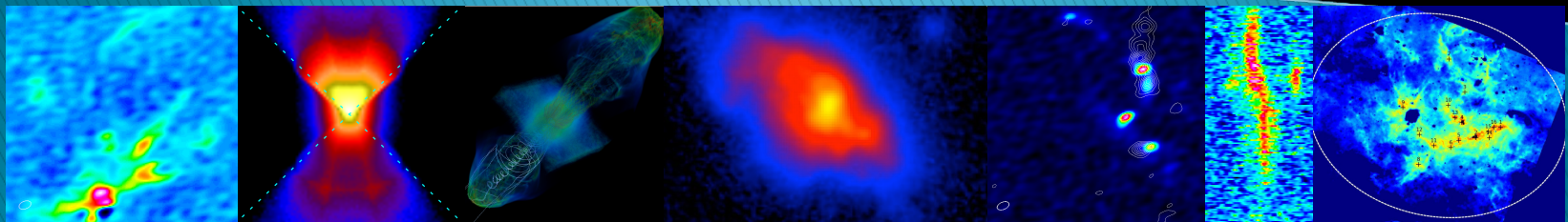


SiO Outflows as Tracers of Massive Star Formation in Infrared Dark Clouds

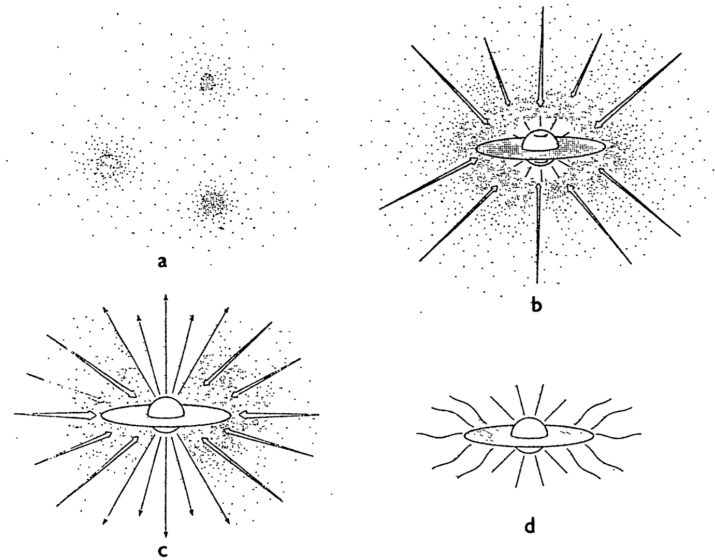
Mengyao Liu, Jonathan C. Tan, Shuo Kong

ISMS, June 20th, 2017



Massive Star Formation

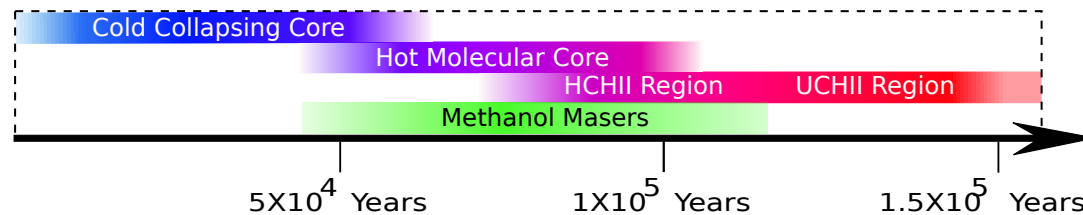
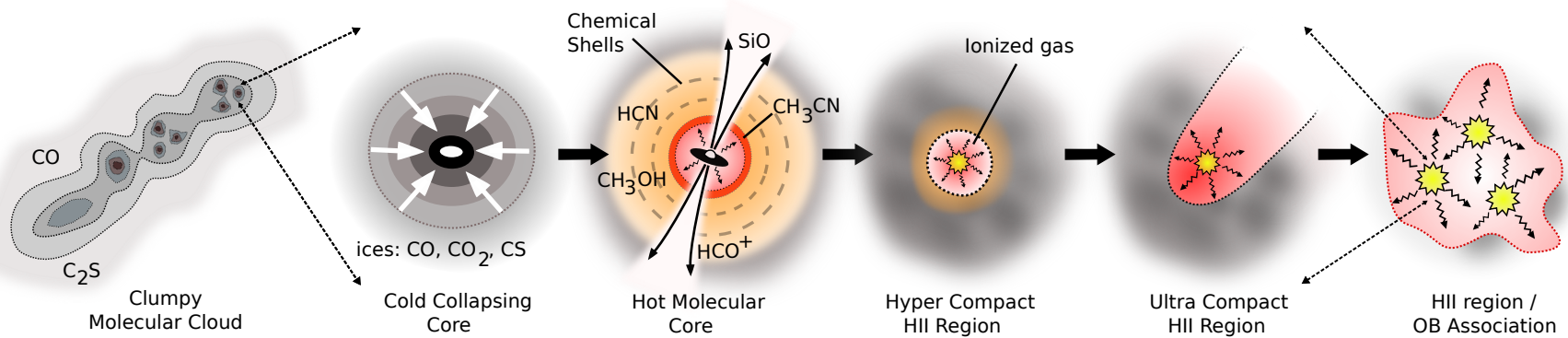
- ▶ “Standard” model of isolated low-mass star formation



(Shu+ 1987)

- ▶ Massive Star Formation??
 - Difficulty in observation
 - Turbulent Core Accretion vs. Competitive Accretion vs. Protostellar Collision

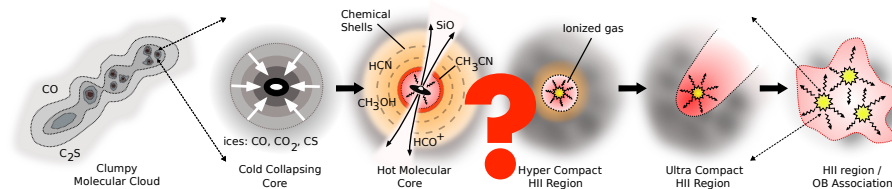
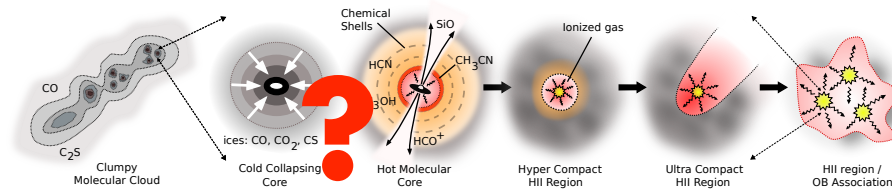
Evolutionary Sequence for Massive Star Formation



(Credit: Cormac Purcell)

Outline

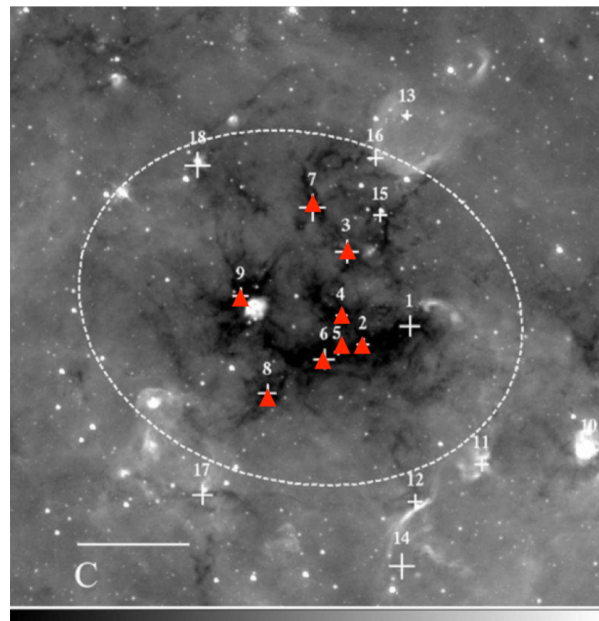
- ▶ Pre-stellar Cores — N_2D^+
- ▶ Early-stage Protostars — SiO
 - SiO detection
 - SiO and 1.3mm continuum
 - SiO and infrared emission
- ▶ Later-stage Protostars — MIR, FIR



A Hunt for Massive Starless Cores

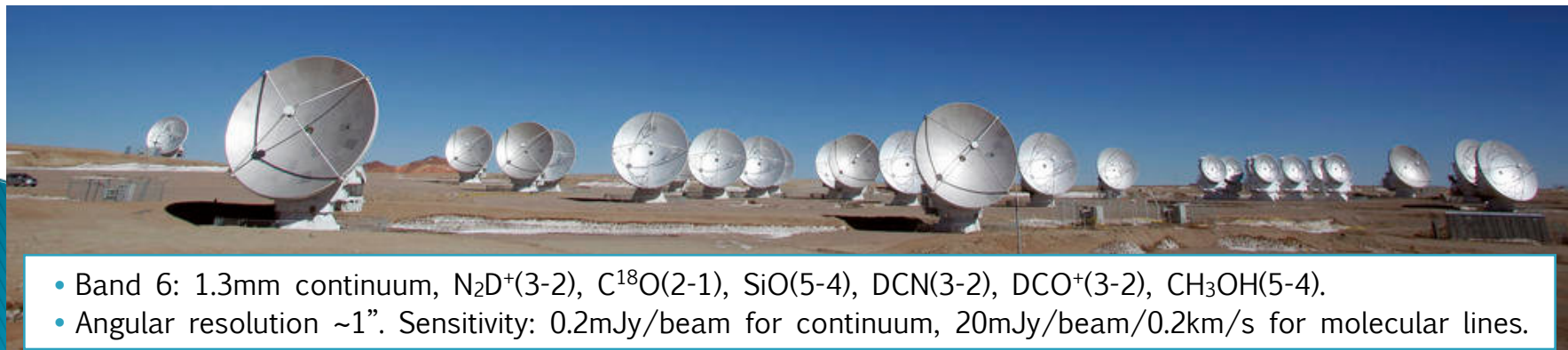
- ▶ 30 clumps in 7 **Infrared Dark Clouds (IRDCs)** (2.4-5.7 kpc)
- ▶ Over 100 N_2D^+ cores identified as **pre-stellar** candidates (Kong+ 2017)
- ▶ SiO outflows as a tracer of **protostars** (Liu+ in prep.)

IRDC-C Spitzer $8\mu\text{m}$



(Butler & Tan 2009)

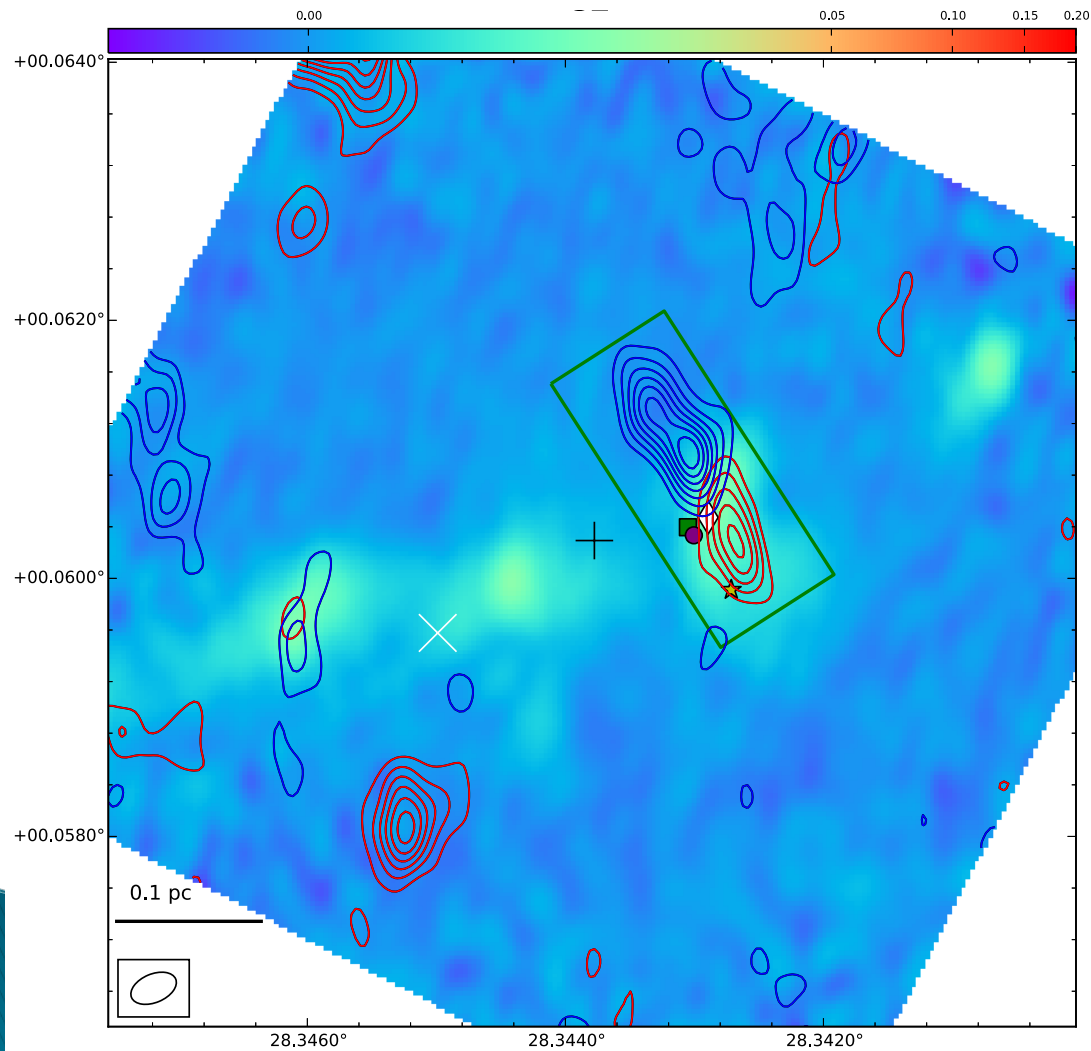
ALMA Cycle 2



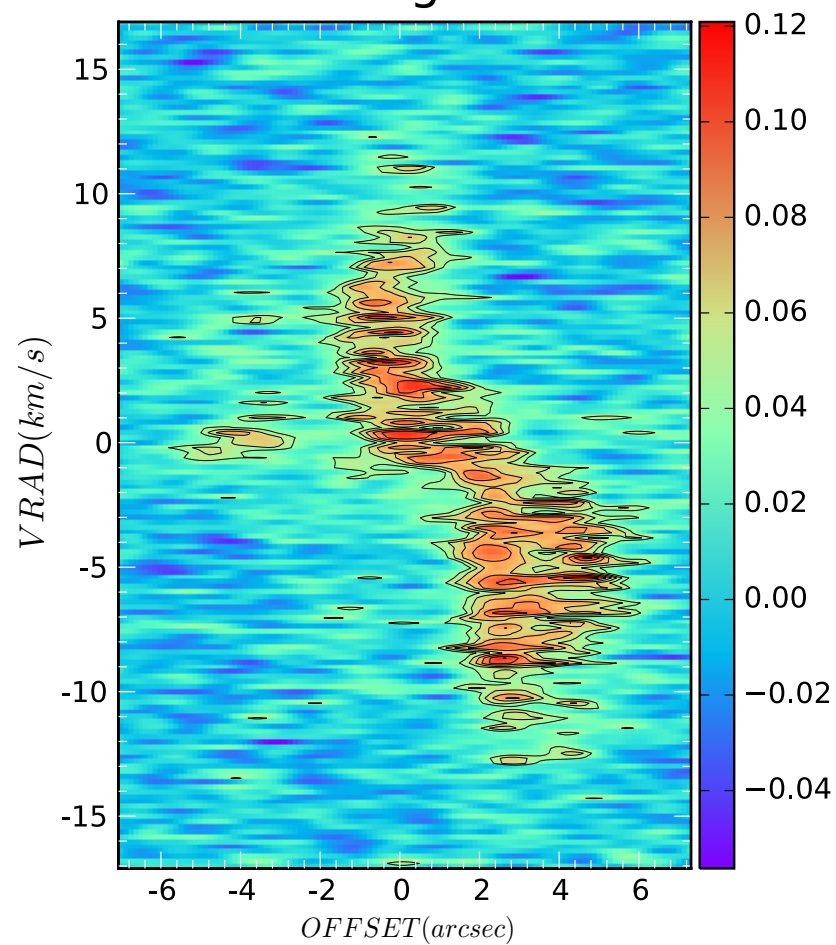
- Band 6: 1.3mm continuum, $\text{N}_2\text{D}^+(3-2)$, $\text{C}^{18}\text{O}(2-1)$, $\text{SiO}(5-4)$, $\text{DCN}(3-2)$, $\text{DCO}^+(3-2)$, $\text{CH}_3\text{OH}(5-4)$.
- Angular resolution $\sim 1''$. Sensitivity: 0.2mJy/beam for continuum, 20mJy/beam/0.2km/s for molecular lines.

C2

SiO(5-4) over 1.3mm continuum

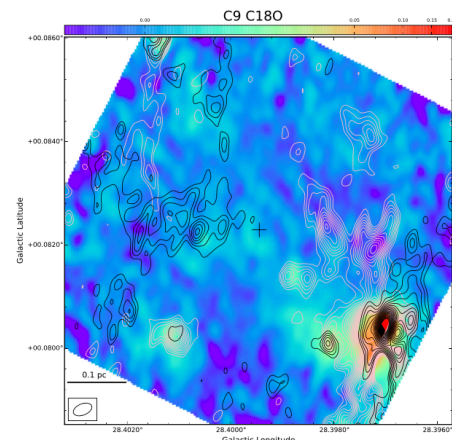
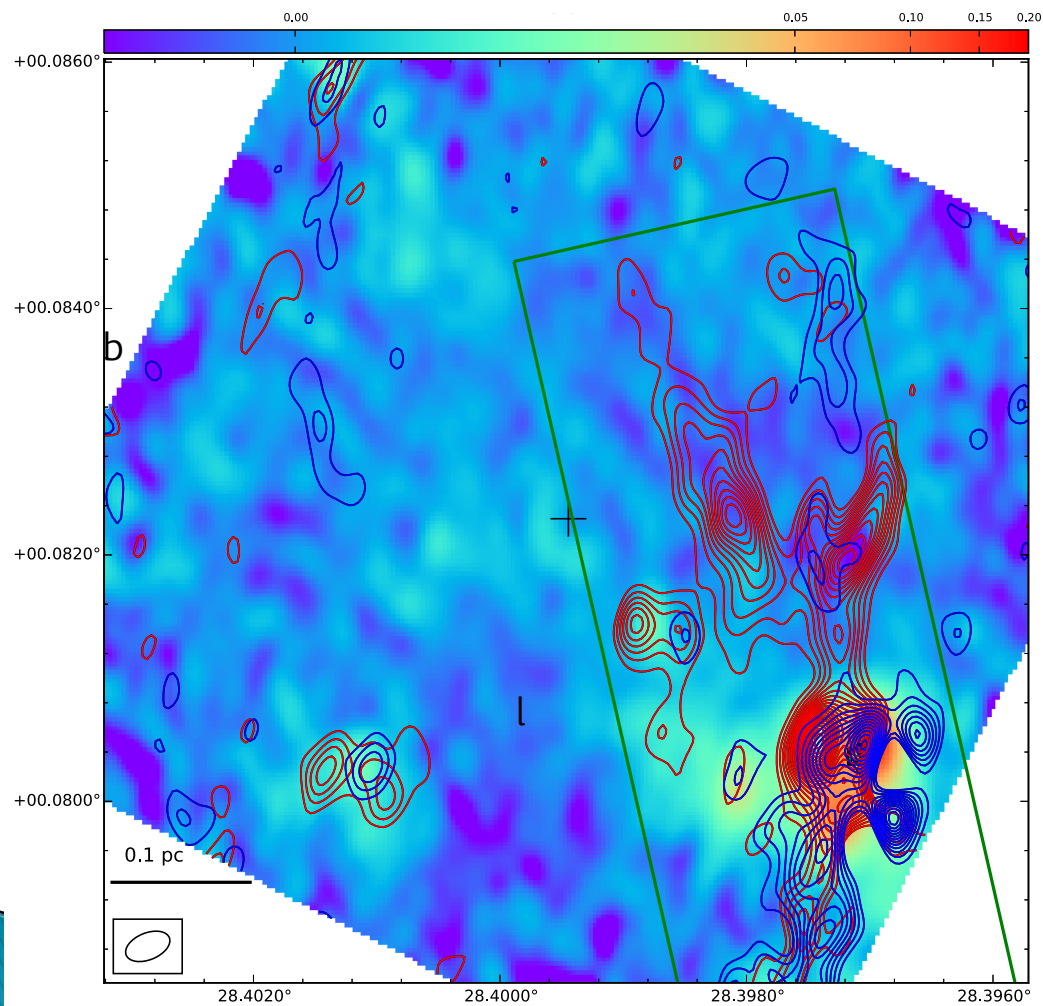


PV Diagram

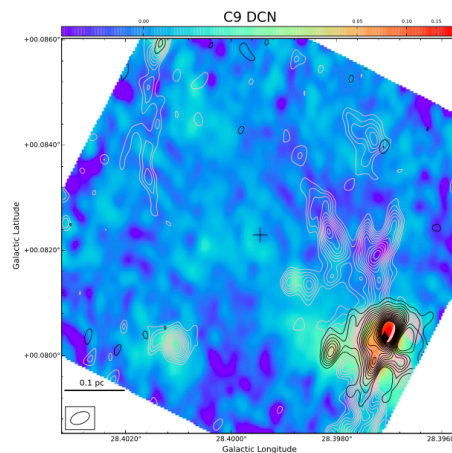


C9

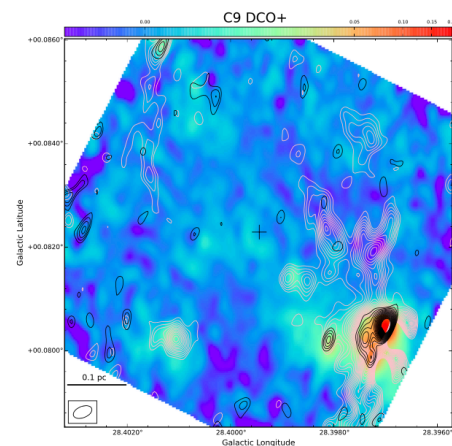
SiO(5-4) over 1.3mm continuum



C^{18}O



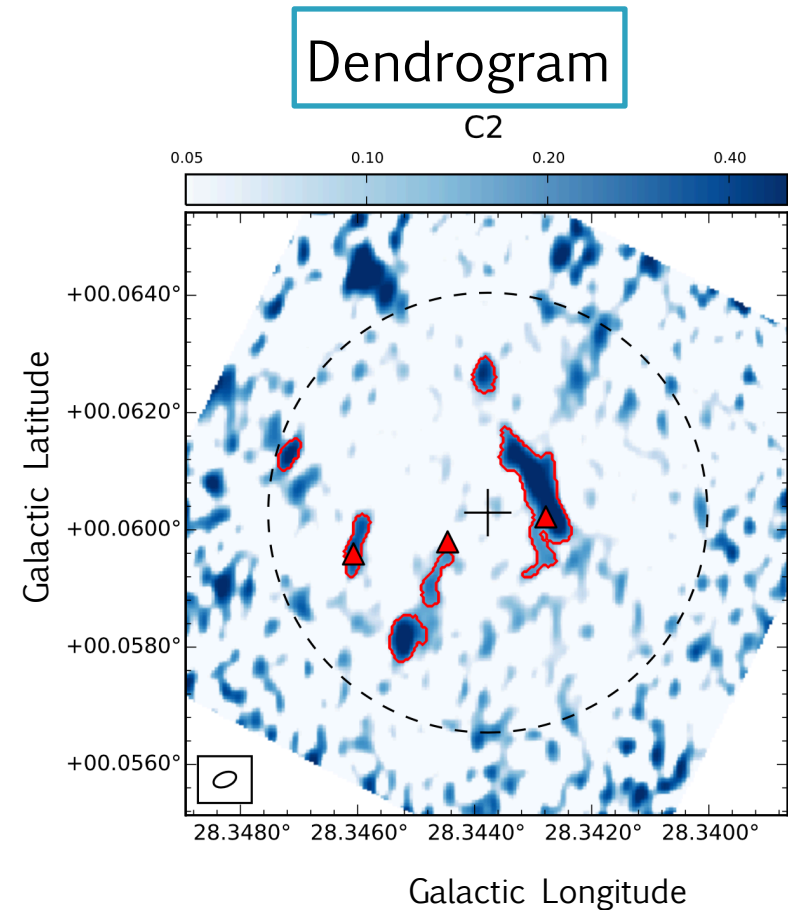
DCN



DCO^+

SiO Detection

- ▶ Detected SiO emission in 20 out of the 30 clumps.
- ▶ Detection rate: 67%
 - 95% López-Sepulcre et al. 2011 for IR-dark clumps
 - 61% Csengeri et al. 2016 for IR-quiet clumps
- ▶ 17 clumps: SiO & continuum & dense gas
- ▶ 6 clumps: SiO stronger than 10σ & continuum & dense gas



SiO and Continuum Cores

- ▶ 17 clumps: SiO & 1.3mm continuum & dense gas
- ▶ 4 high-mass cores (7-370M \odot):
A1, C2, C9, D9
- ▶ 6 intermediate-mass cores (2-15M \odot):
A3, B2, C4, C6, D6, H5
- ▶ But we miss flux...

T for cores: 20 - 50 K

SiO Outflow Properties

► Mid- to early-B type stars

- Mass outflow rates \sim 10^{-5} to a few $\times 10^{-3} M_{\odot}/\text{yr}$
- Momentum rates \sim 10^{-4} to $10^{-2} M_{\odot} \text{ km/s/yr}$

(Arce et al. 2007)

- LTE, optically thin
- T for outflows: 18K
- SiO abundance: $\text{H}_2/\text{SiO} \sim 10^9$

Table 3. Estimated physical parameters for SiO outflows

Source	$M_{\text{out}}^{\text{blue}}$ (M_{\odot})	$L_{\text{flow}}^{\text{blue}}$ (pc)	$t_{\text{dyn}}^{\text{blue}}$ (10^3 yr)	$M_{\text{out}}^{\text{red}}$ (M_{\odot})	$L_{\text{flow}}^{\text{red}}$ (pc)	$t_{\text{dyn}}^{\text{red}}$ (10^3 yr)	M_{out} (M_{\odot})	P_{out} ($M_{\odot} \text{ km s}^{-1}$)	E_{out} (10^{43} erg)	\dot{M}_{out} ($10^{-4} M_{\odot} \text{ yr}^{-1}$)
B1	0.004	0.03	5.23	0.170	0.13	2.42	0.17	1.88	35.41	0.71
B2	0.035	0.08	15.36	0.261	0.15	7.72	0.30	1.01	4.75	0.36
C2	0.147	0.12	8.43	0.063	0.08	4.98	0.21	1.66	15.29	0.30
C6	0.245	0.21	13.47	0.211	0.08	5.28	0.46	4.35	48.16	0.58
C9	0.839	0.20	11.43	1.434	0.39	16.97	2.27	24.39	316.19	1.58
H6	0.002	0.00	0.03	0.030	0.04	1.52	0.03	0.16	1.24	0.78

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(Arce et al. 2007)

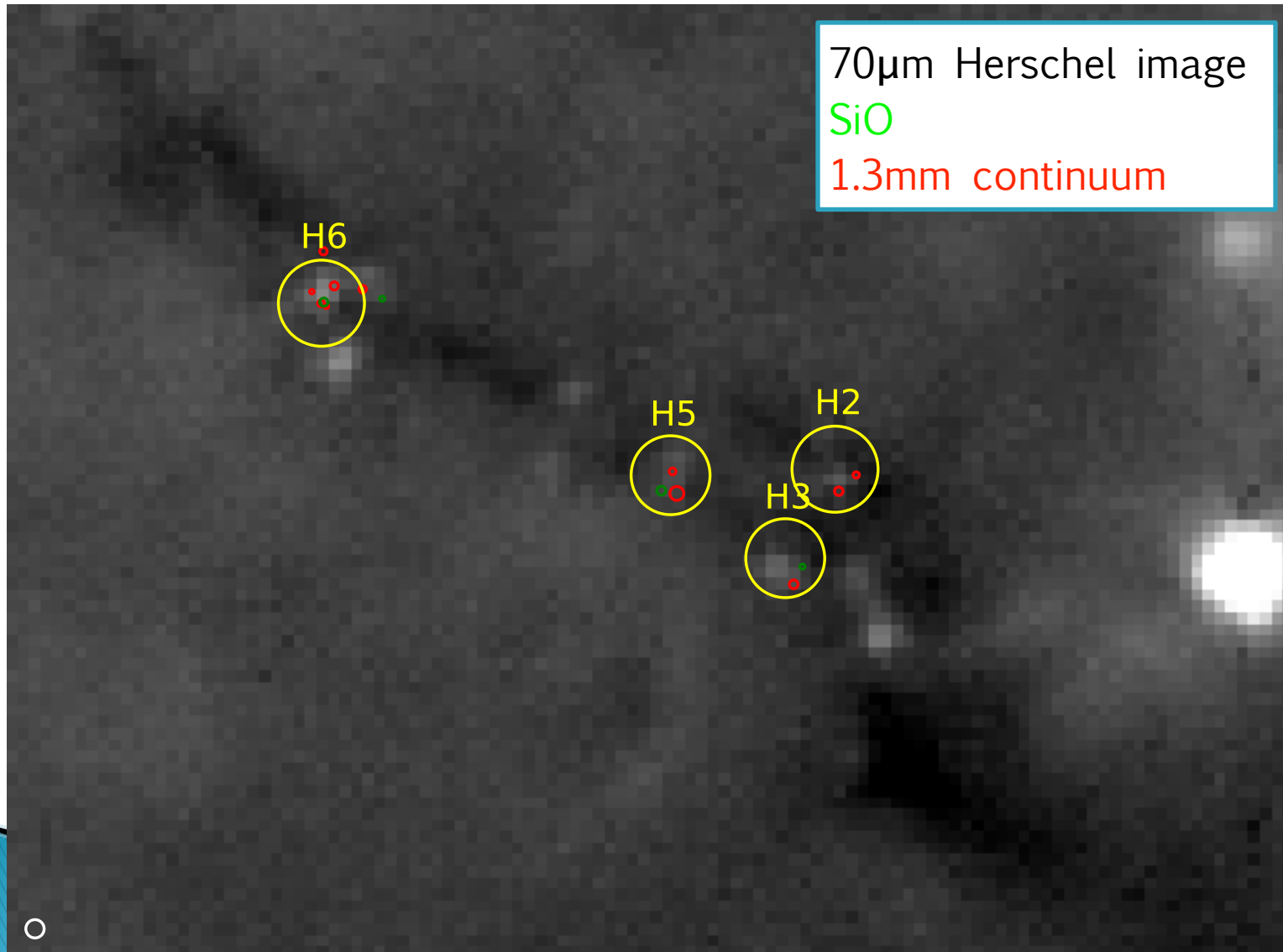
Early-stage or SiO not tracing the full extent

- LTE, optically thin
- T for outflows: 18K
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Infrared Emission



Infrared Emission

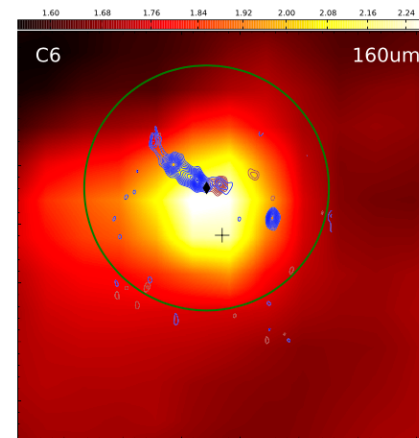
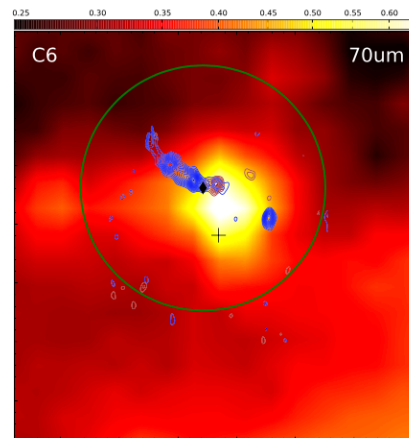
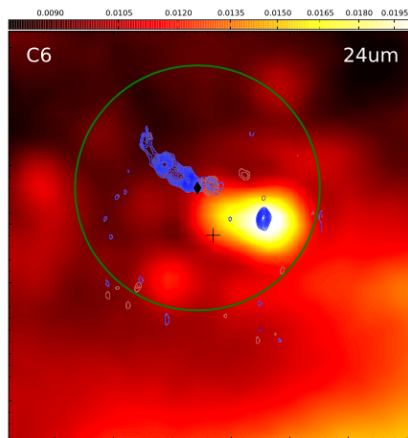
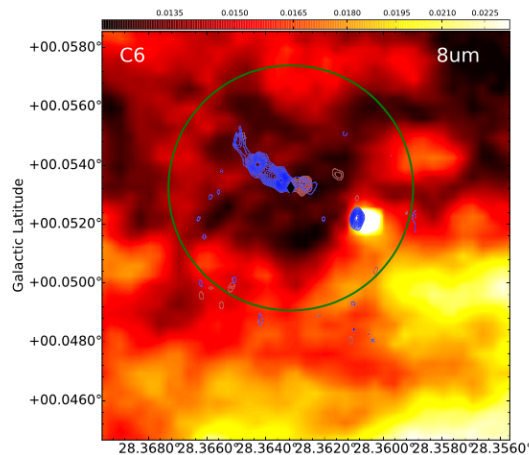
8 μ m

24 μ m

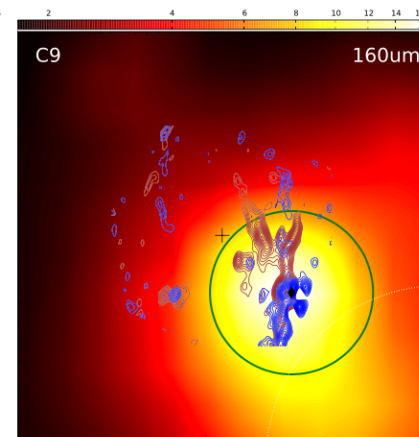
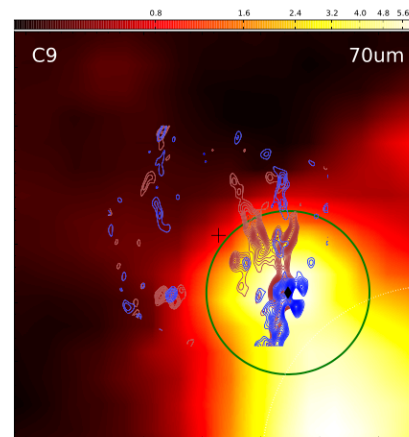
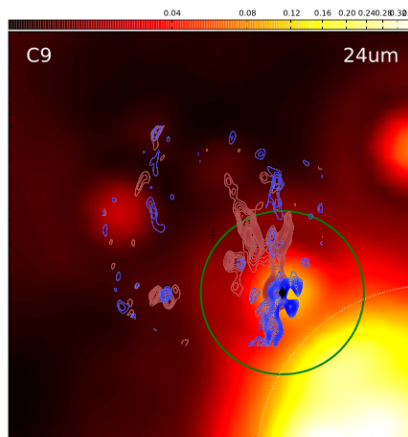
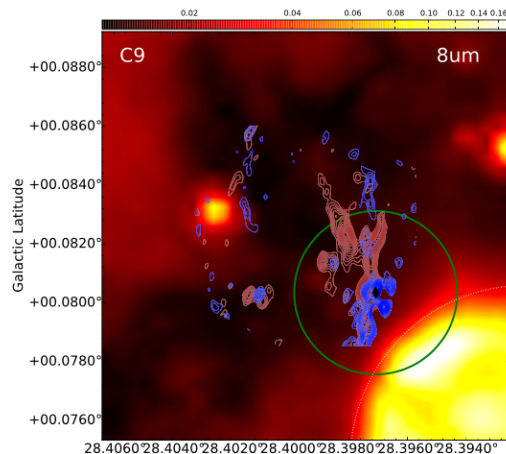
70 μ m

160 μ m

C6

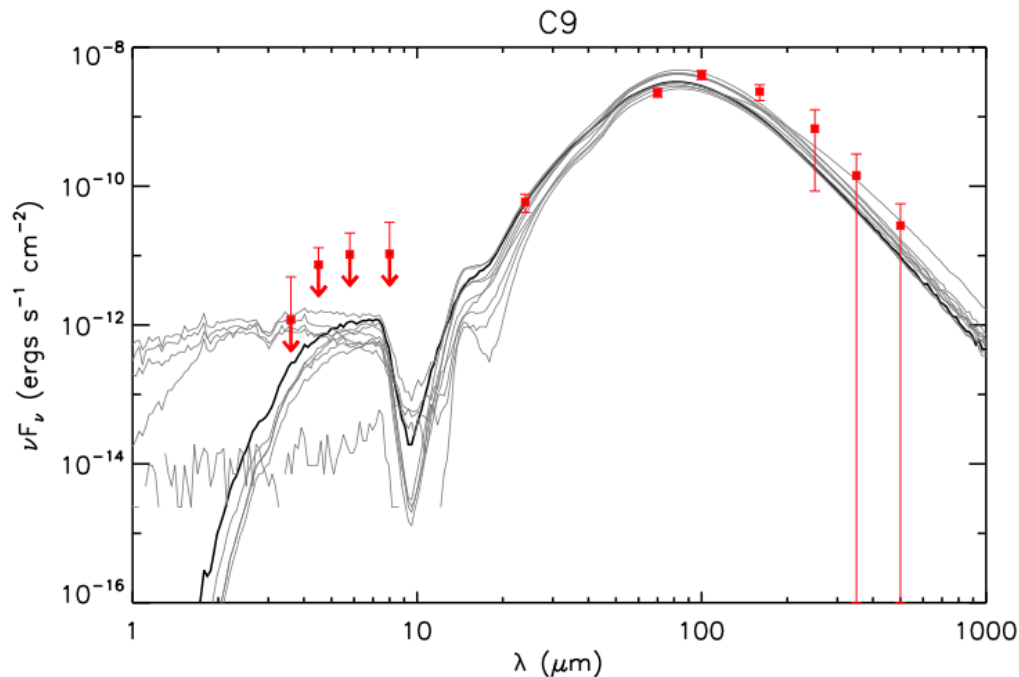


C9



Infrared Emission

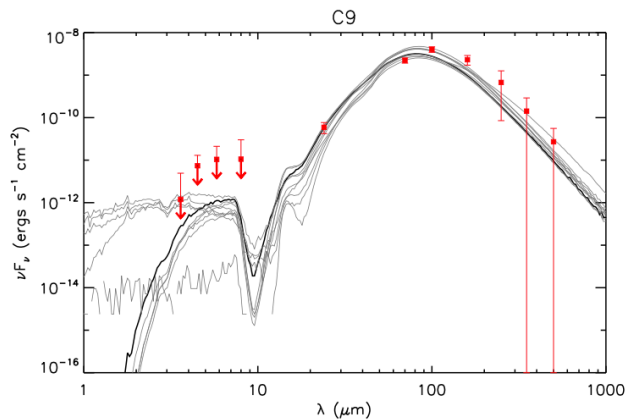
- ▶ Aperture photometry
- ▶ SED fitting
 - Zhang & Tan Radiative Transfer (RT) Models
 - Based on Turbulent Core Accretion Scenario
 - Five free parameters: M_c , Σ_{cl} , m_* , θ_{view} and A_V



Infrared Emission

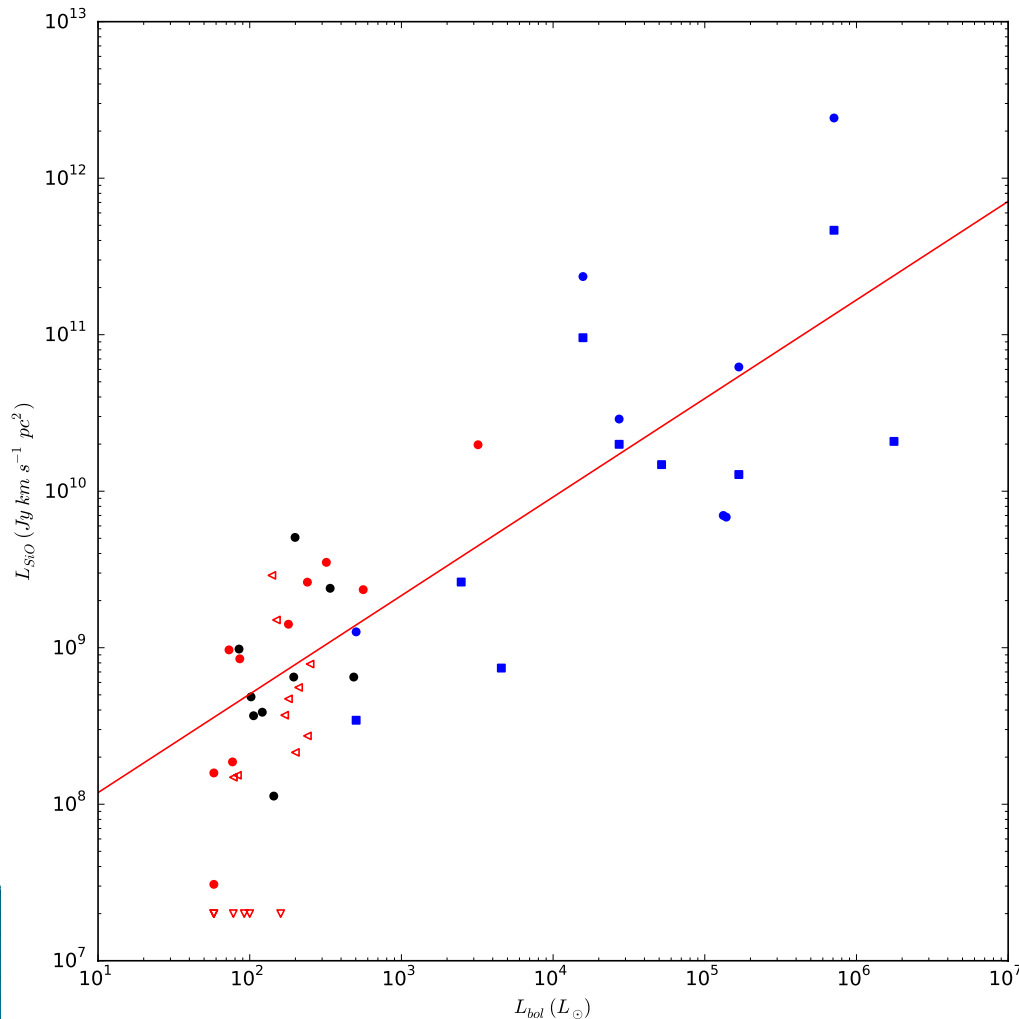
- ▶ Aperture photometry
- ▶ SED fitting

- Luminosity $\sim 10^1\text{-}10^3 L_{\odot}$, C9 $< 5 \times 10^3 L_{\odot}$
- Returned protostellar mass $\sim 0.5\text{-}4 M_{\odot}$



- ☒ Lack of MIR emission
 - ☒ Low luminosity
 - ☒ Low current stellar mass
- > Early Stage

L_{SiO} vs. L_{bol}



- ▶ L_{SiO} tend to be proportional to L_{bol} in a large L_{bol} span
- More powerful shocks?

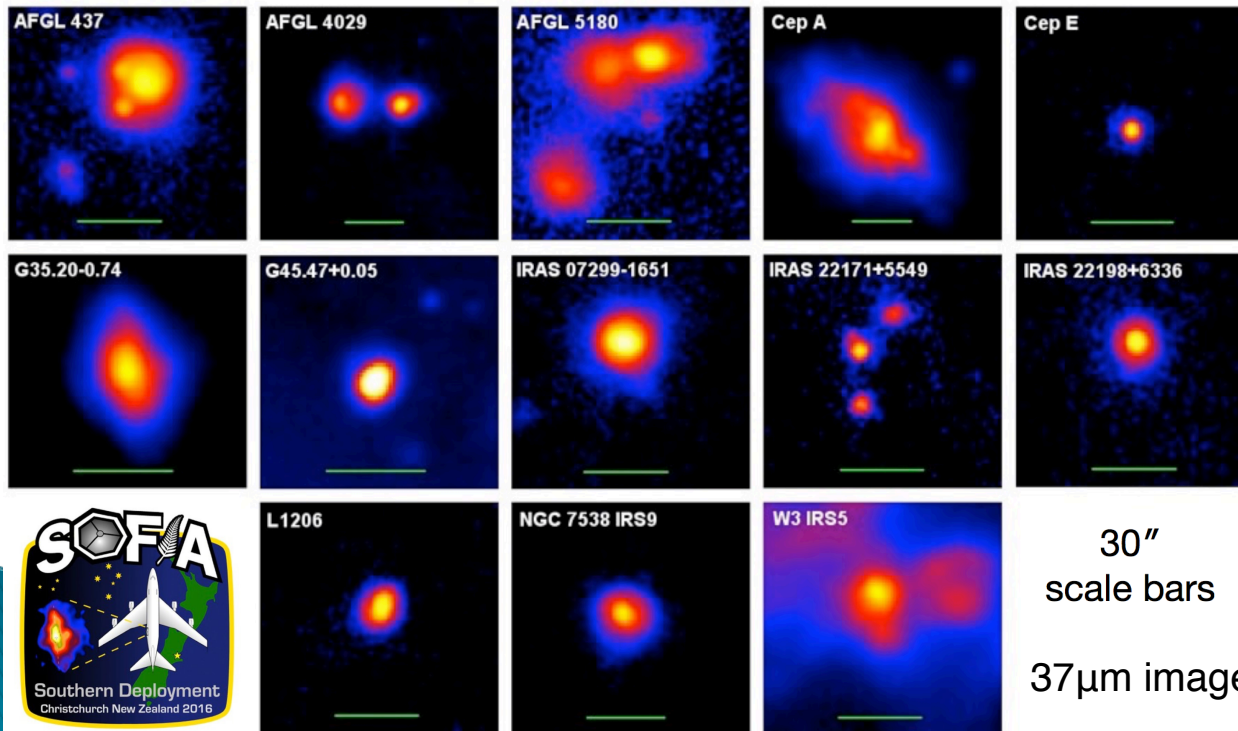
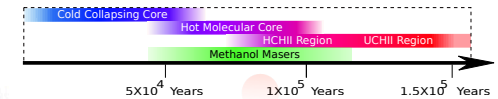
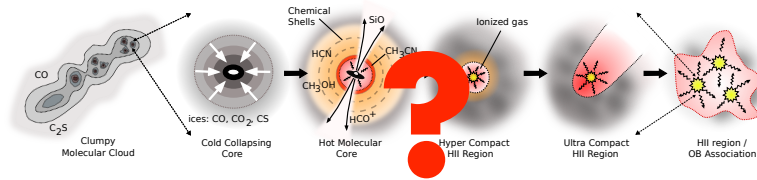
SiO (5-4) data in this paper
SiO (2-1) data from Duarte-Cabral et al. (2014)
SiO (5-4) data from Csengeri et al. (2016)

$$f(x) = 0.63x + 7.44$$

$$\alpha = 0.63 \pm 0.08$$

Later-stage Protostars

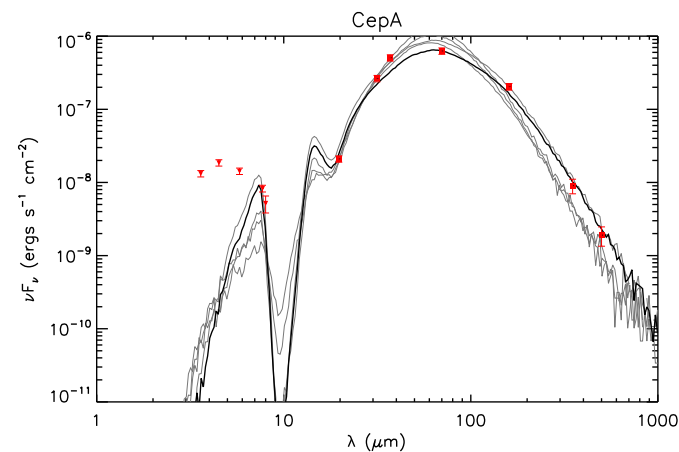
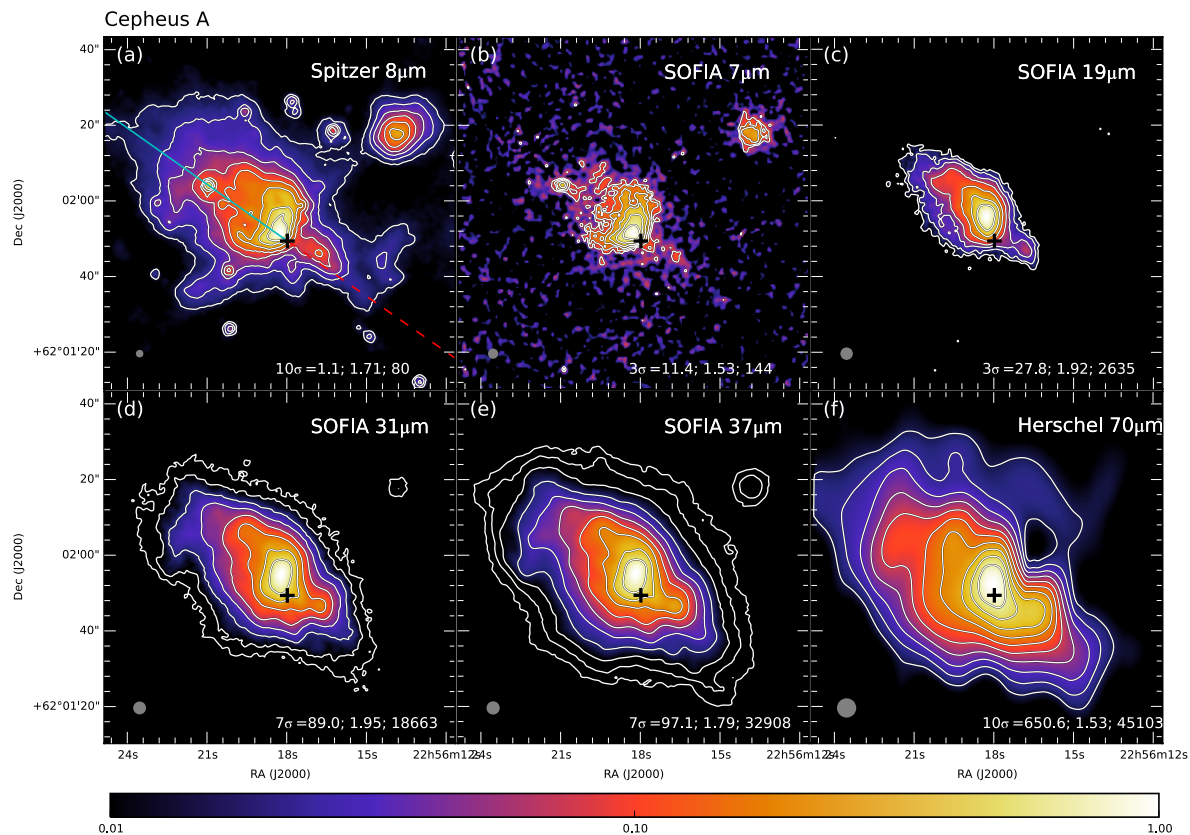
► SOFIA MAssive (SOMA) Star Formation Survey



30"
scale bars
37μm images

- 10 to 40μm images
- 22 protostars observed by the end of Cycle 4



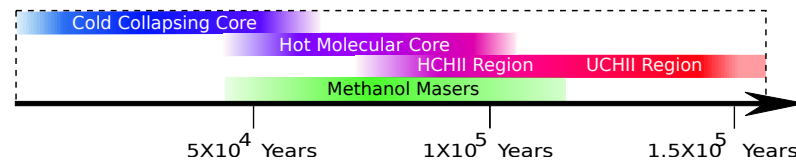
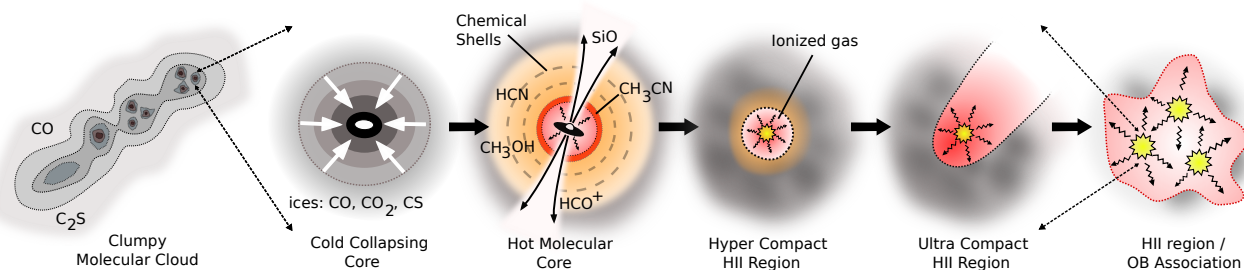
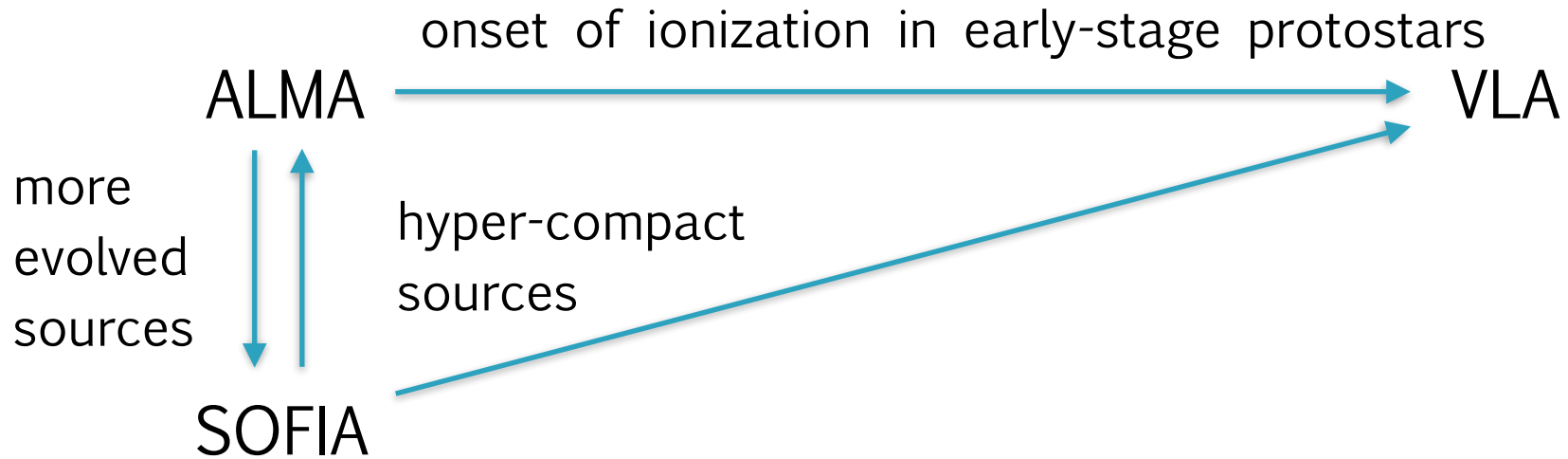


SED fitting with Zhang
& Tan RT models

(De Buizer+ 2017)

- High resolution MIR and FIR images which reveal heated outflow cavities.
- Extended MIR emission that aligns with known outflows
- Brighter on the near-facing, blue-shifted side, more symmetric at longer wavelengths
- SEDs can be well fit by Zhang & Tan RT models and yield key physical parameters

Future Work



(Credit: Cormac Purcell)

Take-away

- ▶ Characterize sources from pre-stellar phase to hyper-compact phase in different high-mass star forming regions with different tracers.
- ▶ SiO outflows seem to be a valid tracer of massive protostars in IRDCs.

Thanks!

