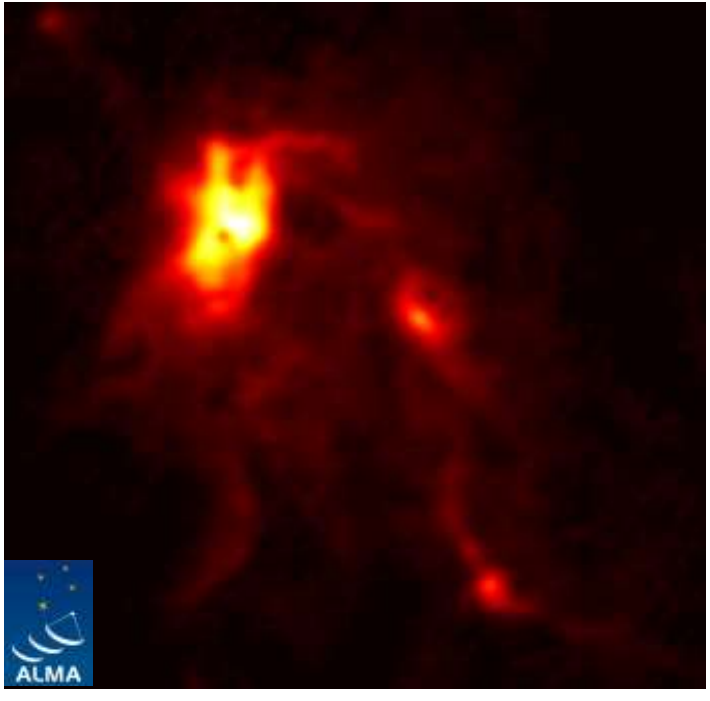
The Extraordinary Outburst in NGC6334I-MM1:
Rise of Dust and Emergence of 6.7 GHz Masers



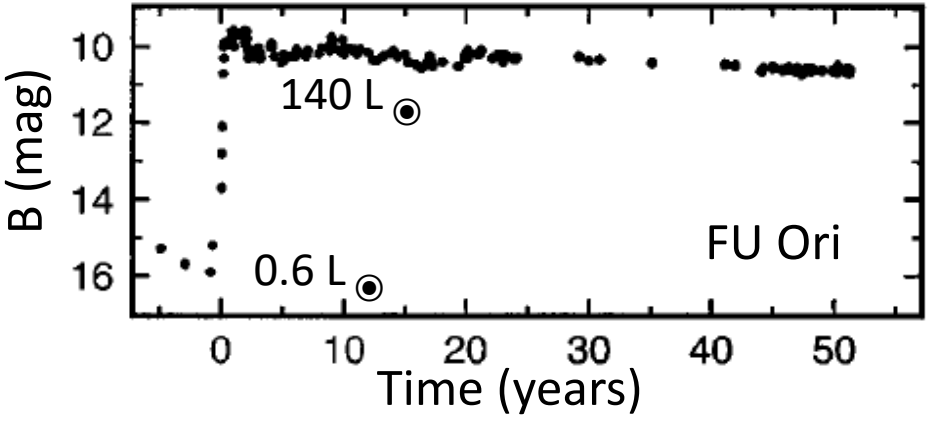
1 mm image of NGC6334I - 200 AU resolution

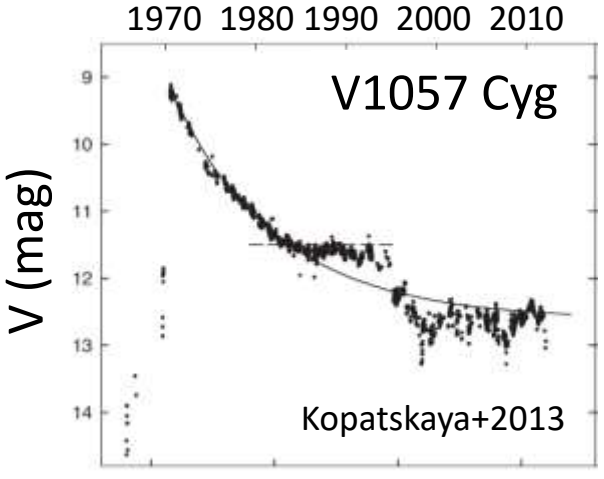
Todd Hunter (NRAO/NAASC)
Crystal Brogan (NRAO/NAASC)
Claire Chandler (NRAO)
James Chibueze (SKA South Africa, NorthWest Univ.)
Claudia Cyganowski (Univ. of St. Andrews)
Rachel Friesen (Univ. of Toronto)
Tomoya Hirota (NAOJ)
Remy Indebetouw (NRAO/ U. Virginia)
Gordon MacLeod (HartRAO, South Africa)
Cherise Thesner (NorthWest University)
Ken Young (Harvard-Smithsonian Ctr. for Astrophysics)

IAU Symposium 336: Astrophysical Masers: Unlocking the
Mysteries of the Universe; Cagliari, Italy; September 4-8, 2017

Introduction: Evidence for episodic accretion

- Classical FU Ori stars: Kenyon & Hartmann (1996)
  >100x brightness boost lasting for decades



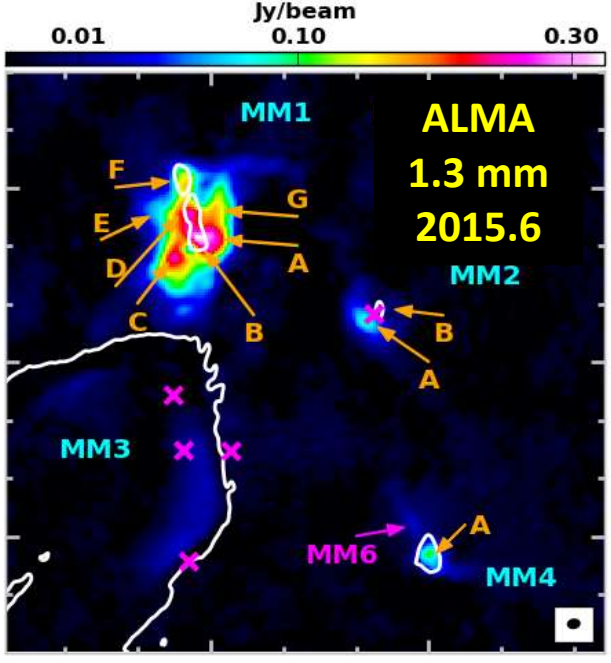


- Spitzer c2d Legacy results: most YSOs are underluminous relative to evolution models with a constant or decaying accretion rate (Evans+2009)
- UKIDSS & VVV surveys finding hundreds of Near-IR variable YSOs (Lucas+2017)

Massive YSO: S255IR-NIRS3 (Caratti o Garatti+2016, Moscadelli+2017)

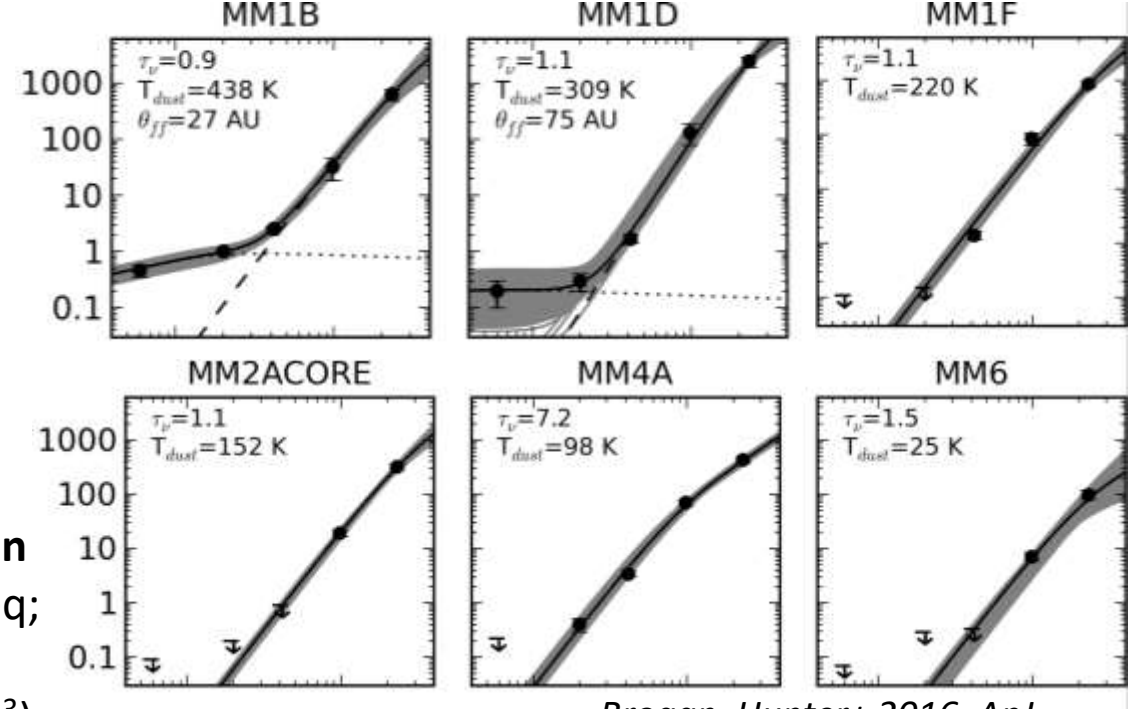
- Flared by 30x at 60um between 2009-2015; accompanied by 6.7 GHz flare (Fujisawa+2015)
- Luminosity rose 6x (up to >1e5 $L_{\odot}$), now fading after a few years (Stecklum talk on Monday)

NGC 6334 I: Protocluster with a diversity of members



- **Nearby**: 1.3 kpc [maser parallax of I(N), Chibueze+2014]
- **Heavily-obscured:** only MM3 seen at 18um, DeBuizer+2002

SED models: the MM sources other than MM1 and the UCHII region MM3 can be fit by dust emission alone



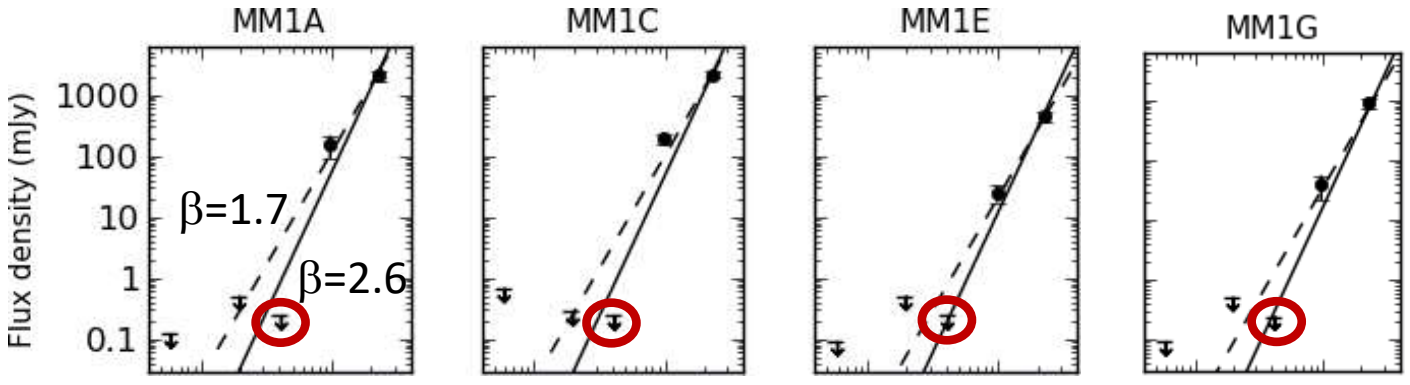
Dust sources MM1B and D also show free-free emission (VLA):

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

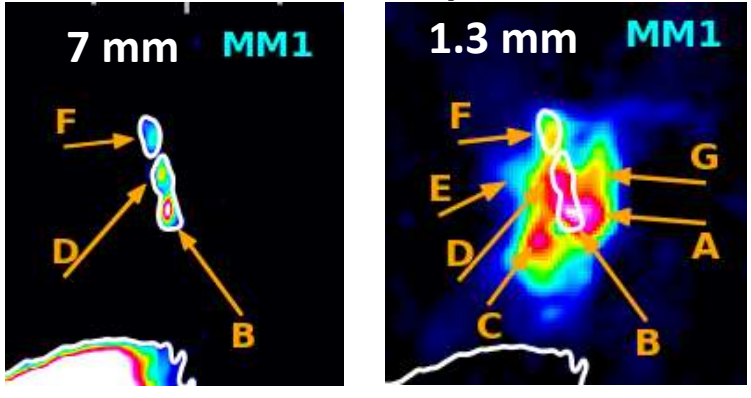
D: 300 K dust plus jet (n_e=3x10^5 cm^{-3})

Brogan, Hunter+ 2016, ApJ

However: Some MM1 components should have shown much brighter 7mm emission than observed. Mystery!



Brogan, Hunter+ 2016



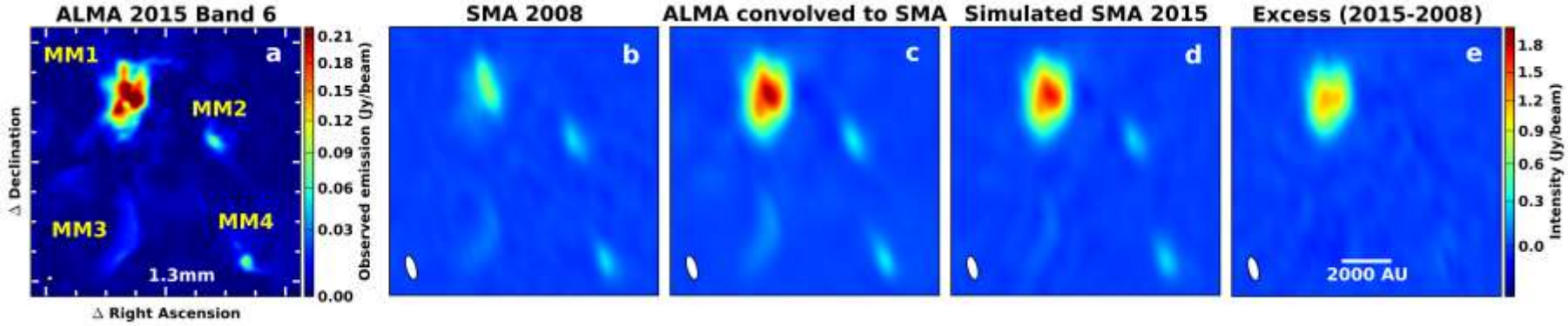
Possible explanations:

Time Variable?

or

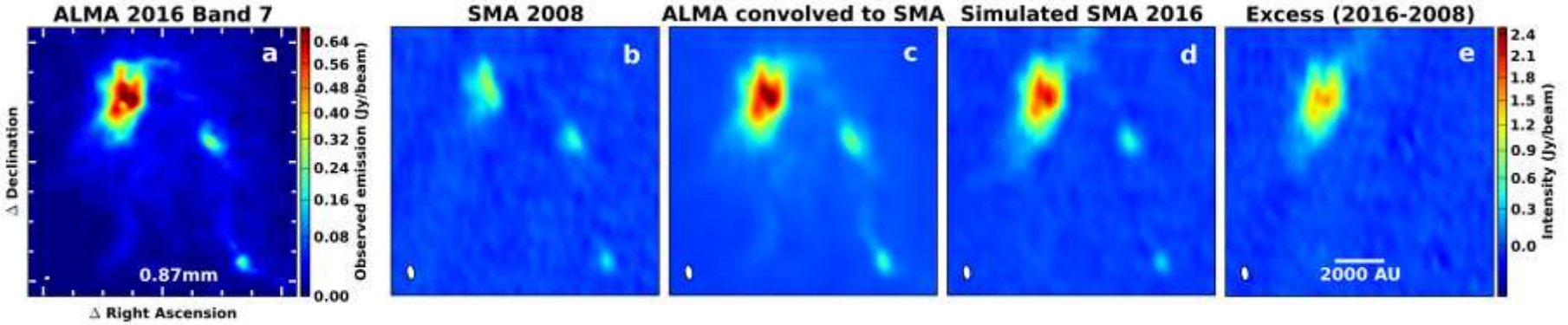
Unusual dust properties?

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



MM1 Band 6 flux density: 2008.6 SMA: 2.34 Jy versus 2015.6 ALMA: 10.8 Jy

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



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

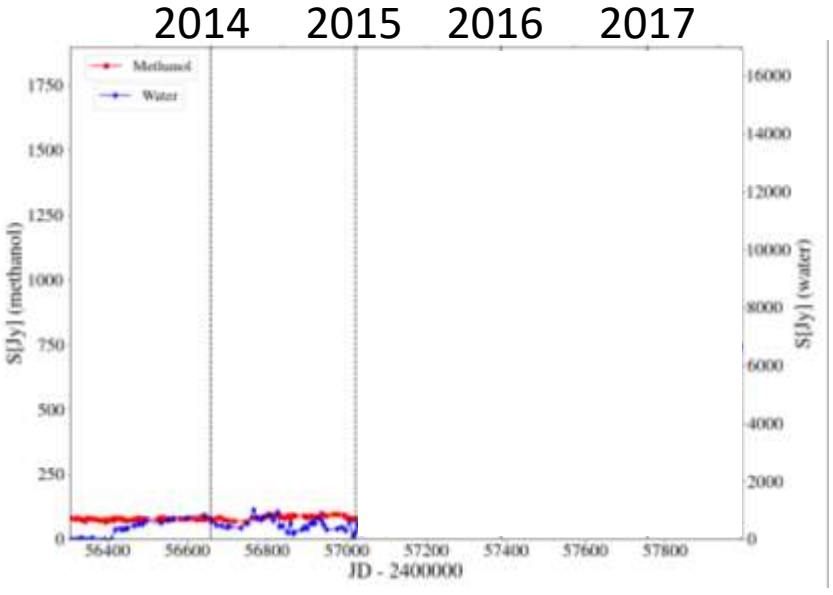
- Spectral index of excess is 2.6 – confirms it is dust

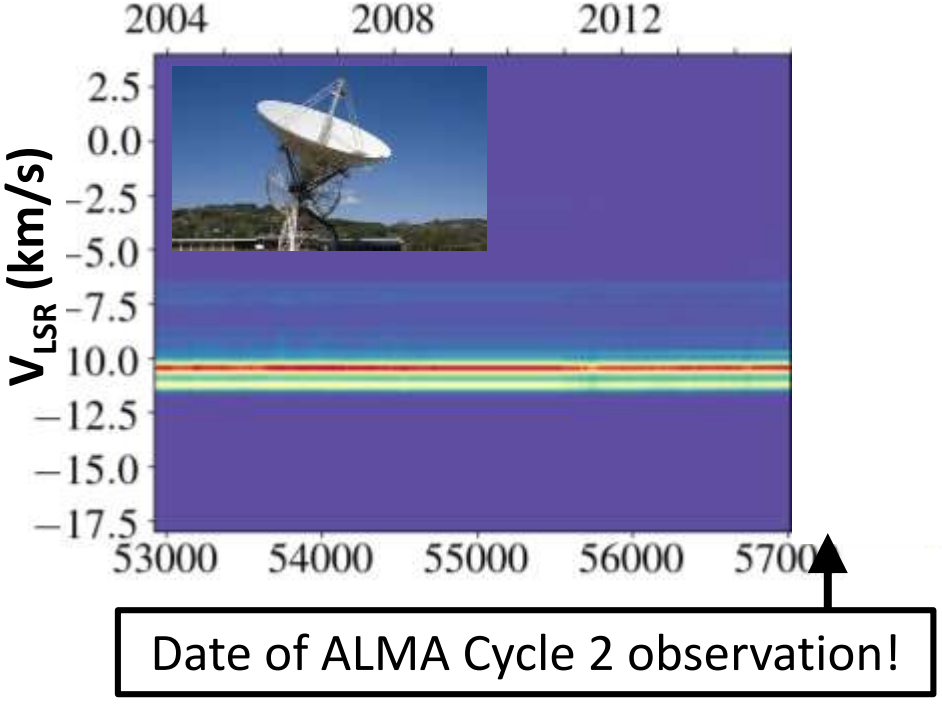
Hunter, Brogan+ 2017 ApJL

Maser outburst – single dish monitoring & VLA imaging

- HartRAO 26m dish South Africa: 2 decades monitoring H2O, OH; CH3OH (Goedhart+2004)
- Beginning in January 2015: a 40x increase in 22 GHz H2O and 6.7 GHz CH3OH masers!

-7.2 km/s Methanol & Water over time





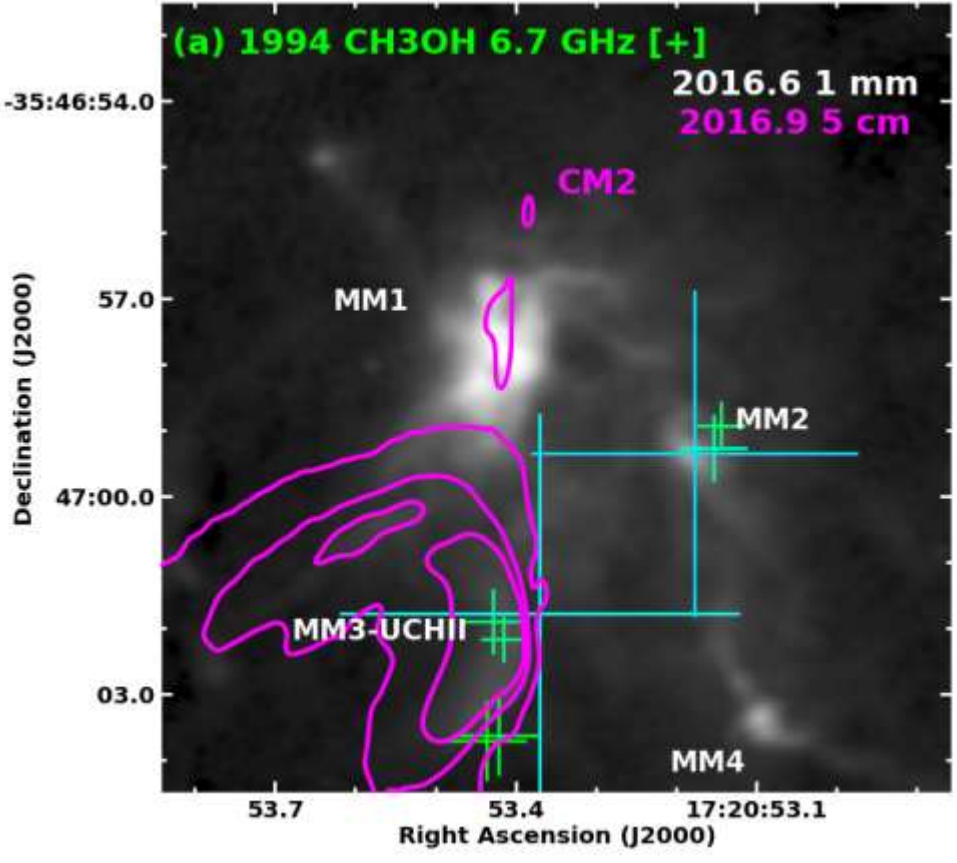
Macleod et al. 2017 in preparation.

See **Poster 21** for more details.

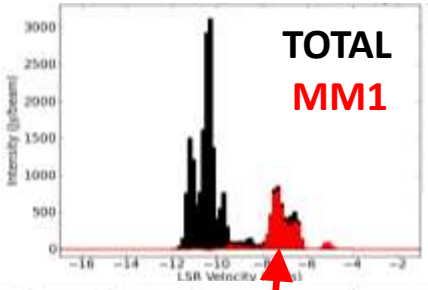
Traditional location of 6.7 GHz masers in older observations (e.g. Walsh+1998)

ATCA 1994.6

Spot size $\propto \sqrt{\text{flux}}$



VLA-A follow-up: First detection of CH3OH maser toward MM1!

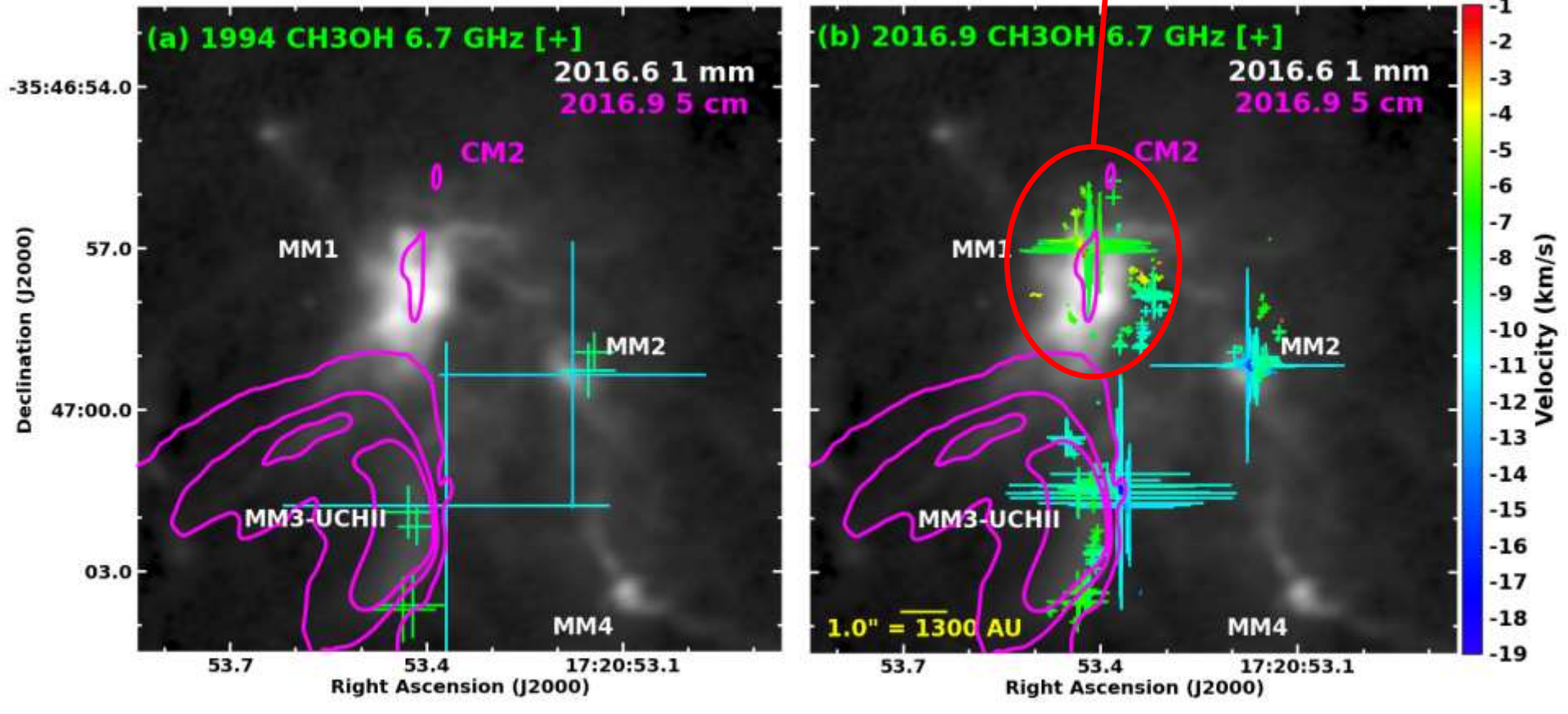


Not seen here in 1988, 1992, 1994, 2005, 2011 ...

ATCA 1994.6

Spot size $\propto \sqrt{\text{flux}}$

VLA 2016.9



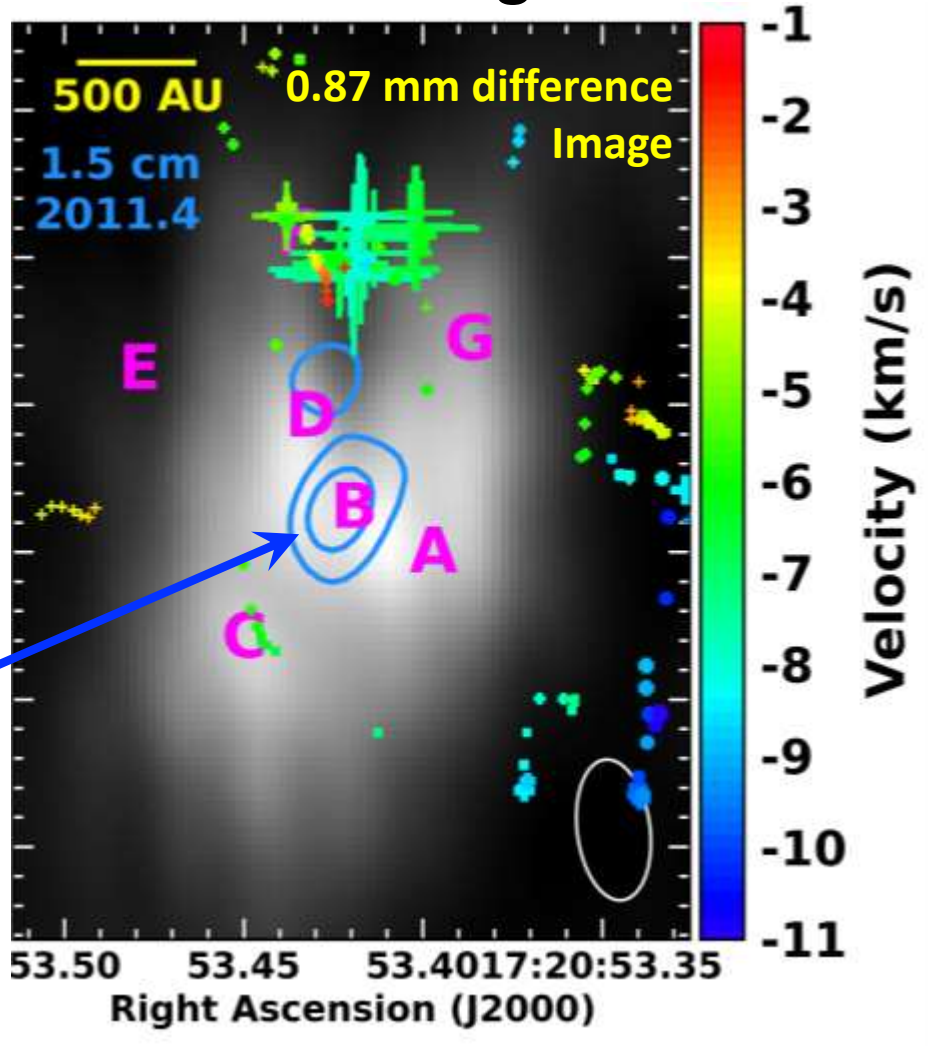
Difference image (2016-2008): Which source brightened?

- Excess centered on HCHII region MM1B, but adjacent sources also increased….
- **Suggests dust was heated by a sudden increase in the accretion rate of MM1B**
- Outburst can heat dust cocoon rapidly (Johnstone+2013), 1200au/c = 1 week

- $T_{brightness}$ increased from 33 to 96K (2.9x)
- $L_{bol} \propto T^4$ implies an increase in L_{bol} by 70x
- 1.3 mm $T_{brightness}$ & angular size gives a lower limit to post-outburst $L_{bol} > 42000\ L_\odot$

MM1B's 1.5 cm flux in 2011.4 required: ionizing photon rate: log(N_L)=43.9 →1300 $L_\odot$
On ZAMS, this is B2 star (Thompson 1984)

Conclusion: Progenitor a deeply-embedded 6$M_\odot$ ZAMS star!

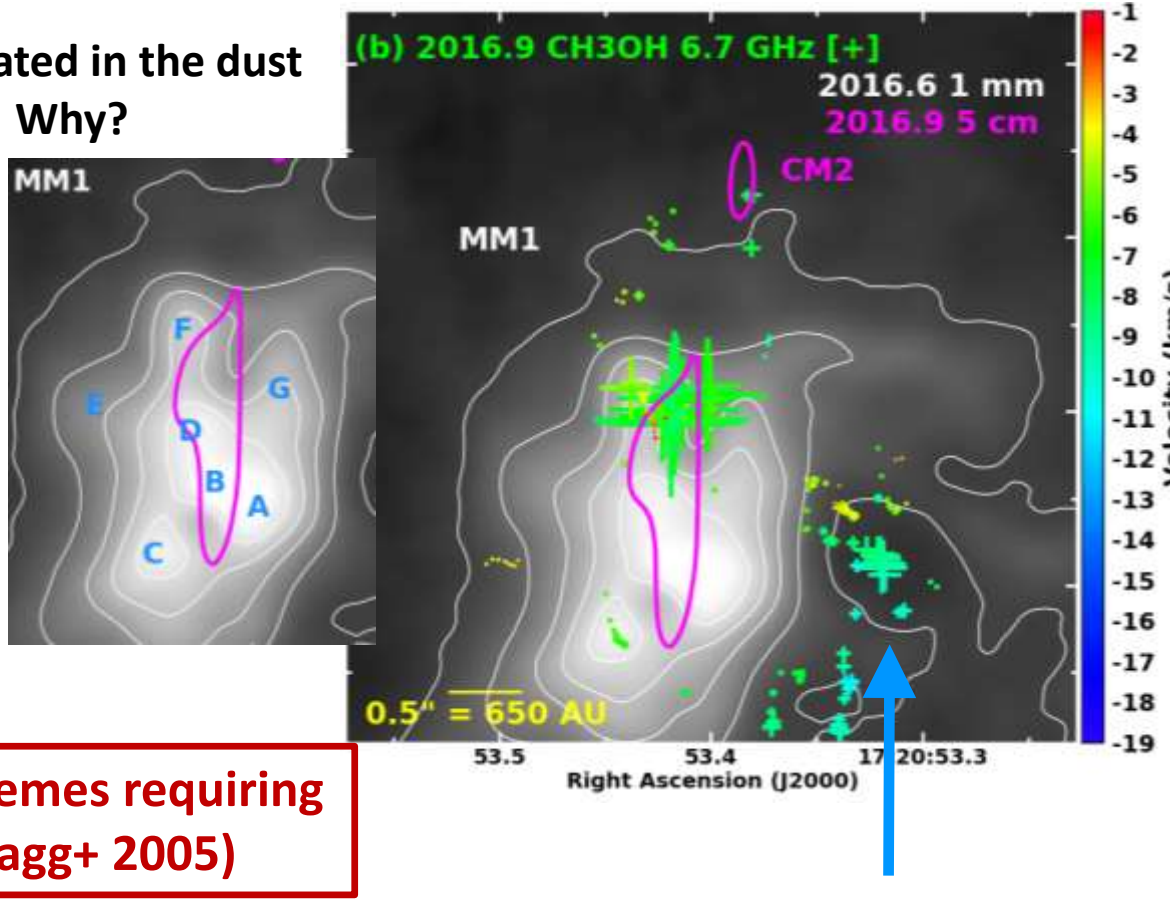


What explains the location of the masers?

1. Strongest maser spots are located in the dust cavity between MM1F and G. Why?

- Jet has previously excavated this cavity and its density is low enough to support maser.
- IR pumping radiation coming from adjacent ≈150K dust sources MM1F and MM1G.

2. No spots on central HCHII protostar MM1B, nor on MM1D. T_{dust}>250K, but the densities are likely too high



Consistent with pumping schemes requiring $n < 10^8$ cm^{-3} and T > 100K (Cragg+ 2005)

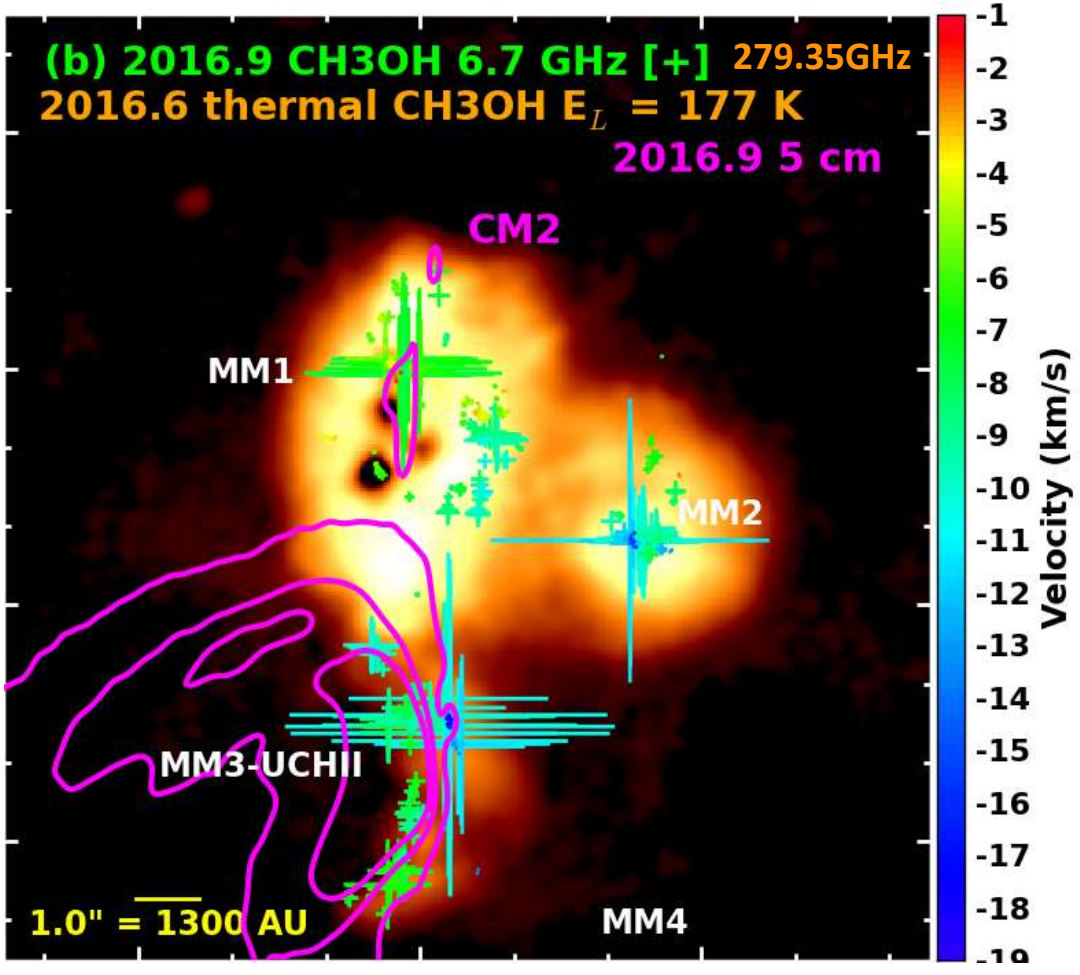
But what about the other masers to the west and north ?

Other maser locations coincide with warm thermal CH3OH

Dust continuum peaks appear in absorption in lines with E_{Lower}< 300 K

Maser spots west and north of MM1 reside in area of <u>abundant</u> thermal gas

Warm CH3OH also observed along MM3-UCHII ionization front, coincident with the masers

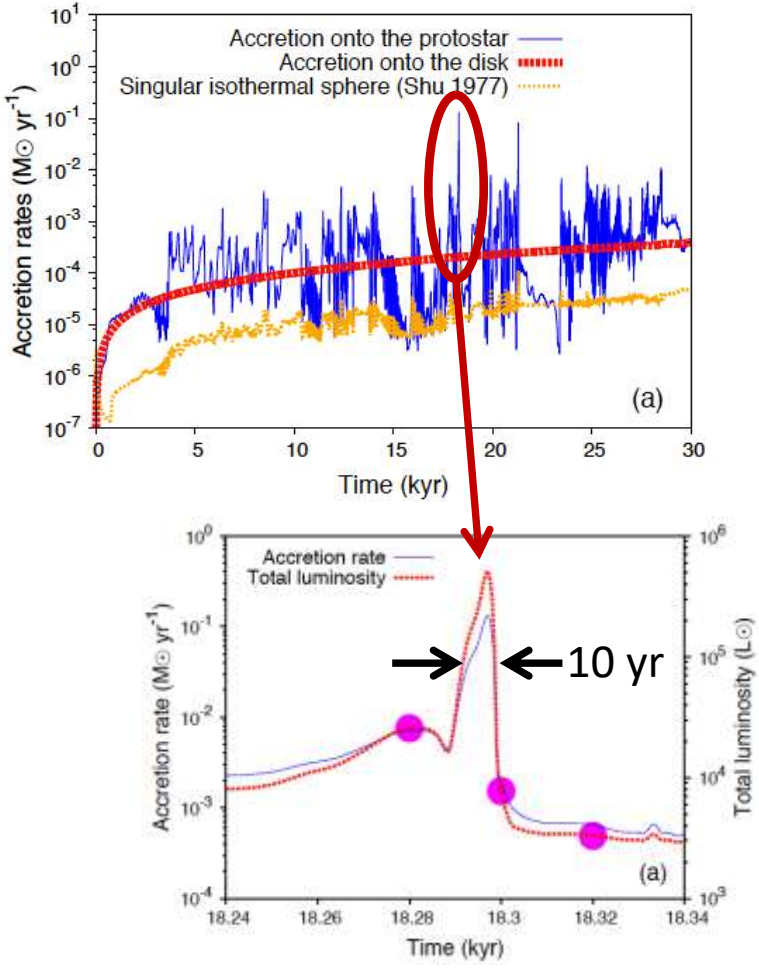


Large accretion events are expected

Meyer et al. (2017):
numerical radiation hydrodynamic simulations, including gas self-gravity & radiative feedback (Kuiper & Klessen 2013).

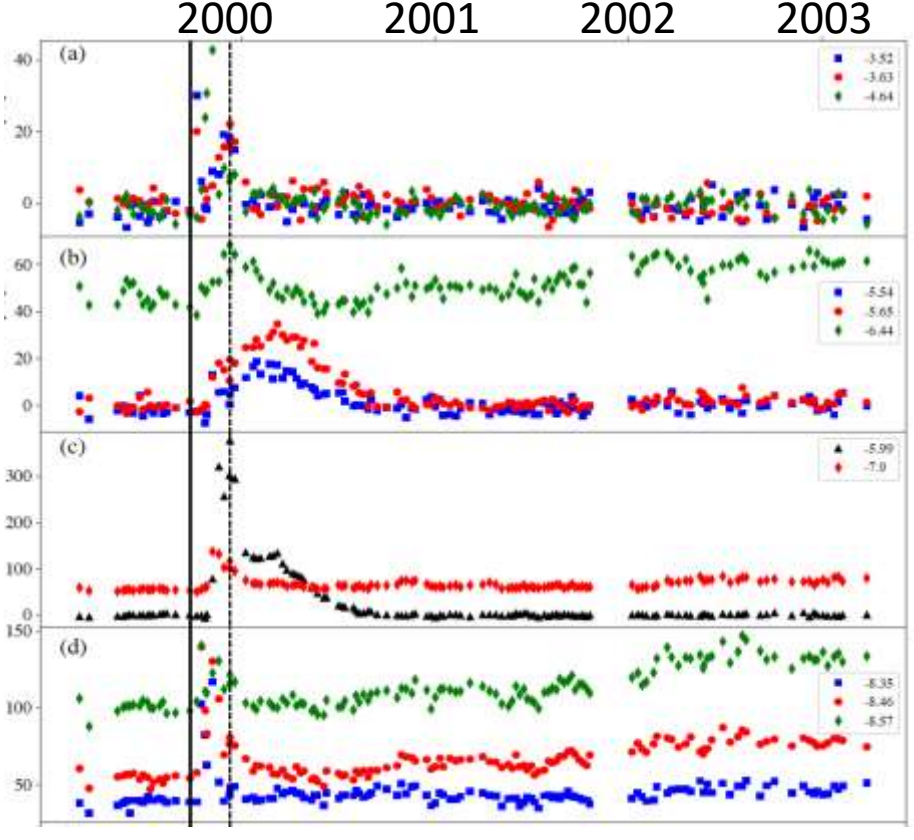
- Produces bursts in accretion rate of a factor of 100:
  - Yields 50x boost in luminosity for 10 yr
  - Large bursts separated by few 1000 yr
- **MM1 outburst of 70x is a rare event!**
- Smaller events are also expected. Is there evidence?

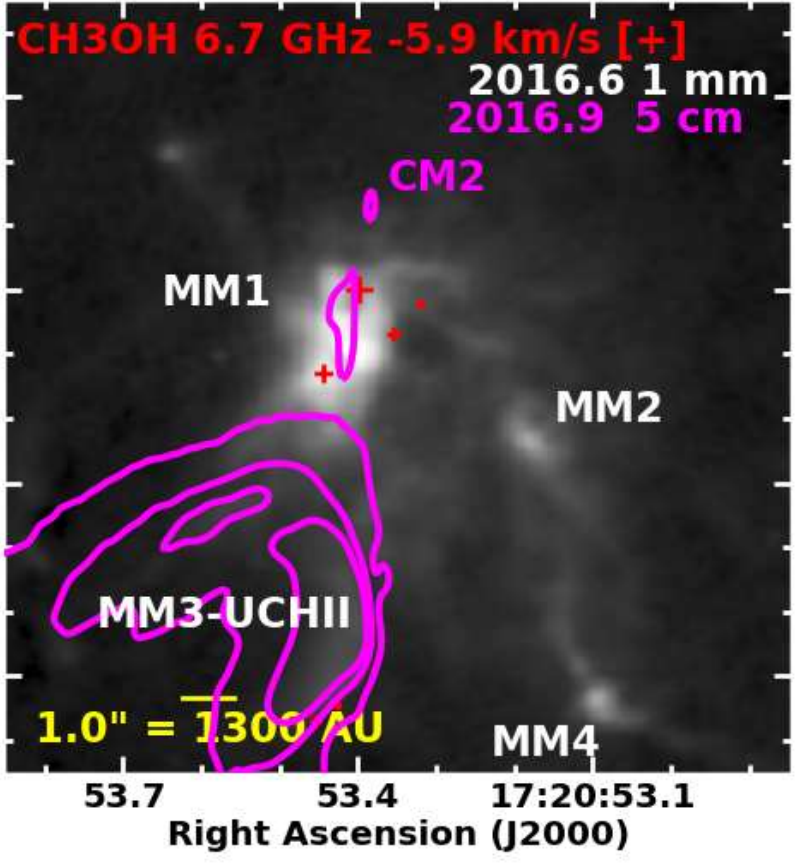
Large clump accreted.



December 1999 “mini-burst” in single-dish spectra

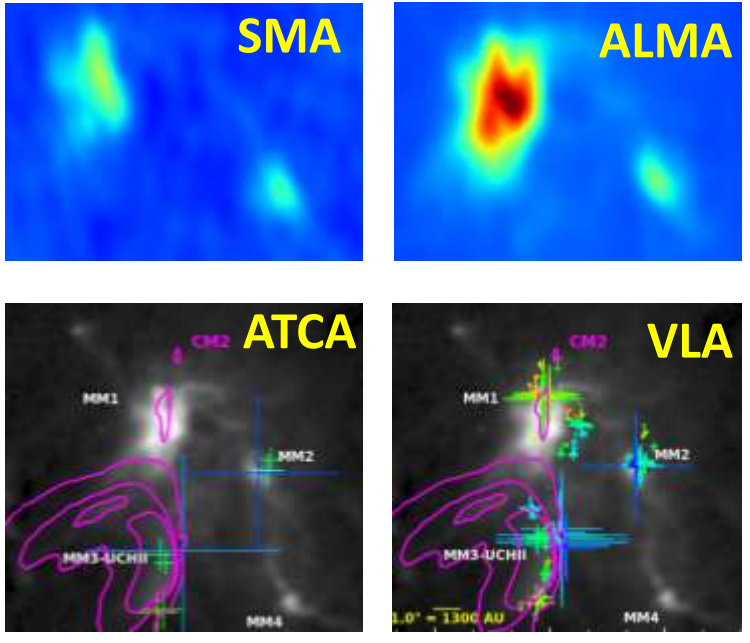
- -5.9 km/s went to >100 Jy for 6 months (Goedhart+2004, Macleod+2017 in preparation)
- -5.9 km/s in 2016.9 cube is on MM1 (7.7 Jy)
- **Evidence for smaller outburst, recurring event!**





Summary and Conclusions:

- Dust continuum outburst in NGC6334I - MM1
  - Lum. increase of 70 times (≈1300 to 90000 $L_{\odot}$)
  - Progenitor consistent with B2 ``ZAMS'' star [See the following presentation by C. Brogan on how it has evolved since the outburst]
- Appearance of Class II CH3OH masers
  - Strongest spots are along jet-carved cavity
  - No spots on the driving protostar/HCHII region
  - Evidence for "mini" precursor event in 1999
- **Monitoring of masers, mm dust, cm free-free emission continues; SOFIA 25/37um proposed**

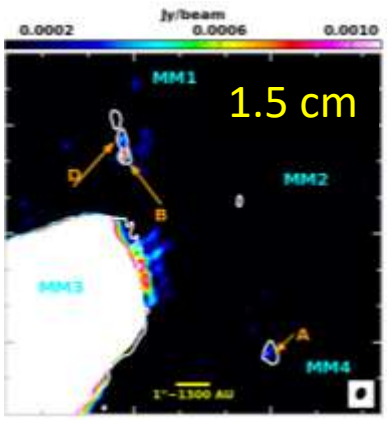


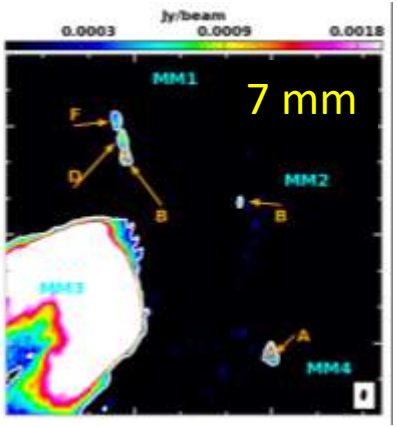
Lessons learned:

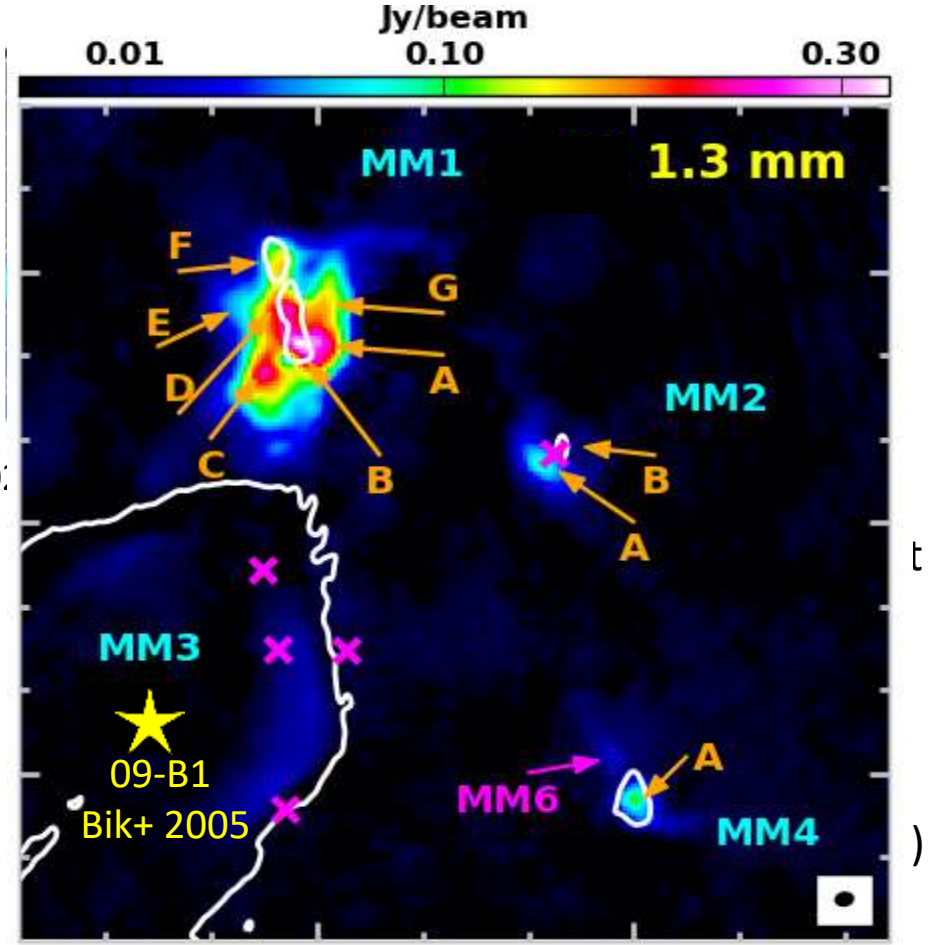
1. Single-dish maser monitoring is important to catch these events!
2. Follow-up with mm interferometry is essential! Outburst would not have been easily seen by single-dish: it's only 30% of JCMT flux in 18" beam (Sandell 1994).

Extra slides

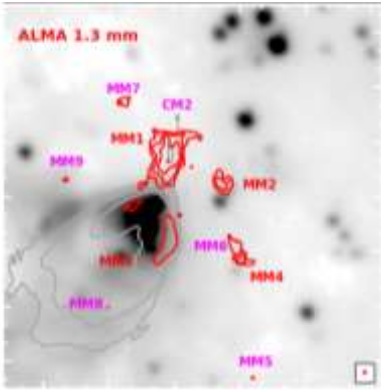
Multi-wavelength view of NGC 6334 I: only UC HII region is seen in IR



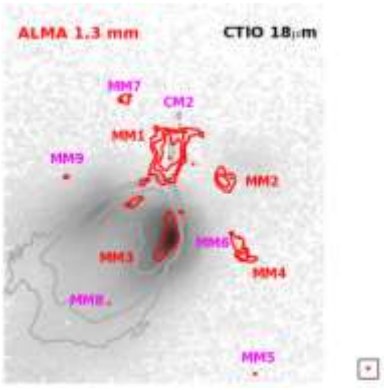




VLT HAWK-I K_s



CTIO 18 um (DeBuizer+ 200



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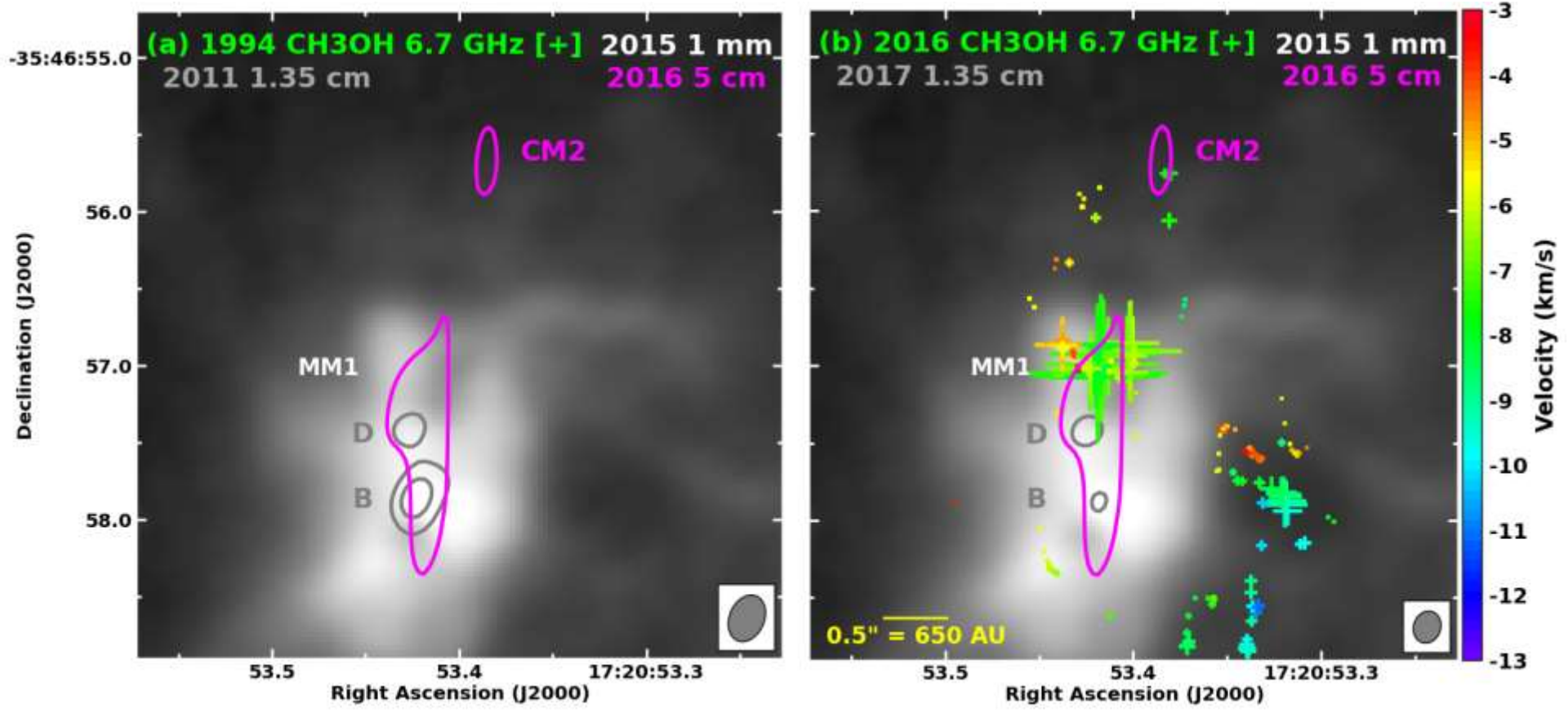
Brogan, Hunter+ 2016, ApJ, 832, 187


(a) 1994 CH3OH 6.7 GHz [+]
2015 1 mm
2011 1.35 cm
2016 5 cm
CM2
MM1
D
B
(b) 2016 CH3OH 6.7 GHz [+]
2015 1 mm
2017 1.35 cm
2016 5 cm
CM2
MM1
D
B
0.5" = 650 AU
-35:46:55.0
56.0
57.0
58.0
Declination (J2000)
53.5
53.4
17:20:53.3
Right Ascension (J2000)
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
Velocity (km/s)

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

The post-outburst luminosity of 90000 $L_\odot$ can arise by…

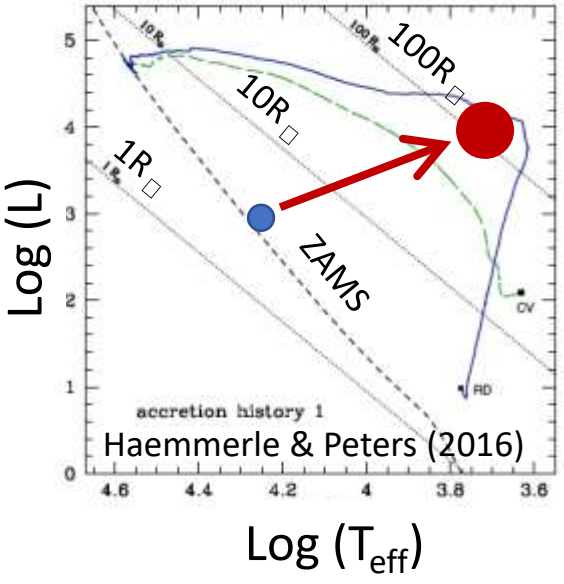
Case 1: "Disk-mediation":
a 0.1 $M_\odot$ gas fragment is absorbed by disk then drains onto $5M_\odot/3R_\odot$ protostar over **100 years** at $\dot{M}=10^{-3}$ $M_\odot$**/yr:**

$$L_{acc}=GM\dot{M}/R = 0.24\ L_{edd}$$

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



Temporary change of location on HR diagram



How to distinguish?

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

Crazy line forest (Band 7 version)

