# The First Billion Years of the Universe

## Rising Galaxies

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陳科榮
**EACOA Fellow, ASIAA/NAOJ**
**ASIOP Friday Seminar, Mar. 2 2018**

# East Asian Core Observatories Association (EACOA)

Japan Taiwan China Korea

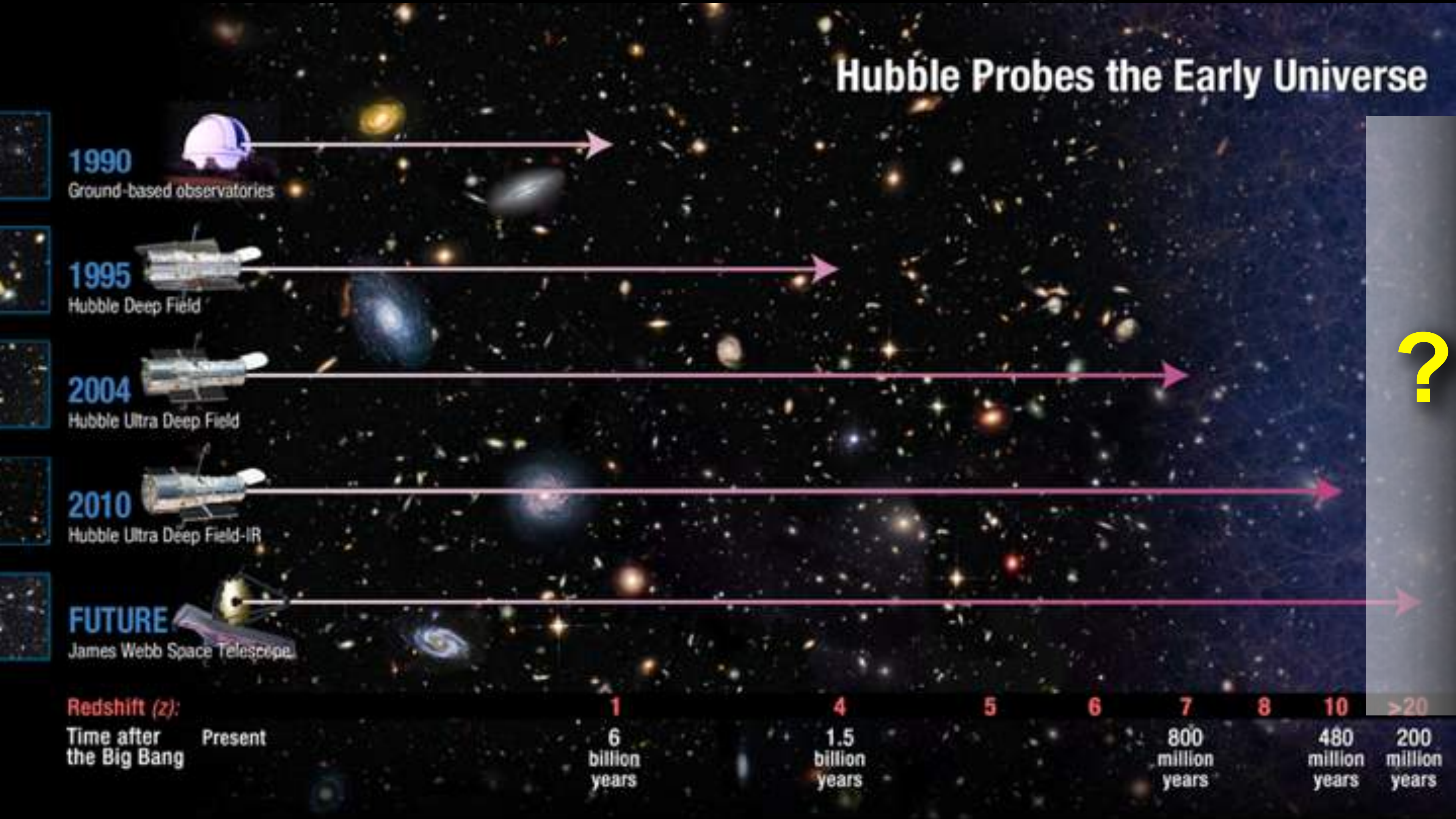
## EACOA Postdoctoral Fellowship

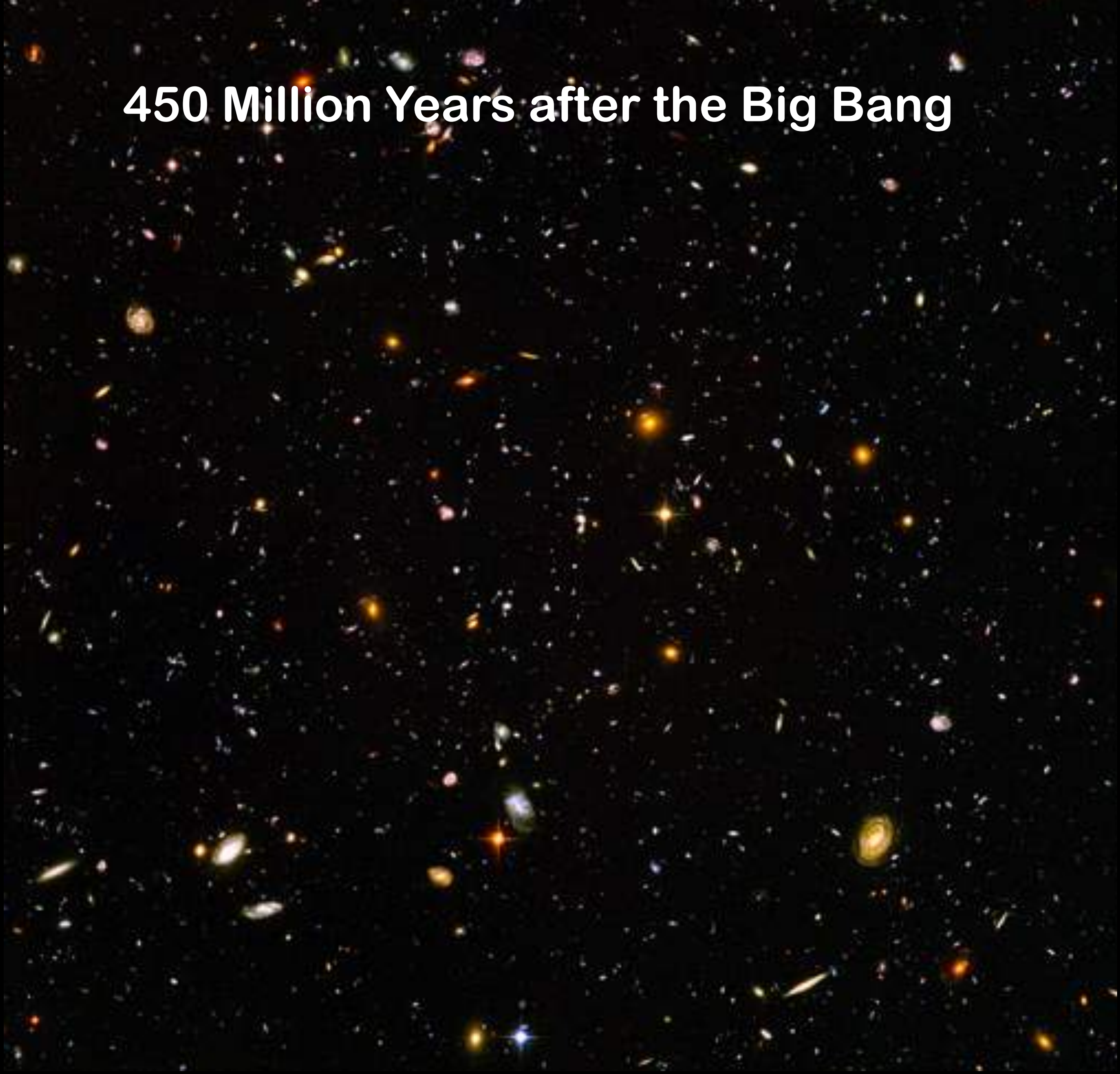
- 3 year duration (used to 5 year when I applied)
- 100% Freedom
- $20,000+ annual research fund
- $60,000 annual stipend (tax-free, comparable to $80-90K before tax in USA )
- $4,000 relocation
- Fellows are free to select at least two host institutions from the EACOA member institutions and have the opportunity to access all research facilities run by the EACOA member institutes, including the LAMOST, Subaru Telescope, CFCA, ALMA, etc.

# The Explosion Group at ASIAA


Since Sep. 2017 ~

# History of Universe






HST (10 days)

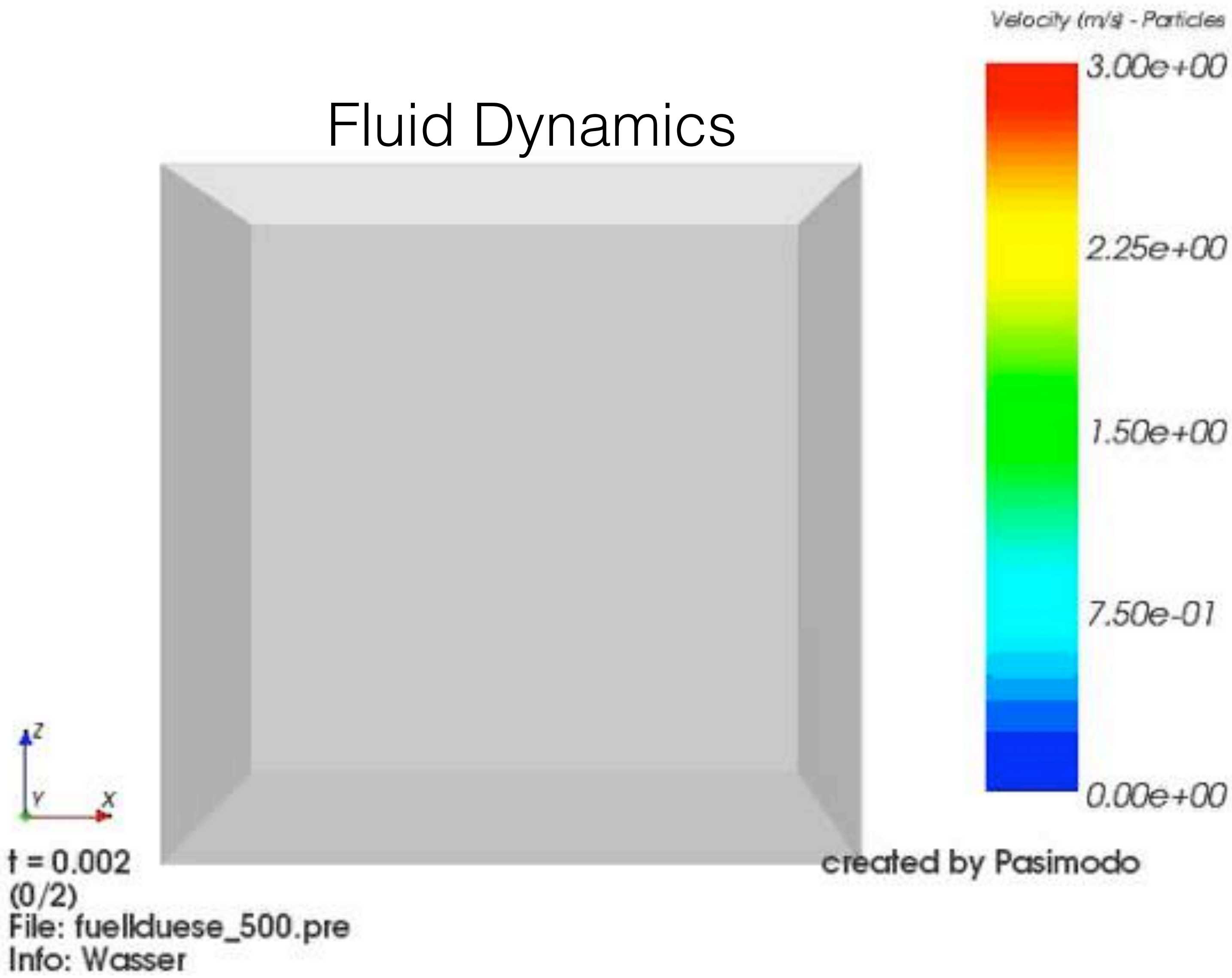
# The Beginning of Story


Prof. Alexander Heger
Larkins & Future Fellow
Monash University


Prof. Volker Bromm
Trumpler Award Winner
UT-Austin

# Simulation based on Fundamental Physics Laws

Fluid Dynamics

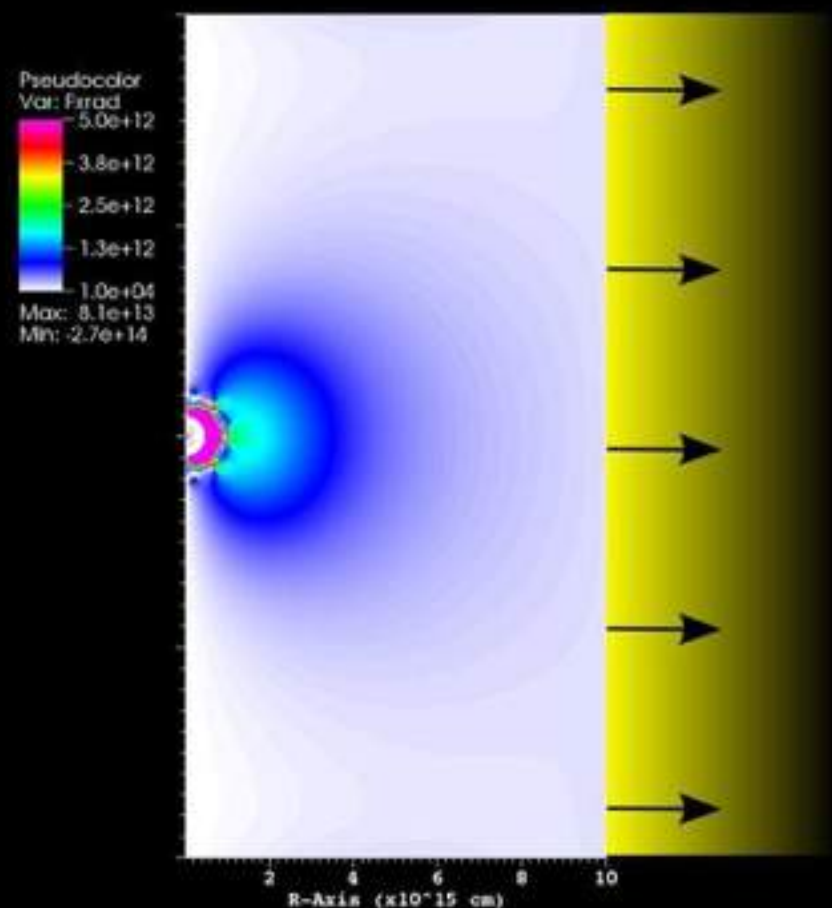



**Lehnart, et al. (2009)**

# Mixing of Coffee and MilK

# Cosmology, star formation, supernovae etc

Supercomputers are required to theoretical astrophysical models !!!




1D models

Stellar Evolution > Explosions
> lights > yields

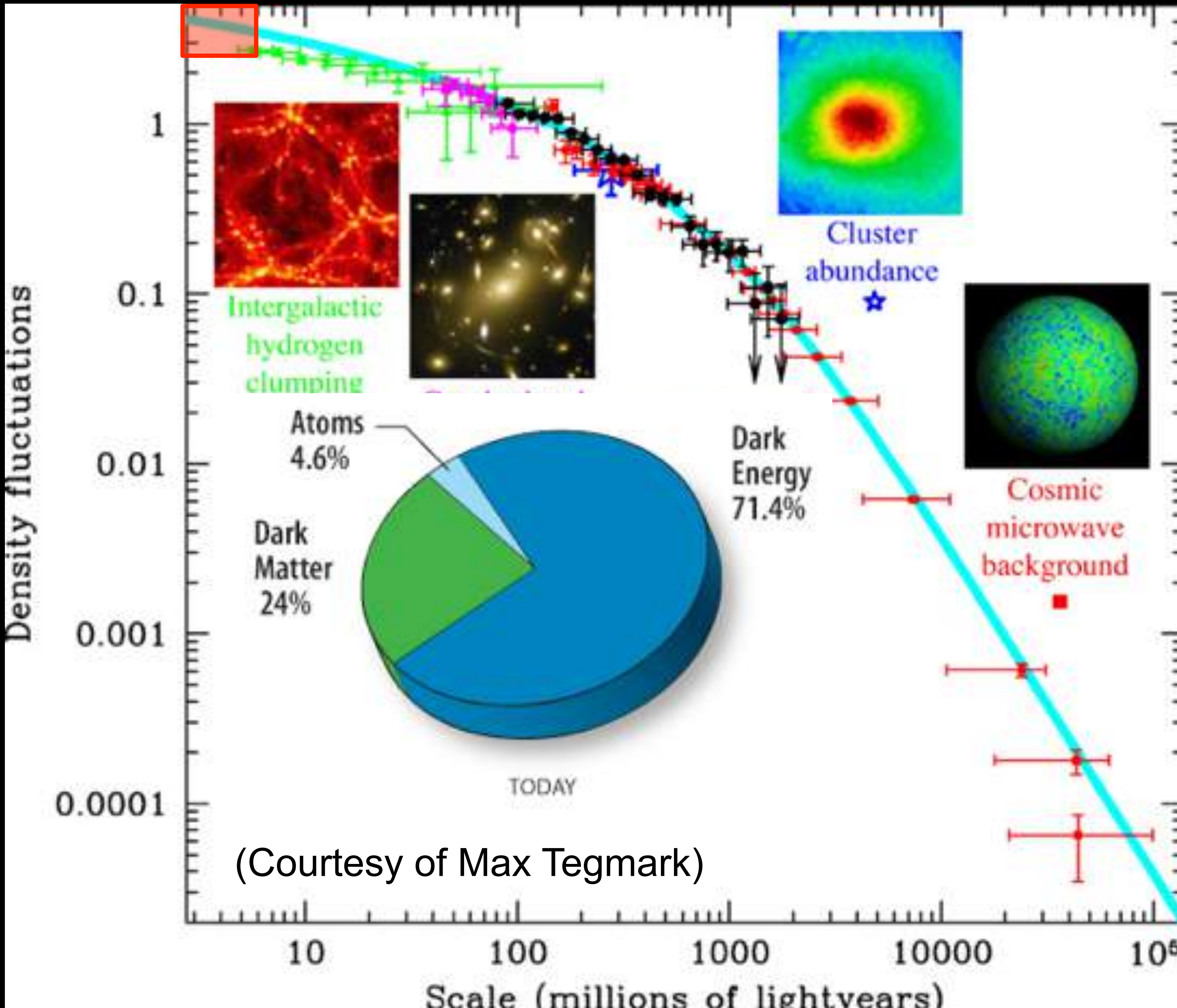
Crazy Multi-D models

Stellar Evolution > Explosions
> lights > yields

**Observations !!!**

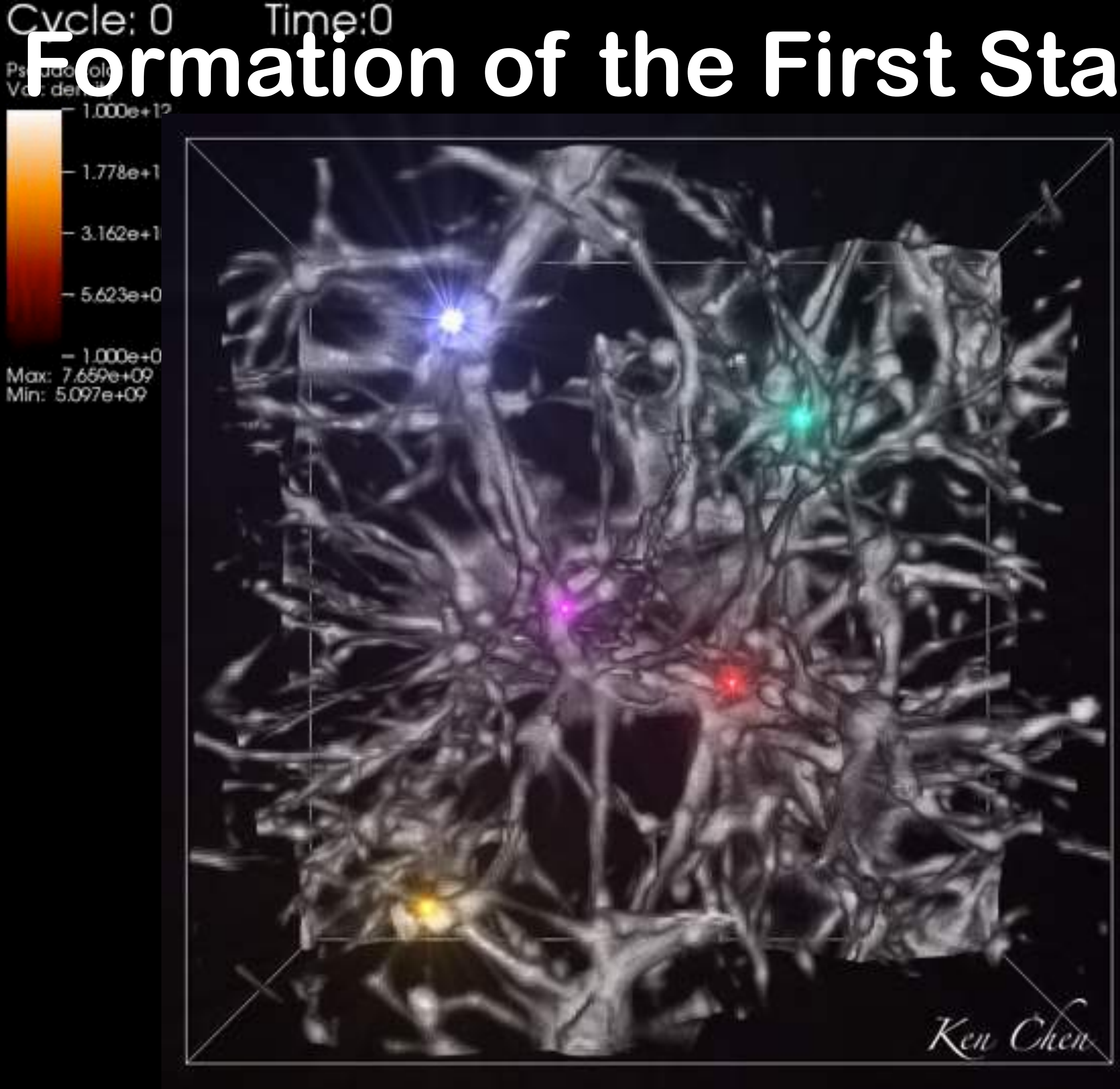
# The Telescope for Simulators

# Initial Conditions for the Cosmos



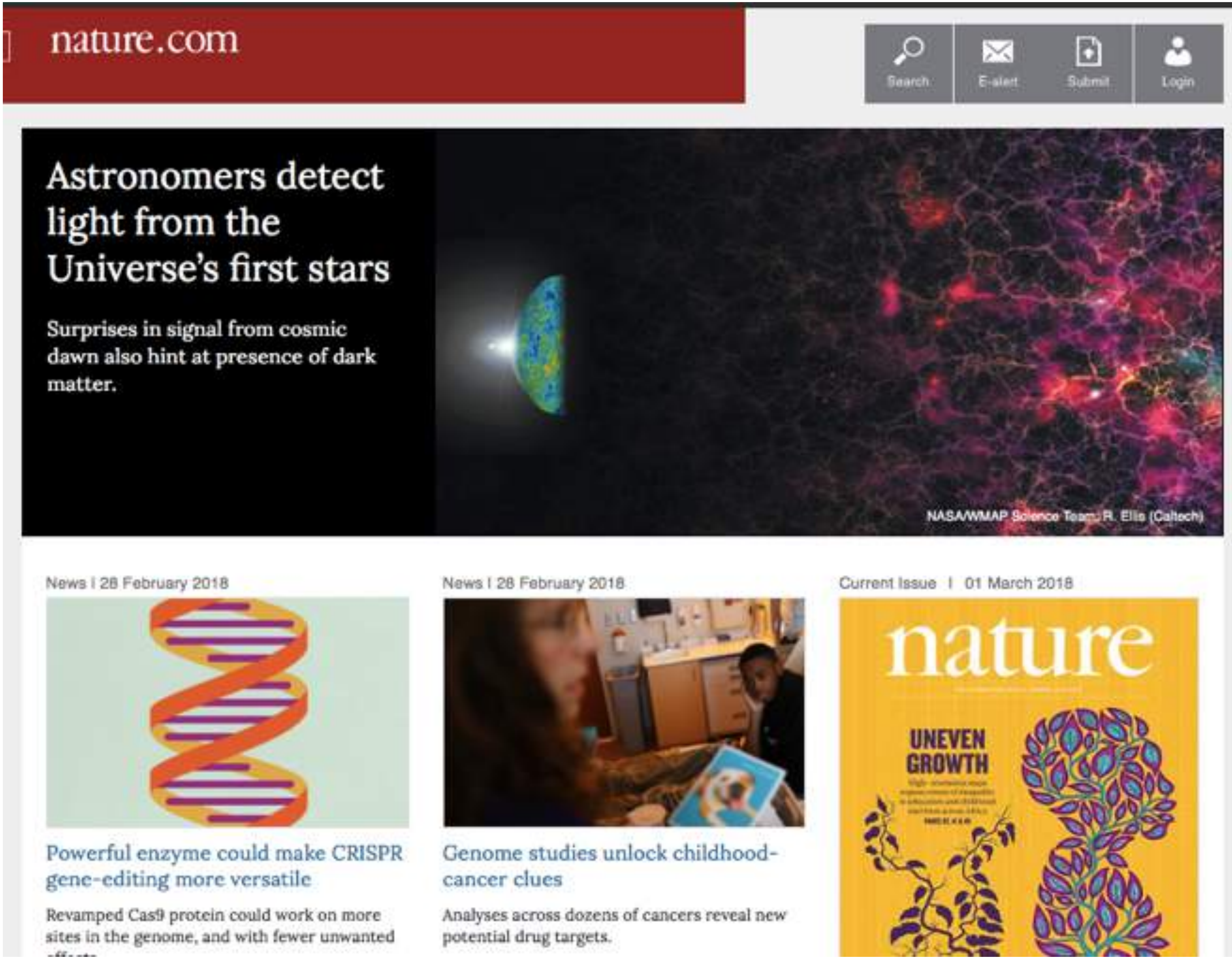

(Courtesy of Max Tegmark)

# Formation of the First Stars



# Formation of the First Star!

Courtesy of Hirano



nature.com

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# Astronomers detect light from the Universe's first stars

Surprises in signal from cosmic dawn also hint at presence of dark matter.

NASA/WMAP Science Team; R. Ellis (Caltech)

News | 28 February 2018

## Powerful enzyme could make CRISPR gene-editing more versatile

Revamped Cas9 protein could work on more sites in the genome, and with fewer unwanted effects.

News | 28 February 2018

## Genome studies unlock childhood-cancer clues

Analyses across dozens of cancers reveal new potential drug targets.

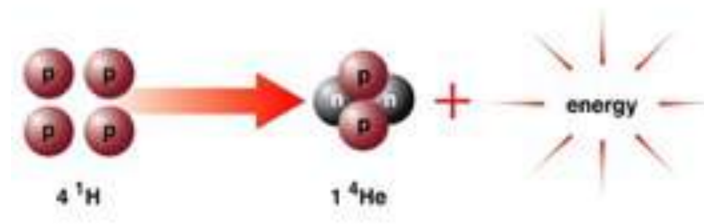
Current Issue | 01 March 2018

# Periodic Table

H 1

Big Bang fusion

He 2



## Low Energy SNe

$12\,M_\odot < M^* < 60\,M_\odot$

Trigger: iron core collapse

Dynamite: G-energy and neutrino

Characteristics:

1. 10,000+ fainter than normal SN
2. Almost no Ni ejecta
3. Strong mixing during fallback

Chen+ MNRAS 467 4731 (2017)

## Magnetar-powered SNe

$30\,M_\odot < M^* < 45\,M_\odot$

Trigger: iron core collapse

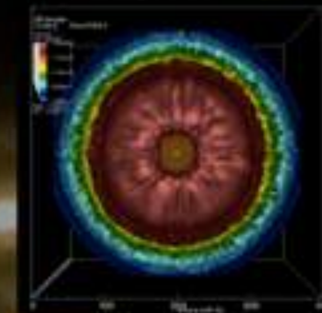
Dynamite: magnetar energy

Characteristics:

1. Luminous SN or GRB
2. $< 0.1\,M_\odot$ Ni
3. Radiation breakout at early on

Chen+ ApJ 832 73 (2016)

## Pulsational Pair-Instability SNe



$80\,M_\odot < M^* < 140\,M_\odot$

Trigger: e+/e- creation instability

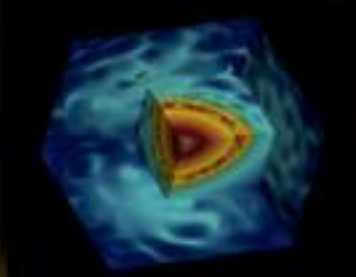
Dynamite: explosive C/O burning

Characteristics:

1. Several eruptions
2. Multi-SNe (one superluminous)
3. Mixing during shell collisions

Chen+ ApJ 792 28 (2014)

## Pair-Instability SNe



$140\,M_\odot < M^* < 250\,M_\odot$

Trigger: e+/e- creation instability

Dynamite: explosive O/Si energy

Characteristics:

1. faint or superluminous SN
2. 0.2 to $30\,M_\odot$ Ni
3. Mixing by reverse shock or burning

Chen+ ApJ 792 44 (2014)

## GR Instability SNe

$54{,}000\,M_\odot < M^* < 56{,}000\,M_\odot$

Trigger: GR instability

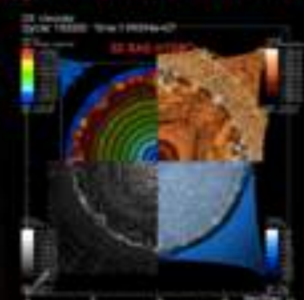
Dynamite: explosive He burning

Characteristics:

1. Energetic explosion ~ 1E55 erg
2. No Ni and no superluminous
3. Mixing by burning

Chen+ ApJ 790 162 (2014)

## Radhydro models of Exotic SNe

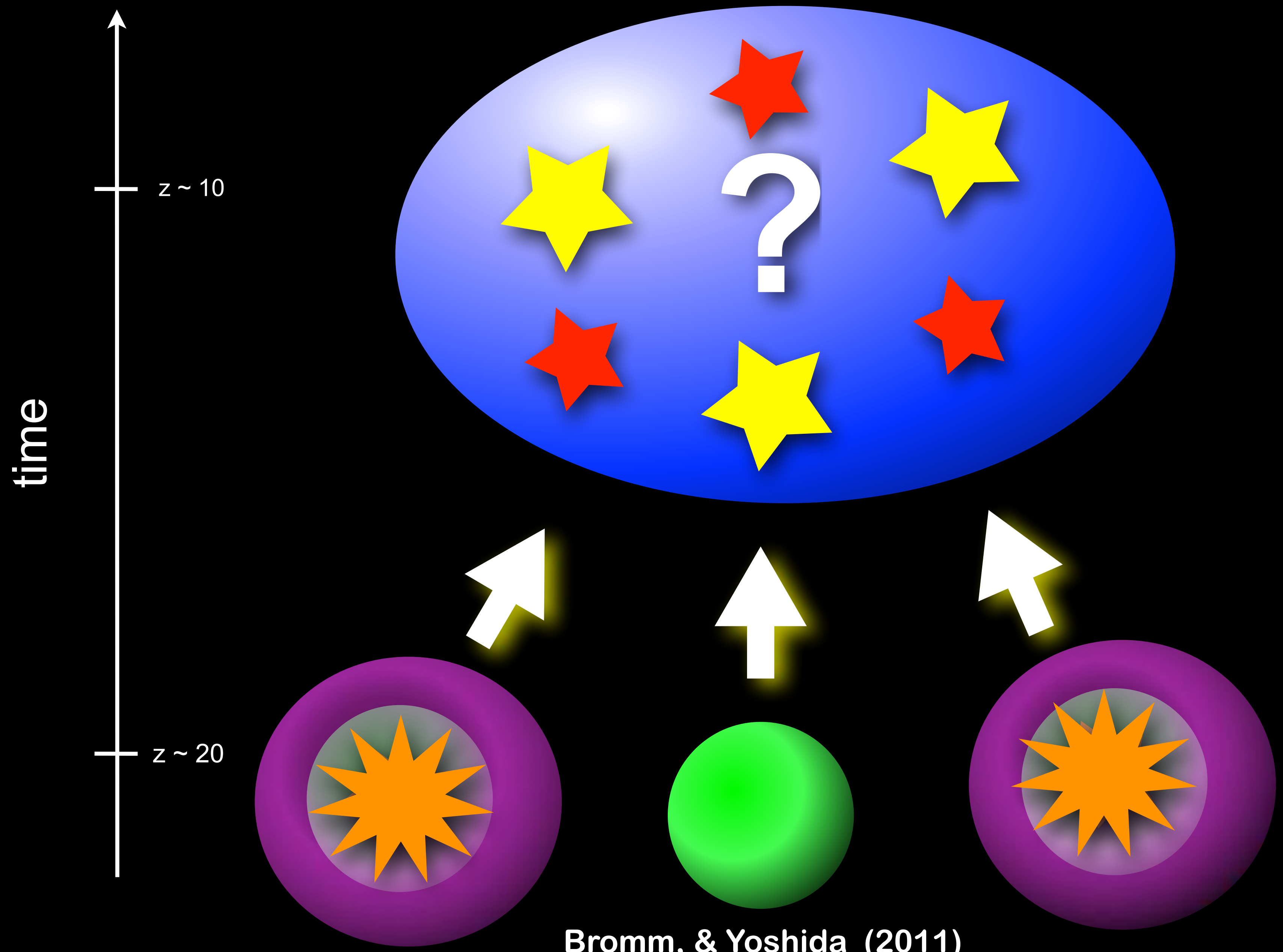


$30\,M_\odot < M^* < 140\,M_\odot$

To advance the state of the art in synthetic light curves and spectra for SNe of massive stars. We perform multidimensional radiation hydrodynamics simulations to obtain their light curves and use time-dependent monte carlo radiative transfer calculations to retrieve the detailed spectra that can be directly compared to actual data.

Chen, Woosley, Zhang. In prep

# How did the First Galaxies Form?




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

# Cosmological Simulations

Chen+ ApJ (2015)

## 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

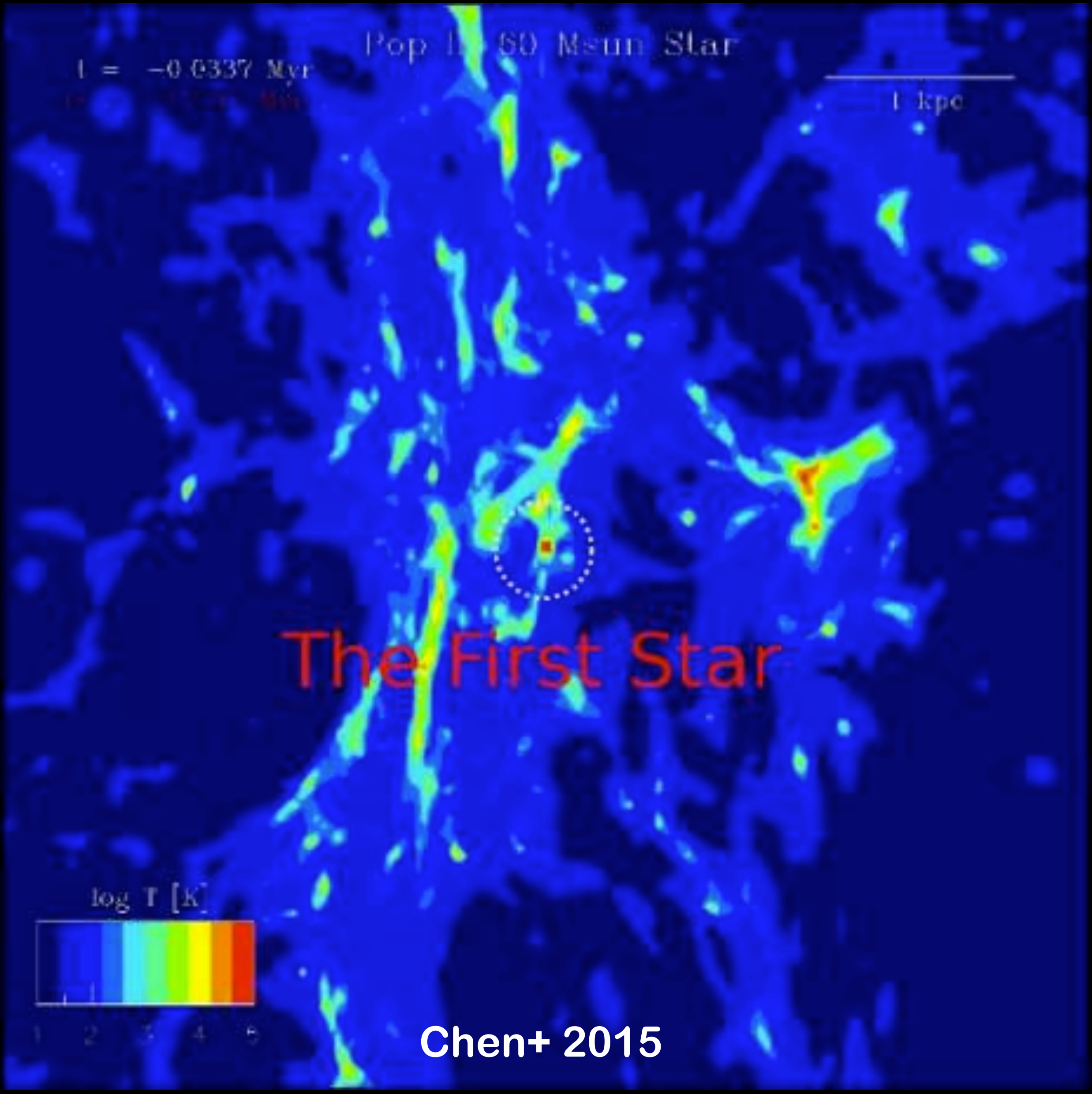
## Possible radiative feedbacks

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

## Chemical enrichment

1. SN feedback

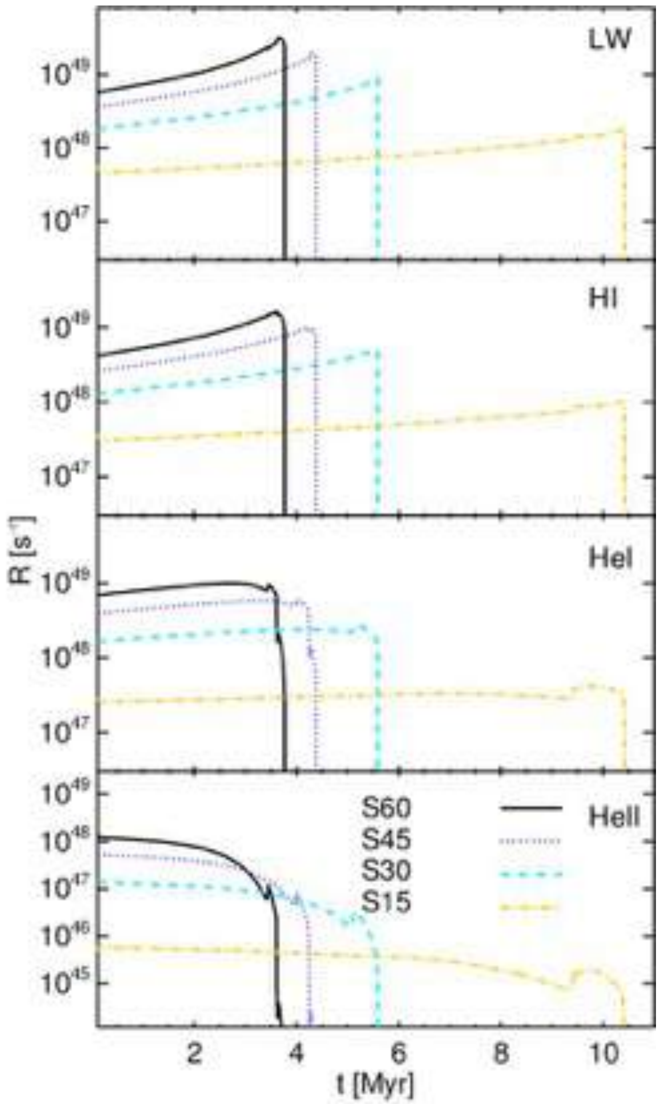
Detailed Stellar Models



Pop III 60 Msun Star
t = -0.0337 Myr
1 kpc
The First Star
log T [K]
1 2 3 4 5


Chen+ 2015

# 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

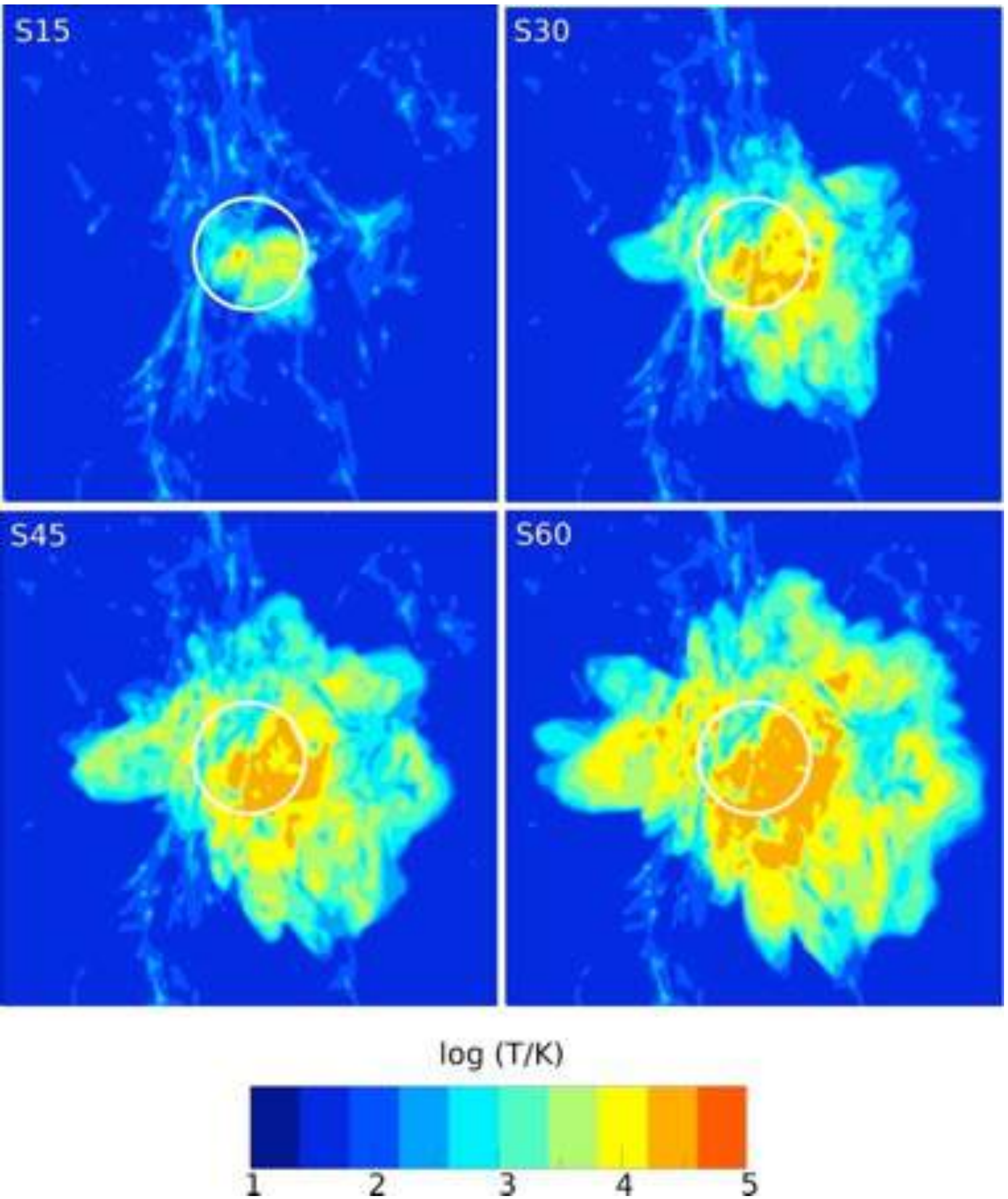
| $X^a$ | Type | Masses | $E^b$ | mass ejection | Notes |
|---|---|---|---|---|---|
| | | ($M_\odot$) | (B) | | |
| S | SN | $\lesssim 25$ | 1.2 | all but $\sim 1.5\,M_\odot$ | leaves neutron star |
| B | BH | $\gtrsim 25$ | 0 | None | complete collapse to BH |
| H | HN | $\lesssim 25$ | 10 | $\sim 90\,\%$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

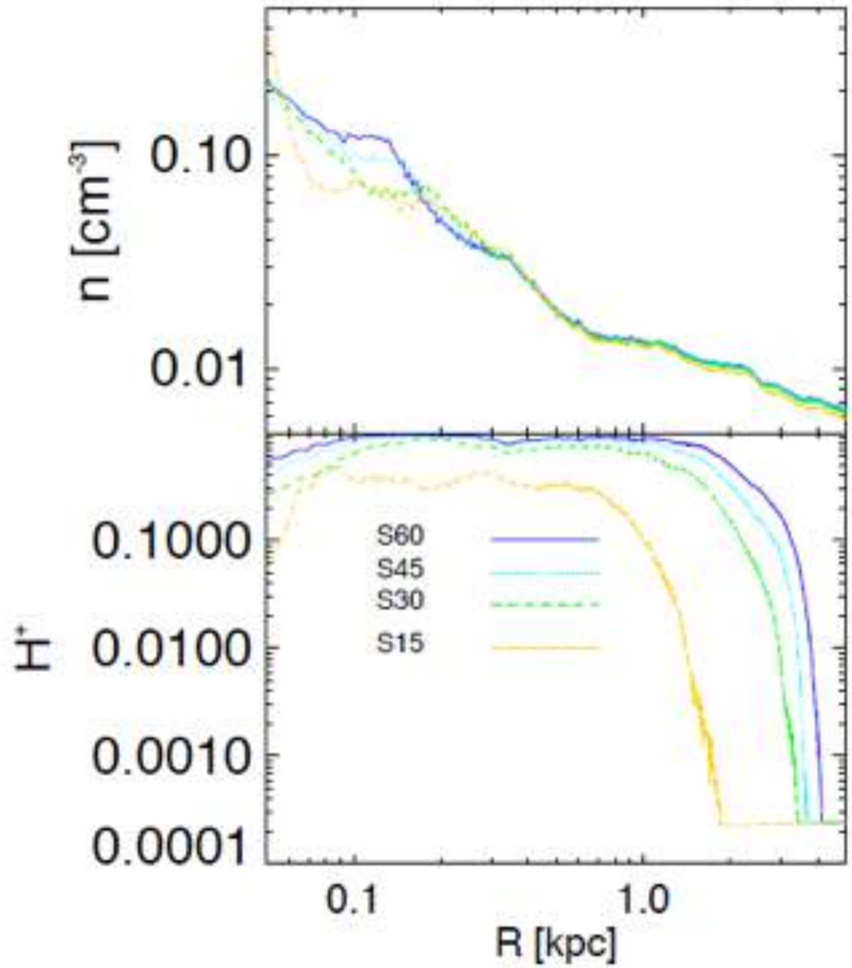
Table 10.2 Summary of assumed stellar fate characteristics: [a] sentinel used in model names to indicate fate of star. [b] Explosion energy.

| 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 |

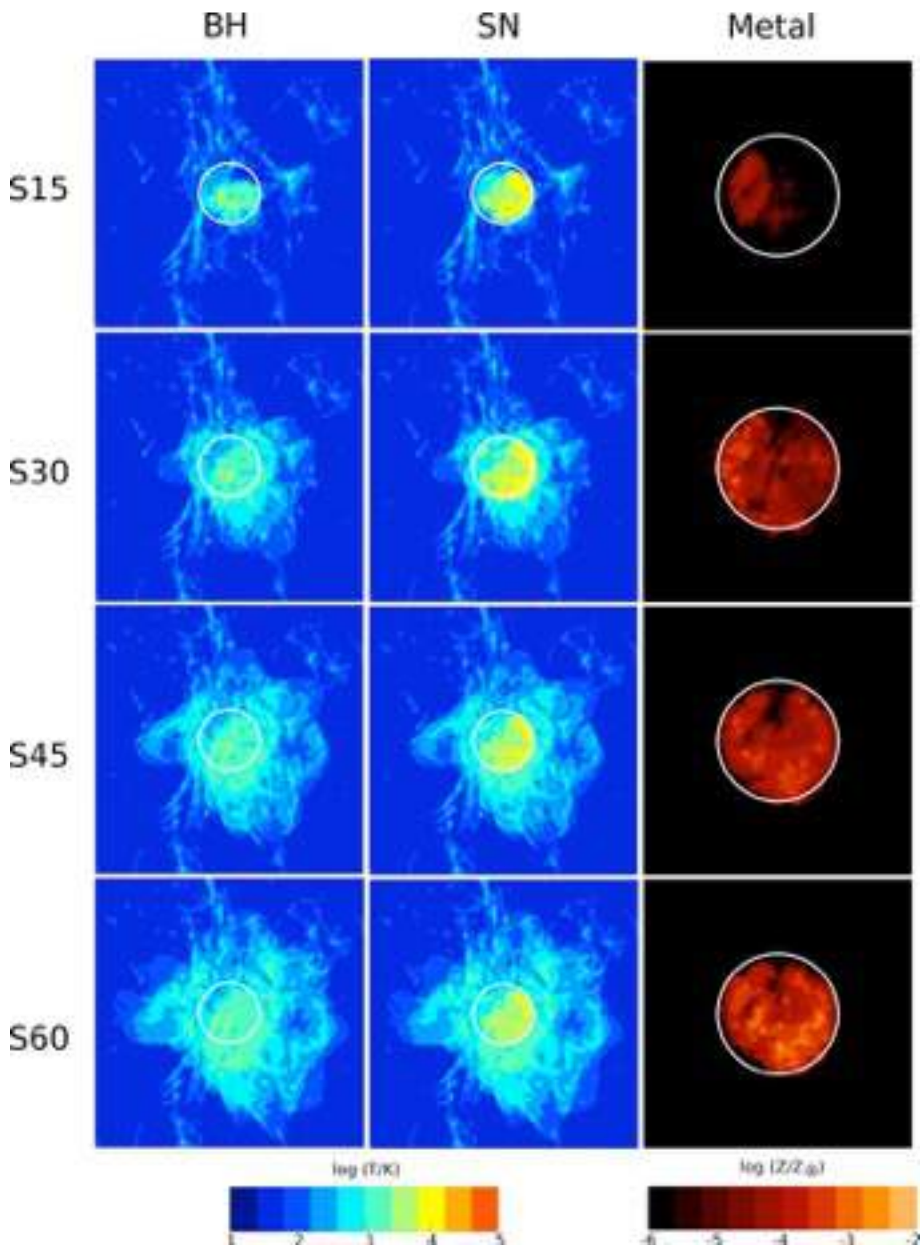
Table 10.3 Number of ionizing photons emitted over the lifetime of a star.

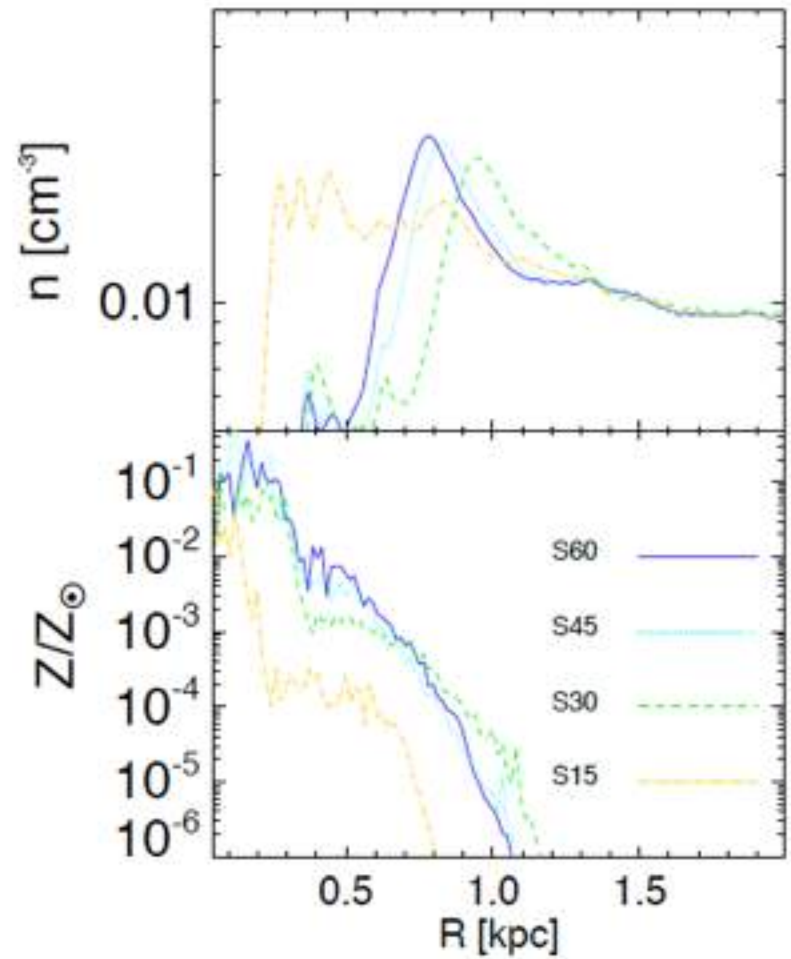
# Radiative Feedback



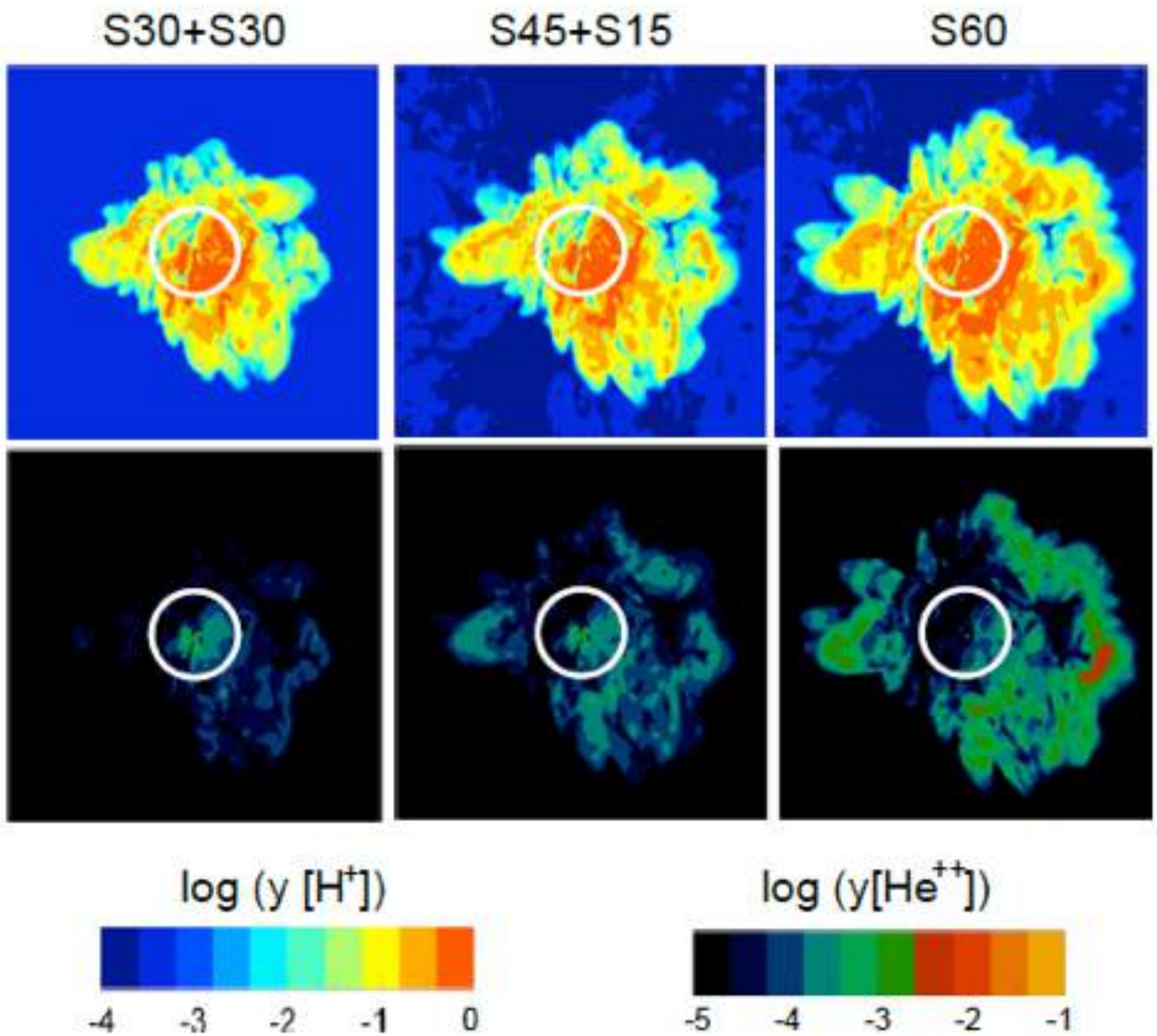



# Radiative+Supernova Feedback

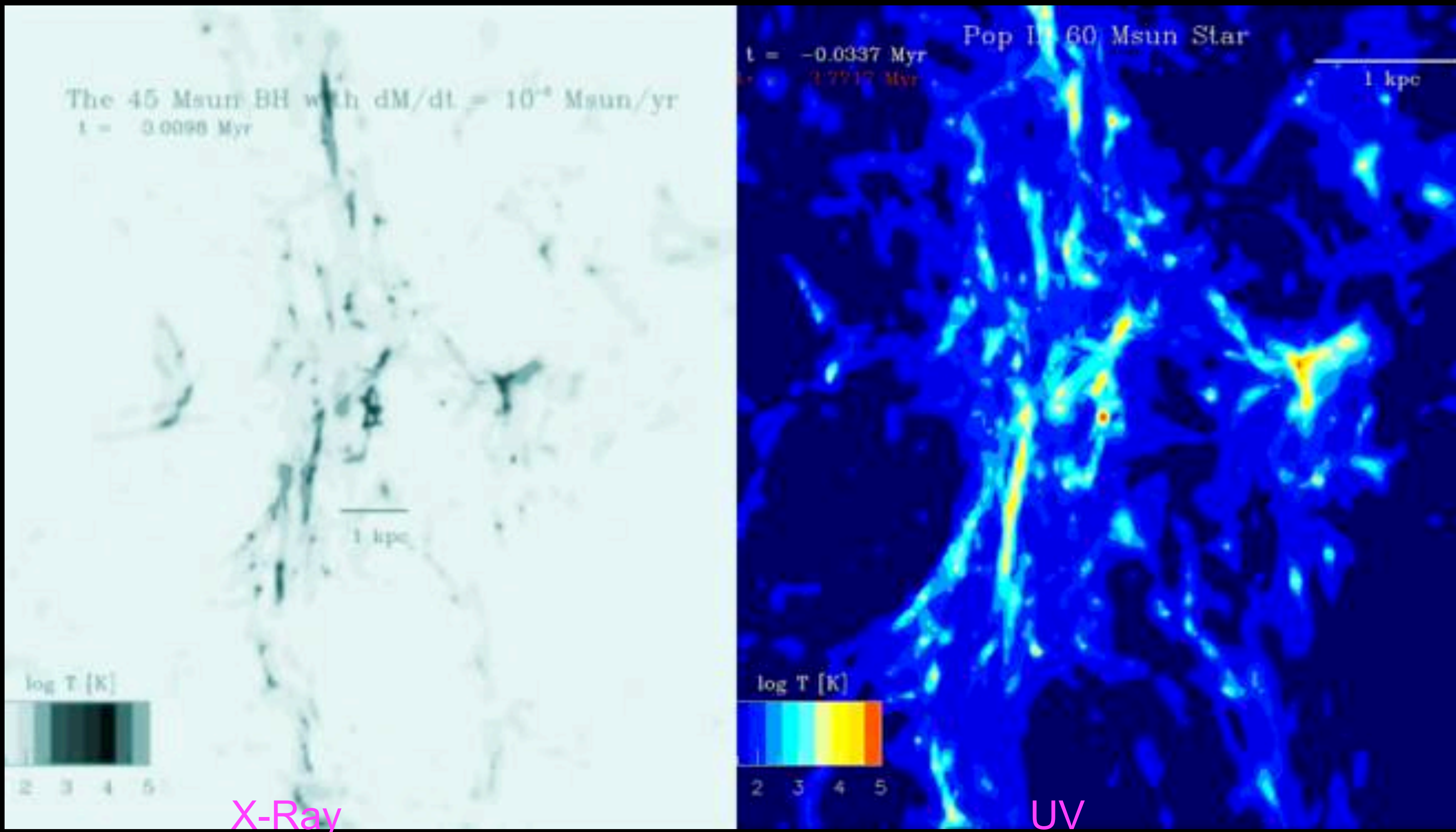


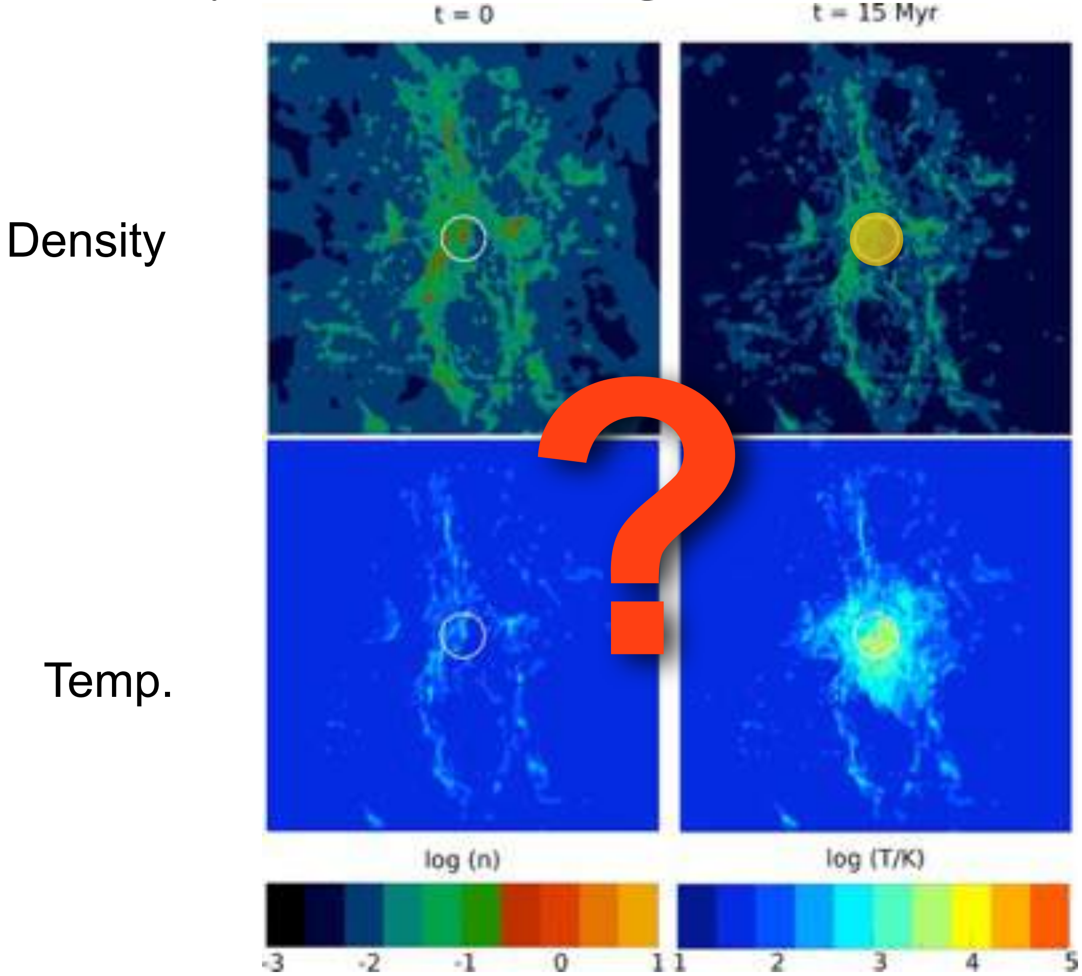
# Radiative Feedback (Binaries)



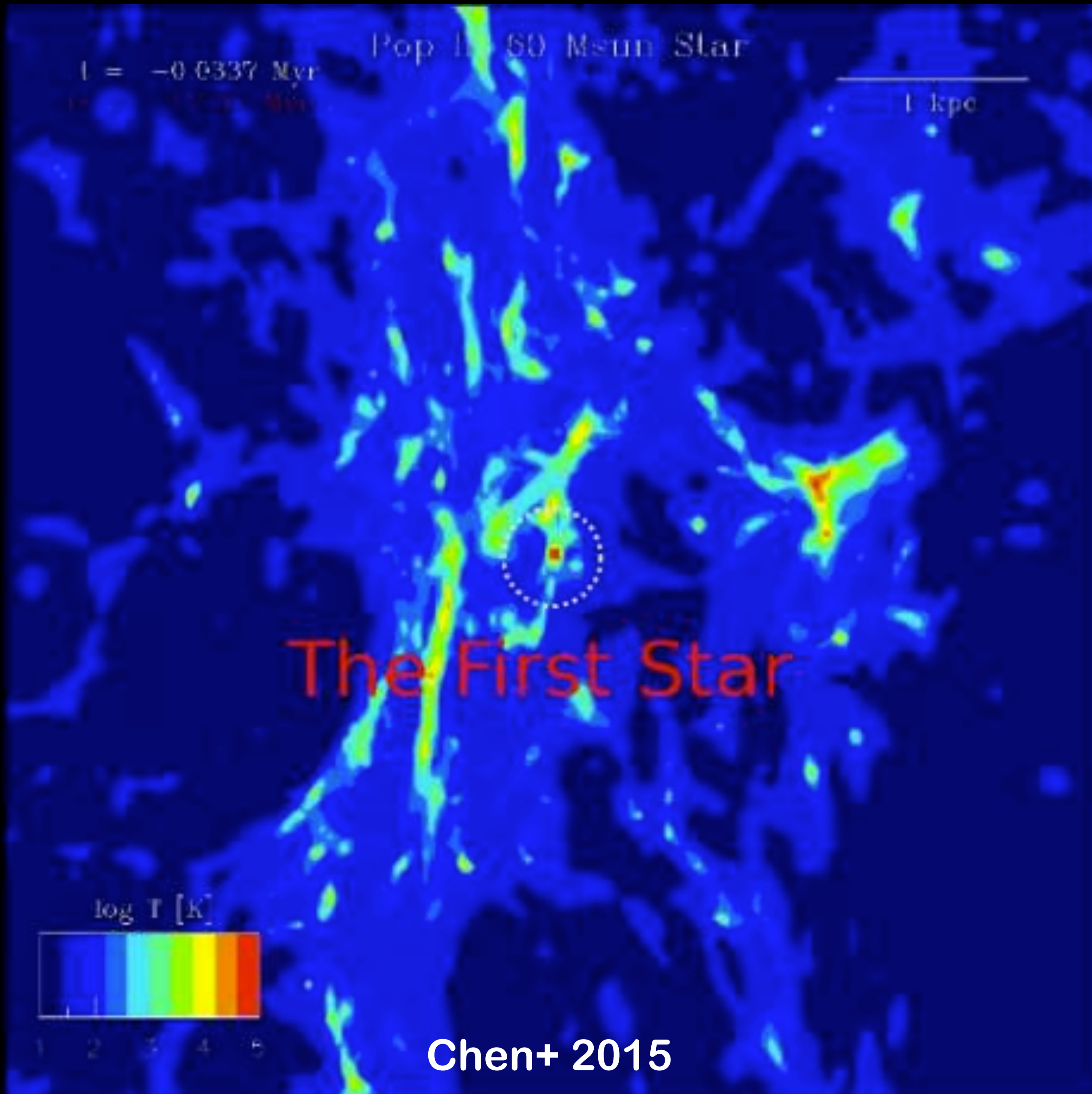
# Radiative Feedback of X-ray and UV



# Properties of Large Scale Structure

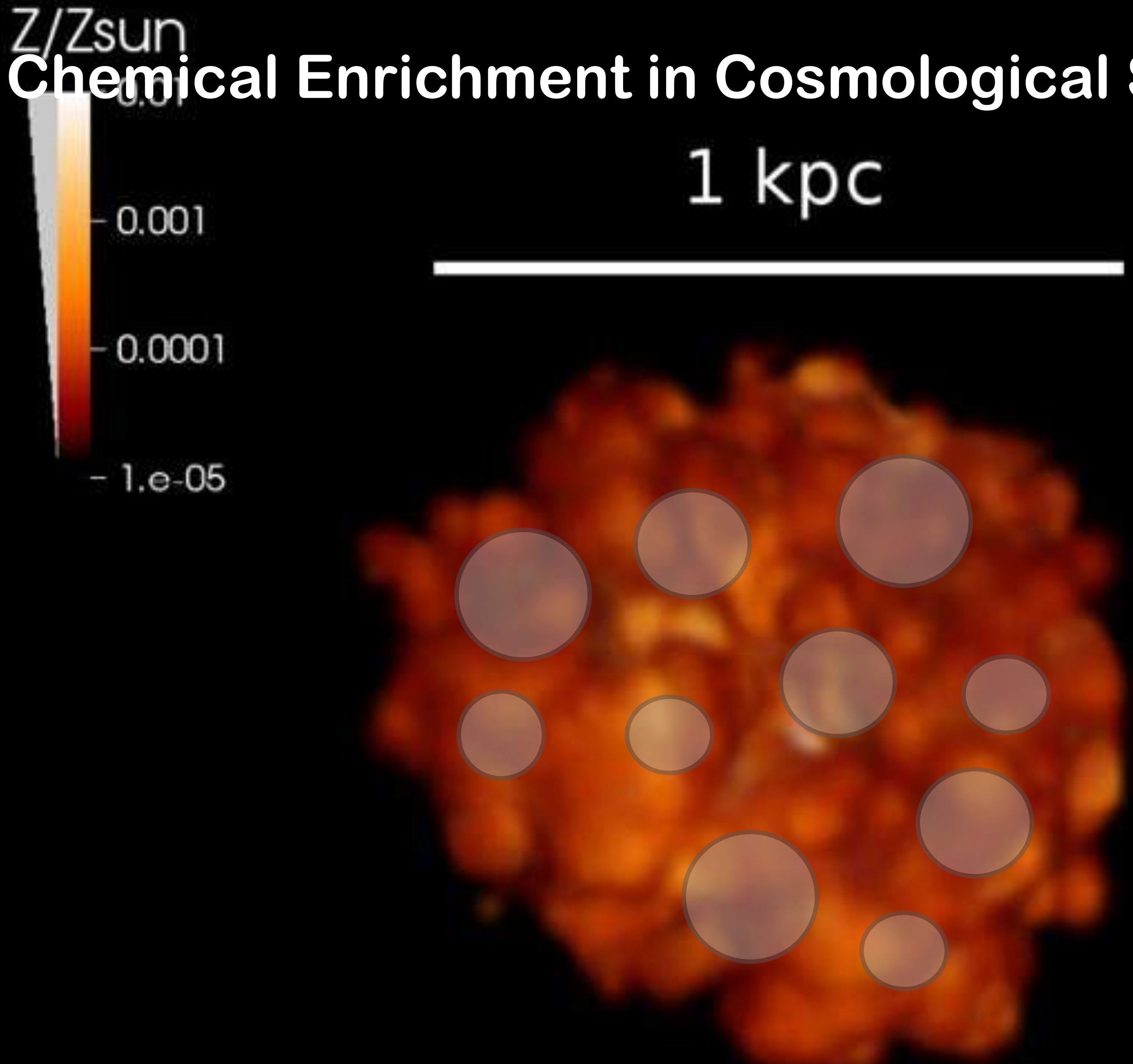



| | radiation | SN metal |
|---|---|---|
| single star | strong | weak |
| binary star | weak (x-ray) | strong |



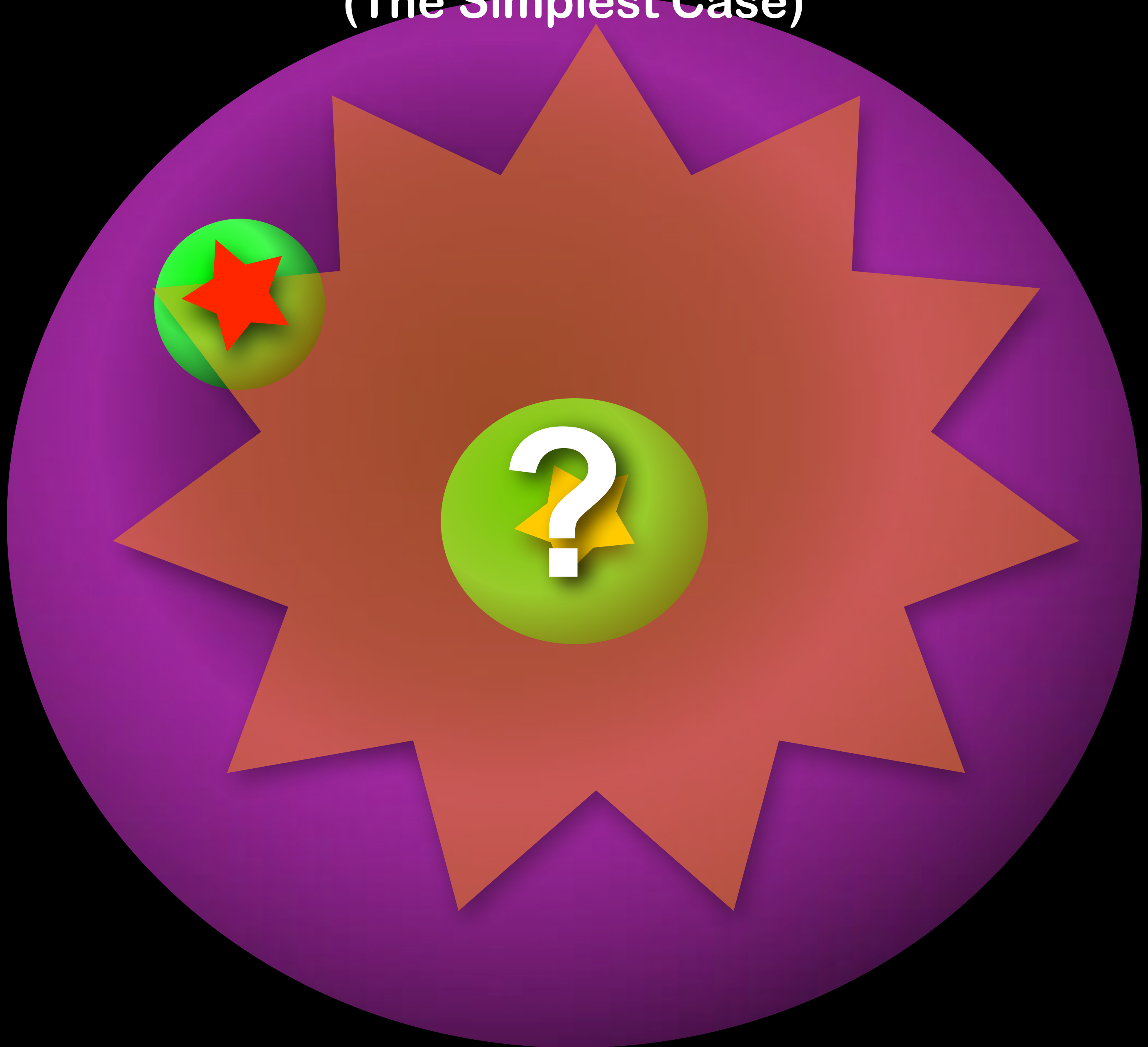

Chen+ 2015

# Chemical Enrichment in Cosmological Simulations




Chen+ 2015

# How did the first stars regulate the star formation in nearby halo?
(The Simplest Case)

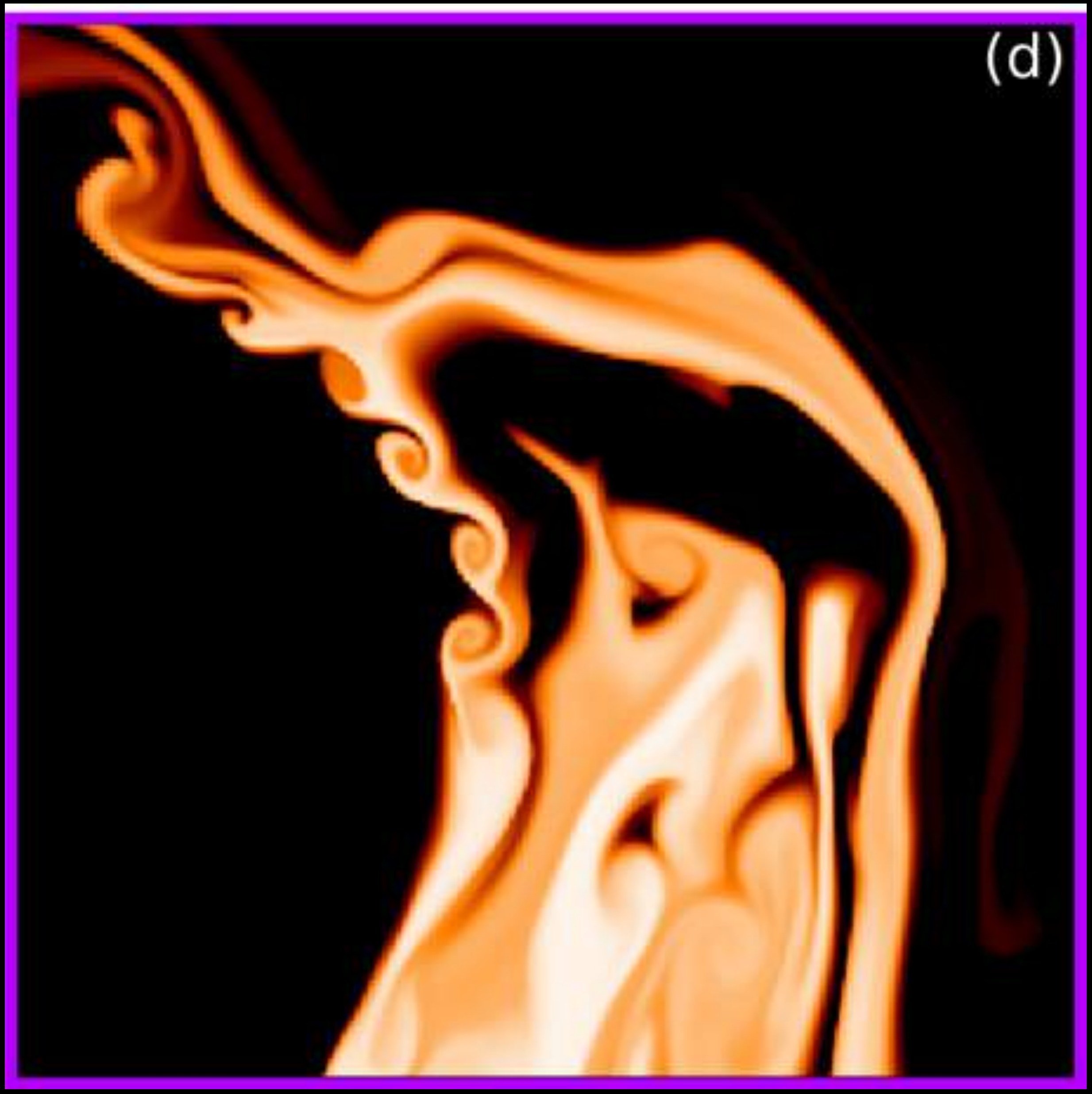


# Chemical Enrichment in Reality?

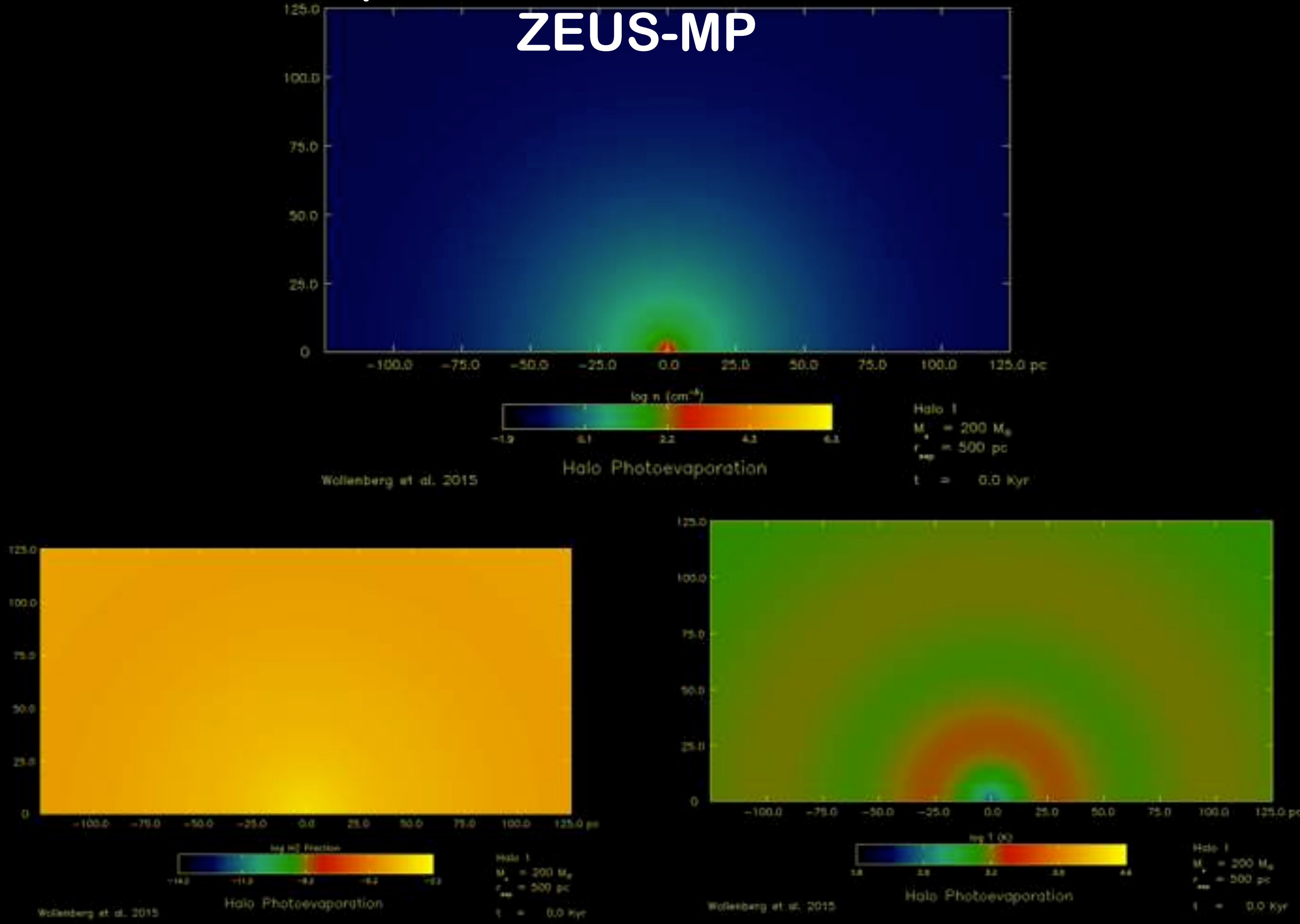
**DM Halo (松本城)**

**SN Metals （初代武士？）**

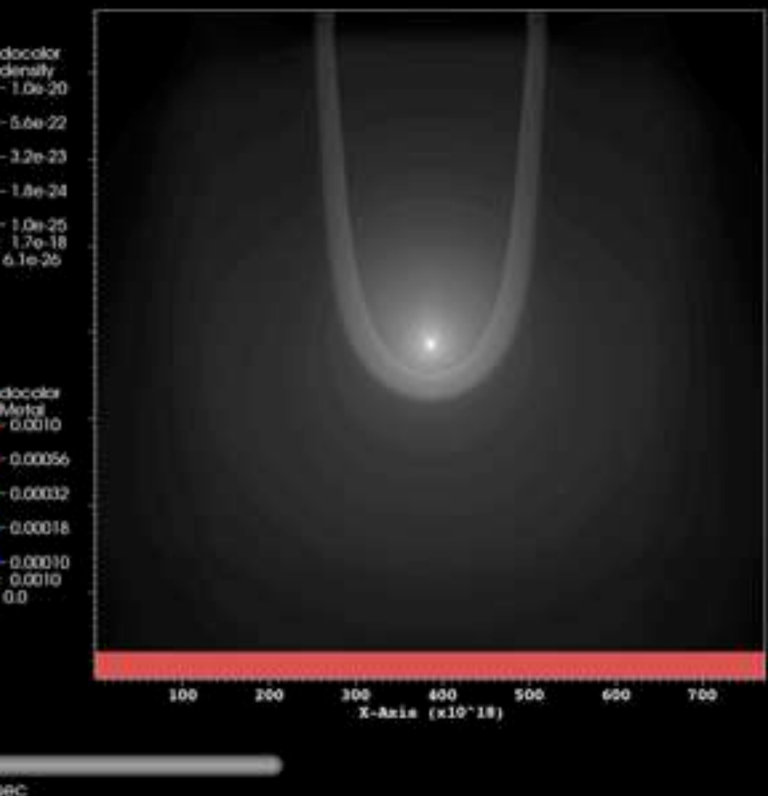
# Resolving the small scales



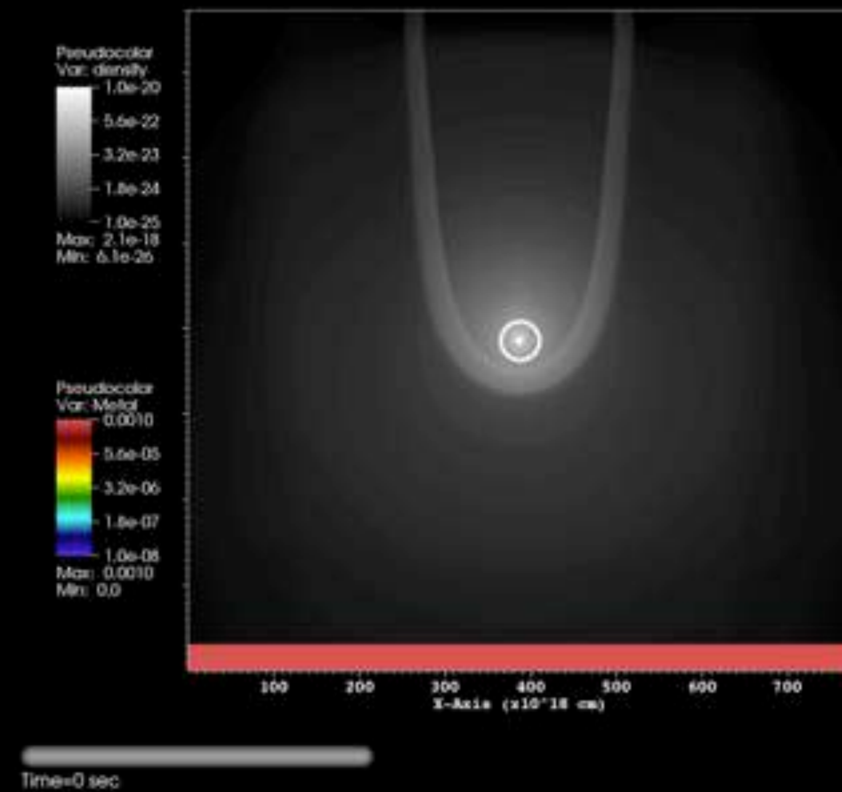
# The Impact of Radiative Feedback
## ZEUS-MP



# The impact of supernovae to nearby halos



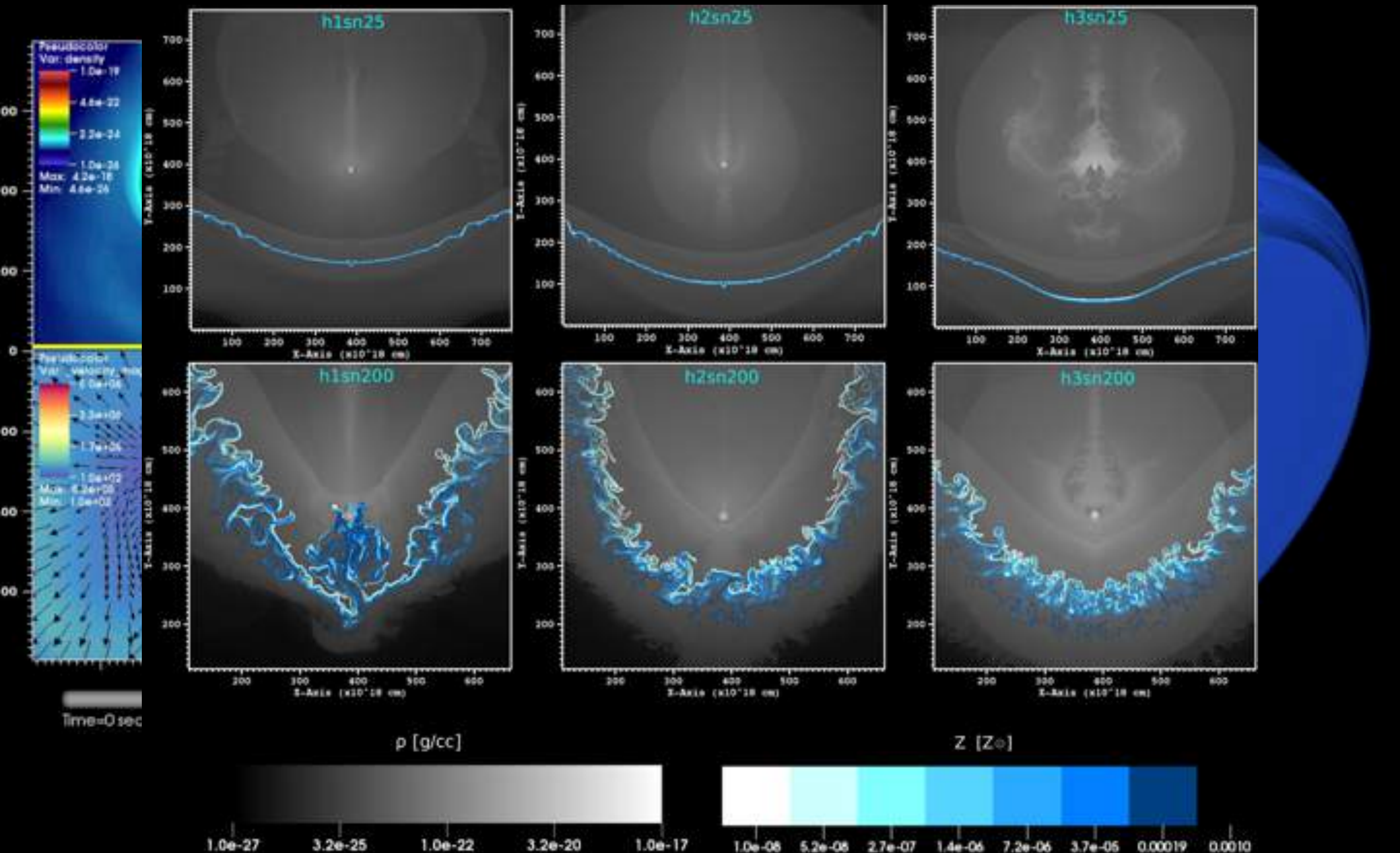

Strong SNe




Real SNe

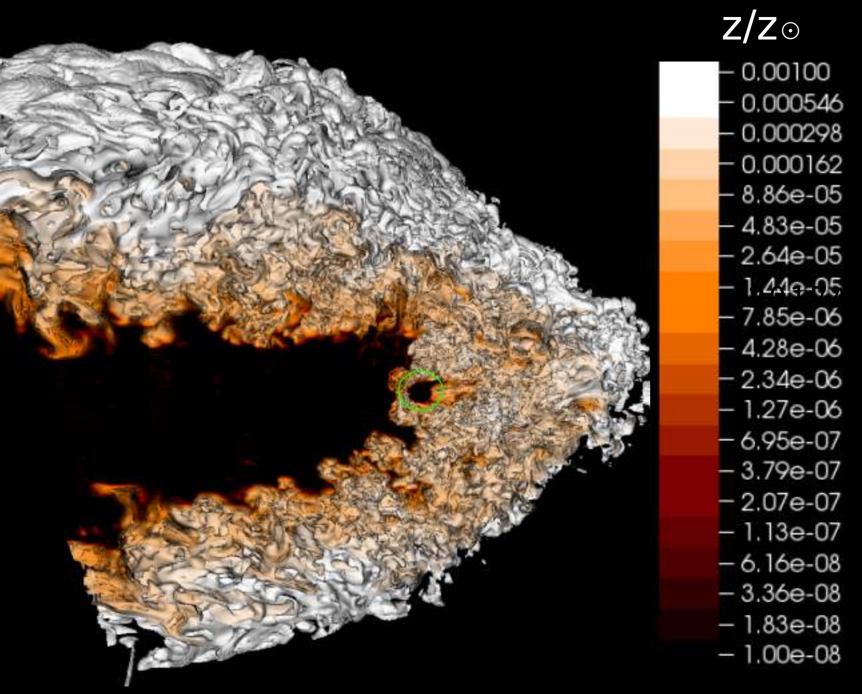
# SN chemical enrichment in the realistic setup

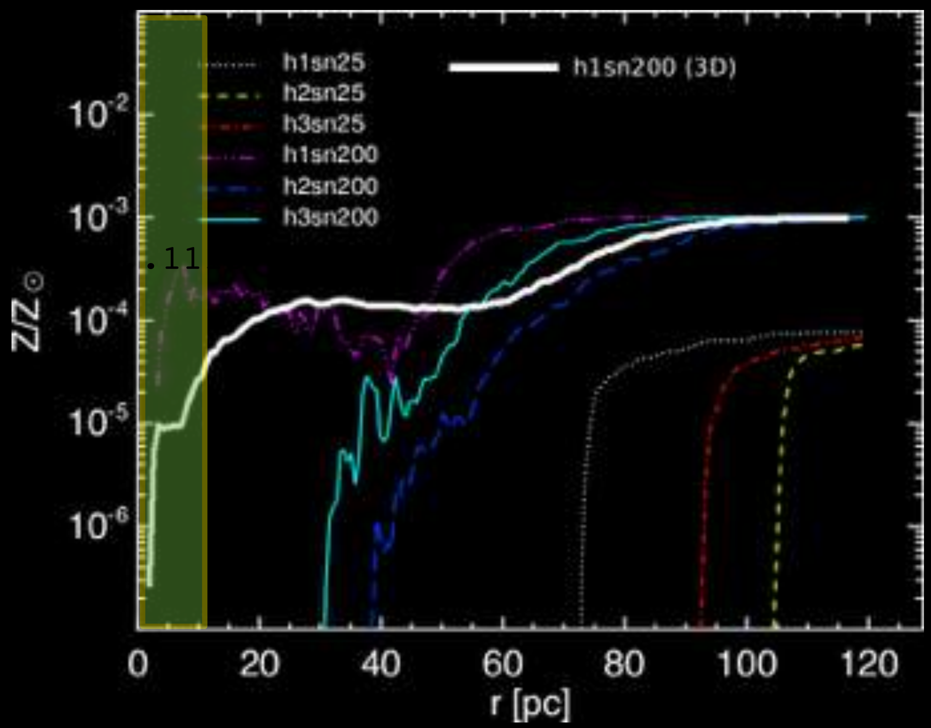
**Chen+ ApJ 844 111 (2017)**



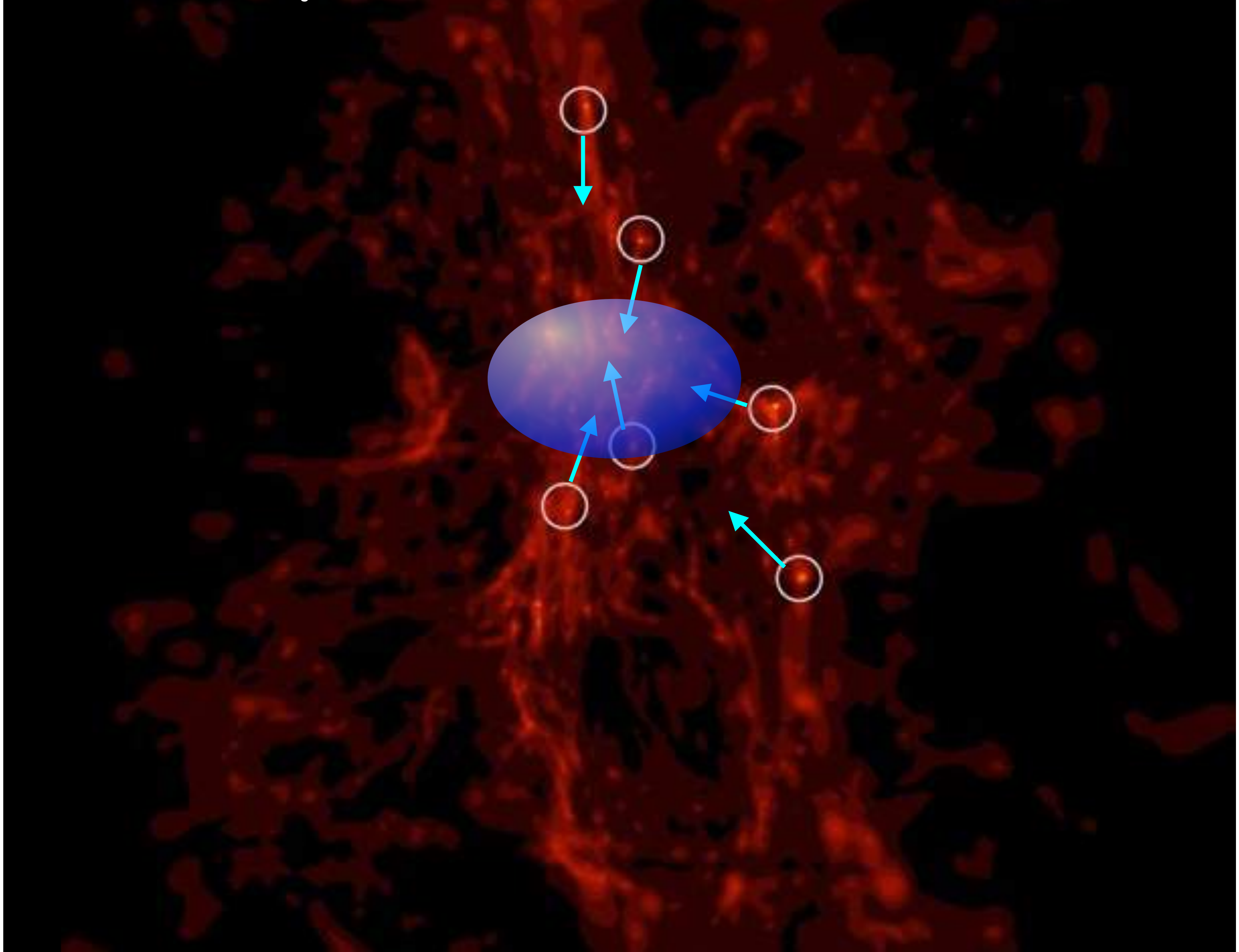
# How deep can the metal go ??

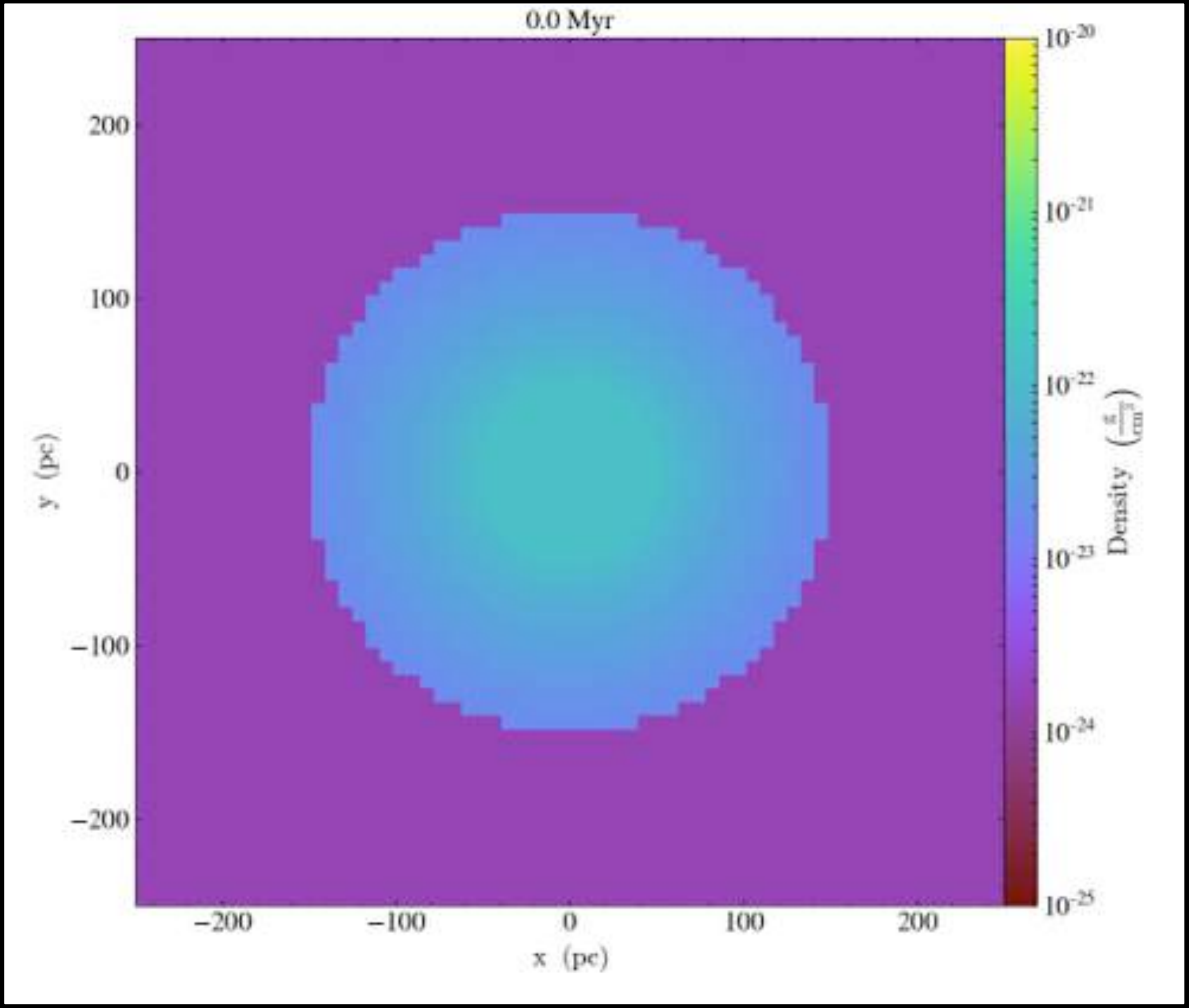
**Chen+ ApJ 844 111 (2017)**

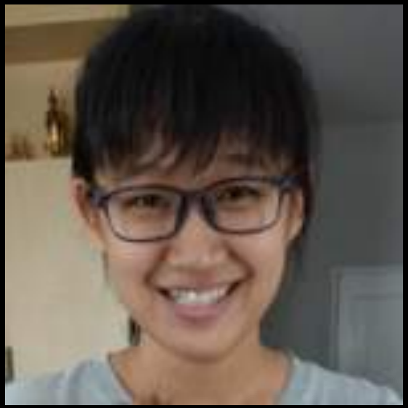


# From Pop III IMF to the First Galaxies





Spherical Collapse

- Self-Gravity
- Chemical cooling
- Velocity Turbulence
- Star formation with feedback like mass ejection and UV radiation, etc.


趙子翔 Tzu-Hsiang Chao (ASIAA)

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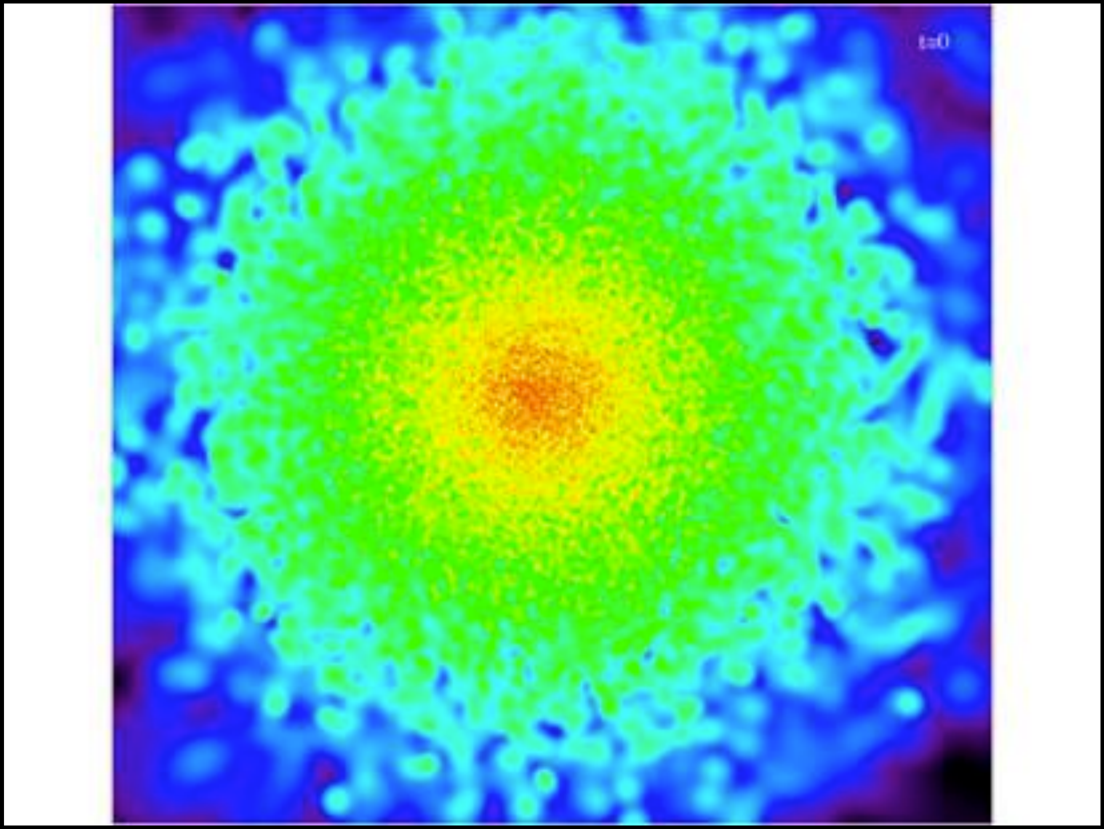
**Early universe - first stars, BHs**
**Numerical simulation**
**Data visualization**




# Isolate Disk Galaxy

- Toomre Q=1 disk (critical stable between gravity, thermal pres., and differential rotation.)
- Bulge with Hernquist profile

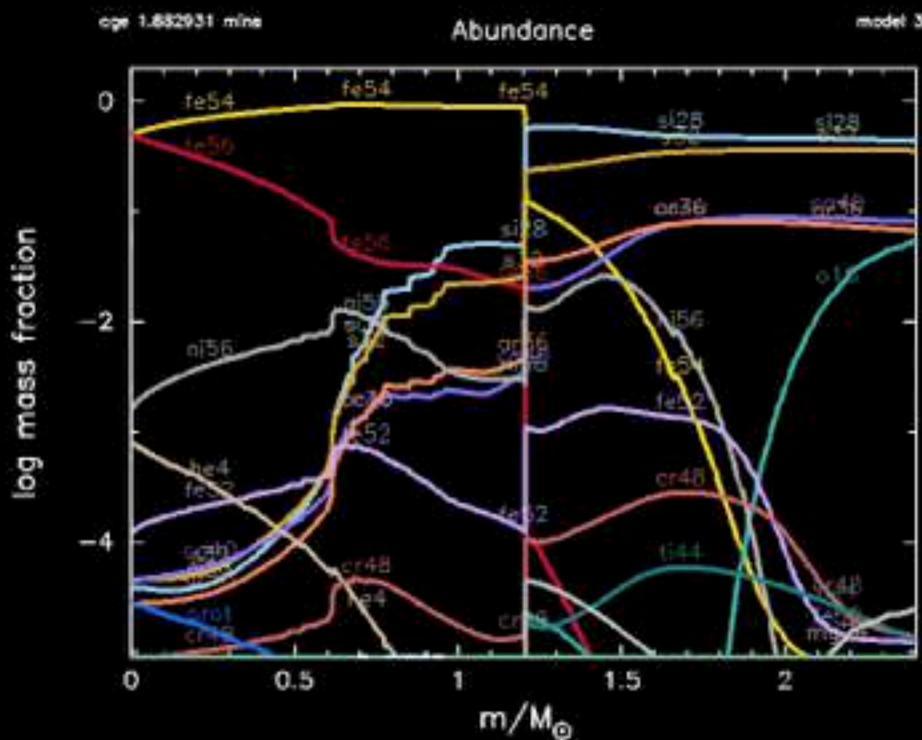
$$\Phi_{\text{bulge}}(r) = \frac{-GM_{\text{bulge}}}{r+c}$$

with $M_{\text{bulge}} = 3.4 \times 10^{10}\, M_{\odot}$ and $c = 0.7\text{kpc}$

- Extended Hernquist-profile, isotropic dispersion supported dark matter halo.
- A thin gas disk
- And a super-massive black hole

# Physics enabled:

- Star formation under virial criteria
- Stellar-wind feedback.
- Optically thin radiative cooling
- Self-gravity



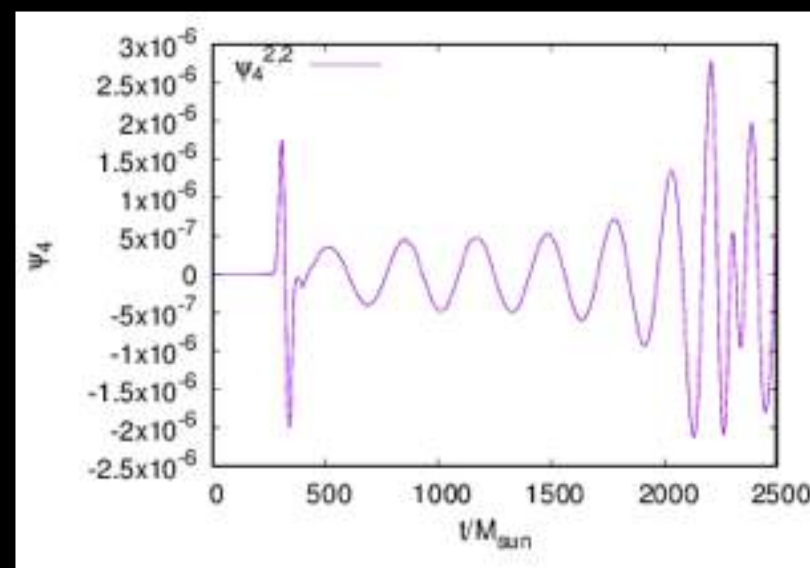

This movie showed a massive star's abundance of each elements during the last few hours in its life.

We can see the change is very violent and dramatic!

Simulation of Binary neutron star merging
with Einsteintoolkit(GRMHD code)
By Chia-Hui Lin(林家暉)

**Evolution of density distribution**
**ADM mass = 3.251 solar mass**
**Initial Separation = 45 km**

**Gravitational waveform**
**Detection distance = 300 km**
**Time unit = 5 μs**




JWST may have a chance to check this scenario
First light is expected in 2018

# Many thanks for your attention

My work has been kindly supported by:

East Asian Core Observatories Association (EACOA)

NAOC

NAOJ

Korea Astronomy and Space Science Institute

ASIAA

GRUBER FOUNDATION

IAU

ZAH

Office of Science
U.S. Department of Energy

NSF

NERSC

STARLIGHT

CFCA
Center for Computational Astrophysics

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

lrz