Outflows and Disks of Brown Dwarfs with SMA, CARMA and ALMA

Ngoc Phan-Bao

HCMIU-Vietnam National University

Collaborators:
Paul Ho (CfA, ASIAA), Chin-Fei Lee (ASIAA), Eduardo Martín (CAB)

Hot Planets and Cool Stars
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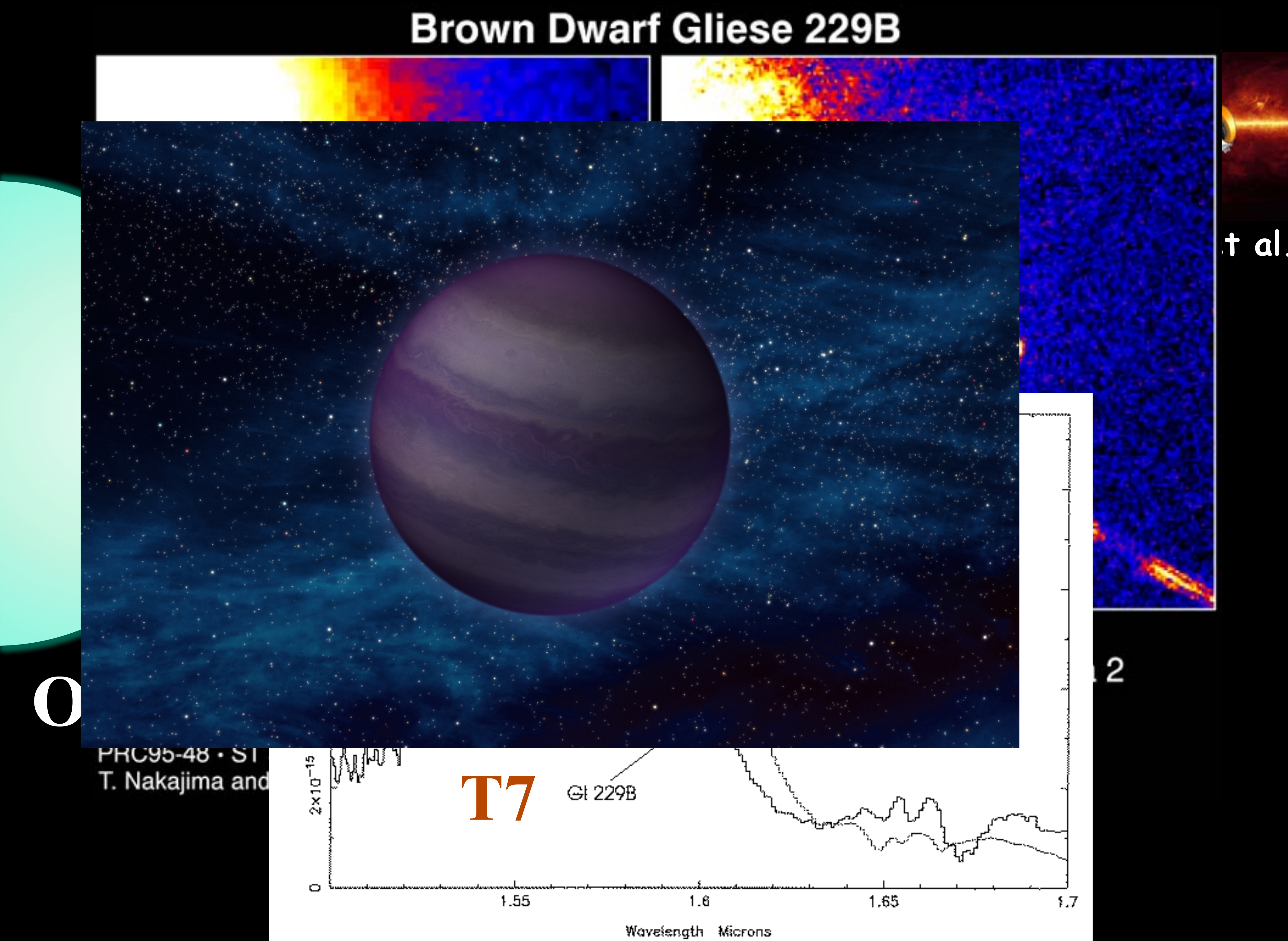
Image credit: CfA/Harvard

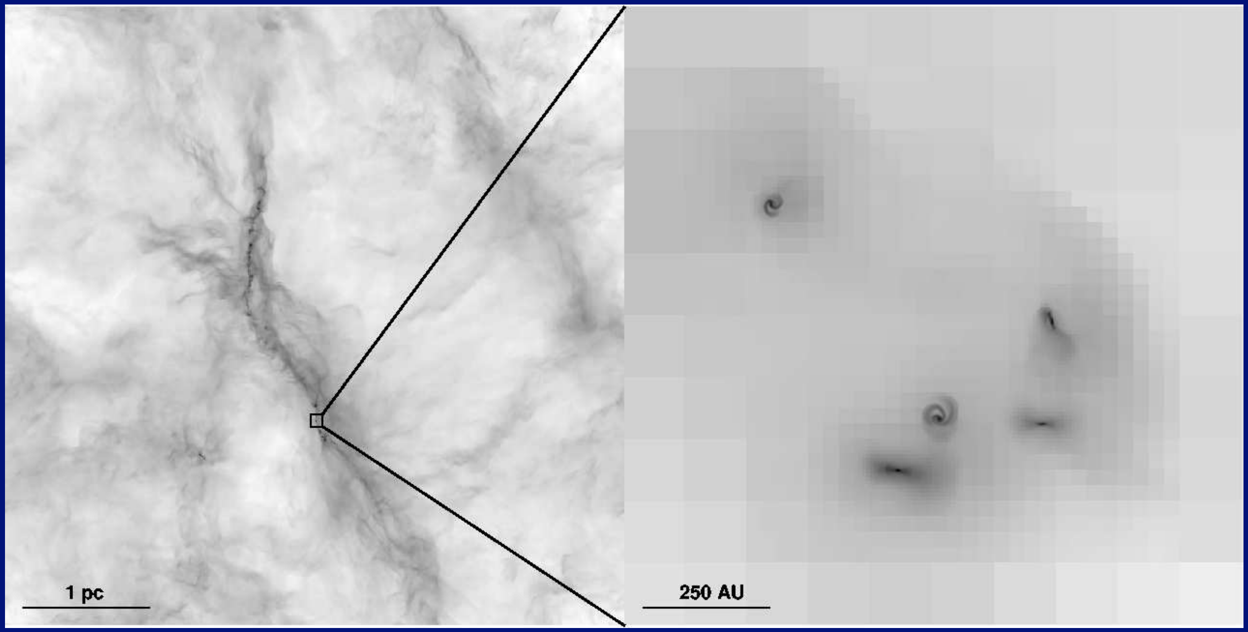
Outline

- ✓ The origin of brown dwarfs
- ✓ Observations of brown dwarf outflows and disks with SMA, CARMA and ALMA
- ✓ Summary

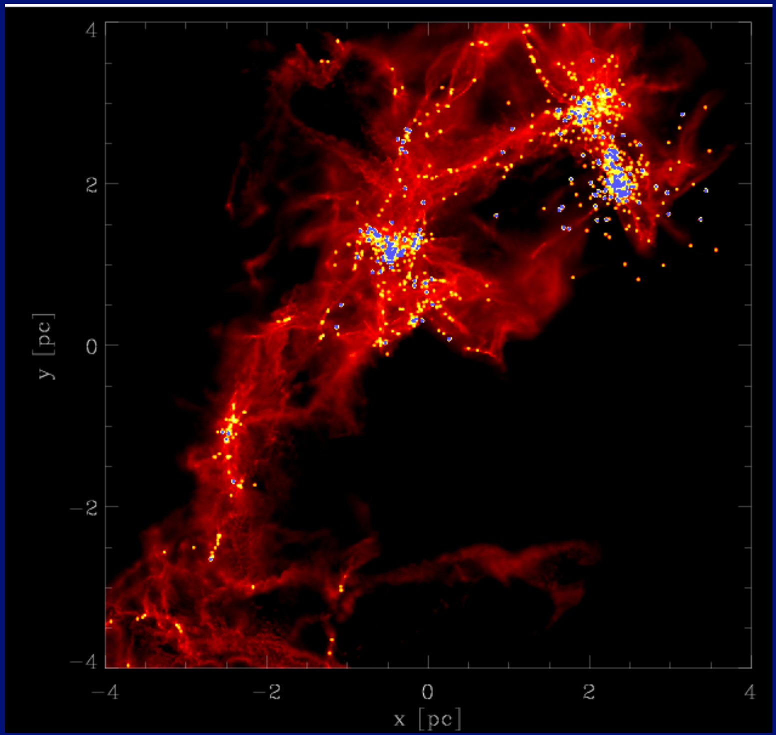

Brown Dwarf Gliese 229B
t al.
2
O
PRC95-48 • ST
T. Nakajima and
T7
Gl 229B
2x10^-15
0
1.55
1.6
1.65
1.7
Wavelength Microns

The origin of brown dwarfs

- Major issue in making a brown dwarf: Balance between requirement of very low mass core formation and prevention of subsequent accretion of gas
- Two major models:
  - **Star-like models**: very low-mass cores formed by turbulent/gravitational fragmentation (Padoan & Nordlund 2002, Bonnell et al. 2008) are dense enough to collapse

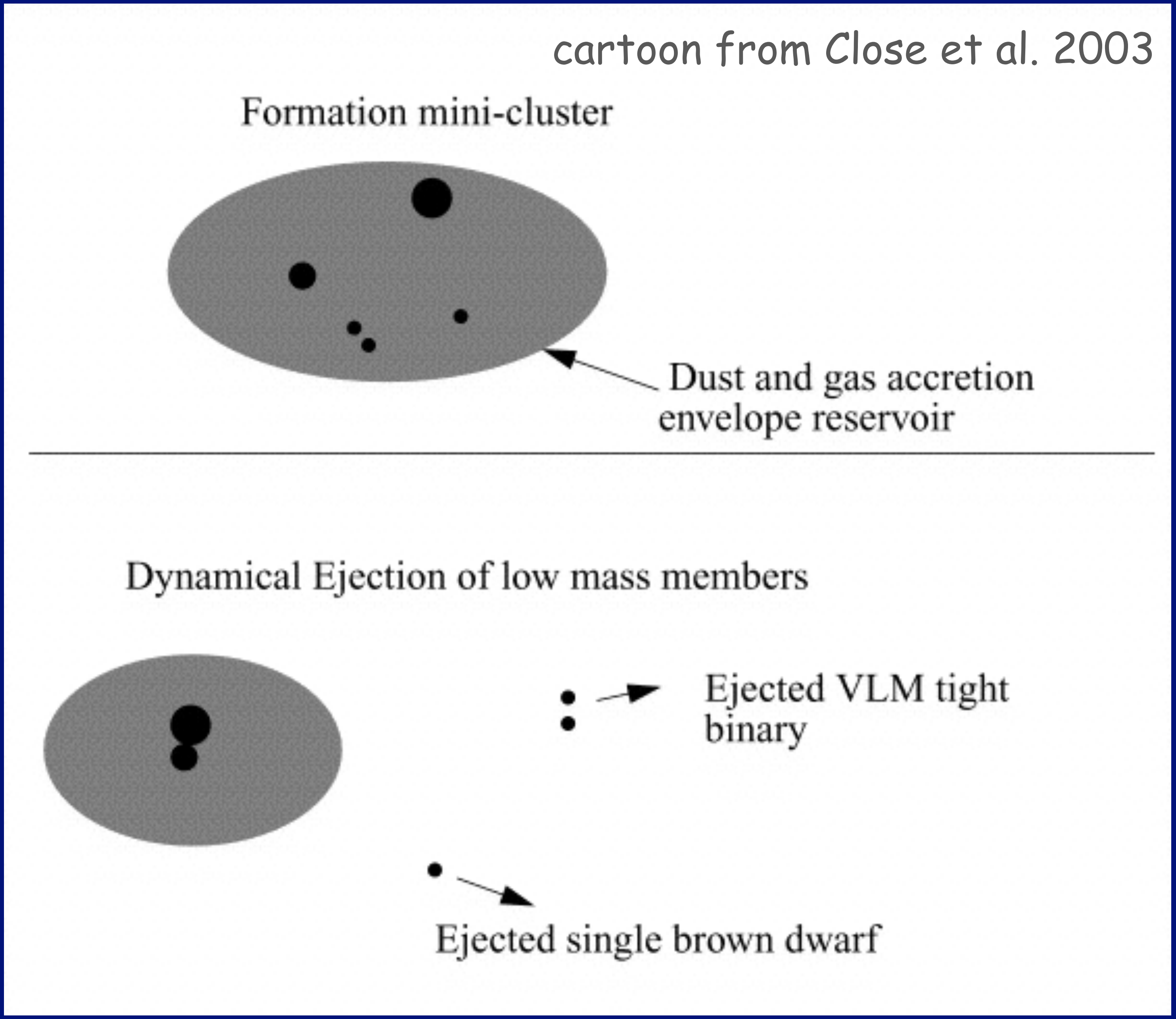


Turbulent fragmentation (Padoan et al.)

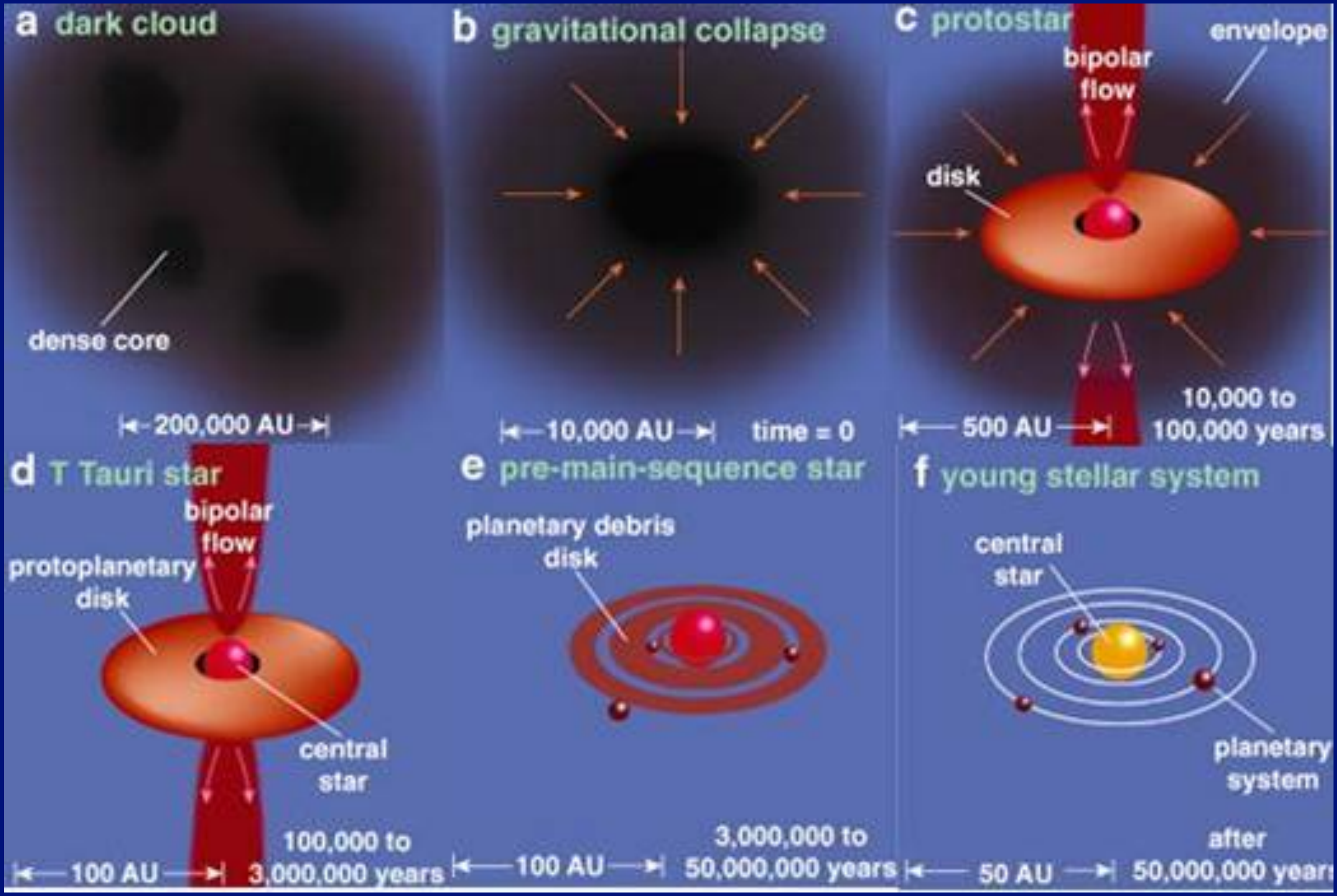


Collapse & fragmentation (Bonnell et al.)

– **Ejection model**: very low-mass embryos are ejected from multiple systems (Reipurth & Clarke 2001, Bate et al. 2004)



- Observations: Statistical properties of BDs such as IMF, binarity, velocity dispersion, disks, accretion, jets…show a continuum with those of stars.
- A typical picture of star formation:



Source: Spitzer Science Center

- Key to understand early stages of BD formation:

Molecular outflows (velocity, size, outflow mass, mass-loss rate) offer a very useful tool to identify and study BD classes 0, I, II.

Observations of brown dwarf outflows and disks with SMA, CARMA and ALMA

A. Molecular Outflows

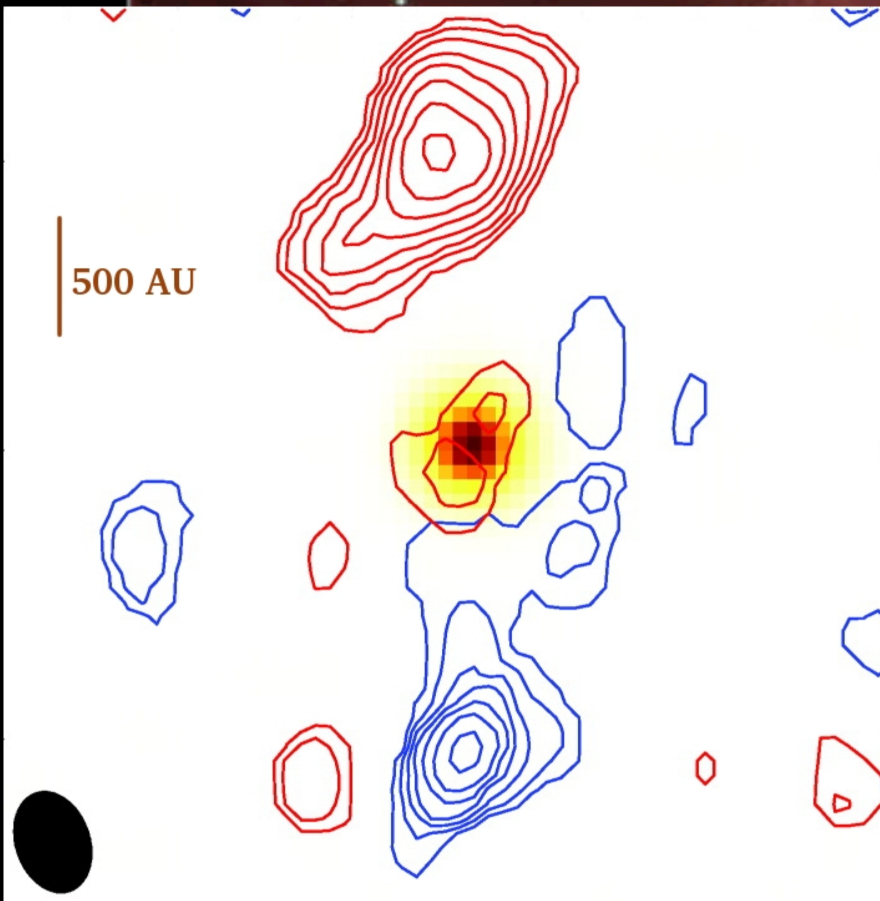
- Overview:
  - 3 detections of molecular outflow from Very-Low Luminosity Objects (VELLOs): IRAM 04191+1522; L1014-IRS and L1521F-IRS
  - only one L1014-IRS (class 0/I, Bourke et al. 2005) whose the outflow process is characterized
  - the sources are embedded in dust and gas, so it is very difficult to determine the mass of the central objects and their final mass
- We search for molecular outflows from class II young BDs that are reaching their final mass

- **Sample:** 2 BDs in ρ Ophiuchi and 6 (1 VLM star + 5 BDs) in Taurus (mass range: 35 M_J – 90 M_J). <u>All are in class II</u>.

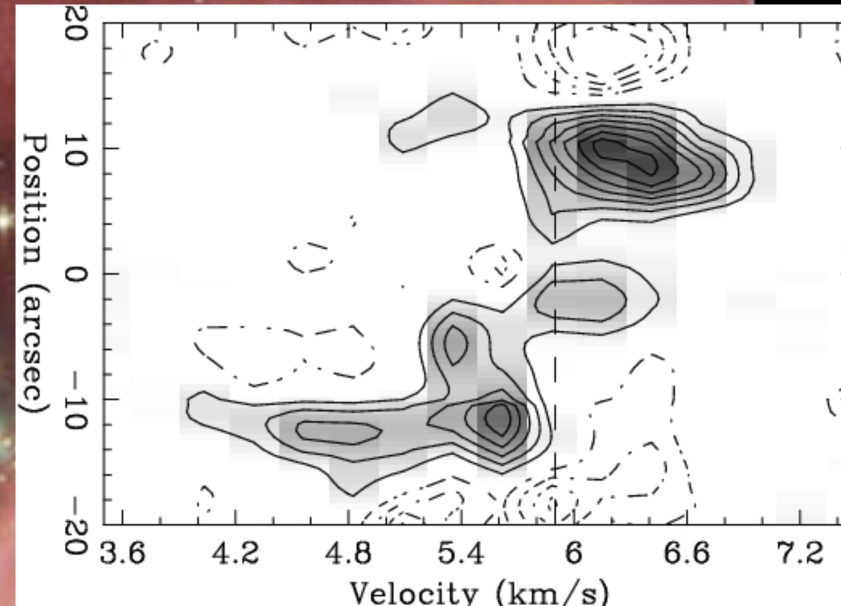
- **Observations:**
  - ✓ 2008-2010 with SMA and CARMA
  - ✓ We search for CO 2-1 (230 GHz, 1.2 mm)
  - ✓ SMA: compact, 3.6"x2.5", 0.25 km/s
  - ✓ CARMA: D, 2.8"x2.5 ", 0.18 km/s

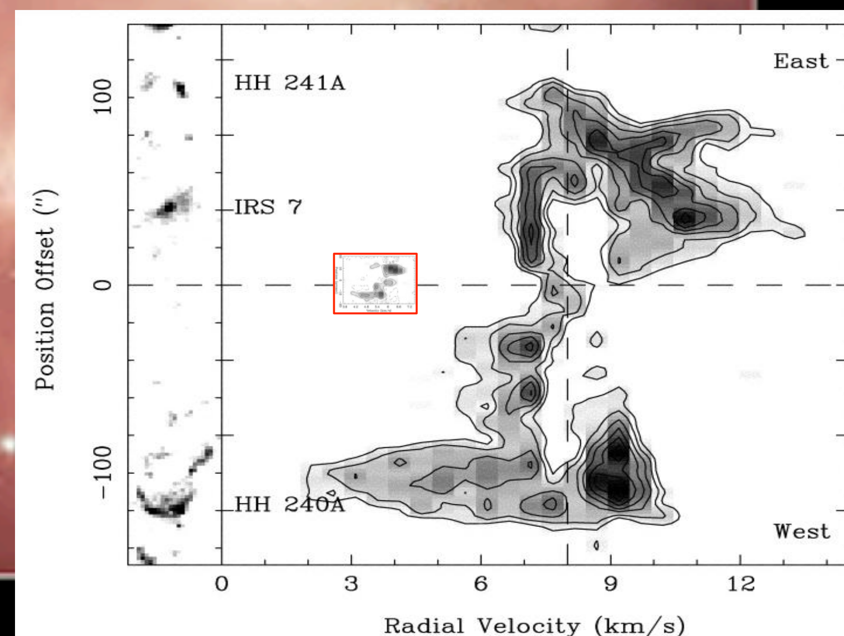
ISO-Oph 102, 60 M_J, ρ Ophiuchi

CO J=2→1 MAP (230 GHz)



Phan-Bao et al. 2008, ApJL



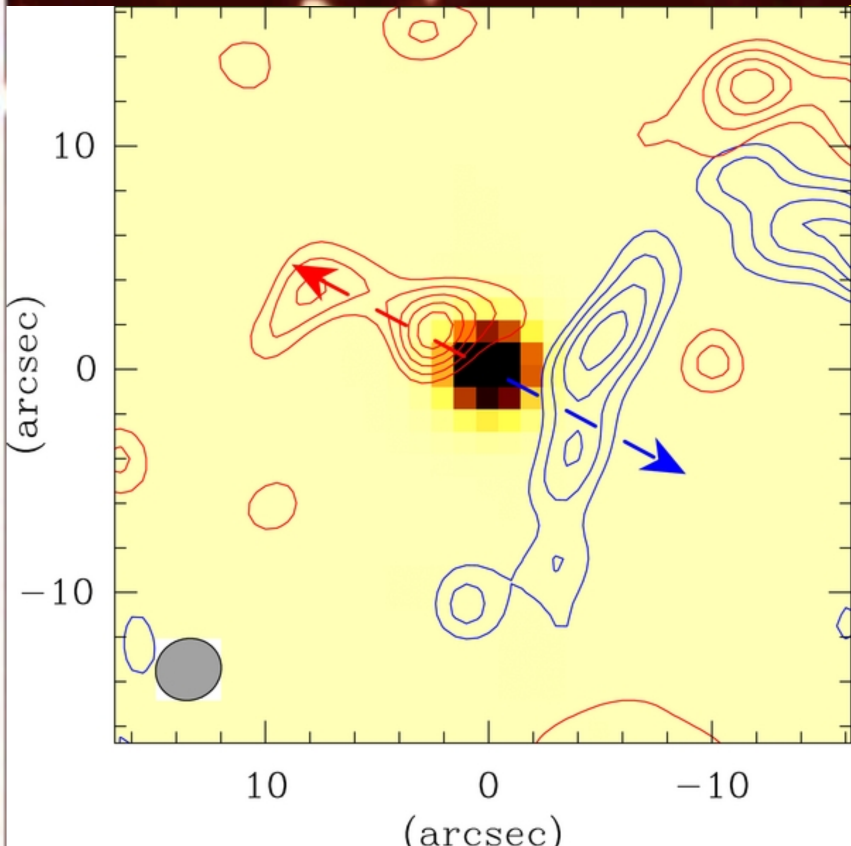


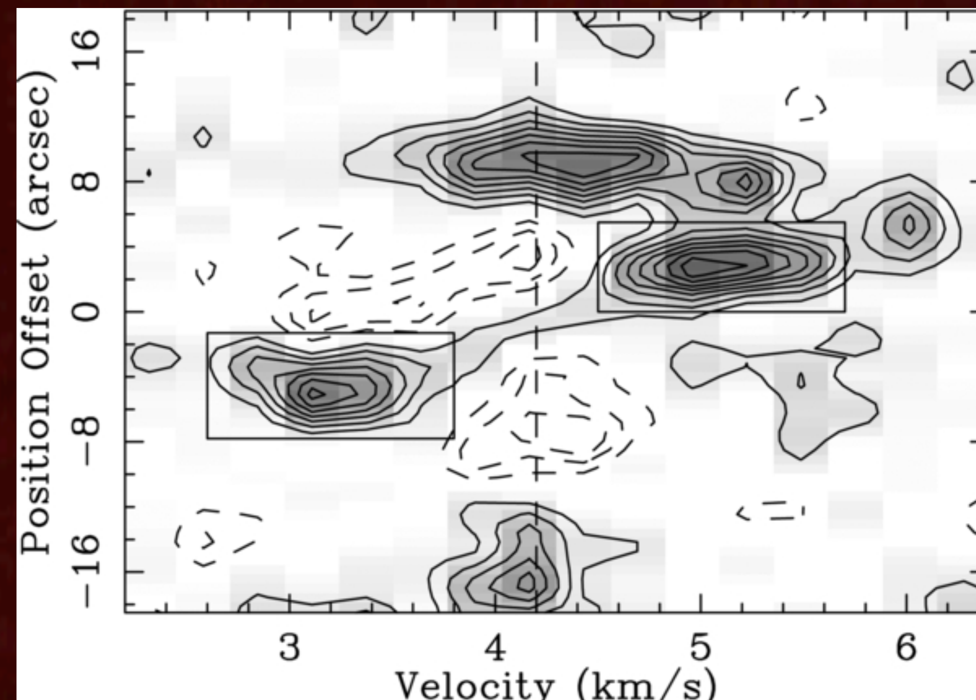
Lee et al. 2000

Star Formation in the Rho Ophiuchi Cloud
NASA / JPL-Caltech / L. Allen (Harvard-Smithsonian CfA)
ssc2008-03b

MHO 5, 90 M_J, Taurus

CO J=2⊠1 MAP (230 GHz)





Phan-Bao et al. 2011, ApJ

Observations of brown dwarf outflows and disks with SMA, CARMA and ALMA

Target	Array	Mass (M_J)	Log $\dot{M}_{acc}$ ($M_\odot$/yr)	Log$M_{outflow}$ ($M_\odot$)	Log$\dot{M}_{mass-loss}$ ($M_\odot$/yr)	Reference papers
ISO-Oph 102	SMA	60	-9.0	-3.8	-8.9	PB2008, ApJL
2M 0441	CARMA	35	-11.3	-	-	PB2011, ApJ
ISO-Oph 32	SMA	40	-10.5	-	-	
2M 0439	CARMA	50	-11.3	-	-	
MHO 5	SMA	90	-10.8	-4.2	-9.1	
2M 0414	CARMA	75	-10.0	-	-	PB2012, in prep.
2M 0438	CARMA	70	-10.8	-	-	
GM Tau	SMA	73	-8.6	-4.9	-10.3	

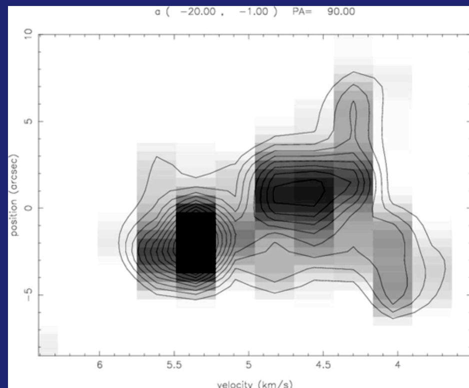
- BD Outflow Properties:
  - Compact: 500-1000 AU
  - Low velocity: 1-2 km/s
  - Outflow mass: 10^{-4}-10^{-5} $\mathbf{M_\odot}$ (low-mass stars: 10^{-1} $\mathbf{M_\odot}$)
  - Mass-loss rate: 10^{-9}-10^{-10} $\mathbf{M_\odot/yr}$ (low-mass stars: 10^{-7} $\mathbf{M_\odot/yr}$)
- What we can learn from our observations:
  - BD outflow is a scaled down version (a factor of 100-1000) of the outflow process in stars
  - Supporting the scenario that BDs form like stars
  - BD outflow properties are used to identify/study BD formation at earlier stages (class 0, I)

presented in Constellation10, Tenerife, 2010

Core

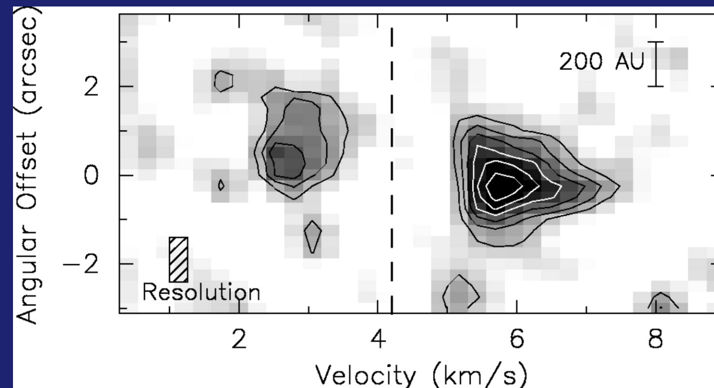
?

Class 0 (?)



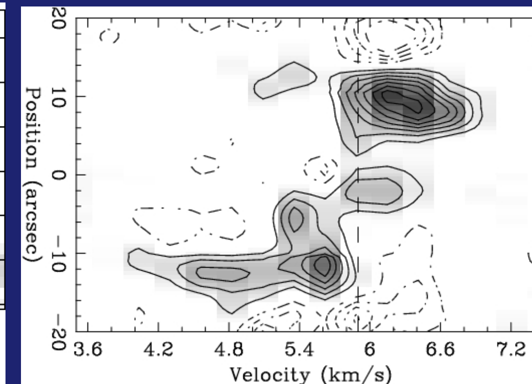
Phan-Bao et al., in prep.

Class I (?)



Bourke et al. 2005

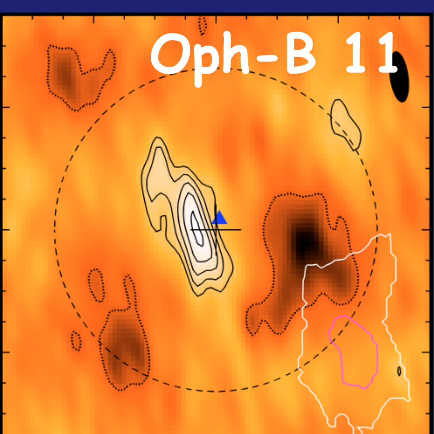
Class II BD



Phan-Bao et al. 2008

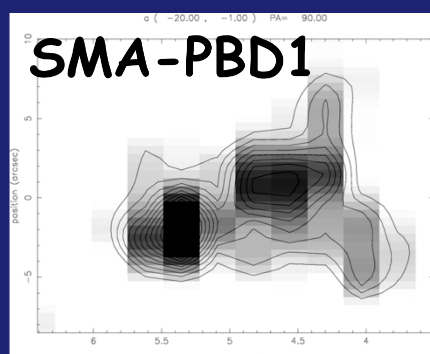
Now, Hot Planets and Cool Stars, Munich, 2012

Core



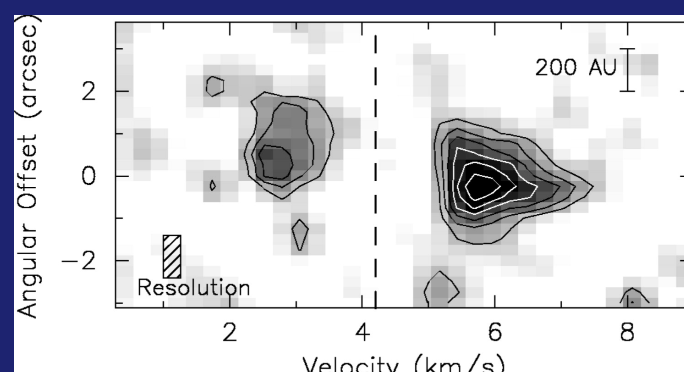
Andre et al. 2012

Class 0



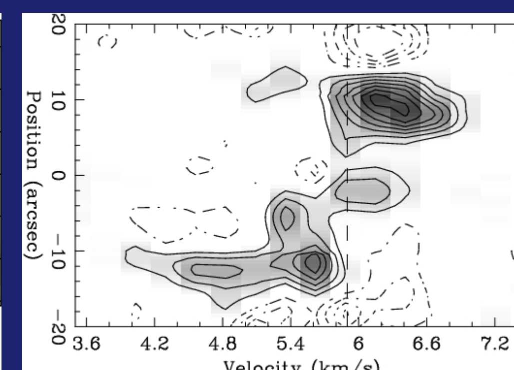
Phan-Bao et al.
Kauffmann et al. 2011
Palau et al. 2012

Class I



Bourke et al. 2005

3 Class II BDs

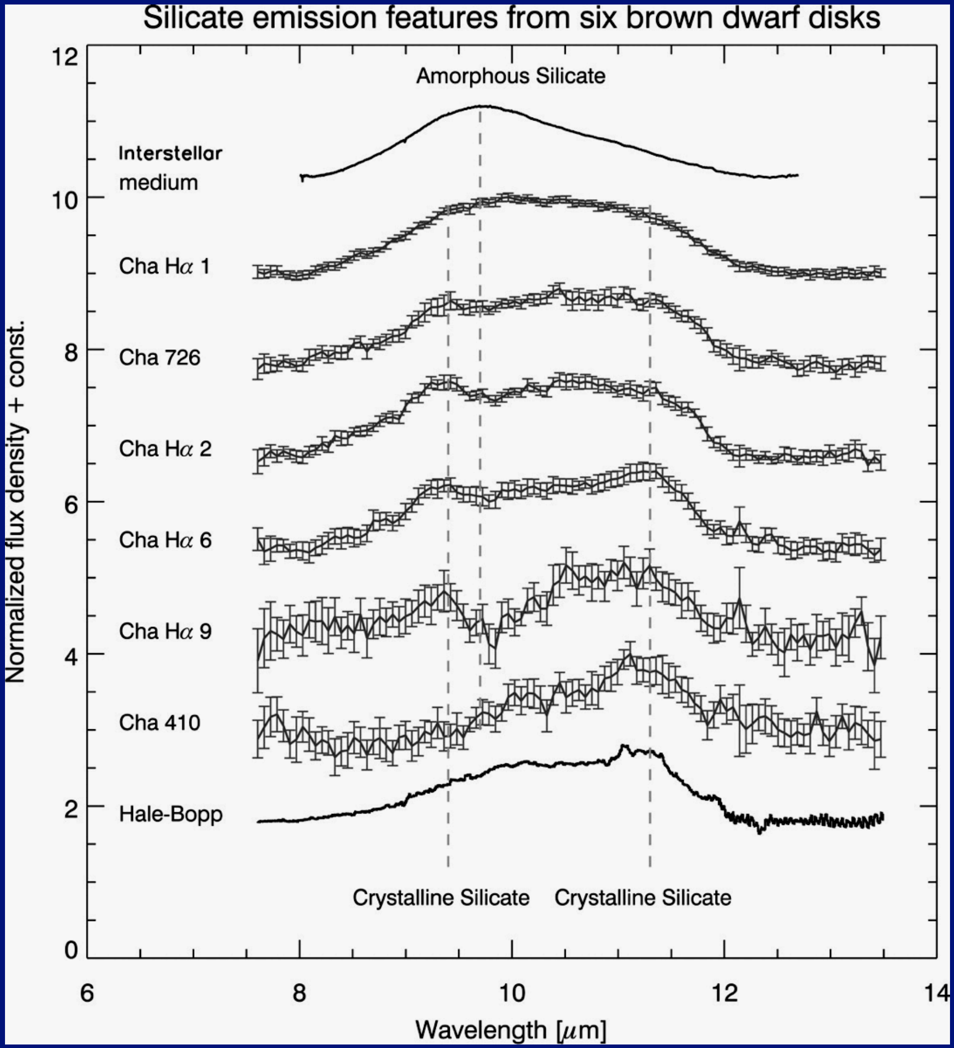


Phan-Bao et al. 2008
Phan-Bao et al. 2011
Phan-Bao et al. in prep.

B. BD Disks

i) Detections of grain growth, crystallization, and dust settling occurring in brown dwarf disks have been reported (e.g., Apai et al. 2005, Riaz 2009):

- **These detections demonstrate that planets can form around BDs**



Apai et al. 2005

ii) BD disk properties from SEDs:

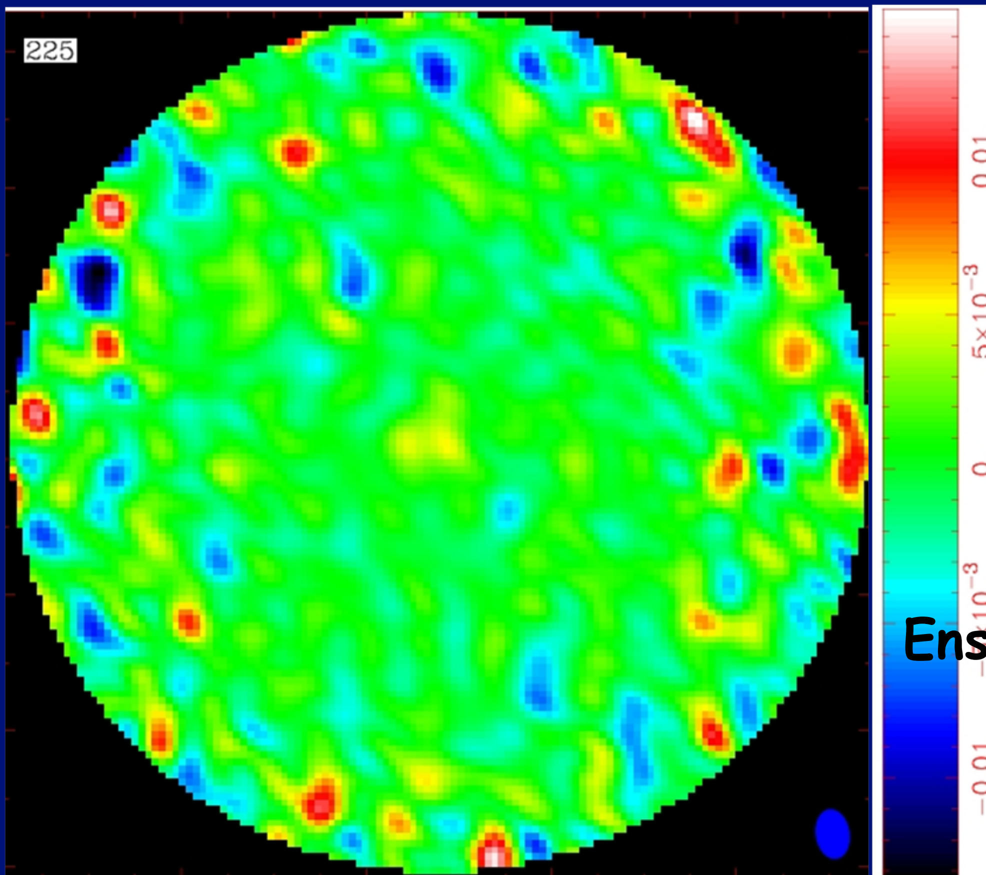
- ✓ 20 M6-M9 in Taurus (Scholz et al. 2006):
  - Disk masses: 0.4 – 1.2 M_J
  - Disk radii: >20% with >10 AU (10-100 AU)

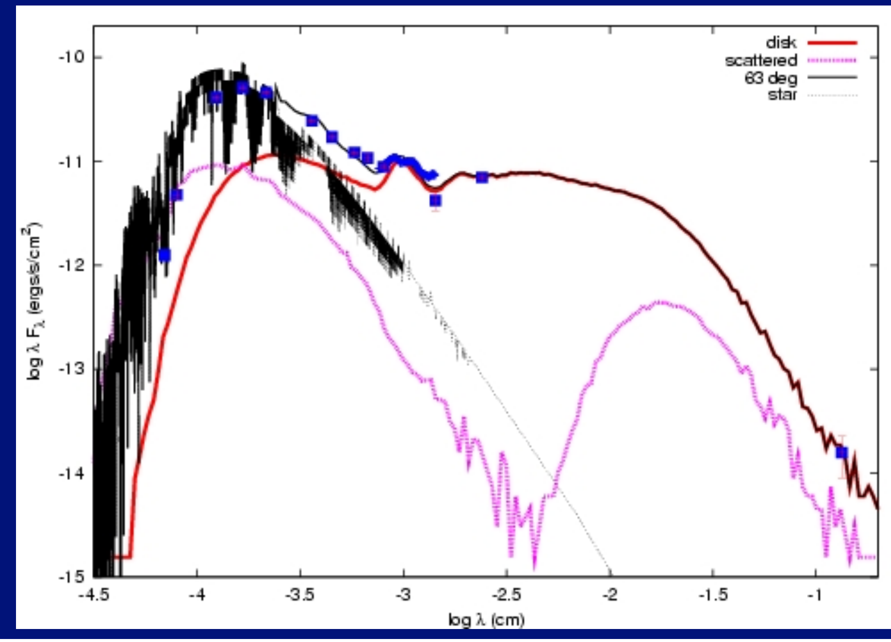
It is unlikely that Jupiter-mass planets are frequent around BDs

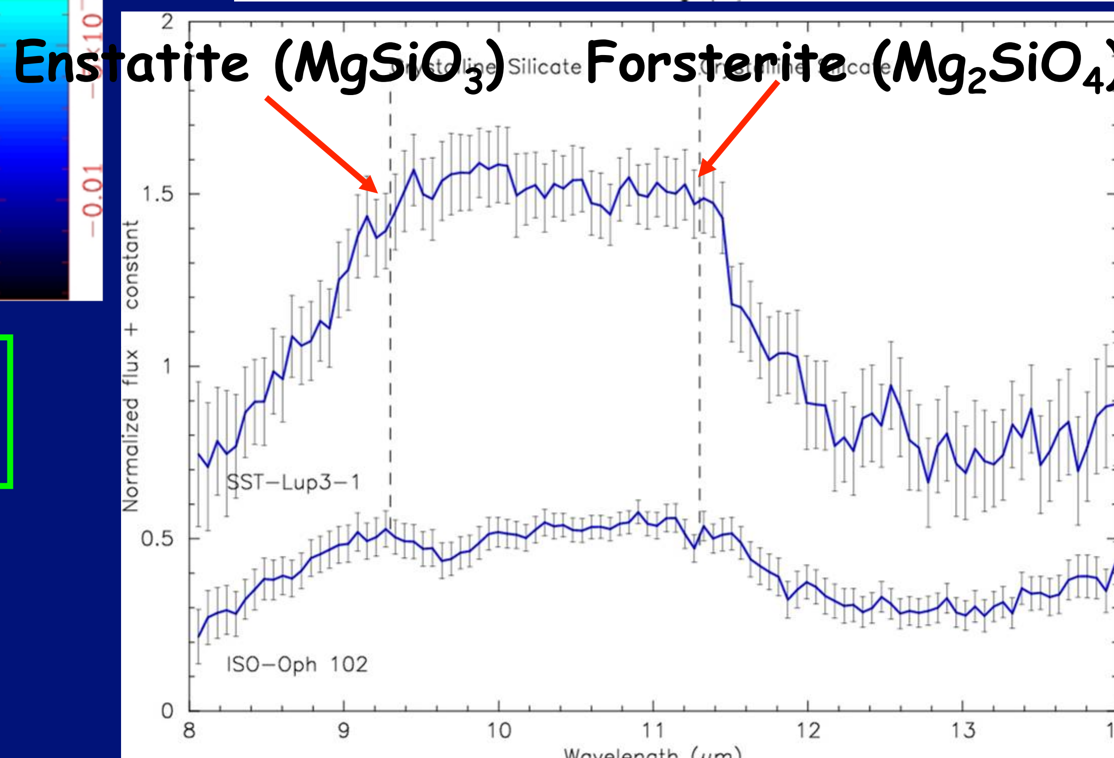
iii) So far, no direct imaging of any BD disks has been done:

Therefore it is important to map a BD disk to obtain disk parameters, hence to understand how planets form around BDs

ISO-Oph 102: 7±3 mJy, an excellent target for ALMA

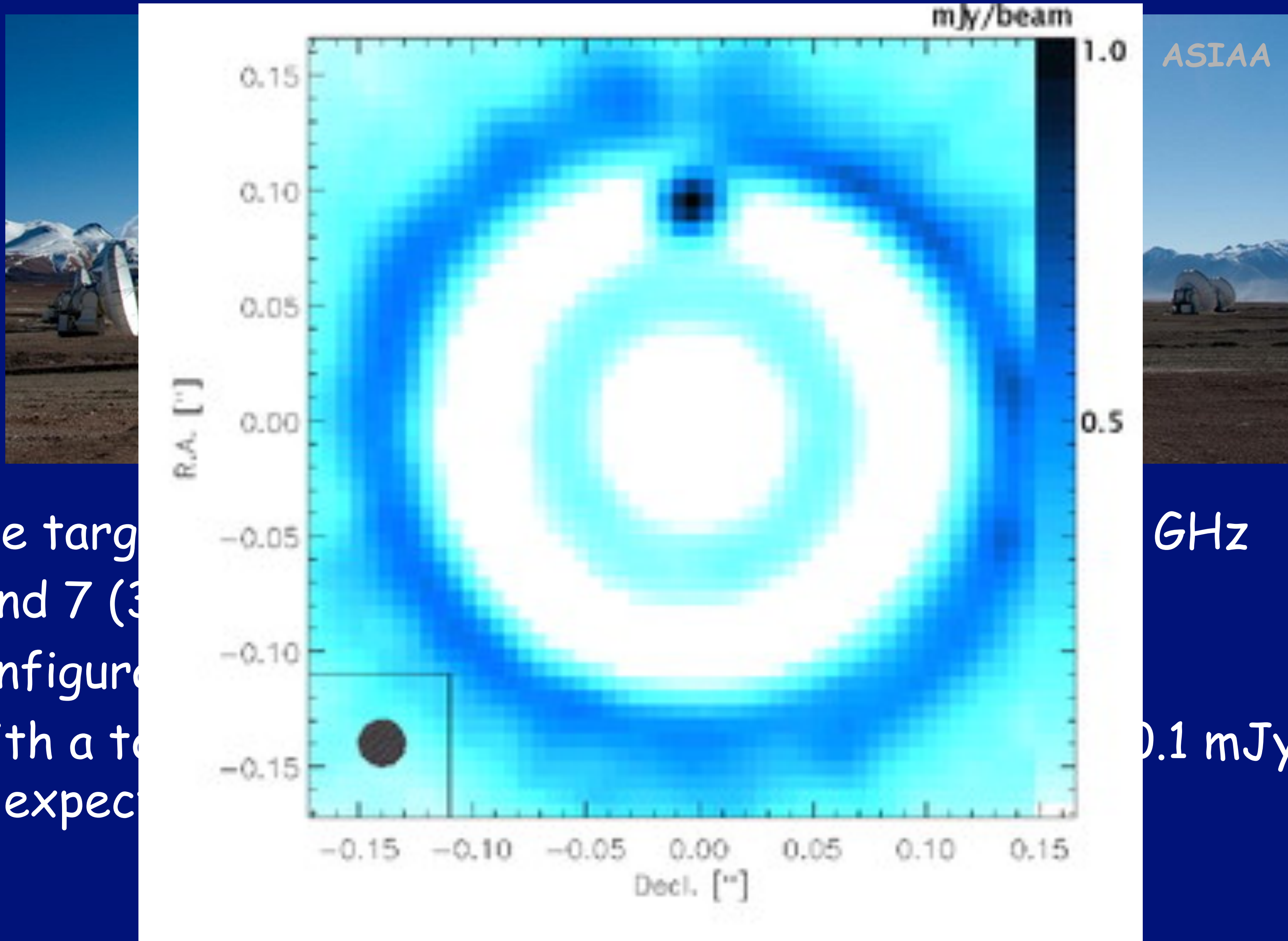






- Disk Mass: 8 M_J
- Outer disk radius: 80 AU

How does the disk of ISO-Oph 102 look like with ALMA?



- The targ ... GHz
- Band 7 (3
- Configur
- With a t ... .1 mJy), an expec

Simulation from Wolf & D'Angelo 2005

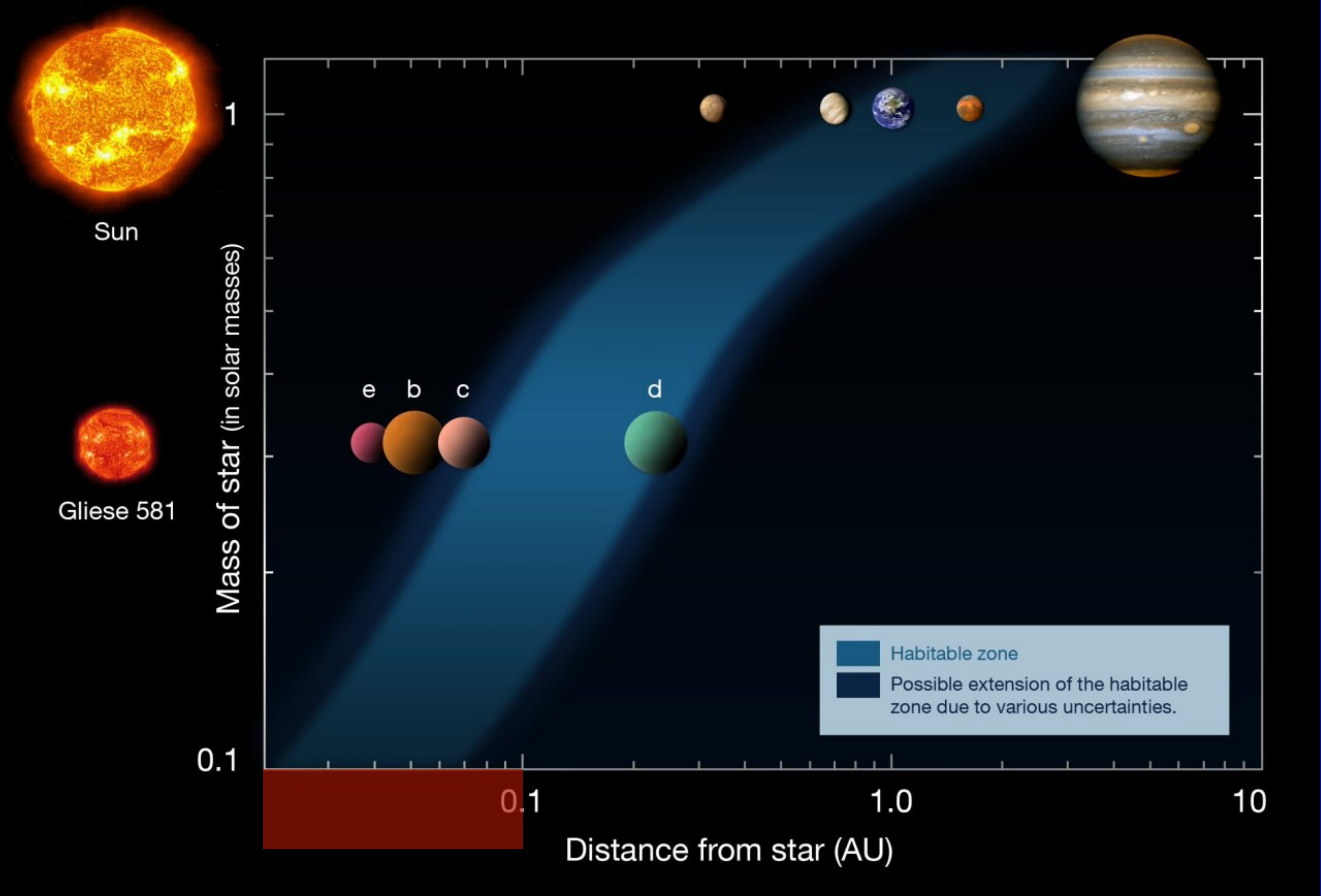

Sun
Gliese 581
1
0.1
Mass of star (in solar masses)
e
b
c
d
0.1
1.0
10
Distance from star (AU)
Habitable zone
Possible extension of the habitable zone due to various uncertainties.

Image: ESO

Summary

- ✓ BDs can form like low-mass stars in a scaled down version with a factor of 100-1000

- ✓ Some giant planets close to the brown dwarf-planet boundary can form like BDs

- ✓ ALMA is able to resolve VLM star/BD disks, helping us understand planet formation around VLM stars and BDs.

Thank you for your attention!

Many thanks to the organizers of the conference!