日本天文学会春季年会　企画セッション
「東京大学アタカマ天文台のサイエンス戦略」
2016年3月16日

TAOによる銀河形成研究の新展開

筑波大学　計算科学研究センター

梅村　雅之

銀河形成の謎を解く

宇宙最初の星はいかなるものだったのか？　最初の銀河はどのように生まれたのか？

巨大ブラックホールはなぜ存在するのか？

赤方偏移1000
(38万年)

宇宙の晴れ上がり

宇宙暗黒時代

初代星の誕生 — 原始ガスから生まれる星の質量は？

初代ブラックホールの誕生 — 巨大ブラックホールの種は何か？

赤方偏移10
(5億年)

宇宙再電離（宇宙の夜明け）

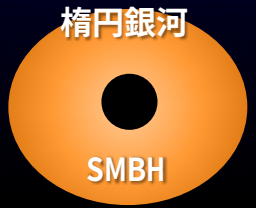
銀河形成時代

初代銀河の誕生 — 初代銀河はどのように生まれ，どのように再電離と関係したのか?

巨大ブラックホール形成 — 超臨界降着はあったか？

巨大ブラックホール形成 — 合体は起きたか？

超巨大ブラックホール（SMBH）ー銀河バルジ関係



なぜ銀河バルジ質量の1/1000なのか？

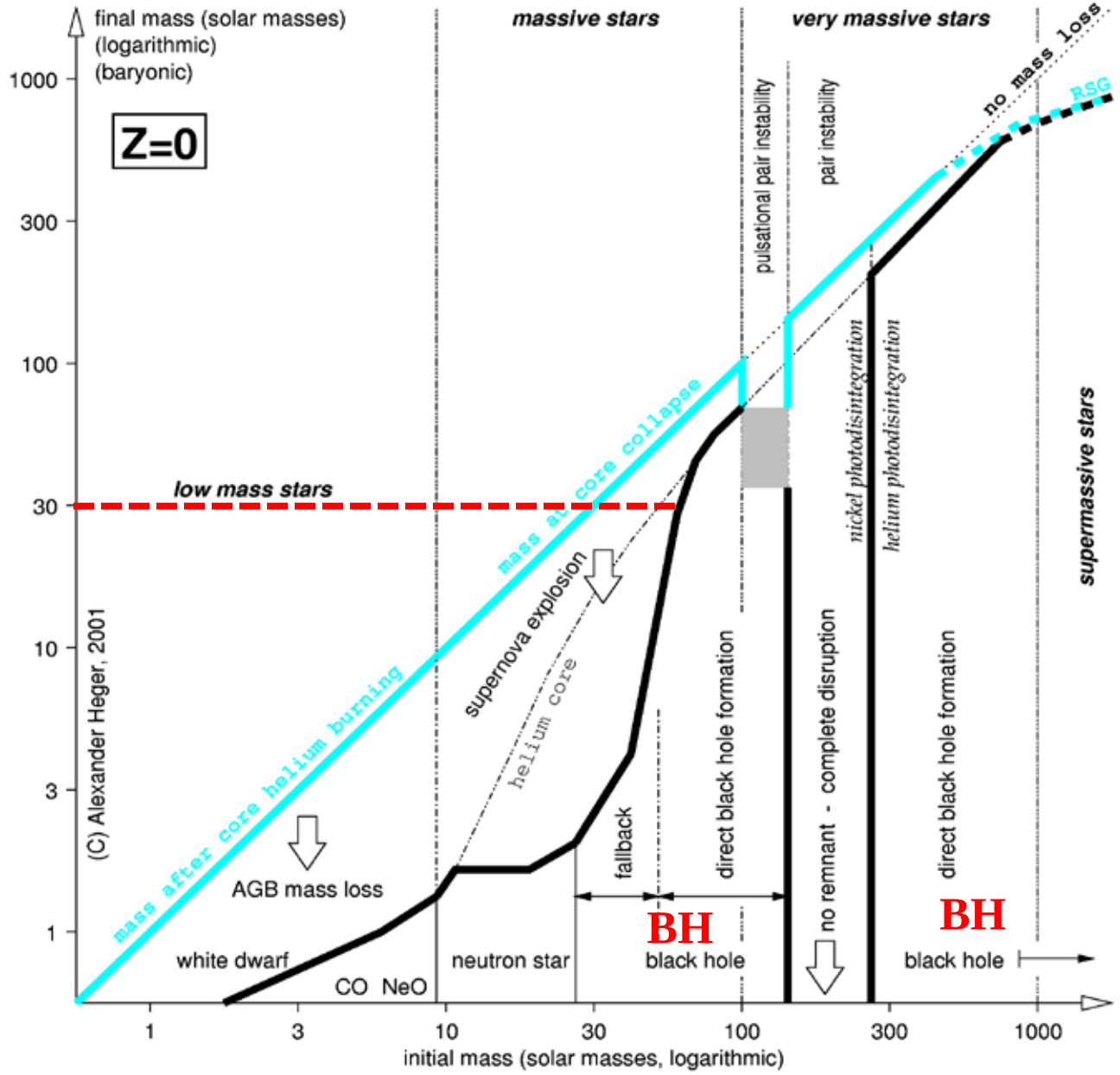
銀河宇宙時代

赤方偏移 0
(138億年)

初代星の誕生

Pop III Star Evolution

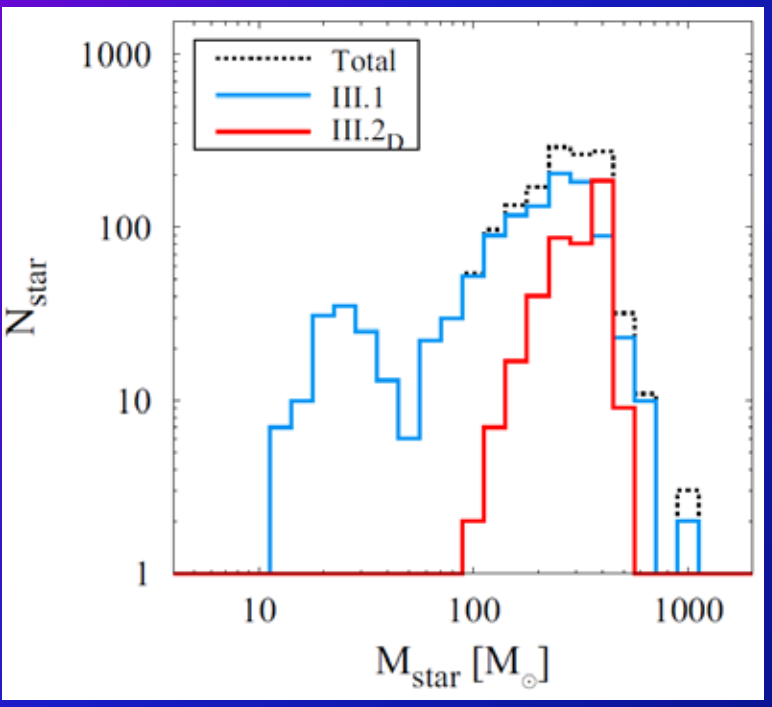
Heger & Woosley 2002, ApJ, 567, 532



初代星の質量は？

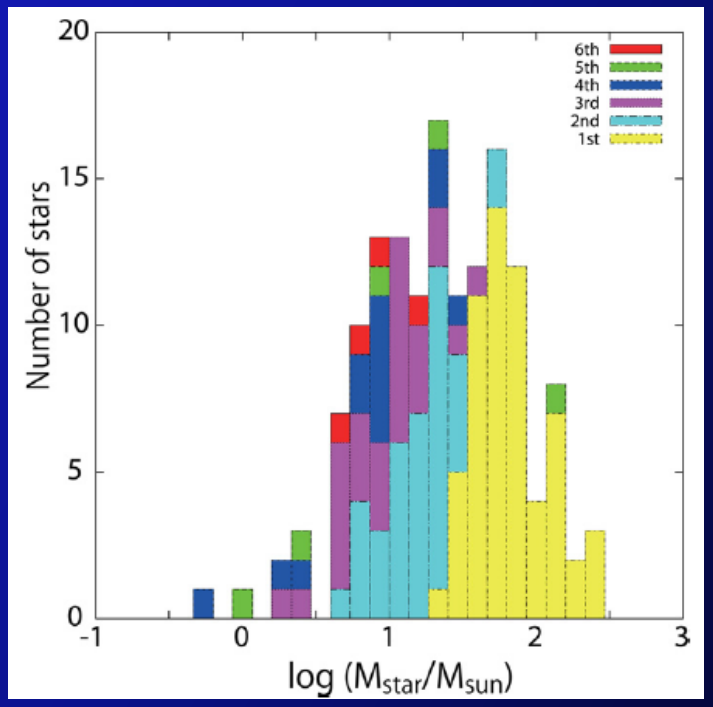
- a few 100$M_\odot$
  (Abel et al. 2000; Bromm et al. 2002; Yoshida et al. 2006)
- bimodal of ~ 1$M_\odot$ & a few 100$M_\odot$ (Nakamura & Umemura 2001)
- several 10$M_\odot$ (Clark et al. 2011)
- about 40$M_\odot$ (Hosokawa et al. 2011)
- a few ~ 10$M_\odot$ (Greif et al. 2011)

Runaway

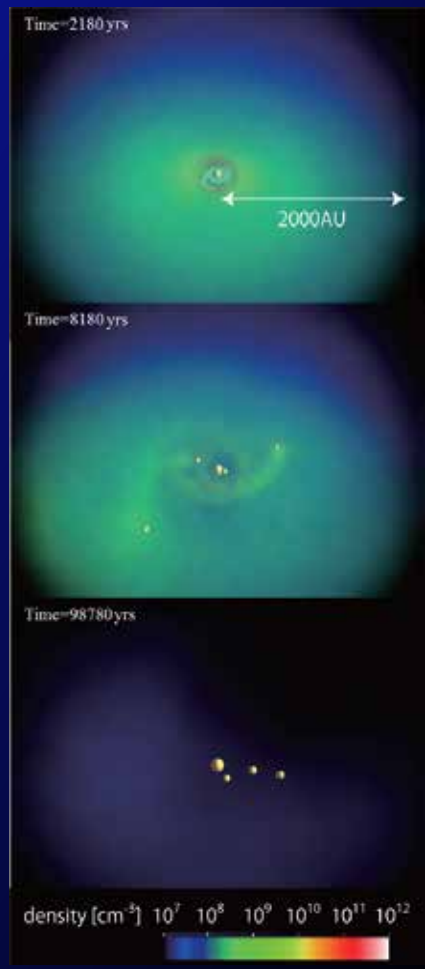


Hirano et al. MNRAS **448,** 568 (2015)

Accretion

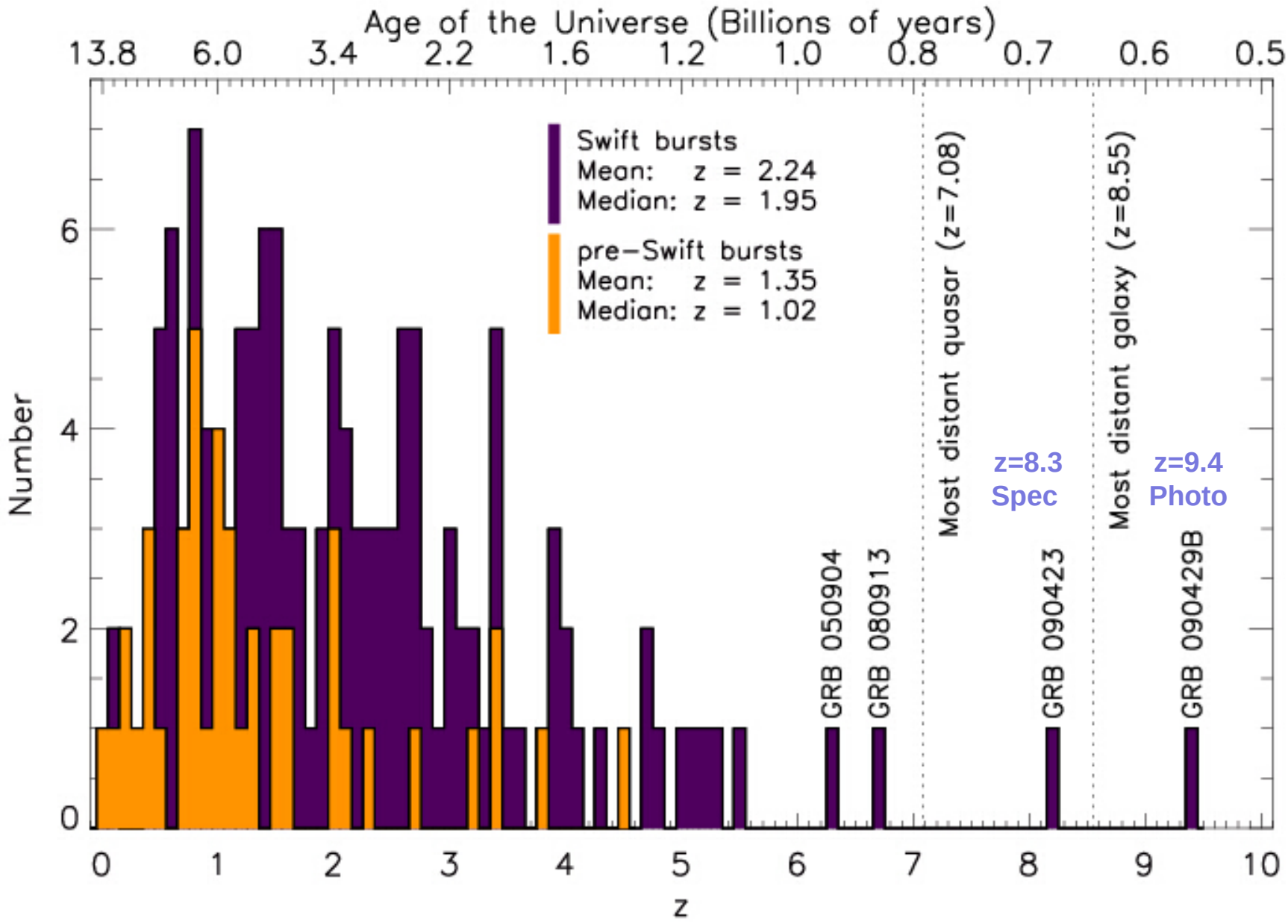


Susa, et al. ApJ, **792**, 32 (2014)



GRB赤方偏移分布

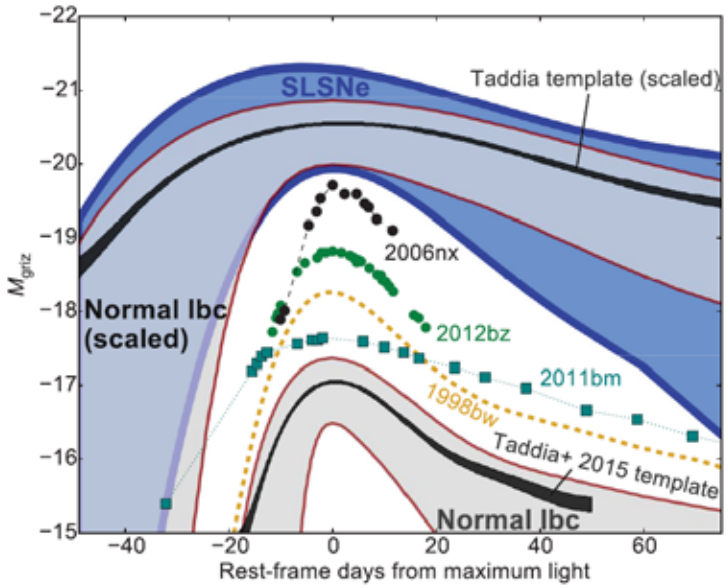
z=11.1
galaxy

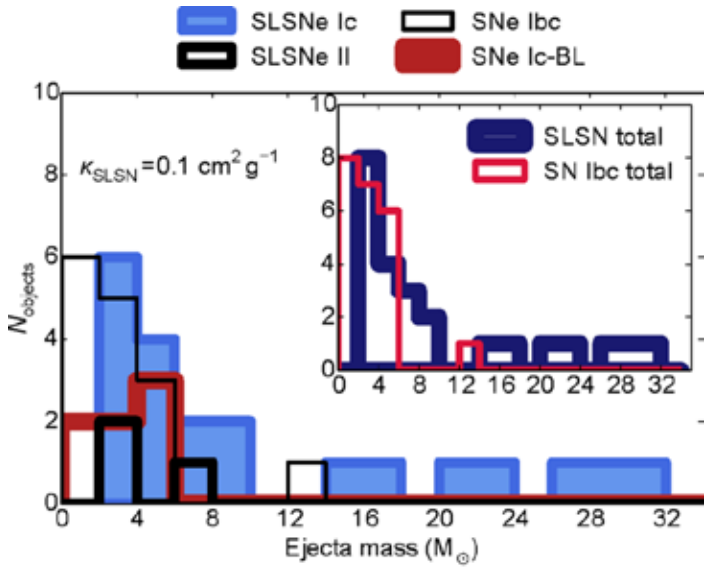


http://www.raunvis.hi.is/~pja/GRBsample.html

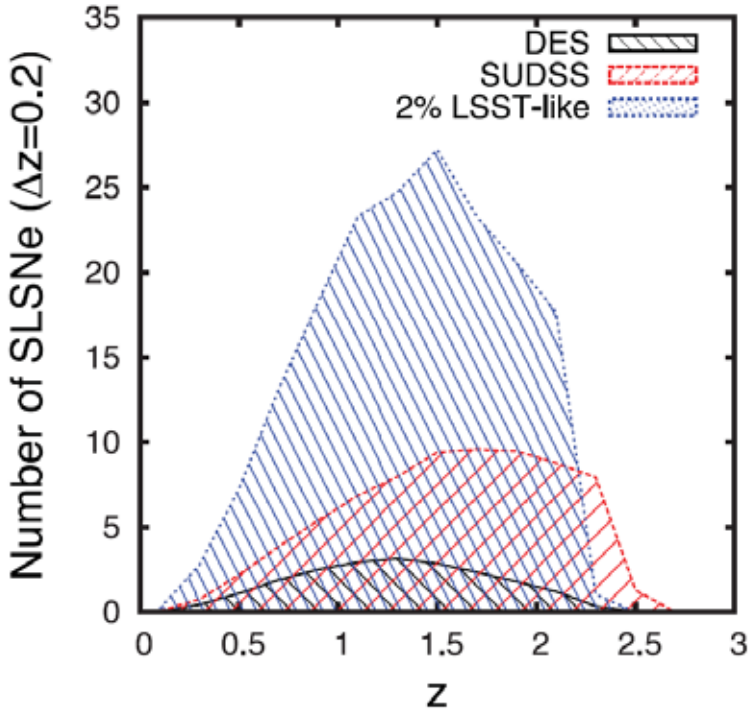
SLSNe: Superluminous Supernovae

Nicholl et al. MNRAS **452,** 3869–3893 (2015)



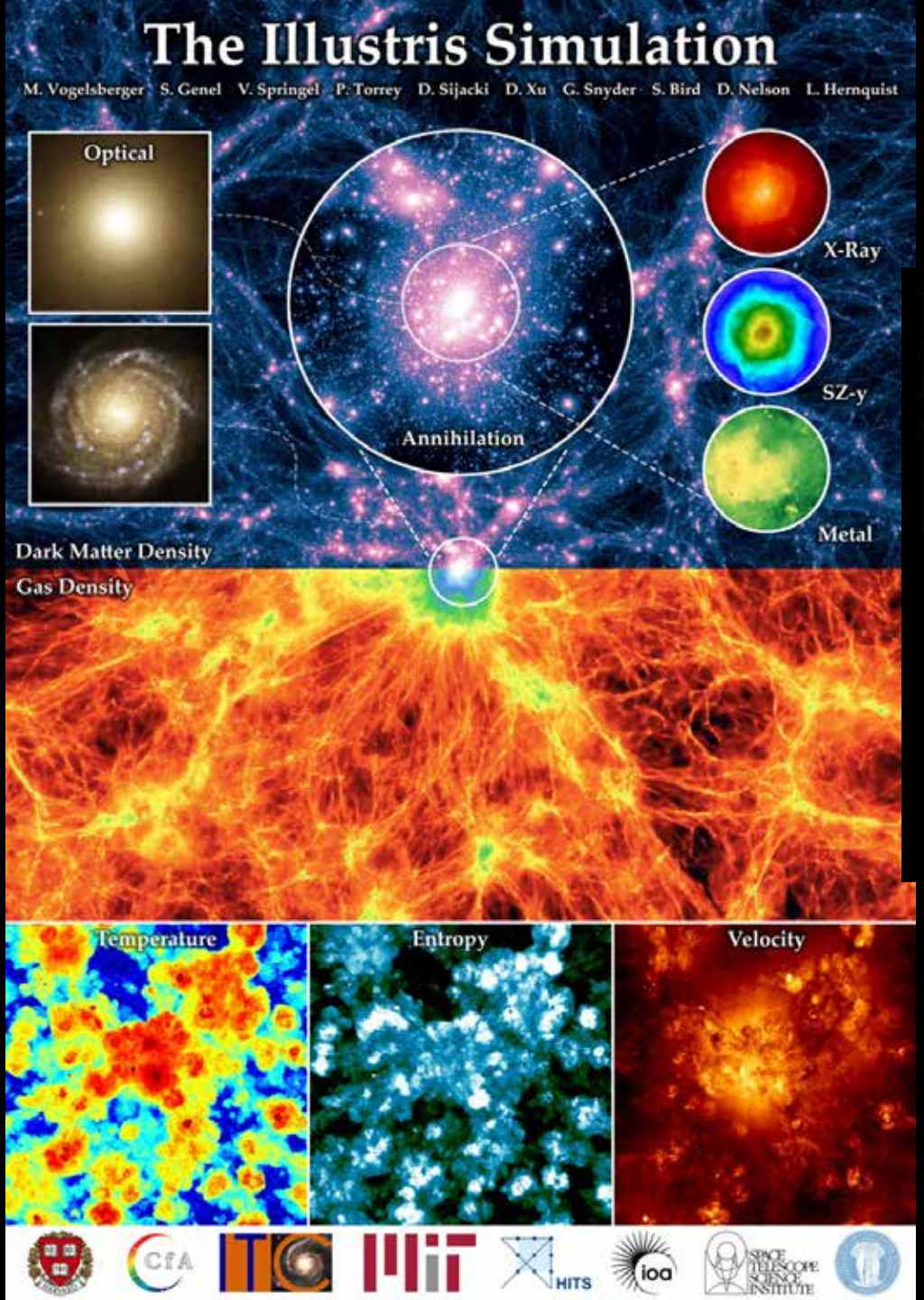


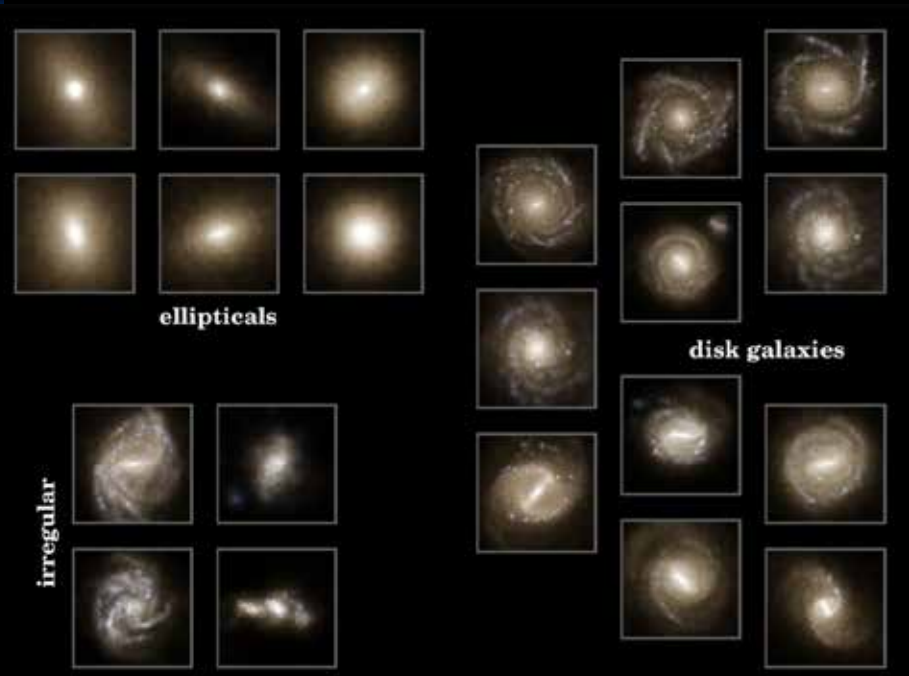
- $m > 50 M_\odot$ の星の爆発（PISNの可能性も？）
- これまで $z < 2.5$ で観測
- TAOによる赤外観測



Scovacricchi et al. MNRAS **456,** 1700–1707 (2016)

初代銀河の形成





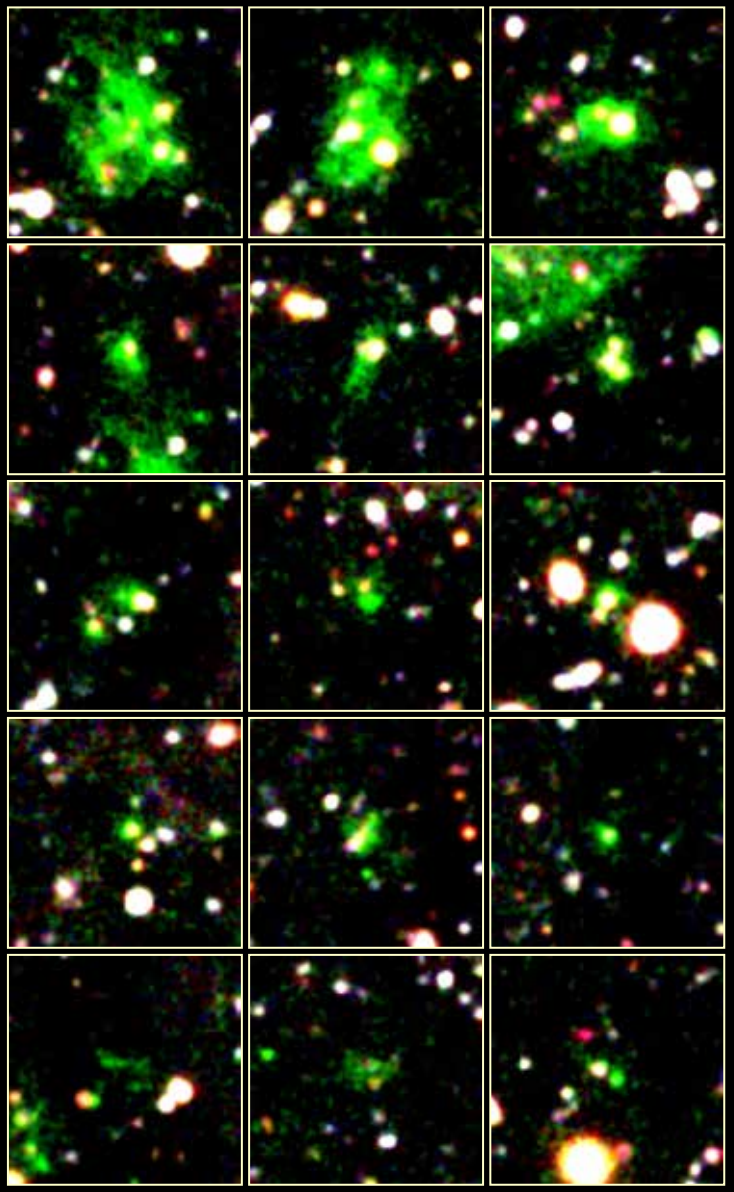
Vogelsberger et al. 2014, nature, 509, 177

ライマンα輝線天体(LAE)

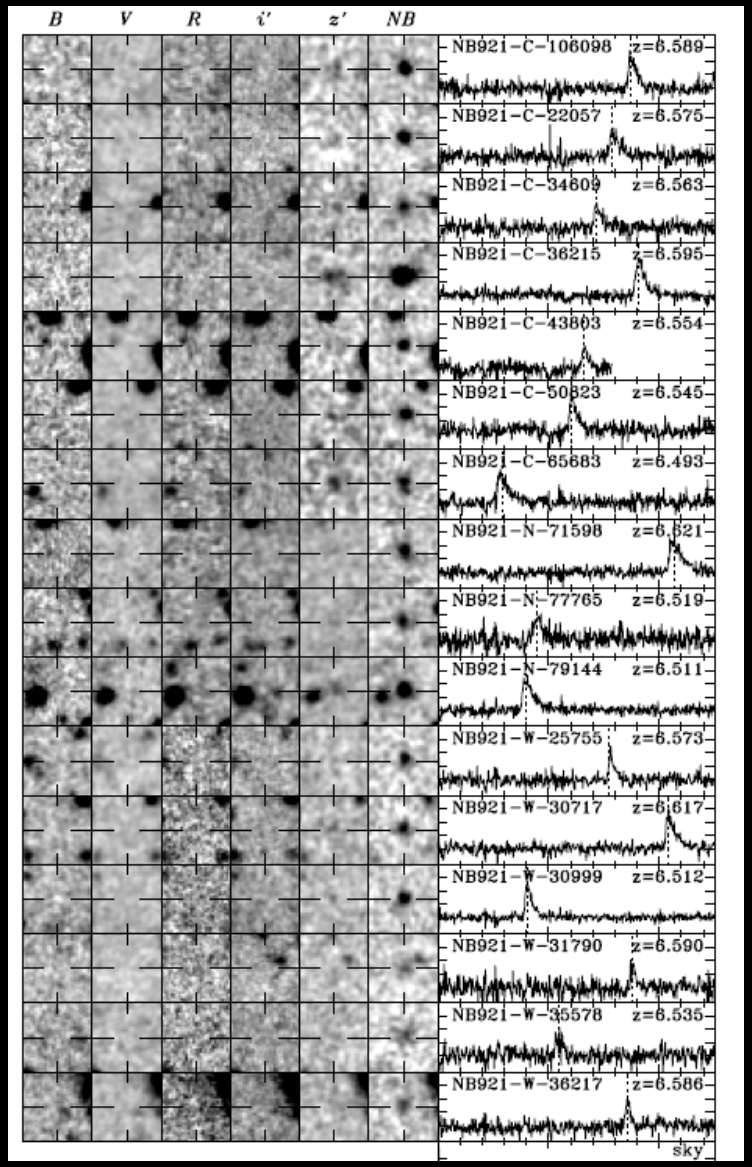
z～3

$L=10^{8}$-$10^{10}L_{e}$

z～7



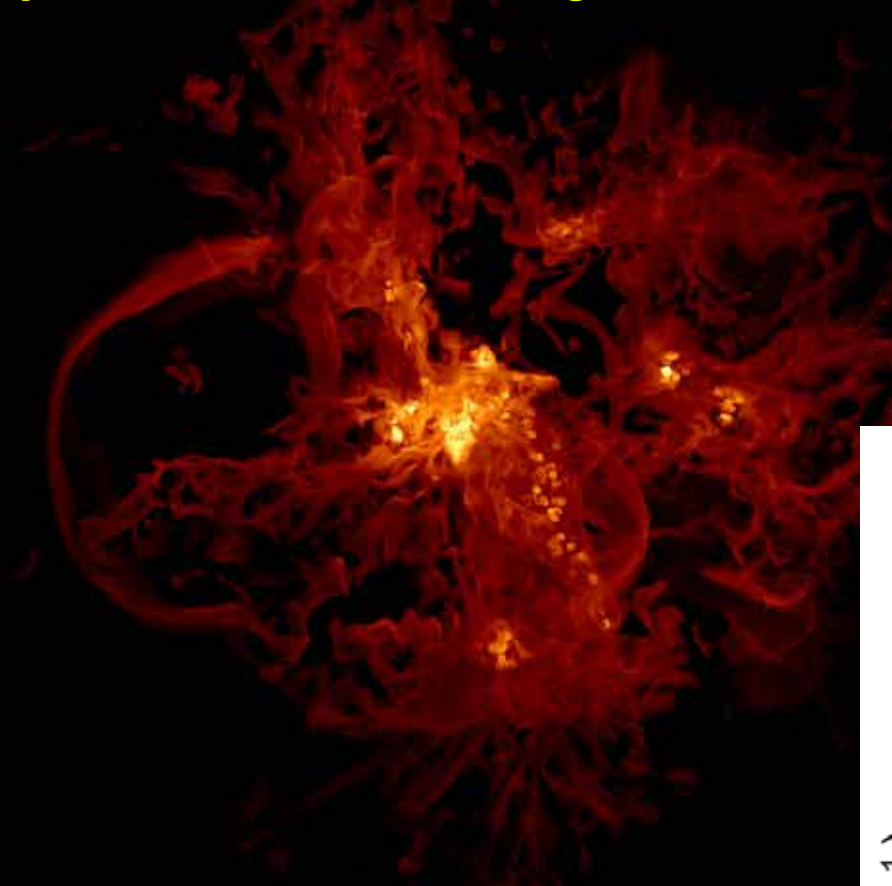
Matsuda et al 2004, ApJ, 128, 569



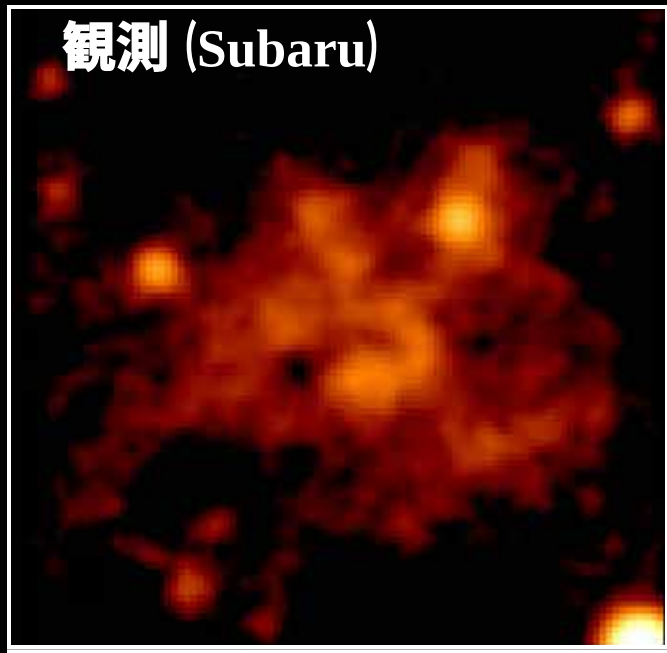
Ouchi et al. 2010, ApJ, 723, 869

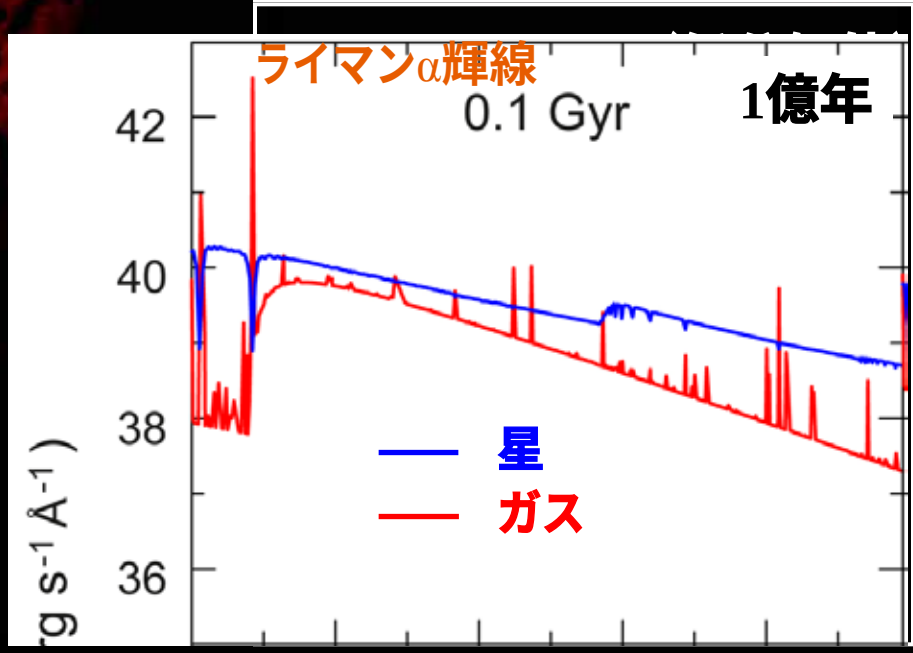
超新星爆発モデル

Ly a emission = cooling shells



Mori and Umemura, 2006,
Nature, 440, 644

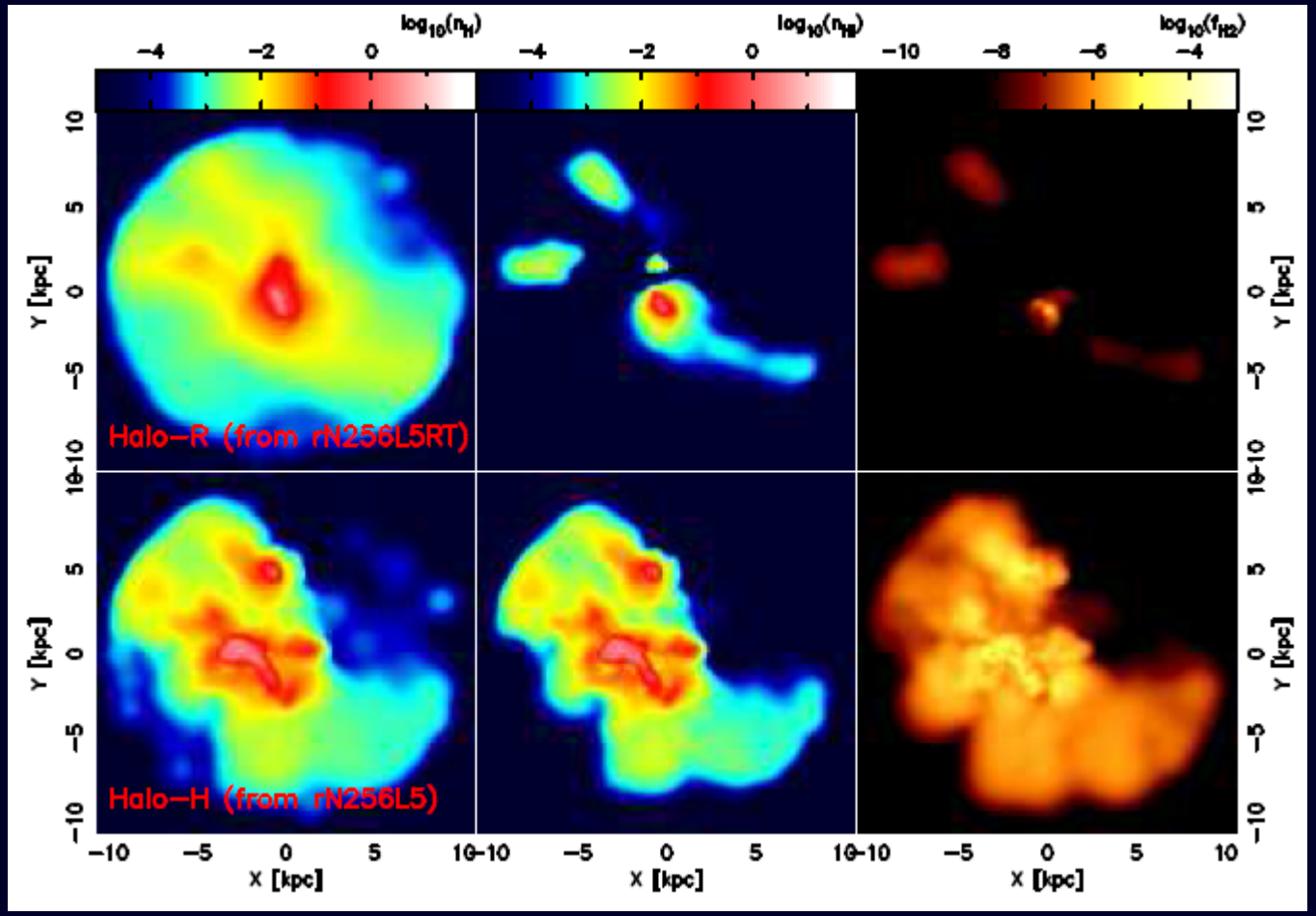




光電離モデル

光電離モデル+SN（内部＆外部電離輻射）

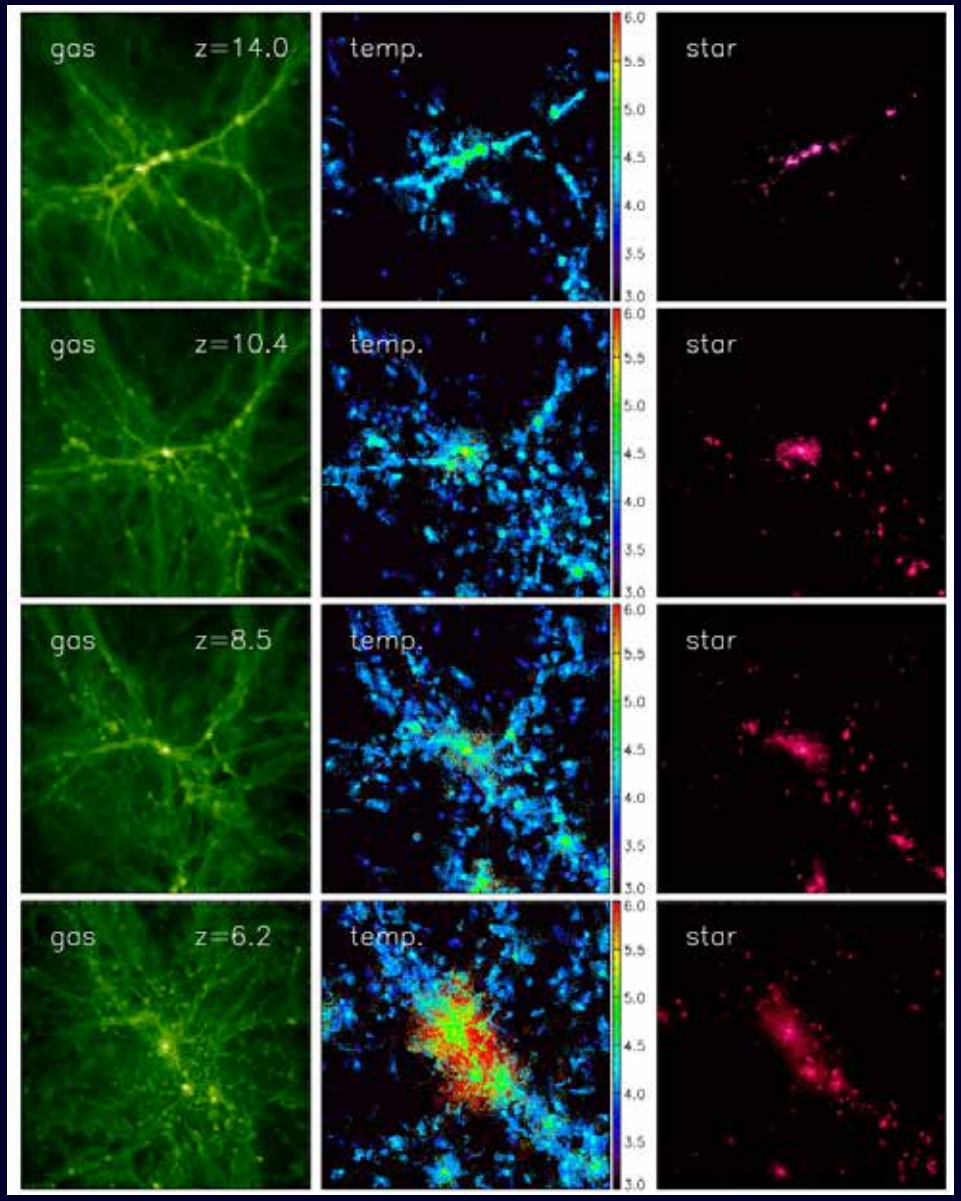
Ly a emission = recombination in HII regions



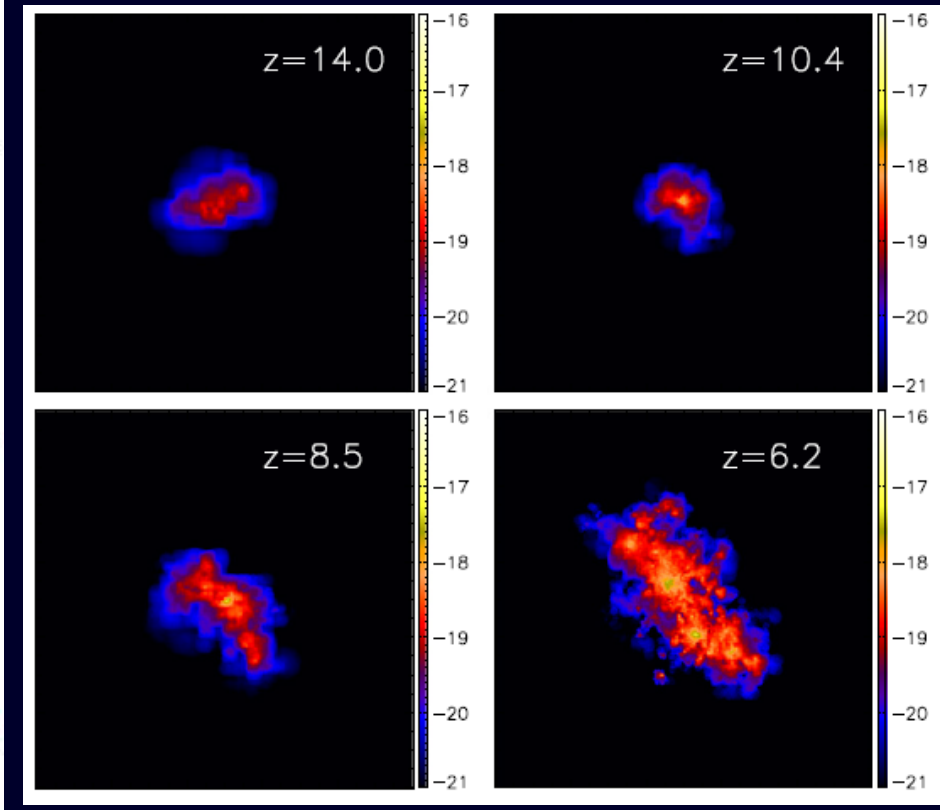
Hesegawa & Semelin 2012, MNRAS, 428, 154

MU, Susa, Hasegawa, Suwa & Semelin 2012, PTEP, 01A306 (23pp)

Cold Accretion モデル



Ly a emission = cooling radiation



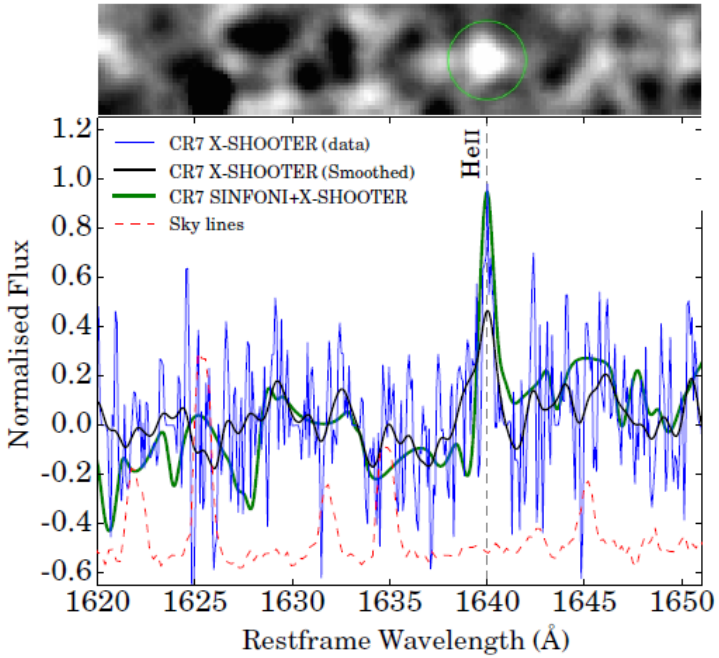
Yajima et al 2015, 801, 52

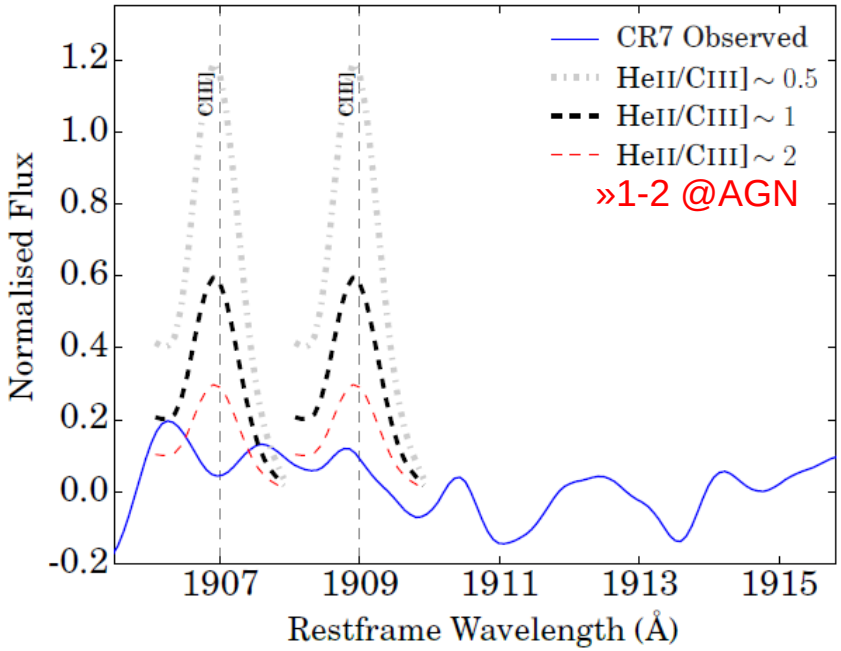
HeII detection in CR7

Sobral et al. 2015, ApJ, 808, 139

COSMOS/Ultra VISTA Fields
VLT (X-SHOOTER, SINFONI, FORS2), Keck (DEMIOS)
CR7 : z=6.604 (L_{Lya}=8.5´ 10^{43} erg/s)
cf. Himiko: z=6.54 (L_{Lya}=2.5´ 10^{43} erg/s)

J-band excess 6s detection of HeII 1640 Å (S/N=6)
F_{HeII}=4.1´ 10^{-17} erg/s/cm^2
FWHM=130±30 km/s
HeII/Lya=0.23
NV/Lya<1/70, CIII]/HeII<0.4 (weak metal line emission)
NV1240, NIV1487, CIV1549, OIII]1661, OIII]1666, NIII]1750: undetected





CR7は何者か

Possible sources for high luminosity, high EW Ly a and HeII

1) Cooling radiation (Faucher-Gigu`ere et al. 2010)

- $L_{Lya}=10^{44}$ erg/s ® $M_{halo}>5´10^{11} M_¤$
- expected number density~10^{-5}Mpc^{-3} @z~6.6 consistent with obs.

HeII/Lya < 0.1

broader Lya line

2) Strong AGN (De Breuck et al. 2000)

HeII FWHM~1000 km/s

strong metal lines (NV, OIII], CIII])

3) Wolf-Rayet (WR) stars (Shirazi & Brinchmann 2012; Erb et al. 2010)

line FWHM~3000 km/s

many metal lines

4) Direct collapse black hole (Johnson et al. 2011)

- high HeII/Lya
- no metal line

strong X-ray emission

broad line emission

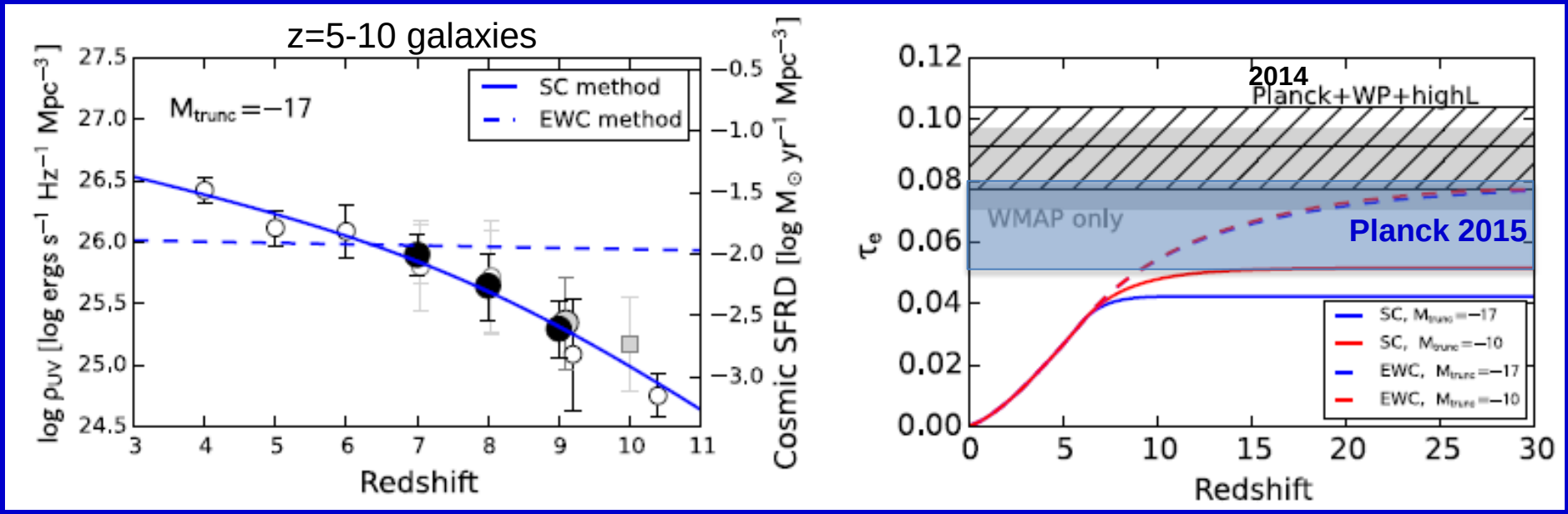
much lower Lya & HeII luminosities

5) PopIII stars (Schaerer 2003; Raiter et al. 2010)

- HeII FWHM~100 km/s
- HeII/Lya~0.1 ® HeII/Lya~0.2-0.3 due to HI absorption
- no metal line

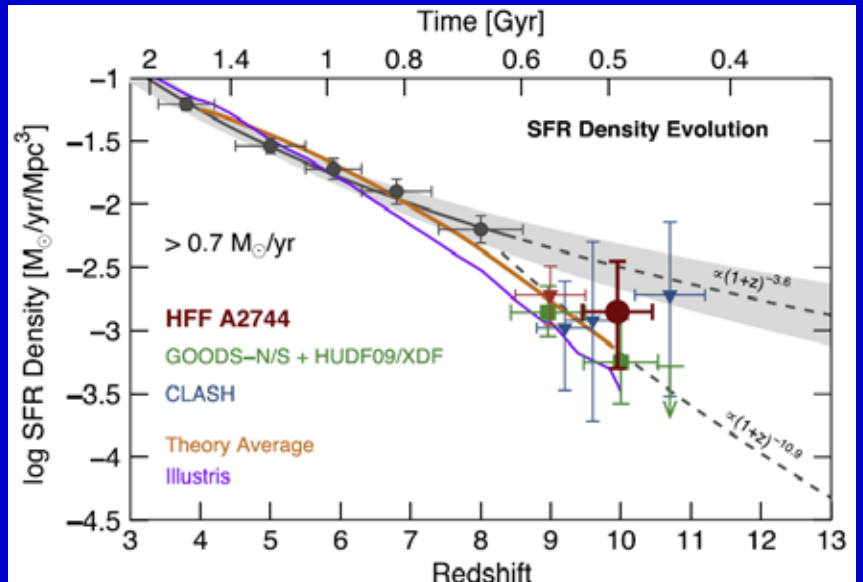
原始銀河の光度関数と宇宙再電離

Ishigaki et al, 2015, ApJ, 799,12



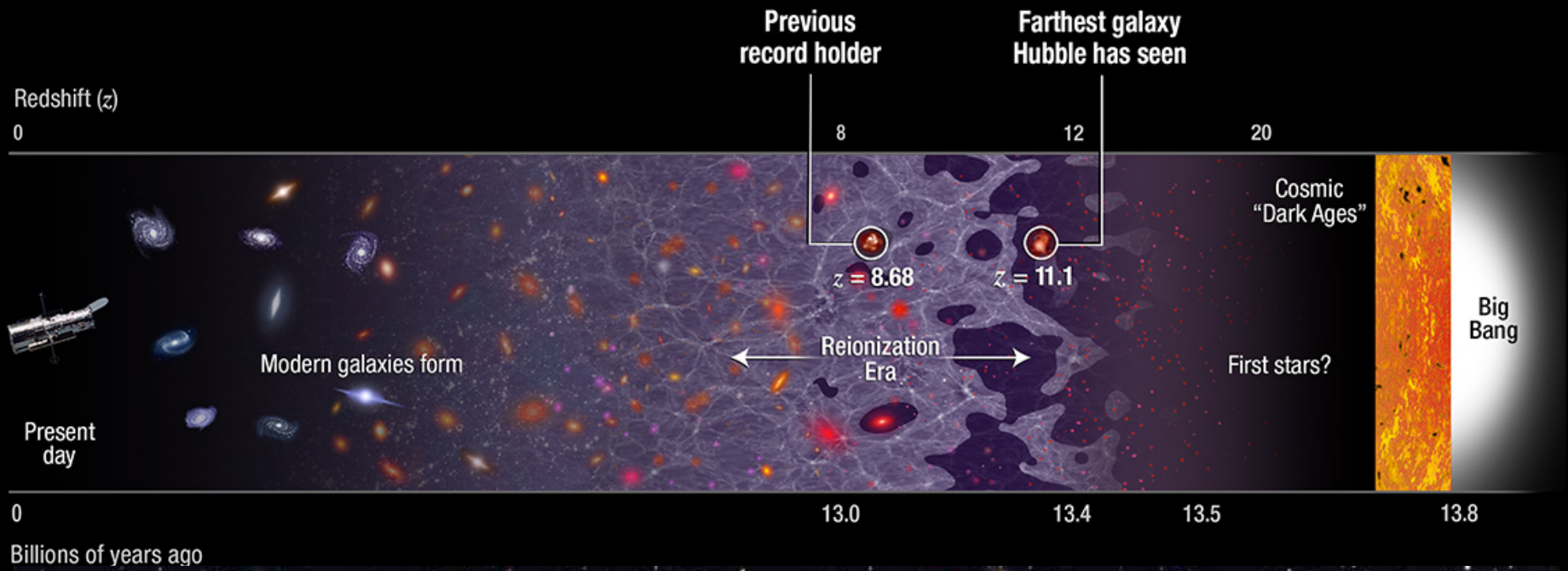
Cosmic Star Formation Rate Density at z〜10

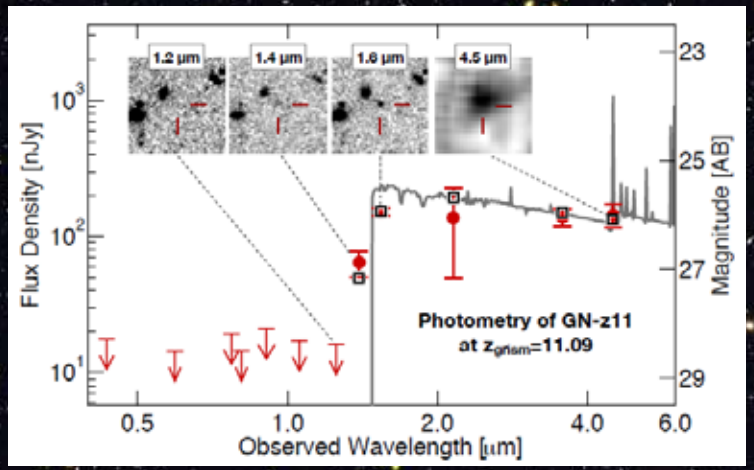
Oesch et al. 2015, ApJ, 808,104



z=11.1銀河の発見

Oesch et al. 2016, arXiv:1603.00461





巨大ブラックホールの起源

超巨大ブラックホール起源：7つの疑問

2020年代を見据えて

Q1：初代ブラックホールは星質量（数～10M$_\odot$）だったのか大質量（数万～数10万M$_\odot$）だったのか

Q2：Building block はどこにあるのか（宇宙論的SMBH形成）

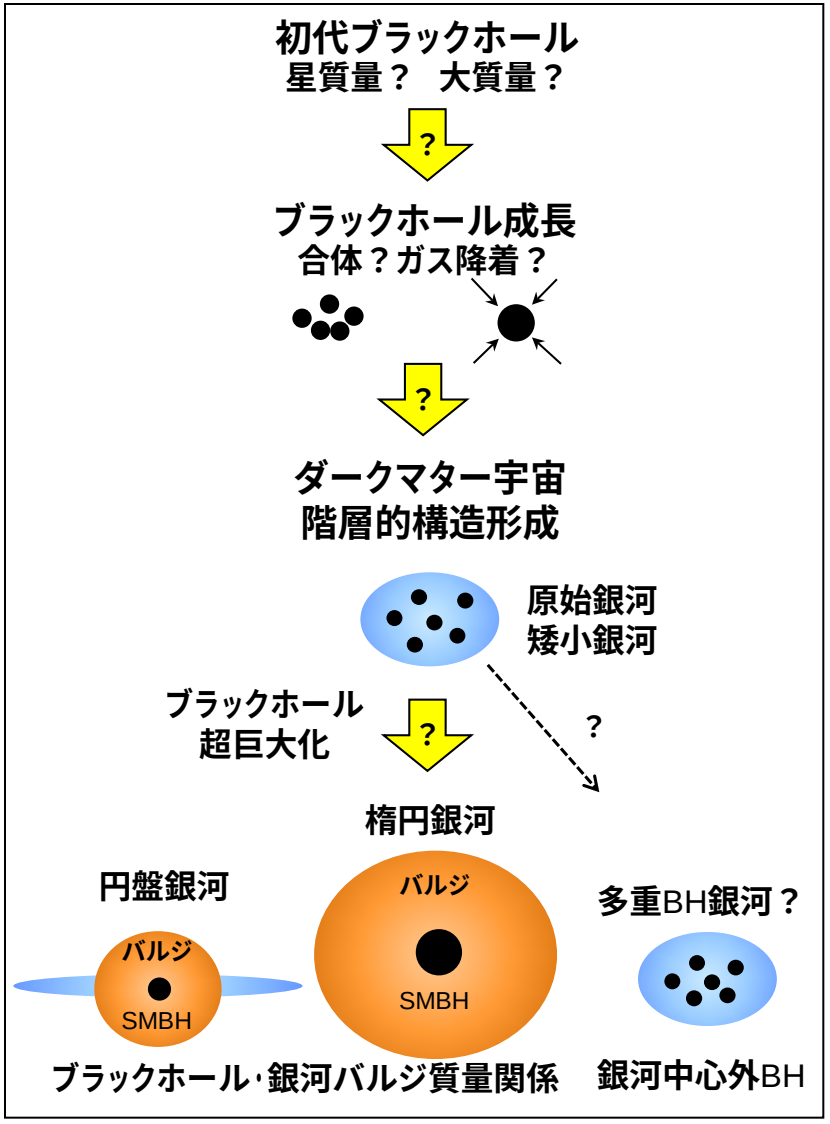
Q3：SMBHは質量降着で成長したのか合体で成長したのか

Q4：SMBHはなぜ銀河バルジ質量の1000分の1になっているのか

Q5：SMBHは銀河中心にしかできないのか

Q6：SMBHの"ダウンサイジング"は何を意味しているのか

Q7：矮小楕円銀河にはなぜSMBHはないのか

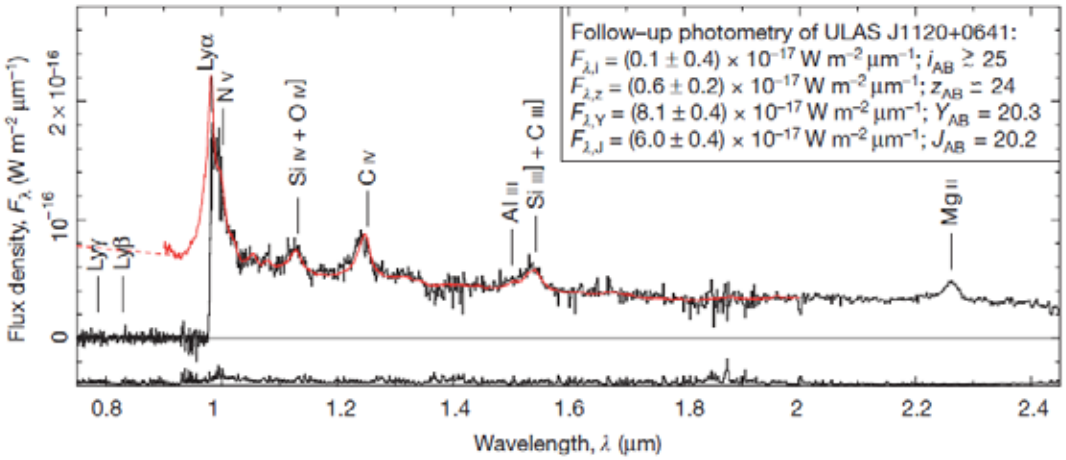


z=7.085 QSO

Mortlock et al. 2011, nature, 474, 616

$L = 6.3' 10^{13} L_{\odot}$, $M_{BH} = 2' 10^{9} M_{\odot}$

Eddigton Ratio $n_E = 1.2$ (Super-Eddigton Accretion)



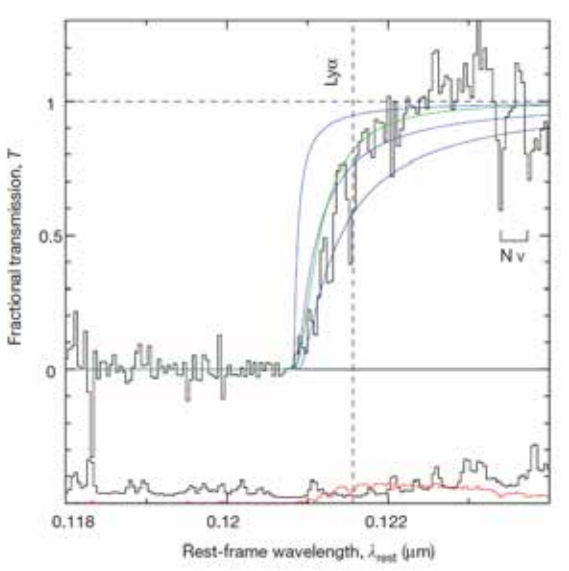


Figure 4 | Rest-frame transmission profile of ULAS J1120+0641 in the region of the Lyα emission line, compared to several damping profiles. The transmission profile of ULAS J1120+0641, obtained by dividing the spectrum by the SDSS composite shown in Fig. 1, is shown in black. The random error spectrum is plotted below the data, also in black. The positive residuals near 0.1230 μm in the transmission profile suggest that the Lyα emission line of ULAS J1120+0641 is actually stronger than average, in which case the absorption would be greater than illustrated. The dispersion in the Lyα equivalent width at a fixed C IV equivalent width of 13% quantifies the uncertainty in the Lyα strength; this systematic uncertainty in the transmission profile is shown in red. The blue curves show the Lyα damping wing of the intergalactic medium for neutral fractions of (from top to bottom) $f_{H\,I} = 0.1$, $f_{H\,I} = 0.5$ and $f_{H\,I} = 1.0$, assuming a sharp ionization front 2.2 Mpc in front of the quasar. The green curve shows the absorption profile of a damped Lyα absorber of column density $N_{H\,I} = 4 \times 10^{20}$ cm^{-2} located 2.6 Mpc in front of the quasar. These curves assume that the ionized zone itself is completely transparent; a more realistic model of the H I distribution around the quasar might be sufficient to discriminate between these two models[25,27]. The wavelength of the Lyα transition is shown as a dashed line; also marked is the N V doublet of the associated absorber referred to in the text.

z=6.30 QSO

Xue-BingWu et al. 2015, nature, 518, 512

$$L=4.29\acute{}\ 10^{14}L_{\odot}\ ,\ M_{\rm BH}=1.2\acute{}\ 10^{10}M_{\odot}$$

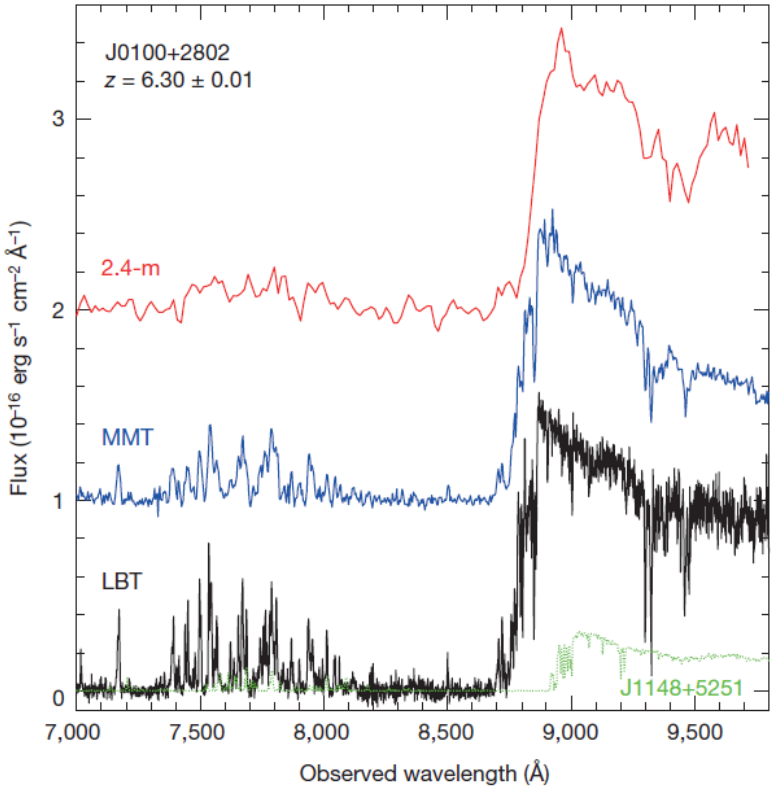


Figure 1 | The optical spectra of J0100+2802. From top to bottom, spectra taken with the Lijiang 2.4-m telescope, the MMT and the LBT (in red, blue and black colours), respectively. For clarity, two spectra are offset upward by one and two vertical units. Although the spectral resolution varies from very low to medium, in all spectra the Lyα emission line, with a rest-frame wavelength of 1,216 Å, is redshifted to around 8,900 Å, giving a redshift of 6.30. J0100+2802 is a weak-line quasar with continuum luminosity about four times higher than that of SDSS J1148+5251 (in green on the same flux scale)[1], which was previously the most luminous high-redshift quasar known at $z = 6.42$.

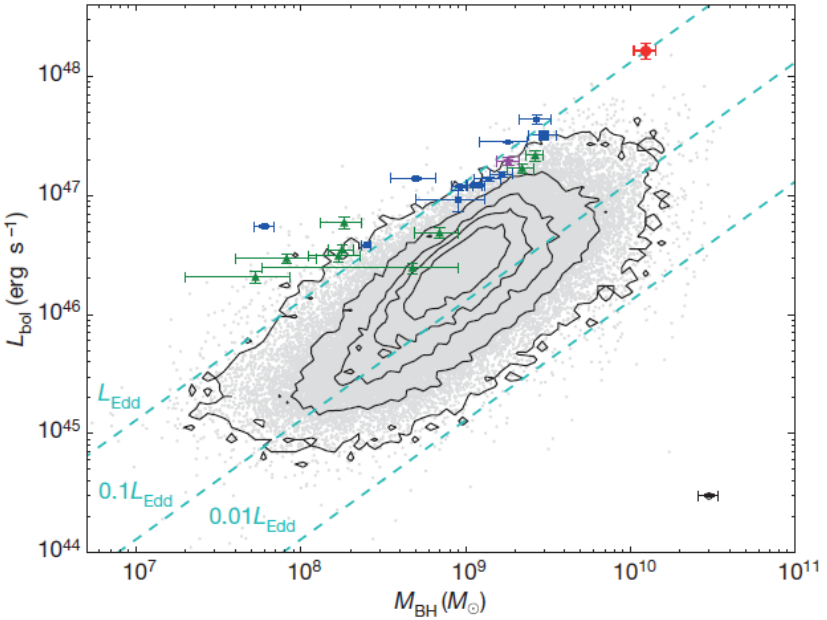


Figure 4 | Distribution of quasar bolometric luminosities, $L_{\rm bol}$, and black-hole masses, $M_{\rm BH}$, estimated from the Mg II lines. The red circle at top right represents J0100+2802. The small blue squares denote SDSS high-redshift quasars[2,10,12], and the large blue square represents J1148+5251. The green triangles denote CFHQS high-redshift quasars[11,12]. The purple star denotes ULAS J1120+0641 at $z = 7.085$ (ref. 6). Black contours (which indicate 1σ to 5σ significance from inner to outer) and grey dots denote SDSS low-redshift quasars[21] (with broad absorption line quasars excluded). Error bars represent the 1σ standard deviation, and the mean error bar for low-redshift quasars is presented in the bottom-right corner. The dashed lines denote the luminosity in different fractions of the Eddington luminosity, $L_{\rm Edd}$. Note that the black-hole mass and bolometric luminosity are calculated using the same method and the same cosmology model as in the present Letter, and the systematic uncertainties (not included in the error bars) of virial black-hole masses could be up to a factor of three[27].

Eddington Growth of z=7.085 QSO SMBH

$$M_{BH}(t) = M_0 \exp\left(\frac{\eta_E}{t_E}\, t\right), \quad t_E \equiv \frac{M}{\dot{M}_E} = 4.5 \times 10^7 \left(\frac{\eta}{0.1}\right) \mathrm{yr}$$

$$z_{PopIII} = 20 \; (t = 1.83 \times 10^8 \mathrm{yr}), \; M_0 = 30 M_e$$

$$z_{QSO} = 7.085 \; (t = 7.83 \times 10^8 \mathrm{yr}), \; M_{BH} = 2 \times 10^9 M_e$$

Eddington ratio $\eta_E = 1.4$

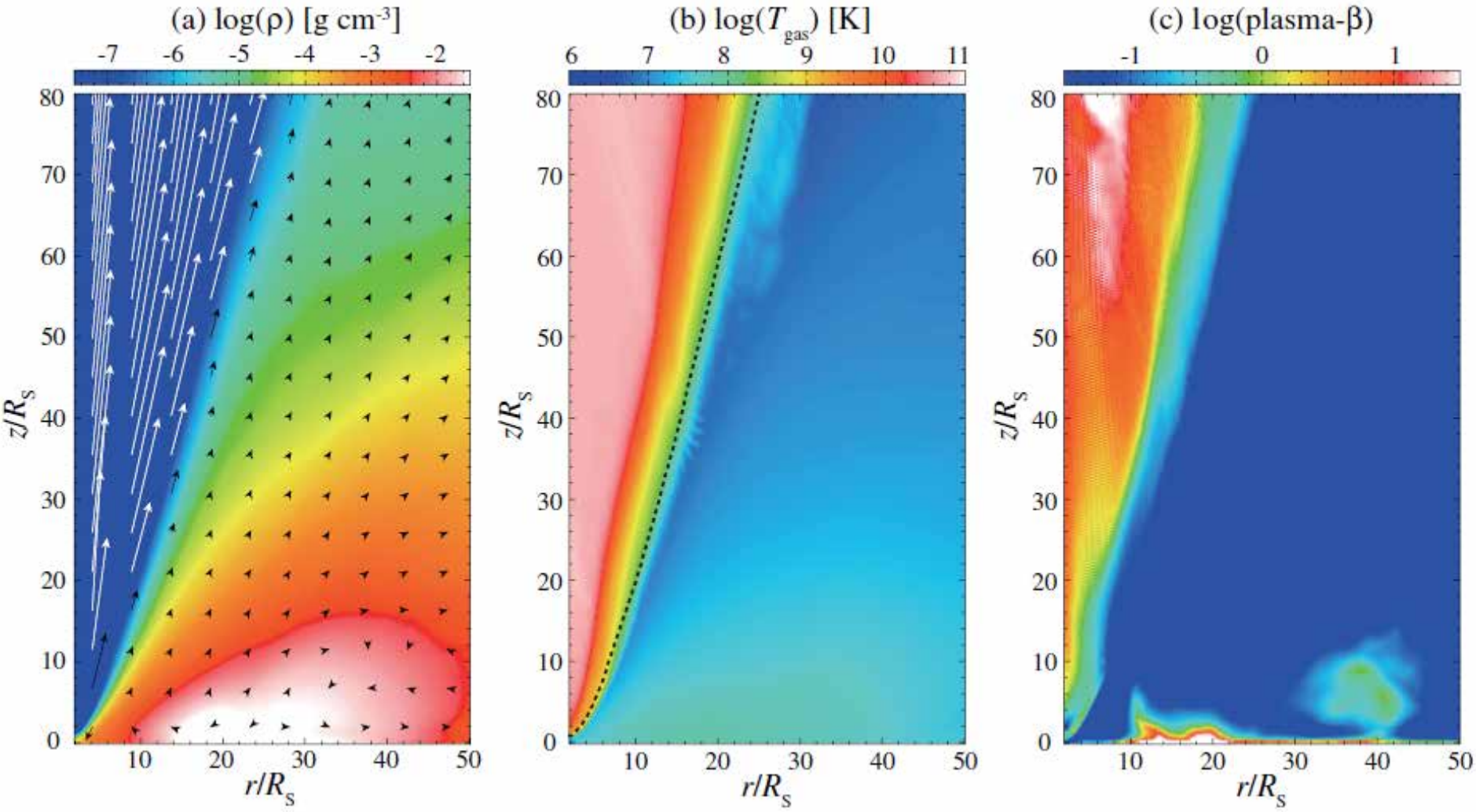
Eddington Growth of z=6.30 QSO SMBH

Eddington ratio $\eta_E = 1.3$

Super-Eddington Acccretion & UFO (Ultra-Fast Ourflow)

Ohsuga & Mineshige 2011, ApJ, 736, 2

2D Radiation Magneto-hydrodynamical simulation

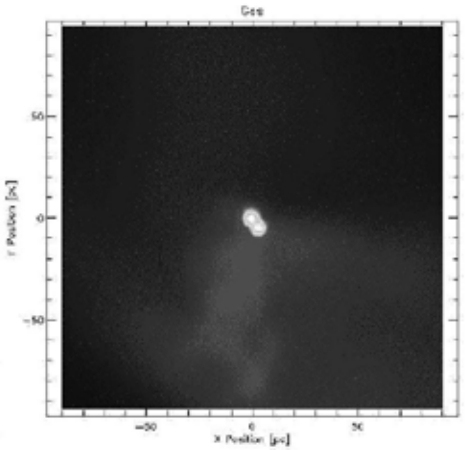


Direct Collapse to Massive Black Holes
超大質量星形成

Suppression of H2 cooling by UV background

Bromm & Loeb 2003, ApJ, 596, 34

$5' 10^6 M_\odot$ MBH binary



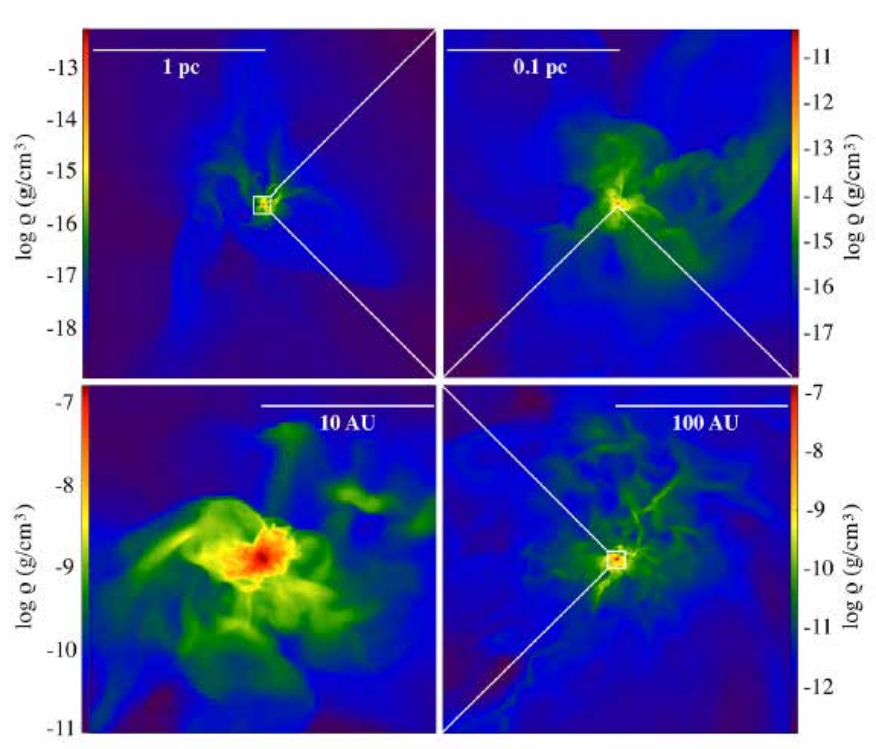
Cold Accretion Shock model

Inayoshi & Omukai 2012, MNRAS, 422, 2539

Warm cloud collapse model

Inayoshi, Omukai, Tasker 2014, MNRASL **445,** L109

$>10^5 M_\odot$ MBH



GW150914 の7つの意義

重力波（GW150914）初検出!!!

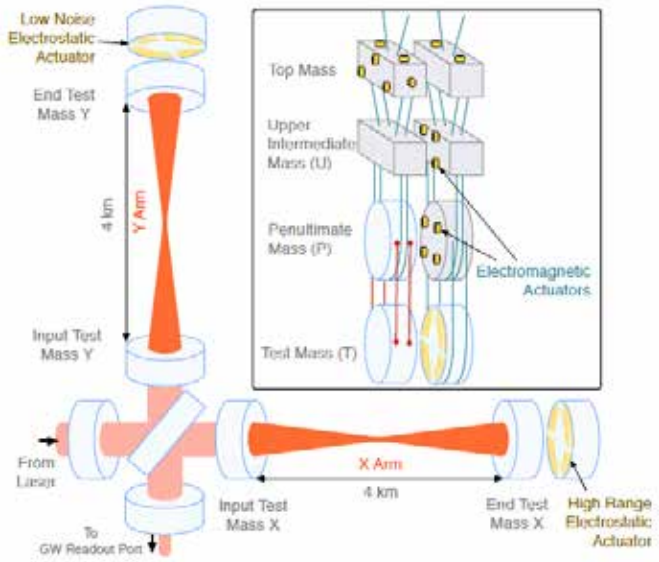
Advanced LIGO, Sep 14, 2015, 09:50:45 UTC
(Abbott et al. 2016a, b, c, d, e, f, g, h, i)
36M$_\odot$, 29M$_\odot$ブラックホールの合体（z＝0.09）

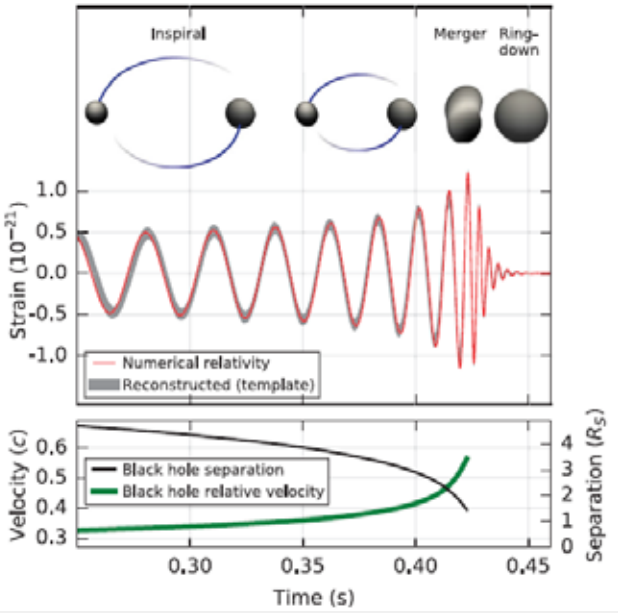
Pop III の可能性

7つの意義

① 一般相対論の強い重力場の初検証
② ブラックホールの地平線の初確認
③ 重い星質量ブラックホール（～30M$_\odot$）の初確認
④ バイナリー・ブラックホールの初確認
⑤ ブラックホール合体の初確認
⑥ ブラックホール合体が重力波で起こることを初確認
⑦ ブラックホール成長における合体の重要性

Quadruple suspension system



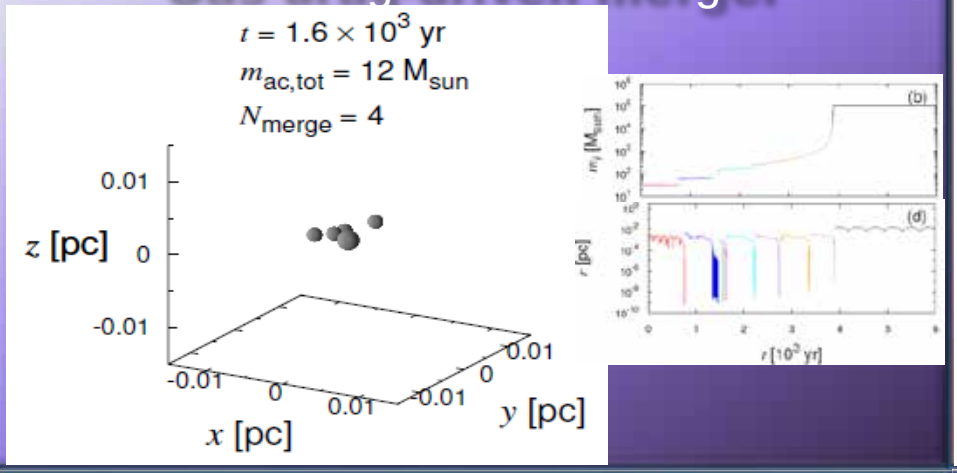


Mergers of 30 $M_\odot$ Black Holes

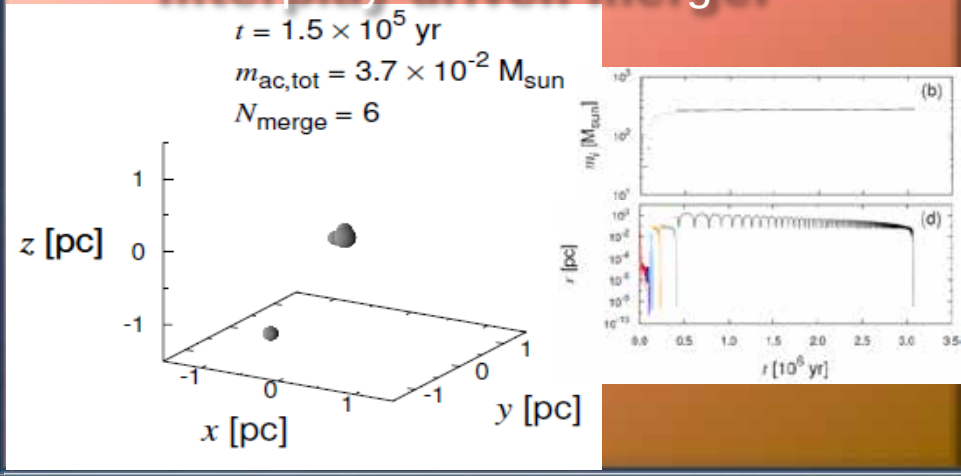
(Tagawa, Umemura, et al. 2015, MNRAS 451, 2174; 2016 arXiv:1602.08767)

Post-Newtonian N-body Simulations (2.5PN=GW)

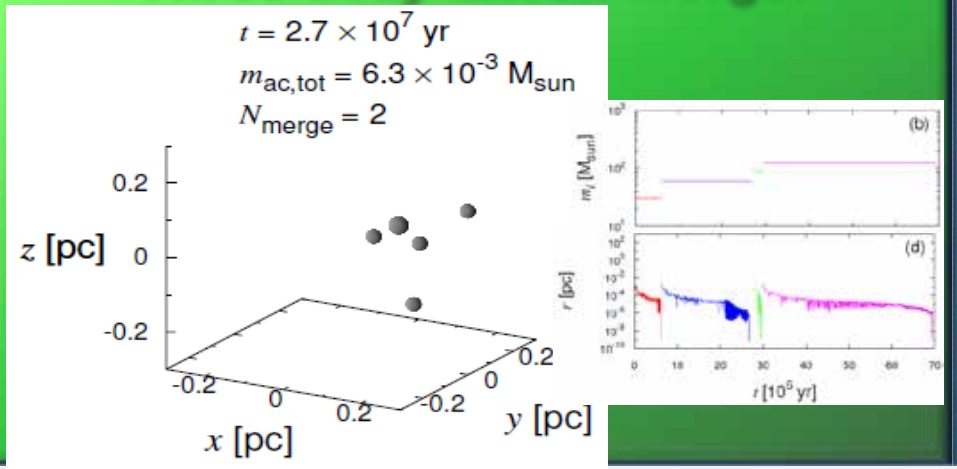
Type A
Gas drag-driven merger



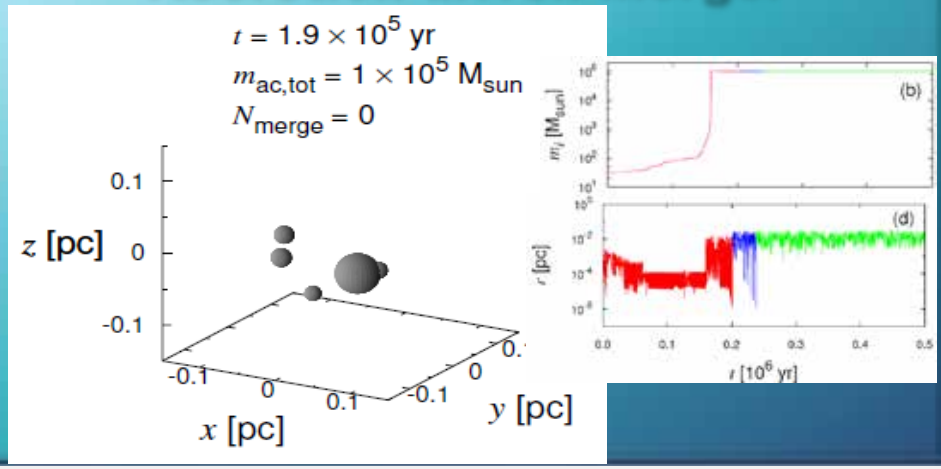
Type B
Interplay-driven merger



Type C
Three body-driven merger



Type D
Accretion-driven merger



30M⊙ブラックホールの合体
(Tagawa, Umemura, et al. 2015, 2016)

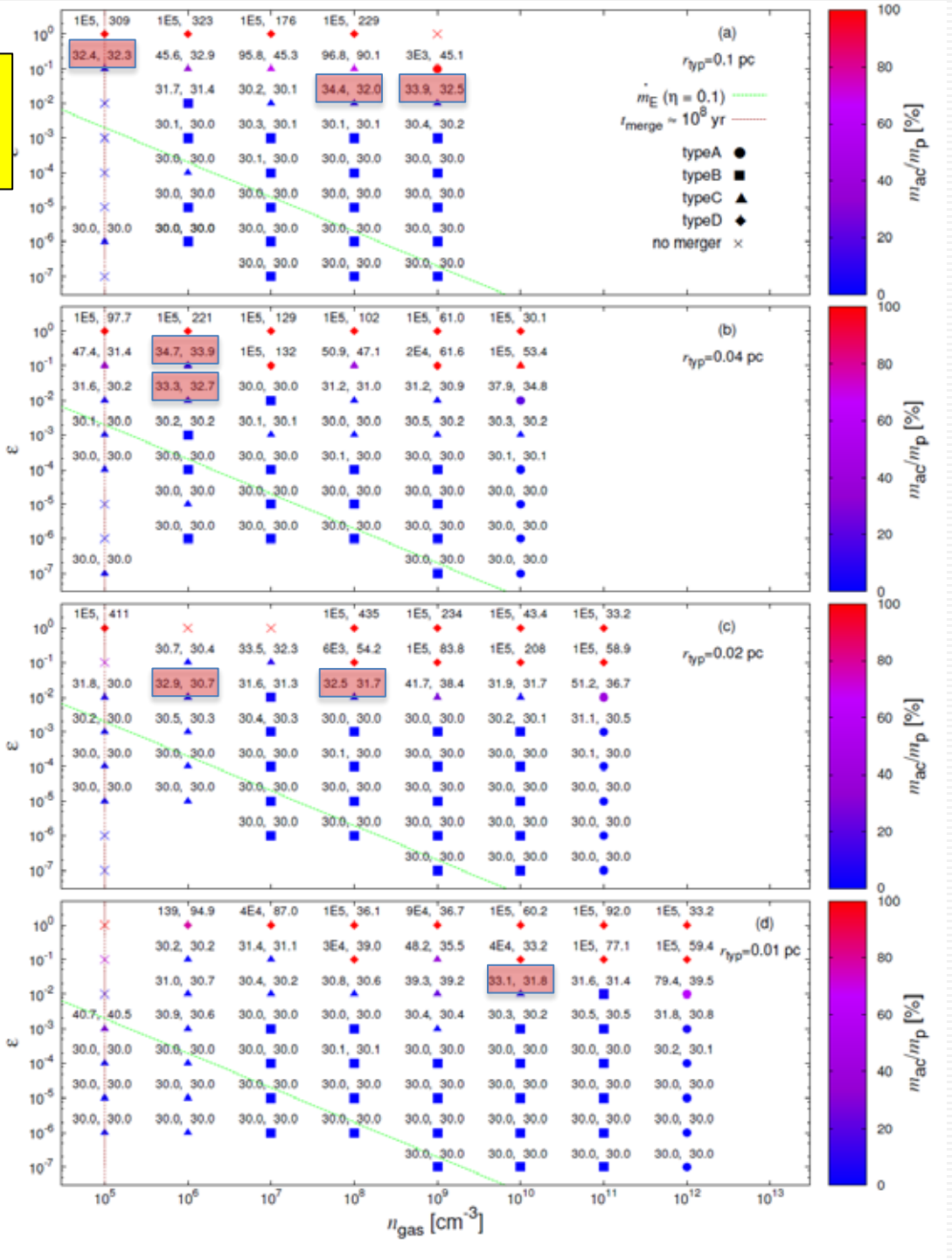
Post-Newtonian N体計算
2.5PN=GW

重力波(GW150914)検出

Advanced LIGO (Abbott et al. 2016)

$m_1 = 36^{+5}_{-4} M_\odot$　$m_2 = 29^{+4}_{-4} M_\odot$

- GW150914のブラックホール質量に合うのは，全て3体相互作用による合体
- 降着質量は，数M⊙の寄与がある



Counterpart in Hard X-Ray

Fermi GBM Observations of LIGO Gravitational Wave event GW150914

(Connaughton et al. 2016)

Ø GW150914 **の**0.4s**後に** >50 keV **で** weak transient source (a false alarm probability of 0.0022)

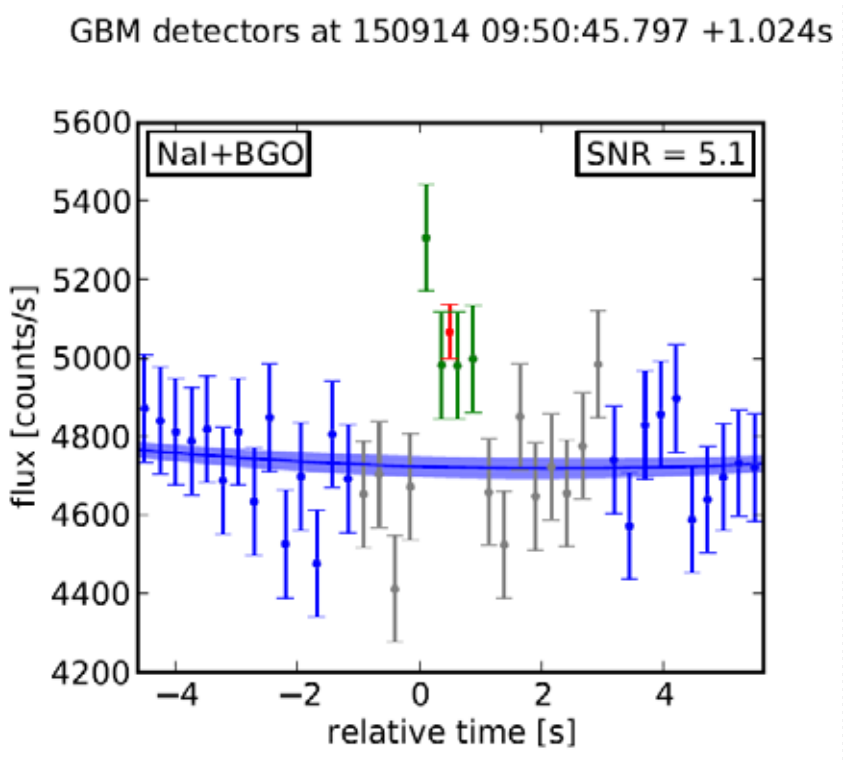
Ø Luminosity between 1 keV and 10 MeV = 1.8×10^{49} erg s^{-1}

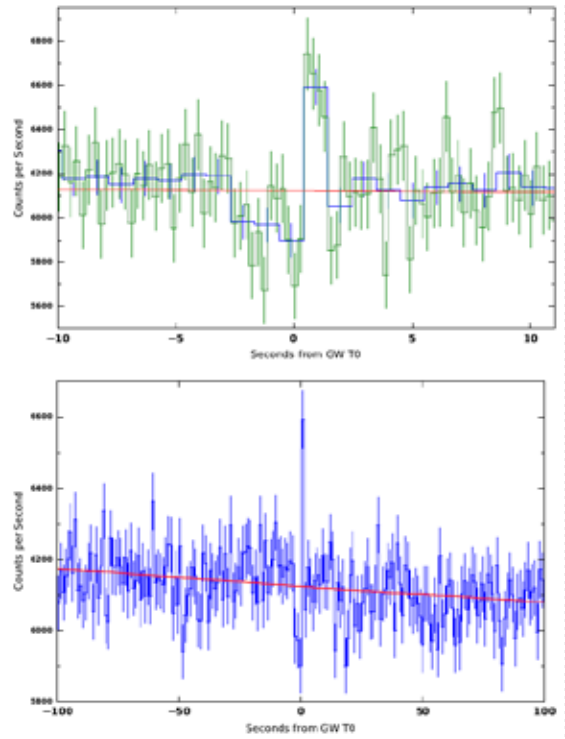
Ø **方向ははっきり決まらないが,** GW150914**とは矛盾しない**

Ø **他の** astrophysical, solar, terrestrial, or magnetospheric activity **とは相関せず。**

Ø **weak short Gamma-Ray Burst を示唆**

Ø **これまで,** stellar mass black hole binary merger **から予想されていたわけではない。**





TAOへの期待
(SWIMS)

- **First Stars**
  - High-z GRB, SLSNeからIMFへの制限
- **First Galaxies**
  - 初期進化史
  - HeII Ba a Emitter の観測
  - z>8 再電離期の銀河光度関数の決定
- **First Massive BHs**
  - 初期成長過程の解明
  - (超臨界降着かBH合体成長か)