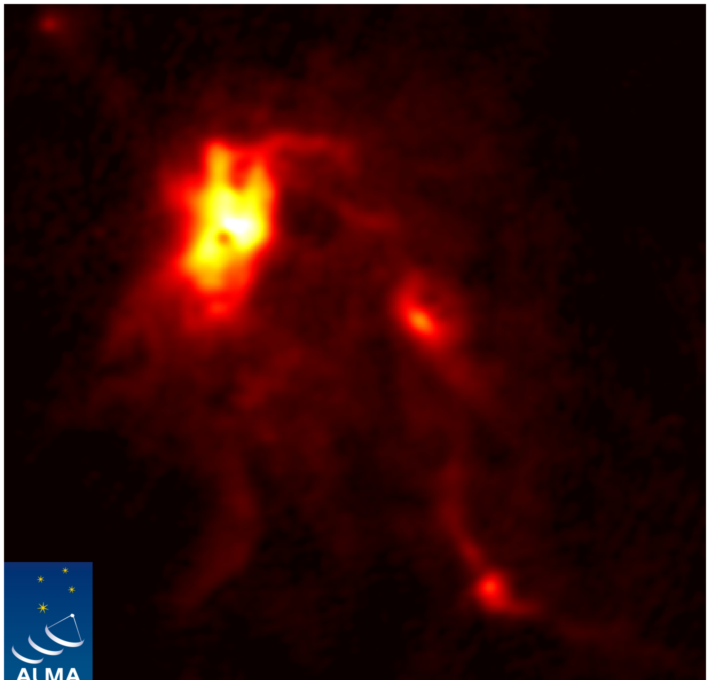
An accretion outburst in NGC6334I-MM1: New insights into massive protostellar evolution



1 mm image of NGC6334I - 200 AU resolution

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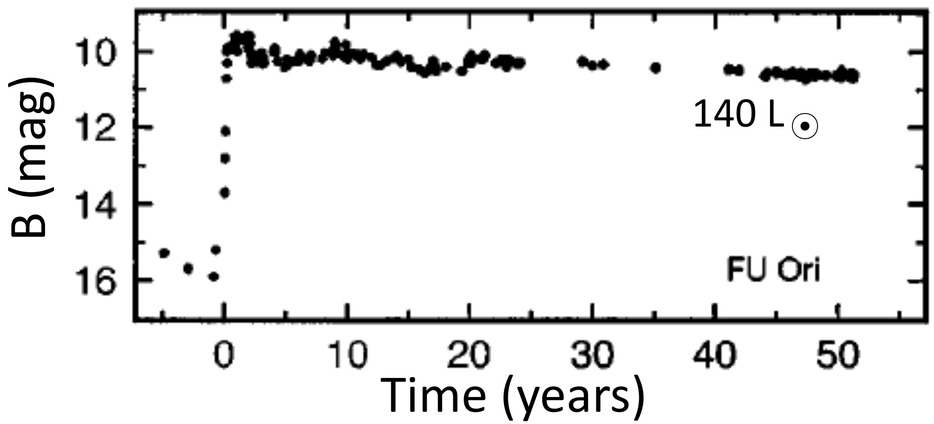
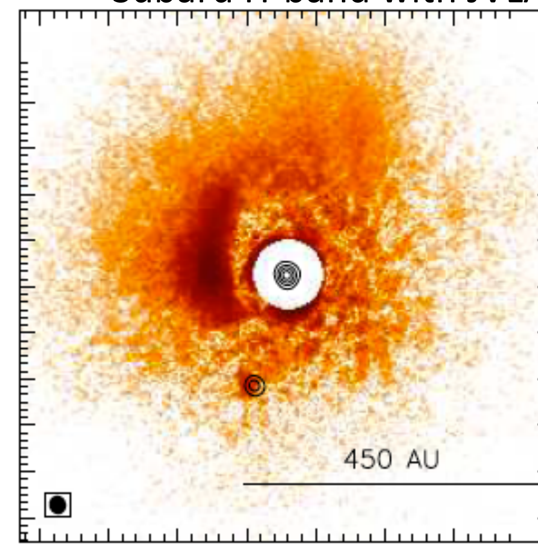
Lots of evidence for episodic accretion

- Classical FU Ori stars: Kenyon & Hartmann (1996)
  - >100x brightness boost lasting for decades
  - Increased accretion rate through disk (Liu+2017)



Subaru H-band with JVLA



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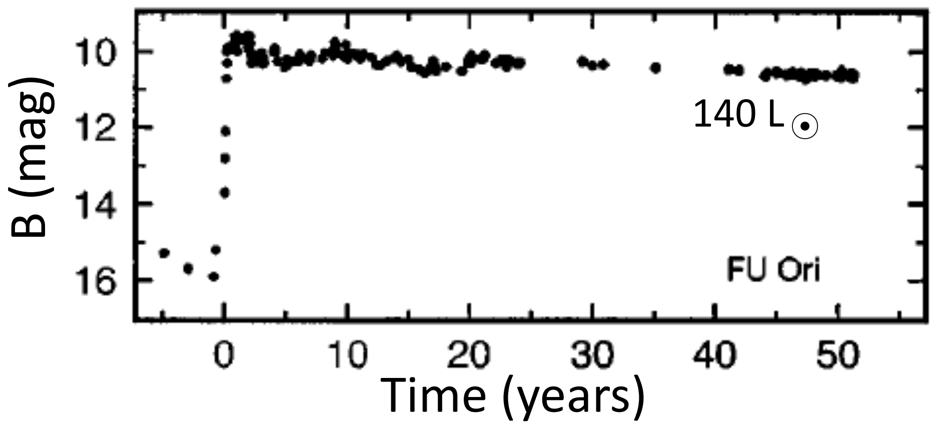

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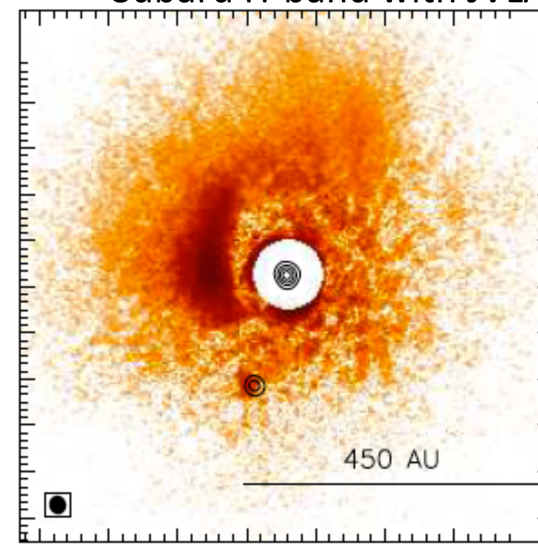


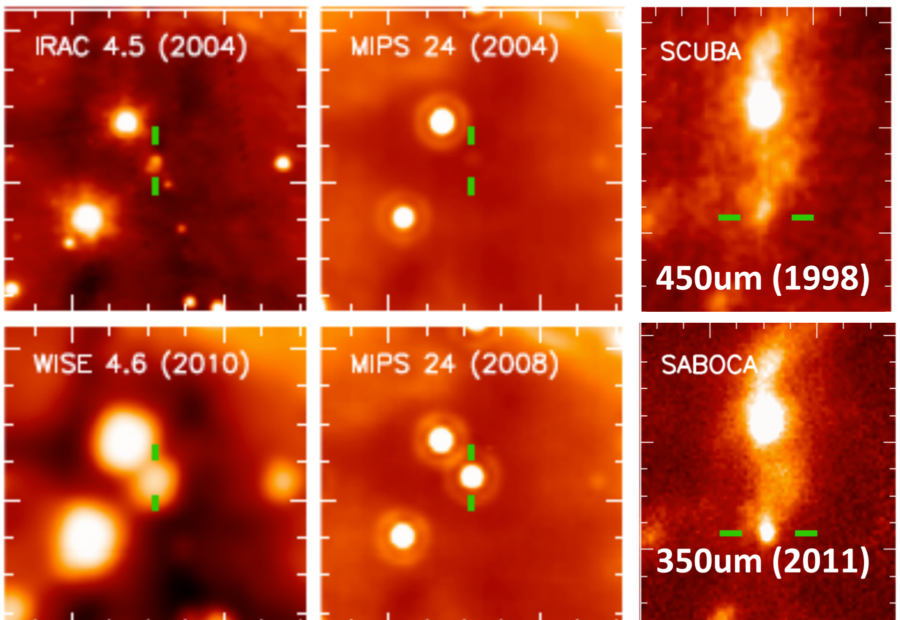
- Spitzer c2d Legacy results: most YSOs are underluminous relative to evolutionary models with a constant or decaying accretion rate (Evans et al. 2009)
- Also see Poster PM19 (Lucas) on UKIDSS & VVV surveys finding hundreds of Near-IR variable YSOs

First outbursts recently identified in younger protostars

Low-mass Class 0: HOPS 383

(Safron et al. 2015)

- Flared by 35x at 24um between 2004-2008
- Luminosity rose by x30-50 (from 0.2 $L_\odot$ to 6-10 $L_\odot$), no significant fading over 6 years
- Similar to FU Ors, but 15x less luminous



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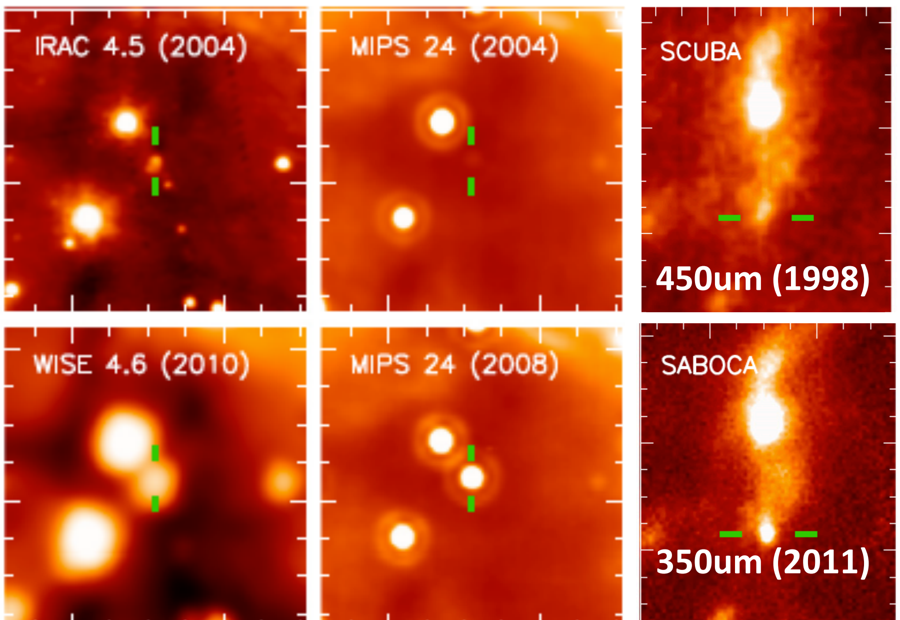
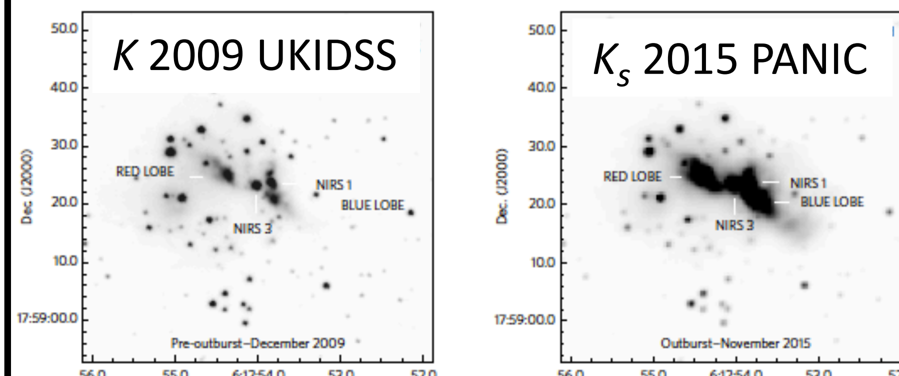


Massive YSO: S255IR-NIRS3

(Caratti o Garatti et al. 2016)

- Flared by 30x at 60um between 2009-2015
- Luminosity rose 6x (0.29e5 to 1.6e5 $L_\odot$) with no fading over 1.5 years; E ~ 10^{46} erg

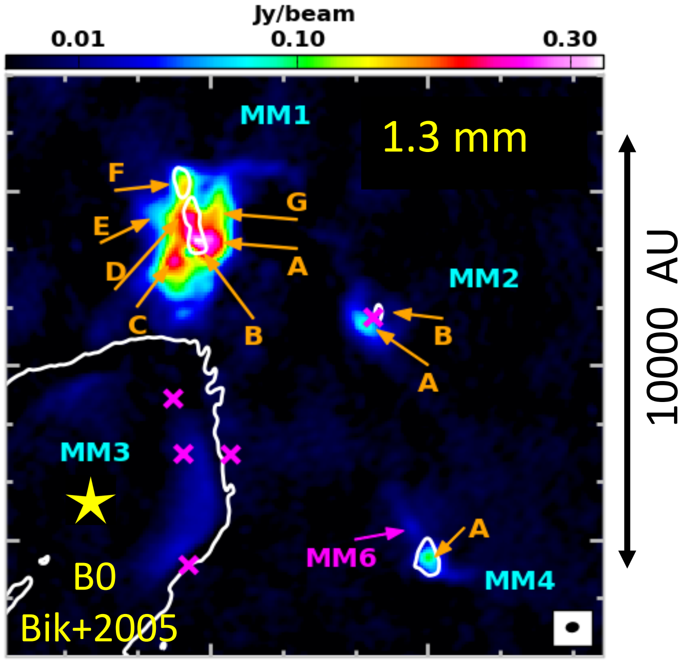


Dust in surrounding envelope is heated rapidly:

$t_{heating} = E_{abs}/L_{abs}$ << photon travel time
(Johnstone et al. 2013)

t_{photon} = 1200AU / c = **1 week**, 5000 AU~month

NGC6334 I: Diversity of members from SED models



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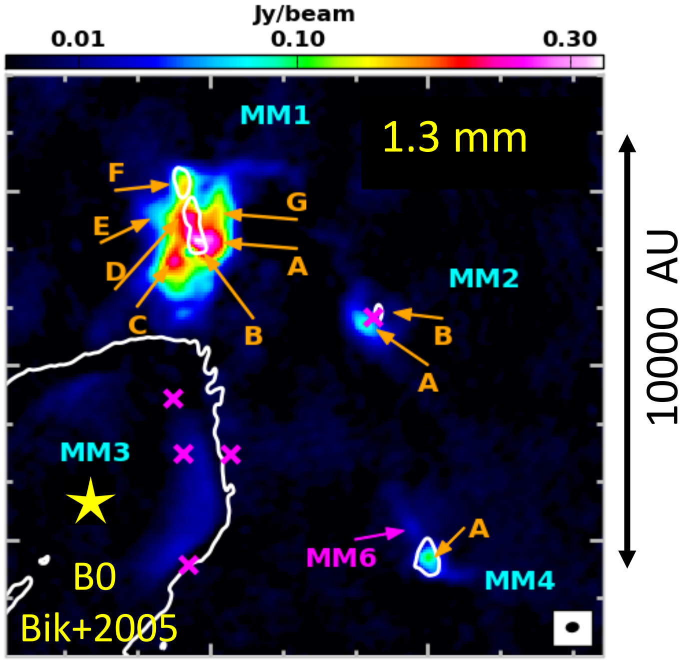

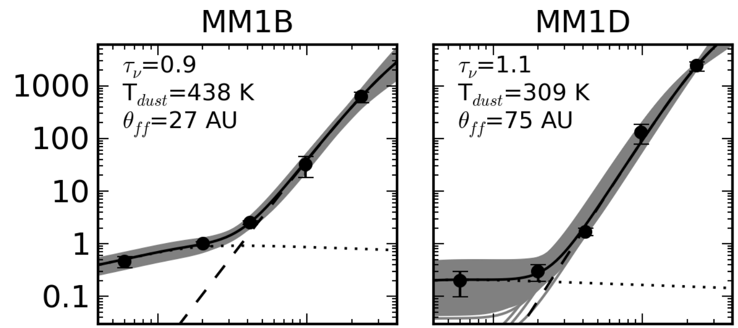

JVLA reveals that MM1 dust sources B and D also show free-free:

B: Hypercompact HII region (n_e=3x10^6 cm^{-3}), high turnover frequency; hottest dust (440 K)

D: 300K dust plus jet (n_e=3x10^5 cm^{-3})

Brogan, Hunter+ 2016, ApJ

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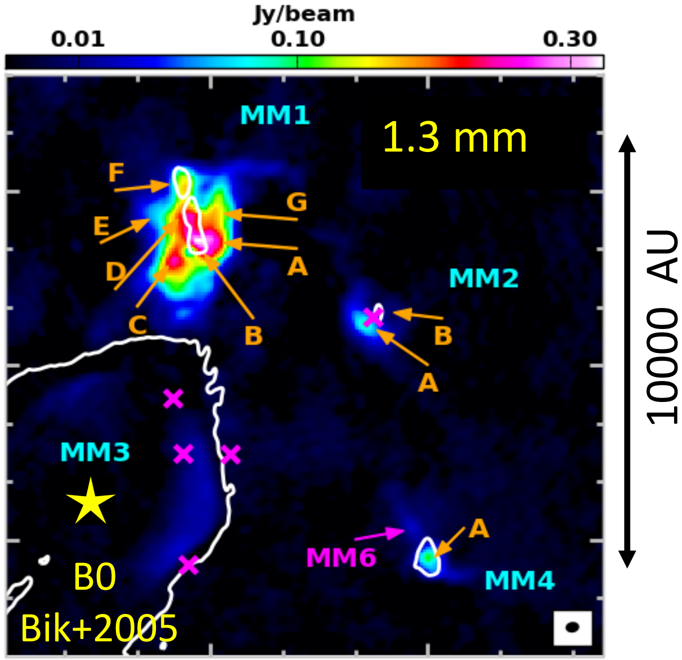

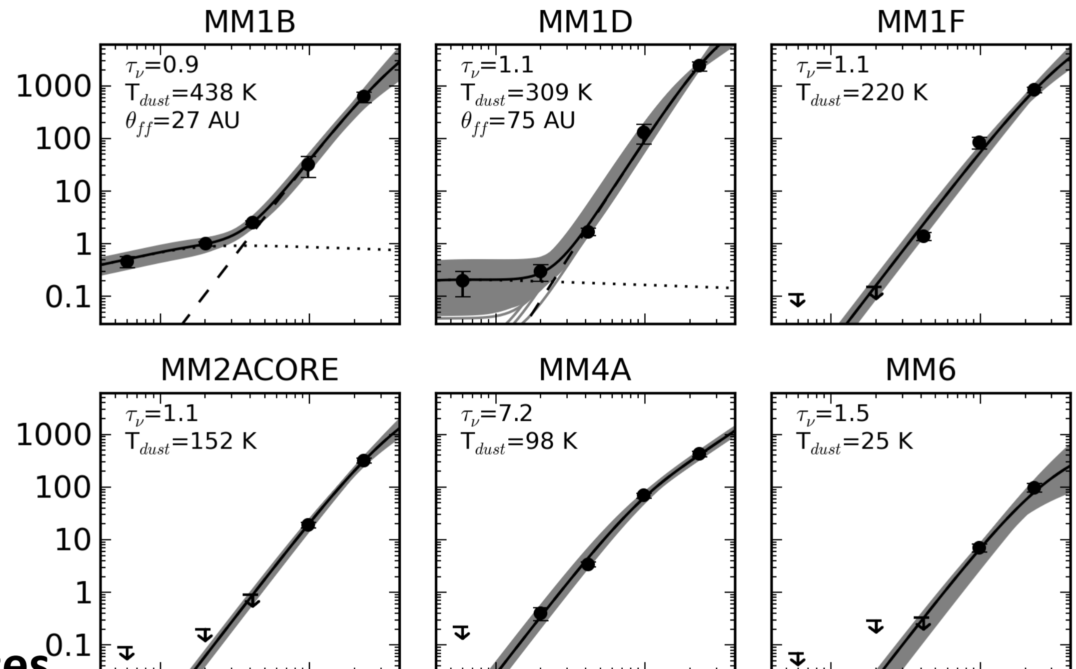

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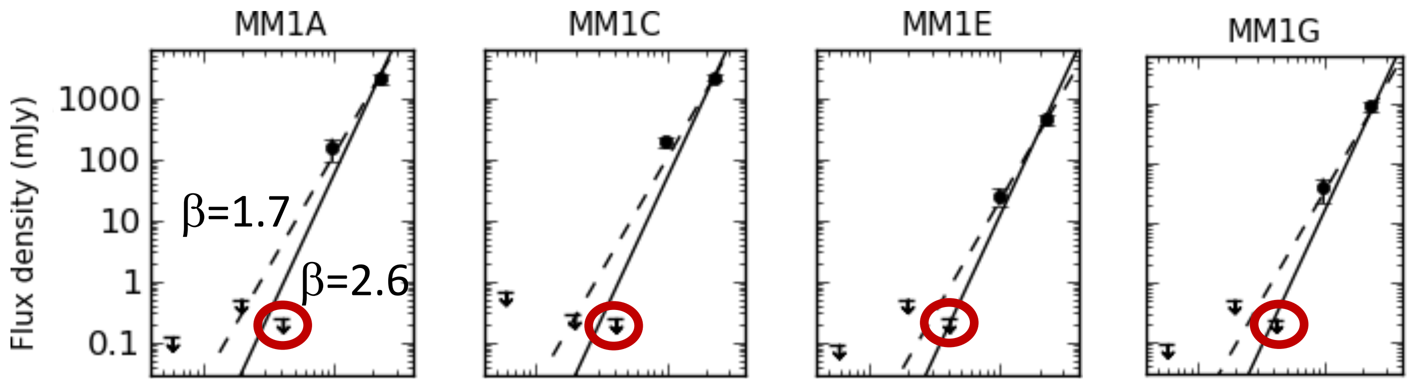
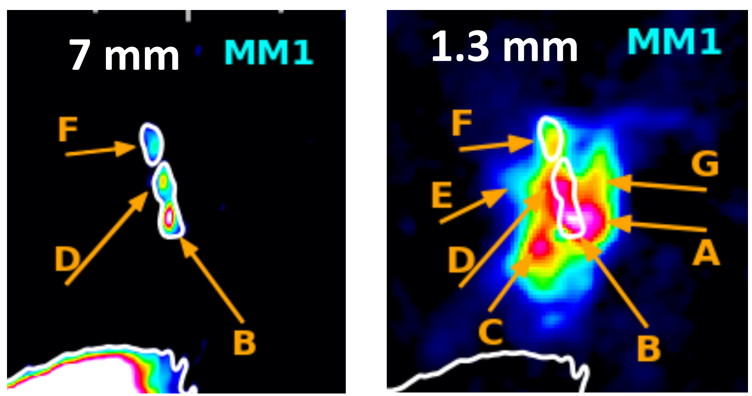
The MM sources other than MM1 and the UCHII can be fit by dust emission alone

Brogan, Hunter+ 2016, ApJ

Mystery: Some components of MM1 should have shown <u>much</u> brighter 7mm emission than observed





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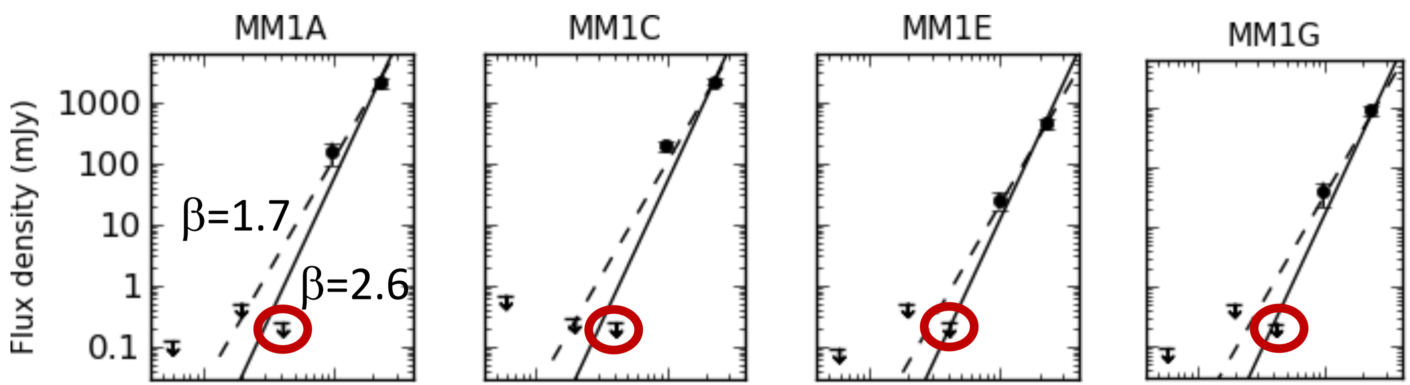
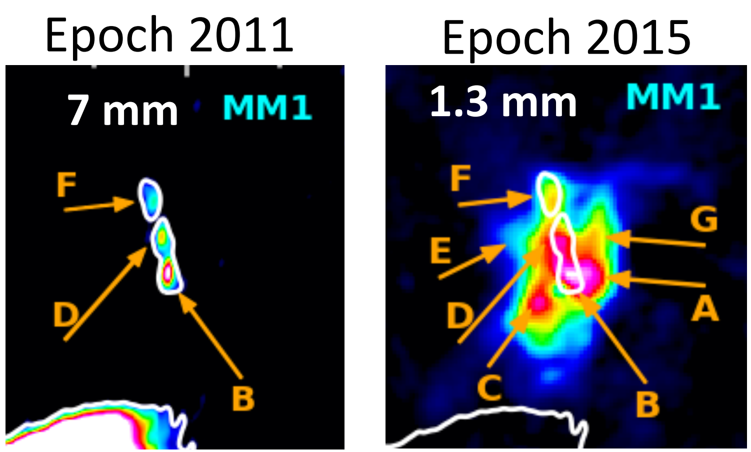




Possible explanations:

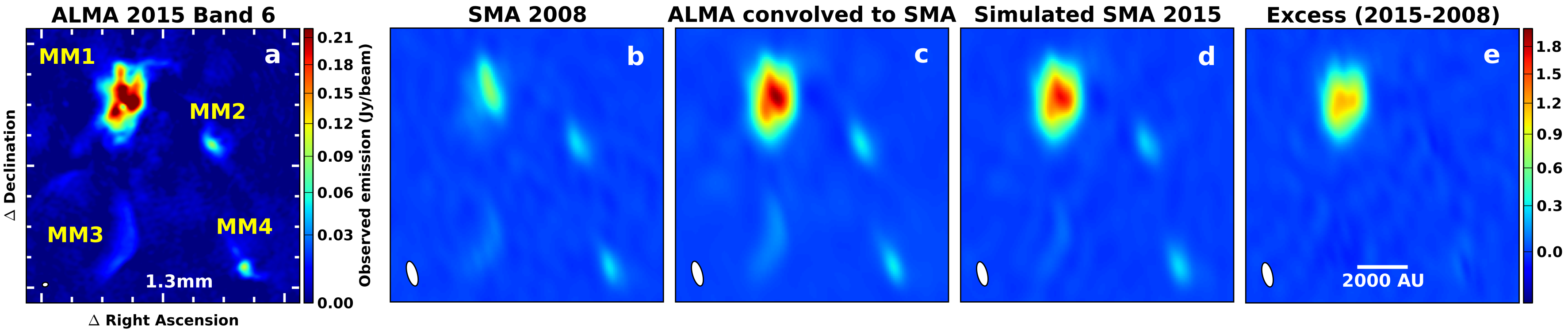
Time Variable?

or

Unusual dust properties?

Brogan, Hunter+ 2016, ApJ

An extraordinary brightening in Band 6 & 7 (2008-2015)



MM1 Band 6 flux density: 2008 SMA: 2.34 Jy Versus 2015 ALMA: 10.8 Jy

- Simulation: SMA could have recovered: 9.4 Jy
- Increase = factor of 3.9! No change in other 3 massive cluster members.

Hunter, Brogan+ 2017

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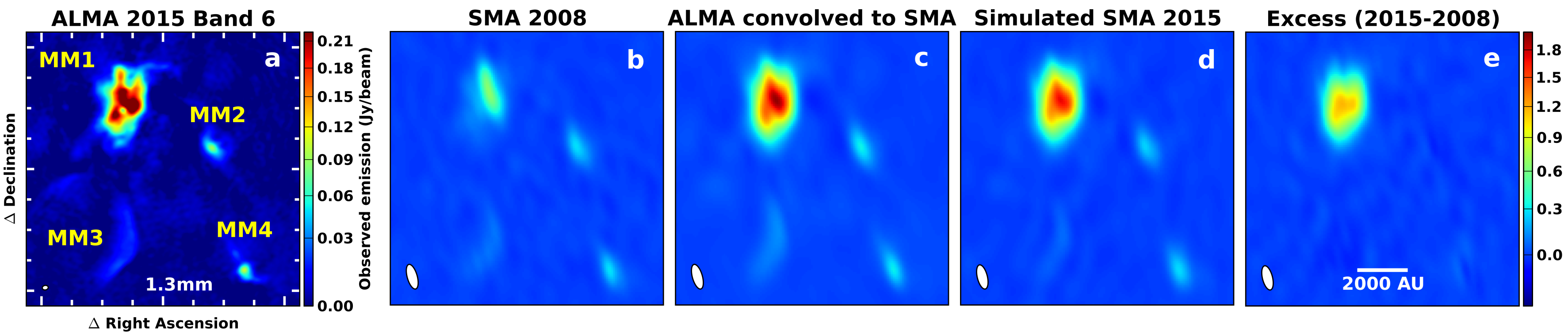

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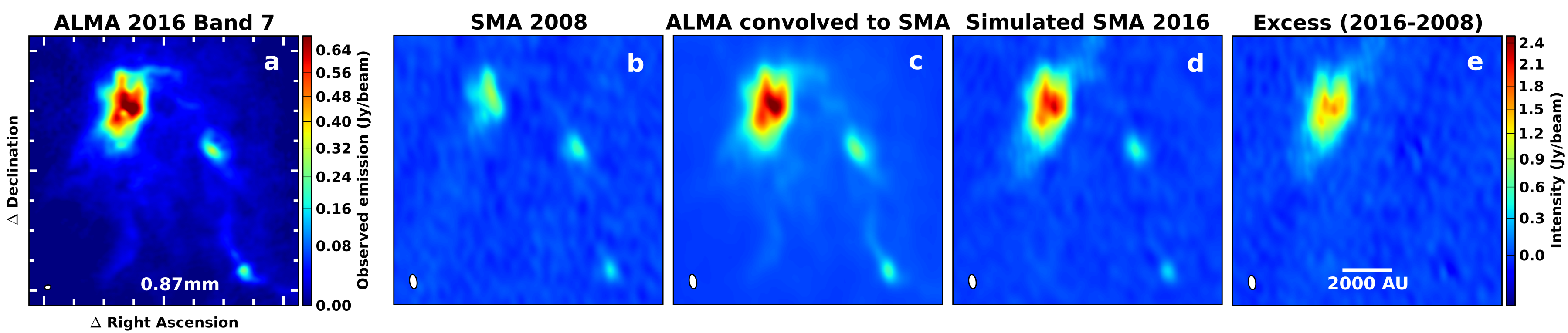


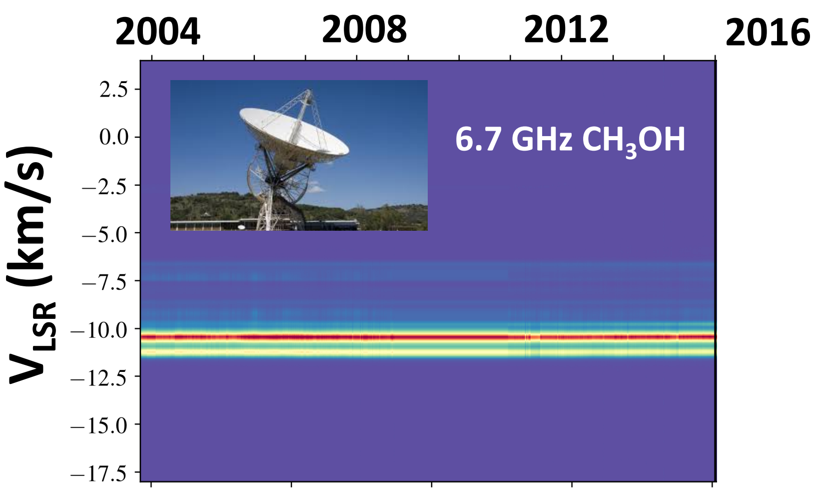
MM1 Band 7 flux density: Increase = 21 Jy = factor of 4.2. No fading over a year.

- Spectral index of excess is 2.6 – confirms it is dust (β=0.6)

Hunter, Brogan+ 2017

Maser outburst – single dish monitoring & VLA imaging

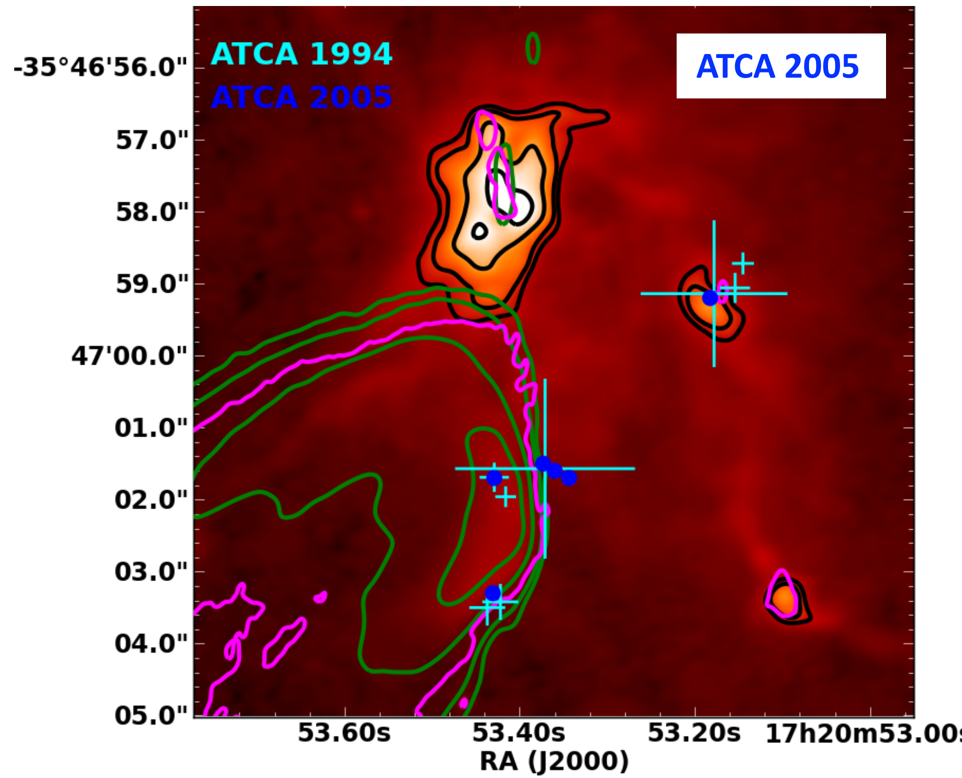
- HartRAO 26m dish in South Africa: 13 years of monitoring multiple species (water, methanol, OH)
- 40x increase in 22 GHz water and 6.7 GHz methanol masers



6.7 GHz masers:

- Require IR pump: dust > 150K, n=10^{8} cm^{-3} (Sobolev+1997)
- Associated exclusively with massive YSOs (Minier+2003)
- Thought to trace phase prior to UCHII region (Breen+2010)

Pre-outburst



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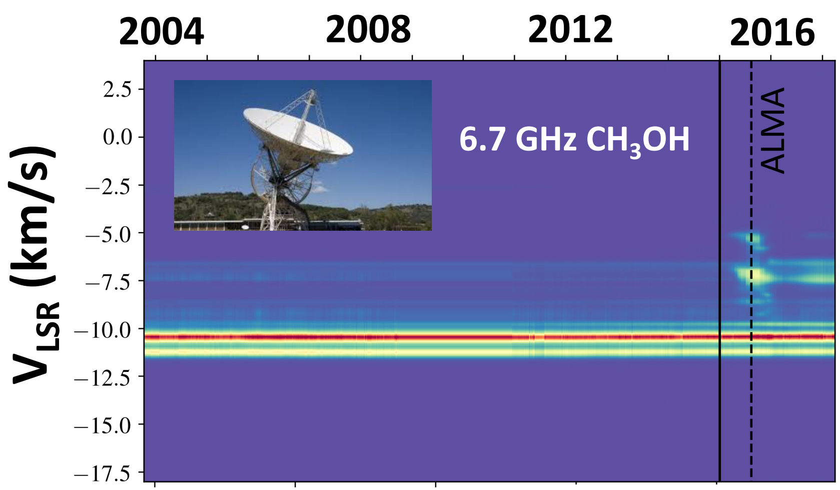
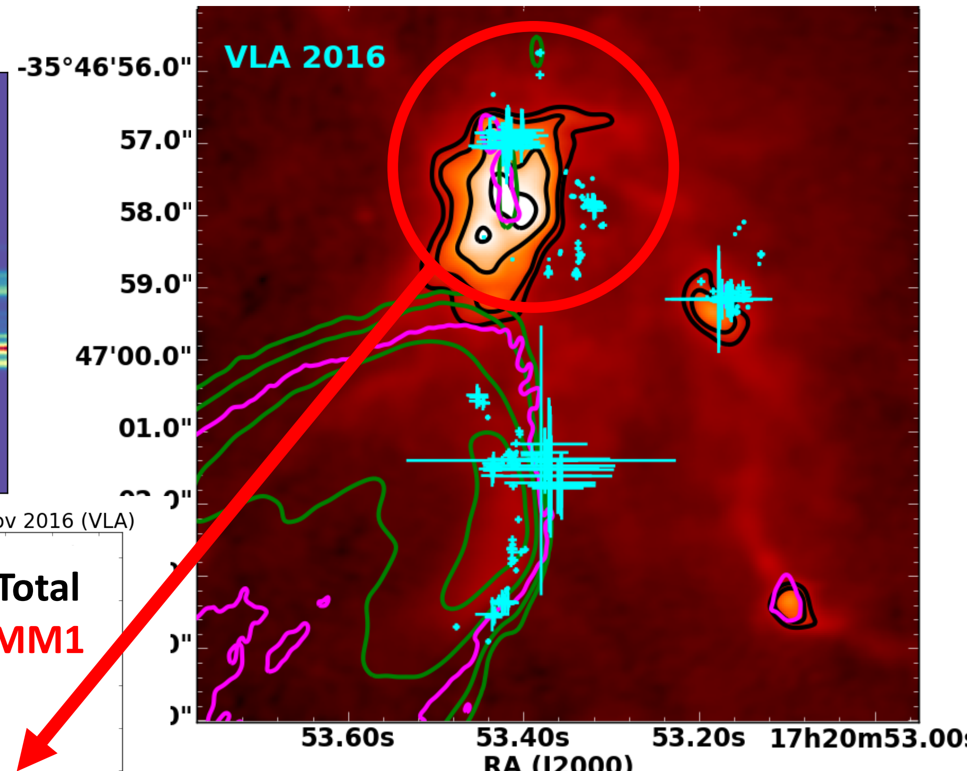


Post-outburst



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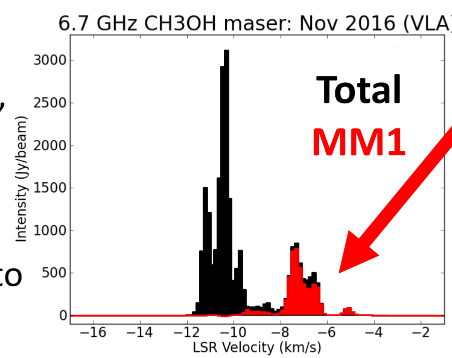


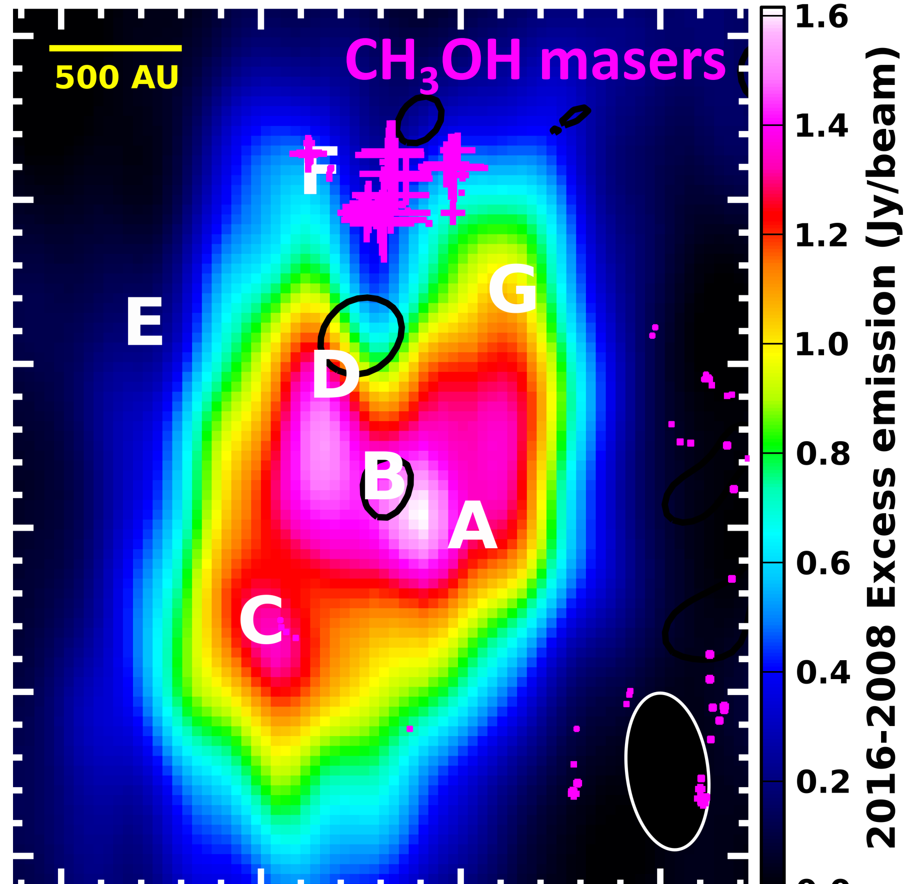
First ever detection of 6.7GHz maser in MM1

Excess 870um image (2016-2008): Which source(s) brightened?

- **Excess** centered on HCHII region MM1B
- Ionizing photon rate of 30au HCHII region: log(N_L)=44, T=18,000K (**B3 sp. type**)

- But adjacent sources also increased – Suggests that surrounding dust was heated by an “accretion event” in MM1B

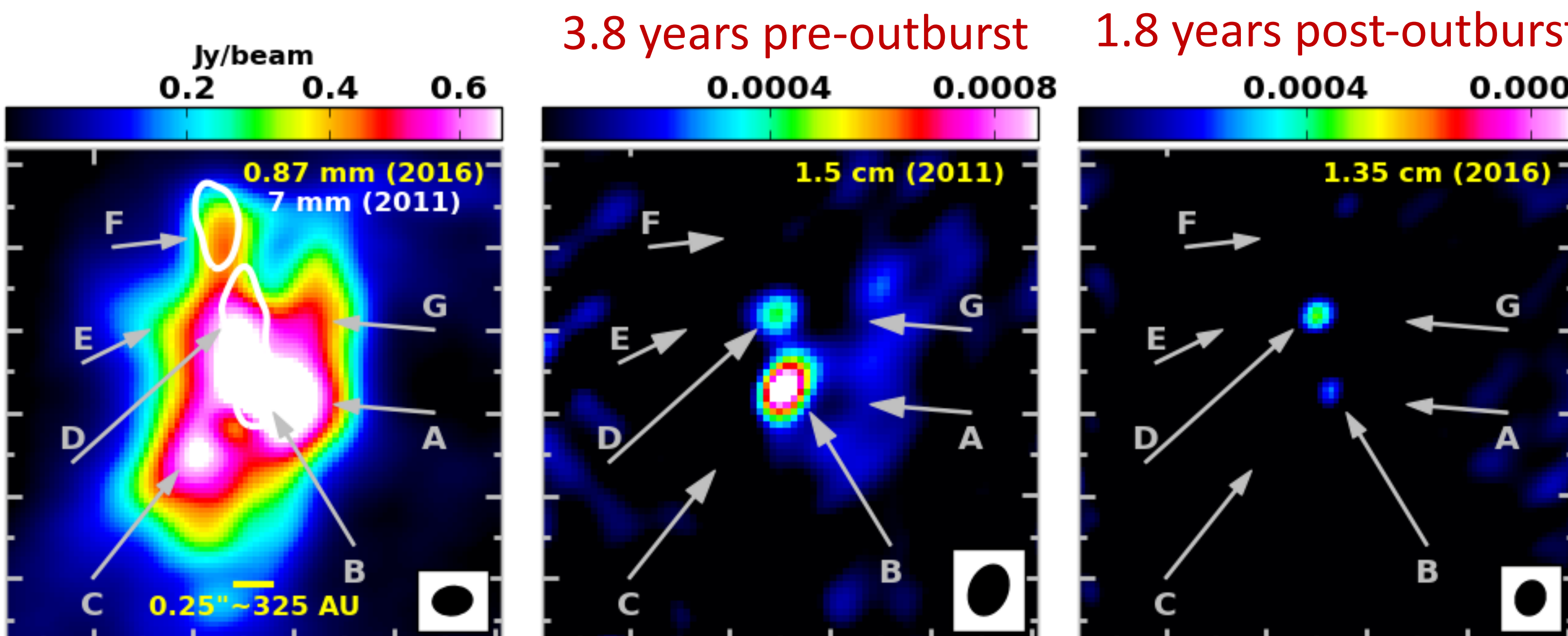
- $T_{brightness}$ increased from 33 to 96K; T_{dust}
- L ~ T_{dust}^4 implies an increase by 70x
- $T_{brightness}$ & size gives a lower limit to **post-outburst luminosity > 42000 L$_\odot$**
- Implies **pre-outburst luminosity ~600L$_\odot$**
- 600 L$_\odot$ on ZAMS is 16,500 K star of 5M$_\odot$ (**B4 sp. type**, Ekström+2012) with R$_*$=3R$_\odot$



Conclusion: spectral type B3~B4

VLA DDT follow-up at 1.5 cm: HC HII region has dimmed

- Free-free emission has dimmed by a factor of 4x as of Nov. 2016 (from 1.1 to 0.27 mJy)
- MM1D (jet) is constant to within 6%, confirming the relative calibration
- Recombination timescale = $1/n_e\alpha_H$ = only 38 days for $n_e = 10^6$ cm^{-3}
- SED model: FWHM=30au, but grav. radius of 5 $M_\odot$ star is 44 au for c_s=10 km/s (trapped!)

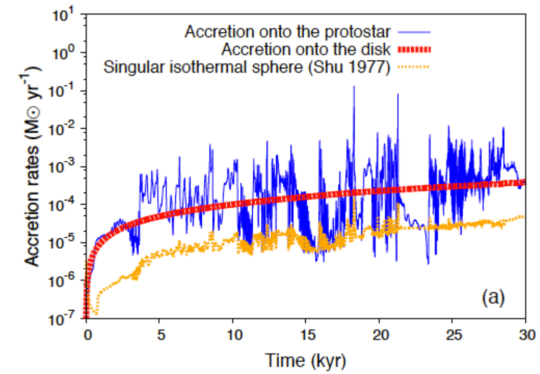


Variability in HC HII regions due to accretion is expected (Galván-Madrid+2011, Peters+2010)

Large accretion events onto protostar are expected

Example: Meyer et al. 2016: numerical radiation hydrodynamic simulations, including gas self-gravity & radiative feedback (Kuiper & Klessen 2013)

- Produces bursts in accretion rate of a factor of 100:
  - Yields x50 luminosity boost for 10 yr
  - Large bursts separated by few 1000 yr



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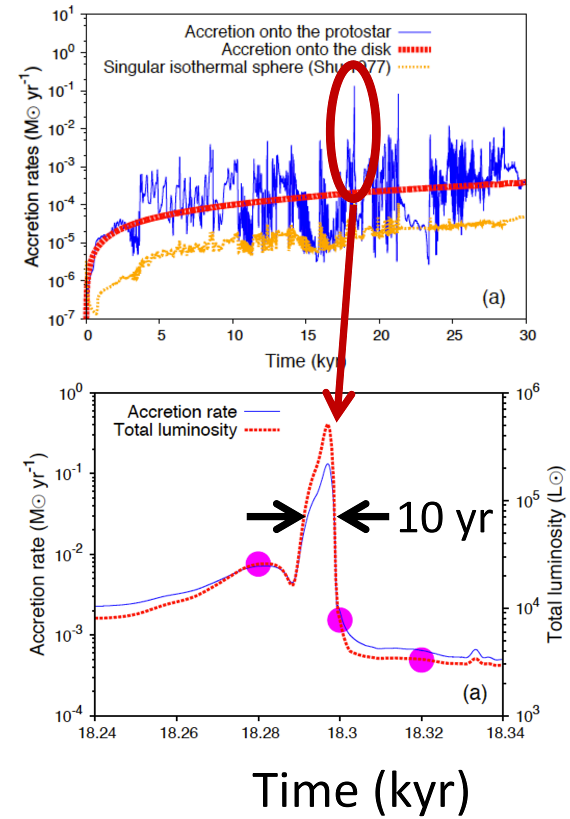

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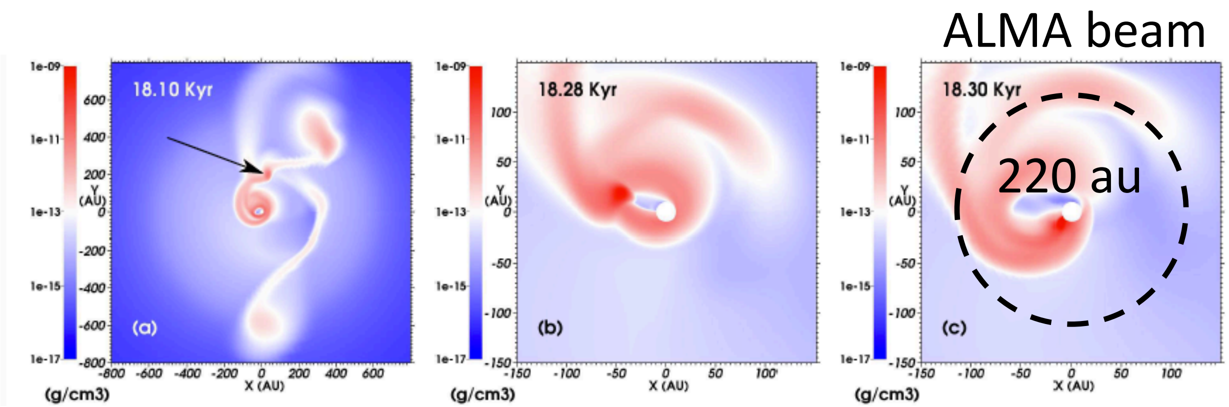

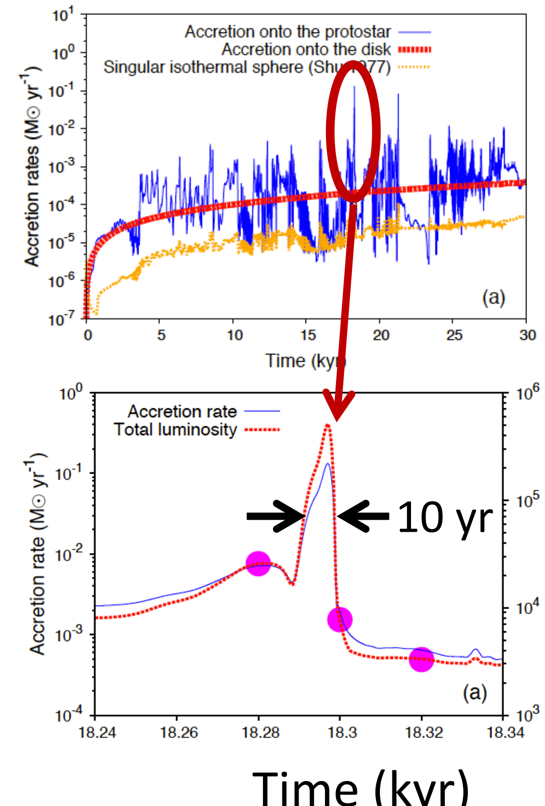

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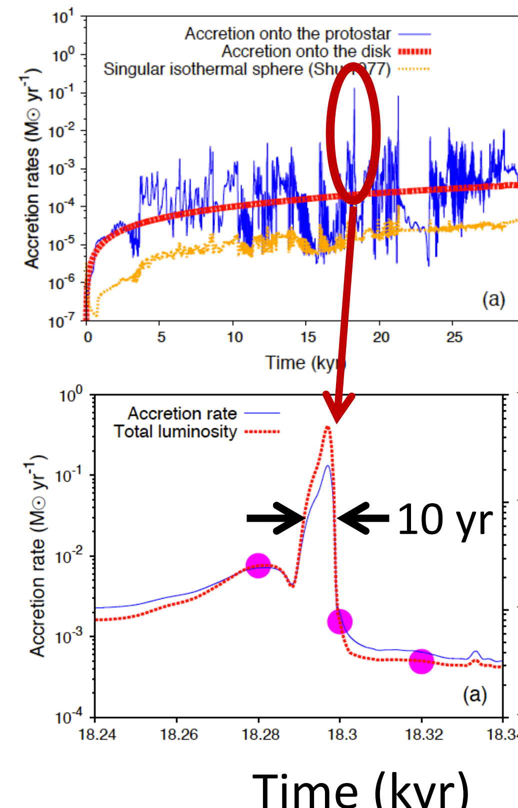
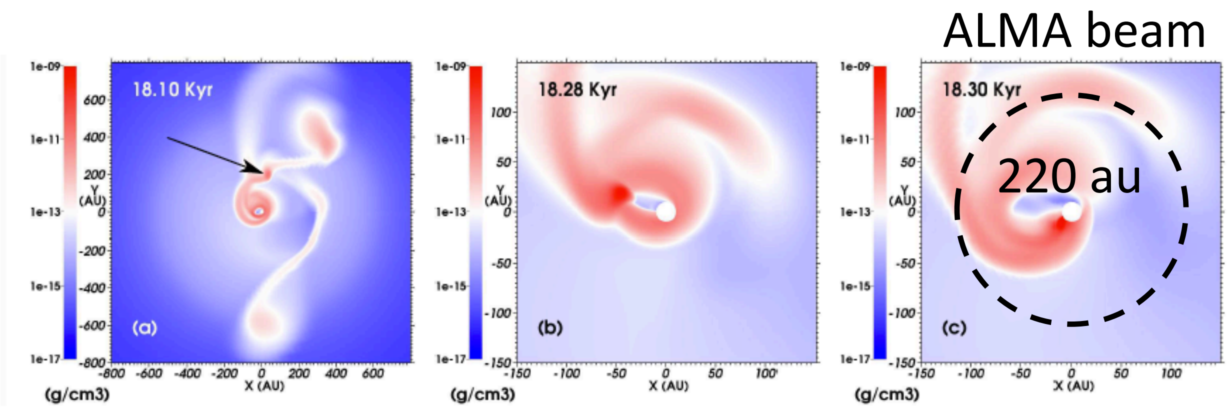


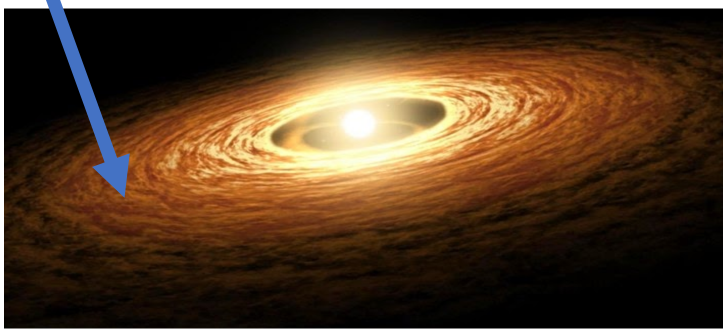


Resolving these structures requires < 0.1” beam, even in nearby sources at 1 kpc

Accretion as luminosity source: yes!, but in what form?

The post-outburst luminosity of 42000 $L_\odot$ can arise by...

Case 1: "Disk-mediation":
a 0.1 $M_\odot$ gas fragment is absorbed by disk then drains onto 5$M_\odot$/3$R_\odot$ protostar over **100 years** at **$\dot{M}=10^{-3}$ $M_\odot$/yr:**
$L_{acc}=GM\dot{M}/R$ = 42000 $L_\odot$ = 0.24 L_{edd}



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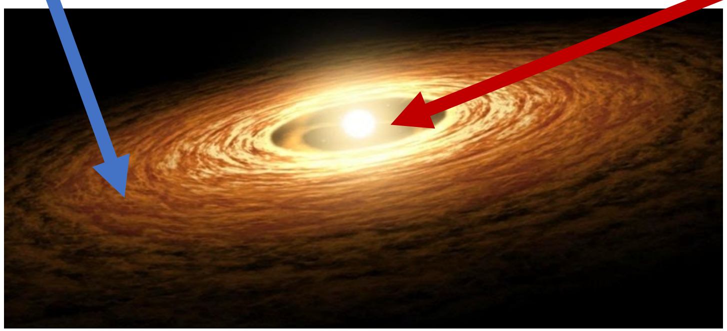
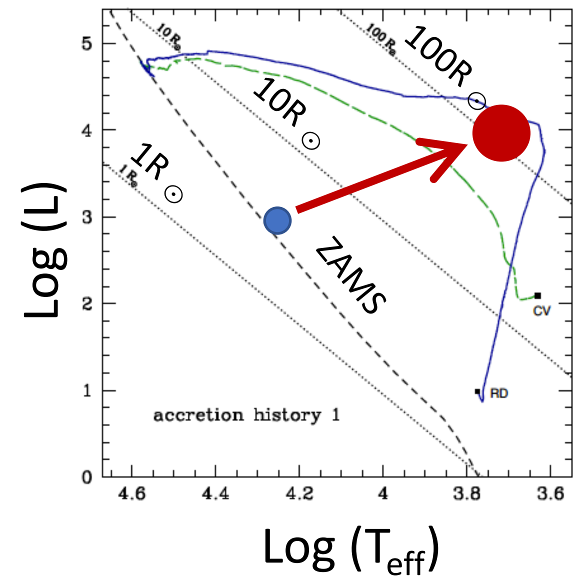
Case 2: "Direct accretion": gas fragment hits protostar, creating a shock which leads to a new photosphere at a larger radius (dropping the UV flux) and cools radiatively for Kelvin-Helmholtz time: GMM_*/RL ~ **a few yrs** (depending on fragment mass)



Temporary change of location on HR diagram



Haemmerle & Peters (2016)

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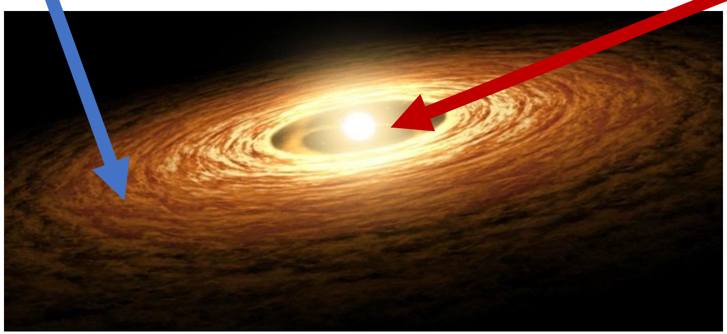

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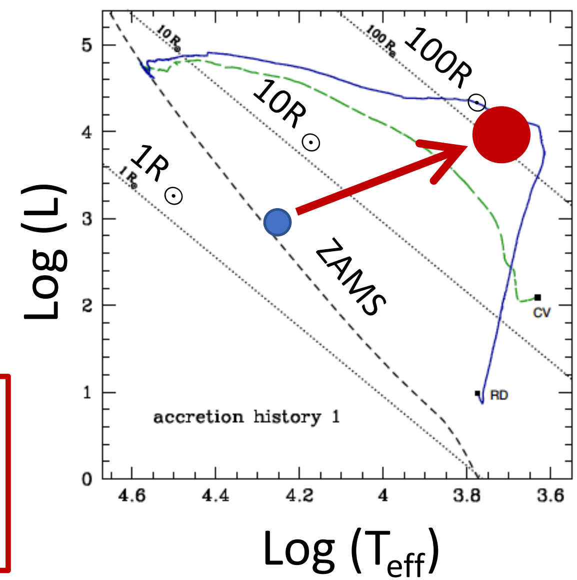
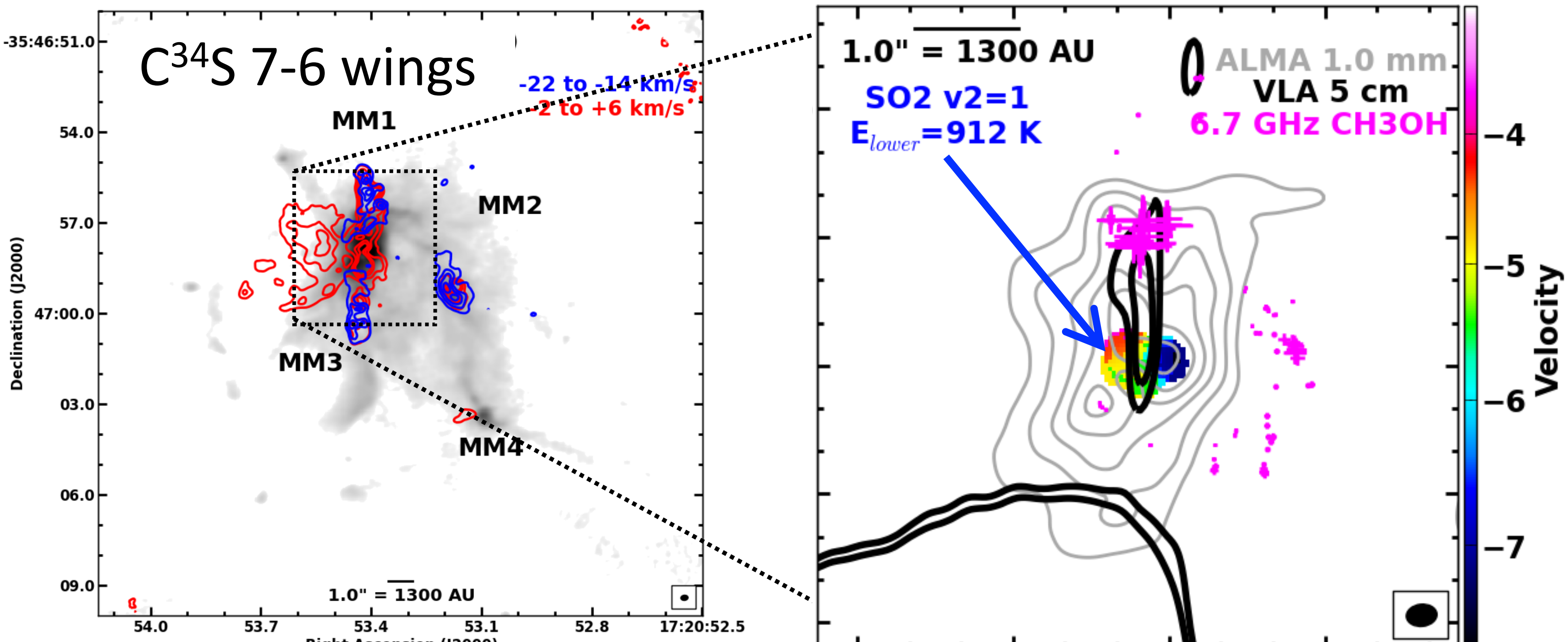


Haemmerle & Peters (2016)

How to distinguish?
- Long-term: measure lifetime of outburst
- Short-term: Do we see a disk?

Do we see any evidence for disk/outflow structure? Yes

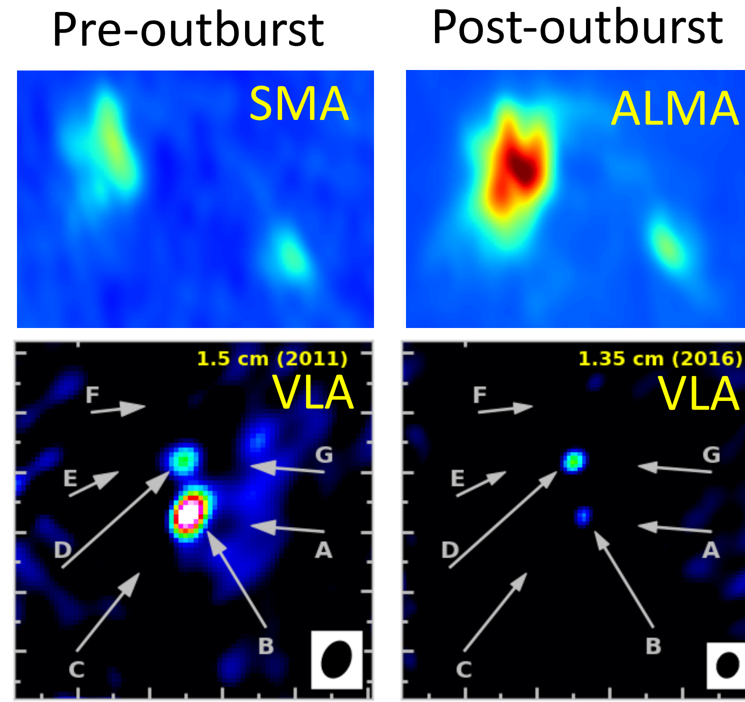
- Very few of the thousands of the ALMA 1 mm hot-core lines are unblended!
- $C^{34}S$ (7-6) bipolar N/S structure (t_{dyn}~10^3 yr), and contains the flaring CH_3OH masers
- Vibrationally-excited SO_2 shows compact east-west velocity gradient centered on MM1B and perpendicular to the 6 cm jet pointing toward the flaring masers.

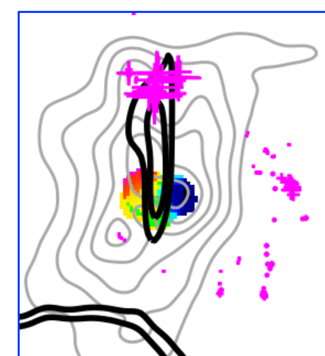


Δv=+-3 km/s over r=450 AU implies 4.6 $M_\odot/\sin^2 i$ ~ 5 $M_\odot$ = consistent with B4 star

Summary and Conclusion:

- Recent outbursts in YSOs show similar features:
  - Factors of 6-70x increase in luminosity
  - Sustained for many years (ongoing)
- NGC6334I-MM1 dust continuum outburst is accompanied by:
  - Dimming of the HCHII region by a factor of 4: <u>evidence for suppression of UV photons</u>
  - Candidate compact disk/outflow system: disk traced by hot SO_2, outflow traced by $C^{34}S$ and 6 cm jet direction, and maser flare
- **Consistent with a B4 ZAMS star accreting >= $0.1M_\odot$ in a short period.** Understanding the details requires further monitoring and modeling





Future caution: Millimeter outburst would not have been easily seen with 0.1 pc resolution: only amounts to 30% of the JCMT flux in 18” beam (Sandell 1994).