ALMA observations of the FU Orionis-type young eruptive star V346 Nor

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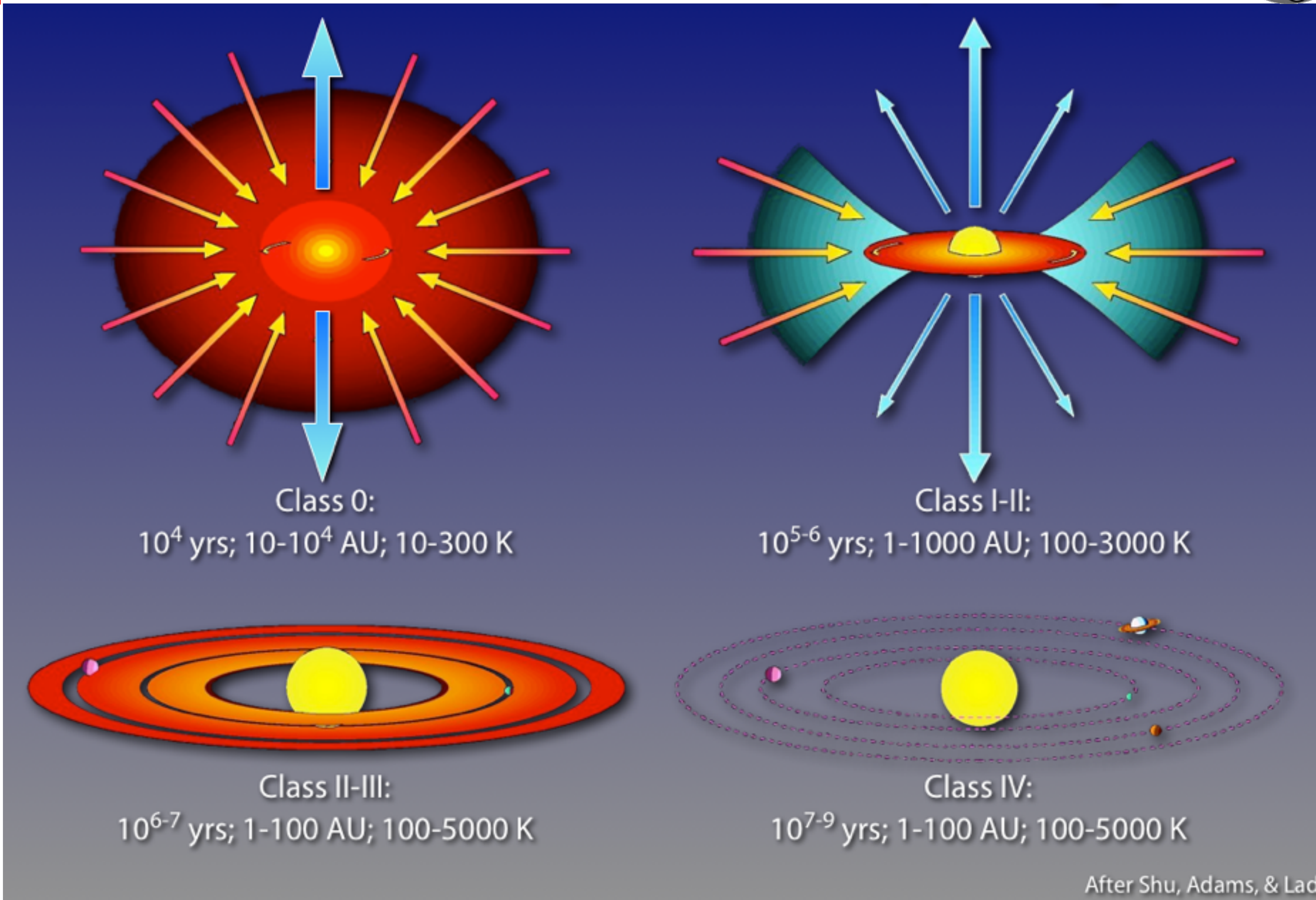
Introduction

- PhD at **Konkoly Observatory** (Budapest, Hungary), 2009
- Half year at the **Spitzer Science Center** (Pasadena, CA), 2006
- Three years at **Leiden Observatory** (The Netherlands), 2008 – 2011
- Three years at the **European Space Agency** (ESA/ESTEC, The Netherlands), 2011 – 2014
- **Tenure track position at Konkoly Observatory** (2014 –)
- Current funding from the **Hungarian Academy of Sciences**: “Dynamics of circumstellar disks – star and planet formation in the ALMA era” (2014 – 2019)
- Furute funding from the **European Research Council**: “SACCRED – Structured ACCRetion Disks: initial conditions for planet formation in the time domain” (ERC-StG 716155) (2017 – 2022)

Structure of the talk

- Introduction to episodic accretion
- Open questions
- Our target: V346 Nor
- New ALMA observations:
  - 1.32 mm continuum
  - J = 2–1 line for ^{12}CO, ^{13}CO, and $C^{18}O$
- Our ongoing millimeter CO surveys of FUors

The isolated star formation paradigm



Time-variable accretion

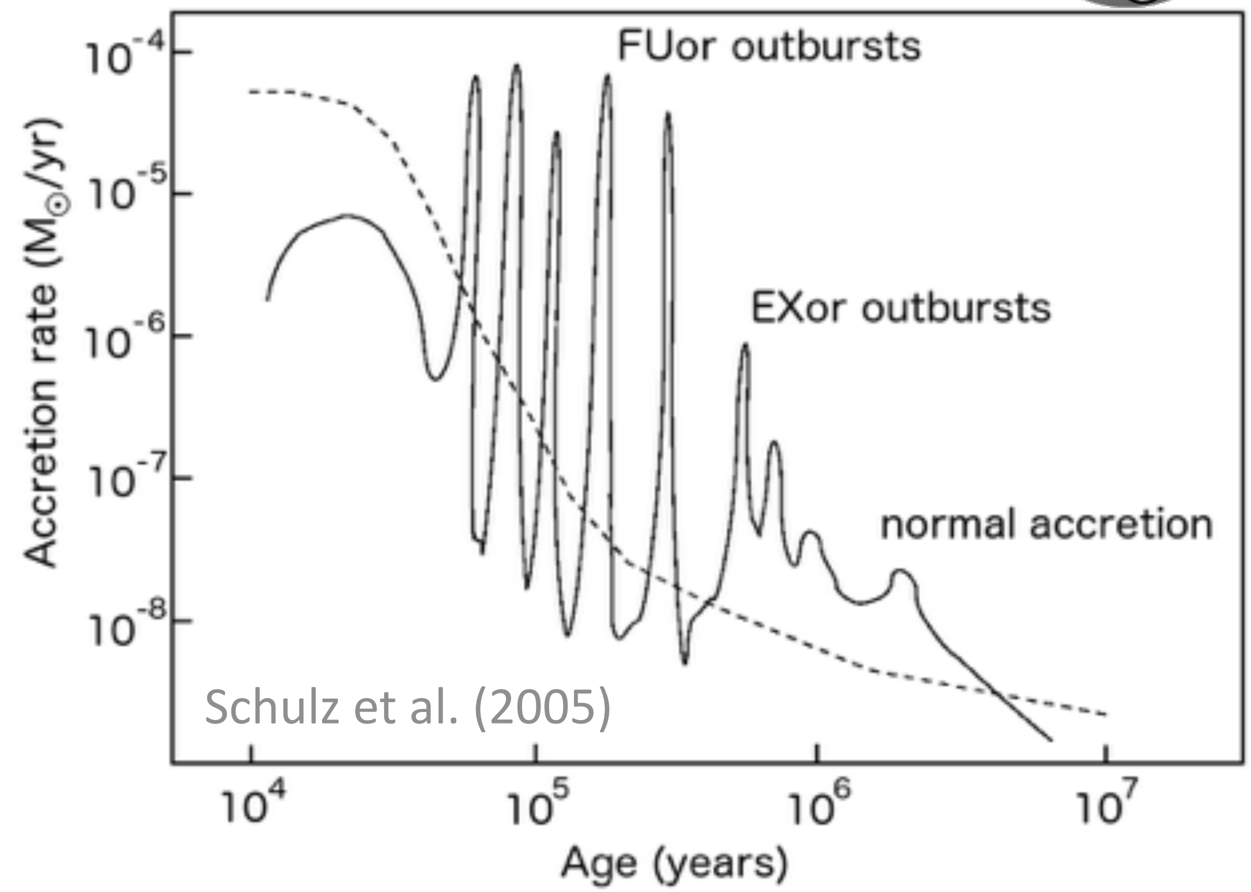
Long-term evolution

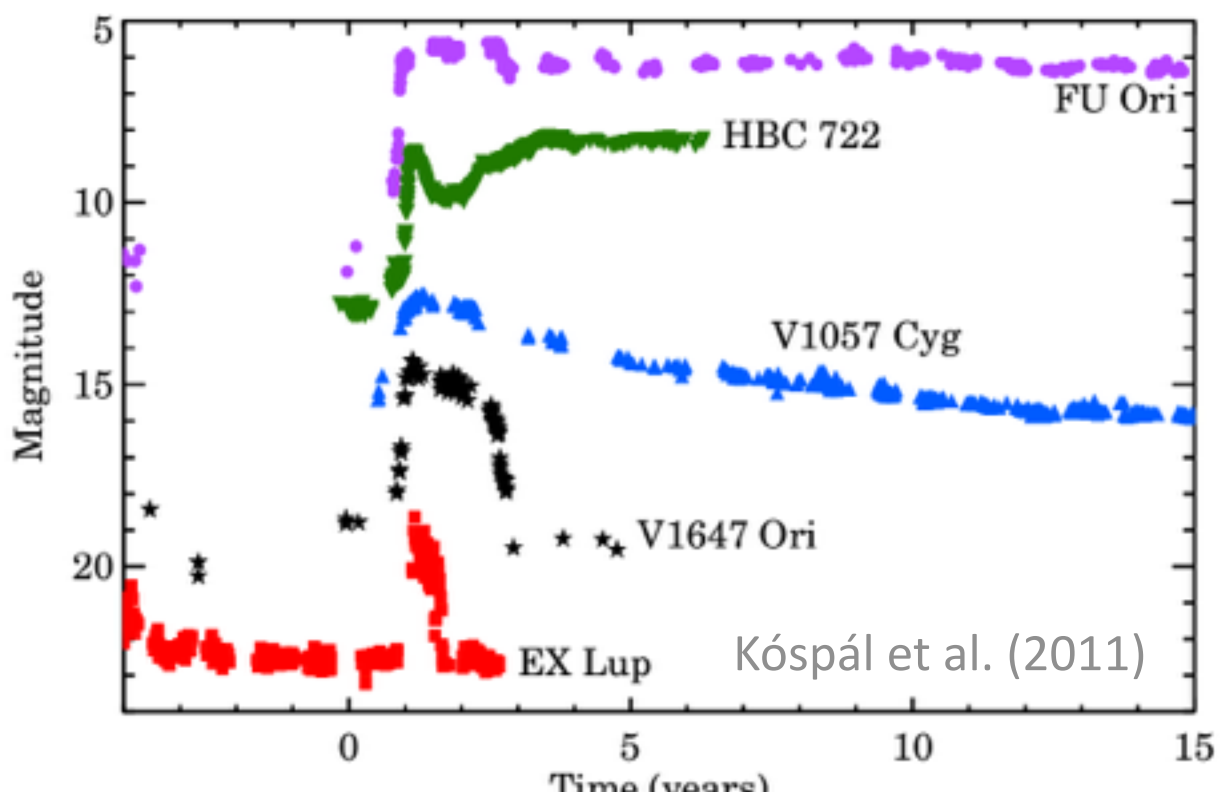
+

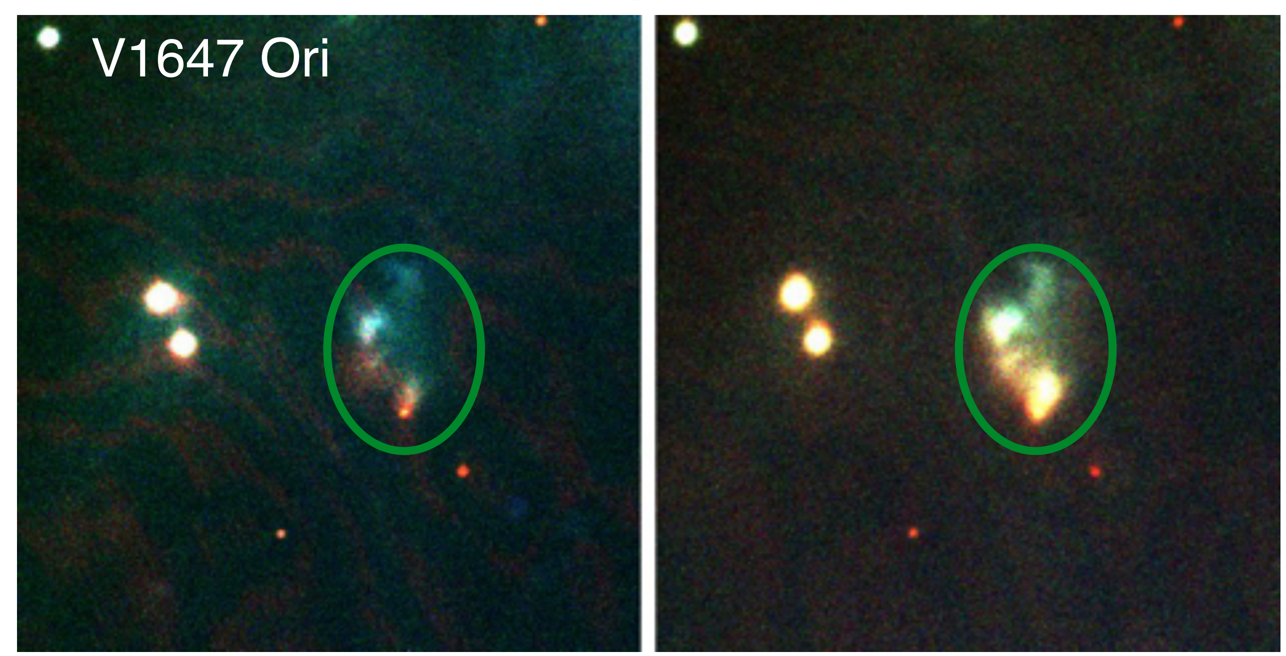
Instability-driven accretion outbursts

Most **spectacular** appearance:

young eruptive stars



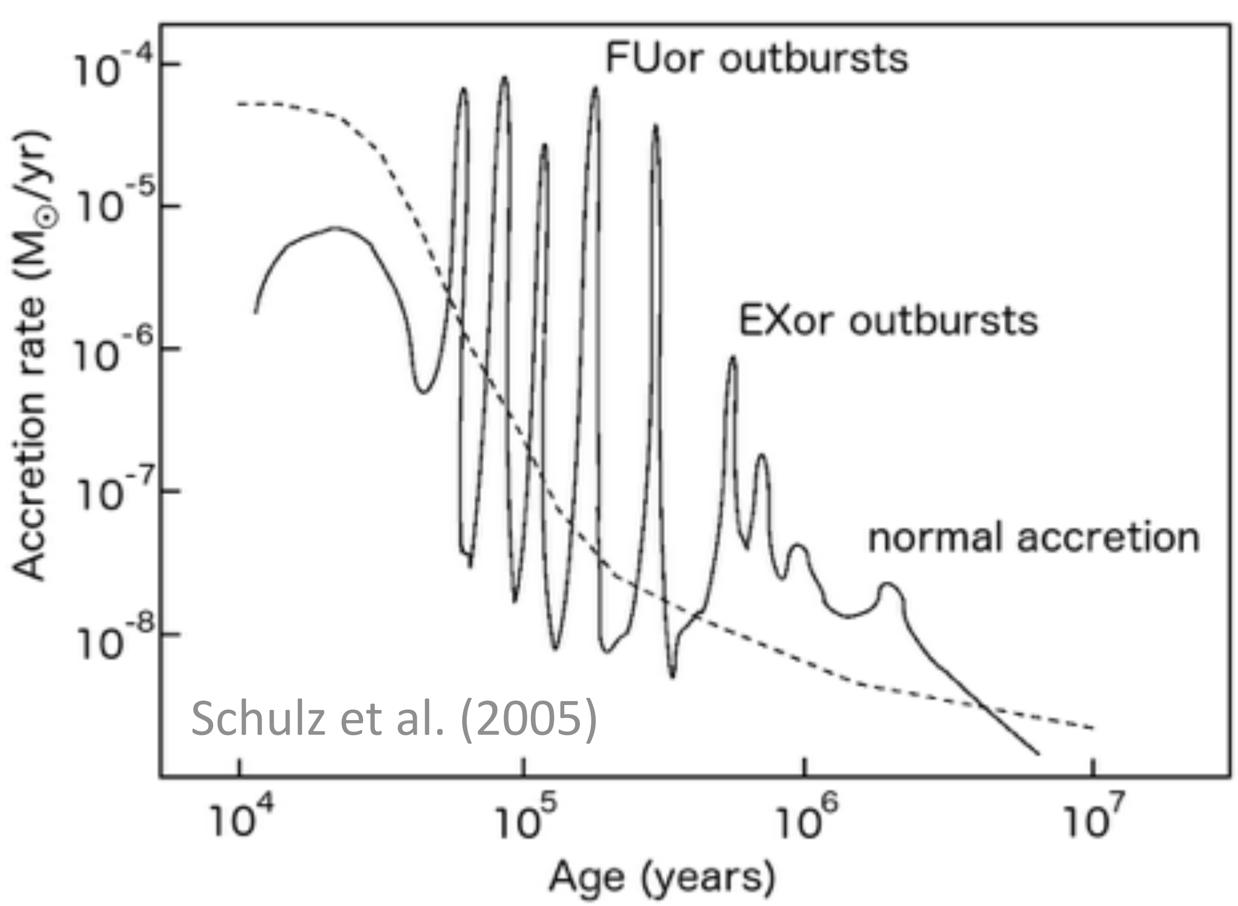




Kóspál et al. (2005)

FU Orionis-type objects (FUors)

- Episodic, high accretion outbursts of young stars
- Three reasons why FUors are interesting:
  - **Build stars and (maybe) solve the protostellar luminosity problem**



- Accretion rate: 10^{-4} $M_\odot$/yr → 0.01 $M_\odot$ in about 100 yrs
- A few dozen outbursts are enough to build a low-mass star
- Star spends most time in quiescence, this could explain the average low luminosity of protostars

FU Orionis-type objects (FUors)

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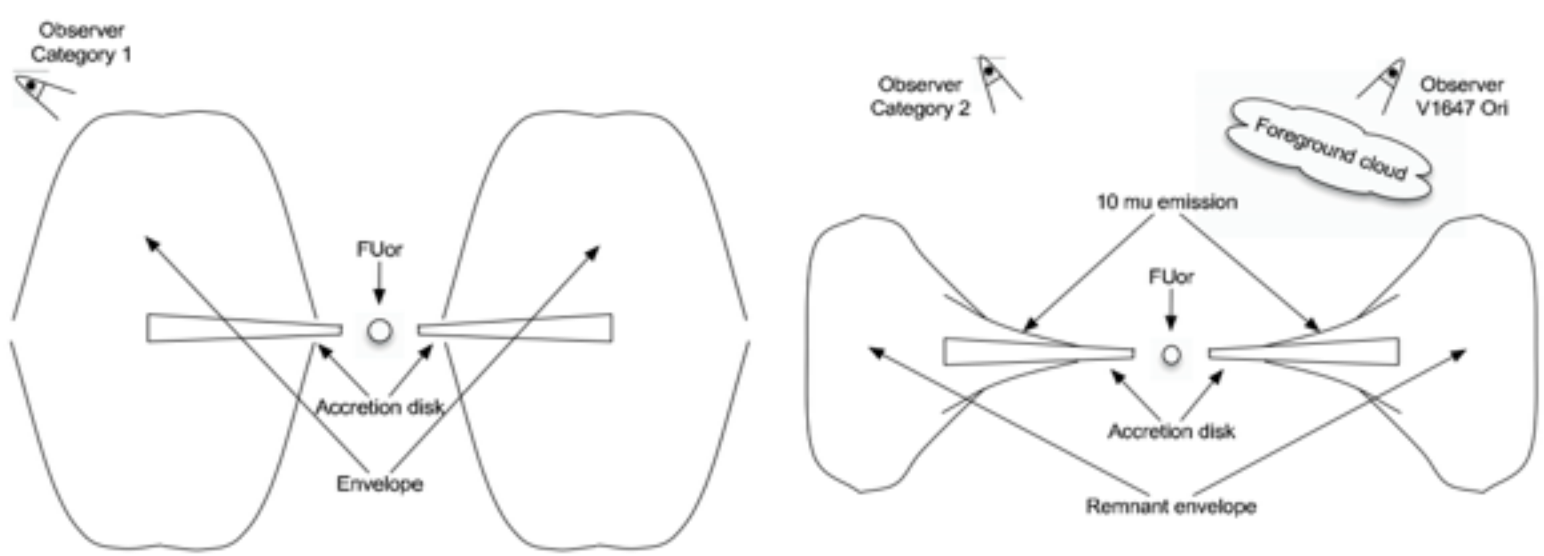
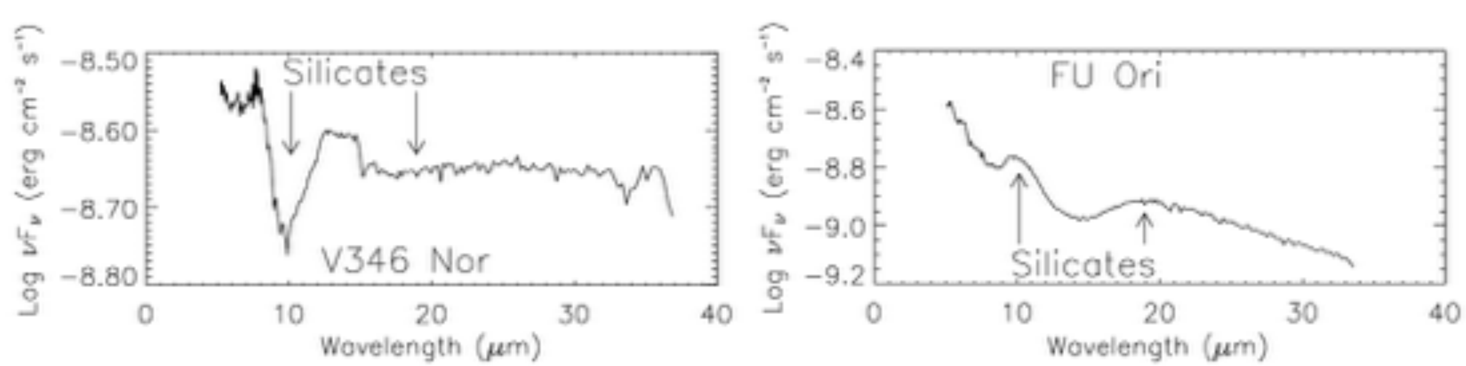
- Three reasons why FUors are interesting:
  - Build stars and (maybe) solve the protostar’s luminosity problem
  - **Make the protostars optically visible**



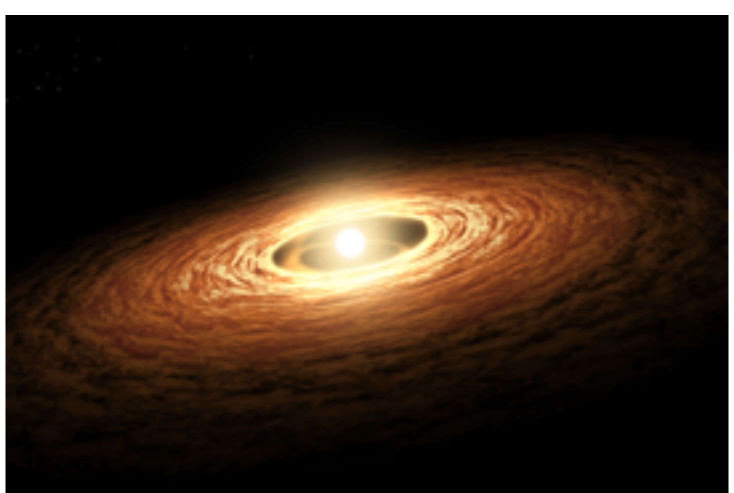
Quanz et al. (2007)



Green et al. (2006)

FU Orionis-type objects (FUors)

- Episodic, high accretion outbursts of young stars
- Three reasons why FUors are interesting:
  - Build stars and (maybe) solve the protostar's luminosity problem
  - Make the protostars optically visible
  - **Set time-variable initial conditions for terrestrial planet formation**



Ábrahám et al. (2009)

- In outburst: several 100 $L_{\odot}$
- Inner disk: dust grains evaporate, crystallize, ice mantles disappears, snowline moves outward
- Return to the inital state needs time, may have a cumulative effect

Open questions

- Mass of FUors (few progenitors are known)?
- Mass and size of FUor disks and envelopes (tranditional claim: large)?
- Infall rate from the envelope onto the disk? Mismatch between infall rate, transport rate within the disk, and accretion rate onto the star?
- Information on the infalling material (origin, path, processing, chemical composition)?
- Envelope dispersal: do we see the expected diversity? How does the dispersal happen? Can we see the predicted evolutionary trend in the gas?
- Is the “FUor phase” equivalent to the Class I/II transition?

Why ALMA?

- **FUor outbursts are intense episodes in the intimate relationship between the young star and its environment**
- **Two-way interaction:**

?

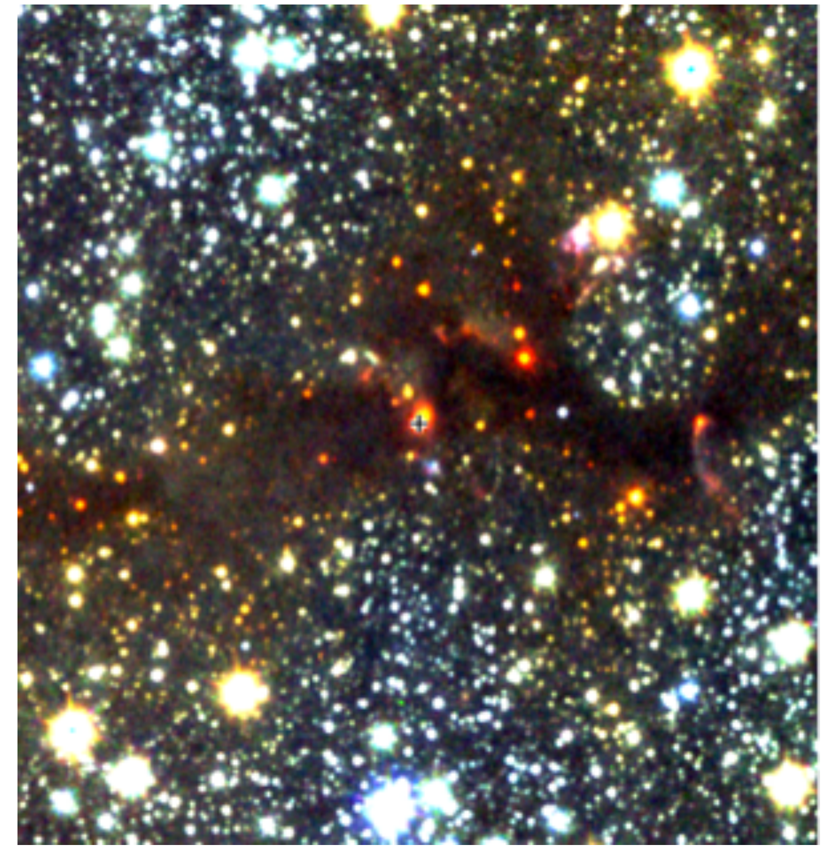
inhomogeneous circumstellar matter ⇄ time-variable accretion

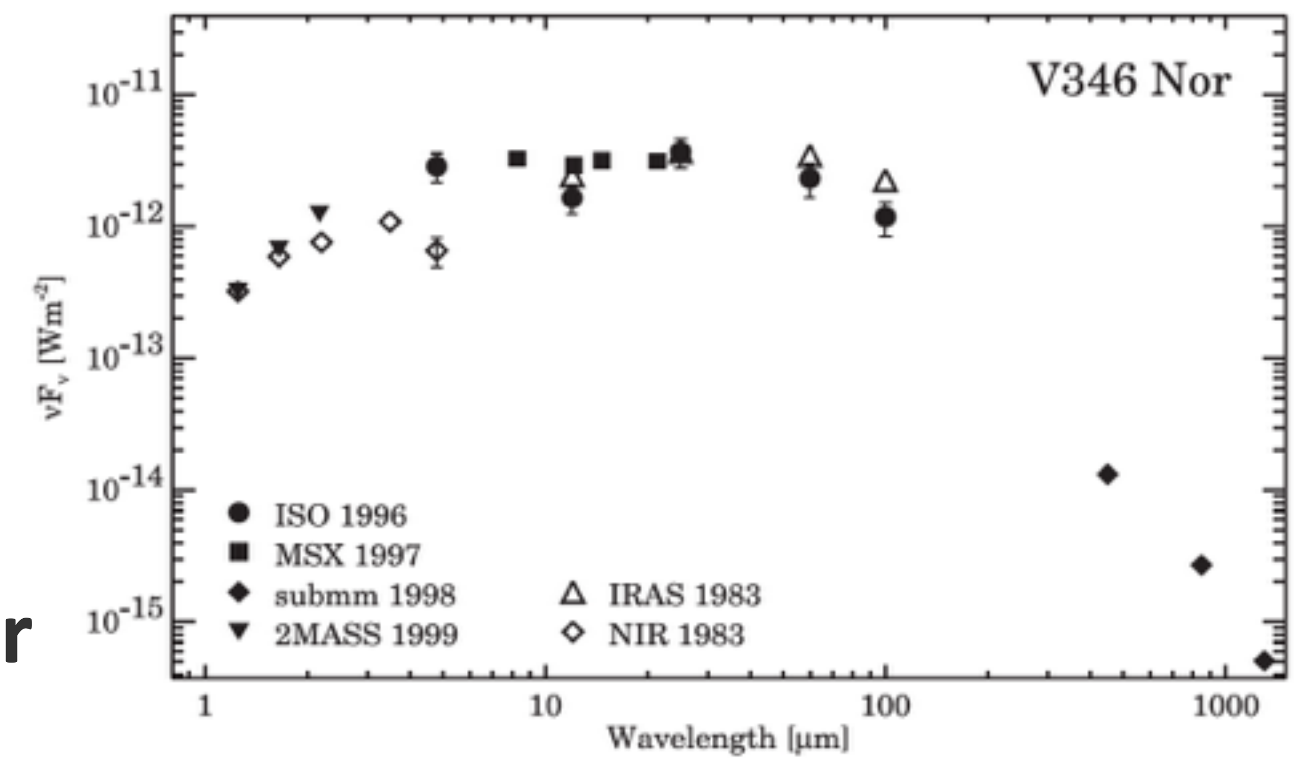
?

- **ALMA can:**
  - detect disks and envelopes (sensitivity)
  - reveal their structure (spatial resolution)
  - extract kinematics (spectral resolution)

Our target: V346 Nor

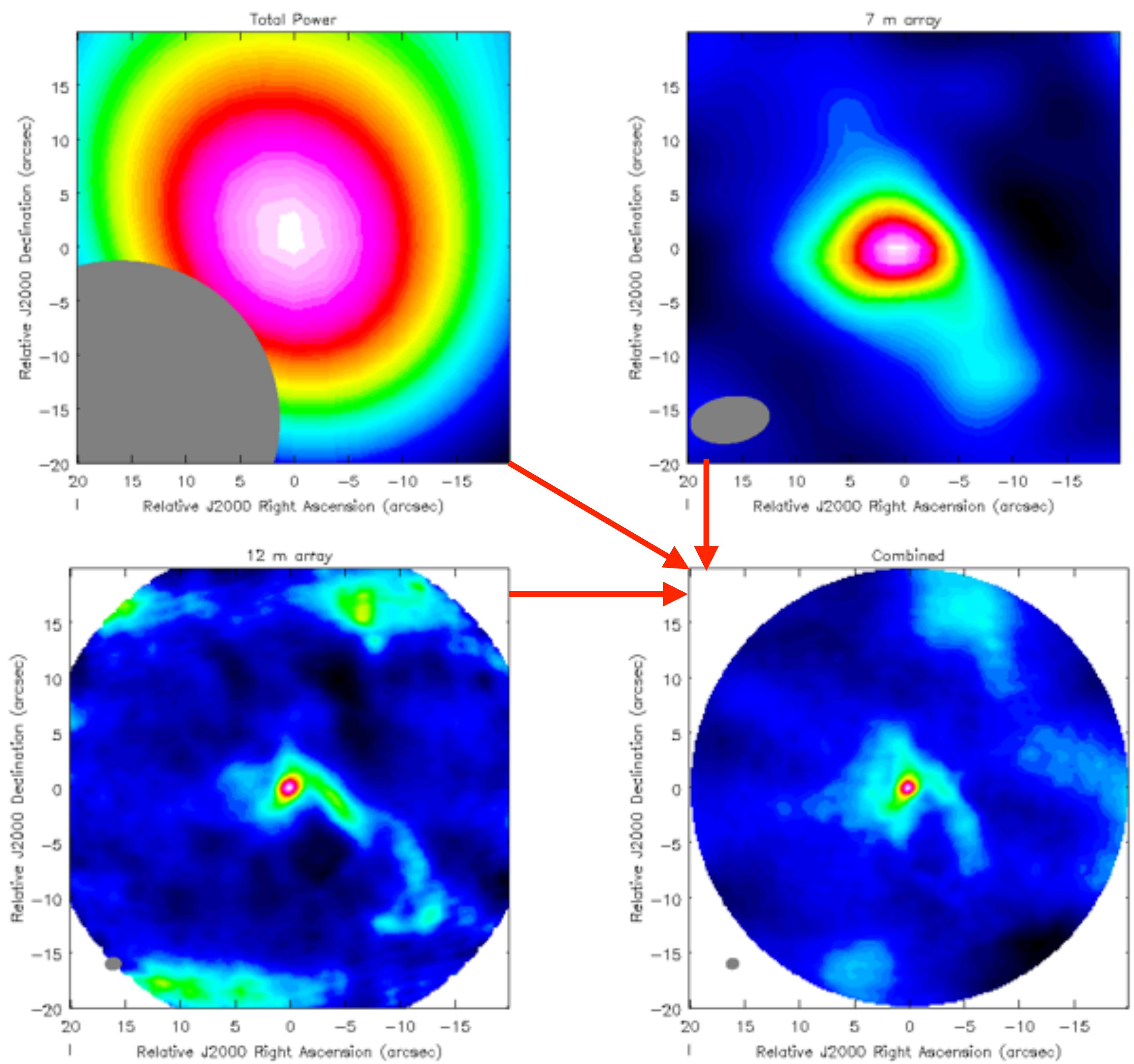
- **Outburst** in about 1980 (Graham 1983)
- **Southern** object (RA = 16 h, DEC = –44°)
- Location: Norma 1, Sa 187, **d = 700 pc** (Reipurth 1981)
- SED indicates a **massive envelope** (0.5 – 1 M⊙) (Sandell & Weintraub 2001, Ábrahám et al. 2004)
- Associated with a Herbig-Haro object (HH 57) and a **molecular outflow** (Evans et al. 1994)





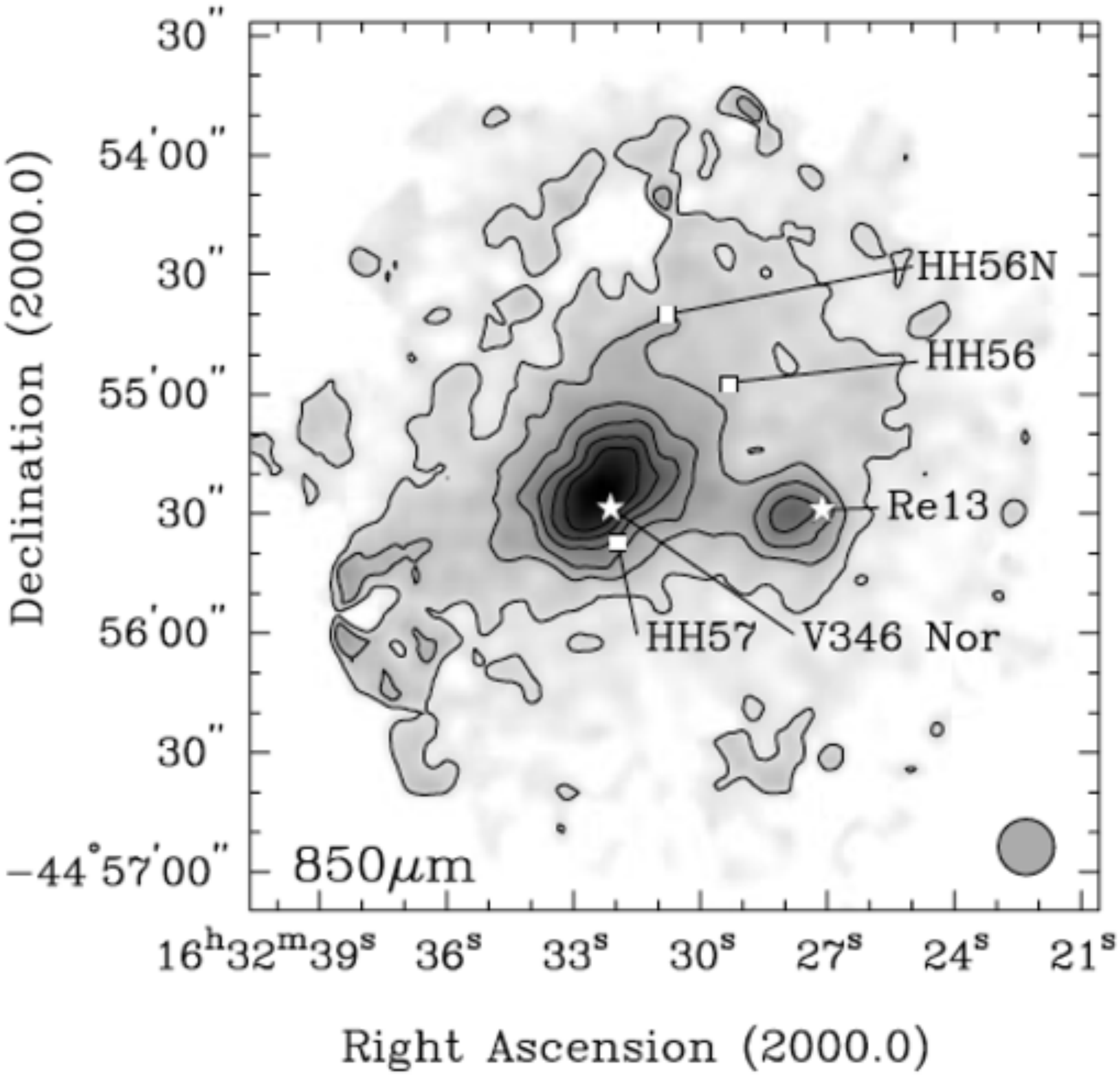
ALMA observations of V346 Nor

- J=2–1 line of ^{12}CO, ^{13}CO, and $C^{18}O$, 1.3 mm continuum in one single setting in B6
- Cycle 2 (PI: Kóspál, observations: 2015 Apr – 2016 Jan)
- 12 m array observations (2 h on-source correlation time)
- ACA (5 h on-source correlation time)
- Total Power Antennas



Continuum results

JCMT/SCUBA 850 µm

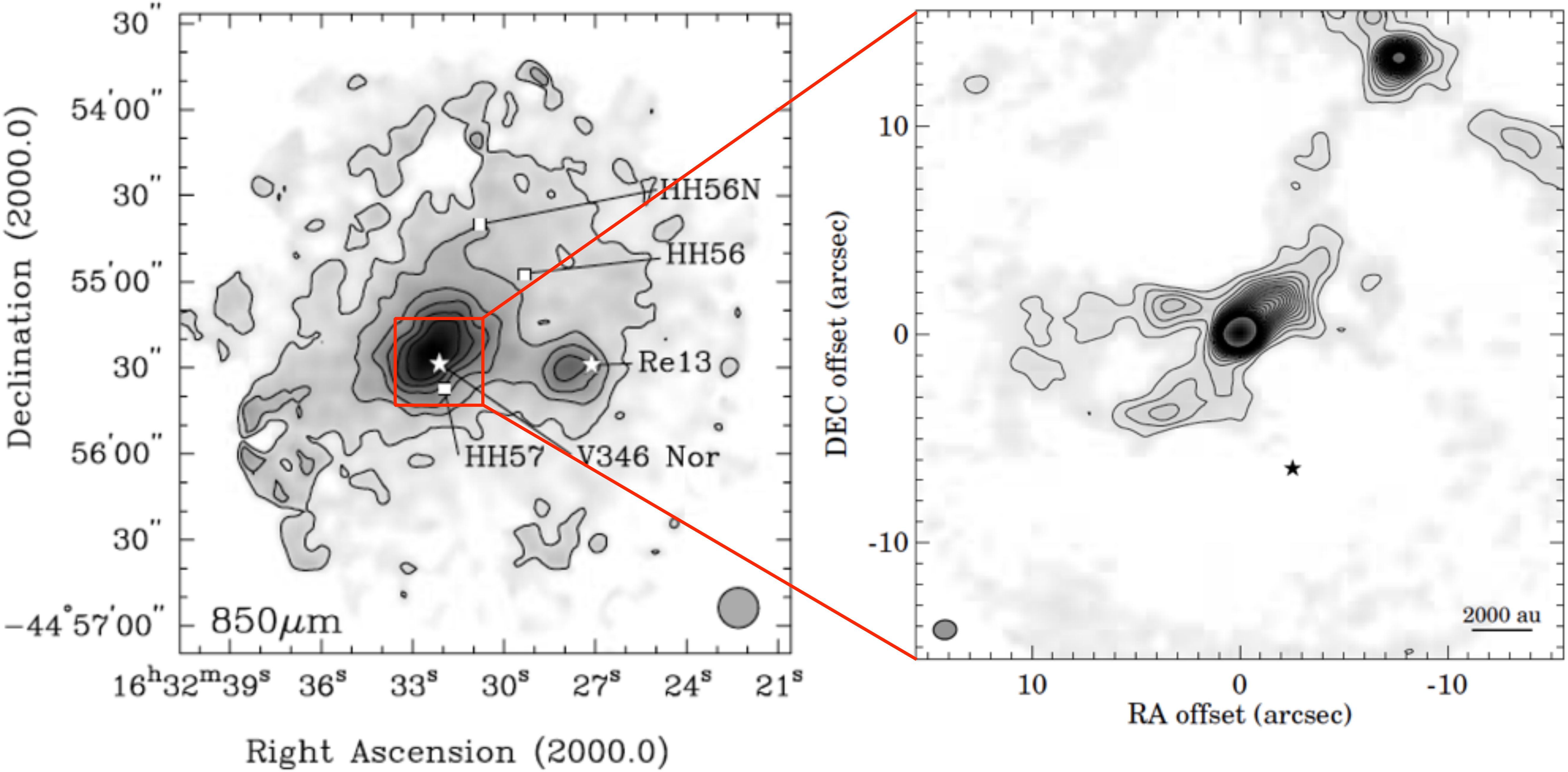


Sandell & Weintraub (2001)

Continuum results

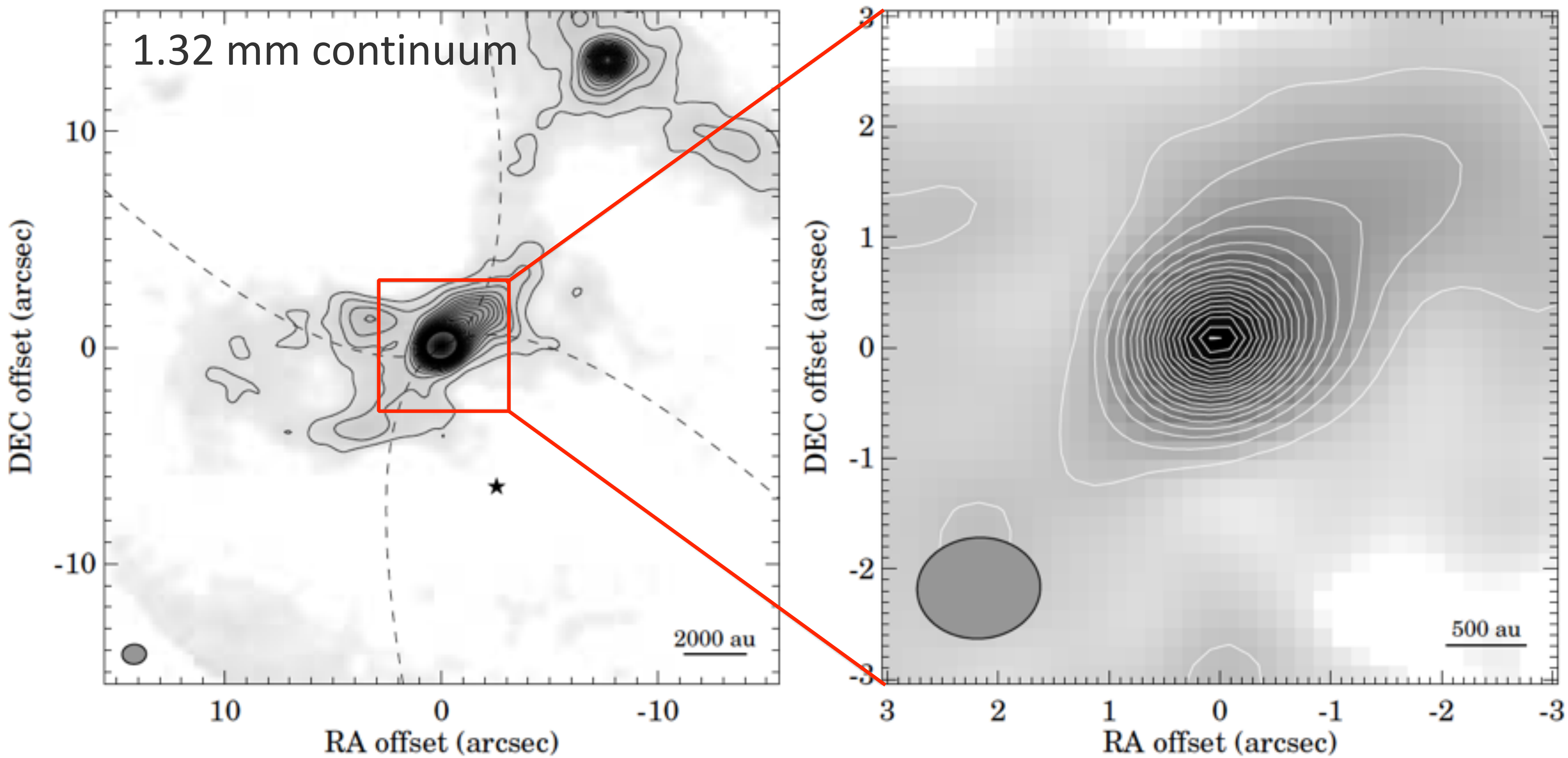
JCMT/SCUBA 850 µm

ALMA 1.32 mm



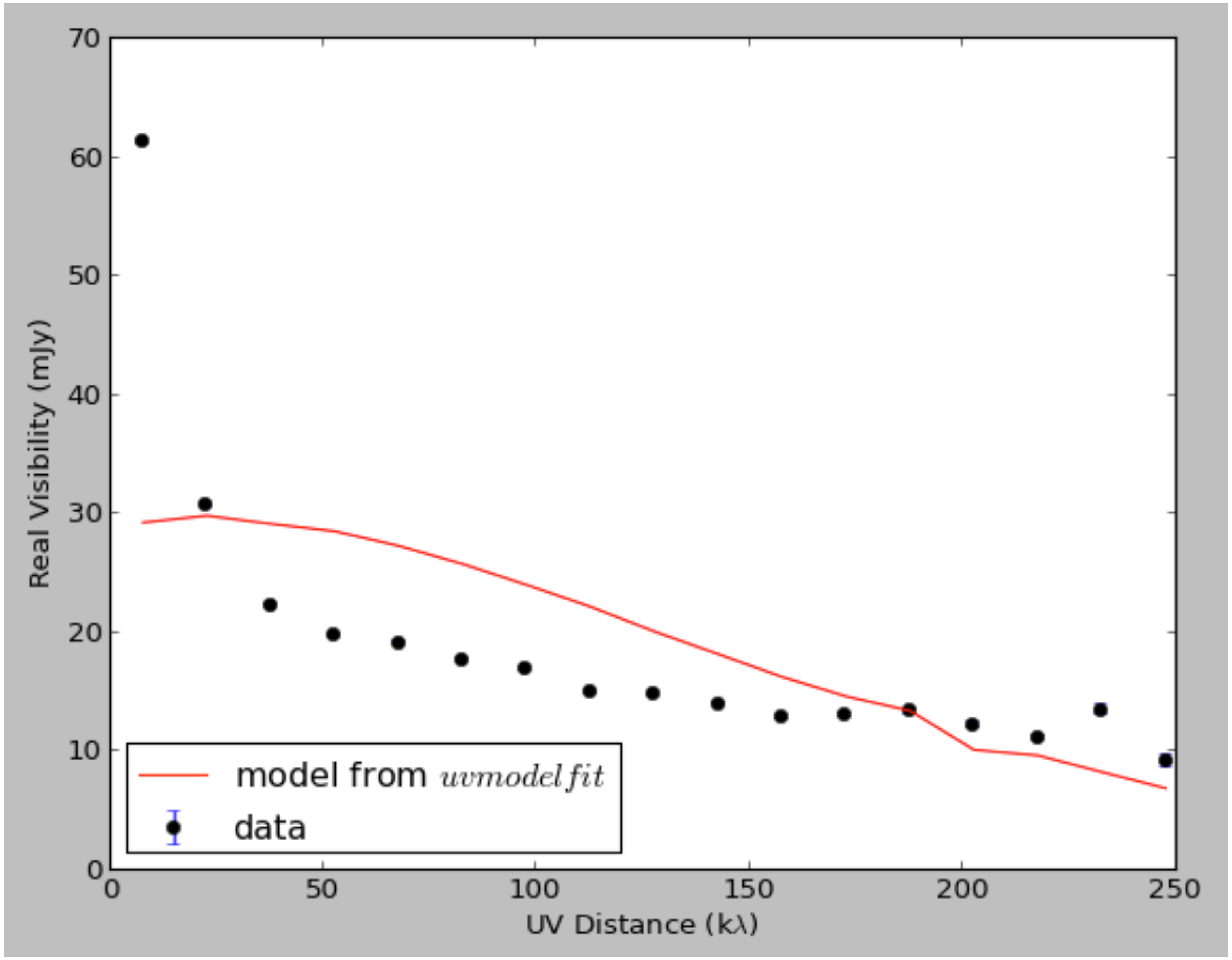
Sandell & Weintraub (2001)

Continuum results



- 70 µJy rms noise, peak centered on the optical stellar location
- Elongated central source (<0.2” x 0.9” → i > 77°; total mass: 0.1 – 0.3 M⊙)
- Fainter, extended emission tracing the outflow cavity walls

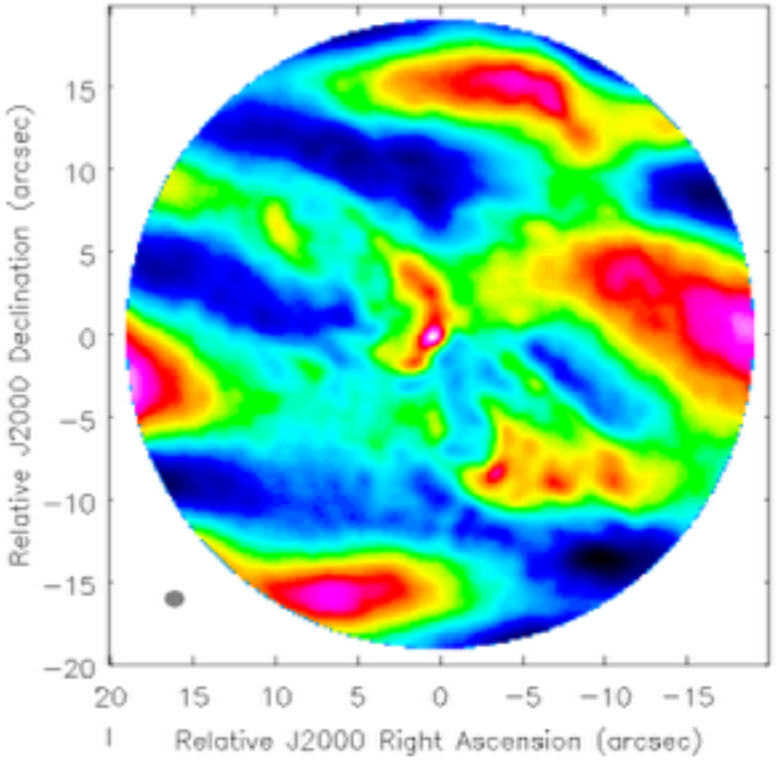
Continuum results



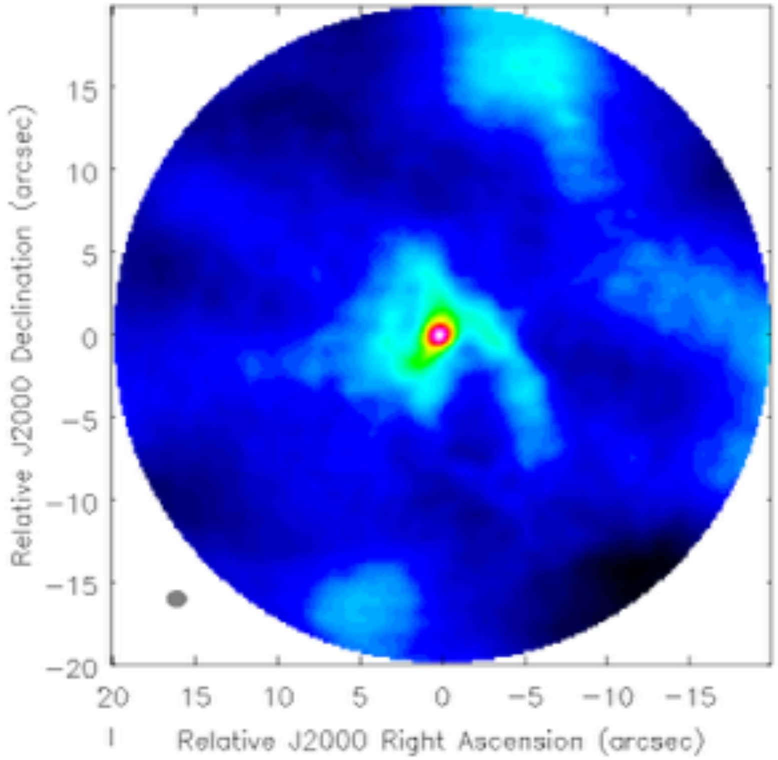
- Cannot be fitted with a single Gaussian in the visibility space

CO integrated intensity maps

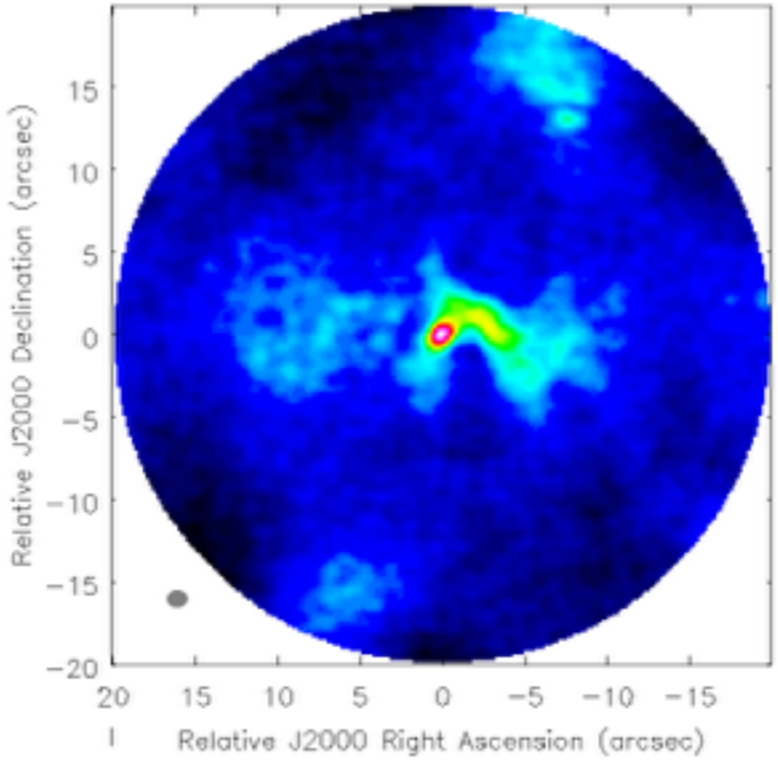
^{12}CO



^{13}CO



$C^{18}O$



CO integrated intensity maps

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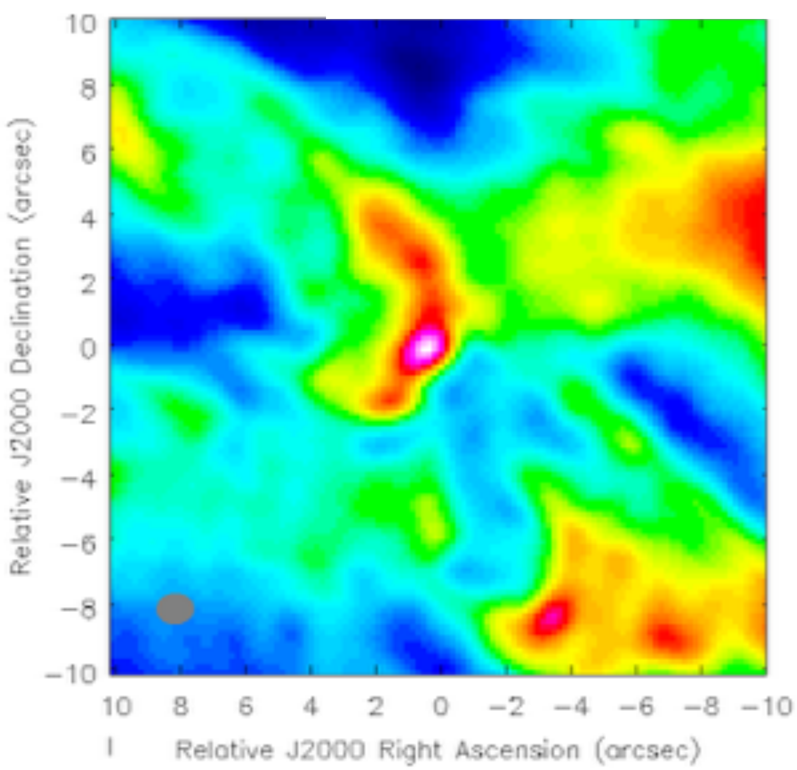
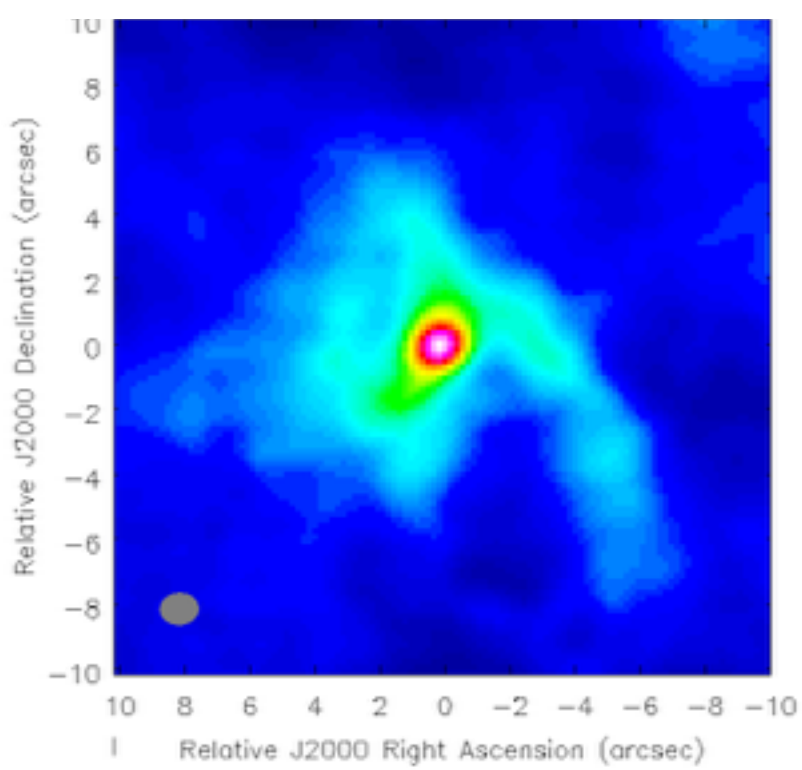
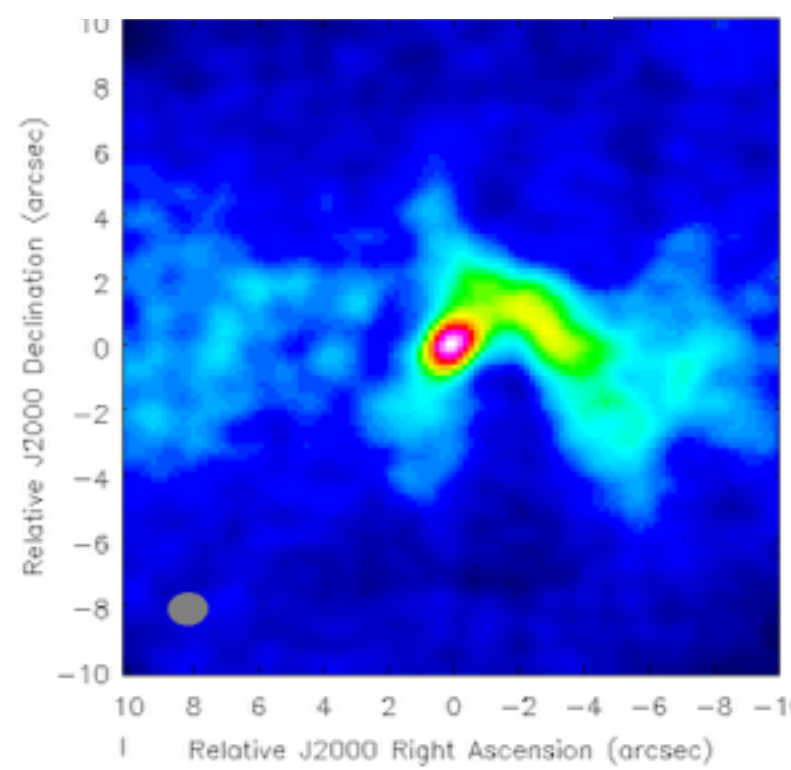


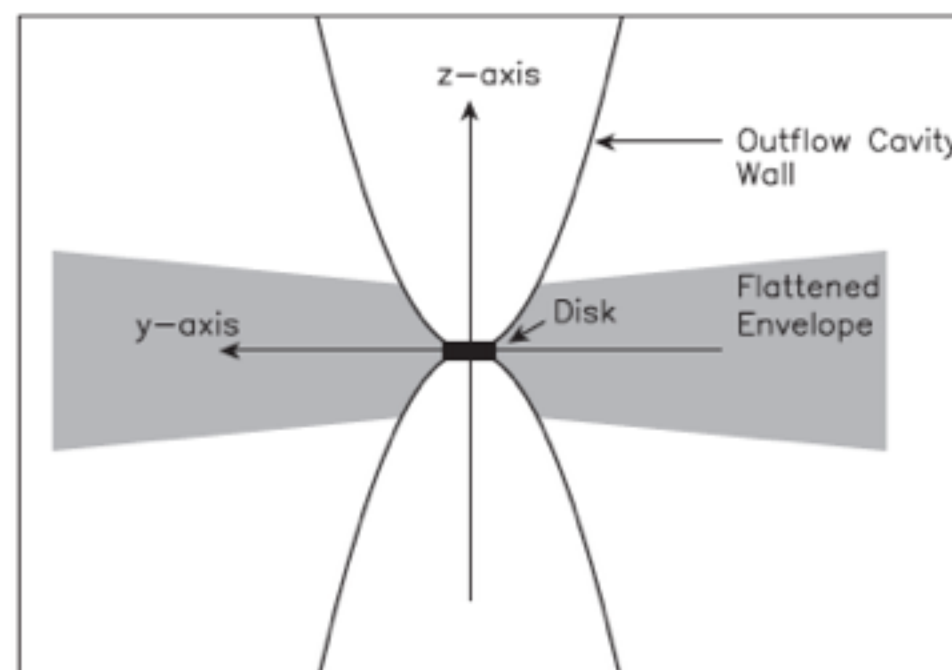
^{13}CO



$C^{18}O$

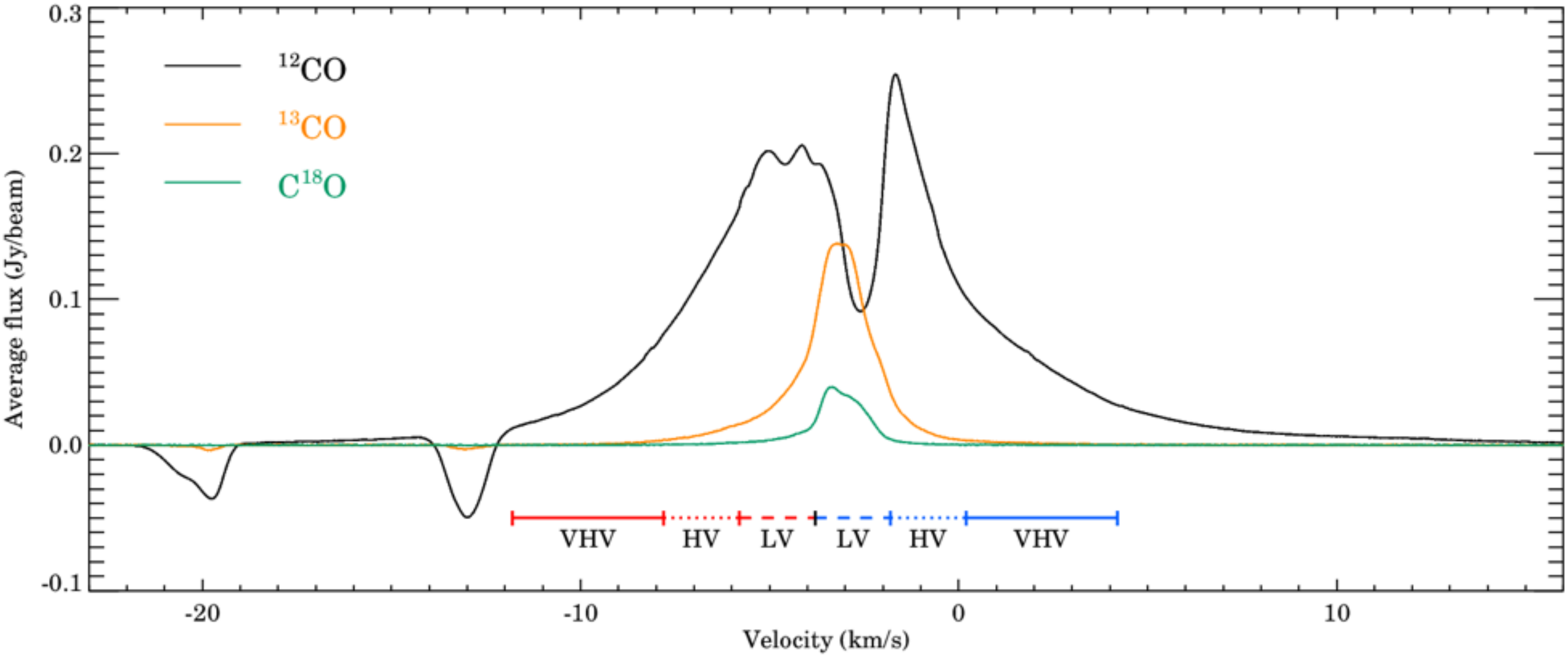


- Structure is very similar to that of typical Class 0 protostellar systems
- Compact disk + flattened envelope + jet + outflow cavity walls (not all of them visible in CO)



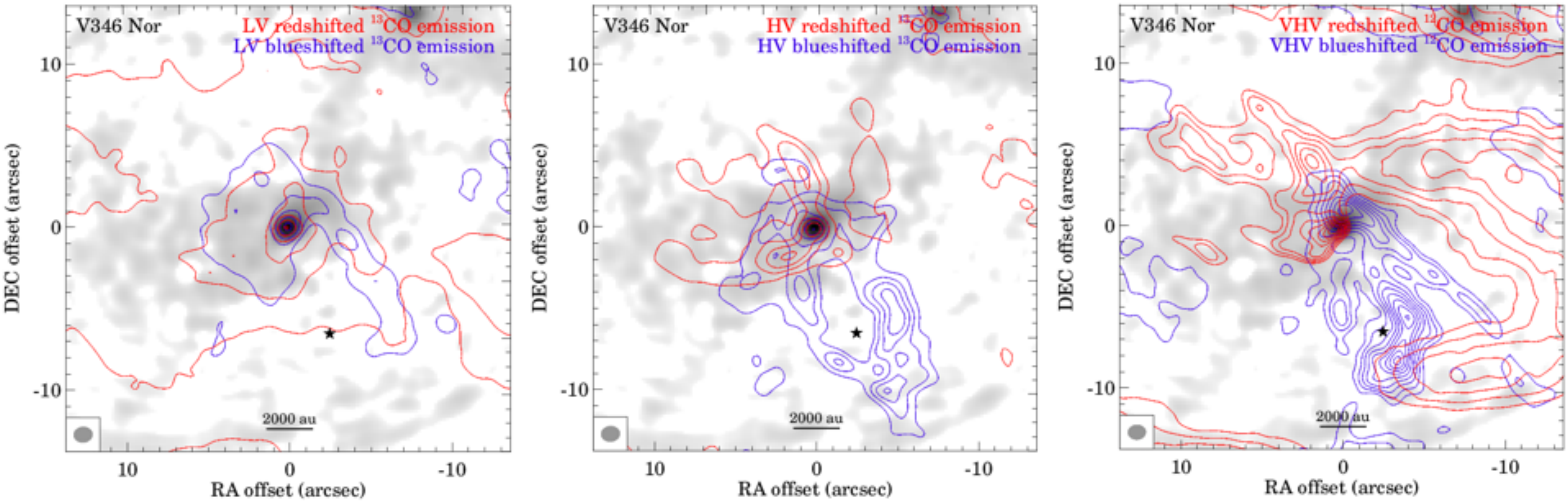
Lee et al. (2014)

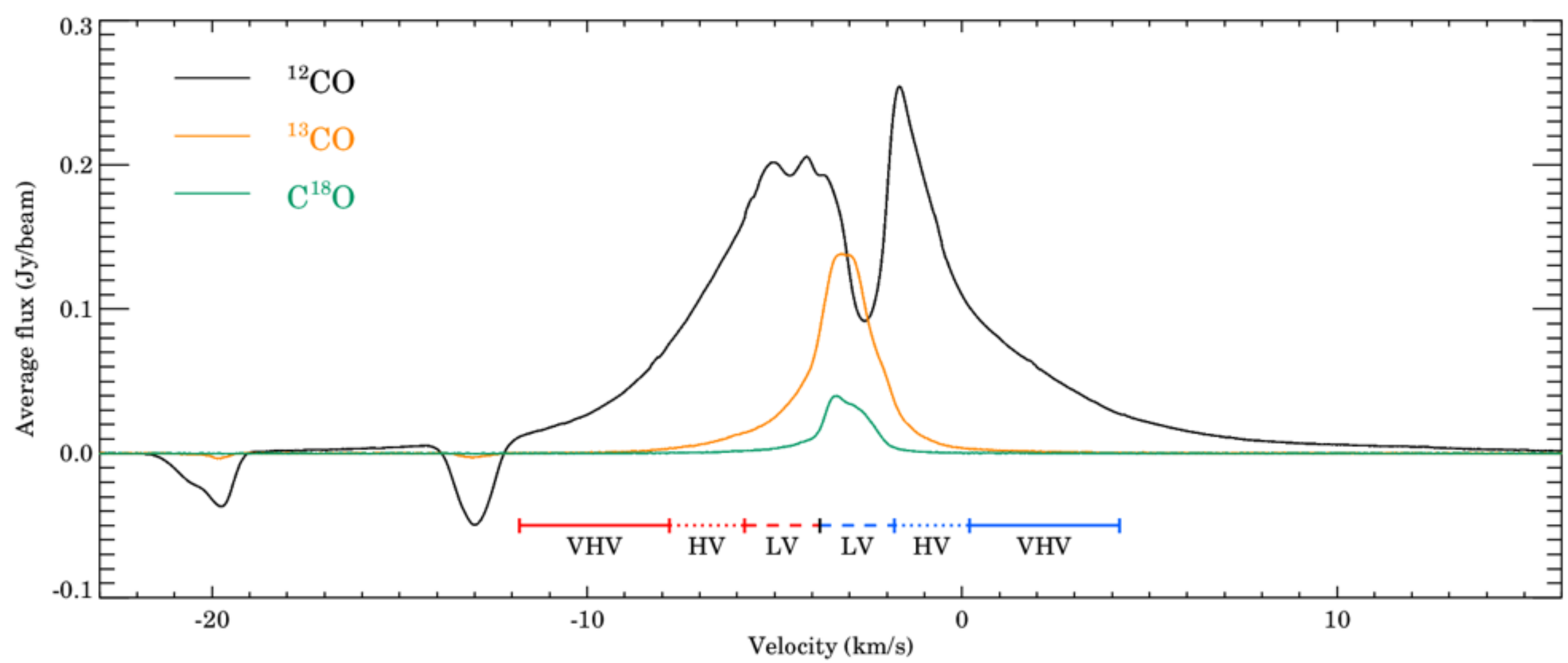
CO line profiles



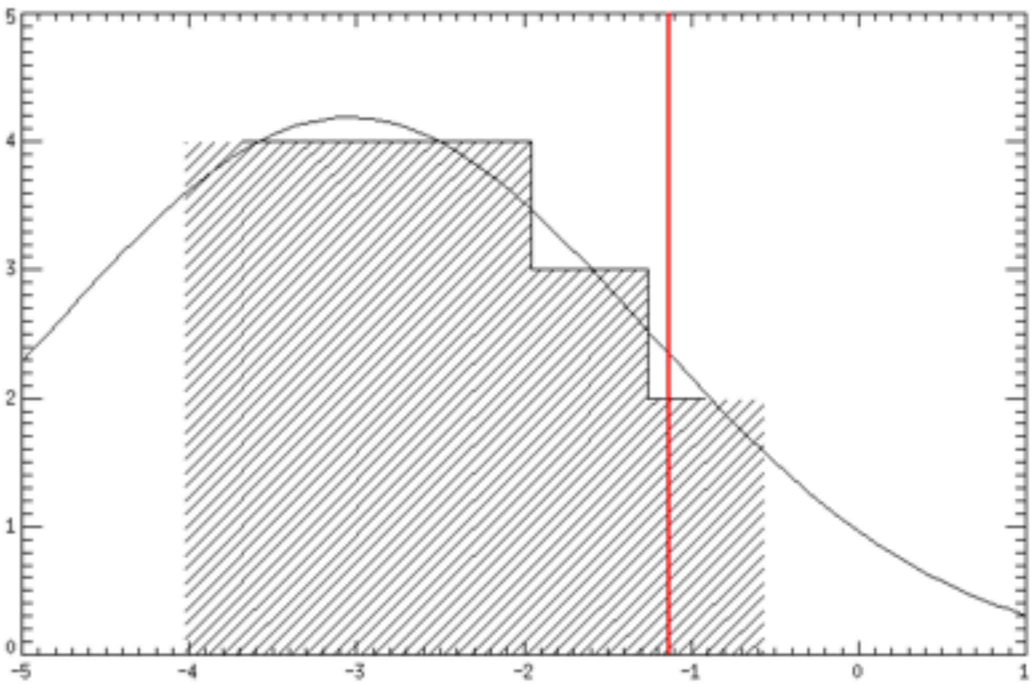
CO outflows

low velocity | high velocity | very high velocity

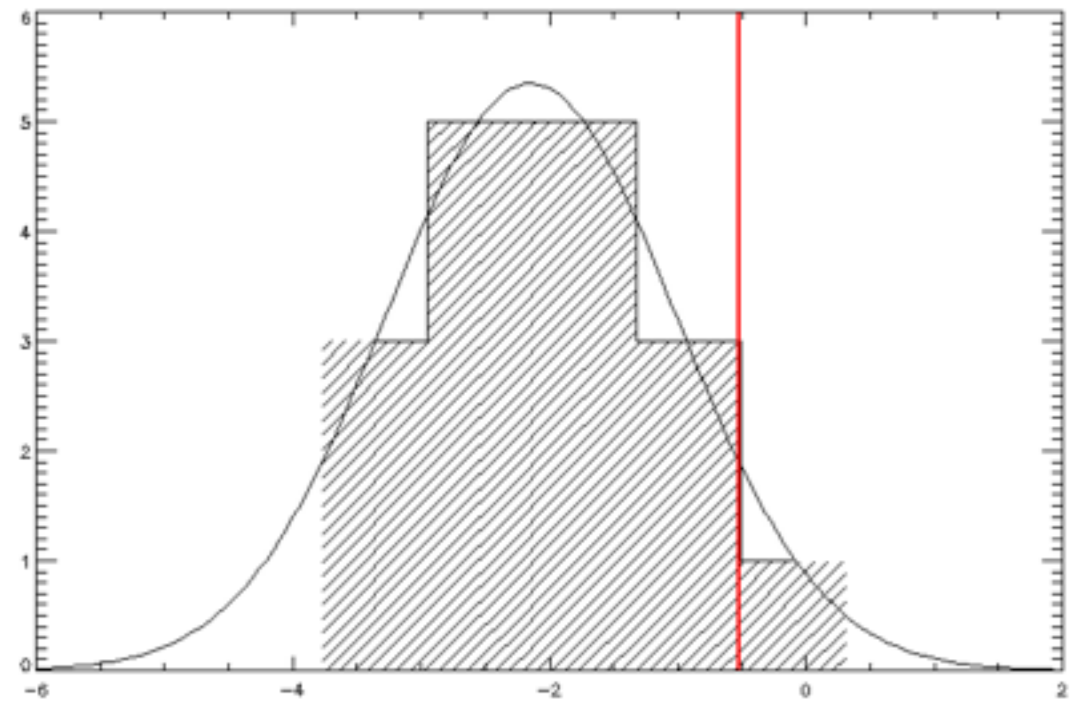




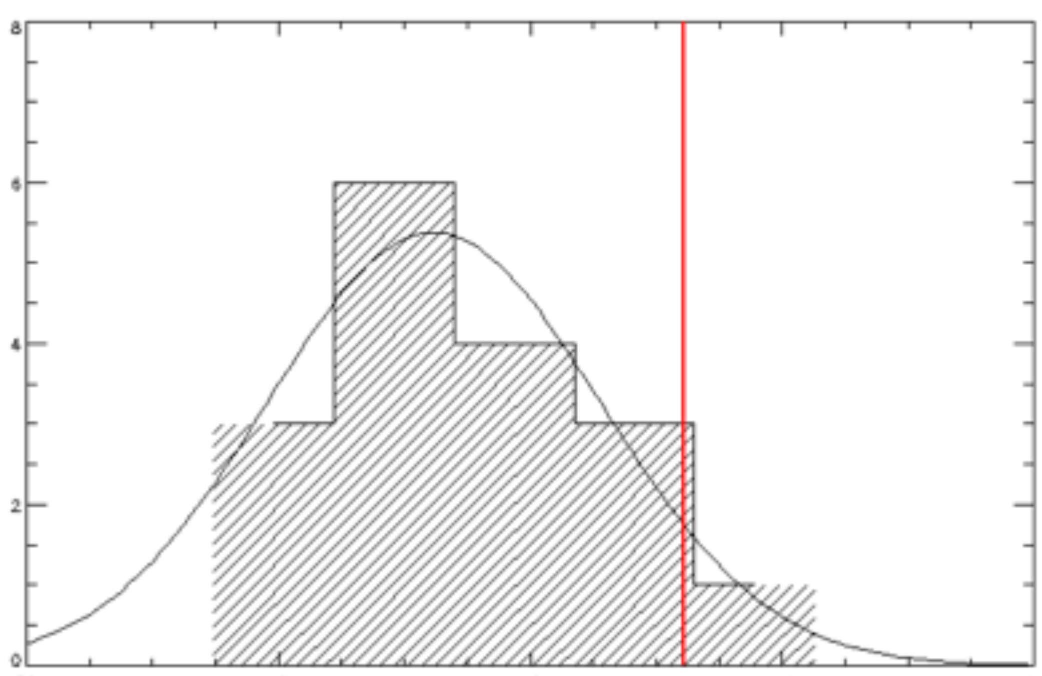
Outflow masses, momenta, energies



log (Mass / M⊙)



log (Momentum / M⊙.km/s)



log (Energy / erg)

Comparison to a sample of 28 molecular outflows driven by low-mass protostars

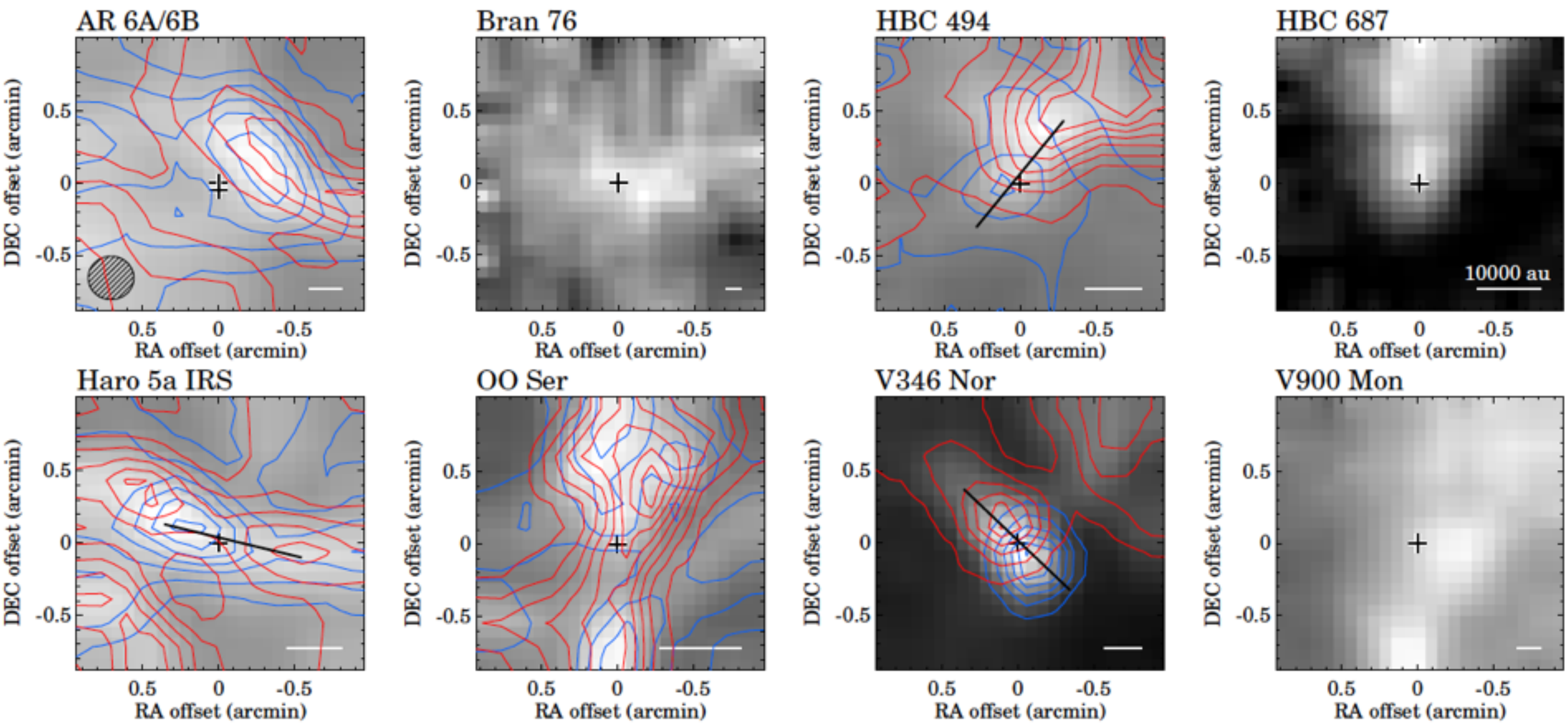
(Dunham et al. 2014)

Our ongoing mm CO surveys for FUors

- **APEX**: AR 6A/6B, Bran 76, HBC 494, Parsamian 21, Haro 5a IRS, OO Ser, V346 Nor, V900 Mon (J=3–2 for ^{12}CO and ^{13}CO, J=4–3 for ^{12}CO); Kóspál et al. (submitted)
- **IRAM PdBI + 30 m**: V1057 Cyg, V1515 Cyg, V1735 Cyg, V2492 Cyg, HBC 722, RNO 1B/1C, V733 Cep (J=1–0 for ^{13}CO and C^{18}O); Fehér et al. (in prep.)
- **ALMA** Cycle 2: V346 Nor (J=2–1 for ^{12}CO, ^{13}CO, and C^{18}O); Kóspál et al. (in prep.)
- **APEX**: L1551 IRS 5, V582 Aur, V883 Ori, HBC 494, V2775 Ori, FU Ori, V1647 Ori, V899 Mon, V960 Mon, Z CMa, IPTF 15afq, V723 Car, GM Cha (J=3–2 for ^{12}CO and ^{13}CO, J=4–3 for ^{12}CO); (observations just finished)
- **ALMA** Cycle 4: AR 6A/6B, Bran 76, Parsamian 21, Haro 5a IRS, OO Ser, V900 Mon, Z CMa, L1551 IRS 5, V899 Mon, and V960 Mon (J=2–1 for ^{12}CO, ^{13}CO, and C^{18}O) (observations in progress)
- **IRAM NOEMA + 30 m**: V899 Mon, V900 Mon, V960 Mon, V582 Aur (J=1–0 for ^{13}CO and C^{18}O); (observations in progress)
- **JCMT**: RNO 1B/1C, V1057 Cyg, V1515 Cyg, V1735 Cyg, V2492 Cyg, HBC 722, V733 Cep (J=3–2 for ^{12}CO and ^{13}CO); (observations are in the queue)

Ongoing FUor survey (APEX)

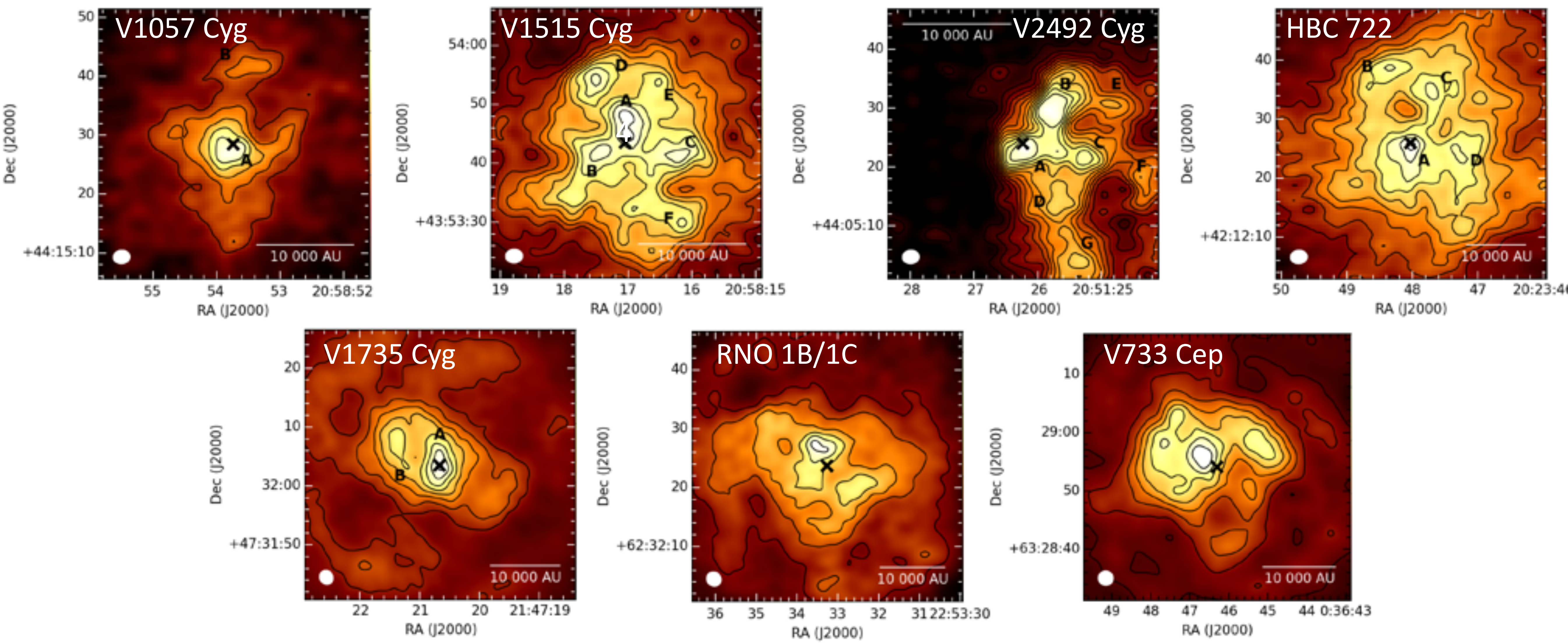
APEX ^{12}CO integrated intensity + red- and blueshifted outflows



Kóspál, Ábrahám, Csengeri, et al. (submitted)

Ongoing FUor survey (IRAM)

IRAM PdBI ^{13}CO integrated intensity



Fehér et al. (in prep.)

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- Orsolya Fehér (Konkoly Observatory)
- Michiel Hogerheijde (Leiden Observatory)
- Christian Brinch (Univ. Copenhagen)
- Michael Dunham (Harvard-Smithsonia CfA)
- Eduard Vorobyov (Univ. Vienna)
- Thomas Henning (MPIA Heidelberg)

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