初代星形成
an overview

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Summary

+ 初代星の典型mass、mass分布、連星率、スピンを明らかにすることが目標

+ 特に、進化後半(原始星形成後)の研究がここ数年の中心的話題
(with 3D輻射[or磁気]流体シミュレーション)

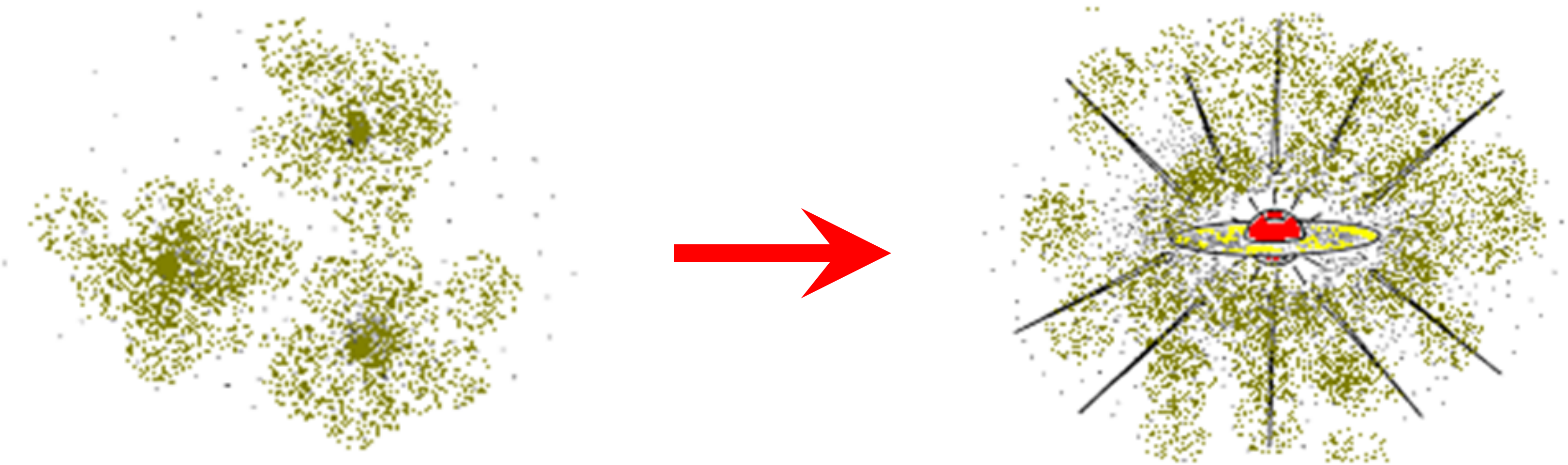
+ 典型mass: a few x 10-100 $M_{\odot}$、mass分布: $<0.1M_{\odot}$から$>1000M_{\odot}$まで?
※この他の特性も含め、シミュレーション設定(分解能、duration)の依存性大
※磁場など十分取り入れられていない効果もあり

+ massive tight binary (separation < 10AU) → BH−BH merger(GW)が期待
関心が集まっている (ただし、こうした系は銀河系にもあるが、形成過程不明)

星形成のながれ

Collapse(前期)段階
ガス雲が自己重力により収縮

Accretion(後期)段階
原始星へ周囲からガスがふりつもる



ガス雲質量: $M_\mathrm{J} \propto \rho^{-1/2} T^{3/2}$
(free-fall time = sound crossing time)

EOS: $P \propto \rho^{\gamma} \rightarrow M_\mathrm{J} \propto \rho^{(3\gamma-4)/2}$

γ<4/3のとき ρ↑⇒ M_J↓; 不安定→collapse

γは冷却過程によって決まる

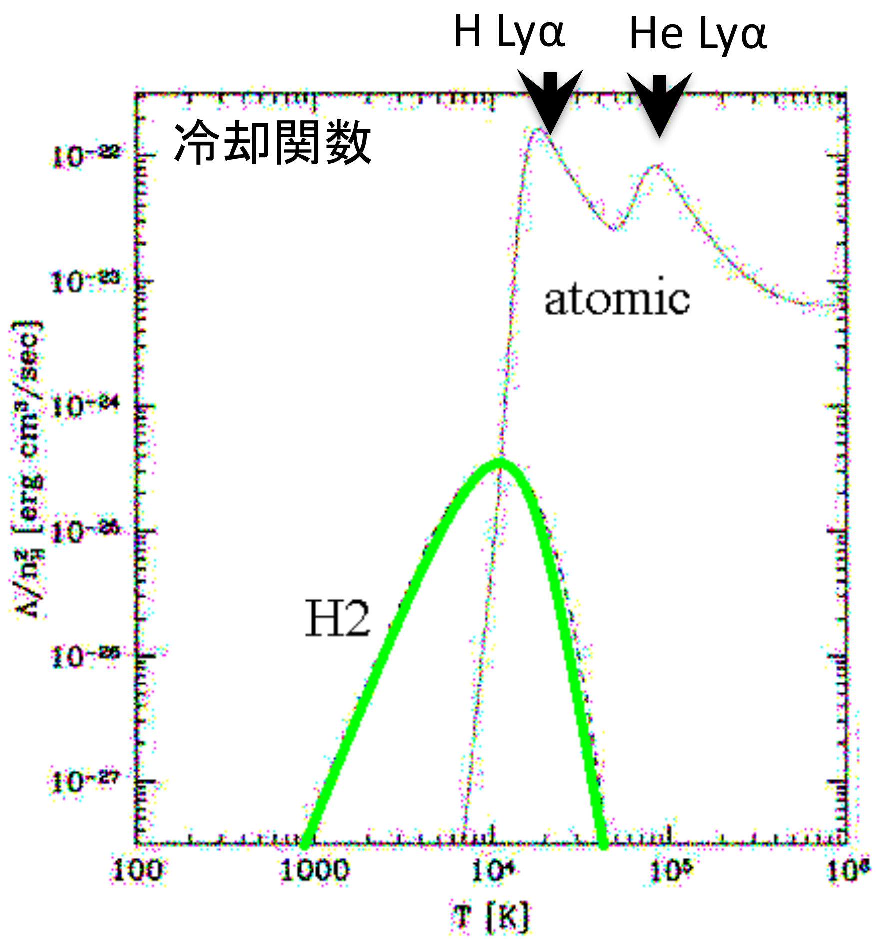
冷却効率がさがり (γ>4/3)
星の種(=原始星)が生まれる

原始星への降着率:

$$\boxed{\dot{M} \sim \frac{M_\mathrm{J}}{t_{ff}} \propto T^{1.5}}$$

ガス冷却剤 = H_2分子

銀河系($Z=Z_\odot$) :ダスト熱放射
初期宇宙($Z=0$) :ダストが存在しない。他の効率の悪い冷却剤に頼る
水素分子の回転-振動励起輝線



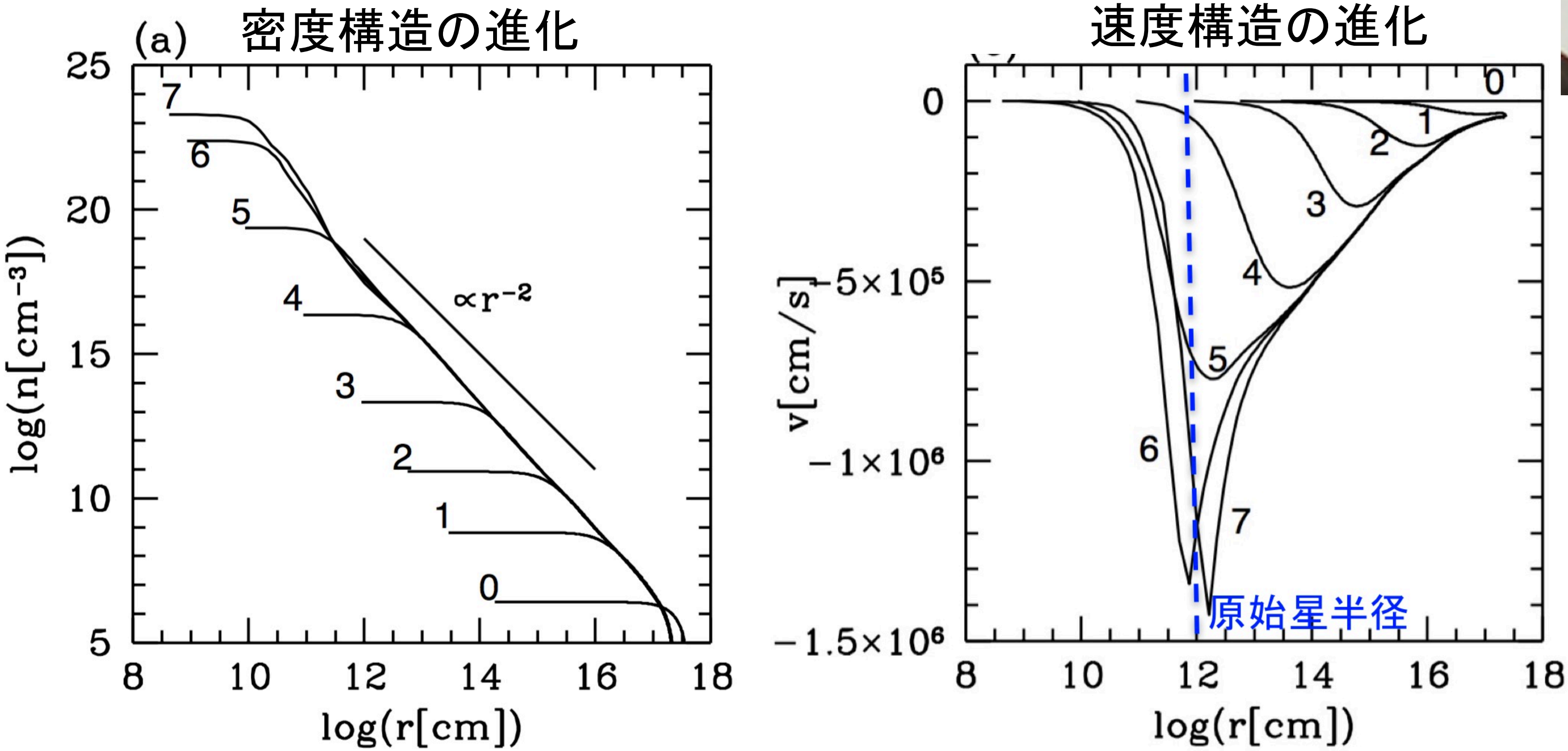
最低エネルギー遷移:
$\Delta E(J=2 \rightarrow 0,\ v=0)=510K$

H2輝線で冷えるガス雲温度は
数百ー数千K

初期宇宙: 星形成の際の冷却剤
銀河系: 高温shock tracer

Early Collapse Stage

Omukai & Nishi 1998 1次元球対称(RHD) + 化学計算



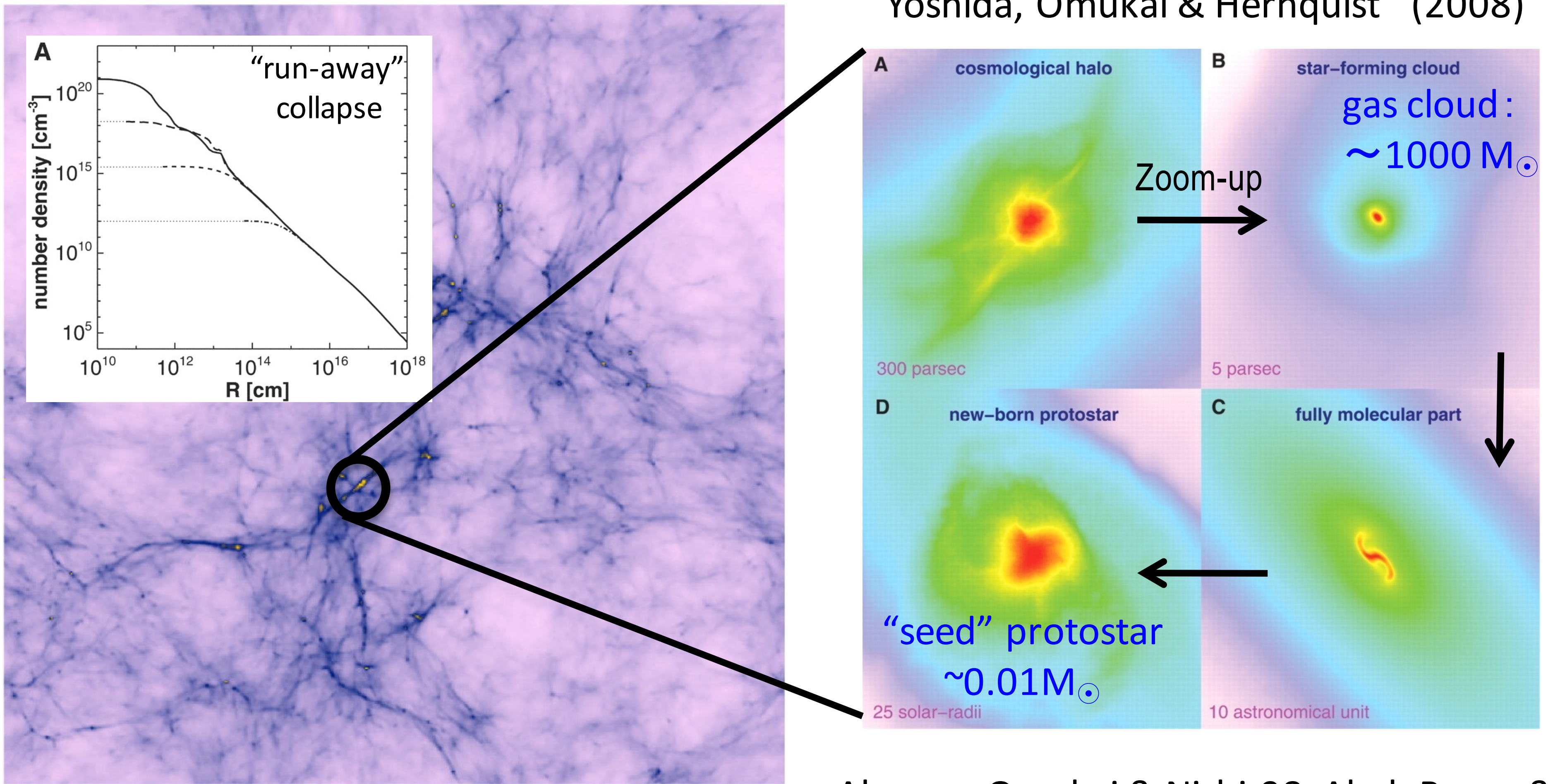
+ 自己相似的run-away collapseでガス雲収縮がすすむ

+ 最終的に～1g/ccまで密度が上がったら冷却効率が悪くなり、原始星が誕生 (質量～$0.01M_{\odot}$)

Early Collapse Stage

The early evolution until the formation of a protostar is *relatively* well-established. Full 3D cosmological simulations can follow this.

Yoshida, Omukai & Hernquist (2008)



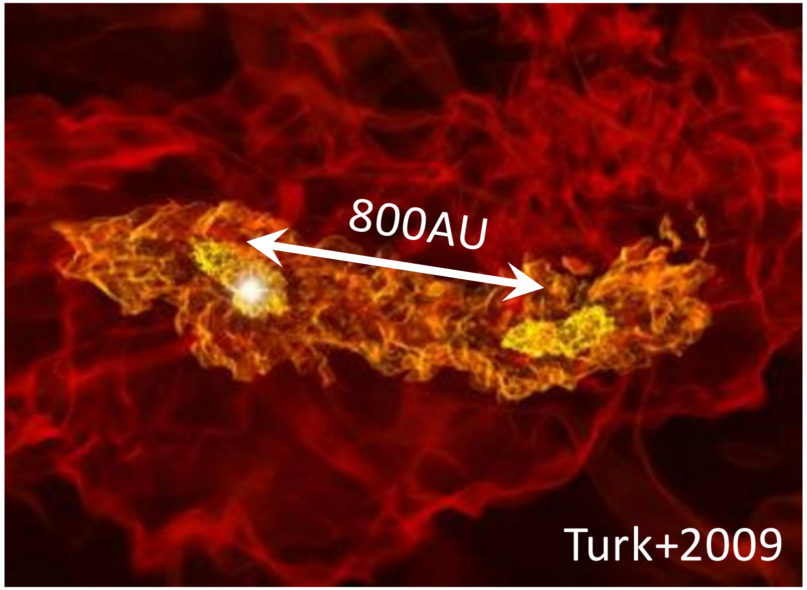
Also see Omukai & Nishi 98; Abel, Bryan & Norman 02; O'shea & Norman 07 etc.

前期段階の課題

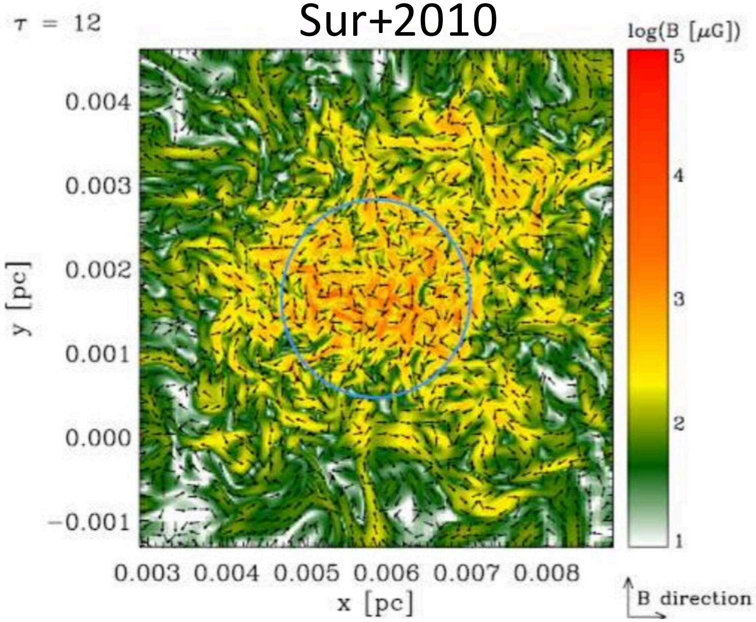
❖ Formation of wide binaries

Gravitational fragmentation occasionally occurs in the early collapse stage

+ w/ large separations of 〜 10^3 AU or more (Turk+09; Hirano+14; Stacy+16 etc)
+ About 〜5% of primordial clouds? (Hirano+14)
+ Evolve to wide binaries?



Sur+2010



❖ Magnetic fields

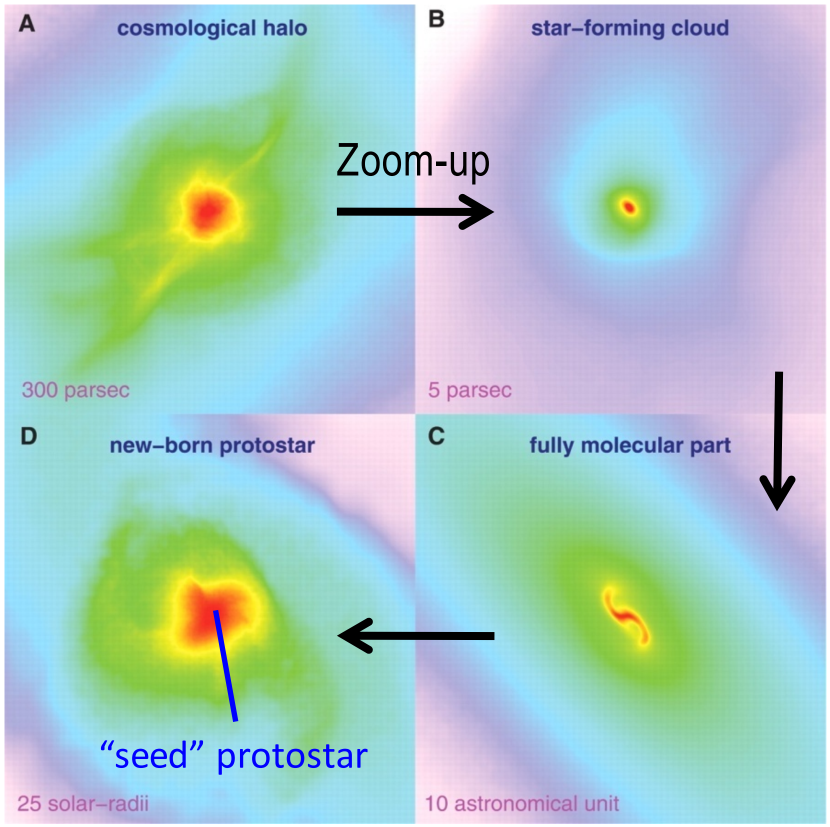
Amplified by turbulent dynamo during the collapse? (Schleicher+10; Sur+10,12; Schober+12; Federrath+12; Turk+12; etc).

…should be also important in the later stage (e.g., Tan & Blackman 04; Machida & Doi 13)

First Stars: How massive?

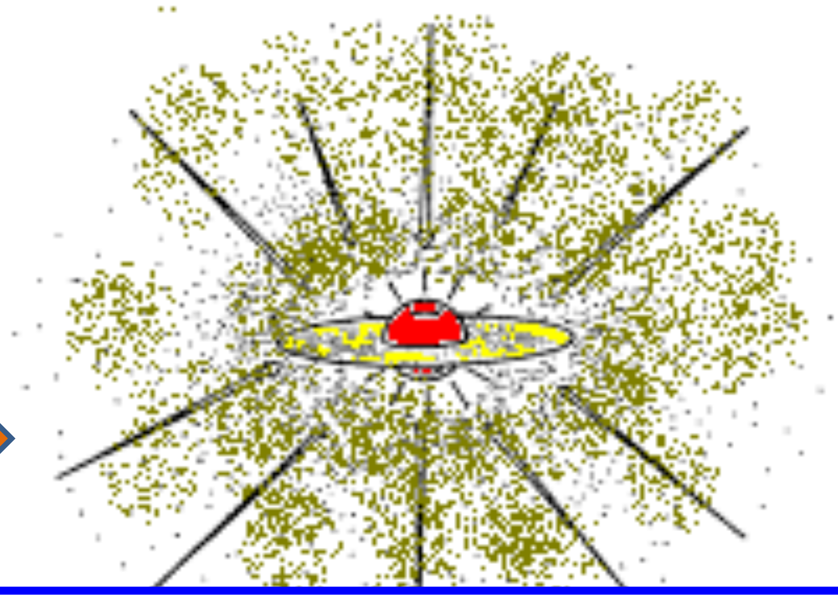
early collapse stage $\Rightarrow$ late accretion stage

Yoshida, Omukai & Hernquist (2008)



$10^{-2}\,M_\odot$ protostar

surrounded by $>10^{3}\,M_\odot$ gas envelope

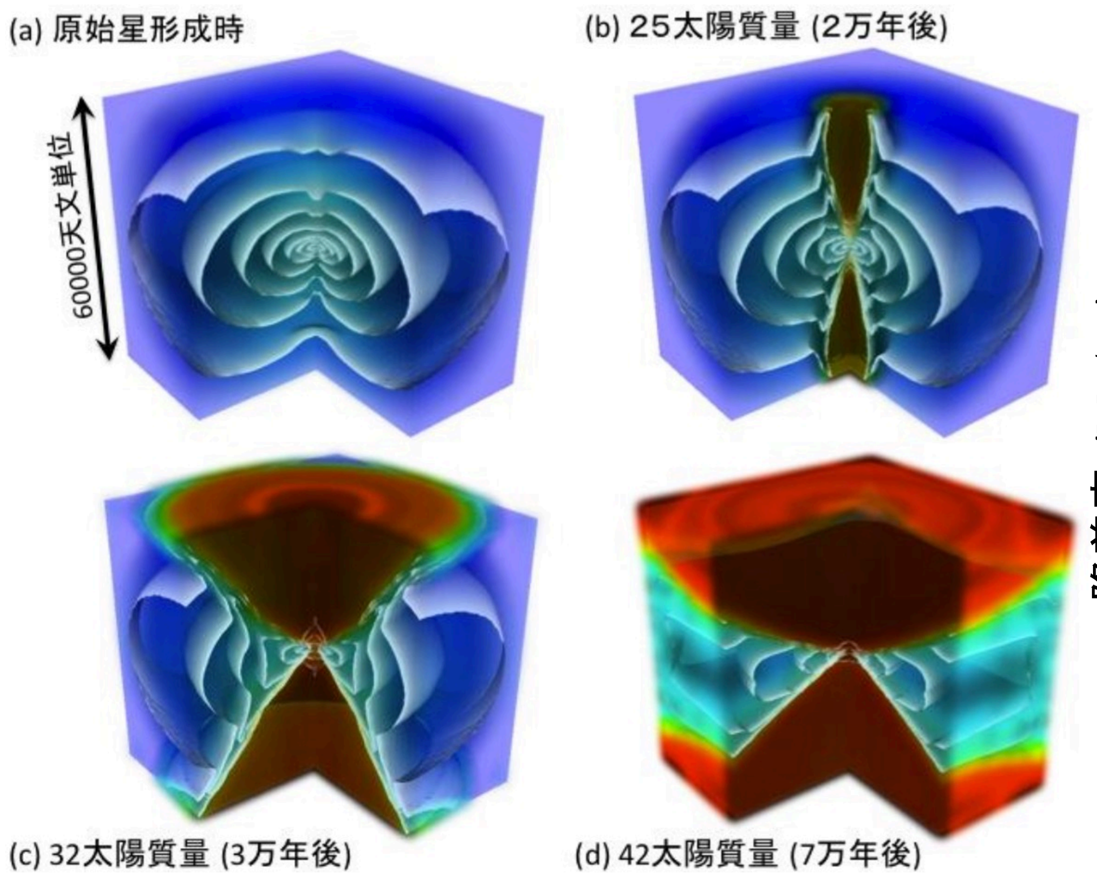


$$\dot{M} \sim \frac{M_{\rm J}}{t_{ff}} = \frac{c_s^3}{G} \sim 7 \times 10^{-4} M_\odot/{\rm yr} \left(\frac{T}{300\ {\rm K}}\right)^{3/2}$$

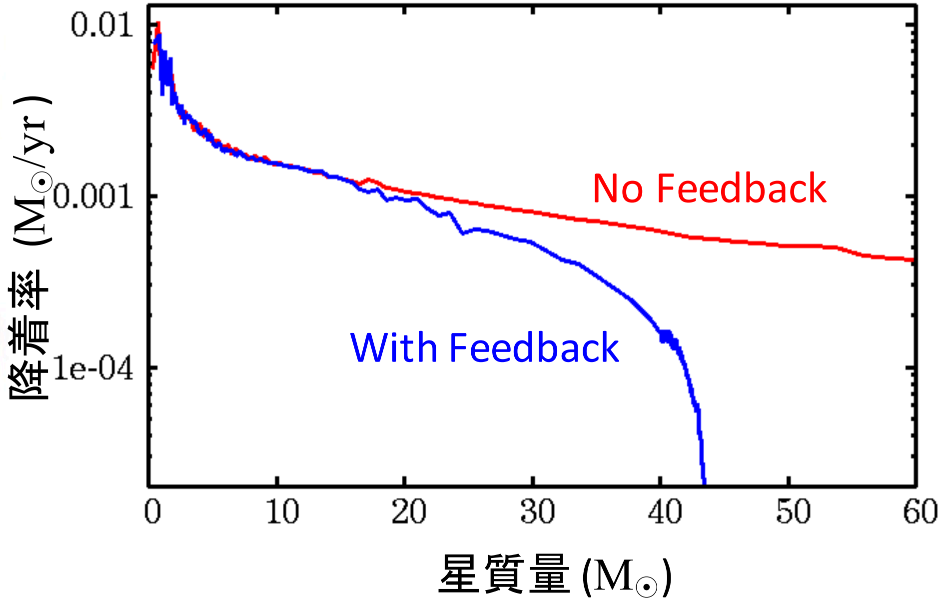
for stellar lifetime (～Myr) → ～$1000M_\odot$ star

後期段階の研究が重要

2D RHD + Stellar Evolution



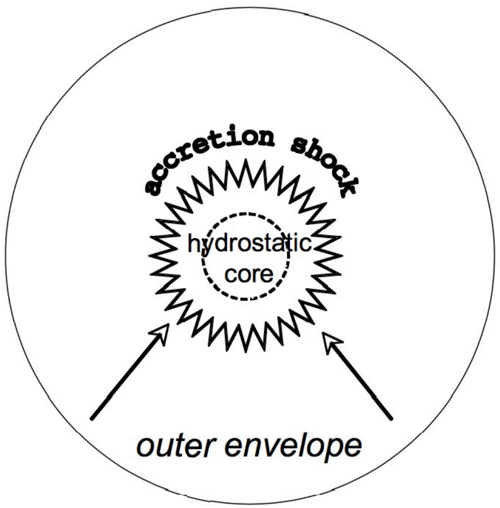
TH+11, 12; Hirano et al. 14
(also see Mckee & Tan 08)



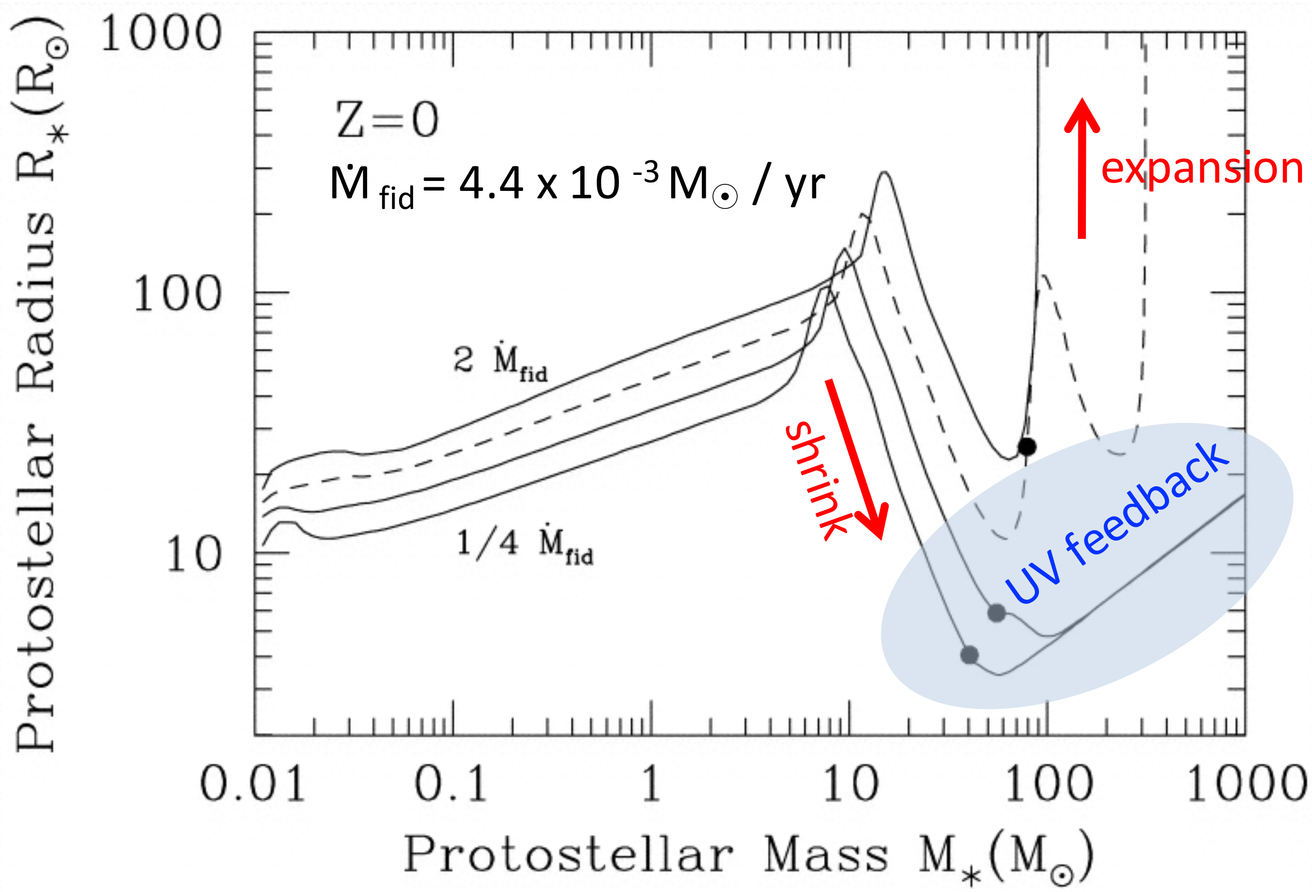
- Acc. rate is significantly reduced by the stellar UV feedback
- Mass accretion is shut off when the stellar mass is ～43 $M_\odot$

Protostellar Evolution

e.g., Omukai & Palla 03

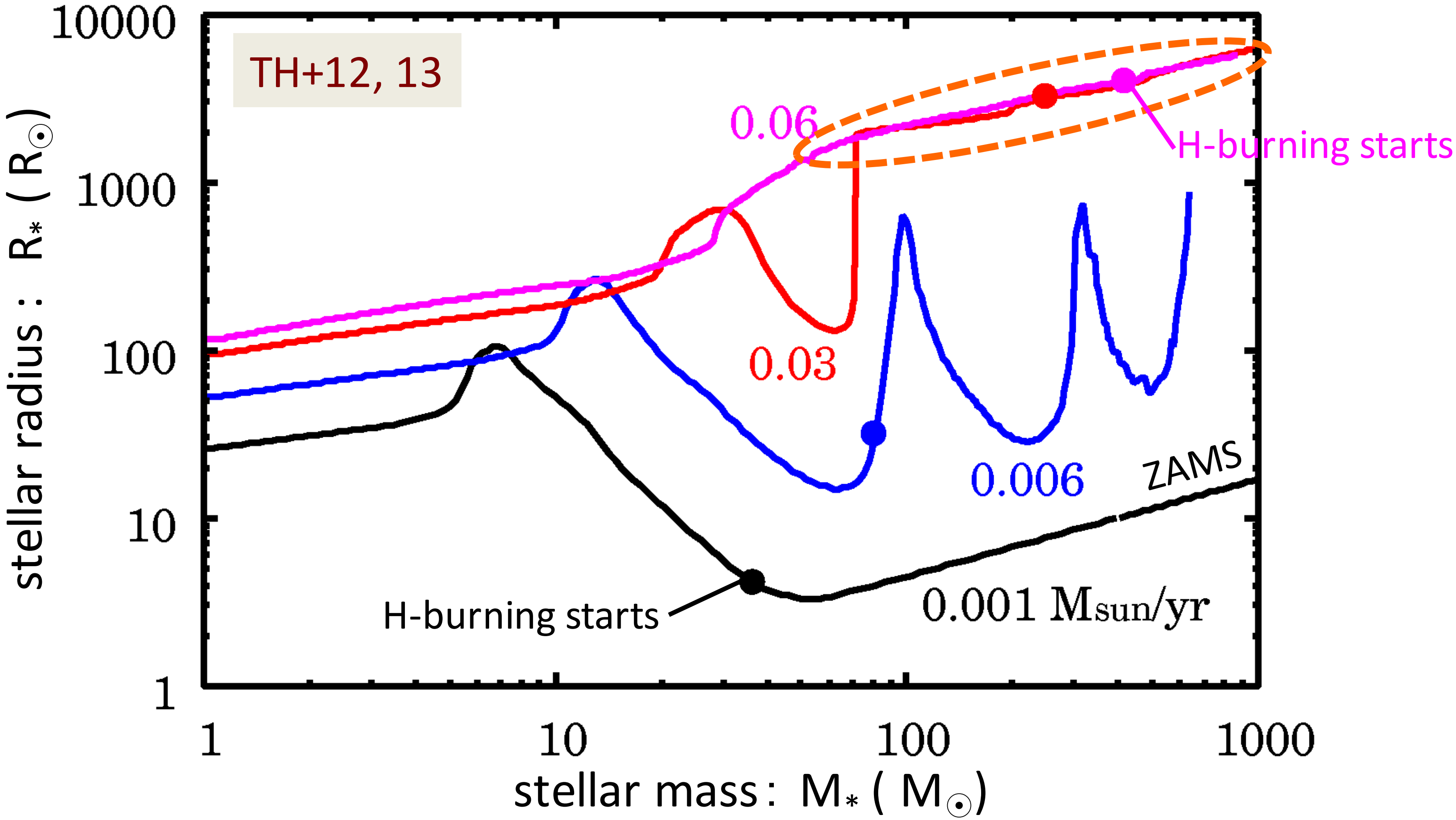


the stellar evolution with accretion



+ The UV feedback operates when the star shrinks
+ When the star shrinks depends on different accretion rates
+ Stellar evolution was followed *simultaneously* with RHD simulations in TH11

"Supergiant Protostar"



With very rapid accretion > 0.01 $M_\odot$/yr, the protostar never contracts to reach the ZAMS stage, but continues to expands.

(→星風: 仲内くん話、回転: 高橋実道くん話)

８月のFirst Star V会議 (@Hidelbrg)でabstract集を見ていると…

P2.17 - The final fates of accreting supermassive stars

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The discovery of enormous (billion Solar mass) high-redshift quasars challenges our understanding of the early Universe: how did such massive objects form in the first billion years? A popular model is the "direct collapse" scenario: An atomically-cooled gas cloud of primordial composition accretes rapidly onto a single stellar core, ultimately collapsing through the general relativistic instability after reaching $\approx 100,000$ Solar masses and forming an initial supermassive seed black hole. To date, the full evolution of such supermassive stars, from protostar up to and including relativistic collapse, has not been followed in detail. We present the results of such calculations using the stellar evolution code KEPLER, incorporating implicit hydrodynamics, GR corrections, and a detailed treatment of nuclear burning processes. We find that the final mass converges on the hydrostatic limit of $\approx 150,000$ Solar masses only at the highest accretion rates. We discuss the response of the supermassive star to accretion, and the evolutionary state at the time of collapse for a wide range of accretion rates. Finally, we close by discussing observational prospects.

我々も進めていたのに! しかしなぜかポスターが貼られることはなかった…そして…

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THE FINAL FATES OF ACCRETING SUPERMASSIVE STARS

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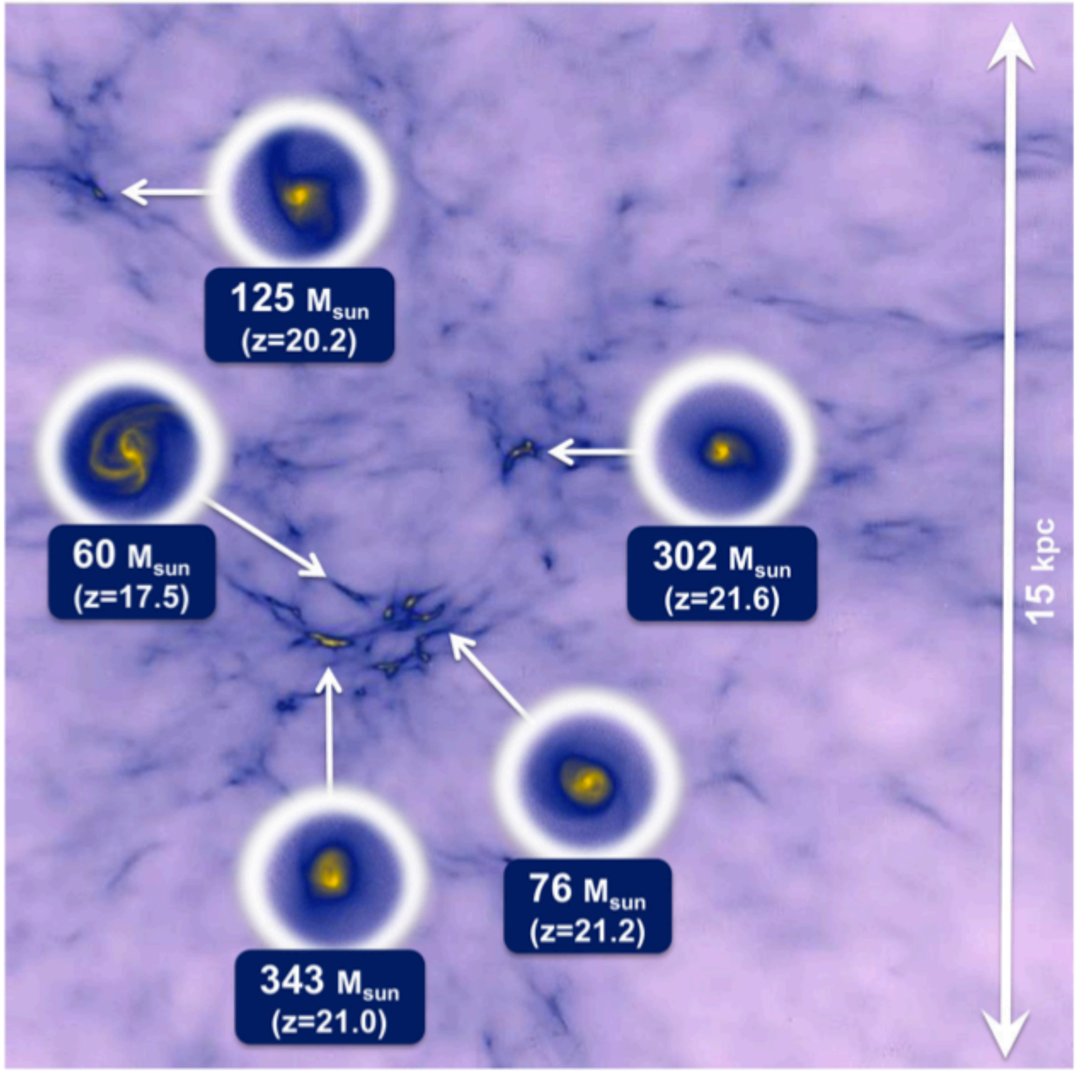
ABSTRACT

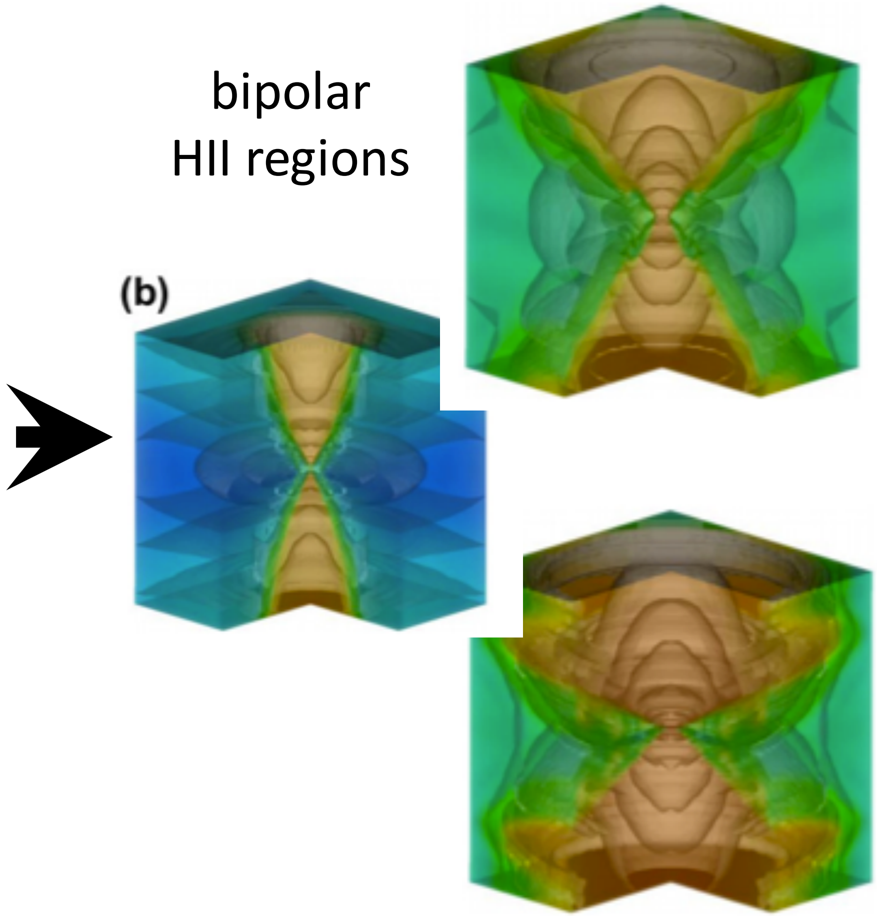
The formation of supermassive stars (SMSs) via rapid mass accretion and their direct collapse into black holes (BHs) is a promising pathway for sowing seeds of supermassive BHs in the early universe. We calculate the evolution of rapidly accreting SMSs by solving the stellar structure equations including nuclear burning as well as general relativistic (GR) effects up to the onset of the collapse. We find that such SMSs have a less concentrated structure than a fully convective counterpart, which is often postulated for non-accreting ones. This effect stabilizes the stars against GR instability even above the classical upper mass limit $\gtrsim 10^5\, M_\odot$ derived for the fully convective stars. The accreting SMS begins to collapse at the higher mass with the higher accretion rate. The collapse occurs when the nuclear fuel is exhausted only for cases with $\dot{M} \lesssim 0.1\, M_\odot\,\mathrm{yr}^{-1}$. With $\dot{M} \simeq 0.3$–$1\, M_\odot\,\mathrm{yr}^{-1}$, the star becomes GR unstable during the helium-burning stage at $M \simeq 2$–$3.5 \times 10^5\, M_\odot$. In an extreme case with $10\, M_\odot\,\mathrm{yr}^{-1}$, the star does not collapse until the mass reaches $\simeq 8.0 \times 10^5\, M_\odot$, where it is still in the hydrogen-burning stage. We expect that BHs with roughly the same mass will be left behind after the collapse in all the cases.

We did it! →梅田さん話

Forming >100 Pop III Stars

Pick up a number of the star-forming clouds found in cosmological simulations (e.g., O'Shea & Norman 07). The later evolution is followed until the stellar mass is fixed by UV feedback. (Hirano et al. 14, 15)

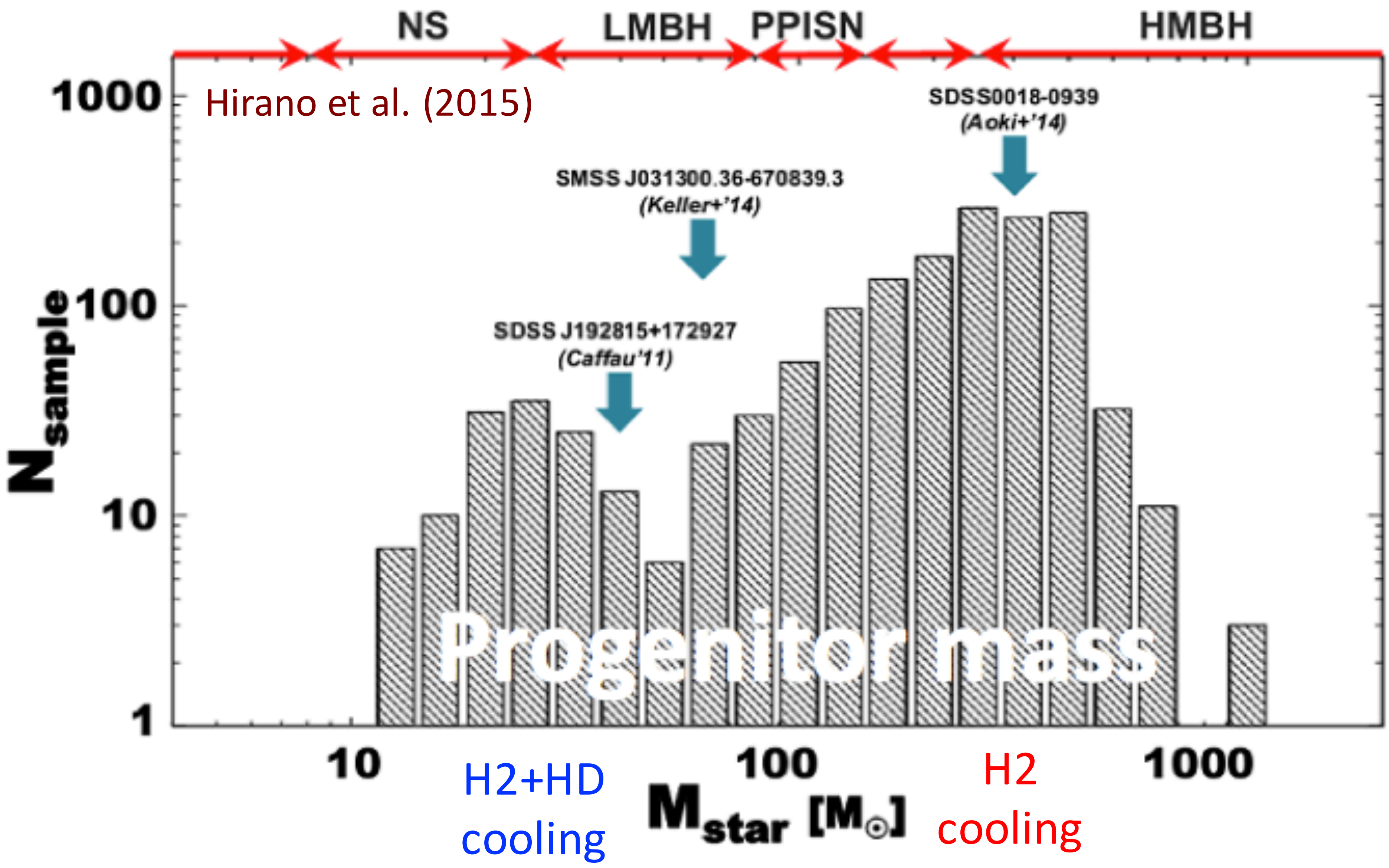




local 2D radiation-hydro simulations
+ stellar evolution

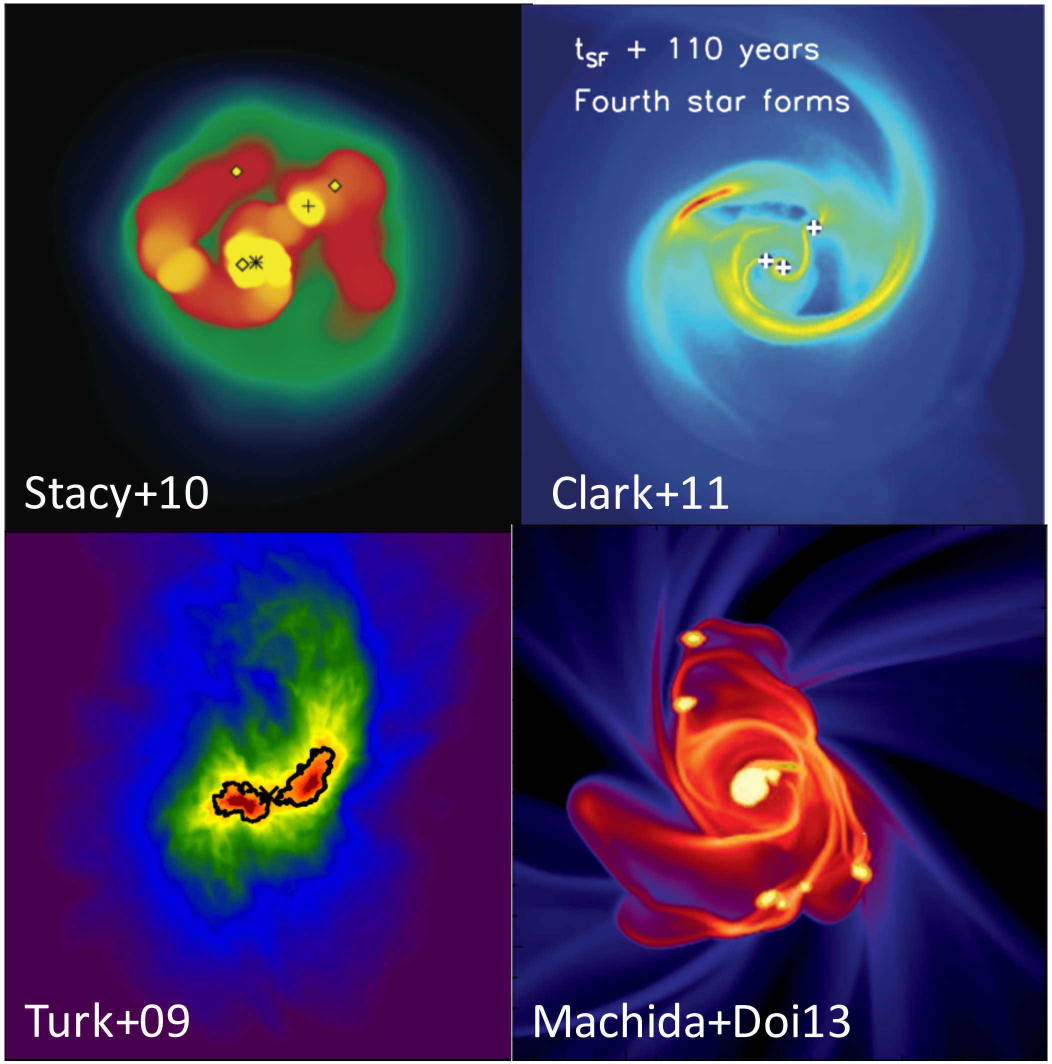
The "Mass Spectrum"

With more than 1000 (!) star-forming clouds taken from cosmological simulations



Disk Fragmentation

星周円盤重力不安定: global spiral armが成長して角運動量輸送
しかし、(円盤内のmass transfer) < (円盤へのinfall rate) で分裂



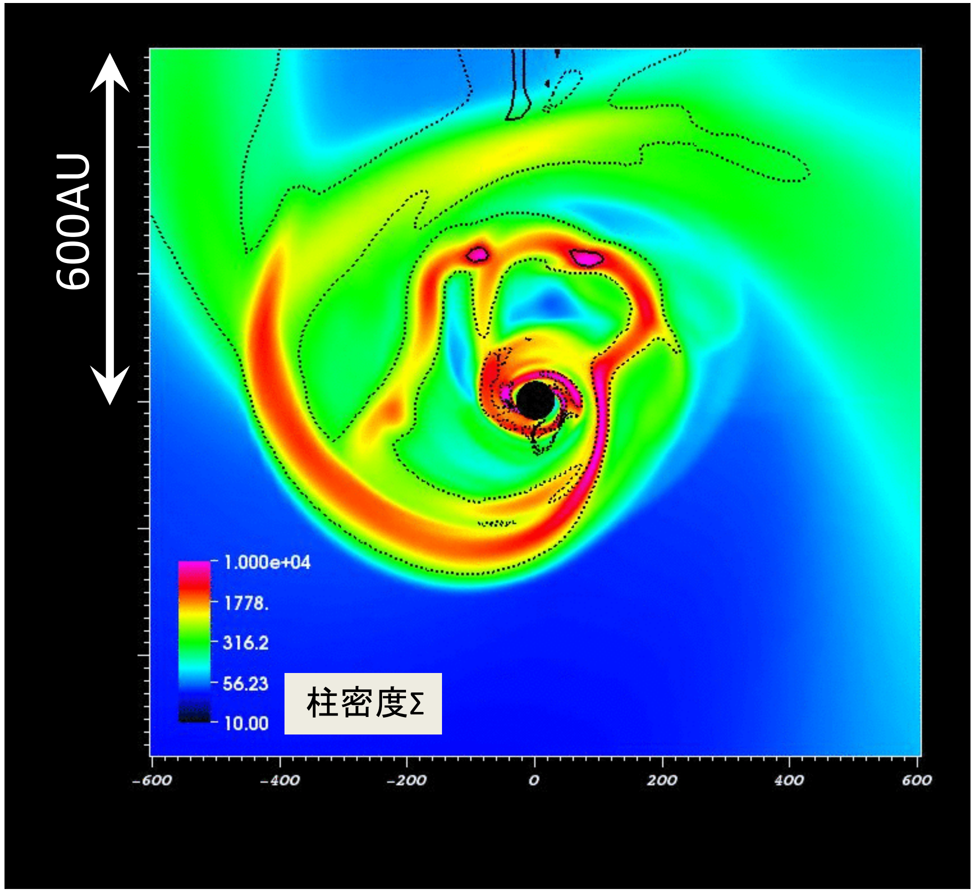
単独あるいは少数の
大質量星?

低質量の星を多数
含む星団?

Tight binariesの形成mode?

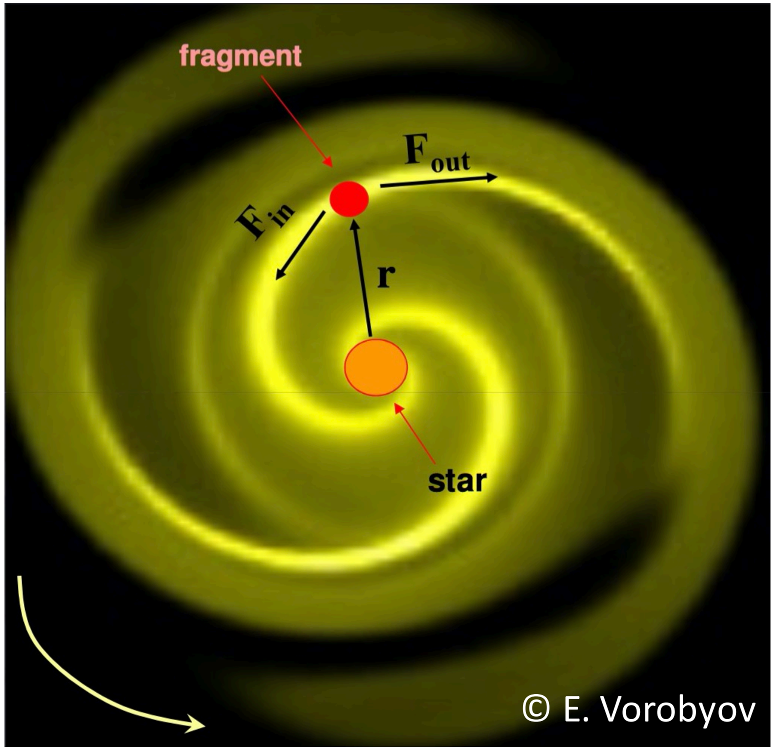
Inward Migration of Fragments

Evolution over ～100 yrs



Contour: Toomre Q parameter
solid: Q=0.1, dotted: Q=1.0
(from TH et al. 2016)

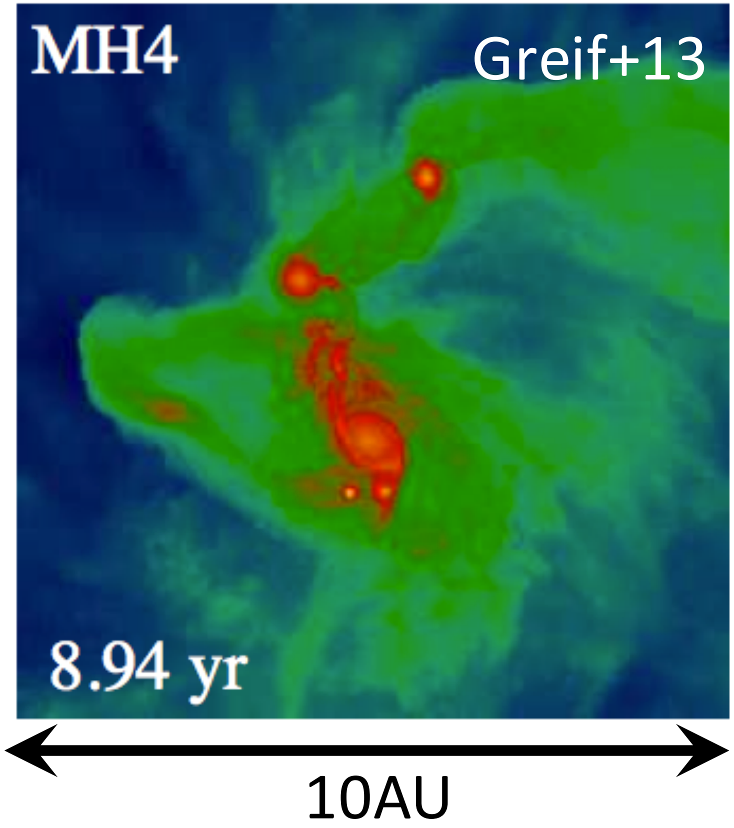
Fragments can rapidly migrate inward toward the central star, causing the burst accretion or merger

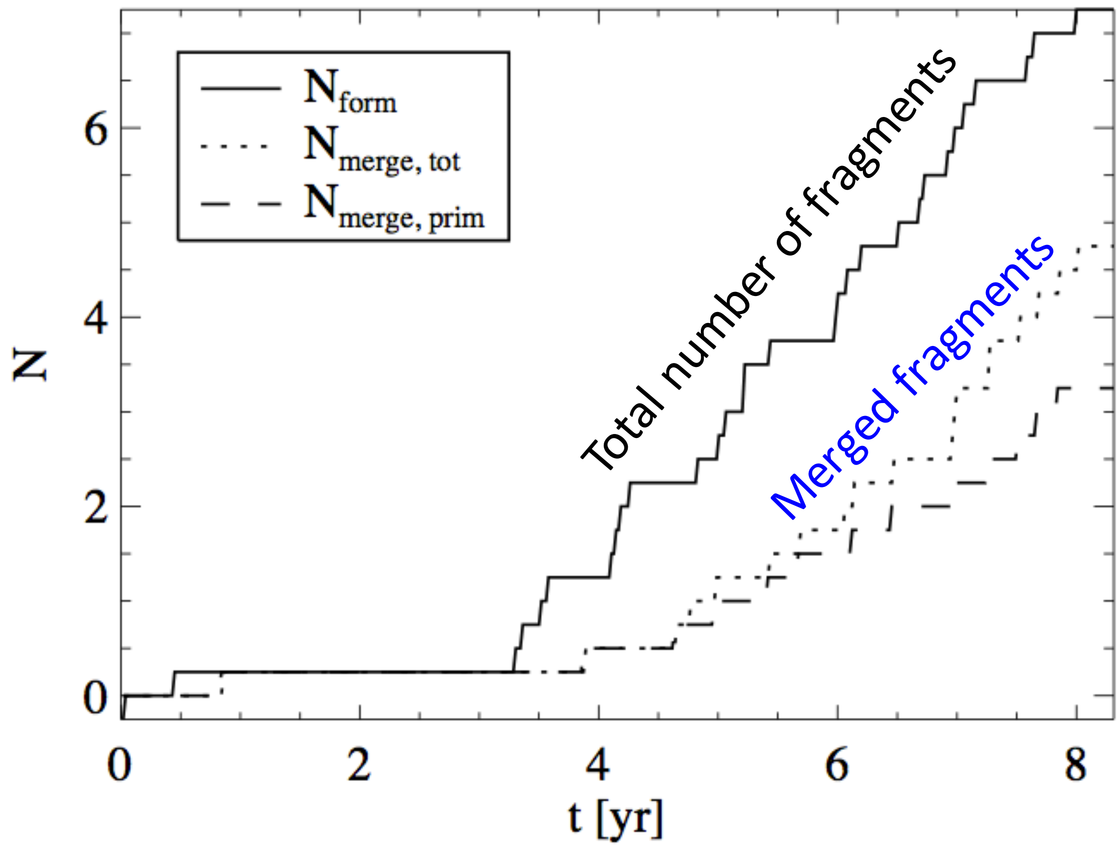


F_{in}, F_{out}が及ぼすトルクの競合

大抵F_{out}のトルクが上回る
(今は外層から円盤への降着もあり)

Fragments can merge again



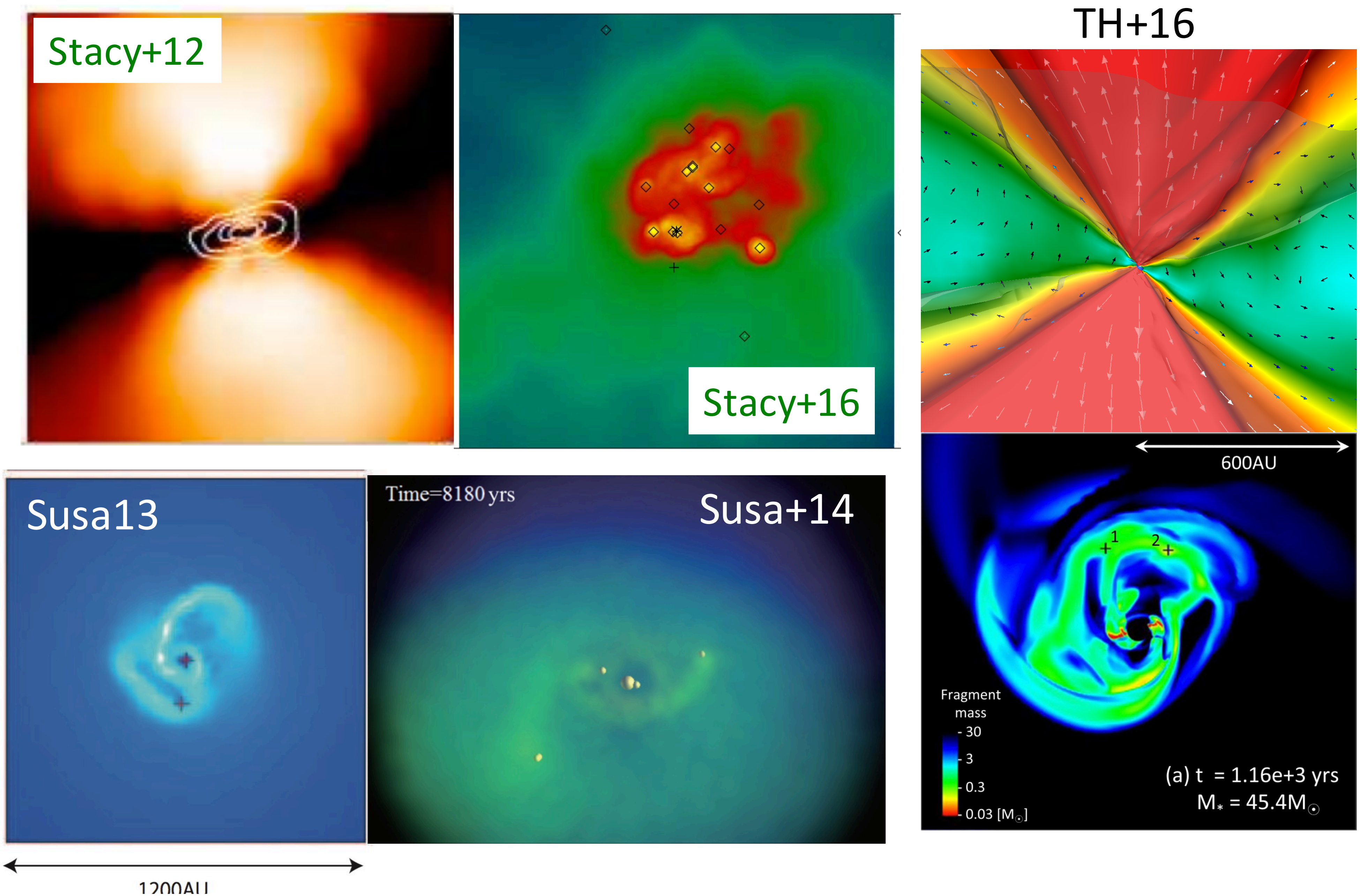


About 2/3 of the fragments merged away, 1/3 survived via e.g., ejection

Merged fragments typically migrate inward via gravitational torque over local free-fall timescale

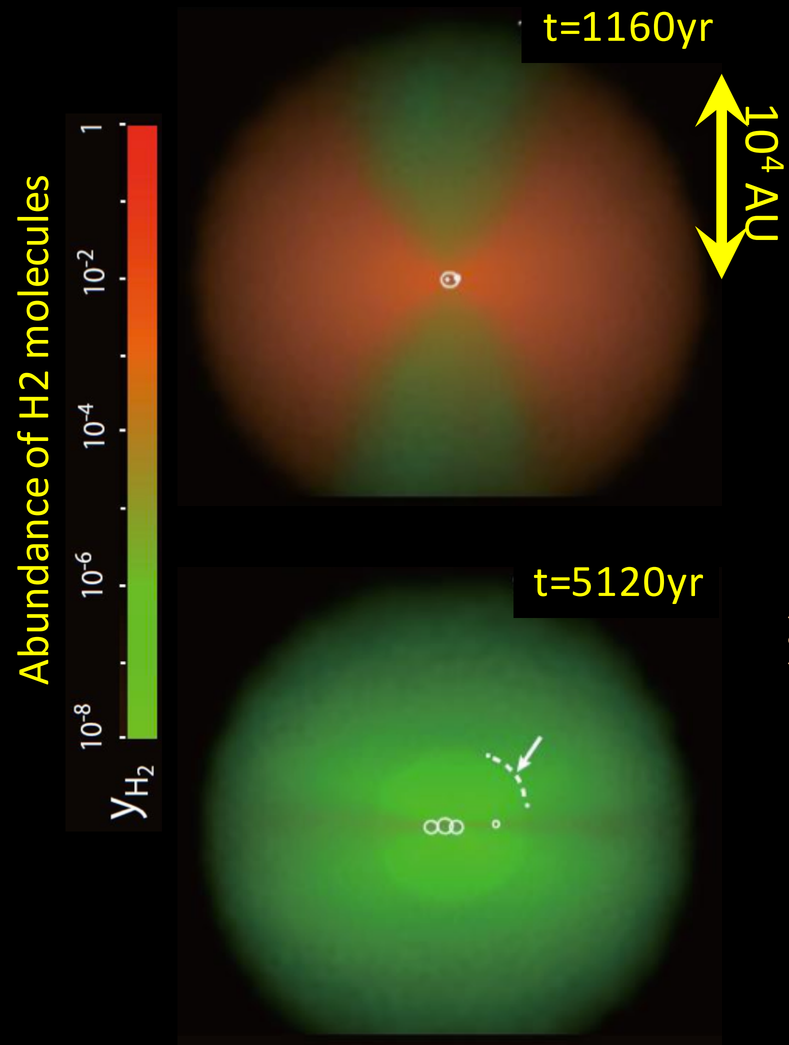
High-mass stars will still form even with lots of fragmentation?

UV feedback + Fragmentation

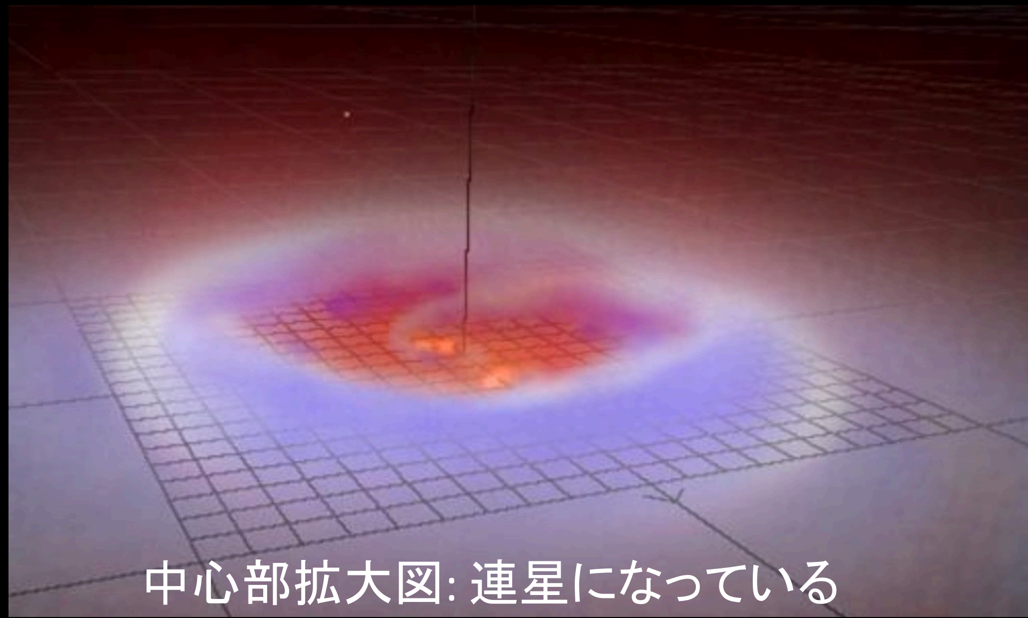


Susa+13,14

3次元RHD計算(円盤分裂 + feedback)

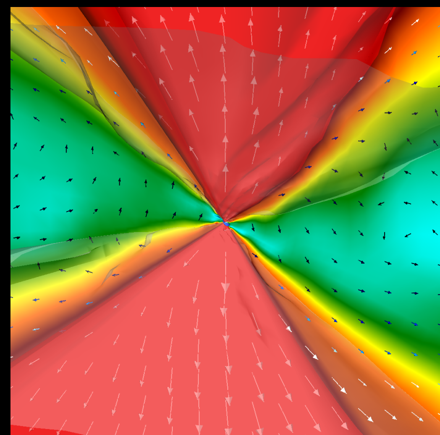


H2 photodissociation



※ only with dissociation (H2破壊) feedback

TH+16 →
ionizing + dissociating
feedback



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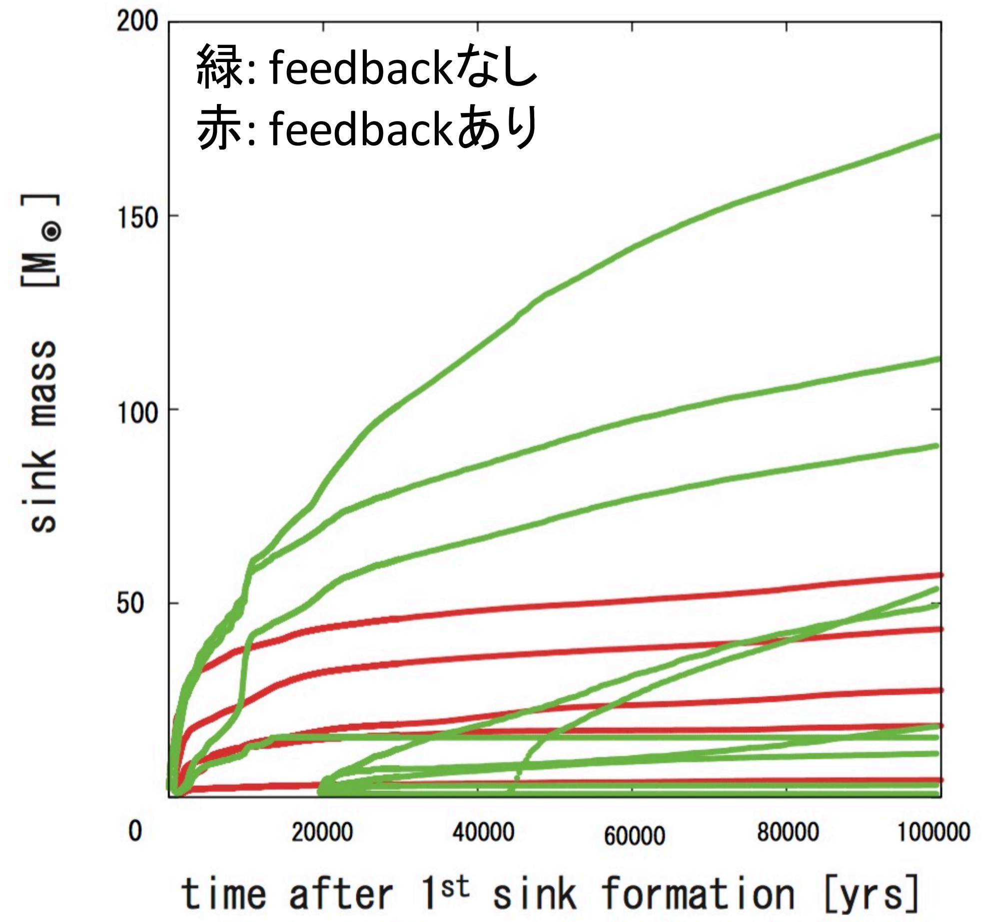
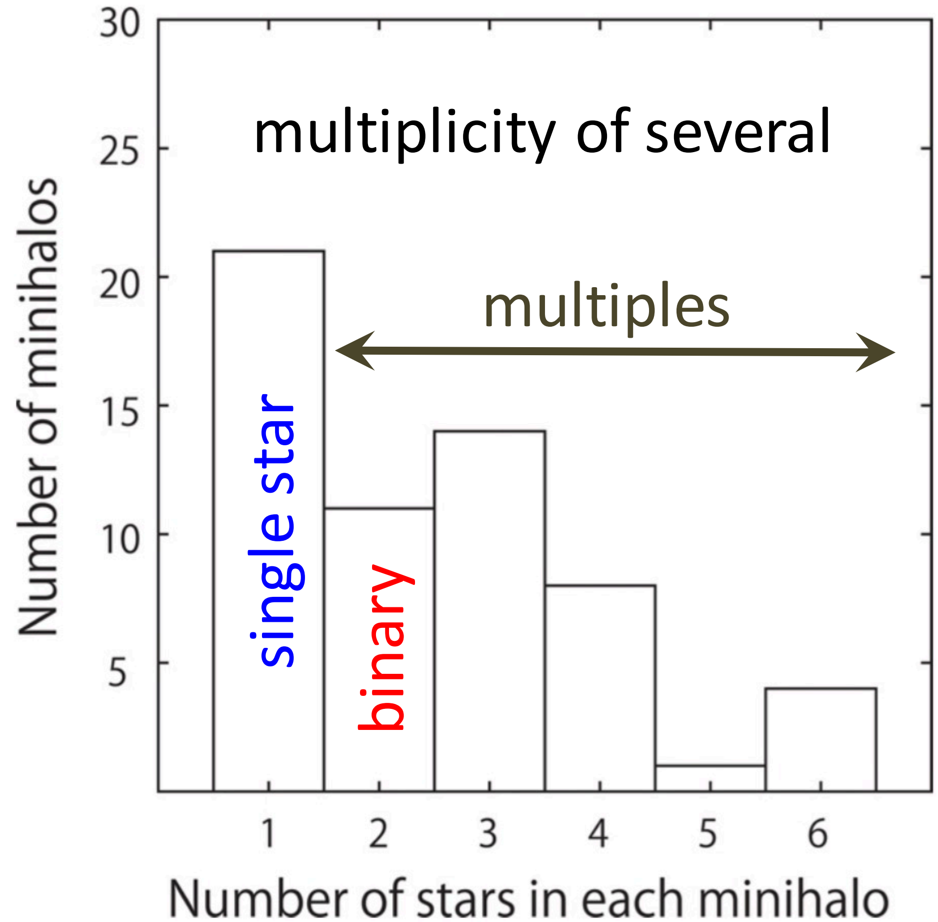
Mass Accretion History



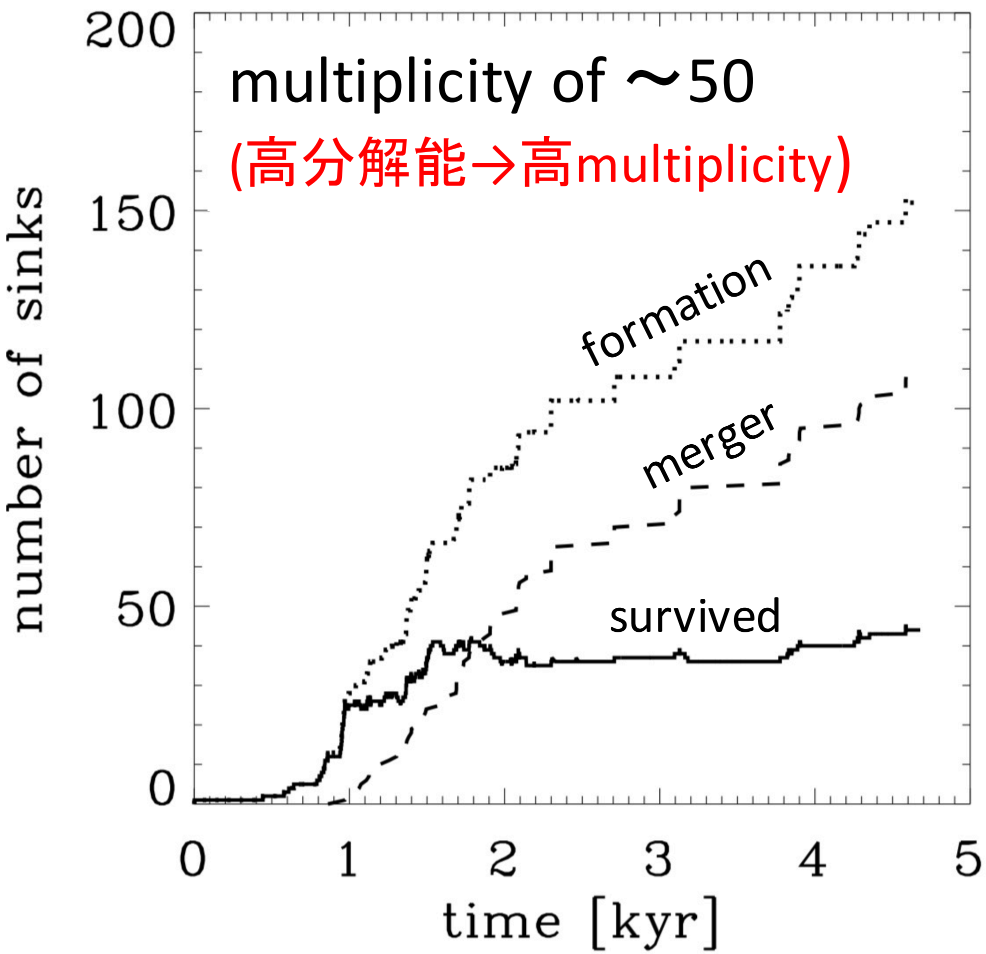
Haloあたりstellar multiplicity

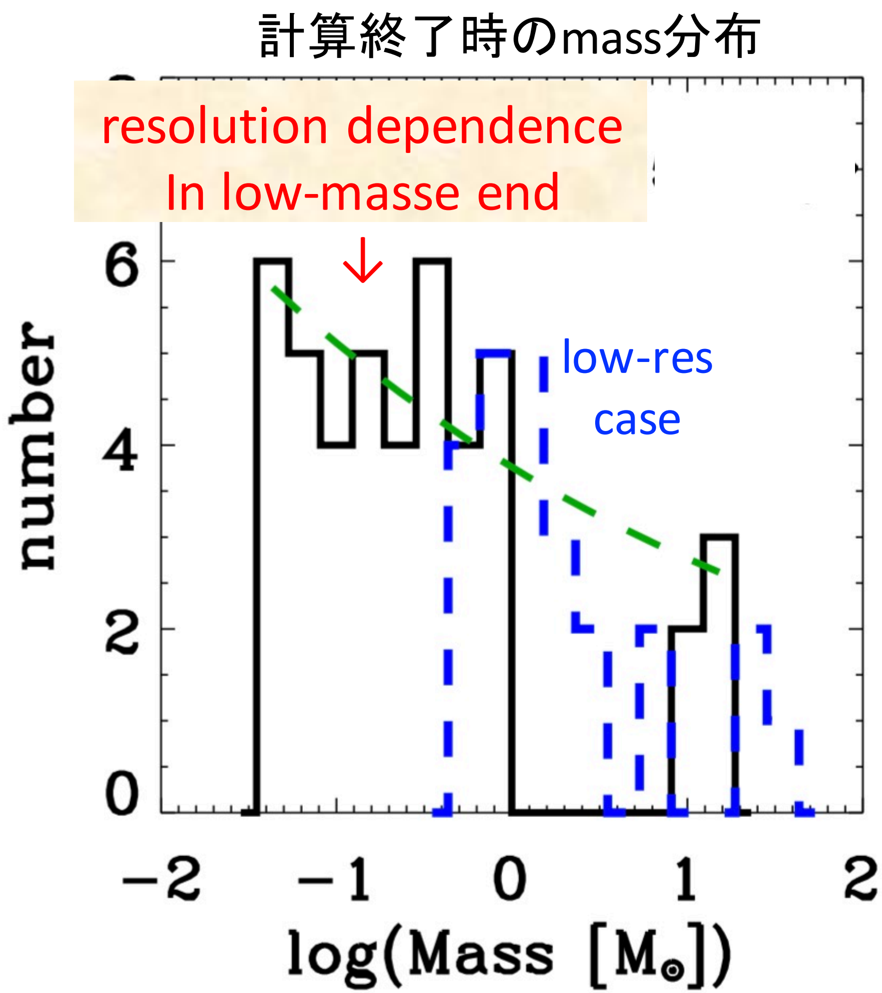


～2/3はmultiples (※星同士は合体せずと仮定)

Stacy+16

Stacy, Bromm, & Lee (2016); ionizing + dissociating feedback,
w/ 1 mini halo, following 5000 yrs with ～1AU resolution (x10 higher)

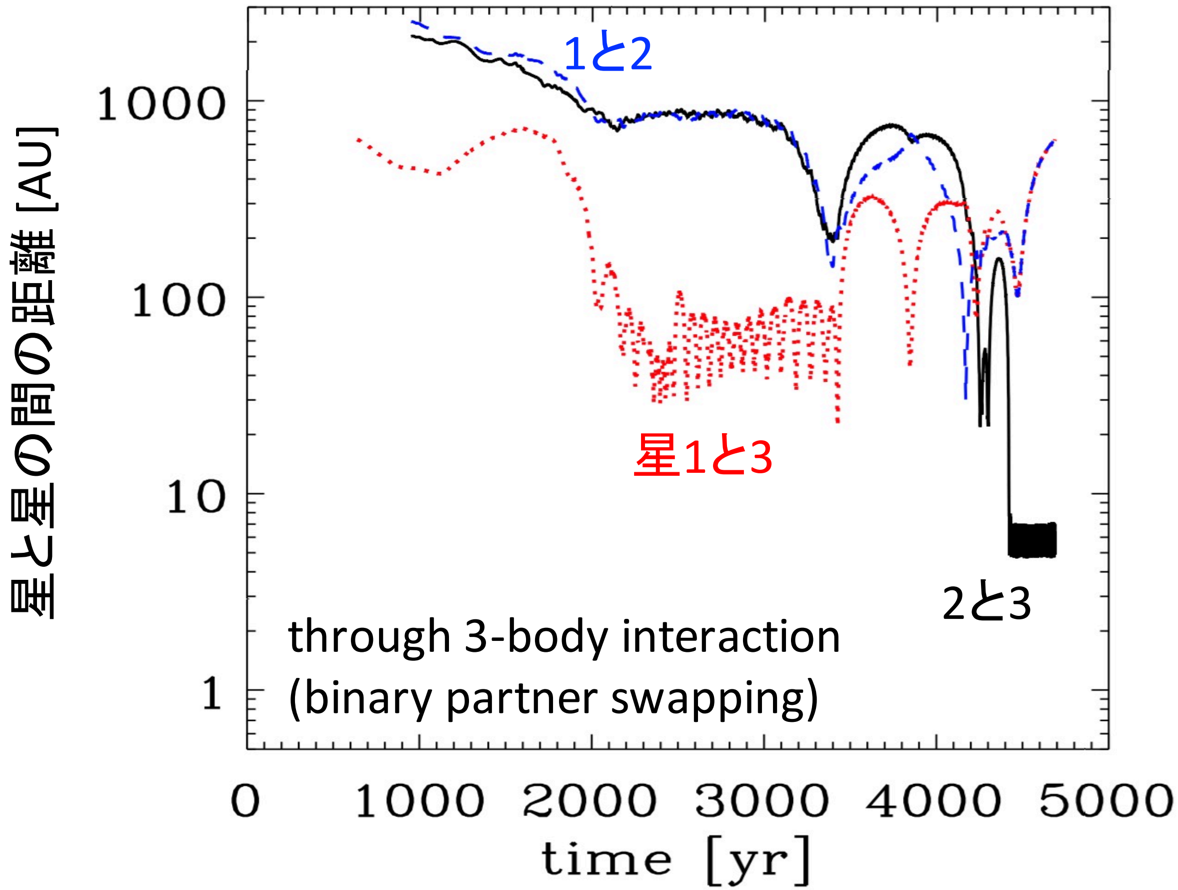


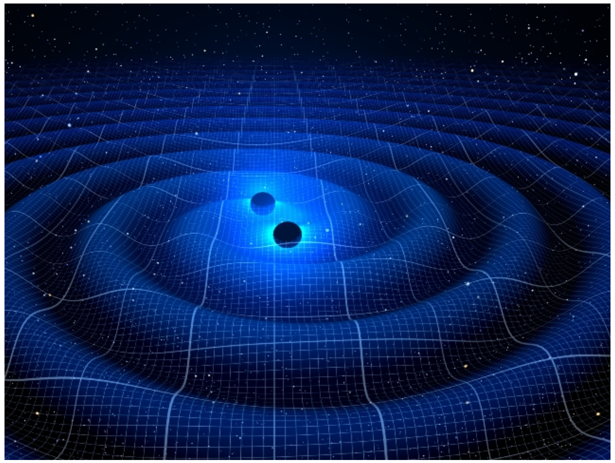


Massive tight binary?

Stacy, Bromm, & Lee (2016)

1 massive tight binary
$13M_\odot + 14M_\odot$
with ～5AU separation





LIGO GW detection ⇒ Massive BH-BH binary
as Pop III star remnants?

→ 稲吉くん話 (e.g., Kinugawa+14; Hartwig+16;
Inayoshi+16; Dvorkin+16)

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