Feedback Processes
A Theoretical Perspective

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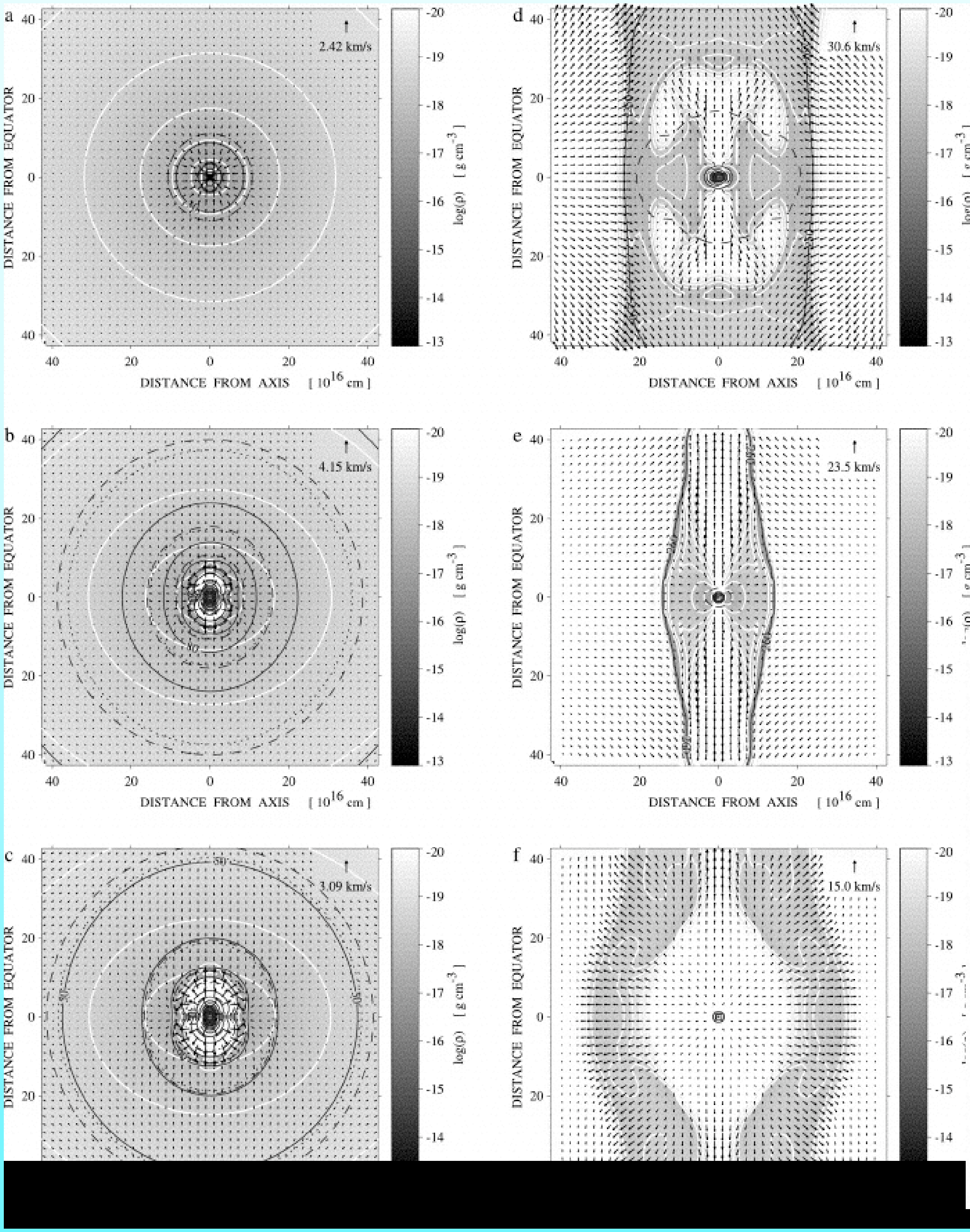
Small scale feedback

- jets
- wide-angle outflows
- accretion luminosity
- line-driven winds
- ionizing radiation

are these what limit the mass of massive stars?

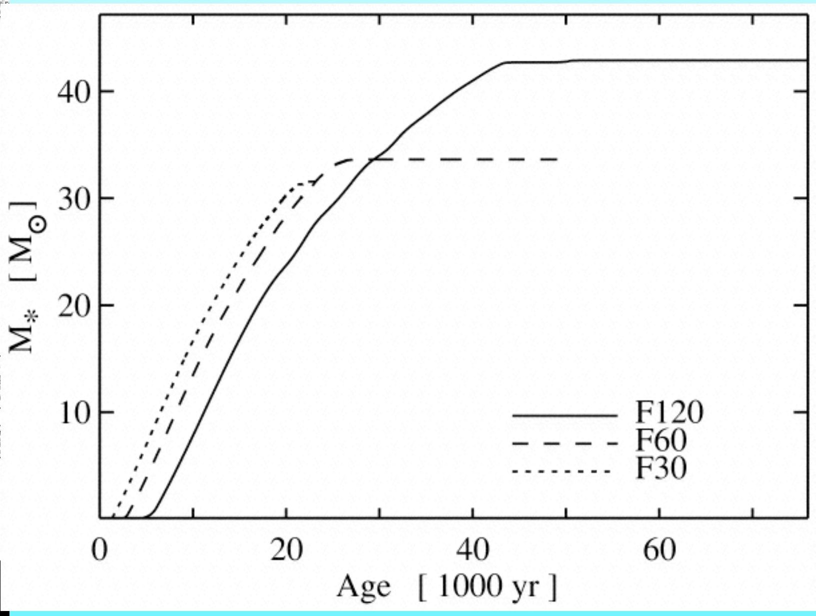
Does feedback allow OB stars?

- Spherical models say no:
  - above 30 $M_{sun,}$ radiation pressure on standard interstellar dust prevents accretion (Wolfire & Cassinelli 87)
- But:
  - better dust treatment
  - 2D & 3D effects
  - or even just high accretion rates in high pressure cores

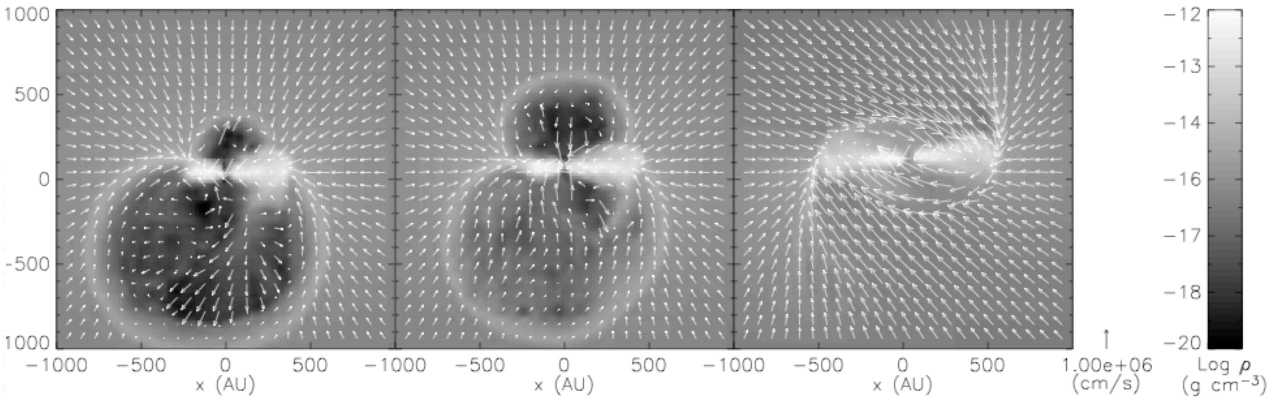


Yorke & Sonnhalter 02

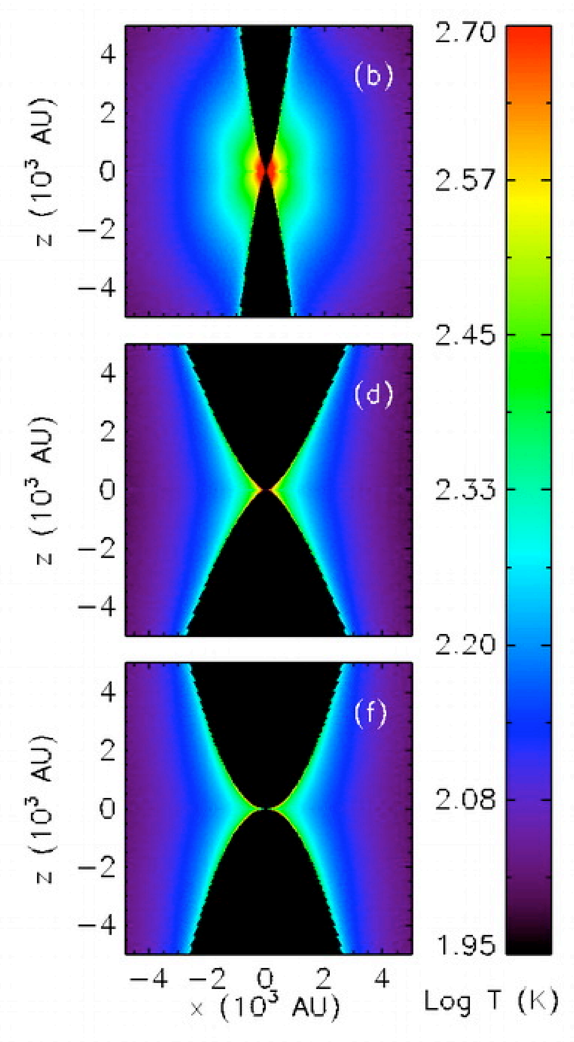
2D frequency depdt RT
nested grid models
reached limiting mass
of 30-45 solar masses
regardless of initial mass



4 Krumholz, Klein, & McKee 05

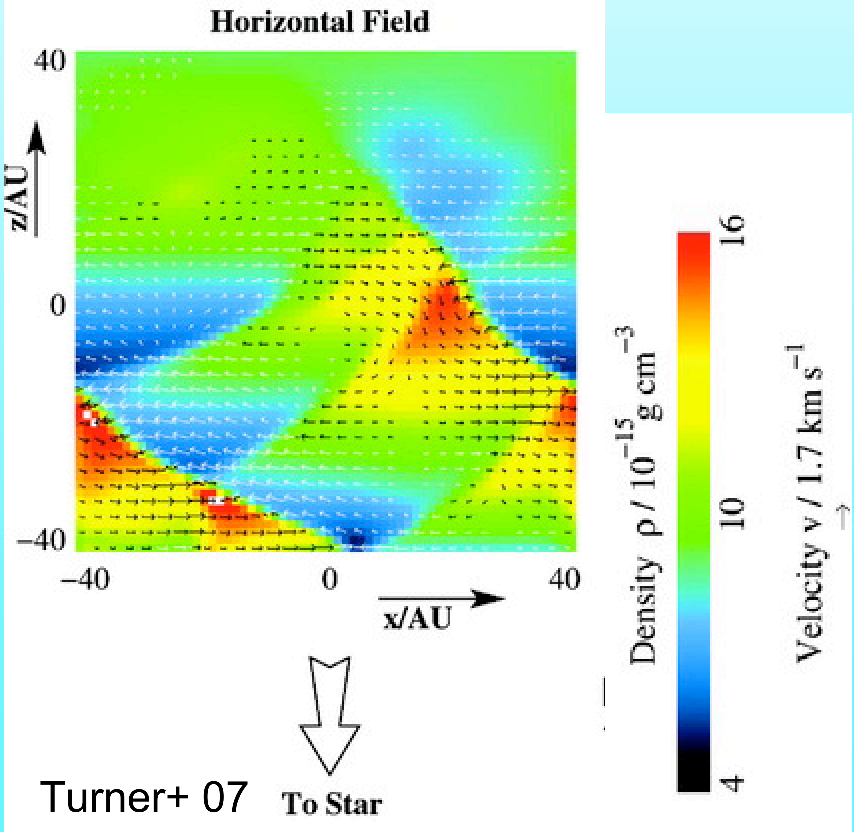


outflow cooling



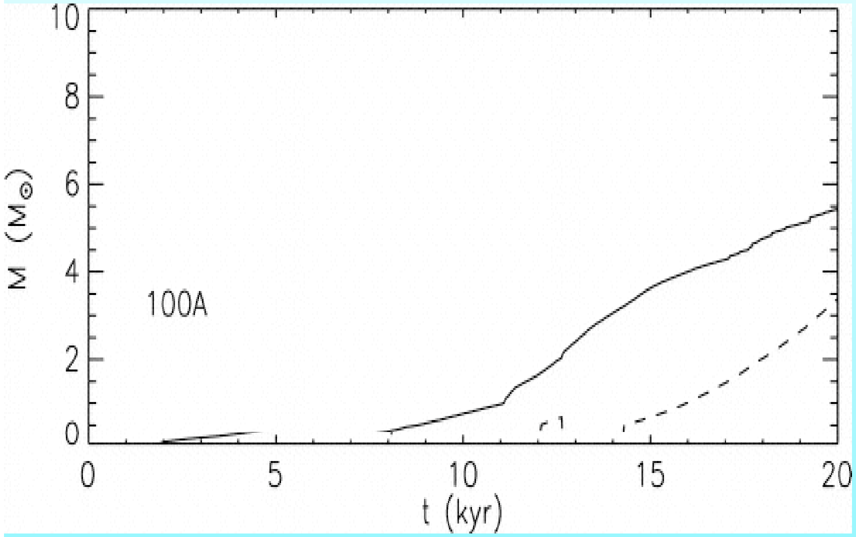
Krumholz+ 05

photon bubbles



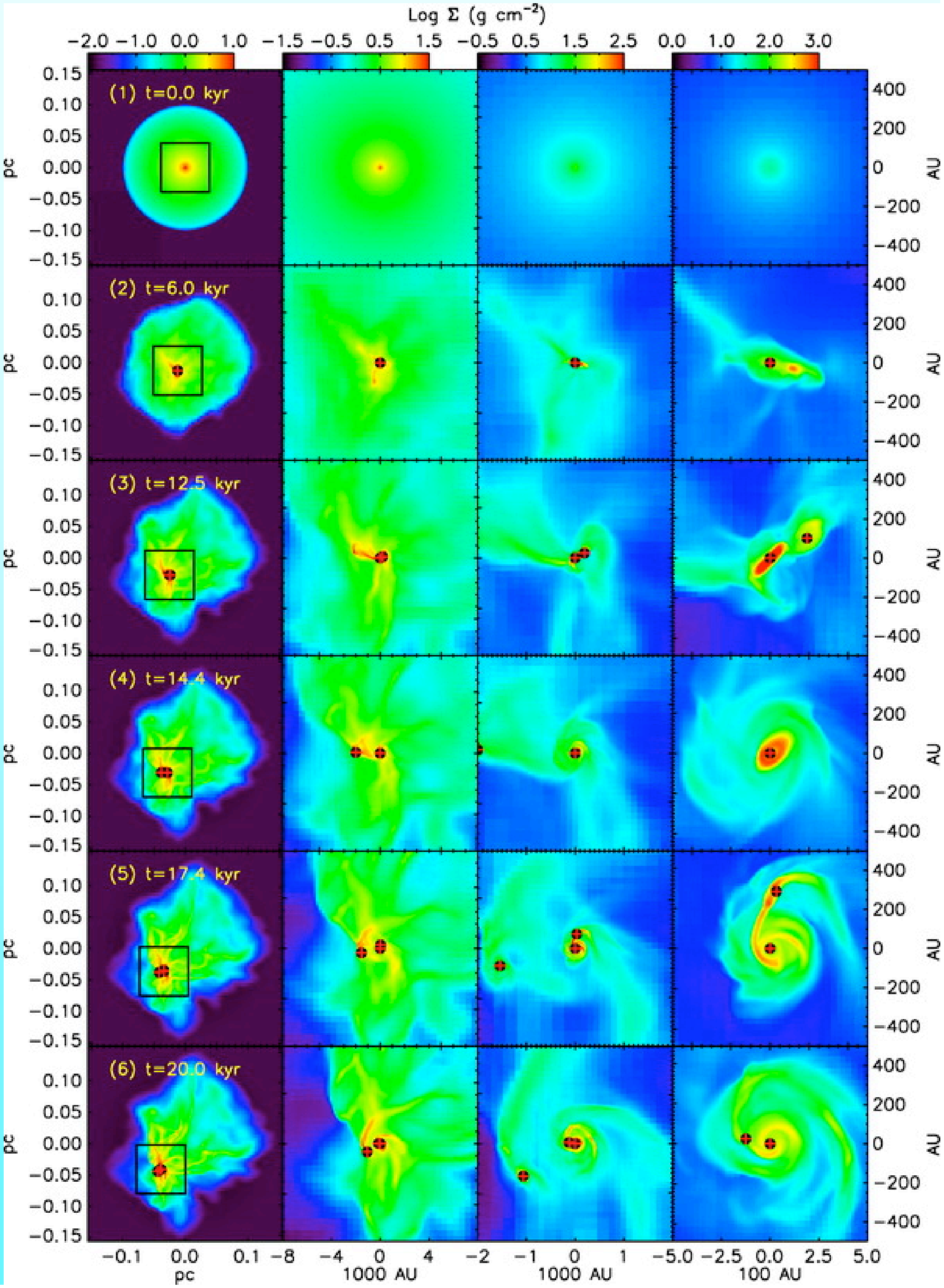
Turner+ 07

3D grey RT
using multiple
dust species,
T depdt. opacity
AMR



only reaches
10 solar masses
in this publication,
but “still growing”

Krumholz+ 07



First conclusion:

Good news: Large stars can grow despite radiation pressure.

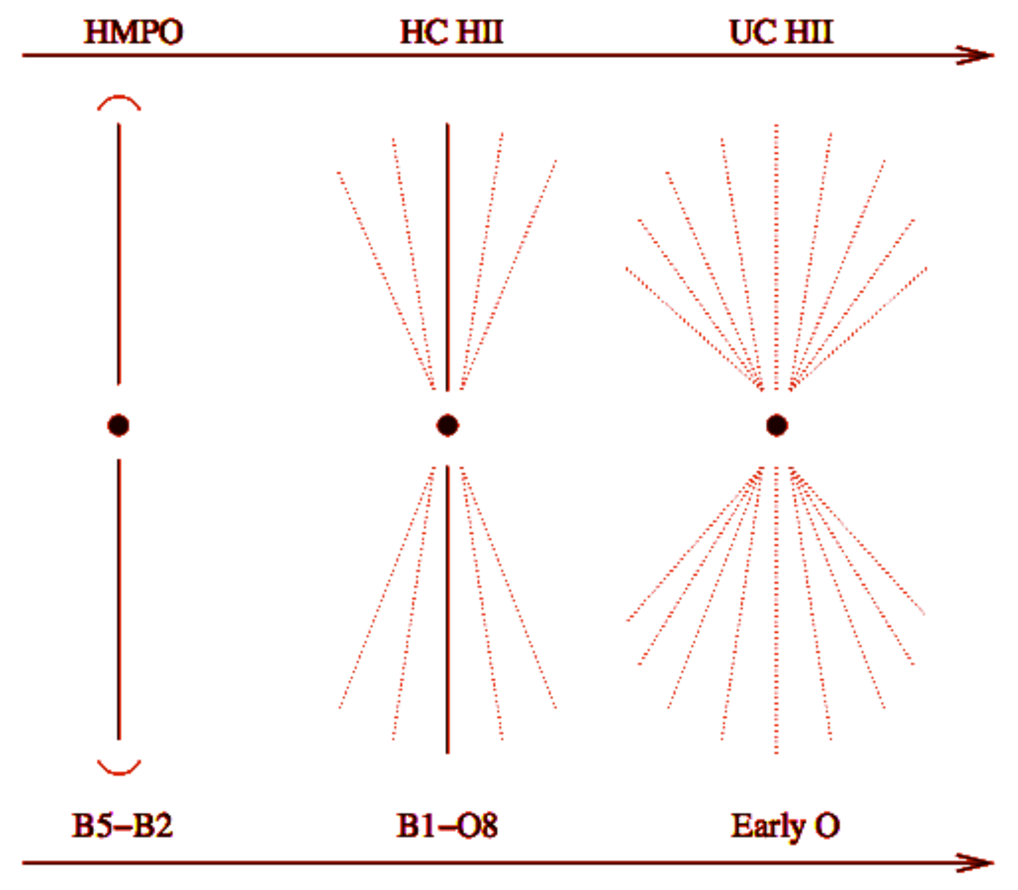
- What determines upper mass limit?
  - – feedback?
    - increasing strength of feedback dominant
  - – fragmentation?
    - exhaustion of mass reservoir dominant
    - or disk fragmentation cutting off accretion
  - – collision?
    - density of stars dominant
- Existence of apparent upper mass limit at $\sim 100 - 150\ \mathrm{M}_{\odot}$ (e.g. Figer 05) argues for feedback or disk fragmentation.
- IMF may be determined more by cloud fragmentation and, perhaps collision.

Evolutionary Sequence?

Massive stars reach main sequence during accretion.

winds begin even before accretion finishes.

Note that no O stars have yet been found with collimated jets (Shepherd 03, Sollins+ 04, Arce+ 07) or disks (Cesaroni+ 07).

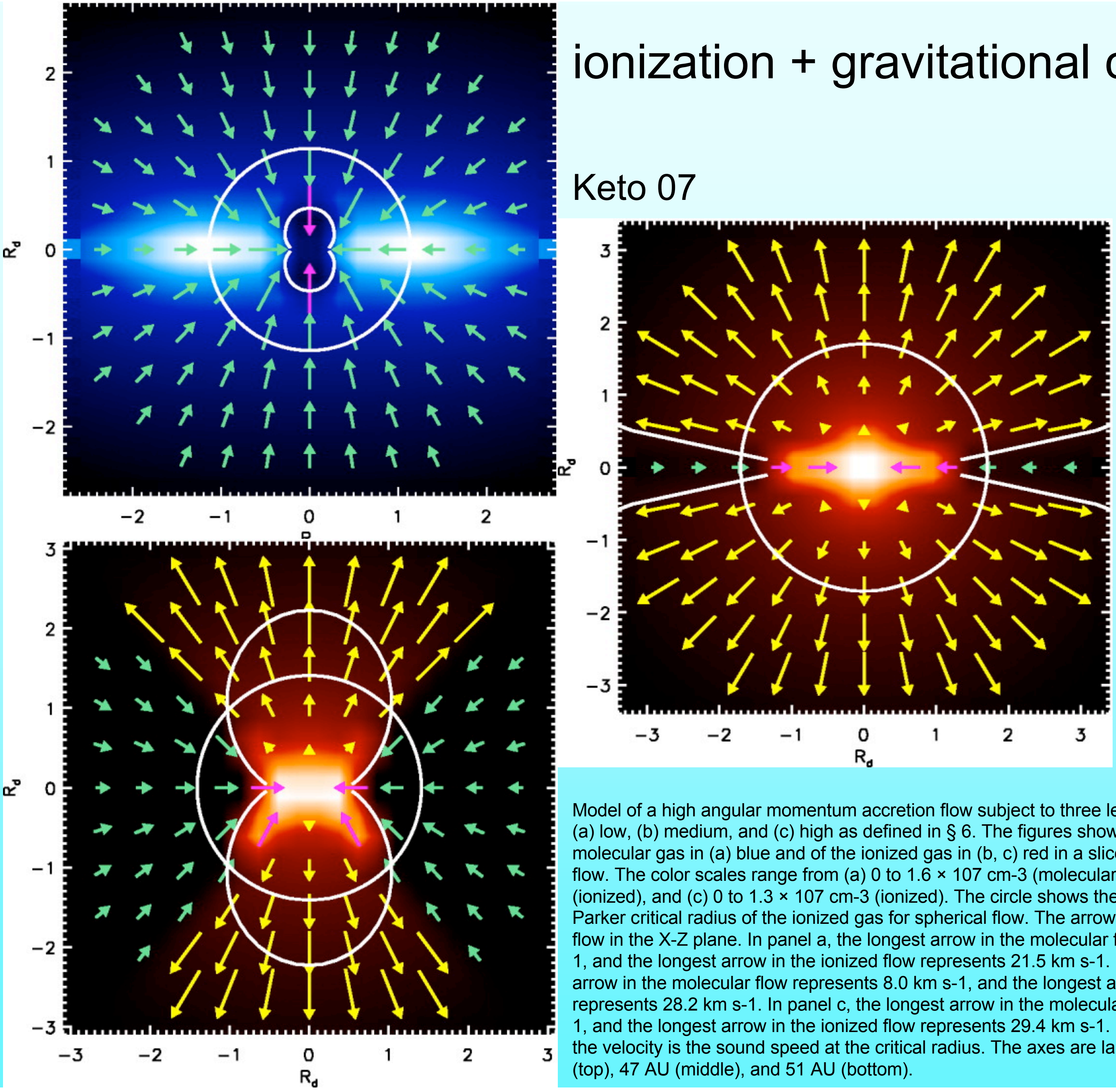


Beuther & Shepherd 05

ionization + gravitational confinement

Keto 07

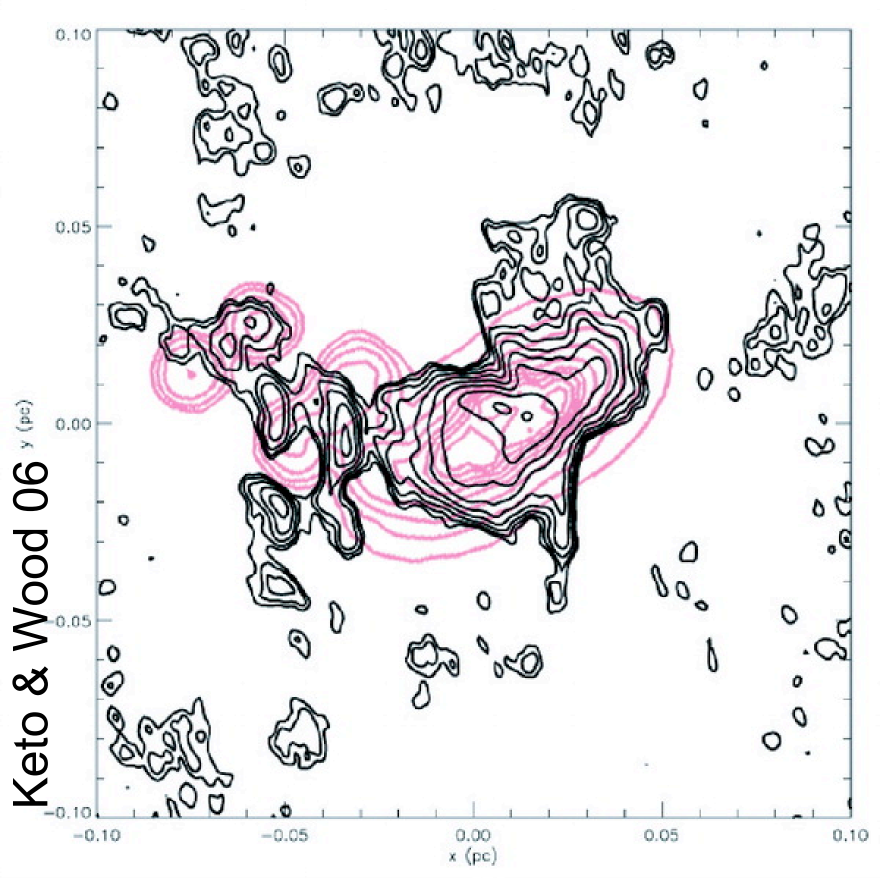
compare Bondi-Parker radius to ionization radius



see Beltrán talk for example

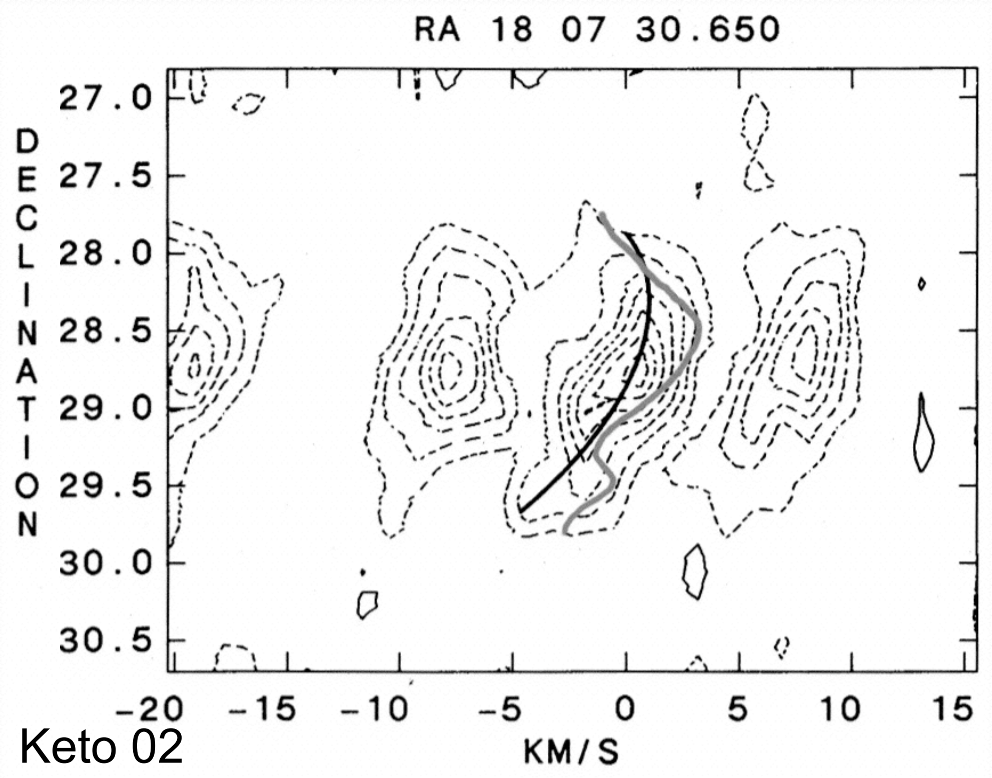
Model of a high angular momentum accretion flow subject to three levels of ionizing radiation, (a) low, (b) medium, and (c) high as defined in § 6. The figures show the log of the density of molecular gas in (a) blue and of the ionized gas in (b, c) red in a slice in the X-Z plane of the flow. The color scales range from (a) 0 to 1.6 × 107 cm-3 (molecular), (b) 0 to 1.2 × 107 cm-3 (ionized), and (c) 0 to 1.3 × 107 cm-3 (ionized). The circle shows the location of the Bondi-Parker critical radius of the ionized gas for spherical flow. The arrows show the velocity of the flow in the X-Z plane. In panel a, the longest arrow in the molecular flow represents 26.6 km s-1, and the longest arrow in the ionized flow represents 21.5 km s-1. In panel b, the longest arrow in the molecular flow represents 8.0 km s-1, and the longest arrow in the ionized flow represents 28.2 km s-1. In panel c, the longest arrow in the molecular flow represents 5.4 km s-1, and the longest arrow in the ionized flow represents 29.4 km s-1. In the ionized outflow flow, the velocity is the sound speed at the critical radius. The axes are labeled in units of Rd, 42 AU (top), 47 AU (middle), and 51 AU (bottom).

G10.6–0.4 shows accretion of ionized gas at $10^{-4}\ M_{\odot}\ yr^{-1}$ onto a 500 $M_{\odot}$ cluster



Keto & Wood 06

Model of the continuum emission at 1.3 cm from star cluster G10.6–0.4. on top of the observed radio continuum. The model shows an ionized accretion disk and ionized globules in the clumpy gas around the disk. The model is a Terebey et al. (1984) accretion disk with a centrifugal radius of 3500 AU, and an infall rate of 10-4 M⊙ yr-1 onto a 500 M⊙ cluster with additional density fluctuations imposed on the otherwise smooth structure of the underlying accretion flow. The angular scale is set for a distance of 6 kpc. The contour levels in the data start at 1 mJy beam-1 and increase in half magnitude levels.



Keto 02

Position-velocity diagram of NH3(1,1) in absorption (dotted lines) in front of the G10.6–0.4 H II region from Keto, Ho, & Haschick (1988). Three hyperfine lines of the NH3(1,1) transition are shown in the center of the figure as well as a fourth at the left edge. The heavy dark line across the contours of the main hyperfine absorption line is a model for the line center velocity of the ammonia as a function of position (see text). The slope of this line across the H II region indicates rotation, while the C or arc shape indicates the infall. The infall is also defined by other indicators as explained in Keto et al. (1988). The contour interval is 0.03 Jy beam-1 in a 0&farcs;3 beam. The lighter solid line is the intensity-weighted average velocity of the H66α line derived from Fig. 2 by tracing the velocities of the recombination line emission along the long axis of the H II region.

photoevaporating disks

see further work by:

Lizano+ 96
Johnstone+ 98
Lugo+ 04

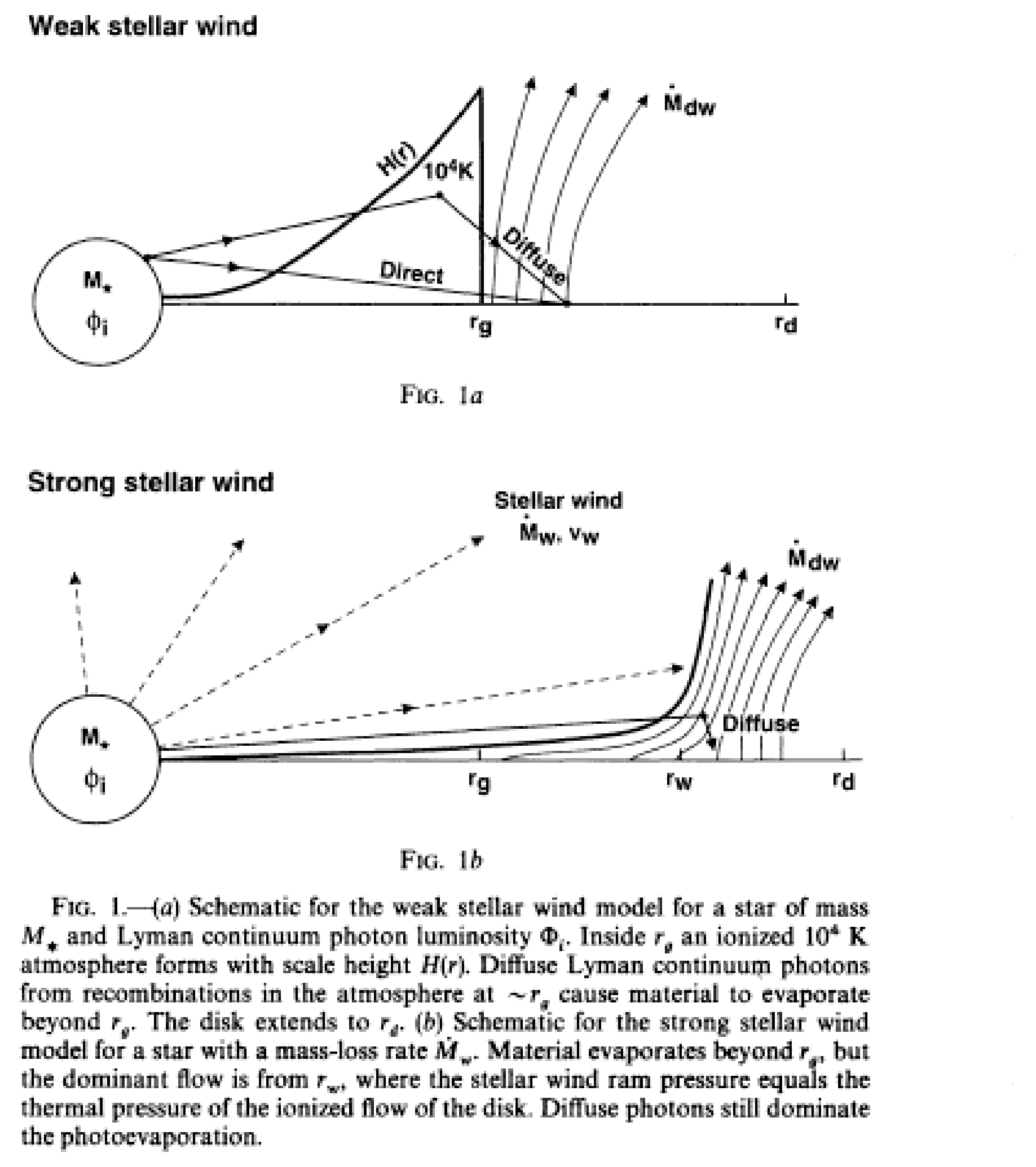
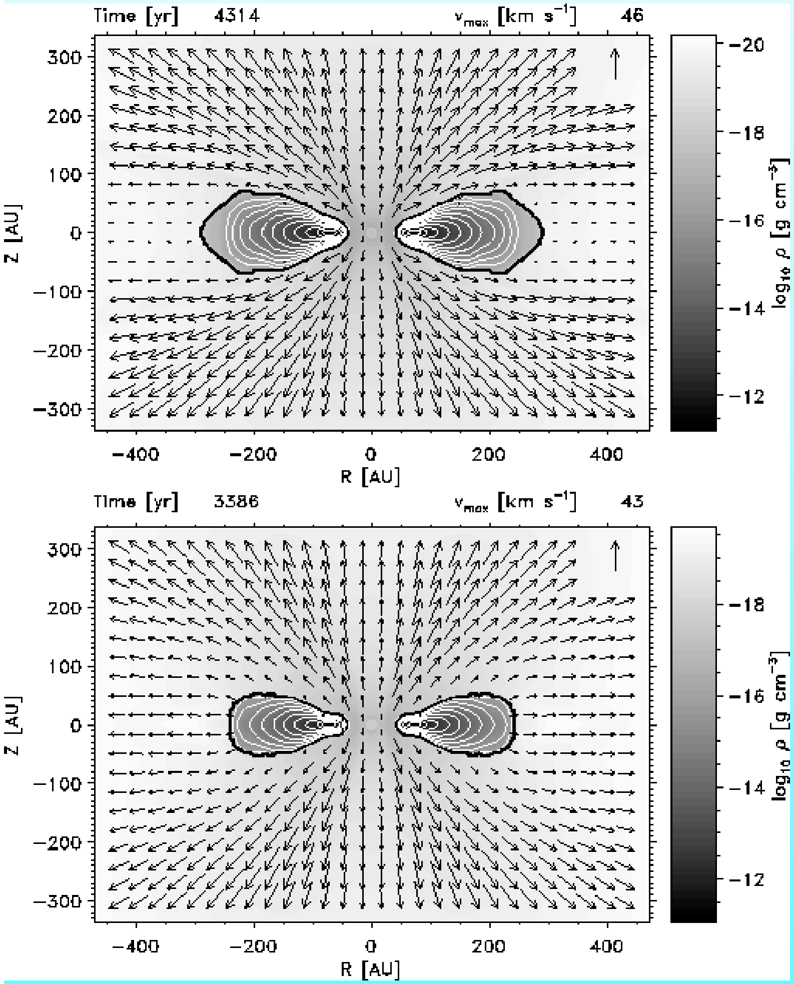


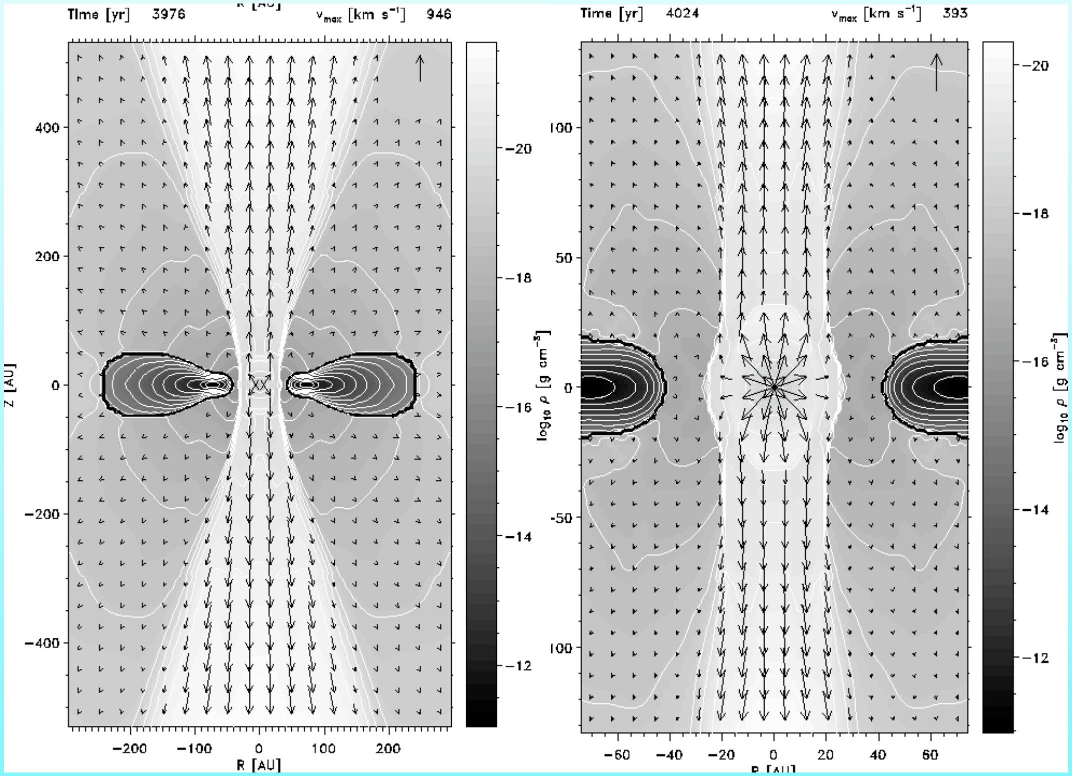
FIG. 1.—(*a*) Schematic for the weak stellar wind model for a star of mass M_* and Lyman continuum photon luminosity Φ_i. Inside r_g an ionized 10^4 K atmosphere forms with scale height $H(r)$. Diffuse Lyman continuum photons from recombinations in the atmosphere at $\sim r_g$ cause material to evaporate 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+ 94

no dust vs dust



400 km/s vs 1000 km/s wind



Richling & Yorke 97

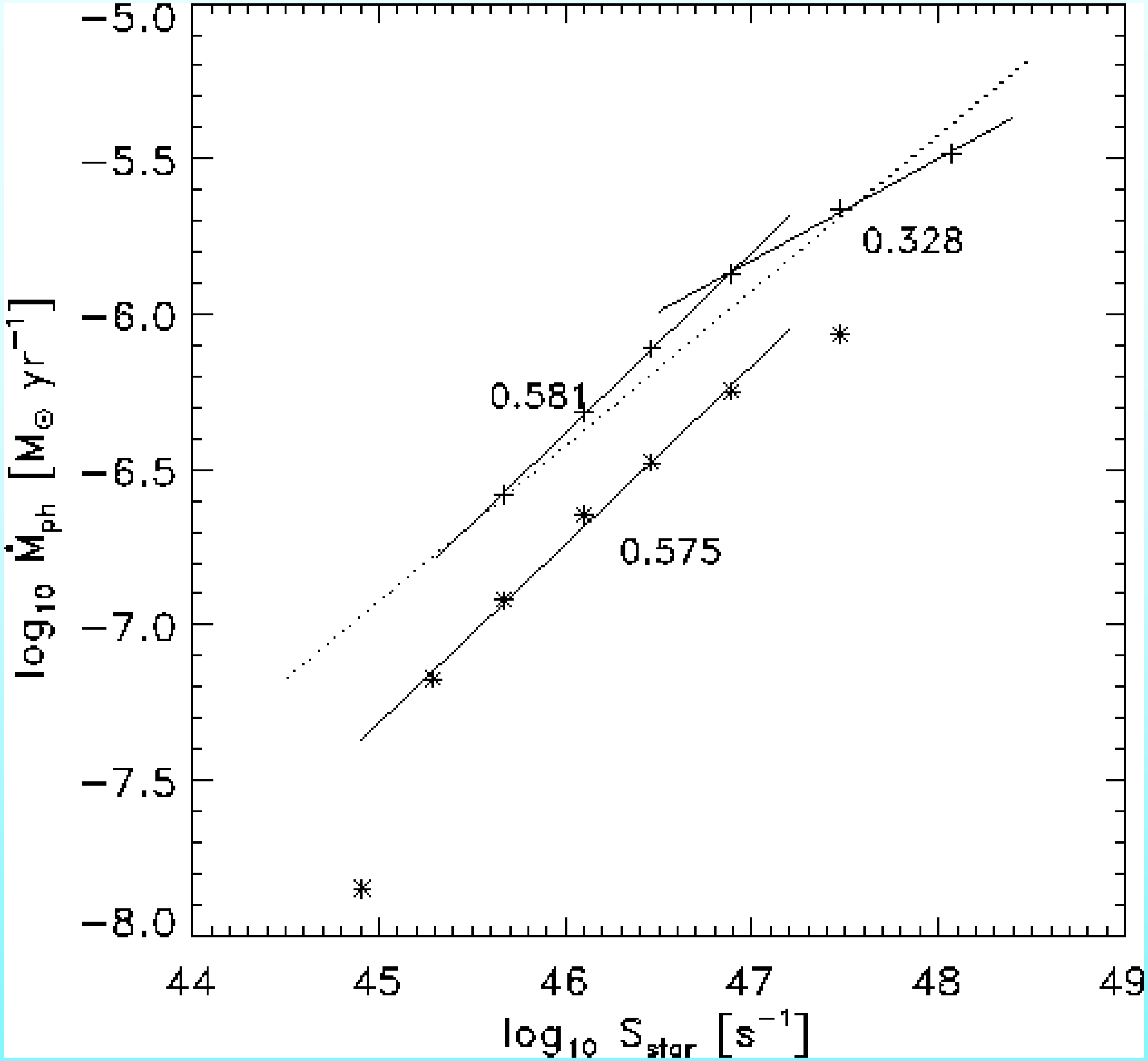
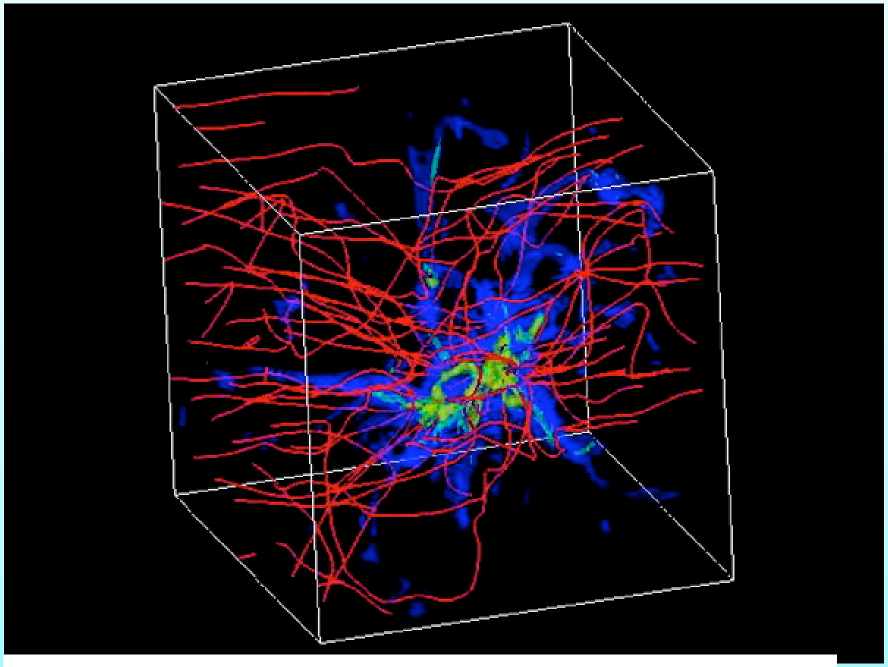


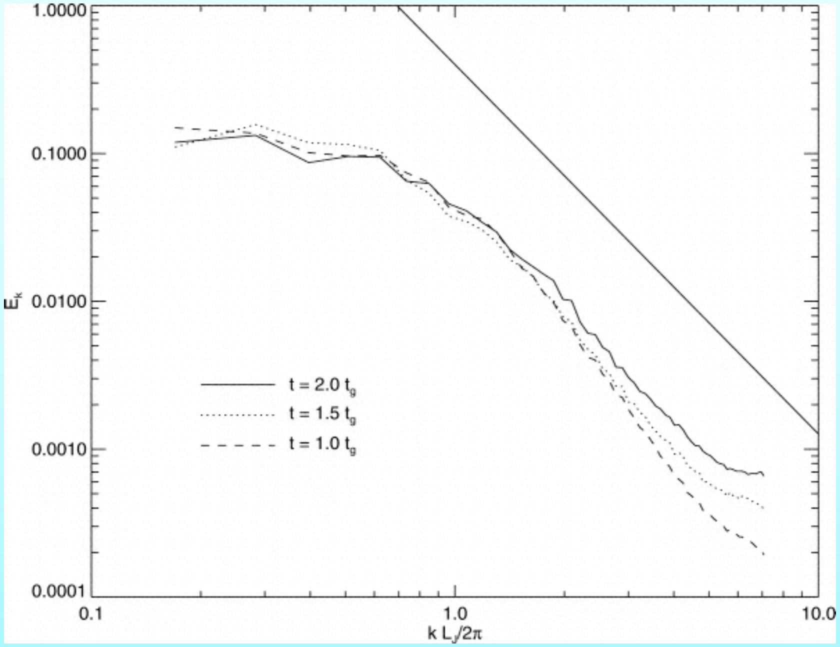
Fig. 7. Dependence of the photoevaporation rate on the stellar photon rate. The stars(crosses) are results from simulations without(with) dust scattering (cases A+D and C+E). Straight lines are the result of a power law fit; they are labeled with the appropriate power law index. The dotted line is taken from HJLS.

Richling & Yorke 97

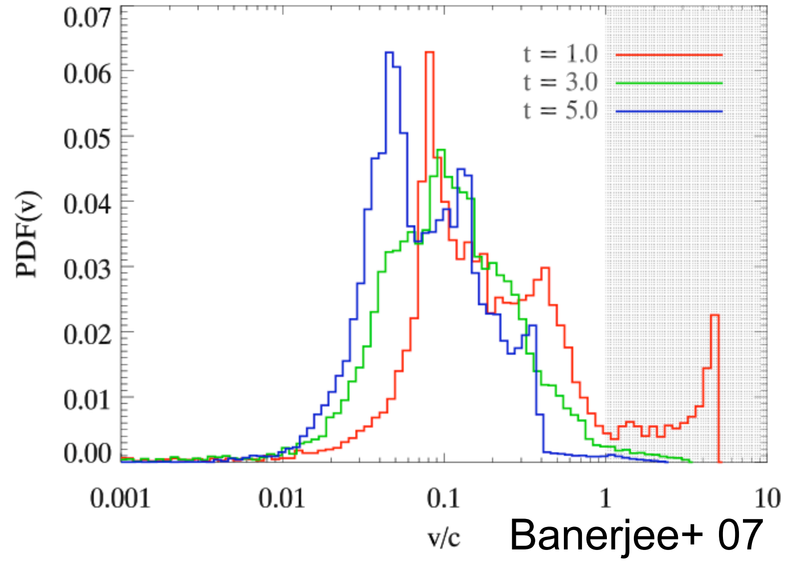
Outflows suggested to support cluster-forming cores; but can they limit accretion?



Z. Li & Nakamura 07



prominent break in power spectrum close to outflow length, not yet observed (Ossenkopf & Mac Low 02 for Polaris flare, though no cluster there)



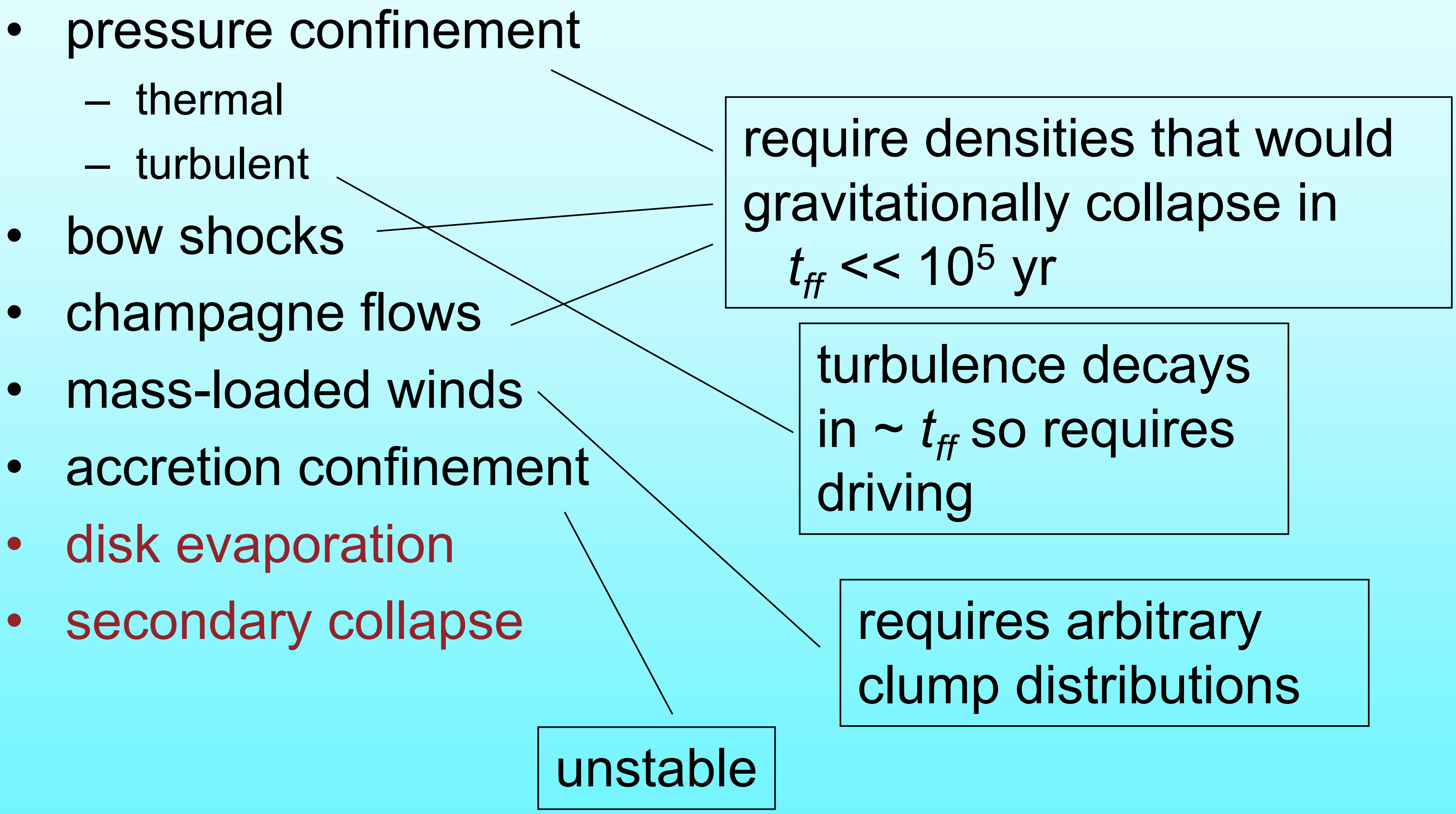
Banerjee+ 07

Mach 5 jet leaves little super-sonic material

Ultracompact H II regions

- Lifetime problem: if every UC H II region seen surrounds an OB star, UC H II lifetime is 10^5 yr, but dynamical age is only 10^4 yr
- Must distinguish between genuinely young massive stars (hypercompact regions?) and other causes.
- These objects are probably the most easily observed consequences of ionizing feedback.

Confinement of UC H II regions



- pressure confinement
  - thermal
  - turbulent
- bow shocks
- champagne flows
- mass-loaded winds
- accretion confinement
- disk evaporation
- secondary collapse

require densities that would gravitationally collapse in $t_{ff} << 10^5$ yr

turbulence decays in ~ t_{ff} so requires driving

requires arbitrary clump distributions

unstable

arguments & references summarized in Mac Low+ 07

Second conclusion:

Bad news: We don’t know what stops large stars from growing larger, though we have multiple suspects.

Large-scale feedback

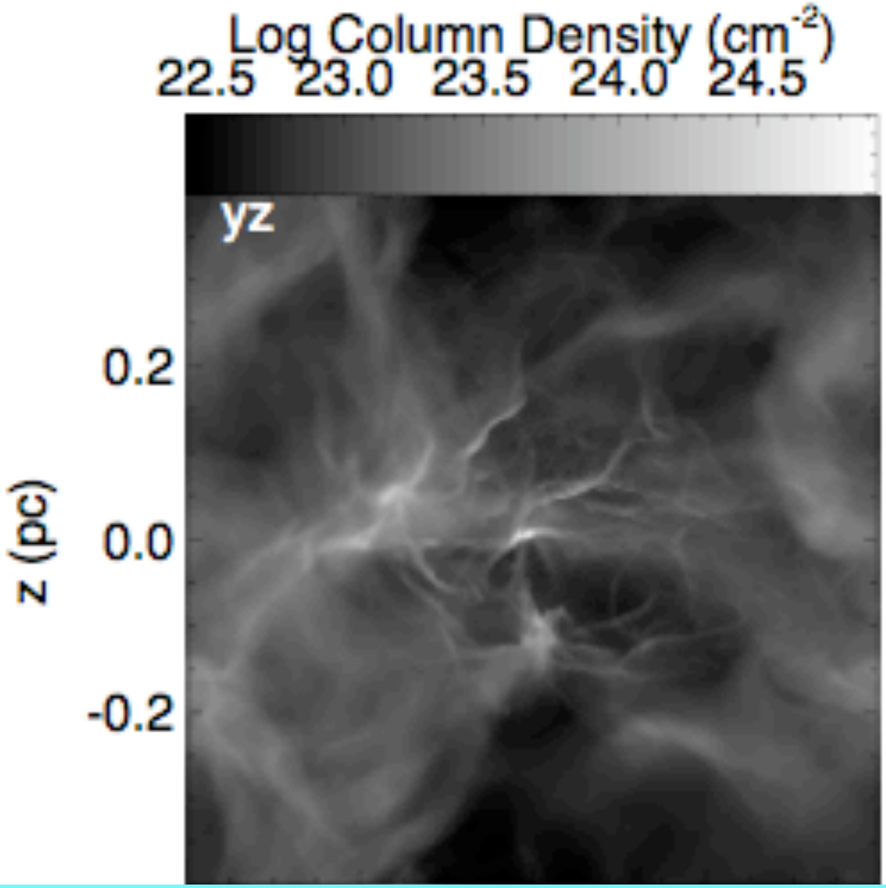
- ionizing radiation
- line-driven stellar winds
- supernovae

Do these support molecular clouds for many dynamical times?

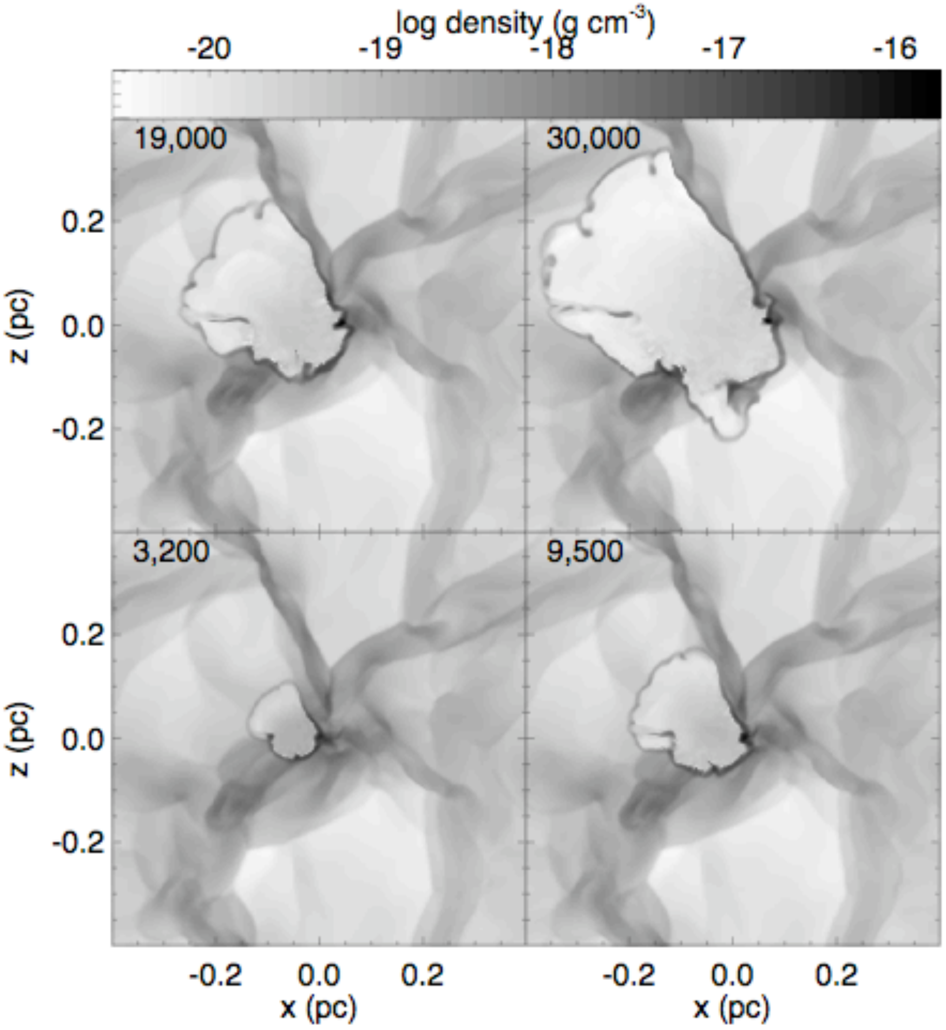
Can feedback sustain star formation: is the triggering efficiency above unity?

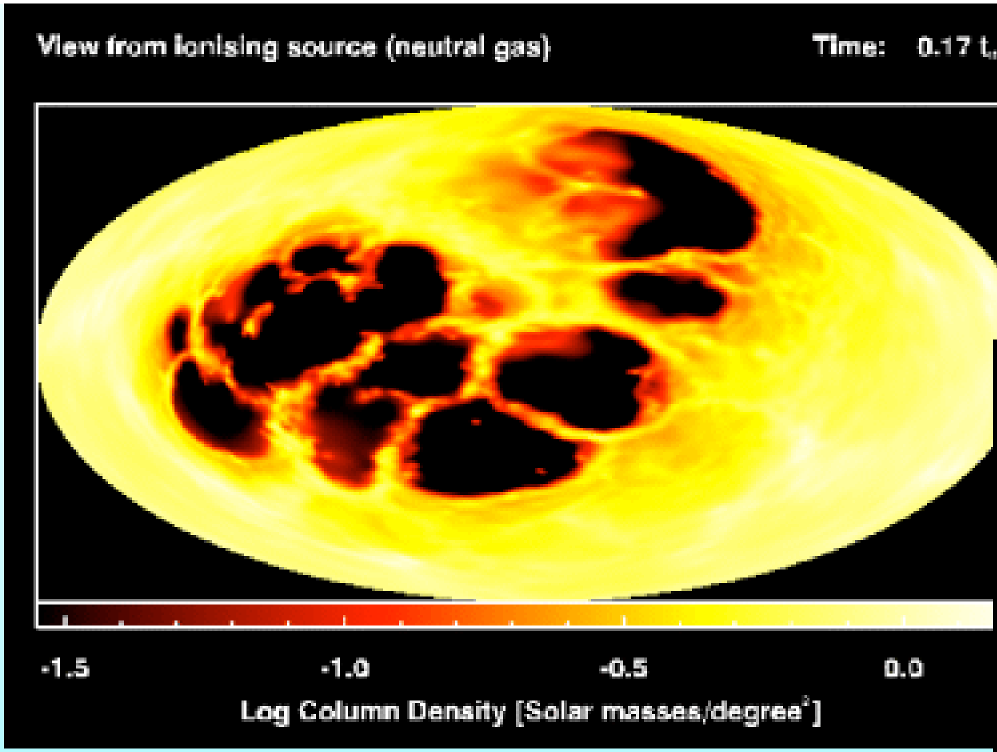
Does something “trigger” gravitational collapse and star formation?

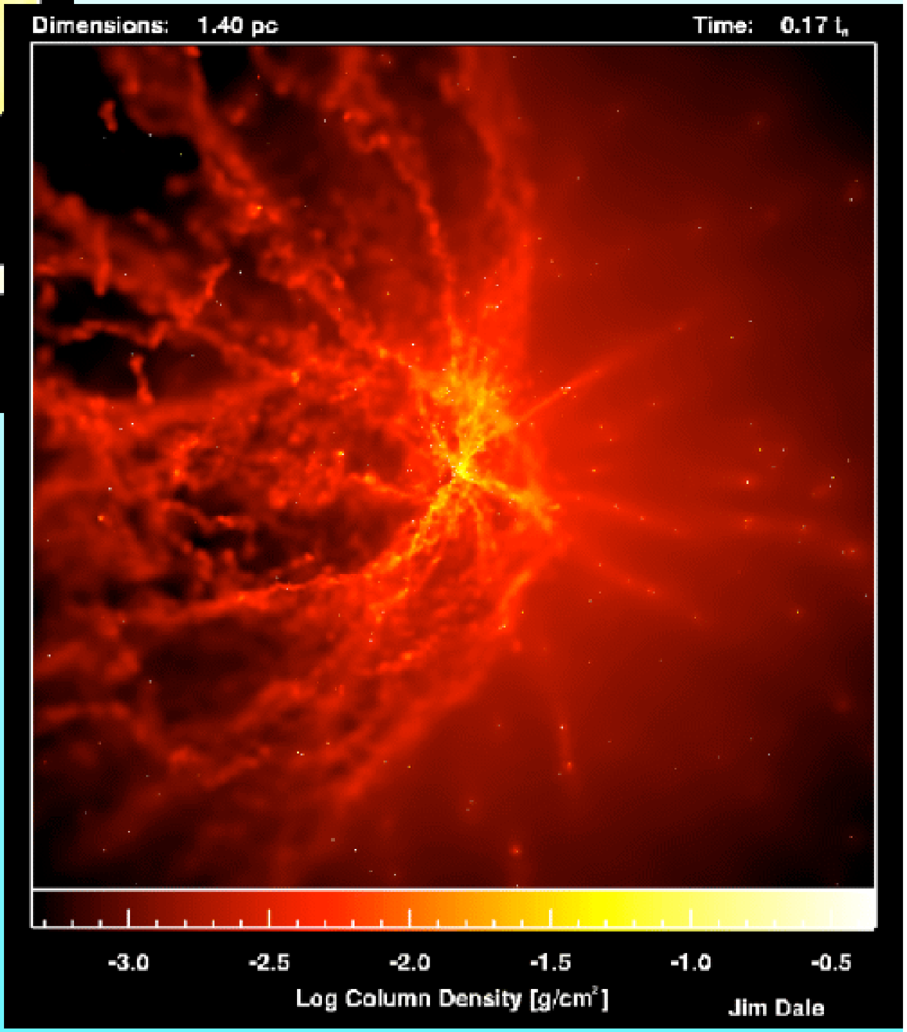
H II regions?



Mac Low+ 07





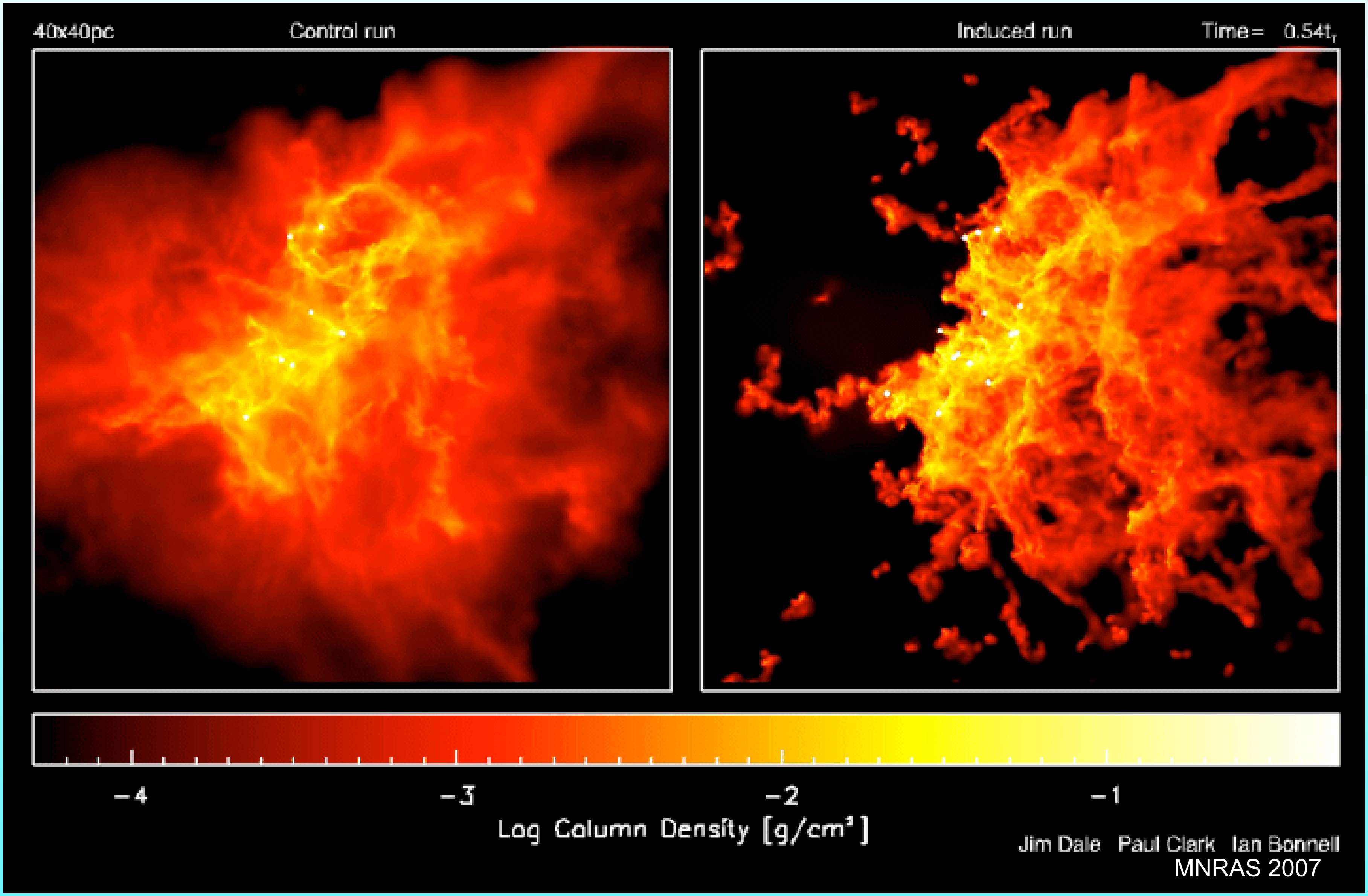


- clumpy gas allows blowout of ionization front
- denser regions resist ionization, continue to collapse
- ambiguous triggering efficiency (both positive, negative effects)

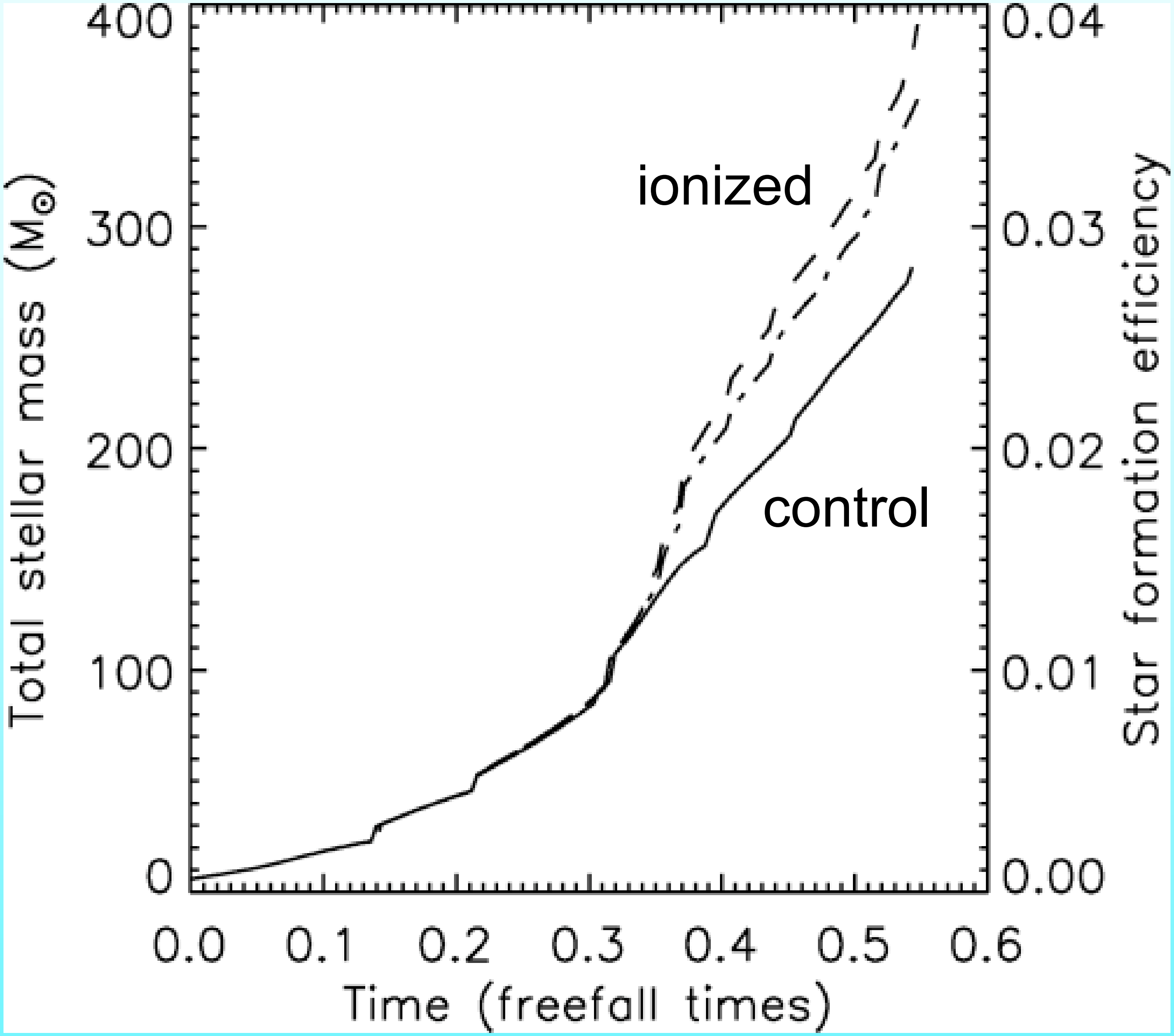
Dale+ 05

control

ionized



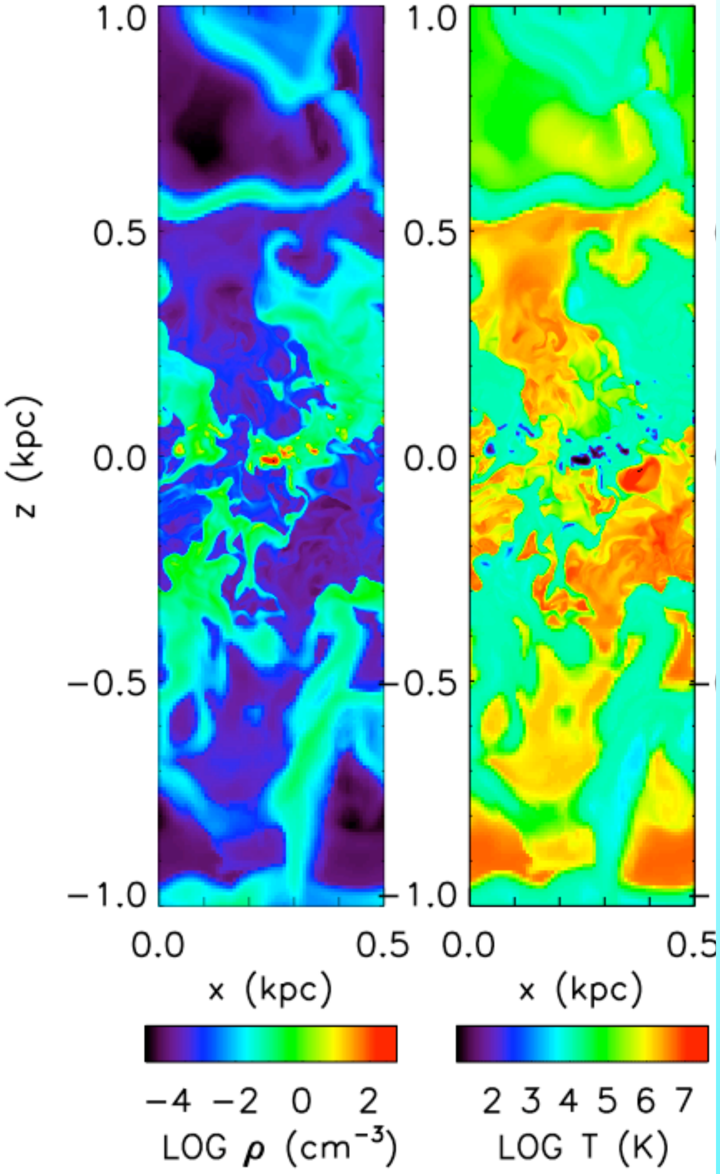
Jim Dale Paul Clark Ian Bonnell
MNRAS 2007

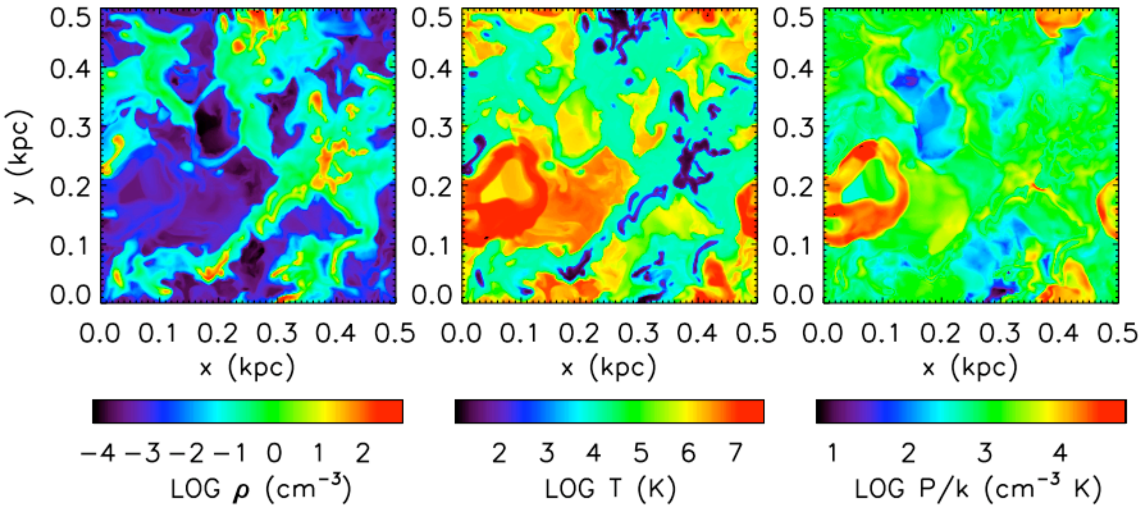


inefficient
triggering

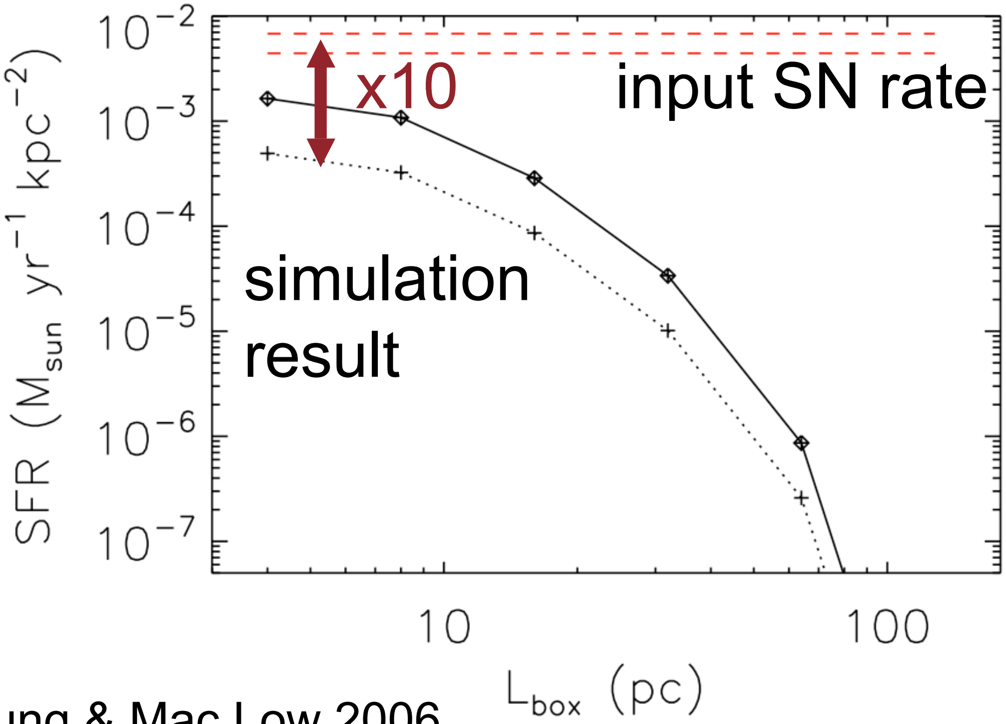
Figure 5. Plot of total stellar mass and fractional star formation efficiency in the control run (solid line), in the feedback run (dashed line) and in the feedback run, excluding cores whose formation is triggered (dash–dotted line). Dale, Clark, & Bonnell 2007

what about supernovae?





Flash models of stratified, SN-driven ISM



x10

input SN rate

simulation result

Joung & Mac Low 2006

Third conclusion:

Triggering of star formation present, but inefficient (10% effect)

Also see N. Mizuno+ 07, who estimate that H II region triggering drives at most 10-30% of star formation in Galaxy.

How long-lived are molecular clouds?

$t_{GMC} = 10 t_{ff}$

$t_{GMC} = t_{ff} = t_{cross}$

turbulent envelopes
supercritical cores
Krumholz+ 06

turbulent envelopes
shock compressed cores
Padoan+ 07

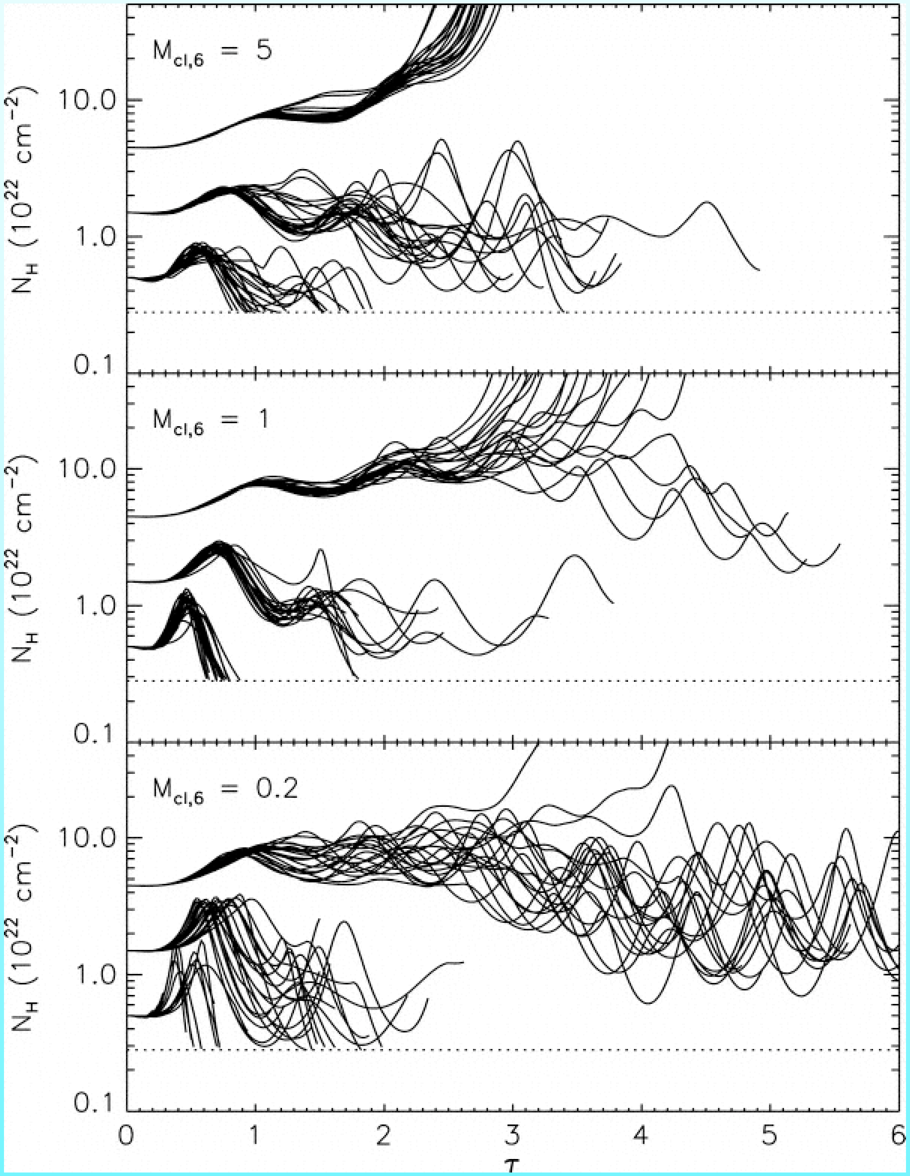
subcritical envelopes
subcritical cores
Mouschovias+ 06

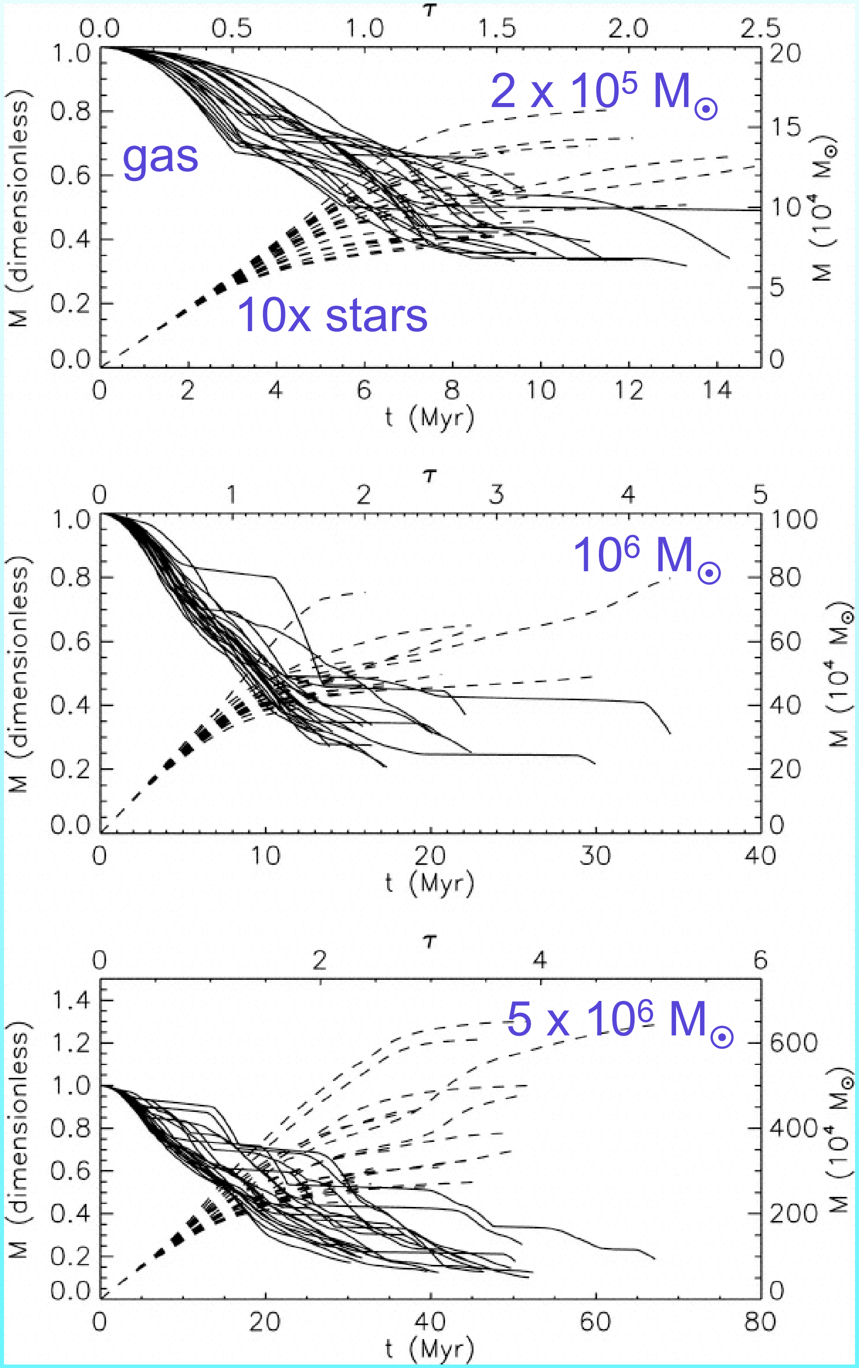
subcritical envelopes
critical cores
Elmegreen 07

Ballesteros-Paredes+ 99

Y. Li+ 06 - galactic scale

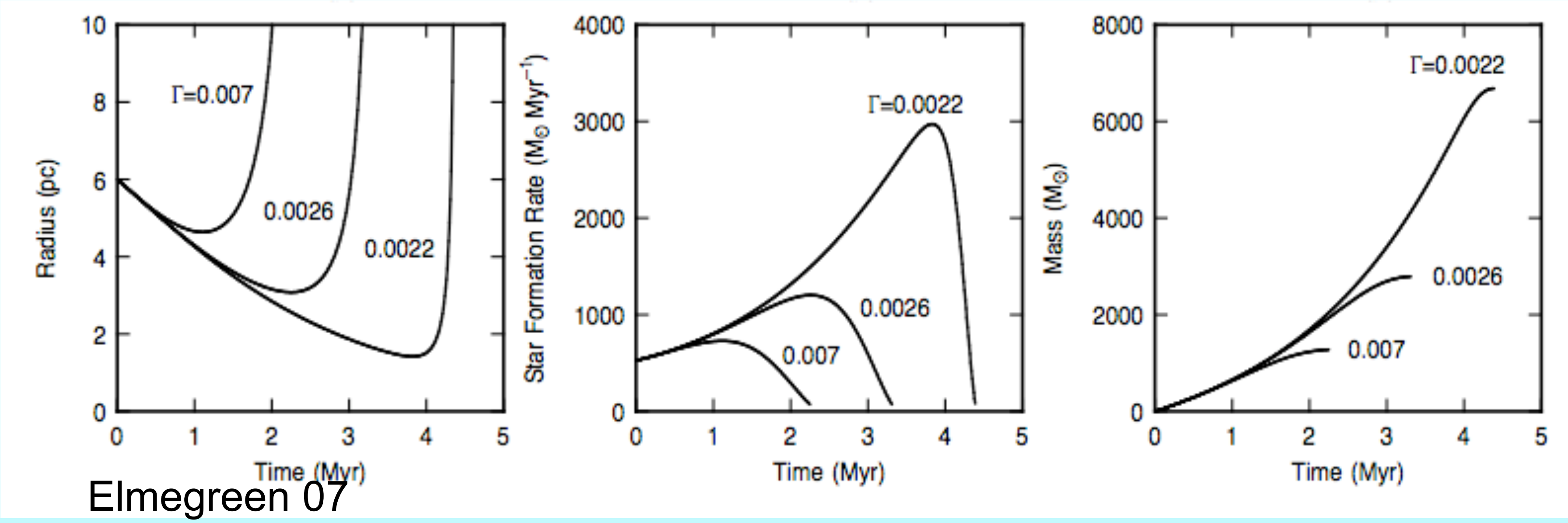
Krumholz+ 06





also see similar work by

Huff & Stahler 06

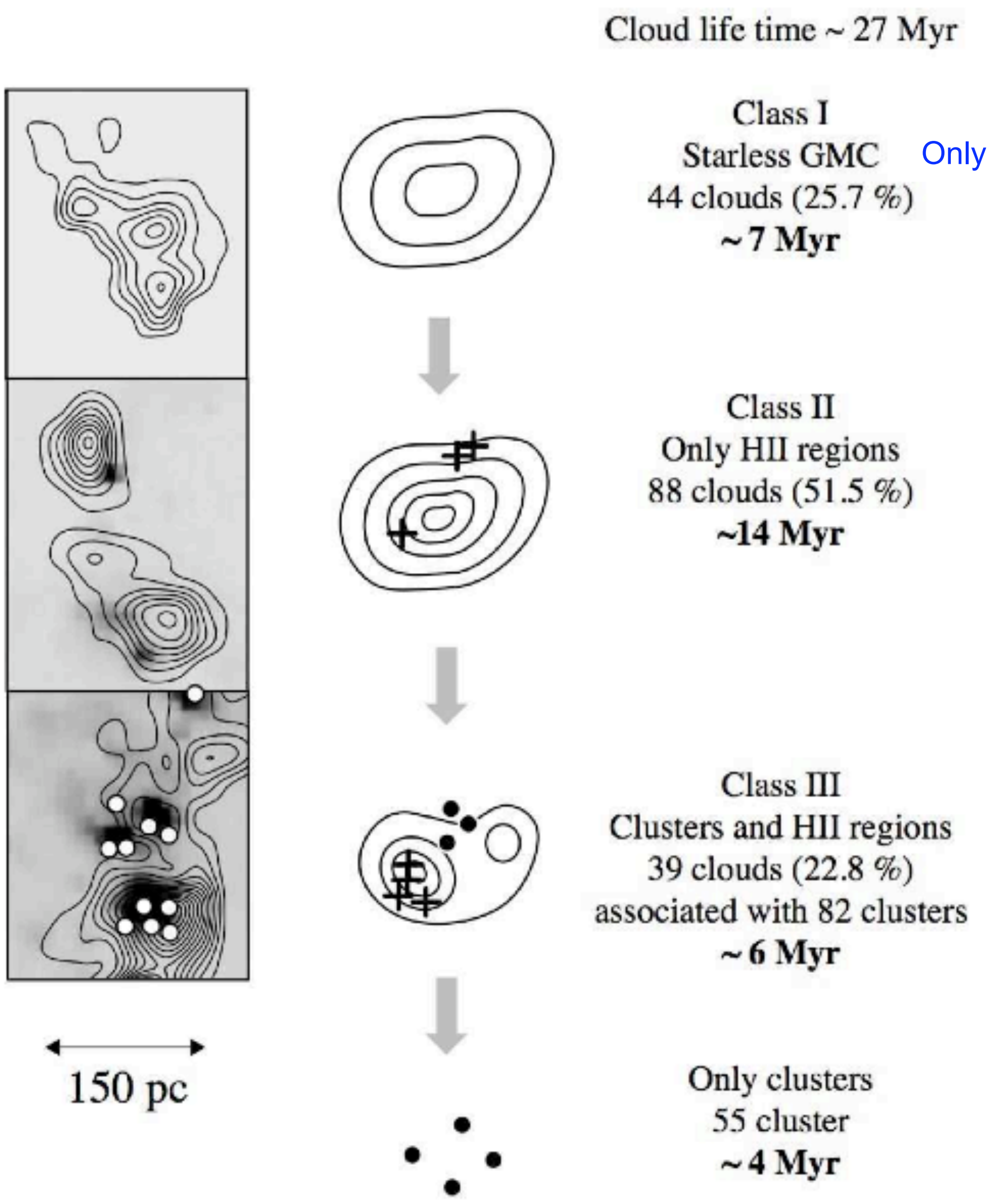


Elmegreen 07

10^4 $M_\odot$ cloud
"H II" feedback

spherical cloud core rather than filamentary GMC

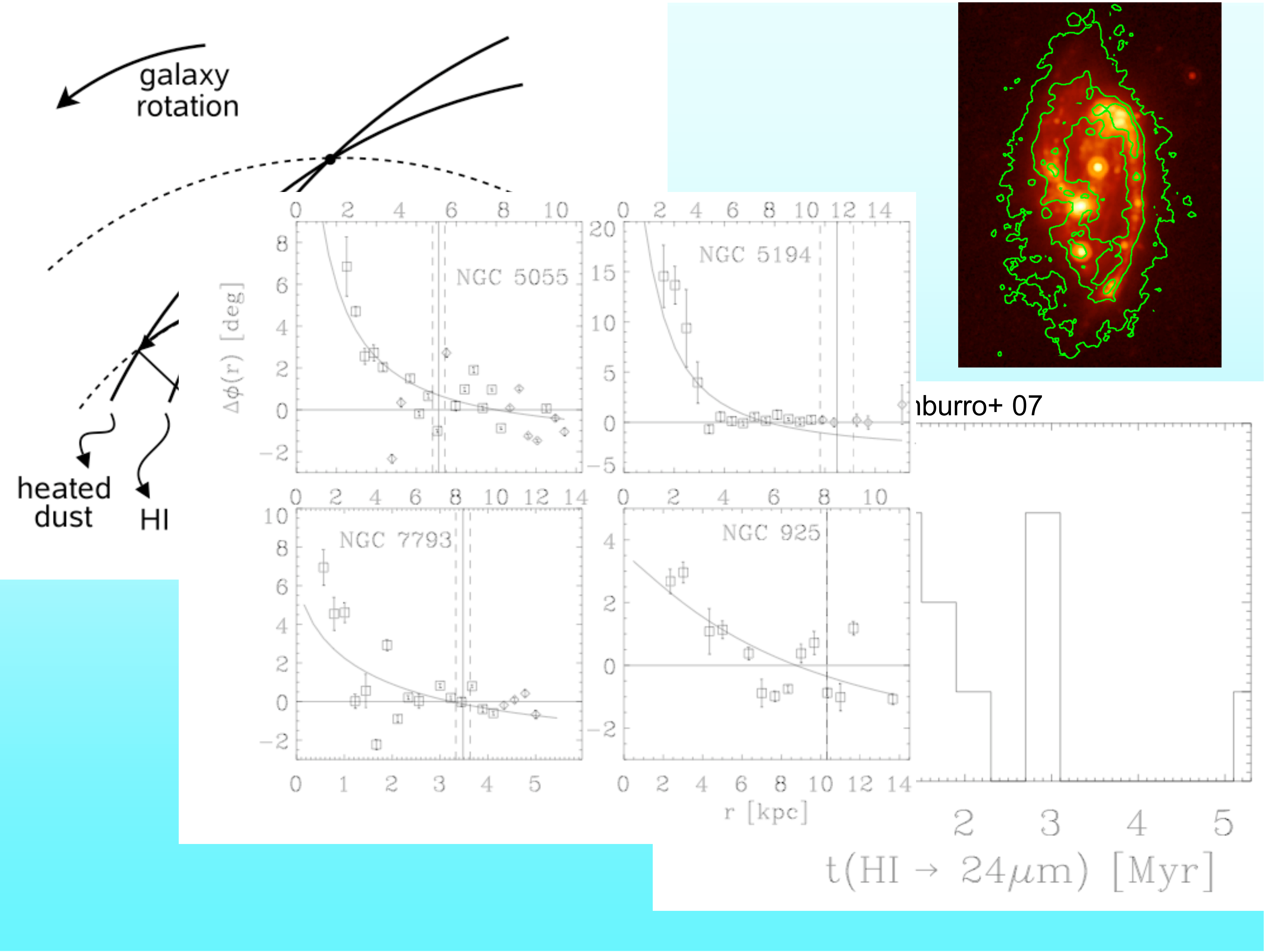
LMC cloud lifetimes



Only YSOs

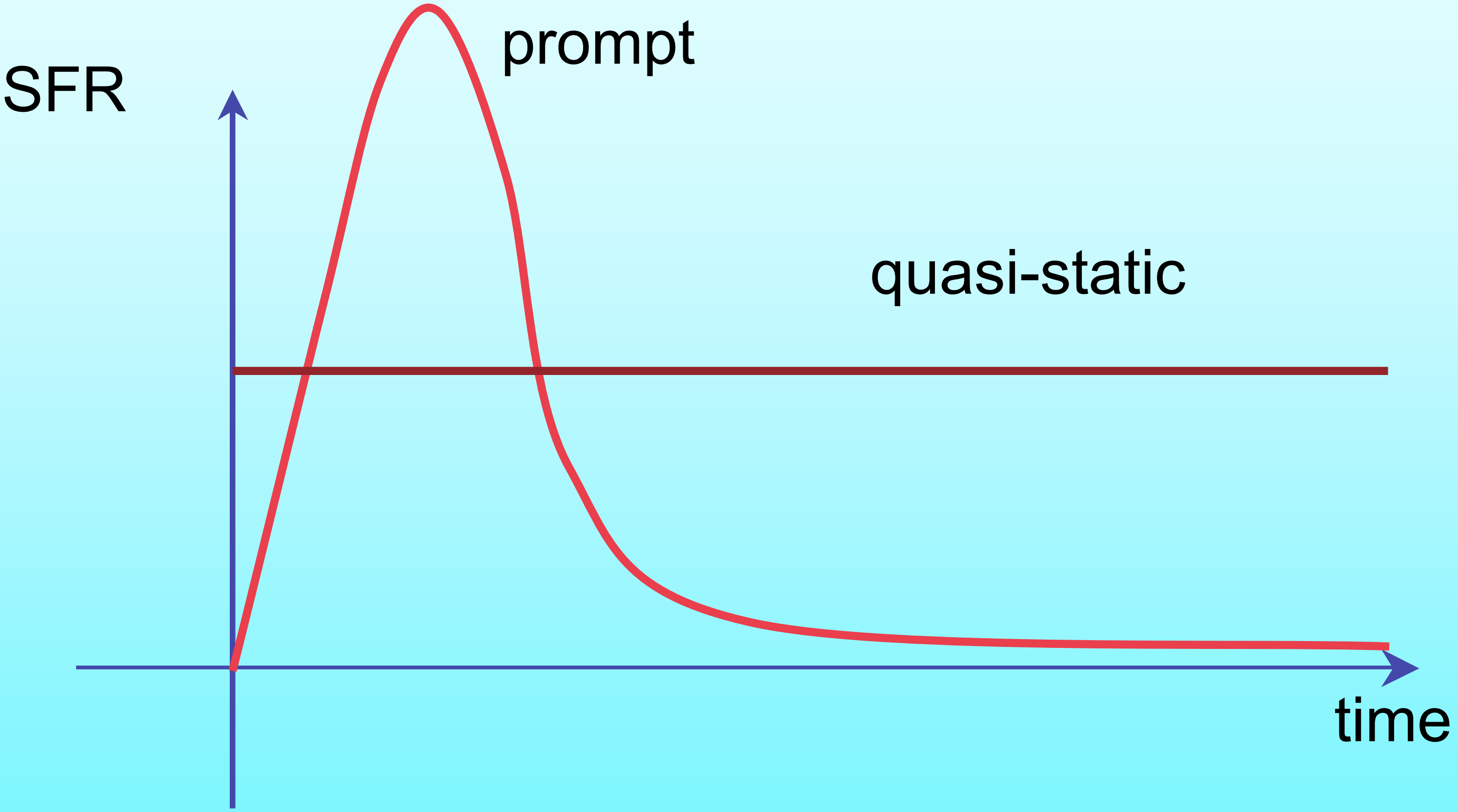
Blitz, Fukui+ 06

so-called "starless GMCs" actually have Spitzer YSOs within them (Gruendl+ 07)


galaxy
rotation
heated
dust
HI
NGC 5055
NGC 5194
NGC 7793
NGC 925
Δφ(r) [deg]
r [kpc]
0
2
4
6
8
10
12
14
15
20
−2
−5
1
3
5
t(HI → 24μm) [Myr]

ıburro+ 07

So how to reconcile lifetimes?



average gas depletion time may not be instantaneous value

thx for discussion to F. Heitsch…

Fourth conclusion:

Most star formation in GMCs likely prompt, despite feedback.

also see Motte’s talk - fast star formation in individual dense cores in GMC complexes

Conclusions

- Good news: Large stars can grow despite radiation pressure.
- Bad news: We don't know what stops large stars from growing larger, though we have multiple suspects.
- Triggering of star formation present, but inefficient
- Most star formation in GMCs likely prompt, despite feedback