初代星形成シミュレーションの 最近の進展 (2021年以降くらい)

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Astro Theory Group

DIntroduction

OVerall picture of Pop III formation

 \blacksquare Recent topics (2021-)

DConclusions

INTRODUCTION

The first stars: starting point of the formation history of astronomical object

(First star = Pop III star)

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- The properties of the first stars determines the future of the Universe \leftarrow supernovae, stellar radiation, seeding BHs, etc.
- Also, their properties is getting more reachable by observations

← direct obs., binary BH mergers, low-mass survivors, PISNe, GRBs, etc. →衣川さんトーク

Uniqueness of the first stars: possible target for first-principle understanding

Both initial condition and evolution equations are well established

that reduces the comp. cost without sacrificing realism) 5 All we need is comp. power (and/or smart modelling

Big goal of first star studies

Determining the properties of the first stars from the first principle

mass, spin, magnetization, multiplicity, number of stars, mass-ratio, orbital separation, eccentricity, etc.

Note: these properties are not unique due to birth-site individualities and chaotic nature of star formation

- parent halo's mass, size, shape, formation history
- background field (FUV, EUV, X-ray, CR)
- turbulence, fragmentation, 3-body interactions

Pop III mass is of particular interest

Wise+12 based on Heger&Woosley02, Nomoto+06

Pop III mass determines the strength of the feedback (while there is a room for improving the Pop III SN model)

OVERALL PICTURE Simulations from big bang to completion of first star formation

Pop III formation in simulations 1: From Big Bang to first protostar

\Box Cosmological hydro simulations

- Naoki Yoshida,¹ * Kazuyuki Omukai,2 Lars Hernquist³ • starting from cosmological initial condition
- elevant chemical & ther • DM+gas simulation w/ all relevant chemical & thermal processes
- ar forms at $_{\text{sun}}$ (= miniha the center c o) at $10 \lesssim$: \cdot tiny (\sim 0.01 Msun) protostar forms at the center of small DM halo with $\mathsf{M}_\mathsf{DM} \boldsymbol{\sim} 10^{5-10^6}\ \mathsf{M}_\mathsf{sun}$ (= minihalo) at $10\lesssim z\lesssim 30$

Yoshida, Omukai, Hernquist 2008 (Science)

A movie for the birth of first protostar

Hirano et al. (2014) movie credit: Takeda https://youtu.be/2COt_OTAENg

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Pressure 2.1 Formation in simulations 2.1 From first protostar to first star set by the action of gravity and hydrodynamic **cosmological halo star−forming cloud A B** on April 11, 2015
D www.ciencemag.org
...

D Zoom-in radiation hydro simulations

Hosokawa, Omukai, Yoshida, Yorke 2011 (Science) l
C

 \sim 0110 cm \sim 0110 cm \sim 0110 cm \sim of kiloparsecs in length (~1023 cm). The smallest length scale—the so-called local Jeans length,

 $\overline{}$ as galaxies and quasars (1, 2) that were in place when the universe was less than 1 billion years old, or about 5% of its current age. Moreover, these studies have shown that other luminous objects must have been present even earlier. For example, the most distant known quasar, SDSS-J4010, contains substantial amounts of heavy elements such as carbon, oxygen, and iron as well as dust grains (3). The set of \mathcal{S} are not of cosmic origin, but must have been formed earlier in massive stars before being expelled by supernovae and stellar winds, and then incorporated into the material that later condensed

- *To whom correspondence should be addressed. E-mail: • tiny protostar grows to massive star $($ > 10M_{sun} $)$ by accreting surrounding gas
	- gas accretion is quenched by stellar radiation feedback
	- final mass of star is \sim 40 M_{sun} in this case

(see McKee&Tan 2008 for analytical argument)

Pressure 20 Fould Foully 1999 III formation in simulations 3: Formation as binary/multiple stars set by the action of gravity and hydrodynamic **cosmological halo star−forming cloud A B** on April 11, 2015
D www.
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D Zoom-in radiation hydro simulations with 3D AMR Downloaded from KS, Matsumoto, Hosokawa, Omukai, Hirano (2020,2023)

 \sim 0110 cm \sim 0110 cm \sim 0110 cm \sim of kiloparsecs in length (~1023 cm). The smallest length scale—the so-called local Jeans length,

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- *To whom correspondence should be addressed. E-mail: • 2D simulations in Hosokawa+ (2012) cannot deal with binary/multiple systems
	- 3D simulations existed but with some problems
		- \checkmark SPH (Stacy+12,16, Susa+14) \leftarrow hard to follow EUV feedback (Susa13)
		- spherical-grid (Hosokawa+16) \leftarrow low off-center res., central-star FB only
	- 3D AMR simulations have found that the first stars form as massive binaries/multiples (KS+20,23)

simulation set-up

- code: SFUMATO-RT (Matsumoto07, KS+20)
- $r \approx 64$ and the Jeans length is equal to a half the Jeans length for ~ 1 • $n_{sink} = 10^{11}$ cm⁻³, $\Delta x_{min} = 4$ au, $r_{sink} = 64$ au $\frac{1}{2}$
- 2 rsink. • minimum # of cells/Jeans length : 16
- ϵ + $=10^5$ is evolution contactor formation • $t_{end} = 10^5$ yr since protostar formation

The RT of the direct photons from each protostar is solved A system of wide massive multiple stars

t: time after 1st sink formation) (t: time after 1st sink formation) protostar formation, which happens 14

Figure 5. The local FUV intensity field, *^J*21, in the same comoving cosmological volume with (3 *^h*−¹ Mpc)³ at *^z* ⁼ 25, 20, 19.5, 19, and 15. The colour from single case to statistics Pop III formation in simulations 4:

- stars have relatively large masses, clustering around [≃]400 M⊙. We discuss the redshift-dependence of the mass distribution in Sec- \leftrightarrow Milky-Way ordinary stars (\sim 1M_{sun})
- This Pop III IMF is based on 2D simulations

final time in simulations!

respectively. The local FUV radiation field decreases with decreasing redshifts (from left- to right-hand panels), because the typical stellar mass becomes lower

 \leftarrow confirmation of this conjecture with large sample is future work $\left\vert \cdot\right\vert ^{16}$ We study the physical properties of the 1540 primordial star-forming

is calculated for the radius *R*enc, whose enclosed mass is equal

recent progress and open questions

RECENT TOPICS (2021-)

(orange reference: publication since 2021)

2021年以降の論文に関して見落としがあったら教えてください!

最近の初代星レビュー論文: Klessen & Glover (2023)

Tegmark+97, Schauer+21, Kulkarni+21, Correa Magnus+23, Lenoble+23 Halo 7/8 ²⁸⁹ 1.8 [×] ¹⁰⁶ Yes ⁰ ¹ (N) 314 *L. Correa Magnus et al.* $H_{\rm eff}$ 312 μ 312 μ 9 μ

- **FIGURE 1.** Mass Group of the beginning of the simulation \mathbf{F} $\binom{10}{2}$ $\mu = 1 M_{sun}$) • Enzo, 高解像度計算 (M_{DM}=1M_{sun})
- the moment of moment \sim 1000 \pm $\overline{}$ diase shows the forms that forms the forms that $\overline{}$ HALO 12 The red stars in the red stars in the time of the time $\overline{1}$ algorithm places Halo 3 before the cores have settled as can be observed when comparing \sim \mathcal{W} is the subhalo subhalo within HD is also not finished by \mathcal{W} algorithm places Halo 3 before the cores have settled as can before the comparing particle and density slices. • 一つのミニハロ一中で複数の初代星形成領域(3ハロー/12ハロー)

shock heating that would occur from gaseous collisions. This unique

shock heating that would occur from gaseous collisions. This unique

 h the simulation λ

 \mathcal{S}

it merges in the halo 谷のガス雪の雷力収縮に $\sum_{i=1}^n$ in $\sum_{i=1}^n$ is labelled as 12∗. The two mixed two mixed values of the two mixed values of the two mixed values of the two mixed values of two mixed values of two mixed values of two mixed values of two mixe $\frac{1}{2}$ matrix in the simulation are matrix i Overplotted in <u>1915 of the fits of are fits of a</u>re fits of and the fits of and the background radiation radiation χ II and π the μ radiation of \pm \pm ・木汁の住胖か里女 $\sum_{i=1}^n |i+i| \leq \frac{1}{n}$ attributed to the large amount of the blastwave of the blastwave of the blastwave of the blastwave). The blast MAI CHRIGHT IN GLATIN だいだい \mathbf{H} and \mathbf{H} rises with cooling from metals \mathbf{H} end of the merger. Within its dense the star particle with α 4言 †告 • 2~4生 /八 +申 仲纪 ナ ▶ 大小 大 | 下 Vノ ナ土 ガキ ん gas temperatures may seem surprising since the merger with Halo 2 is still ongoing, the evacuated state of Δ $\overline{\mathcal{L}}$ if side. The dynamics of this interaction are quite interesting since the merging halo brings with it a significant amount of gas asthe merging α halo is at the star formation star formation star formation star for \mathcal{F}_1 the subhalo taking roughly $\mathcal{A}^{\mathcal{A}}$ and $\mathcal{A}^{\mathcal{A}}$ and $\mathcal{A}^{\mathcal{A}}$ and $\mathcal{A}^{\mathcal{A}}$ and $\mathcal{A}^{\mathcal{A}}$ $H. \mathsf{k}$. The overall time-scale of the merger is uncertainty since attributed to the large amount of the blastwave Γ is the blastwave). The blastwave Γ is the blastwave of turbulence caused by the blastwave of turbulence caused by the blastwave of turbulence caused by the blastwave H maior merger かって空 • SN後のガス雲の重力収縮にmajor mergerが影響 end of the merger. Within its densest cell (where the star particle will = 芒:火 //+ ⁄∩ ↓️ titl 4 ·⁄k <u> スリア ポリオン・エット アルジェット スピア アルブル はいしゃ スピア しゅうしゅ</u> gas temperatures may seem surprising since the merger with Halo 2 is still ongoing, the evacuated state of Δ \sim \times minimizes the evacuated state of \sim side. The dynamics of this interaction are quite interesting since the merging halo brings with it a significant amount of gas asthe merging 初代星の多様な形成環境・条件の理解が重要 the subhalo taking roughly 10 → 石山さんトーク しゅうしょう

Turk+12

Truelove条件 NJ =4 は重力 収縮を記述するのに全然不十分

Higashi+21, 22

- \uparrow \uparrow • 落下するガスの運動エネルギーをソース ₅ に重力収縮中に乱流が増幅・飽和
- 結果の収束には N_J>256 (cf. N_J>32 in $\mathbb{E}\left\{\begin{array}{rcl} \mathbb{E}\left\{\begin{array}{rcl} \mathbb{E}\left\{\begin{array}{rcl} \mathbb{E}\left\{\mathbb{E}\left\{\mathbb{E}\left\{\mathbb{E}\left\{\mathbb{E}\left\{\mathbb{E}\left\{\mathbb{E}\left\{\mathbb{E}\left\{\mathbb{E}\left\{\mathbb{E}\left\{\mathbb{E}\left\{\mathbb{E}\left\{\mathbb{E}\left\{\mathbb{E}\left\{\mathbb{E}\left\{\mathbb{E}\left\{\mathbb{E}\left\{\$ Federrath+11) が必要そう

 τ 大抵の場合、重力収縮中のガスはいます。 a_p
approximately consistent with the final densities power and the final densities of Federrath and al. 2005 超音速乱流状態にあると考えられる レンス

Figure 14. Evolution of the turbulent velocity as a function of mean density in models RM32–RM512 for γeff = 1.09. The different colors correspond to different

原始星形成直後の進化 $\mathcal{R} \mathcal{F}$ #2 hV IEI \mathcal{R} (/) 推 \mathcal{F} discs. The *Q* parameter determines whether perturbations in an where $\mathcal{L}_{\mathcal{A}}$ is the disc, the disc, " the disc, " the surface density density density density density density and \mathbf{r} the special speed of the speed of the gas. We replace the epicopality frequency \mathbf{r} ̄ ̄ 1日 까슴 足 #2 HV I自 /分 (/ discs. The *Q* parameter determines whether perturbations in an \sim the epicyclic frequency of the disc, \sim the surface density of the surface d Δ - Δt can be so the gas. We replace the epicone the epicone the epicone speed of the epi \boldsymbol{y} iei $\boldsymbol{y} \in \boldsymbol{H}$, which is appropriate for \boldsymbol{y} discs. The *Q* parameter determines whether perturbations in an

Figure 5. Density projections in a cube of side length 10 au that show the evolution of the protostellar system. Each row corresponds to a different minihalo. also result in different runtimes. The density squared along the density squared along the line of sight, which lies perpendicular to the line of sight, which lies perpendicular to the line of sight, which lies perpendicu 0mukai&Nishi98, Yoshida+08, Greif+12, Luo+18, Kimura+23 12 14 16 18 $s = 1$ secondary protostars that merge with the primary protostar, and of p

 \sim scale of the accretion radius, and instead the mass is accreted on \sim Side Length. To AO C_{ideal} aneth: 10.11 \mathbf{M} and \mathbf{M} \mathbf{H} of the secondary protothe scale of the accretion radius, and instead the mass is accreted on to the single particles. The single particles in the *Q particles.* The *Q particles in the Si*ngle at the *Q particle at the Single at 2* particles. The *Q particle at the Single at 2* particles. The *Q particle at the Si* \mathbf{E} and \mathbf{E} and \mathbf{E} is reflected by \mathbf{E} radii \mathbf{E} reflecting, which is reflected by \mathbf{E} $t_{\rm eff}$ of the accreted on α is accreted on α to the sink particles. The *Q* parameter therefore does not diverge at $s₁$ radii, but decreases to well below unity, which is reflected by $s₁$

not surprising, since these studies typically do not resolve the gas on

*^t*grav ⁼ [|]*l*[|]

Note that positive values indicate that the angular momentum per unit mass is increasing, while negative values indicate that it is decreasing. Finally, numerical torques are expected to be signifi-

not surprising, since these studies typically do not resolve the gas on

 $\mathbf{I}_{\rm eff}$

survive. Red diamonds denote a positive value, and blue crosses denote a negative value. For better visibility, we have smoothed the lines in the bottom two panels over a small period of time.

 A number of important conclusions \mathbb{R}^n ure. First, the time-scales for gravitational torques to operate are smaller than those for pressure gradients, showing that the former are more important. Secondly, the predominance of negative values in the bottom left-hand panels shows that gravitational torques typically lead to a decrease of the angular momentum of the protostars, while the opposite is the case for the torques exerted by pressure gradients. Finally, the time-scales for gravitational torques to operate are generally close to the survival time, showing that gravitational torques are indeed responsible for the migration of the protostars to the centre of the cloud. A closer look at the evolution of individual protostars also shows that the dips and peaks in the timescale profiles correlate well with those in the distance and angular momentum. For example, the solid line in MH2 shows a clear peak in the distance and angular momentum at about *t*/*t*surv = 0.5, which is accompanied by a momentary increase of *t*grav to positive values. In a second example, the distance and angular momentum of the protostar denoted by the dotted line in MH3 continuously decline, which is reflected by an extended period of negative gravitational torques. Although not entirely apparent from the bottom panels, due to the smoothing applied to the profiles, the torques acting on the

 \mathbb{R}^n secondary protostars in each halo, which in addition survive until the end of the simulation (note that in MH1 only one secondary protostar survives). In this case, and in contrast to Fig. 11, gravitational

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protostars are also highly variable in time.

not surprising, since these studies typically do not resolve the gas on

Greif+12

- AREPO (moving mesh), $\Delta x \sim 10^{-4}$ au
- 32cpu x 3month? (意外と計算軽い?)
- 原始星を解像した計算
- 原始星形成後10yrまでのみ
- ガス雲の分裂と合体
- 拡散光は単純化して記述

→ガスの温度構造の不定性

• この方向の研究は10年ほどあまり進まず

✔ 光学的厚みが非常に大きな領域を計

算するための工夫

Kimura+23

超大質量星形成に対応した設定(高い

- 原始星と降着円盤の境界は不明瞭
- 成長途上の原始星からどのような輻射 が出てフィードバックするか?

星の内部まで考慮した輻射流体計算

Turbulent : Face-on

Turbulent : Edge-on

 -10^{17}

 $\begin{bmatrix} 7 \\ -10^{15} & \frac{5}{15} \end{bmatrix}$

 10^{13}

 10^{5}

 $10⁴$

 $\left[\mathrm{X}\right]$

 $[L_{\odot}]$

 $4\pi r^2 F_r$ 10^{5}

3. Results

• SFUMATO-RT + new M1 RT module

原始星内部の拡散光の輻射輸送

- 実際の化学・熱進化を再現
- 降着率、Mdot〜1M_{sun}/yr)

 -10^{4}

wachida+08, Clark+11, Susa19, Prole+22, Riaz+23, Kirihara+24, Park+24, Saavedra-Bastidas+24 **vartut**

Susa19

- シミュレーションに基づ分裂と合体 の解析的モデル Nfrag $\propto t^{0.3}$
- 周星円盤の分裂と分裂片同士の 合体をモデル化

様々な状態方程式を仮定した計算 によると、分裂の仕方は状態方程式 に依って大きく変わりそう $\leftarrow \gamma$ eff大きいと分裂しにくい

 $P = K \rho$ reff

Hosokawa et al. (2016) cut cooling 1010–10¹² cm−³ Cosmological,5 halos,RF/NF, polar coord.

-
- 解像度が高いほど分裂片の数が増加
- high-mass側の質量も低下
- ← 別のシミュレーションではhigh-mass側は寡占的成長 $\frac{1}{\sqrt{2}}$ increase sections of the IMFs represent since $\frac{1}{\sqrt{2}}$ represent sinks equal to the IMFs represent sinks equal to the IMFs represent to the IMFs represent to the IMFs represent to the IMFs represent to th (Saavedra-Bastidas+24)

vertical dashed lines show the Jeans mass at the sink particle creation **『リルでC応甲 川町以区と刀リる木けは:** 寡占的成長と総中流的成長を分ける条件は?

50, 100, 200, 300, and 400 yr after the formation of the fist sink, for ρsink =

- 初期に回転していない近接連星の合体過程のSPH計算
- shown in panel (c), spiral structures appear just before the coalescence. After that, the system immediately coalesces (see α or the black crosses represent the epoch when α 角湄動畳が佰始星のスピンと て • 軌道角運動量が原始星のスピンとして引き抜かれることで合体
- panel (d)). Panel (d) shows the distribution of the resulting Let us describe the process from panel (a) to panel (b) in する方法だと過大評価 \overline{y} , the protostars begin to spin due to spin due to angular momentum \overline{y} 3.3. Timescale of Coalescence • 軌道角運動量とスピンの相互作用はsink粒子だとゼロ、EOSを硬く

(detailed analysis is described in Section 3.4). The stars keep spinning up, and their spin angular velocity matches their orbital angular velocity eventually, at which the system is tidally locked. This tidal interaction effectively reduces the いちのの 御作 御作 する いっぽん こうしょう こうしょう こうしゅう binary stars becomes smaller. The gas with a large angular This section discusses the relationship between the time to 申足を作んメカニズムけ? 近接連星を作るメカニズムは? → 定成さんトーク 低解像度のシミュレーションで合体をどう扱うべきか?

- ガス雲からの星団形成計算
- IMFの金属量依存性がメインテーマだが、 一番金属度の低い計算に着目
- SPHだが電離フィードバックが効く
- 電離フィードバックをSPHで解くのは難し いが(Susa13)高解像度により克服?
	- \checkmark M_{SPH} = 3x10⁻⁵ M_{sun}, r_{sink} \sim 1au
	- ✔ 質量解像度はSusa+14の約100倍
- 小質量の初代星も形成(M<0.8Msunで現 在まで生存)
- high-mass側が寡占的に成長

due to the stellarfeedback but the H II region does not develop at this moment. At *t* = 0.54Myr (epoch C), the H II region begins to expand around the ejected 降着期最後までの計算も解像度頑張れる?

runaway massive star. The star-forming gas is completely evaporated and the star formation is quenched at *t* = 0.72 Myr (epoch D).

- 乱流ダイナモによって磁場が増幅しsaturation
- Alfvenic で、 cases with *A* cases with *A*init = 10−9 G (purple), 10−9 G (purple), 10−9 G (cod), and 10−7 G (cod - saturation伎に倣场ほ保々に悧つ dashed lines represent the cases with an additional values with an additional values α , respectively, α and the differences between them will be discussed in Section 4.3.1.3.3. σ $d\theta$ is a set of the cases with an orientation $d\theta$ • saturation後に磁場は徐々に揃う

 $\frac{1}{2}$ in the early state with $\frac{10}{2}$ case wit the magnetic field is amplified slowly by the non-linear dynamo from the $\begin{bmatrix} \mathbf{r} & \mathbf{$ l 异 Ciよてのよ*)*は恢丁は兄りイレ 9 | ← Higashi+24のポリトロープ高解像度計算ではそのような様子は見られず energy on the smallerscale *Ek,*mag(*k*) approaches the turbulent energy *Ek,*turb(*k*) faster in the evolution (Fig. 8, top). *Ek,*turb(*k*) faster in the evolution (Fig. 8, top).

beginning; and in the sub-Alfvenic ´ case with *^B*init ⁼ ¹⁰−⁵ ^G (blue), the 而極性拡散による加熱が効くという解析的予想(Schleicher+09)を否定 \mathbf{F} is \mathbf{F} formation is larger in the formulation in the formulation in the formulation in the form energy density on the smallest scale in our simulations, i.e. *k* = 30*k*J, カくといっ解析旳予想(Schleicher+09)を合定 energy density on the smallest scale in our simulations, i.e. *k* = 30*k*J, - 両極性拡散による加熱が効くという解析的⁻ • 両極性拡散による加熱が効くという解析的予想(Schleicher+09)を否定 ー begins when the magnetic field energy becomes comparable to

ダイナモによる磁場の増幅は多くのグループが確認 増幅の結果どんな磁場構造になるかは不確か reaches equipartition on the largest turbulent-driving scale (∼*k*J), 増幅の結果どんな磁場構造にな_∙ **ACO** D. IN THE CASE OF THE CASE THE CASE THE THE THIS OCCURS AT *N*C ∞ THIS OCCURS AT *NC* ∼7 G, we see that the construction of the constr $\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ $\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ $\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ クループが確認 case proceeds in a very similar way, as the magnetic similar way, as the magnetic similar way, as the field is so strong that its force quickly erases the turbulence in the - latter computer computer energy spectra and the strong conduction of the strong conduction and the strong co
生法になるかは不確か magnetic field even in the turbulent case in the same manner as in spectra of *Ek,*mag and *Ek,*turb decay rapidly below this scale due to the バイナエによる磁場の増幅は多くのグループが確認 $\overline{\mathbf{A}}$ 道になるかほか傩か the magnetic to turbulent energy spectra *Ek,*mag*/Ek,*turb as a function **【幅の結果どんな磁場構造になるかは不確か─────────**───── bottom panels show the cases of *^B*init ⁼ ¹⁰−⁷ G, ¹⁰−⁶ G, and ¹⁰−⁵ G, i.e. *Ek,*mag(30*k*J) ∼ *Ek,*turb(30*k*J). From Fig. 7, we can clearly iden-*^B*init ⁼ ¹⁰−⁸ ^G (Fig. 7a) and at *ⁿ*^c [∼] ¹⁰⁹ cm−³ for the case of

ceeds in a roughly spherical fashion (see Fig. 4, left two columns). As expected for the kinematic dynamo (Section 2), the magnetic

The kinematic stage comes to an end and the non-linear stage begins when the magnetic field energy becomes comparable to the turbulence energy on the smallest scale in the simulations,

*^B*init ⁼ ¹⁰−⁸ ^G (Fig. 7a) and at *ⁿ*^c [∼] ¹⁰⁹ cm−³ for the case of

Our results also show that launching MHD outflows needs a strong coherent field. In the case of *^B*init ⁼ ¹⁰−⁶ G, outflows are launched

ceeds in aroughly spherical fashion (see Fig. 4, left two columns). As expected for the kinematic dynamo (Section 2), the magnetic

Omukai+01, Brom&Loeb03, KS+14, Wise+19, Chon&Omukai20, Woods+21,23, Latif+22, Kiyuna+23,24, Chiaki+23, Reinoso+23, Regan23, Patrick+23, Toyouchi+23, Prole24a,b, Regan&Volonteri24, Ventura+24

- 特殊な環境下では、始原ガス雲から超大質量星(M~105Msun) が形成すると考えられている
	- → 超新星を経ずに直接重力崩壊して超巨大BHの種に
	- → 場合によっては超新星爆発も起こる?
- 最近もいろいろ研究が進められているが、時間の都合により今 回は紹介しない

→ 喜友名さん、藤林さん、梅田さんトーク

ONE MORE TOPIC: FIRST STARS IN FIRST GALAXY SIMULATIONS

Simulations of first galaxy formation can be directly tested by observations in the JWST era

"Bottom-up" simulations of first galaxies

al the first galaxy forn the large-scale physical lav $\mathsf I$ Reve evolution. Figs 4 and 5 illustrate the evolution for this case in the H II regions start to expand into low-density regions at 4.7 Myr (Figs Reveal the first galaxy formation by combining simulations that solve the large-scale physical law and knowledge on small-scale processes

on POP IIIの星質量の理解を初代銀河形成シミュレーションに統合 POP II IMFの理解の統合 → 石田さんトーク

4-2, 5-2). Unlike the case with *Z* = 1 Z⊙, dense filaments are easily

Pop III star formation site in a first galaxy simulation *^R*cl = 0*.*272 pc*, M*cl = 720 *^M*Ø*, ^M*˙ cl = 0*.*⁰⁰⁴⁵² *^M*Ø*/*yr *M*pop3*,*H15 = 349*.*5 *M*Ø*,* z=2.23976288e+01 *x*⁰ = (°0*.*17*,* 0*.*00*,* °0*.*98) *y*⁰ = (°0*.*37*,* 0*.*93*,* 0*.*07) $\frac{1}{0}$

Test run with the new Pop III model

The new run follows a different history due to higher Pop III mass

For instance, second Pop III formation proceeds differently

Pop III フィードバックの星質量依存性 → 松田さんトーク 初代星形成を始めとする小スケール研究の成果を統合すること で、 カΠノキキ98 河形式市の古の次に泊てこした日指す!!

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CONCLUSIONS

Conclusions: studies of first stars

Big goal

determining the properties of the first stars from the first principle

Current understanding

- First stars form via H₂ cooling in minihalos at $10 \lesssim z \lesssim 30$
- B-field is amplified with turbulence during cloud collapse
- Multiple protostars are seeded by gas fragmentation
- First stars form as massive multiple-star systems

Future topics

- diversity in Pop III forming environment
- long-term evolution with small-scale fragmentation/merger
- protostar-scale dynamics with radiative transfer
- origin, amplification and role of B-field
- first-galaxy studies based on first-star understanding