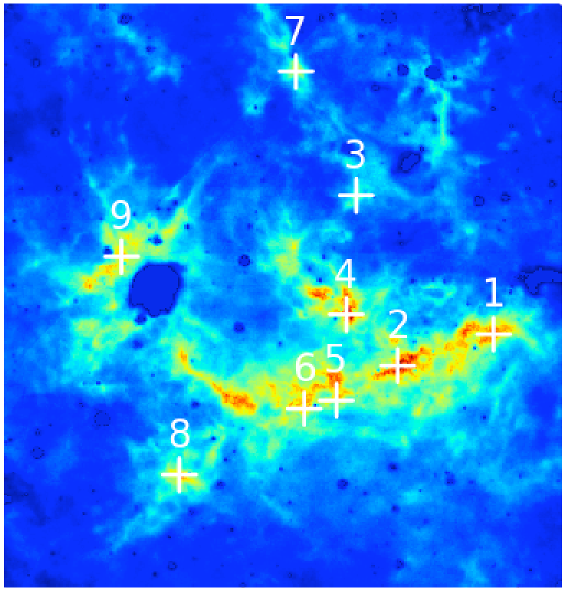
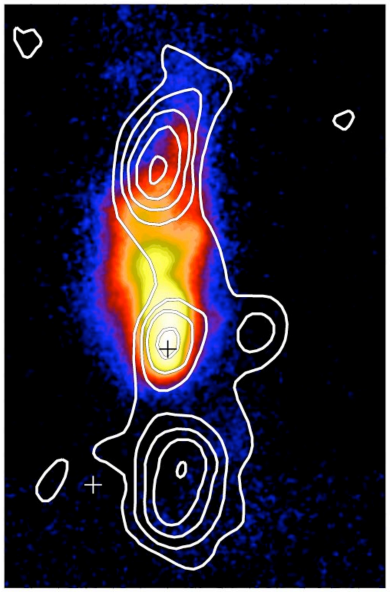
# **Massive Star Formation:** From Testing Basic Formation Scenarios to Quantitative Constraints on Core Accretion Theory



IRDC G28.4 (Cloud C) (Butler & Tan 09)



MYSO G35.2N (De Buizer 06)

ONC (McCauchrean 01)

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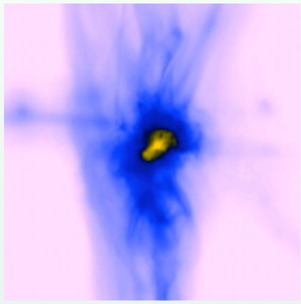
Charles Telesco (UF)
Barbara Whitney (SSI)
Yichen Zhang (UF)

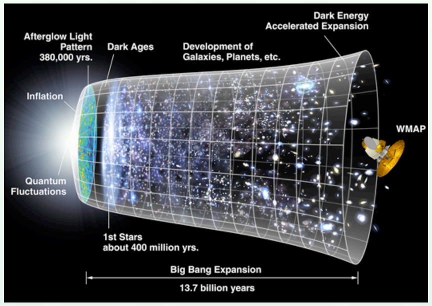
# Outline

- Introduction
  - why study massive star formation?
  - why is it difficult?
  - open questions: formation theories
- Initial Conditions
  - Infra-Red Dark Clouds (IRDCs)
  - Massive Starless Cores?
- Massive Protostars
  - Overview of expected properties
  - Radiative transfer modeling
  - SOFIA FORCAST observations of G35.2N

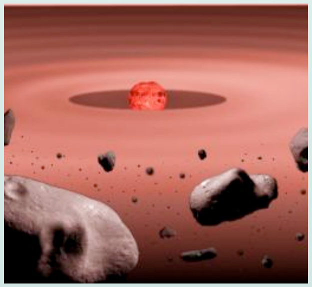
# Why study massive star formation?



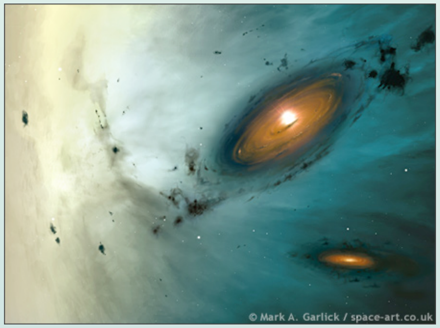
The **First (Pop III) Stars** were likely massive, some potentially supermassive stars, reionizing the universe and producing the first metals.



**Galaxies form and evolve** by forming **star clusters**, where the influence of massive stars is paramount. Massive stars are what tend to be seen in distant galaxies.



**Planets form** from the crumbs left over from star formation. Planet & star formation in star clusters can be influenced by massive star feedback.



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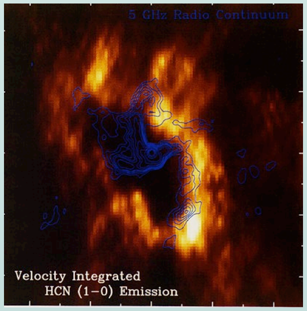
**Supermassive black hole formation** may be via massive star clusters or Pop III stars.
**Supermassive black hole accretion** is likely to be regulated by star formation.



# Why not to work on massive star formation...

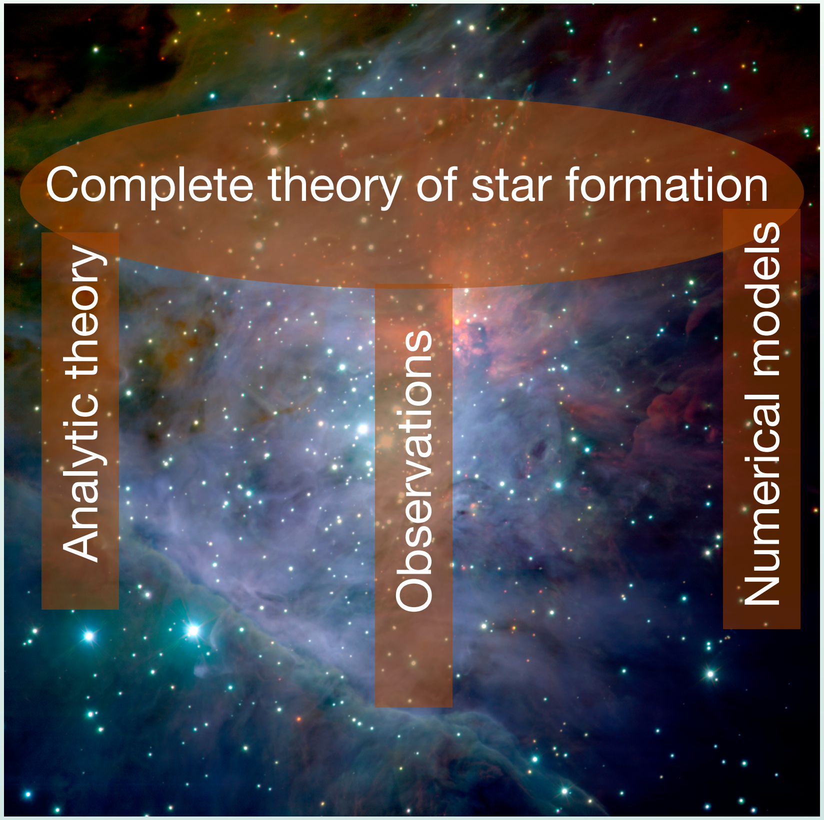
A complicated, nonlinear process

Physics:

Gravity vs pressure (thermal, magnetic, turbulence, radiation, cosmic rays) and shear.

Heating and cooling, generation and decay of turbulence, generation (dynamo) and diffusion of B-fields, etc.

Chemical evolution of dust and gas.



Wide range of scales (~12 dex in space, time) and multidimensional.

Uncertain/unconstrained initial conditions/boundary conditions.

Some notation:

Core -> star or close binary

Clump -> star cluster

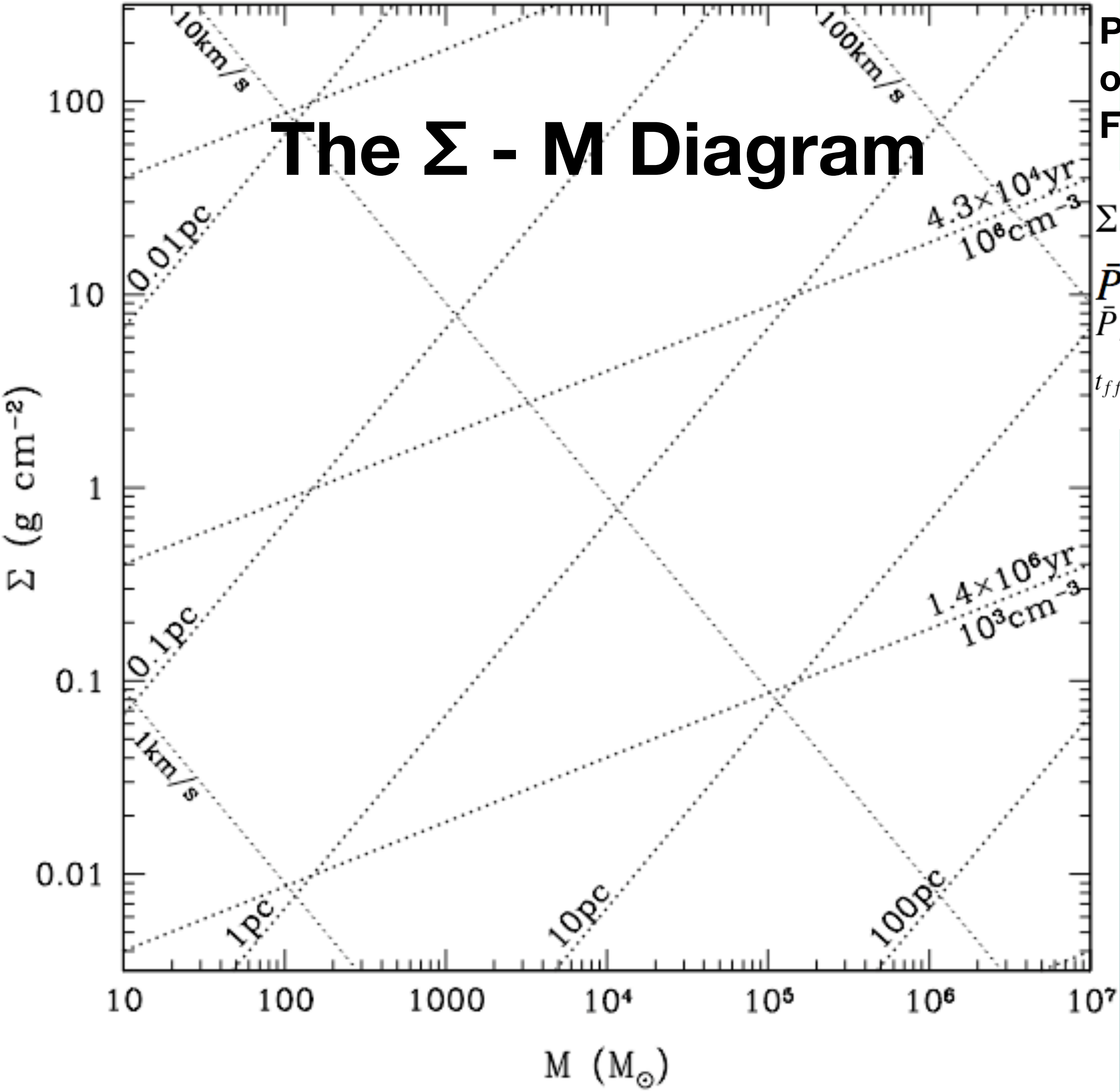
# Massive Star Formation: Open Questions

- Causation: external triggering or spontaneous gravitational instability?
- Initial conditions: how close to equilibrium?
- Accretion mechanism: [turbulent/magnetic/thermal-heat]-regulated fragmentation vs competitive accretion
- Timescale: fast or slow (# of dynamical times)?
- End result
  - Initial mass function (IMF)
  - Binary fraction and properties
  - Initial cluster mass function (ICMF)
  - Efficiency and Rate (& relation to galaxy-scale)

How do these properties vary with environment?

**Physical Properties of Massive Star-Forming Regions**

# The Σ - M Diagram



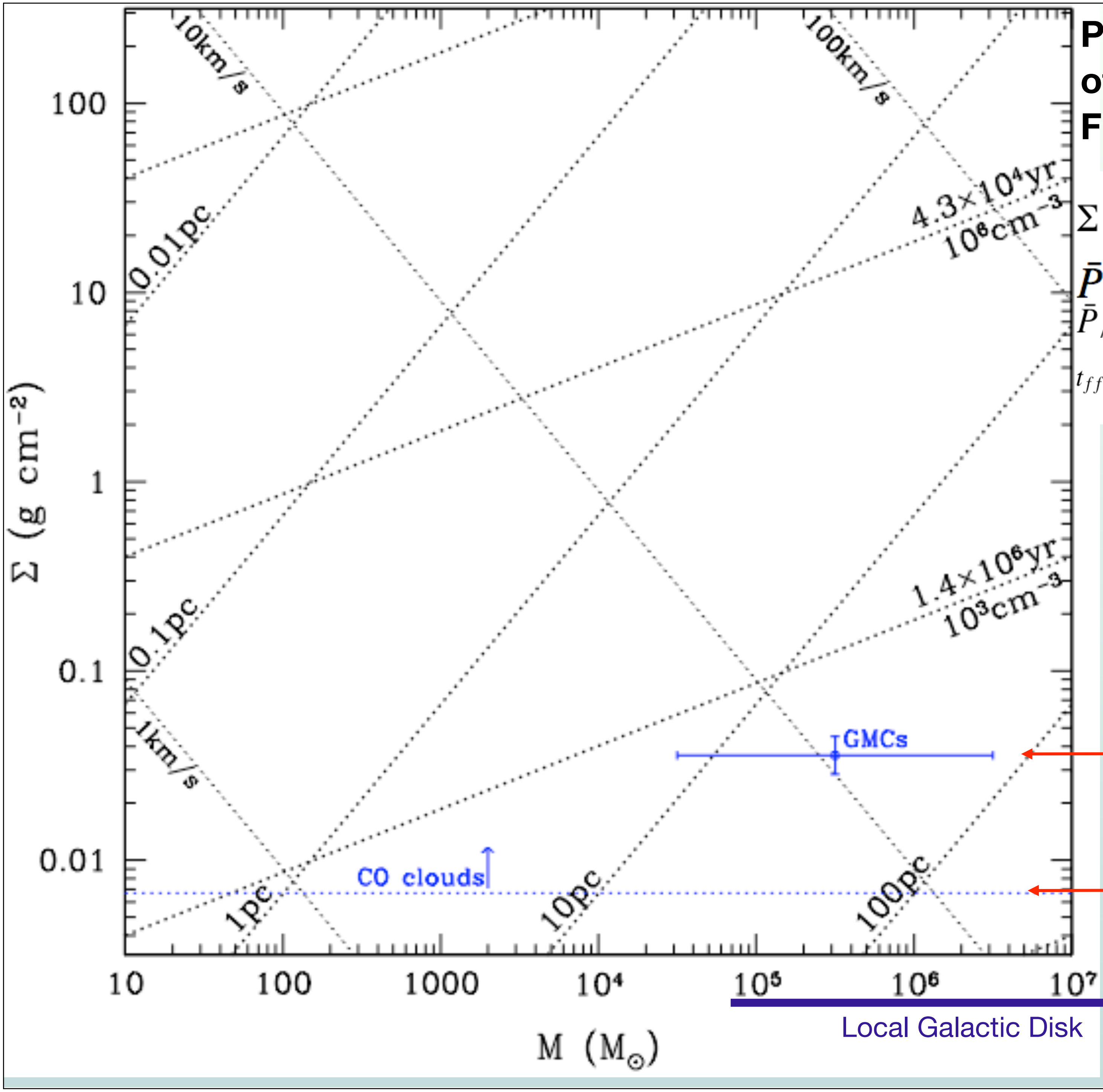
$$\Sigma \equiv \frac{M}{\pi R^2}$$

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

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

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

# Physical Properties of Massive Star-Forming Regions



Local Galactic Disk

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

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

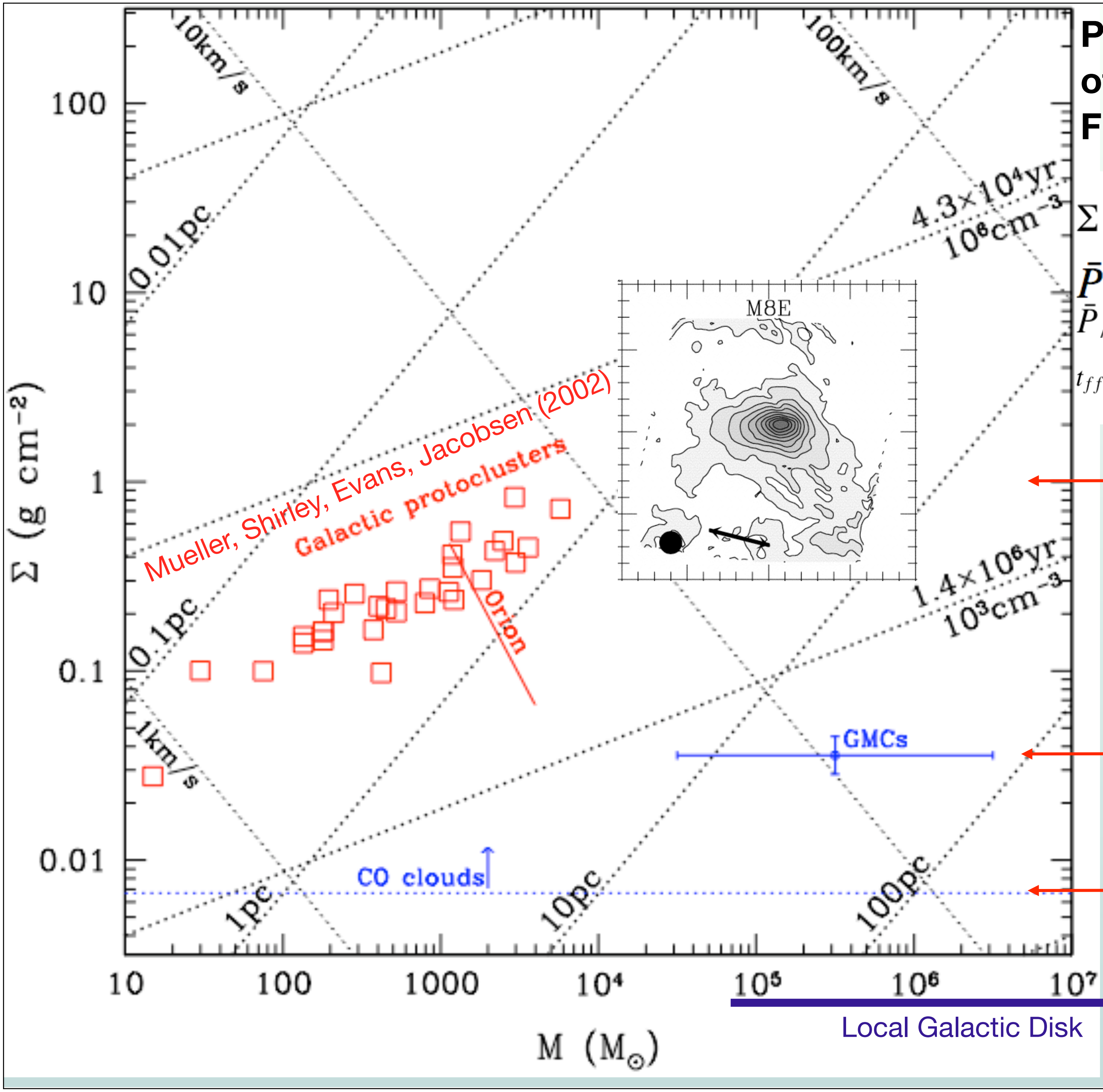
$$t_{ff} = \left(\frac{3\pi}{32G\rho}\right)^{1/2}$$

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

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

$\Sigma\sim10\ M_\odot\ pc^{-2}$

# Physical Properties of Massive Star-Forming Regions



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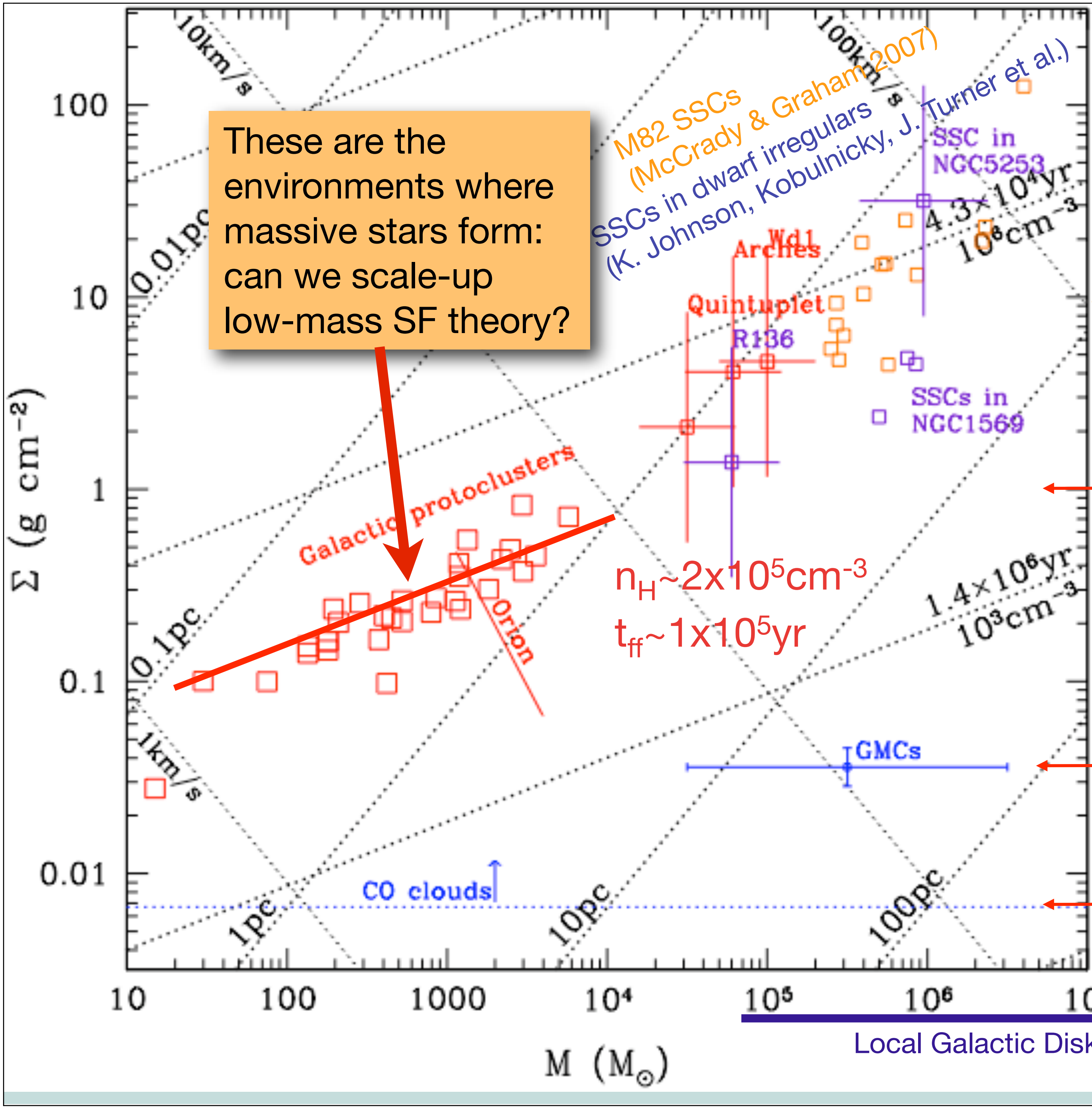

These are the environments where massive stars form: can we scale-up low-mass SF theory?

$n_H \sim 2\times10^5 cm^{-3}$

$t_{ff} \sim 1\times10^5 yr$

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

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Local Galactic Disk $\Sigma \sim 10\ M_\odot\ pc^{-2}$

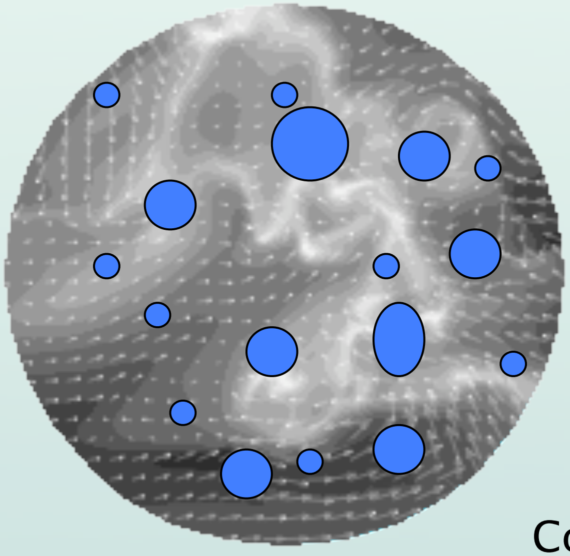
# Massive Star Formation Theories

Stahler, Palla, Ho 2000; Beuther, Churchwell, McKee, Tan 2007; Zinnecker & Yorke 2007

## Core Accretion

Myers & Fuller 1992; Caselli & Myers 1995;
McLaughlin & Pudritz 1997;
Yorke & Sonnhalter 2002;
McKee & Tan 2002, 2003;

Stars form from "cores", $M_{core} \sim 2m_*$, which fragment from the clump



$$\bar{P} = \phi_P G \Sigma^2$$

If in equilibrium, then self-gravity is balanced by internal pressure: B-field, turbulence, radiation pressure (thermal P is small)

Cores form from this turbulent medium: at any given time there is a small mass fraction in unstable cores. These cores collapse quickly to form individual stars or binaries.

## Equilibrium Star Cluster Formation

Tan, Krumholz, McKee (2006)

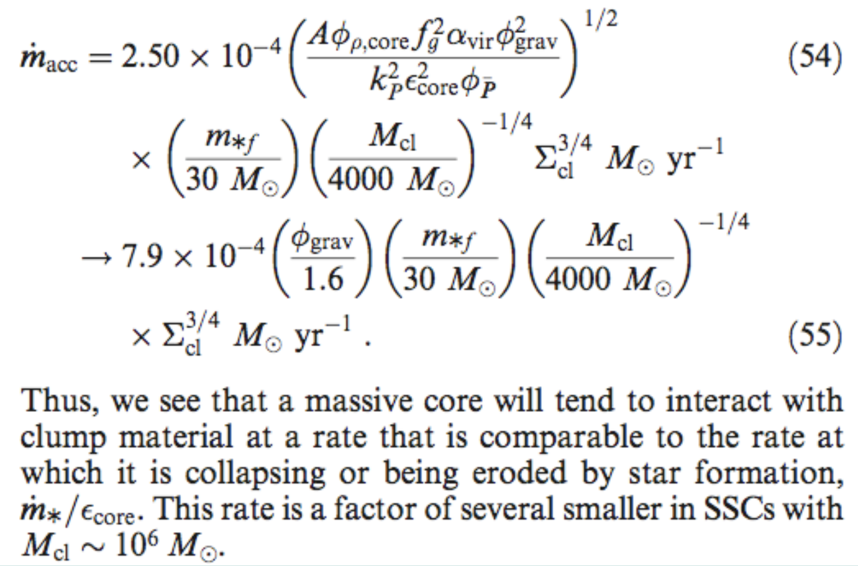
Small SFE per free-fall time ~0.02

Formation time >= several to many $t_{ff}$

->Age spreads ~>Myr in clusters

Turbulence maintained by protostellar winds (see also Nakamura & Li 2007)

## Core continues to accrete from clump



$$\dot{m}_{\rm acc} = 2.50 \times 10^{-4} \left( \frac{A \phi_{\rho,\rm core} f_g^2 \alpha_{\rm vir} \phi_{\rm grav}^2}{k_P^2 \epsilon_{\rm core}^2 \phi_{\bar{P}}} \right)^{1/2} \times \left( \frac{m_{*f}}{30\ M_\odot} \right) \left( \frac{M_{\rm cl}}{4000\ M_\odot} \right)^{-1/4} \Sigma_{\rm cl}^{3/4}\ M_\odot\ {\rm yr}^{-1} \quad (54)$$

$$\rightarrow 7.9 \times 10^{-4} \left( \frac{\phi_{\rm grav}}{1.6} \right) \left( \frac{m_{*f}}{30\ M_\odot} \right) \left( \frac{M_{\rm cl}}{4000\ M_\odot} \right)^{-1/4} \times \Sigma_{\rm cl}^{3/4}\ M_\odot\ {\rm yr}^{-1} . \quad (55)$$

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 $M_{\rm cl} \sim 10^6\ M_\odot$.

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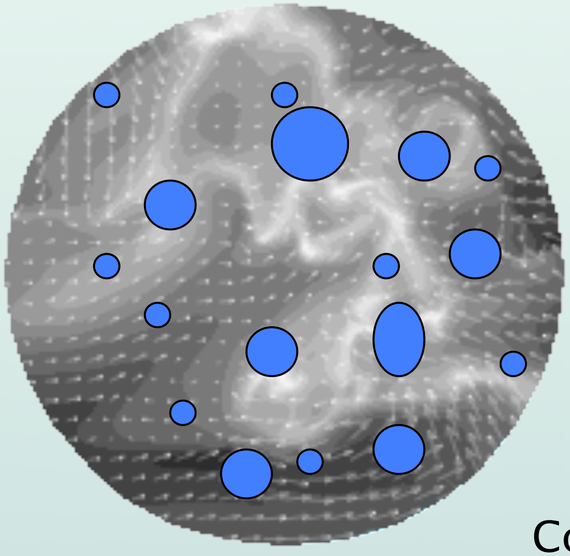

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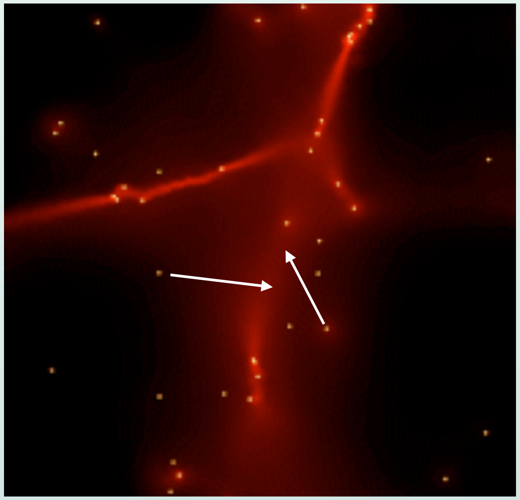
## Competitive Accretion

Bonnell, Clarke, Bate, Pringle 2001;
Bonnell, Vine, & Bate 2004;
Schmeja & Klessen 2004;
Wang, Li, Abel, Nakamura 2010;

Stars gain most mass by Bondi-Hoyle accretion of ambient gas

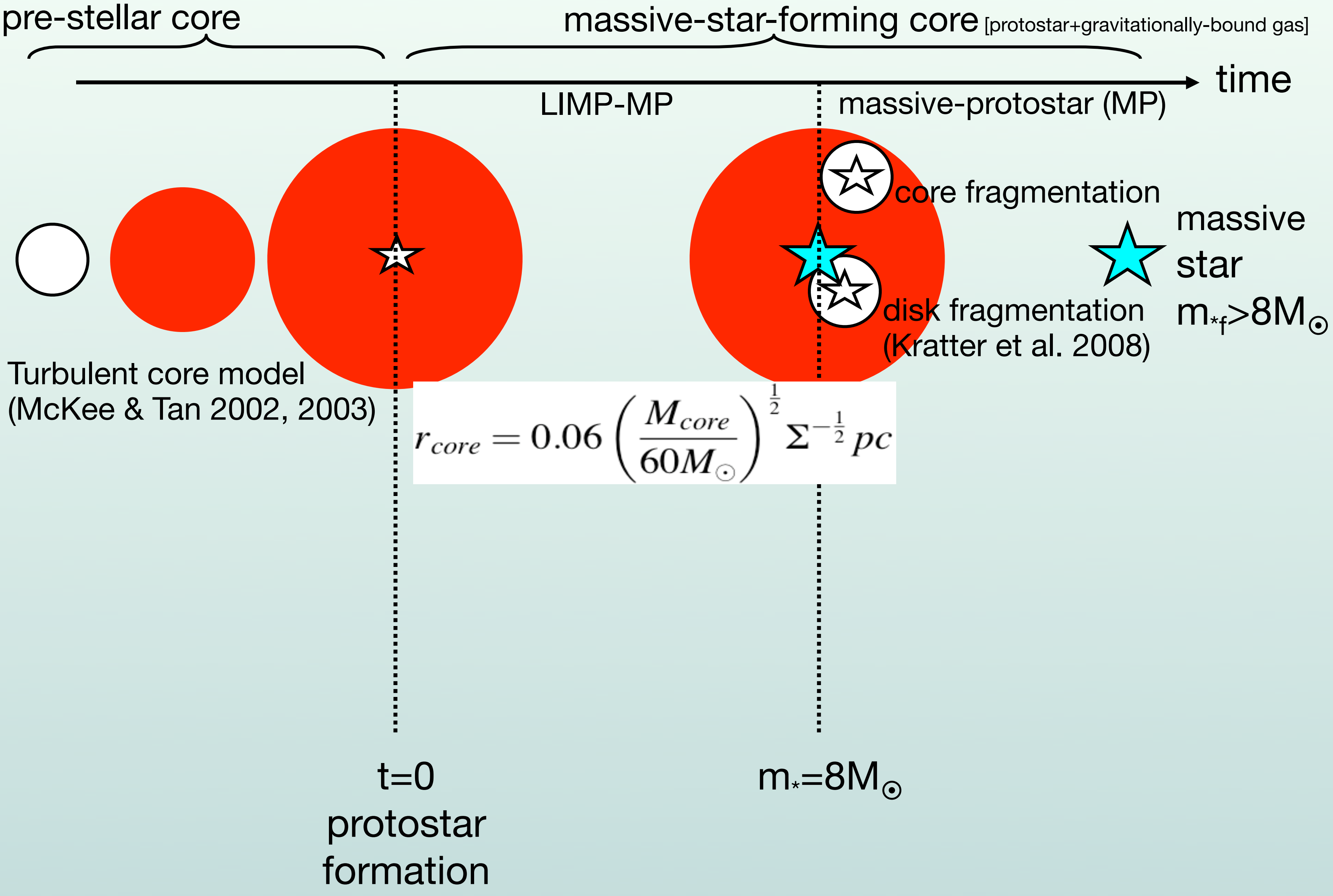


Based on simulations including only thermal pressure.

Requires global collapse of clump (Krumholz, McKee & Klein 2005)

# Schematic Differences Between Massive Star Formation Theories

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



pre-stellar core

massive-star-forming core [protostar+gravitationally-bound gas]

time

LIMP-MP

massive-protostar (MP)

core fragmentation

massive star $m_{*f}>8M_\odot$

disk fragmentation (Kratter et al. 2008)

Turbulent core model (McKee & Tan 2002, 2003)

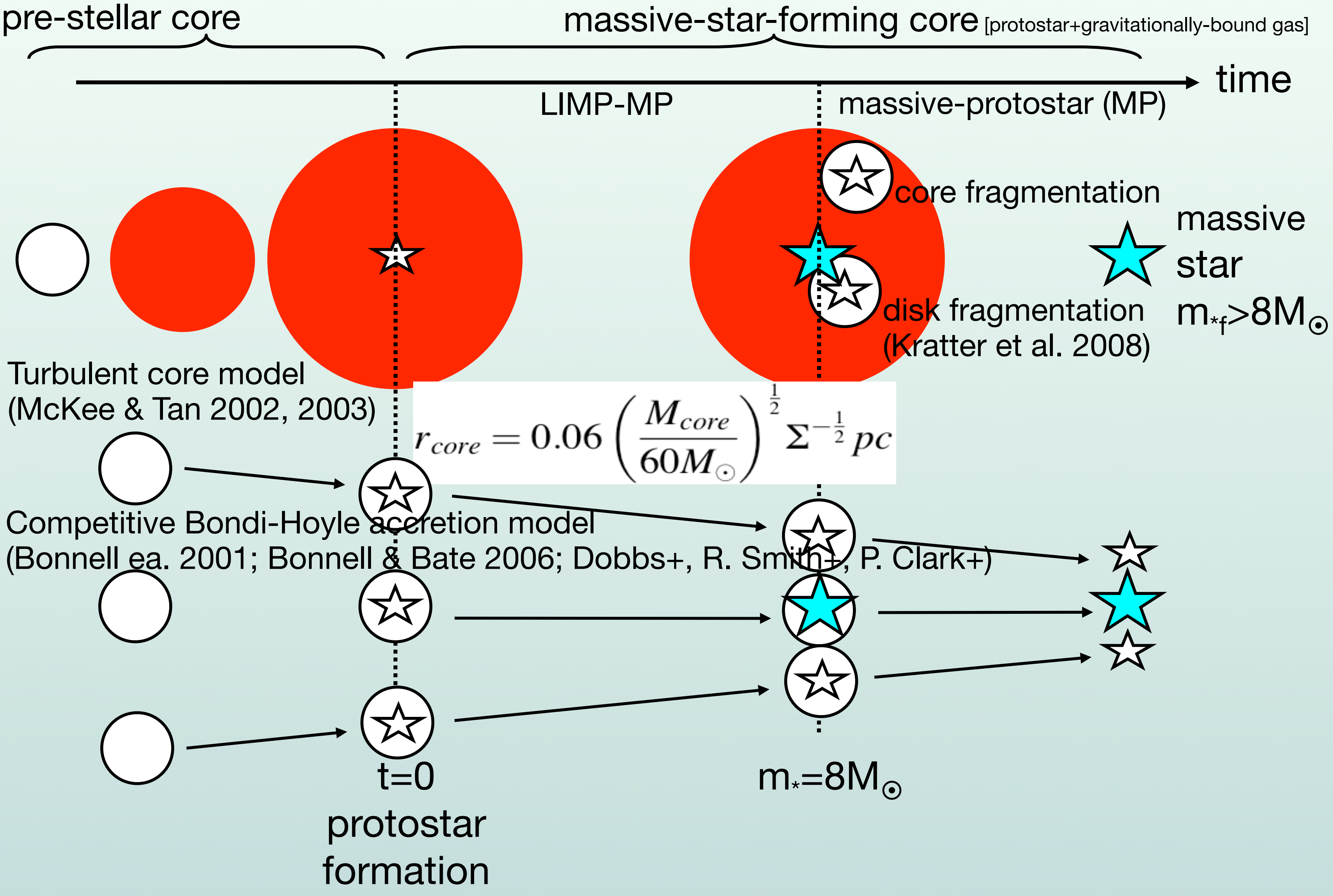
$$r_{core} = 0.06 \left(\frac{M_{core}}{60M_\odot}\right)^{\frac{1}{2}} \Sigma^{-\frac{1}{2}} pc$$

t=0
protostar
formation

$m_*=8M_\odot$

# Schematic Differences Between Massive Star Formation Theories

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



pre-stellar core

massive-star-forming core [protostar+gravitationally-bound gas]

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t=0 protostar formation

$m_*=8M_\odot$

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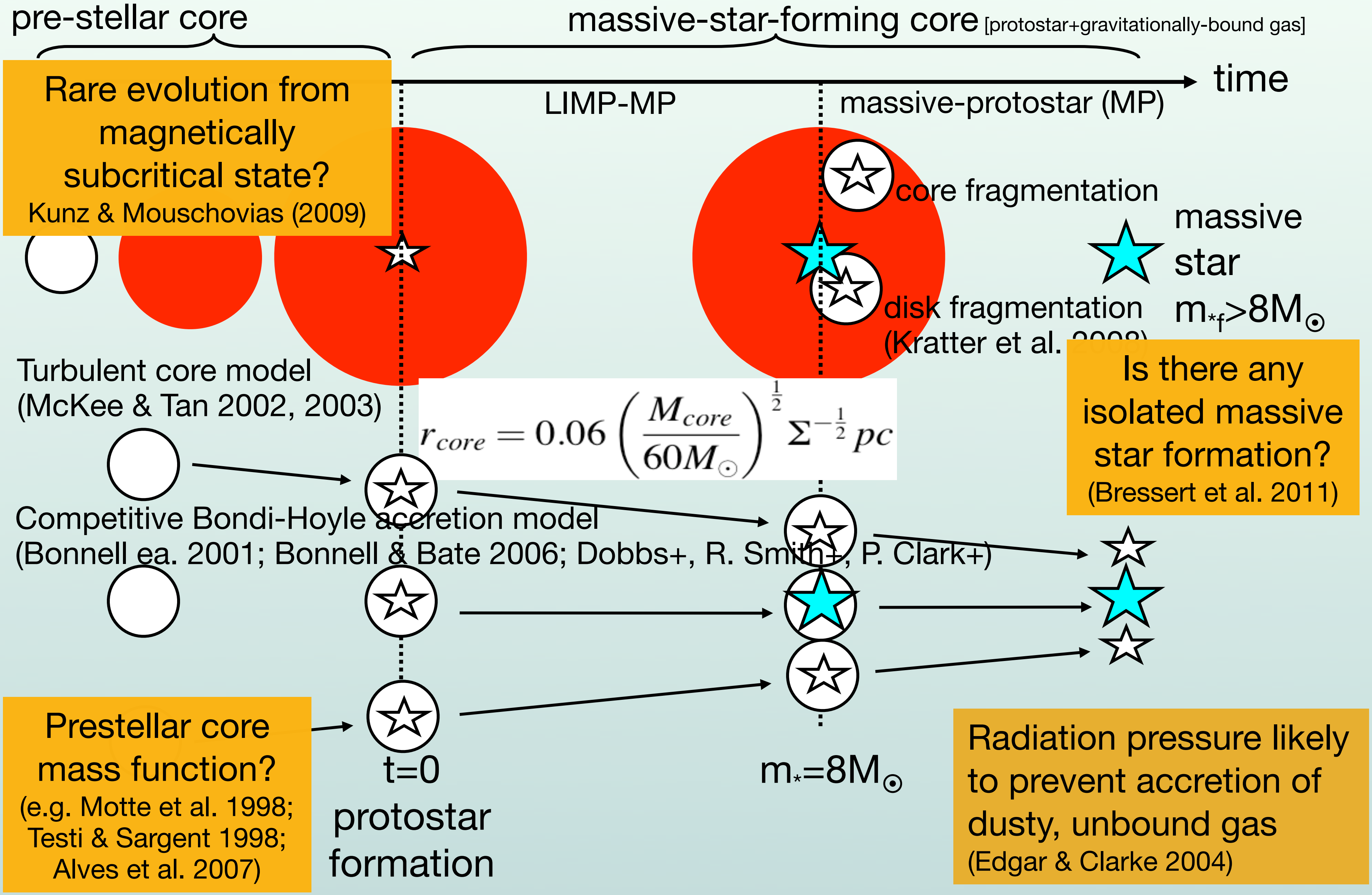
Beuther, Churchwell, McKee, Tan (2007); Tan (2008)



pre-stellar core

massive-star-forming core [protostar+gravitationally-bound gas]

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LIMP-MP

massive-protostar (MP)

Rare evolution from magnetically subcritical state?
Kunz & Mouschovias (2009)

core fragmentation

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$m_{*f} > 8M_\odot$

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Is there any isolated massive star formation?
(Bressert et al. 2011)

Competitive Bondi-Hoyle accretion model
(Bonnell ea. 2001; Bonnell & Bate 2006; Dobbs+, R. Smith+, P. Clark+)

Prestellar core mass function?
(e.g. Motte et al. 1998; Testi & Sargent 1998; Alves et al. 2007)

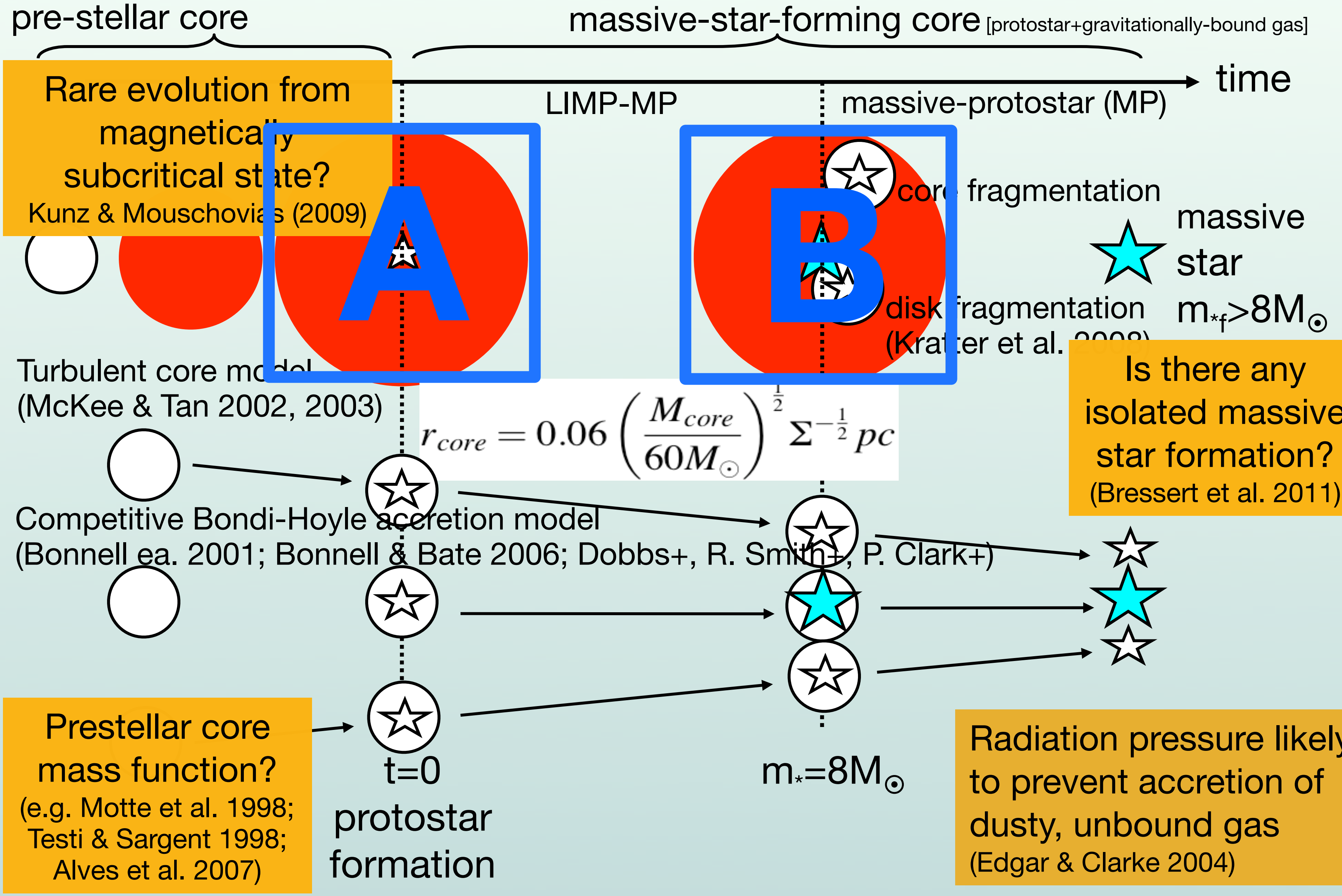
t=0
protostar
formation

$m_* = 8M_\odot$

Radiation pressure likely to prevent accretion of dusty, unbound gas
(Edgar & Clarke 2004)

# Schematic Differences Between Massive Star Formation Theories

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



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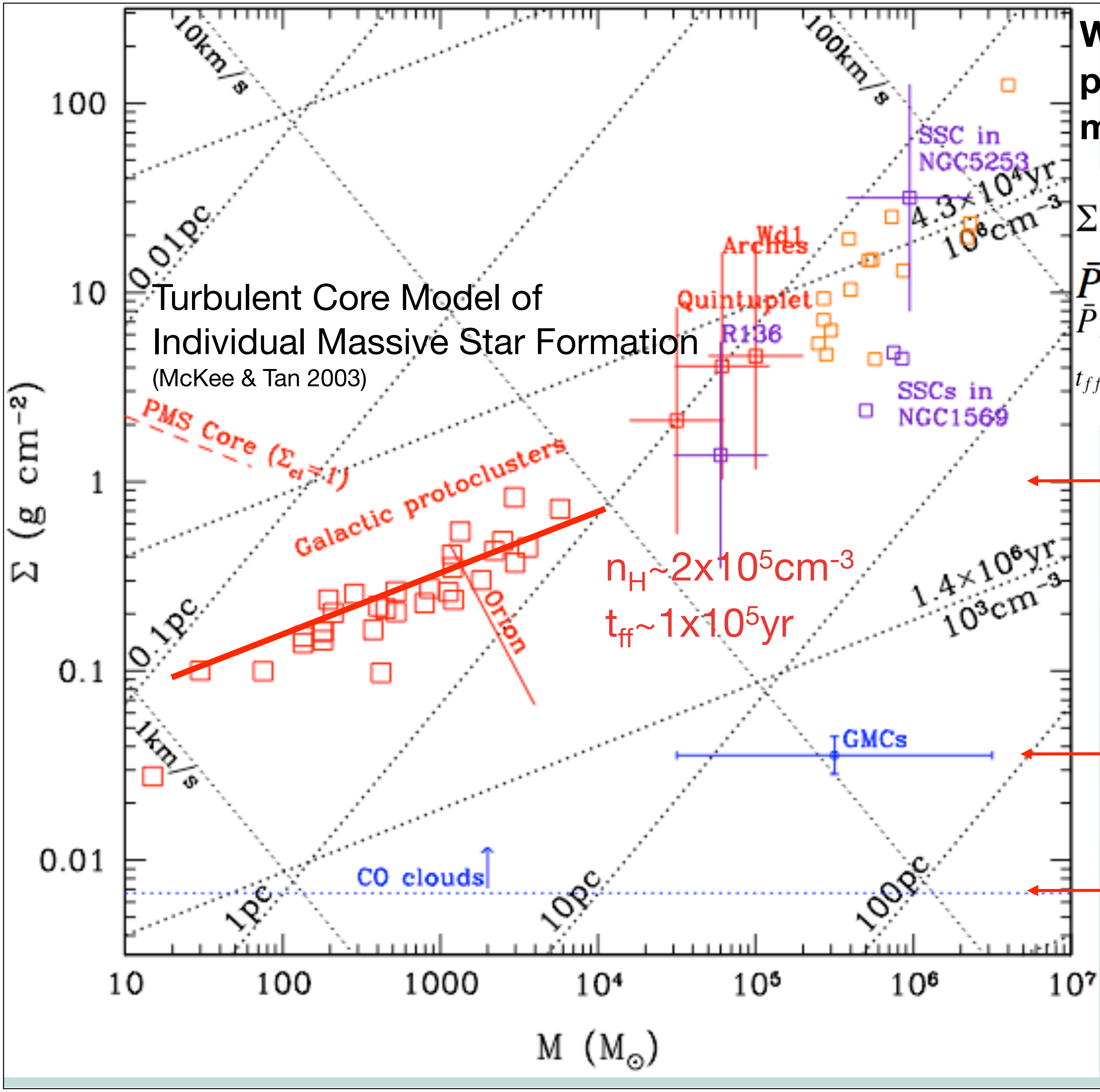
# What are the pressures where massive stars form?



Turbulent Core Model of Individual Massive Star Formation

(McKee & Tan 2003)

$n_H$~$2\times10^5$cm$^{-3}$

$t_{ff}$~$1\times10^5$yr

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

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

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

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

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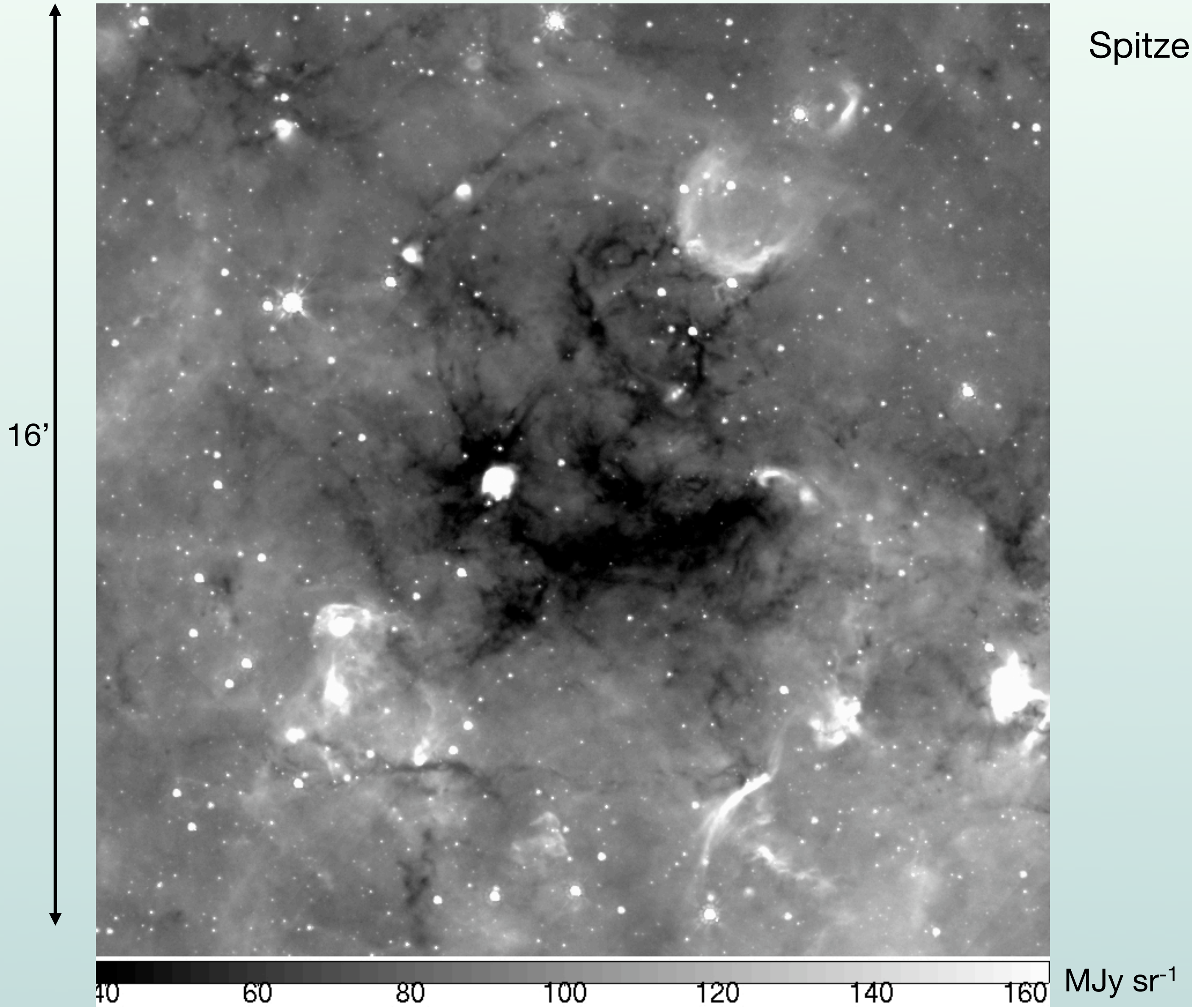
# Mid-IR Extinction Mapping of Infrared Dark Clouds

(Butler & Tan 2009, 2011; see also Peretto & Fuller 2009; Ragan et al. 2009; Battersby et al. 2010)

**G28.37+00.07**



Spitzer - IRAC 8$\mu$m (GLIMPSE)

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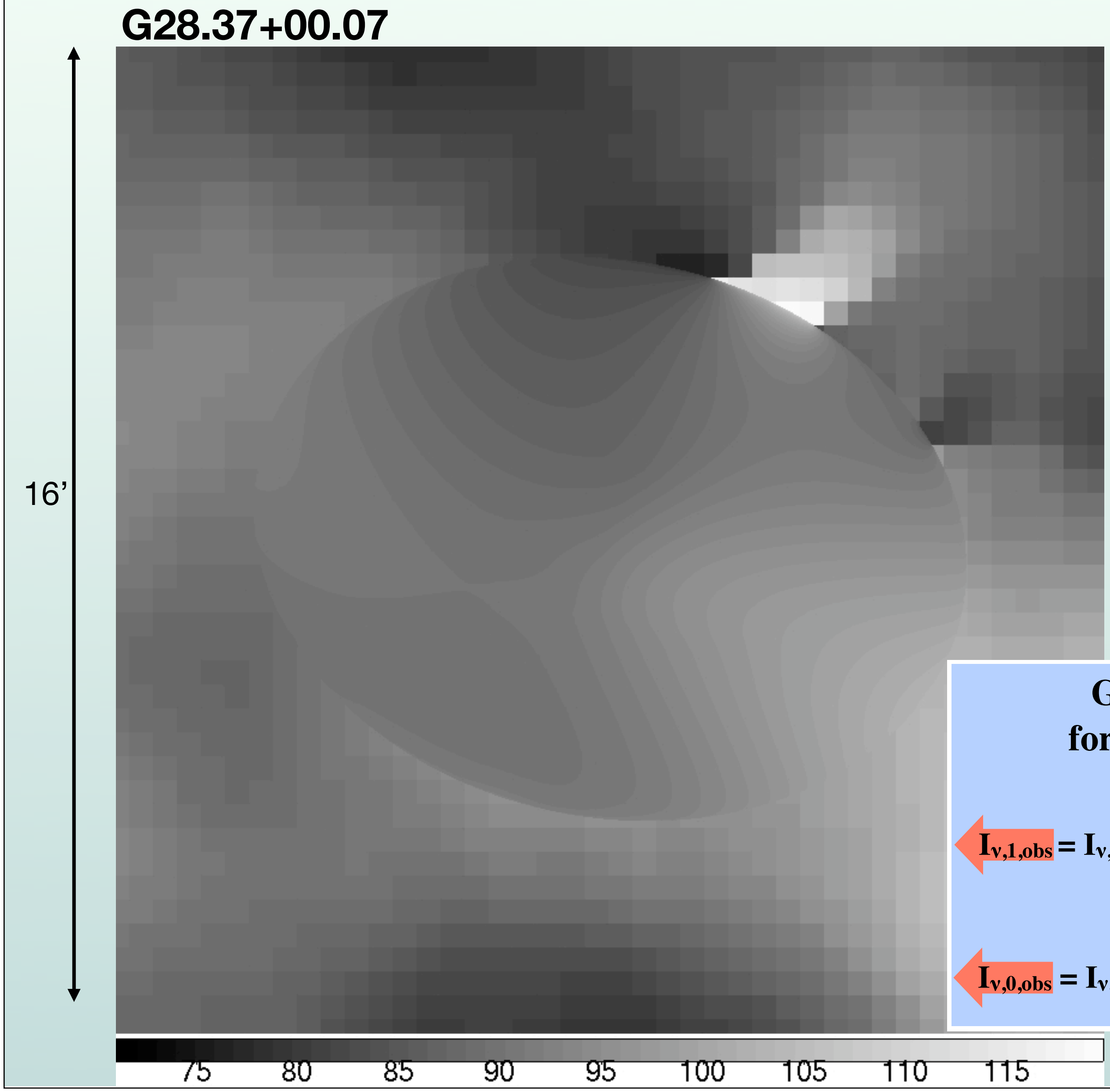

Spitzer - IRAC 8μm (GLIMPSE)

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

**Galactic foreground**

**Galactic background**

IRDC

Core A

Core B

$\mathbf{I_{\nu,1,obs} = I_{\nu,fore} + I_{\nu,1}}$ ← $\mathbf{I_{\nu,1}}$ ← $\mathbf{I_{\nu,0}}$

$\mathbf{I_{\nu,0,obs} = I_{\nu,fore} + I_{\nu,0}}$ ← $\mathbf{I_{\nu,0}}$

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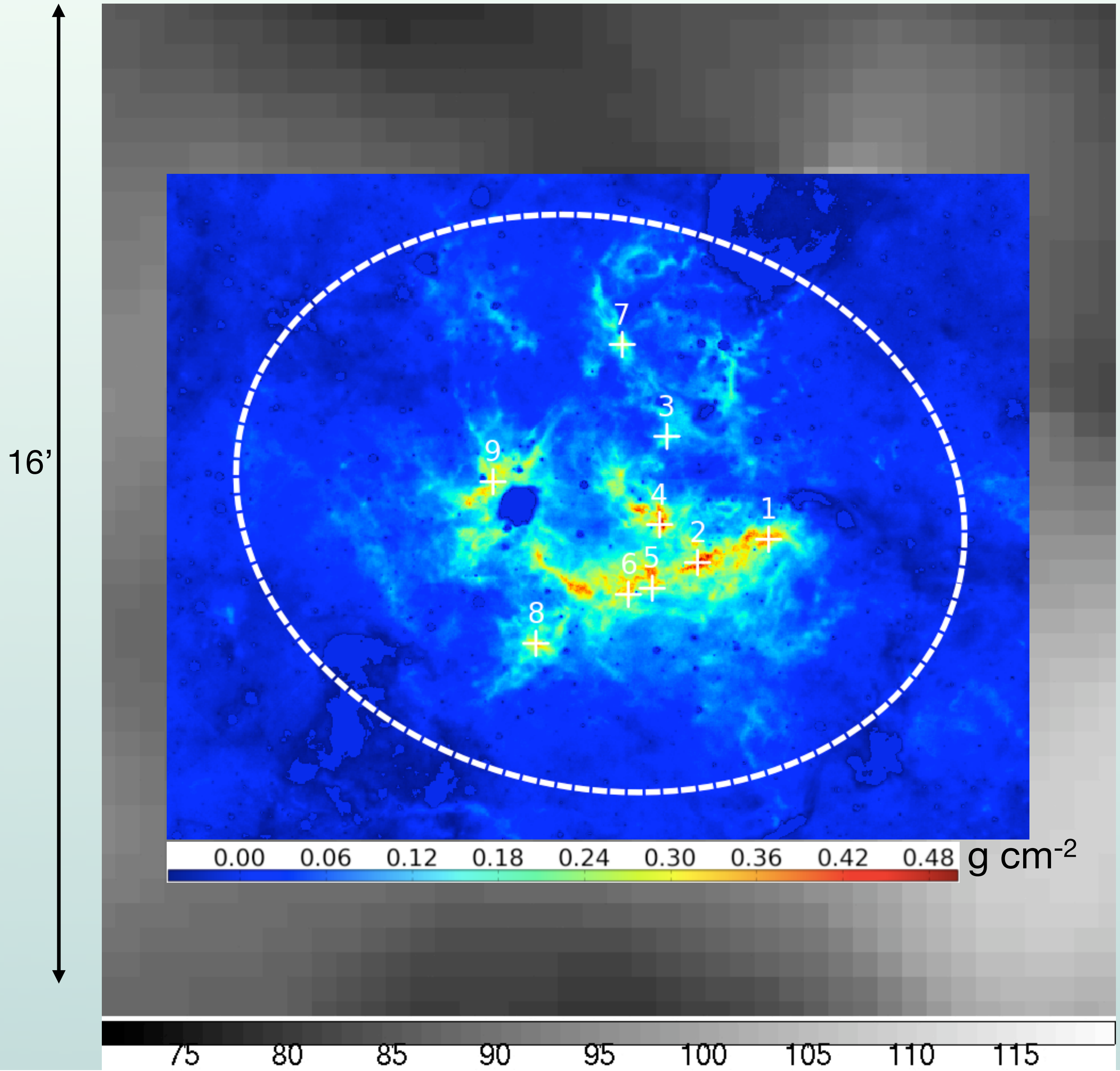


Spitzer - IRAC 8$\mu$m (GLIMPSE)

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

Correct for foreground ->
Choose nearby clouds.
BT09: analytic model
BT11: observed saturation in independent cores

**~Arcsecond scale maps of regions up to $\Sigma$ ~0.5 g cm$^{-2}$; independent of dust temp.**

Distance from molecular line velocities -> M($\Sigma$)

# Massive starless cores

Cores with power law density structure

$$\rho_c(r) = \rho_{\mathrm{s,c}}\left(\frac{r}{R_{\mathrm{c}}}\right)^{-k_{\rho,c}}$$

$$k_{\rho,c} = 1.8$$

They contain many thermal Jeans masses.

B-fields may be suppressing fragmentation within the core.

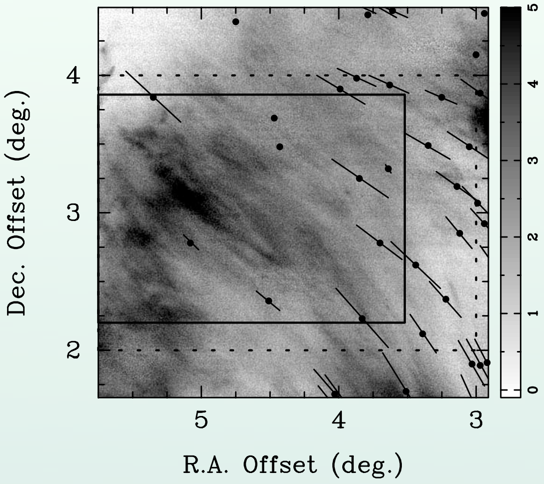
$$M_{\mathrm{BE}} = 1.182\frac{c_{\mathrm{th}}^4}{\left(G^3 P_{s,\mathrm{core}}\right)^{1/2}} \rightarrow 0.0504\left(\frac{T}{20\ \mathrm{K}}\right)^2 \frac{1}{\Sigma_{\mathrm{cl}}}\ M_\odot$$

Magnetic Critical Mass (Bertoldi & McKee 1992)

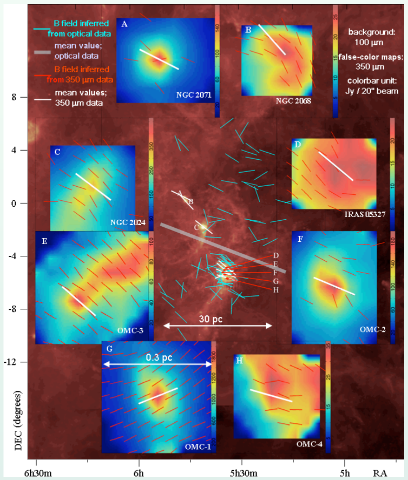
$$M_B = 79 c_\Phi^3 \left(\frac{R}{Z}\right)^2 \frac{\bar{v}_A^3}{(G^3\bar{\rho})^{1/2}} = 1020\left(\frac{R}{Z}\right)^2\left(\frac{\bar{B}}{30\,\mu\mathrm{G}}\right)^3\left(\frac{10^3\ \mathrm{cm}^{-3}}{\bar{n}_{\mathrm{H}}}\right)^2\ M_\odot$$

$n_H$~$10^5$cm$^{-3}$, B~200μG -> $M_B$~100 $M_\odot$

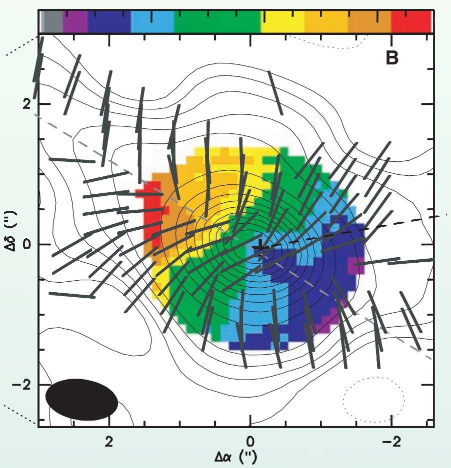
# Strong magnetic fields in star-forming regions



Taurus (Heyer et al. 2008)

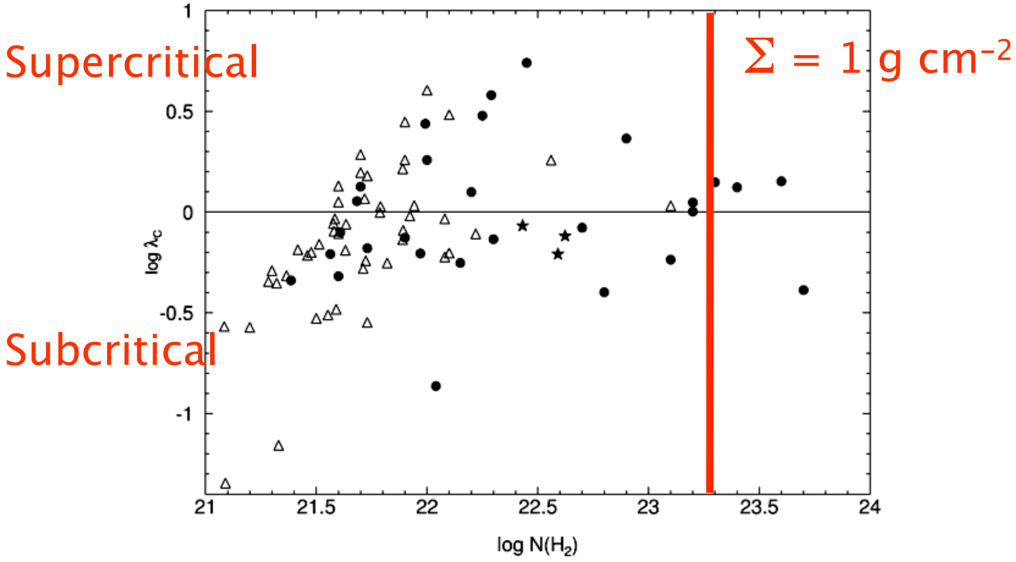


Correlation of field orientations from ~100pc to <1pc scales (Hua-bai Li et al. 2009)



Girart et al. (2009)

Strength of B–field vs. Σ (Crutcher 2005; Falgarone et al. 2008)



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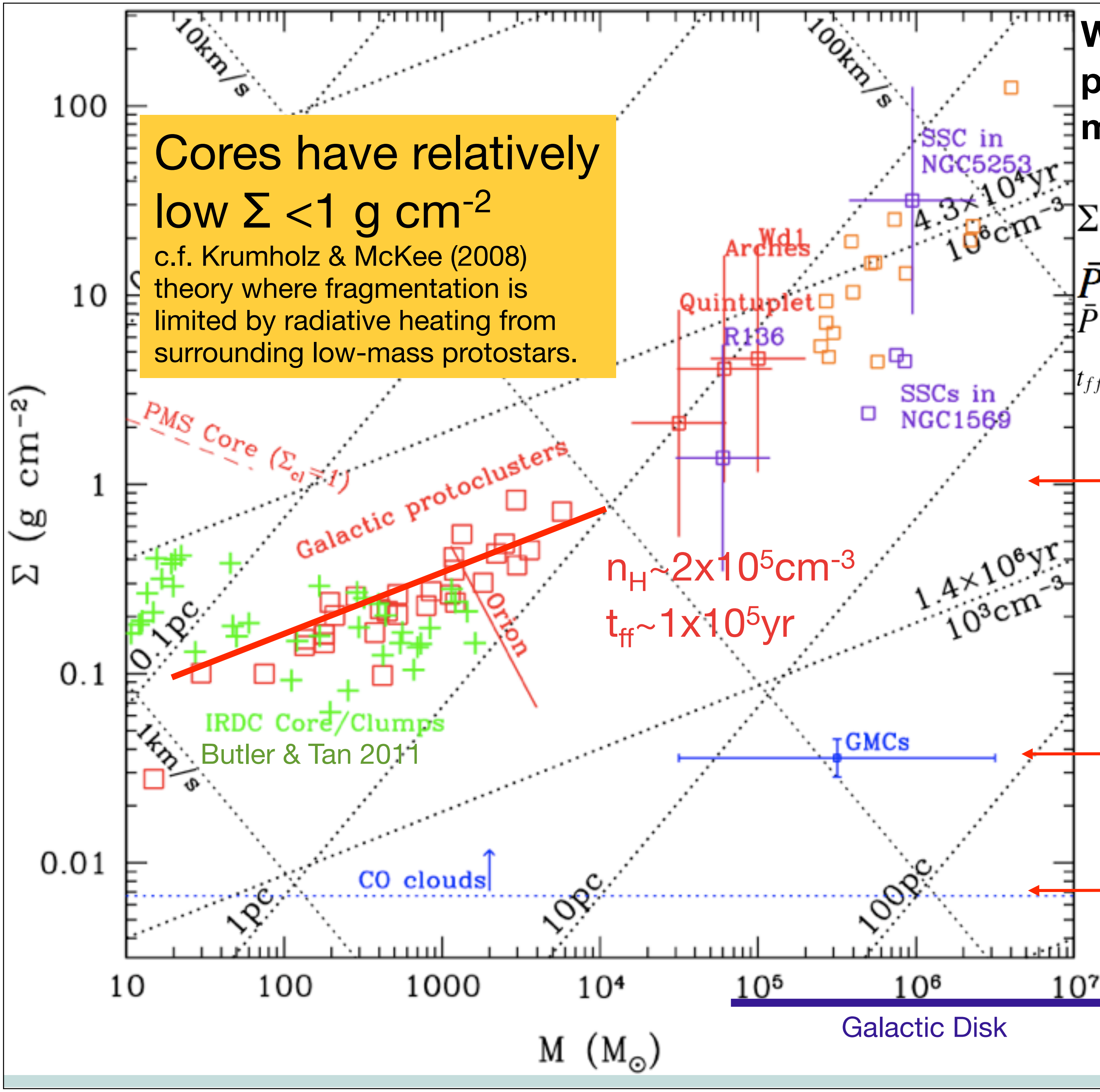


Cores have relatively low Σ <1 g cm$^{-2}$

c.f. Krumholz & McKee (2008) theory where fragmentation is limited by radiative heating from surrounding low-mass protostars.

$n_H \sim 2\times10^5 \mathrm{cm}^{-3}$

$t_{ff} \sim 1\times10^5 \mathrm{yr}$

Butler & Tan 2011

Galactic Disk

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

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

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

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

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

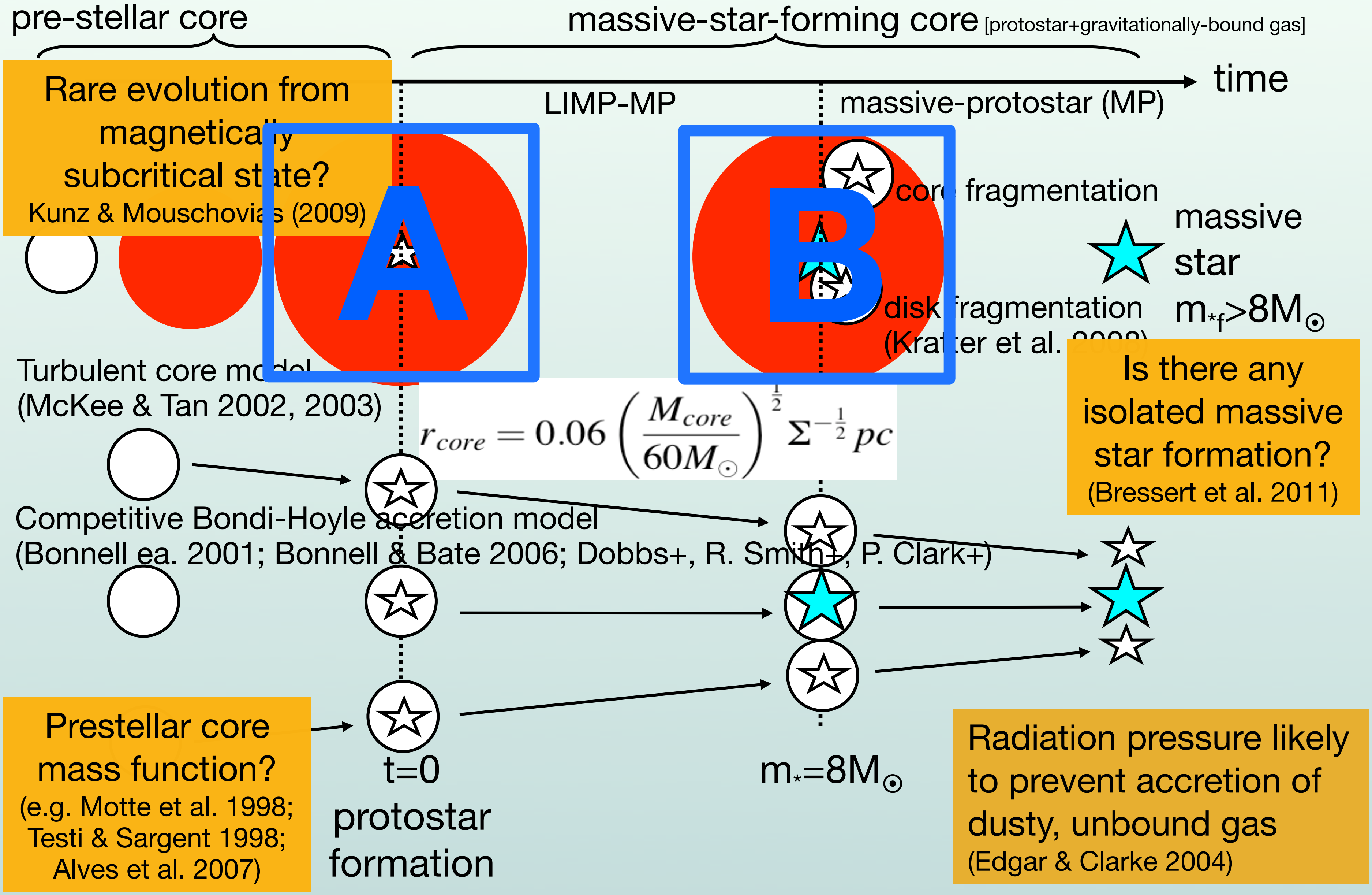
$A_V=7.5$
$A_{8\mu m}=0.30$
$N_H=1.6\times10^{22}\mathrm{cm}^{-2}$
$\Sigma=180\ M_\odot\ \mathrm{pc}^{-2}$

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

$\Sigma\sim10\ M_\odot\ \mathrm{pc}^{-2}$

# Schematic Differences Between Massive Star Formation Theories

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



$m_{*f} > 8M_\odot$

Turbulent core model
(McKee & Tan 2002, 2003)

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

Competitive Bondi-Hoyle accretion model
(Bonnell ea. 2001; Bonnell & Bate 2006; Dobbs+, R. Smith+, P. Clark+)

t=0
protostar formation

$m_* = 8M_\odot$

Rare evolution from magnetically subcritical state?
Kunz & Mouschovias (2009)

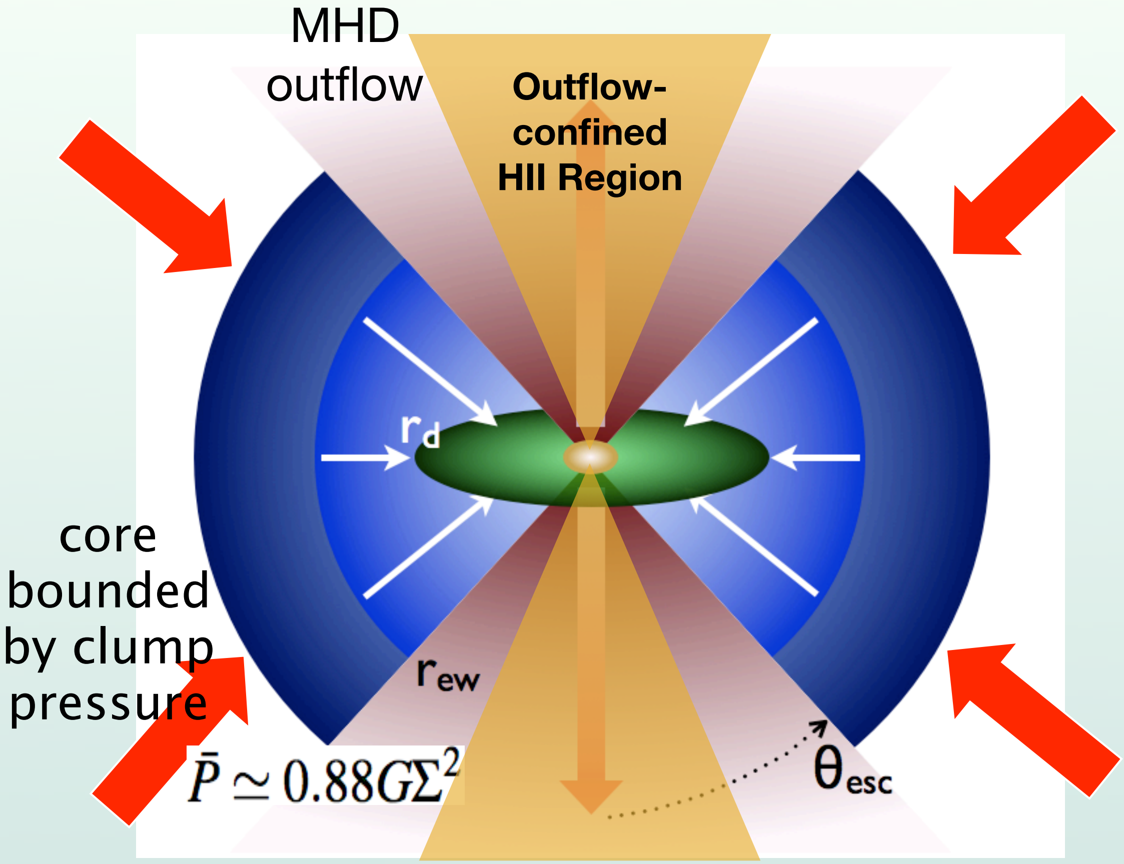
Is there any isolated massive star formation?
(Bressert et al. 2011)

Prestellar core mass function?
(e.g. Motte et al. 1998; Testi & Sargent 1998; Alves et al. 2007)

Radiation pressure likely to prevent accretion of dusty, unbound gas
(Edgar & Clarke 2004)

# Massive Protostars

MT03, TM, in prep.



core bounded by clump pressure

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

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

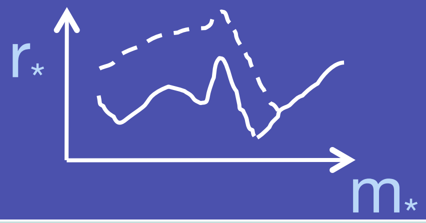
$$r_{disk} = 1200 \frac{\beta}{0.02} \left(\frac{M_{core}}{60 M_\odot}\right)^{\frac{1}{2}} \Sigma^{-\frac{1}{2}}\, AU$$

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

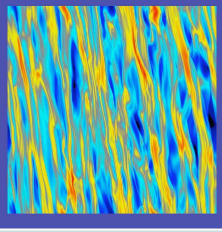
Final mass accretion rate

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

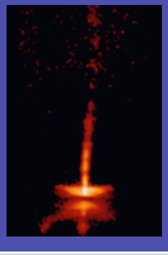
Protostellar evolution



Disk structure

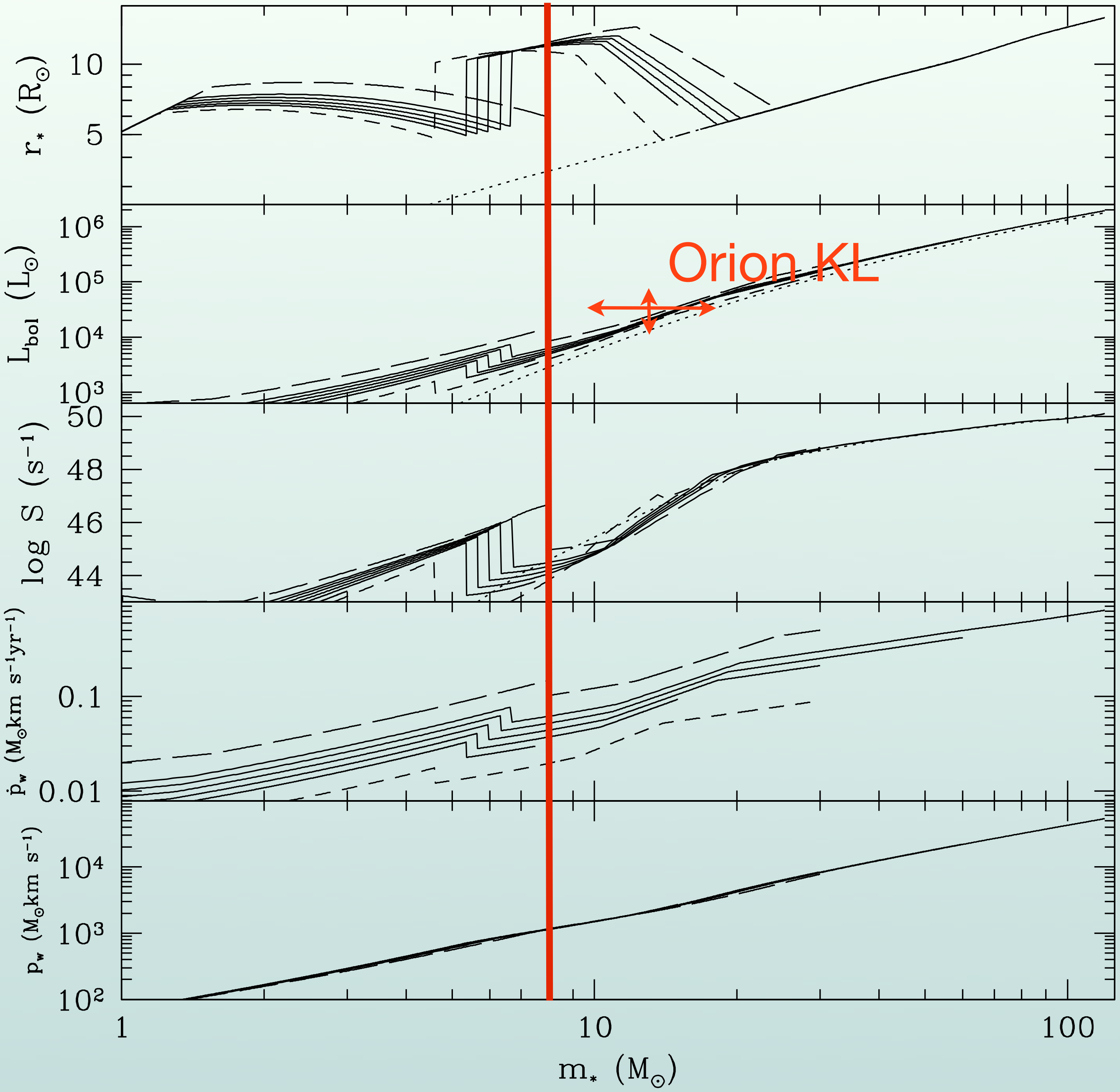


Outflows



# Protostellar Evolution

[Tan & McKee 2003; see also Hosokawa & Omukai 2009]



Radius

Luminosity

protostar+boundary layer+disk

Ionizing L.

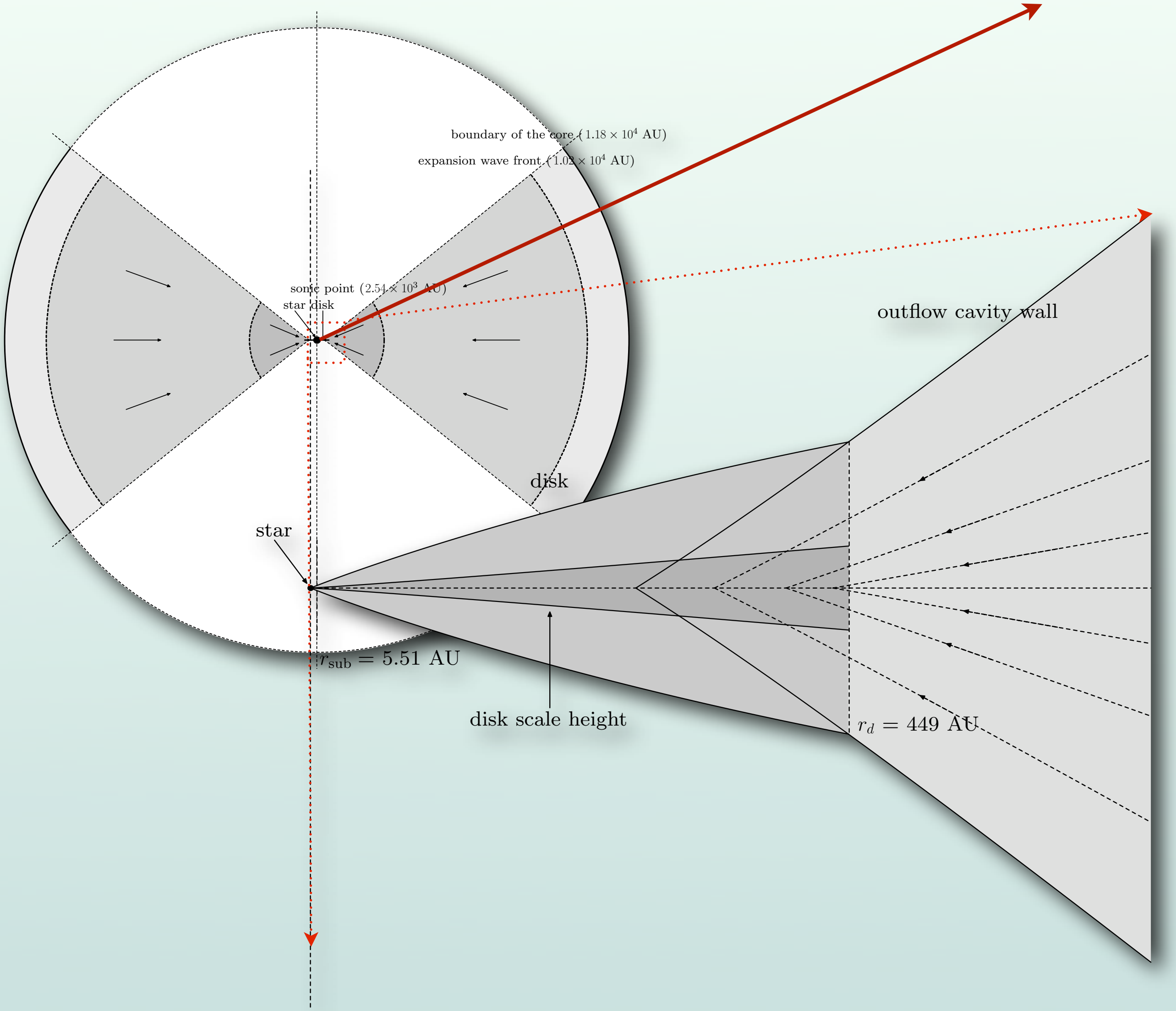
Outflow momentum flux

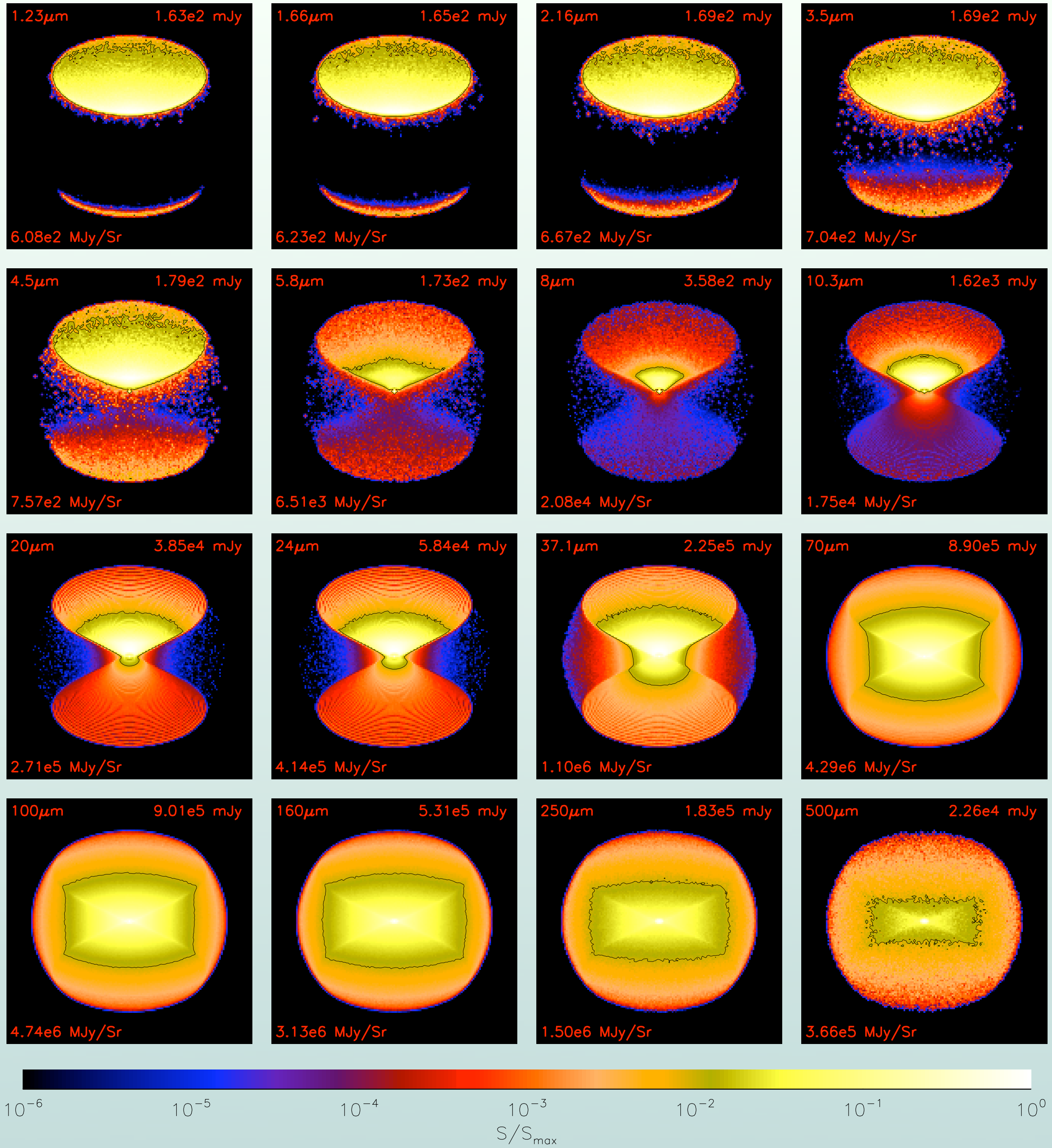
(scaled from Najita & Shu 94)

Total outflow momentum

# Continuum Radiative Transfer Modeling

Zhang & Tan (2011)



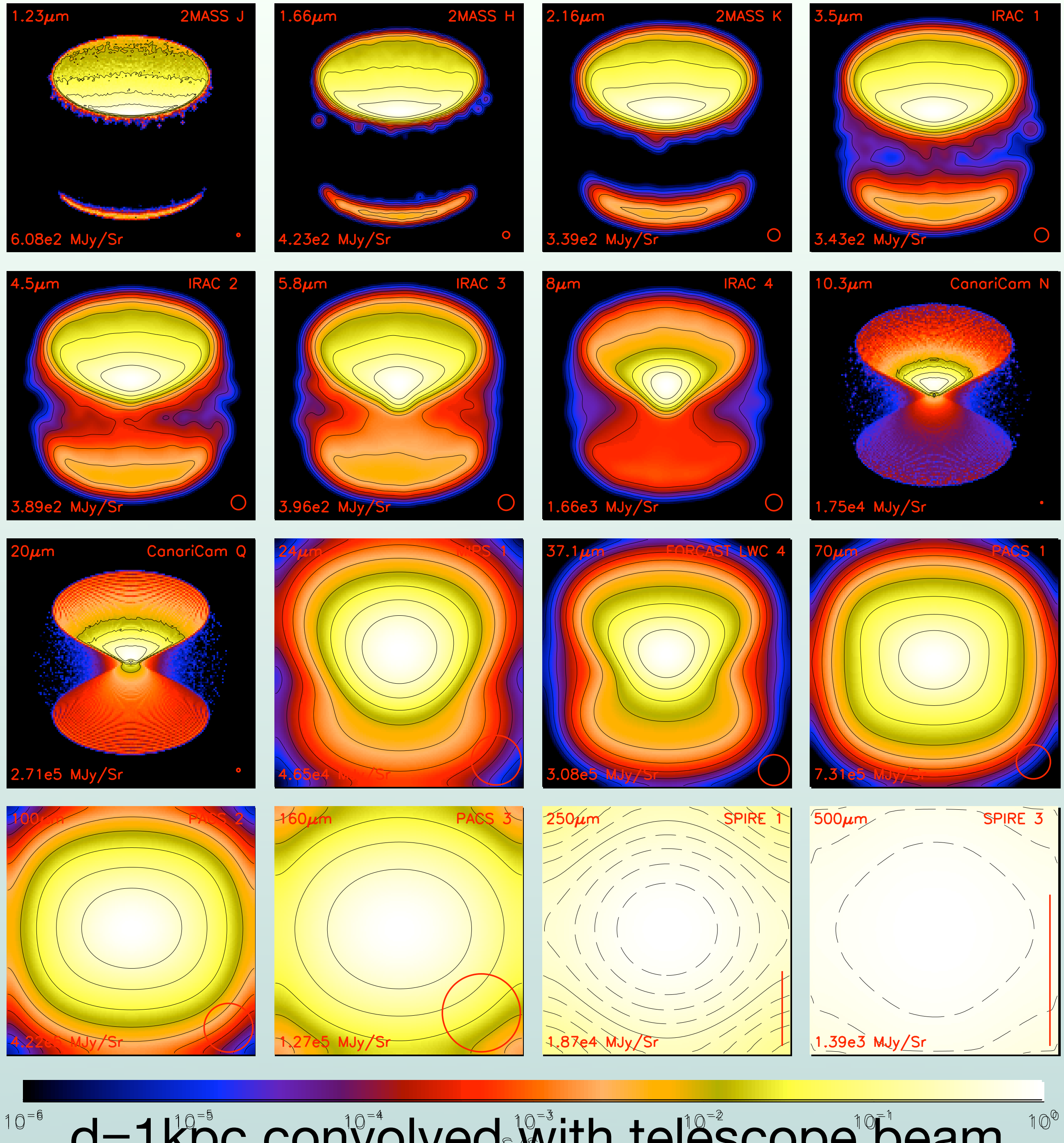


# Radiative Transfer Models

Zhang &Tan (2011)
see also:
Robitaille et al. 2006;
Molinari et al. 2008;
Johnston et al. 2011

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

$\Sigma = 1\ \mathrm{g\ cm^{-2}}$
$M_{core} = 60\ M_{\odot}$
$m_{*} = 8\ M_{\odot}$
$m_{disk} = m_{*}/3$
$L_{bol} = 6\times10^{3}\ L_{\odot}$



d=1kpc convolved with telescope beam

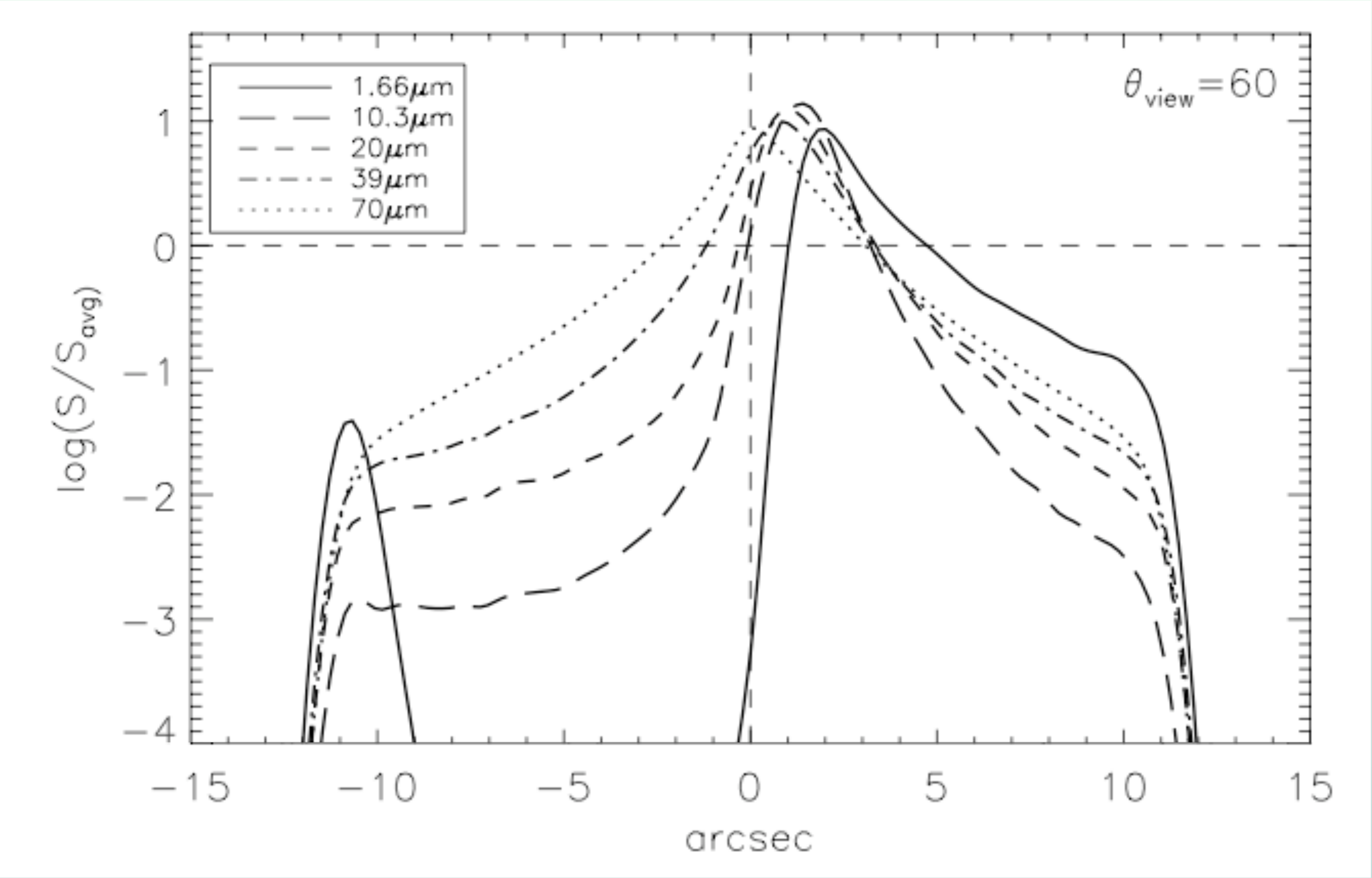
# Radiative Transfer Models

Zhang &Tan (2011)
see also:
Robitaille et al. 2006;
Molinari et al. 2008;
Johnston et al. 2011

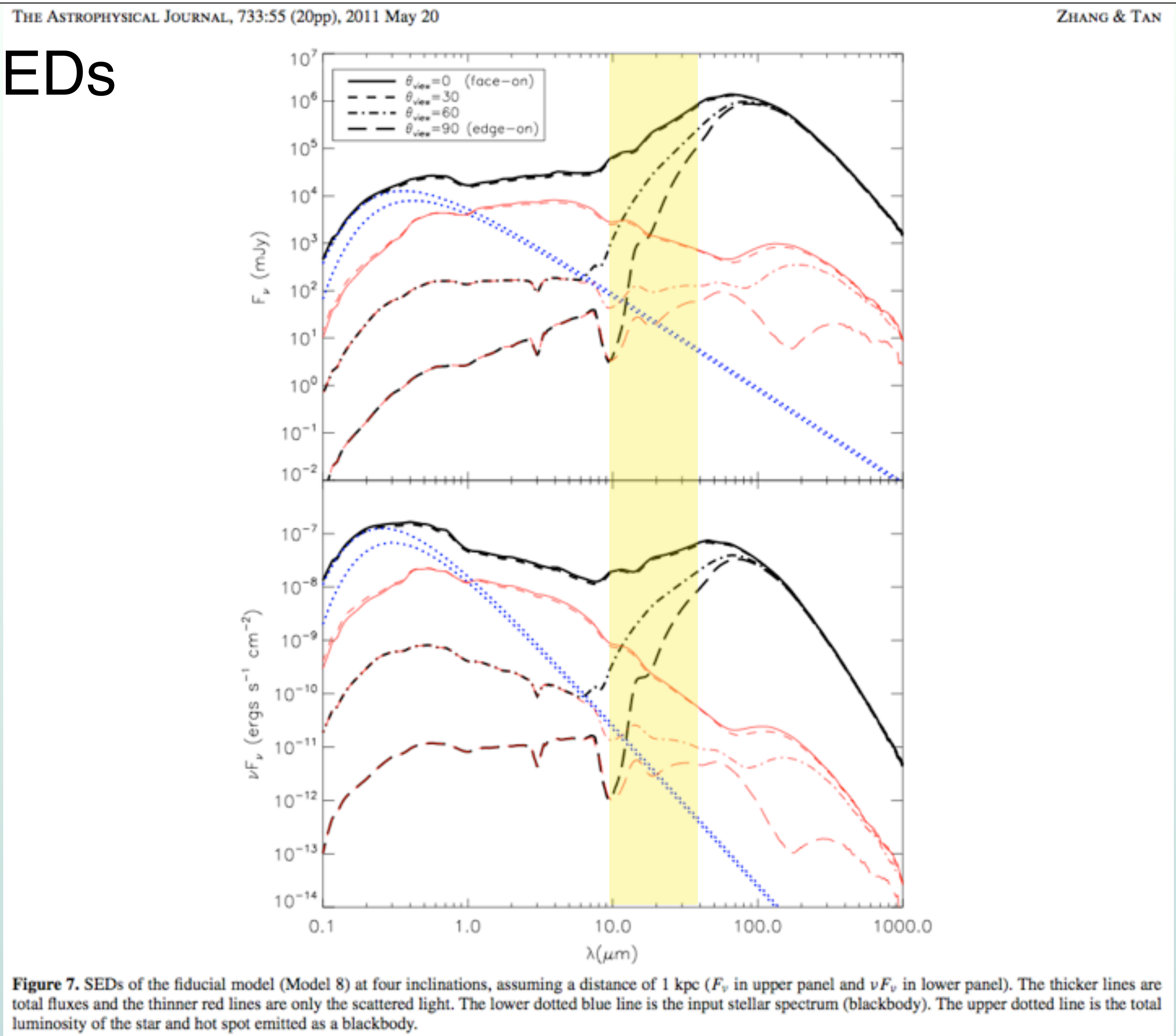
Rotation and outflow axis inclined at 60° to line of sight.

$\Sigma = 1\ \mathrm{g\ cm^{-2}}$
$M_{core} = 60\ M_{\odot}$
$m_{*} = 8\ M_{\odot}$
$m_{disk} = m_{*}/3$
$L_{bol} = 6\mathrm{x}10^{3}\ L_{\odot}$

# Flux Profile along Outflow Axis



# SEDs



THE ASTROPHYSICAL JOURNAL, 733:55 (20pp), 2011 May 20 ZHANG & TAN

**Figure 7.** SEDs of the fiducial model (Model 8) at four inclinations, assuming a distance of 1 kpc ($F_\nu$ in upper panel and $\nu F_\nu$ in lower panel). The thicker lines are total fluxes and the thinner red lines are only the scattered light. The lower dotted blue line is the input stellar spectrum (blackbody). The upper dotted line is the total luminosity of the star and hot spot emitted as a blackbody.

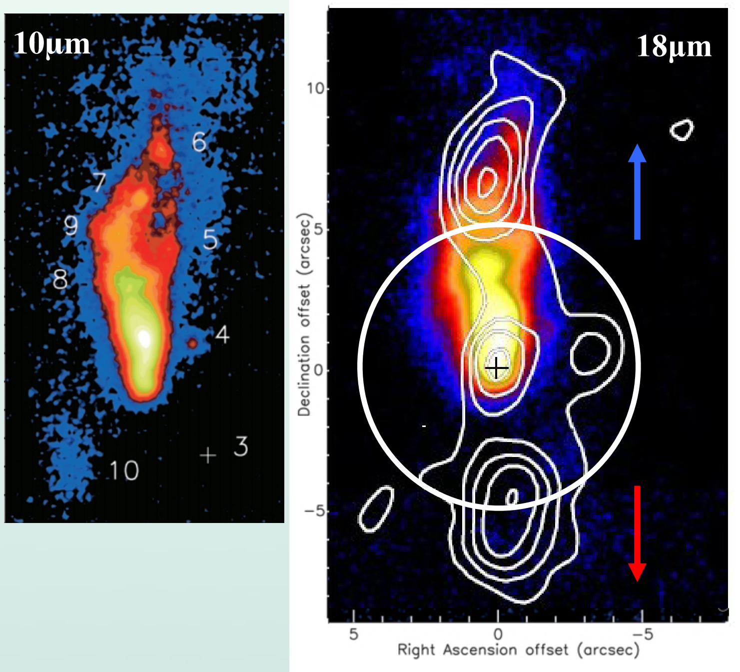
# Mid IR Emission from the Outflow Cavity

## G35.2N

d=2.3 kpc

$L_{MIR}$~$1.6x10^3 L_\odot$

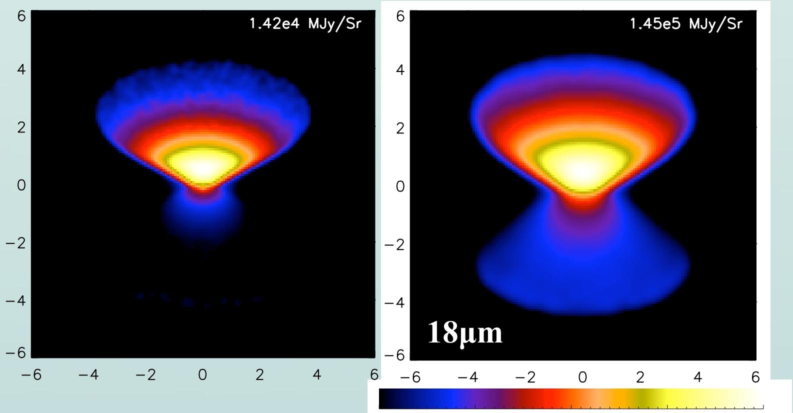
(De Buizer 2006)



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

$m_* = 8\ M_\odot$

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



# Mid IR Emission from the Outflow Cavity

G35.2N

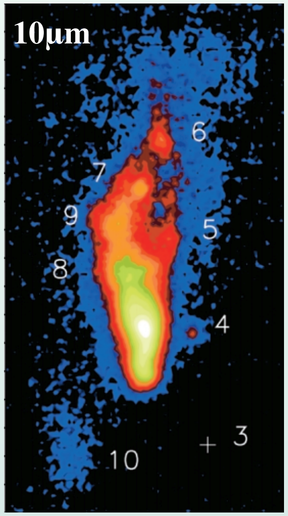
d=2.3 kpc

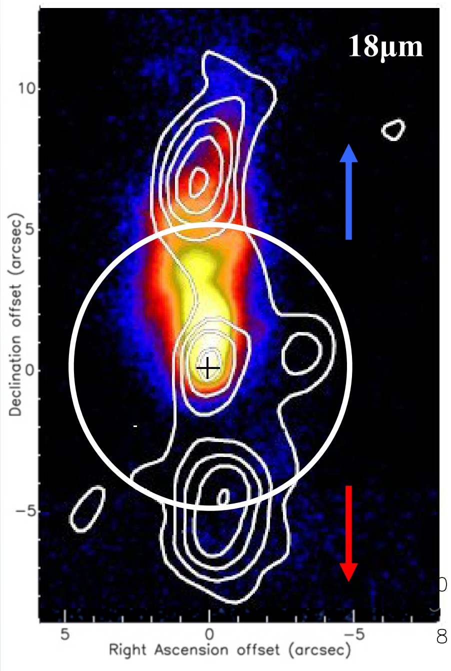
$L_{MIR}$~$1.6x10^3 L_\odot$

(De Buizer 2006)


Gemini-T-ReCS


SOFIA-FORCAST

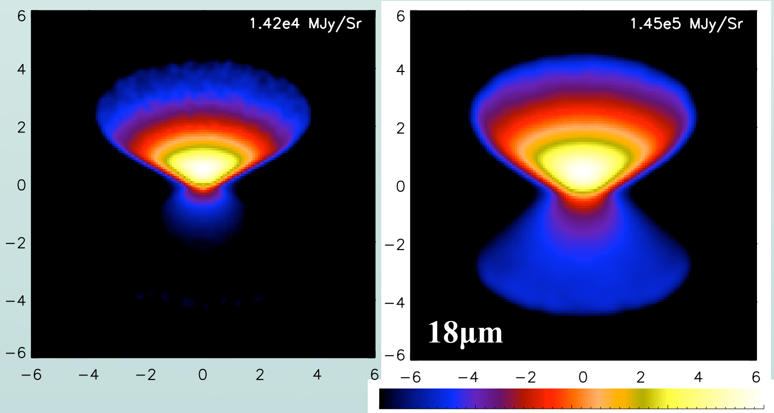


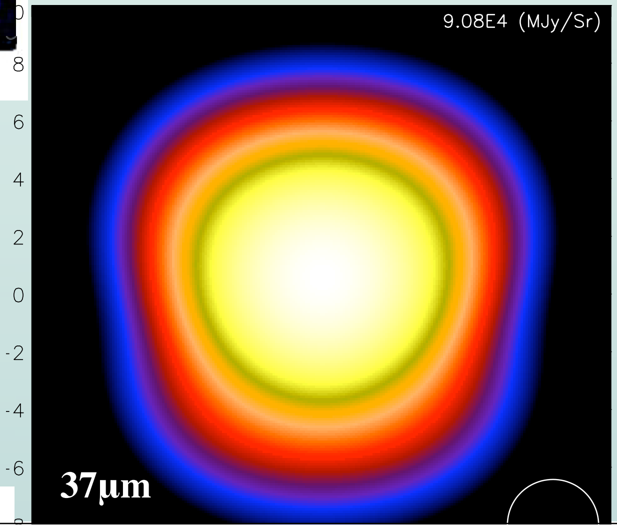


Rotation and outflow axis inclined at 60° to line of sight.

$m_* = 8 M_\odot$

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





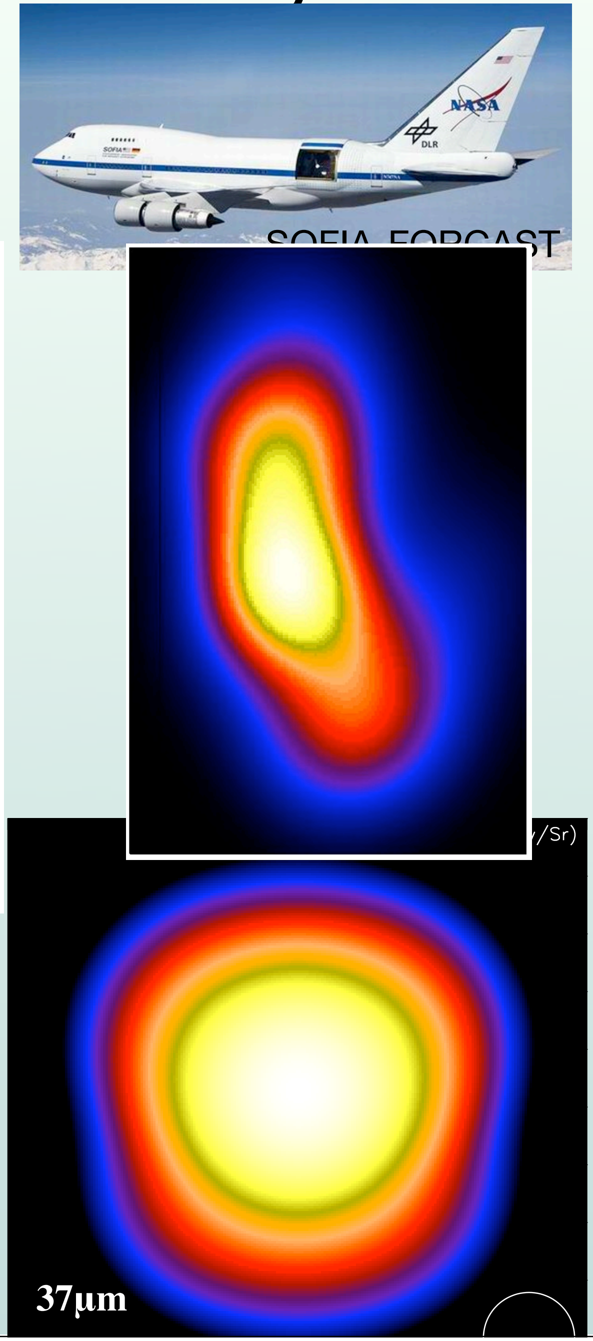
# Mid IR Emission from the Outflow Cavity

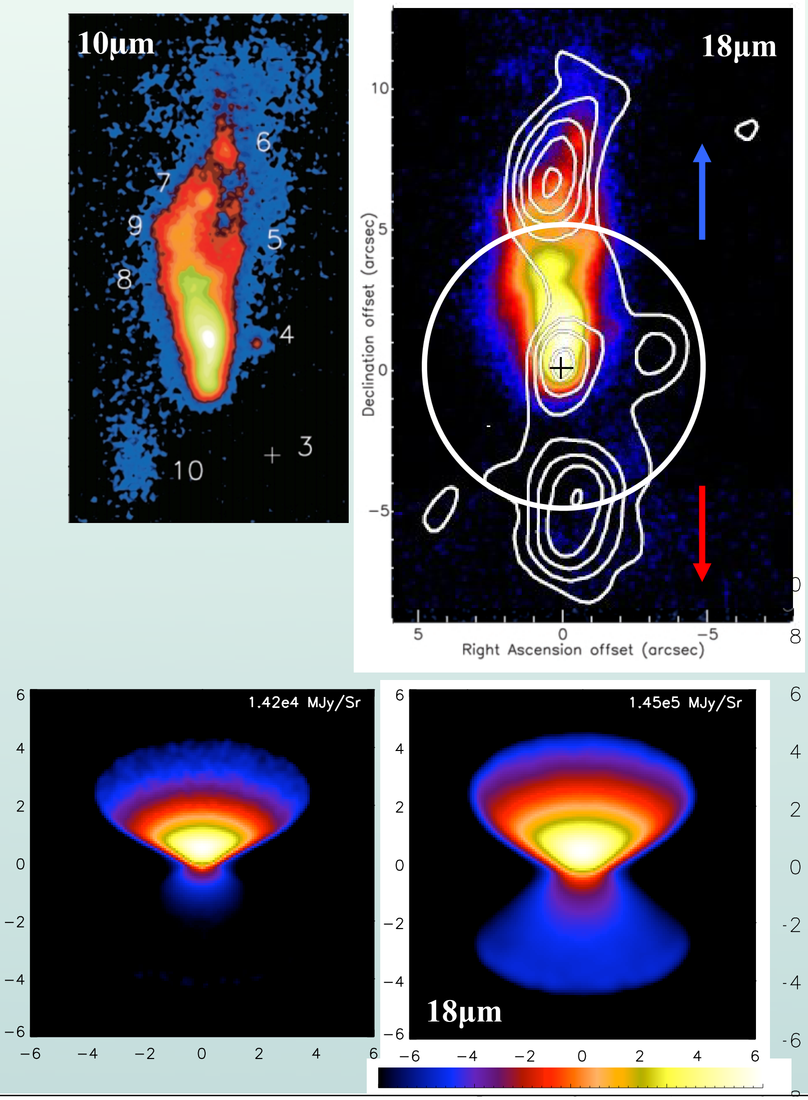
## G35.2N

d=2.3 kpc

$L_{MIR}$~1.6x$10^3 L_\odot$

(De Buizer 2006)





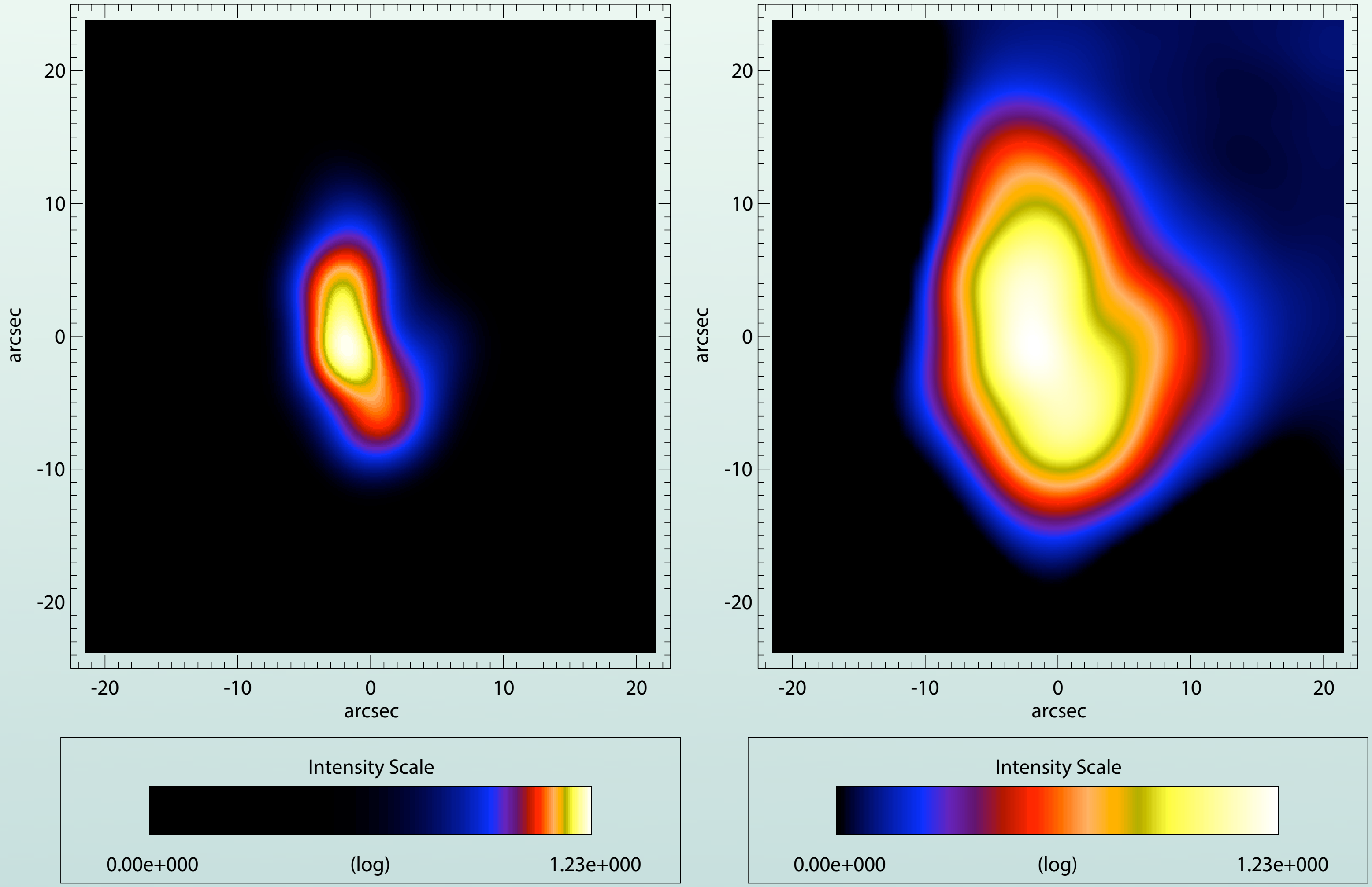
Rotation and outflow axis inclined at 60° to line of sight.

$m_* = 8\ M_\odot$

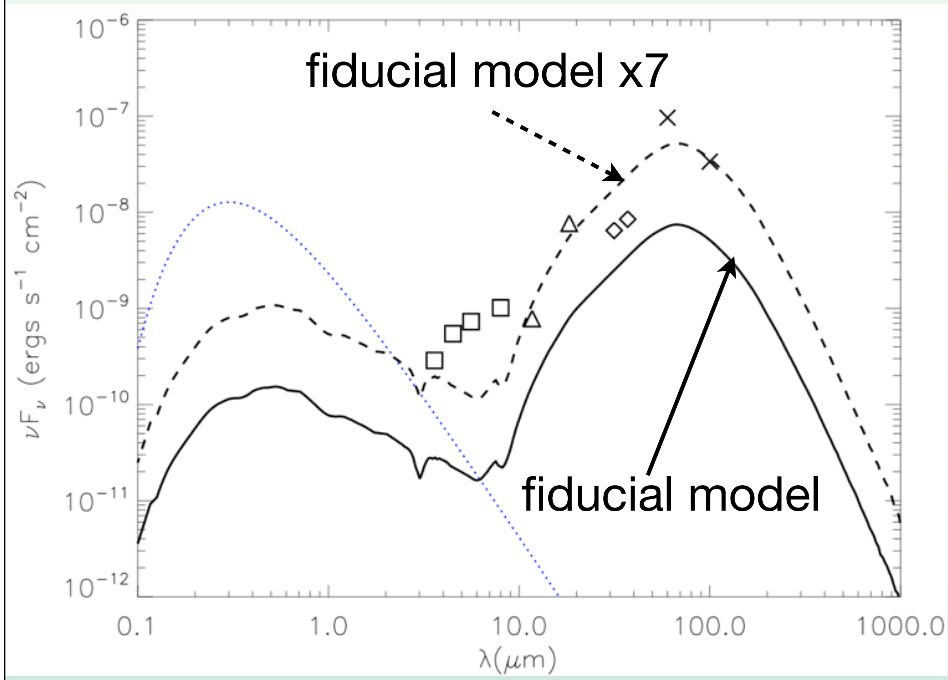
$L_{bol} = 6\times10^3\ L_\odot$

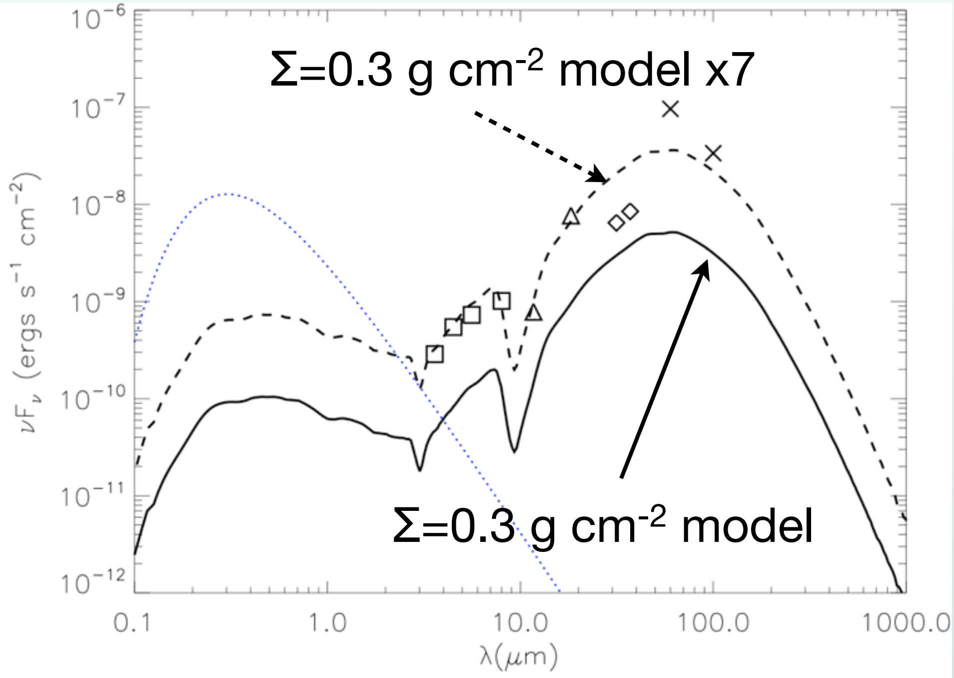
# Extended Faint Emission

G35 (SOFIA 37 micron)



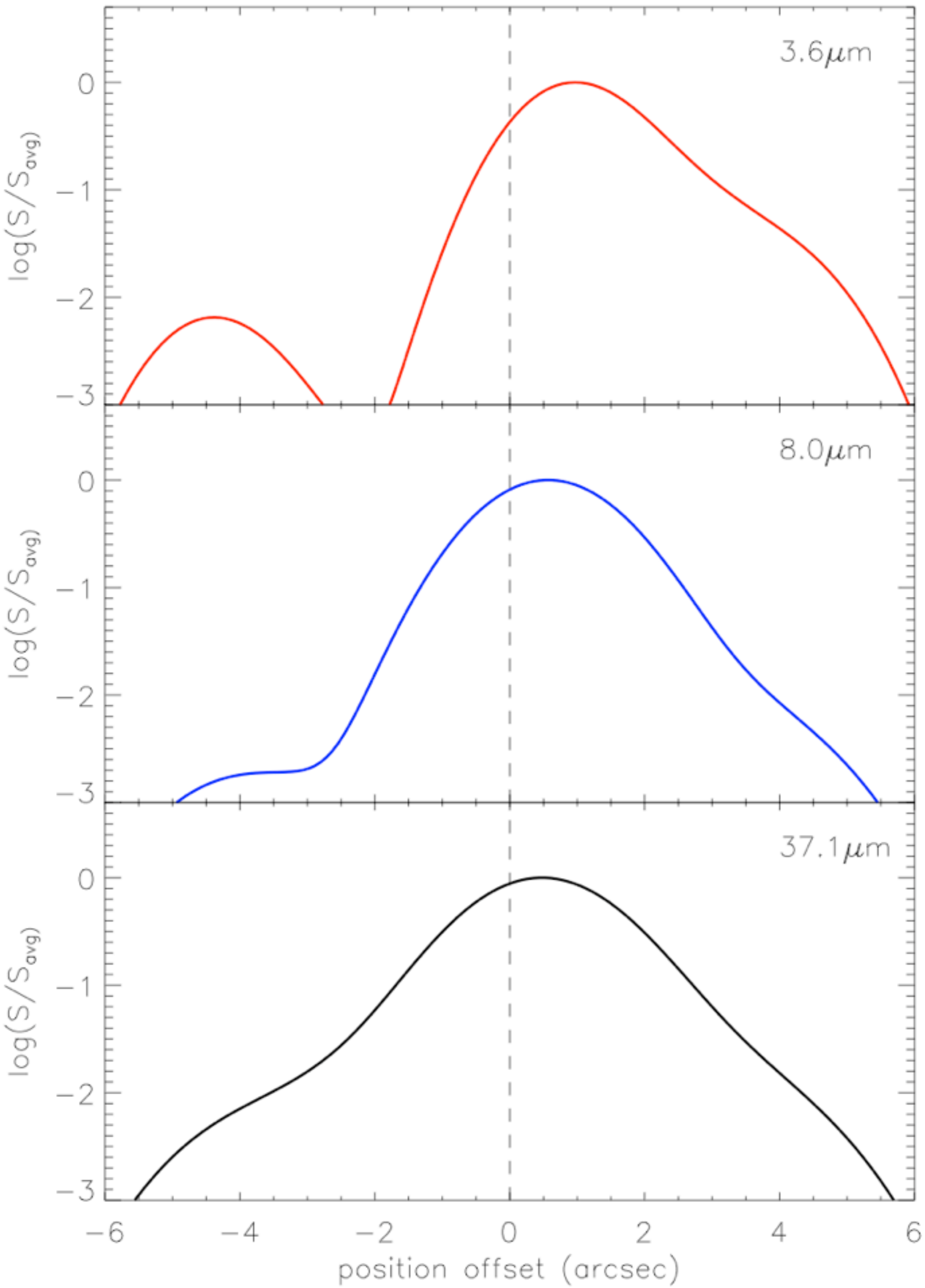
# SED of G35.2N


fiducial model x7
fiducial model
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
$10^{-10}$
$10^{-11}$
$10^{-12}$
$\nu F_\nu$ (ergs s$^{-1}$ cm$^{-2}$)
0.1
1.0
10.0
100.0
1000.0
$\lambda(\mu m)$


$\Sigma$=0.3 g cm$^{-2}$ model x7
$\Sigma$=0.3 g cm$^{-2}$ model
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
$10^{-10}$
$10^{-11}$
$10^{-12}$
$\nu F_\nu$ (ergs s$^{-1}$ cm$^{-2}$)
0.1
1.0
10.0
100.0
1000.0
$\lambda(\mu m)$

# Flux Profile Along Outflow Axis

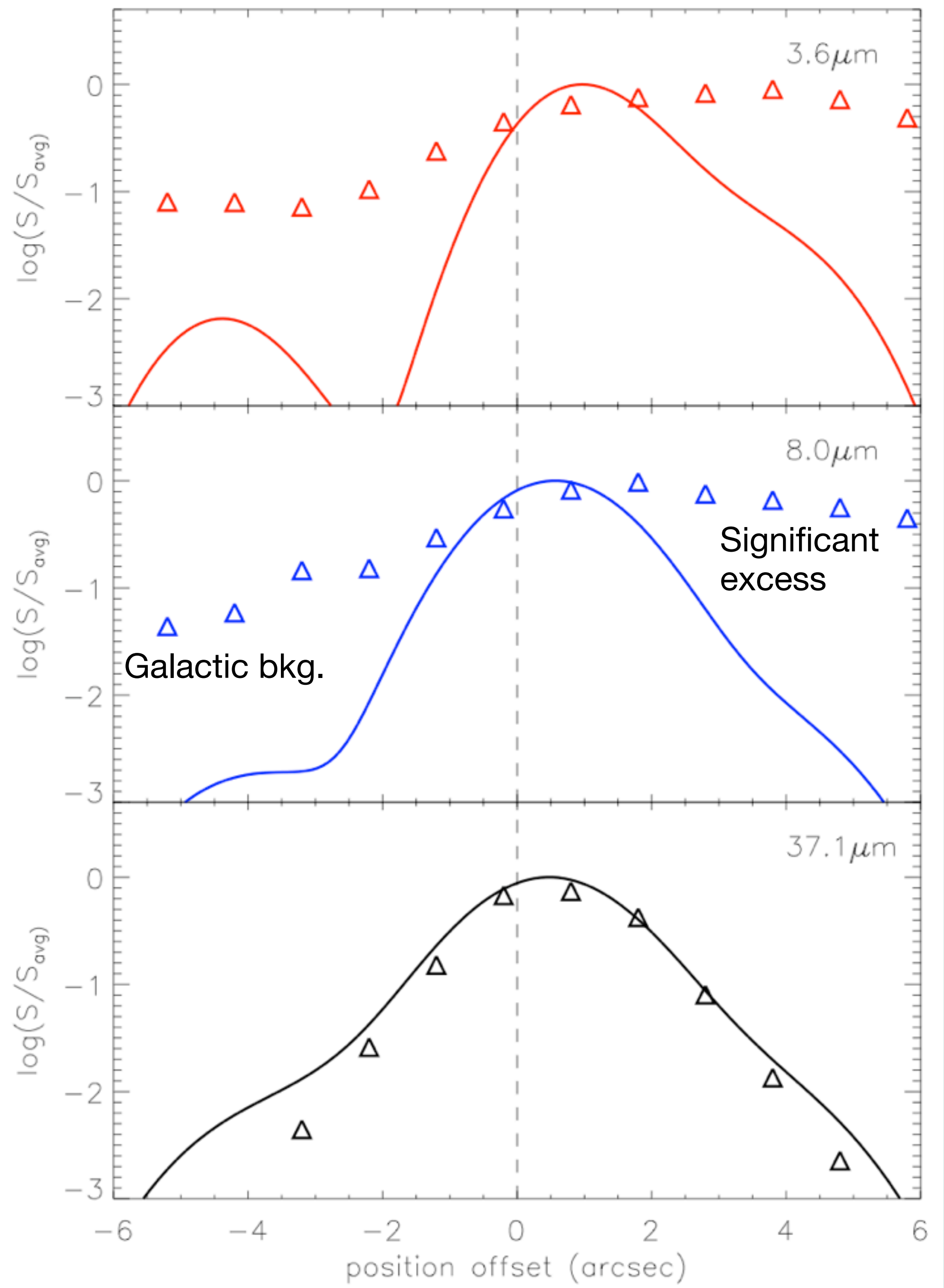
For fiducial model (solid lines) at 2.3kpc, convolved with IRAC and SOFIA beams.



# Flux Profile Along Outflow Axis

For fiducial model (solid lines) at 2.3kpc, convolved with IRAC and SOFIA beams.

Triangles show the observed profiles.

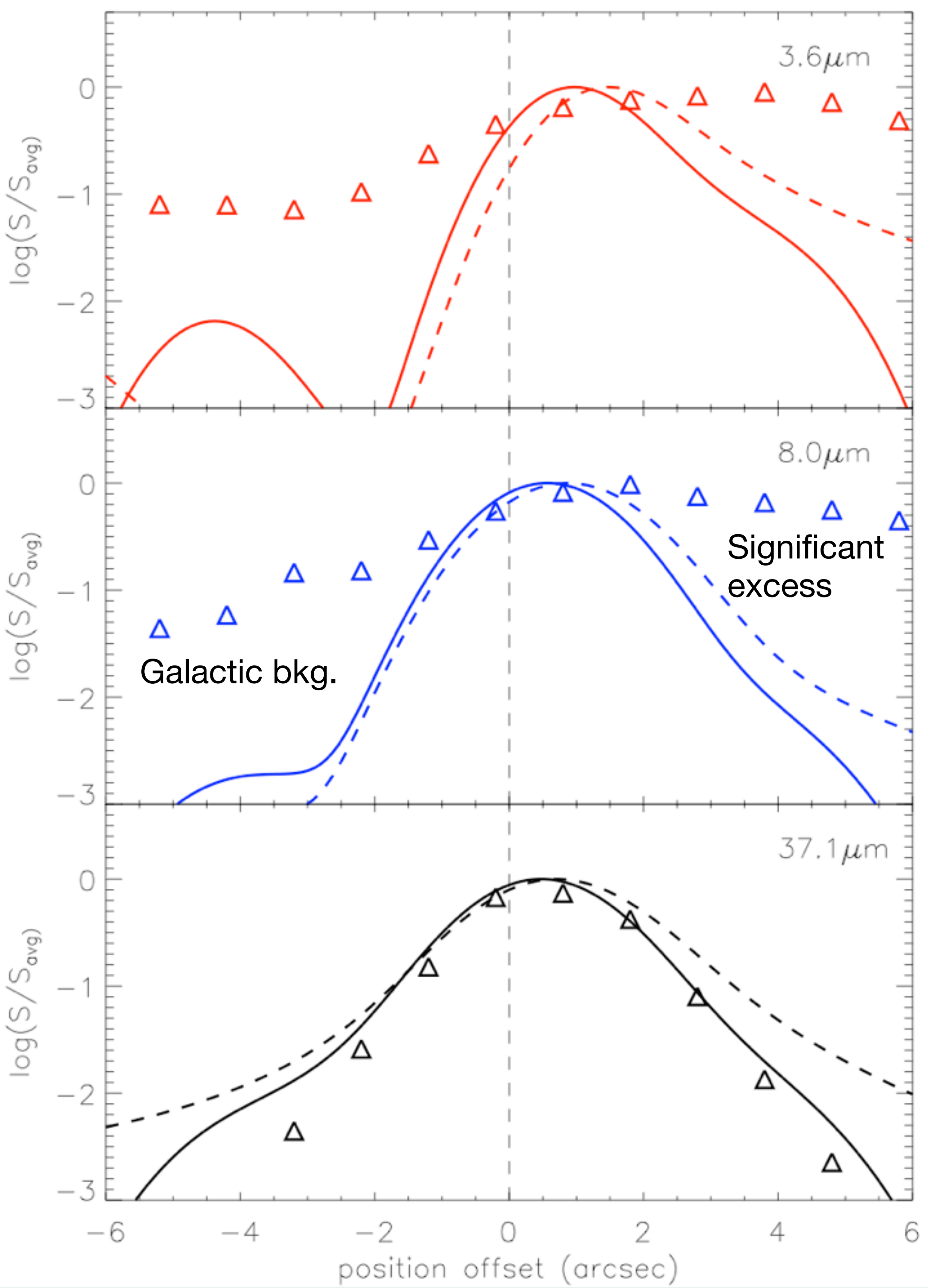


# Flux Profile Along Outflow Axis

For fiducial model (solid lines) at 2.3kpc, convolved with IRAC and SOFIA beams.

Triangles show the observed profiles.

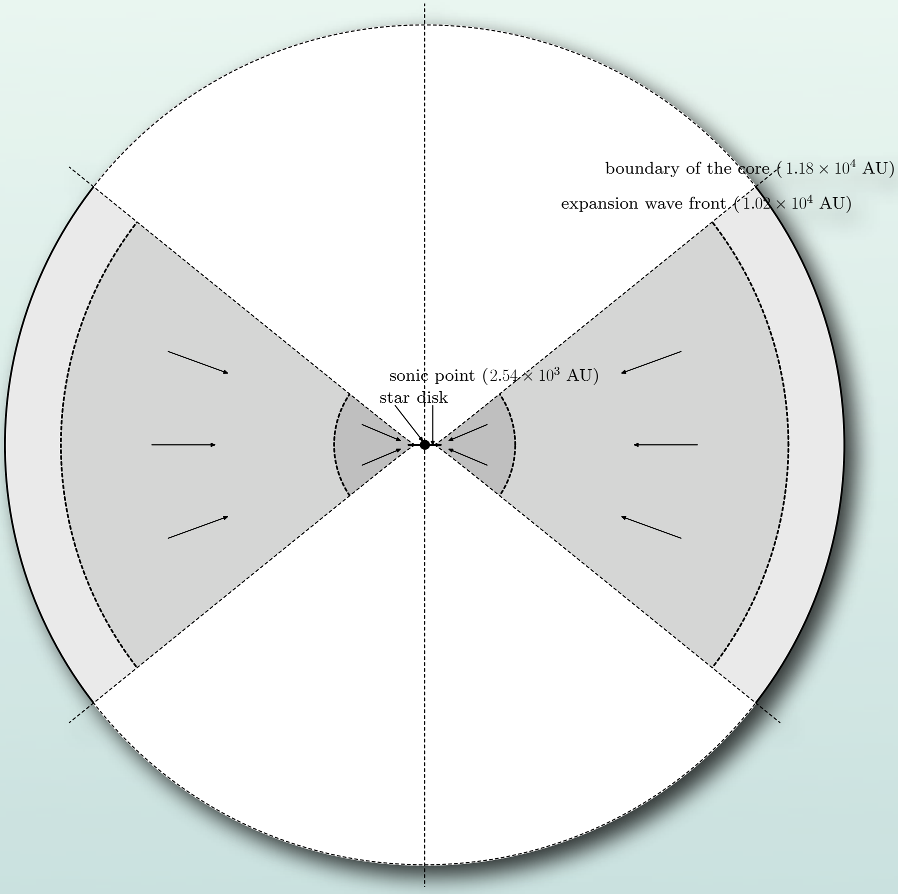
Dashed lines show $\Sigma = 0.3$ g cm$^{-2}$ model.

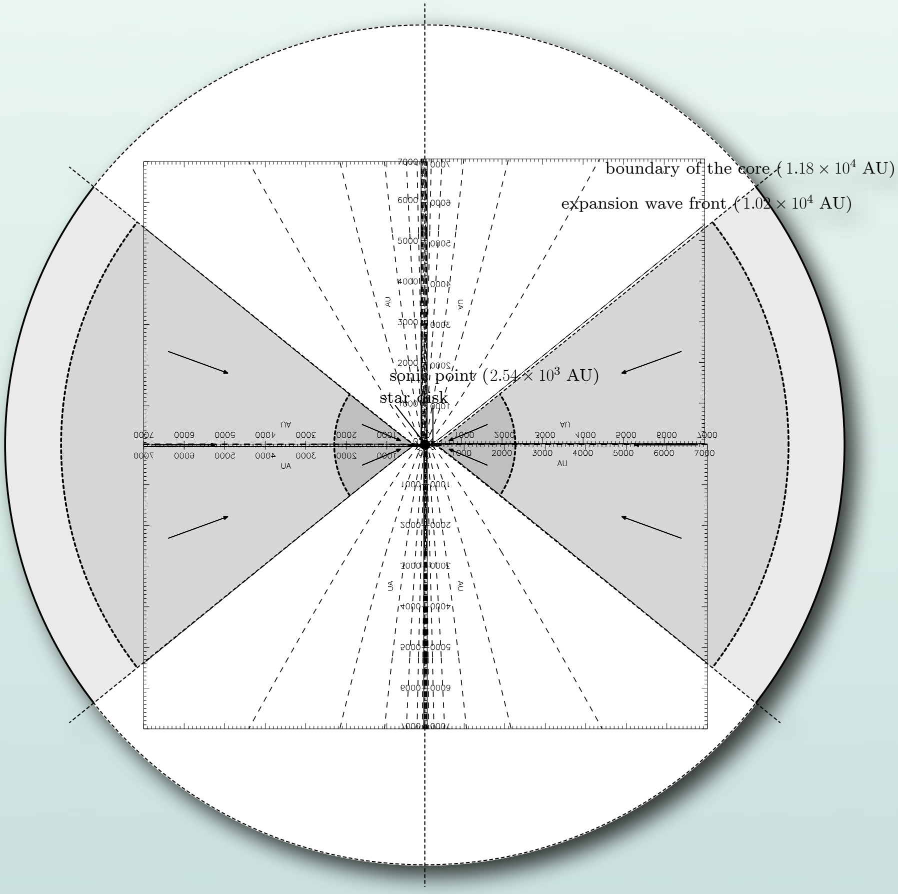


Significant excess

Galactic bkg.

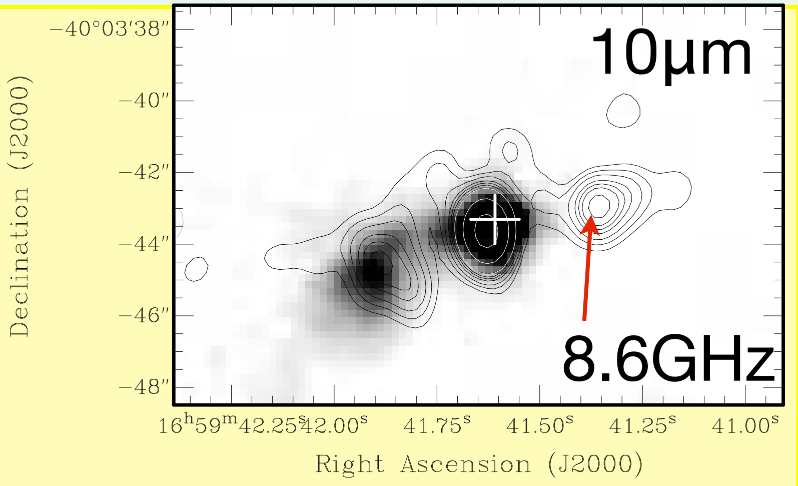
# Including Dusty Outflow May Help Resolve the Discrepancy





# G35.2N is not alone

A number of other ionized HCHIIs seen in nearby sources
(e.g. van der Tak & Menten 2005; Guzmán et al. 2010)



IRAS 16562-3959
Guzmán et al. (2010)

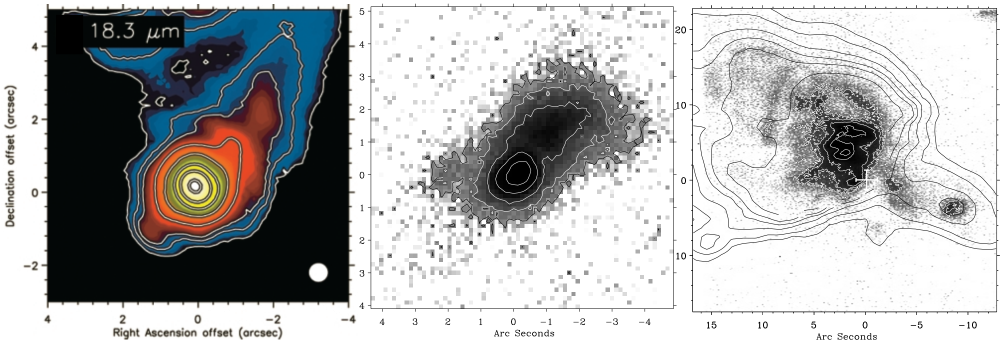
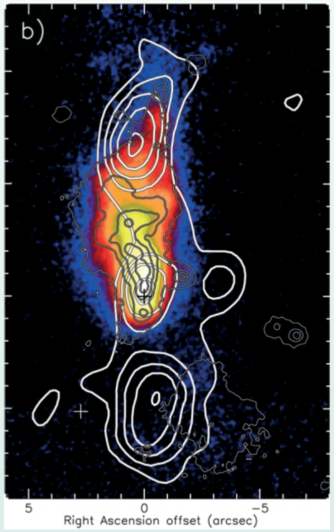


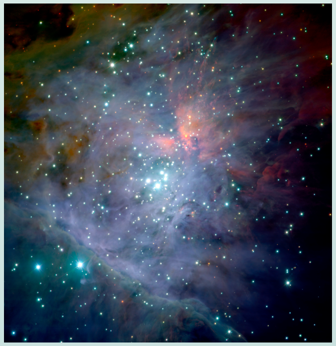
*Figure 4: (a) Left: NGC7538 IRS1 at 18.3μm (De Buizer & Minier 2005); (b) Middle: IRAS 20126+4104 at 24.5μm (De Wit et al. 2010); (c) Right: Cep A at 24.5μm (shaded+light contours) and 8μm (dark contours) (De Wit et al. 2010).*

# Conclusions: The Formation of Massive Stars



**Massive star formation:**

- Sometimes appears to be a scaled-up version of low-mass star formation: massive starless cores, ordered B-fields, rotating toroids, some claims of disks, collimated outflows & outflow-confined HII regions.
- “Core Accretion Model” invokes turbulent/magnetic support of rare, massive cores & ~pressure equilibrium w/ surrounding clump.
- Fragmentation inside core may be limited by B-fields, rather than radiative heating.
- Detailed Radiative Transfer modeling and comparison to MIR/FIR observations, including SOFIA-FORCAST, can provide powerful constraints on the Core Accretion model.



**Star Cluster Formation:**

- SFE per free-fall time from turbulent gas is low, ~few%.
- Formation of “rich”, bound (total SFE >20%) star clusters should take many free-fall times, i.e. >~1Myr.
- Clump reaches ~equilibrium; turbulence maintained by outflows.

# Orion

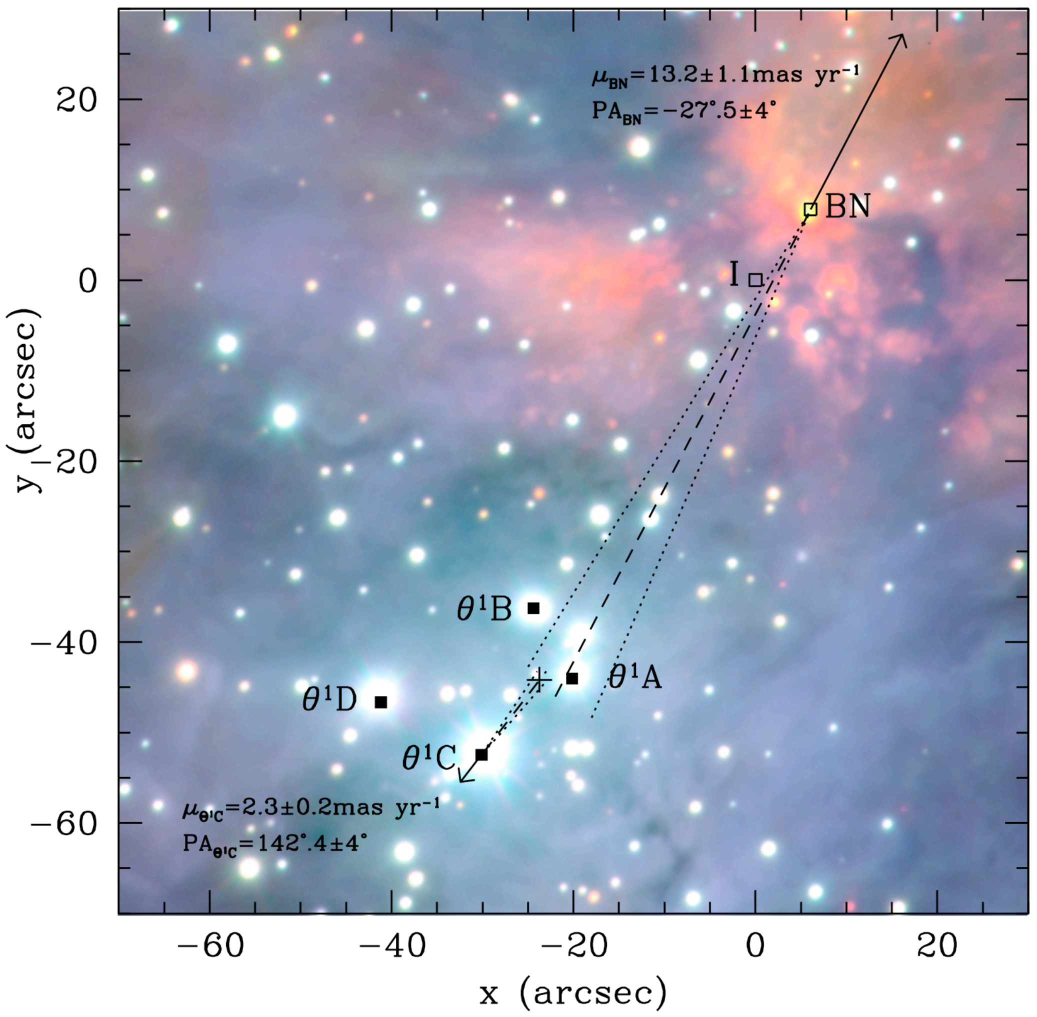
# Orion

**Orion KL**

CISCO ($H_2$ (v=1-0 S(1)) – Cont)

Subaru Telescope, National Astronomical Observatory of Japan

January 28, 1999



Cluster frame proper motions of BN (Gomez et al. 2008; Tan 2008) and θ¹C (van Altena et al. 1988), tracing back to a common origin about 4500 years ago, shown by the cross.

Close passage of BN within ~300 AU of the KL protostar (source I), 500 years ago, would have tidally perturbed the accretion disk, enhanced accretion, and thus enhanced the outflow (Tan 2004, 2008).

cf. Bally & Zinnecker (2005), who argue for ejection of BN from source I.

# Constraining source I from reflected NIR spectra

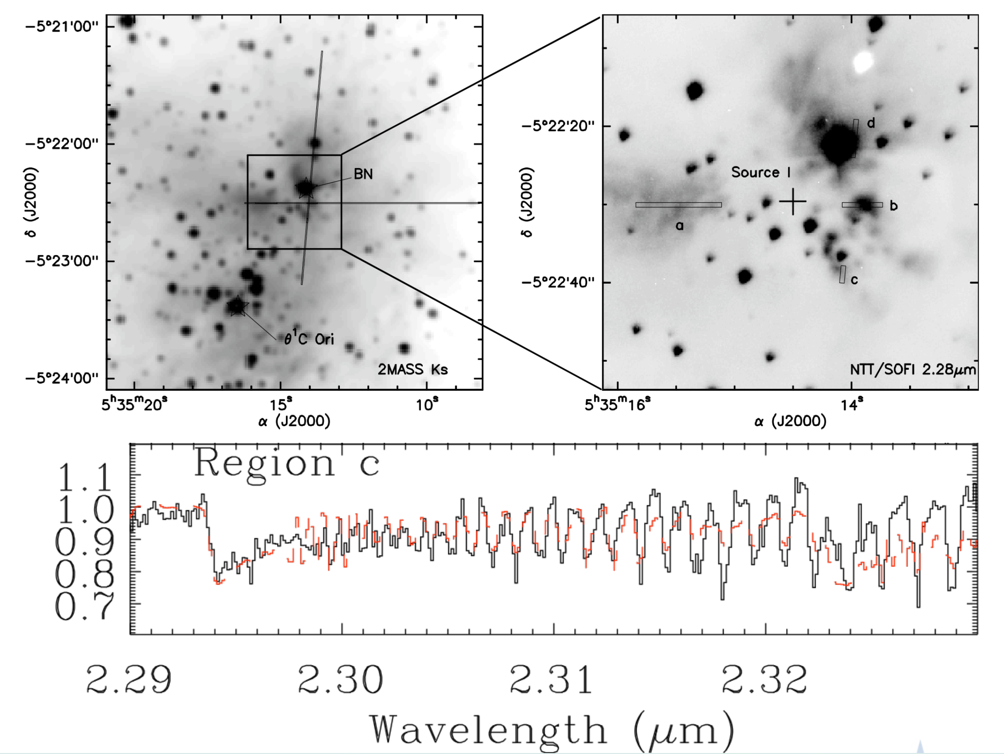
Testi, Tan, Palla 2010

NIR light from source I escapes along the outflow cavity aligned NW-SE (Minchin et al. 1991). Some of this light is scattered towards us by dust, and the spectrum can be used to constrain properties of the protostar.

Morino et al. (1998) found $T_{phot}$ ~4000K

If from a massive protostar, requires large size (~300 $R_{sun}$). Such sizes can be achieved if the average accretion rate is >~$4\times10^{-3} M_{sun}$/yr (Hosokawa & Omukai 2009), >> than expected from the Core Accretion Model (McKee & Tan 2003).

Or, the large size may indicate the star is rotating close to break-up, which would predict large rotational broadening of the spectral features.



We observed the NIR reflection spectrum with the VLT at higher spectral resolution than Morino et al., finding 1D velocity dispersions of ~<30 km/s.

We expect most NIR emission comes from the disk.

The narrow profiles constrain protostar + disk models: a $10 M_{sun}$ protostar with a large current accretion rate of ~few $\times10^{-3} M_{sun}$/yr is favored. Such a large accretion rate may be the result of the recent perturbation of the disk by close passage of BN.