{dP}{dr} = -\frac{Gm}{r^2}\varrho(1+\frac{P}{\rho c^2})(1+\frac{4\pi r^3 P}{mc^2})(1-\frac{2Gm}{rc^2})^{-1}$$

Chen, Physics Today, Jan. 2015
Chen, Monthly Images, Nature, Oct. 2014



An exploding supermassive star

Supermassive black holes—millions to billions times more massive than the Sun—reside at the center of almost every galaxy, and they power distant, bright quasars that already existed when the universe was only a billion years old. But understanding how such supermassive black holes could form so early in the universe is a challenge. Some theoretical models suggest that they could have

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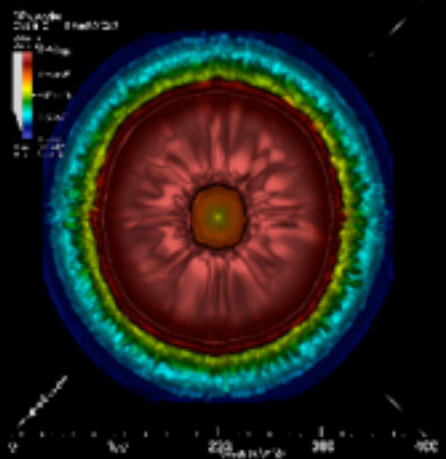
Take Home Message I

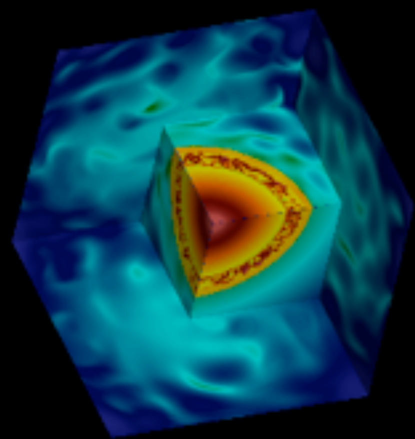
Pulsational Pair-Instability SN (PPSN)



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

1. e+/e- creation instability
2. Several eruptions
3. Die as Fe-core collapse SNe
4. Multi-SNe (one superluminous)
5. Mixing during shell collisions

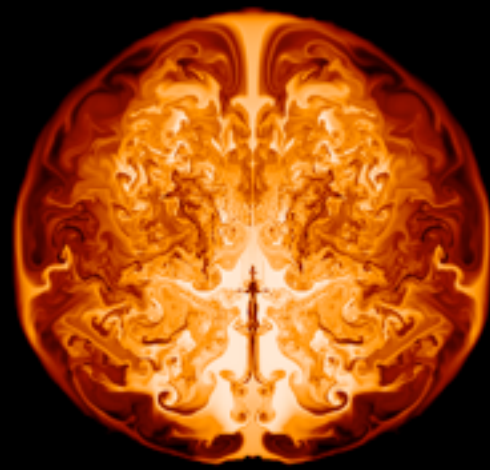
Pair-Instability SN (PSN)



$150\ M_\odot < M^* < 250\ M_\odot$

1. e+/e- creation instability
2. One powerful explosion
3. Lots of Ni (up to 30+ $M_\odot$)
4. Mixing due to burning and hydro instabilities

GR-Instability SN (GSN)



$M^* \sim 55{,}000?\ M_\odot$

1. GR instability
2. Explosive burning helium
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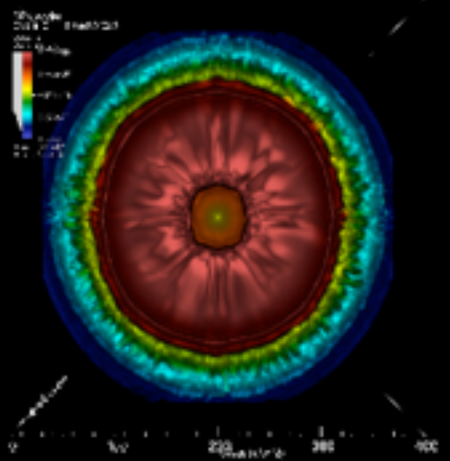
4. Mixing due to burning instability

Explosion energy ~ 10^{55} erg

Take Home Message I

Pulsational Pair-Instability SN (PPSN)



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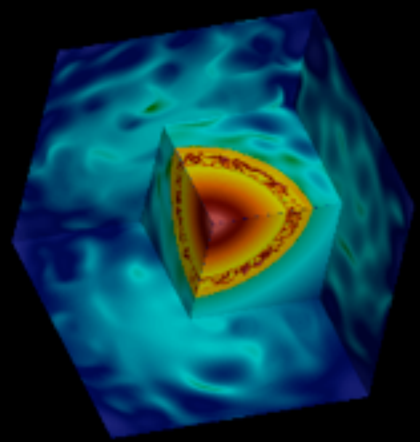

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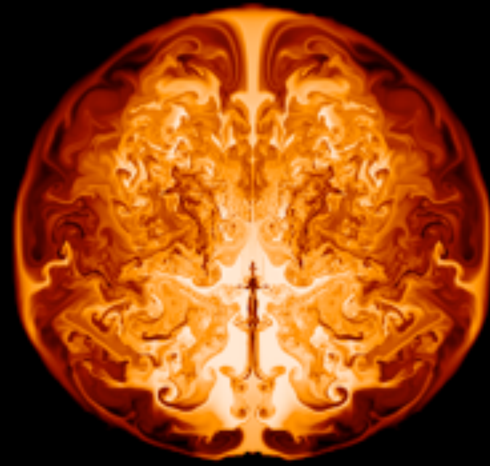

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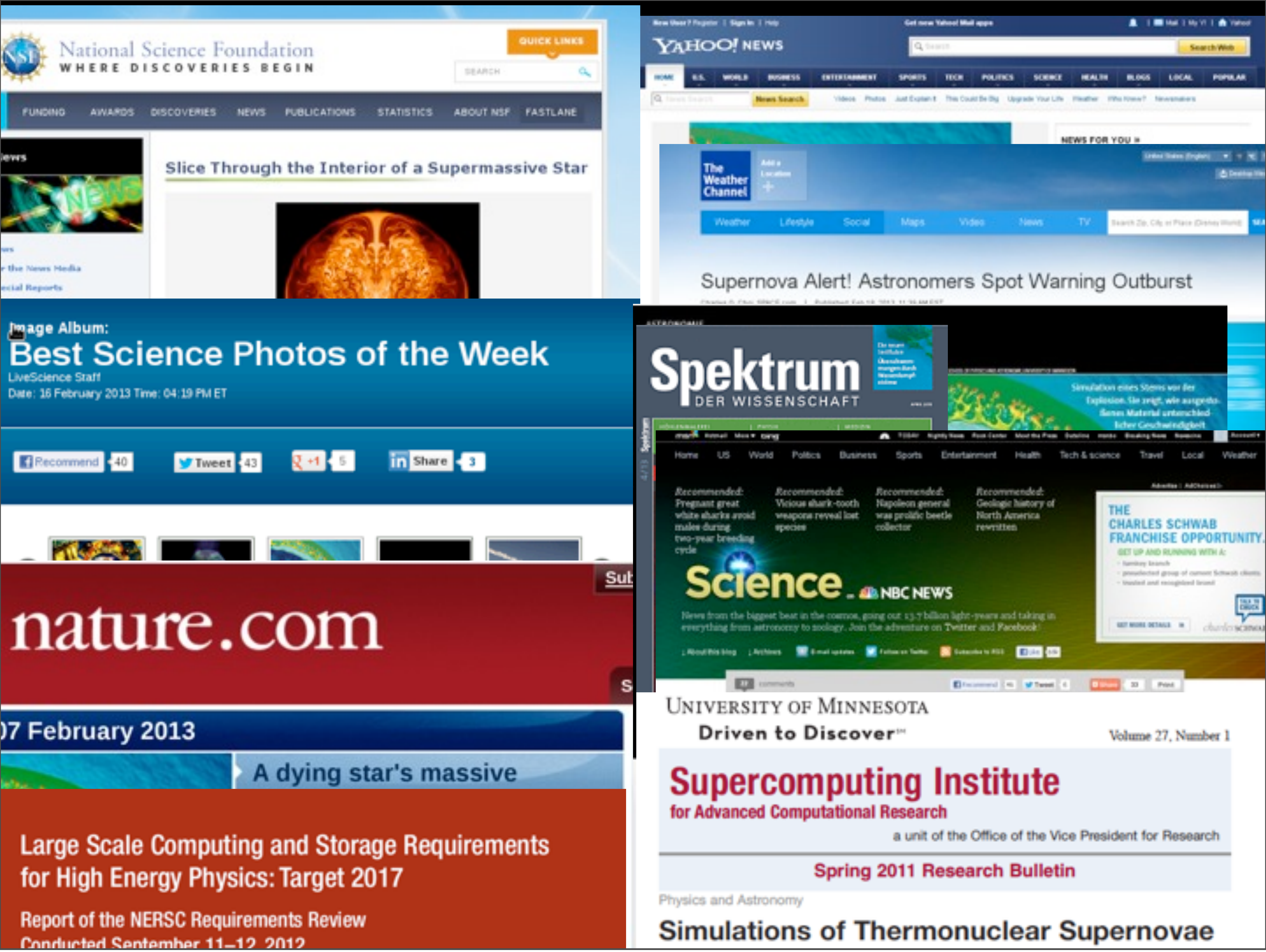
Big impact to the early Universe !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nature.com
07 February 2013
A dying star's massive
Large Scale Computing and Storage Requirements for High Energy Physics: Target 2017
Report of the NERSC Requirements Review
University of Minnesota
Driven to Discover
Volume 27, Number 1
Supercomputing Institute
for Advanced Computational Research
a unit of the Office of the Vice President for Research
Spring 2011 Research Bulletin
Physics and Astronomy
Simulations of Thermonuclear Supernovae

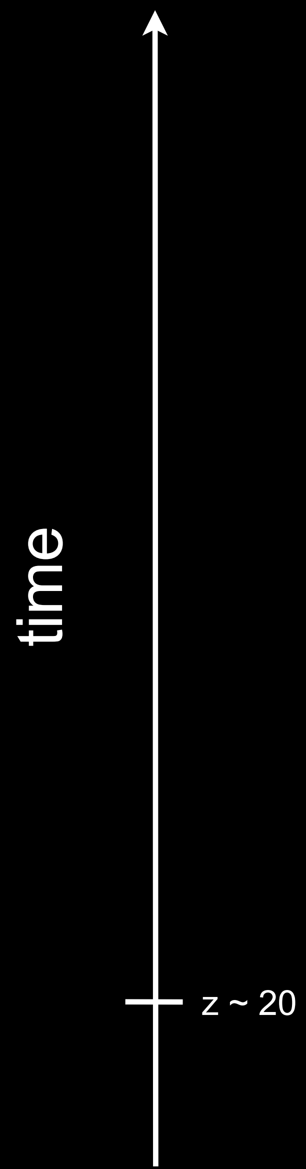

450 Million years after the Big Bang (HUDF)

How did the First Galaxies Form?

time

Bromm, & Yoshida (2011)

How did the First Galaxies Form?



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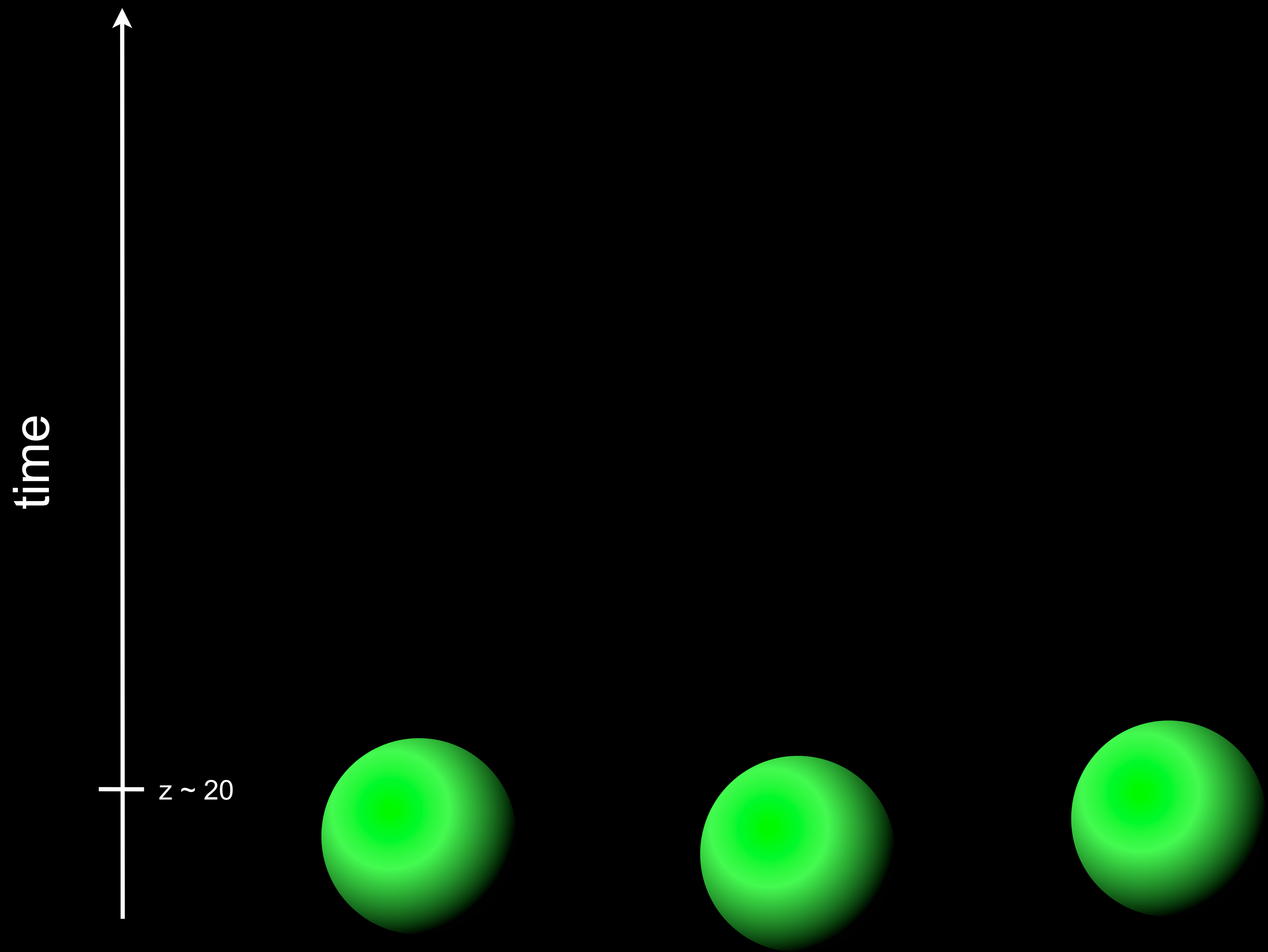

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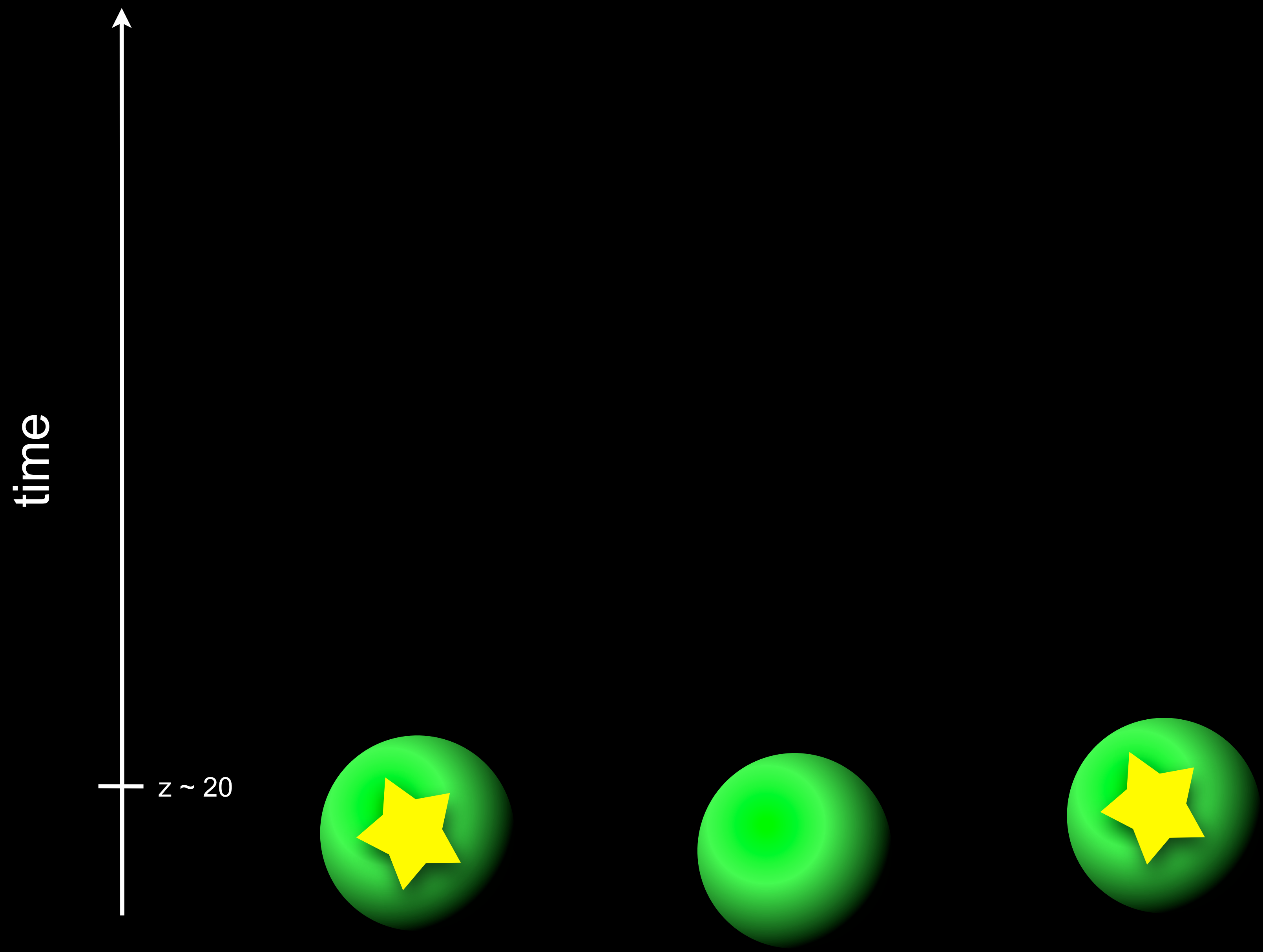

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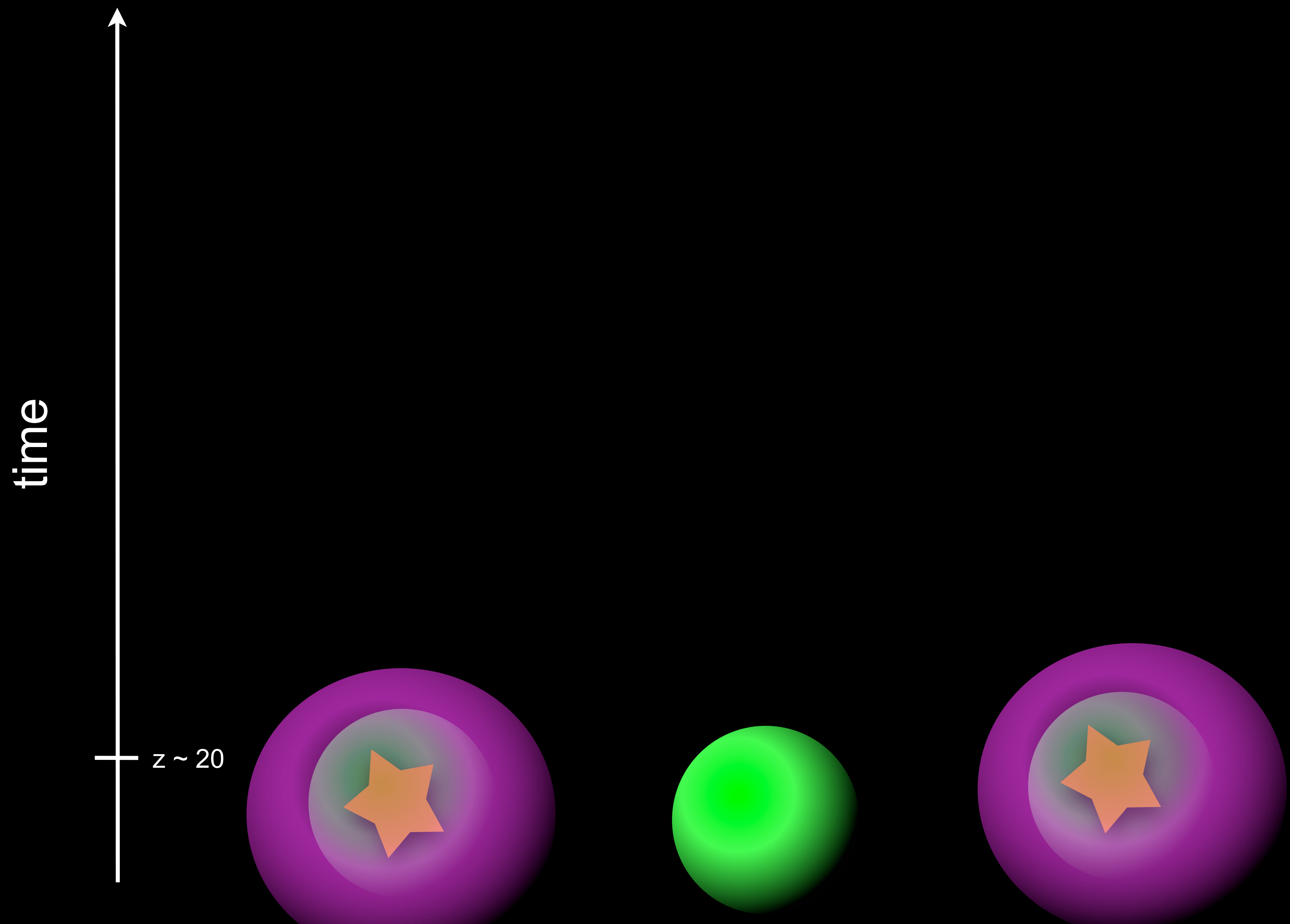

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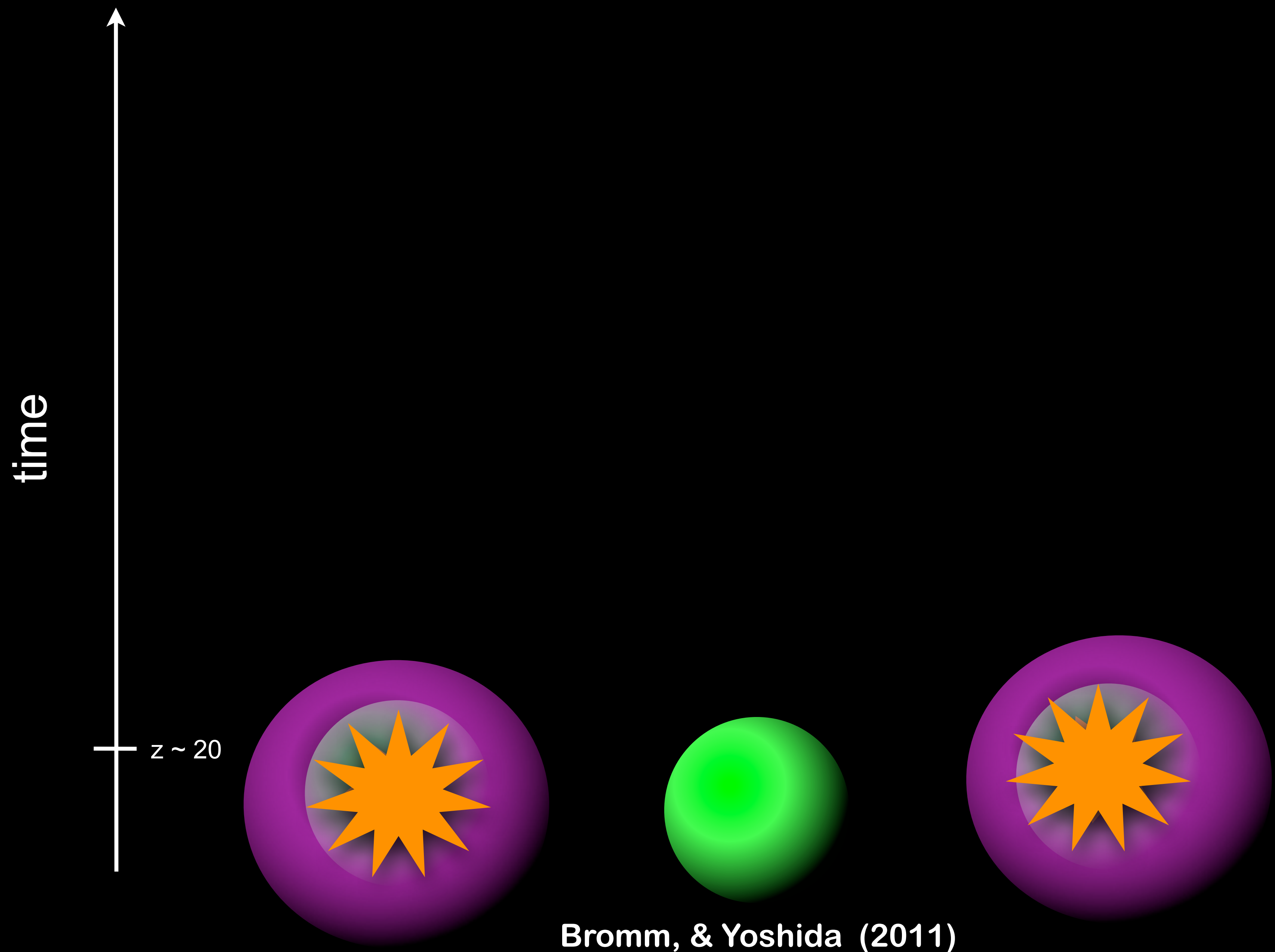

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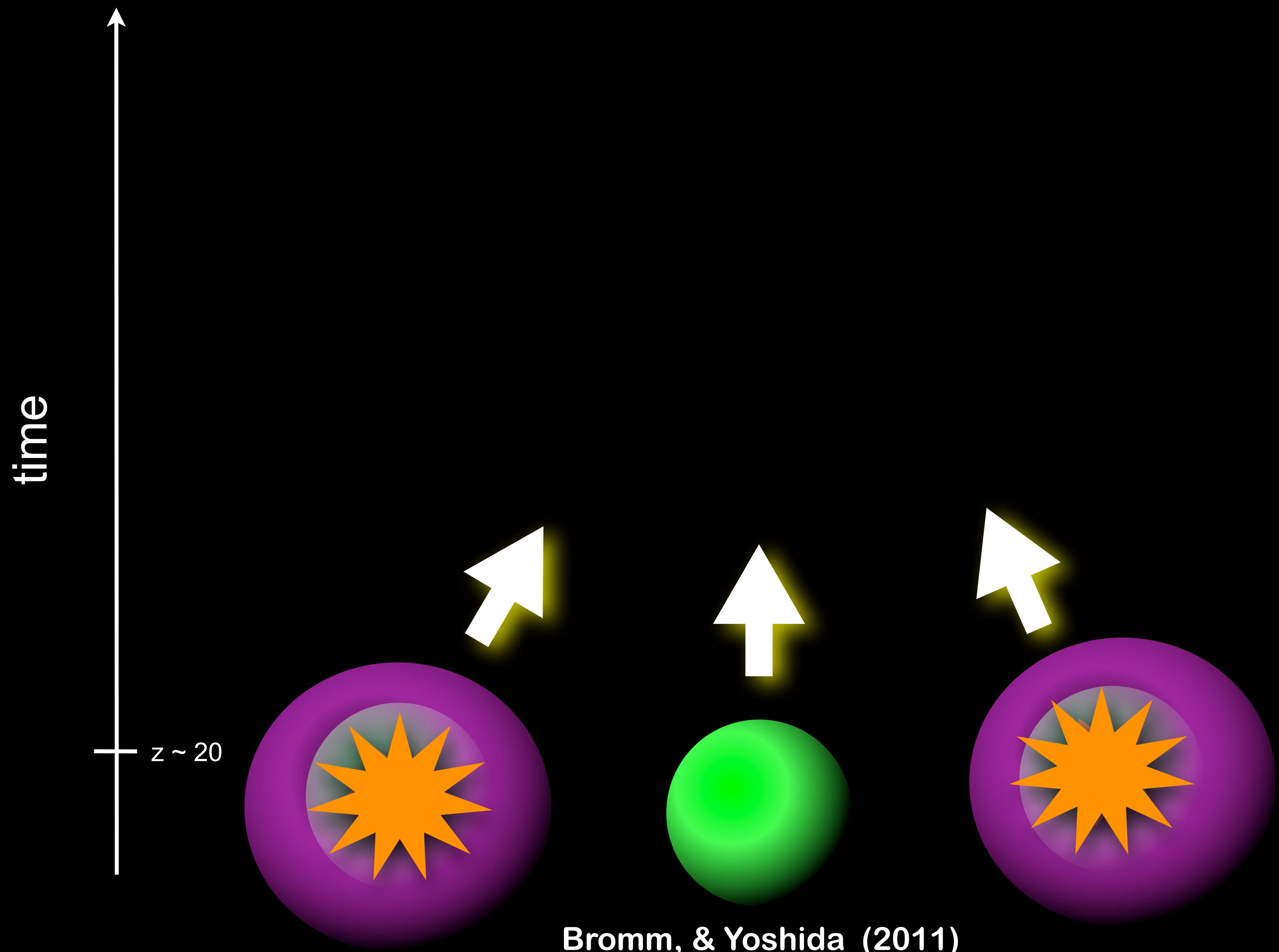

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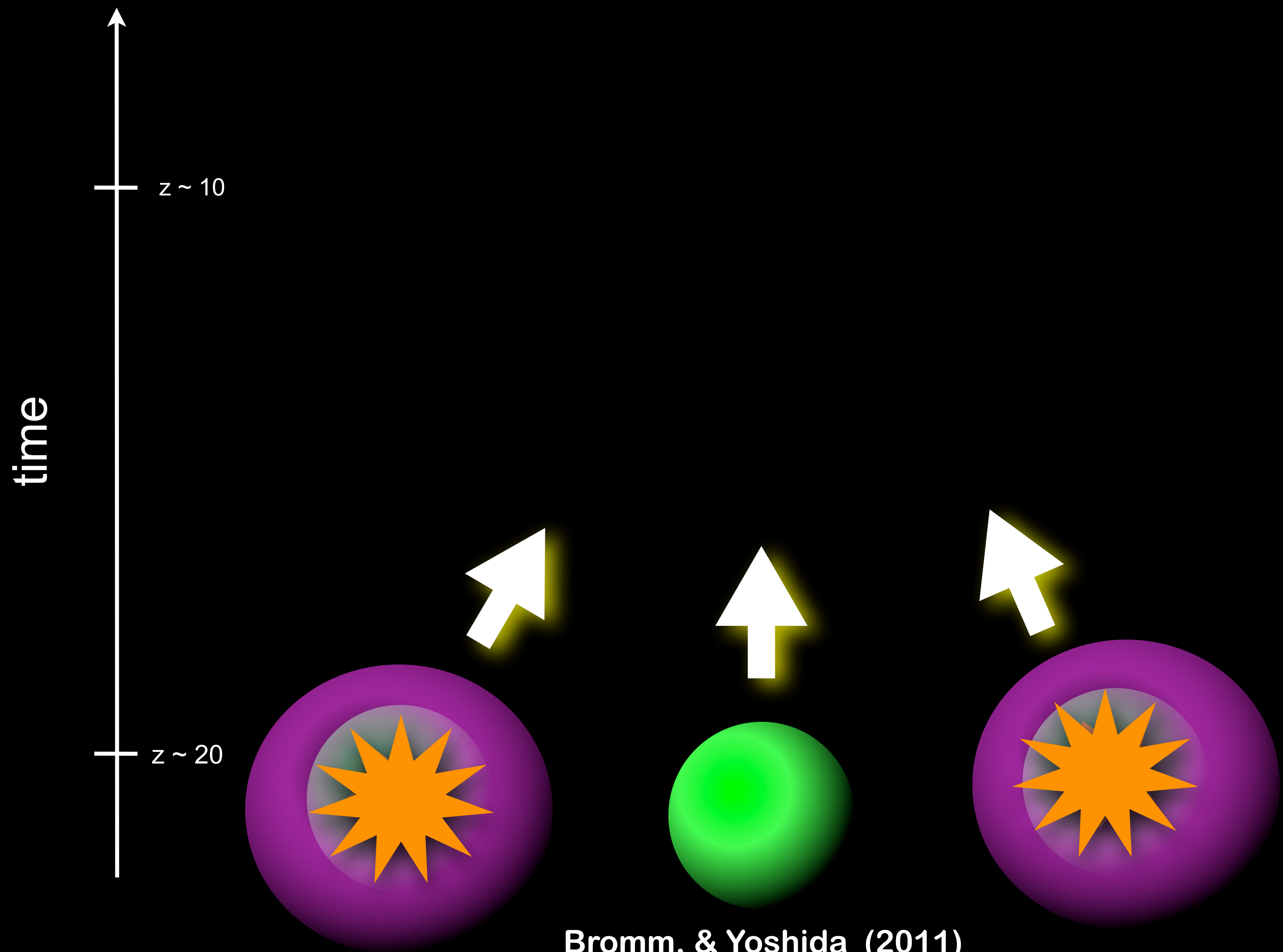

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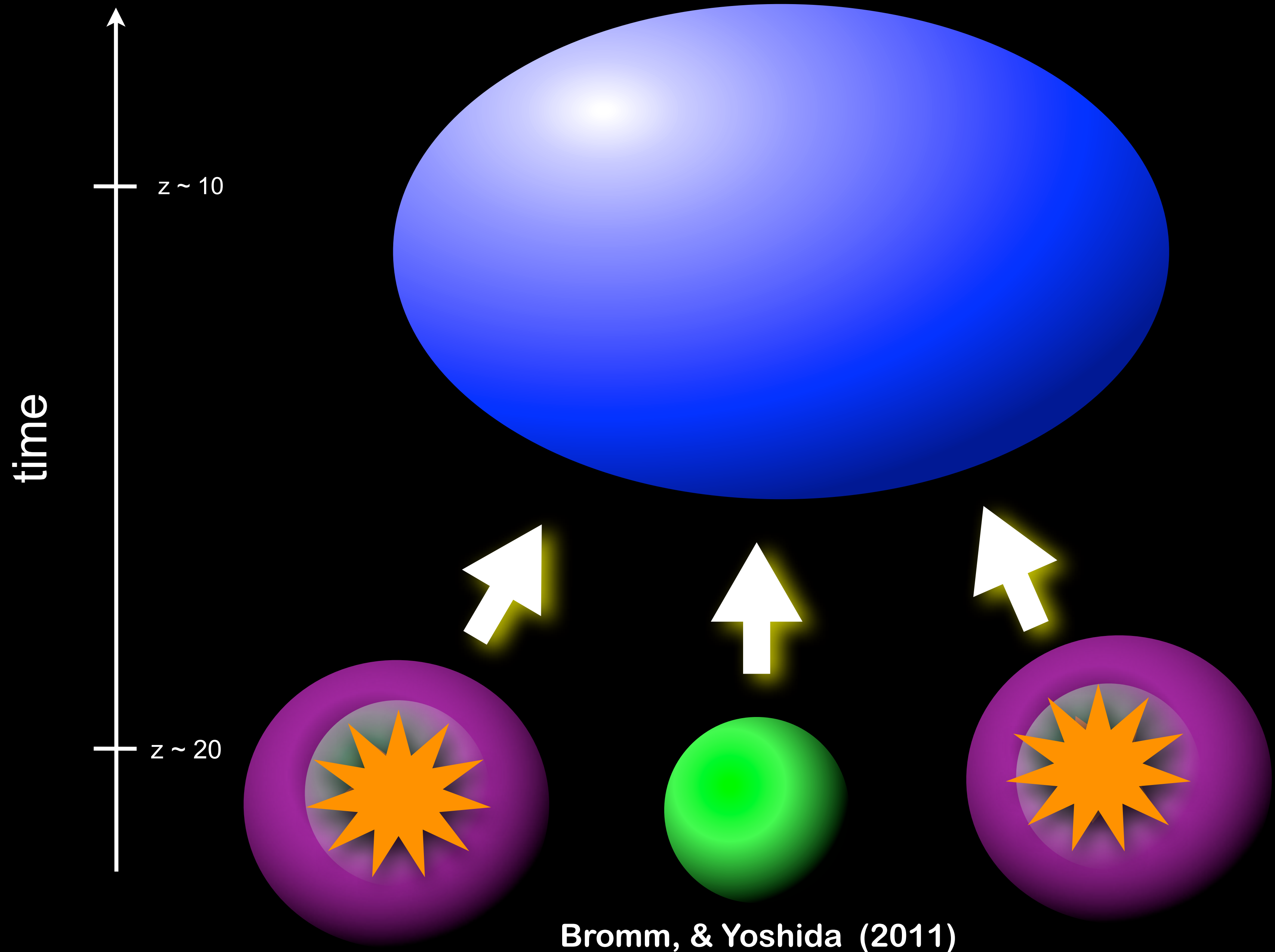

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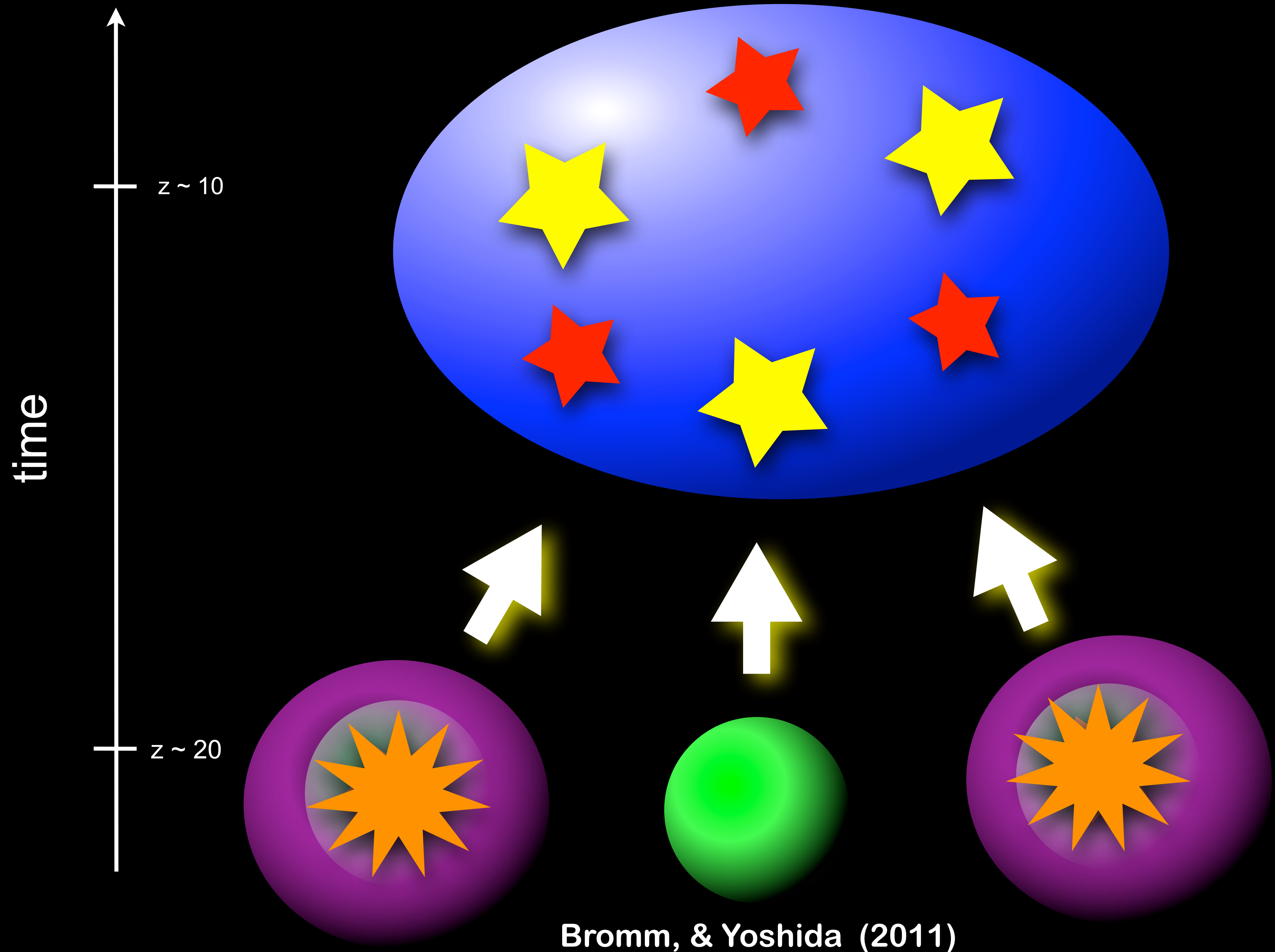

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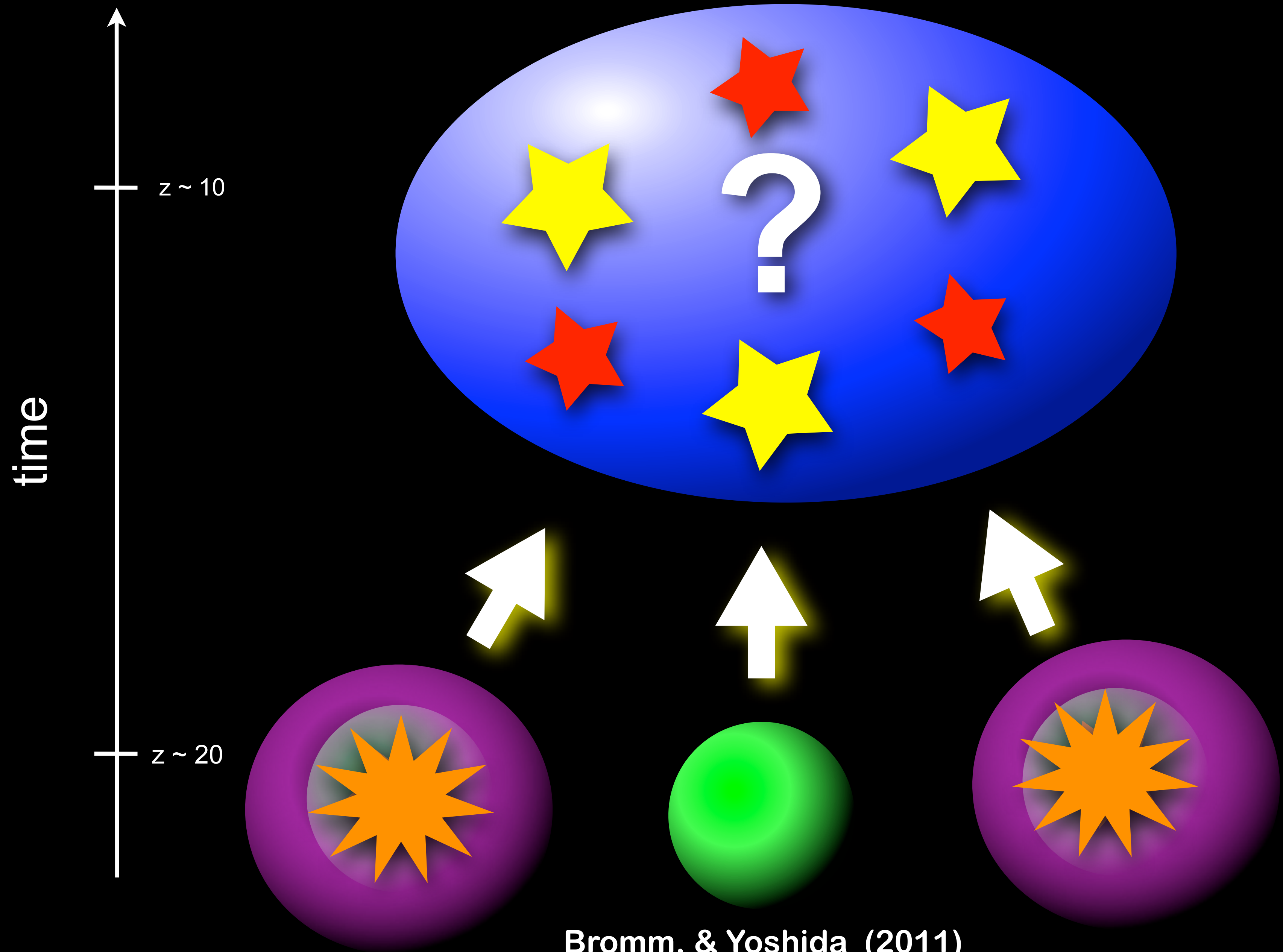

Bromm, & Yoshida (2011)

Characters of the First Galaxies

Bromm, & Yoshida (2011)

- Mass scale ~ 10^8 $M_\odot$
- Redshift ~ 10
- Self-bound system.
- Affected from the previous stellar feedback
- Hosted the Pop III and Pop II stars

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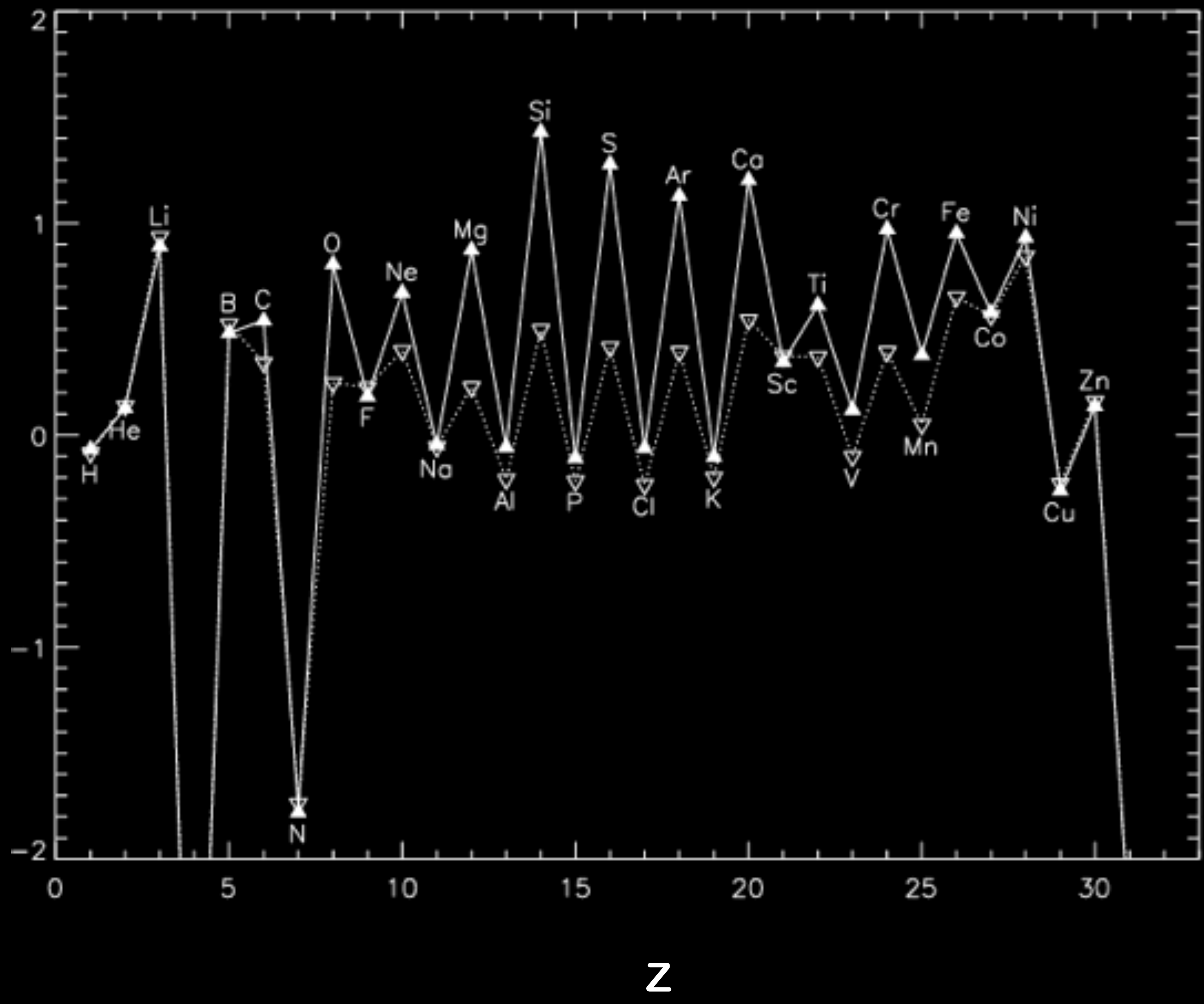

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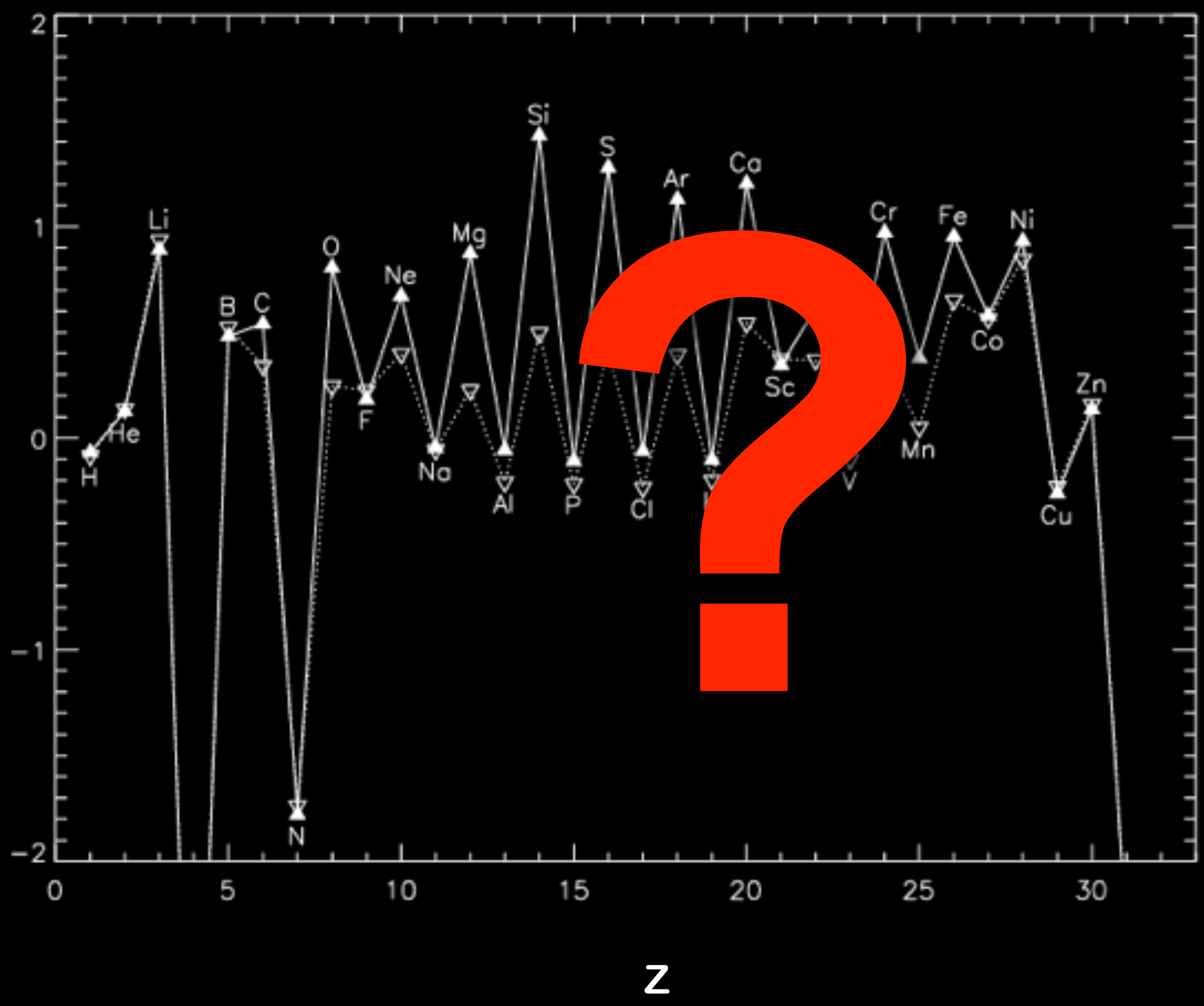

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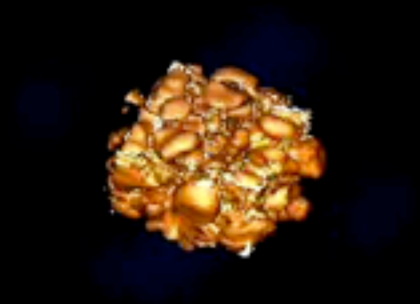

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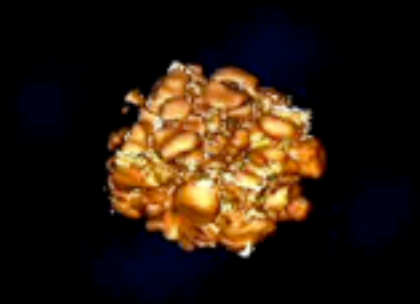
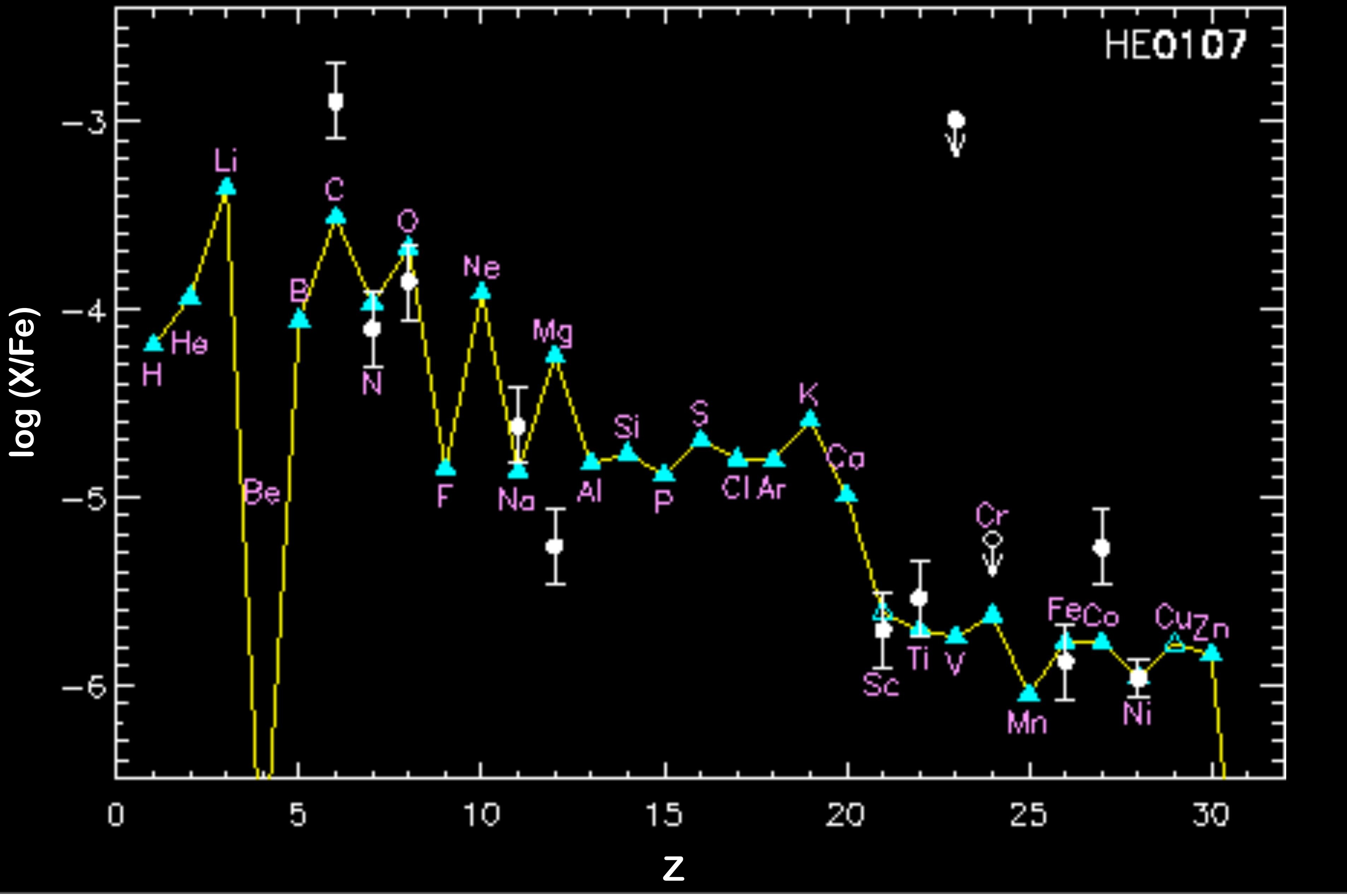
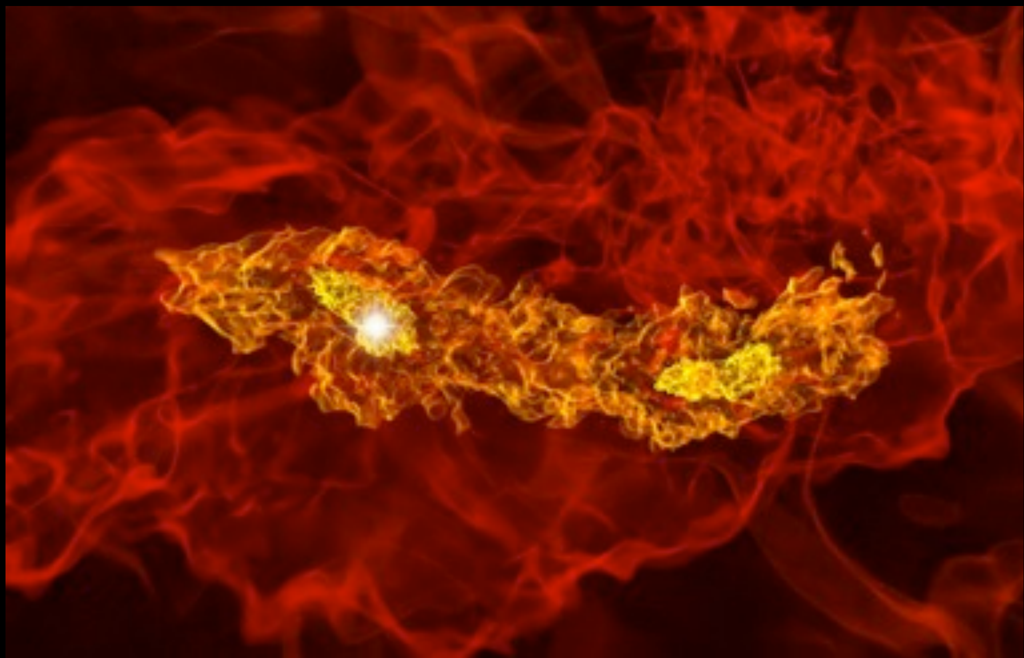


Fe-core Collapse SNe
Nordhaus+ 2010
Using CASTRO

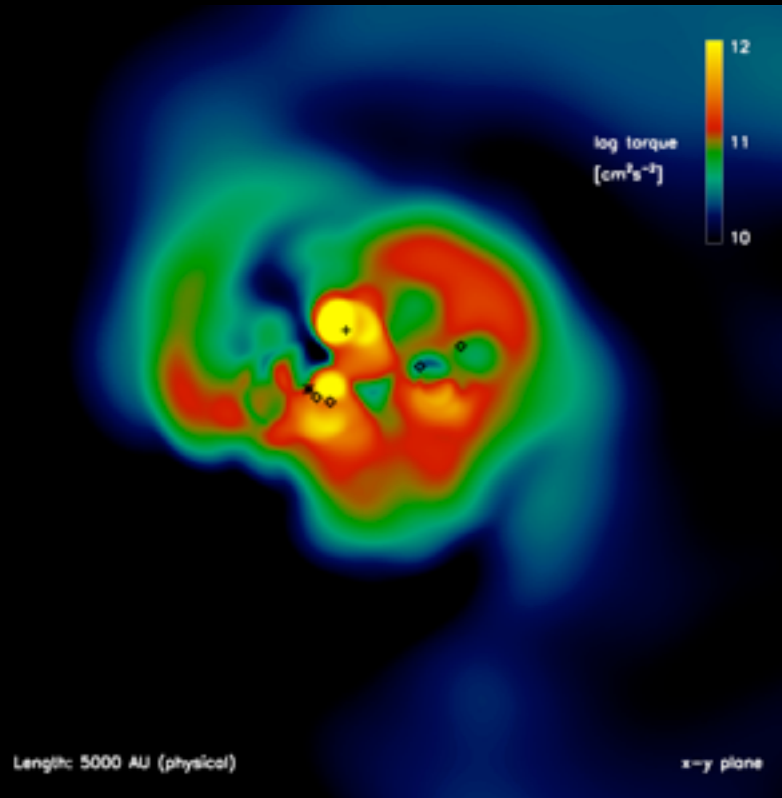
Chemical Abundance ?



The First Binaries



Turk+ (2009)



Stacy+ (2011,2012)

Cosmological Simulations

Chen+ ApJ (2015a)

Gadget-2 (Springel 2005)

1. Star formation
2. Radiative transfer
3. Diffusion mixing
4. Chemical cooling

Bromm+ 2002,2003 Johnson+ 2007

Greif+ 2009, 2010 Jeon+ 2012

Possible radiative feedbacks

1. Ionizing photons
2. SN shock reheating
3. X-Ray Binaries

Chemical enrichment

1. SN feedback

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Chen+ ApJ (2015a)

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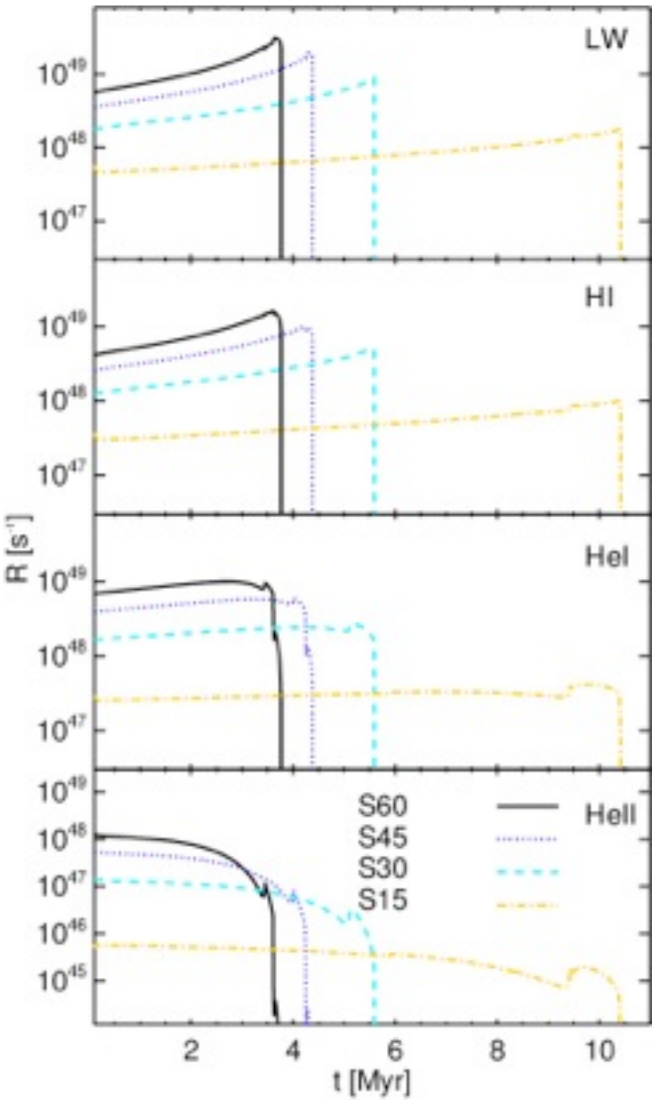
Detailed Stellar Models

Single Star Models



Mass	MS	post-MS	total	fates	metals (SN/HN)
($M_\odot$)	(Myr)	(Myr)	(Myr)		($M_\odot$)
15	9.478	1.031	10.51	SN	1.388
30	5.208	0.509	5.77	BH, HN	6.876
45	3.995	0.394	4.39	BH, HN	13.26
60	3.426	0.345	3.77	BH, HN	20.66

Table 10.1 Stellar lifetimes and fates

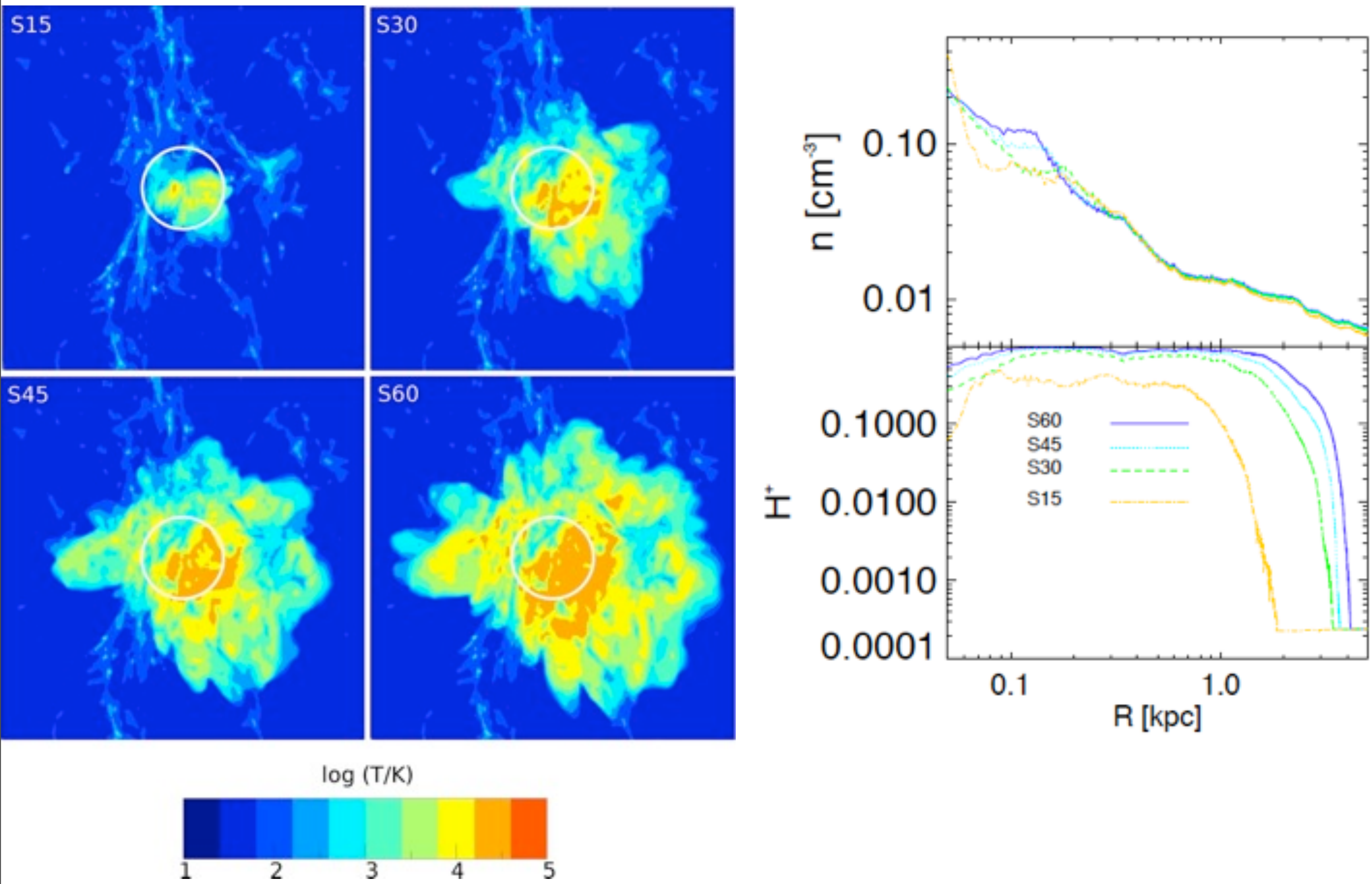
X^a	Type	Masses	E^b	mass ejection	Notes
		($M_\odot$)	(B)		
S	SN	$\lesssim 25$	1.2	all but $\sim 1.5\,M_\odot$	leaves neutron star
B	BH	$\gtrsim 25$	0	None	complete collapse to BH
H	HN	$\lesssim 25$	10	$\sim 90\,\%$	big explosion, leaves black hole

Table 10.2 Summary of assumed stellar fate characteristics: [a] sentinel used in model names to indicate fate of star. [b] Explosion energy.

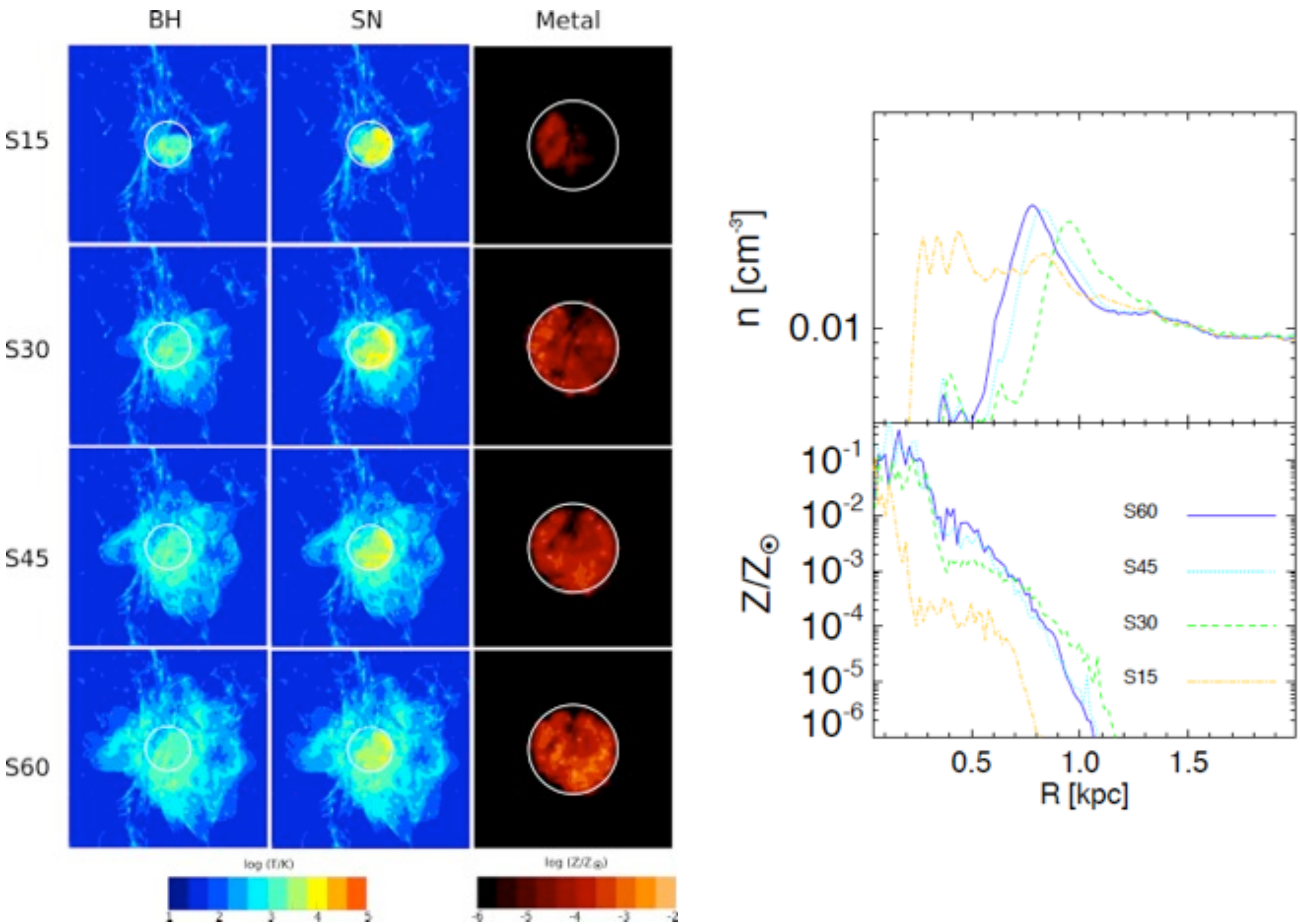
Mass	HI	HeI	HeII
($M_\odot$)	(10^{63})	(10^{63})	(10^{61})
15	0.64	0.16	0.10
30	1.82	0.72	1.37
45	2.98	1.45	4.34
60	4.18	2.21	8.31

Table 10.3 Number of ionizing photons emitted over the lifetime of a star.

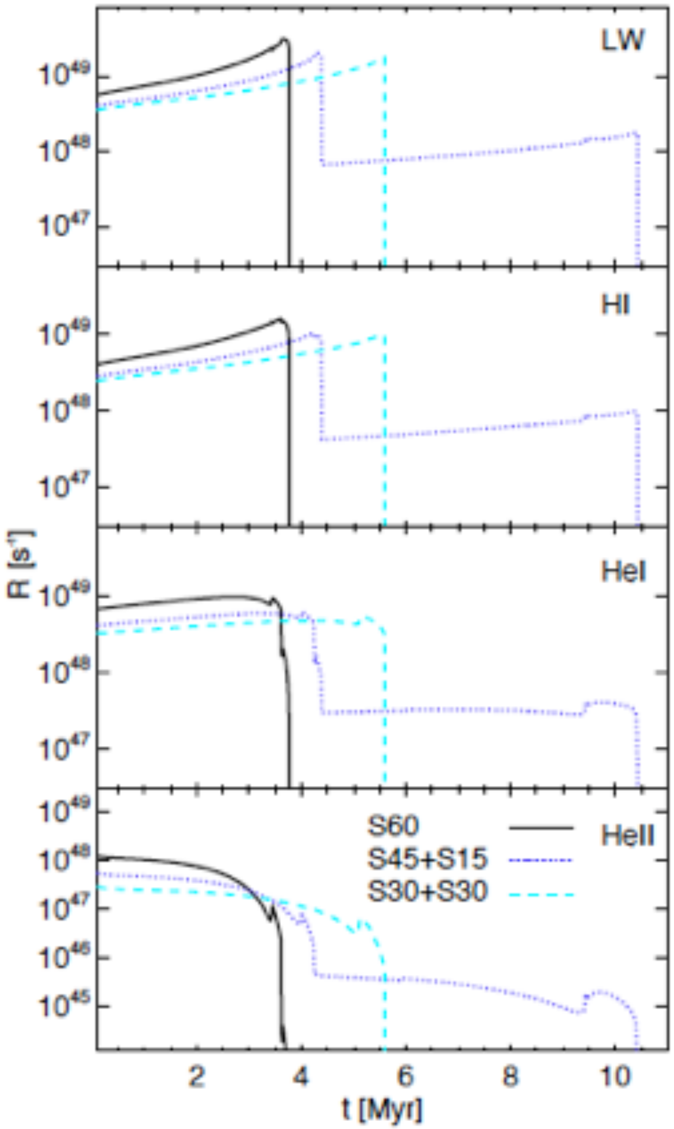
Radiative Feedback



Radiative+Supernova Feedback



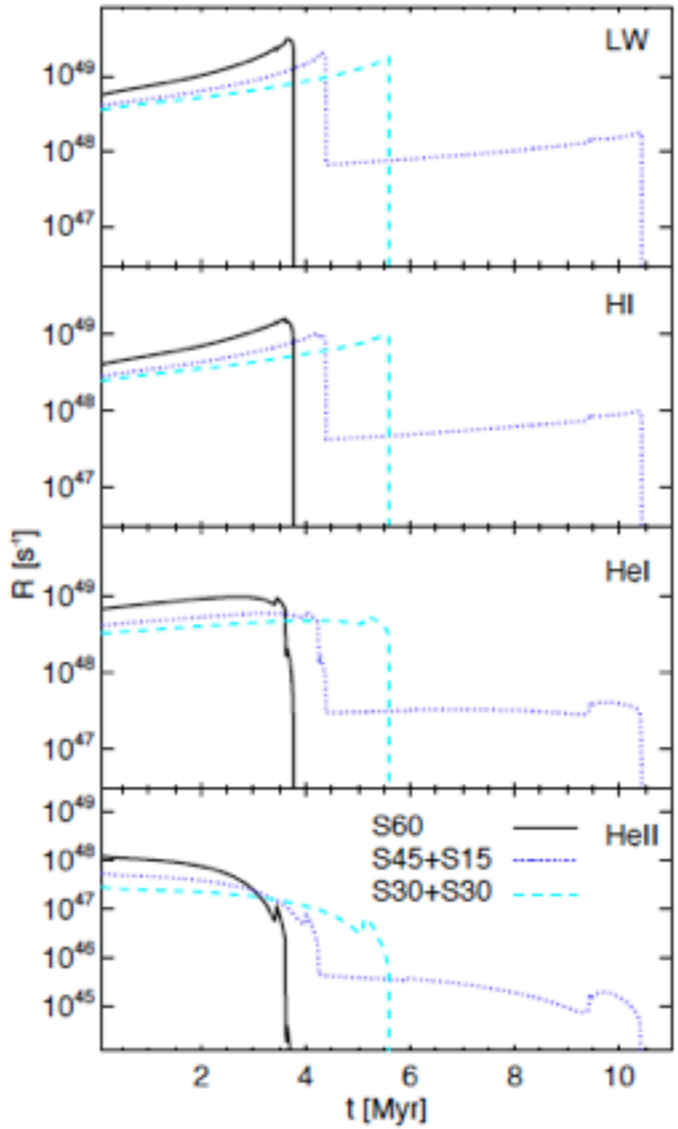
Binary Models



Binary	HI (10^{63})	HeI (10^{63})	HeII (10^{61})	t_*^a (Myr)
S30+S30	3.64	1.44	2.74	5.77
S45+S15	3.62	1.61	4.43	10.51
S60	4.18	2.21	8.31	3.77

Case	Masses ($M_\odot$)	Separation (distance)	Fate 1	Fate 2	metals (SN/HN) ($M_\odot$)
I	30+30	wide	HN	HN	13.74
II	30+30	wide	BH	BH	0.00
III	45+15	close	BH	..	0.00
III	45+15	close	HN	..	13.26
IV	60	..	HN	..	20.66

Binary Models



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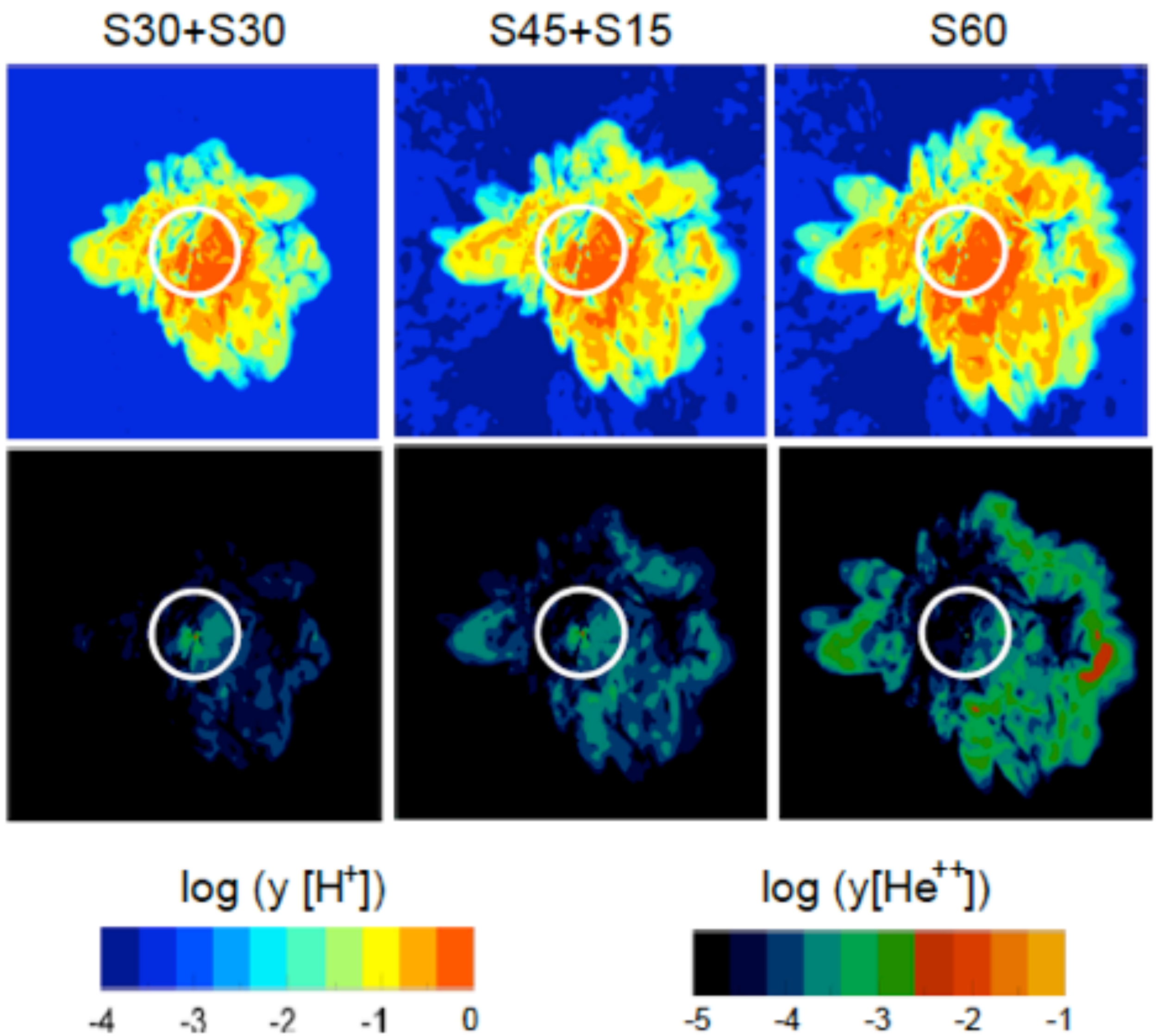
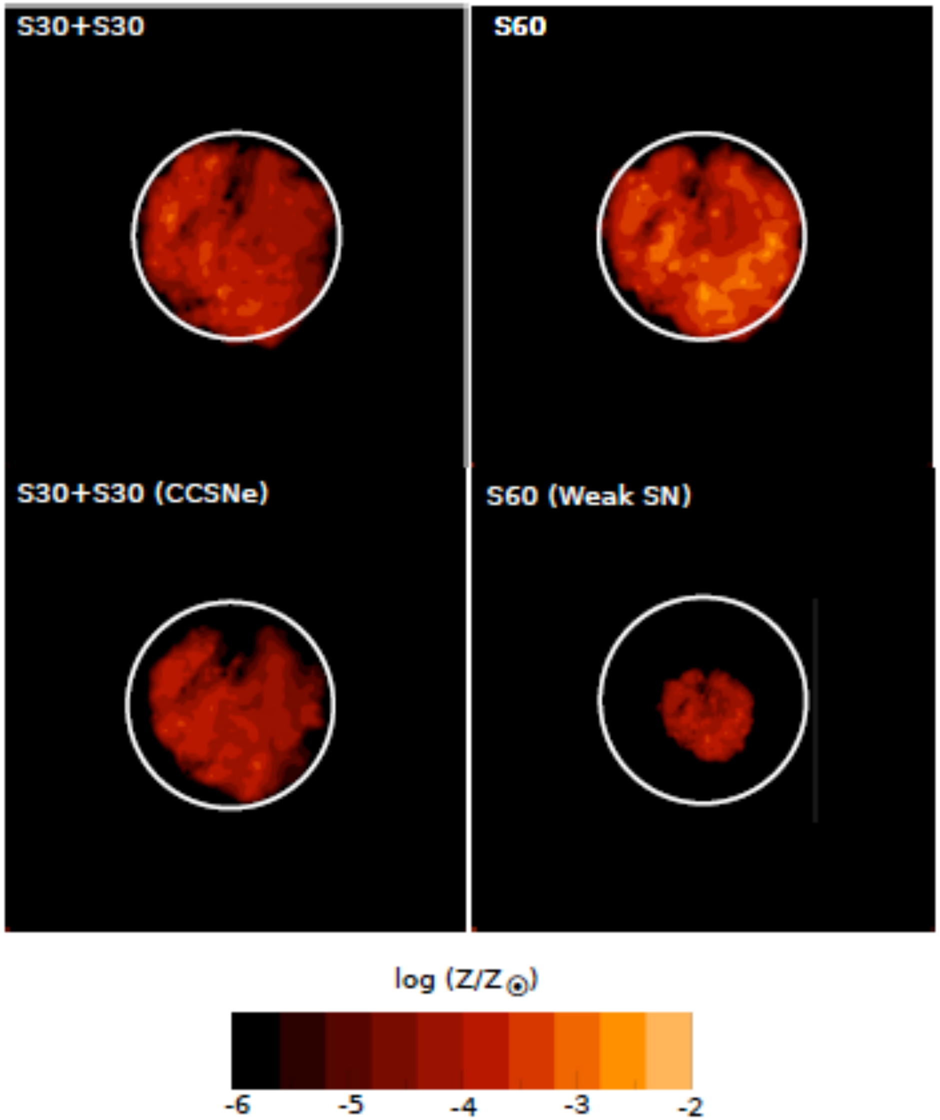
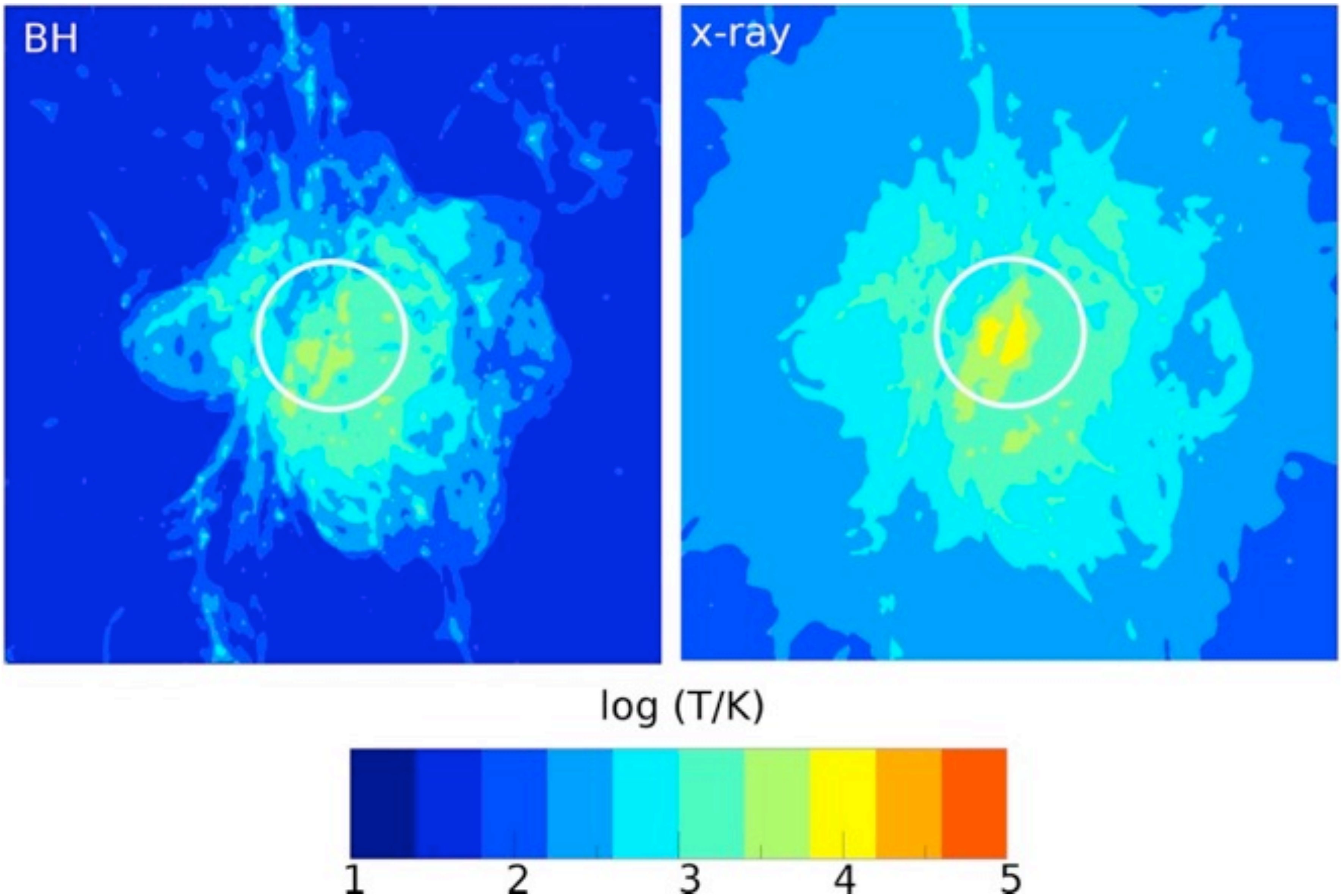
Radiative Feedback (Binaries)



SN Feedback (Binaries)




BH
x-ray
log (T/K)
1
2
3
4
5

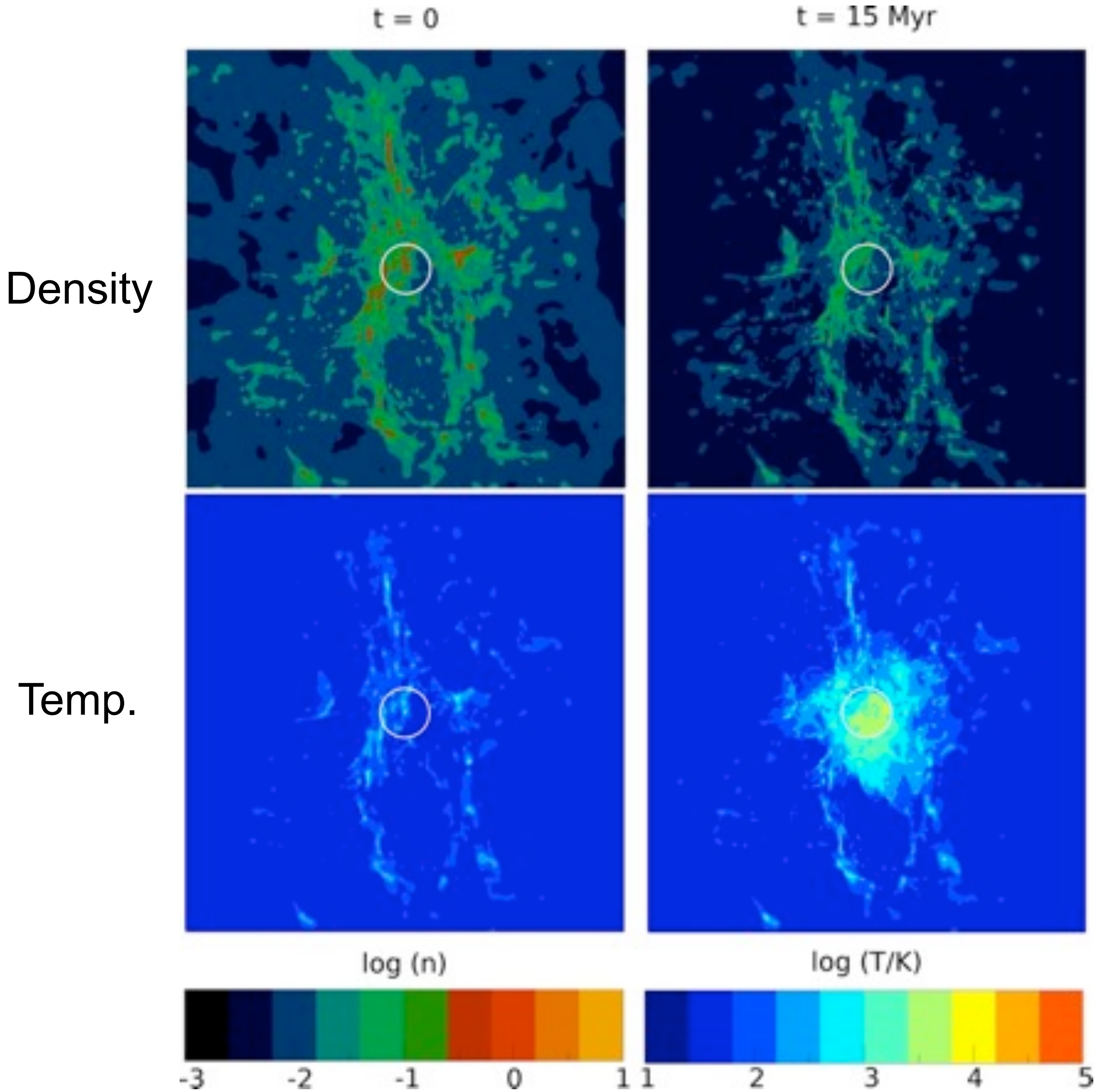
The Impact of the First Stars, Supernovae, and Binaries

Ken Chen

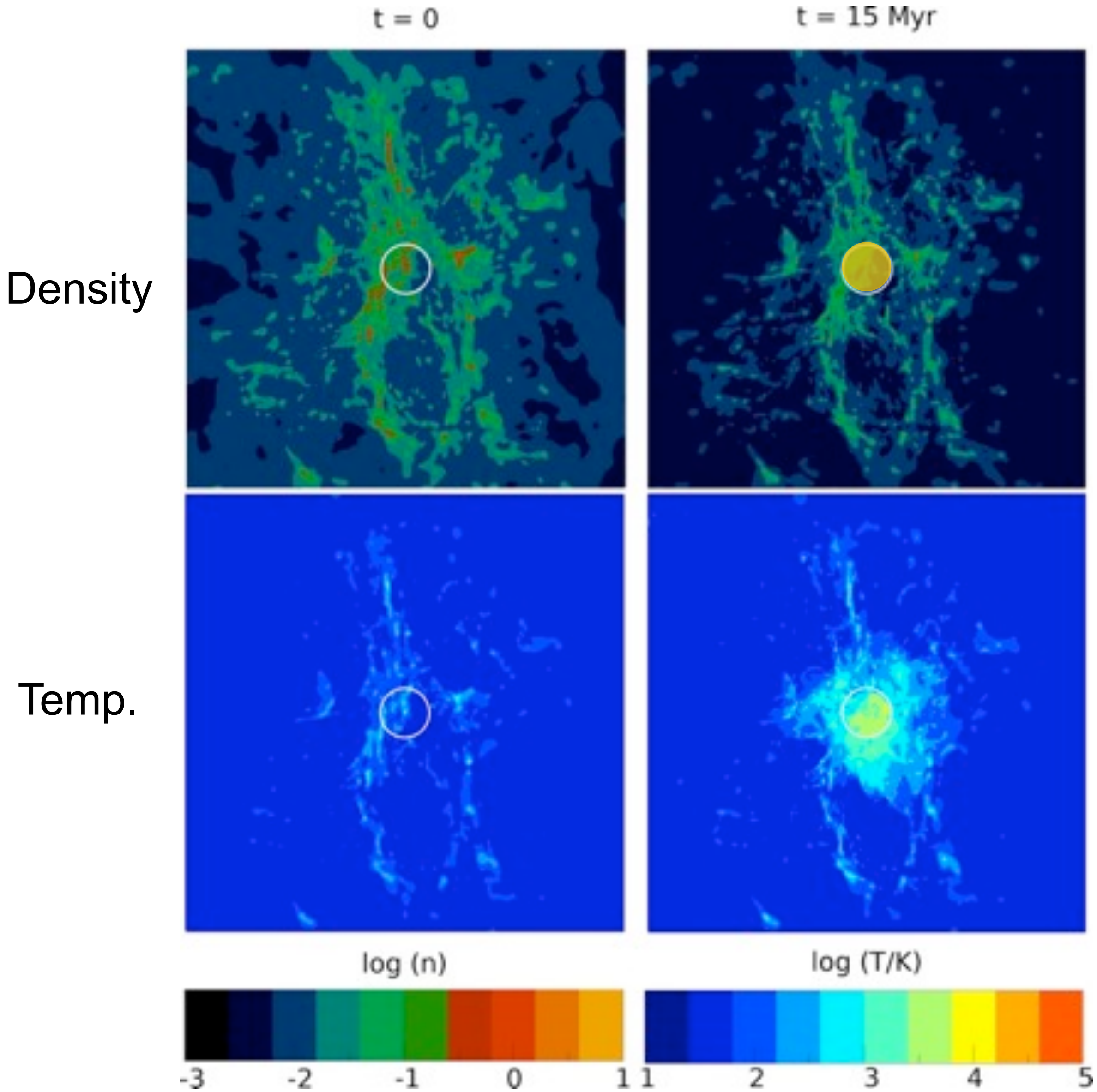
University of Minnesota

Background music: Pirates Of The Caribean

Properties of Large Scale Structure



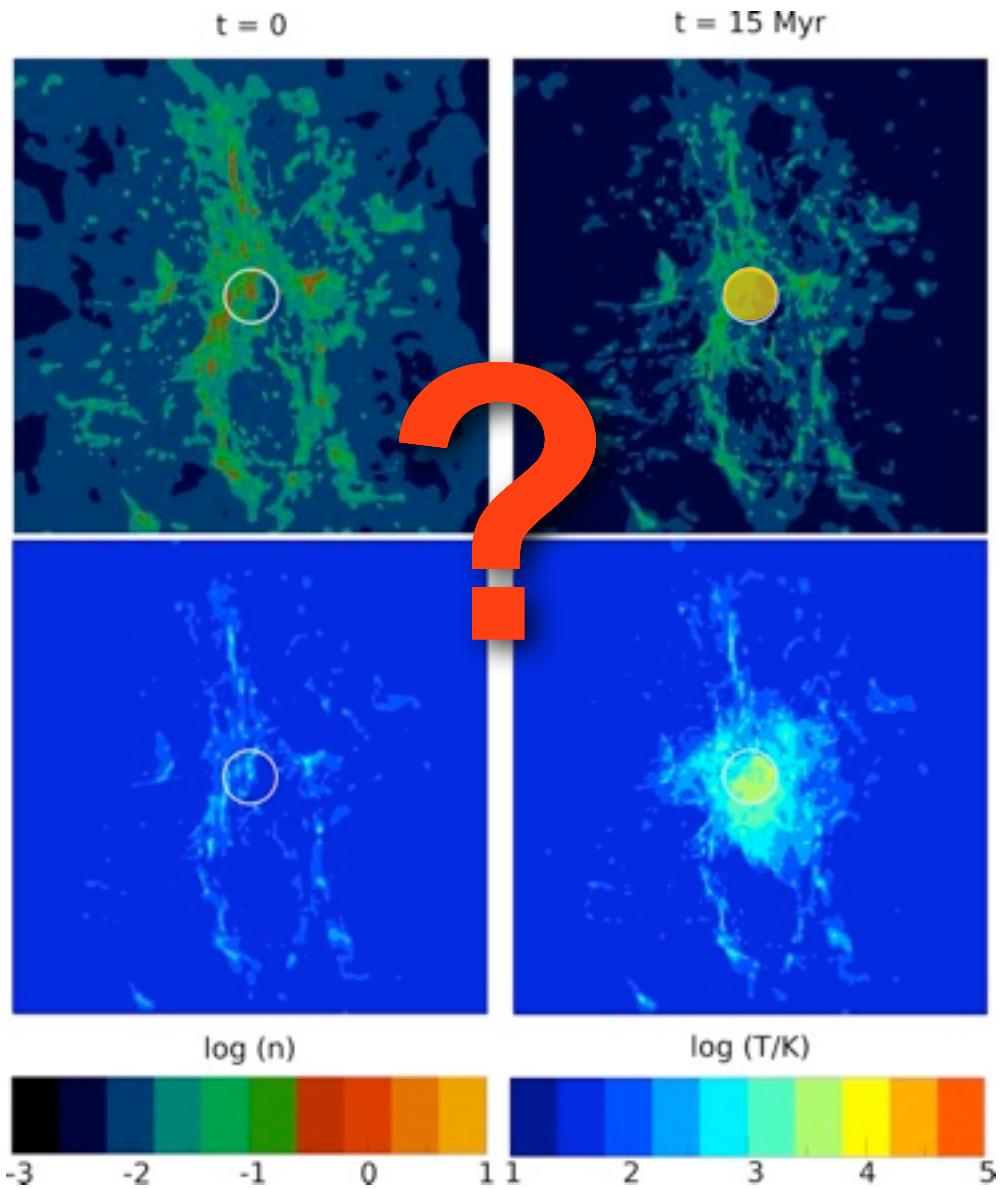
Properties of Large Scale Structure



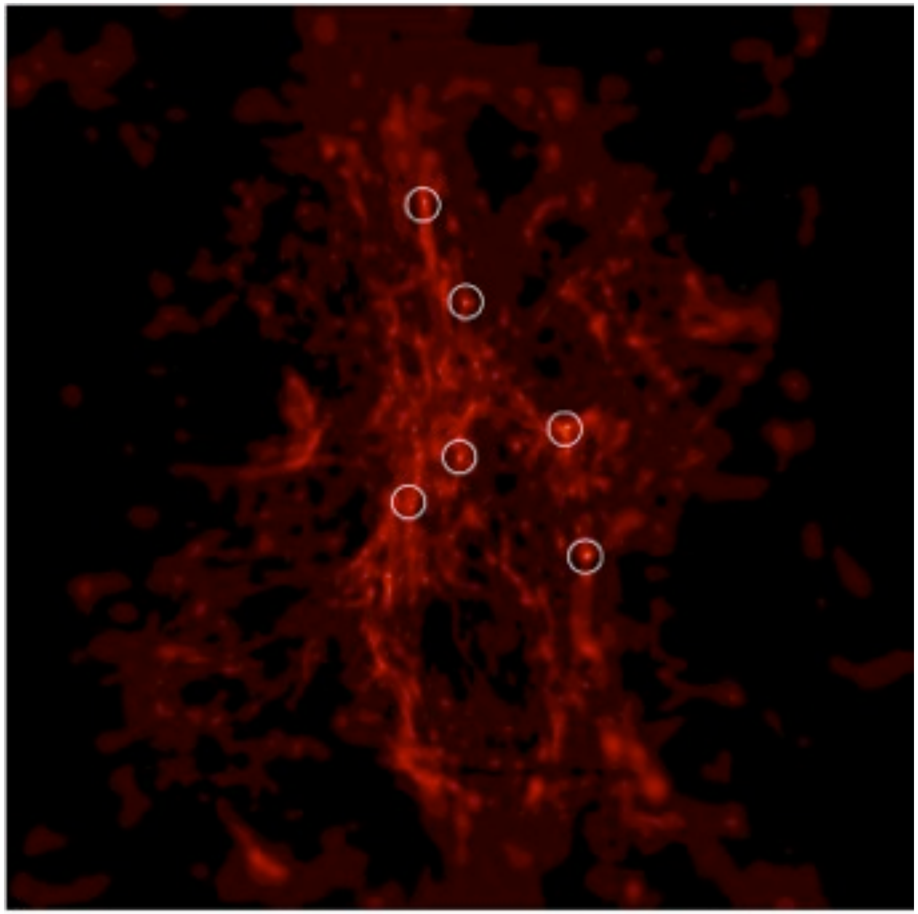
Properties of Large Scale Structure

Density

Temp.



The First Galaxies



	radiation	SN metal
single star	strong	weak
binary star	weak (x-ray)	strong

What's New

Magnetar

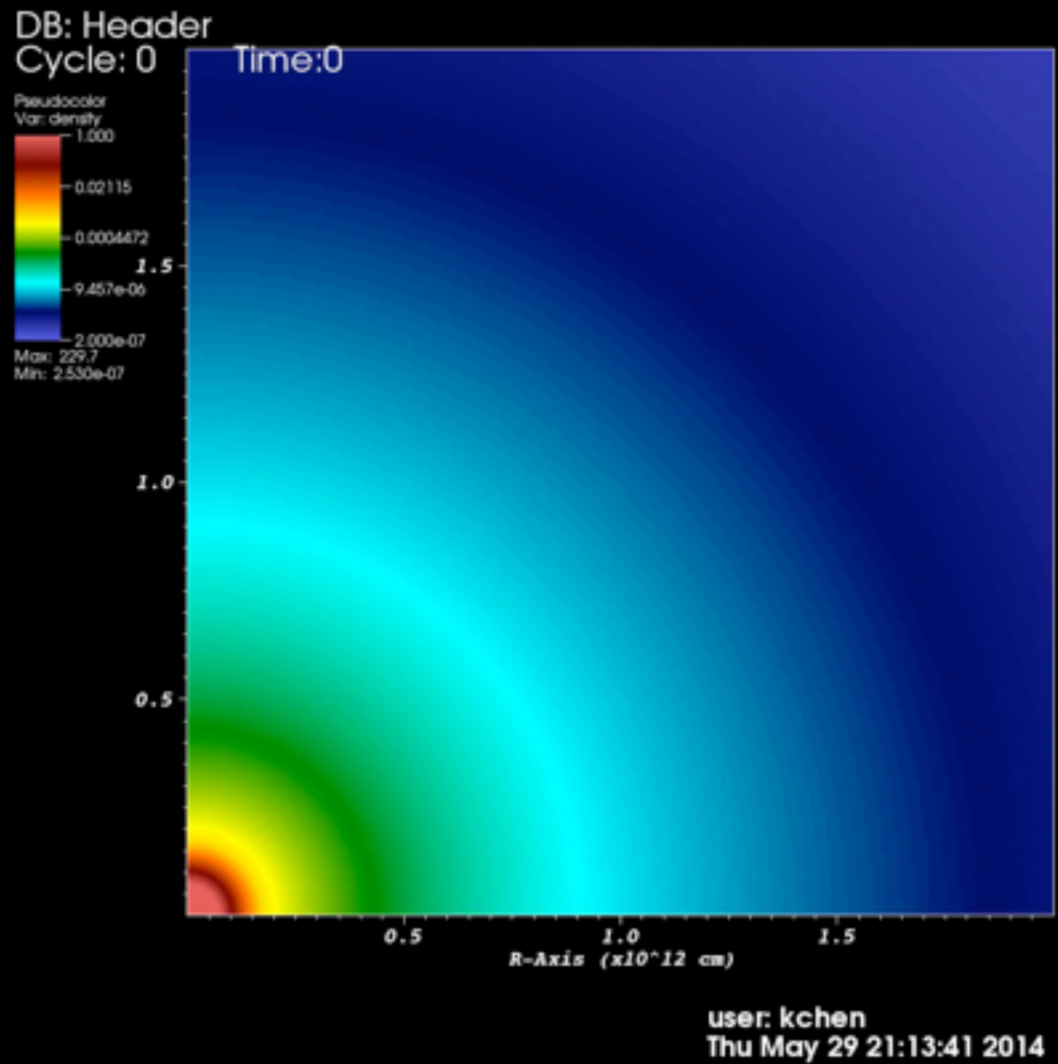
30 M☉ > M* > 15 M☉

Chen+ 2015b to be submitted

Magnetar

30 M☉ > M* > 15 M☉

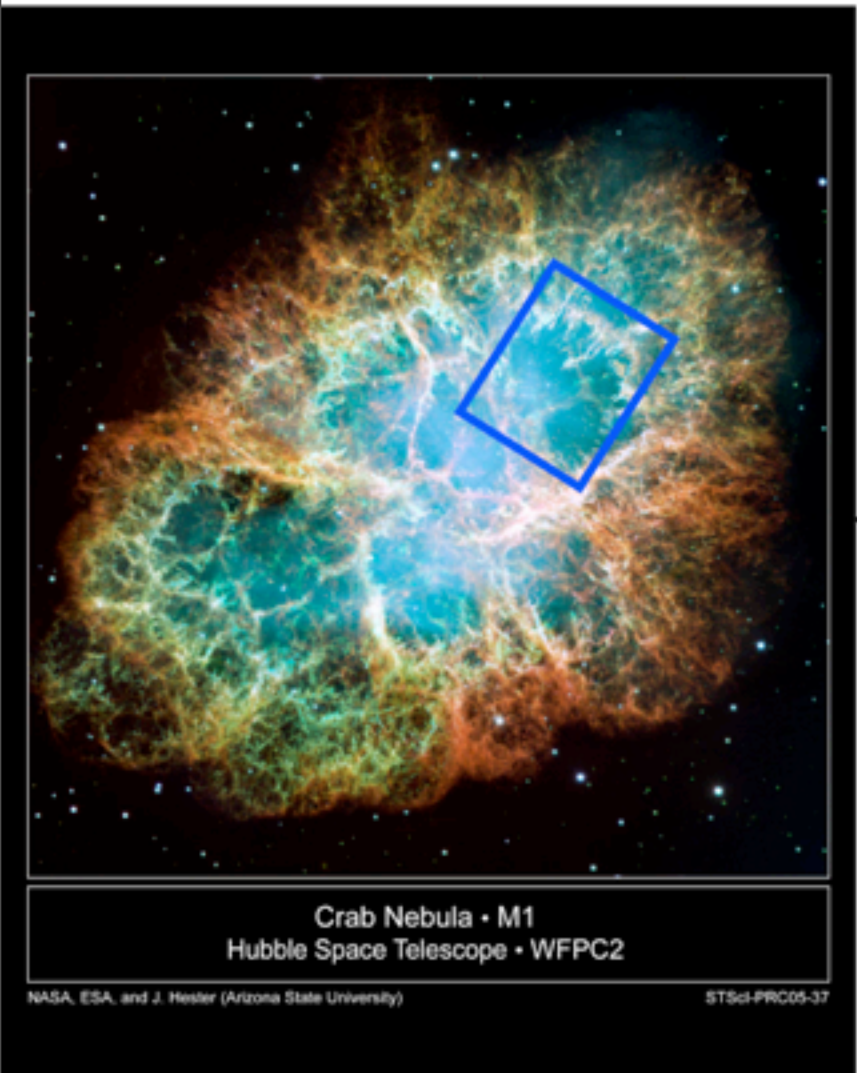
Chen+ 2015b to be submitted

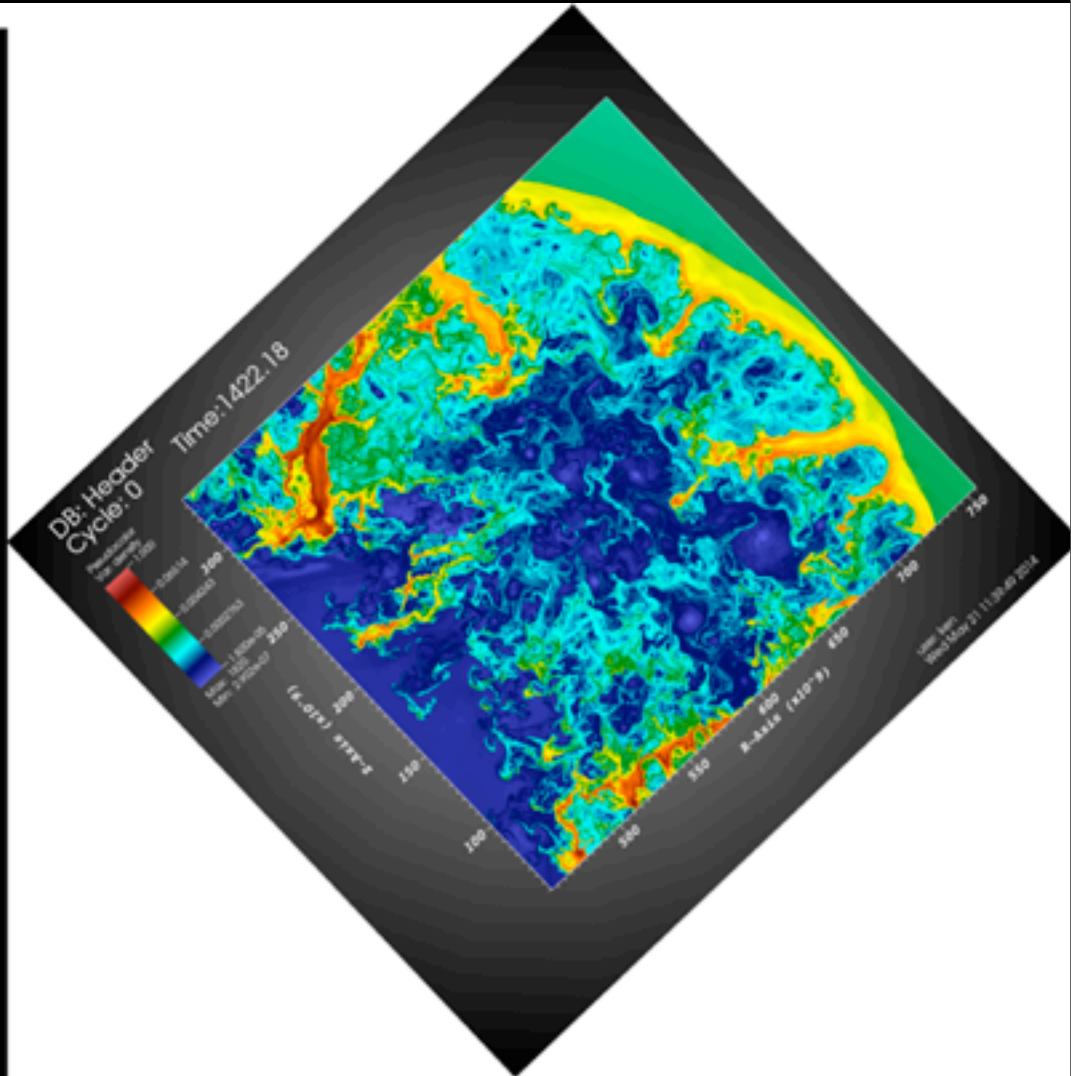


Magnetar

30 M⊙ > M* > 15 M⊙

Chen+ 2015b to be submitted





Hypernova and GRB !!!

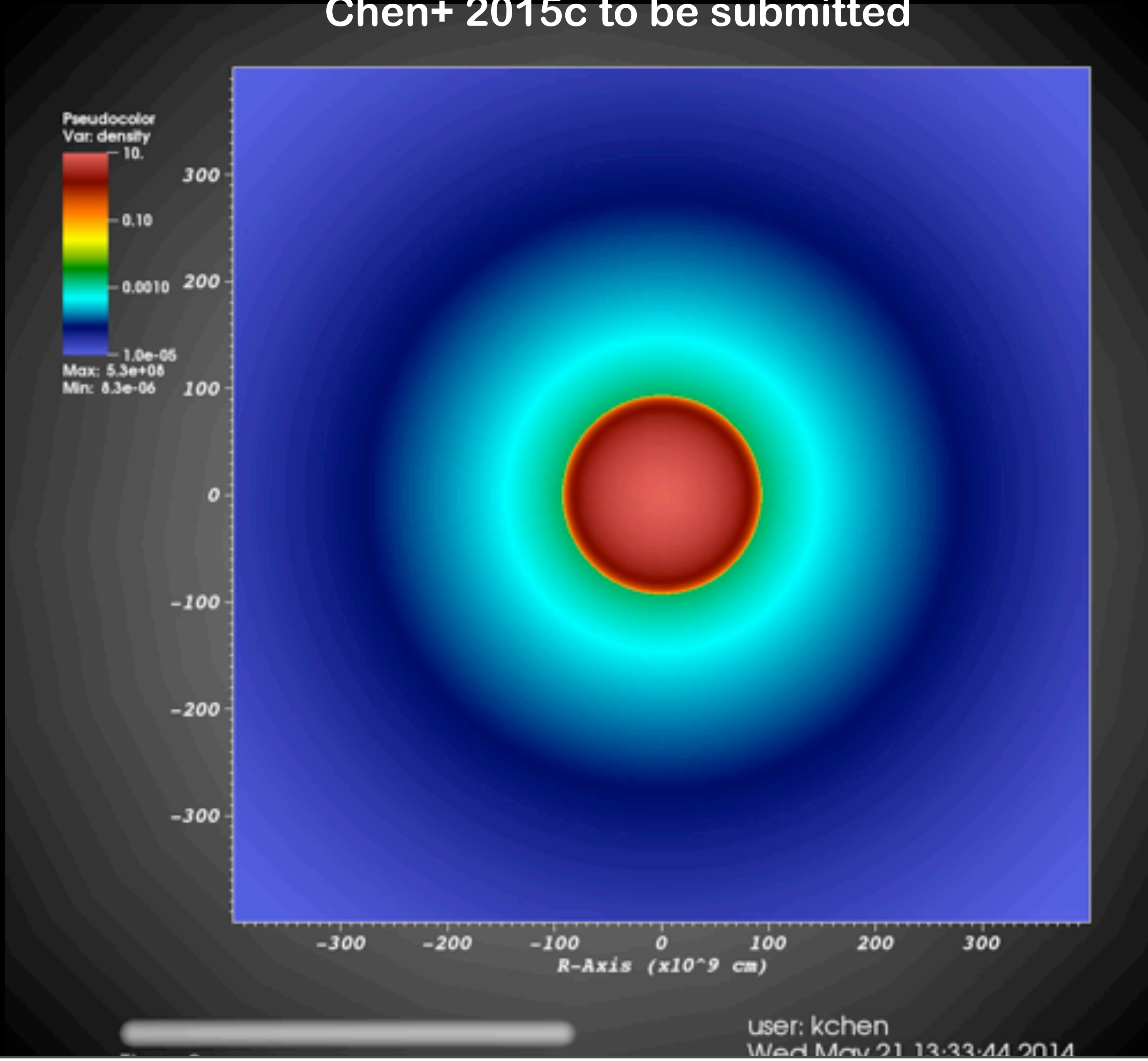
60 M☉ > M* > 30 M☉

Chen+ 2015c to be submitted

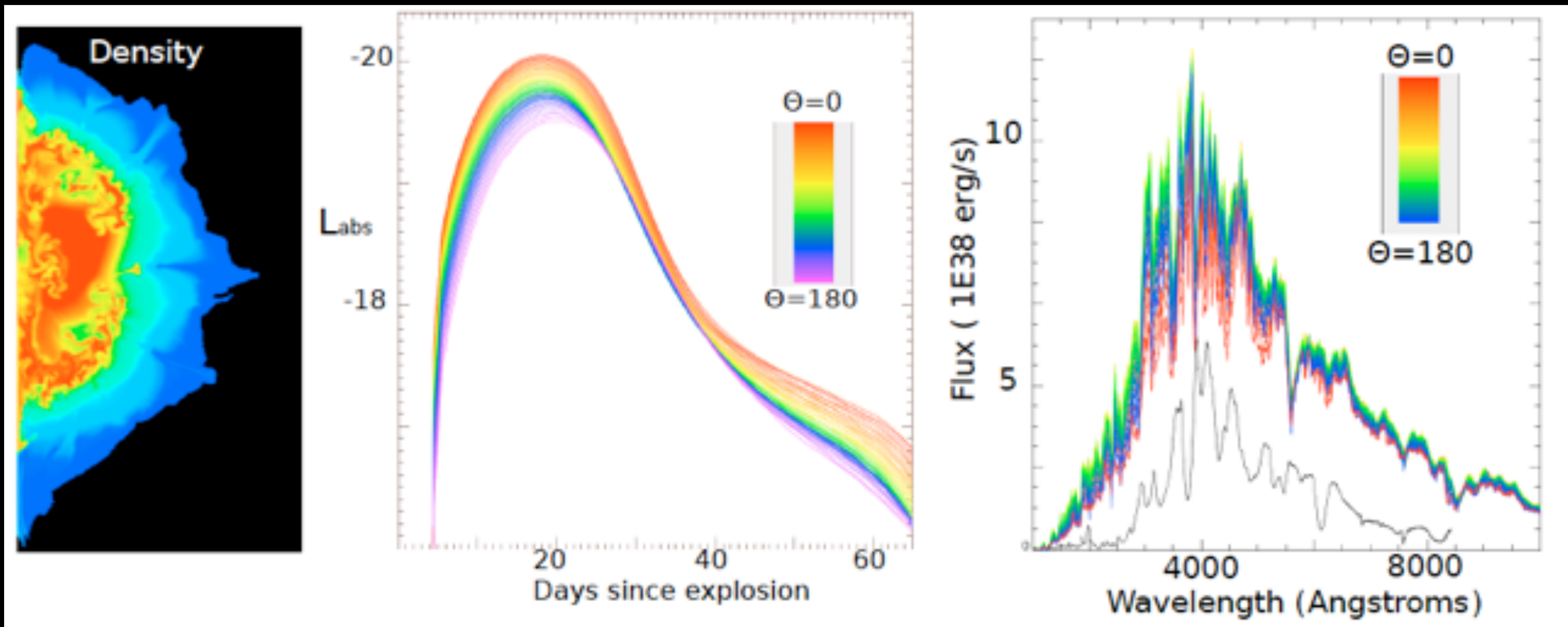
Hypernova and GRB !!!

60 M☉ > M* > 30 M☉

Chen+ 2015c to be submitted

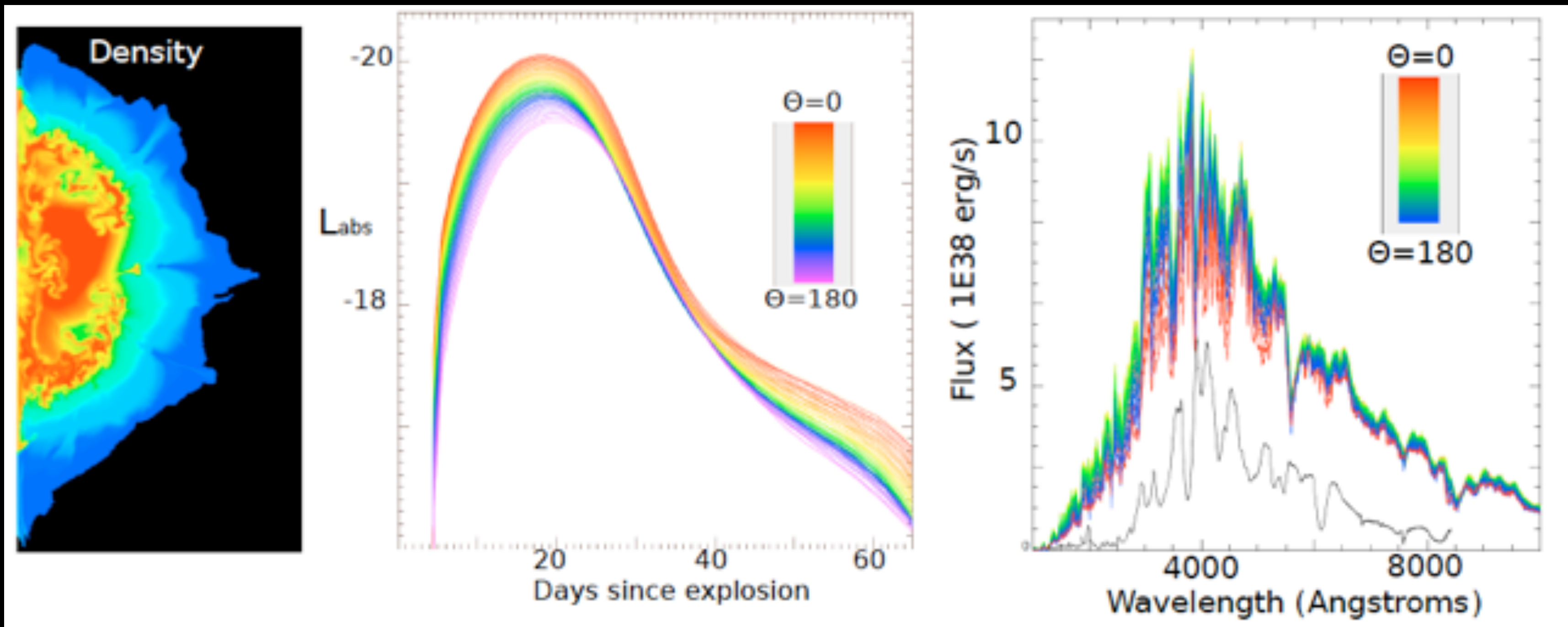


Current and coming research projects: Realistic SN observational Signatures



A Type Ia Example from Kasen+ 2008

Current and coming research projects: Realistic SN observational Signatures

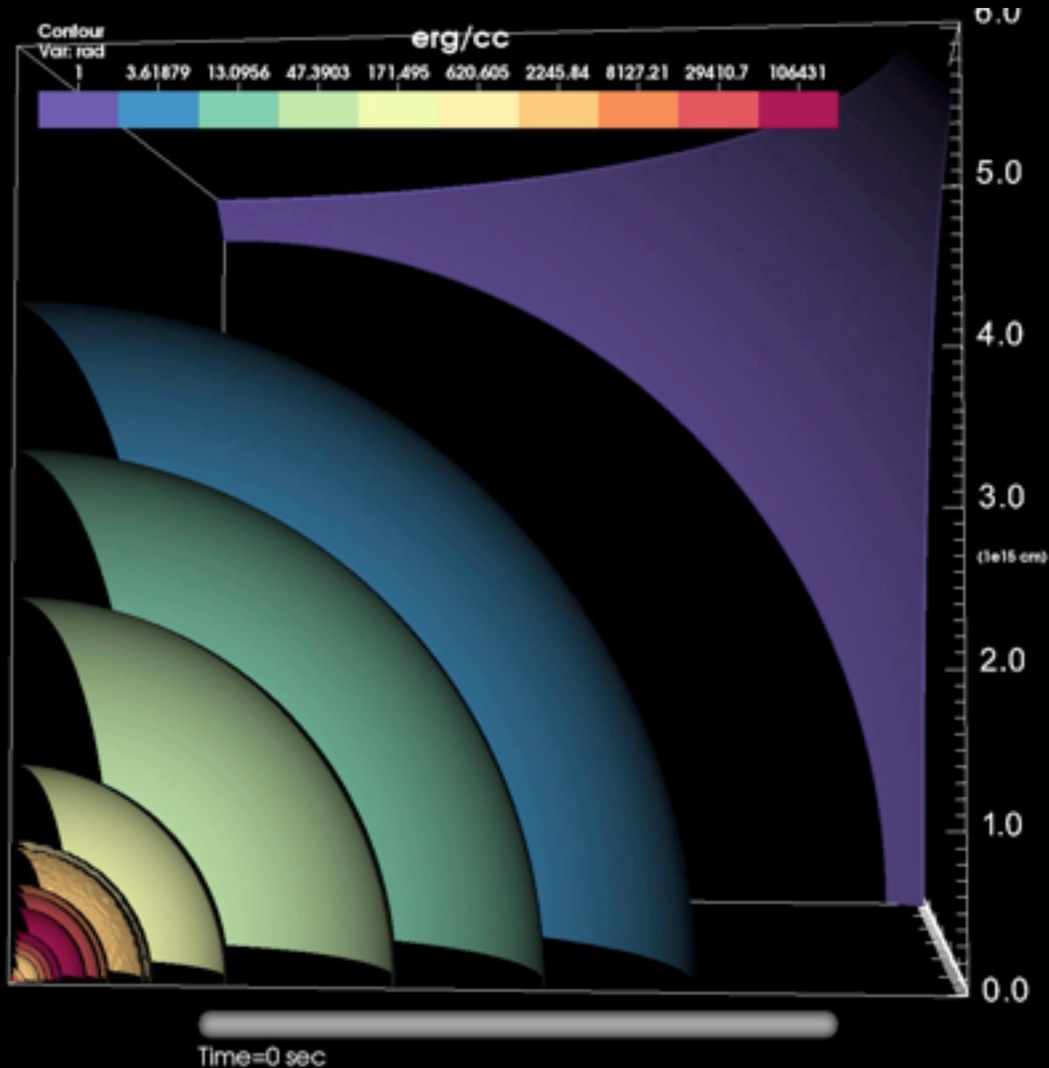


A Type Ia Example from Kasen+ 2008

Multidimensional Radiation Transport Simulations of Exotic SNe !!

3D Radiation Transport Simulation of PPSNe

Chen+ in prep.



3D Radiation Transport Simulation of PPSNe

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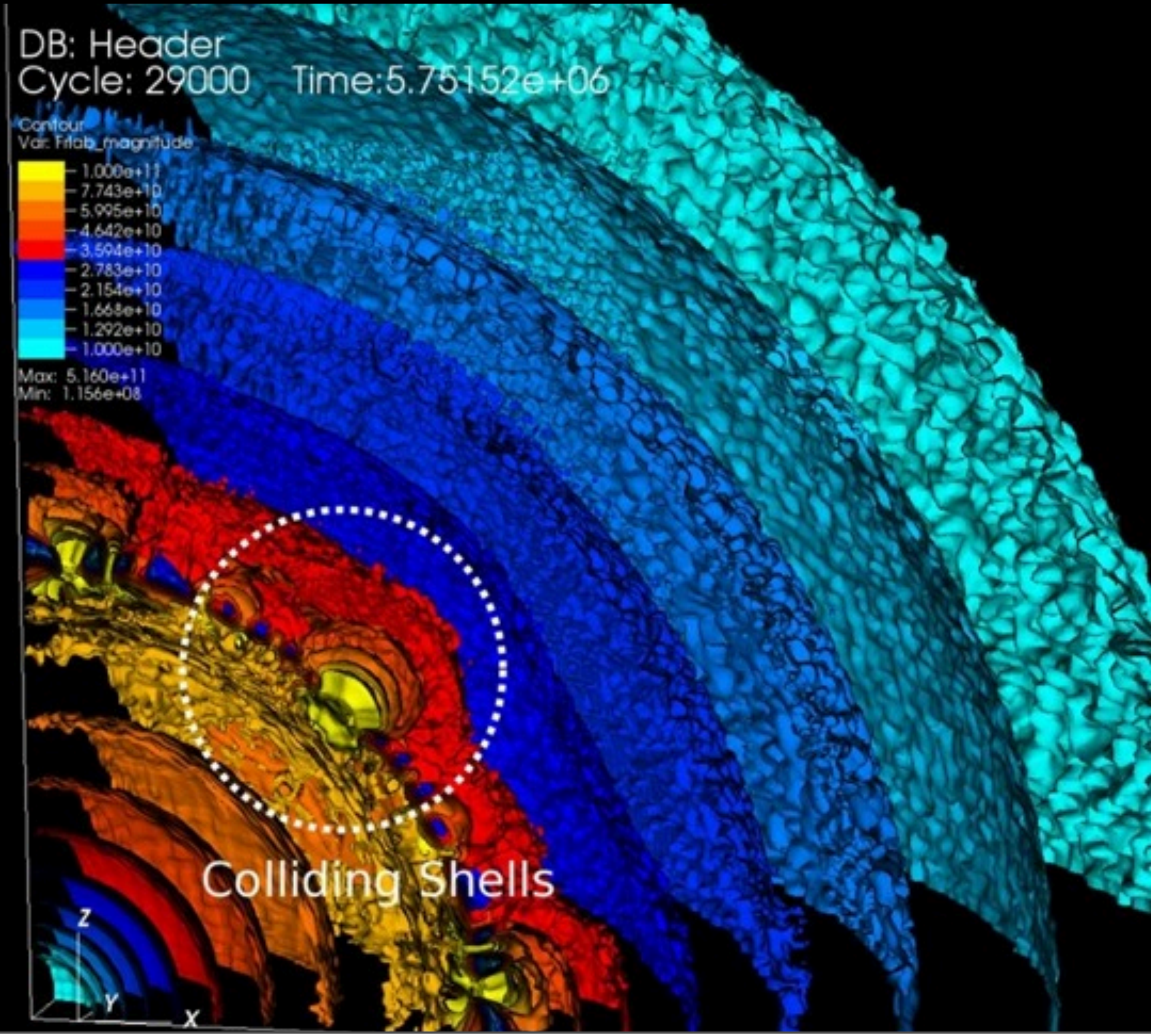

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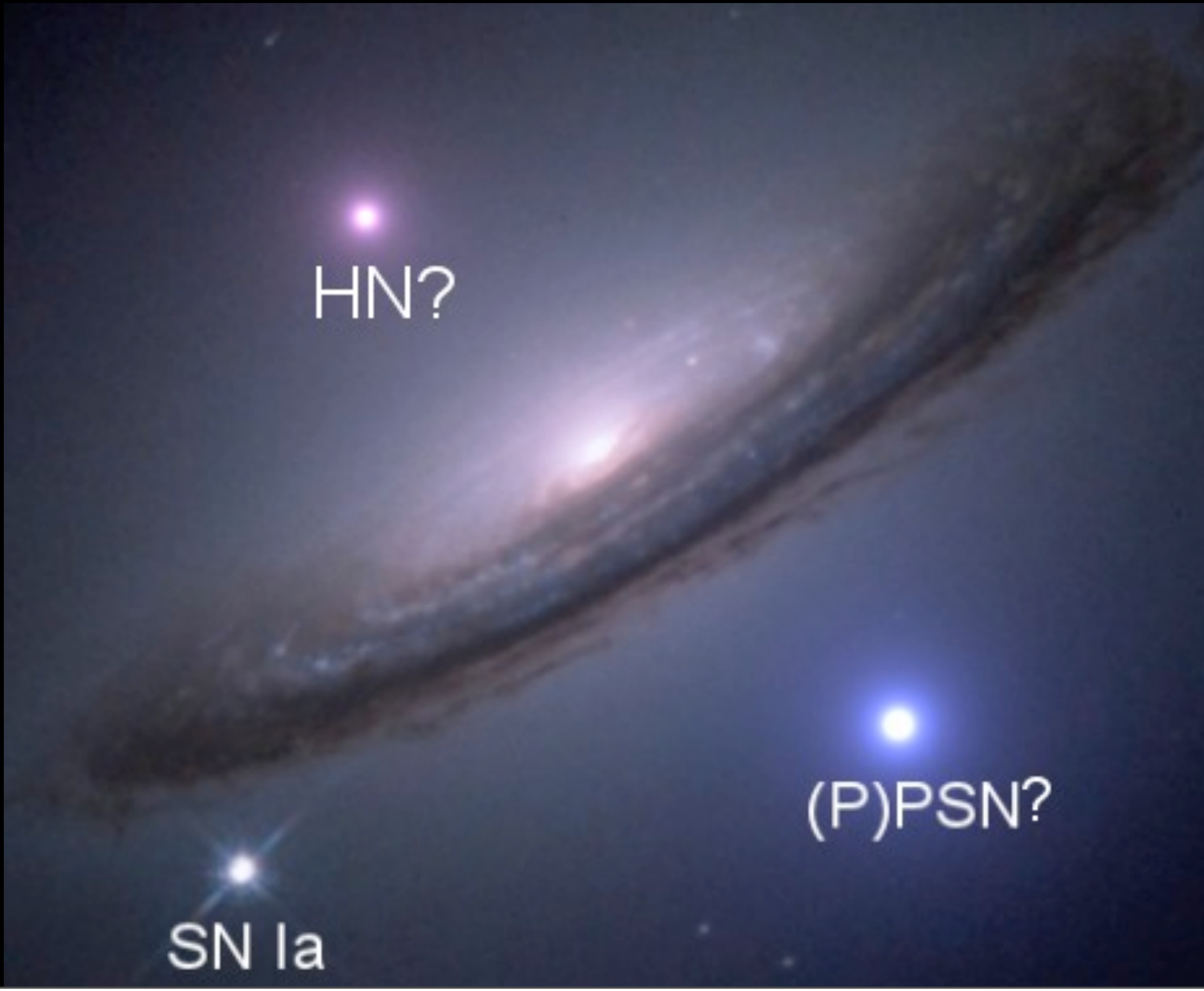

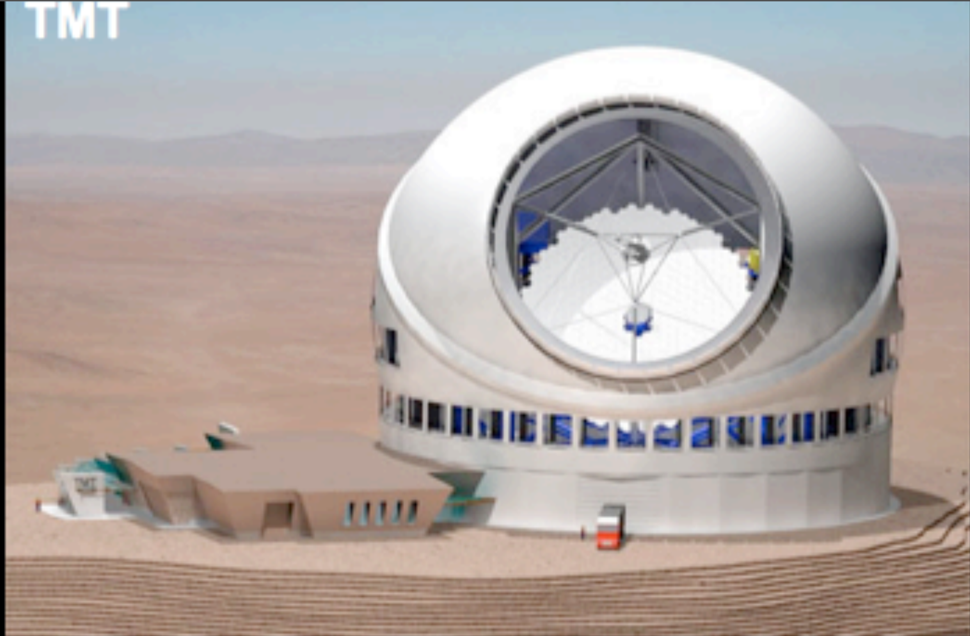
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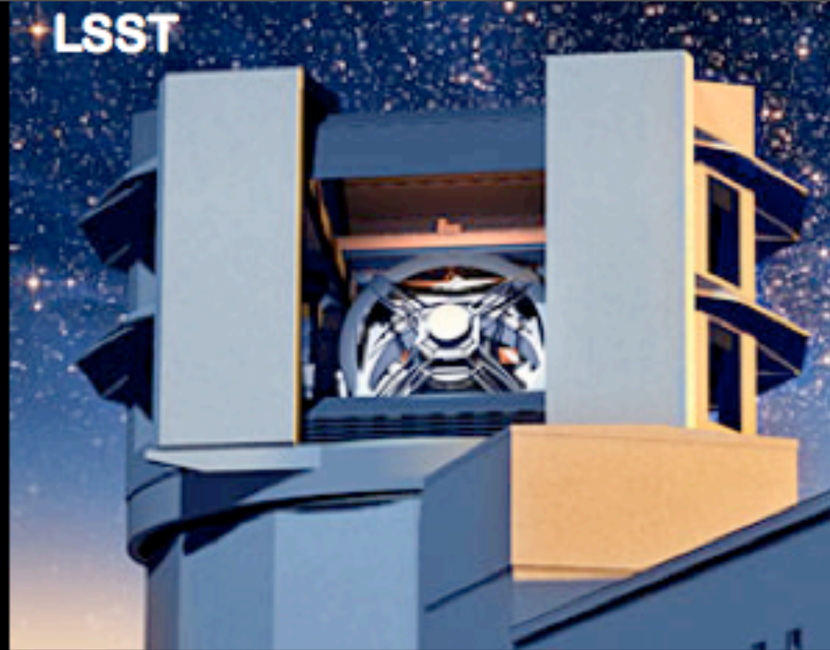
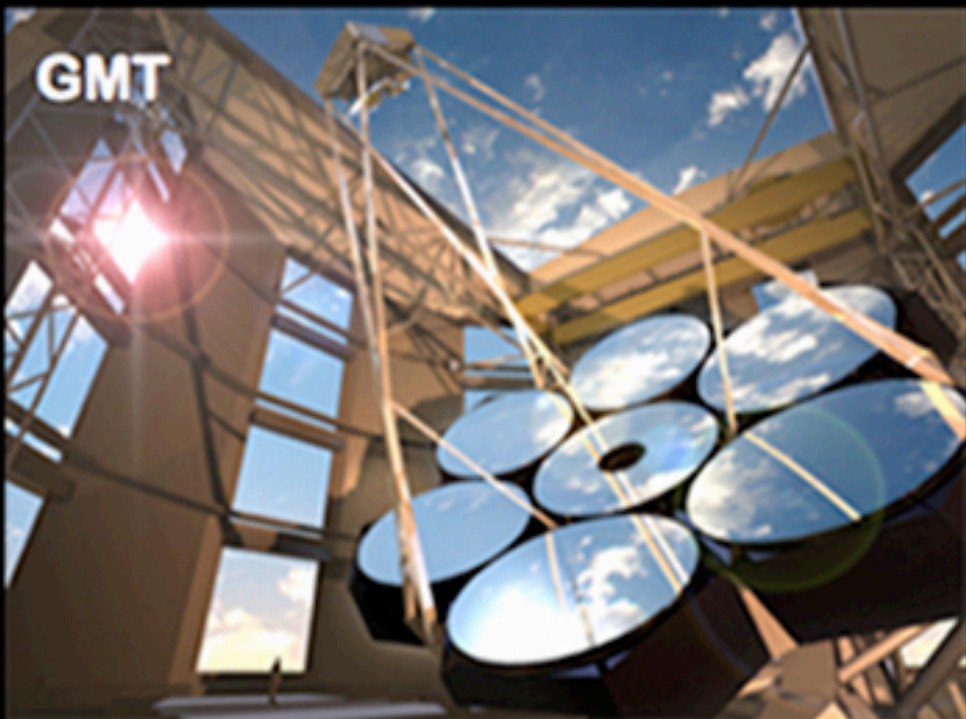
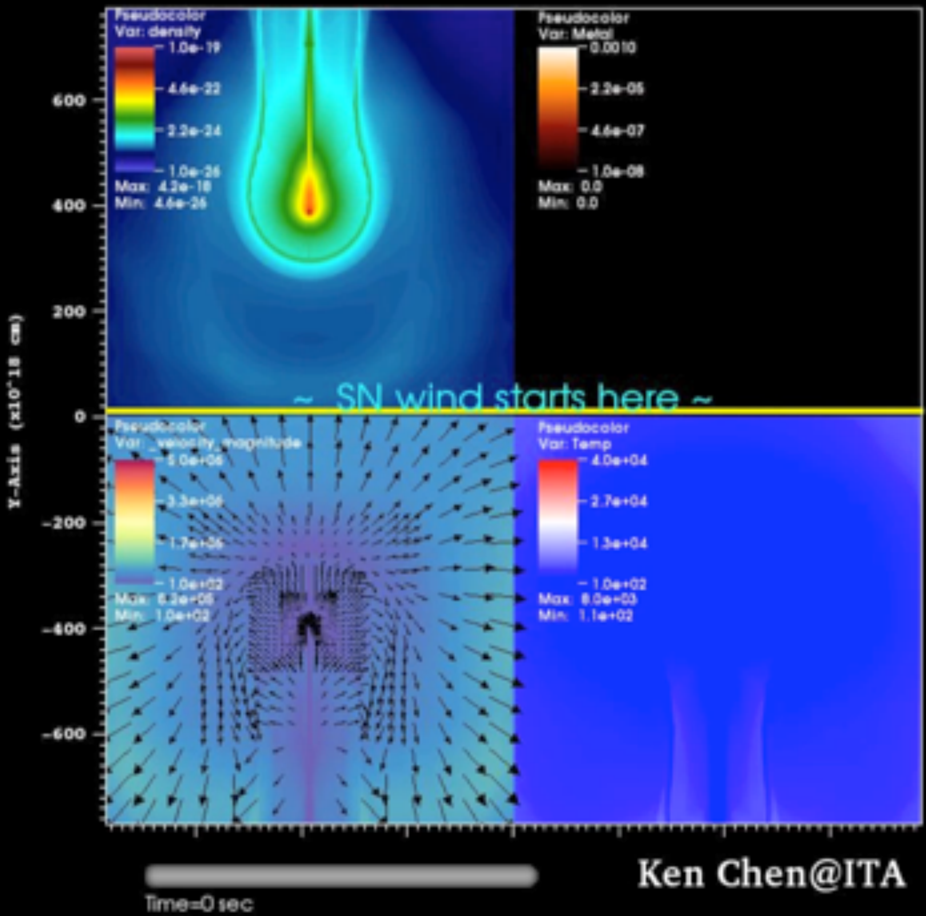
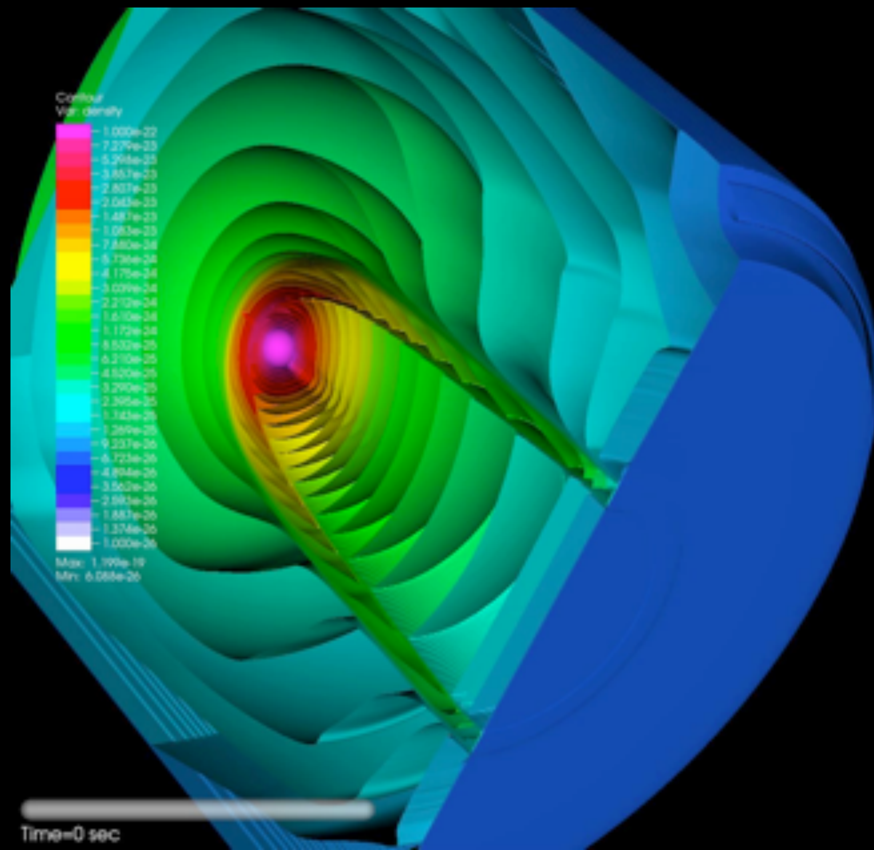

LSST

GMT

JWST

SN chemical enrichment of a pristine halo

Chen in prep.





Many thanks for your attention

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East Asian Core Observatories Association (EACOA)

NAOC

NAOJ

Korea Astronomy and Space Science Institute

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