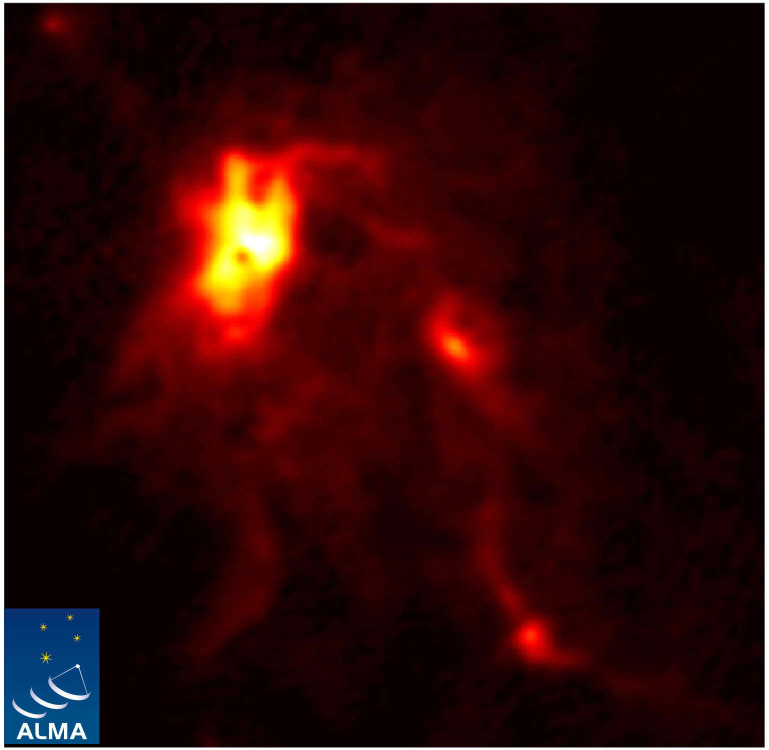
JVLA detection of dramatic changes in the outbursting massive protostar NGC6334I-MM1B

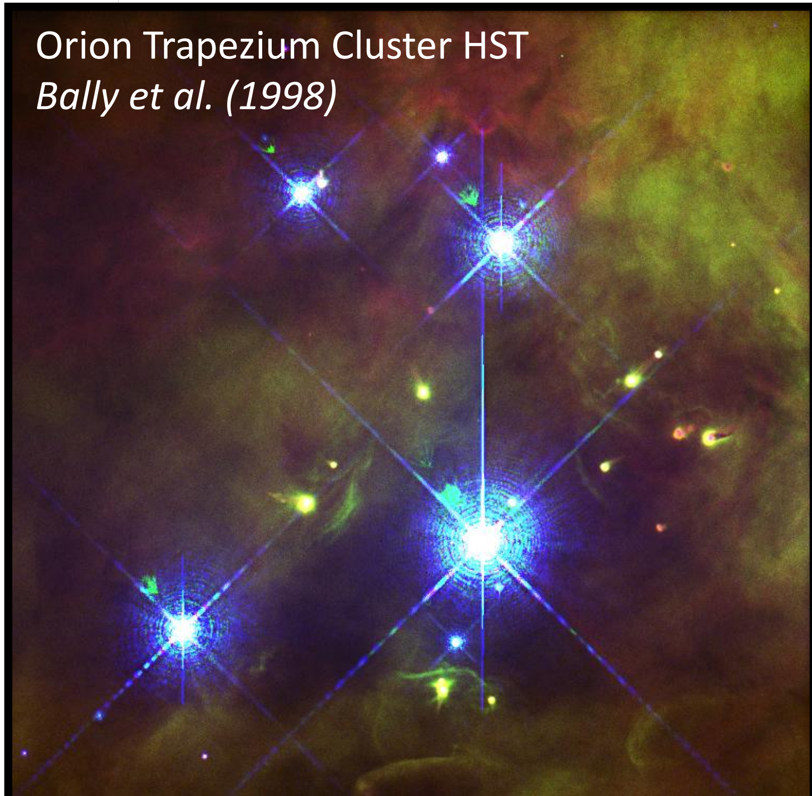


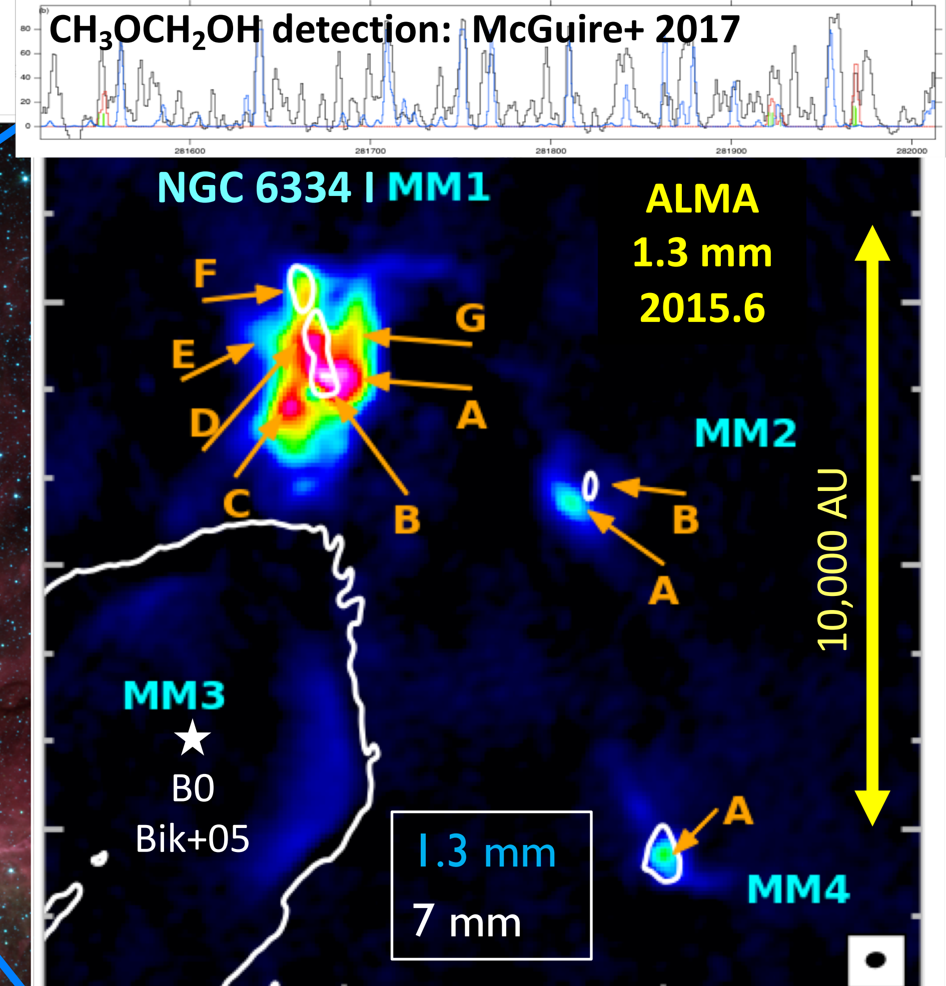
1 mm image of NGC6334I - 200 AU resolution

Todd Hunter (NRAO/NAASC)
Crystal Brogan (NRAO/NAASC)
James Chibueze (SKA South Africa, NorthWest Univ.)
Claudia Cyganowski (Univ. of St. Andrews)
Rachel Friesen (NRAO/NAASC)
Tomoya Hirota (NAOJ)
Gordon MacLeod (HartRAO)
Brett McGuire (NRAO)
Derck Smits (UNISA, South Africa)

Tracing the Flow: Galactic Environments and the Formation of Massive Stars
Lake Windermere, UK - 02-06 July 2018

NGC 6334 ``Mini-starburst''





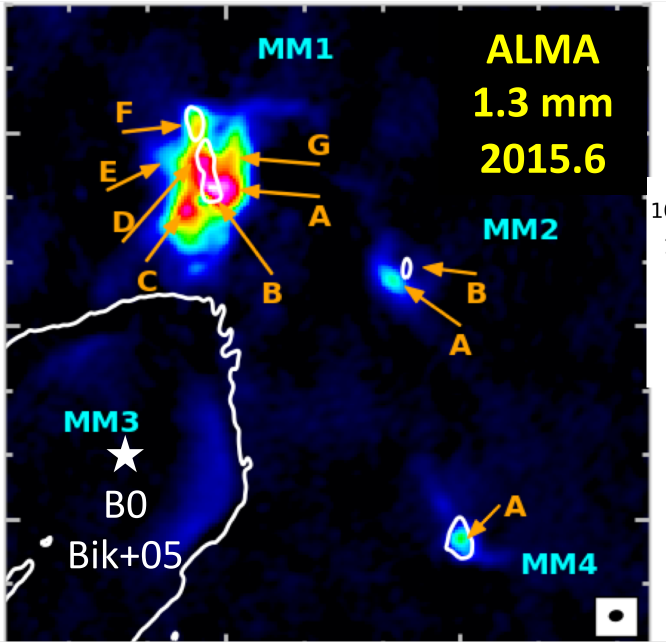
See Poster by Medina et al. on compact radio sources in this region

First ALMA Image: Cycle 2, 1.3 mm
Resolution: 0."17 (220 au)

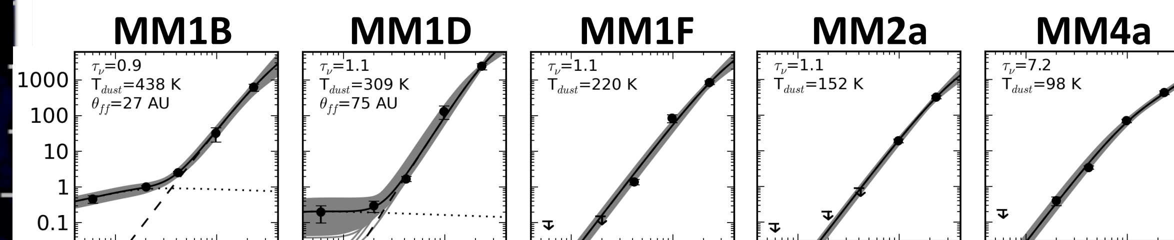
Heavily-obscured: only MM3 seen at 18μm (DeBuizer+2002)

NGC 6334 I: A Diverse Protocluster

Brogan, Hunter+ 2016, ApJ



SED models: other than MM1B+D and the UCHII region MM3, most MM sources can be fit by dust emission alone



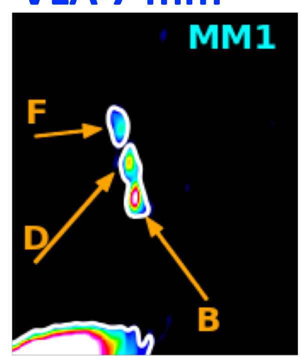
However, some MM1 components should have shown <u>much</u> brighter 7mm dust emission than observed in 2011.3. Mystery!

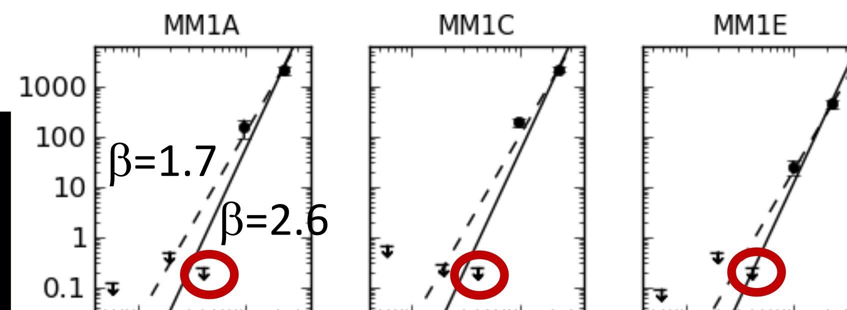
Dust sources MM1B and D also show free-free emission (VLA):

B: Hypercompact (HC) HII region
($n_e=3x10^6$ cm^{-3}, hot dust 440 K)

D: Jet+250K dust ($n_e=3x10^5$ cm^{-3})

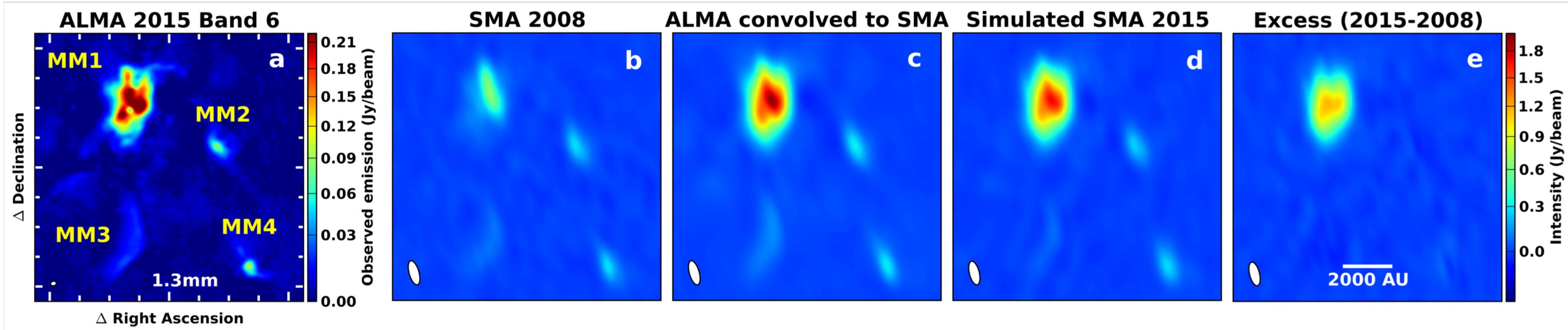
Epoch 2011.3
VLA 7 mm





Fit would require non-physical β values. Suggests they are **time-variable!**

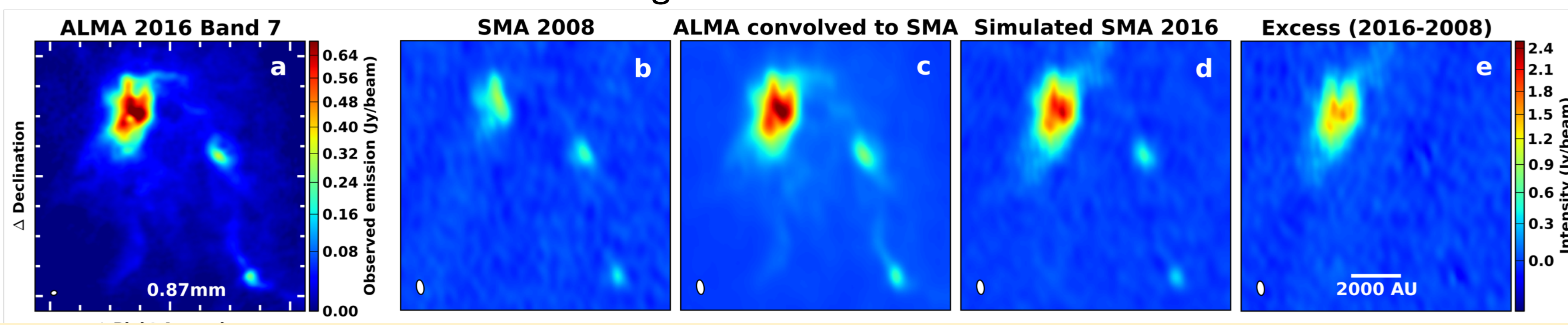
Extraordinary submillimeter brightening (between 2008-2015)



MM1 Band 6 flux density: 2008.6 SMA: 2.34 Jy vs. 10.8 Jy in 2015.6 ALMA

Hunter, Brogan+ 2017, ApJL

- CASA Simulation: SMA could have recovered: 9.4 Jy
- Increase = factor of 3.9! No change in other 3 sources. **Excess centered on MM1B HCHII**



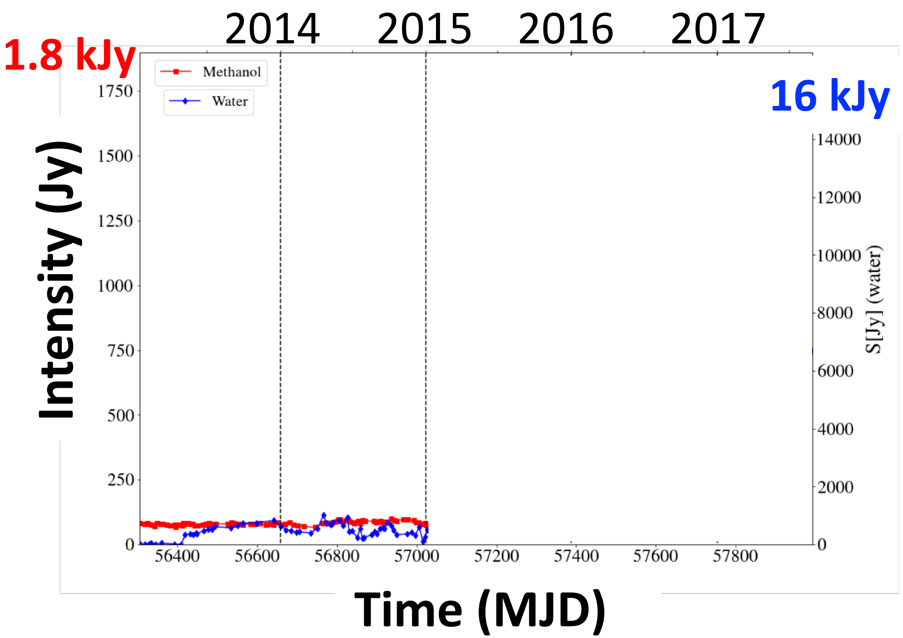
MM1 Band 7 flux density: Consistent increase = 21 Jy = factor of 4.2

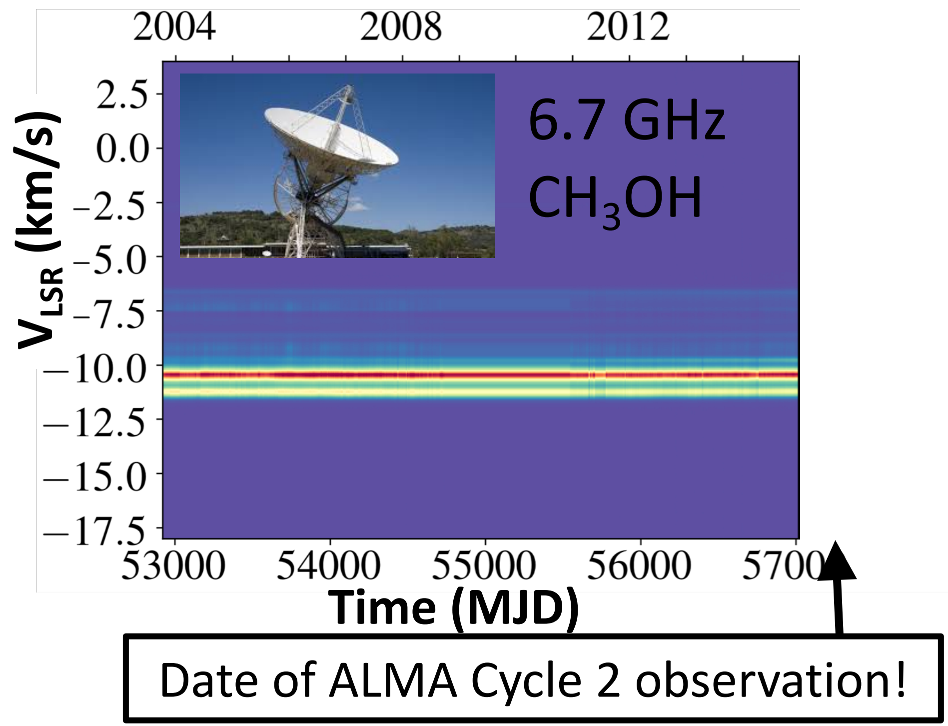
Spectral index of excess: 2.6 (dust); Planck T_B up by x 2.9 → **Luminosity up factor of 70±20**

Unprecedented maser outburst: single dish monitoring

- HartRAO 26m dish South Africa: 2 decades monitoring H_2O, OH, CH_3OH (Goedhart+2004)
- Starting in Jan. 2015: 10 maser lines flared; 30x increase in 22 GHz H_2O and 6.7 GHz CH_3OH

-7.2 km/s Methanol & Water over time

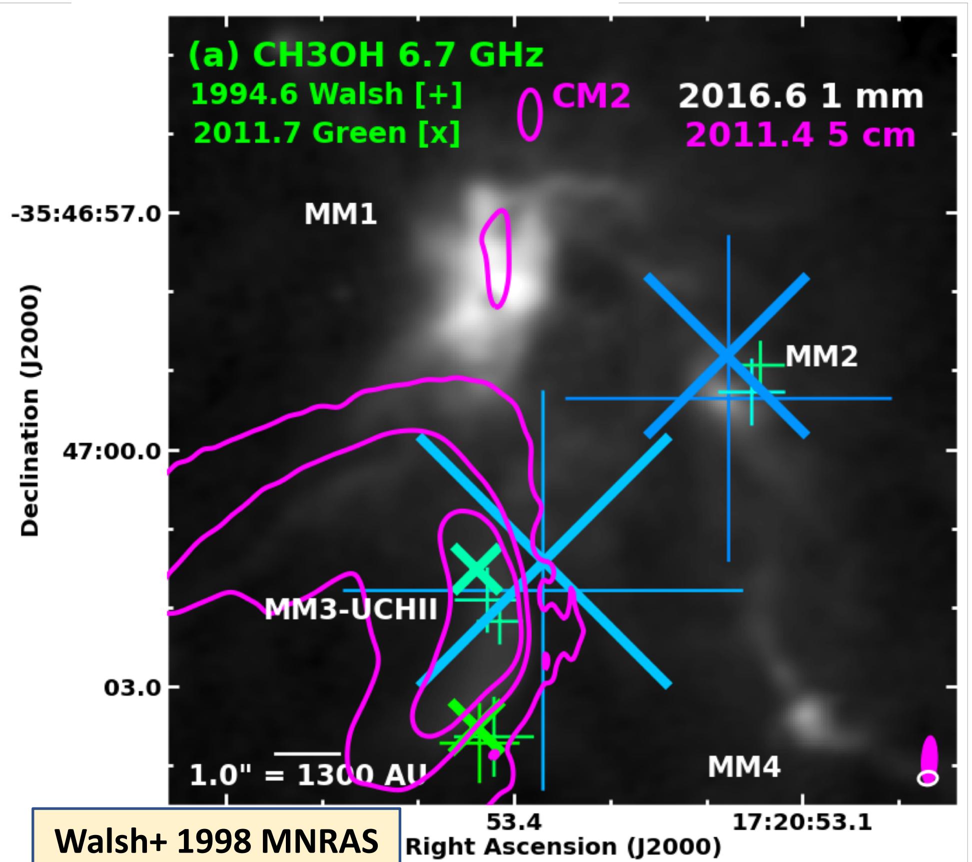




G. MacLeod+ 2018, MNRAS

Location and strength of CH_3OH masers in older observations

ATCA 1994 & 2011   Spot size $\propto \sqrt{\text{flux}}$



Walsh+ 1998 MNRAS

Important fact:

Class II CH_3OH masers are pumped by mid-IR (20-30 μm) photons (Sobolev+ 1997), in gas n_H=10^{4-8} cm^{-3}

Will respond to a luminosity outburst if the optical depth between masing gas and the protostar is not too high.

Some periodic sources are seen: see Poster 20 by K. Sugiyama

VLA-A follow-up: First detection of CH_3OH masers toward MM1!

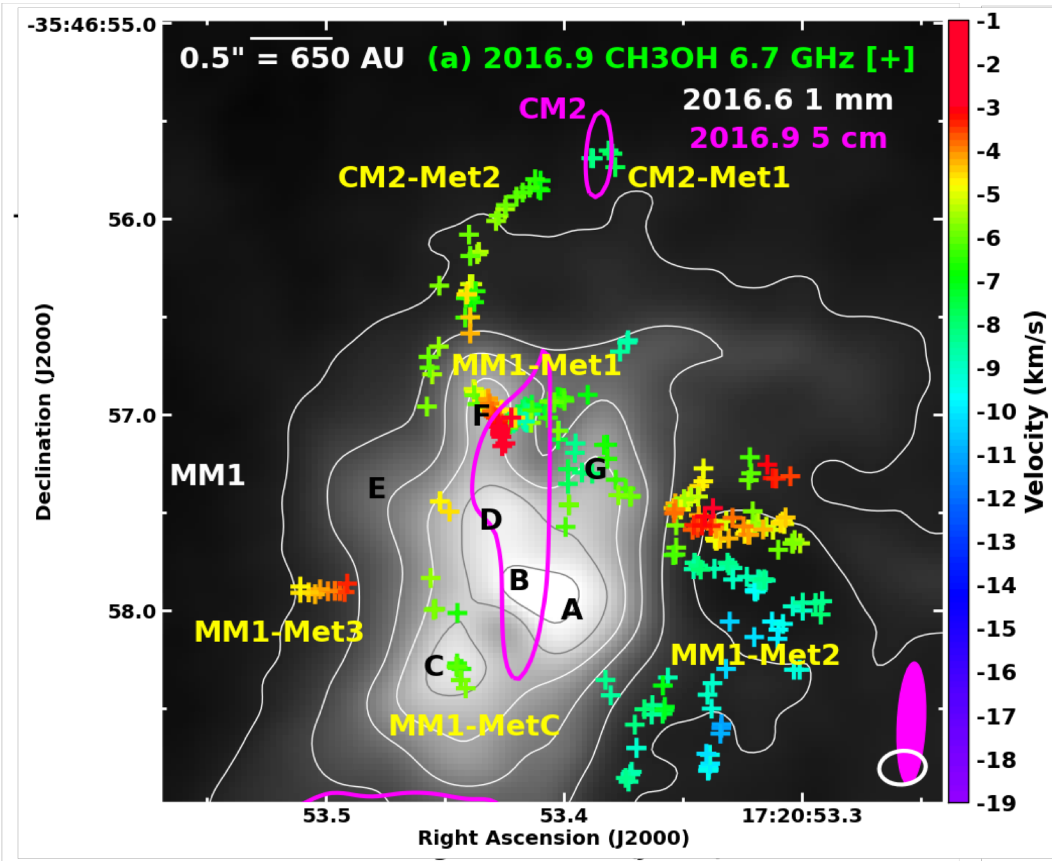
Hunter, Brogan et al. 2018, ApJ

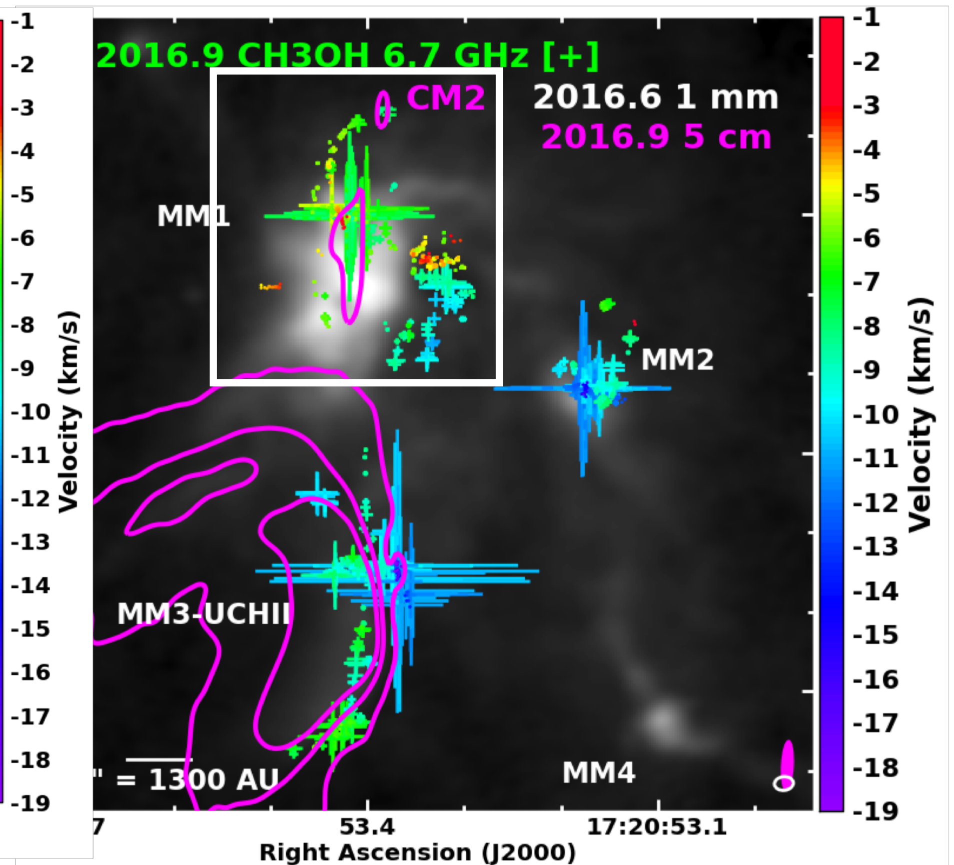
Not seen here in 1988, 1992, 1994, 2005, 2011 ...

ATCA 1994 & 2011

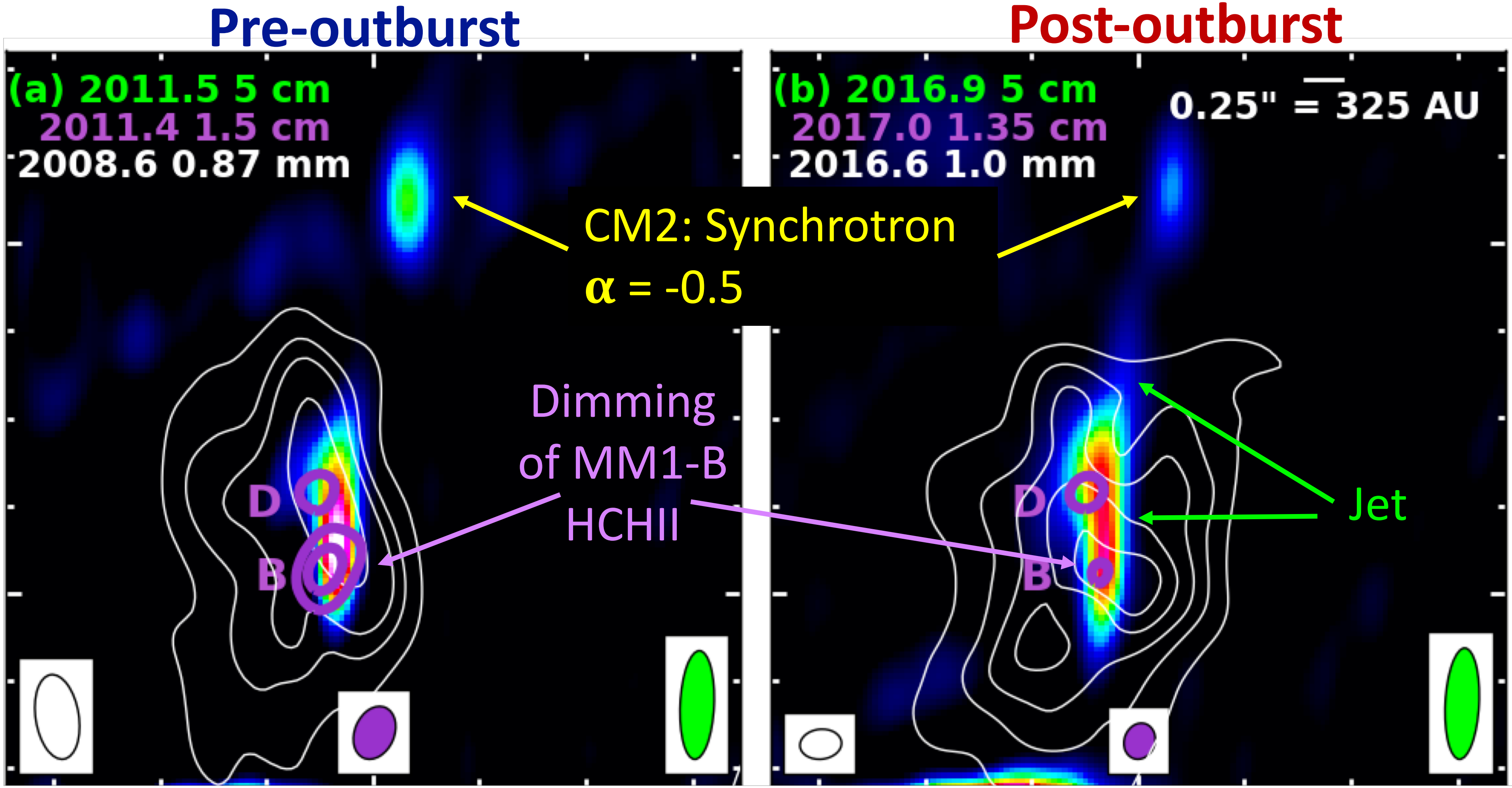
Spot size $\propto \sqrt{\mathbf{flux}}$

VLA 2016.9





Evolution of free-free emission in MM1



See Simon Purser's talk on jets on Friday

Brogan, Hunter+, in prep

Dimming of MM1B free-free emission

Source	1.5 cm 2011.4	1.35 cm 2017.0
MM1D	0.76 ± 0.1 mJy	0.73 ± 0.05 mJy
MM1B	1.78 ± 0.11	0.35 ± 0.03

EPOCH 2017.0 1.35 cm:

- MM1B **dimmed** by factor of **5.4** since 2011.4
- MM1D consistent with no change (± 10%)

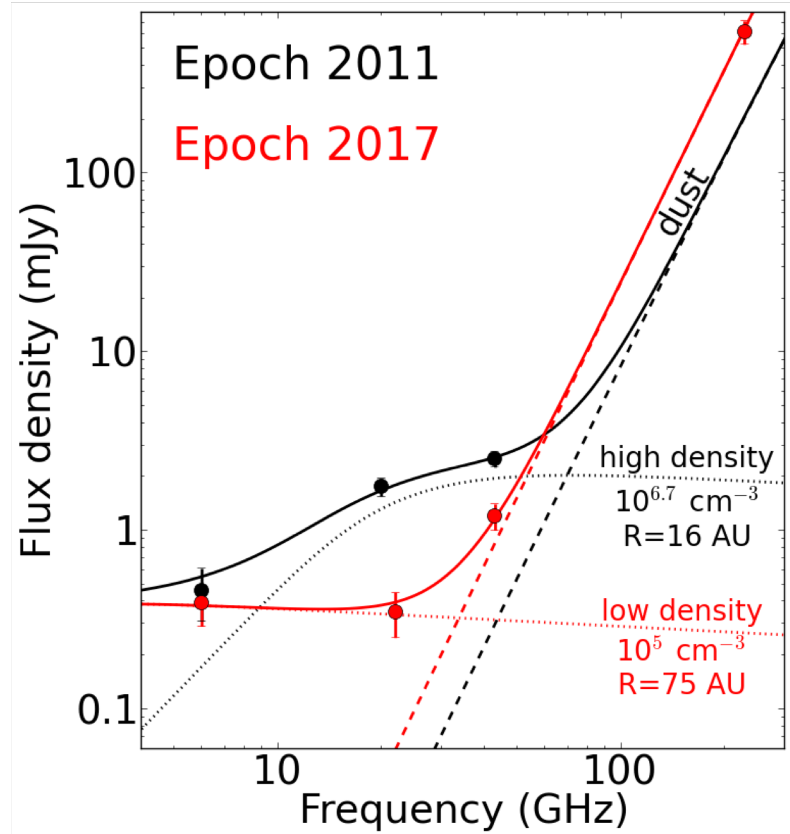
EPOCH 2017.7 0.7 cm:

- MM1B **dimmed** by only **2.5x**, dust now dominates
- MM1D consistent with no change (±15%)

These changes suggest a drop in UV photons.

By disentangling the change in dust contribution, we can model the before/after SED with 2 components:

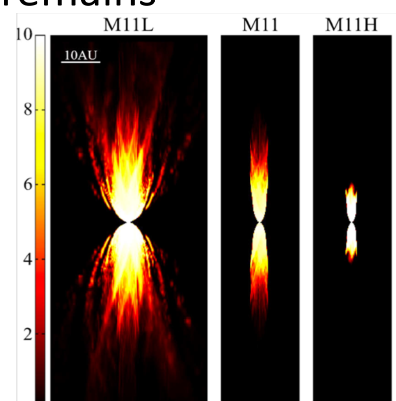
1) a compact high density HC HII region that vanishes
2) a low density (bipolar) jet that remains



Brogan, Hunter+, in prep

Tanaka et al. 2017 model predicts a drop in cm flux density after an accretion burst, but . . .

- L_{BOL} is unchanged
- Turnover frequencies (hence model densities) are much higher



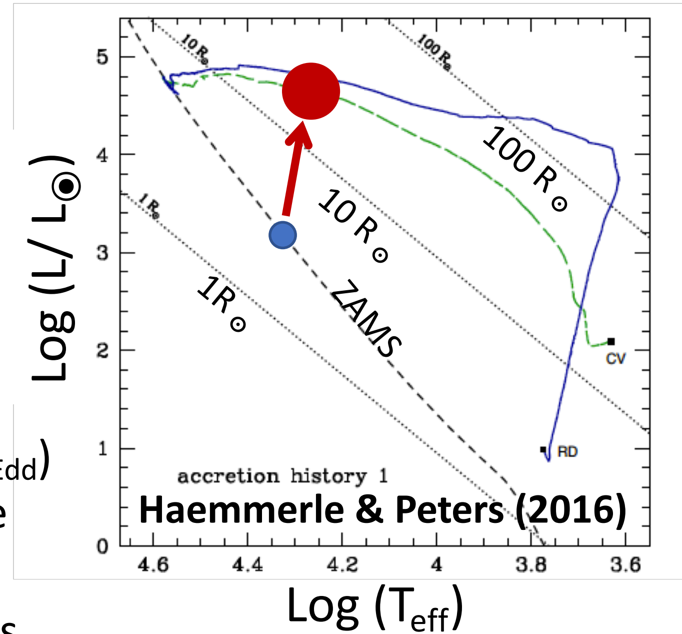
Protostellar bloating: Explains mm flaring and cm dimming

Pre-outburst Star:

- 1.5 cm flux density → **B2 star** (ZAMS) with $M \approx 6\ M_\odot$
- $L \approx 10^3\ L_\odot$ consistent with luminosity lower limit from dust envelope brightness temperature: ($L > 600\ L_\odot$)
- HCHII region diameter: 32 au (gravitationally-trapped)

Post-outburst Star:

- 70x luminosity boost (mm Tb) implies $7 \cdot 10^4\ L_\odot$ ($\approx 1/3\ L_{Edd}$)
- Loss of HC HII region requires lower T_{eff}, so it must have also expanded by ≈10x (3.3 to 33 $R_\odot$) ⇒ **B3 supergiant**
- After bloating, HC HII region cooling time ≈ only 2 weeks
- Similar amount of bloating predicted by accretion models of: Hosokawa & Omukai (2009) for $\dot{M} = 10^{-3}\ M_\odot\ yr^{-1}$ and Haemmerle & Peters (2016) variable accretion models



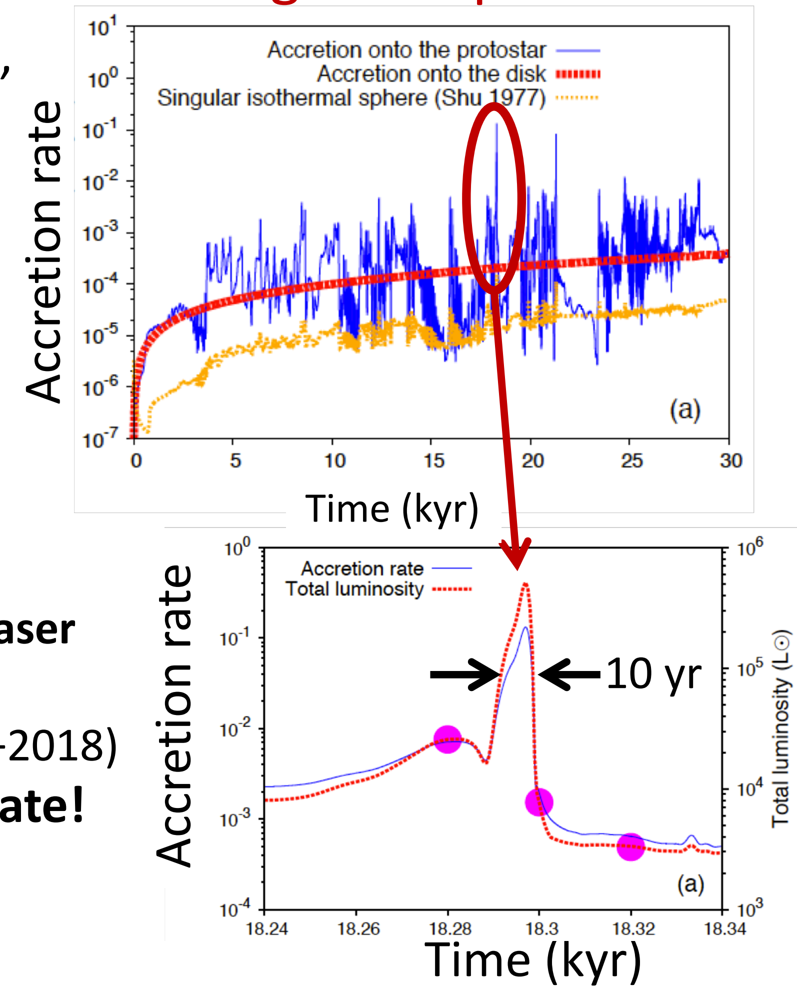
Large accretion events are expected

Meyer et al. 2017, 2018; poster by Kuiper:

Numerical radiation hydrodynamic simulations, including gas self-gravity & radiative feedback

- Produces bursts in accretion rate up to 100x
  - Yields 50x boost in luminosity for ~10 yr
  - Large bursts separated by a few 1000 yr
- MM1B outburst of 70x is a rare event
  - **Massive counterpart to an FU Ori event!**
- But smaller events are also expected….
  - e.g. **S255IR-NIRS3** flared in luminosity by 6x (Caratti o Garatti+ 2016) along with **CH_3OH maser flare** (Fujisawa+ 2015, Moscadelli+ 2017) and increased jet emission 13 mo. later (Cesaroni+2018)
- **CH_3OH masers <u>can</u> be a probe of accretion rate!**

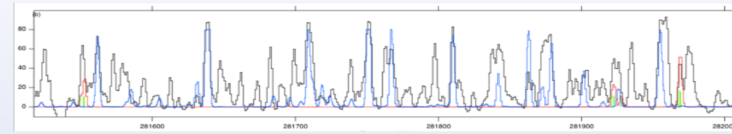
Large clump accreted.



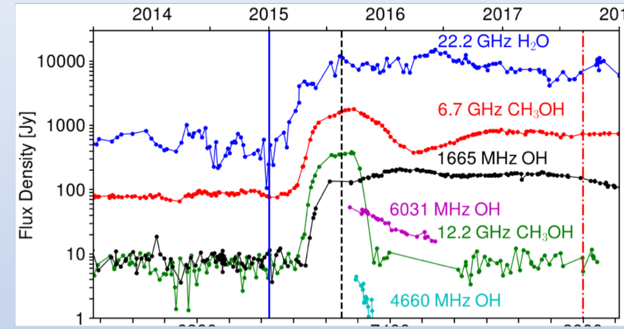
Implications for Massive SF

- **Outbursts provide a natural way to enrich a hot core by evaporating COMs from dust**
  - **Hot core = ``low-pass filter'' of past outbursts? (Taquet+ 2016)**
  - **Evidence in low-mass YSOs:** Frimann+17: sublimation radius is too large for L_{FIR} in many objects (SMA survey)
- **6.7 GHz maser monitoring is a powerful tool!**
  - Once position is established with VLA (Hunter+ 2018), single-dish light-curve of specific velocity component can probe protostar's variability / accretion rate
- **Bloating may not be a single stage, but repeating**
  - Variability of other HCHII regions (Galvan-Madrid+ 2008)

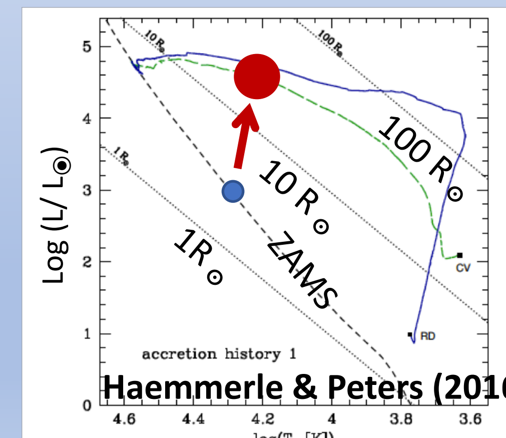
Future work: Monitor dust, free-free and masers
ALMA: Cycle 6 and VLA: A & B configurations



CH_3OCH_2OH detection: McGuire+ 2017, ApJL



MacLeod+ 2018 MNRAS 478, 1077



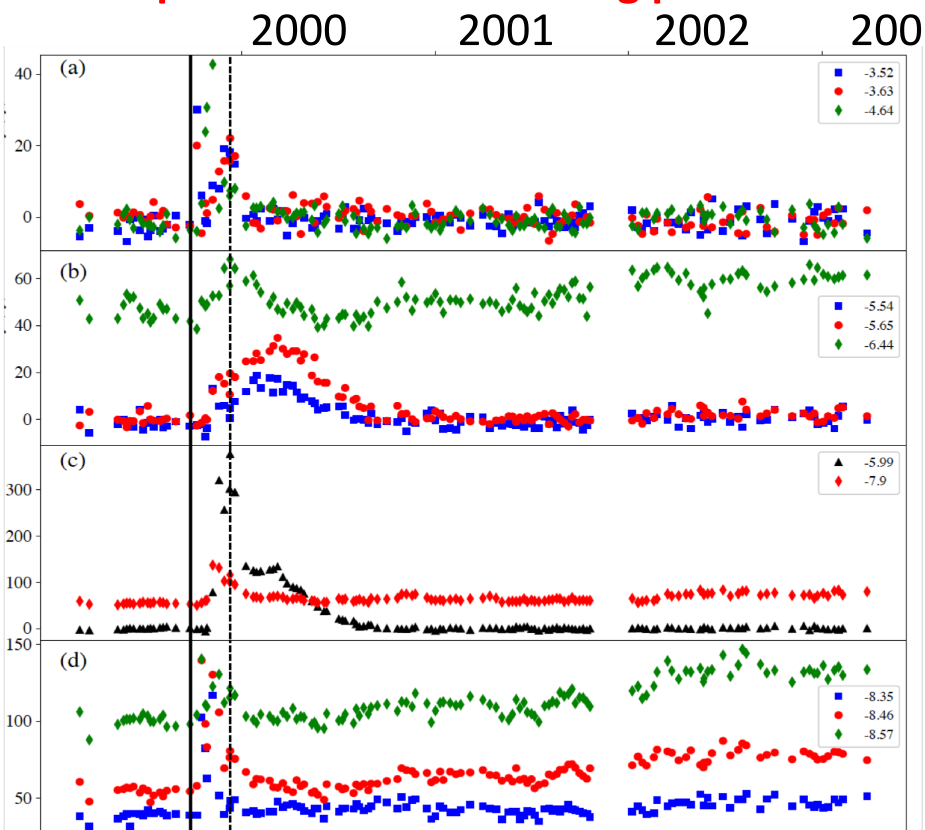
Haemmerle & Peters (2016)

T. Hunter 2018-07-05

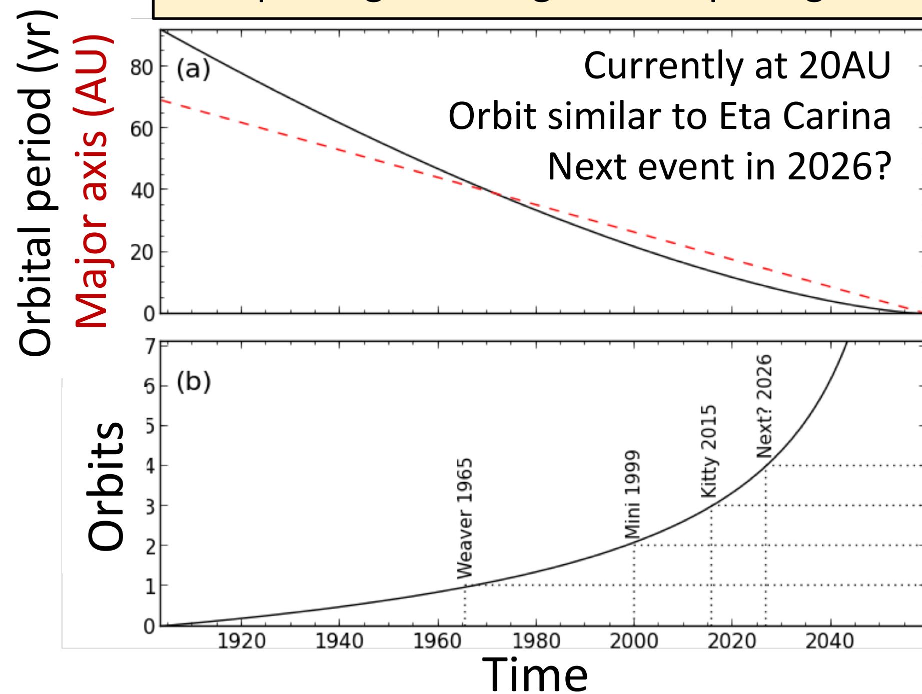
Extra slides

A smaller event in NGC6334I: Dec. 1999 maser "mini-burst"

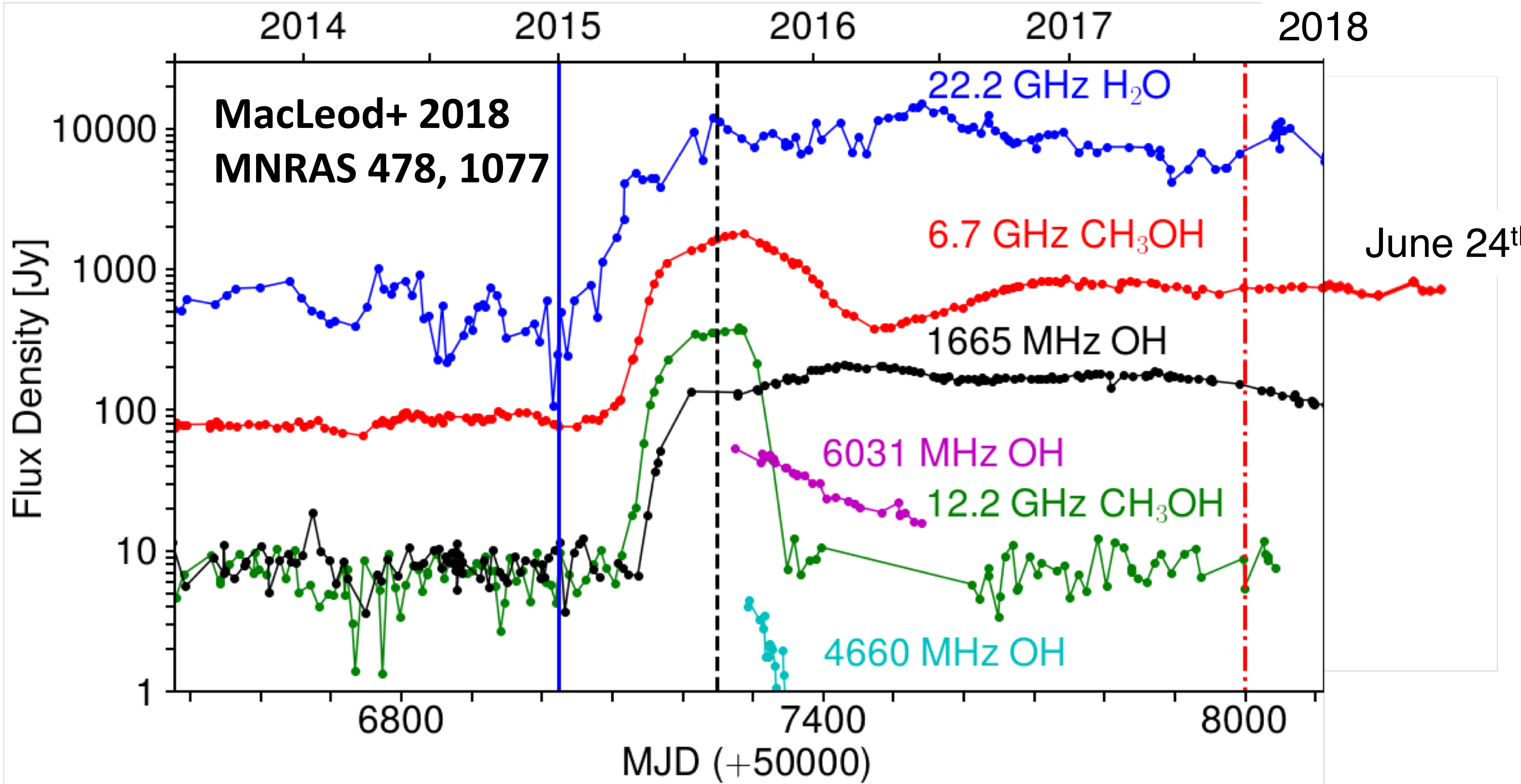
- -5.9 km/s CH_3OH maser component went to >100 Jy for 6 months (Goedhart+2004)
- -5.9 km/s in 2016.9 cube is on MM1 (7.7 Jy)
- **A pre-cursor or a recurring phenomenon?**



MacLeod et al. 2018 MNRAS
Speculate that 3 known outbursts can be fit by decaying orbit of a binary system embedded in gas (Stahler 2000). More of clump being accreting on each passage?



Some Key Questions: (1) Is there a mediating disk? (see next talk!)
(2) How long will the outburst last?
(3) Were there previous outbursts?

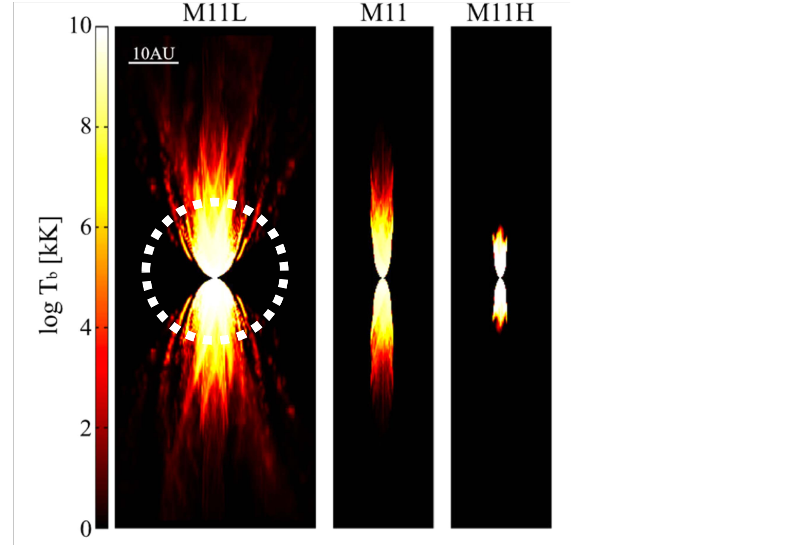


Dimming of MM1B: Alternative interpretation as ionized cavity

Tanaka et al. 2017 model: assumes accretion outburst will increase the density of ionized outflow cavity, reducing its extent

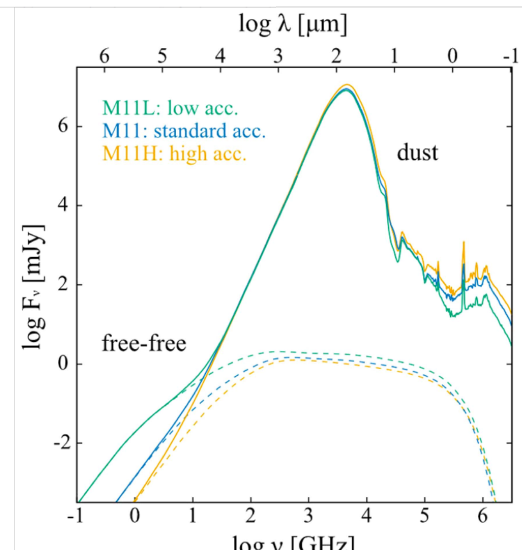
Pros:

- Leads to lower cm flux density
- Size would be unresolved to a 200 au beam, both before and after outburst

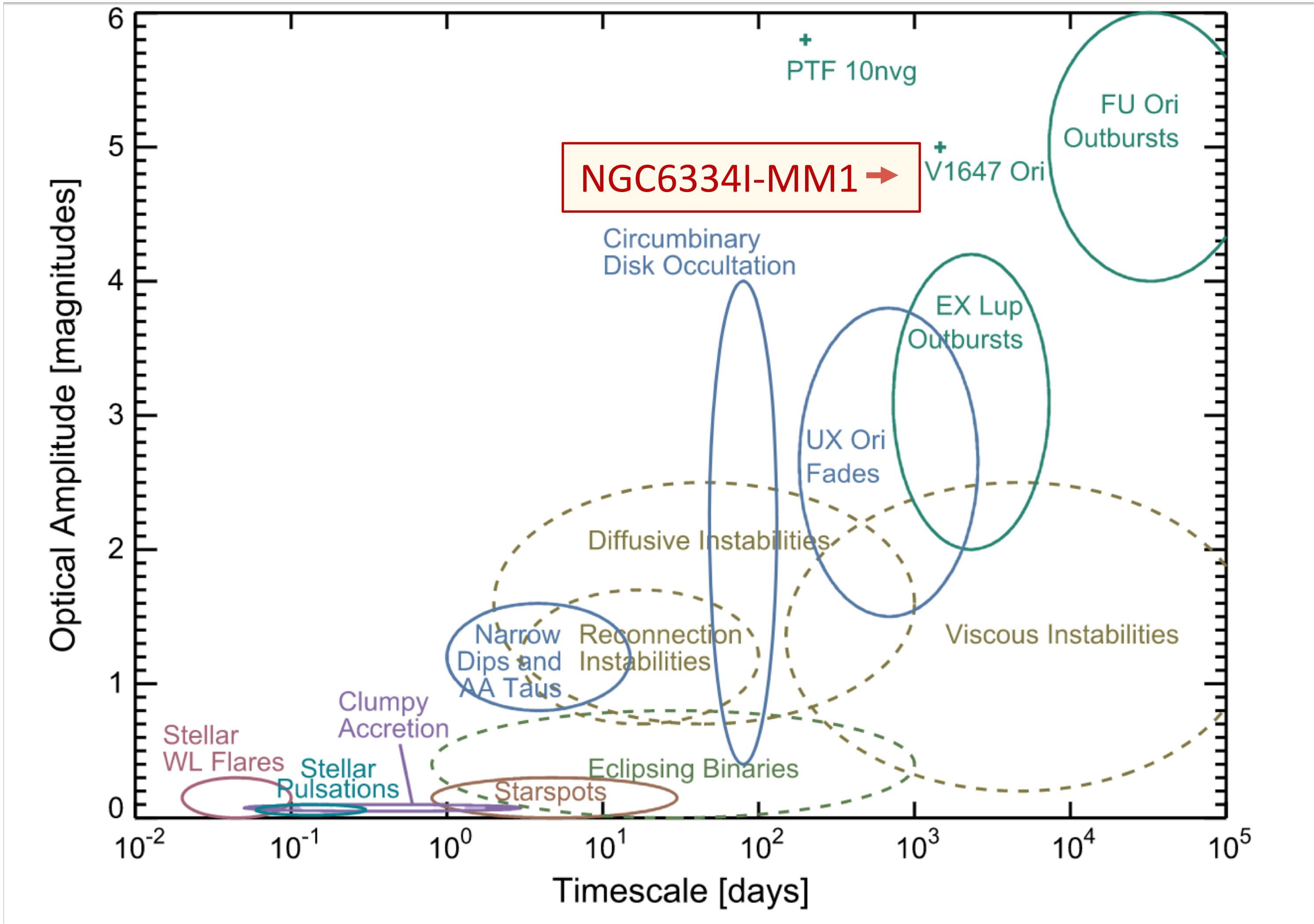


Cons:

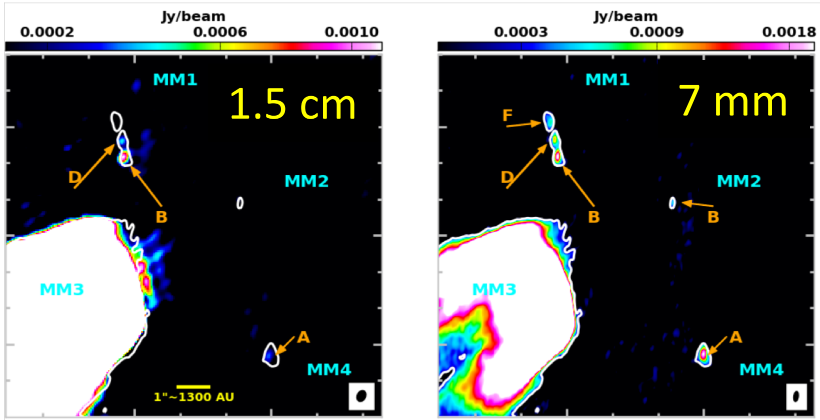
- Does not predict any change in luminosity, hence no millimeter continuum outburst
- Has a very high turnover frequency (>200 GHz) which is inconsistent with post-outburst SED of MM1B
- Model is for 11 Msun protostar (after K-H contraction phase of Hosokawa & Omakai)
- If pre-outburst $\dot{M} \approx 10^{-6}\ M_\odot\ yr^{-1}$ = 57 $L_\odot$ < 6% of ZAMS Luminosity



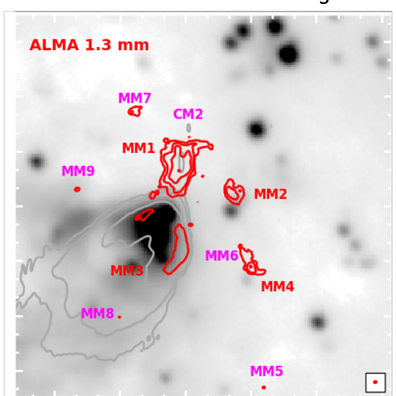
YSO variability phenomena: Hillenbrand & Findeisen 2015



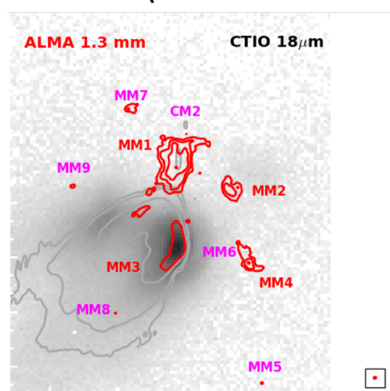
Multi-wavelength view of NGC 6334 I: only UC HII region is seen in IR

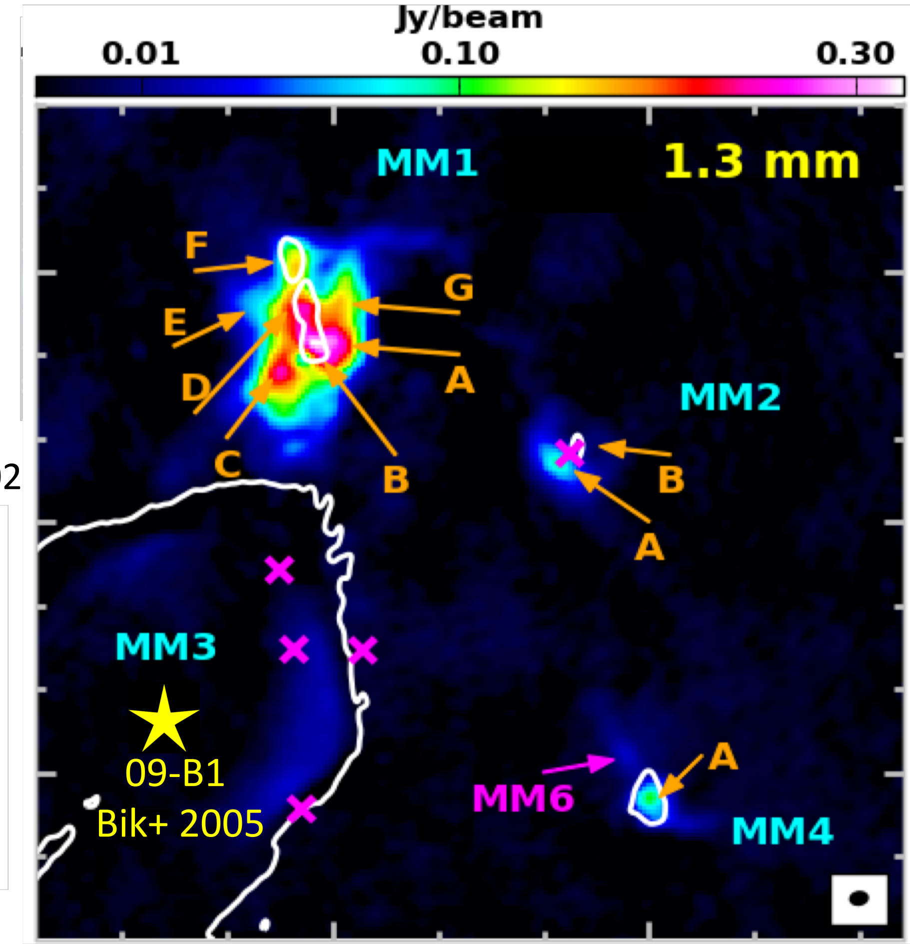


VLT HAWK-I K_s



CTIO 18 um (DeBuizer+ 2002





Brogan, Hunter+ 2016, ApJ, 832, 187

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 abundant thermal gas

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