# The Crucial Role of FIR Measurements for Characterizing MYSO Accretion Bursts

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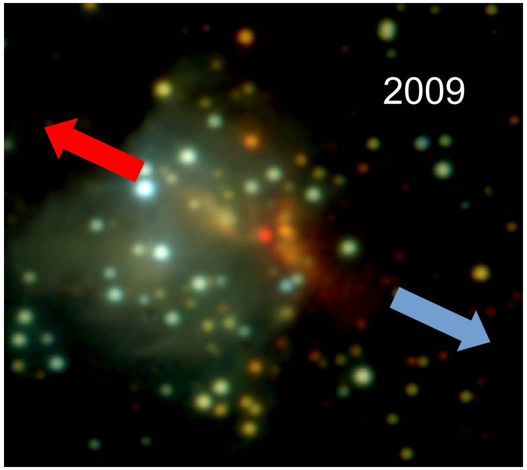
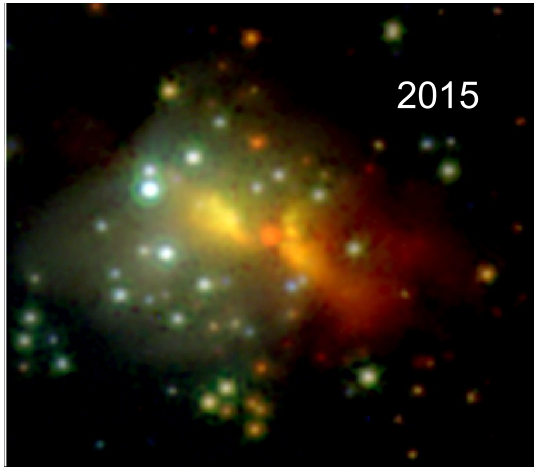
- **The first MYSO accretion bursts**
- **What do they tell us?**
- **G358 - A splendid event with an afterglow**
- **NIRS3 - Witnessing a burst over the years**
- **Conclusions, issues and prospects**




NIR pre-burst and burst images of S255IR-**NIRS3** (Stecklum+ 2016)

# Accretion Bursts from MYSOs ?

Accretion bursts are well known for low-mass YSOs for quite some time (Herbig 1966). Circumstellar disks are cause or mediator of episodic accretion (Hartmann & Kenyon 1996). A large fraction of the stellar mass is assembled during these events (Audard+ 2014).

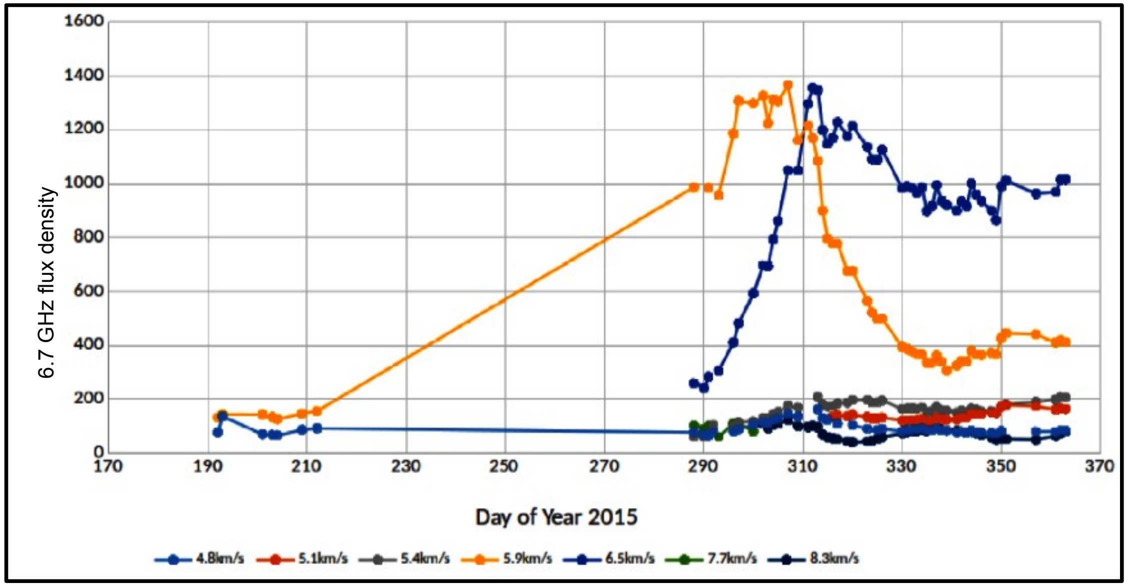
How about massive YSOs ($M_* \gtrsim 8\ M_\odot$) ?

- MYSOs are more rare than low-mass YSOs
- MYSOs are more distant on average
- MYSOs are still embedded when reaching the ZAMS

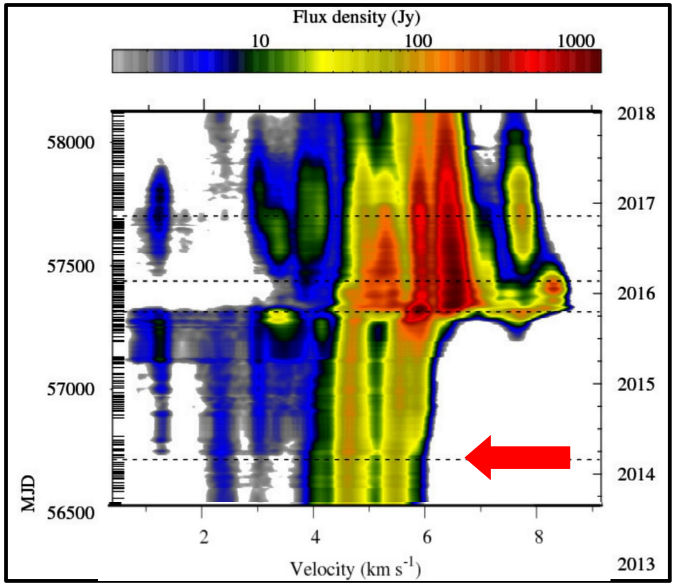
But they are generally associated with Class II methanol masers (Breen+ 2013) which are excited by mid-IR emission (Menten 1991, Cragg+ 2005). Thus, changes of the MIR radiation will imprint on the maser flux.

# Accretion Bursts from MYSOs – The First Events

## An extraordinary coincidence – bursts of two different MYSOs in 2015 !

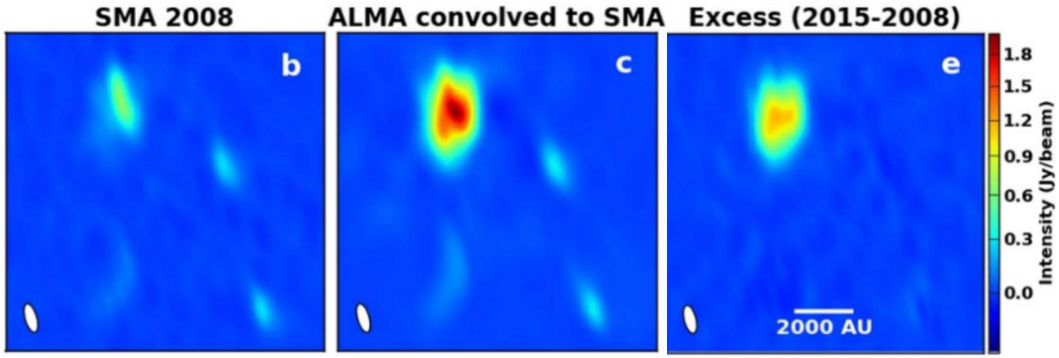



Light curves of 6.7 GHz Class II methanol masers of S255 (Fujisawa+ 2015)

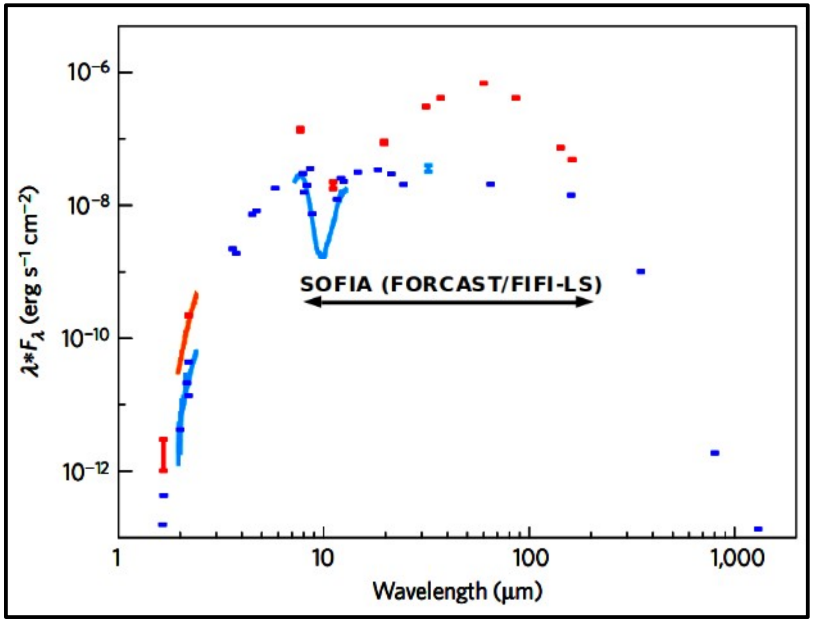



Dynamic maser spectrum of the **NIRS3** burst (Szymczak+ 2018)

The burst from the deeply embedded MYSO **NGC6334I-MM1** was detected in the (sub)mm (Hunter+ 2017). The images show the 1.3 mm flux excess of beam-matched ALMA and pre-burst SMA observations. The burst was accompanied by maser flares as well.



# Accretion Bursts from MYSOs – What do They Tell Us ?




Pre-burst (blue) and burst (red) SEDs (right) of **NIRS3** (Caratti o Garatti+ 2017)

MYSO SEDs peak in the FIR which made SOFIA **essential** for estimating *L*.

Burst timescale *Δt* from the NIR light curve for objects seen face-on (G323) or from the maser variability (upper limit).

$E_{acc}$, *Δt* point to burst mechanism, e.g., disk instability or protoplanet accretion.

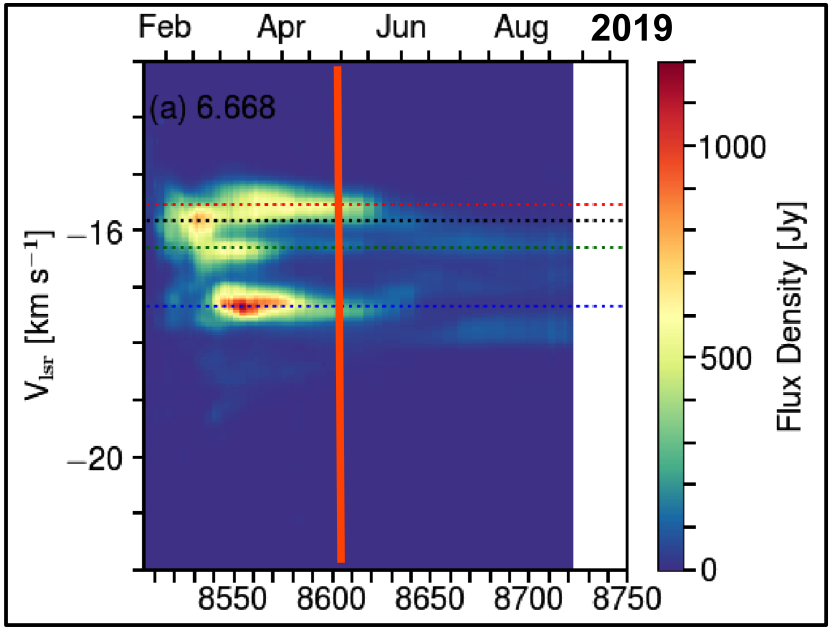
Derivation of $M_{acc}$ requires knowledge of $M_*$, $R_*$ which are difficult to obtain for MYSOs. Bloating can be an issue too.

| Object | $M_*$ [$M_\odot$] | $L_{pre}$ [$10^3$ $L_\odot$] | $L_{peak}$ [$L_{pre}$] | $\Delta L$ [$10^3$ $L_\odot$] | $t_{rise}$ [yr] | $\Delta t$ [yr] | $\dot{M}_{acc}$ [$10^{-3}$ $M_\odot\,yr^{-1}$] | $E_{acc}$ [$10^{45}$ erg] | $M_{acc}$ [$M_{Jup}$] |
|---|---|---|---|---|---|---|---|---|---|
| G323.46-0.08 (G323)* | 23 | 60 | 5.4 | 260 | 1.4 | 8.4 | 0.8 | 90 | 7 |
| S255IR-**NIRS3*** | 20 | 30 | 5.5 | 130 | 0.4 | 2.5 | 5 | 12 | 2 |
| **G358**.93-0.03-**MM1*** | 12 | 5.0 | 4.8 | 19 | 0.14 | 0.5 | 1.8 | 2.8 | 0.5 |
| NGC 6334I MM1* | 6.7 | 3 | 16 | 44 | 0.6 | >8 | 2.3 | >40 | >0.4 |
| V723 Car | 10? | ≈ 4 | | | 4 | ≈ 15 | | | |
| M17 MIR | 5.4 | 1.4 | 6.4 | 7.6 | | 9-20 | ≈ 2 | | |

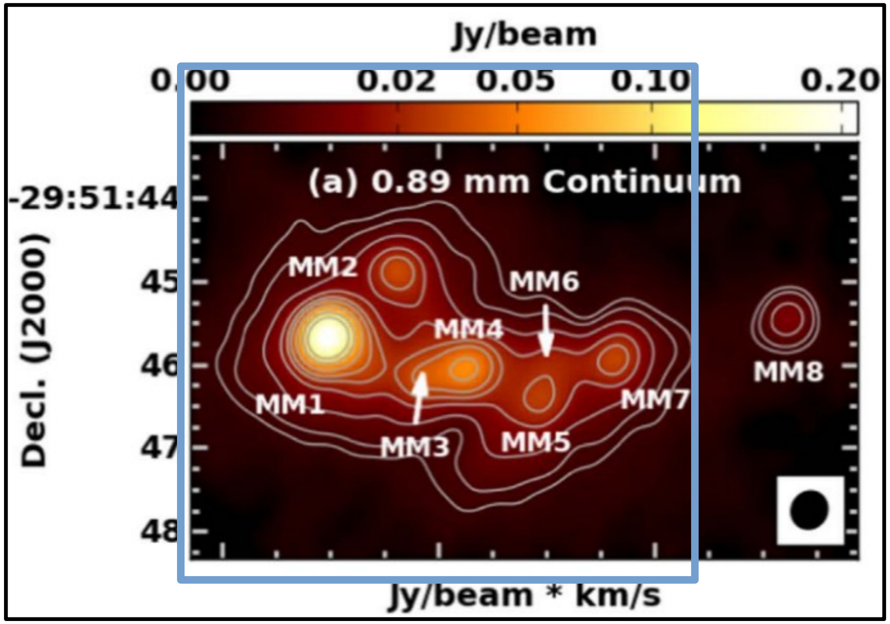
Compilation of MYSO accretion burst properties (Wolf+ subm.). The involved energies and time scales indicate quite a diversity. Objects marked with an asterisk featured maser flares.

# M2O's First Catch: G358-MM1

At the IAU Symposium 236 the Maser Monitoring Organization (M2O) was founded. Its 1st alert (Sugiyama+ 2019) became a great success (3 Nature papers).



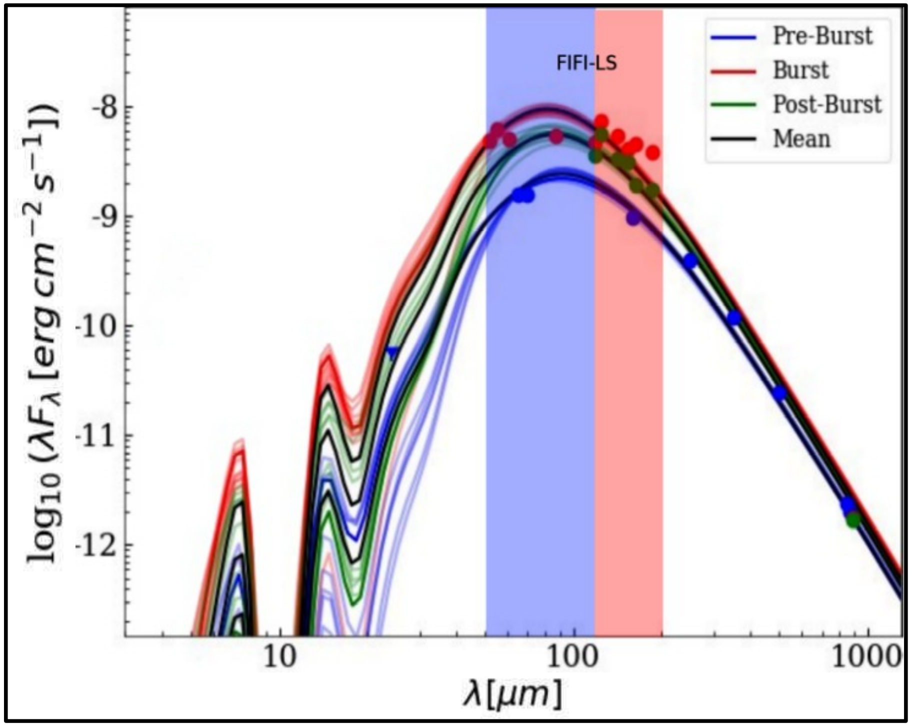

Dynamic spectrum of the 6.7 GHz masers of **G358.** The red line marks the date of our first FIFI-LS observations (thanks to Hal for accepting the DDT).



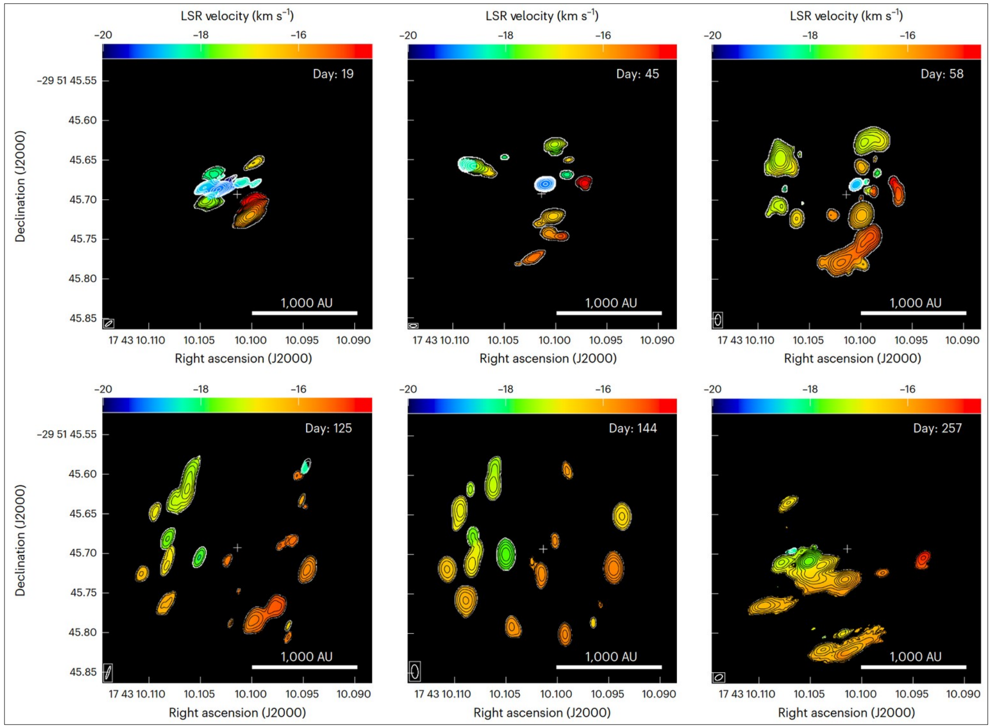

ALMA map and contours of the 0.89 mm dust continuum emission (Brogan+ 2019). **MM1** is the maser host. The blue square marks the FIFI-LS pixel size in the blue channel.

Both our NIR imaging and the ALMA observations could not unambiguously confirm an increase of the fluxes. This was only possible with SOFIA observations.

# G358-MM1: Evidence for the Burst Afterglow and Heatwave




Static fits to the pre-burst, burst and post-burst SEDs of **G358-MM1** (Stecklum+ 2021). Establishing these SEDs required the removal of contributions from the other components of the embedded cluster. A FIR excess is still present 1.5 years after the burst peak.

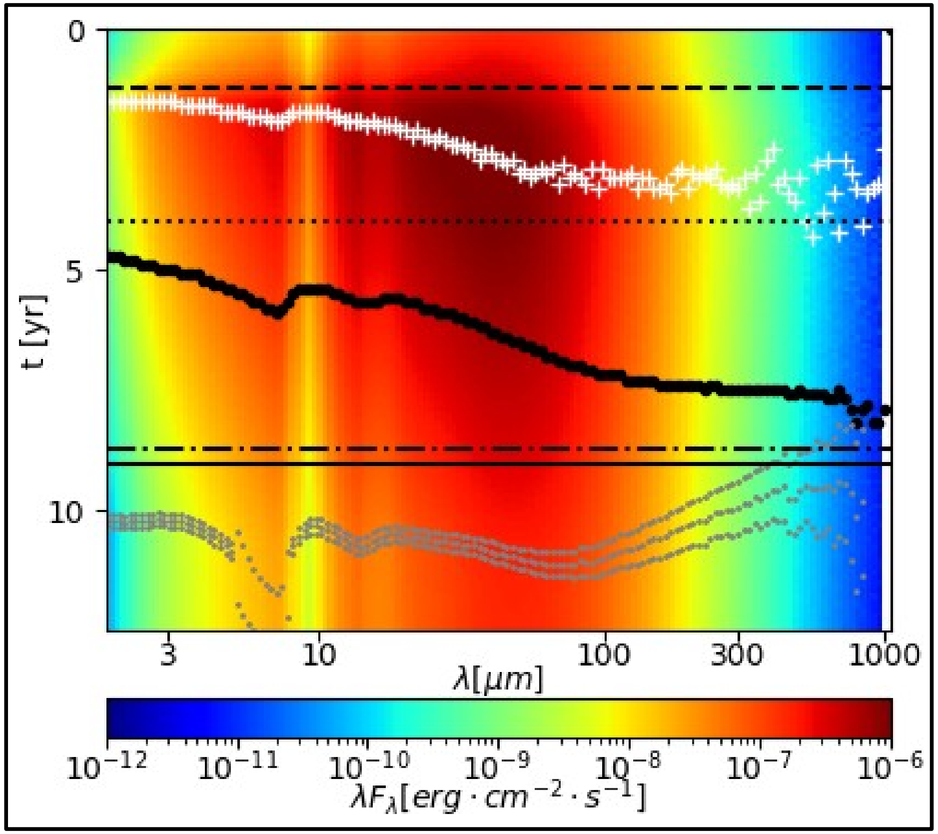



Subluminal ringlike expansion of the maser caused by the heatwave propagation in the disk (Burns+ 2023). The return to a more centralized emission after the burst indicates a similar state as in the pre-burst stage.

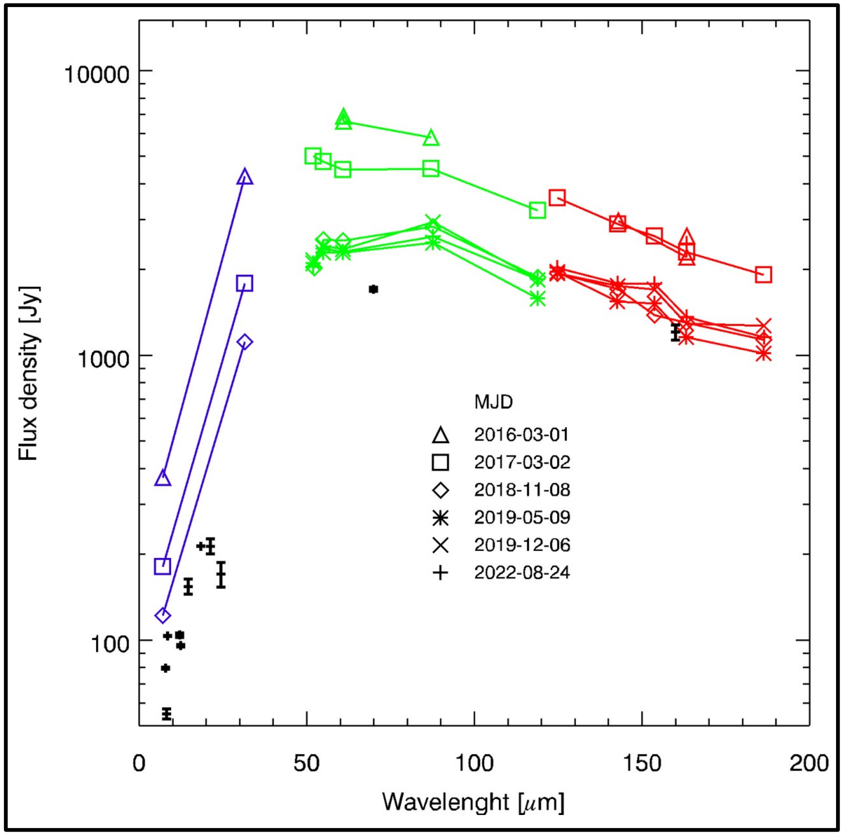
The afterglow results from the high optical depths which slow down the radiative energy transfer → $\Delta t_E \gtrsim \Delta t_{acc}$

The maser rotation curve points to a proto-stellar mass of 11.5±4.8 $M_*$.

# Dust Continuum Flux Variability – Model and NIRS3 Results

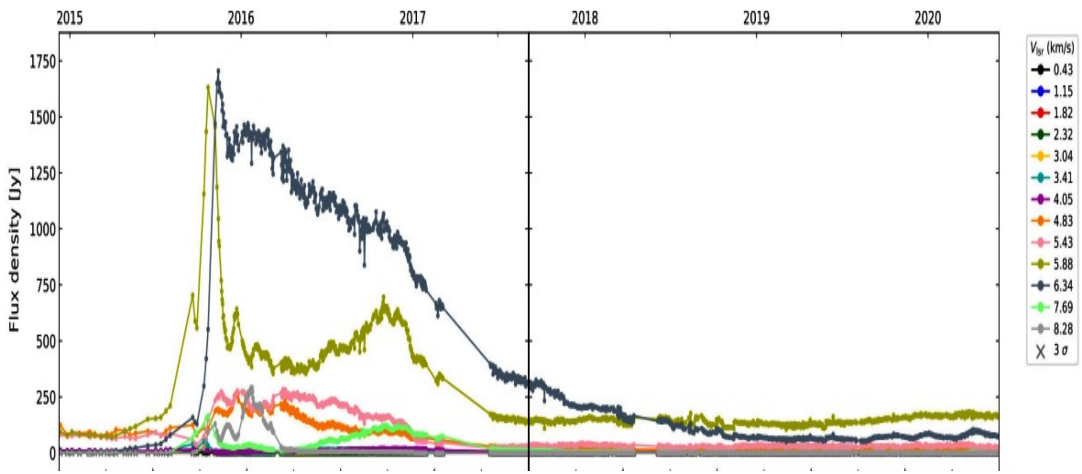



Dynamic SED for an accretion burst model. The dashed line marks the time of the accretion peak while the white crosses denote the time of the peak emission. The time lag increases with wavelength and inclination (not shown here).



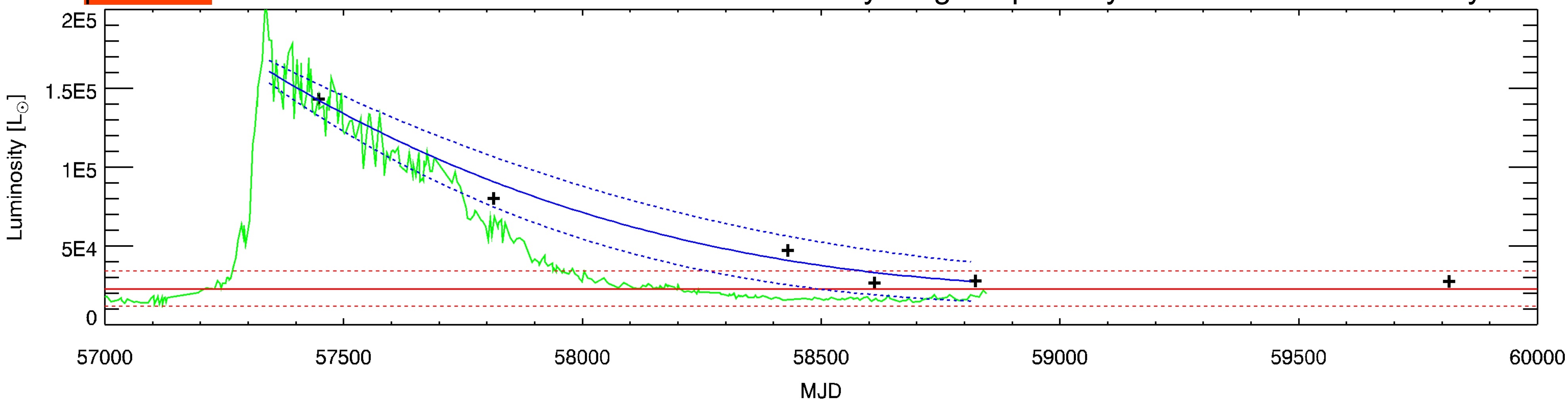

**NIRS3** pre-burst SED (black symbols) and fluxes from FORCAST (blue) and FIFI-LS (green, red). The pre-burst level has been reached again at the longest wavelengths, but an excess is still present at 50...100 µm.

# The Temporal Record of the NIRS3 Burst



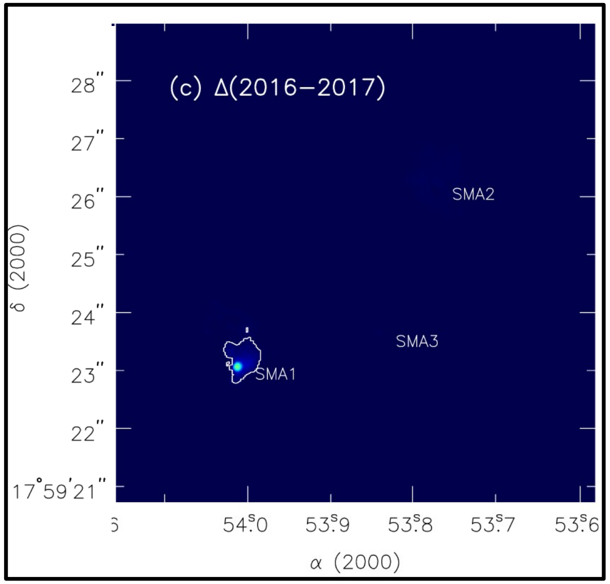

Light curves of the 6.7 GHz maser components (© Ibaraki)

Apparent bolometric luminosity and scaled integrated maser flux (© Torun). The horizontal line marks the pre-burst value. The dashed lines indicate the luminosity range implied by the extinction uncertainty.

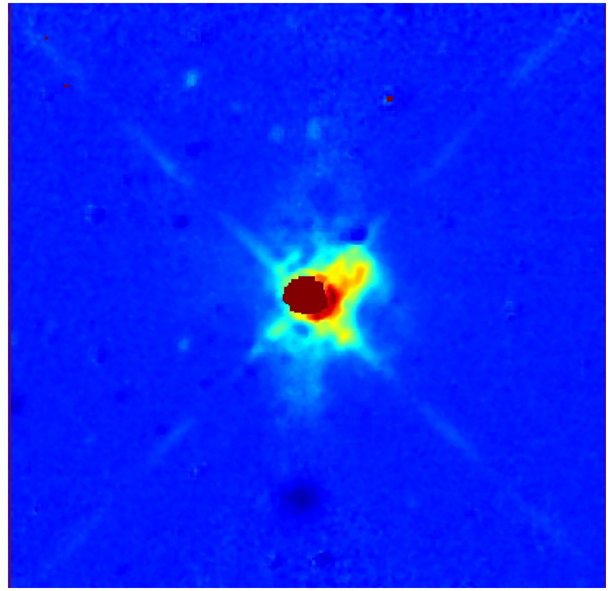



The comparison shows the presence of an afterglow and a post-burst luminosity exceeding the pre-burst one by ~20%. $E_{acc}$ is twice as high as in Caratti+ (2017).

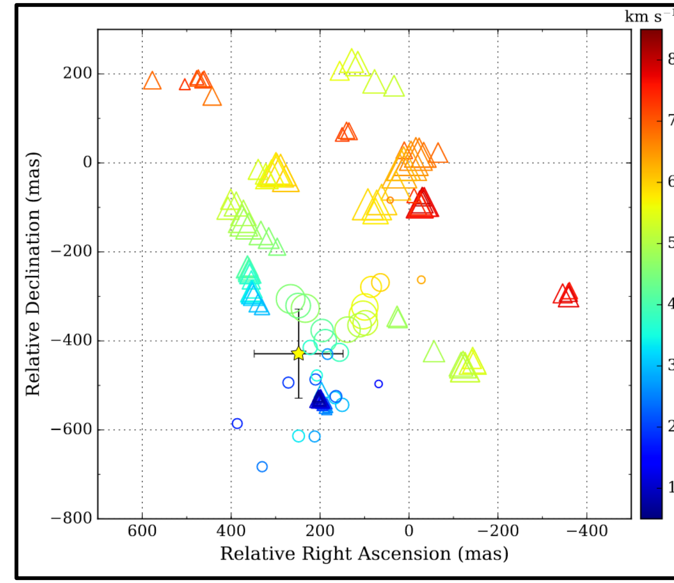
# The Impact of the NIRS3 Burst on its Environment



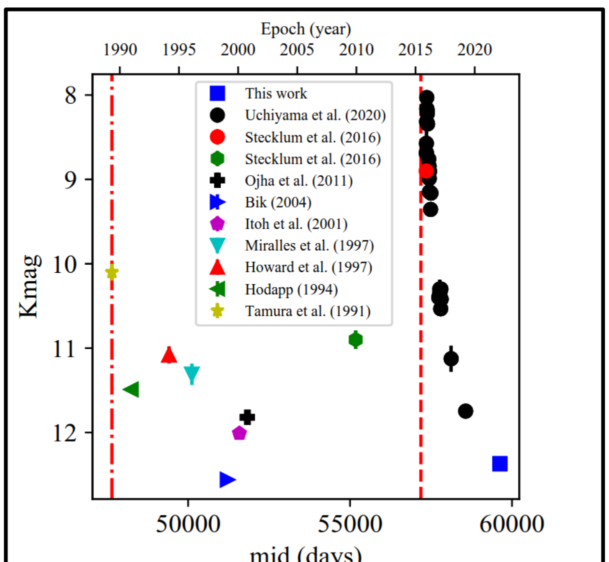

ALMA 900 μm difference image (Liu+ 2018)



NEOWISE 3.4 μm ratio image spring 2016/2014




Maser relocation (Szymczak 2018): Circles (pre-burst), triangles (burst)




K light curve (Fedriani+ 2023)

While the NIR flux is also back to the pre-burst level, the blue FIFI-LS channel still shows elevated values. Together with the activity features toward the NW, it indicates that burst affected the dust distribution by lowering the optical depth in this direction. Probably, the disk chemistry there was altered as well.

This suggests that episodic accretion will shape the protostellar environment over time, and contribute to its dispersal.

# Conclusions, Issues, and Prospects

- The SOFIA Mission and the first MYSO accretion bursts had a perfect timing.
- The FIR observing capability of SOFIA was crucial to derive the burst energies.
- The few HMYSO bursts point to a range in strength/duration and properties of the protostars.
- The shutdown of SOFIA terminates most of this research once the present data has been analyzed.
- FIR observations at higher resolution are required to overcome source confusion.
- Future facilities should be capable to be on transients quickly and follow them as long as required.
- A space-based FIR interferometer would be the ultimate facility (Leisawitz+ 2023).

# Thanks SOFIA !


The SOFIA mirror will be on display at the German Optical Museum (DOM) in Jena (re-opens in 2027).