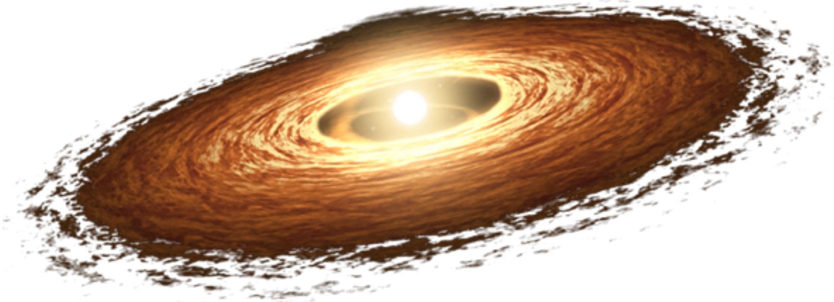
A sharp view of the circumstellar disks of young eruptive stars

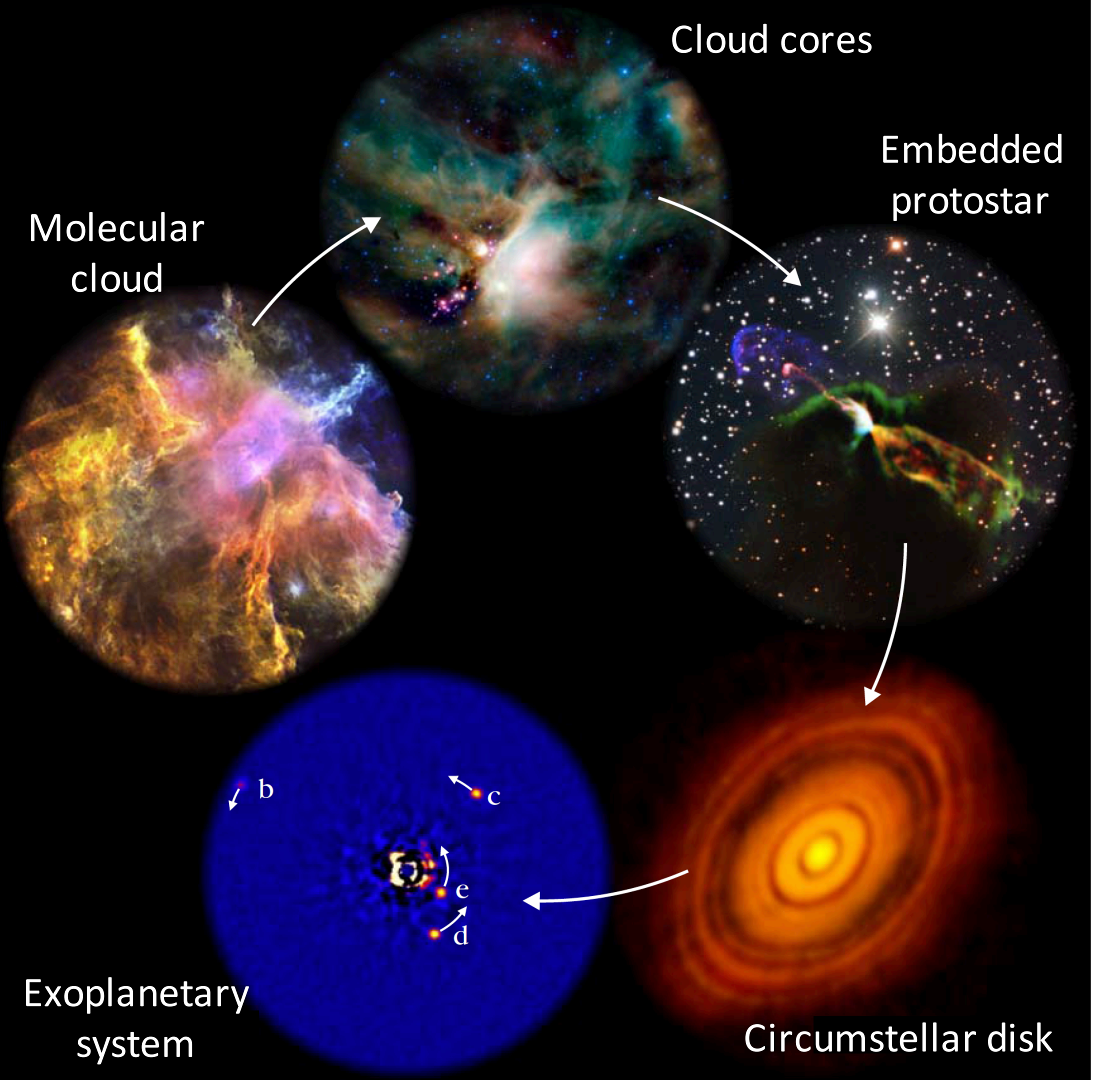


Ágnes Kóspál

SACCRED ERC SG Research Group

Konkoly Observatory, Budapest, Hungary

2020 June 29



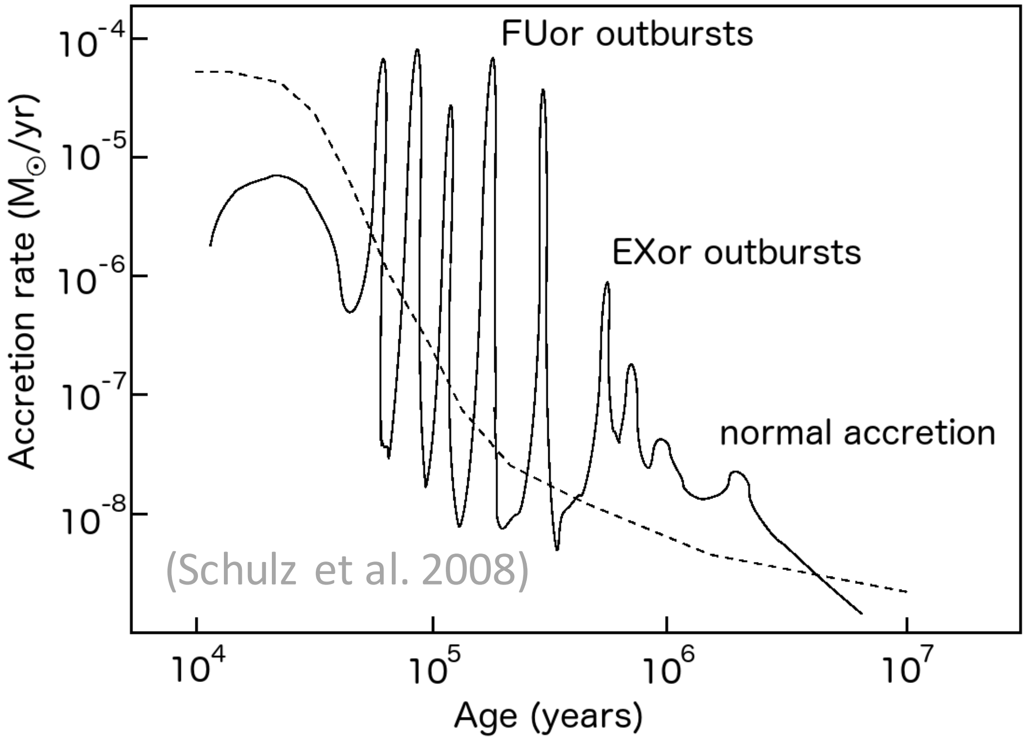
The formation of Sun-like stars

- **General paradigm** of the formation of low ($< 2\,M_\odot$) and intermediate ($2 - 8\,M_\odot$) mass stars

- **Complicated process** with many details

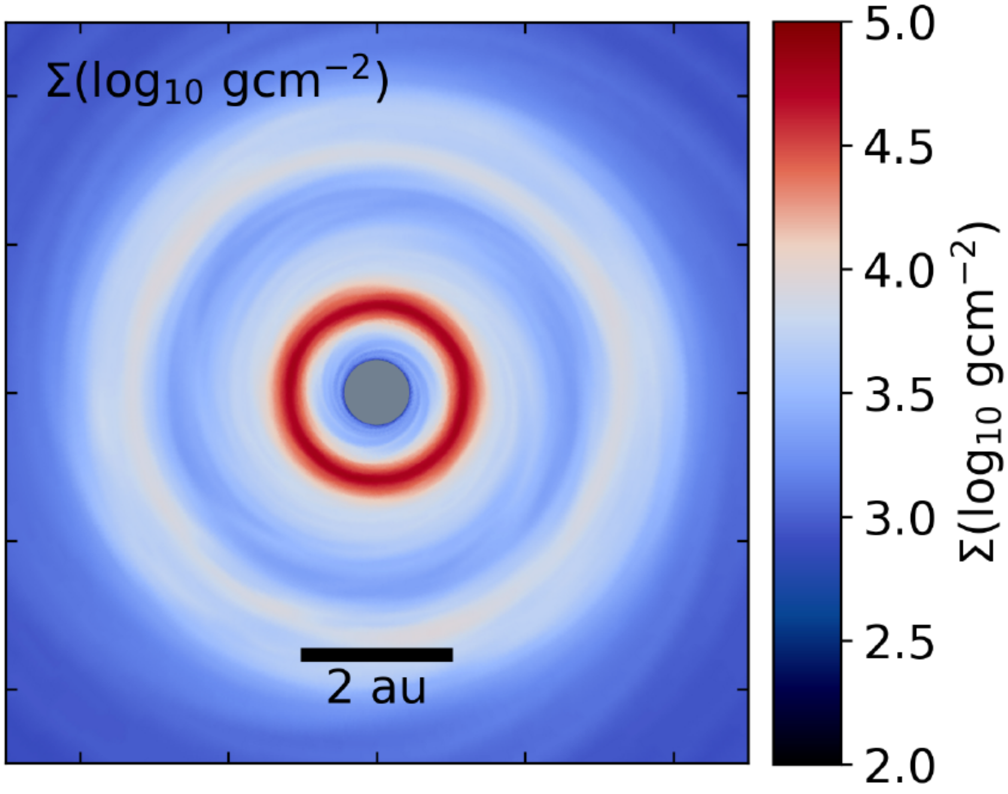
- Spatial scales: $1\,R_\odot$ … 1 pc
- Densities: 10^3 … 10^{13} cm^{-3}
- Temperatures: 10 … 1000 K

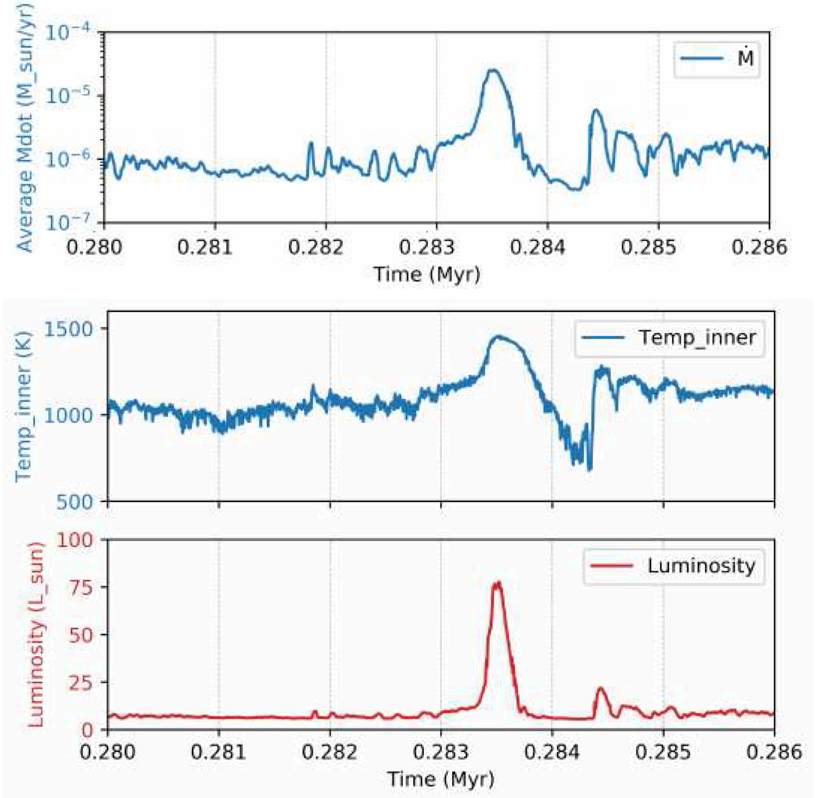
Episodic accretion in star formation



- First concept: protostellar accretion and disk evolution are **smooth** processes over $10^5 - 10^6$ years
- **In reality: accretion is inhomogeneous** in space and time
- Accretion rate may vary by several orders of magnitude
- Indications from **numerical** studies
- Indications from **observations**

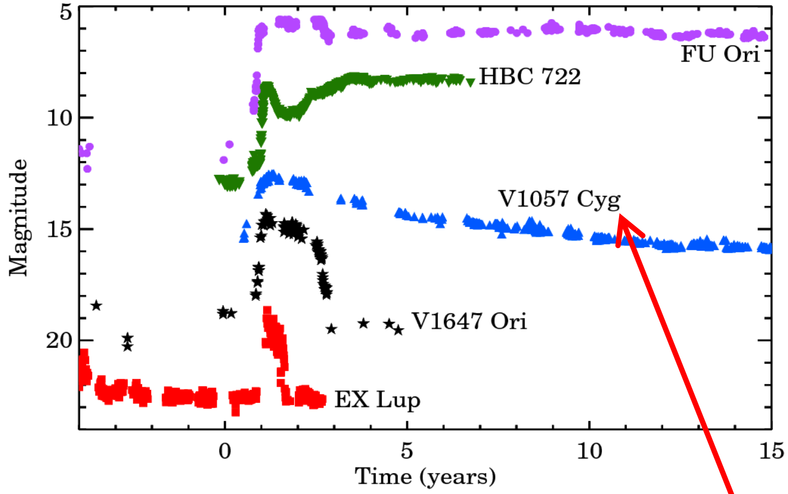
Episodic accretion in numerical studies

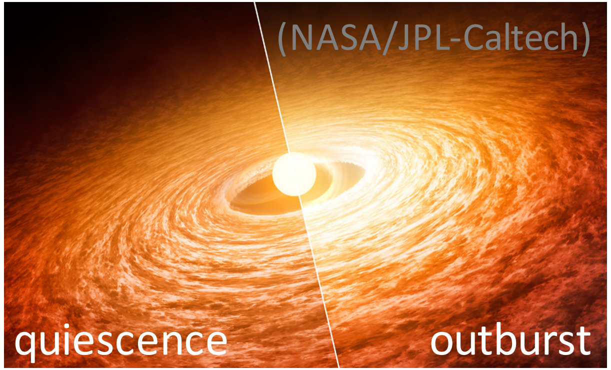




e-poster #492 by Kundan Kadam

Episodic accretion in observations



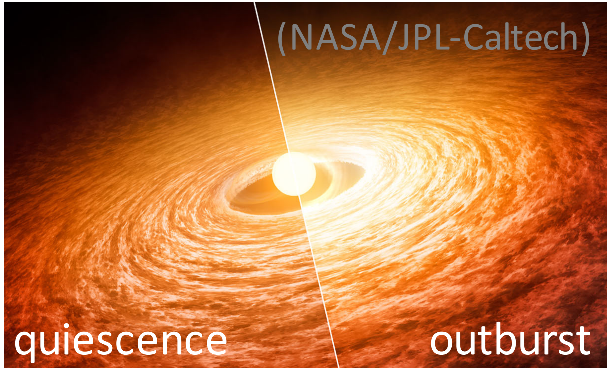


e-poster #692 by Zsófia Szabó

- **Young eruptive stars:** brightening by 3 – 5 mag in the optical and infrared wavelength ranges
- **Bolometric luminosity** increases from few $L_\odot$ to few 100 $L_\odot$
- **Accretion rate** increases by several orders of magnitude
- Affects different properties of the disk:
  - **structure**
  - **mineralogy**
  - **chemistry**

Motivation / open questions

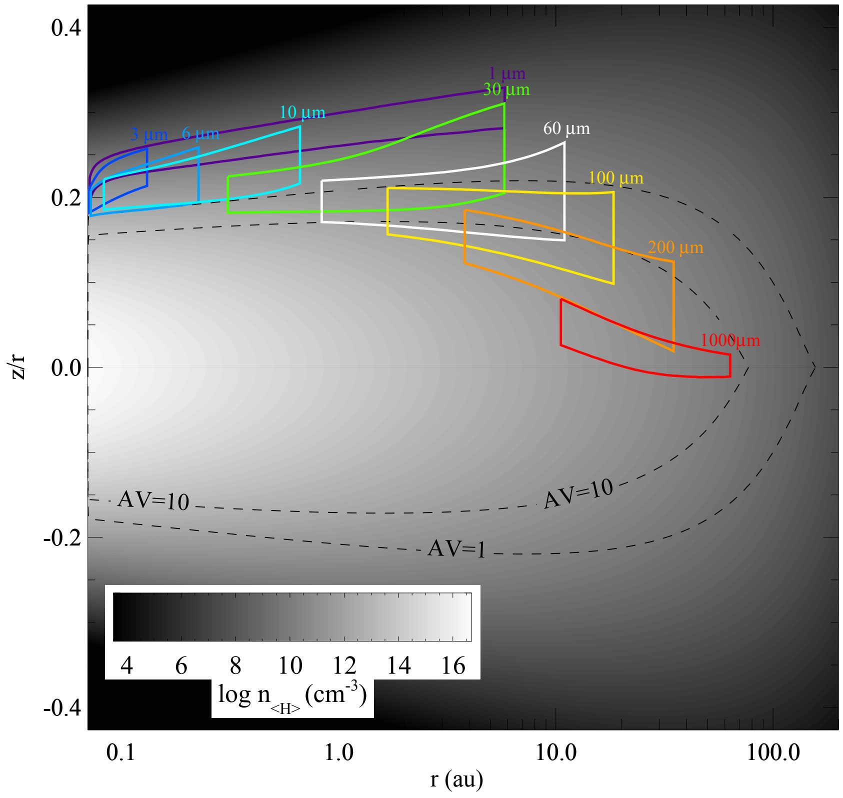
- **Do all Sun-like young stars go through eruptive phases?**
- Typical FUor outburst:
  - peak accretion rate up to $10^{-4}\ M_\odot$/yr
  - 100-year-long outburst
  - star collects 0.01 $M_\odot$ or 10 M_{Jupiter} in one outburst



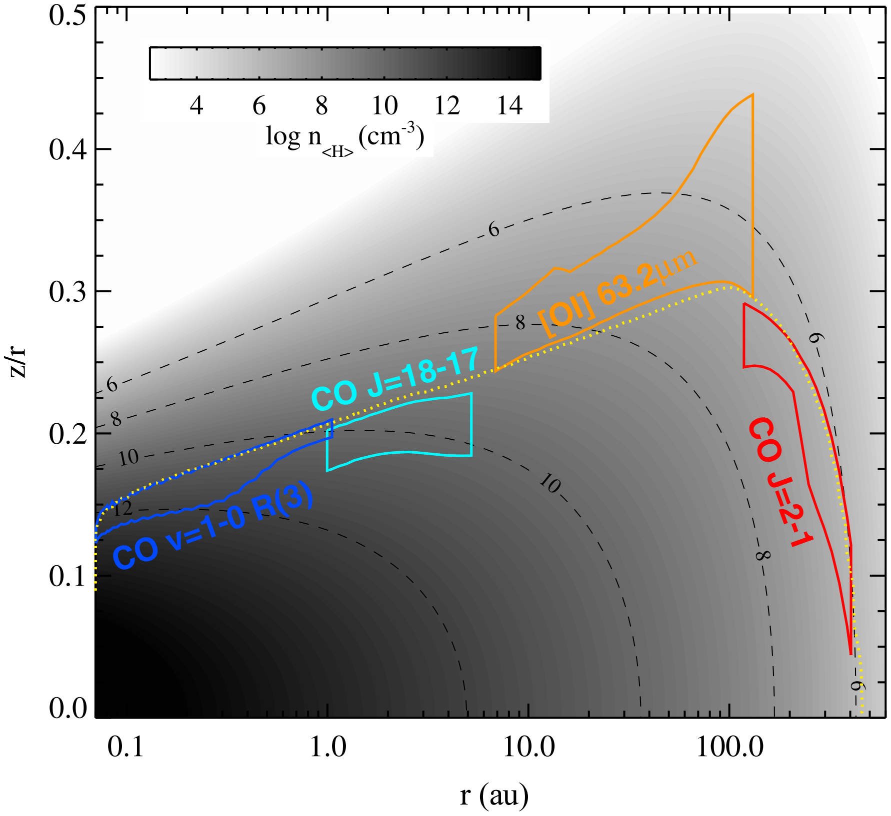
- Disk must be **very large and very massive** with interesting substructures
- Is this really true? Do the observations support this?
- Disks of young eruptive stars need to be measured at high spatial resolution

How do we measure the disk?

dust



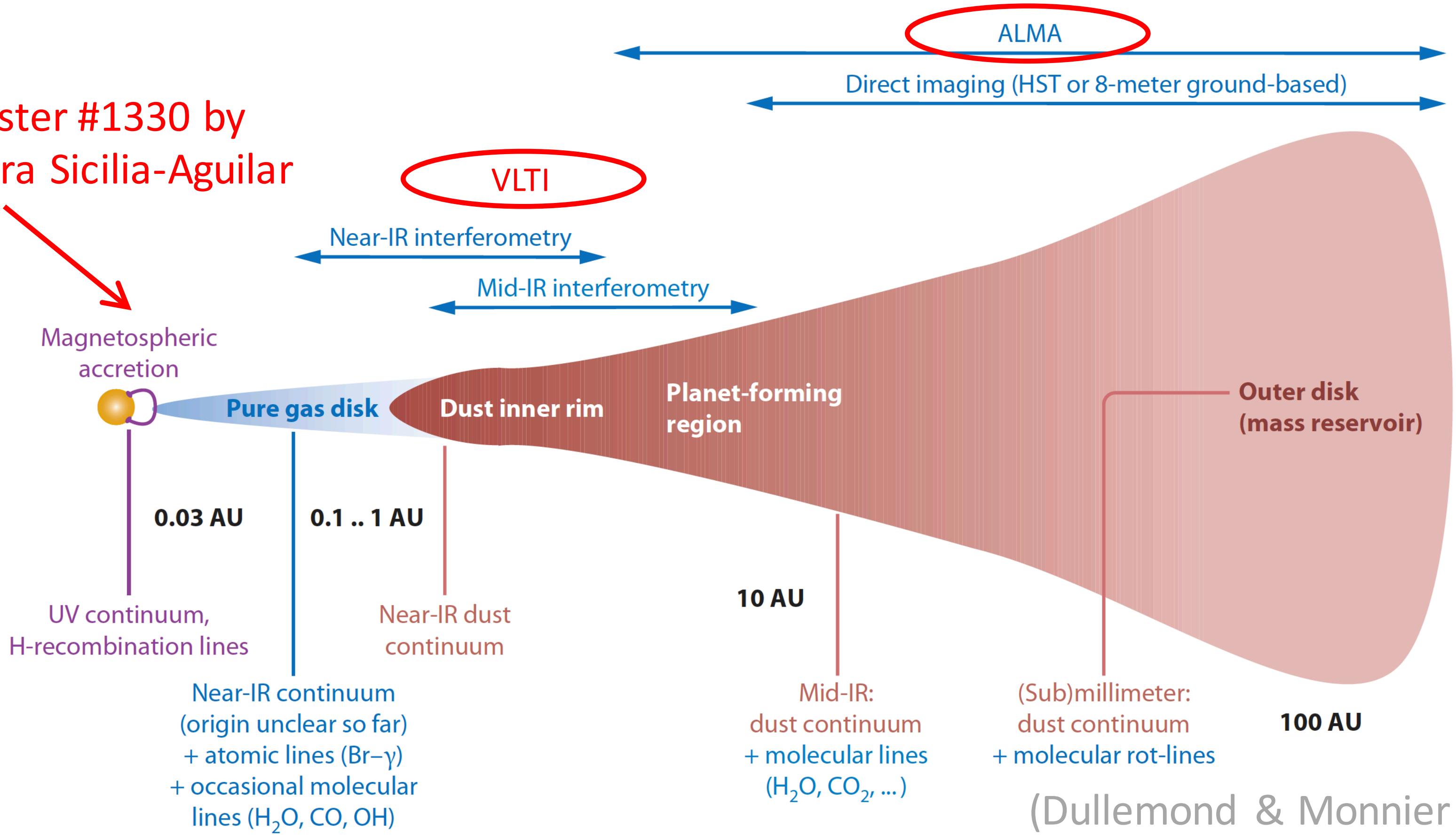
gas



(Woitke et al. 2016)

Why do we need interferometry?

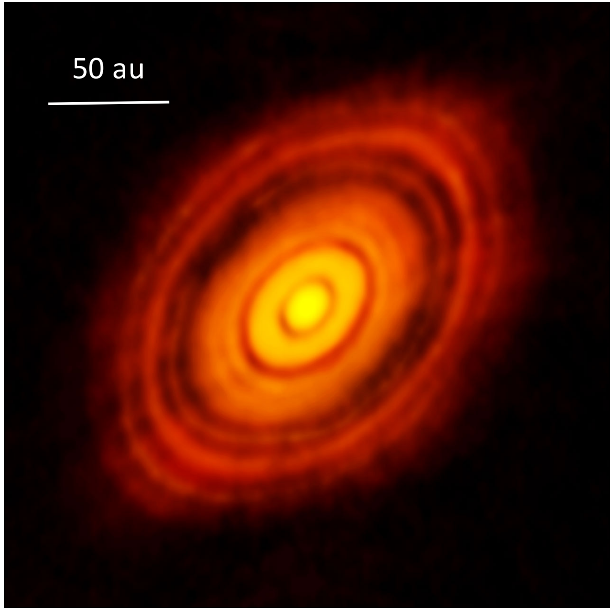
e-poster #1330 by
Aurora Sicilia-Aguilar



(Dullemond & Monnier 2010)

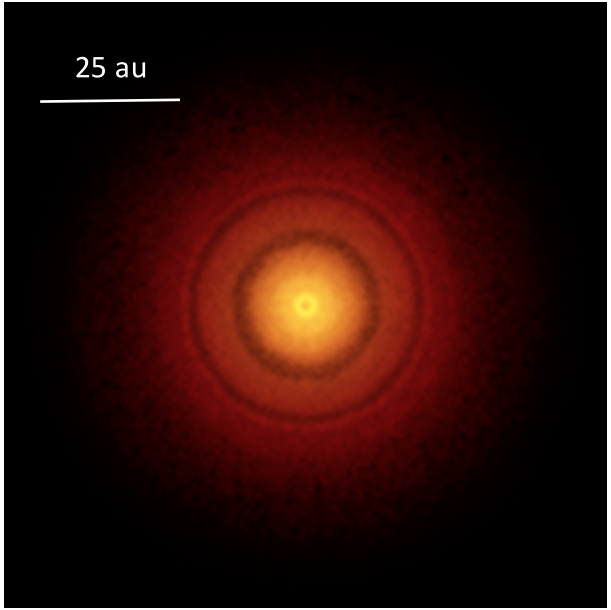
ALMA images of circumstellar disks

HL Tau



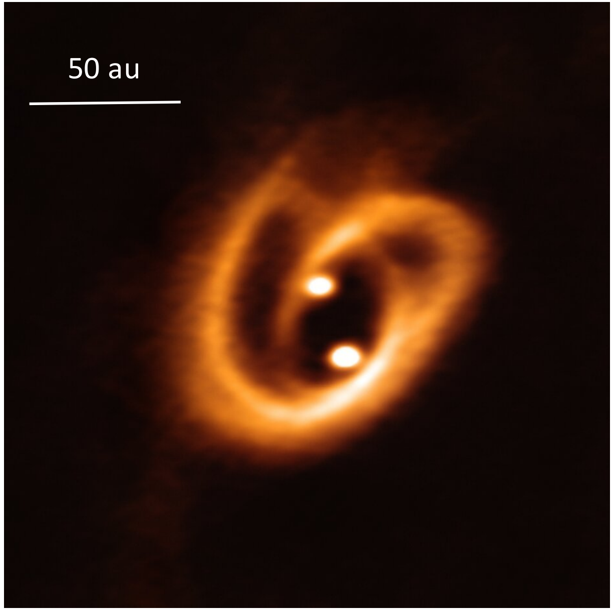
ALMA (ESO/NAOJ/NRAO)

TW Hya



S. Andrews (Harvard-Smithsonian CfA); B. Saxton (NRAO/AUI/NSF); ALMA (ESO/NAOJ/NRAO)

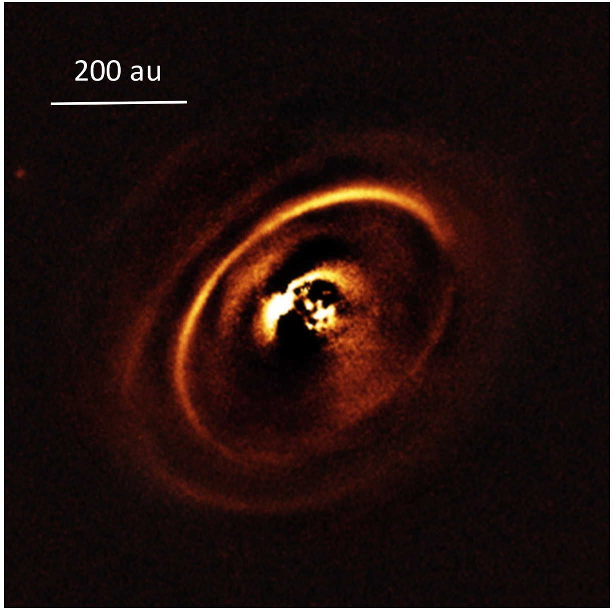
“Cosmic Pretzel”



ALMA (ESO/NAOJ/NRAO), Alves et al. (2019)

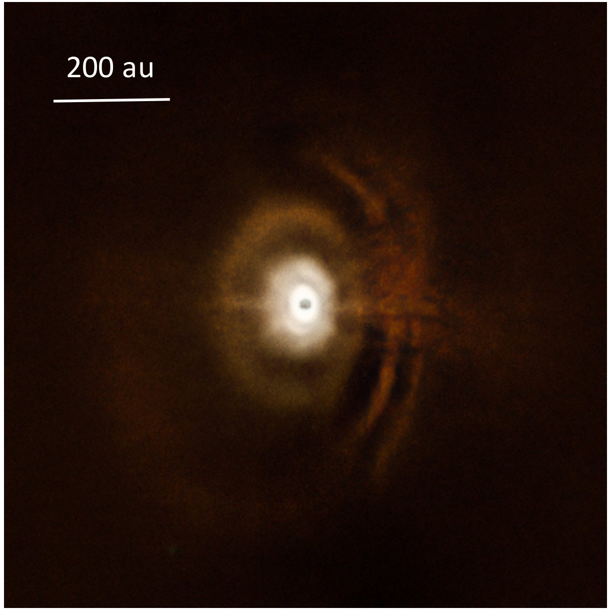
VLT/SPHERE images of circumstellar disks

RX J1615



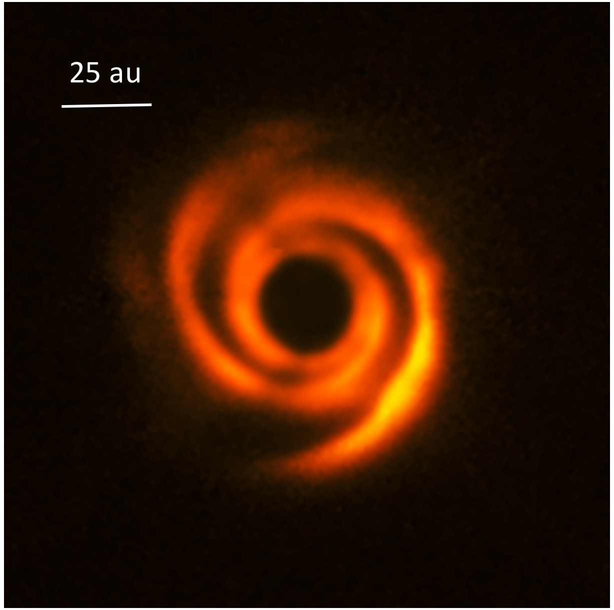
ESO, J. de Boer et al. (2016)

HD 97048



ESO, C. Ginski et al. (2016)

HD 135344B



ESO, T. Stolker et al. (2016)

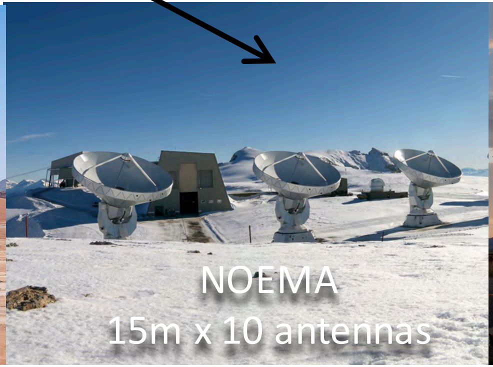
How do we measure young eruptive stars?

near and mid-infrared

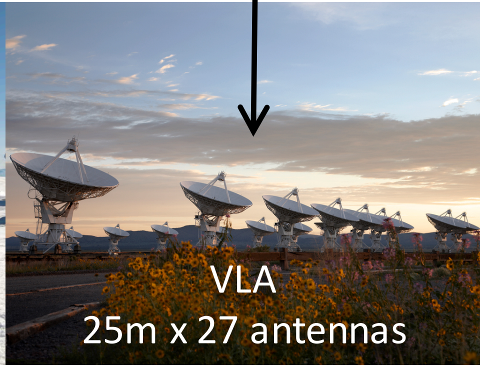
(sub)millimeter

radio

www.almaobservatory.org

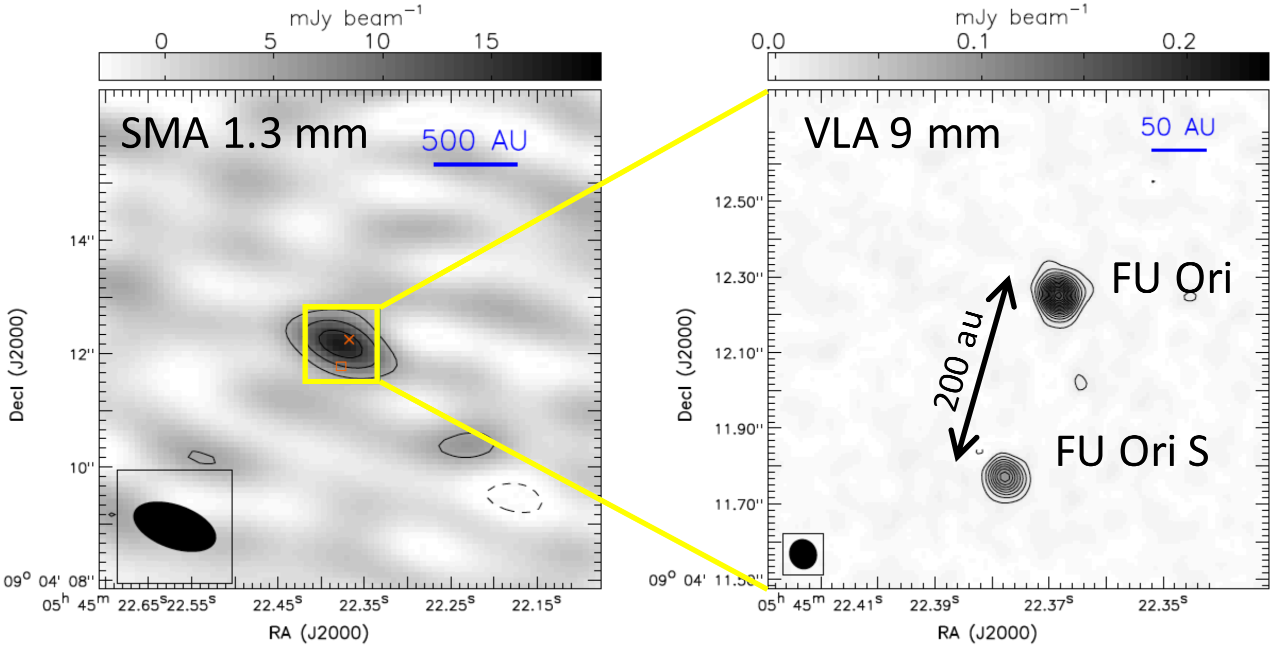


www.iram-institute.org



(NRAO/AUI/NSF)

Millimeter images of FU Orionis

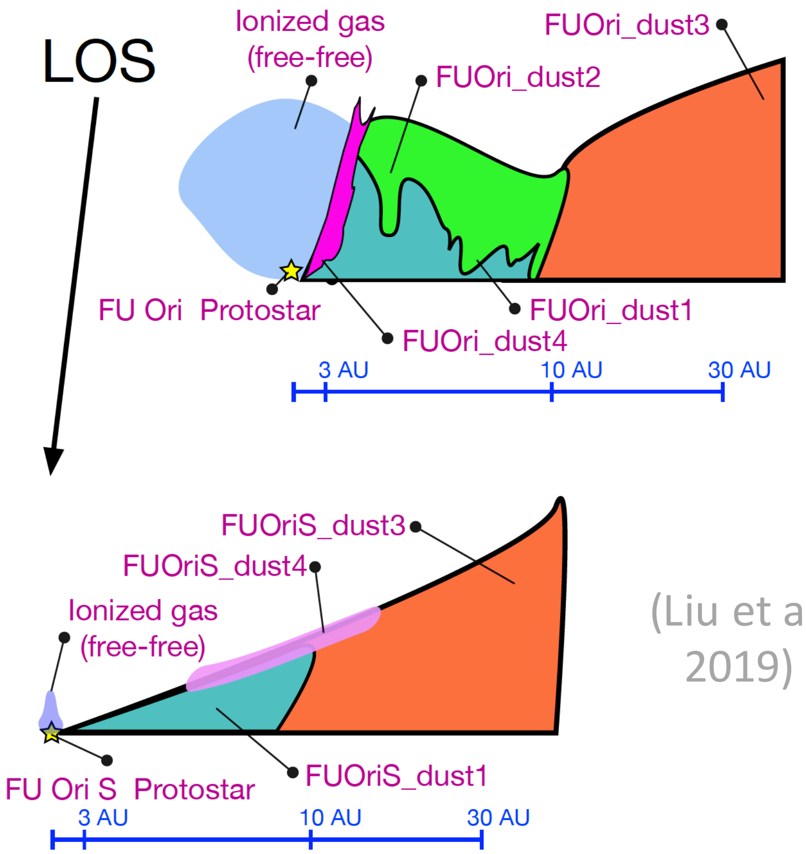


(Liu et al. 2017)

- VLA 9 mm dust continuum with 0.07″ beam
- Deconvolved sizes:
  FU Ori: 6.3 x 5.2 au
  FU Ori S: 4.4 x 2.3 au
- Additional ALMA (2 and 3 mm) and VLTI/GRAVITY (2 μm) observations

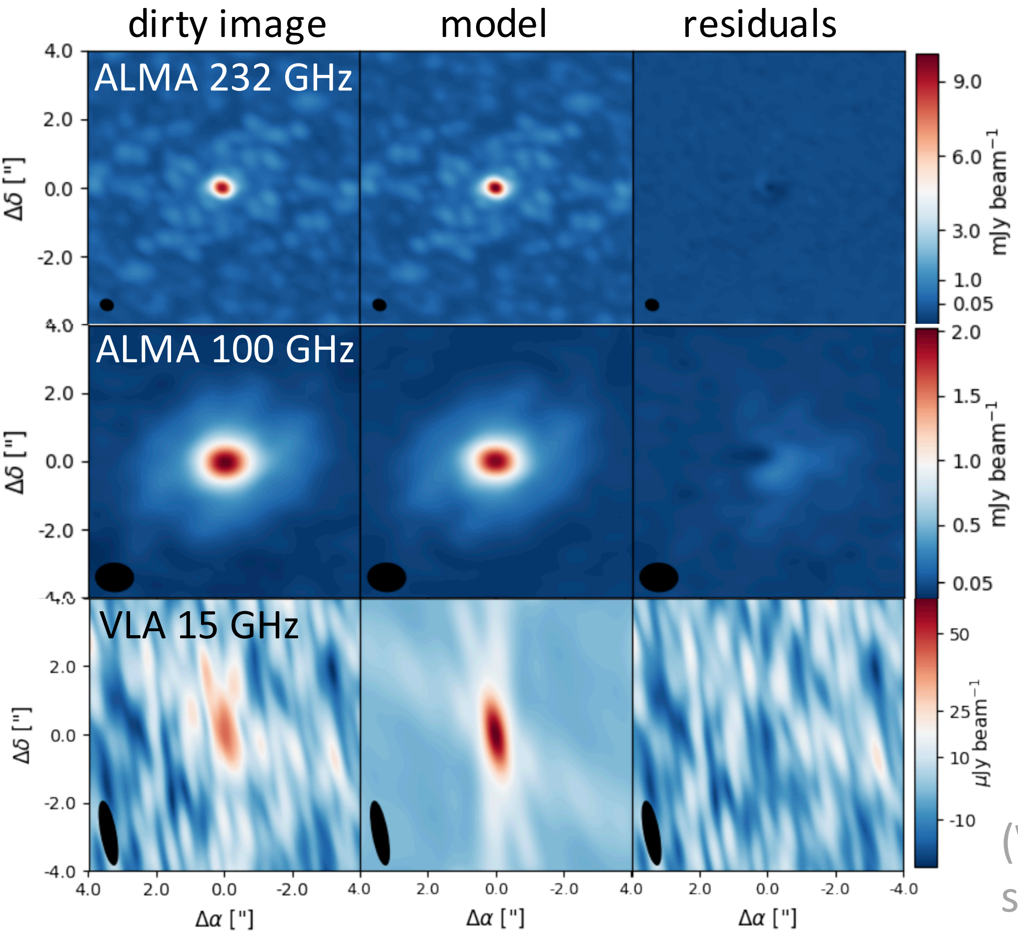
A schematic picture of the FU Ori + FU Ori S system

- Combination of **several emission components**
- Free-free emission from ionized gas
- Thermal emission from optically thick and optically thin dust components with different temperatures and maximal grain sizes
- **The disk of FU Ori is surprisingly small**



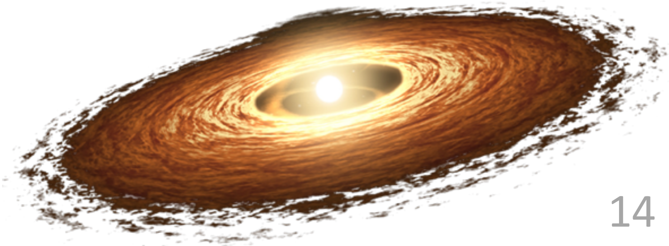
(Liu et al. 2019)

Millimeter images of EX Lupi



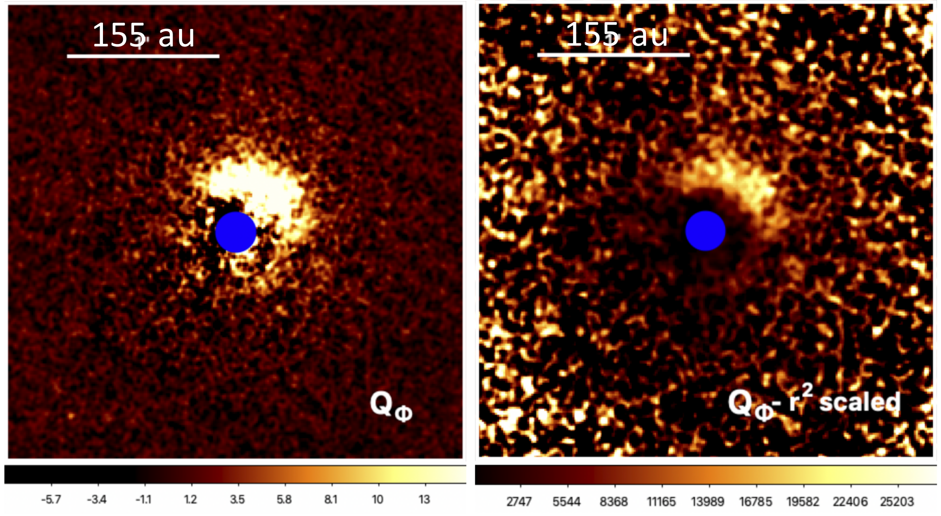
- ALMA 1.3 – 3 mm images are consistent with a disk with a characteristic radius of 45 au and total mass of 0.01 $M_\odot$
- VLA cm emission suggests a non-thermal component, likely stellar (gyro)synchrotron and free-free disk emission

(White et al. submitted)



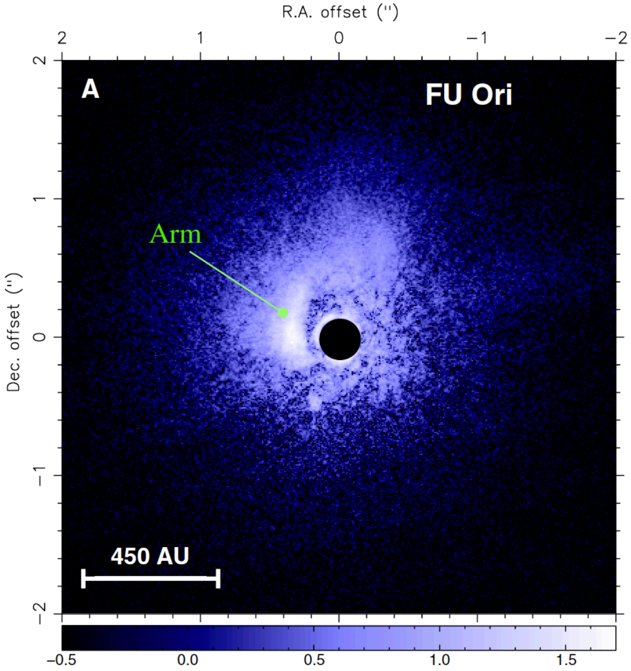
Scattered light images of FU Ori and EX Lup

SPHERE/IRDIS H band image of EX Lup



- Continuous circumstellar disk with a cavity?
- Illuminated wall of the outer disk?
- Shadowed disk? (Rigliaco et al. 2020)

Subaru/HiCIAO K band image of FU Ori

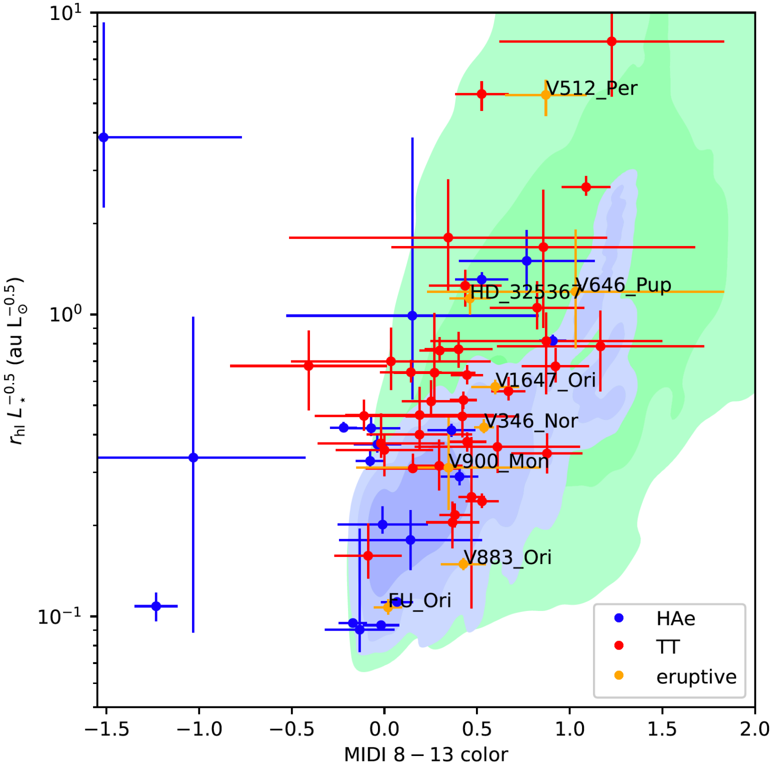


(Liu et al. 2016)

VLTI observations of young eruptive stars

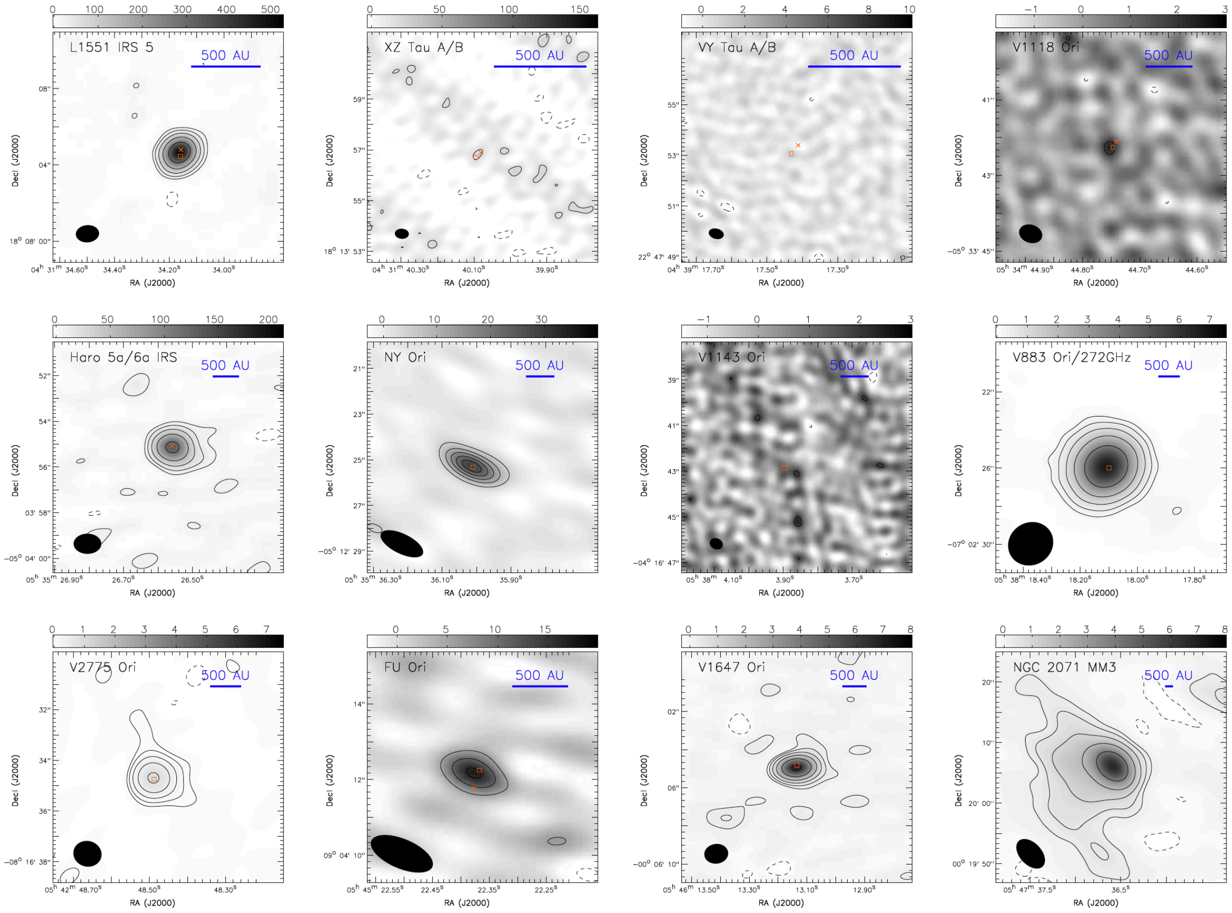
- **MIDI** observed a **sample of 11** FUor- and EXor-type **young eruptive stars**
- MIDI provided spectrally resolved visibilities in the 8 – 13 µm range, we fitted half-light radii
- **No significant difference in the structure of the inner disk** (within a few au)
- **MATISSE** observed FU Ori and V900 Mon, will observe V346 Nor

e-poster #685 by Péter Ábrahám



(Varga et al. 2018, Gabányi et al. in prep.)

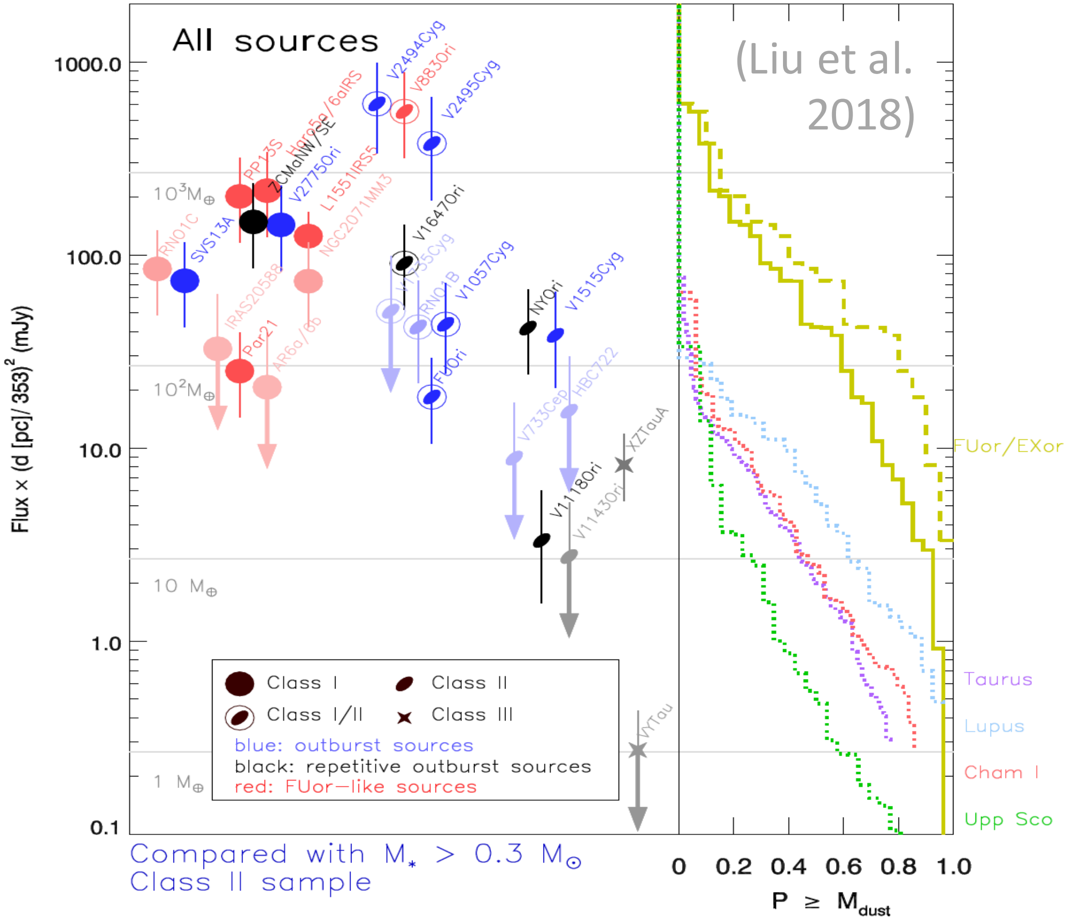
SMA survey of 29 young eruptive stars



- Sample of 29 FUor- and EXor-type young eruptive stars
- 1 mm dust continuum emission with ~1″ beam
- 21 detections

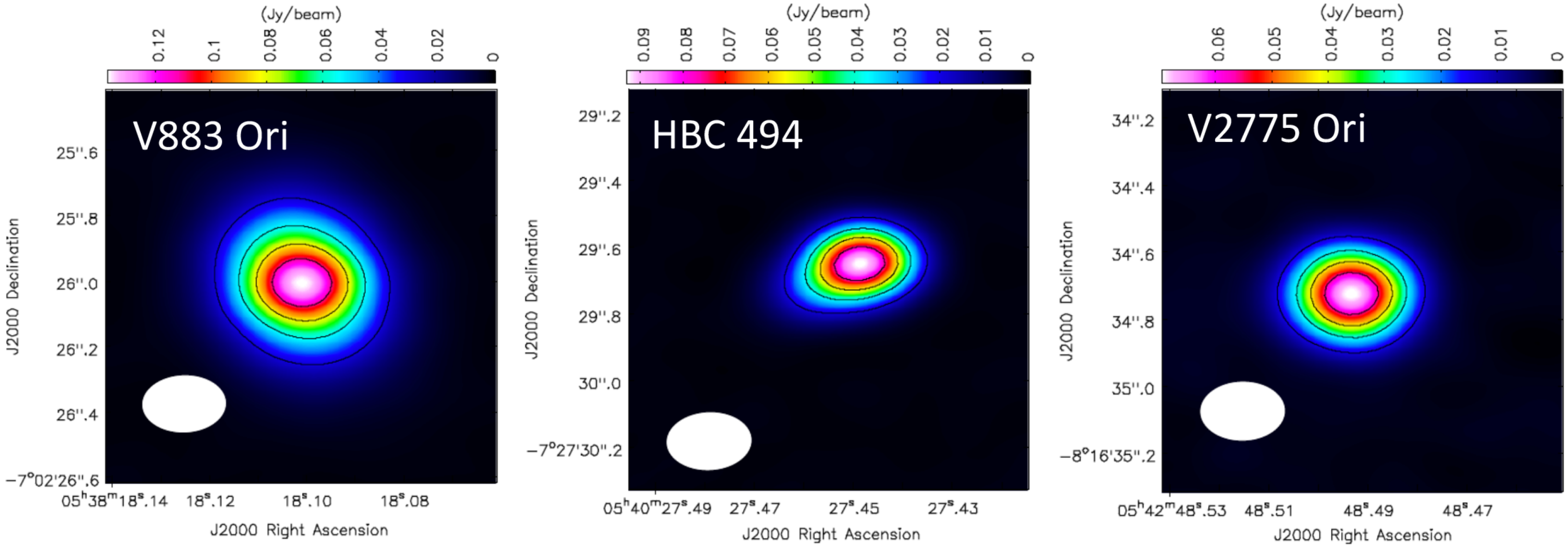
(Liu et al. 2018)

SMA survey of 29 young eruptive stars



- Targets show systematically **higher mm luminosities** than Class II young stellar objects
- Binaries and multiple systems are systematically fainter than the rest of the sample
- Hints for millimeter flux variability

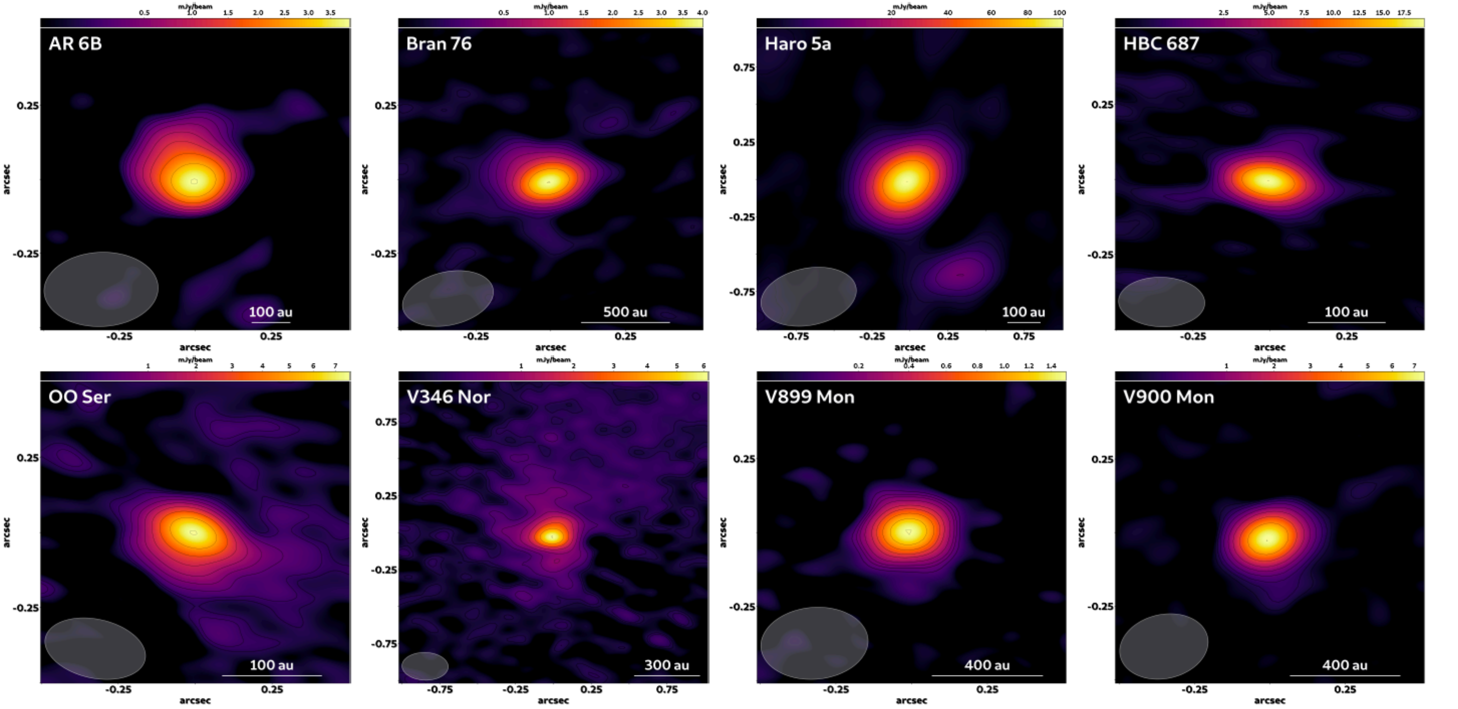
ALMA observations of FUors



(Cieza et al. 2018)

- 3 FUors at 1.3 mm continuum with 0.25″ x 0.17″ beam
- Disk characteristic radii: 21 – 42 au, disk masses: 0.08 – 0.57 $M_\odot$

ALMA survey for a large FUor sample

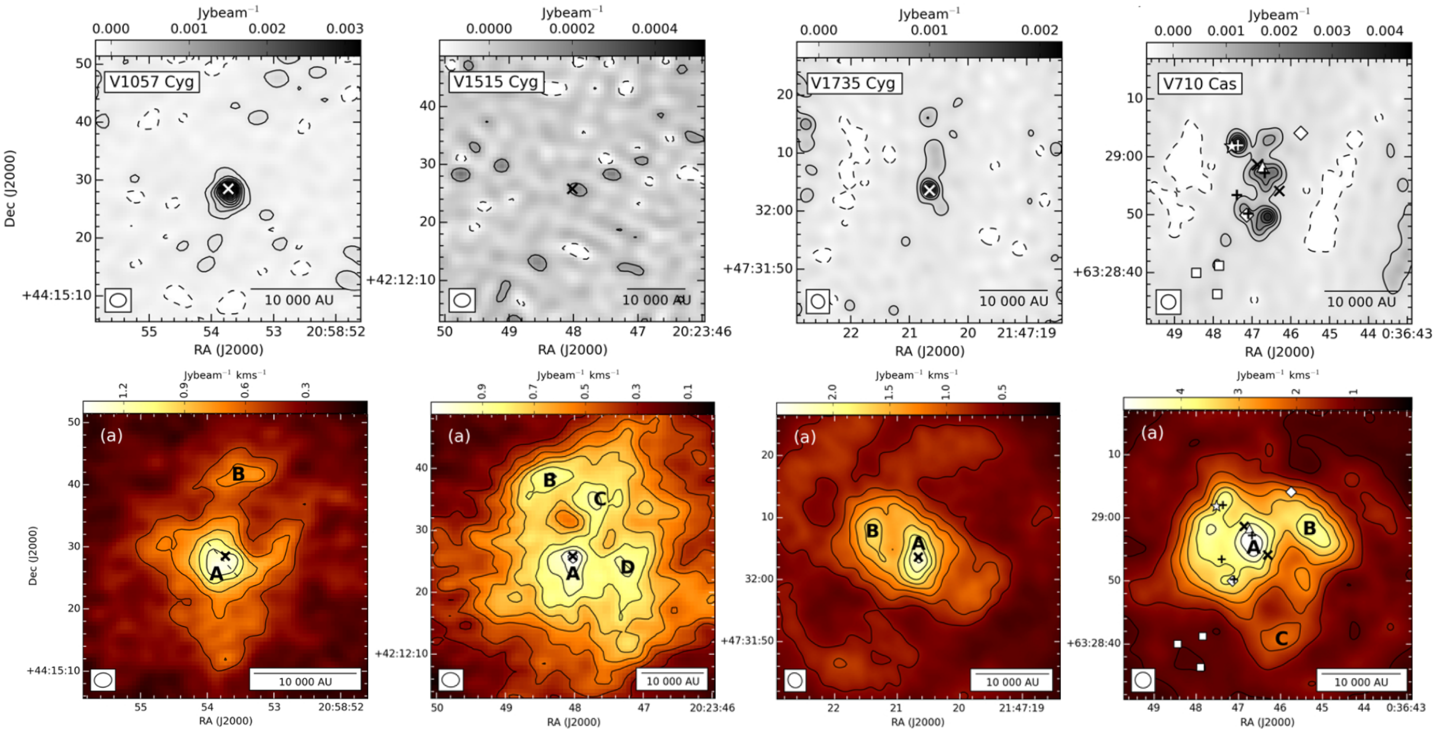


(Kóspál et al. in prep.)

- 10 FUors at 1.3 mm continuum with 0.15″ beam
- Disk characteristic radii: 15 – 75 au, total disk masses: 0.01 – 0.81 $M_\odot$

Comparable to total mass collected in one outburst

IRAM interferometry survey of northern FUors

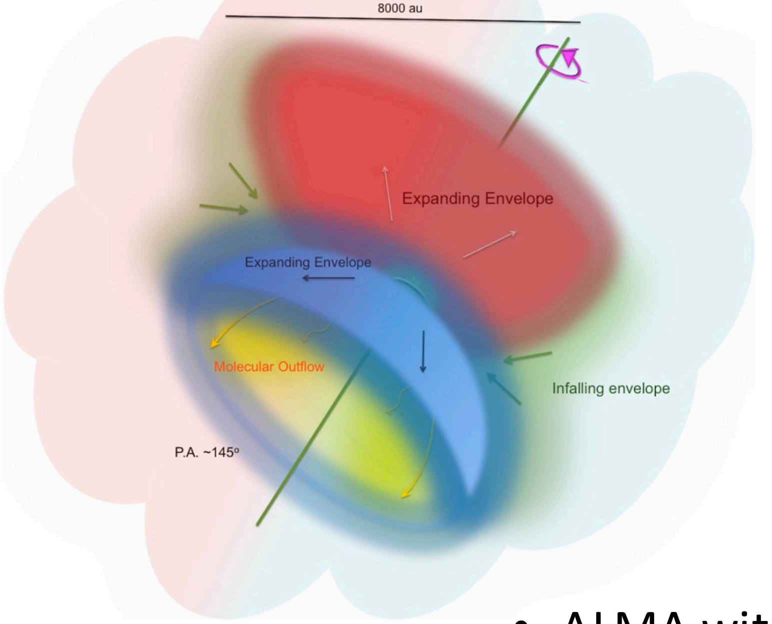


(Fehér et al. 2017)

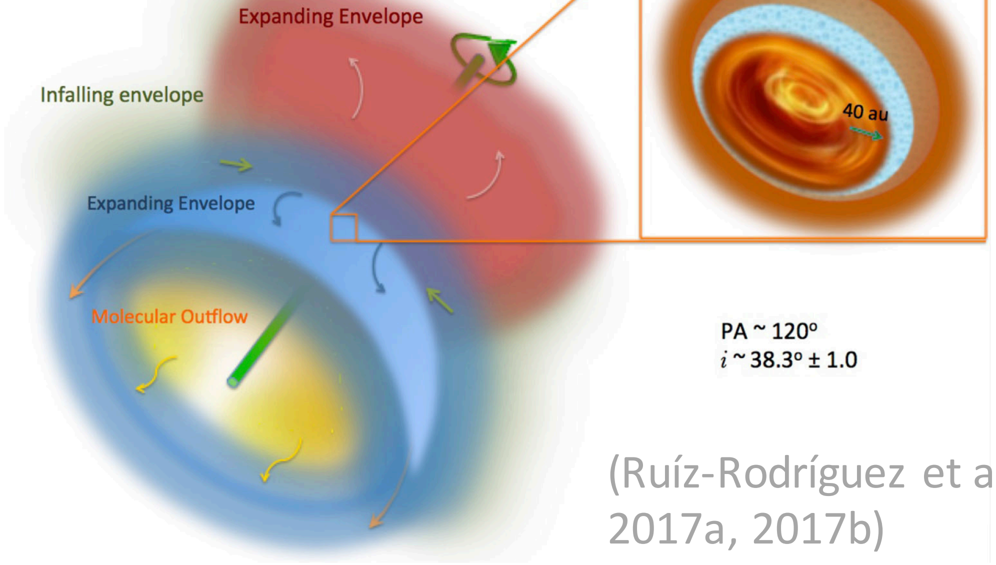
- 7 FUors (too far to the north for ALMA)
- IRAM 30m+PdBI
- 3mm continuum ^{13}CO, $C^{18}O$ J=1–0
- Extended CO emission with clumps **heated** by the central stars

Sub-arcsecond resolution CO line data

HBC 494



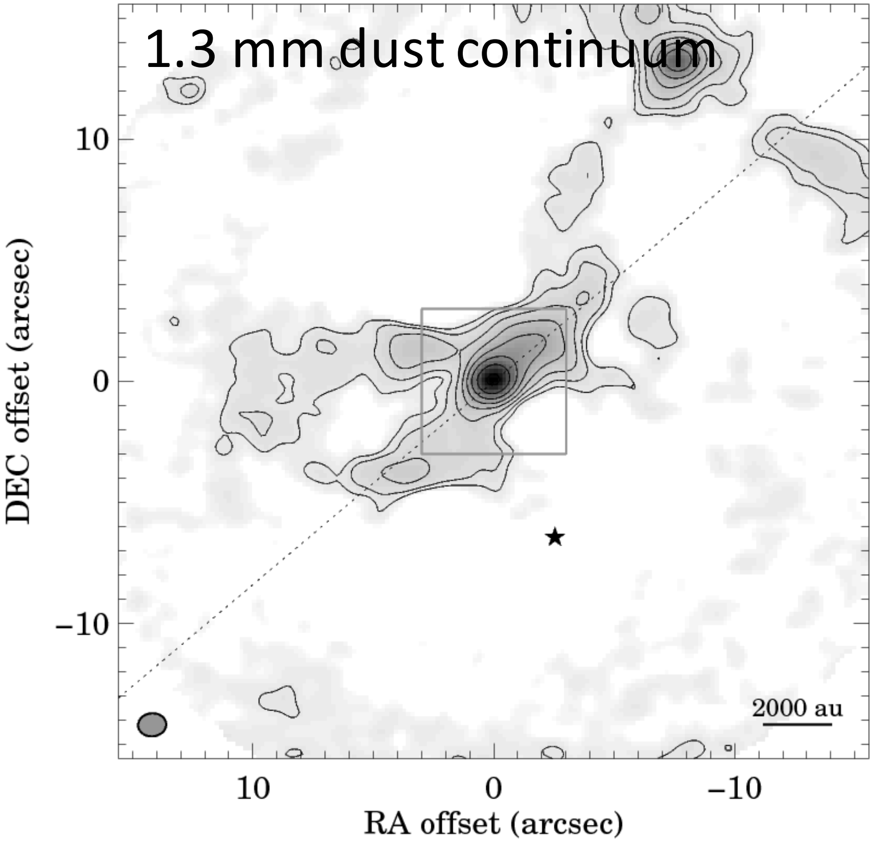
V883 Ori

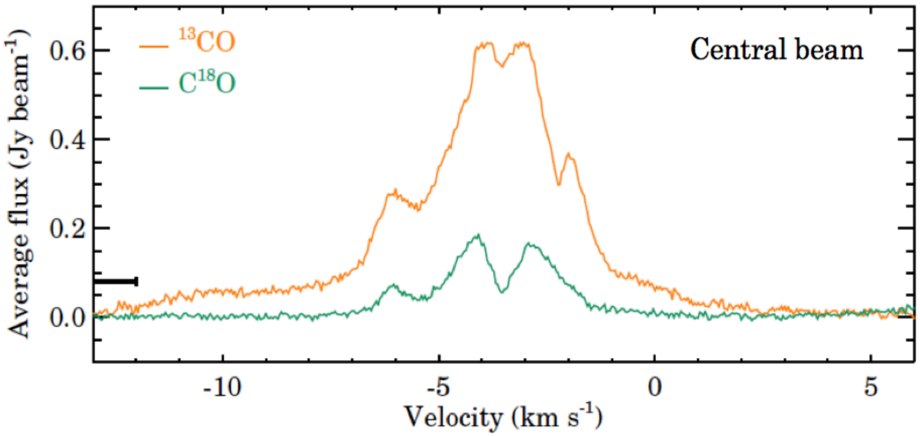


(Ruíz-Rodríguez et al. 2017a, 2017b)

- ALMA with ~0.3″ beam, 0.04 – 0.08 km/s velocity resolution
- Similar structures in both sources with wide, slow outflows

The ALMA view of V346 Nor

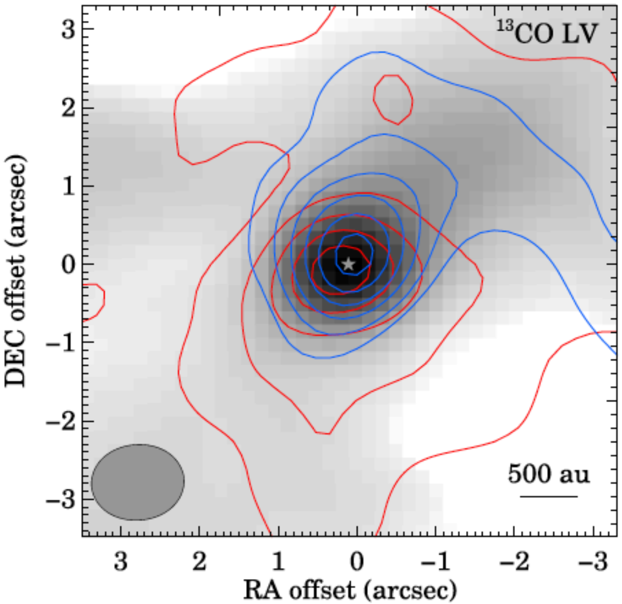


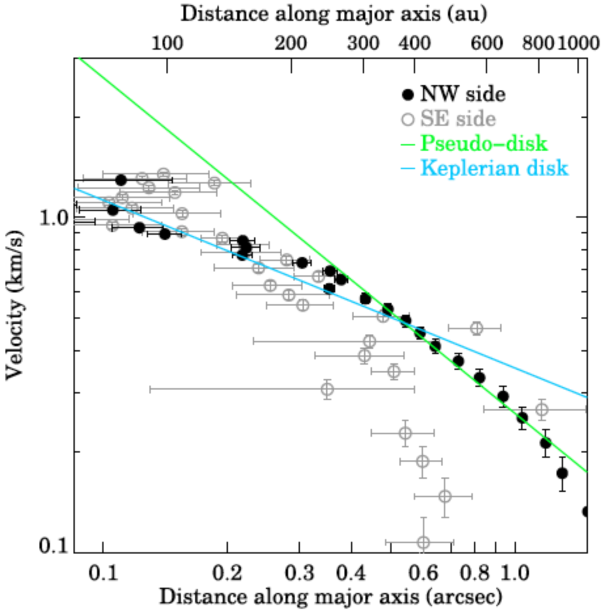


- ~1″ beam
- 0.04 km/s velocity resolution
- Double-peaked line profile indicates **rotation**

(Kóspál et al. 2017)

Accretion – infall mismatch in the V346 Nor system





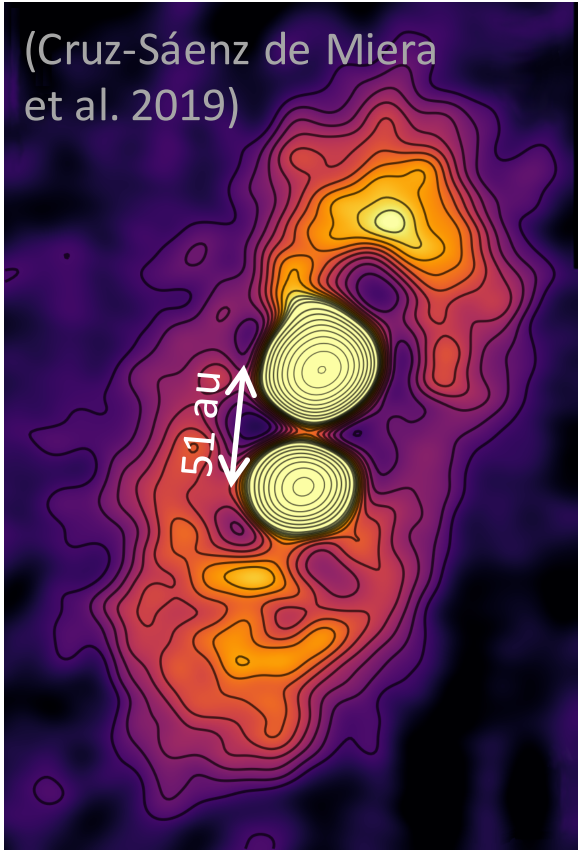
- Within *r* = 350 au: Keplerian disk ($v \sim r^{-0.5}$)
- Between *r* = 350 – 700 au: pseudo-disk ($v \sim r^{-1}$, infall + rotation)

- Infall rate: $\dot{M}_{\rm infall} = 6 \times 10^{-6}\ M_\odot$/yr
- Quiescent accretion rate: $\dot{M}_{\rm acc} < 4 \times 10^{-7}\ M_\odot$/yr

mismatch → **pile-up and accretion bursts**

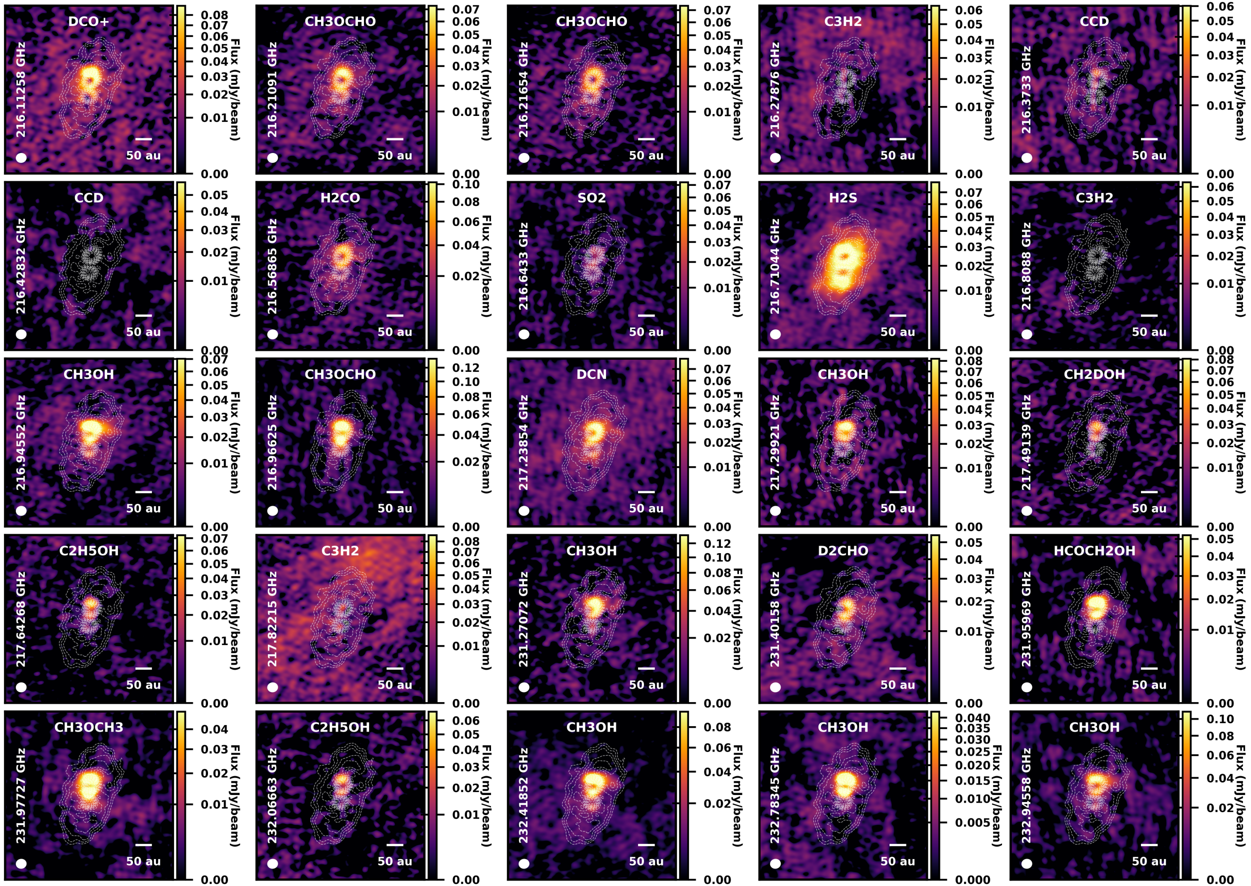
(Kóspál et al. 2017)

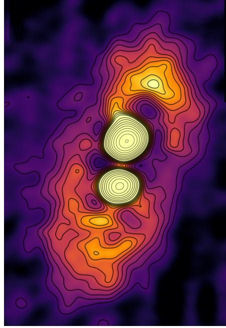
The L1551 IRS 5 binary system



- ALMA 1.3 mm continuum observations of two circumstellar disks and a circumbinary ring

Accidental astrochemisty with ALMA





- L1551 IRS 5
- “Continuum” window is full of lines
- ALMA is a powerful machine for **astrochemistry**
- Deuterium chemistry, methanol chemistry, …

e-poster #713 by Cruz-Sáenz de Miera

Summary

- **Young eruptive stars (FUors, EXors)** are young stars exhibiting powerful accretion-related outbursts
- Eruptions may constitute a so-far largely overlooked but potentially **fundamental** phase of the formation of Sun-like stars
- We want to understand whether the disks of young eruptive stars are **typical or special**
- I showed results from our extensive research program, characterizing young eruptive stars at **different wavelengths and spatial resolutions**
- **Many FUor disks seem to be small and massive**
- **EXor disks are rather typical, some even low-mass**
- More observations and more modeling is needed for a conclusive result