Bursting methanol masers in high-mass star-forming regions – a need for high quality counterpart data

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Cosmic masers

→ Masers appear naturally in the interstellar medium.

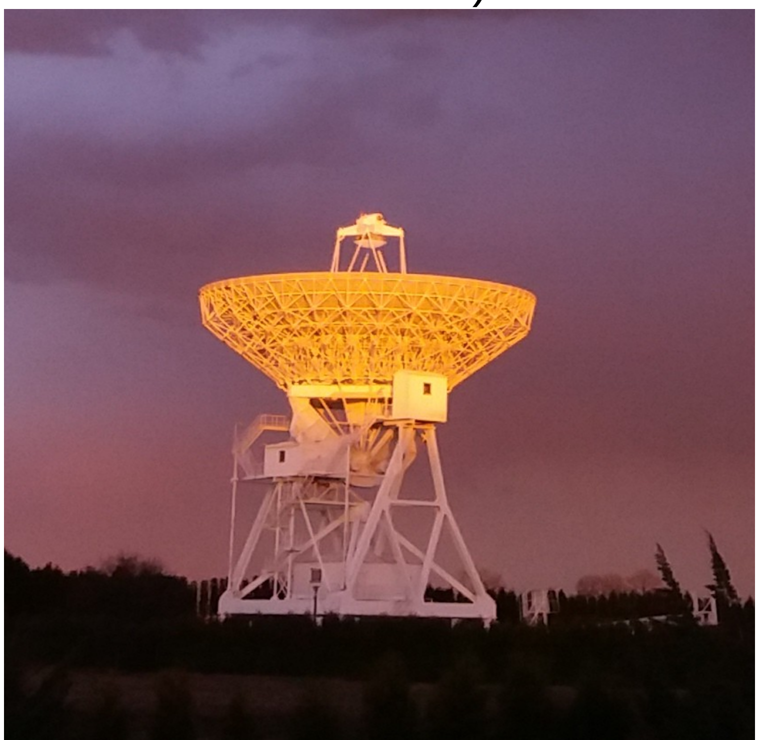
→ Maser emission from OH, H_2O, CH_3OH, SiO appears in regions close to **newly born high-mass** and **low-mass stars,** and **evolved stars**.

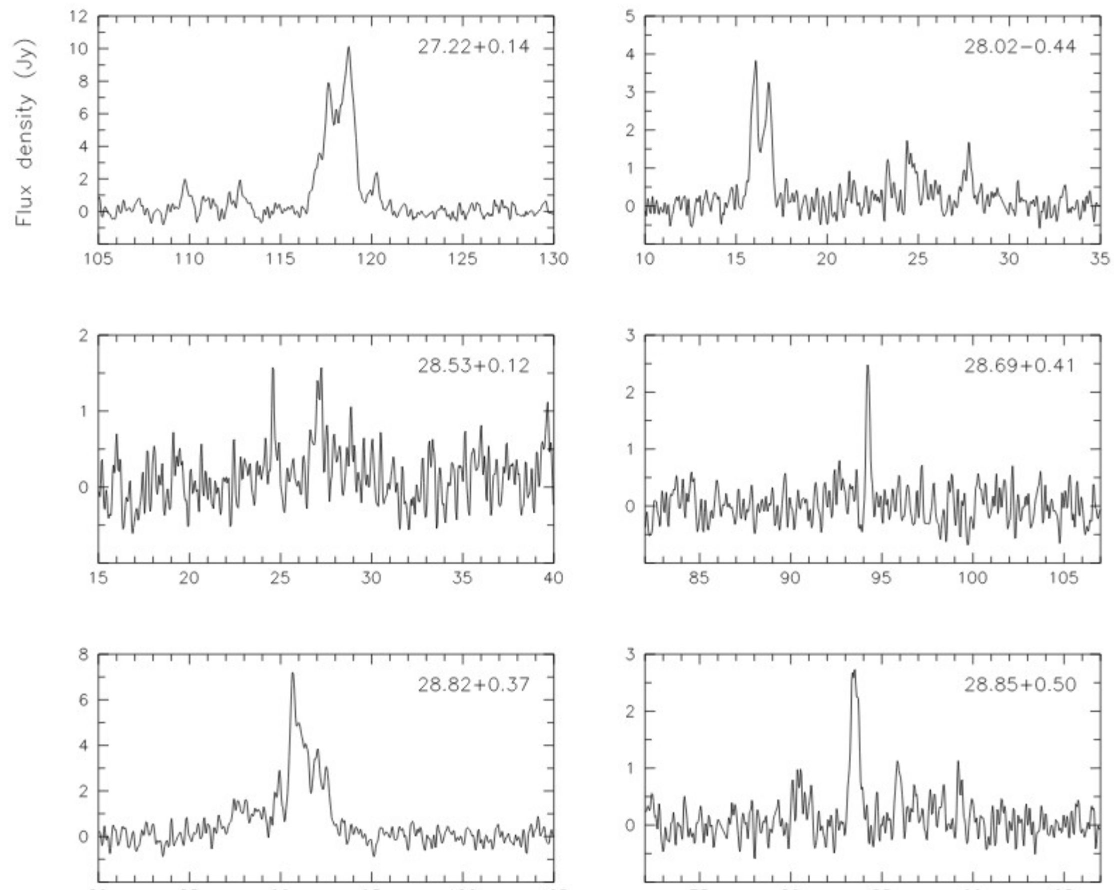
→ **The 6.668518 GHz (in short 6.7 GHz or 4.5 cm) methanol maser transition is exclusively related to High-Mass Young Stellar Objects (HMYSOs).**

Toruń spectral line observations

- Since more than 23 years we have been observing HMYSOs at the 6.7 GHz methanol maser transition. The C-band receiver is sensitive and was upgraded in 2012-2016 via the NSC grant.

Szymczak et al. (2000,2002,2018)
(blind survey of the 6.7 GHz methanol masers line)





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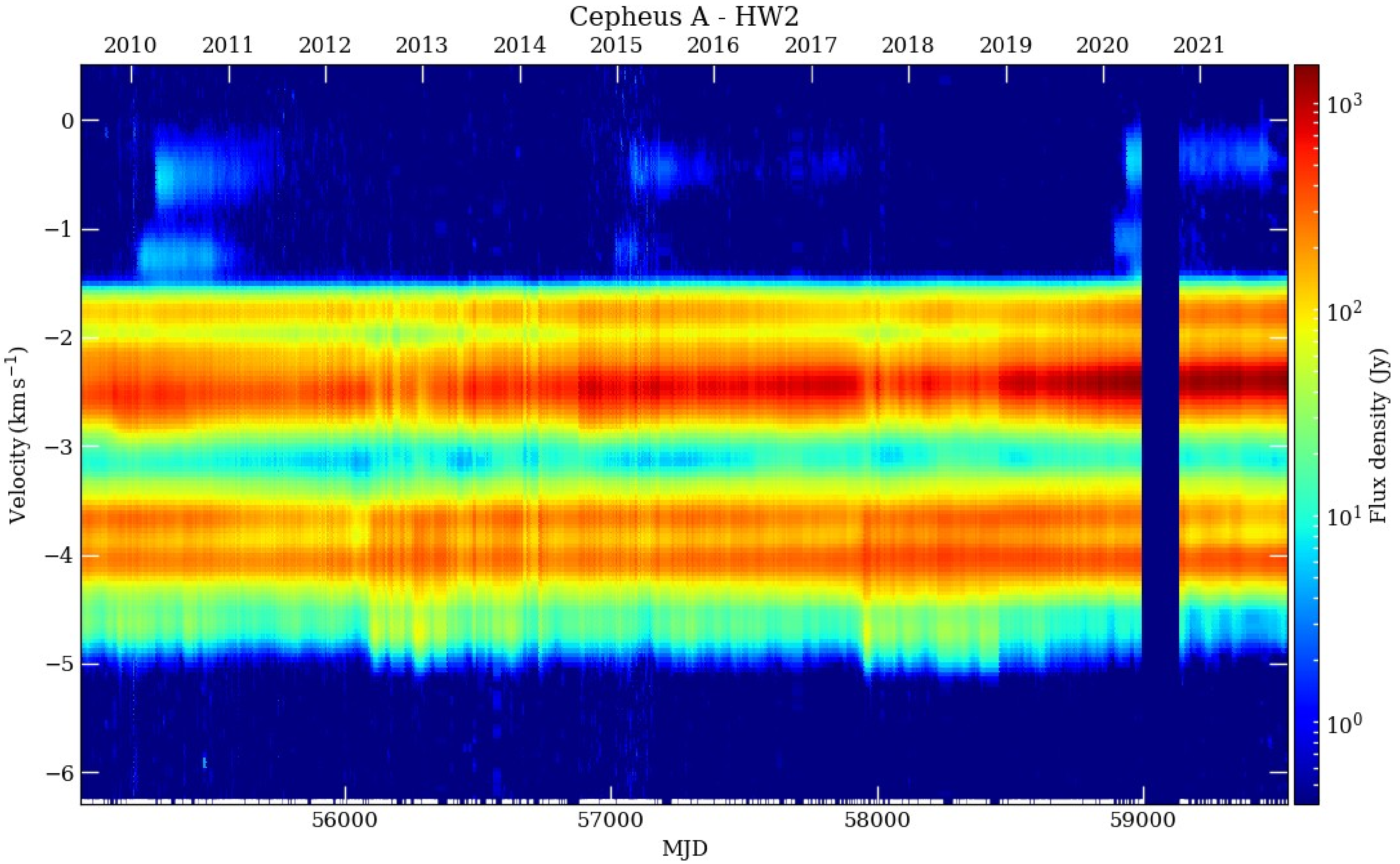
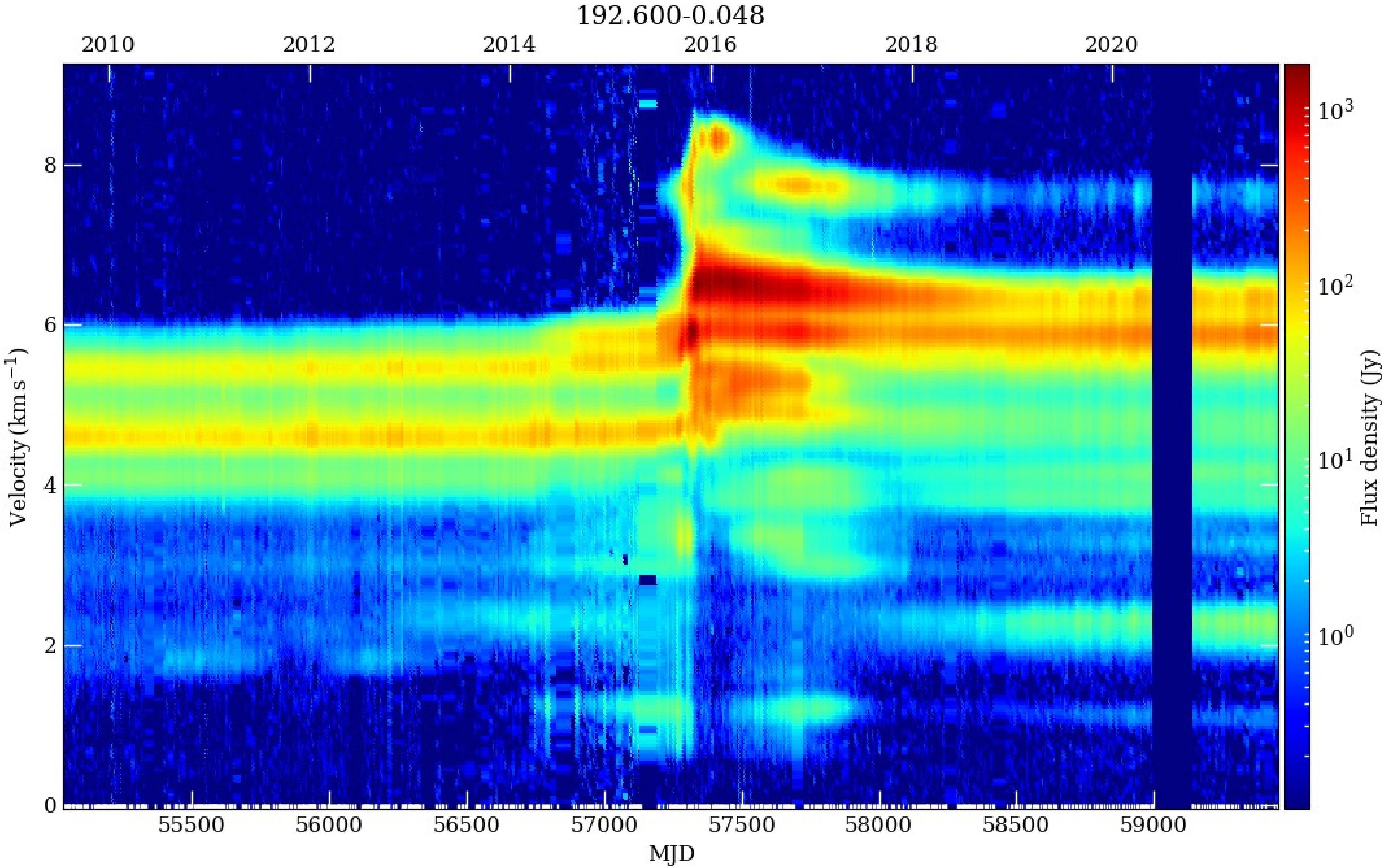
Single-dish: monitoring of maser emission



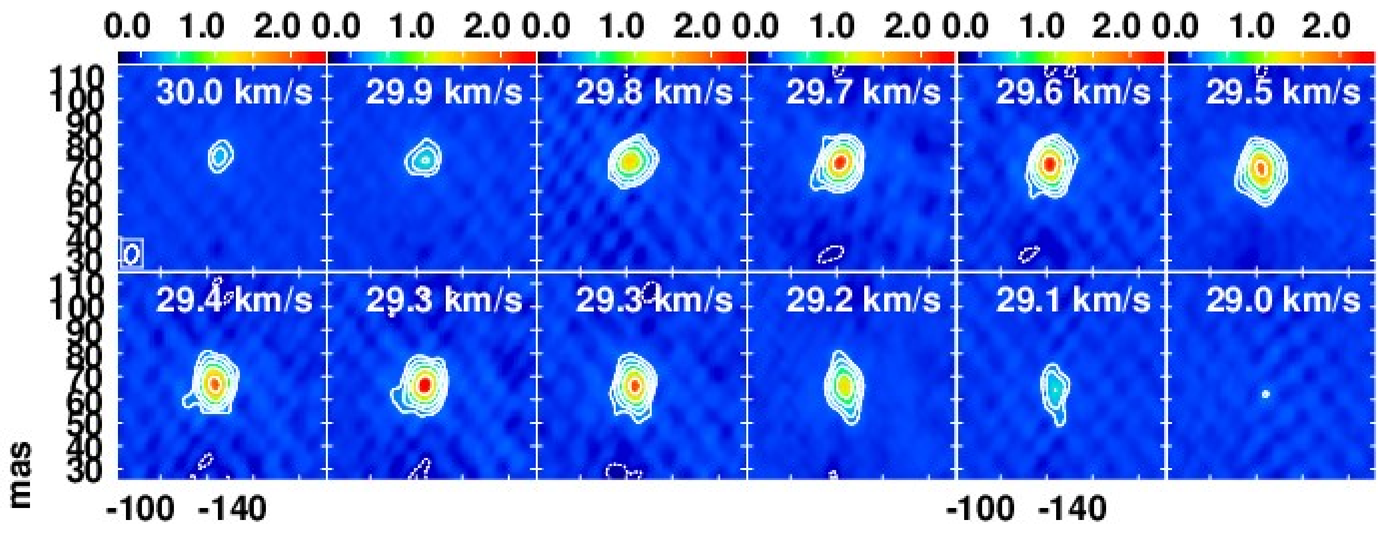


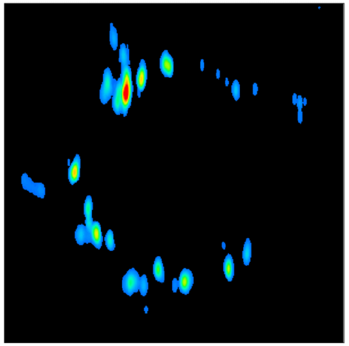
192.600-0.048
2010
2012
2014
2016
2018
2020
Velocity (km s^{-1})
0
2
4
6
8
55500
56000
56500
57000
57500
58000
58500
59000
MJD
10^0
10^1
10^2
10^3
Flux density (Jy)

Spectral line observations using radio interferometers

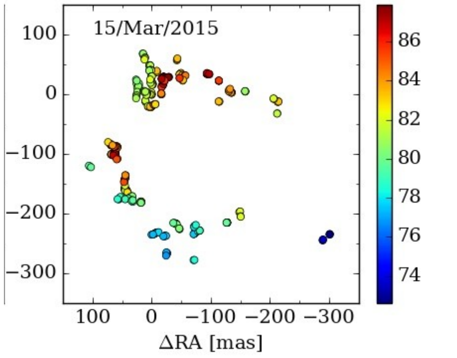
E.g. **6.7 GHz methanol maser** observations (spectral line mode):
90 m/s resolution and beamsize ca. 6 mas x 8 mas.

Masers are compact and bright – good tracers of gas kinematics.





Bartkiewicz et al. 2020



JIVE
Joint Institute for VLBI
ERIC

EUROPEAN vlbi NETWORK

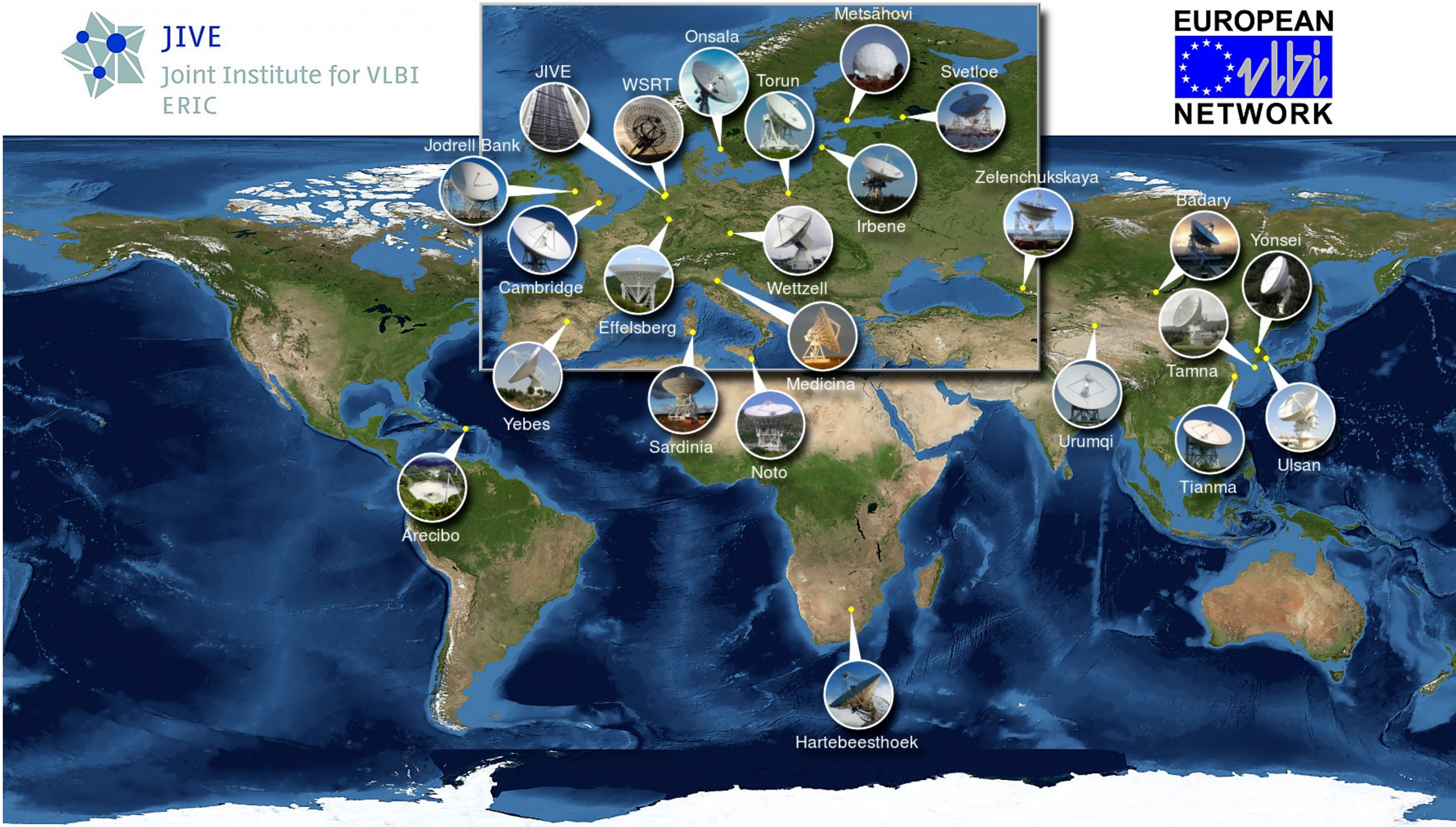
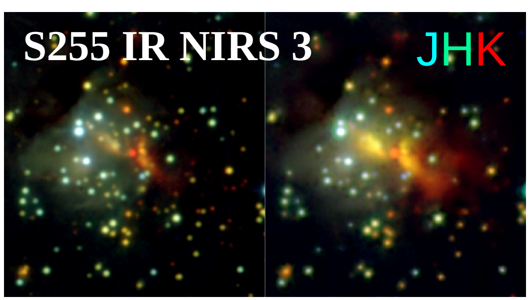
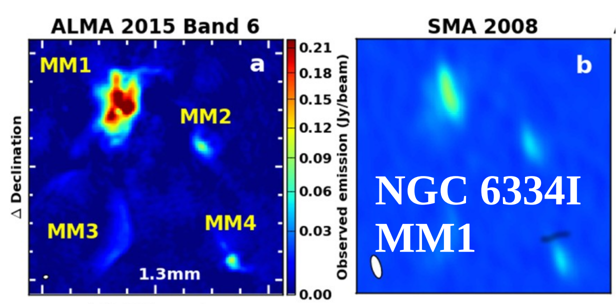


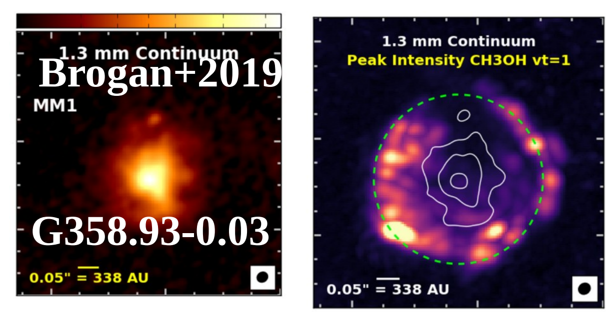
Image by Paul Boven (boven@jive.eu). Satellite image: Blue Marble Next Generation, courtesy of Nasa Visible Earth (visibleearth.nasa.gov).

Four outbursts have been detected and studied so far:

- S255IR NIRS 3: ~20 $M_\odot$ (Caratti o Garatti+2017; Moscadelli +2017; Szymczak+2017; Liu+2018; Cesaroni+2018; Uchiama+2019)
- NGC 6334I MM1: ~20 $M_\odot$ (Hunter+2017,2018; Brogan+2018; McLeod+2018)
- G358.93-0.03 MM1: ~10 $M_\odot$ (Brogan+2019; MacLeod+2019; Breen+2019; Burns+2020; Stecklum+2021)
- G323.46-0.08: ~8 $M_\odot$ (Proven-Adzri+2019; Wolf+ in prep)



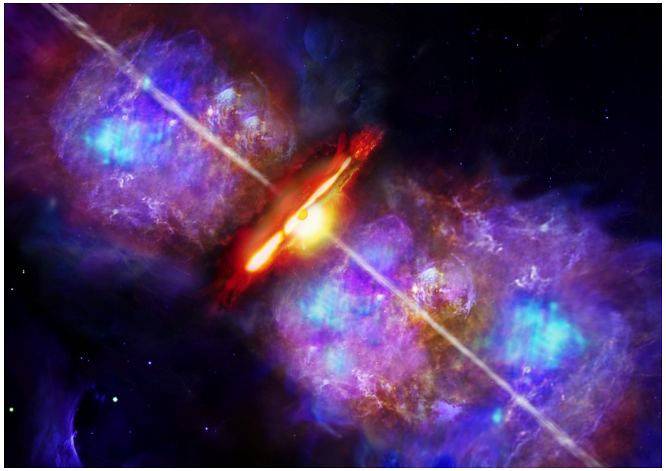




Main characteristics of HMYSO bursts

Despite the small sample we see large variety of physical properties as in low-mass bursts:

- Rising time: from 3 months to 1 year,
- Length: from 7 months to 6 years (1 still active after 6 yrs) ,
- Increase in L_{bol} (ΔL_{acc}): from 6 to 70 times (i.e. from few 10^3 to few 10^5 $L_\odot$)
- Accretion rates in burst: up to several 10^{-3} $M_\odot$/yr,
- Released energy: from few 10^{45} to several 10^{46} erg,

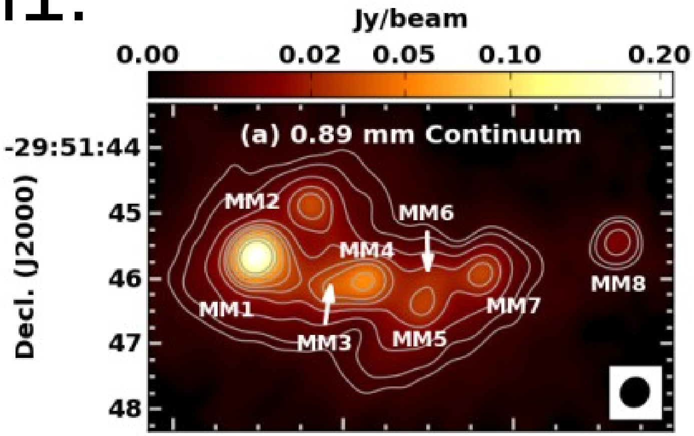


We have… episodic bursts/accretion!

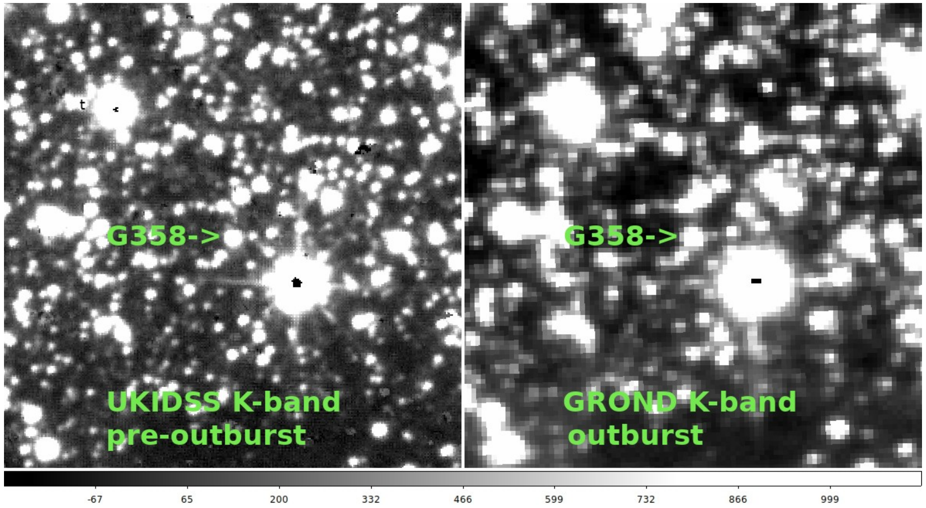
- Recent numerical simulations suggest that all present-day high-mass young stellar objects (HMYSOs) exhibit variable accretion rates and associated episodic bursts (Meyer et al. 2017, 2021).
- They spend up to 2% in the bursting phase, in which they can accrete up to 50% of their final mass (Meyer et al. 2019).
- This process is well related to luminous outbursts.
- **All bursts were preceded by methanol maser flares easily detected by single-dishes. Medium-sized dishes are necessary for the monitoring surveys.**

Brogan et al. 2019

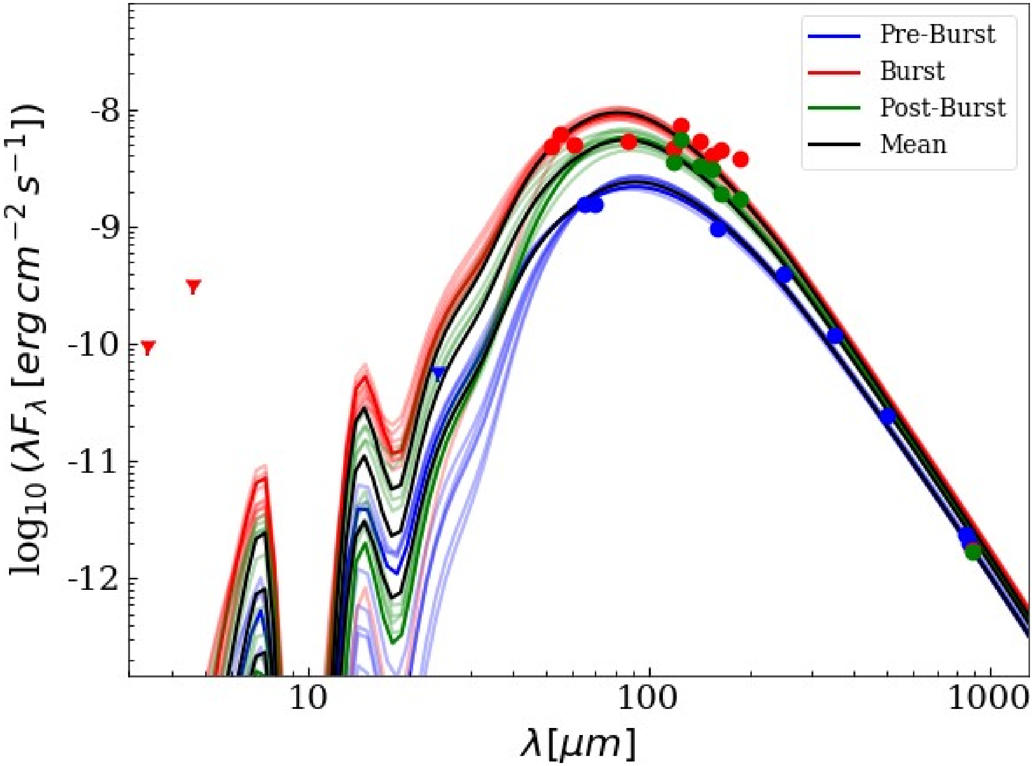
G358.93-0.03-MM1:



- 6.7 GHz CH_3OH burst (ATel)
- HMYSO at d ~ 6.7 kpc, located in a cluster,
- Follow-up by M2O team:
  wealth of masering lines in H_2O, OH, CH_3OH flaring and new maser species HDO, HNCO, $^{13}CH_3OH$ discovered,
- No detection of mm variability,
- No detection in NIR.



Confirmation of the accretion burst by SOFIA



Burst parameters:

ΔL_{acc} = (1.8+/-0.5)x10^{5} $L_\odot$

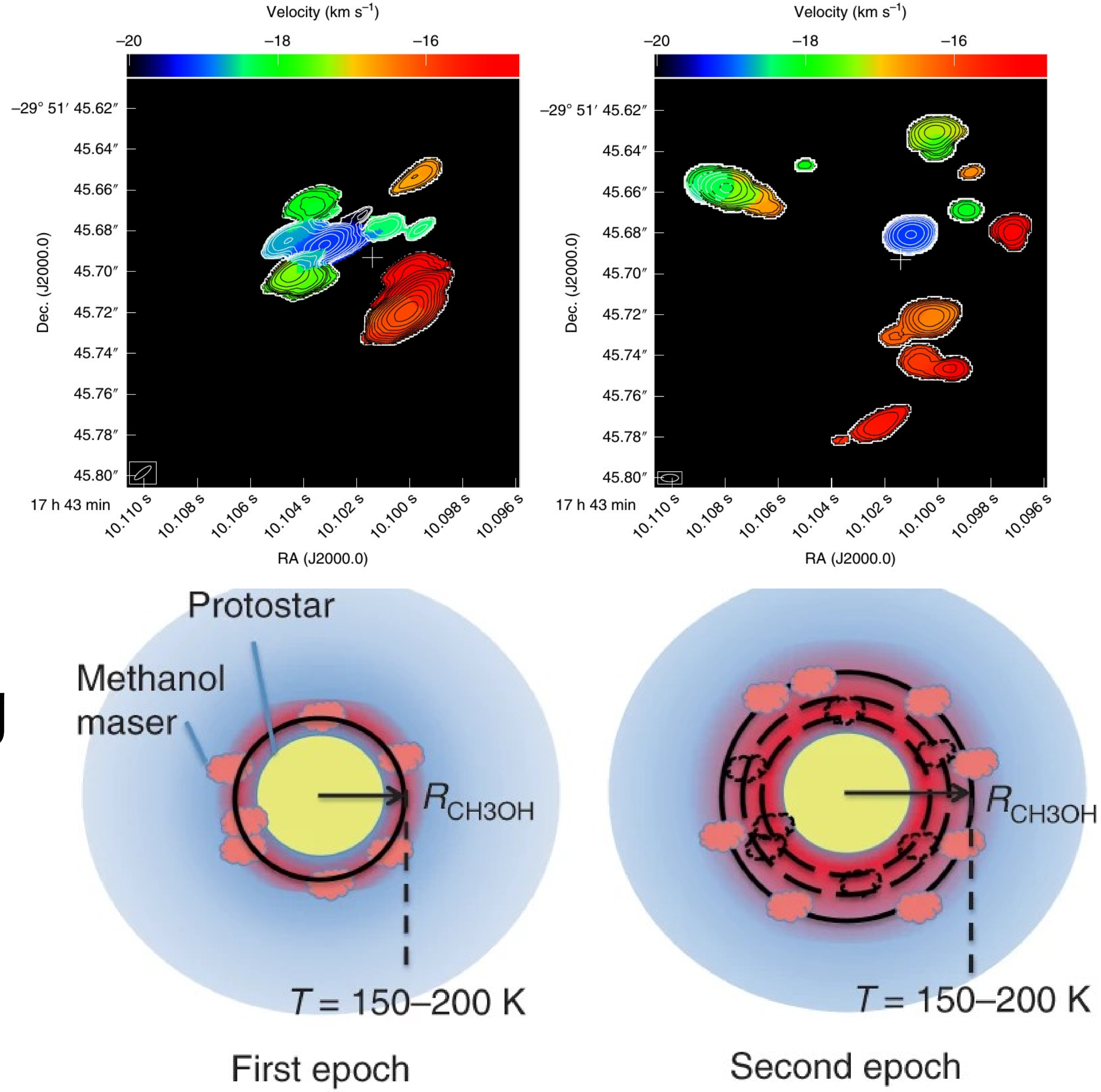
ΔM_{acc}= (5.3+/-11/4)x10^{-4} $M_\odot$/yr

(with M_*=9.7 $M_\odot$ & R_*=3.9 $R_\odot$)

accreted mass ~ 180 M_{Earth}

Stecklum et al. (2021)

Evidence for propagation of heat wave induced by the accretion burst as seen using methanol masers.

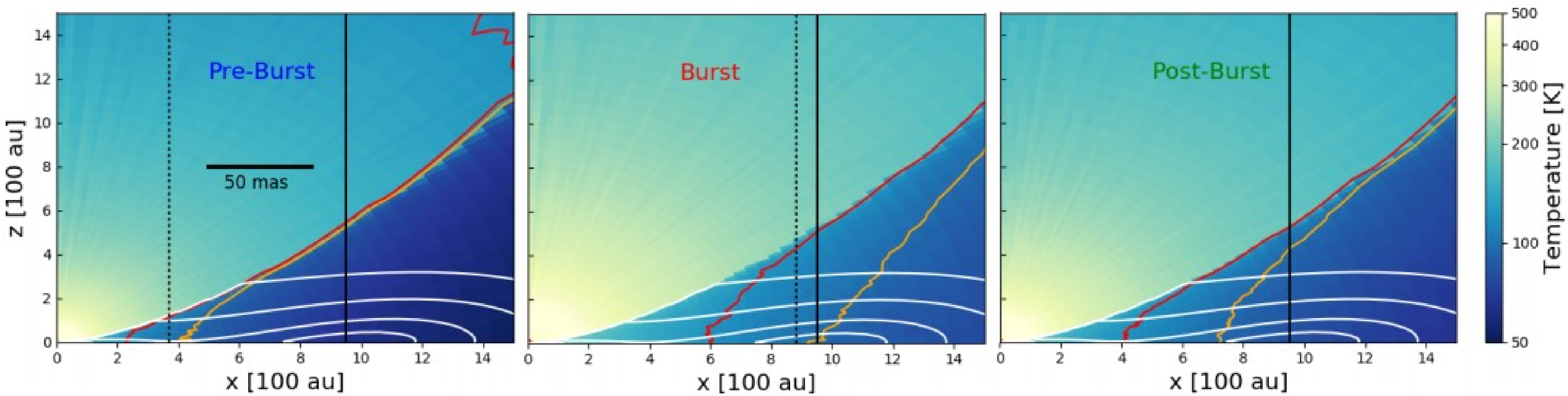


Burns et al. (2020)

Methanol maser relocation (radiative transfer calculations)

Methanol maser ring

disk edge



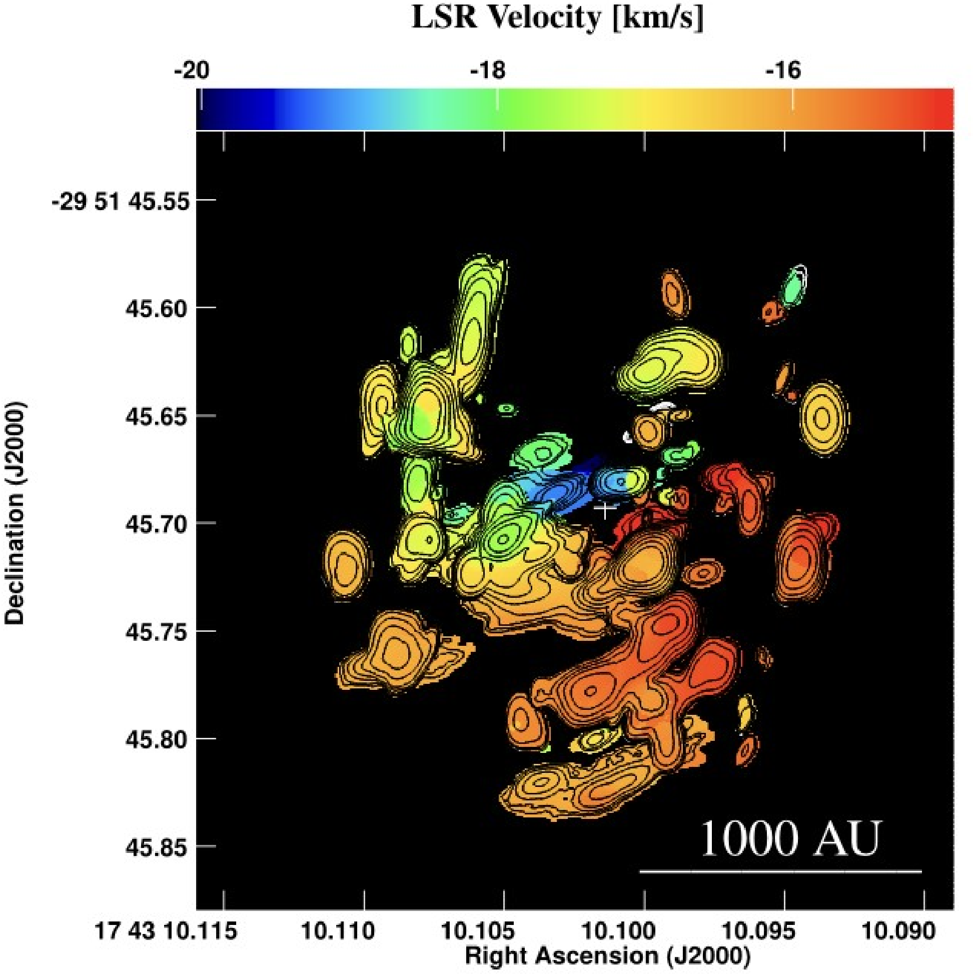
Methanol desorption **red:** ~ optimum 120-125 K, **yellow:** limit 94 K

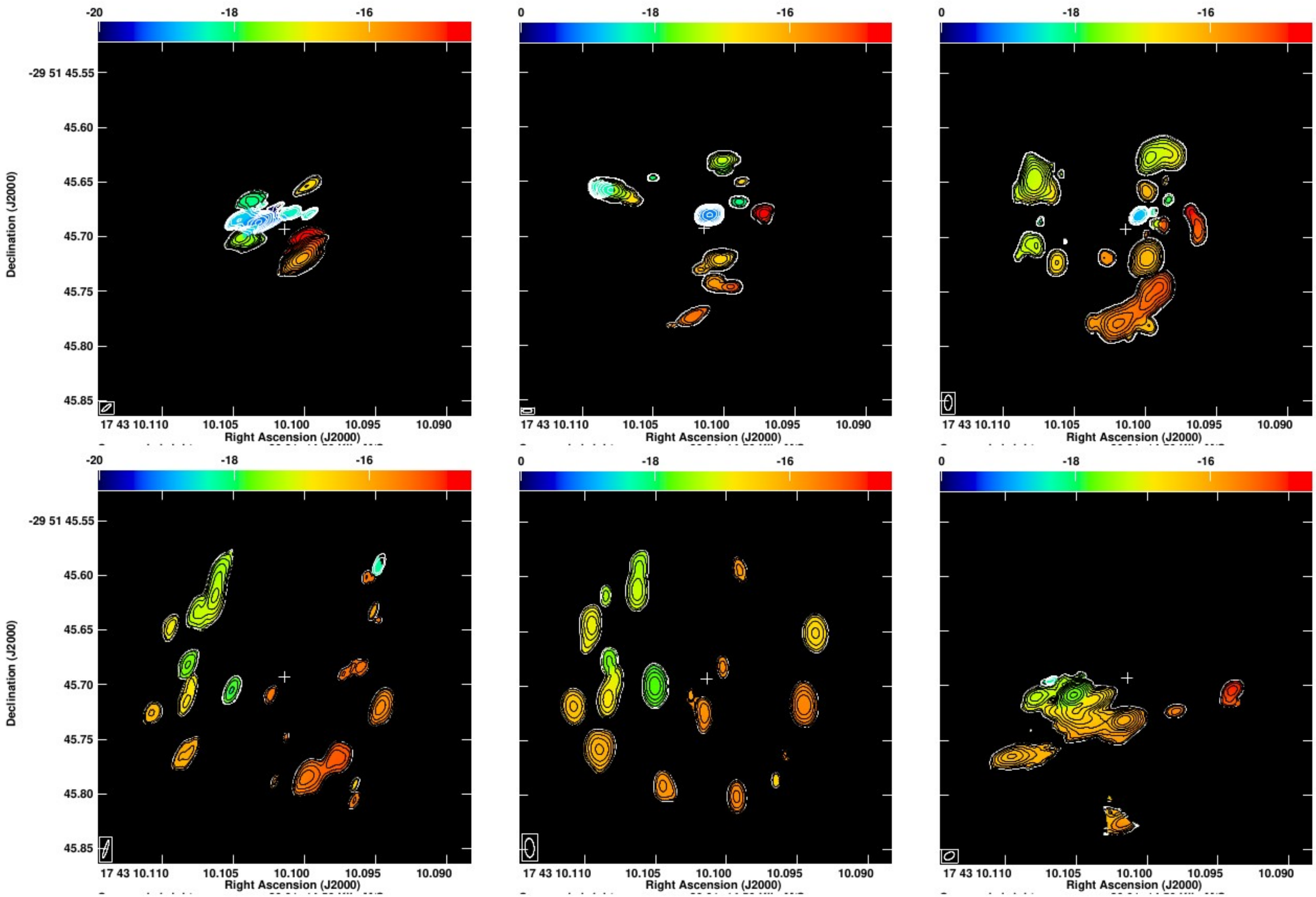
Stecklum et al. (2021)

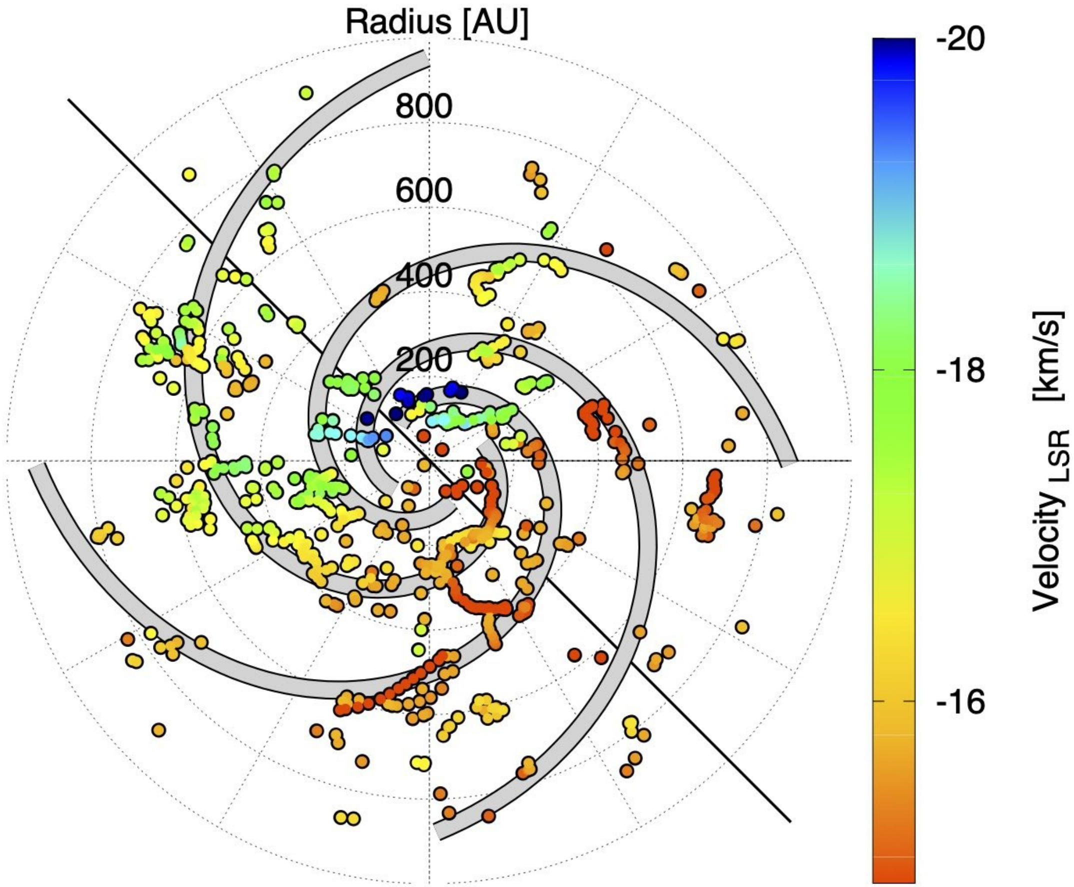
Further investigation of G358

"A Keplerian disk with a four-arm spiral birthing an episodically accreting high-mass protostar" Ross et al. 2023 Nature Astronomy

- 25 radio telescopes were used, from Oceania, Asia, Europe and America.




-20
-18
-16
0
Declination (J2000)
-29 51 45.55
45.60
45.65
45.70
45.75
45.80
45.85
17 43 10.110
10.105
10.100
10.095
10.090
Right Ascension (J2000)

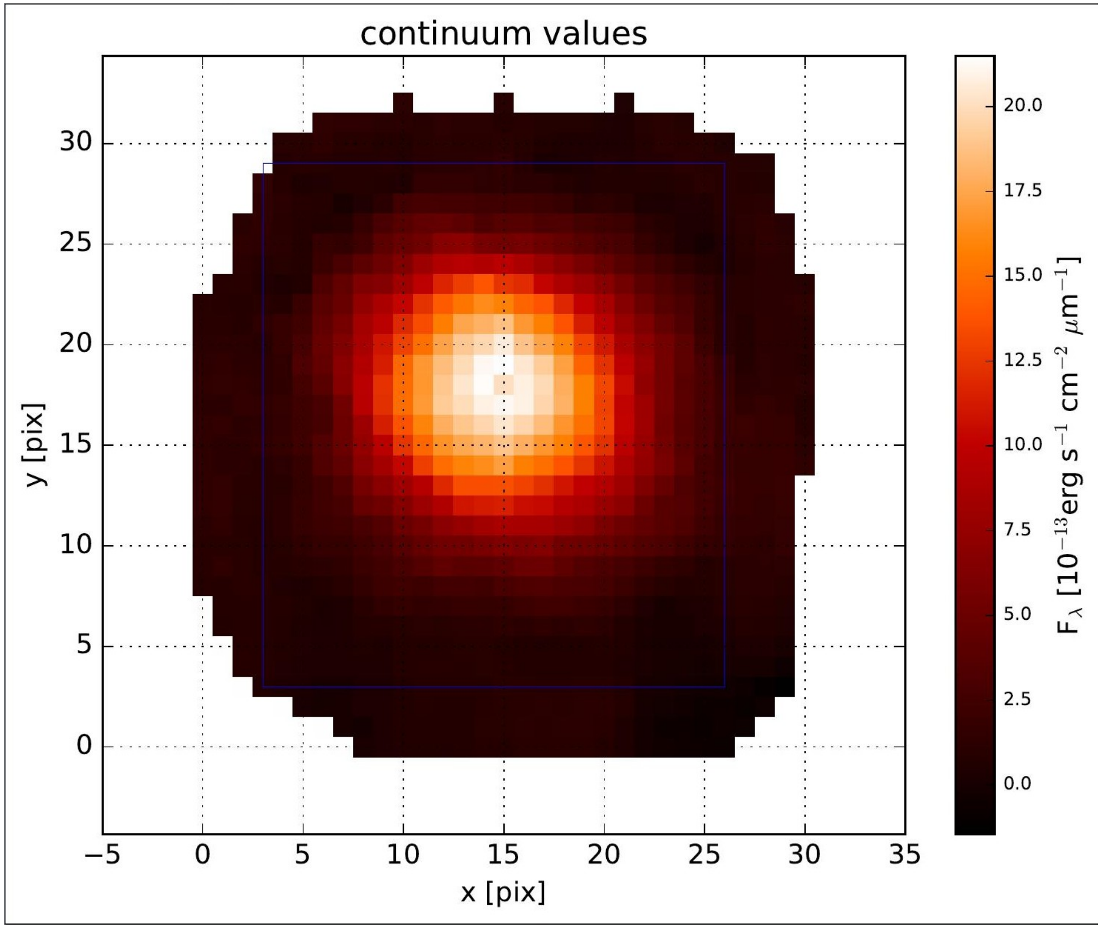


G358-MM1 has four spiral arms which wrap beautifully around the protostar. The spiral arms help to feed disk material down to the center of the system where it can reach the protostar and feed it.

We “just” need to catch the burst

- M2O (A global community for maser-driven astronomy) established in Cagliari, Sardinia during the IAU Maser Symposium in 2017: https://www.masermonitoring.com/

Toruń - Thüringer Landessternwarte Tautenburg collaboration



1 px = 1“

Methanol masers at 6.7 GHz are radiatively excited which is the underlying cause for the radio-IR connection.

G107.298+5.639 at 63 μm obtained using SOFIA on 2019 (PIs: **Jochen Eislöffel, Bringfried Stecklum**)

Periodic maser sources – PhD project.

Summary

→ Multifrequency and multi-epoch studies are key to understand high-mass star-formation,

→ VLBI helps to derive scenarios going on in these dense regions thanks to angular and velocity resolution,

→ CH_3OH maser flares are excellent proxies for accretion variability in HMYSOs,

→ Disk-mediated accretion bursts observed from low- to high-mass YSOs,

→ Systematic single-dish observations are needed.

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