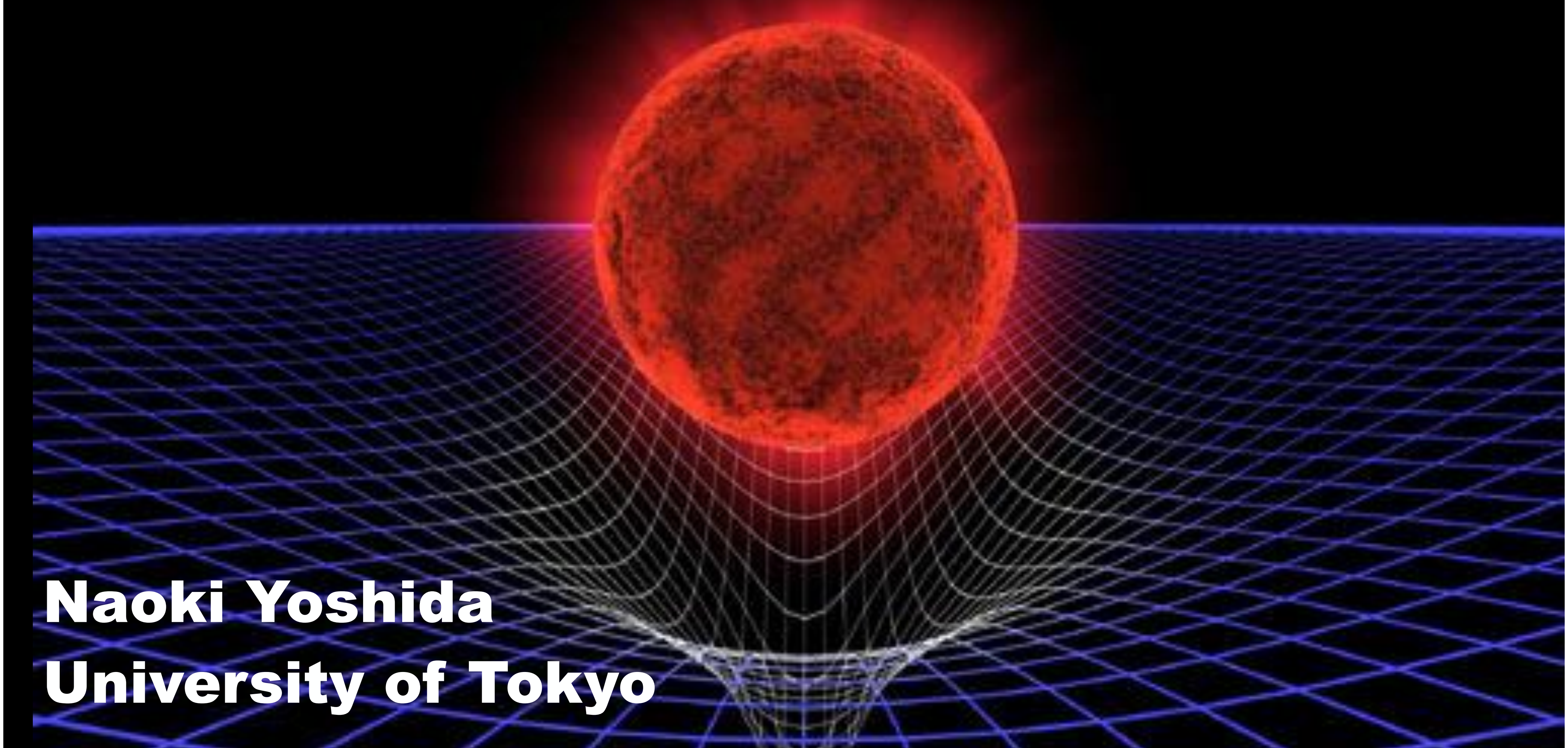
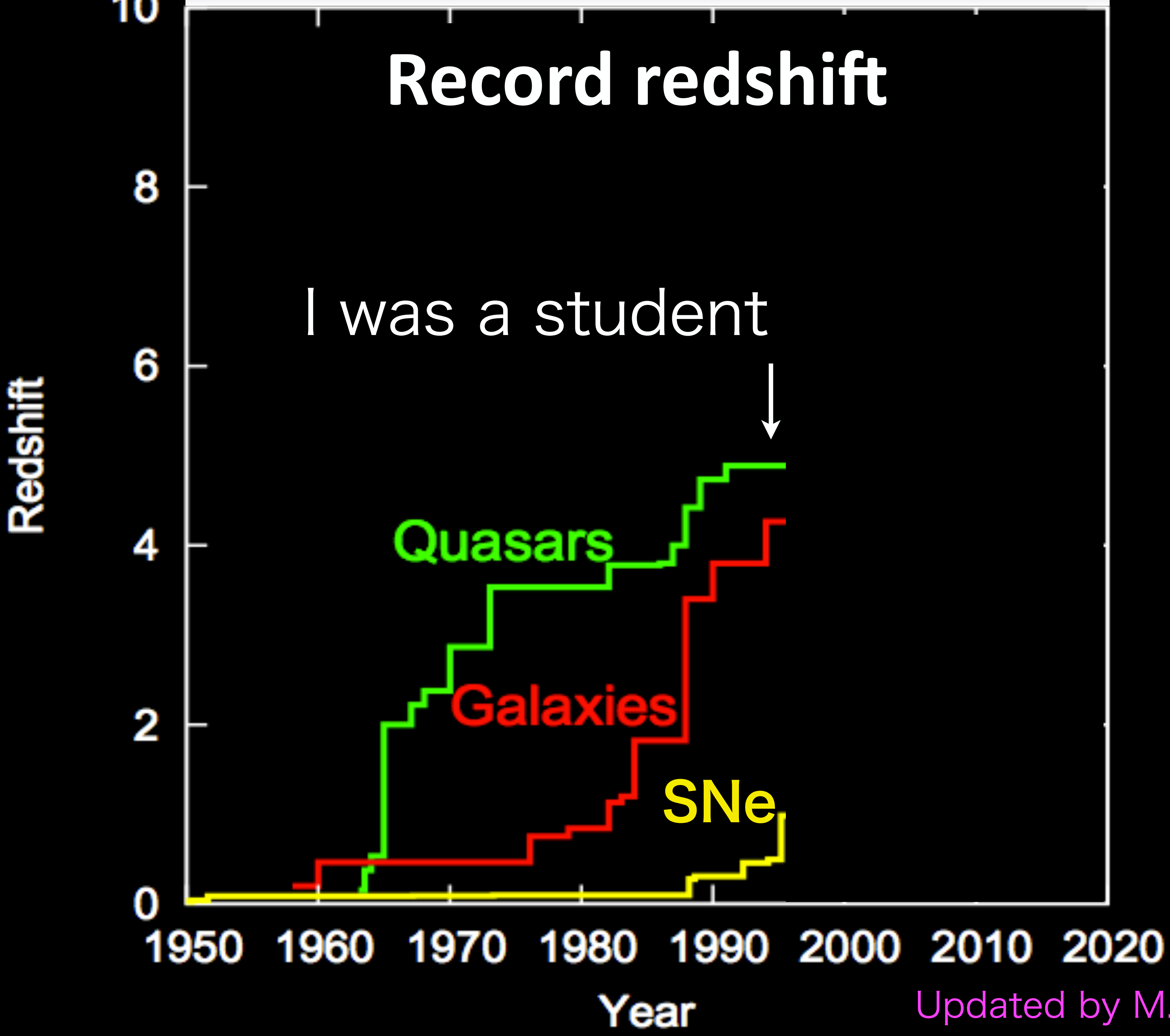
Formation of Primordial Stars and Blackholes

Star Formation in Very Different Environment



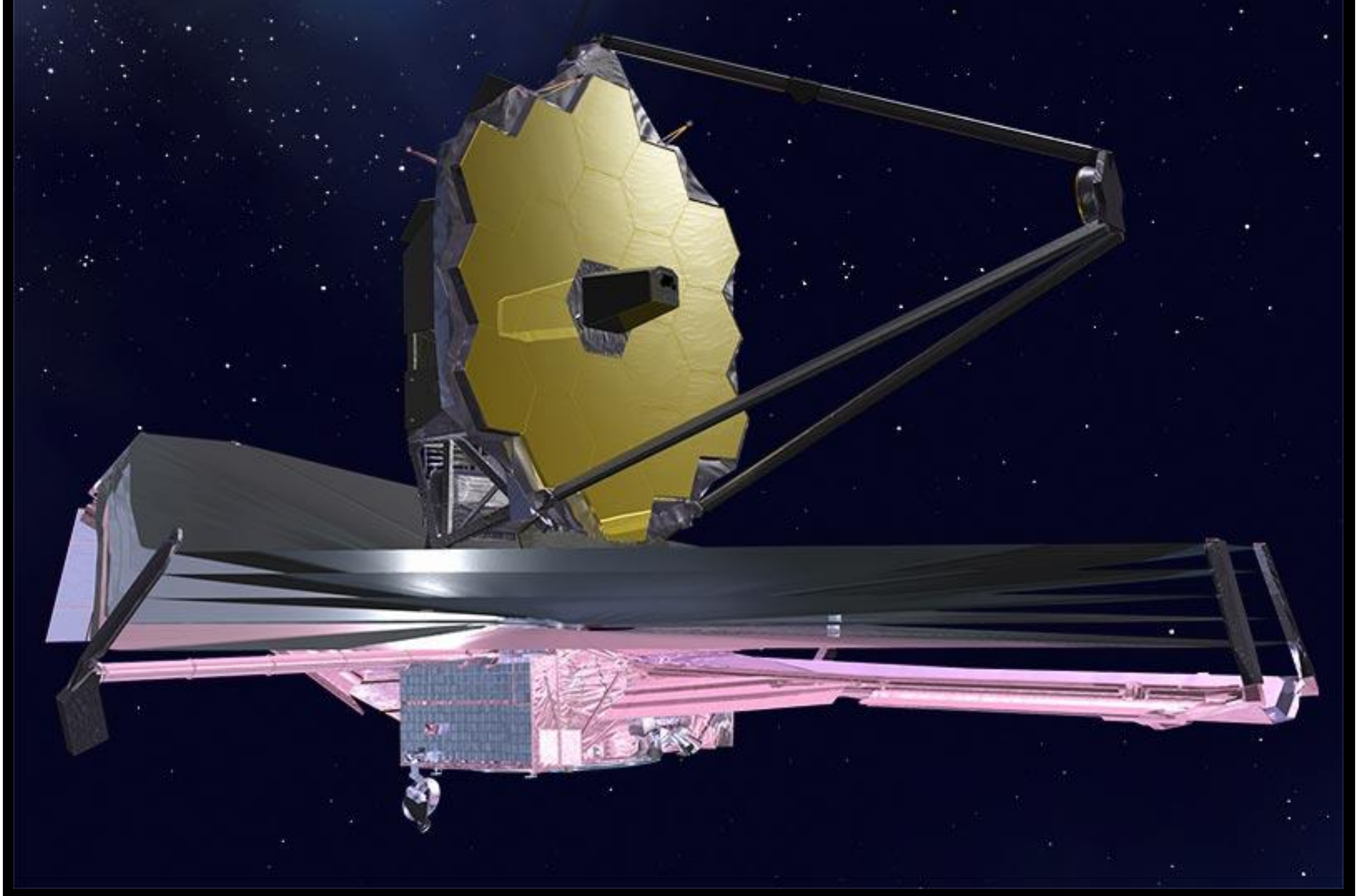
Naoki Yoshida
University of Tokyo

Our playground (or workplace)

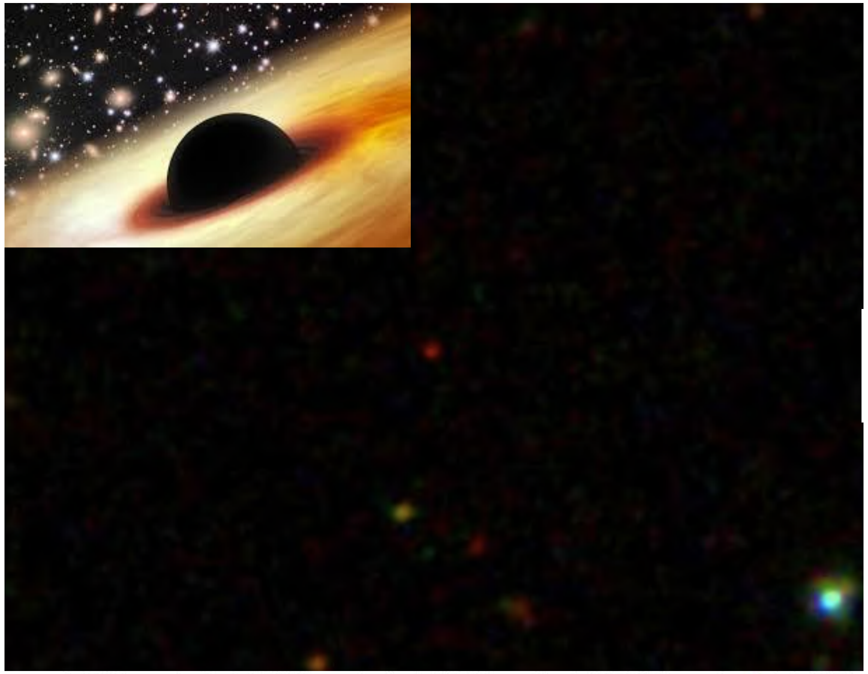


Updated by M. Tanaka

James Webb Space Telescope (2018-)



A young, monstrous blackhole

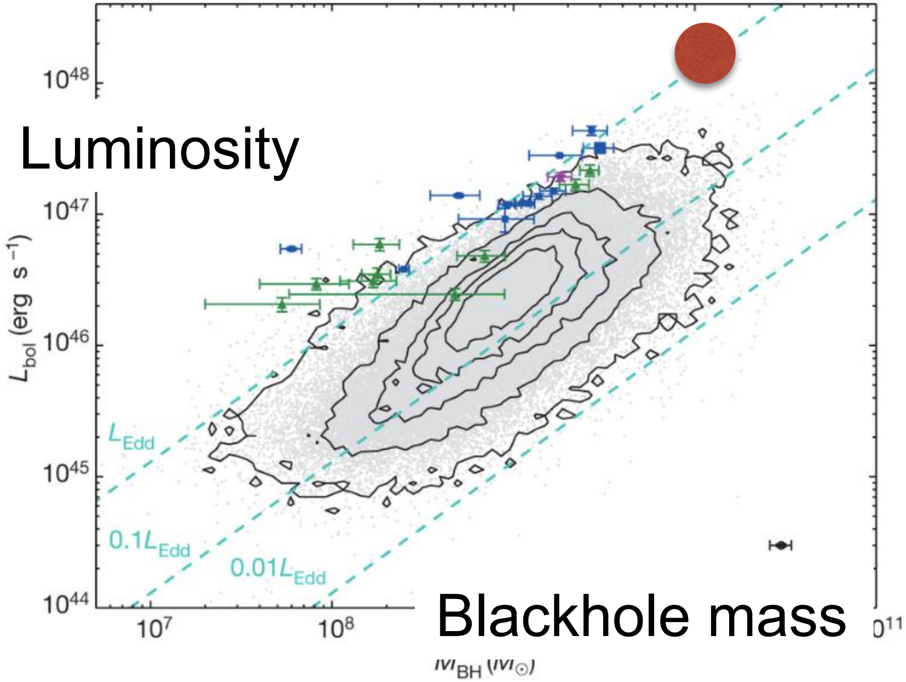


Wu et al. Nature 2015

SDSS J0100+2802

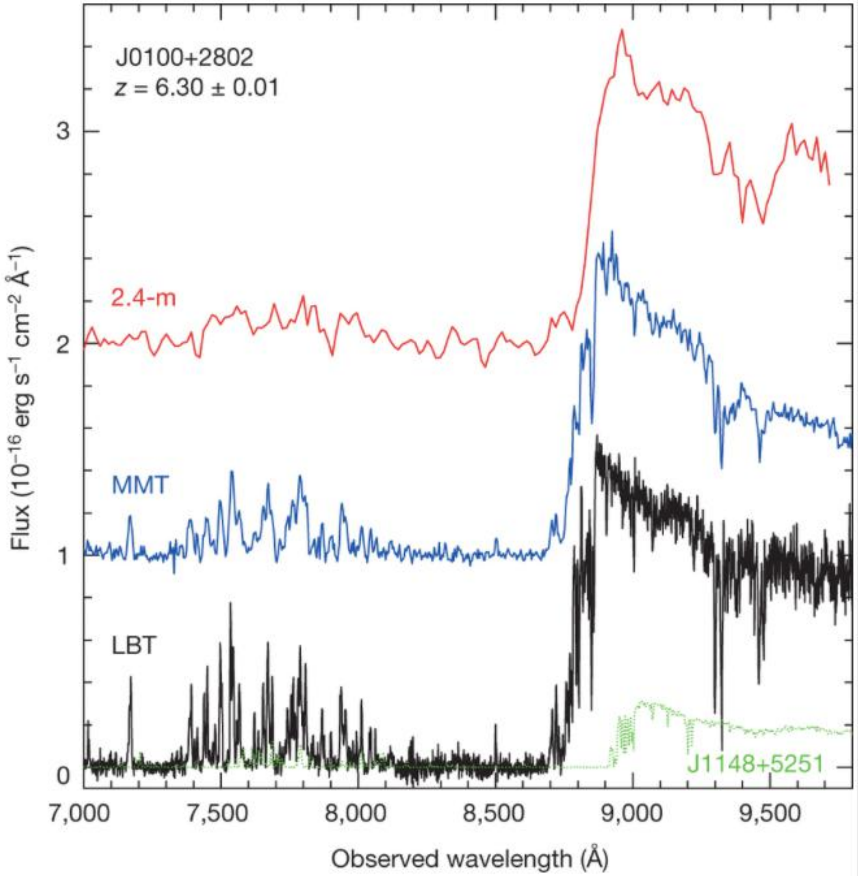
12 billion solar-masses

0.9 Gyrs after the big bang

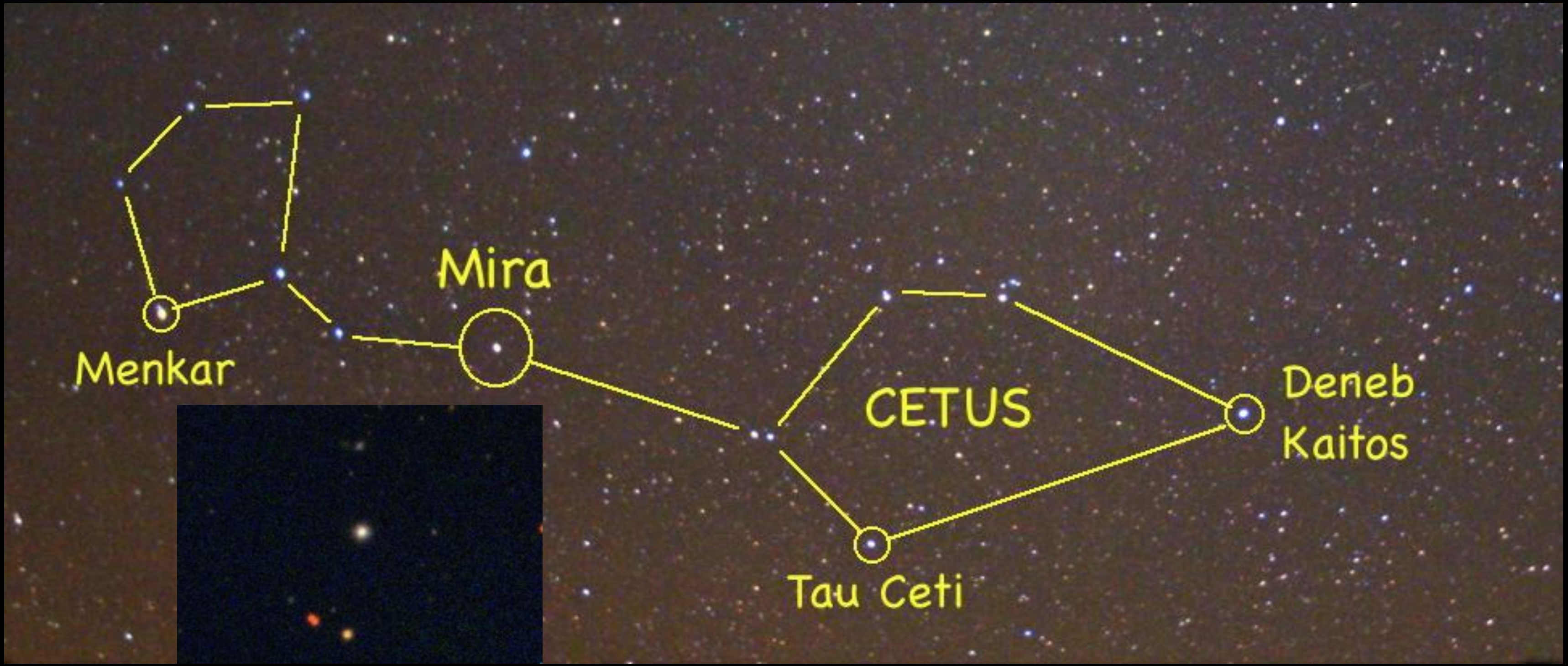


Luminosity

Blackhole mass



Hunting for the oldest stars

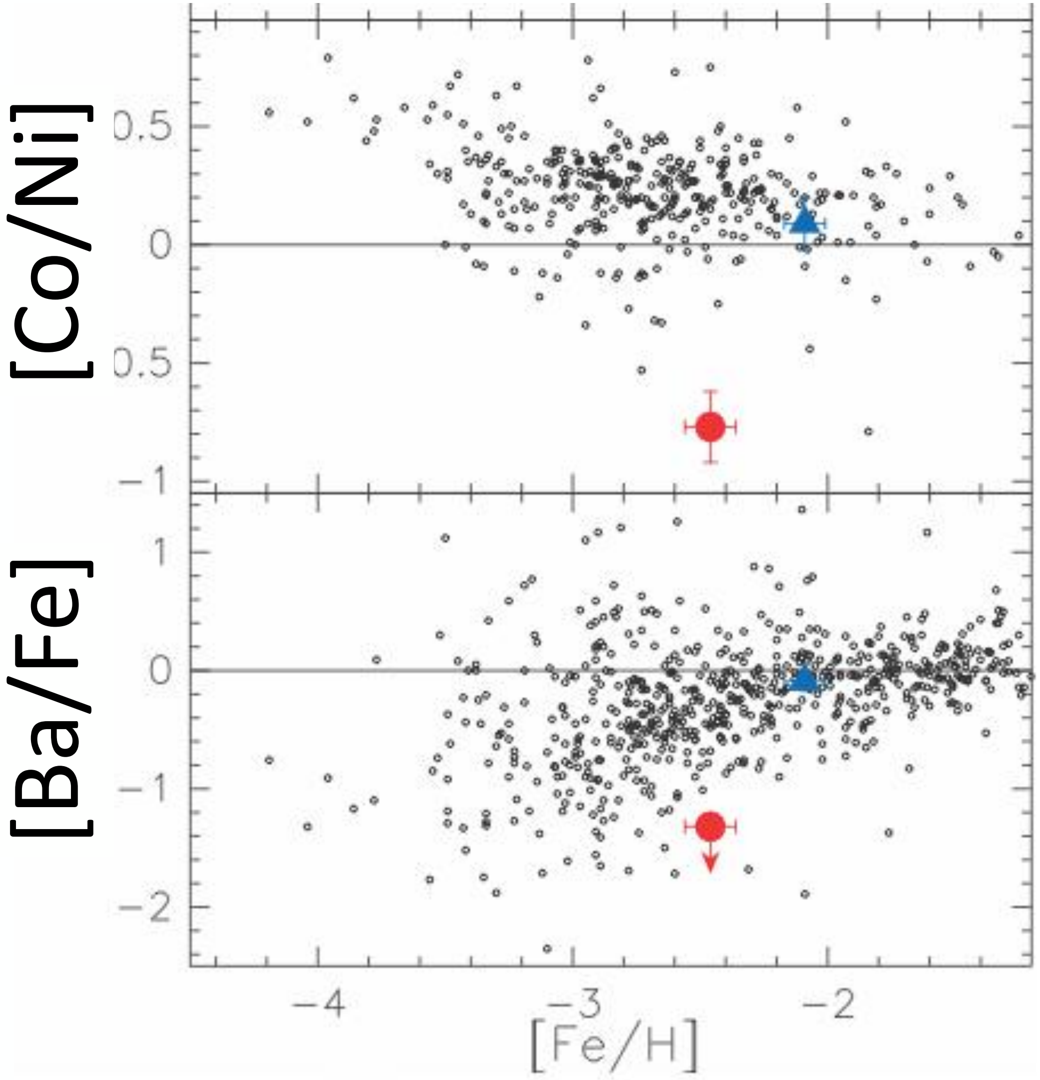


A low-mass ($<1 M_{\mathrm{sun}}$), low-metallicity star.

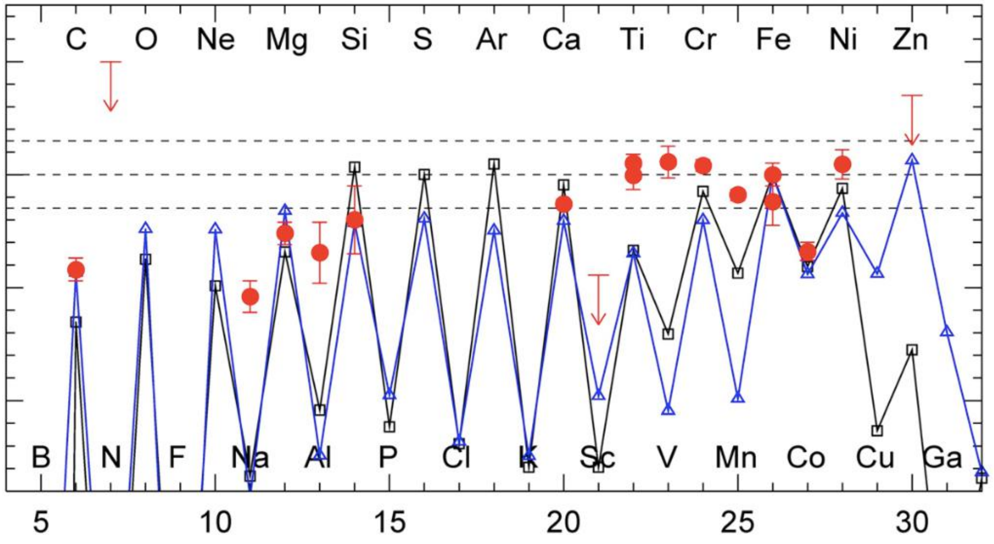
A messenger from the early universe.

A second-generation star ?

Elemental abundance of SDSS J1820.5-093939.2

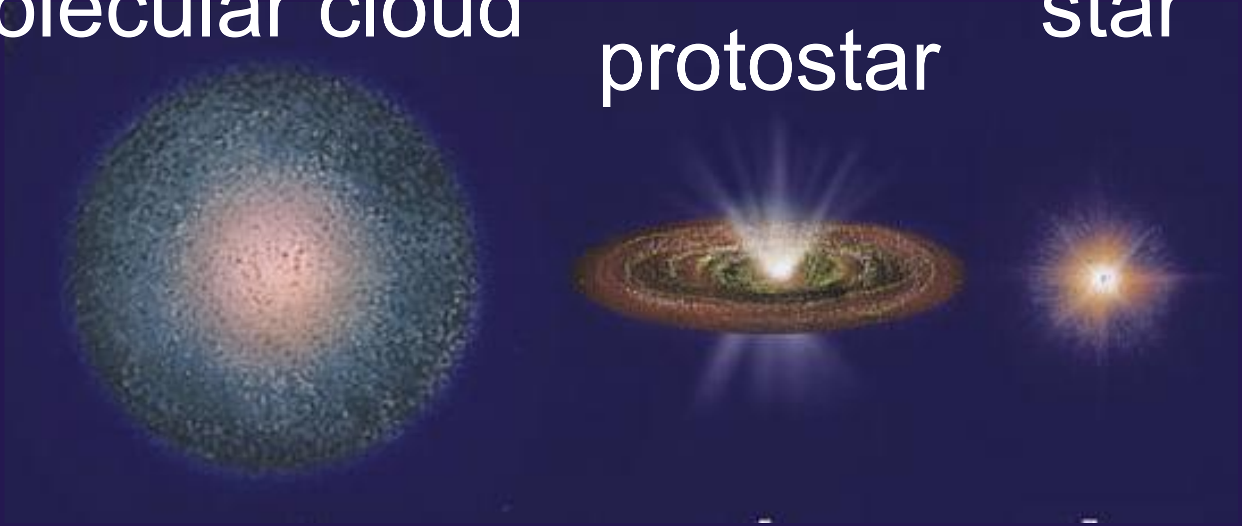


Very different yield from core-collapse supernova:
low α/Fe, low Co/Fe etc
Signatures of a pair-instability supernova
of progenitor mass > 200 M_{sun}



Aoki et al. 2014, Science

THEORY OF STAR FORMATION

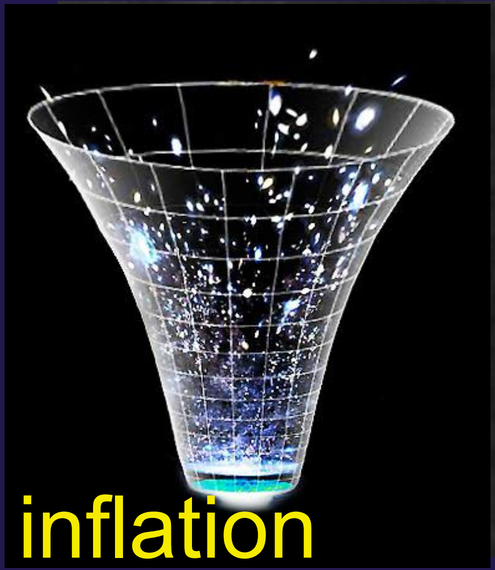


molecular cloud

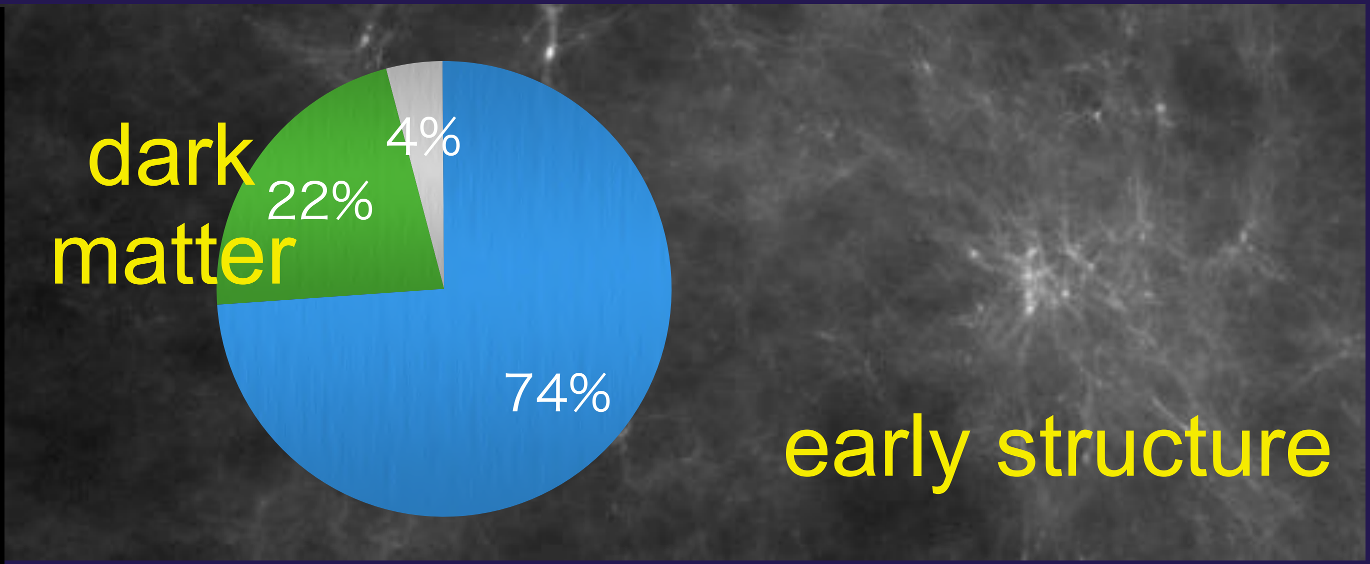
protostar

star

STANDARD COSMOLOGICAL MODEL



inflation

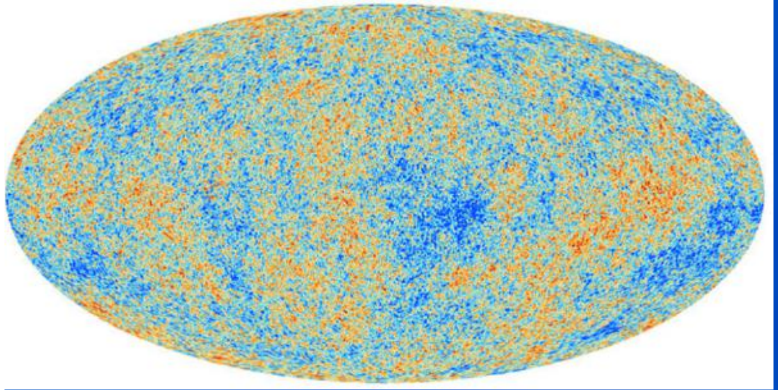


dark matter

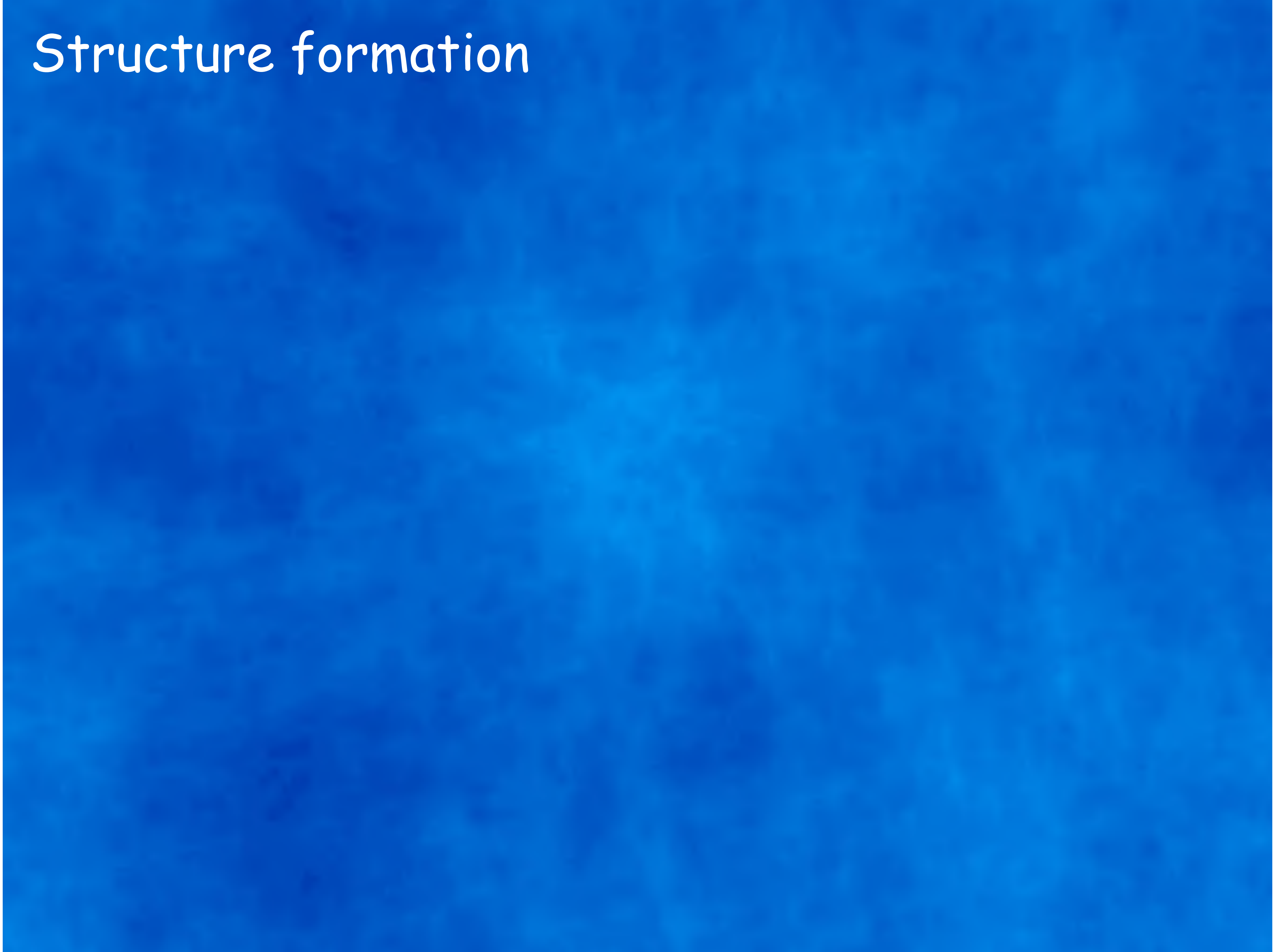
early structure

In the beginning,
there was a sea of light elements
and dark matter...

and tiny ripples left over
from the Big Bang

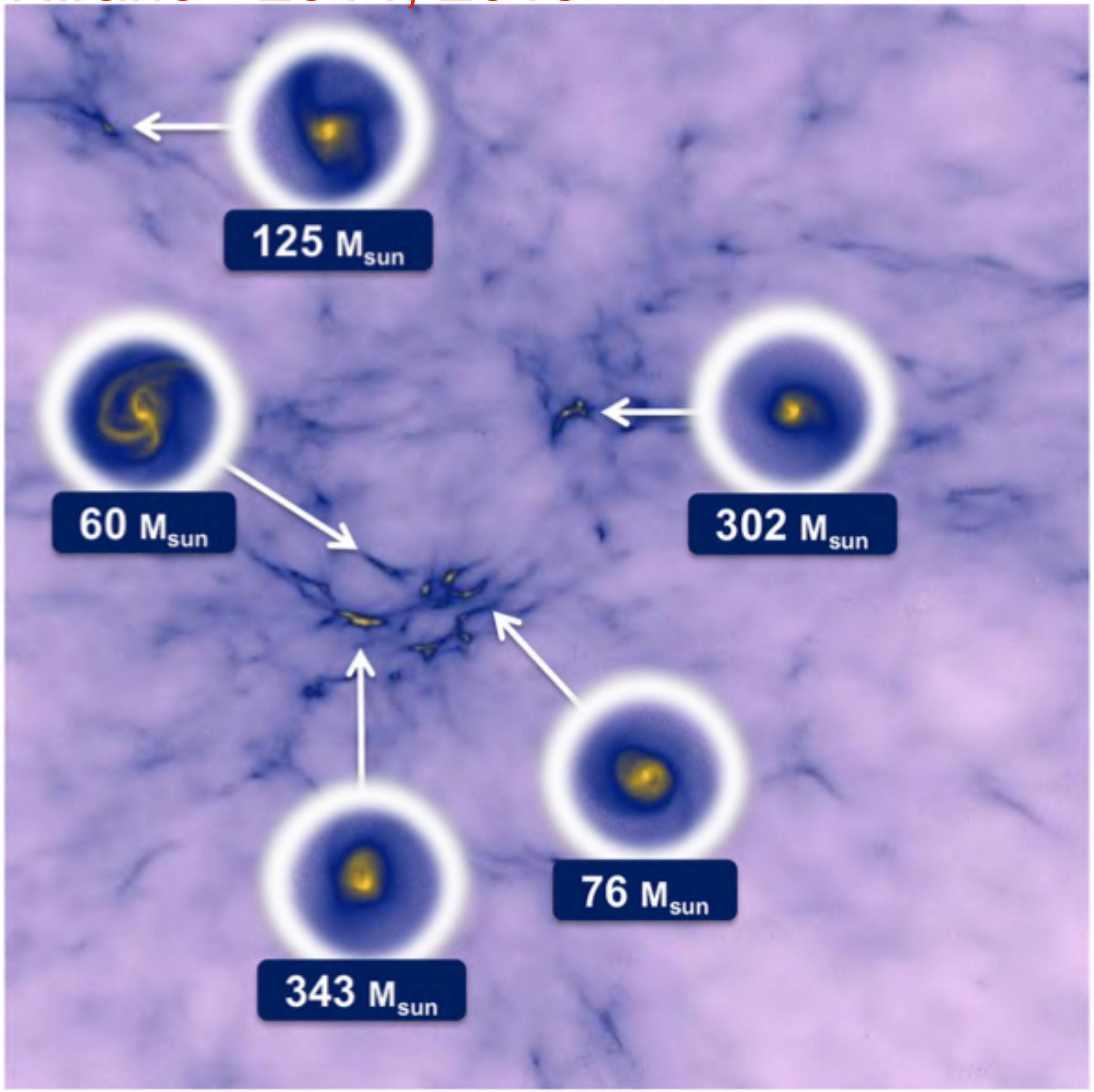


Structure formation



One hundred first stars

Hirano+ 2014; 2015



Cosmological hydro simulation

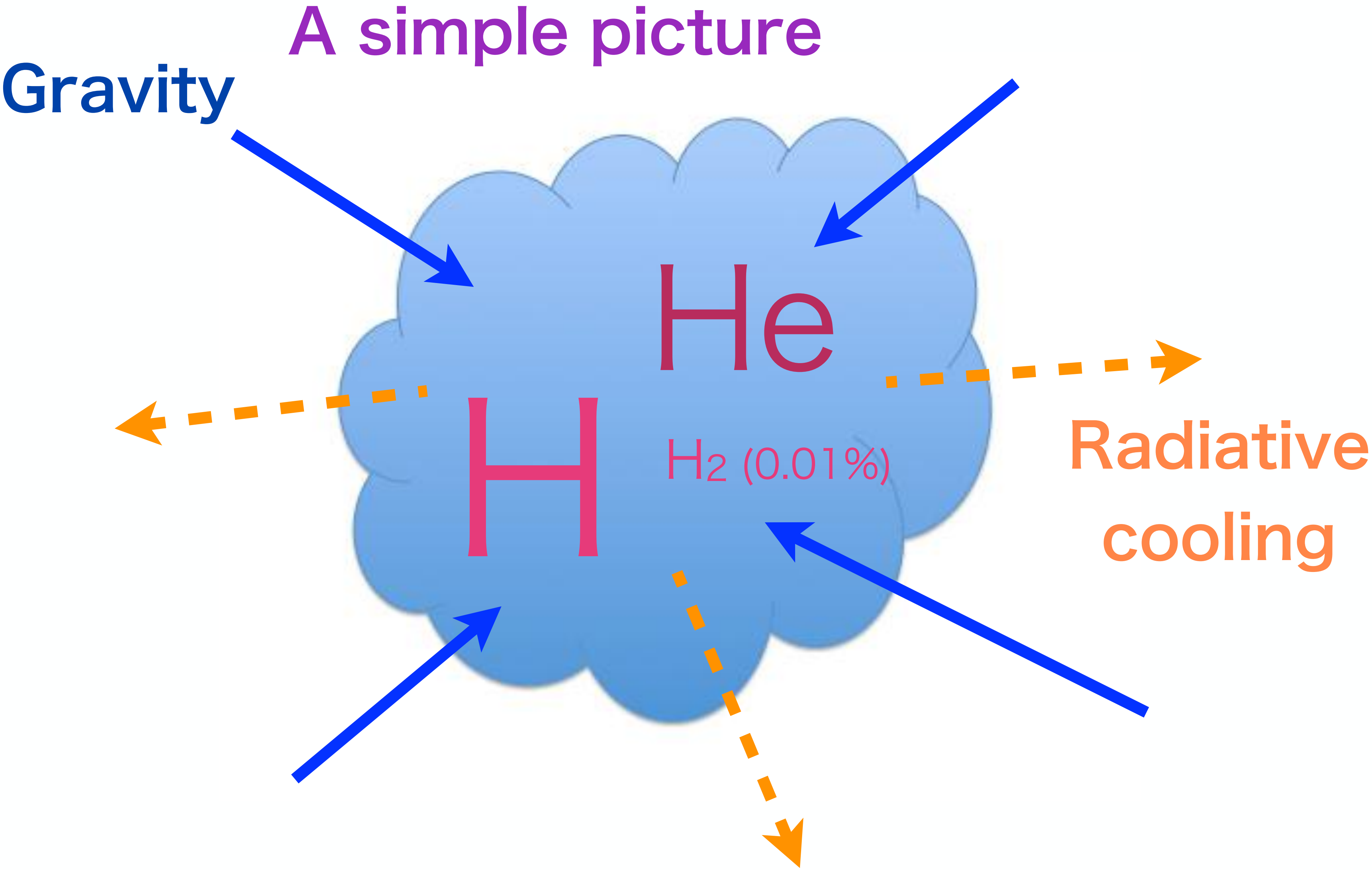
+

radiation-hydro sim. of protostellar evolution

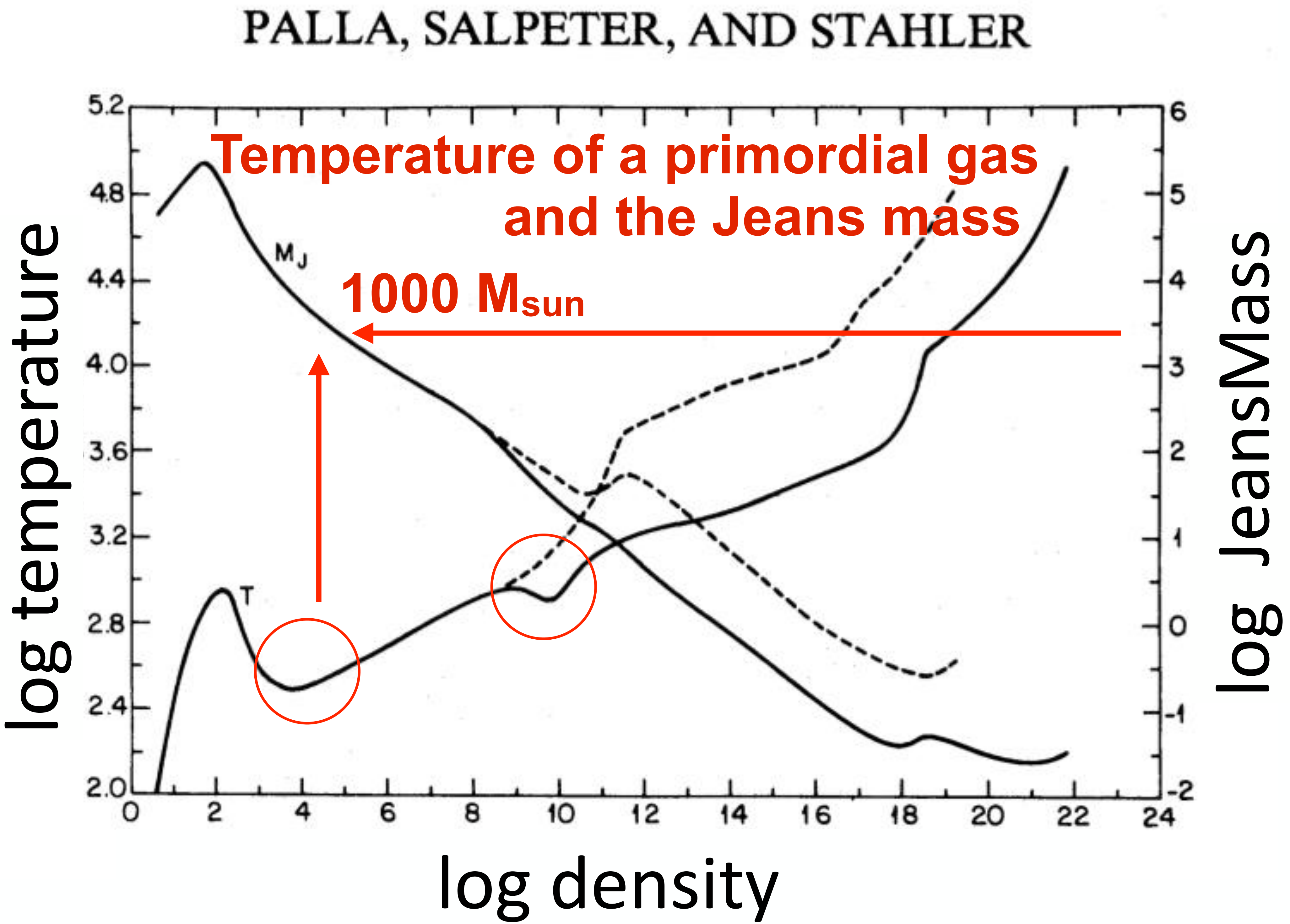
100 star forming clouds located in a cosmological volume.

Mass distribution of the first stars

PRIMORDIAL GAS CLOUD



Temperature of a primordial gas and the Jeans mass



HYDROGEN CHEMISTRY

Low density (~10^4 /cc)

$$\mathrm{H} + \mathrm{e} \rightarrow \mathrm{H}^- + h\nu$$

$$\mathrm{H}^- + \mathrm{H} \rightarrow \mathrm{H}_2 + \mathrm{e}$$

Slow process

Photo-attachment

+

H2 formation

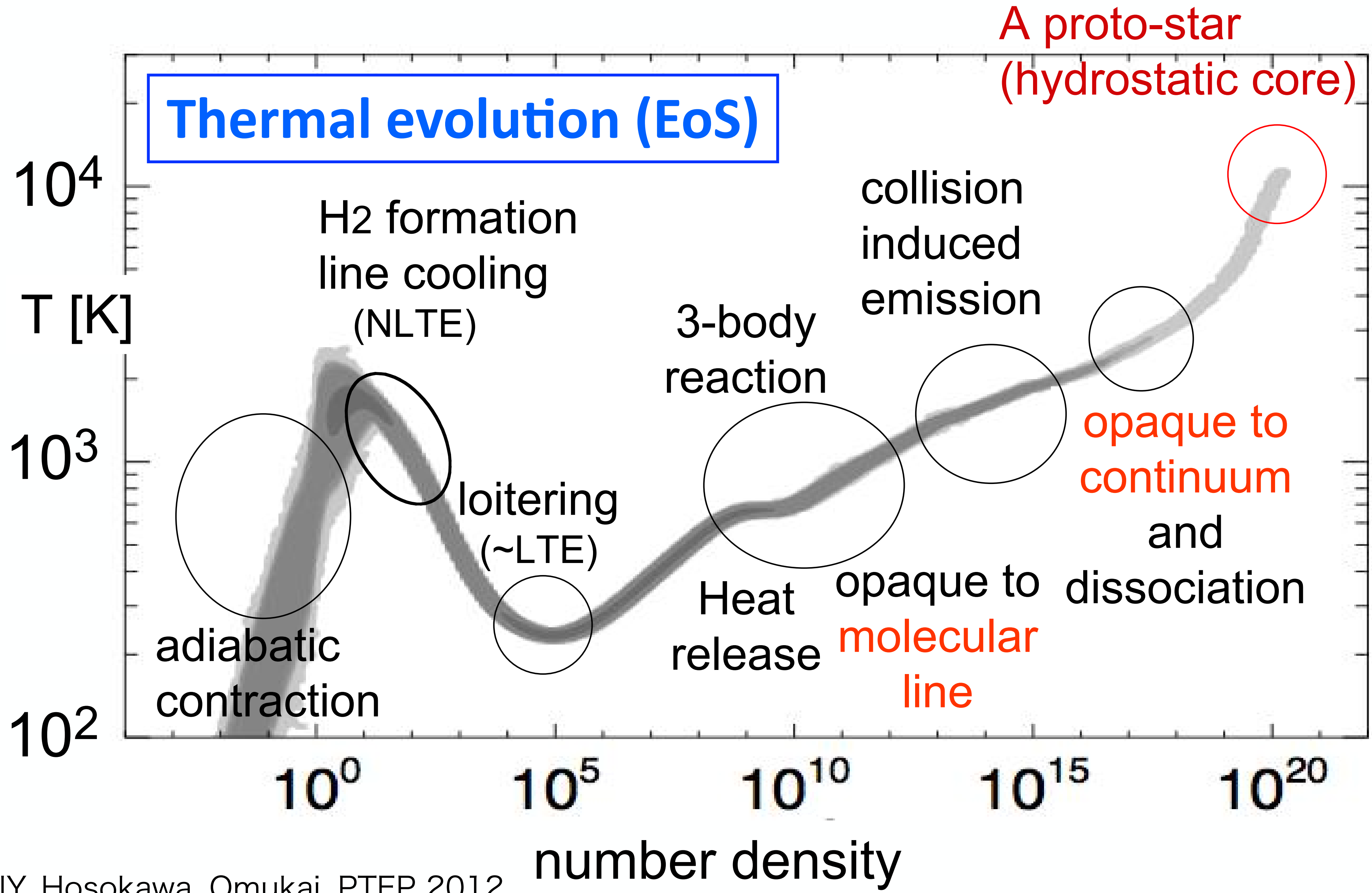
High density (~10^8 /cc)

$$\mathrm{H} + \mathrm{H} + \mathrm{H} \rightarrow \mathrm{H}_2 + \mathrm{H}$$

$$\mathrm{H} + \mathrm{H} + \mathrm{H}_2 \rightarrow 2\mathrm{H}_2$$

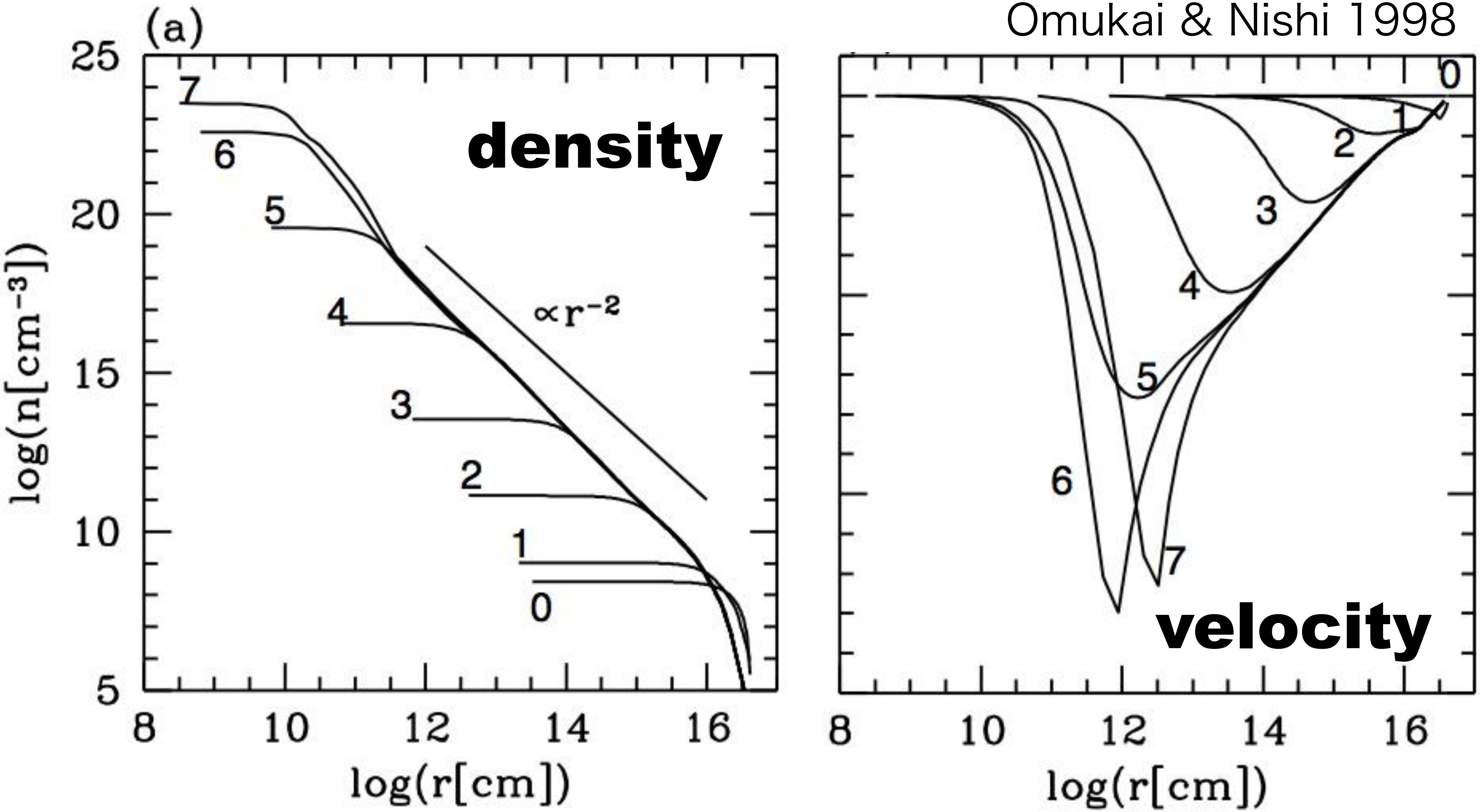
Rapid three-body reactions

CHEMISTRY AND RADIATION TRANSFER



NY, Hosokawa, Omukai, PTEP 2012

SELF-SIMILAR COLLAPSE

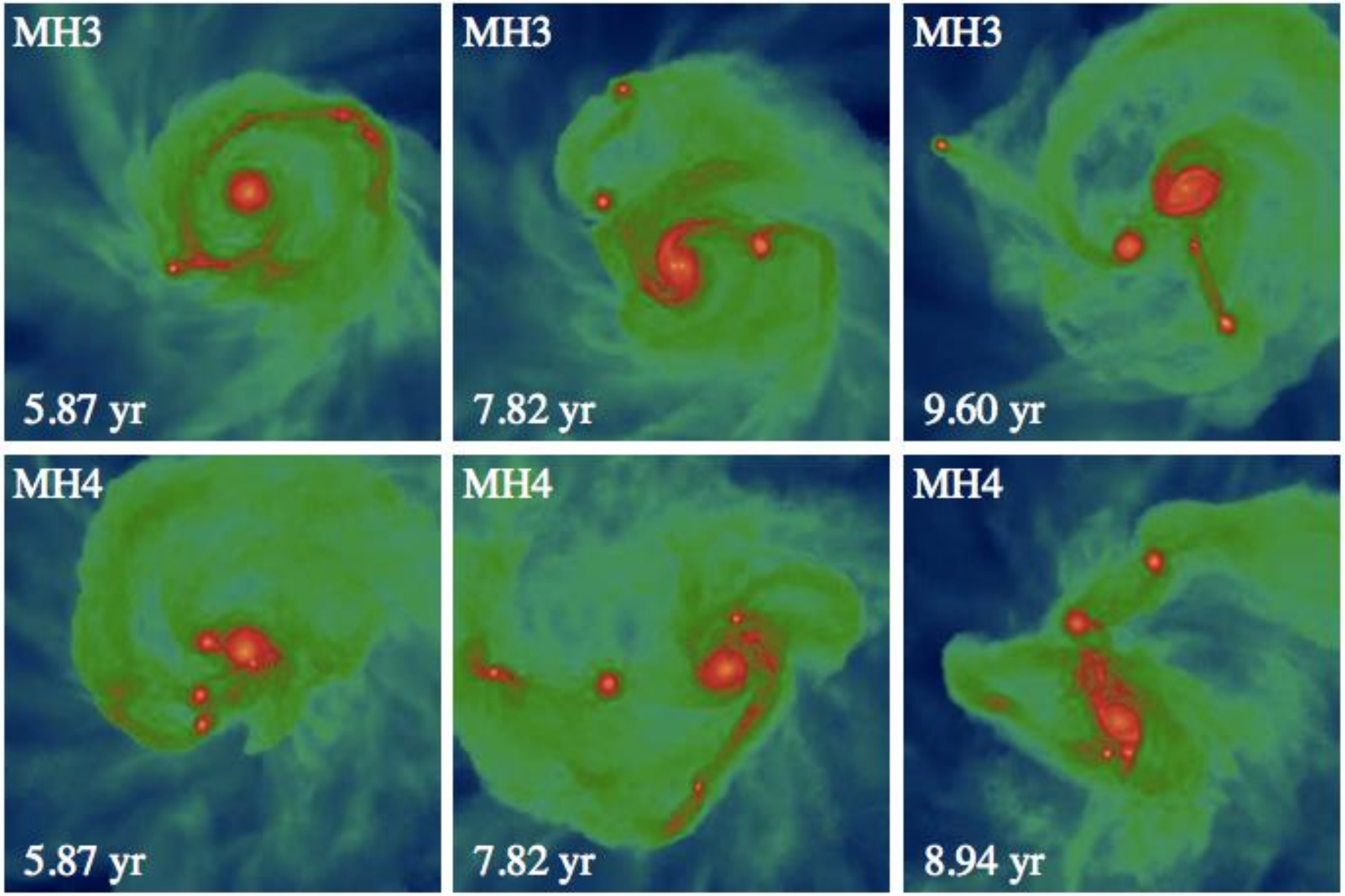


Omukai & Nishi 1998

Formation of a hydrostatic core when *n* ~ 10^{21}

Post-collapse phase: accretion

Fragmentation of a proto-stellar disk

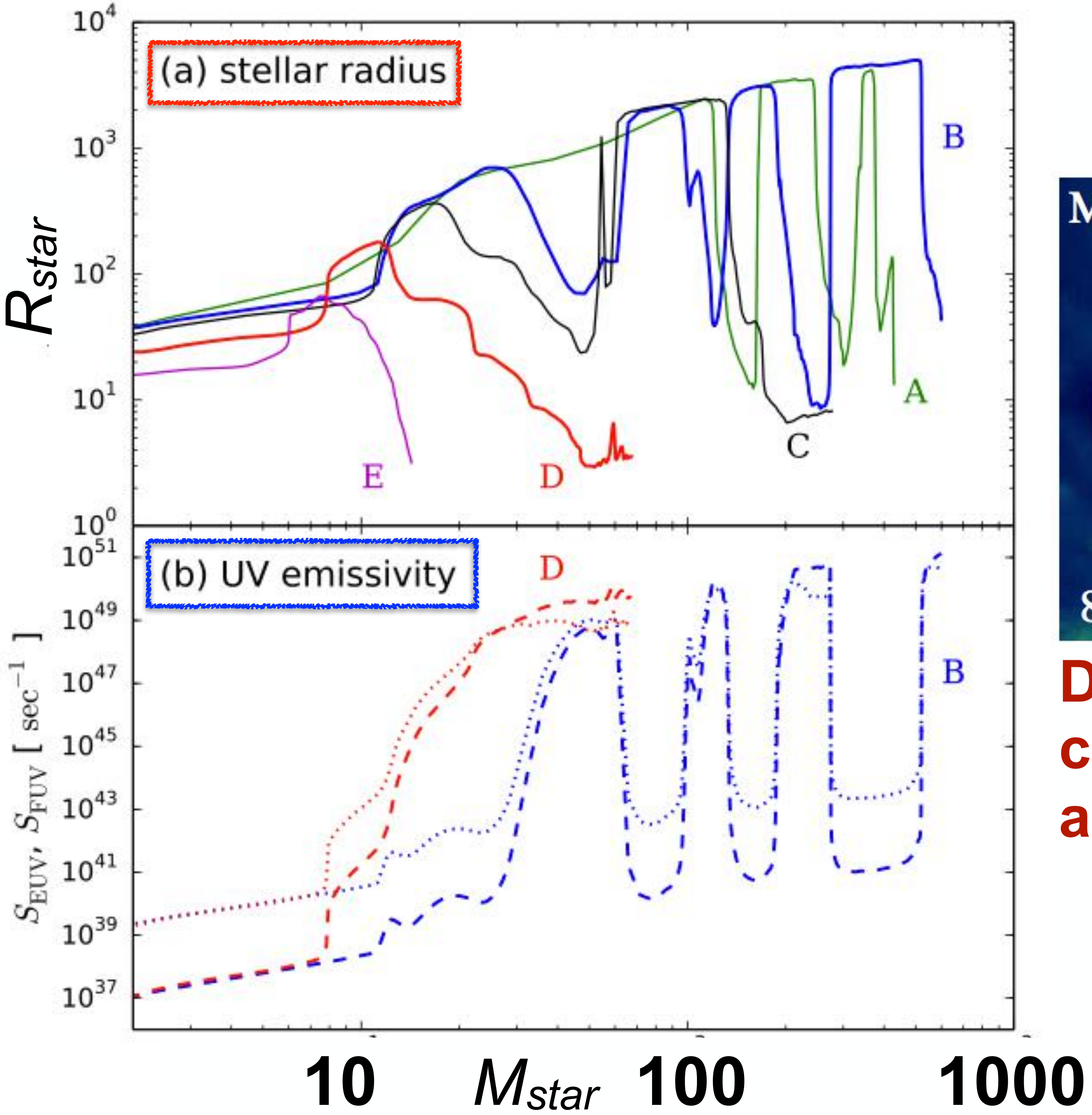


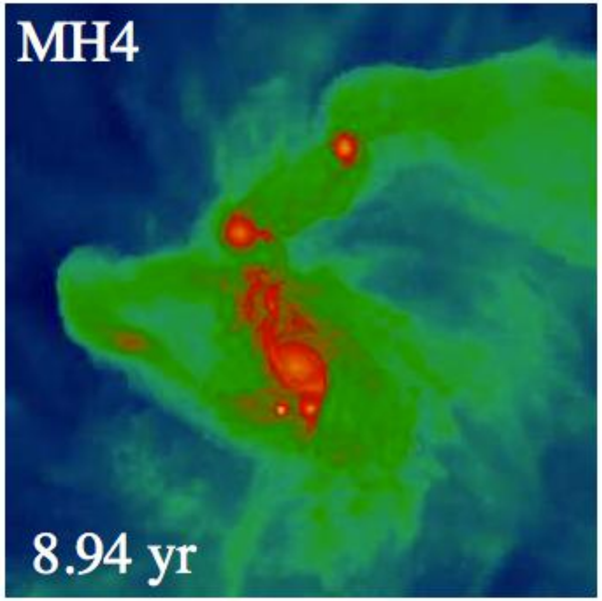
Small fragments are merged onto the central protostar on an orbital time scale

“Gravo-viscous accretion”

Greif, Bromm, Clark, Glover, Smith, Klessen, NY, Springel, 2012

ACCRETION BURSTS





Disk fragmentation causes sporadic accretion "burst"

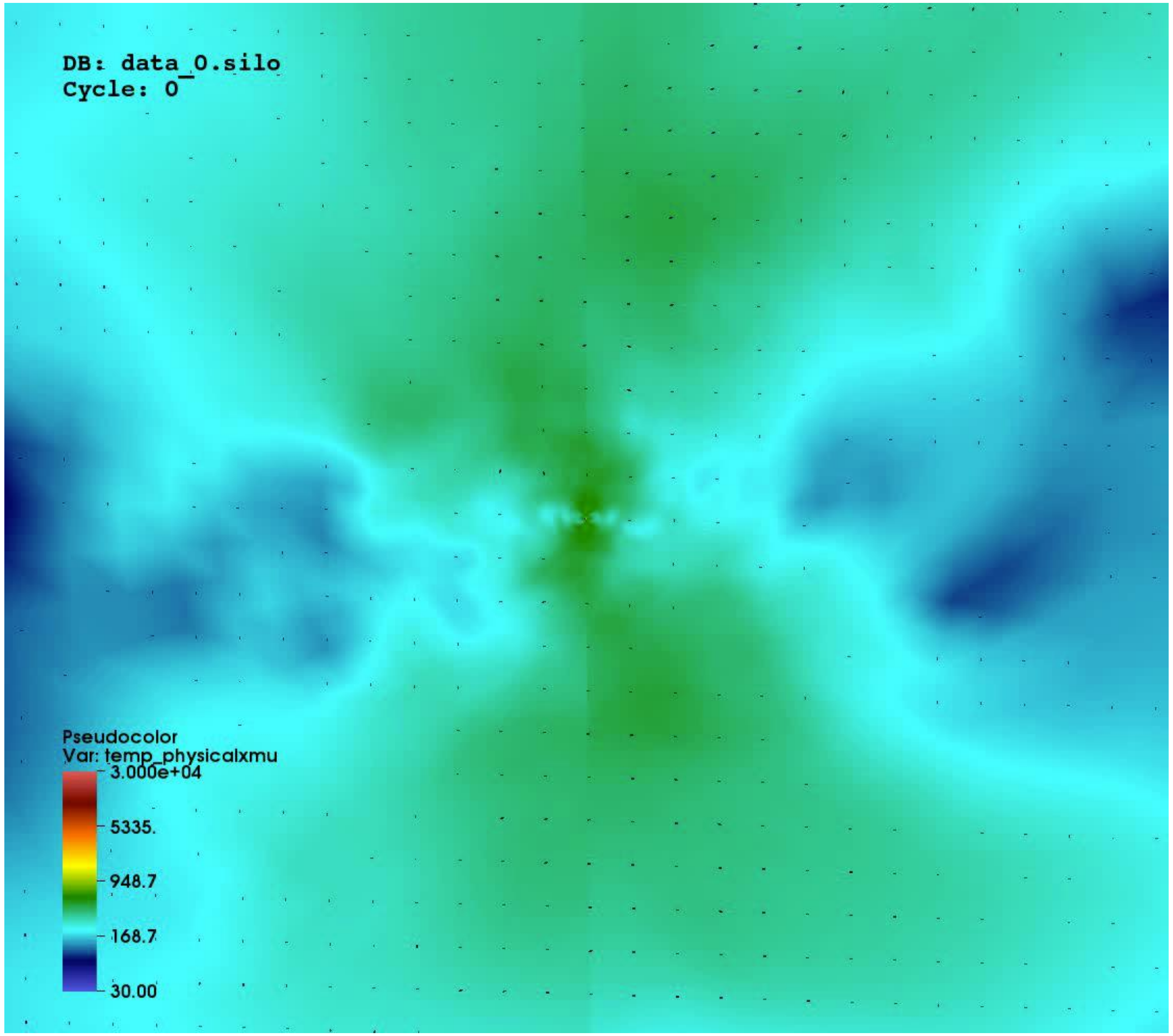
Greif+ 2012
Vorobyov+ 2014
Sakurai+2015

Protostars grow through gas accretion, mergers, plus, protostellar feedback over ~ 100,000 years

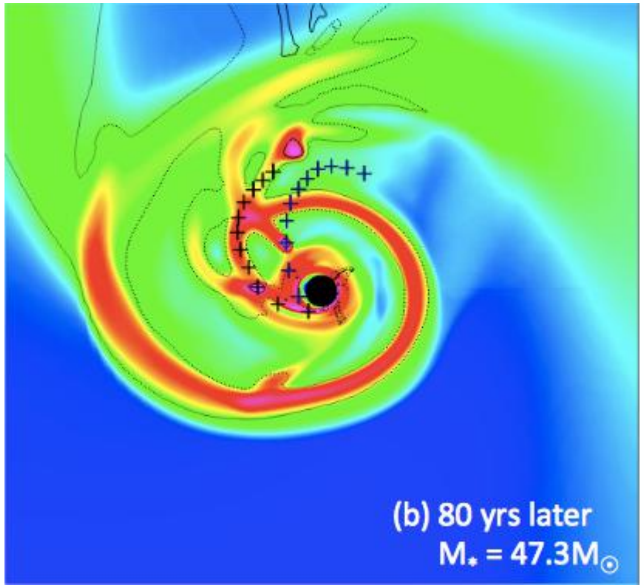
The Key Question

How and when does a first star stop growing ?

PROTO-STELLAR FEEDBACK



3D radiation-hydro. simulation by T. Hosokawa

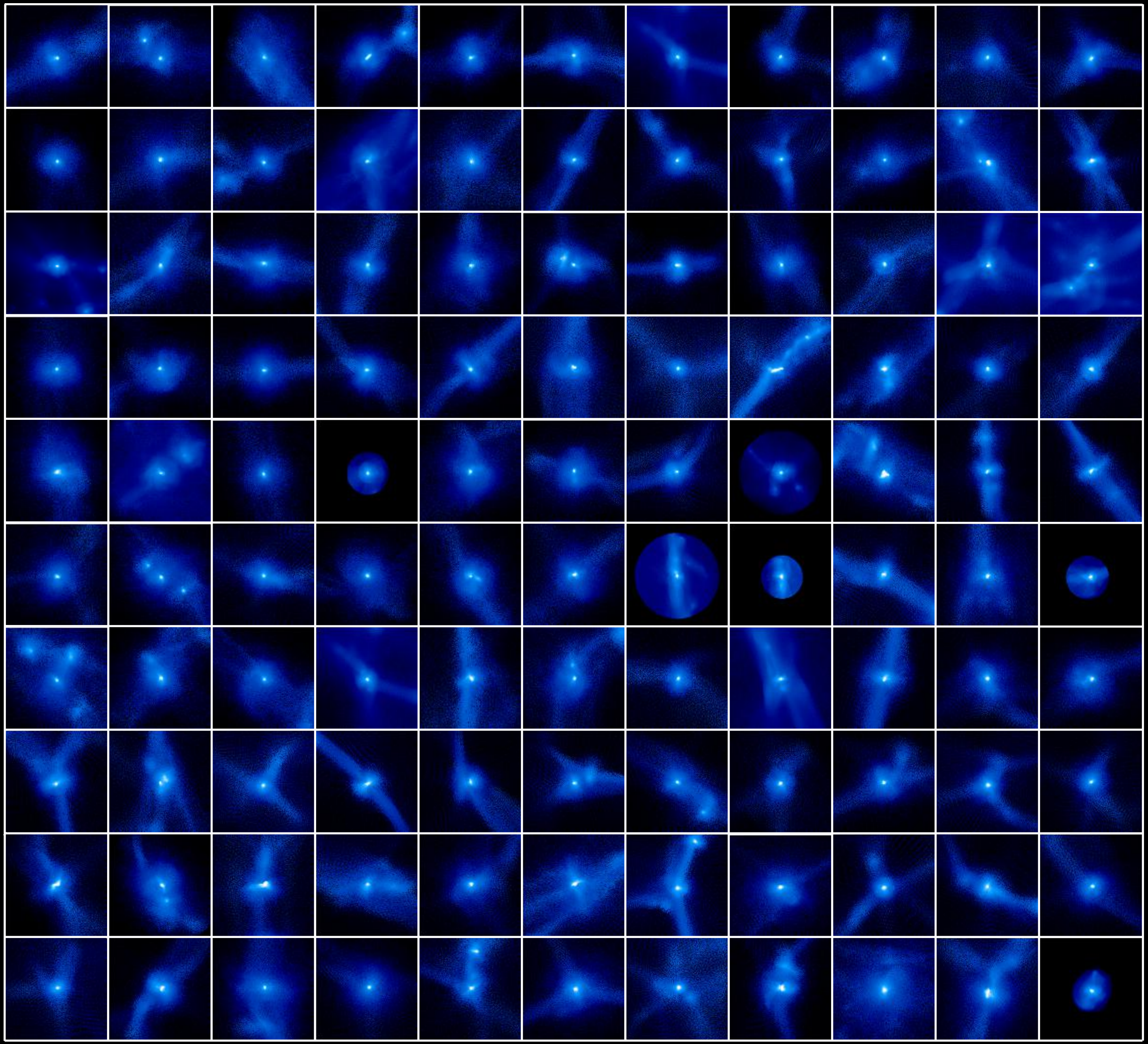


Accretion
vs
bi-polar HII regions

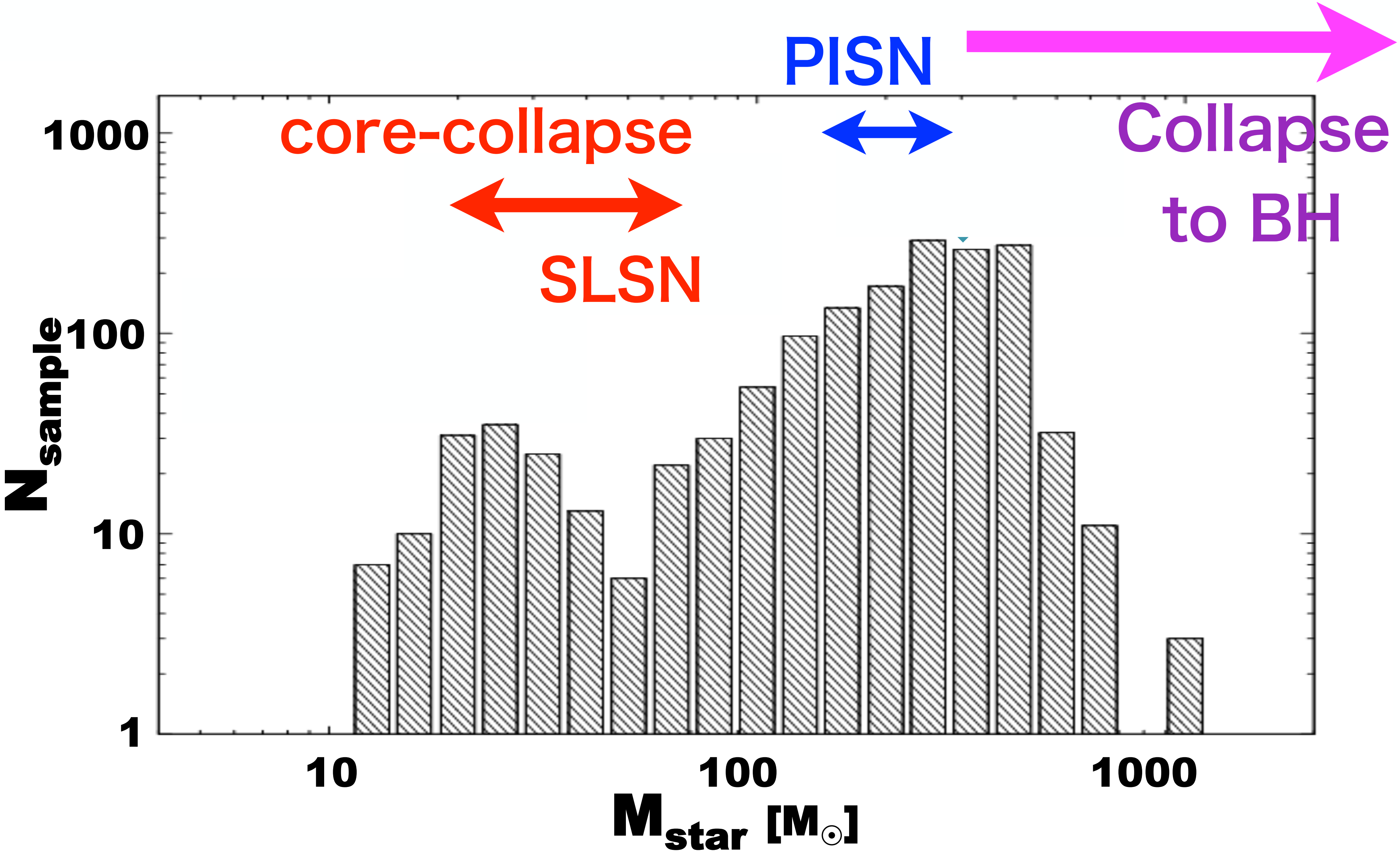
Self-regulation mechanism:

McKee-Tan08; Stacey+12; Hosokawa+16

One hundred first stars



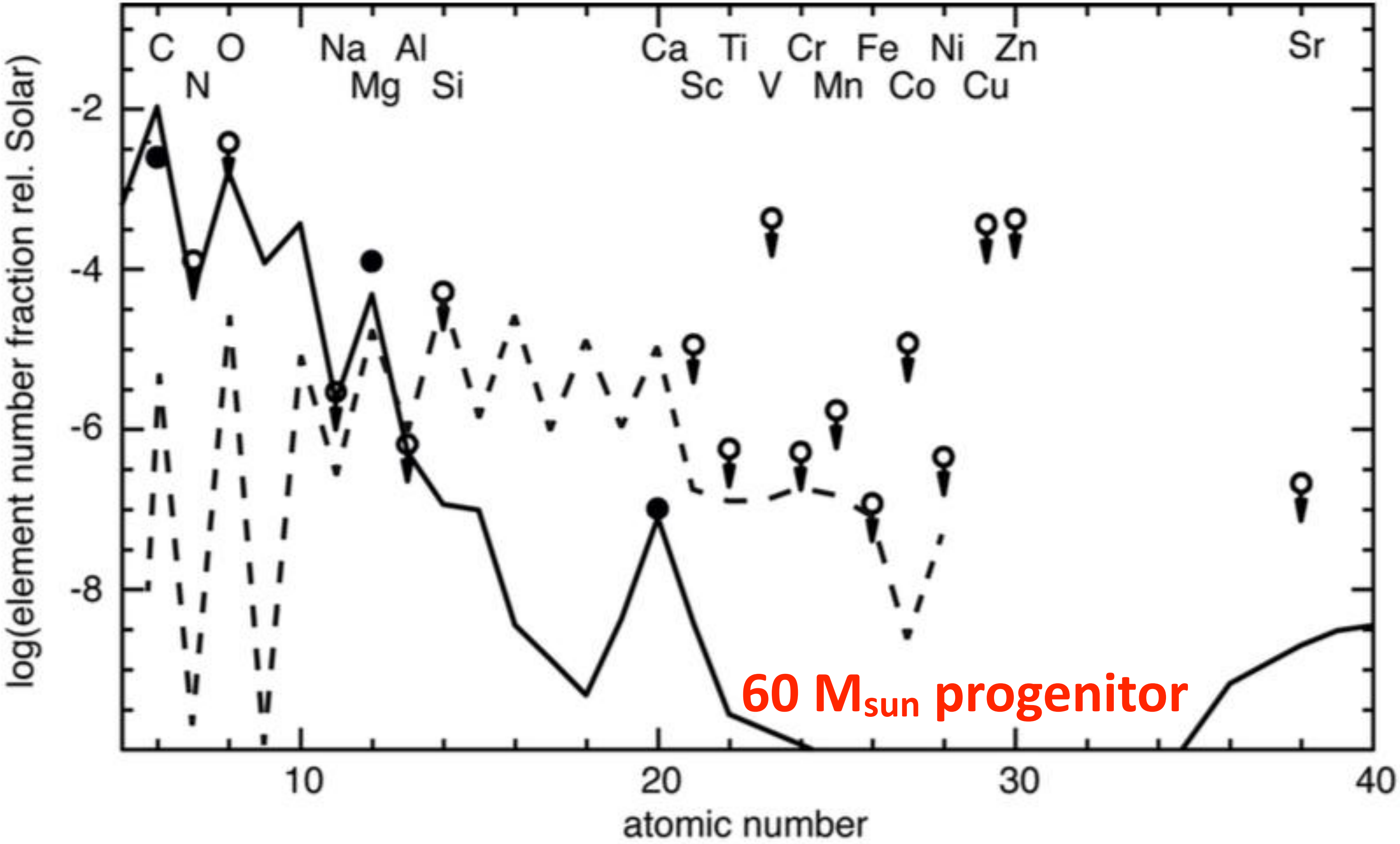
Final stellar masses



Hirano et al. '14

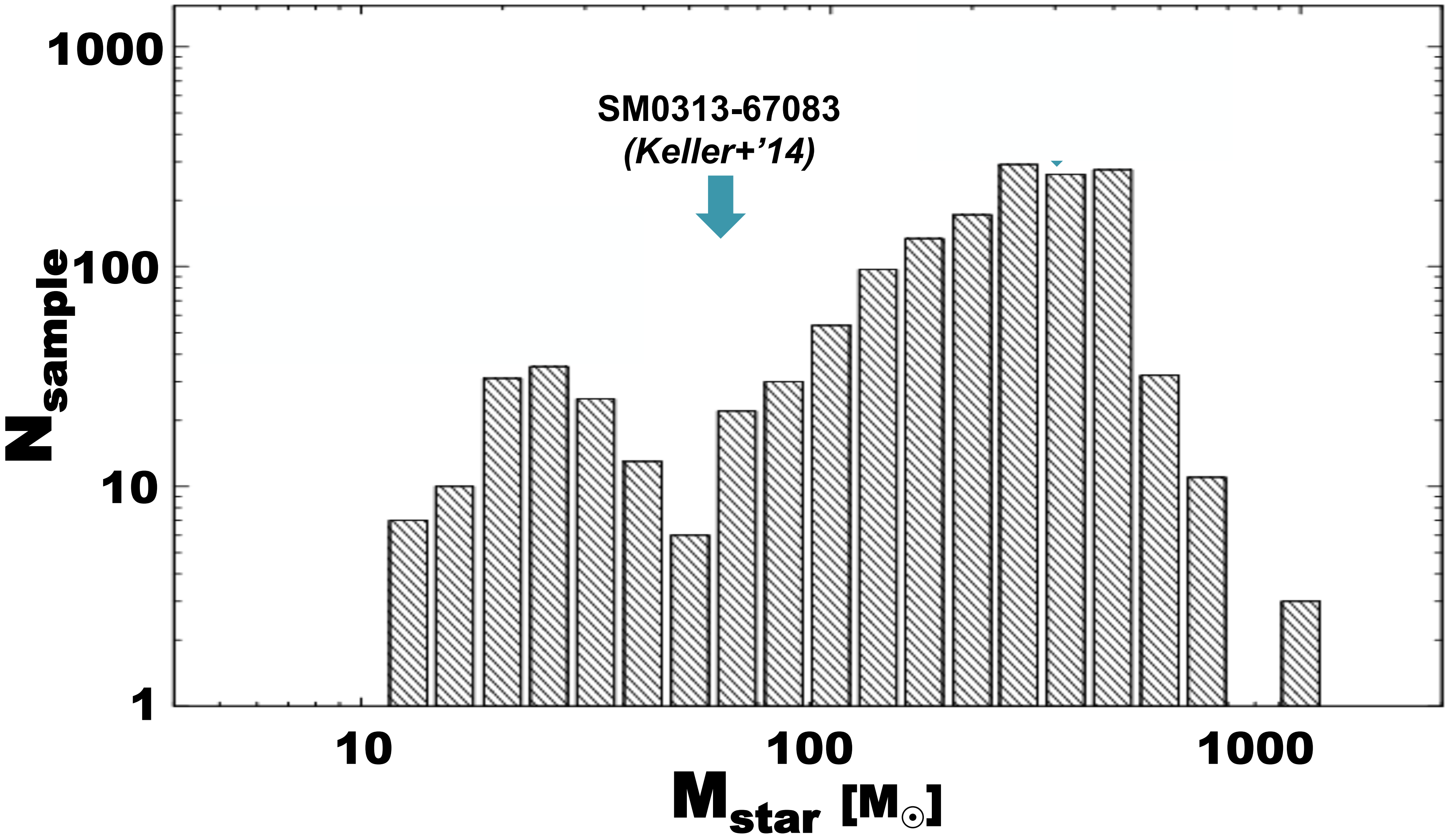
EMP star and progenitor mass

SMSS J0313 Keller et al. 2014, Nature; arxiv1505.03756



60 M_{sun} progenitor

Progenitor PopIII mass

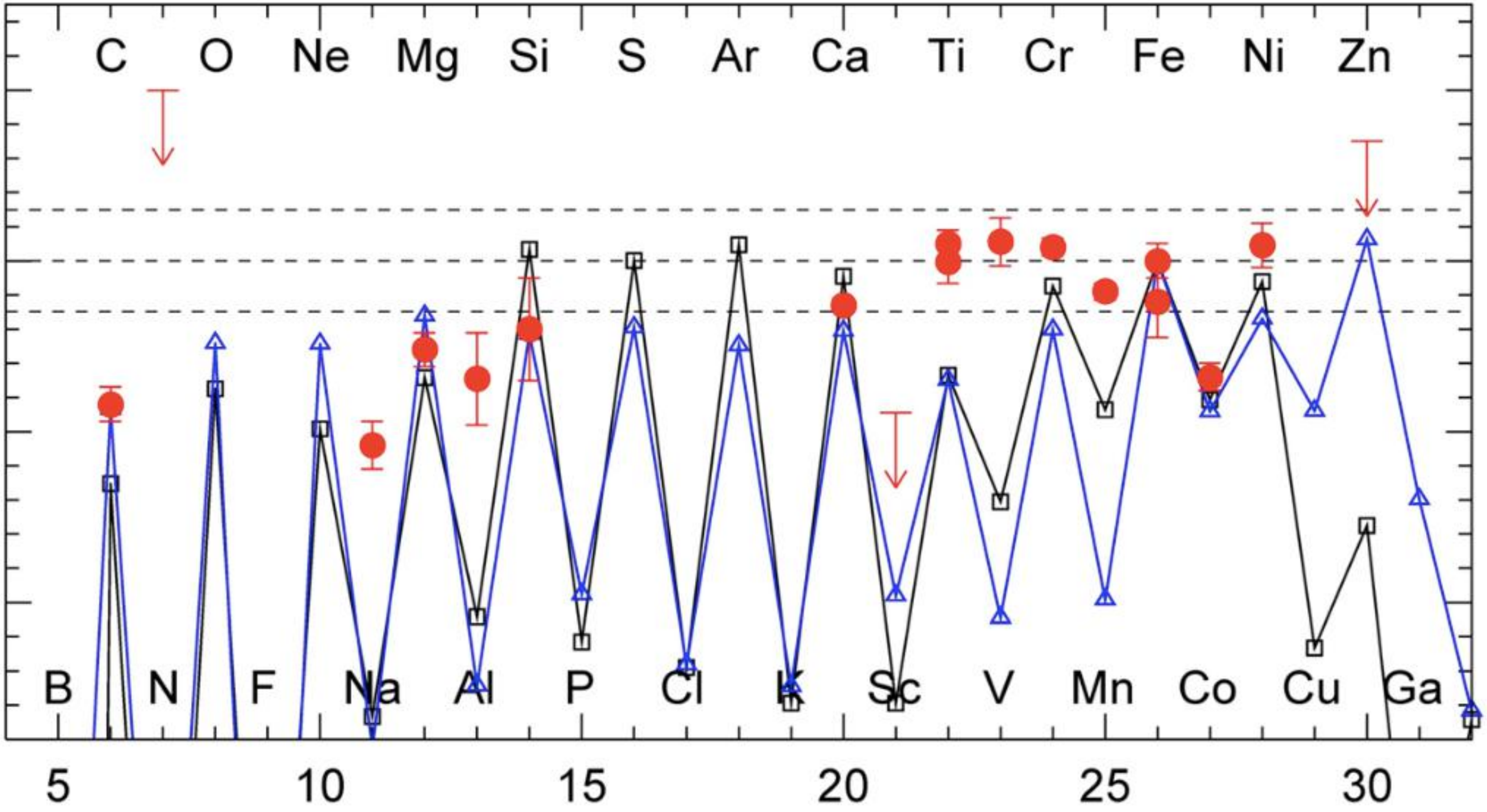


Hirano et al. '14

Another example

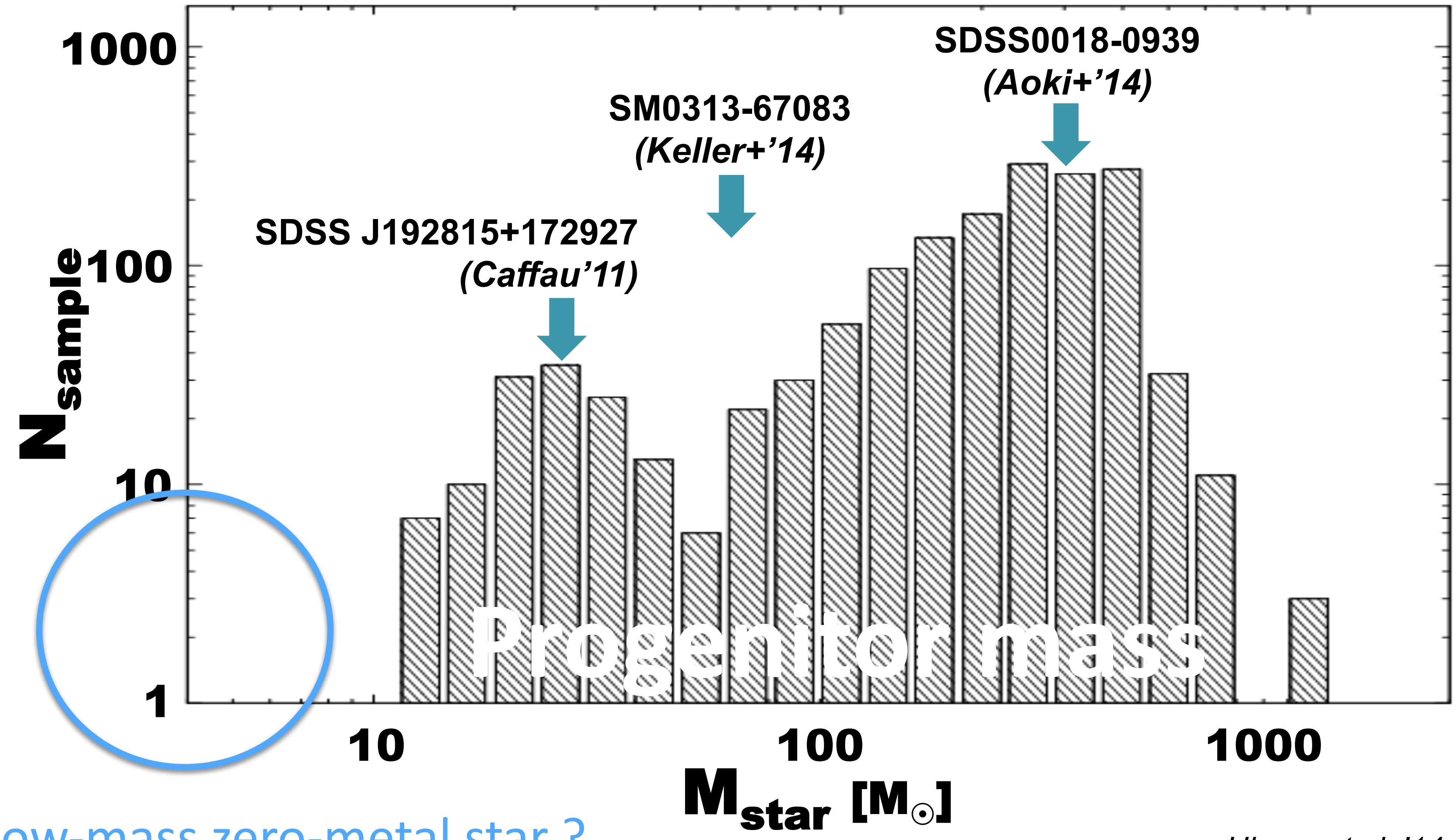
SDSS J1820.5-093939.2

Aoki et al. 2014, Science



SN models of 300-1000 M_{sun} progenitor

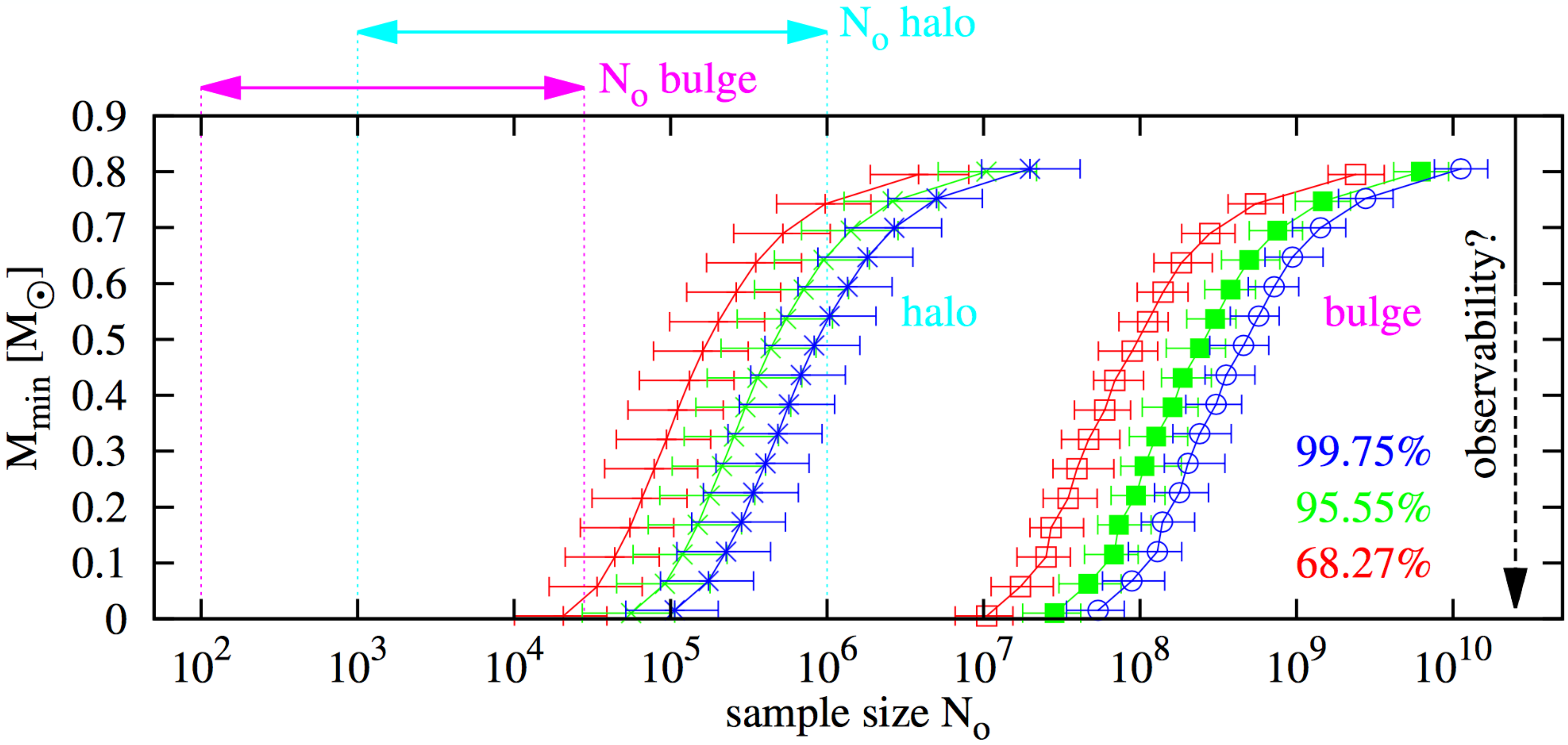
Progenitor PopIII masses



Low-mass zero-metal star ?

Hirano et al. '14

Constraints on low-mass Pop III

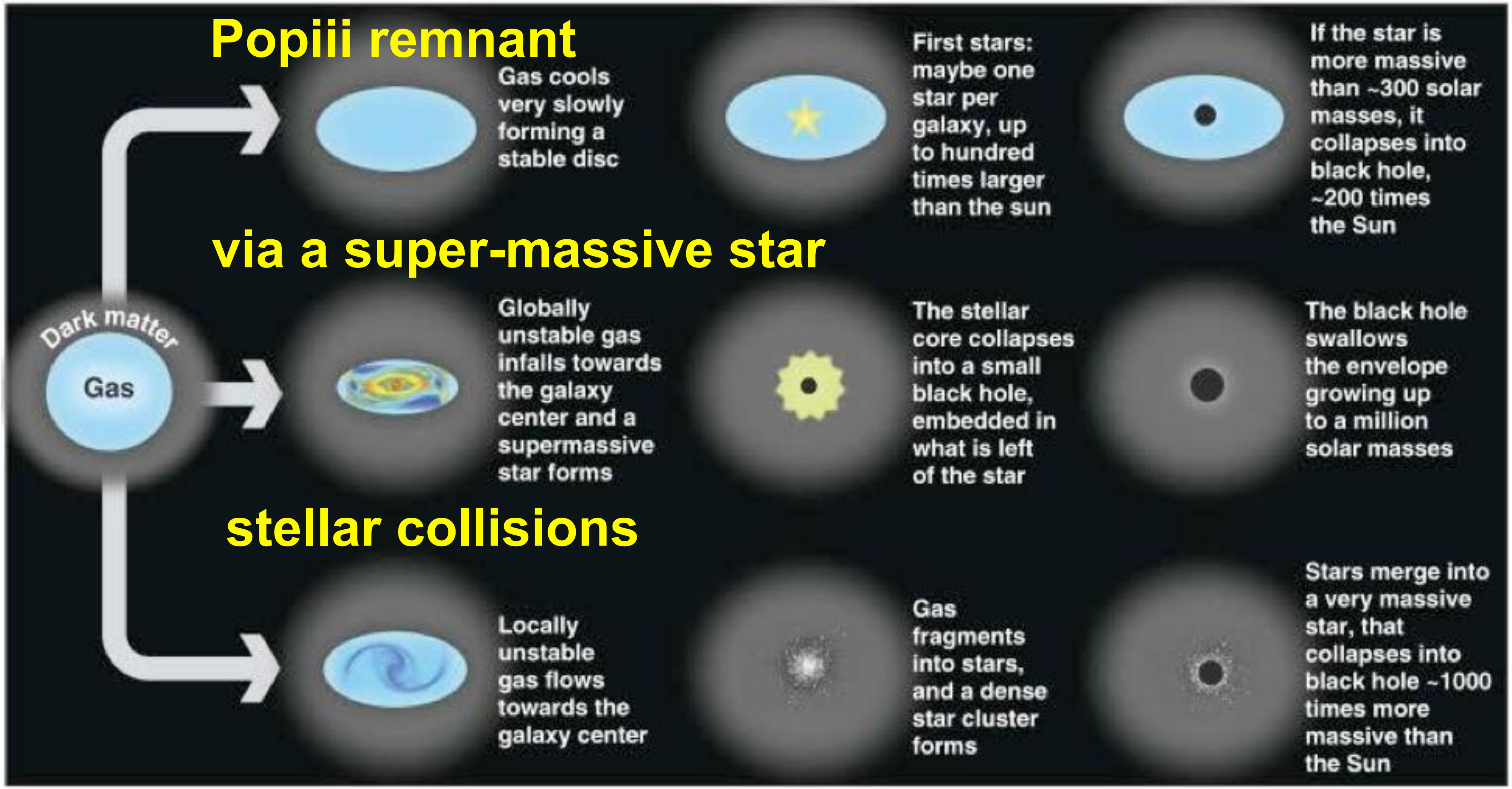


Hartwig et al. 2015:

Strong constraints on <0.6M$_{sun}$ star from the dearth of zero-metal halo stars

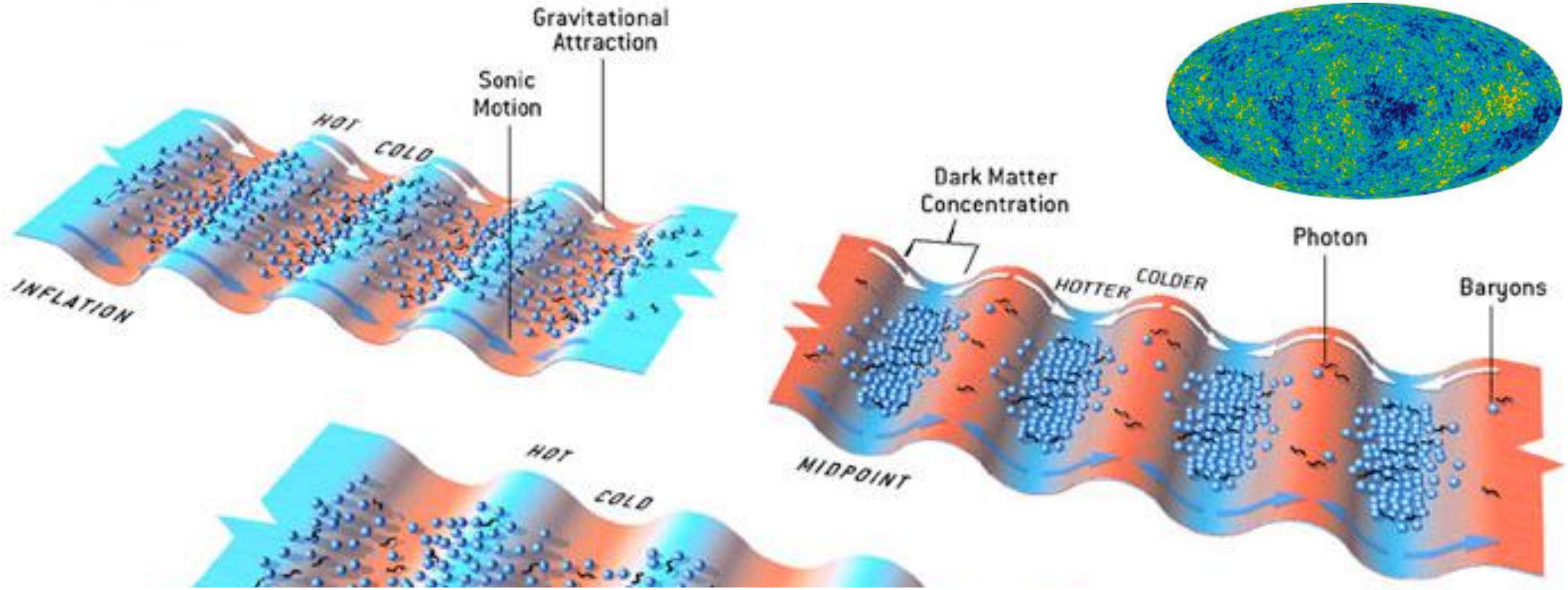
First Blackholes

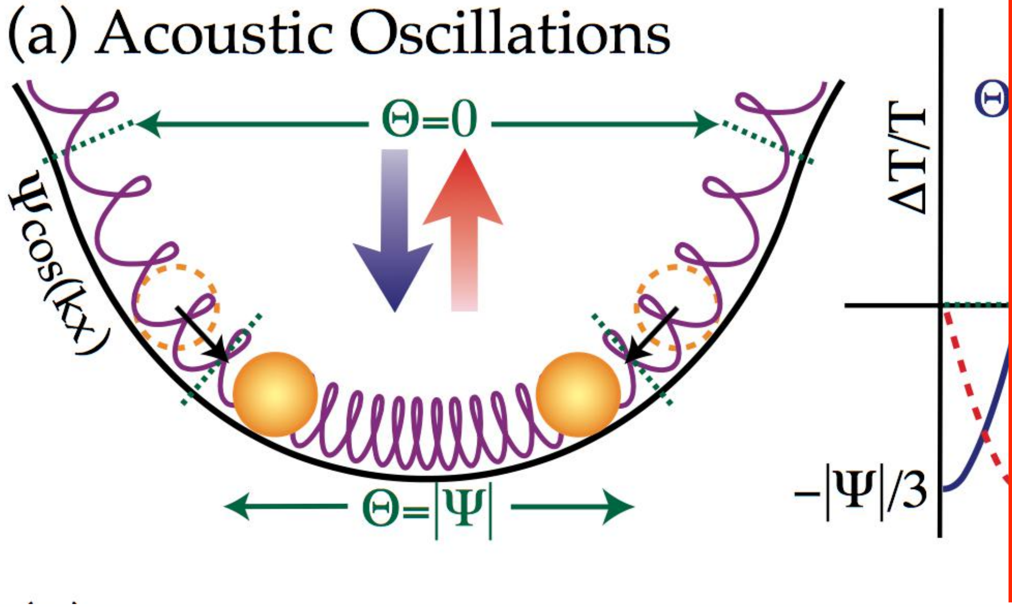
Blackhole seeds: Rees diagram

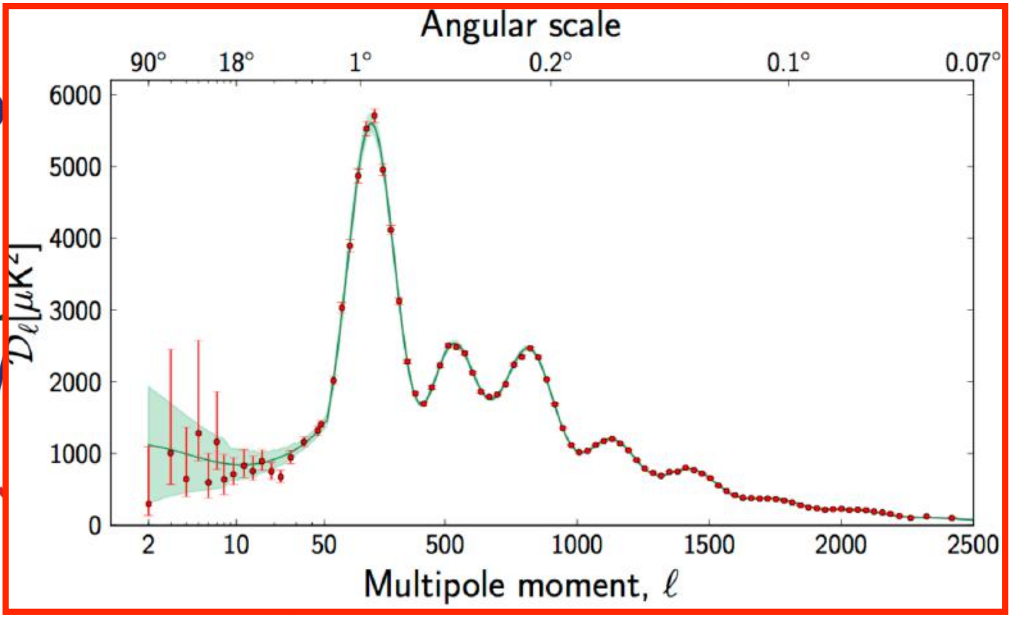


Volonteri 2012, Science

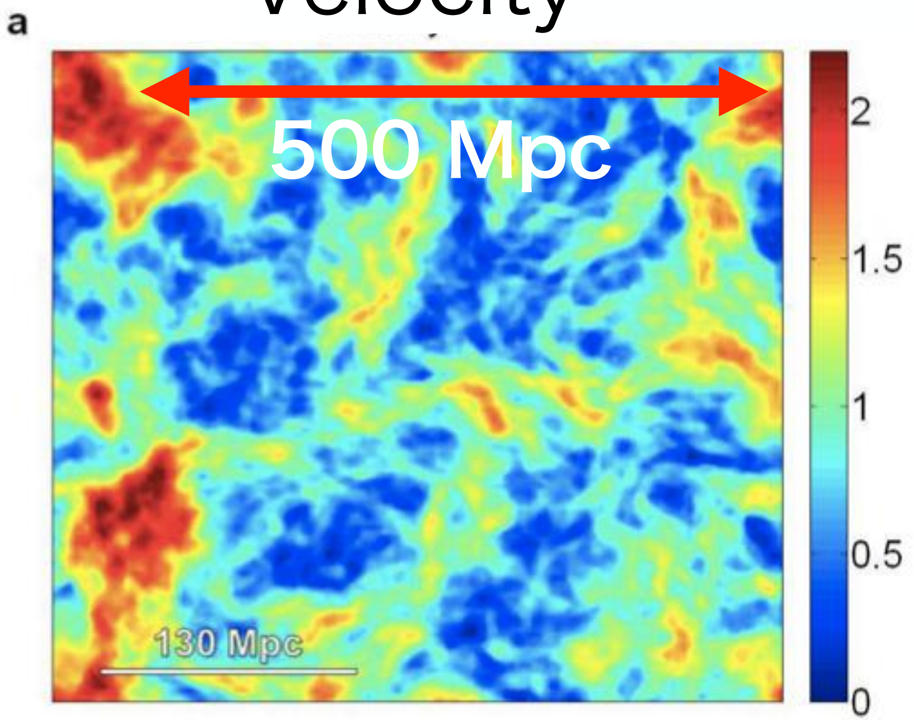
Baryon Acoustic Oscillations



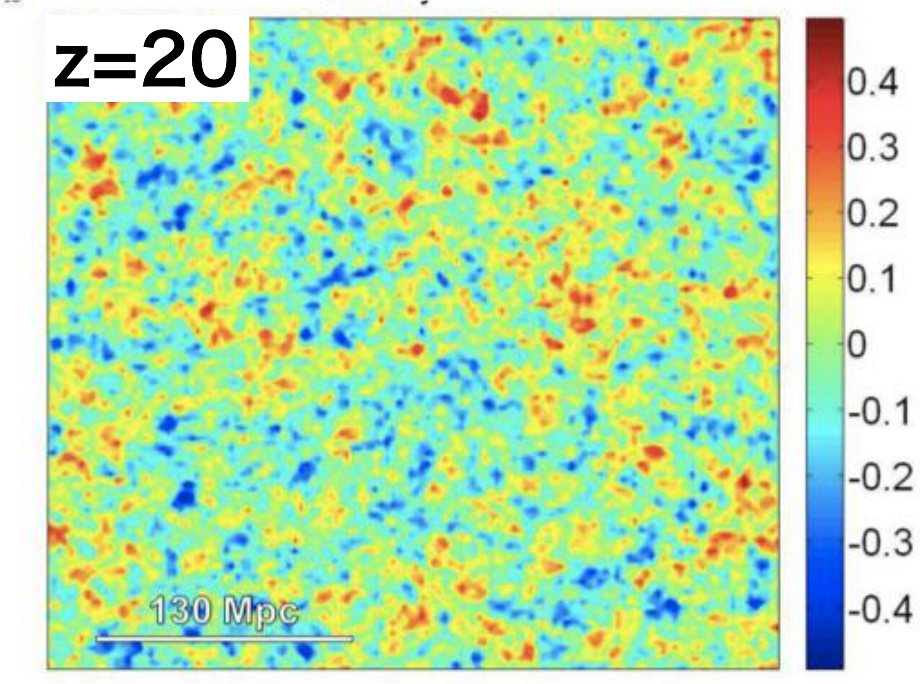




Supersonic streams

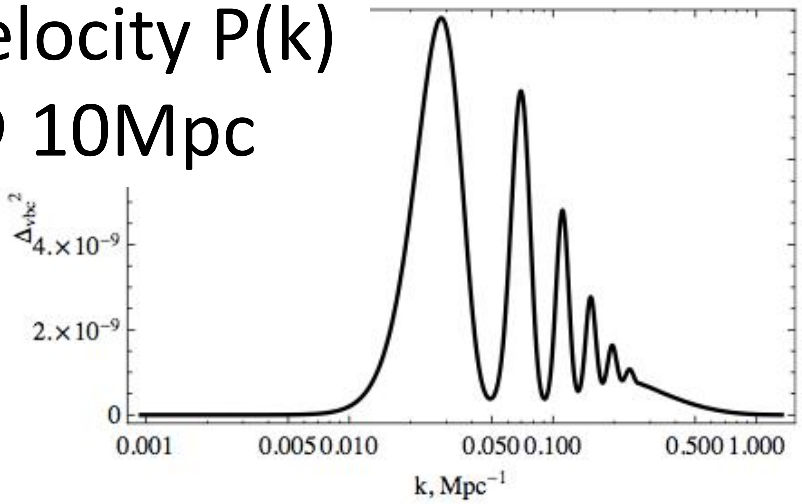


Velocity



Density

velocity P(k)
@ 10Mpc

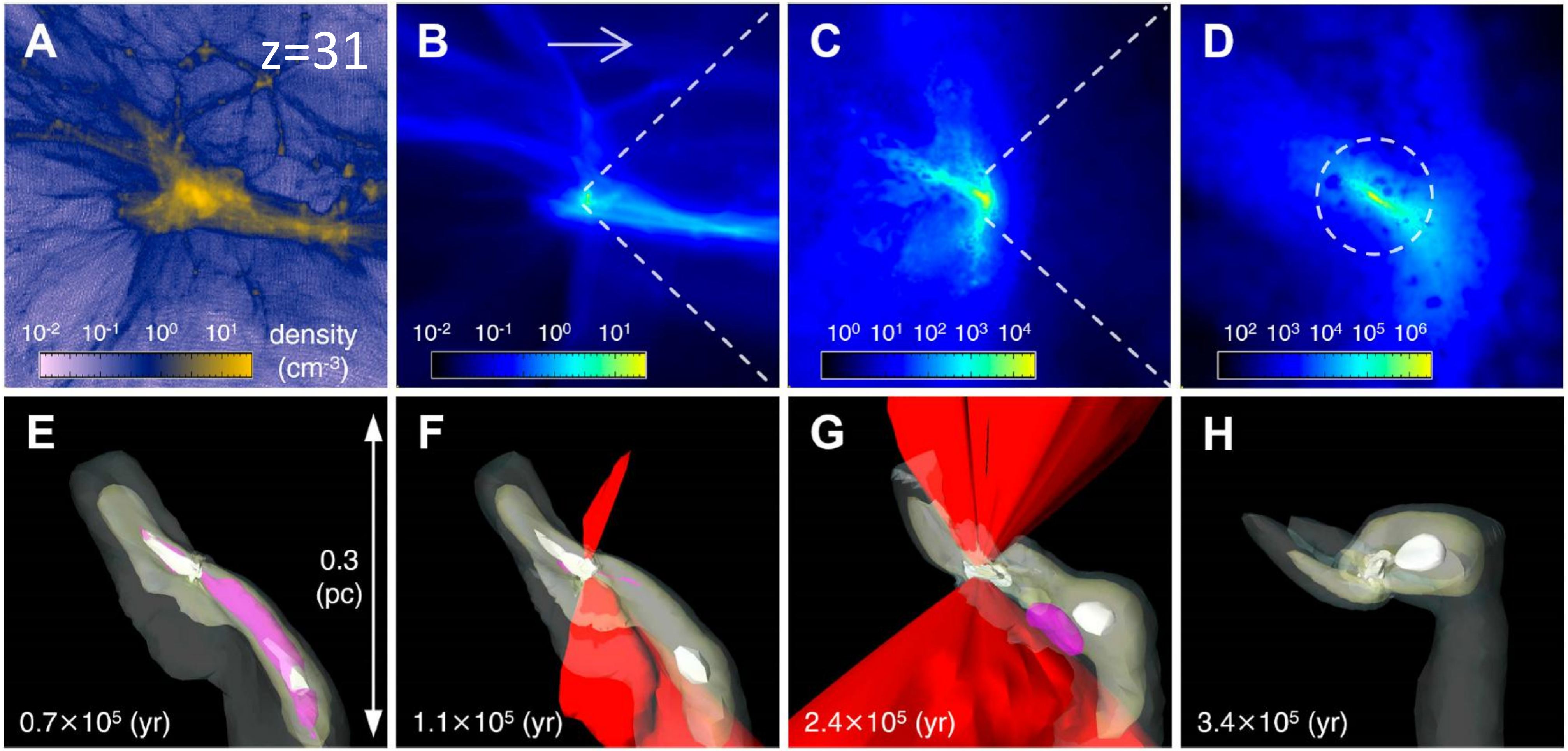


Relative motions between gas and dark matter

Tseliakhovich & Hirata 2011;
Visbal+ 12; Fialkov+ 12

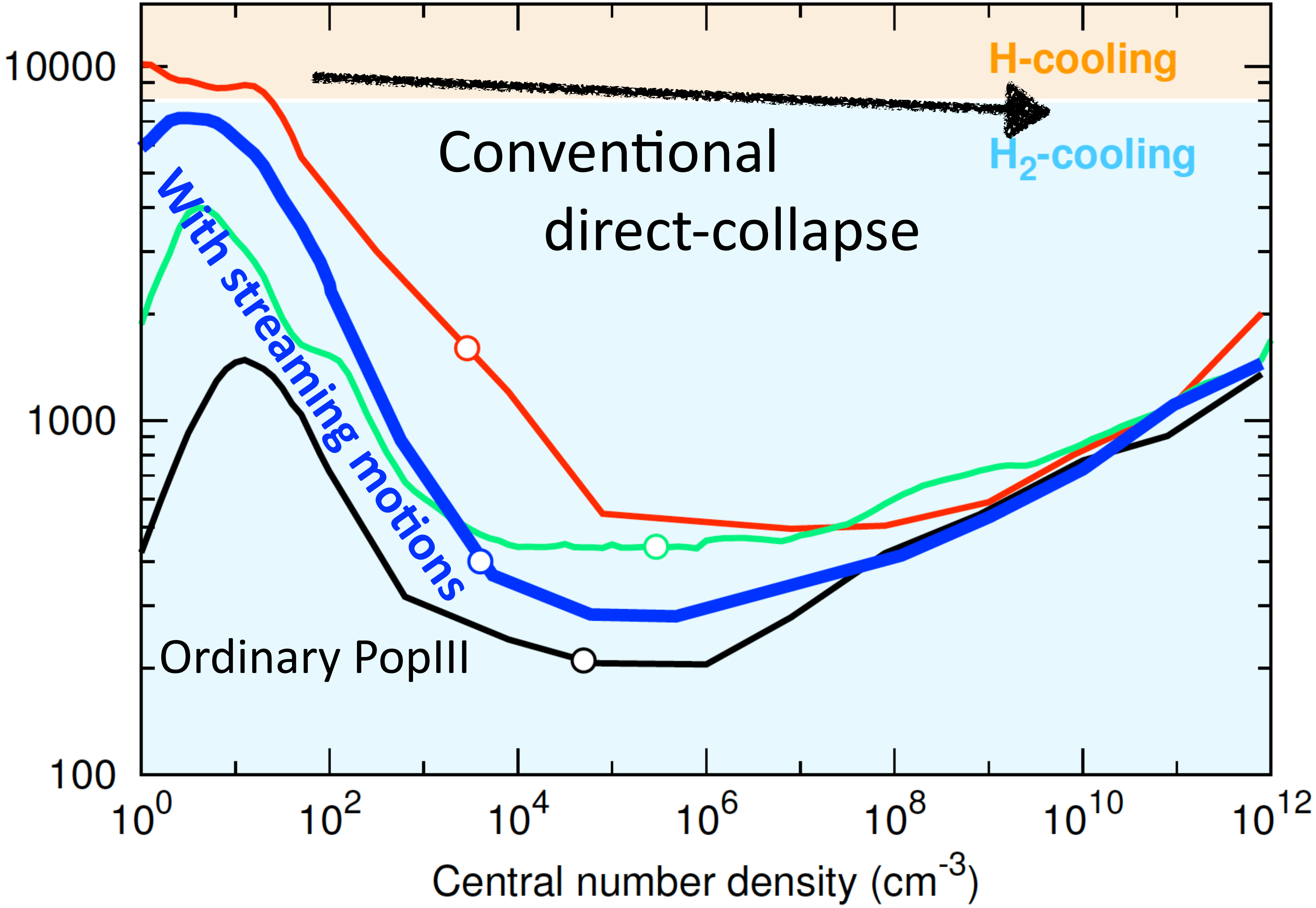
Supersonic gas streams drive BH formation

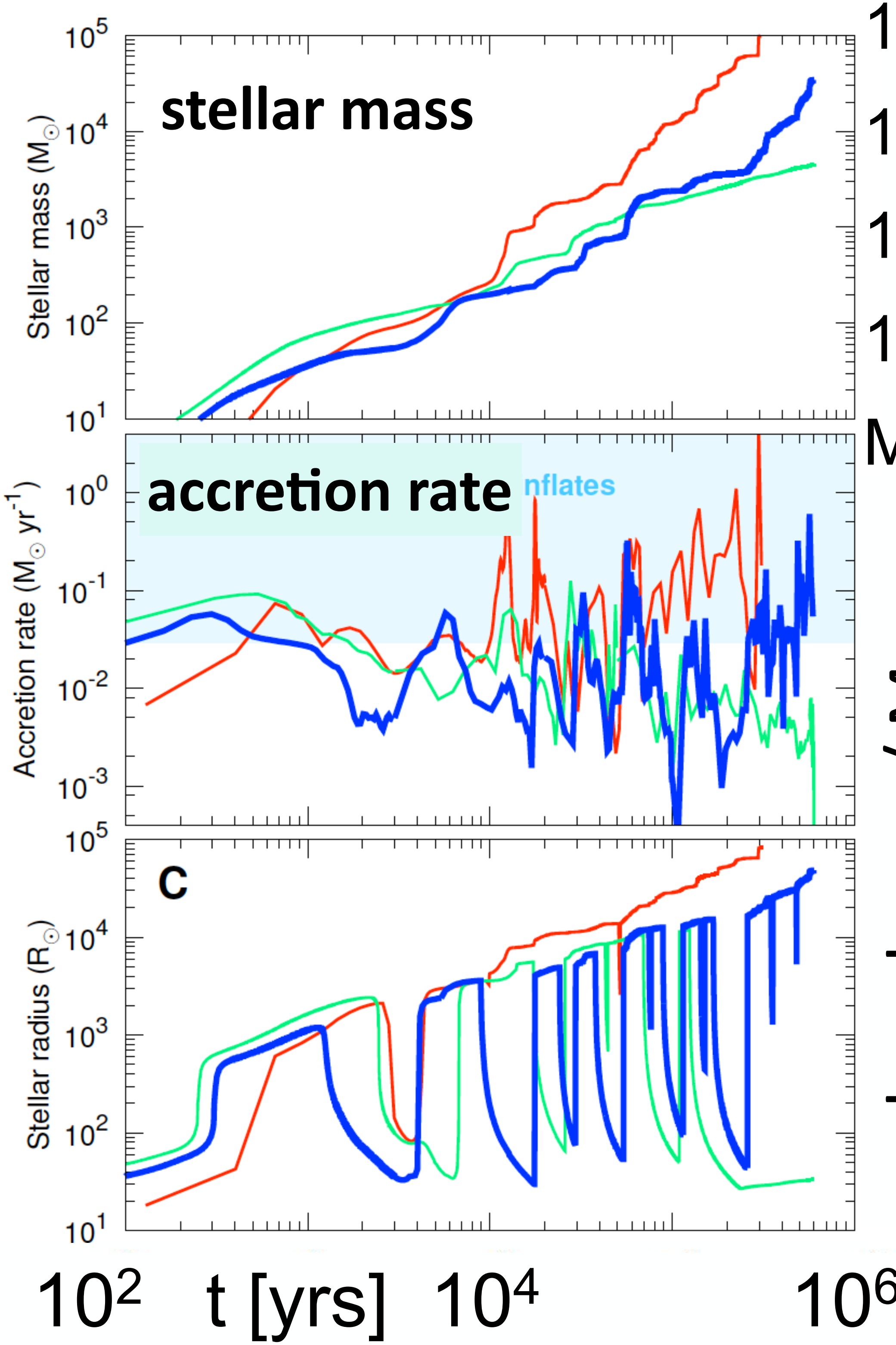
A high-density region with 3-σ streaming velocity (90 km/s @ z=1089)



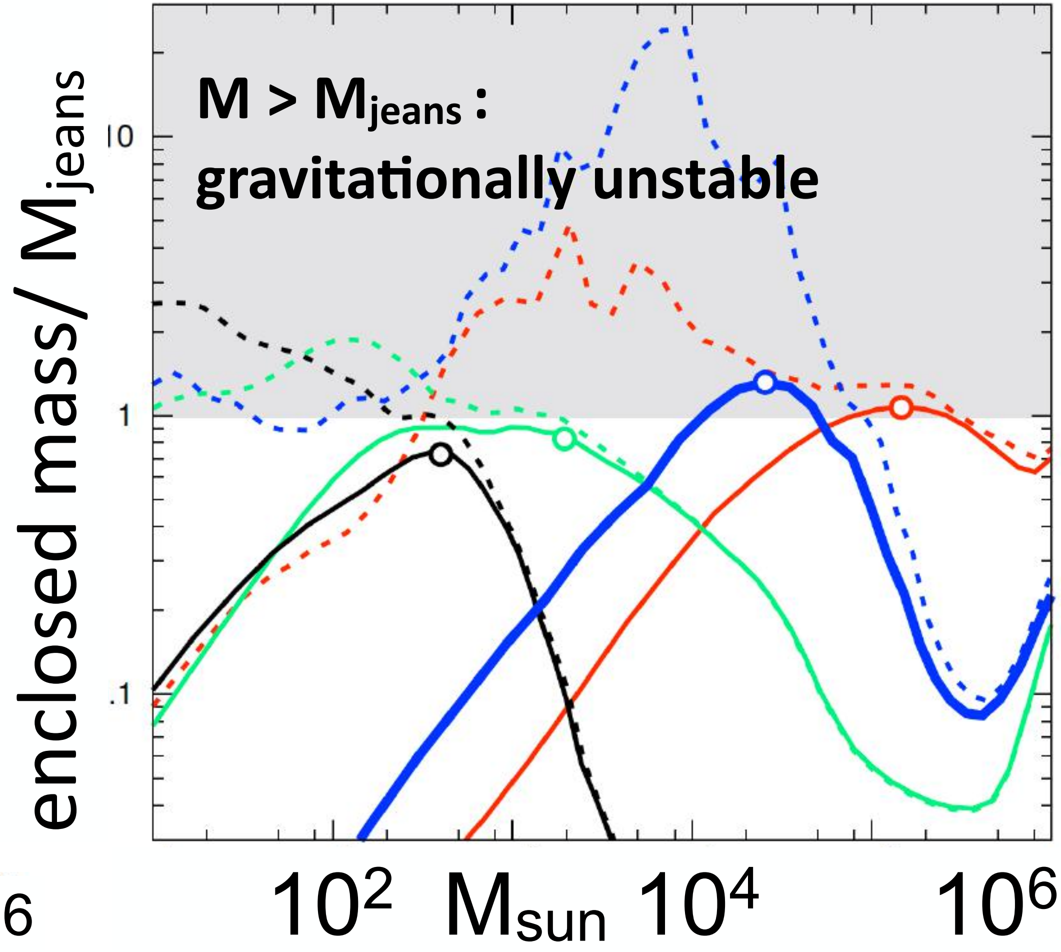
Hirano, Hosokawa, NY, Kuiper, 2017

Failed direct-collapse

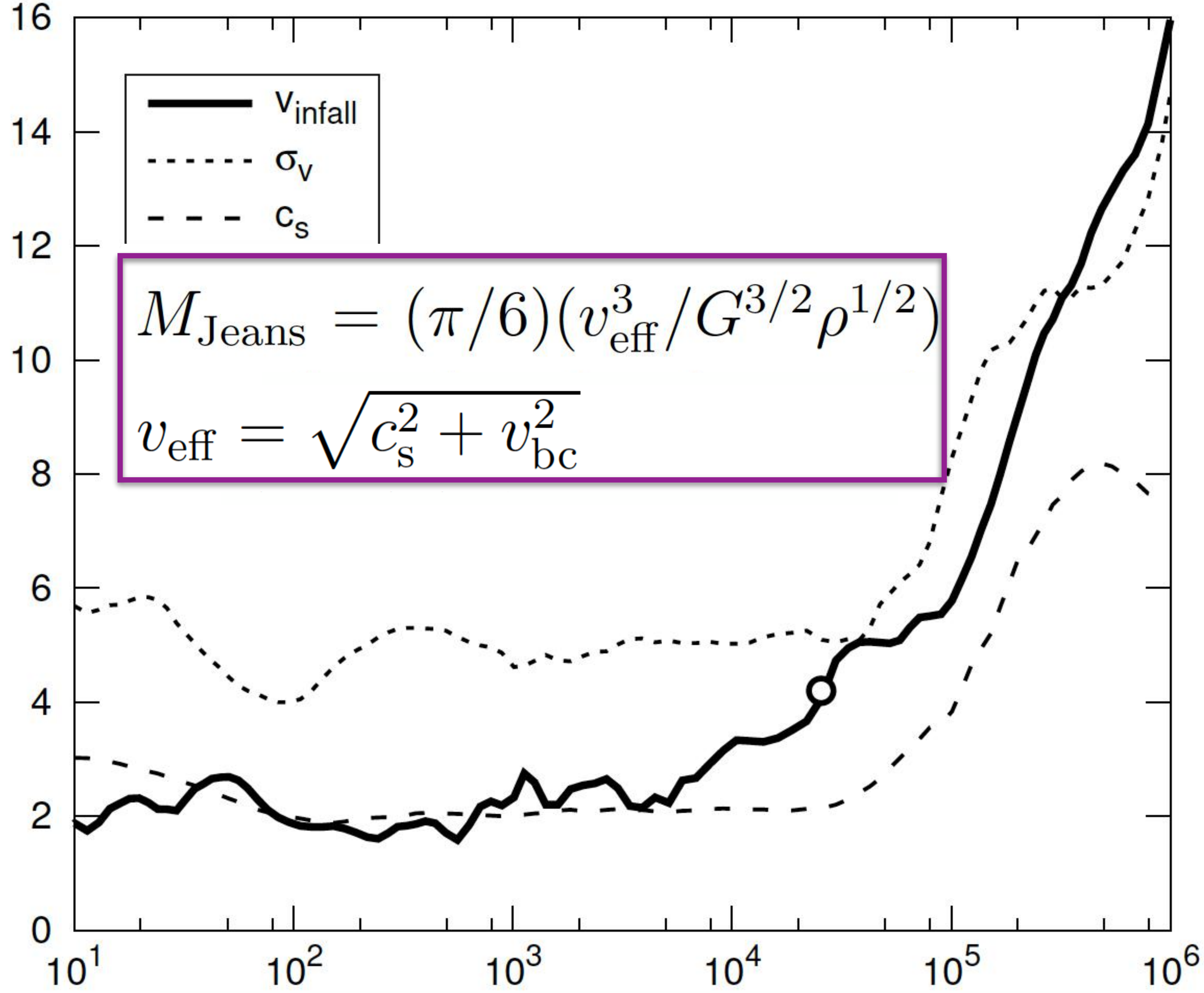




← M_* gets 40000 M_{sun} !
H_2 formation and
cooling does not
delay the growth



Turbulent core collapse



$$M_{\rm Jeans} = (\pi/6)(v_{\rm eff}^3/G^{3/2}\rho^{1/2})$$

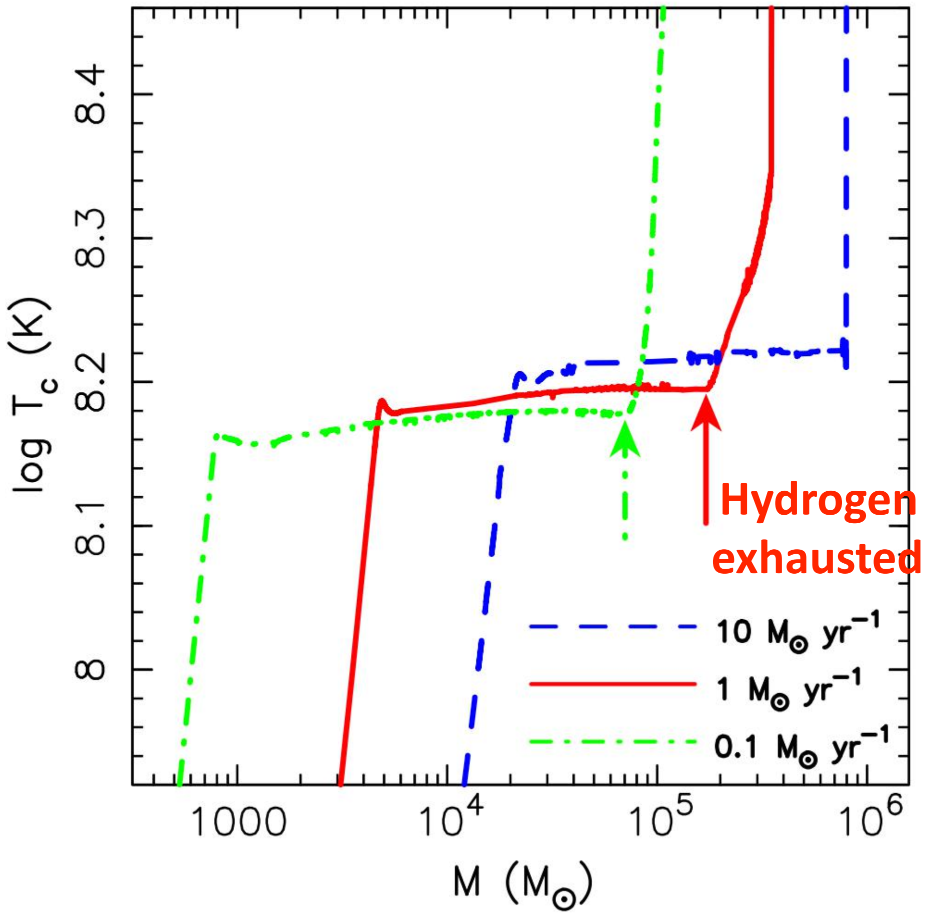
$$v_{\rm eff} = \sqrt{c_{\rm s}^2 + v_{\rm bc}^2}$$

Infall velocity and velocity dispersion

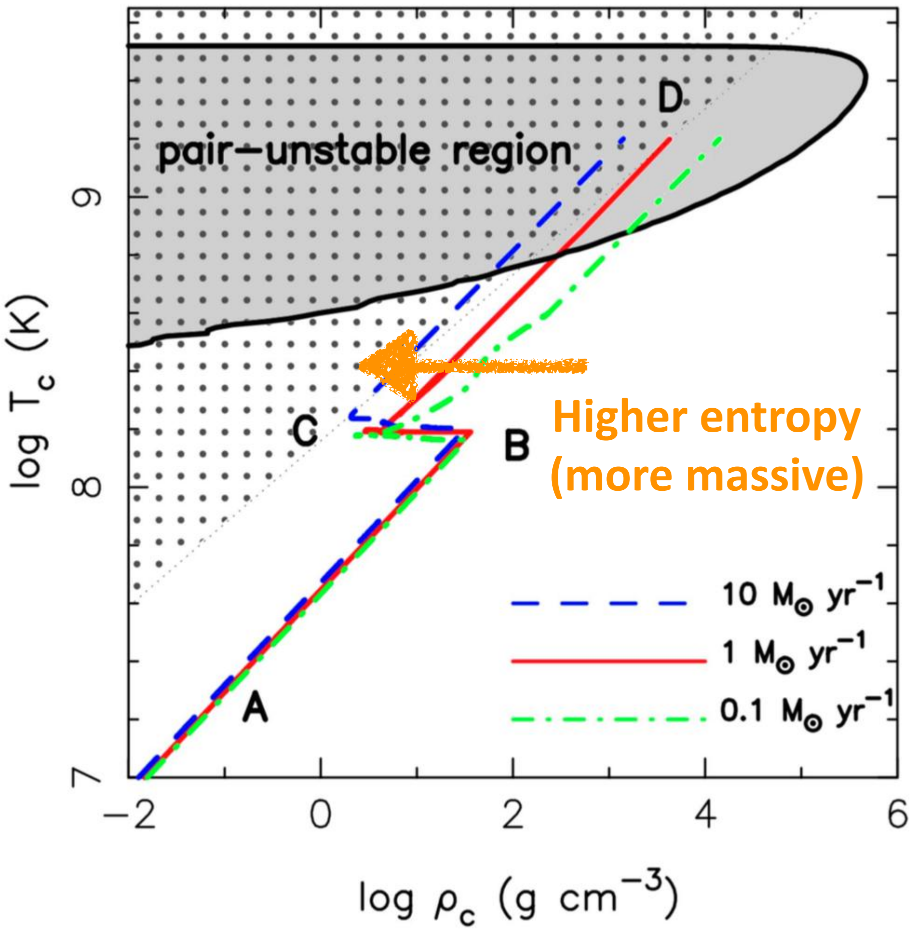
Enclosed gas mass (~ radial profile)

Core Collapse of Accreting SMS

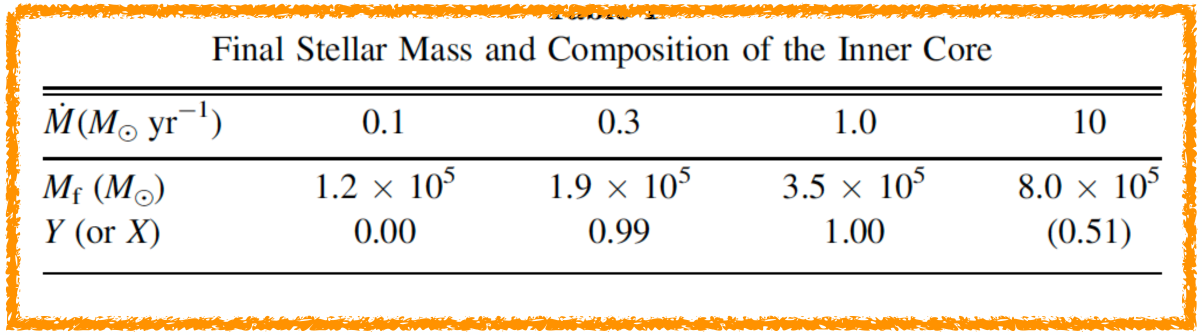
Umeda, Hosokawa, Omukai, NY 2016, ApJL



Hydrogen exhausted



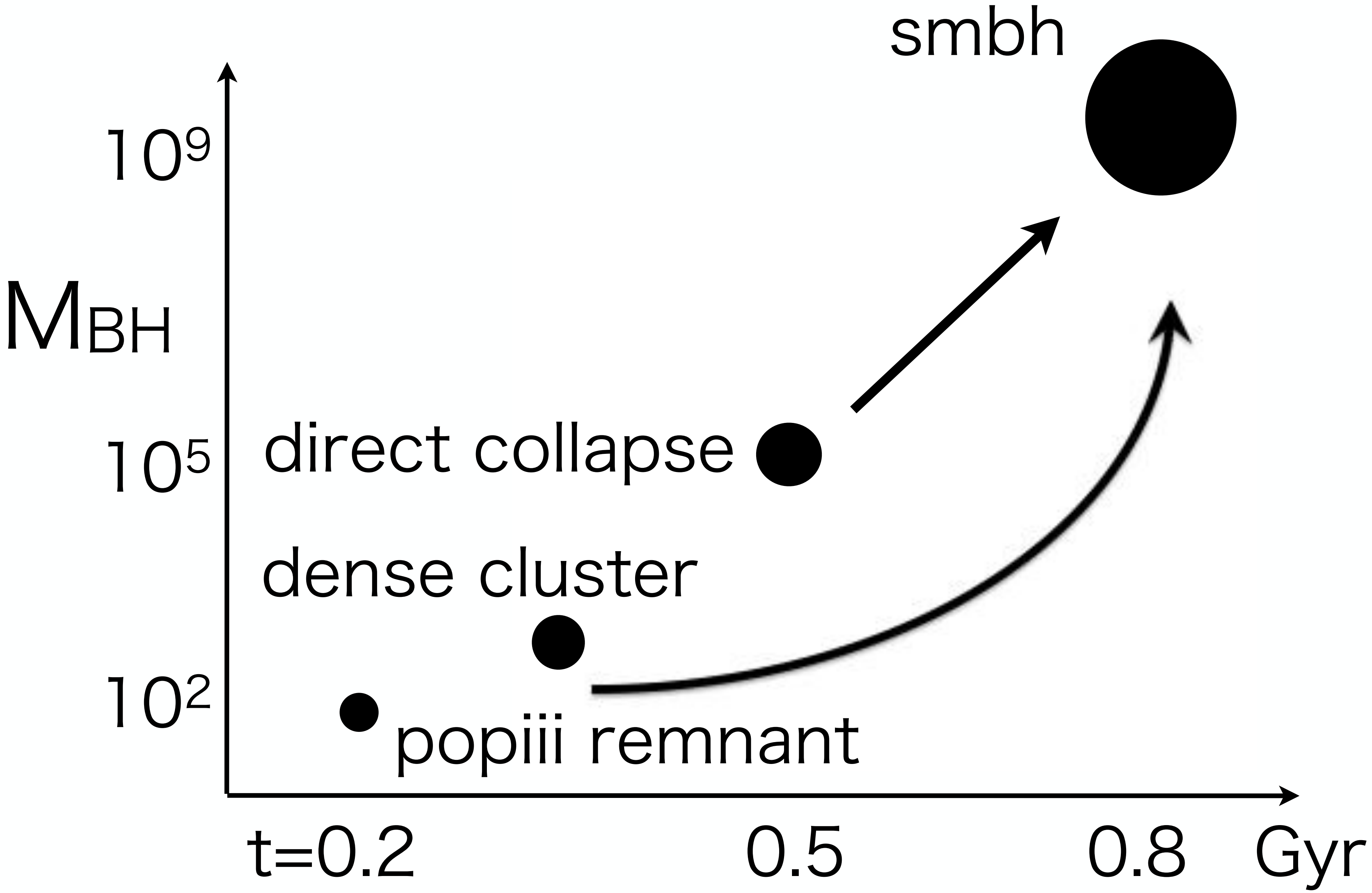
Higher entropy (more massive)



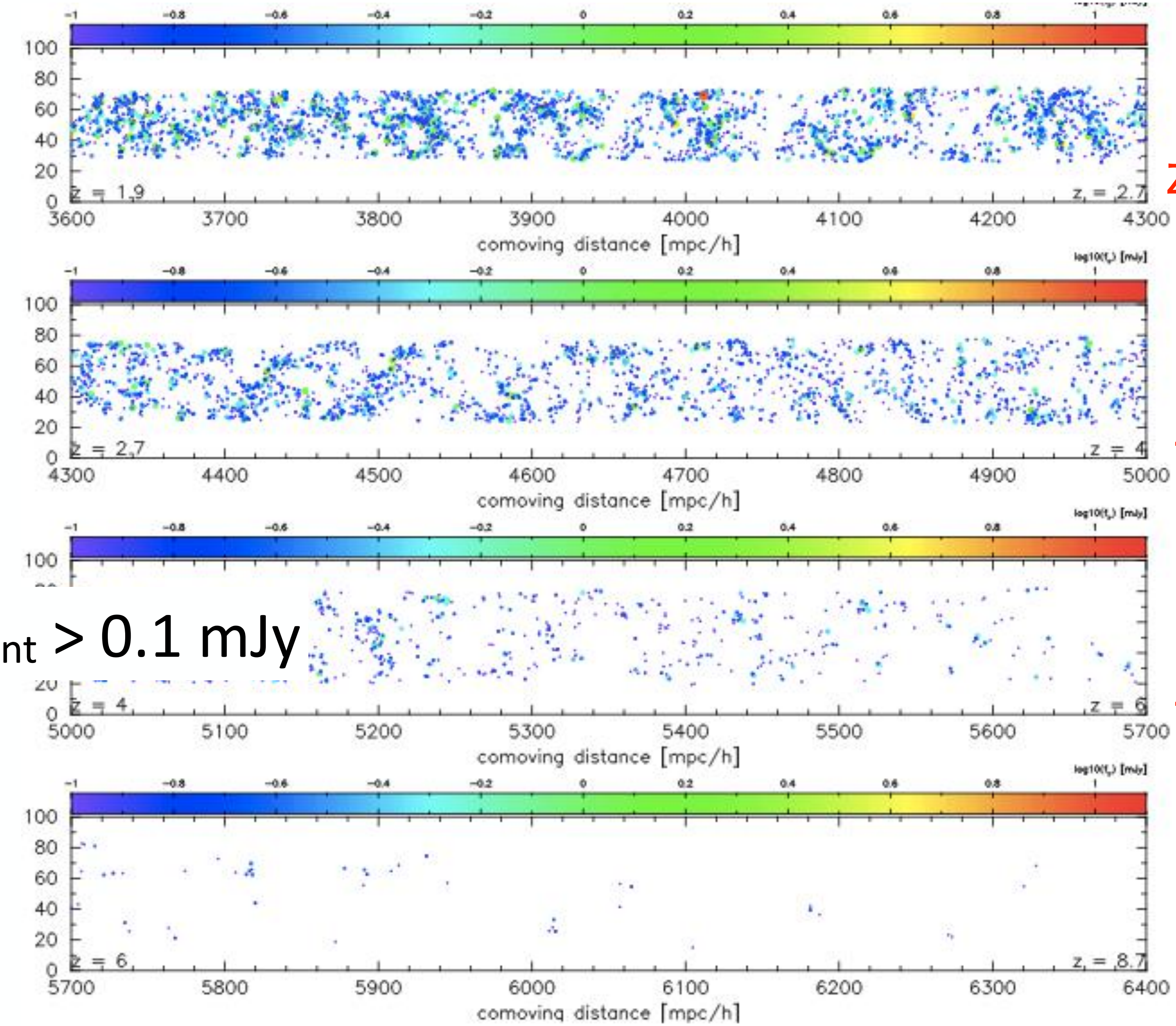
Final Stellar Mass and Composition of the Inner Core

$\dot{M}$ ($M_\odot$ yr^{-1})	0.1	0.3	1.0	10
M_f ($M_\odot$)	1.2×10^5	1.9×10^5	3.5×10^5	8.0×10^5
Y (or X)	0.00	0.99	1.00	(0.51)

Blackhole growth: Johnson plot



Star-forming galaxies on the lightcone



z=2.7

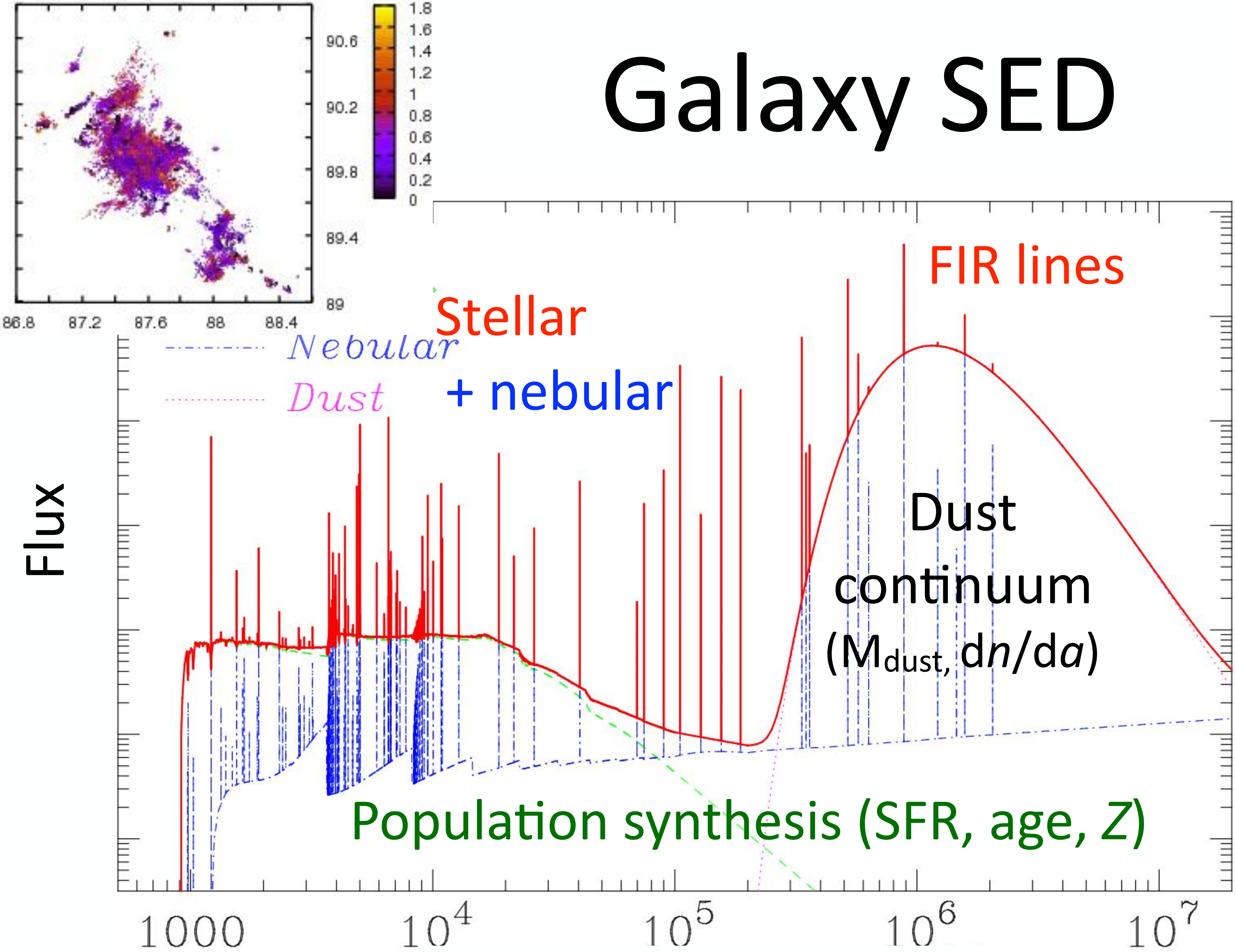
z=4

$F_{cont} > 0.1$ mJy

z=6

z=8.7

Galaxy SED



Stellar + nebular

FIR lines

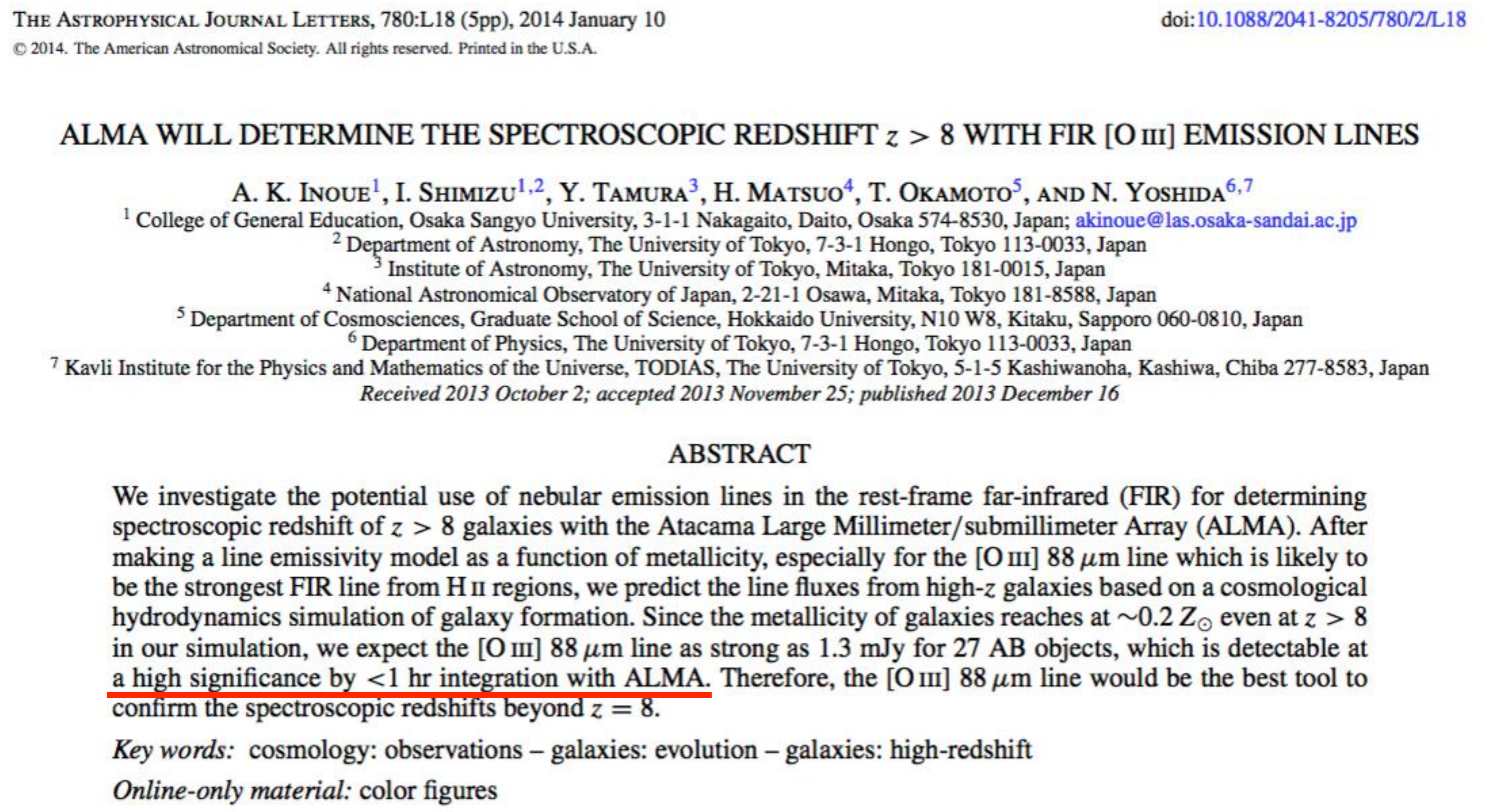
Dust continuum (M_{dust}, dn/da)

Population synthesis (SFR, age, Z)

Flux

Rest-frame wavelength

Shimizu et al. 2014, 2016



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

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ABSTRACT

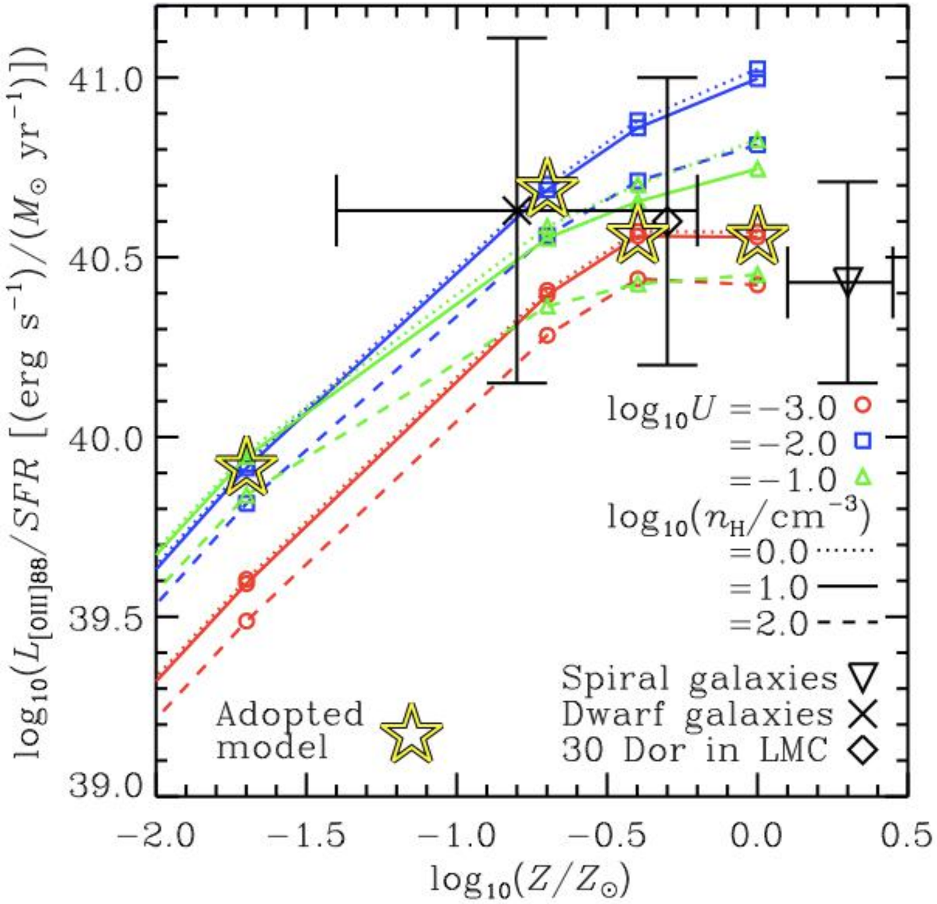
We investigate the potential use of nebular emission lines in the rest-frame far-infrared (FIR) for determining spectroscopic redshift of $z > 8$ galaxies with the Atacama Large Millimeter/submillimeter Array (ALMA). After making a line emissivity model as a function of metallicity, especially for the [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 $z = 8$.

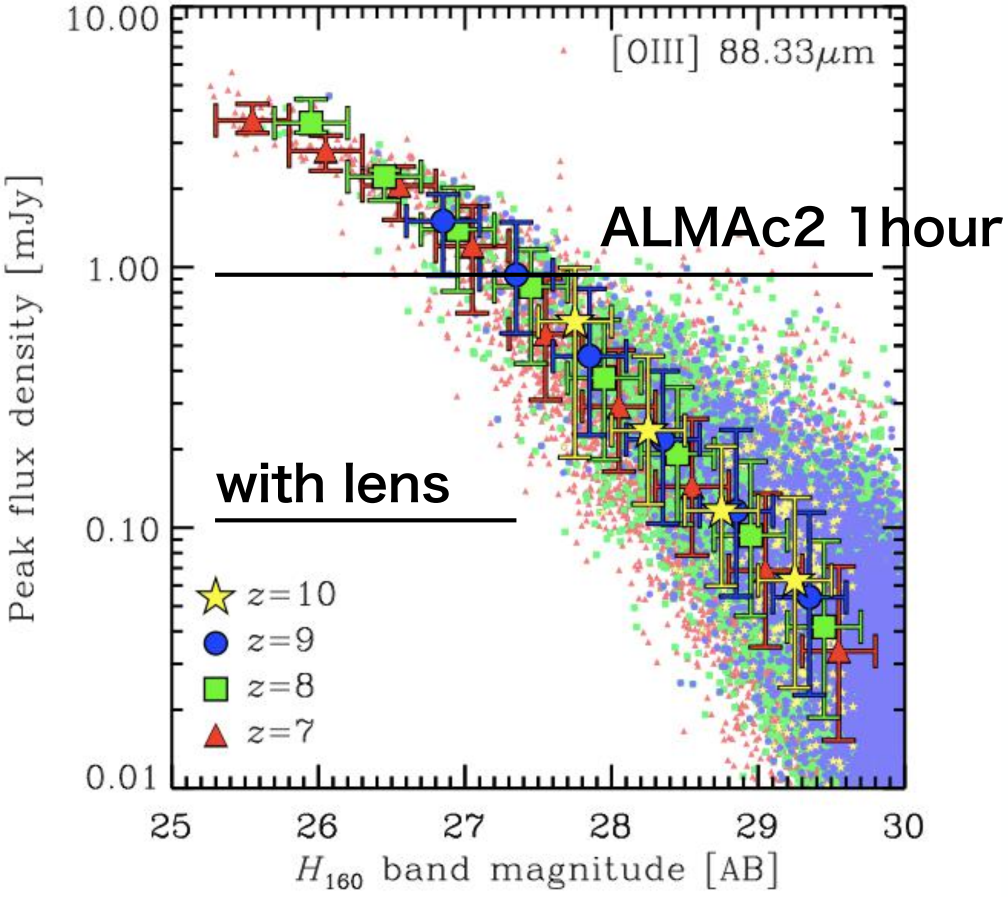
Key words: cosmology: observations – galaxies: evolution – galaxies: high-redshift

Online-only material: color figures

High-z OIII emitters

Prediction from our cosmological simulations





ALMAc2 1hour

with lens

Inoue et al. 2014

Proposal + observation in 2015

Previous talk
by A. Inoue

Astronomers Find Most Distant Oxygen in Universe

Jun 17, 2016 by Enrico de Lazaro

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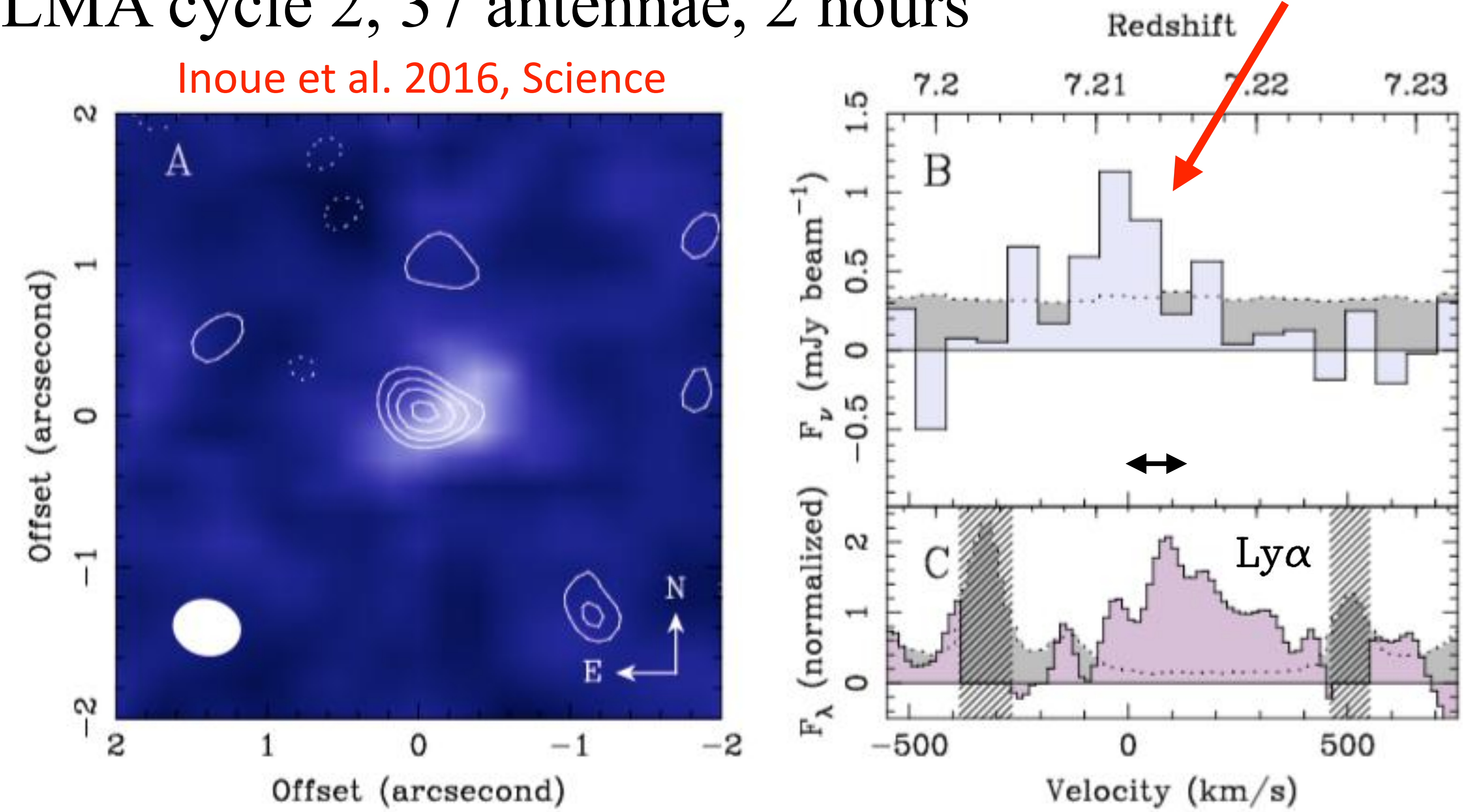
Astronomers using the Atacama Large Millimeter/submillimeter Array (ALMA) have found the most distant oxygen yet seen in the Universe, in a galaxy 13.1 billion light-years from Earth.

ALMA cycle 2, 37 antennae, 2 hours

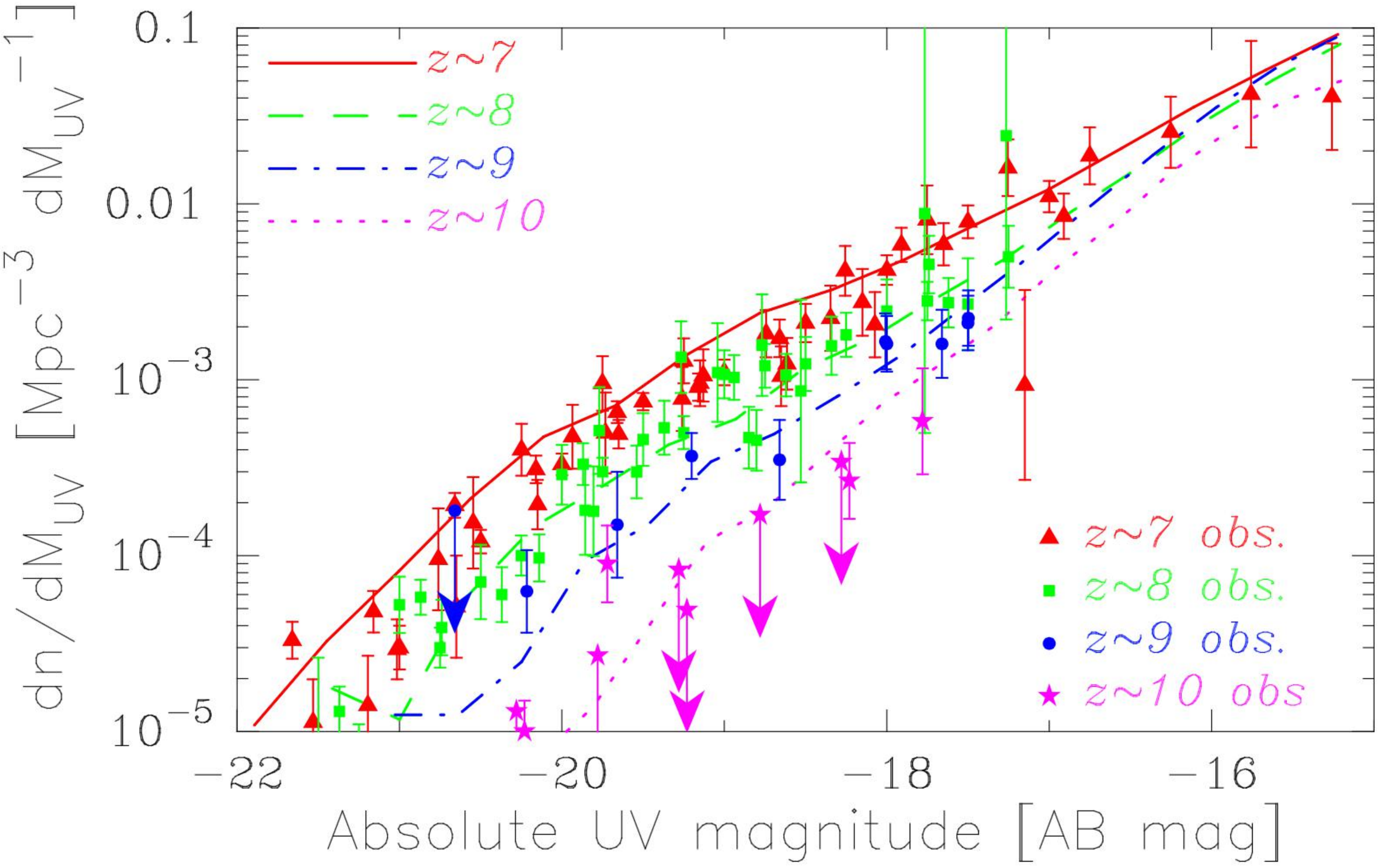
Inoue et al. 2016, Science



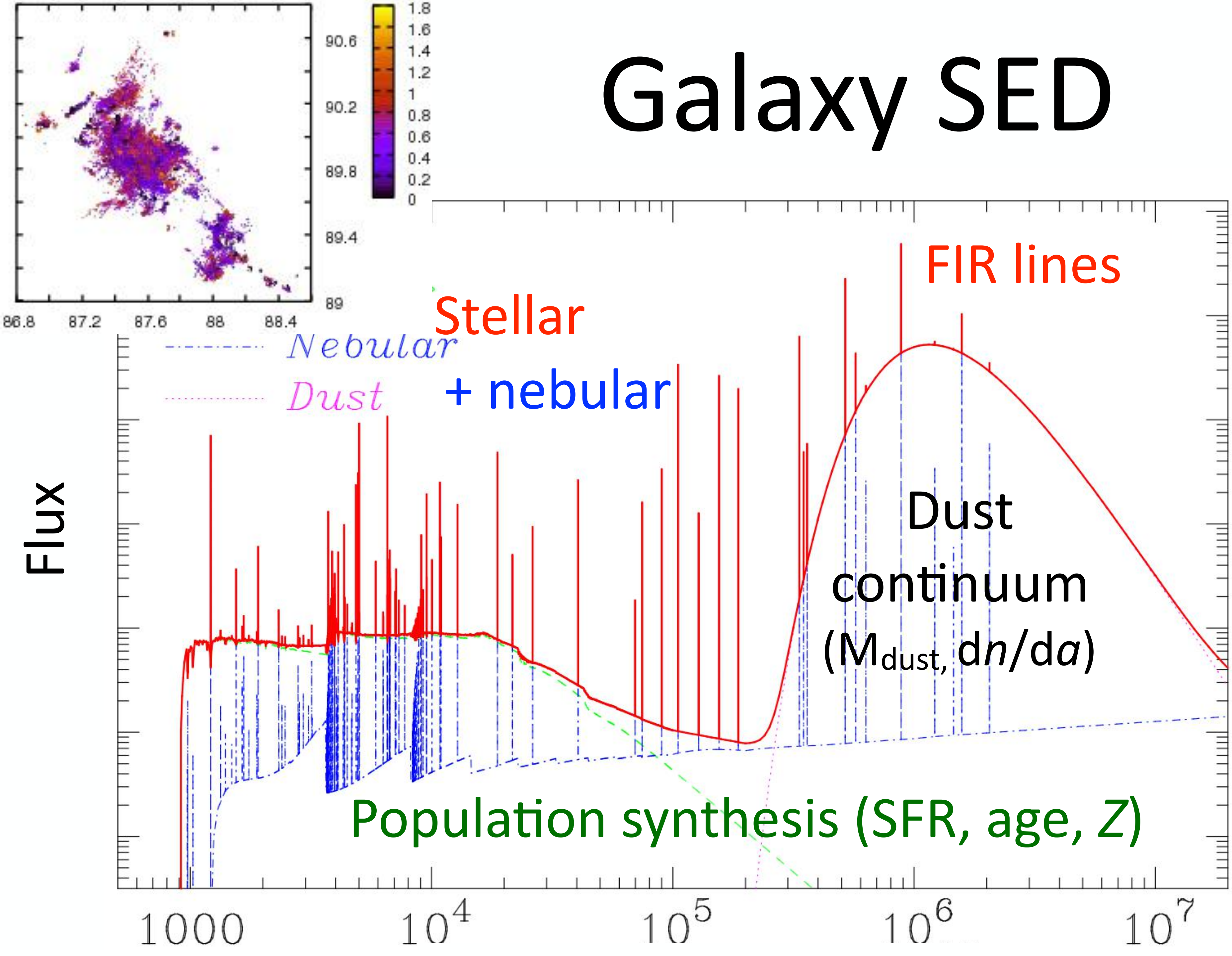
5 σ detection of [OIII]!!!

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

UV luminosity function



Galaxy SED



FIR lines

Stellar + nebular

Flux

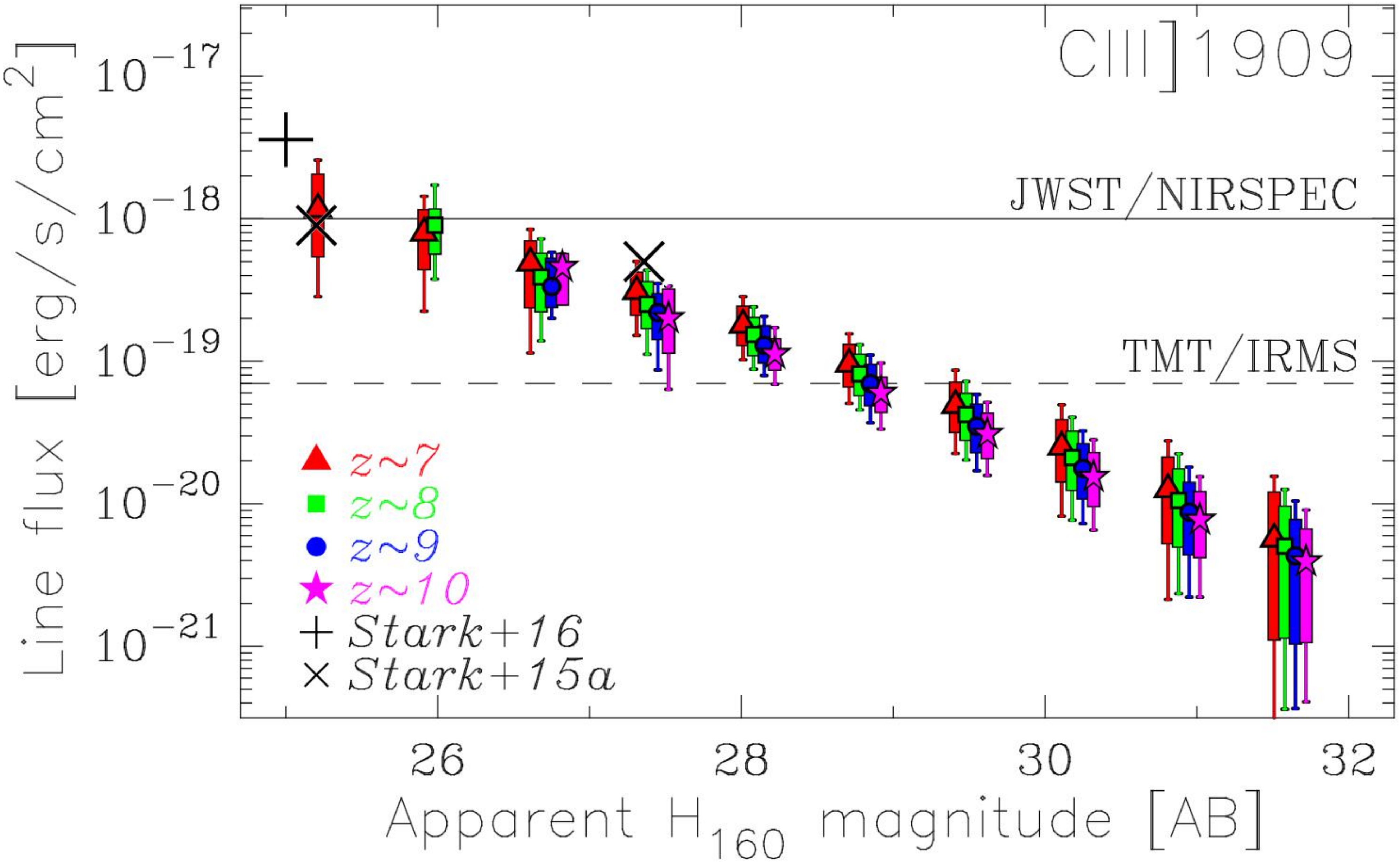
Dust continuum ($M_{\rm dust}$, dn/da)

Population synthesis (SFR, age, Z)

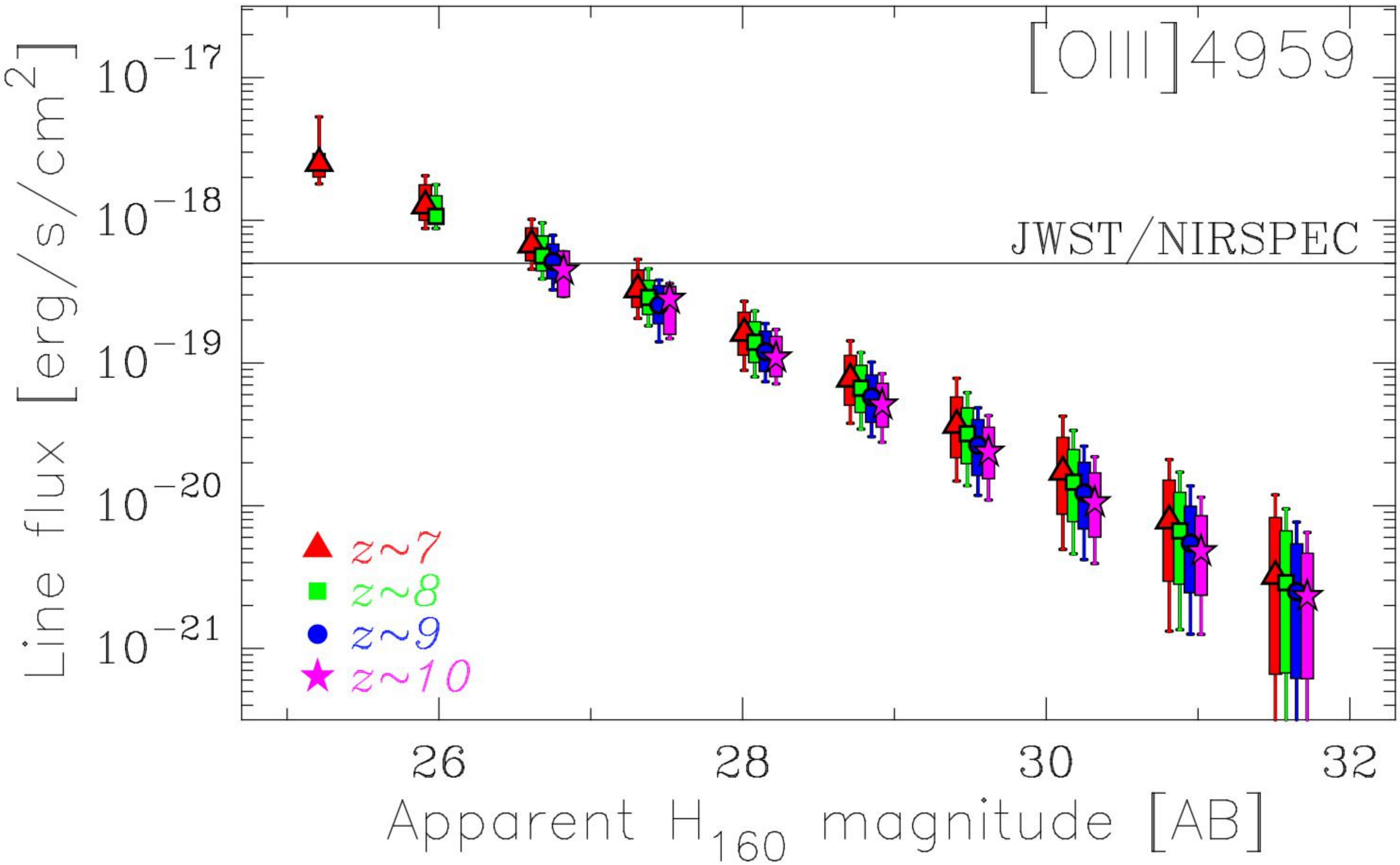
Rest-frame wavelength

Shimizu et al. 2014, 2016

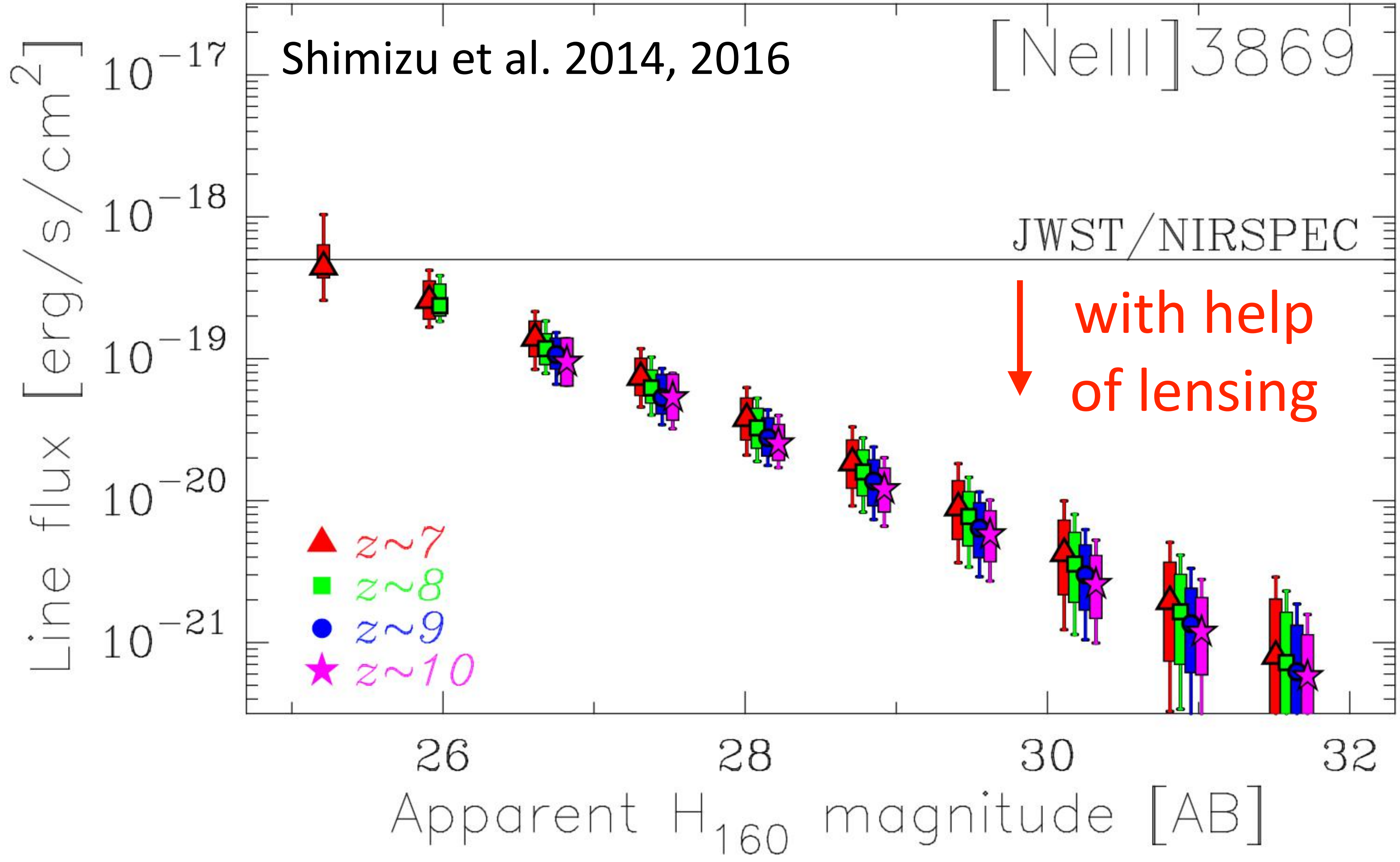
Line flux: Ciii]



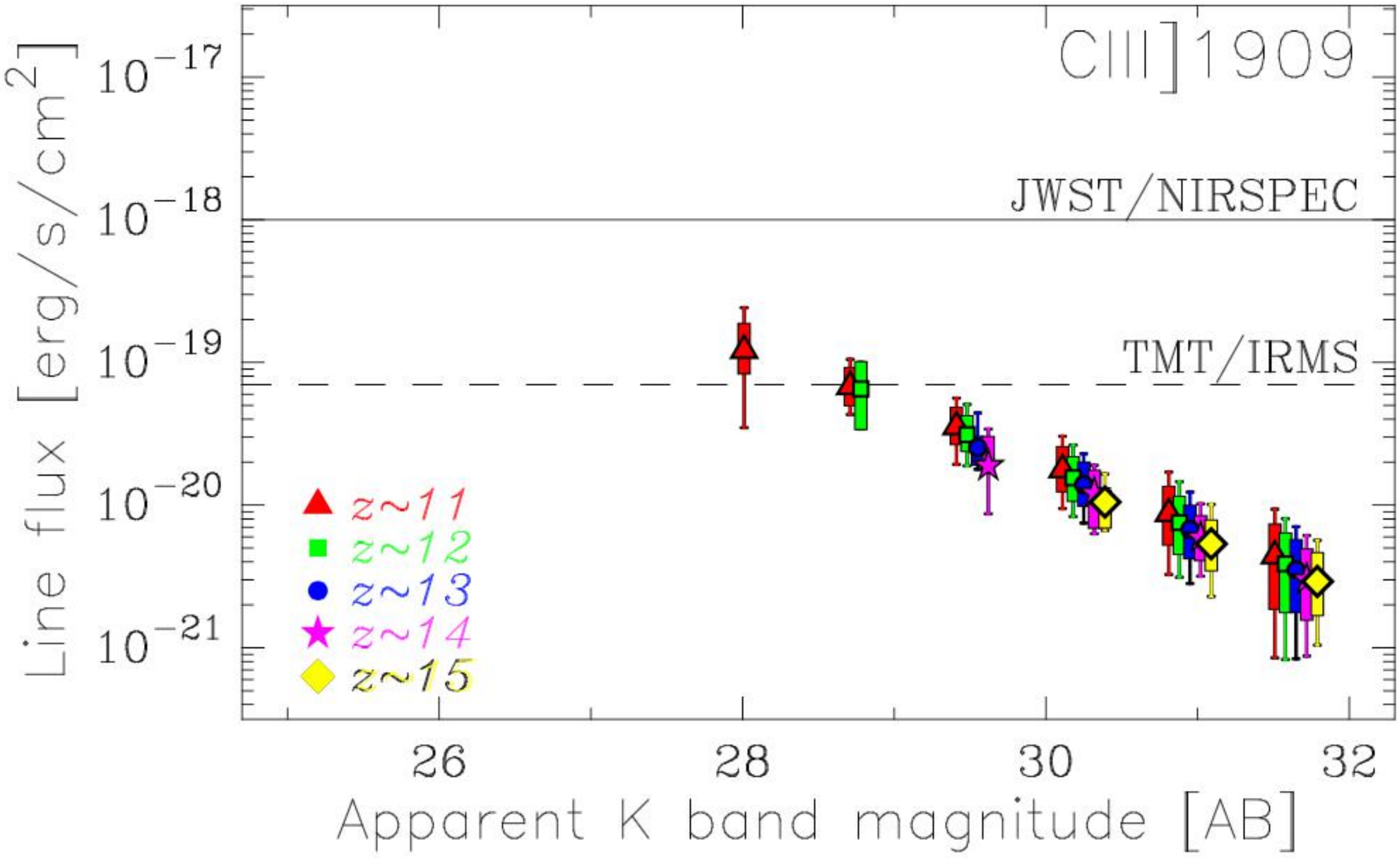
Line flux: [OIII]



Line flux: Neon III



z > 10 galaxies



James Webb Space Telescope (2018-)