ALMA mapping of the gas and dust in a hybrid debris disk

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esa

Herbig Ae/Be stars, Santiago, Chile, April 7−11, 2014

Circumstellar disks

Primordial disks: disks around pre-main sequence stars

- Mass is dominated by gas, only a few % in dust grains
- Dust dynamics is determined by the gas
- Planetesimals and planets may form in the disk
- Gas content is removed by accretion/photoevaporation within 10 Myr

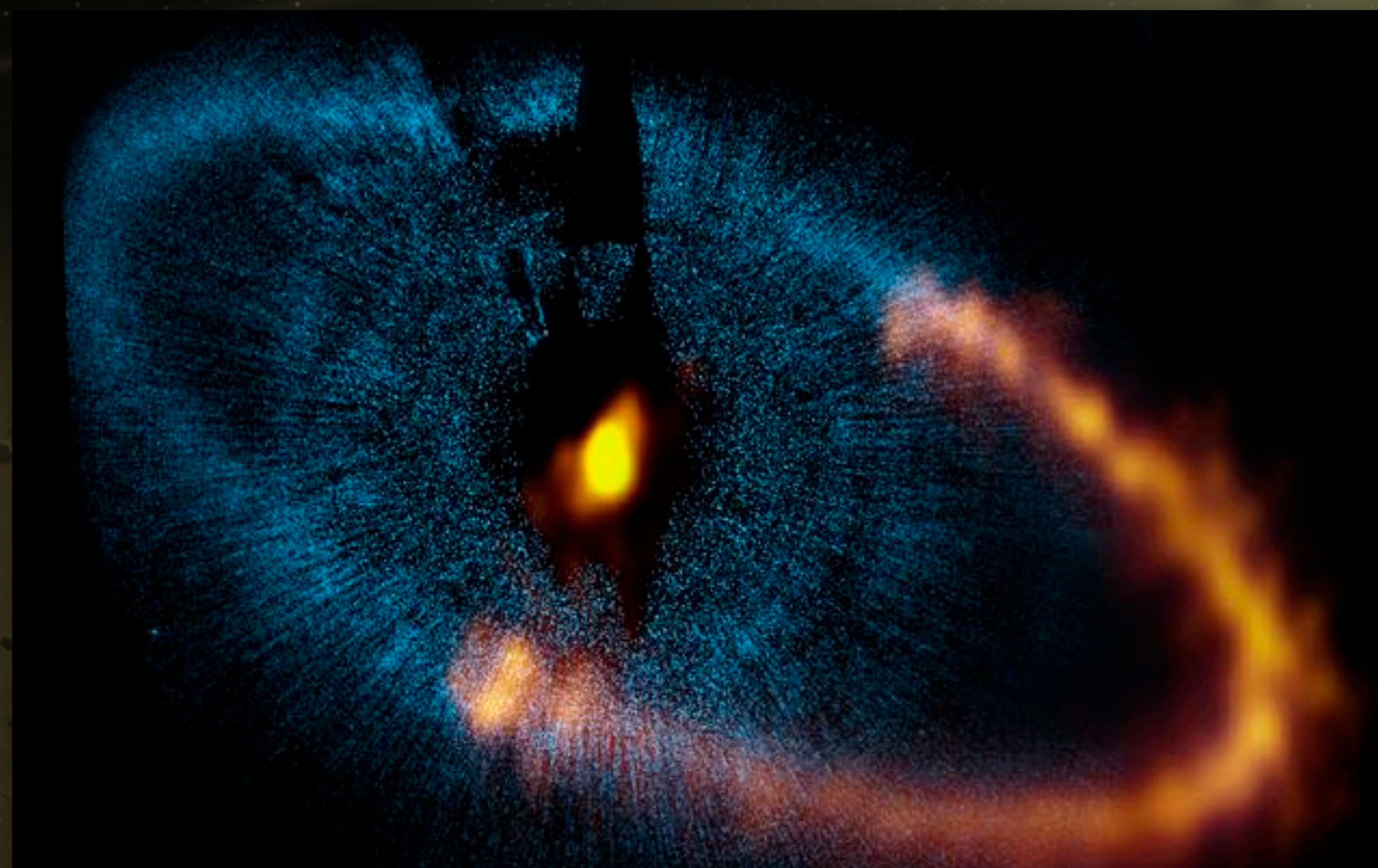
Debris disks: disks around main sequence stars

- Mass is dominated by dust, amount of gas negligible
- Without gas, the lifetime of dust grains is very short
- Dust grains are continuously replenished by collisions/evaporation of planetesimals (second generation dust)

Debris disks

Dust content: typically < 0.5 $M_\oplus$

- Scattered light at optical/near-IR wavelengths
- Thermal emission at IR/submm/mm wavelengths

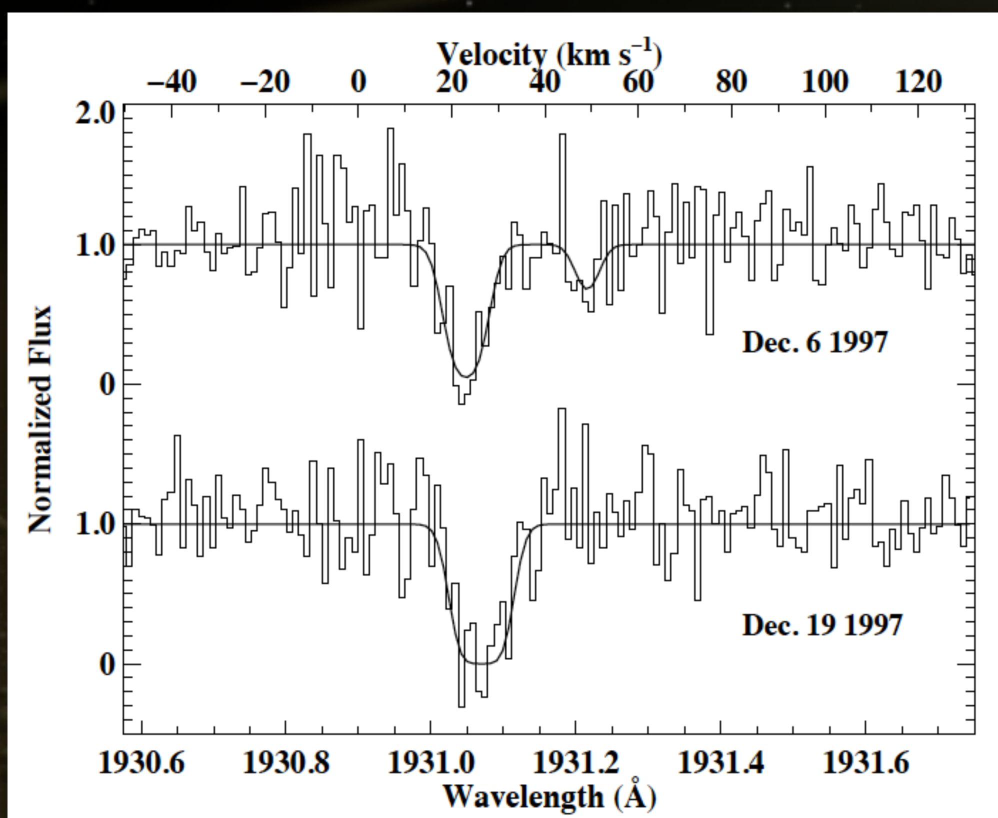


Fomalhaut (Boley et al. 2012, Kalas et al. 2005)

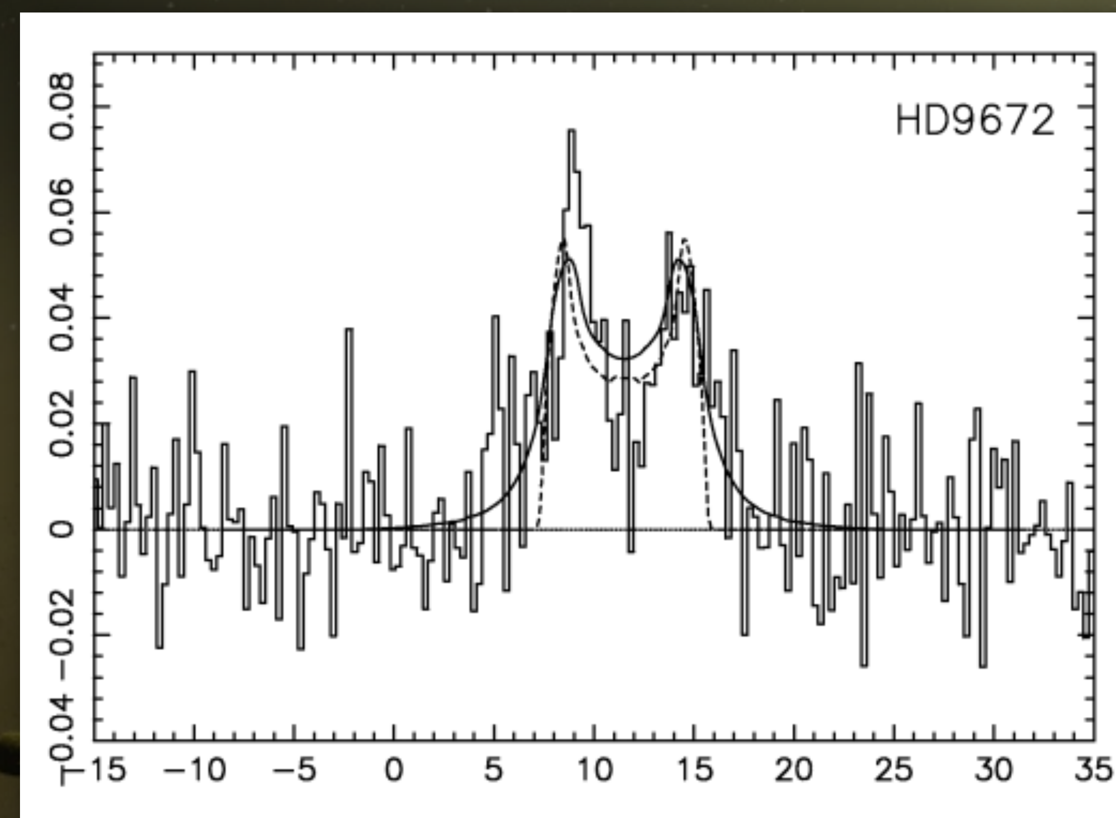
Debris disks

Gas content: very rare, only a handful of detections

- Absorption lines in edge-on disks (UV, optical)
- CO emission at submillimeter wavelengths
- Highly debated whether residual primordial or secondary

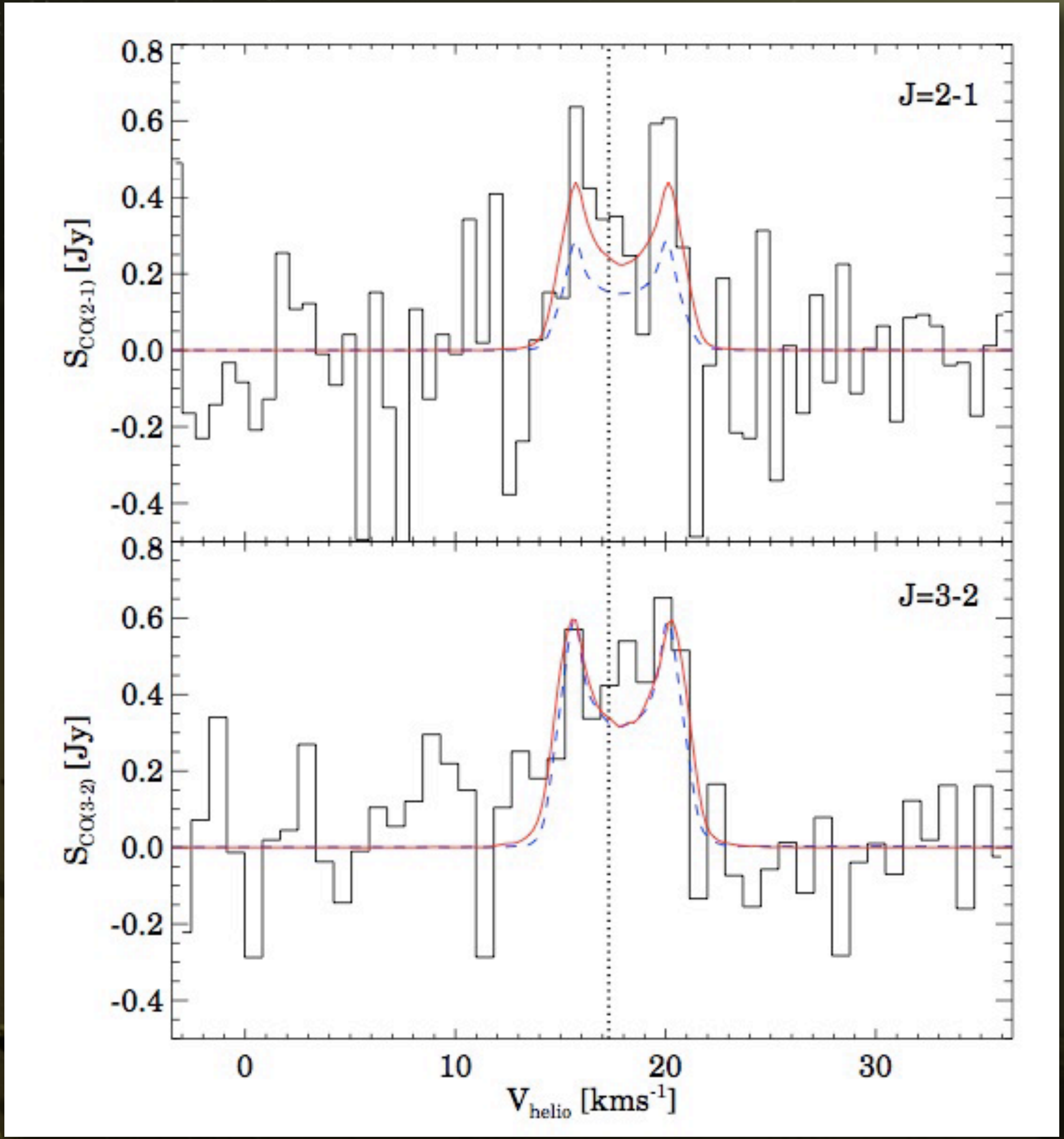


β Pic, 12 Myr (Roberge et al. 2000)
see also poster #9 by Dent et al.



49 Cet, 40 Myr (Dent et al. 2005)

Gas in debris disks?



- CO survey of debris disk with moderate to high fractional luminosity with APEX
- Discovery of the second debris disk with cold CO content (after 49 Cet)

Moór et al. (2011)

Our target: HD 21997

Age: 30 Myr (member of the Columba moving group)

Spectral type: A3 IV/V

Distance: 72 pc

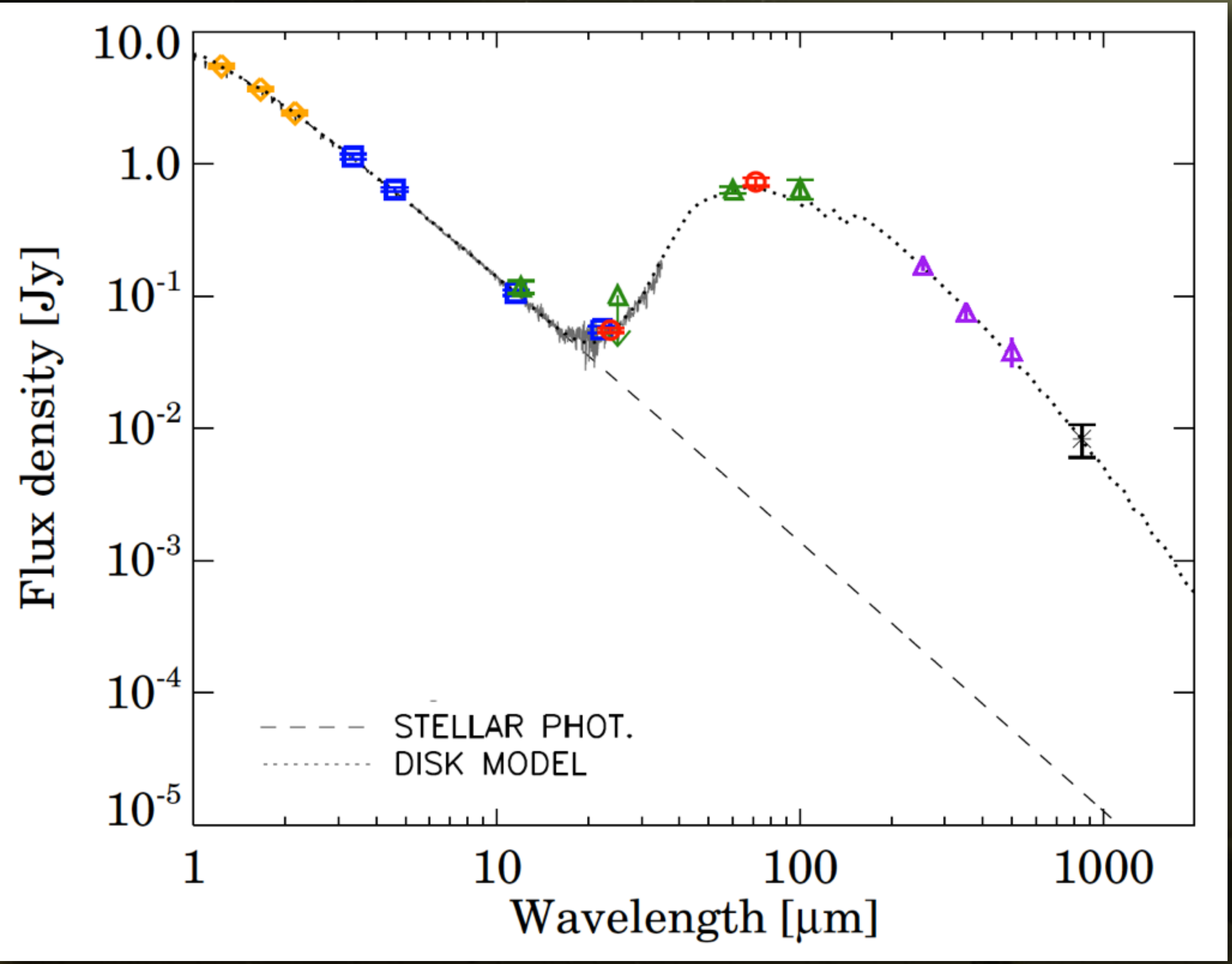
L_{frac}: 5.9 x 10^{-4}

M_{dust}: 0.23 $M_{\oplus}$

SED fitting:

R_{in}: 76 AU

R_{out}: 200 AU



Moór et al. (2006, 2011)

Motivation

- No spatially resolved observations of HD 21997 had been available at any wavelength
- SED, single dish CO observation: not enough due to degeneracies
- Spatially resolved observations are needed
- With ALMA we would directly determine the
  - radial structure
  - azimuthal structure
  - amount of gas

http://almaobservatory.org

ALMA observations

ALMA Cycle 0 measurements

Project 2011.0.00780.S (PI: Á. Kóspál)

November 3 – December 31, 2011

Compact configuration

Beam sizes between 1.1" and 1.9"

14 – 16 antennas

Band 7 (275–373 GHz)

- ^{12}CO (3–2)
- ^{13}CO (3–2)
- CS (7–6)
- Continuum

Band 6 (211–275 GHz)

- ^{12}CO (2–1)
- ^{13}CO (2–1)
- $C^{18}O$ (2–1)

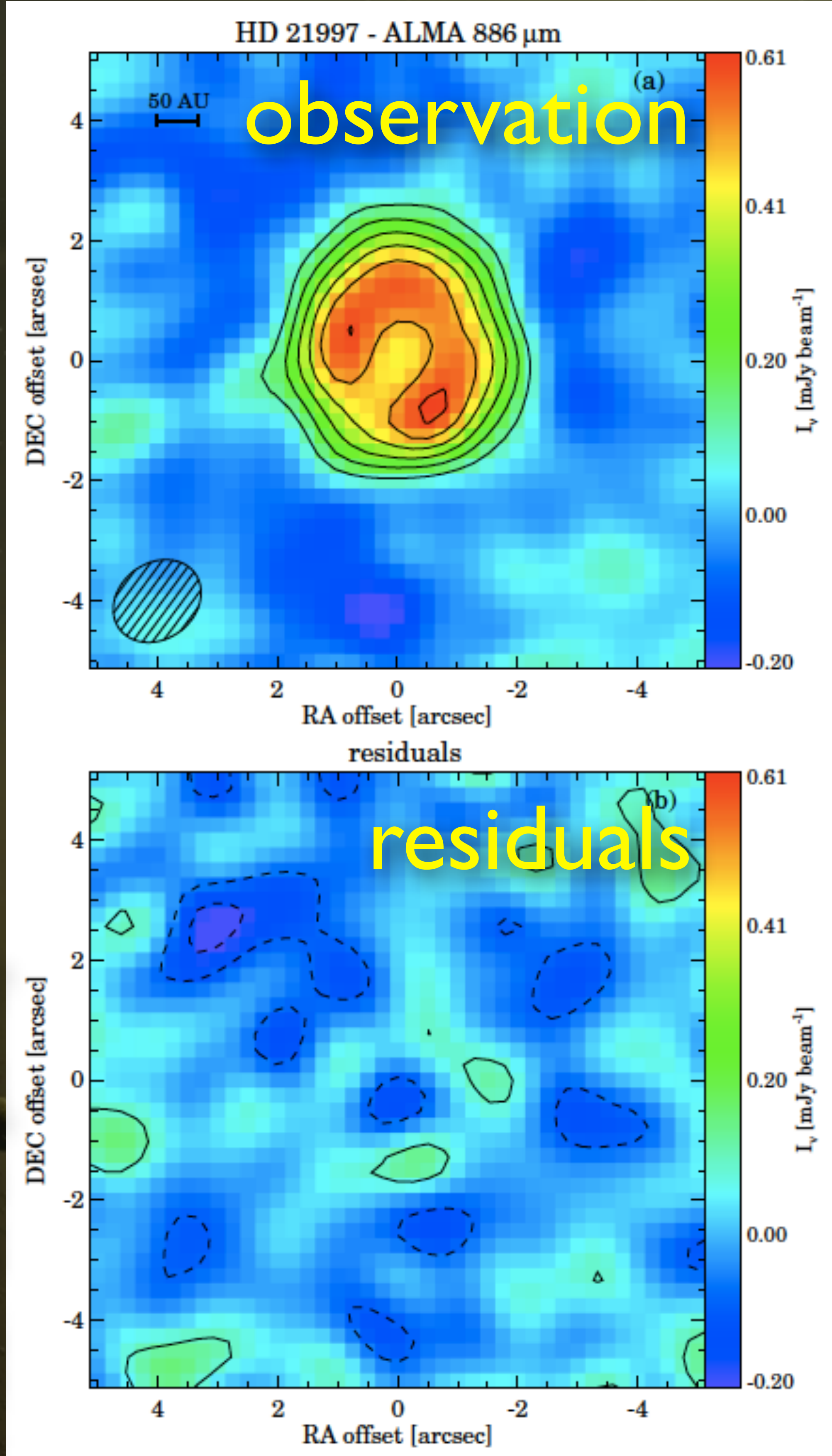
Continuum at 870 µm

1 σ rms = 45 µJy/beam

Model image + SED simultaneously:

DEBris disk RAdiative transfer code (DEBRA; Olofsson et al. 2012)

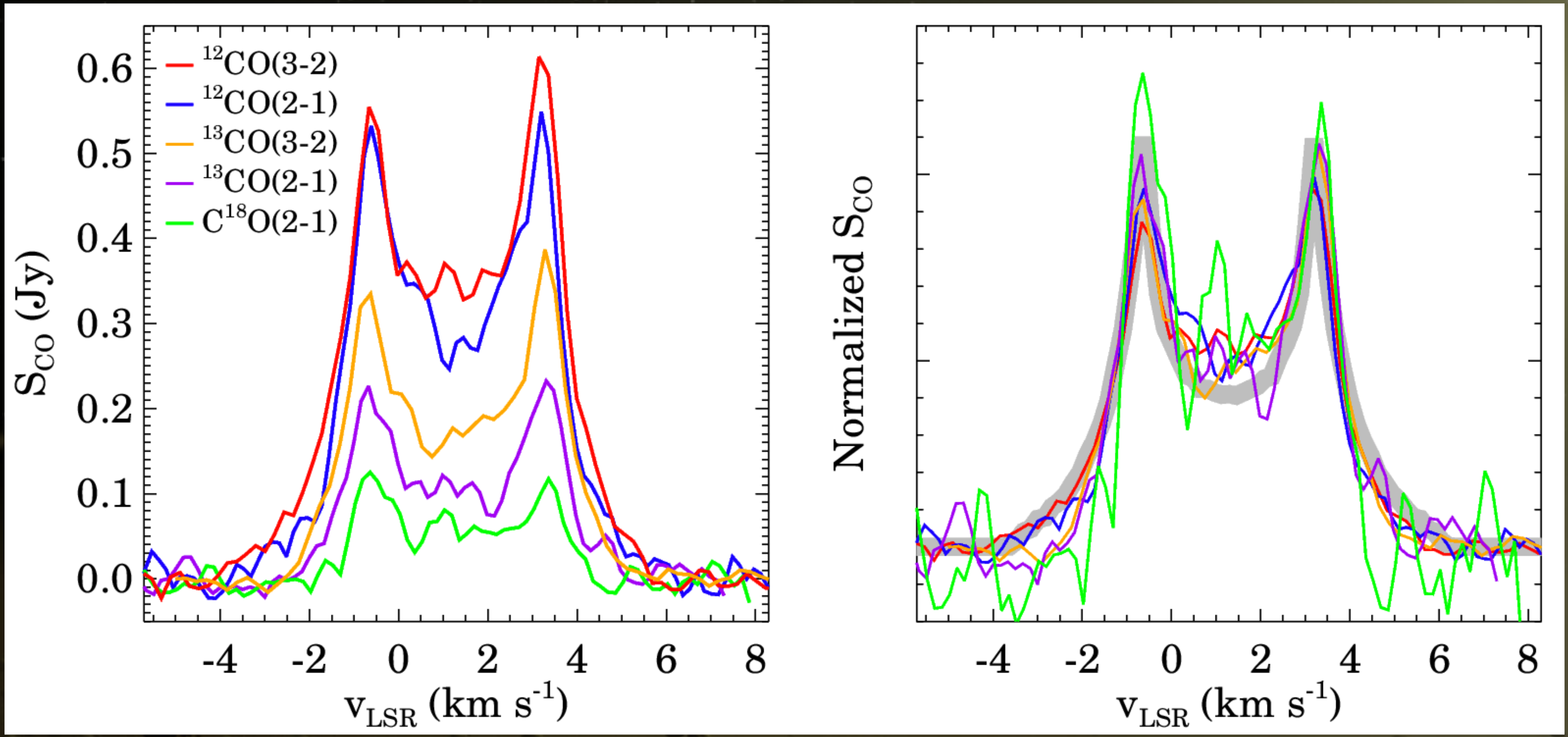
- r_{in} = 62 ± 13 AU
- r_{out} = 150 ± 47 AU
- i = 32.9 ± 3.1 deg
- p = − 2.4 ± 4.5
- s_{min} = 6 µm
- M_{dust} = 0.09 ± 0.03 $M_\oplus$



Moór et al. (2013)

Á. Kóspál: HD 21997

CO spectra



Kóspál et al. (2013)

Optical depth:

$\tau(C^{18}O) = 0.6$

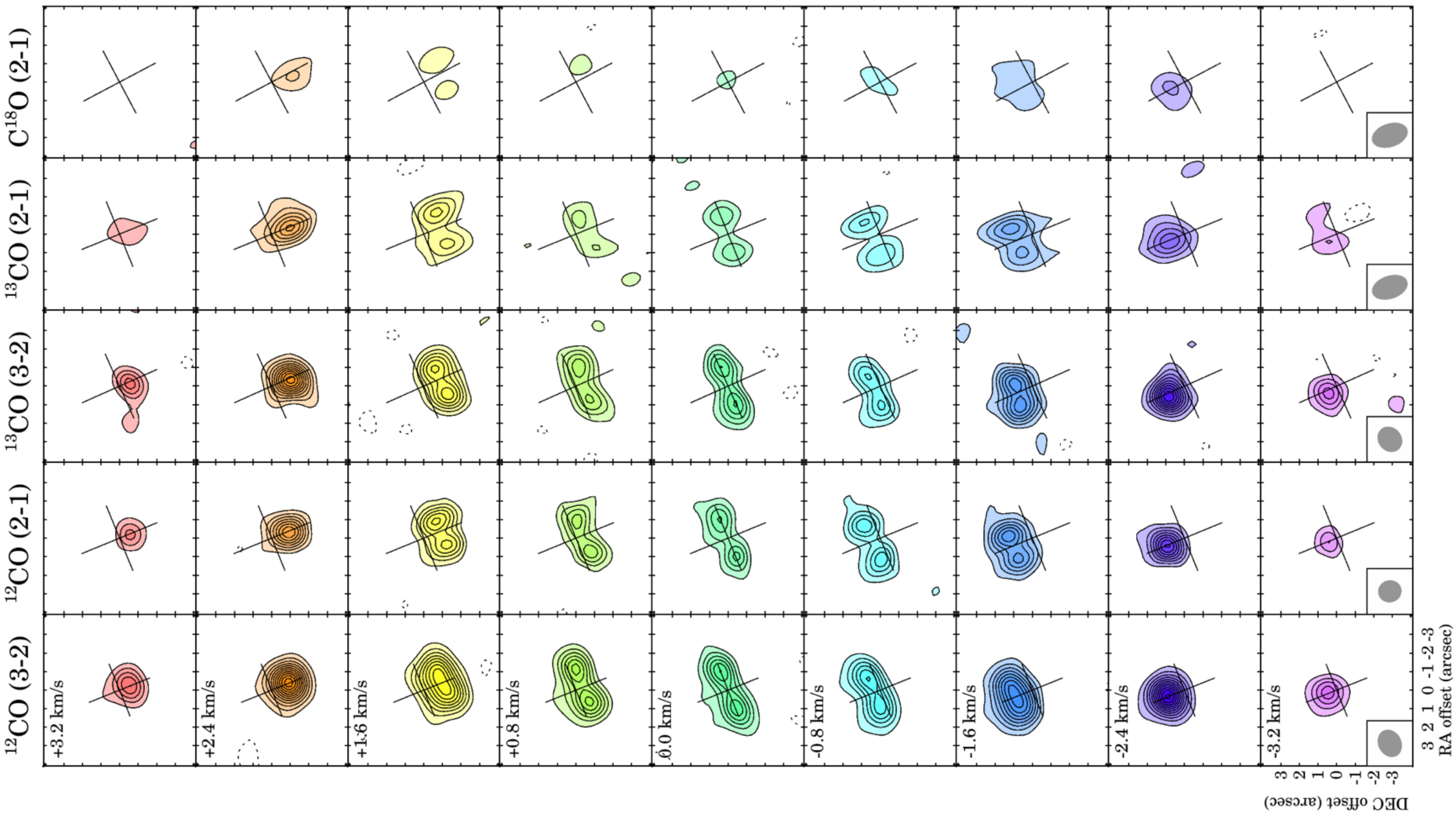
$\tau(^{13}CO) = 1.5 - 4.5$

$\tau(^{12}CO) = 100 - 300$

Temperature: 6 − 9 K

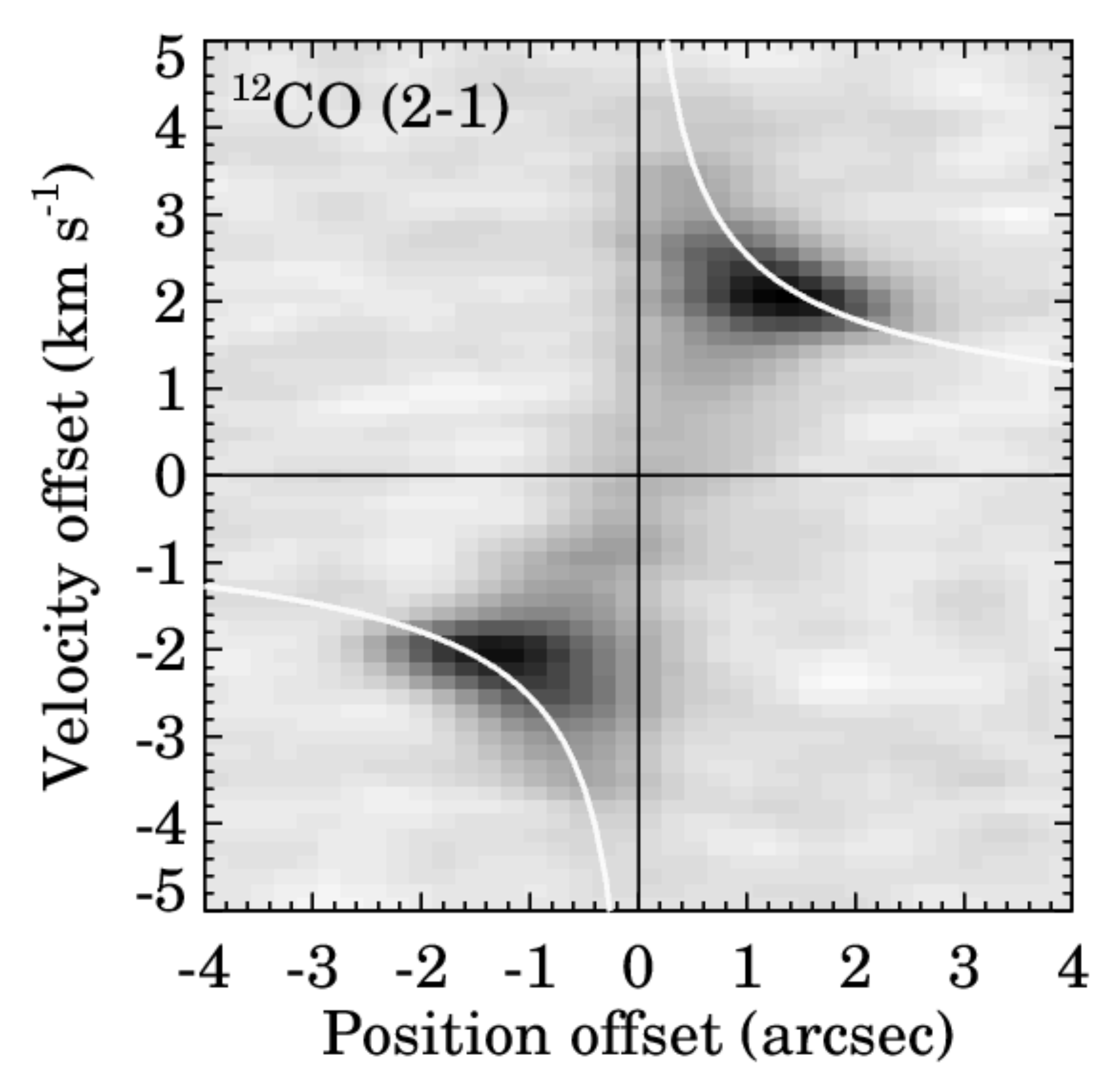
CO mass: 0.04 − 0.08 $M_\oplus$

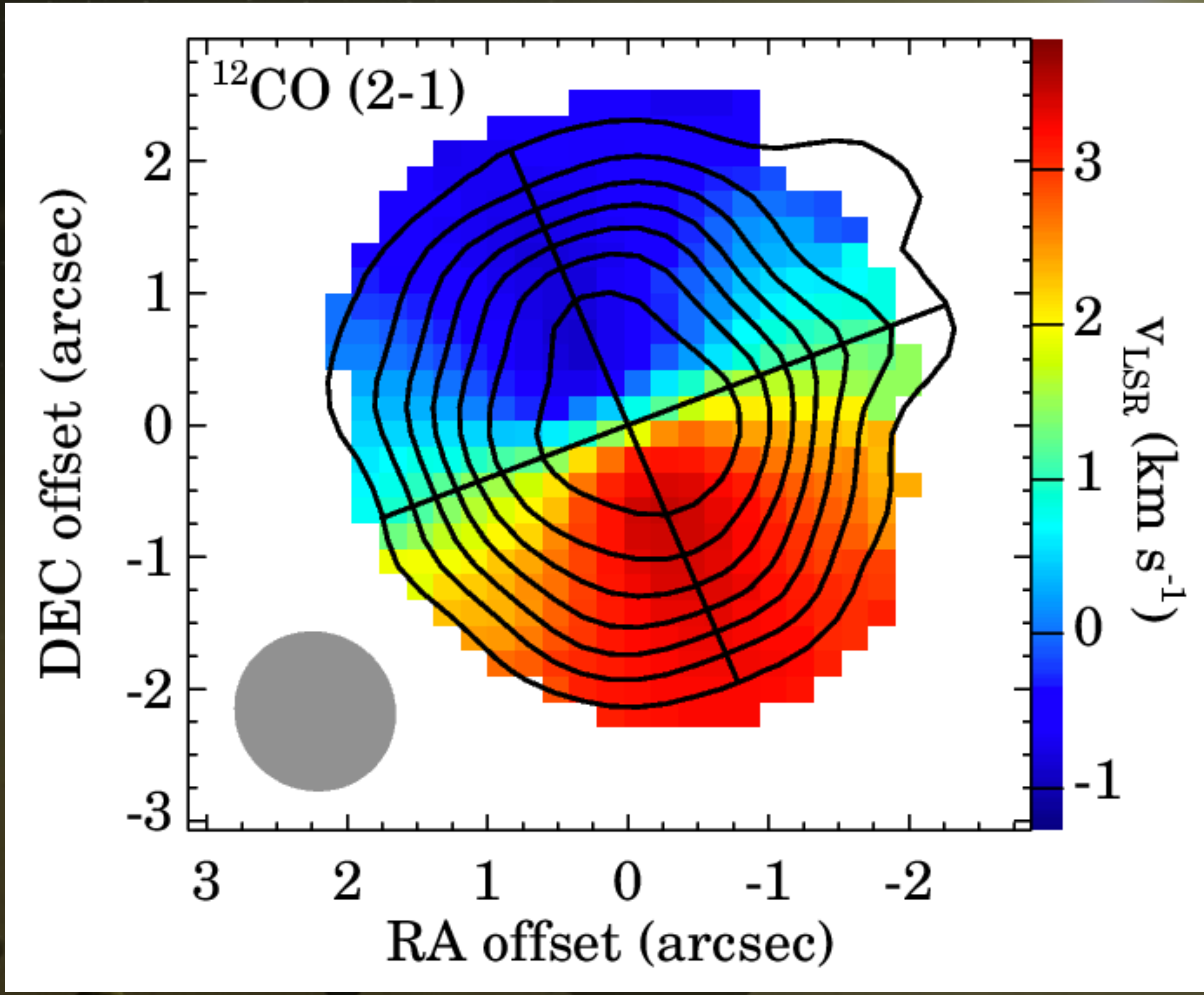
Channel maps



Kóspál et al. (2013)

PV diagram and velocity map





Kóspál et al. (2013)

Simple analytical disk model

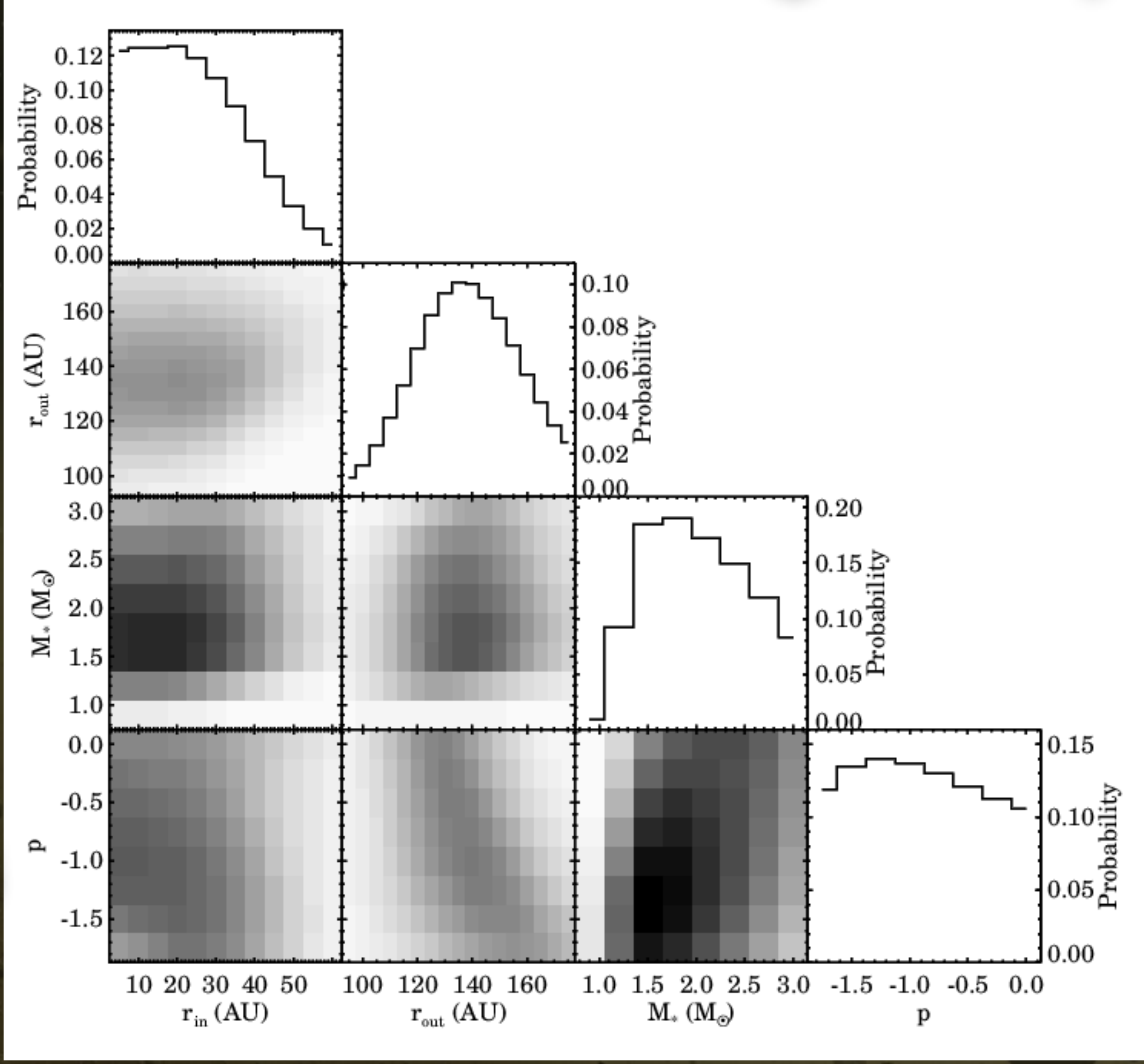
Non-physical model to reproduce the observed geometry of the CO emission

Five parameters:

- inner disk radius: r_{in}
- outer disk radius: r_{out}
- disk inclination: i
- stellar mass: M_*
- power-law exponent of the brightness profile: p

Altogether 104408 models

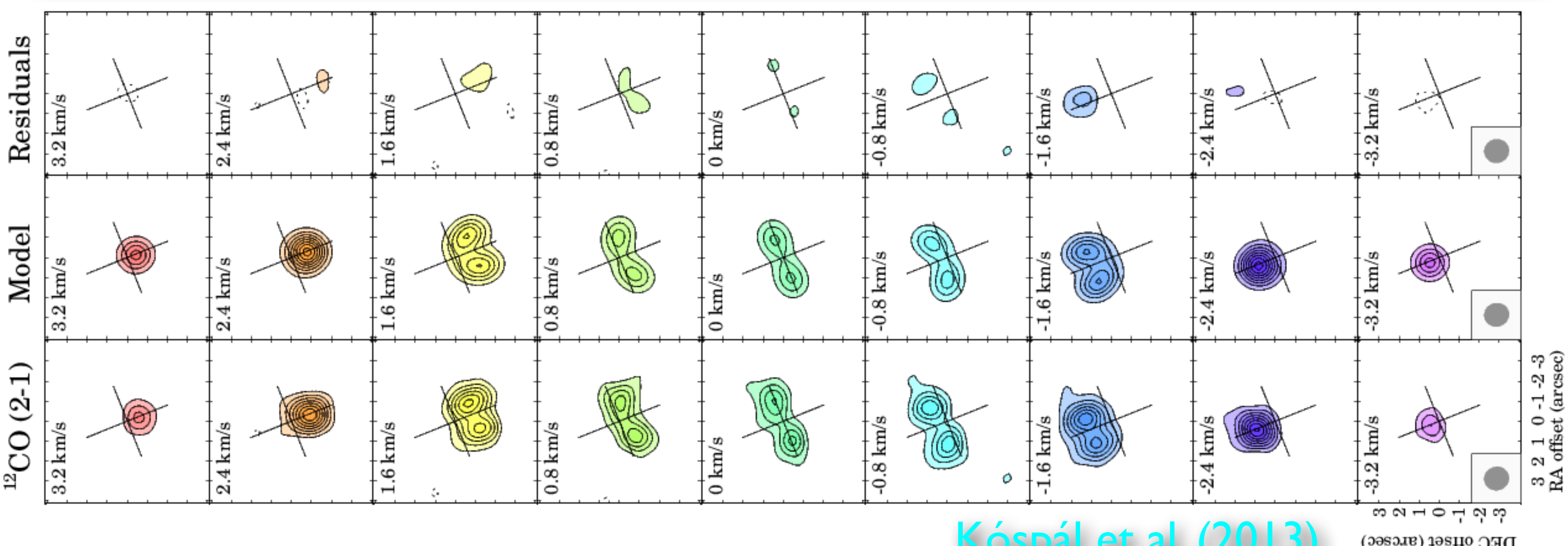
Bayesian analysis



Kóspál et al. (2013)

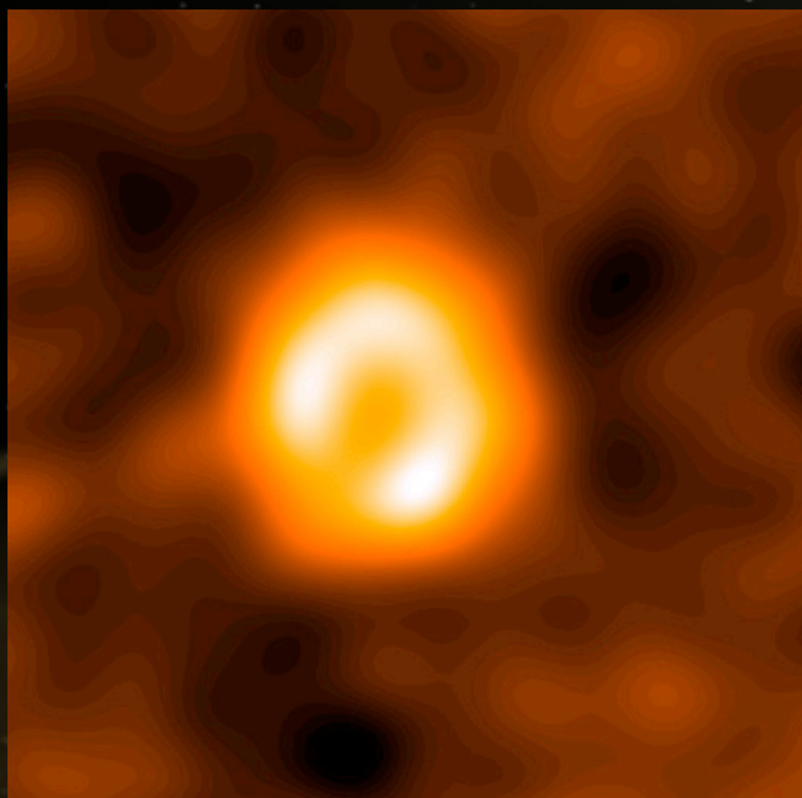
Best-fit disk model

Parameter	Unit	Explored range	Best value
Inner radius	AU	5 ... 60	< 26
Outer radius	AU	95 ... 175	138 ± 20
Inclination	deg	25 ... 39	32.6 ± 3.1
Stellar mass	$M_\odot$	0.9 ... 3.0	$1.8^{+0.5}_{-0.2}$
Brightness exponent	–	0 ... –1.75	–1.1 ± 1.4



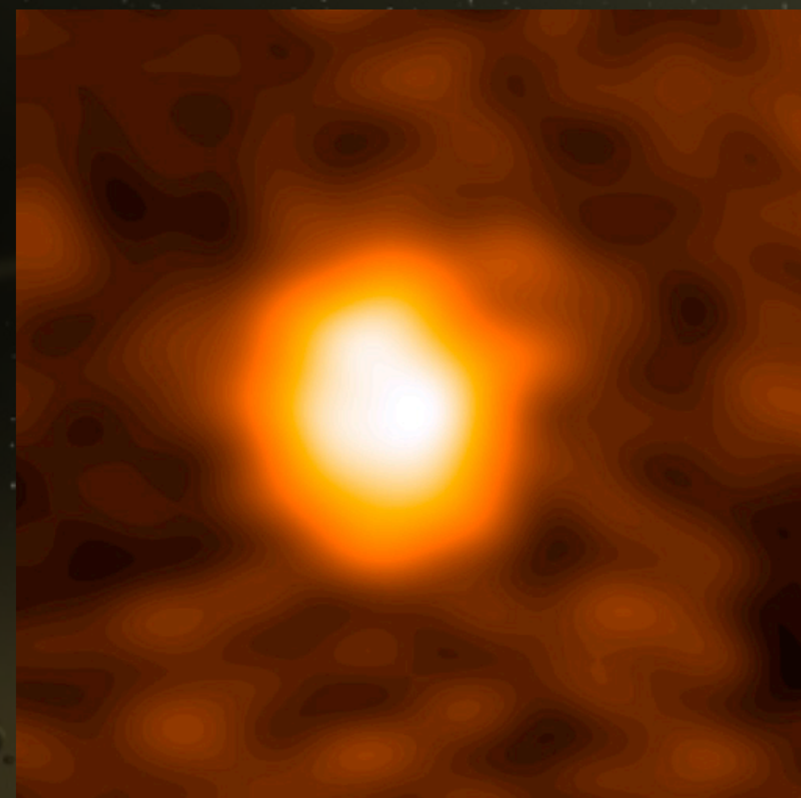
Kóspál et al. (2013)

Dust and gas are not co-colocated!



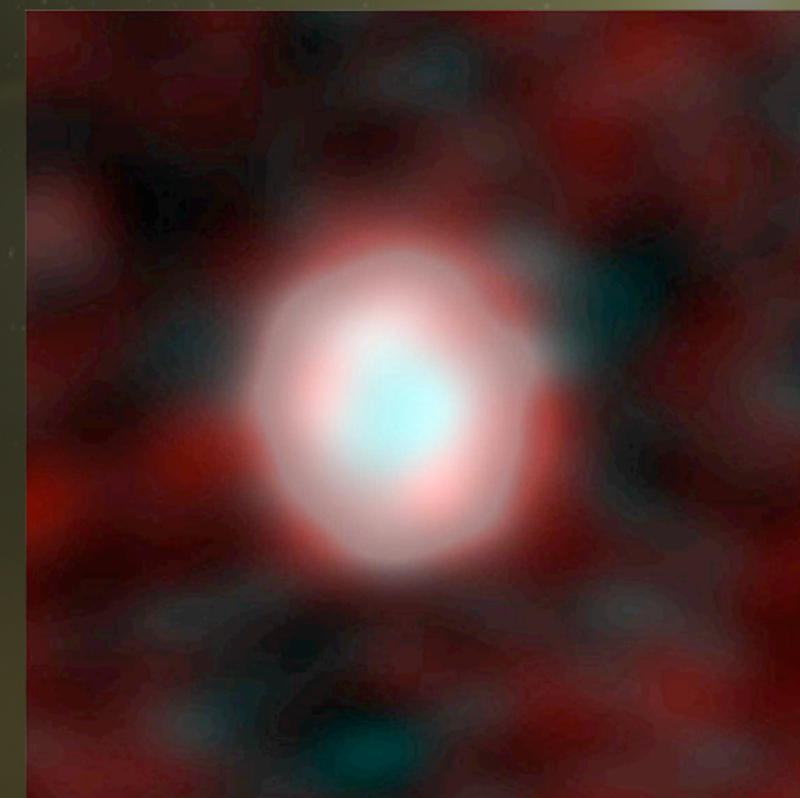
Dust disk:

r_{in} = 62 ± 13 AU



Gas disk:

r_{in} < 26 AU



Composite image from our MPIA press release:
Dust in red
Gas in cyan

The origin of the CO gas

Secondary origin: not likely

- Debris disk with pure secondary gas
- No H_2 in the disk, only CO (and maybe some H_2O)
- CO lifetime: < 30 000 yr for ^{12}CO, < 6000 yr for $C^{18}O$
- Gas production rate needed: 10^{19} kg/yr
    - Typical gas production rate in solar system comets: $10^9 - 10^{10}$ kg/yr
    - Continuous gas production of $10^{10} - 10^{11}$ comets needed
    - The complete destruction of 6000 Hale-Bopp-like comets every year
- If both dust and gas are secondary, they should be co-located

The origin of the CO gas

Primary origin: our preferred scenario

- Hybrid disk: primordial gas + secondary dust
- CO survived for 30 Myr → needs effective shielding (H_2)
- Assuming CO/H_2 of 10^{-4}, CO lifetimes are 2 orders of magnitude higher than without H_2 shielding
- Total gas mass (including H_2): 26 − 60 $M_\oplus$
- Gas-to-dust ratio: 300 − 700
- Explains why the dust and gas are not co-located
- Number density in the midplane is high enough for collisional excitation → LTE → low excitation temperatures cannot be explained

Further plans

- Obtain better spatial resolution CO observations → where is the inner edge of the gas disk?
- Look for other molecular species → confirm primordial scenario; measure abundance ratios
- Understand disk chemistry → How could the gas be so cold? How could it have survived for so long?
- Look for more gaseous debris disks → is HD 21997 the rule or the exception? → General picture of gas evolution

Collaborators

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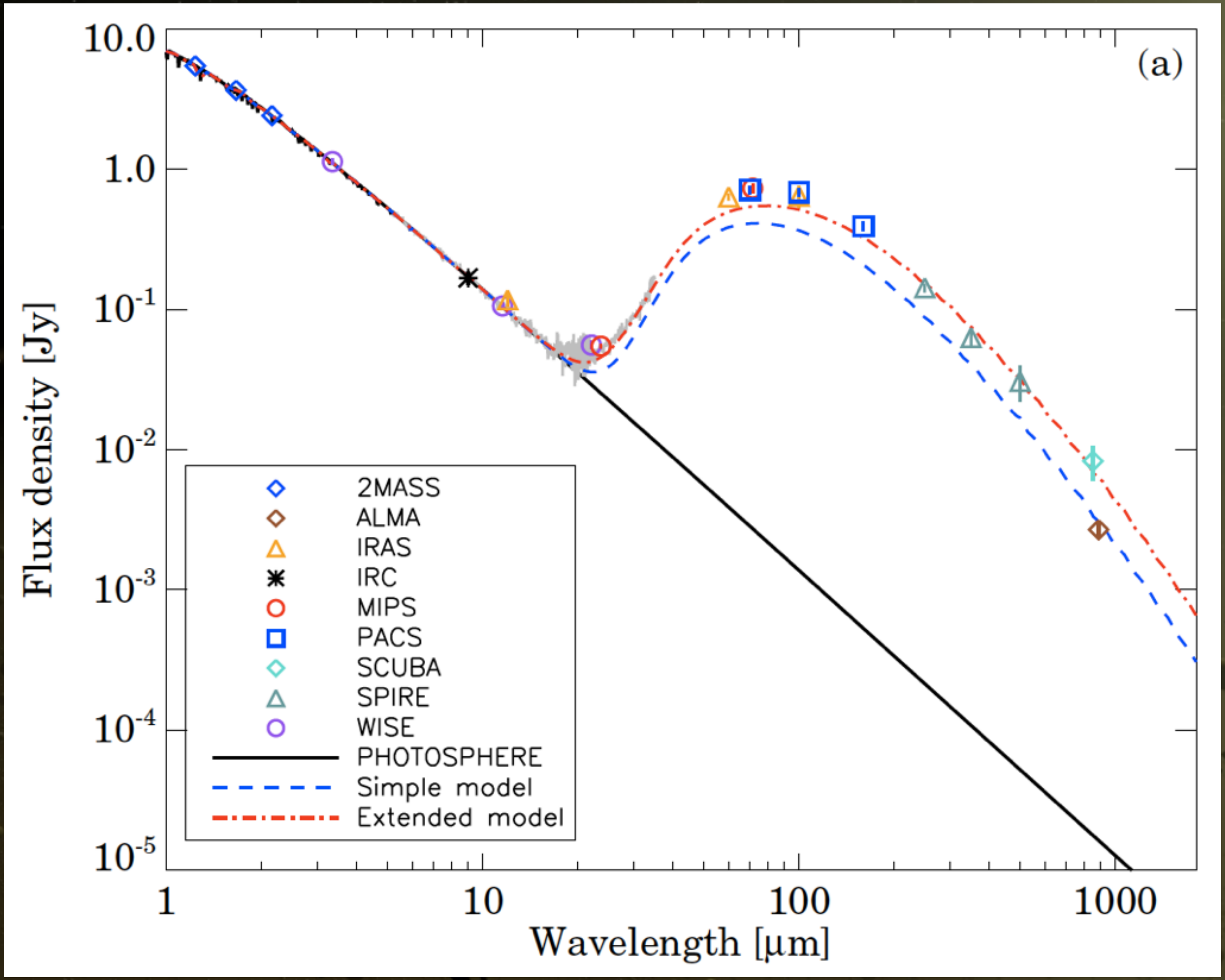
To be continued...
Background image: NASA/JPL-Caltech/T. Pyle (SSC)

The age of HD 21997

Reference	Age	Method
Zuckerman & Song 2004	100 million	location on the HRD
Rhee et al. 2007	50 million	location on the HRD, UVW
Moór et al. 2011	30 million	moving group membership
Tetzlaff et al. 2011	13 million	PMS isochrone
Zorec et al. 2012	238 million	MS isochrone

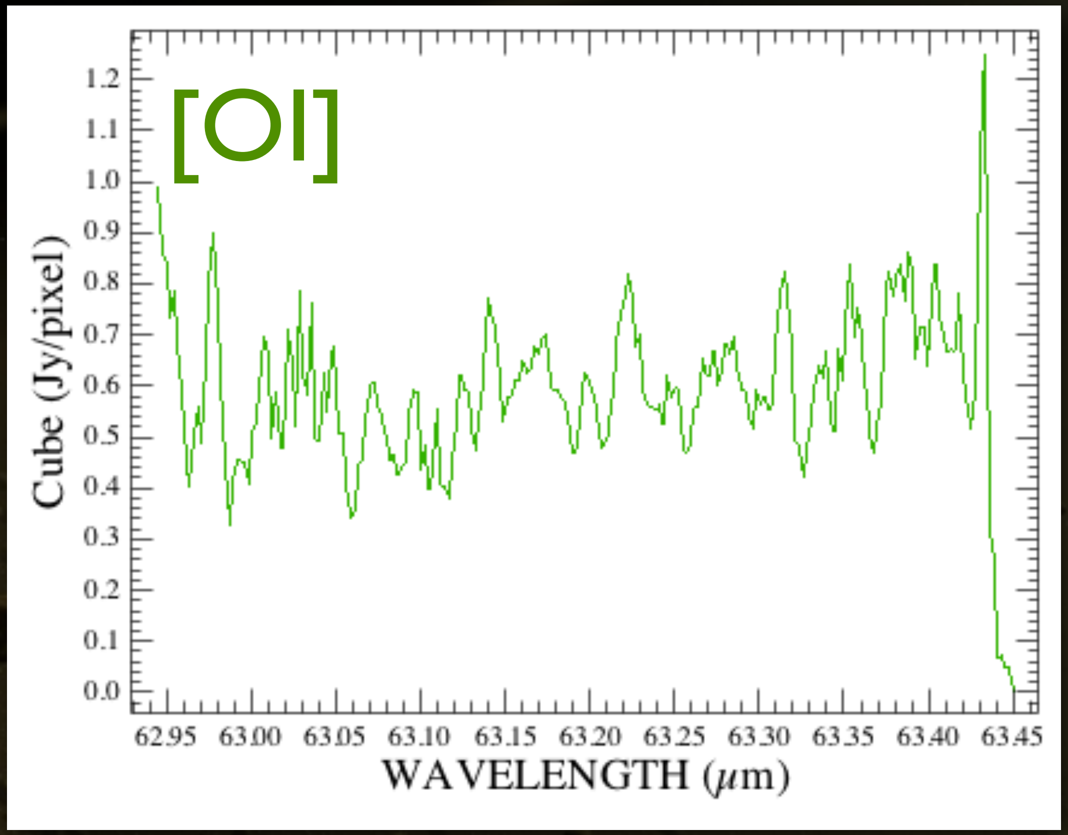
The SED of HD 21997

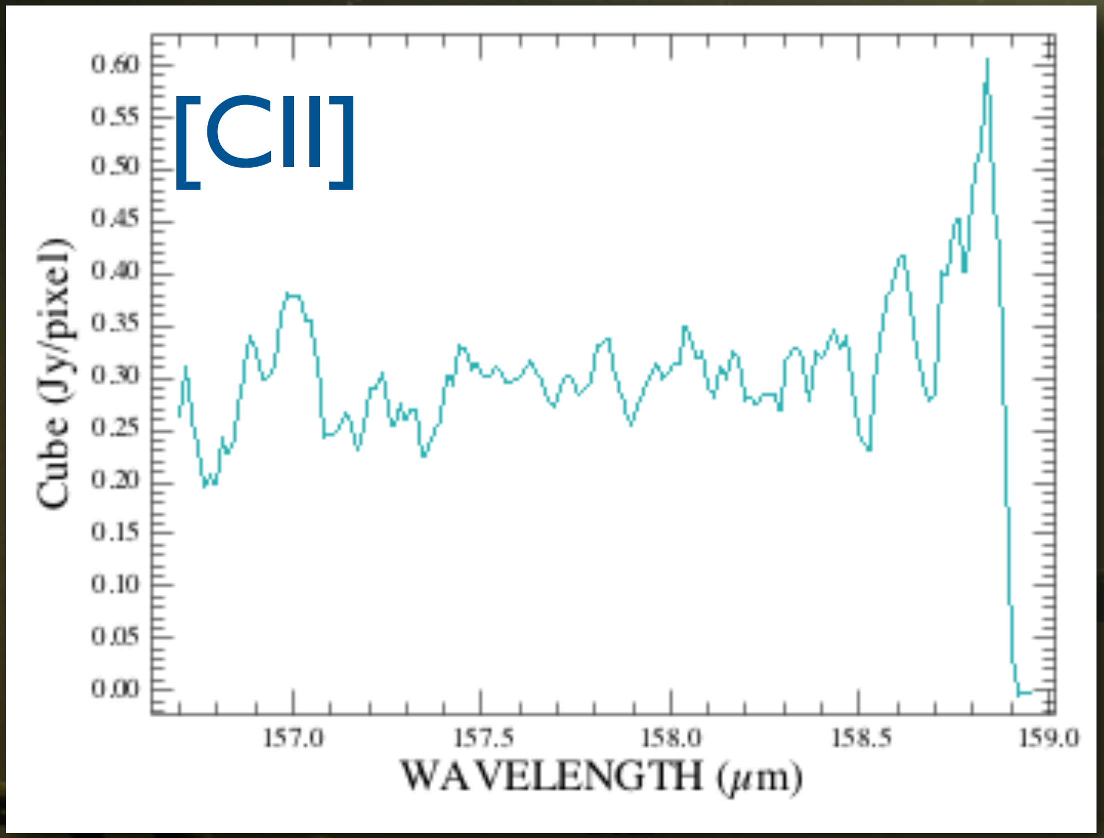


Á. Kóspál: HD 21997

Atomic gas?

Atomic O or C emission is not detected with Herschel





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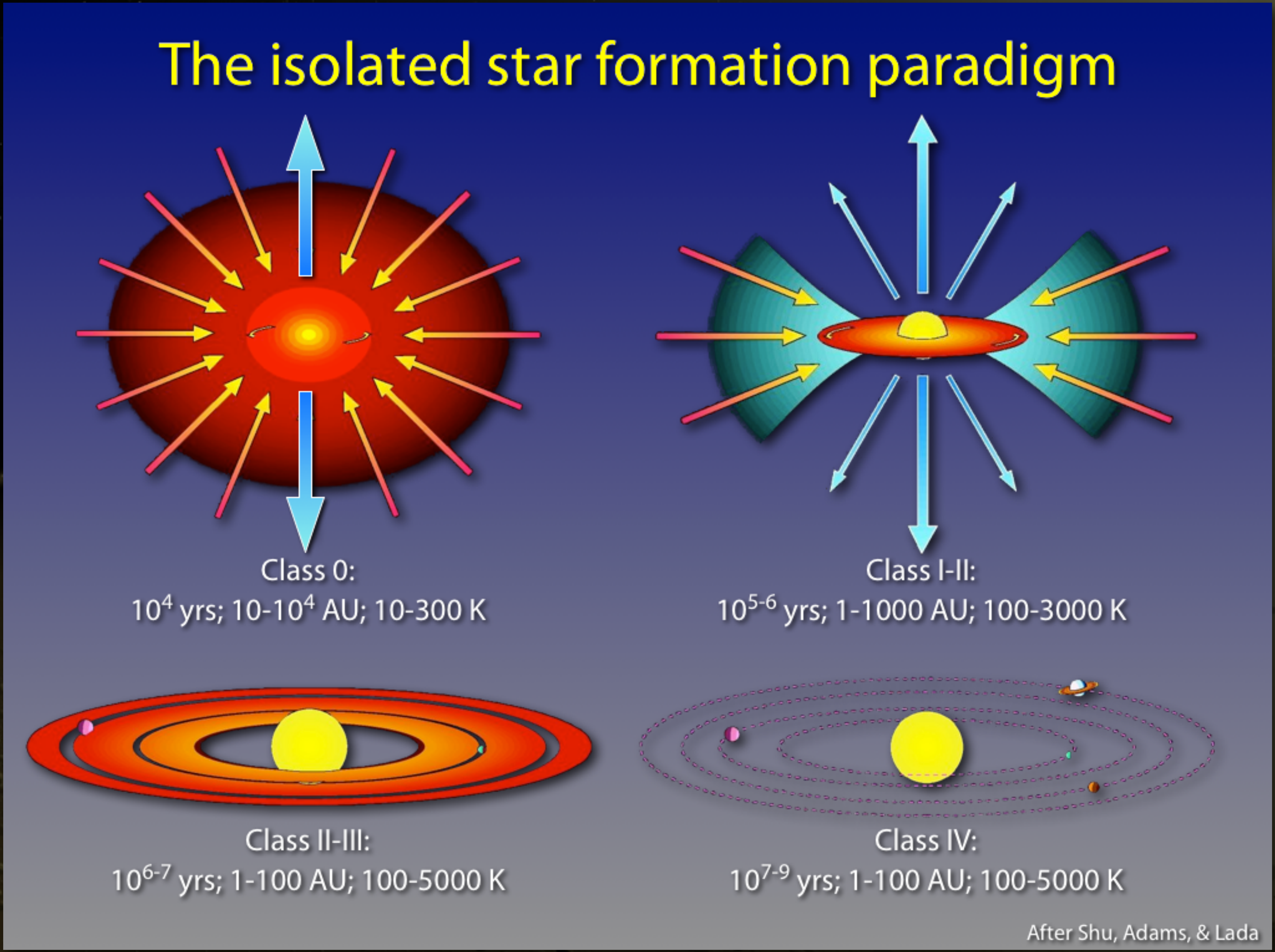

Figure courtesy of Mark McCaughrean