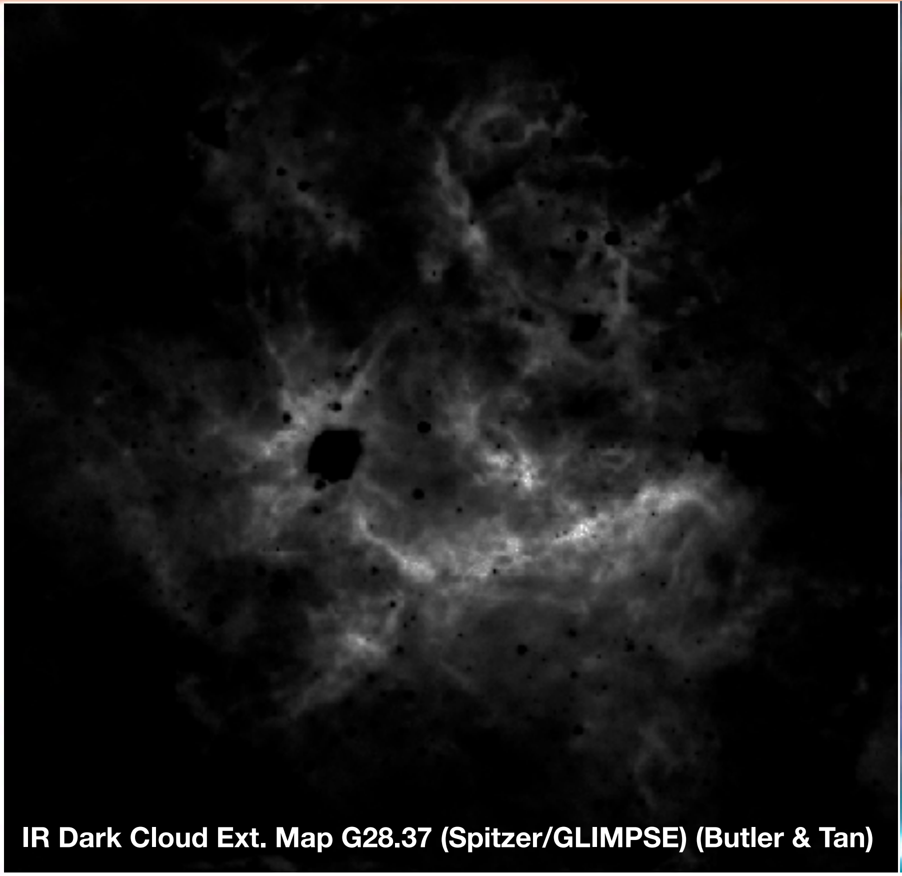
The Birth and Influence of Massive Stars



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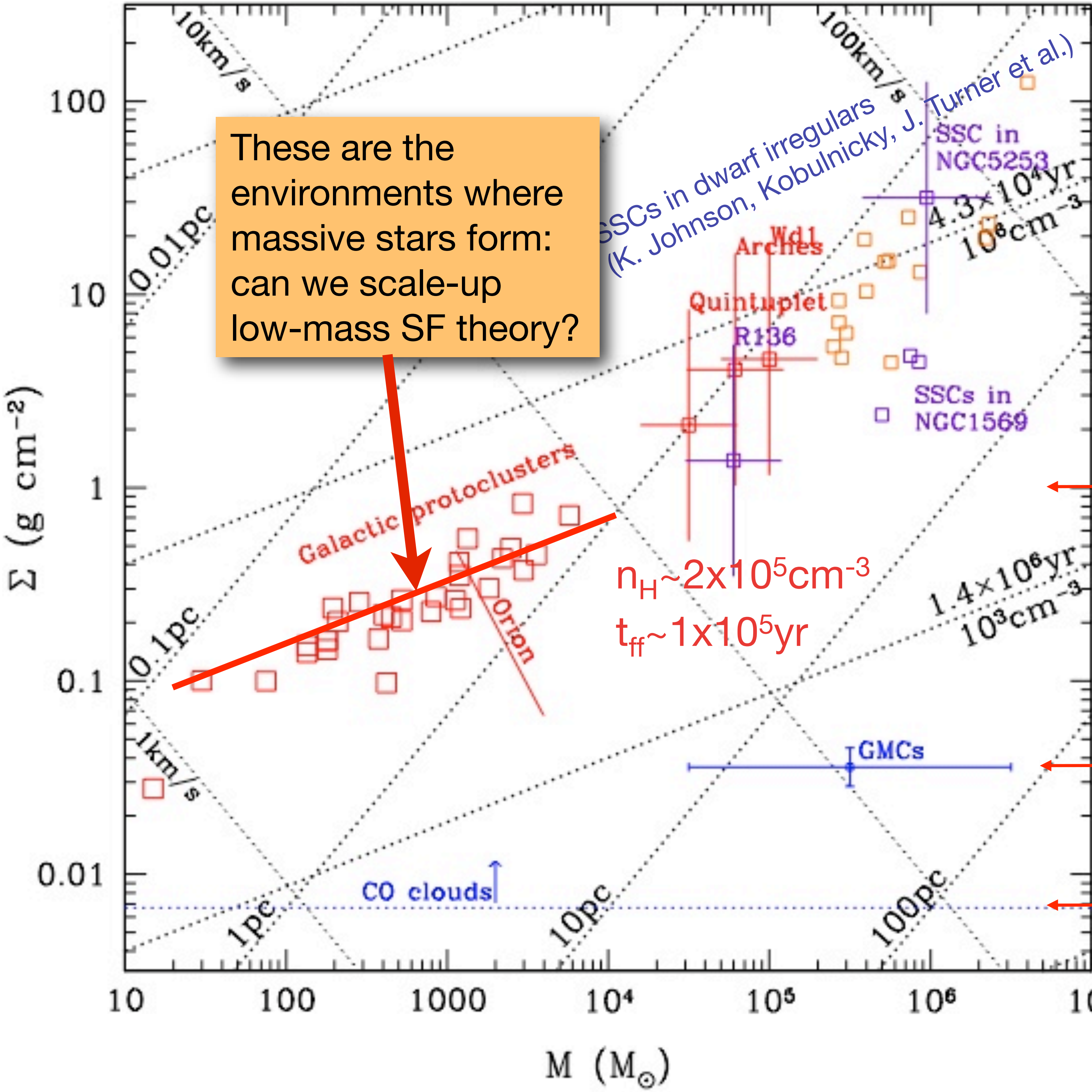
Outline

- Physical properties of massive star-forming regions
- Theoretical scenarios - core accretion, competitive accretion, mergers, etc.
- The “Turbulent Core Accretion” Model
- **Initial conditions:** IRDCs; how are they generated? Does the clump reach pressure equilibrium? Timescale of star cluster formation? Collapse of the core: fragmentation?
- **Massive protostars:** star, disk, outflow formation and evolution. Radiative transfer modeling.
- **Feedback:** outflows, ionization, rad. pressure. On core & clump.

Overview of Physical Scales



$$\Sigma \equiv \frac{M}{\pi R^2}$$

$$\bar{P} \simeq G\Sigma^2$$

$$\bar{P}/k = 4.3\times10^8 \Sigma^2\, K\, cm^{-3}$$

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

$A_V=200$
$A_{8\mu m}=8.1$
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$\Sigma=4800\ M_\odot\ pc^{-2}$

$A_V=7.5$
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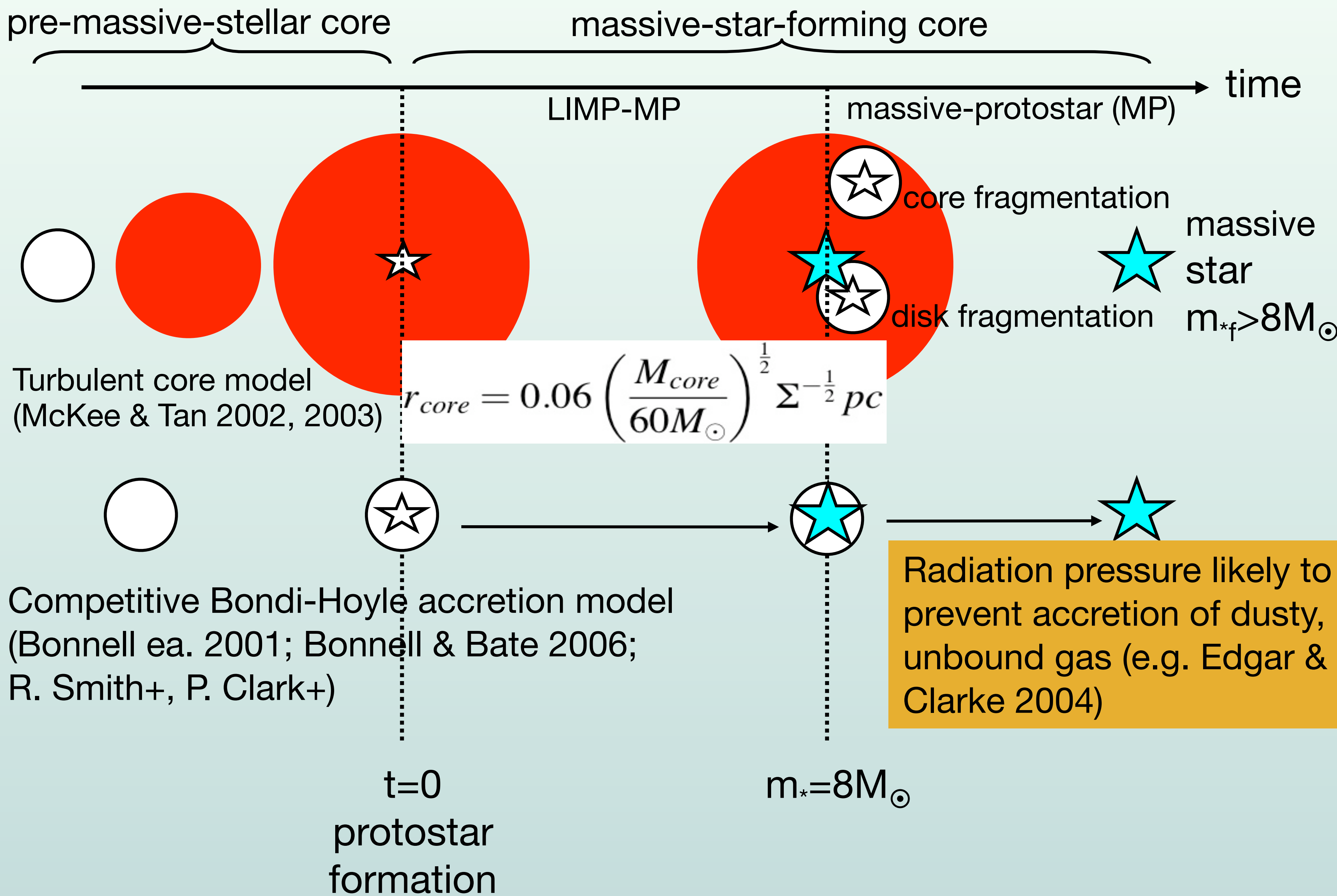
$A_V=1.4$
$N_H=3.0\times10^{21}cm^{-2}$
$\Sigma=34\ M_\odot\ pc^{-2}$

Schematic Differences Between Massive Star Formation Theories

Beuther, Churchwell, McKee, Tan (2007); Tan (2008)



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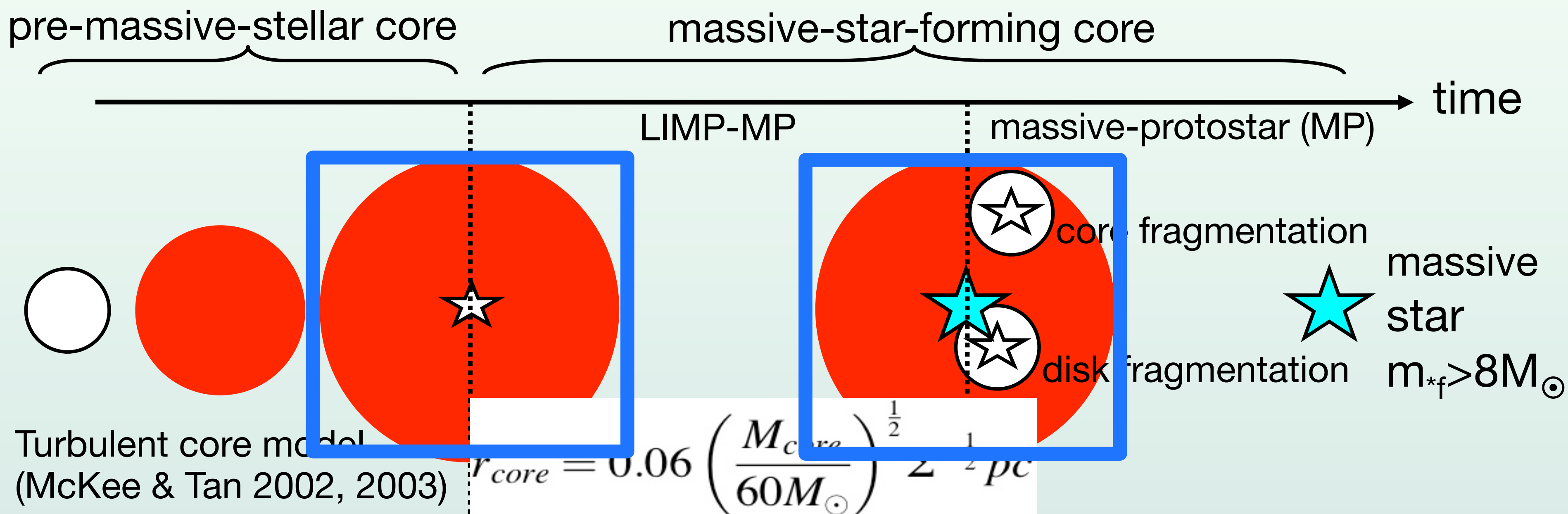

Evolution from magnetically subcritical state?

Core continues to accrete from clump

$$\dot{m}_{\rm acc} = 2.50\times10^{-4}\left(\frac{A\phi_{\rho,\rm core} f_g^2 \alpha_{\rm vir}\phi_{\rm grav}^2}{k_P^2 \epsilon_{\rm core}^2 \phi_{\bar{P}}}\right)^{1/2} \times \left(\frac{m_{*f}}{30\ M_\odot}\right)\left(\frac{M_{\rm cl}}{4000\ M_\odot}\right)^{-1/4}\Sigma_{\rm cl}^{3/4}\ M_\odot\ {\rm yr}^{-1} \quad (54)$$

$$\rightarrow 7.9\times10^{-4}\left(\frac{\phi_{\rm grav}}{1.6}\right)\left(\frac{m_{*f}}{30\ M_\odot}\right)\left(\frac{M_{\rm cl}}{4000\ M_\odot}\right)^{-1/4} \times \Sigma_{\rm cl}^{3/4}\ M_\odot\ {\rm yr}^{-1}\ . \quad (55)$$

Thus, we see that a massive core will tend to interact with clump material at a rate that is comparable to the rate at which it is collapsing or being eroded by star formation, $\dot{m}_*/\epsilon_{\rm core}$. This rate is a factor of several smaller in SSCs with $M_{\rm cl}\sim10^6\ M_\odot$.

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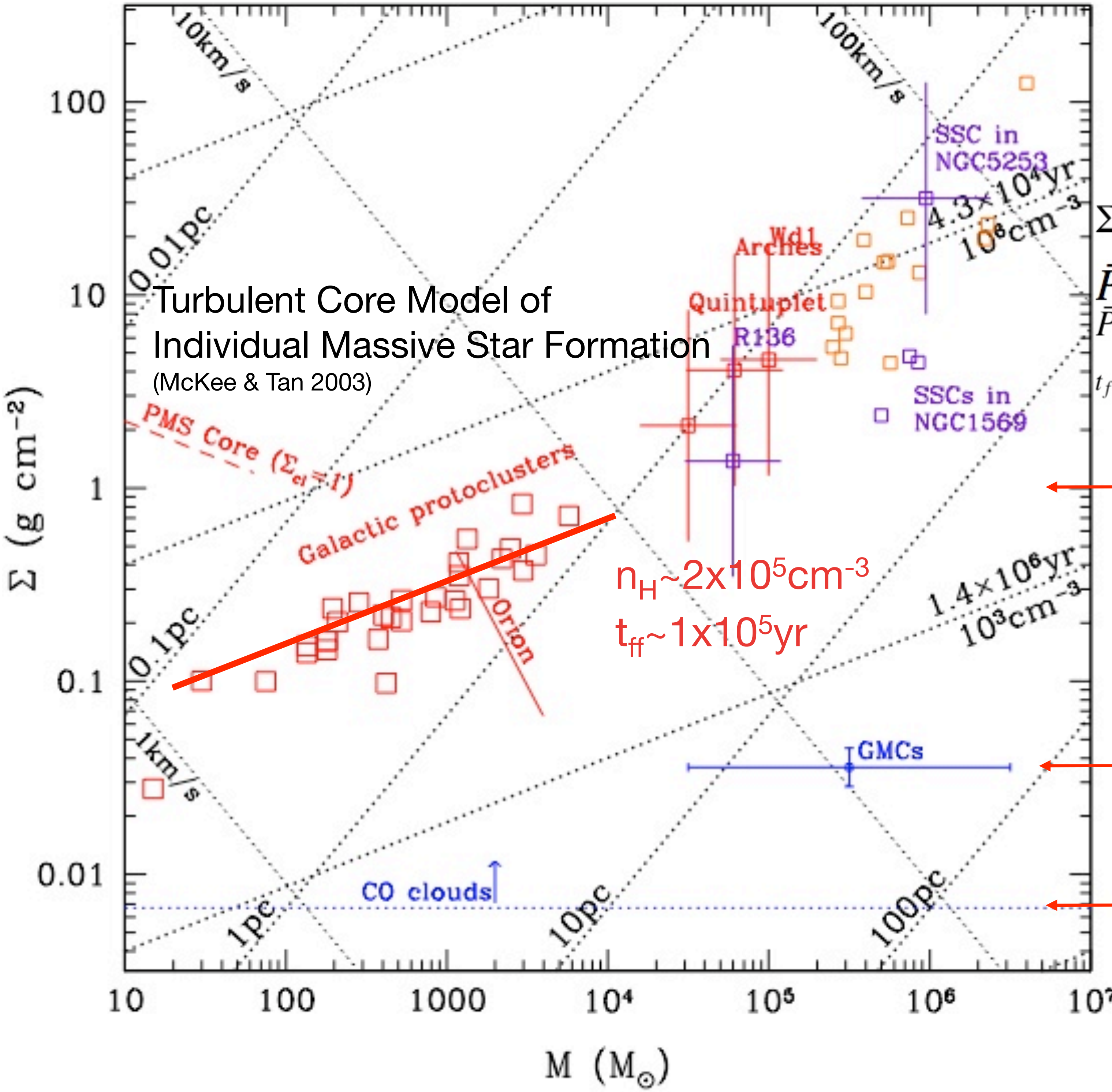

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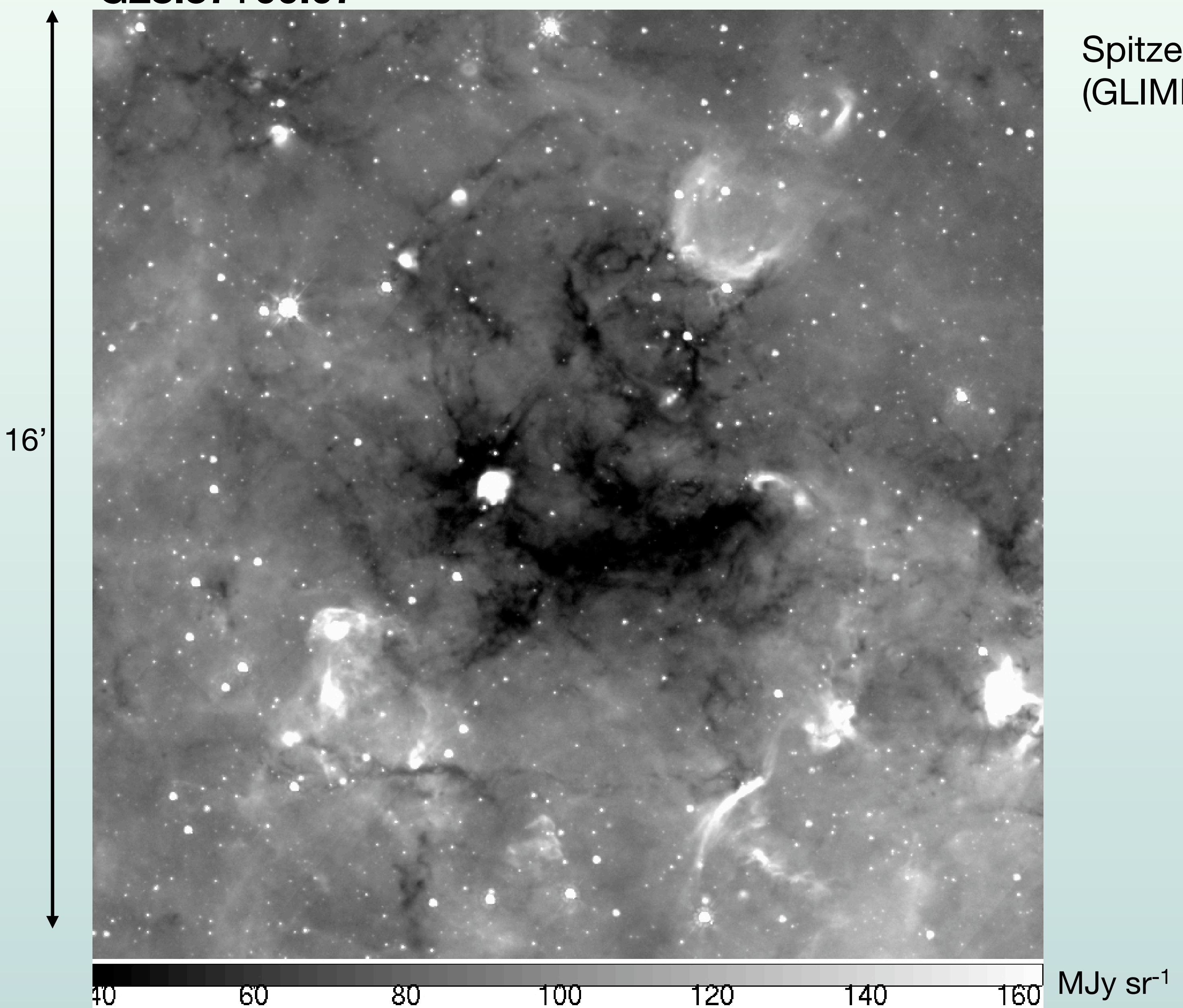
Mid-IR Extinction Mapping of Infrared Dark Clouds

(Butler & Tan 2009; see also Peretto & Fuller 2009; Ragan et al. 2009)

G28.37+00.07



Spitzer - IRAC 8μm
(GLIMPSE)

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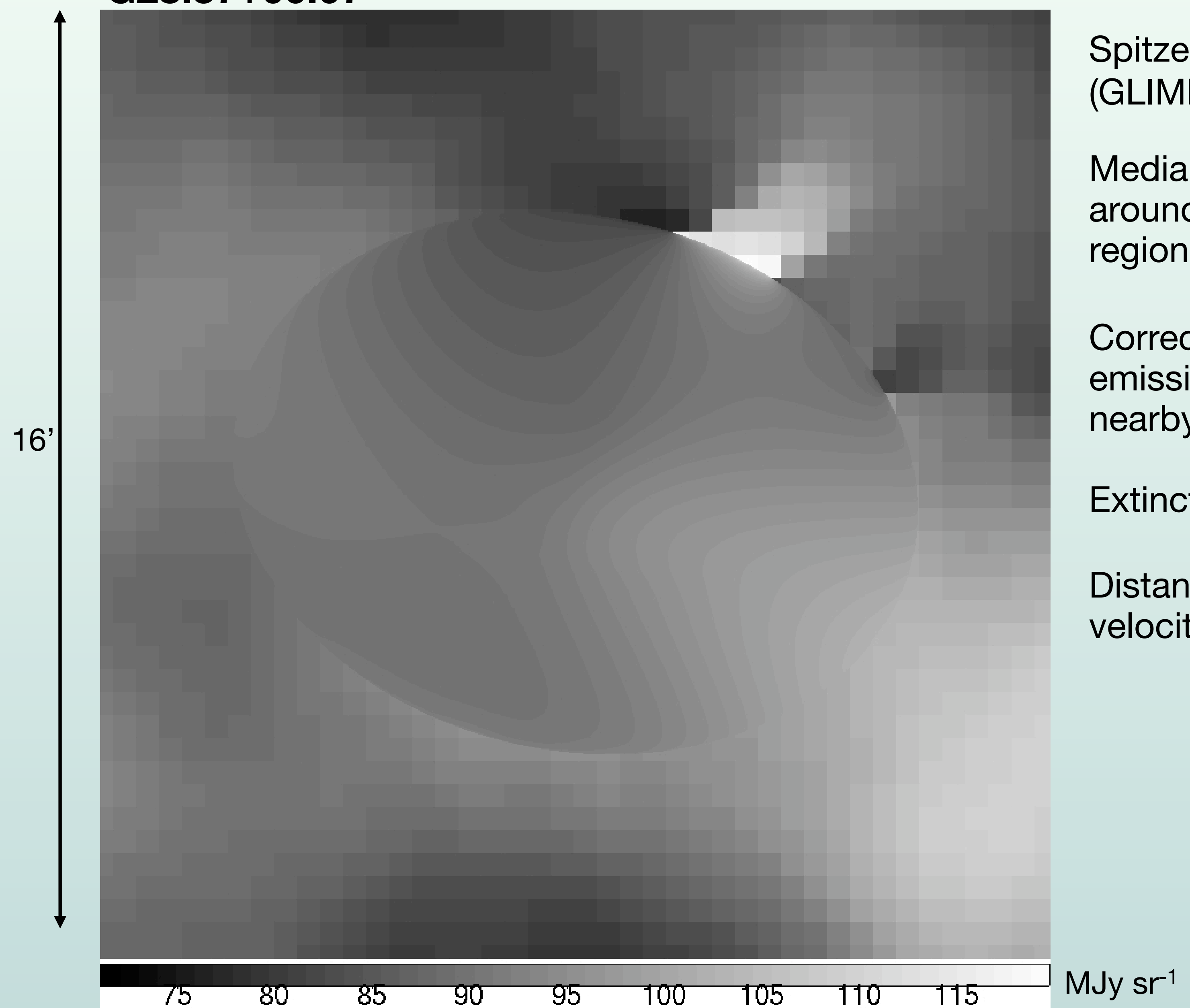

Spitzer - IRAC 8μm (GLIMPSE)

Median filter for background around IRDC; interpolate for region behind the IRDC

Correct for foreground emission - tricky-> choose nearby clouds

Extinction map to derive Σ

Distance from molecular line velocities (GRS) -> M(Σ)

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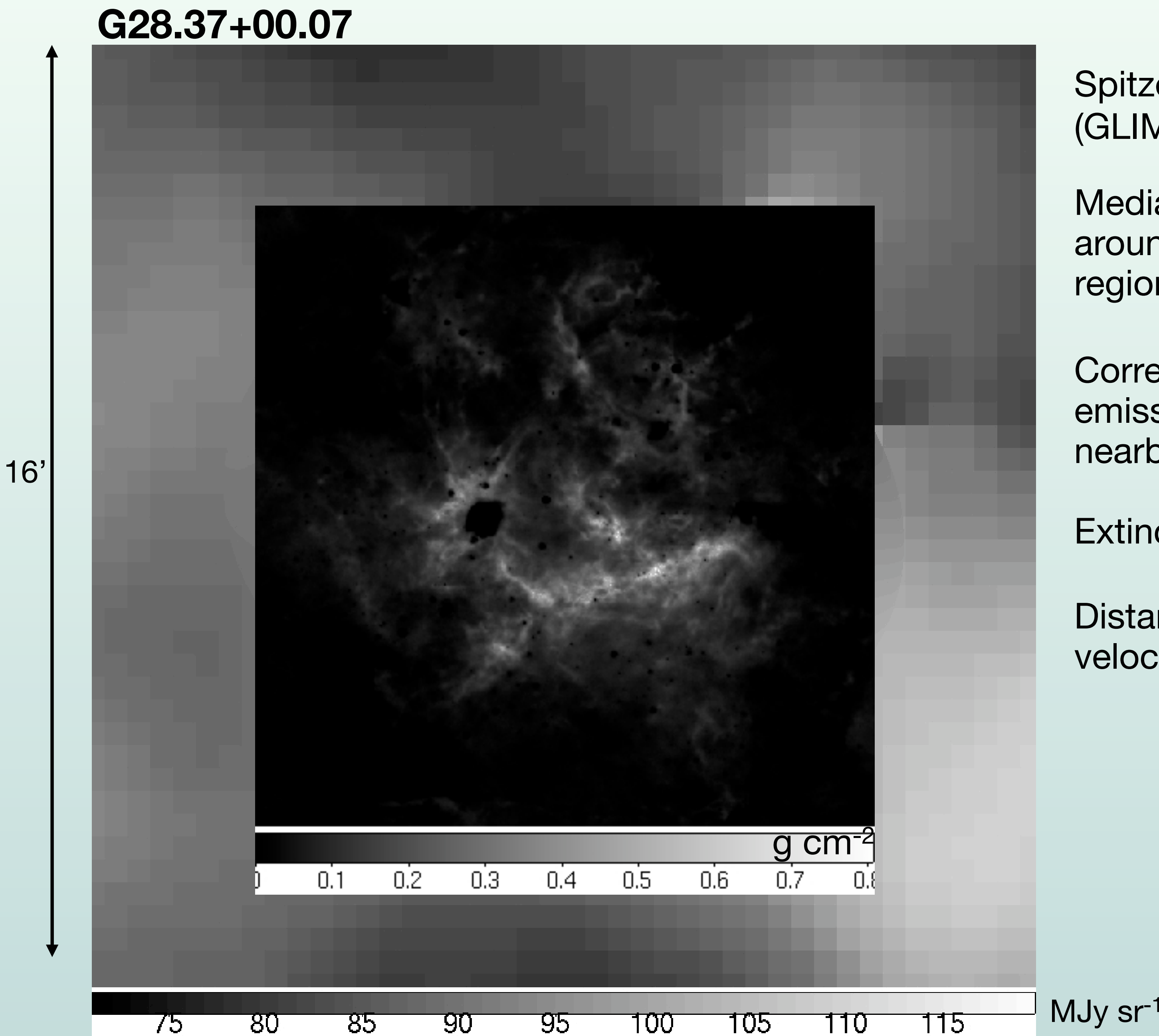

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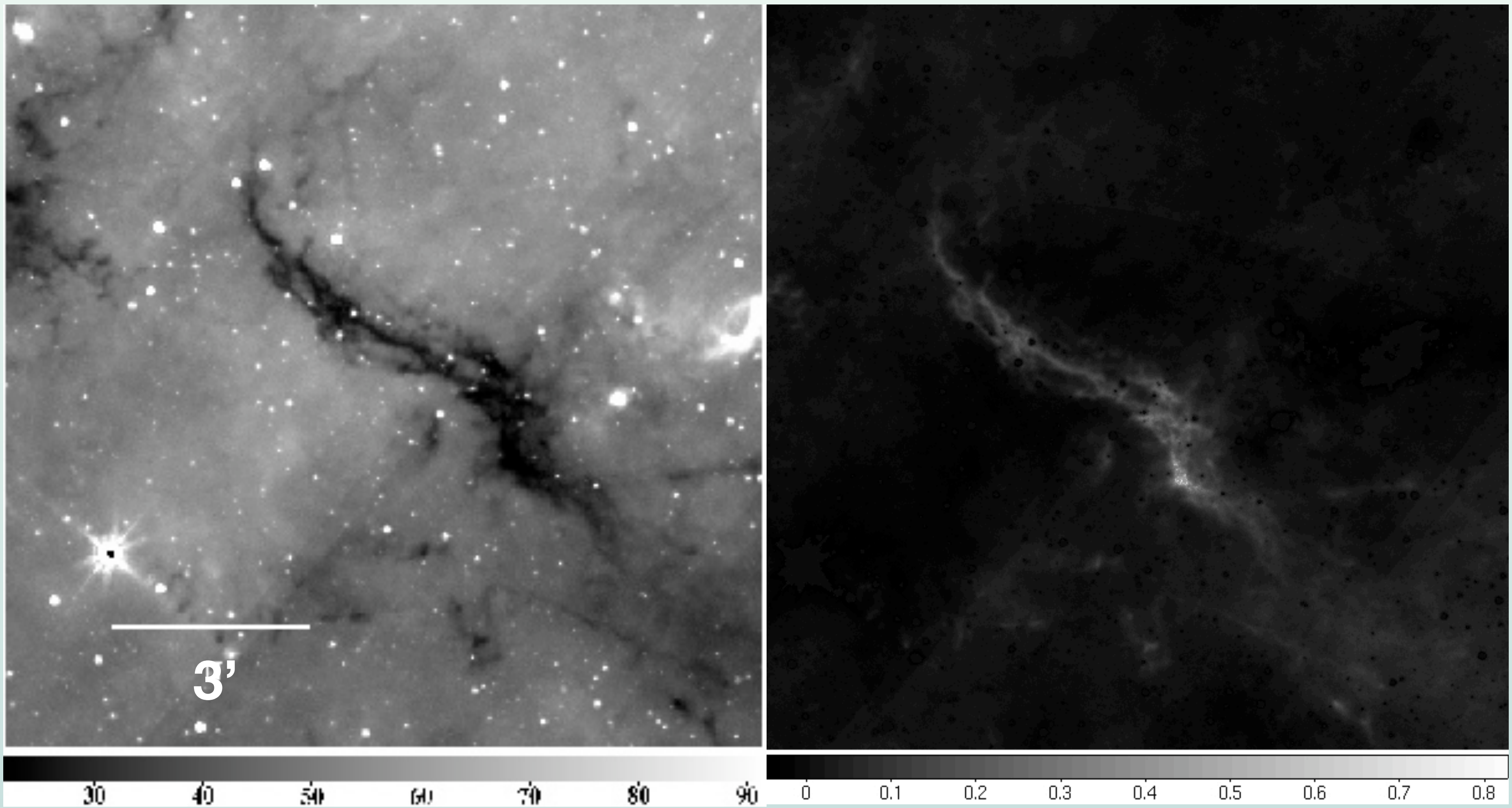
Application to Filamentary IRDCs

Comparison to mm dust emission (Rathborne et al. 2006) and ^{13}CO and $C^{18}O$ line emission (Hernandez & Tan, submitted), give agreements at ~factor of 2 level

G035.39−00.33



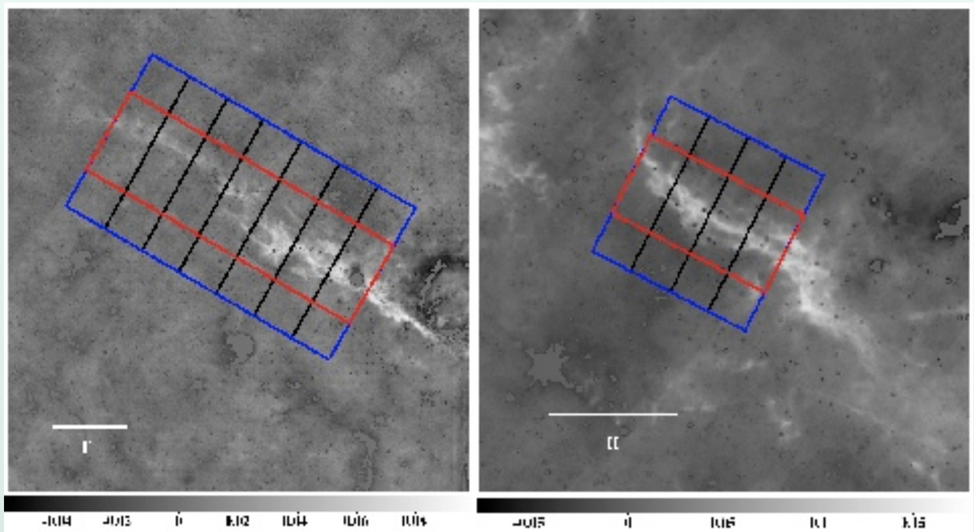
$I_{8\mu m}$ (MJy sr^{-1})

Σ (g cm^{-2})

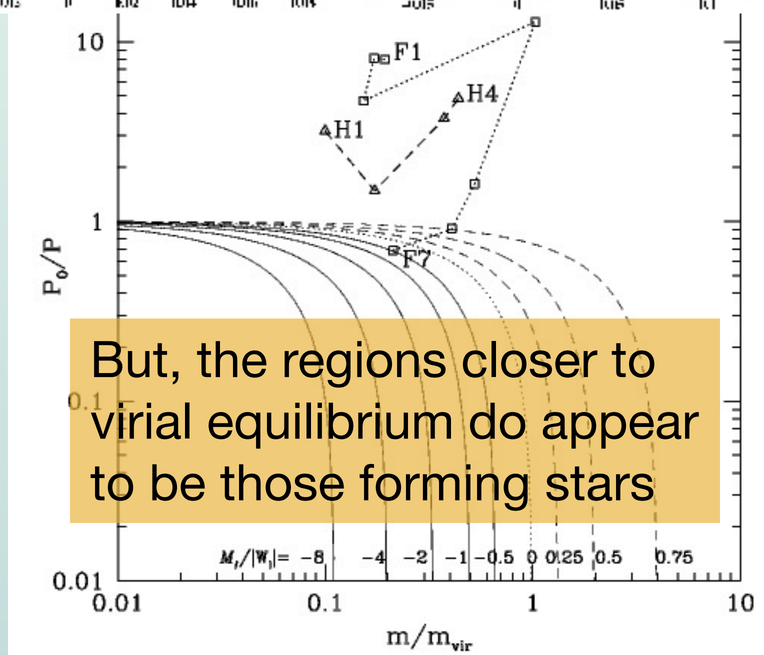
Formation of IRDCs

Some evidence that filamentary IRDCs are not yet virialized:

Filamentary virial analysis of 2 IRDCs
(Hernandez & Tan, submitted)

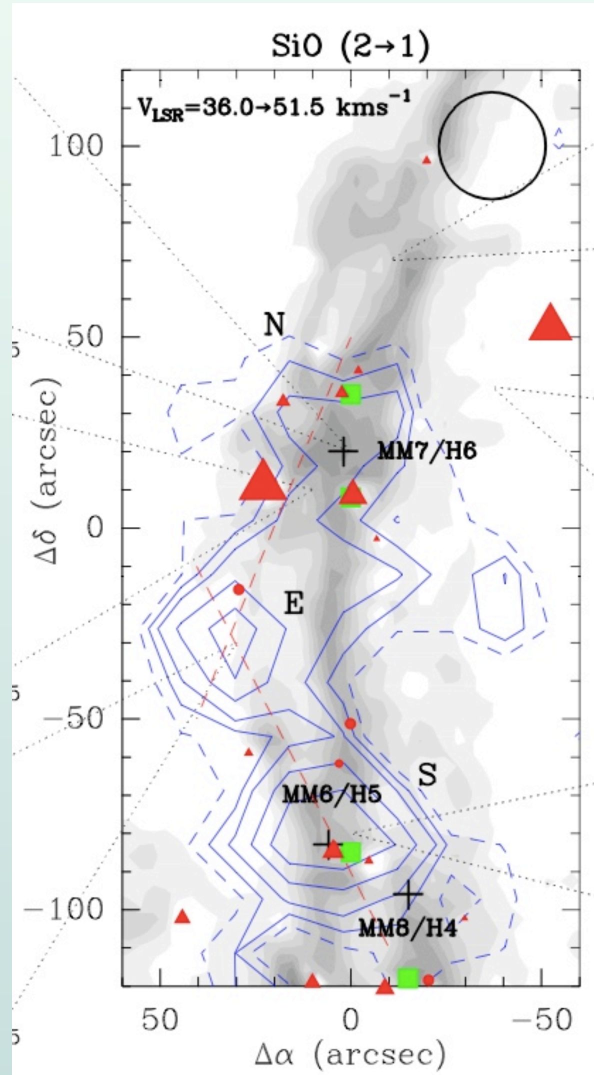


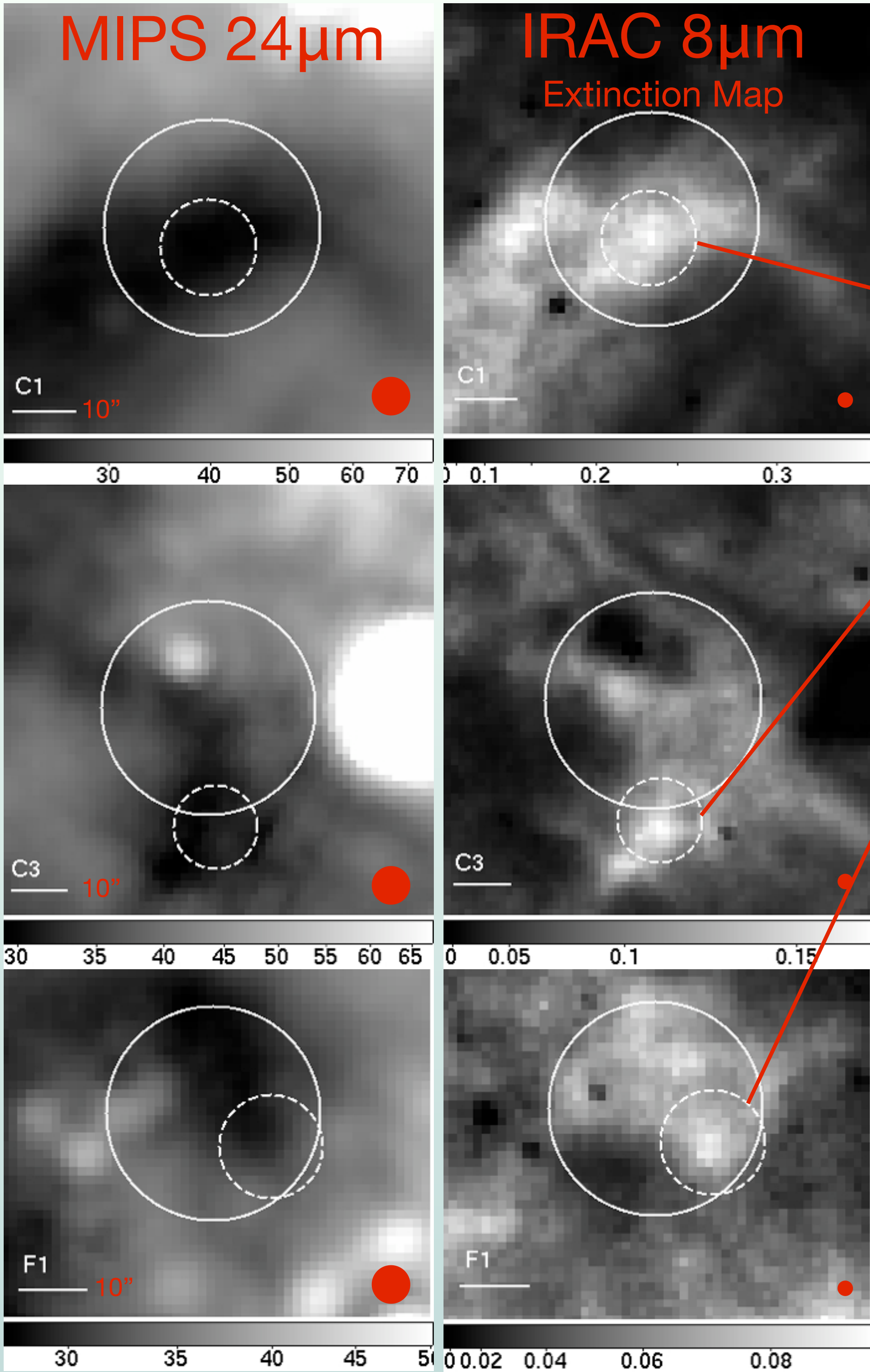
Comparing to models of Fiege & Pudritz (2000)



But, the regions closer to virial equilibrium do appear to be those forming stars

Extended SiO emission along one IRDC
(Jimenez-Serra et al. 2010)





Massive Starless Cores

Butler & Tan (2009), Butler & Tan, in prep.

$\Sigma = 0.26\ \mathrm{g\ cm^{-2}}$ $m_{core} = 205\ M_\odot$

$\Sigma = 0.12\ \mathrm{g\ cm^{-2}}$ $m_{core} = 94\ M_\odot$

$\Sigma = 0.12\ \mathrm{g\ cm^{-2}}$ $m_{core} = 50\ M_\odot$

Cores show central concentration; can fit power law radial density profiles, index ~-1.5. They contain many thermal Jeans masses. B-fields may be suppressing fragmentation within the core.

$$M_{BE} = 1.182 \frac{c_{th}^4}{(G^3 P_{s,core})^{1/2}} \rightarrow 0.0504 \left(\frac{T}{20\ \mathrm{K}}\right)^2 \frac{1}{\Sigma_{cl}} M_\odot$$

$$M_B = 79 c_\Phi^3 \left(\frac{R}{Z}\right)^2 \frac{\bar{v}_A^3}{(G^3 \bar{\rho})^{1/2}} = 1020 \left(\frac{R}{Z}\right)^2 \left(\frac{\bar{B}}{30\ \mu\mathrm{G}}\right)^3 \left(\frac{10^3\ \mathrm{cm^{-3}}}{\bar{n}_H}\right)^2 M_\odot$$

$n_H \sim 10^5 \mathrm{cm^{-3}}$, B~1mG -> $M_B \sim 100\ M_\odot$

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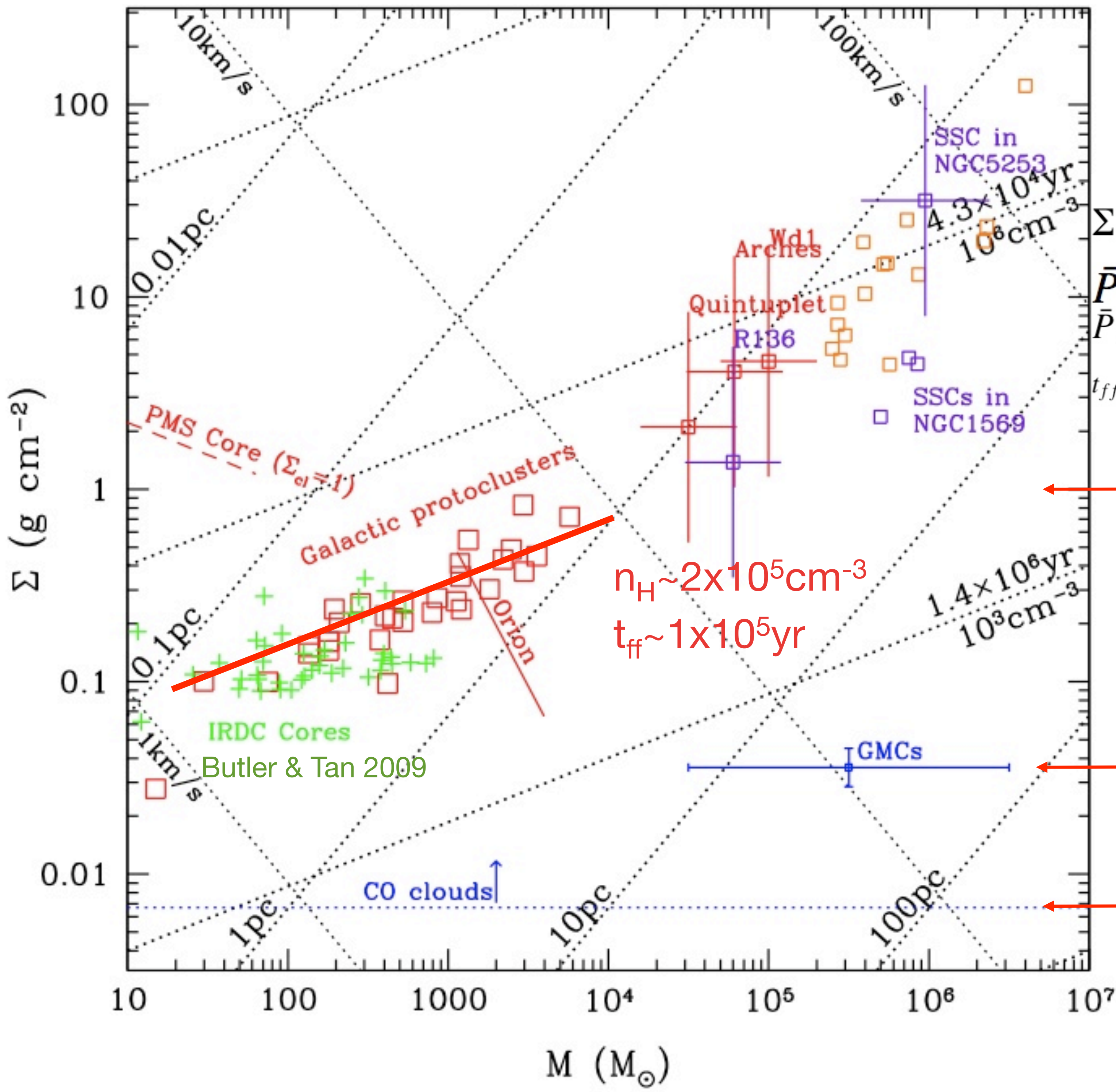

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We expect massive star forming environments exist for $>1t_{ff}$ and so can achieve approx. pressure equilibrium (proto star clusters take $> 1t_{ff}$(central) to form)

Tan, Krumholz, McKee (2006)

IRDC cores have $t_{ff}{\sim}10^5$yr, which is short

Some (most?) star clusters appear to have age spreads $>10^6$yr, e.g. Orion Nebula Cluster median age of 2.5-3Myr (Da Rio et al. 2010)

A plausible mechanism has been identified to maintain turbulence over many t_{ff}: protostellar outflow feedback (Norman & Silk 1980; Nakamura & Li 2007)

While the issue of star cluster formation timescales is still debated (e.g. Elmegreen 2000, 2007; Hartmann & Burkert 2007), it seems likely that $t_{form}>t_{ff}$(central).

Collapse of the Core - Core Fragmentation?

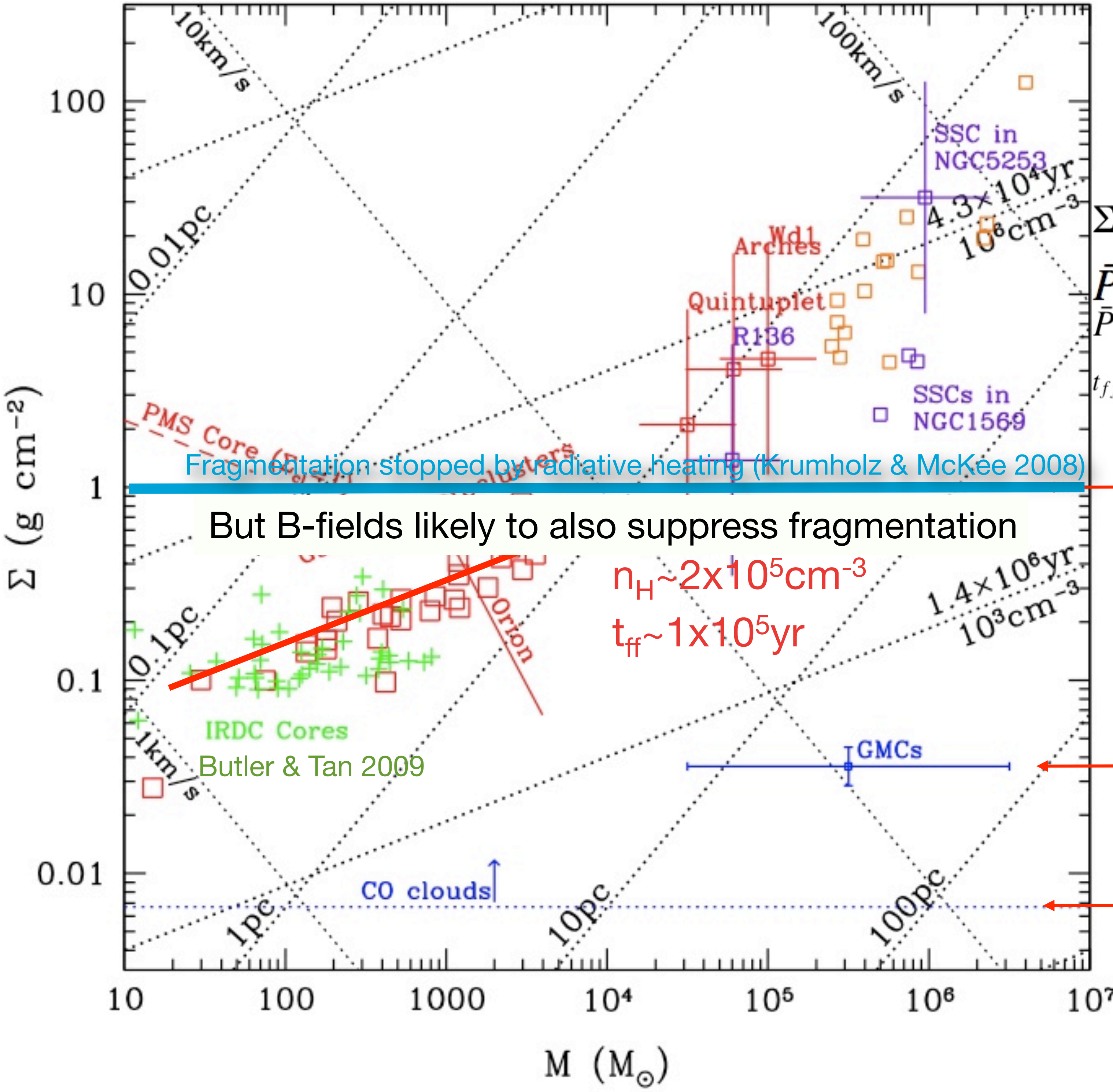
We expect most of these structures will fragment to form star clusters. Most mass -> low-mass stars.

Fragmentation will be reduced by radiative feedback from the central star (Krumholz, Klein & McKee 2007; c.f. Dobbs, Bonnell, Clark 2005).

Fragmentation should be reduced by radiative feedback from surrounding accreting low-mass stars (Krumholz & McKee 2008).

Magnetic field support should increase the “magneto-Jeans” mass and reduce fragmentation: (Machida et al. 2005; Price & Bate 2007, Hennebelle & Teyssier 2008, Duffin & Pudritz 2009). However, see results of Nakamura, Li, Wang, Abel from 2010.

Overview of Physical Scales



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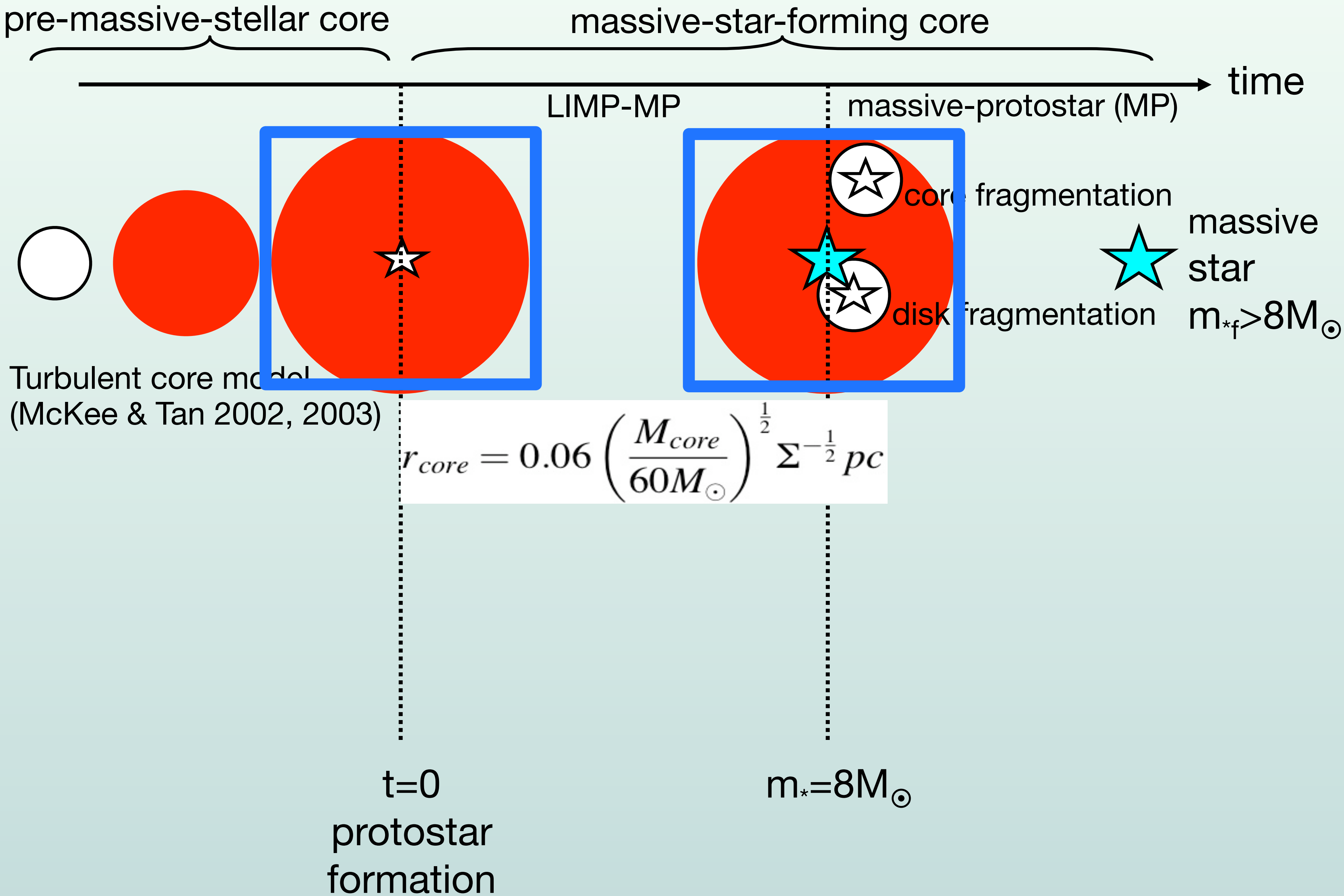
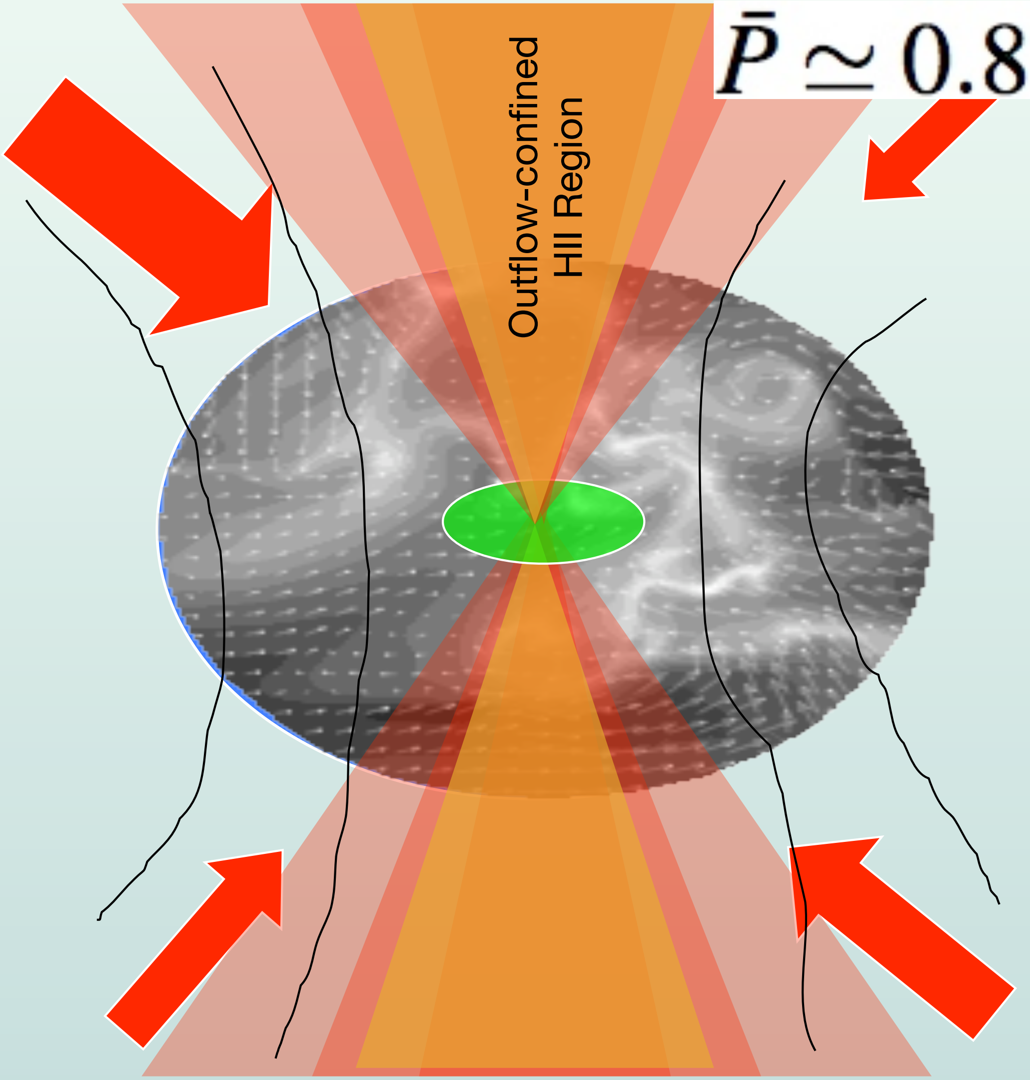


$$r_{core} = 0.06 \left(\frac{M_{core}}{60 M_\odot}\right)^{\frac{1}{2}} \Sigma^{-\frac{1}{2}} pc$$

The later stages of individual massive star formation



$$\bar{P} \simeq 0.88 G\Sigma^2$$

$$r_{core} = 0.06 \left(\frac{M_{core}}{60M_\odot}\right)^{\frac{1}{2}} \Sigma^{-\frac{1}{2}}\, pc$$

$$r_{disk} = 1200 \frac{\beta}{0.02} \left(\frac{M_{core}}{60M_\odot}\right)^{\frac{1}{2}} \Sigma^{-\frac{1}{2}}\, AU$$

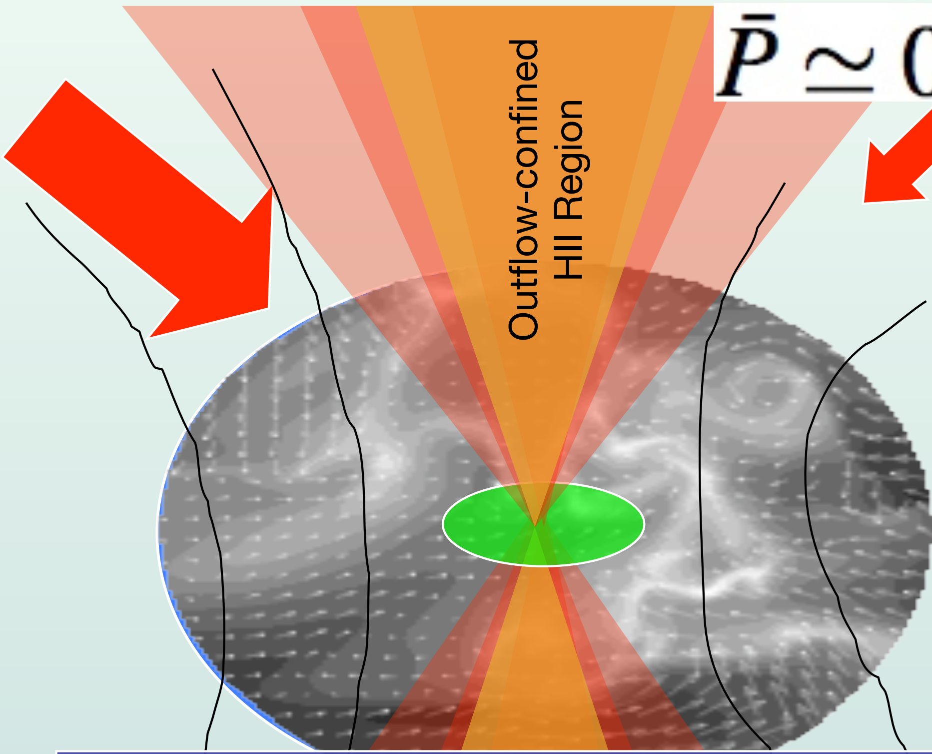
$$t_{*f} = 1.3 \times 10^5 \left(\frac{M_{core}}{60M_\odot}\right)^{\frac{1}{4}} \Sigma^{-\frac{3}{4}}\, yr$$

Final mass accretion rate

$$\dot{m}_* = 4.6 \times 10^{-4} \left(\frac{M_{core}}{60M_\odot}\right)^{\frac{3}{4}} \Sigma^{\frac{3}{4}} M_\odot\, yr^{-1}$$

Support by combination of large & small scale B-fields, and turbulent motions. Core boundaries fluctuate.

The later stages of individual massive star formation



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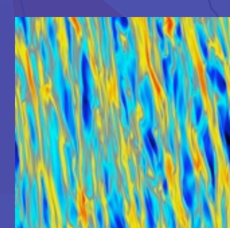
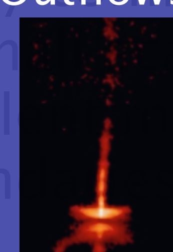
Protostellar evolution

Disk structure



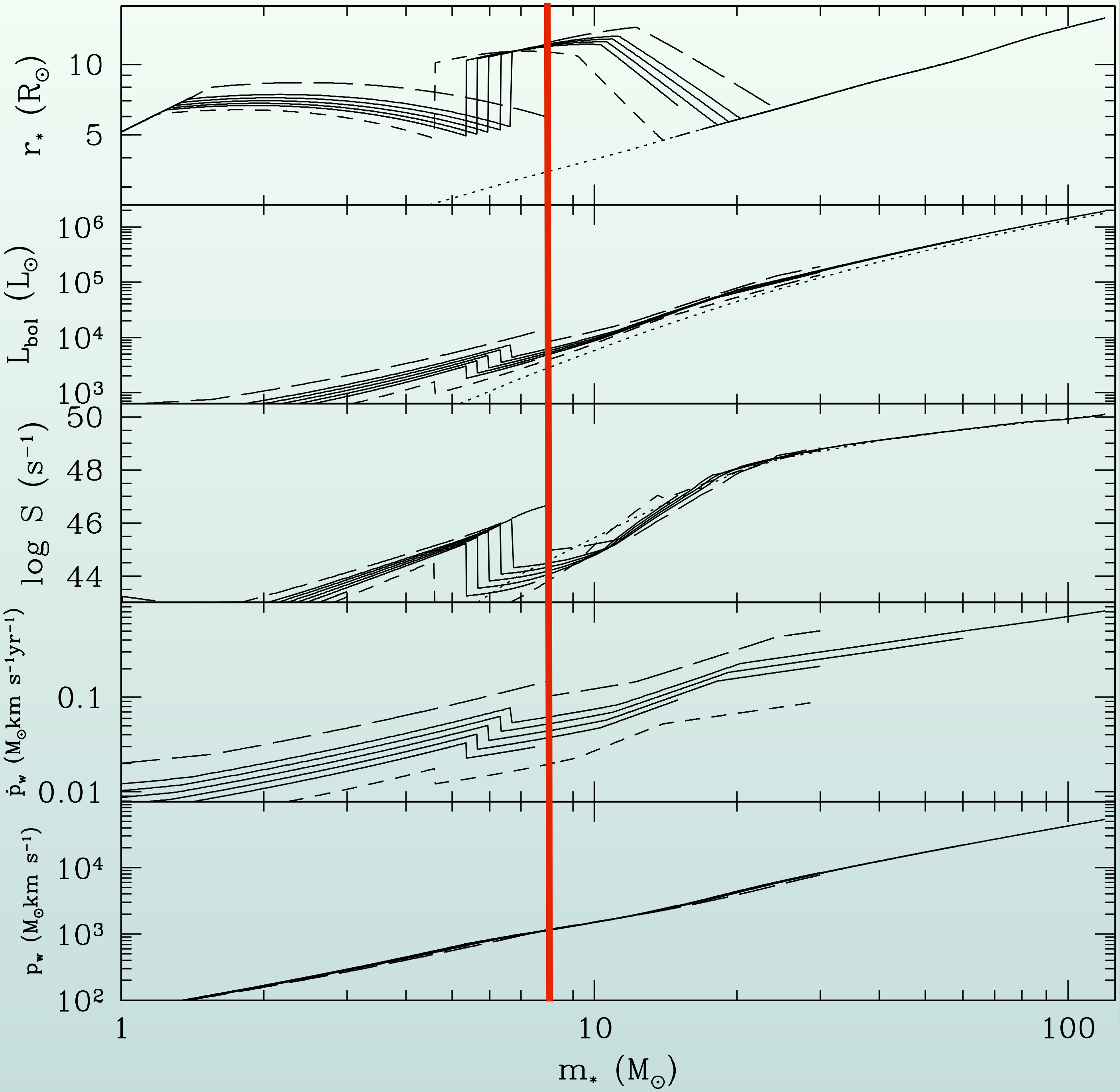
Outflows



Support b ination of
large & sm le B–fields,
and turbul otions.
Core boun fluctuate.

Protostellar Evolution

[see also Hosokawa & Omukai 2009]



Radius

Luminosity
protostar+boundary layer+disk

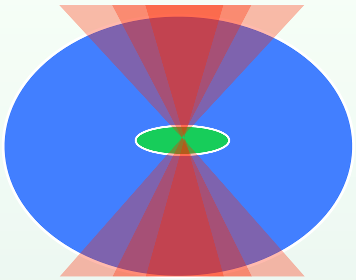
Ionizing L.

Outflow momentum flux
(scaled from Najita & Shu 94)

Total outflow momentum

Core Star Formation Efficiency from Outflow Feedback

Tan & McKee, in prep.



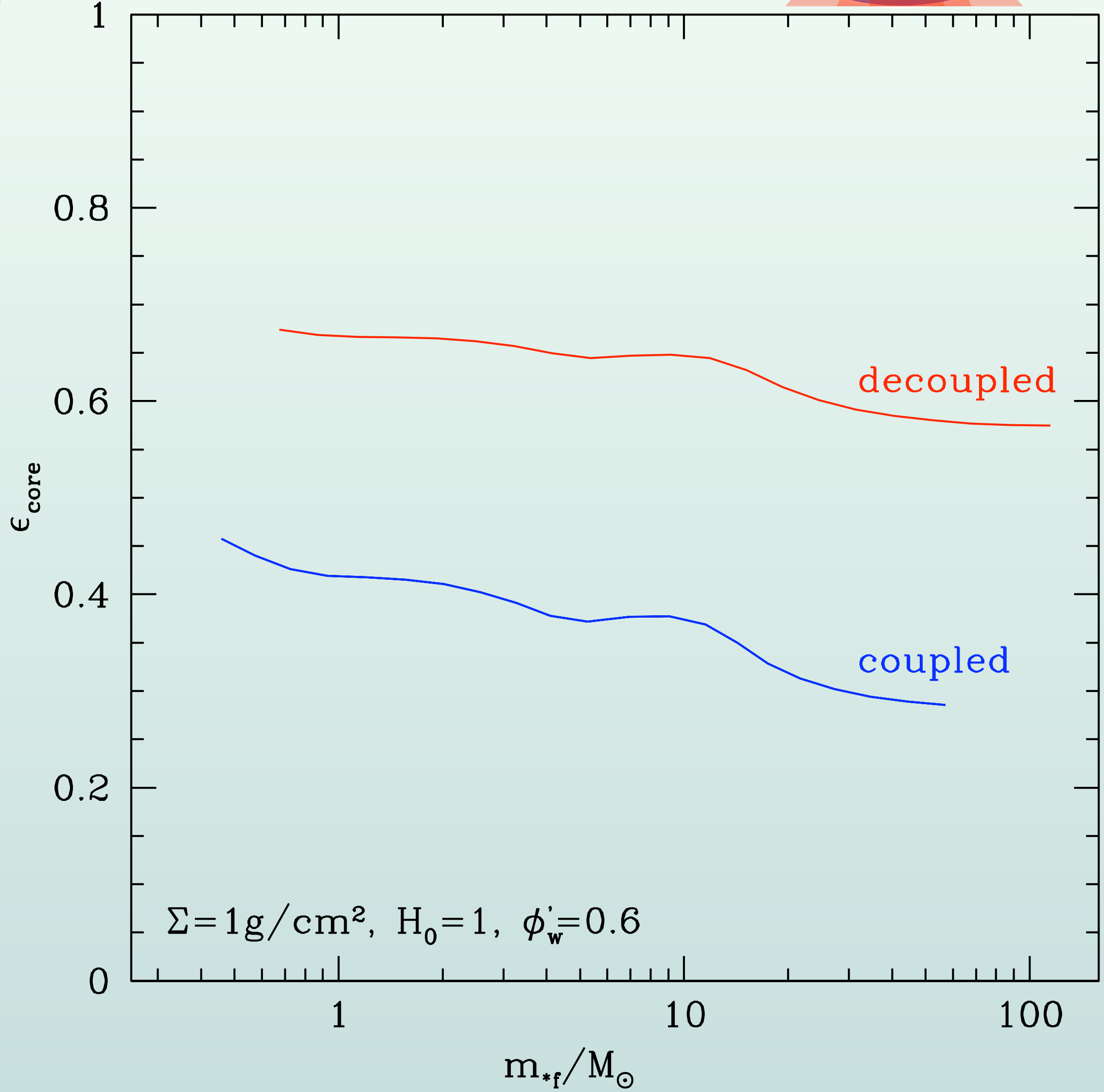
Assuming angular distribution of momentum flux of standard X-wind or disk-wind models (Matzner & McKee 1999),

$$\frac{d\dot{p}_w}{d\Omega} = \frac{\dot{p}_w}{4\pi \ln(2/\theta_0)(\sin^2\theta + \theta_0^2)}$$

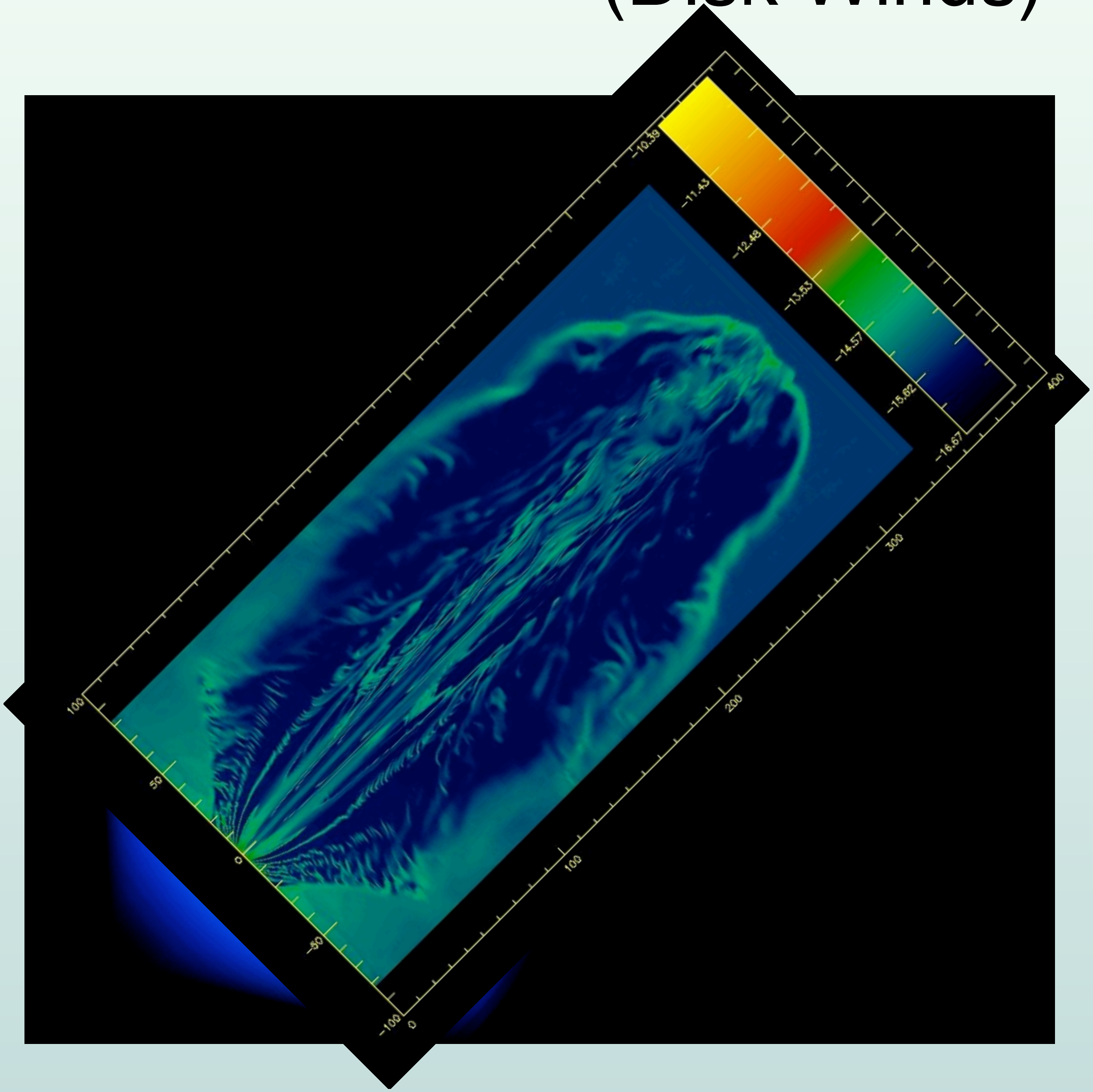
and

$$\dot{p}_w = \dot{m}_w v_w = f_w \dot{m}_* v_w = \frac{f_w v_w}{v_K} \dot{m}_* v_K = \phi'_w \dot{m}_* v_K$$

work out the maximum angle from the rotation/outflow axis at which core gas is expelled, assuming a steady wind that either stays coupled beyond the core radius or decouples. This sets ε_{core} (Matzner & McKee 2000)



Simulations of MHD-Driven Outflows (Disk Winds)



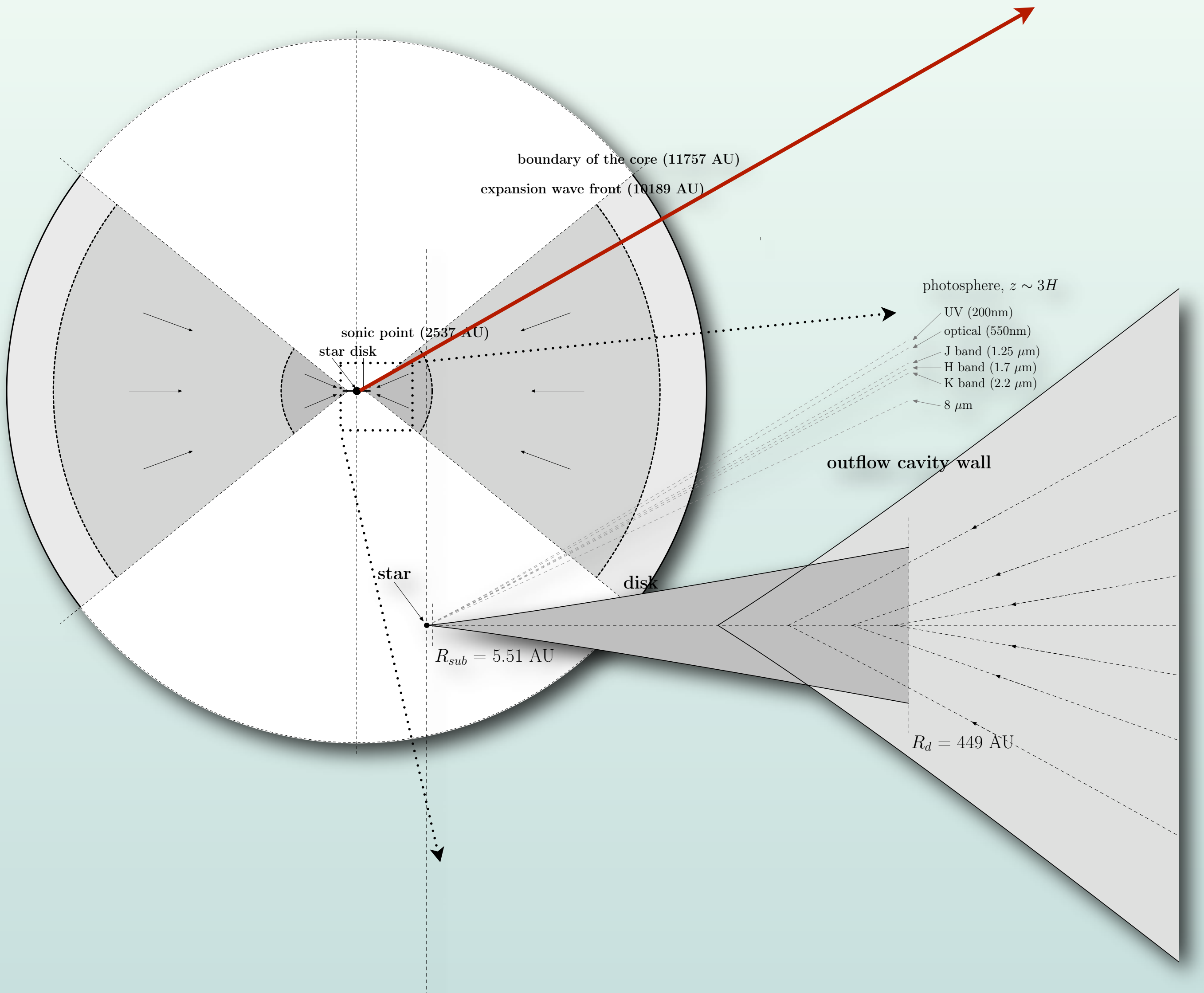
Staff et al. (2010): Zeus simulation of outflows from low-mass protostars.

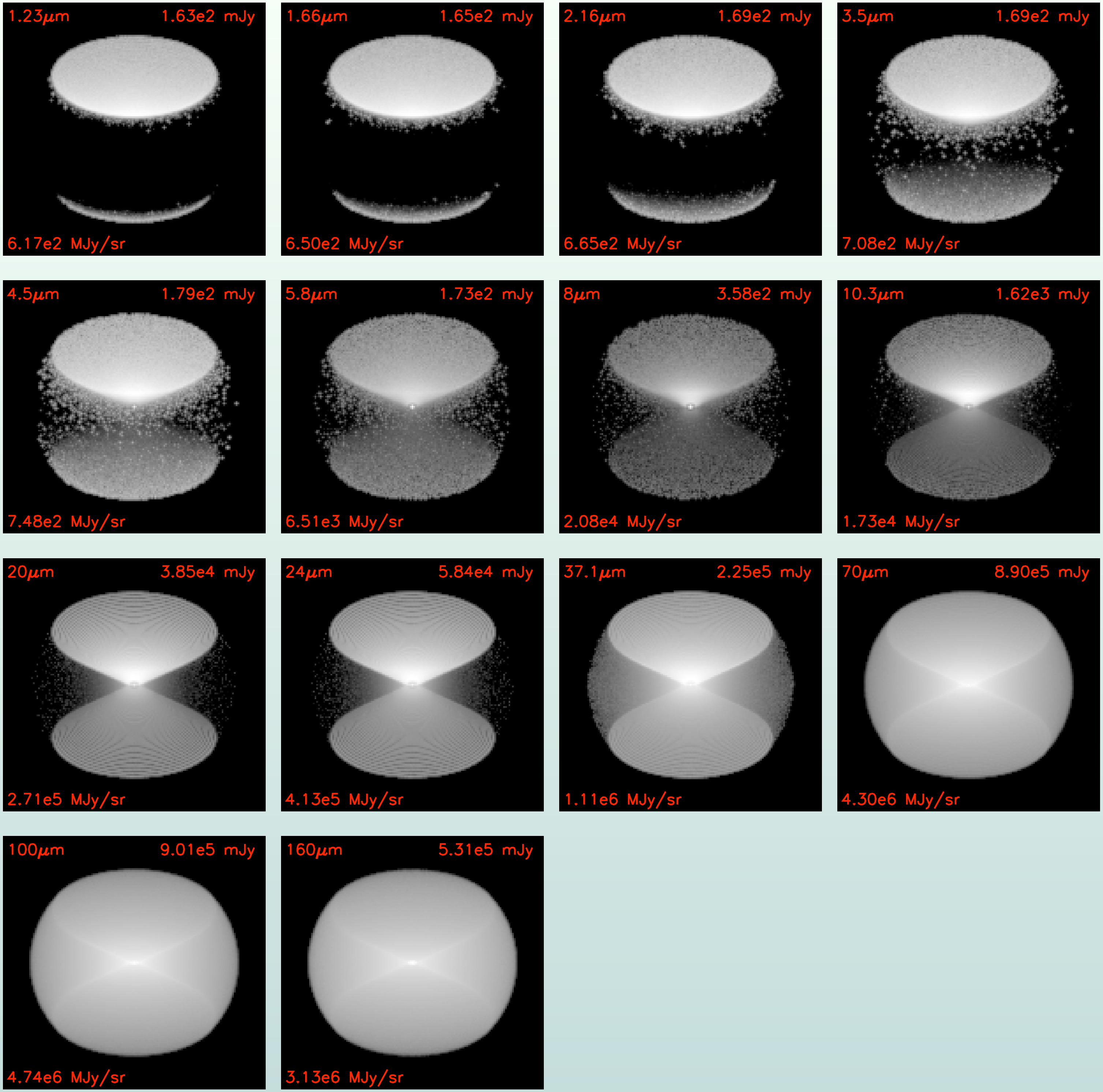
Scaling to case of massive protostar:

$m_* = 8 M_\odot$
$dm_*/dt = 2\times10^{-4} M_\odot/yr$
$dm_w/dt = 0.1 dm_*/dt$
$r_* = 12 R_\odot$
$r_{w,i} = 3 r_*$
$B_{w,i} = 100G$

Radiative Transfer Modeling

Zhang & Tan, in prep.





Radiative Transfer Models

Zhang &Tan, in prep.
see also:
Robitaille et al. 2006;
Molinari et al. 2008.

Rotation and outflow axis inclined at 60° to line of sight.

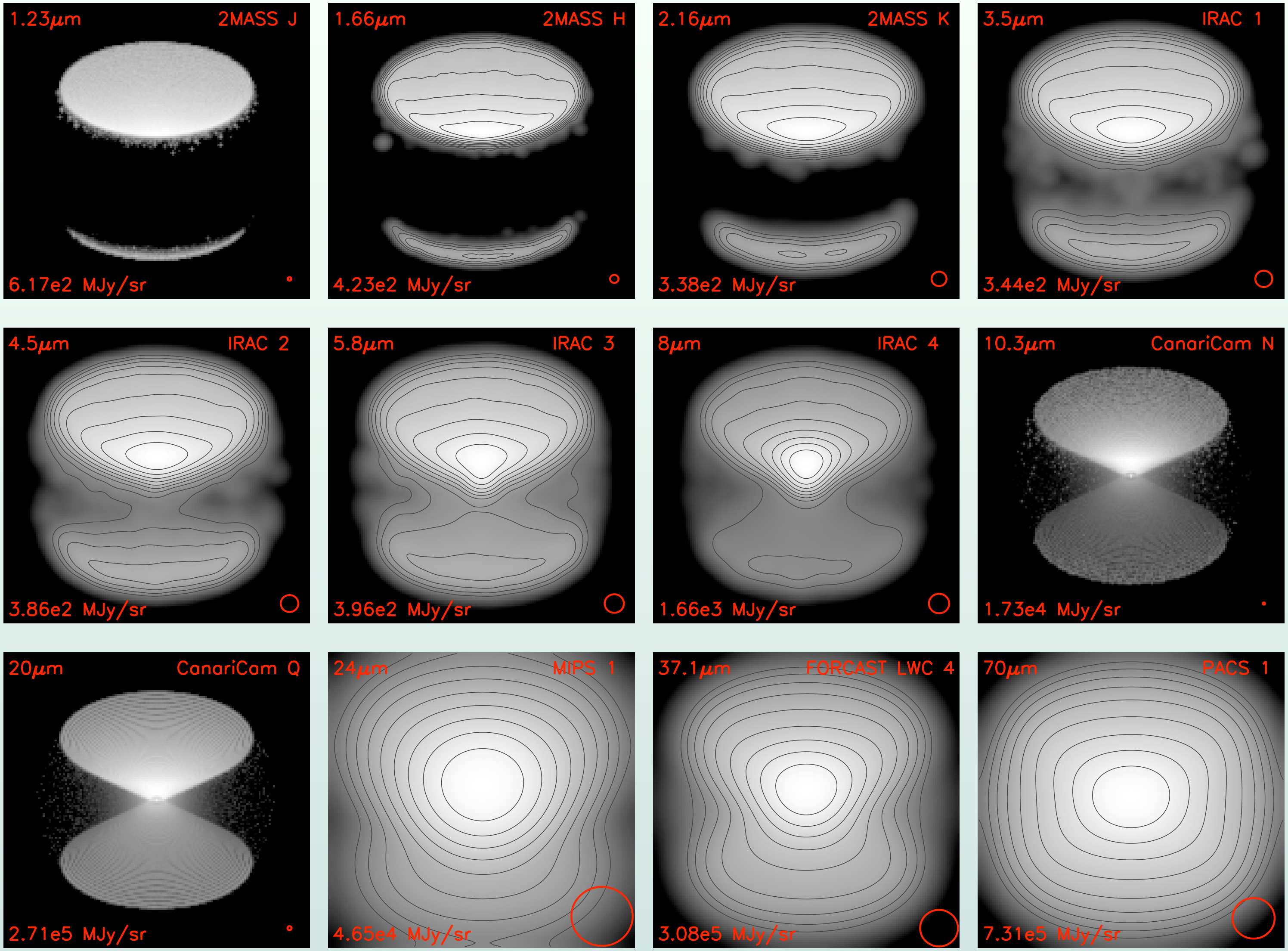
$\Sigma = 1\ g\ cm^{-2}$

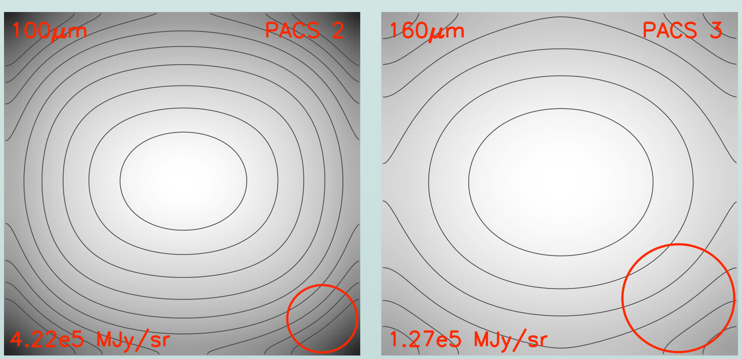
$M_{core} = 60\ M_\odot$

$m_* = 8\ M_\odot$

$m_{disk} = m_*/3$

$L_{bol} = 6x10^3\ L_\odot$





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Zhang &Tan, in prep.
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Rotation and outflow axis inclined at 60° to line of sight.

d=1kpc
convolved with telescope beam

$\Sigma = 1$ g cm^{-2}

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$m_{disk} = m_*/3$

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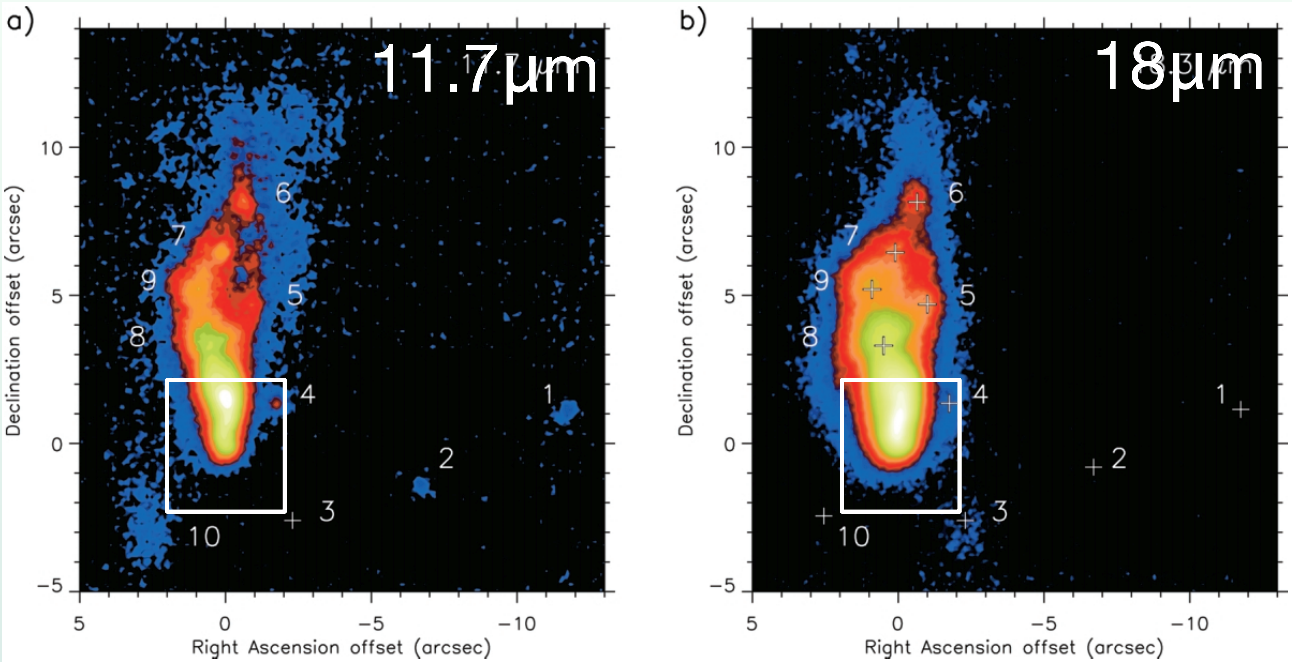
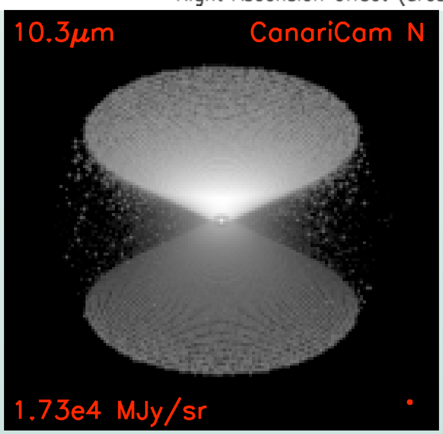
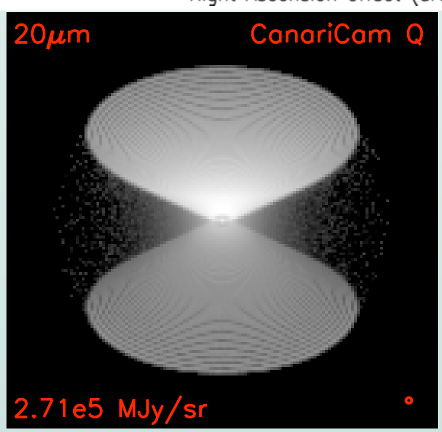
Observations: Mid IR Emission - Outflow Cavity



G35.2N
(De Buizer 2006)
$L_{MIR} \sim 1.6 \times 10^3 L_\odot$





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$m_* = 8\ M_\odot$
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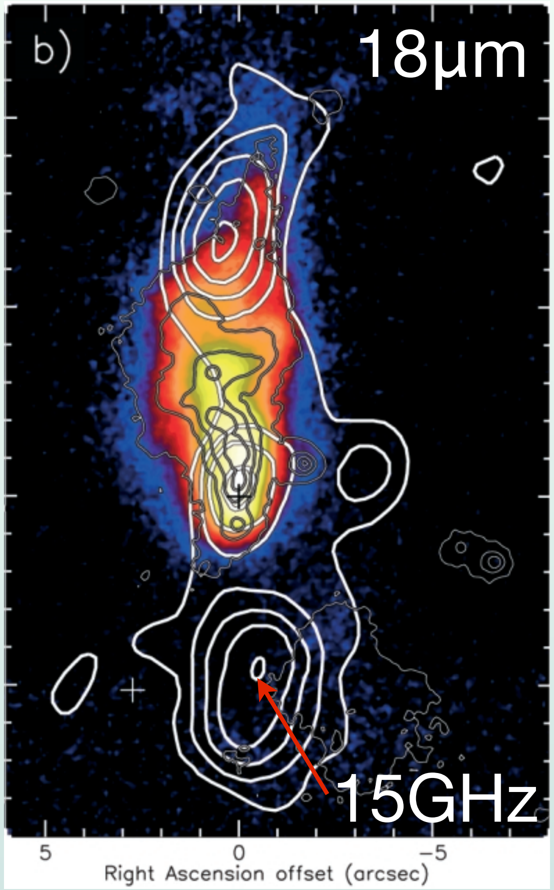
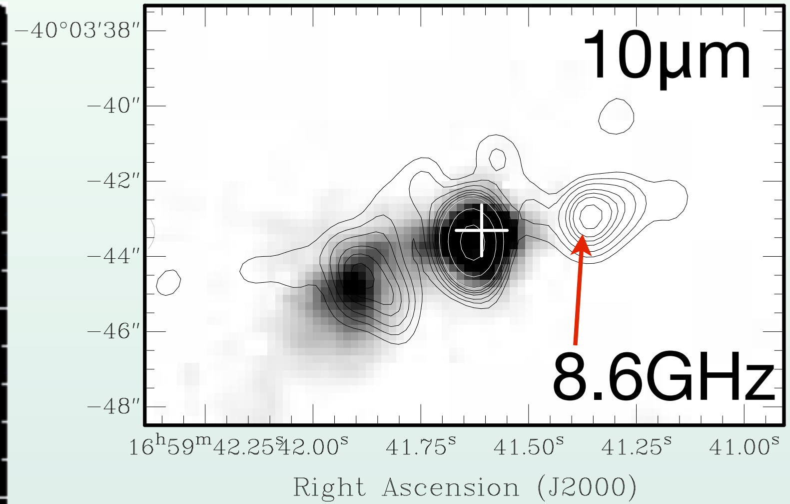
Outflow-Confined HII Regions (Thermal Radio Jets)



G35.2N (De Buizer 2006)



IRAS 16562-3959
Guzmán et al. (2010)

A number of ionized HCHIIs seen in other nearby sources (e.g. van der Tak & Menten 2005 Orion source I: Tan & McKee 2003)

Feedback on the Core

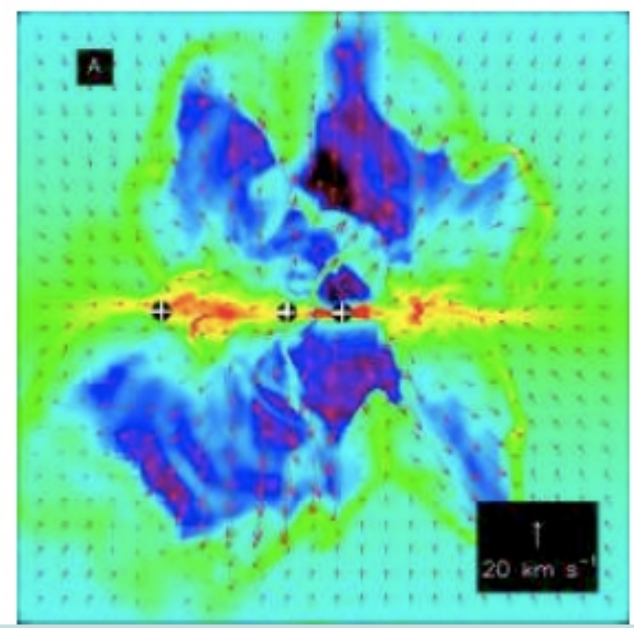
Bipolar MHD outflows are important for setting ε_{core}

Outflows can confine ionizing radiation

Radiation pressure escapes along outflow cavities

Simulations are gradually including more physics, especially radiation pressure (e.g. Yorke & Sonnhalter 2002; Krumholz et al. 2007; Peters et al. 2010), but so far no self-consistent model also including MHD outflows and ionization.

Krumholz et al. 2009



Feedback on the Protocluster

Outflow feedback from low and high-mass stars can maintain turbulence and regulate SFR (Nakamura & Li 2007). We expect that this keeps ε_{ff} ~ 0.01-0.03 and lengthens the star cluster formation timescale (Tan et al. 2006).

Stellar winds unlikely to be important for disrupting dense gas: easily poisoned (McKee, van Buren, Lazareff 1984). But they will compress the HII region into a dense shell.

Ionization is probably most important for destroying molecular gas, and can also disperse dense clumps via rocket effect.

Radiation pressure acting directly on dusty gas will become dynamically important once the stellar content is high.

Supernovae only relevant if $t_{form} > 3$Myr

Some observational constraints

Lopez et al. (2010) study R136 (30 Doradus) finding direct radiation pressure dominates inside ~50pc; then HII thermal pressure.

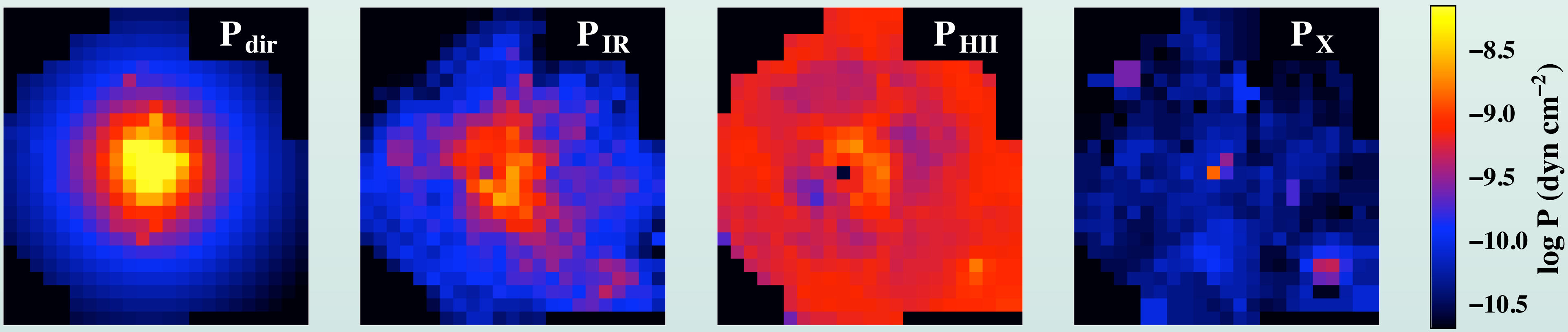
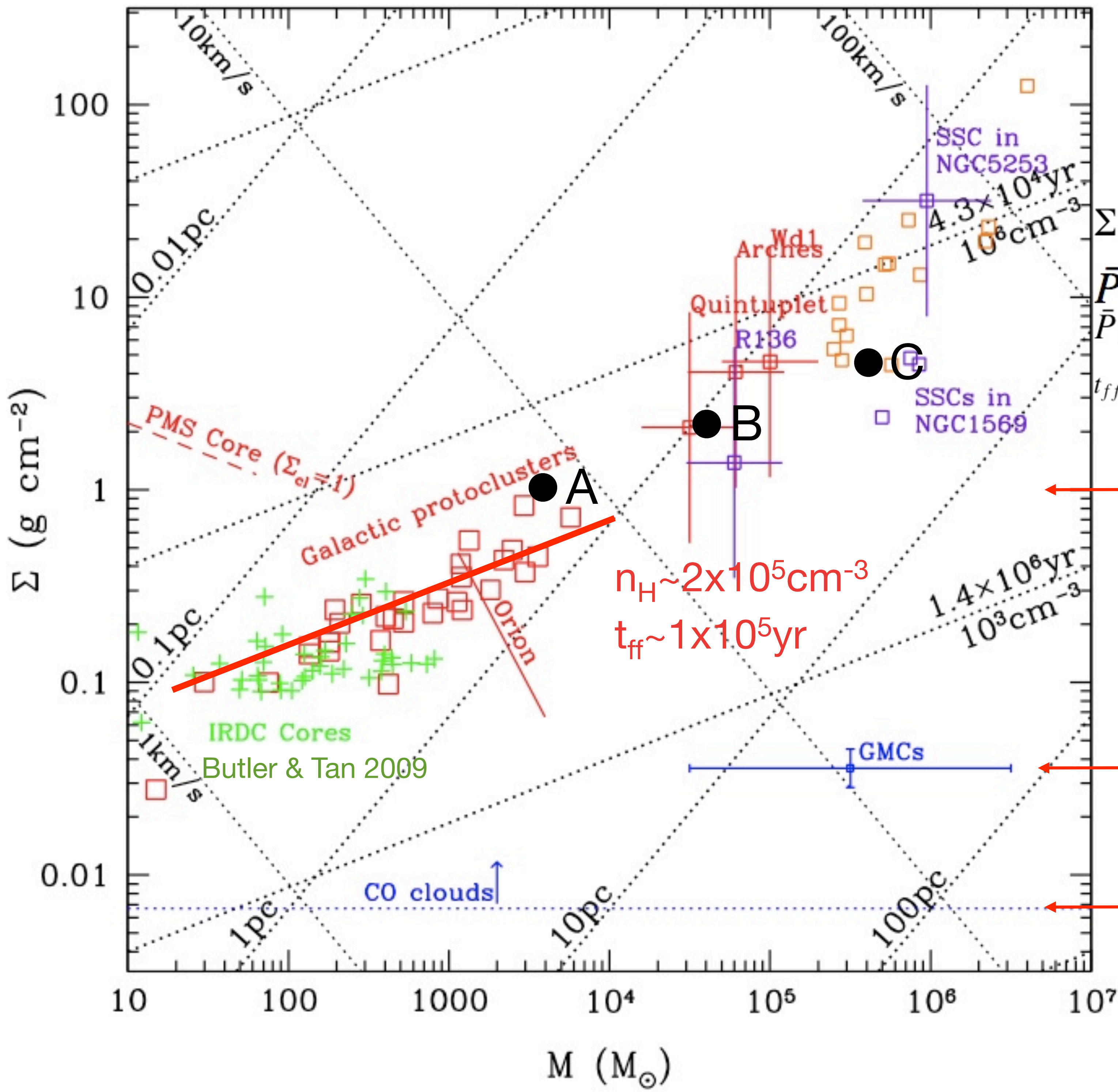


FIG. 12.— Maps of the four pressure components across 30 Dor. All four are on the same color scale to enable visual comparison. Consistent with Fig. 11, $P_{\rm dir}$ dominates in the central few arcminutes, while the $P_{\rm HII}$ dominates at larger distances from R136.



Radiative Feedback

$$\Sigma \equiv \frac{M}{\pi R^2}$$

$$\bar{P} \simeq G\Sigma^2$$

$$\bar{P}/k = 4.3 \times 10^8 \Sigma^2\, K\, cm^{-3}$$

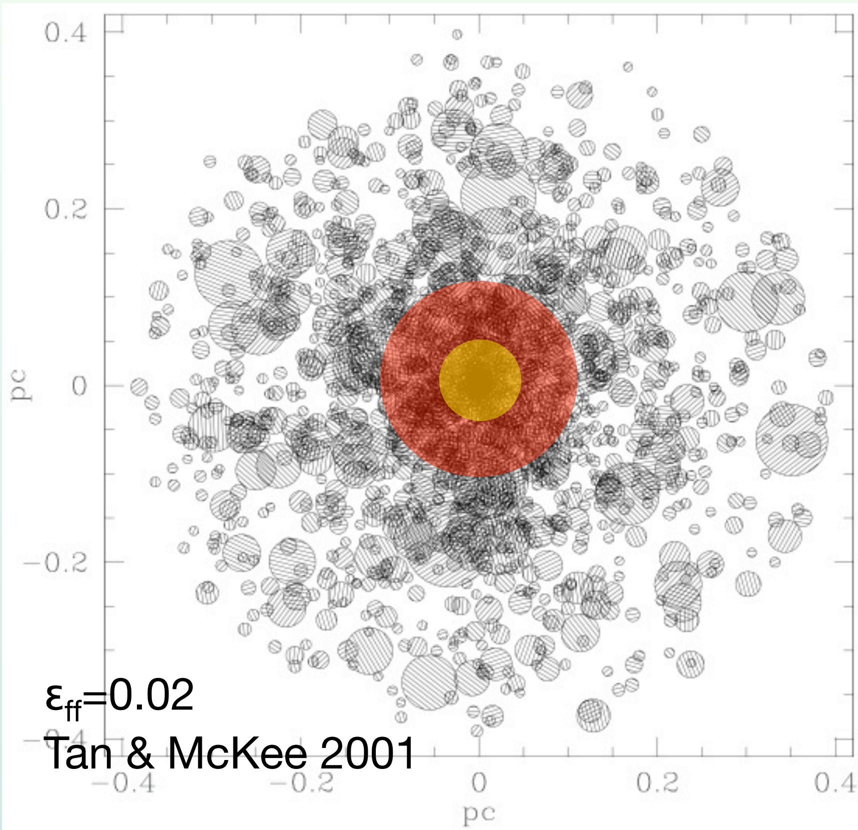
$$t_{ff} = \left(\frac{3\pi}{32G\rho}\right)^{1/2}$$

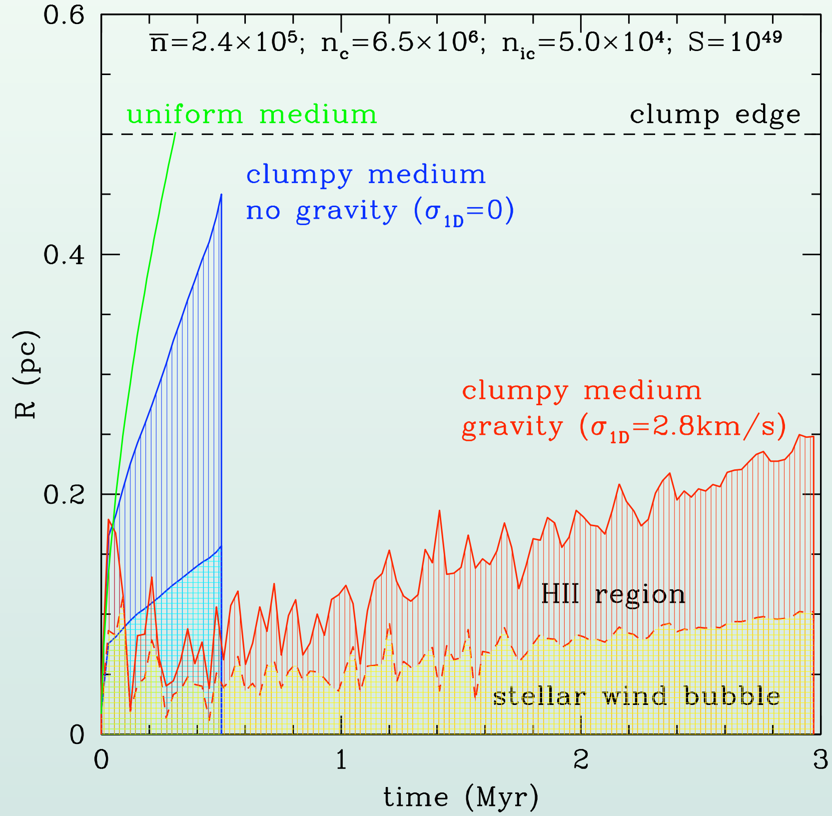
$A_V=200$
$A_{8\mu m}=8.1$
$N_H=4.2\times10^{23}$cm^{-2}
$\Sigma=4800\ M_\odot\ pc^{-2}$

$A_V=7.5$
$A_{8\mu m}=0.30$
$N_H=1.6\times10^{22}$cm^{-2}
$\Sigma=180\ M_\odot\ pc^{-2}$

$A_V=1.4$
$N_H=3.0\times10^{21}$cm^{-2}
$\Sigma=34\ M_\odot\ pc^{-2}$

Ionizing Feedback and Radiation Pressure will eventually disperse the clump gas and halt star formation

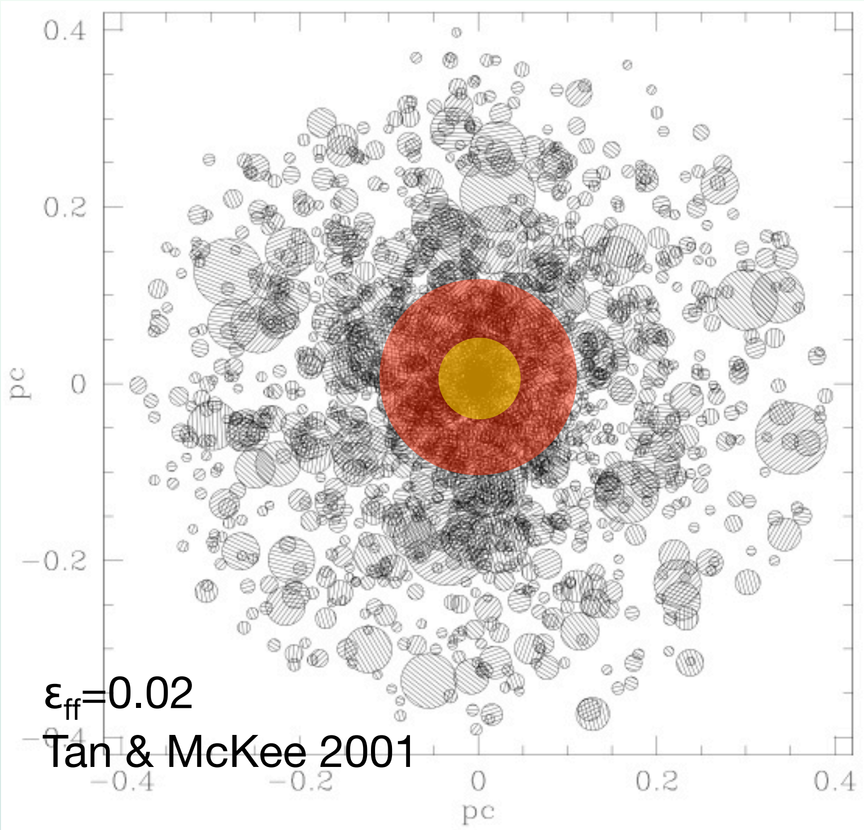




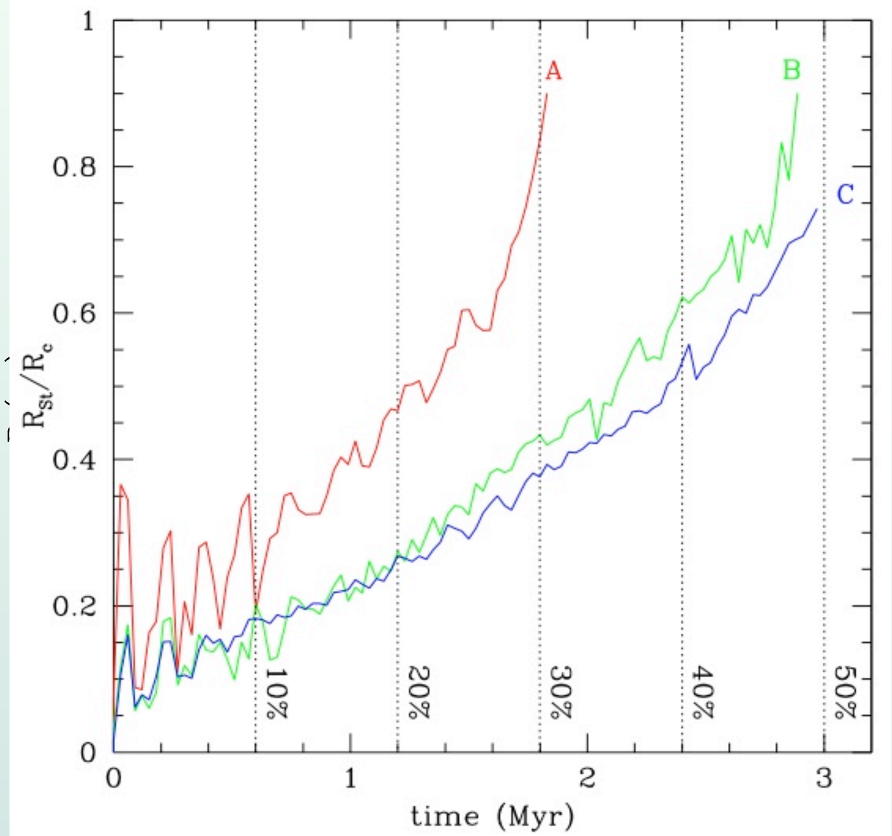
Toy, semi-analytic model for cluster feedback.

See also Krumholz & Matzner (2009) and Fall, Krumholz & Matzner (2010);
Numerical results of Dale, Walch, Ercolano, Gritschneder et al.

Ionizing Feedback and Radiation Pressure will eventually disperse the clump gas and halt star formation



ϵ_{ff}=0.02
Tan & McKee 2001



Toy, semi-analytic model for cluster feedback.

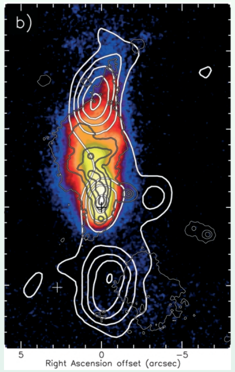
Prediction of age spreads in super star clusters of a few Myr

See also Krumholz & Matzner (2009) and Fall, Krumholz & Matzner (2010);
Numerical results of Dale, Walch, Ercolano, Gritschneder et al.

Conclusions (I)

Is massive star formation a scaled-up version of low-mass star formation?

We see massive pre-stellar and star-forming cores; rotating toroids; ordered B-fields; collimated outflows; outflow-confined HII regions (thermal radio jets).



"Turbulent Core Model": normalize core surface pressure to surrounding clump pressure, i.e. self-gravitating weight. The cores are probably are marginally magnetically super critical, limiting their fragmentation.

If there is a different mechanism, e.g. competitive accretion, stellar mergers, then one would expect some break in the IMF at the mass scale it takes over.

How can competitive accretion, i.e. accretion of dusty gas initially unbound to the protostellar core, overcome radiation pressure feedback for $m_* > 10 M_{sun}$? Mergers require unrealistic stellar densities.

Conclusions (II)

MHD Outflows play a major role in setting SFE from the core. Maybe ionization and radiation pressure help set the max. stellar mass?

Outflows from low and high mass protostars regulate turbulence and star formation in the clump.

Radiation pressure and ionization are likely the dominant destructive feedback mechanisms limiting SFE of the clump. But at the observed high pressures, feedback can be confined up to quite large SFEs ~50%, perhaps relevant to observed trend with Σ_{sfr} (Goddard, Bastien, Kennicutt 2010).