Peering to the Heart of Massive Star Birth:
Constraining Massive Star Formation Theory with SOFIA

Yichen Zhang
(Yale University)

SOFIA Team:

Jonathan Tan (PI, Florida)
Maite Beltran (Arcetri)
James De Buizer (NASA/SOFIA)
Ed Churchwell (Wisconsin)
Göran Sandell (NASA/SOFIA)
Ralph Shuping (NASA/SOFIA)
Jan Staff (Macquarie)
Charles Telesco (Florida)
Barbara Whitney (Wisconsin)

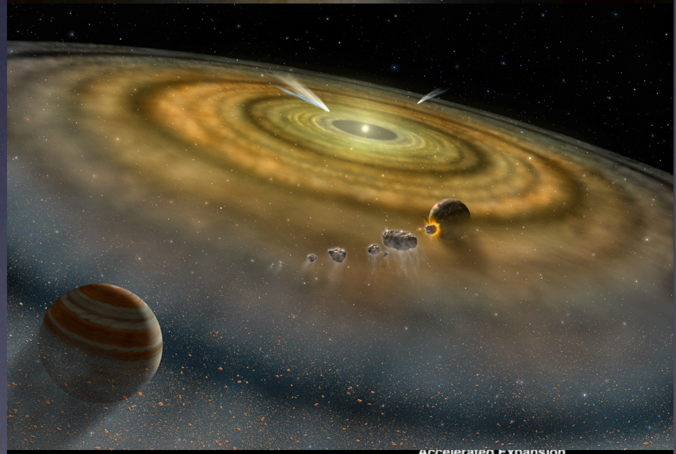
Outline

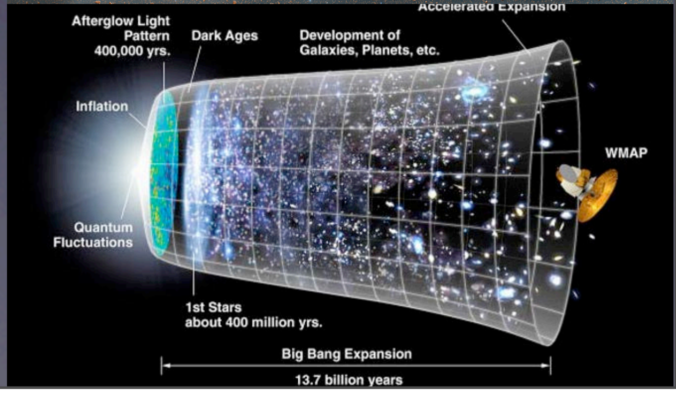
- Introduction: formation theories of massive stars
- Radiation transfer modeling: what do we expect to see?
- SOFIA-FORCAST observations of the massive protostar G35.2-0.74

Introduction

Massive stars are important:

- Feedback (protostellar outflow, stellar wind, HII region, supernovae, etc) to ISM, affect the evolution of galaxies.
- Produce heavy elements.
- Can influence low-mass star / planet formation in clusters.
- First stars: reionize the Universe.





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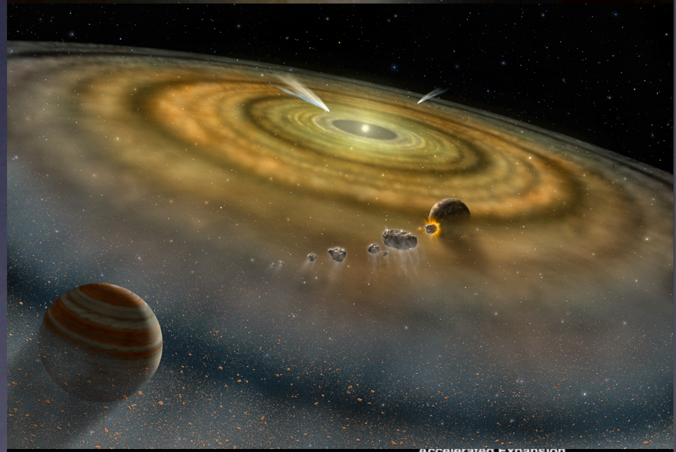
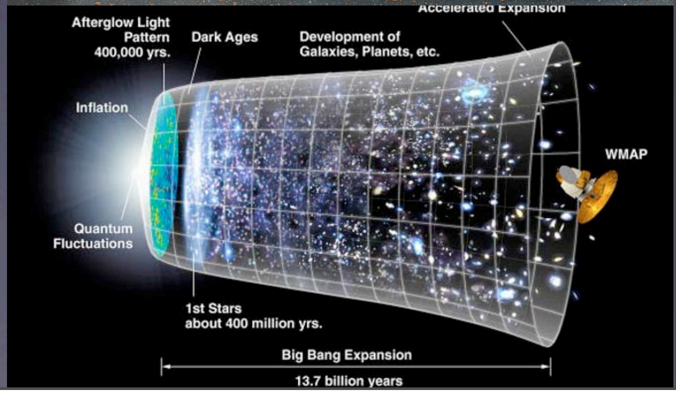
How do they form?

- Similar to the formation of low-mass stars?





Scenarios of Massive Star Formation

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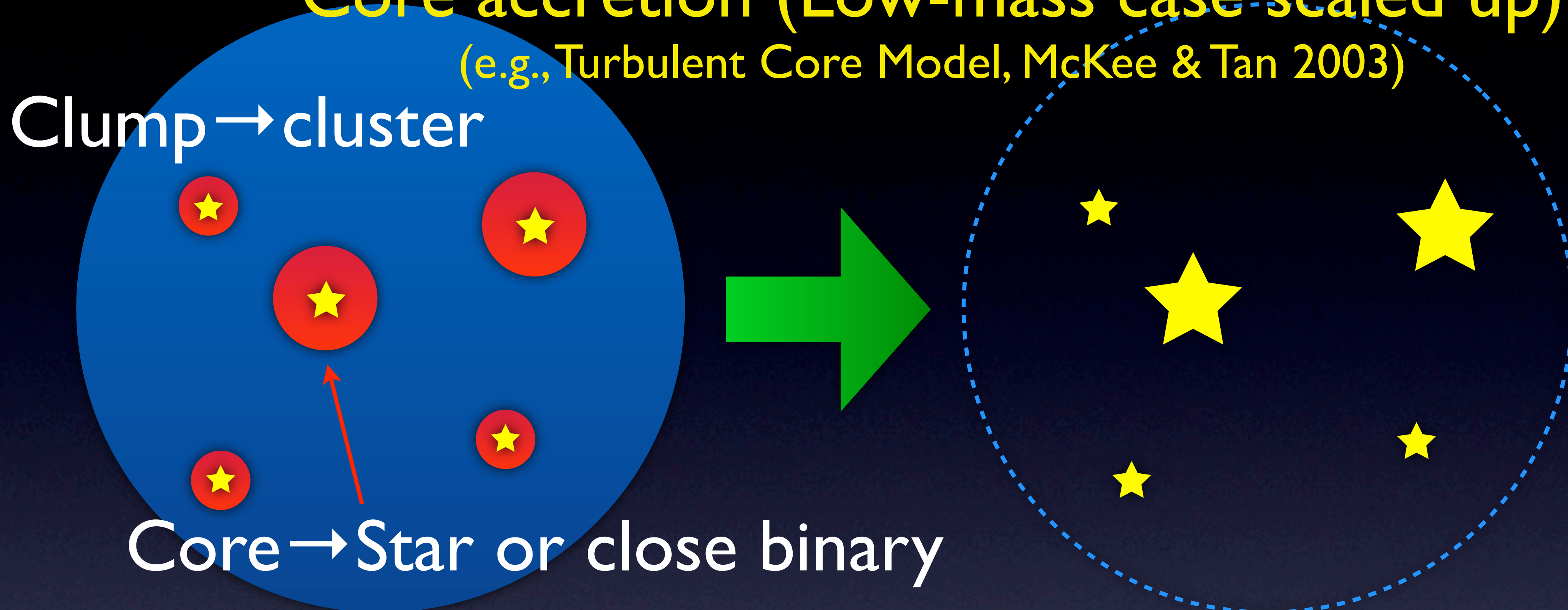
Core accretion (Low-mass case scaled up)

(e.g., Turbulent Core Model, McKee & Tan 2003)



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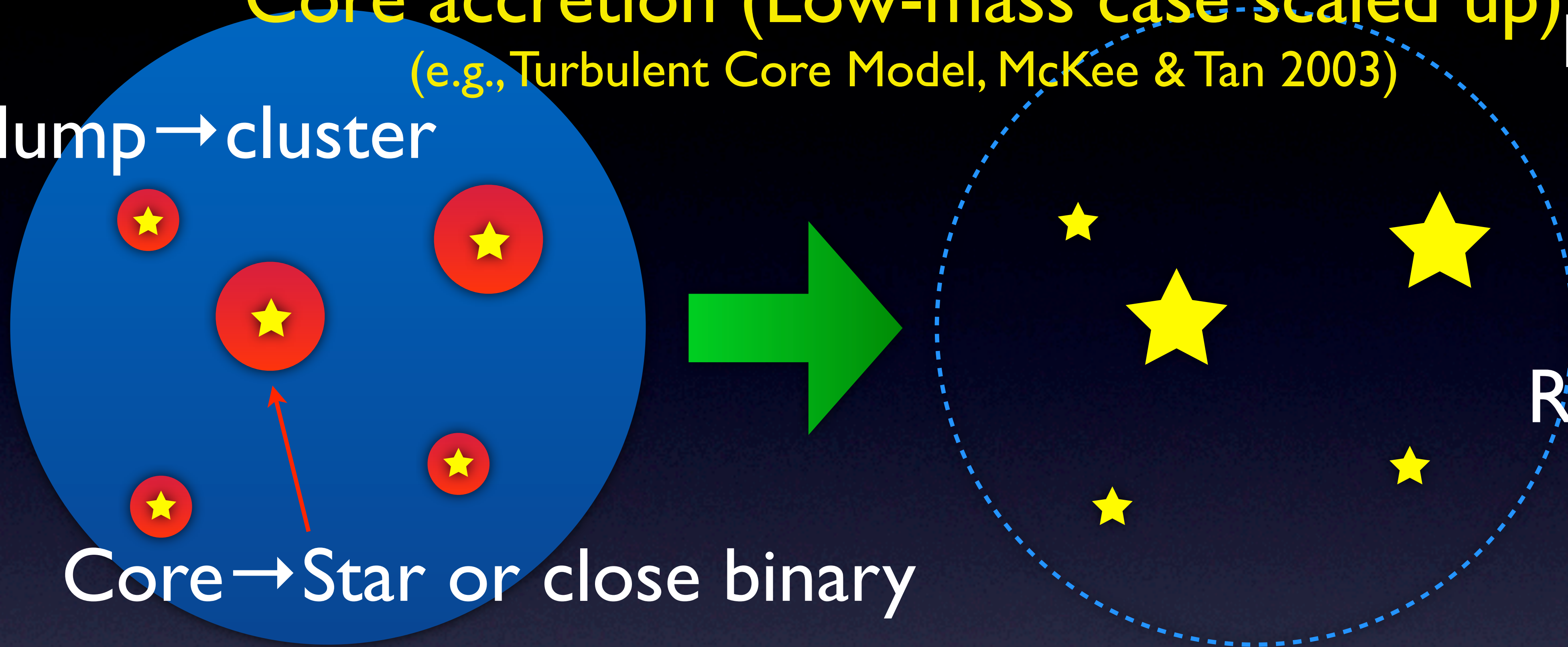
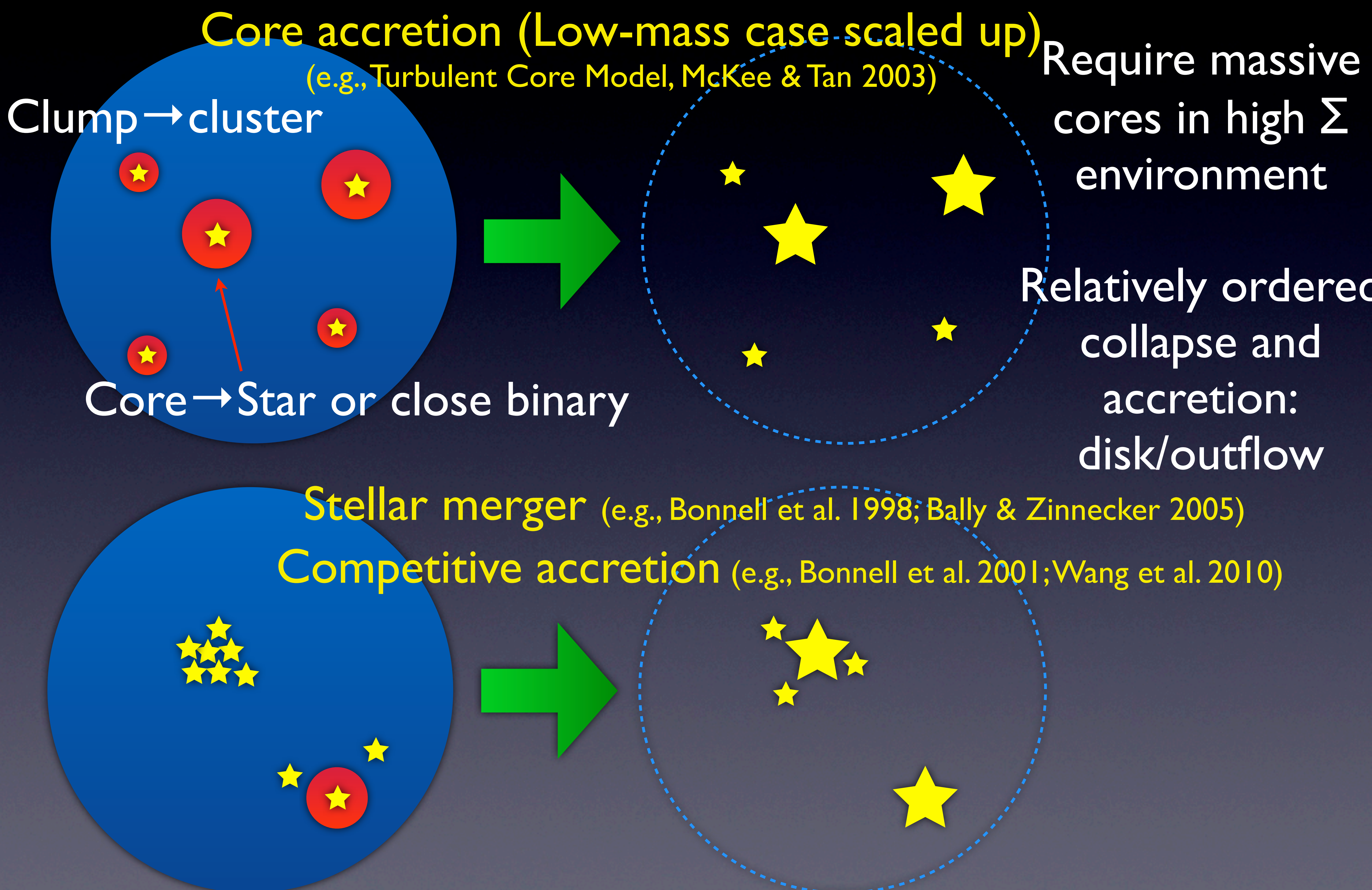


Require massive cores in high Σ environment

Relatively ordered collapse and accretion: disk/outflow

Scenarios of Massive Star Formation



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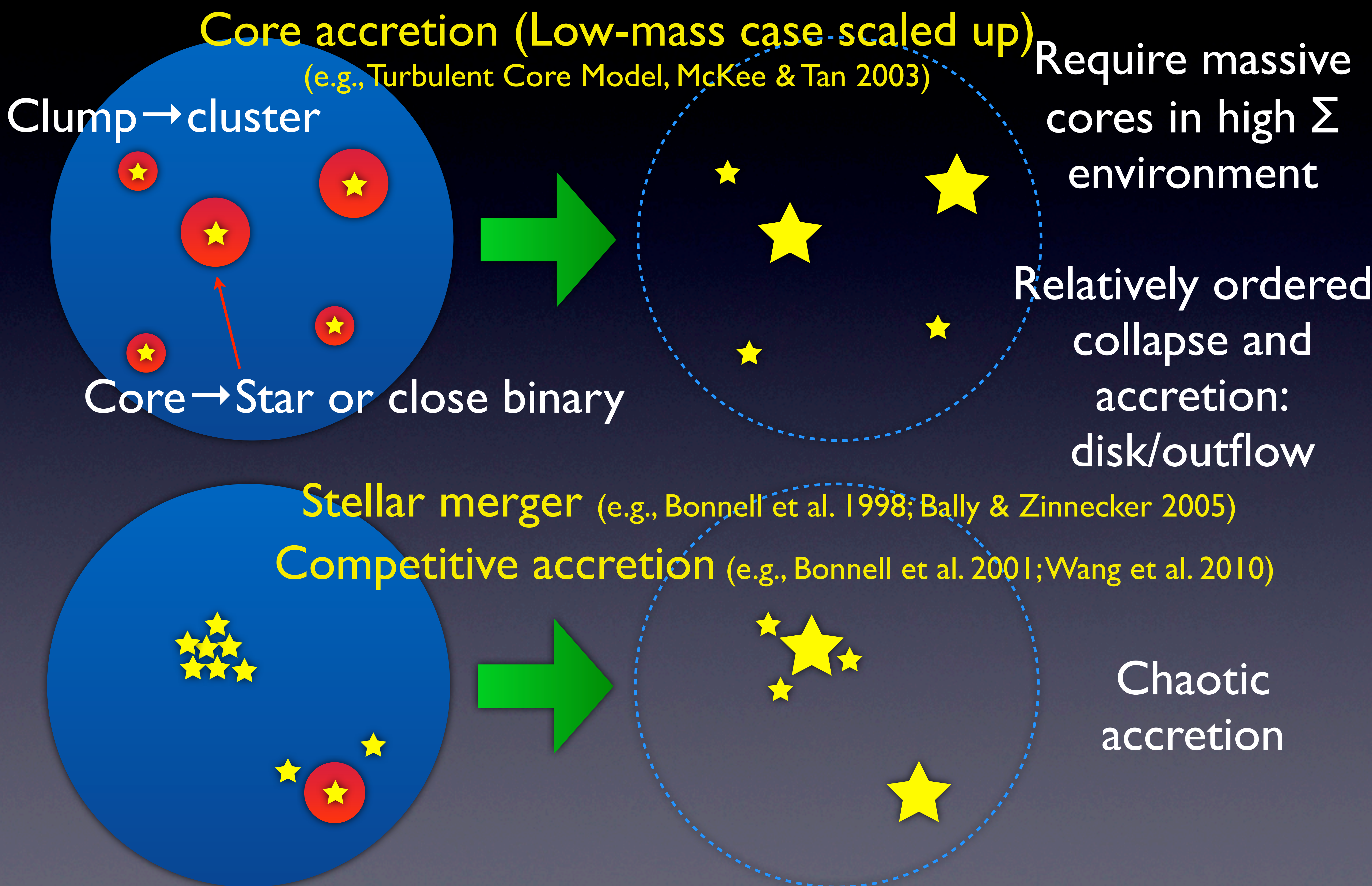


Introduction

Scenarios of Massive Star Formation

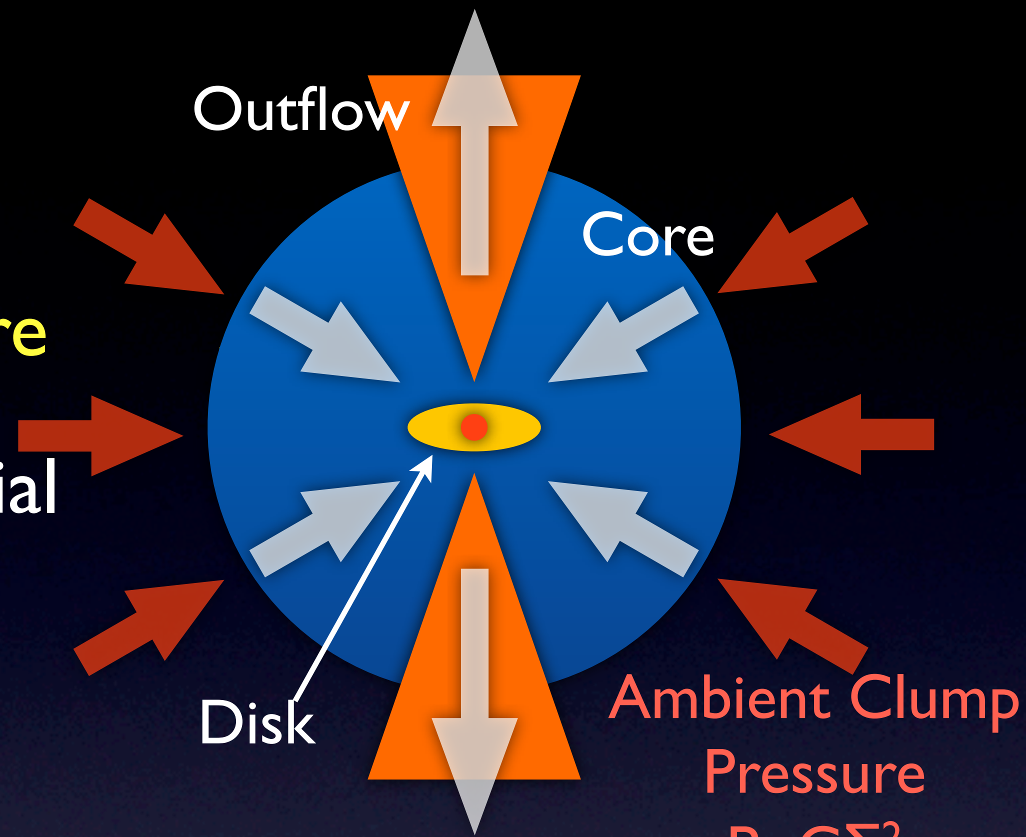
Model	Environmental Conditions	Accretion Mass Supply	Internal Structures
Core Accretion	High surface pressure environments ($\Sigma \sim 1$ g/cm^2)	Preassembled gravitationally bound cores	Relatively ordered collapse; disks/outflows
Competitive Accretion	Clustered environments	Initially unbound material in the star-forming clump	Chaotic
Stellar Merger	Very high stellar density	Low-mass progenitors	Chaotic and explosive

Introduction

Turbulent Core Model

P~GΣ²

- Surface density → Surface pressure of the core
- Initial Conditions: massive starless core in virial equilibrium, and in pressure equilibrium with surrounding medium, singular polytropic sphere, will collapse from inside out



Core→Star or close binary
Clump→cluster

- Size

$$R_{\rm core} = 0.057 \left(\frac{M_{\rm core}}{60\ M_\odot}\right)^{1/2} \Sigma_{\rm cl}^{-1/2}\ {\rm pc}$$

- Accretion rate

$$\dot{m}_* = 4.6 \times 10^{-4} \left(\frac{\epsilon_*}{0.5}\right) \left(\frac{M_{\rm core}}{60\ M_\odot}\right)^{3/4} \Sigma_{\rm cl}^{3/4} \left(\frac{m_{*d,0}}{M_{\rm core}}\right)^{0.5} M_\odot\ {\rm yr}^{-1}$$

- Luminosity

$$L_{\rm acc} = f_{\rm acc} \frac{G\dot{m}_* m_*}{r_*}$$

Introduction

Observational Evidences for Core Accretion

- Massive dense cores
- Outflows
    - Molecular tracers
    - Continuum (outflow cavity)
- Accretion disks
  (Toroids or disks?)

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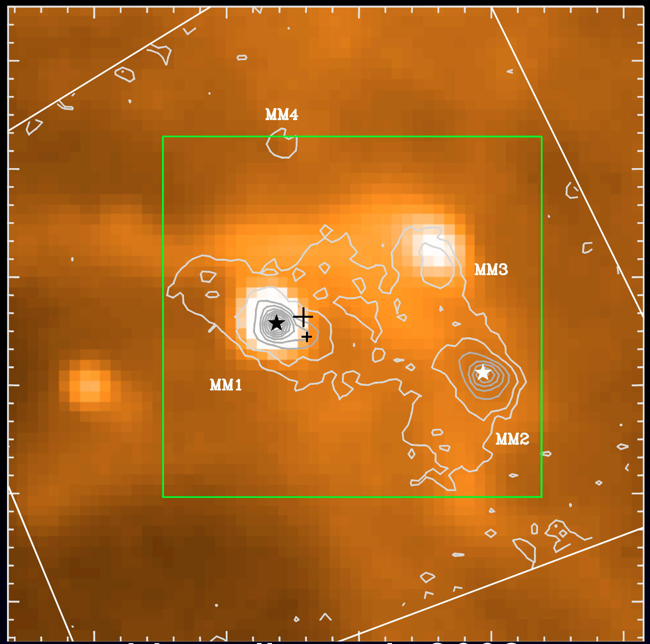
Observational Evidences for Core Accretion



Marseille et al. 2008
See also Bontemps et al. 2010; Motte et al. 2007

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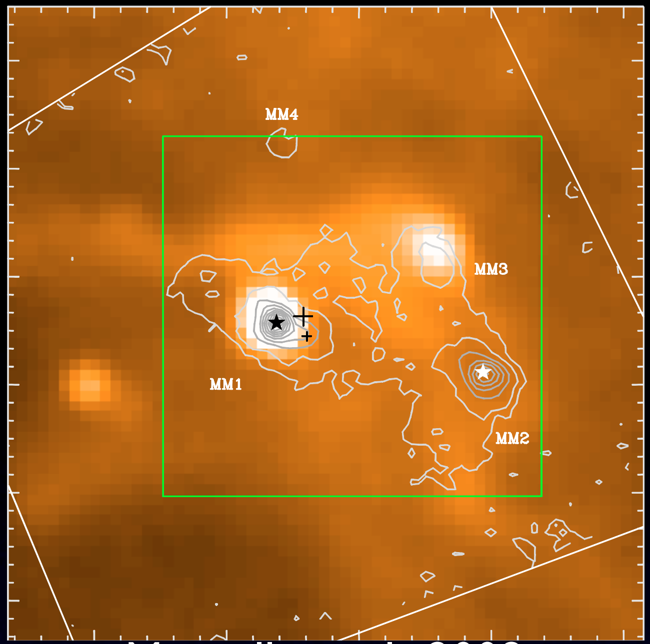

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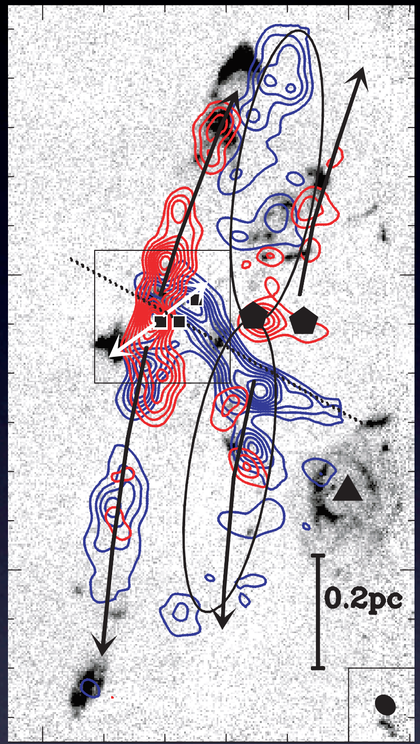
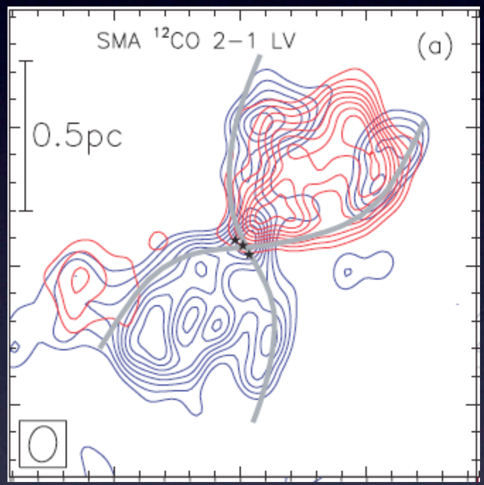


Beuther et al. 2002



Qiu et al. 2009

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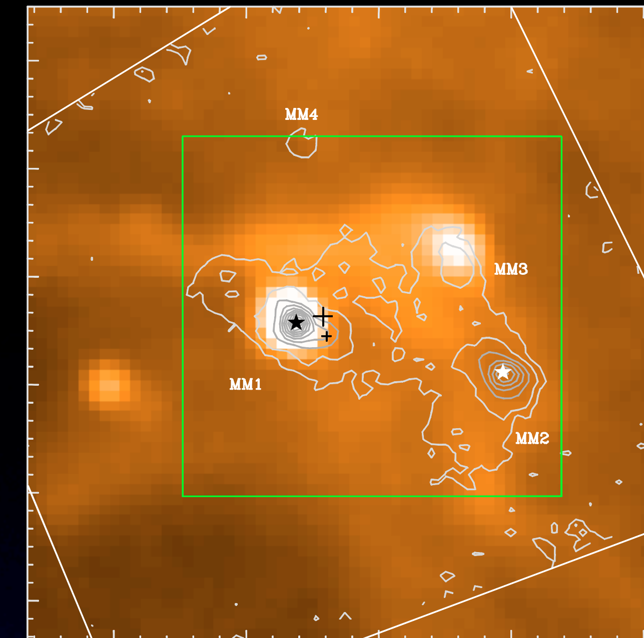

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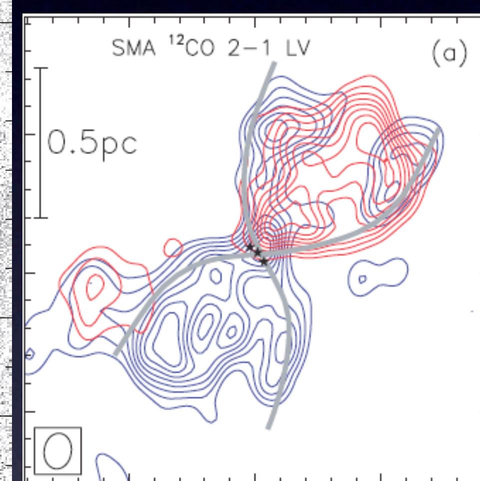

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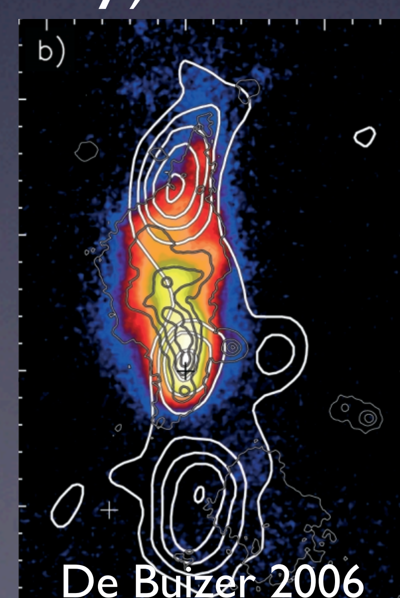

De Buizer 2006

Introduction

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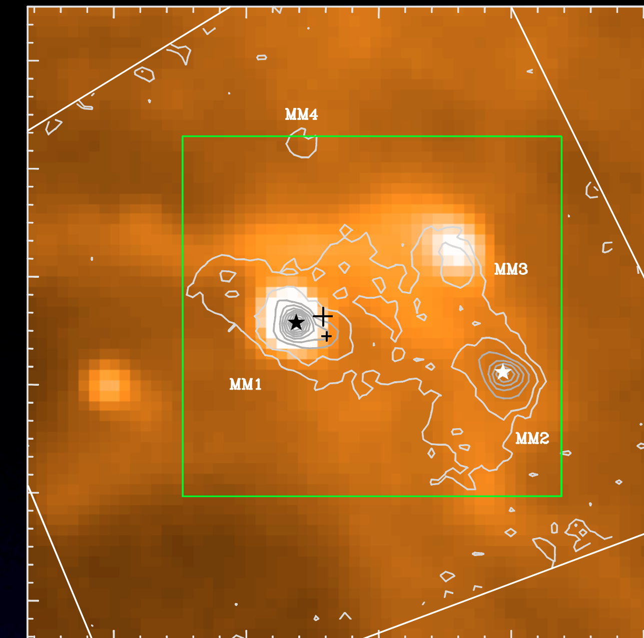

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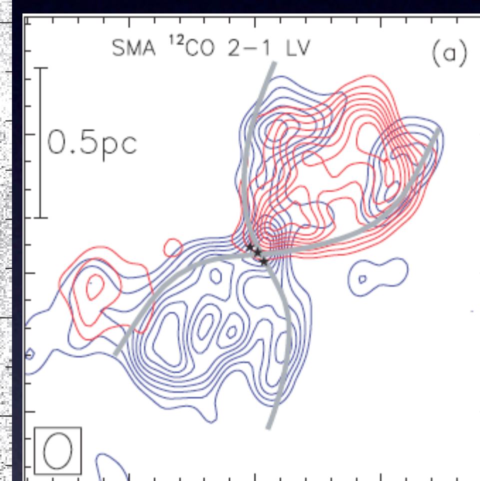

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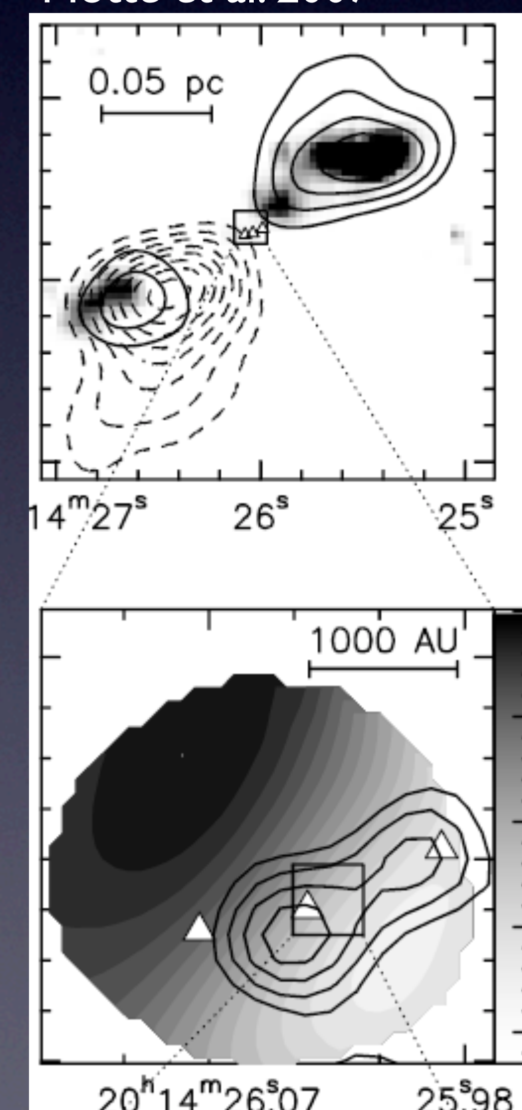
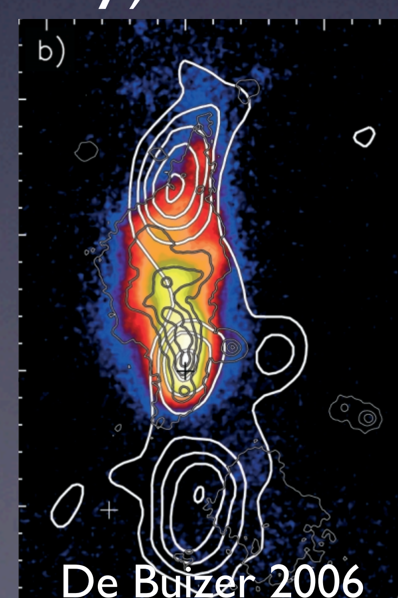


Cesaroni et al. 2007



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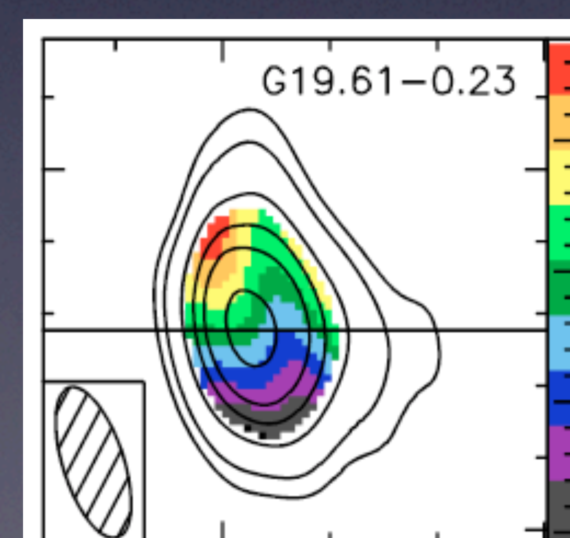


Beltran et al. 2011

Introduction

Radiation transfer:

Linking the observations and theoretical models

Lines: Kinematics, Chemistry, Components, etc.

Continuum: Global parameters, temperatures, etc.

- Robitaille, Whitney, et al. 2006: Monte Carlo method. Large grid, but mainly for low-mass YSOs (low accretion rate, low disk mass, small / simple outflow cavity, no optically thick inner gaseous disk, etc.)
- Molinary et al. 2008: Monte Carlo method. Massive stars, but still simple models (outflow, no gas opacities, etc.)
- Chakrabarti & McKee 2005: Analytical, but only for spherical geometry

We want to construct a fully self-consistent model, with more realistic physics, which is more applicable to the high surface density environments of real massive protostars.

1) Can (and how well) the initial environmental conditions of massive protostars be deduced from the observed spectral energy distributions (SEDs) and/or images?

2) Do the initial conditions deduced from observations agree with those required by the *Core Accretion* theory?

3) Are the observations compatible with the prediction from the *Core Accretion* theory on outflows and disks?

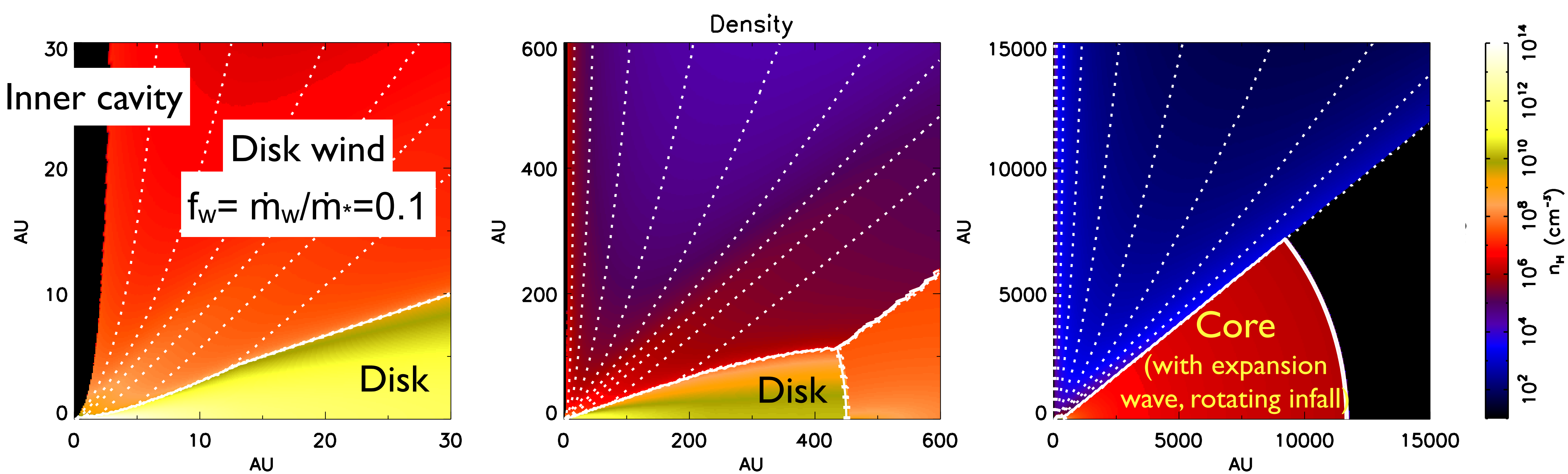
4) Can (and how well) the evolutionary sequence of massive protostars be deduced from the observed SEDs?

Massive Star Formation:

A self-consistent radiation transfer model based on the Turbulent Core model

Zhang, Tan 2011;
Zhang, Tan, McKee 2013
Using the continuum Monte Carlo RT code by Whitney et al., 2003, 2013.

M_{core}=60$M_\odot$, Σ_{cl} = 1g/cm^2 (A_V~200), m_*=8$M_\odot$, $\dot{m}_*$=2.4×10^{-4}$M_\odot$/yr, L_{bol}=6×10^3$L_\odot$, θ_w ~ 51°



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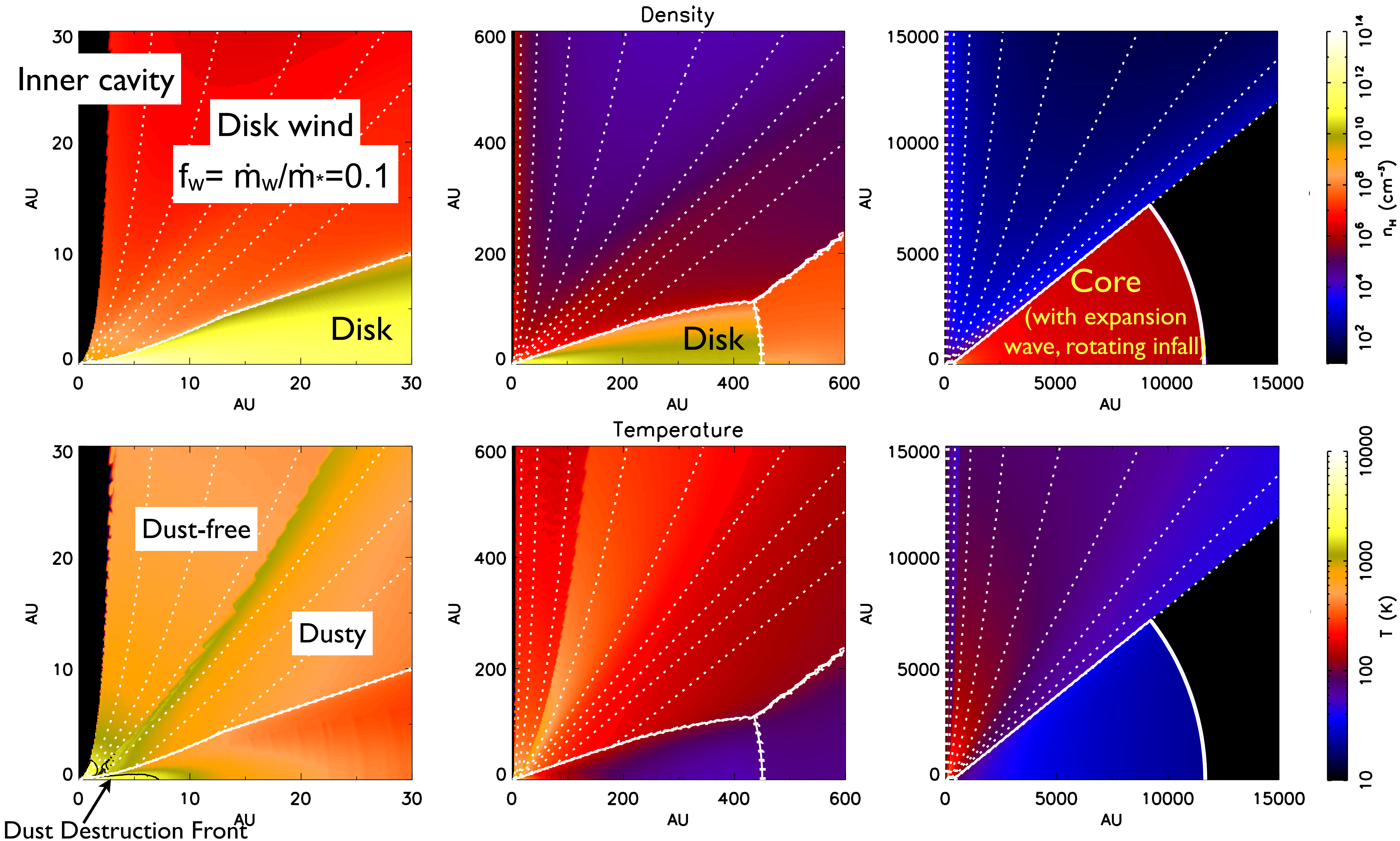

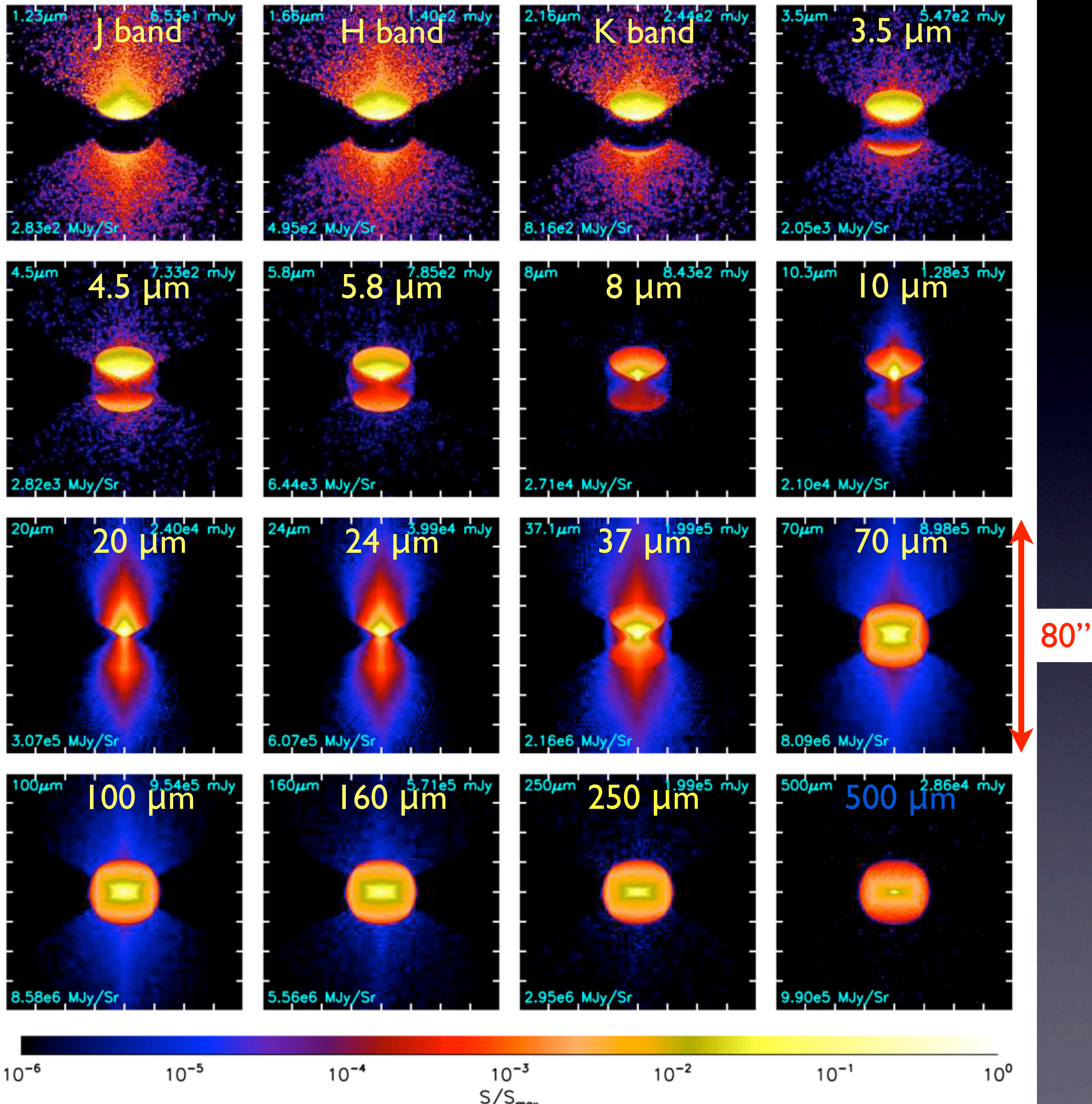

- **Images** at 1 kpc at 60° inclination between line of sight and outflow axis

$M_{core} = 60 M_\odot$
$\Sigma_{cl} = 1 \ g \ cm^{-2}$
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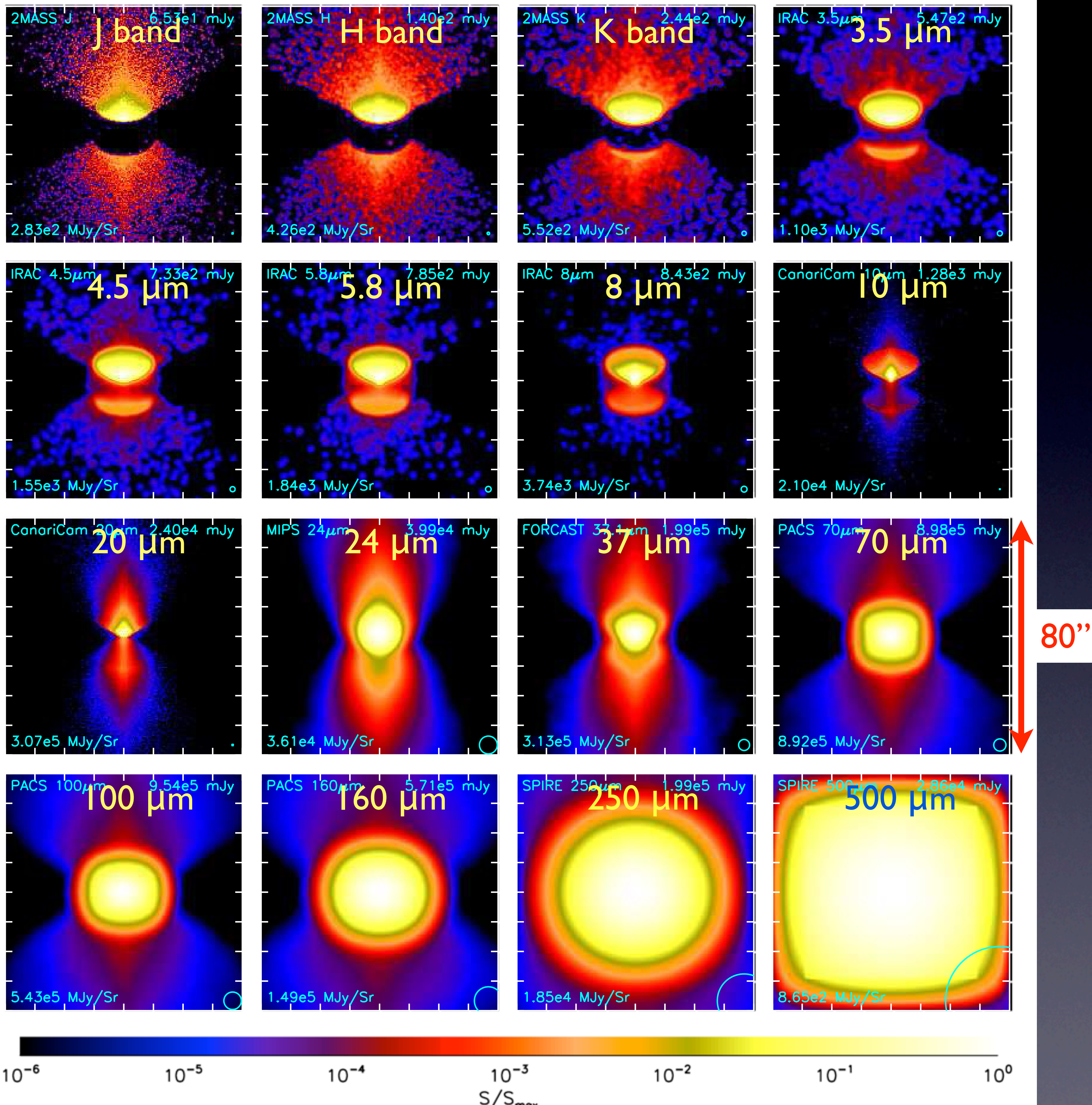

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SEDs

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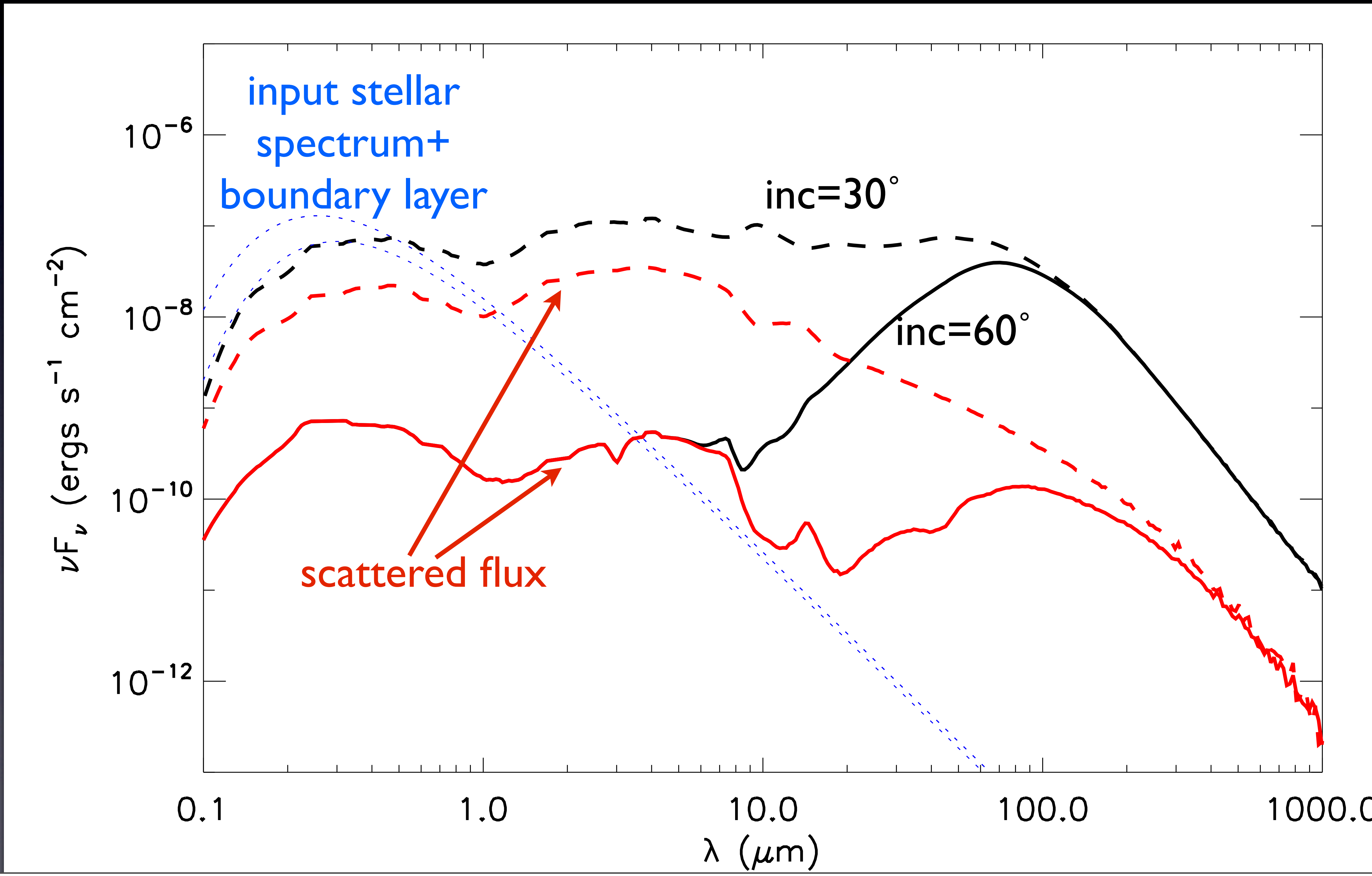

SEDs

$M_{core} = 60 M_\odot$
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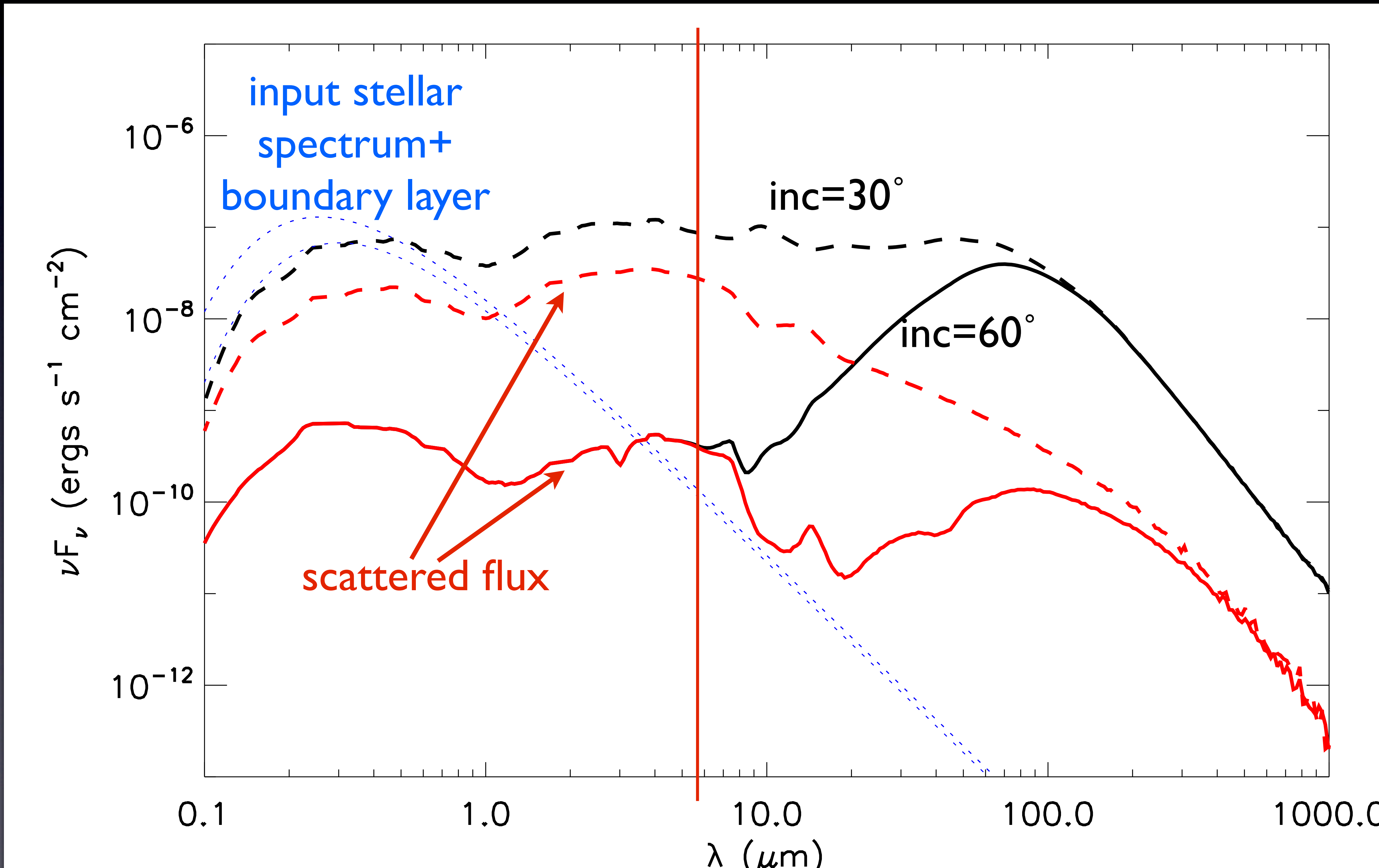
For a higher inclination, the fluxes are scattering-dominated at short wavelengths (up to ~6 μm) and emission-dominated at long wavelengths.



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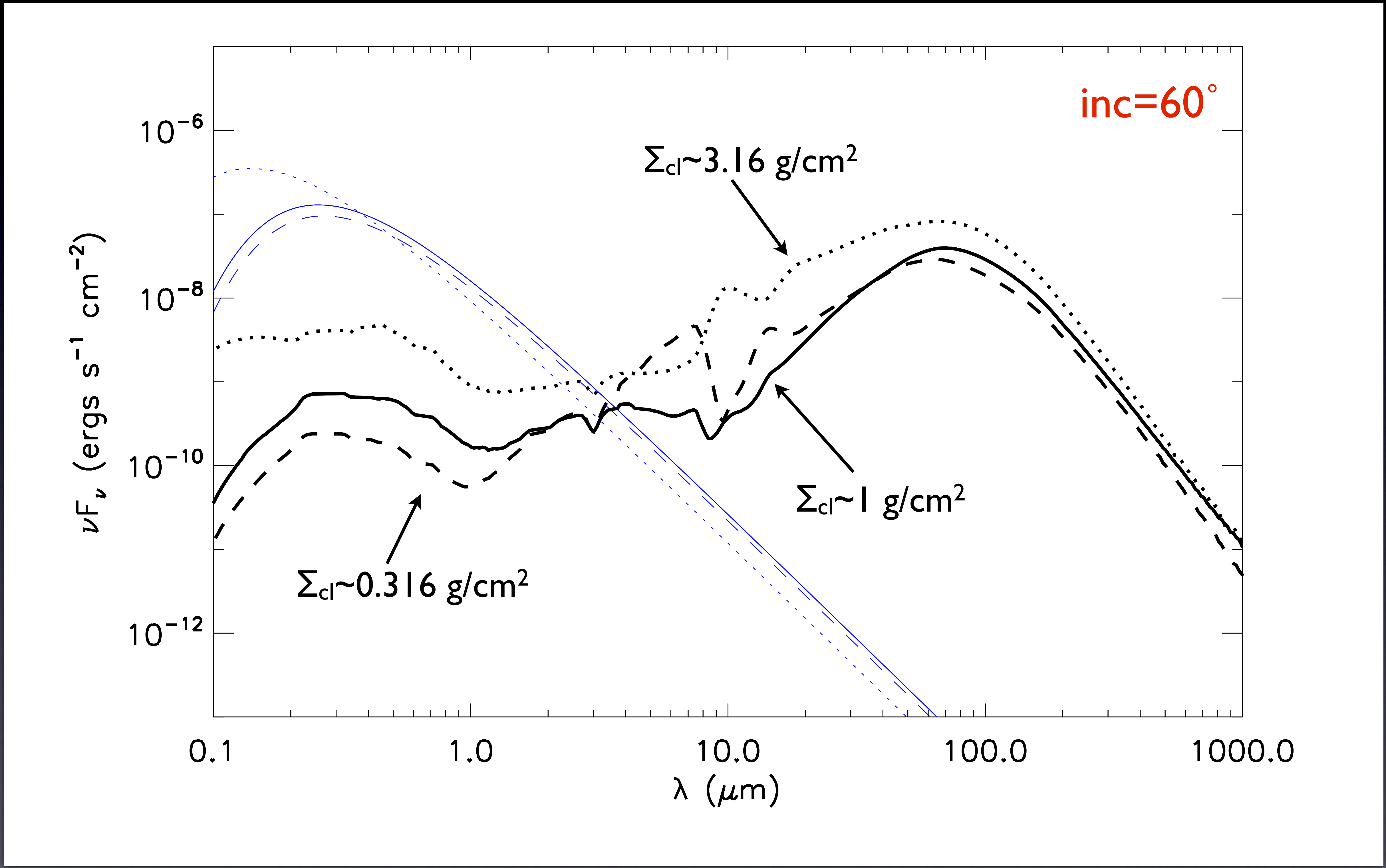

Flashlight Effect

$M_{core} = 60 M_\odot$

$\Sigma_{cl} = 1$ g cm^{-2}

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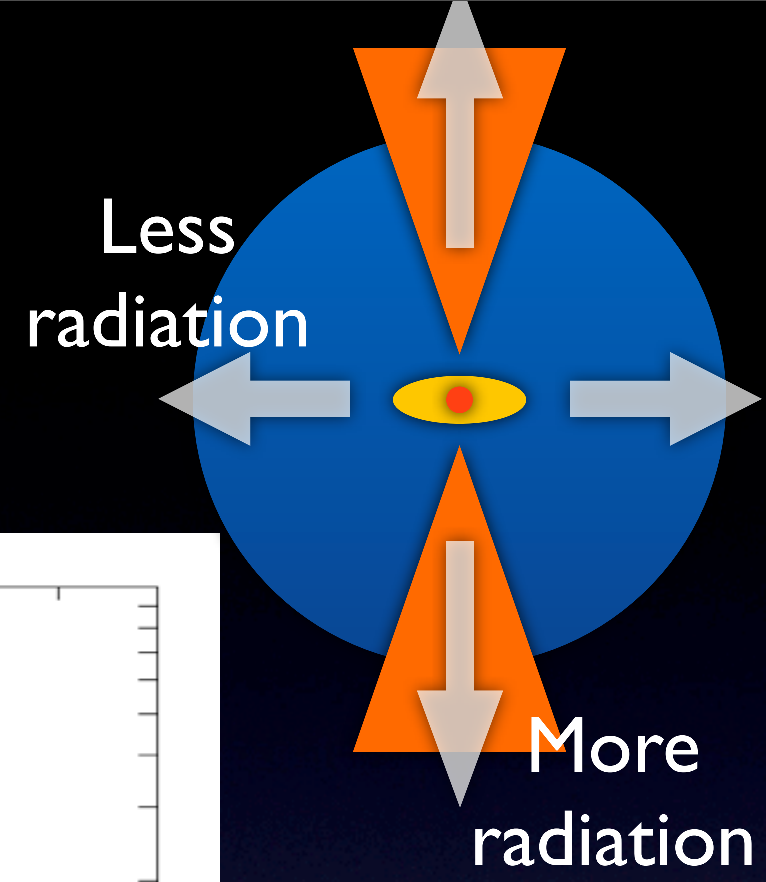
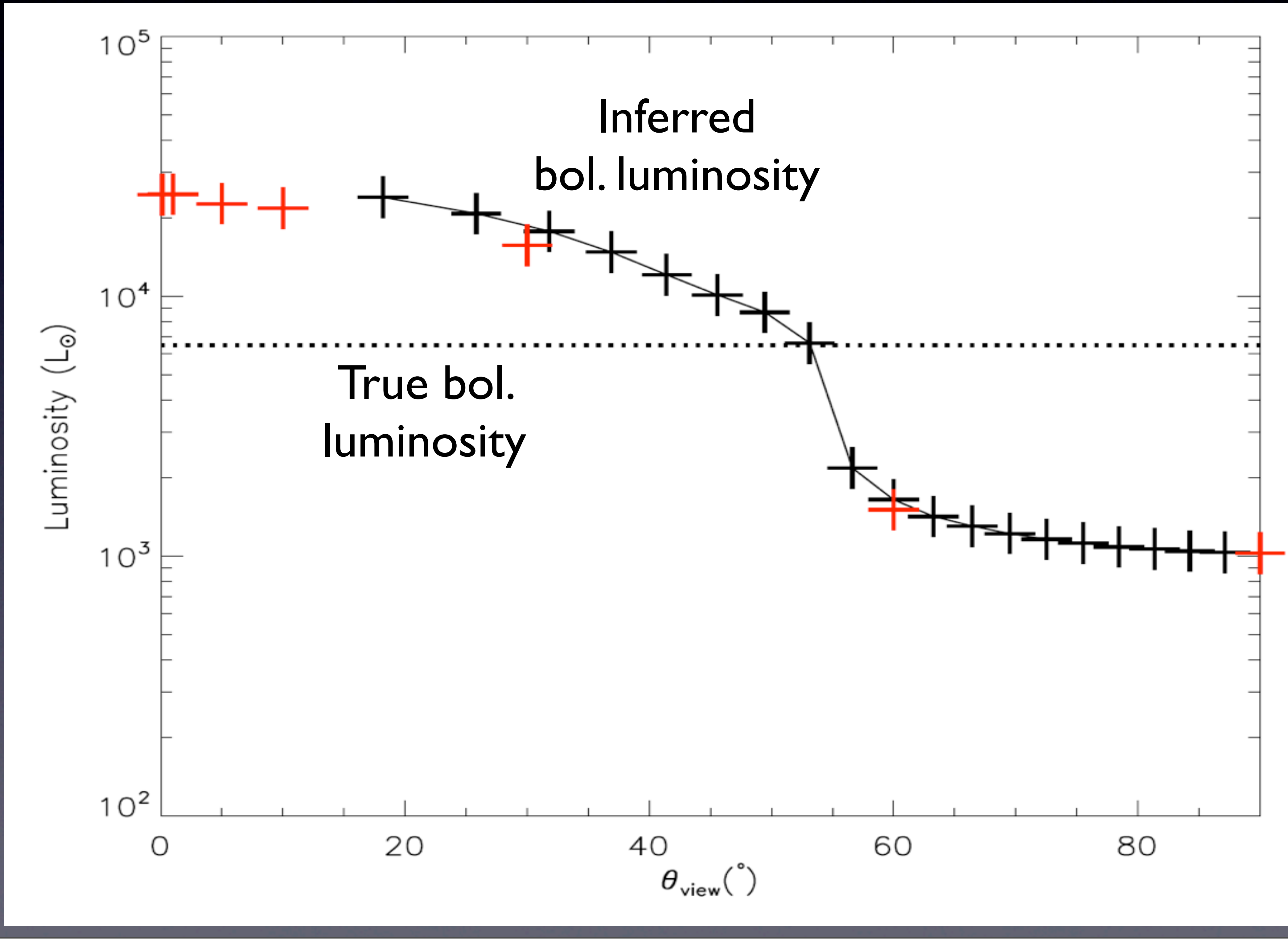
$L_{bol} = 6\times10^3 L_\odot$

$\theta_w \sim 51°$



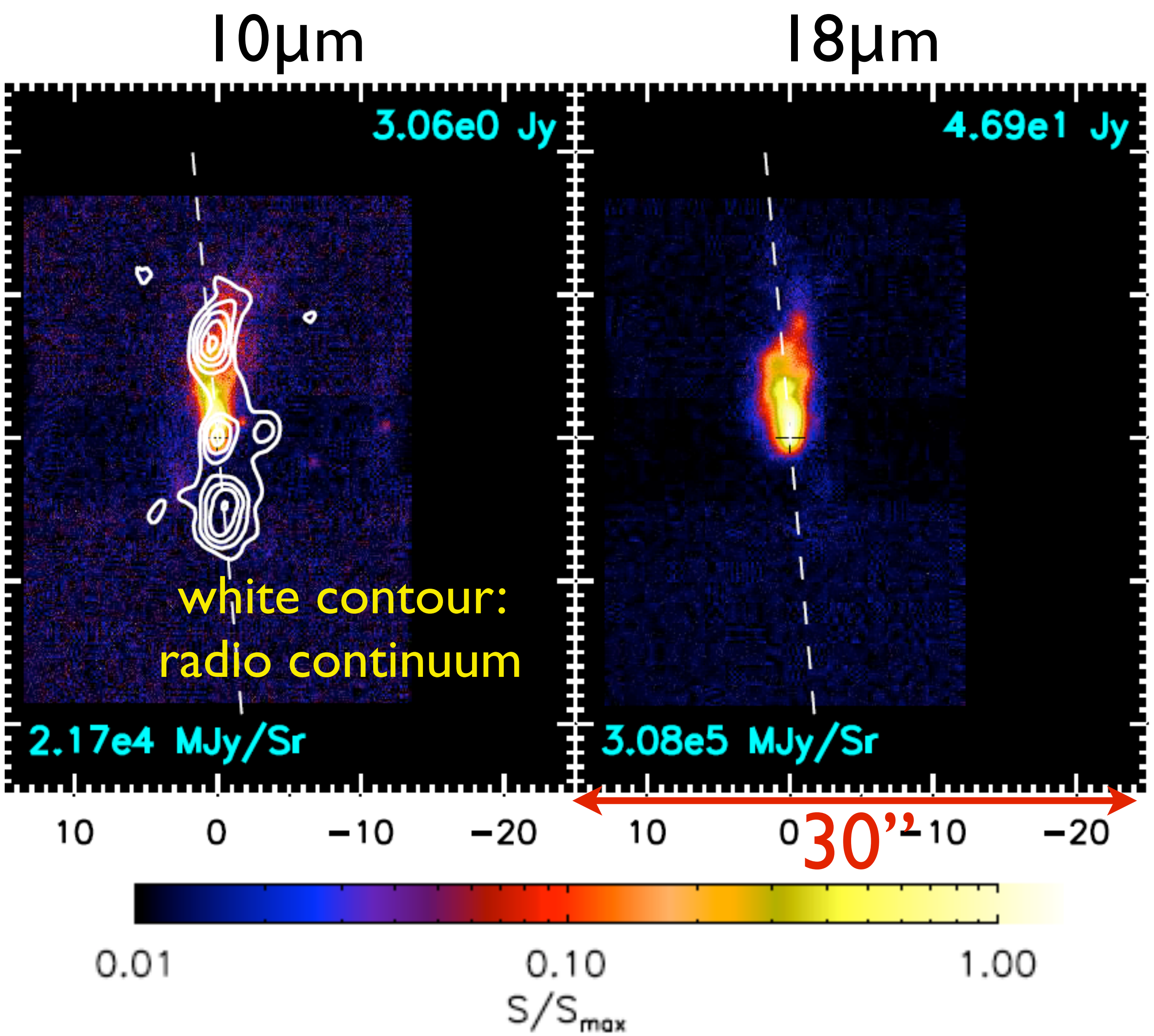


G35.2-0.74: Massive protostar at 2.2 kpc

Zhang, Tan, De Buizer, et al. 2013

See also: De Buizer 06, Birks et al. 06, Gibb et al. 03

Gemini T-ReCS



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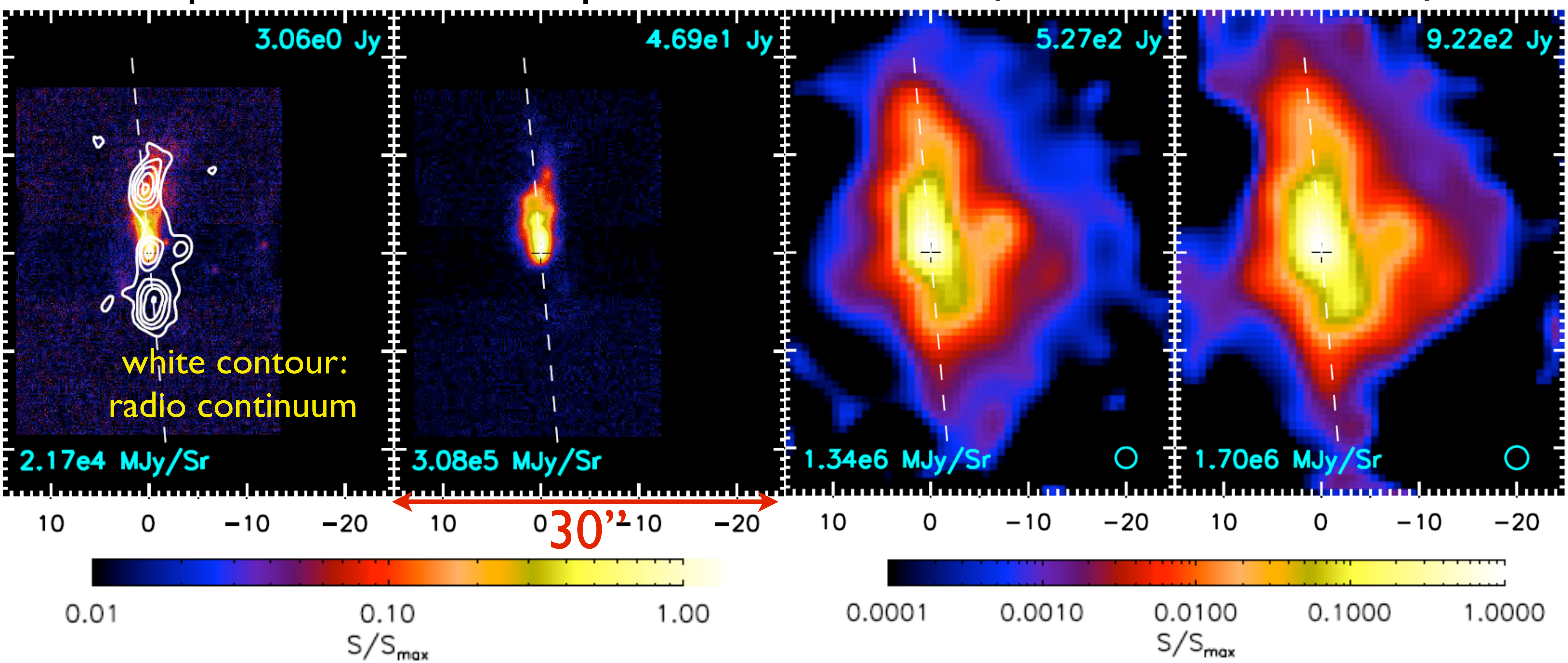
Gemini T-ReCS

SOFIA Forcast Basic Science

10μm 18μm 31μm 37.1μm



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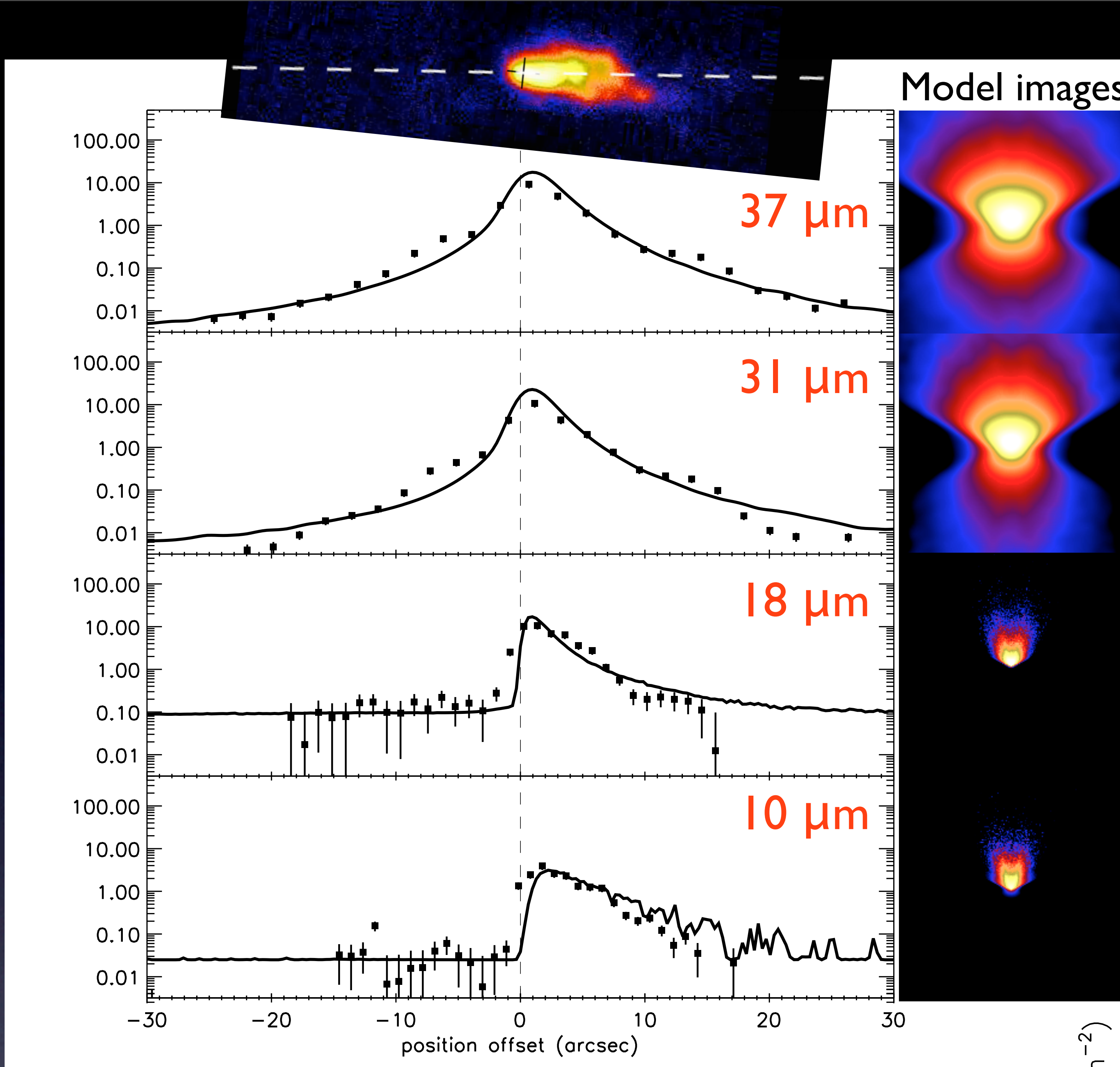


$m_* \sim 34\ M_\odot$

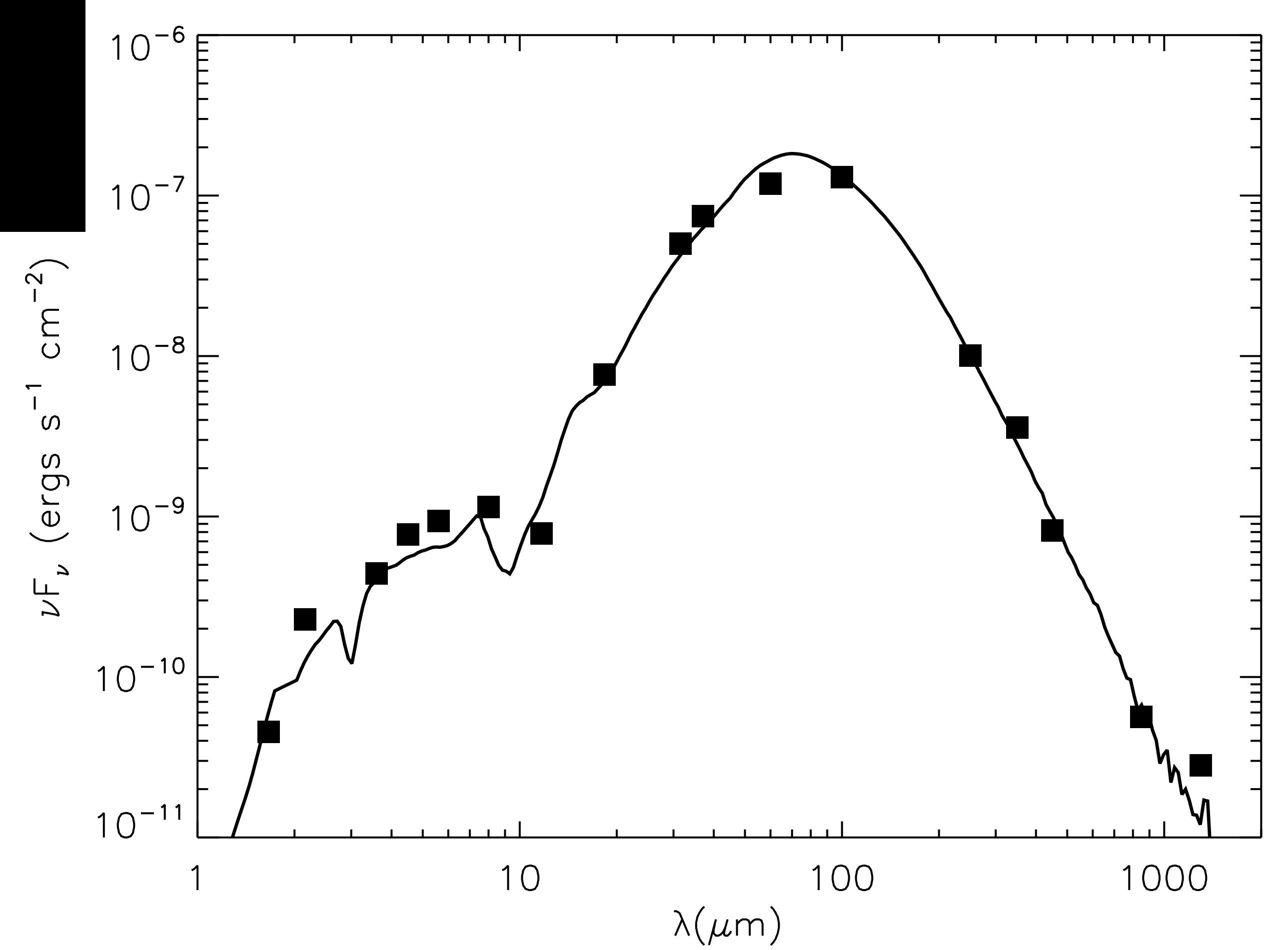
$\Sigma_{cl} \sim 1\ g/cm^2$

$\theta_w \sim 51^\circ$

$\theta_{view} \sim 58^\circ$

$L_{bol} \sim 2.2\times10^5 L_\odot$

$M_{core} \sim 240 M_\odot$



G35.2-0.74: A Massive Protostar at 2.2 kpc

$m_* \sim$ 20-34 $M_\odot$

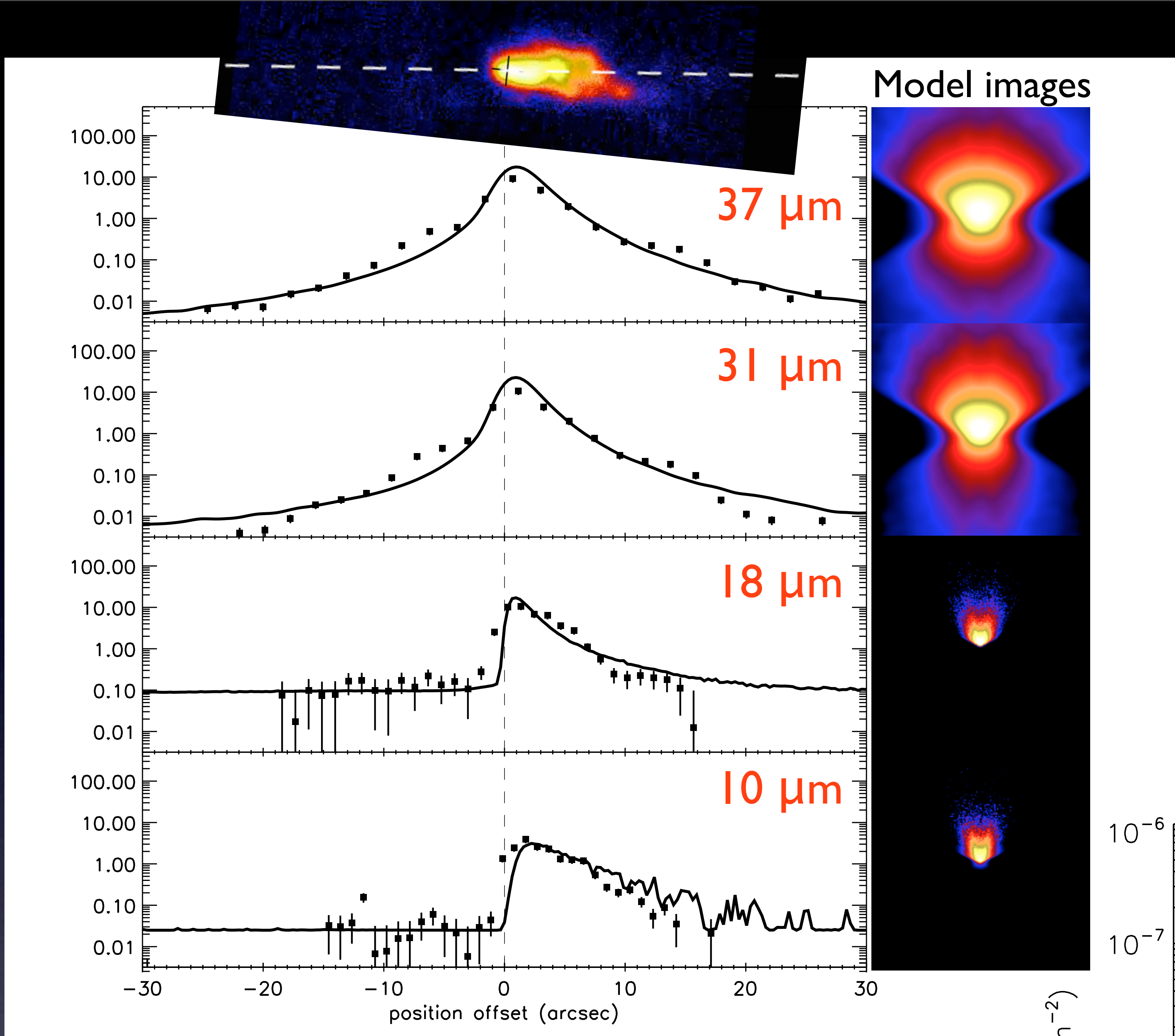
$\Sigma_{cl} \sim$ 0.4-1g/cm^2

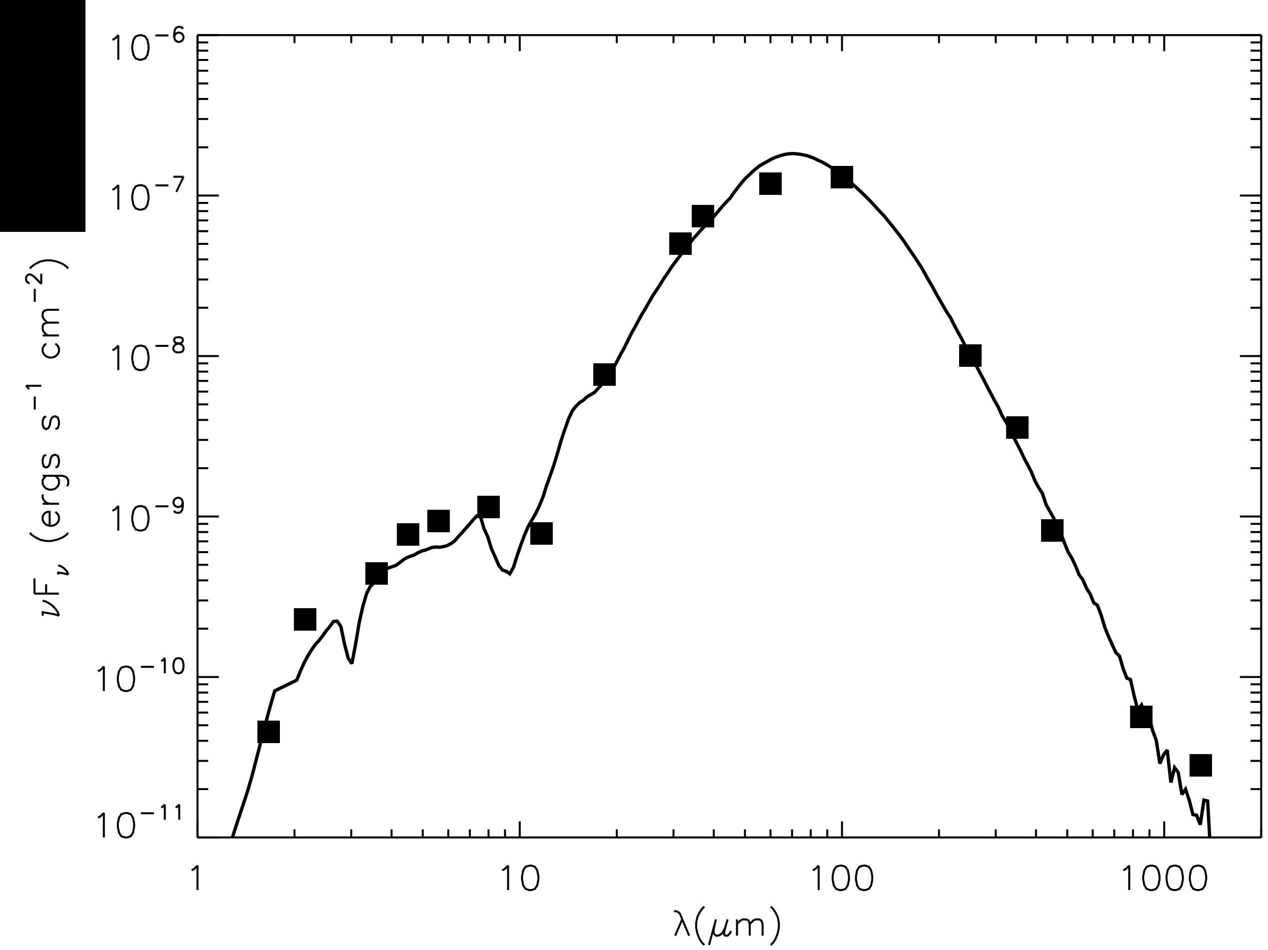
$\theta_w \sim$ 35-51°

$\theta_{view} \sim$ 43-58°

$L_{bol} \sim (0.66\text{-}2.2)\times10^5 L_\odot$

$M_{core} \sim 240 M_\odot$





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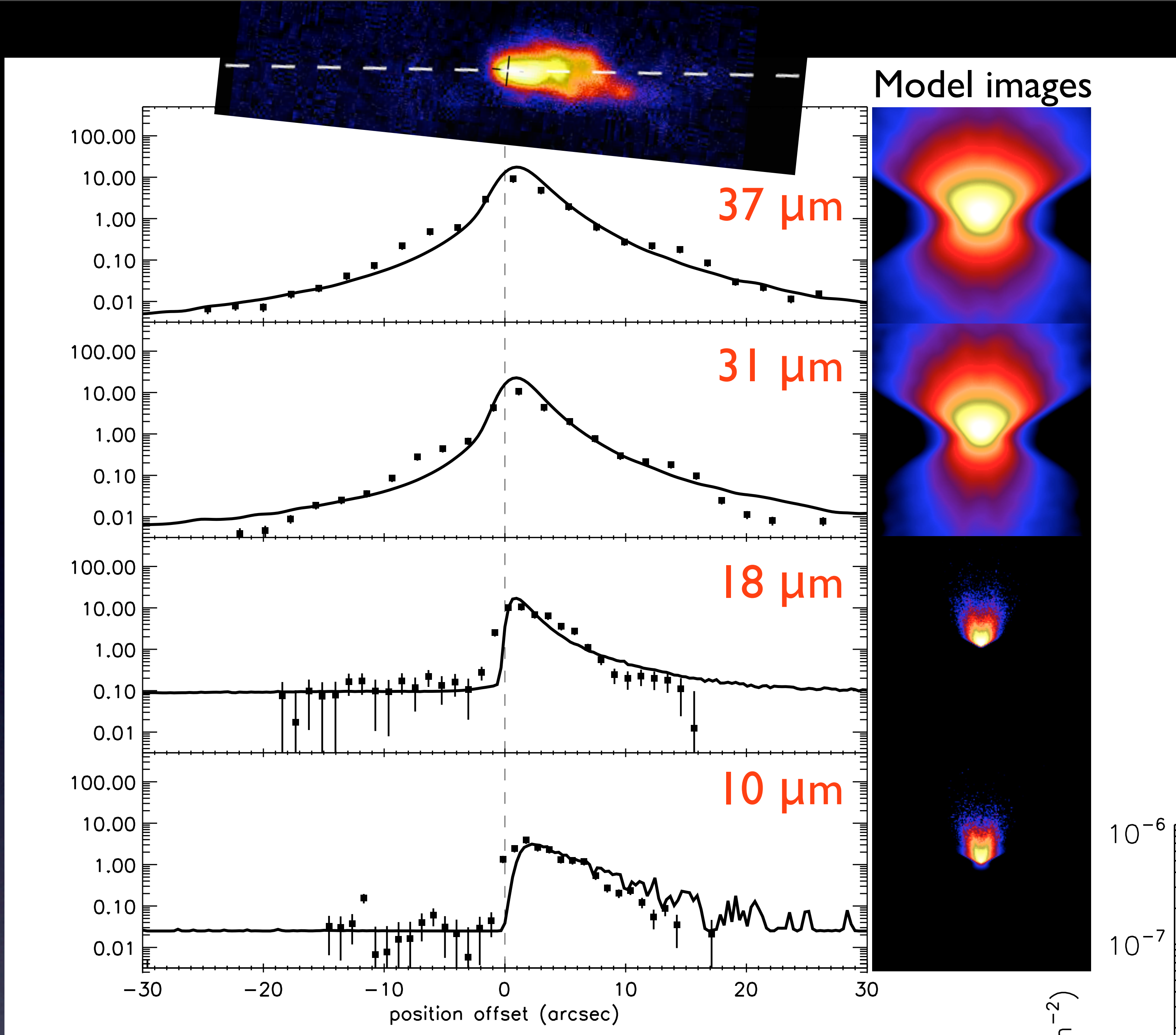

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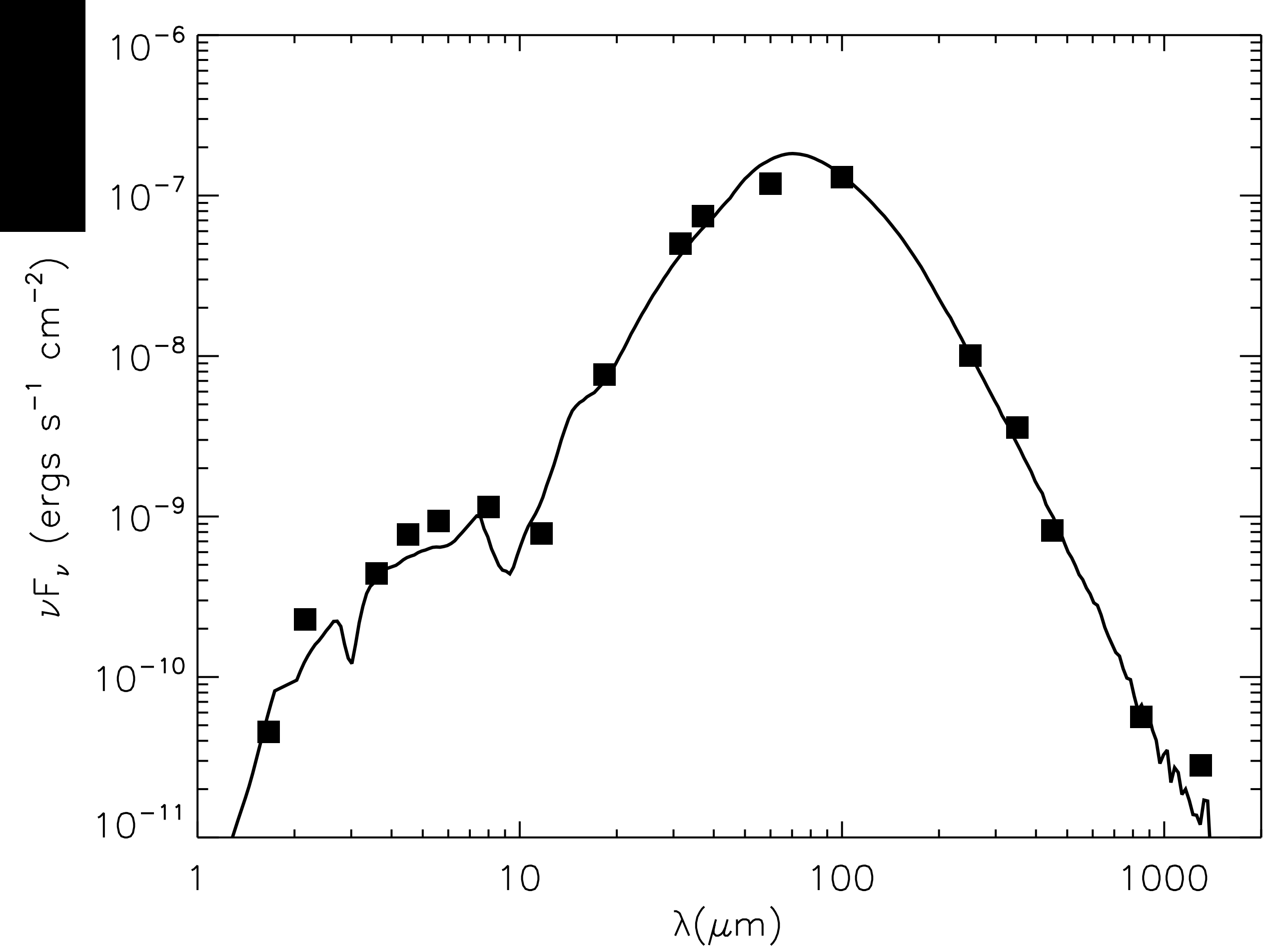
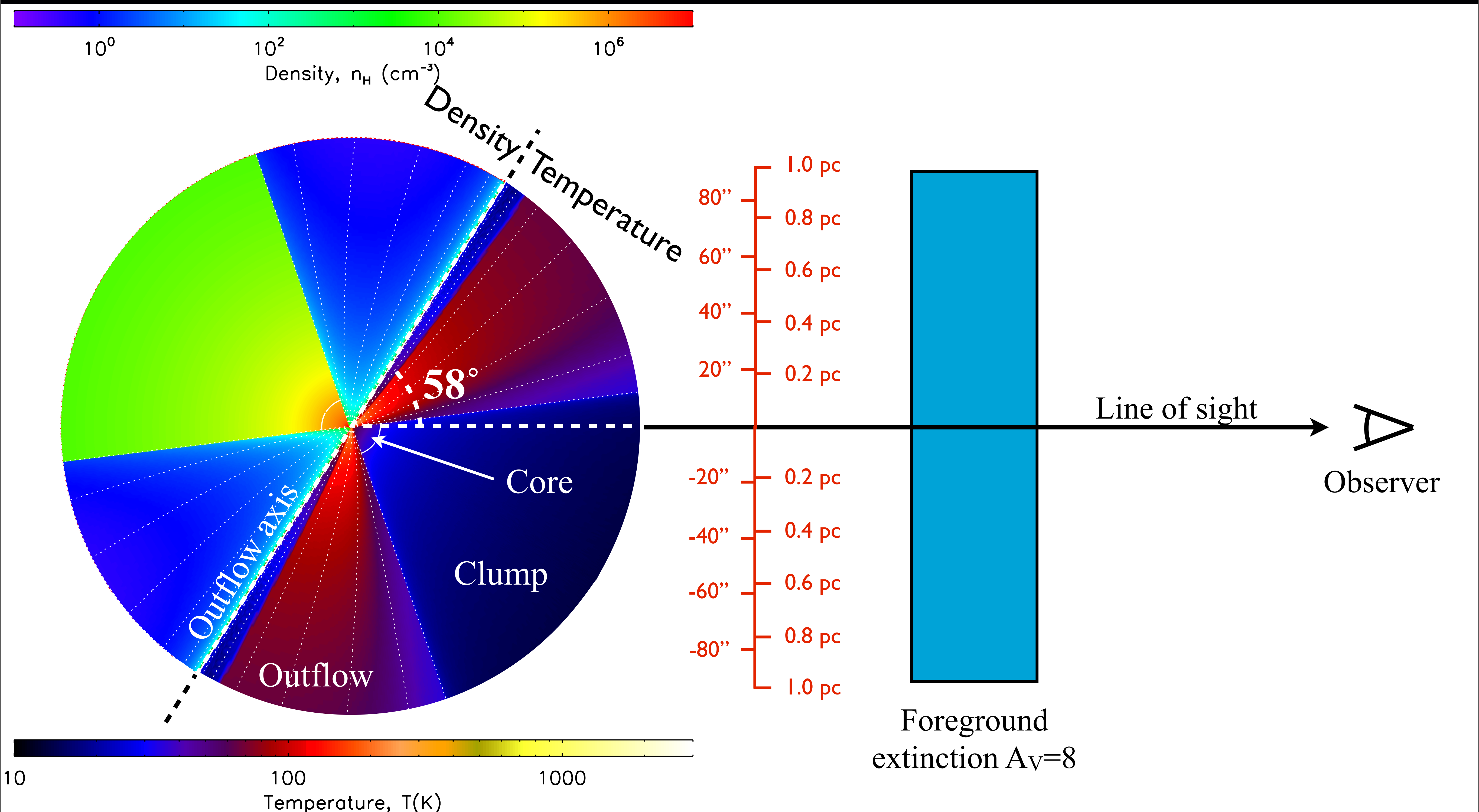


G35.2: a massive protostar forming from a high mass surface density core, via relatively ordered collapse and accretion, which is driving relatively symmetric bipolar outflows

G35.2-0.74: Massive protostar at 2.2 kpc

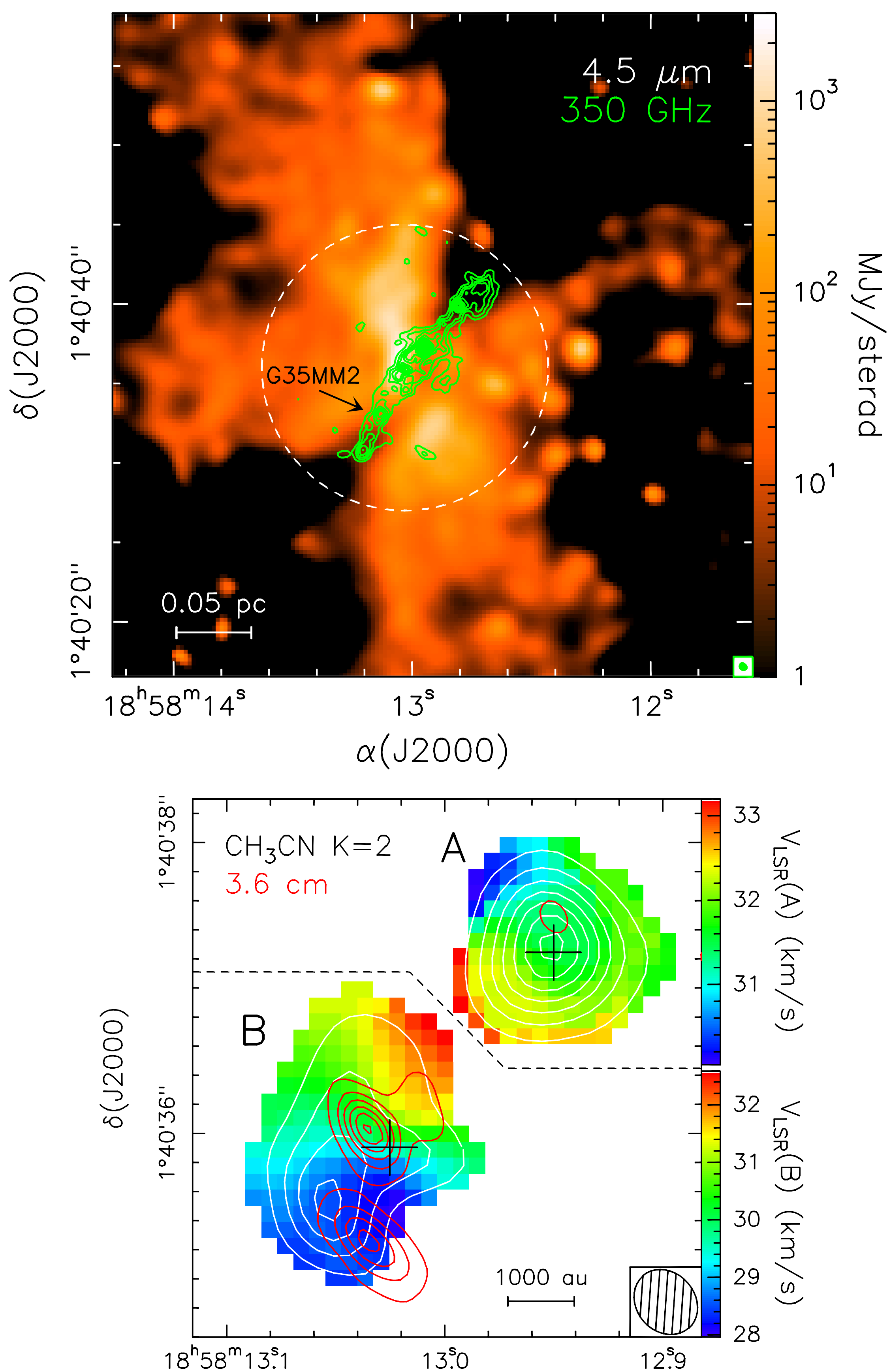
Zhang, Tan, De Buizer, et al. 2013

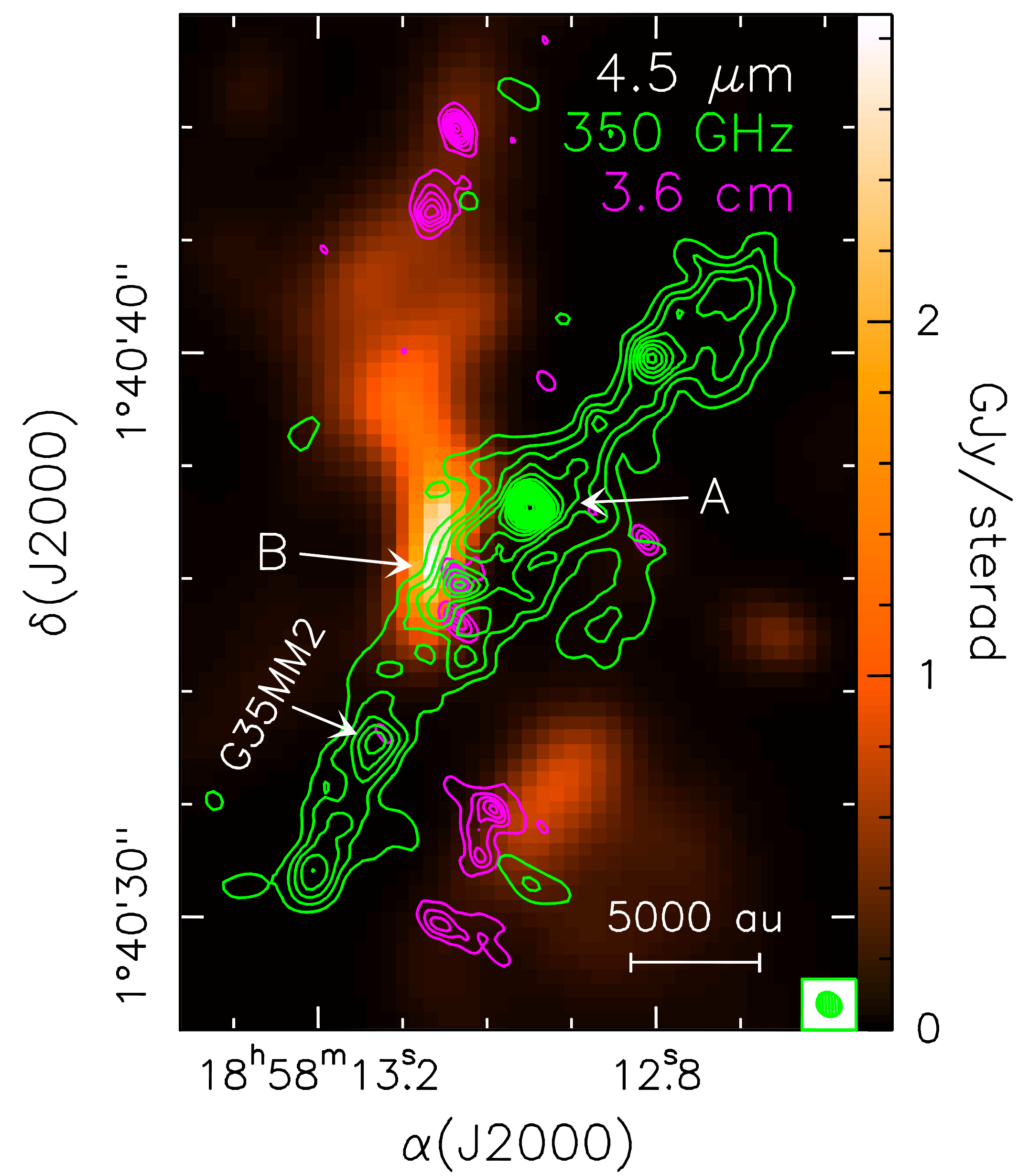
Geometry of the best fitting model



A Keplerian Disk at the Center?

ALMA observation by
Sanchez-Monge et al. 2013

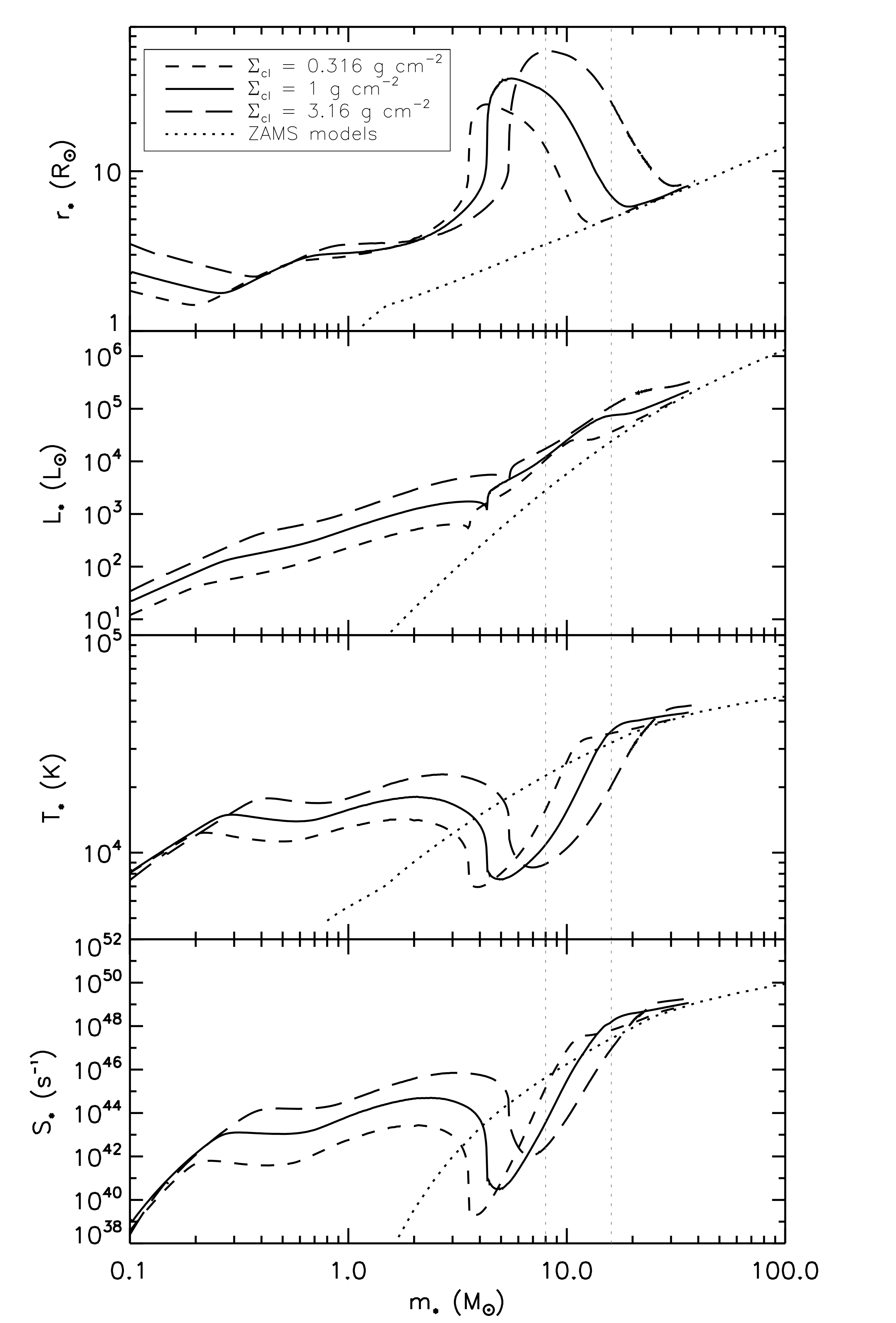




Source B is driving the outflow and contains a binary system of total 18 M⊙ at the center

Evolutionary Sequence

Zhang, Tan, Hosokawa, et al., 2013, in prep.
See also McKee & Tan 2003,
Hosokawa & Omukai 2009,
Hosokawa et al., 2010

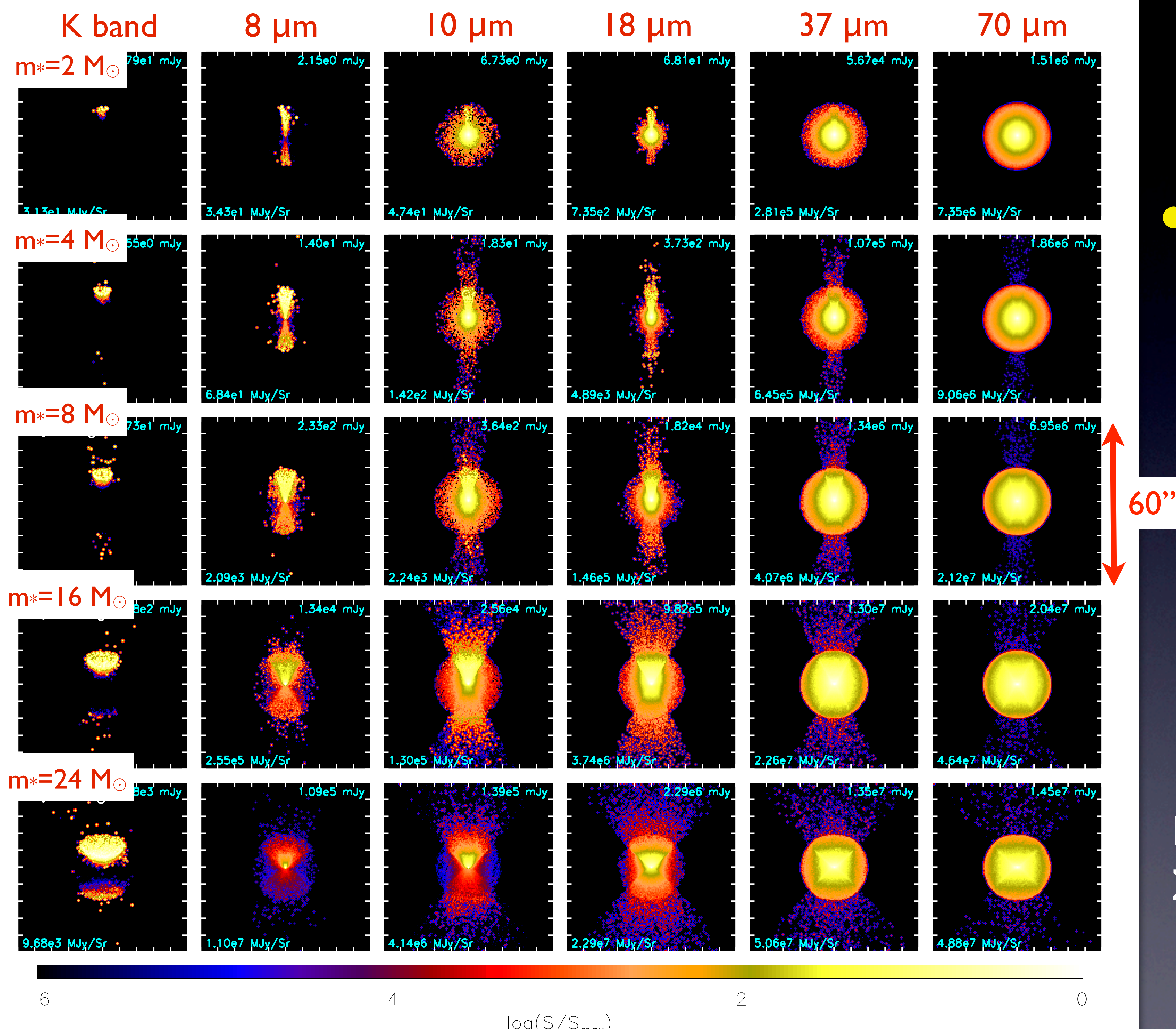


Radius

Luminosity
(protostar+boundary layer)

Temperature
(protostar+boundary layer)

Ionizing Luminosity



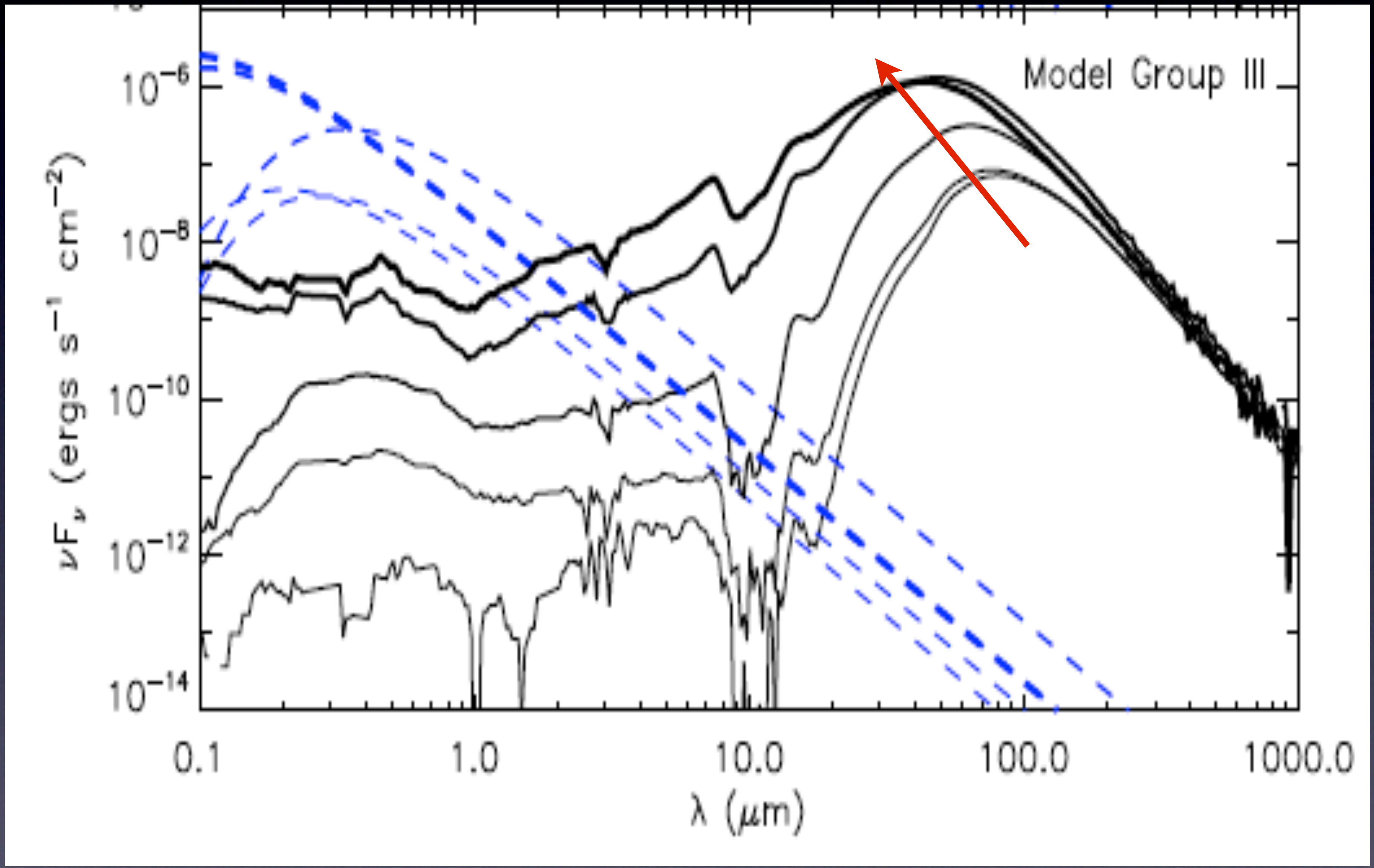
Continuum Monte Carlo RT Modeling:

- **Images** at 1 kpc at 60° inclination between line of sight and outflow axis

$M_{core} = 60 M_\odot$

$\Sigma_{cl} = 1 \text{ g cm}^{-2}$

Evolutionary Sequence: SEDs



$M_{core} = 60M_\odot$

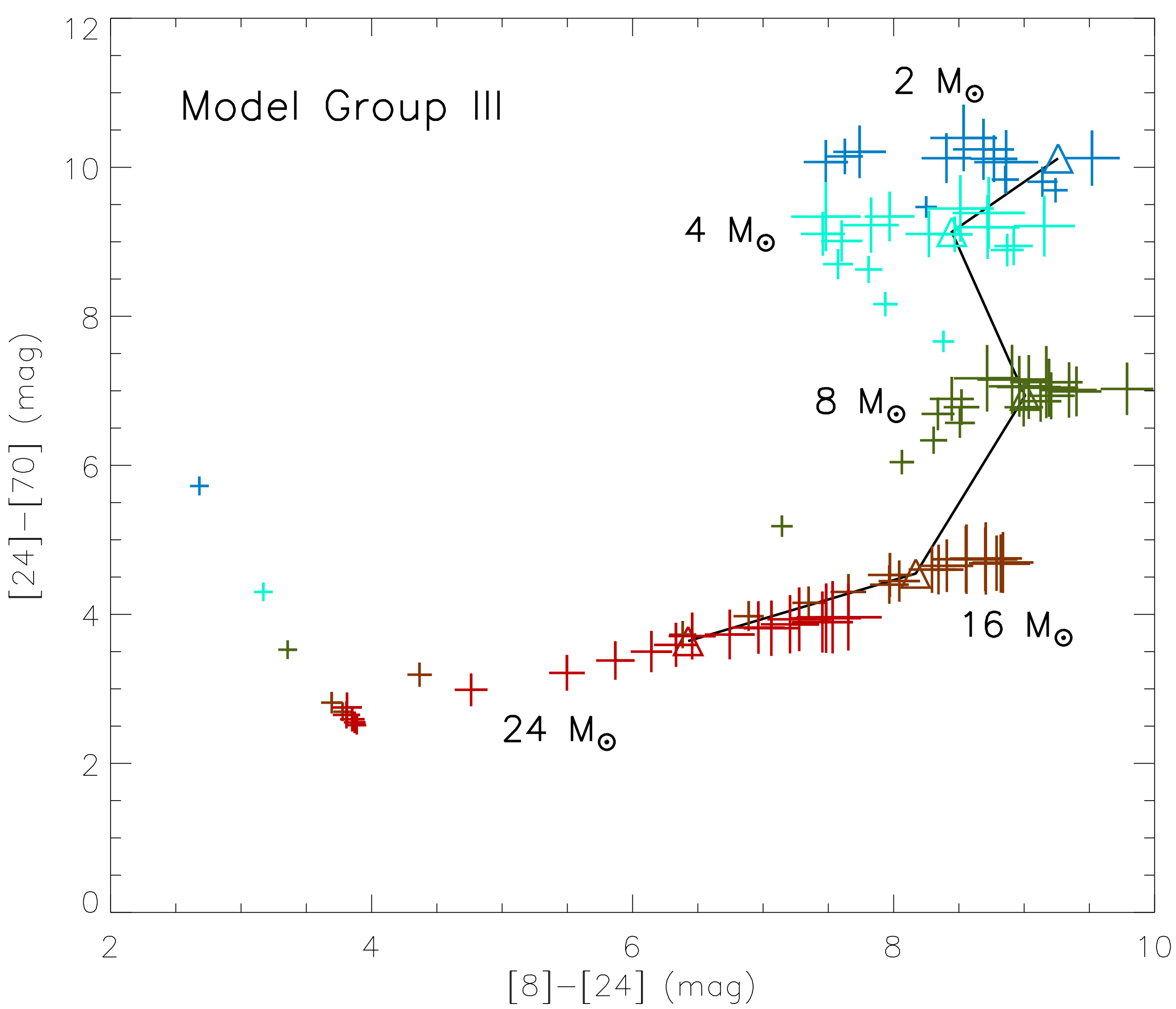
$\Sigma_{cl} = 1$ g cm^{-2}

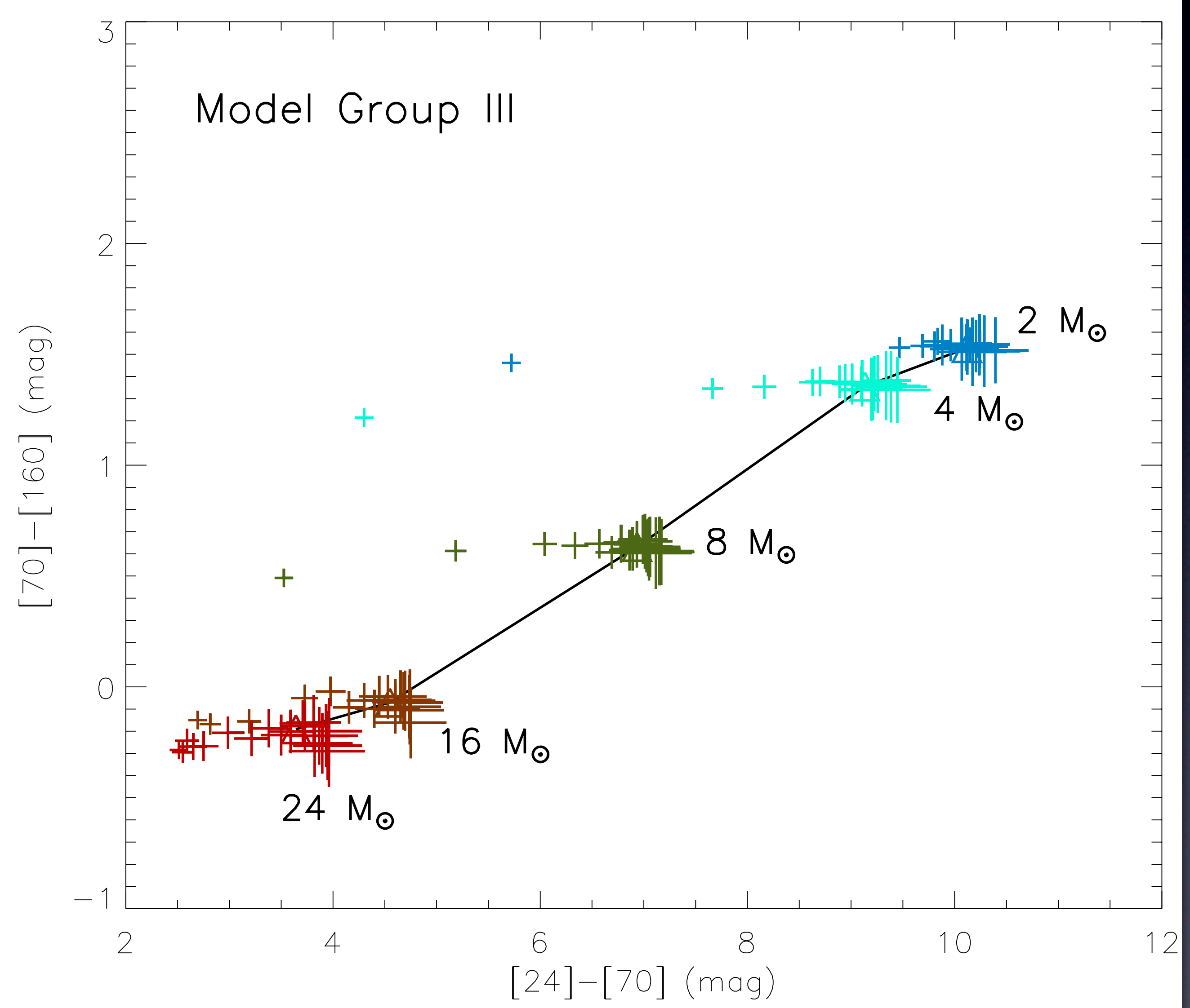
Evolutionary Sequence: Color-color Diagram

$M_{core} = 60 M_\odot$

$\Sigma_{cl} = 1 \text{ g cm}^{-2}$

Crosses: from large to small: from edge-on to face-on





Larger sample of massive protostars needed!

Accepted SOFIA cycle 1 proposal:
6 more sources with luminosity range ~10

IRAS 20126+4104, Cep A, G339.88-1.26, G45.47+0.05 (Observed last month),
IRAS 07299-1651, IRAS 16562-3959

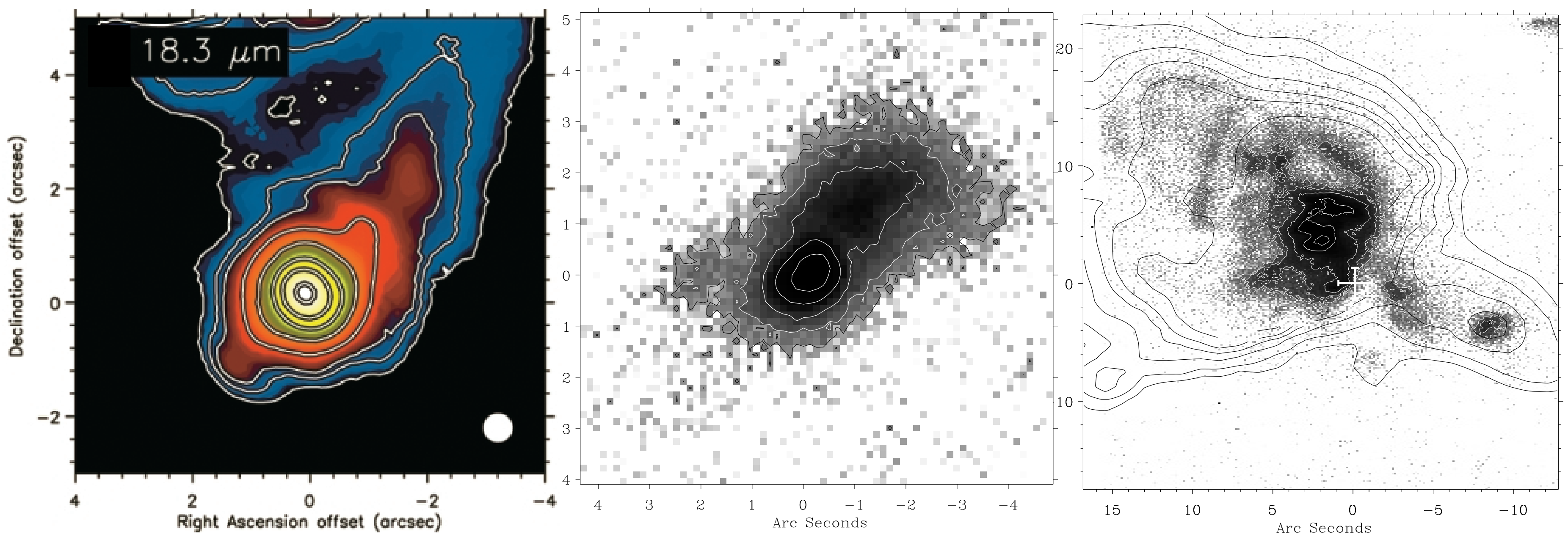


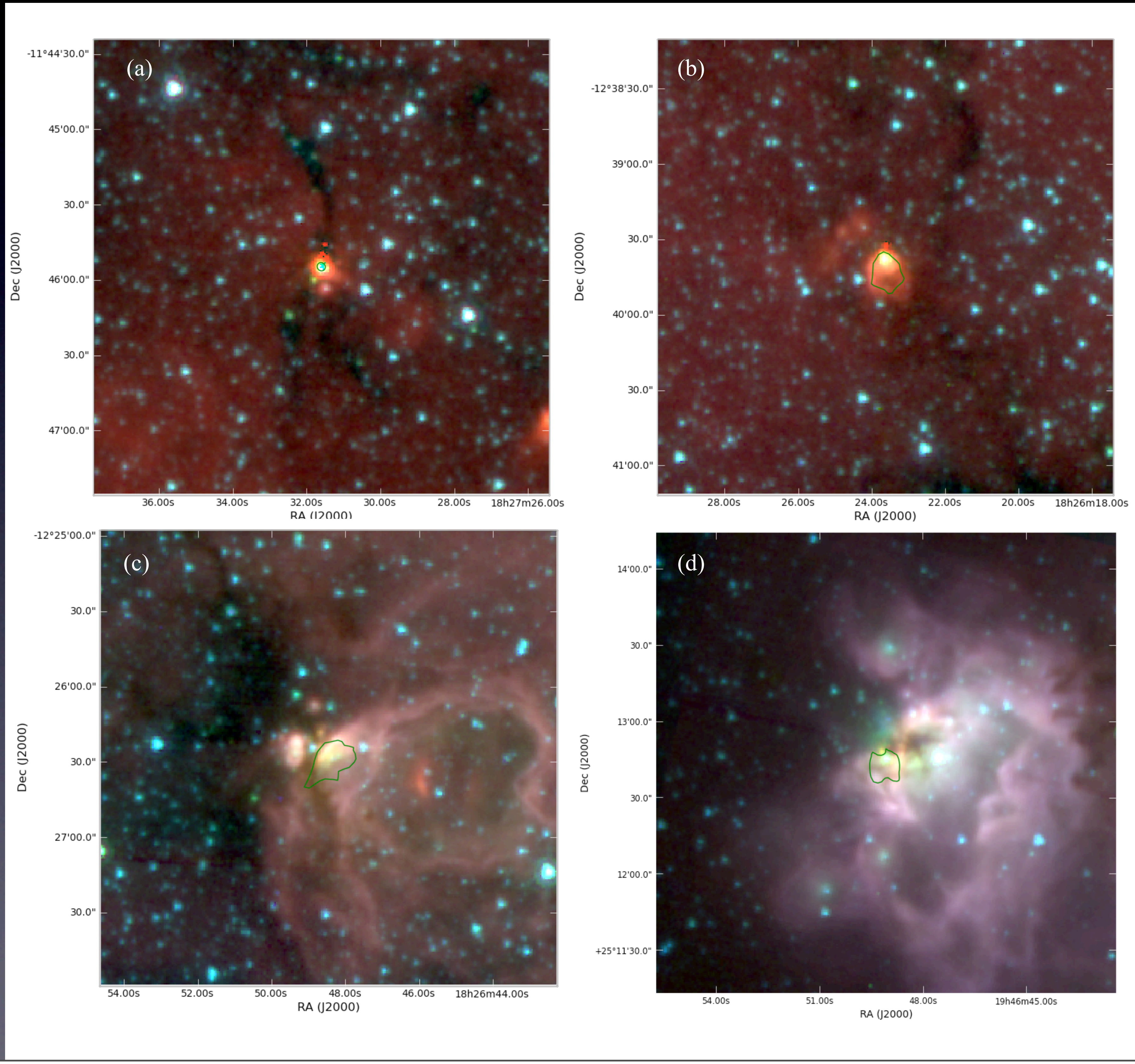
Figure 4: Example images of several of our sources: (a) Left: NGC7538 IRS1 at 18.3μm (De Buizer & Minier 2005); (b) Middle: IRAS 20126+4104 at 24.5μm (De Wit et al. 2010); (c) Right: Cep A at 24.5μm (shaded+light contours) and 8μm (dark contours) (De Wit et al. 2010).

Larger sample of massive protostars needed!

SOFIA cycle II proposal:

Sample of ~50 sources with UCHII region and bright mid-IR emission covering different emission and evolutionary stages.

a) “MIR sources in IRDCs”
b) “Hyper-compact” (G35.2 like)
c) “Ultra-compact”
d) “Clustered sources”



Summary

We have constructed a self-consistent continuum RT model of massive stars forming through *Core Accretion*, and compared the model to observations:

1) Can (and how well) the initial environmental conditions of the massive protostars be deduced from the observed SEDs and/or images? — Yes. Some degeneracy due to the opening angle of the outflow cavity, the resolved intensity profile may help to break this degeneracy.

2) Do these initial conditions agree with those required by the *Core Accretion* theory? — In the case of G35.2, yes. ($\Sigma_{cl} \sim 0.3\text{-}1 g/cm^2$)

3) Do the observations are compatible with the prediction from the *Core Accretion* theory on disks and outflows? — Outflow: yes; Disk: line tracers to confirm.

4) Can (and how well) the evolutionary sequence of massive protostars be deduced from the observed SEDs? — The evolutionary sequences may be reflected from SED, more modeling work need to be done. And a larger sample of massive protostars is needed!

Although our model is highly idealized (symmetric, single protostar, no turbulence, etc.), our results support that massive stars form similarly to low-mass stars.