The First Cosmic Explosions

Simulating the First Supernovae with NERSC Supercomputers

Ke-Jung (Ken) Chen
IAU Gruber Fellow, UC Santa Cruz
NERSC NUG Meeting, LBNL, 02/24/2015

People

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UC Santa Cruz

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UT-Austin

Ann Almgren
Lawrence Berkeley National Lab

Daniel Kasen
UC Berkeley

Weiqun Zhang
Lawrence Berkeley National Lab

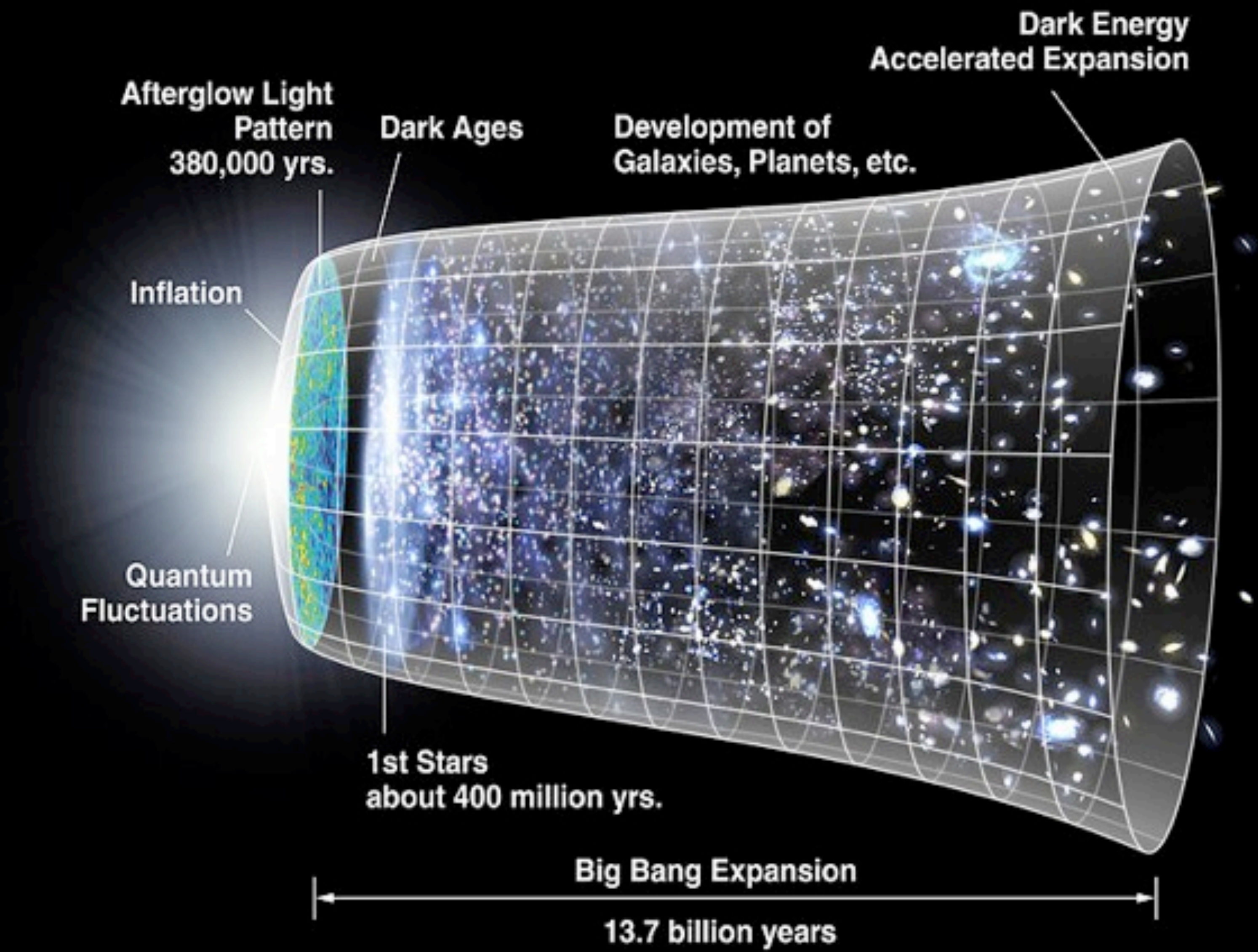
Kill Darkness?

Kill Darkness?

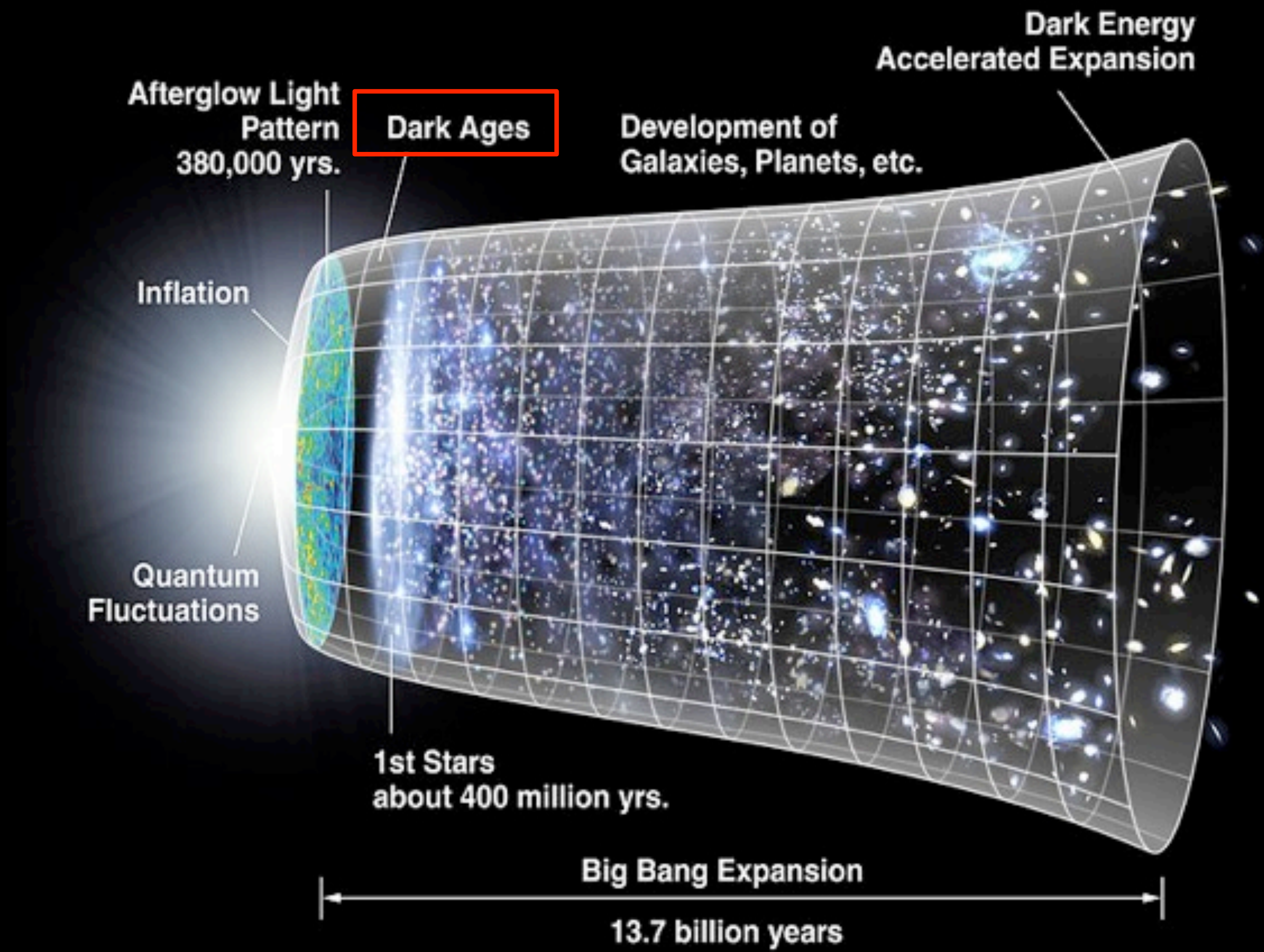
Light !!

Kill Darkness?

History of Universe



History of Universe



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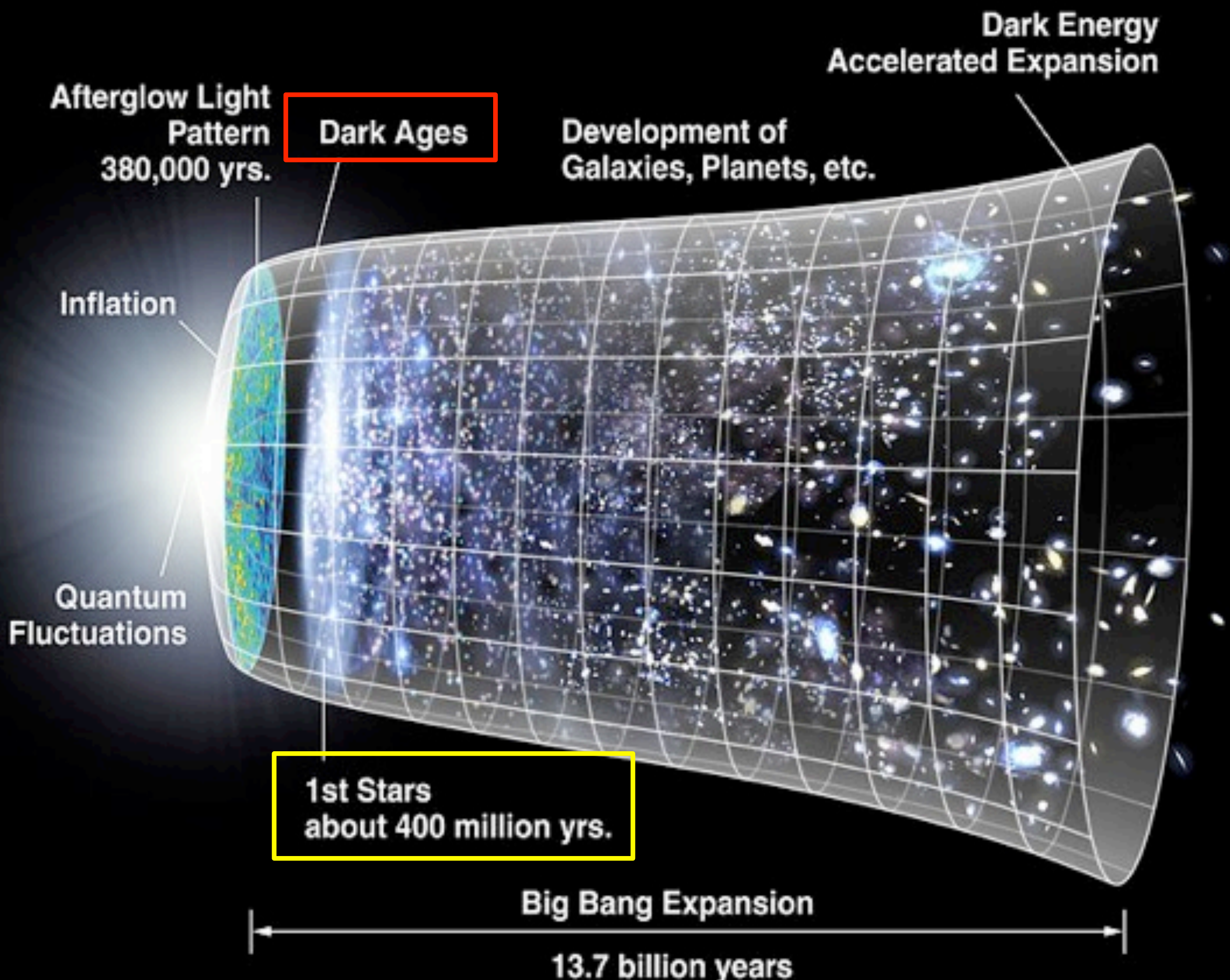

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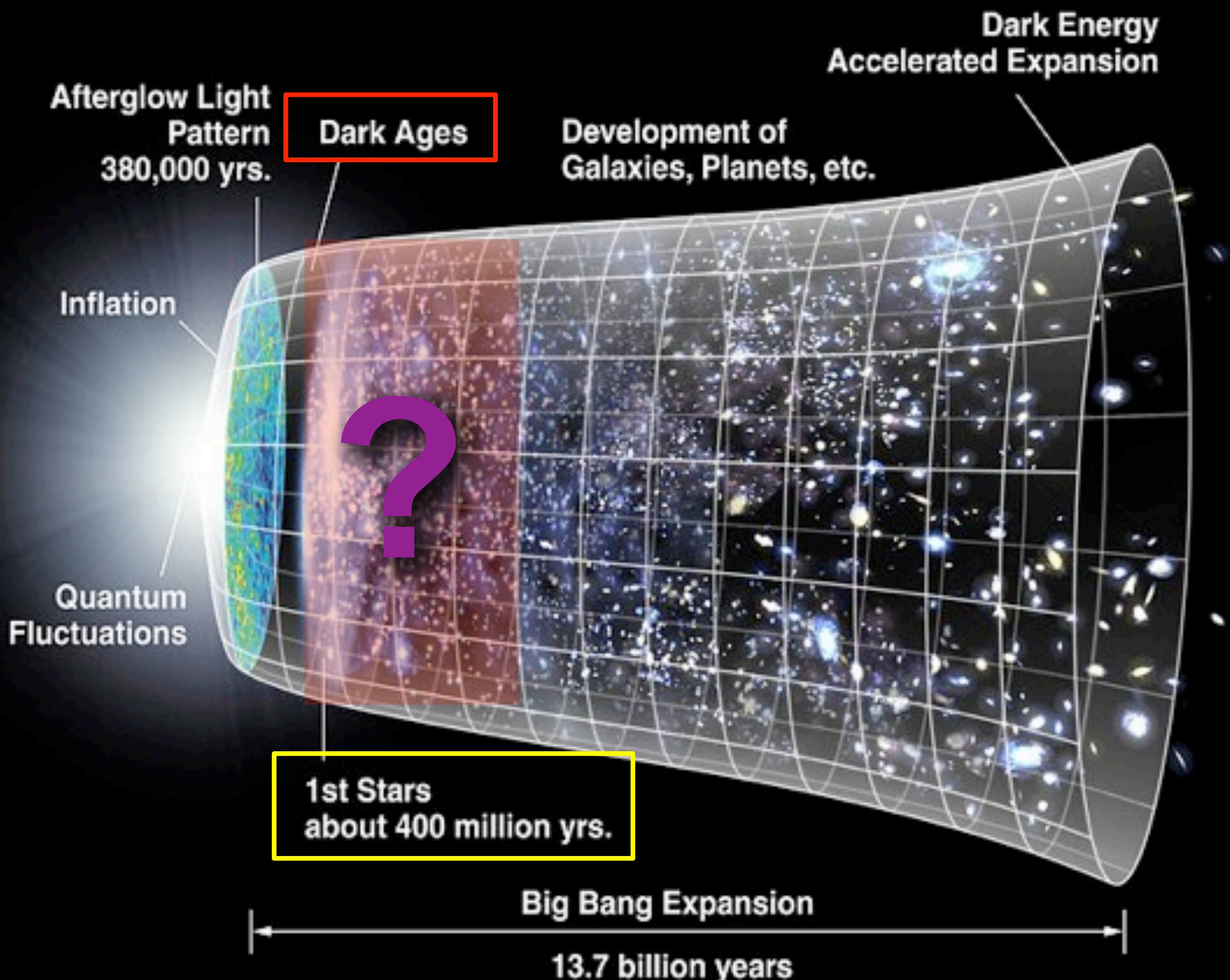

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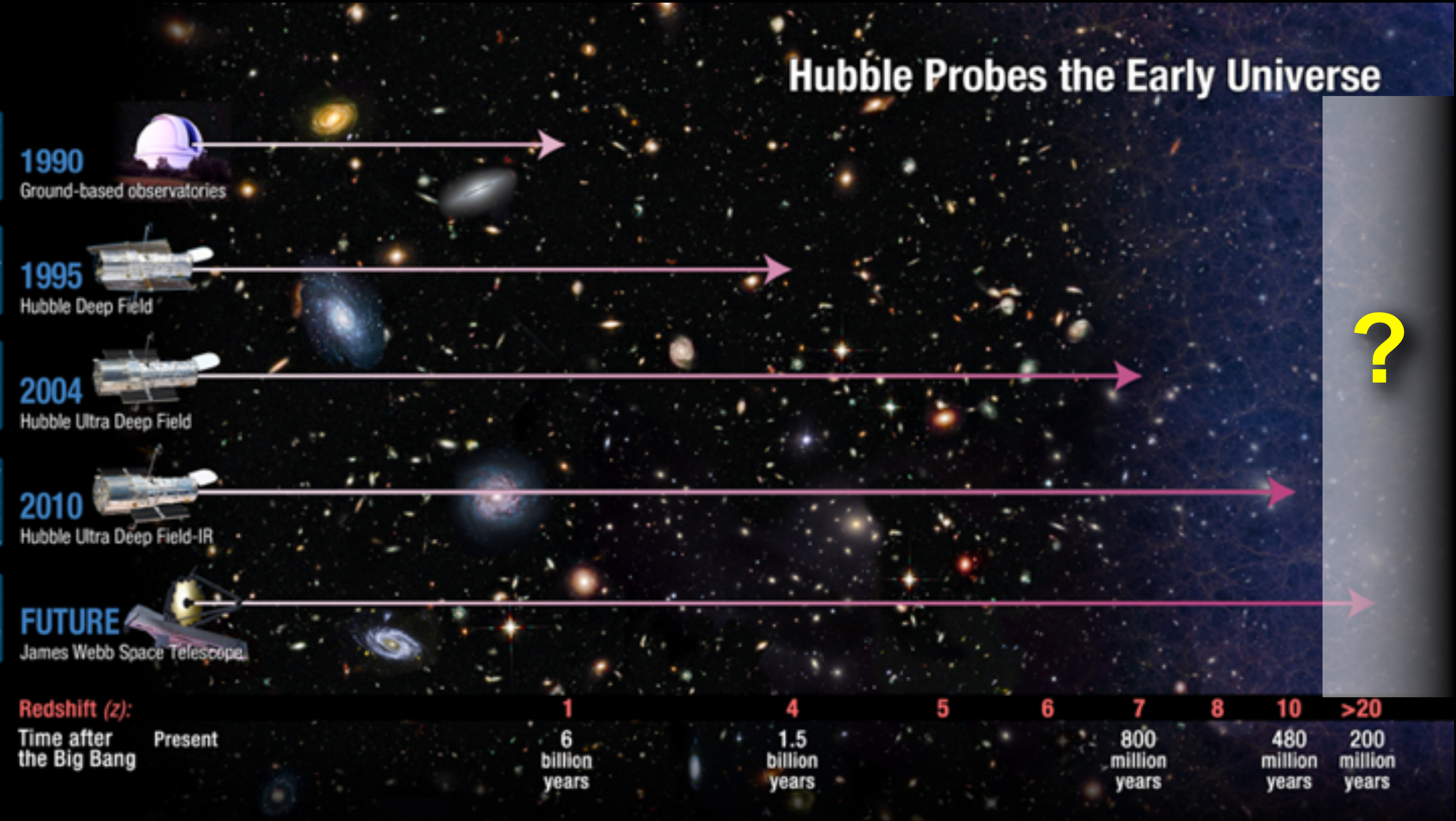

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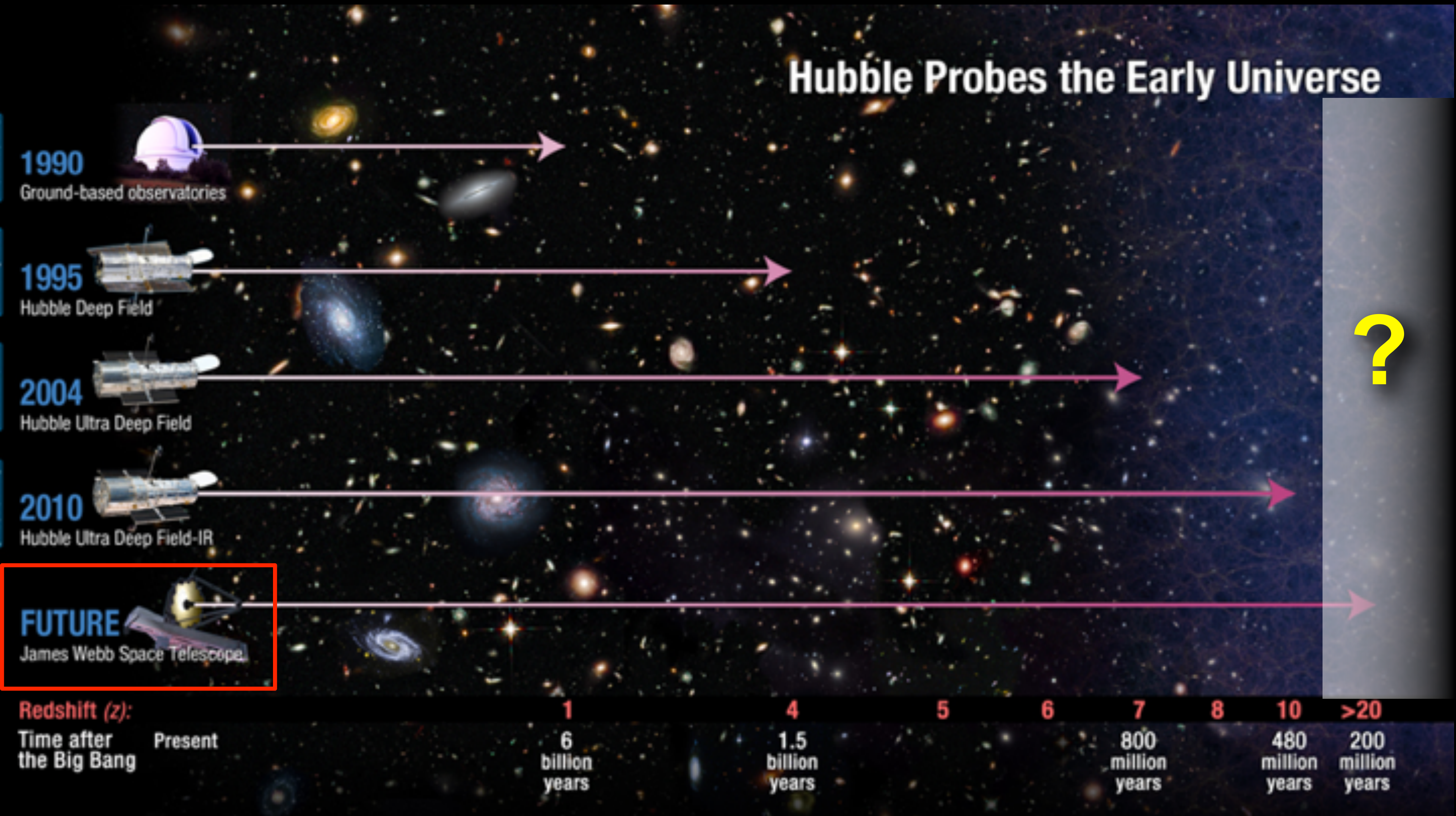
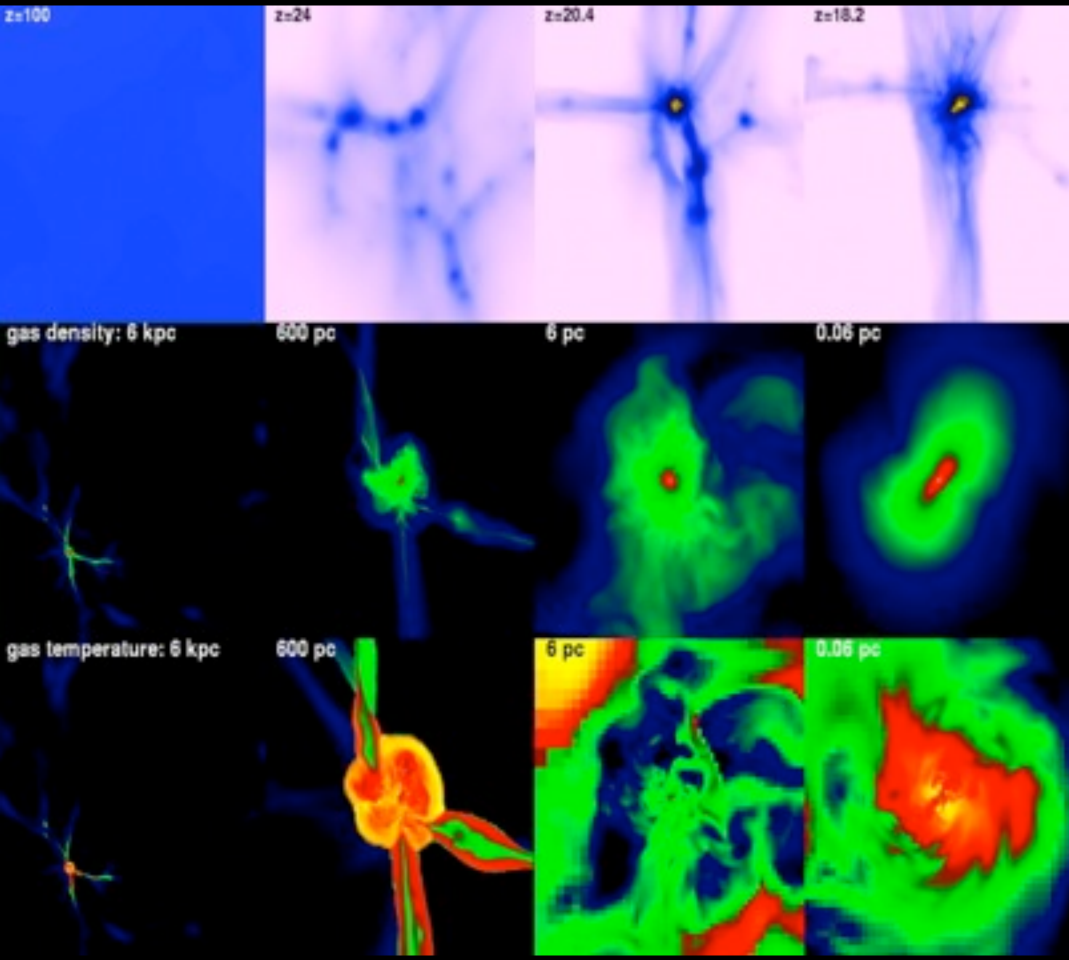
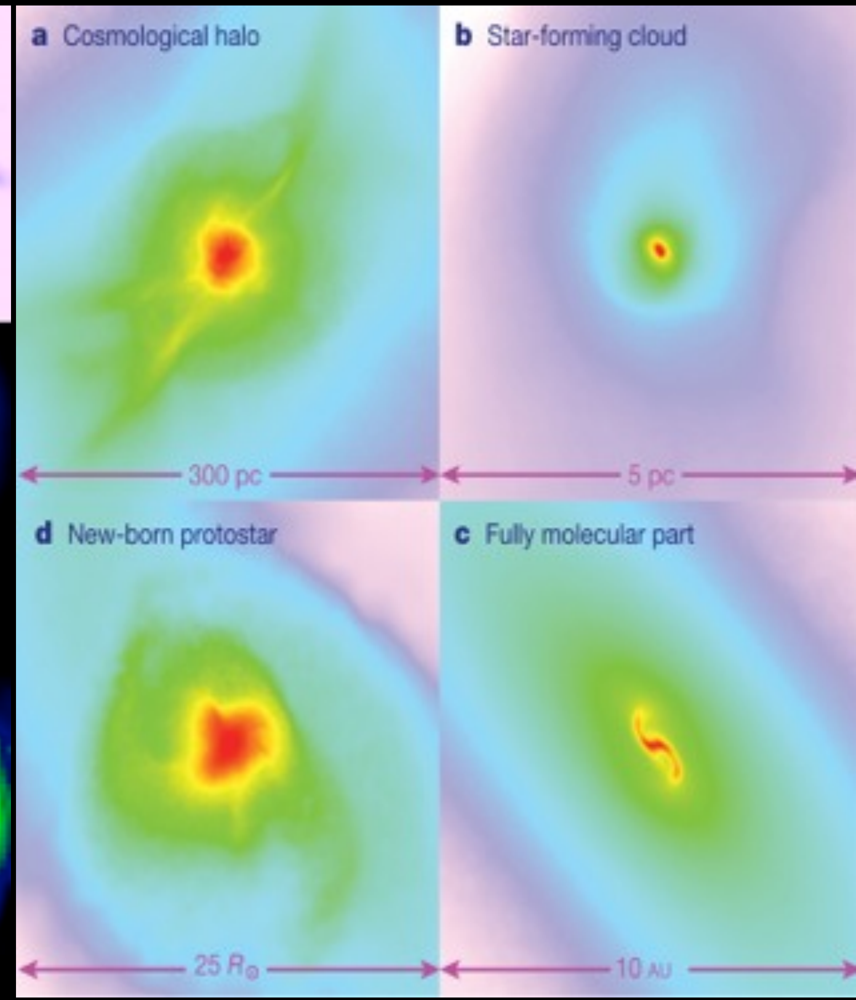


The First Stars

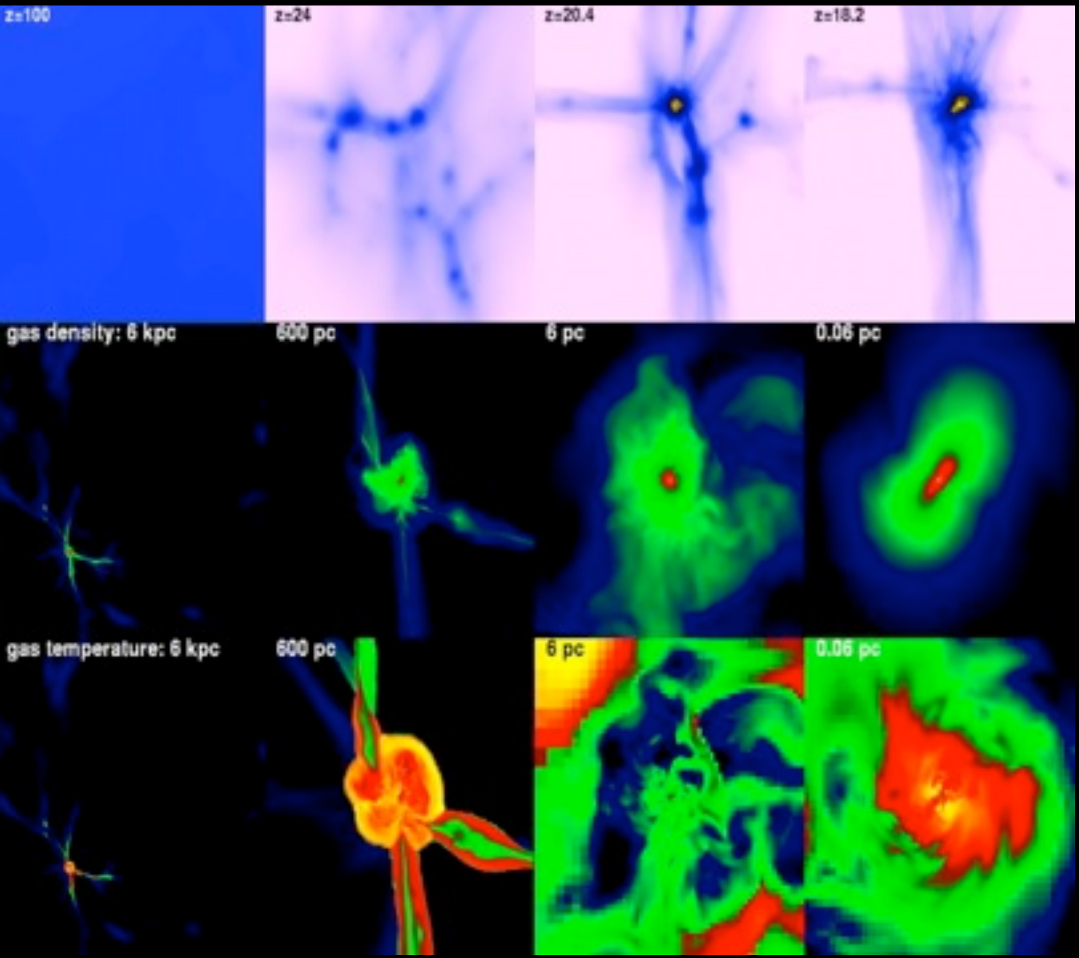


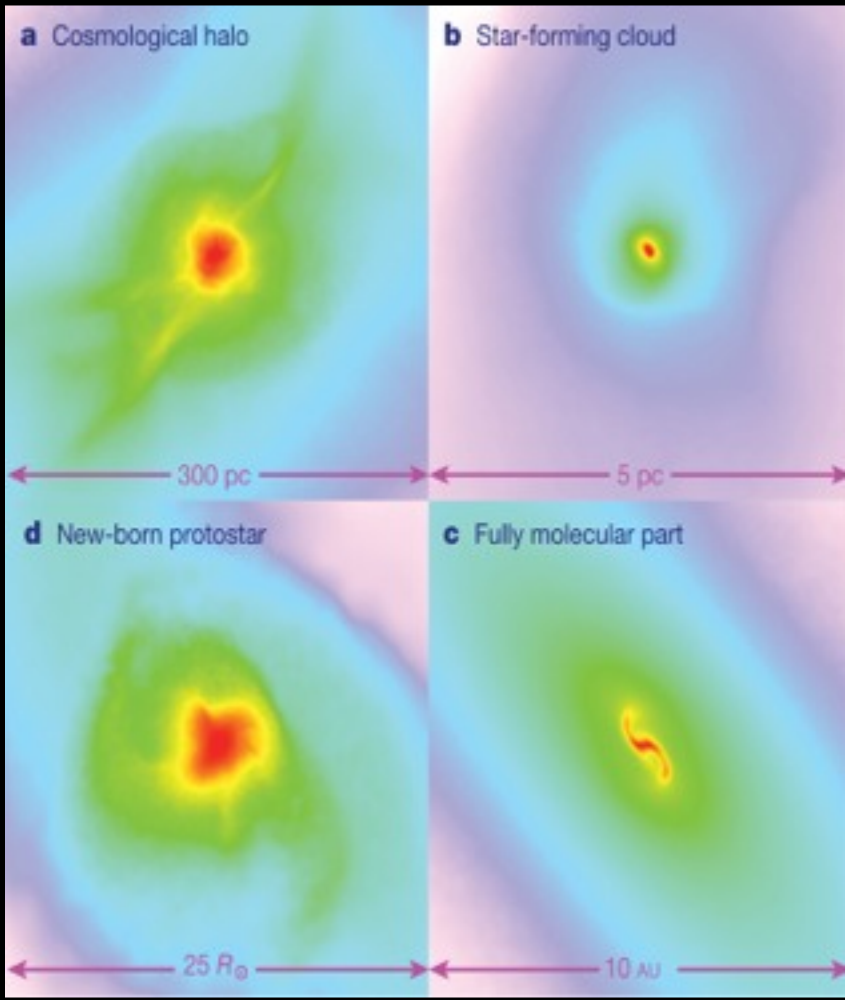


Abel, et al. Science (2002)

Bromm, et al. Nature (2009)

The First Stars





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Bromm, et al. Nature (2009)

Mass Scale ~ 100 $M_\odot$

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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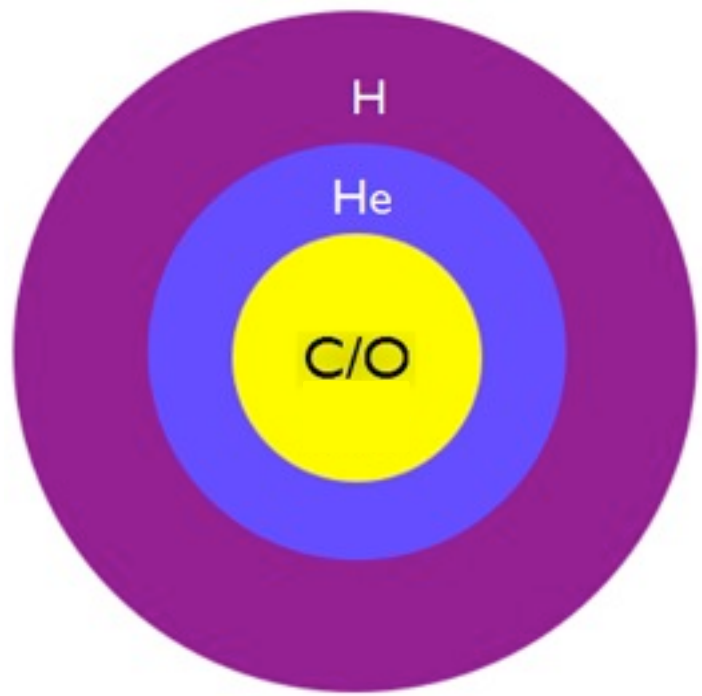
Fate of Very Massive Stars

Star > 80 M$_\odot$



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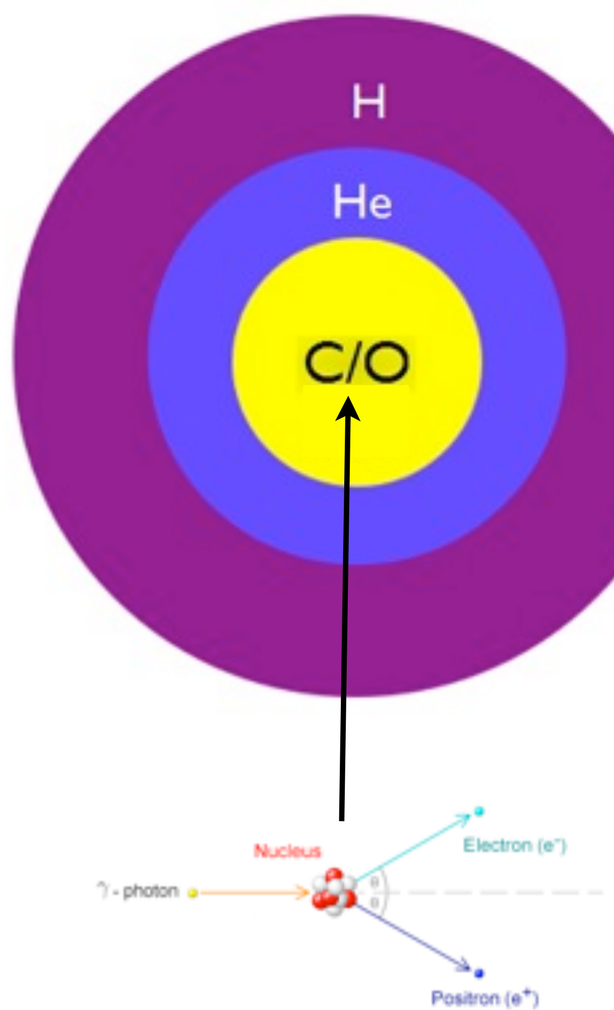
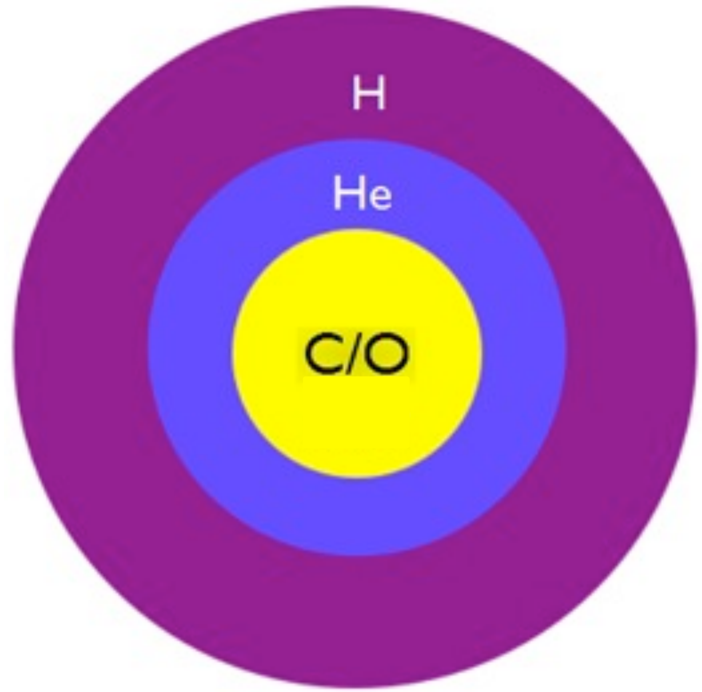


$E_o > 2m_0c^2$, where m_0 is the electron rest mass

Fate of Very Massive Stars

Star > 80 M☉



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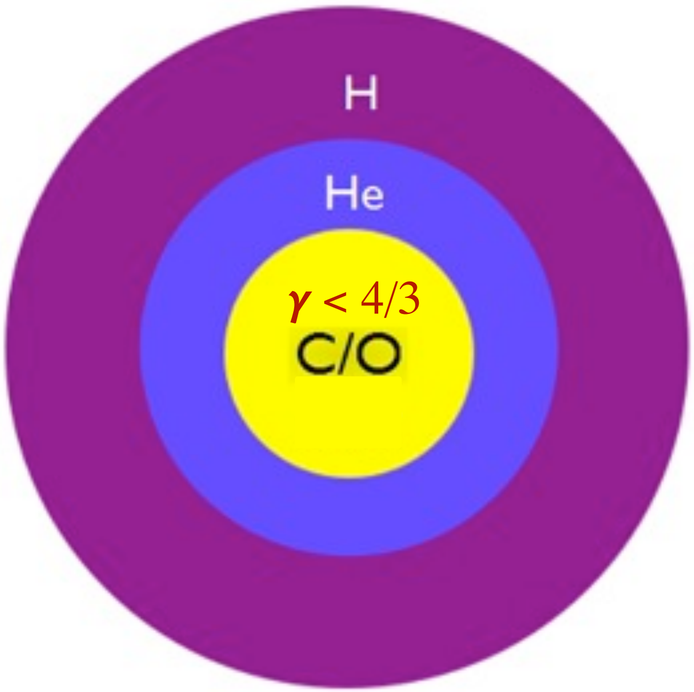

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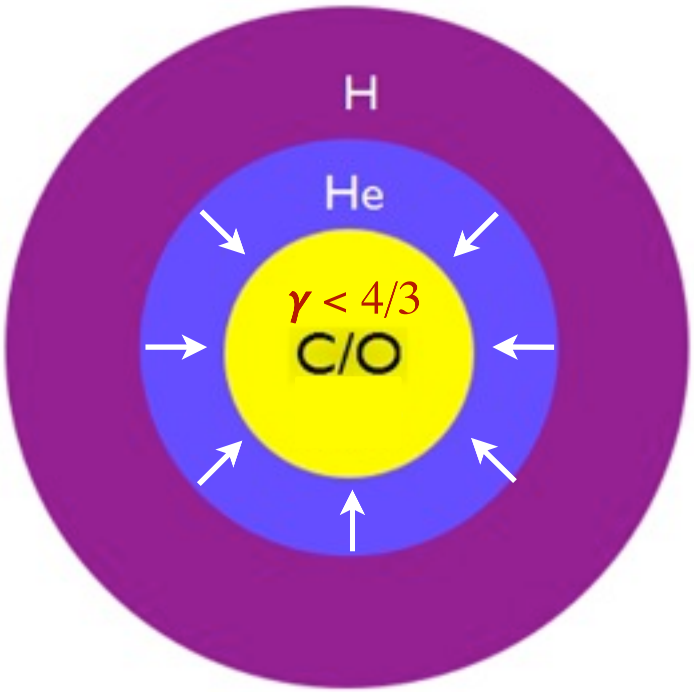

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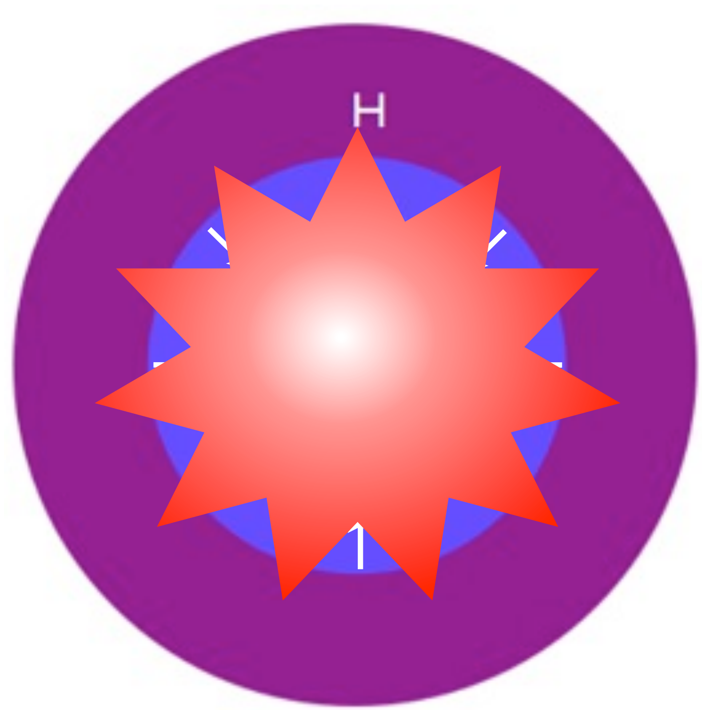

Why do We Care?

Why do We Care?

- The first and biggest cosmic explosions

Why do We Care?

- The first and biggest cosmic explosions
- The first metals

Why do We Care?

- The first and biggest cosmic explosions
- The first metals
- Accessibility in research

Multi-D SN Simulations

1D Models

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

CASTRO (DOE SciDAC, LBNL CCSE)

Massive Parallel, Adaptive Mesh Refinement (AMR), Multi-D, Radiation, Hydro+(Burning, Rotation, GR ...)
(Almgren+ 2010, Zheng+ 2011 2012, Chen+ 2011 2013)

NERSC Supercomputers

Franklin

Hopper

Edison

Multi-D SN Simulations

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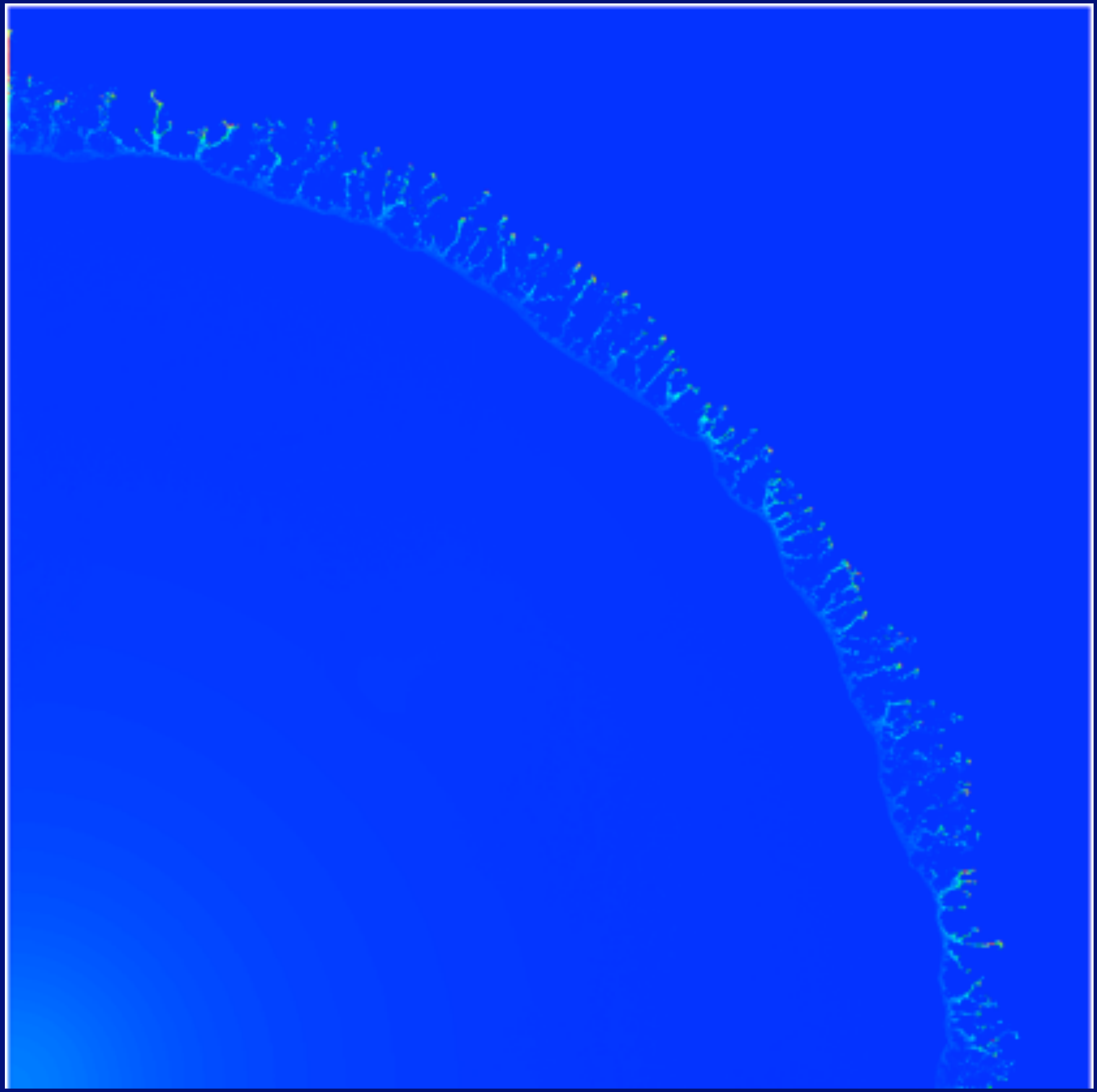
2D Resolution of CASTRO



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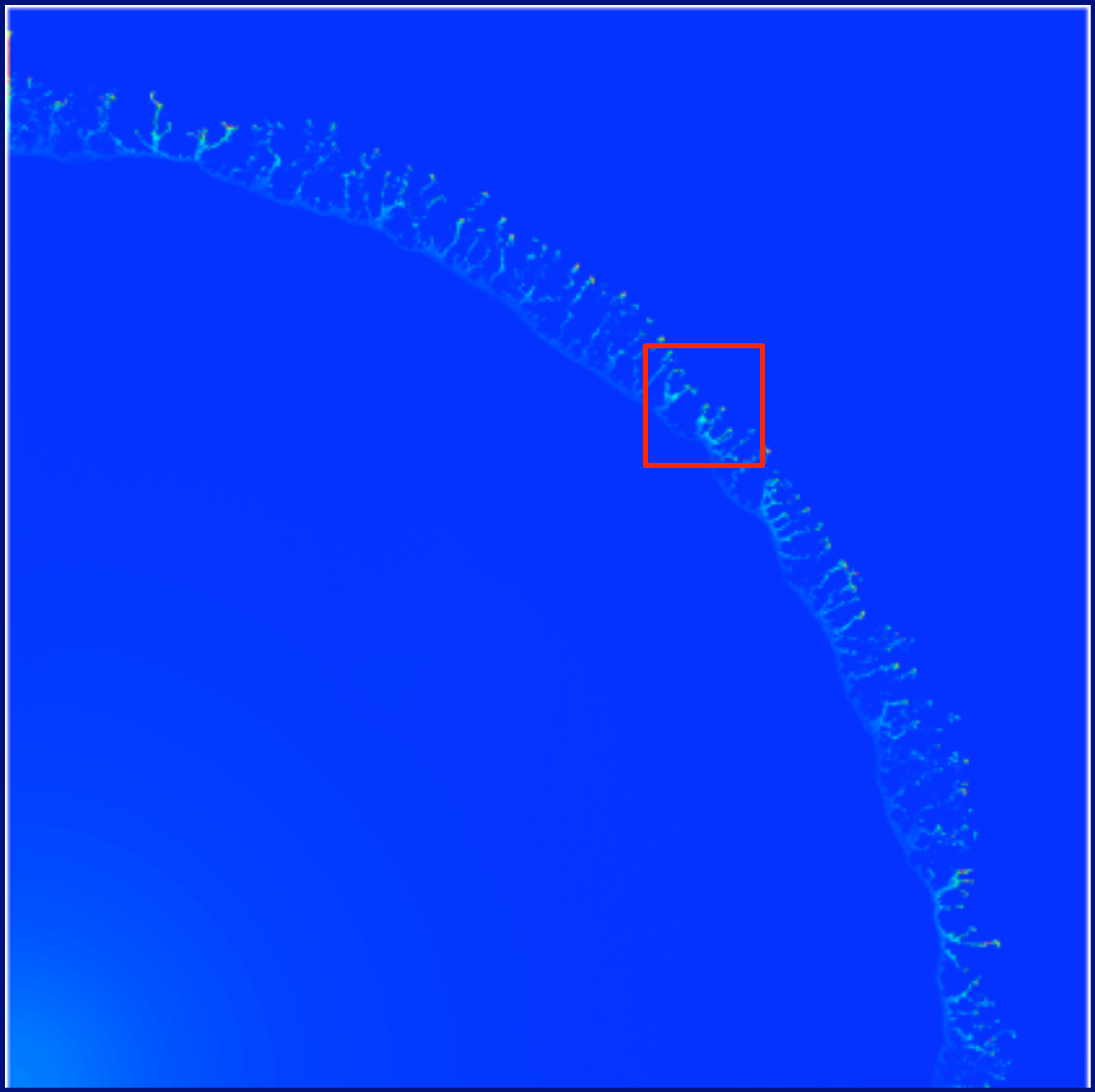

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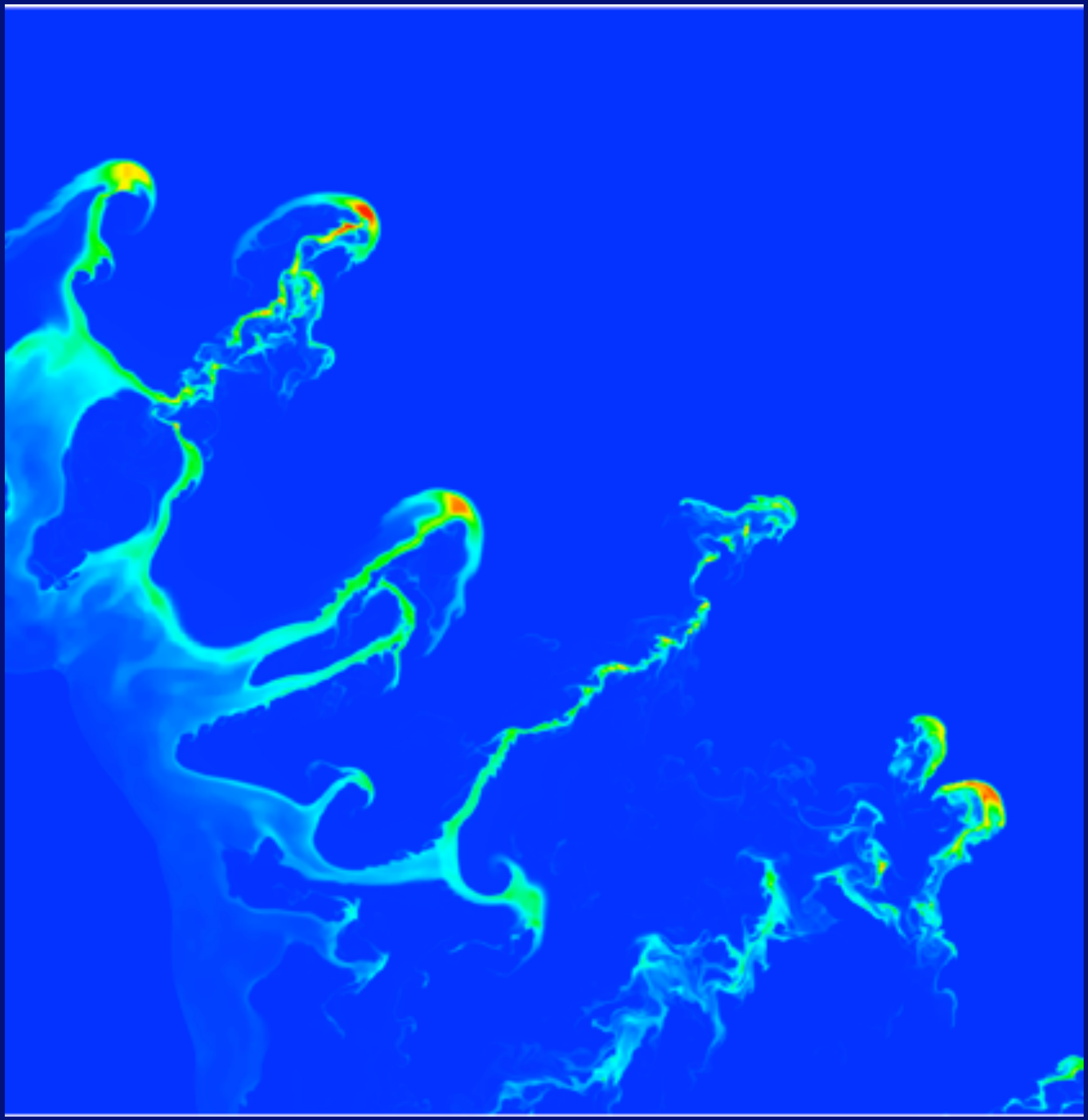

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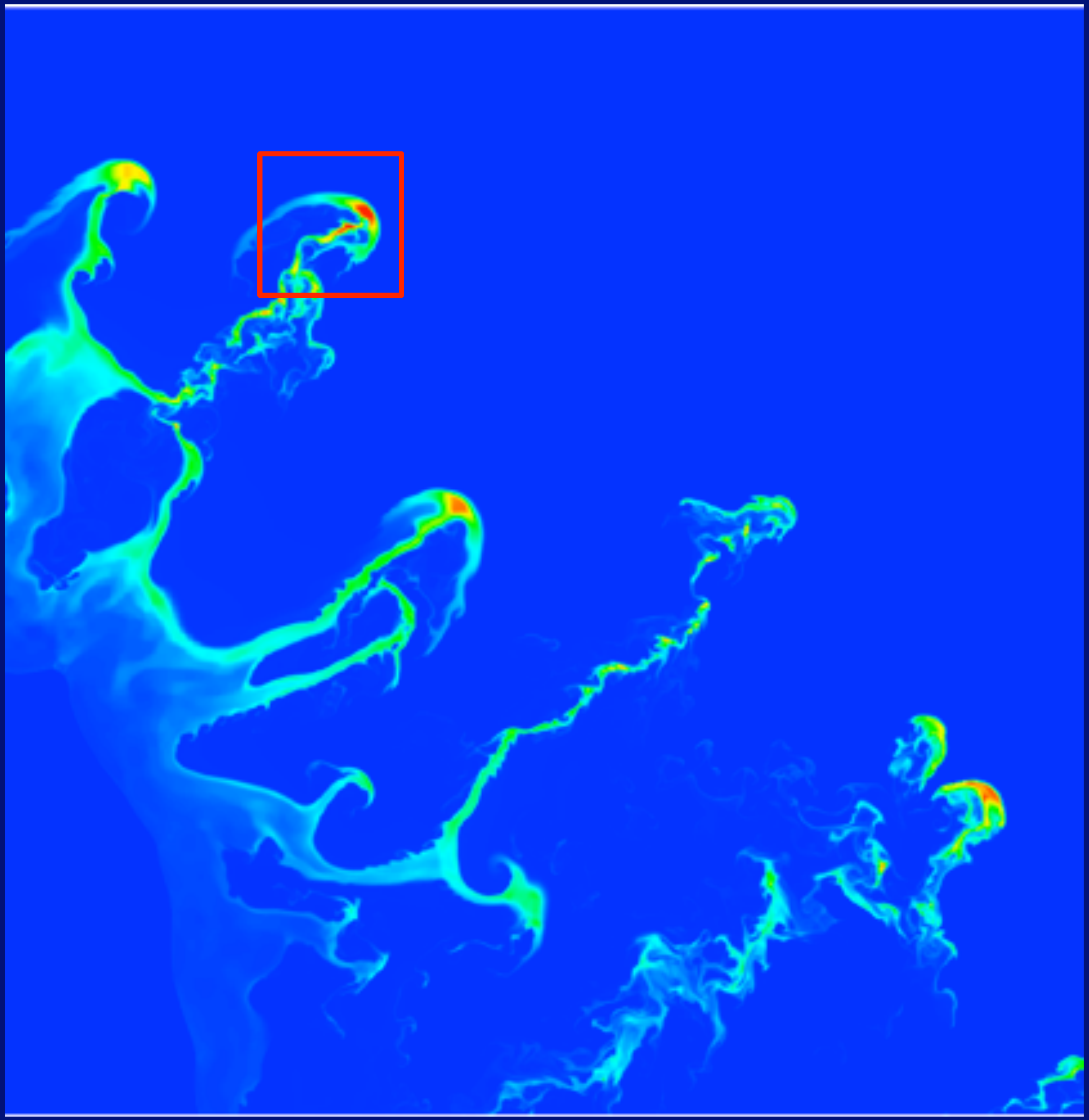
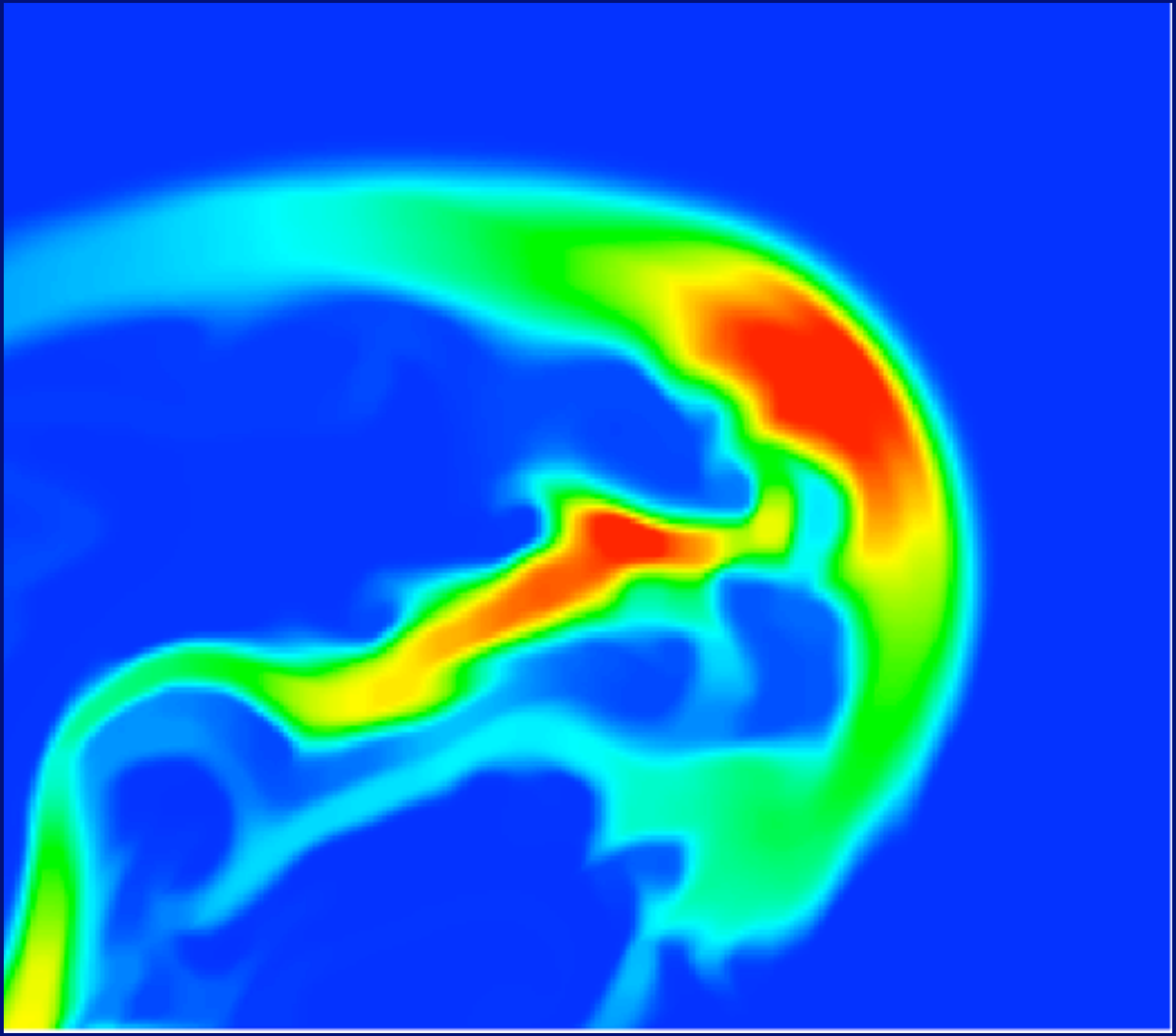
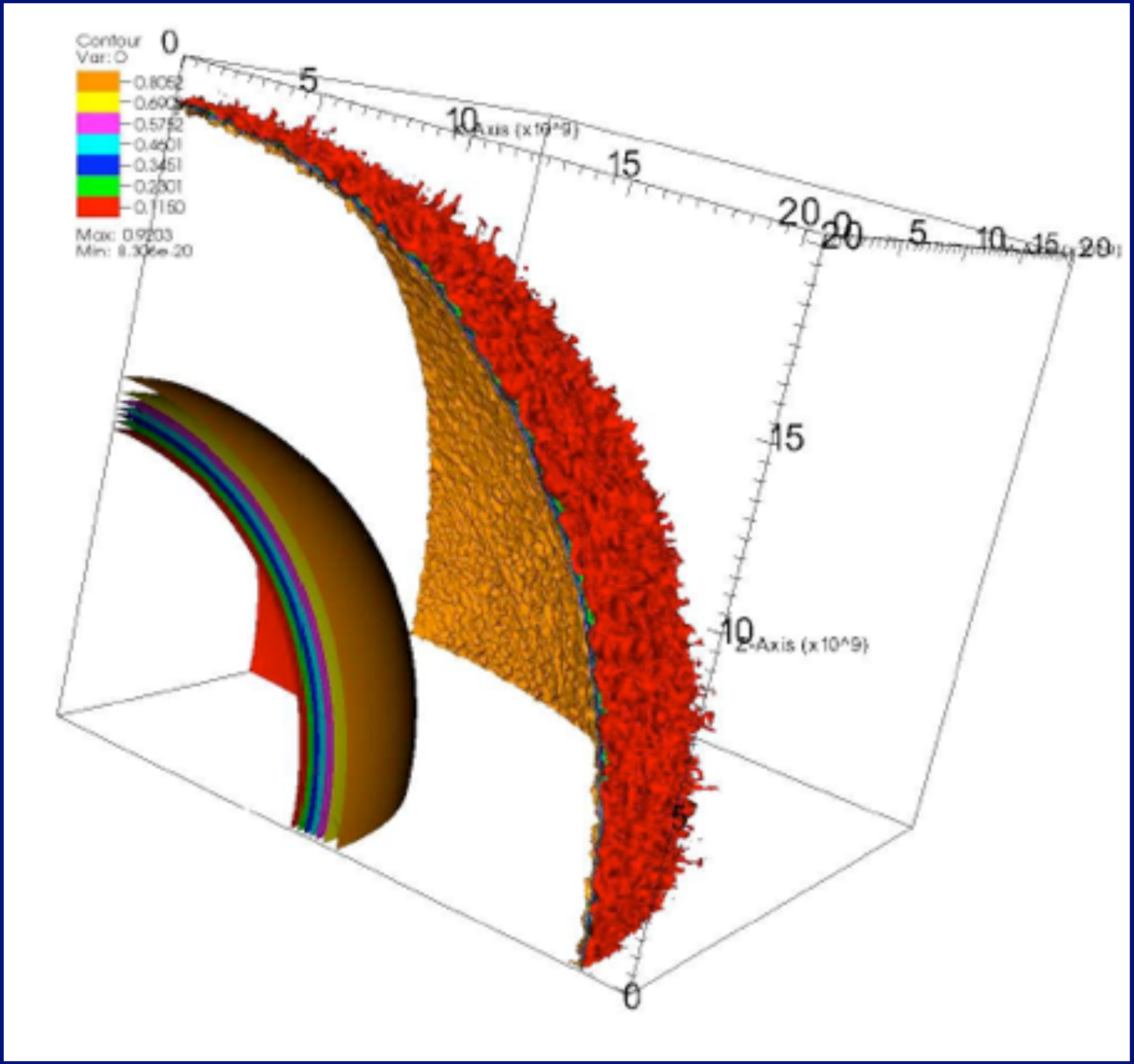


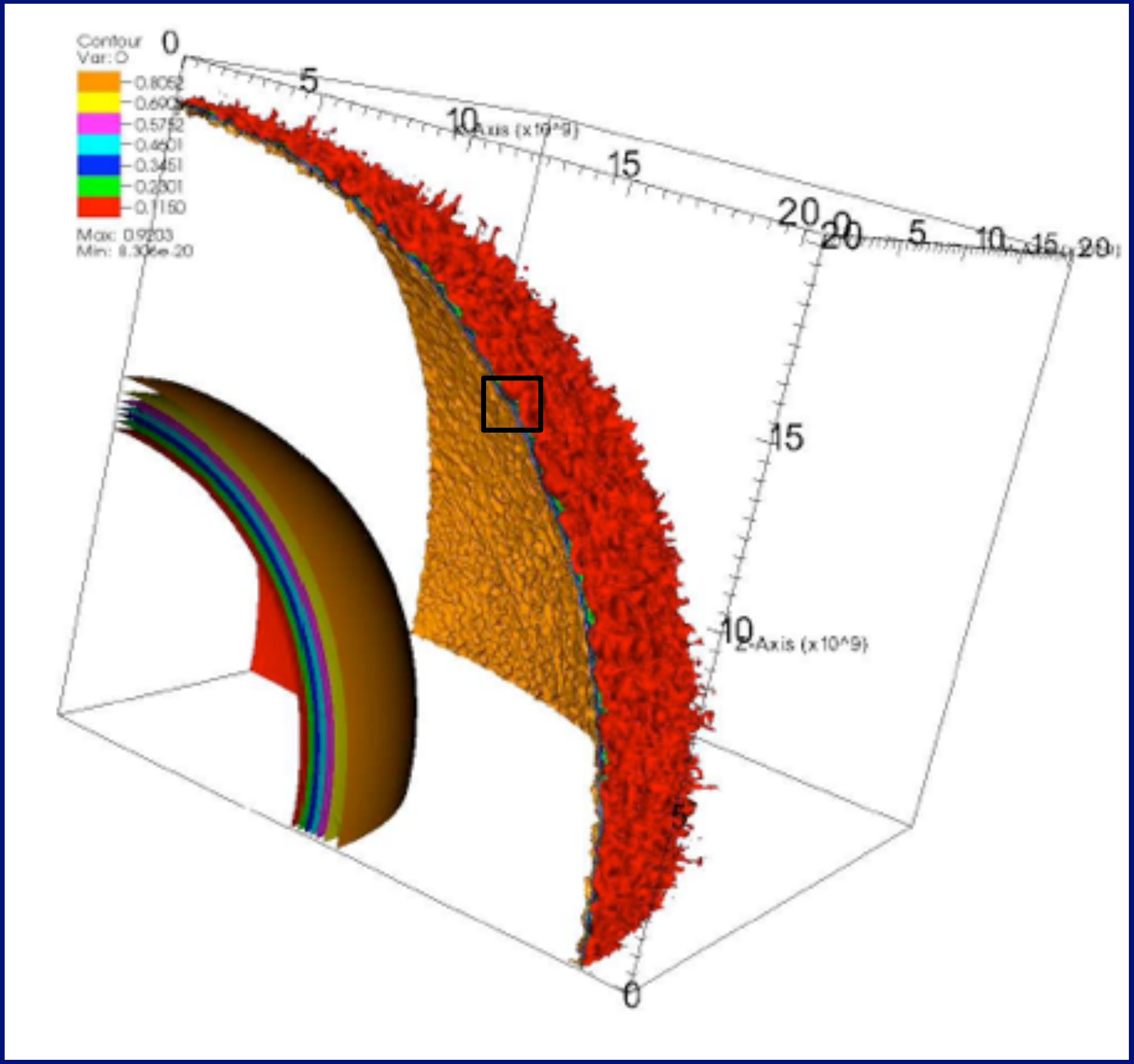
2D Resolution of CASTRO



3D Resolution of CASTRO !



3D Resolution of CASTRO !



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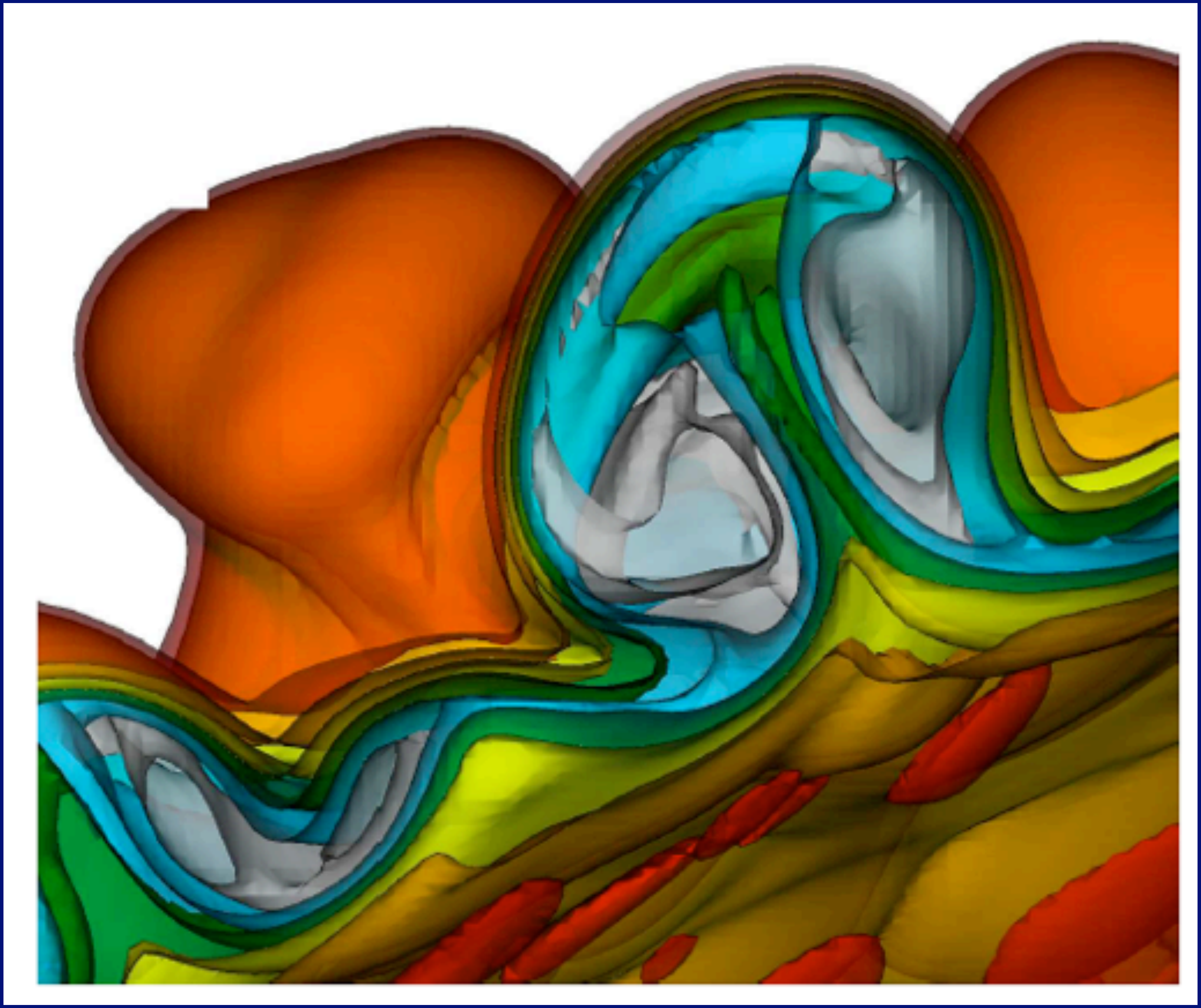
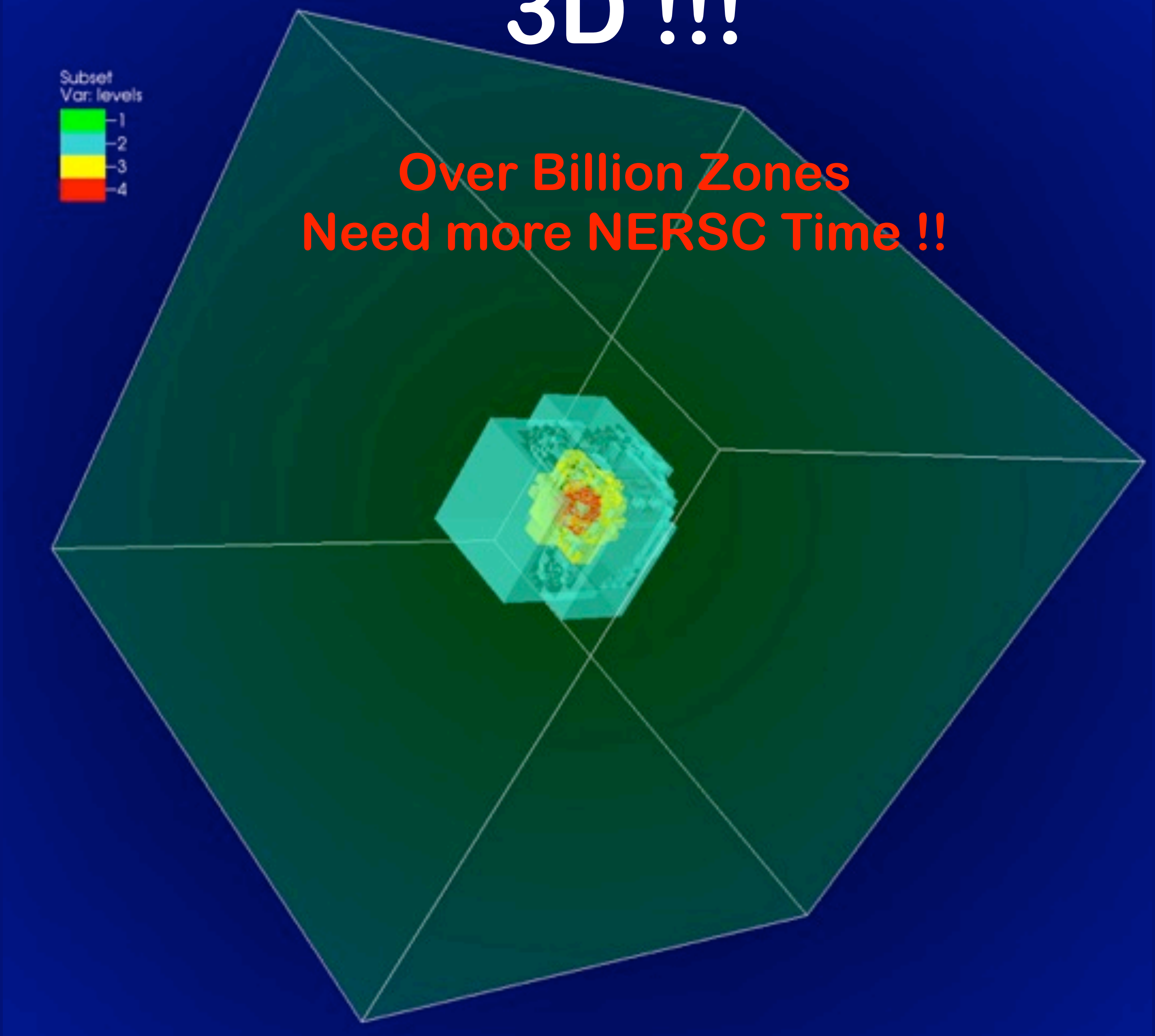


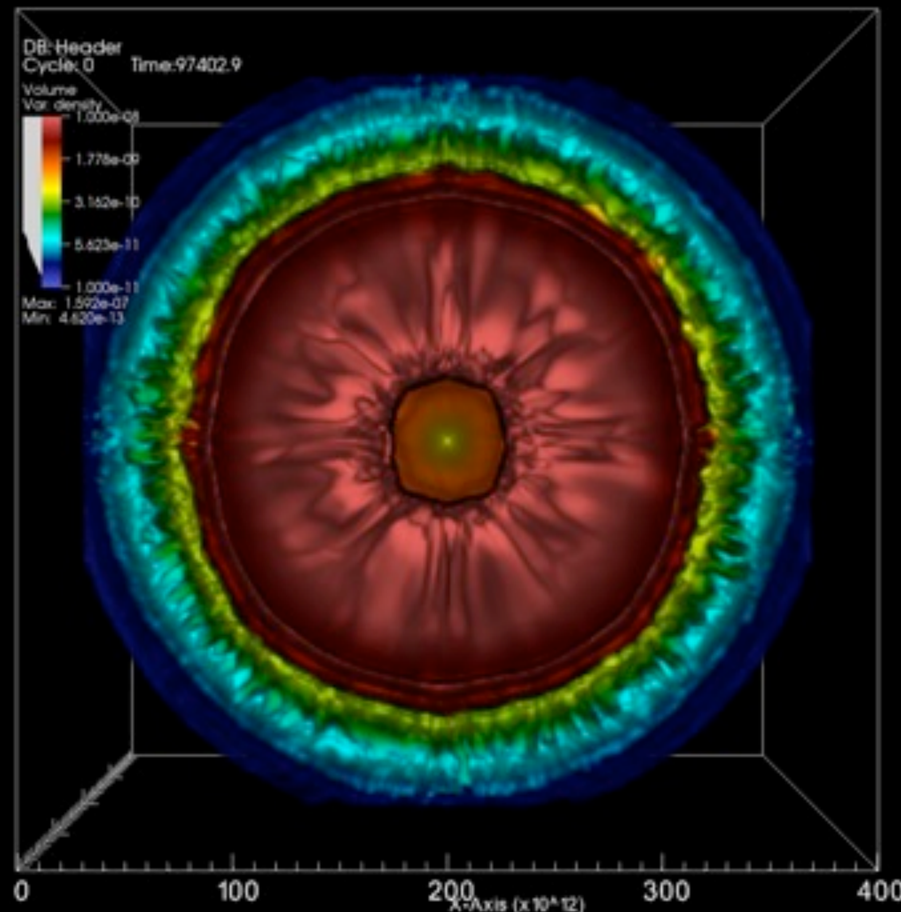
3D !!!

Over Billion Zones
Need more NERSC Time !!



Pulsational Pair-Instability Supernovae (PPSNe)

150 M☉ > M* > 80 M☉



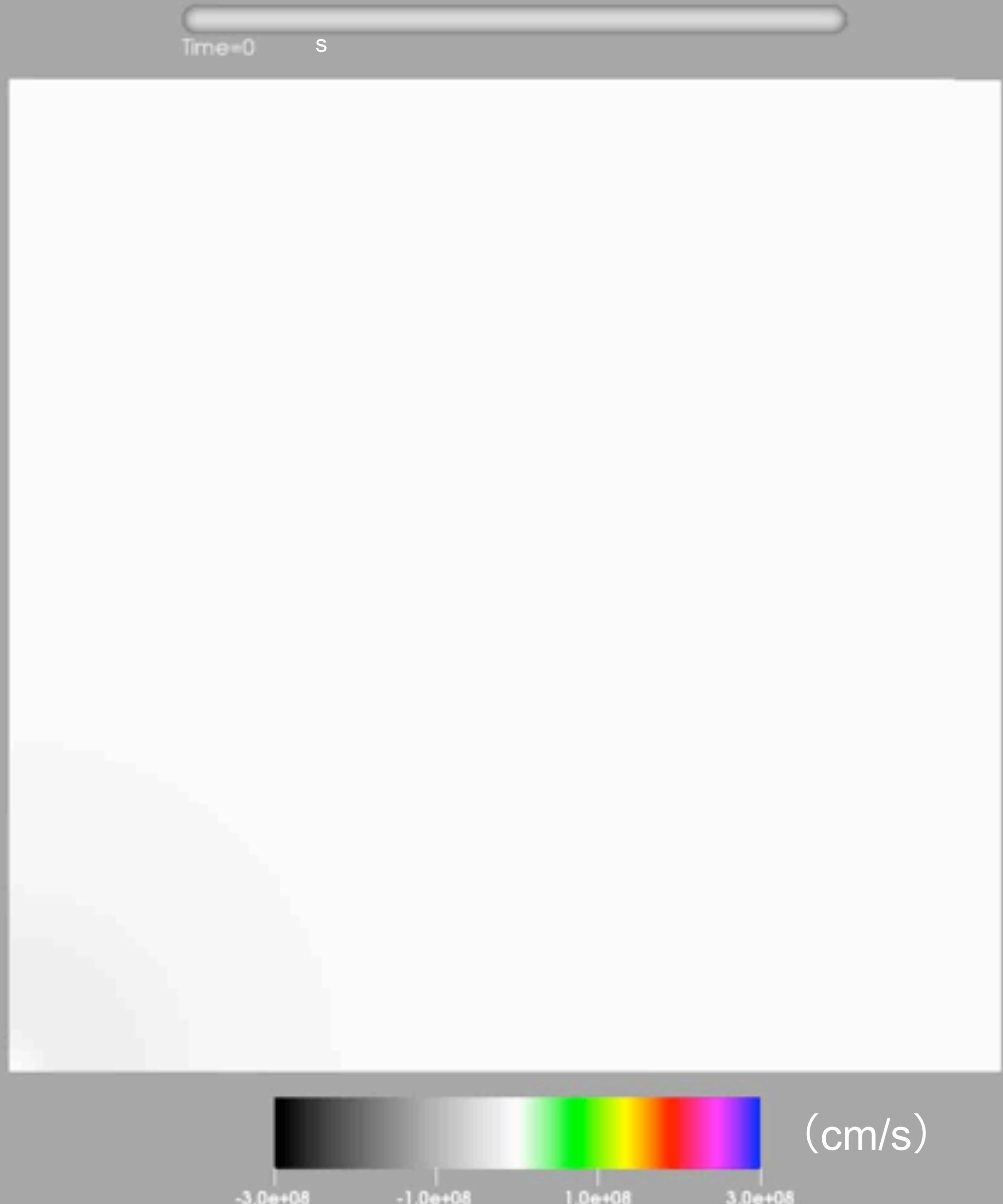
Chen+ ApJ 792 28 (2014a)

Core of 110 M☉ star

s

(cm/s)

Core of 110 M⊙ star



Physical Properties of Colliding Shells

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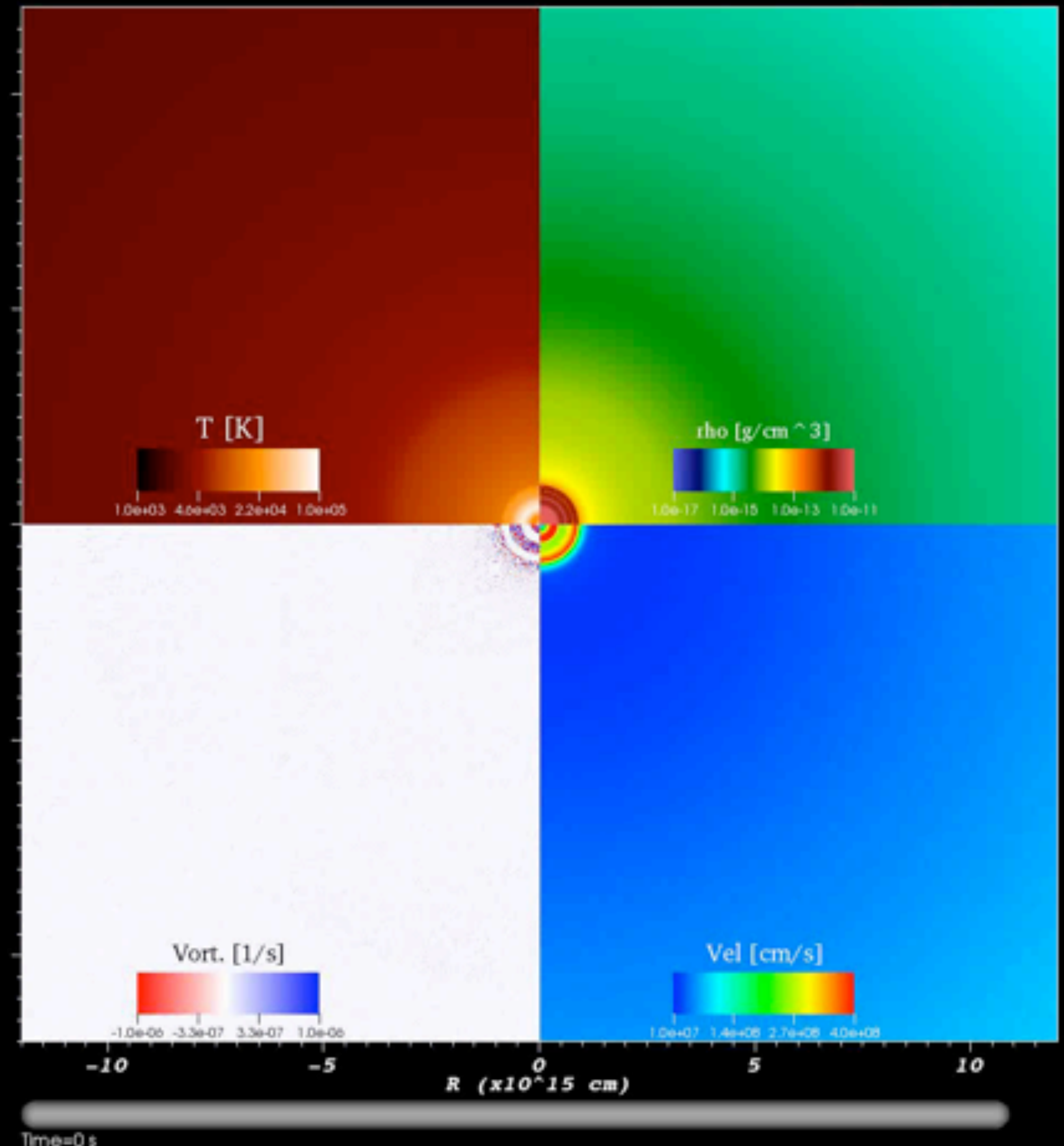
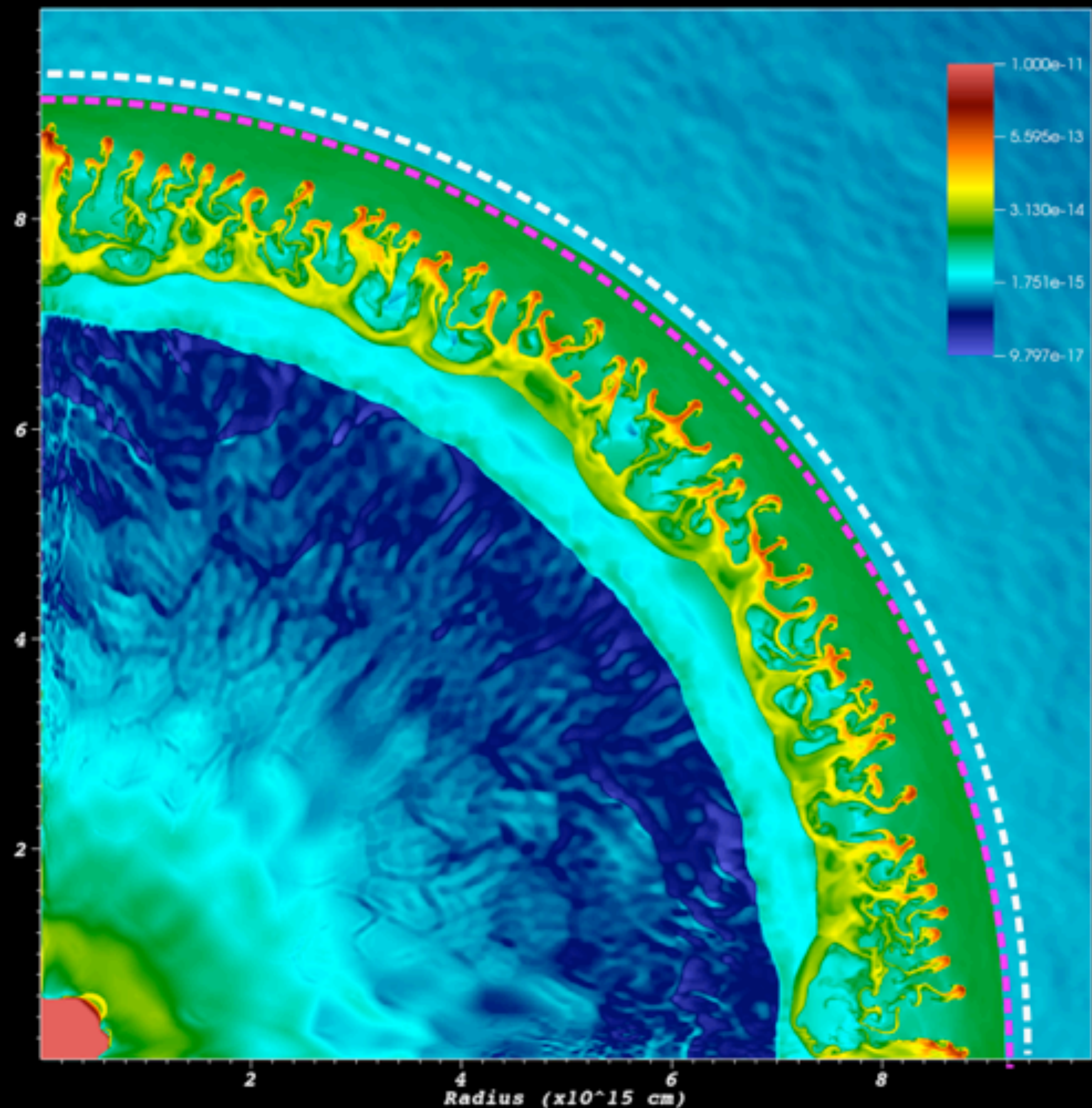


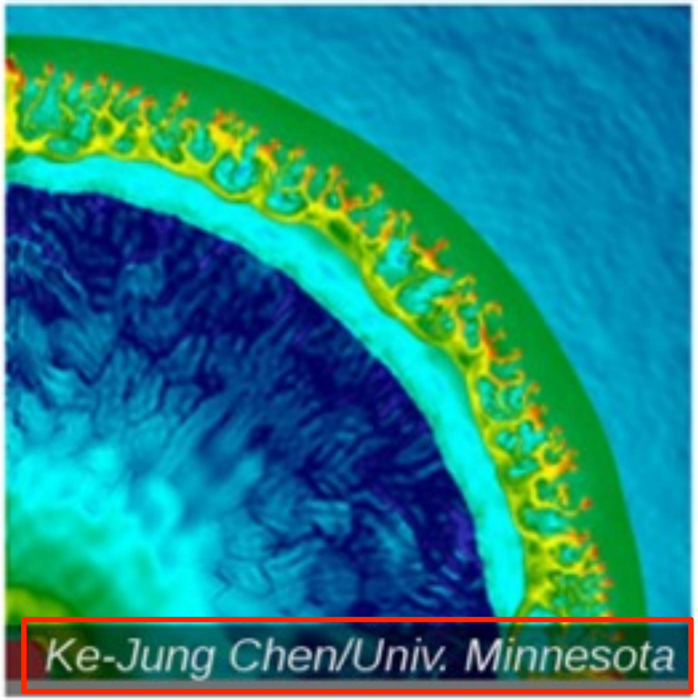
Physical Properties of Colliding Shells



nature.com

Se

07 February 2013



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

A dying star's massive outburst

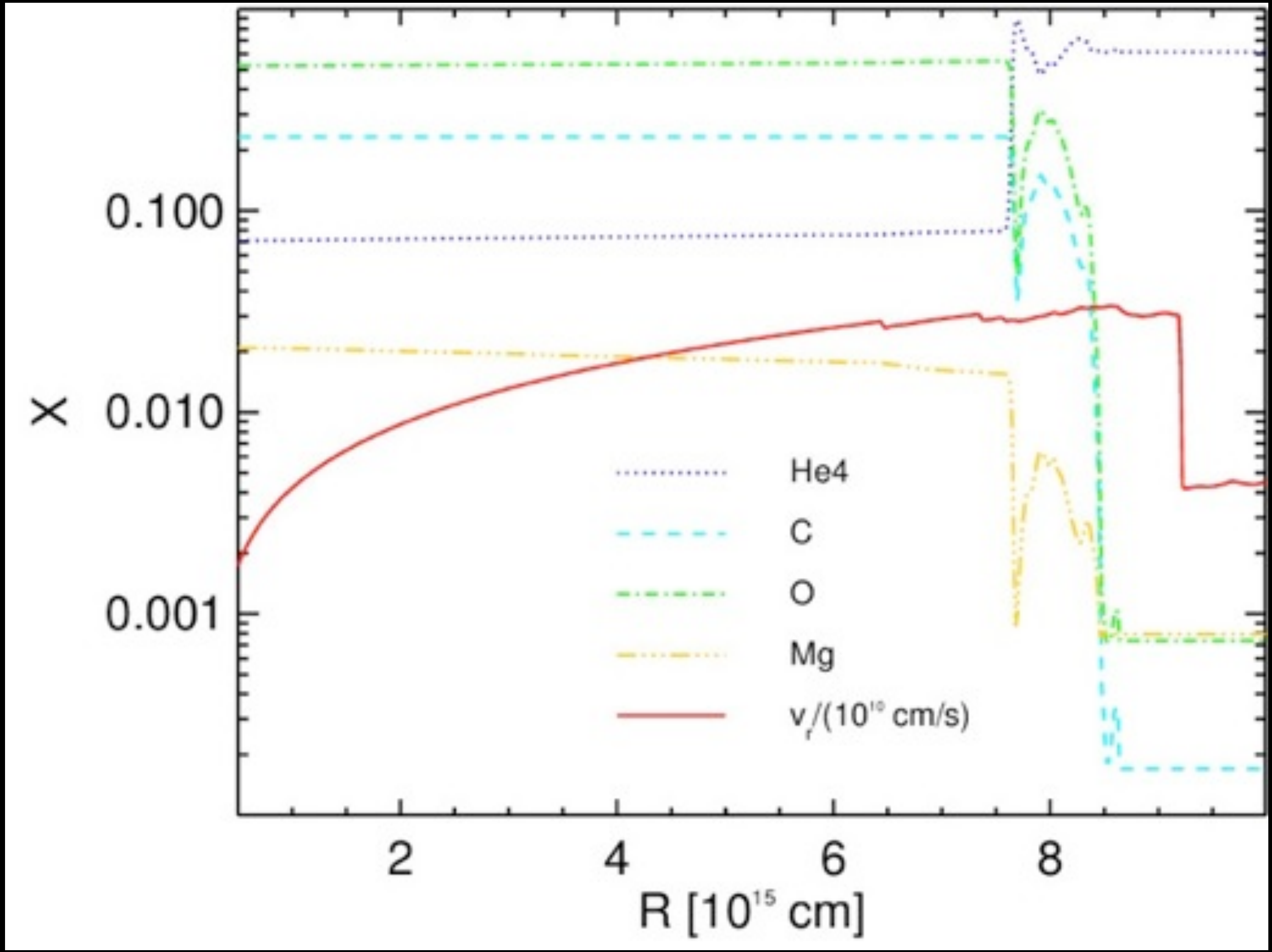
Observations of the final weeks of a massive star, just over a month before it exploded as a supernova, are reported in *Nature* this week.

Latest news

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

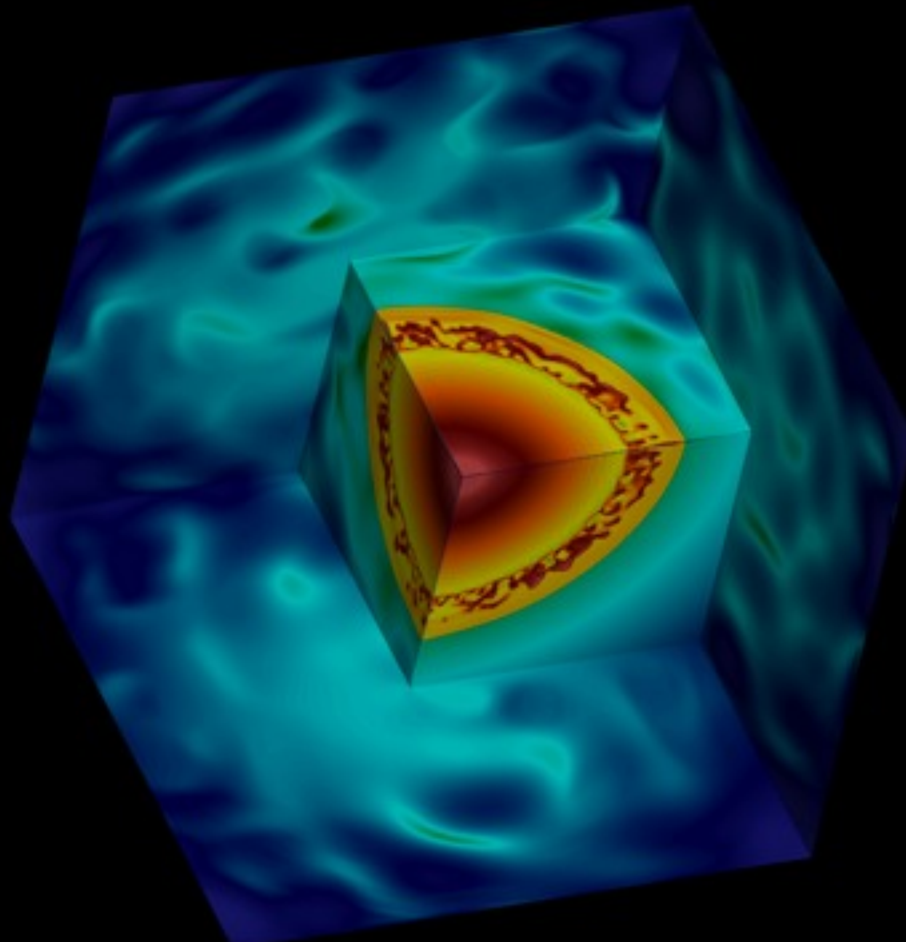
More news from nature

Mixing of PPSNe



Pair-Instability Supernovae (PSNe)

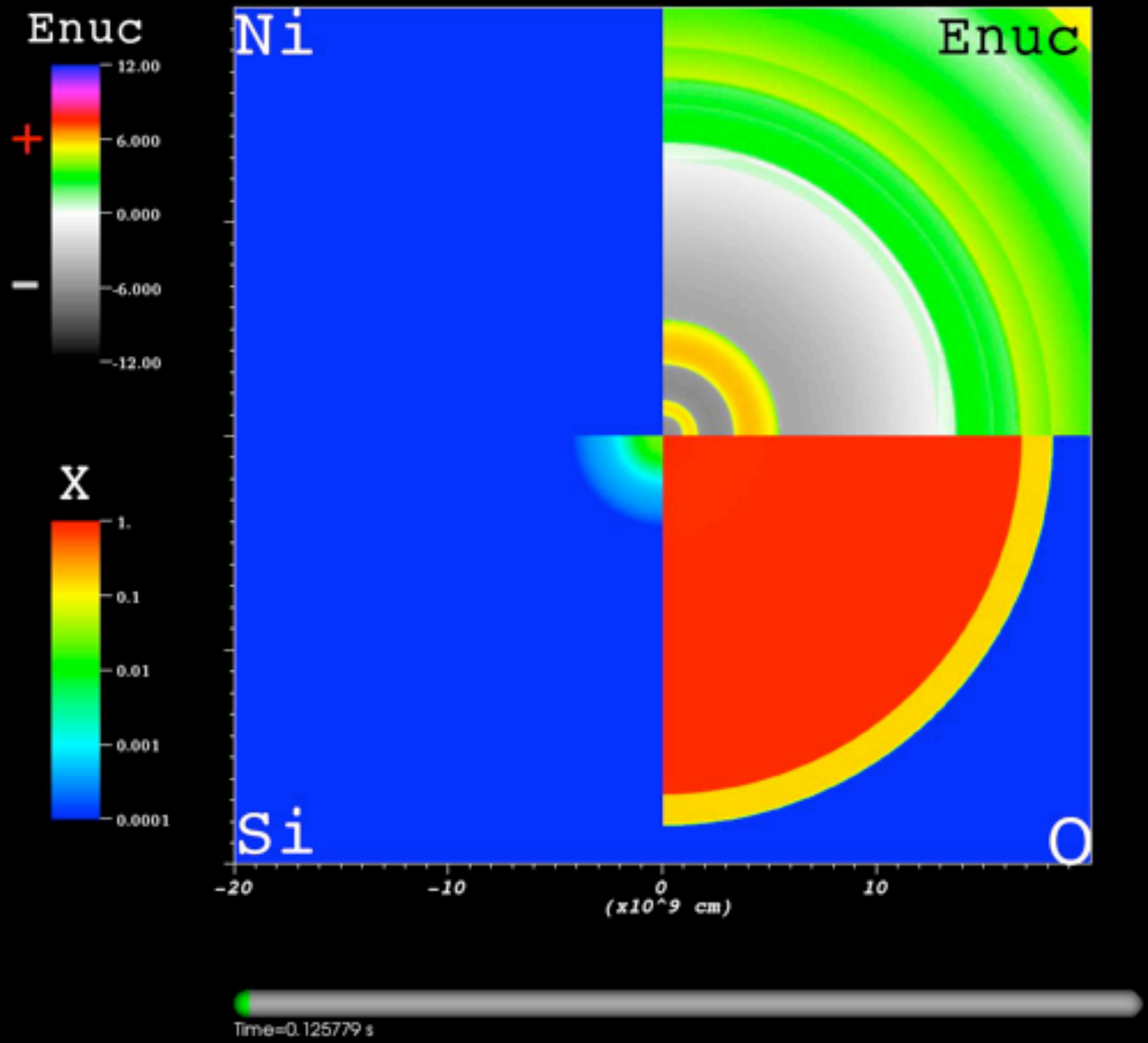
260 M⊙ > M* > 150 M⊙



Chen+ ApJ 792 44 (2014b)

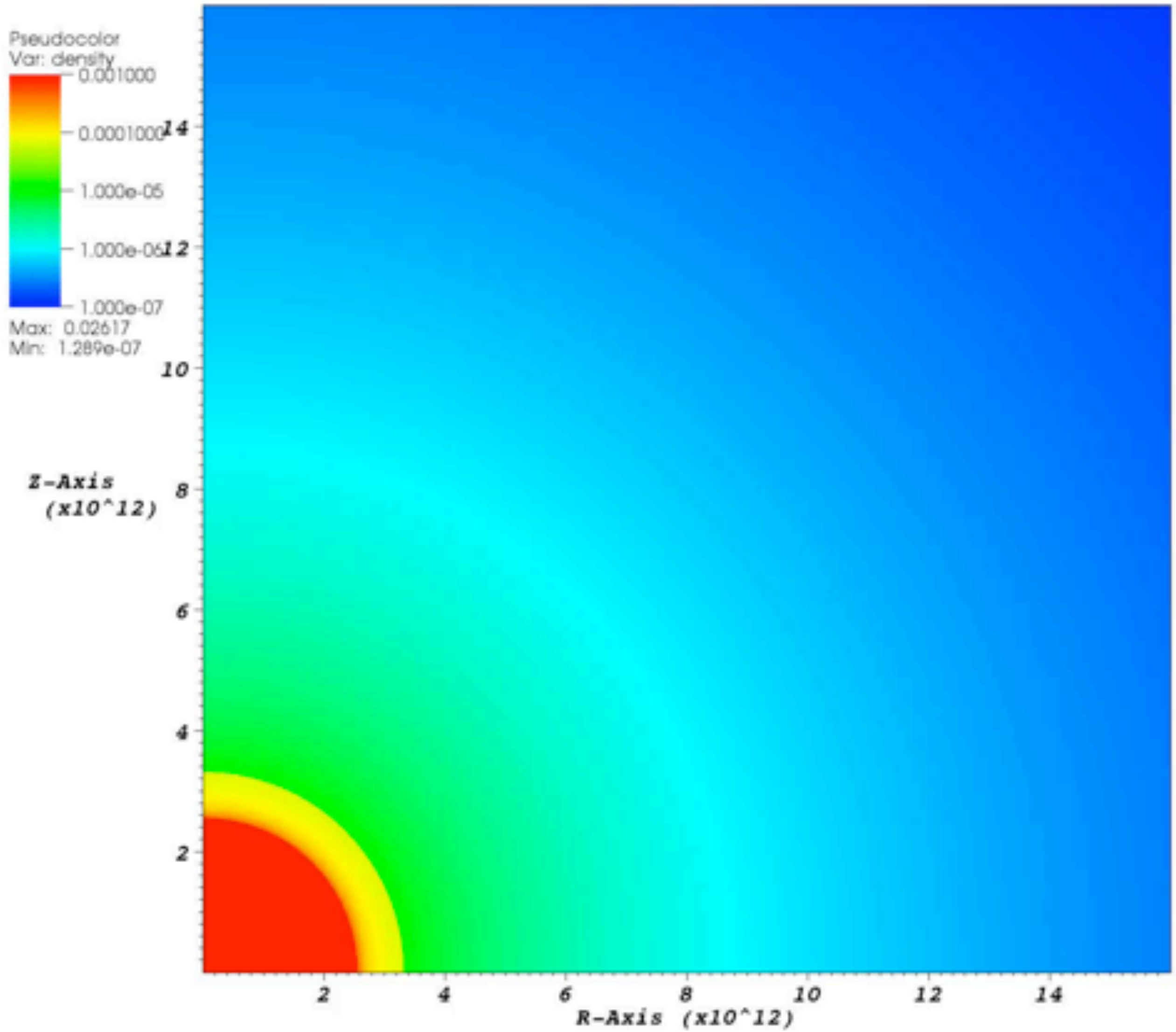
Explosive Burning of 150 M☉ Star

Explosive Burning of 150 M⊙ Star

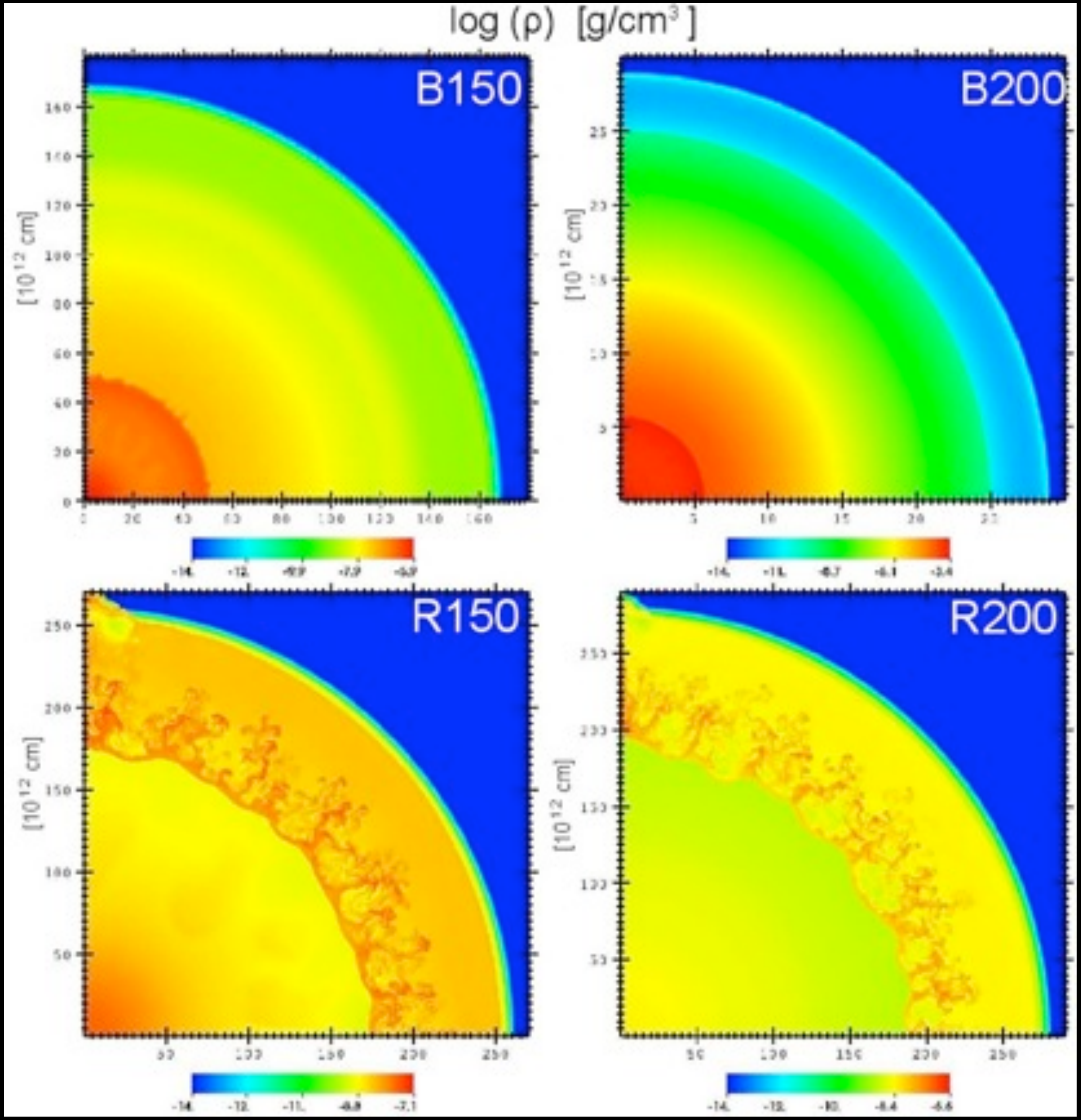


Exploding 200 M$\odot$ Star (2007 bi)

Exploding 200 M☉ Star (2007 bi)



Mixing of PSNe

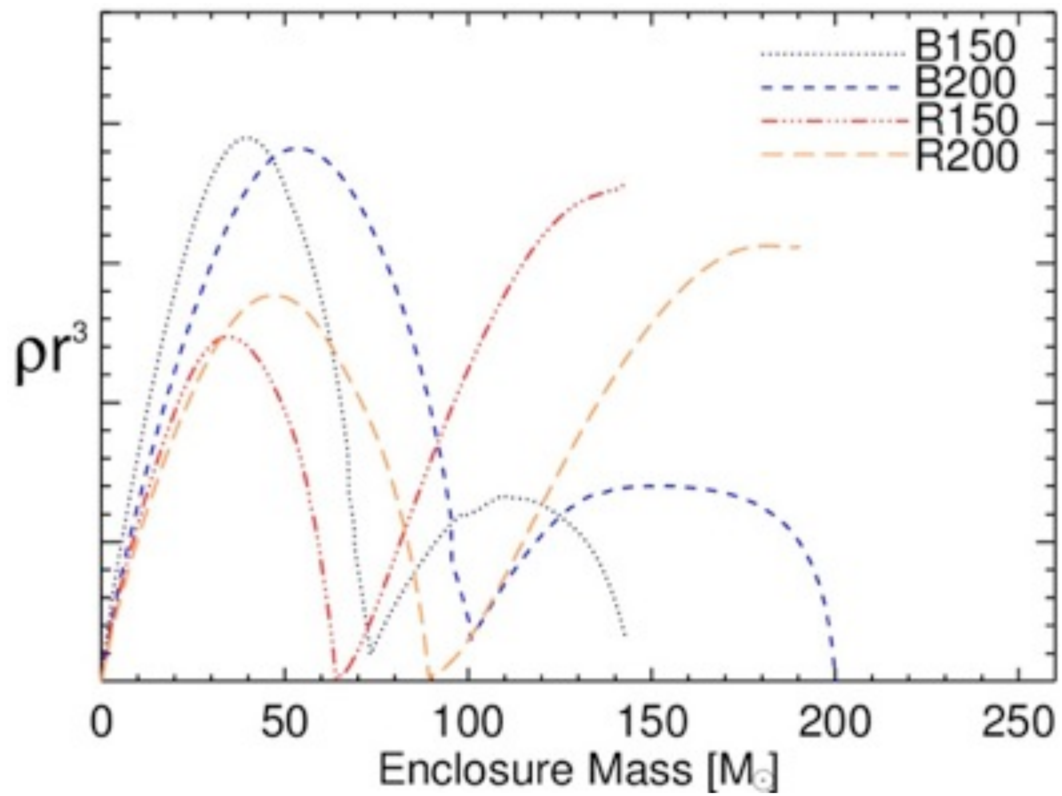


How does mixing occur?

$$\rho = Ar^w$$

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

Sedov, 1959



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

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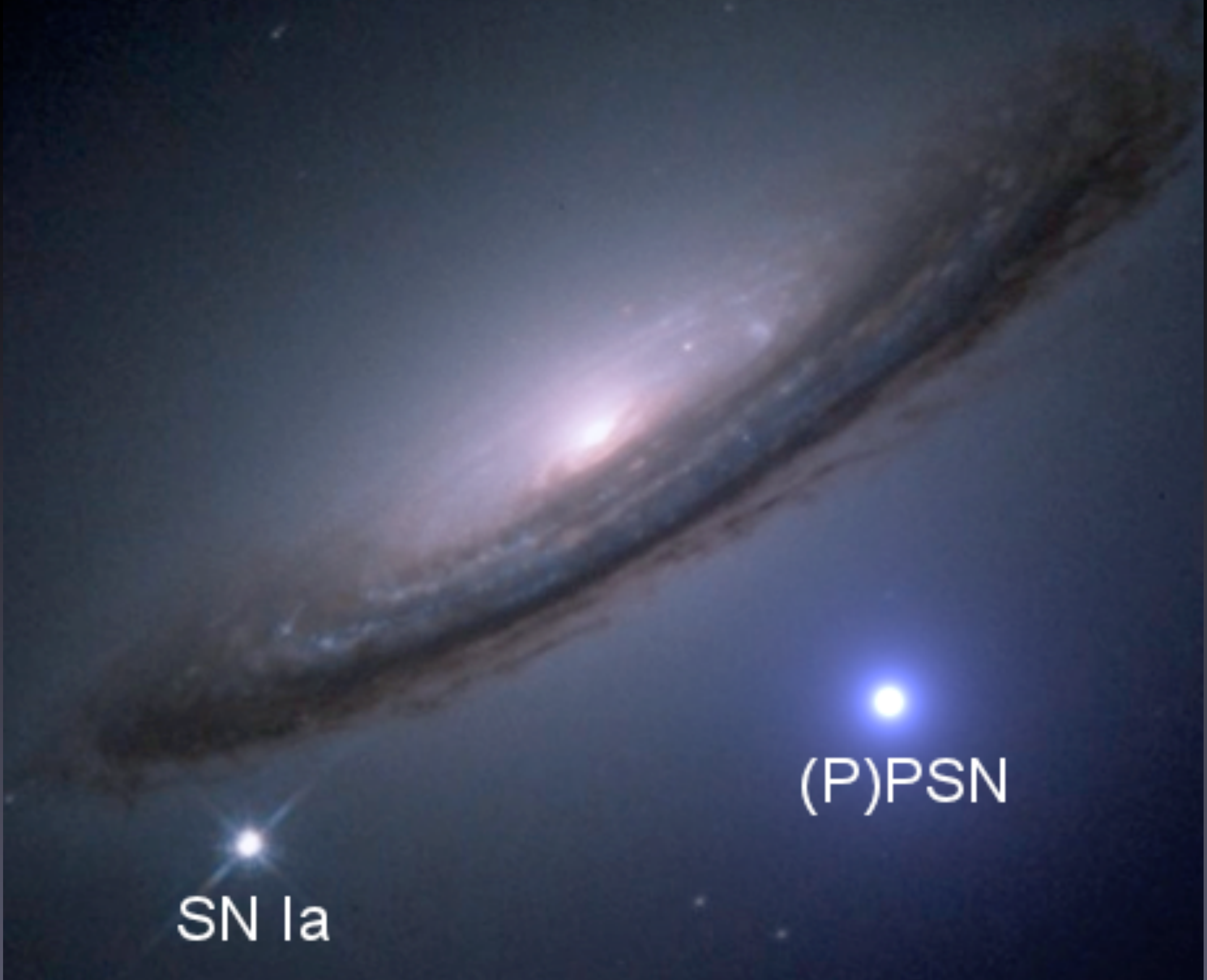
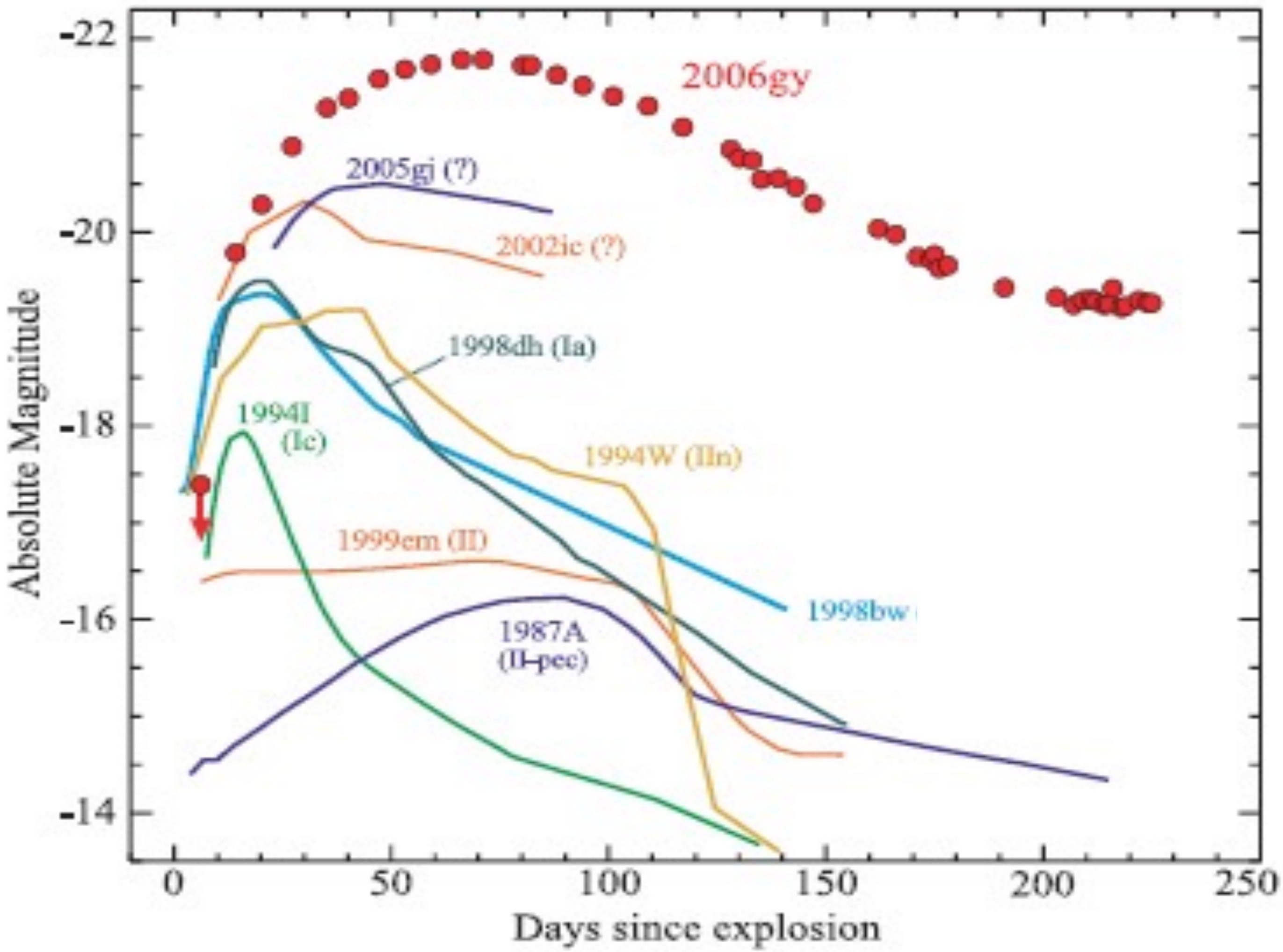
Ni is only slightly mixed out .
The Gamma-Ray emission for PSNe is unlikely.

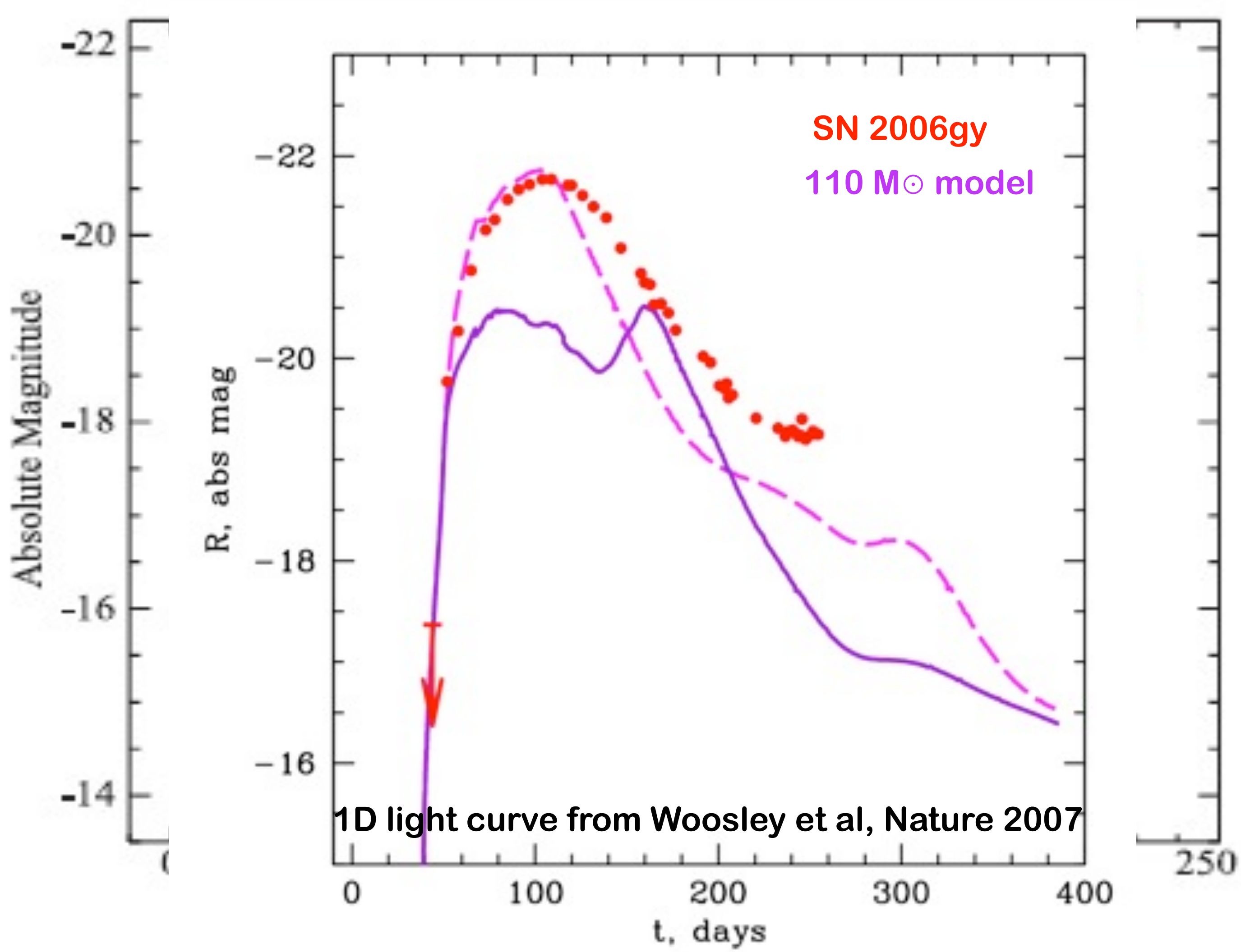

(P)PSN
SN Ia

Super Luminous SNe



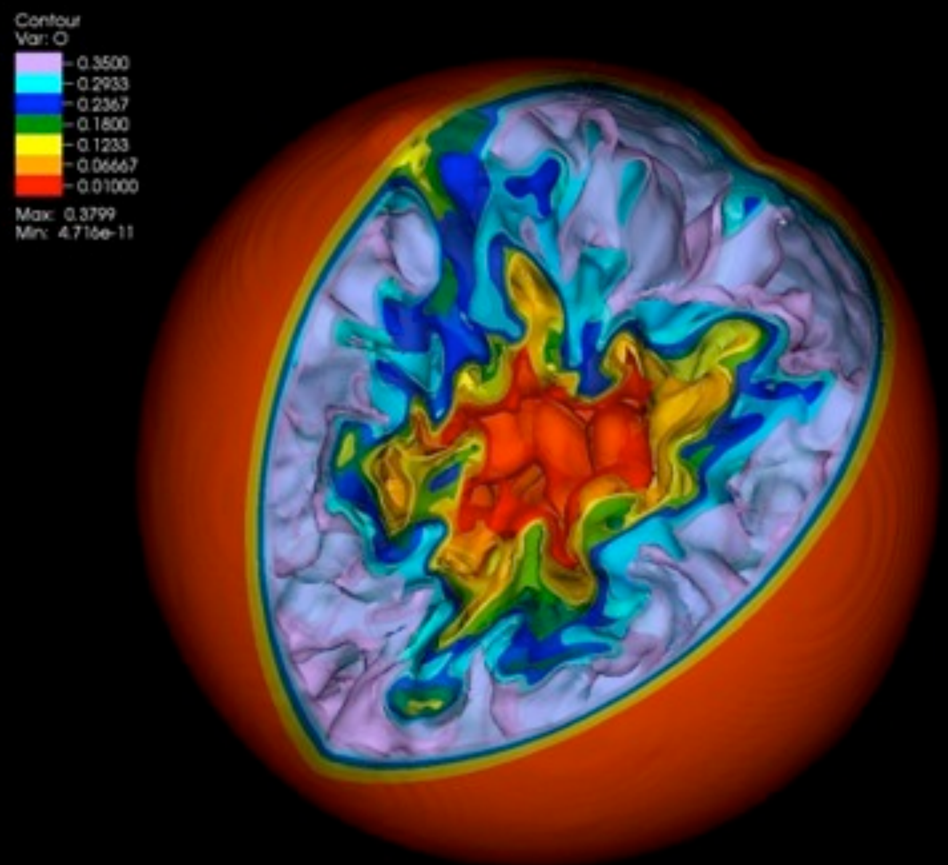
Smith+ 2007

Super Luminous SNe



GR Instability Supernovae (GSNe)

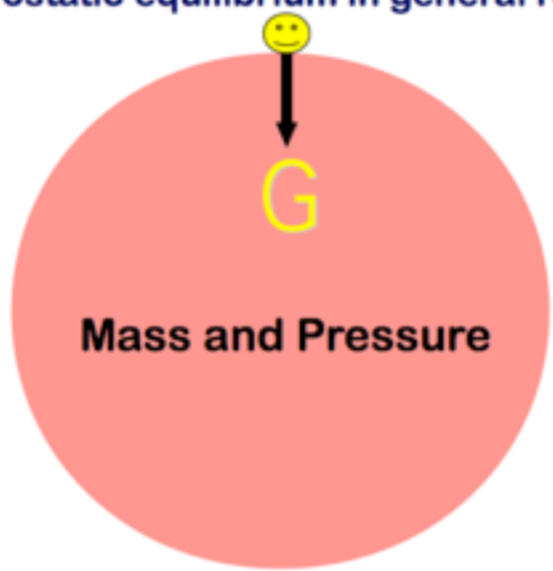
M*>> 100 M☉



Chen+ ApJ 790 162 (2014c)

GR correction for massive stars

(Hydrostatic equilibrium in general relativity)

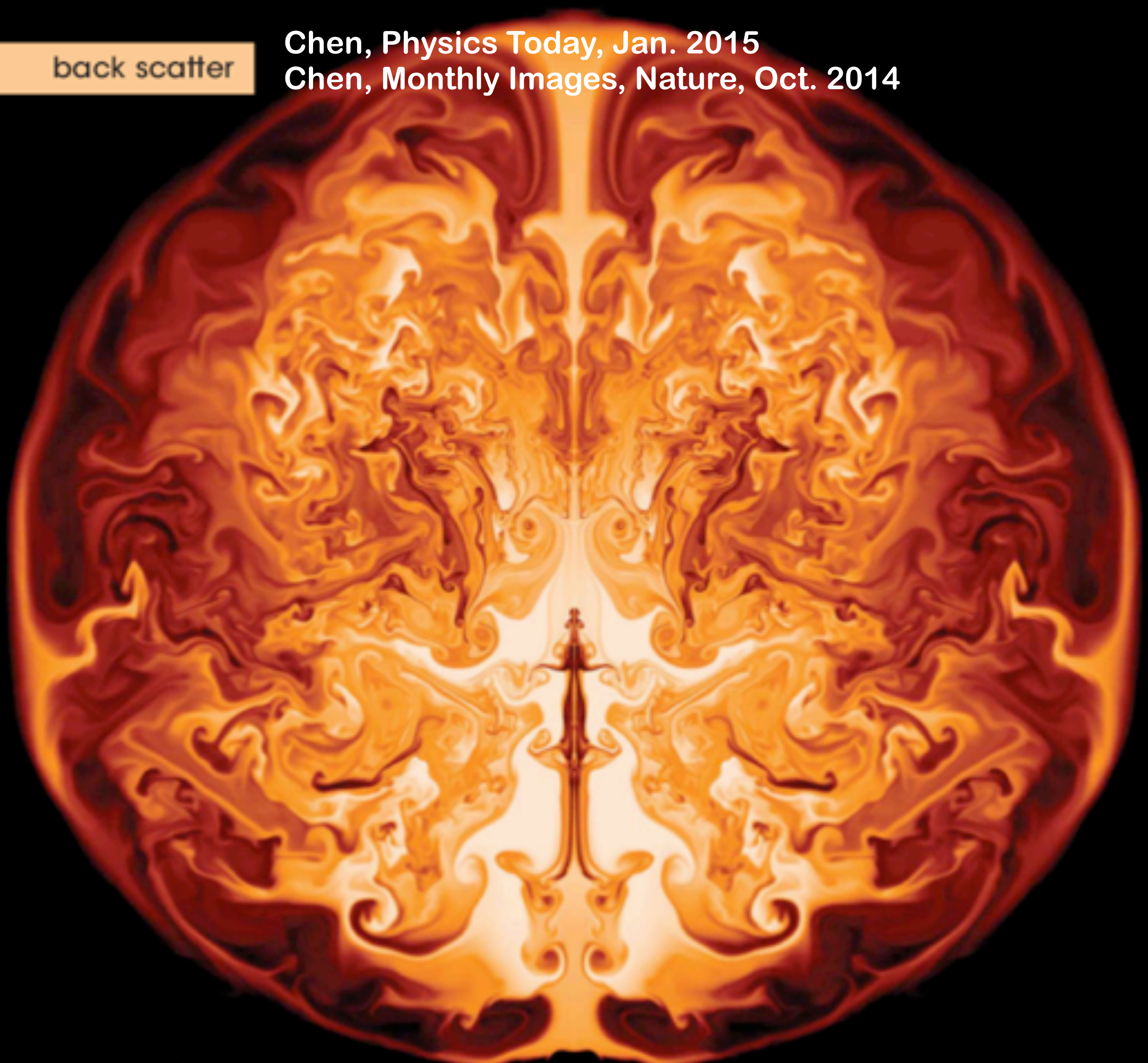


Tolman-Oppenheinmer-Volko equation

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

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

back scatter

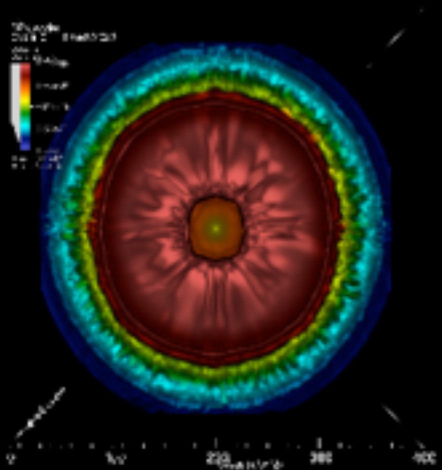


An exploding supermassive star

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

Take Home Message I

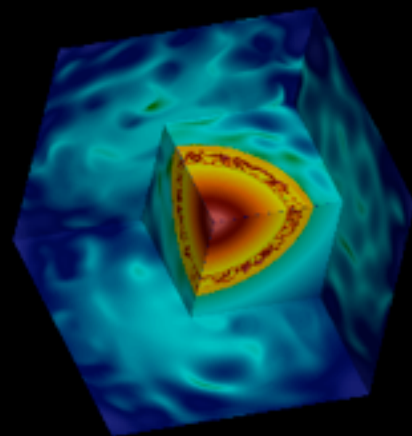
Pulsational Pair-Instability SN (PPSN)



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

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

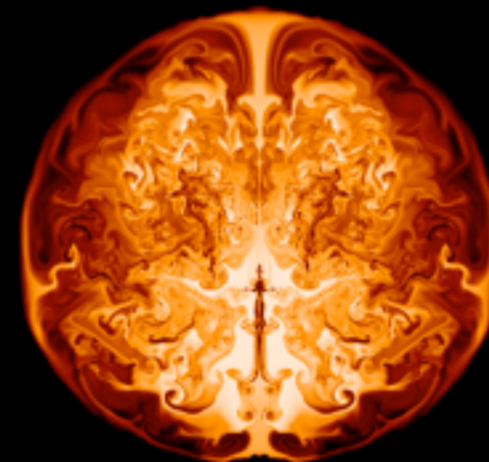
Pair-Instability SN (PSN)



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

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)



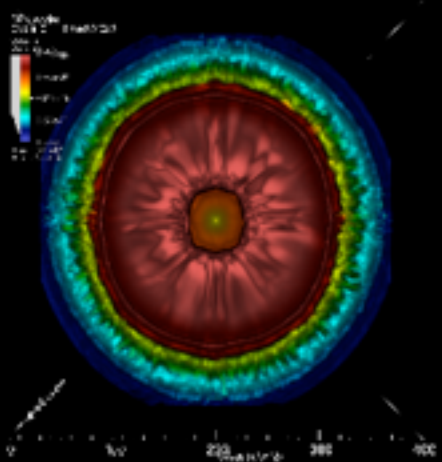
$M^* \sim 55{,}000?\ M_\odot$

1. GR instability
2. Explosive burning helium
3. One giant explosion
4. Mixing due to burning instability

Explosion energy ~ 10^{55} erg

Take Home Message I

Pulsational Pair-Instability SN (PPSN)



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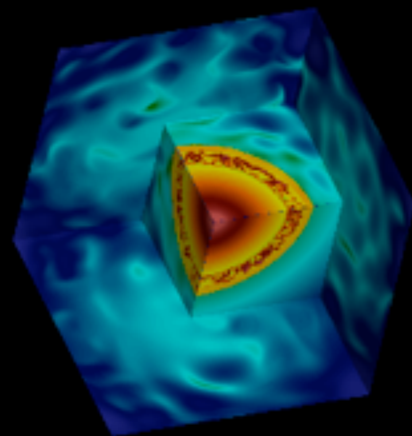

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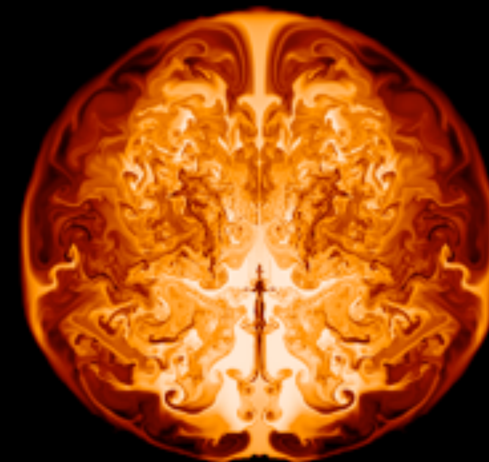

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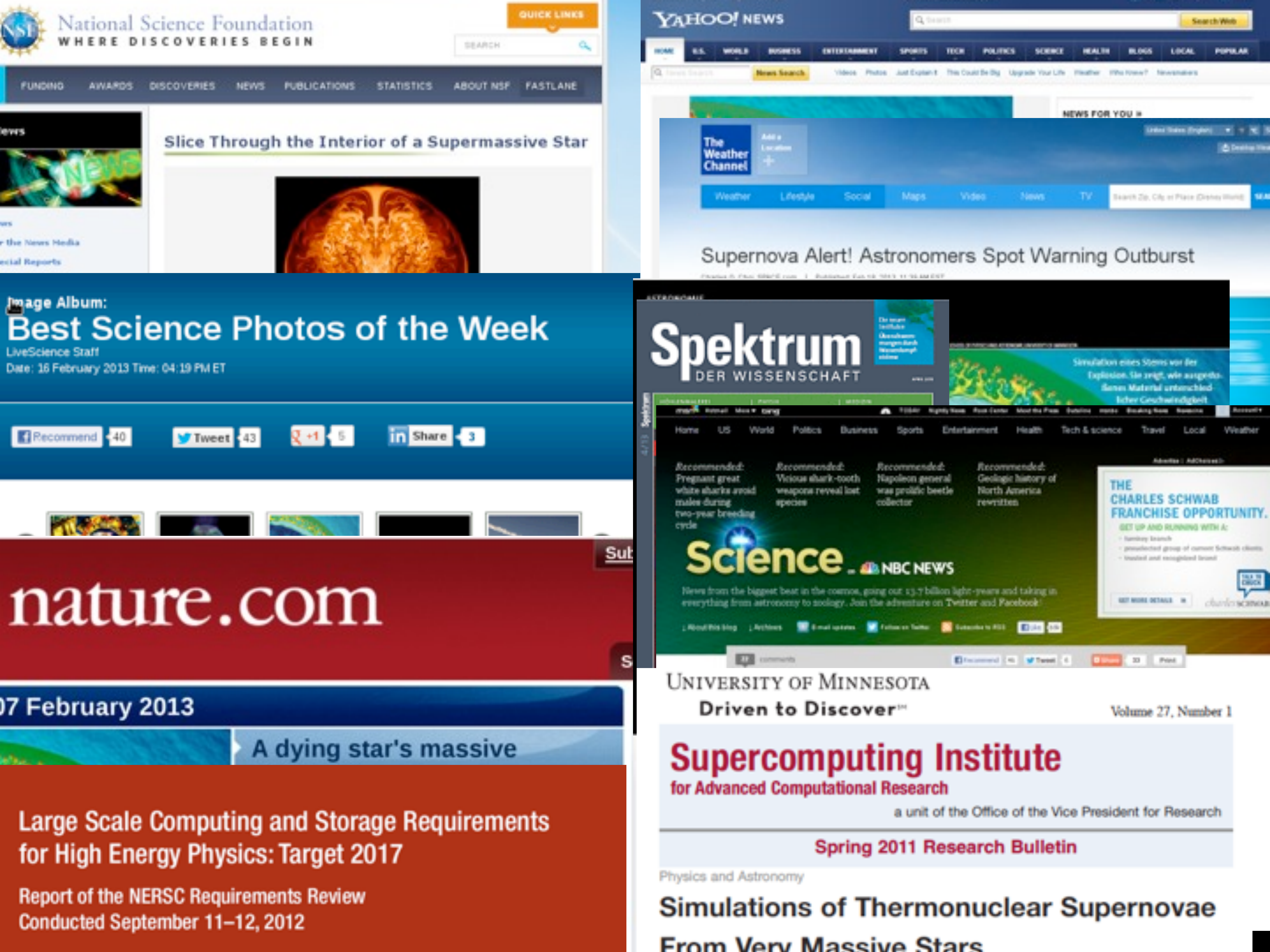
Big impact to the early Universe !


National Science Foundation
WHERE DISCOVERIES BEGIN
Slice Through the Interior of a Supermassive Star
YAHOO! NEWS
The Weather Channel
Supernova Alert! Astronomers Spot Warning Outburst
Image Album:
Best Science Photos of the Week
LiveScience Staff
Date: 16 February 2013 Time: 04:19 PM ET
Spektrum DER WISSENSCHAFT
Science NBC NEWS
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 Conducted September 11–12, 2012
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
From Very Massive Stars

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FUNDING AWARDS DISCOVERIES NEWS PUBLICATIONS STATISTICS ABOUT NSF FASTLANE

Slice Through the Interior of a Supermassive Star

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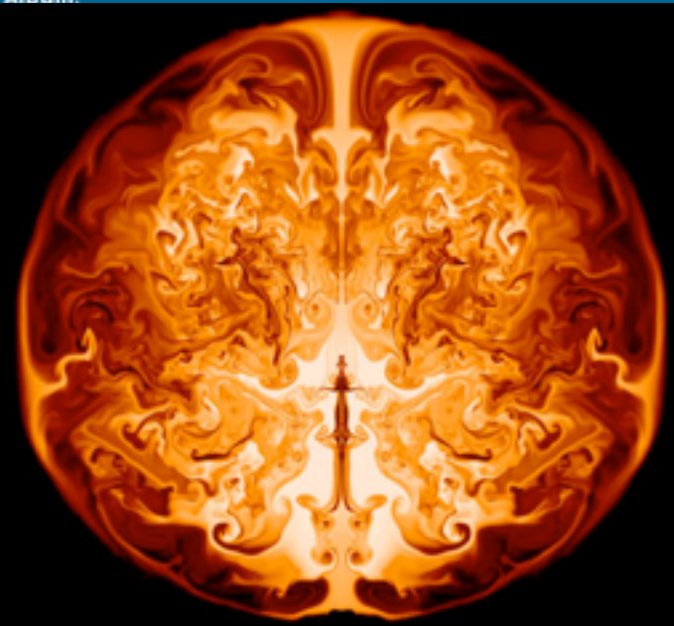
The Weather Channel

Supernova Alert! Astronomers Spot Warning Outburst



With the help of NERSC

Who says you can’t crack open a star?

Watch us!

A dying star's massive

Large Scale Computing and Storage Requirements for High Energy Physics: Target 2017

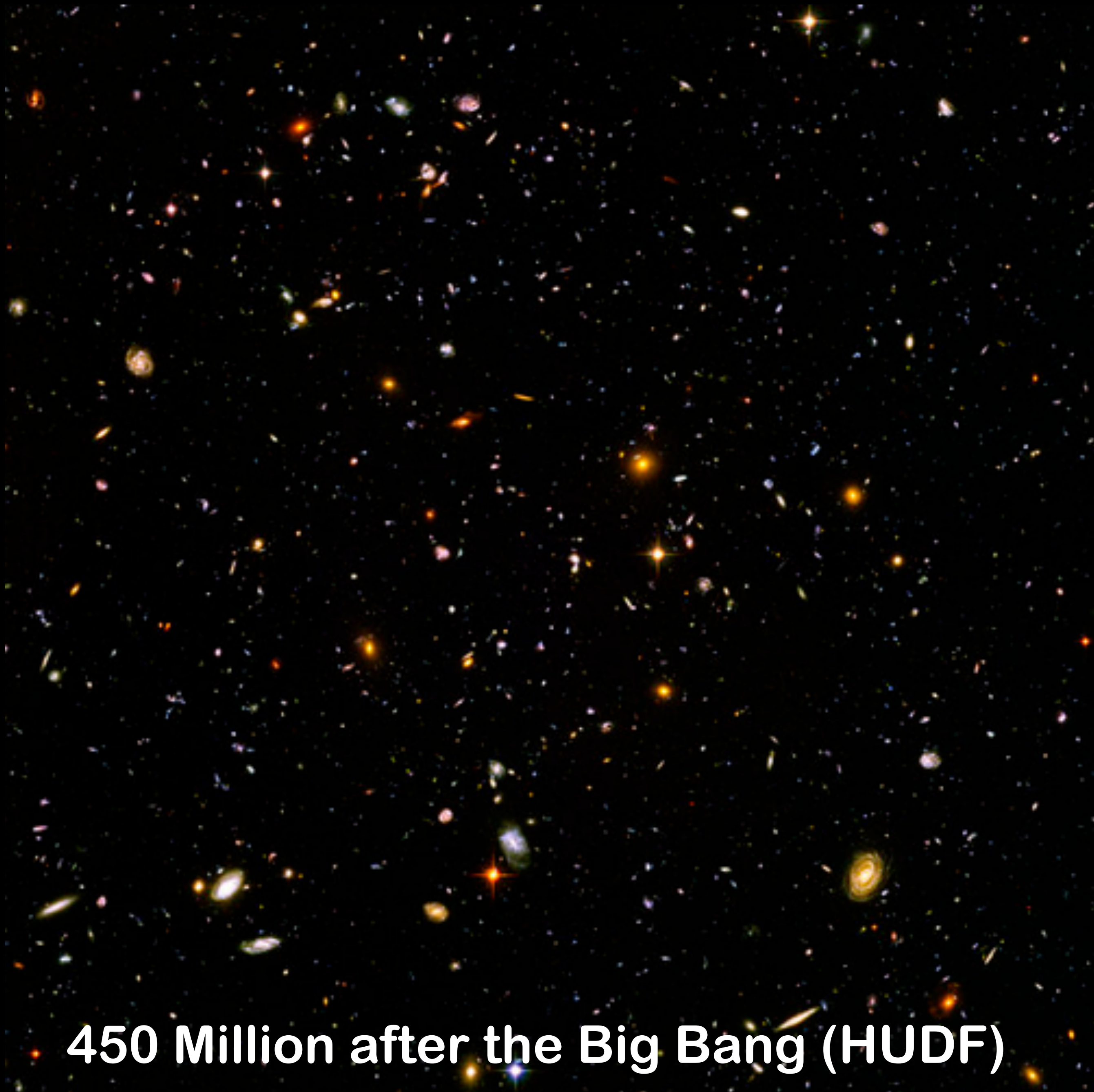
Report of the NERSC Requirements Review Conducted September 11–12, 2012

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 From Very Massive Stars



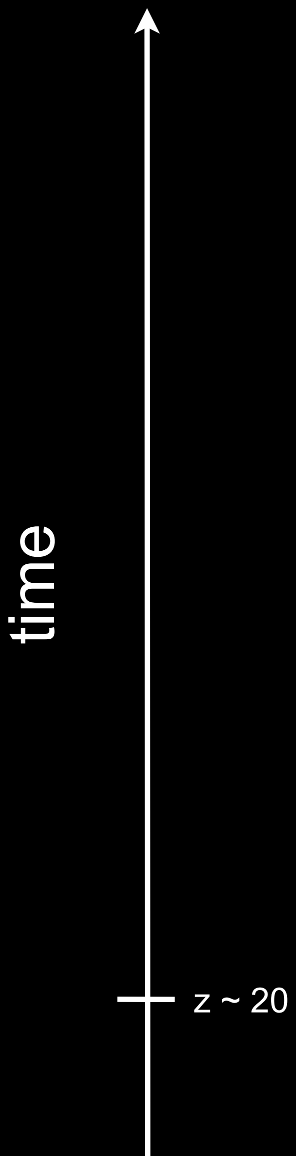
450 Million after the Big Bang (HUDF)

How did the First Galaxies Form?

time

Bromm, & Yoshida (2011)

How did the First Galaxies Form?



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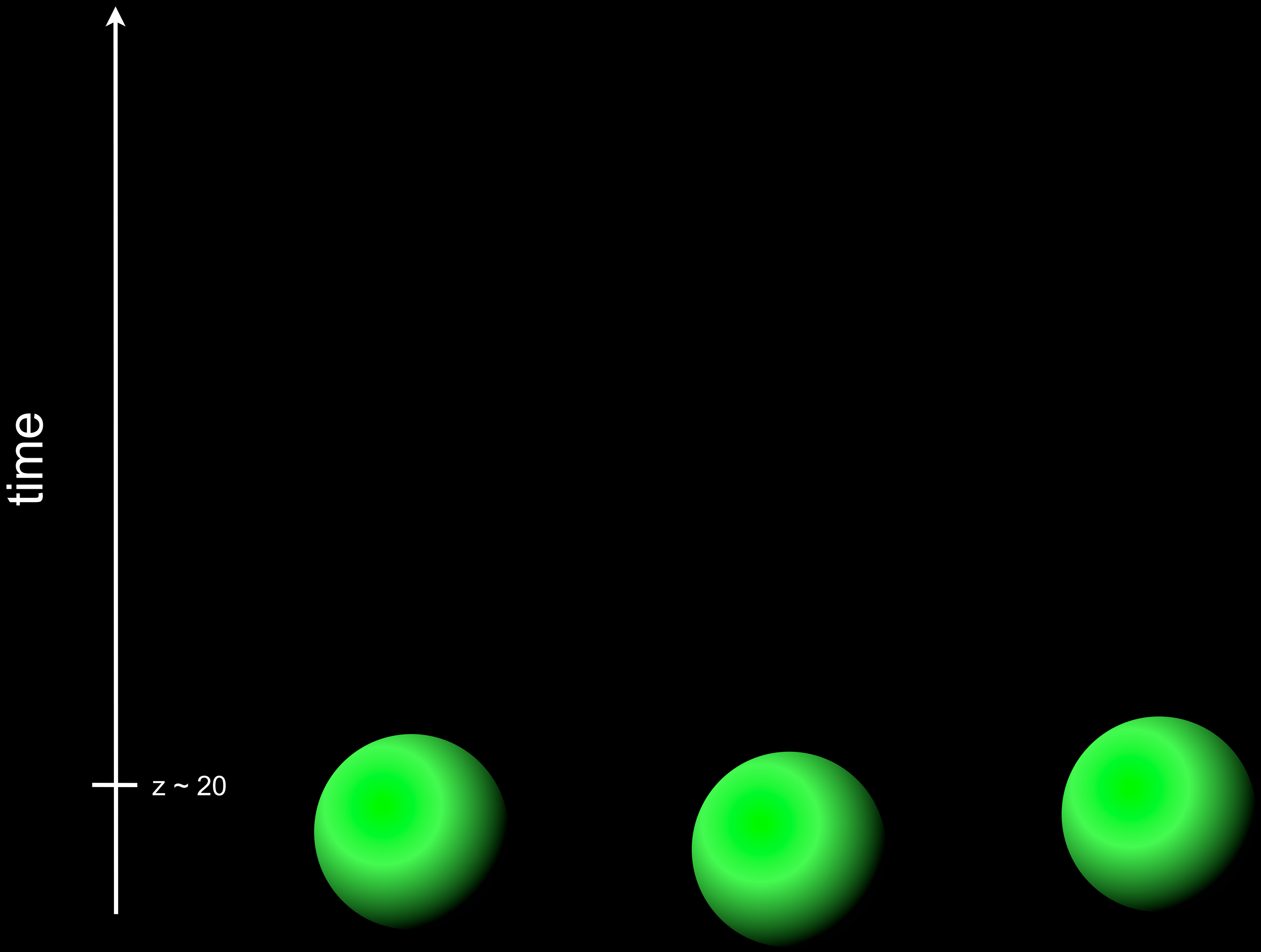

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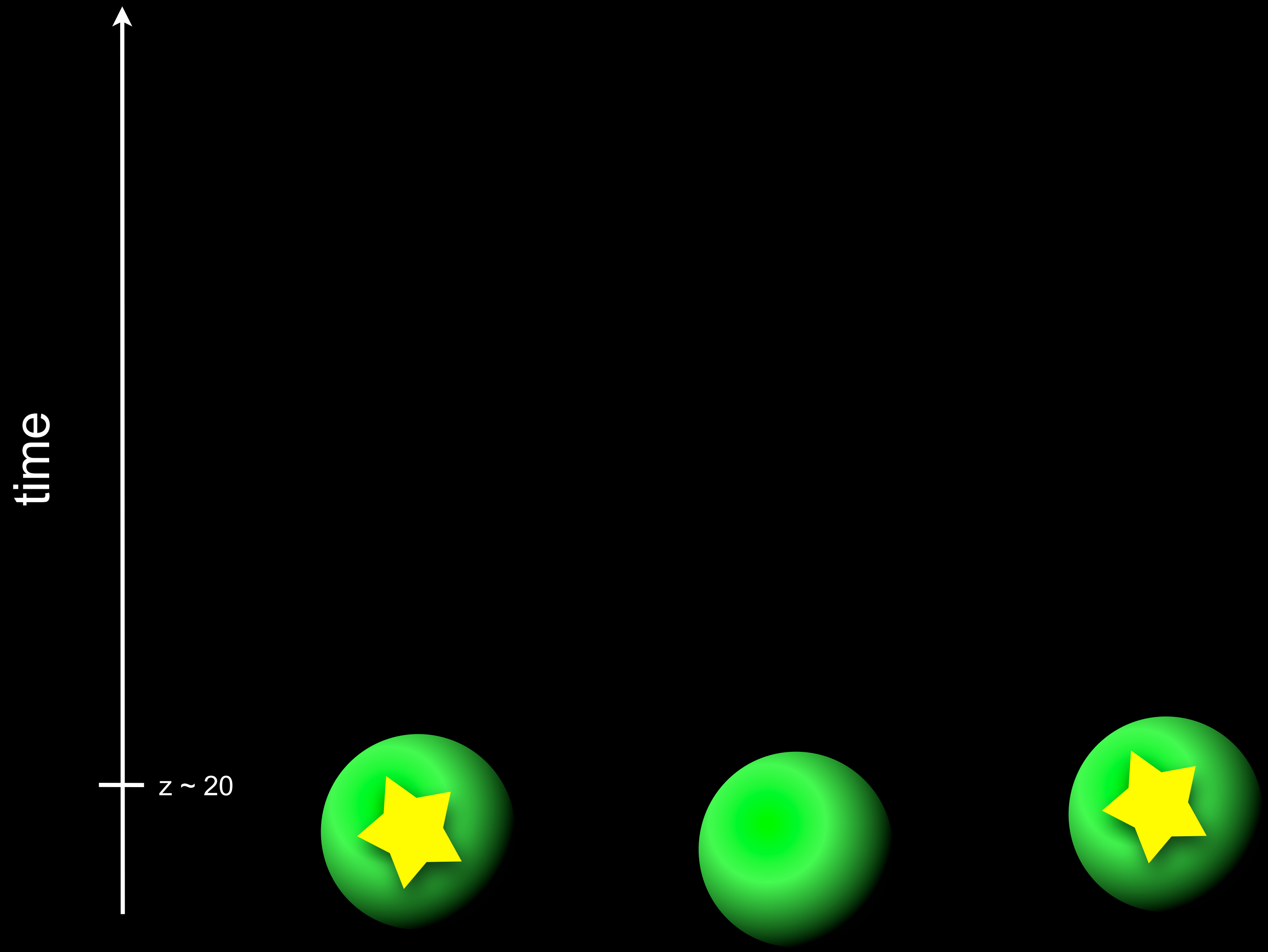

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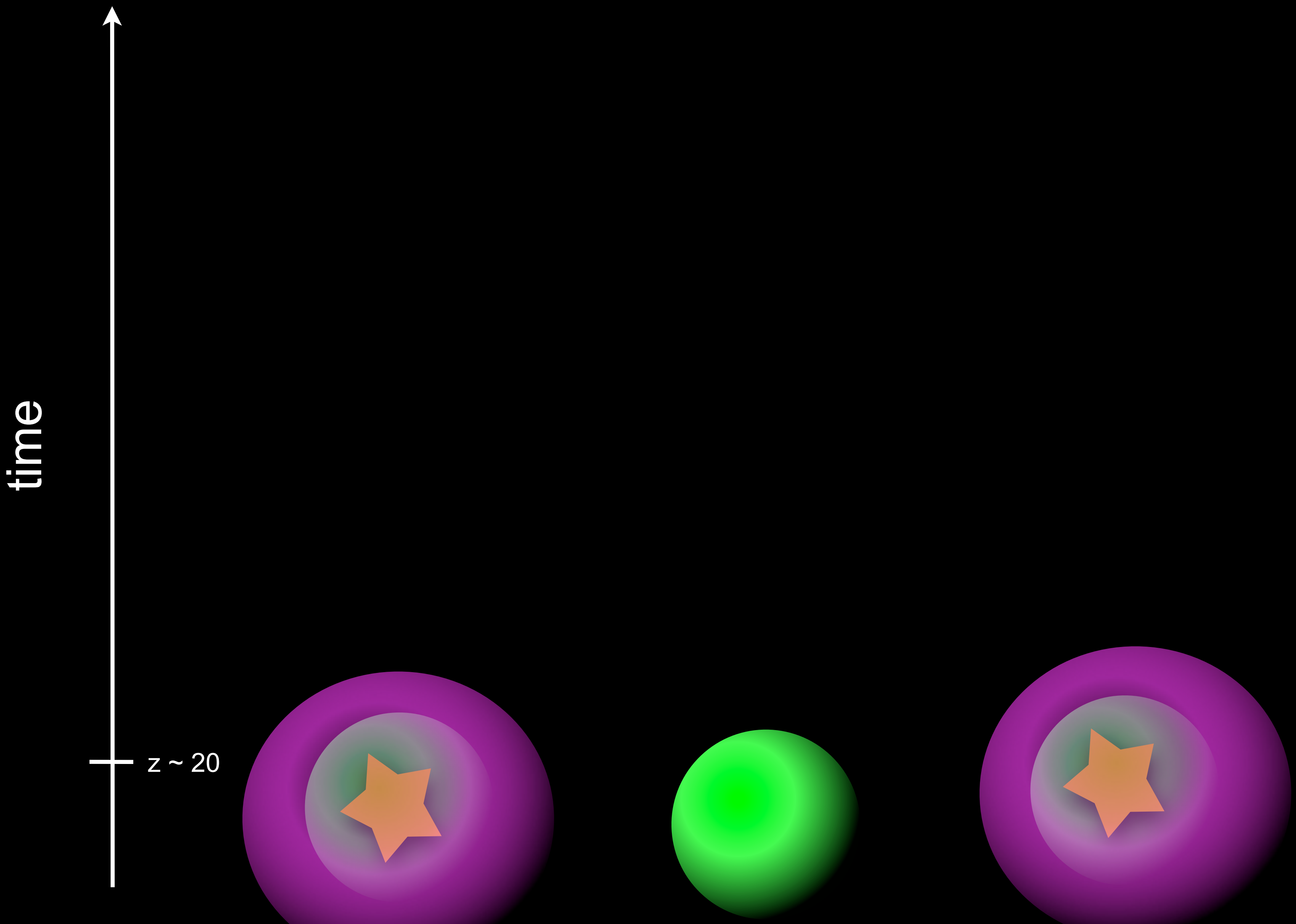

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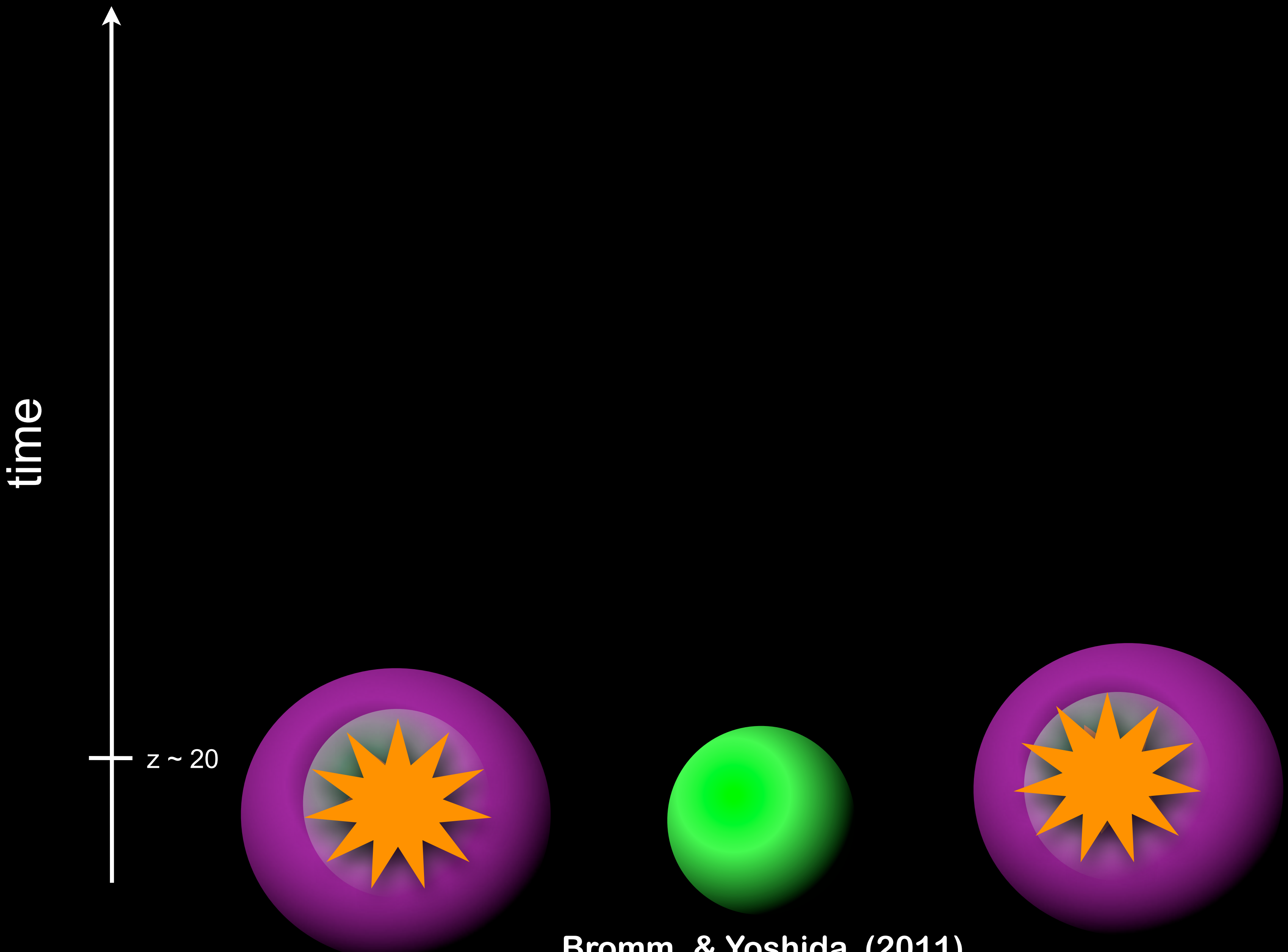

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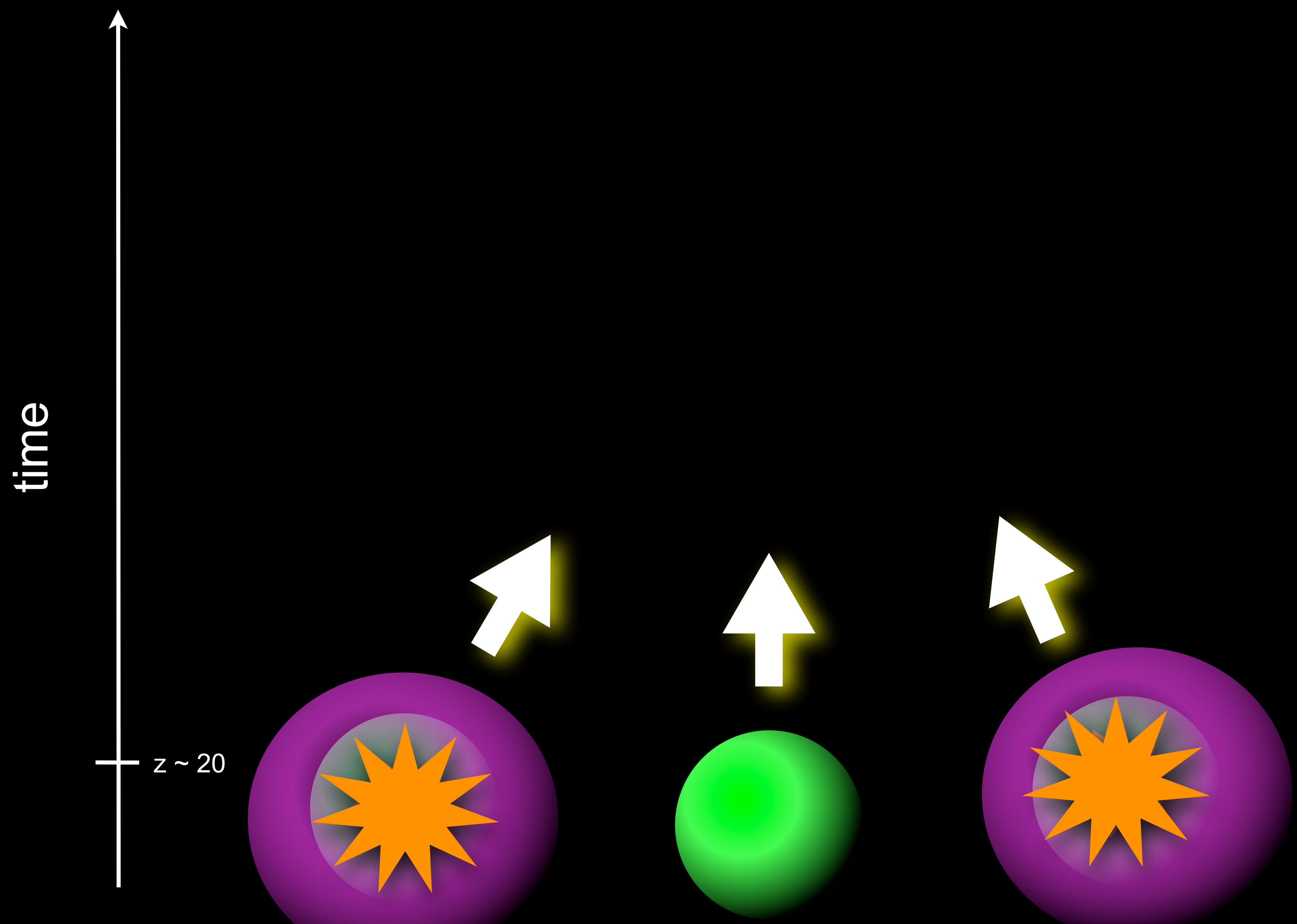

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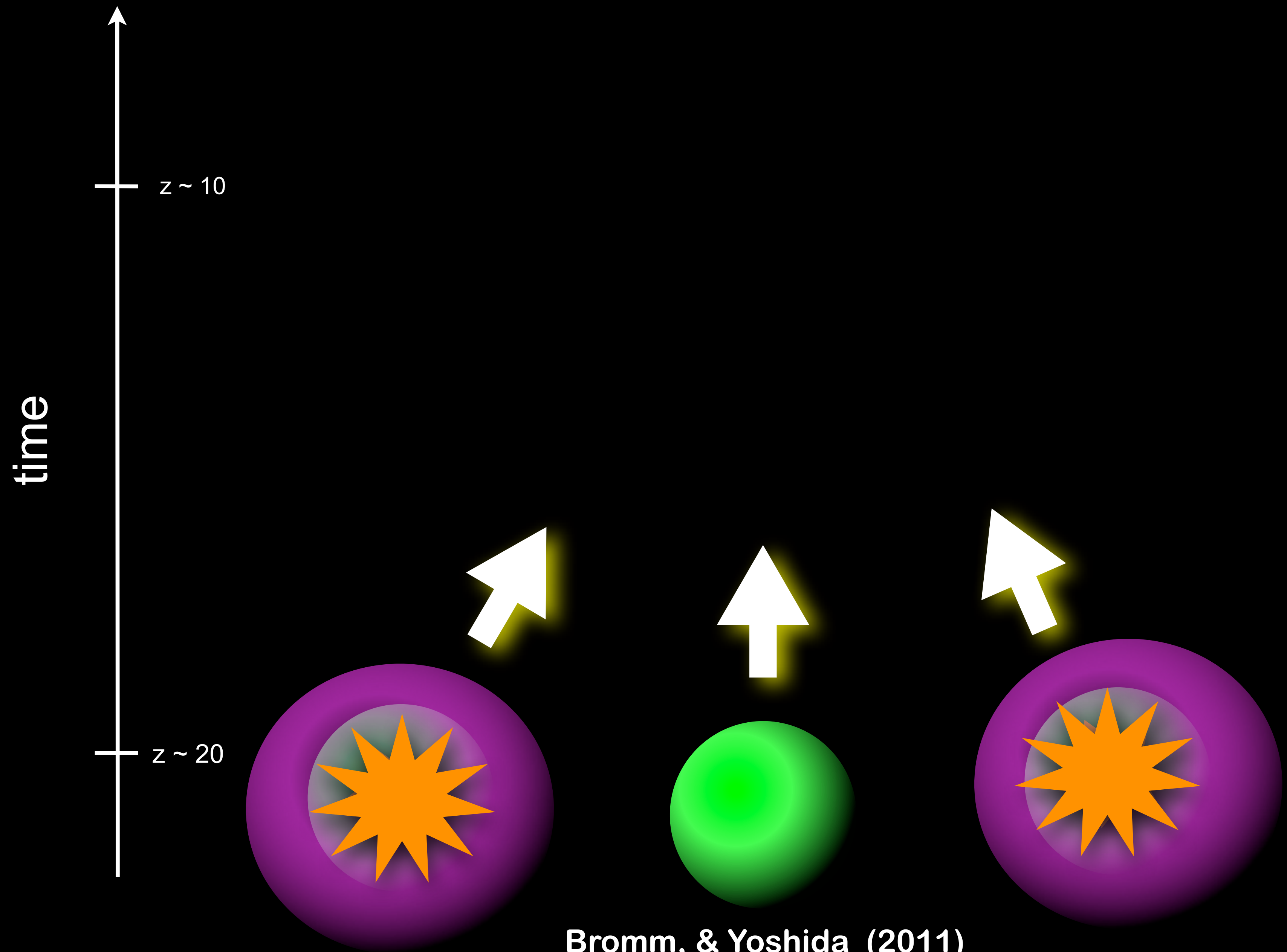

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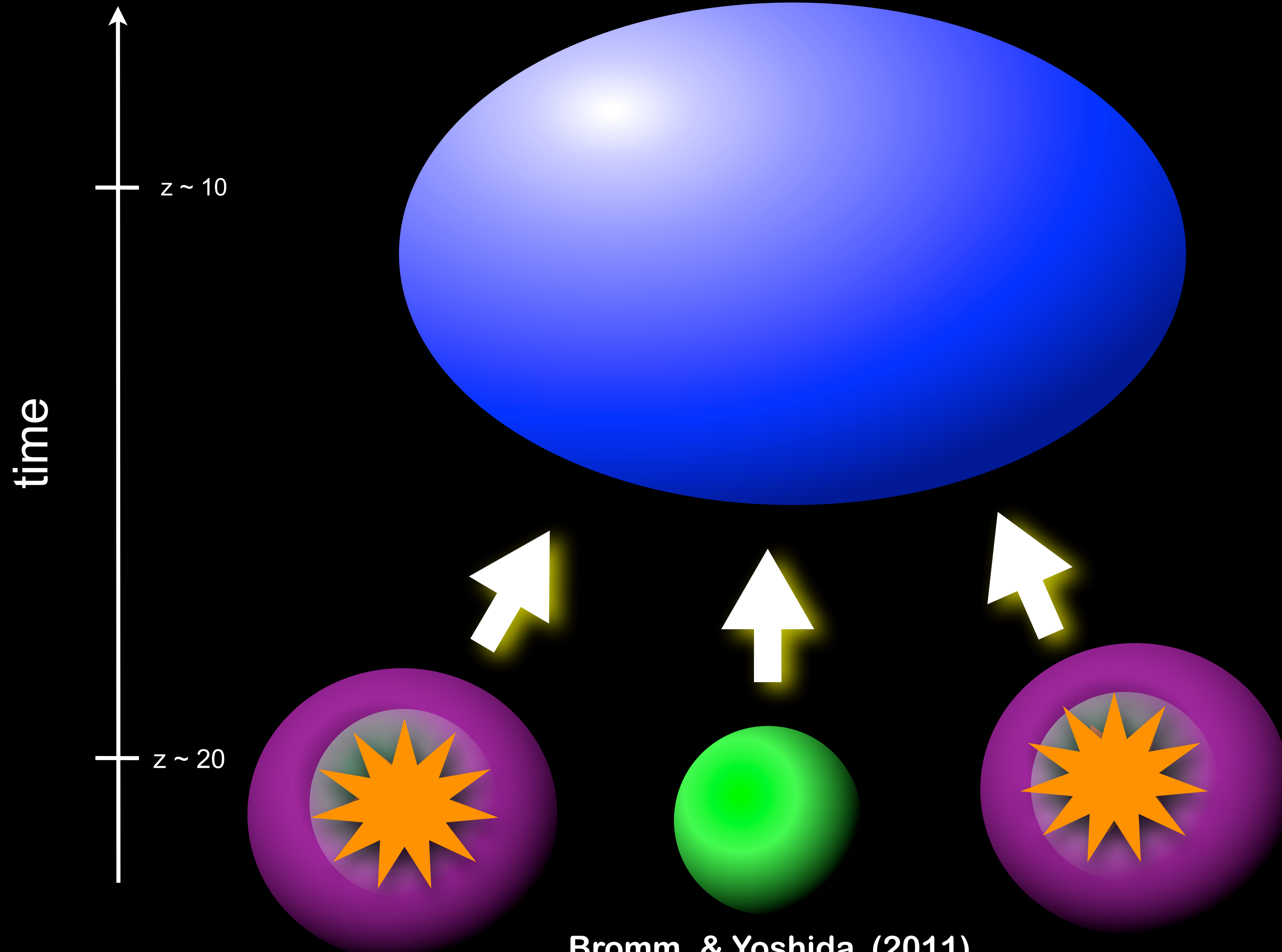

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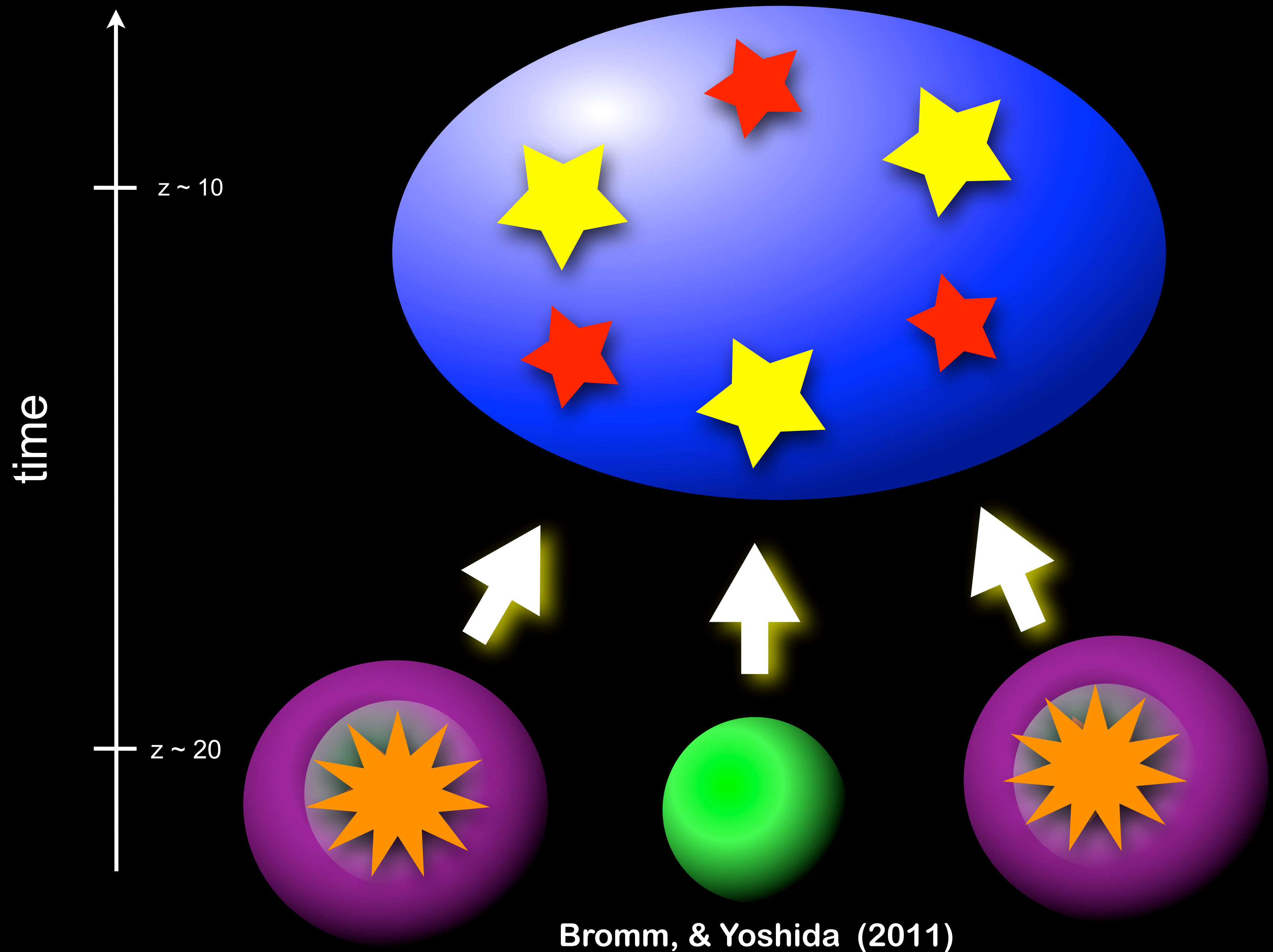

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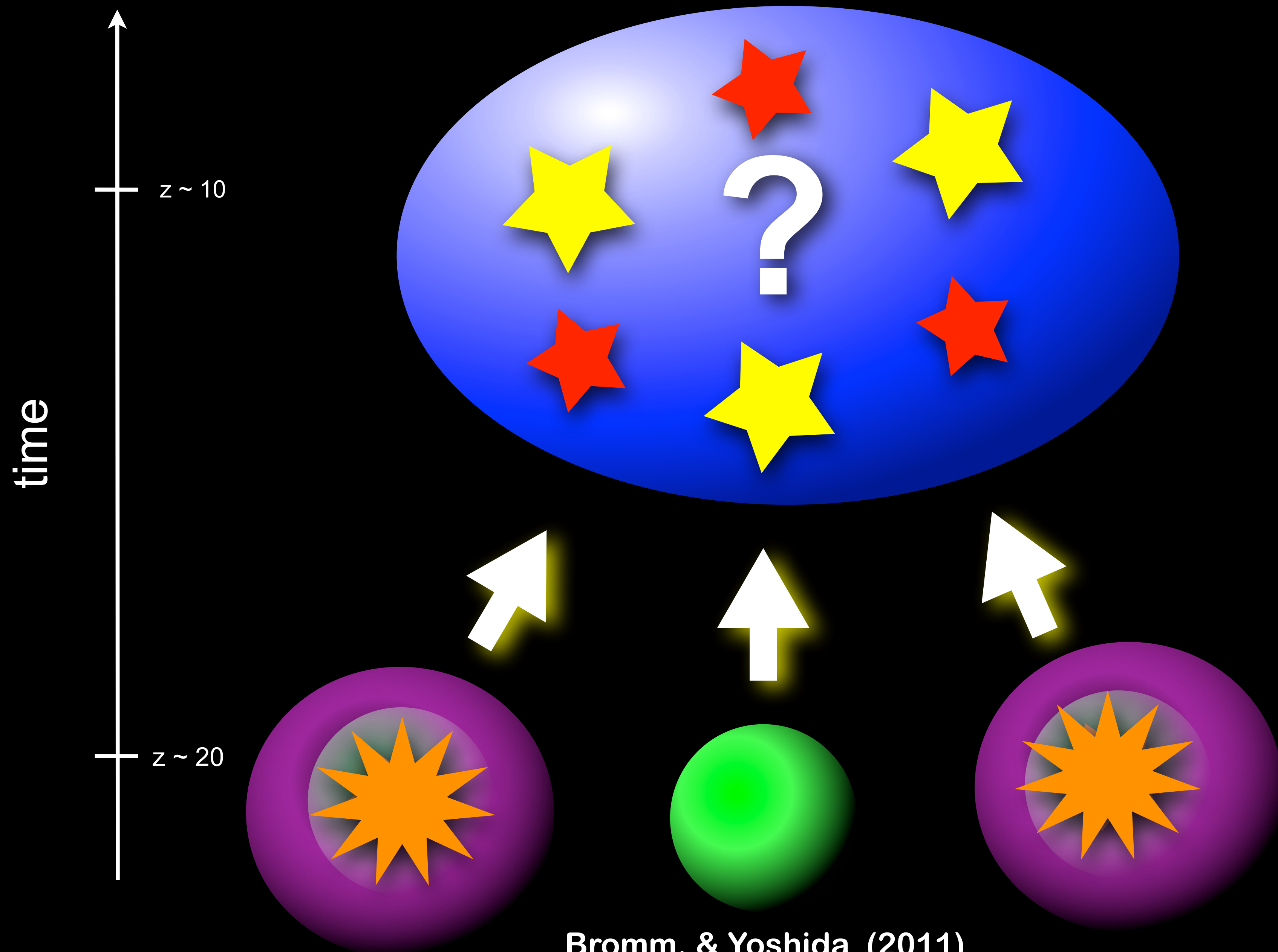

Bromm, & Yoshida (2011)

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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Cosmological Simulations

Chen+ ApJ in press (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

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2. SN shock reheating
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Detailed Stellar Models

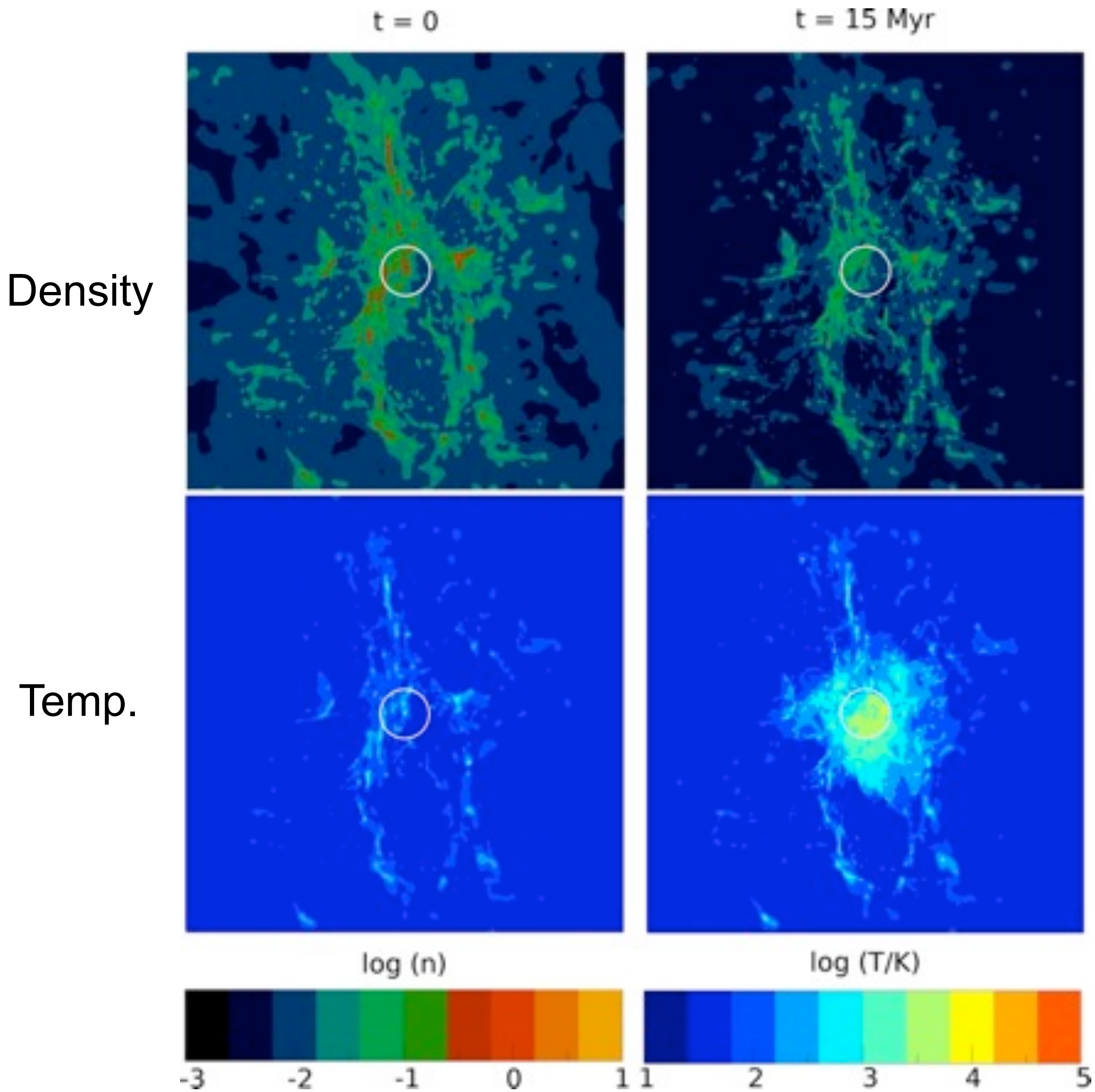
The Impact of the First Stars, Supernovae, and Binaries

Ken Chen

University of Minnesota

Background music: Pirates Of The Caribean

Properties of Large Scale Structure



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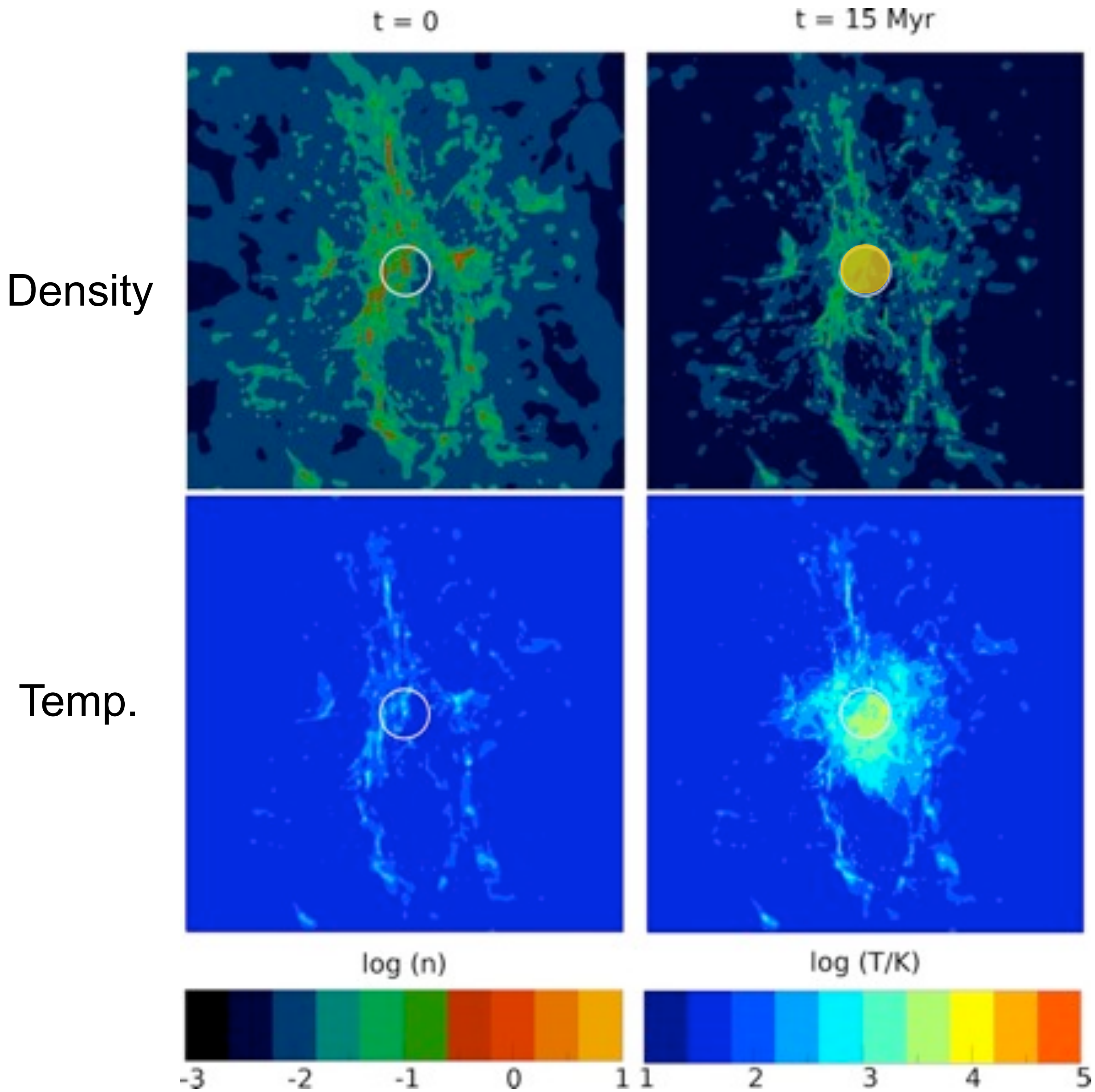

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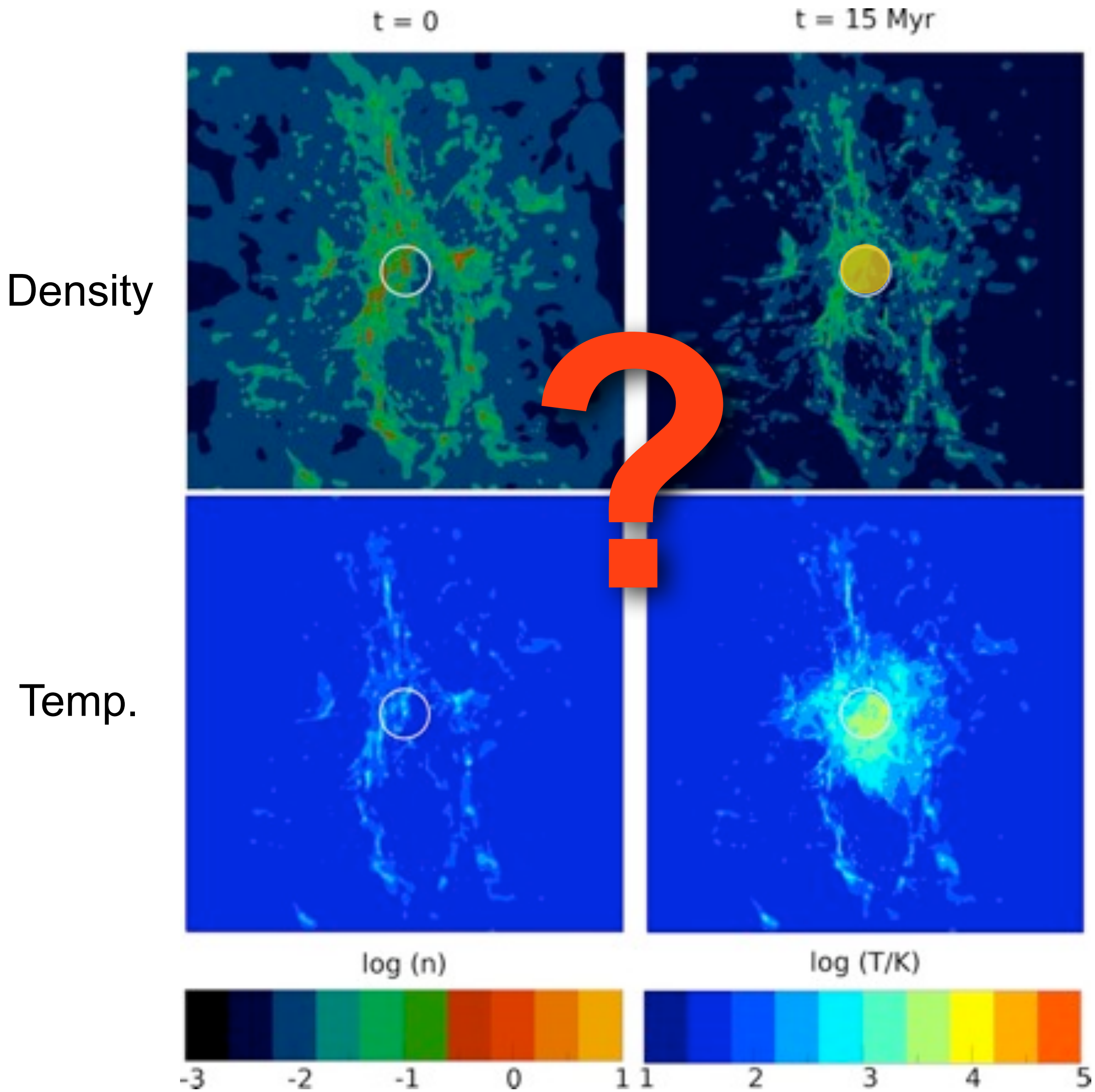

Magnetar

Chen+ 2015b to be submitted

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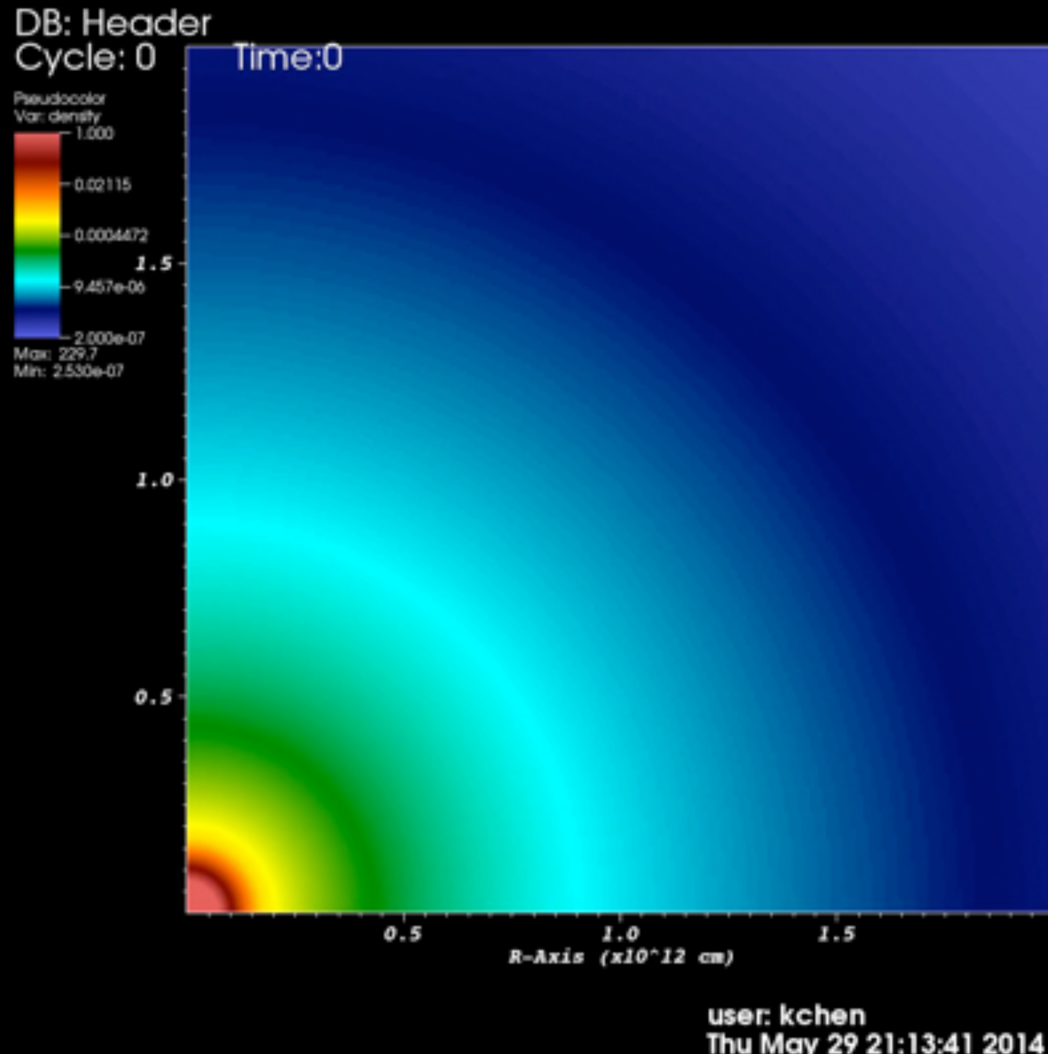

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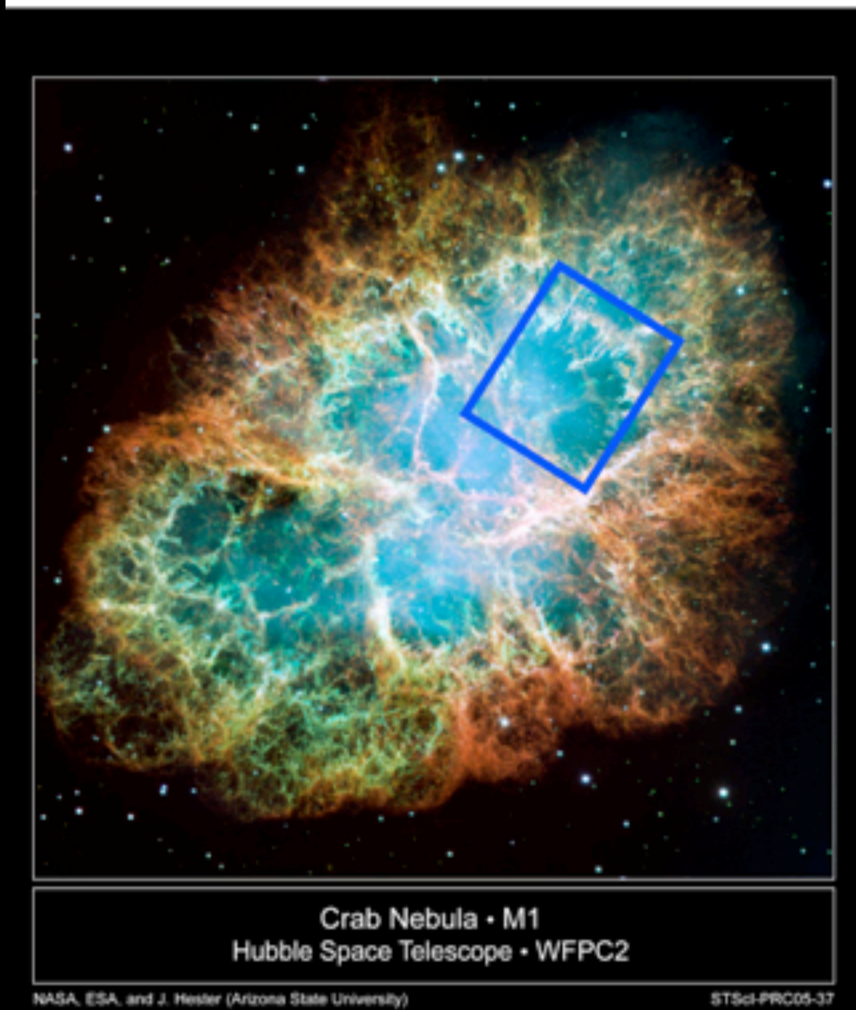

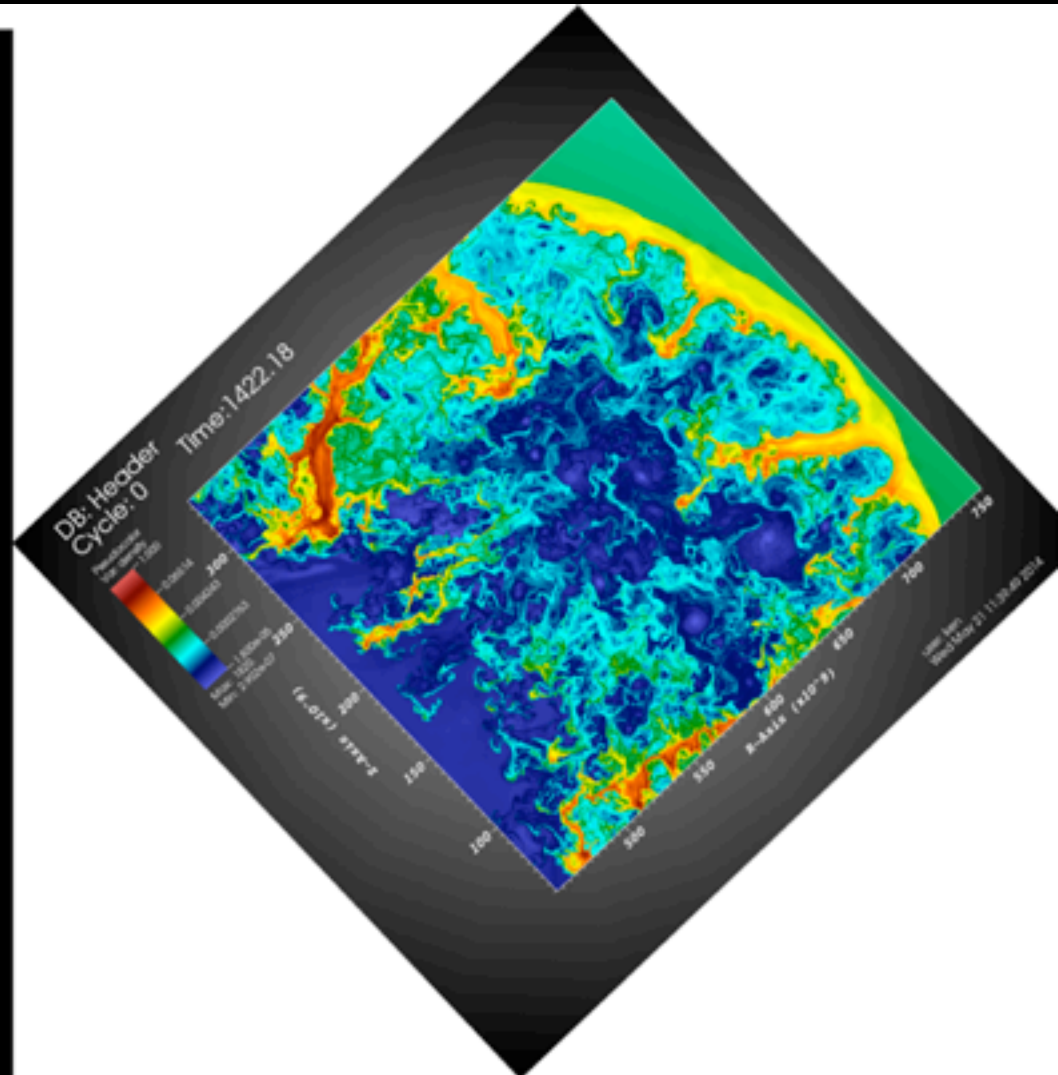

Hypernova and GRB !!!

Chen+ 2015c to be submitted

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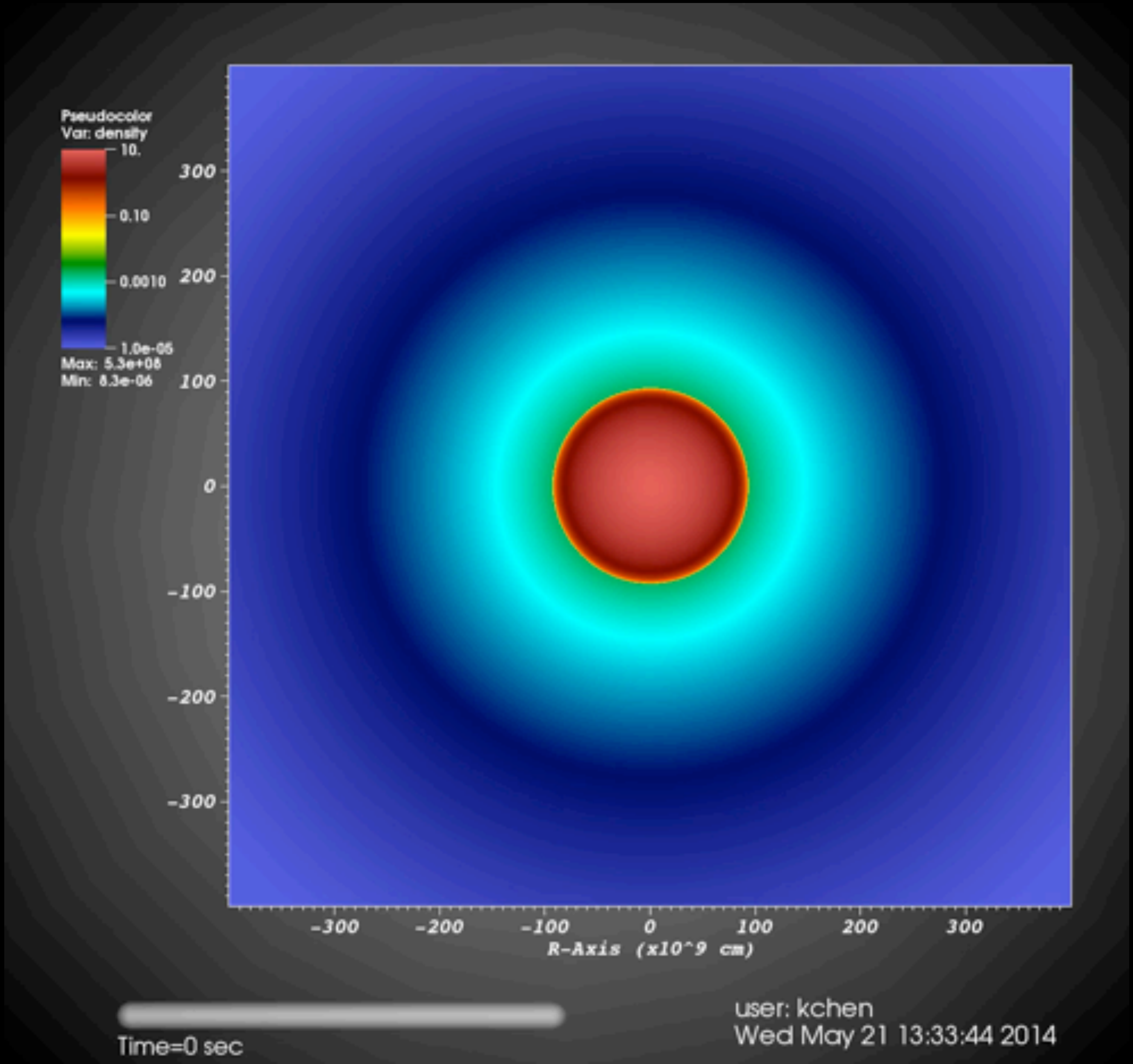
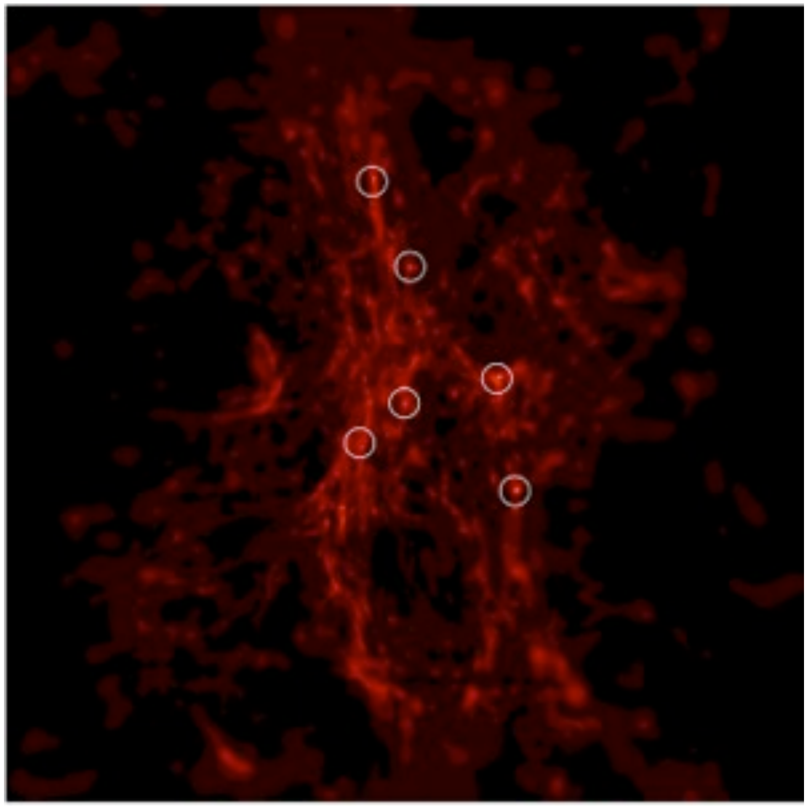
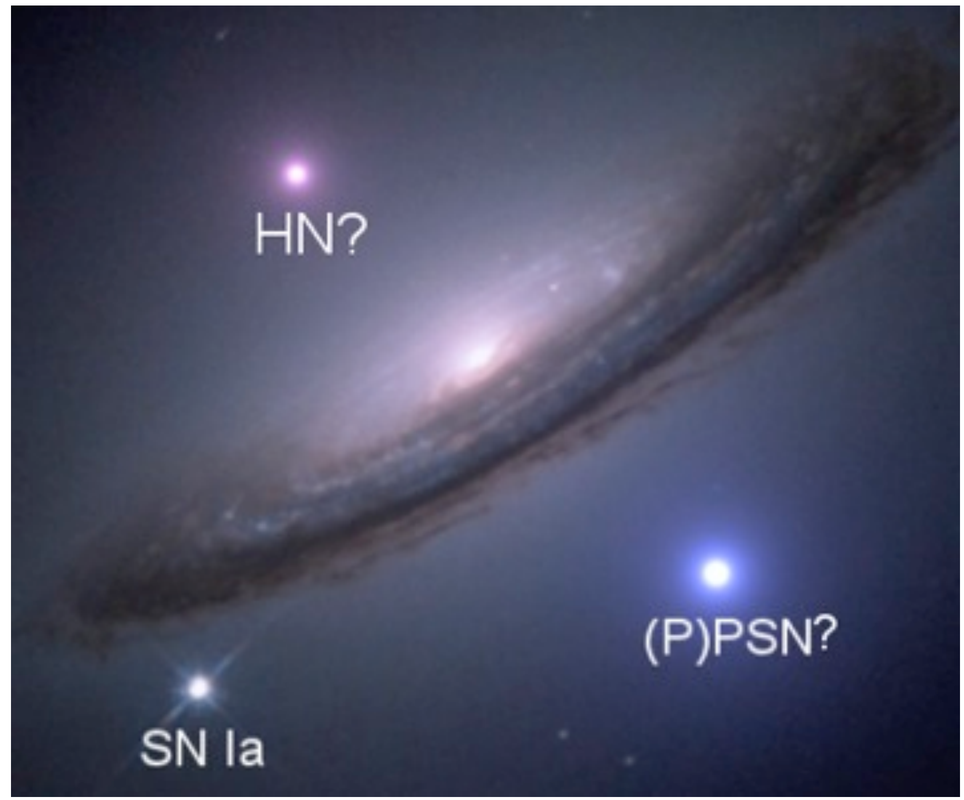


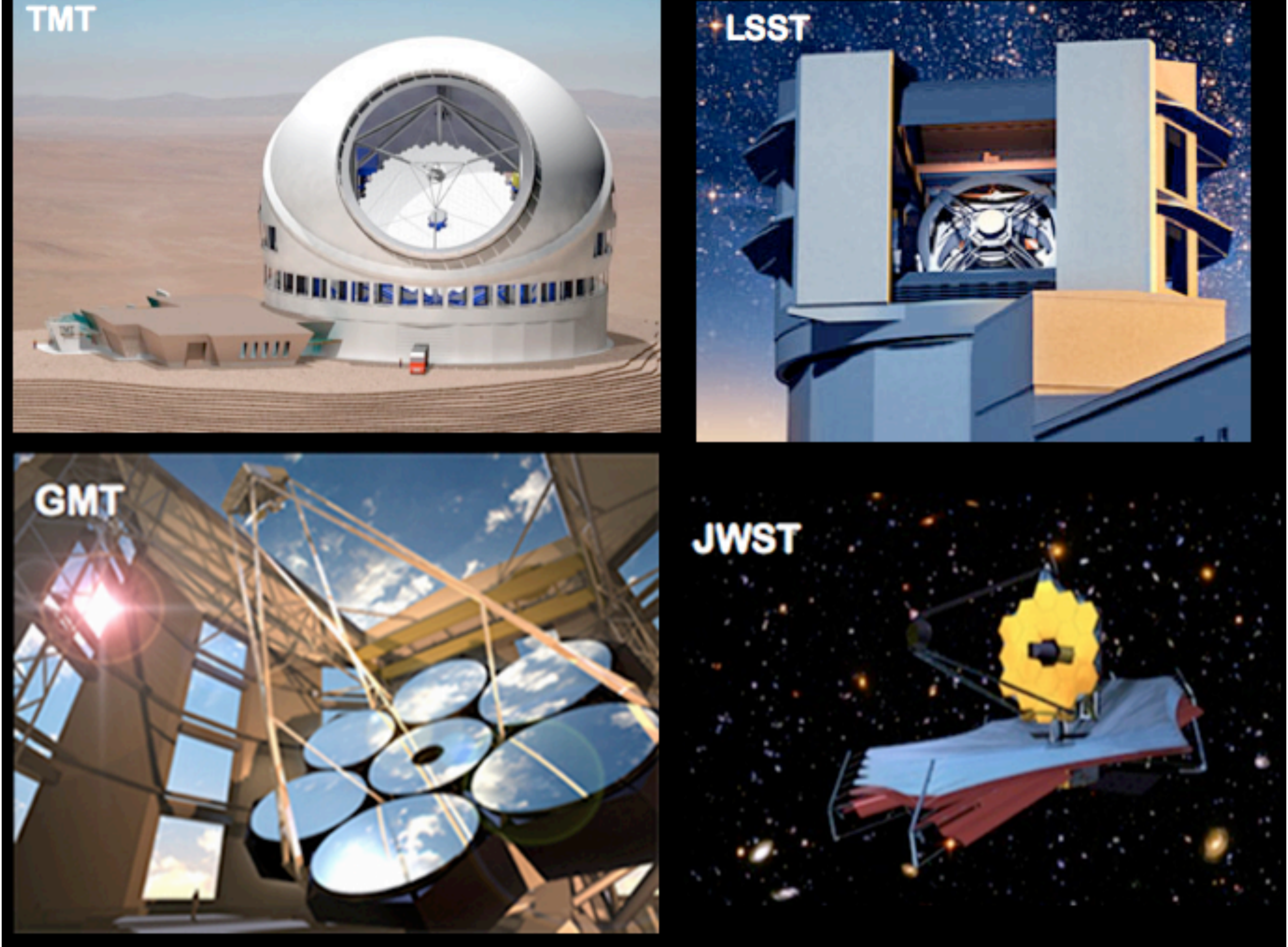
Work in progress with NERSC SC



The First Galaxies



SN Signatures


TMT
LSST
GMT
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Many thanks for your attention

My work has been kindly supported by:

GRUBER FOUNDATION

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U.S. Department of Energy

NERSC

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Scientific Discovery through Advanced Computing

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The Kavli Institute for Theoretical Physics
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