Accretion outburst from a massive protostar: a sequence of extraordinary observational results

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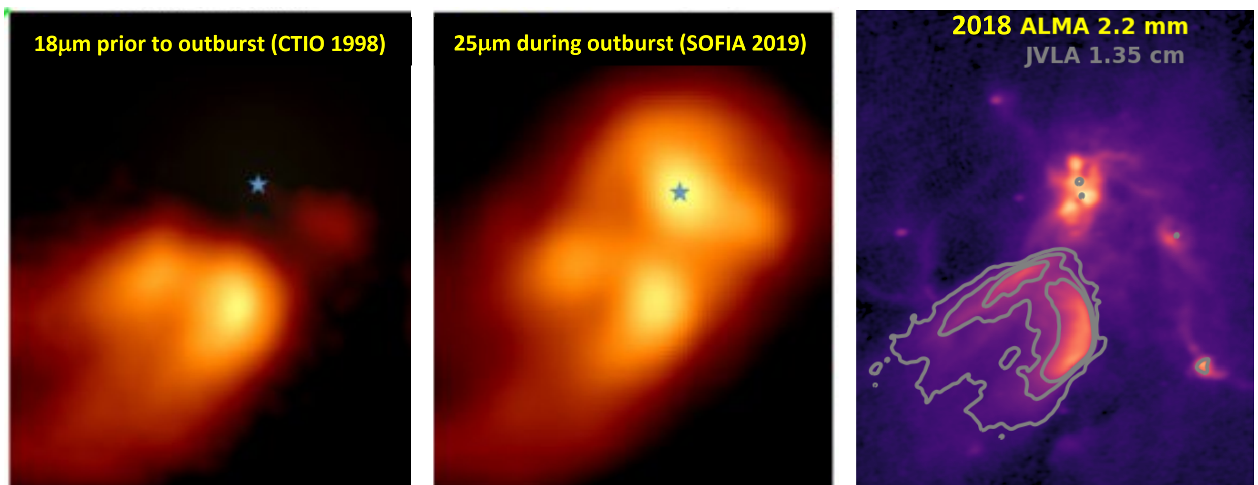
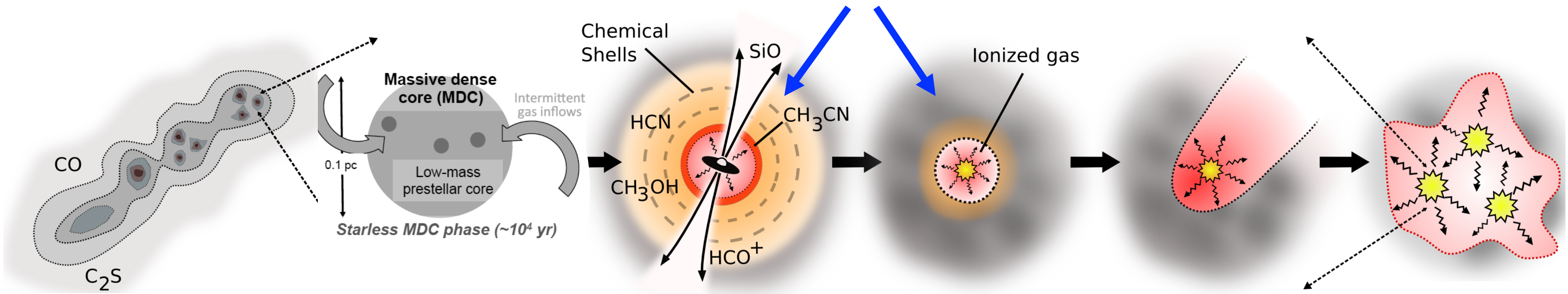


Observation-based stages of Massive Star Formation

COMs: Complex Organic Molecules



clumpy molecular cloud	massive prestellar cores (very elusive)	hot molecular core	hypercompact HII region	ultracompact HII region	HII region / OB association
L ~ several pc	R < 0.1 pc	R < 1000 au		R < 10000 au	R > 0.1pc

Historical context

1980s: IRAS catalog / VLA-identified ultracompact HII regions (Wood & Churchwell 1989)

1990s: Samples of massive YSOs / HMPOs gathered (Molinari+1996, Sridharan+2002)

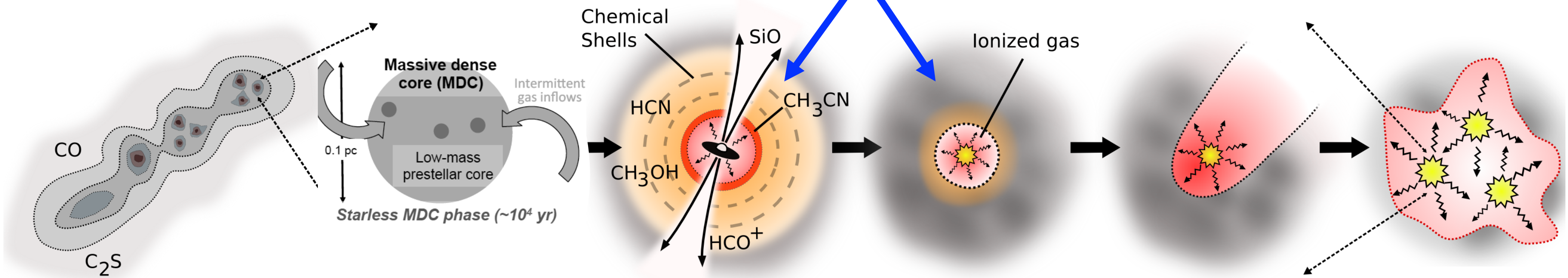
2000s: MSX, Spitzer surveys / IRDCs / EGOs = MYSOs with active outflows (Cyganowski+2008)

2010s: Detailed studies of individual fields / protoclusters

Cartoon credits: C. Purcell, F. Motte

Observation-based stages of Massive Star Formation

COMs: Complex Organic Molecules



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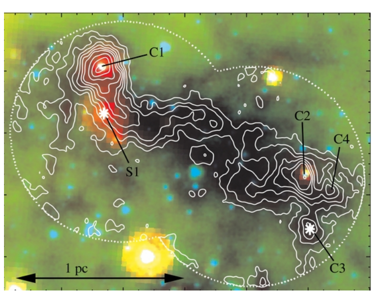
L ~ several pc	R < 0.1 pc	R < 1000 au		R < 10000 au	R > 0.1pc

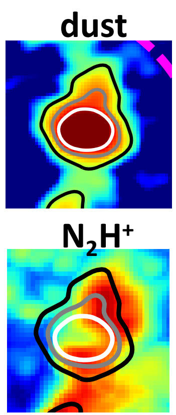
Not distinct stages; incl. EGOs 4.5um

accretion outbursts occur here

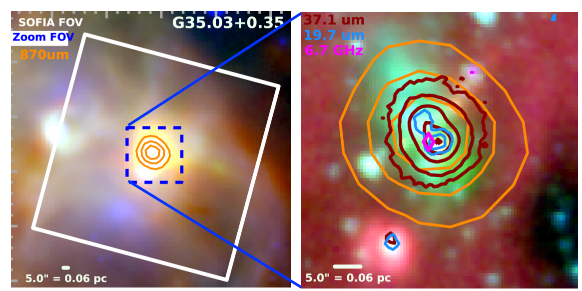
modest time variability (DePree+2018)



e.g. G19.30+0.07
Devine+2011



e.g. G11.92-0.61MM2
Cyganowski+2014



e.g. G35.03+0.35, Towner+2018

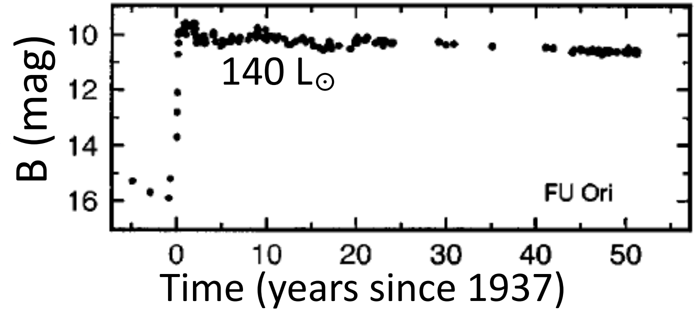
e.g. G29.96-0.02
Kalcheva+2018

Orion Trapezium
Bally+1998

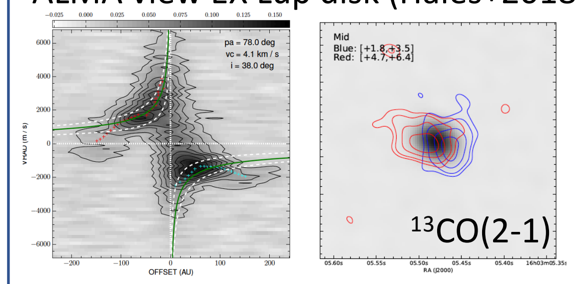
Evidence for Episodic Accretion in Low Mass YSOs

DIRECT EVIDENCE:

- Classical FUORs (named after FU Ori) (Hartmann+2016):
  - T Tau with >5 mag optical increase for 10-100yr ($\dot{M}$: 10^{-6} to 10^{-4} $M_\odot$/yr)
  - thought to be disk thermal instability (Bell & Lin 1994)
  - alternative idea: enlarged atmosphere (Herbig+2003, Larson 1980)
- EXORs (named after EX Lup) (E. Janssen, McLaughlin 1946):
  - smaller: 2-4 mag burst for months–years; can repeat (1929, 1995)
- Class 0 Objects: HOPS 383 (Safron+2015, L rose~40x)

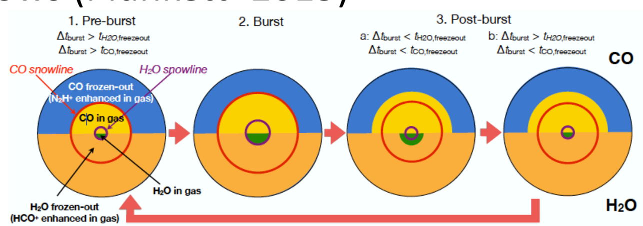


ALMA view EX Lup disk (Hales+2018)

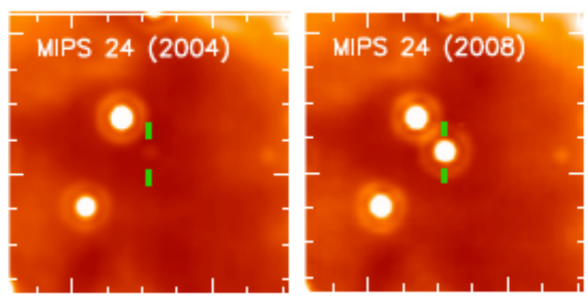


INDIRECT EVIDENCE:

- Spitzer c2d Legacy results (Evans+2009):
  - most YSOs underluminous relative to evolutionary models with a constant or decaying accretion rate
- Episodic molecular outflows (Plunkett+2015)
- Chemical evidence
  - snow line further out than expected for $L_{current}$ (Jorgensen+2020)



HOPS 383

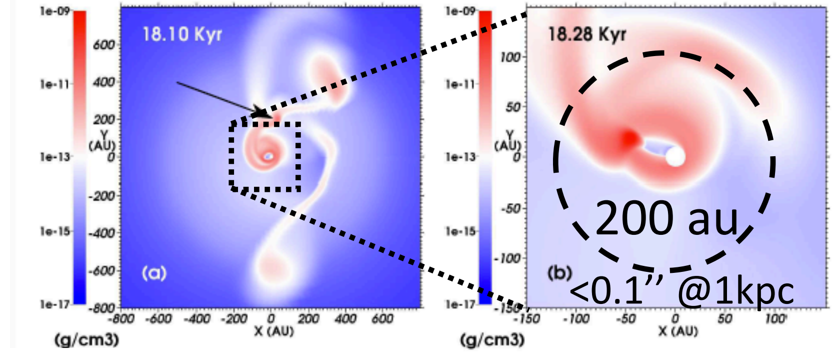


Stars gain > 25% of total mass from episodic accretion (Fischer+2019; Offner & McKee 2011)

Episodic accretion in massive protostars (theoretical)

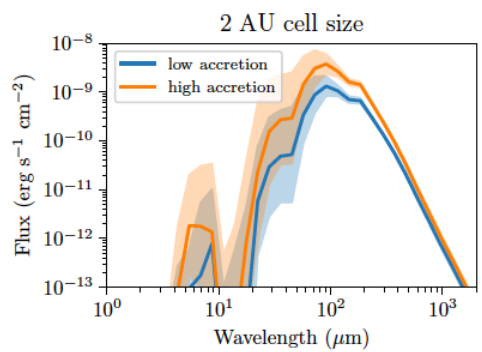
Meyer+2017: numerical radiation hydrodynamic simulations, including gas self-gravity & radiative feedback (Kuiper & Klessen 2013)

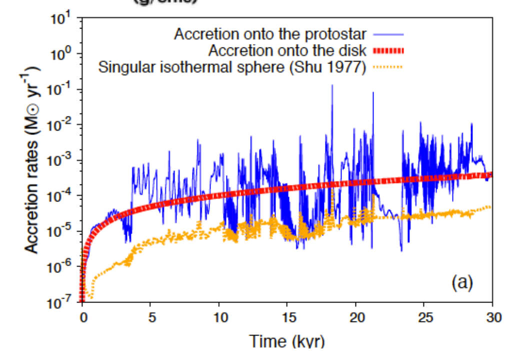
- Fragmentation of infalling material yields bursts in accretion rate up to ~300x background rate
- Largest bursts separated by few 1000 yr



Kuffmeier+2018: adaptive mesh refinement zoom-in simulations

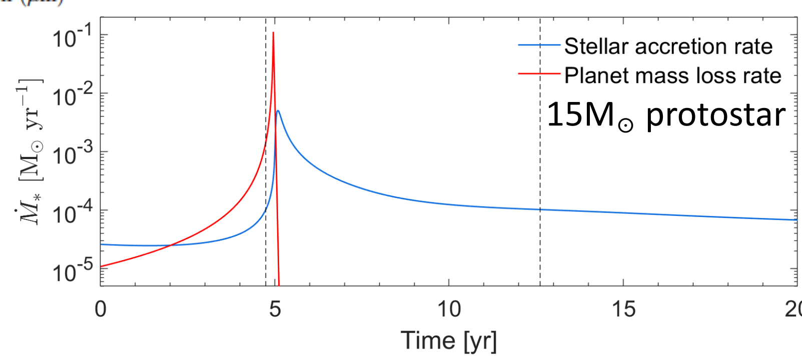
- Gravitational disk instabilities last 10-100yr
- RADMC3d: SED peak shifts to shorter λ at higher $\dot{M}_{acc}$ (see also Johnstone+2013)





Outburst mechanisms explored by Elbakayan+2021

1. Magnetorotational instability activation (t~1000 yr, 10^{-4} $M_\odot$/yr)
2. Thermal instability (t~100yr, 10^{-4} $M_\odot$/yr, FUOR-like)
3. Giant planet ($10R_{Jup}$) disruption: migrates toward star, fills Roche lobe (t~few yr, 5×10^{-3} $M_\odot$/yr)



Hartebeesthoek Radio Observatory news release – 11 Dec 2015

The Cat's Paw Nebula is a region of massive star formation

"A newborn, massive star was formed some 4000 light years from Earth in the Cat's Paw Nebula (NGC 6334), a region of massive star formation. This exciting conclusion was the result of many hours of observation, sighting, detection, and studying and monitoring readings at the Hartebeesthoek Radio Astronomy Observatory."

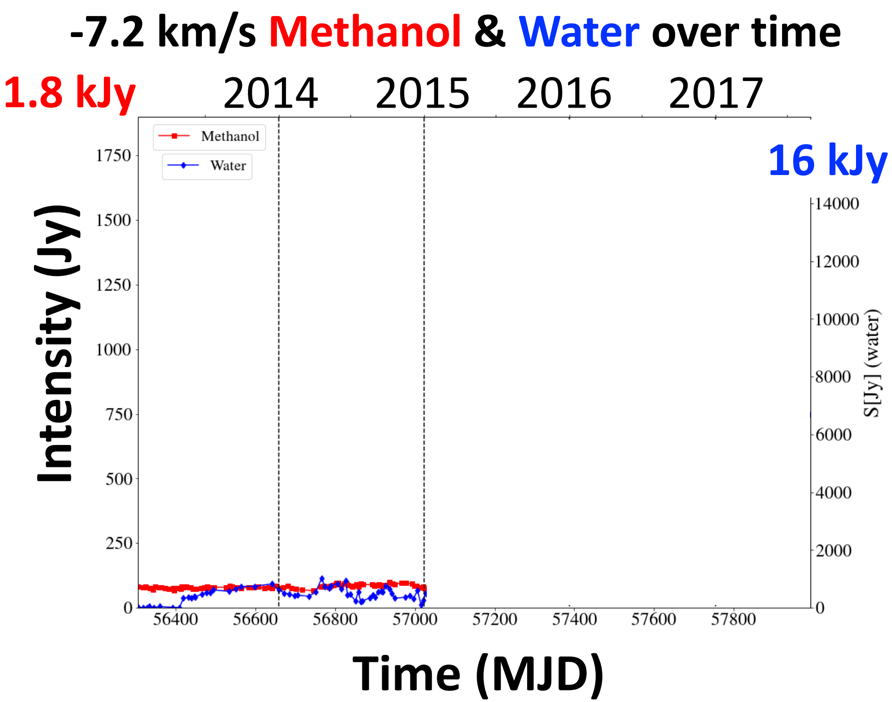
Gordon MacLeod & Derck Smits

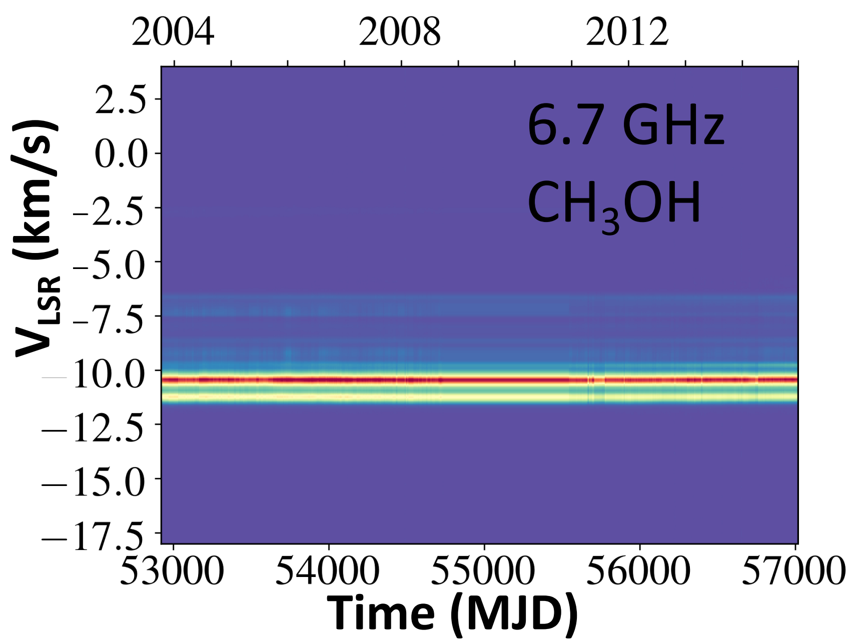
Why did they claim this? …

https://mg.co.za/article/2015-12-11-00-a-star-is-born/

... This is why! An unprecedented maser flare

- HartRAO 26m dish South Africa: 2 decades monitoring H_2O, OH, CH_3OH masers (Goedhart+2004)
- NGC6334I was their calibrator (**δ** = -35° passes near zenith, with strong and stable emission!)
- In Jan. 2015: 10 maser lines in 3 species flared; by 30x in 22 GHz H_2O and 6.7 GHz CH_3OH





G. MacLeod+ 2018 MNRAS, 478, 1077

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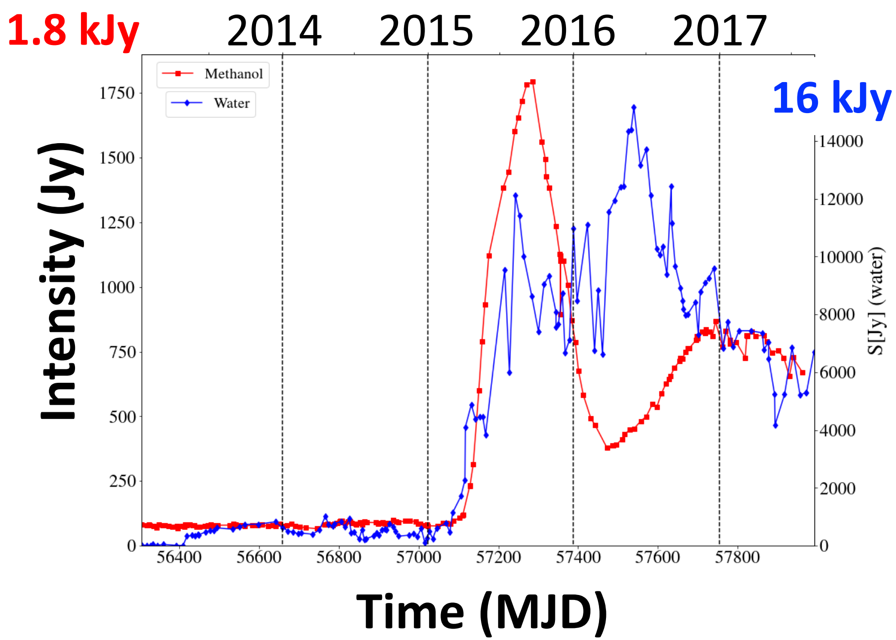
-7.2 km/s Methanol & Water over time



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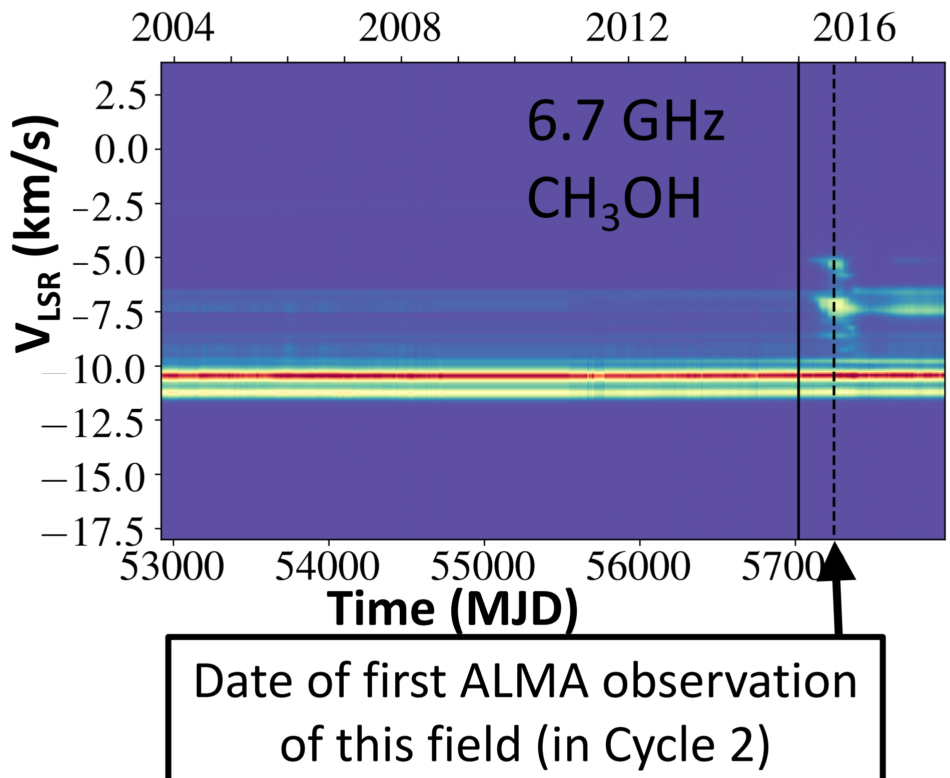
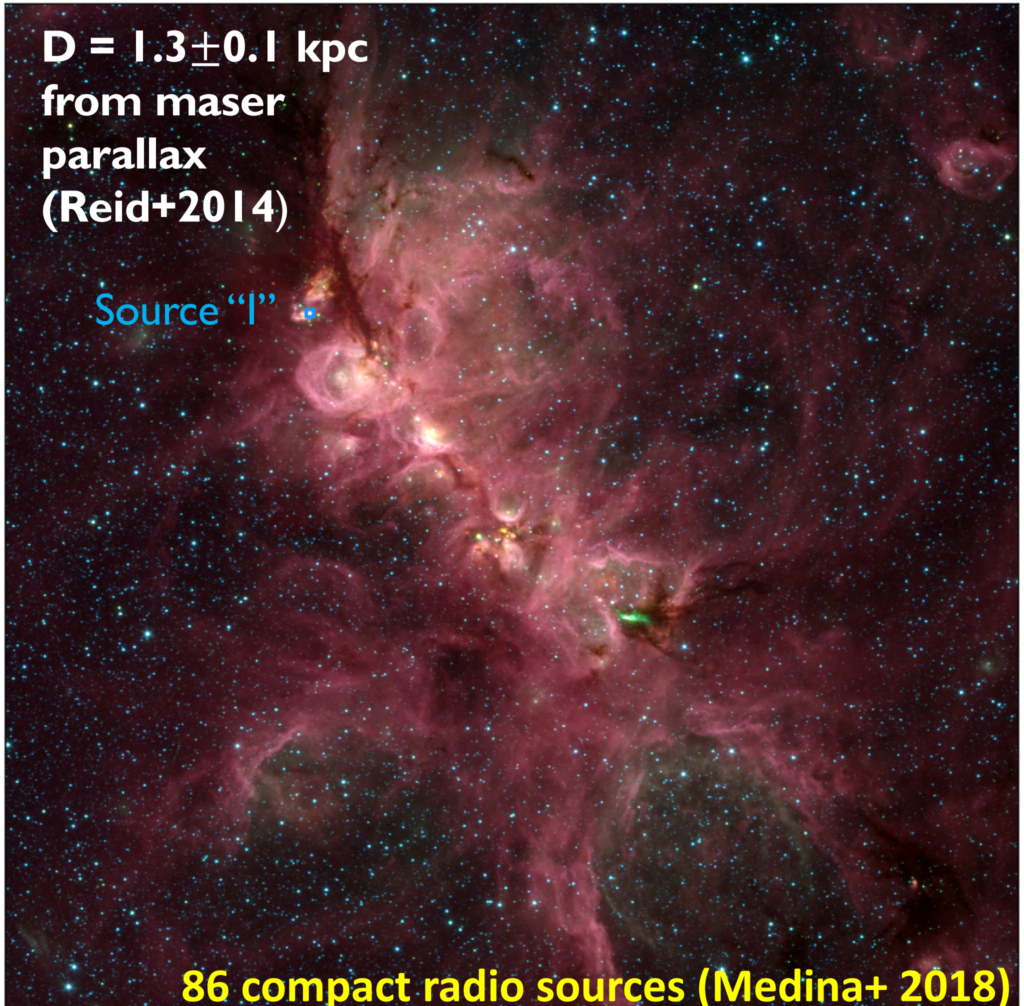


Intro to NGC 6334 ``Mini-starburst'' (Willis+ 2013; 2283 YSOs)

25 ’ = 15 pc



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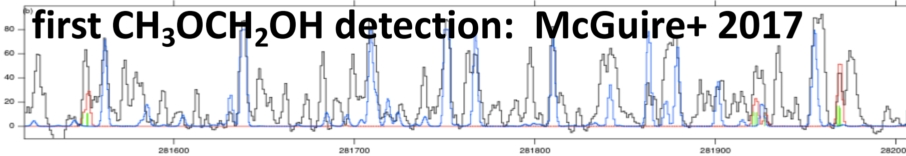
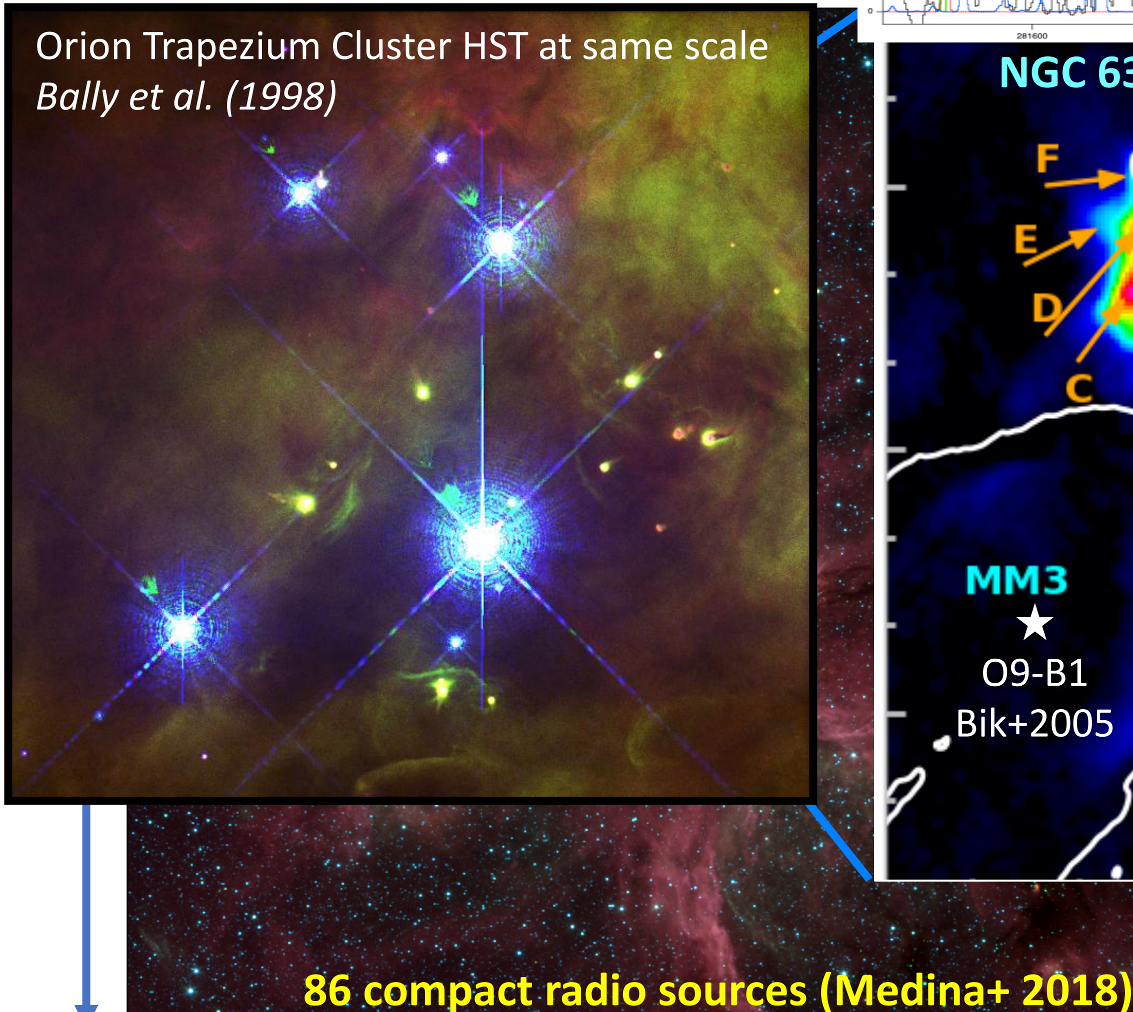
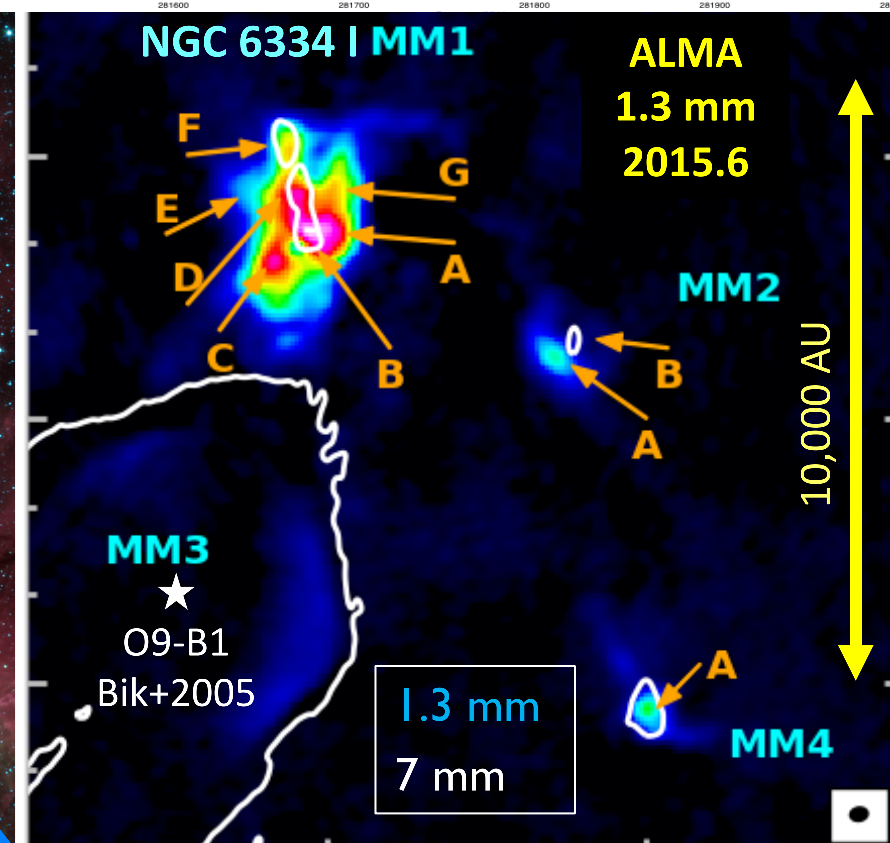


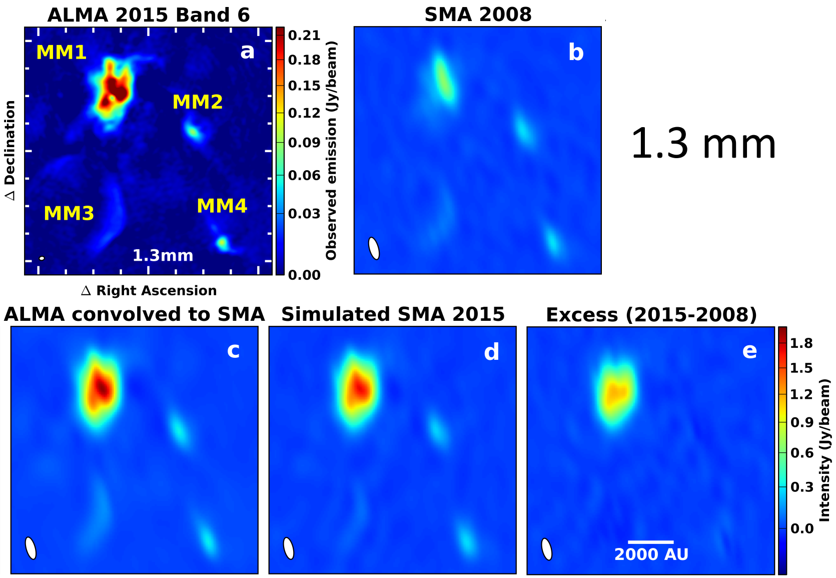




First ALMA Image: Cycle 2, 1.3 mm
Resolution: 0."17 (220 au)
Brogan+2016

NGC6334I mm continuum outburst / maser flare

- Comparison of first ALMA image to SMA image 7 years prior showed a flare in dust emission from MM1 only

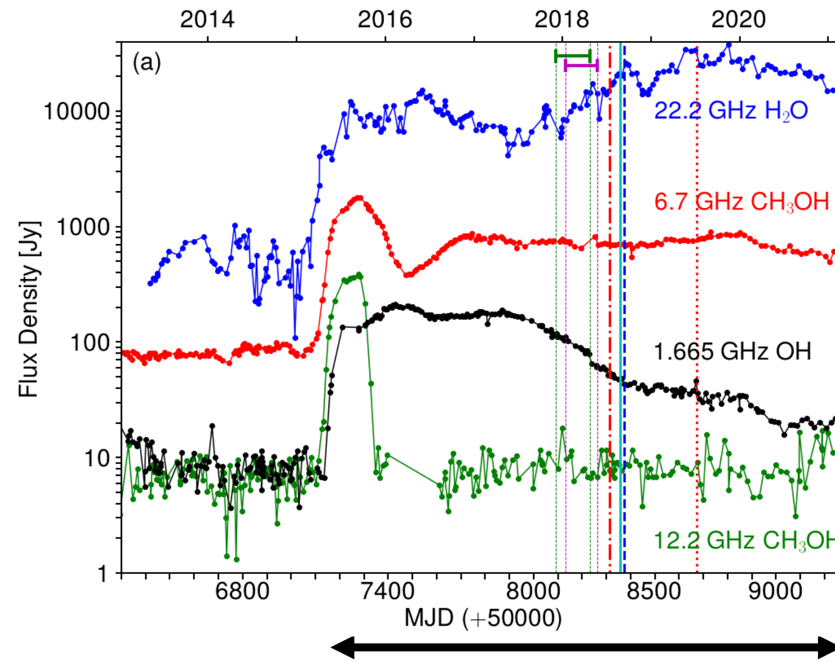


1.3 mm

- Flux density increased by a factor of 4
- No sign of fading after 6 years

(Hunter+2017; 2018, Brogan+2018, MacLeod+2018)

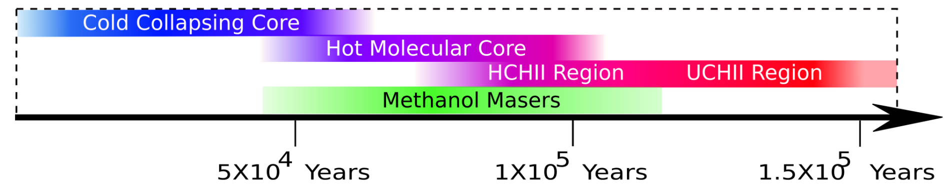
Maser flare means gas was also affected



After 6 years, the methanol maser (and water maser) flares also still going strong

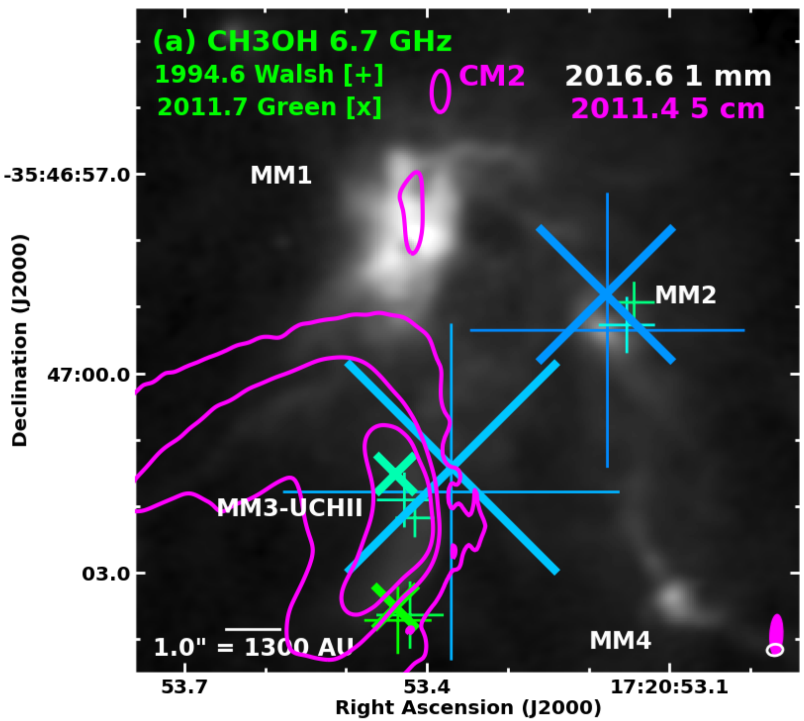
Methanol masers trace a particular stage of massive protostars

- Pumped by mid-IR photons (20-30μm) and cascading through torsional states
- Requires T_{dust} > 100K and dense gas 10^{4-8} cm^{-3}
- Seen **only in** strong radiative environments – **massive star forming regions** close to protostars



The traditional masers in NGC6334I before the outburst:

ATCA 1994 & 2011

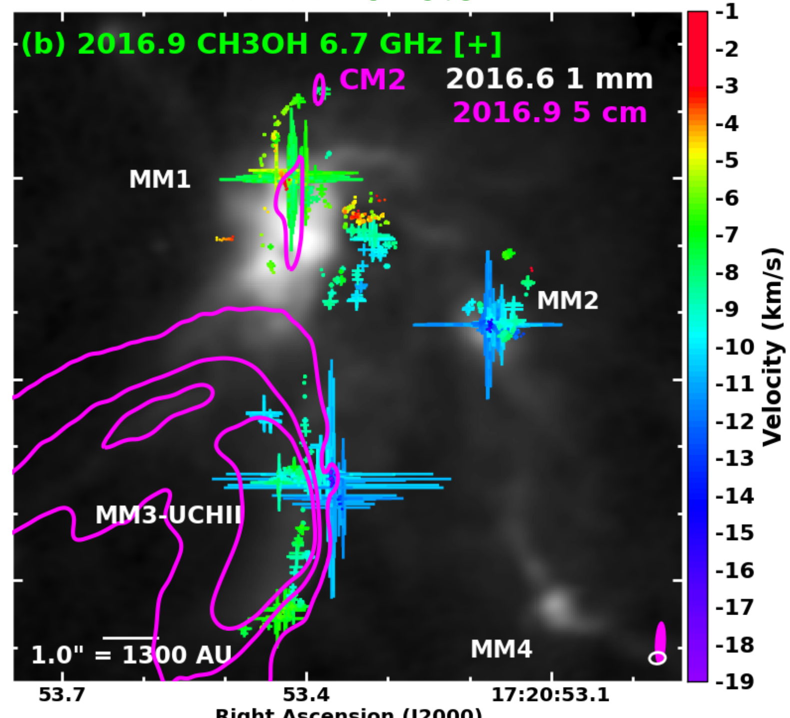


Spot size $\propto \sqrt{\text{flux}}$

Hunter, Brogan+ 2018, ApJ

after the outburst:

VLA 2016.9



New SOFIA and ALMA Observations (Jan 2018 – July 2019)

Hunter+2021, ApJL 912, 17

Table 1. Observing and imaging parameters

	SOFIA		ALMA			
Parameter	FORCAST	HAWC+	Band 4	Band 7	Band 8	Band 9
Project code	07_0156_1	GTO 70_0609_13	2017.1.00661.S	2017.1.00661.S	2017.1.00370.S	2017.1.00717.S
Configuration(s)	...	...	C43-6 & C43-3	C43-5 & C43-2	C43-4	C43-3
Observation date(s)	2019-07-09, -10	2018-07-14	6 executions[a]	4 executions[b]	2018-09-12	2018-08-28
Exposure time (sec)	1781, 1611	448	10215	5149	2118	2365
Flux calibrator	...	...	J1617−5848	J1924−2914[b]	J1924−2914	J2253+1608
Gain calibrator	...	...	J1713−3418	J1717−3342	J1733−3722	J1733−3722
Wavelength(s) λ_1, λ_2 (μm)	25.3, 37.1	53	2173	1005	758	432
Projected uv-range (kiloλ)	$\cdots$	$\cdots$	13 – 1218	13 – 1380	16 – 1613	19 – 1746
Angular resolution	3.2”, 3.5”	5.6”	all bands are ~ 0.3” x 0.2”			

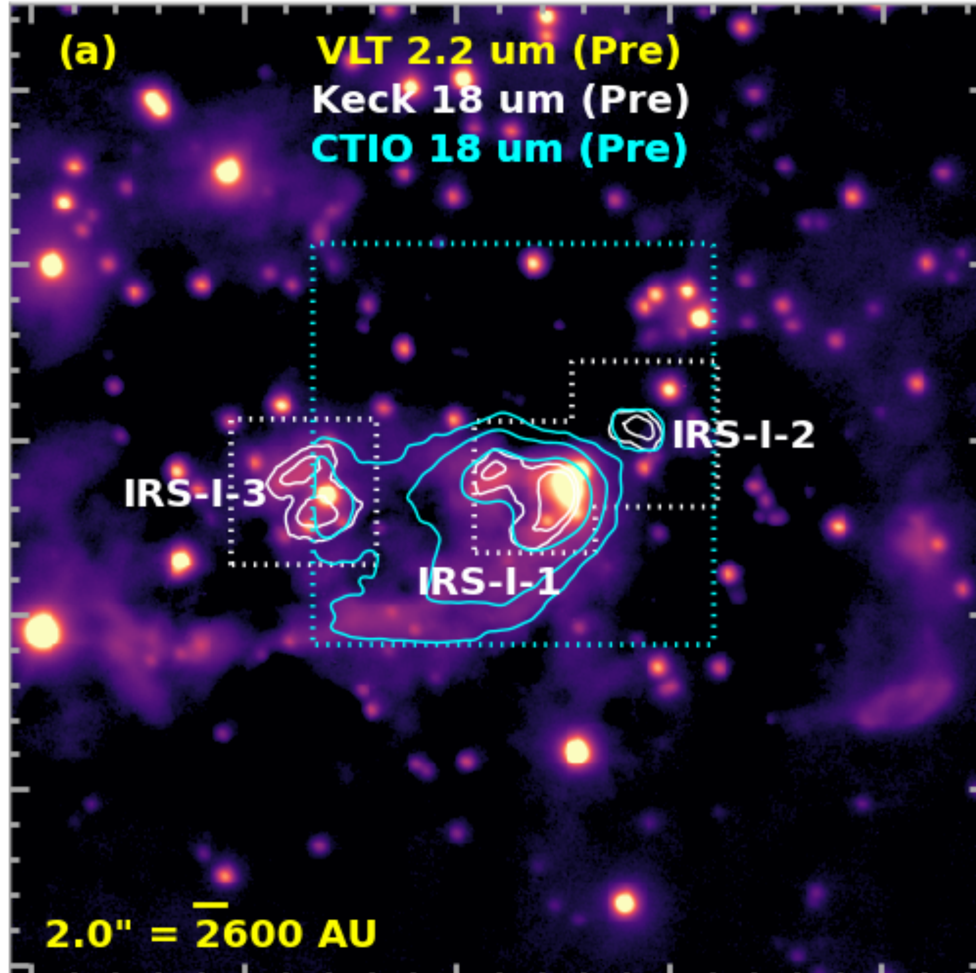
Best pre-outburst infrared images of NGC6334-I (pre-2015)

Archival (2012) VLT K_s image aligned to Gaia DR2

Strongest mm source / hot core (MM1) was undetected:
  at 18um (CTIO, DeBuizer+2000)
  and 8-20um (IRTF, Kraemer+1999)
while MM2 was seen faintly (IRS-I-2)

UCHII region (IRS-I-1) = NGC6334-MM3 dominated the near- and mid-IR:
    central star: kO9-B1 (Bik+2005)
    L_{bol}= 7000 - 100000 $L_\odot$

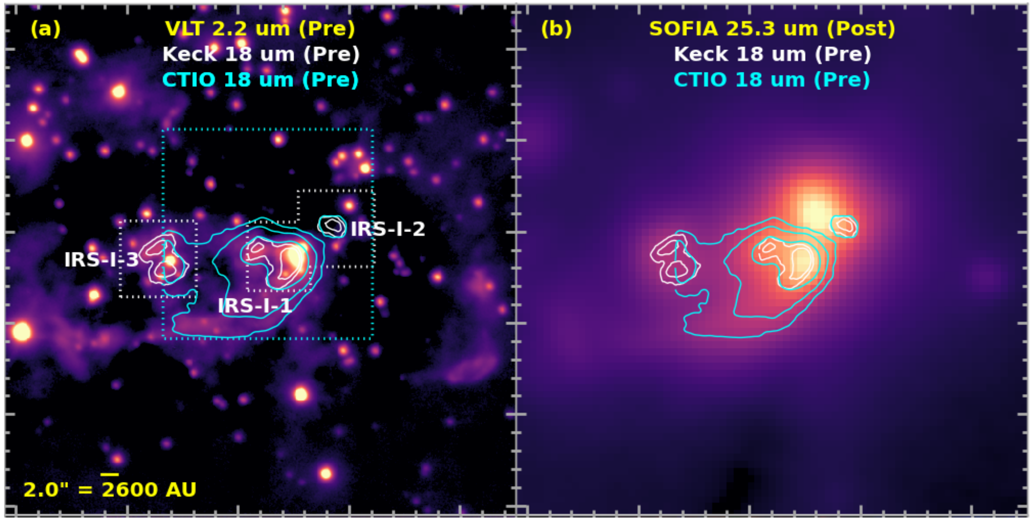
Old 2-100μm data from UKIRT, IRTF, KAO by Harvey & Gatley (1983) yields
    L_{bol} (Σ field) = 90000 $L_\odot$
    (~1/3 of Orion Trapezium stars)

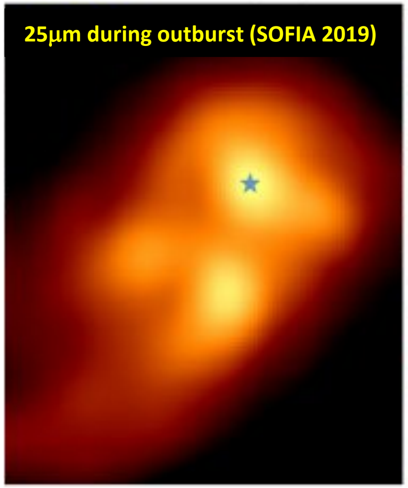


Hunter+2021

Mid-outburst 25um image from FORCAST (August 2019)

MM1 is now the dominant object at λ >= 25 microns!



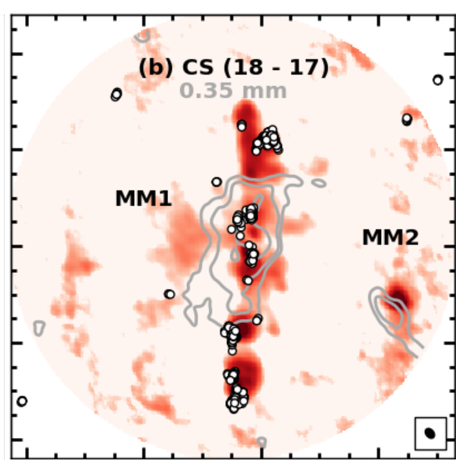


Mid-outburst 25um image from FORCAST (August 2019)

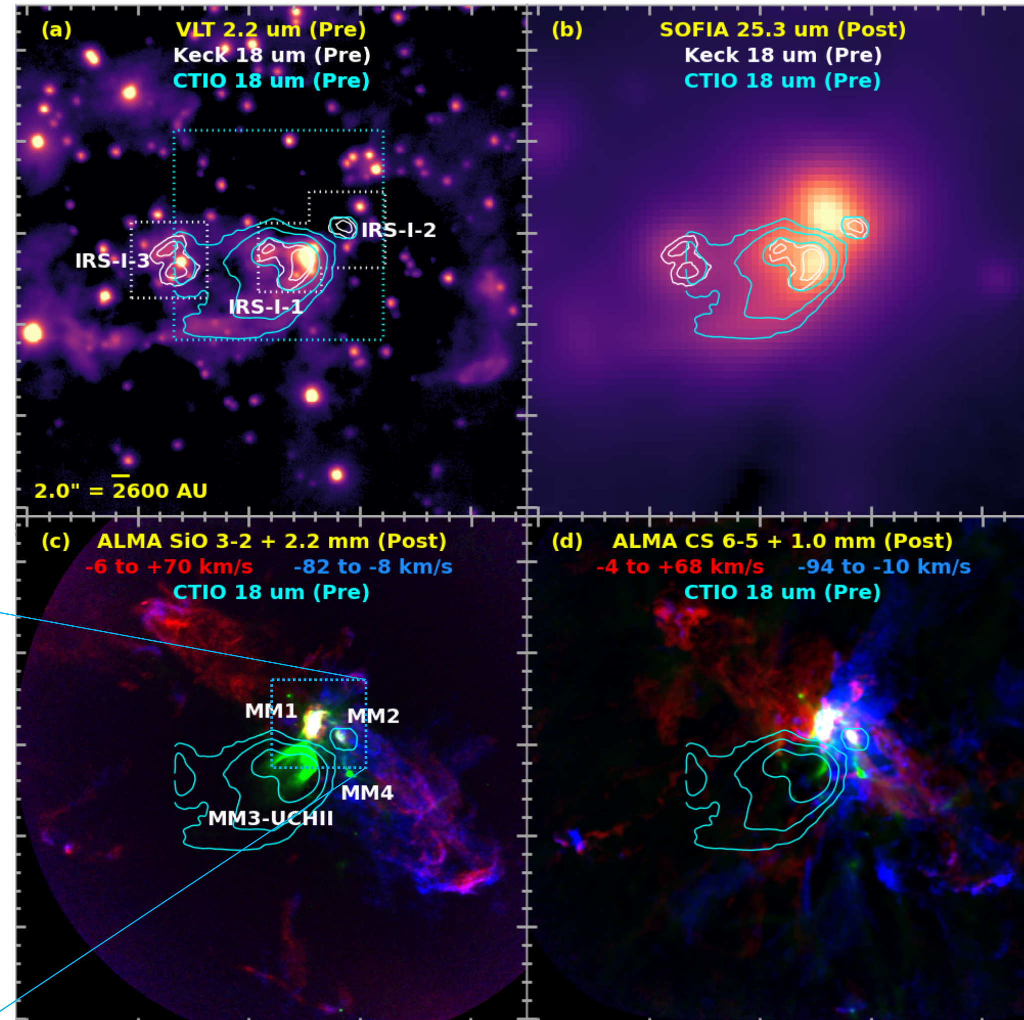
MM1 is now the dominant object at λ >= 25 microns

Multiple outflows from MM1:

1. extended northeast/southwest flow (known from single-dish)
2. compact north/south flow in ALMA Band 10 CS & HDO (Brogan+2018, McGuire+2018)



water maser locations match edges of thermal gas knots



Photometry (FORCAST, HAWC+, ALMA)

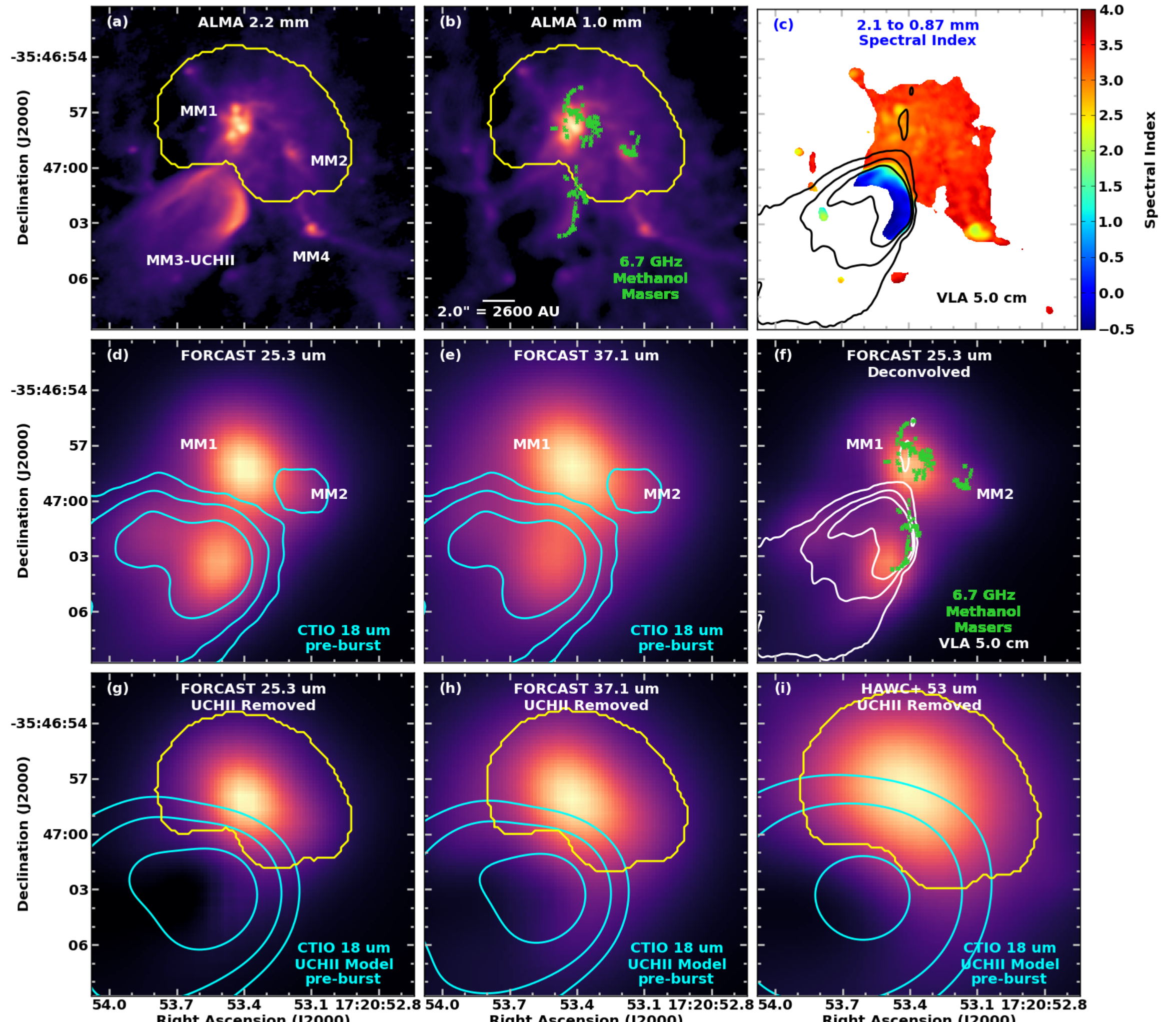
ALMA spectral index image:
MM1 and MM2 dominated by dust emission

Not well separated at $\lambda > 25$

Instead, we measure sum of MM1+MM2, by modeling the UCHII MM3 (cyan contours, row 2) then smoothing & removing it (images in row 3)

Model = CTIO 18um image smoothed and scaled to 25, 37, and 53 um

Aperture size increased w/ λ in proportion to IR beamsize



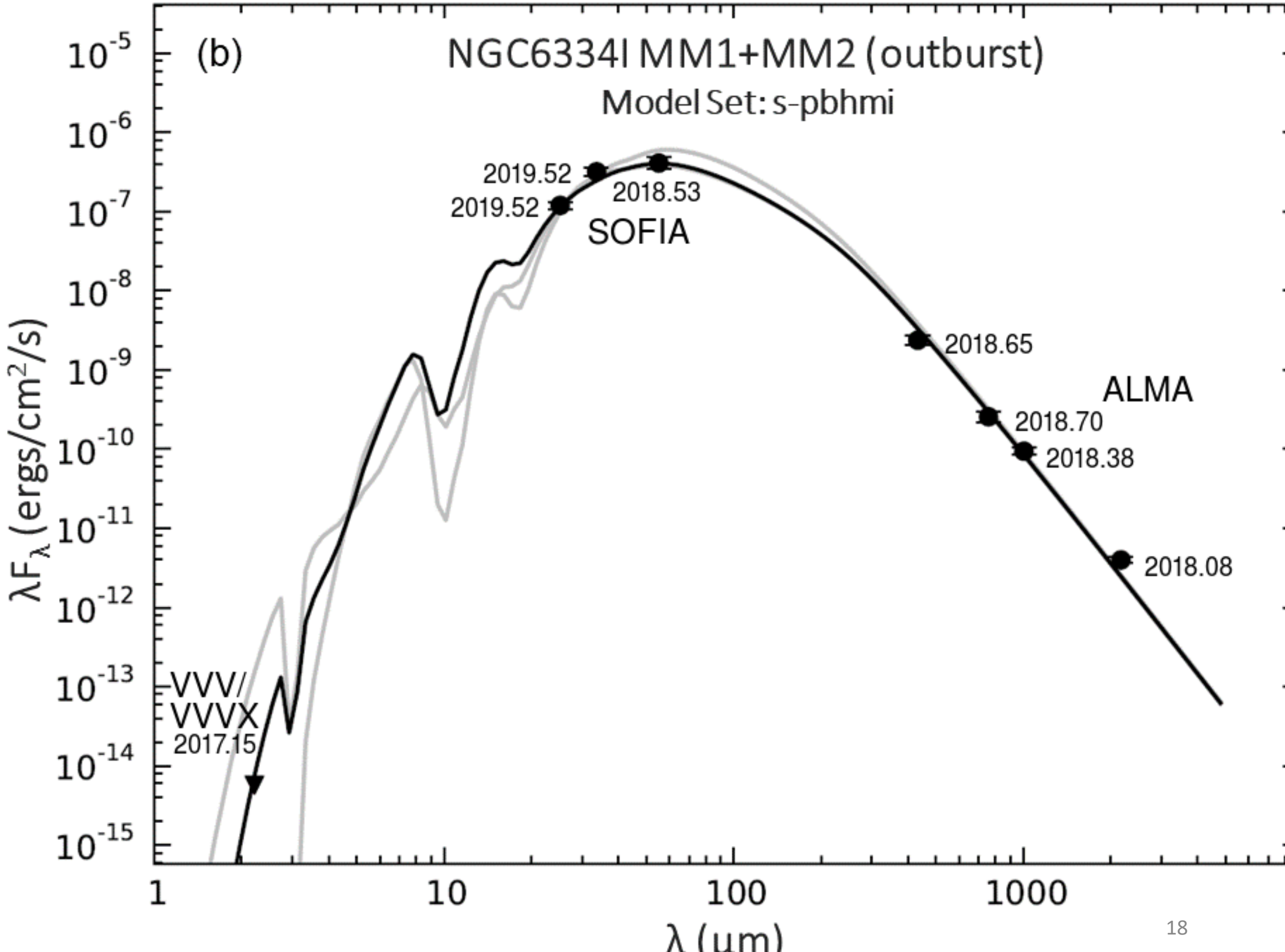
Hunter+2021

Modeling of outburst SED (FORCAST, HAWC+, ALMA)

Used Robitaille (2017) radiative transfer models of MYSOs

Non-detection at 2.2um by VVV/VVVX provides additional constraint

Best fit result:
MM1+MM2 = $49000 \pm 8000\ L_{\odot}$



Hunter+2021

Modeling of pre-outburst SED (Keck, Herschel, SMA)

Used Robitaille (2017) radiative transfer models of MYSOs

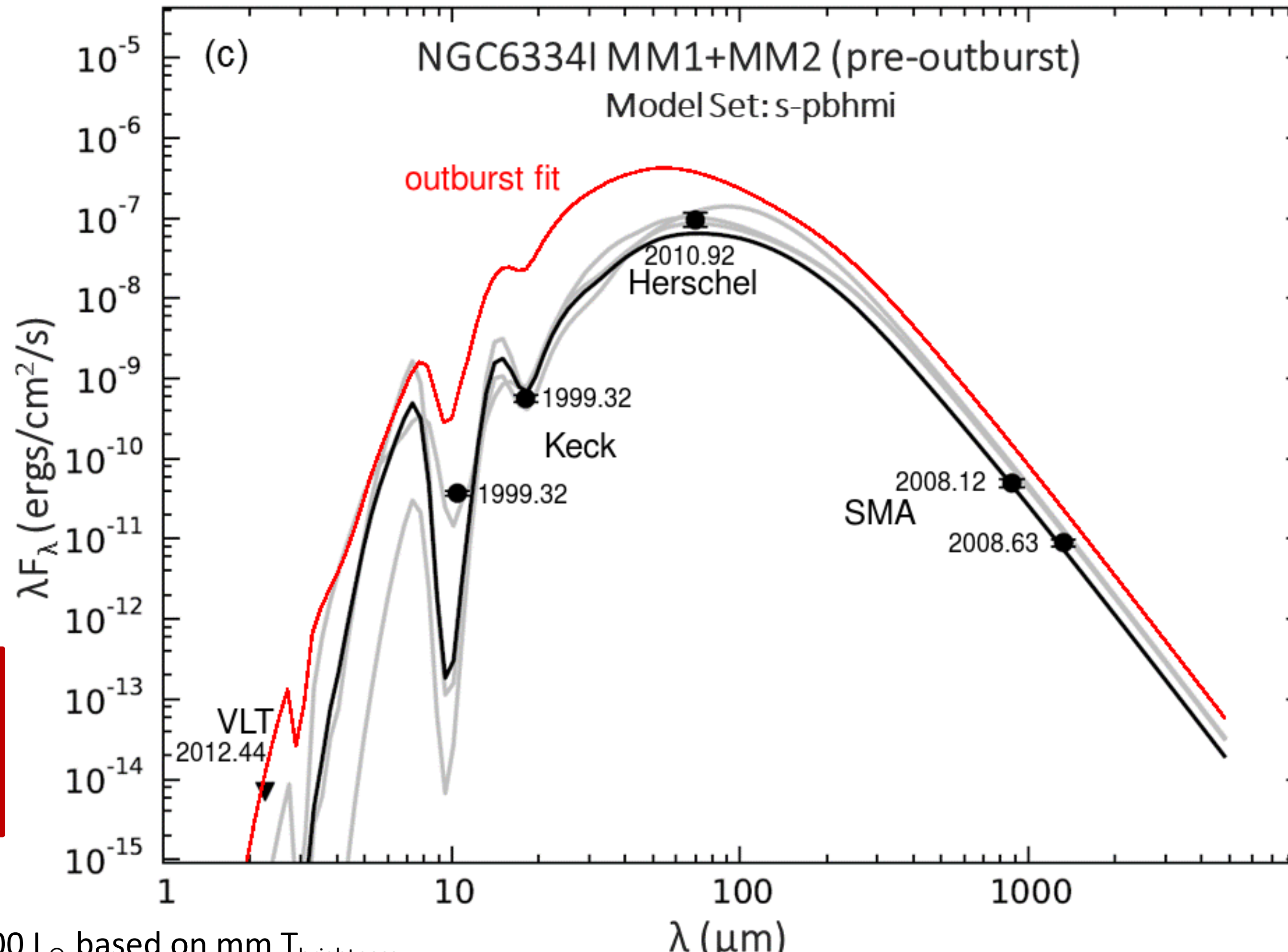
Best fit result:
MM1+MM2 = $4300 \pm 900\ L_\odot$

Pre-outburst apportioning:
(based on mm flux)

MM1: 2900 $L_\odot$

MM2: 1400 $L_\odot$

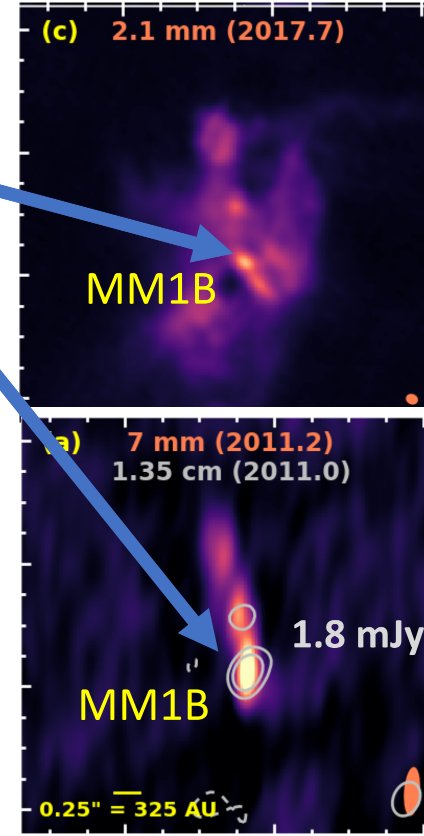
MM1 now* vs. before:
47600 / 2900
Burst ratio = 16.3 ± 4.4



*Hunter+2017 predicted L>42000 $L_\odot$ based on mm $T_{brightness}$

Pre-outburst properties of the progenitor

- MM1B remains point-like to the longest ALMA baselines, solidifying it as the outbursting protostar.
- HCHII region at 1.3cm requires ionizing radiation (ZAMS star?)



ALMA

VLA
preburst

$L_{\text{protostar}}$ = photosphere + accretion luminosity

$$L = 4\pi R_{\text{proto}}^2 \sigma T_{\text{eff}}^4 + G M_* \dot{M}_{\text{acc}} / R_{\text{proto}}$$

simple hypothesis: L split evenly

2900 $L_\odot$ = 1450 $L_\odot$ + 1450 $L_\odot$

M_* = 6.7 $M_\odot$ + 1.8x10^{-5} $M_\odot$/yr "background accretion"

R_* = 2.6 $R_\odot$ (Haemmerle+2013 model for 6$M_\odot$)

$\underbrace{T_{\text{eff}} = 22000}$

B1.5V – B2V ZAMS (Pecaut & Mamajek 2013)

which can produce enough ionizing photons: 2x10^{43} ph/s

MM1B 1.3cm flux in 2011 (1.8 mJy) requires: 1.7x10^{43} ph/s

Conclusion: Progenitor consistent with deeply-embedded B2V star accreting at 2x10^{-5} $M_\odot$/yr

Properties of the outbursting star

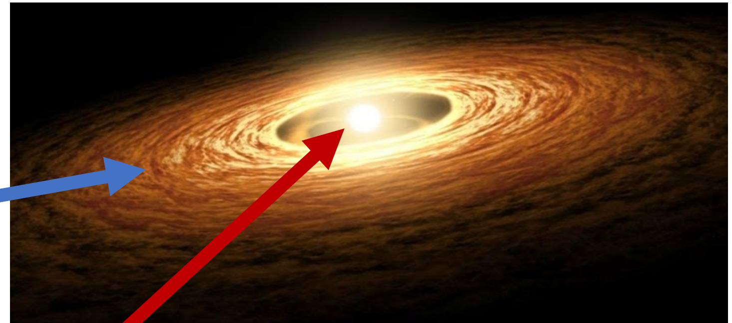
$$L = 4\pi R_{\mathrm{proto}}^2 \sigma T_{\mathrm{eff}}^4 + GM_* \dot{M}_{\mathrm{acc}}/R_{\mathrm{proto}}$$

What is the post-outburst split of luminosity?

Consider two limiting cases:

Case 1) Accretion-dominated, L increase entirely powered by x32 increase in $\dot{M}_{\mathrm{acc}}$ to 5.7×10^{-4} $M_\odot$/yr = 0.6 M_{Jupiter} / yr

$47600\ L_\odot = 1450\ L_\odot + 46150\ L_\odot$

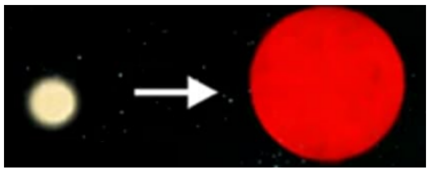


Case 2) Photosphere-dominated: immediate accretion onto protostar, outer layer of star expands radically

$47600\ L_\odot = 46150\ L_\odot + 1450\ L_\odot$

e.g. R_{proto} increases x20 to $50R_\odot$ and T_{eff} drops to 12000 K

Contracts on Kelvin-Helmholtz time (see Hosokawa, Yorke, & Omukai 2010)



How to distinguish?

- Long-term: measure duration and decay profile of outburst
- Short-term: measure drop in ionizing photon flux
- Short-term: look for disk/jet system

Case 3) Somewhere between these extremes:

Interesting fact: A moderate expansion of R_{proto} would enable a higher $\dot{M}_{\mathrm{acc}}$ for same $L_\odot$ by accreting into an expanded outer layer: more efficient!

Reduction of ionizing photons observed!

We see a factor of 5 dimming in VLA 1.3 cm emission from MM1B.

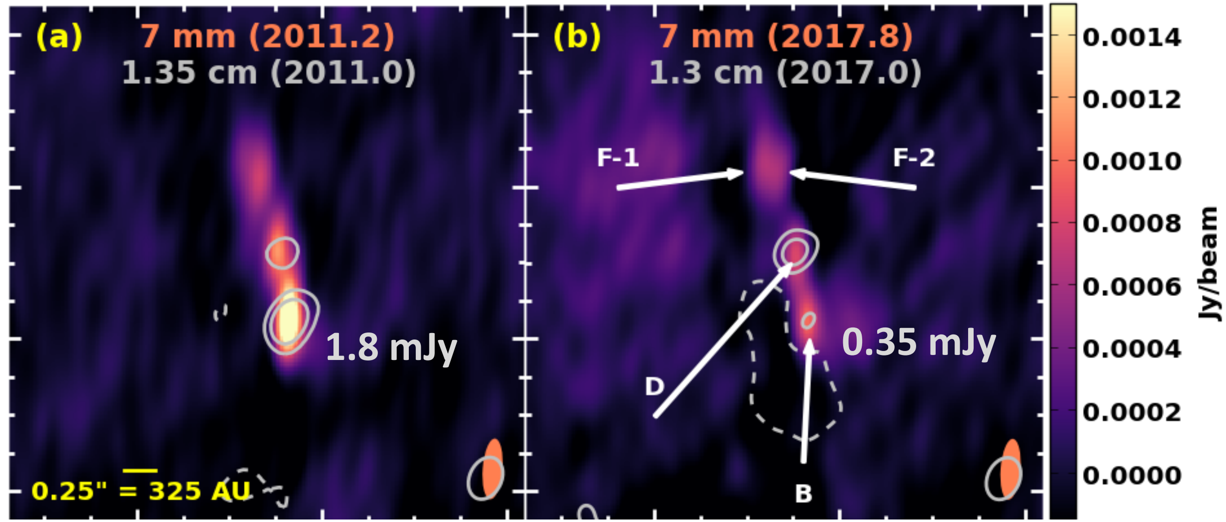
Requires lower T_{eff} and larger R_{proto}

If outburst luminosity remains split equally between accretion

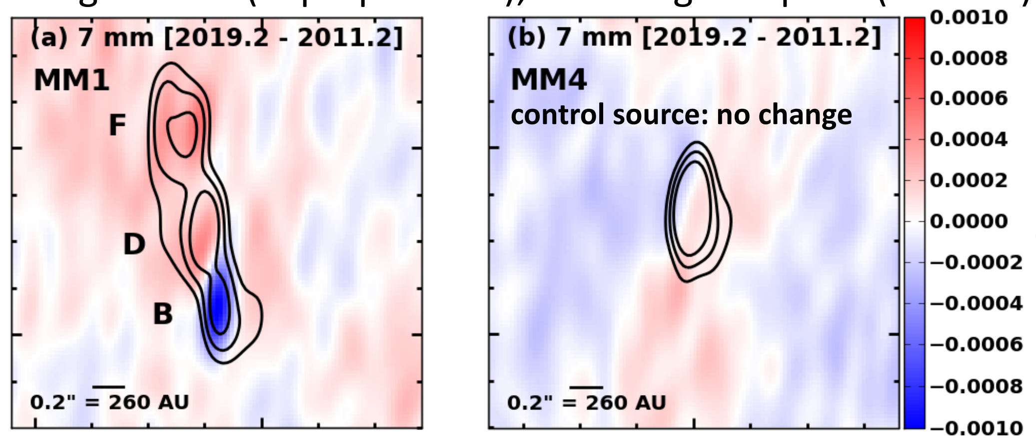
$$L = 4\pi R_{\rm proto}^2 \sigma T_{\rm eff}^4 + GM_* \dot{M}_{\rm acc}/R_{\rm proto}$$

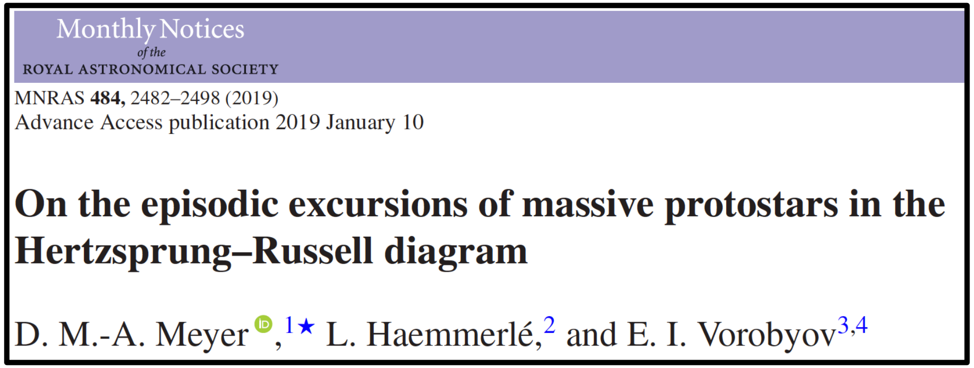
$T_{eff} \sim 16000$ K (down from 22000)
$R_{proto} = 20\ R_\odot$
$\dot{M}_{acc} = 2.3\times10^{-3}\ M_\odot/yr$

- How long will T_{eff} remain low?
- Will the jet flux increase?



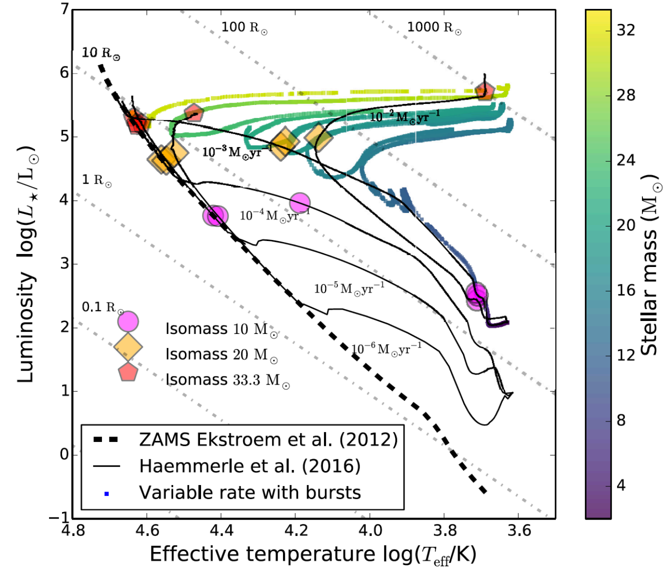
Brogan et al. (in preparation), including 3rd epoch (still low):




Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **484,** 2482–2498 (2019)
Advance Access publication 2019 January 10

On the episodic excursions of massive protostars in the Hertzsprung–Russell diagram

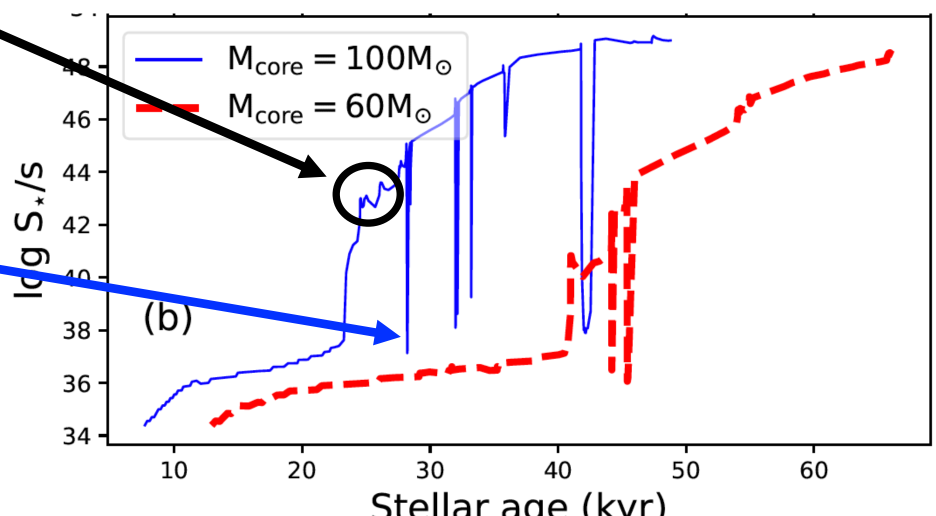
D. M.-A. Meyer,[1★] L. Haemmerlé,[2] and E. I. Vorobyov[3,4]



- Large outbursts cause protostar to make excursions on HR diagram, to lower T_{eff} and ionizing flux (S_*)
- The drop in S_* seen in NGC6334I-MM1B confirms the prediction, but is one of the smaller examples

Prediction: much larger events are expected

Have we found any other events? yes, but even smaller ones…

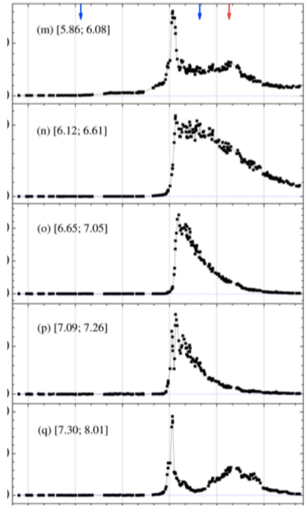


Another outburst in a young MASSIVE protostar

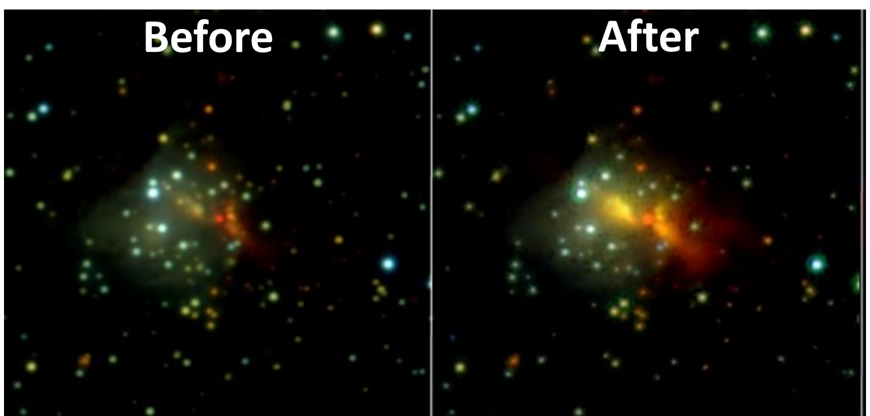
S255IR-NIRS3

- **Discovered via CH_3OH maser flare** (Fujisawa+2015)
- Flared in near-IR to submillimeter
- Luminosity rose ~6x (SOFIA)
- Faded after ~2 years
- 6 cm emission flared 60% after ~1yr (interpreted as jet)

(Caratti o Garatti+2017, Moscadelli +2017, Liu+2018, Cesaroni+2018)



Szymczak+2017



Outbursts in NGC6334I + S255IR led to the formation of **Maser Monitoring Organization** (M_2O) at 2017 IAU conference in Cagliari, Italy

https://MaserMonitoring.org

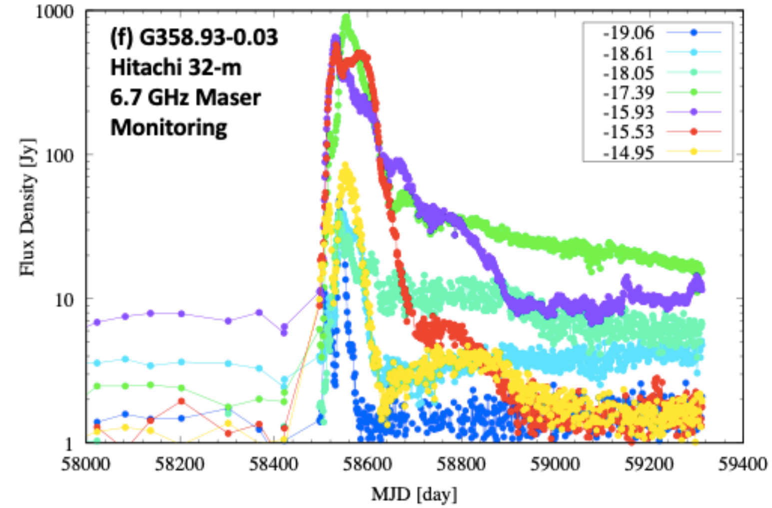
- 77 members
- 16 papers published
- >400 sources being monitored by single dishes
- 11 active ToO proposals across wavelengths:
  - IR (Subaru/SOFIA) - mm (SMA) - cm VLA & VLBI
  - JWST Cycle 1 ToO approved
  - ALMA Cycle 8 ToO (proposed)
  - Plus continued single dish maser monitoring

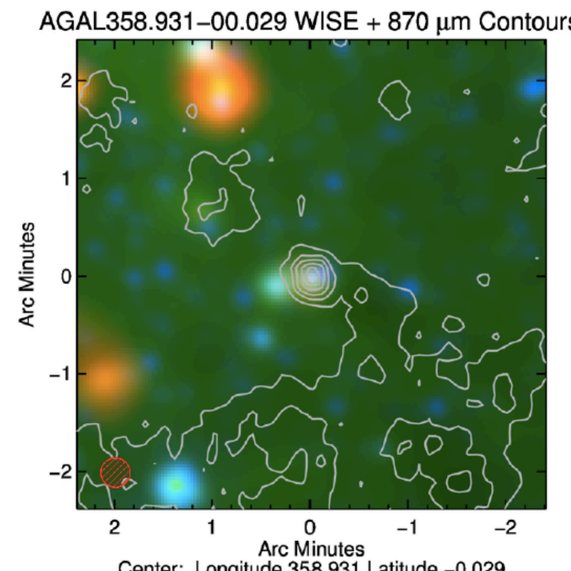
The Fruits of M_2O Labors: A New Massive Protostellar Maser Flare

- **Jan 14, 2019:** Single Dish monitoring at Ibaraki Japan caught **6.7 GHz Class II CH_3OH masers** flaring in the massive star forming region G358.93-0.03 (Sugiyama+ 2019)
- Almost no prior studies of this source: 6.7 GHz Parkes Multibeam maser survey, BOLOCAM (1.1mm), ATLASGAL (0.87mm), *Herschel* Hi-GAL, WISE
- Distance ~ 6.7 kpc (>5 times NGC 6334)

M_2O Collaboration began to follow-up…

https://MaserMonitoring.org

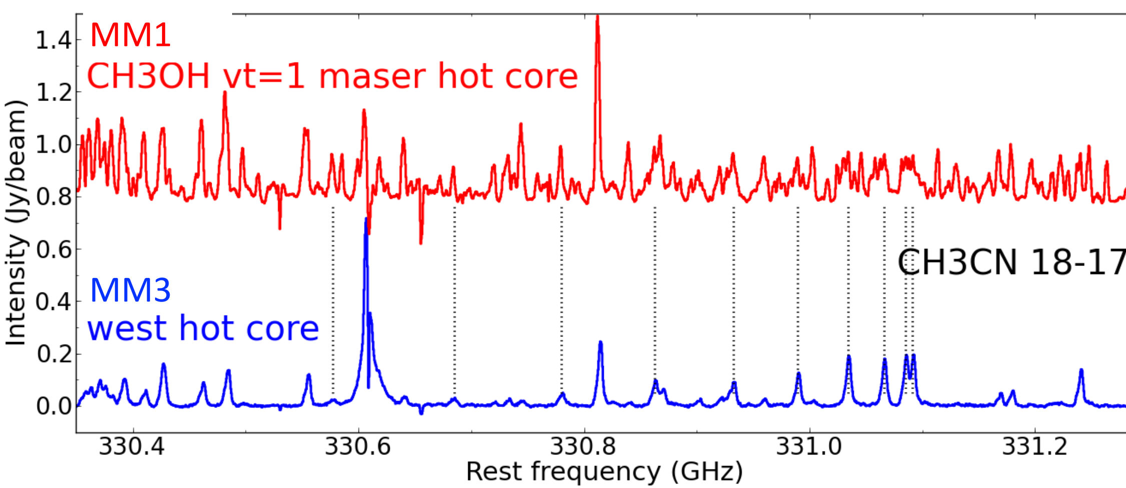


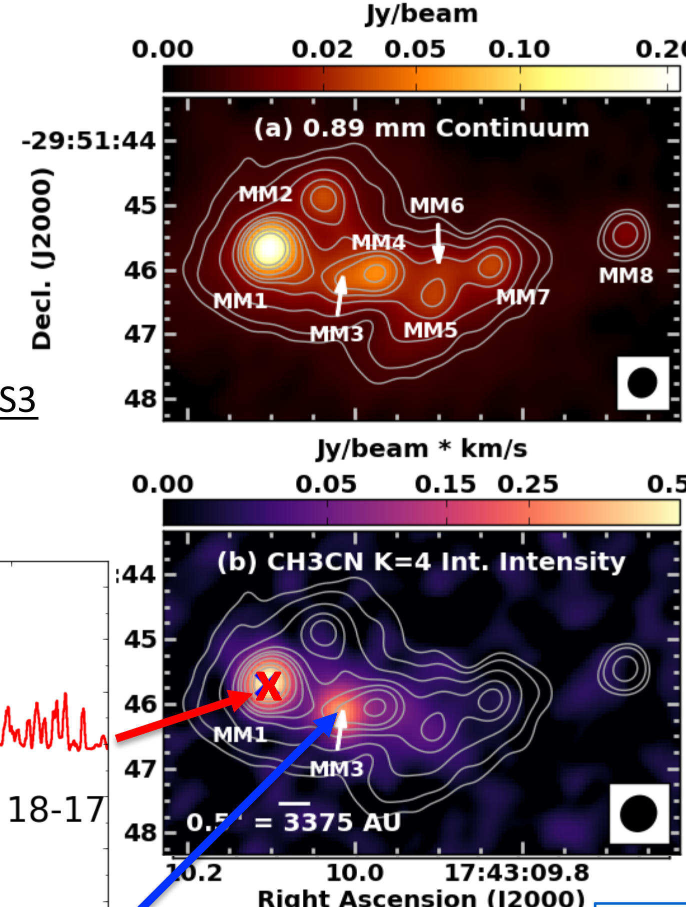


G358.93-0.03 Maser flare origin: A Massive Protocluster with a Hot Core

DDT SMA and ALMA data with 0.5” resolution at
+2 and +3 months after the maser flare began

- Protocluster of 8 mm dust cores, total gas mass of 200$M_\odot$
- MM1 harbors the CH_3OH maser flare
  - Dust continuum increase < 30%
- Distance uncertain, about 6.75 kpc
  - Protocluster Pre-burst L~ 5700 $L_\odot$
- Rich hot core line spectra, like NGC6334I-MM1 & S255IR-NIRS3
  - MM1: Thermal lines well-fit with T_{exc} =172K and T_{bg} = 159K model



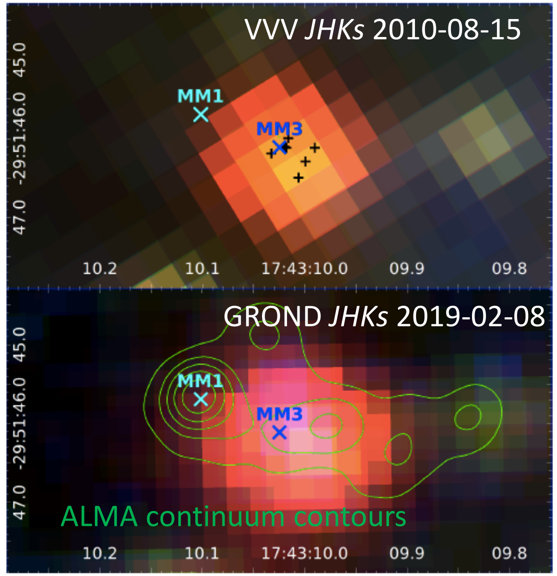


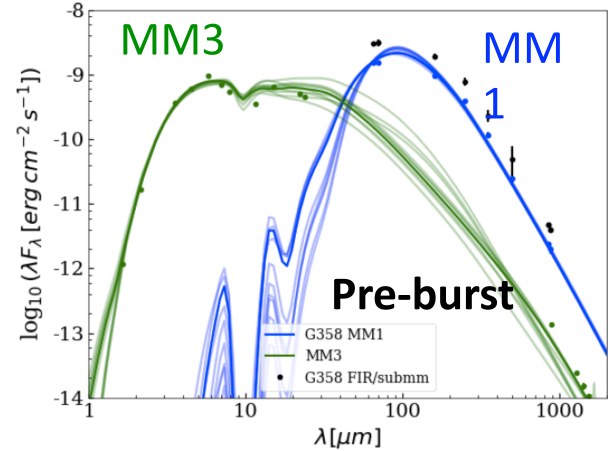
Brogan+2019, ApJL 881, 39

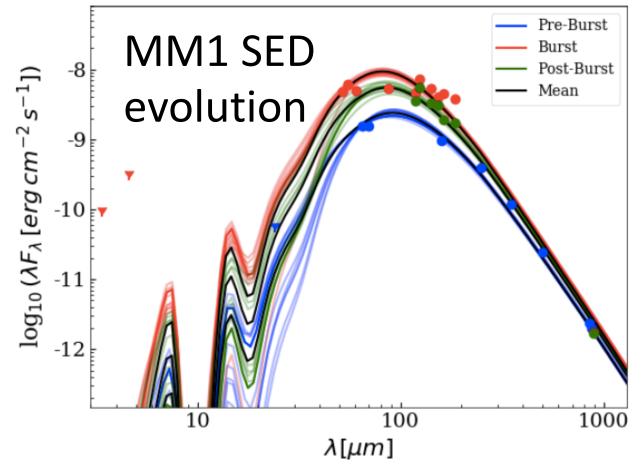
SOFIA was key to measuring burst luminosity in G358.93

- No NIR from MM1, only MM3
- Separated by only 1.5”
- New FIFI-LS plus archival data used to establish MM1 SED at three epochs: pre-burst, burst, and post-burst.
- Hyperion RT code
- *Stecklum+2021 (A&A 646, 161)*

Pre-burst: $5000 \pm 1000\ L_{\odot}$
Burst: $23400 \pm 4000\ L_{\odot}$
Luminosity gain: 4.7 ± 1.8
Post-burst: $12400 \pm 2000\ L_{\odot}$







Time-dependent RT code underway for improved modelling (Stecklum, Harries, Wolf)

For more details, see Bringfried Stecklum’s SOFIA Tele-talk 28-April-2021:
https://www.sofia.usra.edu/science/meetings-and-events/events/ir-observations-flaring-maser-source-revealing-unsteady-growth

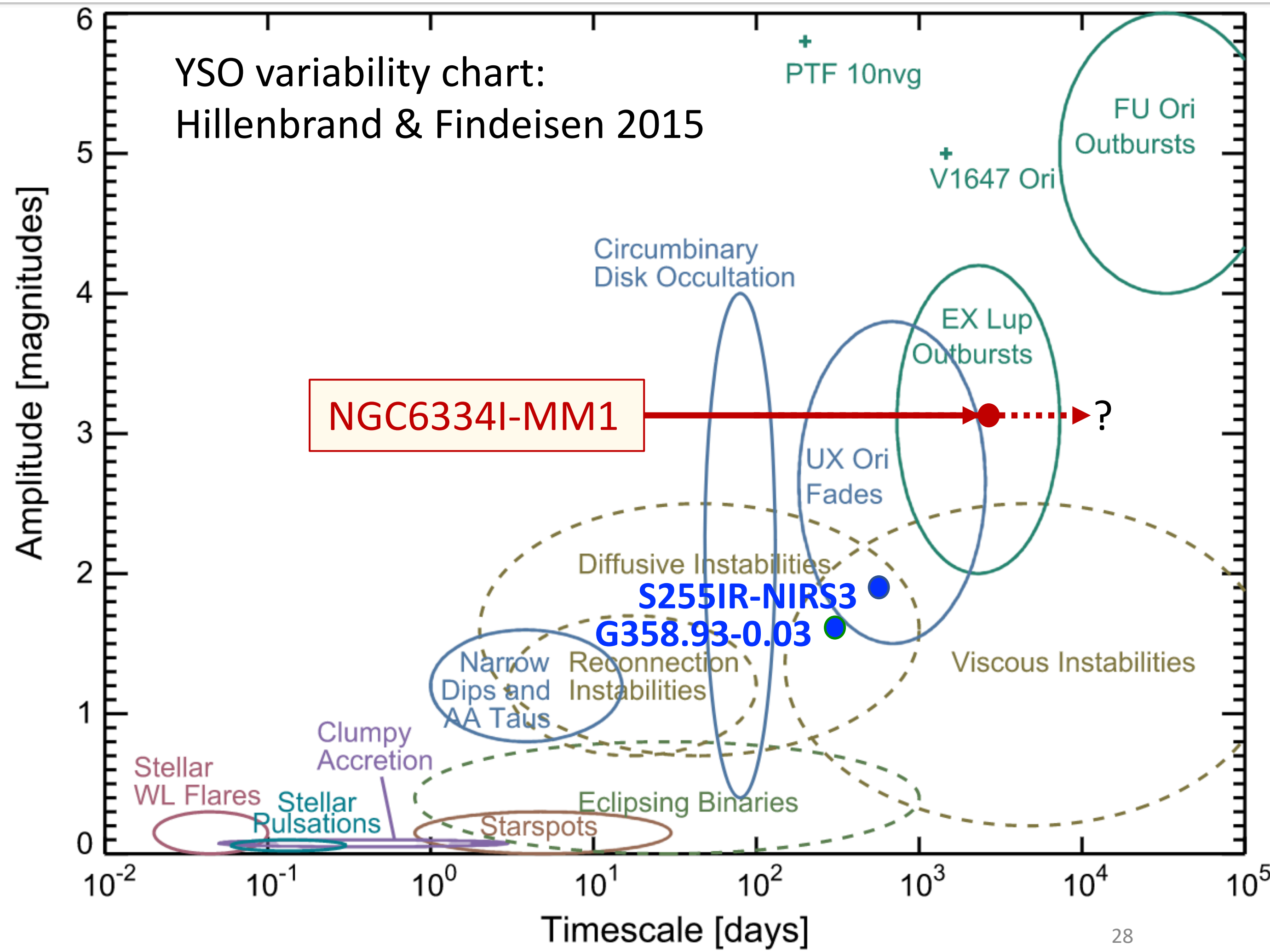
Where do these events fit into zoo of episodic phenomena?

NGC6334I-MM1

- x16.3 increase in L_{bol} (3mag) is similar to EXORs
- Integrated Energy=$\Delta L\ \Delta t$ = $(3.2 \pm 0.6) \times 10^{46}$ erg → largest of all 3 events
- A stellar merger would be 30-300x greater (Bally+2005)

S255IR-NIRS3 and G358.93-0.03

- in the regimes of diffusive and viscous instabilities



Hydrodynamic simulations of accretion in massive protostars

Meyer+2019a,b, and 2021 parameter study predicts:

- massive stars may gain up to 40−60% of mass during outbursts
- Bursts range from M_{acc}~0.01 - 1 $M_\odot$

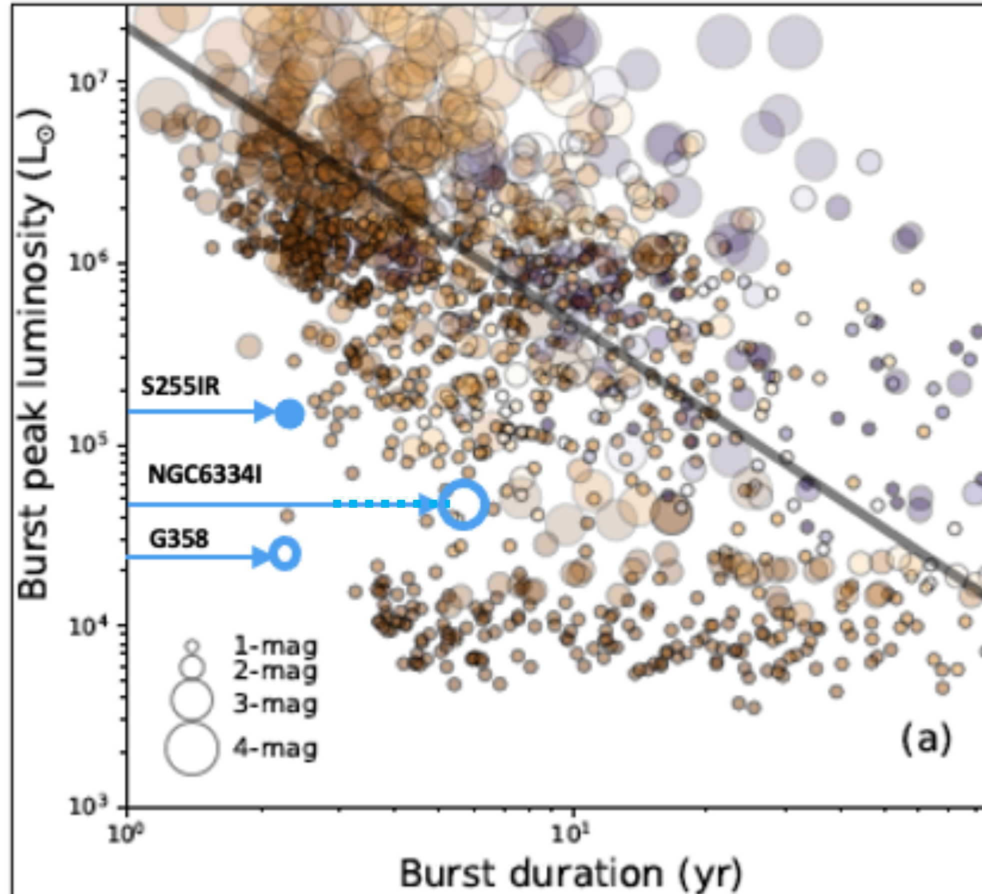
Events observed so far:

All lie in the lower portion of predicted scatter plot of L vs duration (two 2-mag + one 3-mag)

Need more events to constrain models!

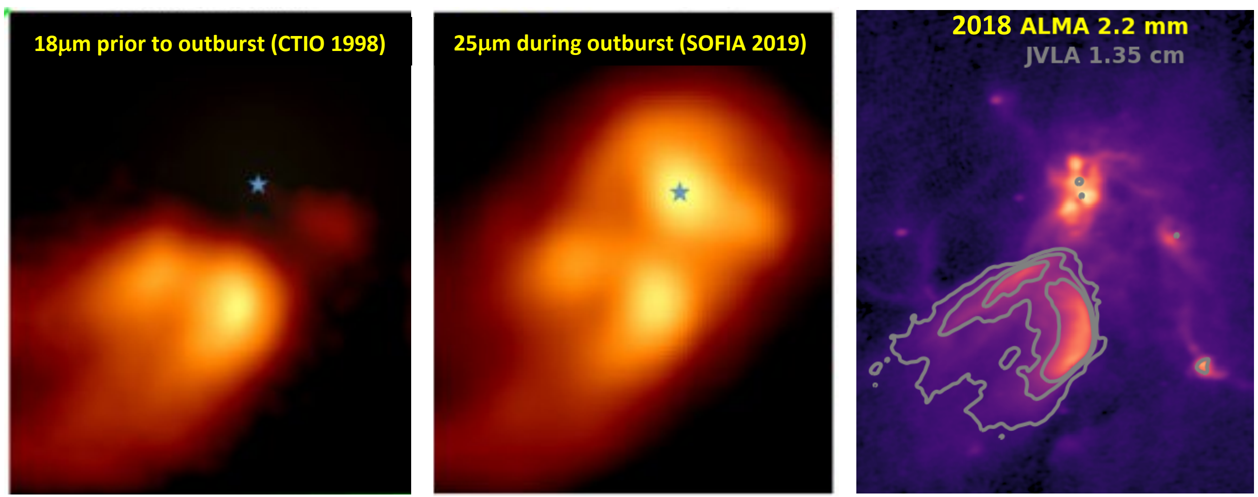
M2O has active trigger proposals:

- ➢ IR (SOFIA) - mm (SMA) - cm (VLA & VLBI)
- ➢ JWST Cycle 1 ToO approved
- ➢ ALMA Cycle 8 ToO (proposed)



Conclusions and Outlook

- In past 5 years, accretion outbursts from massive protostars are established
  - NGC6334I-MM1 is longest in duration and largest in energy
  - All 3 events have arisen from hot cores – repeated outbursts may help form COMs
- More events needed to understand their range and constrain theory
- International collaboration through M_2O is key to further progress
- SOFIA along with ALMA/SMA/VLA are essential to understand physical parameters of protostar and its parent protocluster



Summary of NGC6334I-MM1 outburst and publications (facilities used)

2015 January: outburst begins (found by HartRAO)

First ALMA images (odd mm spectral index noted): Brogan+2016, ApJ 832, 187 (**ALMA**, VLA)

Millimeter outburst recognized: Hunter+2017, ApJL 837, L29 (SMA, **ALMA**, HartRAO)

Maser light curves: MacLeod+2018, MNRAS 478, 1077 (HartRAO, SMA)

Methanol maser imaging: Hunter+2018, ApJ 854, 170 (VLA, **ALMA**)

Water maser imaging: Brogan+2018, ApJ 866, 87 (VLA, **ALMA**)

Chibueze+2021, ApJ 908, 175 (KaVA, VLA, HartRAO)

Outburst SED: Hunter+2021, ApJL 912, L17 (**SOFIA, ALMA**, SMA, CTIO, Keck, VVV, VLT)