COLD UNIVERSE at SUNNY SANTA BARBARA, June 23, 2016

The role of heavy elements in early star-forming gas clouds

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University of Tokyo

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- **The most distant oxygen at z=7.2**

  Cosmo. simulations and ALMA observation

- **Physical processes in a low-Z gas**

  Basics and a 3-D view

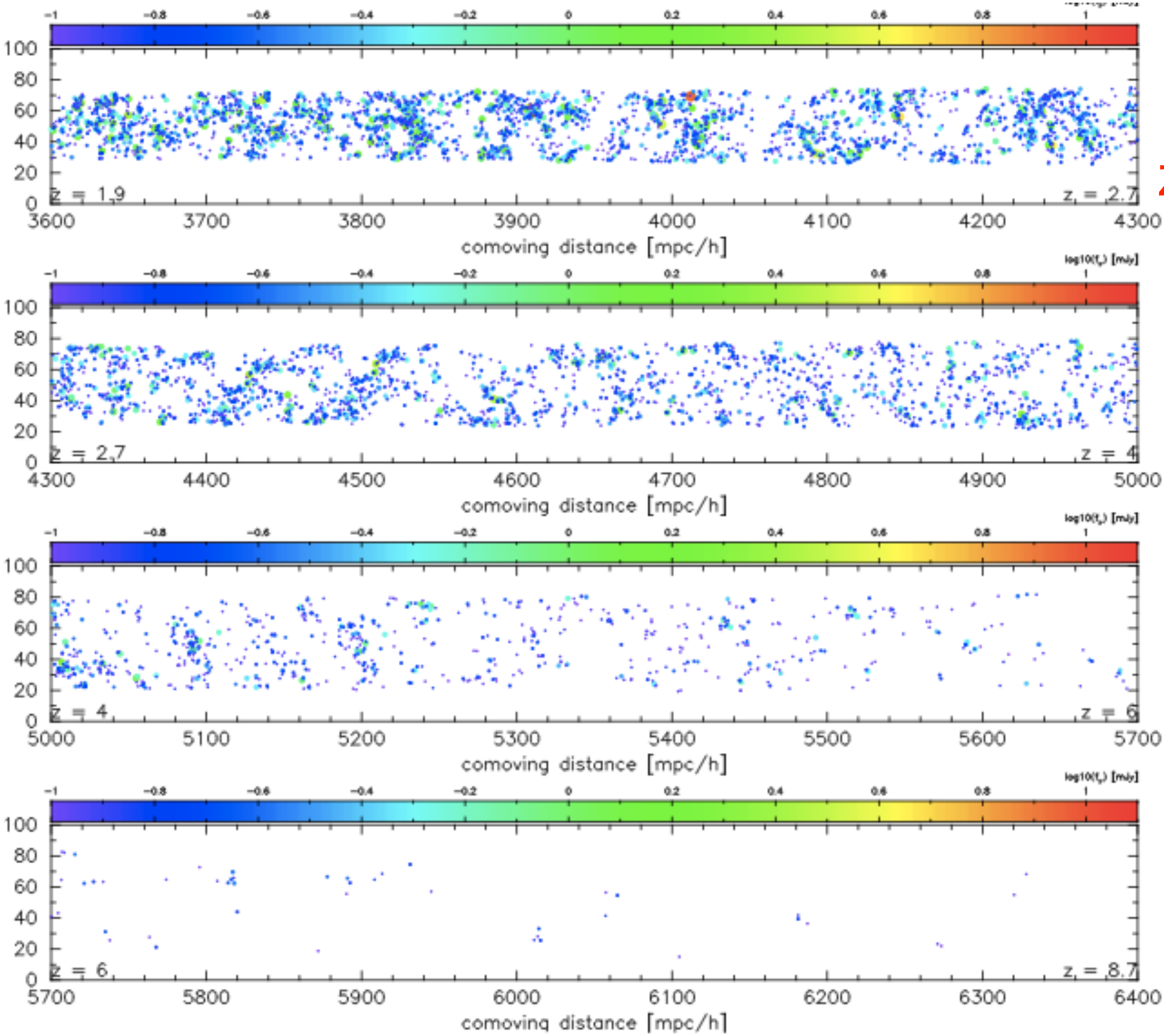
- **How metal-poor stars were born**

  "Filamentation" and disk fragmentation

References:

Inoue et al. Science, 2016
Shimizu, Inoue, Okamoto, NY, 2014; 2016, MN
Chiaki, Marassi, Nozawa, et al. 2015, MN
Chiaki, NY, Hirano, arxiv:1601.00280

Star-forming galaxies on the lightcone



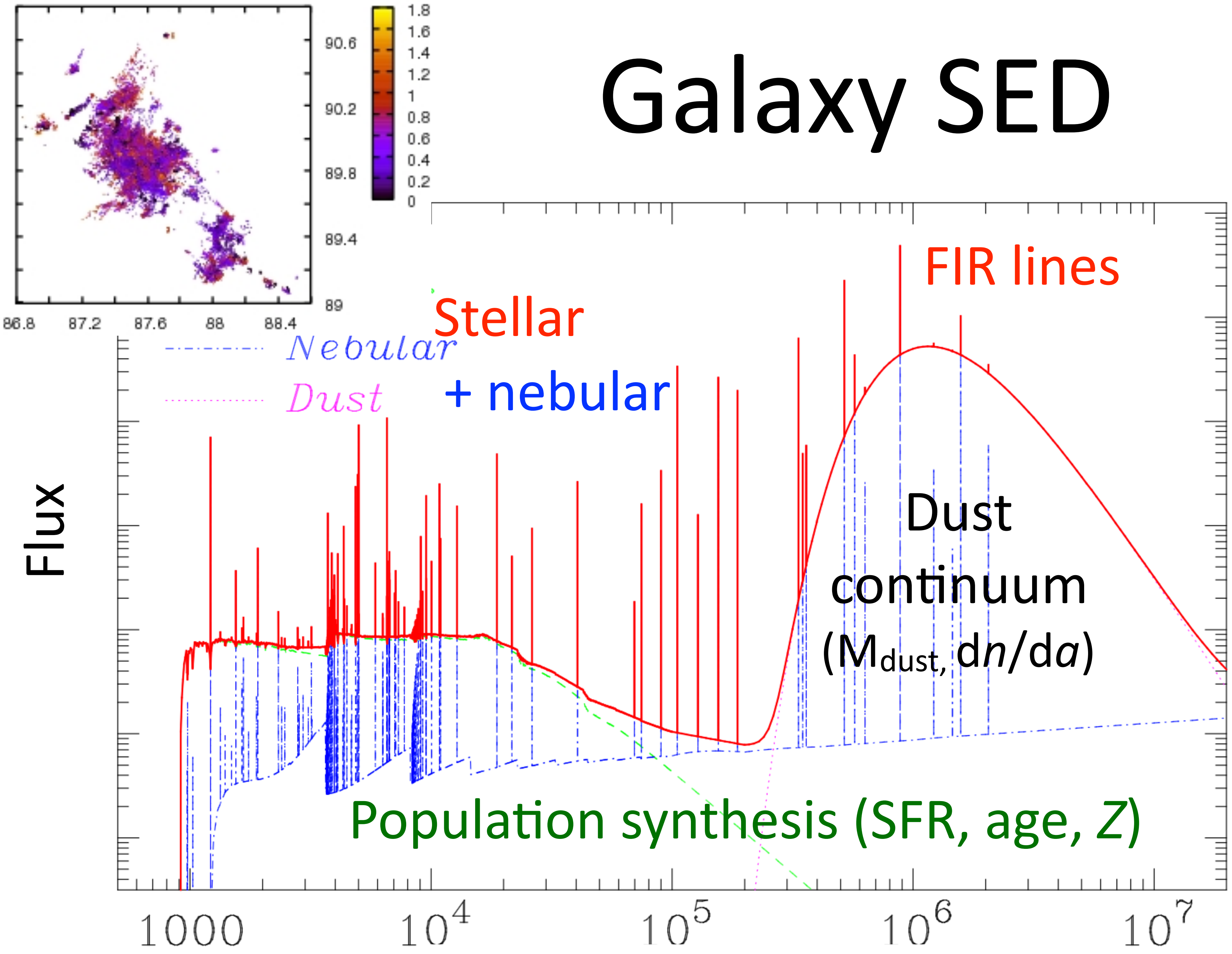
z=2.7

z=4

z=6

z=8.7

Galaxy SED



Stellar + nebular

FIR lines

Dust continuum (M_{dust}, d*n*/d*a*)

Population synthesis (SFR, age, *Z*)

Flux

Rest-frame wavelength

Shimizu et al. 2014, 2016

THE ASTROPHYSICAL JOURNAL LETTERS, 780:L18 (5pp), 2014 January 10 doi:10.1088/2041-8205/780/2/L18

ALMA WILL DETERMINE THE SPECTROSCOPIC REDSHIFT $z > 8$ WITH FIR [O III] EMISSION LINES

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ABSTRACT

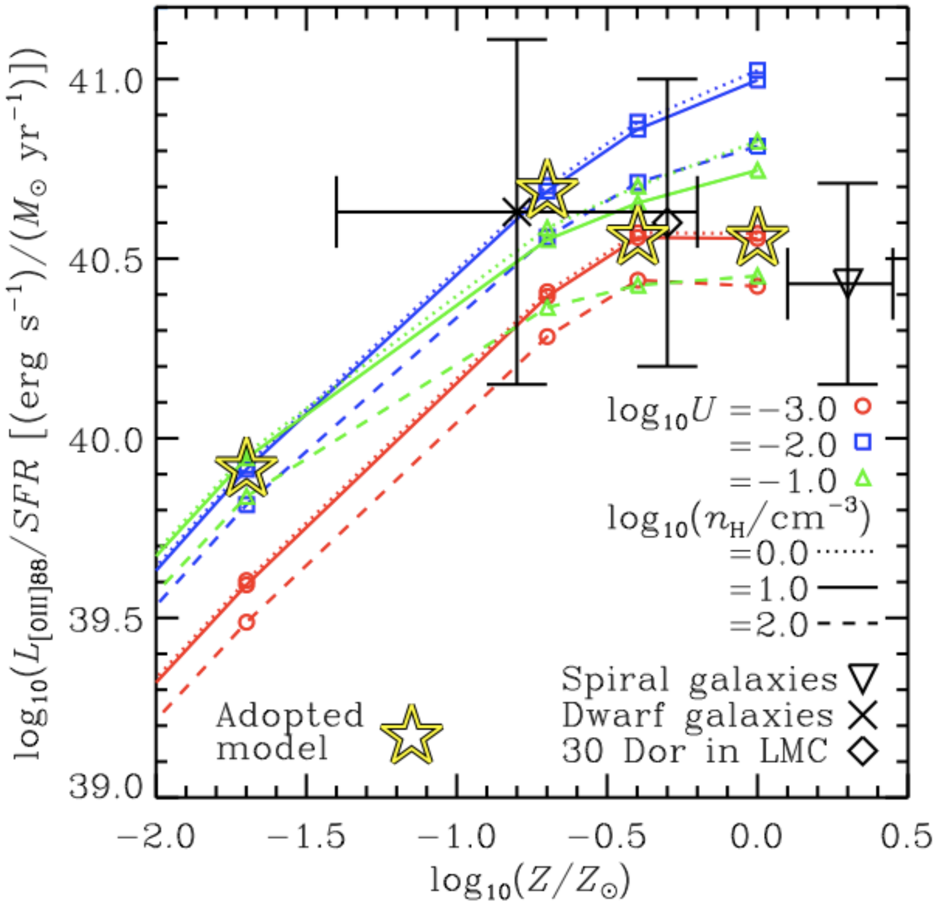
We investigate the potential use of nebular emission lines in the rest-frame far-infrared (FIR) for determining spectroscopic redshift of $z > 8$ galaxies with the Atacama Large Millimeter/submillimeter Array (ALMA). After making a line emissivity model as a function of metallicity, especially for the [O III] 88 μm line which is likely to be the strongest FIR line from H II regions, we predict the line fluxes from high-z galaxies based on a cosmological hydrodynamics simulation of galaxy formation. Since the metallicity of galaxies reaches at $\sim 0.2\,Z_\odot$ even at $z > 8$ in our simulation, we expect the [O III] 88 μm line as strong as 1.3 mJy for 27 AB objects, which is detectable at a high significance by <1 hr integration with ALMA. Therefore, the [O III] 88 μm line would be the best tool to confirm the spectroscopic redshifts beyond $z = 8$.

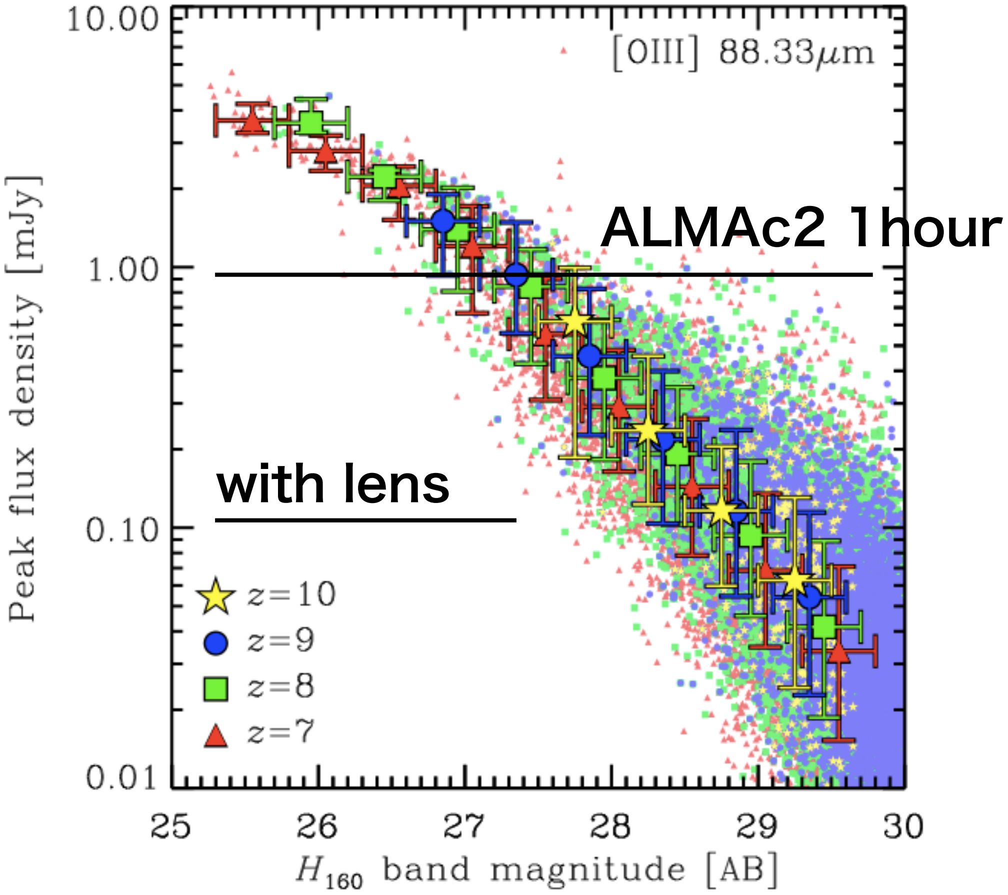
Key words: cosmology: observations – galaxies: evolution – galaxies: high-redshift

Online-only material: color figures

High-z OIII emitters

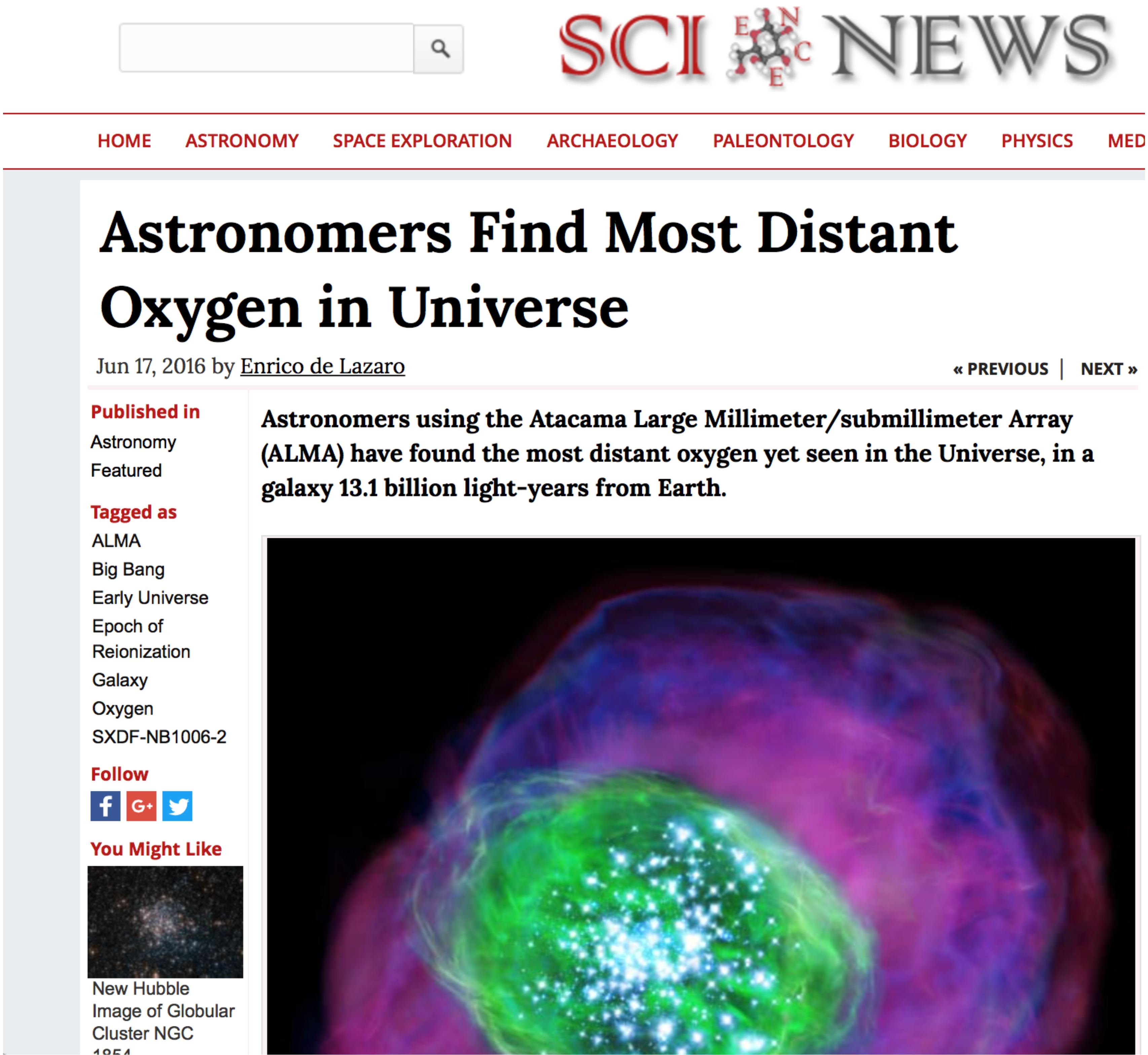
Cosmo. simulation





ALMAc2 1hour

with lens



Astronomers Find Most Distant Oxygen in Universe

Jun 17, 2016 by Enrico de Lazaro

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Early Universe
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Galaxy
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SXDF-NB1006-2

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New Hubble Image of Globular Cluster NGC

Astronomers using the Atacama Large Millimeter/submillimeter Array (ALMA) have found the most distant oxygen yet seen in the Universe, in a galaxy 13.1 billion light-years from Earth.

ALMA cycle 2, 37 antennae, 2 hours

Inoue et al. 2016, Science

5 σ detection of [OIII]!!!

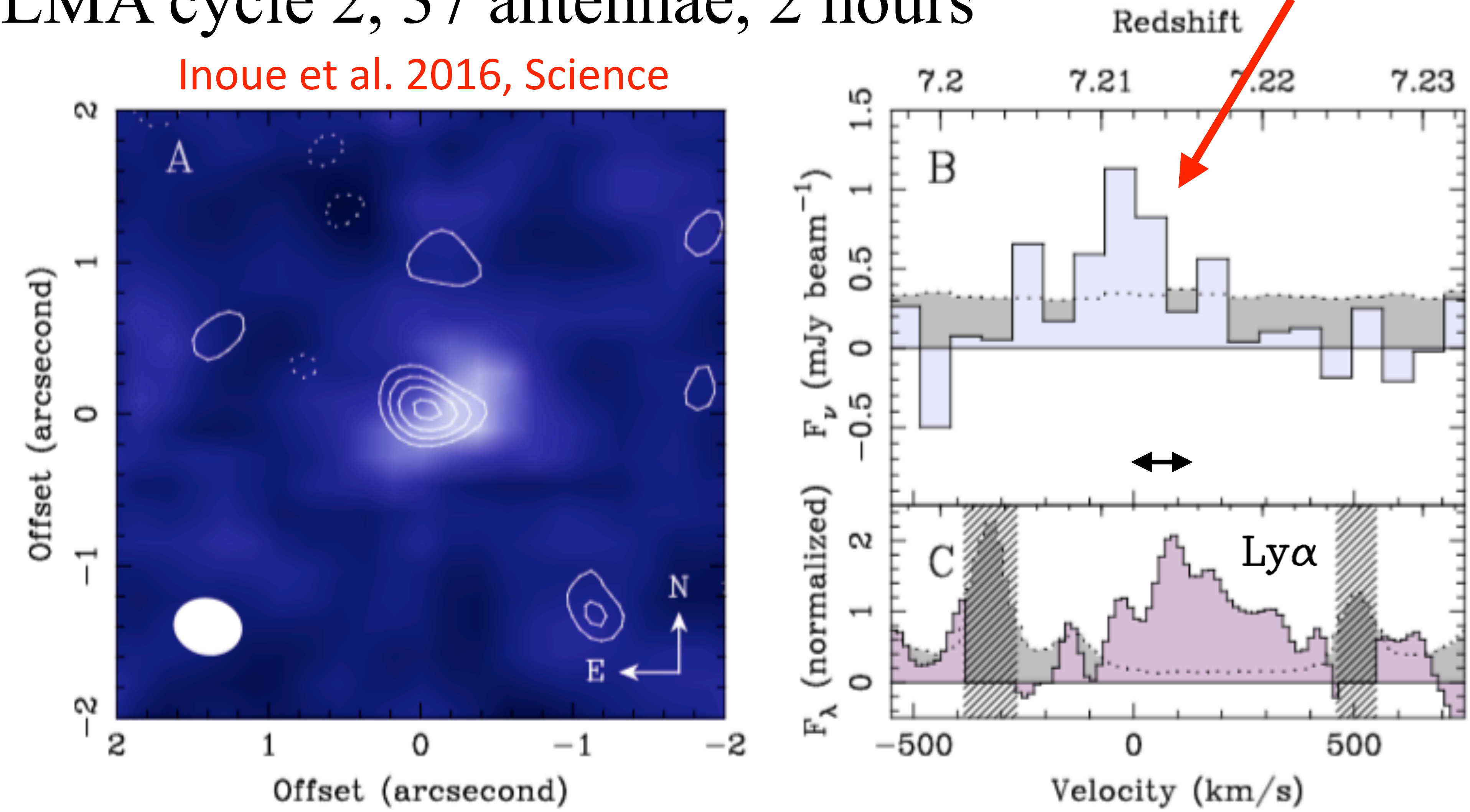
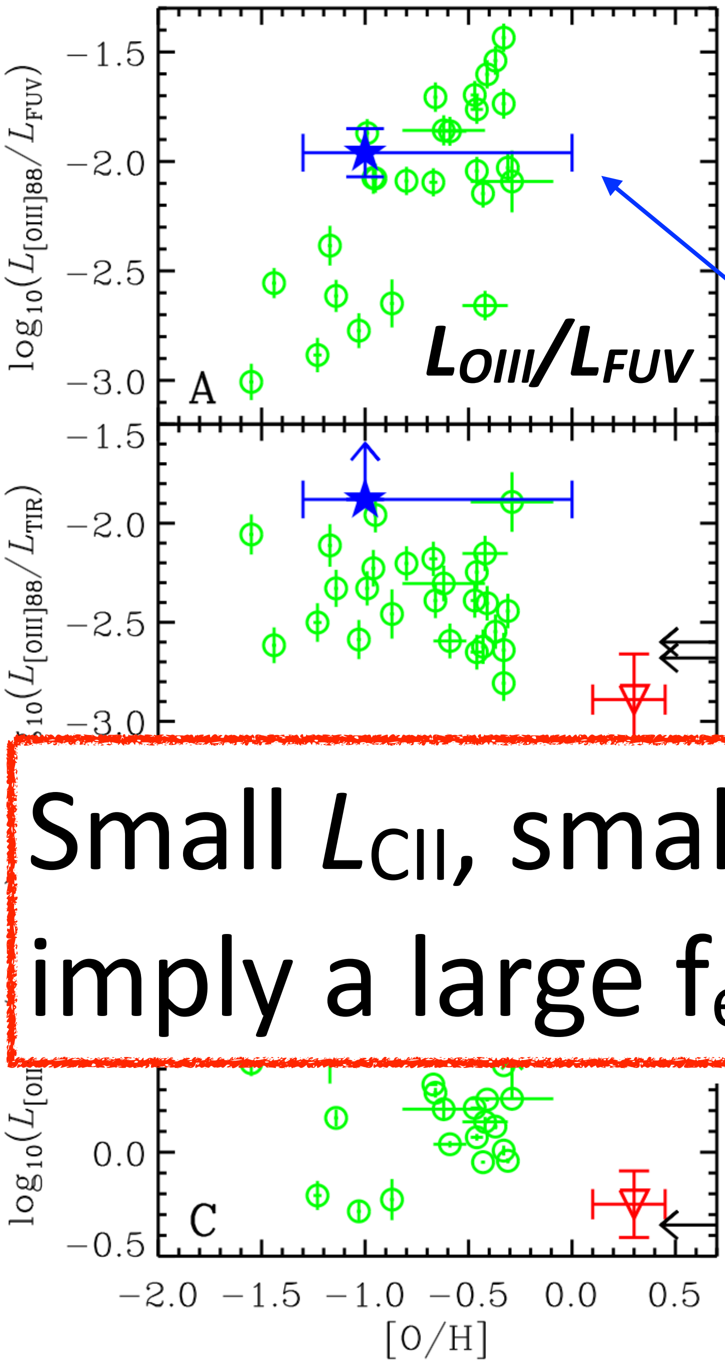
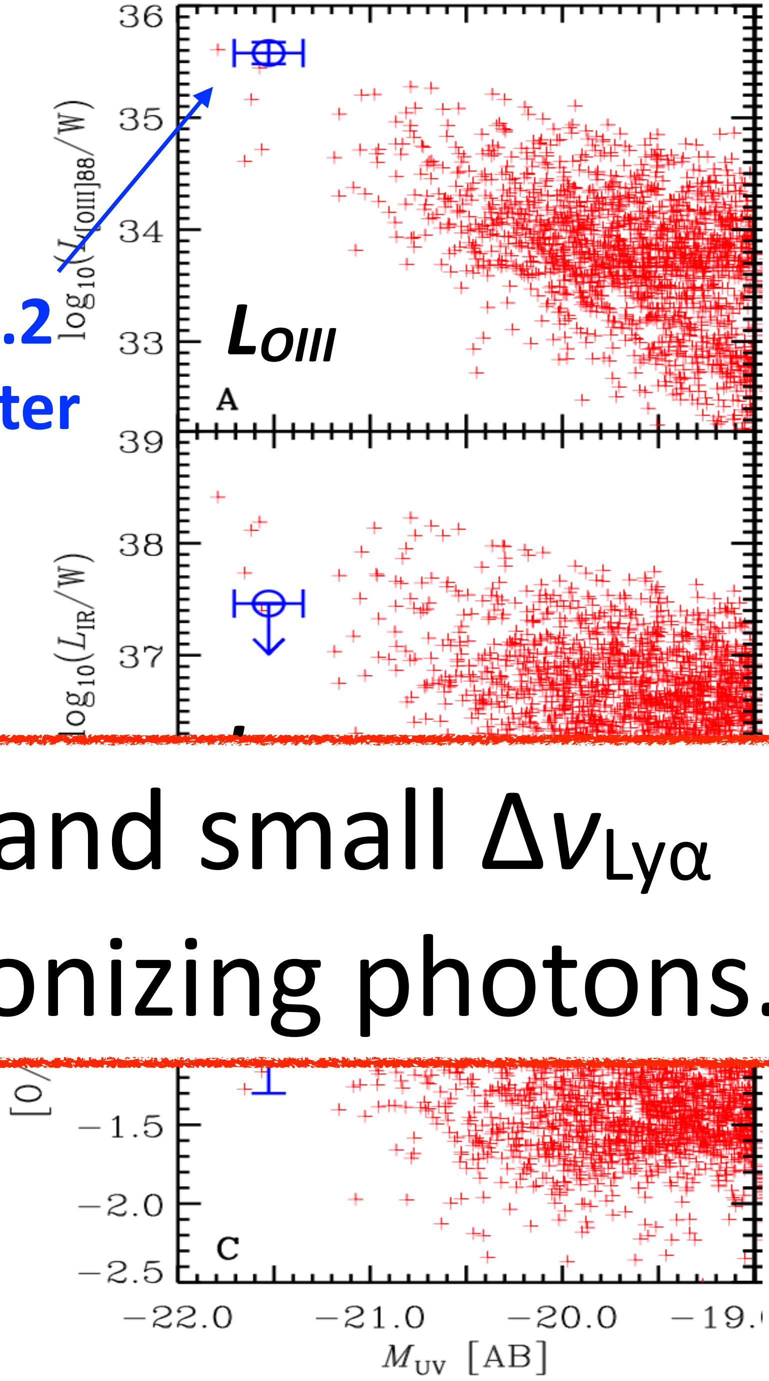


Figure 1: The [O III] 88 μm and Lyα emission images and spectra of SXDF-NB1006-2. (A) ALMA [O III] 88 μm image (contours) is overlaid on Subaru narrow-band Lyα image. Contours are drawn at $(-2, 2, 3, 4, 5)\times\sigma$, where $\sigma = 0.0636$ Jy beam^{-1} km s^{-1}. The negative contours are shown in dotted line. Ellipse at the bottom-left corner represents the synthesized beam size of ALMA. (B) ALMA [O III] 88 μm spectrum with a 70 km $^{-1}$ resolution is shown against the relative velocity with respect to $z = 7.212$. The r.m.s. noise level is shown as

Nearby galaxies



Simulated high-z galaxies



Our z=7.2
OIII emitter

Small $L_{\rm CII}$, small $L_{\rm FIR}$, and small $\Delta v_{\rm Ly\alpha}$ imply a large $f_{\rm esc}$ of ionizing photons.

Thermal evolution and protostar formation in a low-metallicity gas:

1-zone, 1D, and 3D simulations

References:
G. Chiaki, PhD thesis, 2016
Chiaki, Marassi, Nozawa, et al. 2015, MN
Chiaki, NY, Hirano, arxiv:1601.00280

PopIII to PopII transition

Is there a “critical metallicity”
for low-mass star formation ?

If so, what’s the key process ?

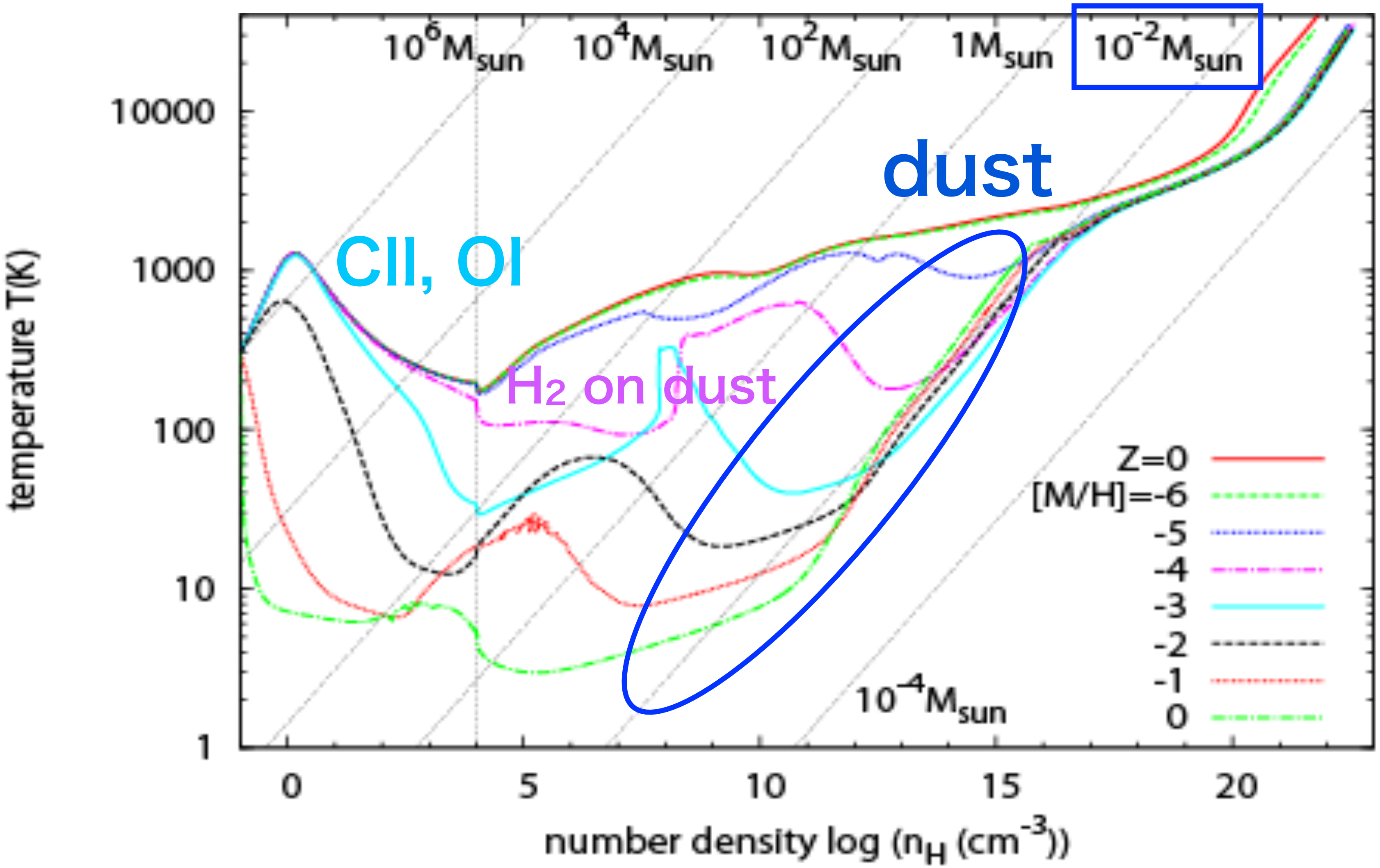
atomic cooling
by C, O
@low-density”

vs.

cooling
by dust
@high density

Thermal evolution

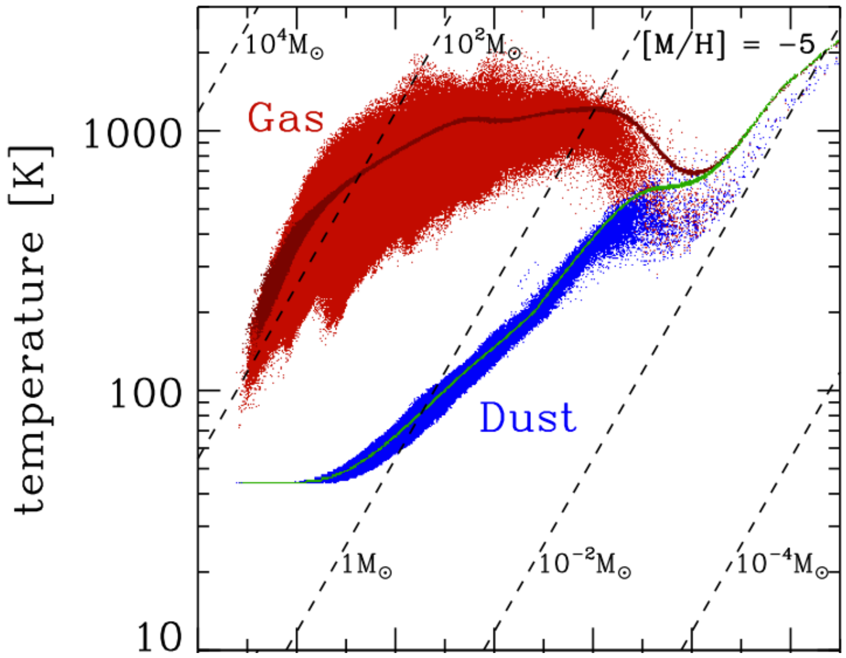
1D chemo-hydrodynamics calculations



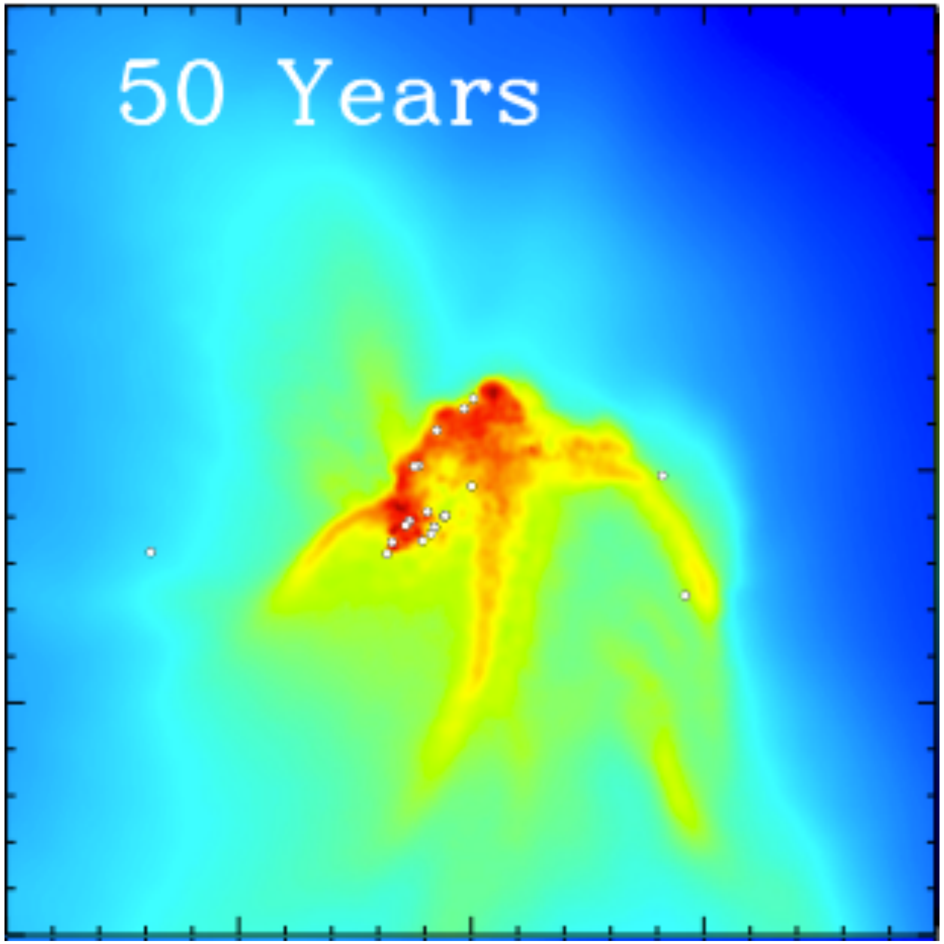
Omukai, Hosokawa, NY, 2010, ApJ

Dust cooling

Dopcke et al. 2011, ApJ

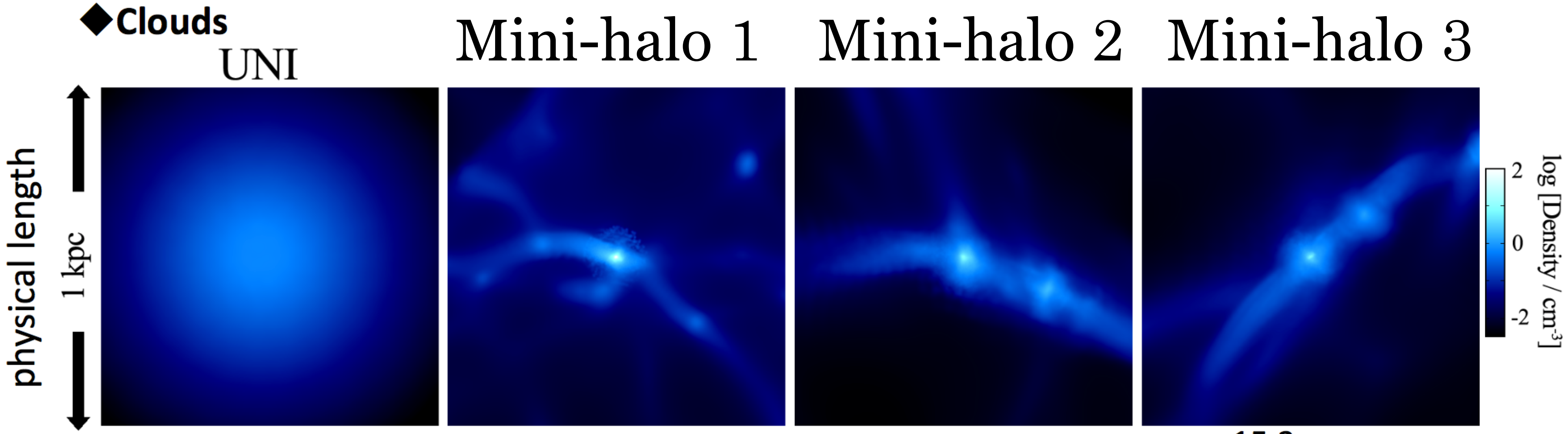


Only dust cooling, no molecules



Initial conditions

◆**Clouds**



$M = 2.3\times10^{6}$ $M_\odot$
$n_{\rm H,ini} = 0.1$ cm^{-3}

z=20.5
$M_{\rm h} = 2.2\times10^{5}$ $M_\odot$
$R_{\rm h} = 26.5$ pc

z=16.2
$M_{\rm h} = 1.5\times10^{5}$ $M_\odot$
$R_{\rm h} = 46.8$ pc

z=15.2
$M_{\rm h} = 1.1\times10^{5}$ $M_\odot$
$R_{\rm h} = 37.5$ pc

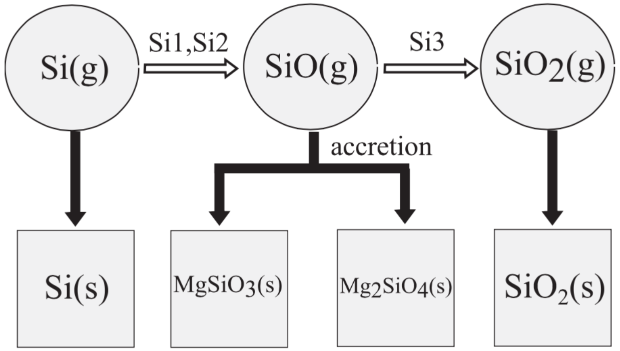
minihalos (MHs; ~10^5 $M_\odot$)
from a cosmological simulation (Hirano et al. 2014)

- ΛCDM model
- Box size: 1 h^{-1} Mpc (comoving)

Cloud	$z_{\rm form}$	$M_{\rm vir}^{\rm dm}$	$M_{\rm vir}^{\rm ba}$	$R_{\rm vir}$	$M_{\rm PopIII}$	α	β	λ	$\varepsilon_{\rm turb}$
UNI	—	0.0×10^{0}	2.2×10^{6}	551	—	0.51	0.0069	0.015	0.350
MH1	20.46	1.4×10^{5}	2.0×10^{4}	26.5	283.9	0.46	0.0049	0.011	0.086
MH2	16.20	1.4×10^{5}	3.7×10^{4}	46.8	751.3	0.48	0.0320	0.050	0.069
MH3	15.15	8.1×10^{4}	1.6×10^{4}	37.5	60.5	0.99	0.0325	0.063	0.067

Chemistry

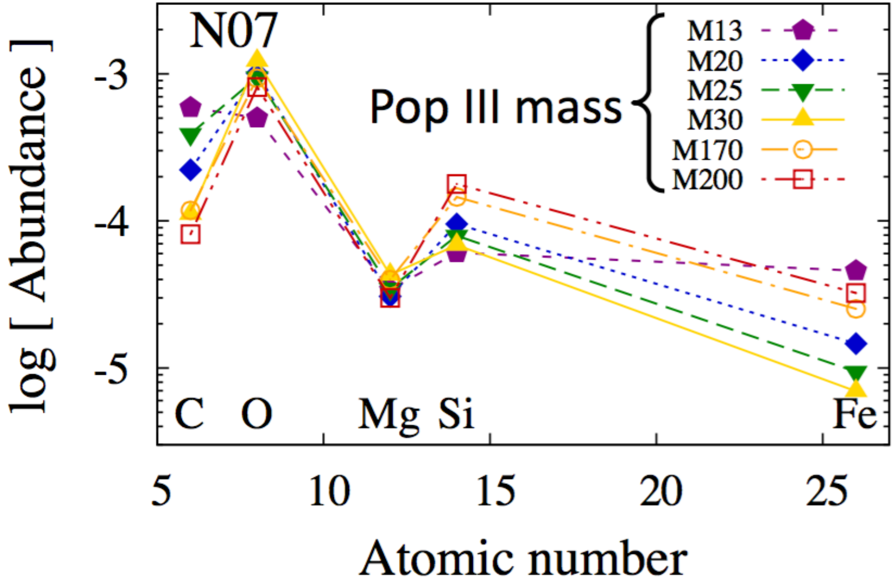
54 reactions for 27 species: H^+, e^-, H, H^-, H_2,
D^+, D, HD, C^+, C, CH, CH_2, CO^+, CO, CO_2,
O^+, O, OH^+, OH, H_2O^+, H_2O, H_3O^+,
O_2^+, O_2, Si, SiO, SiO_2



+

Grain chemistry: metallic silicon (Si), metallic iron (Fe), Mg_2SiO_4, $MgSiO_3$, amorphous carbon (C), SiO_2, MgO, FeS, and Al_2O_3

Nozawa et al. 2007; 2012



Chemical and radiative cooling:

- Transition line cooling
  C II, C I, O I, CO, H_2O, OH
- Dust thermal emission
- H_2 formation heating

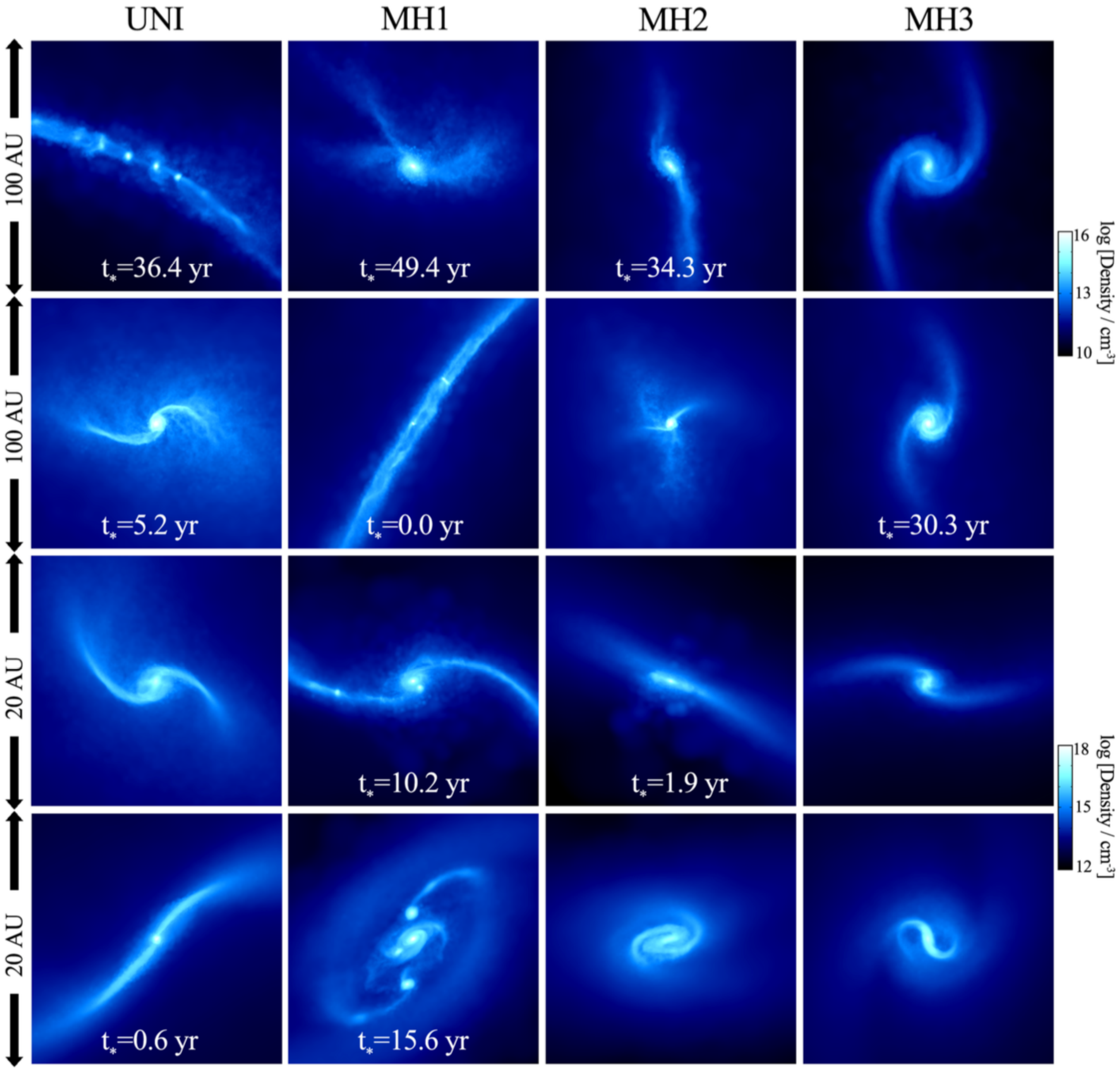
metallicity →

10^{-3} Z_{sun}

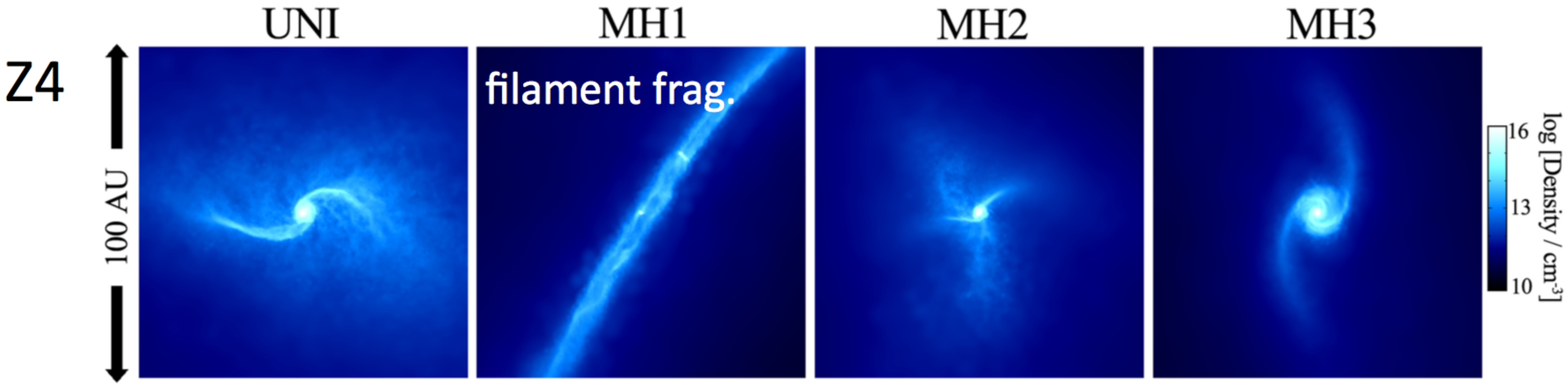
10^{-4}

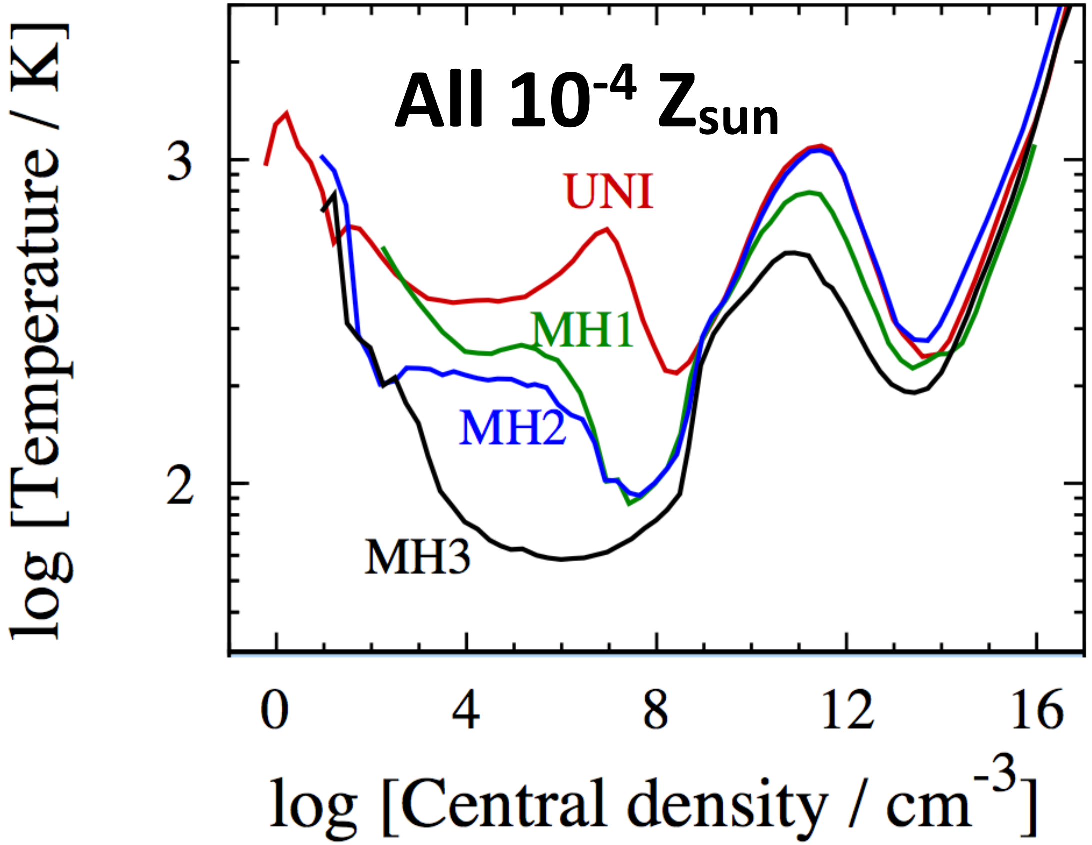
10^{-5}

10^{-6}



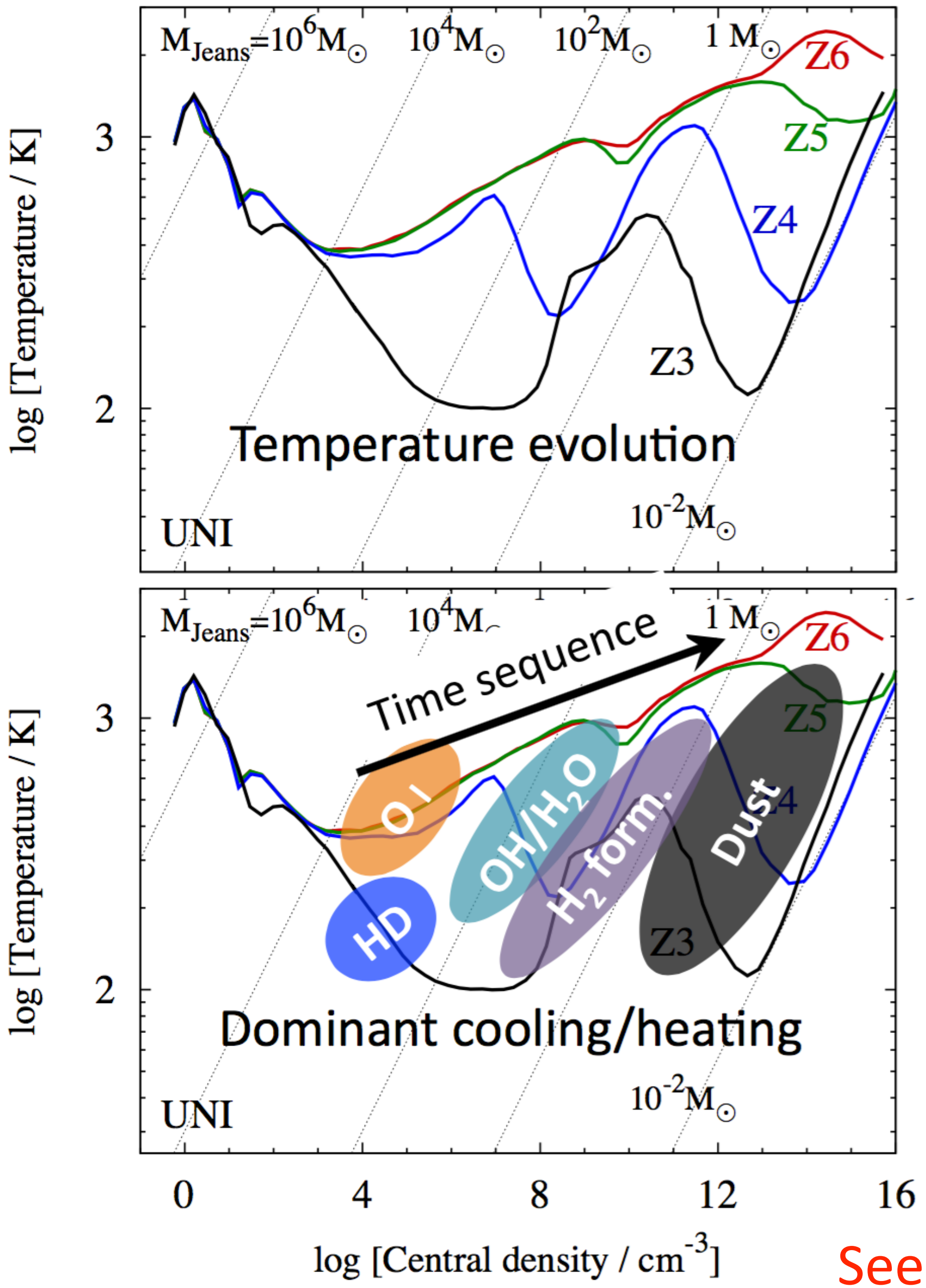
Does metallicity determine everything ?

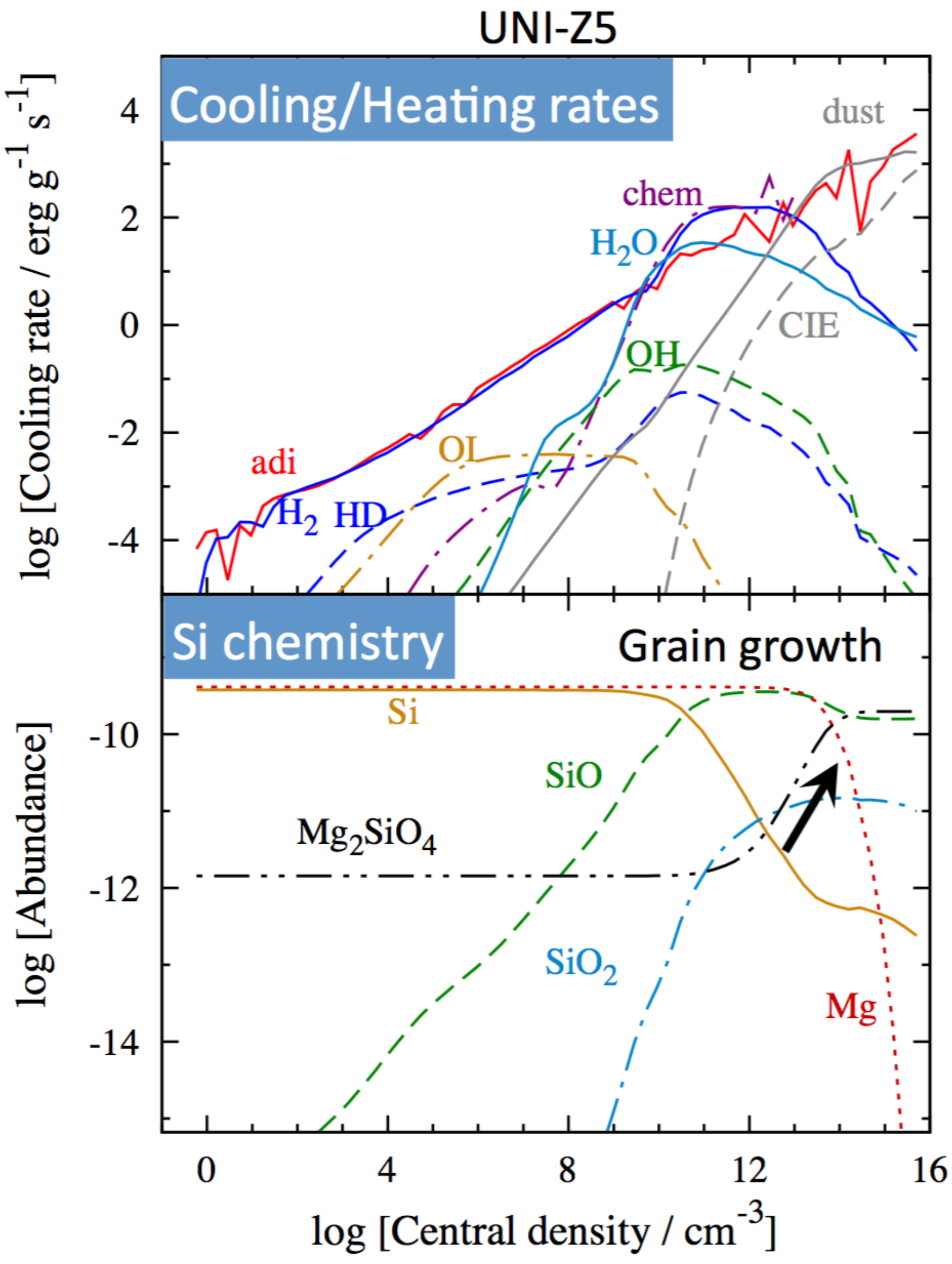




Difference in the thermal evolution as big as differences due to metallicity.

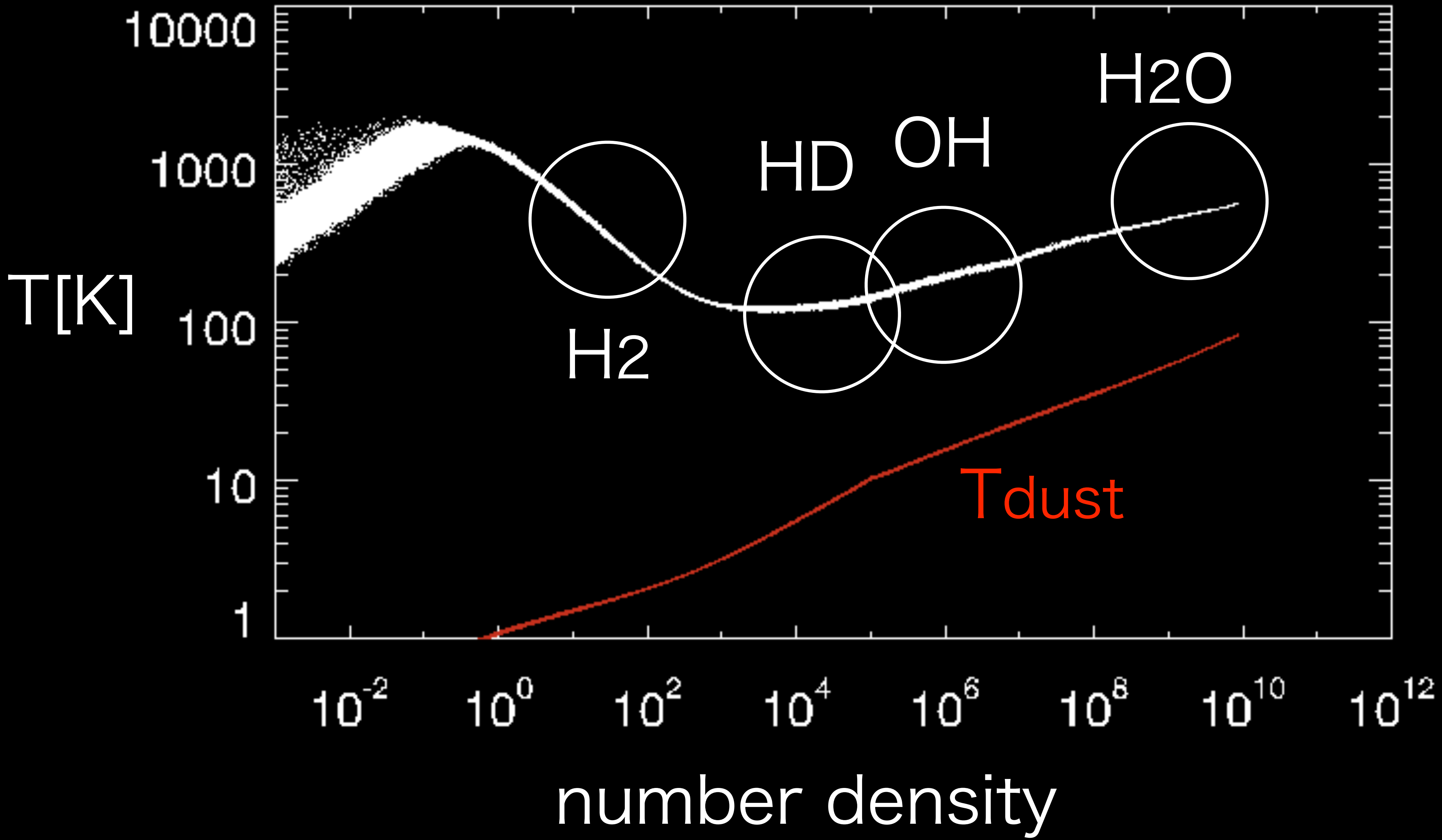
Chemo-thermal evolution



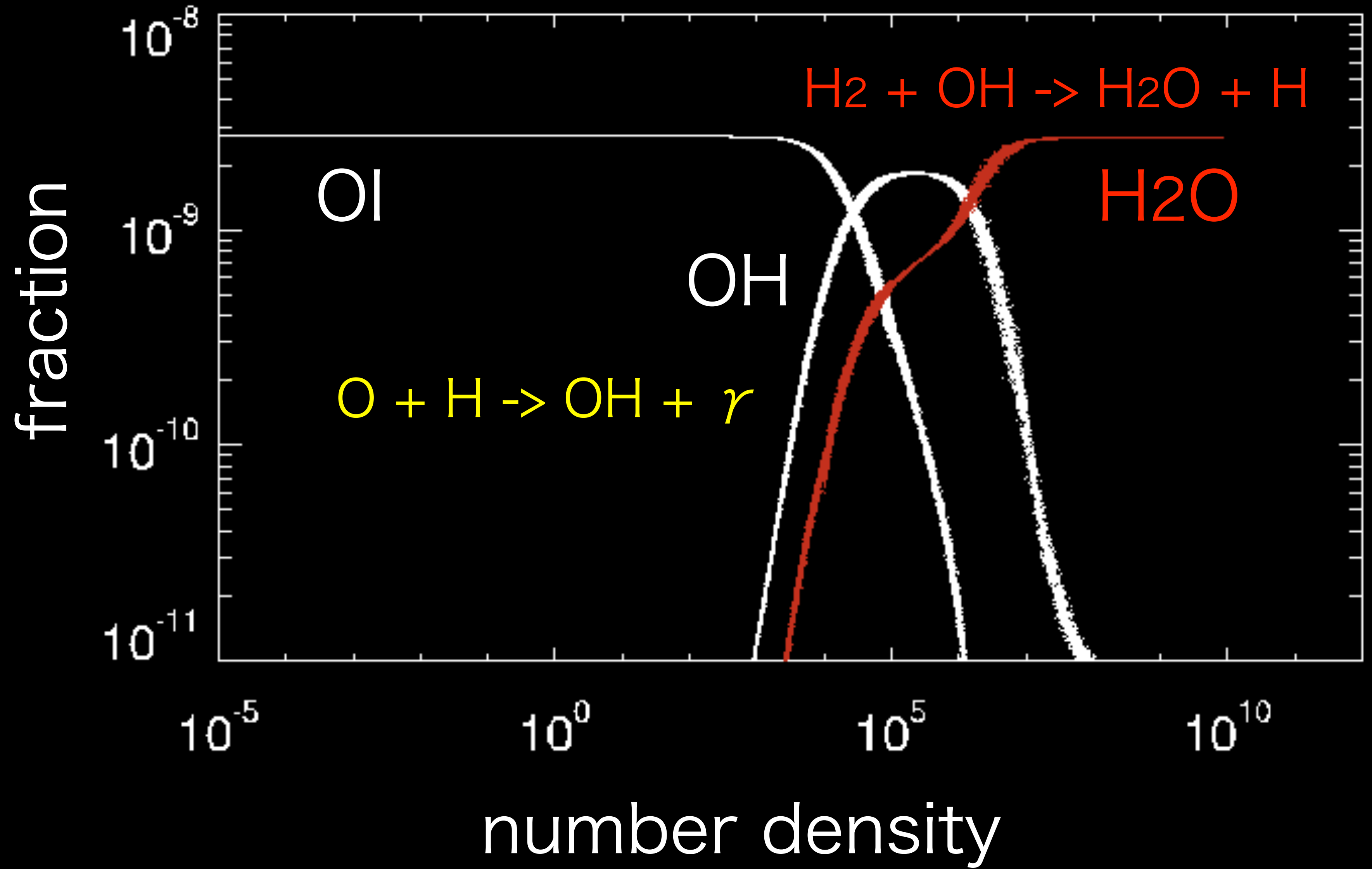


See also Grassi et al. 2015, Bovino et al. 2016

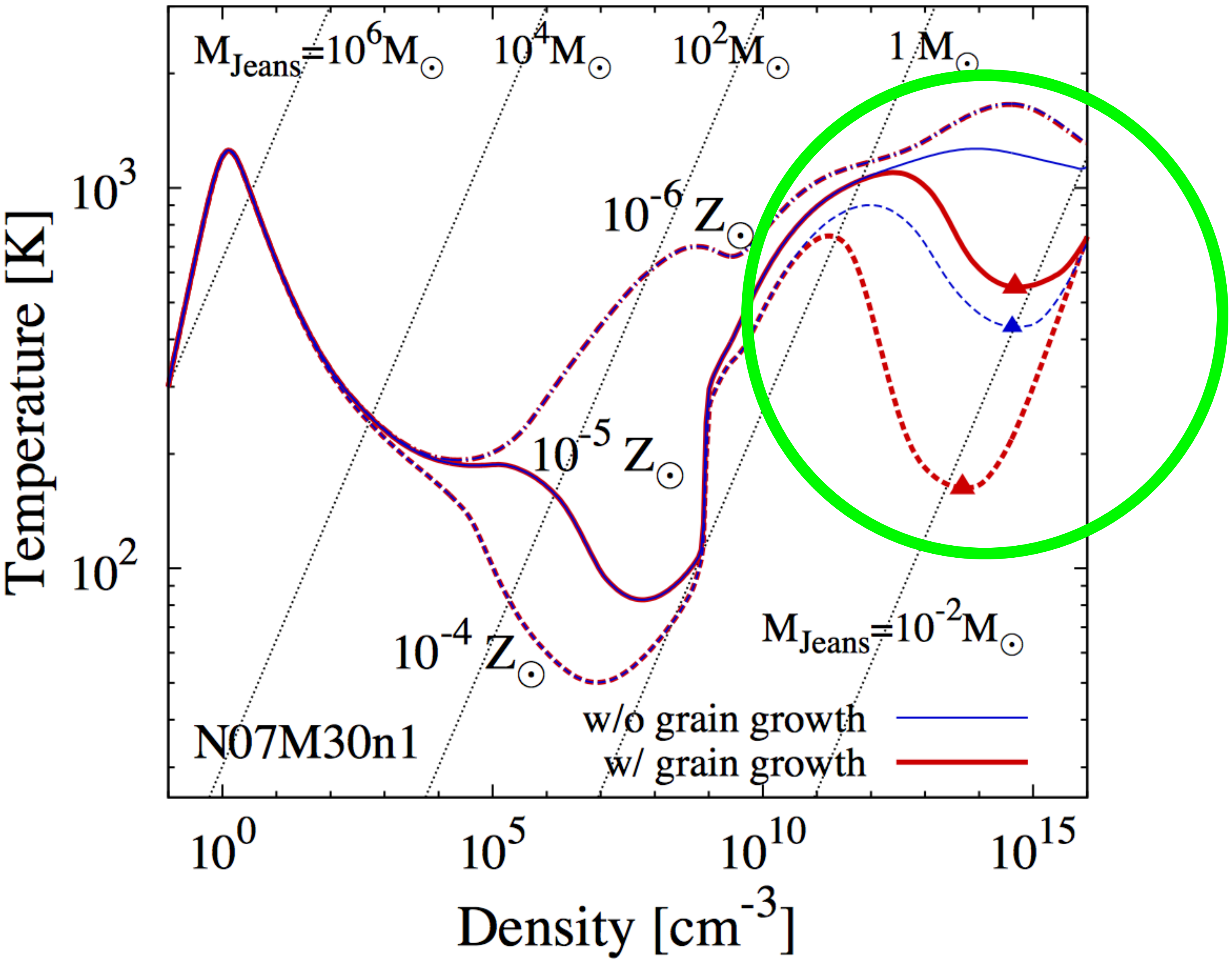
10^{-5} Z_{sun} case



Oxygen chemistry



Dust cooling



Grain growth

sticking probability

number density
of the gas phase atoms

$$\frac{\mathrm{d}r_i}{\mathrm{d}t} = s_i \left(\frac{4\pi}{3}a_i^3\right)\left(\frac{kT_{\mathrm{gas}}}{2\pi m_i}\right)^{1/2} n_i^{\mathrm{gas}}\left(1-\frac{1}{S_i}\sqrt{\frac{T_{\mathrm{dust}}}{T_{\mathrm{gas}}}}\right)$$

saturation factor

radius of a monomer
molecule per *key element (Mg, Si)*

$$\times\ r_{\mathrm{i}}^2 \longrightarrow \frac{\mathrm{d}r_i^3}{\mathrm{d}t} = \frac{\mathrm{d}V_i}{\mathrm{d}t} \propto \underline{n_i \sigma v_i}$$

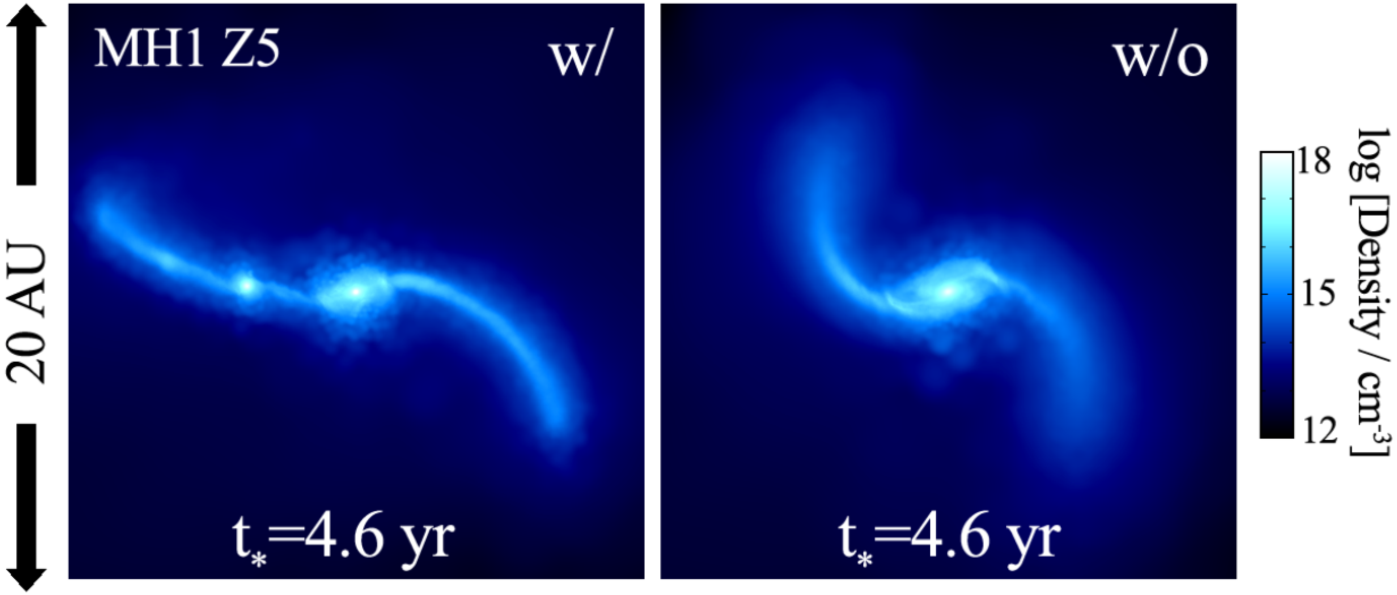
volume increase
per impact

Photo-desorption unimportant without intense radiation.

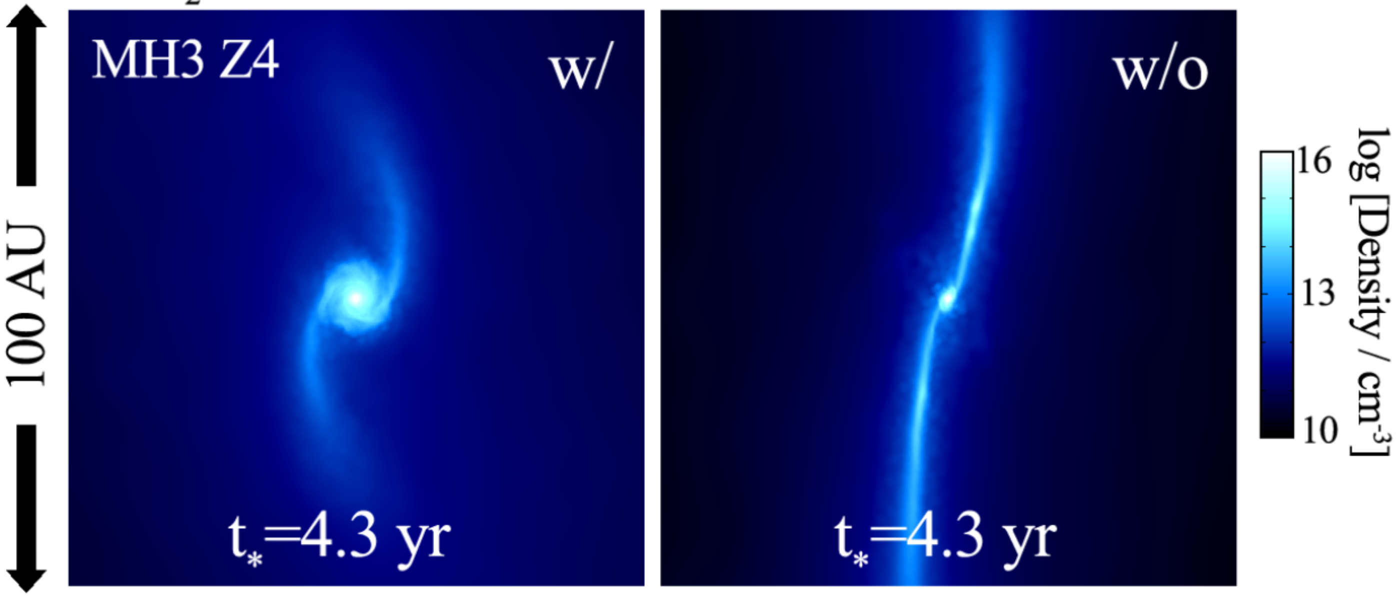
Dust shattering inefficient at < 0.01 Z_{sun} .

Cloud shape

(a) Grain growth

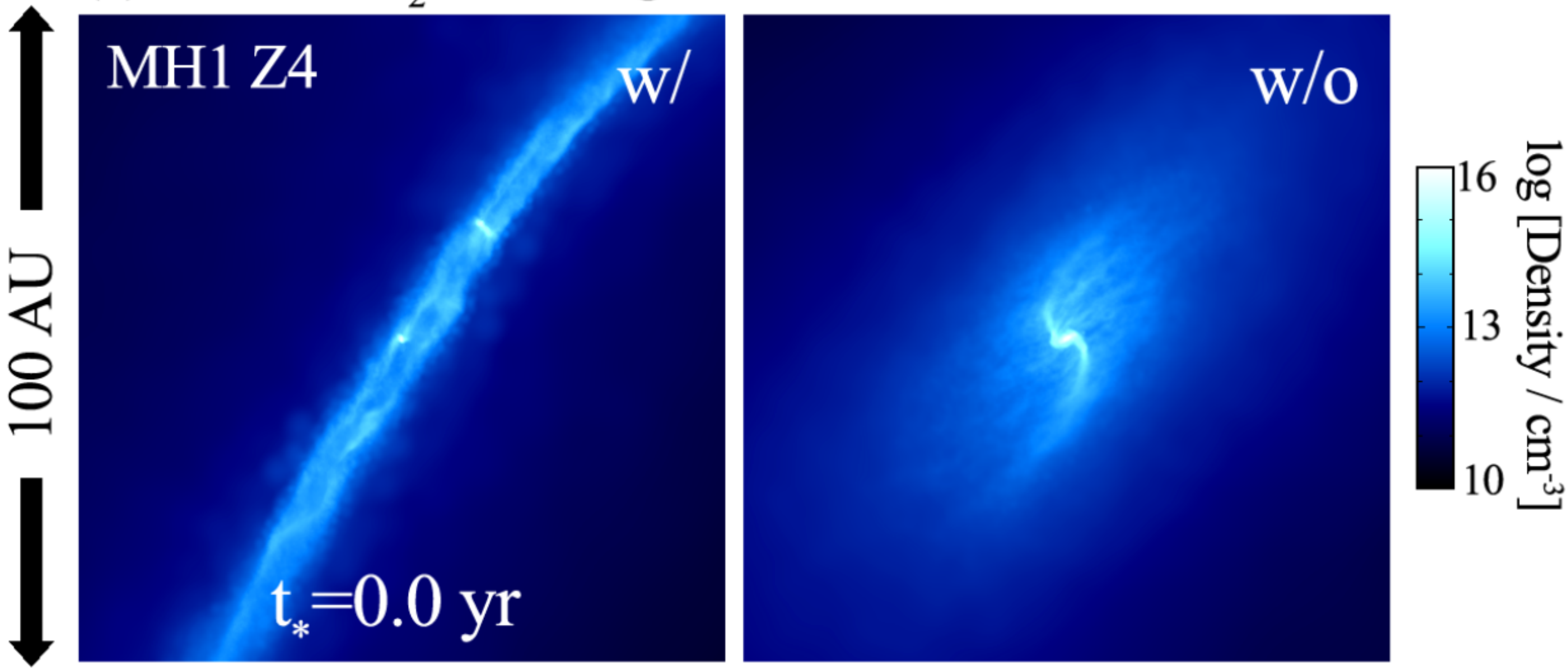


(b) H_2 formation heating

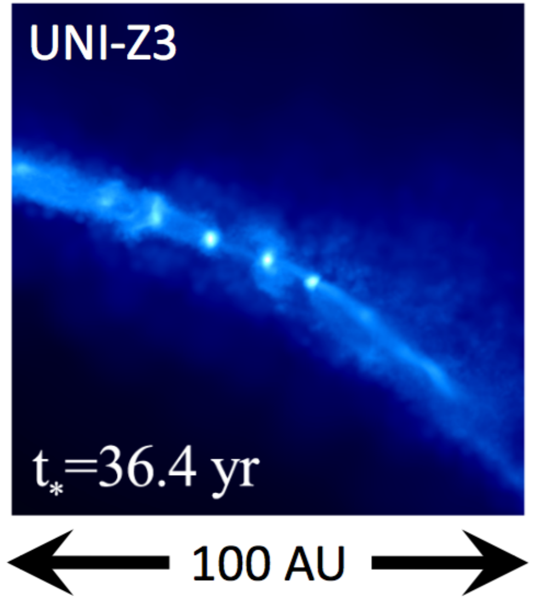


The effect of molecular cooling

(c) OH and H_2O cooling



Filamentation vs disk fragmentation



◆Filament fragmentation

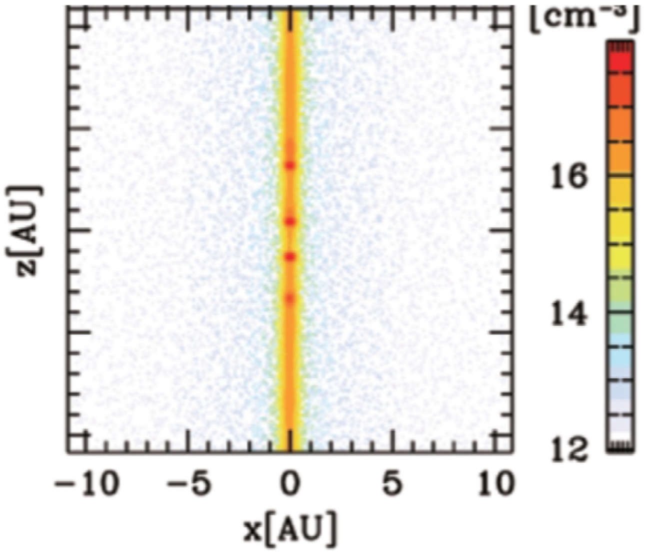
✓Induced by gas cooling

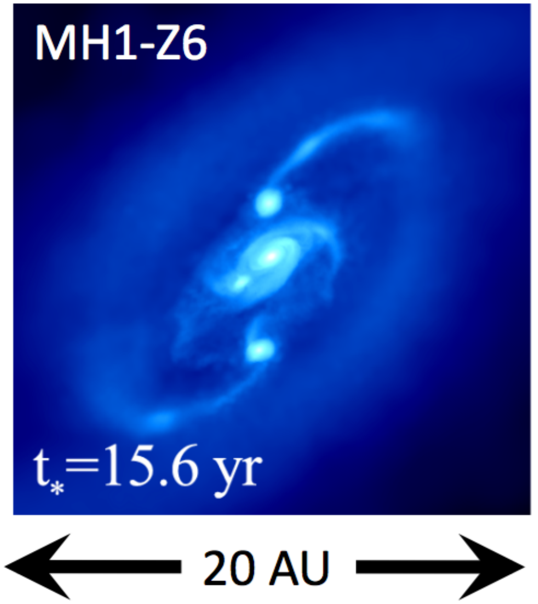
✓Radial (infall) velocity is dominant.

✓ Cores are aligned with a constant separation

(Inutsuka & Miyama 1997; Tsuribe & Omukai 2006; Heigl et al. 2016)

Simulation for polytropic gas
Tsuribe & Omukai (2006)





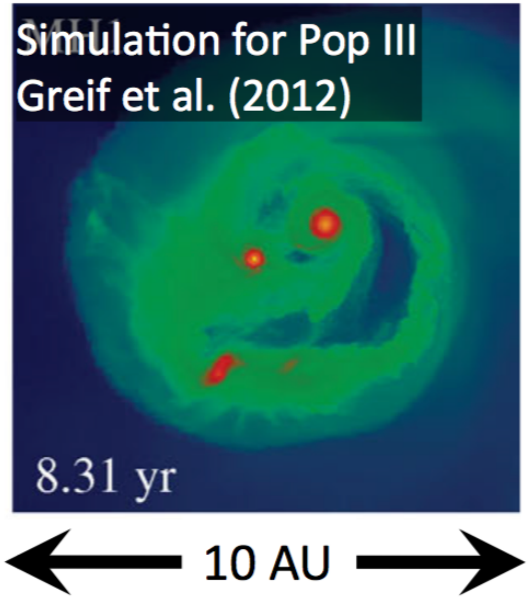
◆Disk fragmentation

✓Induced by self-gravity

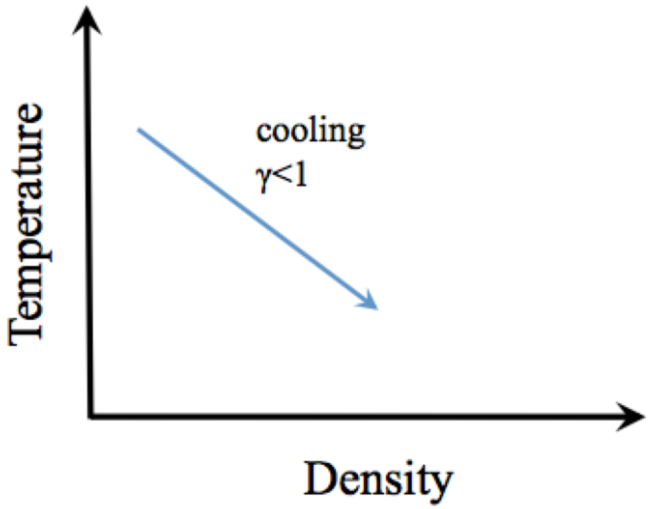
✓Tangential (rotational) velocity is dominant.

✓ Cores are formed in arms

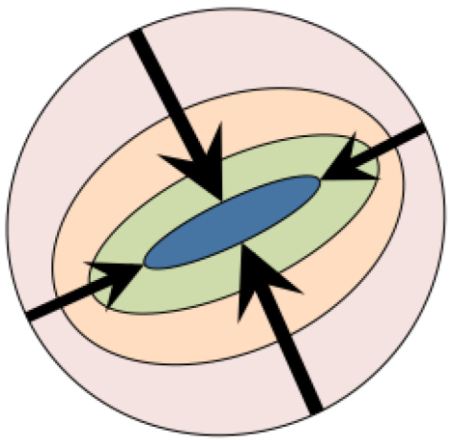
(Gammie et al. 2001; Vorobyov et al. 2010; Zhu et al. 2012)


Simulation for Pop III
Greif et al. (2012)

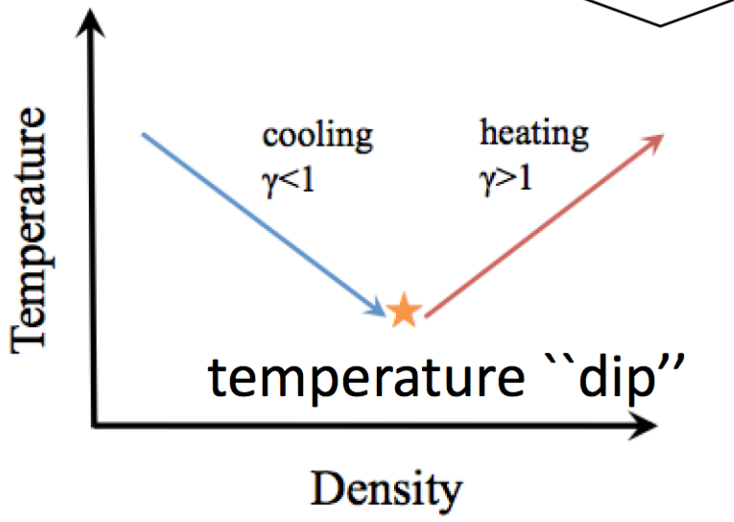
Cloud deformation and temperature dip

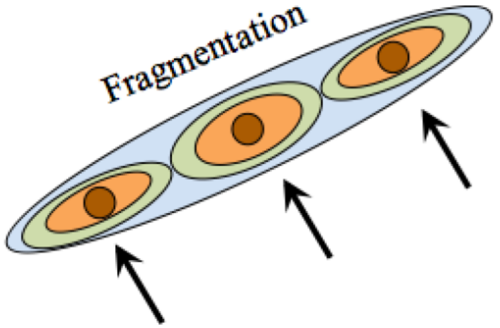


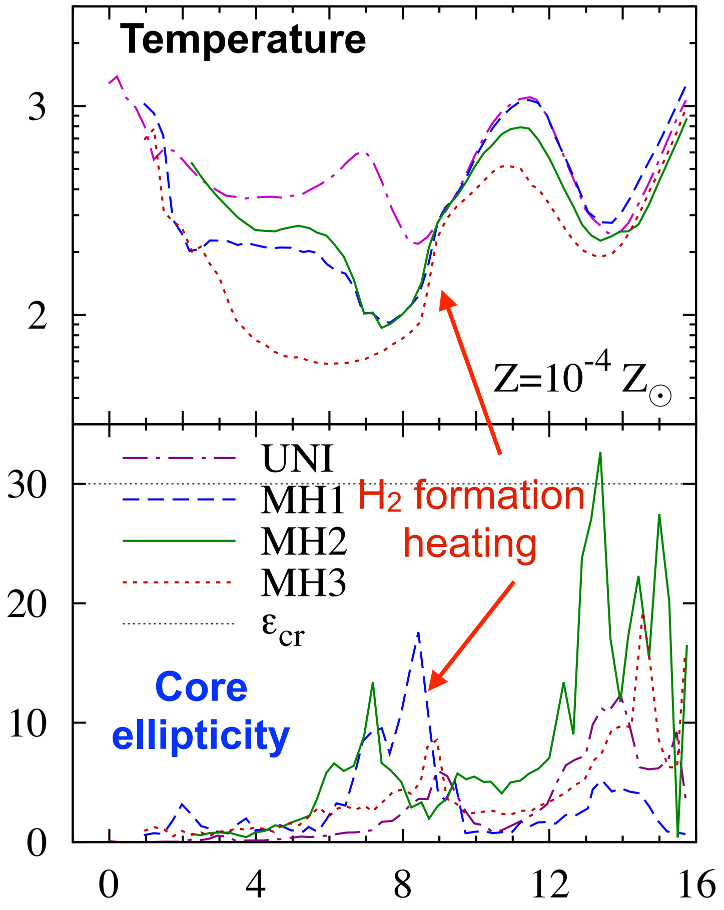
cooling → cloud deformation



A filamentary structure forms







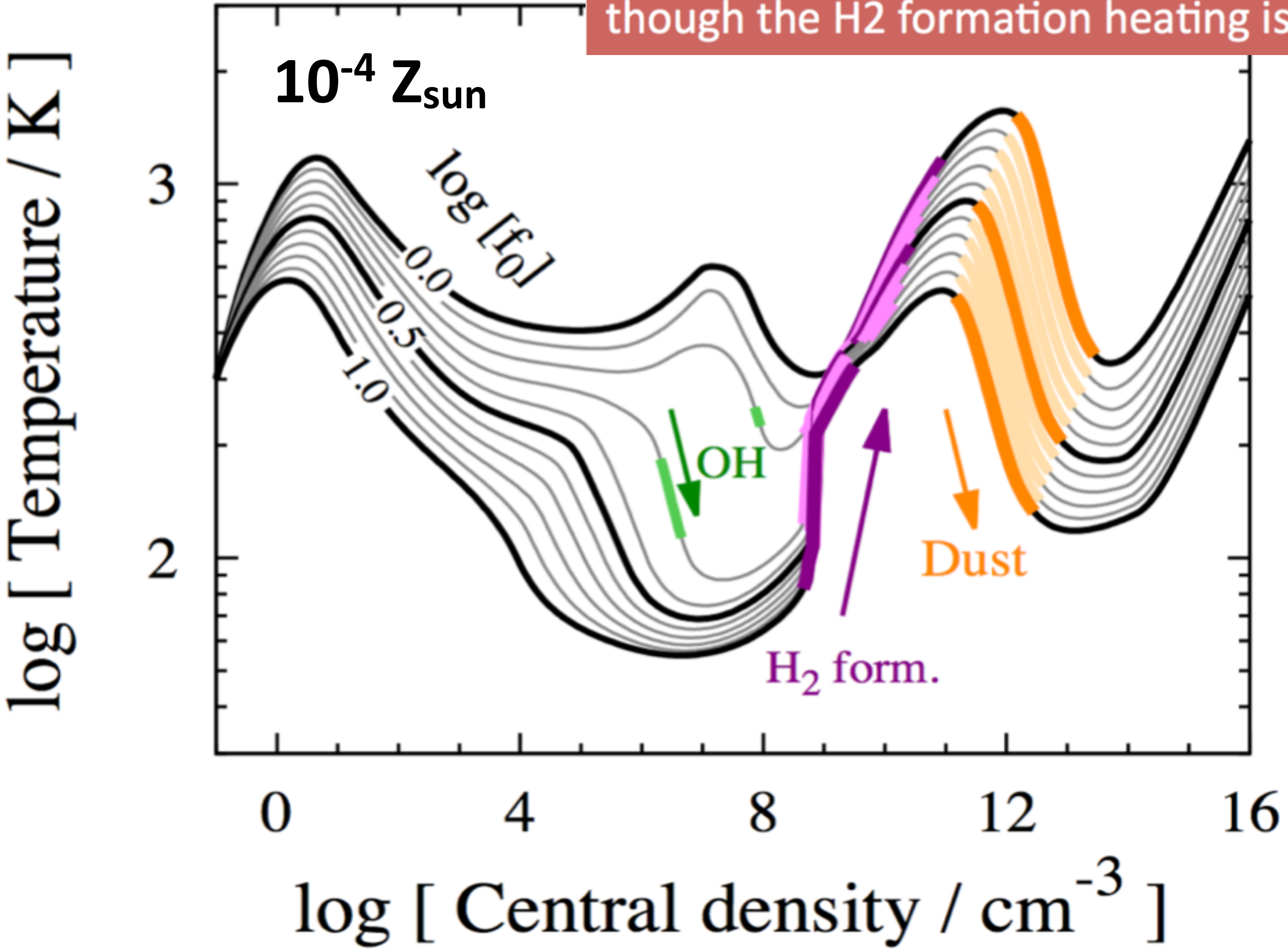
Hanawa & Matsumoto (2000), Lai (2000), Tsuribe & Omukai (2005)

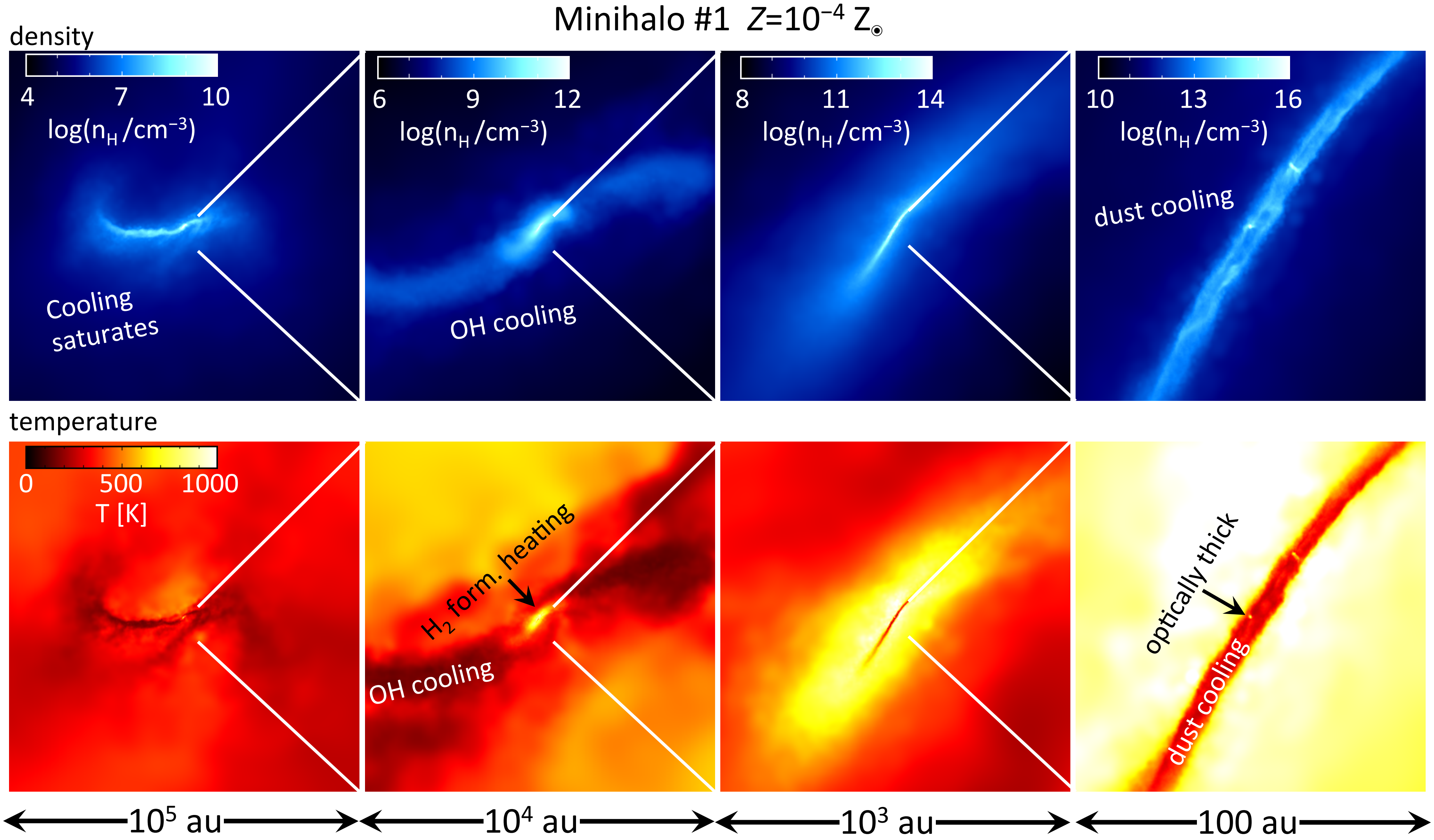
Fragmentation criteria:

(*i*) Dust cooling is efficient, and

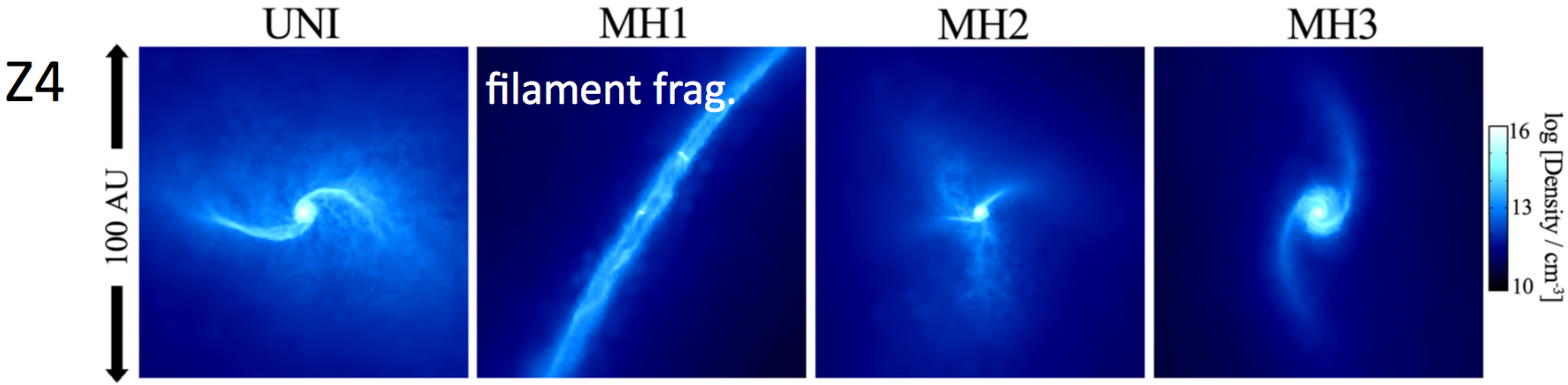
  (*ii*-a) H_2 formation heating is not efficient, or

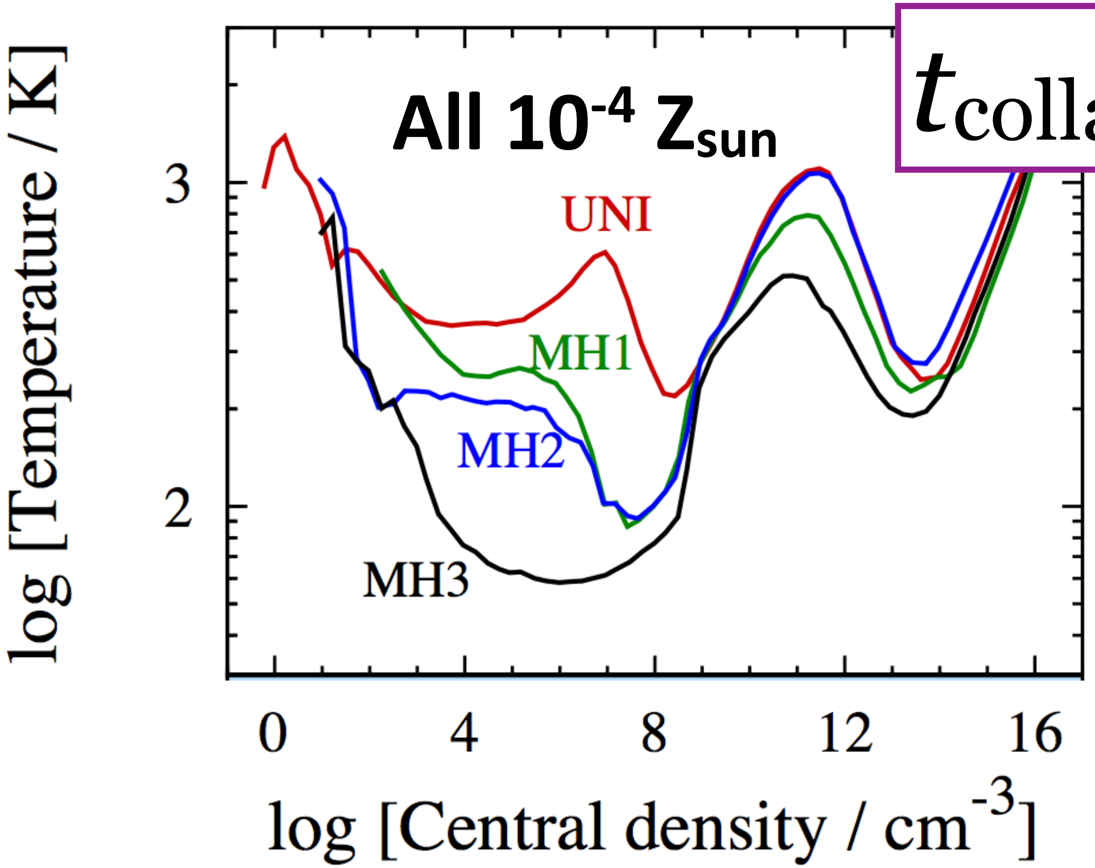
  (*ii*-b) OH or H_2O cooling is efficient even though the H2 formation heating is efficient.




Minihalo #1 $Z=10^{-4}\ Z_\odot$
density
4 7 10 $\log(n_H/\mathrm{cm}^{-3})$
Cooling saturates
6 9 12 $\log(n_H/\mathrm{cm}^{-3})$
OH cooling
8 11 14 $\log(n_H/\mathrm{cm}^{-3})$
10 13 16 $\log(n_H/\mathrm{cm}^{-3})$
dust cooling
temperature
0 500 1000
T [K]
H_2 form. heating
OH cooling
optically thick
dust cooling
10^5 au
10^4 au
10^3 au
100 au

Collapse speed matters



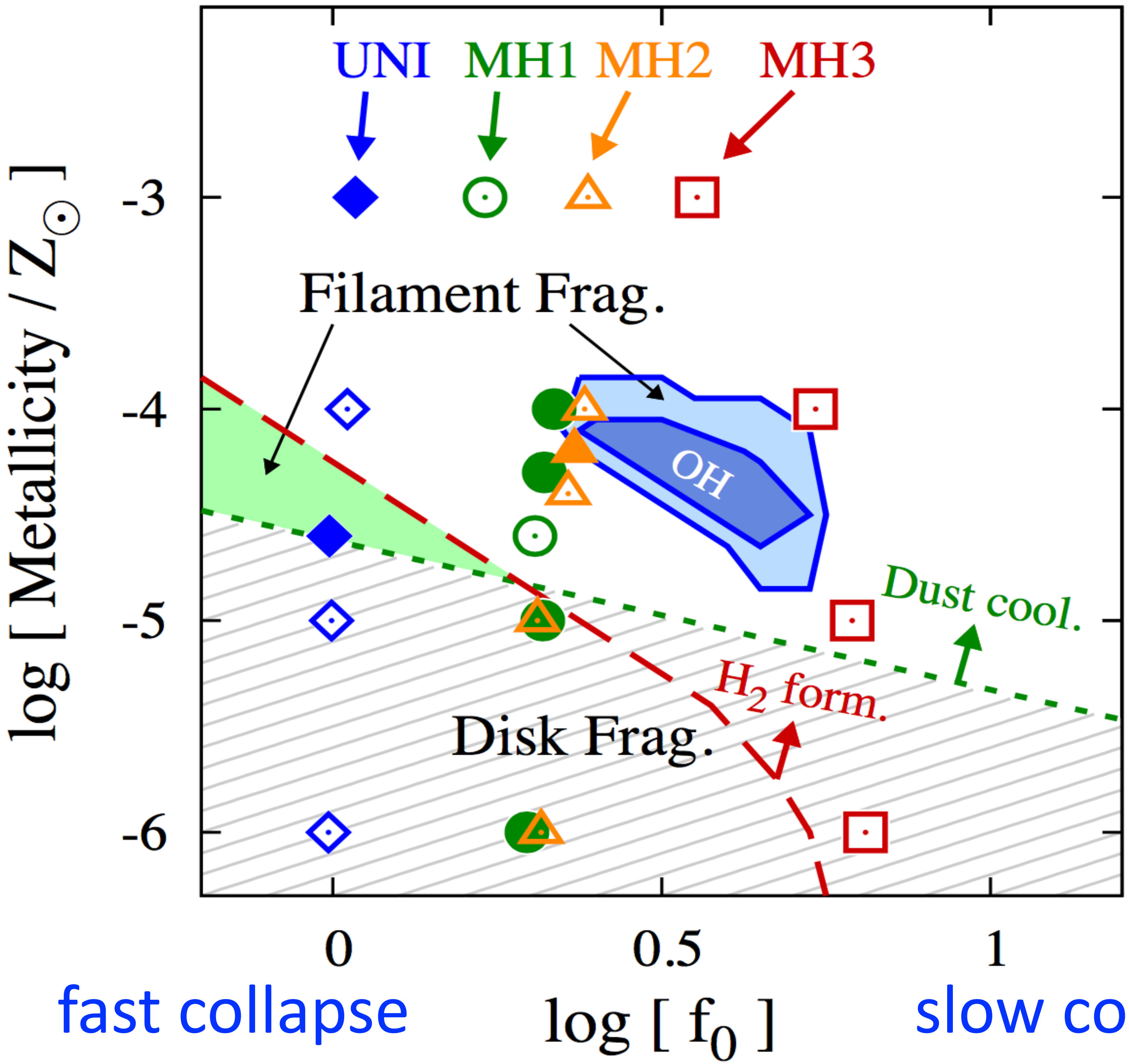


$$t_{\rm collapse} = f_{\rm O}\, t_{\rm collapse}\,(\gamma)$$

The overall collapse speed is characterized by a factor $f_{\rm O}$.

Recall Serena's talk on tuesday.

There are reasons to fragment, but…

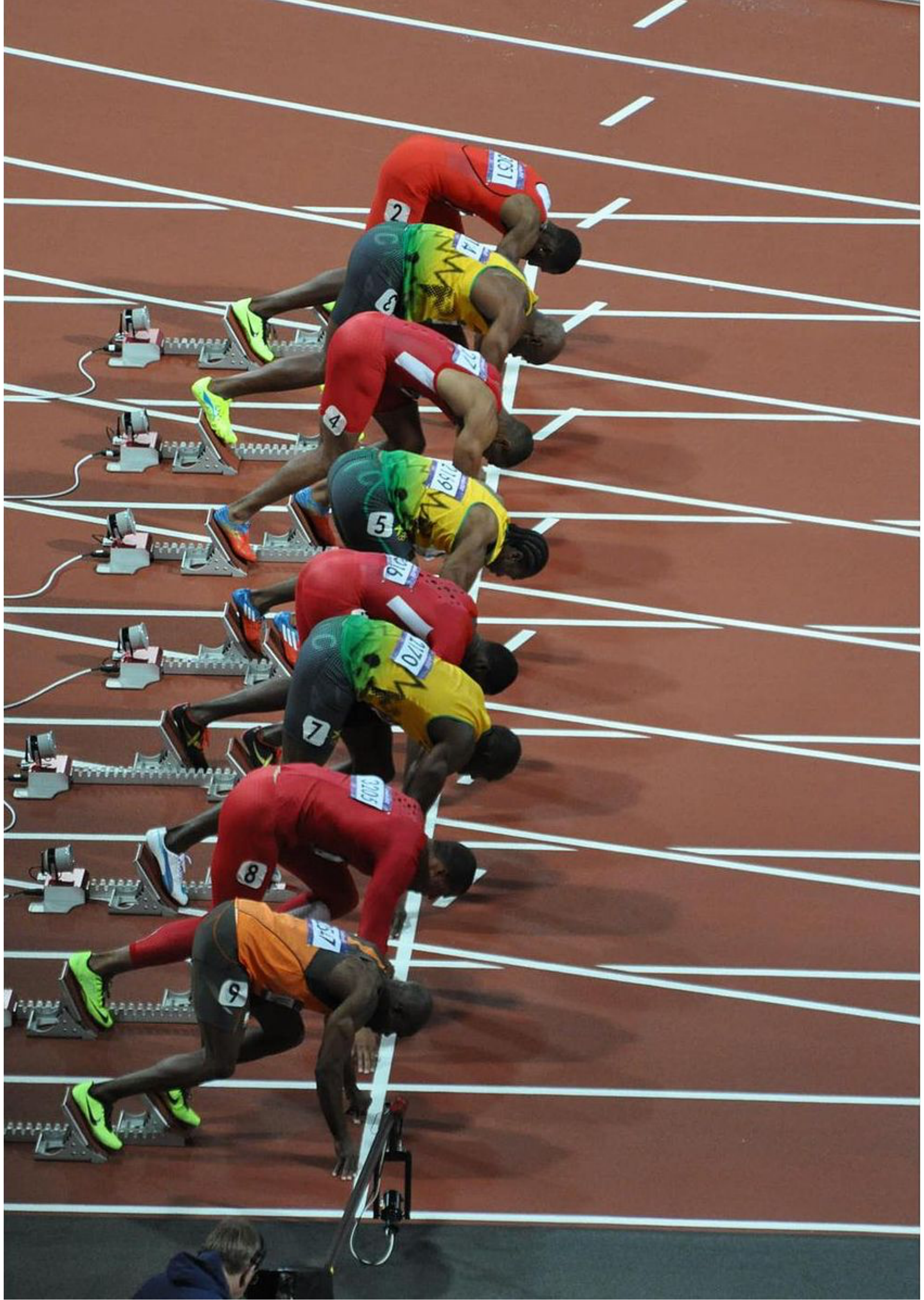


fast collapse

slow collapse

← The 2-parameter description gives a rough guide, but far from complete.

The collapse time factor f_0 contains too many physics (rotation, T, turbulence)

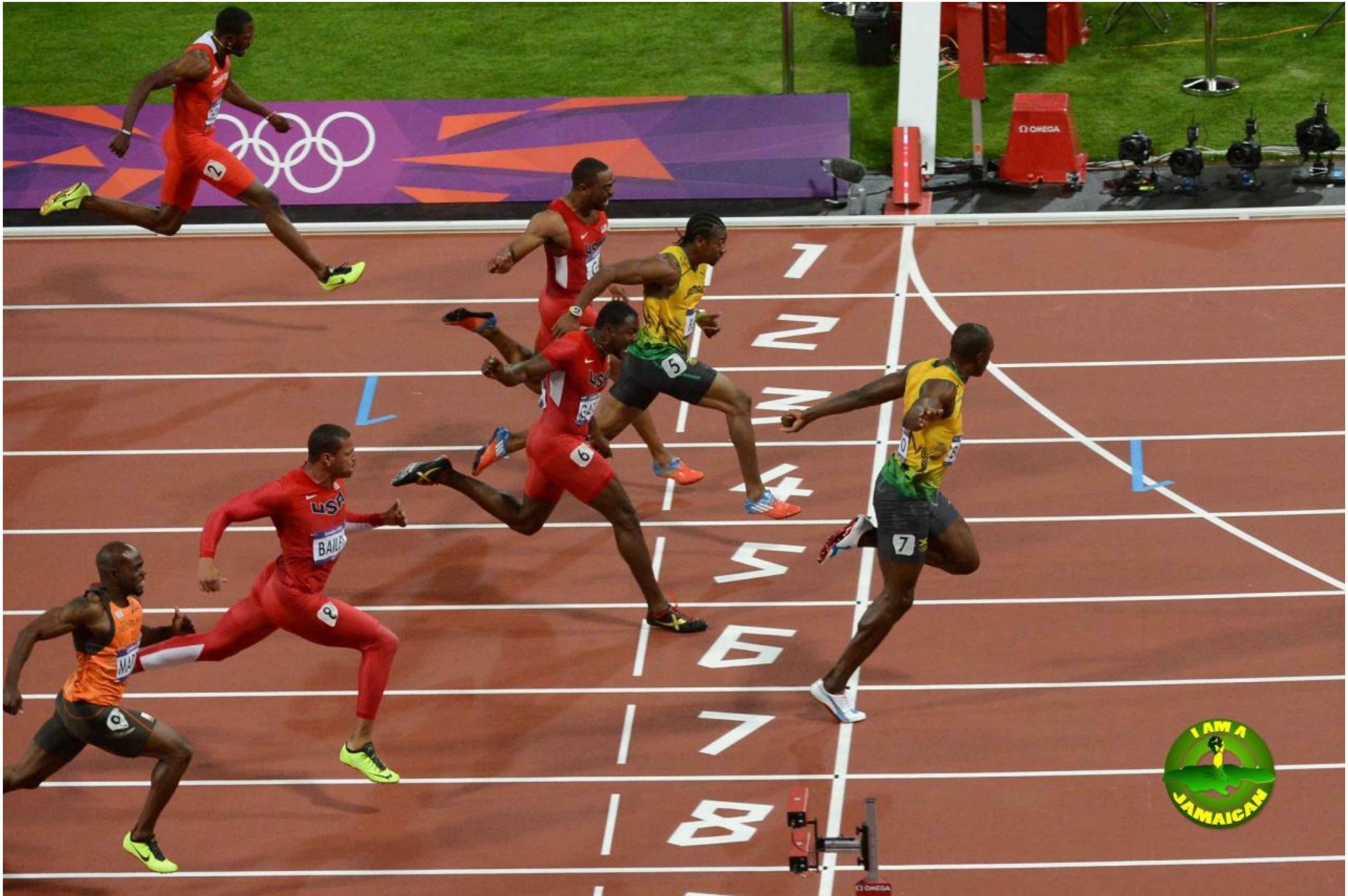


Initial condition
… of 100m final

Which "halo" is gonna produce a big "star" ?

If we are given:

cloud mass, temperature,
metallicity, abundances,
halo spin, merger history,
deg. of turbulence,
etc. etc…


Ω OMEGA
1
2
3
4
5
6
7
8
USA
BAILES
I AM A JAMAICAN

star formation

Theory part summary

- Full physics can be incorporated.
- Thermal evolution couples with cloud deformation and fragmentation.
- Grain growth important at high densities.
- Overall behaviour can be understood also for 0.1-0.01 Z_{sun}
- But needs radiation included properly.
- Implications for metal-poor stars (← talk by Raffaella later)