New Insights Into Primordial Star Formation

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PhD Dissertation Presentation

Special Thanks

- Volker Bromm, advisor
- Thomas Greif
- Early Universe group
- Committee members
  - Avi Loeb
  - Harriet Dinerstein
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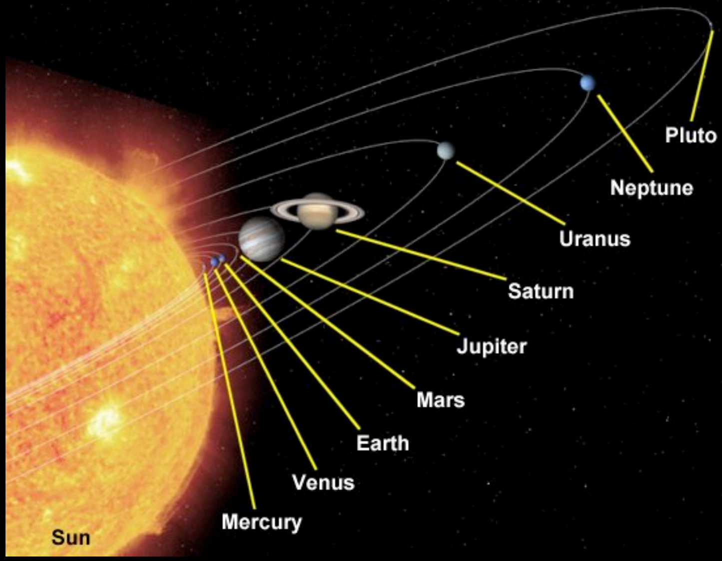
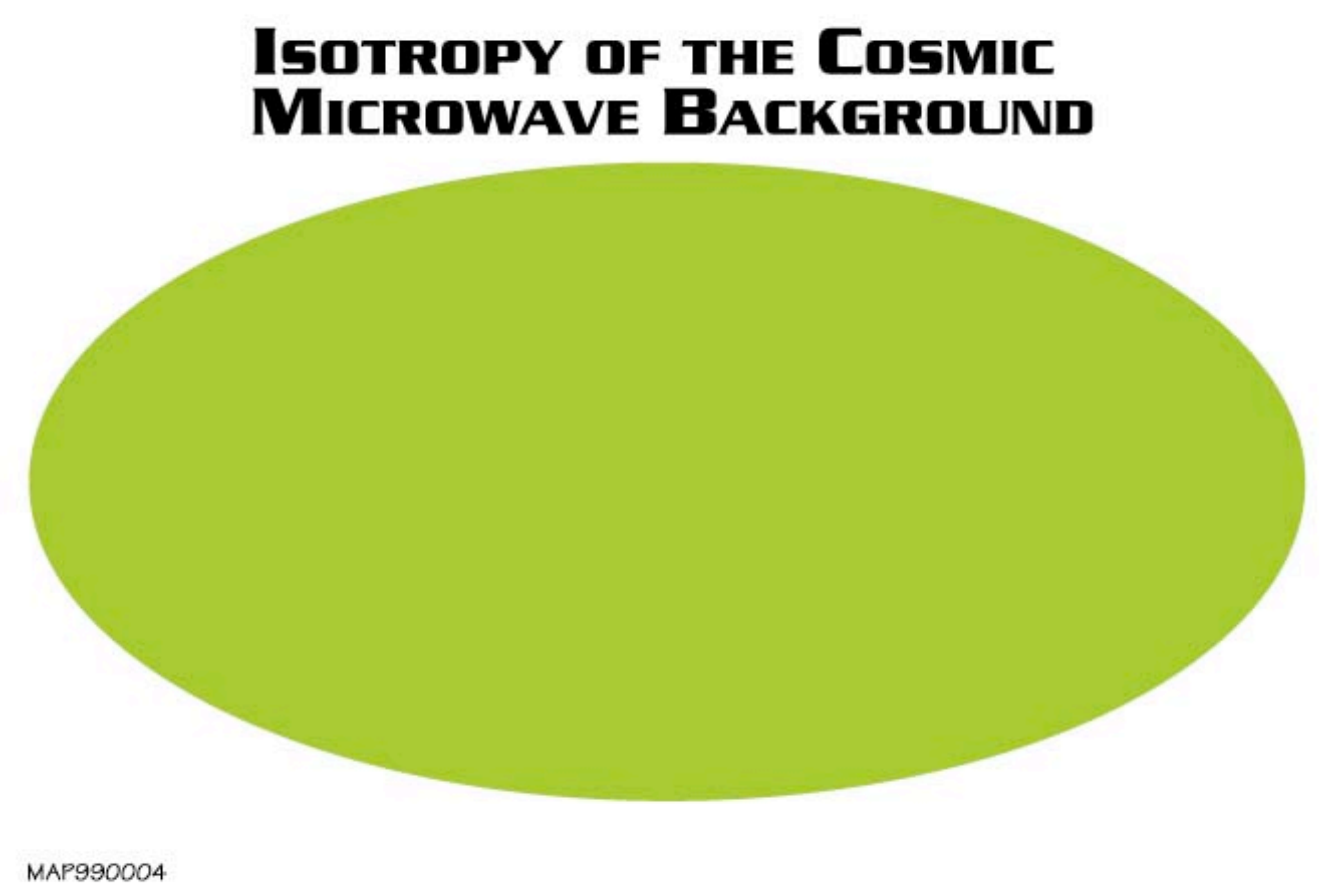
  - Neal Evans
  - Craig Wheeler

The Universe Today

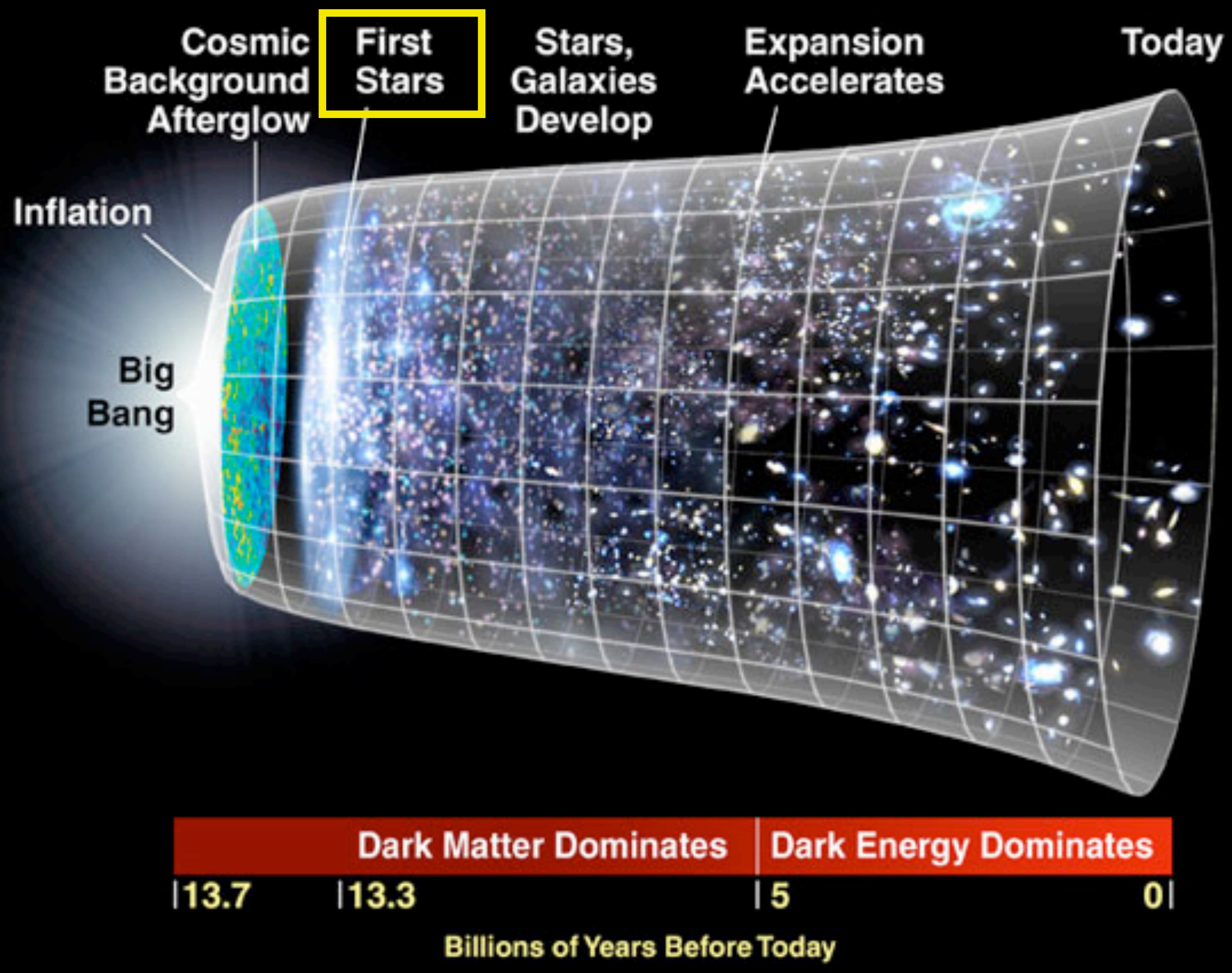


(not to scale)

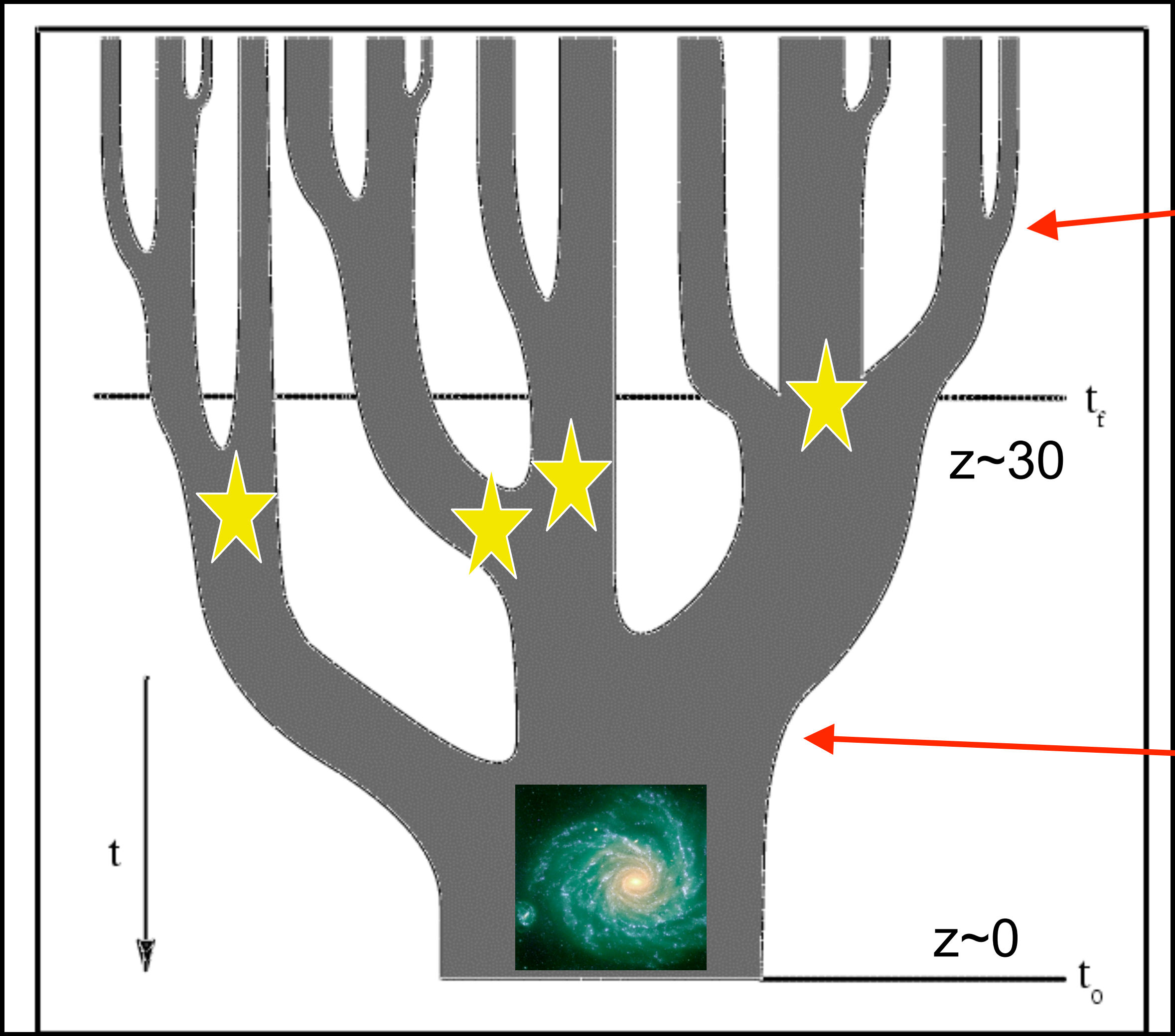
The Universe 14 billion years ago



THE EXPANDING UNIVERSE: A CAPSULE HISTORY



Hierarchical Merging



Smaller DM halos…

Merge to make…

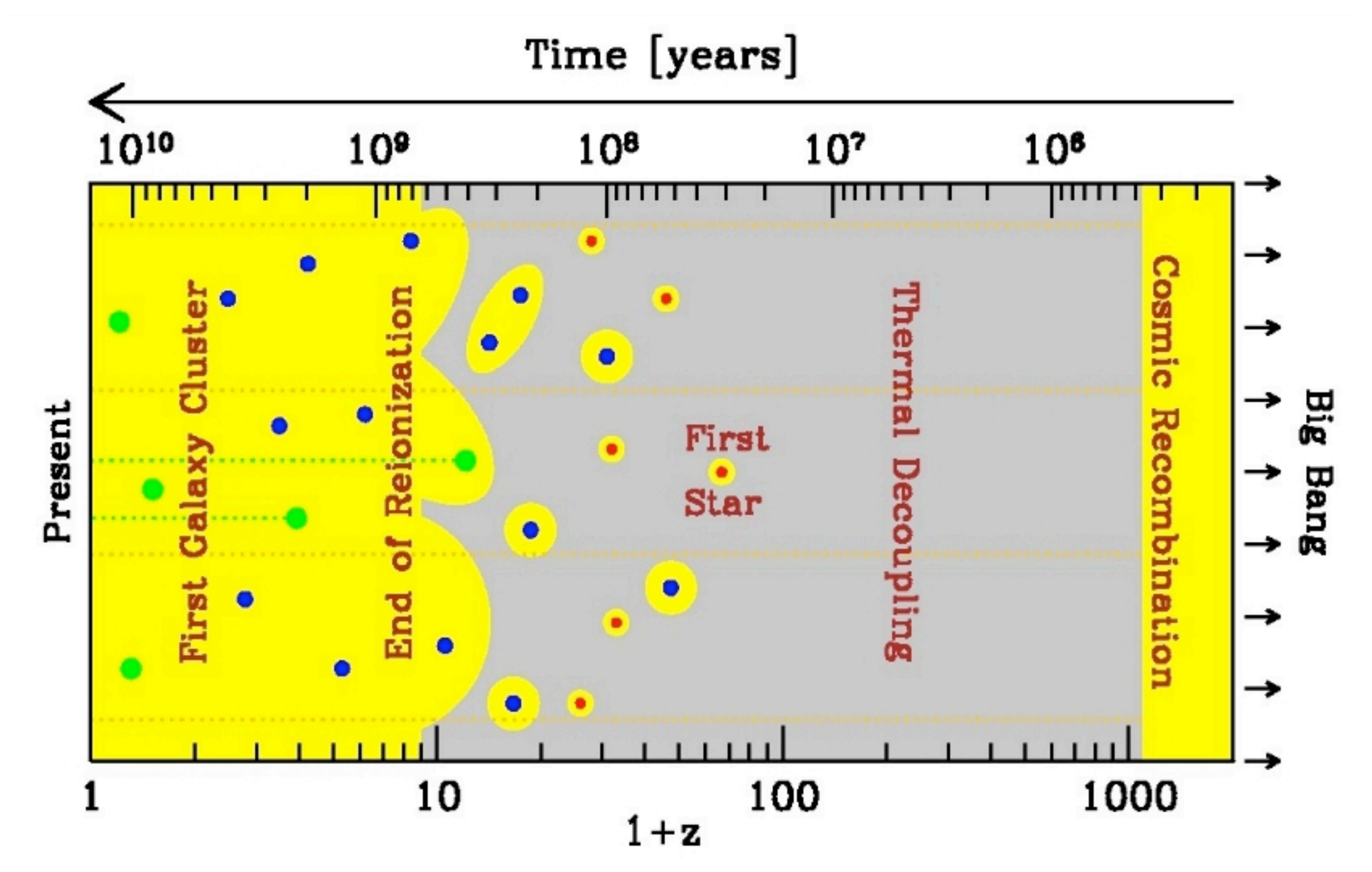
BIGGER DM halos

The First Stars

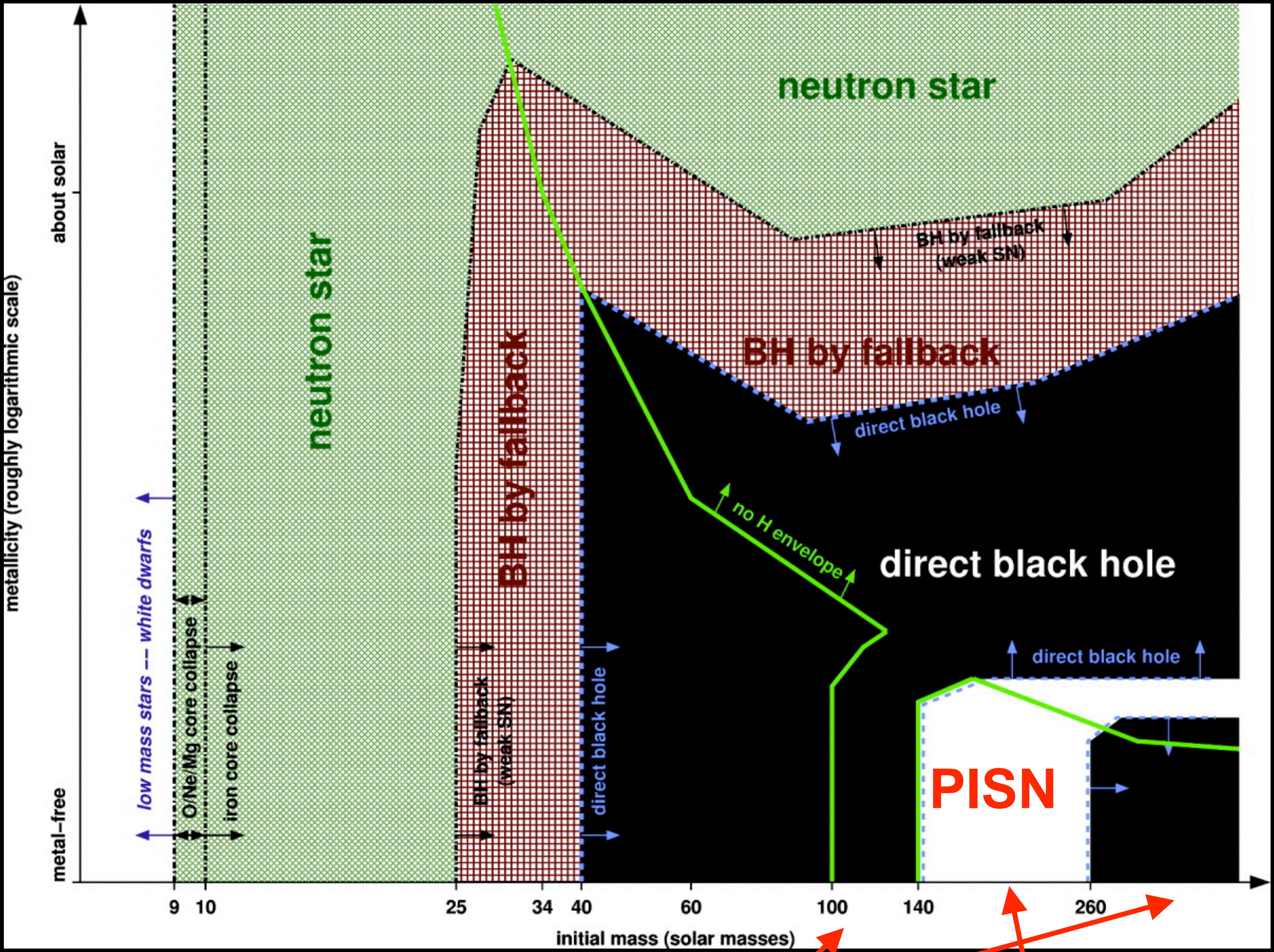
Characteristics:

- Pop III.1 (no metals, no previous feedback)
- Initially formed in $10^6\,M_\odot$ minihalos around $z>20$
- First objects to emit ionizing radiation.
- Began initial metal enrichment of the universe.
- Set the environment for later Pop II star formation (more metals = more cooling, etc.).

Reionization



Possible fates of single non-rotating stars

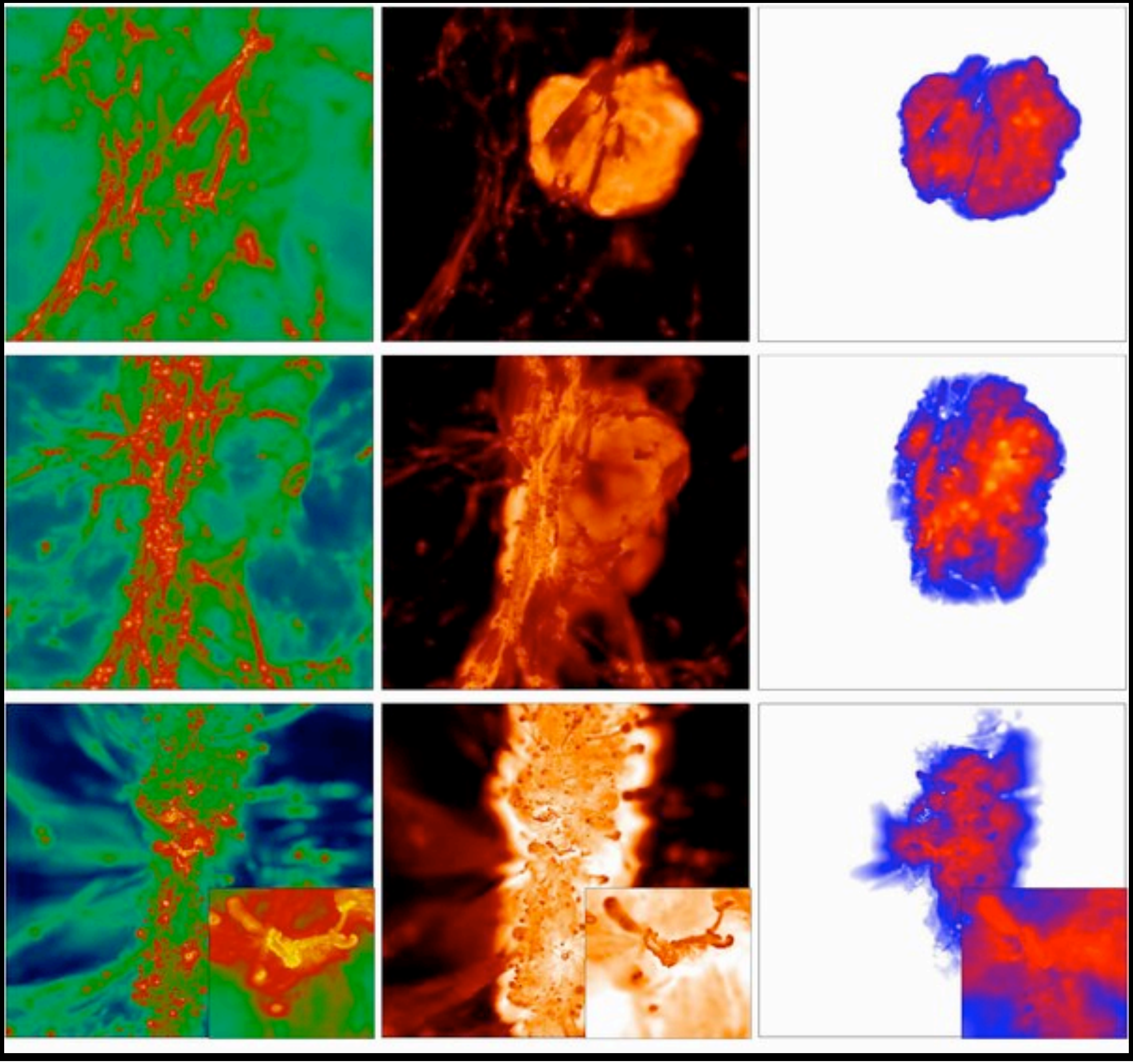


Heger et al. 2003

NO metals

metals

Metal Enrichment



Pop III PISN enrichment of surrounding halos

100 kpc (comoving)

15, 100, 300 Myr

Greif et al 2010

Open Questions

- What role did they play in reionization and metal enrichment?
- What feedback did they exert on later star formation?

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

- What were their typical masses?
- How often did they form in multiples?
- How and when will a Pop III protostar's accretion become shut off by feedback (if this does indeed shut it off)?

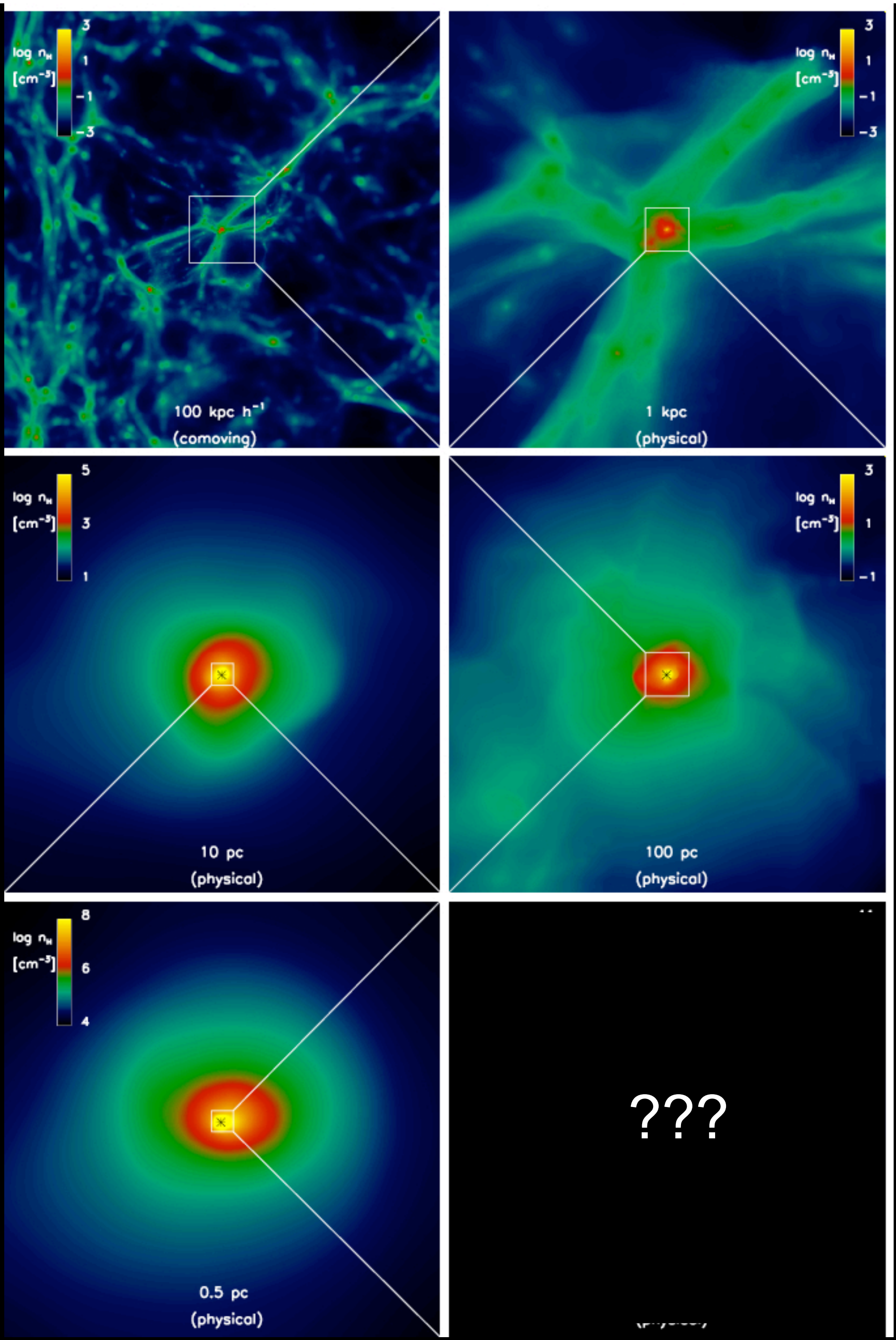
I. Pop III Star Formation Without Feedback

Previous cosmological simulation:

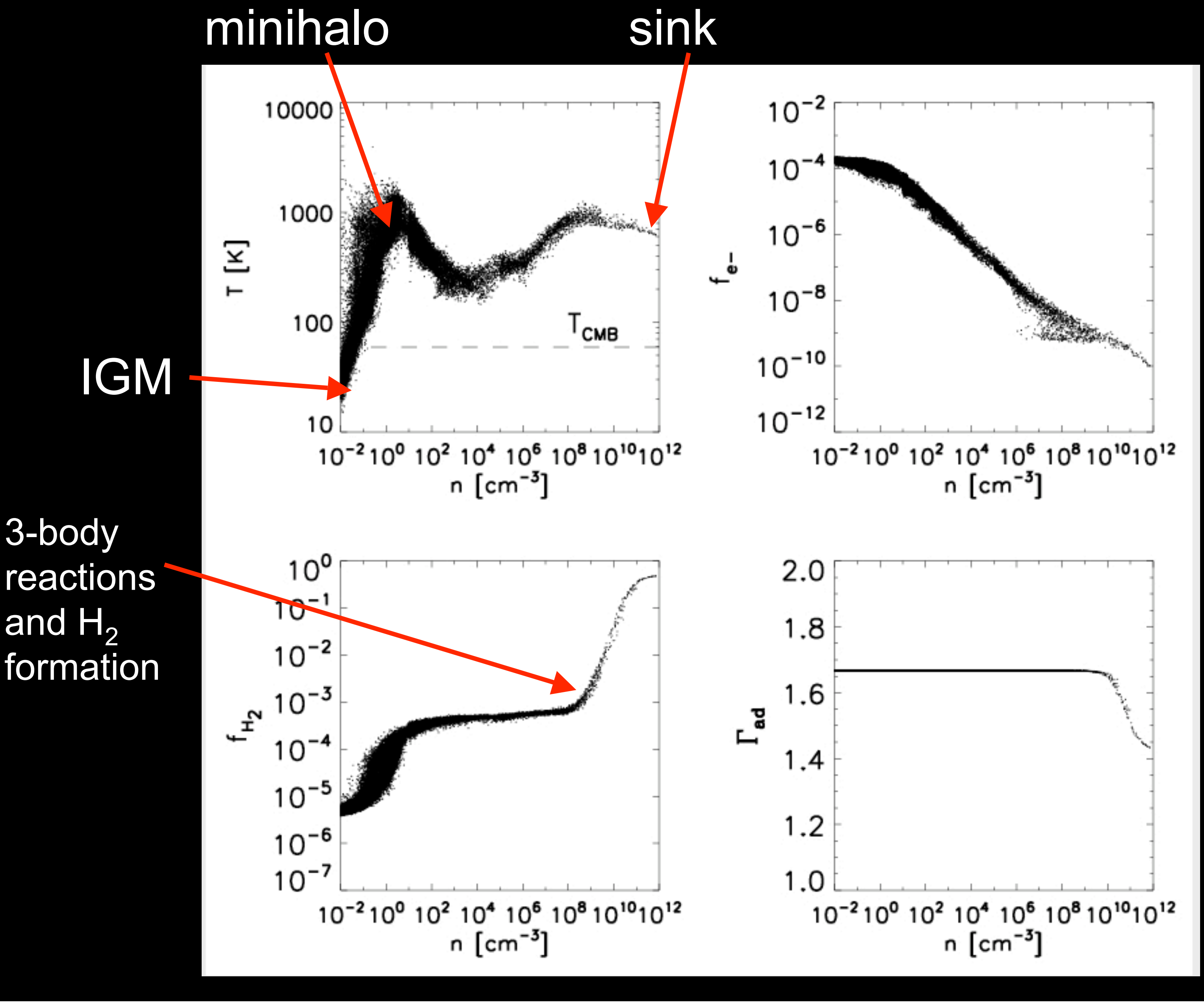
-initialized at $z=100$ according to ΛCDM model

- 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

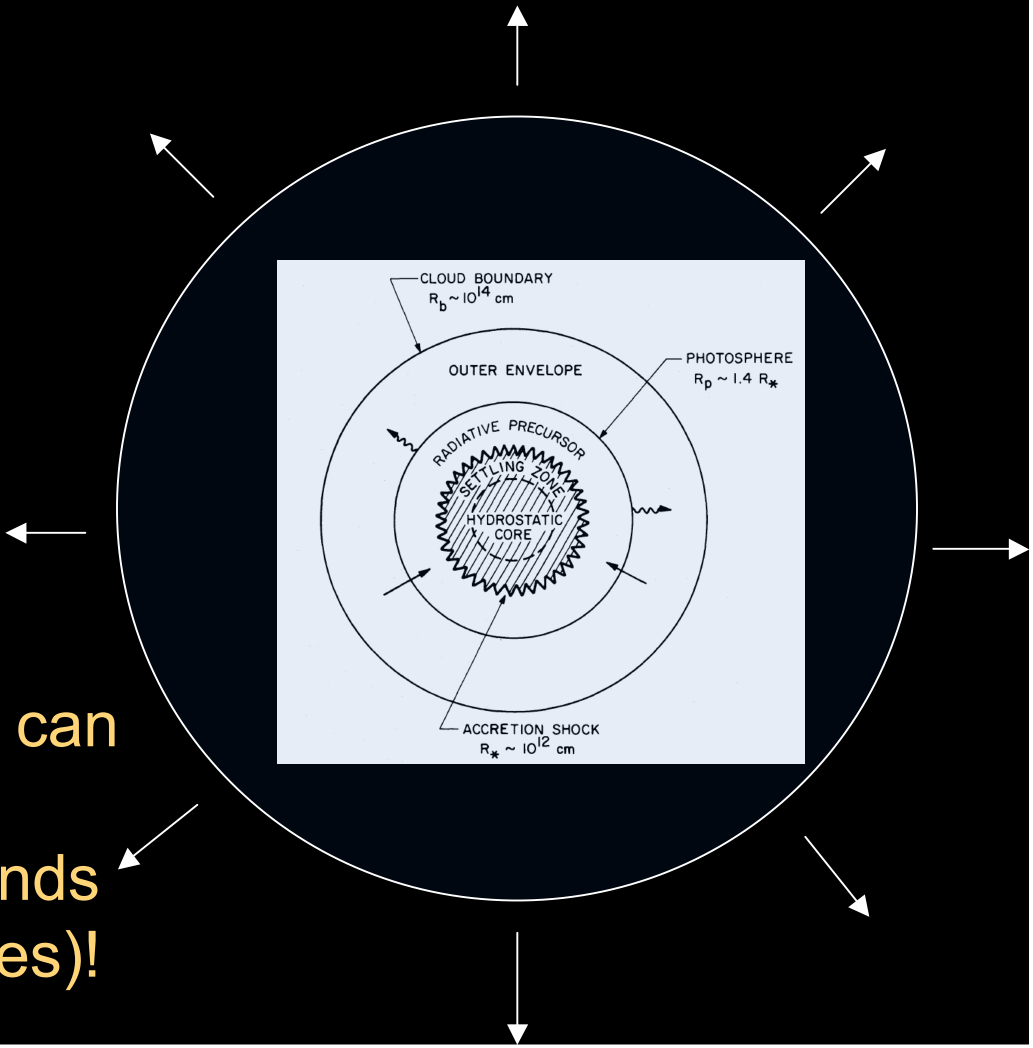


Initial Collapse



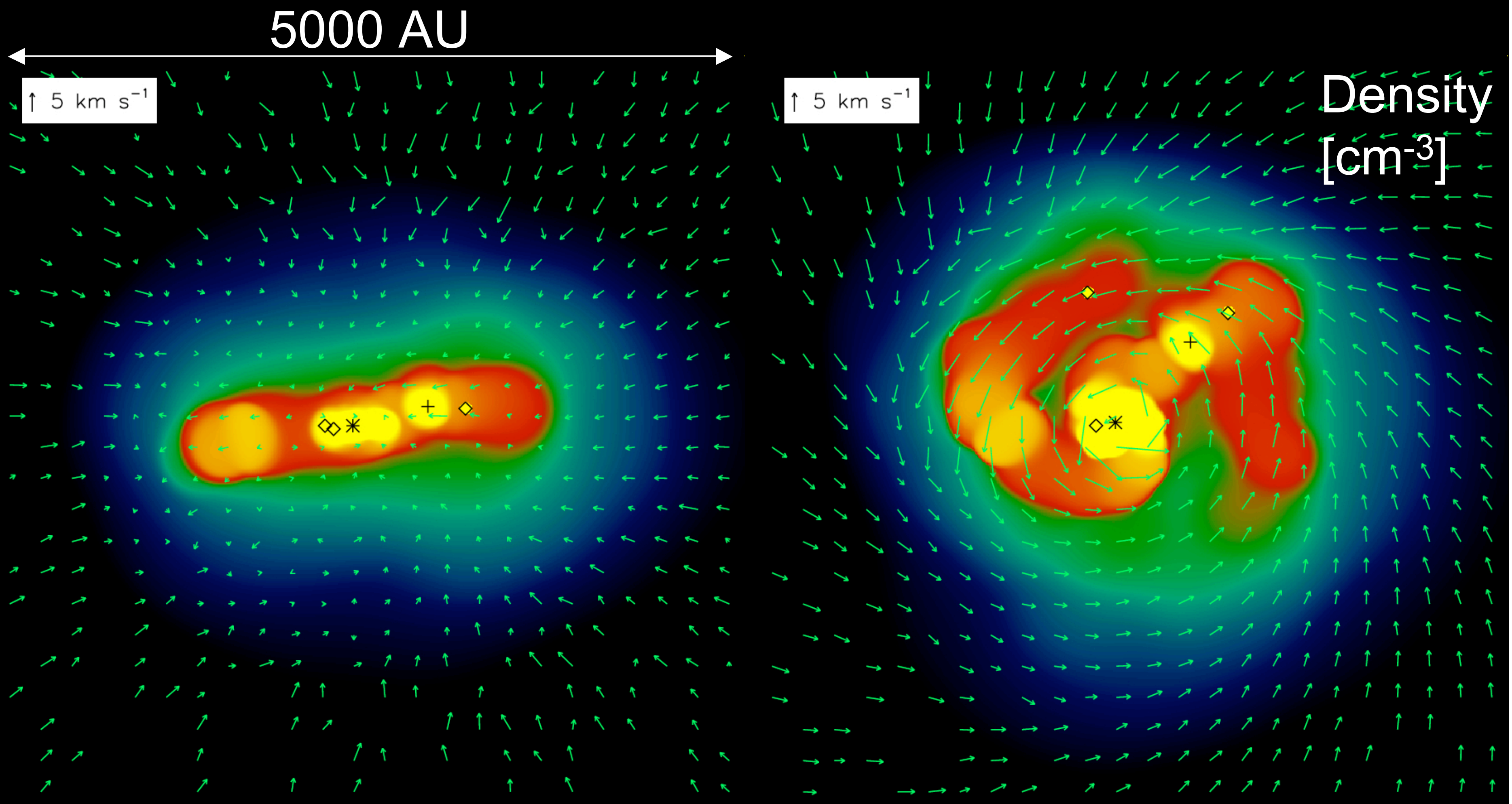
Sink Particles

- $M_{sink} = 1\ M_\odot$
- $n = 10^{12}\ cm^{-3}$
- $r_{acc} \sim 50$ AU
  $\sim 10^{15}$ cm
- $R_\odot \sim 10^{11}$ cm
- Accrete gas particles that fall within r_{acc} of sink



➔ By using sink particles, we can continue following evolution of star-forming gas for thousands more years (~ 100 freefall times)!

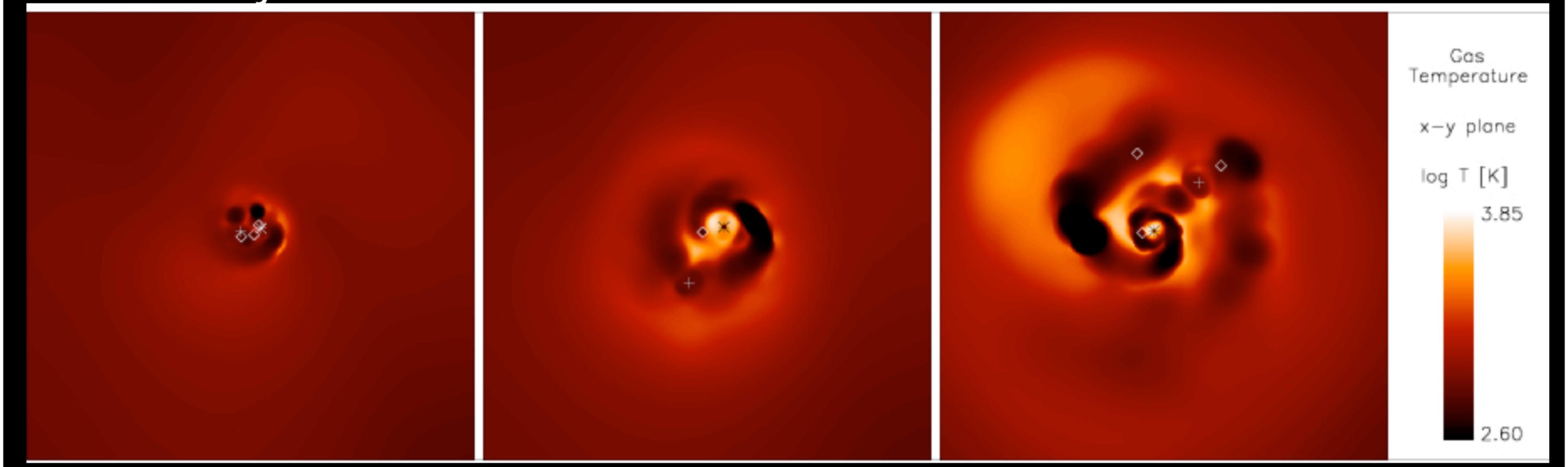
Pop III stars can form in multiples!



Multiple stars form within a disk that has grown to $\sim 40\ M_\odot$ $(t_{acc} = 5000$ yrs$)$

One of the first simulations to show formation of a Pop III multiple system starting from cosmological IC's!

1000 yrs 2000 yrs 5000 yrs



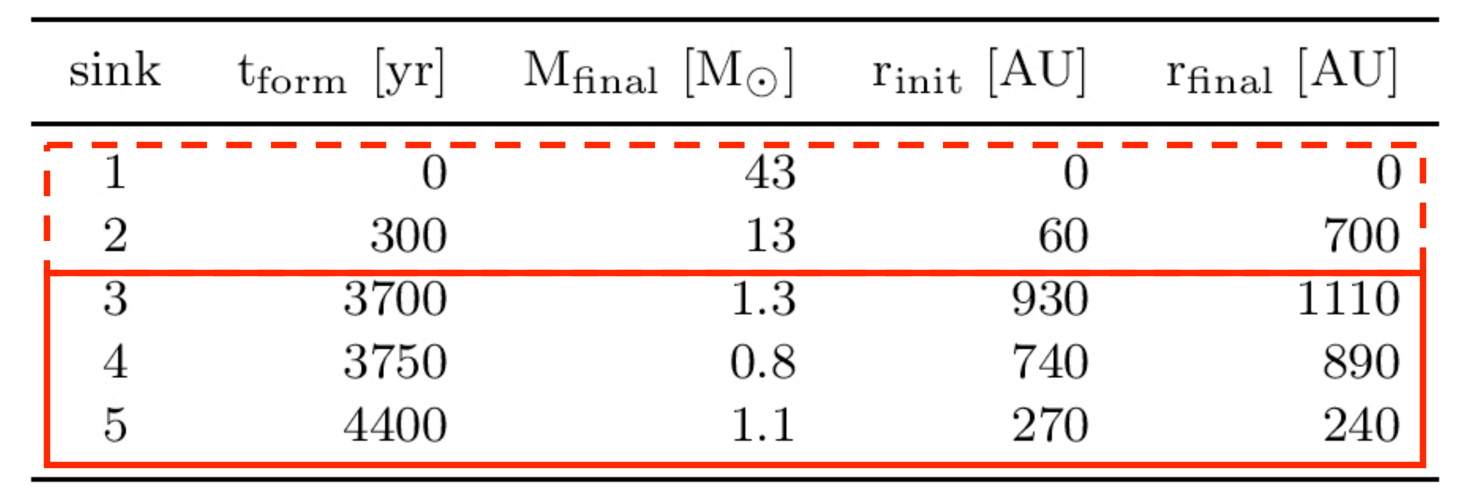
5000 AU

Temperature [K]

Binary and Multiple Formation

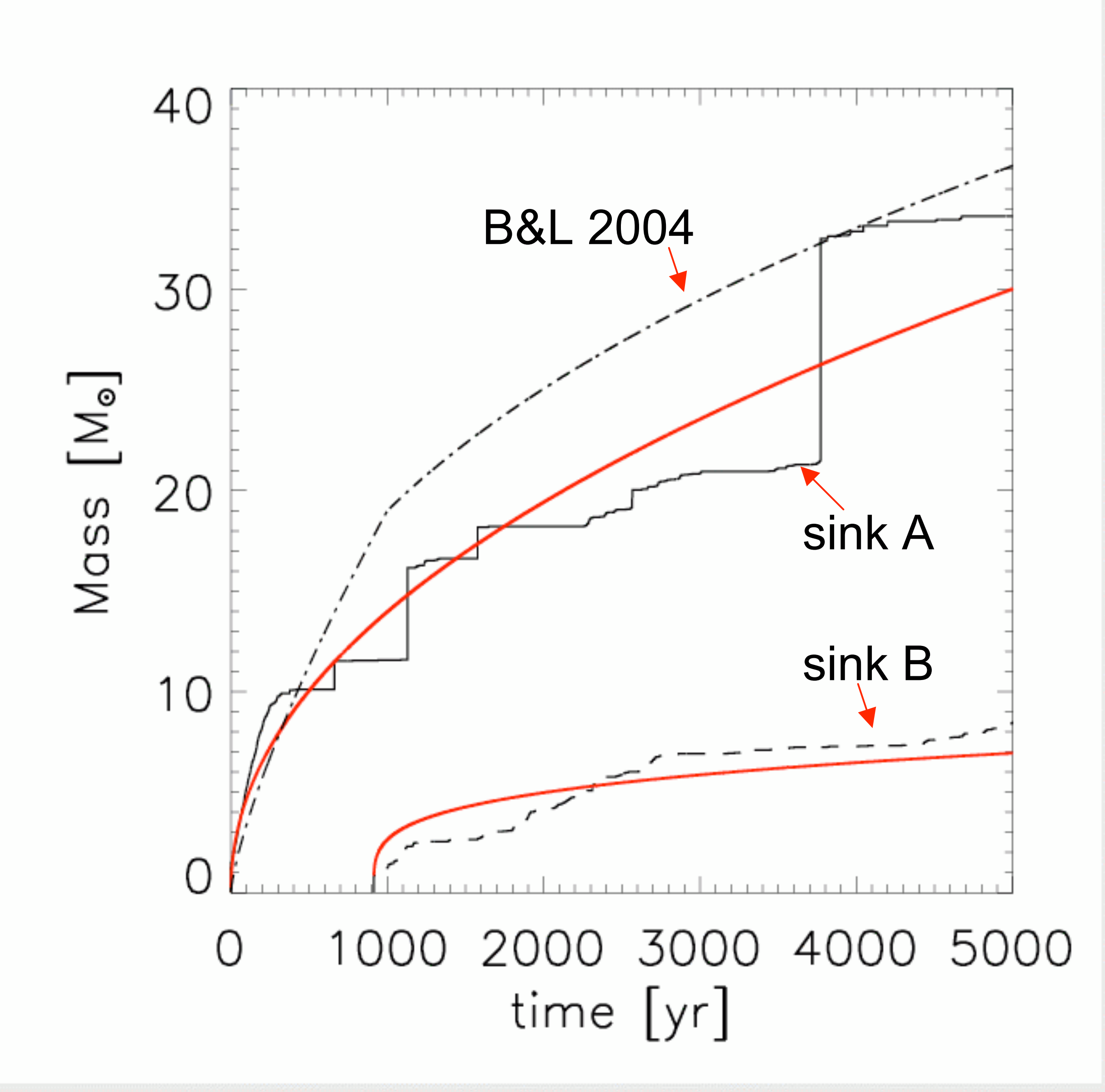
$$Q = \frac{c_s \kappa}{\pi G \Sigma} < 1$$

- Toomre Fragmentation criterion
- Q ~ 0.4 < 1
- Multiple sinks form through disk fragmentation



sink	$t_{\rm form}$ [yr]	$M_{\rm final}$ [$M_\odot$]	$r_{\rm init}$ [AU]	$r_{\rm final}$ [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

Rapid Pop III Accretion Rates



Sink A:
$M_{sink} \sim t^{0.5}$
$dM/dt \sim t^{-0.5}$

Sink B:
$M_{sink} \sim t^{0.25}$
$dM/dt \sim t^{-0.75}$

Current Overview (I)

- Pop III stars can reach tens to hundreds of solar masses

- Disk formation, fragmentation, and binary/multiple formation may be common in Pop III star formation

- Both multiplicity and IMF will be essential in future modeling of Pop III feedback on later star formation and galaxy assembly

- What is the range of typical Pop III masses?
- Any correlations between Pop III masses and other minihalo characteristics?

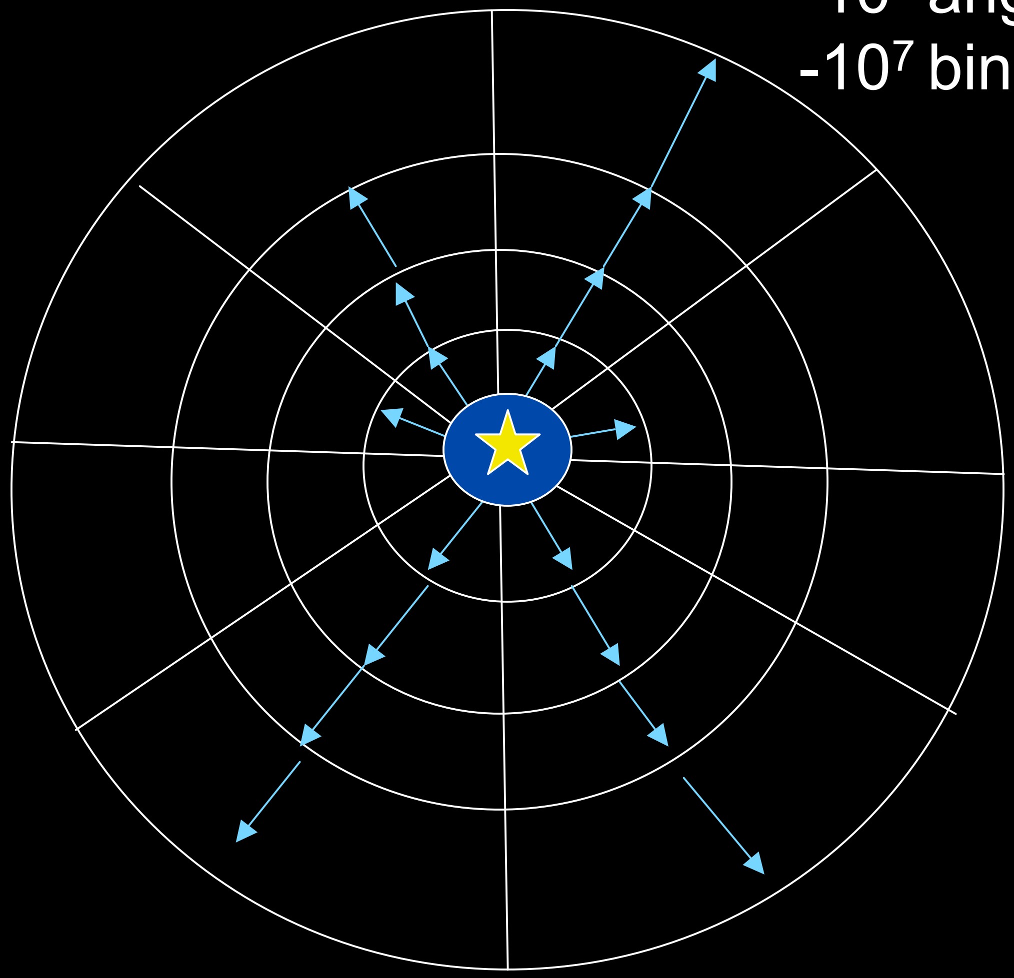
II. Pop III Star Formation With Radiative Feedback

Protostellar Feedback

- Repeat previous cosmological simulation, but with updated H_2 cooling rates
- Model LW radiation and growth of surrounding HII region
- How will radiation alter the growth of the Pop III star?

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

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



The I-front Tracker

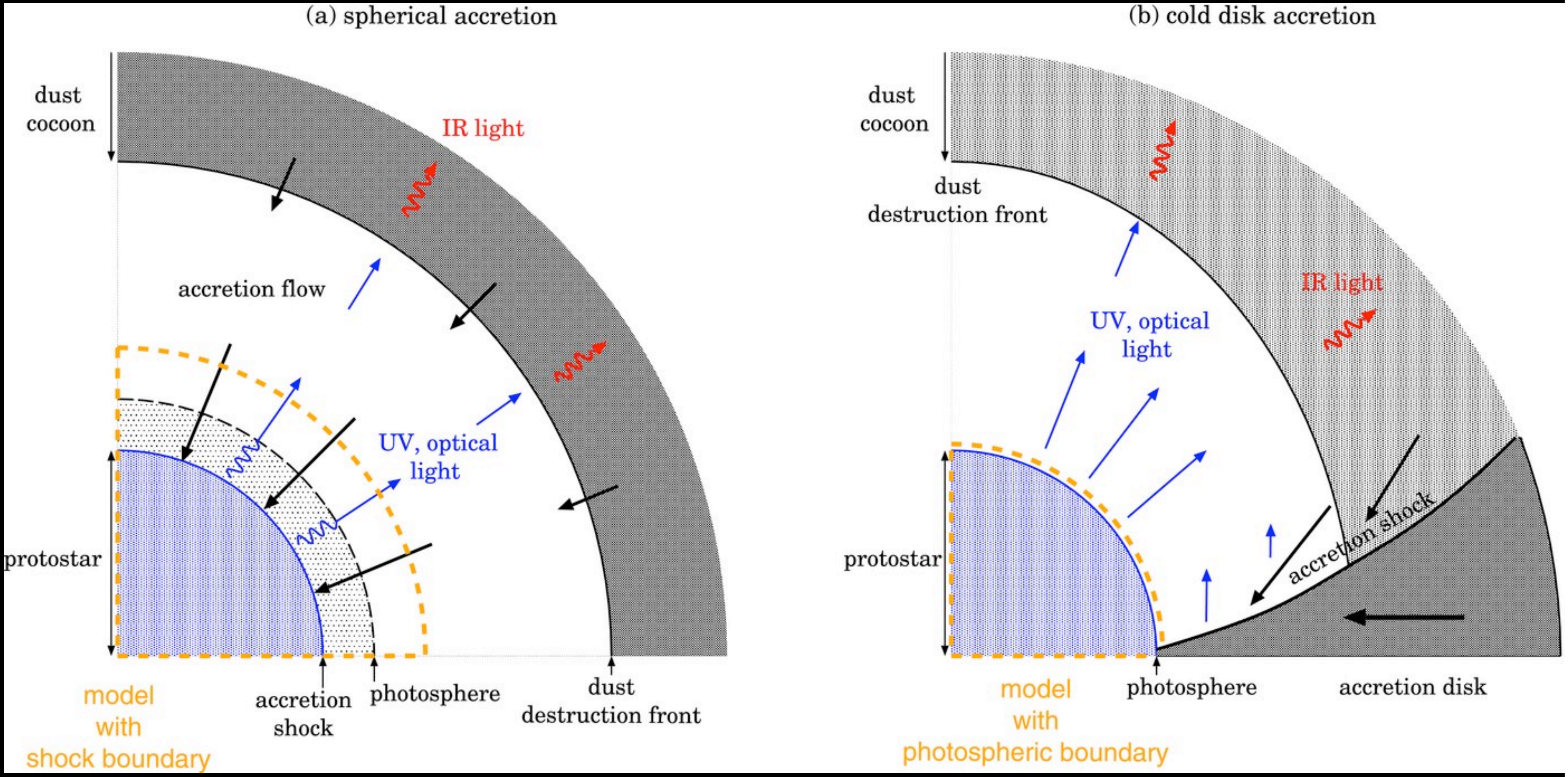
Stromgren Calculation/ Photoionization and Heating Rates

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

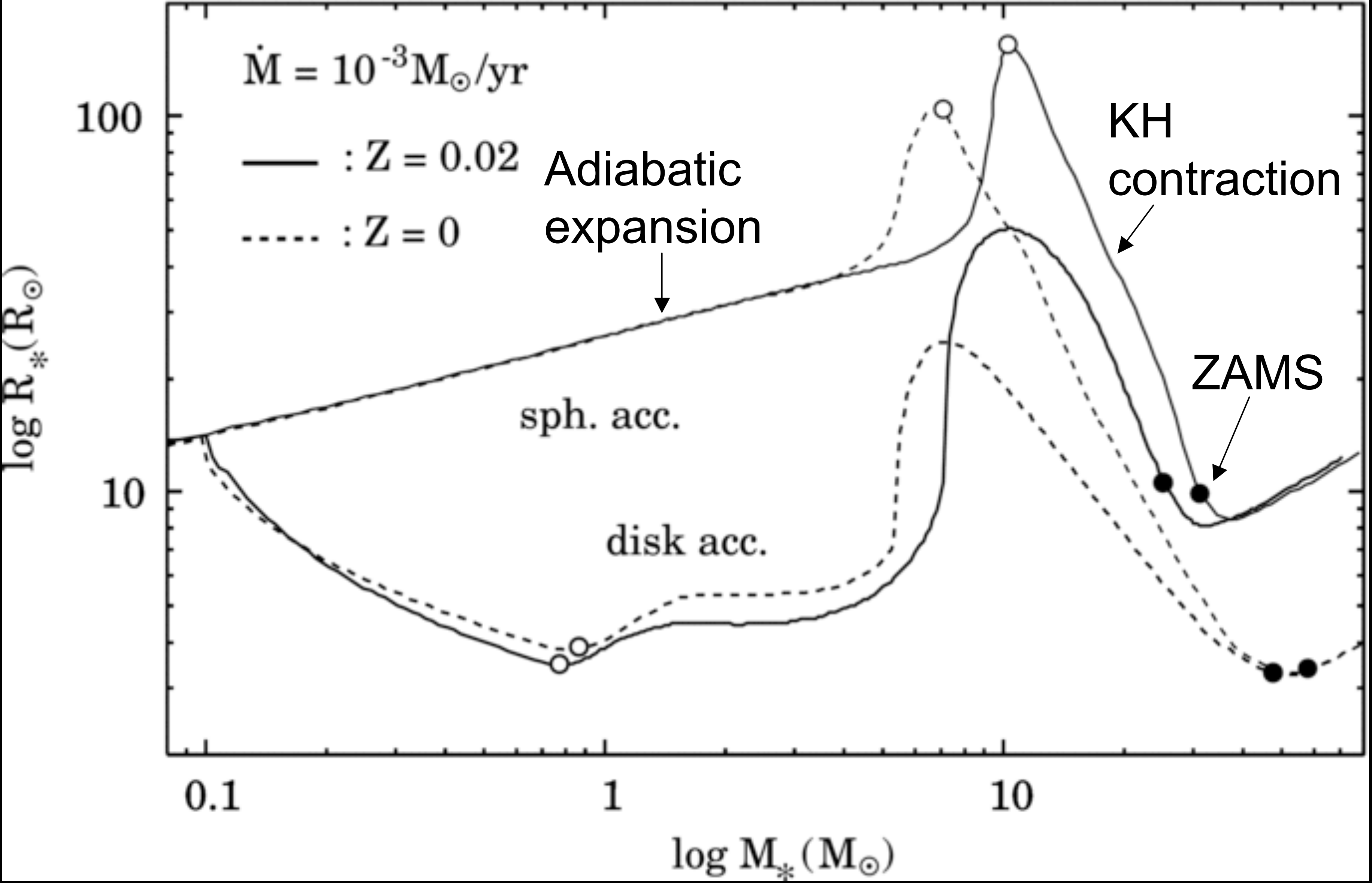
$$k_{\rm ion} = \int_{\nu_{\rm min}}^{\infty} \frac{F_\nu \sigma_\nu}{h\nu} {\rm d}\nu$$

$$\Gamma = n_n \int_{\nu_{\rm min}}^{\infty} F_\nu \sigma_\nu \left(1 - \frac{\nu_{\rm min}}{\nu}\right) {\rm d}\nu \ ,$$

The Protostellar Model

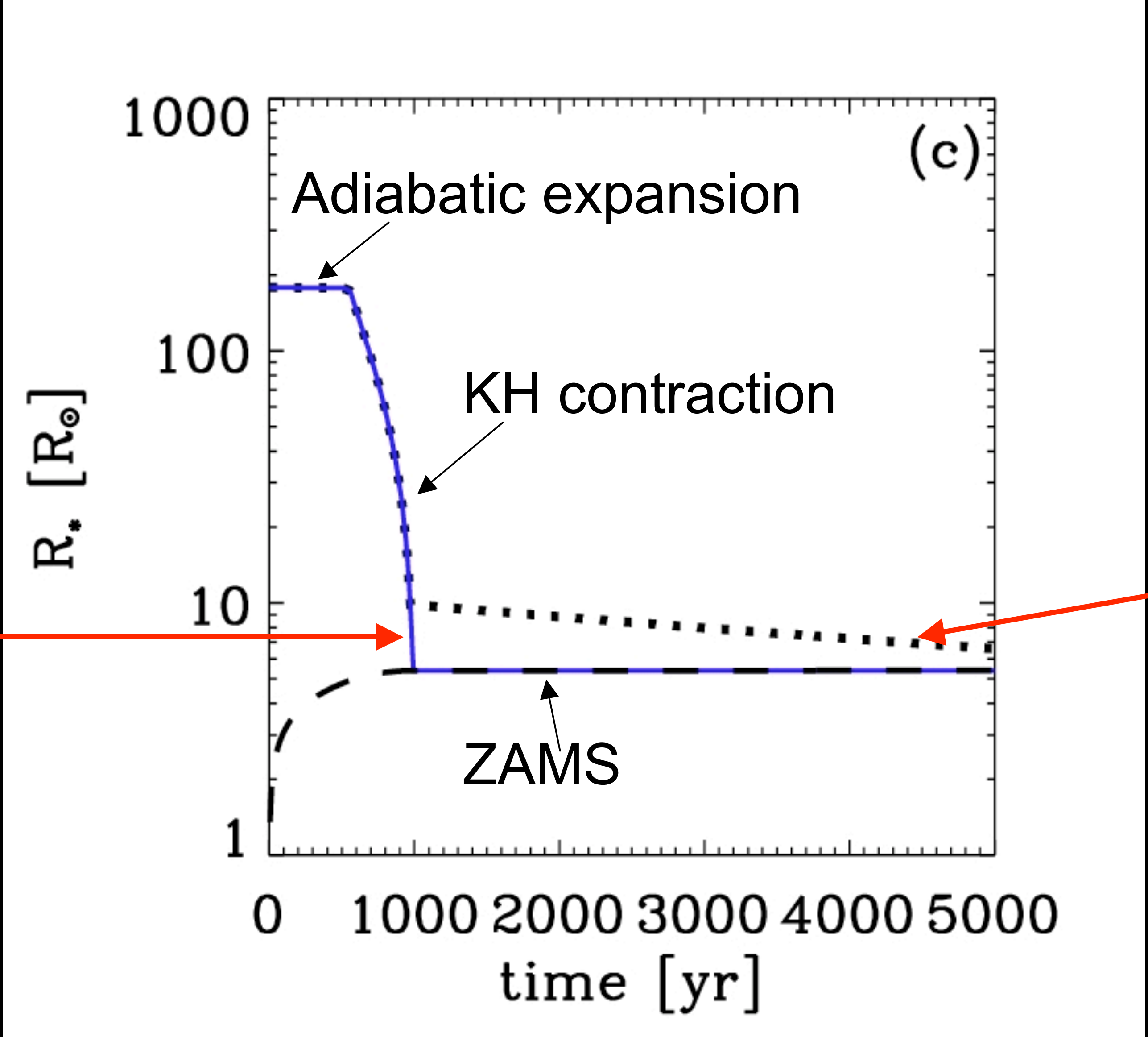


Hosokawa et al. 2010



Hosokawa et al. 2010

The Protostellar Model

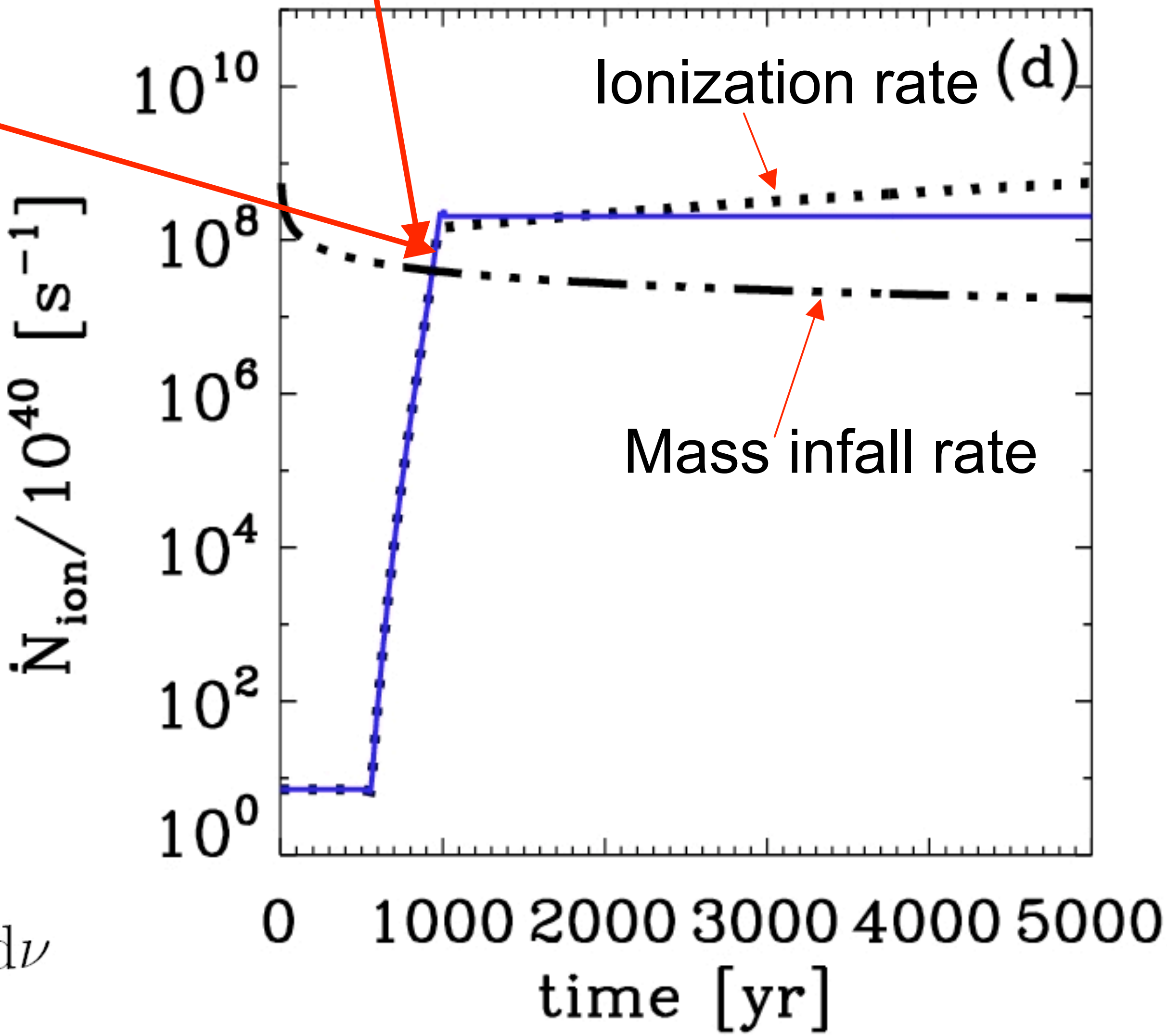


Simulation model

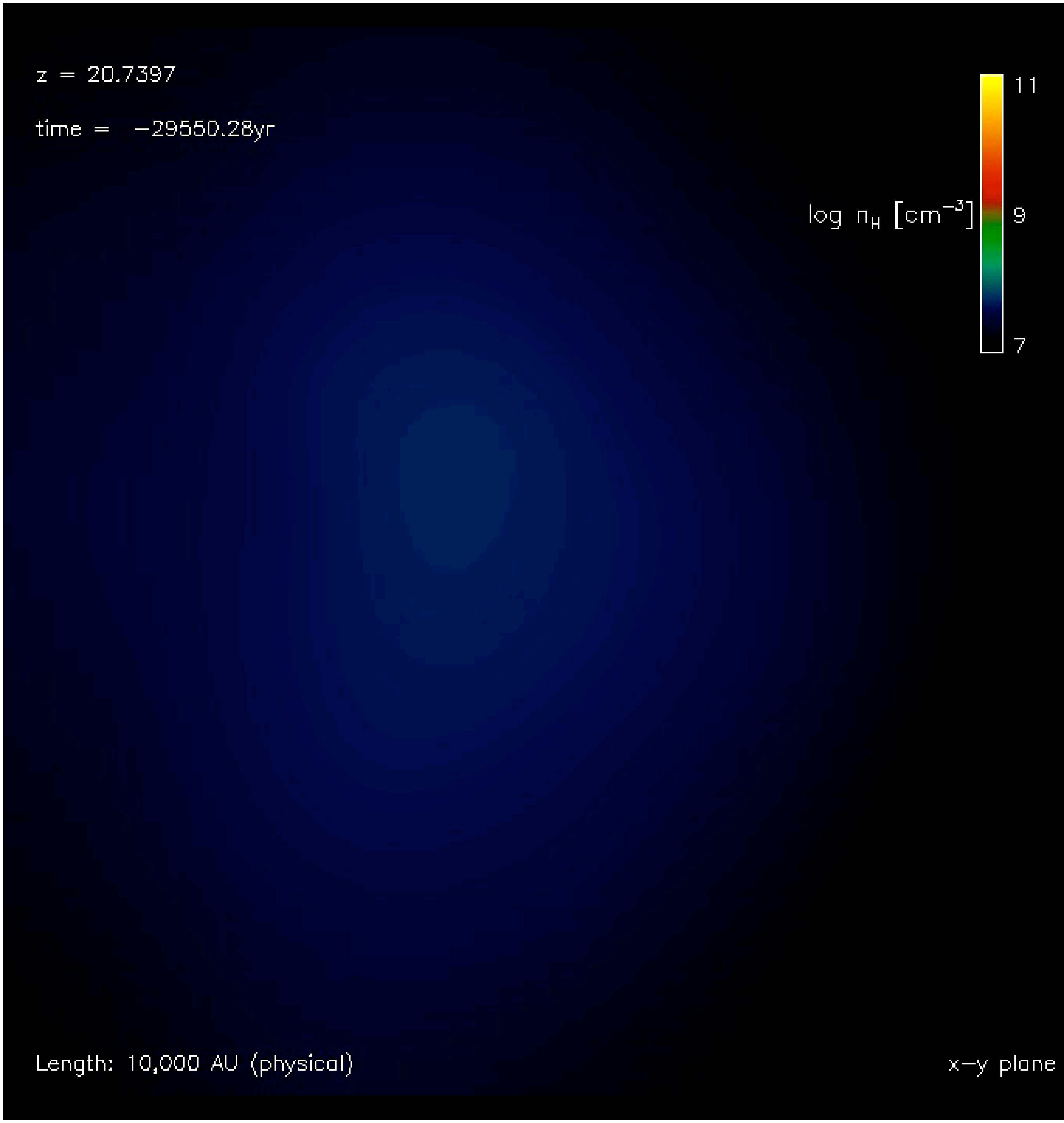
Slow contraction model

I-front breakout

$M_* = 15\ M_\odot$



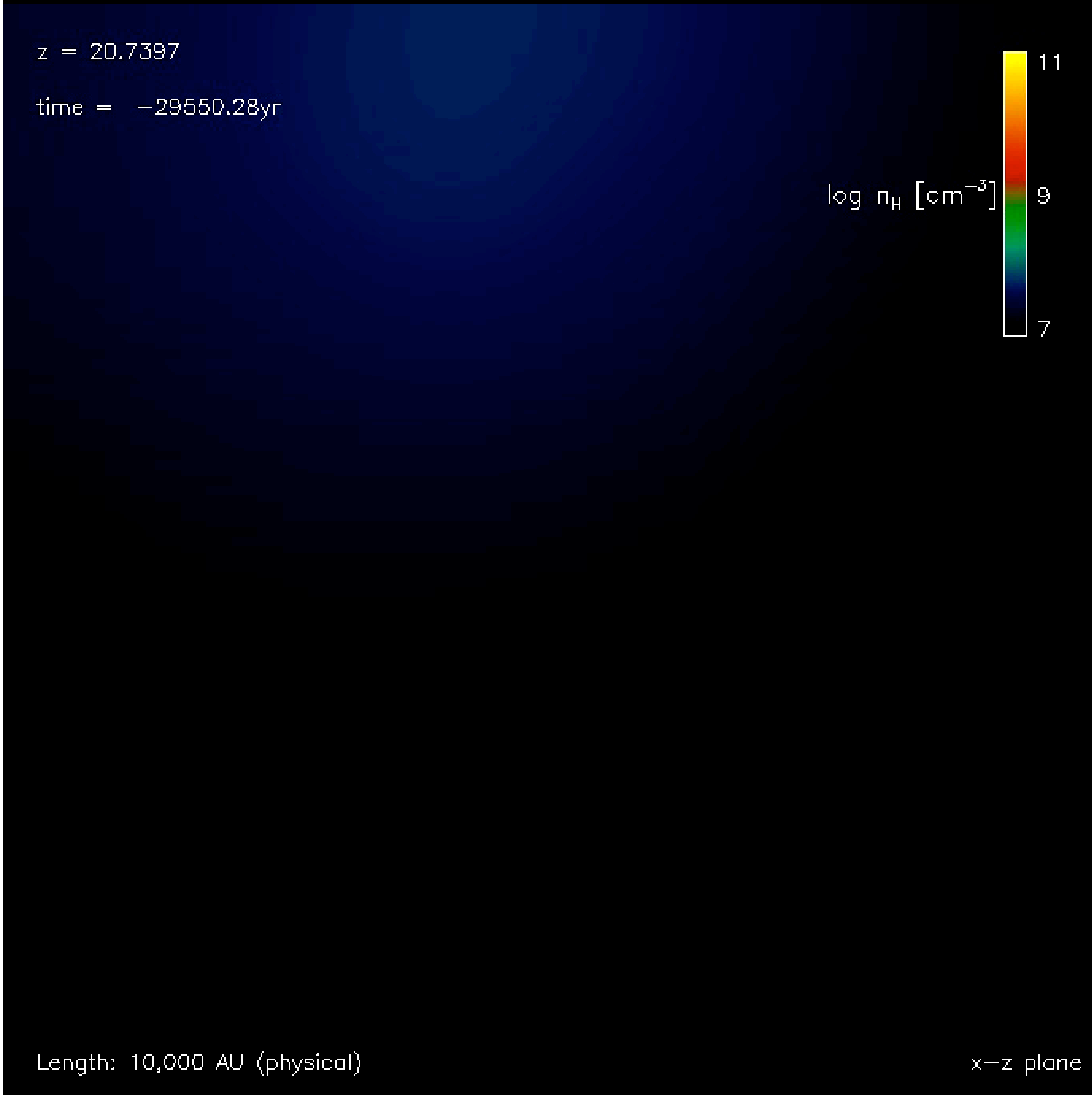
$$\dot{N}_{\rm ion} = \frac{\pi L_*}{\sigma_{\rm SB} T_{\rm eff}^4}\int_{\nu_{\rm min}}^{\infty}\frac{B_\nu}{h\nu}{\rm d}\nu$$



With Feedback

* = main sink

+ = secondary sink

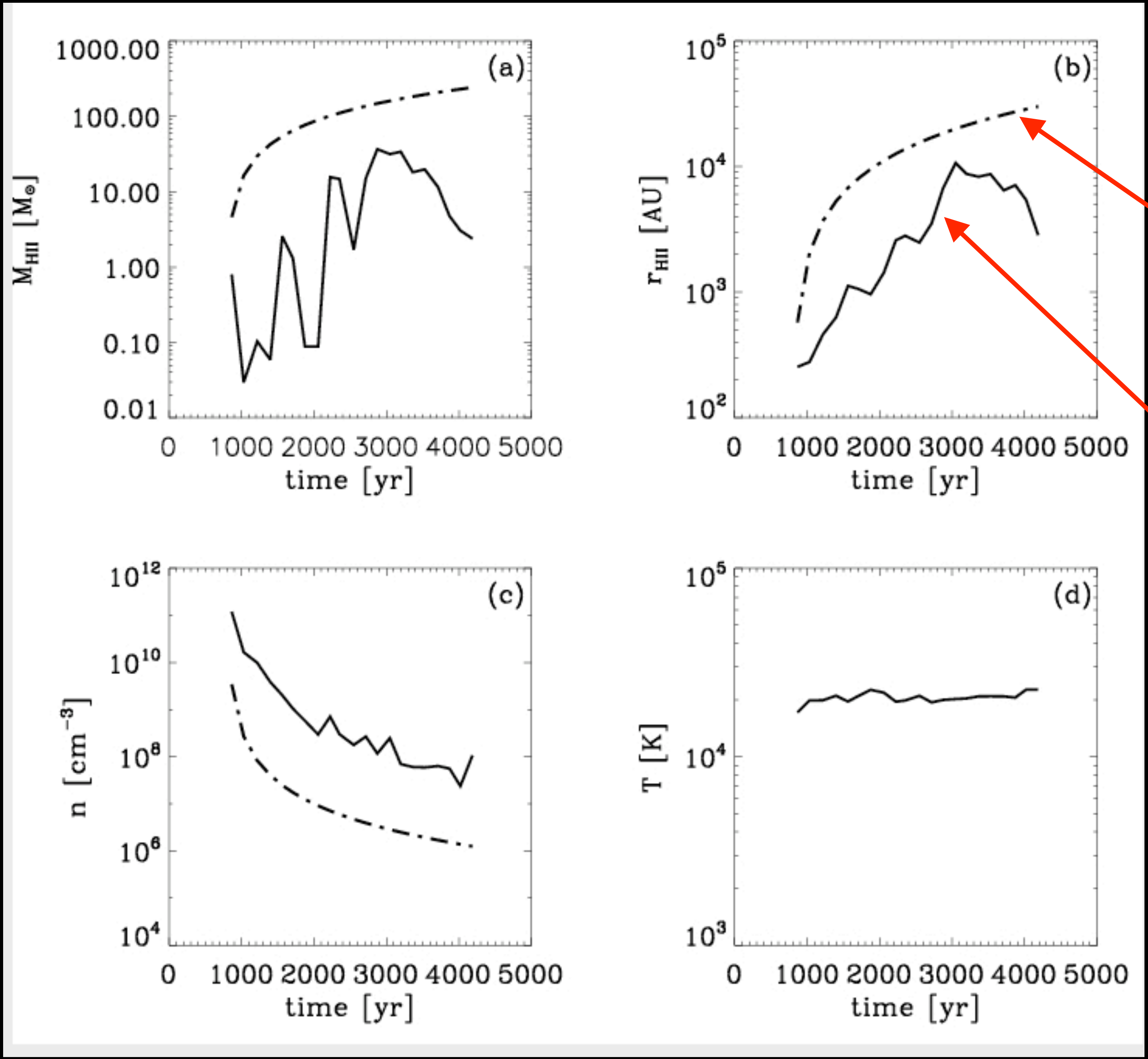


With Feedback

* = main sink

+ = secondary sink

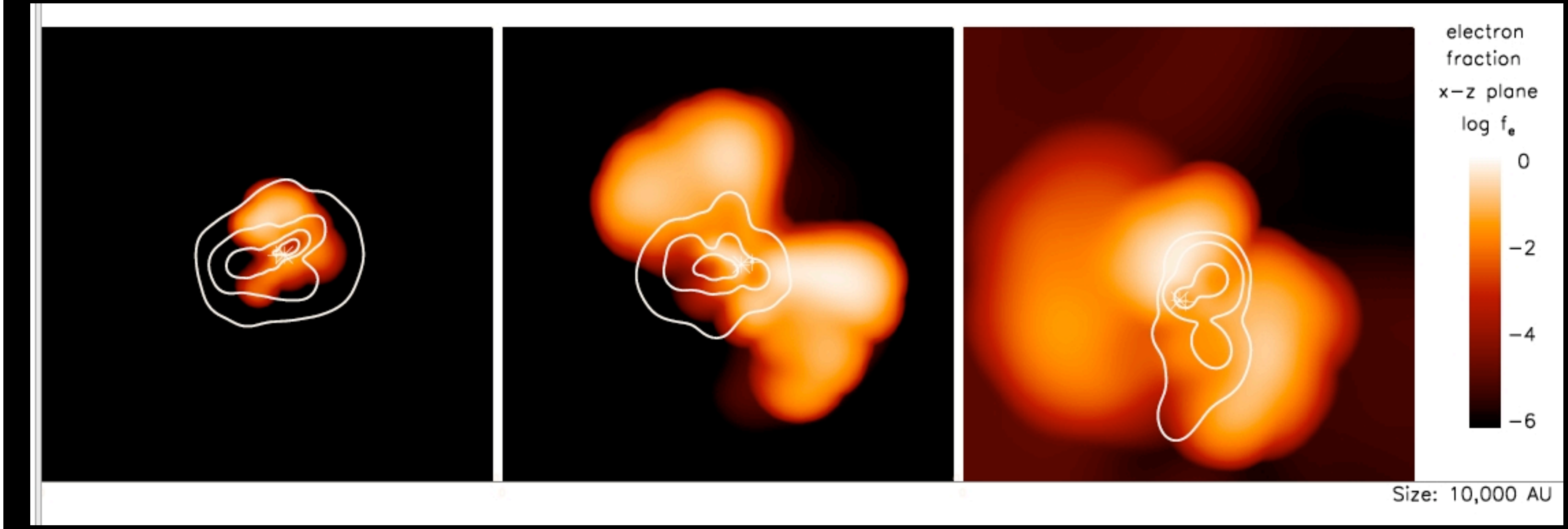
I-front Growth



Analytical Shu solution

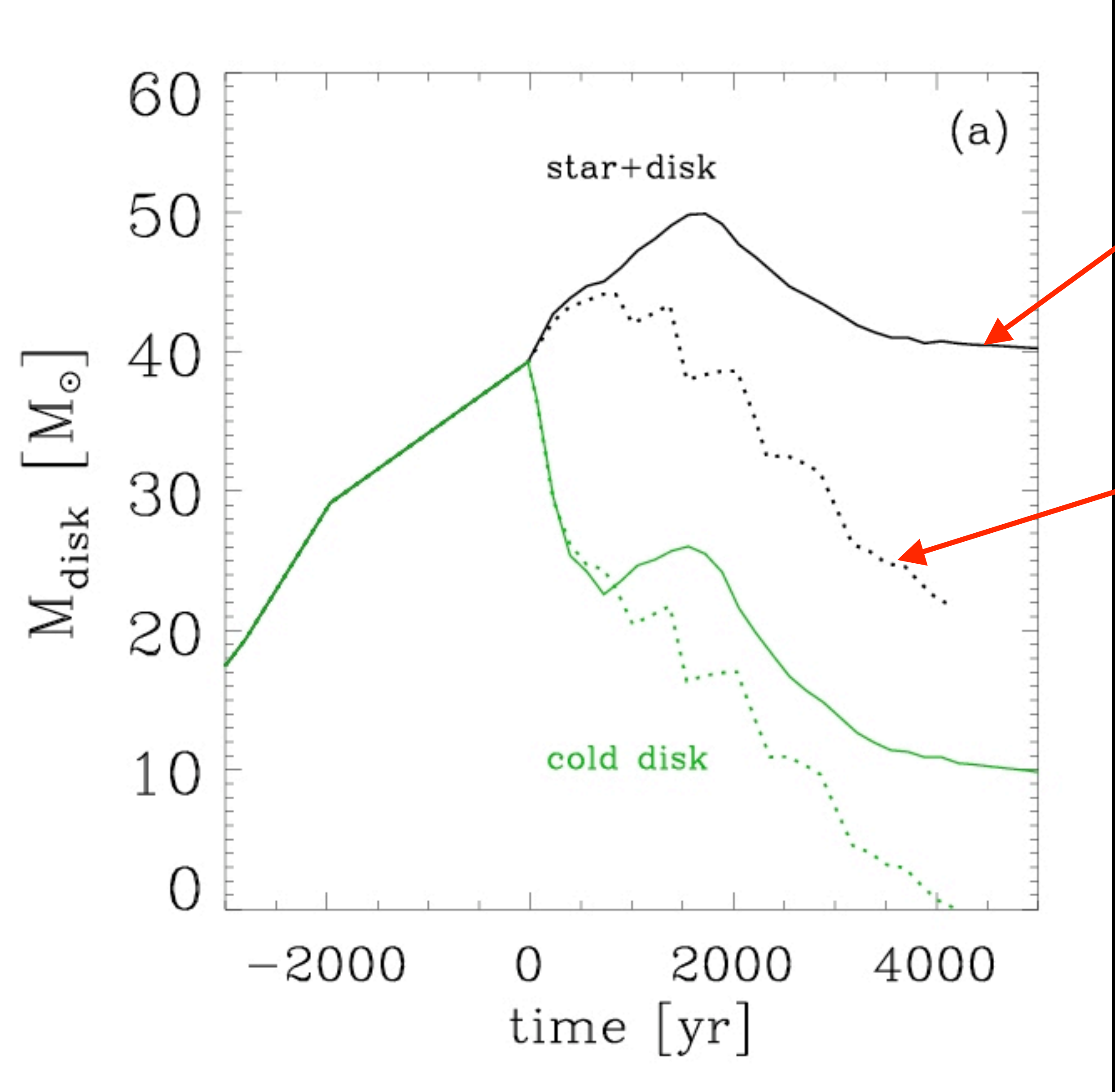
Simulation

I-front Evolves in Morphology



1500 yr 2500 yr 5000 yr

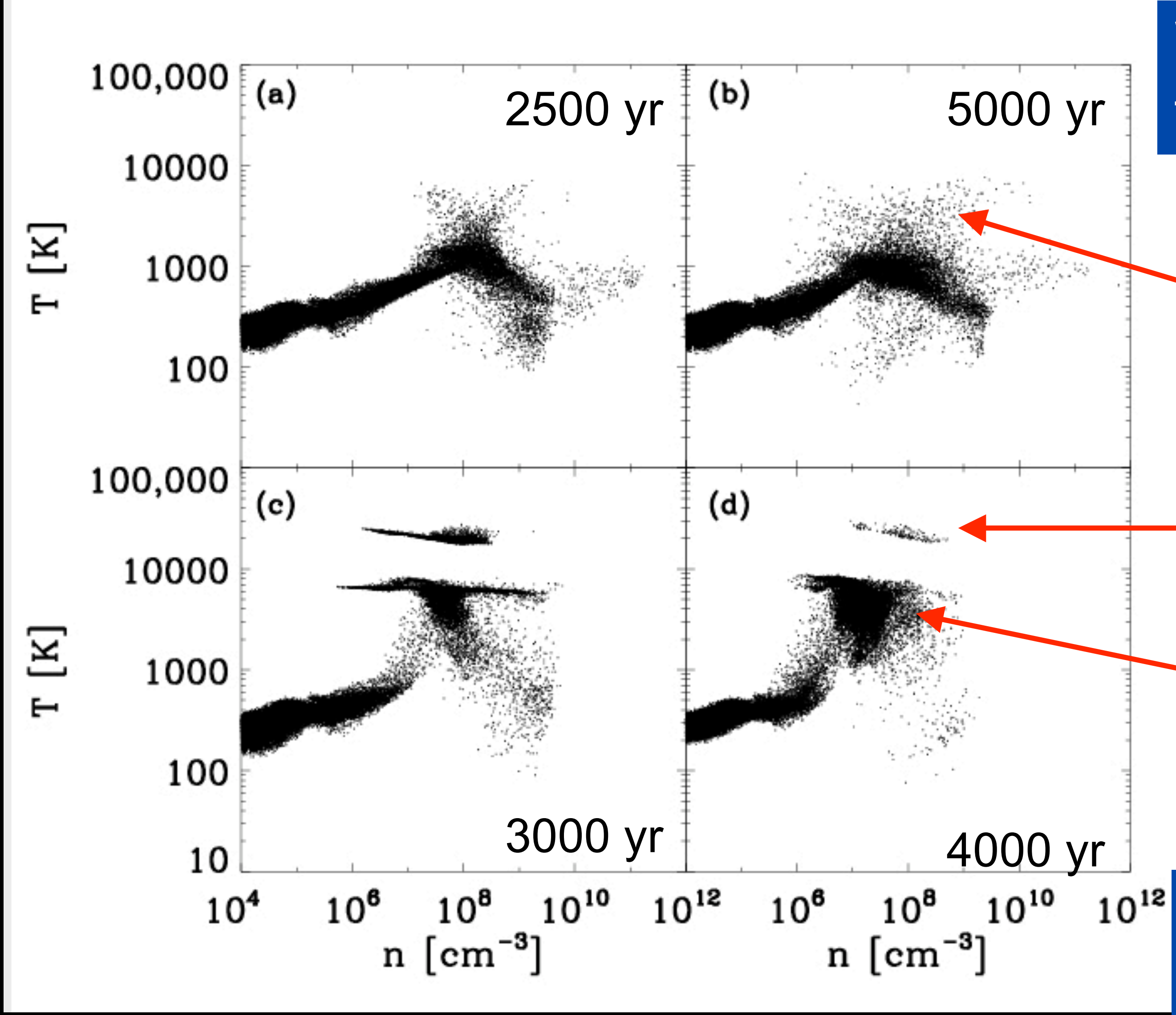
Feedback Halts Disk Growth



No feedback

With feedback

Temperature Structure



Without feedback

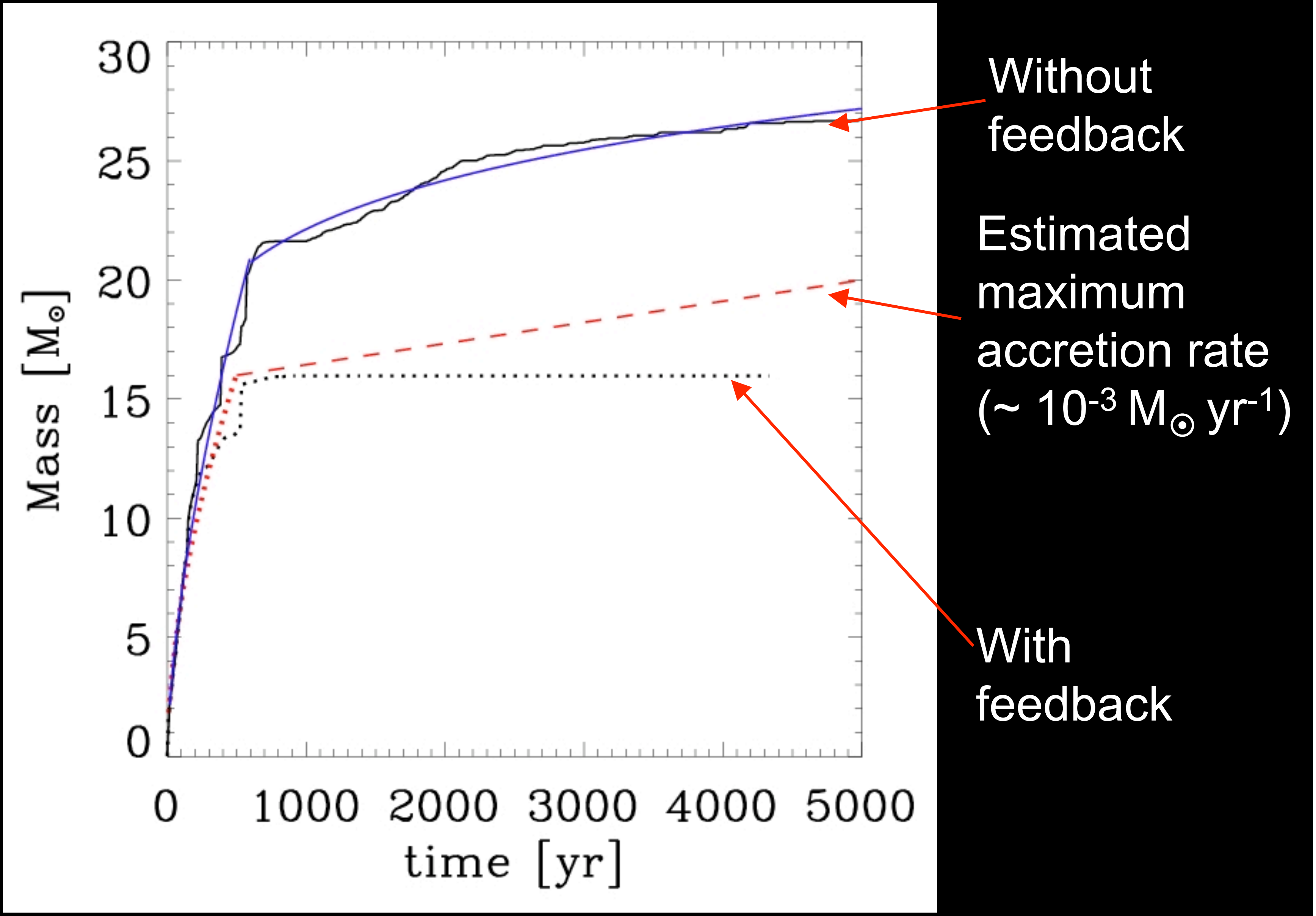
Sink potential well heating

I-front

Warm neutral bubble

With feedback

Reduced Accretion Rate



Without feedback

Estimated maximum accretion rate (~ 10^{-3} M$_\odot$ yr^{-1})

With feedback

Current Overview (II)

- Pop III multiplicity robust to feedback
- Pop III stars can likely reach tens of solar masses, but hundreds of solar masses may be harder
- Non-axisymmetry may enhance radiative feedback effects due to imperfect disk shielding
- N-body dynamics may also disrupt rapid accretion
- Higher resolution sims/more detailed sub-sink modeling of disk shielding will be needed for future work

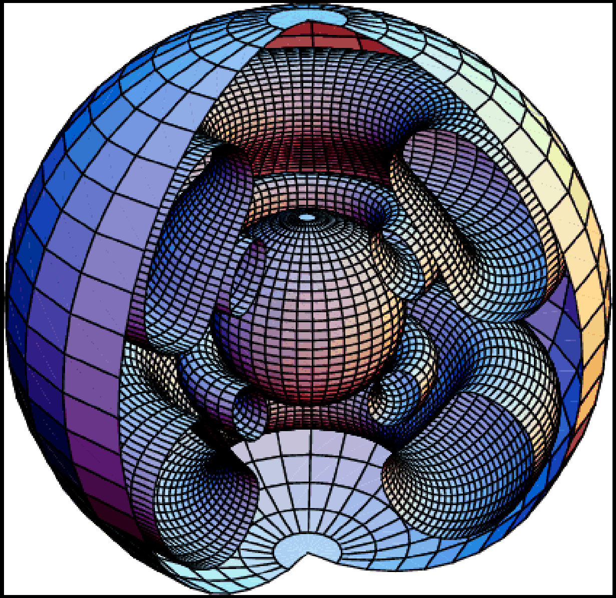
III. Pop III Rotation Rates

Importance of Rotation

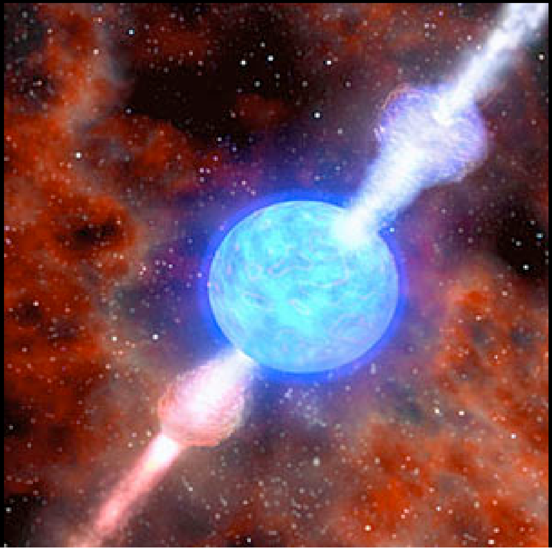
1. Facilitates rotationally induced mixing, which will alter stellar evolution and metal yield.

2. Will lower minimum Pop III MS mass necessary to yield a PISN

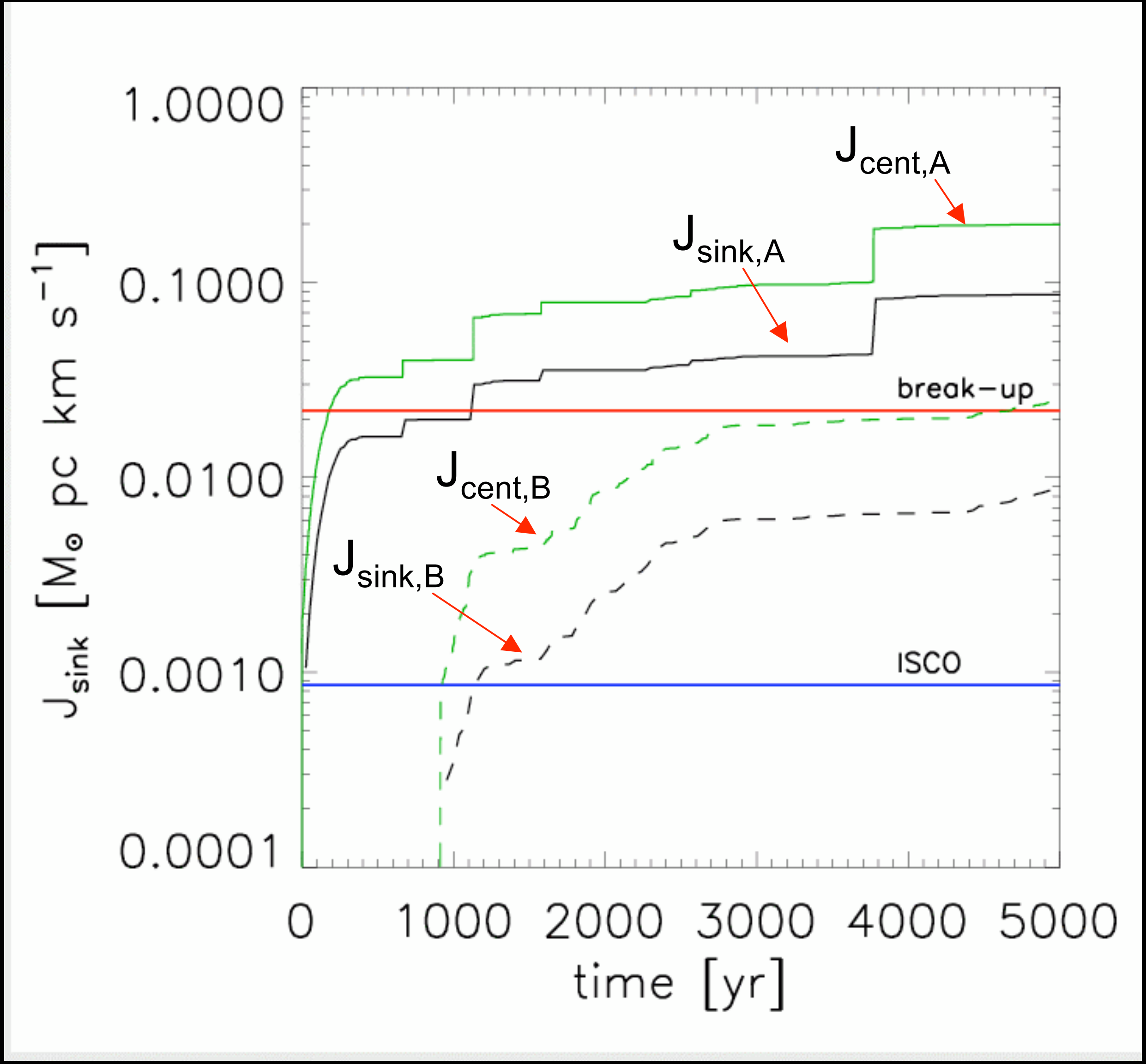
3. Can ultimately power collapsar GRBs if progenitor star is sufficiently massive.



Meynet & Maeder 2002



Sink Accretion of High Angular Momentum



$J_{\rm SPH} = m_{\rm SPH} v_{\rm rot} d$
$J_{\rm sink} = \Sigma m_{\rm SPH} v_{\rm rot} d$

$$r_{\rm cent} = \frac{j_{\rm sink}^2}{G M_{\rm sink}},$$

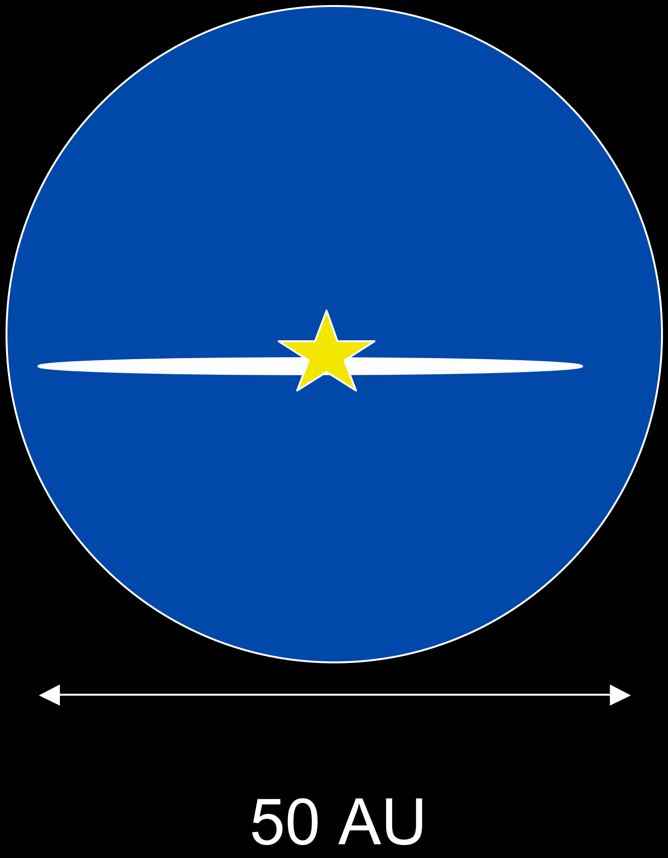
= 10 AU (sink A)
= 6 AU (sink B)

Sub-Sink Keplerian Disk?

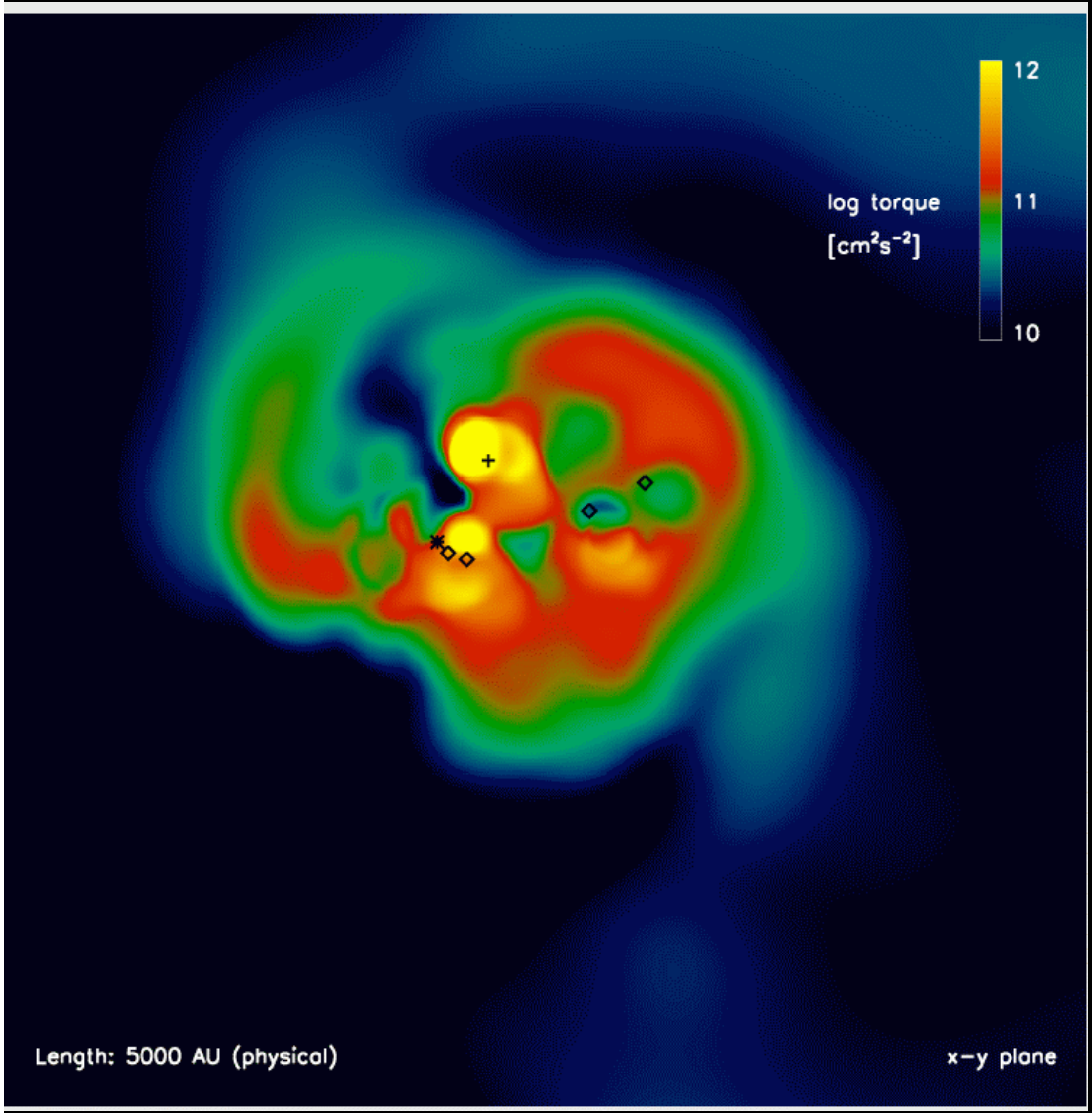
Too much angular momentum for all of it to be deposited onto star.

Some must be deposited onto a disk.

➔Yes, Keplerian disk is likely!



Extrapolation to Stellar Scales



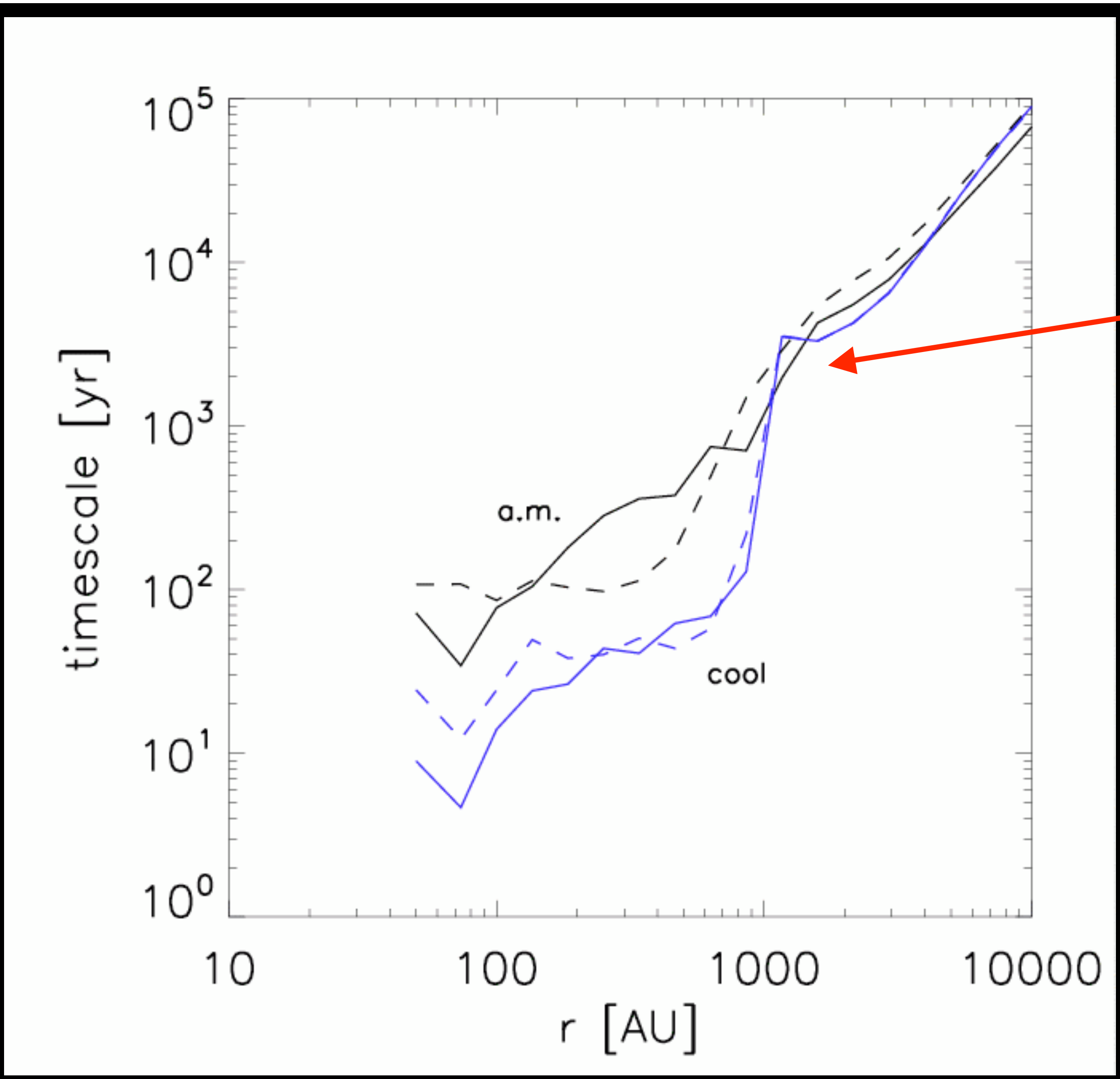
1. Energy comparison:
For gas that falls onto the sinks, ROTATIONAL energy dominates!

$$v_{\rm rot}^2 + v_{\rm rad}^2 + c_{\rm s}^2 \sim \frac{G\,M_{\rm sink}}{r_{\rm acc}}$$

2. Timescale comparison:
Large-scale gravitational torques act on timescales of 100-1000 years, allowing material to fall onto sinks

$t_{\rm cool} < t_{\rm am}$

➔Keplerian disk likely!



1000 AU = Edge of large-scale disk

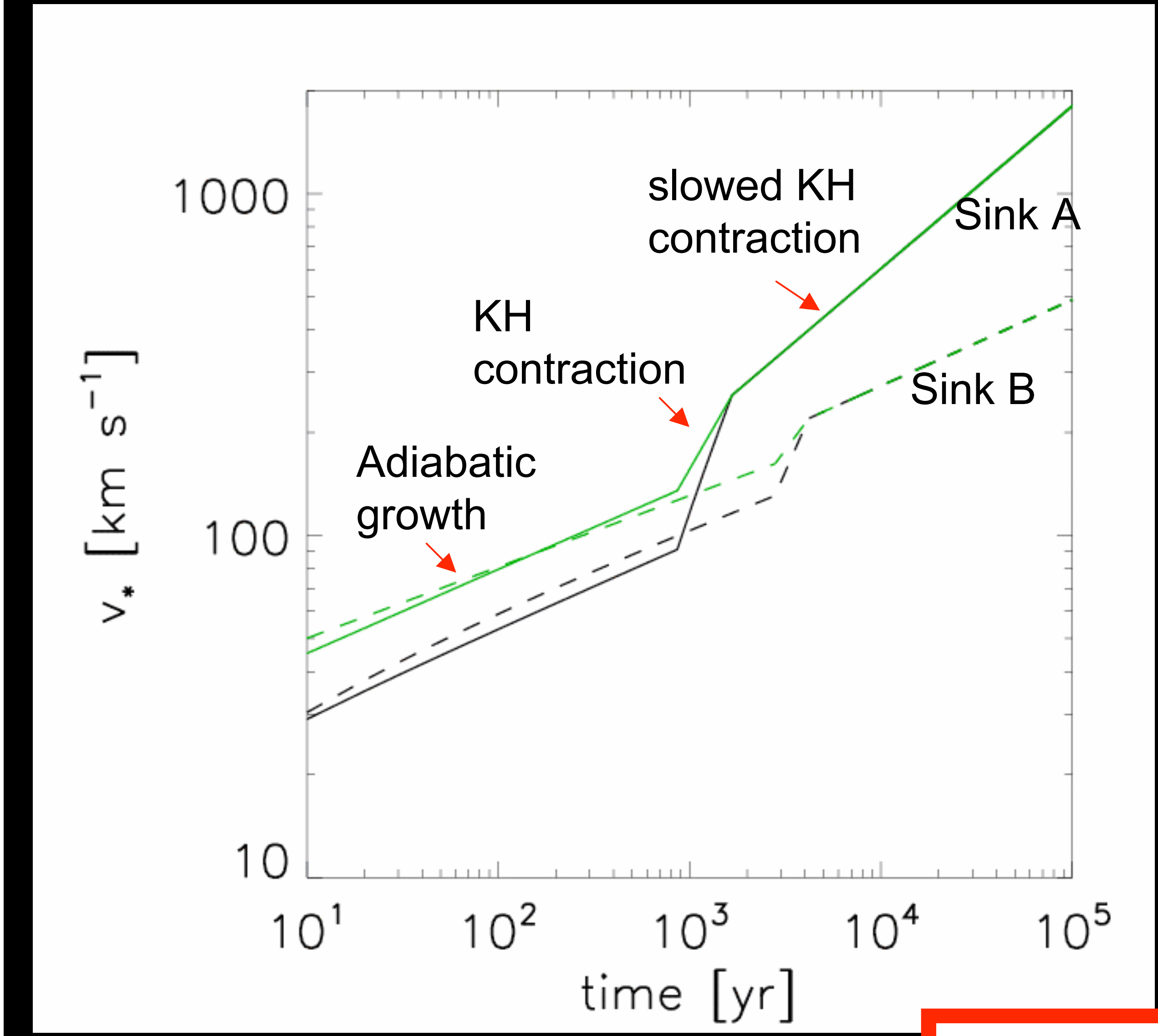
$$t_{\rm cool} \simeq \frac{n k_{\rm B} T}{\Lambda}$$

$$t_{\rm am} \simeq J_{\rm SPH}/|\vec{\tau}_{\rm tot}|$$

$t_{\rm cool} < t_{\rm am}$

$$\begin{aligned}\vec{\tau}_{\rm tot} &= \vec{\tau}_{\rm grav} + \vec{\tau}_{\rm pres} + \vec{\tau}_{\rm visc} \\ &= m_{\rm SPH}\vec{d} \times (\vec{a}_{\rm grav} + \vec{a}_{\rm pres} + \vec{a}_{\rm visc})\end{aligned}$$

Rapid Pop III Rotation



Green = v_{Kep}

Black = v_*

Once star begins KH contraction, it quickly spins up.

➔ Stars reach break-up speeds

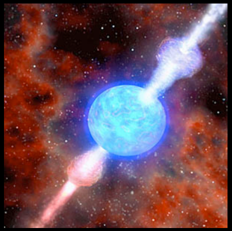
$$v_* = v_{*,\rm Kep} \simeq \sqrt{GM_{\rm sink}/R_*}$$

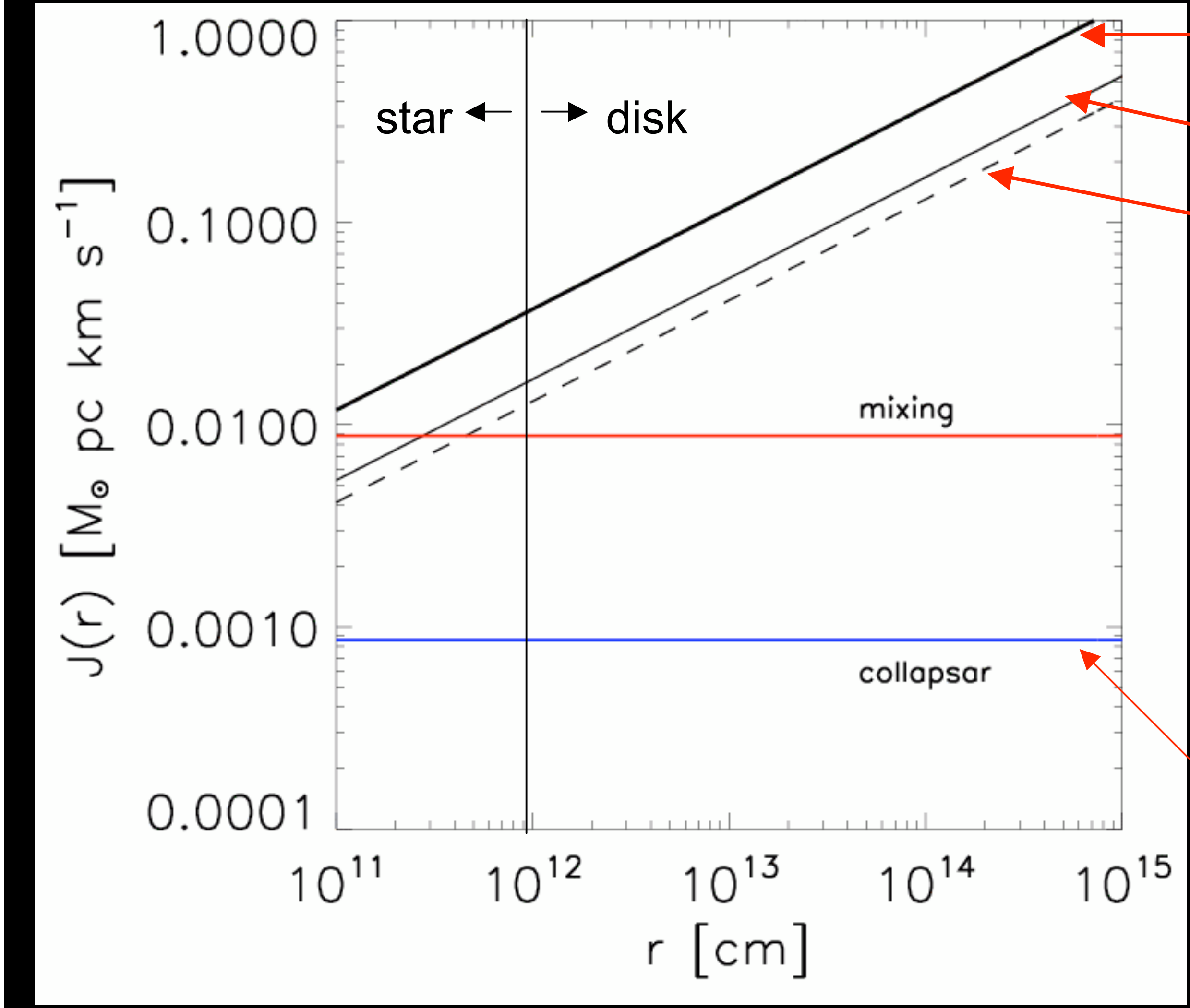
Rotationally Induced Mixing and GRBs

- At rotation speeds above ~ 40% of v_{Kep}, rotationally induced mixing allows star to smoothly transition from H to He burning
- Can avoid red giant phase and become rapidly rotating WR star
- Luminosities, temperatures, lifetimes, and metal yields may be higher
- A massive WR star that retains its angular momentum may collapse to a black hole - disk system to become collapsar GRB

Implications of High Stellar Rotation Rates

1. Rotationally Induced Mixing (no red giant phase, WR star)
2. Collapsar GRBs (accretion disk around remnant BH)





100% Keplerian

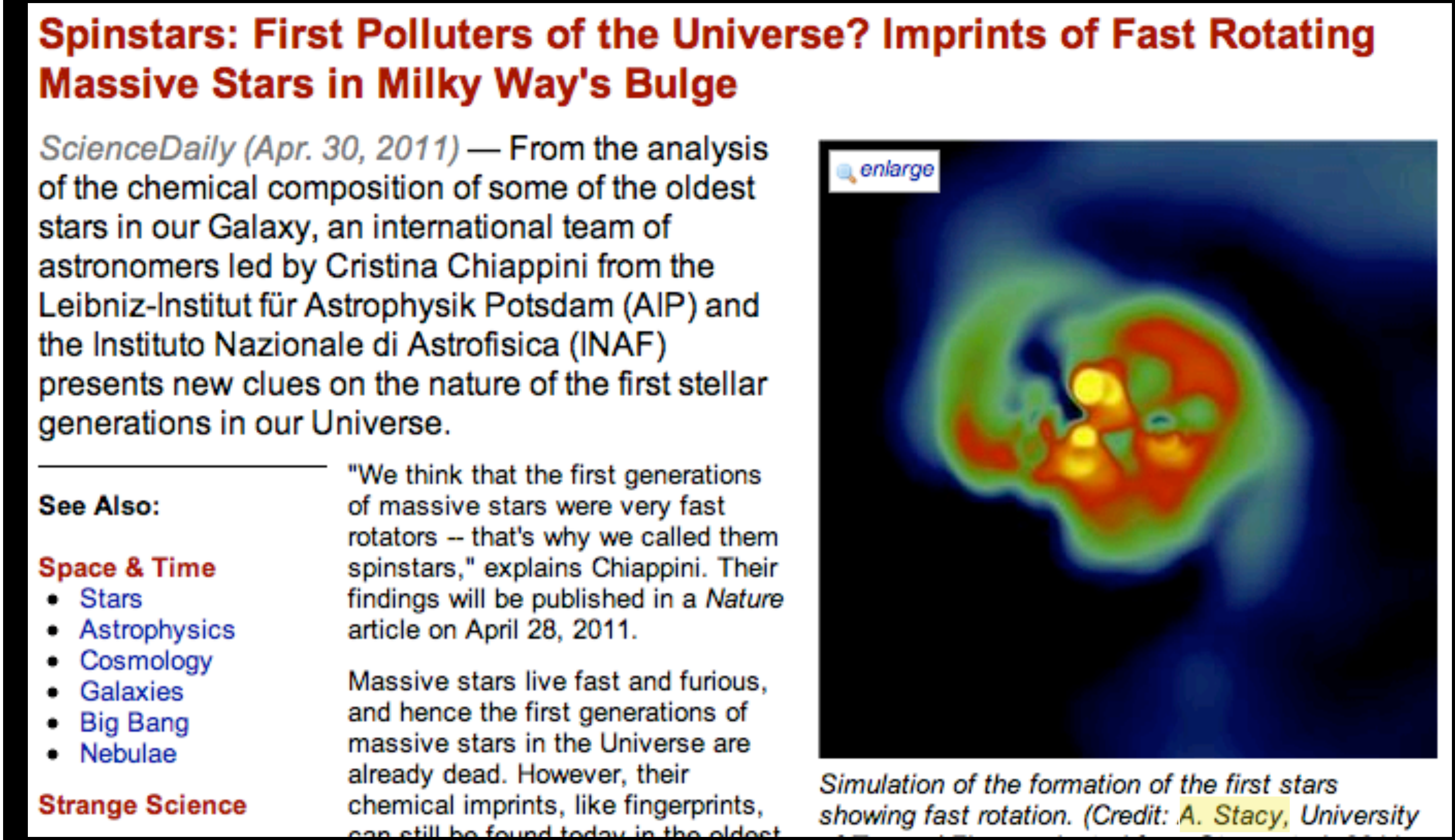
45% Keplerian

35% Keplerian

$$J_{\mathrm{ISCO}} = \sqrt{6} G M_{\mathrm{BH}}^{2} / c$$

Intriguing Observations!

- Chiappini et al., 2011, “Imprints of fast-rotating massive stars in the Galactic Bulge”, Nature, 472, 454
- Found anomalous enhancement in Ba, La, Y, and Sr in old globular cluster NGC 6522
- May have been originally produced by enhanced s-process in rapidly rotating massive stars



Spinstars: First Polluters of the Universe? Imprints of Fast Rotating Massive Stars in Milky Way's Bulge

ScienceDaily (Apr. 30, 2011) — From the analysis of the chemical composition of some of the oldest stars in our Galaxy, an international team of astronomers led by Cristina Chiappini from the Leibniz-Institut für Astrophysik Potsdam (AIP) and the Instituto Nazionale di Astrofisica (INAF) presents new clues on the nature of the first stellar generations in our Universe.

See Also:

Space & Time
- Stars
- Astrophysics
- Cosmology
- Galaxies
- Big Bang
- Nebulae

Strange Science

"We think that the first generations of massive stars were very fast rotators -- that's why we called them spinstars," explains Chiappini. Their findings will be published in a *Nature* article on April 28, 2011.

Massive stars live fast and furious, and hence the first generations of massive stars in the Universe are already dead. However, their chemical imprints, like fingerprints,

Simulation of the formation of the first stars showing fast rotation. (Credit: A. Stacy, University

Current Overview (III)

- Rapidly rotating Pop III stars may also be common

- This may lead to rotationally induced mixing,
  WR Pop III stars, hypernovae, and GRBs

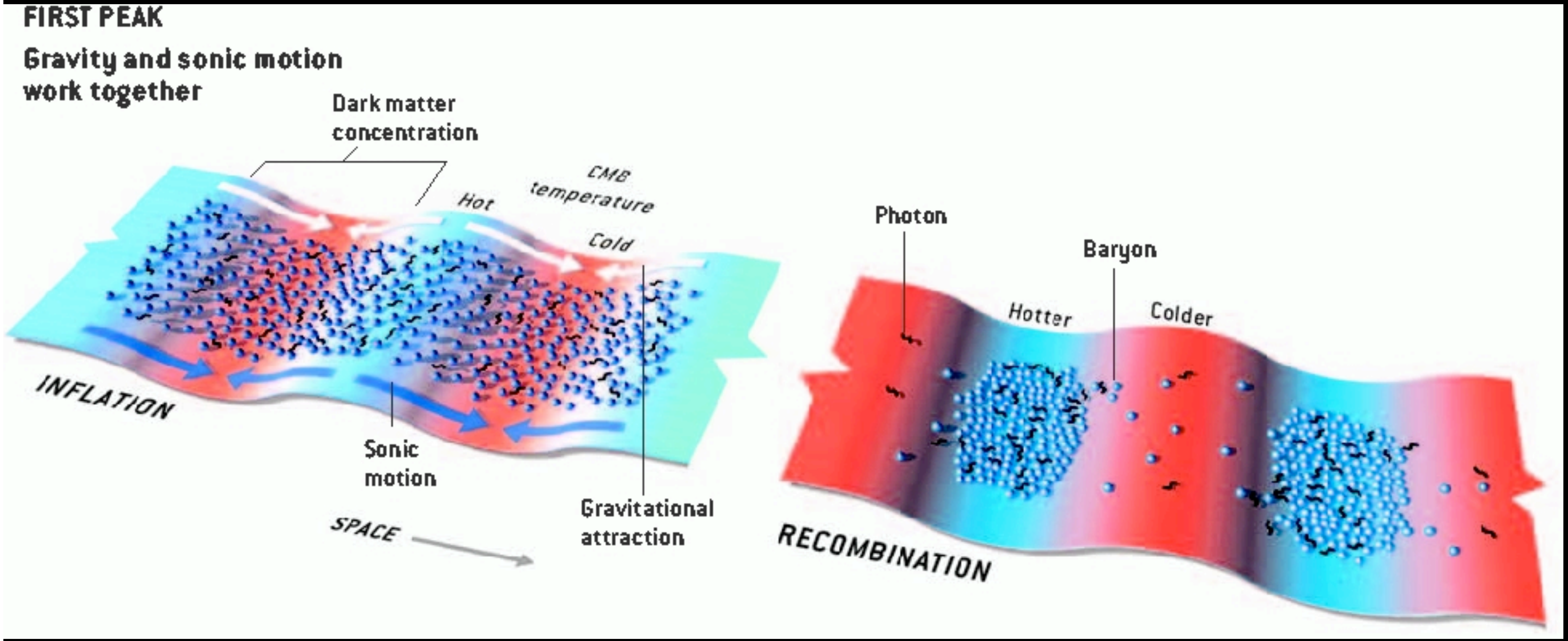
- Rotation will also be essential in future modeling of Pop III feedback on later star formation and galaxy assembly

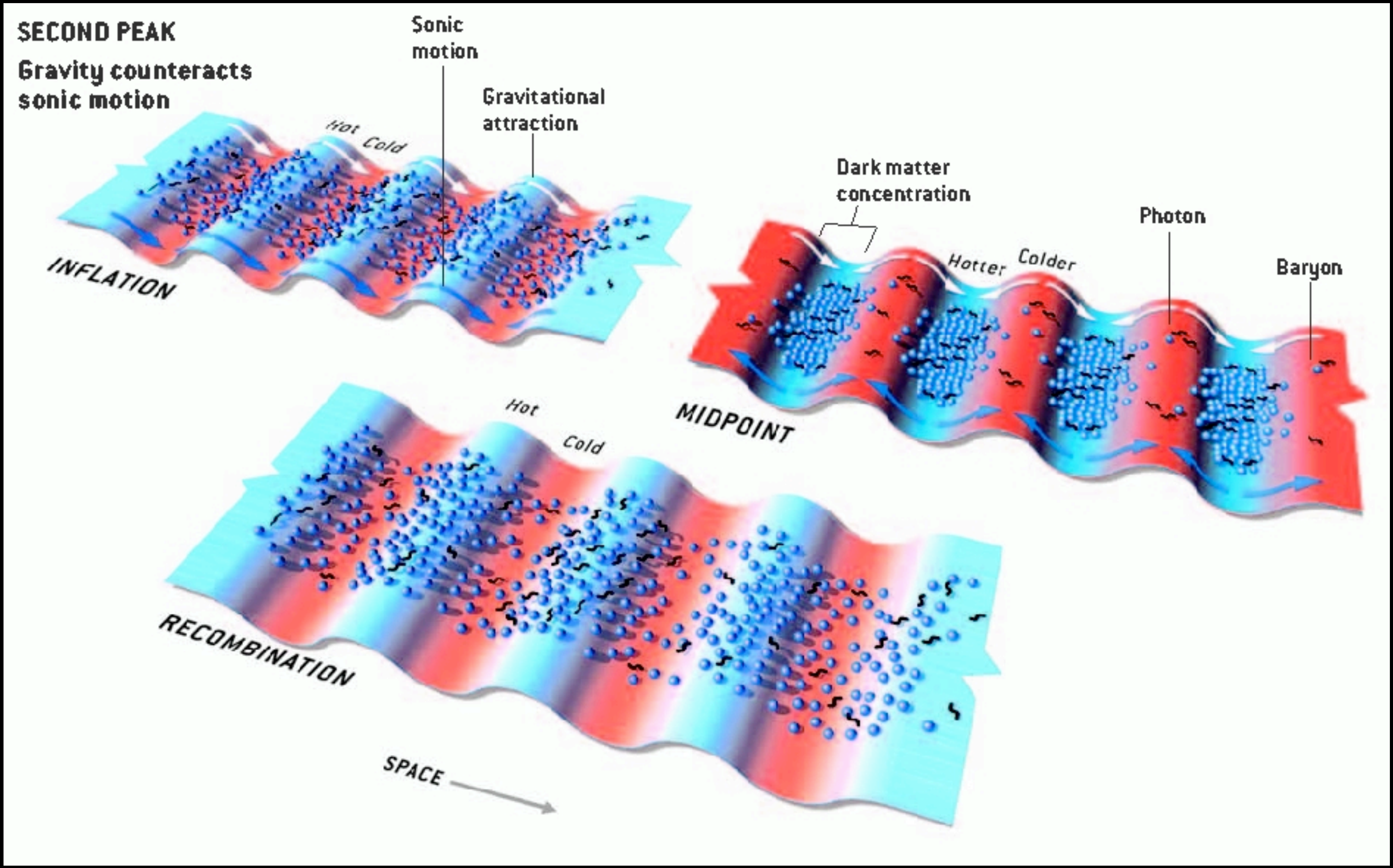
- What are typical rotation rates for Pop III stars?

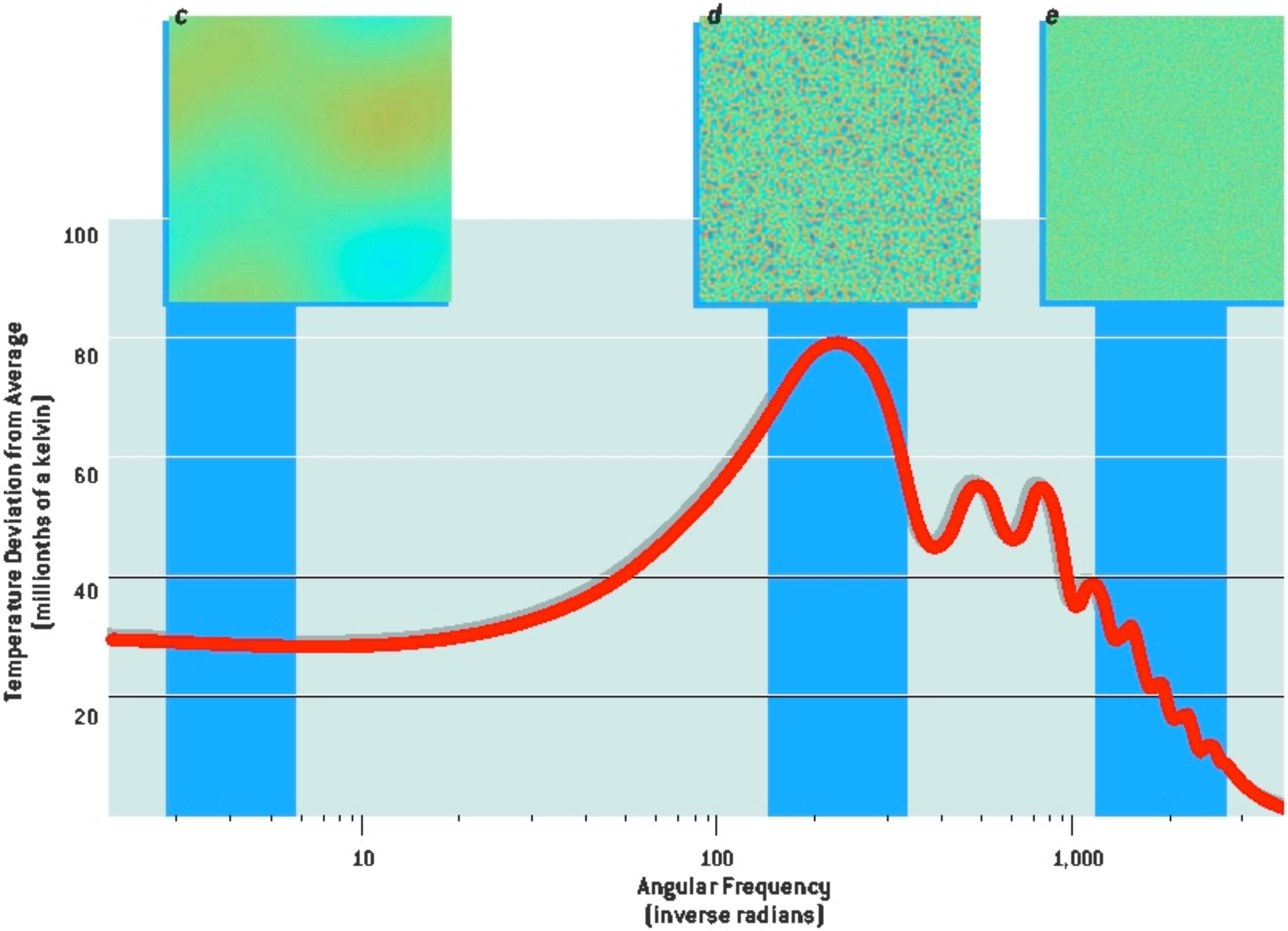
- What is the expected rate of collapsar GRBs?

IV. Pop III Star Formation Under Modified Cosmological Initial Conditions

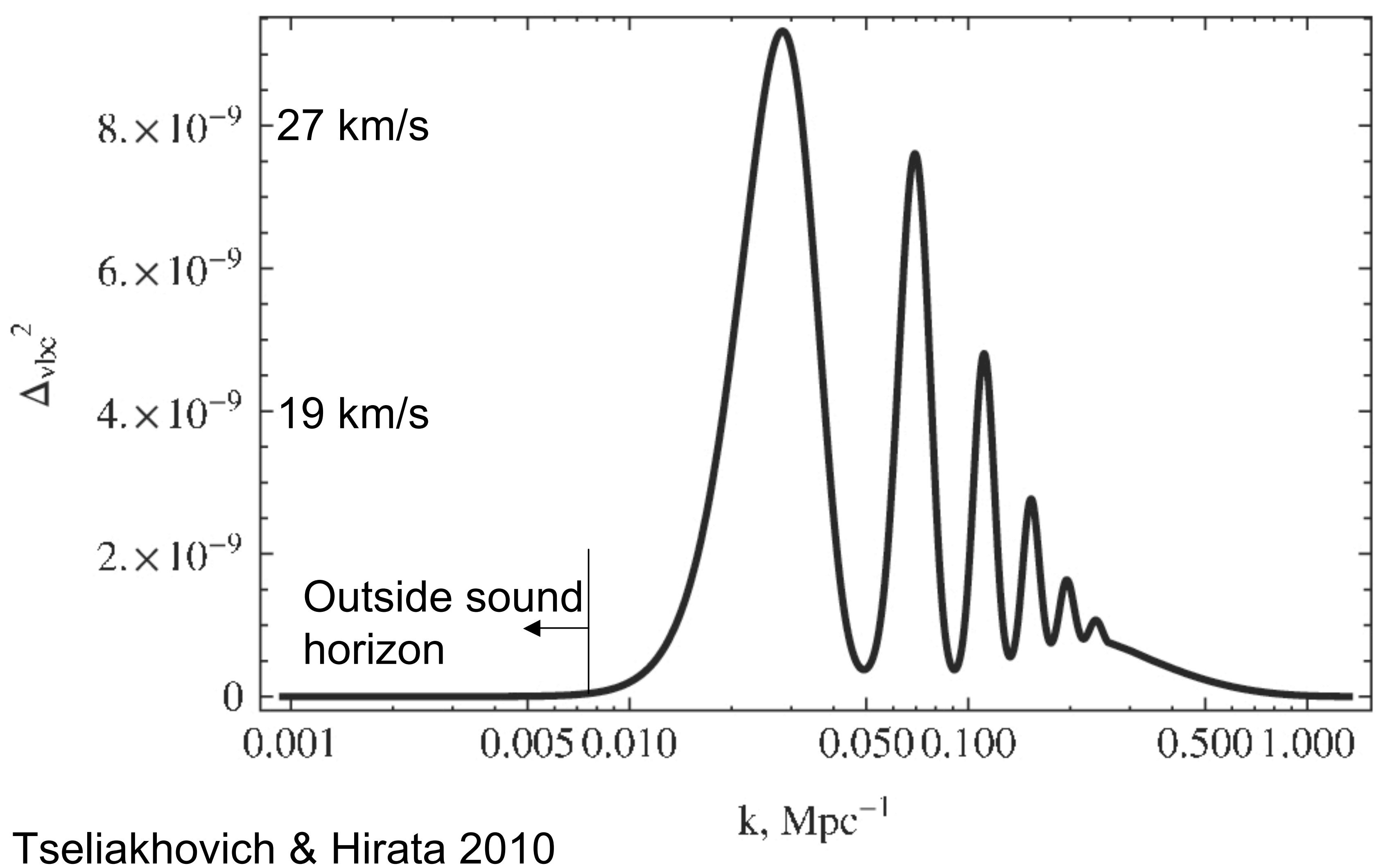
Sound waves before the CMB emission




SECOND PEAK
Gravity counteracts sonic motion
Sonic motion
Gravitational attraction
Hot
Cold
INFLATION
Dark matter concentration
Photon
Baryon
Hotter
Colder
MIDPOINT
Hot
Cold
RECOMBINATION
SPACE


c
d
e
Temperature Deviation from Average
(millionths of a kelvin)
100
80
60
40
20
10
100
1,000
Angular Frequency
(inverse radians)

Power Spectrum of Relative Velocity Fluctuations

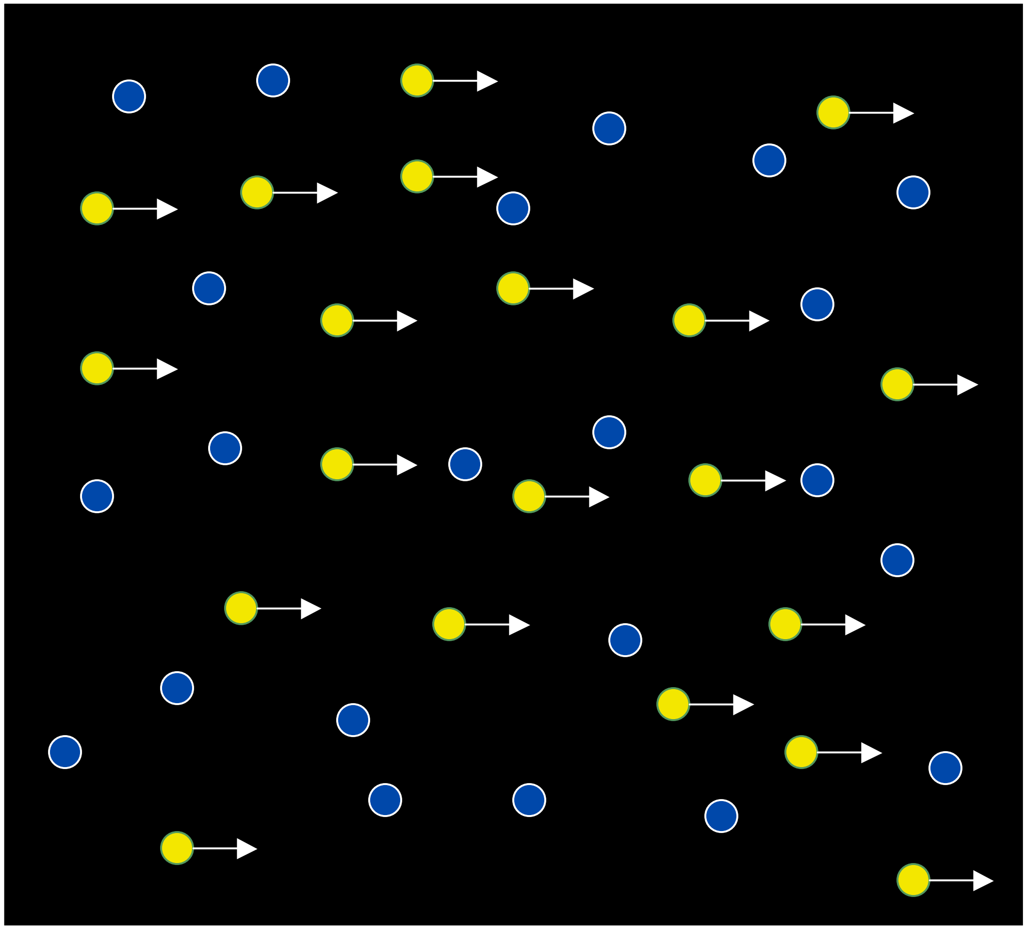


Tseliakhovich & Hirata 2010

Supersonic Relative Streaming

- RMS v_{stream} = 30 km/s at recombination
- c_s = 6 km/s
- ➔ Baryons stream at supersonic velocities relative to DM!
- Velocities are coherent on BAO scale (150 Mpc comoving)

Numerical Test of Gas Evolution to High Densities



● = Gas

● = DM

L_{box} = 140 kpc (comoving.)

$n_{res} = 10^4$ cm^{-3}

$z_{init} = 100$

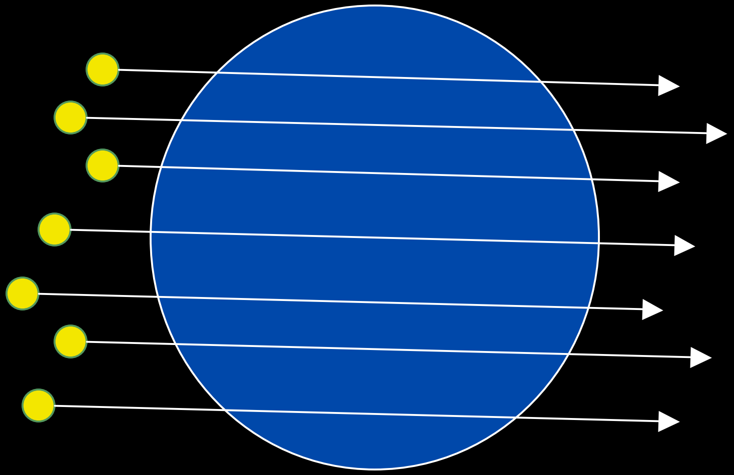
v_{stream} = 0, 3, 10 km/s

Increase of Jeans Mass

$$M_{\mathrm{J}} = \left(\frac{\pi}{6}\right) \frac{c_{\mathrm{s}}^3}{G^{3/2} \rho^{1/2}} ,$$

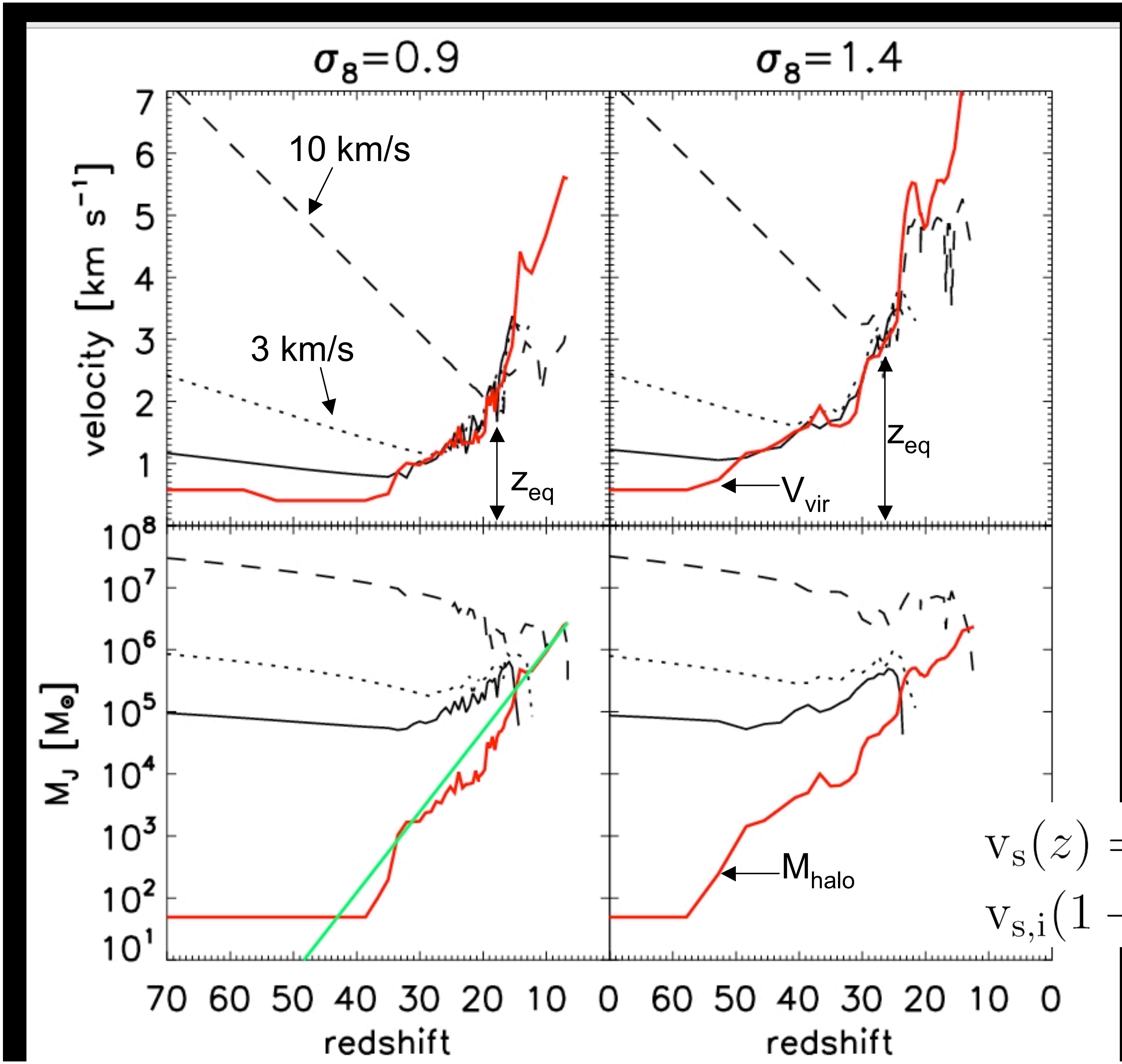
$$\mathrm{v}_{\mathrm{eff}} = \sqrt{c_{\mathrm{s}}^2 + \mathrm{v}_{\mathrm{s}}^2} ,$$

$$M_{\mathrm{vir}}(z) = M_0 e^{\alpha z}$$



DM halo cannot capture streaming gas particles

(until halo mass grows and v_s decreases - Requires $M_{vir} > M_J$)

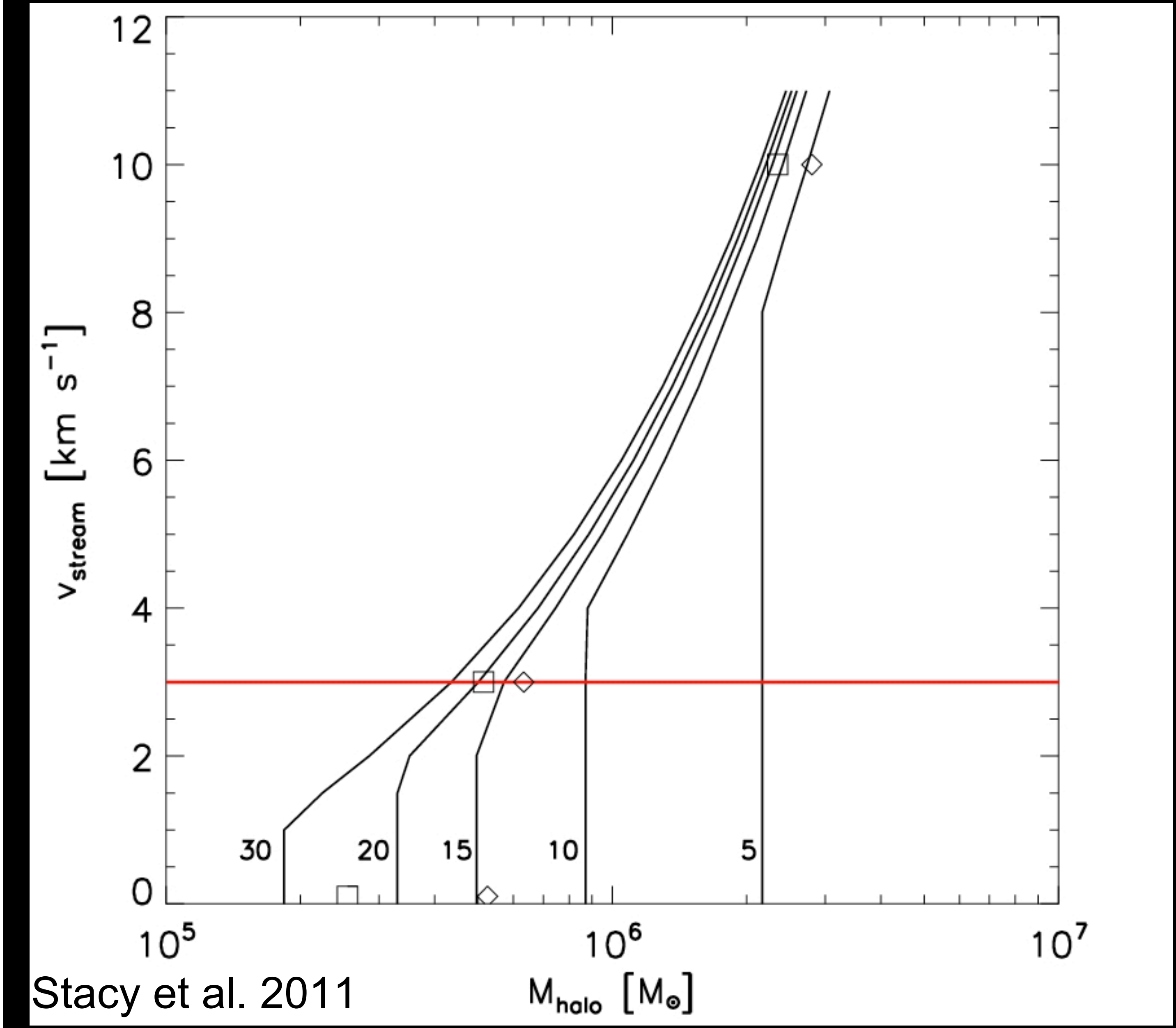


$$\mathrm{v_S}(z) = \mathrm{v_{S,i}}(1+z)/(1+z_\mathrm{i})$$

Delay of Gas Collapse Redshift

	$\sigma_8 = 0.9$	$\sigma_8 = 1.4$
0 km/s	14.4	23.6
3 km/s	12.2	21.3
10 km /s	6.6	12.4

Minimum M_{halo} required for gas collapse at a given redshift



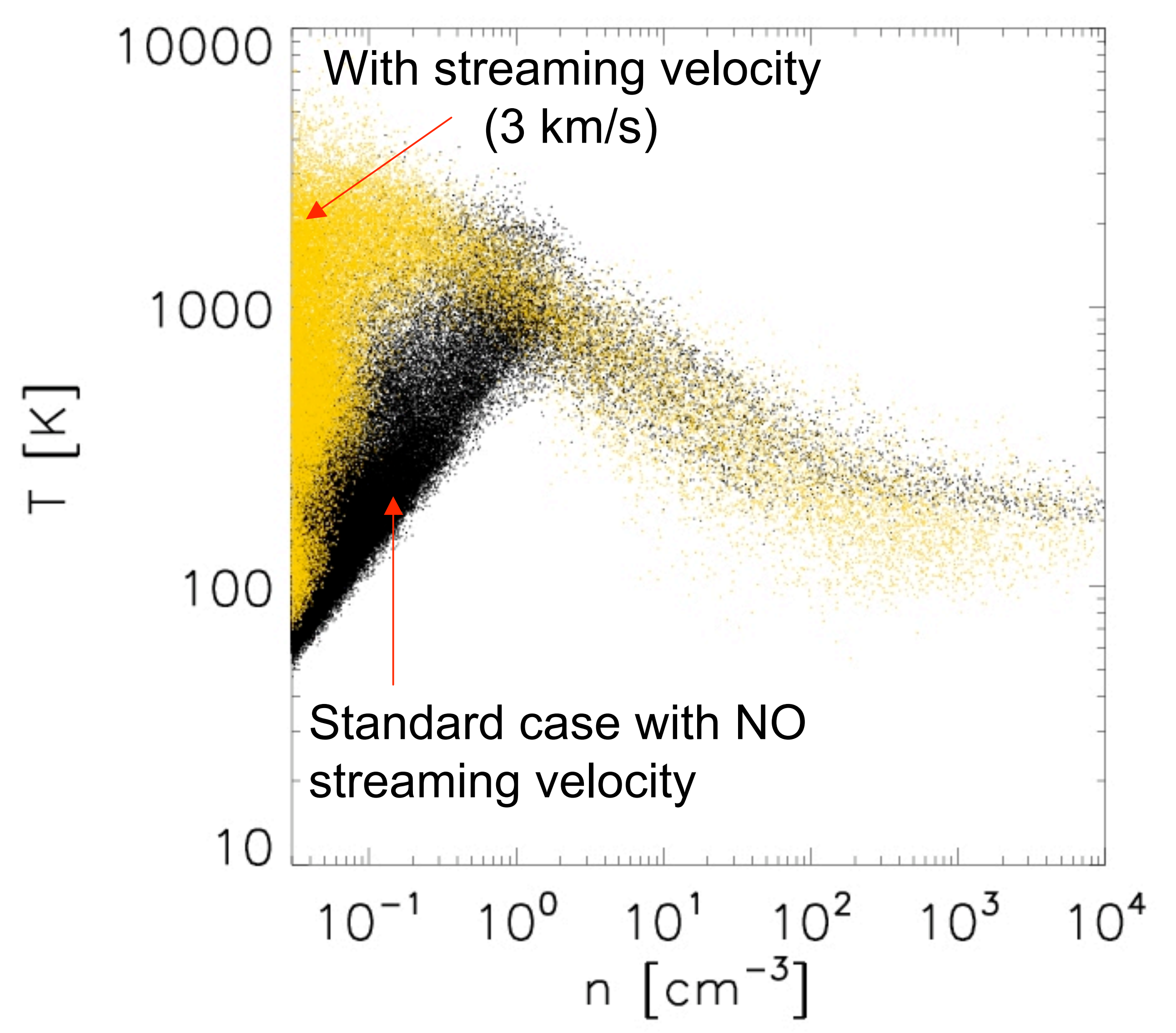
Stacy et al. 2011

M_{halo} increases with v_{stream}

Later collapse redshifts less affected

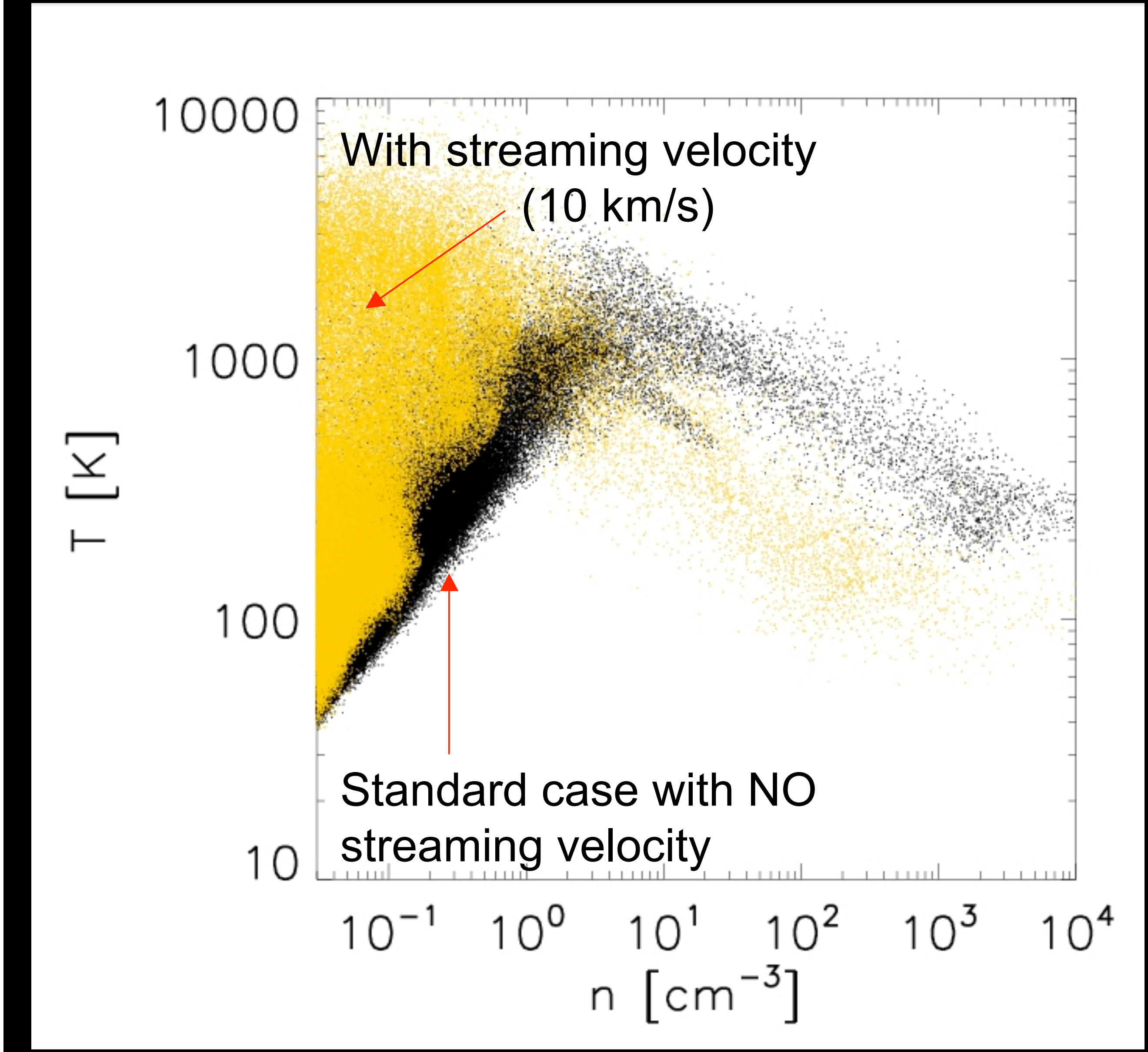
v_s < 3 km/s less affected

Robustness of Thermal Evolution



With streaming velocity (3 km/s)

Standard case with NO streaming velocity



➔Evolution at high densities still unchanged!

Stacy et al. 2011

V. Pop III Star Formation Under a Cosmic Ray Background

Background

- Model effects of SN-generated CRs in early (z=10-20) star-forming regions

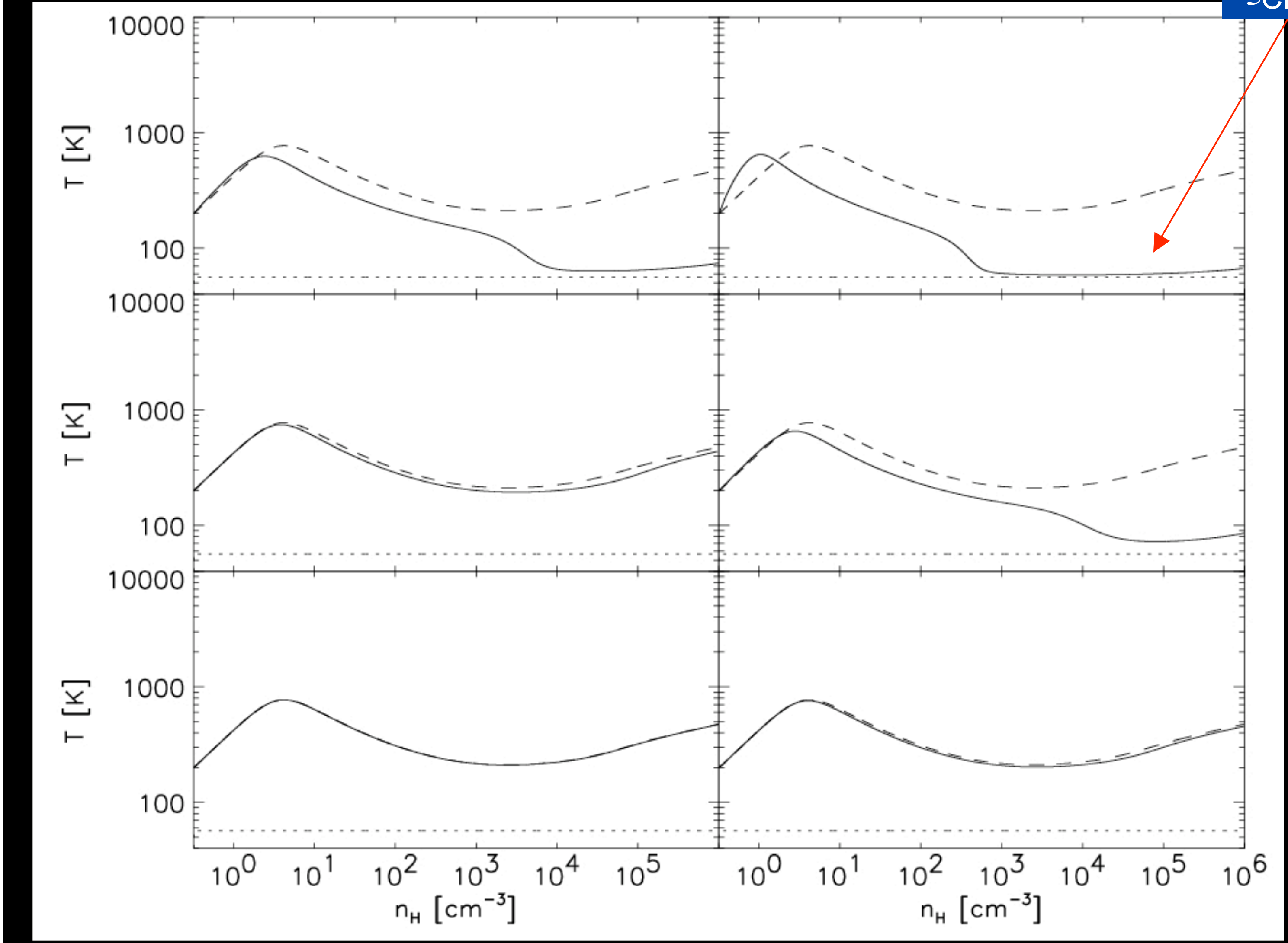
- Focus on CR ionization in these regions, which leads to
  - direct ionization heating
  - increased e^- fraction
    - → increased H_2 and HD abundance
    - → increased molecular cooling

- **Did CRs influence the mass of Pop III stars?**
- **How did CRs change early SFR and IMF?**

Minihalo evolution

Possible cooling to near CMB floor for $\zeta_{CR} > 10^{-19}\,\mathrm{s}^{-1}$

$\Psi_* = 2\times10^{-3}\,M_\odot\,\mathrm{yr}^{-1}\mathrm{Mpc}^{-3}$ $\Psi_* = 2\times10^{-2}\,M_\odot\,\mathrm{yr}^{-1}\mathrm{Mpc}^{-3}$



$\varepsilon_{min} = 10^6\,\mathrm{eV}$

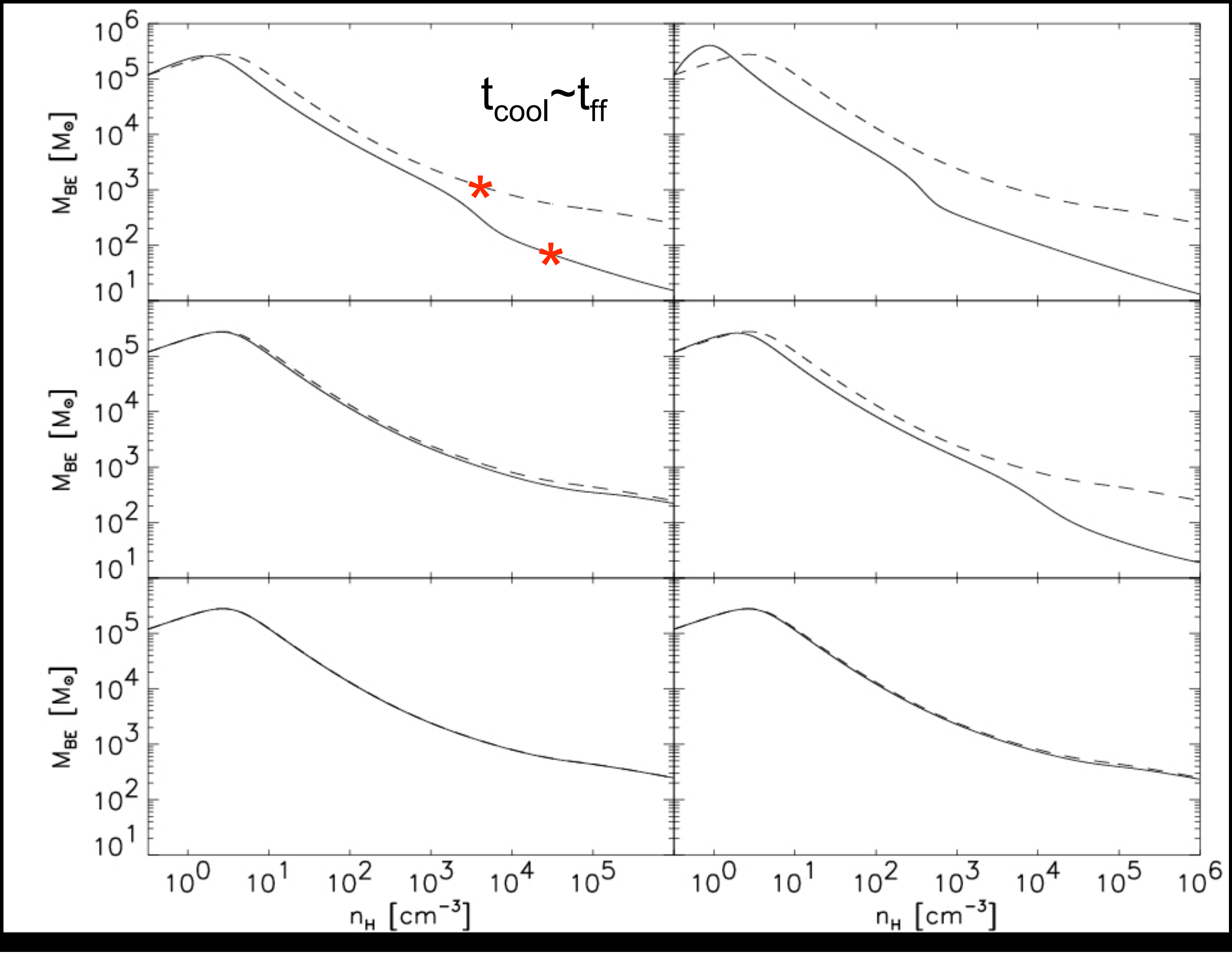
$\varepsilon_{min} = 10^7\,\mathrm{eV}$

$\varepsilon_{min} = 10^8\,\mathrm{eV}$

Fragmentation Scale

$(M_{BE} \propto n^{-1/2}T^{3/2})$

$\Psi_{*}=2\times10^{-3}\ M_{\odot}\,yr^{-1}\,Mpc^{-3}$ $\Psi_{*}=2\times10^{-2}\ M_{\odot}\,yr^{-1}\,Mpc^{-3}$



$\varepsilon_{min}=10^6$eV

$\varepsilon_{min}=10^7$eV

$\varepsilon_{min}=10^8$eV

Conclusions

- Range of Pop III masses is likely very broad.
- Multiple mechanisms, particularly disk fragmentation, will contribute to formation of low mass stars.
- Fragmentation and broad mass range likely to describe Pop III stars even under radiative feedback!
- Rotation will also be key in understanding evolution and death of Pop III stars. GRBs and hypernovae possibly common in early universe.
- Pop III characteristics robust to variation in cosmological ICs.
- Growing understanding of Pop III stars will ultimately increase physical realism of models of later star and galaxy formation.
- Many future observations (e.g. JWST, EXIST…) will need interpretation through continued numerical modeling.

Questions?

THE END

Thank you!