Francesco’s Legacy
Star Formation in Space and Time

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Understanding Primordial Star Formation: Francesco’s Contribution

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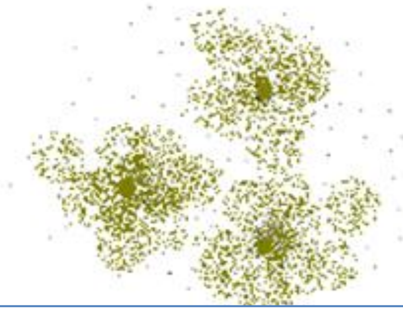
steps toward star formation

PSS/SPS papers (1983-86)

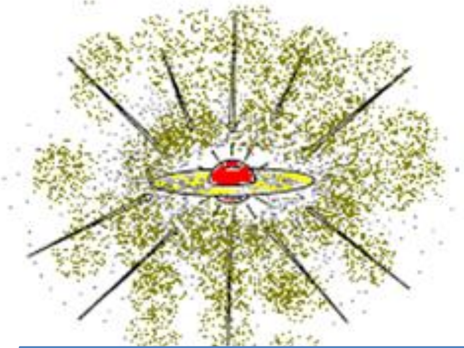
established in '80s

also valid for first star formation

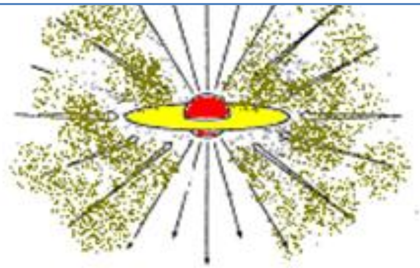
Shu, Adams & Lizano (1987)



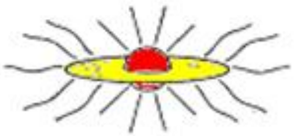
1) "Primordial star formation: the role of molecular hydrogen"
Palla, Salpeter & Stahler (1983)



2) "Primordial stellar evolution: the protostar phase"
Stahler, Palla & Salpeter (1986)



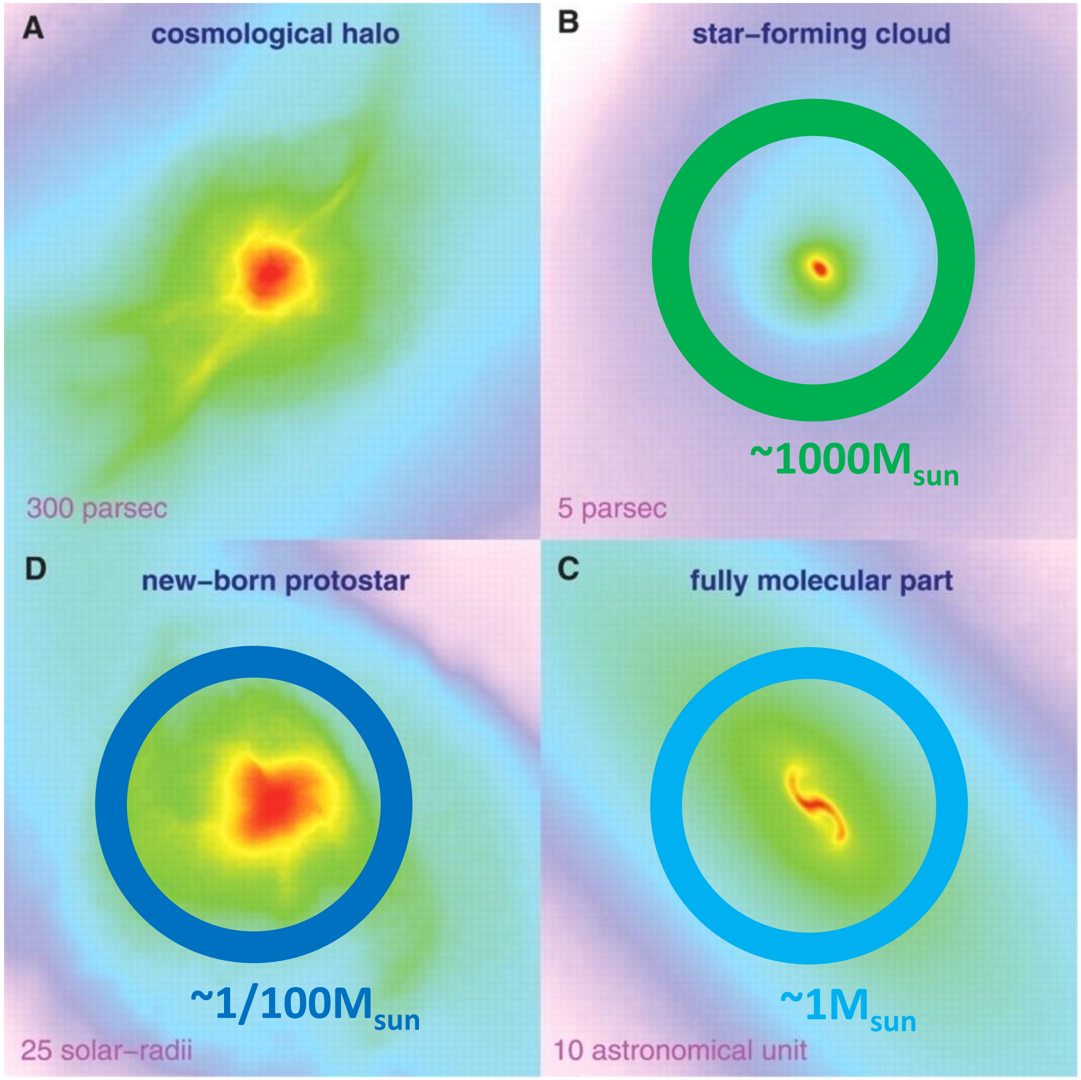
C) accretion stops by some mechanism, e.g., by stellar feedback

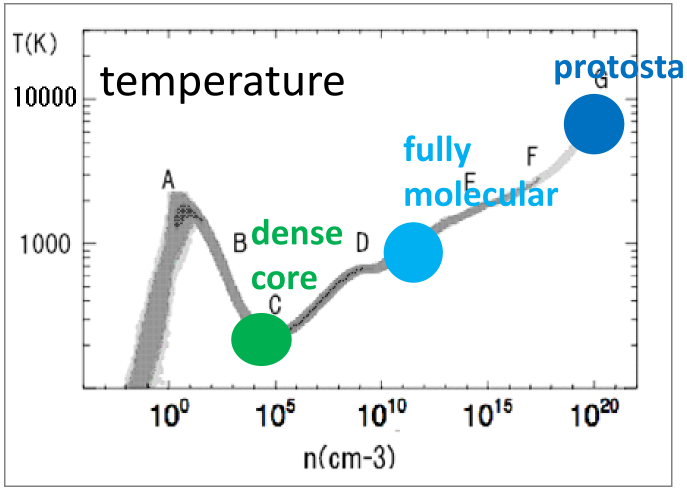


3) "Primordial stellar evolution: the pre-main-sequence phase"
Stahler, Palla & Salpeter (1986)

Prestellar collapse of the first stars: current picture

Yoshida, KO, Hernquist 2008





Important physical scales:

- dense core (~1000M_{sun}) forms at ~10^4cm^{-3}
- central ~1M_{sun} becomes fully H_2 at 10^{11}cm^{-3}
- small ~$10^{-2}M_{sun}$ hydrostatic protostar forms at ~10^{21}cm^{-3}

Prestellar collapse is controlled by H_2 cooling

H_2 formation in primordial gas

At low densities ($<10^8 \mathrm{cm}^{-3}$)

H^- channel : e catalyzed (Peebles & Dicke 1968; Hirasawa+1969)

$H + e \rightarrow H^- + \gamma$

$H^- + H \rightarrow H_2 + e$

dominant in low densities

H_2^+ channel : H^+ catalyzed (Saslaw & Zipoy 1967)

$H + H^+ \rightarrow H_2^+ + \gamma$

$H_2^+ + H \rightarrow H_2 + H^+$

subdominant

(can be important in strong radiation fields)

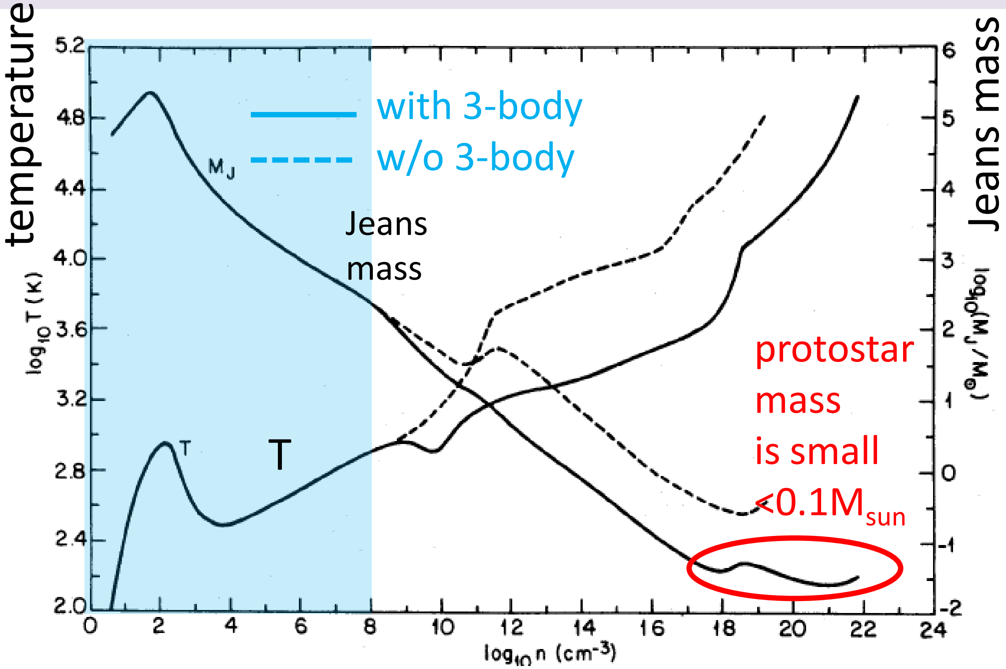
At higher densities ($>10^8 \mathrm{cm}^{-3}$)

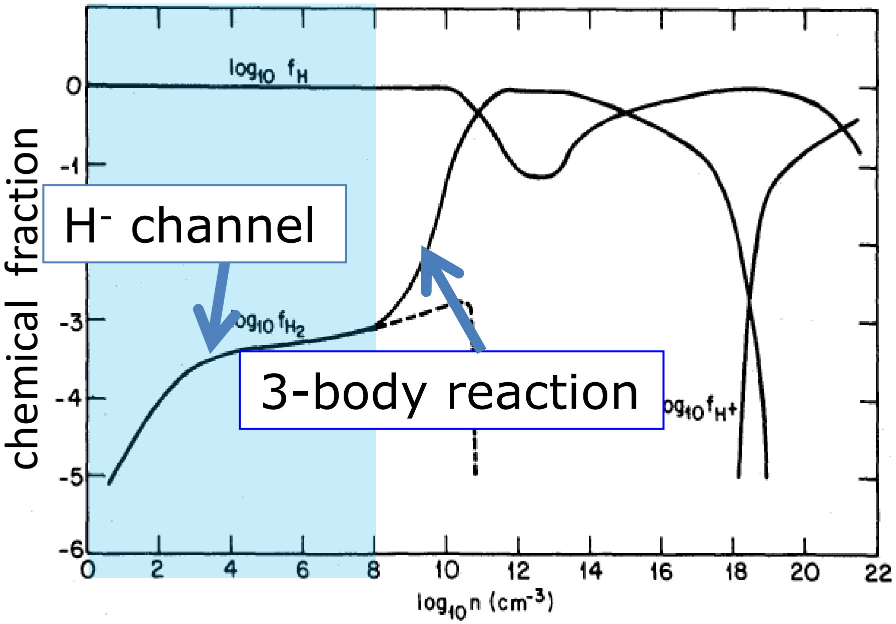
3-body reactions (← Palla, Salpeter & Stahler 1983)

$H + H + H \rightarrow H_2 + H$

$H + H + H_2 \rightarrow H_2 + H_2$.

Effect of 3-body reaction





Palla, Salpeter & Stahlear (1983)

In low densities,
H_2 fraction reaches at most 10^{-3}
by H^{--} channel.

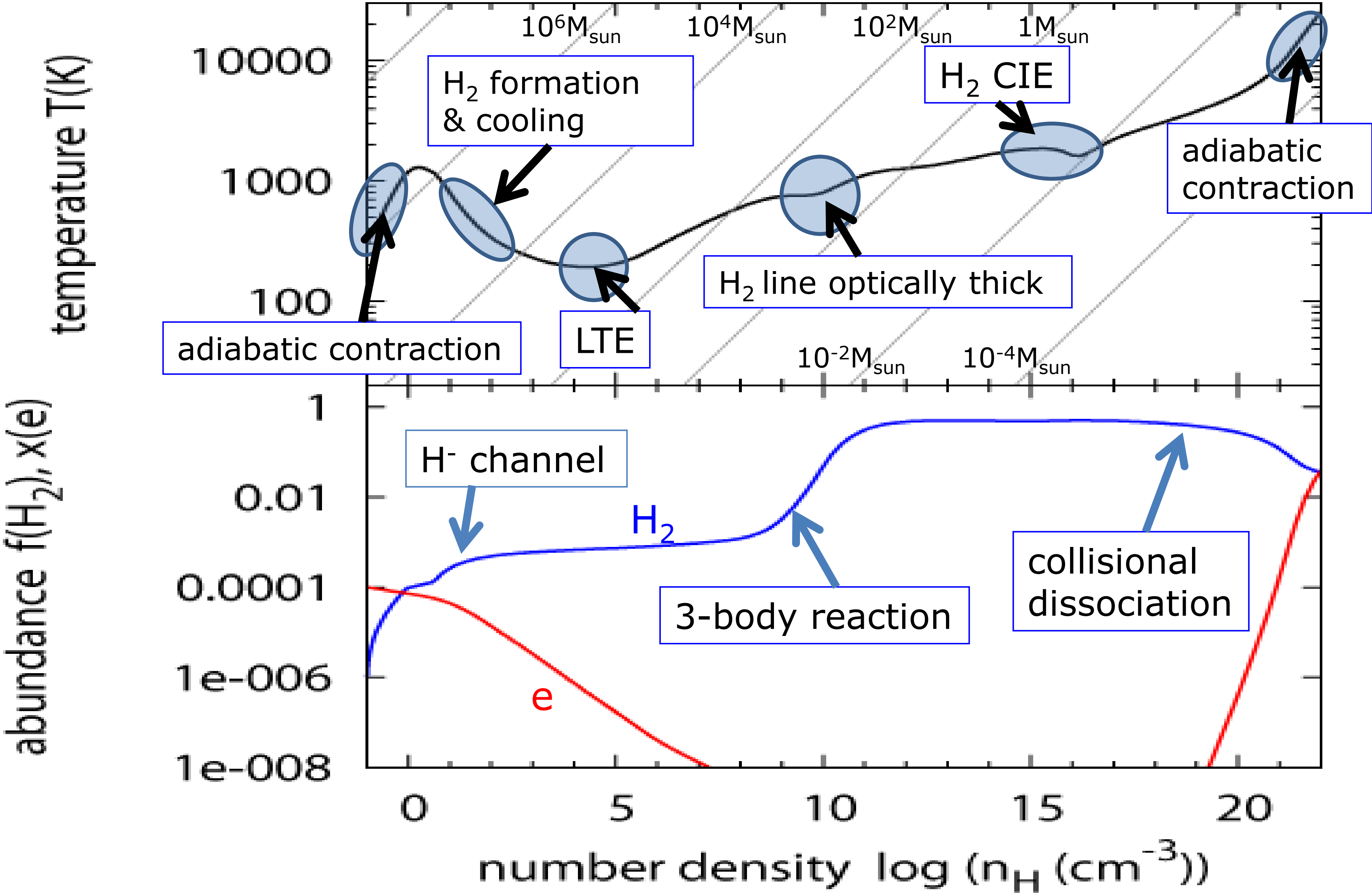
Effect of 3-body reaction is dramatic at >~10^8cm^{-3}

✓all the hydrogen is converted to the molecular form.

✓subsequent temperature evolution is largely altered.

✓Jeans mass falls below 0.1 M$_{sun}$. As a result, a small protostar will be formed.

Thermal evolution of primordial gas: current picture



H_2 formation & cooling

H_2 CIE

adiabatic contraction

H_2 line optically thick

LTE

adiabatic contraction

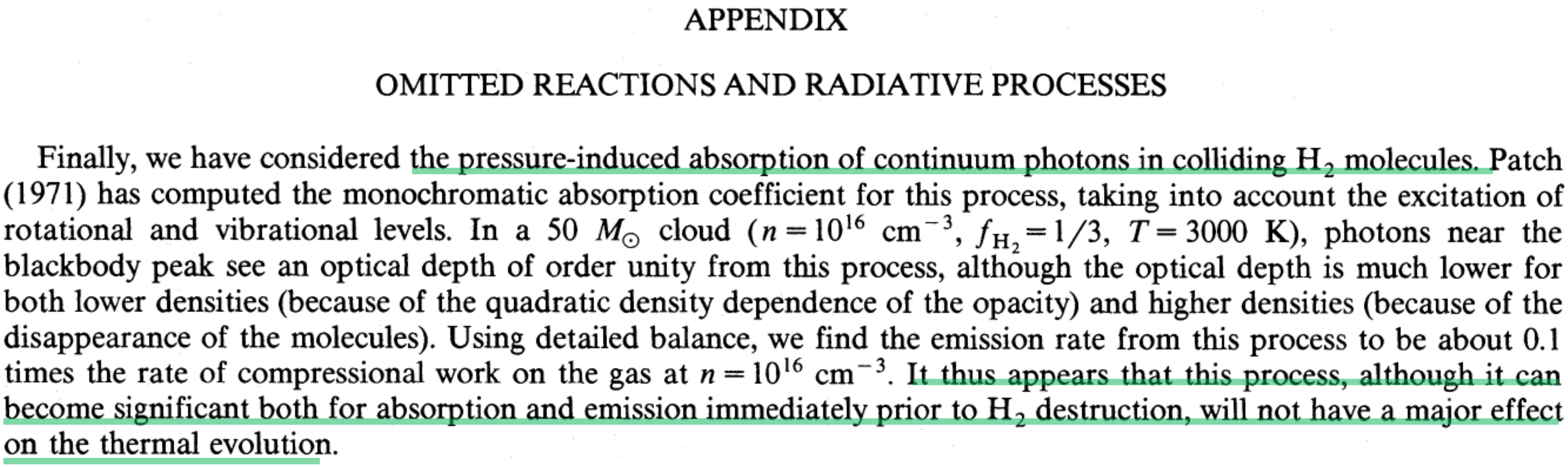
H^- channel

3-body reaction

collisional dissociation

H_2 CIE was already discussed

Palla, Salpeter & Stahler (1983)



APPENDIX

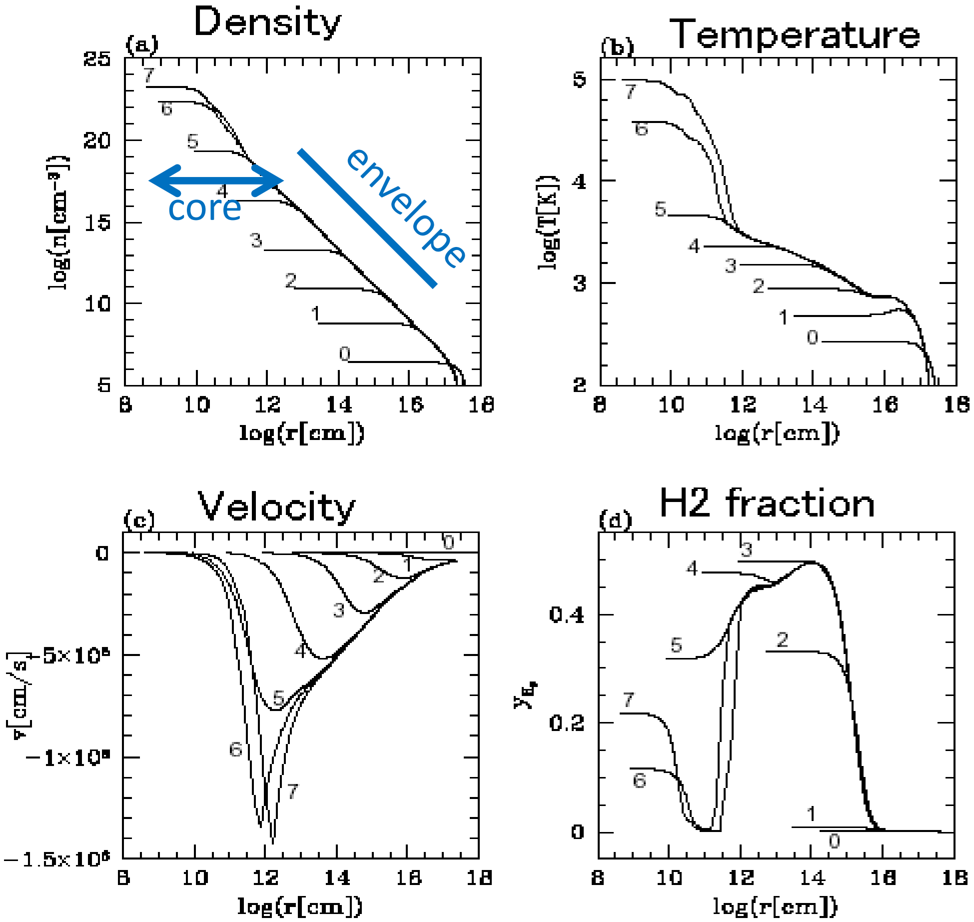
OMITTED REACTIONS AND RADIATIVE PROCESSES

Finally, we have considered the pressure-induced absorption of continuum photons in colliding H_2 molecules. Patch (1971) has computed the monochromatic absorption coefficient for this process, taking into account the excitation of rotational and vibrational levels. In a 50 $M_\odot$ cloud ($n = 10^{16}$ cm^{-3}, $f_{H_2} = 1/3$, $T = 3000$ K), photons near the blackbody peak see an optical depth of order unity from this process, although the optical depth is much lower for both lower densities (because of the quadratic density dependence of the opacity) and higher densities (because of the disappearance of the molecules). Using detailed balance, we find the emission rate from this process to be about 0.1 times the rate of compressional work on the gas at $n = 10^{16}$ cm^{-3}. It thus appears that this process, although it can become significant both for absorption and emission immediately prior to H_2 destruction, will not have a major effect on the thermal evolution.

In reality,
once H_2 CIE cooling becomes important,
H_2 dissociation is delayed for other 2-3 orders of magnitude in density,
which results in further 1-2 orders of magnitude
reduction in formed protostellar mass.

Hydrodynamical evolution

1D radiation hydro calculation
KO & Nishi (1998)



core-envelope structure develops

- envelope contains large mass but does not contribute so much to the optical depth
- effective mass of the cloud decreases during the collapse

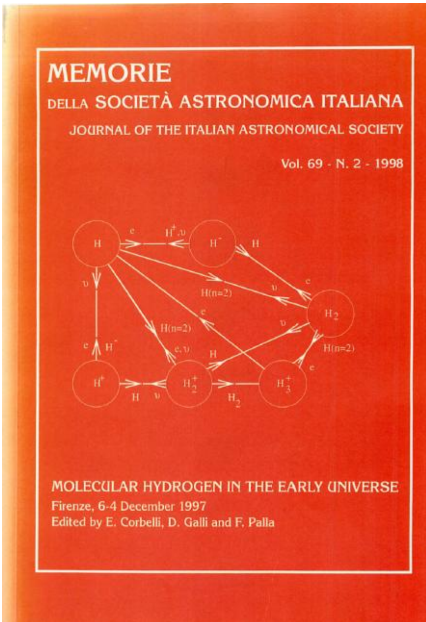
It makes the cloud to cool more efficiently than the homogeneous contraction.

MOLECULAR HYDROGEN IN THE EARLY UNIVERSE
Firenze, 6-4 December 1997
Edited by E. Corbelli, D. Galli and F. Palla

Villa Agape

Francesco: "When and where did the Dark Age end?"

"We know the answer.
Here in Florence in 14th century!"



MEMORIE
DELLA SOCIETÀ ASTRONOMICA ITALIANA
JOURNAL OF THE ITALIAN ASTRONOMICAL SOCIETY
Vol. 69 - N. 2 - 1998

MOLECULAR HYDROGEN IN THE EARLY UNIVERSE
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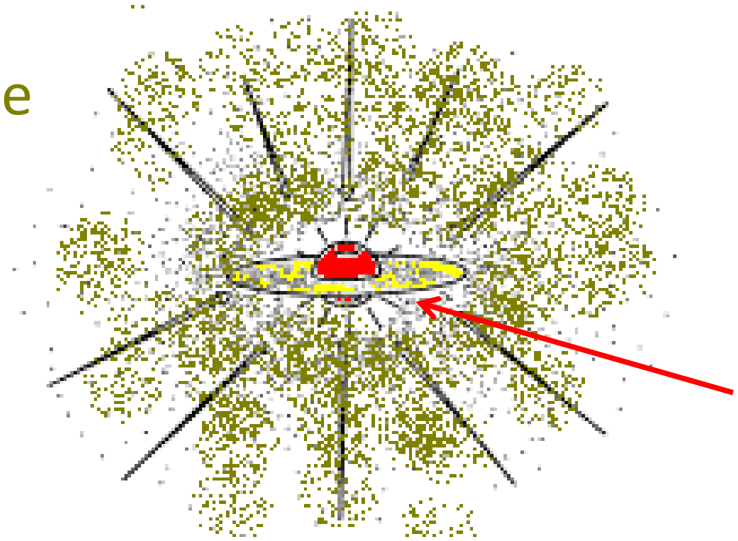
Protostellar evolution

SSP ('86)



accreting envelope
~$1000M_{sun}$

protostar
~$0.01M_{sun}$

mass accertion rate

$$\dot{M} \cong M_J / t_{ff} \cong (c_s t_{ff})^3 \rho / t_{ff}$$

$$\cong c_s^3 / G \propto \mathrm{T}^{3/2}$$

Pop III (1000K) ~$10^{-3}M_{sun}$/yr
Pop I (10K) ~$10^{-6}M_{sun}$/yr,

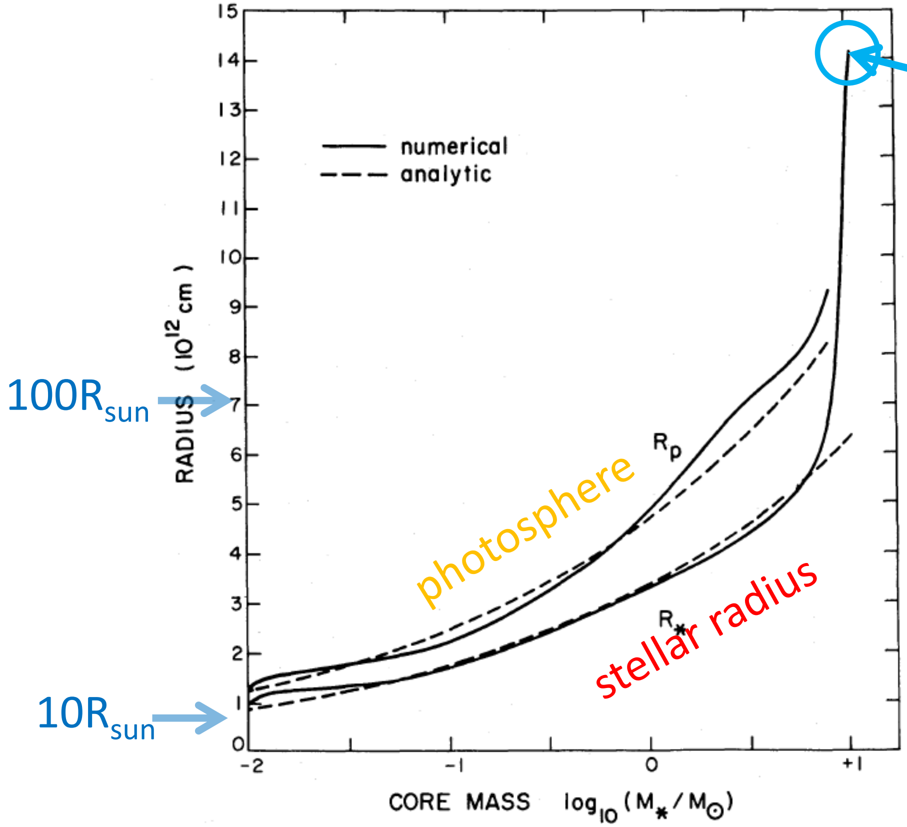
accretion rate much higher in Pop III case

Protostellar evolution by SPS('86)

accretion rate chosen: $dM_*/dt=4.4 \times 10^{-3} M_{sun}/yr$

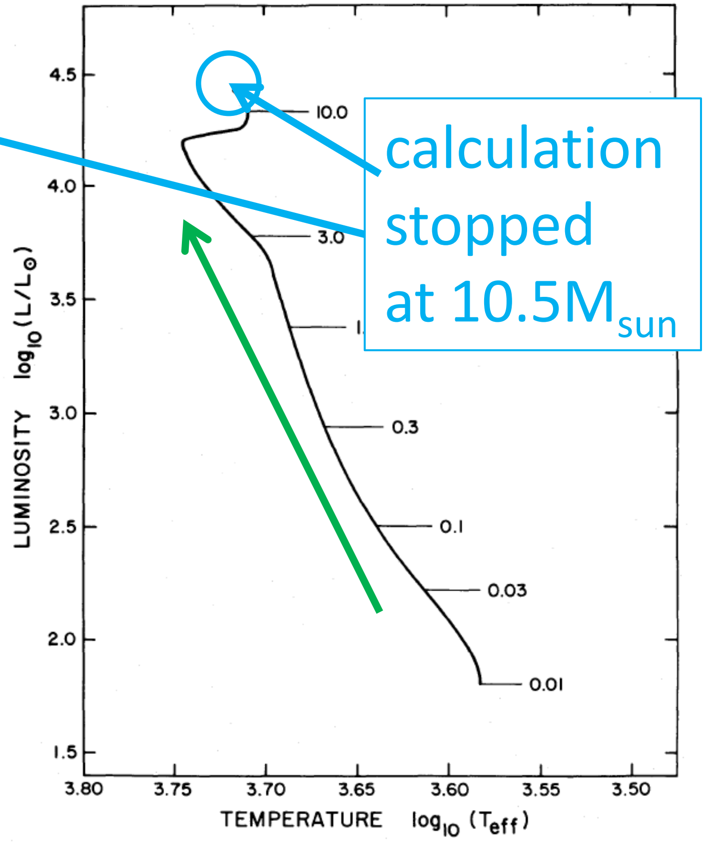
protostellar radius:

much larger (several 10 R_{sun}) than present-day counterpart.



HR diagram:

The protostar evolves almost vertically with T_{eff}~5000K

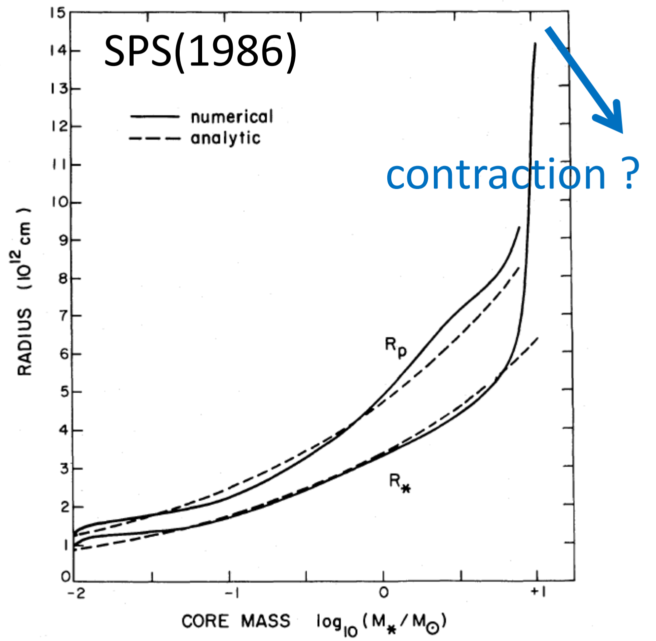


calculation stopped at $10.5M_{sun}$

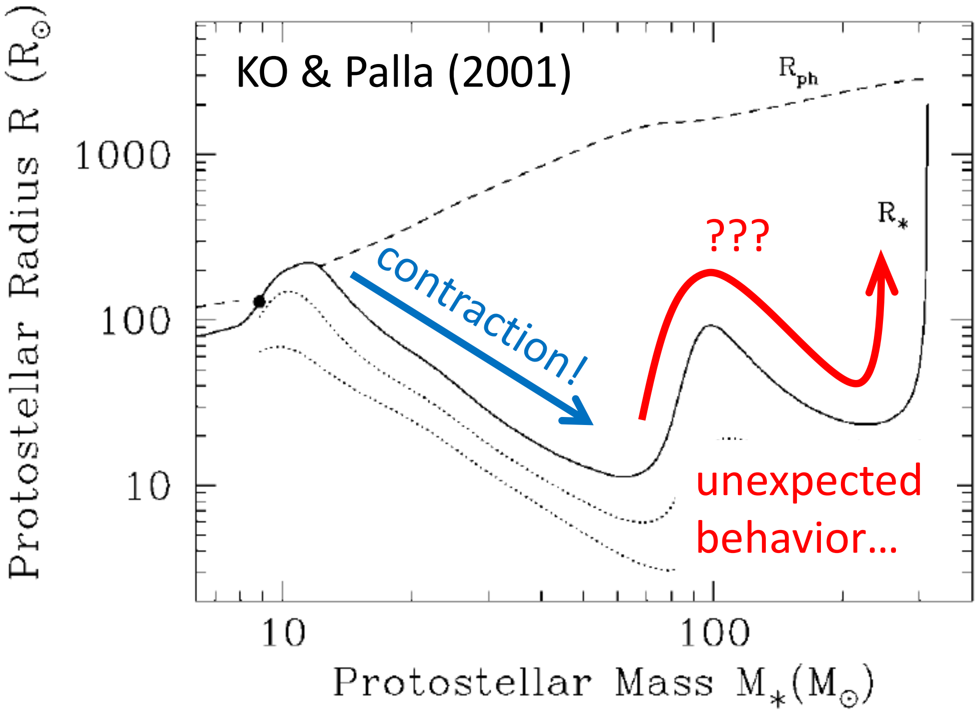
How is the evolution at >10.5M_{sun}?

Although we terminated the calculation at $M_* = 10.5\ M_\odot$, it is clear from the trend of increasing internal luminosity that a fourth phase of rapid core contraction must ensue for higher masses. During this phase, the entropy of the deep interior will drop substantially while the central temperature rises. Eventually, hydrogen will be ignited in the central region.

Yes, it was correct. But things were not so simple….


SPS(1986)

contraction ?


KO & Palla (2001)

contraction!

???

unexpected behavior…

Cases with different accretion rates

KO & Palla (2003)

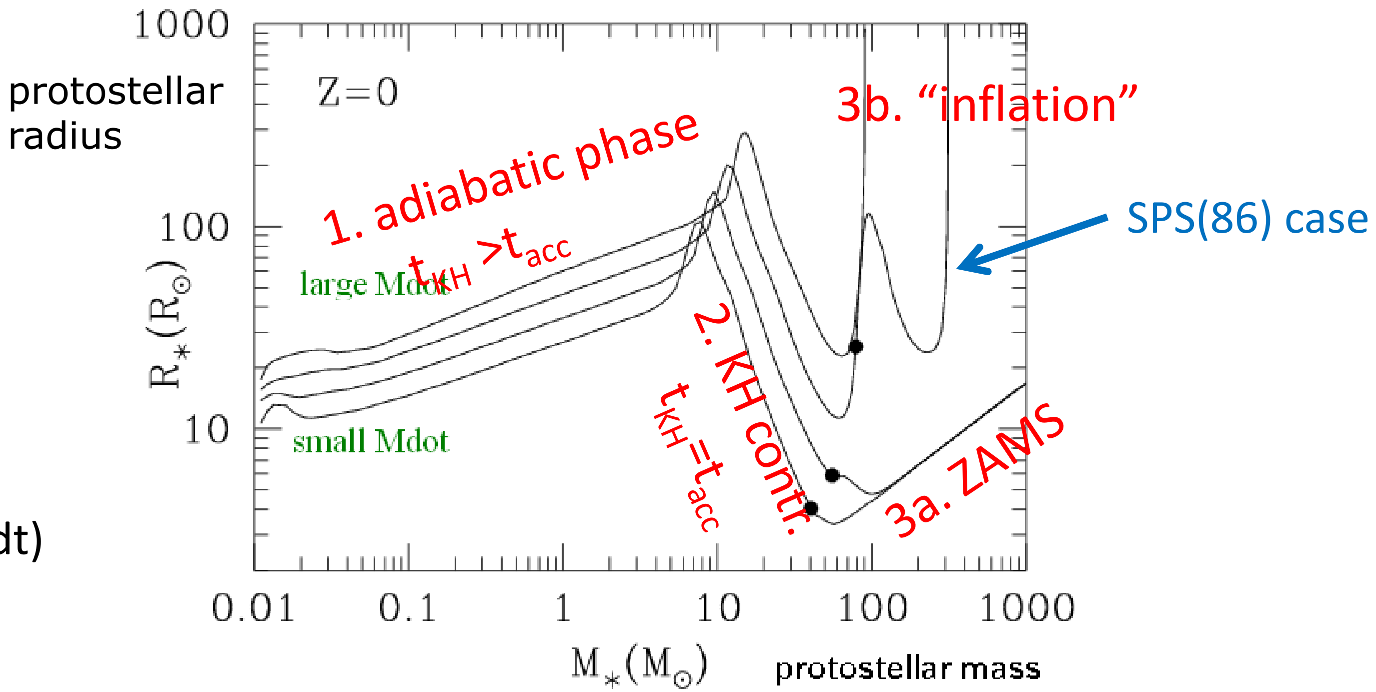
$dM_*/dt = 8.8,\ 4.4,\ 2.2,\ 1.1 \times 10^{-3}\ M_{sun}/yr$

KH time

$t_{KH} = GM_*^2/R_*L_*$

accretion time

$t_{acc} = M_*/(dM_*/dt)$



All protostars go through the adiabatic and the KH contraction phases.

Subsequent phase depends on the accr. rate.

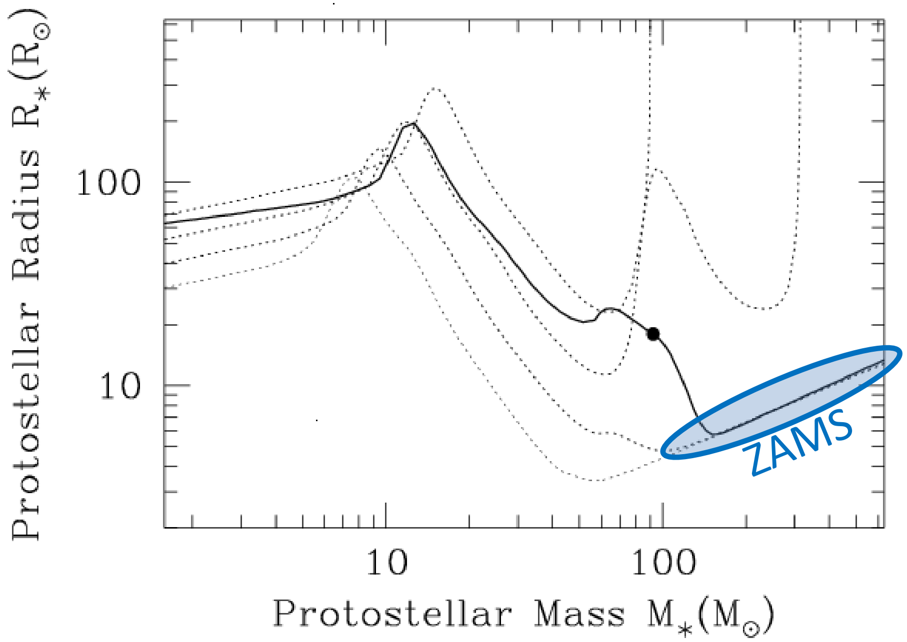
✓With low accretion rate ($<dM/dt_{crit} = 4\ 10^{-3} M_{sun}/yr$):
→the star reaches ZAMS and accretion continues

✓With higher accretion rate ($>dM/dt_{crit}$) :
→the star starts inflating when L ($=L_* + L_{acc}$) becomes close to L_{Edd}.
(the end of accretion?)

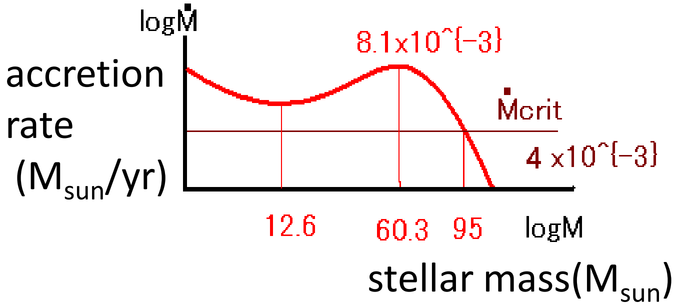
$L_{acc} \propto \dot{M}_*/R_*$

With a realistic accretion history

Abel+(2002) accretion rate



KO & Palla 2003

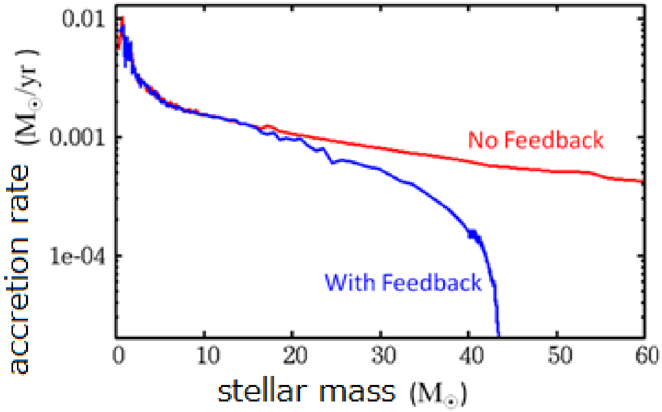


- The protostar reaches ZAMS at ~100Msun.
- Accretion continues w/o stellar inflation.
- Since (MS lifetime~2x10^{6}yr) > (core free-fall time~3x10^{5}yr), most of the core material can accrete within stellar lifetime.

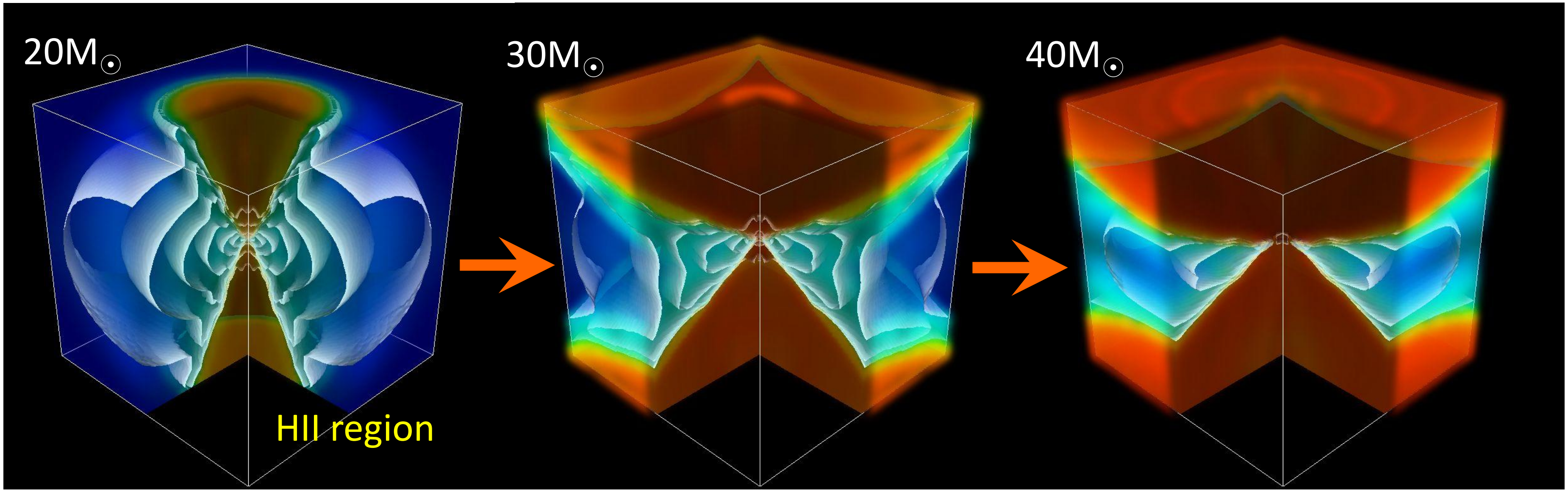
Very massive star (~ a few 100M_{sun}) is formed in spherical accretion case

Feedback-limited mass of first stars

In non-spherical accretion:
mass of first stars is set by
the UV feedback
photoevaporation of disk
(McKee & Tan 08, Hosokawa+11/12,
Stacy+12, Hirano +14, Susa + 2014)



Accretion stops at ~40Msun



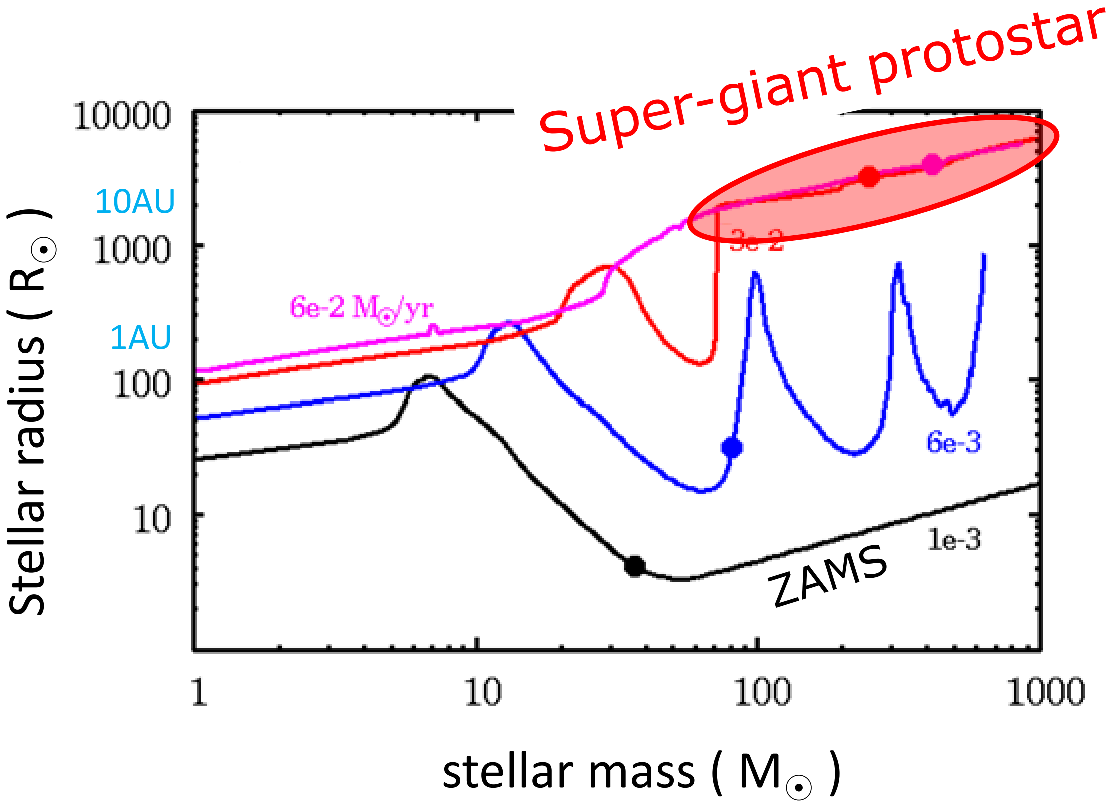
contour: density, color: temperature

Hosokawa, KO, Yoshida, Yorke 2011, 2012

See David Hollenbach and Takashi Hosokawa's talks

What if a very high accretion rate is maintained ?

What happens after protostar inflates?



Hosokawa, Yorke, KO (2012)

- protostar starts inflating when $L \sim L_{Edd}$ with high accr. rate (> 0.01 M_{sun}/yr).
- stellar inflation stops at ~10AU and star becomes super-giant without reaching main-sequence.

Supermassive star will be formed.
→ seed BHs for high-z SMBHs ?

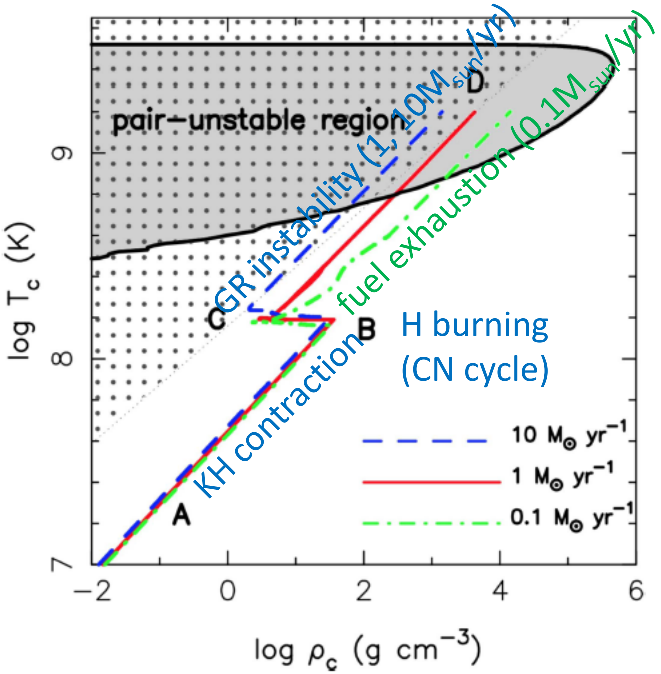
General relativistic collapse

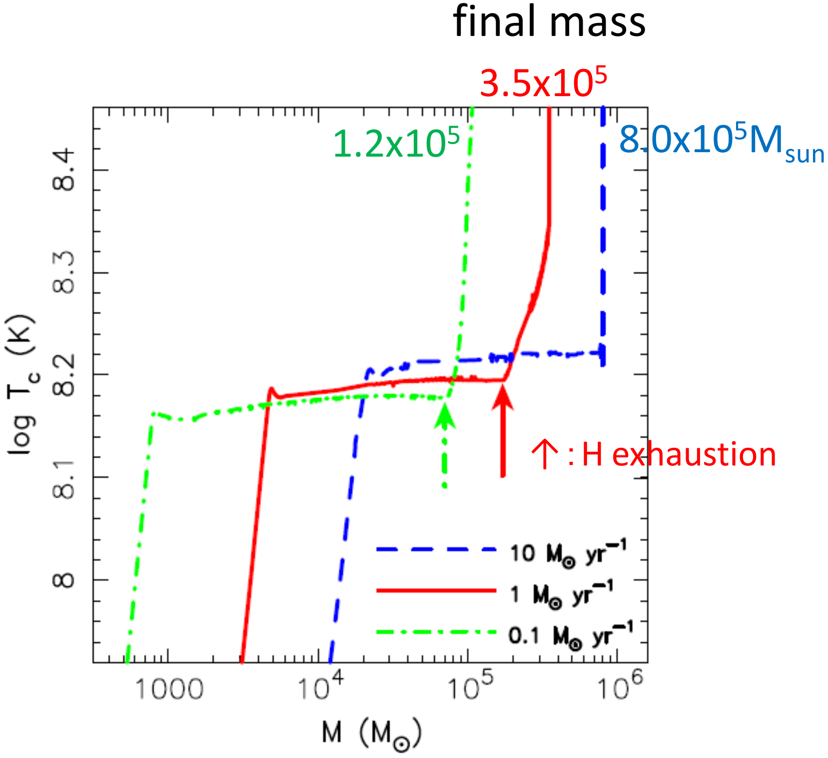
Accretion evolution with

Post Newtonian Gravity

$$G_{eff}=G(1 + P/\rho c^2 + 4\pi r^3P/Mc^2 + 2GM/rc^2)$$

Umeda, Hosokawa, KO & Yoshida 2016





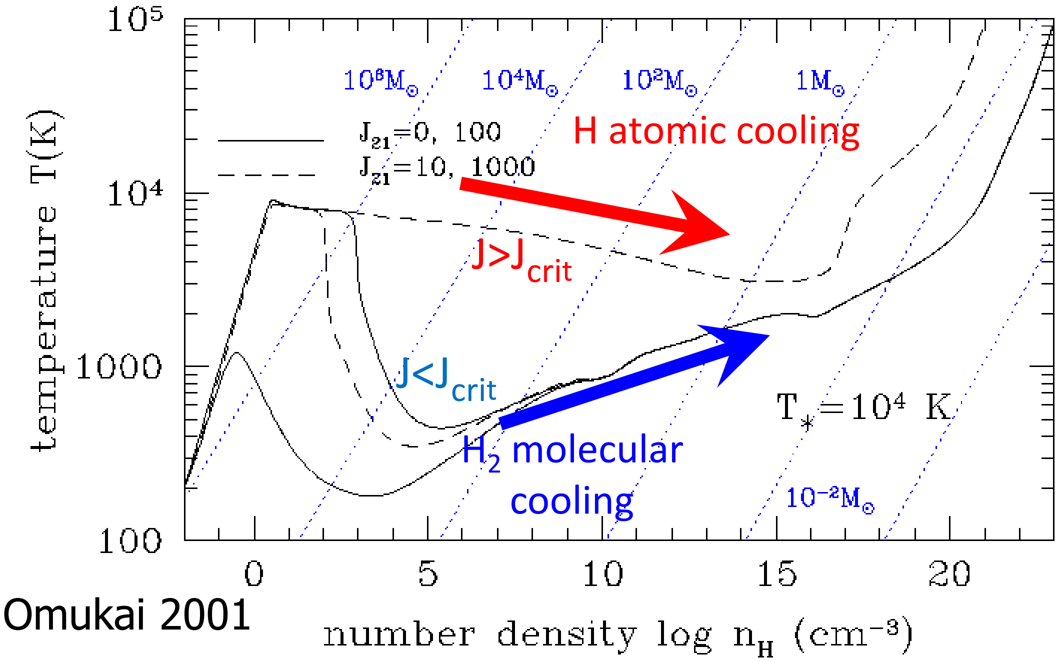
The star collapses at final mass of 10^5-10^6 M_{sun} depending on the mass accretion rate.

How such a high accretion rate is realized?

Possible pathway for super-massive stars:

Atomic-cooling collapse

Bromm & Loeb (2003)



Omukai 2001

If FUV radiation is more intense than the critical value J_{crit}, the cloud cools solely by atomic cooling.

- high temperature (at ~8000K) during the collapse
  → high accretion rate in protostellar phase
  $dM_*/dt \sim 0.06 M_{sun}/yr \, (T/10^4 K)^{3/2}$

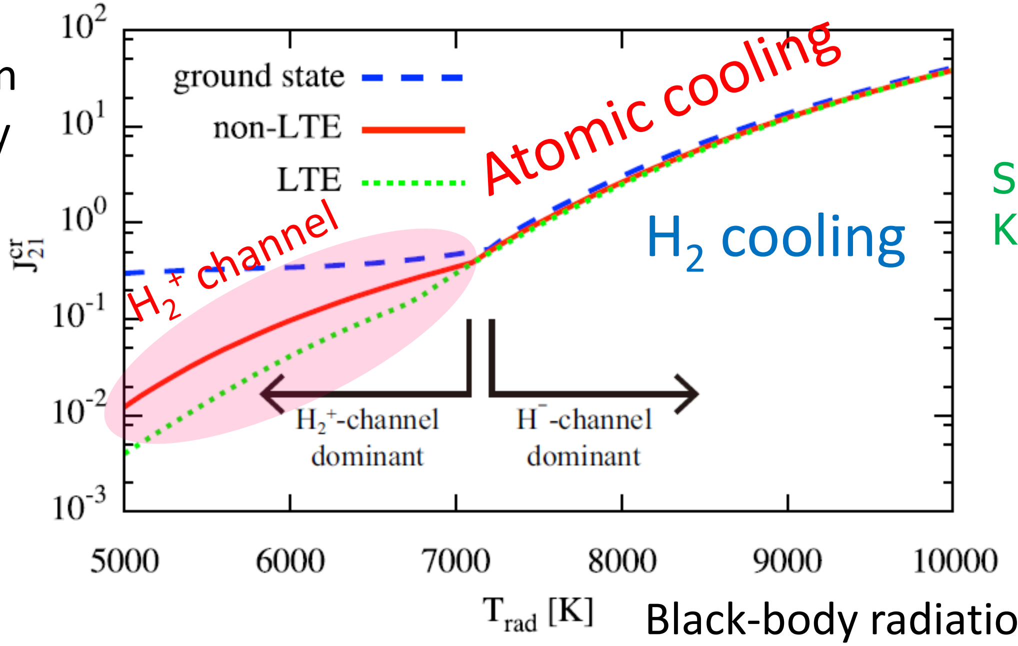
- no rapid cooling phase
  → monolithic collapse

See Dominik Schleicher's talk

How much FUV is needed for atomic-cooling collapse?

J_{crit} vs T_{rad} relation and H_2^+ channel

radiation intensity



Sugimura, Coppola, KO, Galli & Palla 2016

Black-body radiation temperature

•H_2^+ channel (and so its non-LTE level population) is important for radiation field with very soft spectrum T_{rad} < 7000K.

•This justifies the previous estimate for J_{crit} for ordinary young galaxies, which have harder spectrum (T_{rad}~20000K) .

See Kazu Sugimura's poster (#104)

SUMMARY

The prestellar collapse of the first stars is rather well established:

- The gas becomes fully molecular by 3-body reactions at $\sim 10^{11}\mathrm{cm}^{-3}$ and a small protostar is formed at the center at $\sim 10^{21}\mathrm{cm}^{-3}$.

Multi-D simulations for the protostellar evolution are still underway:

- Protostar grows by a rapid accretion at $\sim 10^{-3} M_{\mathrm{sun}}$/yr.
- Protostellar radiative feedback sets the final stellar mass.
- Mass distributions is probably biased to massive objects at a few 10- a few $100 M_{\mathrm{sun}}$

In some unusual circumstances, e.g. in strong FUV fields., supermassive stars might form by atomic cooling.

Francesco has contributed greatly in establishing all this picture

Grazie di cuore Francesco!

First Stars IV, 2012, Kyoto