Recent progress in high-mass star-formation studies

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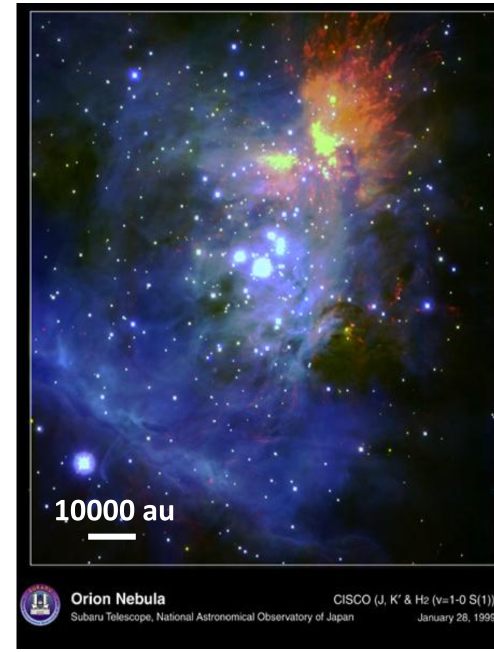
My talk

- Review broad context of high-mass star-formation studies
  - Mainly focus on recent progress of observational studies
  - Not well focus on cosmic cycle of dust and gas

- Contents
  - Introduction
  - Representative recent results, especially from ALMA
  - A few examples of our studies

What is HM star? Why important?

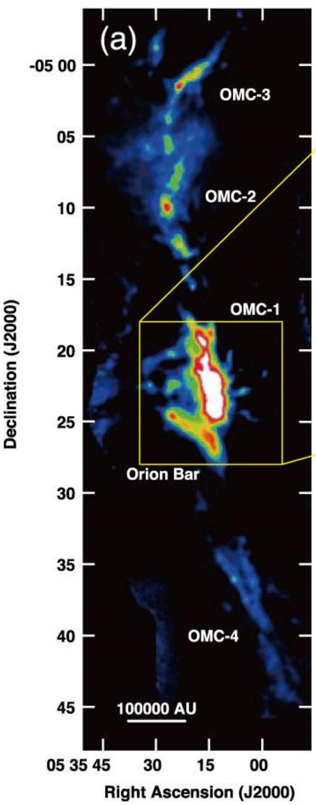
- How high mass (HM)?
  - Early B (B3 and earlier) and O stars
  - More massive than $8M_{Sun}$
  - More luminous than 10^3 L_{Sun}
- Significant impacts on astronomy, astrophysics, and astrochemistry
  - Influences on surroundings by strong UV, wind, explosion, ...

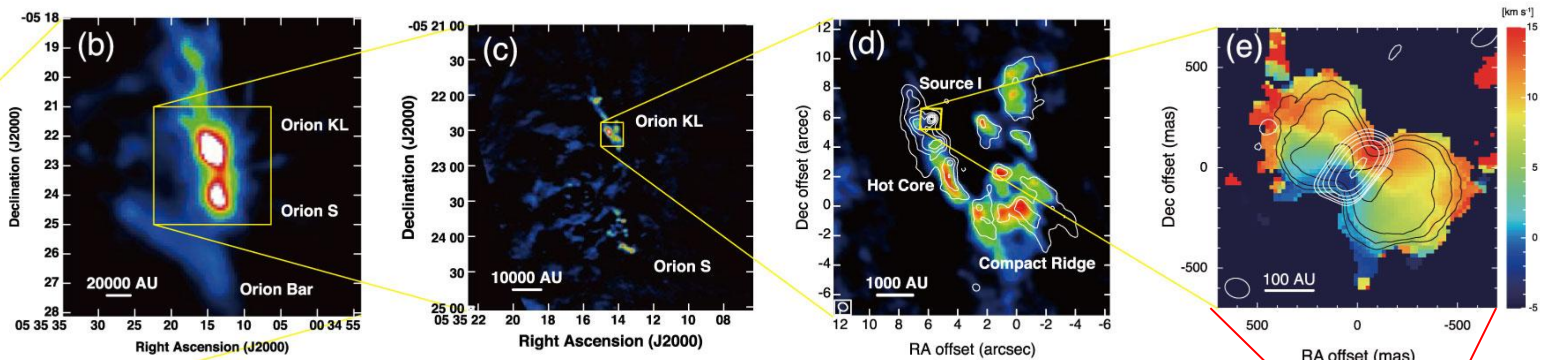


ALMA (ESO/NAOJ/NRAO).
Visible light image: the NASA/ESA Hubble Space Telescope

Scale of high-mass Star-forming regions

- From giant molecular cloud (GMC) complex to high-mass (HM) young stellar object (YSO)
  - Large-scale structures affected by YSO-scale events



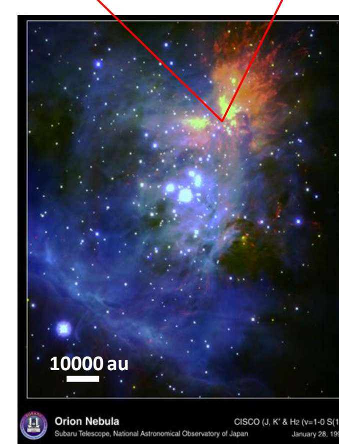


>>10” or >>(sub)pc
10^2-10^4 cm^{-3}
10 K
>>10 M_{Sun}

GMC, IRDC, clump, filament, fragment

0.1-10” or 10^2-10^4 au
>10^5 cm^{-3}
100-1000 K
~10 M_{Sun}

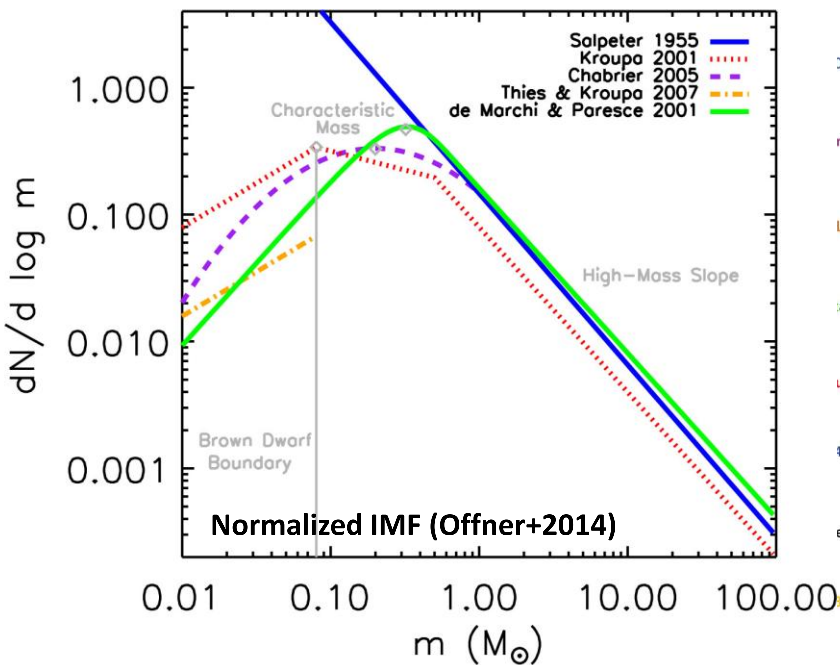
(hot) core, HCHII, disk, outflow, jet, HM-protostar

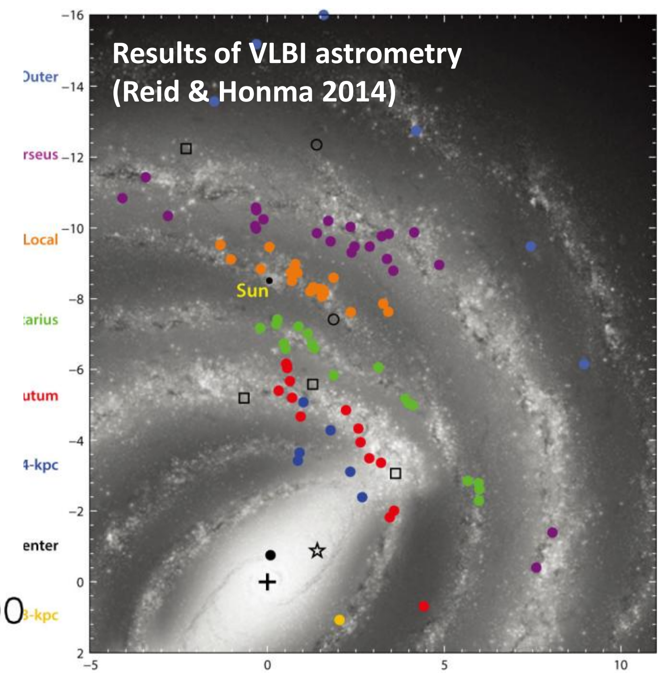


In case of Orion (Hirota+2018)

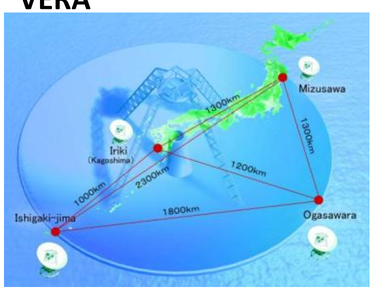
Why so difficult?

- Intrinsic characteristics of HM-YSOs/SFRs
  - 100 times rarer probability than low-mass stars
  - 1000 times shorter lifetime than low-mass stars
  - >10 times larger distances than low-mass SFRs

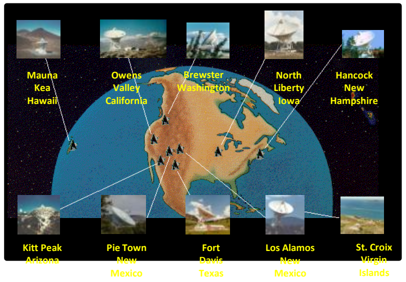




VERA

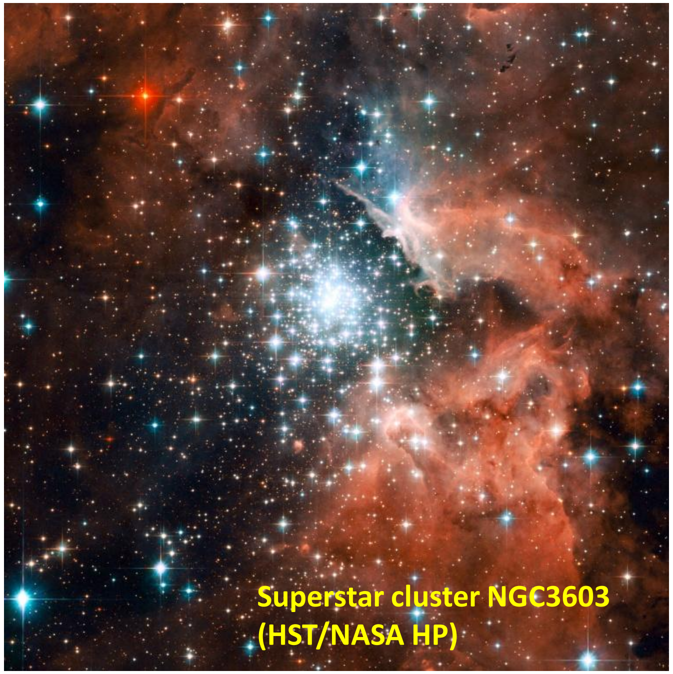


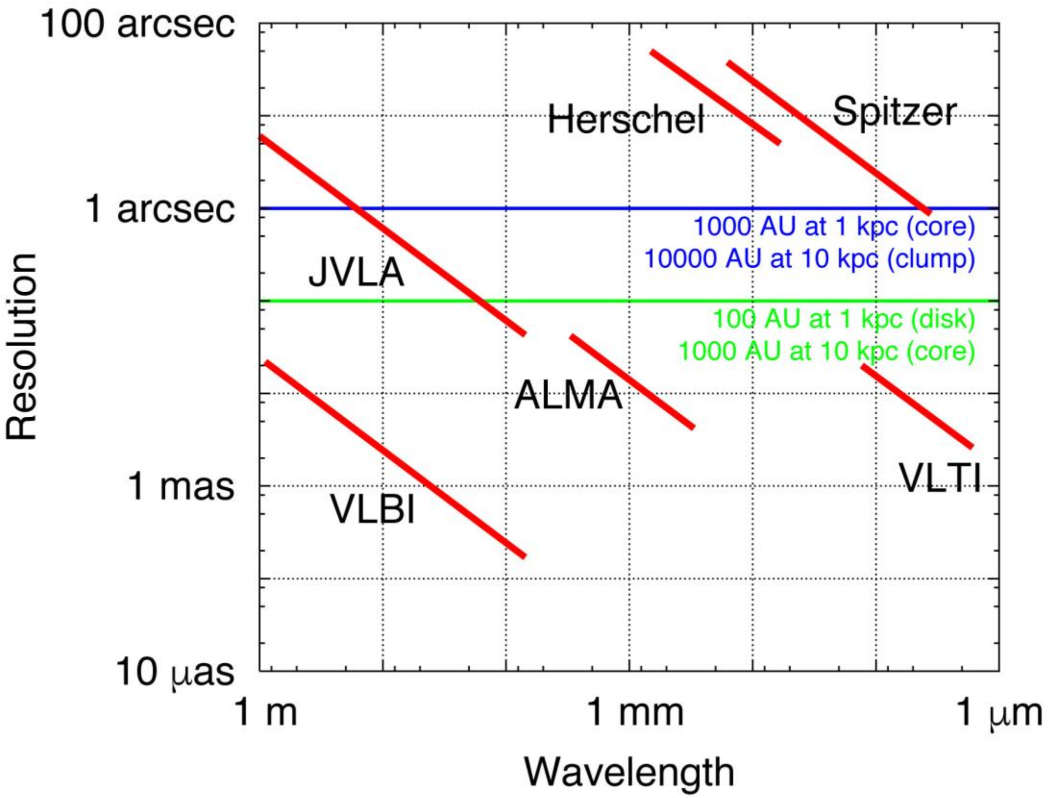
VLBA



Why so difficult?

- Observationally still challenging
  - Usually formed in clusters
  - Extremely high opacities unreachable at IR or shorter wavelengths
  - Only achievable by interferometers to resolve innermost structures





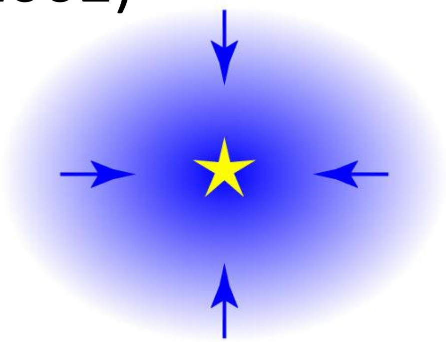
Fundamental questions

- How can HM-protostellar objects accrete their mass within short lifetime against strong feedback?
- What is initial condition for HM star-formation?
- How is stellar initial mass function determined?
- How to solve these problems?
  - Study dynamical properties from host clouds to HM-YSOs
  - Chemistry complementary to physical/dynamical properties
  - Theoretical works also essential to interpret observational results

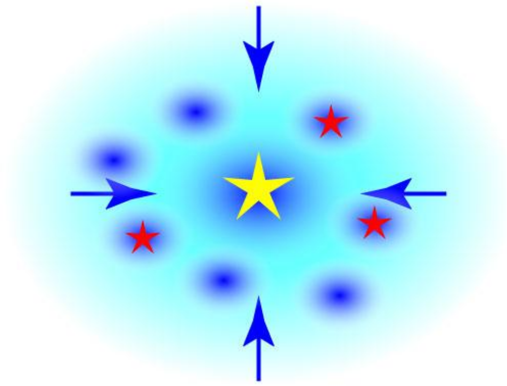
Accretion at clump and core scale

- Two controversial theories

- Turbulent core accretion (e.g. McKee & Tan 2002)
  - Scale-up of low-mass case (monolithic collapse)
  - High mass single YSO (binary or small cluster) formed in a single massive turbulent core
  - Forming disk/outflow system

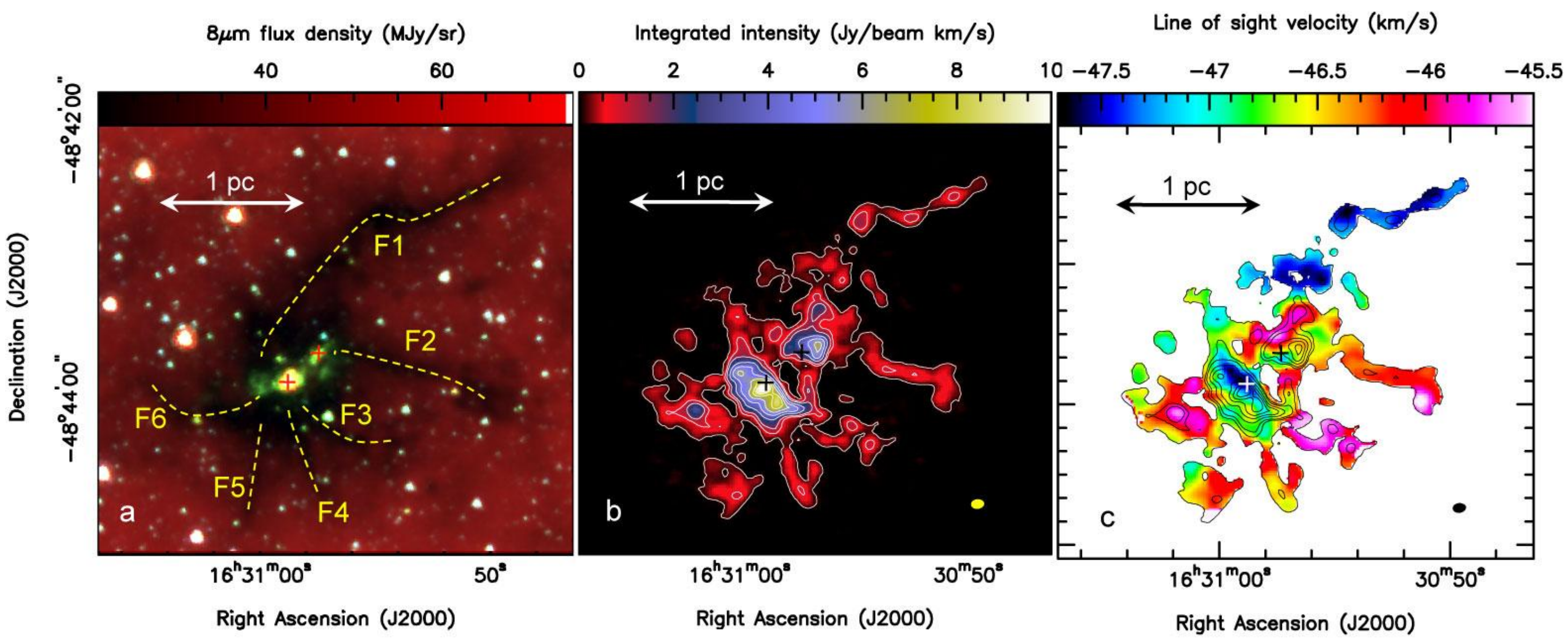


- Competitive accretion (e.g. Bonnel+1997)
  - High mass YSO formed in the center of low-mass cores/YSOs via global collapse
  - Fragmentation into small cores with thermal Jeans mass
  - More disturbed disk/outflow system



Infrared dark clouds (IRDCs)

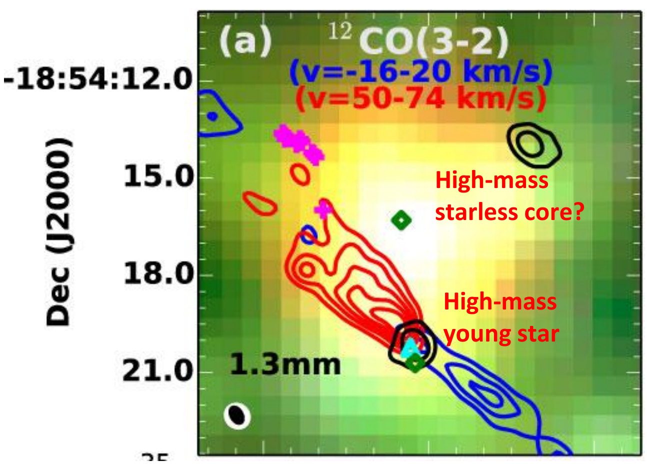
- Good laboratory for investigating initial conditions
  - Characteristic filamentary structures sometimes with global inflow
  - e.g. SDC335; most massive core in the Galaxy (545 M_{Sun} at MM1) at infalling rate of $2.5x10^{-3}$ $M_{Sun}yr^{-1}$; Peretto+2013, Avison+2015)



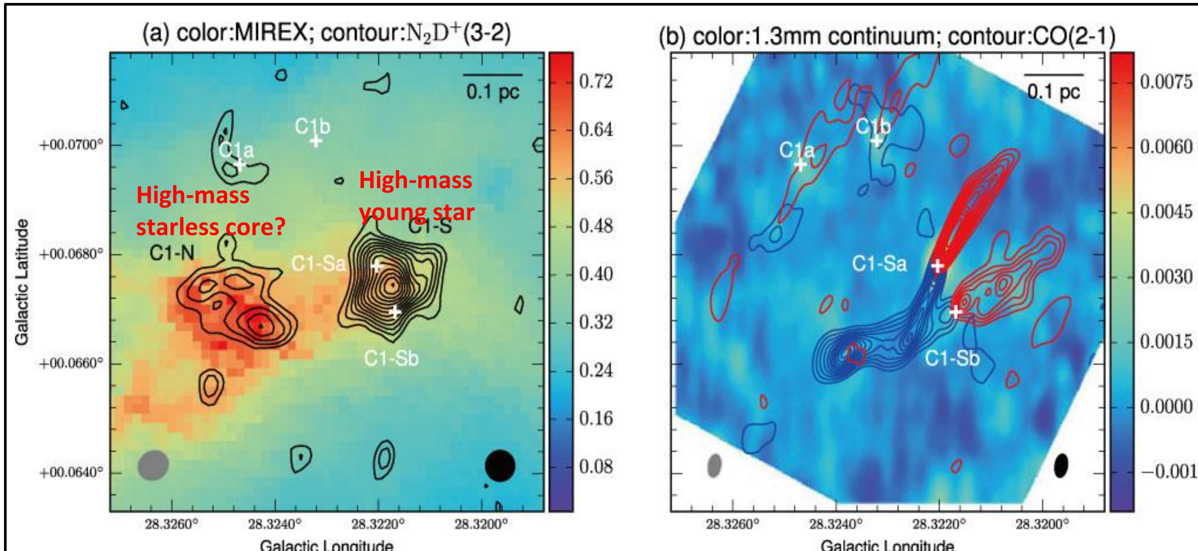
Spitzer image, intensity, and velocity maps of N_2H^+ (1-0) line in SDC335.579-0.272 at 3.25 kpc (Peretto+2013, Avison+2015)

Infrared dark clouds (IRDCs)

- Search for massive starless (prestellar) cores/clumps
  - e.g. G011.92-0.61 MM2; massive (>30 M_{Sun}) core without any sign of star-formation activity (Cyganowski+2014, 2017)
  - e.g. G028.37+00.07; chemically evolved, massive (~60 M_{Sun}), magnetically virialized starless cores (Tan+2013, 2016, Gong+2016)
  - Still rare cases (and still not convincing)



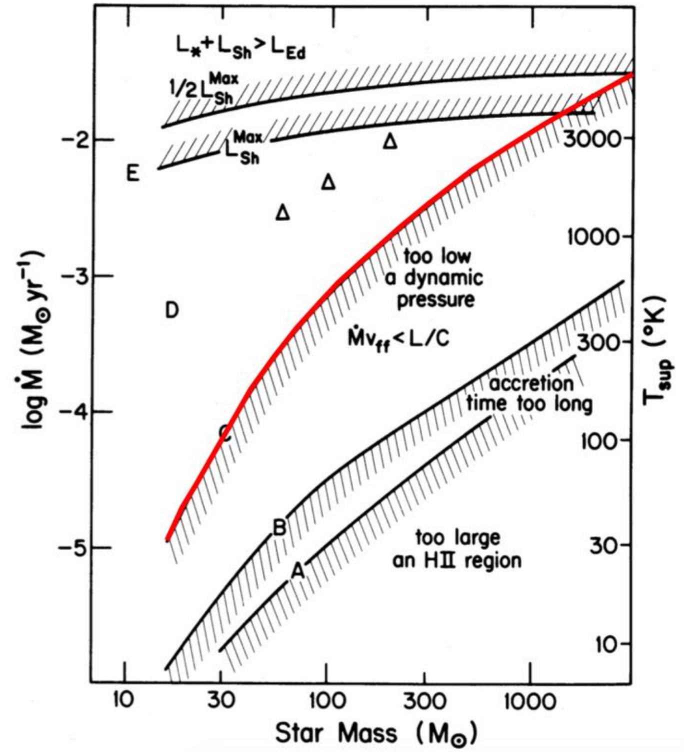
CO (3-2), 1.3mm continuum, and Spitzer maps of G11.92-0.61 at 3.37 kpc (Cyganowski+2014)



N2D+ (3-2) maps superposed on MIR extinction image of Spitzer and CO (2-1) outflow map of IRDC G028.37+ 00.07 at 5 kpc (Tan+2013, 2016, Kong+2016)

Accretion at YSO scale

- Well known feedback problem
  - Accretion suppressed by strong radiation pressure
  - Higher accretion rate than low-mass YSOs
  - Solved by non-isotropic accretion through disk ("flashlight effect"; Yorke & Bodenheimer 1999)



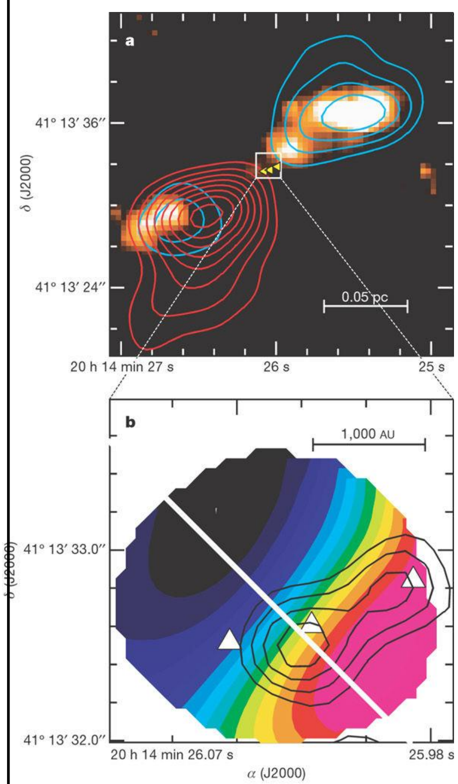
Possible stellar mass as functions of mass accretion rate (Wolfire & Cassinelli 1987)

IR image of IRAS20126+4104, suggesting outflow cavity and edge-on disk (Cesaroni+2013)

Circumstellar disks before ALMA

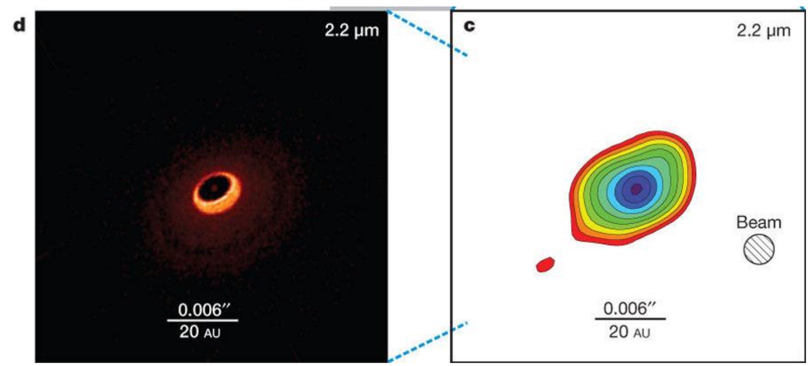
- Discovered by various tools, but mostly in B-type YSOs

Millimeter line (PdBI)



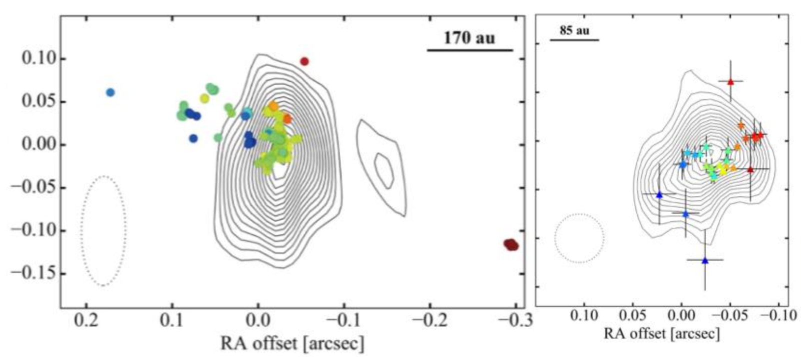
Molecular line maps of IRAS 20126+4104 by PdBI (Cesaroni+2006)

NIR continuum (VLTI)



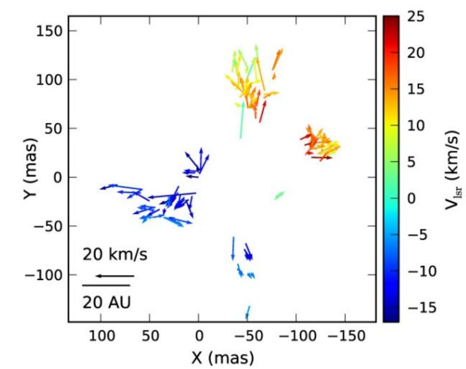
Model and VLTI image of IRAS 13481-6124 (Kraus+2010)

Radio continuum (VLA)

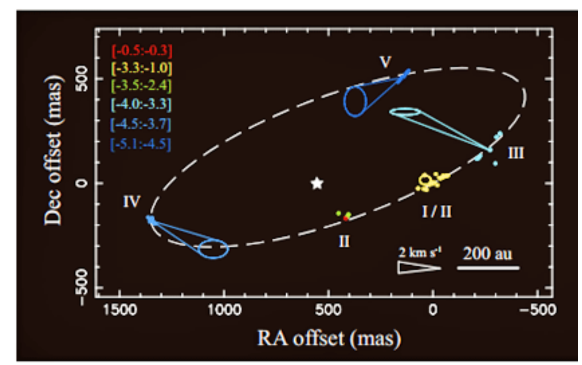


H_2O (left) and CH_3OH (right) masers and VLA continuum map in G353.273+0.641 (Motogi+2017)

Masers (VLBI)



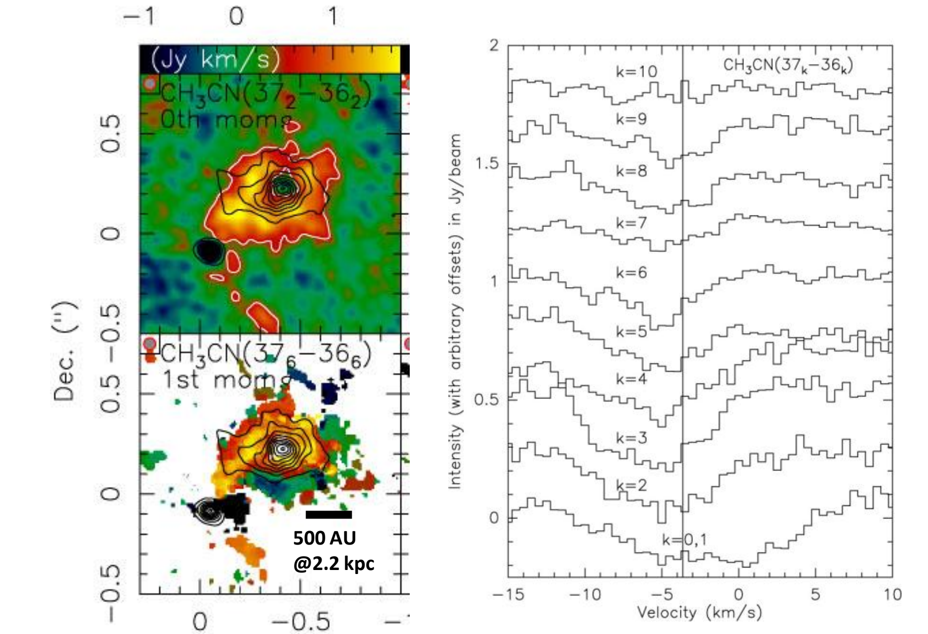
SiO maser map of Orion Source I by VERA (Kim+2008)



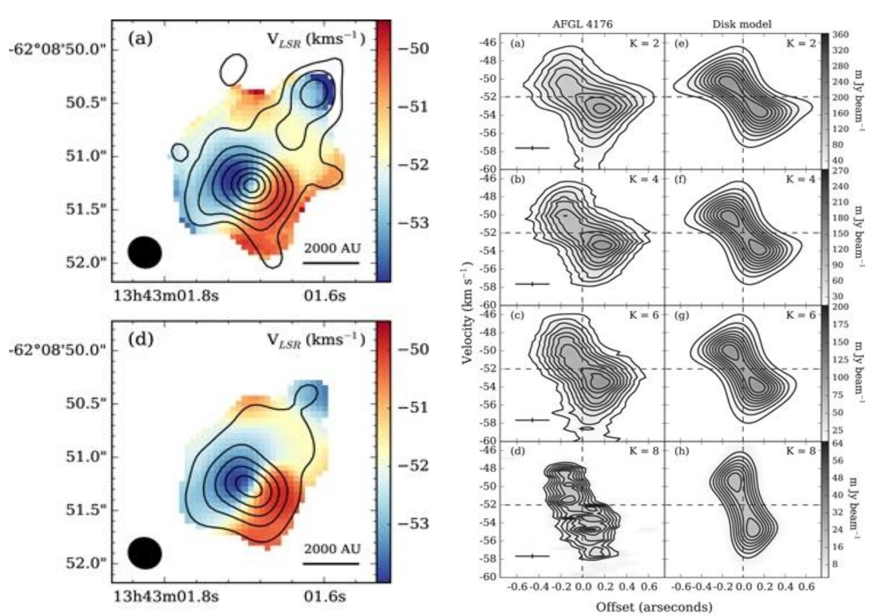
CH_3OH maser map of Cepheus A by JVN(Sugiyama+2014)

Circumstellar disks seen by ALMA

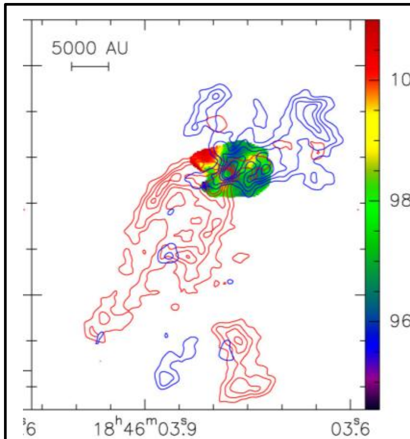
- Even for distant O-stars
  - Keplerian rotation, infall
  - Accretion rate ~$10^{-3} M_{Sun}\ yr^{-1}$
  - More complicated due to outflow, fragment, binary?

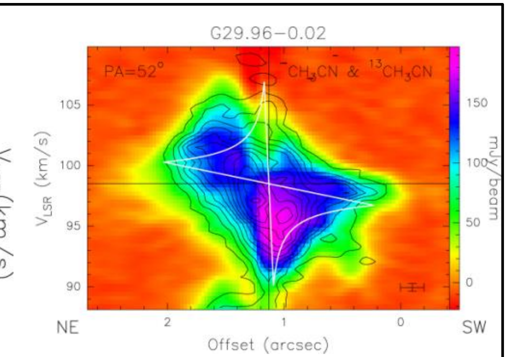


Map and spectra of G351.77-0.54 at 2.2/1 kpc (Beuther+2017)



Keplerian disk around AFGL4176 at 4.2 kpc (Johnston+2015)

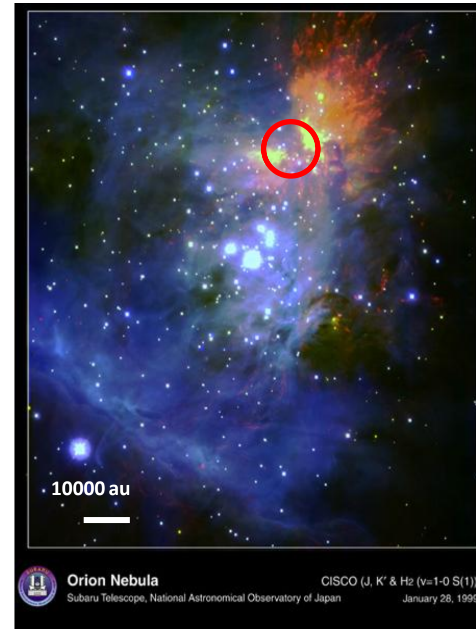




Outflow and disk in G29.96 at 5.26 kpc (Cesaroni+2017)

Case study of disk/outflow in Orion

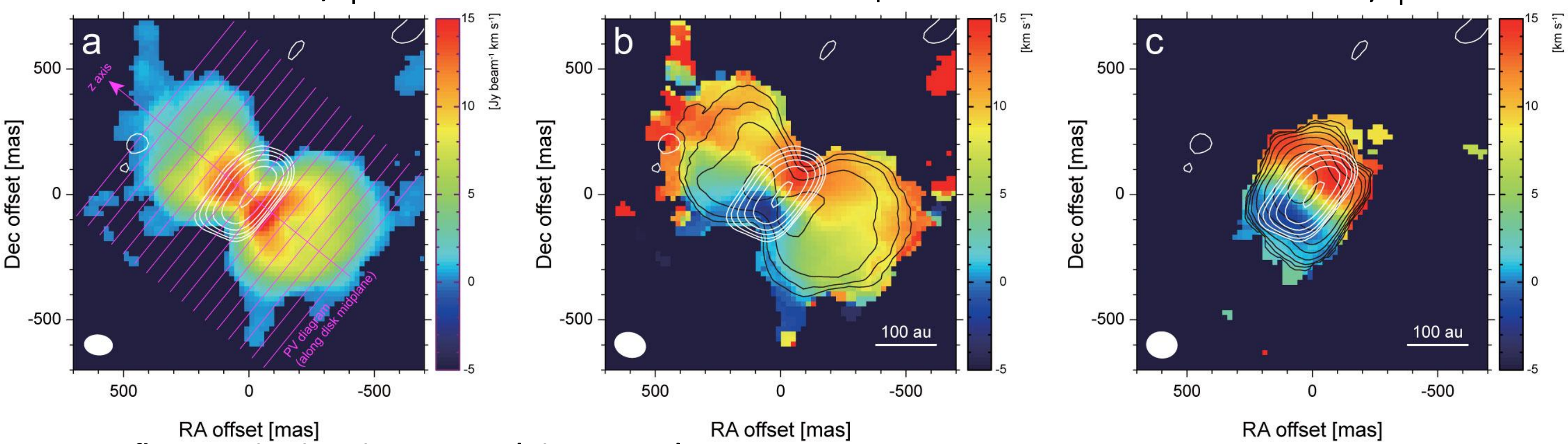
- Radio source I in Orion KL
  - One of the well studied high-mass YSO
  - ALMA observations of high-energy lines at 0.1” resolution (~42 au at 420 pc distance; (Hirota+2007, Menten+2007, Kim+2008)
  - Velocity gradient perpendicular to outflow



Moment 0 of $Si^{18}O$ J=12-11 484 GHz at Band 8, E_l=128 K

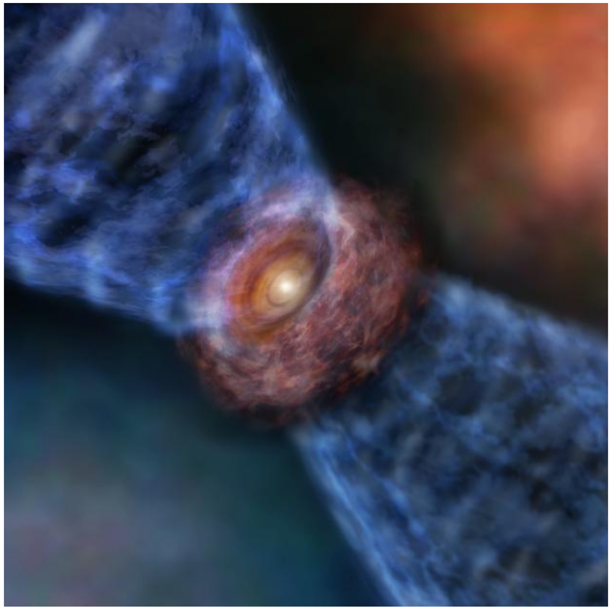
Moment 1 of $Si^{18}O$ J=12-11 484 GHz at Band 8, E_l=128 K

Moment 1 of H_2O v=1 $4_{2,2}$-$3_{3,1}$ 463 GHz at Band 8, E_l=2744 K

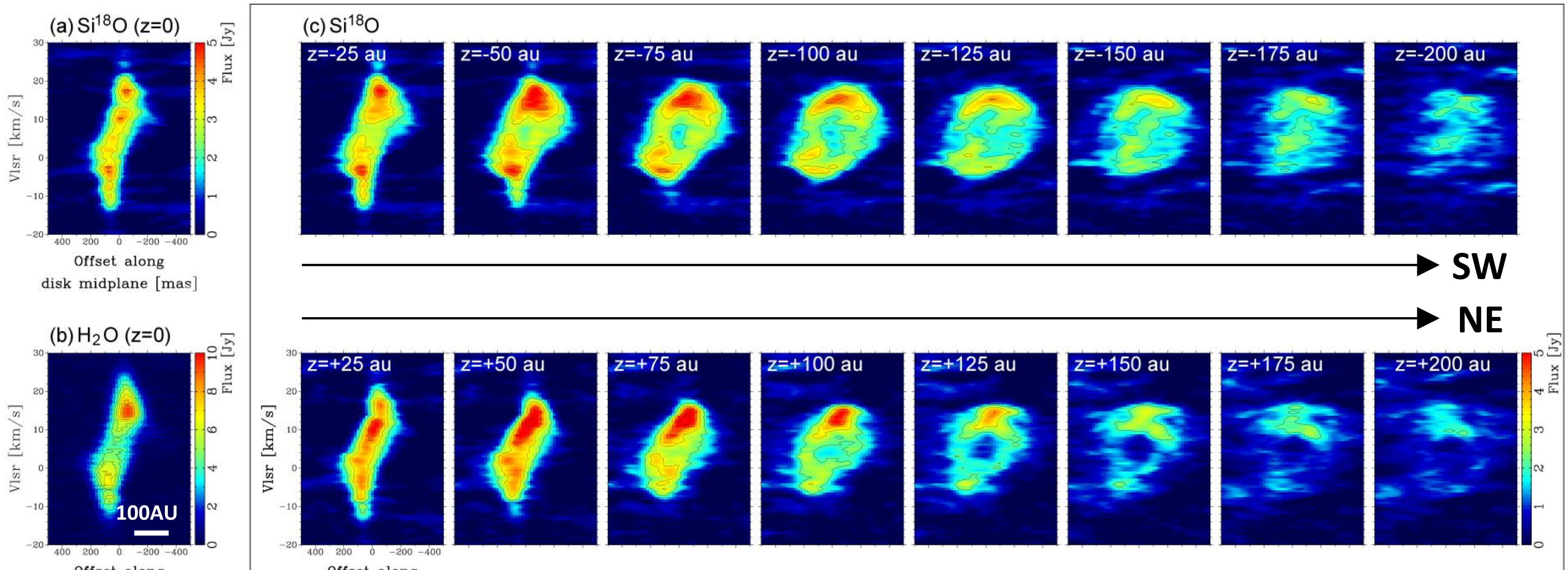


Outflow rotation in Orion Source I (Hirota+2017)

Detailed structure of outflow



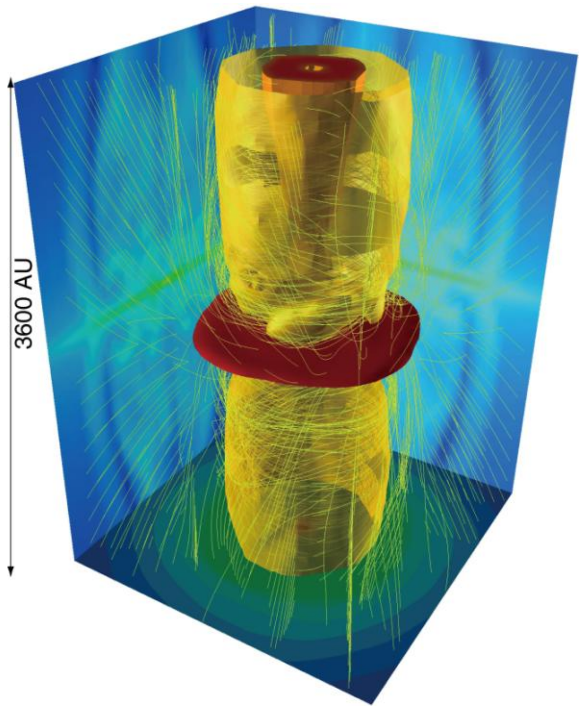
- Rotating and expanding structure
  - Enclosed mass of 8.7+/-0.6 M_{Sun}
  - Centrifugal radii of 21-47 au
  - Velocity of ~10 km s^{-1} (no high velocity jet)
  - Rotating and radially expanding outflow



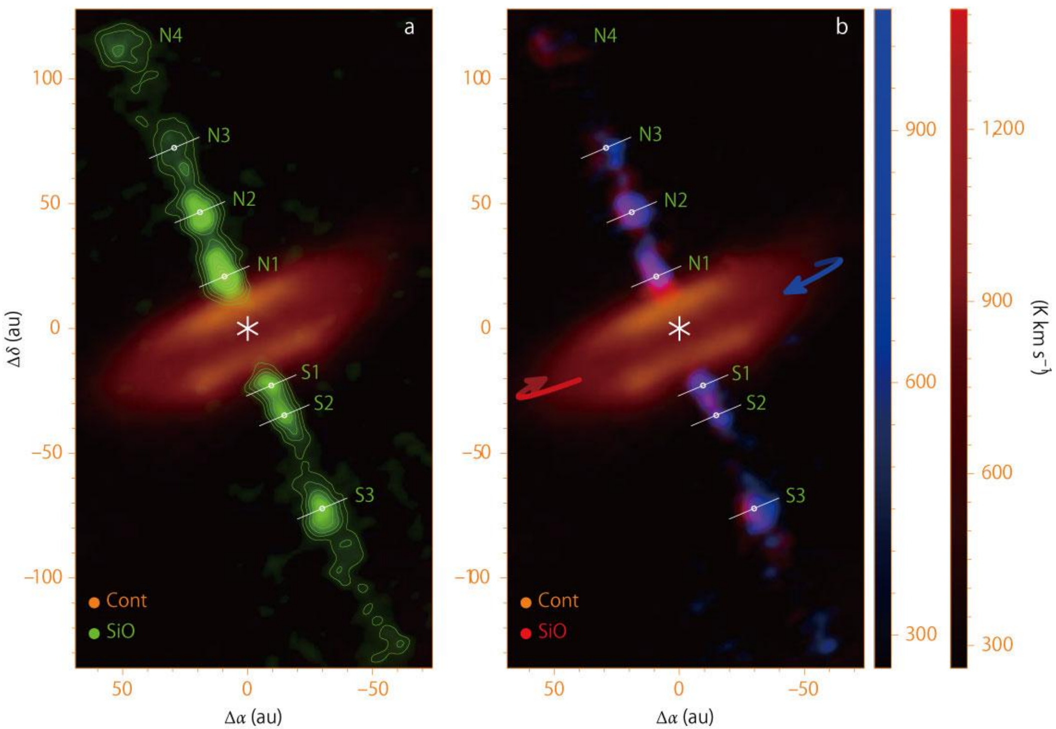
PV diagram in Orion Source I (Hirota+2017)

Evidence of rotating outflow/jet

- Consistent with magneto-centrifugal disk wind model
  - Possible Solution for angular momentum problem
  - Same as low-mass YSOs
  - Still challenging, need more data (see review by Belloche+2013)



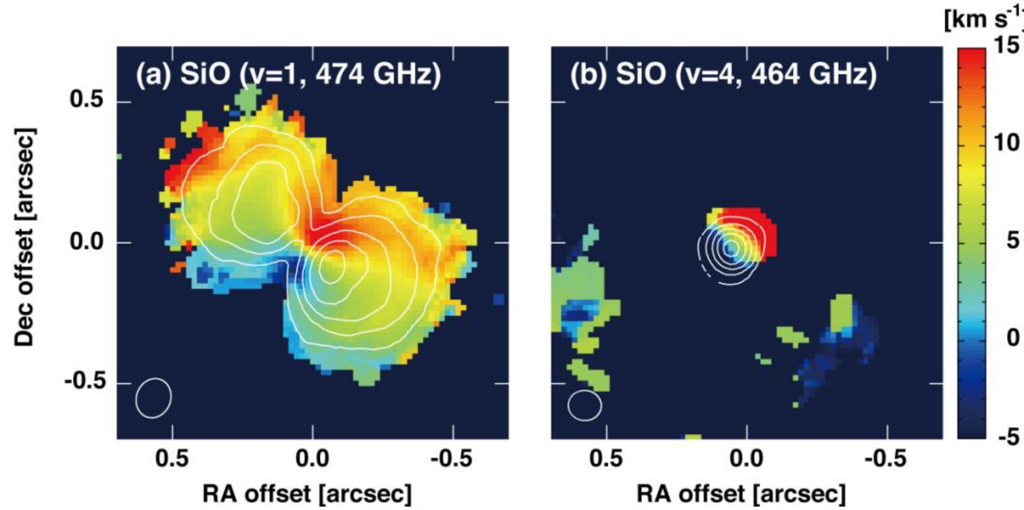
Model of high-mass protostar outflow (Matsushita+2017)



Jet rotation in a low-mass Class 0 protostar HH212 (Lee+2017)

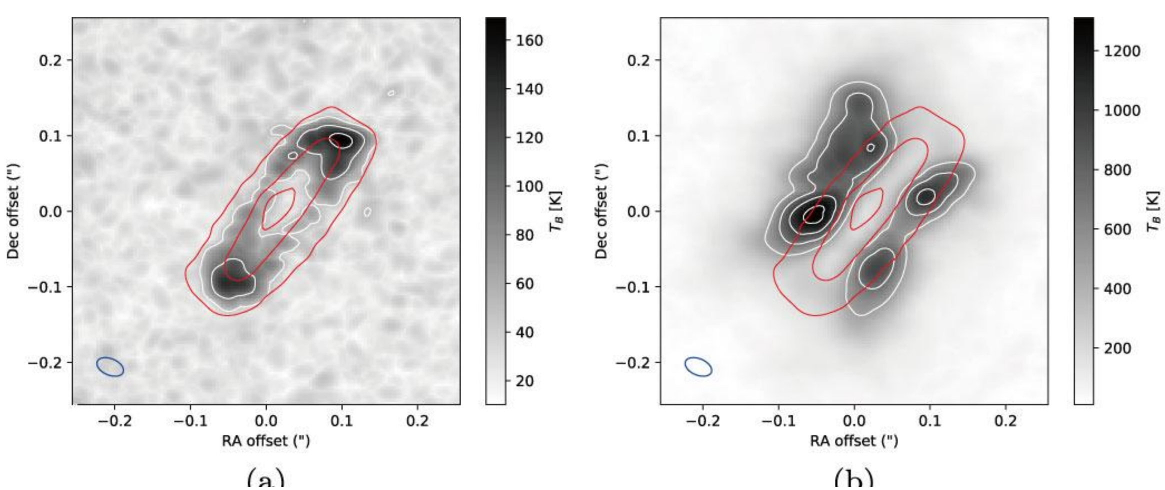
More recent studies

- High excited lines of H_2O, SiO, and their isotopologues
  - Recall Wong's talk (AGB)

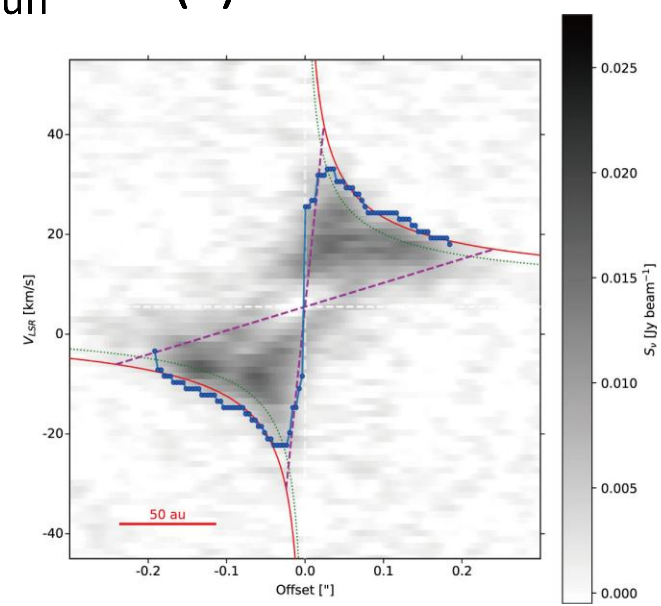


Moment 0/1 maps SiO v=1 and v=4, J=11-10 line (Hirota+2018)

- Keplerian rotation around 15+/-2 M_{sun} YSO(s)

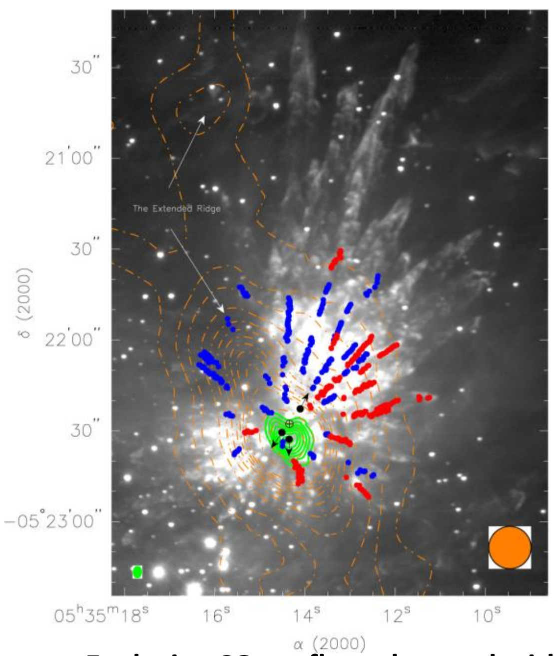


Moment 0 maps of U230.322 and 232 GHz H_2O (v=1) lines (Ginsburg+2018)

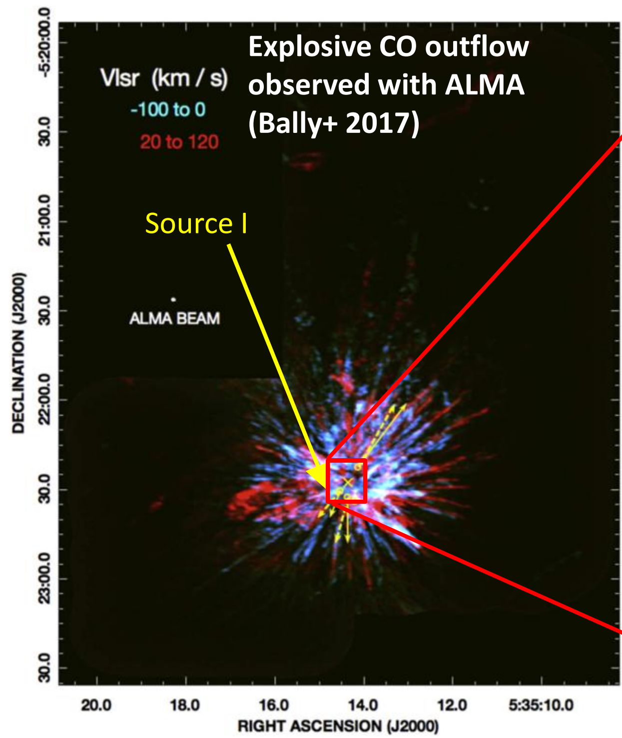


Complex structure of outflows

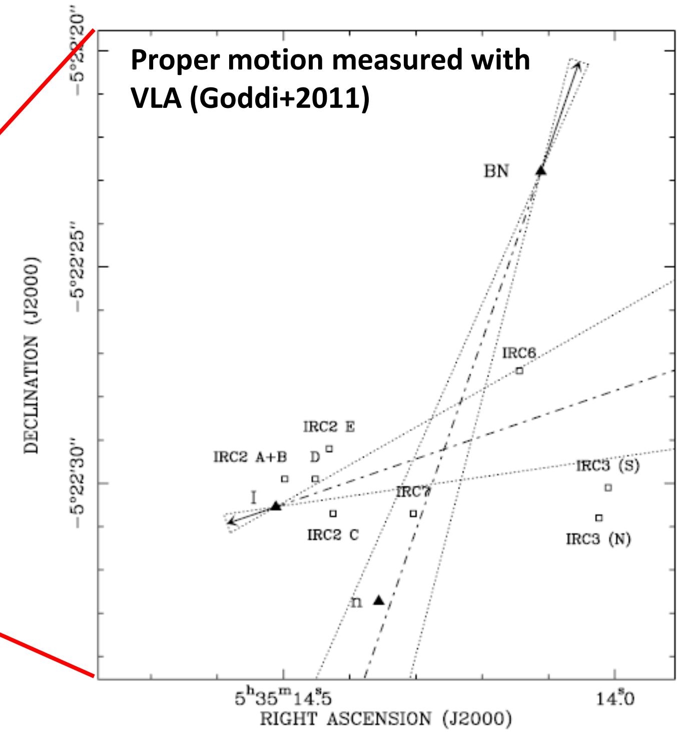
- Bipolar and explosive outflows in Orion KL
  - Energy release of 10^{48} erg via dynamical decay of multiple system (e.g. Rodriguez+2017, Orozco-Aguilera+2017, Bally+2017)
  - Formation of a binary with ~$20M_{Sun}$ (Ginsburg+2018)



Explosive CO outflow observed with SMA (Zapata+2011)



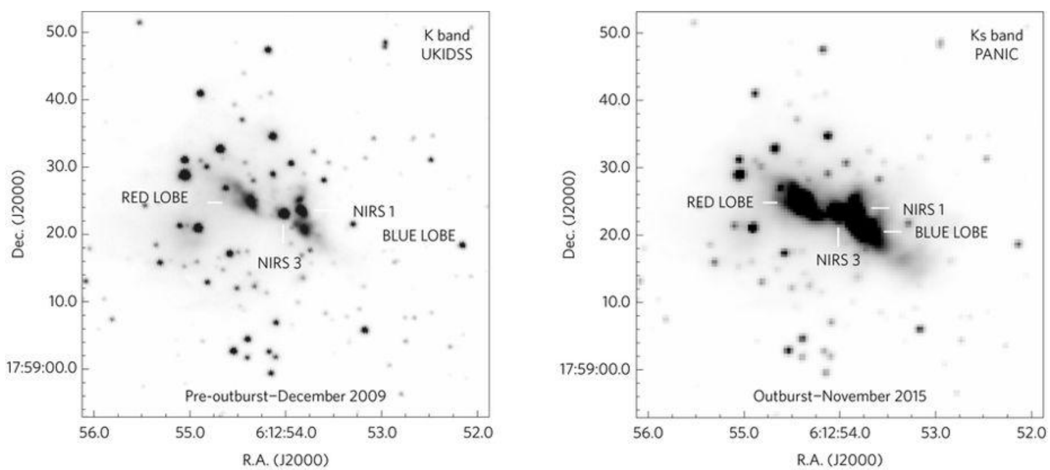
Explosive CO outflow observed with ALMA (Bally+ 2017)

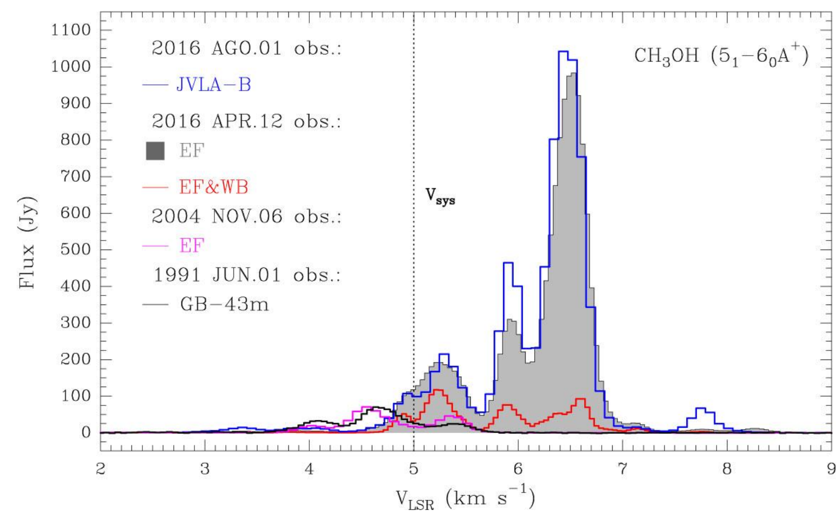


Proper motion measured with VLA (Goddi+2011)

Accretion burst in HM-YSOs

- Luminosity in S255 NIRS3 from $2.9 \times 10^4 L_{Sun}$ to $1.6 \times 10^5 L_{Sun}$
  - First detected by methanol maser flare by single-dish monitoring (Fujisawa+2016, Moscadelli+2017)
  - Subsequent follow-up observations in continuum from IR to radio (Caratti o Garatti+2016, Cesaroni et al. 2018)
  - Suggesting accretion burst with mass accretion rate of 5×10^{-3} M_{Sun}

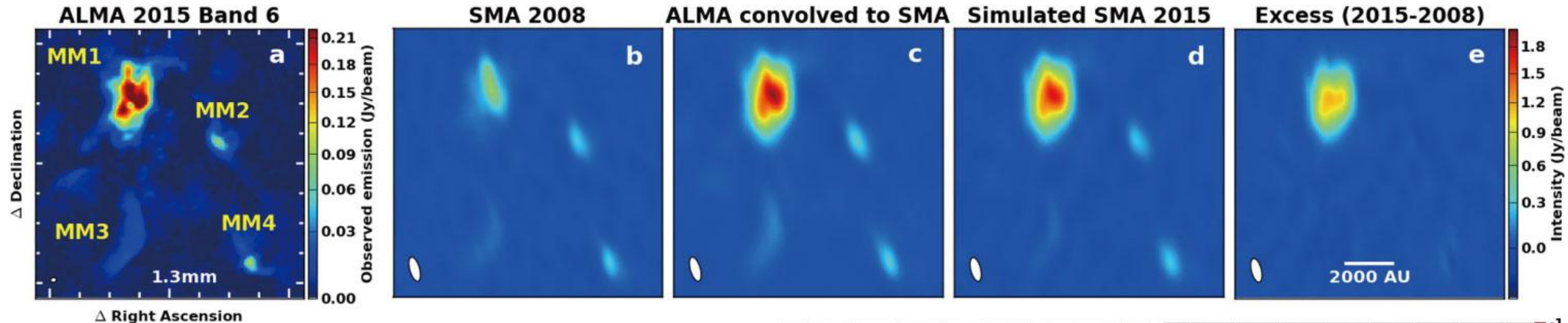


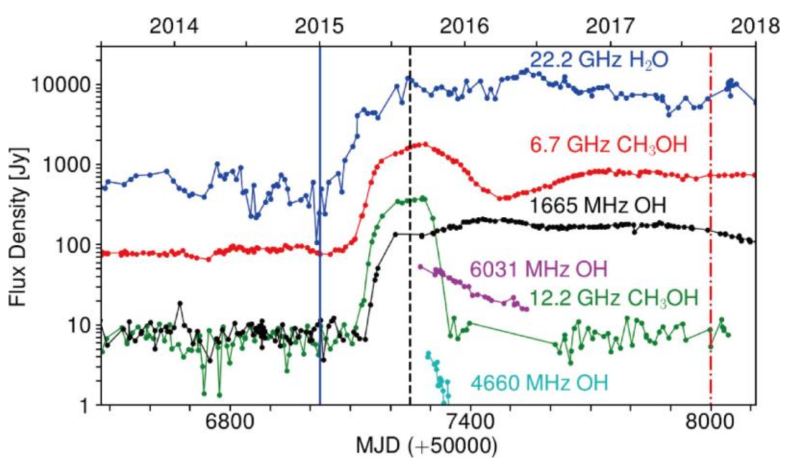


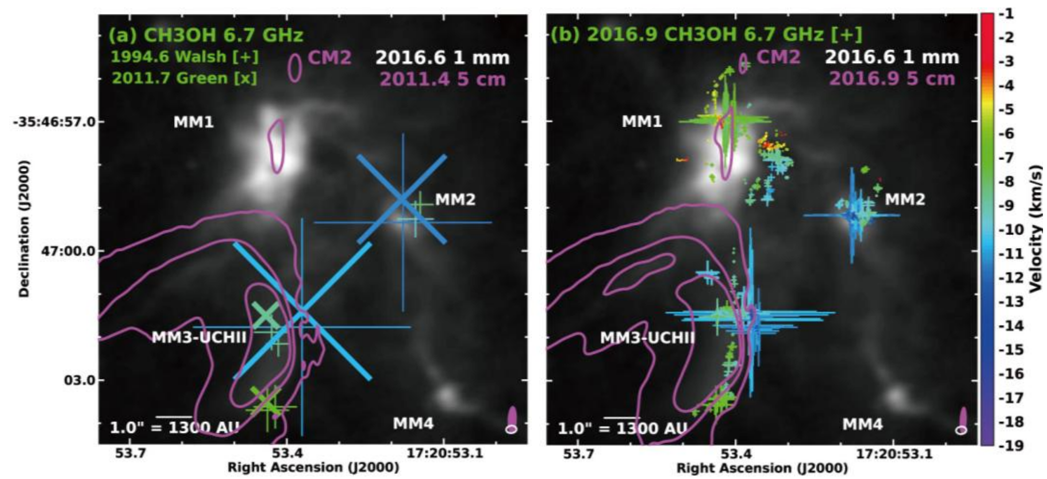
Infrared flare (Caratti o Garatti+2016) and methanol maser flare in S255 at 1.8 kpc (Moscadelli+2017)

Accretion burst in HM-YSOs

- Luminosity increase by 70 ($4.2x10^4L_{Sun}$) in NGC6334I MM1
  - Both continuum and masers (Hunter+2017, MacLeod+2018)
  - Masers can be unique probes for episodic accretion burst







Millimeter and maser outburst in NGC6334I MM1 (Hunter+2017, 2018, MacLeod+2018)

Summary and future prospects

- Observational studies at high resolution/sensitivity reveal
  - Global structure of IRDC clumps/cores
  - Potential but not convincing candidates of massive prestellar cores
  - Disks around O- and B-type YSOs with possibly Keplerian rotation
  - Outflow rotation in Orion Source I similar to low-mass YSOs
  - Episodic accretion burst events also identified by maser variability

- Not discussed in my talk but here emphasize importance of
  - Theoretical works to cover large dynamic range of HM-SFRs
  - Further systematic survey at higher resolution/sensitivity
  - In particular chemistry and polarization (magnetic field)