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）

Kazuyuki Sugimura

(Hokkaido University)

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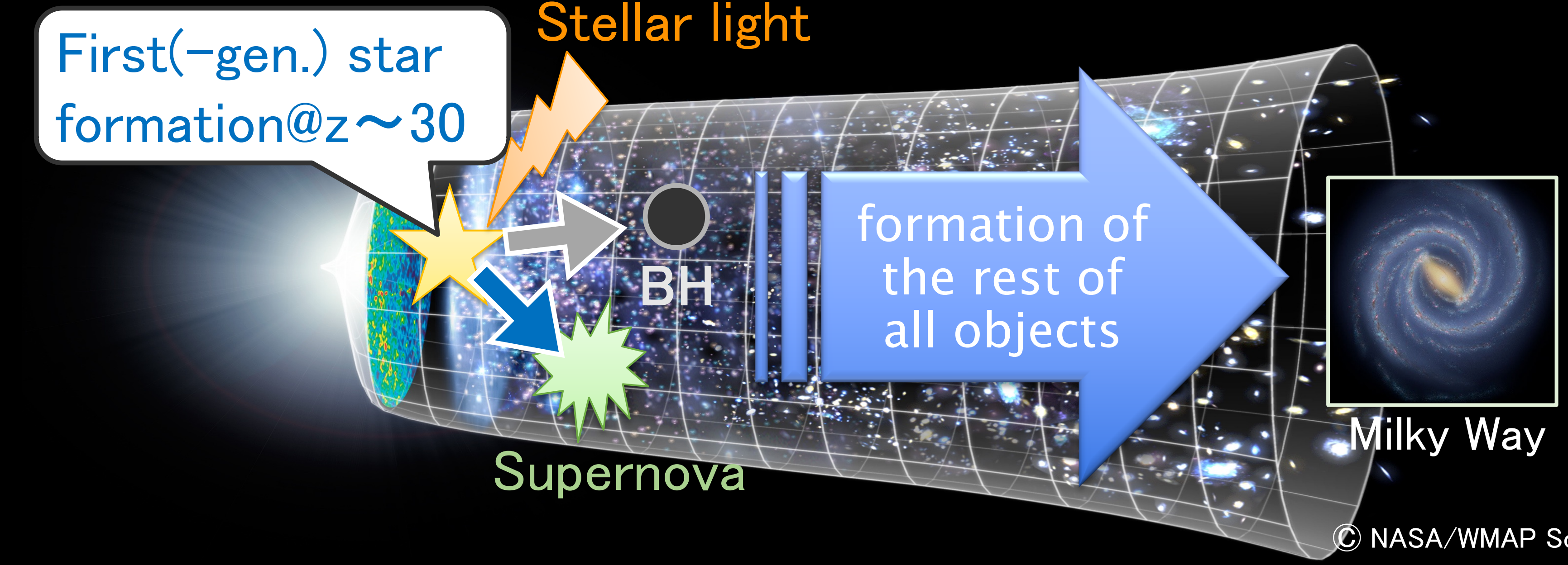
- ☐ Introduction
- ☐ Overall picture of Pop III formation
- ☐ Recent topics (2021-)
- ☐ Conclusions

INTRODUCTION

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

(First star = Pop III star)



Ⓒ NASA/WMAP Science Team

- The properties of the first stars determines the future of the Universe

← supernovae, stellar radiation, seeding BHs, etc.

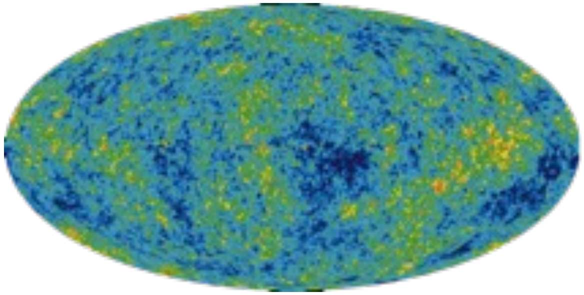
- Also, their properties is getting more reachable by observations

← direct obs., <u>binary BH mergers</u>, low-mass survivors, PISNe, GRBs, etc.

→衣川さんトーク

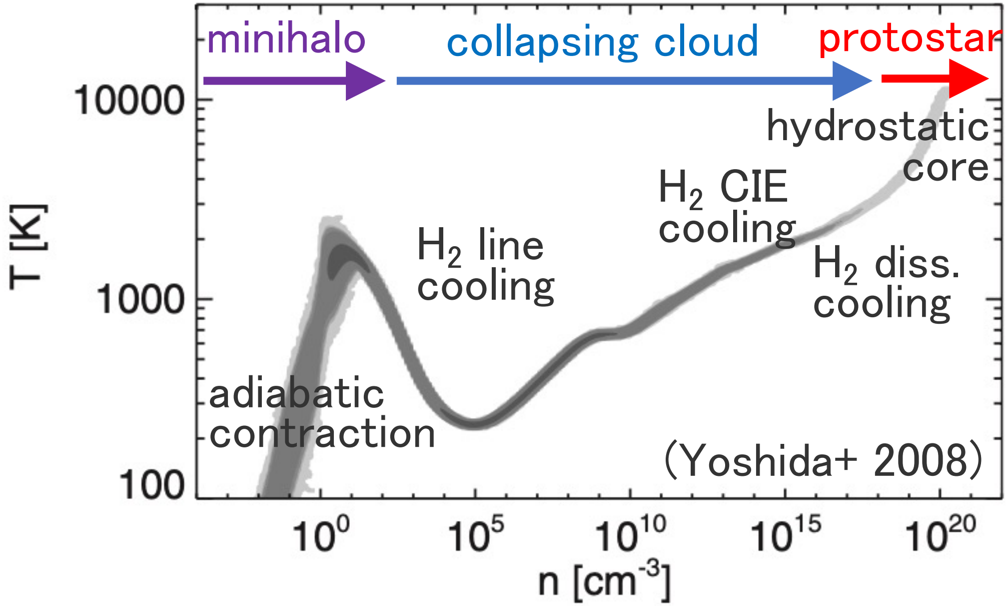
Uniqueness of the first stars: possible target for first-principle understanding

initial condition



CMB fluctuations
from WMAP/Planck

chemical/thermal processes



thermal state of gas at protostar formation

Both initial condition and evolution equations are well established

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

Big goal of first star studies

Determining the properties of the first stars from the first principle

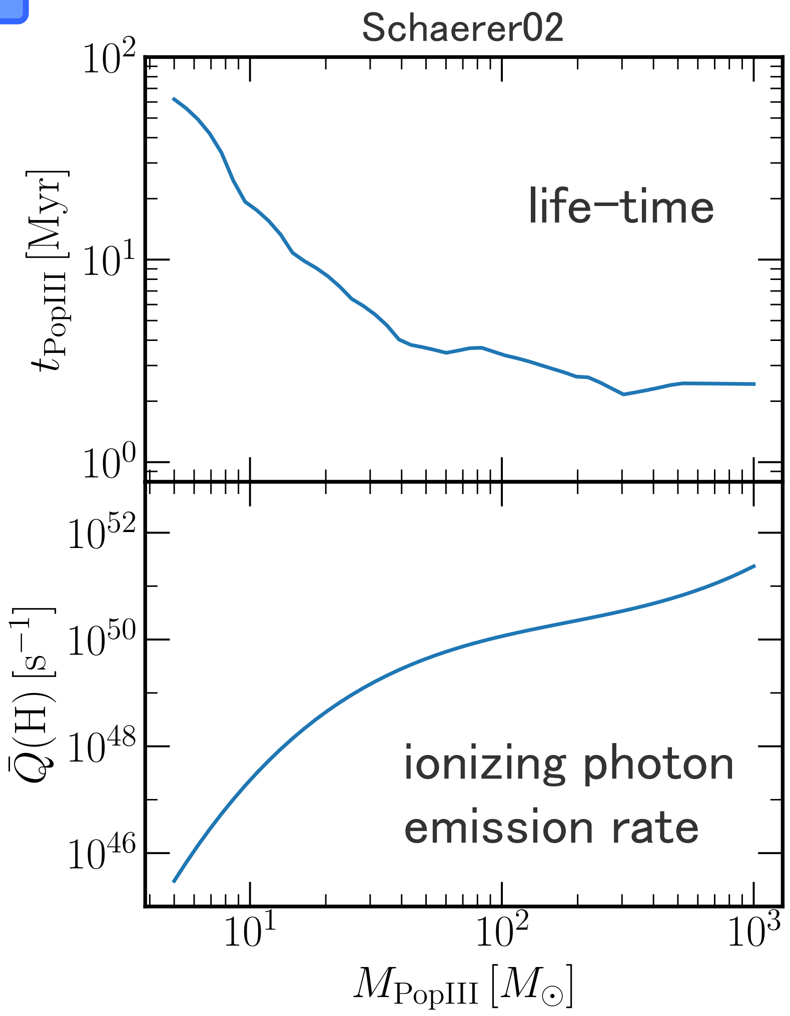
mass, spin, magnetization, multiplicity, number of stars, mass-ratio, orbital separation, eccentricity, etc.

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

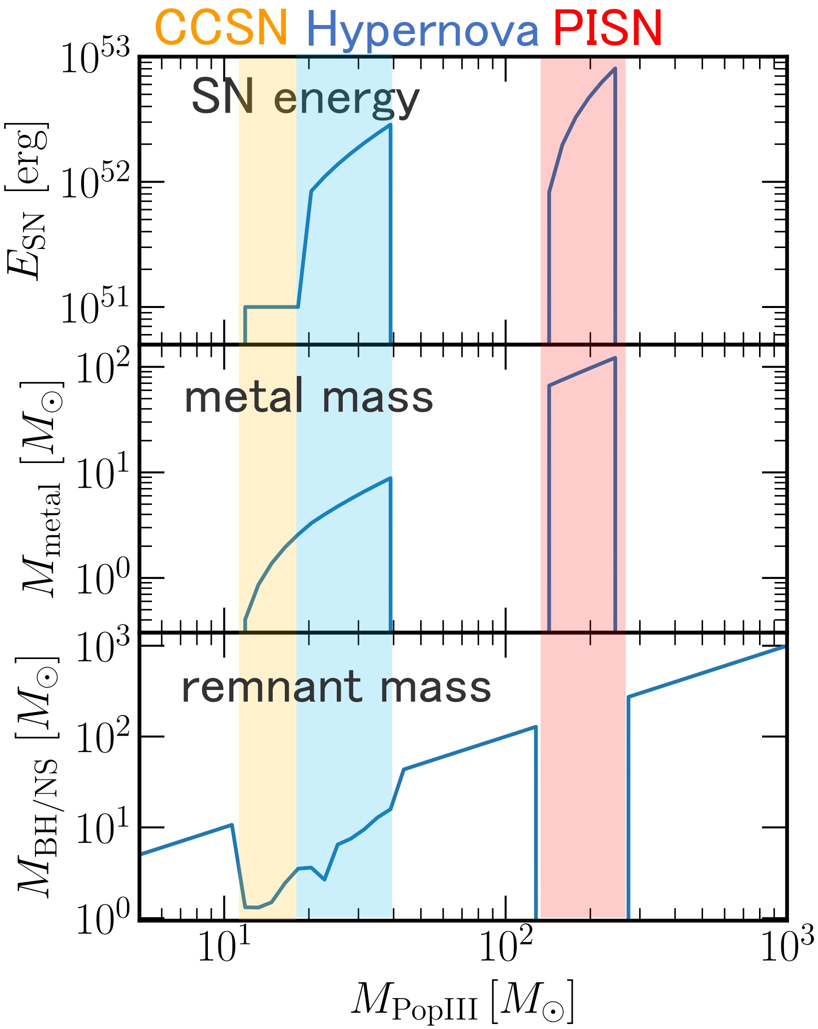
- parent halo's mass, size, shape, formation history
- background field (FUV, EUV, X-ray, CR)
- turbulence, fragmentation, 3-body interactions

Pop III mass is of particular interest

Schaerer02



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



Pop III mass determines the strength of the feedback

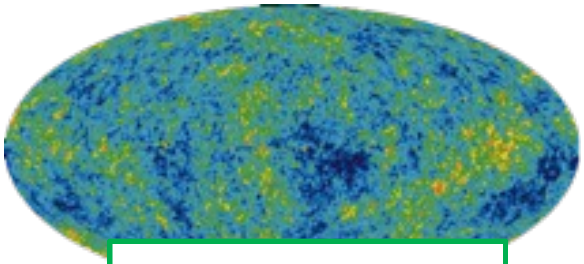
(while there is a room for improving the Pop III SN model)

Simulations from big bang to completion of first star formation

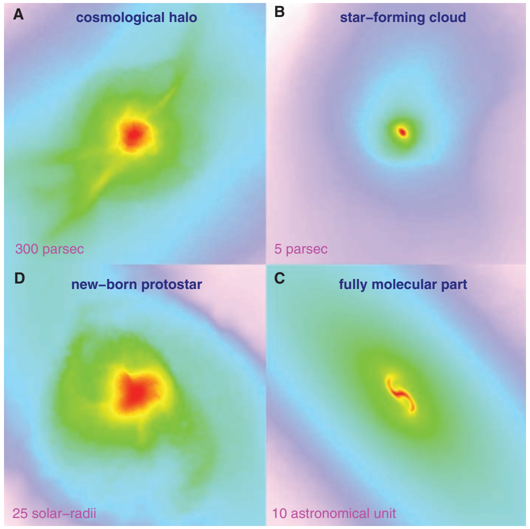
OVERALL PICTURE

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

- Cosmological hydro simulations
  - starting from cosmological initial condition
  - DM+gas simulation w/ all relevant chemical & thermal processes
  - tiny (~0.01 Msun) protostar forms at the center of small DM halo with $M_{DM} \sim 10^5 – 10^6\ M_{sun}$ (= minihalo) at $10 \lesssim z \lesssim 30$

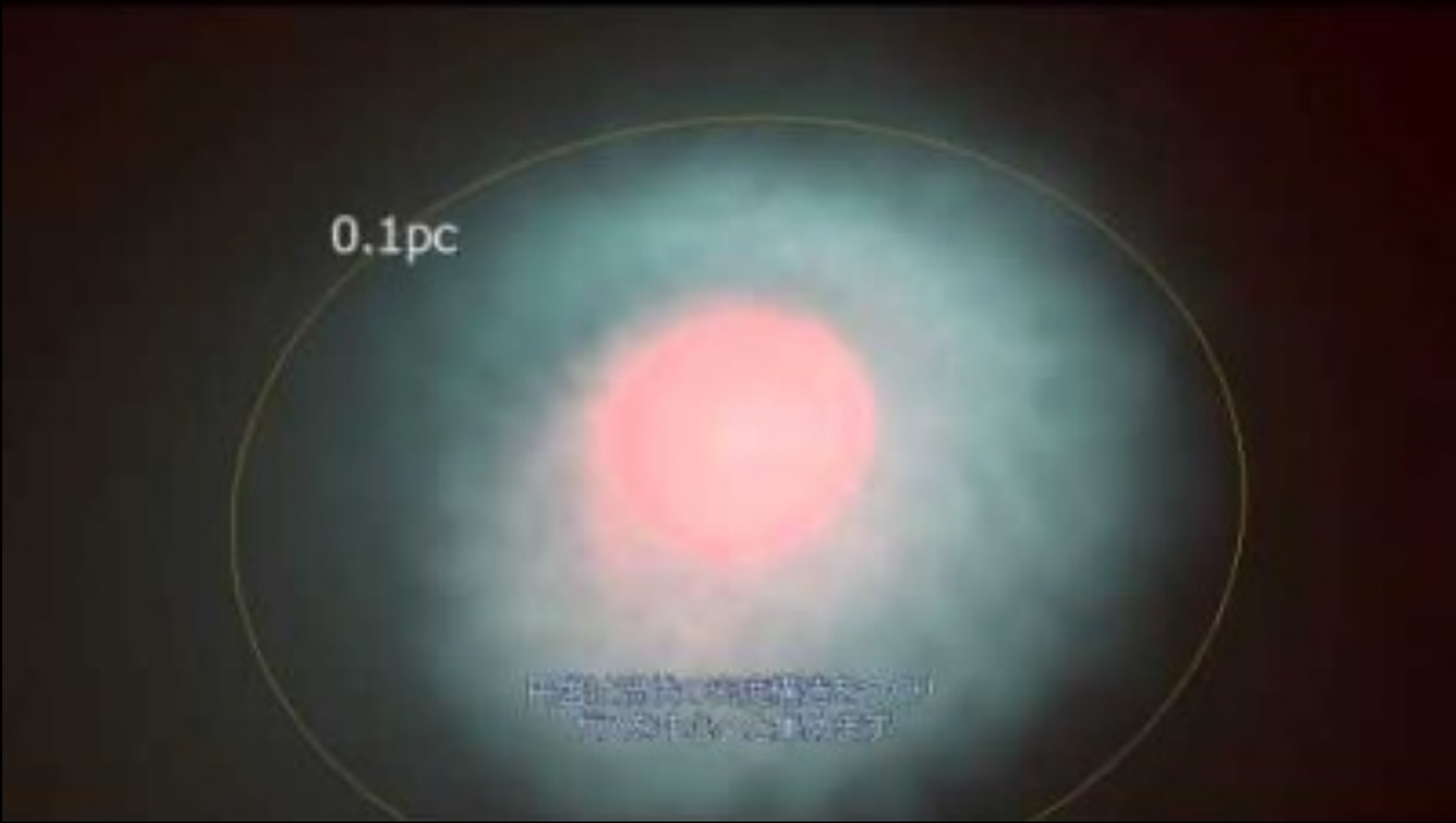


cosmological initial condition



Yoshida, Omukai, Hernquist 2008 (Science)

A movie for the birth of first protostar



https://youtu.be/2COt_OTAENg

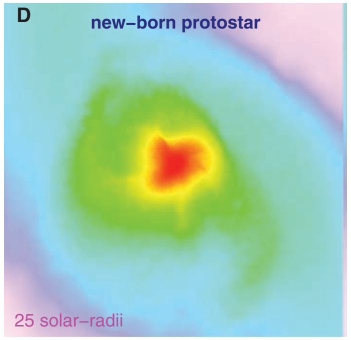
Hirano et al. (2014)

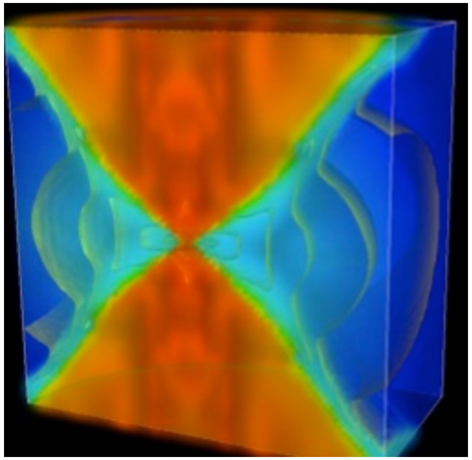
movie credit: Takeda

Pop III formation in simulations 2: From first protostar to first star

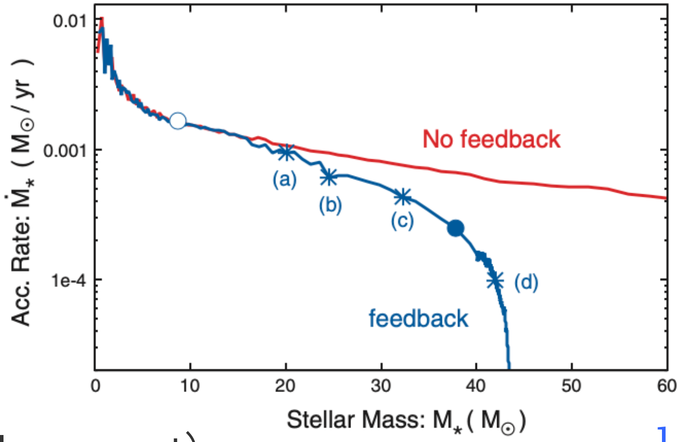
- Zoom-in radiation hydro simulations

Hosokawa, Omukai, Yoshida, Yorke 2011 (Science)





- 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 ∼40 M_{sun} in this case

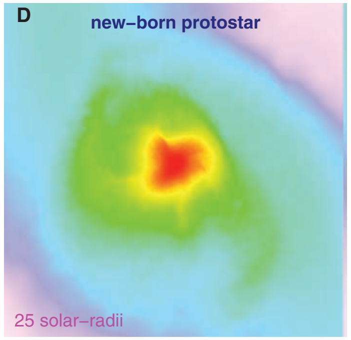


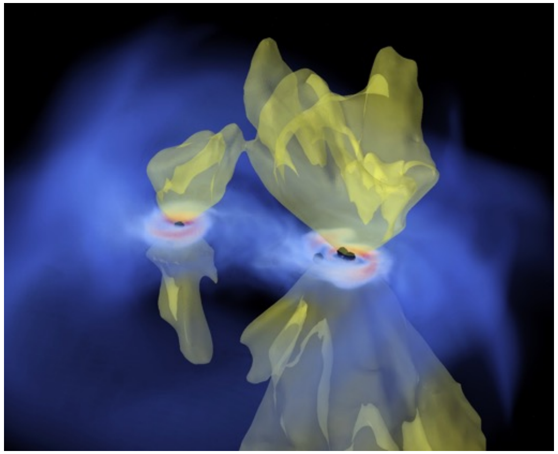
(see McKee&Tan 2008 for analytical argument)

Pop III formation in simulations 3: Formation as binary/multiple stars

☐ Zoom-in radiation hydro simulations with 3D AMR

KS, Matsumoto, Hosokawa, Omukai, Hirano (2020,2023)

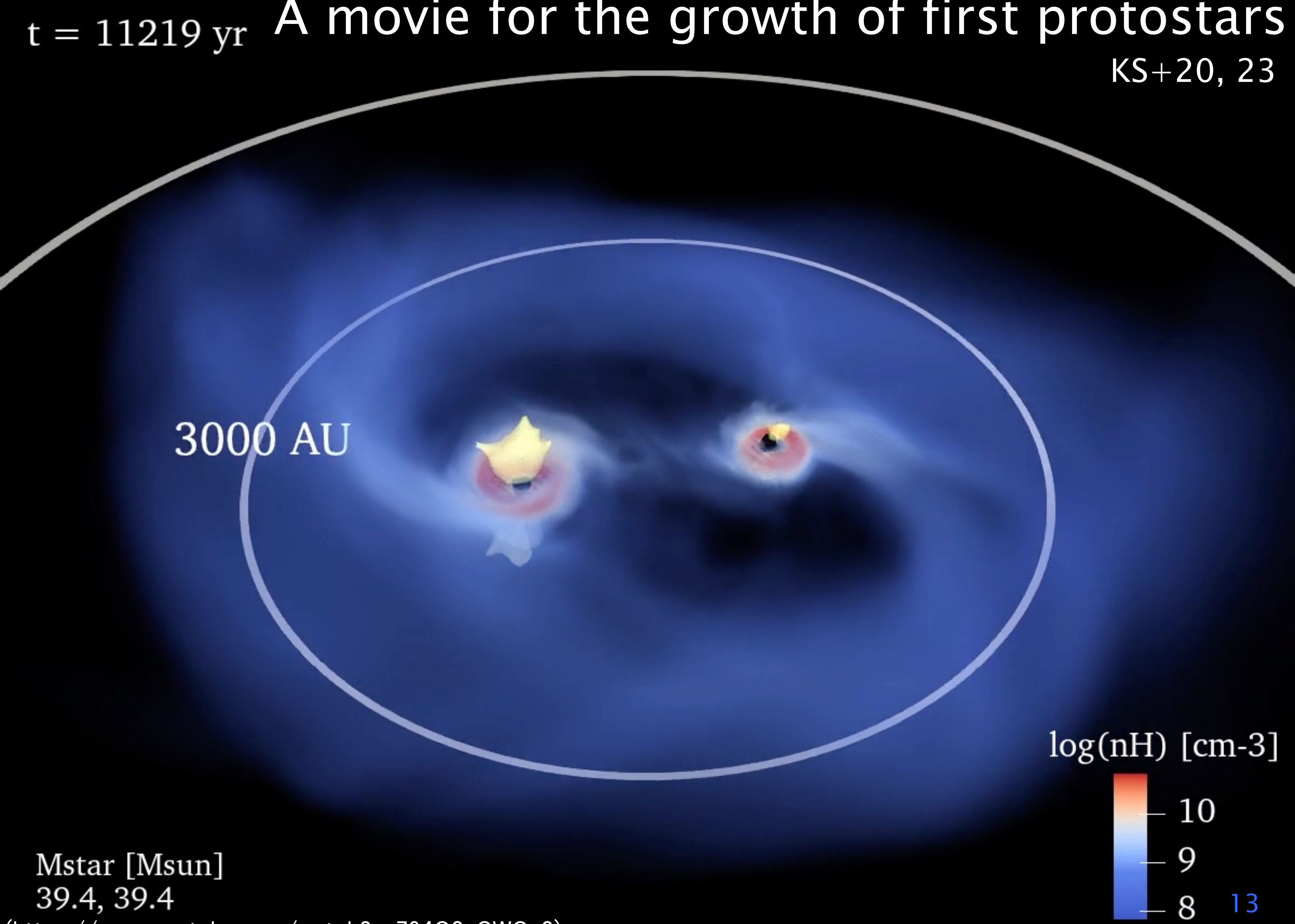




- 2D simulations in Hosokawa+ (2012) cannot deal with binary/multiple systems
- 3D simulations existed but with some problems
  - ✓ SPH (Stacy+12,16, Susa+14) ← hard to follow EUV feedback (Susa13)
  - ✓ spherical-grid (Hosokawa+16) ← low off-center res., central-star FB only
- 3D AMR simulations have found that the first stars form as massive binaries/multiples (KS+20,23)

A movie for the growth of first protostars

KS+20, 23

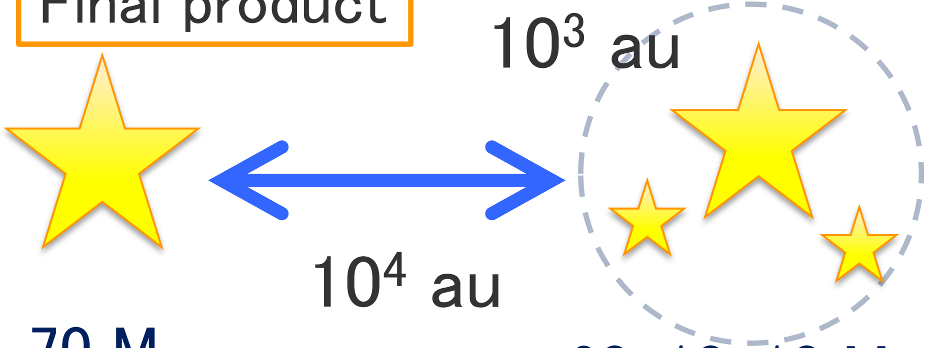


(https://www.youtube.com/watch?v=794O0yGWGp0)

simulation set-up

- code: SFUMATO-RT (Matsumoto07, KS+20)
- $n_{sink}=10^{11}cm^{-3}$, Δx_{min}=4au, r_{sink} = 64au
- minimum # of cells/Jeans length : 16
- t_{end} = 10^5 yr since protostar formation

Final product



10^3 au

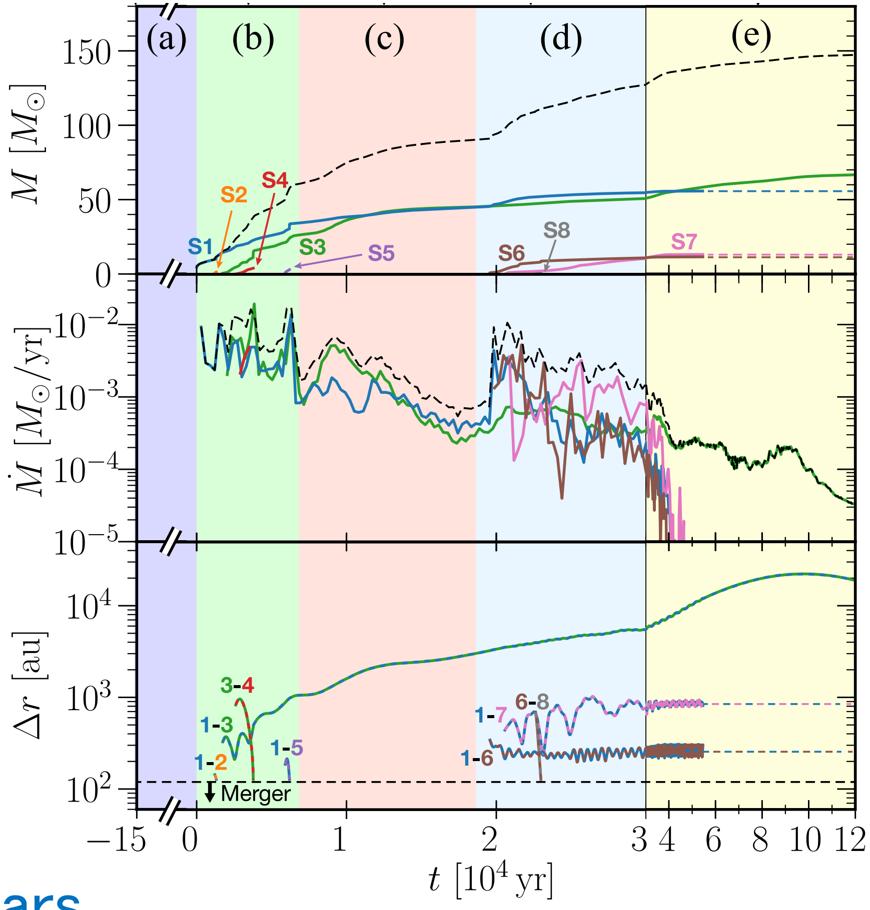
10^4 au

70 M_{sun}

60+10+10 M_{sun}

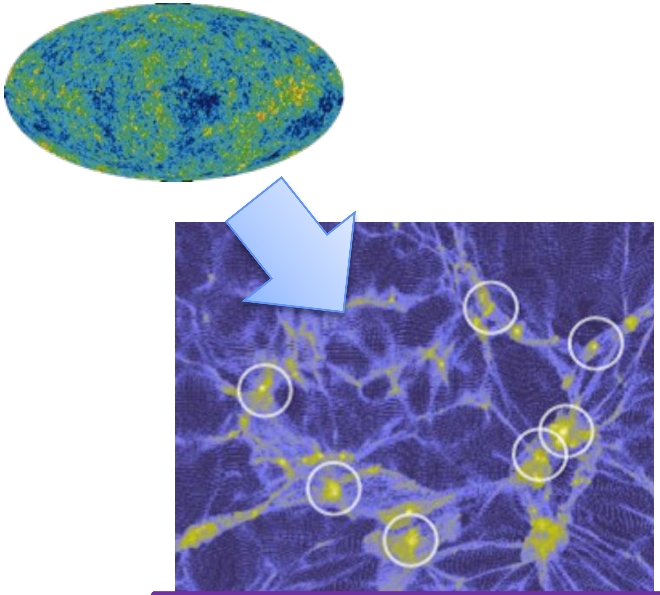
A system of wide massive multiple stars

Protostar (sink) evolution

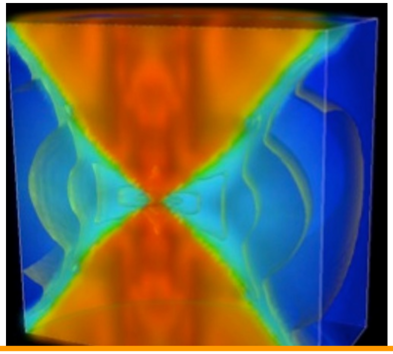


(t: time after 1st sink formation)

Pop III formation in simulations 4: from single case to statistics



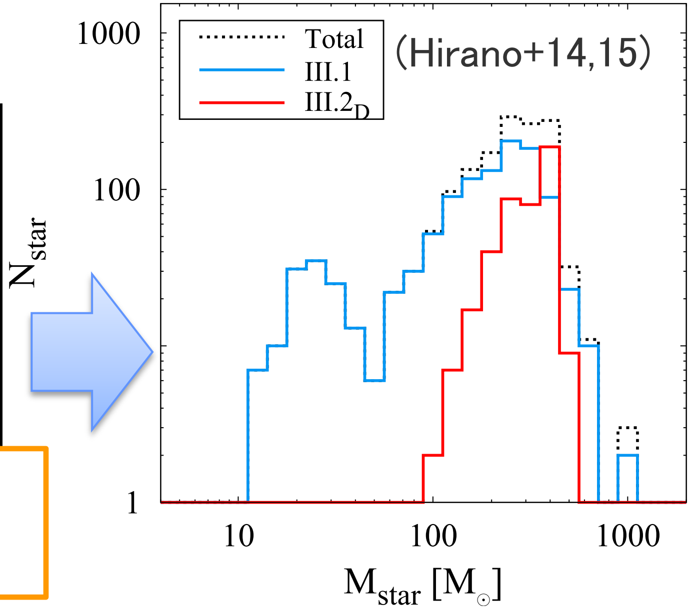
many minihalos in cosmological sims.



star formation in RHD sims.

(cf. Hosokawa+2011)

(see also Susa+14, Stacy+16)



Pop III Initial Mass Function

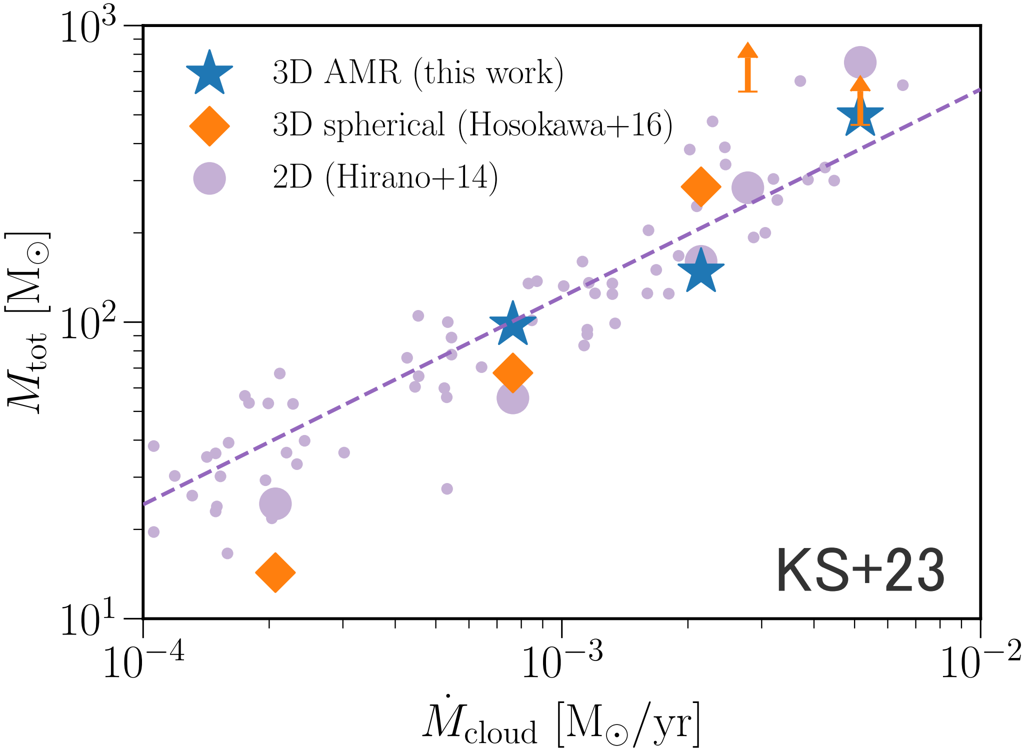
- Pop III stars tend to be massive (～100M_sun)
  ↔ Milky-Way ordinary stars (～1M_sun)
- This Pop III IMF is based on 2D simulations

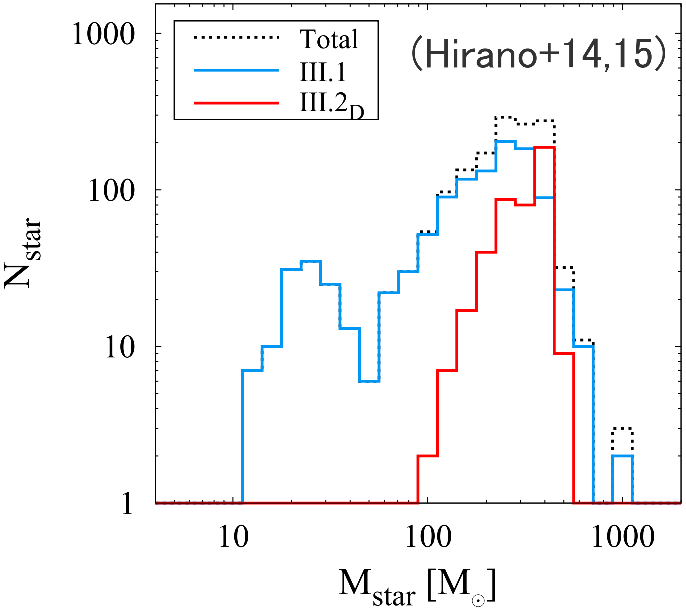
initial = birth-time

↑

final time in simulations!

Pop III formation in simulations 5: statistics based on 3D simulations





mass of a single star (2D)

⇩

total mass of multiple stars (3D)

- Fitting formula from 2D simulations (Hirano+15) seems valid for the total mass of multiple Pop III stars

$$M_{\rm tot} = 250\,M_\odot \left(\frac{\dot M_{\rm cloud}}{2.8\times10^{-3}\,M_\odot\,{\rm yr}^{-1}}\right)^{0.7}$$

← confirmation of this conjecture with large sample is future work recent progress and open questions

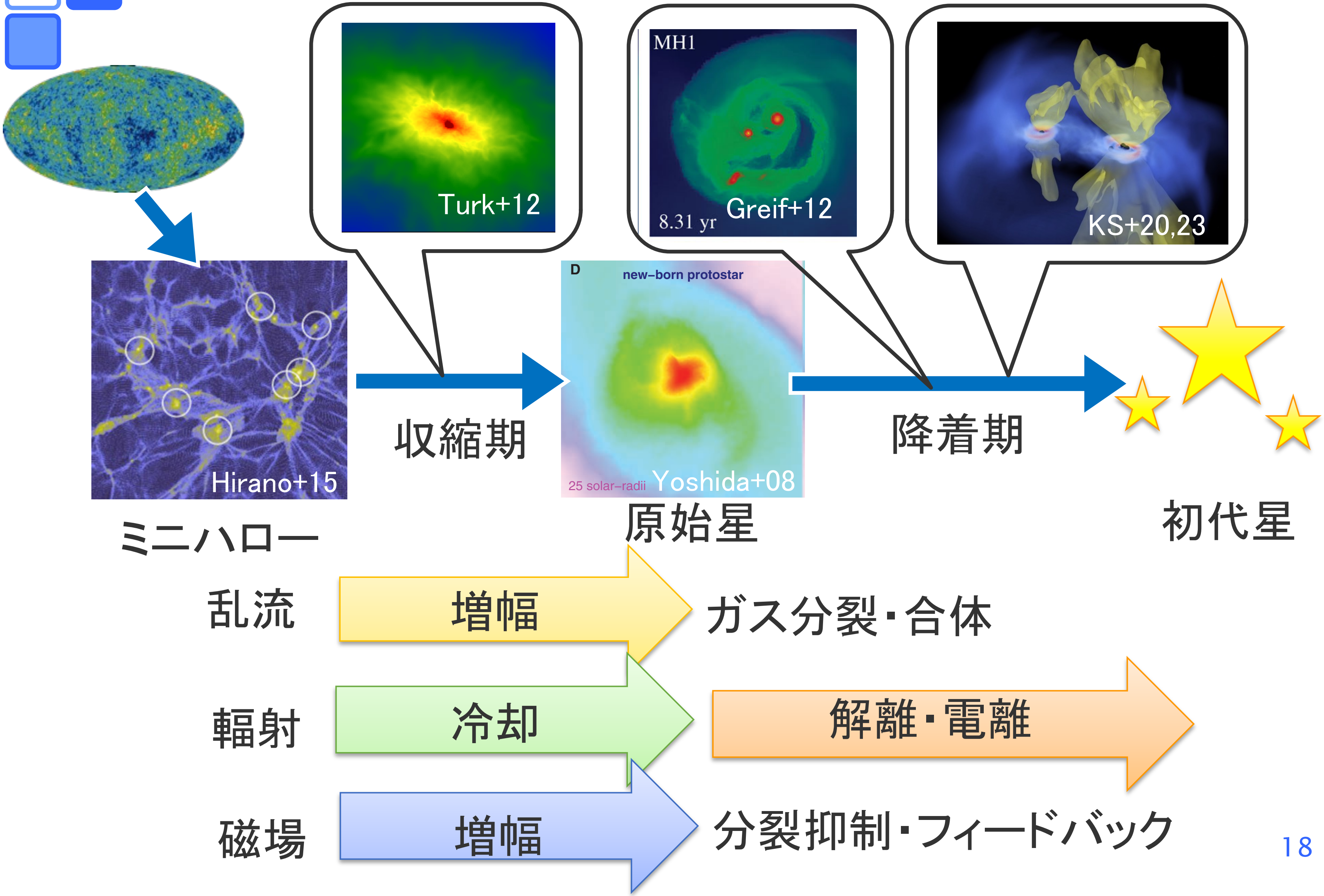
RECENT TOPICS (2021–)

（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）

Topics related to Pop III formation



ミニハロー

収縮期

原始星

降着期

初代星

乱流 増幅 ガス分裂・合体

輻射 冷却 解離・電離

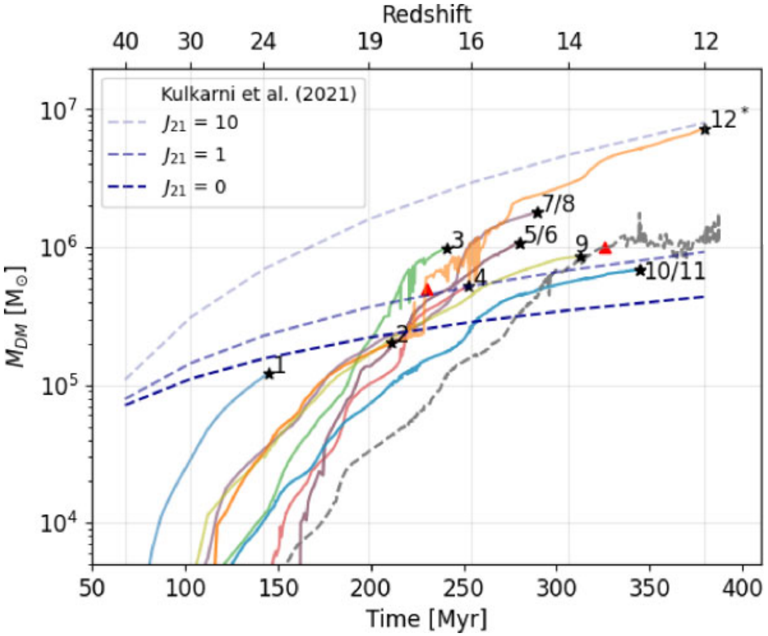
磁場 増幅 分裂抑制・フィードバック

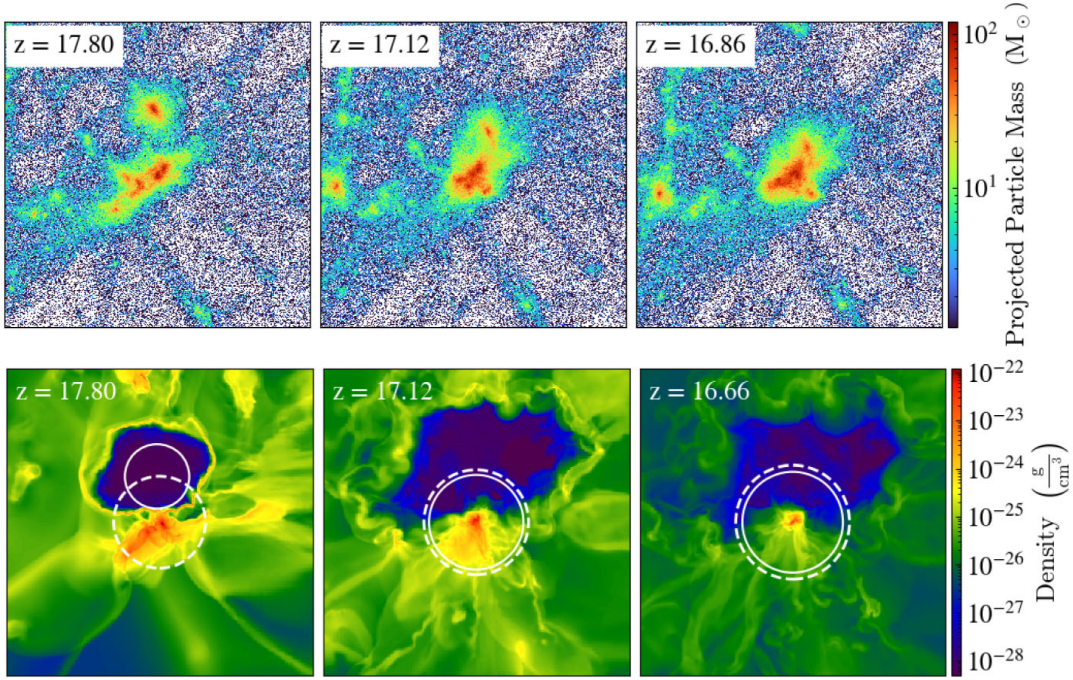
（orange reference: publication since 2021）

ミニハロー内の重力収縮ガス雲形成

Tegmark+97, Schauer+21, Kulkarni+21, Correa Magnus+23, Lenoble+23

Correa Magnus+23





- Enzo, 高解像度計算（M_{DM}=1M_{sun}）
- 一つのミニハロー中で複数の初代星形成領域（3ハロー/12ハロー）
- SN後のガス雲の重力収縮にmajor mergerが影響

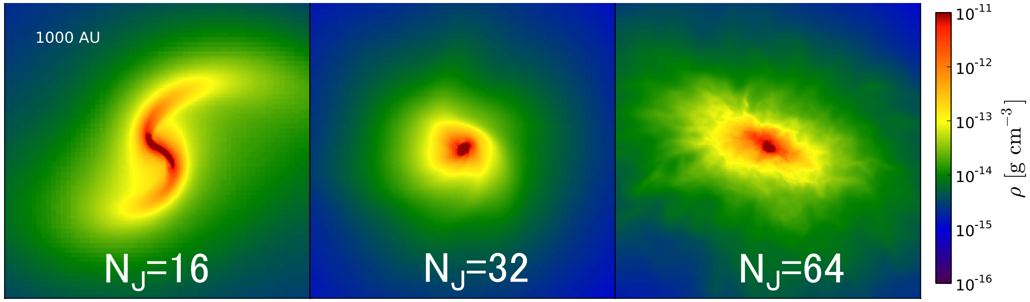
初代星の多様な形成環境・条件の理解が重要

→ 石山さんトーク

重力収縮期の乱流増幅

(Truelove+97), Federrath+11, Turk+12, Higashi+21,22

Key parameter: “Jeans number” $N_J = \lambda_J / \Delta x$

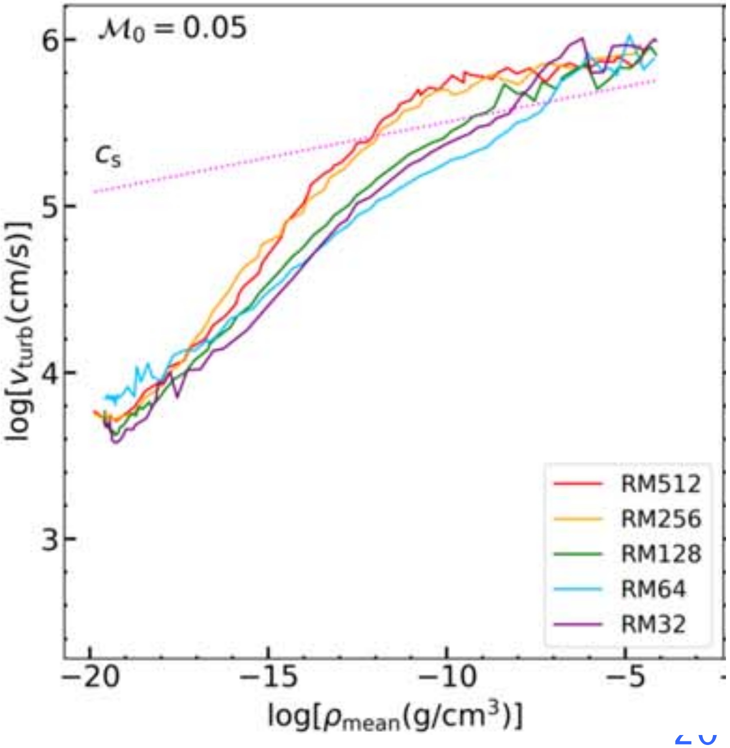


Turk+12

- Truelove条件 N_J=4 は重力収縮を記述するのに全然不十分

Higashi+21, 22

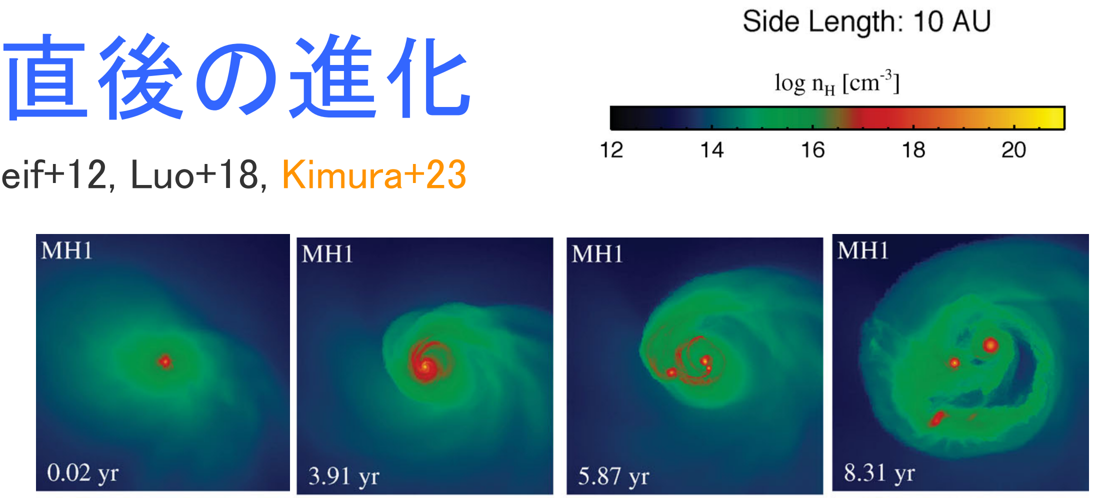
- 落下するガスの運動エネルギーをソースに重力収縮中に乱流が増幅・飽和
- 結果の収束には N_J>256 (cf. N_J>32 in Federrath+11) が必要そう



大抵の場合、重力収縮中のガスは超音速乱流状態にあると考えられる

原始星形成直後の進化

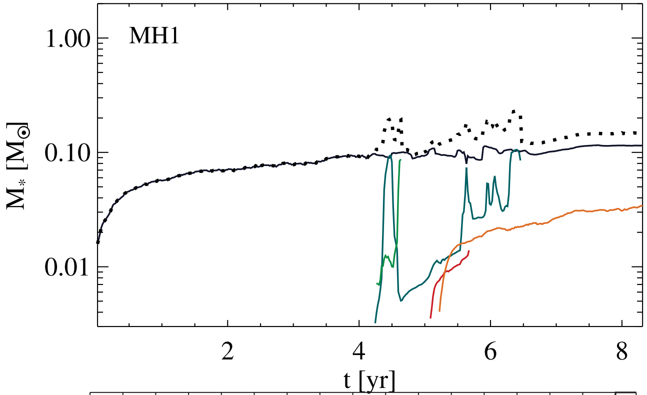
Omukai&Nishi98, Yoshida+08, Greif+12, Luo+18, Kimura+23

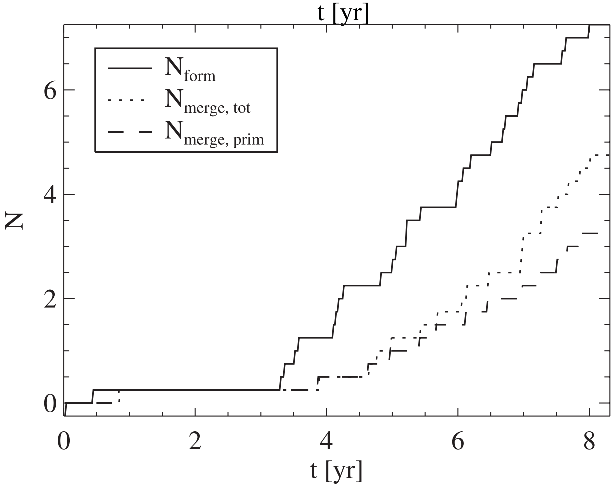


Greif+12

- AREPO (moving mesh), Δx～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

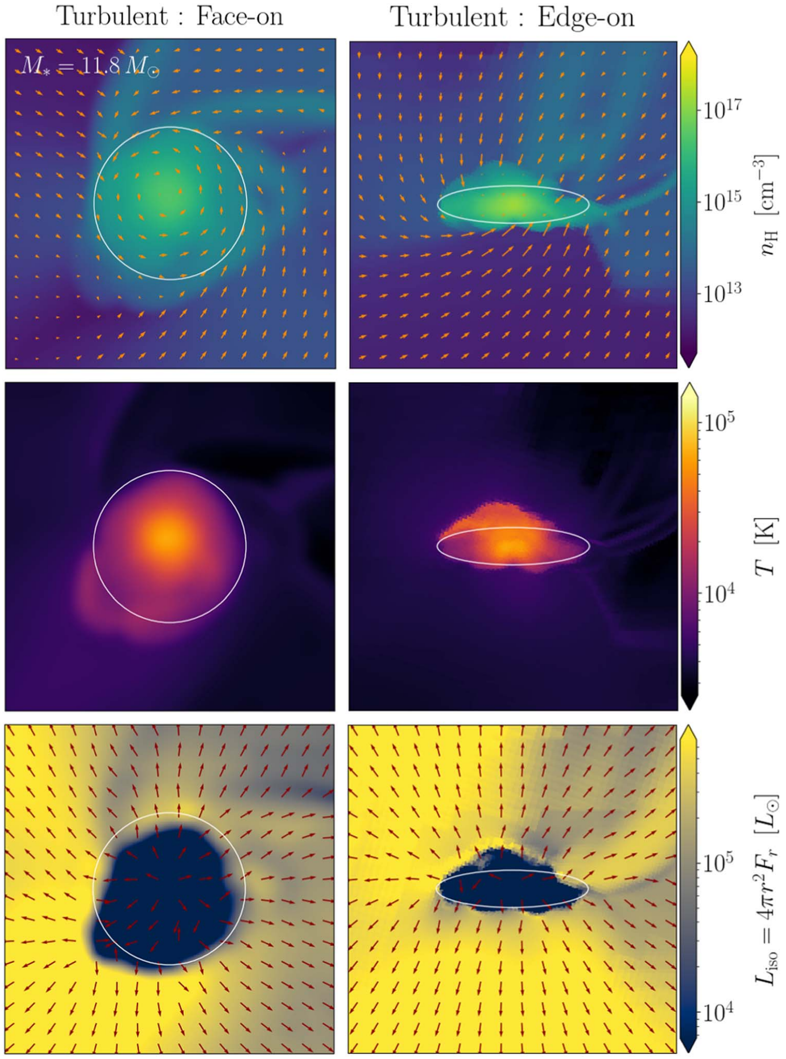




星の内部まで考慮した輻射流体計算

Kimura+23

- SFUMATO-RT + new M1 RT module
- 原始星内部の拡散光の輻射輸送
  - ✓ 光学的厚みが非常に大きな領域を計算するための工夫
  - ✓ 実際の化学・熱進化を再現
- 超大質量星形成に対応した設定（高い降着率、Mdot～1M_{sun}/yr）
- 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？



第一原理的方向性の研究が再始動

降着期のガス分裂・合体

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

Susa19

- シミュレーションに基づ分裂と合体の解析的モデル

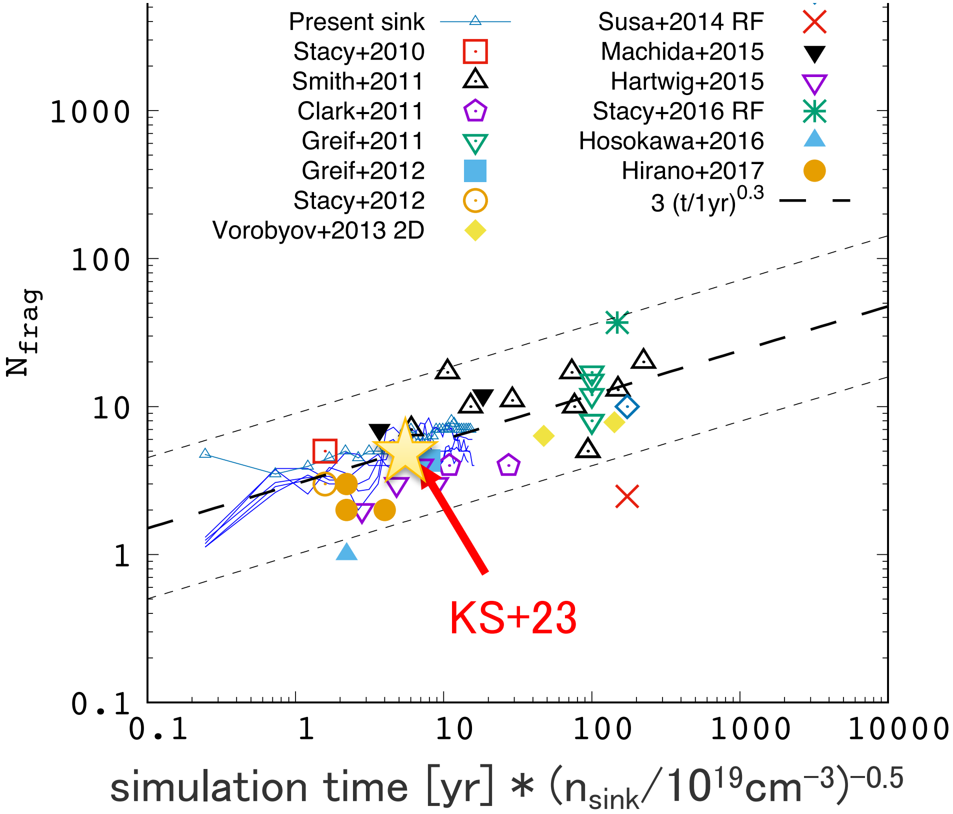
  $N_{frag} \propto t^{0.3}$

- 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

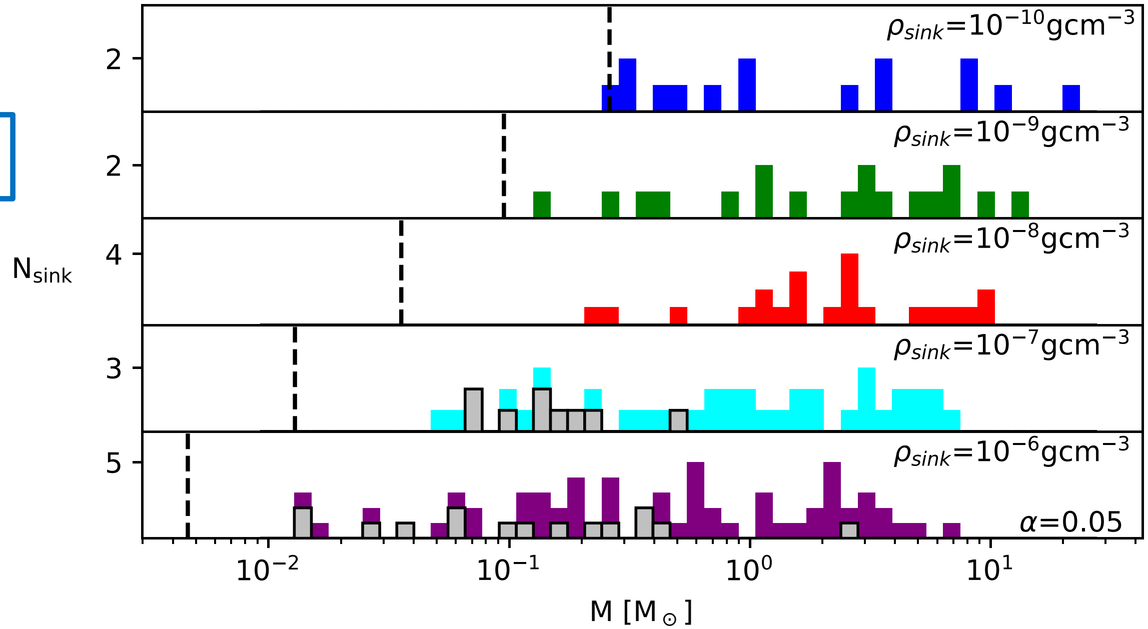
  ←γ_{eff}大きいと分裂しにくい

$$P = K \rho^{\gamma_{eff}}$$



ガス分裂の解像度依存性

Prole+22

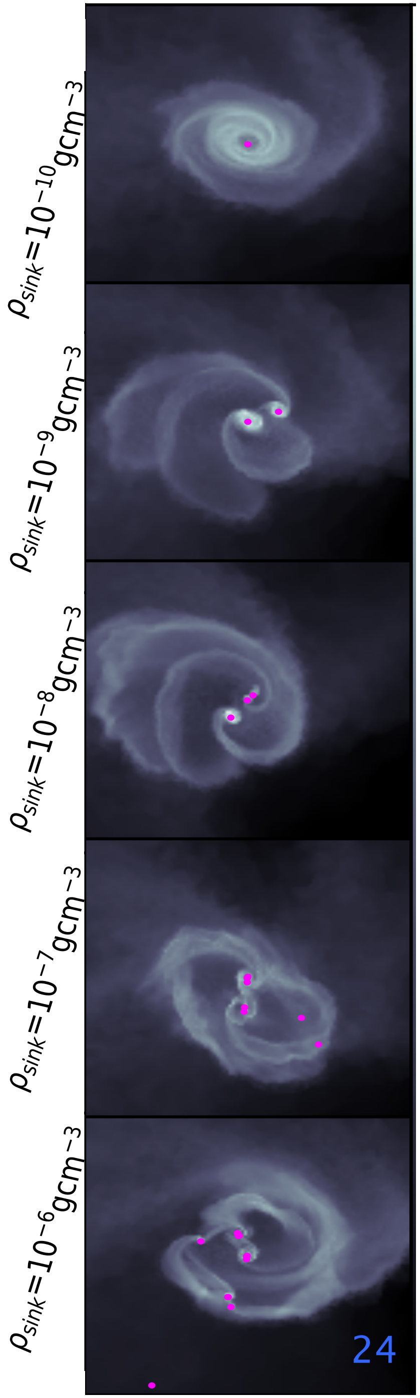


- AREPO, feedback無し、sink粒子密度依存性
- 原始星形成後400年
- sink粒子の質量の合計は解像度に依らない
- 解像度が高いほど分裂片の数が増加
- high-mass側の質量も低下

← 別のシミュレーションではhigh-mass側は寡占的成長

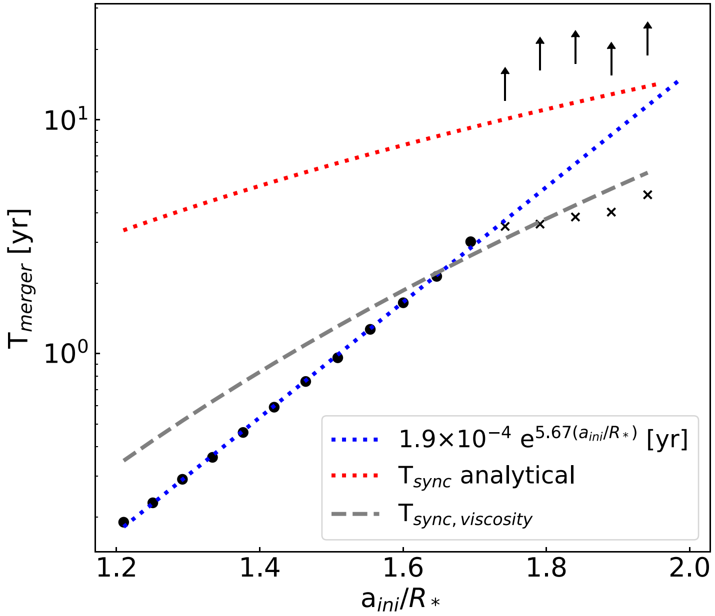
（Saavedra-Bastidas+24）

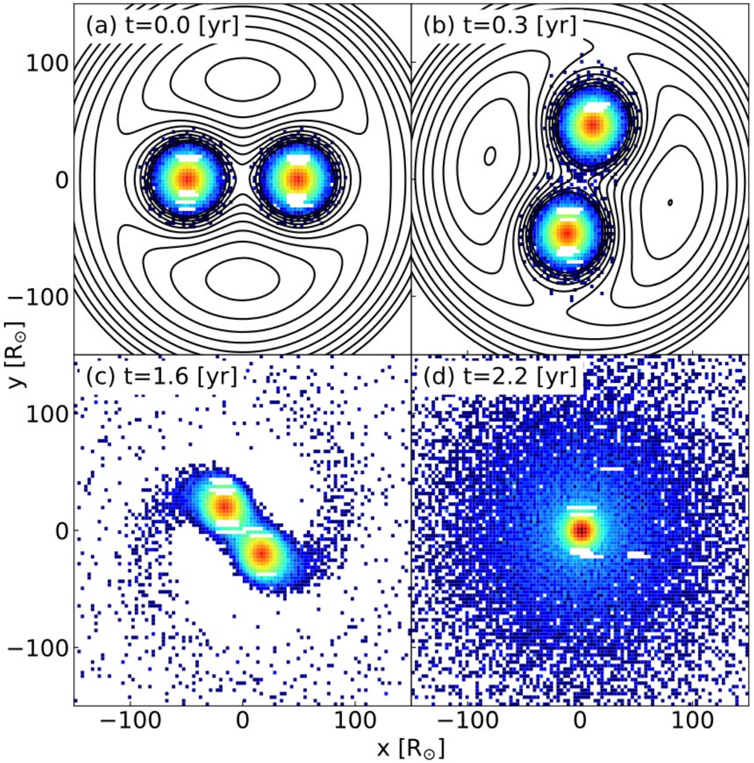
寡占的成長と総中流的成長を分ける条件は？



合体に至る過程

Kirihara+23





- 初期に回転していない近接連星の合体過程のSPH計算
- 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
- 軌道角運動量とスピンの相互作用はsink粒子だとゼロ、EOSを硬くする方法だと過大評価

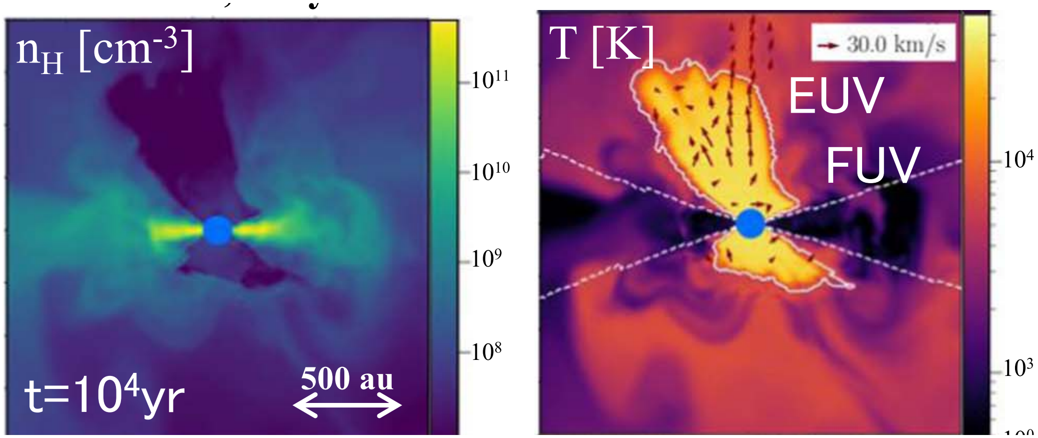
近接連星を作るメカニズムは？　→ 定成さんトーク

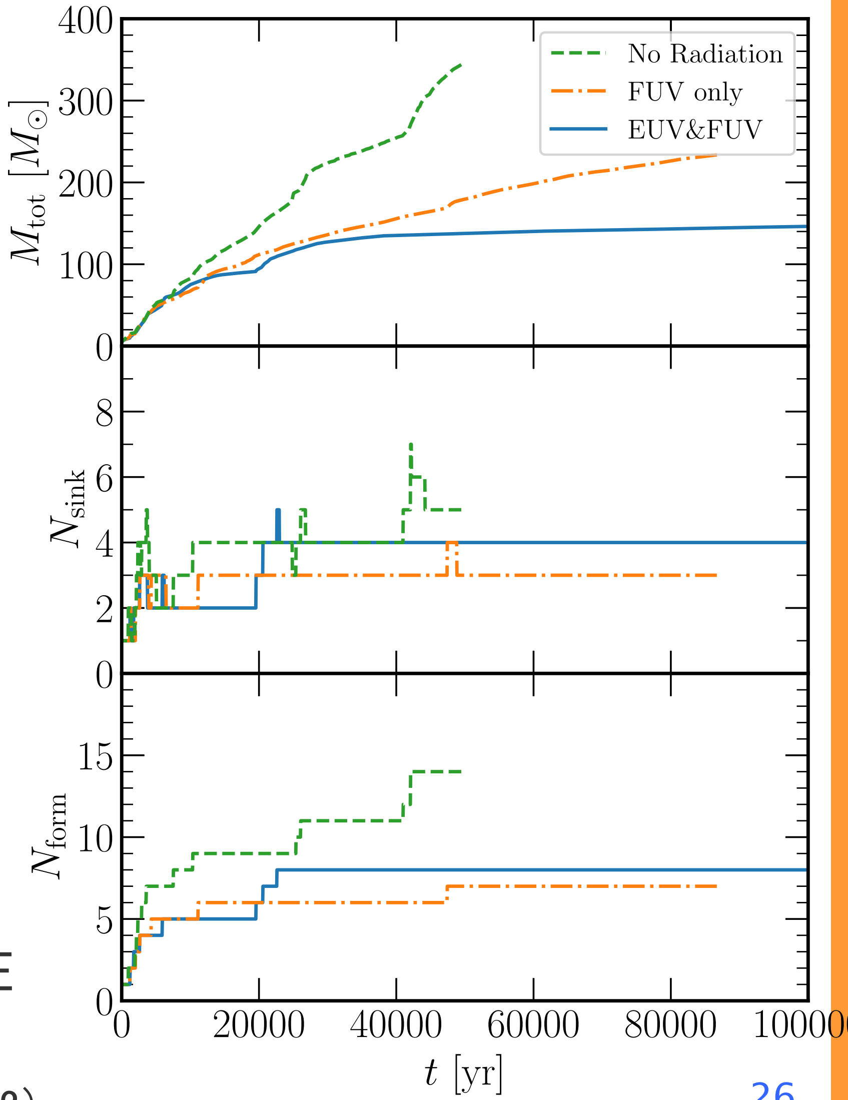
低解像度のシミュレーションで合体をどう扱うべきか？

輻射フィードバック下の原始星成長

McKee&Tan08, Hosokawa+12,16, Stacy+13,16, Susa13, Susa+14, KS+20,23, Latif+22, Jaura+22, Park+23, Toyouchi+23, Sharda&Menon24, Chon+24

KS+20, 23



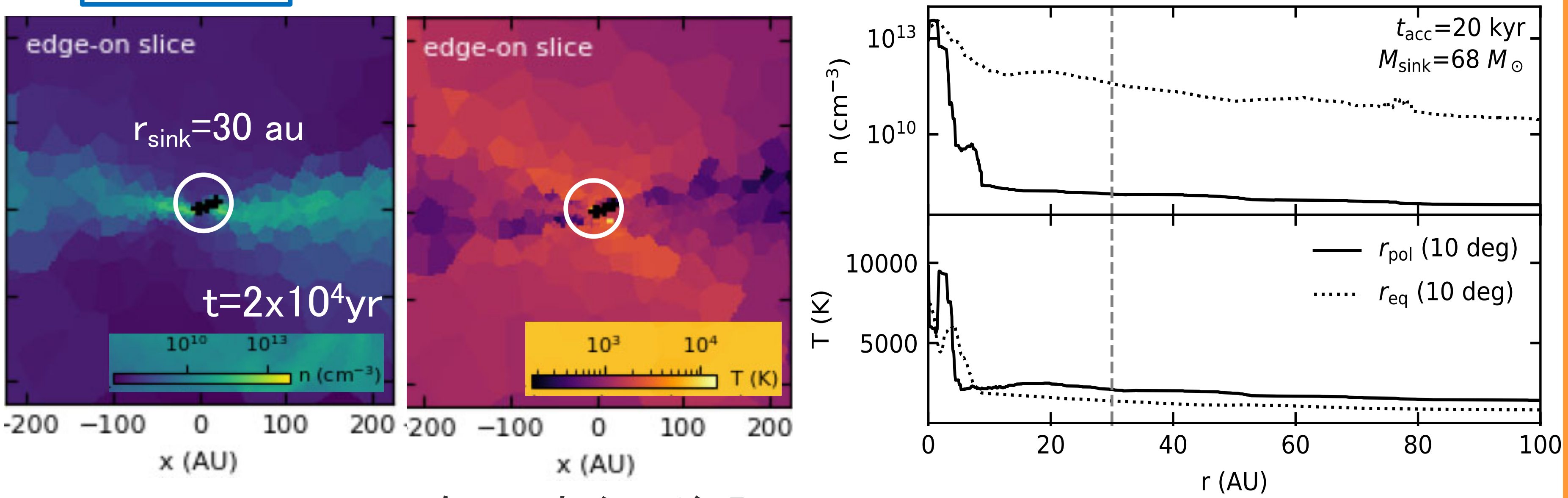


- FUV（H_2解離光子）が初期（～10^4yr）に効く
  - ✓ 降着率・分裂を抑制
- EUV（電離光子）は後で（～3x10^4yr ）効く
  - ✓ 最終的に降着を止める
  - ✓ bipolar電離バブルは前（～10^4yr）から存在
- 複数星の場合も単独星のときと類似

（e.g., McKee&Tan 08, Hosokawa+12）

電離光子が分厚い円盤から出られない？

Jaura+22

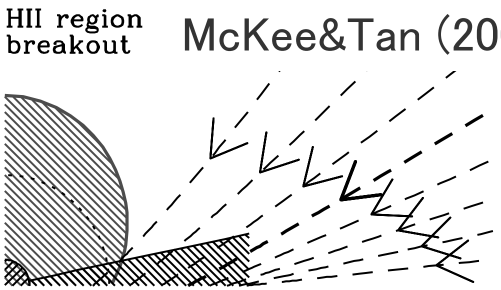


- AREPO、EUV/FUVをsink中心に注入
- EUVは分厚い円盤に全て吸収される
  → フィードバックも効かない
- bipolarな電離バブルの描像と異なる

（e.g., McKee&Tan 08, Hosokawa+12、KS+20,23）

- sink内の重力softeningの影響は？
  - 等温ガスの$H/R \propto cs/\Omega R \propto R^{1/2}$

McKee&Tan (2008)

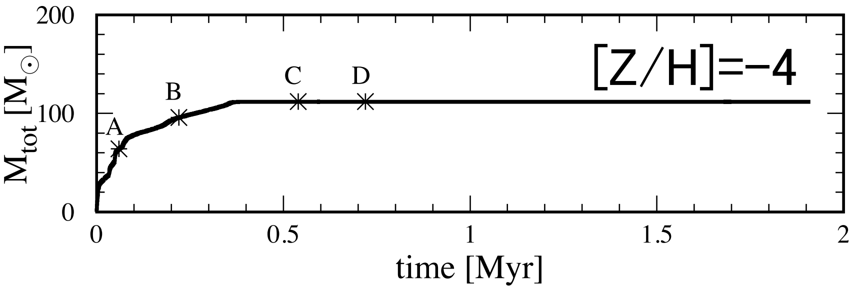


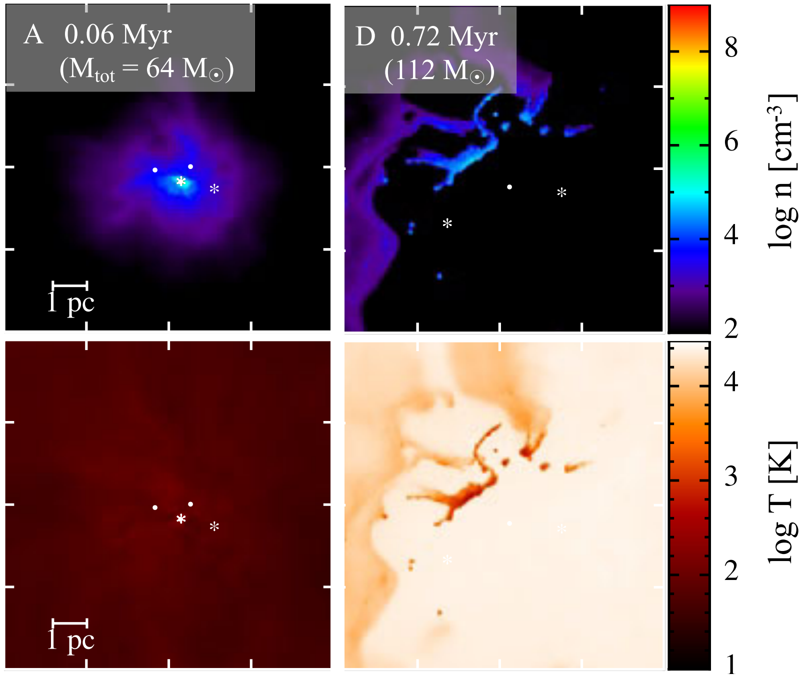
原始星近傍や円盤内側の構造を明らかにするのが重要

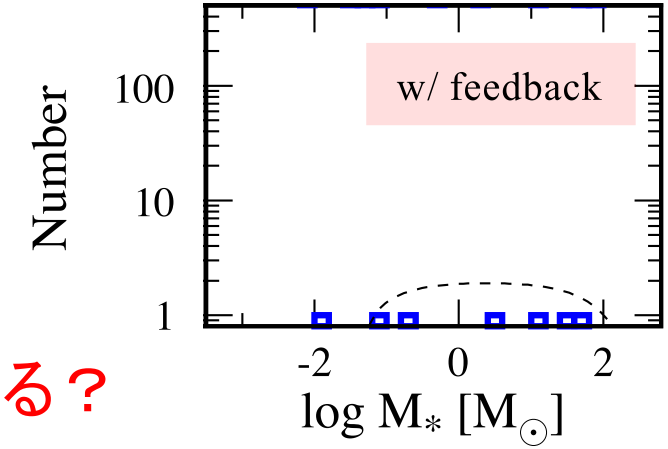
輻射入り高解像度計算

Chon+24 → 大向さんトーク？

- Gadget、EUV/FUV/IR フィードバック
- 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？
  - ✓ M_{SPH} = 3x10^{-5} M_{sun}、r_{sink} ～ 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







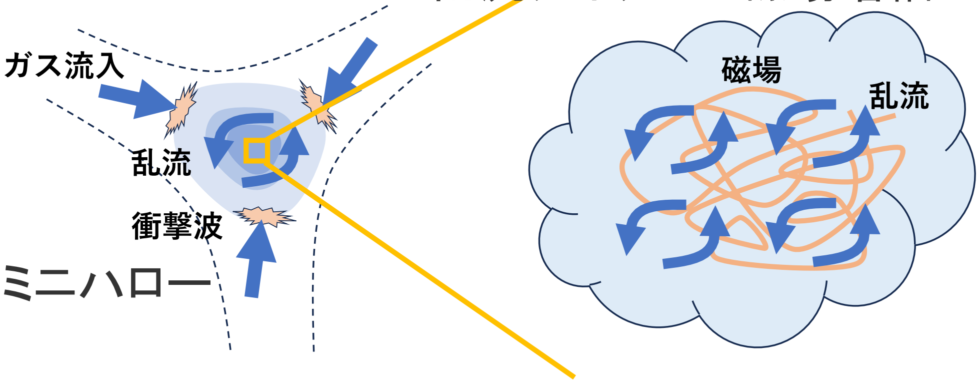
降着期最後までの計算も解像度頑張れる？

初代星と磁場

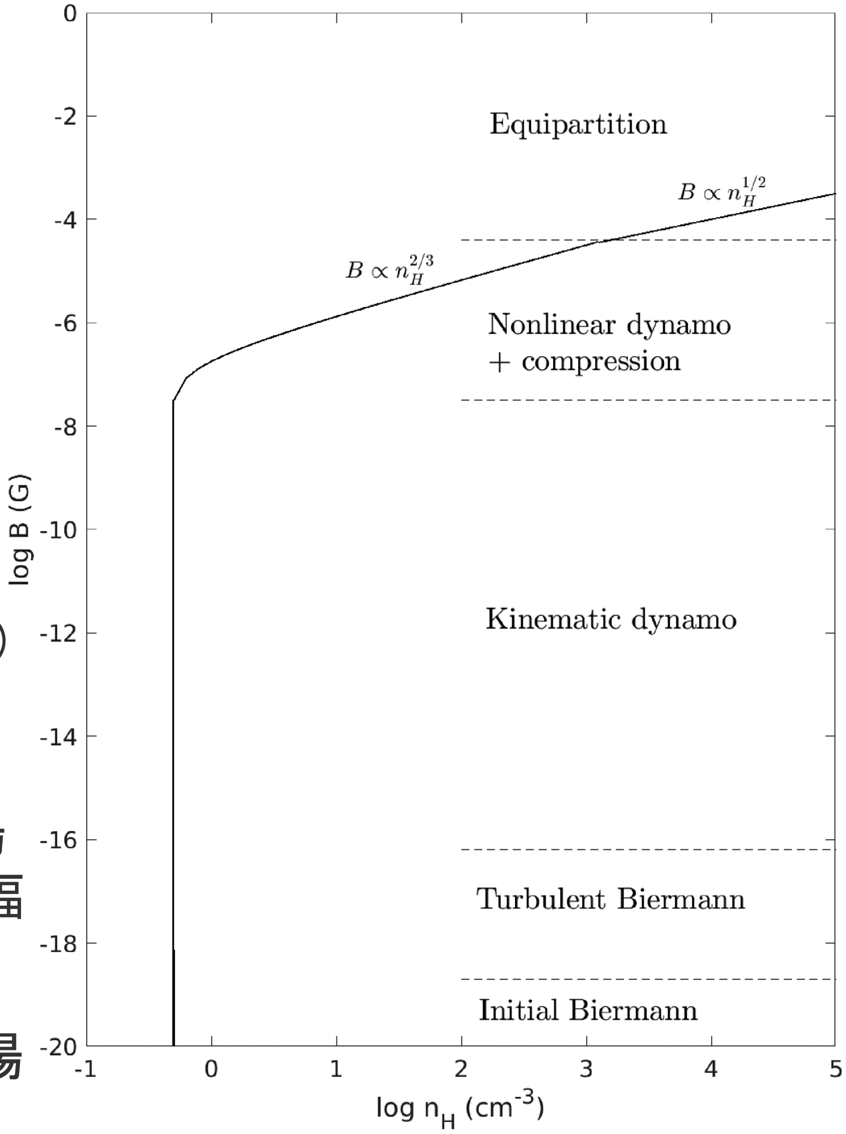
Machida+06,08, McKee+20, Sadanari+21,24, Sharda+21, Stacy+22, Prole+22, Saad+22, Hirano&Machida22, Latif+23, Higashi+24, Diaz+24

McKee+20

ビアマン機構で種磁場生成
乱流ダイナモで磁場増幅

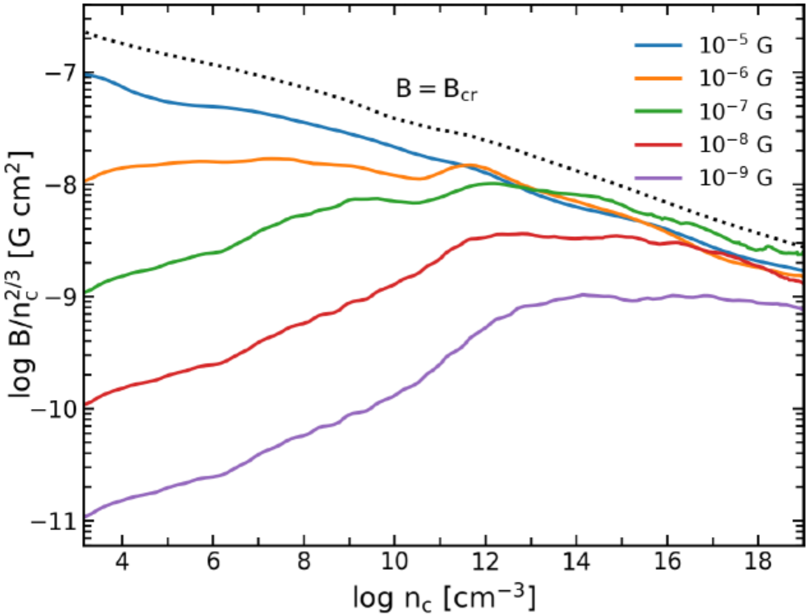


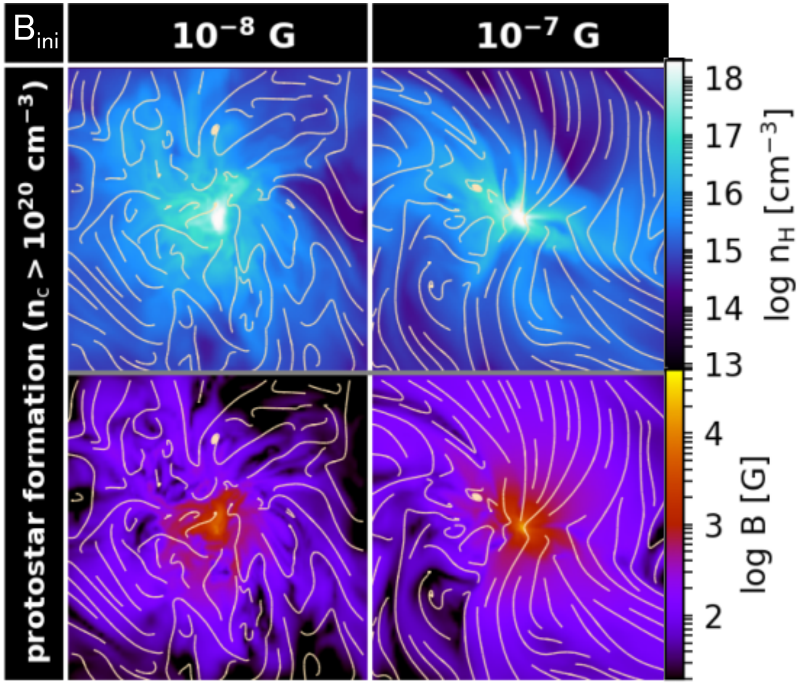
- 多くの研究で初代星形成時の磁場は弱いと仮定されていた (but, e.g., Machida+06,08)
- この論文で解析的に磁場が重要と主張
- ビアマン機構で生成した非常に弱い種磁場 (10^{-16}G) は、乱流ダイナモにより急激に増幅してエネルギー等分配に達する
- この論文のせいかは不明だが、初代星磁場のシミュレーションが流行



重力収縮期の磁場増幅

Sadanari+23





- 乱流ダイナモによって磁場が増幅しsaturation
- saturation後に磁場は徐々に揃う

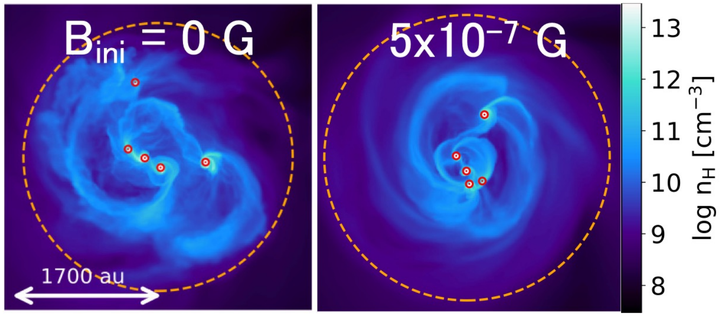
  ← Higashi+24のポリトロープ高解像度計算ではそのような様子は見られず
- 両極性拡散による加熱が効くという解析的予想（Schleicher+09）を否定

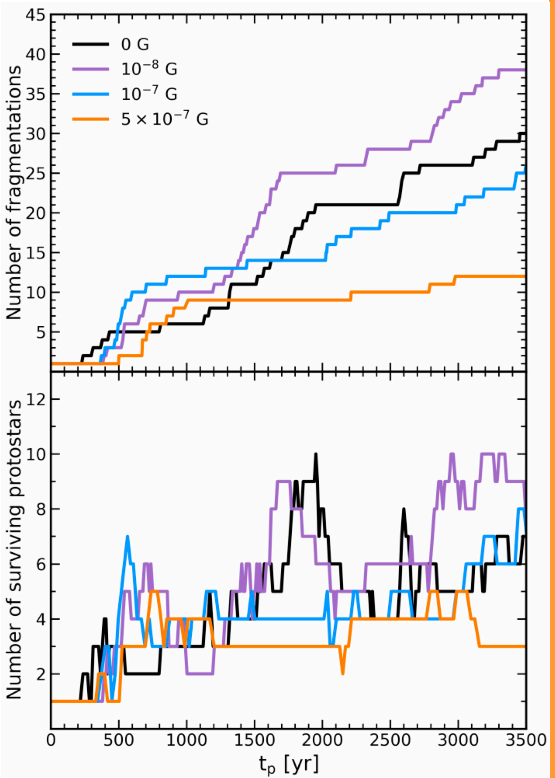
ダイナモによる磁場の増幅は多くのグループが確認
増幅の結果どんな磁場構造になるかは不確か

分裂への磁場の影響

Sadanari+24

- 分裂回数を抑制
- 合体のため原始星数への影響は小さい
- アウトフローは弱い





Prole+21

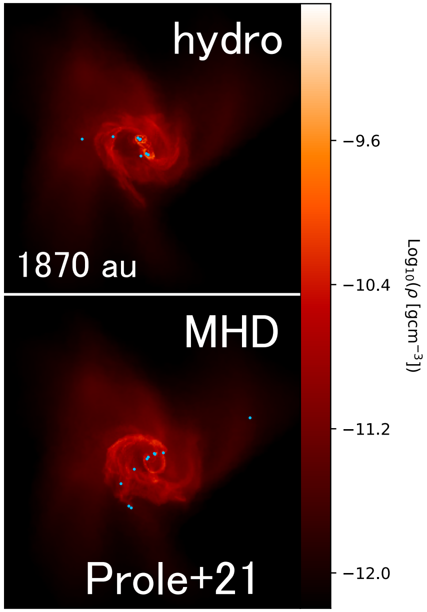
- 分裂への影響は小さい

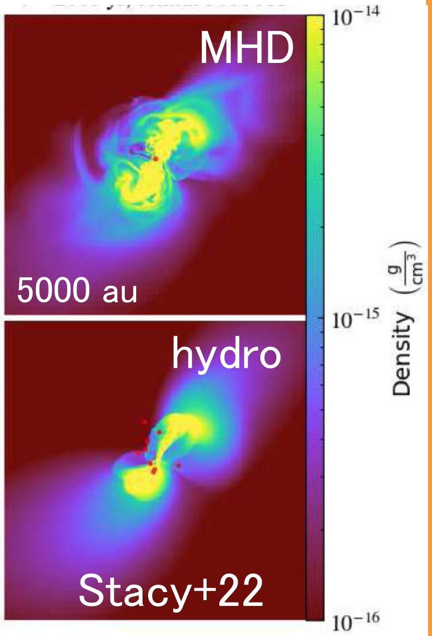
Stacy+22

- 分裂が完全に抑制されて単独星形成

磁場がどのくらい影響するか
グループ毎に結果が異なる

初期磁場の不定性が原因か？





超大質量星形成

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（$M \sim 10^5 M_{sun}$）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

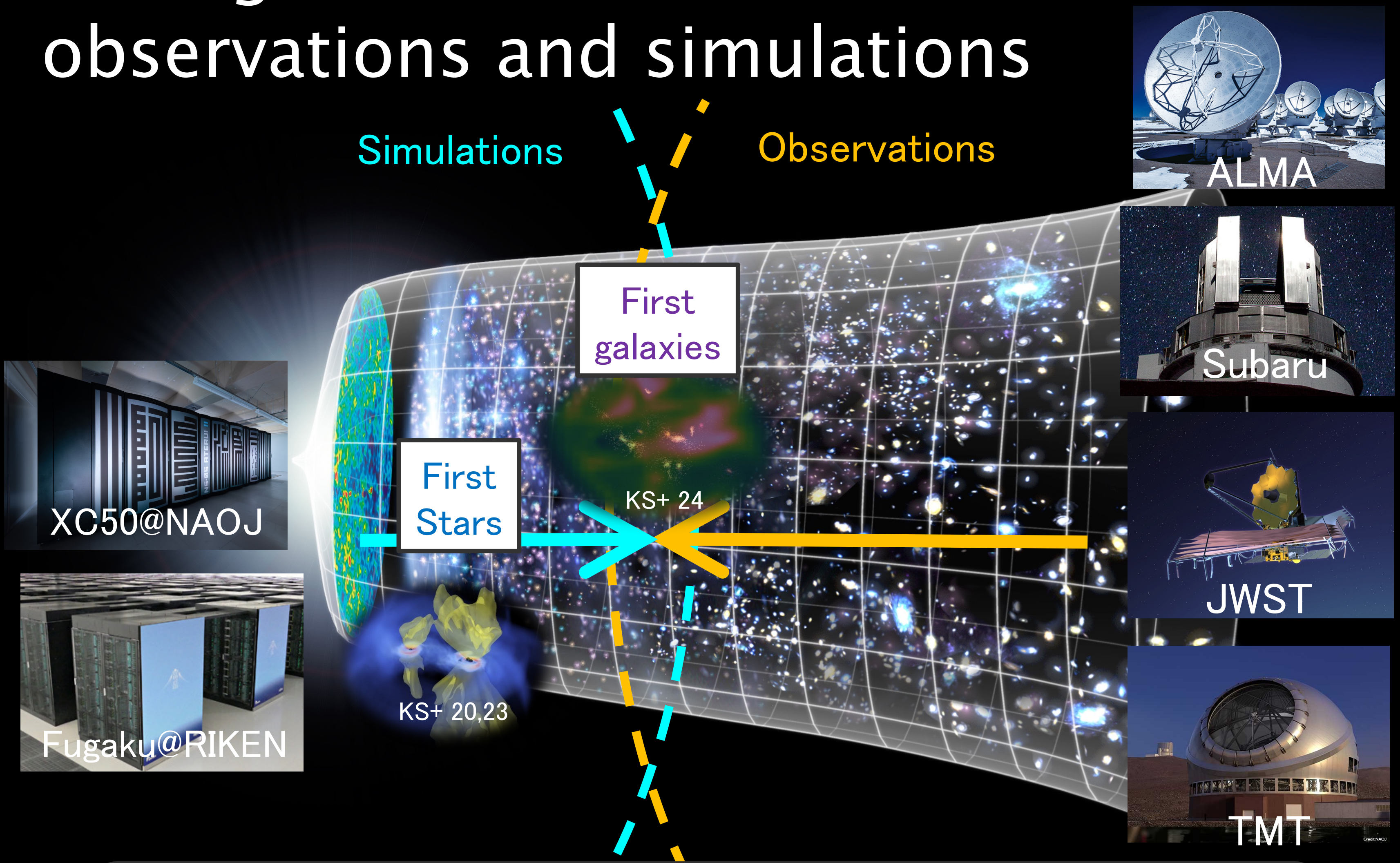
  → 場合によっては超新星爆発も起こる？

- 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

First-galaxies as frontiers for observations and simulations



Simulations

Observations

First galaxies

First Stars

KS+ 24

KS+ 20,23

XC50@NAOJ

Fugaku@RIKEN

ALMA

Subaru

JWST

TMT

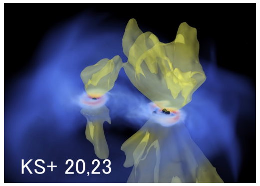
Credit:NAOJ

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

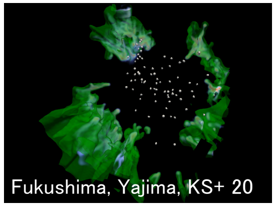
“Bottom-up” simulations of first galaxies

<pc-scale

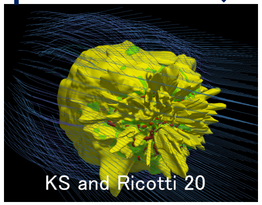
First stars


KS+ 20,23

Pop II clusters


Fukushima, Yajima, KS+ 20

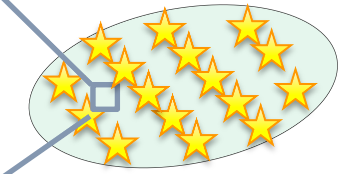
(Supermassive) BHs


KS and Ricotti 20

knowledge on small-scale processes
(not phenomenological models)

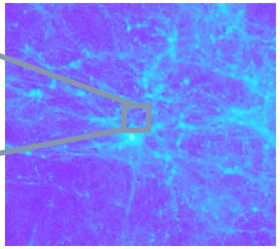
kpc-scale

First galaxy



>Mpc-scale

Large-scale structures



well-established ICs and evolution Eqs
(galaxy formation simulations)

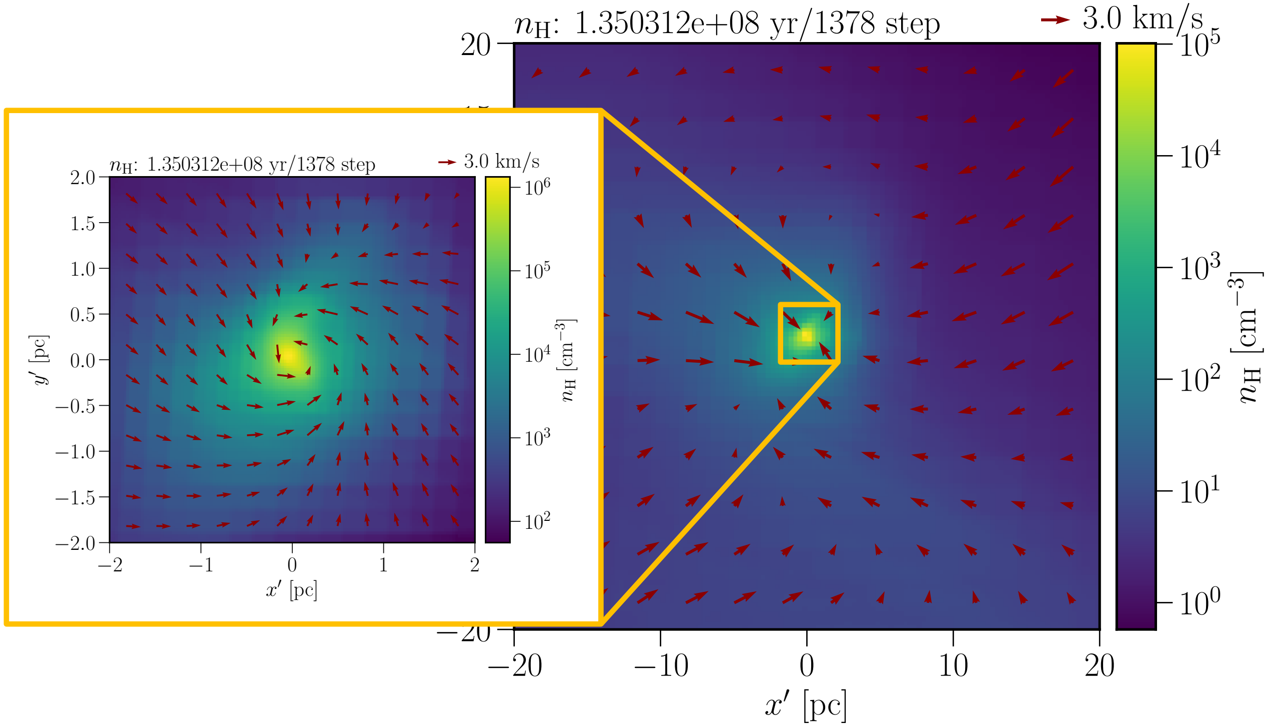
Reveal the first galaxy formation by combining simulations that solve the large-scale physical law and knowledge on small-scale processes

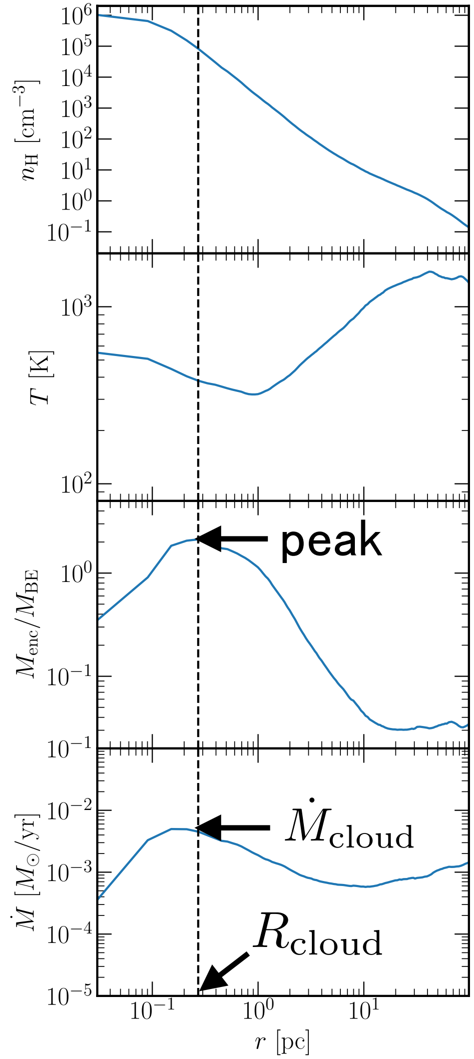
POP IIIの星質量の理解を初代銀河形成シミュレーションに統合

POP II IMFの理解の統合 → 石田さんトーク

Pop III star formation site in a first galaxy simulation

(data provided by Matsuda-kun)



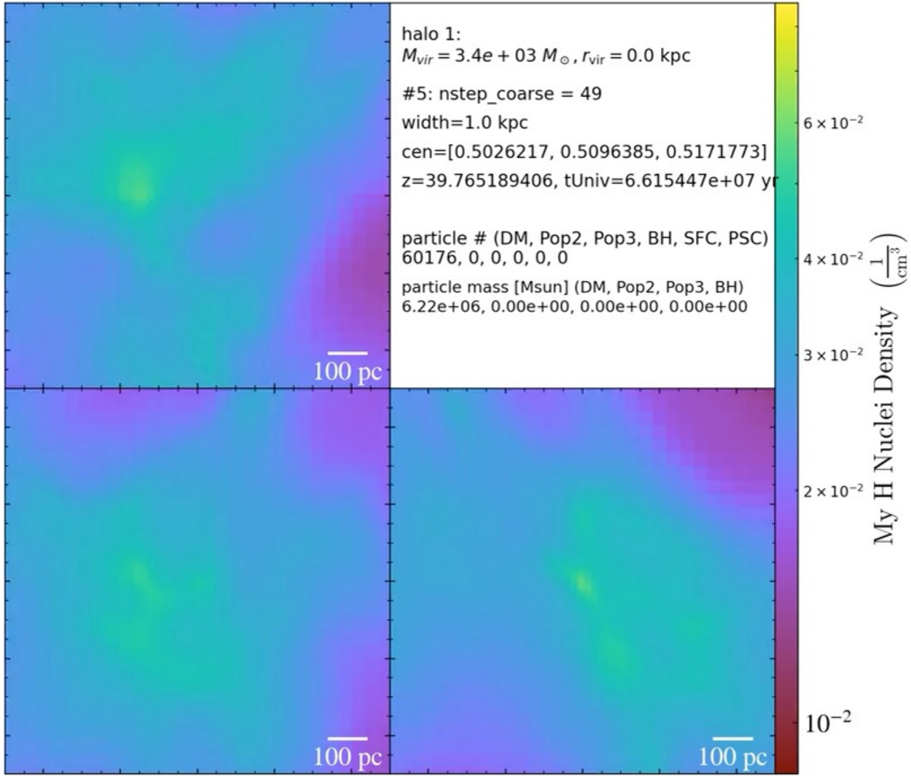


Pop III (total) mass can be estimated with the Hirano15 formula (see also KS+23)

$$M_\mathrm{tot} = 250\, M_\odot \left(\frac{\dot{M}_\mathrm{cloud}}{2.8 \times 10^{-3} M_\odot\,\mathrm{yr}^{-1}} \right)^{0.7}$$

Test run with the new Pop III model

previous model (M_{tot}=120M_{sun})

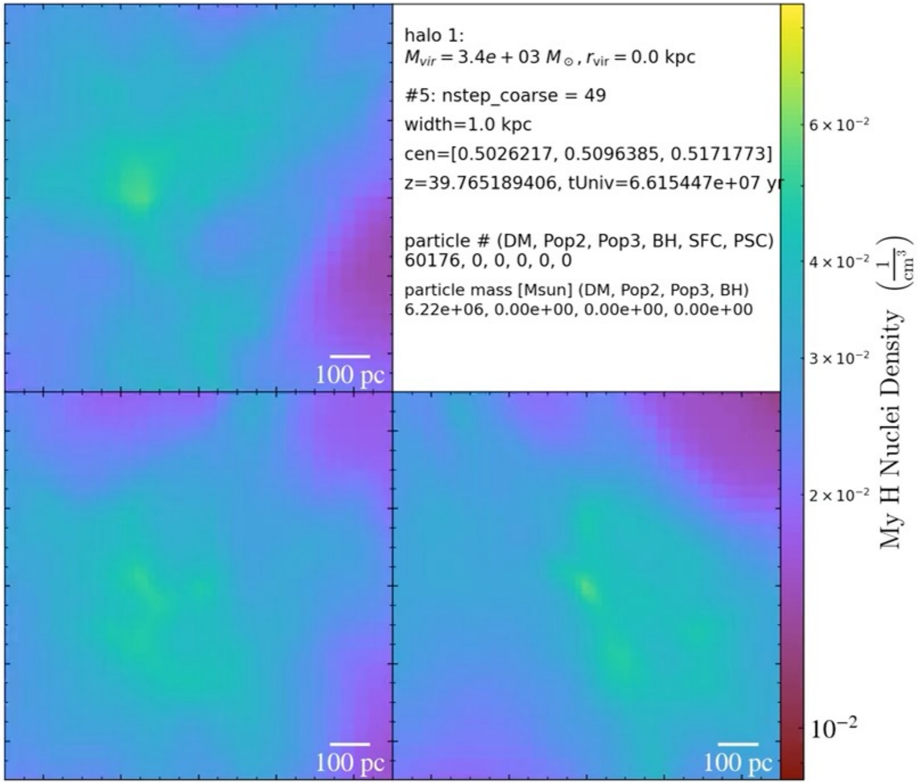


halo 1:
$M_{vir} = 3.4e+03\ M_\odot, r_{vir} = 0.0$ kpc

#5: nstep_coarse = 49
width=1.0 kpc
cen=[0.5026217, 0.5096385, 0.5171773]
z=39.765189406, tUniv=6.615447e+07 y

particle # (DM, Pop2, Pop3, BH, SFC, PSC)
60176, 0, 0, 0, 0, 0
particle mass [Msun] (DM, Pop2, Pop3, BH)
6.22e+06, 0.00e+00, 0.00e+00, 0.00e+00

new model (Mdot-dep M_{tot})



halo 1:
$M_{vir} = 3.4e+03\ M_\odot, r_{vir} = 0.0$ kpc

#5: nstep_coarse = 49
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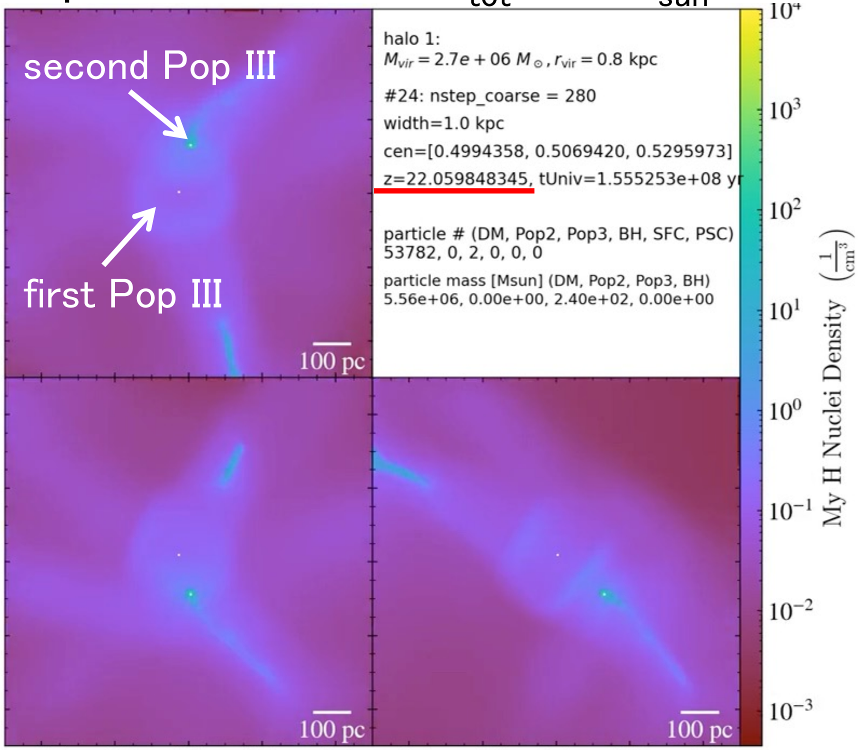
z=39.765189406, tUniv=6.615447e+07 y

particle # (DM, Pop2, Pop3, BH, SFC, PSC)
60176, 0, 0, 0, 0, 0
particle mass [Msun] (DM, Pop2, Pop3, BH)
6.22e+06, 0.00e+00, 0.00e+00, 0.00e+00

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

For instance, second Pop III formation proceeds differently

previous model（M_{tot}=120M_{sun}）



halo 1:
$M_{vir} = 2.7e + 06\ M_\odot, r_{\rm vir} = 0.8$ kpc

#24: nstep_coarse = 280

width=1.0 kpc

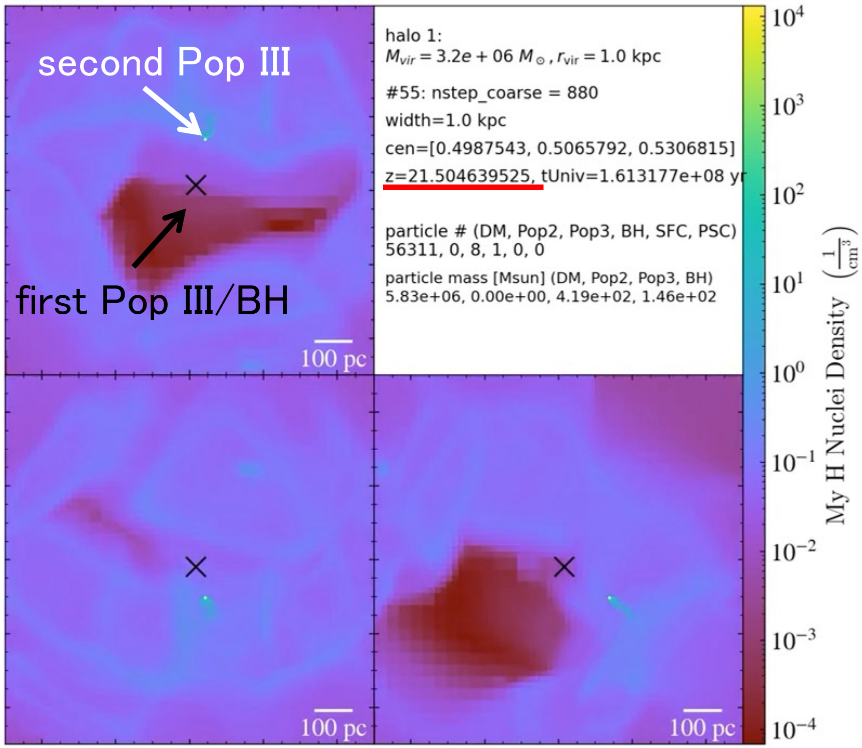
cen=[0.4994358, 0.5069420, 0.5295973]

z=22.059848345, tUniv=1.555253e+08 yr

particle # (DM, Pop2, Pop3, BH, SFC, PSC)
53782, 0, 2, 0, 0, 0

particle mass [Msun] (DM, Pop2, Pop3, BH)
5.56e+06, 0.00e+00, 2.40e+02, 0.00e+00

new model（Mdot−dep M_{tot}）



halo 1:
$M_{vir} = 3.2e + 06\ M_\odot, r_{\rm vir} = 1.0$ kpc

#55: nstep_coarse = 880

width=1.0 kpc

cen=[0.4987543, 0.5065792, 0.5306815]

z=21.504639525, tUniv=1.613177e+08 yr

particle # (DM, Pop2, Pop3, BH, SFC, PSC)
56311, 0, 8, 1, 0, 0

particle mass [Msun] (DM, Pop2, Pop3, BH)
5.83e+06, 0.00e+00, 4.19e+02, 1.46e+02

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、
初代銀河形成の真の姿に迫ることを目指す！！

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 H_2 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