ALMA Science Cases within our Galaxy

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Kyung Hee University

Credit: ALMA (ESO/NAOJ/NRAO)

ALMA Capabilities

- Latitude= -23.029 deg, Longitude = -67.755 deg
  - Targets with $-65^{\circ} <$ Dec. $< +40^{\circ}$
  - Targets with Dec. $> +20^{\circ}$ are subject to significant shadowing
- 54 x 12 m & 12 x 7 m antennae
- baselines up to 16 km
- Receiver bands 3, 4, 5, 6, 7, 8, 9 and 10
  - ($\lambda \sim$ 3.1, 2.1, 1.6, 1.3, 0.87, 0.74, 0.44 and 0.35 mm, respectively)

High Resolution, high Sensitivity, & wide wavelength coverage!!

Table A-1: Angular Resolutions (AR) and Maximum Recoverable Scales (MRS) for the Cycle 5 Array configurations

Config	Lmax	Band	Band 3	Band 4	Band 5	Band 6	Band 7	Band 8	Band 9	Band 10
	Lmin	Freq	100 GHz	150 GHz	183 GHz	230 GHz	345 GHz	460 GHz	650 GHz	870 GHz
7-m Array	45 m	AR	12.5"	8.4"	6.8"	5.4"	3.6"	2.7"	1.9"	1.4"
	9 m	MRS	66.7"	44.5"	36.1"	29.0"	19.3"	14.5"	10.3"	7.7"
C43-1	161 m	AR	3.4"	2.3"	1.8"	1.5"	1.0"	0.74"	0.52"	0.39"
	15 m	MRS	29.0"	19.0"	15.4"	12.4"	8.3"	6.2"	4.4"	3.3"
C43-2	314 m	AR	2.3"	1.5"	1.2"	1.0"	0.67"	0.50"	0.35"	0.26"
	15 m	MRS	22.6"	15.0"	12.2"	9.8"	6.5"	4.9"	3.5"	2.6"
C43-3	500 m	AR	1.4"	0.94"	0.77"	0.62"	0.41"	0.31"	0.22"	0.16"
	15 m	MRS	16.2"	10.8"	8.7"	7.0"	4.7"	3.5"	2.5"	1.9"
C43-4	784 m	AR	0.92"	0.61"	0.50"	0.40"	0.27"	0.20"	0.14"	0.11"
	15 m	MRS	11.2"	7.5"	6.1"	4.9"	3.3"	2.4"	1.7"	1.3"
C43-5	1.4 km	AR	0.54"	0.36"	0.30"	0.24"	0.16"	0.12"	0.084"	0.063"
	15 m	MRS	6.7"	4.5"	3.6"	2.9"	1.9"	1.5"	1.0"	0.77"
C43-6	2.5 km	AR	0.31"	0.20"	N/A	0.13"	0.089"	0.067"	0.047"	0.035"
	15 m	MRS	4.1"	2.7"		1.8"	1.2"	0.89"	0.63"	0.47"
C43-7	3.6 km	AR	0.21"	0.14"	N/A	0.092"	0.061"	0.046"	0.033"	0.024"
	64 m	MRS	2.6"	1.7"		1.1"	0.75"	0.56"	0.40"	0.30"
C43-8	8.5 km	AR	0.096"	0.064"	N/A	0.042"	0.028"	N/A	N/A	N/A
	110 m	MRS	1.4"	0.95"		0.62"	0.41"			

ALMA High Priority Projects:

https://almascience.nrao.edu/observing/highest-pr

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ALMA

Atacama Large Millimeter/submillimeter Array

In search of our Cosmic Origins

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High Priority Projects

Cycle 5

The table below lists ALMA Cycle 5 projects with public metadata, including all Cycle 5 A- and B-graded proposals, any Cycle 5 C-graded proposals with archived observations. The public metadata includes the ALMA Project Code, program title and abstract, investigator names and institutes, the Executive to which the project is assigned (CL=Chile, EA=East Asia, EU=Europe, NA=North America, or OTHER), and the proposal science category (Category 10=Cosmology and the high redshift universe; Category 20=Galaxies and galactic nuclei; Category 31=Interstellar medium, star formation and astrochemistry; Category 41=Circumstellar disks, exoplanets and the solar system; Category 50=Stellar evolution and the Sun).

Clicking on ALMA "Project Code" will spawn an ALMA Science Archive query for the project (if the link returns an empty table, then no archived data exists). Clicking on the "Abstracts" or "CoIs" links will open additional fields in the table with the corresponding metadata.

The metadata for the Grade A Cycle 5 projects are available in a spreadsheet.

Project Code	Title (Abstracts)	PI (COIs)	Exec	Category
2017.1.00001.S	A sub-kpc search for obscured substructures in z ~ 2 star-forming 'main-sequence' galaxies	Wiphu Rujopakarn	EA	10
2017.1.00005.S	The Atomic to Molecular Ratio and Shocks in the Circumnuclear Disk of Centaurus A	Daniel Espada	EA	20
2017.1.00007.S	ODISEA: Ophiuchus DIsk Survey Employing ALMA	Lucas A Cieza	CL	41
2017.1.00009.S	Oscillations and waves contributing to coronal heating on the Sun	Joten Okamoto	EA	50
2017.1.00010.S	Unveiling the Magnetic Field Structures of Super Star Cluster Forming Clump in NGC 5253	Rie E Miura	EA	20
2017.1.00011.S	An ALMA Survey of the dust attenuation in typical star-forming galaxies at z~5	Kristen E K Coppin	EU	10

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ALMA High Priority Projects:

- Category 31:
  - Interstellar medium
  - <u>**Star formation**</u>
  - <u>**Astrochemistry**</u>

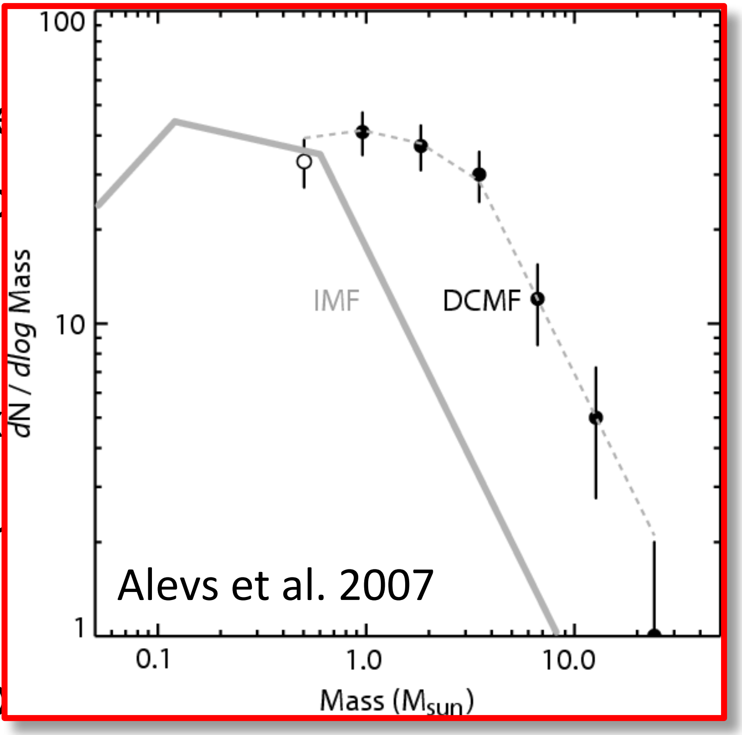
- Category 41
  - <u>**Circumstellar disks**</u>
  - Exoplanets
  - The solar system

Star Formation

- How do stars grow their masses?
  - Massive star formation vs. low mass star formation
  - Episodic accretion (FU Ori objects)
    - traced by ***chemistry***
- Core Mass Function
- The role of Magnetic Field in star formation
- Binary Formation
  - Turbulence fragmentation vs. disk fragmentation
- Grain Growth and Planet Formation
  - **In protostellar or protoplanetary disks**
- ***Complex Organic Molecules***

Core Mass Function

- The IMF is set very early on by the masses of the molecular cores out of which the stars form. The core mass function (CMF), and by consequence the IMF, may depend on the physical and chemical properties of the environment.
- So far, CMFs (and IMFs) have been de (and star clusters) in the solar neighb
- (2017.1.00081.S) PI: Jan Brand
  - in the far-outer reaches of our Galax
- (2017.1.00121.S) PI: Adam Ginsbu
  - in the CMZ in Sgr B2 Deep South
- (2017.1.01355) PI: Frederique Mo
  - In massive proto-clusters in different evolutionary stages

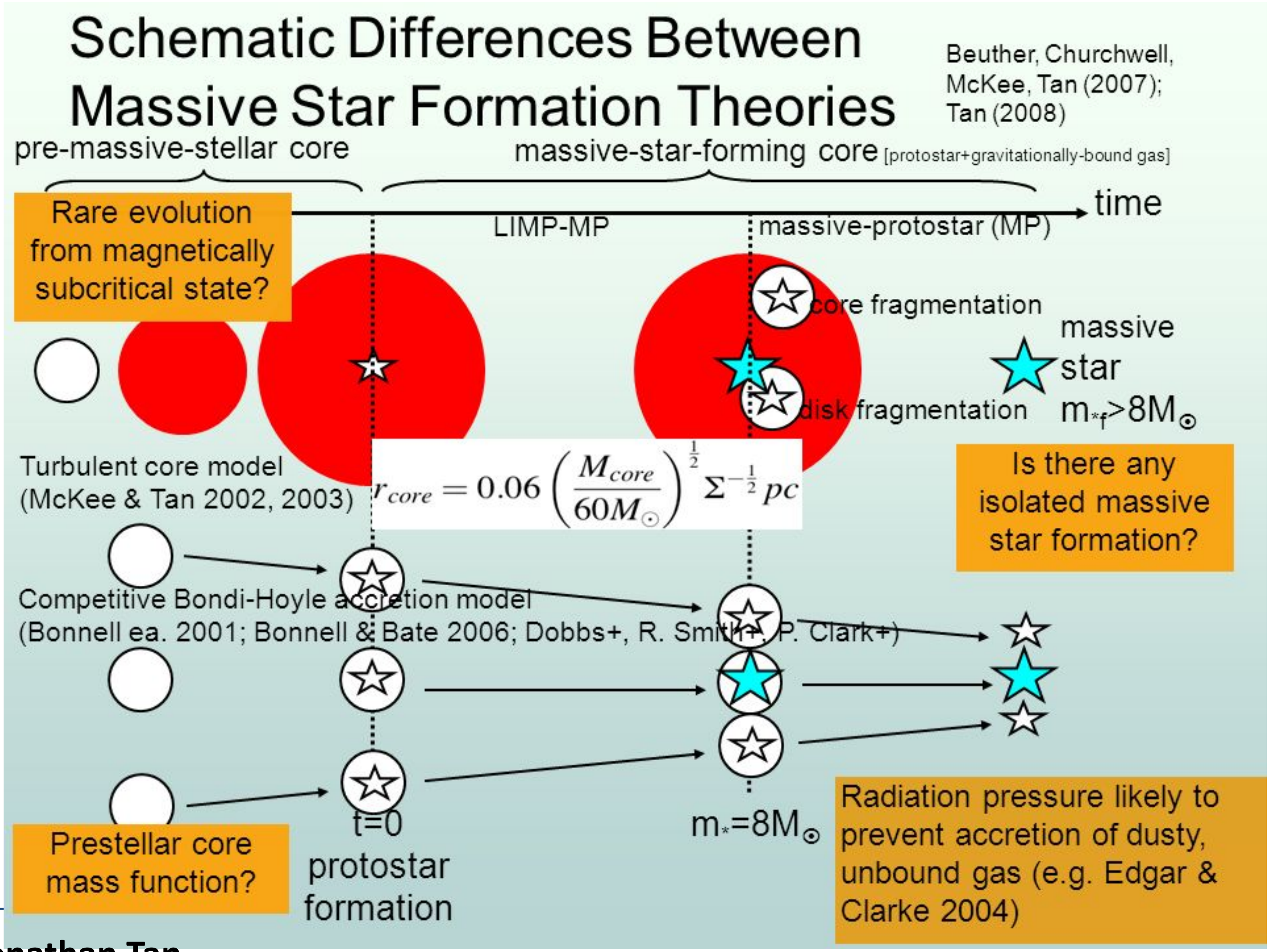


Core Mass Function

- The IMF is set very early on by the masses of the molecular cores out of which the stars form. The core mass function (CMF), and by consequence the IMF, may depend on the physical and chemical properties of the environment.
- So far, CMFs (and IMFs) have been determined in molecular clouds (and star clusters) in the solar neighborhood and the inner Galaxy.

- (2017.1.00081.S) PI: Jan Brand
  - in the far-outer reaches of our Galaxy (R=16 kpc)
- (2017.1.00121.S) PI: Adam Ginsburg
  - in the CMZ in Sgr B2 Deep South
- (2017.1.01355) PI: Frederique Motte
  - In massive proto-clusters in different evolutionary stages

Massive Star Formation



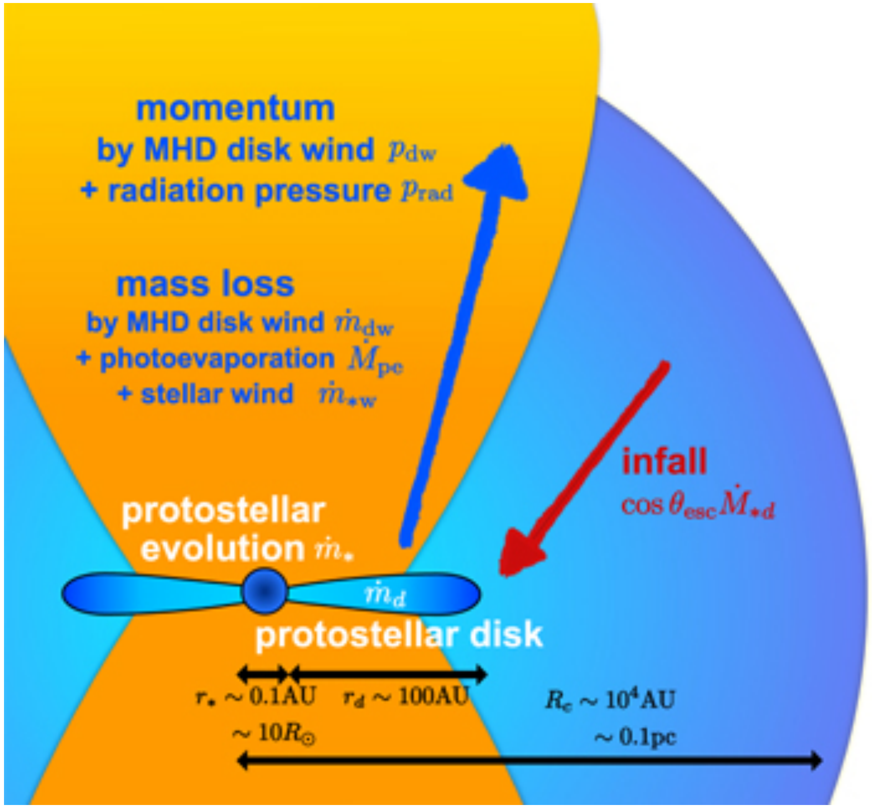
Credit: Jonathan Tan

Massive Star Formation

- **"turbulent core accretion" (Mckee & Tan 2002) vs. "competitive accretion" (Bonnell & Bate 2006)**
- (2017.1.00077.S) PI: Leonardo Bronfman
  - two massive young sources located at the edges of RCW 120
- (2017.1.00226.S) PI: Fabien Louvet
  - in the W43 complex
- (2017.1.00545.S) PI: Tie Liu
  - In 11 protoclusters
- (2017.1.01356.S) PI: Yu-Nung Su
  - In W52e2/e8
- (2017.1.01552.S) PI: Yu Cheng
  - In G286.21+0.17

Core Accretion Model

- Low mass star formation mechanism
- ***Infall*** from envelope to disk & ***accretion*** from disk to protostar
- Protostellar ***disk***
- ***Jets/Outflows***



Tanaka et al. 2017

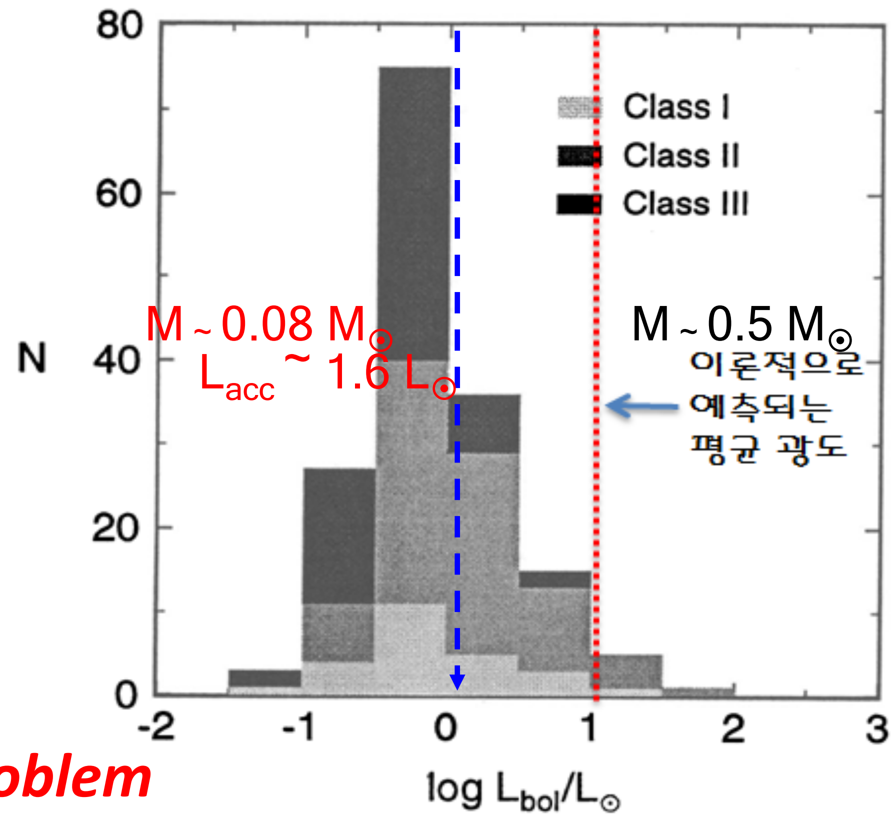
Low Mass Star Formation

- **Accretion Mechanism**
  - **"Continuous accretion" vs. "Episodic accretion"**
  - Continuous Accretion Model (Shu 1977; Shu, Adams & Lizano, 1987)
  - Lowest accretion luminosity of a protostar in the standard model

$$L_{acc} = \frac{GM\dot{M}_{acc}}{R}$$

$$= 1.6 L_{sun}$$

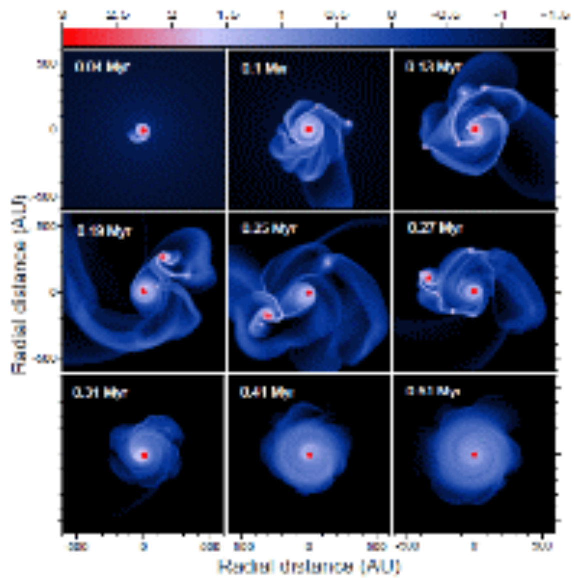
$(\dot{M}_{acc} \sim 2\times10^{-6} M_{sun} yr^{-1}, M = 0.08 M_{sun}, R \sim 3R_{sun})$

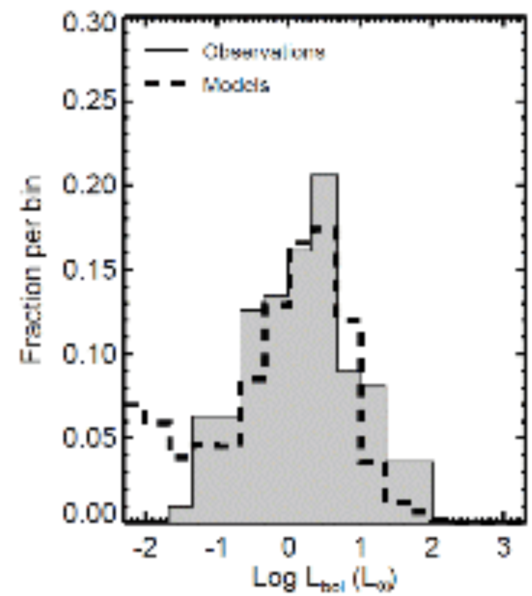


Luminosity Problem

Episodic Accretion Model

- Mass accretion occurs in episodic bursts!
- Two phases (burst & quiescent)
- Extreme ends:
  - ✓ FU Orionis-type objects(FUors) : outburst phase
  - ✓ VeLLOs : quiescent phase





Dunham & Vorobyov (2012)

Burst Accretion: FUors

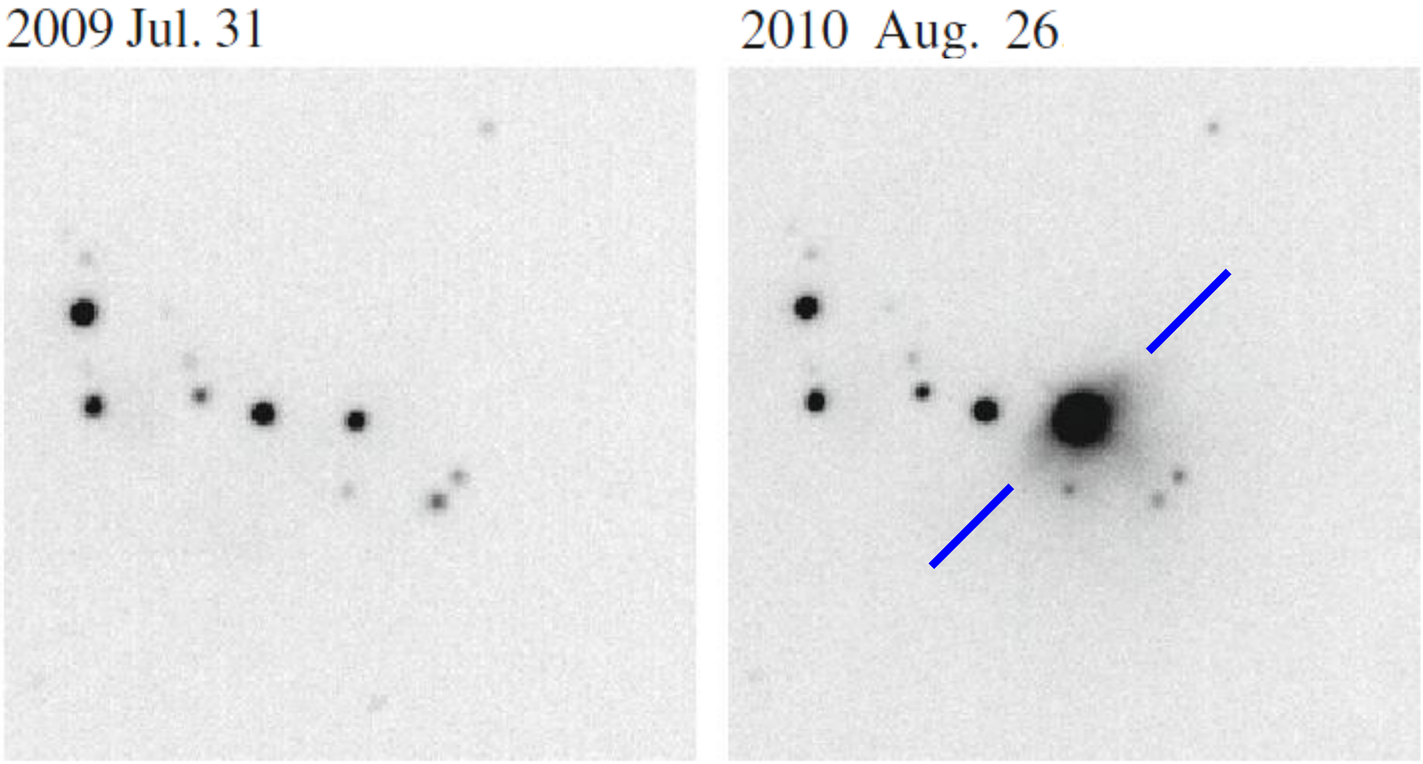
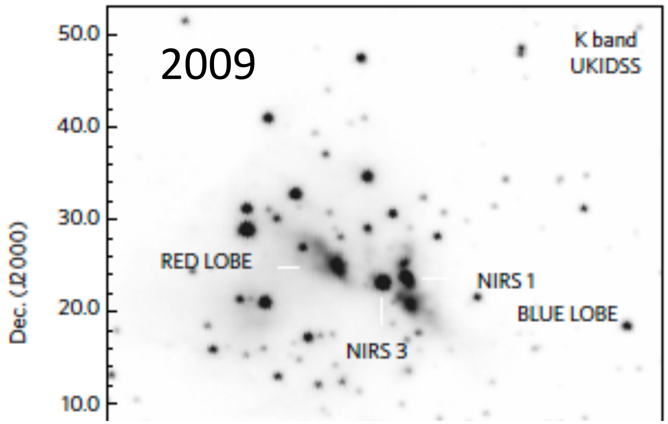
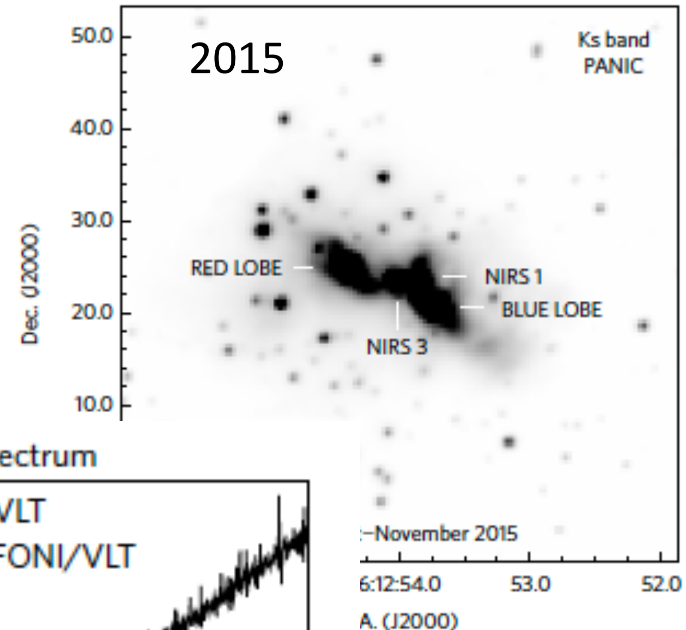
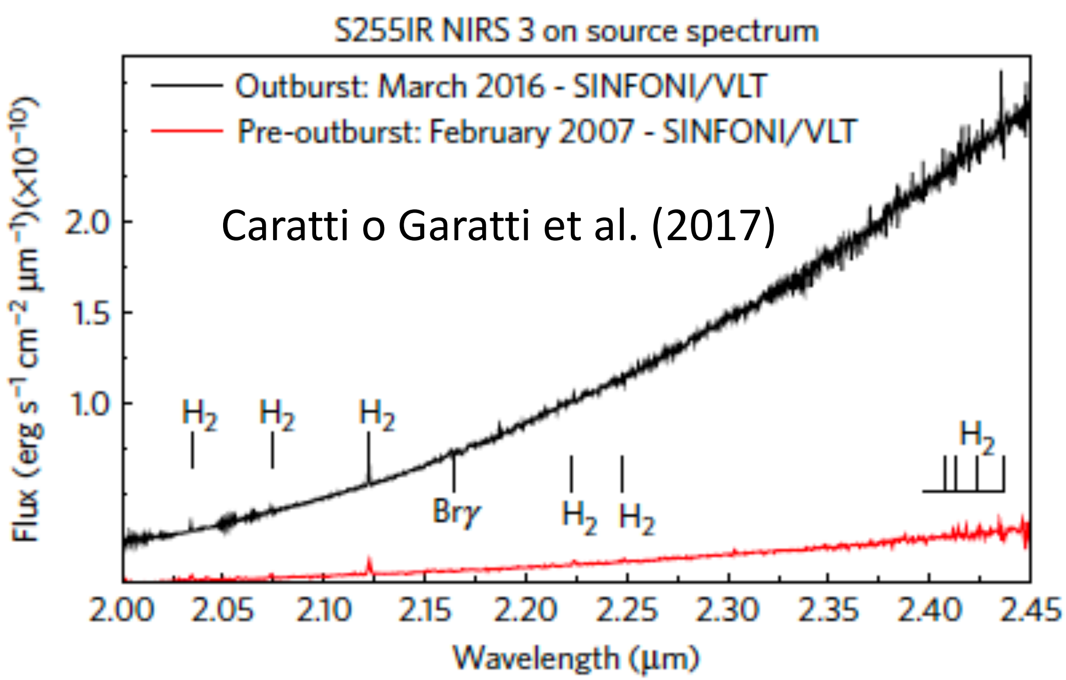


Fig. 2. CCD frames of HBC 722 obtained with the Skinakas Observatory 1.3-m RC telescope through a *R* filter. *Left*: on 2009 Jul. 31. *Right*: on 2010 Aug. 26. The appearance of small reflection nebula around the star is observed on the second frame.

Disk-mediated accretion burst in a high-mass young stellar object (S225IR NIRS 3)

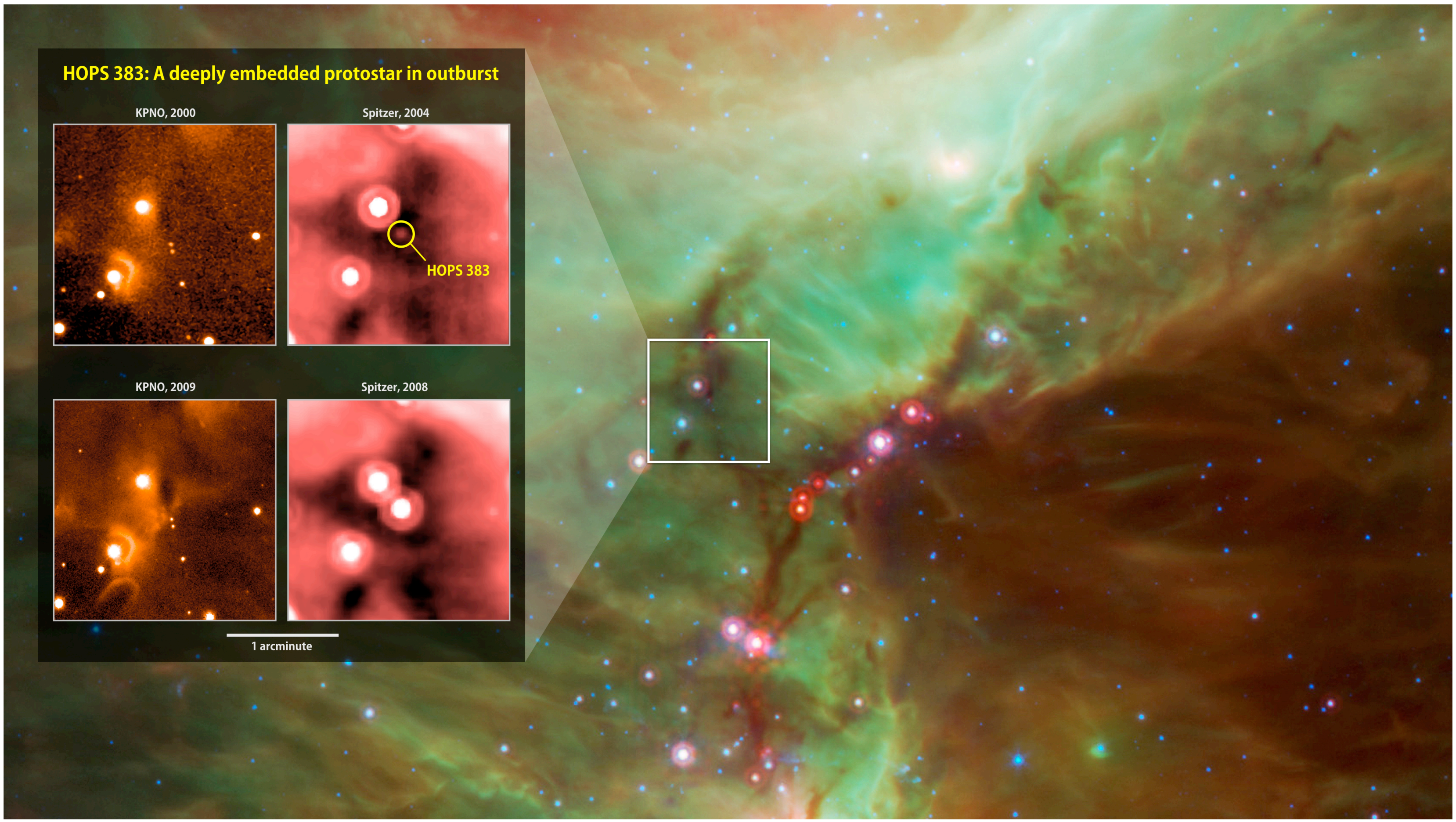




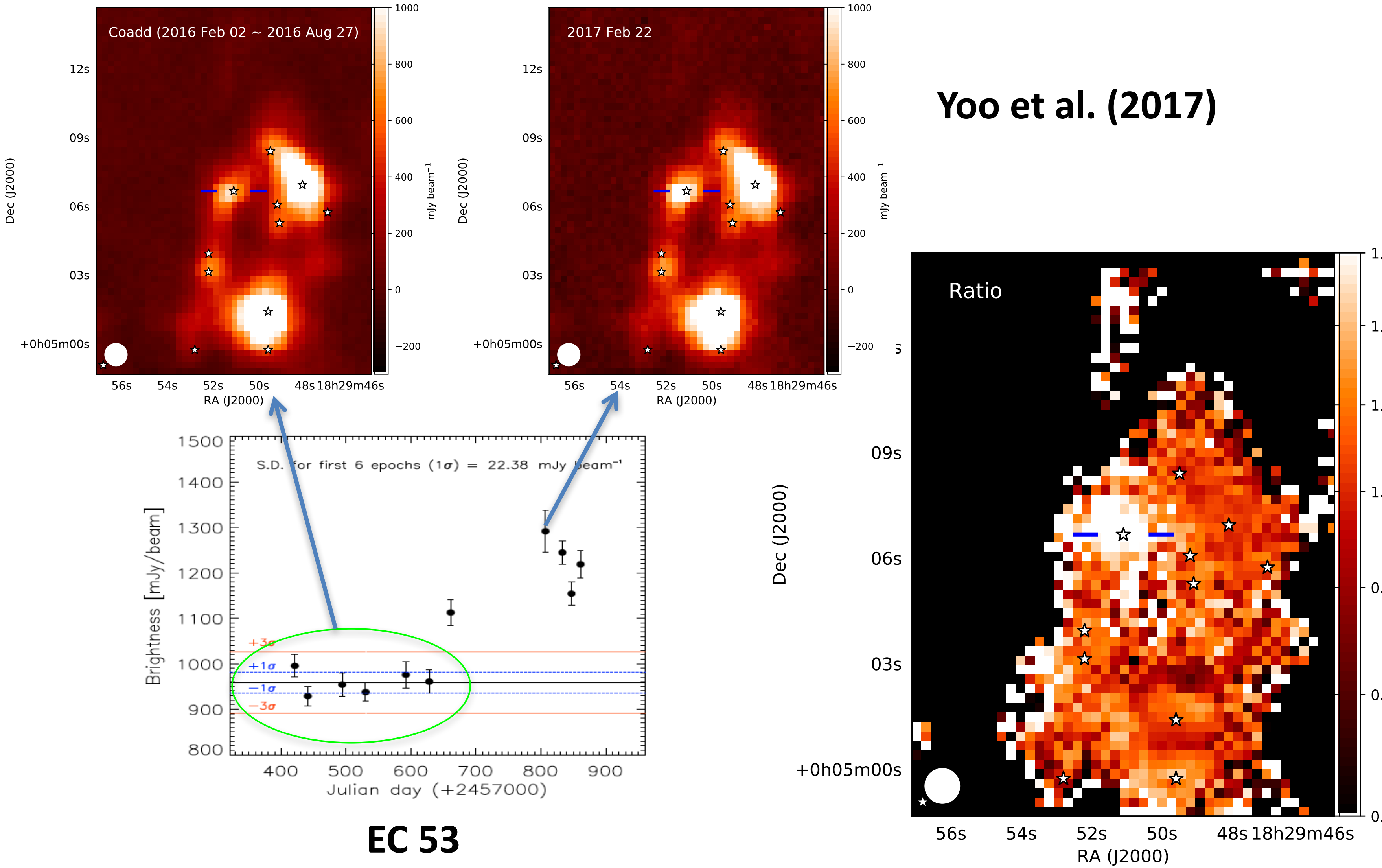


Follow-up ALMA observations: Cycle 4 project 2015.1.00500.S (Zinchenko et al. 2017, 2018)

Outburst in a protostar HOPS 383



A burst accretion detected at submm



Yoo et al. (2017)

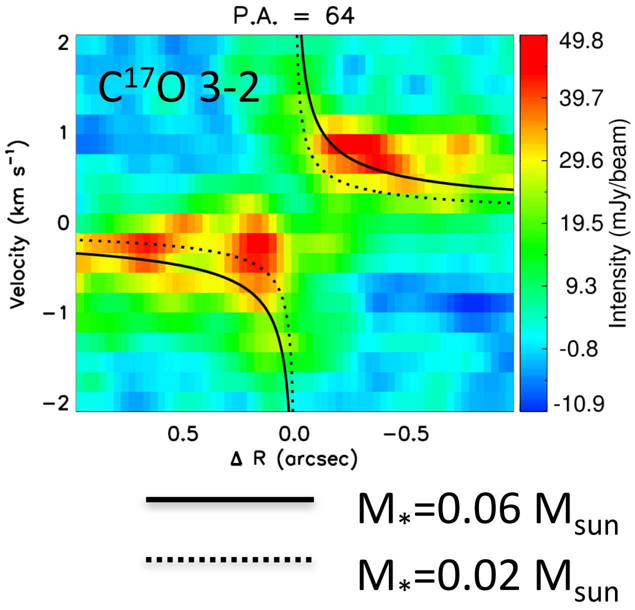
EC 53

ALMA observation of EC 53

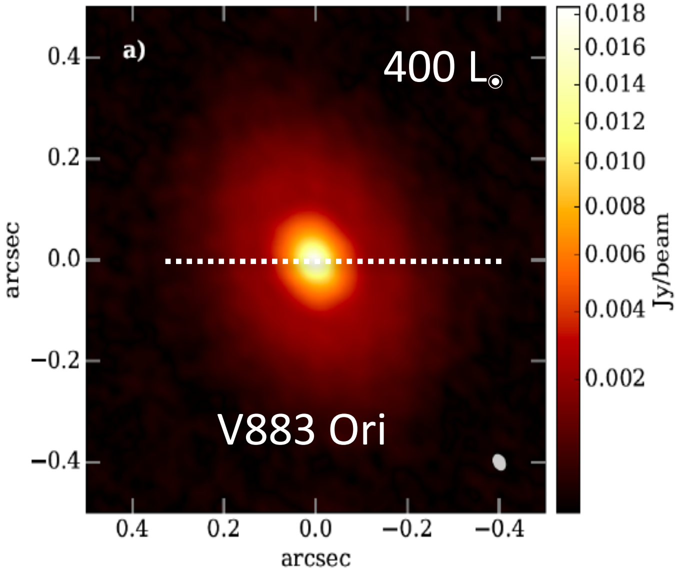
- 2016.01304.T (PI: J.-E. Lee)

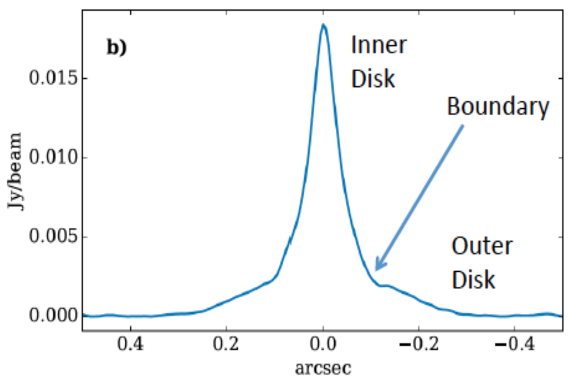
  THE EFFECTS OF BURST ACCRETION ON PHYSICAL AND CHEMICAL PROPERTIES OF PROTOPLANETARY DISKS Observation date: 21 May, 2017

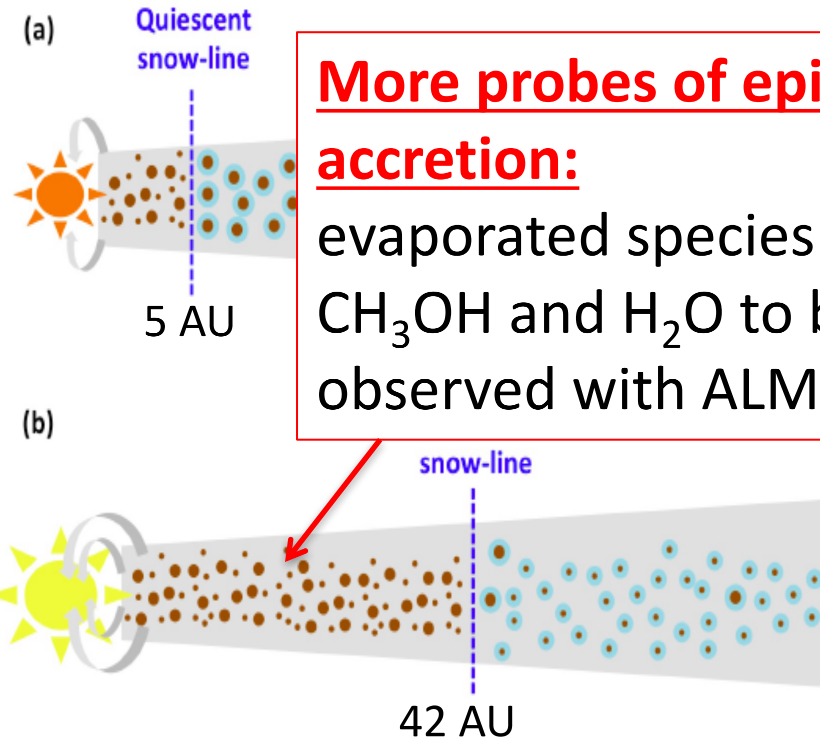
  – Baseline : 11.5m ~ 1.1 km (41 antennas)
  – Spectral Setup : (velocity resolution ~0.22 km/s)
    - $H^{13}CO^+$ J = 4-3
    - CCH N=4-3, J=7/2-5/2 F=4-3 (F=3-2)
    - $C^{17}O$ J= 3-2
    - CH_3OH 70 -60



ALMA for Episodic accretion





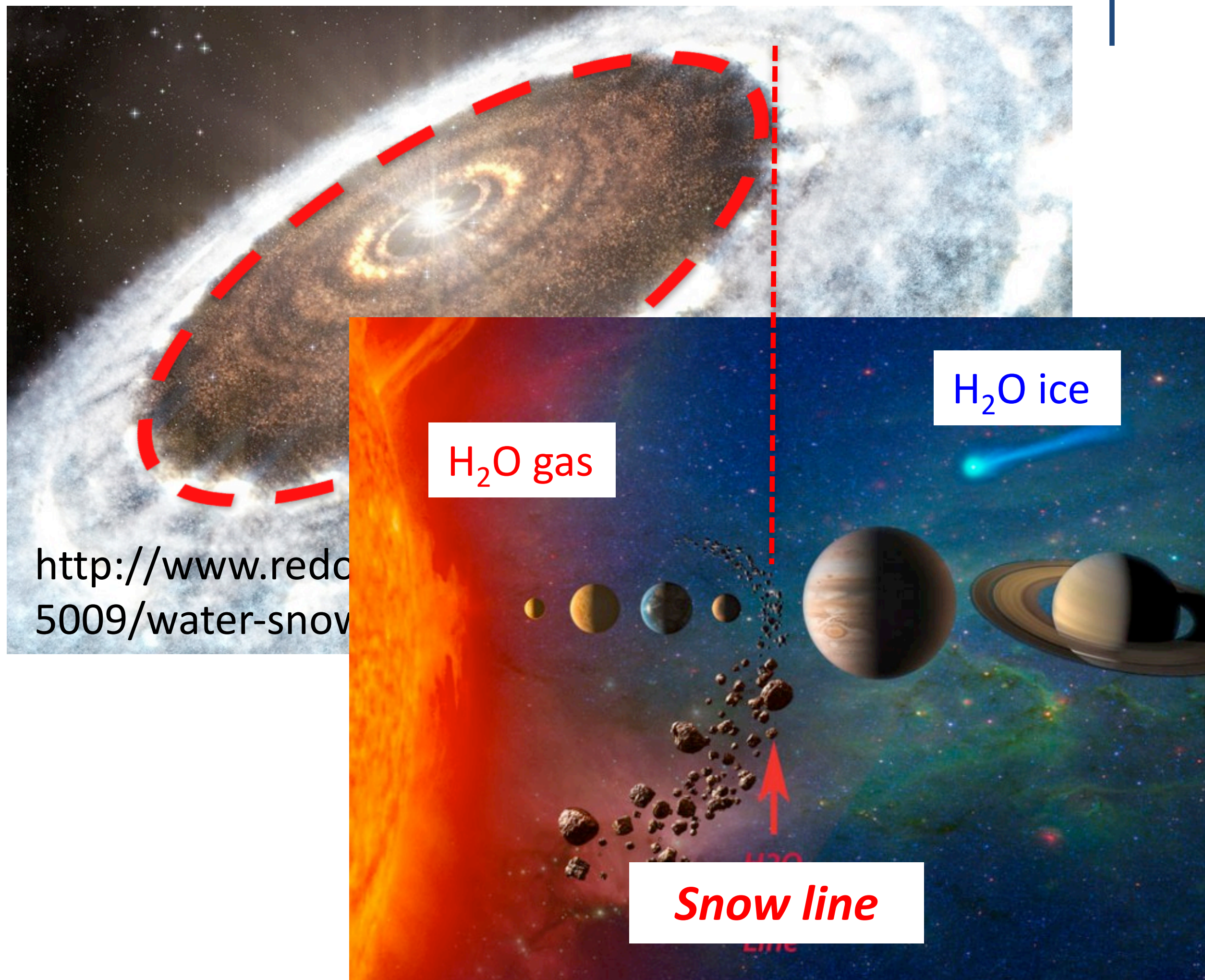


More probes of episodic accretion:
evaporated species such as CH_3OH and H_2O to be observed with ALMA

Cieza et al. (2016)
the ALMA results with ***0.03”*** resolution at 218 GHz & 232.6 GHz

Snowline & Planet Formation

Snow line (T=100 K) divides the protoplanetary disk into terrestrial planet forming zone and Jovian planet forming zone.



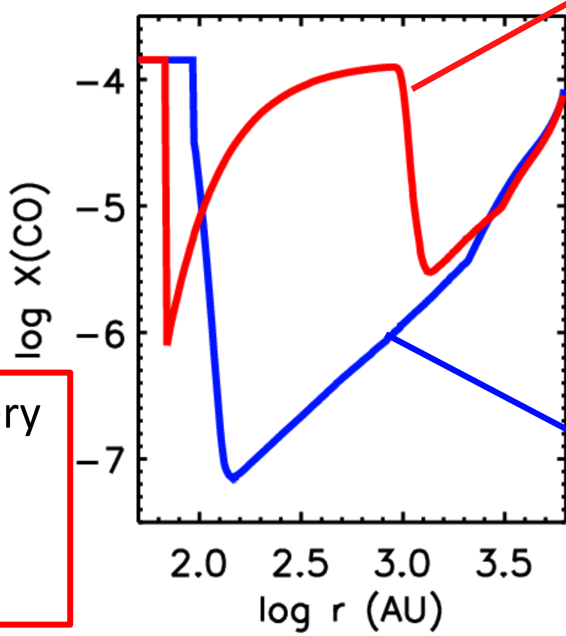
Credit: NASA

Chemical fingerprint of Episodic Accretion

- Episodic accretion process heats up the surrounding material during a burst accretion, but it cools down spontaneously right after the bust accretion stops.
- Chemistry changes responding to the variation of physical conditions with a much longer timescale, keeping the memory of the hot moment even long after the burst accretion ends.
- Therefore, chemical distribution can be used as a fingerprint of episodic accretion.

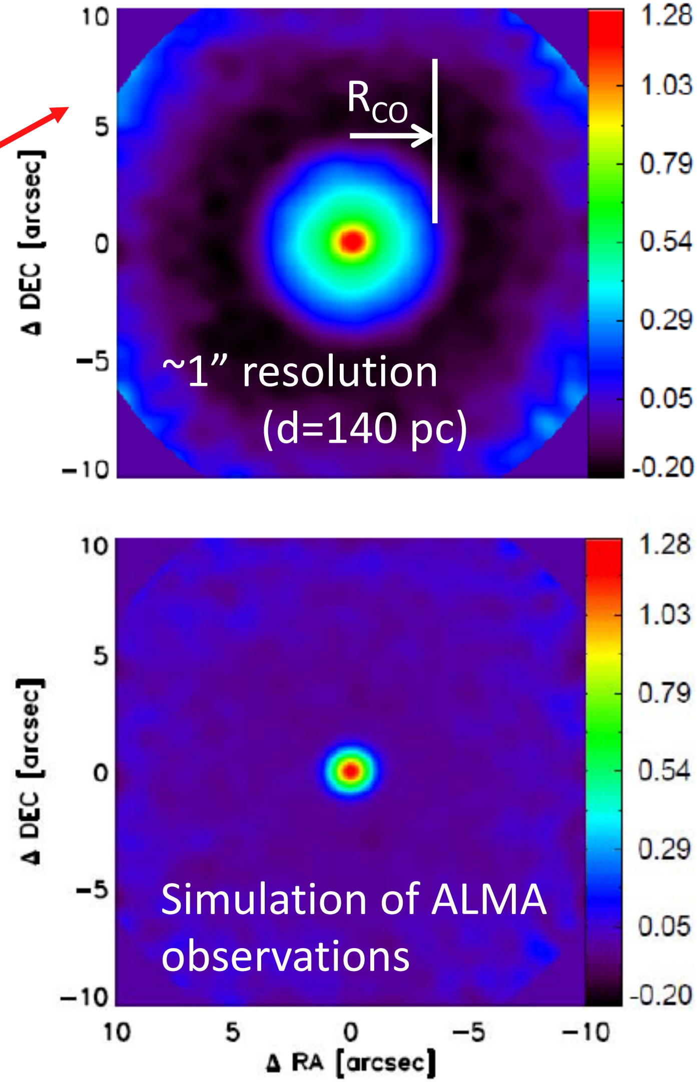
Chemical fingerprint of episodic accretion

Episodic Accretion Model
High abundance of gaseous CO because of previous bursts

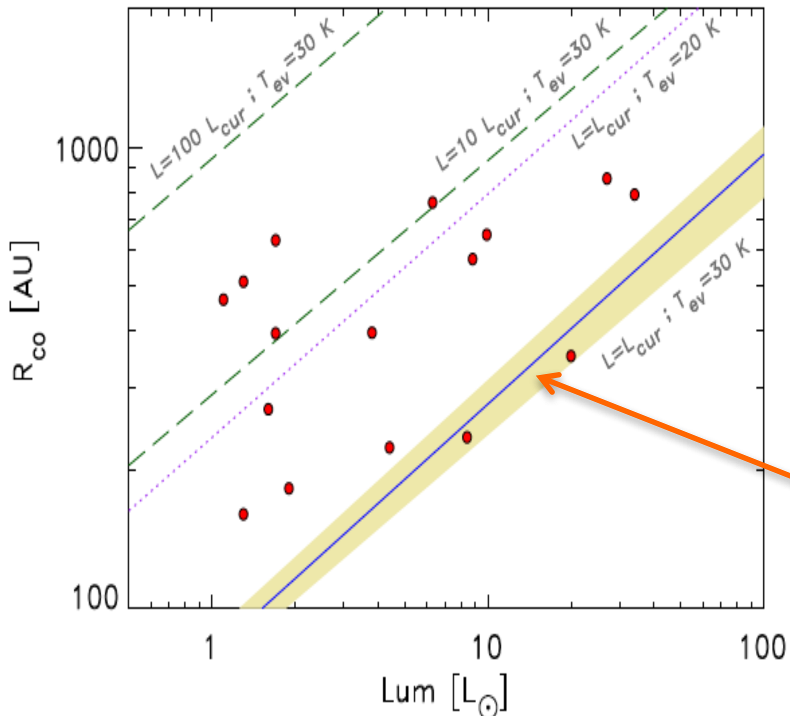


A model for a very low luminosity source
Lee et al. (2007)

Continuous Accretion Model
what expected from the current low luminosity



Chemical fingerprint of episodic accretion



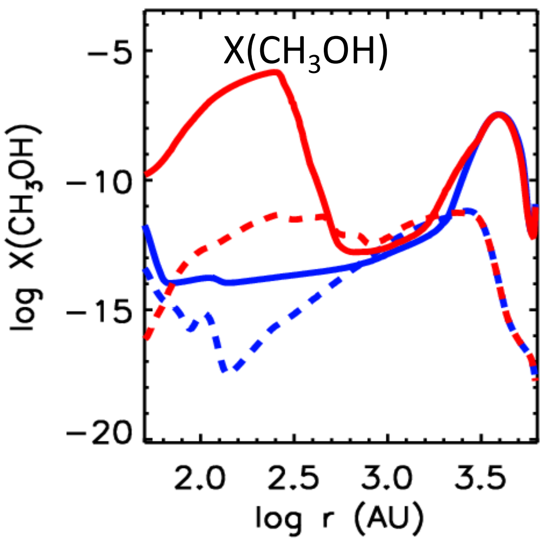
Jorgensen et al. (2015)

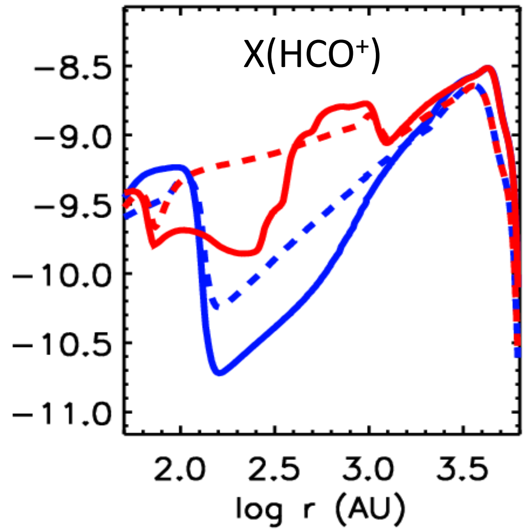
SMA $C^{18}O$ J=2-1 observations of 16 embedded protostars indicate that the radii of CO emission regions are bigger than <u>what expected from their current luminosities</u>.

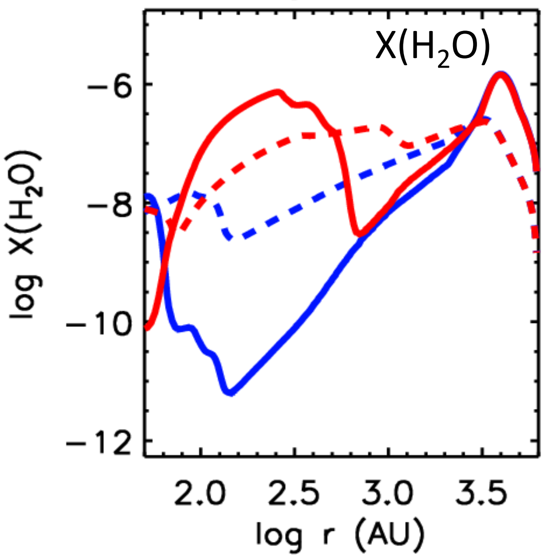
Evidence of burst accretions!!!

See **Hesieh et al. (2018)** for ALMA results (***Cycle 3 project 2015.1.01576.S***)

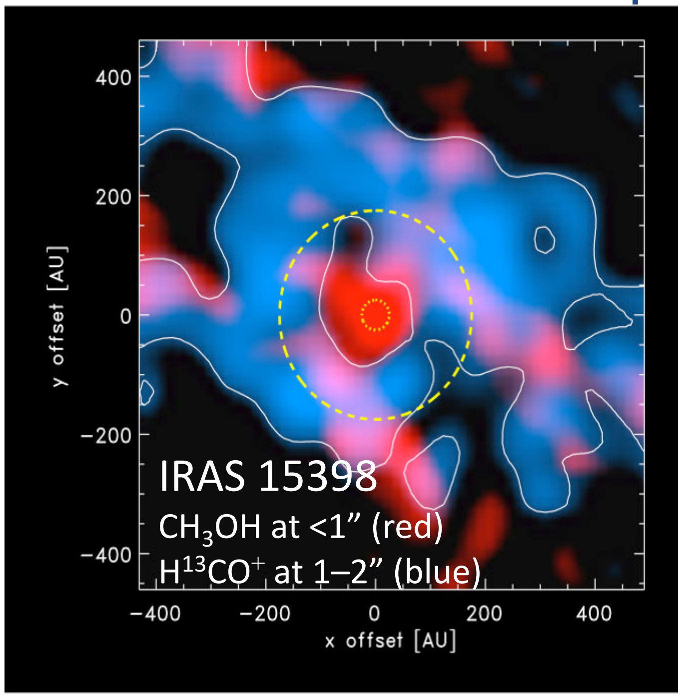
ALMA for Episodic accretion







Lee et al. in prep.



Jorgensen et al. (2013)

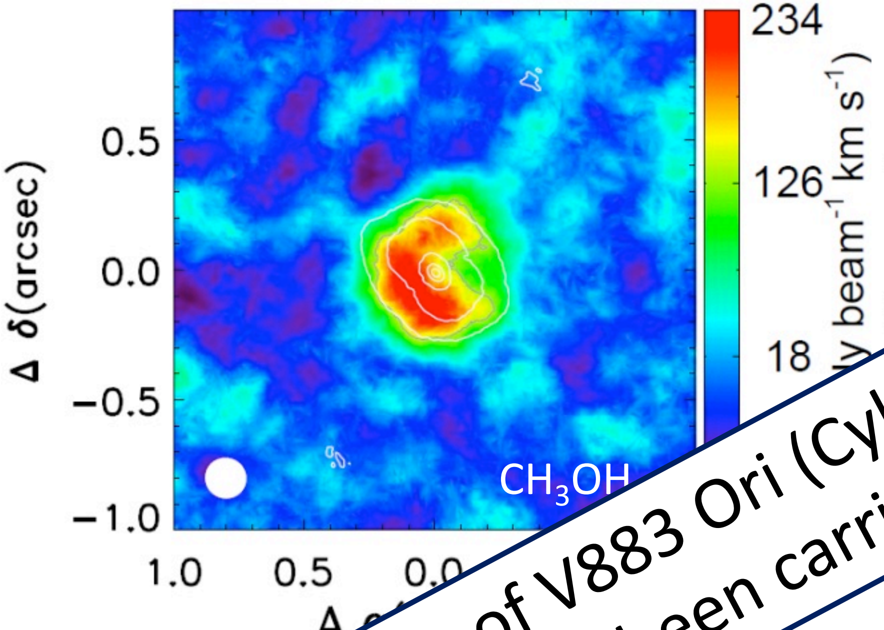
Surface chemistry included

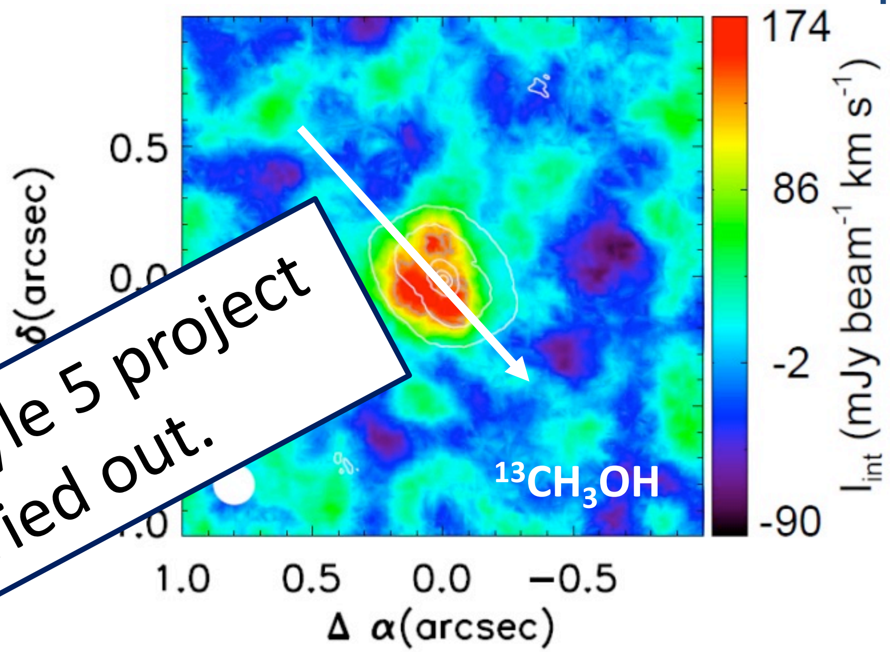
Only gas chemistry considered

Episodic accretion

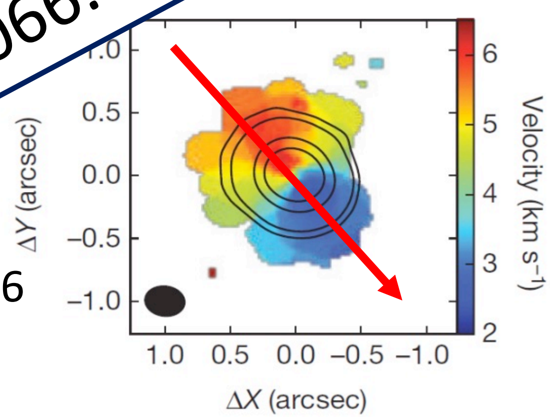
Continuous accretion

ALMA observation of V883 Ori (2016.1.00728.S)

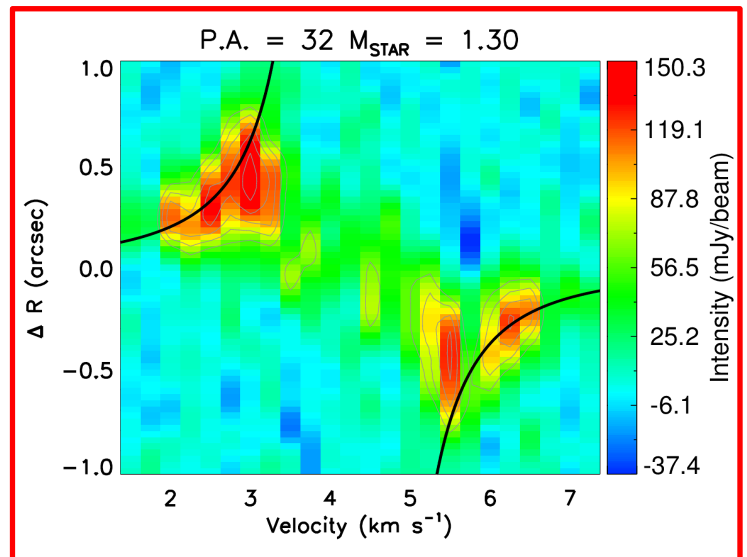




The observation of V883 Ori (Cyle 5 project 2017.1.01066.T) has been carried out.



Cieza et al. 2016
C^{18}O 2-1



Complex Organic Molecules

THE ALMA **PROTOSTELLAR INTERFEROMETRIC LINE SURVEY (PILS)**

Exploring the origin of complex organic molecules in star forming regions

ABOUT PILS

Welcome to the website of the ALMA Protostellar Interferometric Line Survey (PILS). The aim of PILS is to investigate the origin of complex organic molecules seen toward nearby star forming regions. PILS consists of an unbiased line survey of the protostellar binary IRAS 16293-2422 using ALMA. The PILS data cover the full atmospheric window at 0.8 mm (the spectral window from 329 to 363 GHz) with a spectral resolution of 0.2 km/s and full imaging at 0.5 arcsecond angular resolution (60 AU).

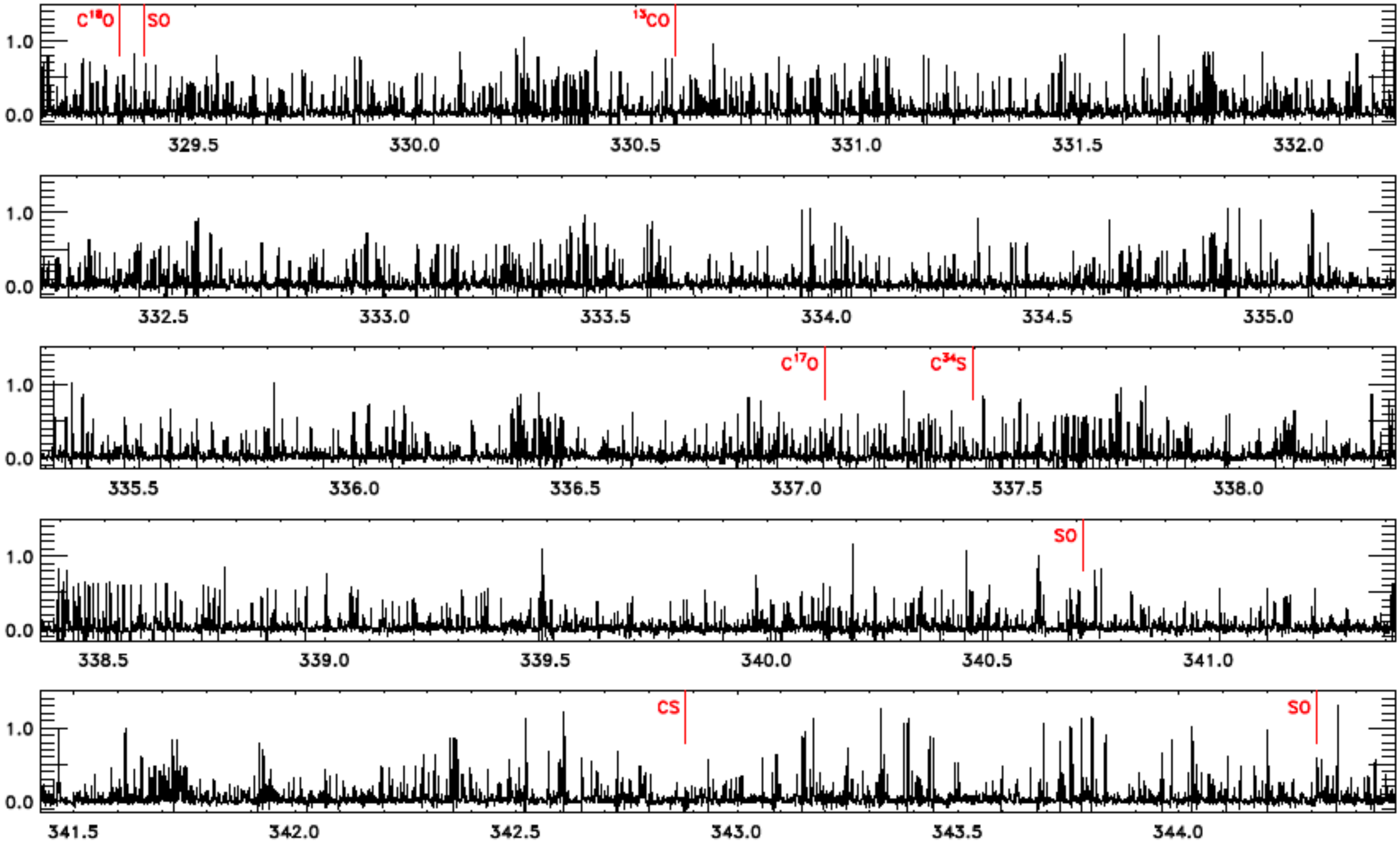
TEAM

The members of the PILS team are Jes Jørgensen (PI), Matthijs van der Wiel, Audrey Coutens, Julie Lykke, Holger Müller, Ewine van Dishoeck, Hannah Calcutt, Per Bjerkeli, Tyler Bourke, Maria Drozdovskaya, Edith Fayolle, Rob Garrod, Steffen Jacobsen, Niels Ligterink, Karin Öberg, Magnus Persson, Susanne Wampfler, Nadia Murillo, Gwendoline Stephan, Sebastien Manigand & Eric Willis

PRESS-RELEASES

3. **"ALMA and Rosetta Detect Freon-40 in Space"**
   PILS detection of methyl chloride toward IRAS 16293 and comet 67P from the Rosetta mission's ROSINA instrument.
2. **"ALMA Finds Ingredient of Life Around Infant Sun-like Stars"**
   Detection of methyl isocyanate on Solar System scales around low-mass protostar from PILS
1. **"Sweet result from ALMA: Building blocks of life found around young star"**
   Historic detection of glycolaldehyde using ALMA Science Verification data (precursor to PILS)

PILS



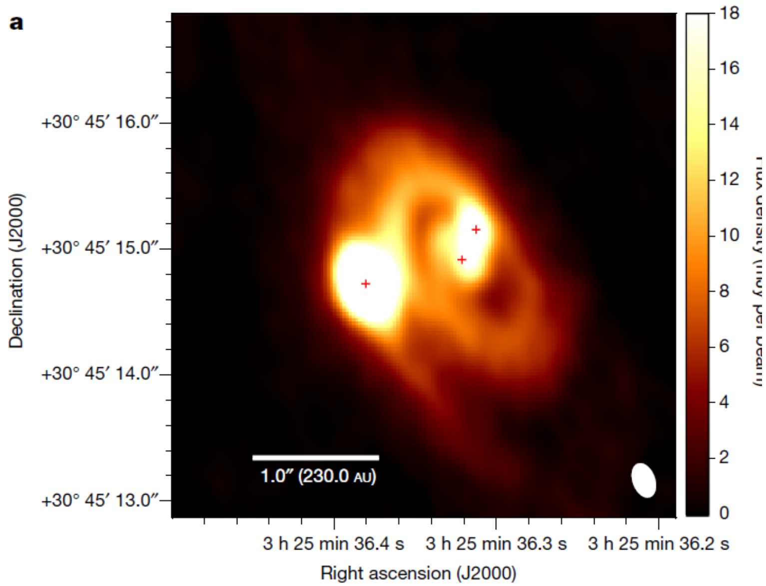
C18O
SO
13CO
1.0
0.0
329.5
330.0
330.5
331.0
331.5
332.0
1.0
0.0
332.5
333.0
333.5
334.0
334.5
335.0
C17O
C34S
1.0
0.0
335.5
336.0
336.5
337.0
337.5
338.0
SO
1.0
0.0
338.5
339.0
339.5
340.0
340.5
341.0
CS
SO
1.0
0.0
341.5
342.0
342.5
343.0
343.5
344.0

Binary Formation

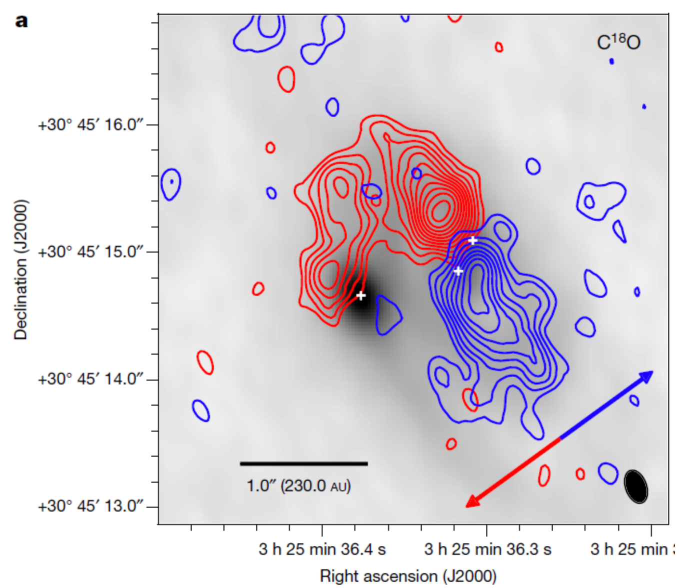
- About half of stars reside in binary or multiple systems (Lada 2006; Duchene & Kraus 2013).
- Binaries form early in star formation.
- Two leading mechanisms of binary formation are:
  - turbulent fragmentation ➔ wide binaries, misaligned stellar spins (Offner et al. 2010, 2016)
  - disk fragmentation ➔ close binaries, aligned stellar spins (Kratter et al. 2010)
- Binaries evolve with time!
  - Close binaries can evolve to wide systems through dynamical processes such as three-body interactions or interactions with cluster members (Marks & Kroupa 2012)
  - Wide binaries can evolve to close binaries through migration (Offner et al. 2010; Bate 2012).

Disk Fragmentation

L1448 IRS 3B



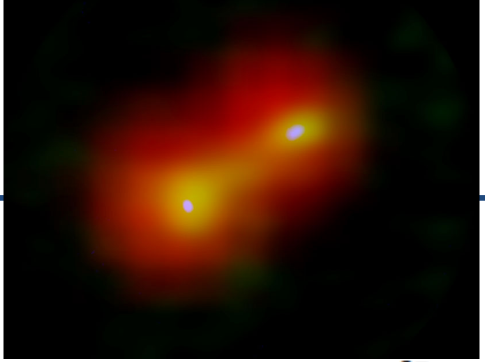
1.3 mm continuum

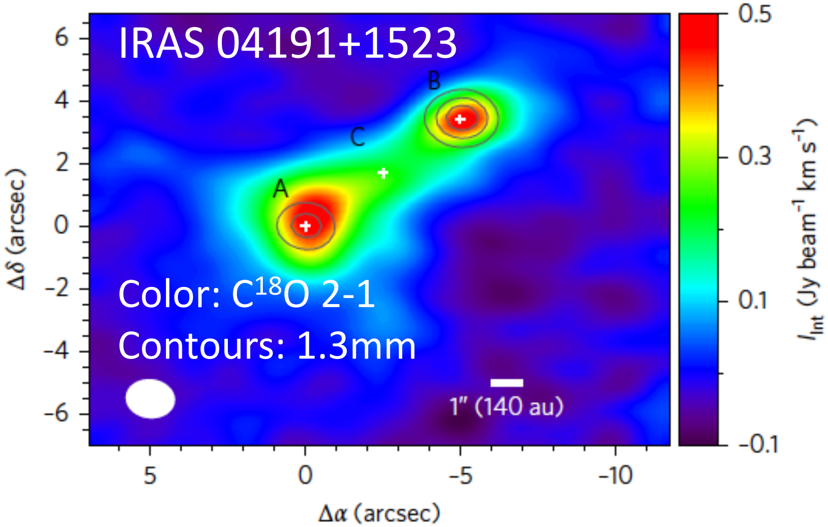


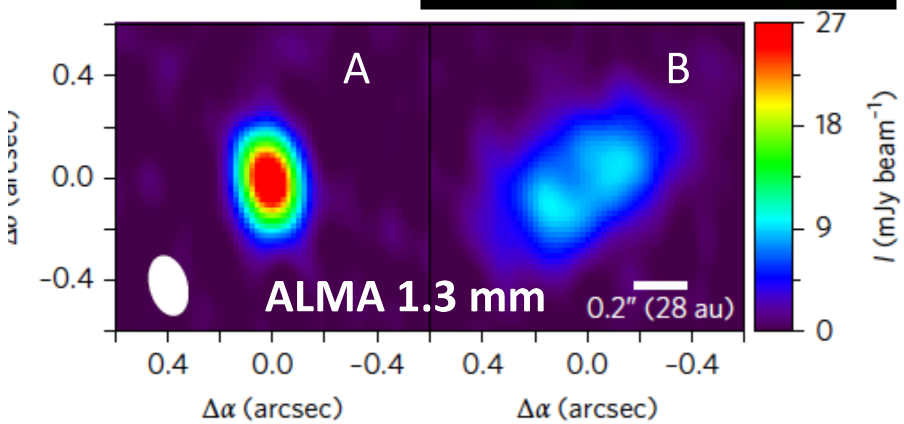
$C^{18}O$ J=2-1

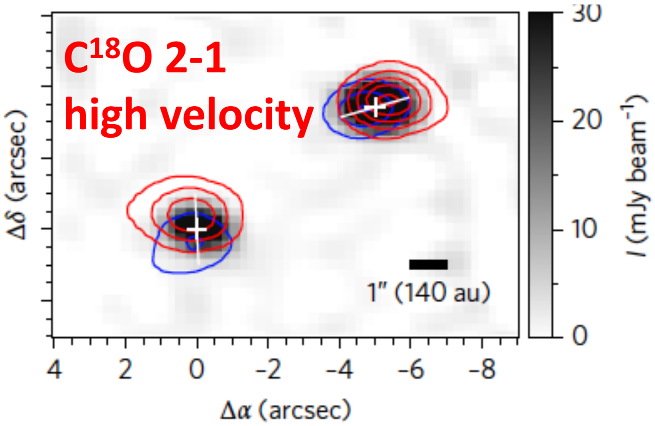
Tobin et al. 2016

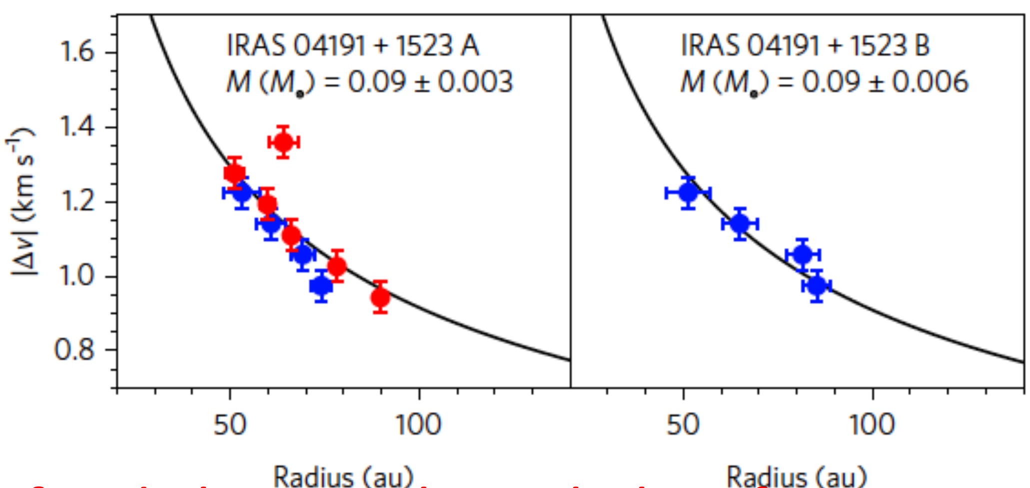
Turbulent Fragmentation











Lee et al. (2017) – *Formtion of wide binaries by turbulent fragmentation*

Grain Growth & Planet Formation in Protoplanetary Disks

HL Tau

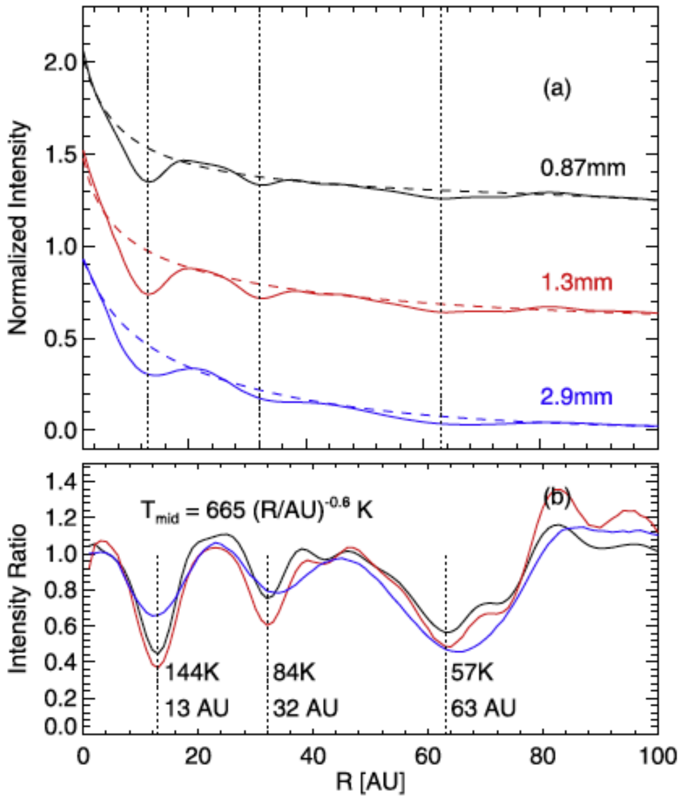
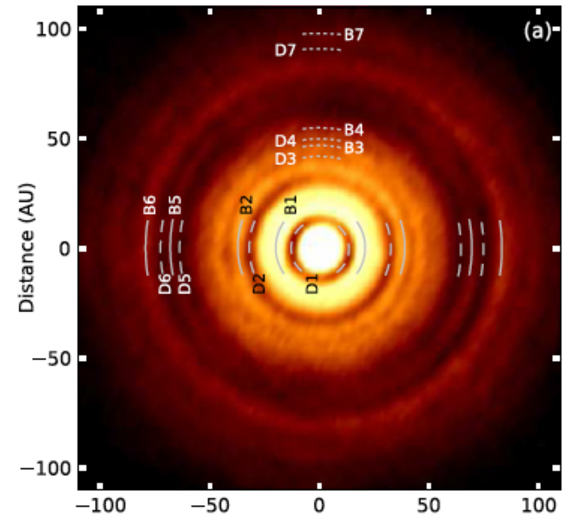
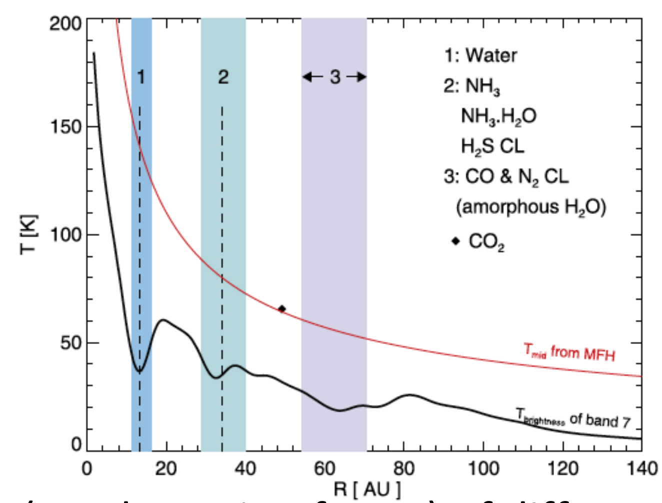


Figure 1. (a) Normalized radial surface brightness distributions of HL Tau at 0.87 (blue), 1.3 (red), and 2.9 mm (black). The solid lines depict the observations, dashed lines the best-fit models (described in Section 3). (b) The observation-to-model surface brightness ratio. The three dotted vertical lines indicate the dip minima.

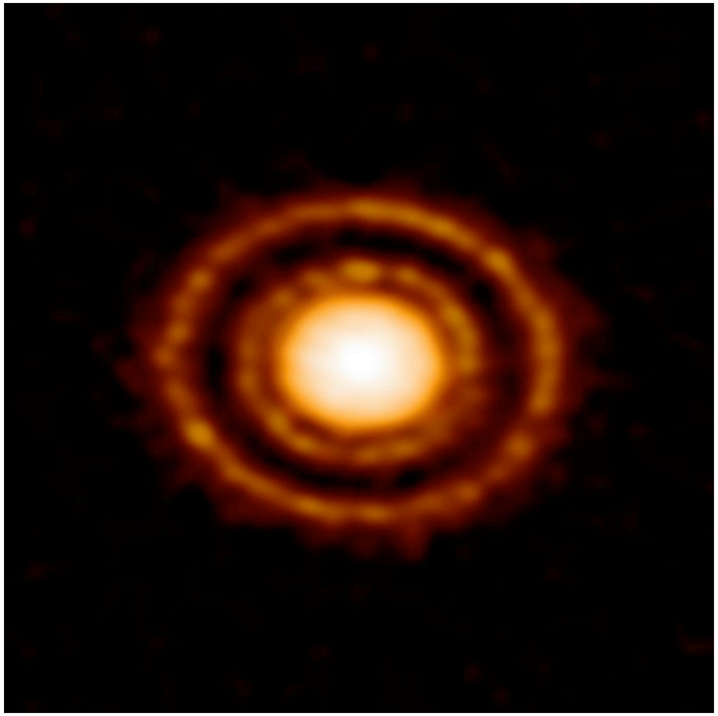




Zhang et al. (2015)

Snow lines (condensation fronts) of different species

The protoplanetary disk AS 209



Credit: ALMA (ESO/NAOJ/NRAO)/
D. Fedele et al.

Evidence of the presence of a Saturn-like planet (0.1 M_J=0.67 M_{Saturn} at 95 AU

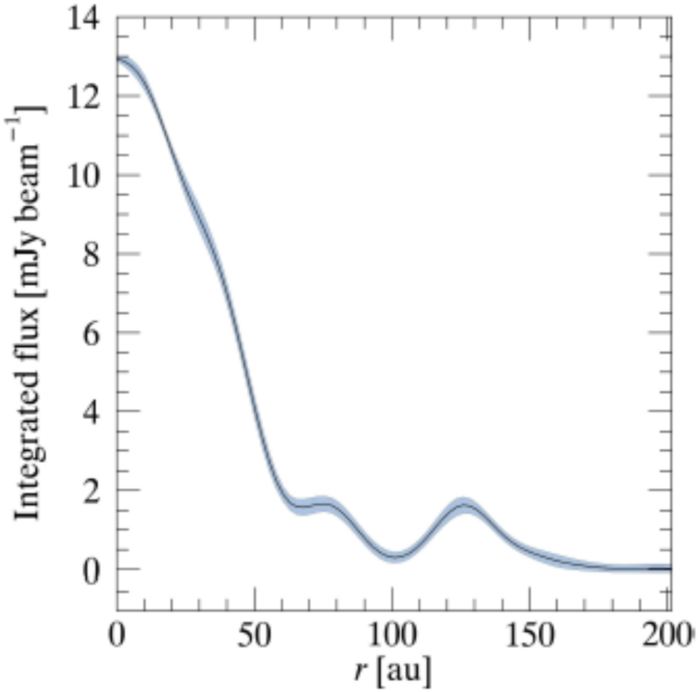


Fig. 2. Radial intensity profile of the 1.3 mm dust continuum emission. The profile is azimuthally averaged after deprojecting for the disk inclination (i = 36°, Sect. 3). The black line shows the mean profile while the shadowed regions indicate the standard deviation along the azimuth angle.

Fedele et al. (2018)
Cycle 3 ALMA program: 2015.1.00486.S


Thank You