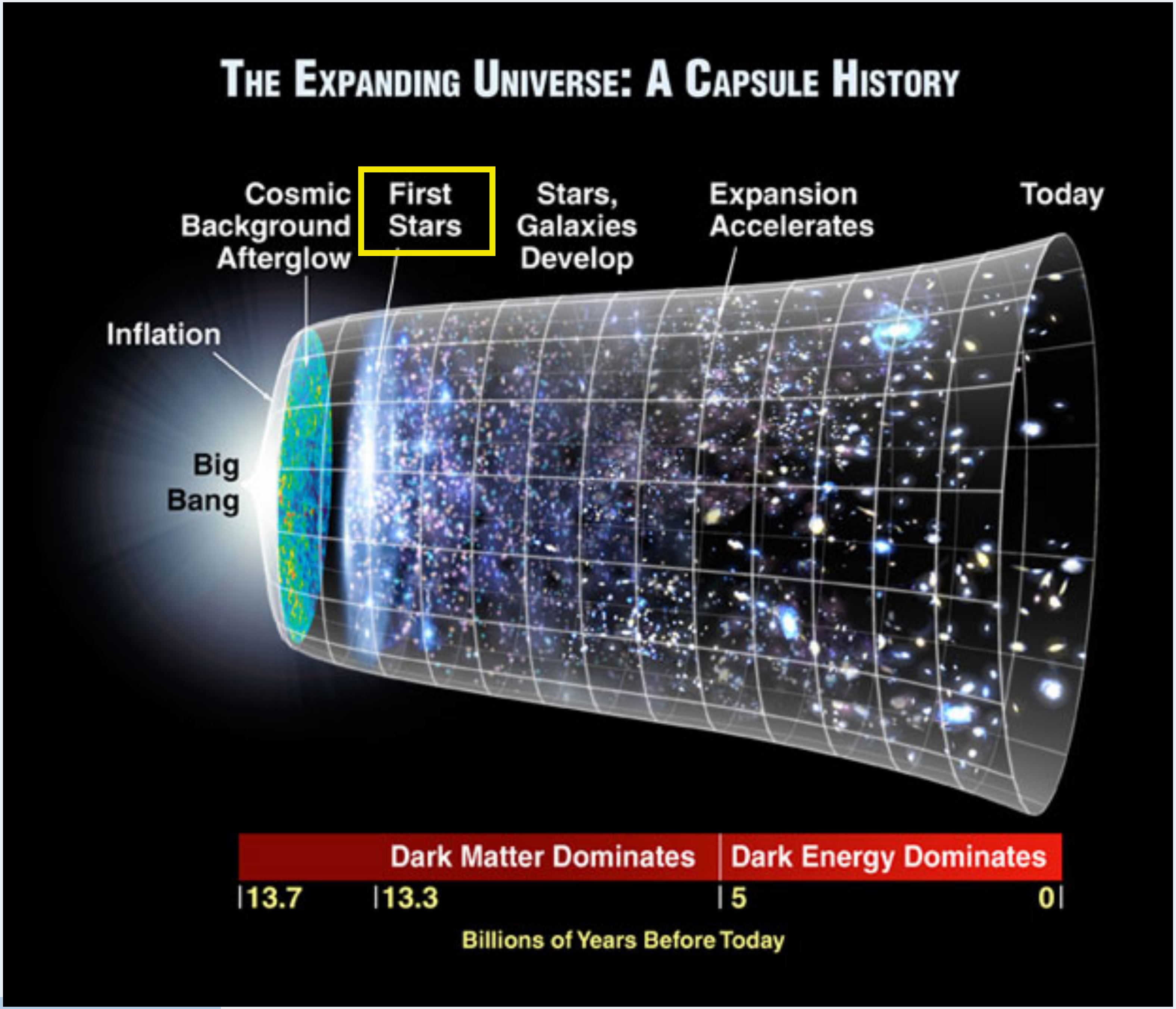
Towards Constraining the IMF of Pop III Stars

Athena Stacy

KITP, April 2014


THE EXPANDING UNIVERSE: A CAPSULE HISTORY
Cosmic Background Afterglow
First Stars
Stars, Galaxies Develop
Expansion Accelerates
Today
Inflation
Big Bang
Dark Matter Dominates
Dark Energy Dominates
13.7
13.3
5
0
Billions of Years Before Today

Hierarchical Merging

Non-SF
DM clumps

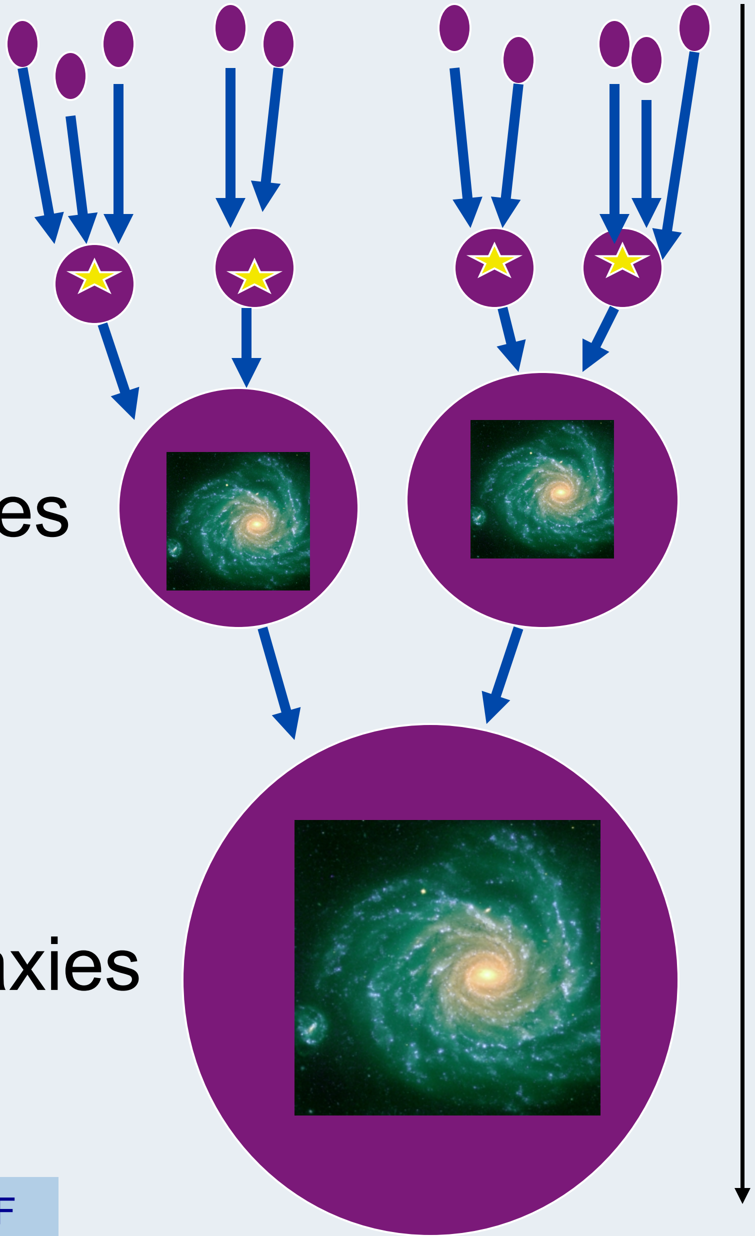
minihalos

z~30

dwarf galaxies

z~10

modern galaxies



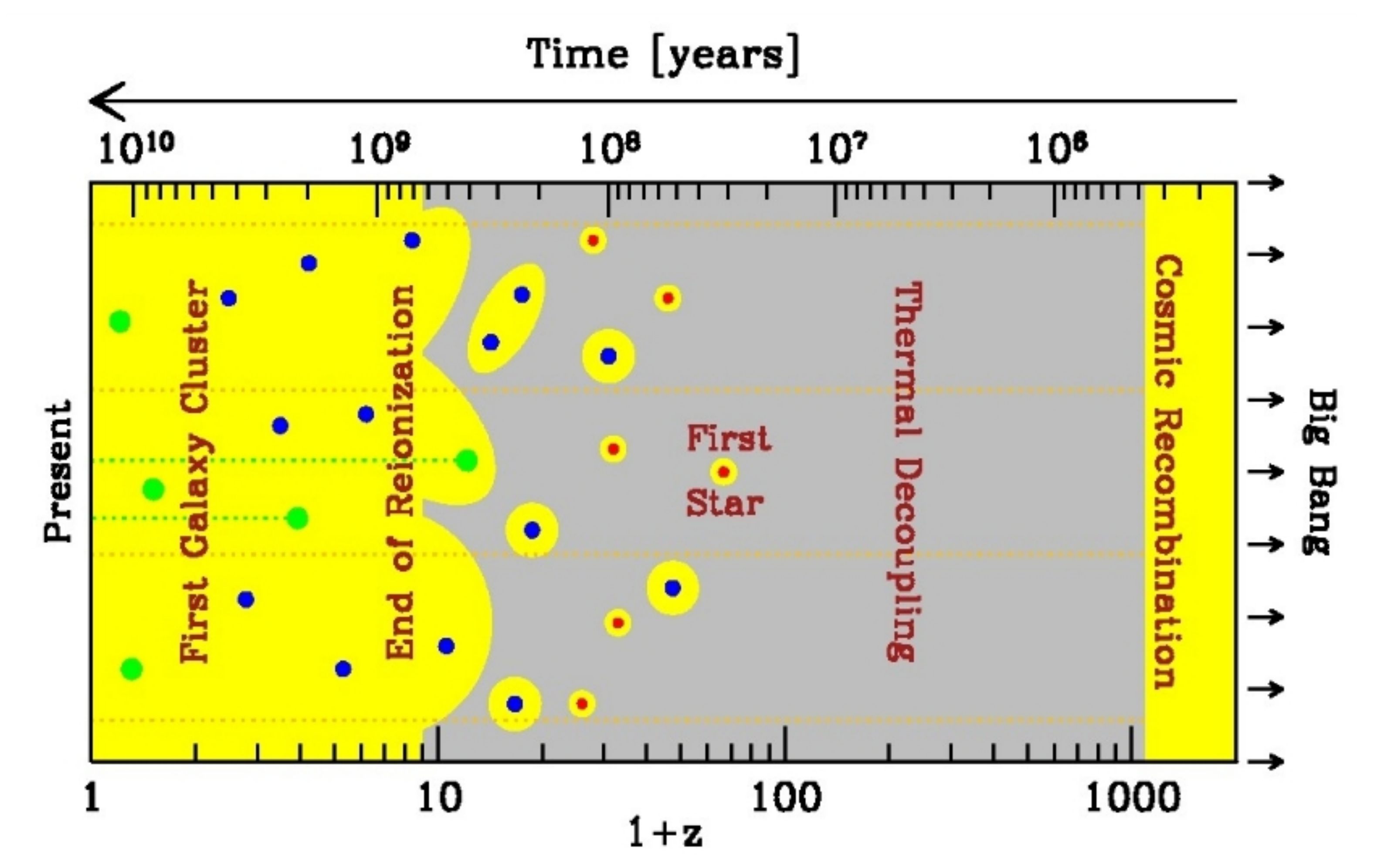
Virial approximation:
$E_{pot} \sim E_{kin} \sim E_{therm}$

$M_{DM\ halo}$ ↑
$T_{vir} \propto M^{2/3}(1+z)$ ↑

- DM clumps form first

- Eventually provides sufficient gravity for gas to collapse and form stars

Pop III stars were first contributors to reionization

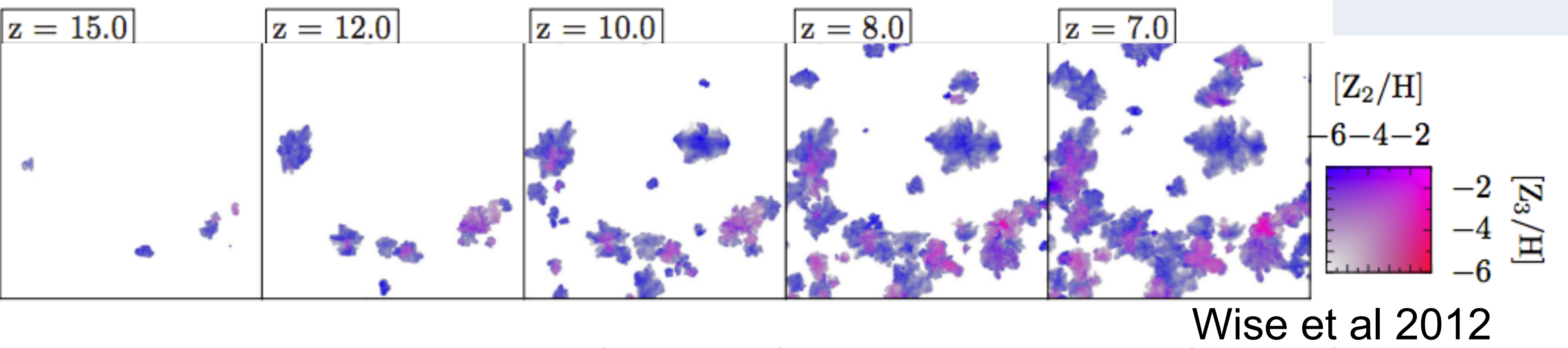


Pop III stars began metal enrichment and set environment for later Pop II generations

Pop III = formed from gas with NO metals. Only coolant is H_2 (and some HD)

Pop II = formed from gas enriched with metals, which were created within stars from previous generations

Pop III stars began metal enrichment and set environment for later Pop II generations



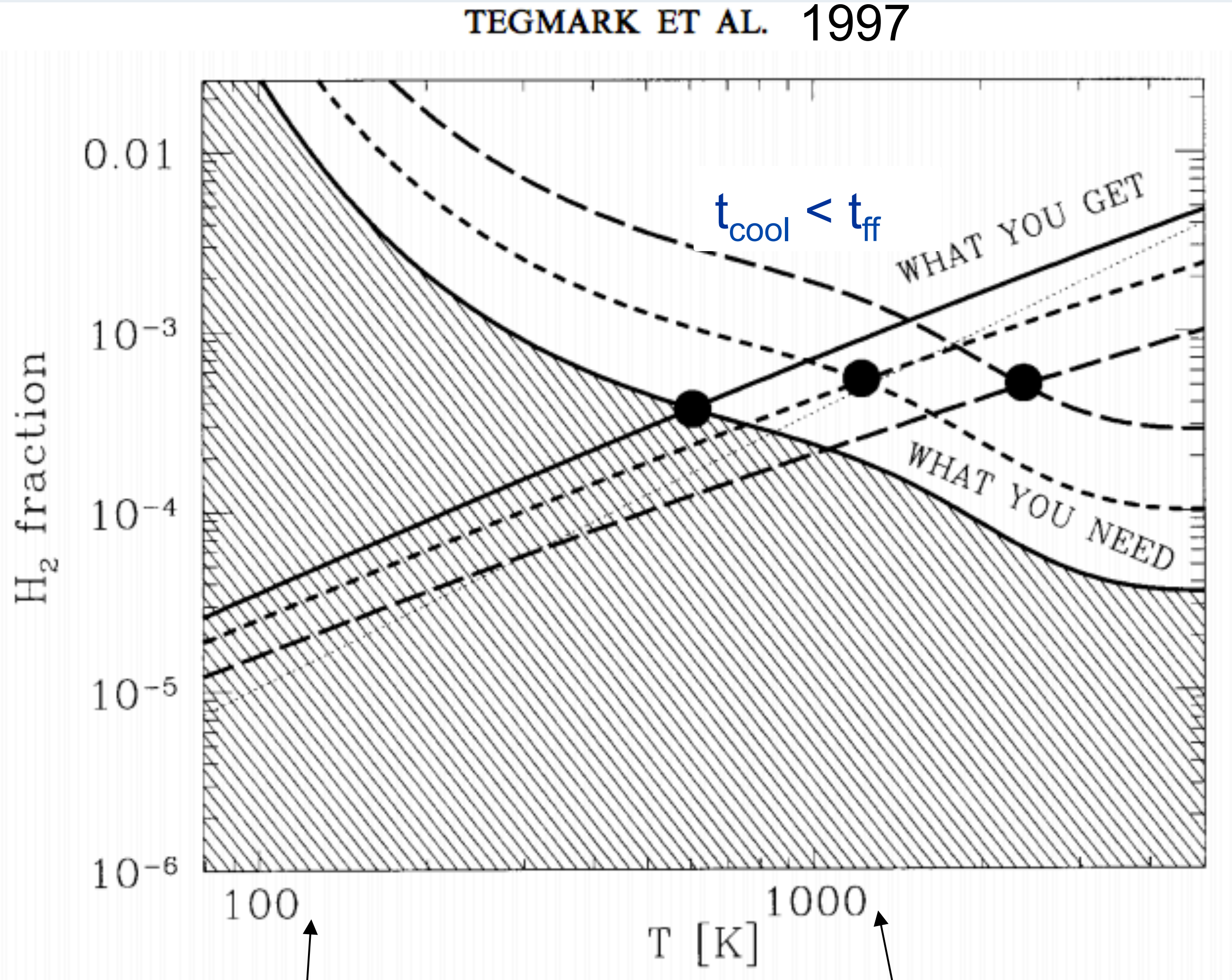
Wise et al 2012

1 Mpc
(comoving)

Pop III = formed from gas with NO metals. Only coolant is H_2 (and some HD)

Pop II = formed from gas enriched with metals, which were created within stars from previous generations

Primordial Gas Cooling Driven by H_2



$M_{DM\ halo} \sim 10^4\ M_\odot$

$M_{DM\ halo} \sim 10^6\ M_\odot$

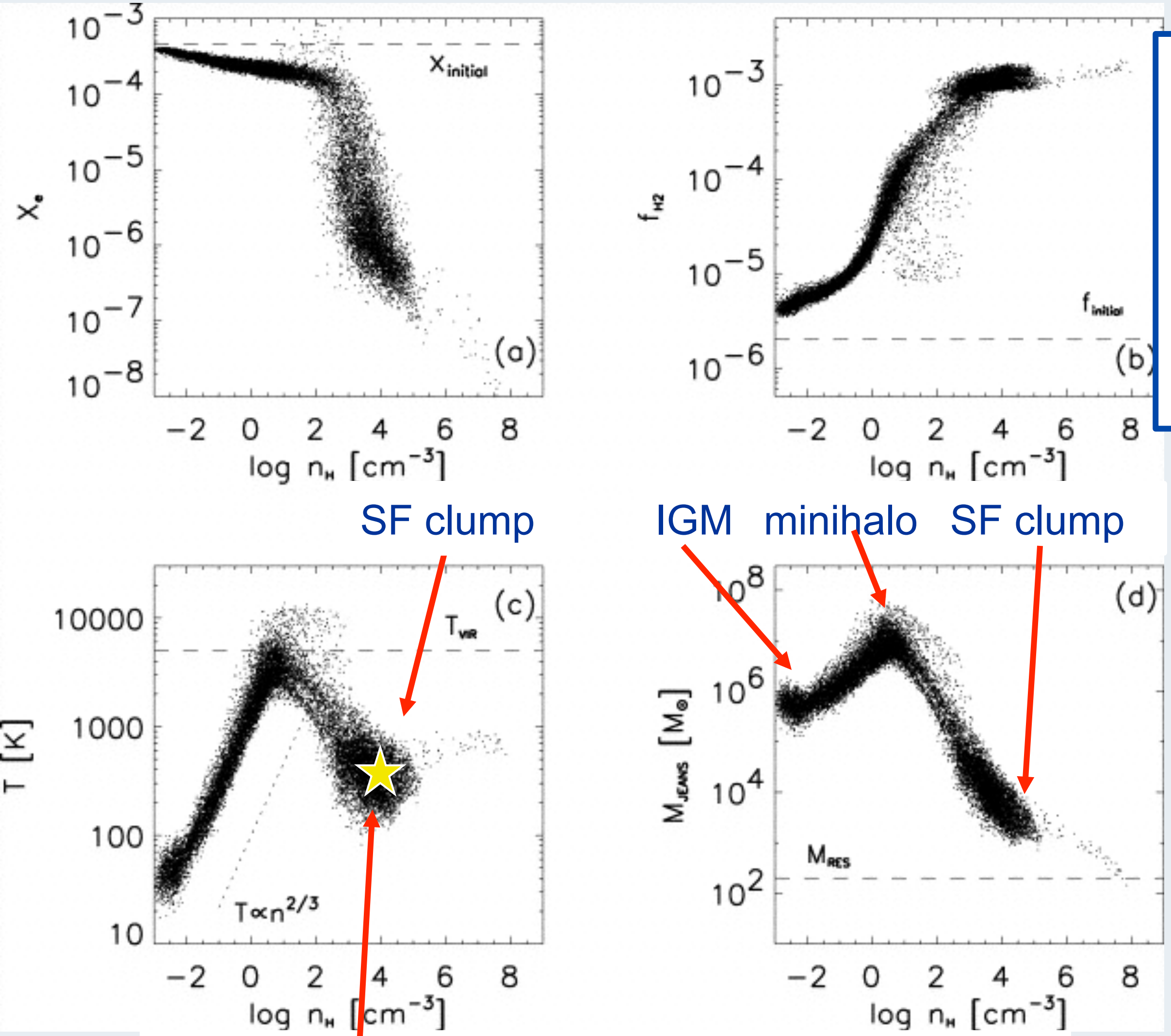
It is only in larger minihalos with mass > $10^6\ M_\odot$ of DM where gas warms enough to form sufficient H_2 for gas collapse and SF.

M_{halo} ↑
T_{gas} ↑
H_2 ↑
t_{cool} ↓

$$t_{cool} \simeq \frac{\frac{3}{2} n k_B T}{\Lambda(n,T)}$$

$$t_{ff} = \left(\frac{3\pi}{32 G\rho}\right)^{1/2}$$

Primordial Gas Cooling Driven by H_2



SF clump

IGM minihalo SF clump

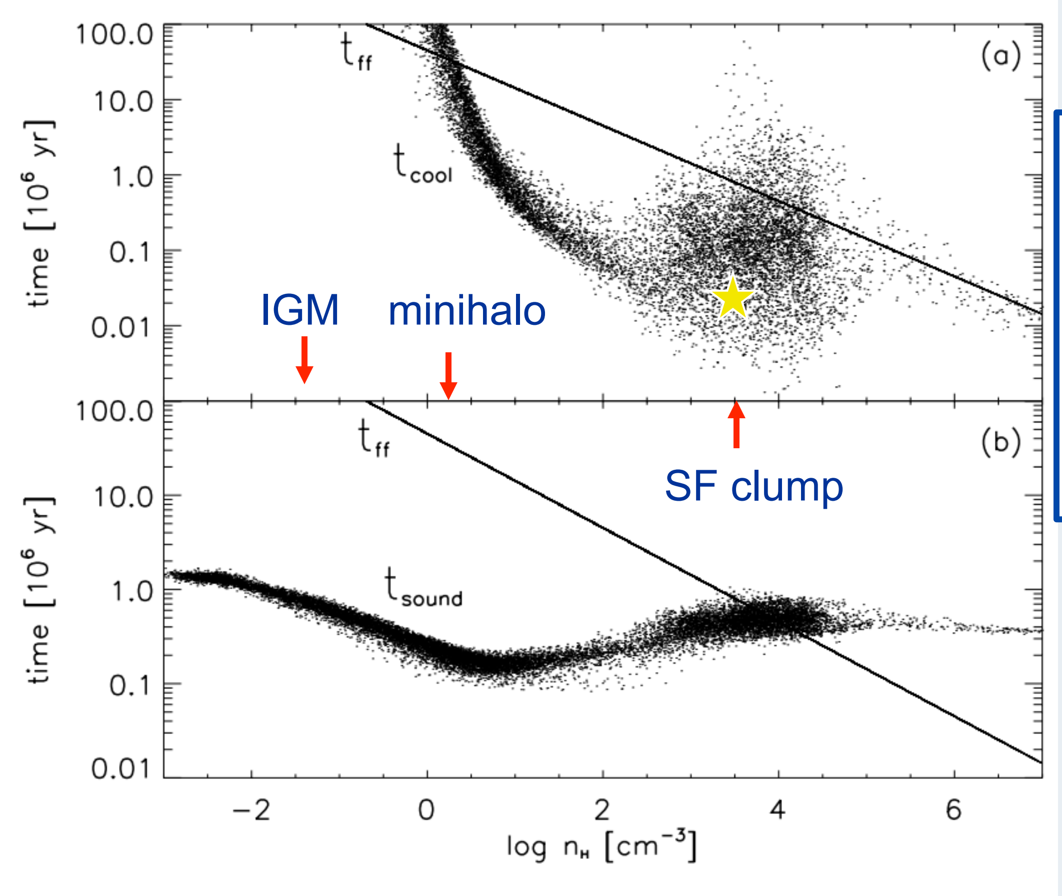
no dust/metal cooling
= higher temps
= faster protostellar accretion rates
= larger Pop III masses than Pop I/II?

$$\dot{M}_{\rm acc} \simeq \frac{M_{\rm J}}{t_{\rm ff}} \simeq \frac{c_s^3}{G} \propto T^{3/2}$$

$$M_{\rm J} \simeq 500 M_\odot \left(\frac{T}{200\,{\rm K}}\right)^{3/2} \left(\frac{n}{10^4\,{\rm cm}^{-3}}\right)^{-1/2}$$

Bromm et al 2002

Primordial Gas Cooling Driven by H_2



no dust/metal cooling
= higher temps
= faster protostellar accretion rates
= larger Pop III masses than Pop I/II?

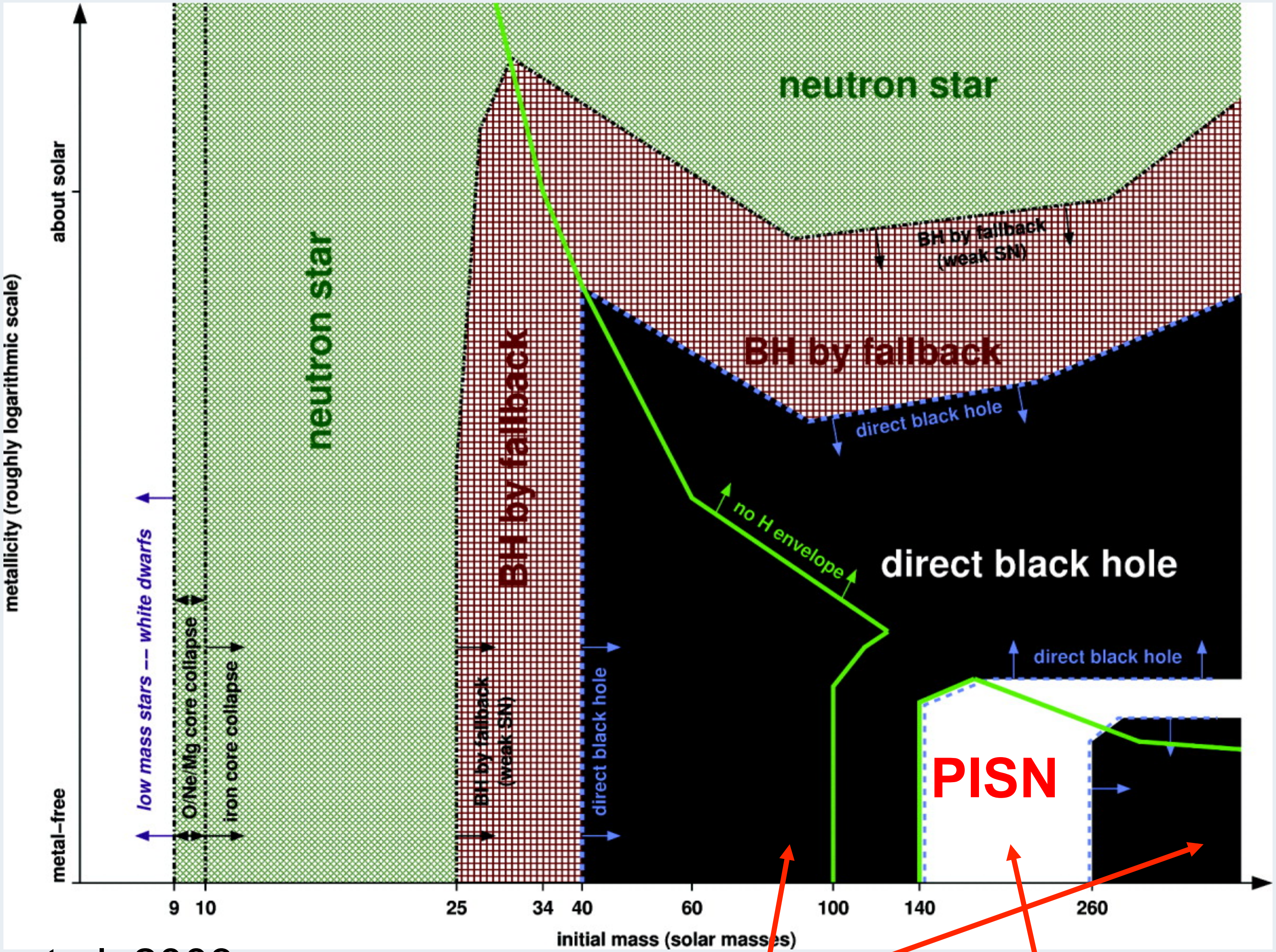
Bromm et al 2002

Possible fates of single non-rotating stars: variation with mass

$Z=Z_\odot$

Metallicity

$Z=0$



Heger et al. 2003

NO metals released by star

All metals ejected by star

Motivating Questions

- What role did Pop III play in reionization and metal enrichment? (Madau 2001, Alvarez 2006, Johnson 2007, Greif 2010, Maio 2010, Wise et al 2010)

- What feedback did Pop III exert on later star formation (i.e. Pop III to Pop II transition)? On early protogalaxy formation?

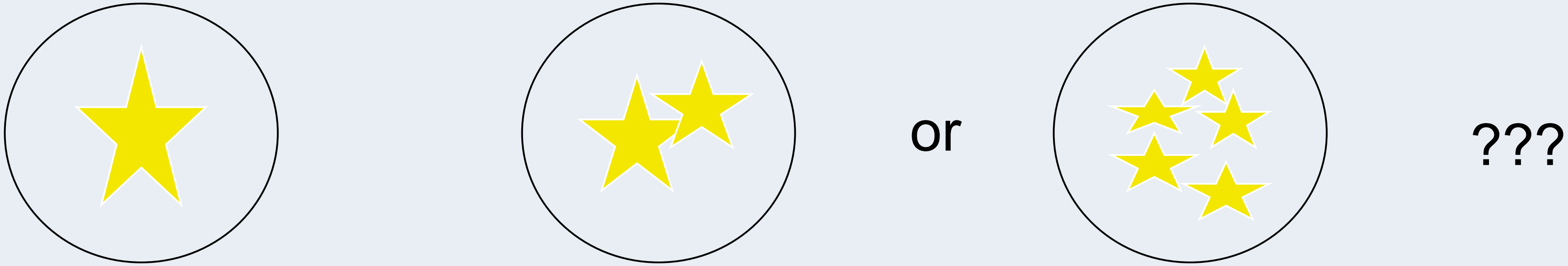
- How long did metal-free star formation and pockets of primordial gas persist in the universe? (e.g. Scannapieco et al. 2005, Muratov et al. 2013)

- What role did Pop III play in seeding the first nuclear black holes?

This depends on the Pop III IMF, SFR, and rotation rates…

- What were their typical masses? (Abel et al 2002, Bromm et al 2004, McKee &Tan 2004/2008)

- What was their typical multiplicity? (Turk et al 2010, Stacy 2010, 2012)



I. Pop III Star Formation Without Feedback

Stacy, Greif, & Bromm, 2010 MNRAS, 403, 45

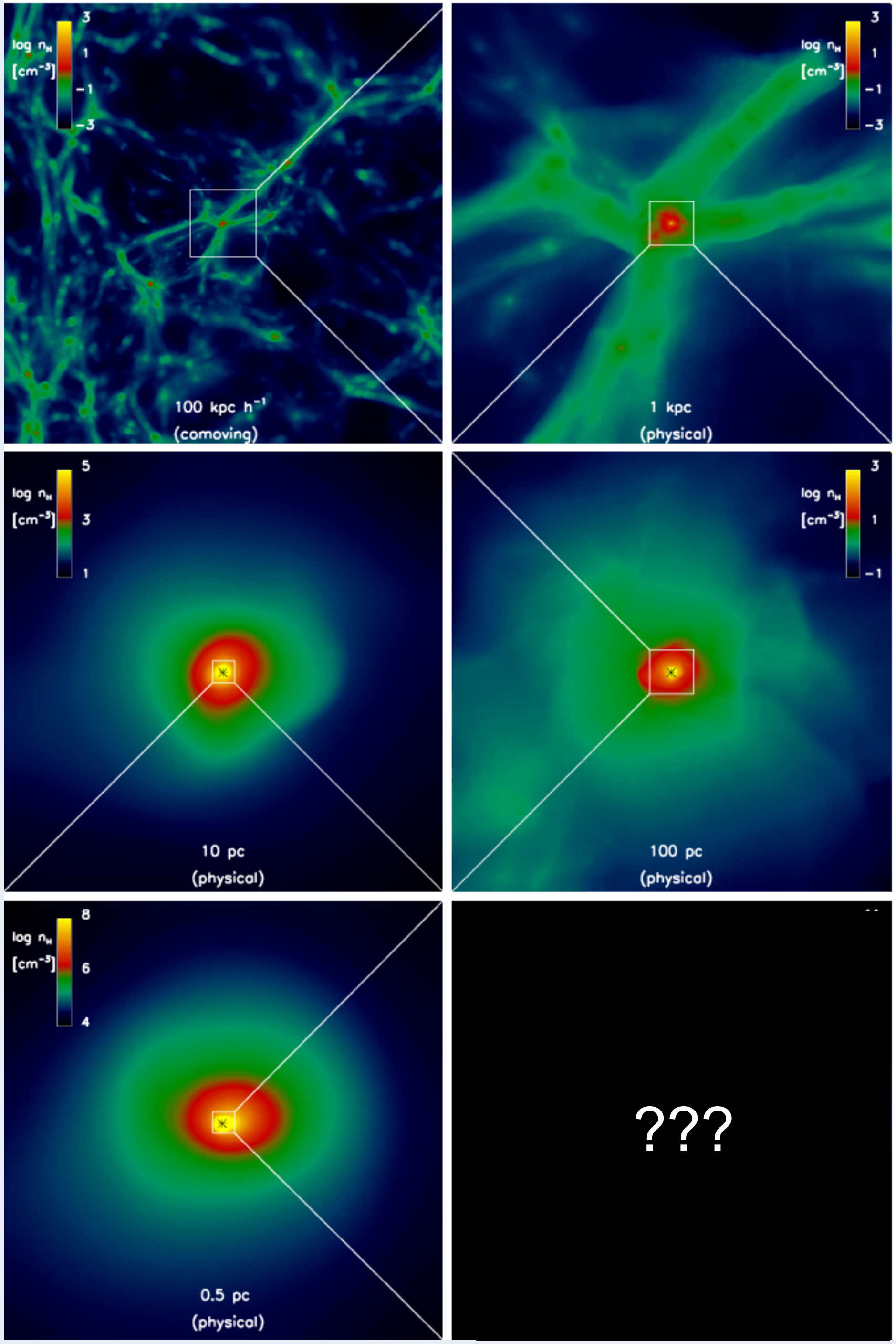
Explore this unobservable epoch of the universe with cosmological simulations!

Gadget (SPH + N-body)

-initialized at z=100 according to ΛCDM model

- followed formation of protostar (sink particle) and subsequent 5000 yr of accretion

- m_{sph} (gas) = 0.015 $M_\odot$
- $M_{res} \sim 1.5 N_{neigh} m_{sph} \sim 1\ M_\odot$ = minimum allowed Jeans mass

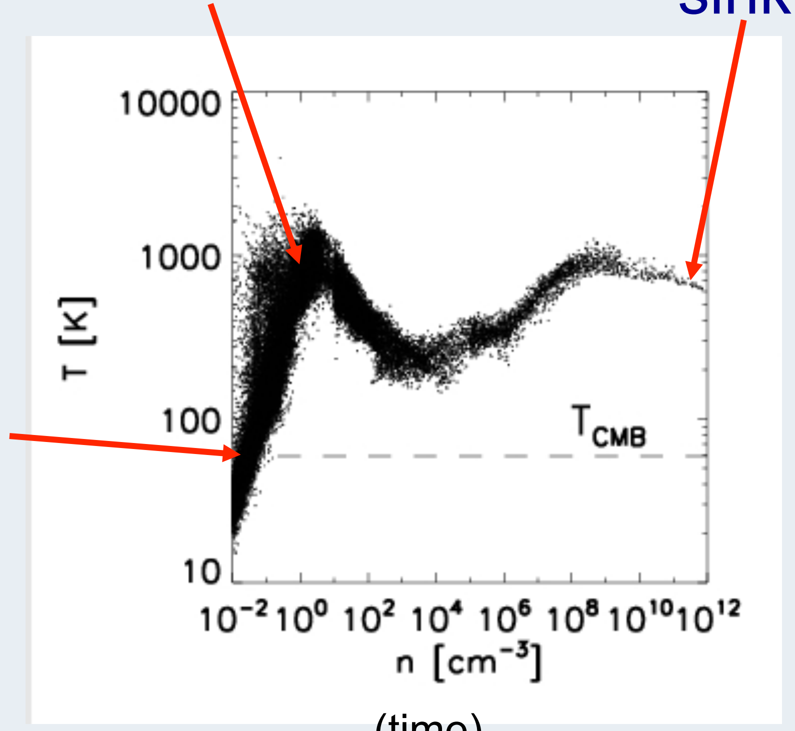


Initial Collapse

minihalo

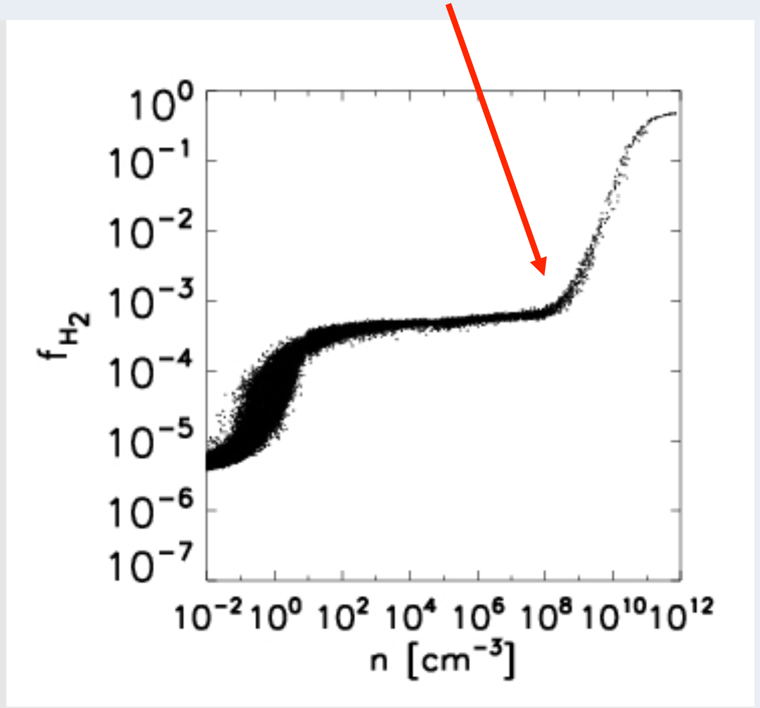
sink

IGM

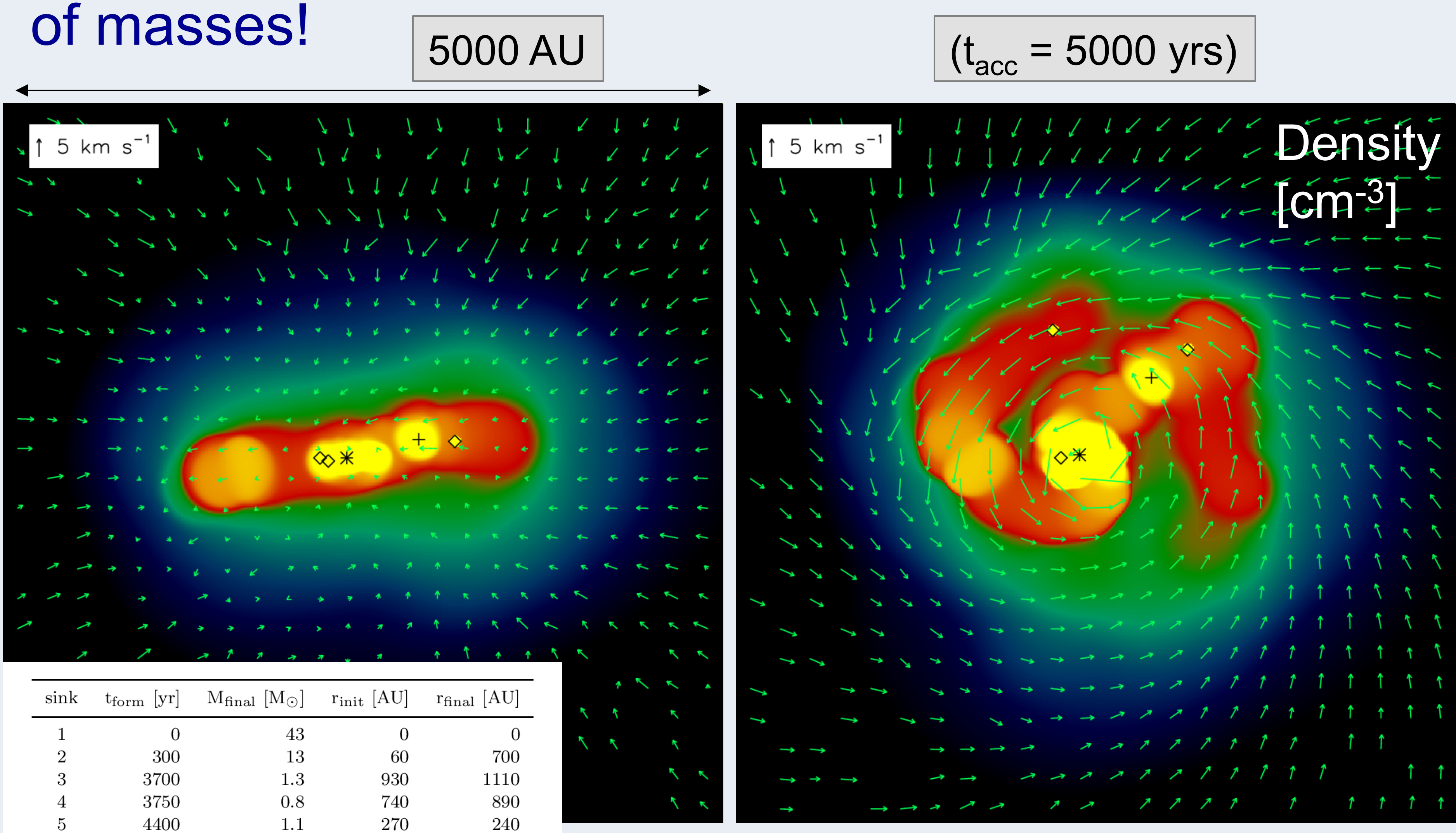


(time)

3-body reactions and H_2 formation



Pop III stars form in multiples and have a wide range of masses!



sink	t_{form} [yr]	M_{final} [$M_\odot$]	r_{init} [AU]	r_{final} [AU]
1	0	43	0	0
2	300	13	60	700
3	3700	1.3	930	1110
4	3750	0.8	740	890
5	4400	1.1	270	240

By 5000 yr, multiple stars with M_* ranging from 1 $M_\odot$ to 30 $M_\odot$ form within a disk that has grown to ~ 40 $M_\odot$. Largest star should later reach > 100 $M_\odot$.

Primordial Disk Satisfies Fragmentation Criteria

- Toomre Fragmentation criterion:
- Q ~ 0.4 < 1
- $t_{cool} < t_{rot}$ and

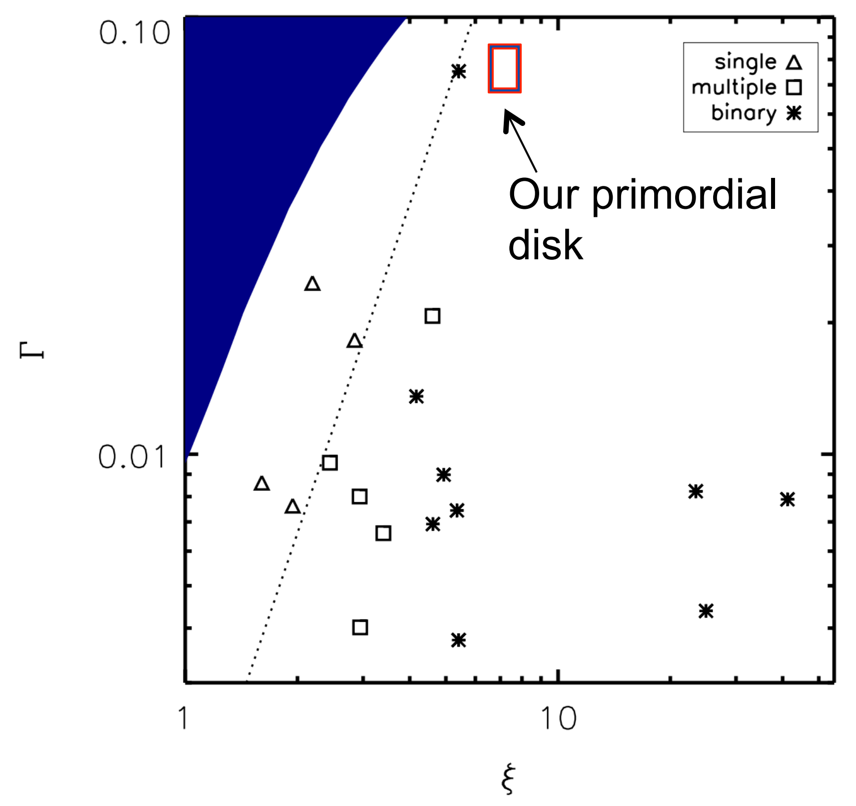
(Gammie 2001, Kratter et al. 2010, 2011)

$$Q = \frac{c_s \kappa}{\pi G \Sigma} < 1$$

$$\dot{M}_{\rm in} \gtrsim c_{\rm s}^3 / G$$

$$\xi = \frac{\dot{M}_{\rm in} G}{c_{s,d}^3}$$

$$\Gamma = \frac{\dot{M}_{\rm in}}{M_{*d} \Omega_{k,\rm in}} = \frac{\dot{M}_{\rm in} \langle j \rangle_{\rm in}^3}{G^2 M_{*d}^3}$$



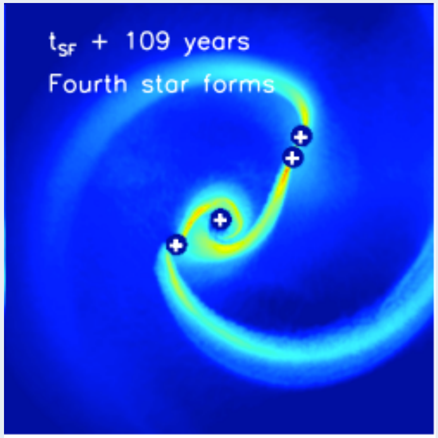
Overview of Part I

- Primordial star-forming gas becomes unstable to secondary fragmentation after initial protostar forms

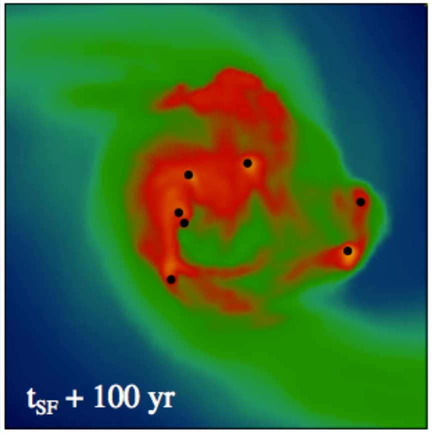
- Pop III stars form in multiples, mostly due to disk fragmentation

- Disk fragmentation may allow for range of Pop III masses to be very broad (some ~1 $M_\odot$ stars)

Also seen by other later sims:



Clark et al 2011



Greif et al 2011

II. Pop III Star Formation With Radiative Feedback

Stacy, Greif, & Bromm, 2012, MNRAS, 422, 290

Protostellar Feedback

- Repeat previous cosmological simulation, but with updated H_2 cooling rates
- Model LW radiation and growth of surrounding HII region
- Also performed a comparison “no-feedback” simulation
- **How will radiation alter the growth of the Pop III star?**

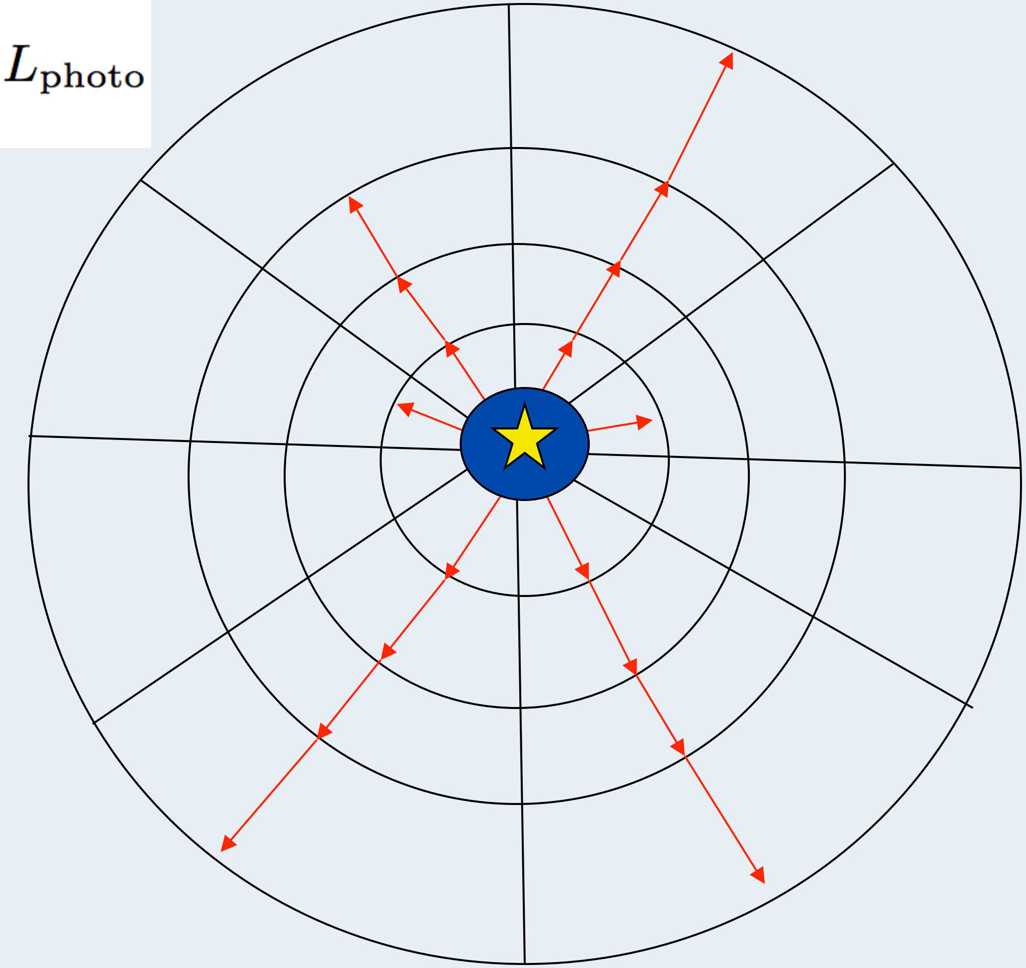
$$n_n r_{\rm I}^2 \frac{{\rm d}r_{\rm I}}{{\rm d}t} = \frac{\dot{N}_{\rm ion}}{4\pi} - \alpha_{\rm B} \int_0^{r_{\rm I}} n_e n_+ r^2 {\rm d}r \ ,$$

$$L_* = L_{\rm acc} + L_{\rm photo} = \frac{G M_* \dot{M}}{R_*} + L_{\rm photo}$$

- 200 radial segments
- 10^5 angular sements
- 2 x10^7 bins

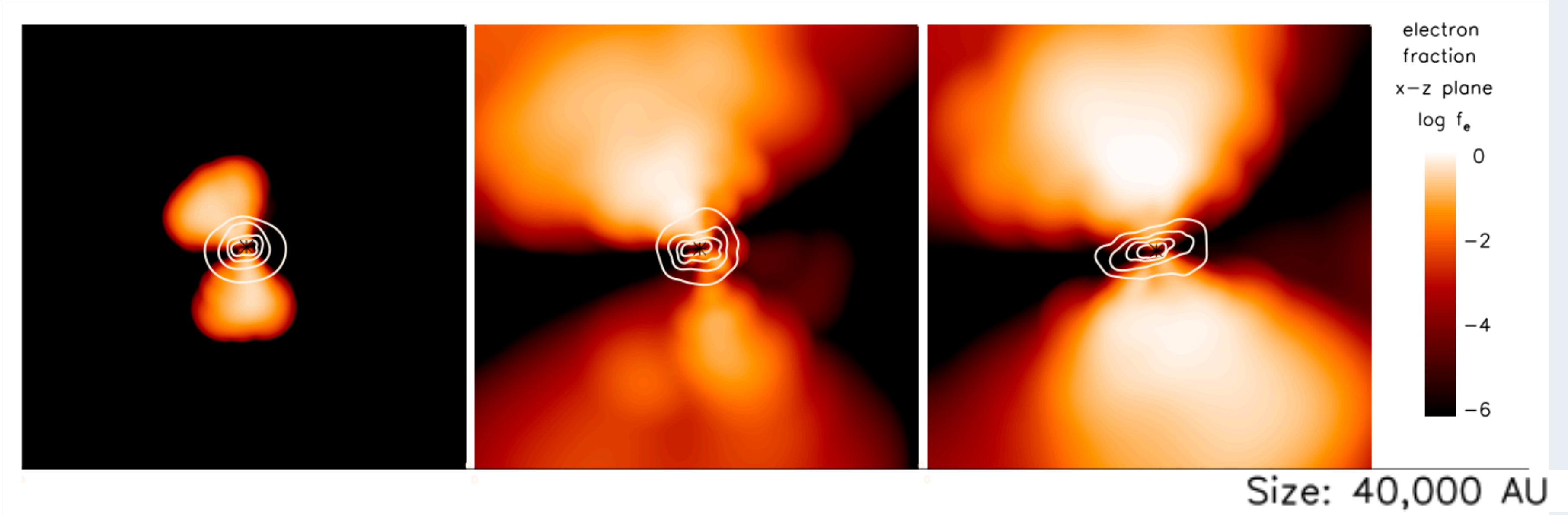
$M_* = M_{\rm sink}$

$R_* = ?$



The I-front Tracker

Adding ionization feedback: I-front emerges, expands beyond size of disk, and greatly slows inflow

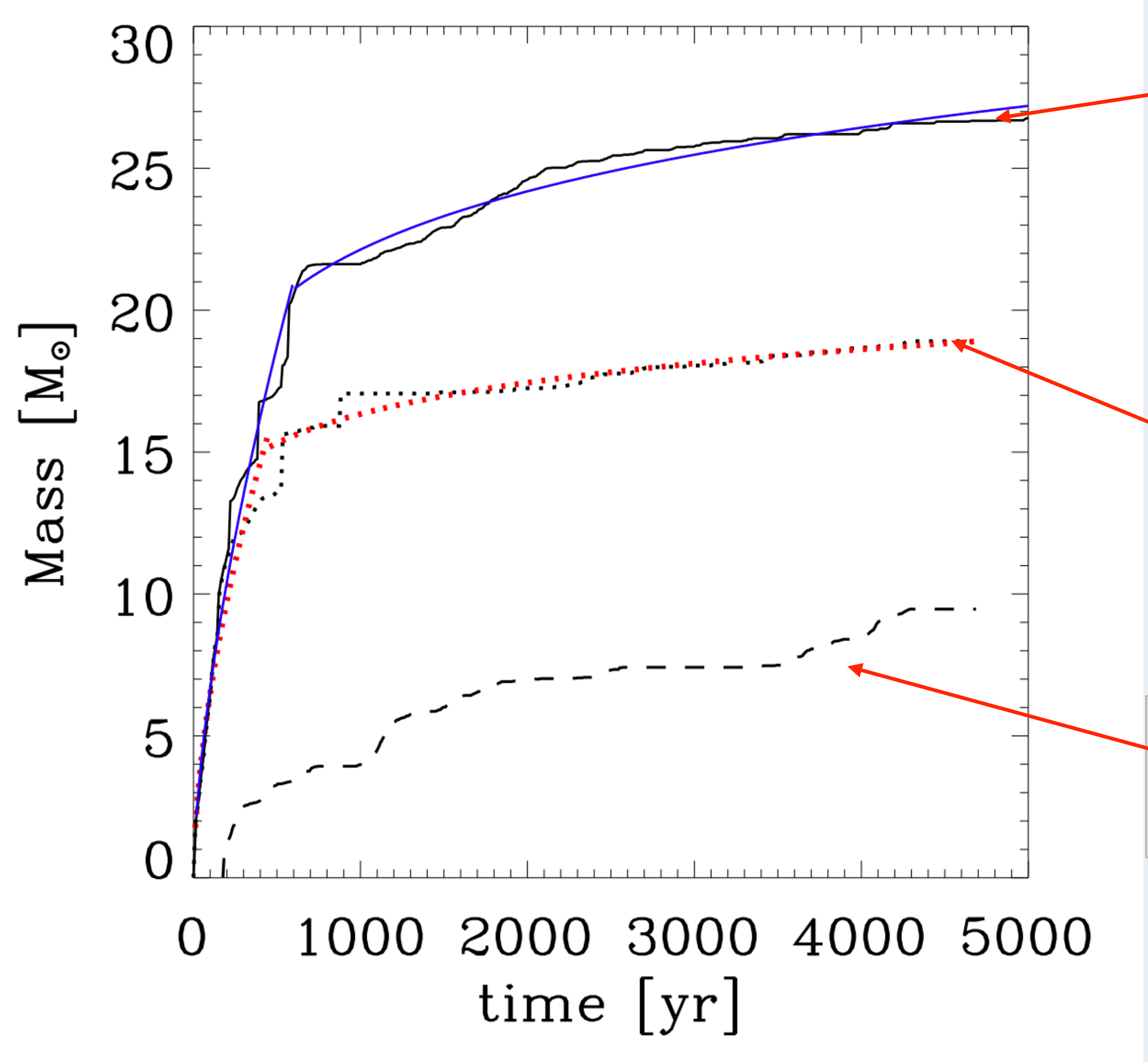


1500 yr

2500 yr

4500 yr

Ionization reduces accretion rate, but massive binary still forms



Without feedback

$M_{sink} \sim t^{0.13}$

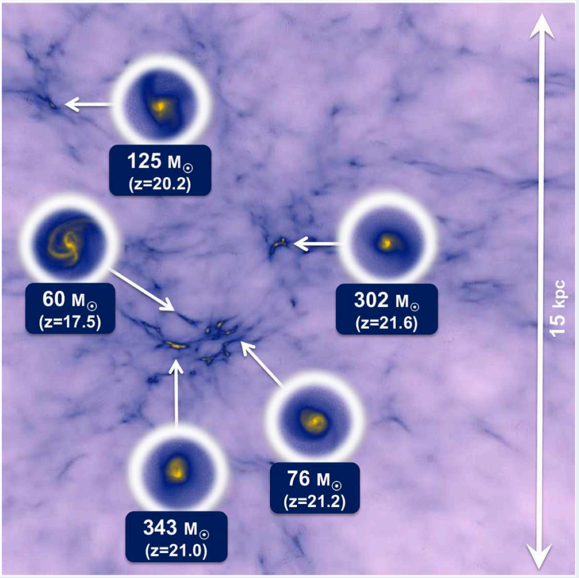
With feedback

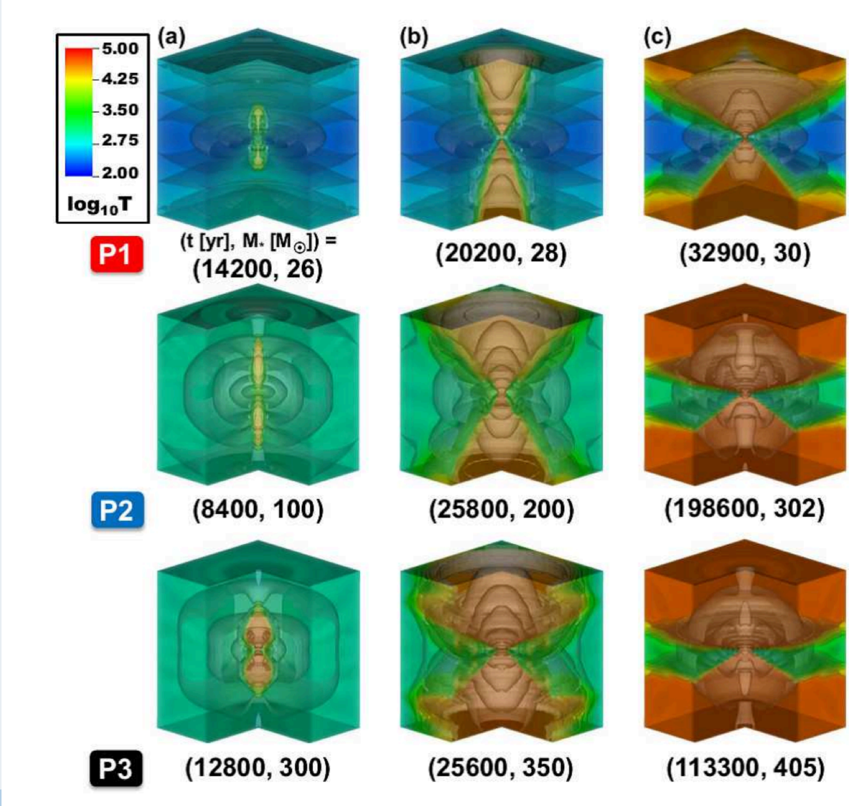
$M_{sink} \sim t^{0.09}$

2nd largest sink (with feedback)

$M_{final} \sim 30\ M_\odot$

Can get more statistics with 2-D simulations





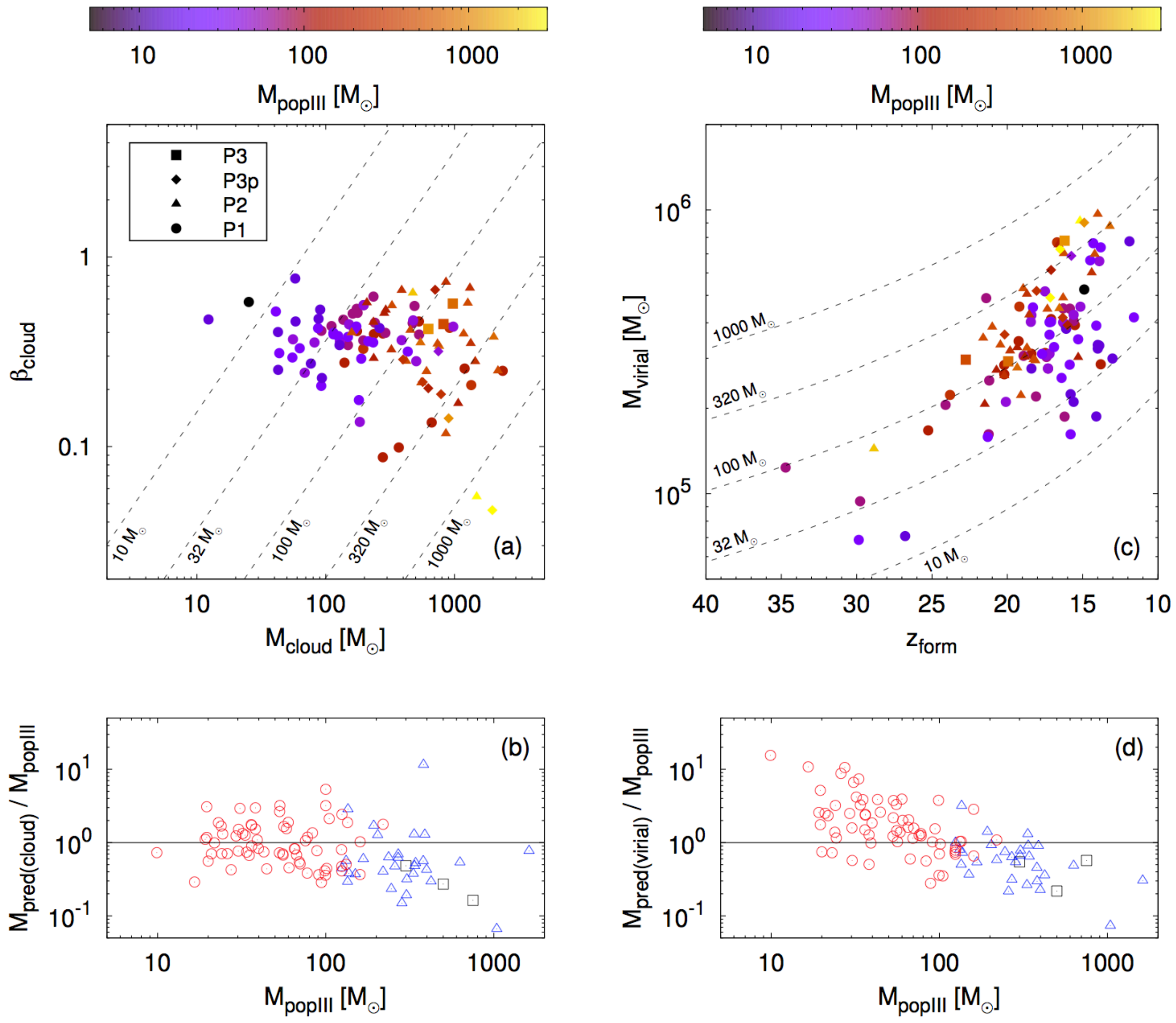
1. Use cosmological 3-D SPH simulations to initialize 2-D AMR simulations

2. Evolve sink particle growth until HII region halts inflow for **100 different minihalos**

NOTE! Follows growth of **only the most massive star** in each minihalo! 2-D sims cannot follow formation of secondary fragmentation

Hirano, Hosokawa, Yoshida et al. 2014

Hirano et al. 2014



Some correlation between $M_{PopIII,max}$, M_{cloud}, and β_{cloud}

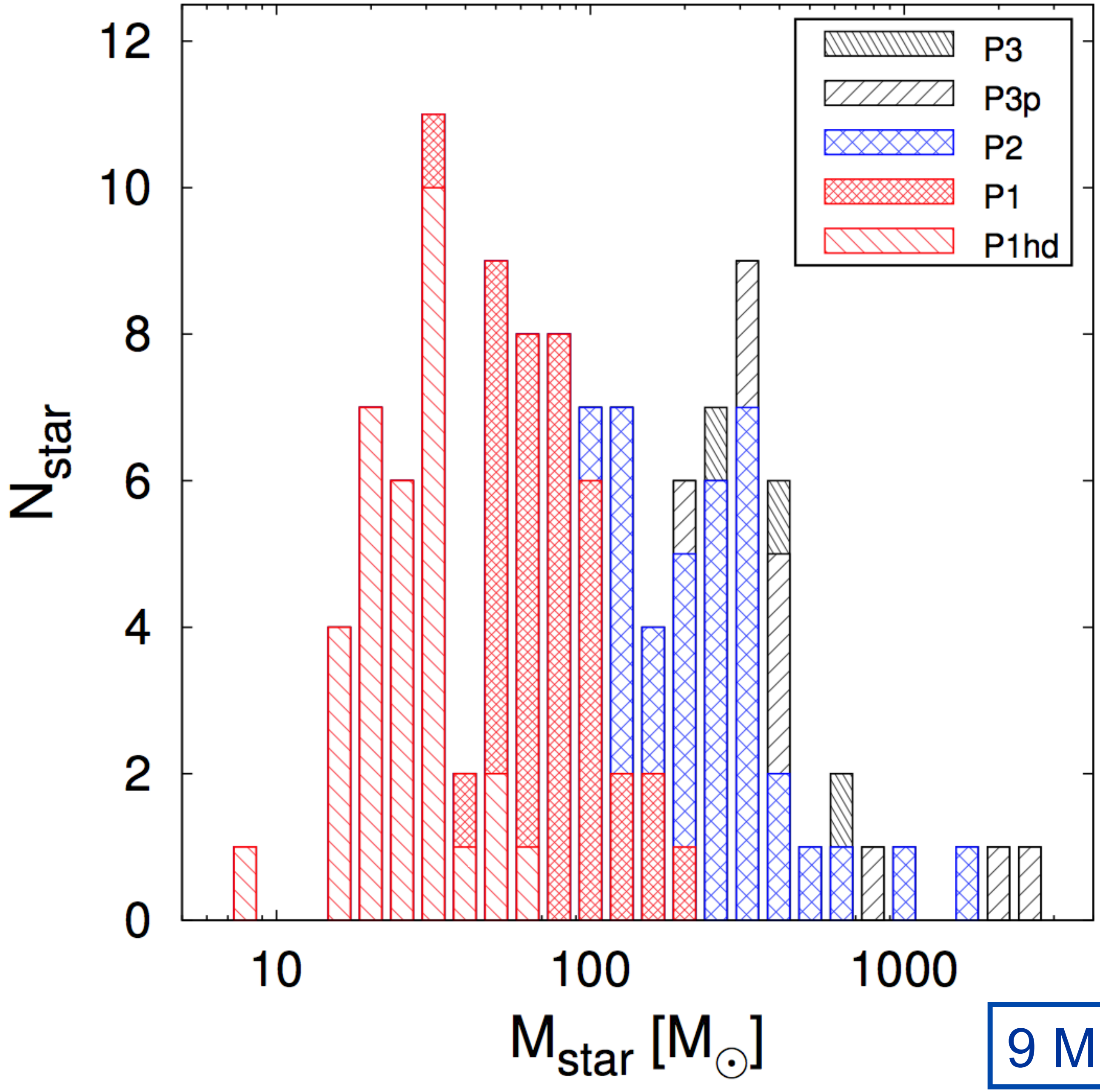
Left: Relation between M_{popIII} , M_{cloud}, and rotation parameter of SF cloud

Right: Relation between M_{popIII} , M_{virial} of minihalo, and formation redshift of minihalo

$$\beta_{\rm cloud} = \frac{\Omega_{\rm cloud}^2 R_{\rm cloud}^3}{3GM_{\rm cloud}}$$

$$M_{\rm popIII} = 100\ {\rm M}_\odot \left(\frac{M_{\rm cloud}}{350\ {\rm M}_\odot} \cdot \frac{0.3}{\beta_{\rm cloud}} \right)^{0.8}$$

$$M_{\rm popIII} = 100\ {\rm M}_\odot \left(\frac{1+z}{20} \right)^3 \left(\frac{M_{\rm virial}}{3 \times 10^5\ {\rm M}_\odot} \right)^2$$



$M_{PopIII,max}$ still has wide range even when accounting for ionizing feedback.

$9\ M_\odot < M_{final} < 2000\ M_\odot$

Hirano et al. 2014

Overview of Part II

- Fragmentation and broad mass range likely to describe Pop III stars even under radiative feedback!

- Possibly massive binaries.

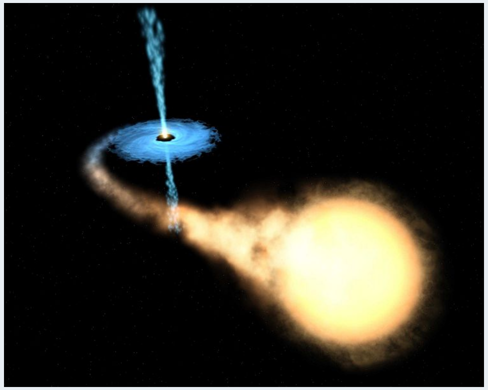
- Pop III stars can likely reach tens of solar masses, but hundreds to one thousand solar masses may be harder.

- In including fragmentation further lowers typical Pop III mass. May explain why PISN signature has not been observed (requires $140M_{\odot} < M_{*} < 260M_{\odot}$).

III. Statistics of Pop III Binaries and Multiple Systems

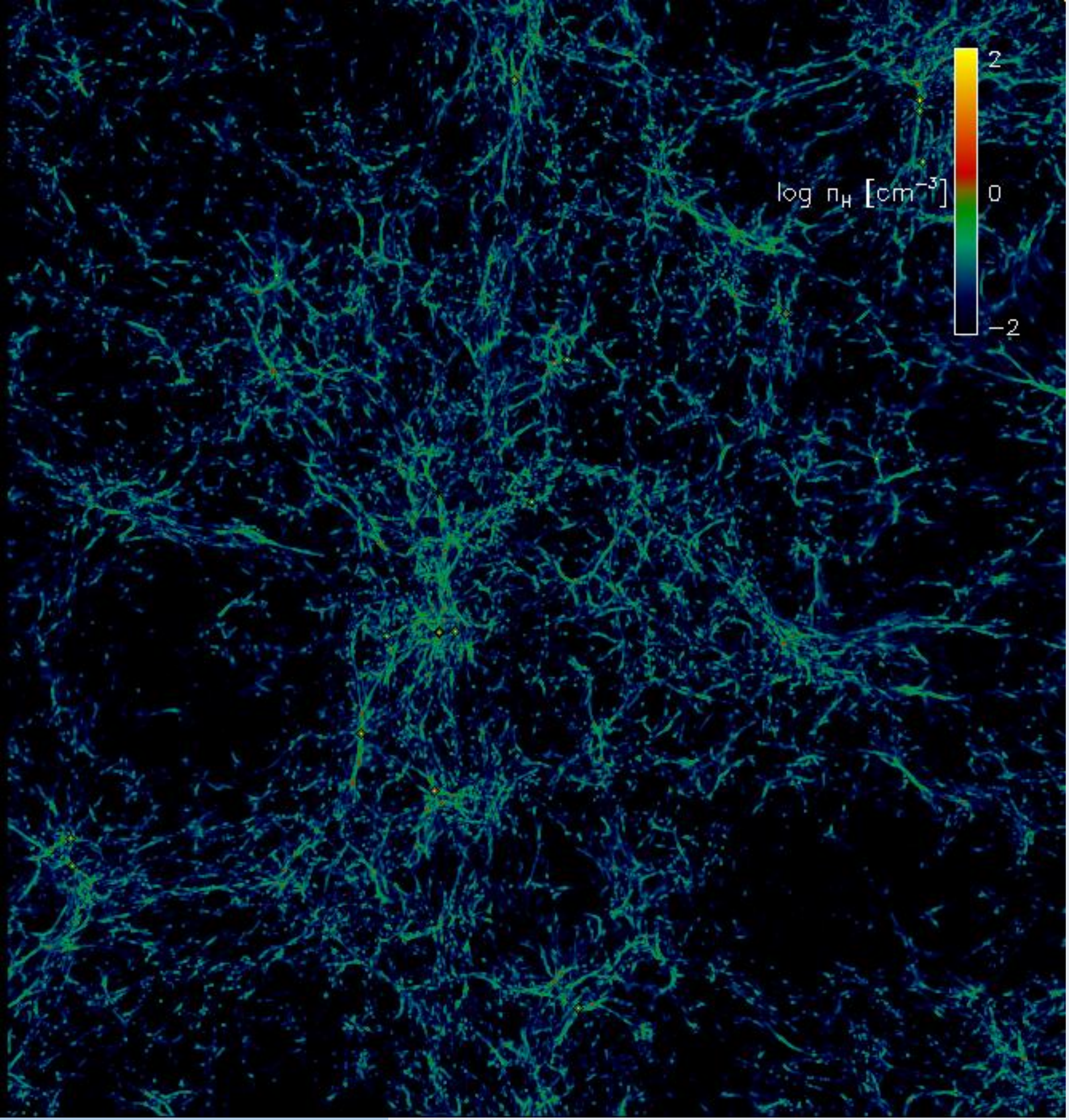
Stacy & Bromm 2013, MNRAS

How do characteristics of stellar clusters vary between minihalos?

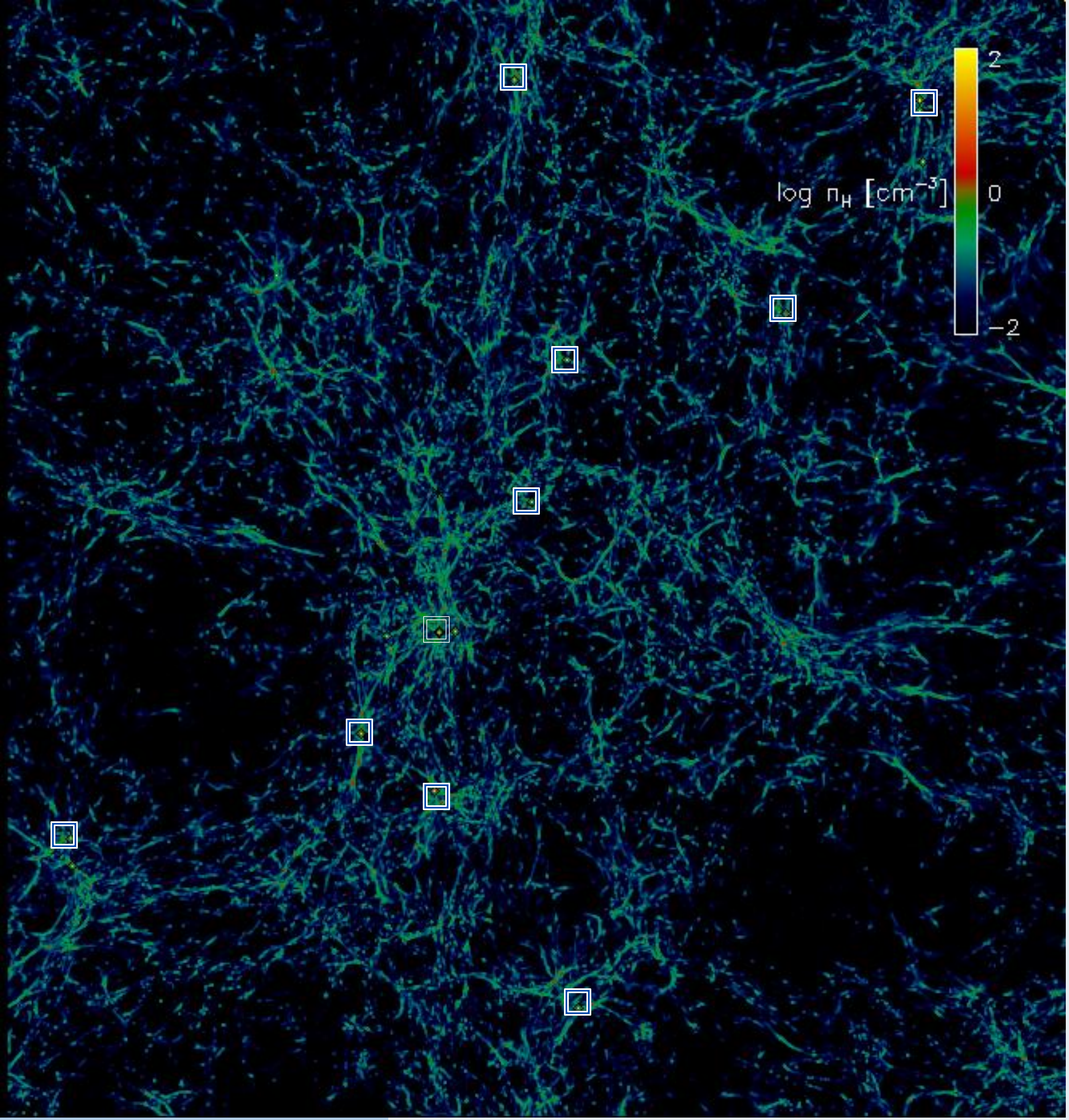


- Binary companions:
  - May spin up star
  - Allow for possible GRBs, HMXB
  - Generate gravitational waves
  - May allow for stellar mergers and “rejuvenation”

- The experiment:
  - Initialize 1.4 Mpc (comoving) box at z=100
  - Pick out first ten minihalos to form in box
  - Evolve to densities of 10^{13} cm^{-3}, resolution length of 20 AU
  - Employ sink particle method to follow evolution of stellar cluster for next 5000 yr



- 1.4 Mpc comoving box
- z=20
- zoom in to resolution of 20 AU

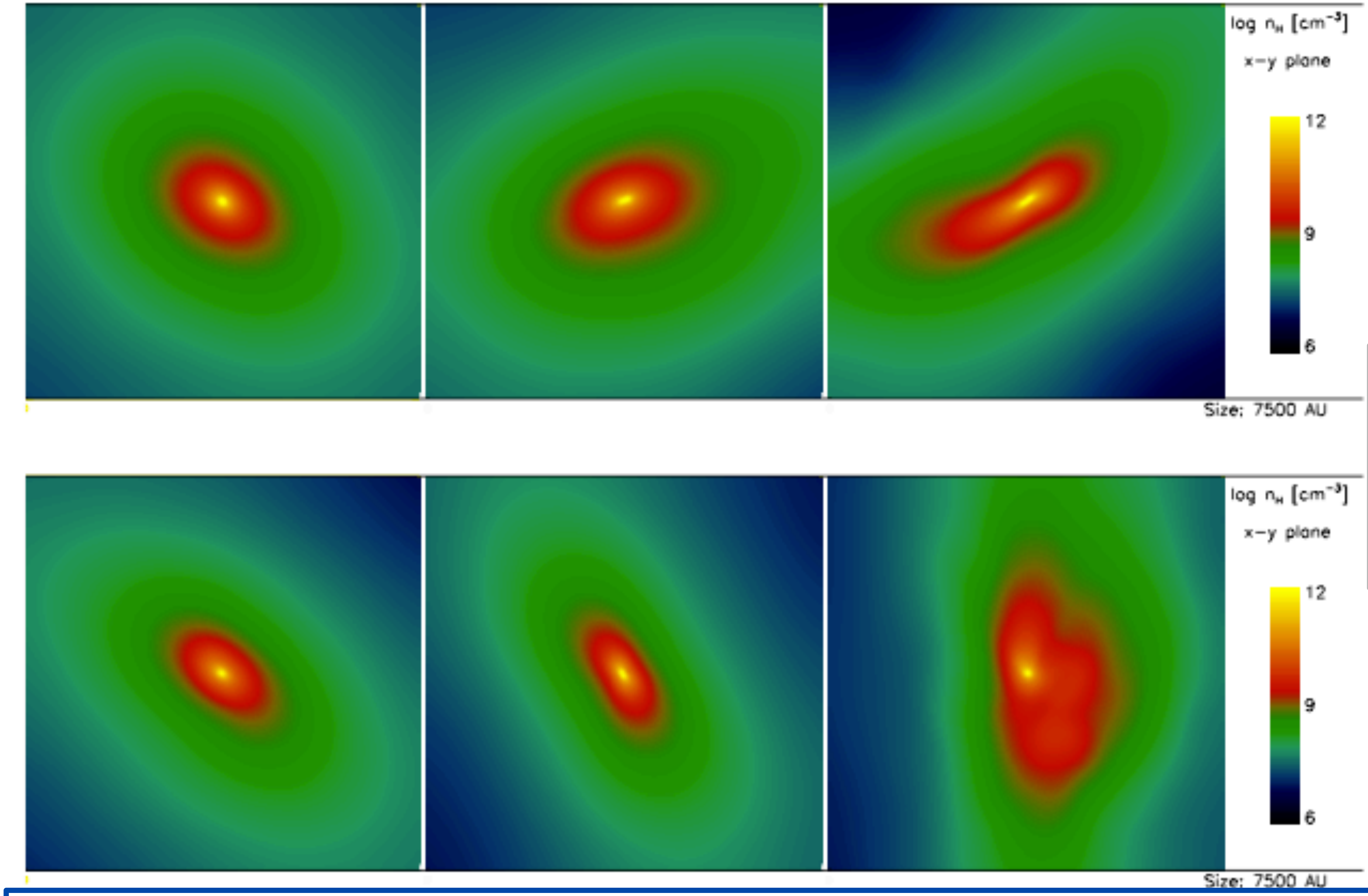


- 1.4 Mpc comoving box
- z=20
- zoom in to resolution of 20 AU

☐ = Pop III SF site!

Note: Feedback not included

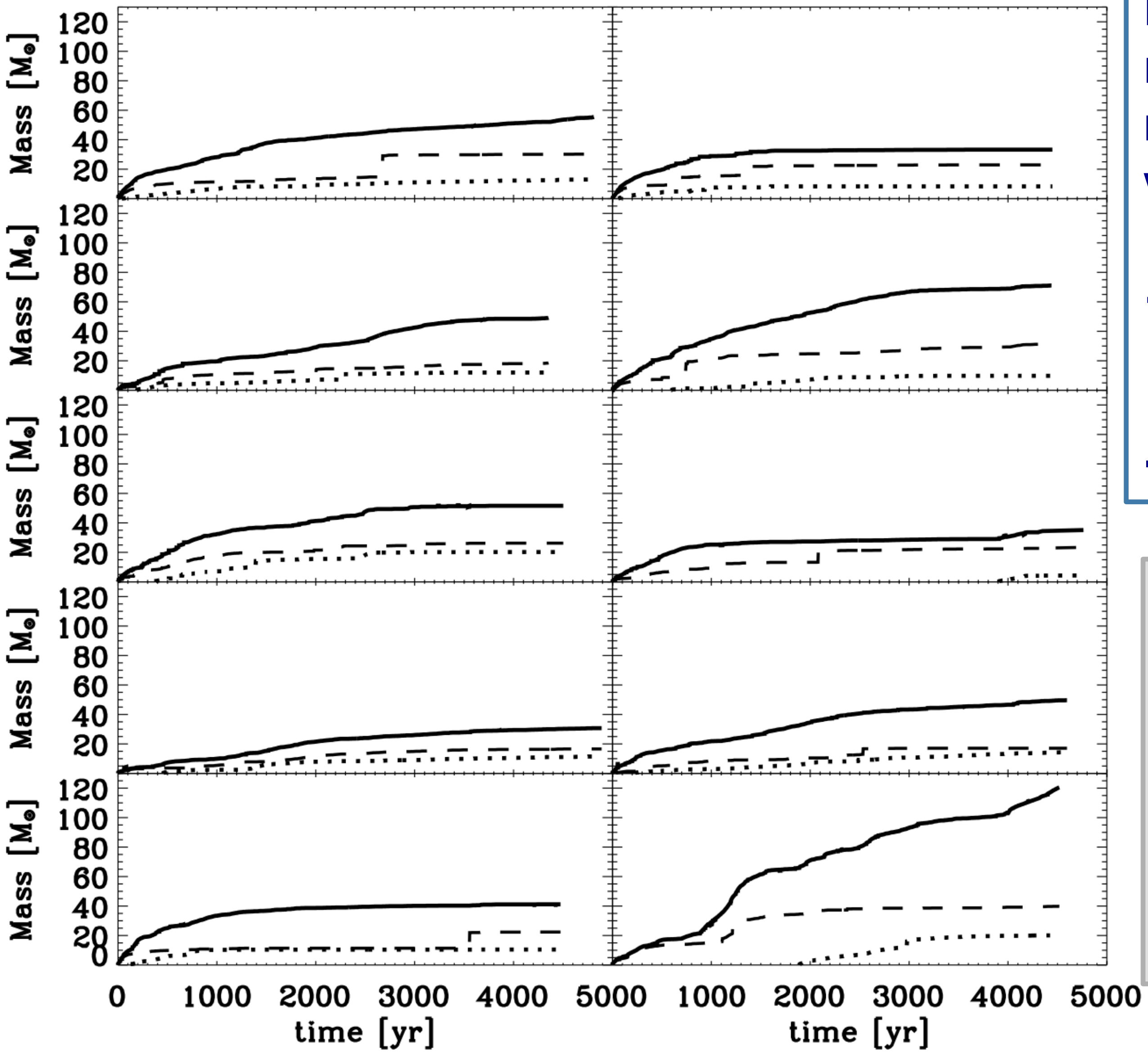
SF regions all initially similar



Gas structure just prior to sink formation

Some variation in degree of flattening and dominance of rotational vs. radial velocity

Variation in Total Sink Growth Rates



Pop III sink accretion rates within different minihalos varies widely.

$120\ M_\odot < M_{*,\ \mathrm{total}} < 20\ M_\odot$

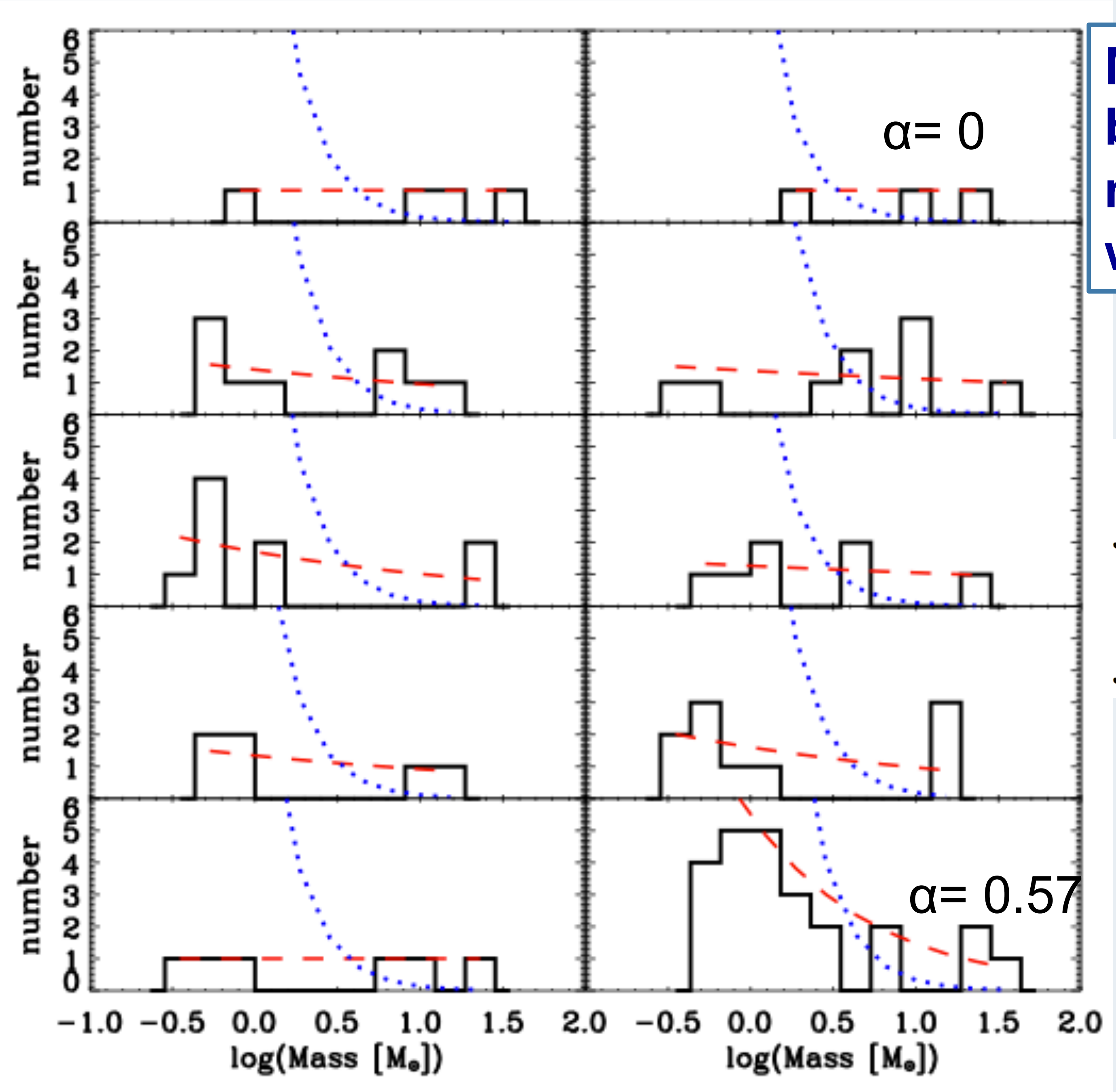
$6\times10^{-3}\ M_\odot/\mathrm{yr}$
$-\ 2.4\times10^{-2}\ M_\odot/\mathrm{yr}$

solid = TOTAL sink mass

dashed = mass of largest sink

dotted = mass of 2nd largest sink

Mass distribution between different minihalos varies widely



$$\mathrm{d}N/\mathrm{d}m \propto M_*^{-\alpha}$$

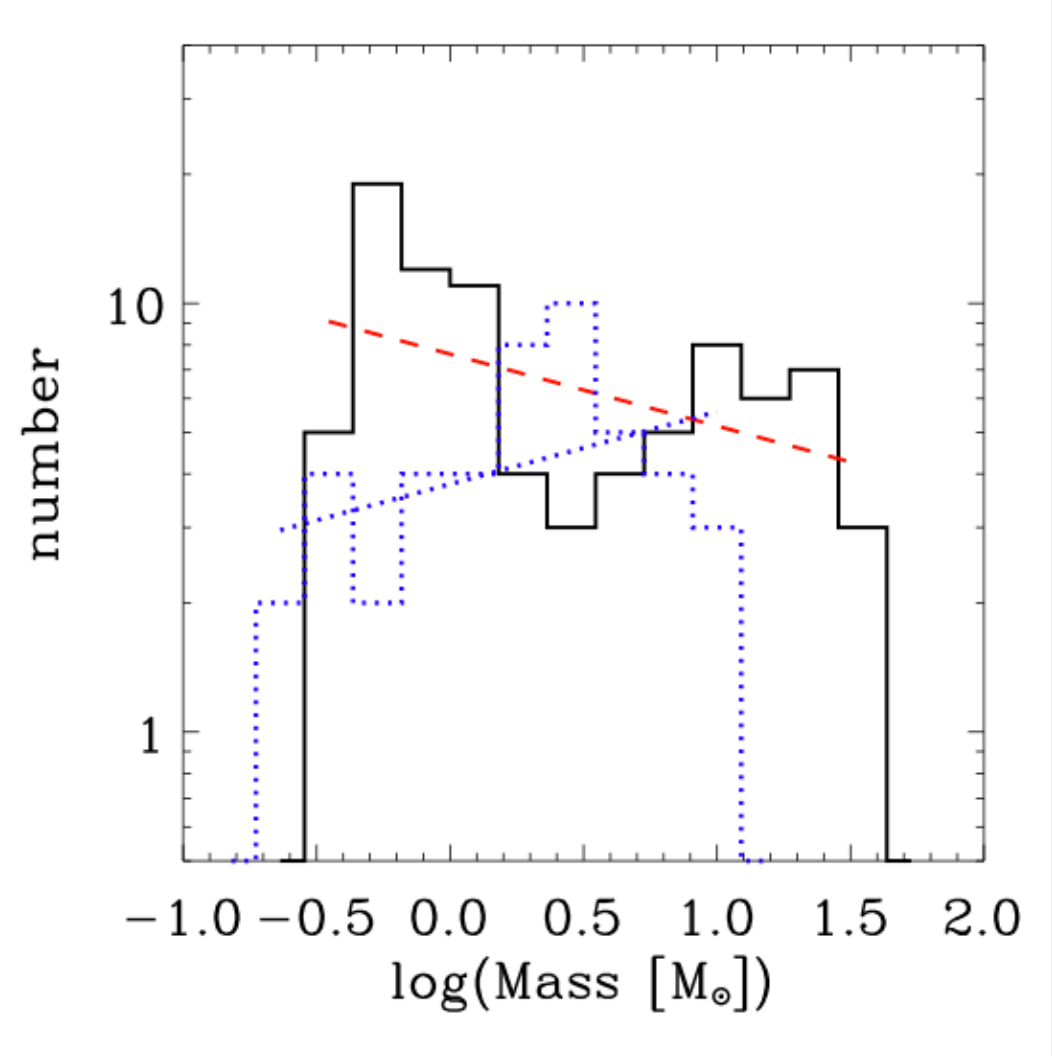
$$\int_{m_{\min}}^{m_{\max}} \frac{\mathrm{d}N}{\mathrm{d}m}\,\mathrm{d}m \propto m^{1-\alpha}$$

$$\int_{m_{\min}}^{m_{\max}} m\frac{\mathrm{d}N}{\mathrm{d}m}\,\mathrm{d}m \propto m^{2-\alpha}$$

Blue dotted – α = 2 (top-heavy)

Red dashed – fit to sim

Overall flat Pop III "IMF"



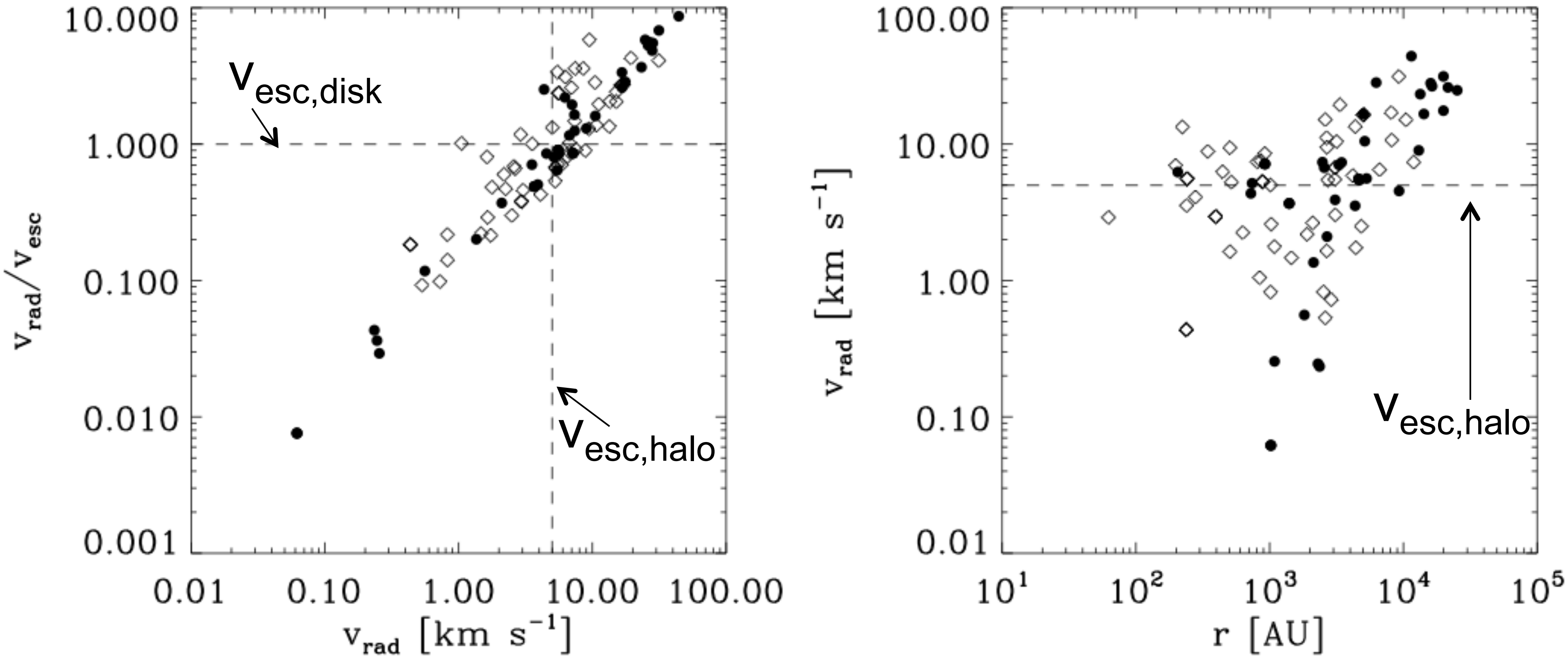
Solid black line – "IMF" from this work after 5000 yr of protostellar accretion

Red line -- α = 0.17

Binary fraction = 36%

Blue dotted line – Greif et al 2011 (α= -0.17; t_{acc} = 1000 yr)

Pop III escape fraction is large!



50% escape stellar disk
and minihalo

$$v_{\rm esc,halo} = \sqrt{\frac{GM_{\rm halo}}{r_{\rm halo}}} \sim 5\,{\rm km\,s^{-1}}$$

$$v_{\rm esc} = \sqrt{\frac{GM_{\rm enc}}{r}}$$

Overview of Part III

- Pop III IMF likely very broad

- Stellar mass distribution varies widely from minihalo to minihalo

- Ejection will terminate accretion onto 50% of stars.

- PISN, GRBs, HMXBs, etc. may possible through rapid stellar rotation and high binary fraction

IV. Unusual Minihalo Hosts: A Low-Mass Pop III Formation Mode

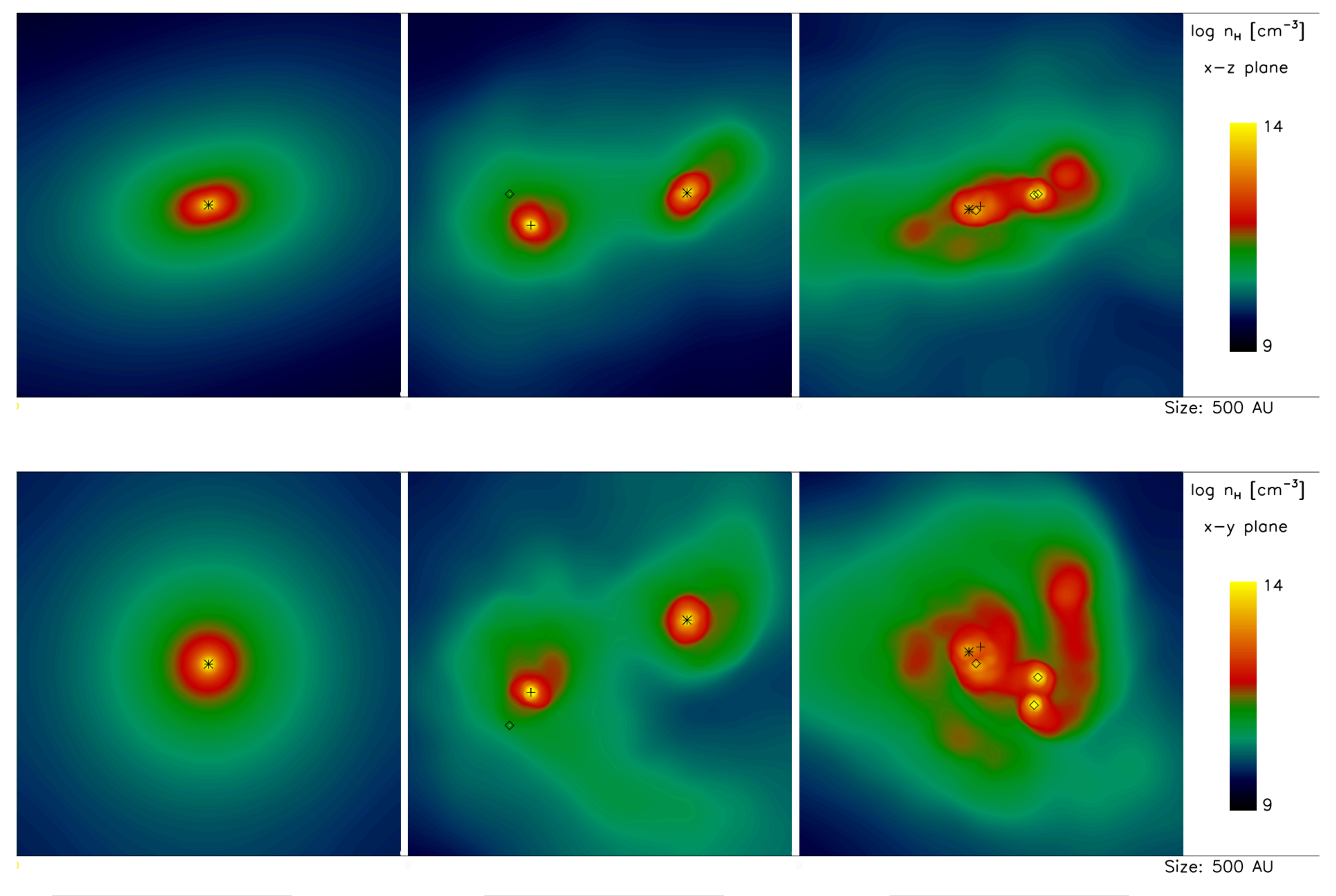
Stacy & Bromm 2014 ApJ

Pop III Low Mass Formation Mode

- Low-mass Pop III Stars:
  - May survive to present day
  - May contain signatures of previous AGB companions

- The experiment:
  - Initialize 140 kpc box at z=100
  - Evolve to densities of 10^{16} cm^{-3}, resolution length of 1 AU
  - Employ sink particle method to follow evolution of stellar cluster for next 5000 yr

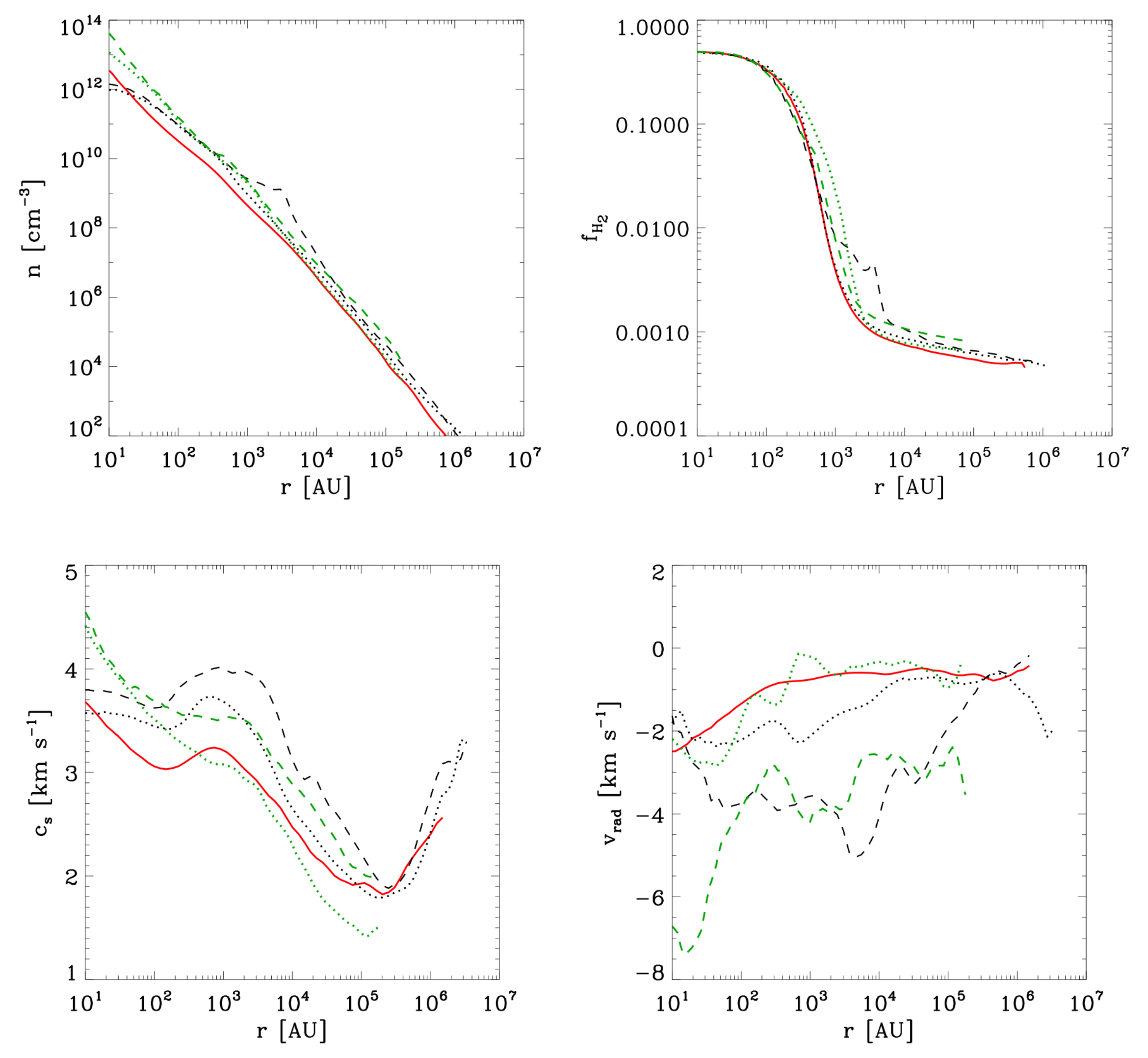
Stars undergo slow disk accretion

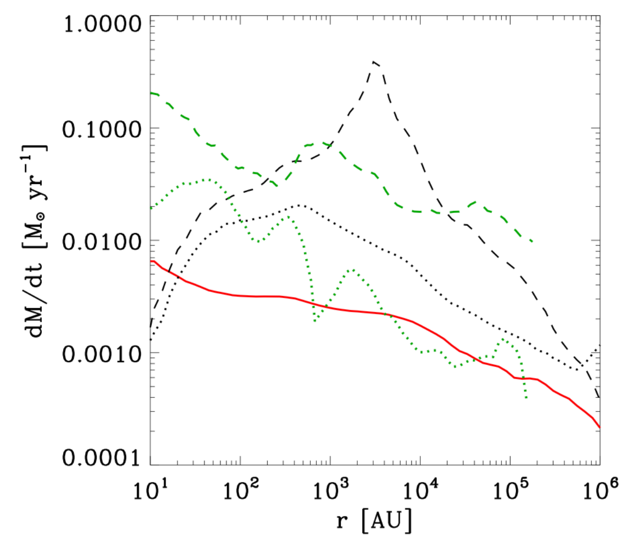


0 yr

1000 yr

4000 yr





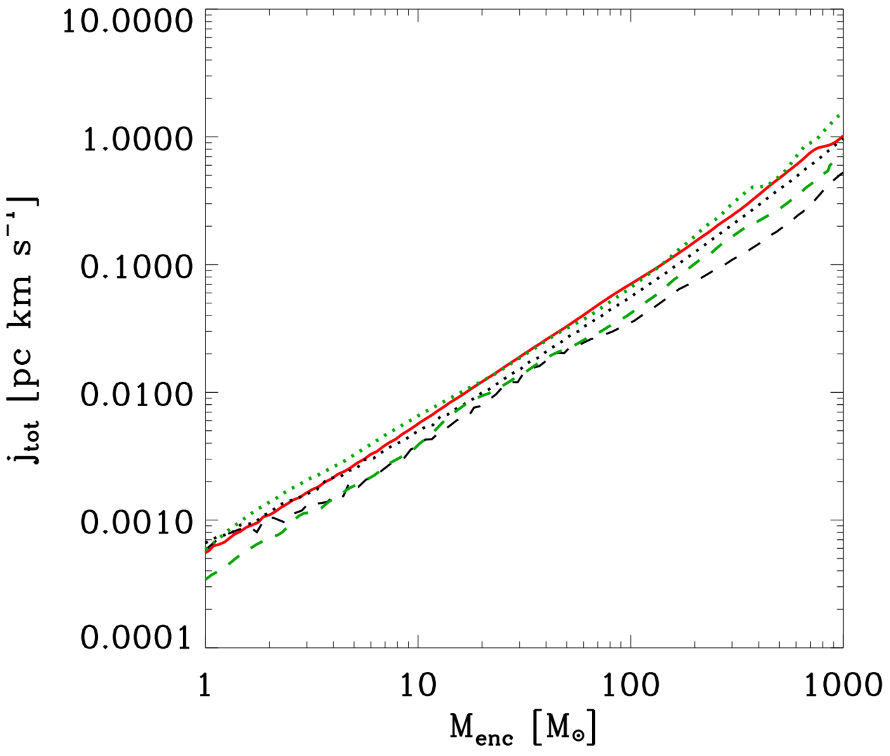
$$\dot{M}_{\mathrm{sph}} = 4\pi r^2 \rho v_{\mathrm{rad}}$$

At a given radius, our minihalo has lower density, temperature, and radial infall velocity.

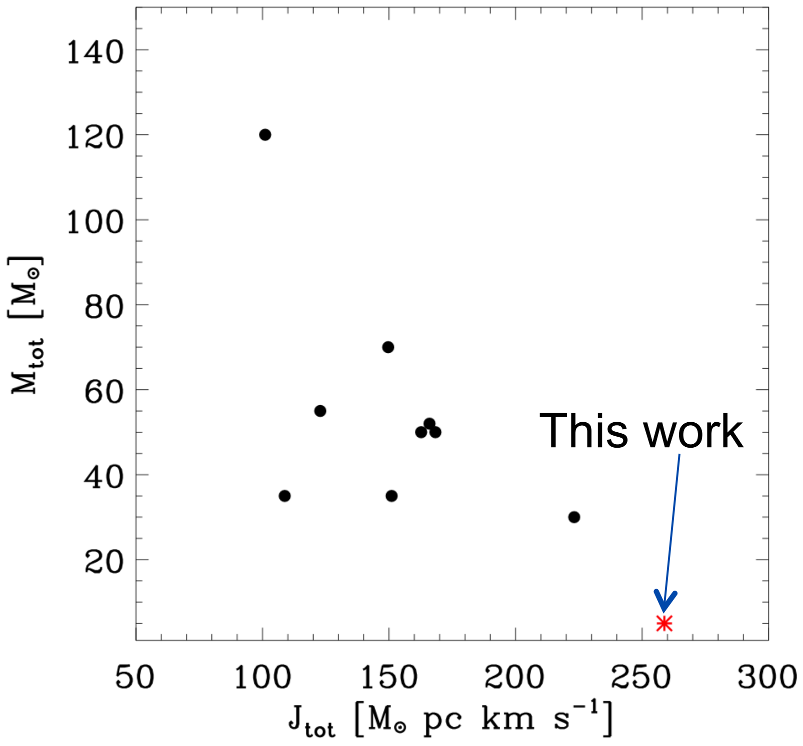
➔slow accretion!

Gas properties at point of initial sink formation:
Red line – this work
Other lines – other minihalos

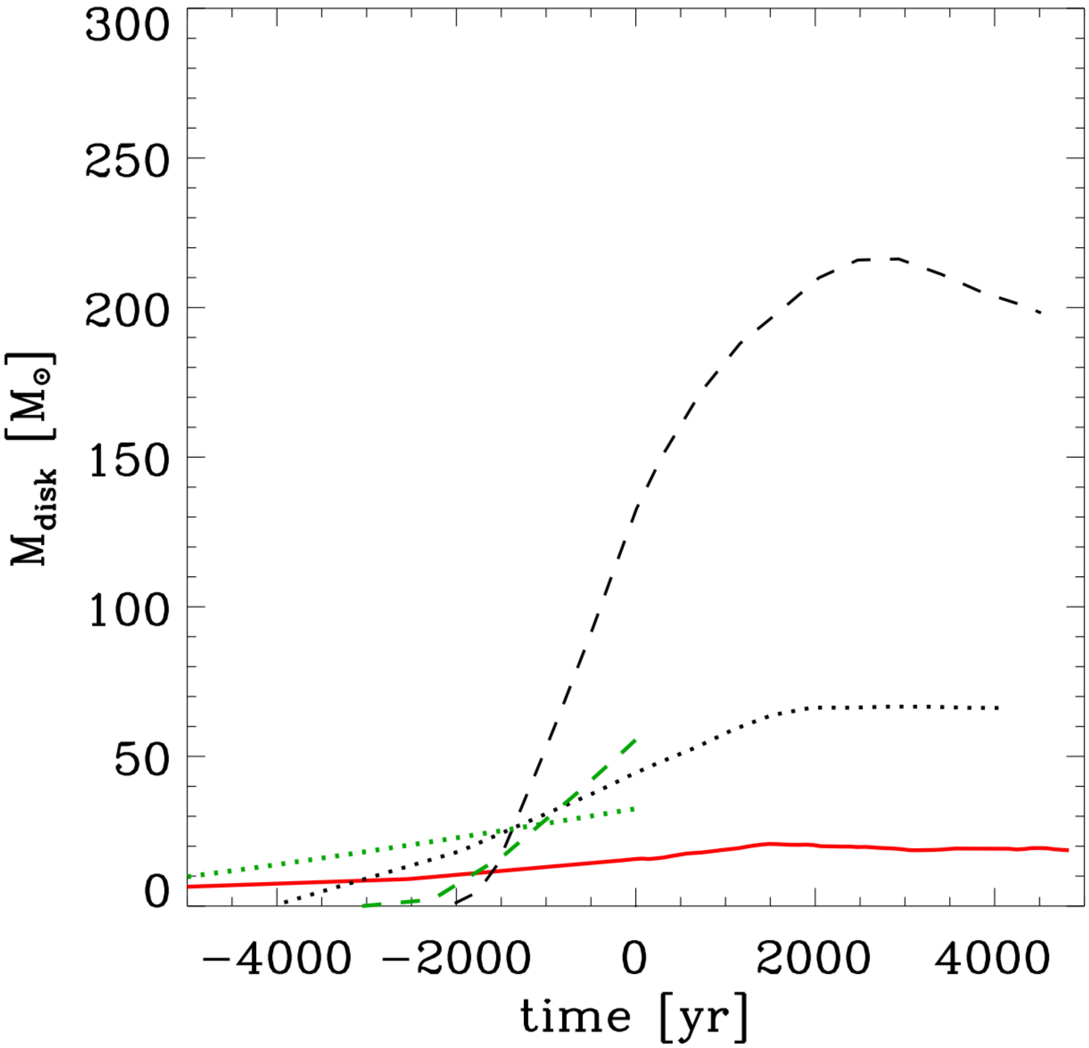
Central SF gas has comparatively high rotational support



Ang. mom. profile at point of initial sink formation:
Red line – this work
Other lines – other minihalos



Total sink mass accreted after 5000 yr for various minihalos versus total angular momentum within central 200 $M_\odot$

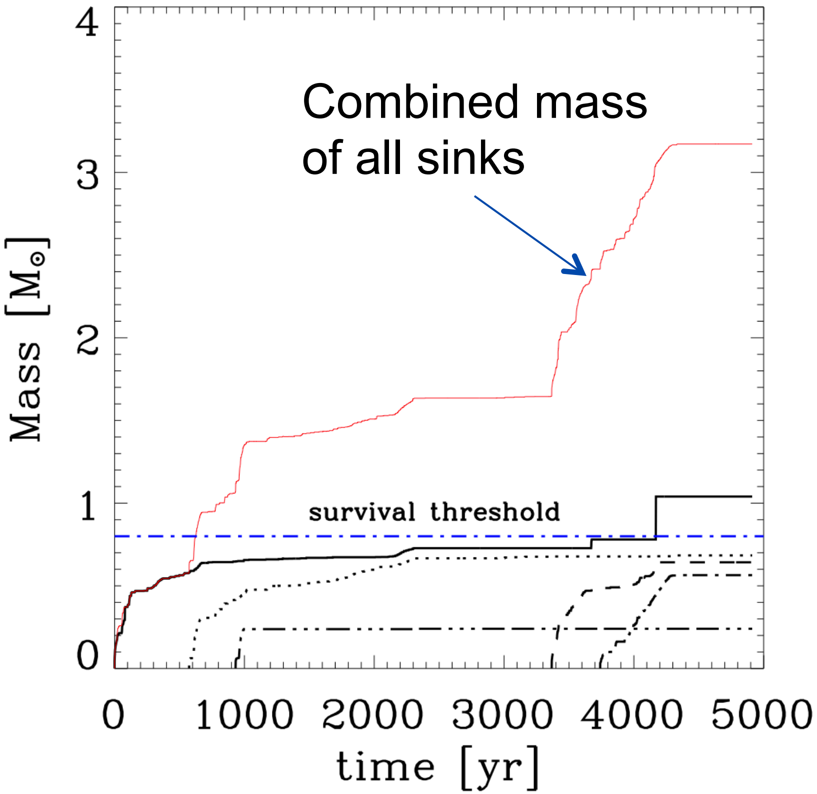


Slow Disk Accretion:

dM/dt ~ 2×10^{-3} $M_\odot$ yr^{-1}
M_{disk} ~ 20 $M_\odot$

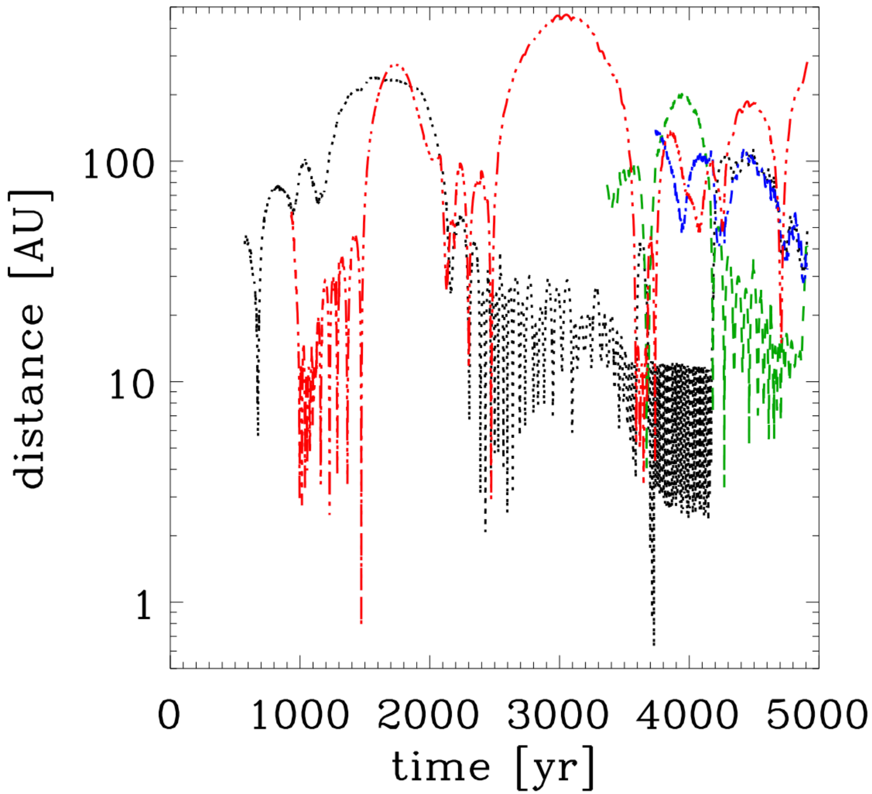
Other lines – primordial disks from other simulations

Red line – This work



Combined mass of all sinks

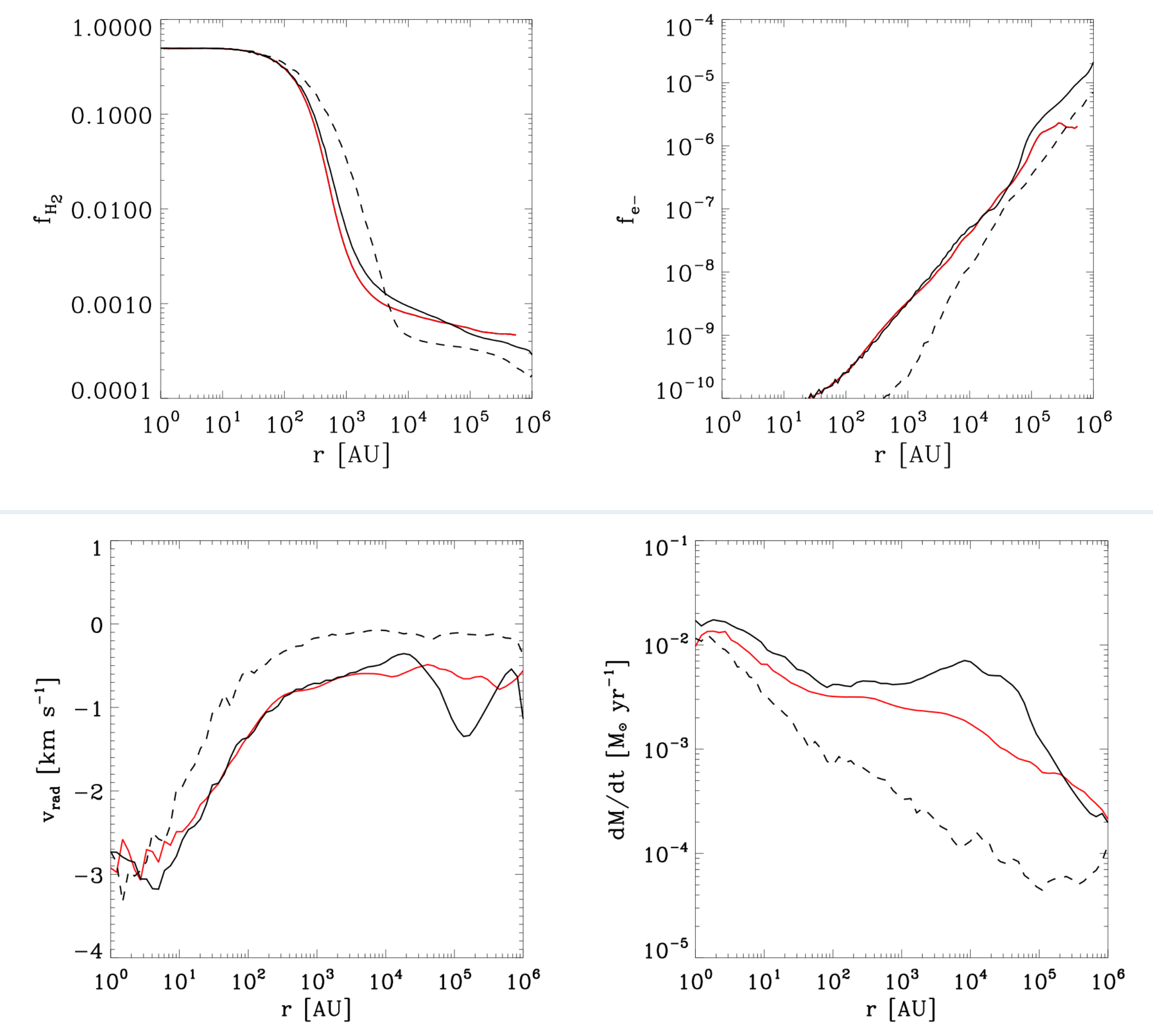
Distance of secondary sinks from most massive sink



Projected Stellar Masses: $M_* \sim 1 - 5\ M_\odot$

- Smallest stars could survive to present day!
- 5 $M_\odot$ stars undergo AGB phase
- Close encounters allow for possibility of tight binaries and mass overflow during larger companion’s AGB phase

Effect of photo-dissociating LW background



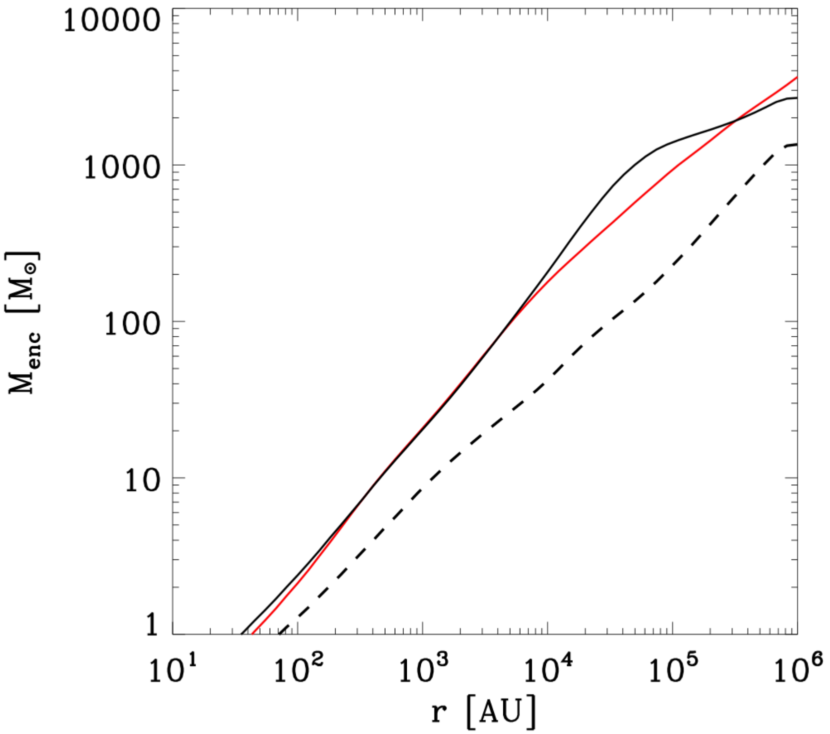
Solid red – $J_{21,0} = 0$
Solid black – $J_{21,0} = 0.1$
Dashed black – $J_{21,0} = 1.0$

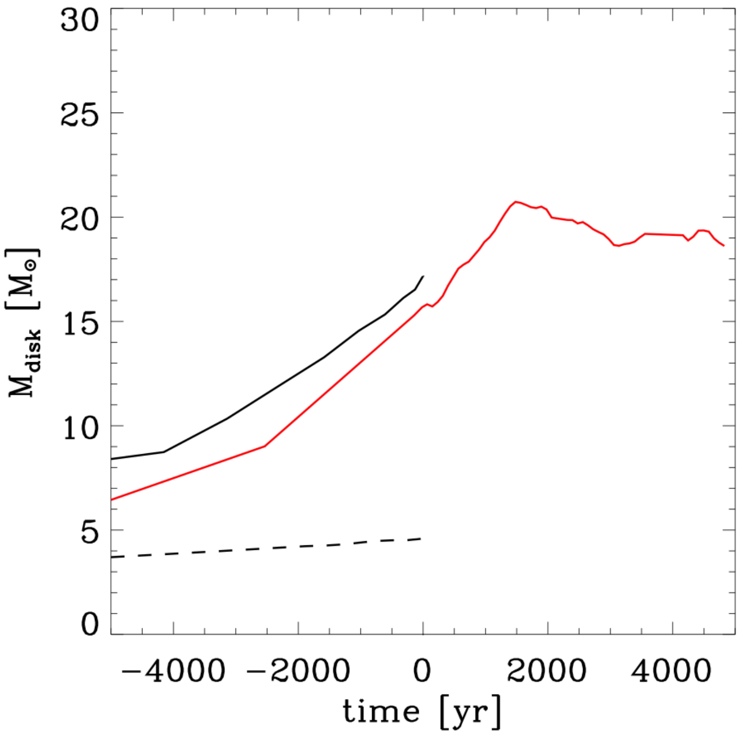
$$J_{21} = J_{21,0} \times 10^{-(z-z_0)/5}$$

$$k_{H_2} = 1.38 \times 10^{-12} f_{\rm shield} J_{21} \ {\rm s}^{-1}$$

-H_2 shielding limits LW effects on central gas

-LW background has moderate but not monotonic effect on gas properties.





Solid red – $J_{21,0} = 0$
Solid black – $J_{21,0} = 0.1$
Dashed black – $J_{21,0} = 1.0$

Disk accretion rate is still slow!

Resulting stellar accretion rate and Pop III masses still likely to be unusually small.

Overview of Part IV

- Pop III IMF extends to very low masses in some minihalos, even under the influence of a range of global LW backgrounds.

- Some Pop III stars may survive to present day.

- These stars may carry signatures of enrichment by mass overflow of previous AGB companions.

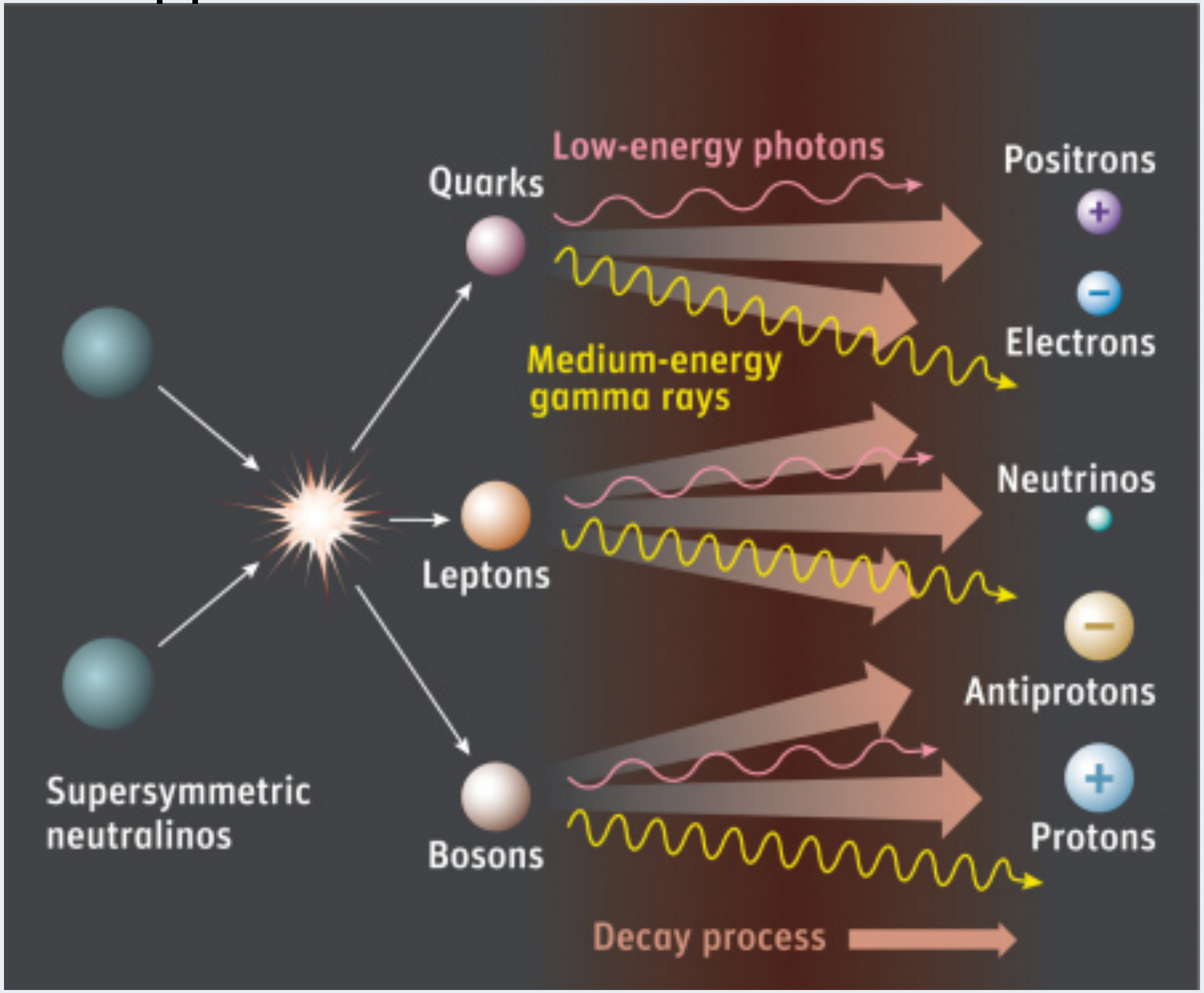
- For a range of global LW backgrounds, H_2 shielding will prevent prevent significant changes to the low Pop III accretion rates.

V. Pop III Formation Under Dark Matter Effects

Stacy, Pawlik, Bromm, & Loeb 2014, MNRAS

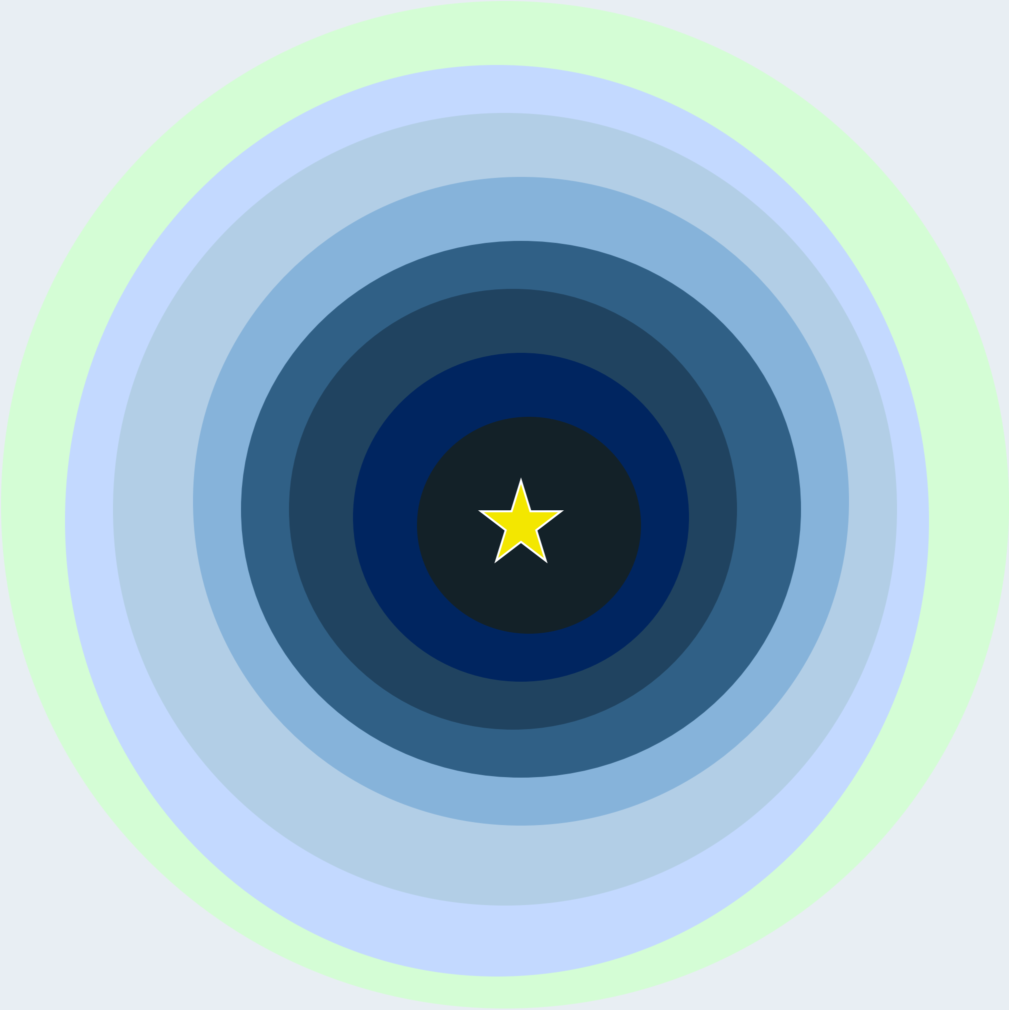
Dark Matter annihilation important for Pop III stars?

Can high-energy photons released from DMA heat SF gas, or replace/supplement nuclear fusion?



(www.nasa.gov, Sky and Telescope, Gregg Dinderman)

Pop III stars form in regions of high DM density



May lead to extremely massive and luminous Pop III stars

a.k.a. “dark stars”

-R_* ~-T_{eff} too low to ionize
 1 AU
-Accretion unimpeded for long time

(e.g., Freese et al. 2008,
 Spolyar et al. 2008, Iocco
et. al 2008, Natarajan et al. 2009)

DM heating and capture rates

1. DM heating ➔ delayed protostellar contraction
➔ prolonged accretion (M$_*$ reaches 10^5 M$_\odot$?)

$$\Gamma_{\rm DM} \propto \rho_{\rm DM}^2 \langle \sigma_a v \rangle / m_{\rm WIMP}$$

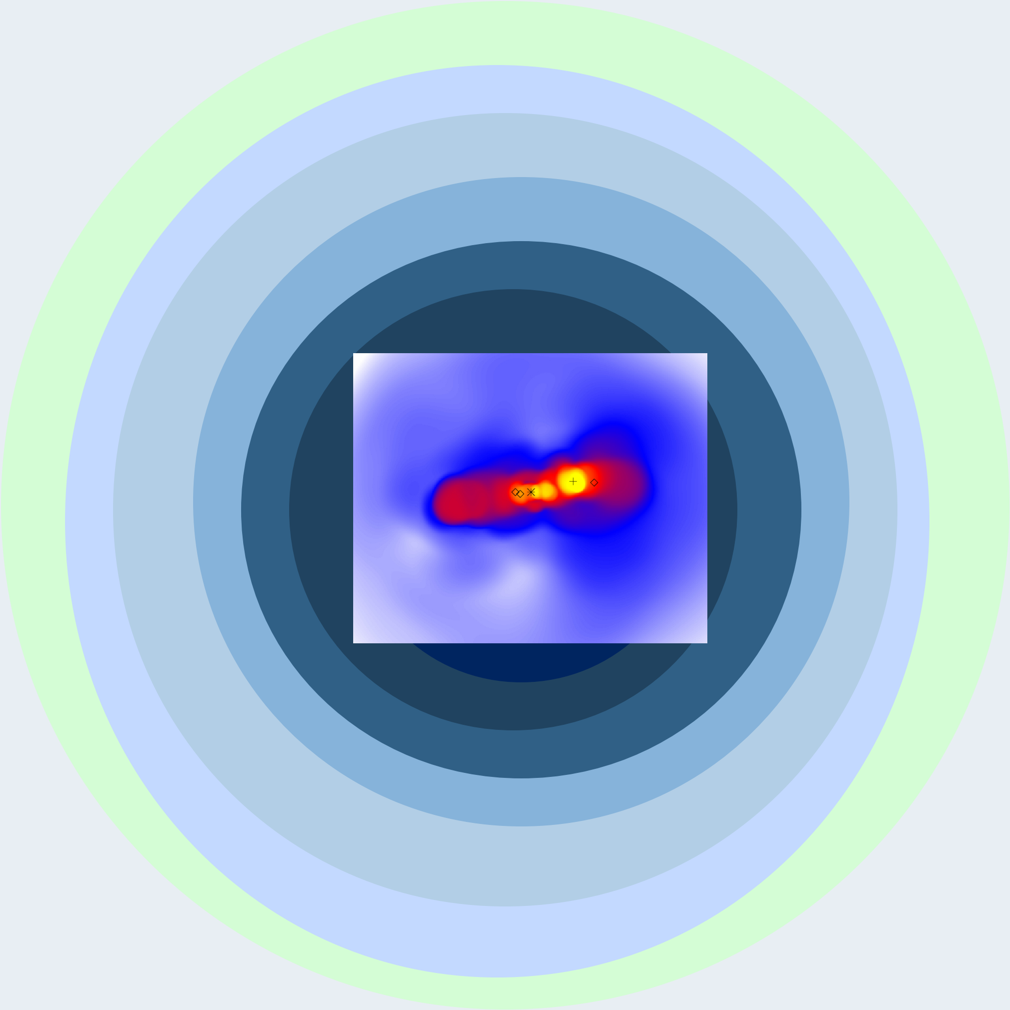
2. DM capture by MS star ➔ burn DM instead of hydrogen
➔ prolonged stellar lifetime (to z=0?)

$$C = 9.2 \times 10^{47} s^{-1} \left(\frac{M_*^2}{R_*} \right) \left(\frac{\rho_{\rm DM}}{10^{11} {\rm GeV\,cm^{-3}}} \right) \times \left(\frac{\sigma_0}{10^{-38} {\rm cm}^2} \right) \left(\frac{m_{\rm WIMP}}{100 {\rm GeV}} \right)^{-1} .$$

Higher DM density ➔ greater effect on gas and stars

1. Will this still work when following gas and DM in 3-D?

2. What if gas still fragments? How will that change evolution of DM density?



Test Simulations

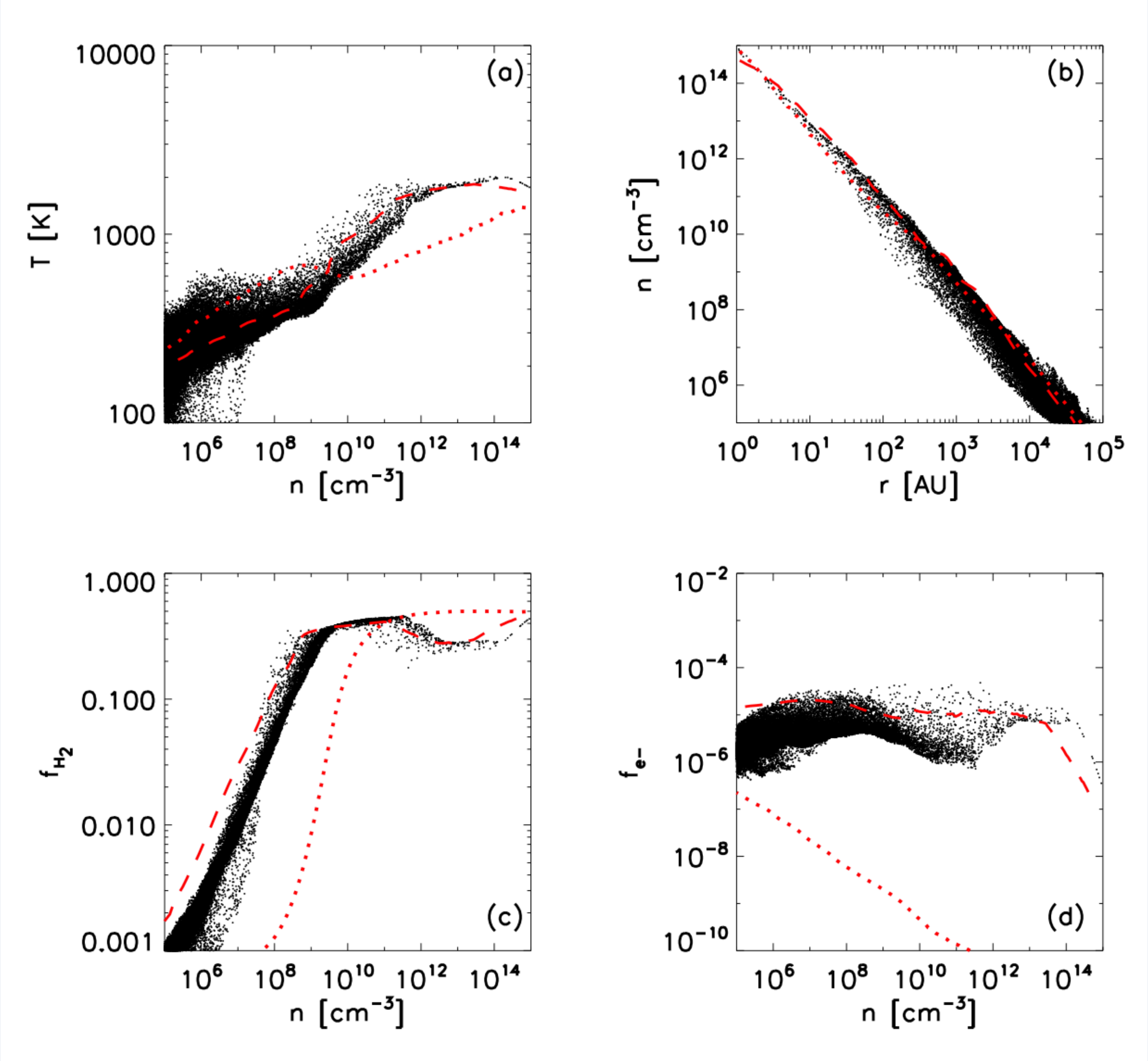
Name	DM profile type	m_x (GeV/c^2)	$n_{\rm frag}$	$M_{*,\rm tot}$ [$\rm M_\odot$]
no-DMA	no DMA	N/A	3	7
DMA-A1	analytic, Smith et al. (2012)	100	N/A	N/A
DMA-A2	analytic, $\rho \propto r^{-2}$	100	4	14
DMA-L2	live, $\rho \propto r^{-2}$	100	7	16

$$\rho_x = 6000 \left(\frac{r}{1\rm pc}\right)^{-2} \frac{\rm GeV}{c^2} \rm cm^{-3}$$

DMA-A1
Analytic DM profile remains constant

$$\rho_x = 5 \times 10^4 \left(\frac{r}{1\rm pc}\right)^{-1.8} \frac{\rm GeV}{c^2} \rm cm^{-3}$$

DMA-A2
DMA-L2 at t=0
‘Live’ DM particles with m_{DM} ~4×10^{-4} $M_\odot$ are added to simulation box immediately after initial sink formation

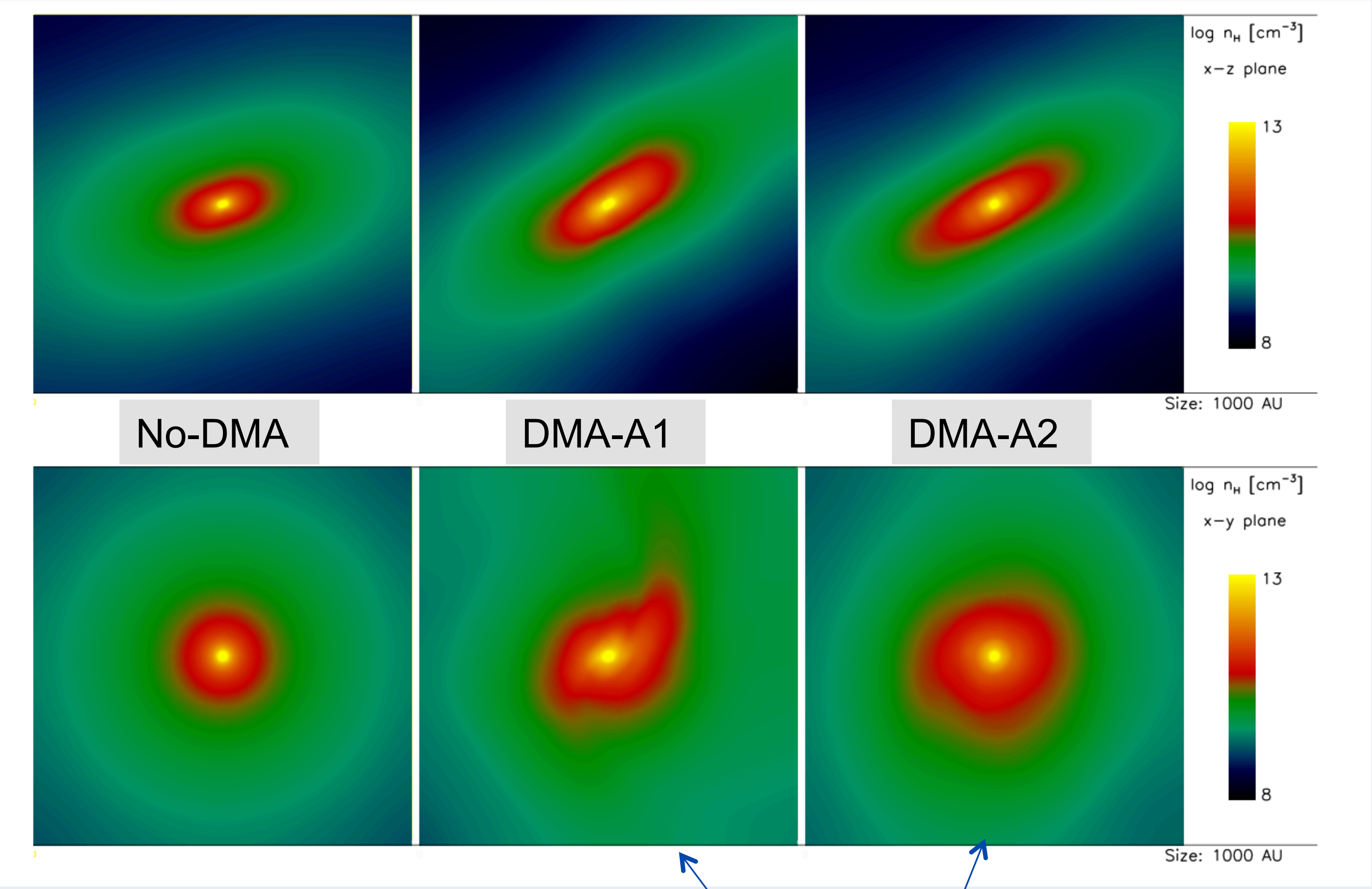


Black dots – DMA-A2
Red dashed – DMA-A1
Red dotted – no-DMA

DMA leads to:

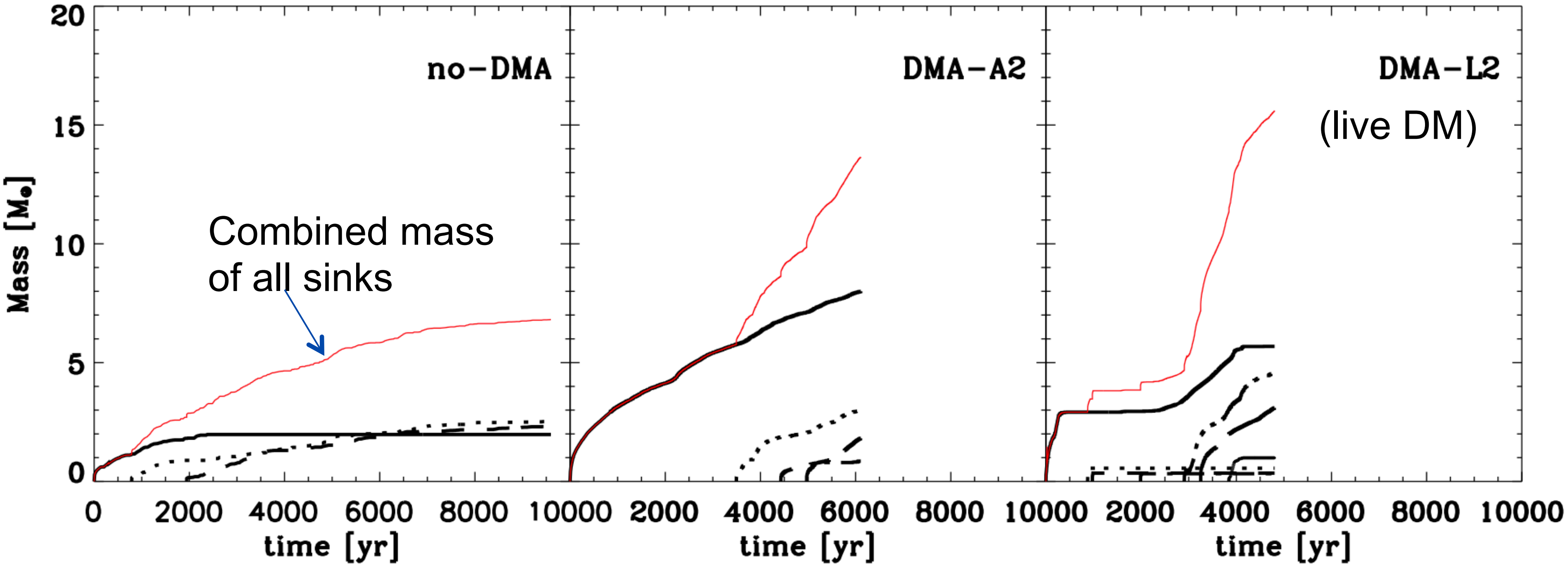
- Warmer gas at high densities
- H_2 formation at lower densites
- Higher e^- fraction

DMA speeds initial collapse to high densities



Collapse occurs by 10^5 yr earlier

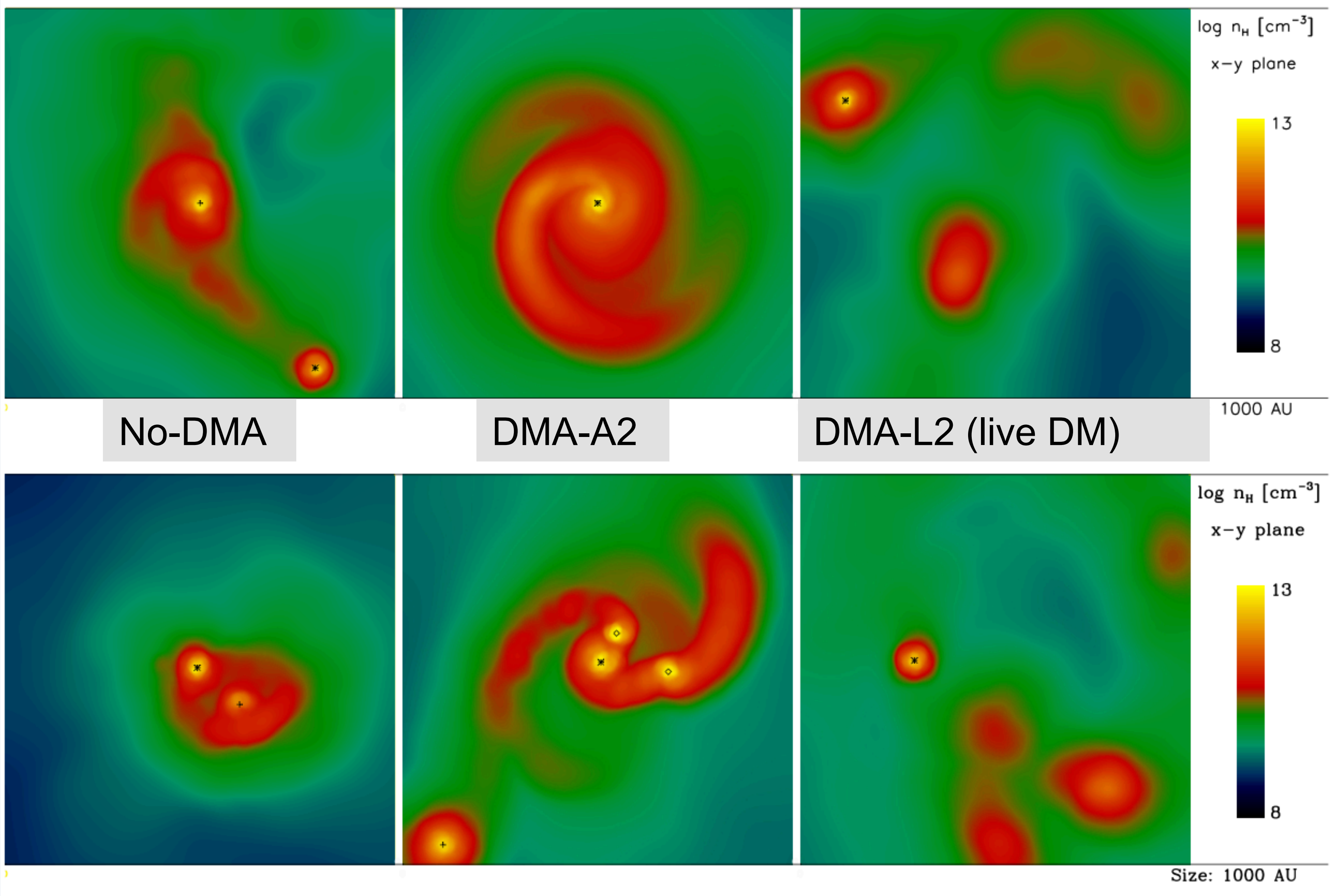
DMA delays fragmentation, but does not prevent it!



Combined mass of all sinks

(live DM)

DMA does not prevent fragmentation!

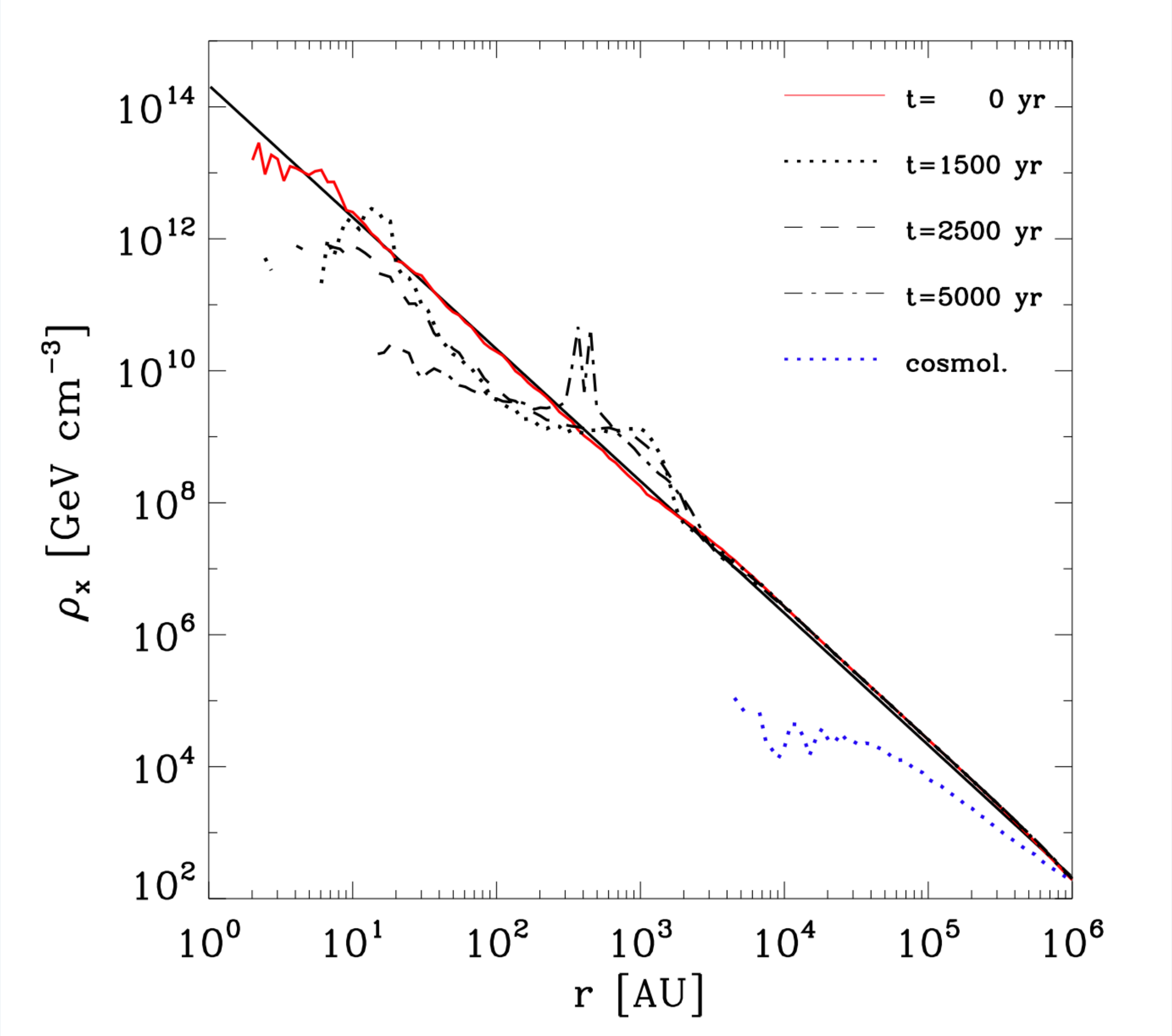


No-DMA

DMA-A2

DMA-L2 (live DM)

Central DM density declines over time



Mutual gravitational interaction between gas and DM scatters DM to low densities.

Overview of Part V

- DMA is ineffective in suppressing gas collapse and subsequent fragmentation

- Formation of long-lived dark stars is unlikely

- DMA effects may still be significant in the early collapse and disk formation phase of primordial gas evolution

What about observational constraints?

Direct signatures

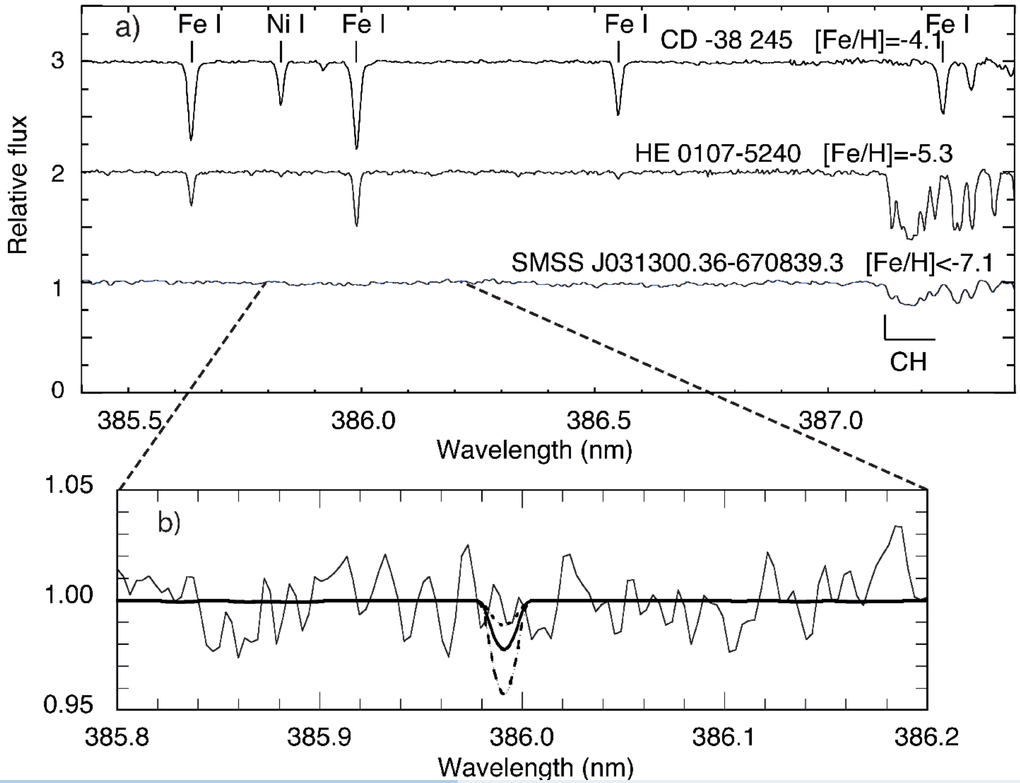
- JWST cannot observe MS Pop III stars at high redshift (z~20).

- Observation of an actual low-mass Pop III star in the Milky Way?
  -> None yet detected. Possibly but unlikely.

- Observation of a PISNe or GRB?
  -> Perhaps with JWST, JANUS, etc. (e.g. Hummel et. al 2012, Pan et. Al 2012; but PISN identification is difficult! Cannot be seen as transient, but candidates might be identifiable through photometric variation.)

Indirect evidence and signatures

- **Stellar and dwarf archaeology**
  - Pop III SNe abundance signatures in nearby lowest-Z stars
  - PISN signature yet to be observed in a stellar atmosphere
  - But Note: Oldest stars and lowest-Z stars not necessarily the same. E.g., one Pop III SNe can already significantly enrich its surroundings to $10^{-3}\ Z_\odot$ (e.g. Greif et al 2010)



SMSS J031300.36-670839.3

- No Fe detected!
- $Z < 10^{-7.1}\ Z_\odot$

Star most likely seeded by a single faint 60 $M_\odot$ SN

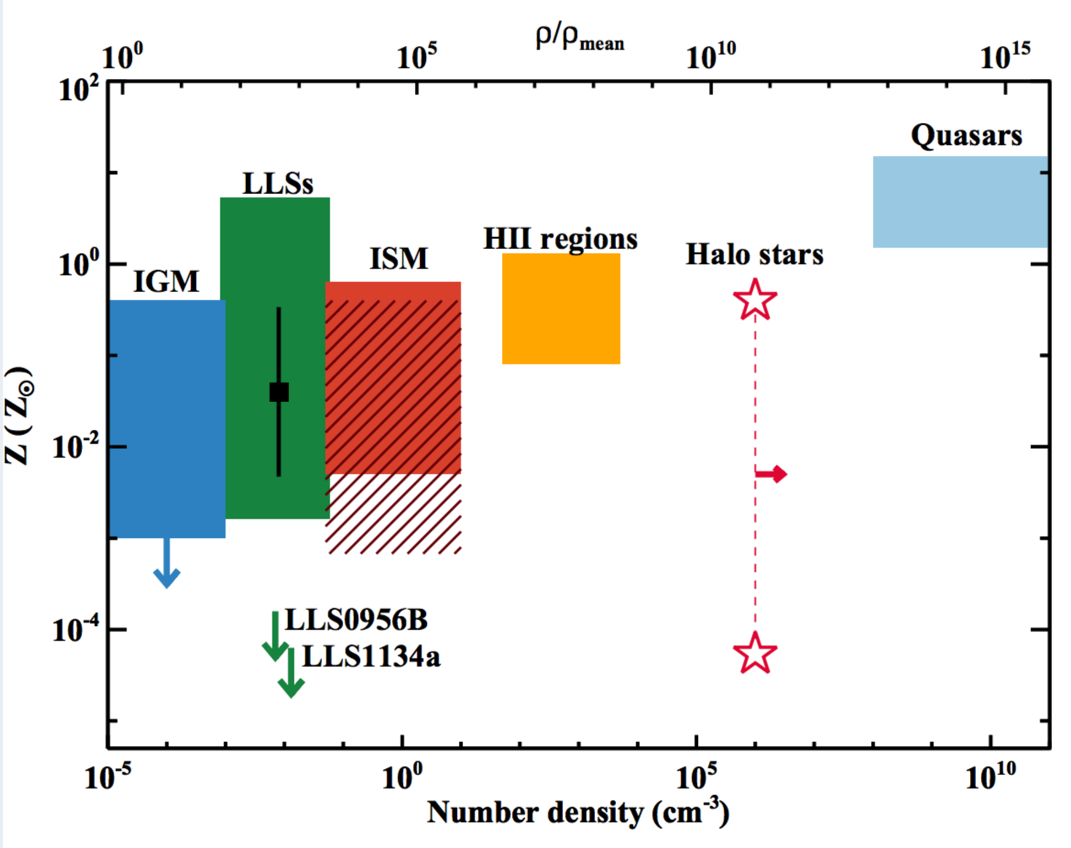
Keller et al 2014, Nature

Indirect evidence and signatures, cont'd

- **DLAs and LLS**
  - -- Simcoe et al. (2012) reported observations of extremely low metallicity or possibly metal-free gas within a *z* ~ 7 damped Ly-α system
  - -- Fumagalli et al. (2011) reported the detection of metal-free gas within Lyman-limit systems at *z* ~ 3.

-Gas may fuel Pop III SF down to z ~3 ?

- Mixing of metals within the IGM is an inefficient and inhomogeneous process



Conclusions

- **Pop III IMF likely to be broad (1 $M_\odot$ to >100 $M_\odot$) but still top-heavy, even under radiative feedback.**
- **Some correlation between Pop III multiple accretion rate and angular momentum of SF clump (but NOT, e.g., with spin of minihalo)**
- **Binarity, N-body dynamics, and stellar ejections important considerations for Pop III growth and evolution**

For the Future

- **Questions remain!**
  - How will previous results change under influence of B-fields? Winds? Jets and outflows? (Turk et al, Machida et al., etc.)
  - How will Pop III systems evolve over longer timescales?
  - What percentage of Pop III stars undergo binary mass transfer and/or mergers?
  - Can we find further correlations between minihalo/cloud environment and Pop III stars?

- **Continued numerical exploration will allow for improved predictions for future observations:**
  - rate at which we may observe Pop III CCSNe, PISNe, and GRBs
  - number low-mass Pop III stars in Milky Way and nearby dwarfs galaxies
  - chemical abundances within low-Z MW halo stars, nearby dwarf galaxies, DLAs
  - Growing understanding of Pop III stars will ultimately increase physical realism of models of the formation of later stellar generations and the assembly of high-redshift (z>10) galaxies which will be observed by, e.g., JWST.