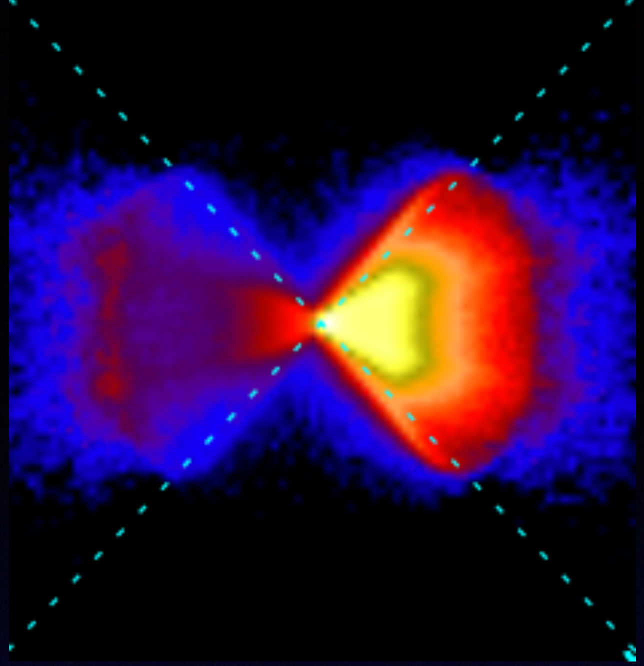
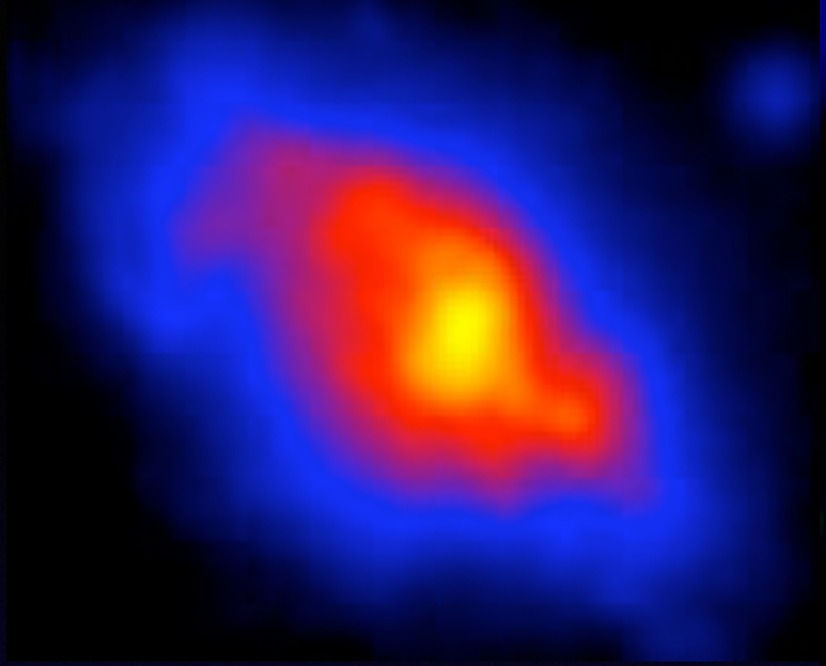
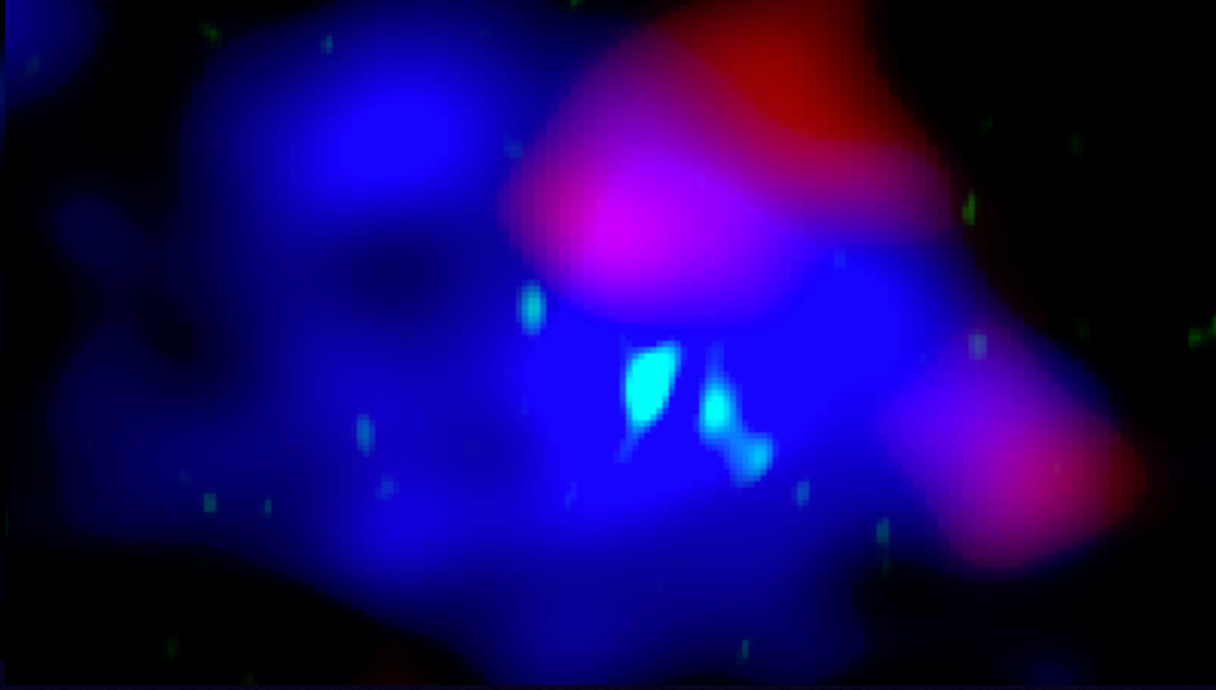




The Evolution of Outflows from High-Mass Stars

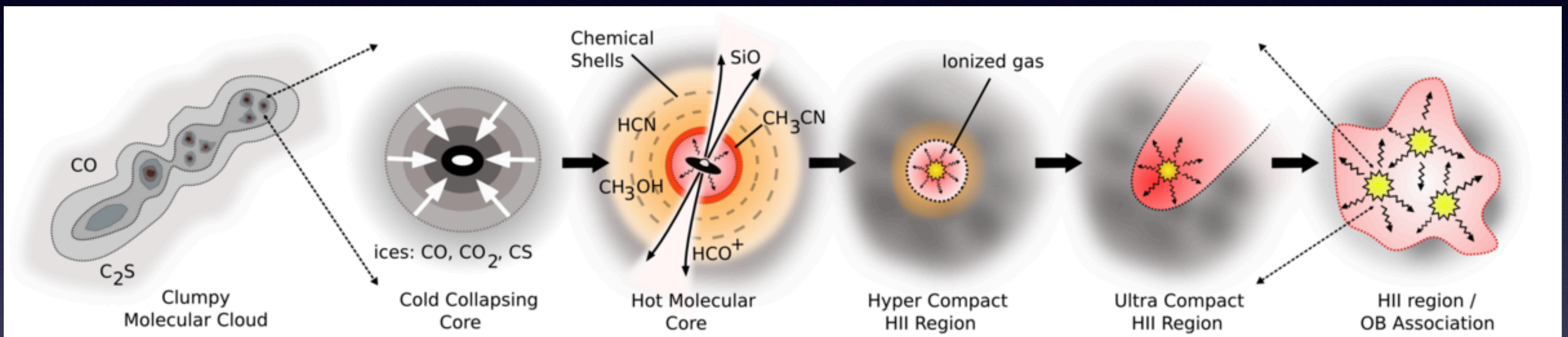
Viviana Rosero

University of Florida

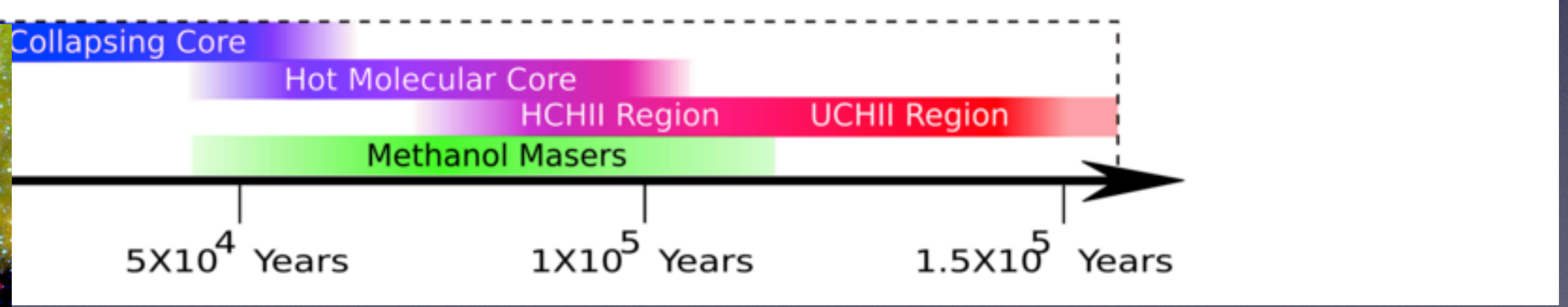
Collaborators: Jonathan Tan (UF), Kei Tanaka (UF), Yichen Zhang (RIKEN) , Mengyao Liu (UF/UVa), James De Buizer (SOFIA-USRA), Peter Hofner (NMT), Mark Claussen (NRAO), Stan Kurtz (IRyA), Riccardo Cesaroni (INAF-Arcetri), Esteban Araya (WIU), Karl Menten (MPIfR), Friedrich Wyrowski (MPIfR), Carlos Carrasco-González (IRyA), Luis F. Rodríguez (IRyA), Laurent Loinard (IRyA), Simon Ellingsen (UTAS)

NM Symposium Socorro, NM 11.03.17

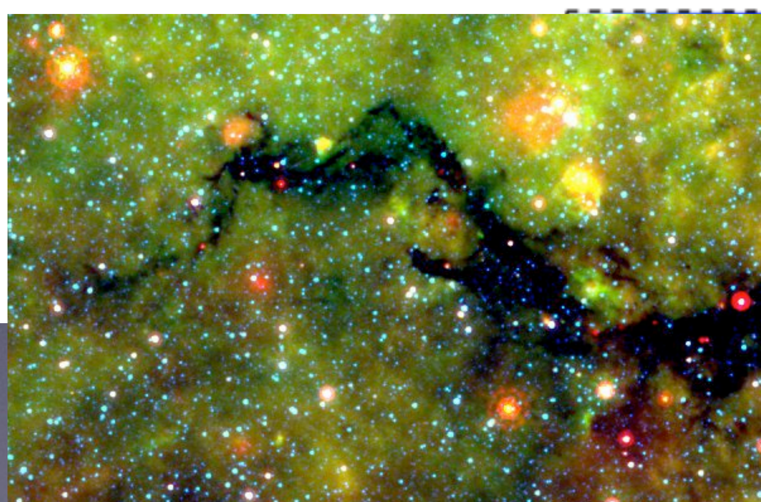
High-Mass Star Formation



starless protostellar ZAMS



IRDC?



Credit: NASA, JPL-Caltech

Cartoon from Cormac Purcell

Rosero et al. 2016

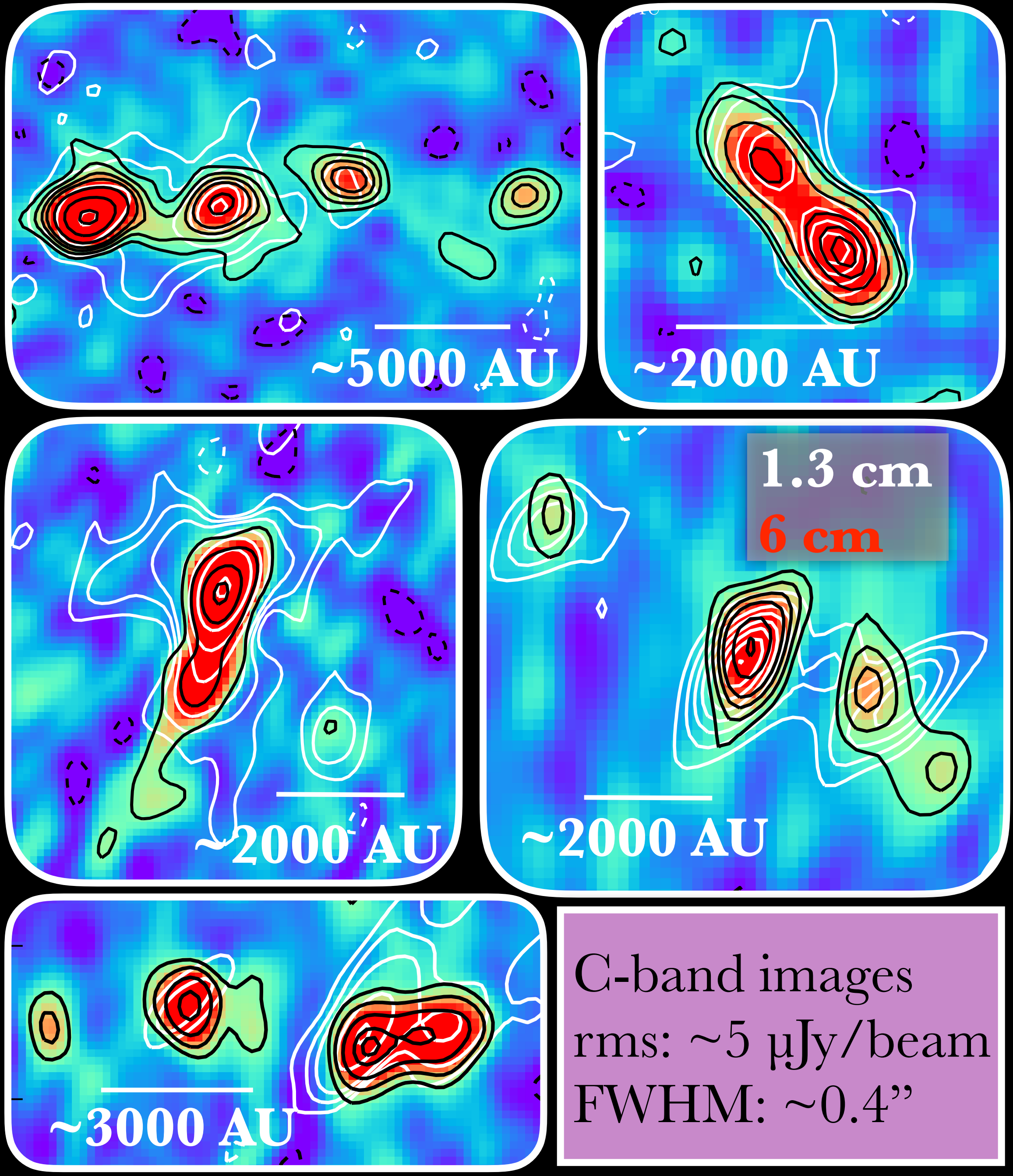
Previous Work: Dissertation

Radio continuum may be detectable at weak levels in all HMCs

- 58 regions: 70 mm-associated radio sources
- Detection Rate:

Age?

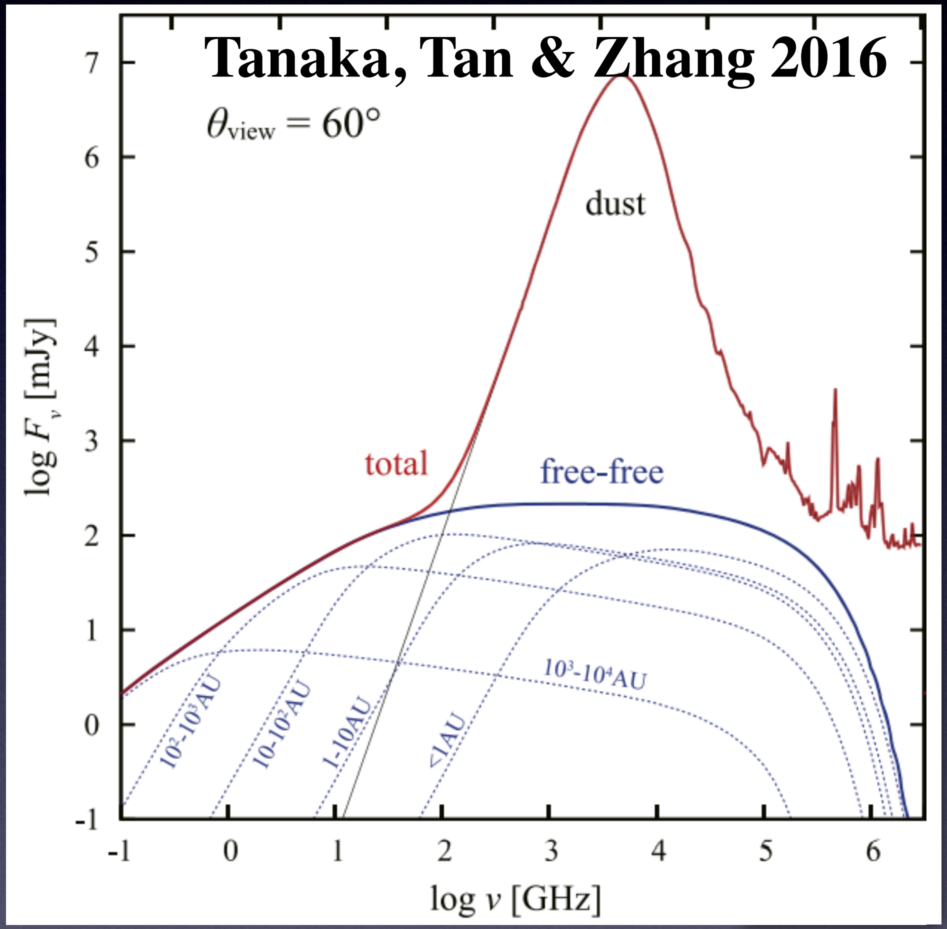
  - 1/18 CMC: 6%
  - 8/15 CMC-IR: 53%
  - 25/25 HMC: 100%
- 12 ionized jets (+13 wind/jets candidates)
- Early stages of ionization are in the form of jets



C-band images
rms: ~5 μJy/beam
FWHM: ~0.4”

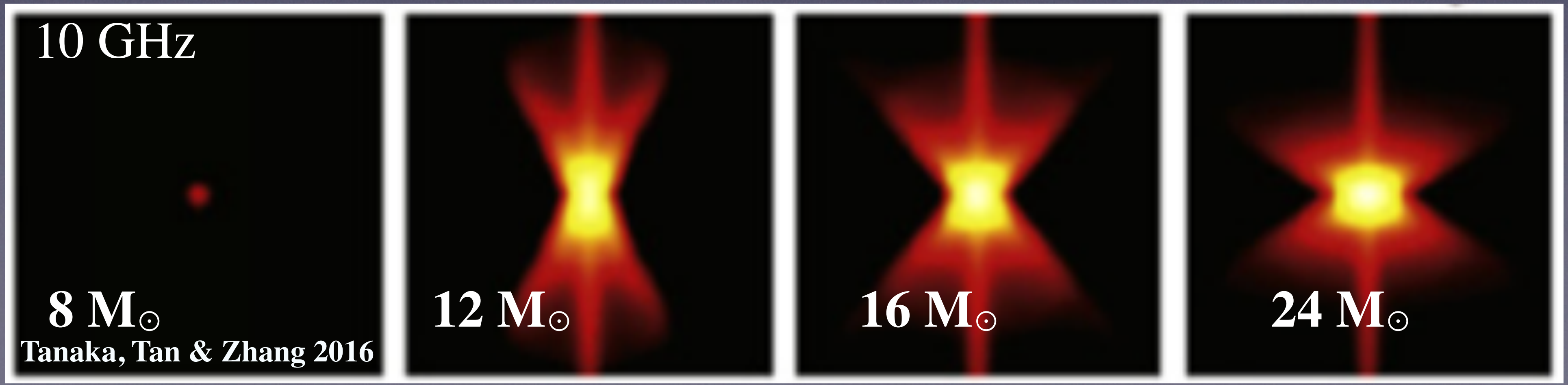
Ionized Jets

Predicted SED



Tanaka, Tan & Zhang (2016):
early stages of ionization

Predicted Radio Continuum



Expanded Sample

Probing different environments, evolutionary stages and core masses

Total of ~70 sources

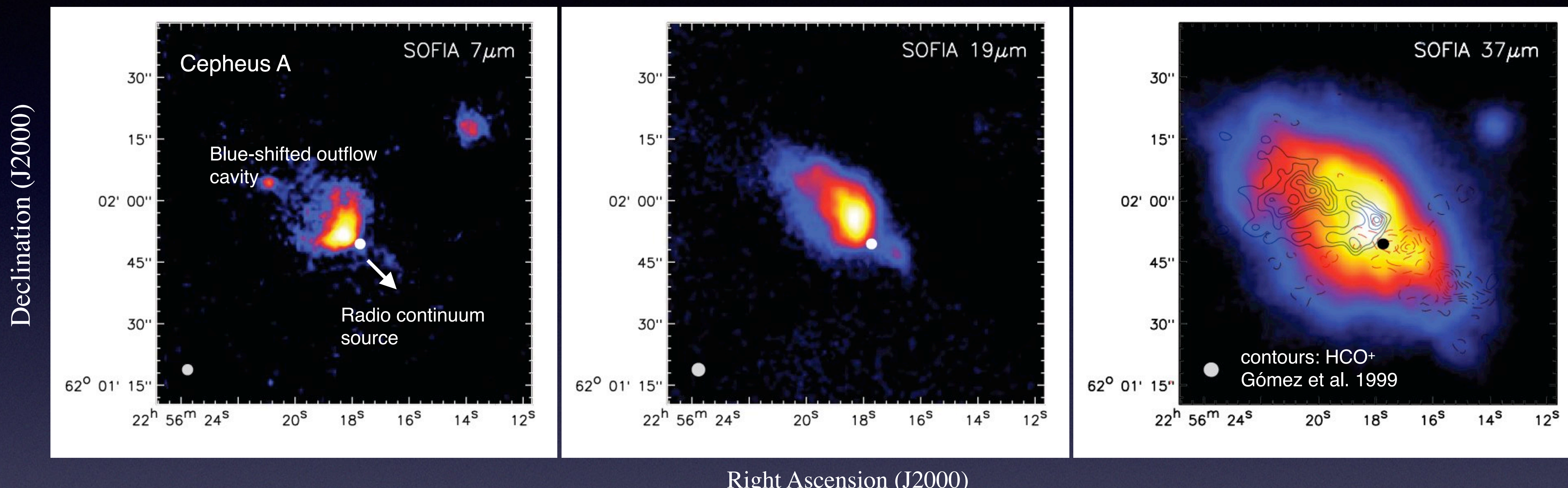
Dissertation Survey: Early stages of high-mass star formation (Rosero et al. 2016)

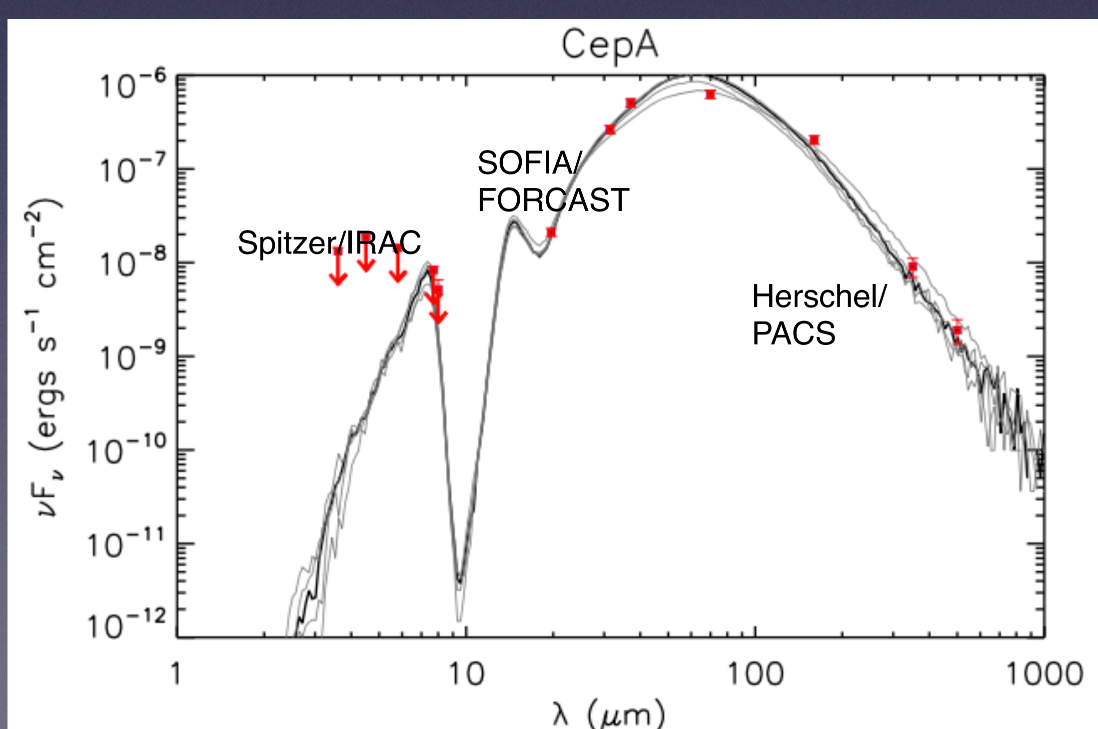
SOFIA Massive (SOMA) Star Formation Survey: IR-based survey (De Buizer et al. 2017).

22 observed + SOFIA cycle 6 approved (PI: Tan)

SOMA Paper I: De Buizer et al. 2017

SOMA Survey



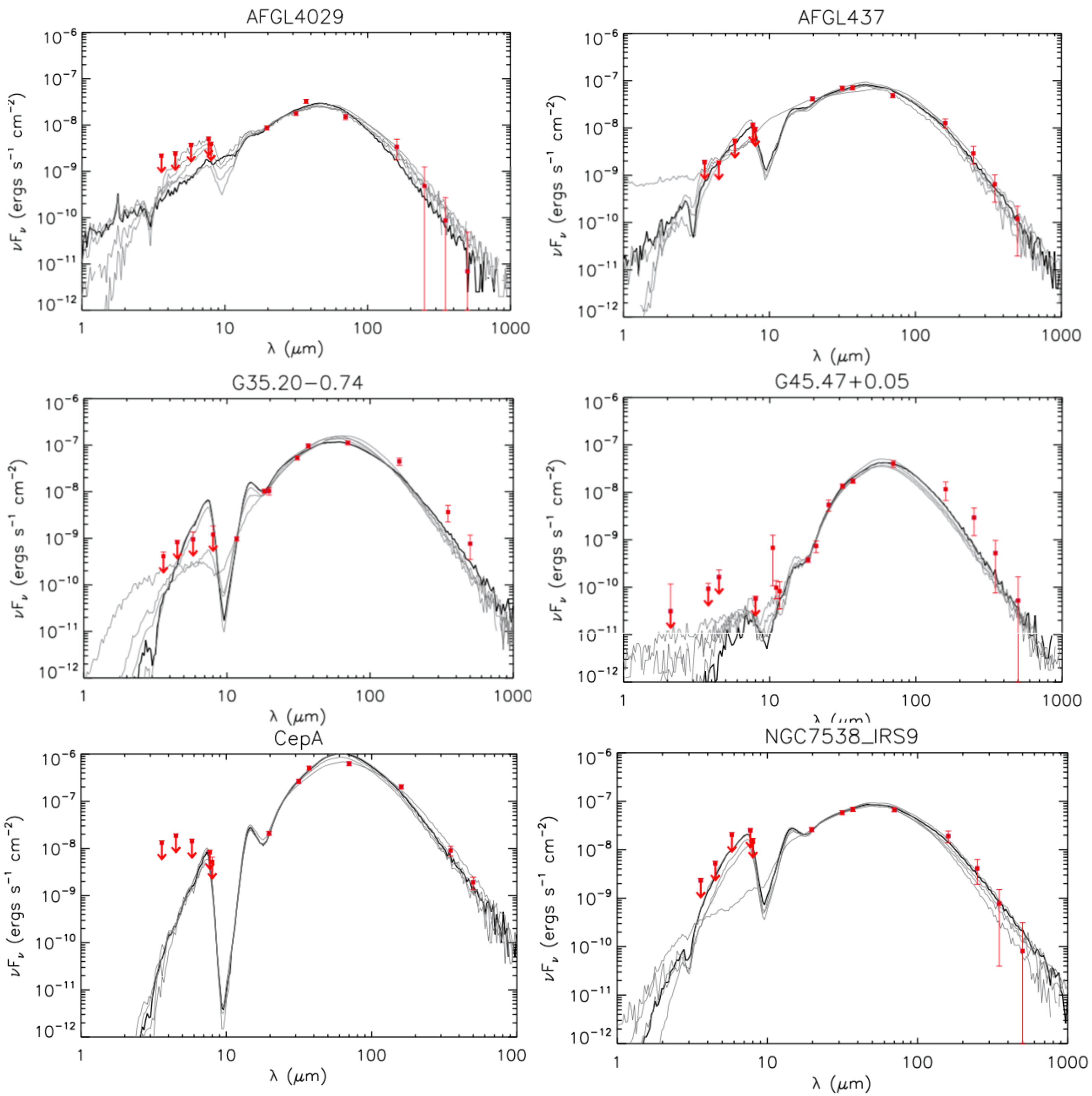


SOFIA FORCAST 10 - 40 μm

Resolution: ≲3”

Zhang & Tan (2014; 2017) RT model based on core accretion scenario

SOMA Paper I: De Buizer et al. 2017



Zhang & Tan (2014; 2017)

Free parameters:

M_c, Σ_{cl}, $m_\star$, θ_{view}, A_v

VLA Survey: Expanded Sample

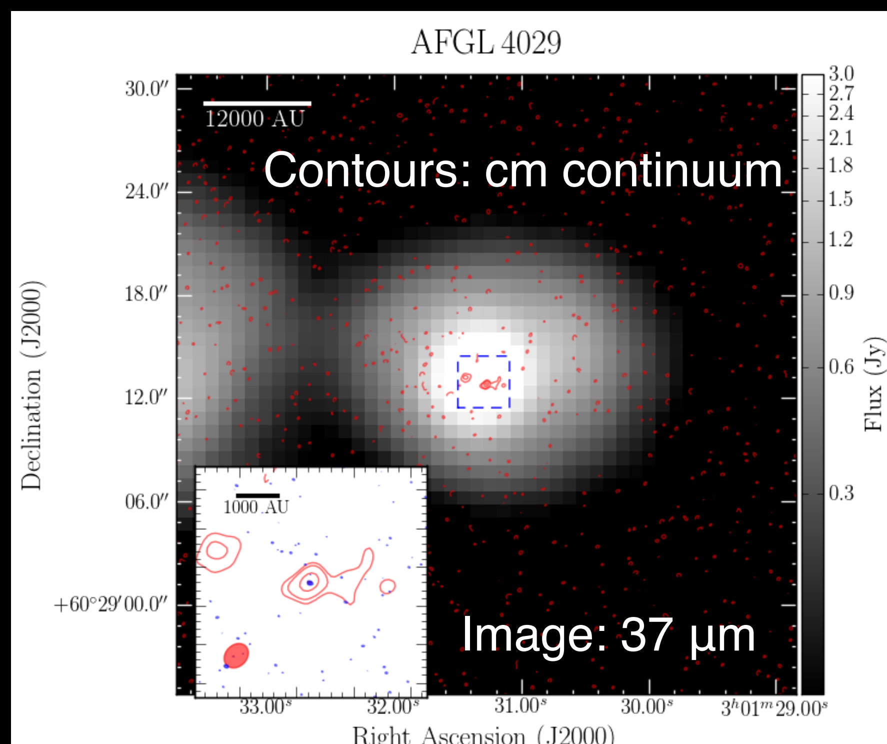
Very sensitive observations at 1.3 and 6 cm

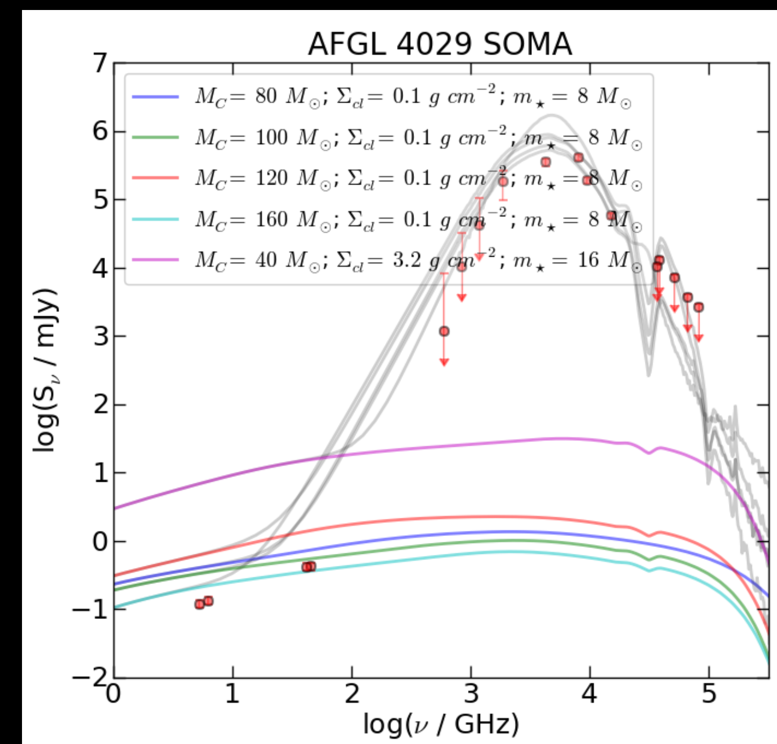
- Radio continuum fluxes to constrain the ionizing luminosity of the source
- Precise location of the protostar
- Nature: ionized jet vs HII region?
- Multiplicity

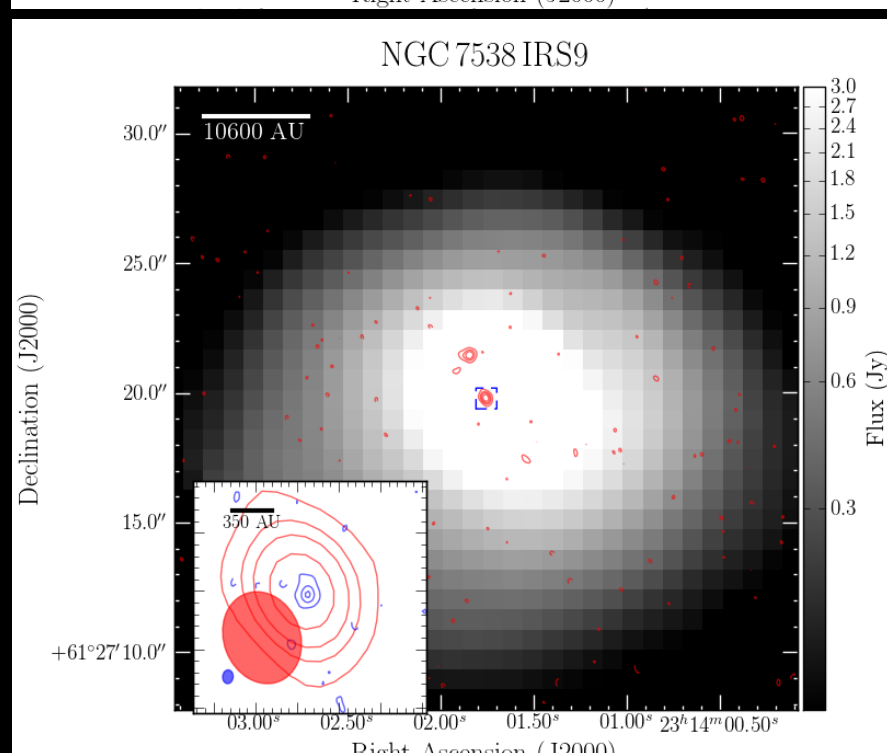
Preliminary Results

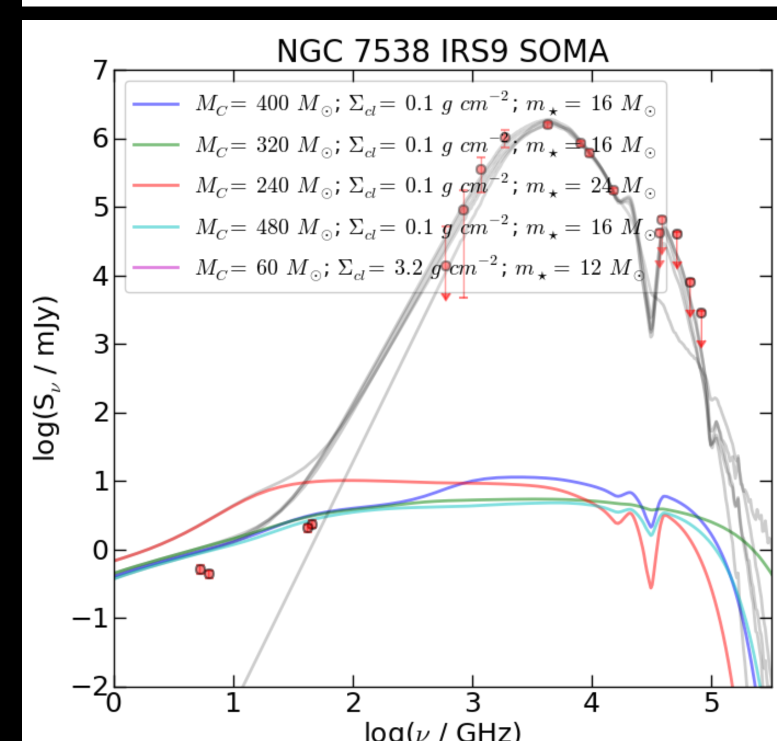
Radio continuum is highly effective at breaking degeneracies encountered in the IR only analysis

Color lines: Predicted free-free component from Tanaka, Zhang and Tan 2016









Gray lines: Five best fits to the Zhang & Tan models

Rosero et al. in prep

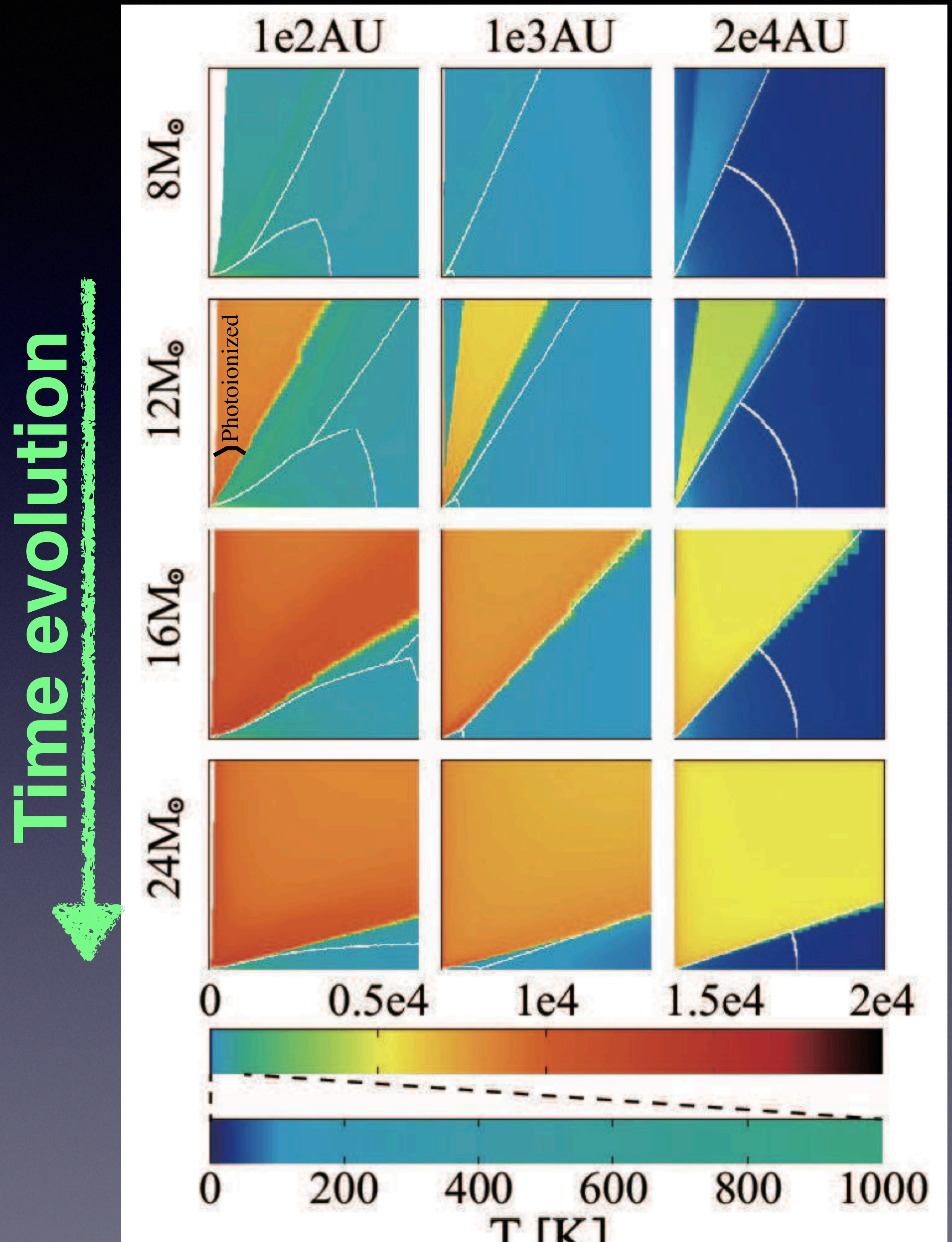
ALMA Follow-up: observations

- 10 CMC-IR and HMCs
- Average distance ~ 5 kpc
- $L_{bol} \sim 800 - 6 \times 10^4\ L_{\odot}$
- Cycle 3 at Band 3 (PI: Rosero)
- SiO (2-1), HCO^+, $H^{13}CO^+$(1-0), HCN, CS, $H^{13}CN$…
- Cycle 5 (PI: Rosero; time granted for 8 SOMA sources)

Credit: ALMA (ESO, NAOJ, NRAO)

Goal: Outflow Structure and Evolution

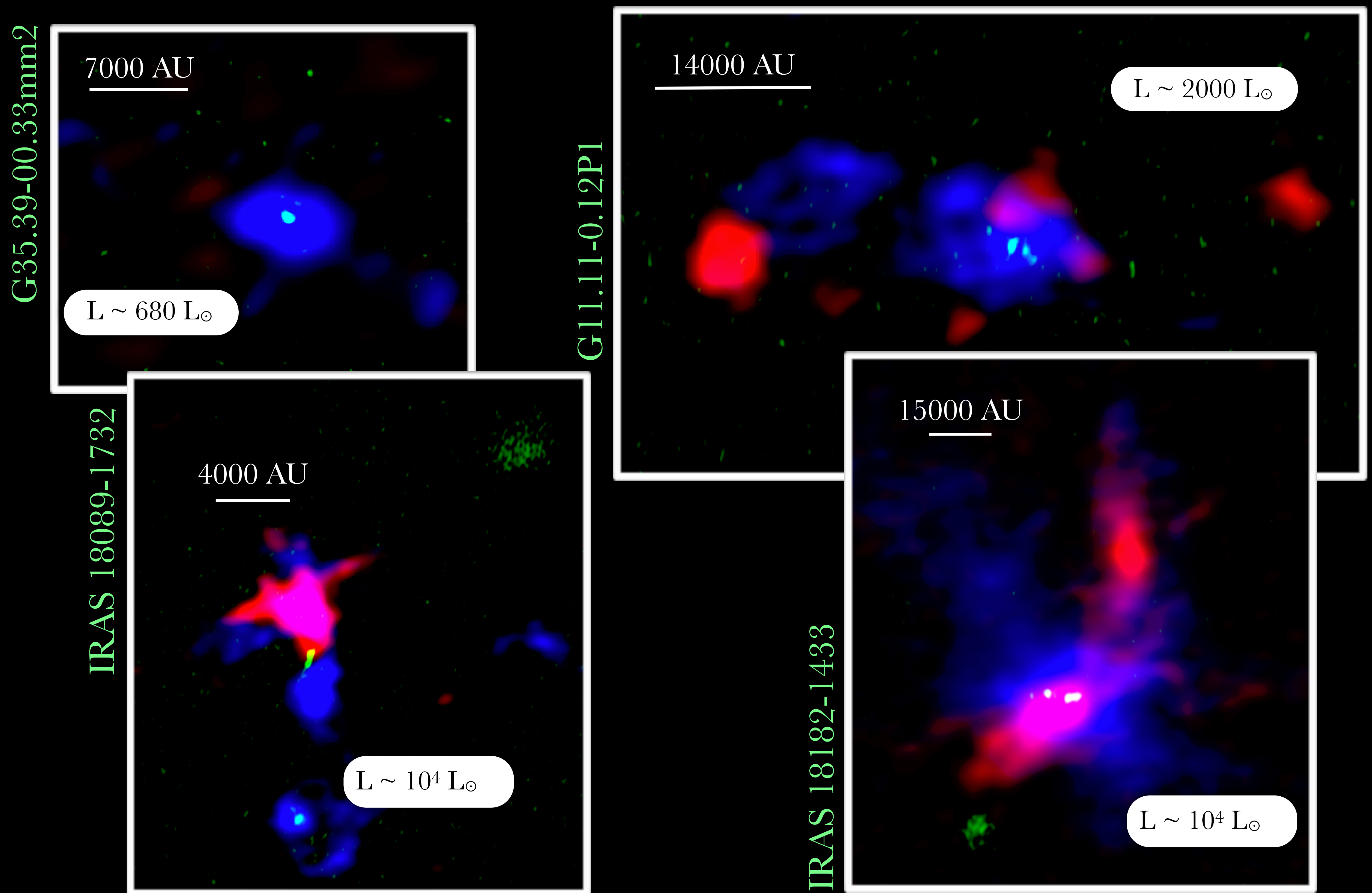
- Connection between ionized (~10^3-10^4 au) and molecular (>10^4 au) components of the flow
- **Evolution**: Outflow characteristics (e.g., opening angle, momentum rate) changing with time?
- **Properties**: energetics (e.g., $\dot{P}$, $\dot{M}$), spatial and kinematical structure, disentangle proto-clusters, association with ionized jets



Tanaka, Tan & Zhang 2016

ALMA High-Mass Protostar Observations: Molecular Outflows

HCO^+ : entrained (or infall) material, SiO: shocked material, C-band: ionized material



ALMA High-Mass Protostar Observations: Molecular Outflows

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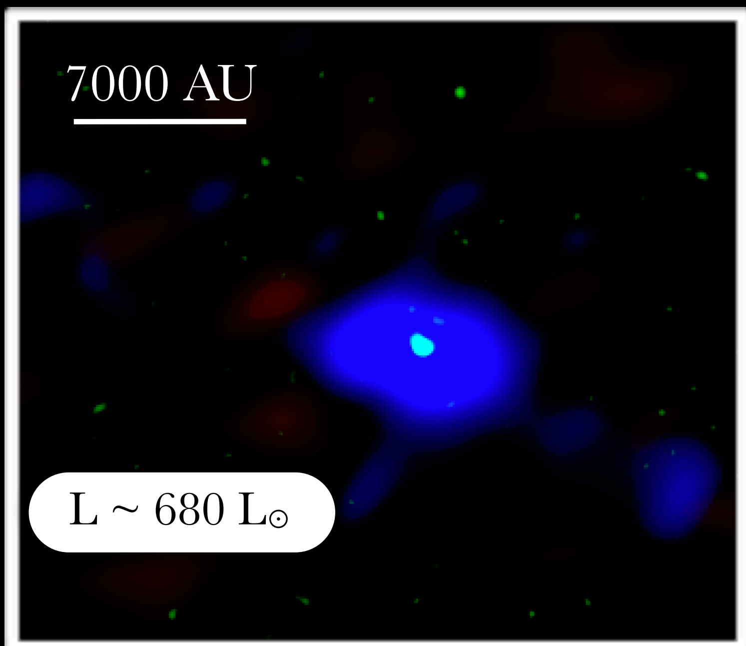

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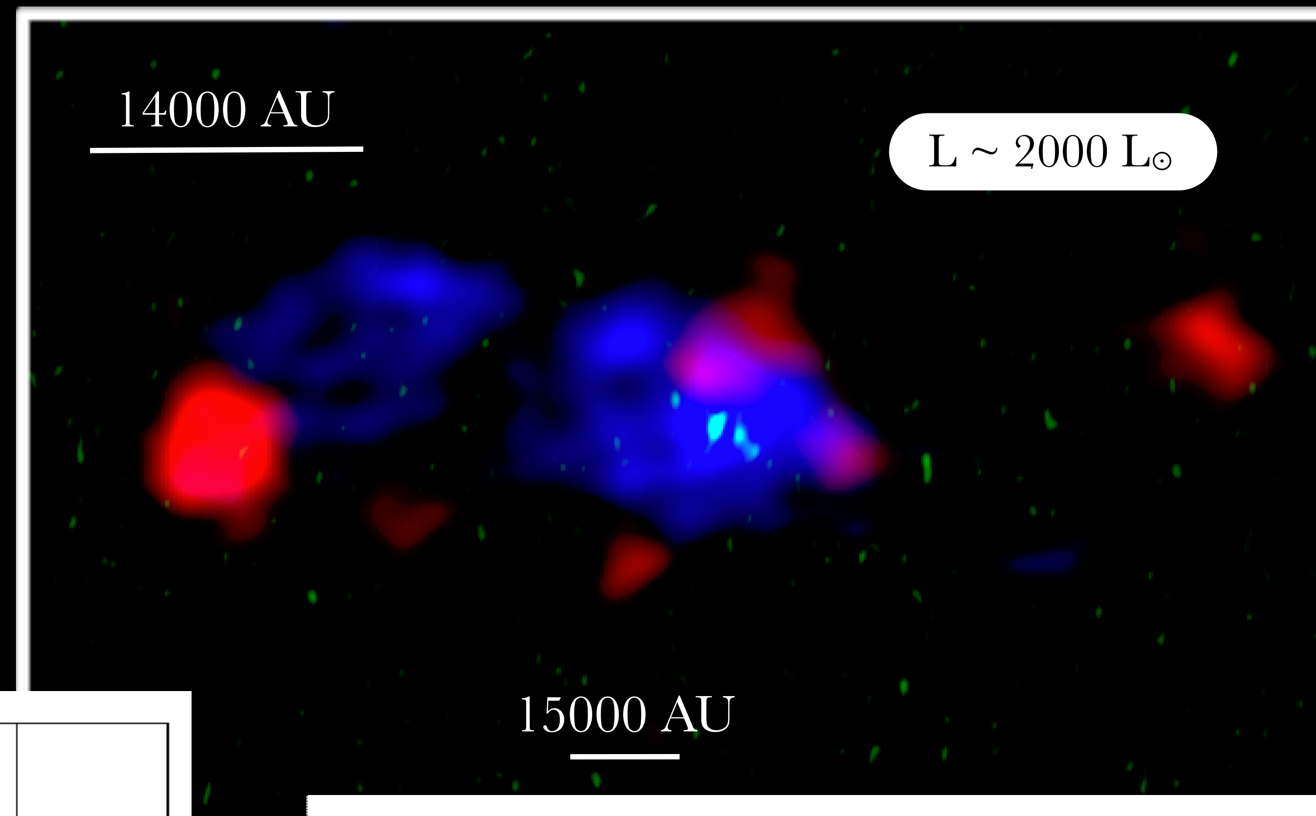
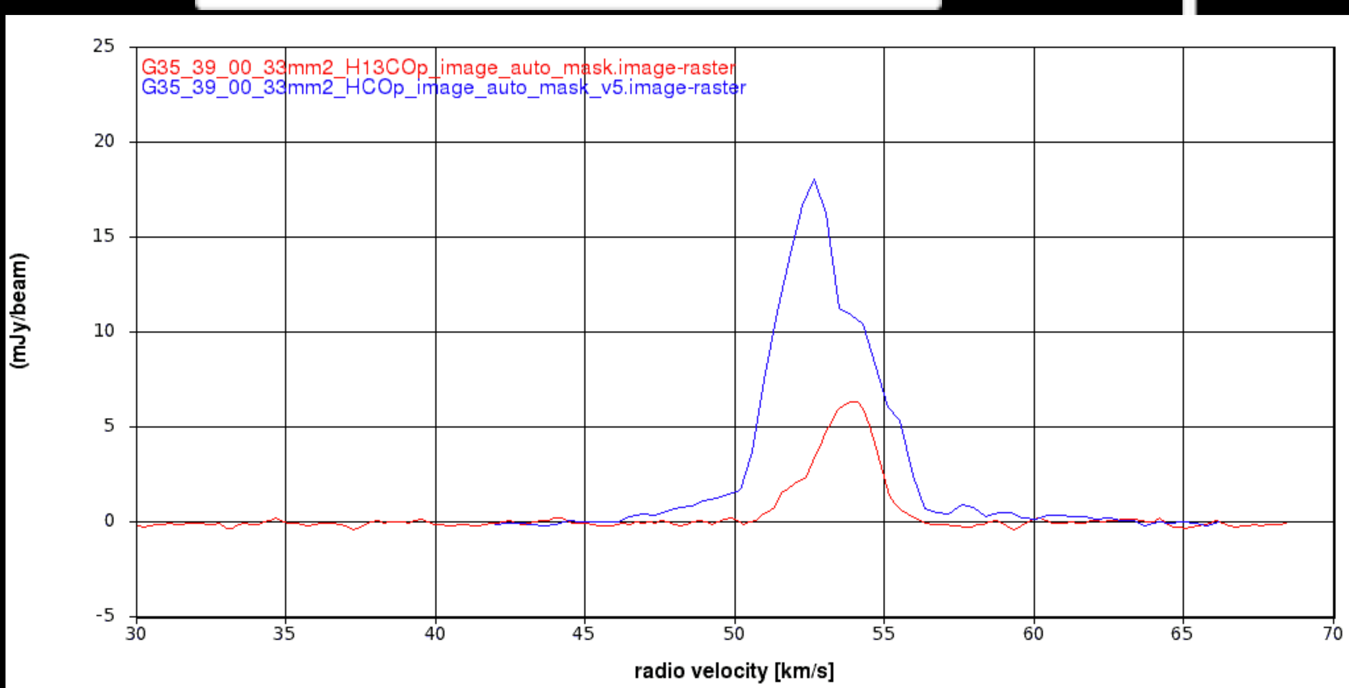
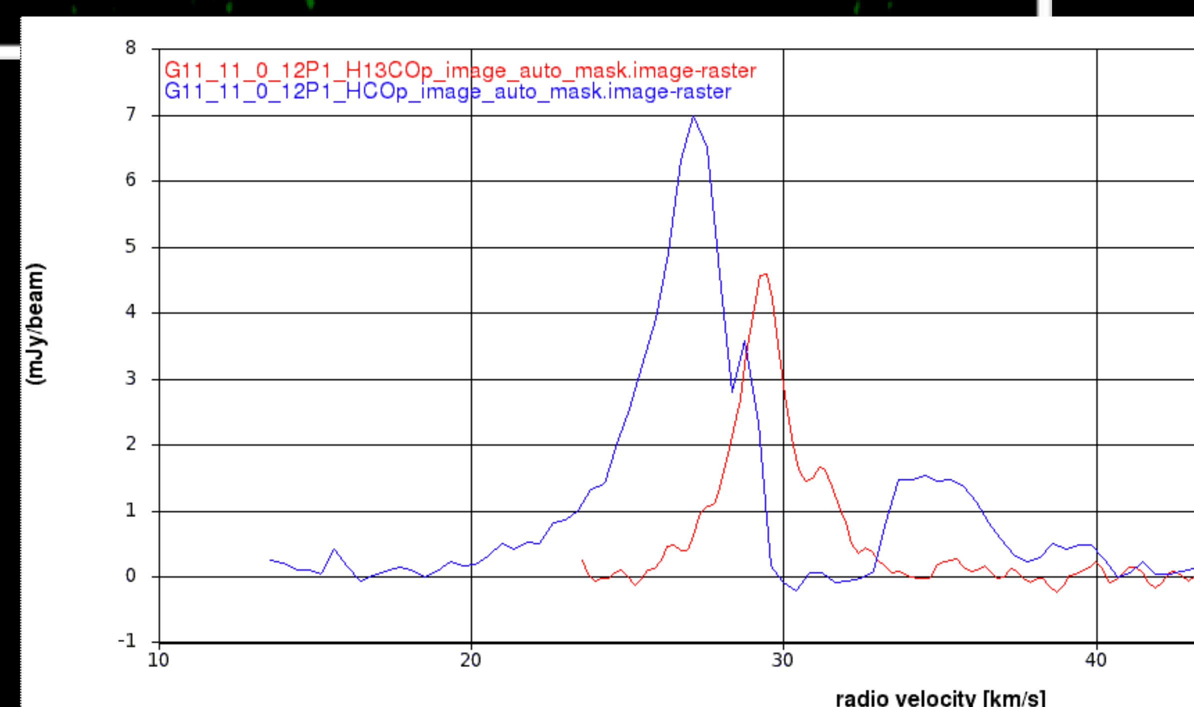
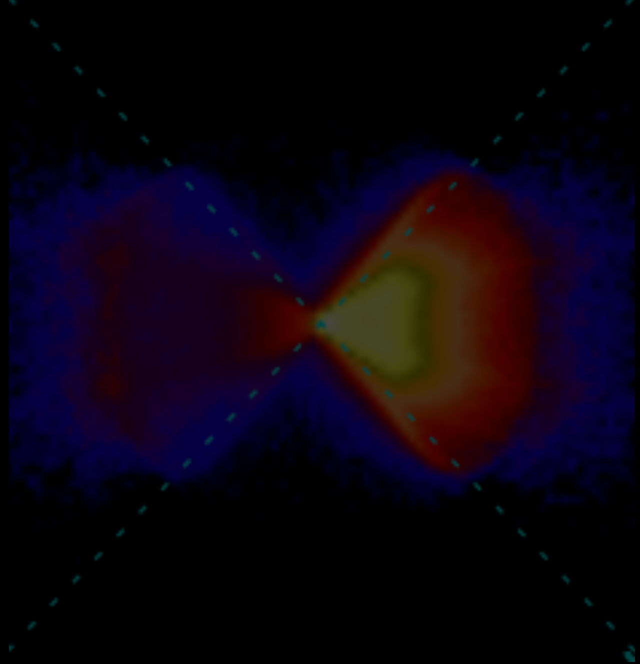


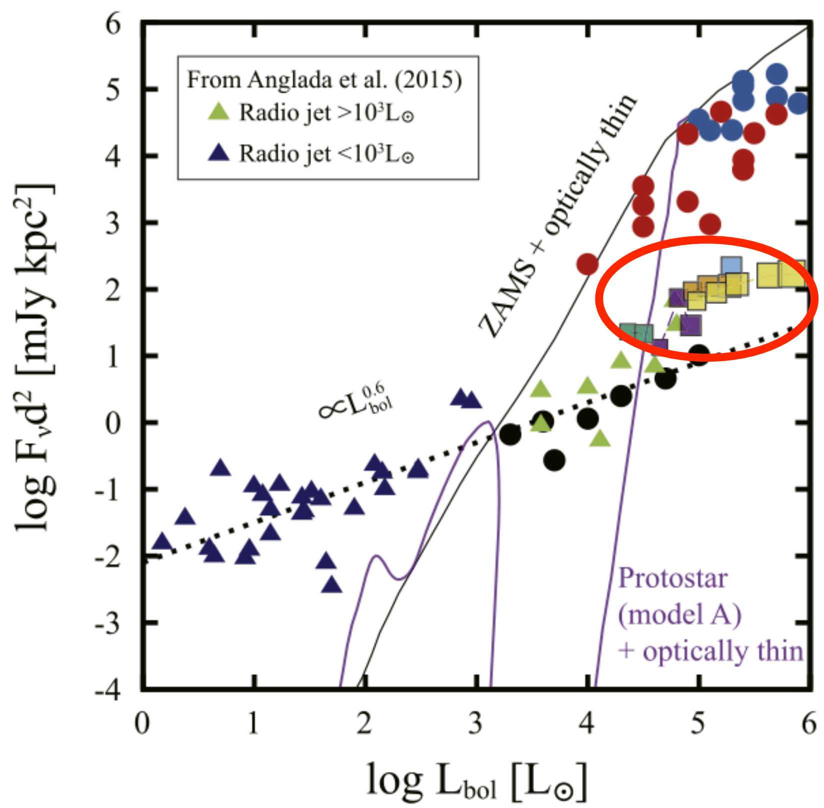


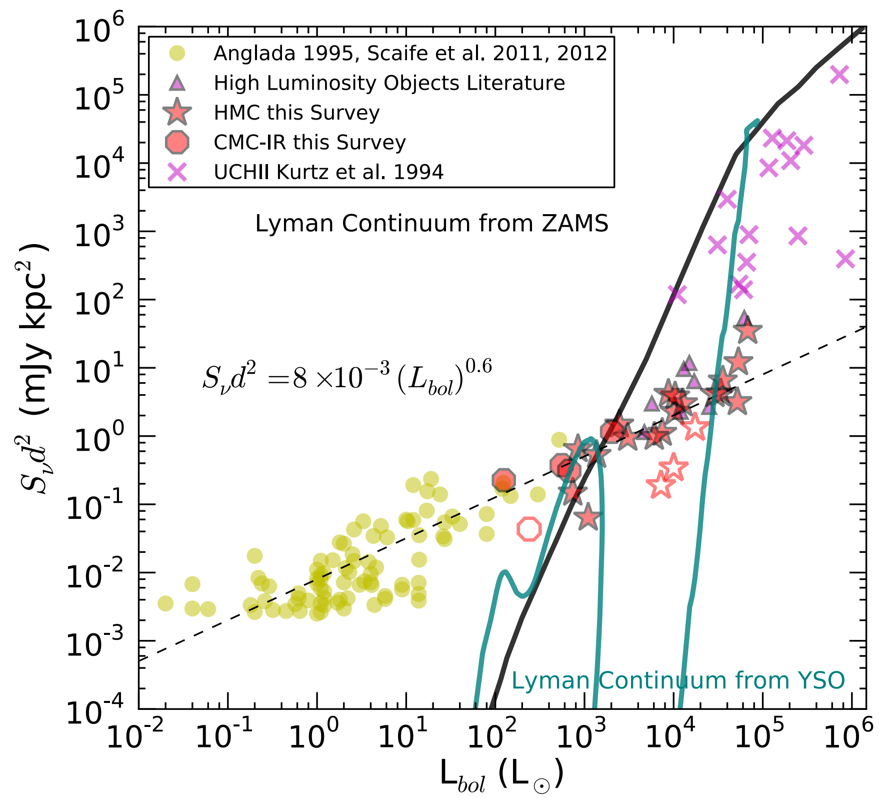


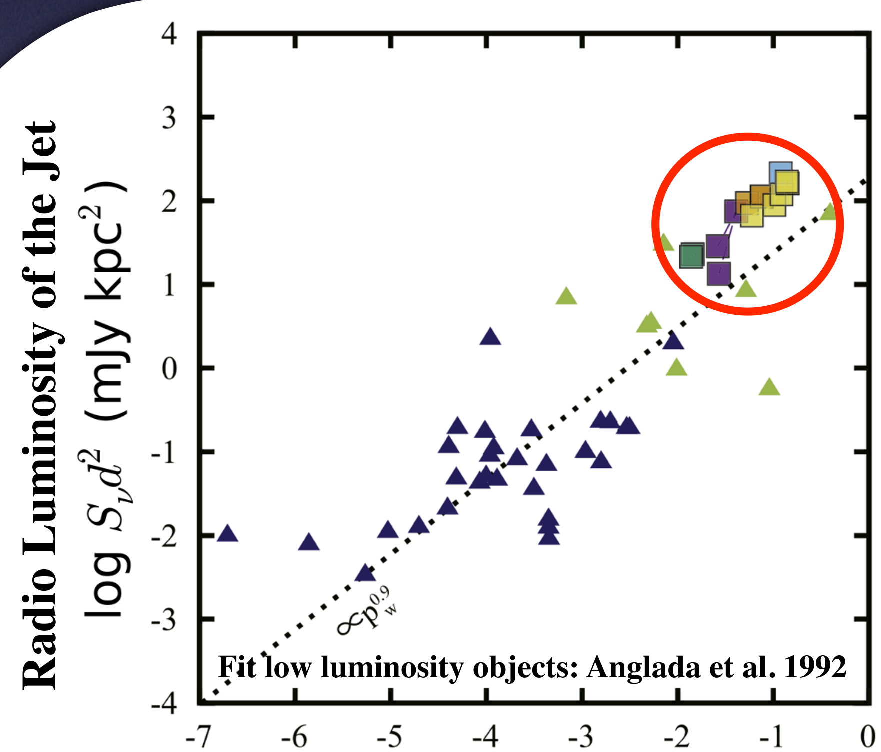


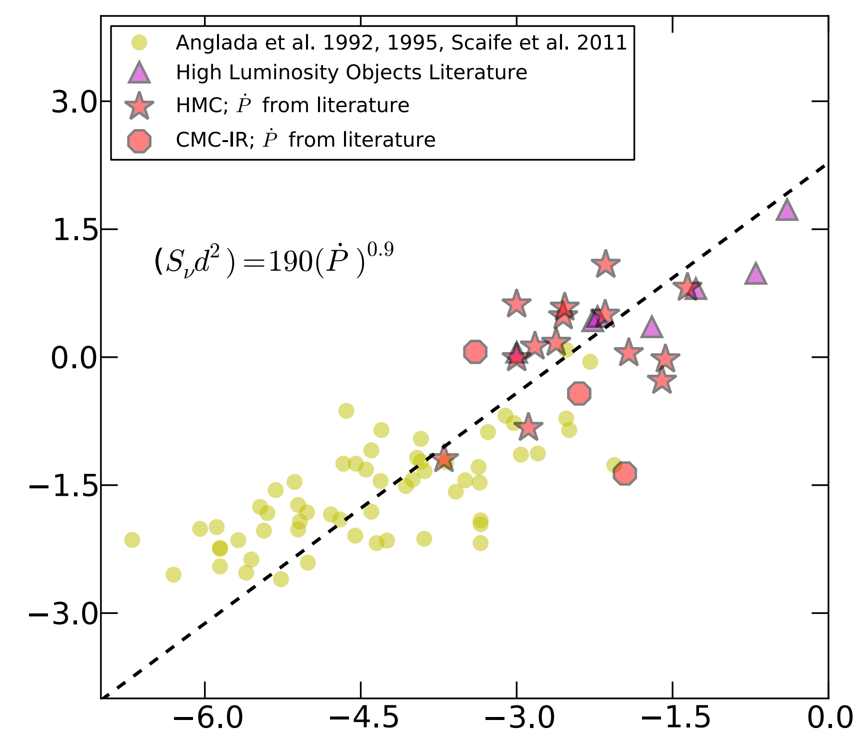
Summary

- Large sample (~ 70 sources) of high and intermediate mass stars
- Outflow cavities shape MIR to FIR morphology and SED
- Comprehensive comparison with theoretical models
- Fitting of IR SED alone has significant degeneracies
- Radio continuum is highly effective at breaking degeneracies
- Kinematic information is important to advance this study









log $\dot{P}$ (M⊙yr^{-1} km s^{-1})

Momentum Rate of the Outflow

Evolution of protostellar properties with mass

Evolutionary $t_{acc} = \dfrac{m_*}{\dot{m}_*}$

Thermal adjustment $t_{KH} = \dfrac{Gm_*^2}{L_* r_*}$

Timescales

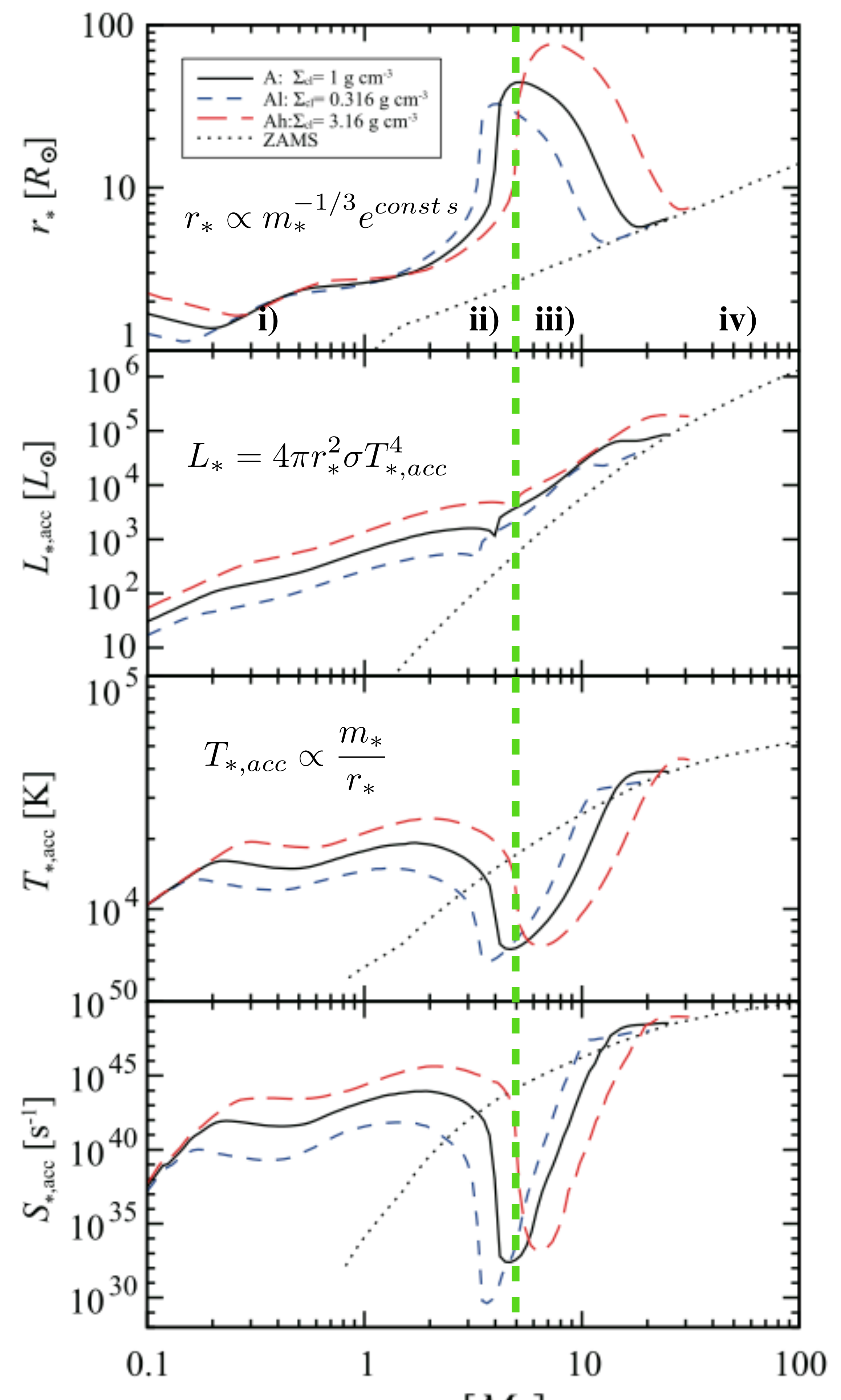
Equations from Hosokawa & Omukai 2009

i) $t_{acc} < t_{KH}$: star accreting

ii) $t_{acc} \approx t_{KH}$: star swelling

iii) $t_{acc} > t_{KH}$: star contracts

iv) ZAMS: central T increases



Tanaka et al. 2016

ALMA + VLA High-Mass Protostar Observations: molecular outflows, ionized jets, masers, hint for disks?