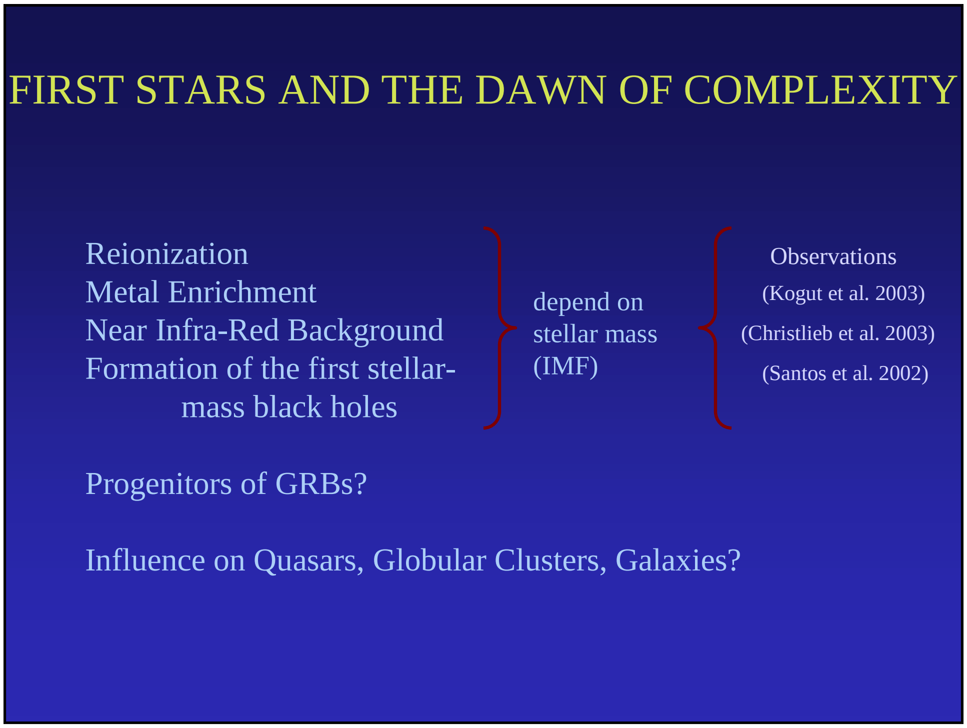
THE FORMATION OF THE FIRST STARS

with Jonathan Tan



FIRST STARS AND THE DAWN OF COMPLEXITY

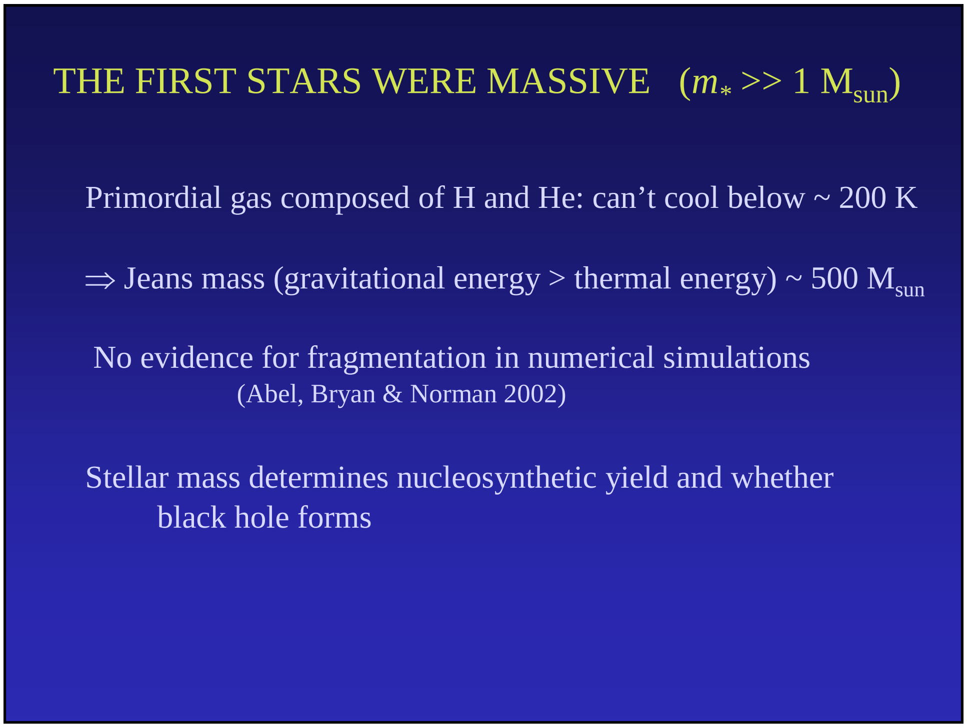
Reionization
Metal Enrichment
Near Infra-Red Background
Formation of the first stellar-mass black holes

} depend on stellar mass (IMF) {

Observations
(Kogut et al. 2003)
(Christlieb et al. 2003)
(Santos et al. 2002)

Progenitors of GRBs?

Influence on Quasars, Globular Clusters, Galaxies?



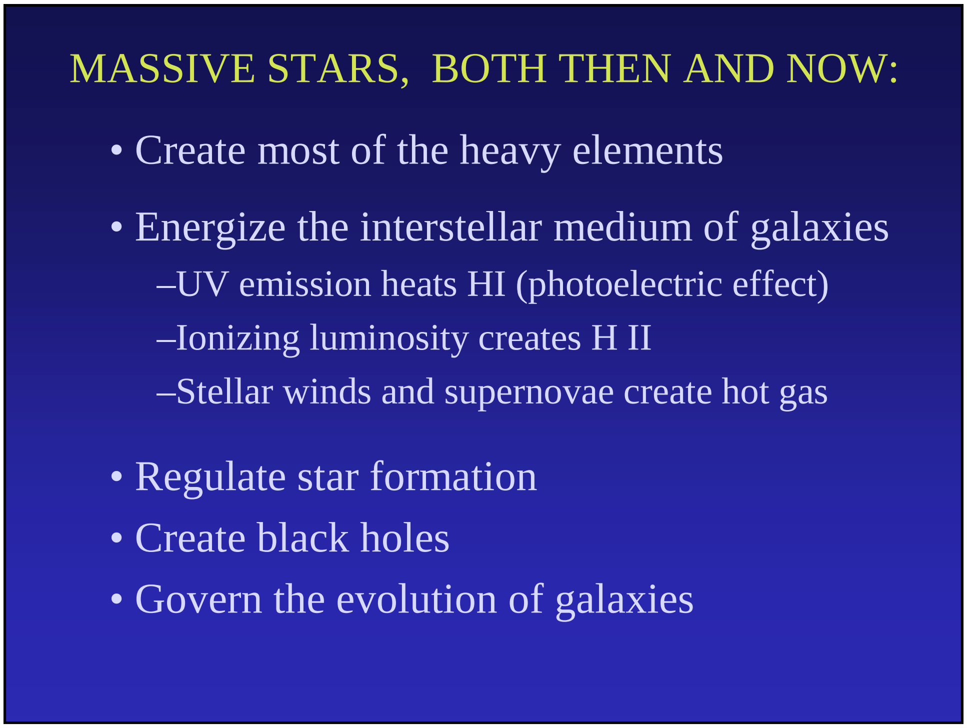
THE FIRST STARS WERE MASSIVE ($m_* >> 1\ M_{sun}$)

Primordial gas composed of H and He: can’t cool below ~ 200 K

$\Rightarrow$ Jeans mass (gravitational energy > thermal energy) ~ 500 M_{sun}

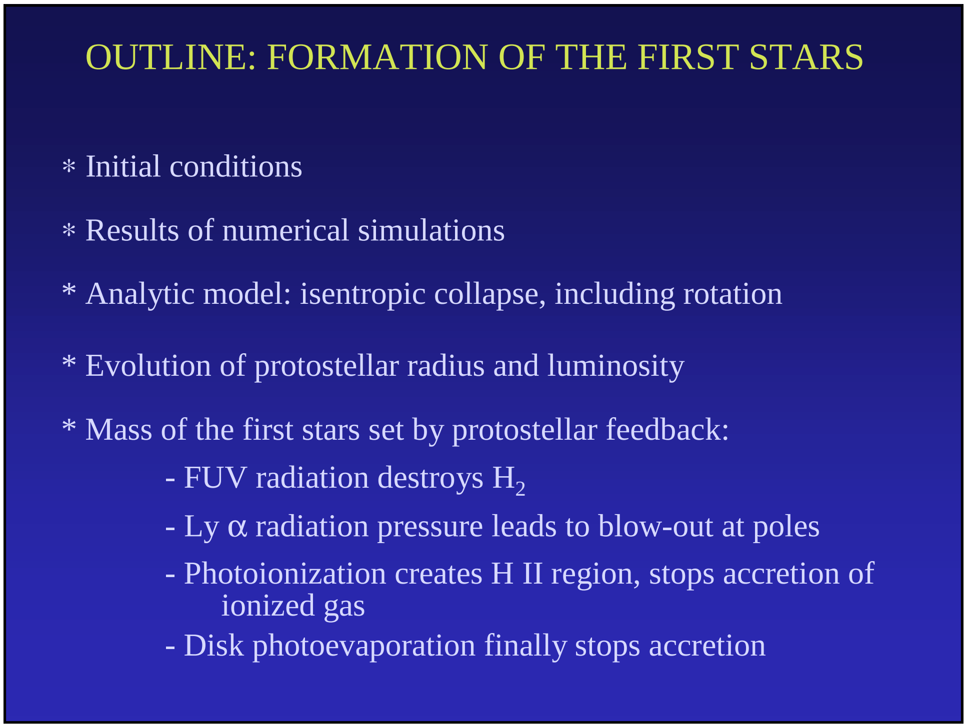
No evidence for fragmentation in numerical simulations
(Abel, Bryan & Norman 2002)

Stellar mass determines nucleosynthetic yield and whether black hole forms



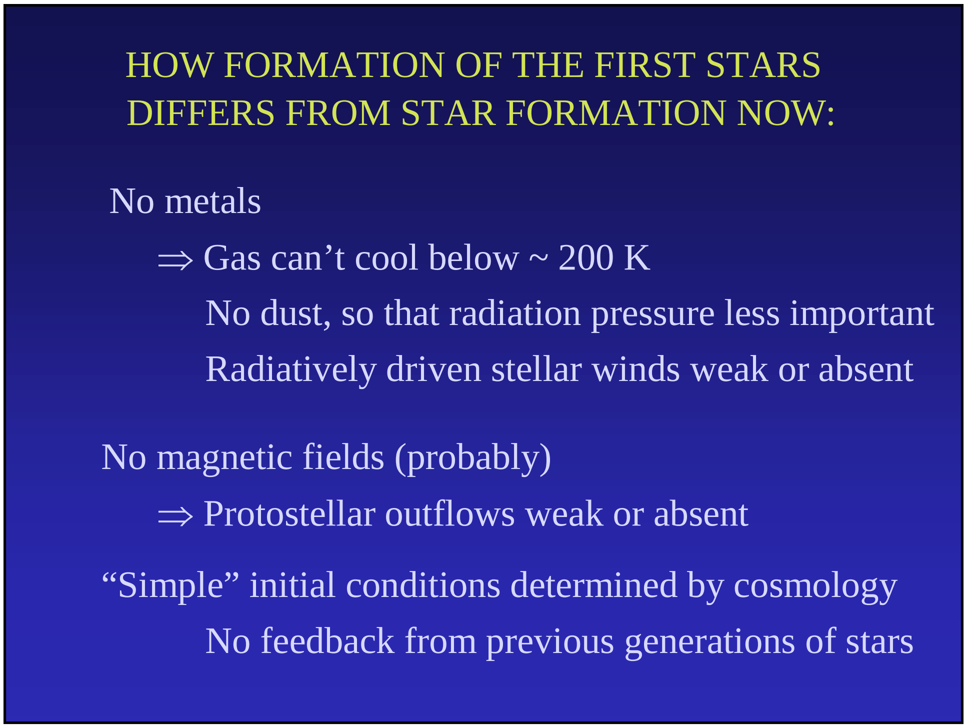
MASSIVE STARS, BOTH THEN AND NOW:

- Create most of the heavy elements
- Energize the interstellar medium of galaxies
  - –UV emission heats HI (photoelectric effect)
  - –Ionizing luminosity creates H II
  - –Stellar winds and supernovae create hot gas
- Regulate star formation
- Create black holes
- Govern the evolution of galaxies



OUTLINE: FORMATION OF THE FIRST STARS

- ⁎ Initial conditions
- ⁎ Results of numerical simulations
- * Analytic model: isentropic collapse, including rotation
- * Evolution of protostellar radius and luminosity
- * Mass of the first stars set by protostellar feedback:
    - FUV radiation destroys H_2
    - Ly α radiation pressure leads to blow-out at poles
    - Photoionization creates H II region, stops accretion of ionized gas
    - Disk photoevaporation finally stops accretion



HOW FORMATION OF THE FIRST STARS DIFFERS FROM STAR FORMATION NOW:

No metals

⇒ Gas can’t cool below ~ 200 K

No dust, so that radiation pressure less important

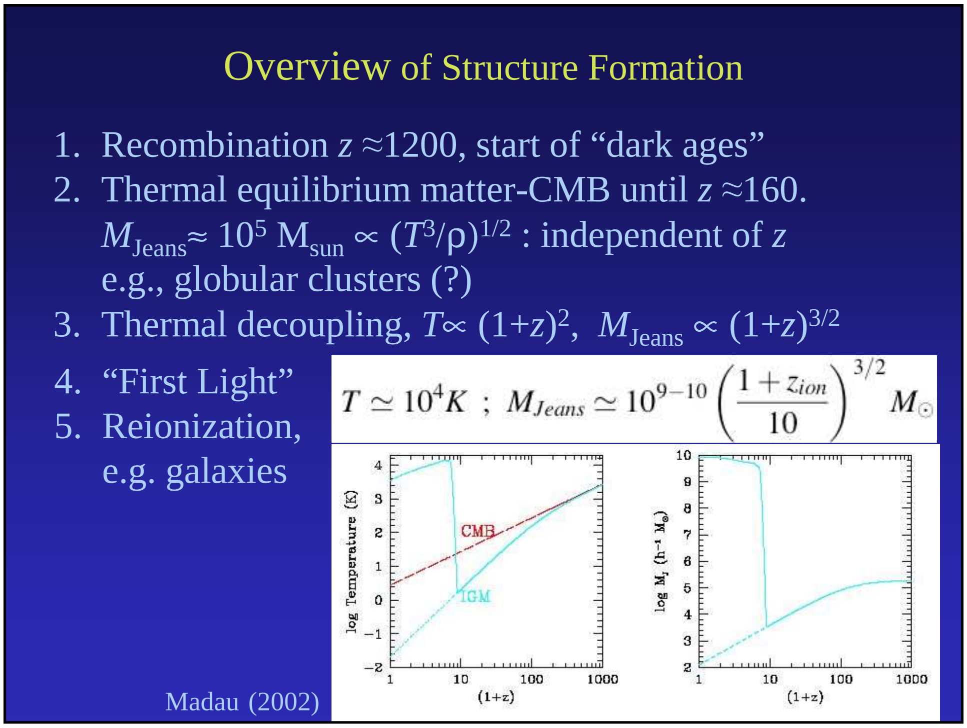
Radiatively driven stellar winds weak or absent

No magnetic fields (probably)

⇒ Protostellar outflows weak or absent

“Simple” initial conditions determined by cosmology

No feedback from previous generations of stars

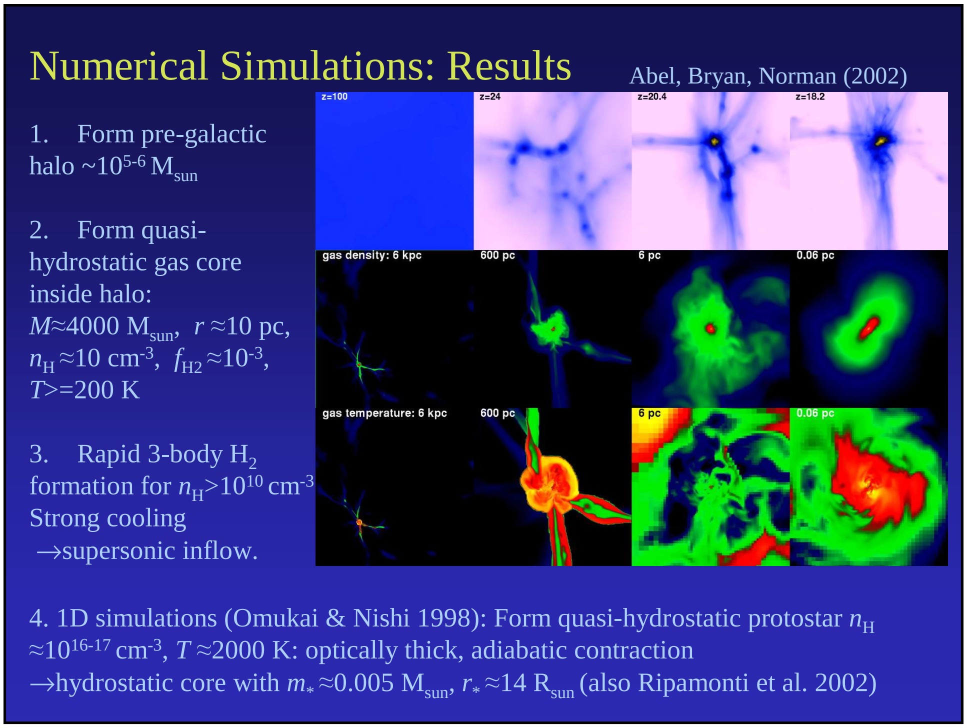


Overview of Structure Formation

1. Recombination $z \approx 1200$, start of "dark ages"
2. Thermal equilibrium matter-CMB until $z \approx 160$.
   $M_{\mathrm{Jeans}} \approx 10^5\, M_{\mathrm{sun}} \propto (T^3/\rho)^{1/2}$: independent of z
   e.g., globular clusters (?)
3. Thermal decoupling, $T \propto (1+z)^2$, $M_{\mathrm{Jeans}} \propto (1+z)^{3/2}$
4. "First Light"
5. Reionization,
   e.g. galaxies

$$T \simeq 10^4 K \;;\; M_{Jeans} \simeq 10^{9-10}\left(\frac{1+z_{ion}}{10}\right)^{3/2} M_{\odot}$$

Madau (2002)



Numerical Simulations: Results

Abel, Bryan, Norman (2002)

1. Form pre-galactic halo ~$10^{5-6}\, M_{\mathrm{sun}}$

2. Form quasi-hydrostatic gas core inside halo:
   $M \approx 4000\, M_{\mathrm{sun}}$, $r \approx 10$ pc,
   $n_H \approx 10$ cm^{-3}, $f_{H2} \approx 10^{-3}$,
   $T >= 200$ K

3. Rapid 3-body H_2 formation for $n_H > 10^{10}$ cm^{-3}
   Strong cooling
   →supersonic inflow.

4. 1D simulations (Omukai & Nishi 1998): Form quasi-hydrostatic protostar $n_H \approx 10^{16\text{-}17}$ cm^{-3}, $T \approx 2000$ K: optically thick, adiabatic contraction →hydrostatic core with $m_* \approx 0.005\, M_{\mathrm{sun}}$, $r_* \approx 14\, R_{\mathrm{sun}}$ (also Ripamonti et al. 2002)

ZENO'S PARADOX (ALMOST) IN COMPUTATIONS OF STAR FORMATION

Time step $\Delta t \propto 1/(G\rho)^{1/2}$

Truelove et al. (1998) calculations of star formation now:

Density increase of $10^9 \Rightarrow \Delta t$ decrease of $10^{4.5}$

ABN (2002) calculations of primordial star formation:

Density increase of $10^{17} \Rightarrow \Delta t$ decrease of $10^{8.5}$

In both cases, calculation stopped before formation of protostar.

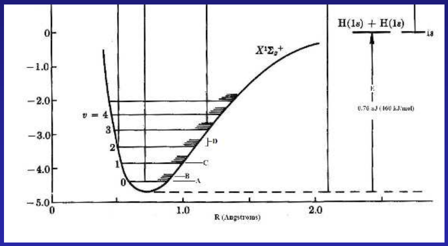
Currently impossible to numerically follow the hydrodynamics of core collapse past the point of protostar formation

$\Rightarrow$ need analytic approach

The initial conditions for primordial star formation

Trace H_2 formation:

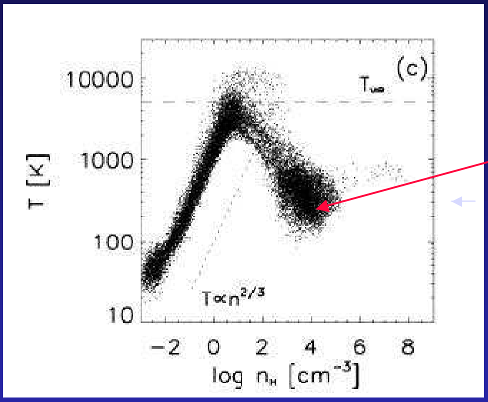
$$H + e^- \rightarrow H^- + \gamma$$
$$H + H^- \rightarrow H_2 + e^-$$



$T_{\rm min} \sim 200$ K, $n_{\rm crit} \sim 10^4$ cm^{-3}
$M_{\rm BE} \sim 500$ M$_{\rm sun}$ $c_s \sim 1.2$ km/s

ISENTROPIC COLLAPSE

(Tan & McKee 2004)



Bromm, Coppi & Larson (2002)

Initial conditions for collapse set by physics of H_2:

$n \sim 10^4$ cm^{-3}, $T \sim 200$ K

$M \sim 500$ M_{sun}

Partially molecular, primordial gas contracts as

$$P = K\rho^{\gamma}$$

with $\gamma = 1.09$ (Omukai & Nishi 98) to 1.11 (Ripamonti ea. 02)

Hence, collapse is approximately isentropic (K= const) with $\gamma \approx 1.10$

Turbulence is weak (ABN 2002)

Simulation by ABN (2002) consistent with expected density structure for γ =1.1:

Let $\rho \propto r$^(-k_ρ)

Hydrostatic equilibrium for polytropes, $P \propto \rho^{\gamma}$, then implies

$$k_\rho = 2/(2-\gamma)$$

$$= (22/9) = 2.22$$

Δt = 200 yr

Δt = 1.5 kyr

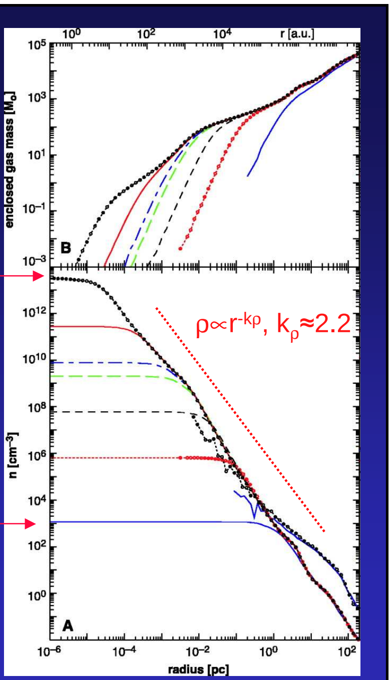
Δt = 3 kyr

Δt = 30 kyr

Δt = 0.3 Myr

Δt = 9 Myr

z = 19



COLLAPSE OF ISENTROPIC SPHERE $(P = K\rho^{\gamma})$

Yahil 1983; McLaughlin & Pudritz 1997

Basis of Turbulent Core model for contemporary massive star formation (McKee & Tan 2002, 2003)

Allow for subsonic inflow (Hunter 1977)

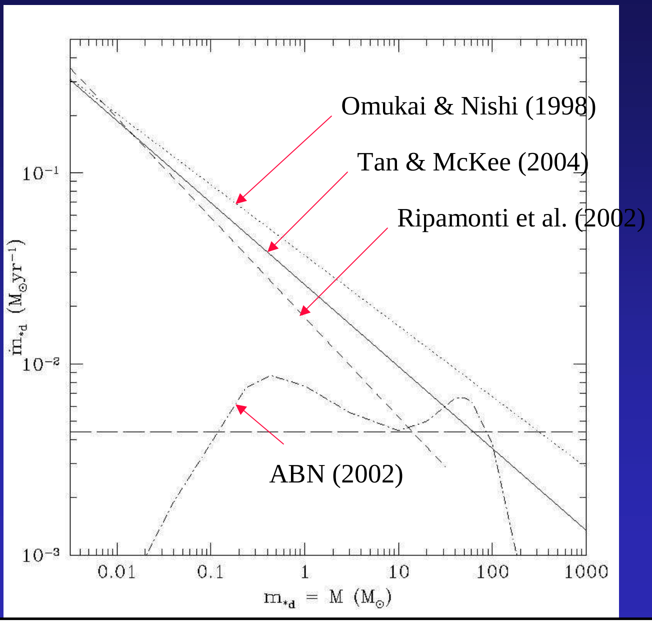
Result:

$\dot{m}_* = 0.0036\, m_2^{-3/7}$ $M_{sun}\ yr^{-1}$: accretion rate

$t_* = 3 \times 10^4\, m_2^{10/7}$ yr: star formation time

where $m_2 = m_*/100\ M_{sun}$

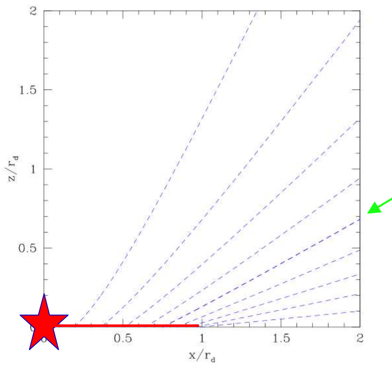
COMPARISON WITH NUMERICAL MODELS



Note: ABN curve based on estimate from infall rate *prior* to protostar formation

ROTATION AND THE FORMATION OF A CIRCUMSTELLAR DISK

Geometry of Streamlines



Conserve J during free-fall
inside sonic point (Ulrich 1976)

Outer region of subsonic inflow:

ABN find $f_{\rm Kep} = v_{\rm rot}/v_{\rm Kep} \sim 0.5$

Inner region of supersonic inflow:

angular momentum conserved

Circumstellar disk forms with radius r_d related to sonic radius r_0:

$r_d = f^2_{Kep} r_0 \rightarrow 1860\ m_2^{9/7}$ AU

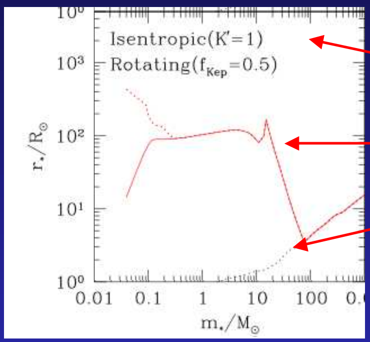
where $m_2 = (m_*/100\ M_{\rm sun})$

EVOLUTION OF THE PROTOSTAR: RADIUS

Generalize Nakano et al. (1995, 2000) to include rotation

Initial condition:
$m_* = 0.04\ M_{\rm sun}$
$r_* = 14\ R_{\rm sun}$
(Ripamonti et al. 02)

Rotation:
$f_{\rm Kep} = v_{\rm rot}/v_{\rm Kep}$

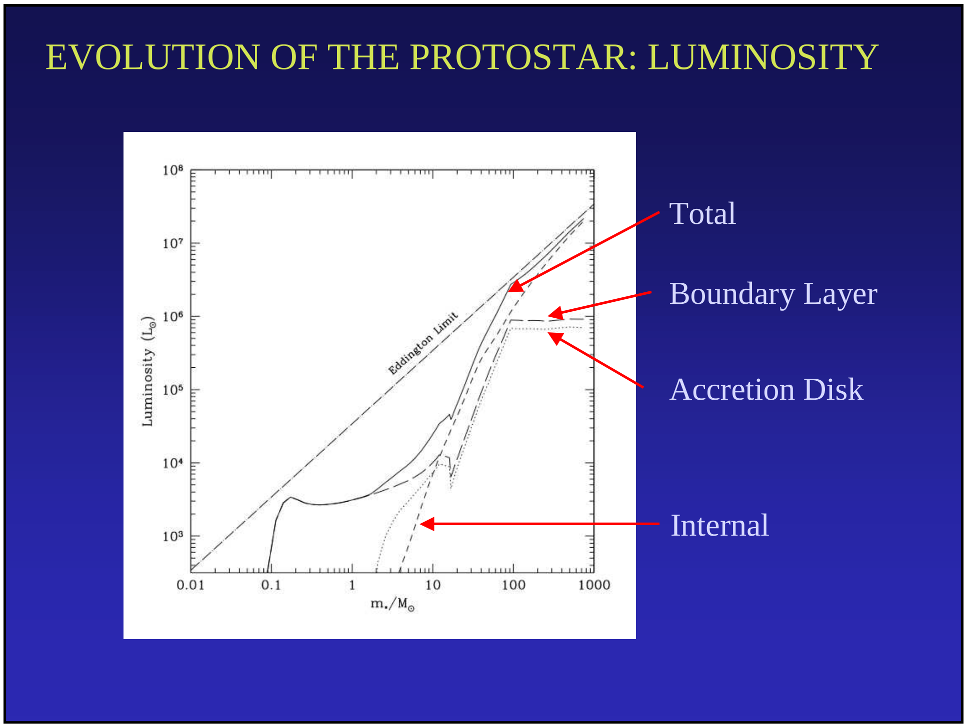


Photosphere

Accretion Shock

Main Sequence
(Schaerer 2002)

Comparison with Stahler et al. (1986), Omukai & Palla (2001)
Protostar is large (~100 $R_{\rm sun}$) until it is older than $t_{\rm Kelvin}$
Contraction to main sequence
Accretion along main sequence
EFFECT OF ROTATION ON PHOTOSPHERE KEY FOR FEEDBACK



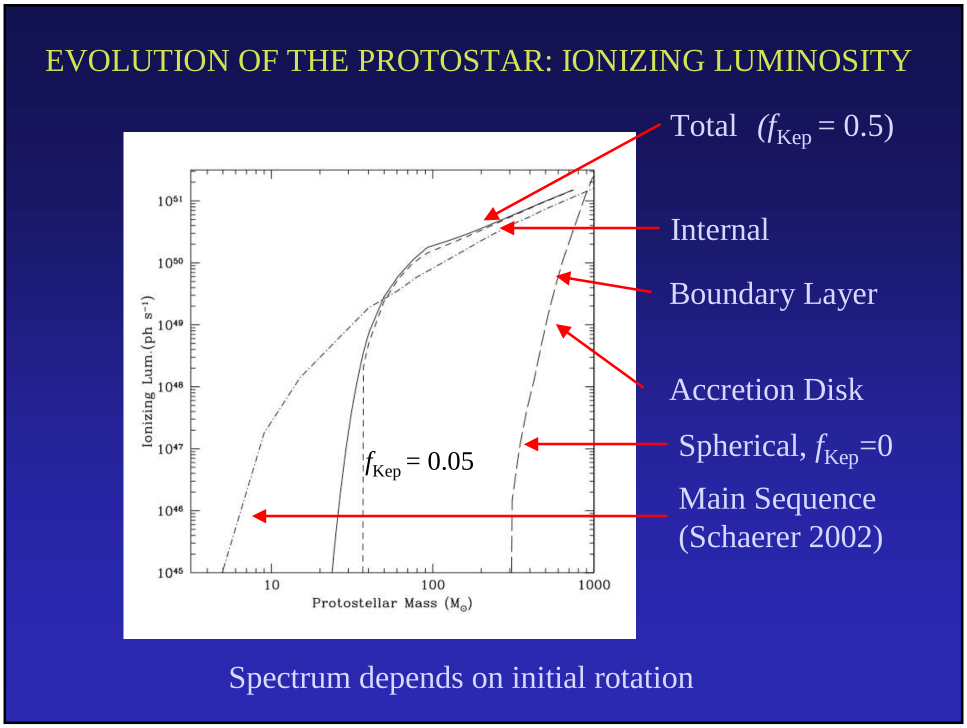
EVOLUTION OF THE PROTOSTAR: LUMINOSITY

Total

Boundary Layer

Accretion Disk

Internal



EVOLUTION OF THE PROTOSTAR: IONIZING LUMINOSITY

Total ($f_{\mathrm{Kep}} = 0.5$)

Internal

Boundary Layer

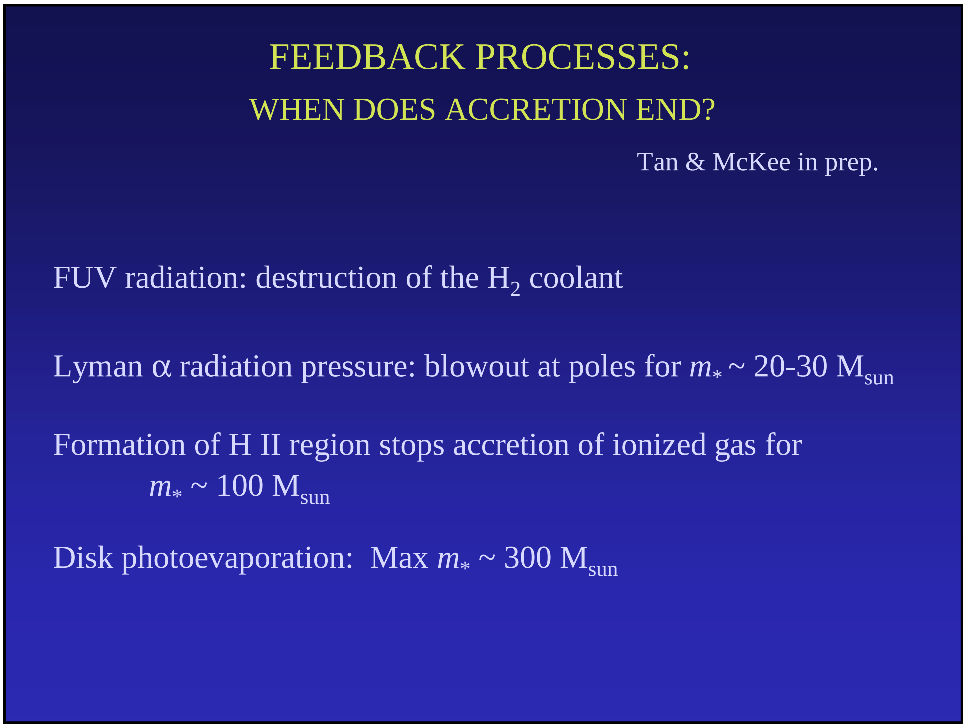
Accretion Disk

$f_{\mathrm{Kep}} = 0.05$

Spherical, $f_{\mathrm{Kep}}=0$

Main Sequence
(Schaerer 2002)

Spectrum depends on initial rotation



FEEDBACK PROCESSES:
WHEN DOES ACCRETION END?

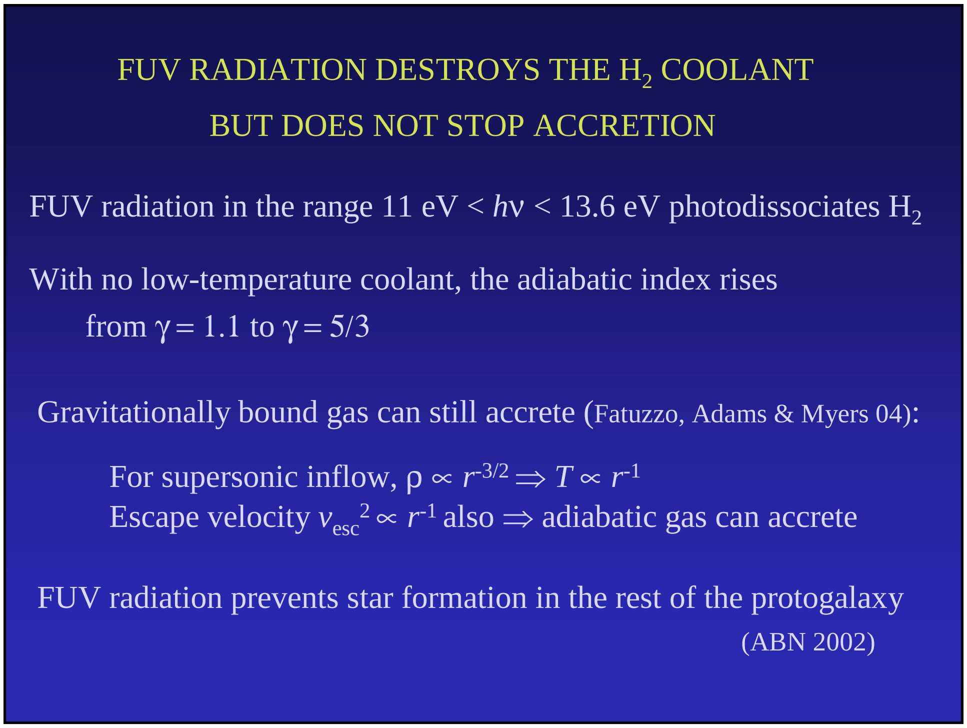
Tan & McKee in prep.

FUV radiation: destruction of the H_2 coolant

Lyman α radiation pressure: blowout at poles for $m_* \sim$ 20-30 M_{sun}

Formation of H II region stops accretion of ionized gas for
$m_* \sim 100\ M_{sun}$

Disk photoevaporation: Max $m_* \sim 300\ M_{sun}$



FUV RADIATION DESTROYS THE H_2 COOLANT
BUT DOES NOT STOP ACCRETION

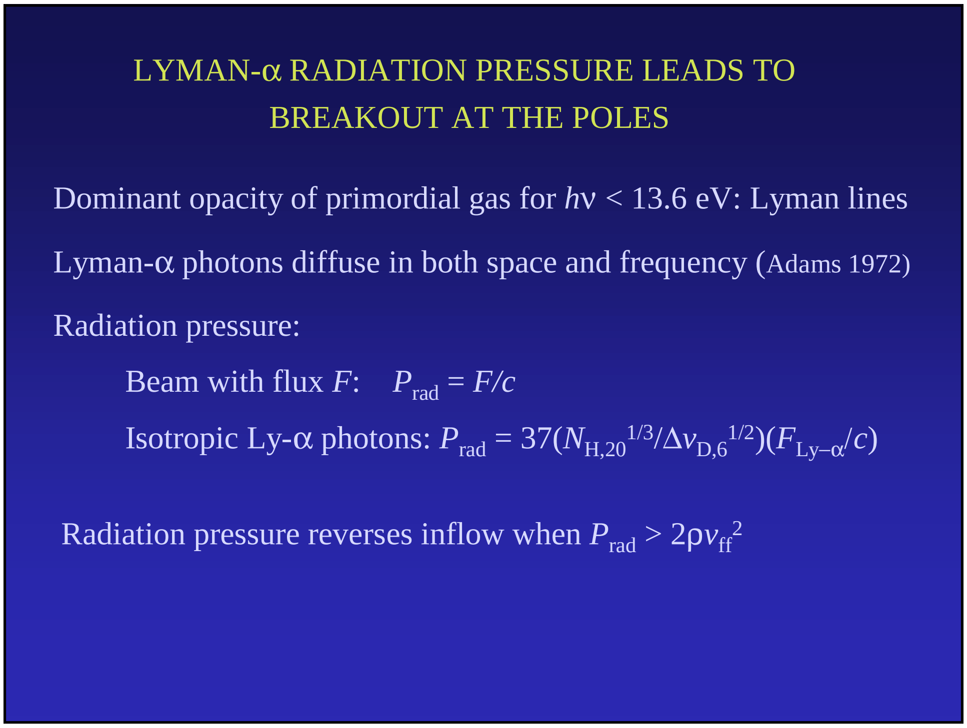
FUV radiation in the range 11 eV < $h\nu$ < 13.6 eV photodissociates H_2

With no low-temperature coolant, the adiabatic index rises
from $\gamma = 1.1$ to $\gamma = 5/3$

Gravitationally bound gas can still accrete (Fatuzzo, Adams & Myers 04):

For supersonic inflow, $\rho \propto r^{-3/2} \Rightarrow T \propto r^{-1}$
Escape velocity $v_{esc}^2 \propto r^{-1}$ also $\Rightarrow$ adiabatic gas can accrete

FUV radiation prevents star formation in the rest of the protogalaxy
(ABN 2002)



LYMAN-α RADIATION PRESSURE LEADS TO BREAKOUT AT THE POLES

Dominant opacity of primordial gas for $h\nu < 13.6$ eV: Lyman lines

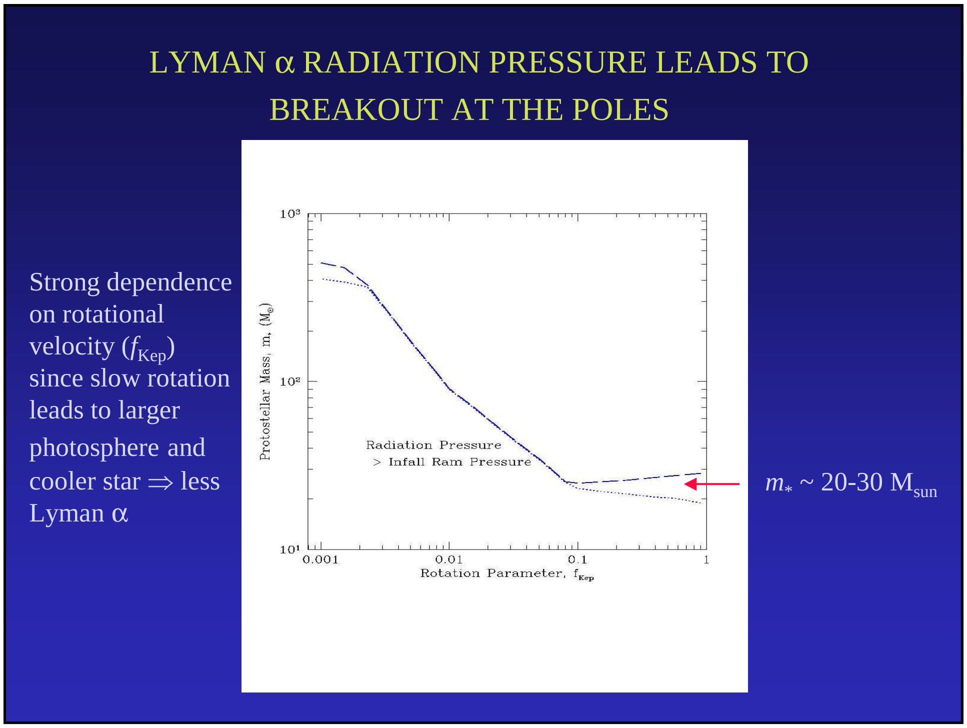
Lyman-α photons diffuse in both space and frequency (Adams 1972)

Radiation pressure:

Beam with flux F: $P_{\rm rad} = F/c$

Isotropic Ly-α photons: $P_{\rm rad} = 37(N_{\rm H,20}{}^{1/3}/\Delta v_{\rm D,6}{}^{1/2})(F_{\rm Ly-\alpha}/c)$

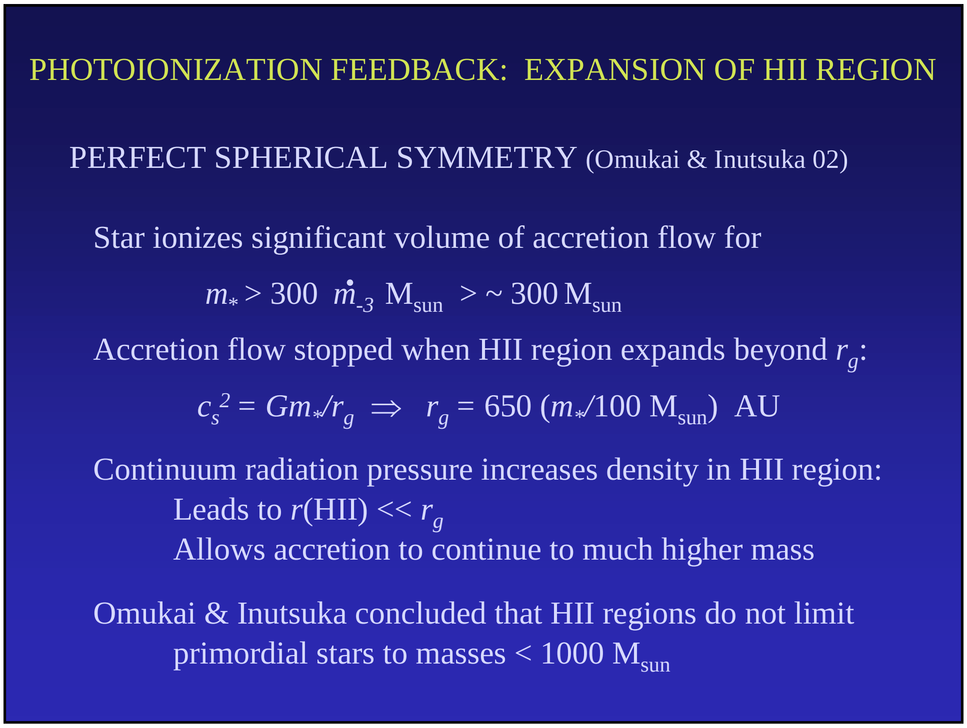
Radiation pressure reverses inflow when $P_{\rm rad} > 2\rho v_{\rm ff}^2$



LYMAN α RADIATION PRESSURE LEADS TO BREAKOUT AT THE POLES

Strong dependence on rotational velocity ($f_{\rm Kep}$) since slow rotation leads to larger photosphere and cooler star ⇒ less Lyman α

$m_* \sim 20\text{-}30\ {\rm M_{sun}}$



PHOTOIONIZATION FEEDBACK: EXPANSION OF HII REGION

PERFECT SPHERICAL SYMMETRY (Omukai & Inutsuka 02)

Star ionizes significant volume of accretion flow for

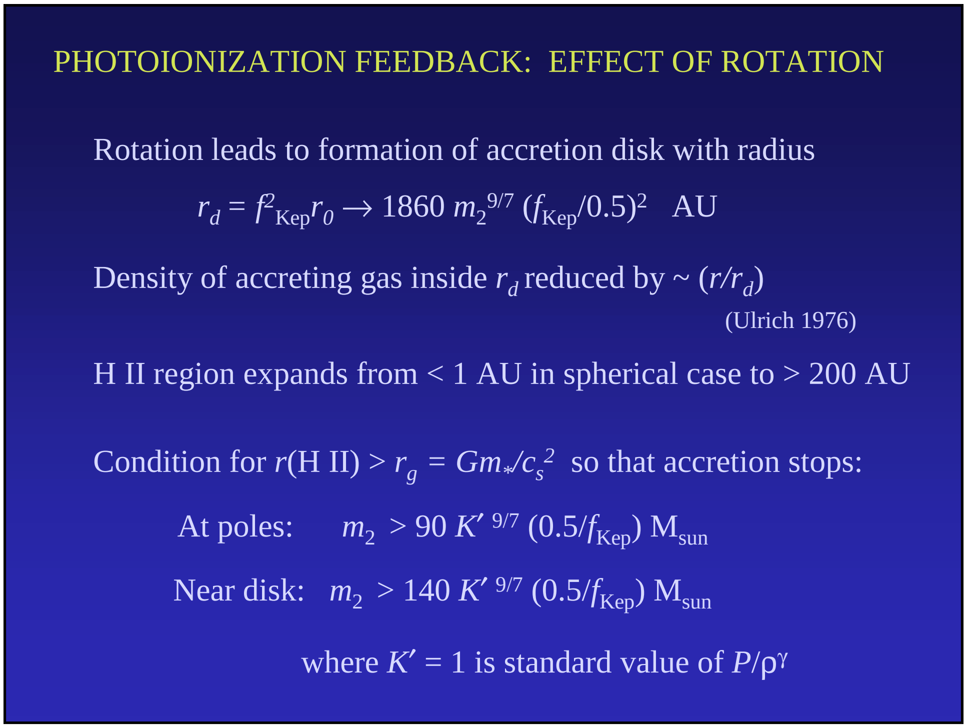
$$m_* > 300\ \dot{m}_{-3}\ \mathrm{M_{sun}}\ \ > \sim 300\ \mathrm{M_{sun}}$$

Accretion flow stopped when HII region expands beyond r_g:

$$c_s^2 = Gm_*/r_g \ \Rightarrow\ r_g = 650\ (m_*/100\ \mathrm{M_{sun}})\ \ \mathrm{AU}$$

Continuum radiation pressure increases density in HII region:
Leads to $r(\mathrm{HII}) << r_g$
Allows accretion to continue to much higher mass

Omukai & Inutsuka concluded that HII regions do not limit primordial stars to masses $< 1000\ \mathrm{M_{sun}}$



PHOTOIONIZATION FEEDBACK: EFFECT OF ROTATION

Rotation leads to formation of accretion disk with radius

$$r_d = f^2_{\mathrm{Kep}} r_0 \rightarrow 1860\ m_2^{9/7}\ (f_{\mathrm{Kep}}/0.5)^2\ \ \mathrm{AU}$$

Density of accreting gas inside r_d reduced by $\sim (r/r_d)$

(Ulrich 1976)

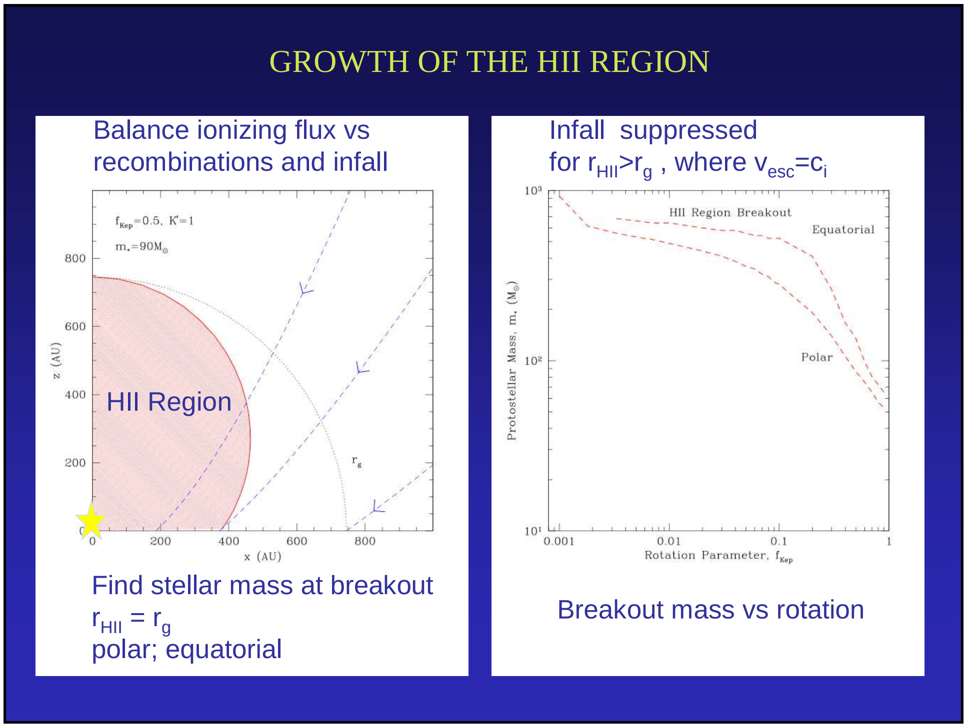
H II region expands from < 1 AU in spherical case to > 200 AU

Condition for $r(\mathrm{H\ II}) > r_g = Gm_*/c_s^2$ so that accretion stops:

At poles: $m_2 > 90\ K'^{\,9/7}\ (0.5/f_{\mathrm{Kep}})\ \mathrm{M_{sun}}$

Near disk: $m_2 > 140\ K'^{\,9/7}\ (0.5/f_{\mathrm{Kep}})\ \mathrm{M_{sun}}$

where $K' = 1$ is standard value of P/ρ^γ



GROWTH OF THE HII REGION

Balance ionizing flux vs recombinations and infall

Find stellar mass at breakout

$r_{HII} = r_g$

polar; equatorial

Infall suppressed for $r_{HII} > r_g$, where $v_{esc}=c_i$

Breakout mass vs rotation

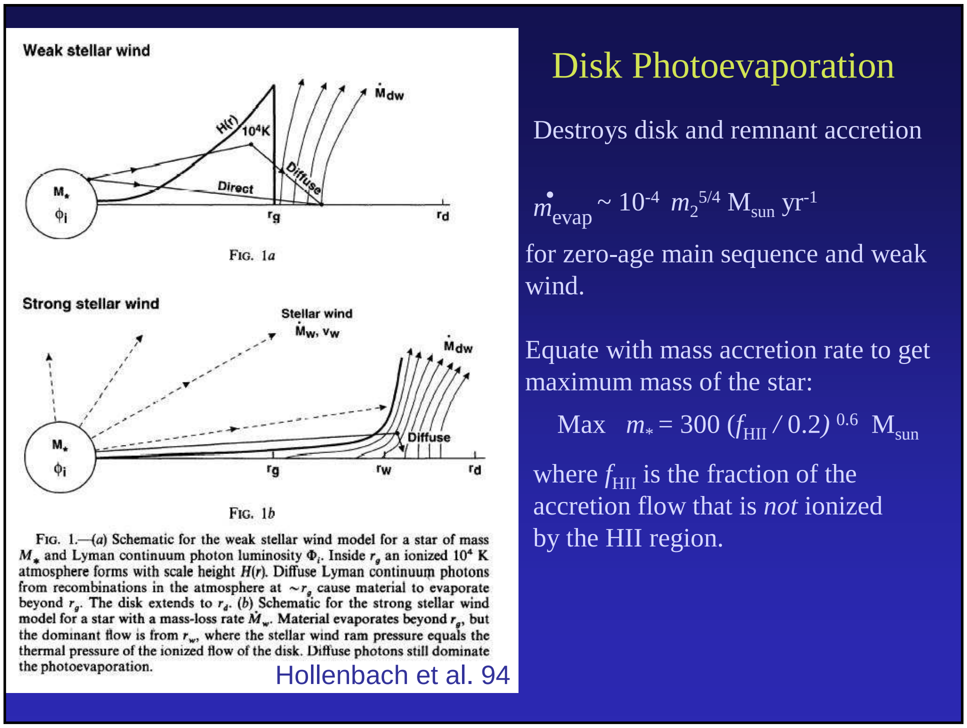


FIG. 1*a*

FIG. 1*b*

FIG. 1.—(*a*) Schematic for the weak stellar wind model for a star of mass M_* and Lyman continuum photon luminosity Φ_i. Inside r_g an ionized 10^4 K atmosphere forms with scale height $H(r)$. Diffuse Lyman continuum photons from recombinations in the atmosphere at $\sim r_g$ cause material to evaporate beyond r_g. The disk extends to r_d. (*b*) Schematic for the strong stellar wind model for a star with a mass-loss rate $\dot{M}_w$. Material evaporates beyond r_g, but the dominant flow is from r_w, where the stellar wind ram pressure equals the thermal pressure of the ionized flow of the disk. Diffuse photons still dominate the photoevaporation.

Hollenbach et al. 94

Disk Photoevaporation

Destroys disk and remnant accretion

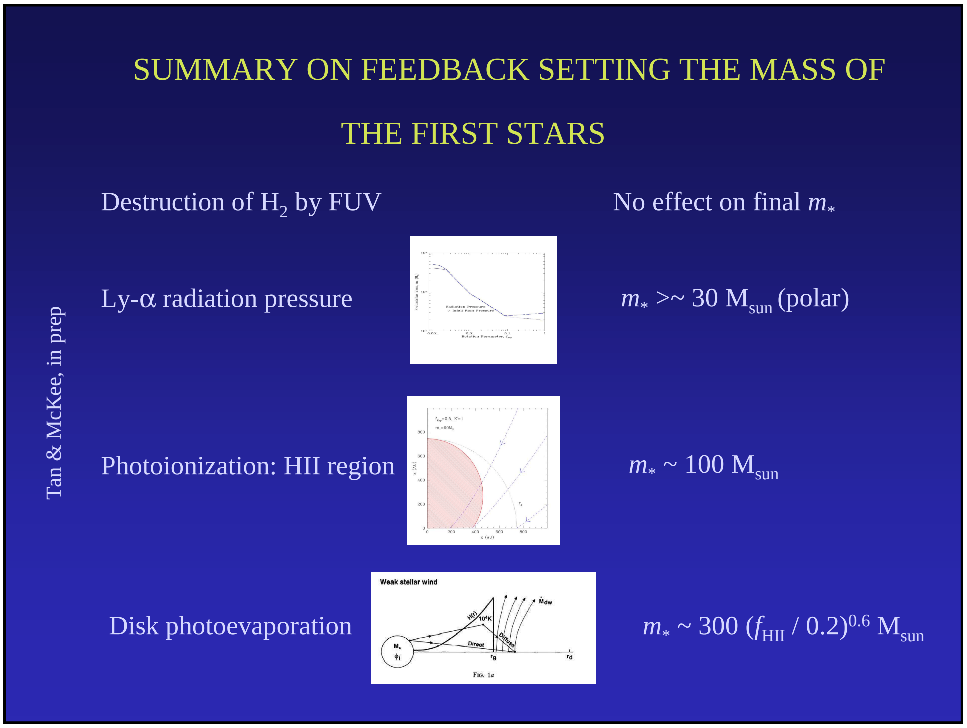
$\dot{m}_{evap} \sim 10^{-4}\ m_2^{5/4}\ M_{sun}\ yr^{-1}$

for zero-age main sequence and weak wind.

Equate with mass accretion rate to get maximum mass of the star:

$$\text{Max}\quad m_* = 300\ (f_{HII} / 0.2)^{0.6}\ M_{sun}$$

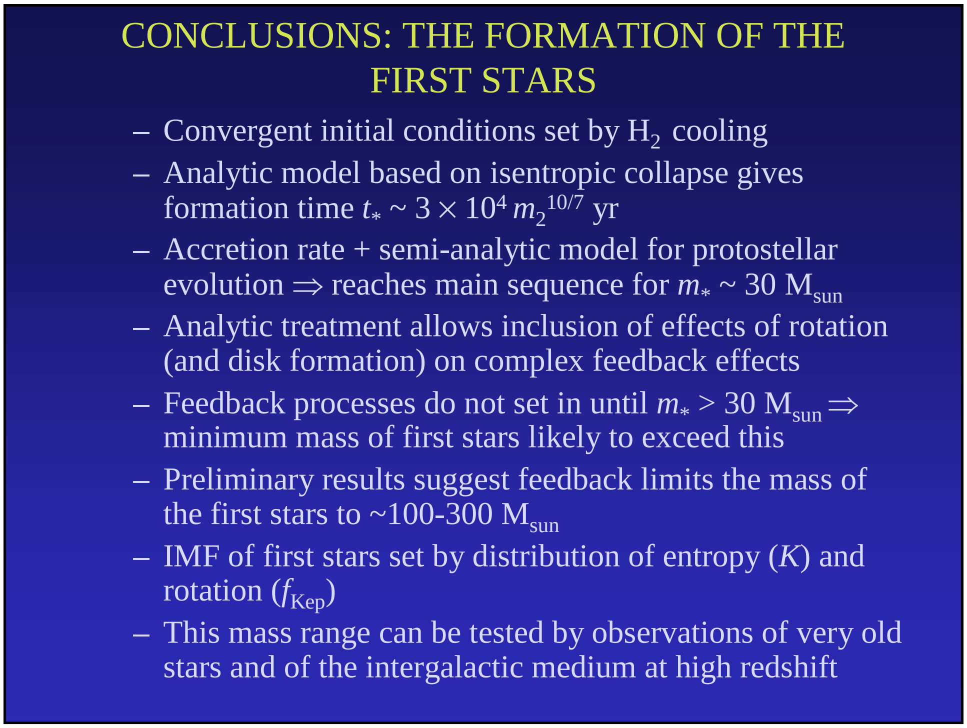
where f_{HII} is the fraction of the accretion flow that is *not* ionized by the HII region.



SUMMARY ON FEEDBACK SETTING THE MASS OF THE FIRST STARS

Tan & McKee, in prep

Destruction of H_2 by FUV	No effect on final m_*
Ly-α radiation pressure	$m_* >\sim 30$ M_{sun} (polar)
Photoionization: HII region	$m_* \sim 100$ M_{sun}
Disk photoevaporation	$m_* \sim 300\ (f_{HII} / 0.2)^{0.6}$ M_{sun}



CONCLUSIONS: THE FORMATION OF THE FIRST STARS

- Convergent initial conditions set by H_2 cooling
- Analytic model based on isentropic collapse gives formation time $t_* \sim 3 \times 10^4\, m_2^{10/7}$ yr
- Accretion rate + semi-analytic model for protostellar evolution ⇒ reaches main sequence for $m_* \sim 30$ M_{sun}
- Analytic treatment allows inclusion of effects of rotation (and disk formation) on complex feedback effects
- Feedback processes do not set in until $m_* > 30$ M_{sun} ⇒ minimum mass of first stars likely to exceed this
- Preliminary results suggest feedback limits the mass of the first stars to ~100-300 M_{sun}
- IMF of first stars set by distribution of entropy (K) and rotation (f_{Kep})
- This mass range can be tested by observations of very old stars and of the intergalactic medium at high redshift