Gas inside the 97 au cavity around the transition disk Sz 91: ALMA + Herschel

MAD

Millenium Nucleus For Disk Research with Alma

Héctor Cánovas (U. Valparaiso)

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Claudio Cáceres (U. Valparaiso)

Francois Ménard (U. Chile, Santiago)

Christophe Pinte (U. Chile, Santiago)

Geoff Mathews (U. Hawaii)

Lucas Cieza (U. Diego Portales, Santiago)

Simon Cassasus (U. Chile, Santiago)

Antonio Hales (ALMA)

Jonathan Williams (U. Hawaii)

Pablo Roman (U. Chile, Santiago)

Adam Hardy (Valparaiso)

1) The "Transition Disk" class

2) Introducing Sz 91

3) ALMA result & SED

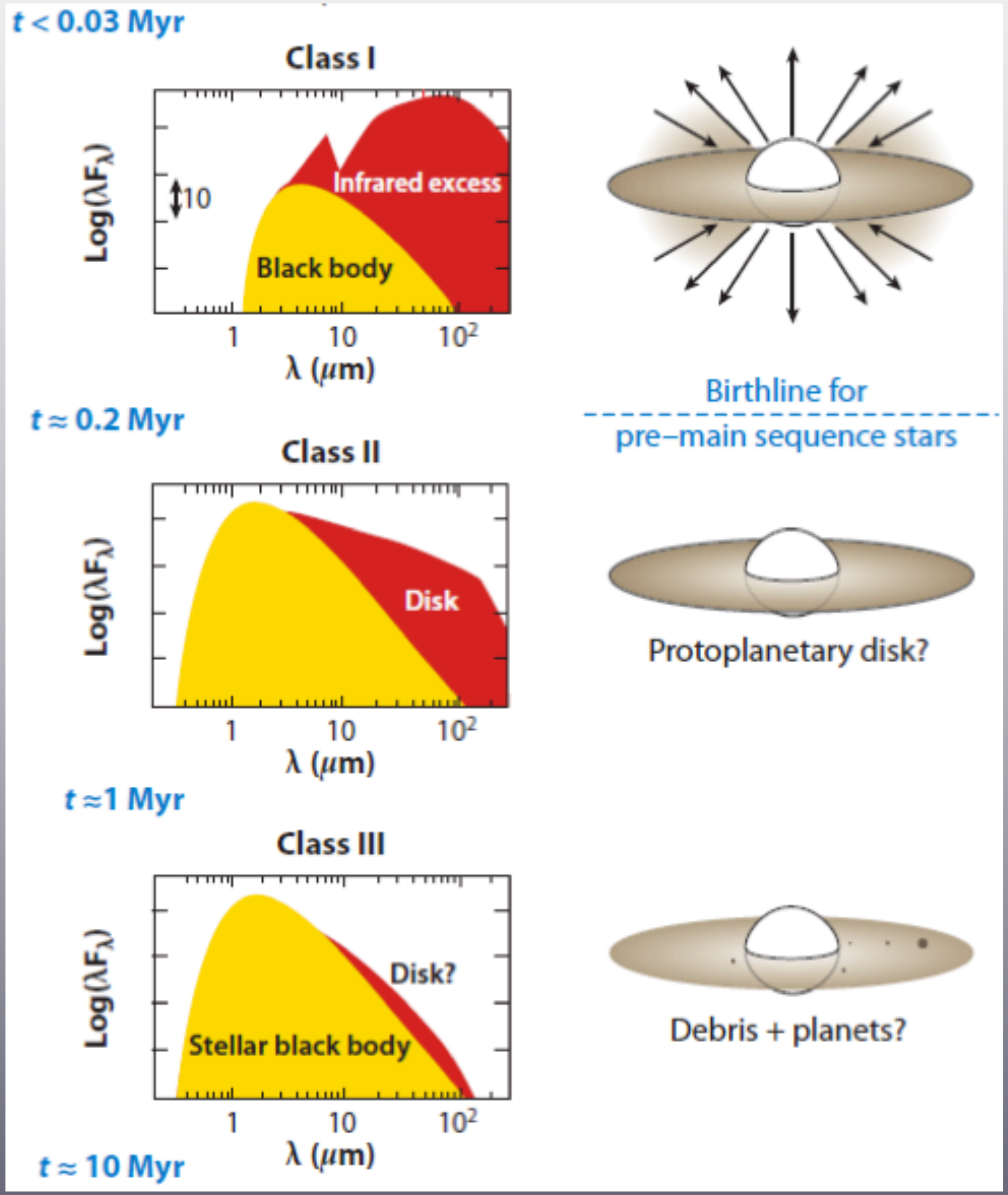
4) Radiative Transfer Modeling

5) Results & Implications for Planet Formation

MAD

Universidad de Valparaíso CHILE

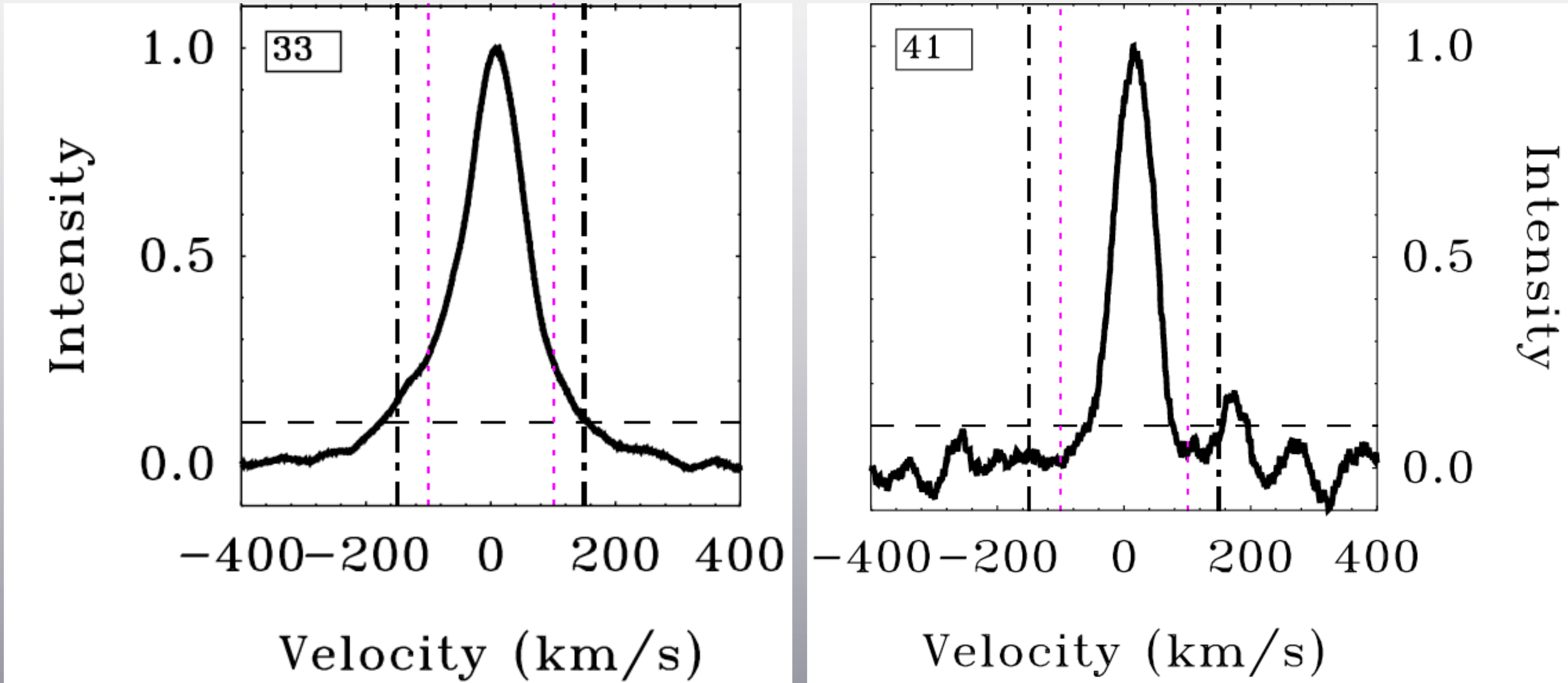
Protoplanetary Disks: SED



1. SED is KEY to identify protoplanetary disks
2. Disk's evolution is FAST.
3. Protoplanetary disks are the BIRTHPLACES of planets.

Charles Lada 1987

Early Stellar Evolution: ACCRETION (Hα)



Accreting T Tauri (CTT's)

NON-Accreting T Tauri (WTT's)

Adapted from Cieza et al. 2012

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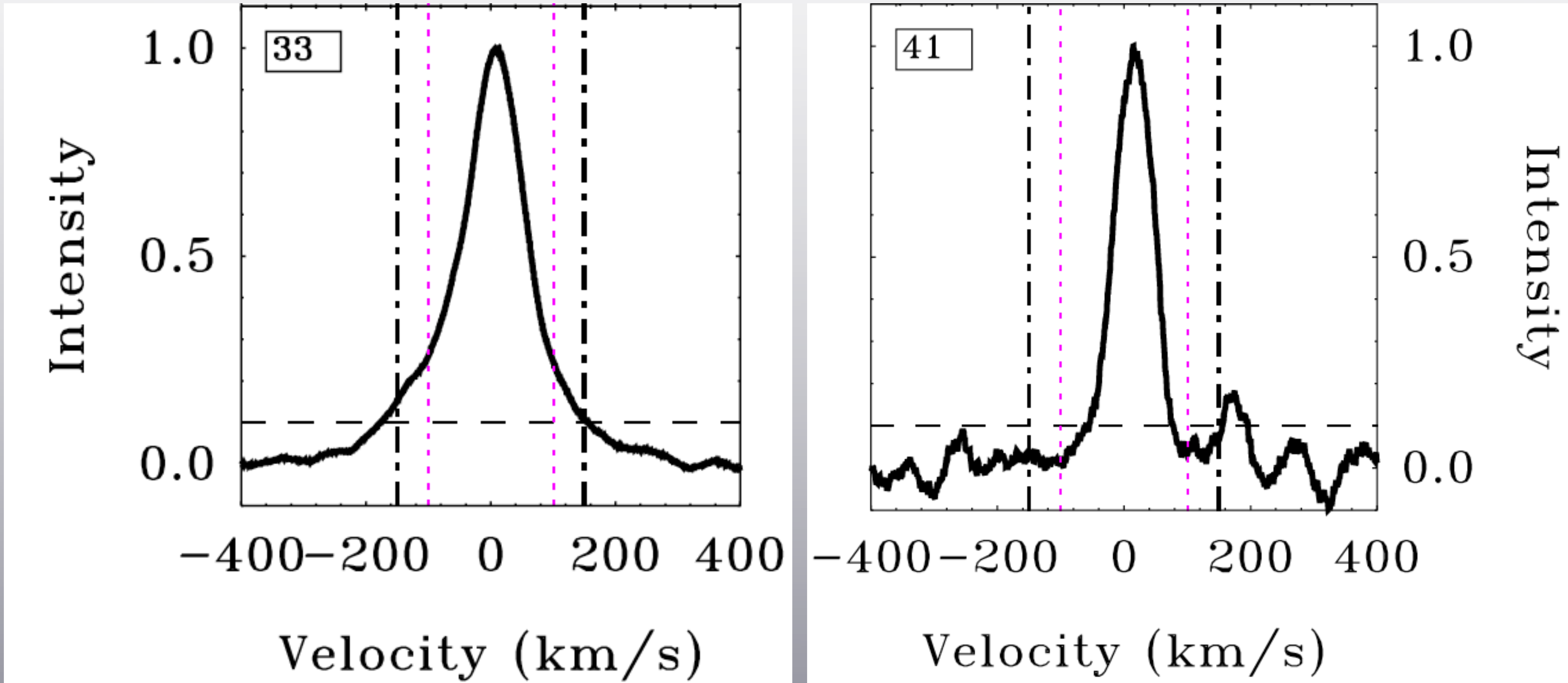

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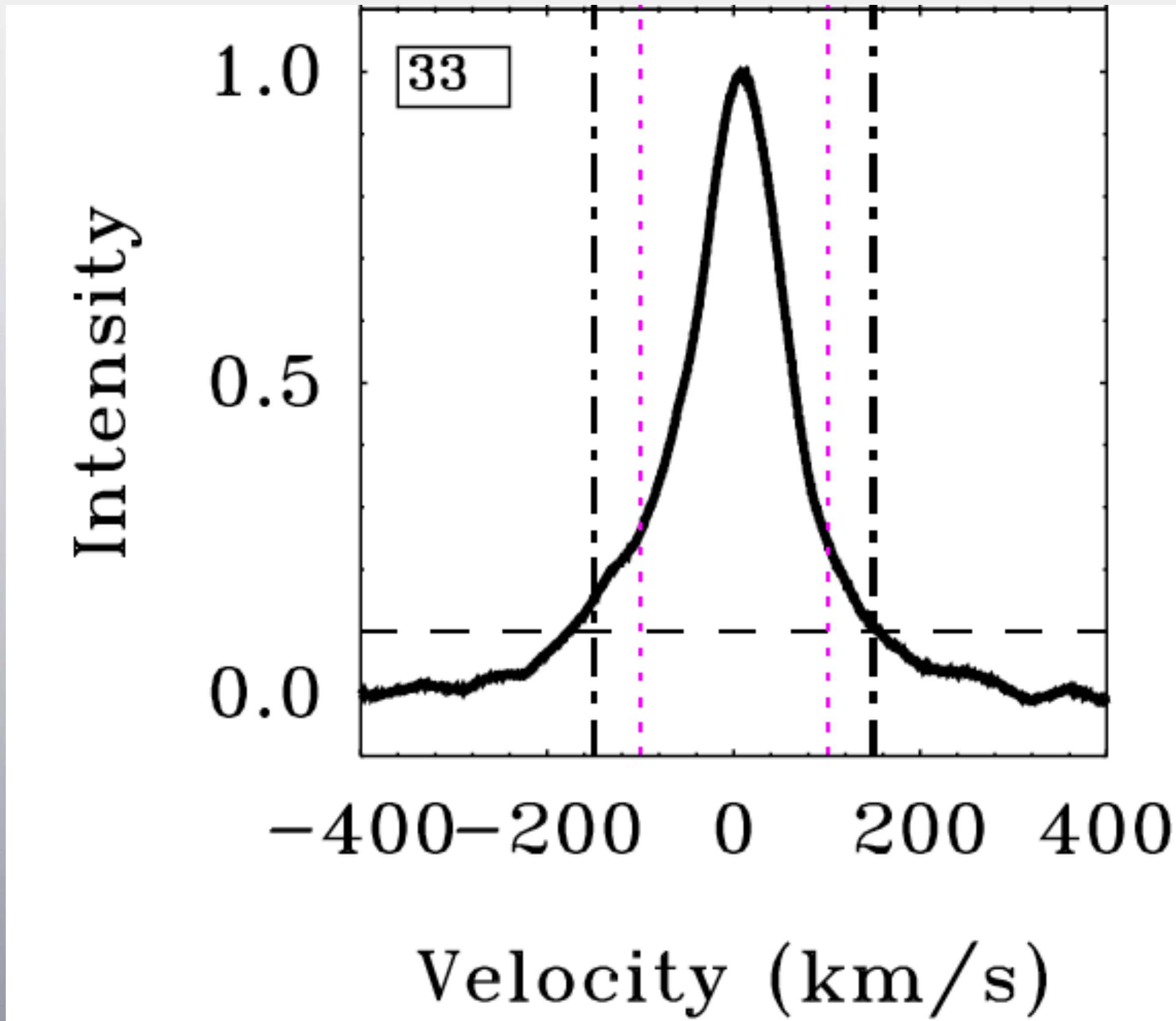

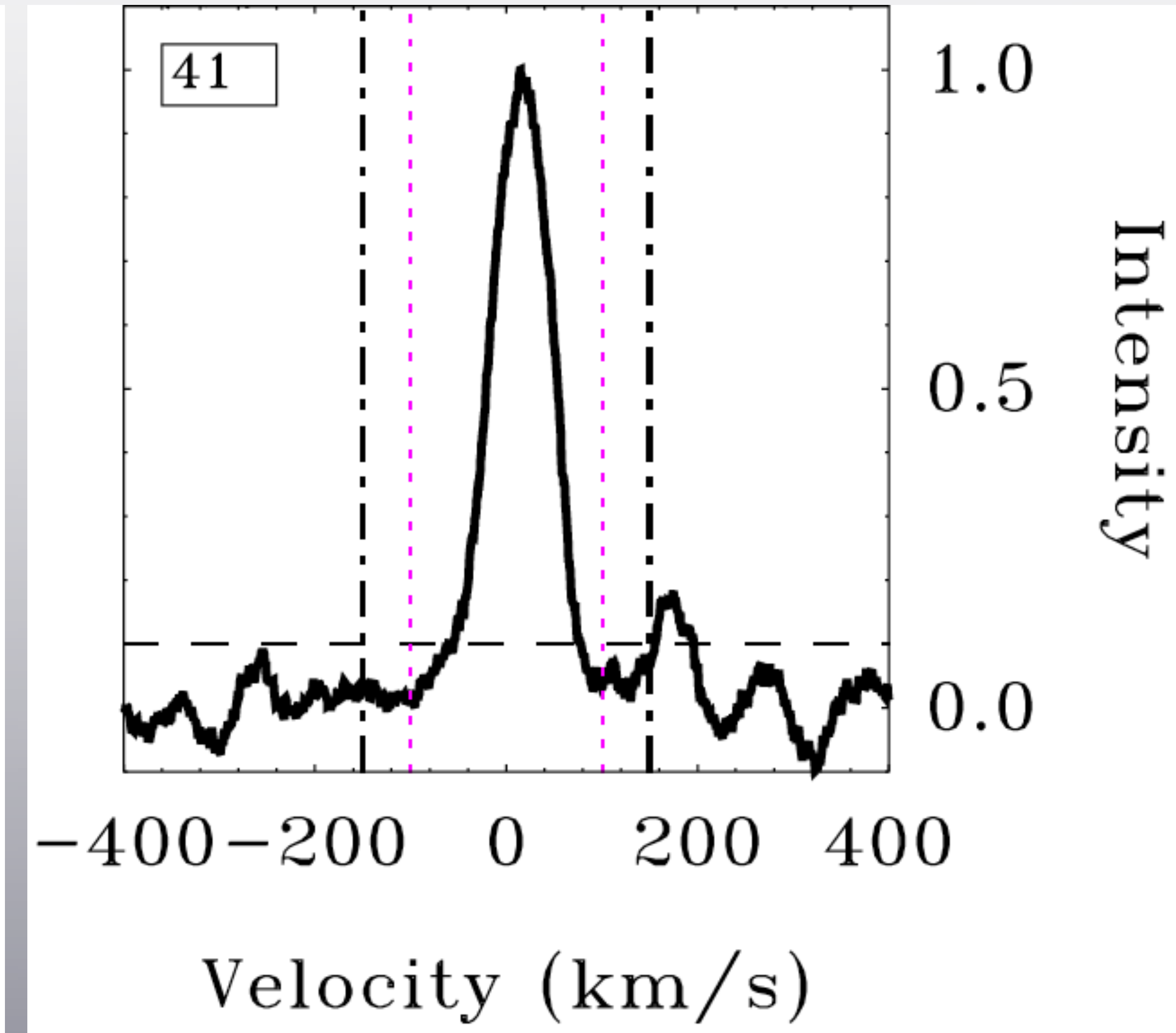

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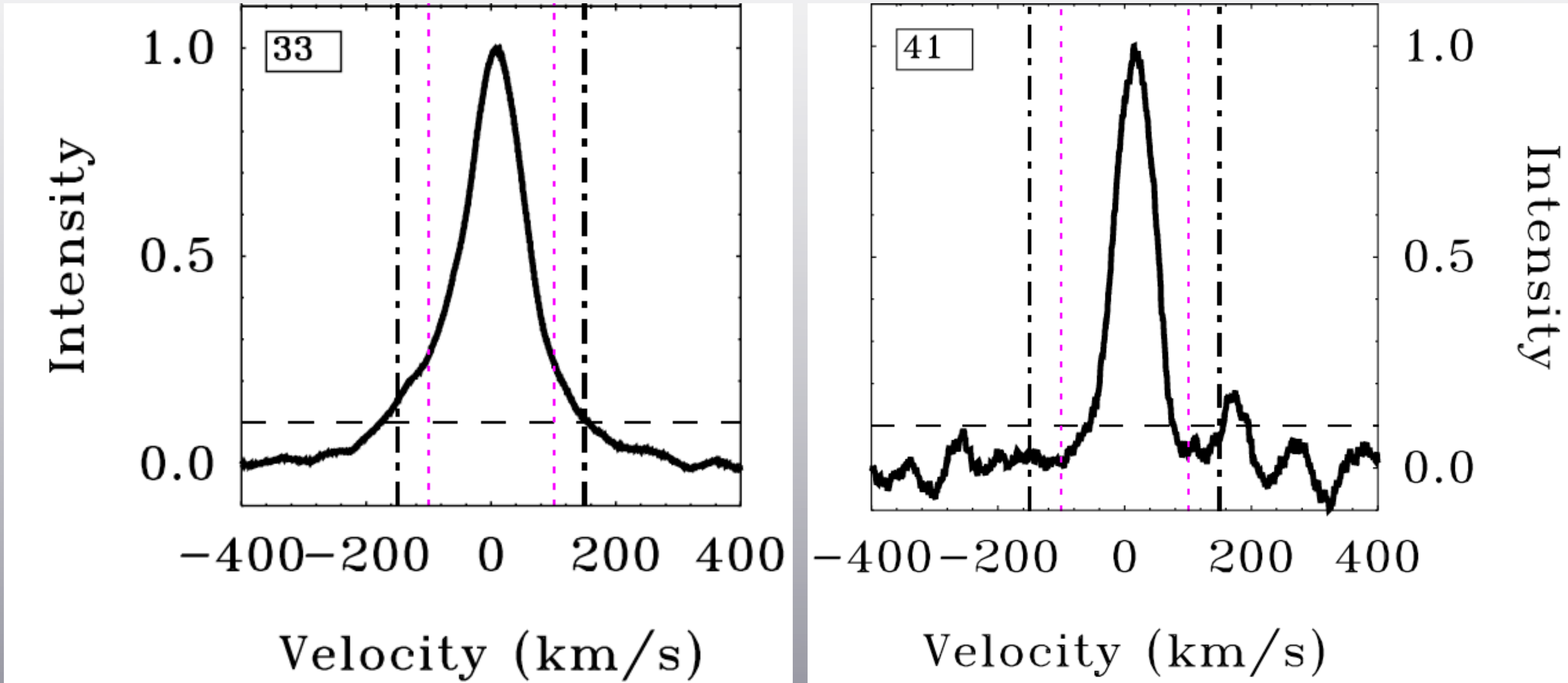

Accreting T Tauri (CTT's)

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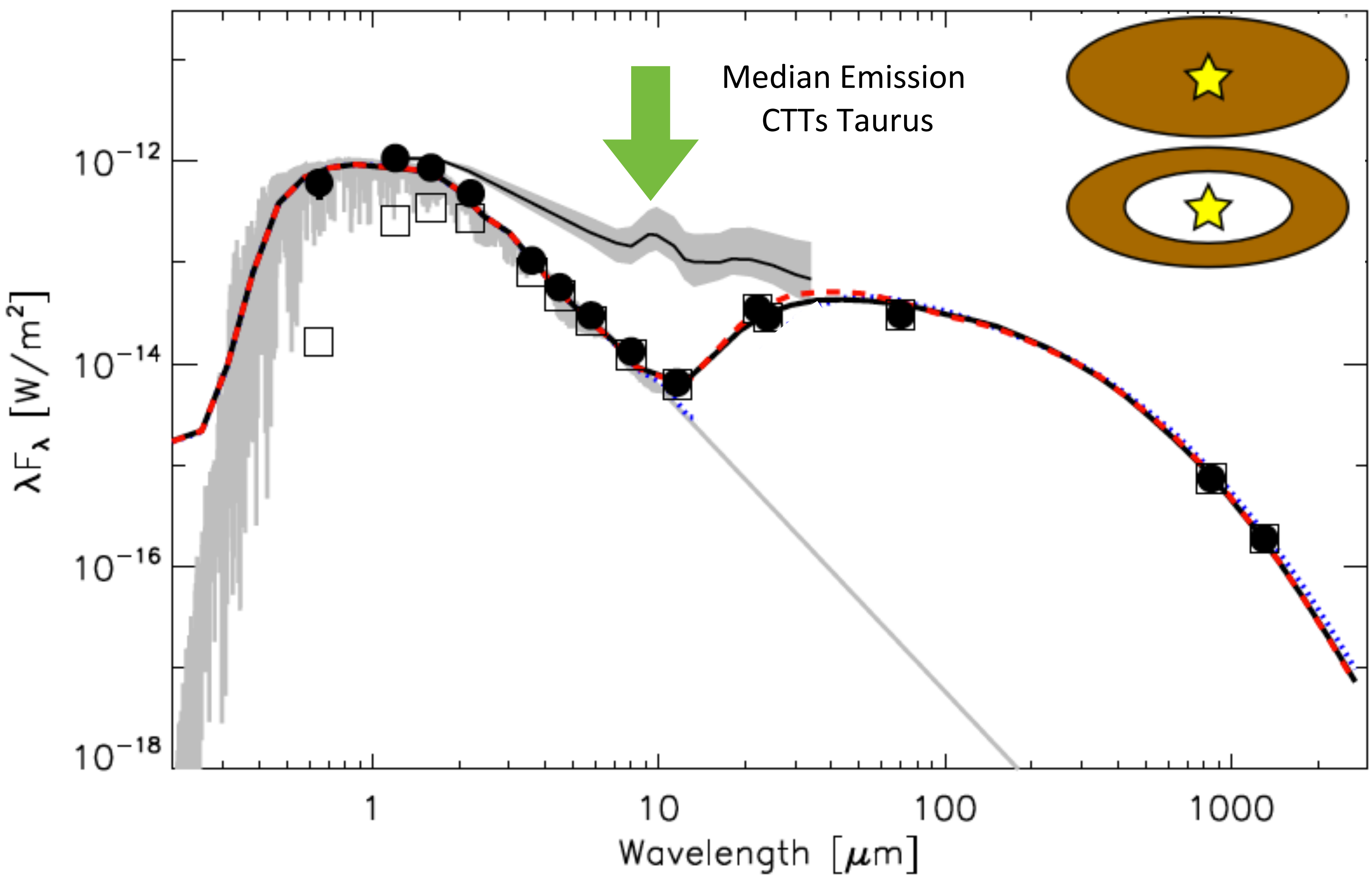
TD's??

Adapted from Cieza et al. 2012

Transition disks: flux depletion at NIR



SED Adapted from Cieza et al. 2012, Strom et al. 1989

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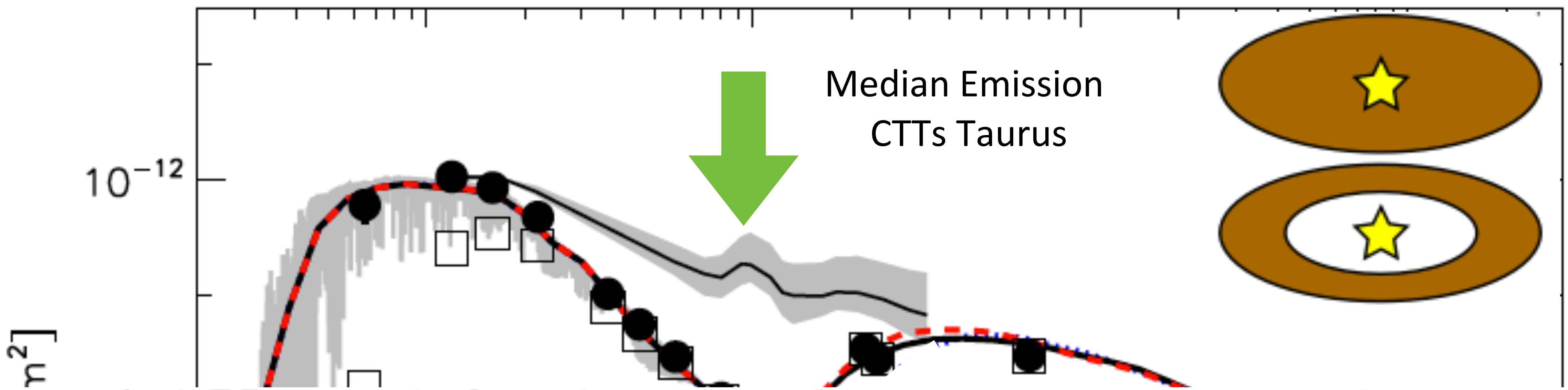

$r > 1$ AU), and the absence of excess emission at $\lambda < 10$ μm (which implies absence of warm dust in the inner disk, $r < 1$ AU) may diagnose *disk clearing* in the inner regions of the disk. If so, these observations may represent the first astrophysical evidence of disks *in transition* from massive, optically thick structures that extend inward to the stellar surface, to low-mass, tenuous, perhaps post-planet-building structures.

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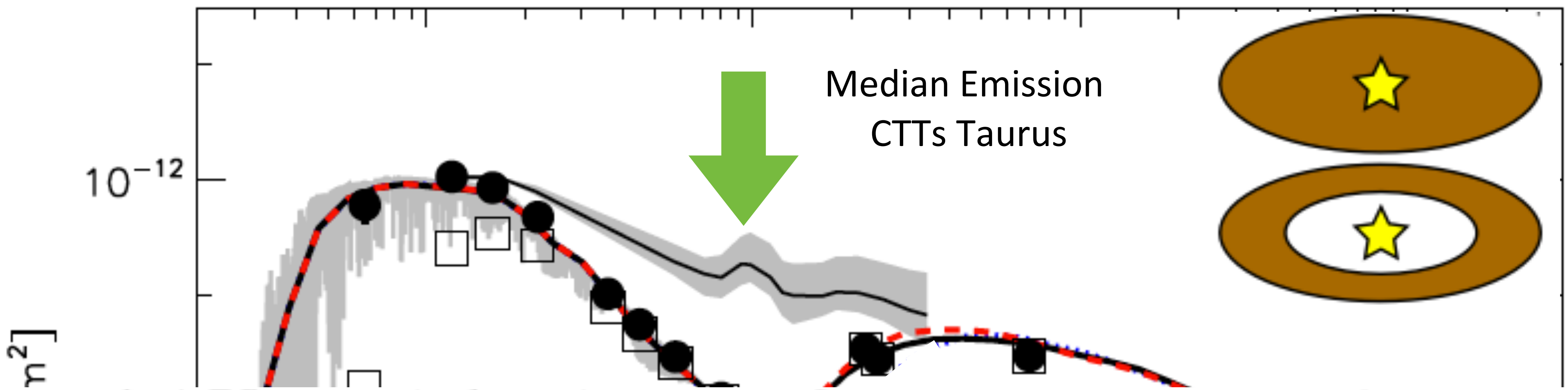

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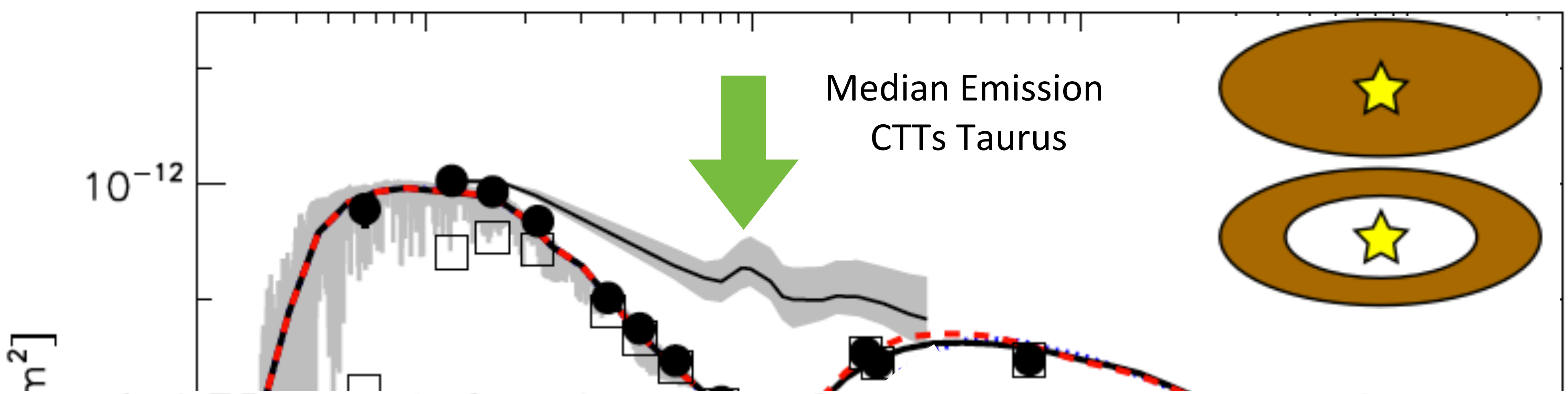

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Wavelength [μm]

SED Adapted from Cieza et al. 2012, Strom et al. 1989

"The state-of-the-art": direct images of TDs

HD 142527, NaCo/VLT

HD 135344, GPI/Gemini

MWC 758, SPHERE/VLT

HD 135344, MagAO/Magellan

Canovas et al. 2013, Wahhaj et al. 2015, Menard et al. (in prep.), SPHERE consortium

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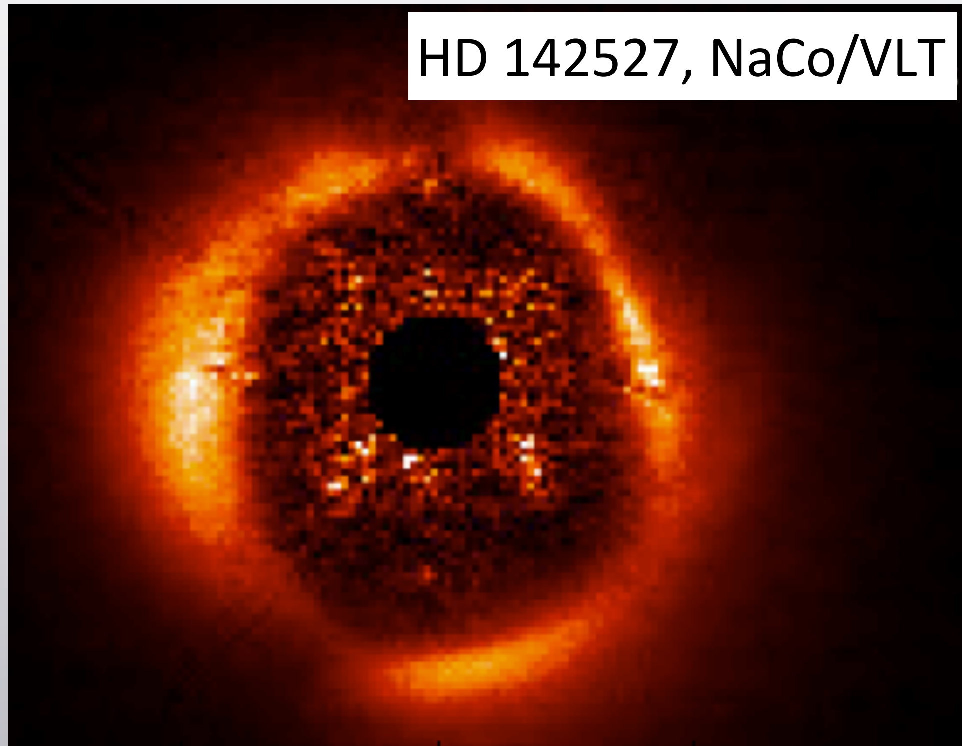
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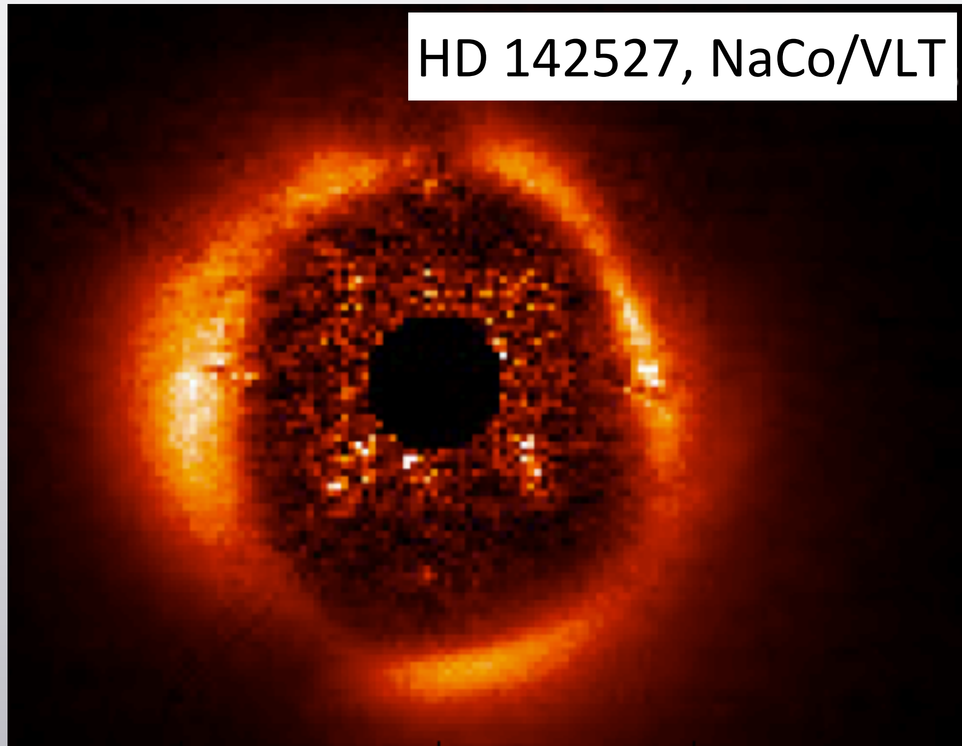

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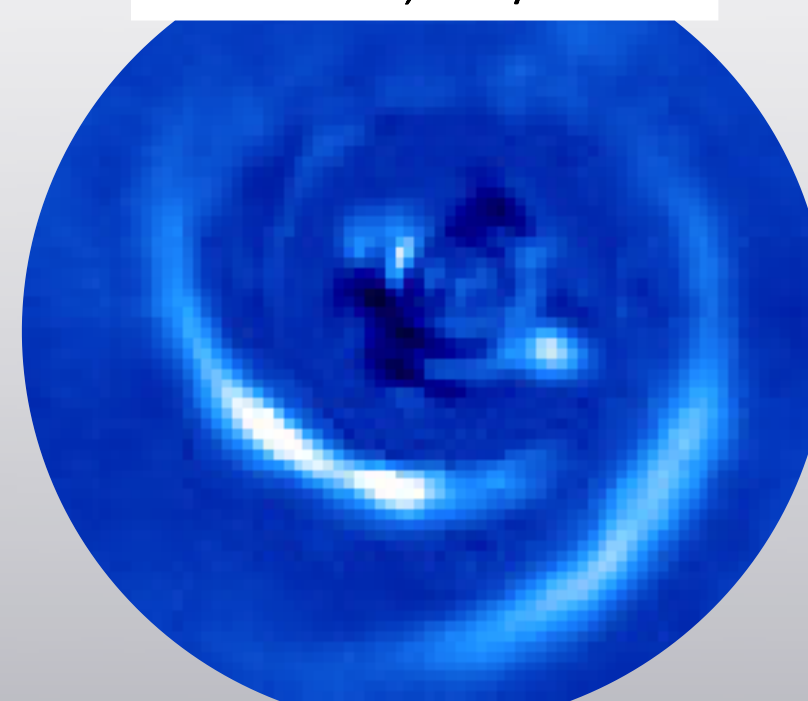

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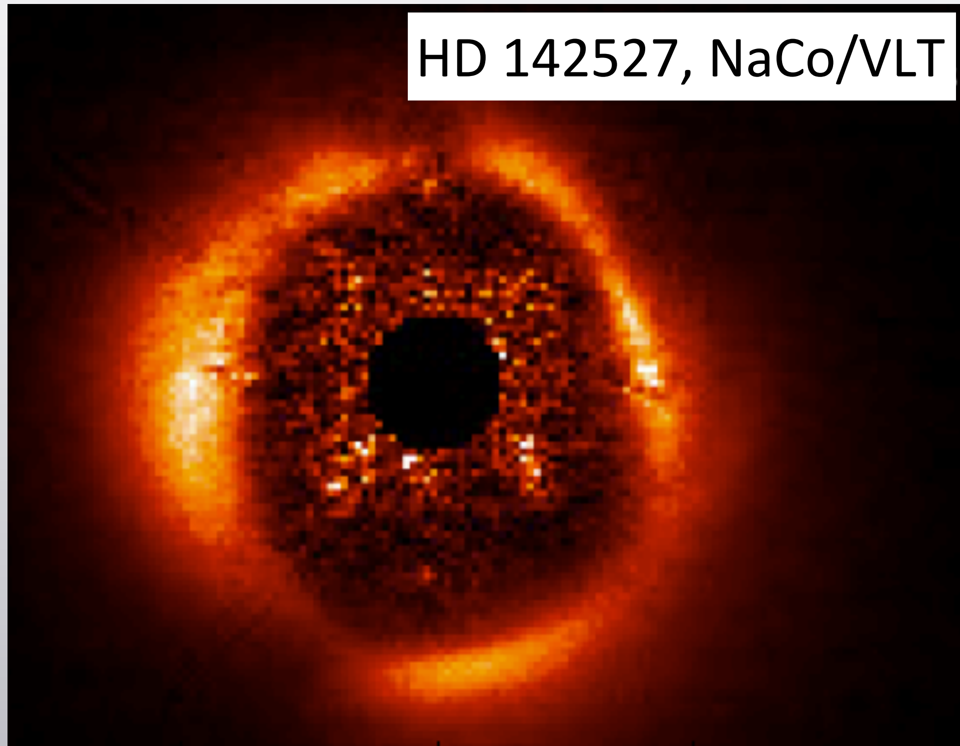

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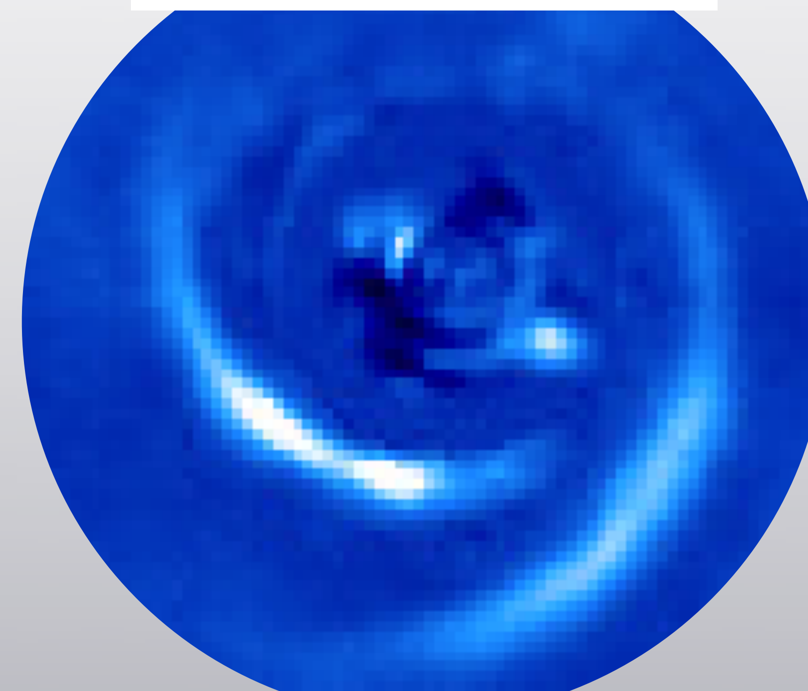

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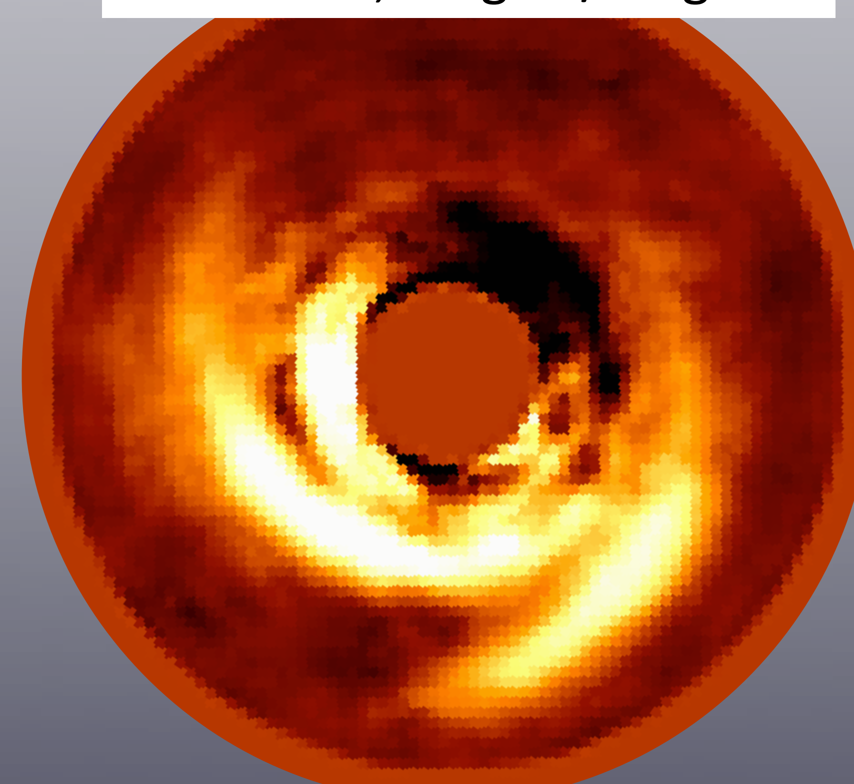

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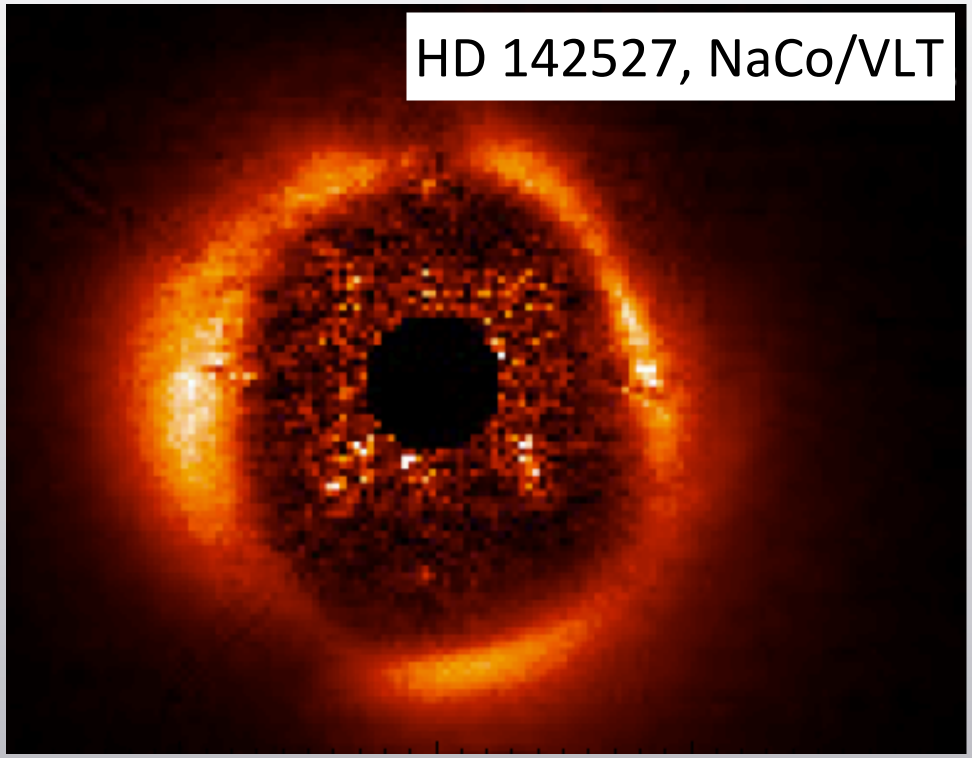

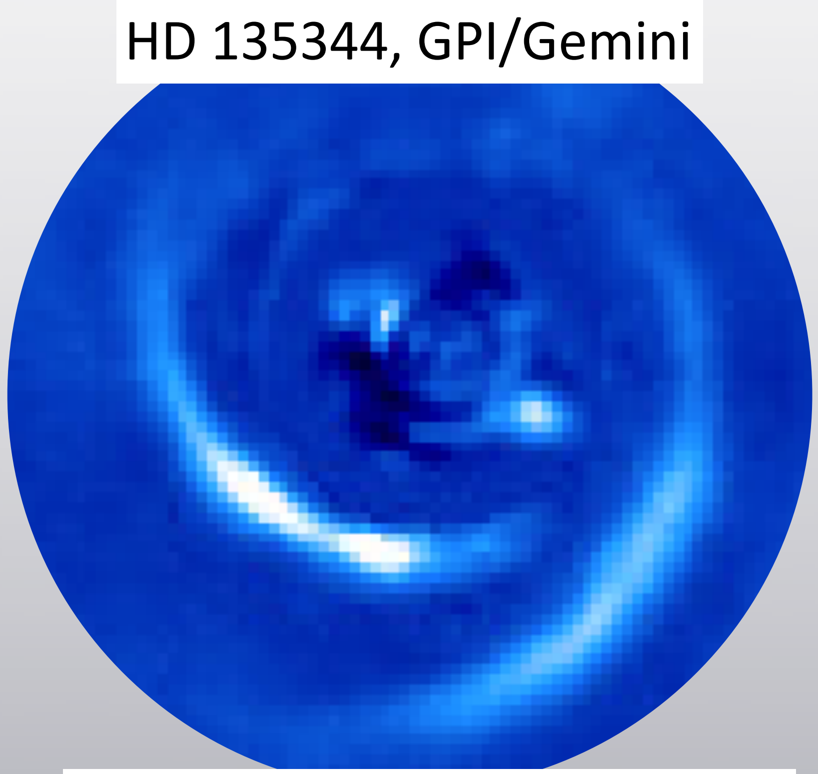

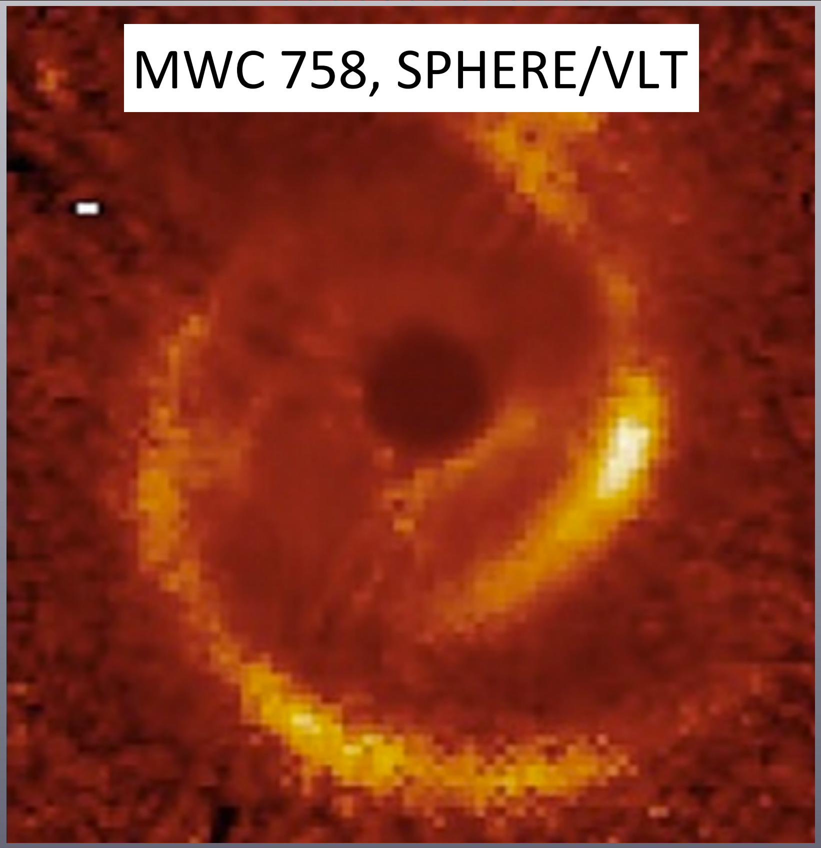

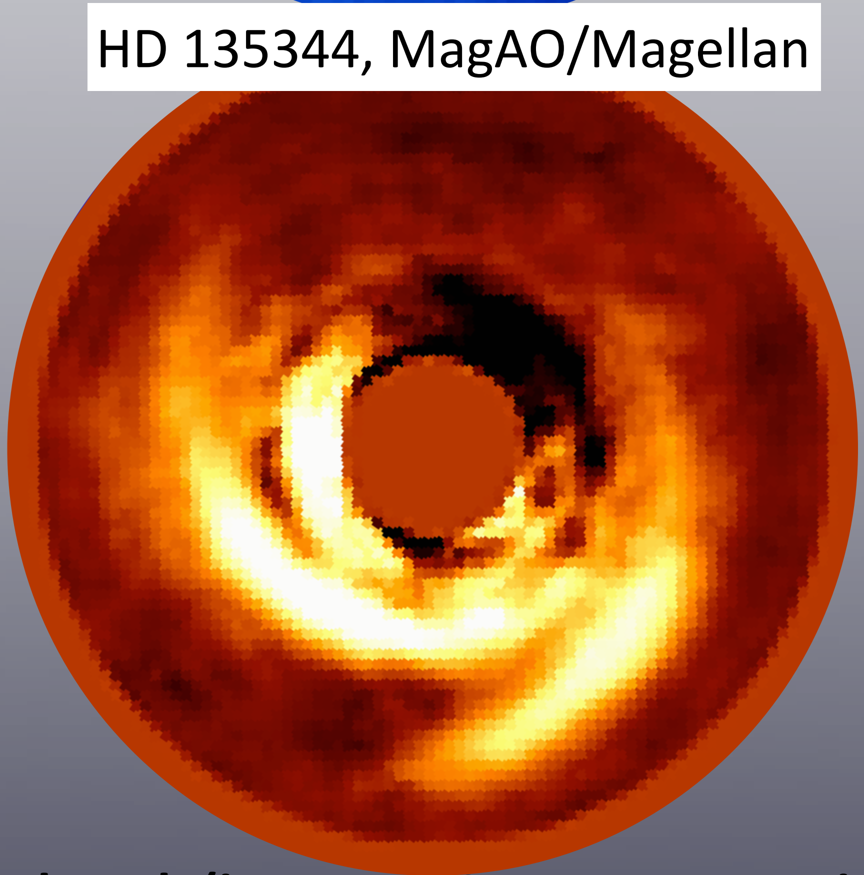

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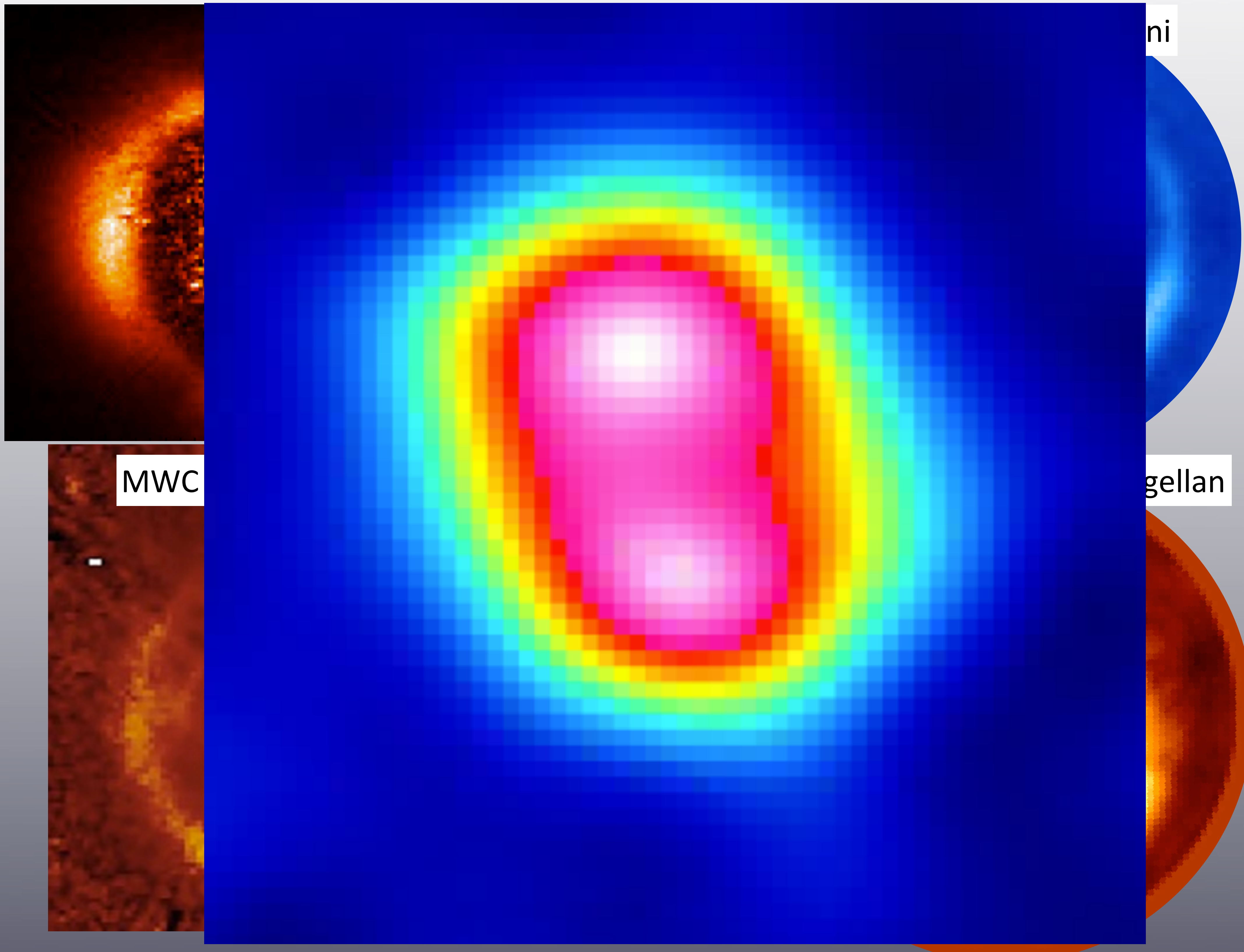

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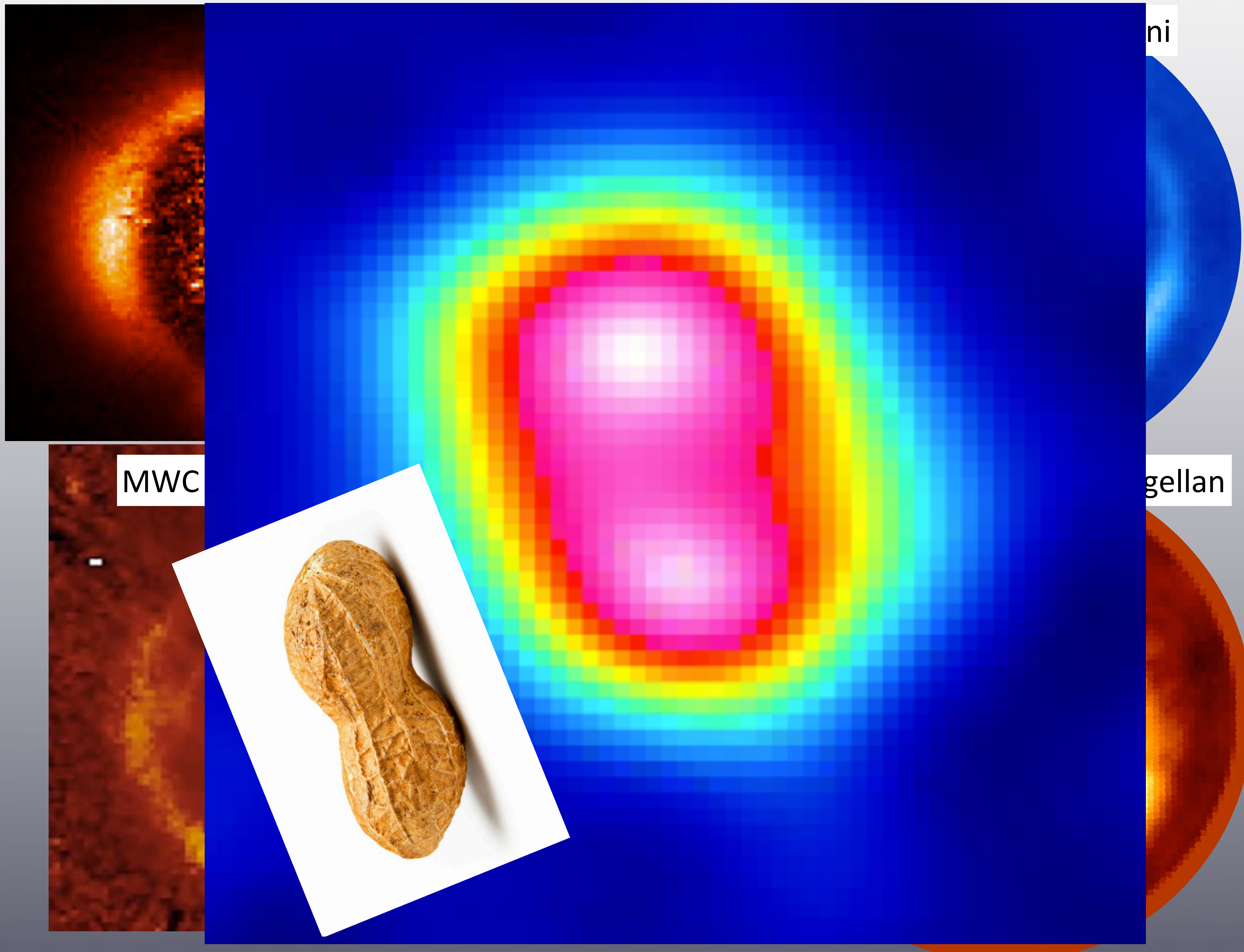

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Sz 91: Basic data

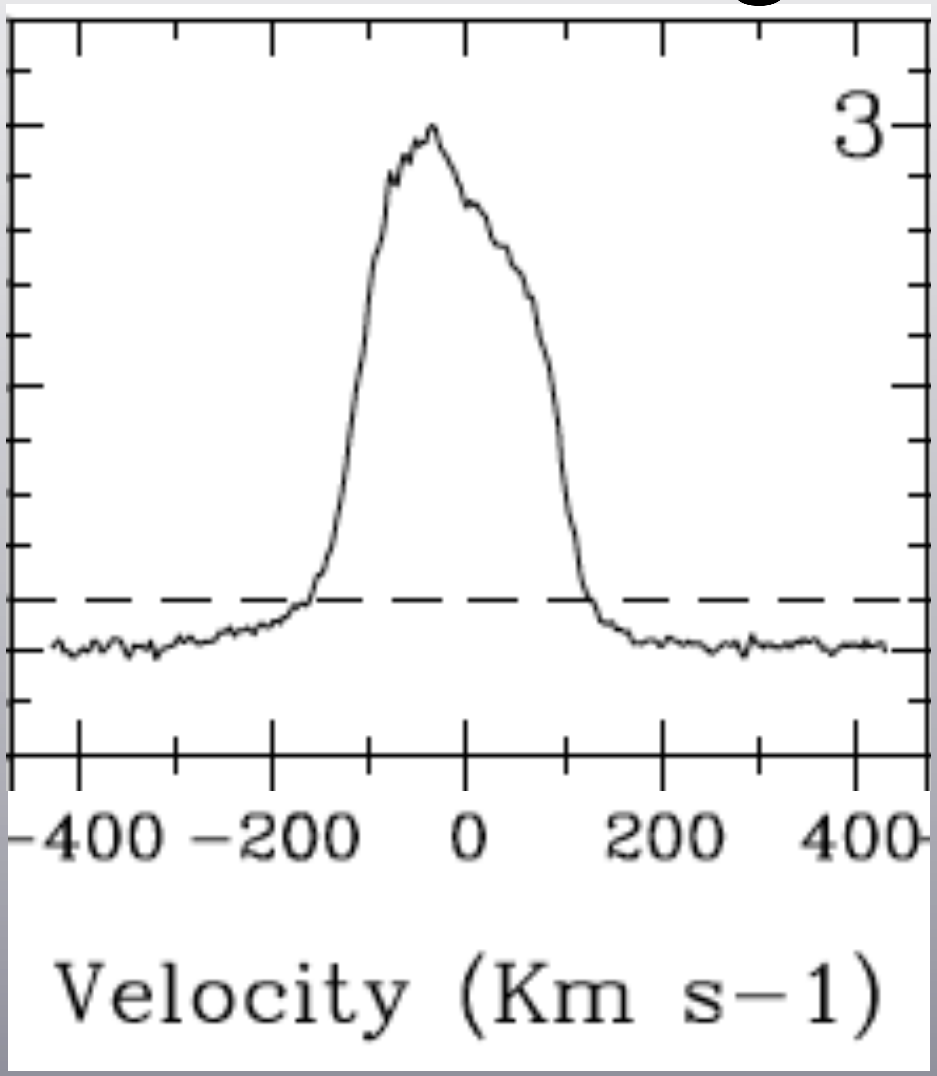
- Lupus III Star Forming Region
- distance ~ 200 pc
- Age ~< 1 Myr
- Spt ~ M1.5
- $M_\star$ ~ 0.47 $M_\odot$
- $R_\star$ ~ 1.46 $R_\odot$

THE NATURE OF TRANSITION CIRCUMSTELLAR DISKS. II. SOUTHERN MOLECULAR CLOUDS*

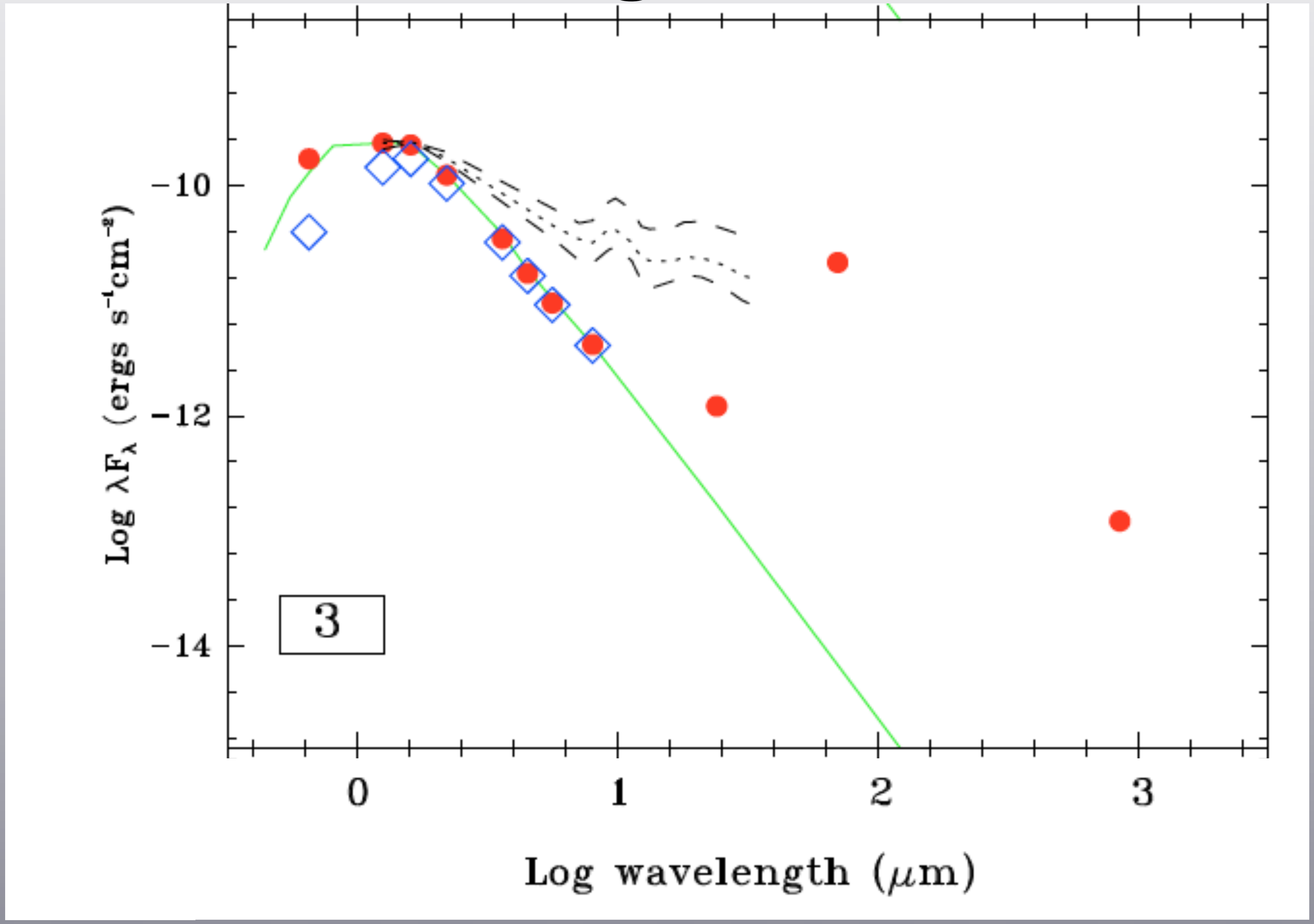
Gisela A. Romero[1,2,3], Matthias R. Schreiber[1], Lucas A. Cieza[4,9], Alberto Rebassa-Mansergas[1], Bruno Merín[5], Analía V. Smith Castelli[3,6], Lori E. Allen[7], and Nidia Morrell[8]

Sz 91: Basic data

Hα: accreting



SED: Large Inner Hole



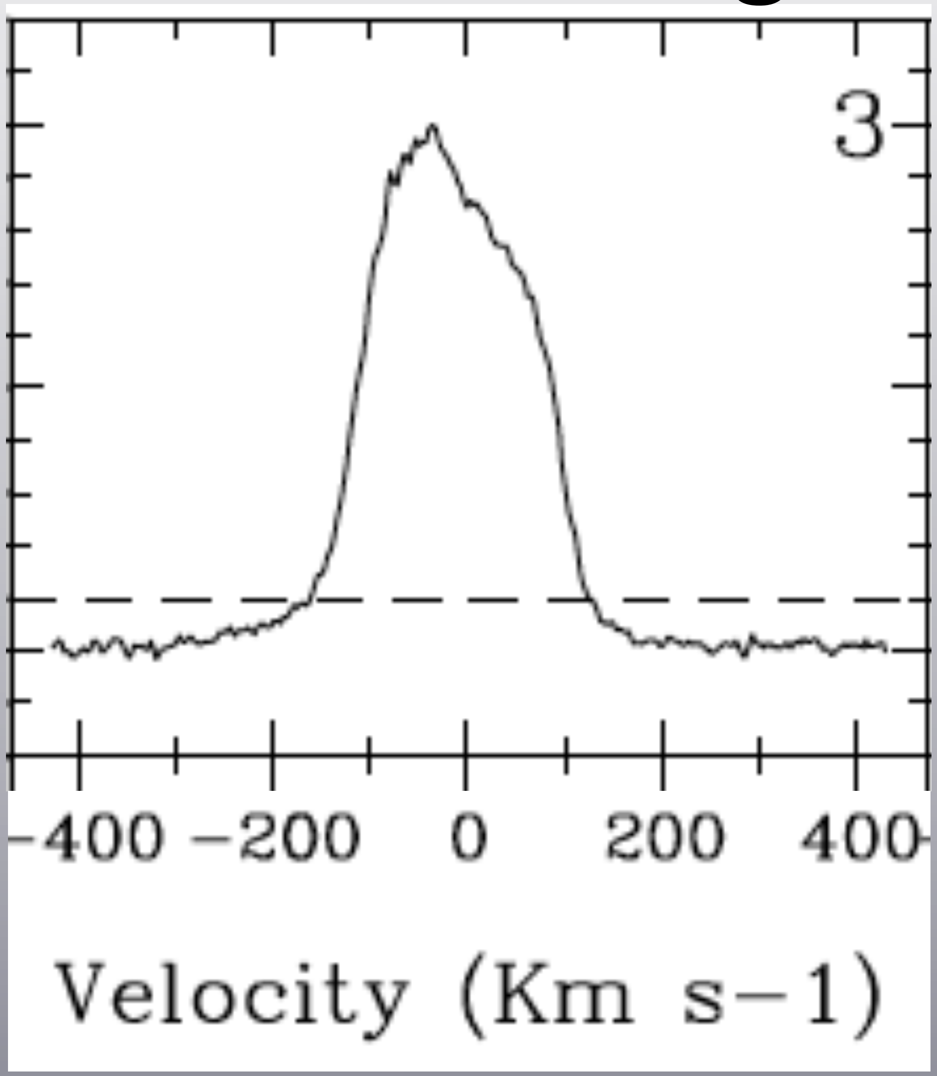
No stellar companions detected

Direct Imaging + Radial Velocity

Romero et al. 2012

Sz 91: Basic data

Hα: accreting



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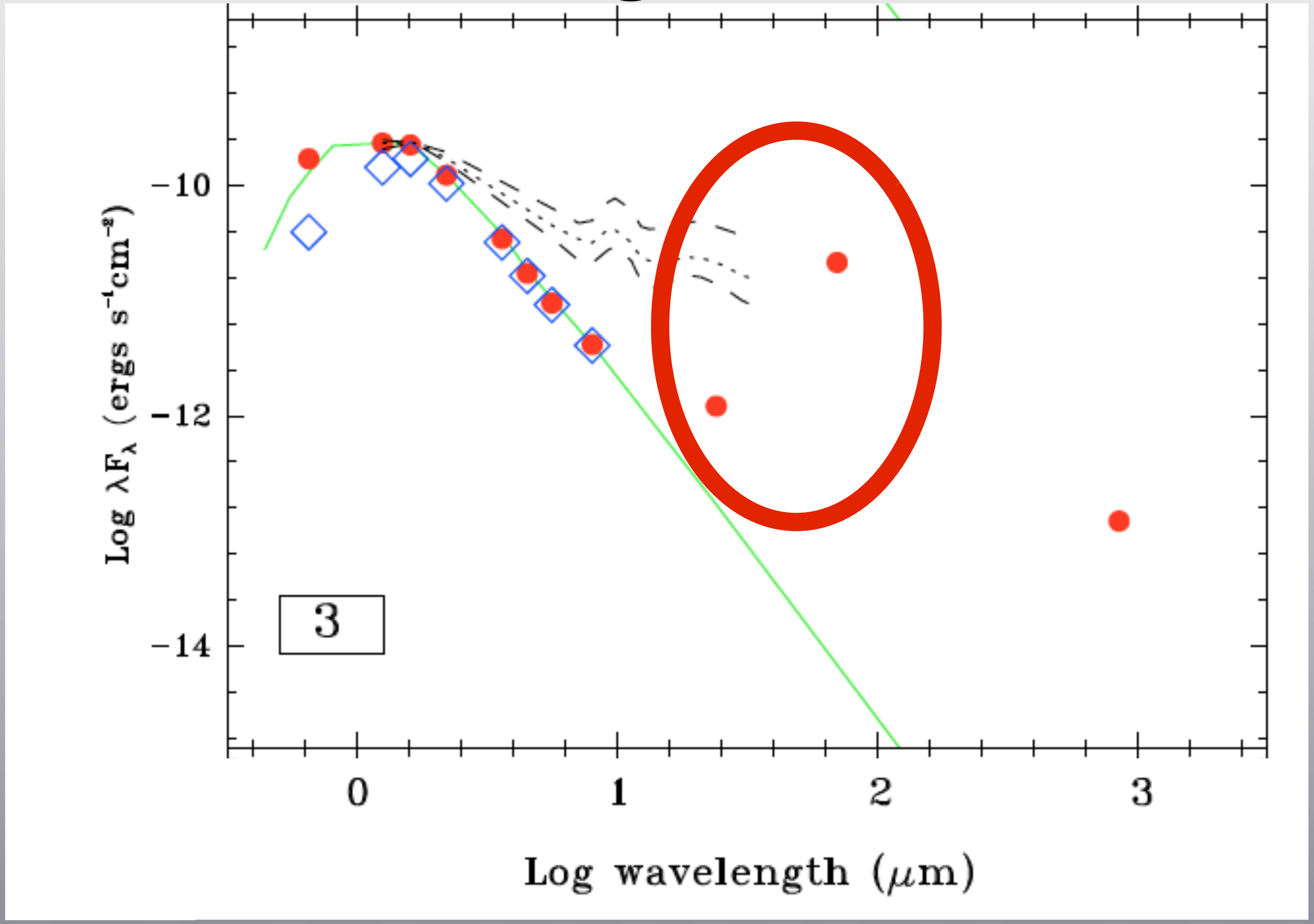

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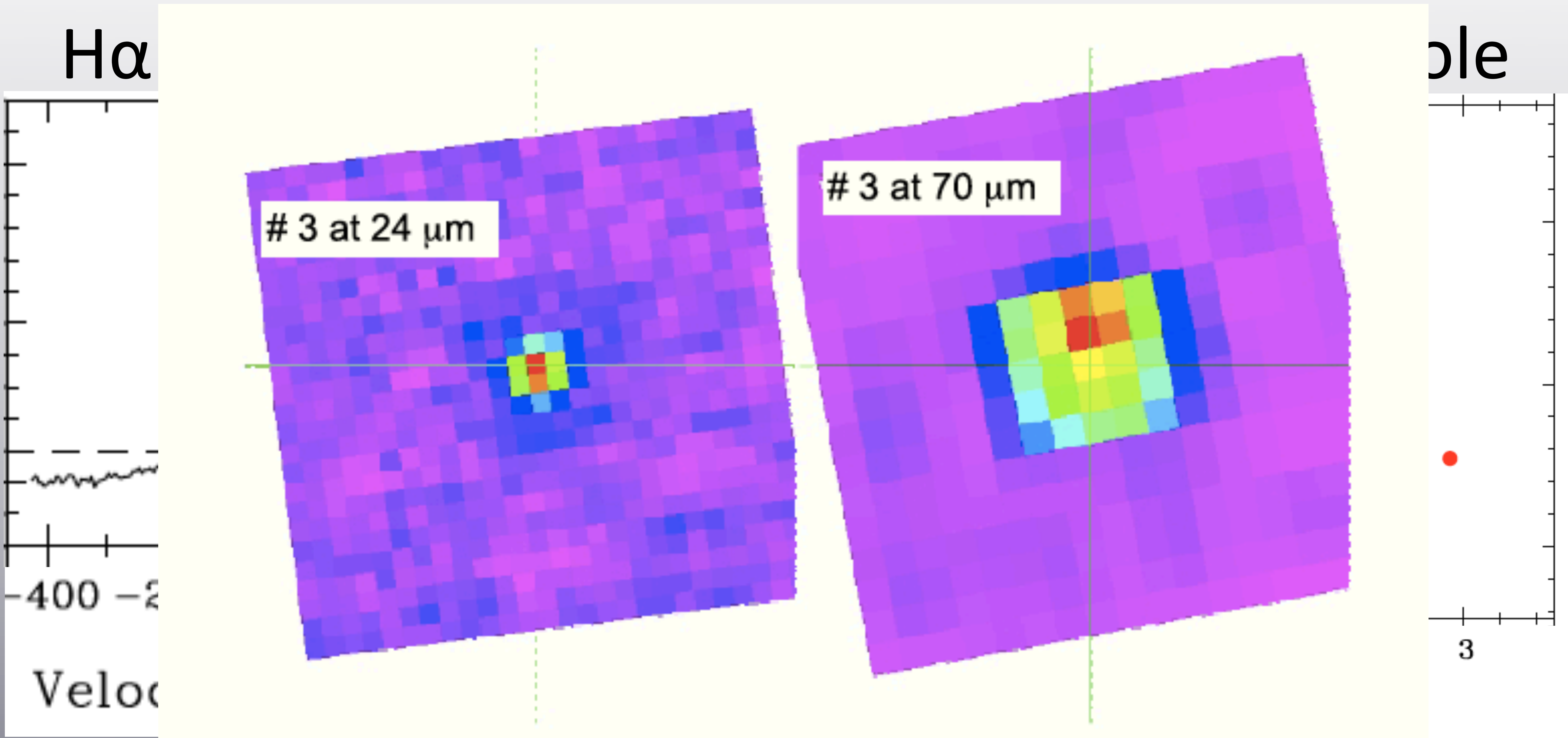

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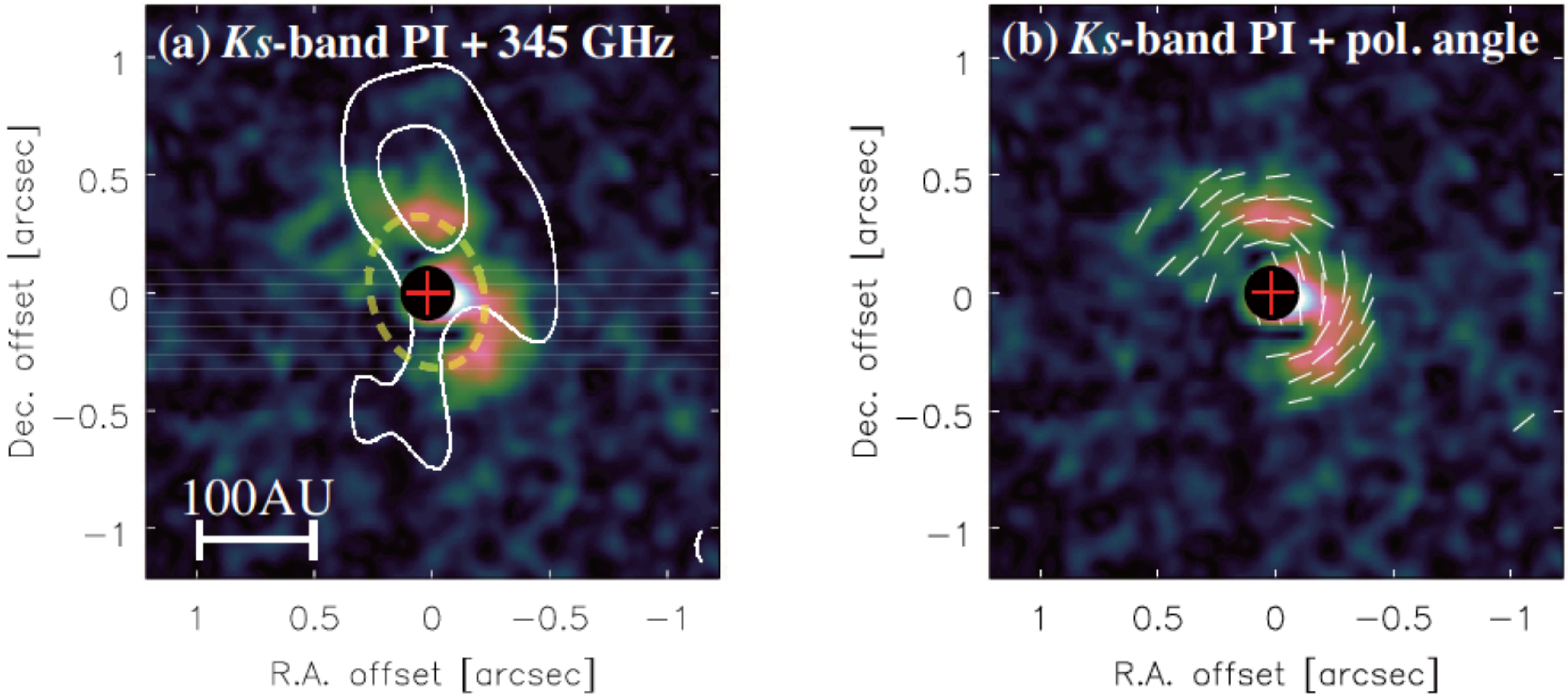
Romero et al. 2012

Sz 91: 2014 Subaru & SMA



NIR & 870 µm cavity of r ~65 au

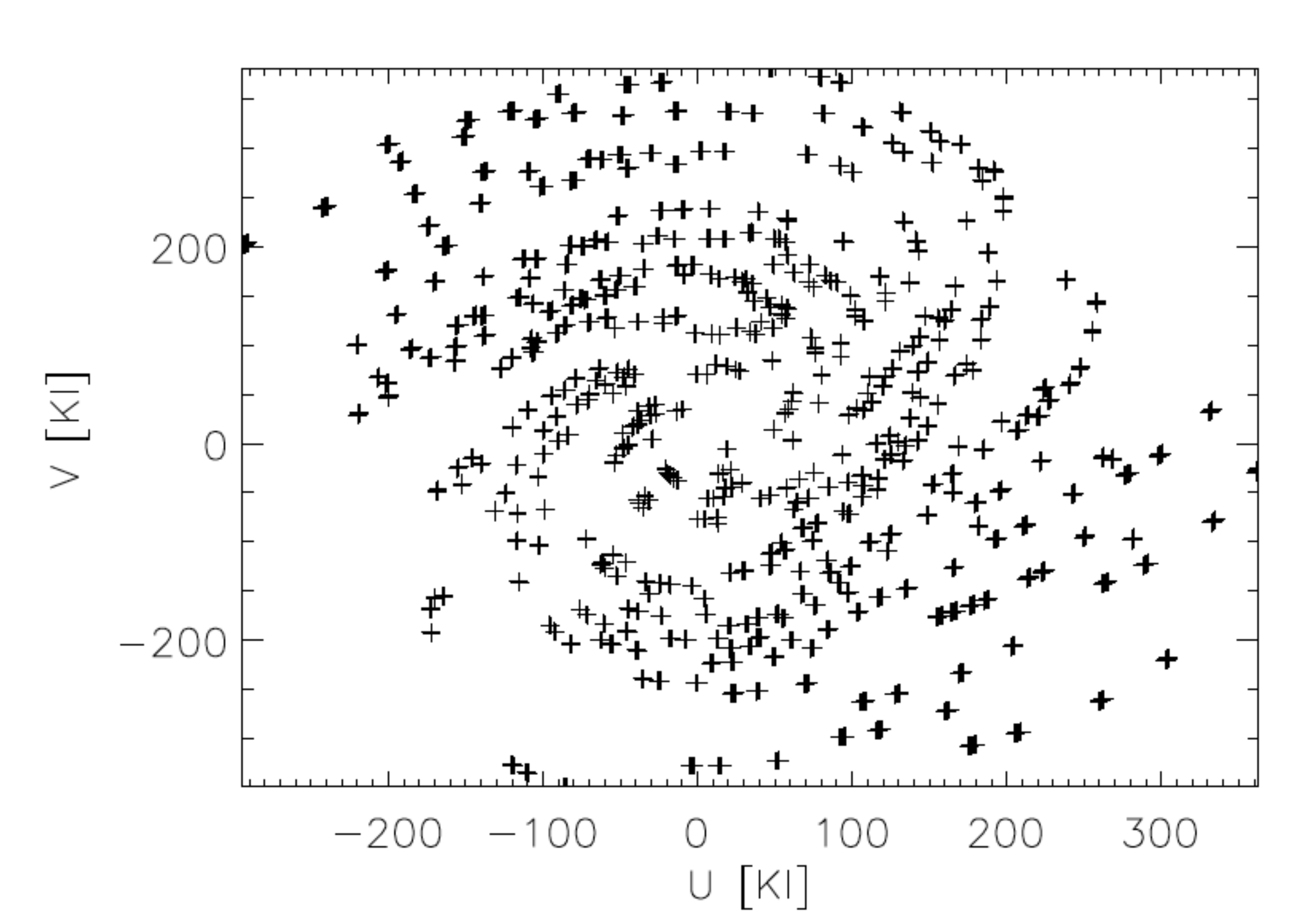
Tsukagoshi et al. 2014

ALMA Cycle 0: 20 (12m) Antennas

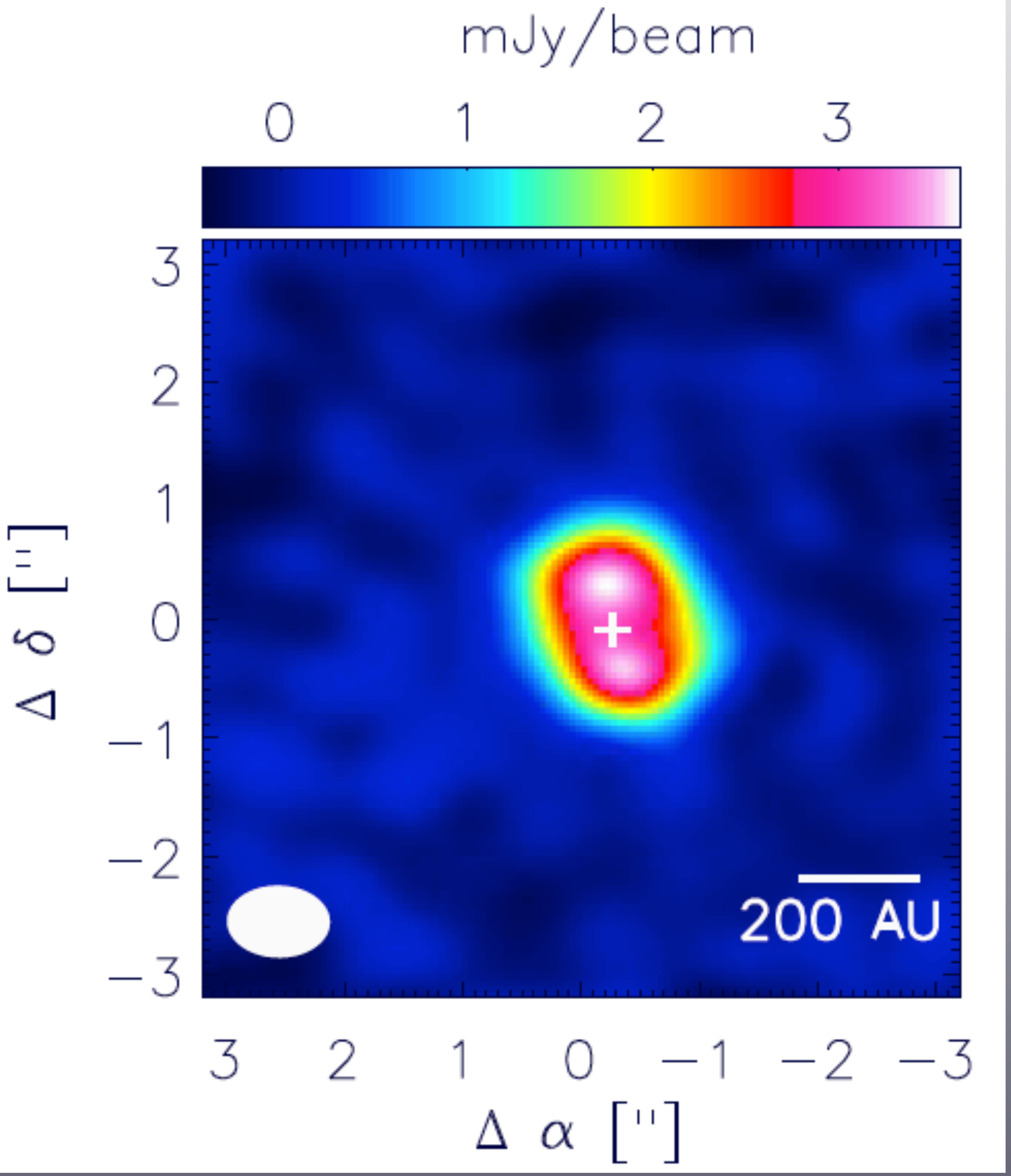
- High Spatial resolution
- High Spectral resolution
- High Sensitivity

ALMA data: Continuum (dust) 1.3mm

Observed: UV plane

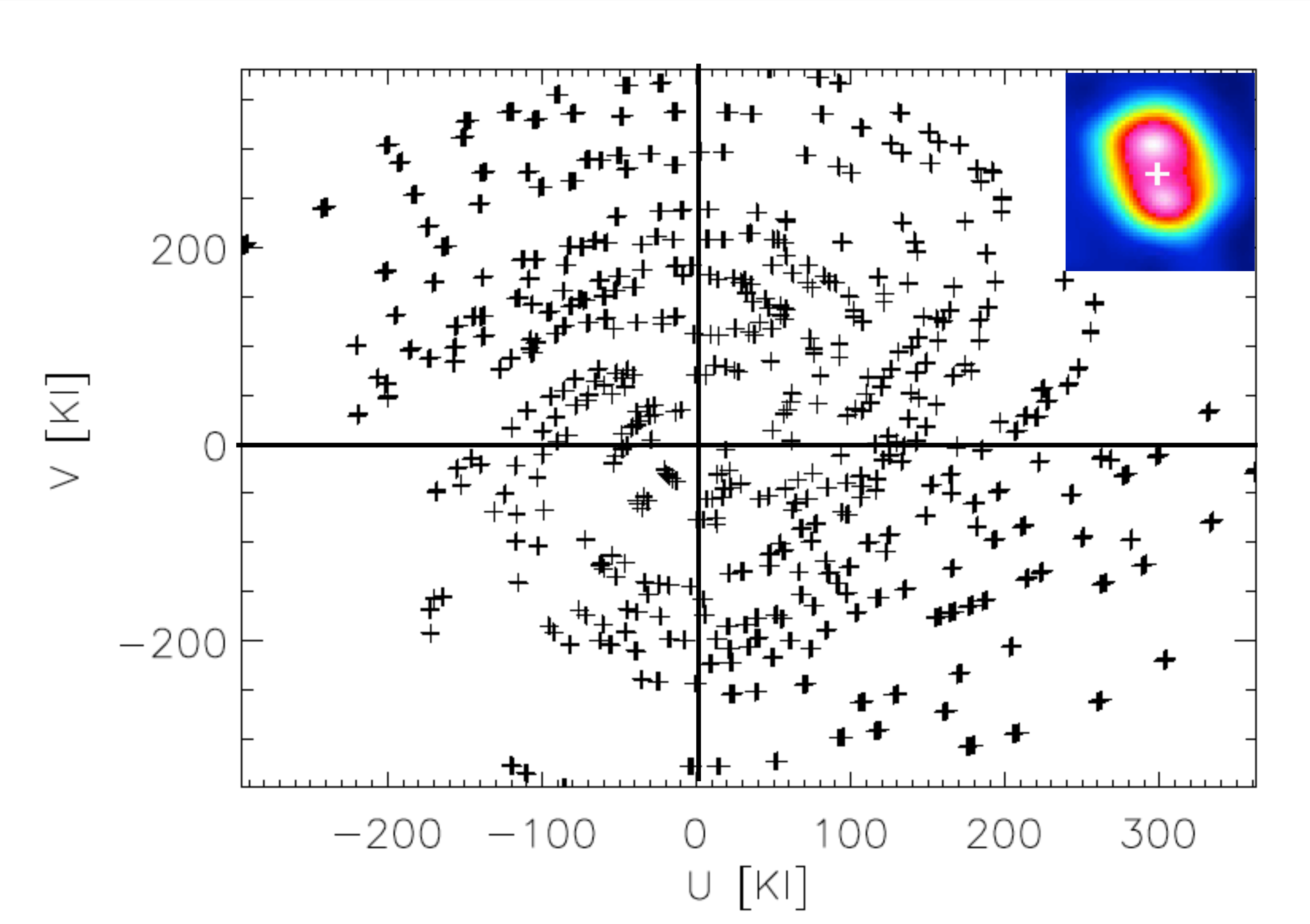


"cleaned"



Canovas et al. 2015

Decoding the UV plane: >70 au cavity



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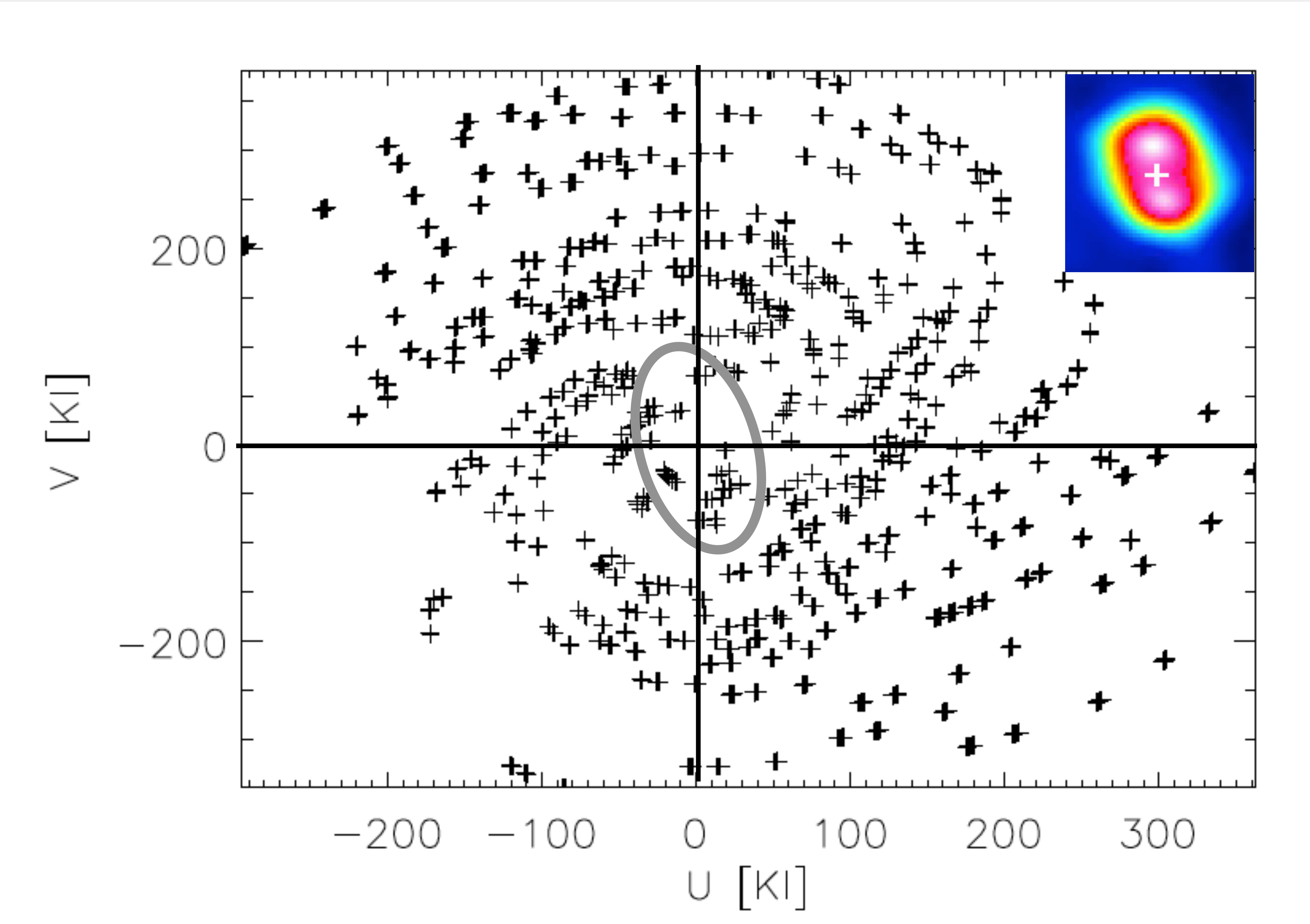

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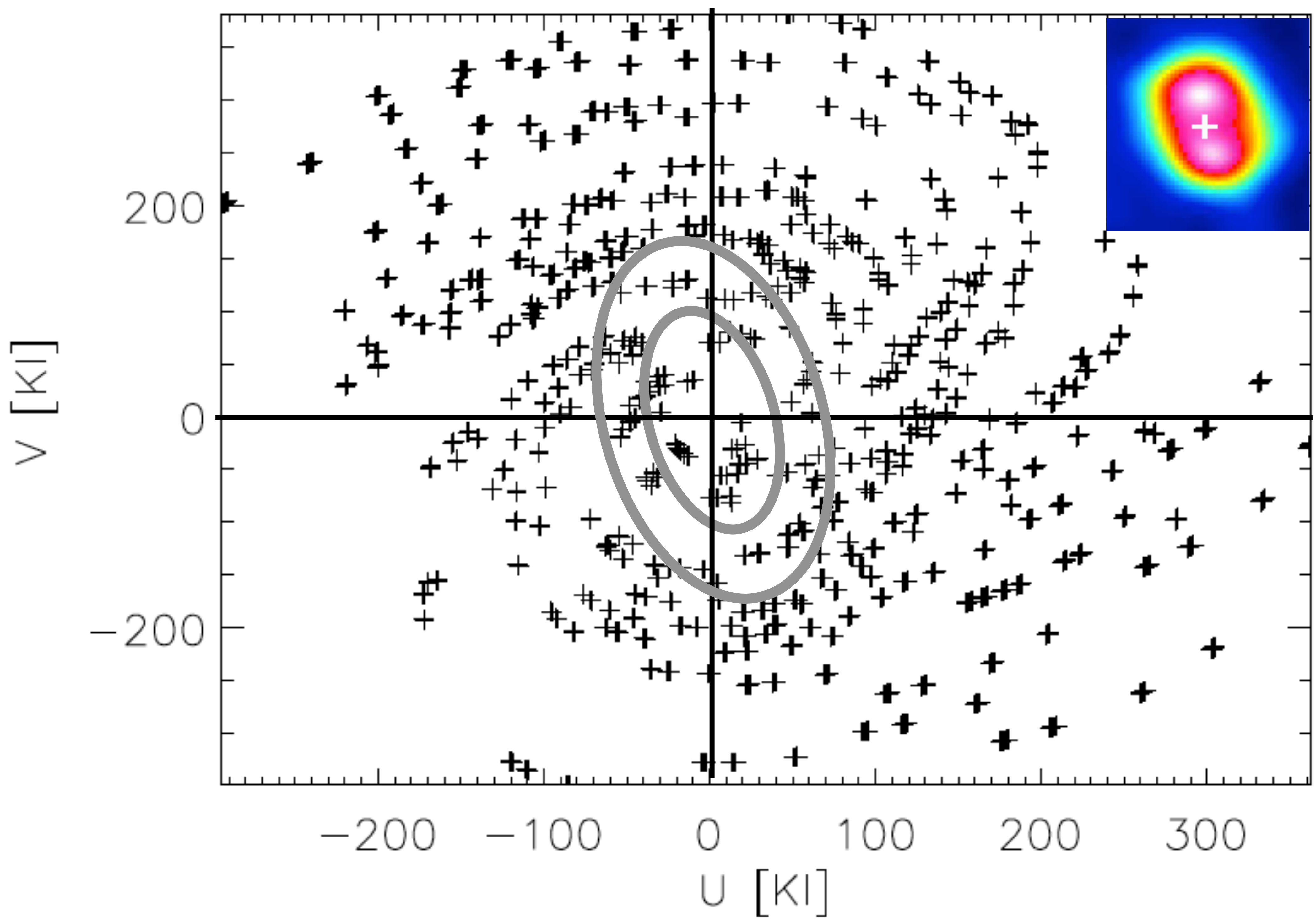

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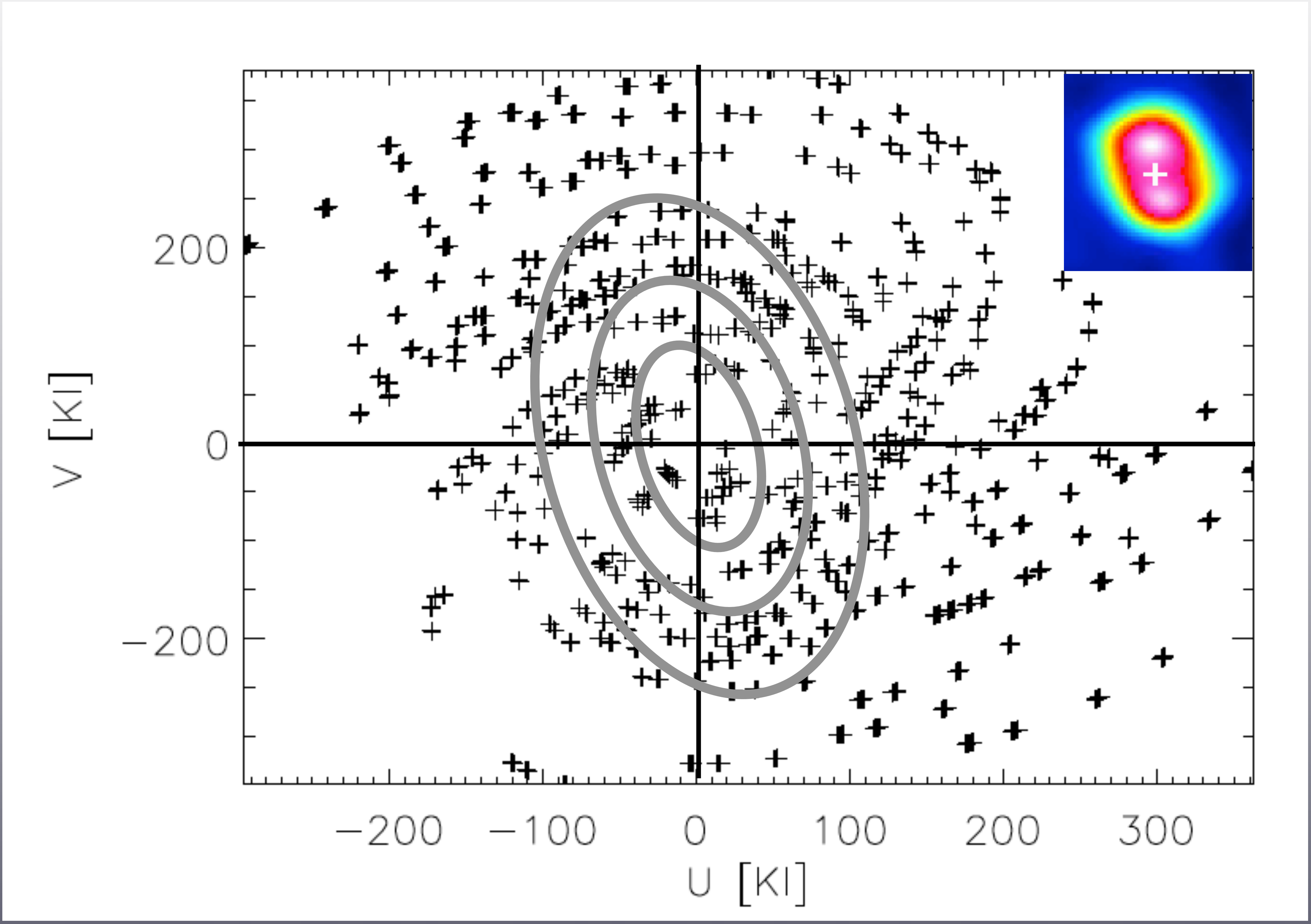

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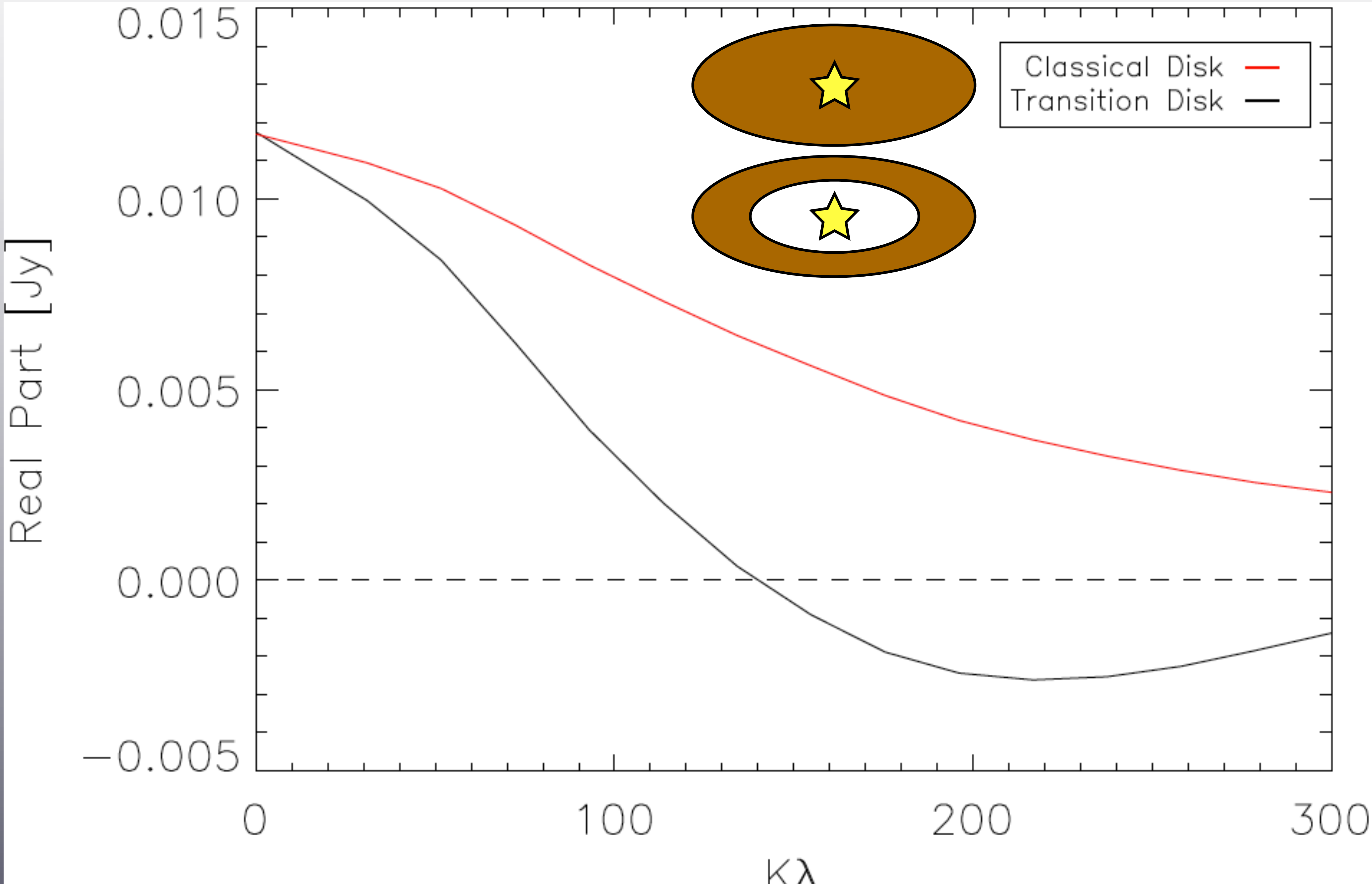

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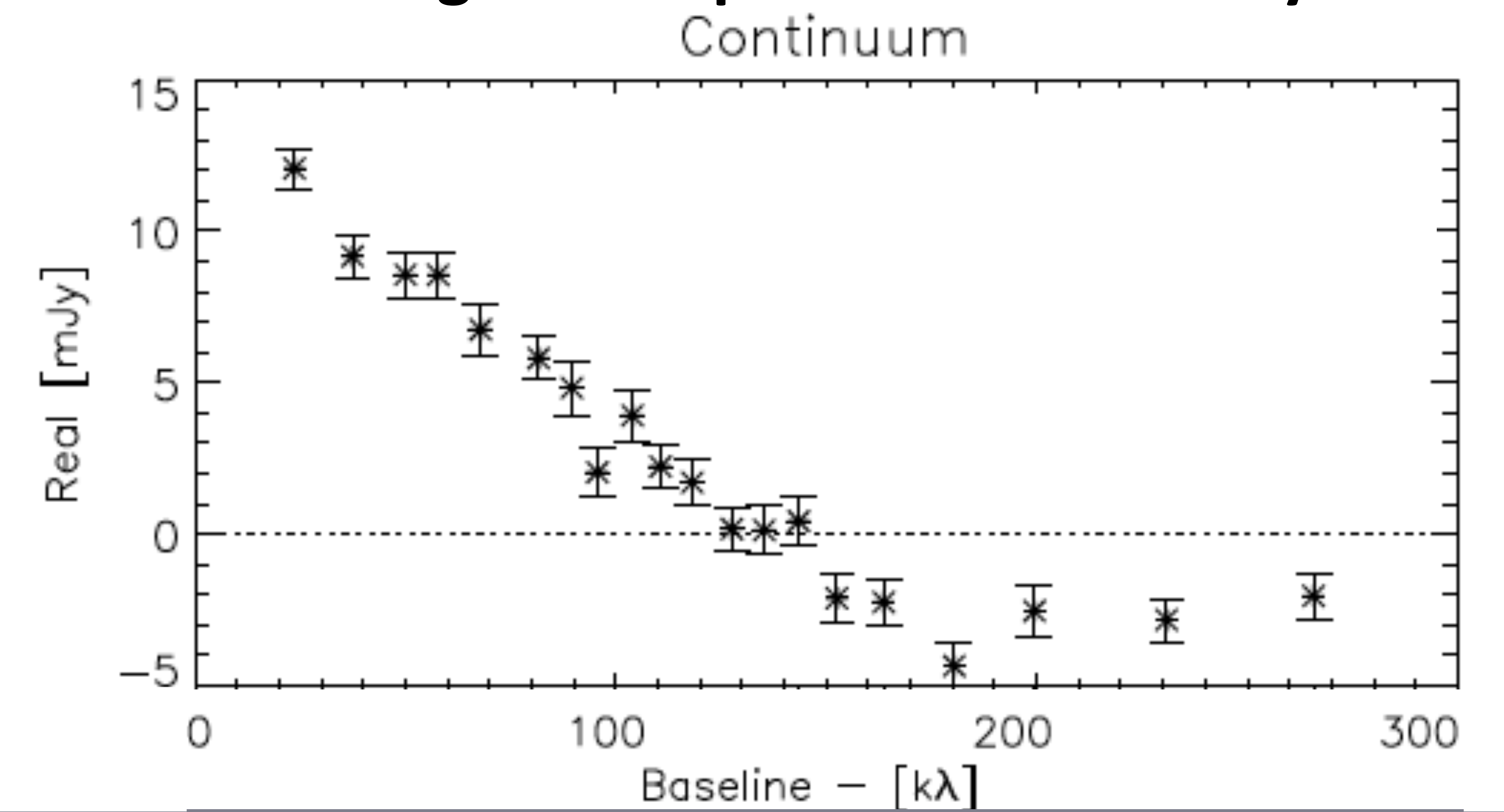
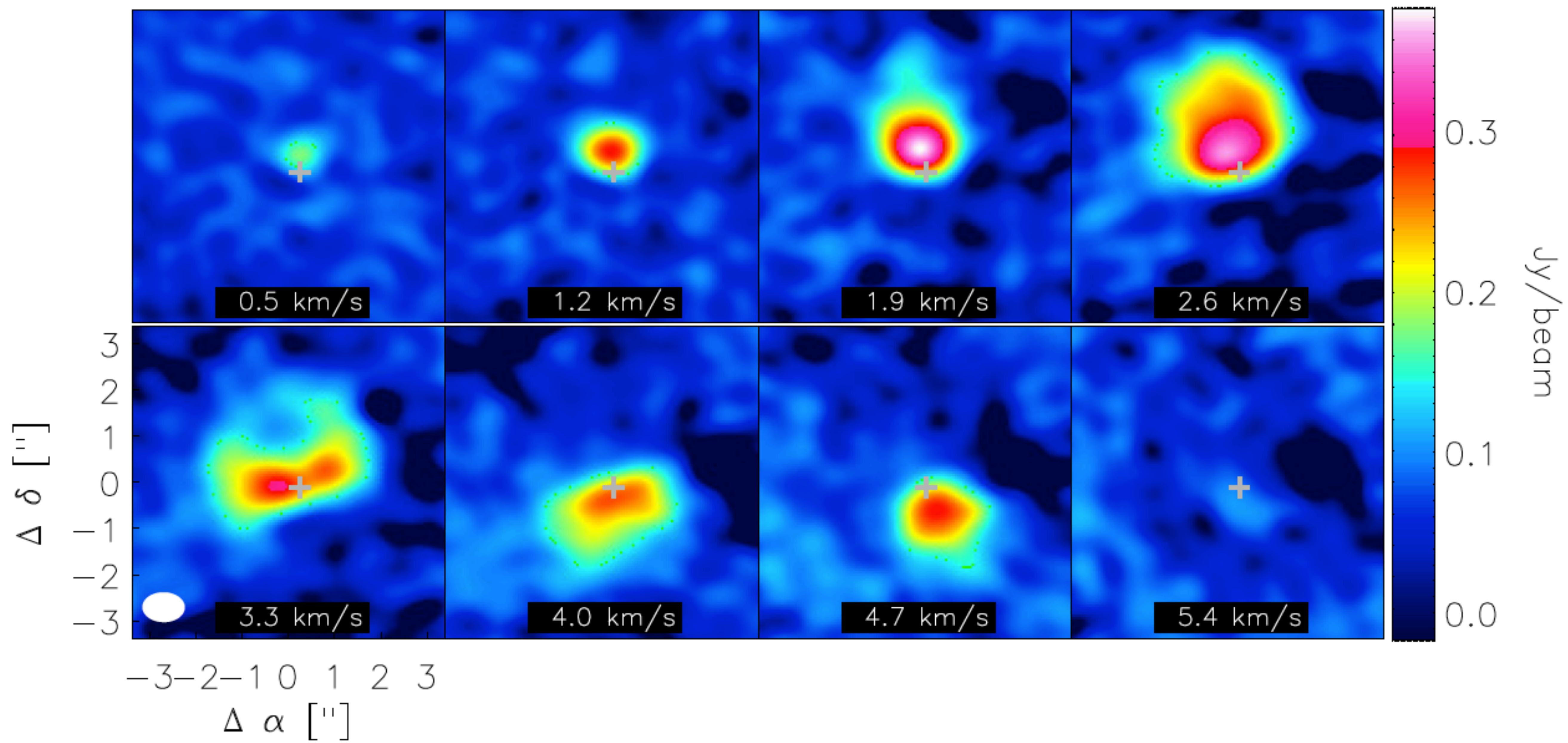


ALMA data: 12CO(2-1)



Assym. CO Profile: Cloud Emission :(

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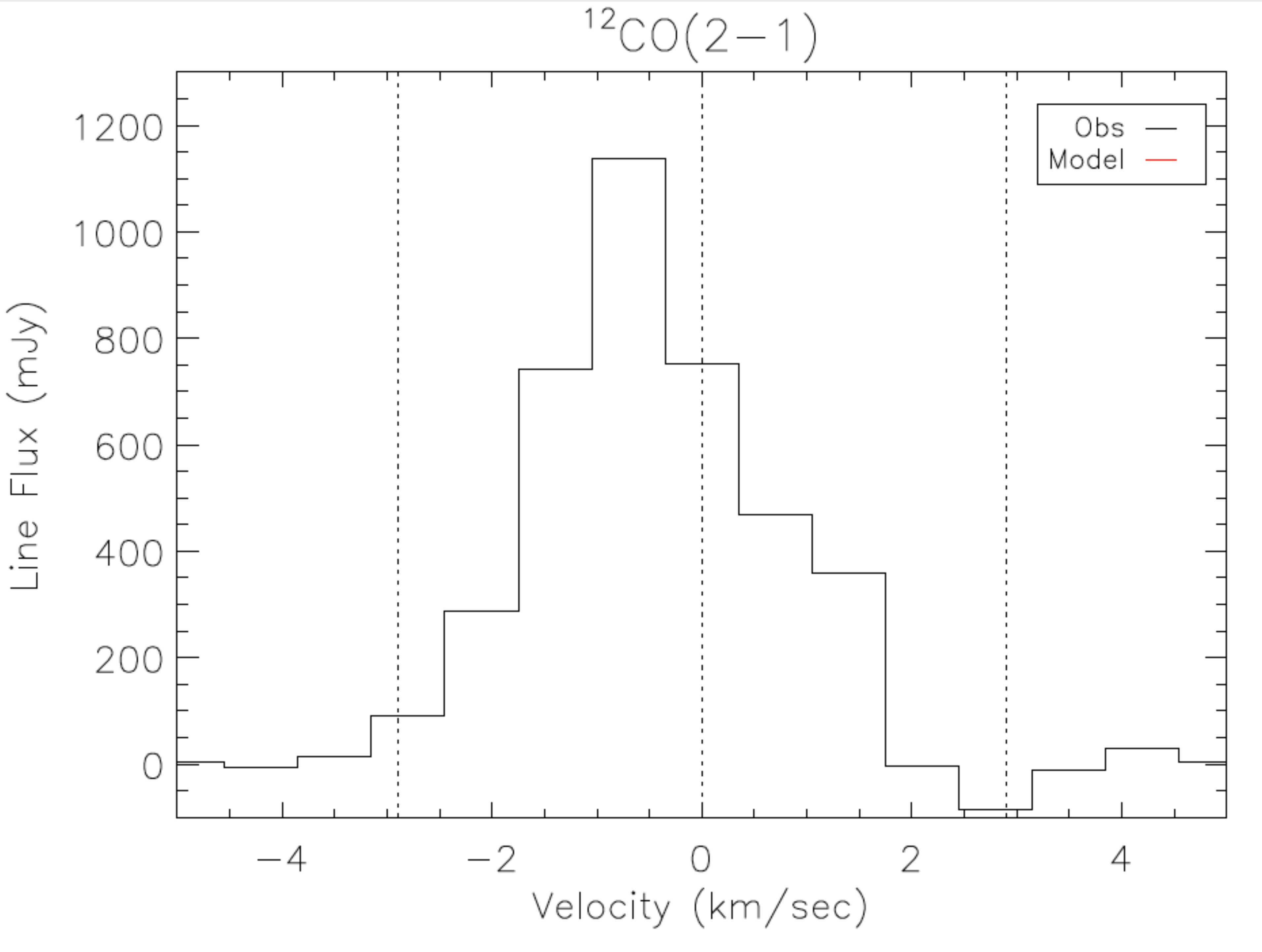
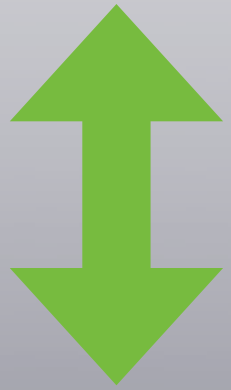


CO @ -2.9 km/s

Kep. Rotation



CO down to 28 au!

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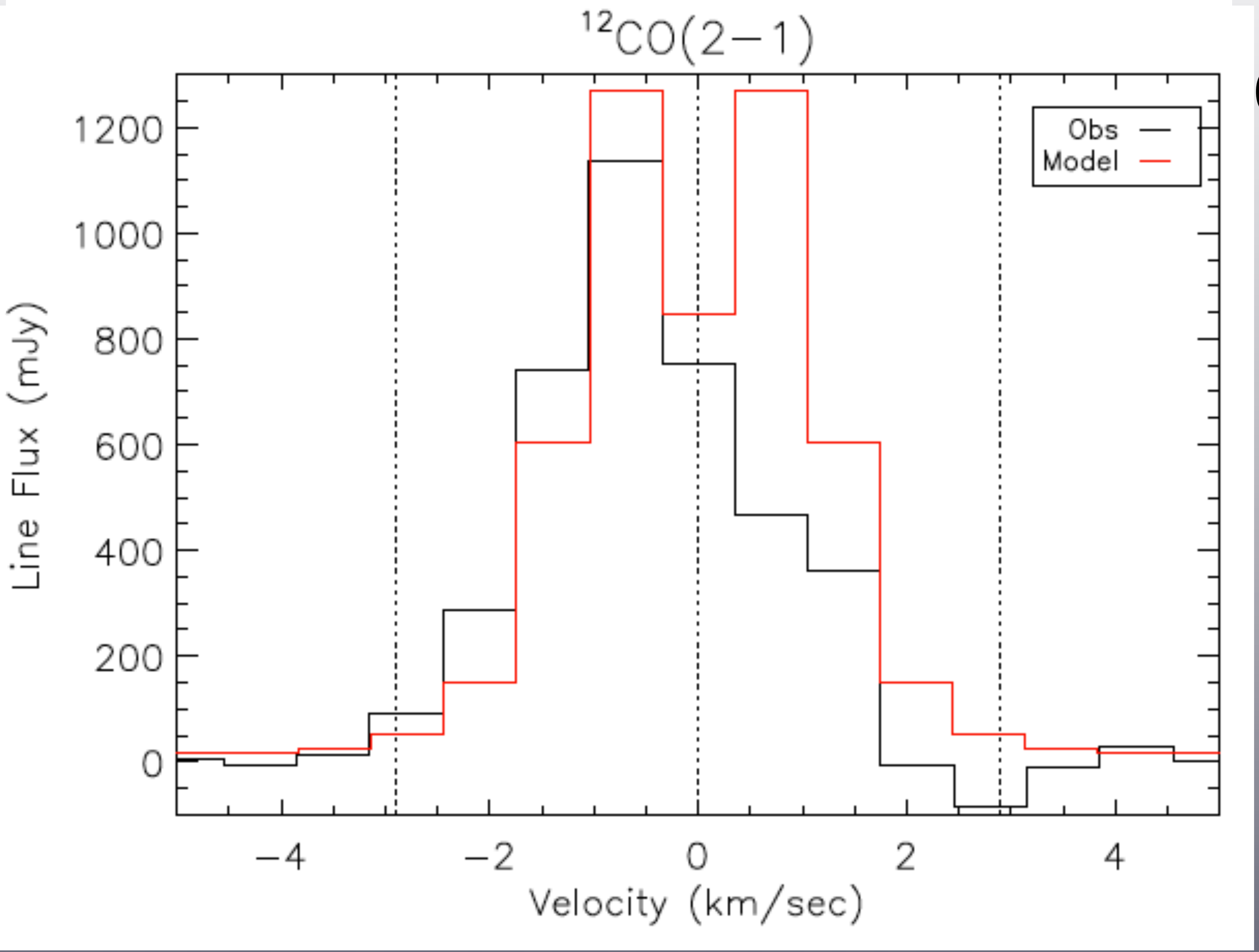
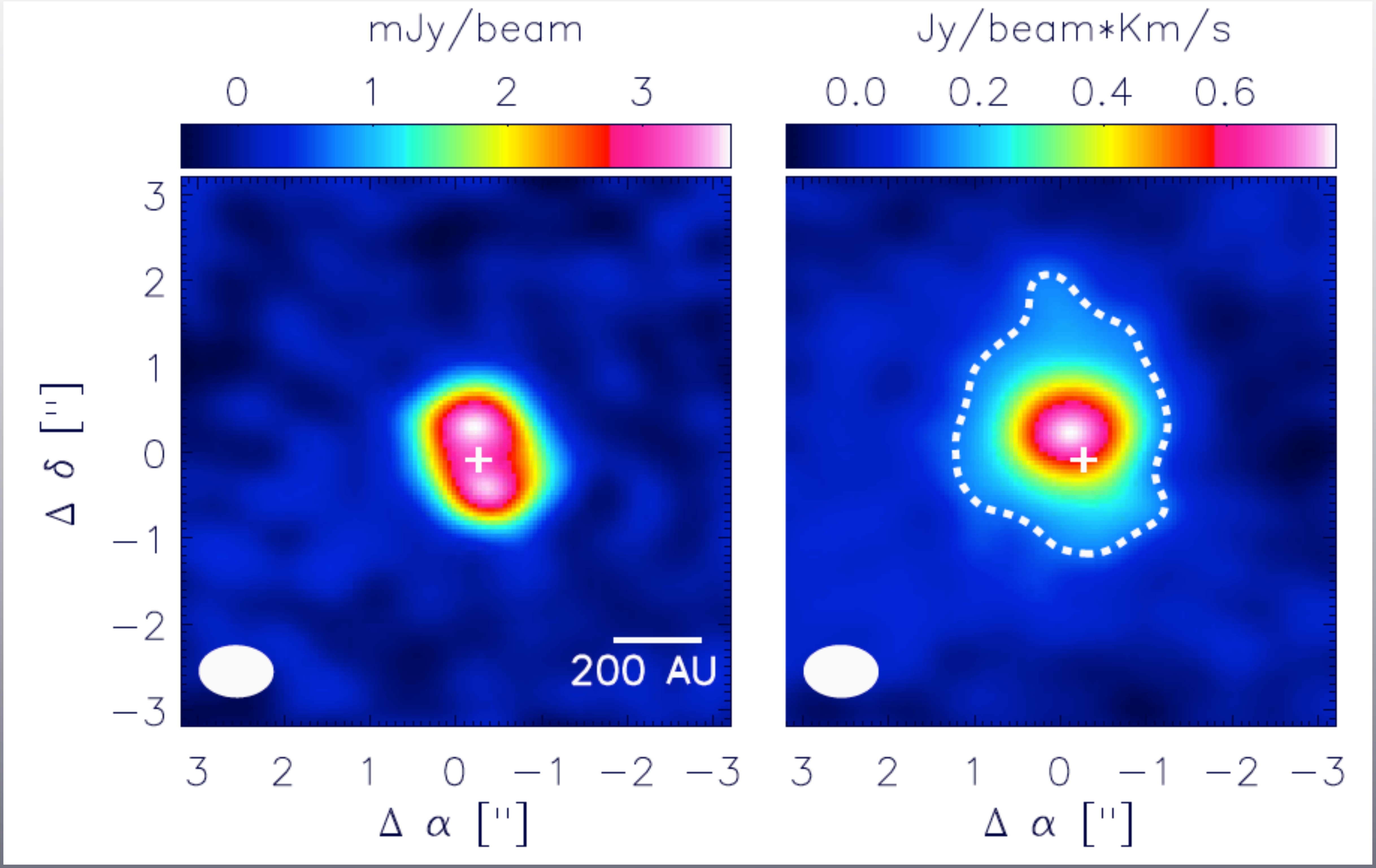


CO @ -2.9 km/s

Kep. Rotation

CO down to 28 au!

Outer Disk CO > Dust

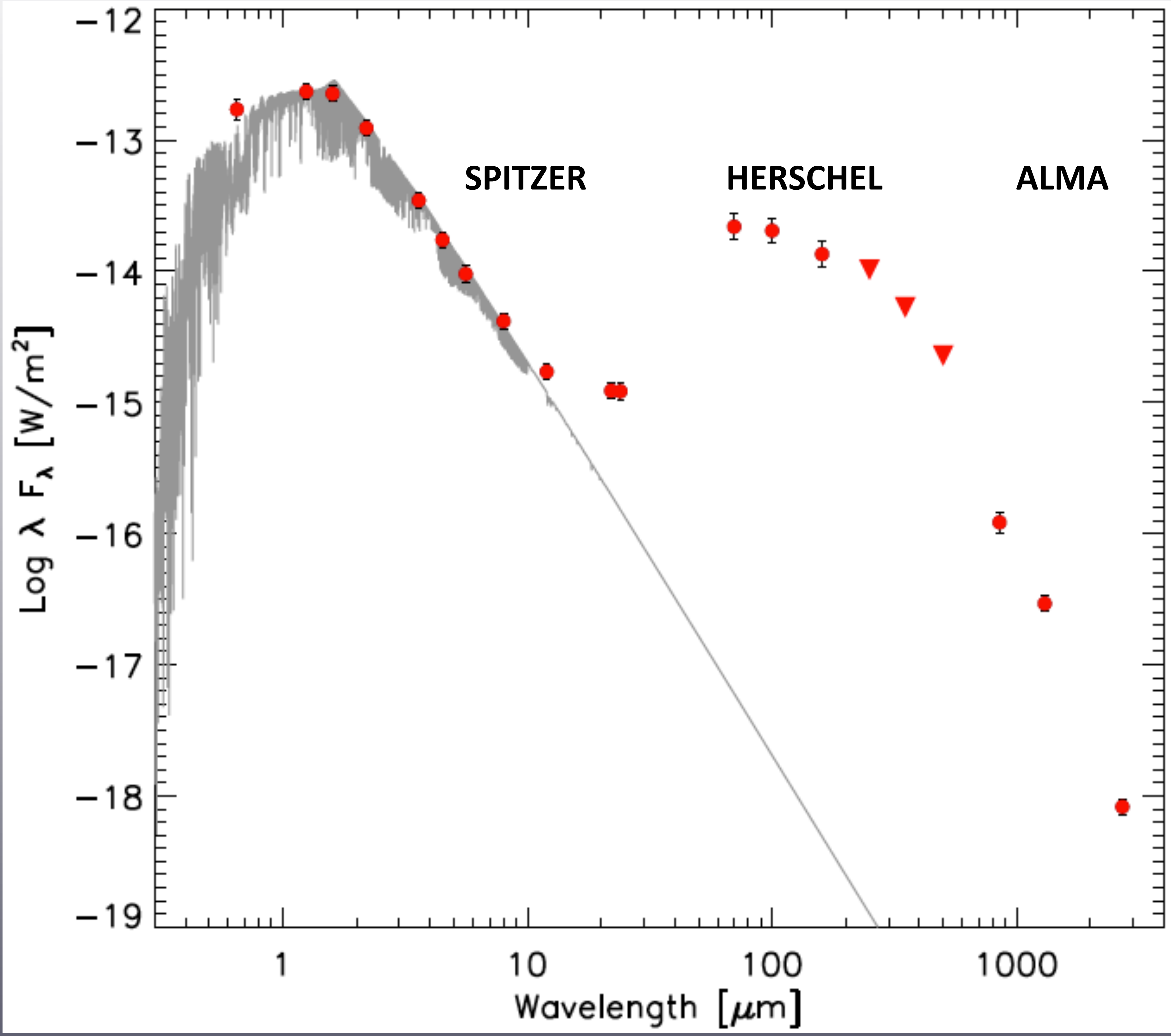


SED: Thermal Structure (dust)

NO IR excess < 12 µm

22/24 µm excess

>70 µm excess
(Herschel + ALMA)



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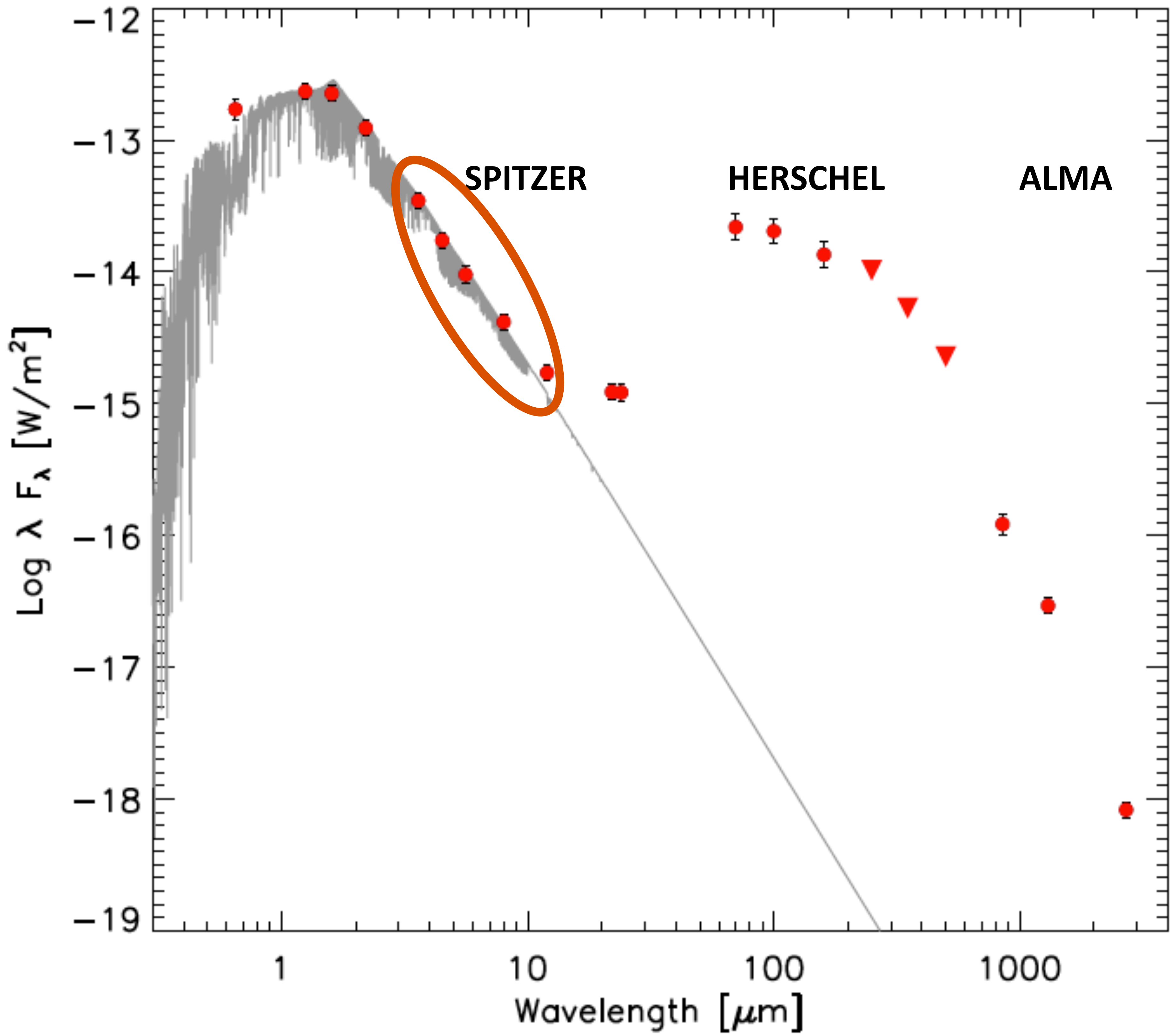

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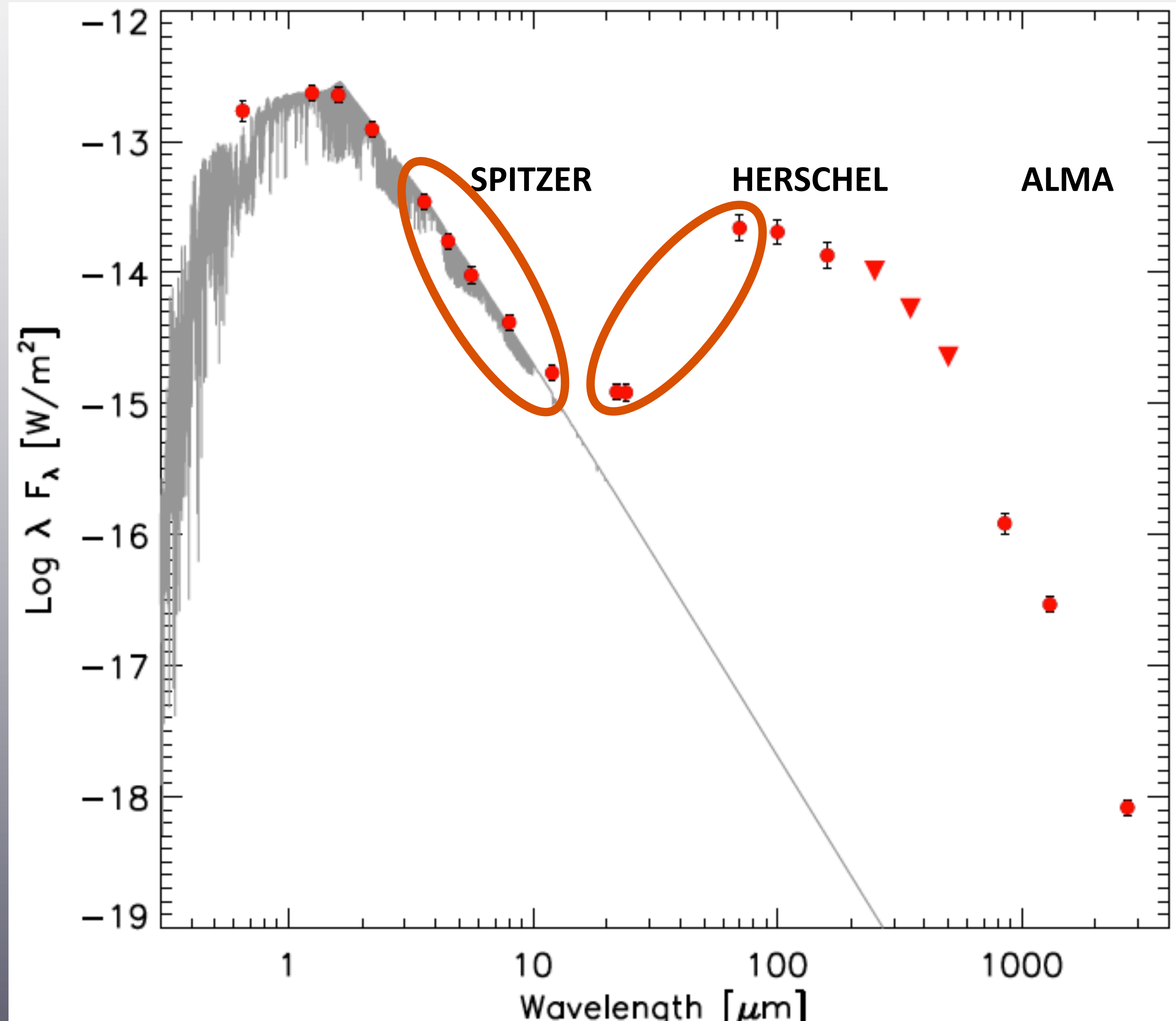

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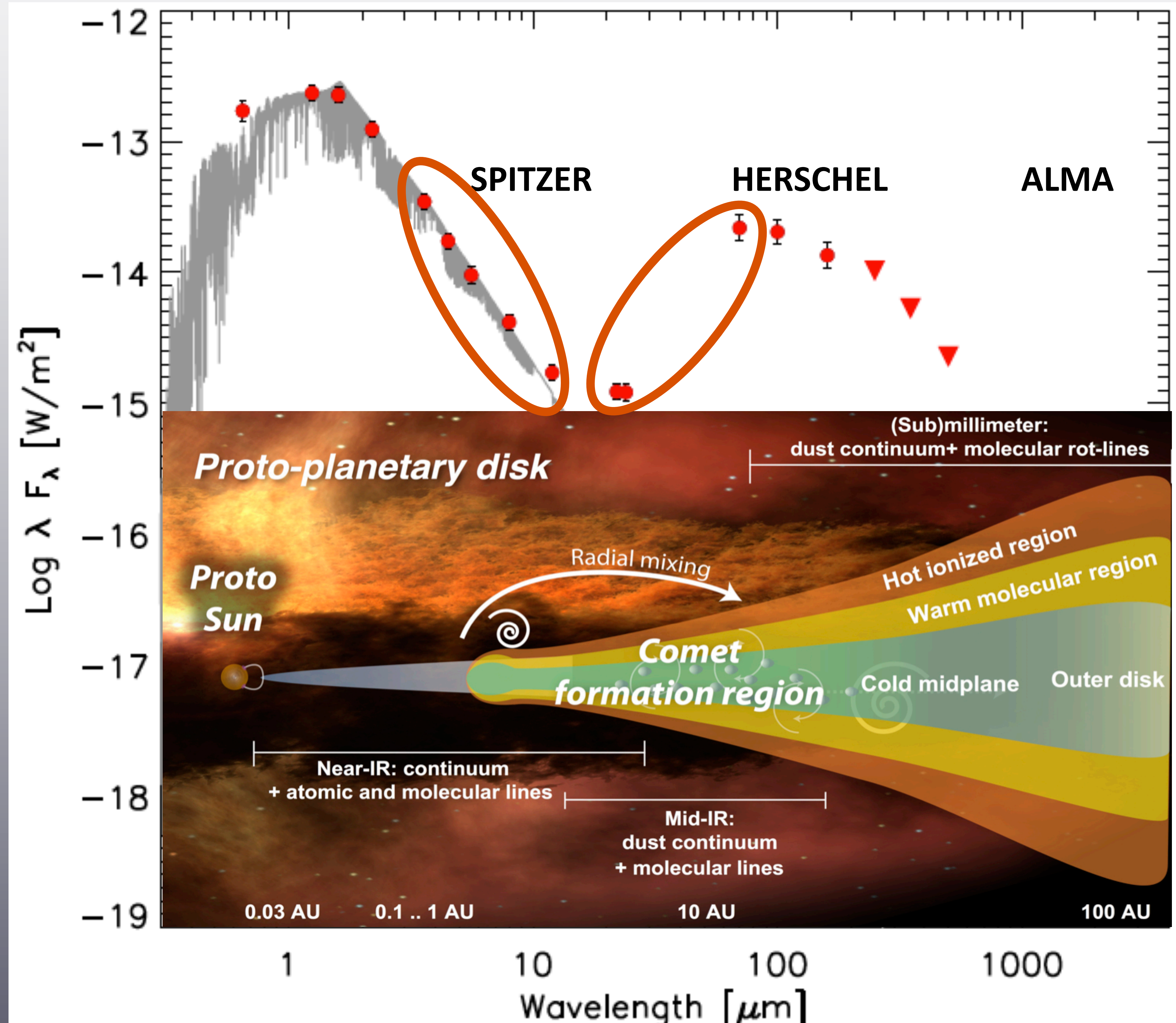
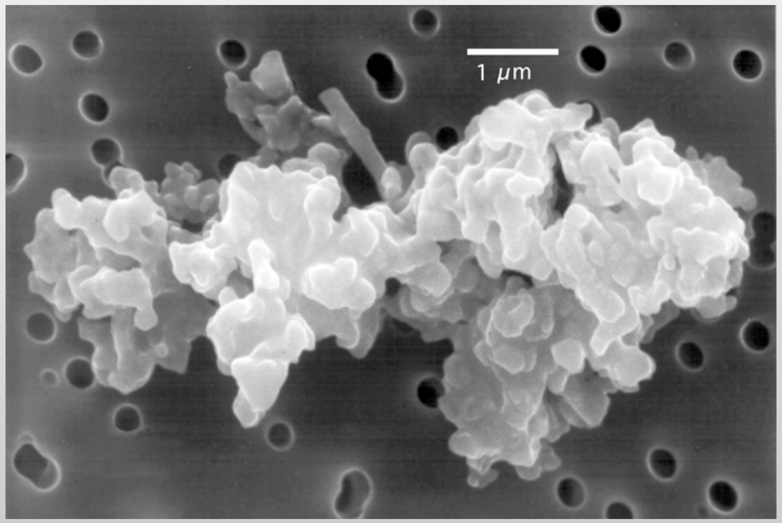
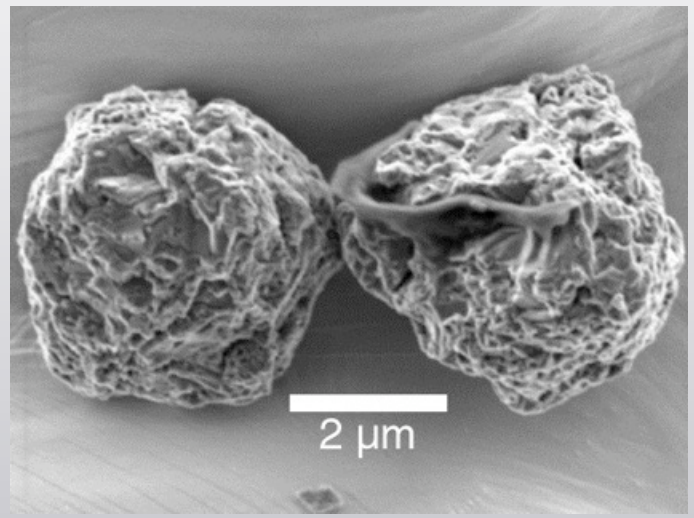


Radiative Transfer model





COMPLEX!!

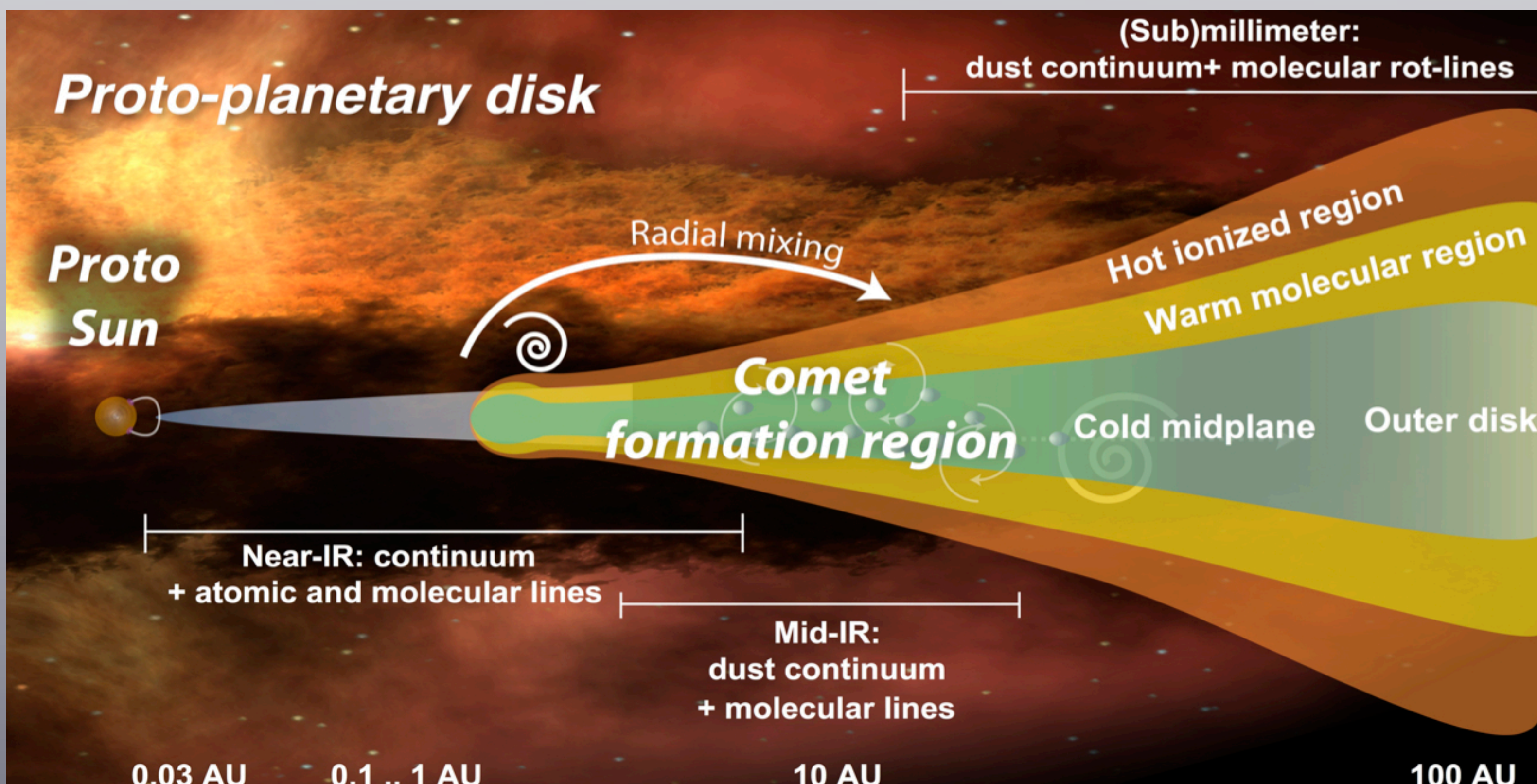
$$dn(a) \propto a^{-p} da$$

$$\Sigma(r) = \Sigma_C \, r^{-\gamma} \exp\left[-\left(\frac{r}{R_C}\right)^{2-\gamma}\right]$$

$$H(r) = H_0 (r/100\mathrm{au})^{\psi}$$

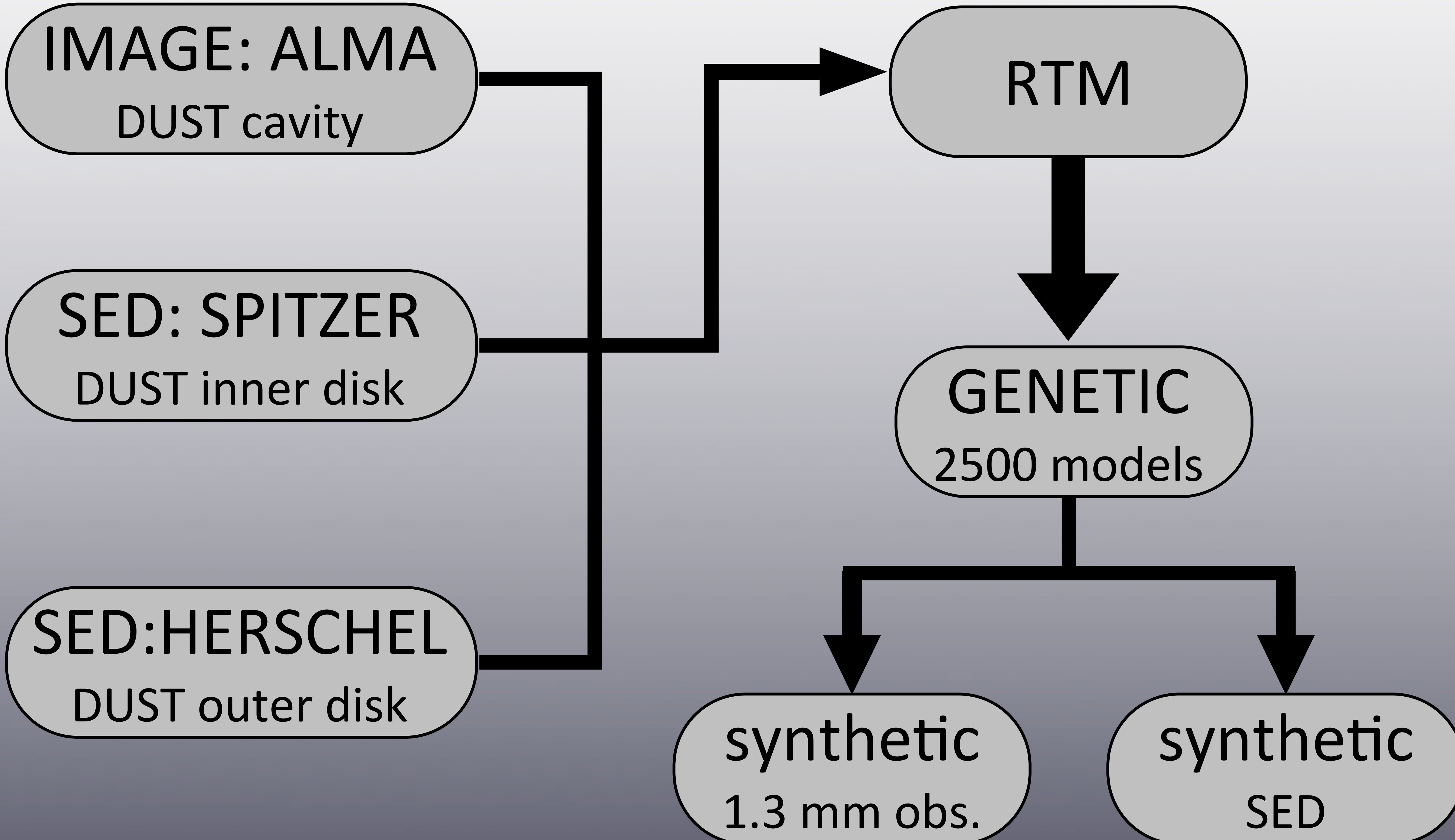
$$V_{th} = \sqrt{2k_\mathrm{b} T_\mathrm{CO} / m_\mathrm{CO}}$$

$$\rho(r,z) = \rho(r,0) \exp\left[-\frac{z^2}{2H(r)^2}\right]$$

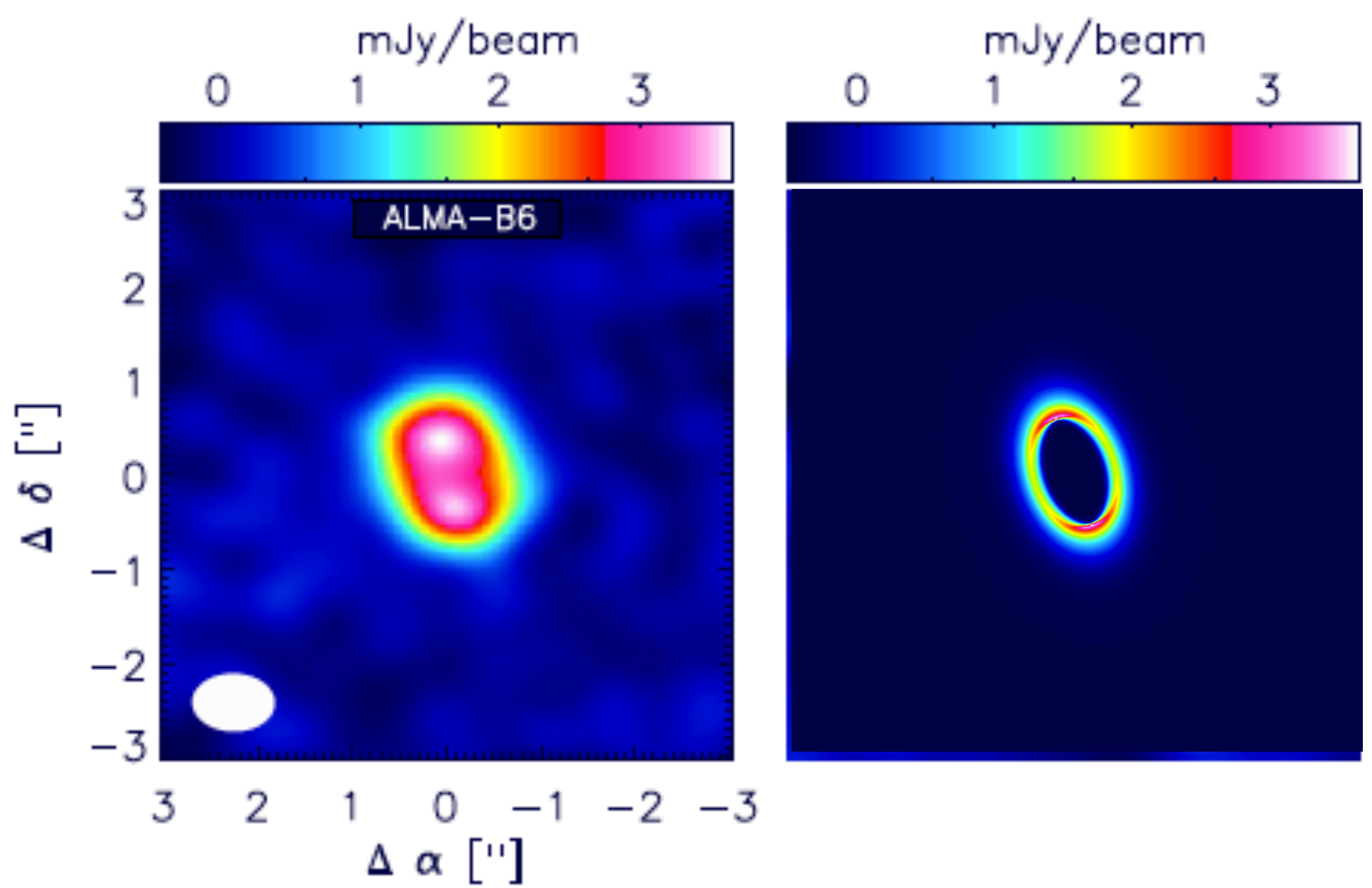


MCFOST, Pinte et al. 2006

MODELING APPROACH



Radiative Transfer results



Canovas et al. 2015

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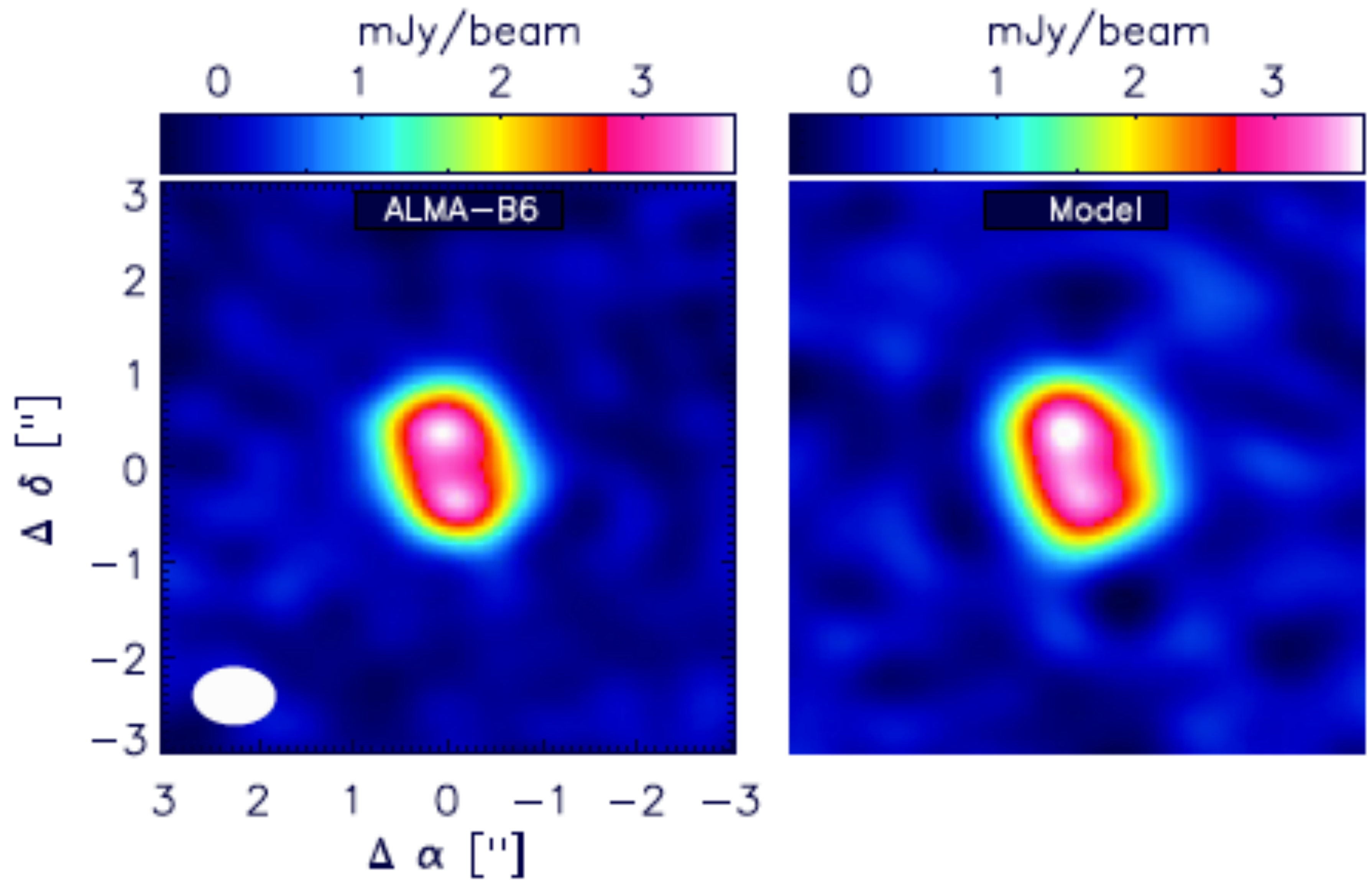

Canovas et al. 2015

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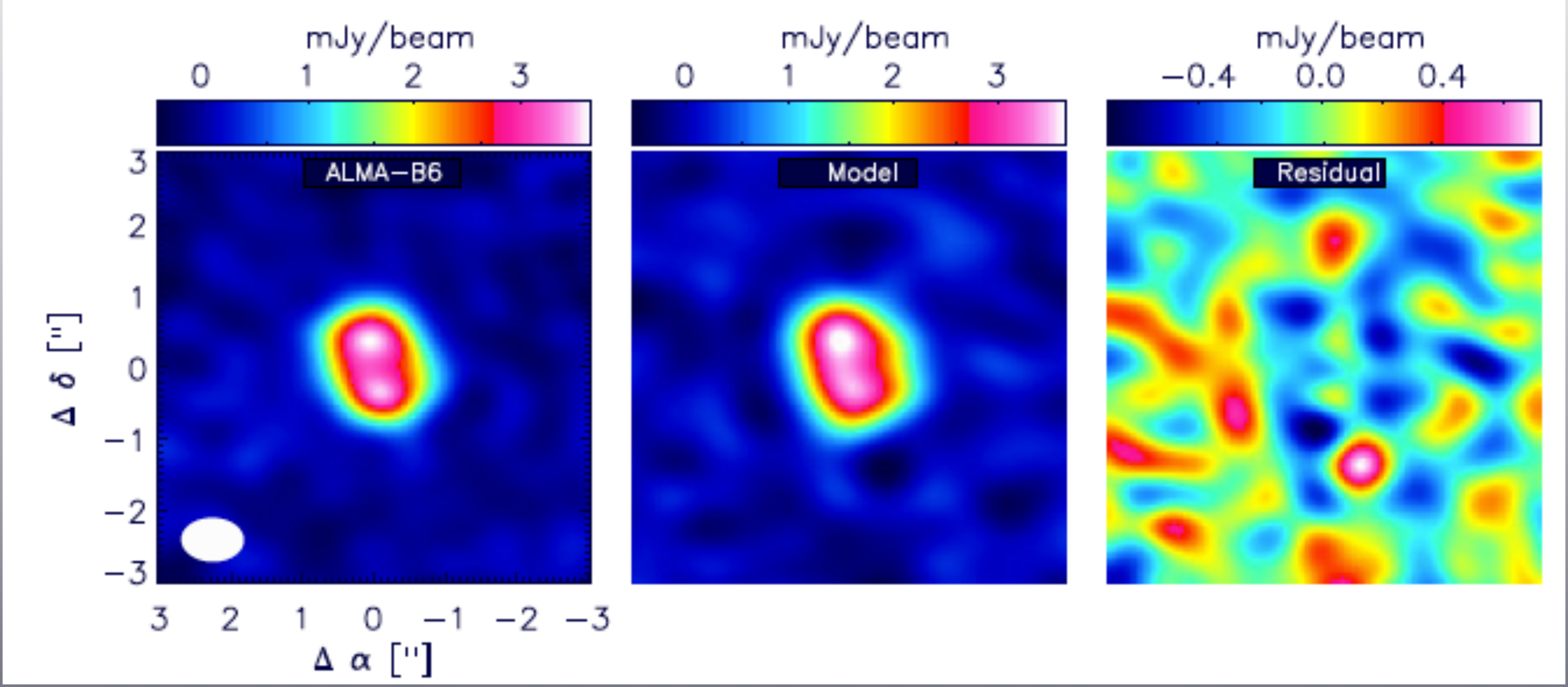

Canovas et al. 2015

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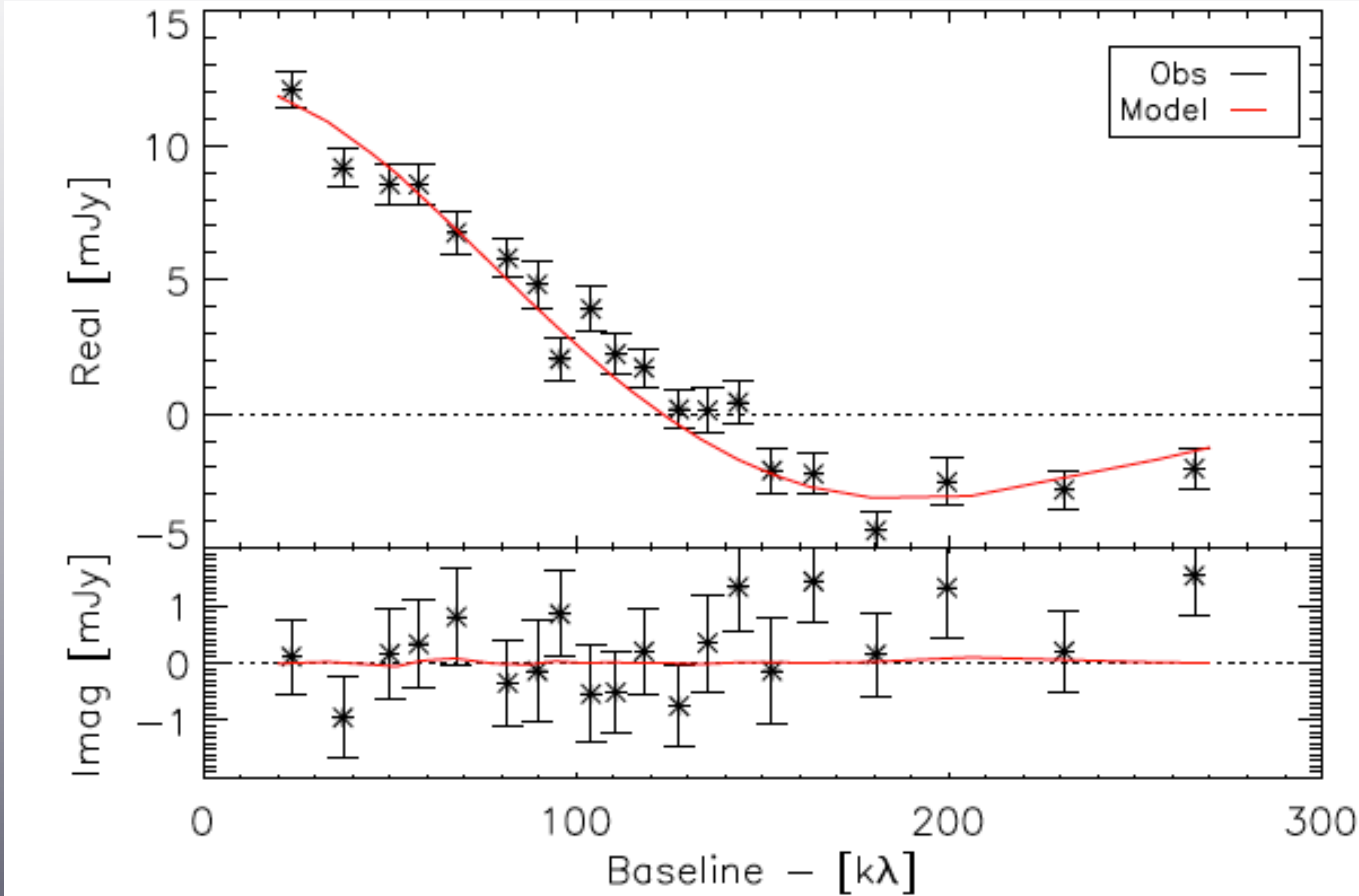

Canovas et al. 2015

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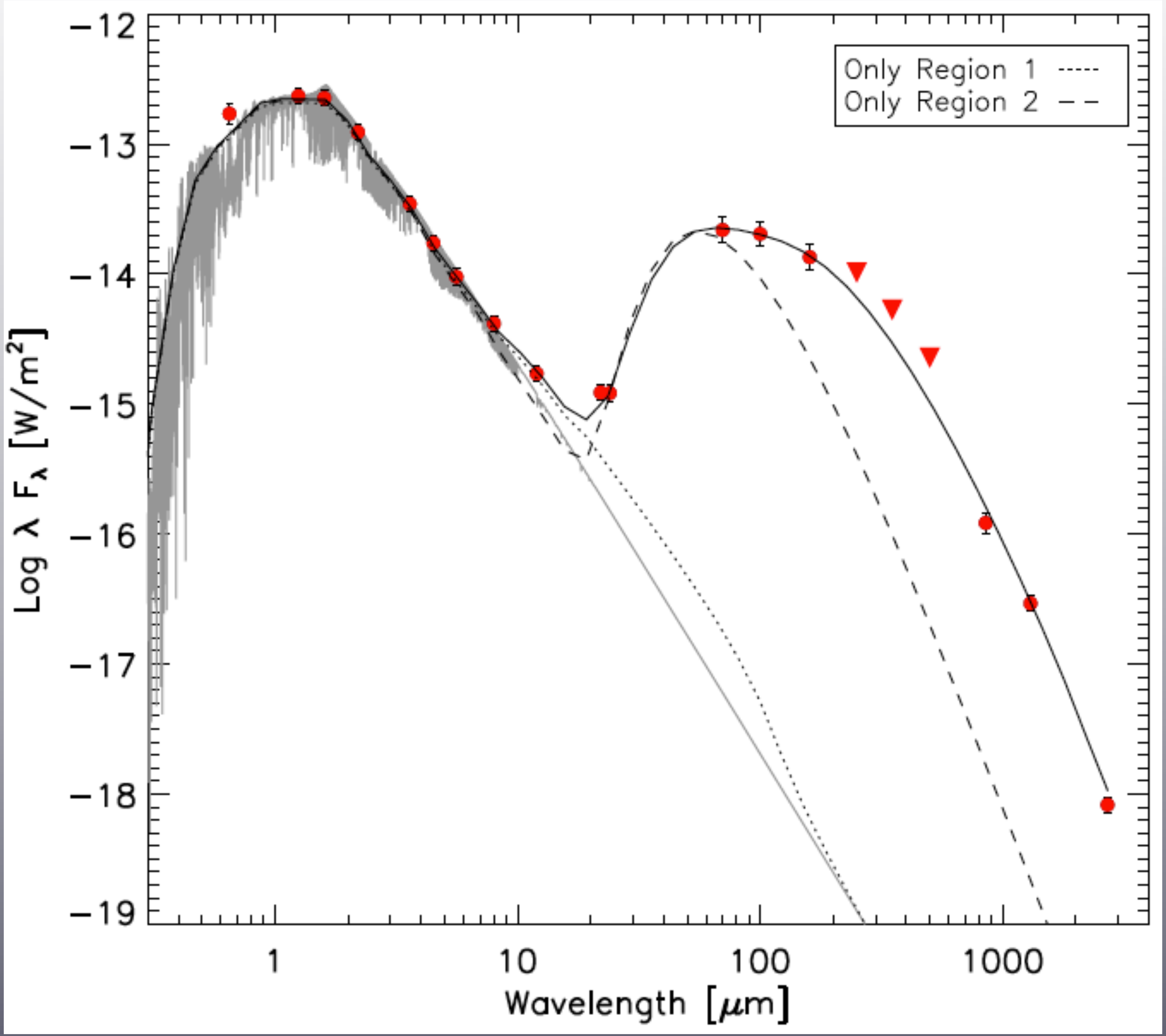
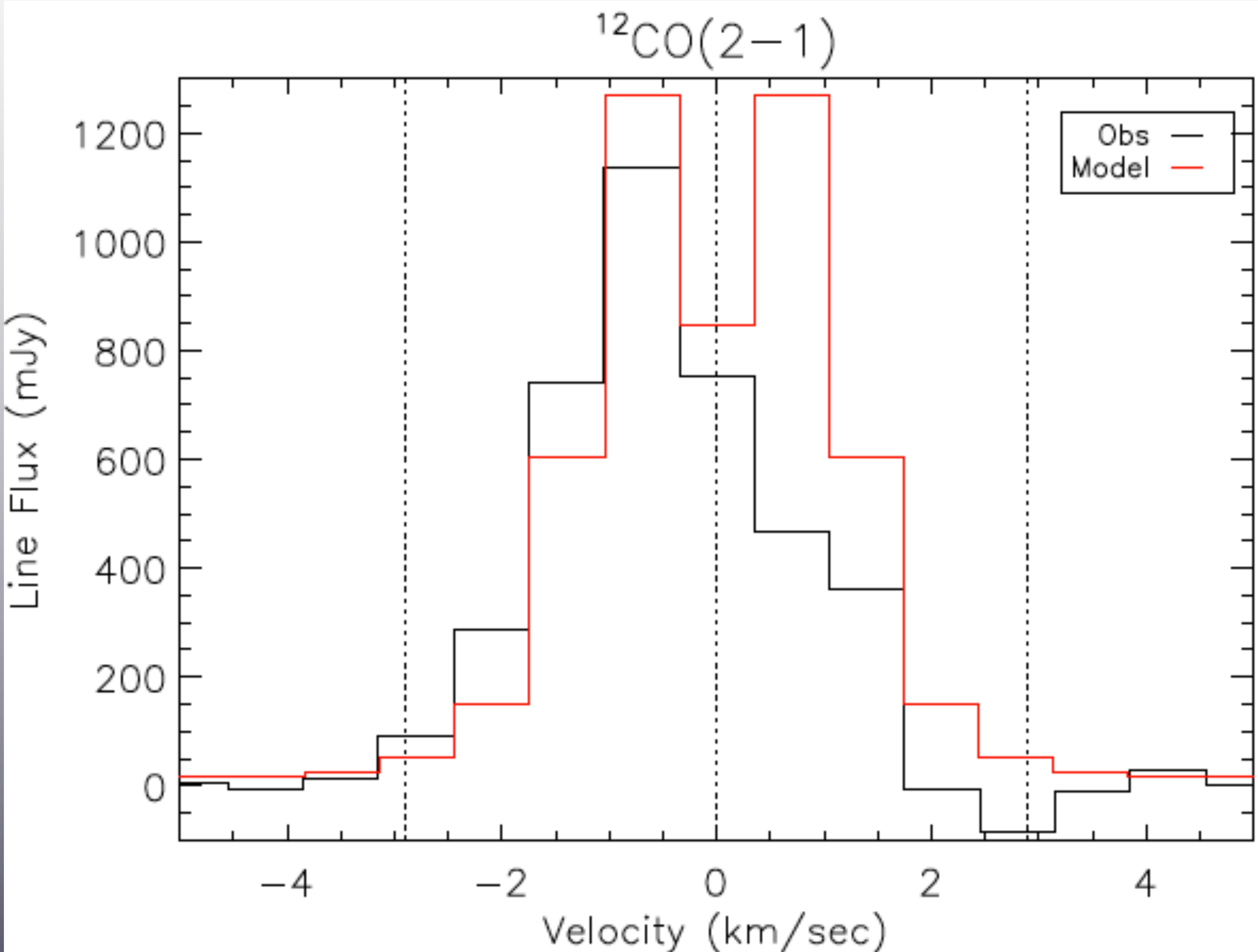
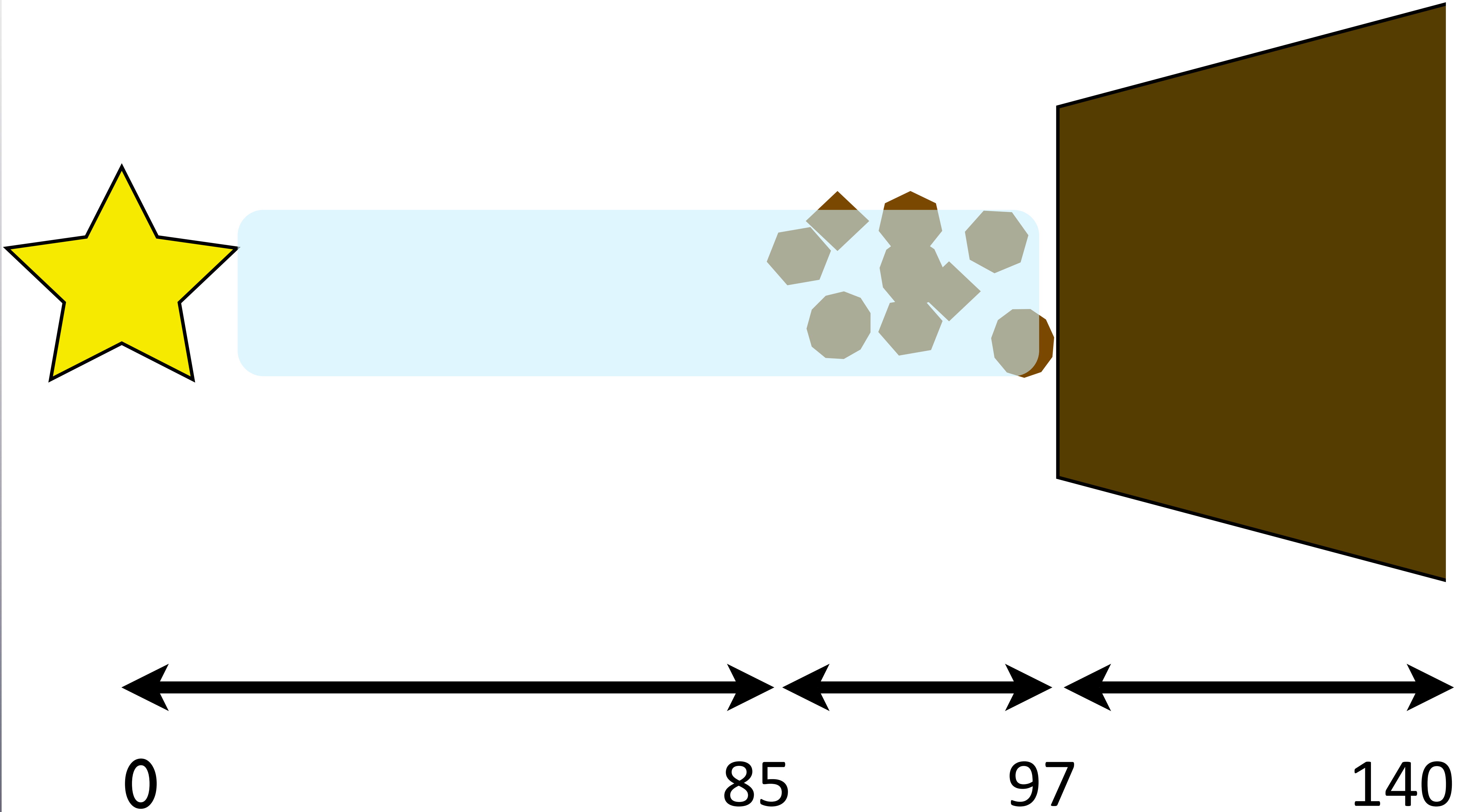


Canovas et al. 2015

Radiative Transfer results



Simplifying quite a lot



summarizing

- 97 au cavity: largest cavity around <1 $M_{\odot}$ stars! (average r to Pluto: 39.5 au)
- Cavity divided in 2 sub-zones
- CO inside the cavity
- Compact outer disk
- Disk Mass ~14.3 M_Earth

Andrews et al. 2012

- 97 au … ⊙ stars!
  (averag…
- Cavity …
- CO insi…
- Compa…
- Disk M…

Name	M_d ($M_\odot$)	R_{cav} (AU)	M_* ($M_\odot$)
(1)	(2)	(6)	(8)
MWC 758	0.008	73	1.8
SAO 206462	0.026	46	1.6
LkHα 330	0.024	68	2.2
SR 21	0.006	36	2.0
UX Tau	0.007	25	1.5
SR 24 S	0.045	29	2.0
DoAr 44	0.007	30	1.3
LkCa 15	0.055	50	1.01
RX J1615−3255	0.128	30	1.1
GM Aur	0.070	28	0.84
DM Tau	0.040	19	0.53
WSB 60	0.028	15	0.25

Andrews et al. 2012

WHY SZ 91 IS A STRONG PLANET FORMING CANDIDATE(s)? (I)

Current explanations for inner cavities in TD's:

- Photoevaporation
- Grain Growth
- Binarity
- Planet Formation

Owen et al. 2012, , Birnstiel et al. 2012, and several others

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- Dust "filtration/size segregation"
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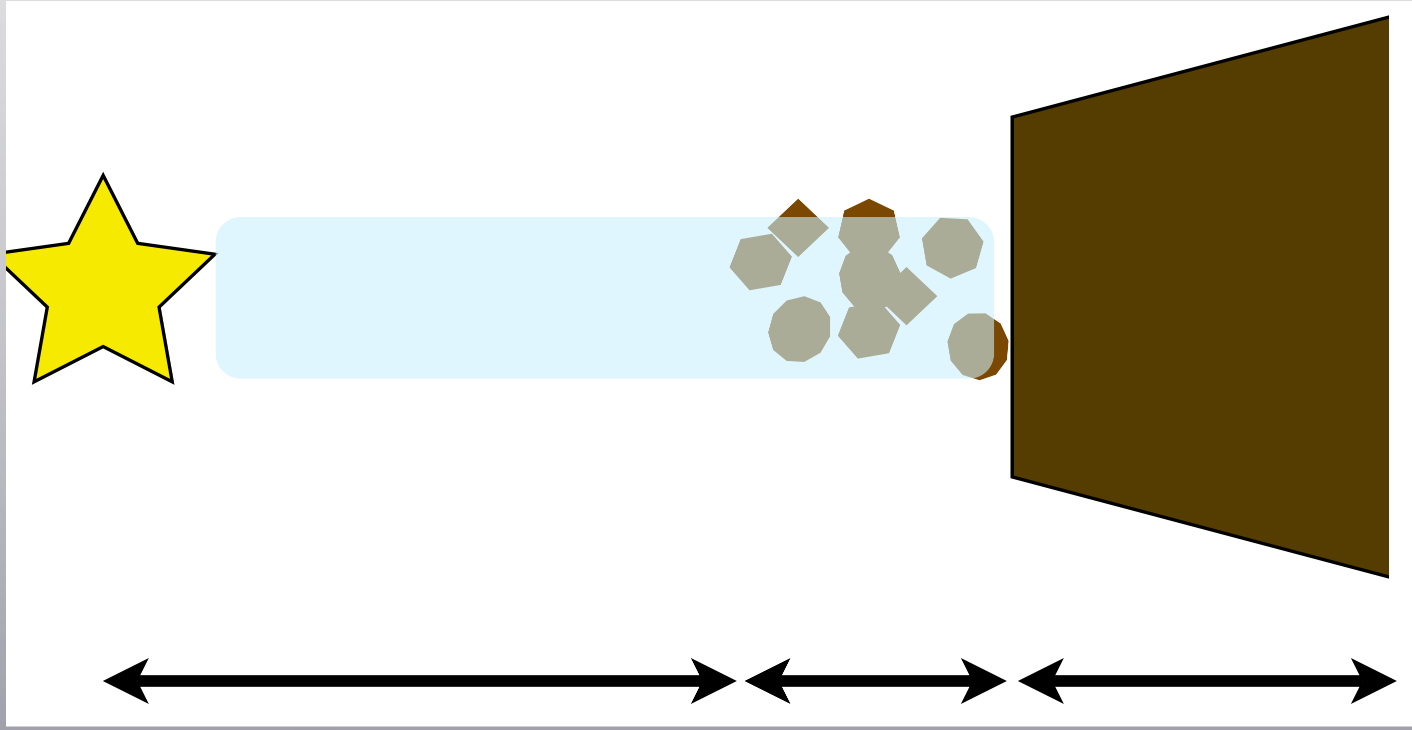
2-zones cavity: a common signature in planet-forming candidates??



- DM Tau
- RX_1615.3-3255
- RX_1633.9-2442
- J160421.7-213028

Next steps...

- ALMA Cycle 2 data (hopefully soon!...)
- High-Res multi-epoch spectra (UVES/VLT)
- Planet Hunting (let's hope)

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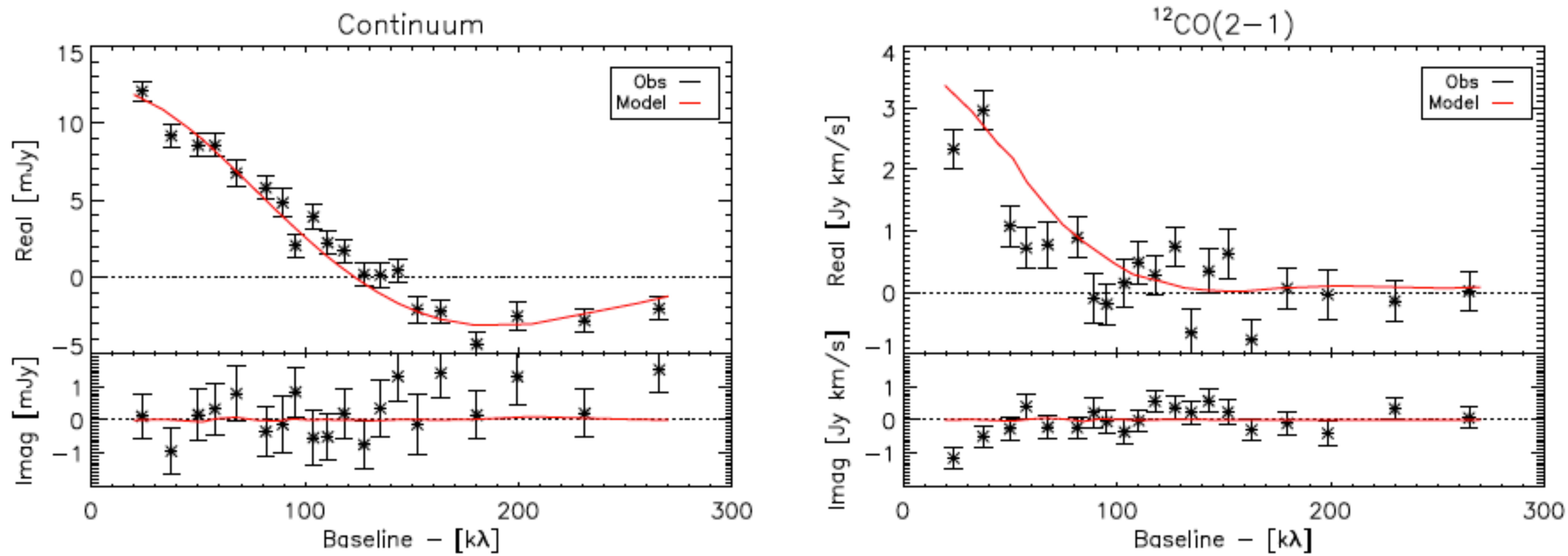
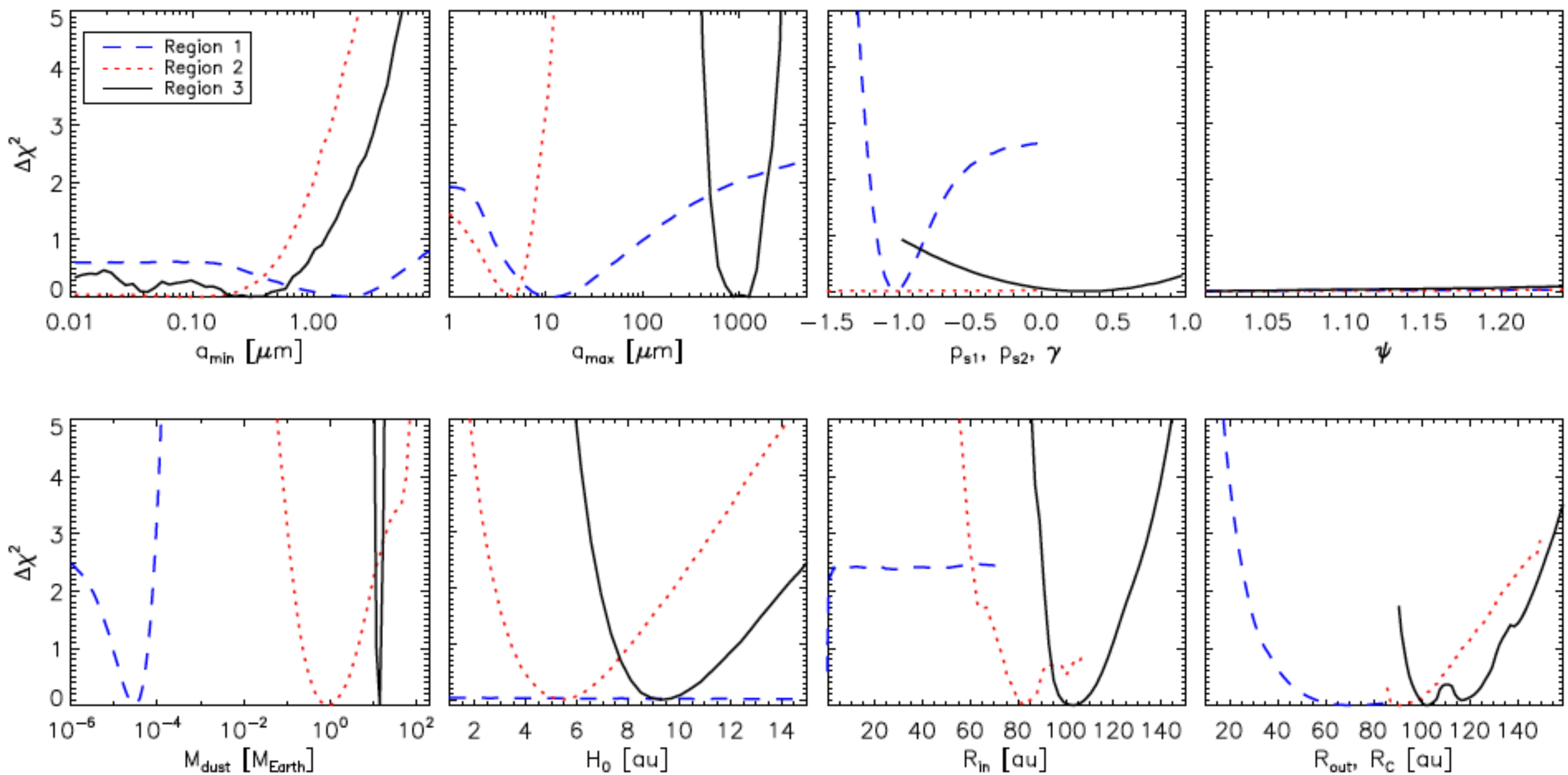
THANKS


Continuum
Obs
Model
Real [mJy]
Imag [mJy]
Baseline – [kλ]
12CO(2–1)
Real [Jy km/s]
Imag [Jy km/s]


Region 1
Region 2
Region 3
Δχ²
0.01 0.10 1.00
a_{min} [μm]
1 10 100 1000
a_{max} [μm]
−1.5 −1.0 −0.5 0.0 0.5 1.0
p_{s1}, p_{s2}, γ
1.05 1.10 1.15 1.20
ψ
10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2}
M_{dust} [M_{Earth}]
2 4 6 8 10 12 14
H_0 [au]
20 40 60 80 100 120 140
R_{in} [au]
20 40 60 80 100 120 140
R_{out}, R_c [au]

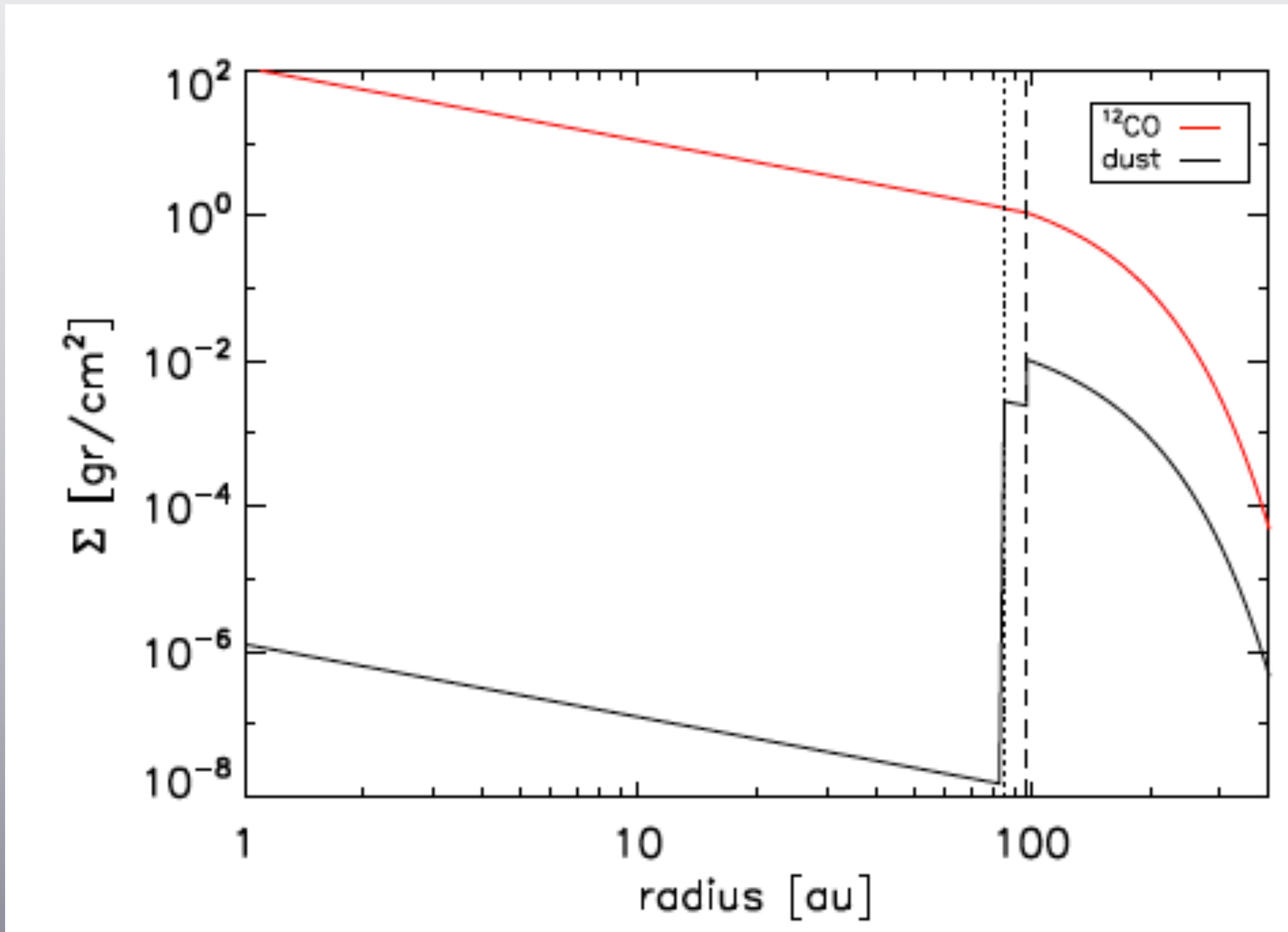


Table 3: Model Results. Fixed parameters are listed above the line.

Parameter	Value
$T_\star$	3720 K
$R_\star$	1.46 $R_\odot$
$M_\star$	0.47 $M_\odot$
d	200 pc
i	49.5°
PA	18.2°
p	3.5
$a_{\min_1}, a_{\max_1}$	$2, 15\mu$m
$a_{\min_{2,3}}$	0.05μm
H_{0_1}	5 au
$p_{s_{1,2}}$	1
γ	0.3
$\psi_{1,2,3}$	1.15
M_{dust_1}	1×10^{-4} $M_\oplus$
R_1	0.025 au
$a_{\max_2}$	5μm
$a_{\max_3}$	1000μm
R_{out_1}	85 au
R_{in_2}	85 au
R_{out_2}	97 au
R_{cav}	97 au
R_C	100 au
M_{dust_2}	0.7 $M_\oplus$
M_{dust_3}	14.3 $M_\oplus$
H_{0_2}	5 au
H_{0_3}	10 au
$\log(\Sigma_{100_1})$	-8.20 $[gr/cm^2]$[a]
$\log(\Sigma_{100_2})$	-2.95 $[gr/cm^2]$[a]
$\log(\Sigma_C)$	-1.98 $[gr/cm^2]$[a]