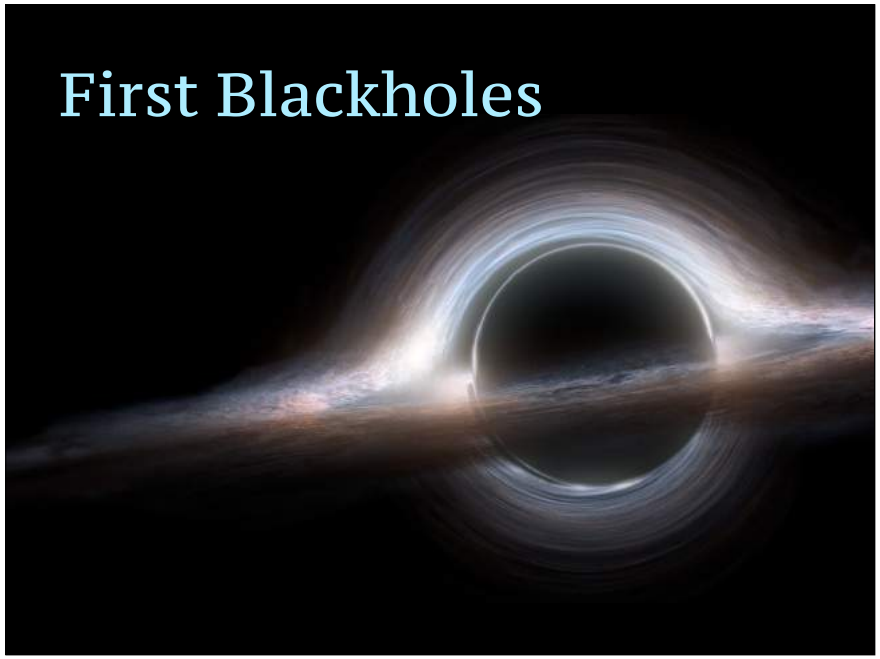
Lecture 3

Aftermath of the First Stars

NAOKI YOSHIDA
UNIVERSITY OF TOKYO

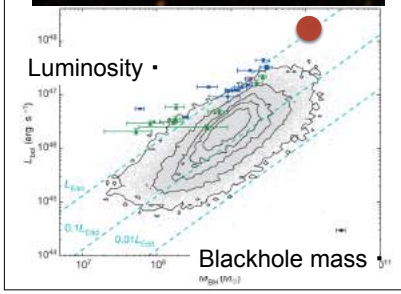
ADVANCED SUMMER SCHOOL 2019 "FIRST LIGHT"

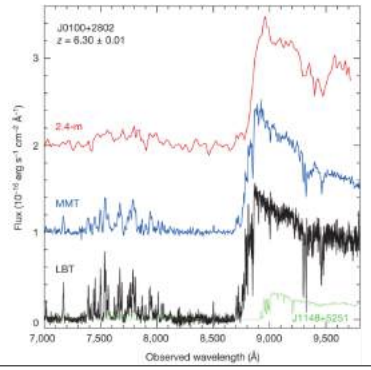
First Blackholes



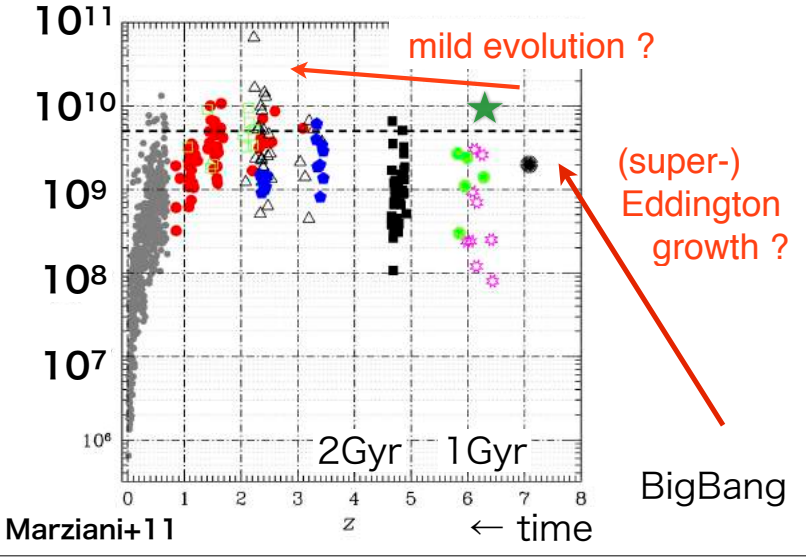
A young, monstrous blackholeㆍ

Wu et al. Nature 2015
SDSS J0100+2802
12 billion solar-masses
0.9 Gyrs after the big bangㆍ

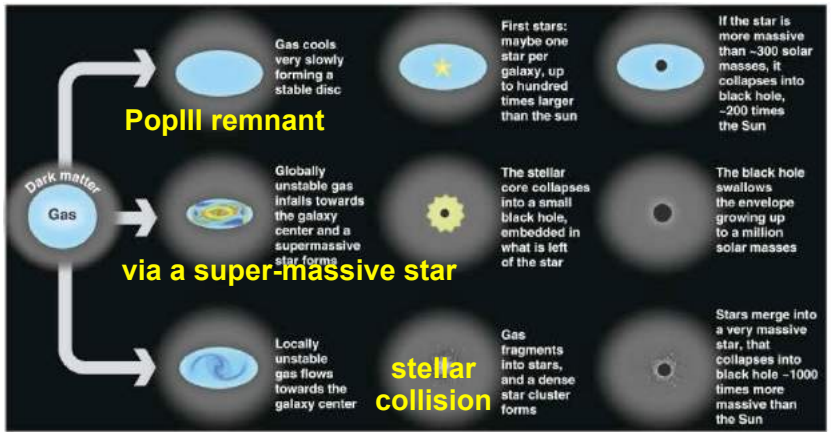




Blackhole mass



Blackhole seeds: Rees diagram



Volonteri 2012, Science

BH seed formation models

- Remnants of the first stars

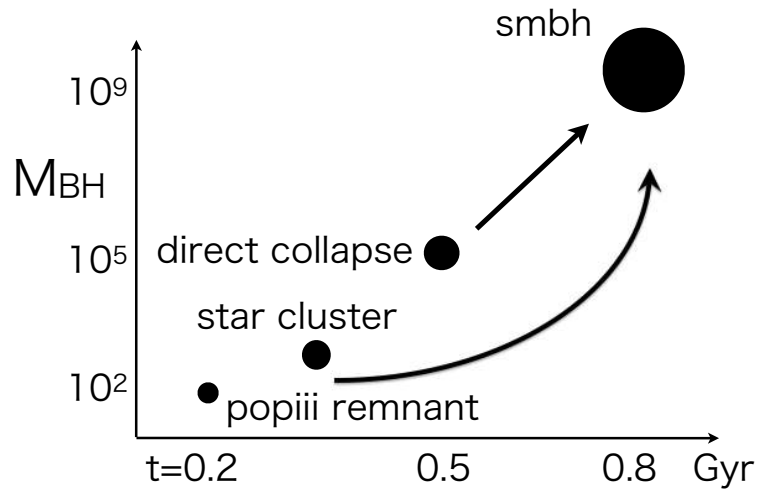
  Primordial stars > 300 Msun

- Direct collapse of a massive gas cloud

  UV radiation driven model
  Turbulent collapse induced by streaming motions

- Stellar collisions in dense star cluster

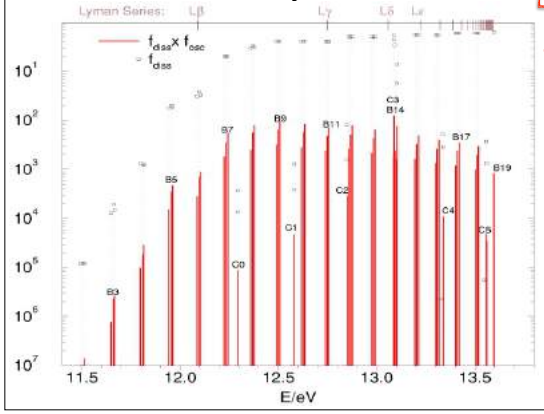
Blackhole growth: Johnson plot



Direct collapse model

Radiative feedback from first stars and galaxies

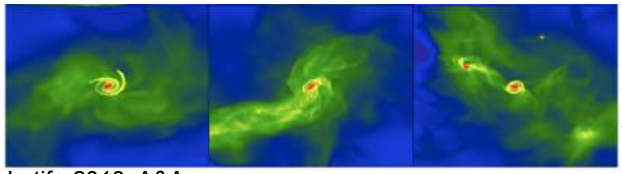
Photo-dissociation by Far-UV radiation: $H_2 + \gamma \rightarrow H + H$



Two-step Solomon process by Lyman-Werner photons (11.48 - 13.6 eV)

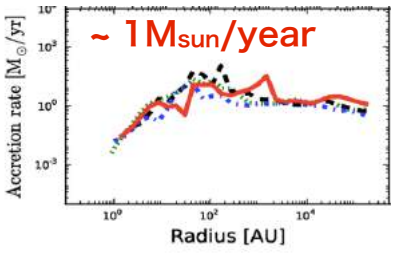
H_2 formation and hence H_2 cooling are suppressed.

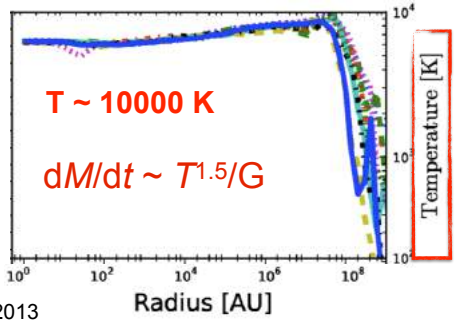
Direct collapse model



Formation of super-massive star ~ 10^5 Msun

Latif+ 2013, A&A

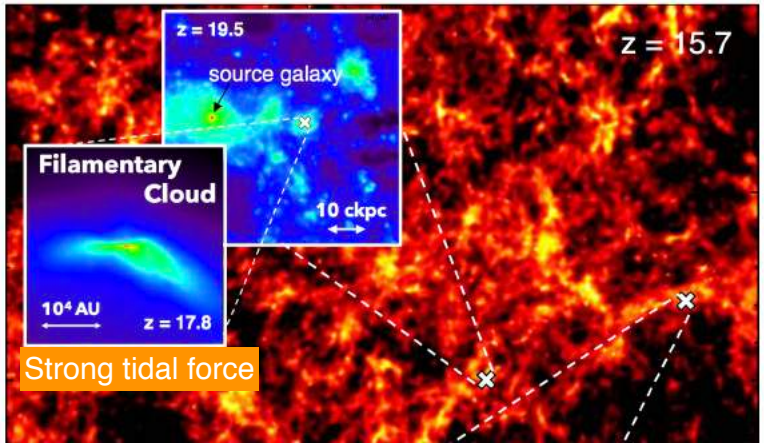




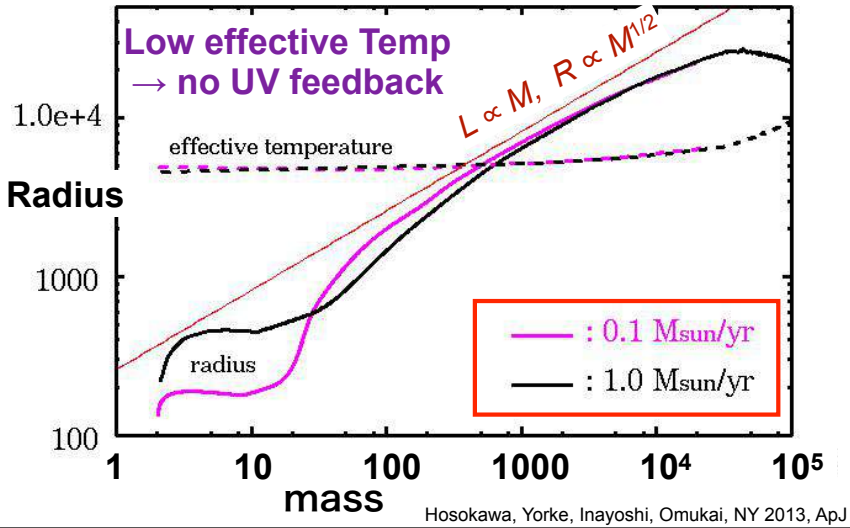
See also Regan & Haehnelt 2011; Choi+2013

Cosmological conditions

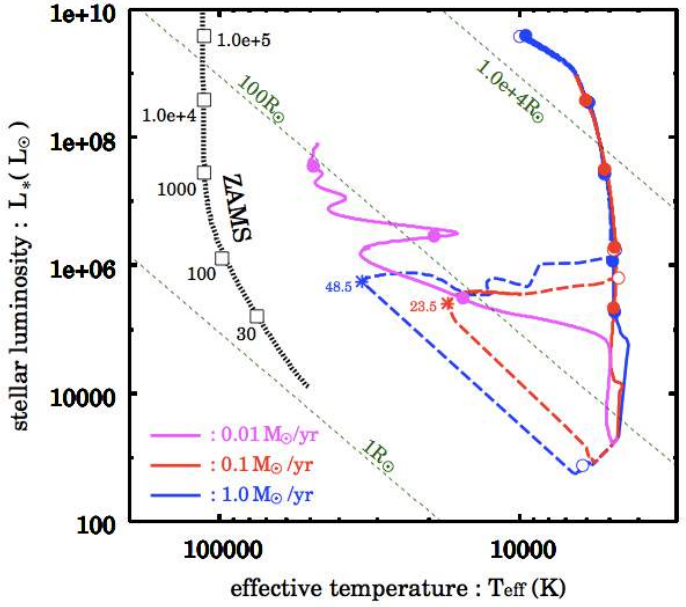
Chon & Latif 2017; Chon+ 2018



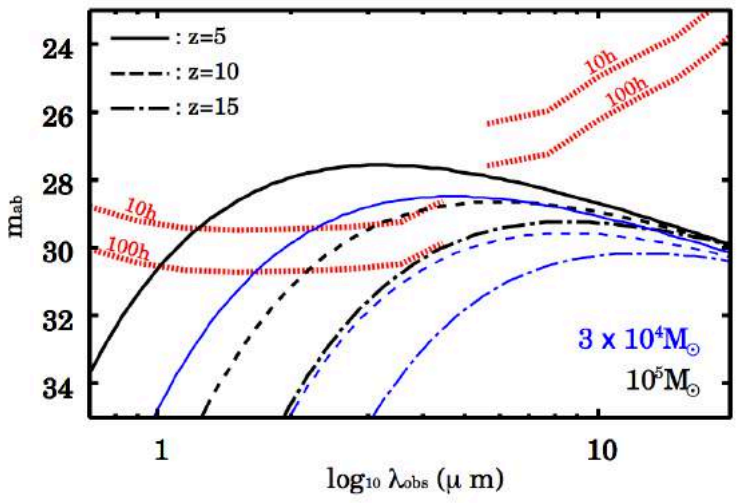
Stellar evolution



Hosokawa, Yorke, Inayoshi, Omukai, NY 2013, ApJ

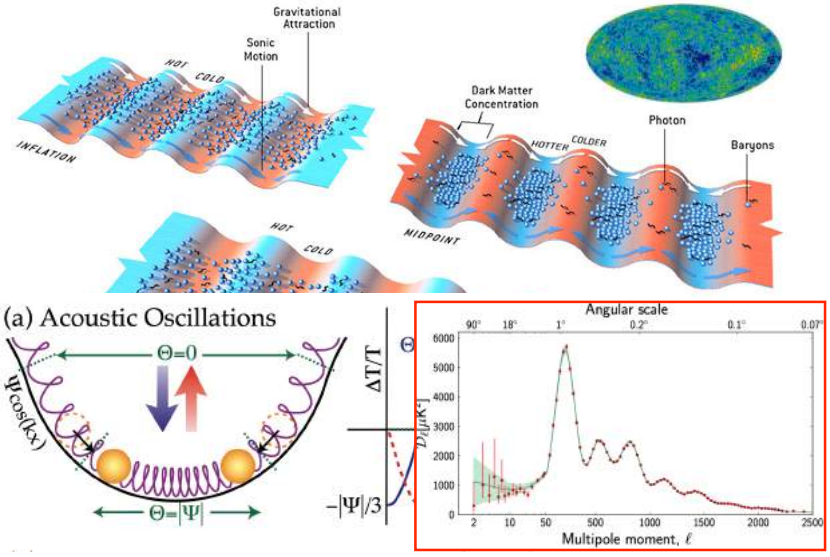


JWST will see it!

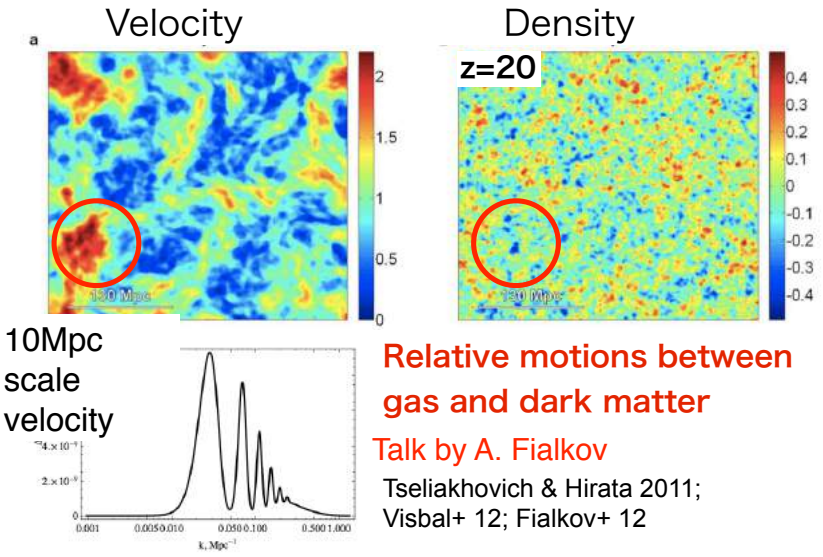


Early universe

Acoustic Oscillations



Supersonic stream



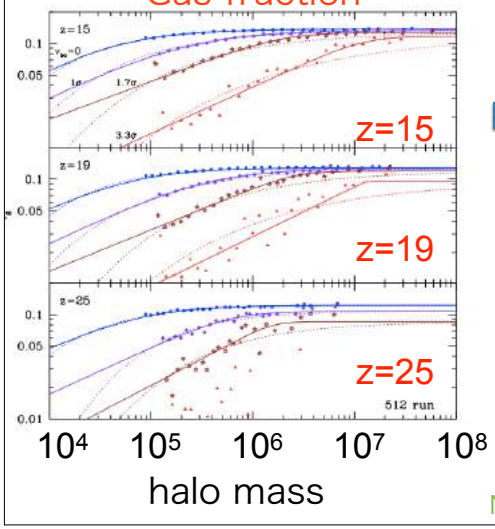
Relative motions between gas and dark matter

Talk by A. Fialkov

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

Reduced Baryon Fraction

Gas fraction



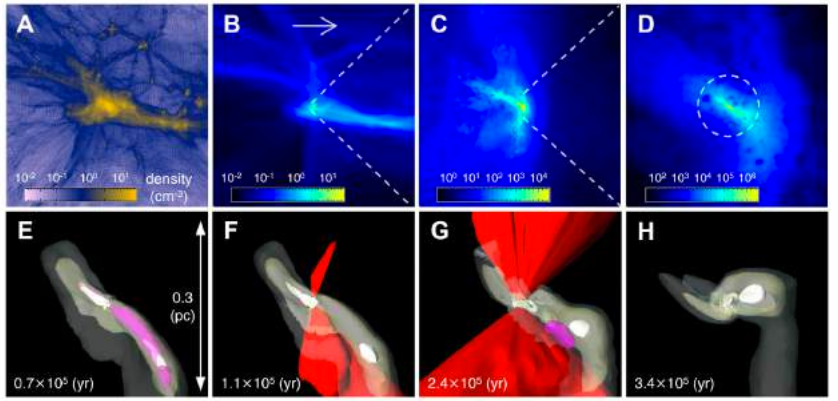
Strong wind

Halo's gravitational potential

Naoz, NY, Gnedin 2011;2013

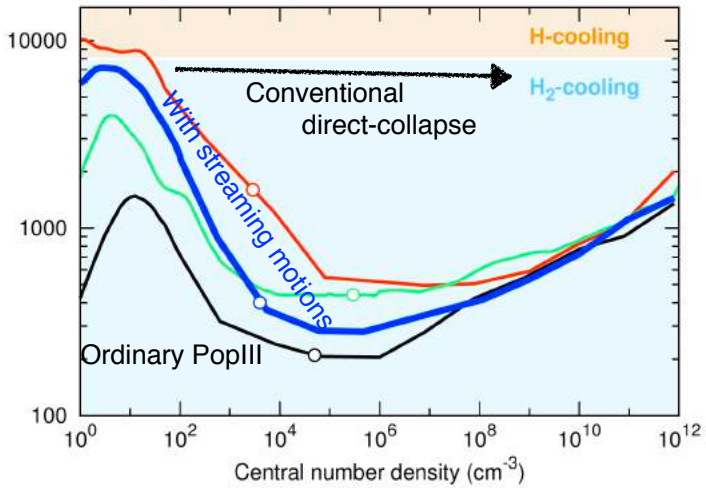
Supersonic gas streams drive BH formation

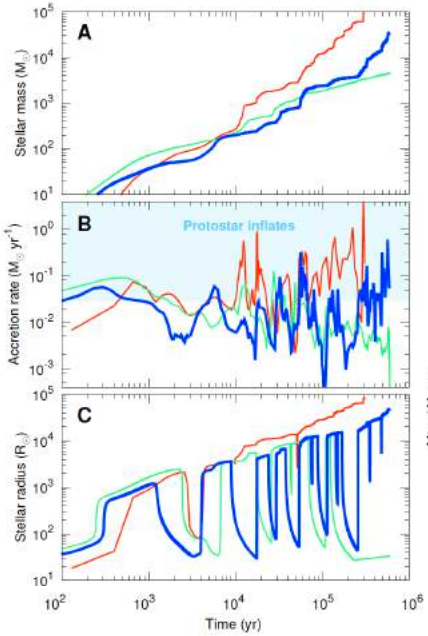
A high-density region with 3-σ streaming velocity (90 km/s @ z=1089)



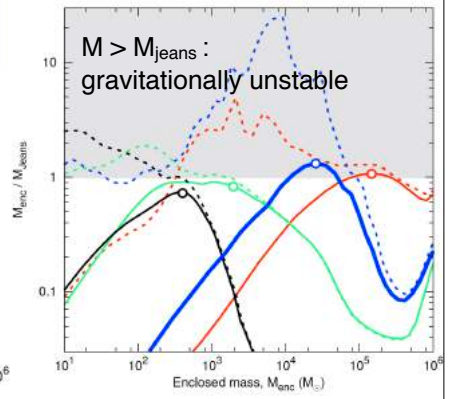
Hirano, Hosokawa, NY, Kuiper, 2017

Failed direct-collapse

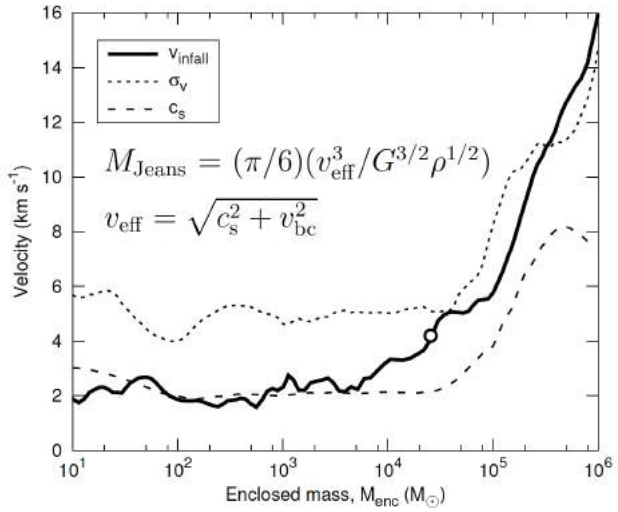




← M* > 10000 M_{sun}
H_2 formation and cooling at high-densities does not delay the cloud collapse

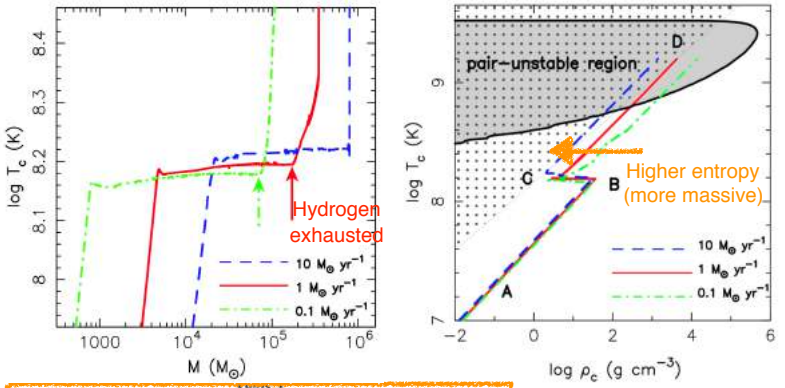


The role of turbulence



Core evolution of accreting stars

Umeda+ 2016, ApJL



Final Stellar Mass and Composition of the Inner Core

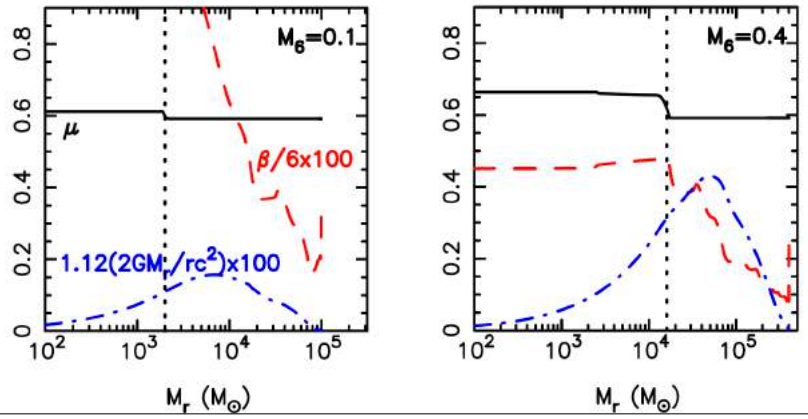
$\dot{M}$($M_\odot$ yr^{-1})	0.1	0.3	1.0	10
M_f ($M_\odot$)	1.2×10^5	1.9×10^5	3.5×10^5	8.0×10^5
Y (or X)	0.00	0.99	1.00	(0.51)

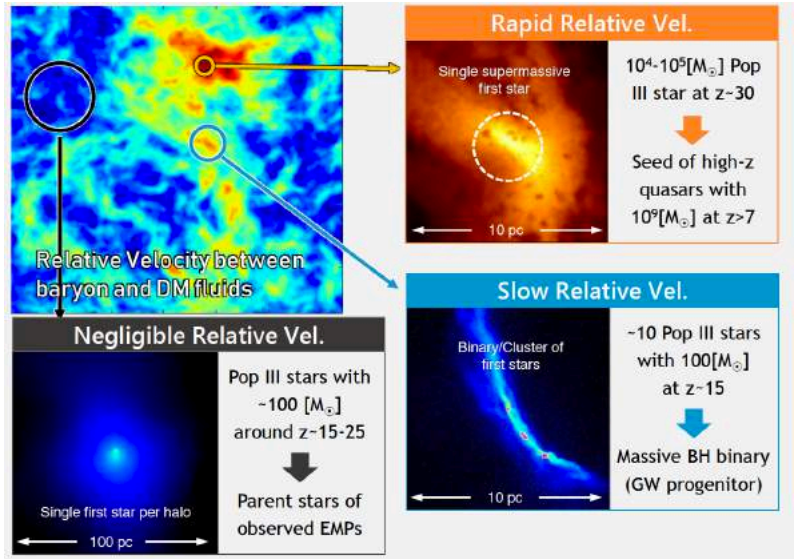
In stellar interior, the effective EoS is

$\Gamma = 4/3 + \beta/6 + O(\beta^3)$. β : gas/total pressure

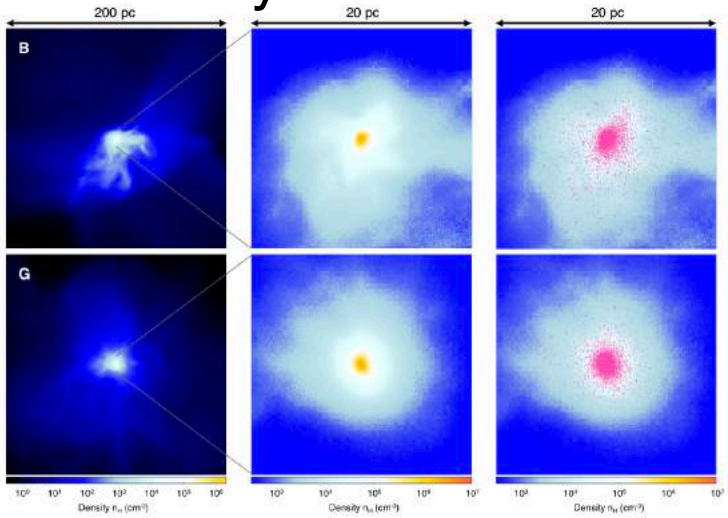
The core is General Relativistically unstable if

$\Gamma < 4/3 + 1.12\,(2GM/Rc^2)$.



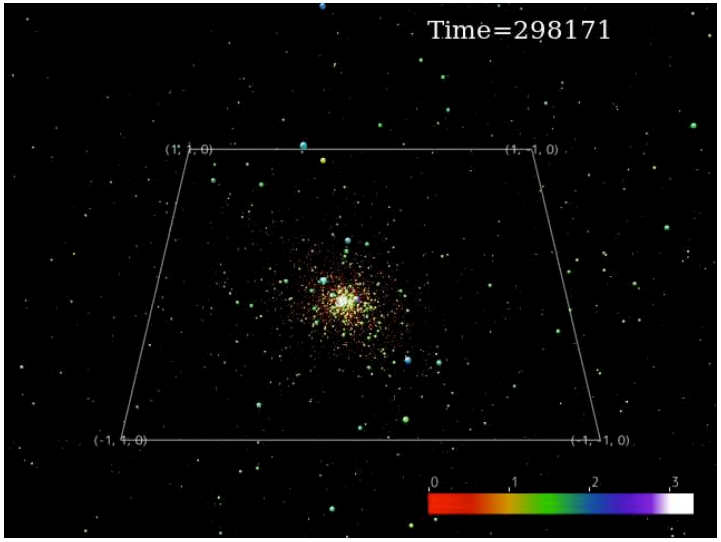


Run-away stellar collisions



$M_{halo} > 10^7\ M_{sun}$, $M_{cluster} \sim 10^5\ M_{sun}$, $z > 10$

Mass segregation and runaway collisions



Star collision rate

The central star grows at a rate

$$\frac{\mathrm{d}m_r}{\mathrm{d}t} = N_{\rm coll}\,\delta m_{\rm coll}$$

The collision rate is governed by 3-body binary formation

$$\dot{n}_{\rm bf} \sim 10^{-3}\frac{N_c}{t_{\rm rlx}}$$

where t_{rlx} is the system relaxation time (Goodman 1989, Makino 1990, etc)

$$t_{\rm rlx} = \left(\frac{R_c^3}{GM_c}\right)^{1/2}\frac{N_c}{8\ln\Lambda_c}$$

Then we estimate

$$N_{\rm coll} \sim 10^{-3} f_c \frac{N_c}{t_{\rm rlx}}$$

with f_c being some uncertain factor of collision per binary

Mass growth rate

A massive star with m falls in at a timescale of

$$t_{\rm f} \sim 3.3\frac{\langle m\rangle}{m}\,t_{\rm rlx}$$

So the mimimum mass of the stars that fall in within t is

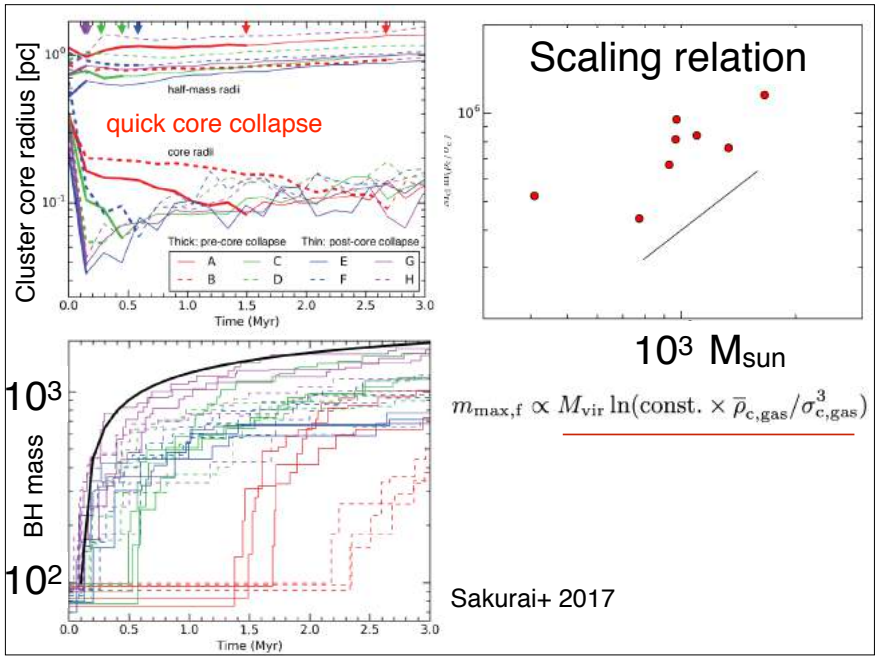
$$m_{\rm f} \sim 1.9 M_\odot \frac{1{\rm Myr}}{t}\left(\frac{R_c}{1{\rm pc}}\right)^{3/2}\left(\frac{M_c}{1M_\odot}\right)^{1/2}(\ln\Lambda)^{-1}$$

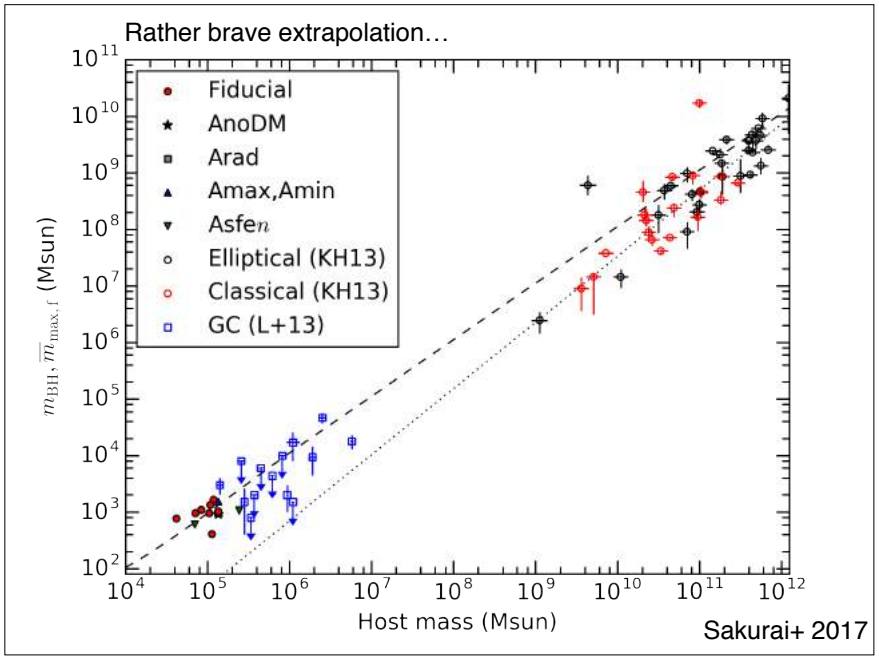
Empirically, with a "universal" secondary mass distribution, the average mass gain per collision is

$$\delta m_{\rm coll} \sim 4 m_{\rm f} \;\rightarrow\; \delta m_{\rm coll} \sim 4\,\frac{t_{\rm rlx}}{t}\,\langle m\rangle \ln\Lambda c$$

Finally, we estimate

$$\frac{\mathrm{d}m_r}{\mathrm{d}t} = N_{\rm coll}\,\delta m_{\rm coll} = 4\times 10^{-3} f_c \frac{N_c\langle m\rangle}{t}\ln\Lambda c$$





Formation of metal-poor stars

PopIII to PopII transition

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

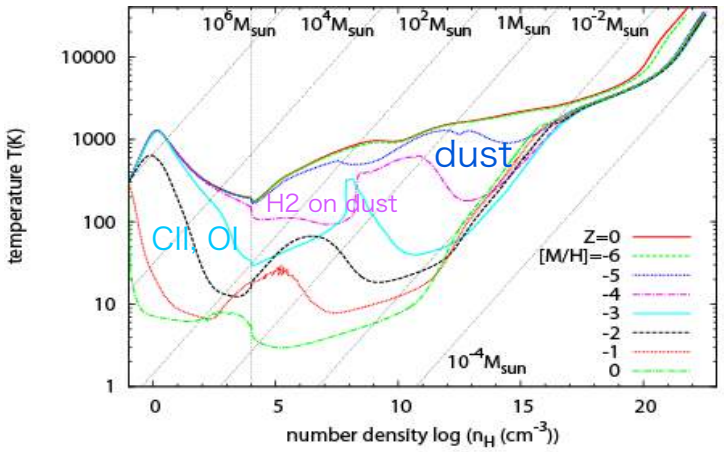
If so, what’s the key process ?

atomic cooling by C, O @low-density”

vs.

cooling by dust @high density

Spherical collapse calculation

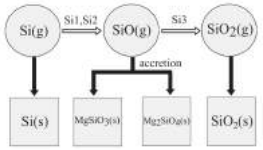


Omukai et al. (2010)

"Minimal" chemistry

54 reactions for 27 species:

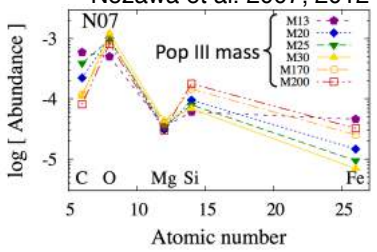
H^+, e^-, H, H^-, H_2, D^+, D, HD,
C^+, C, CH, CH_2, CO^+, CO, CO_2,
O^+, O, OH^+, OH, H_2O^+, H_2O, H_3O^+,
O_2^+ , O_2, Si, SiO, SiO_2

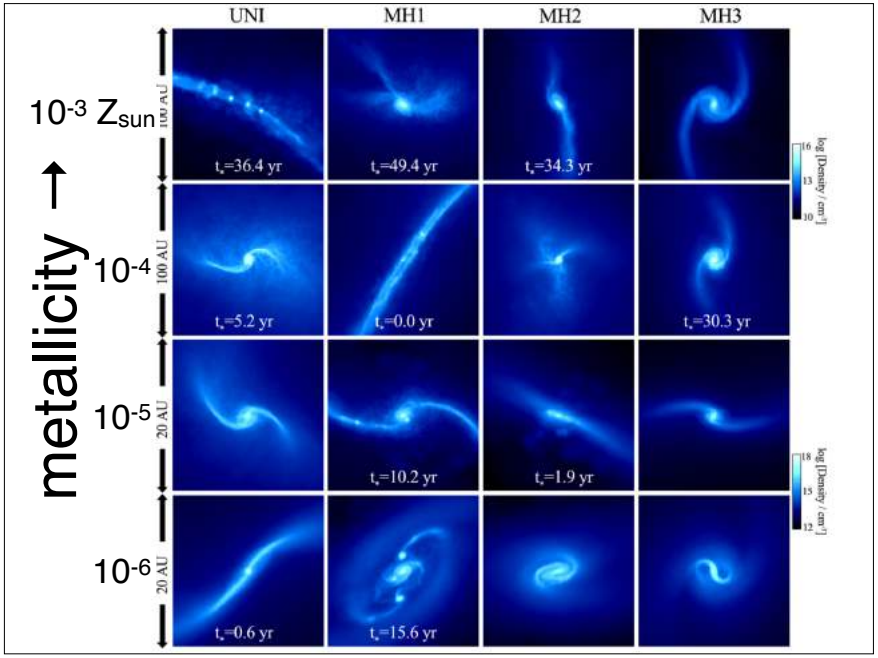


Grain chemistry: metallic silicon (Si), metallic iron (Fe), Mg_2SiO_4, $MgSiO_3$, amorphous carbon (C), SiO_2, MgO, FeS, and Al_2O_3

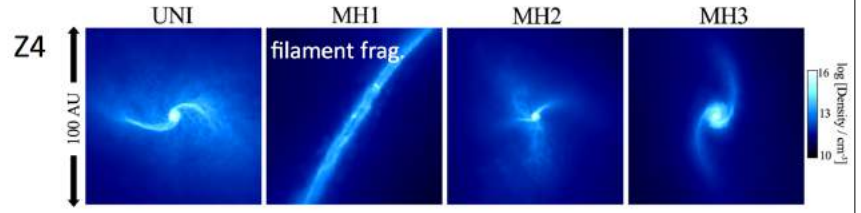
Nozawa et al. 2007; 2012

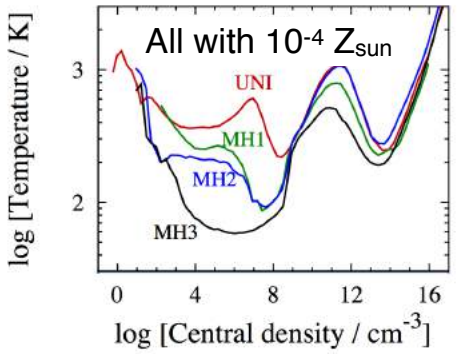
Chemical and radiative cooling
- Transition line cooling
  C II, C I, O I, CO, H_2O, OH
- Dust thermal emission
- H_2 formation heating





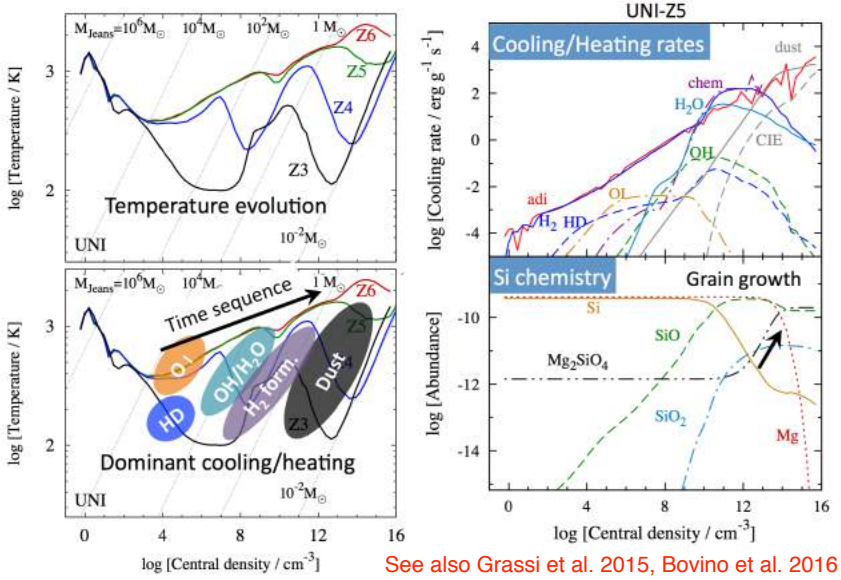
Does metallicity determine everything ?





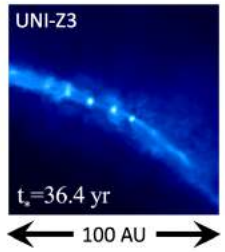
Difference in the thermal evolution as big as differences caused by metallicity.

Chemo-thermal evolution



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

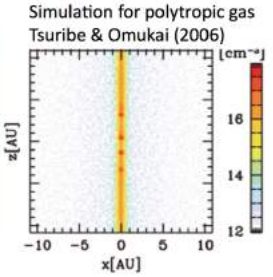
"Filamentation" vs disk fragmentation



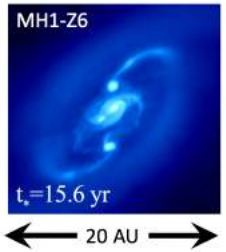
Thermal process

◆Filament fragmentation
- ✓Induced by gas cooling
- ✓Radial (infall) velocity is dominant.
- ✓Clumps are aligned with a constant separation

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

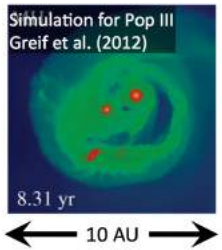


Gravitational instability

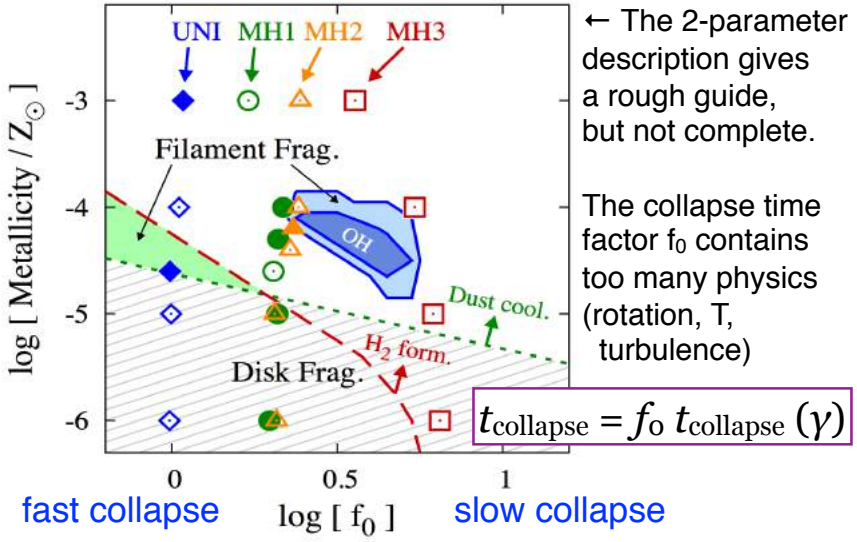


◆Disk fragmentation
- ✓Induced by self-gravity
- ✓Tangential (rotational) velocity is dominant.
- ✓Clumps are formed in arms

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



There are reasons to fragment



← The 2-parameter description gives a rough guide, but not complete.

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

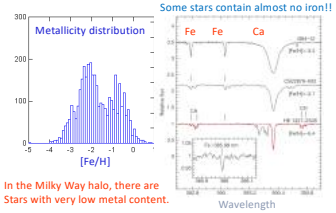
$$t_{\rm collapse} = f_0\, t_{\rm collapse}\,(\gamma)$$

Do you still remember these ? Hopefully…

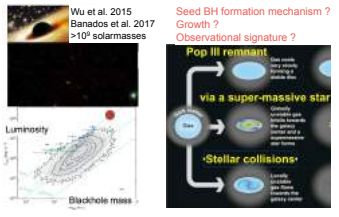
OLDEST STARS IN OUR BACKYARD

Low-mass ($<1M_{\rm sun}$), extremely iron-poor star.
Metallicity below 4.5 x 10^{-5} *that of the sun.*
Caffau et al. 2012, Nature

A SECOND-GENERATION STAR ?



MONSTROUS BLACKHOLE AT EOR



FASCINATION WITH CURRENT ASTRONOMY & COSMOLOGY

- Peculiar, small and old stars in our Milky Way.
- Existence of monstrous blackholes at the most distant place.
- Small polarization signatures in the cosmic microwave background radiation.

These are seemingly different, and unrelated issues. But they are actually connected to each other within the big picture or the whole story of our universe.

Summary

- Super-computer simulations show a wide range of masses for primordial stars, including those heavier than 300 M_{sun}.
- There are a few paths to form very massive (10^5 Msun) stars, that collapse to BHs. Early streaming motions might have played a vital role.
- Second generation stars with low metallicities include low-mass stars. Possibly the origin of Galactic extremely metal-poor stars.

Research Frontier:

Open Questions for you

The mass of the first stars

- What is the lower/upper mass limit for PopIII ?
- What is the role of dark matter ?
- Were low-mass PopIII formed (brwn dwrfs) ? Where are they now ?
- Did pair-instability supernovae occur at high-z ? How do we detect and identify by JWST ?

Open Questions

First blackholes

- How does BH (seed) formation fits in the current cosmology, and, should it actually ?
- The final growth problem, from 10^6 to 10^9
- Did BH(QSOs)@z>6 contribute to reionization ?
- Where are the PopIII remnant blackholes now ? Are they still around in the Galaxy ?

Subaru High-z Exploration of Low-luminosity Quasars (SHELLQs). V. Quasar Luminosity Function and Contribution to Cosmic Reionization at $z = 6$

Yoshiki Matsuoka[1], Michael A. Strauss[2], Nobunari Kashikawa[3,4,5], Masafusa Onoue[4,5,6], Kazushi Iwasawa[7], Ji-Jia Tang[8],

THE ASTROPHYSICAL JOURNAL LETTERS, 813:L8 (6pp), 2015 November 1 doi:10.1088/2041-8205/8

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COSMIC REIONIZATION AFTER PLANCK: COULD QUASARS DO IT ALL?

PIERO MADAU[1] AND FRANCESCO HAARDT[2,3]

[1] Department of Astronomy & Astrophysics, University of California, 1156 High Street, Santa Cruz, CA 95064, USA
[2] Dipartimento di Scienza e Alta Tecnologia, Università dell'Insubria, via Valleggio 11, I-22100 Como, Italy

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The Goldilocks problem of the quasar contribution to reionization

Enrico Garaldi,[1]★† Michele Compostella,[2,3] and Cristiano Porciani[1]

[1] Argelander Institut für Astronomie der Universität Bonn, Auf dem Hügel 71, 53121 Bonn, Germany
[2] Max Planck Institute for Astrophysics, Karl-Schwarzschild Straße 1, 85741 Garching, Germany
[3] Max Planck Computing and Data Facility, Gießenbachstraße 2, 85741 Garching, Germany

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ABSTRACT

The detection of an unexpectedly large number of faint candidate quasars (QSO) at $z \geq 4$ has motivated Madau and Haardt to investigate a reionization scenario in which active galactic nuclei dominate the photon budget at all times. Their analytical study reveals that this picture is in agreement with the evolution of the H I volume fraction in the intergalactic medium (IGM) and the optical depth to Thomson scattering of the cosmic microwave background. We employ a suite of hydrodynamical simulations post-processed with a radiative transfer code to further investigate the properties of such a reionization history. In particular, we generate

Open Questions

3. Metal-poor stars

Star formation in the first galaxies

- What is the key mechanism that enables the formation of low-mass stars ?
- How and where were EMP stars formed ?
- Is there a “critical metallicity” or “dusticity” ?

- How rapidly was the IGM metal-enriched ?
- Why do early star formation and present-day star-formation differ so much ?