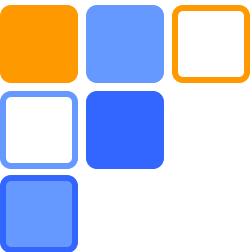


初代星形成シミュレーションの 最近の進展 (2021年以降くらい)





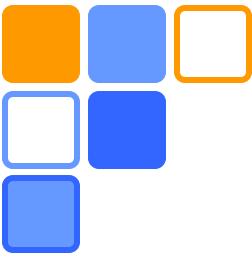
Contents

□ 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)

First(-gen.) star
formation@ $z \sim 30$

Stellar light

BH

Supernova

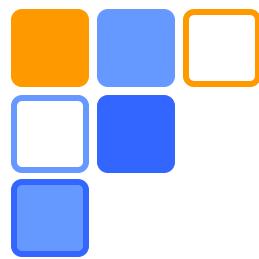
formation of
the rest of
all objects



Milky Way

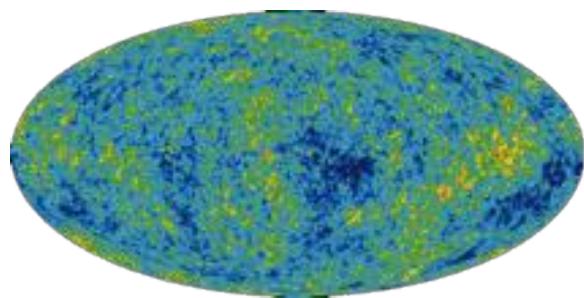
© NASA/WMAP Science Team

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

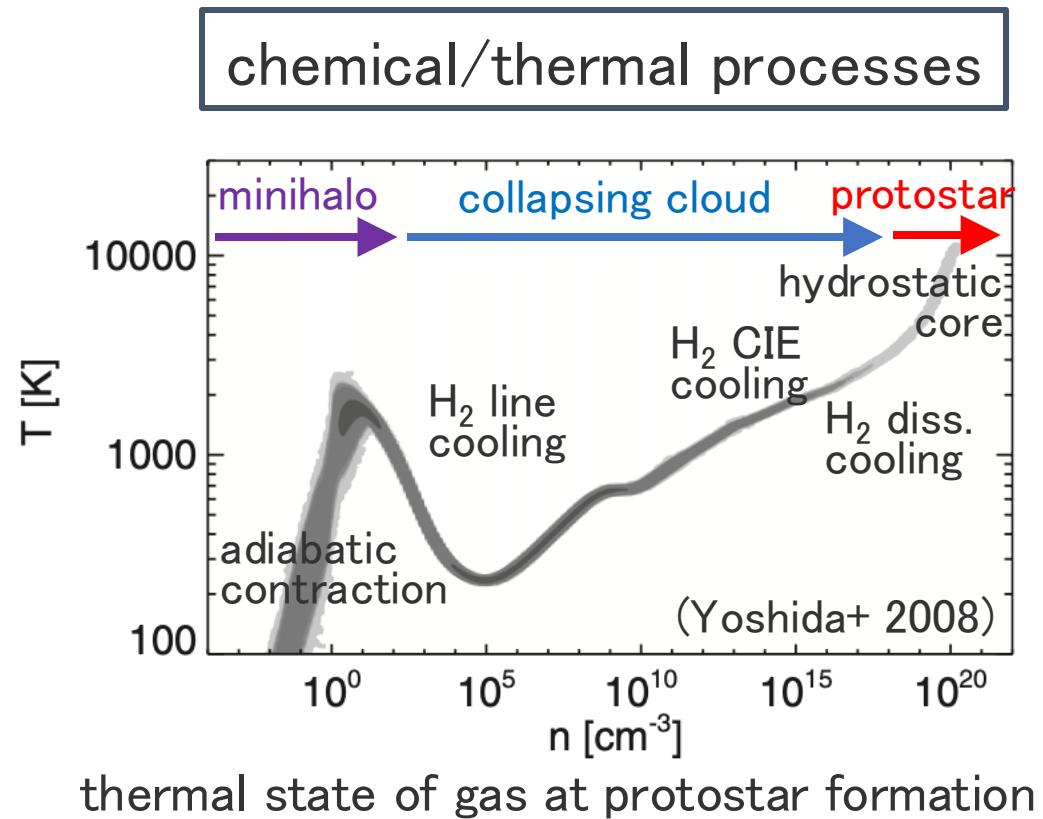


Uniqueness of the first stars: possible target for first-principle understanding

initial condition



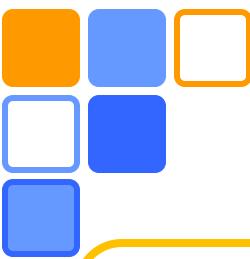
CMB fluctuations
from WMAP/Planck



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) 5



Big goal of first star studies

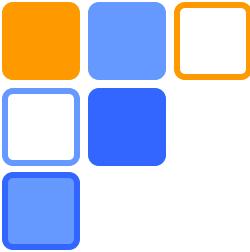
Determining the properties of the first stars from the first principle



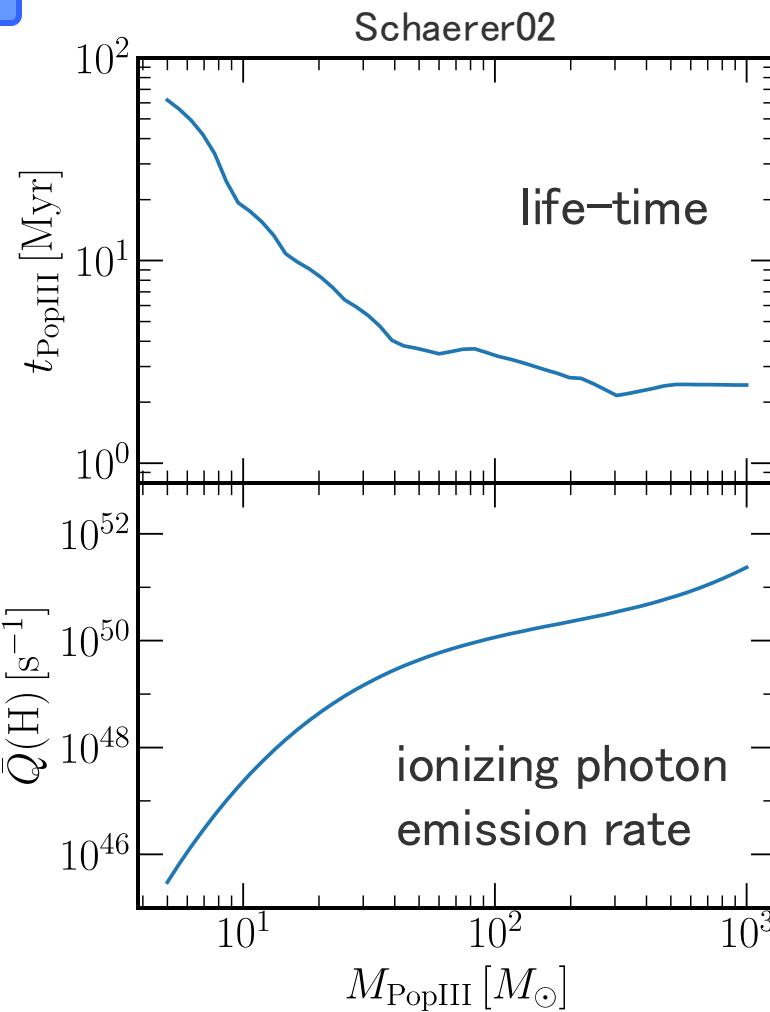
mass, spin, magnetization, multiplicity, number of stars,
mass-ratio, orbital separation, eccentricity, etc.

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

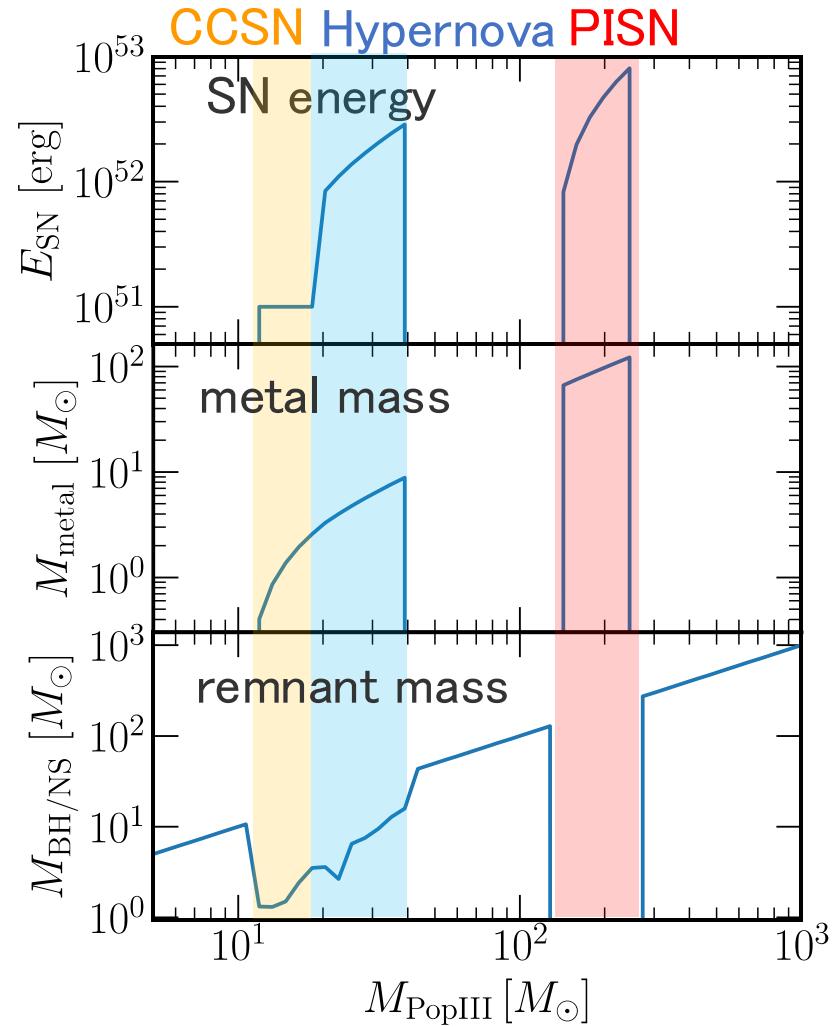
- parent halo's mass, size, shape, formation history
- background field (FUV, EUV, X-ray, CR)
- turbulence, fragmentation, 3-body interactions



Pop III mass is of particular interest

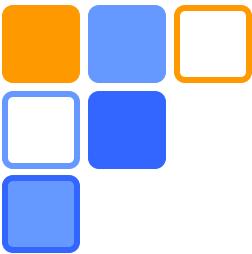


Wise+12 based on Heger&Woosley02, Nomoto+06



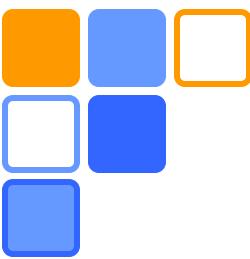
Pop III mass determines the strength of the feedback

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



Simulations from big bang to completion of first star formation

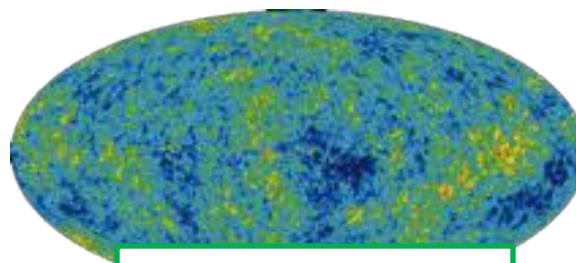
OVERALL PICTURE



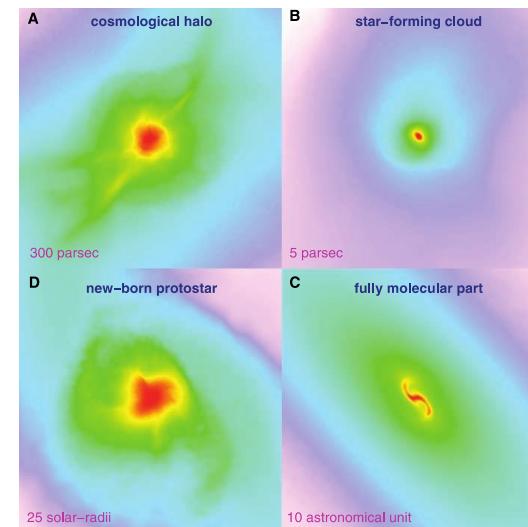
Pop III formation in simulations 1: From Big Bang to first protostar

□ Cosmological hydro simulations

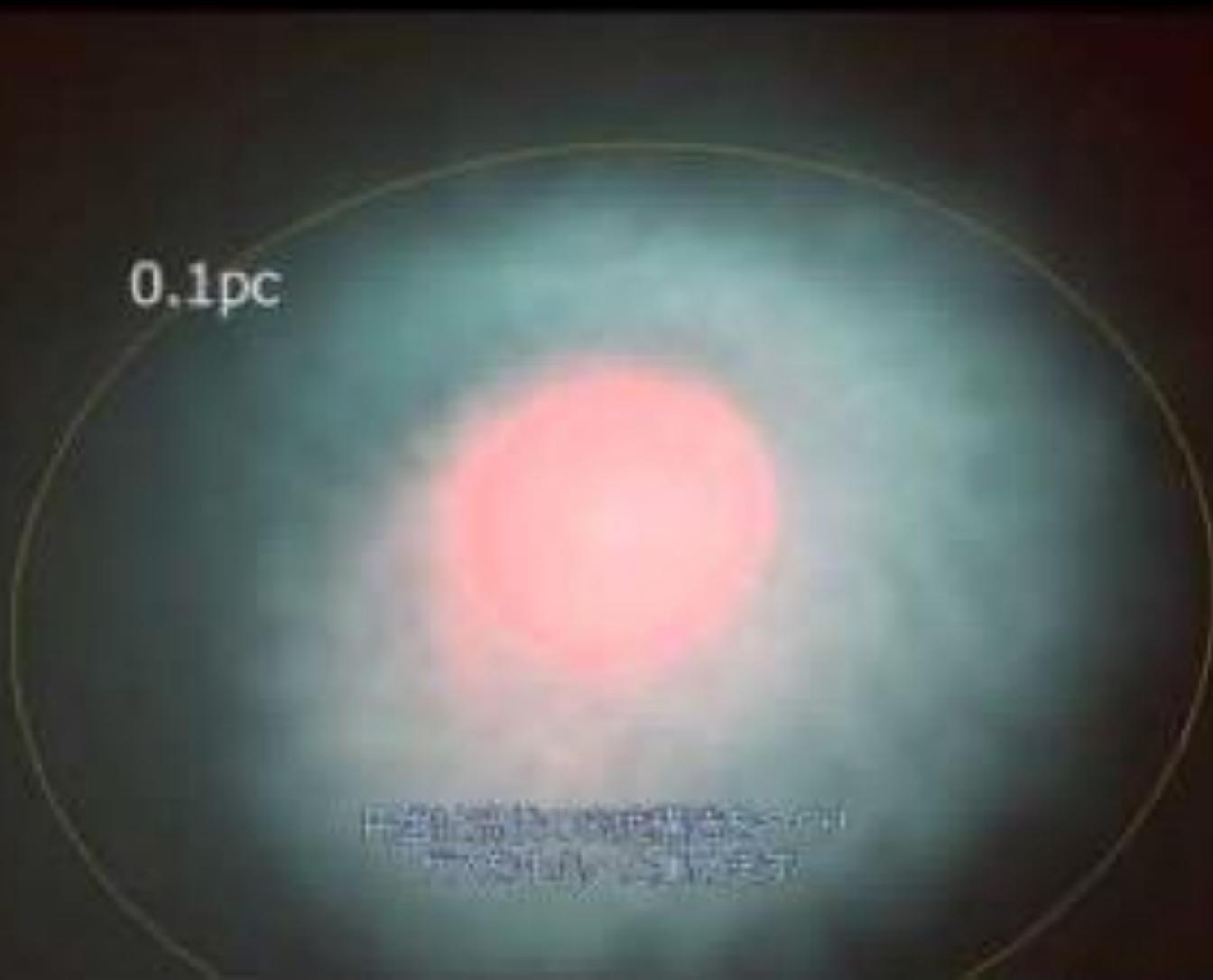
- starting from cosmological initial condition
- DM+gas simulation w/ all relevant chemical & thermal processes
- tiny (~ 0.01 Msun) protostar forms at the center of small DM halo with $M_{\text{DM}} \sim 10^5\text{--}10^6$ M_{sun} (= minihalo) at $10 \lesssim z \lesssim 30$



cosmological
initial condition



A movie for the birth of first protostar

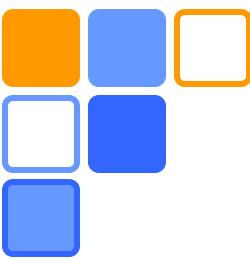


<https://youtu.be/2COt OTAENg>

Hirano et al. (2014)

10

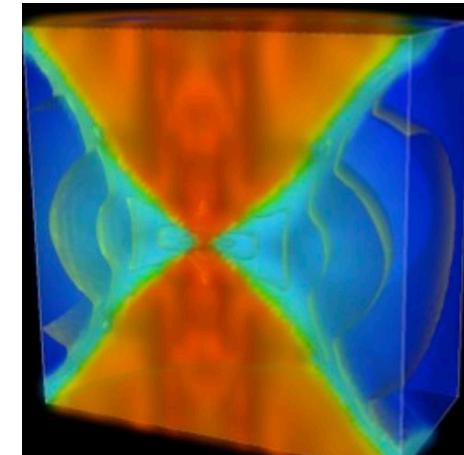
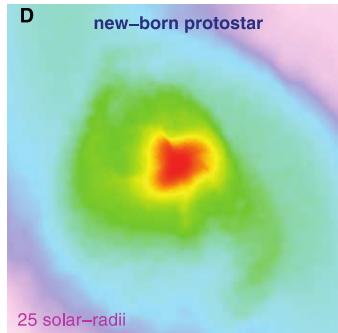
movie credit: Takeda



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

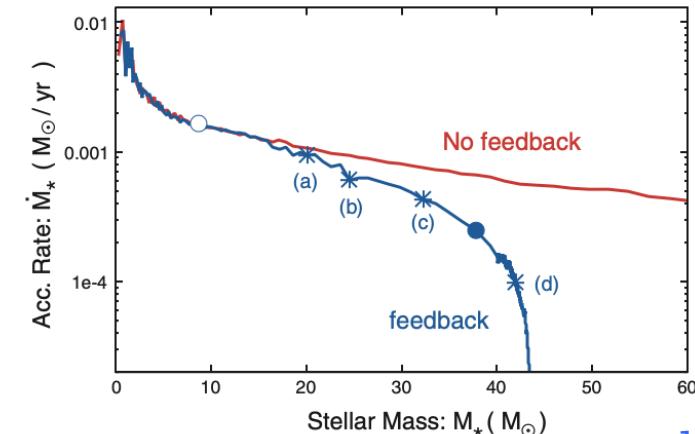
Zoom-in radiation hydro simulations

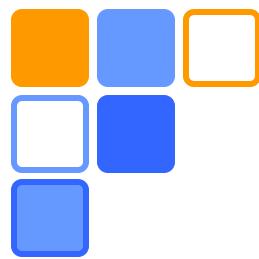
Hosokawa, Omukai, Yoshida, Yorke 2011 (Science)



- tiny protostar grows to massive star ($>10M_{\text{sun}}$) by accreting surrounding gas
- gas accretion is quenched by stellar radiation feedback
- final mass of star is $\sim 40 M_{\text{sun}}$ in this case

(see McKee&Tan 2008 for analytical argument)

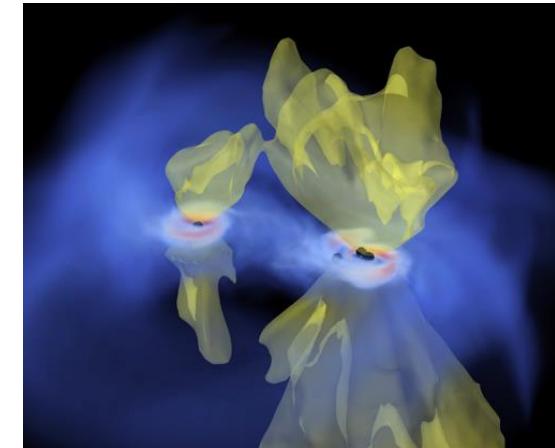
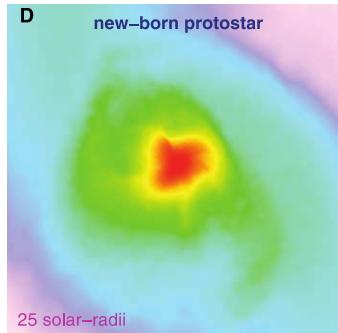




Pop III formation in simulations 3: Formation as binary/multiple stars

□ Zoom-in radiation hydro simulations with 3D AMR

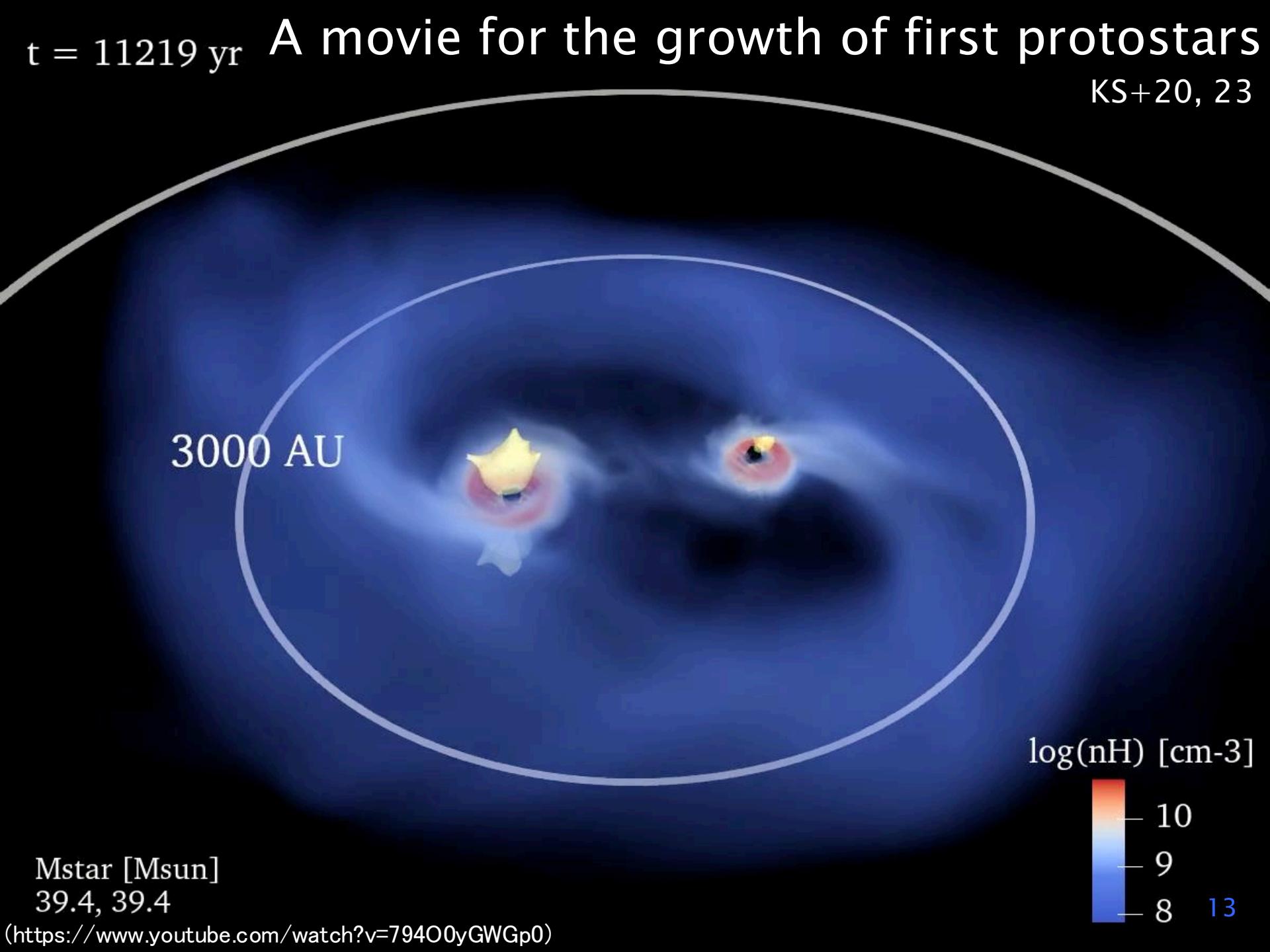
KS, Matsumoto, Hosokawa, Omukai, Hirano (2020,2023)



- 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)

$t = 11219$ yr A movie for the growth of first protostars

KS+20, 23

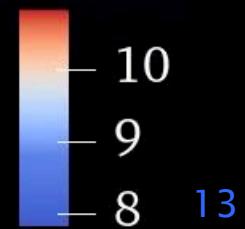


3000 AU

Mstar [Msun]
39.4, 39.4

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

$\log(nH)$ [cm⁻³]



simulation set-up

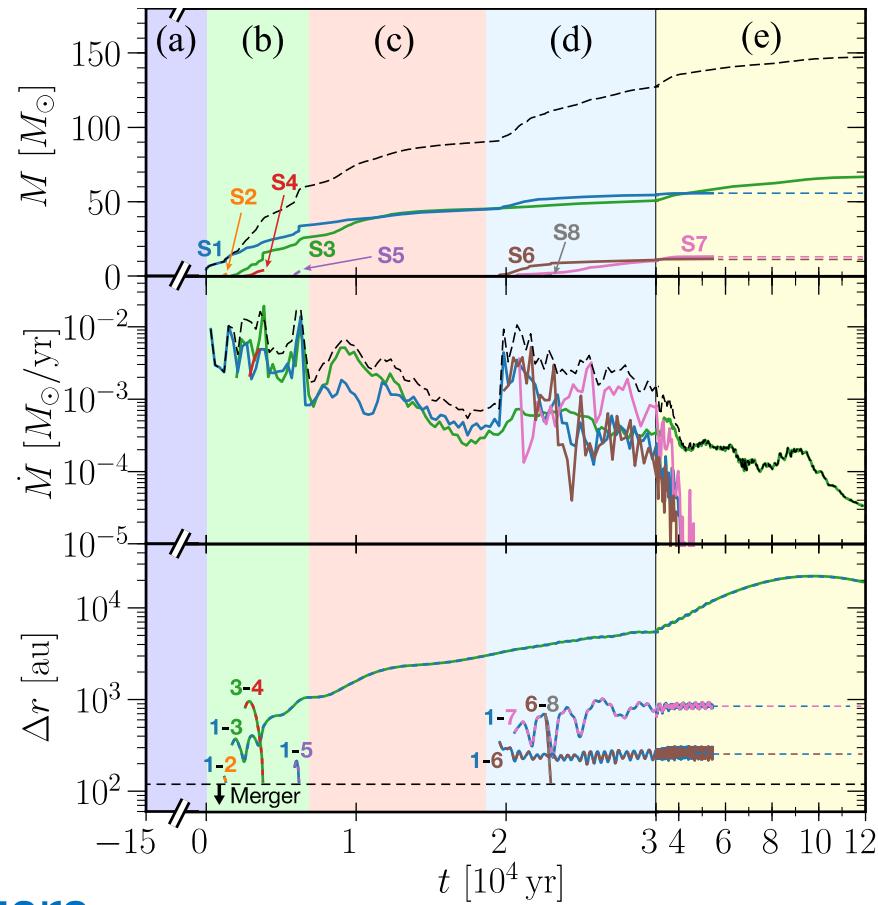
- code: SFUMATO-RT (Matsumoto07, KS+20)
- $n_{\text{sink}} = 10^{11} \text{ cm}^{-3}$, $\Delta x_{\text{min}} = 4 \text{ au}$, $r_{\text{sink}} = 64 \text{ au}$
- minimum # of cells/Jeans length : 16
- $t_{\text{end}} = 10^5 \text{ yr}$ since protostar formation

Final product

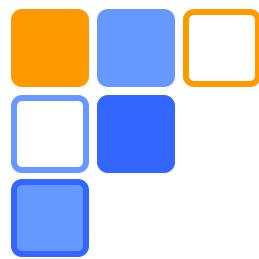


A system of wide massive multiple stars

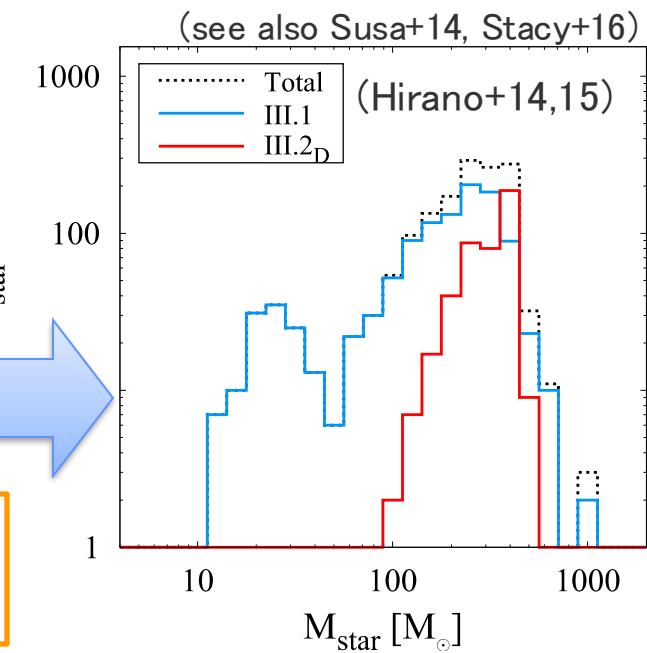
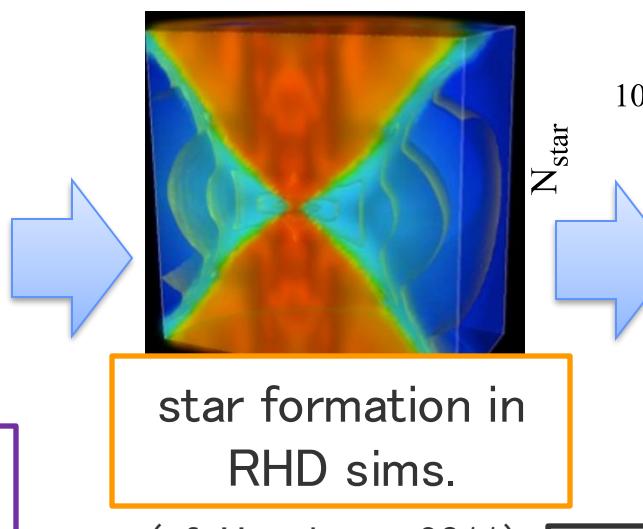
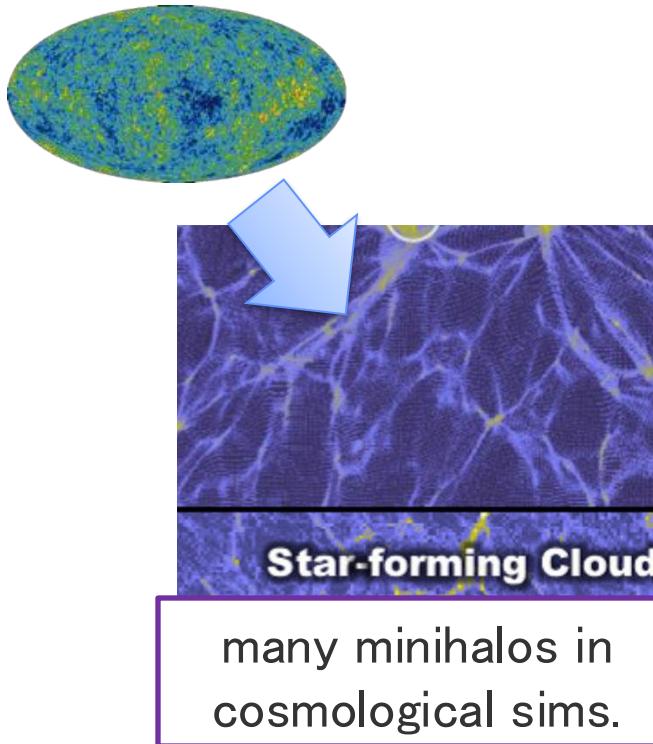
Protostar (sink) evolution



(t : time after 1st sink formation)



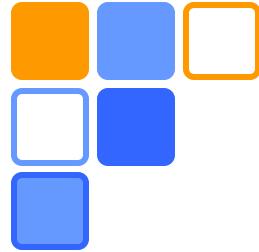
Pop III formation in simulations 4: from single case to statistics



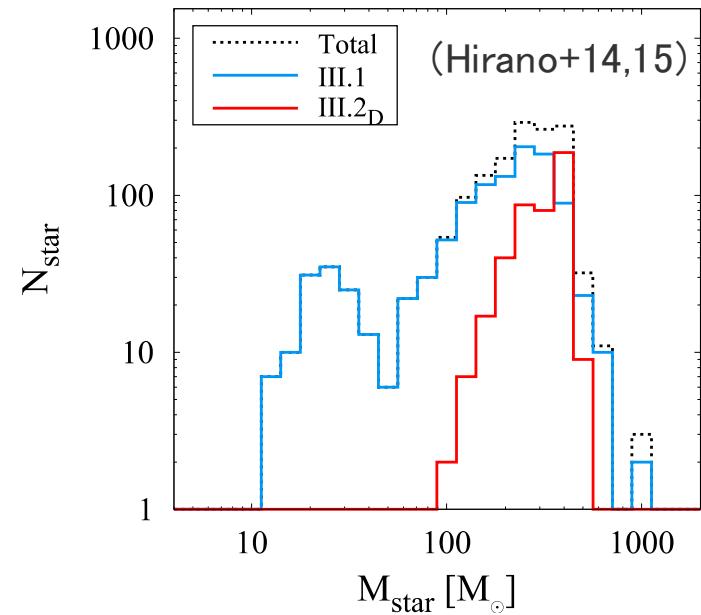
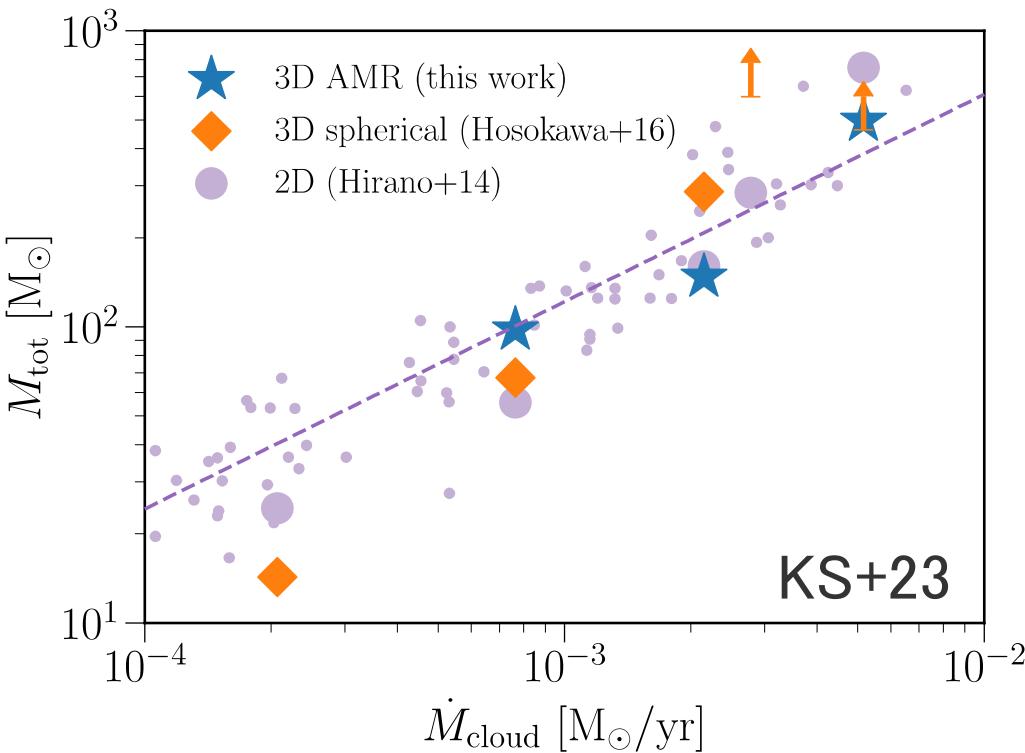
- Pop III stars tend to be massive ($\sim 100 \text{M}_{\text{sun}}$)
 \leftrightarrow Milky-Way ordinary stars ($\sim 1 \text{M}_{\text{sun}}$)
- This Pop III IMF is based on 2D simulations

initial = birth-time

↑
final time in simulations!



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



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

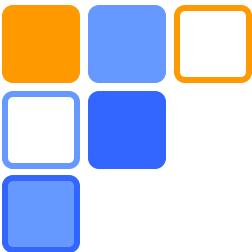
$$M_{\text{tot}} = 250 \text{ } M_\odot \left(\frac{\dot{M}_{\text{cloud}}}{2.8 \times 10^{-3} M_\odot \text{ yr}^{-1}} \right)^{0.7}$$

← confirmation of this conjecture with large sample is future work

mass of a single star (2D)



total mass of multiple stars (3D)



recent progress and open questions

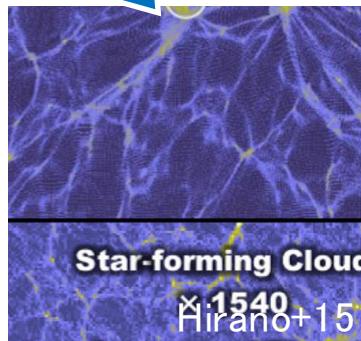
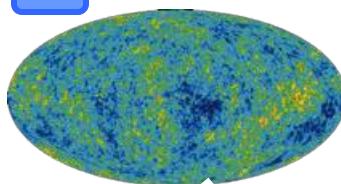
RECENT TOPICS (2021-)

(orange reference: publication since 2021)

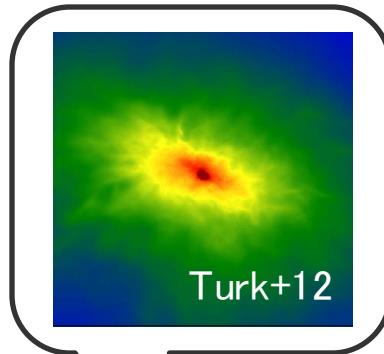
2021年以降の論文に関して見落としがあったら教えてください！

最近の初代星レビュー論文: Klessen & Glover (2023)

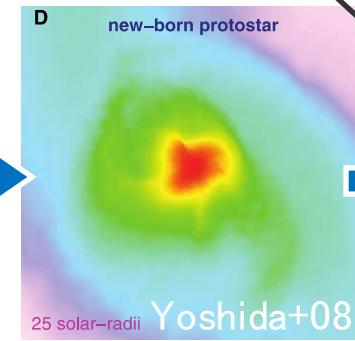
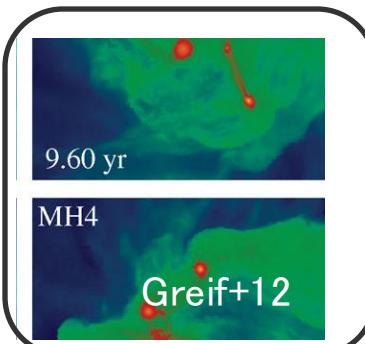
Topics related to Pop III formation



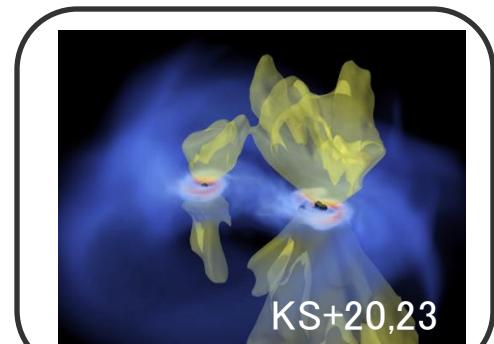
ミニハロー



収縮期



原始星



降着期

初代星

乱流

増幅

ガス分裂・合体

輻射

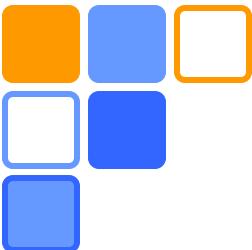
冷却

解離・電離

磁場

増幅

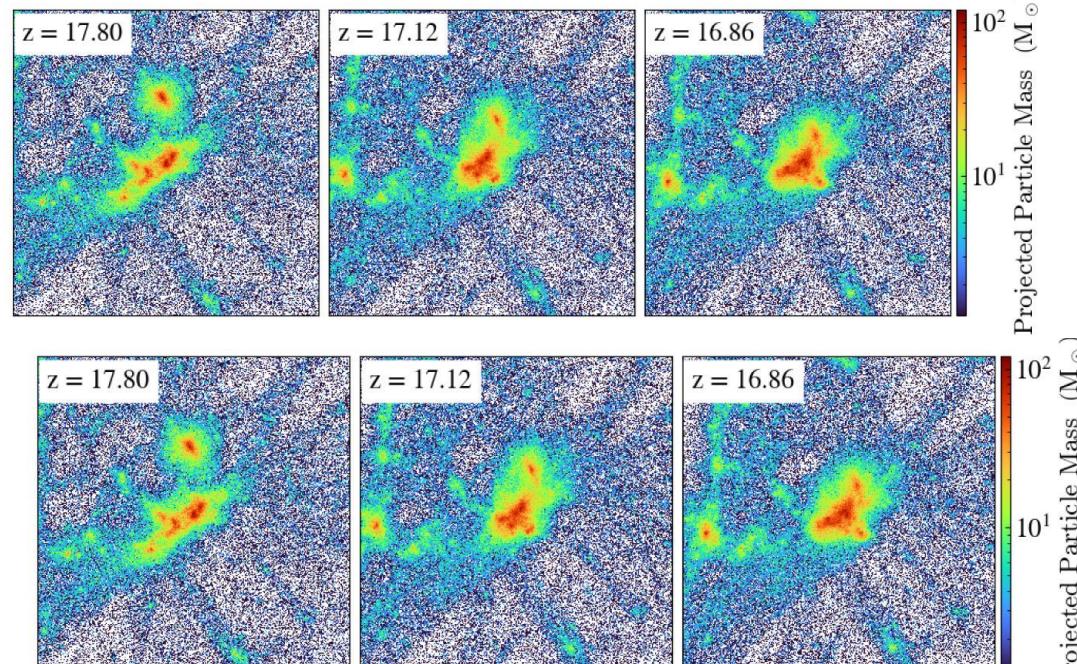
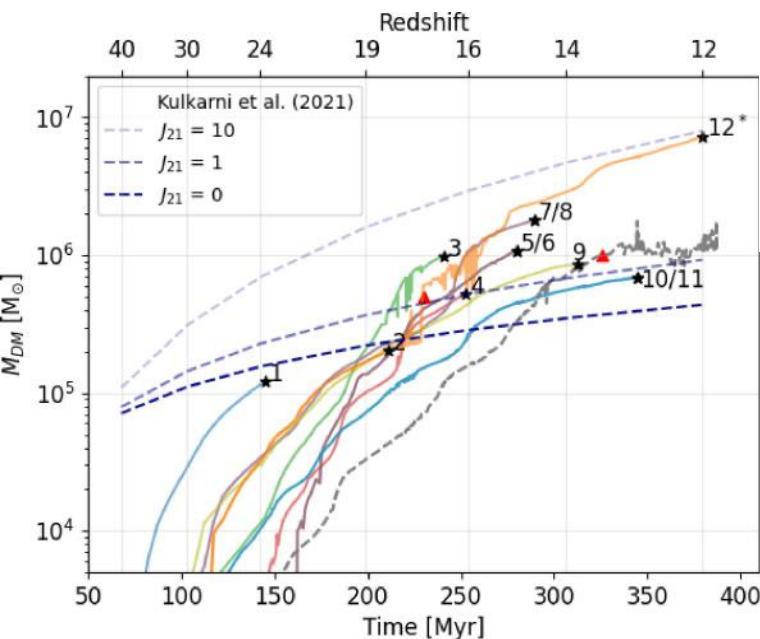
分裂抑制・フィードバック



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

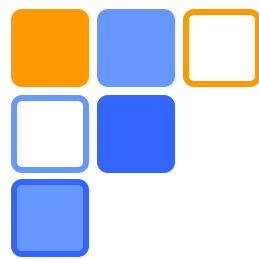
Correa Magnus+23



- Enzo, 高解像度計算 ($M_{DM} = 1 M_{\odot}$)
- 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



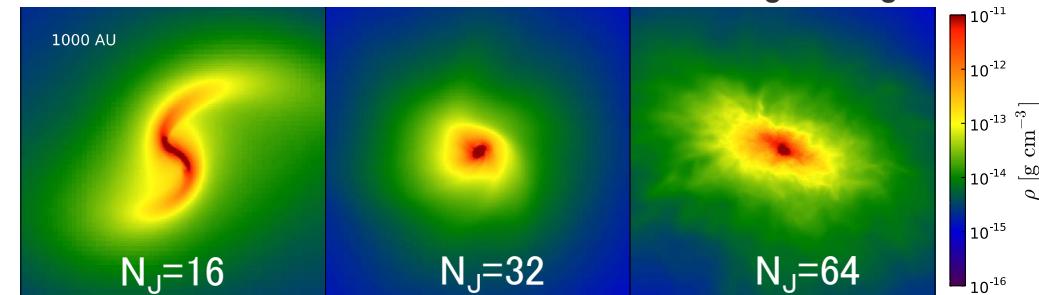
重力収縮期の乱流増幅

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

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

Turk+12

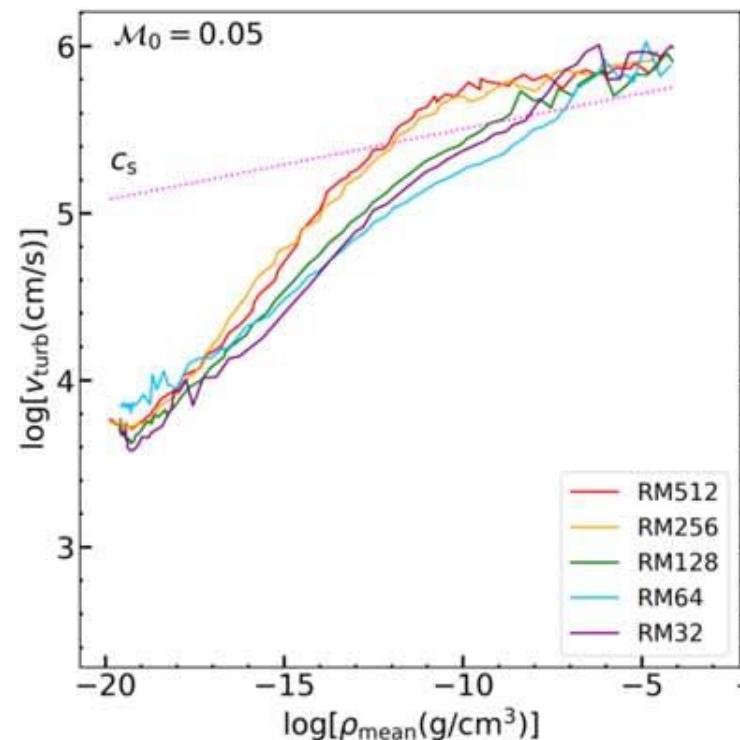
- Truelove条件 $N_J=4$ は重力収縮を記述するのに全然不十分



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

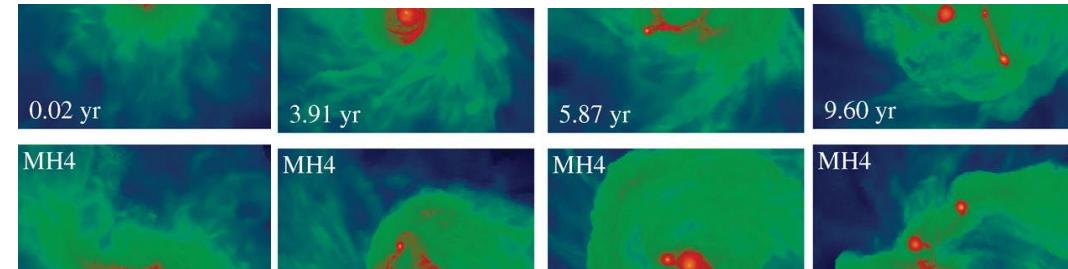
大抵の場合、重力収縮中のガスは超音速乱流状態にあると考えられる



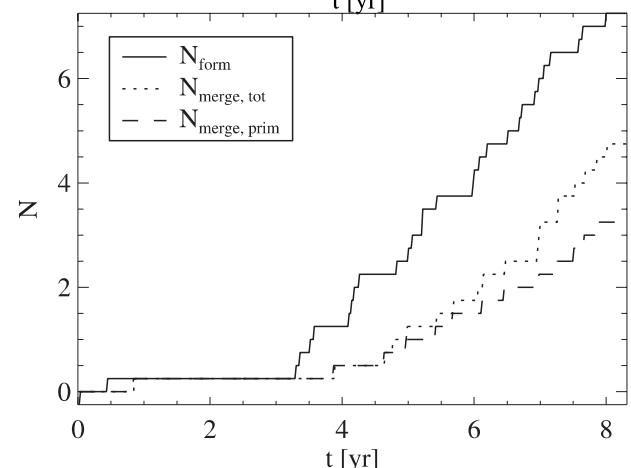
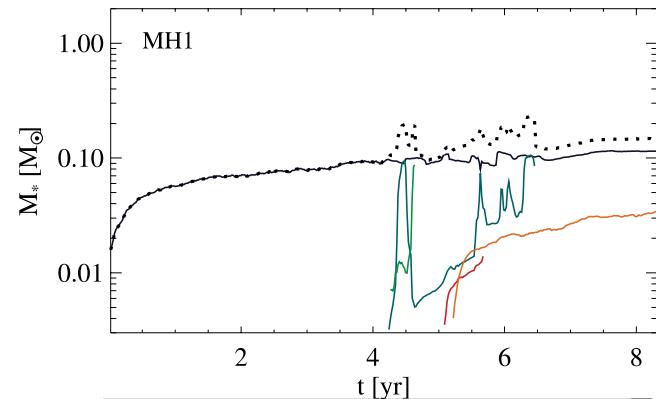
原始星形成直後の進化

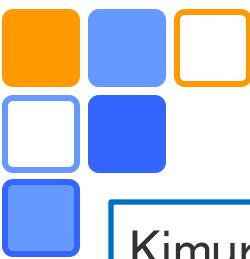
Omukai&Nishi98, Yoshida+08, Greif+12, Luo+18, Kimura+23

Greif+12



- AREPO (moving mesh), $\Delta x \sim 10^{-4}$ 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

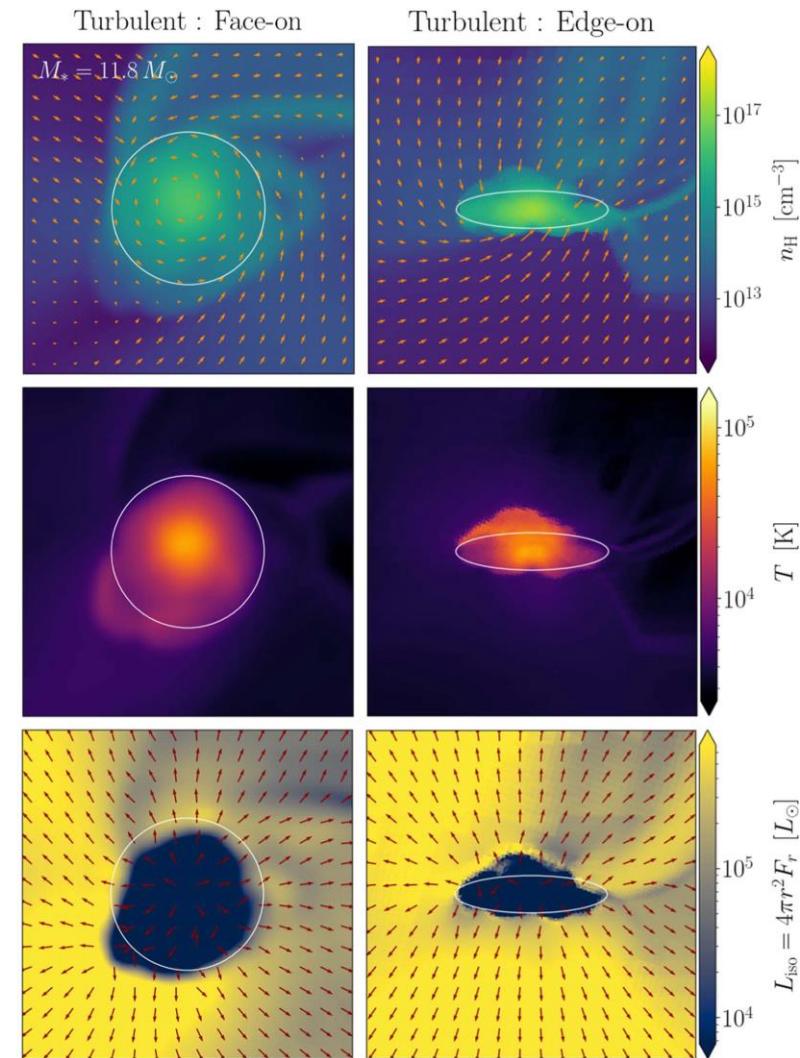




星の内部まで考慮した輻射流体計算

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、 $\dot{M}_{\text{dot}} \sim 1 M_{\text{sun}}/\text{yr}$)
- 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, Kirihsara+24, Park+24, Saavedra-Bastidas+24

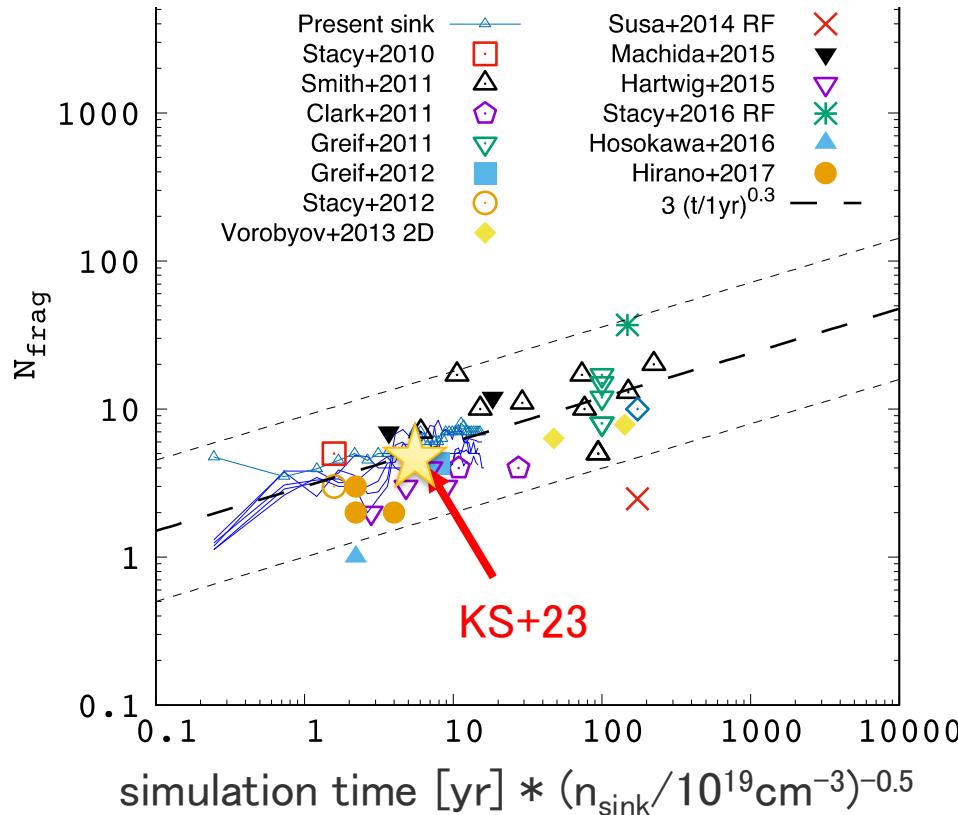
Susa19

- シミュレーションに基づく分裂と合体の解析的モデル

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

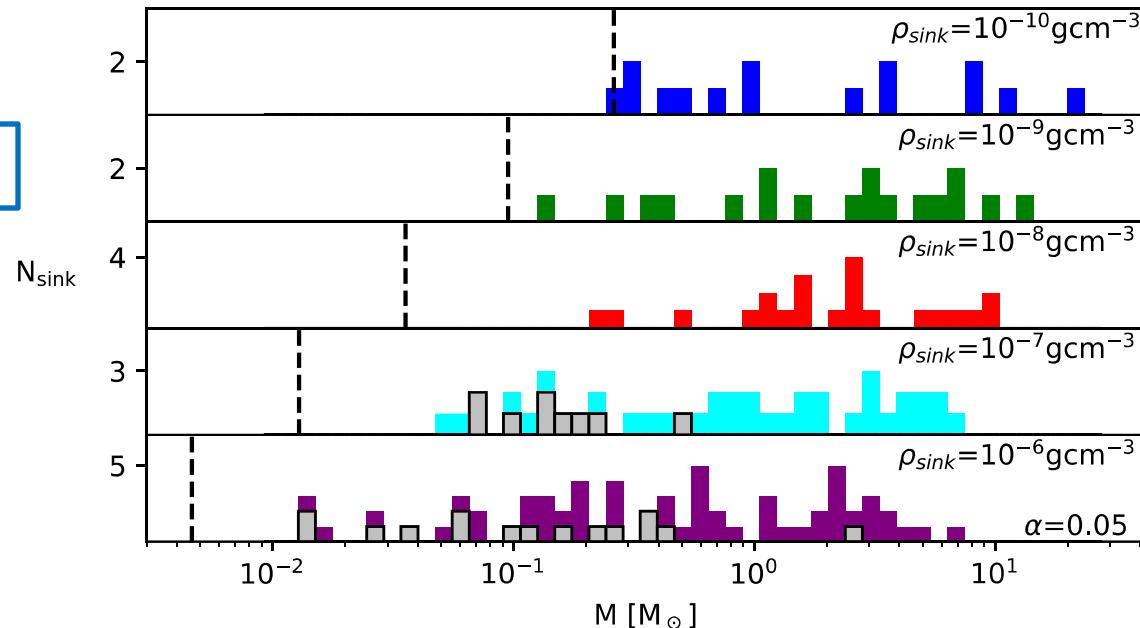
- 周星円盤の分裂と分裂片同士の合体をモデル化
- 様々な状態方程式を仮定した計算によると、分裂の仕方は状態方程式に依って大きく変わりそう
 $\leftarrow \gamma_{\text{eff}}$ 大きいと分裂しにくい

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



ガス分裂の解像度依存性

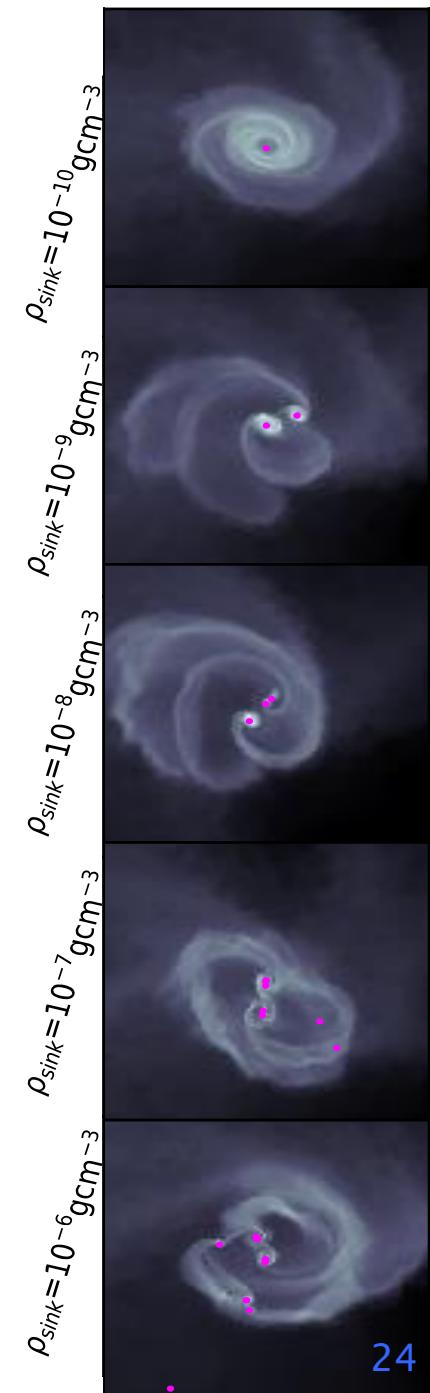
Prole+22



- 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

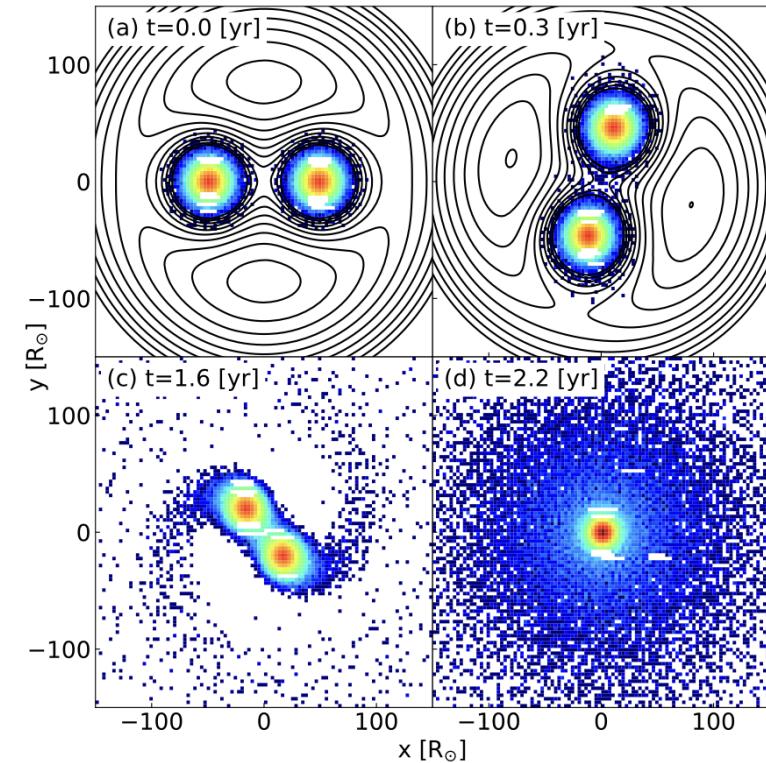
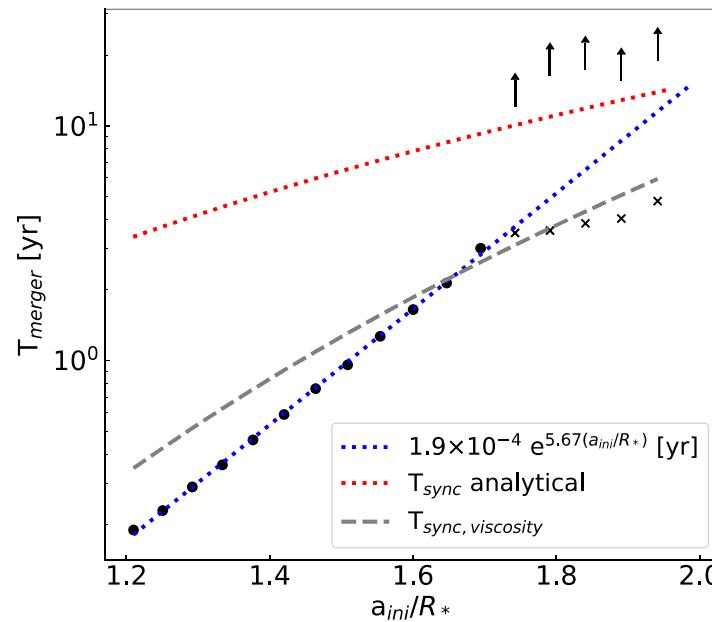
(Saavedra-Bastidas+24)

寡占的成長と総中流的成长を分ける条件は？



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て合体
- 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

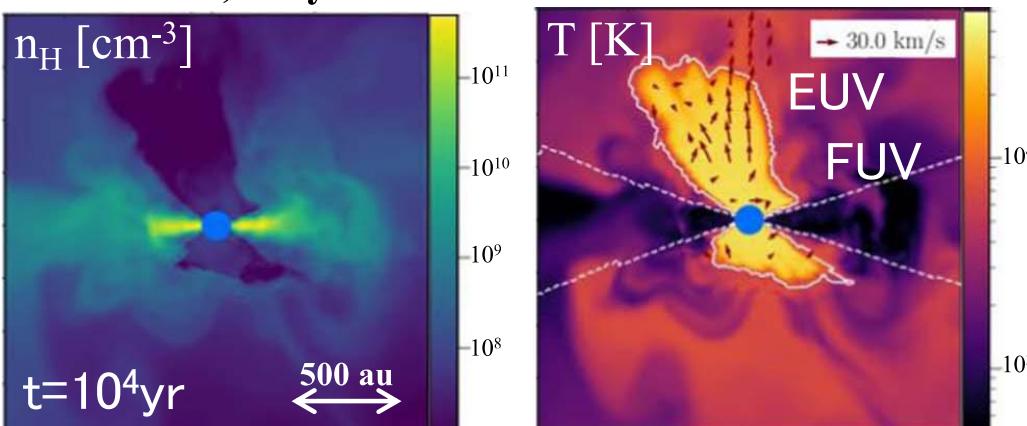
低解像度のシミュレーションで合体をどう扱うべきか?



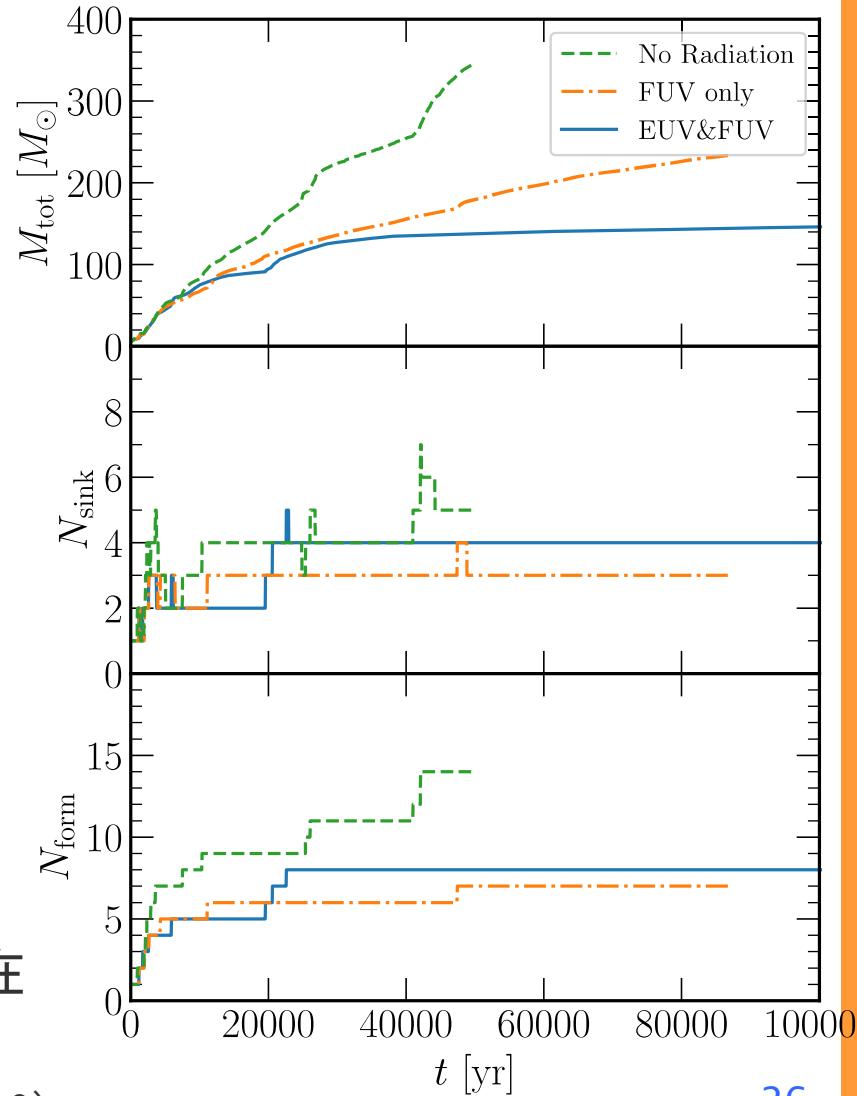
輻射フィードバック下の原始星成長

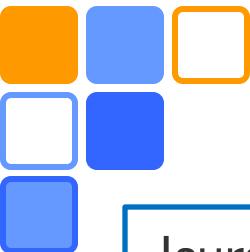
McKee&Tan08, Hosokawa+12,16, Stacy+13,16, Susa13, Susa+14, KS+20,23, Latif+22, Jaura+22, Park+23, Toyouchi+23, Sharda&Menon24, Chon+24

KS+20, 23



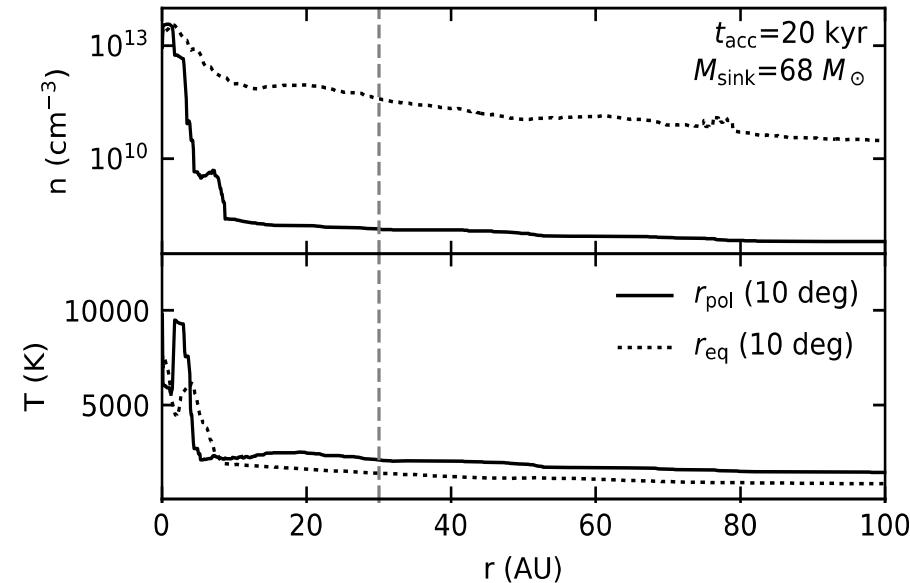
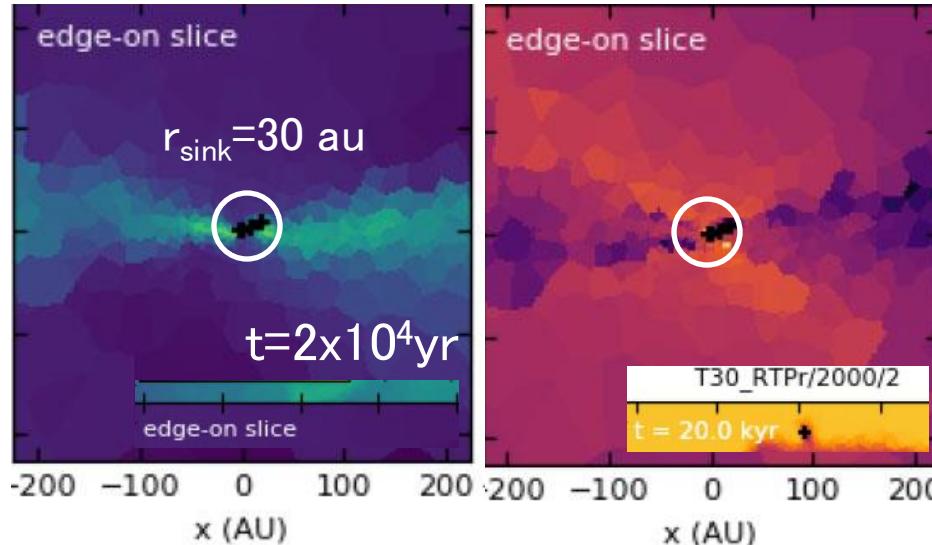
- FUV(H_2 解離光子)が初期($\sim 10^4$ yr)に効く
 - ✓ 降着率・分裂を抑制
- EUV(電離光子)は後で($\sim 3 \times 10^4$ yr)効く
 - ✓ 最終的に降着を止める
 - ✓ bipolar電離バブルは前($\sim 10^4$ yr)から存在
- 複数星の場合も単独星のときと類似
(e.g., McKee&Tan 08, Hosokawa+12)





電離光子が分厚い円盤から出られない？

Jaura+22

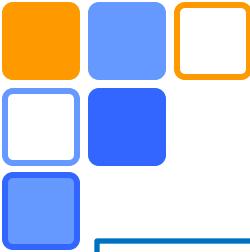


- AREPO、EUV/FUVをsink中心に注入
- EUVは分厚い円盤に全て吸収される
→ フィードバックも効かない
- bipolarな電離バブルの描像と異なる
(e.g., McKee&Tan 08, Hosokawa+12, KS+20,23)
- sink内の重力softeningの影響は？
 - 等温ガスの $H/R \propto c_s/\Omega R \propto R^{1/2}$

原始星近傍や円盤内側の構造を明らかにするのが重要

HII region breakout McKee&Tan (2008)



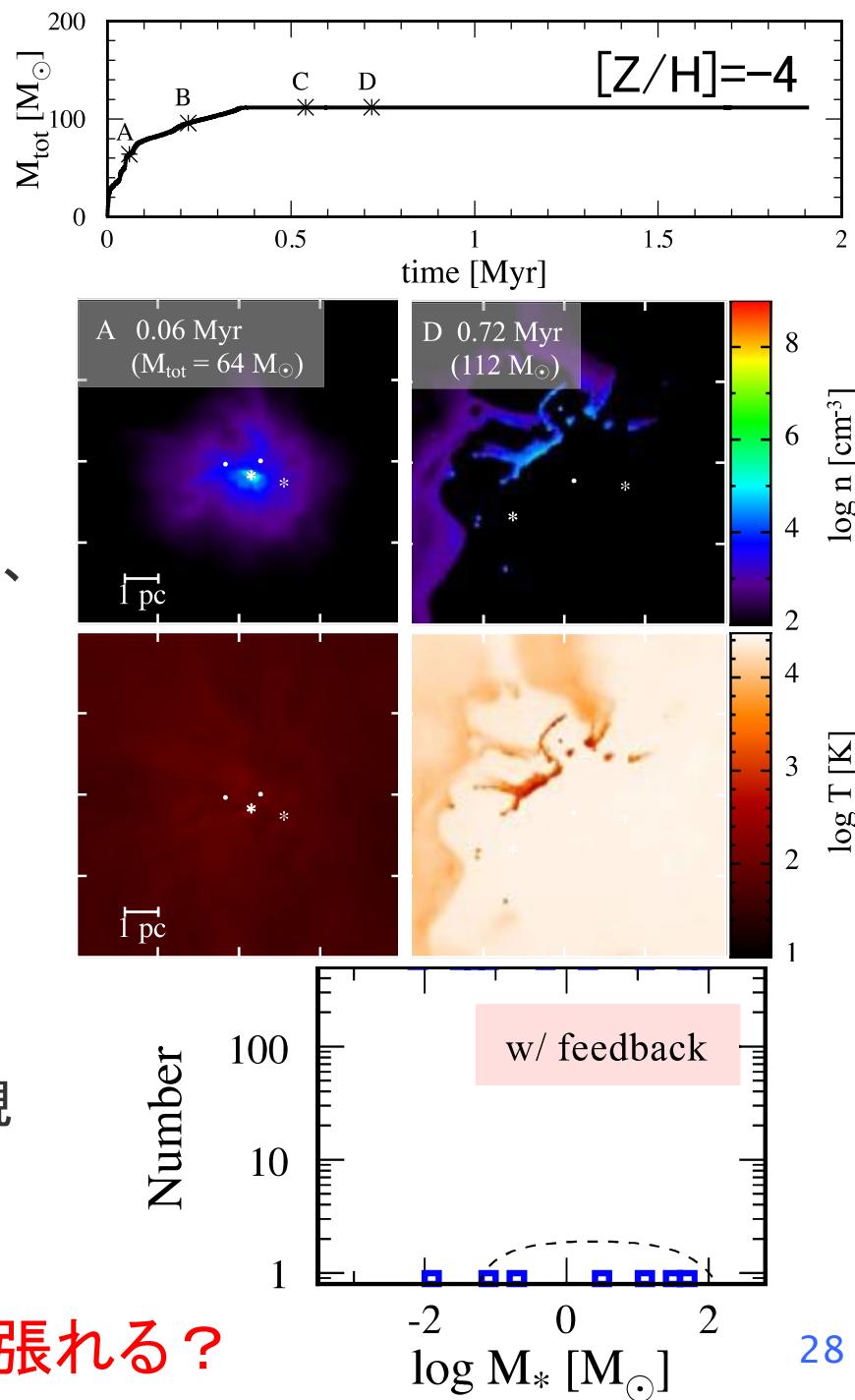


輻射入り 高解像度計算

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?
- ✓ $M_{\text{SPH}} = 3 \times 10^{-5} M_{\text{sun}}$ 、 $r_{\text{sink}} \sim 1 \text{au}$
- ✓ 質量解像度はSusa+14の約100倍
- 小質量の初代星も形成($M < 0.8 M_{\text{sun}}$ で現在まで生存)
- high-mass側が寡占的に成長

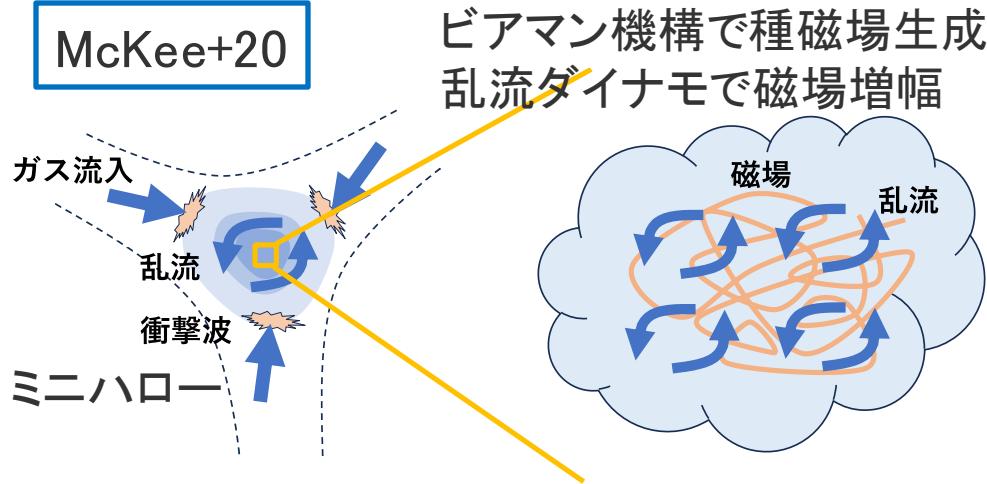
降着期最後までの計算も解像度頑張れる?



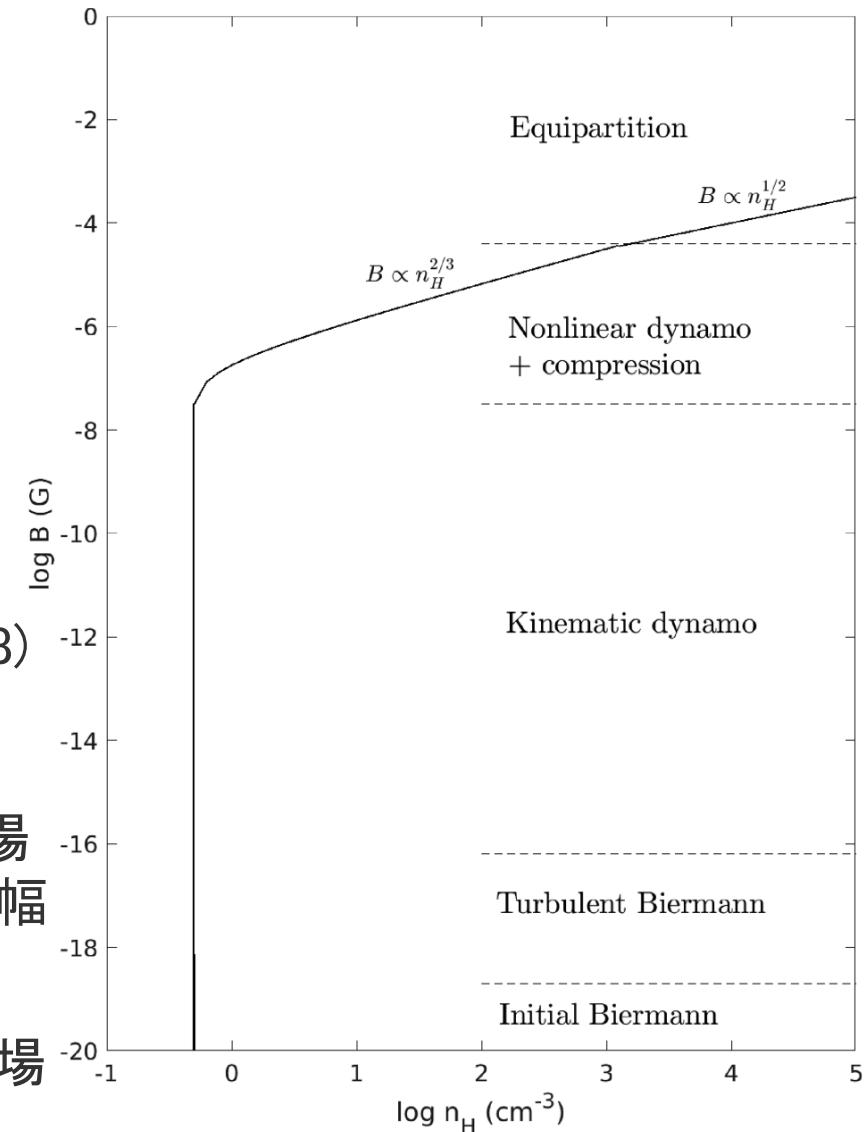
初代星と磁場

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

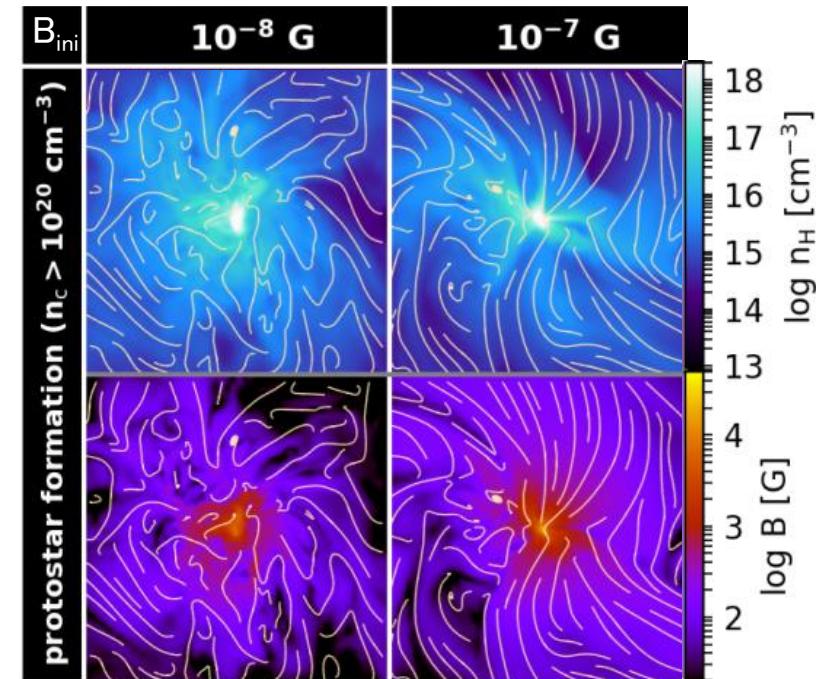
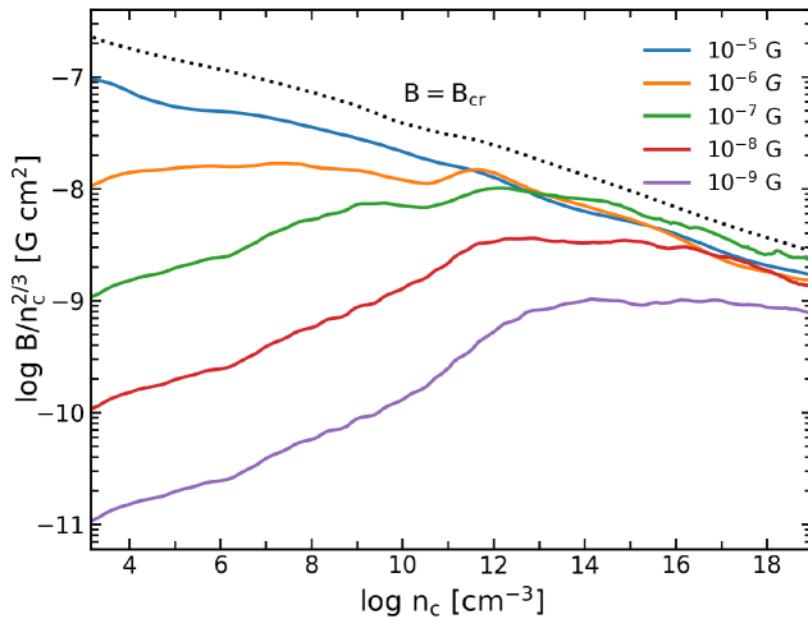


- 多くの研究で初代星形成時の磁場は弱いと仮定されていた (but, e.g., Machida+06,08)
- この論文で解析的に磁場が重要と主張
- ビアマン機構で生成した非常に弱い種磁場 (10^{-16} G) は、乱流ダイナモにより急激に増幅してエネルギー等分配に達する
- この論文のせいかは不明だが、初代星磁場のシミュレーションが流行



重力収縮期の磁場増幅

Sadanari+23



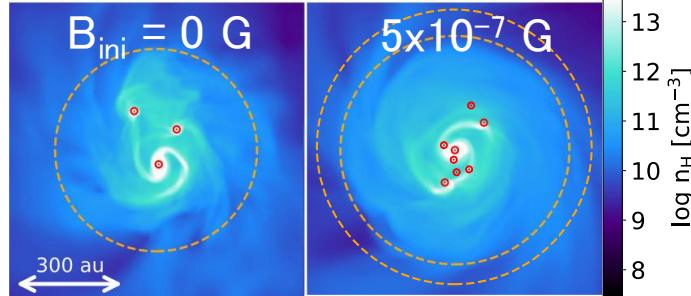
- 乱流ダイナモによって磁場が増幅しsaturation
- saturation後に磁場は徐々に揃う
← Higashi+24のポリトロープ高解像度計算ではそのような様子は見られず
- 両極性拡散による加熱が効くという解析的予想(Schleicher+09)を否定

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+21

- 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

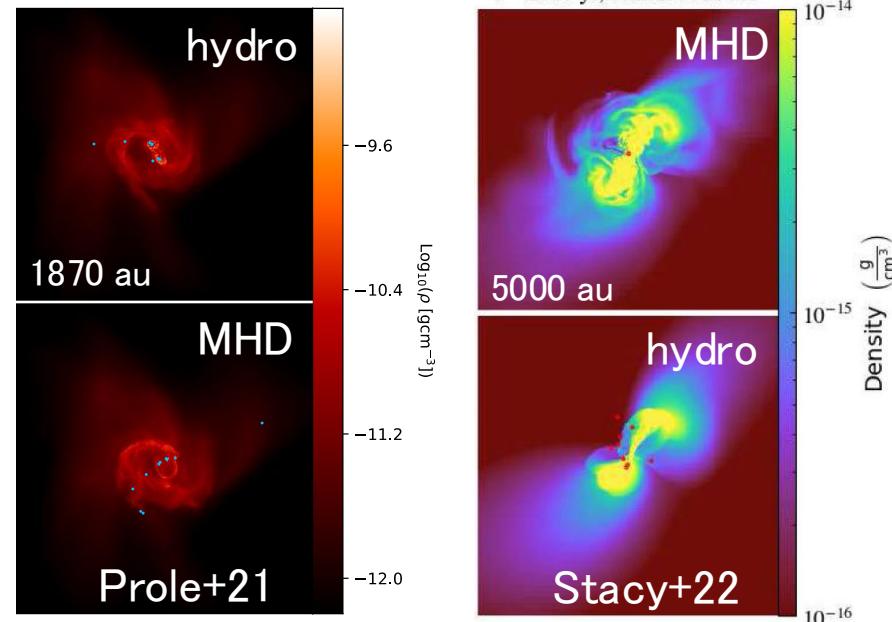
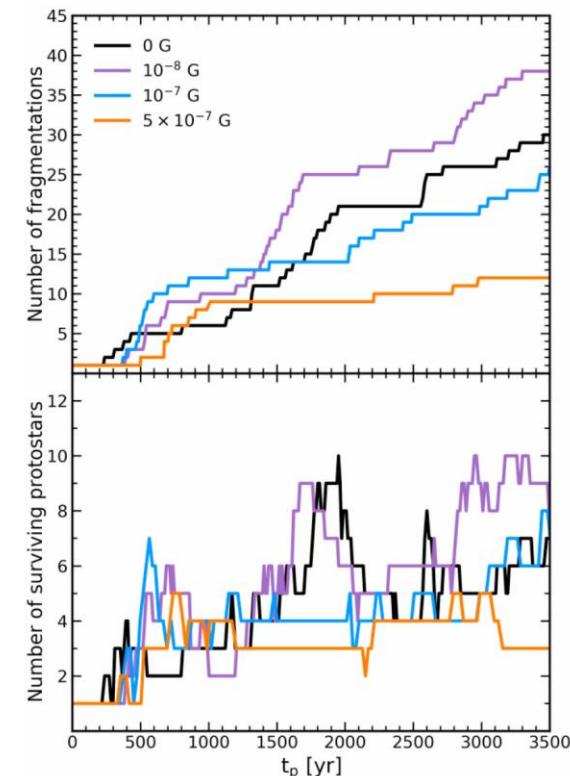
- 分裂への影響は小さい

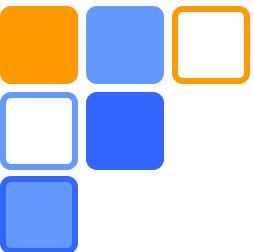
Stacy+22

- 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？

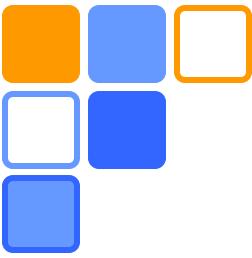




超大質量星形成

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 ($M \sim 10^5 M_{\text{sun}}$) 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



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