

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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Monash University



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UC Santa Cruz



Volker Bromm
UT-Austin



Ann Almgren
Lawrence Berkeley National Lab



Daniel Kasen
UC Berkeley



Weiqun Zhang
Lawrence Berkeley National Lab

Kill Darkness?



Kill Darkness?

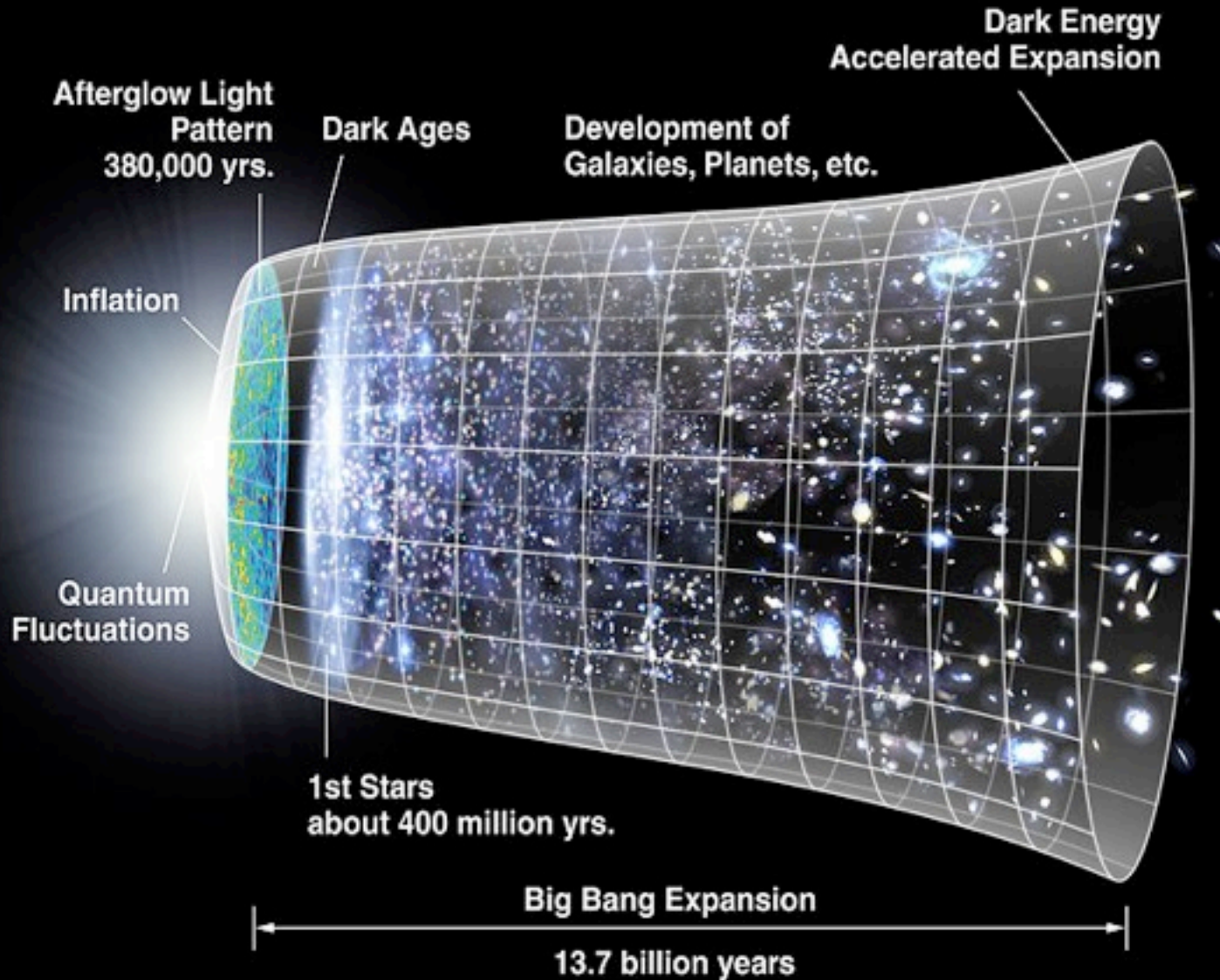


Light !!

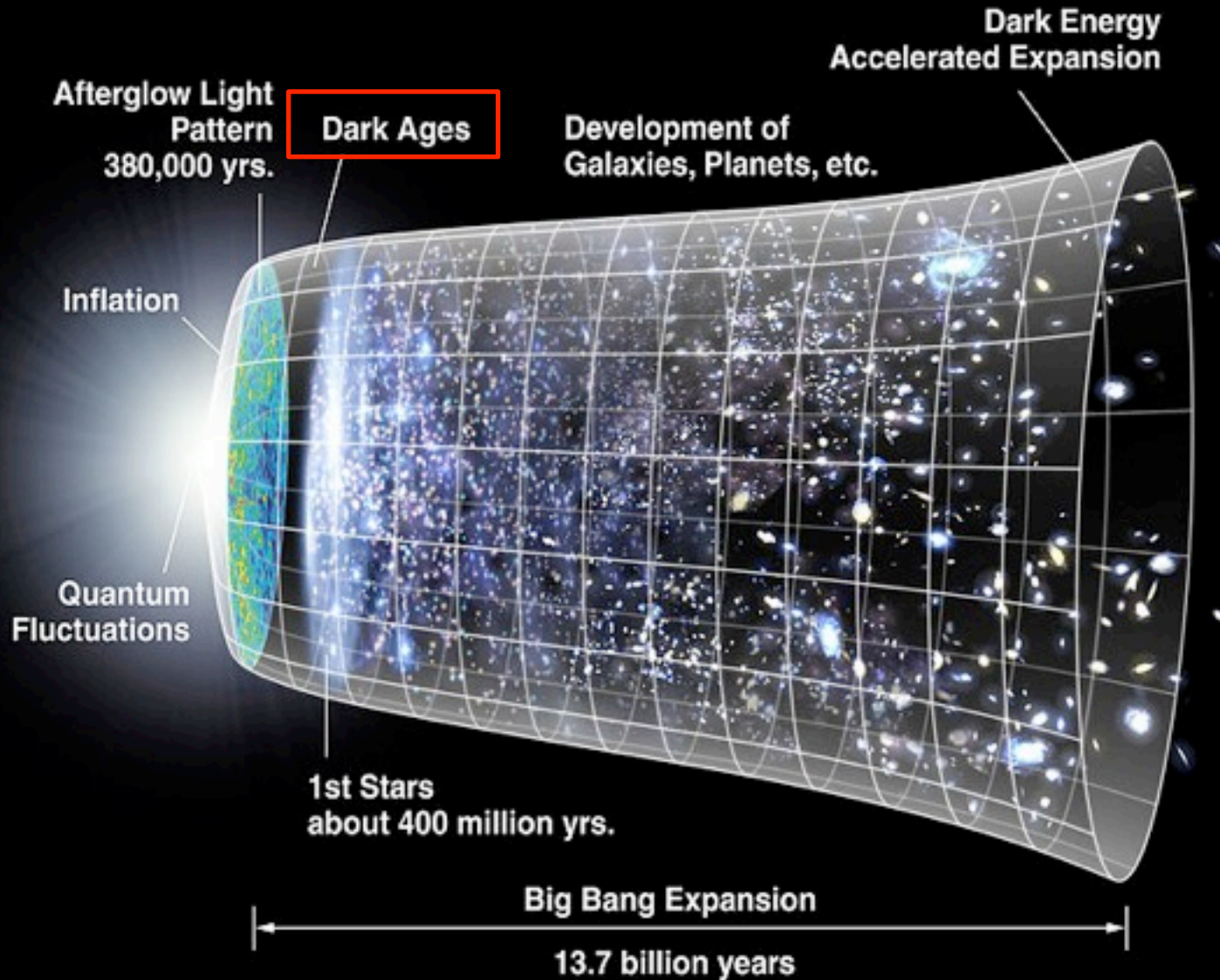
Kill Darkness?



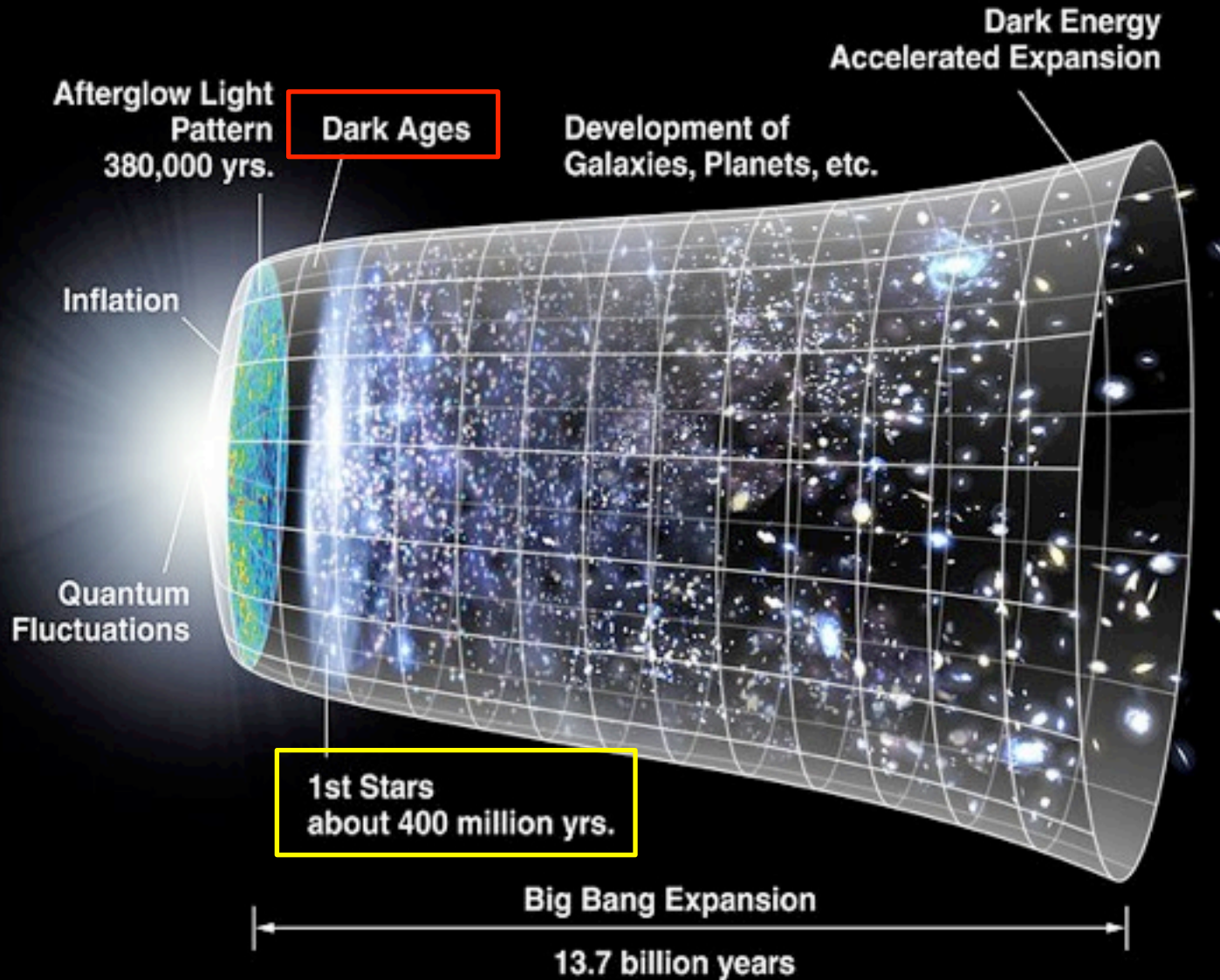
History of Universe



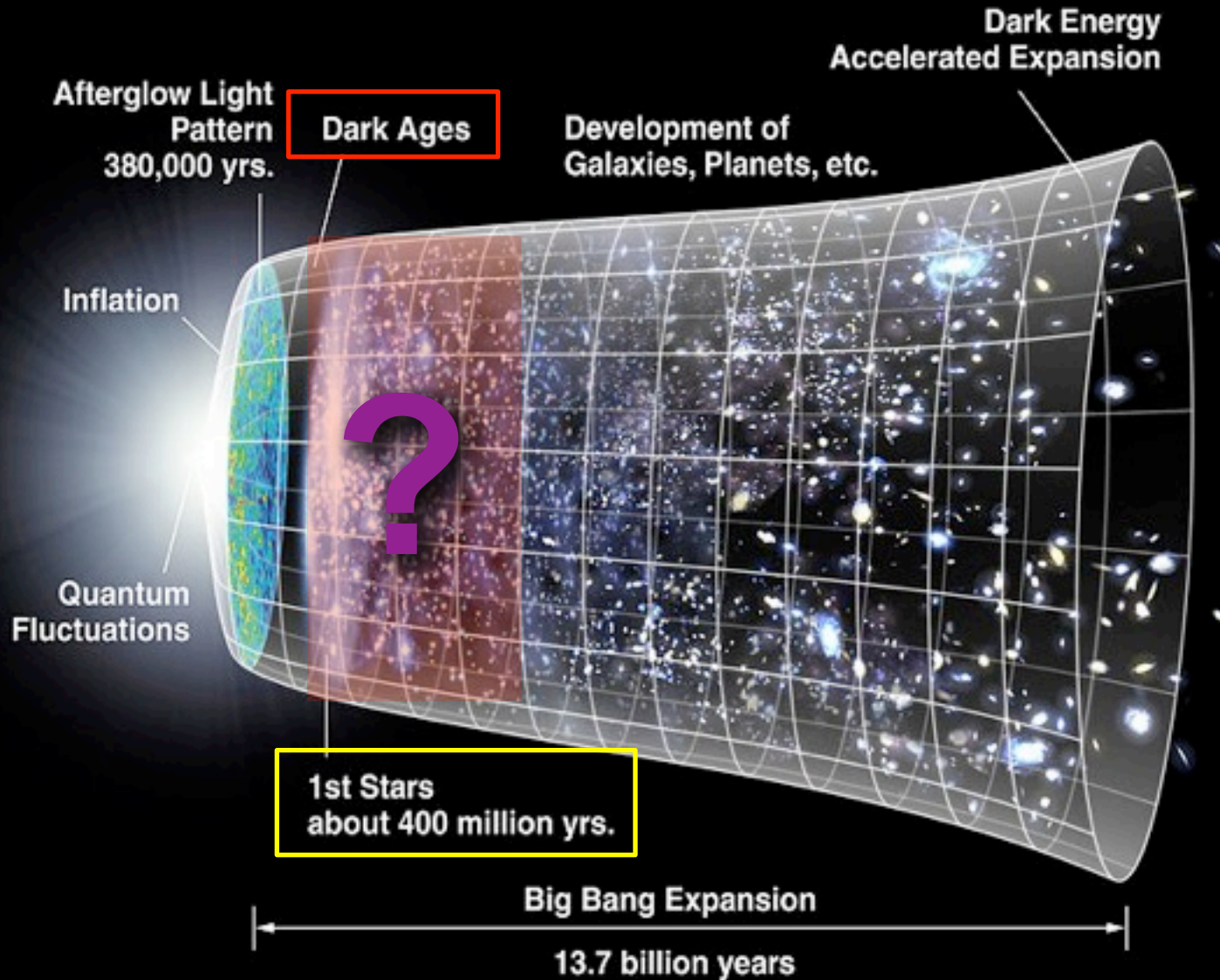
History of Universe



History of Universe



History of Universe



History of Universe

Hubble Probes the Early Universe

?

1990

Ground-based observatories

1995

Hubble Deep Field

2004

Hubble Ultra Deep Field

2010

Hubble Ultra Deep Field-IR

FUTURE

James Webb Space Telescope

Redshift (z):

Time after
the Big Bang

Present

1

6
billion
years

4

1.5
billion
years

5

6

7

800
million
years

8

10

480
million
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>20

200
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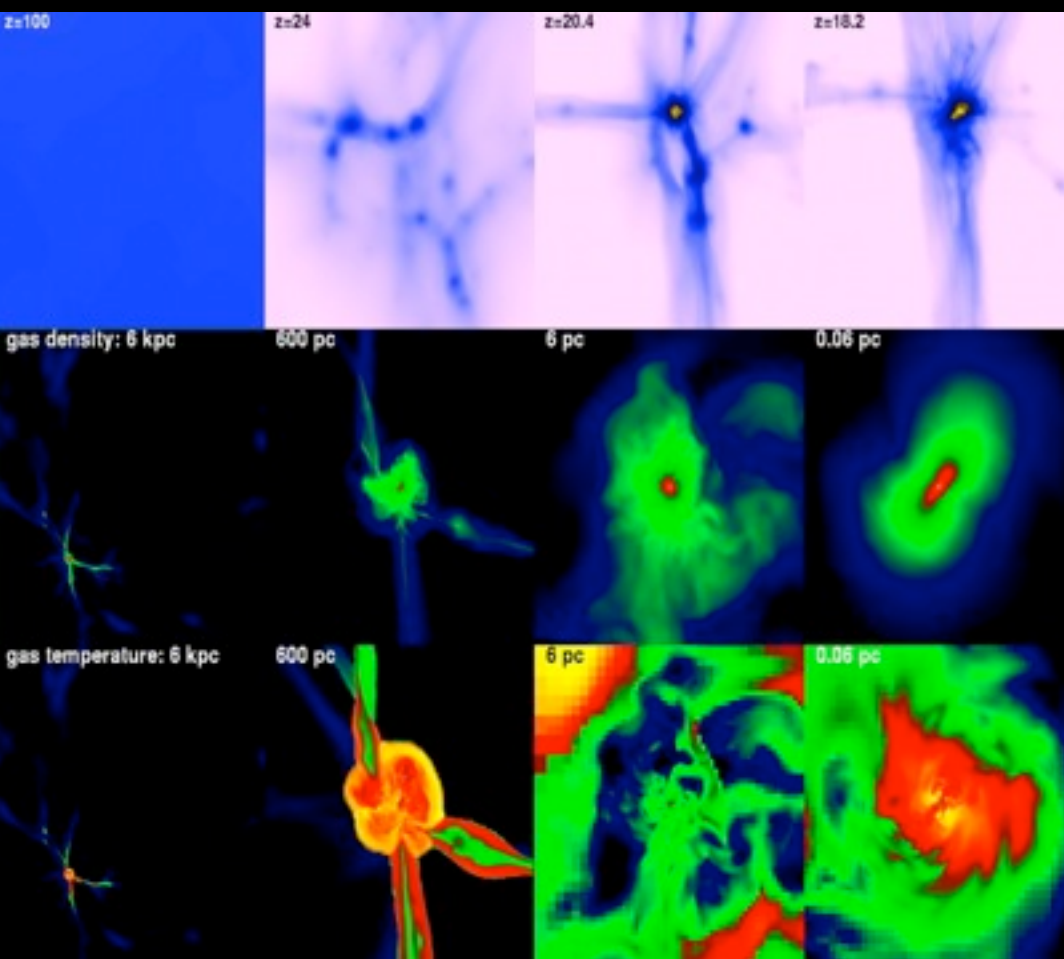
10

480
million
years

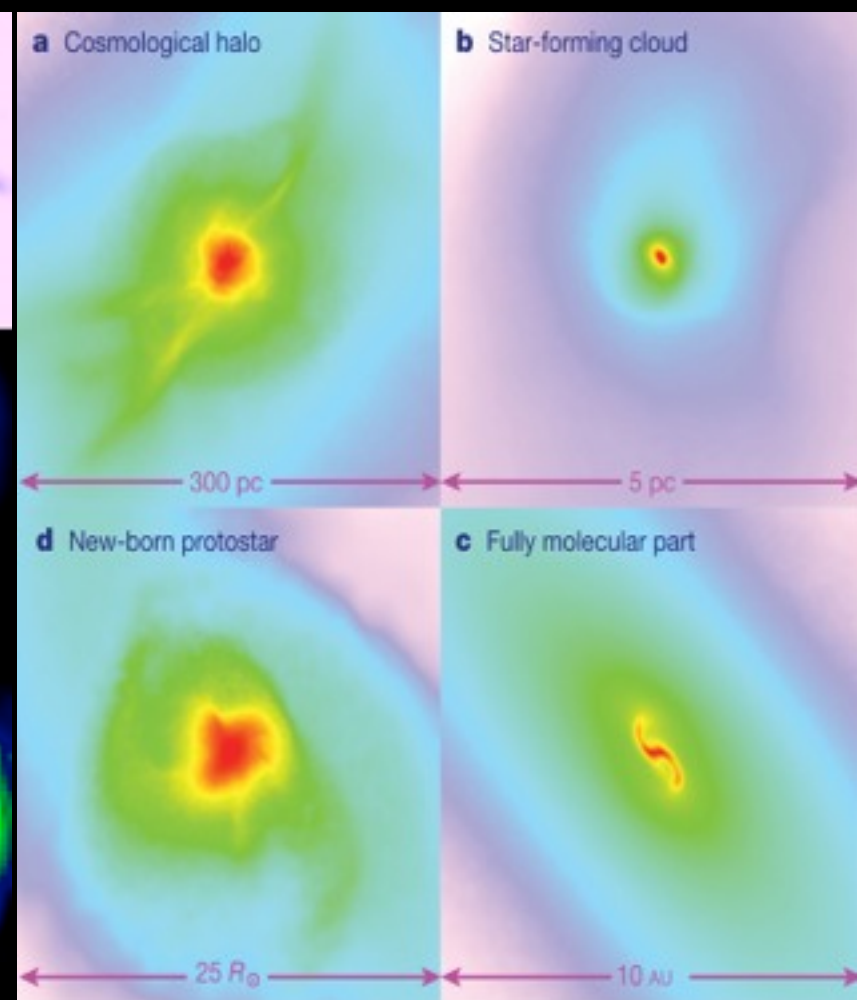
>20

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The First Stars

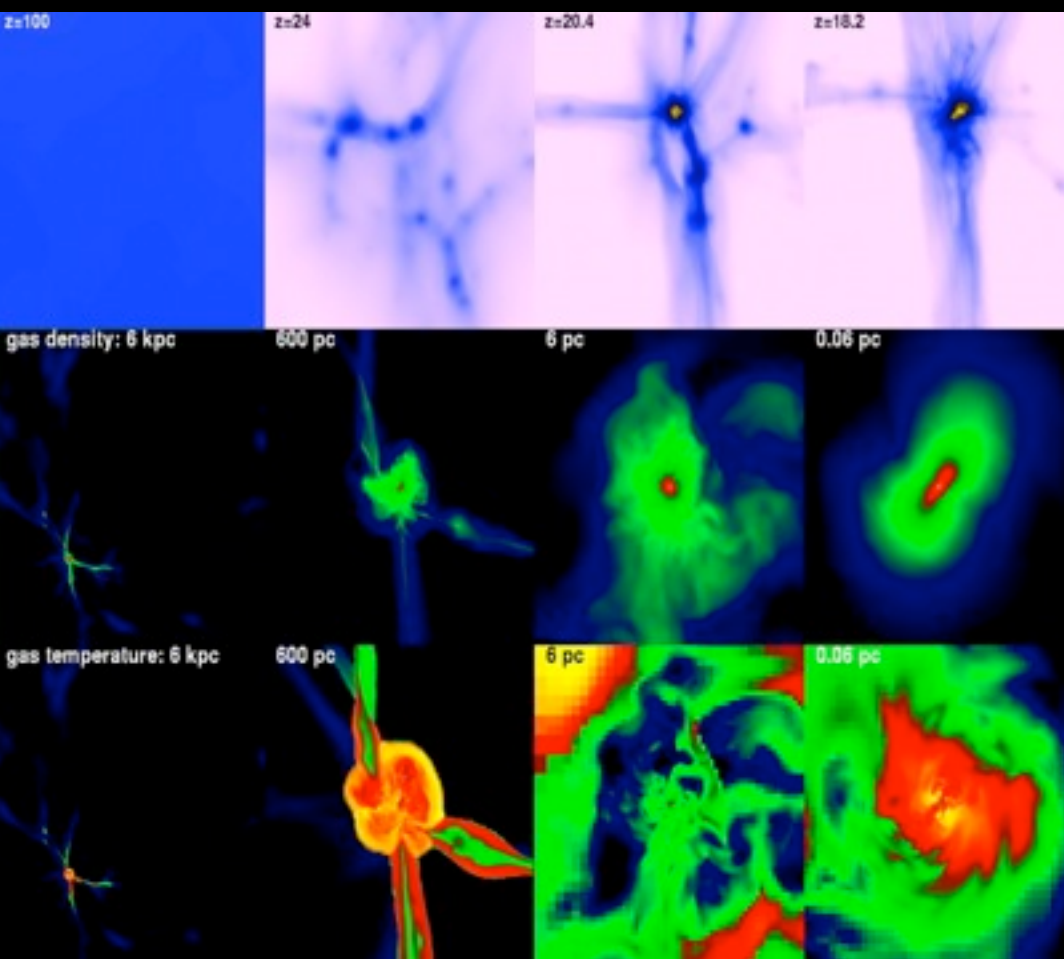


Abel, et al. Science (2002)

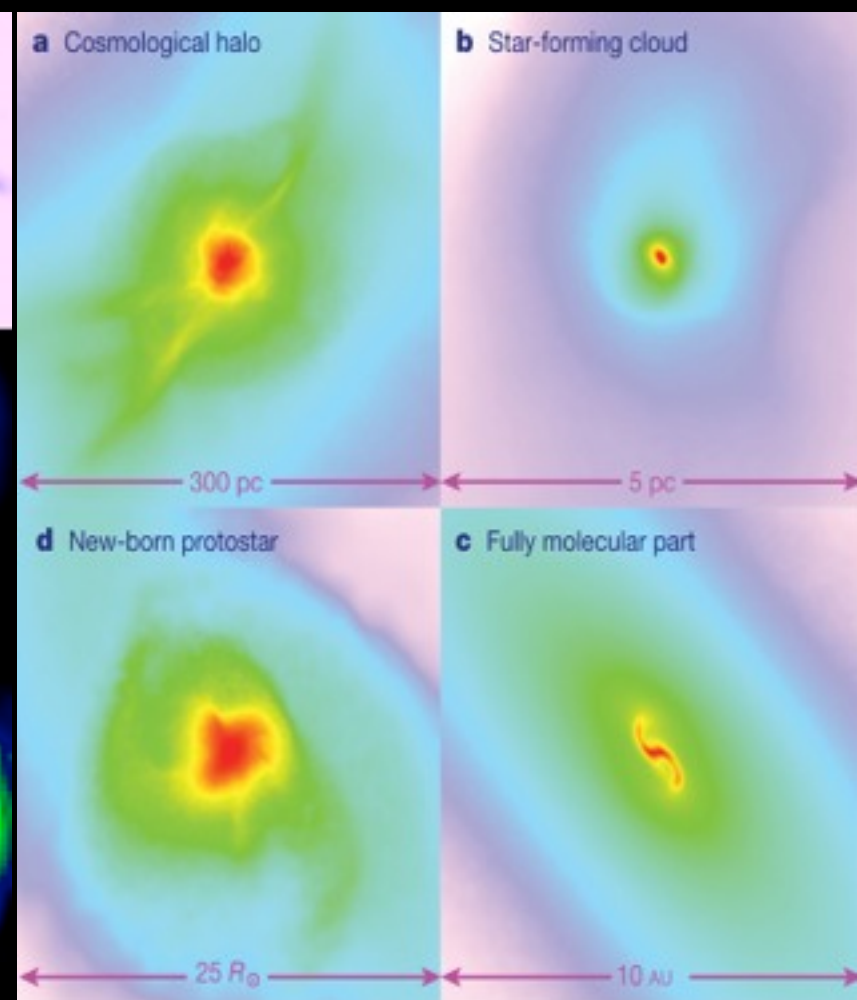


Bromm, et al. Nature (2009)

The First Stars



Abel, et al. Science (2002)



Bromm, et al. Nature (2009)

Mass Scale $\sim 100 M_{\odot}$

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 ☉

The Death of Massive Stars

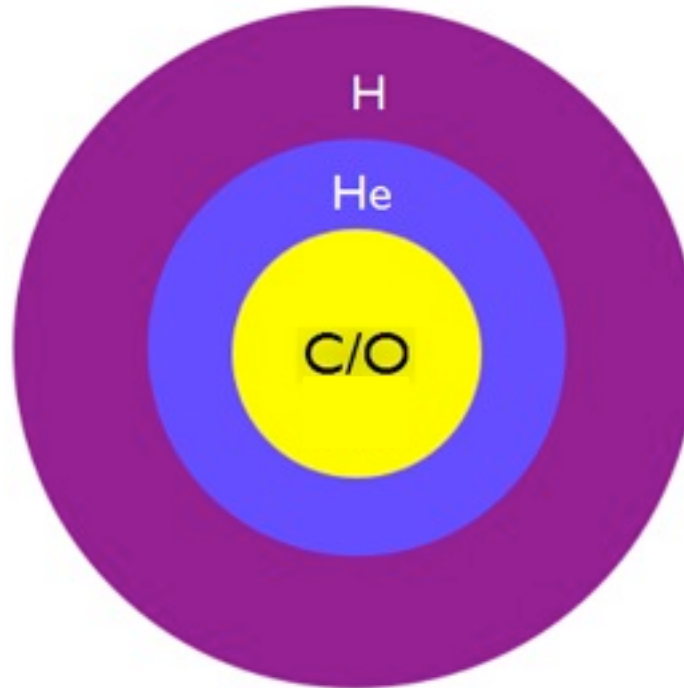
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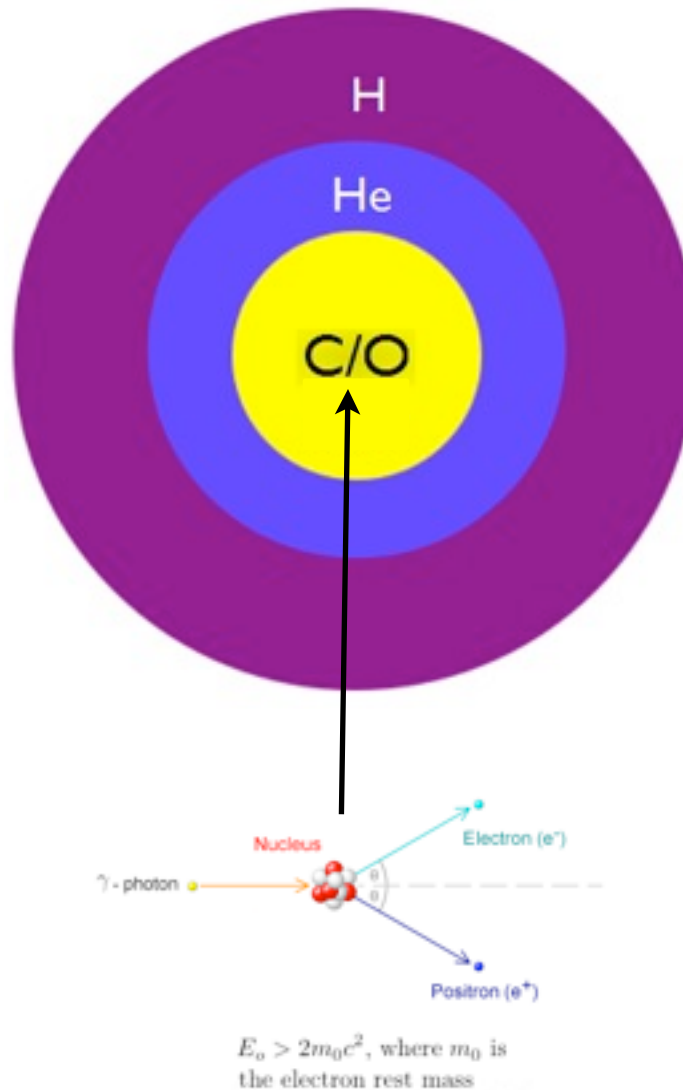
Fate of Very Massive Stars

Star $> 80 M_{\odot}$



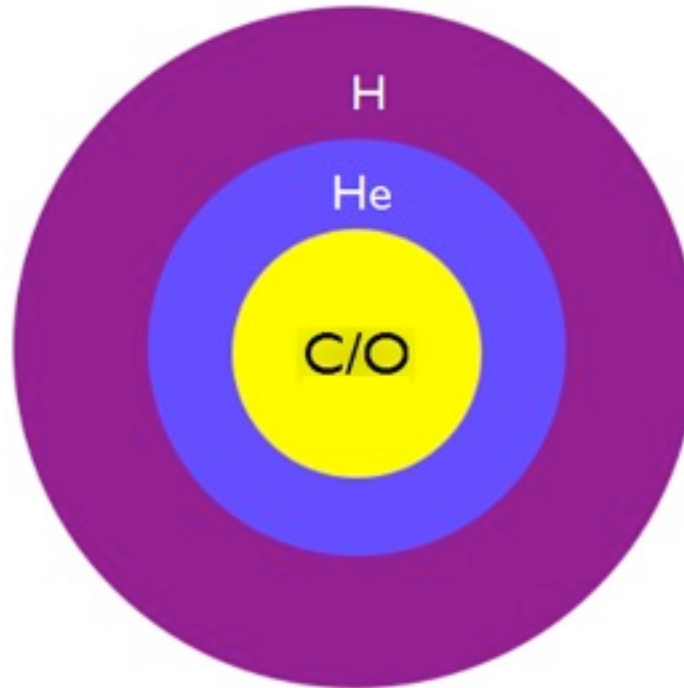
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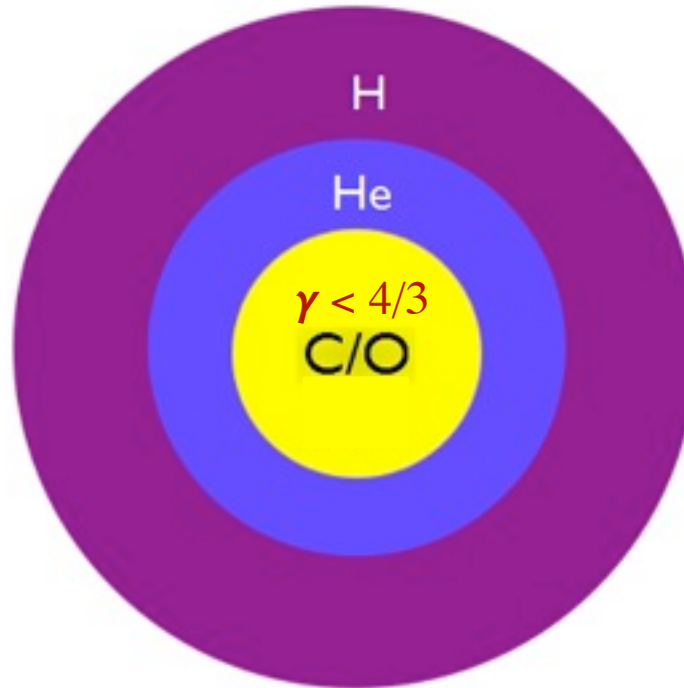
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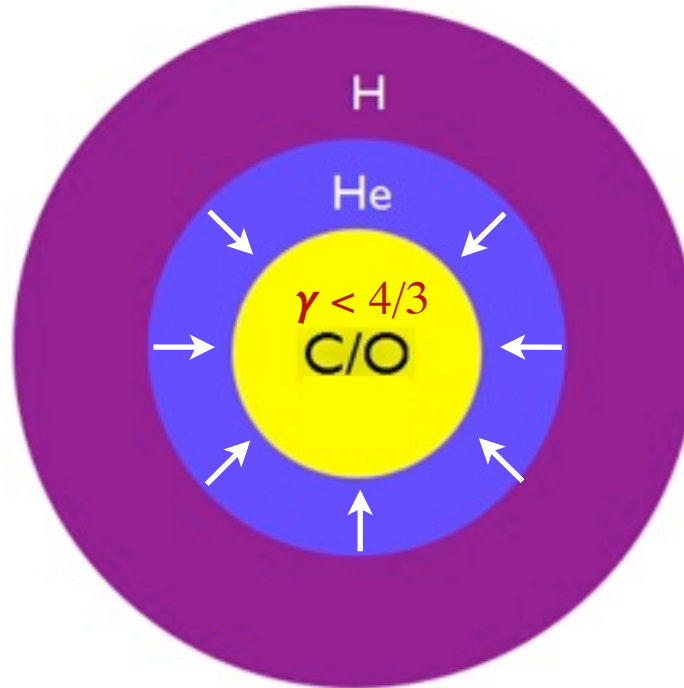
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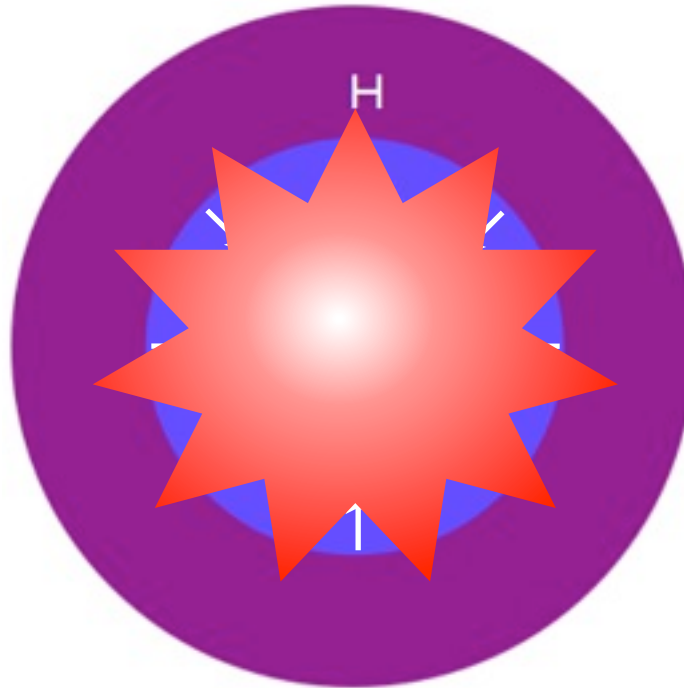
Fate of Very Massive Stars

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Fate of Very Massive Stars

Star $> 80 M_{\odot}$



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 $M_{\odot}$ Stars (Woosley+ 2007, priv. comm.)

150 - 250 $M_{\odot}$ 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

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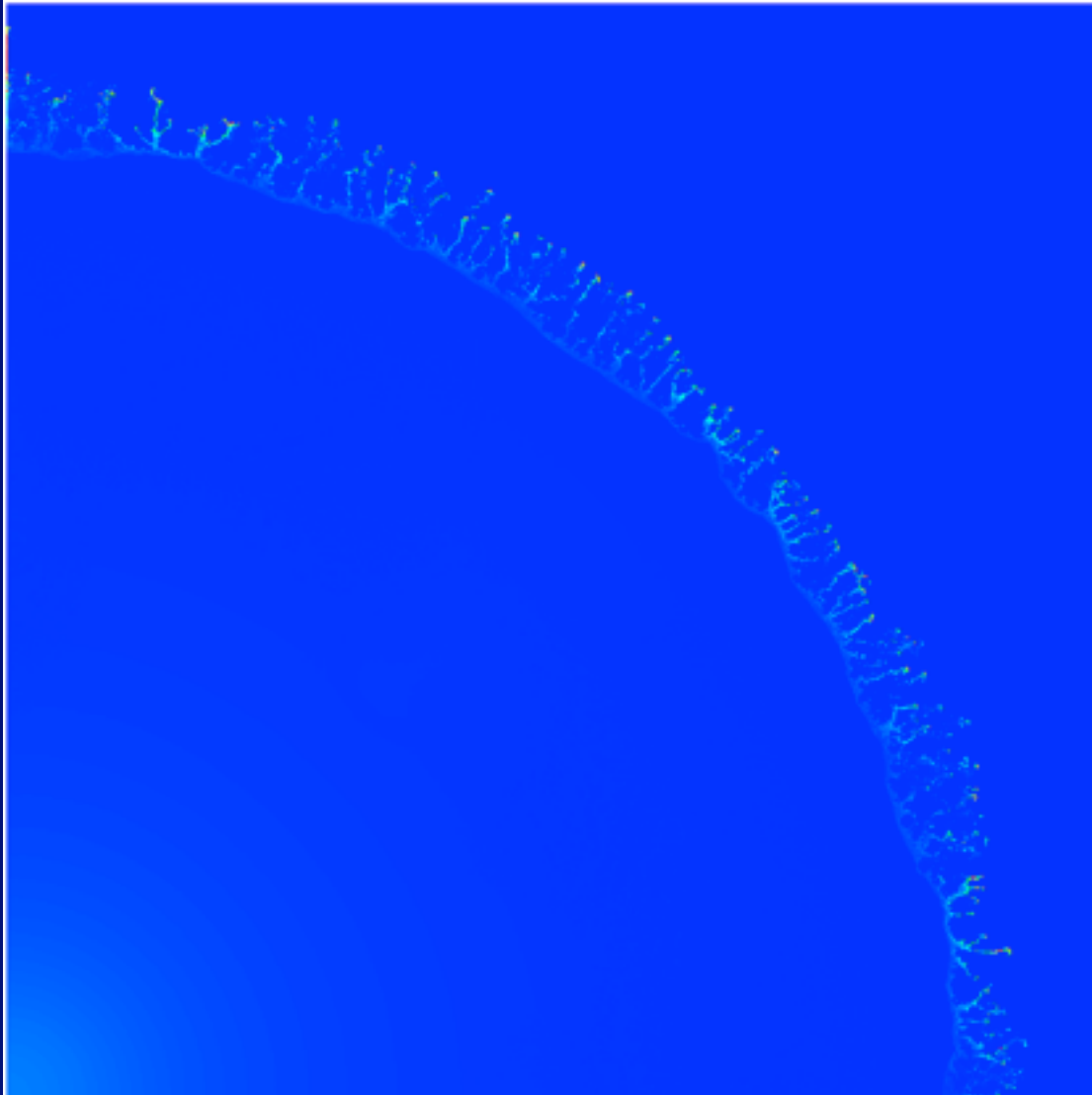
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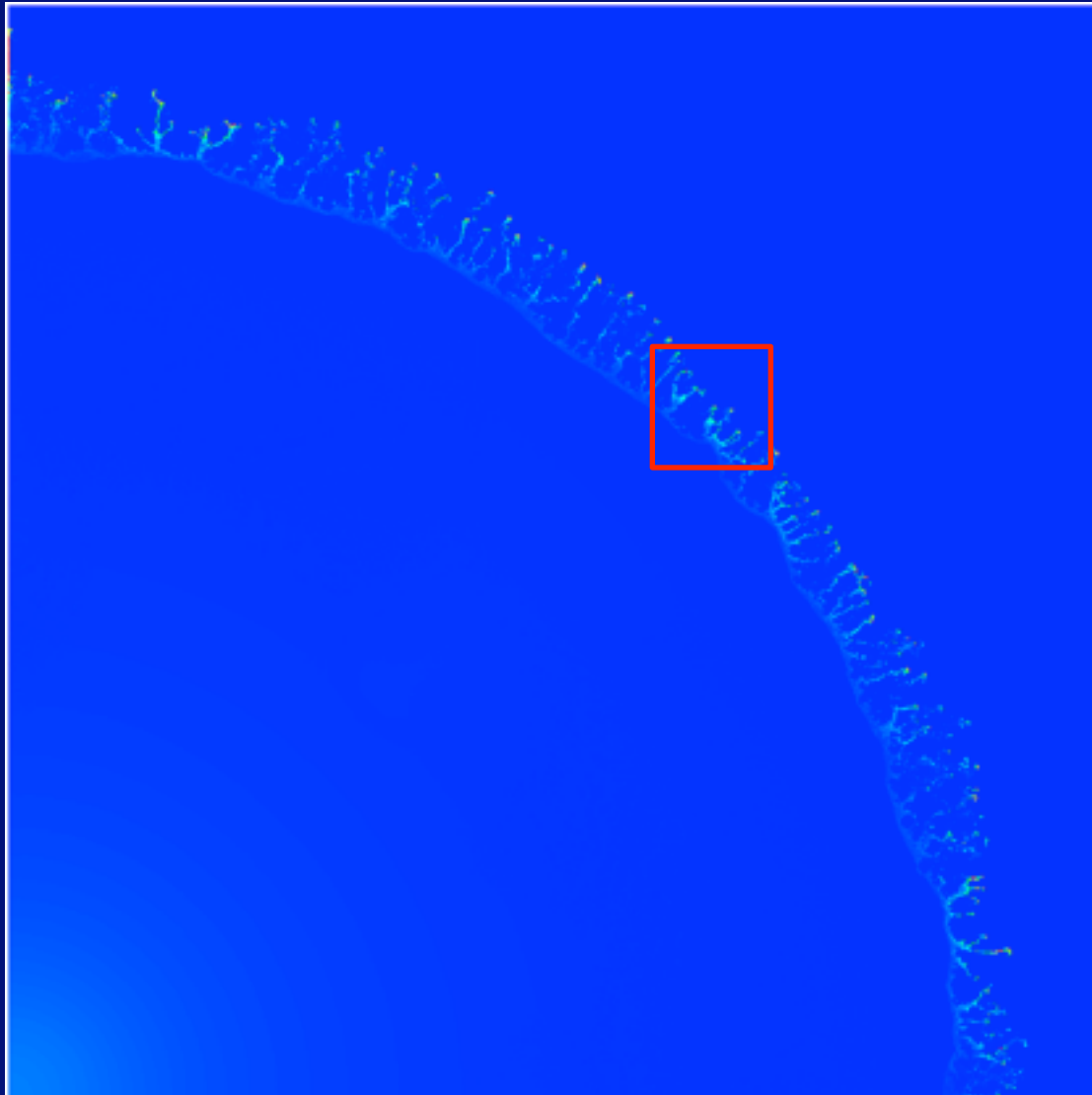
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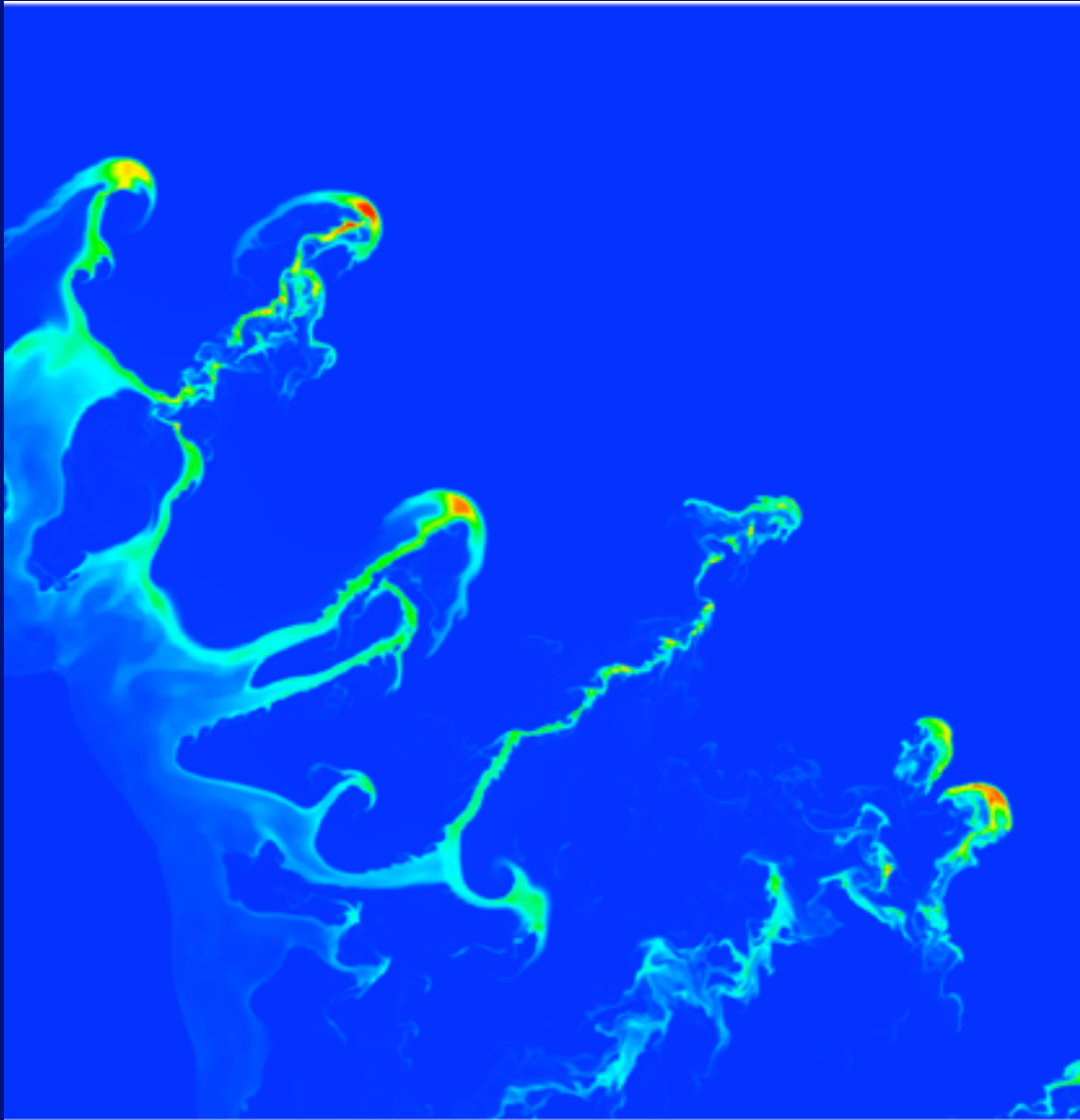
2D Resolution of CASTRO



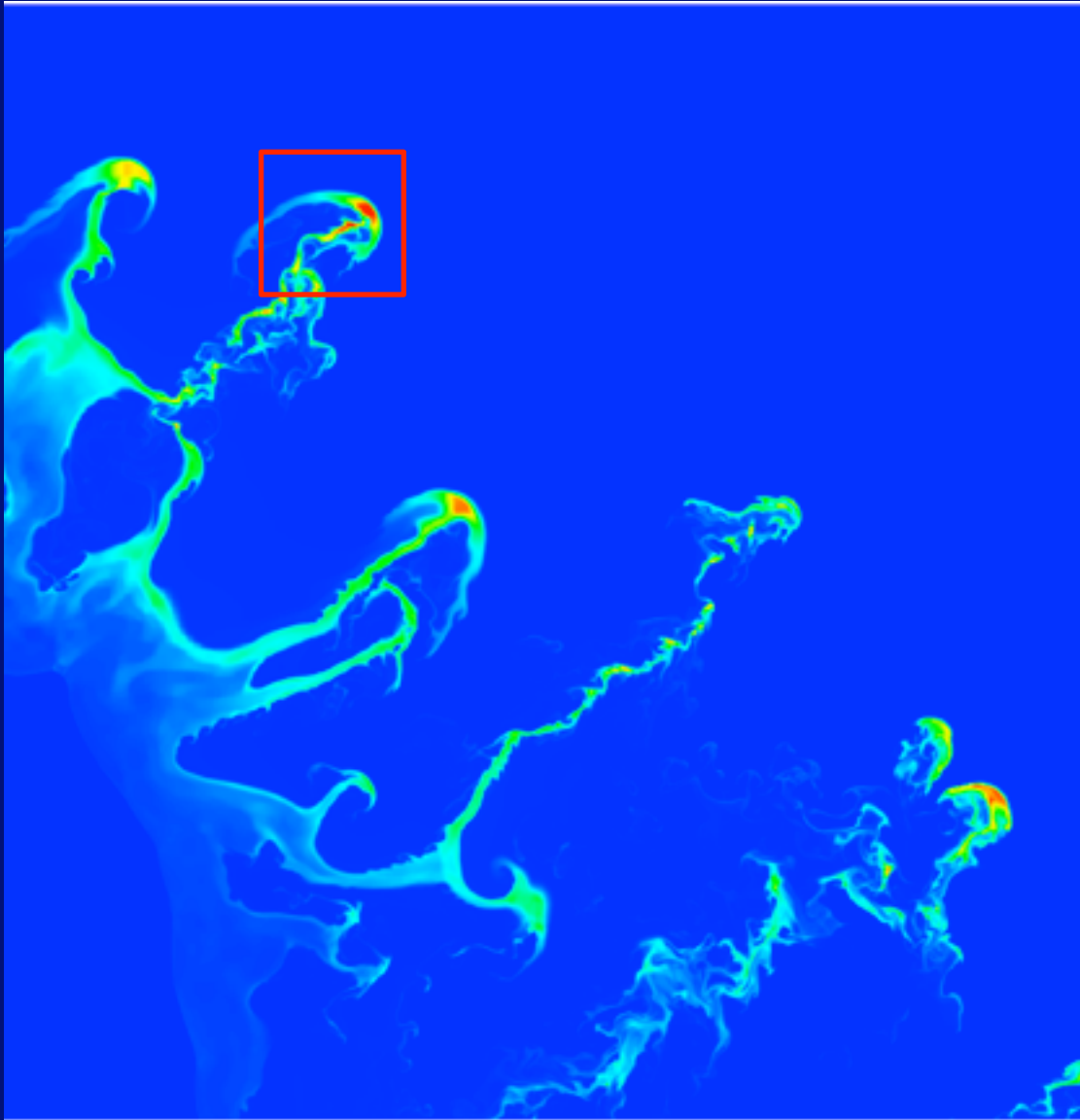
2D Resolution of CASTRO



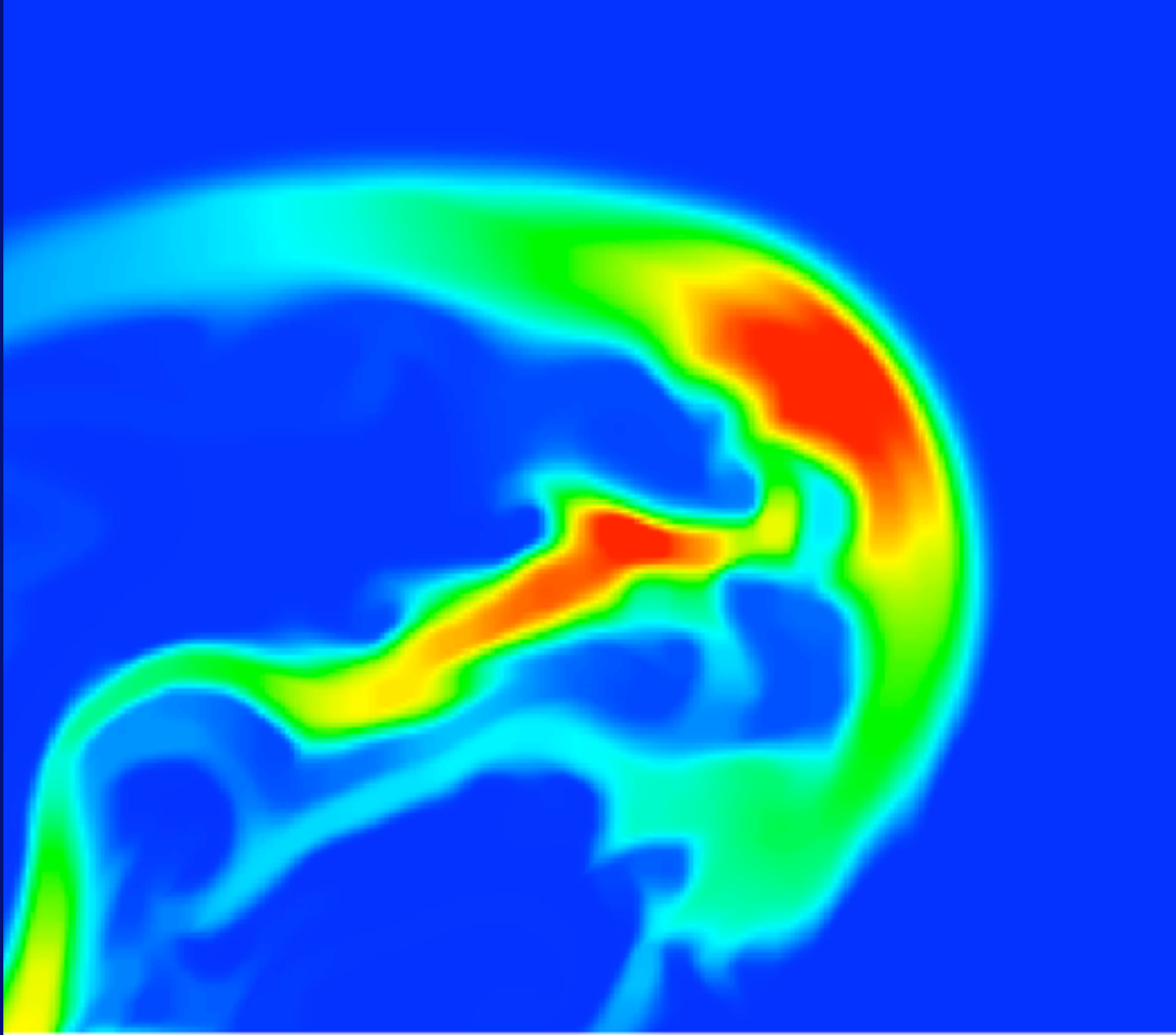
2D Resolution of CASTRO



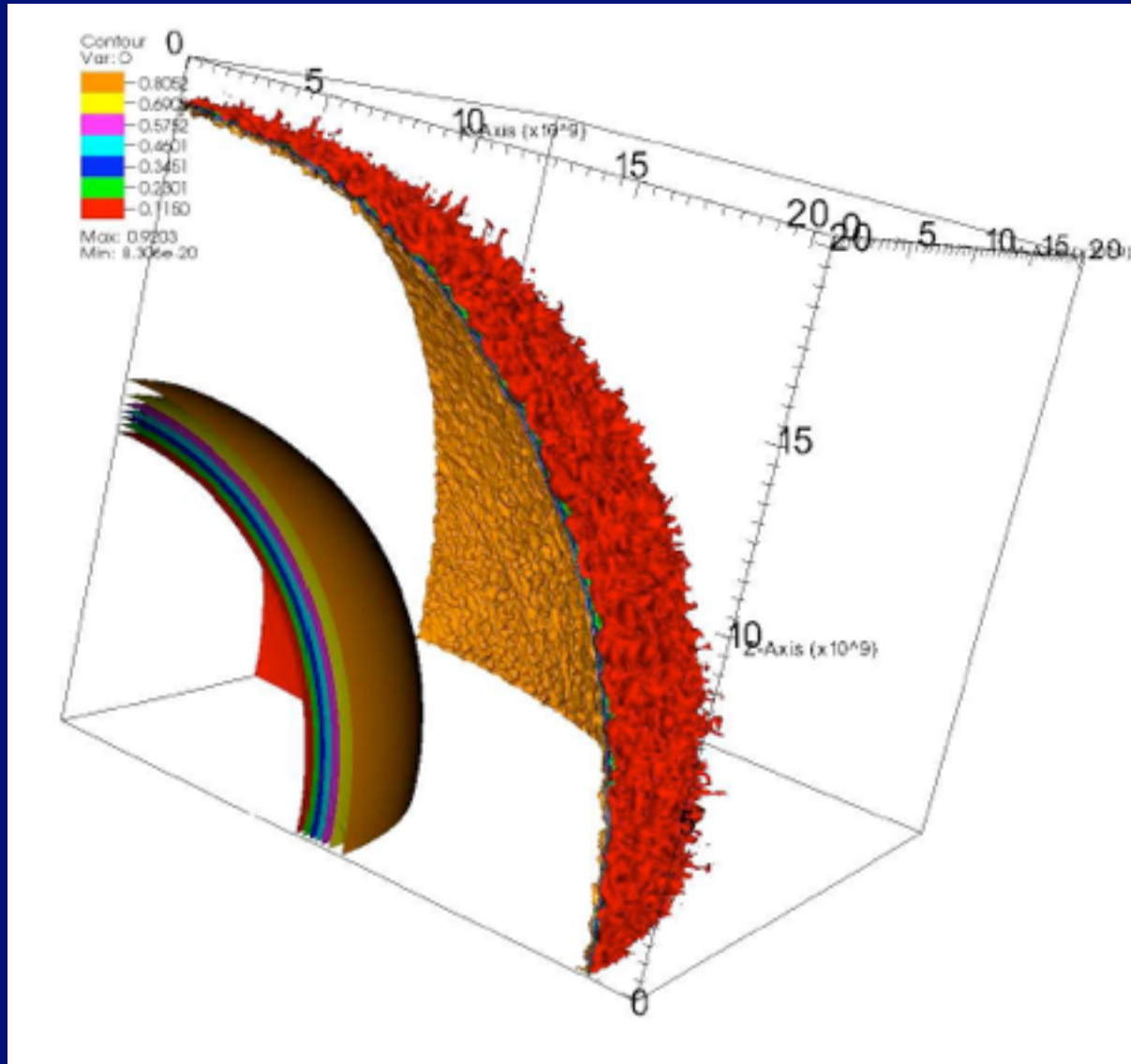
2D Resolution of CASTRO



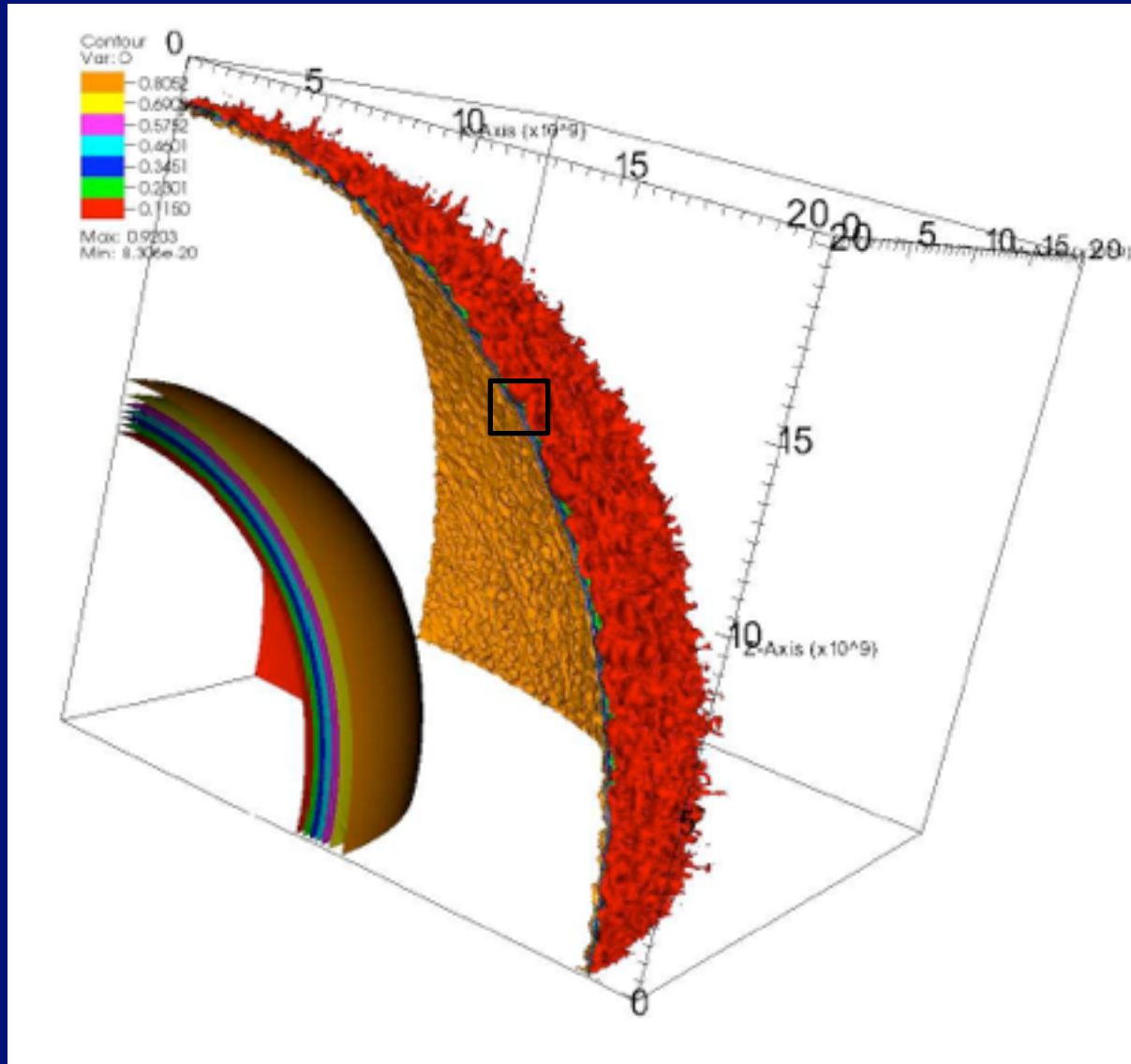
2D Resolution of CASTRO



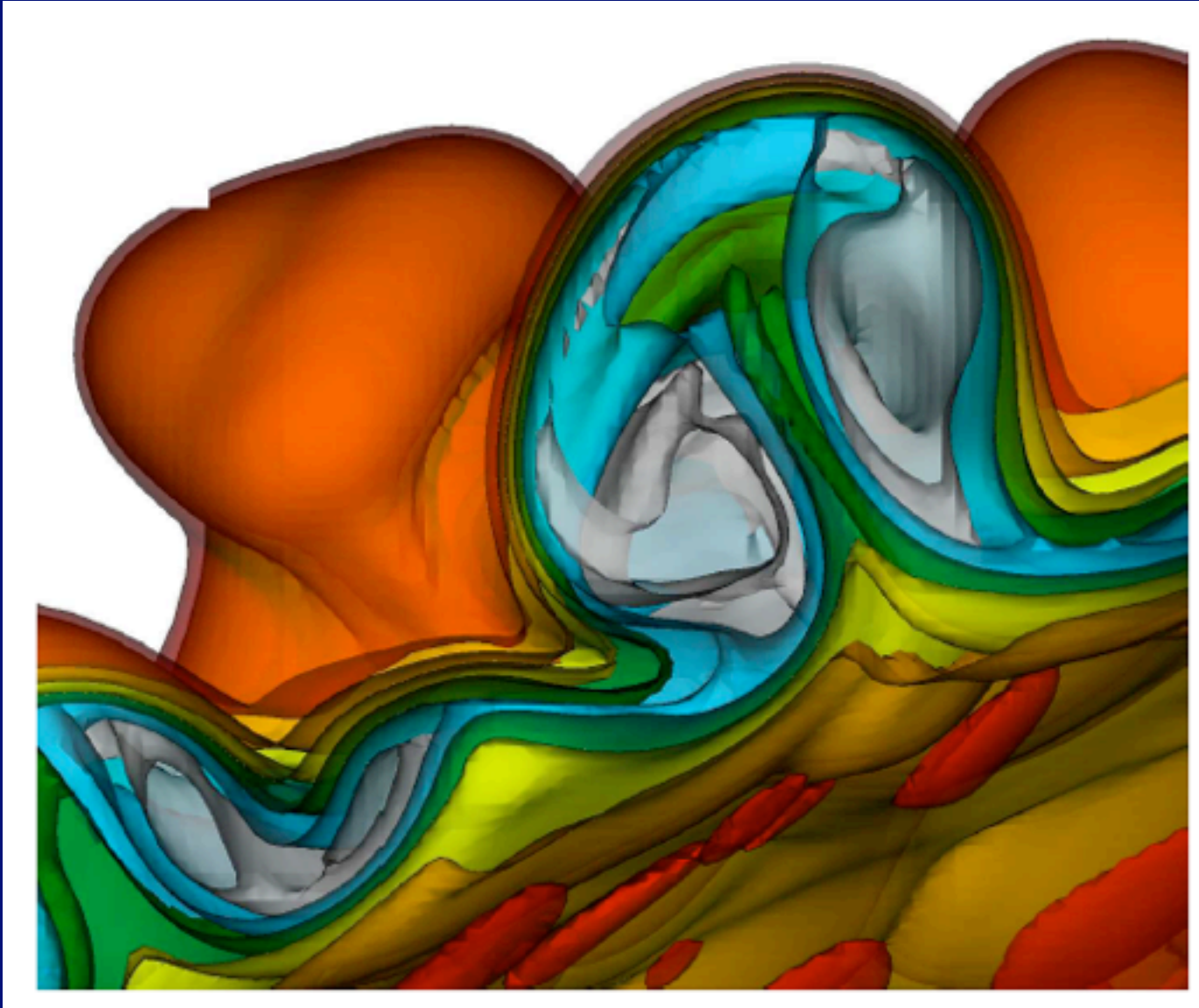
3D Resolution of CASTRO !



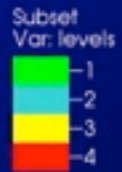
3D Resolution of CASTRO !



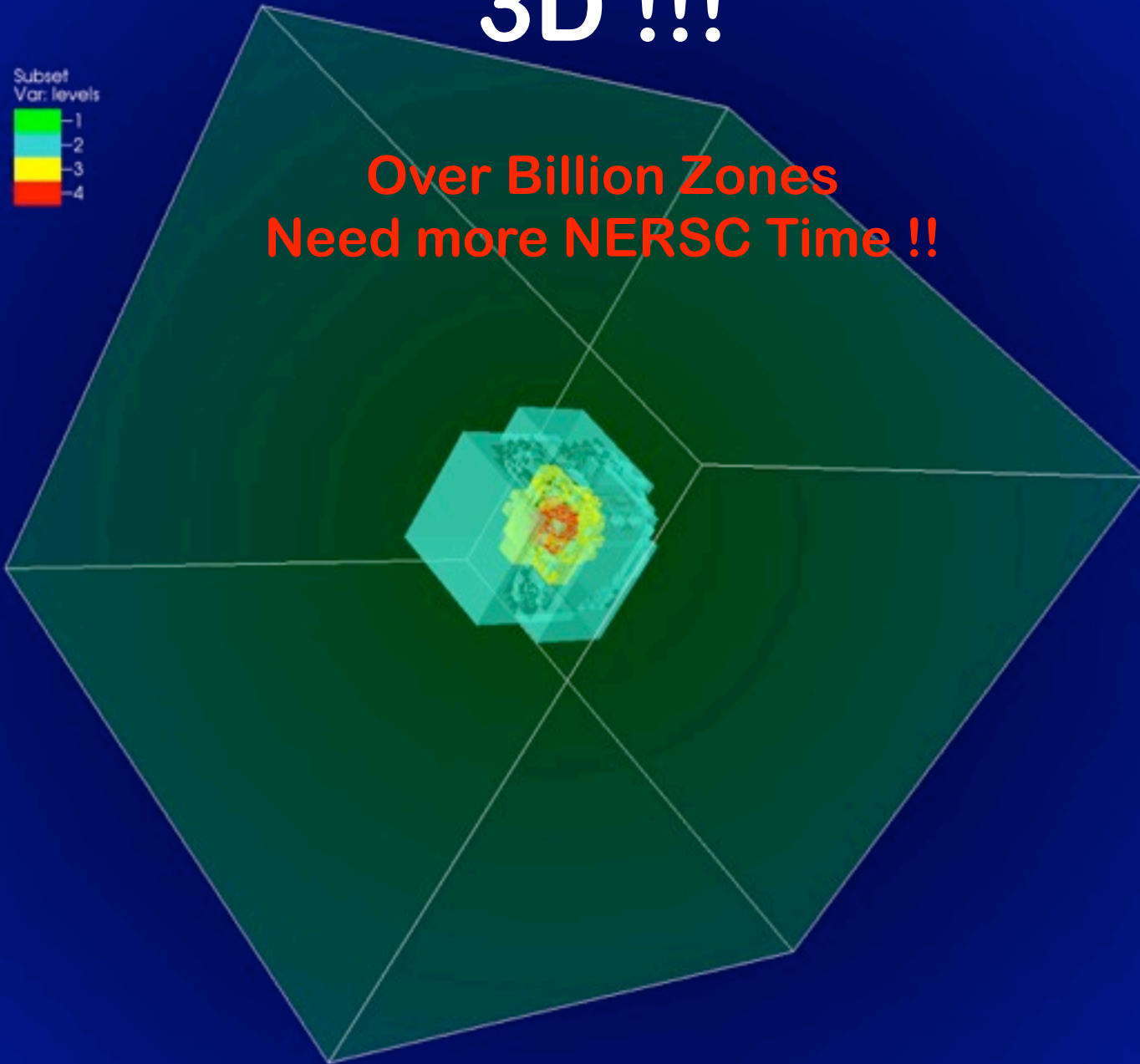
3D Resolution of CASTRO !



3D !!!

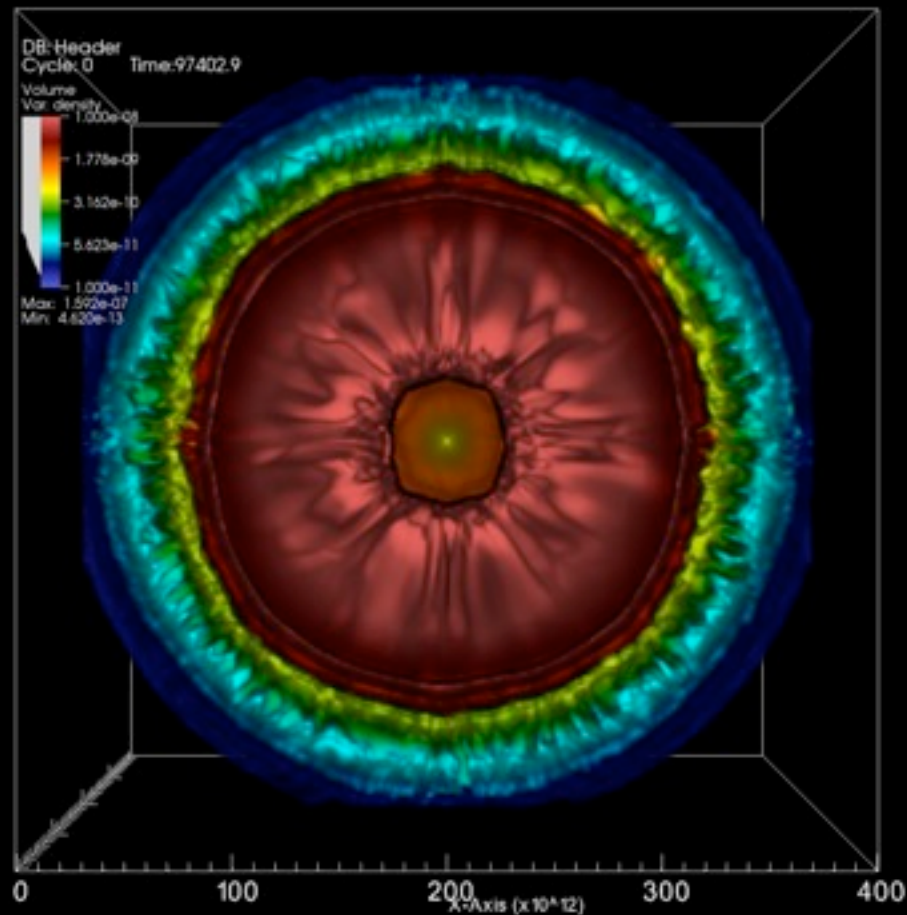


Over Billion Zones
Need more NERSC Time !!



Pulsational Pair-Instability Supernovae (PPSNe)

$$150 M_{\odot} > M^* > 80 M_{\odot}$$



Chen+ ApJ 792 28 (2014a)

Core of 110 $M_{\odot}$ star

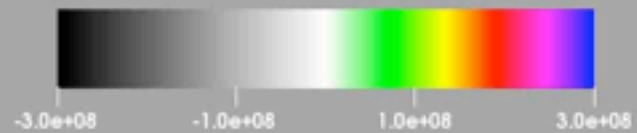
s

(cm/s)

Core of 110 $M_{\odot}$ star

Time=0

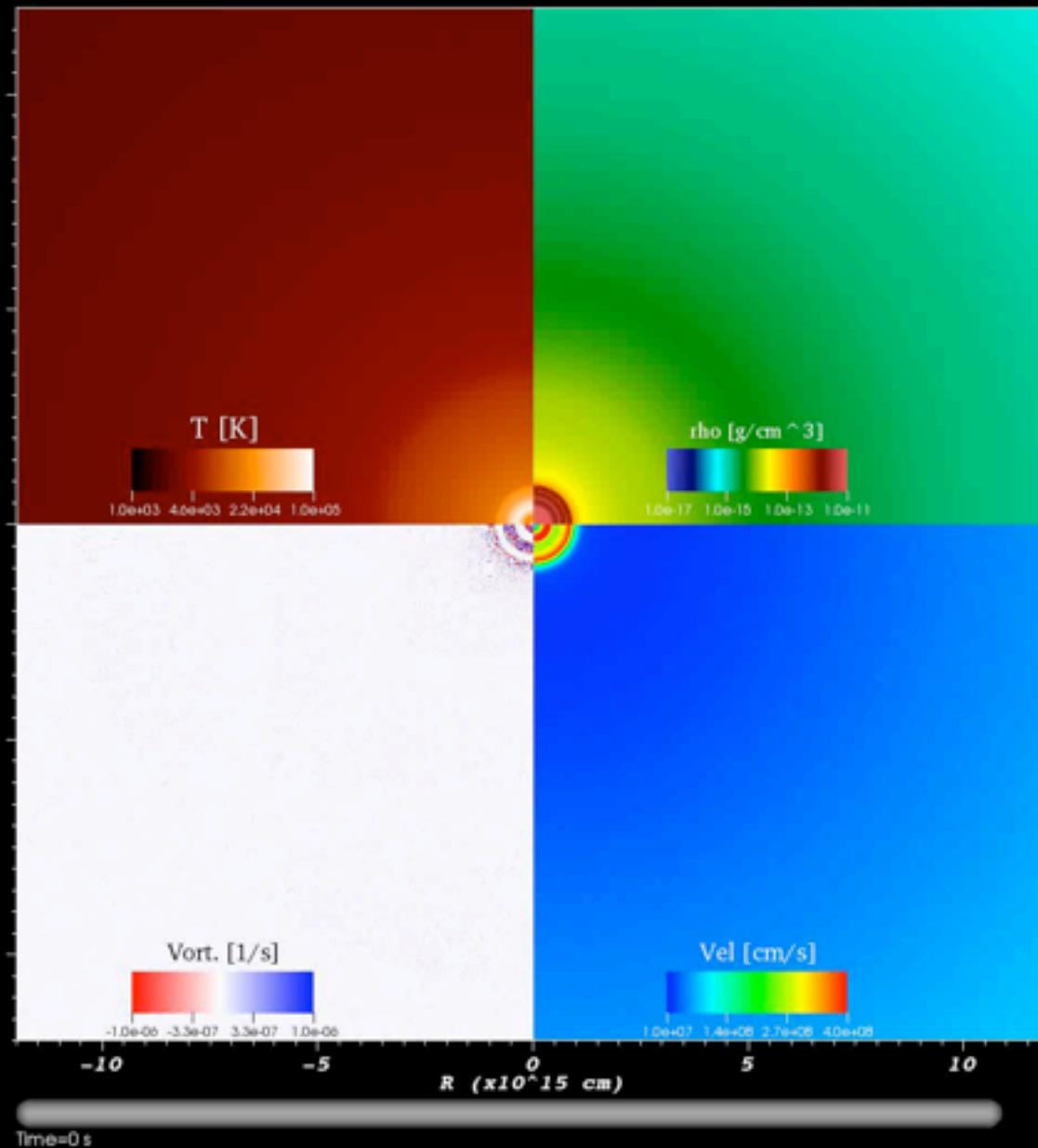
s



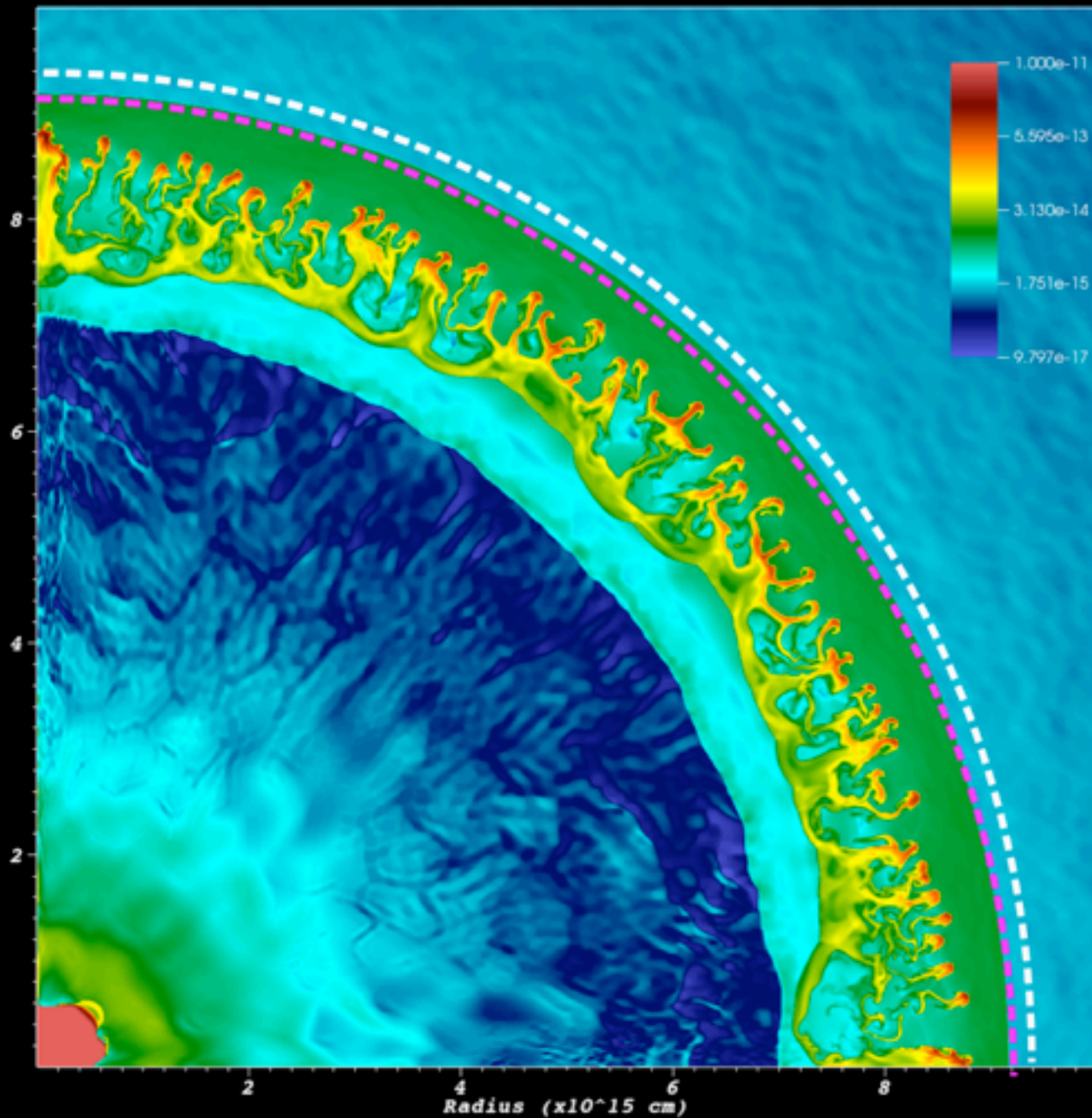
(cm/s)

Physical Properties of Colliding Shells

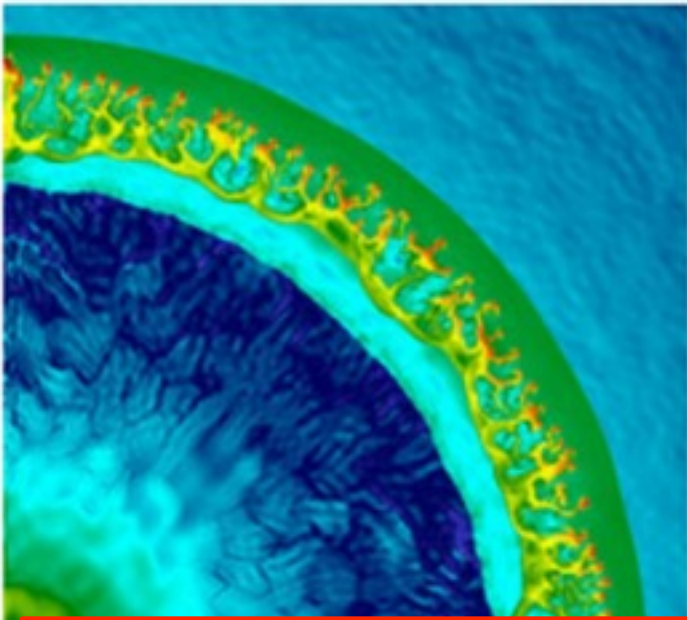
Physical Properties of Colliding Shells



Physical Properties of Colliding Shells



07 February 2013



Ke-Jung Chen/Univ. Minnesota

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.

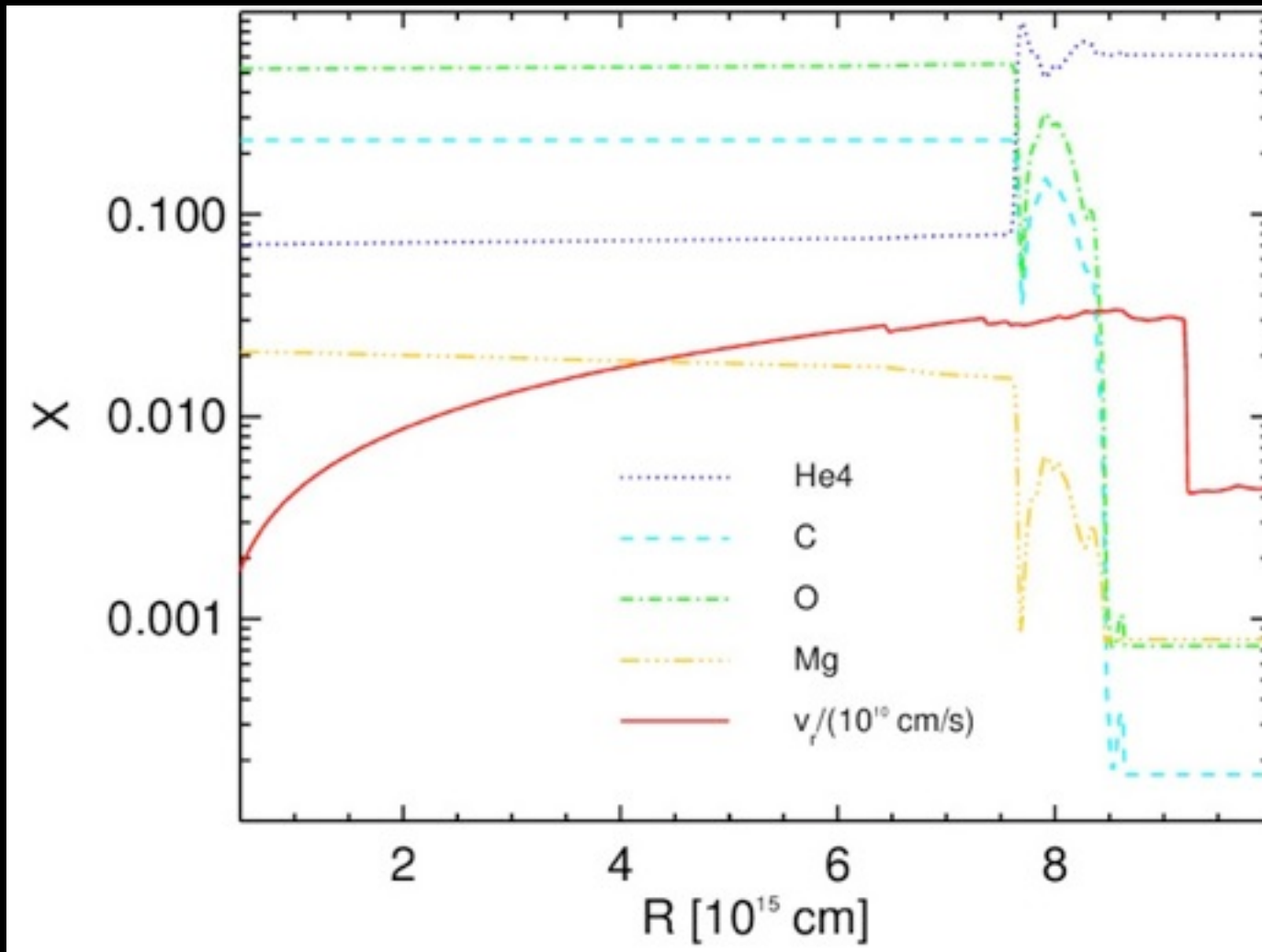
Latest news

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

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

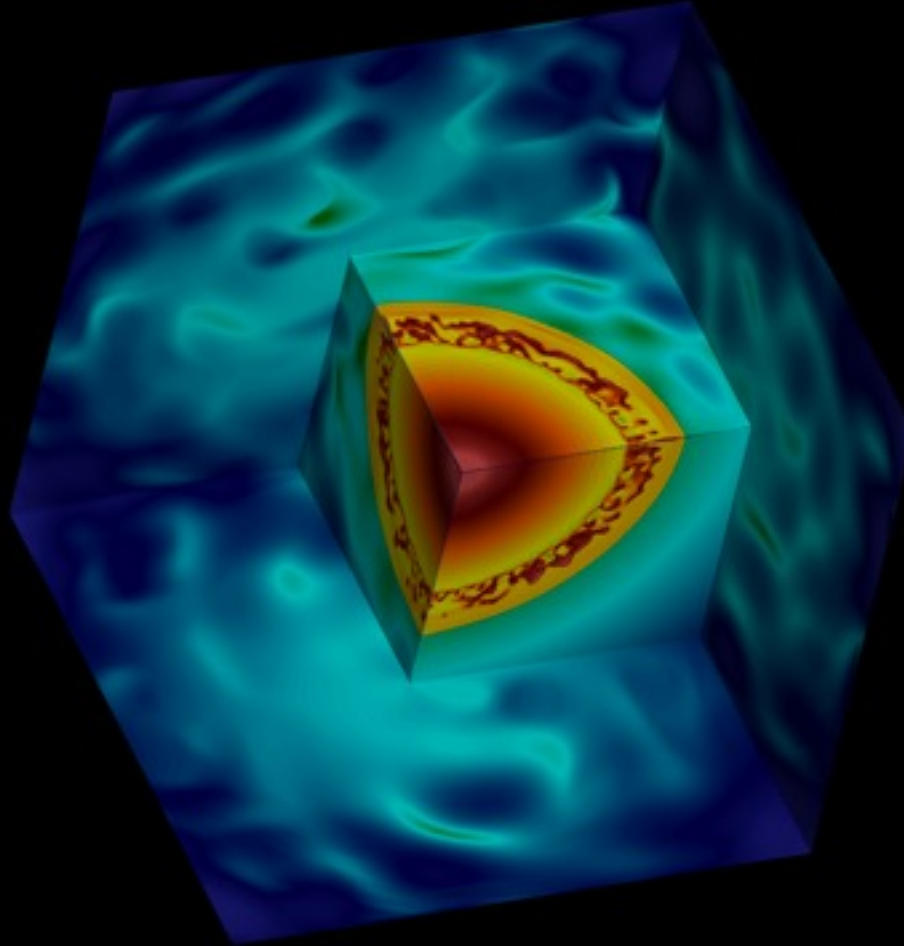
[More news from nature](#) ►

Mixing of PPSNe



Pair-Instability Supernovae (PSNe)

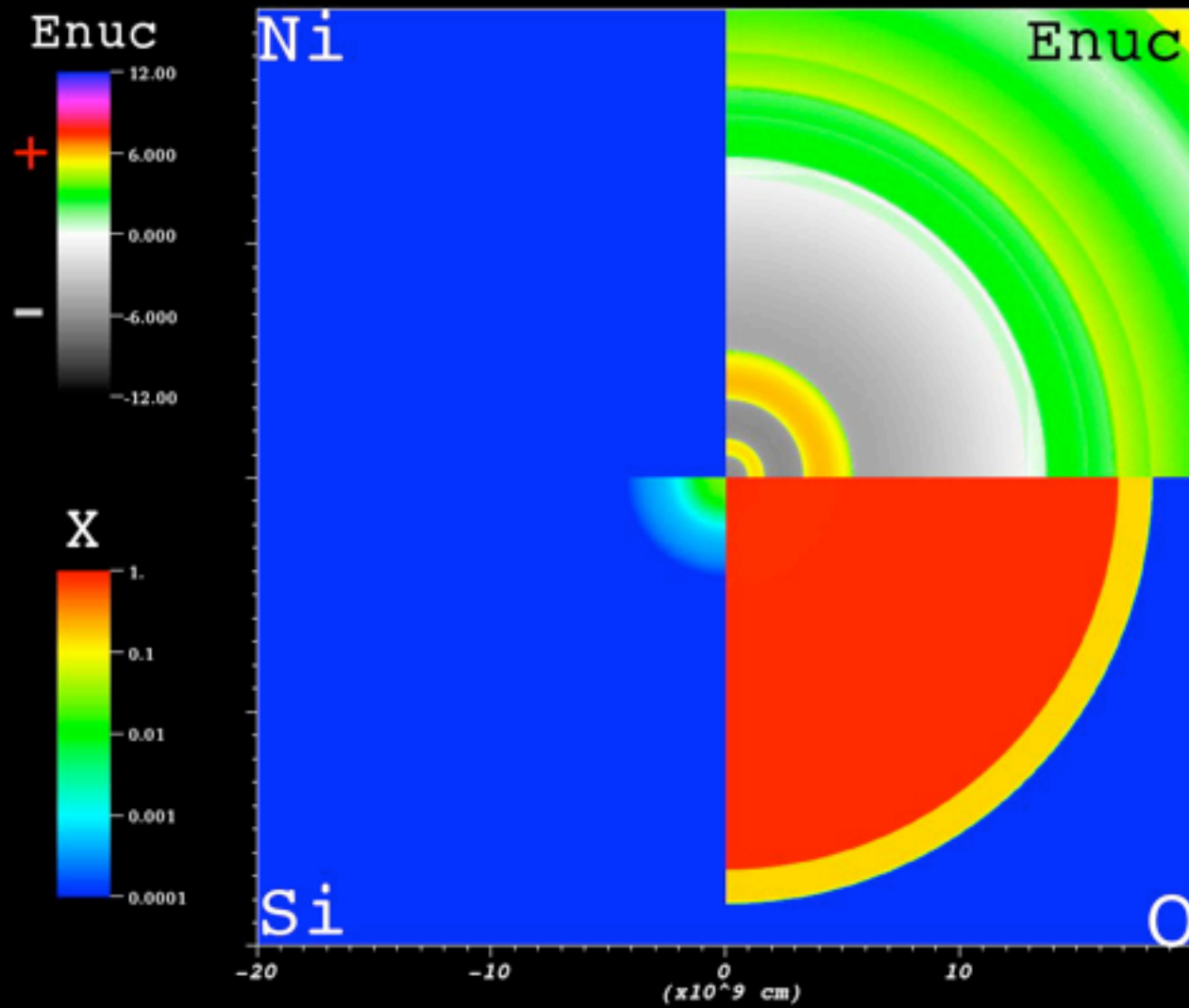
$$260 M_{\odot} > M^* > 150 M_{\odot}$$



Chen+ ApJ 792 44 (2014b)

Explosive Burning of $150 M_{\odot}$ Star

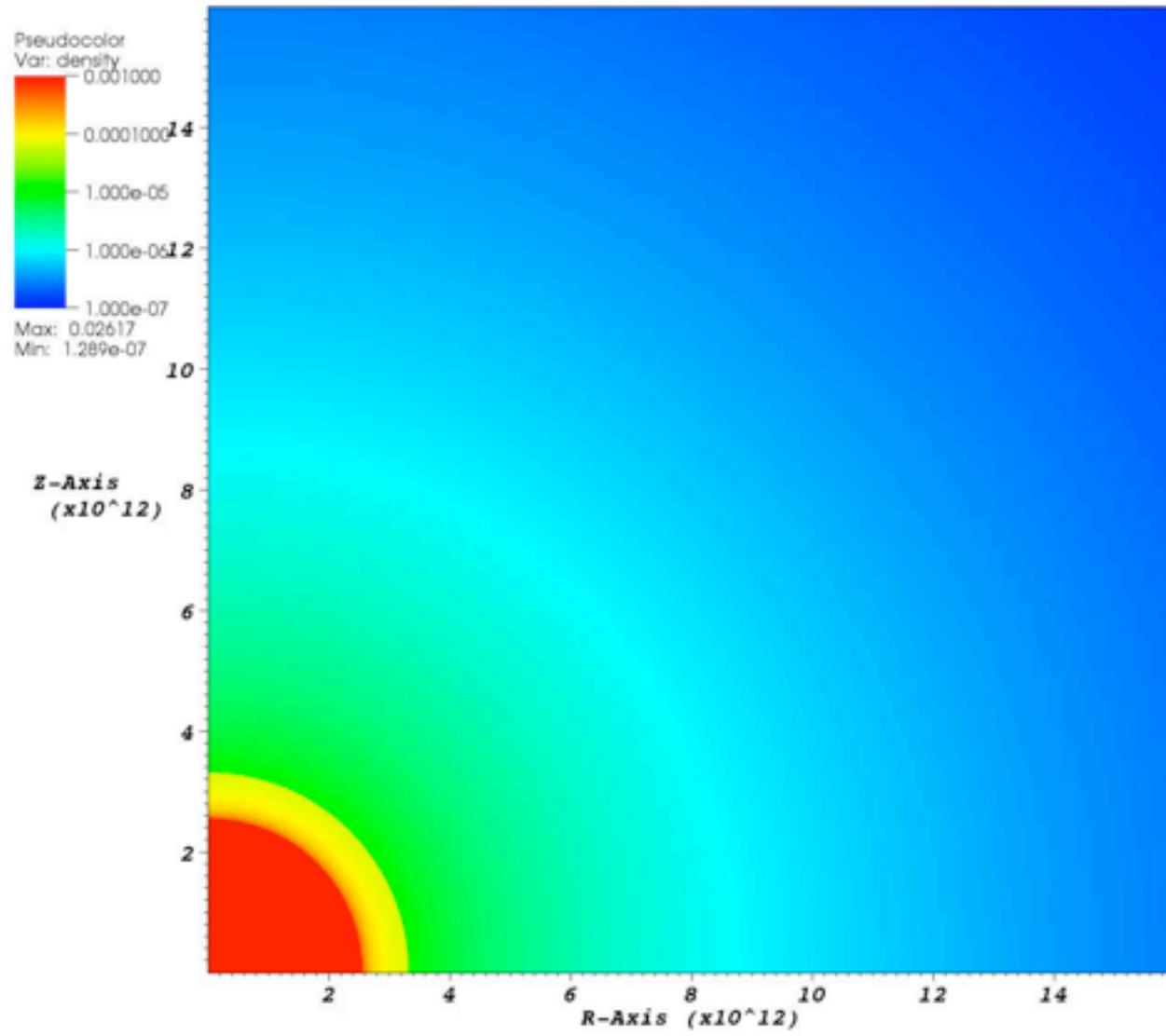
Explosive Burning of 150 M $\odot$ Star



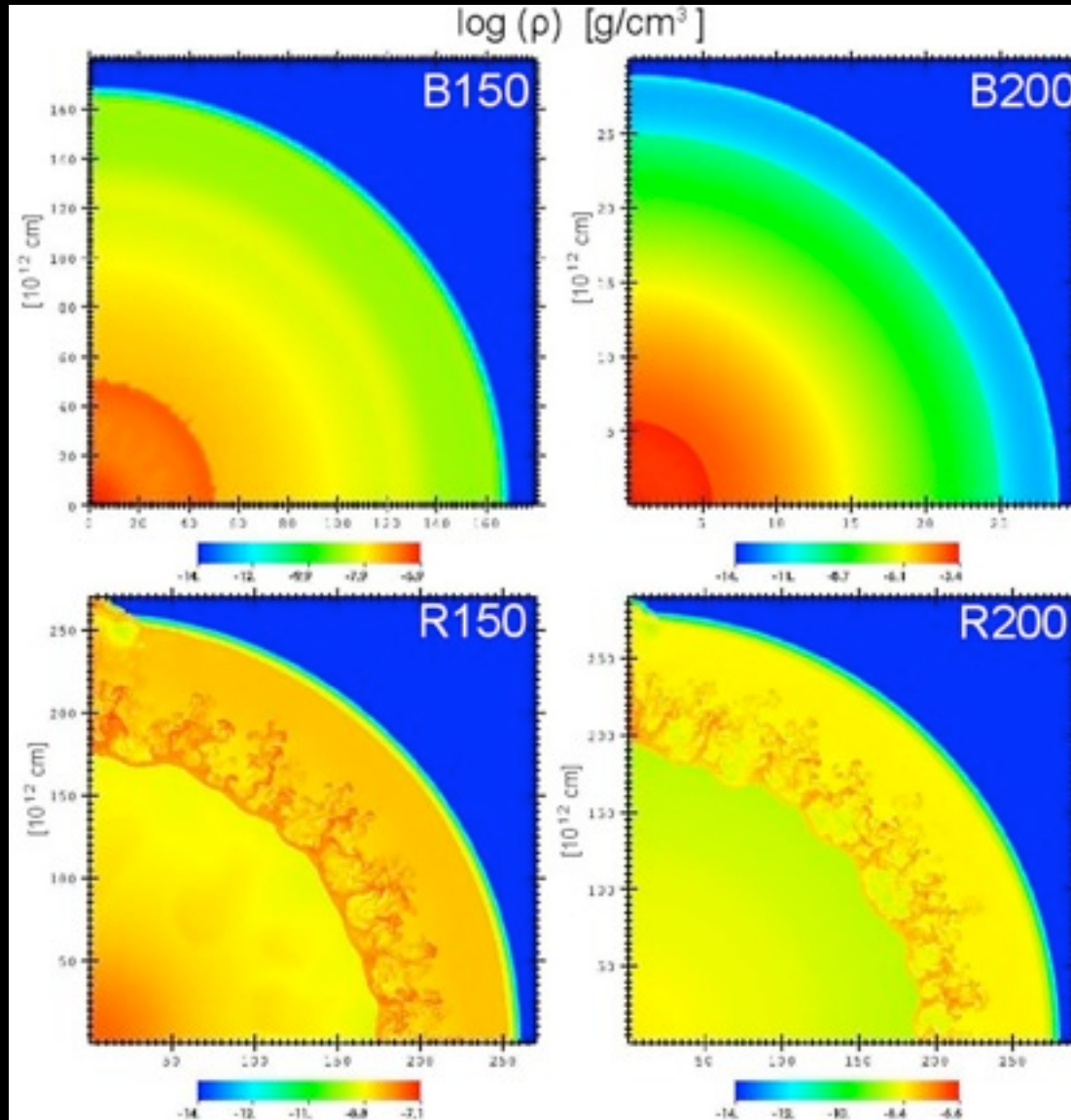
Time=0.125779 s

Exploding 200 $M_{\odot}$ Star (2007 bi)

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



Mixing of PSNe

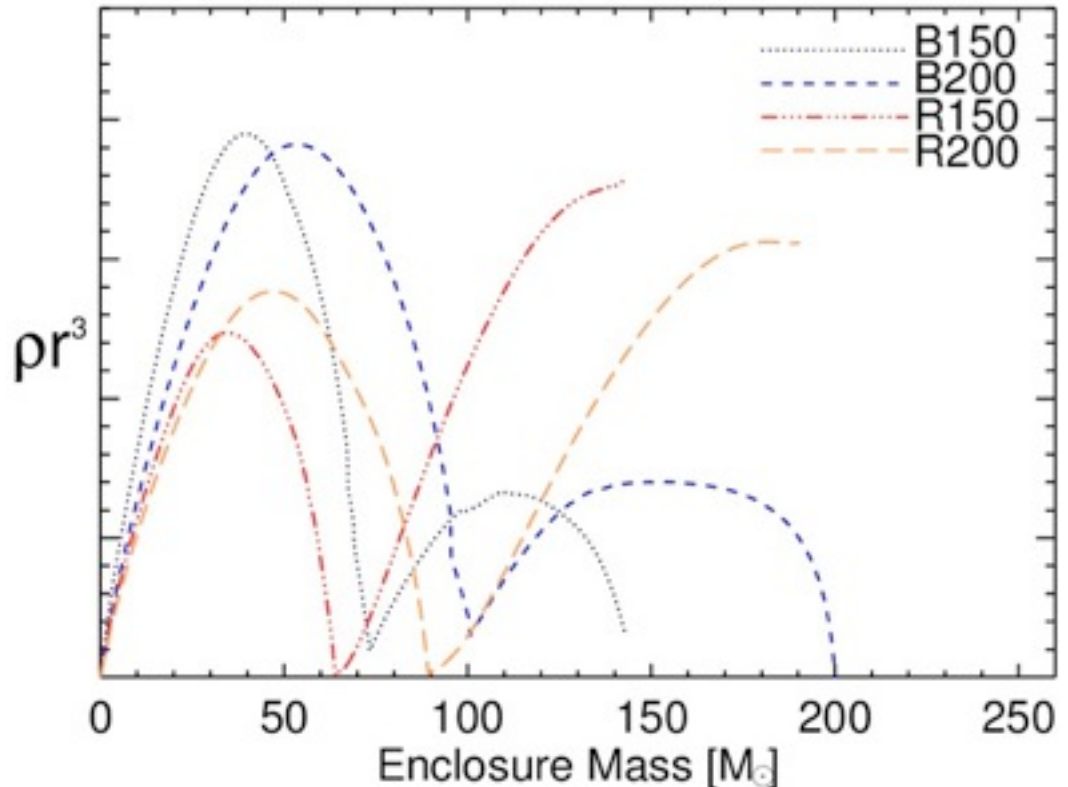


How does mixing occur?

$$\rho = Ar^w$$

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

Sedov, 1959



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

Results

Model	Mass [$M_{\odot}$]	Core [$M_{\odot}$]	E [10^{52} erg]	Ni [$M_{\odot}$]	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.

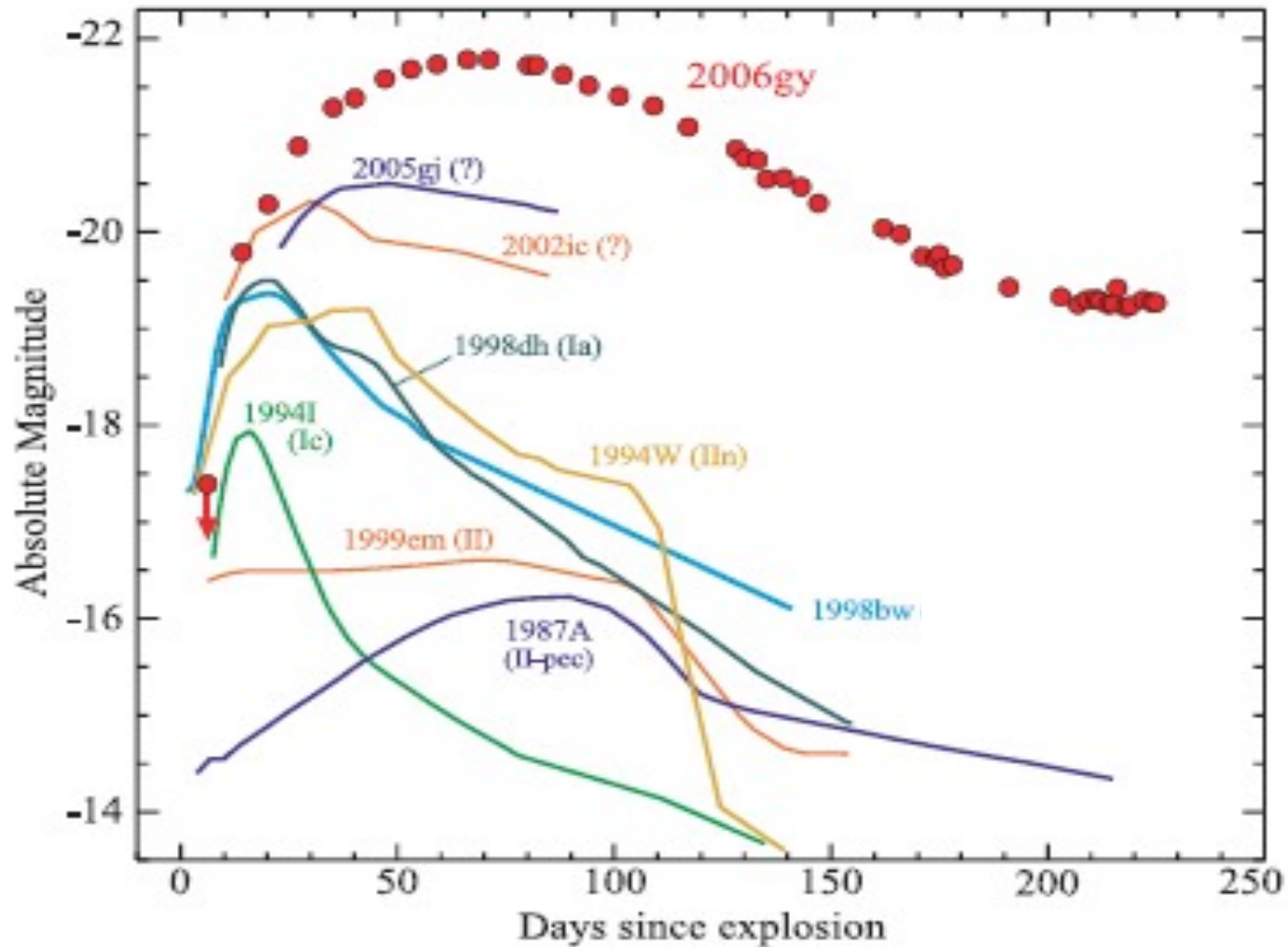


A photograph of a galaxy, likely a spiral galaxy, viewed at an angle. The galaxy's core is a bright, reddish-white point of light. The spiral arms are visible, showing a mix of blue and reddish-brown colors, possibly indicating star formation or dust. Two bright stars are visible in the foreground. One star, labeled 'SN Ia', is a white point of light with a prominent four-pointed diffraction pattern. The other star, labeled '(P)PSN', is a blue point of light. The background is a dark, deep blue sky.

SN Ia

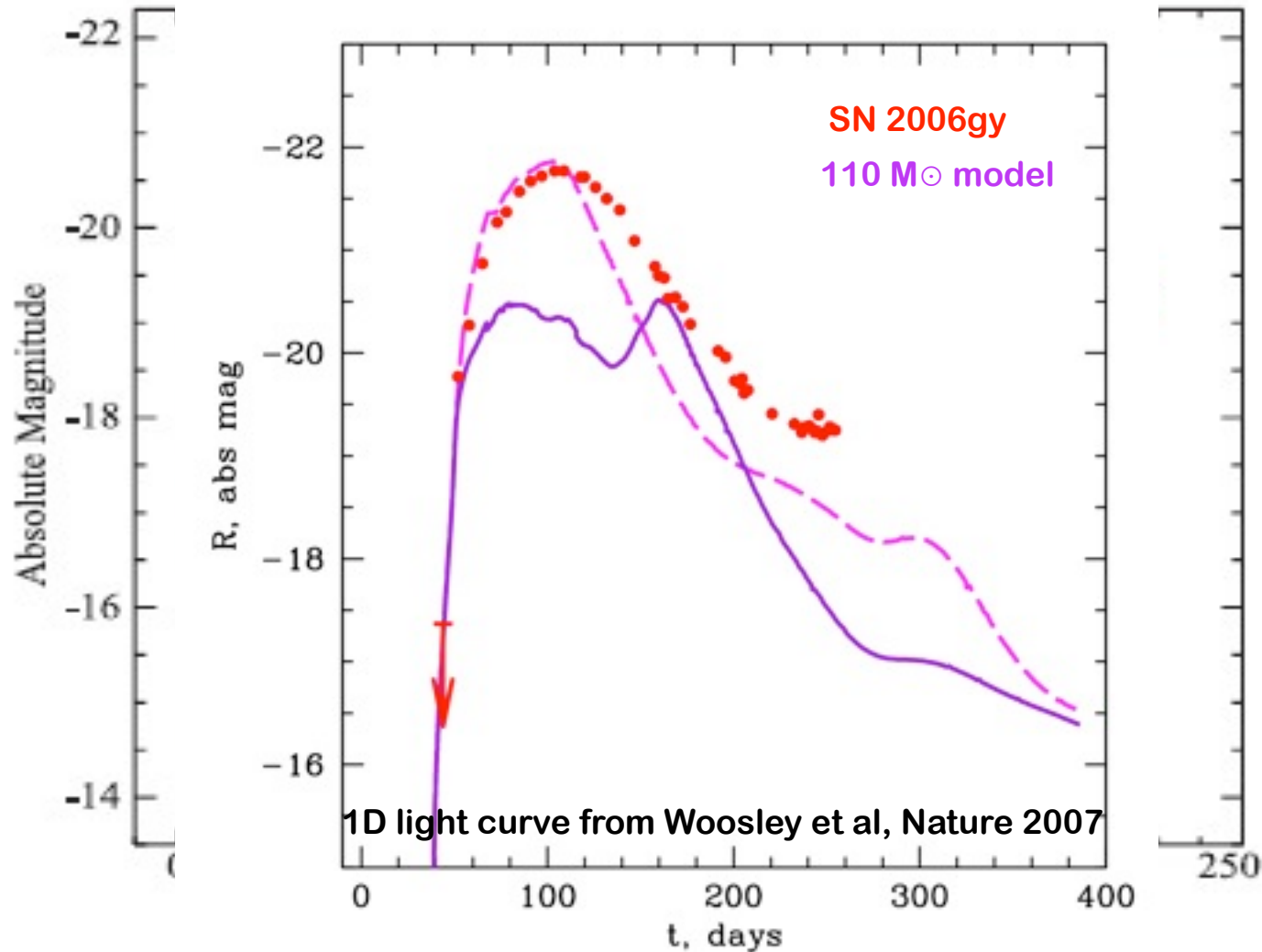
(P)PSN

Super Luminous SNe



Smith+ 2007

Super Luminous SNe

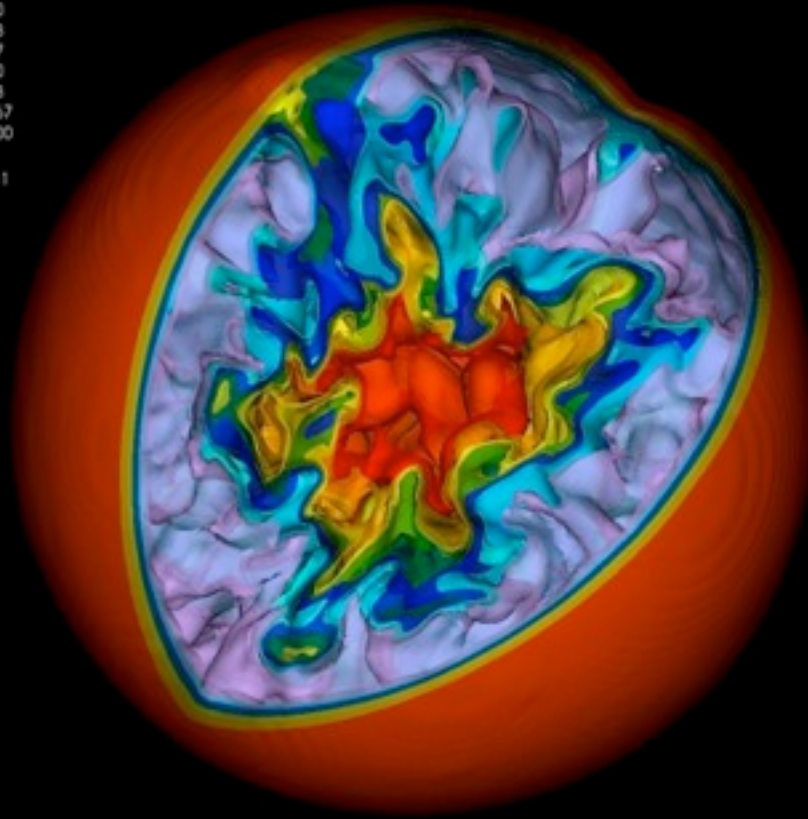


Smith et al 2007

GR Instability Supernovae (GSNe)

$$M^* \gg 100 M_{\odot}$$

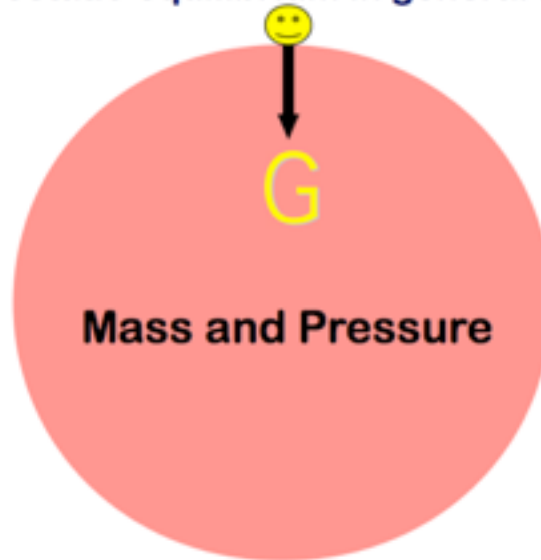
Contour
Var: O
0.3500
0.2933
0.2367
0.1800
0.1233
0.06667
0.01000
Max: 0.3799
Min: 4.716e-11



Chen+ ApJ 790 162 (2014c)

GR correction for massive stars

(Hydrostatic equilibrium in general relativity)

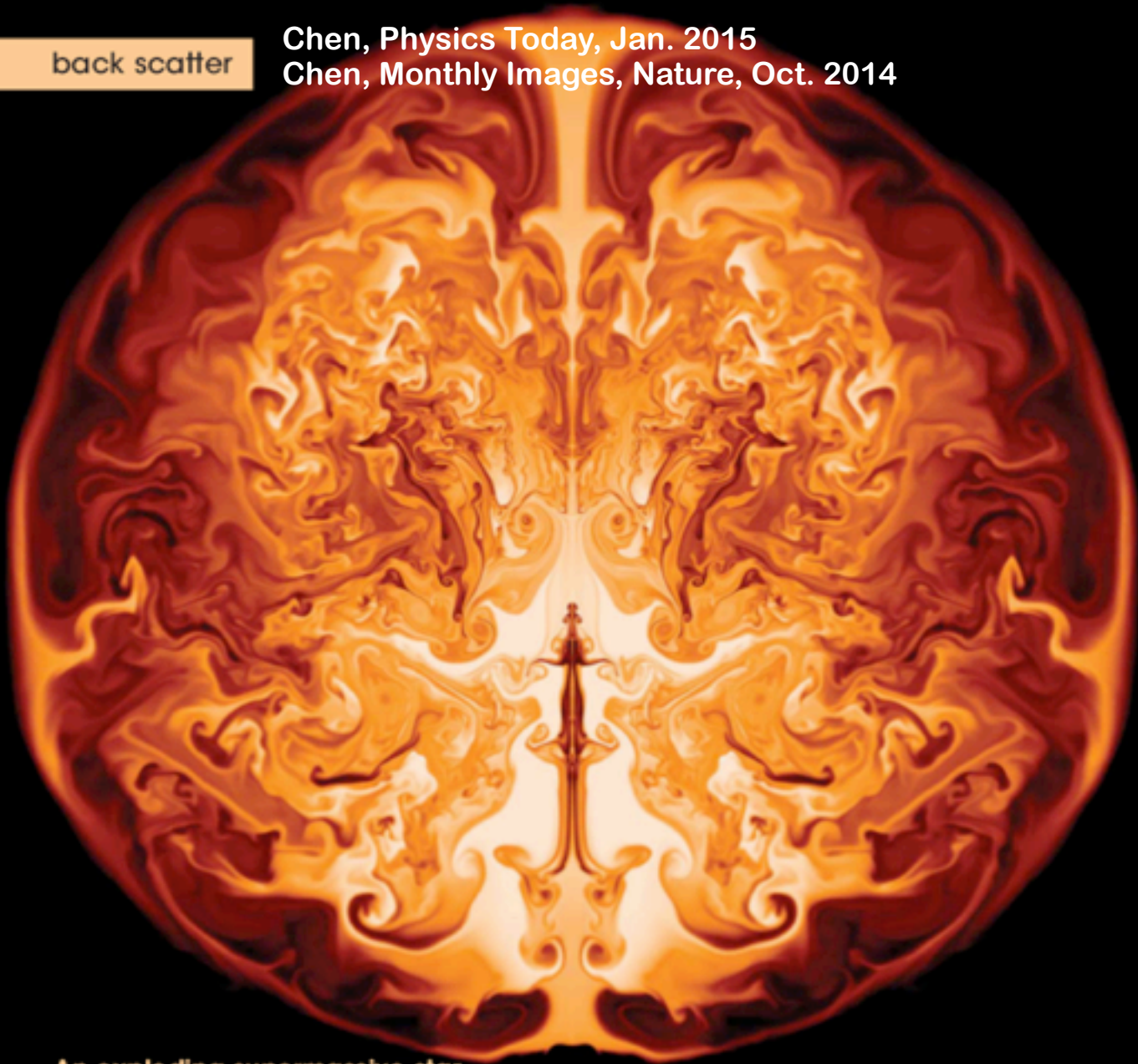


Tolman-Oppenheimer-Volk equation

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

back scatter

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

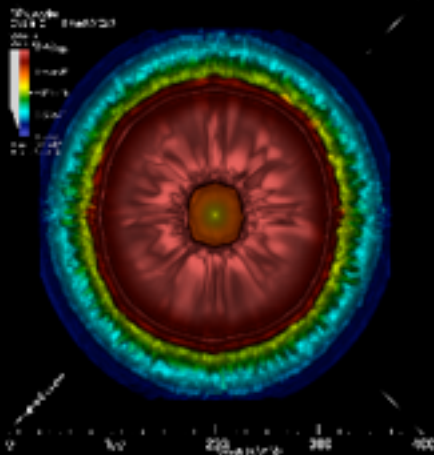


An exploding supermassive star

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

Take Home Message I

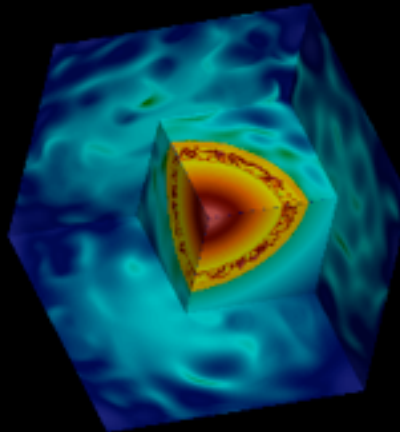
Pulsational Pair-Instability SN (PPSN)



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

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

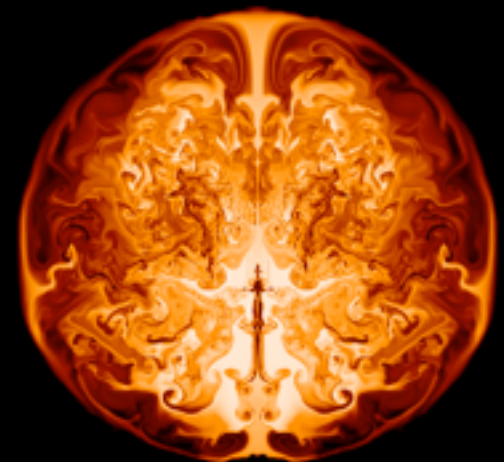
Pair-Instability SN (PSN)



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

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)

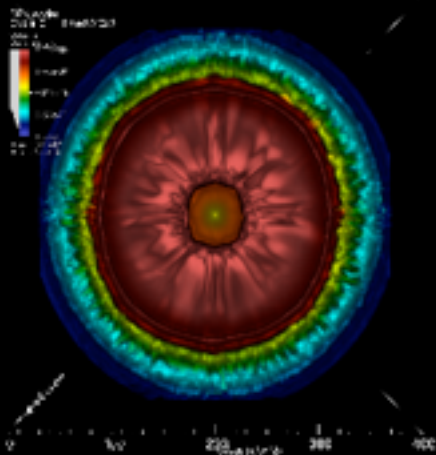


$$M^* \sim 55,000? M_{\odot}$$

1. GR instability
 2. Explosive burning helium
 3. One giant explosion
 4. Mixing due to burning instability
- Explosion energy $\sim 10^{55}$ erg

Take Home Message I

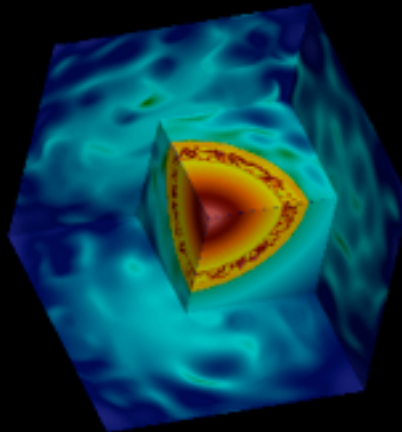
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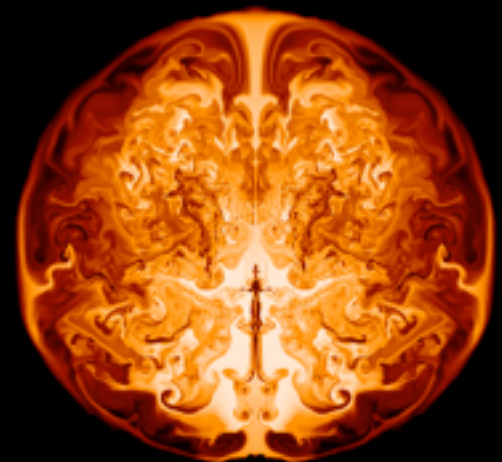
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Big impact to the early Universe !

National Science Foundation
WHERE DISCOVERIES BEGIN

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FUNDING AWARDS DISCOVERIES NEWS PUBLICATIONS STATISTICS ABOUT NSF FASTLANE

Slice Through the Interior of a Supermassive Star

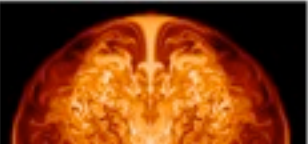


Image Album:
Best Science Photos of the Week
LiveScience Staff
Date: 16 February 2013 Time: 04:19 PM ET

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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
Conducted September 11–12, 2012

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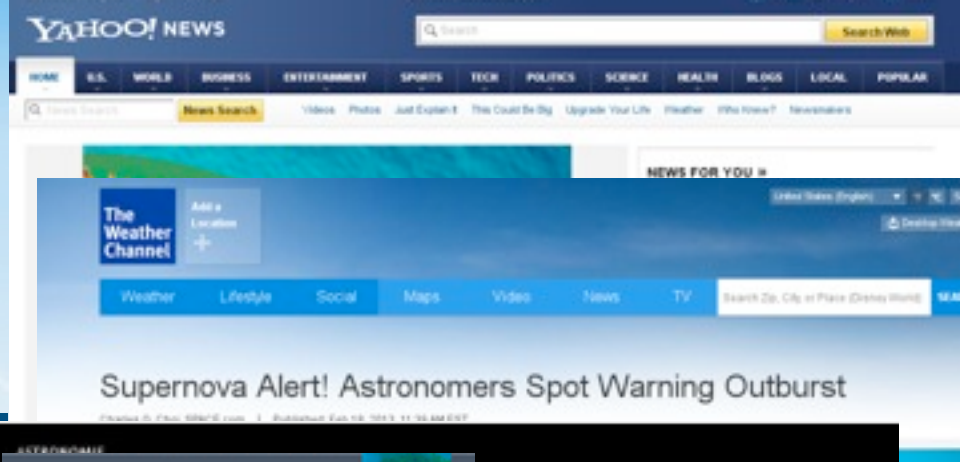
for Advanced Computational Research

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Spring 2011 Research Bulletin

Physics and Astronomy

Simulations of Thermonuclear Supernovae From Very Massive Stars



With the help of NERSC
Who says you can't
crack open a star?
Watch us!





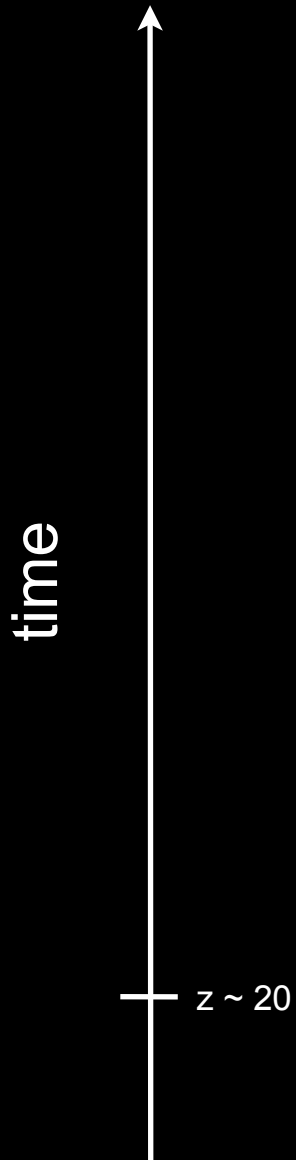
450 Million after the Big Bang (HUDF)

How did the First Galaxies Form?



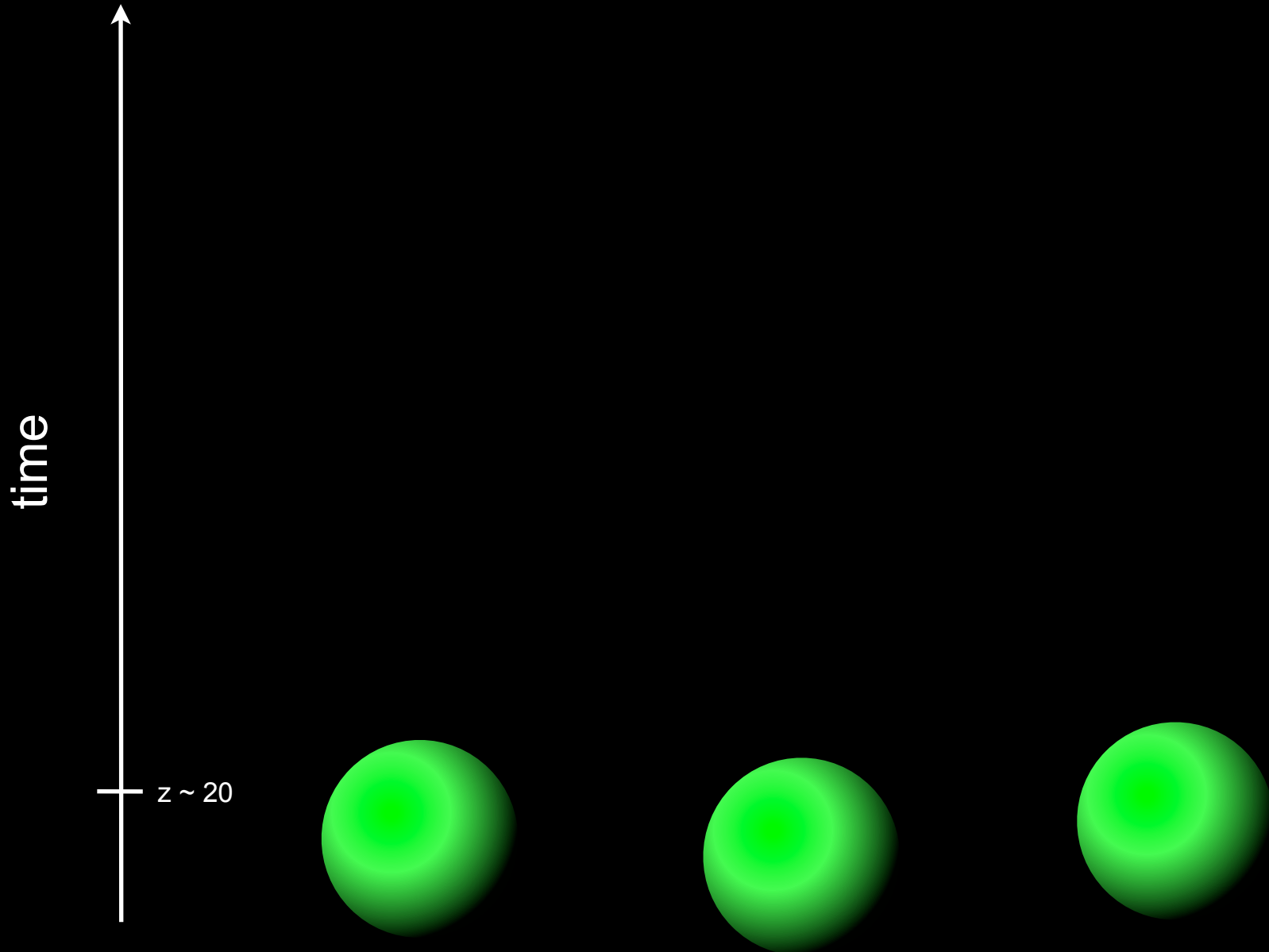
Bromm, & Yoshida (2011)

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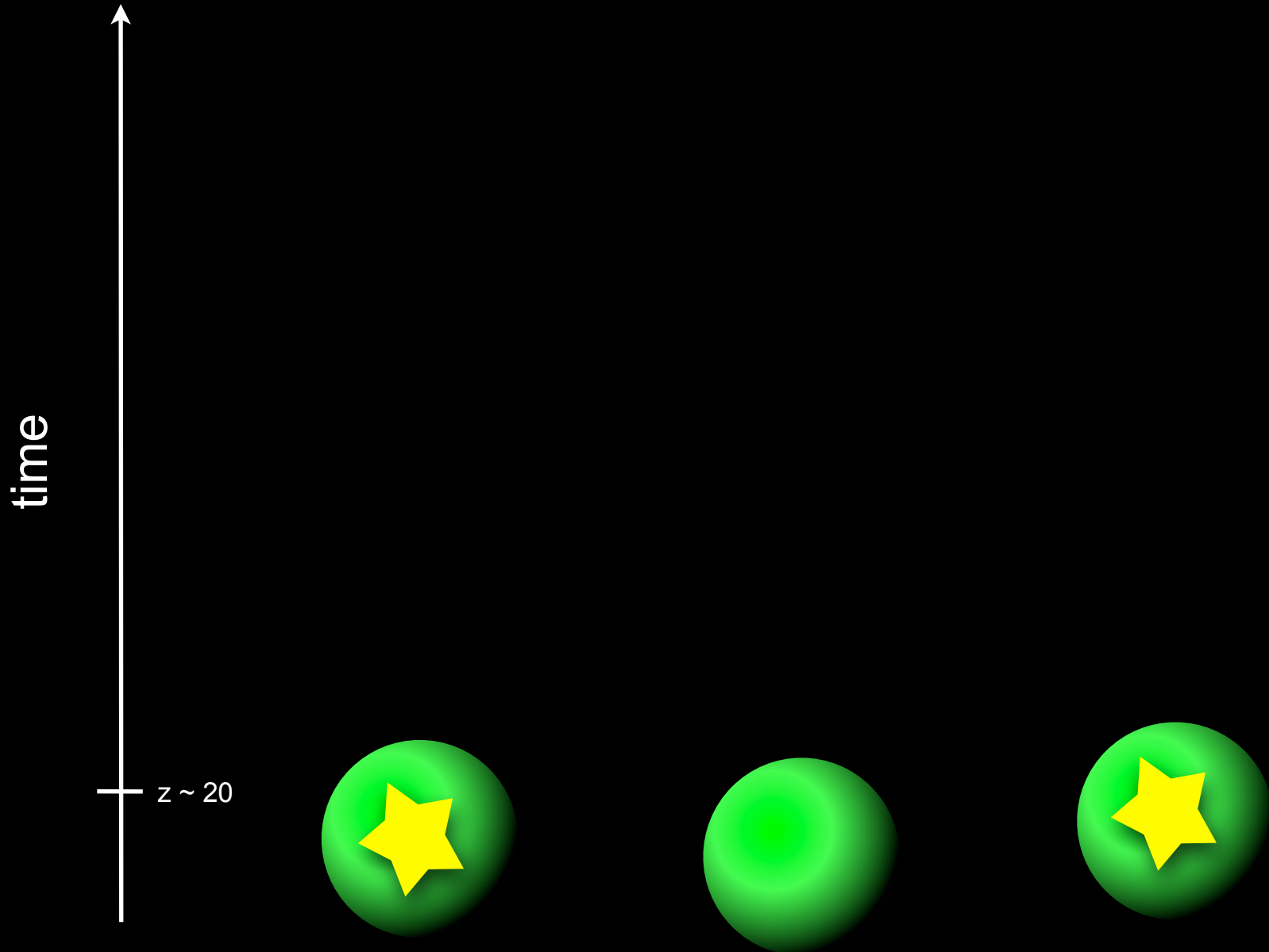
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How did the First Galaxies Form?



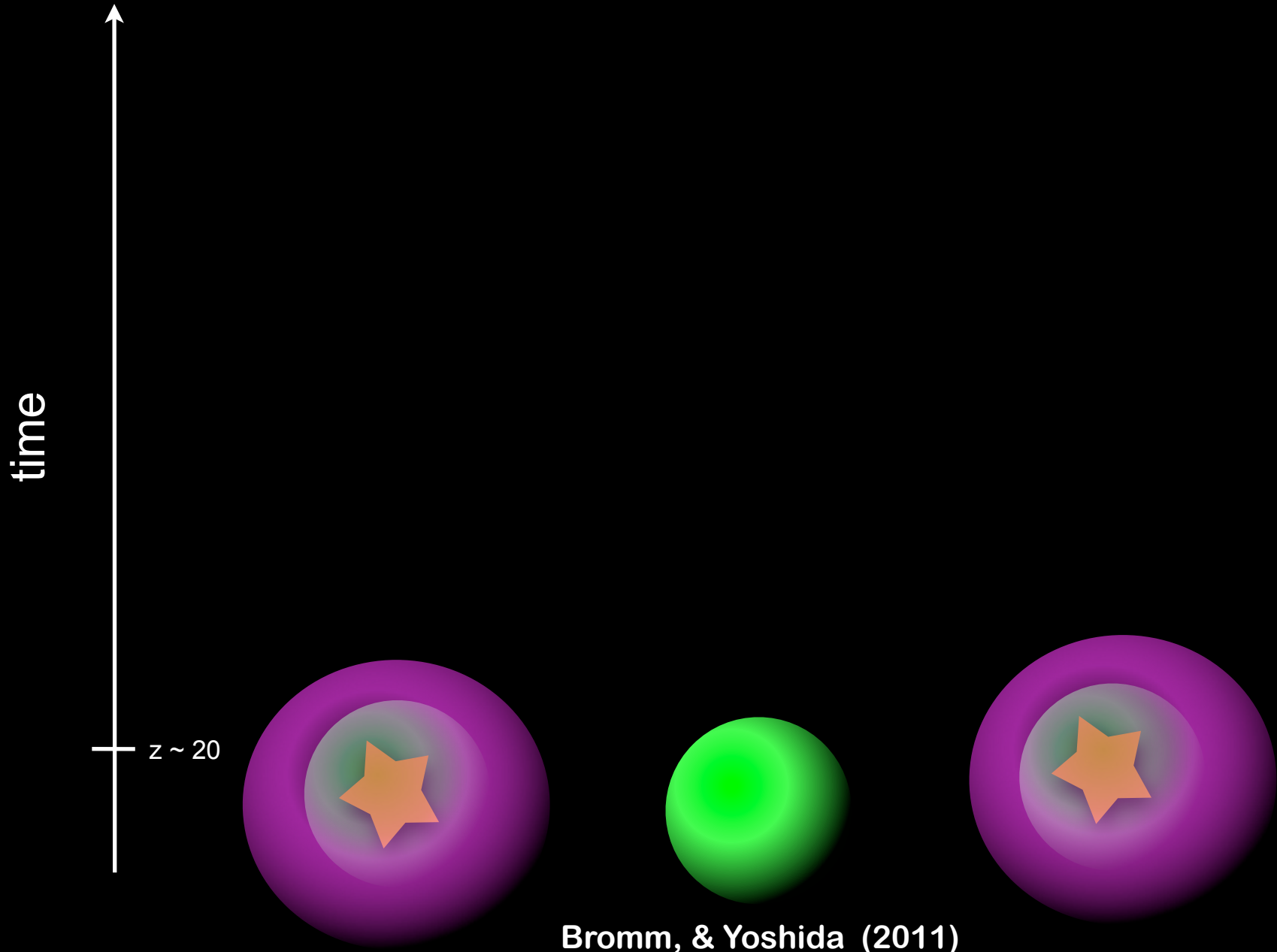
Bromm, & Yoshida (2011)

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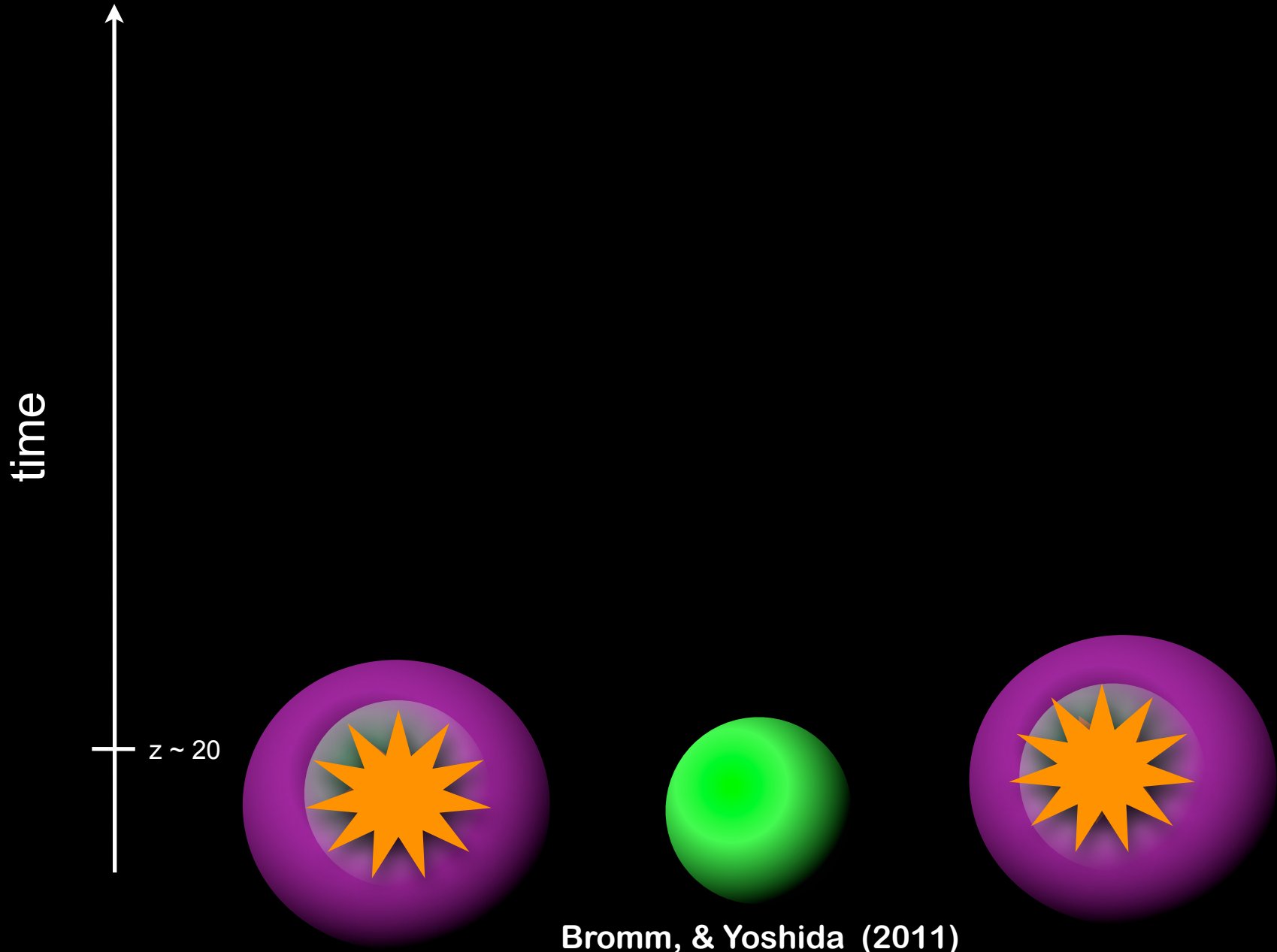


Bromm, & Yoshida (2011)

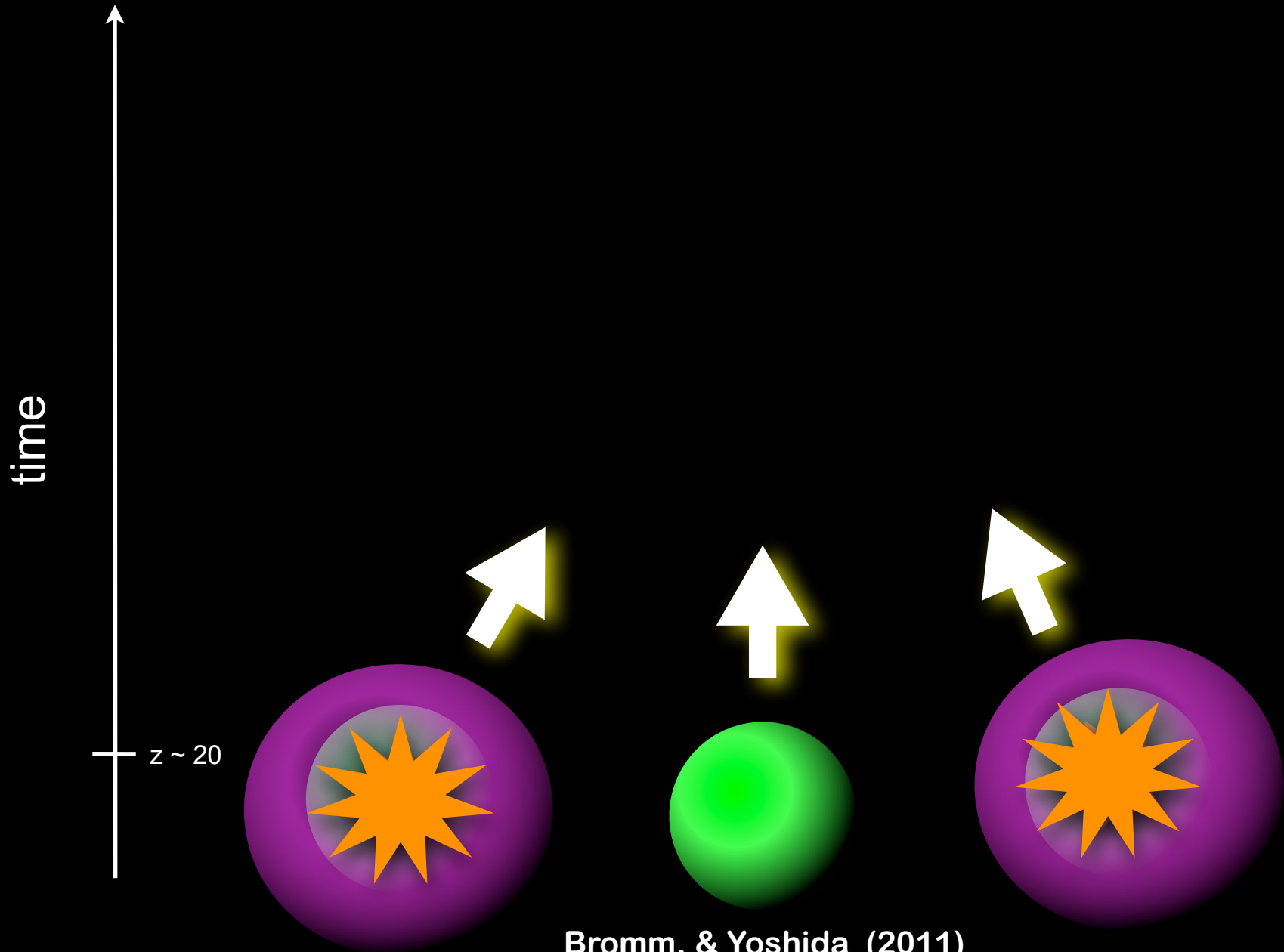
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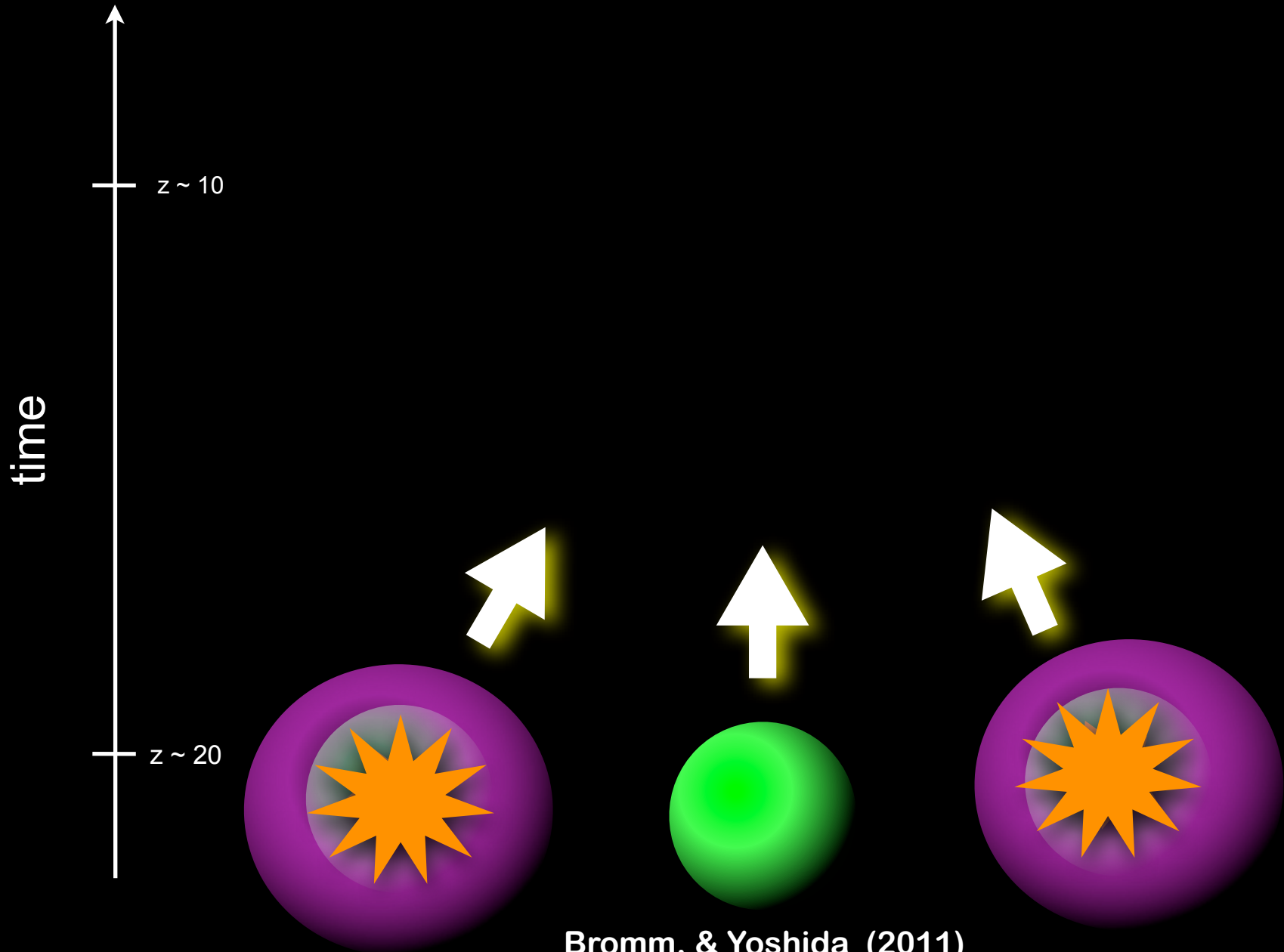


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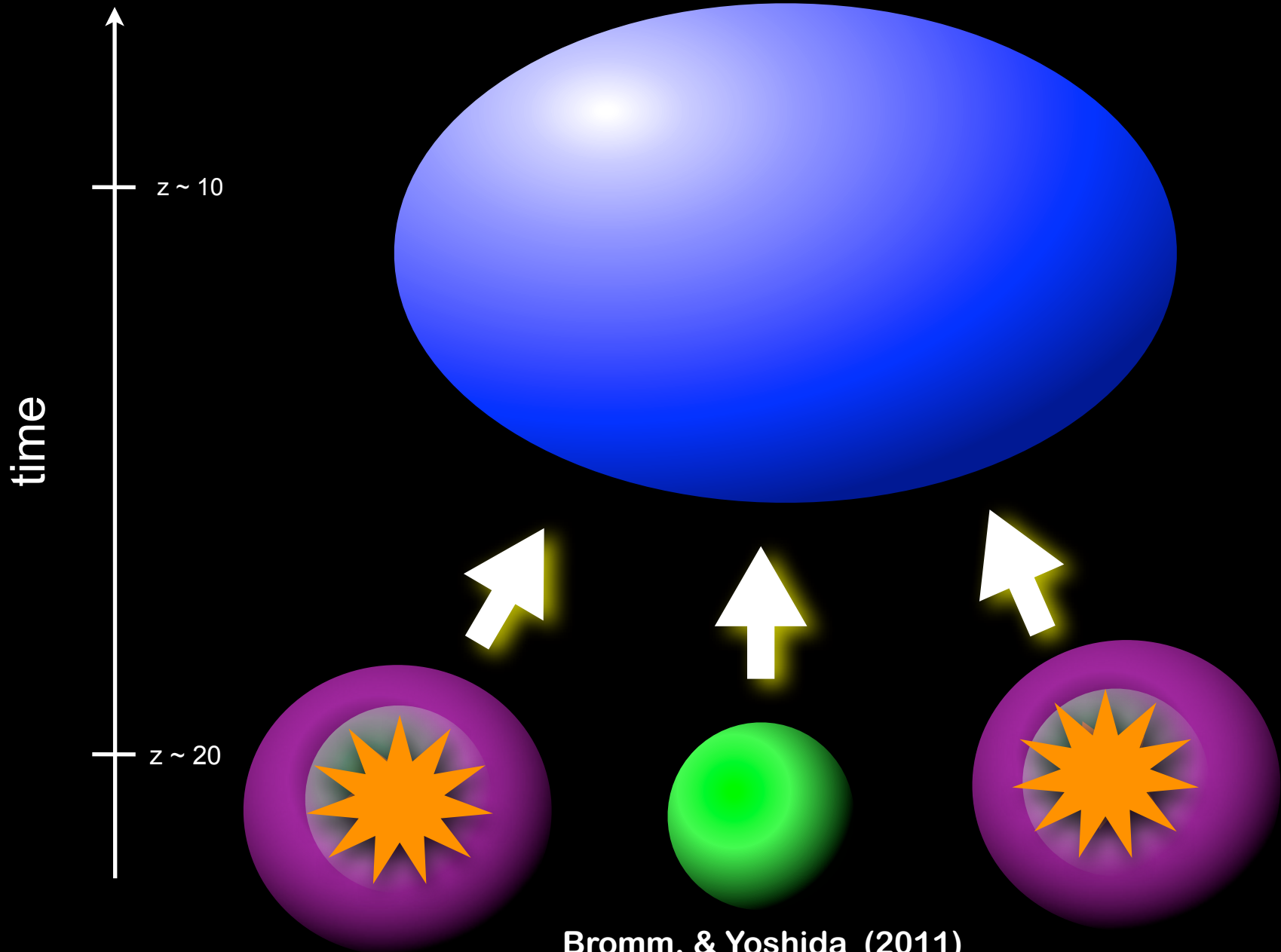
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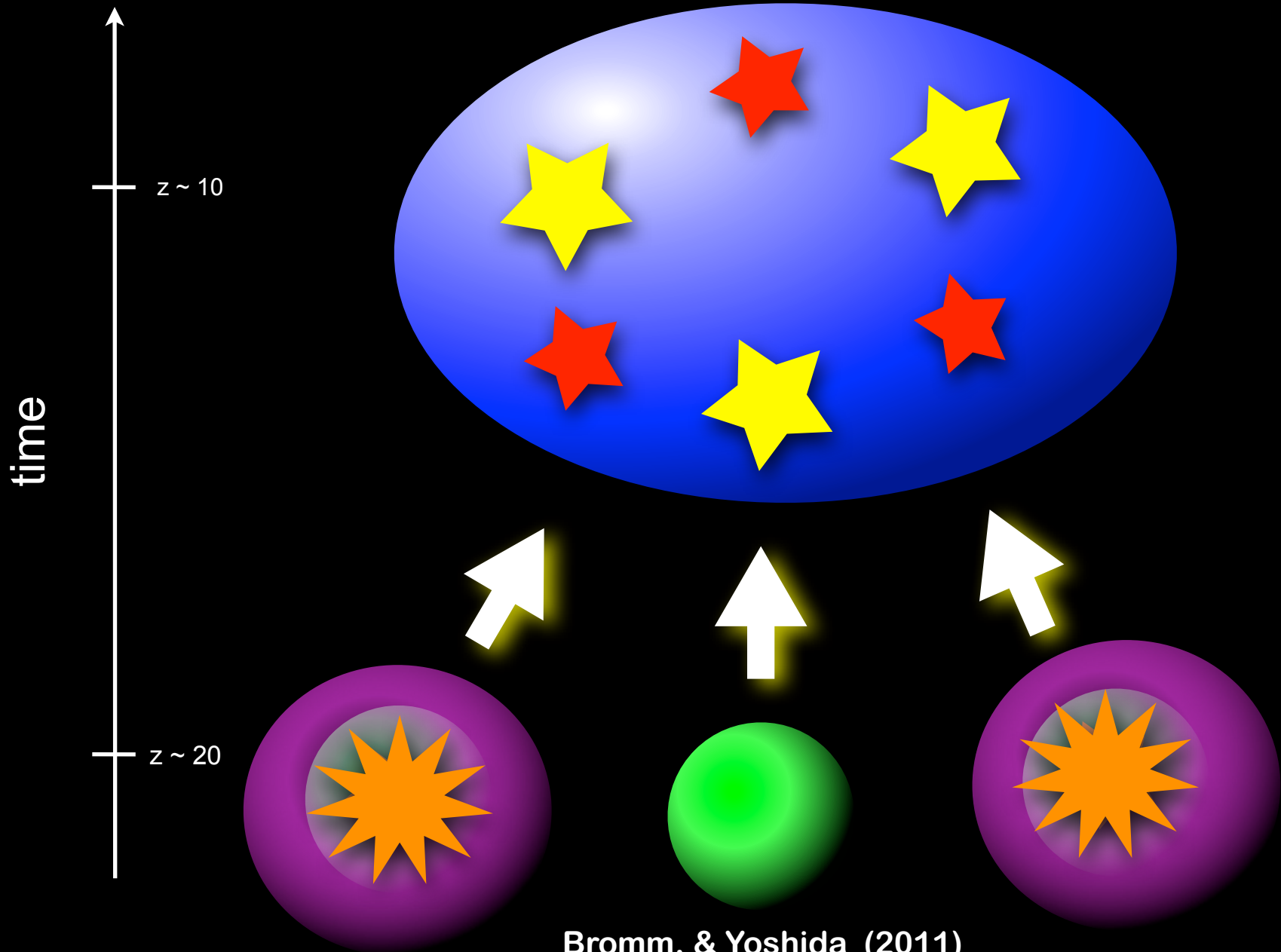
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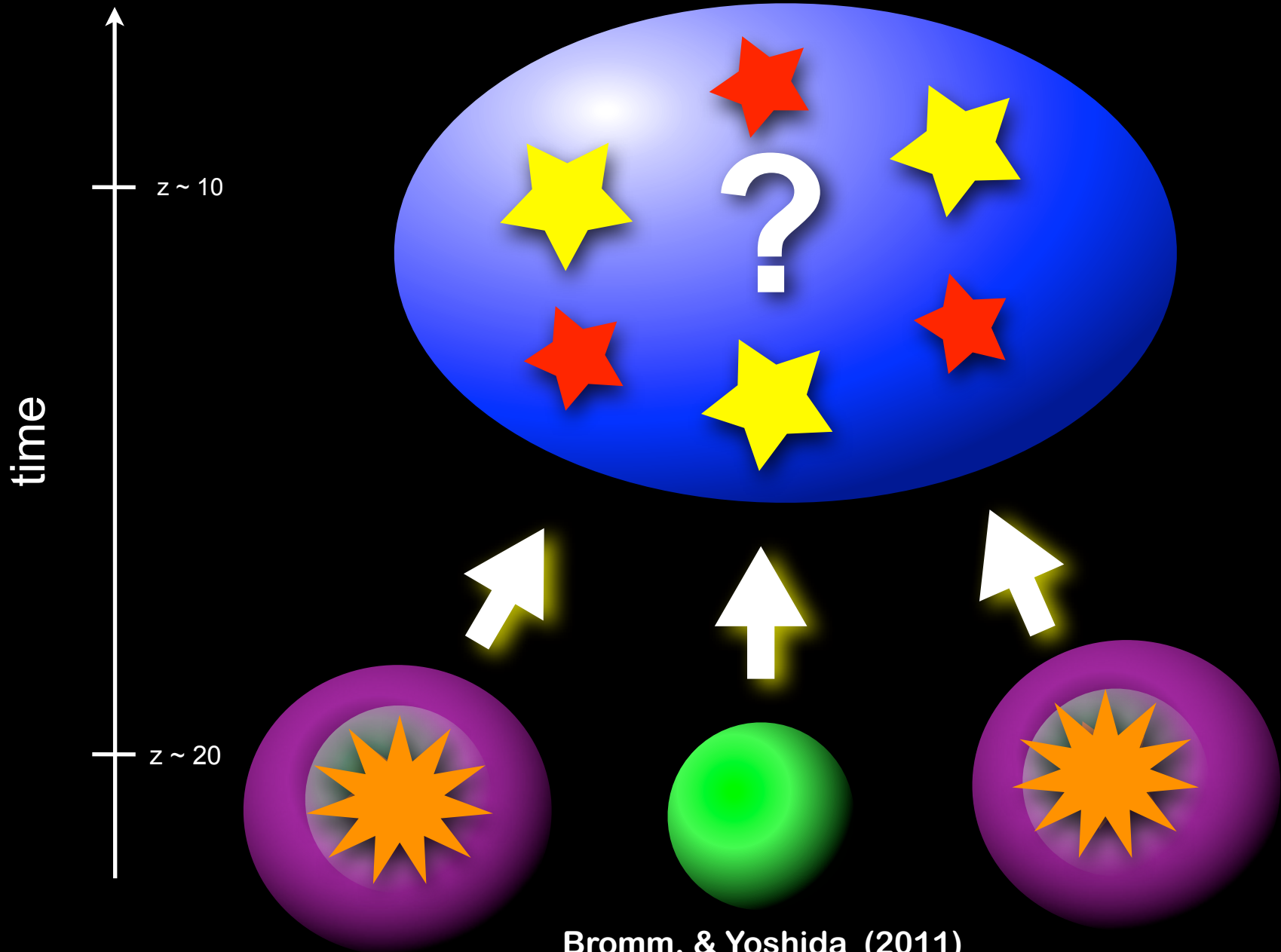
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Characters of the First Galaxies

Bromm, & Yoshida (2011)

- Mass scale $\sim 10^8 M_{\odot}$
- Redshift ~ 10
- Self-bound system.
- Affected from the previous stellar feedback
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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

1. Ionizing photons
2. SN shock reheating
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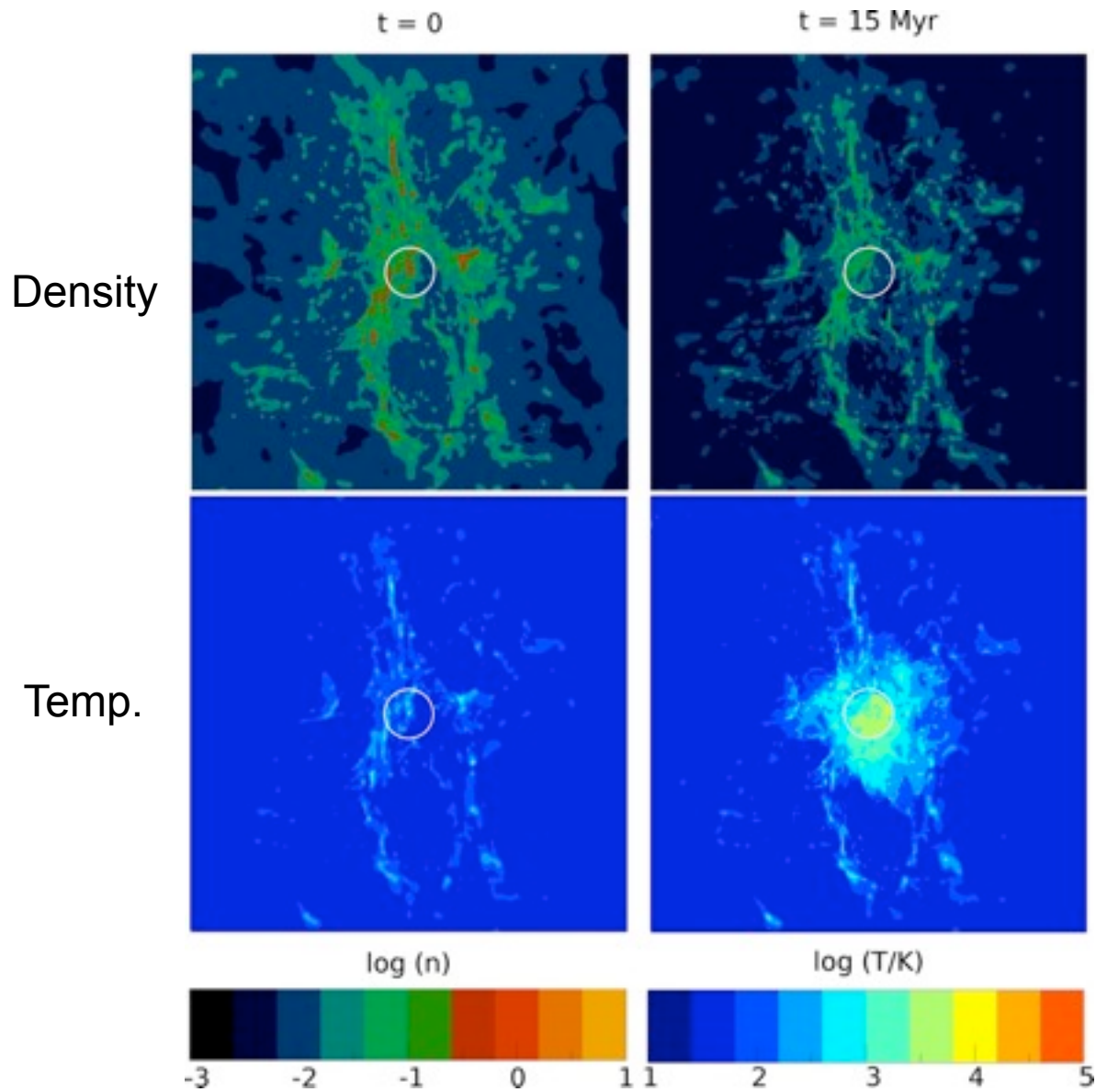
The Impact of the First Stars, Supernovae, and Binaries

Ken Chen

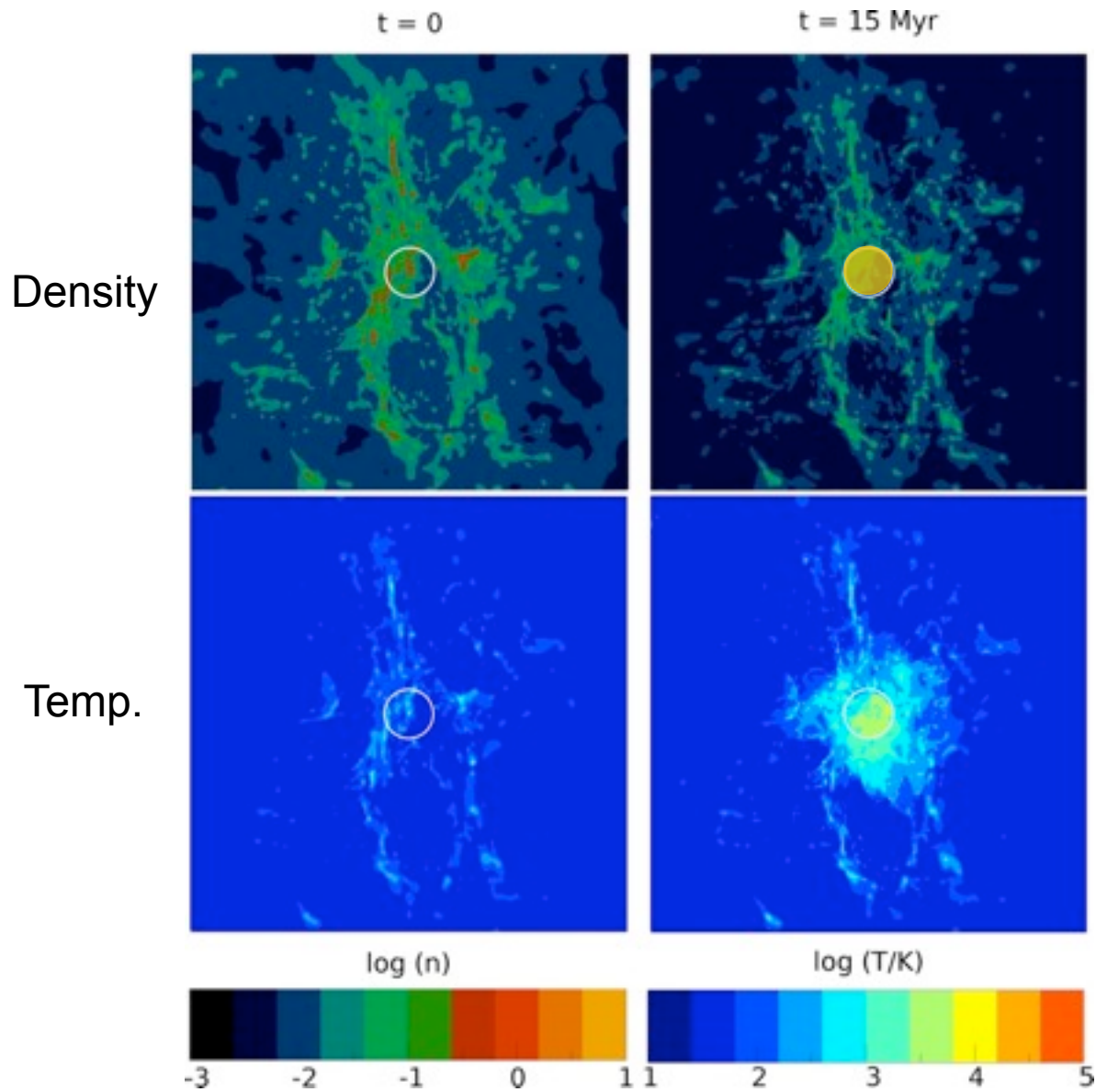
University of Minnesota

Background music: Pirates Of The Caribbean

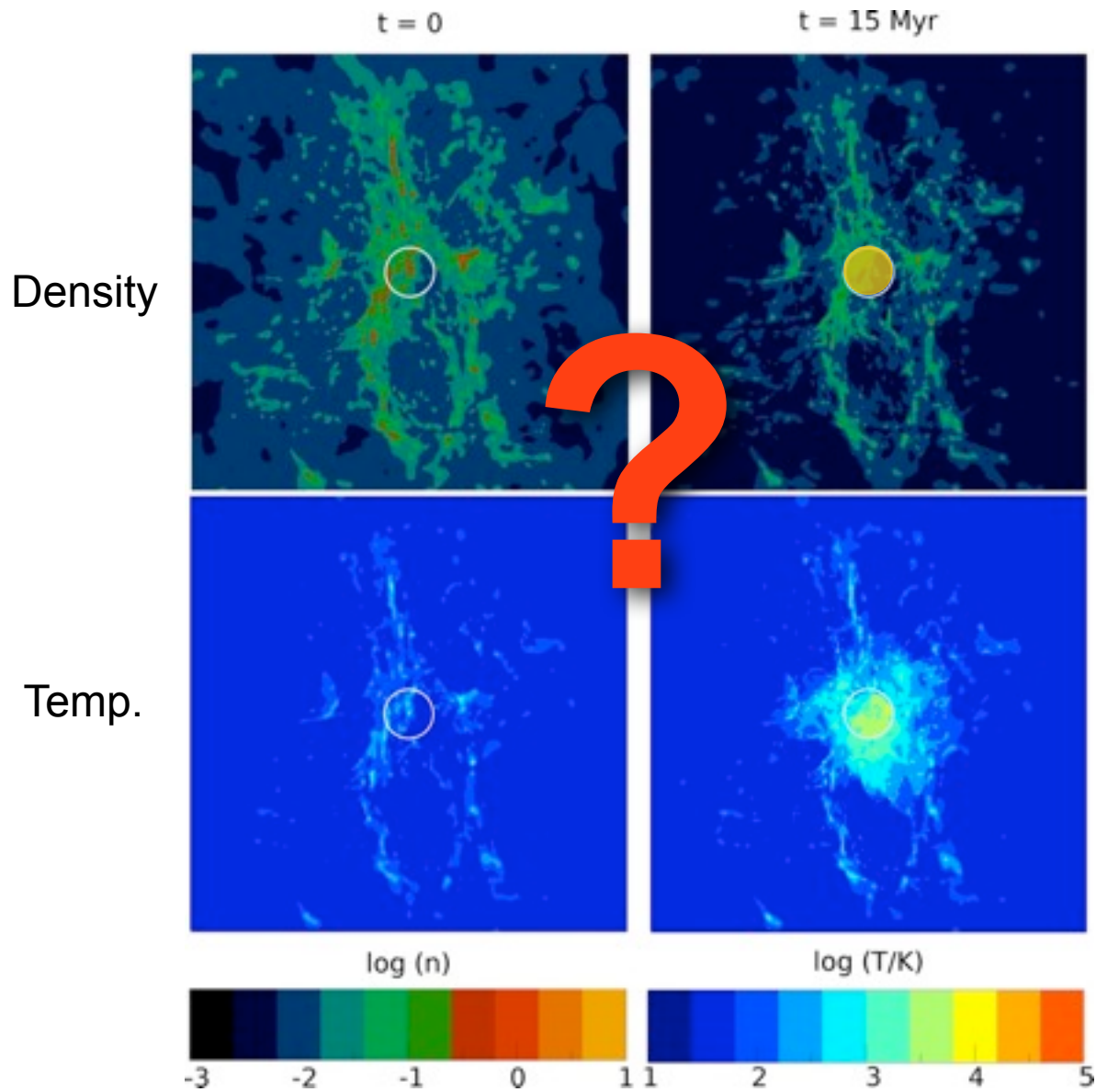
Properties of Large Scale Structure



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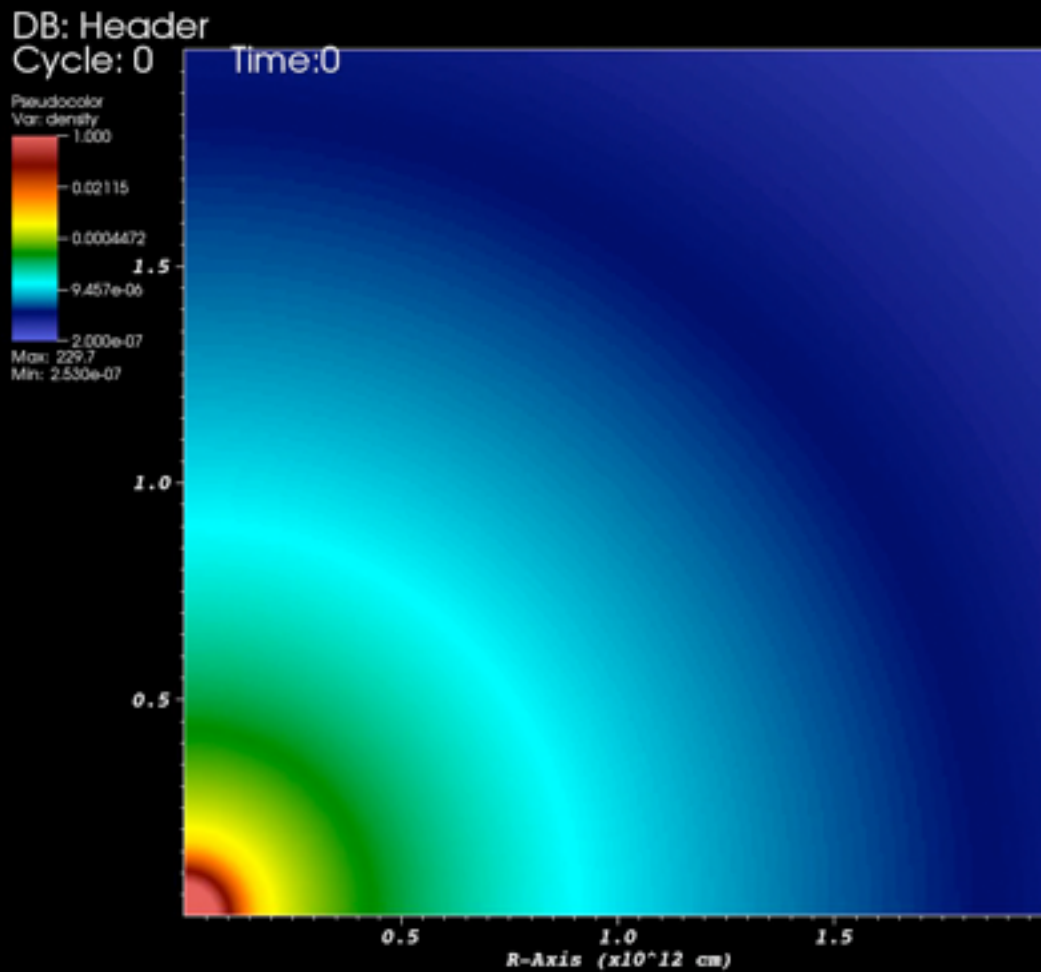


Magnetar

Chen+ 2015b to be submitted

Magnetar

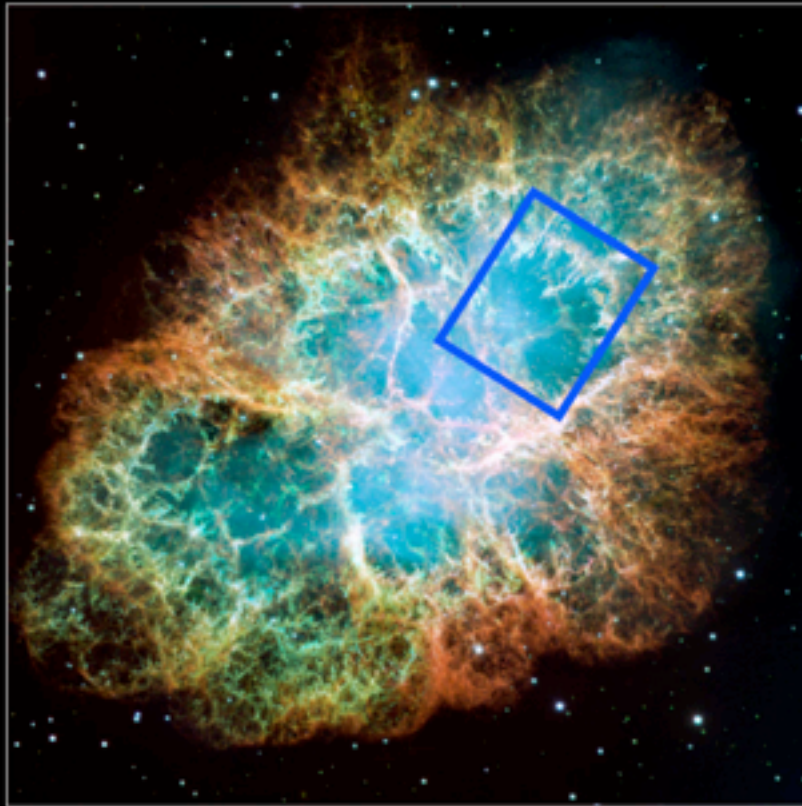
Chen+ 2015b to be submitted



user: kchen
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Magnetar

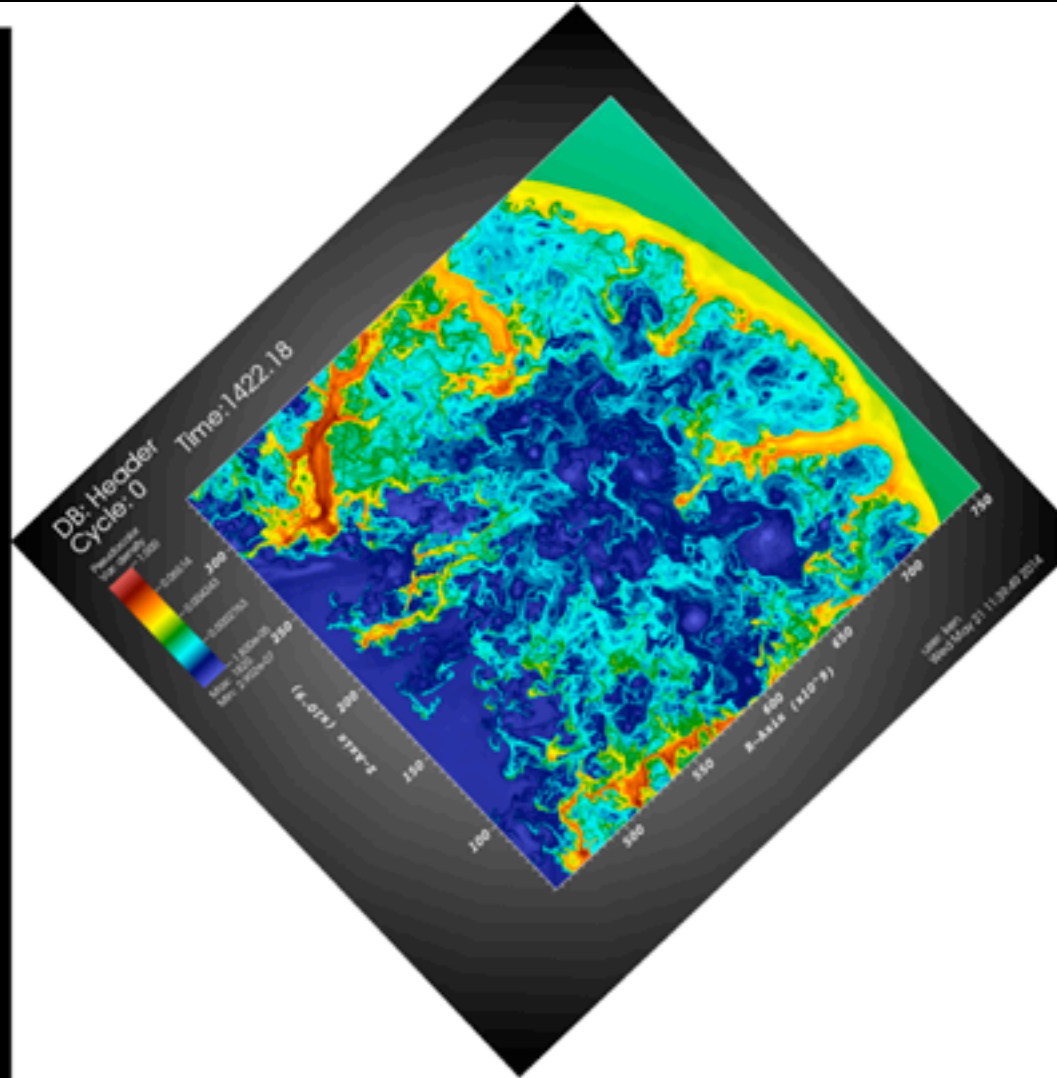
Chen+ 2015b to be submitted



Crab Nebula • M1
Hubble Space Telescope • WFPC2

NASA, ESA, and J. Hester (Arizona State University)

STScI-PRC05-37

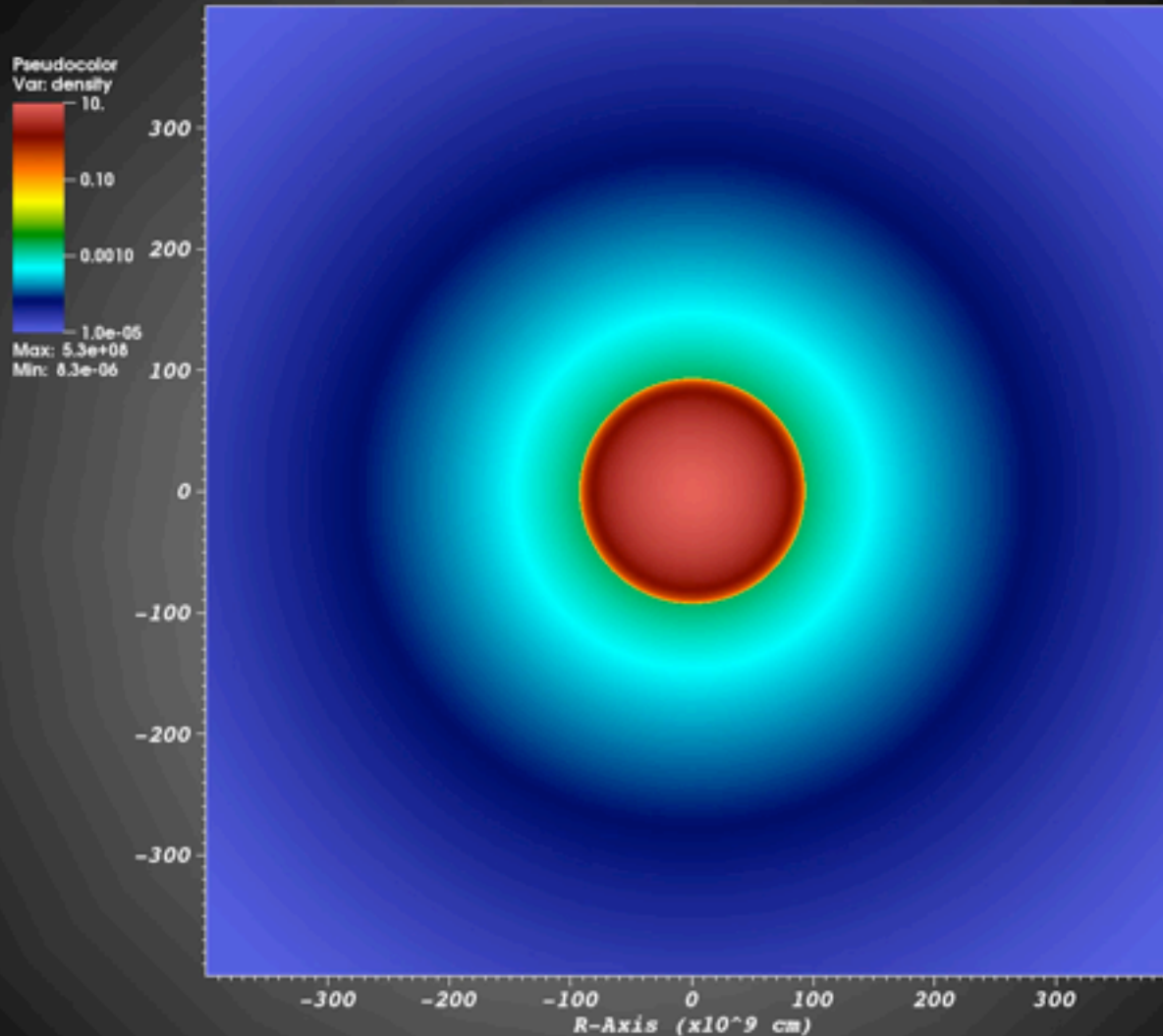


Hypernova and GRB !!!

Chen+ 2015c to be submitted

Hypernova and GRB !!!

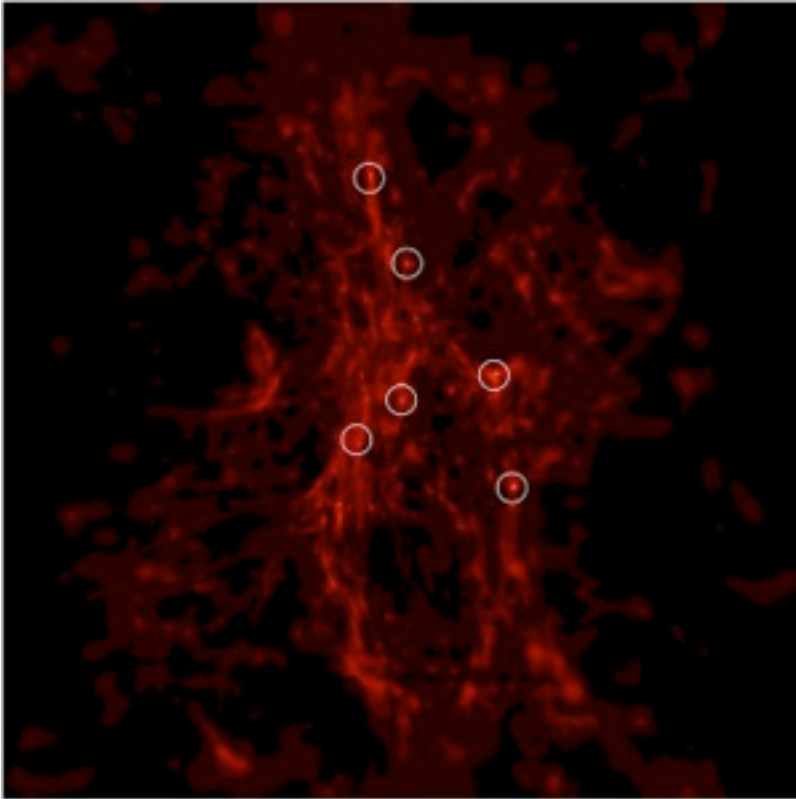
Chen+ 2015c to be submitted



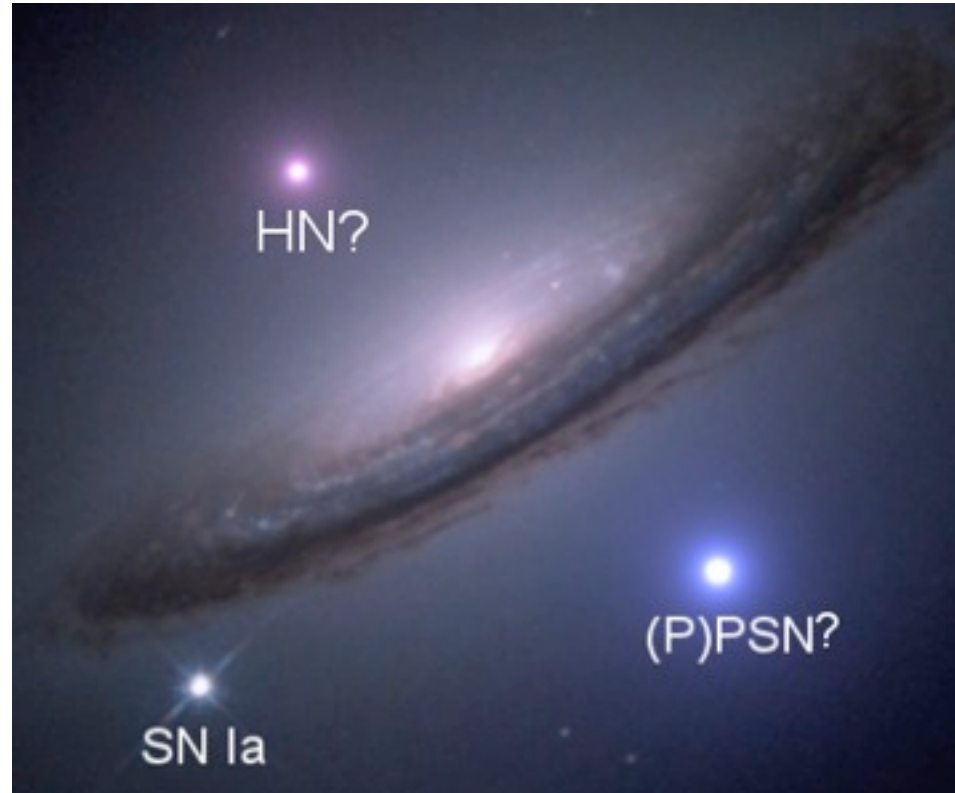
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Work in progress with NERSC SC



The First Galaxies



SN Signatures

TMT



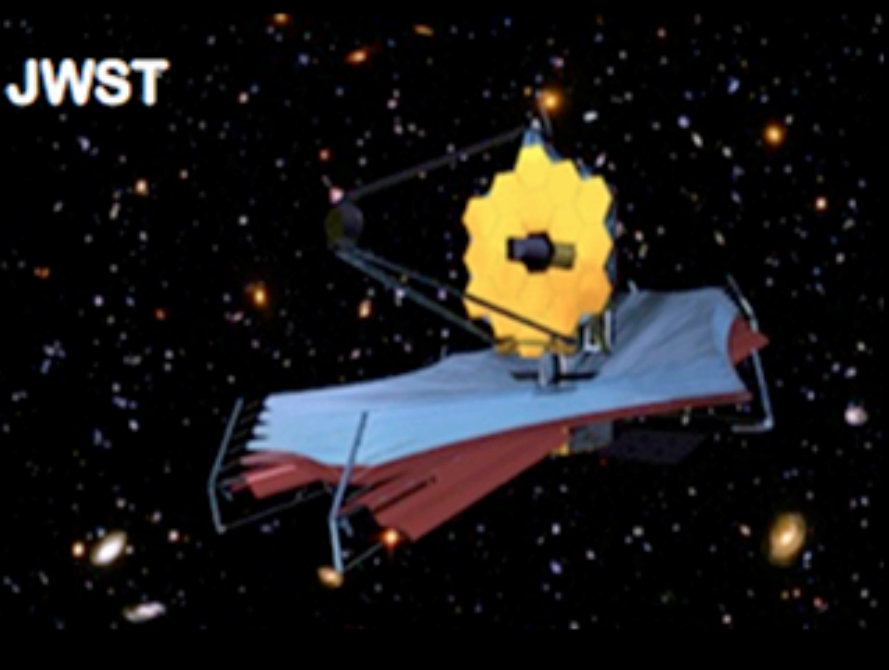
LSST



GMT



JWST





Many thanks for your attention



My work has been kindly supported by:



Office of Science
U.S. Department of Energy



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SANTA CRUZ
1965–2015

THE ORIGINAL
AUTHORITY ON
QUESTIONING
AUTHORITY