Ten years of VLTI:
from first fringes to core science

Disks around young stars

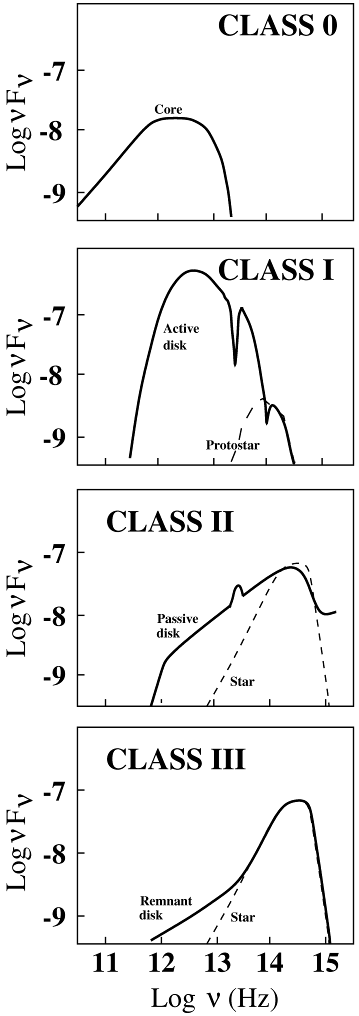
Andrea Isella

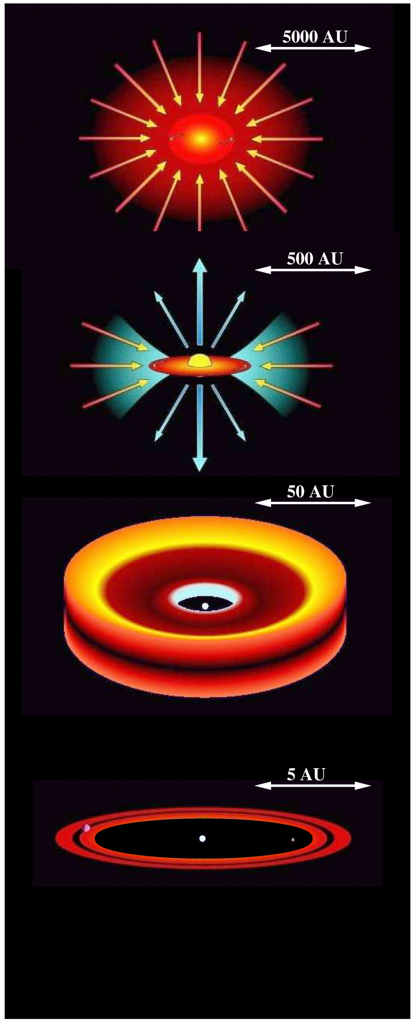
Caltech

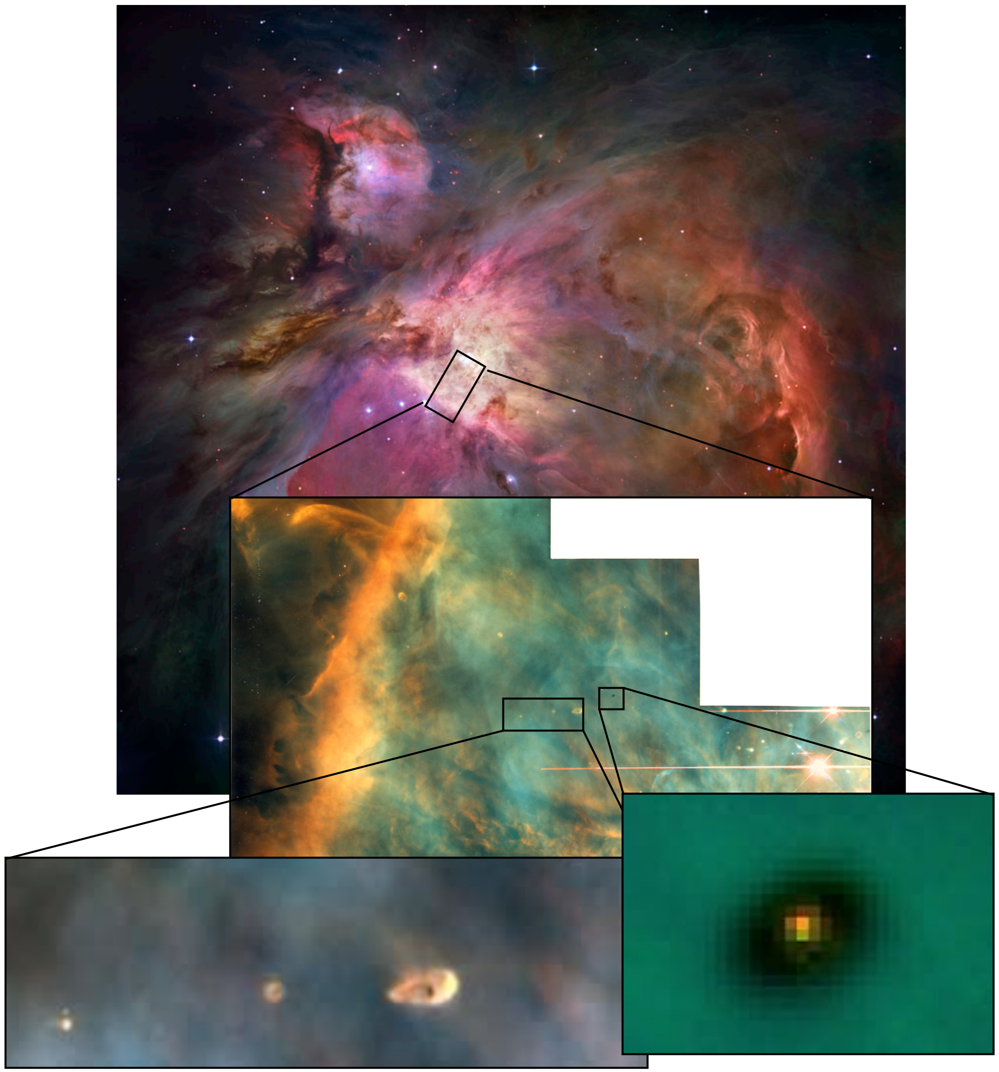
CARMA
Combined Array for Research in Millimeter-Wave Astronomy

NSF

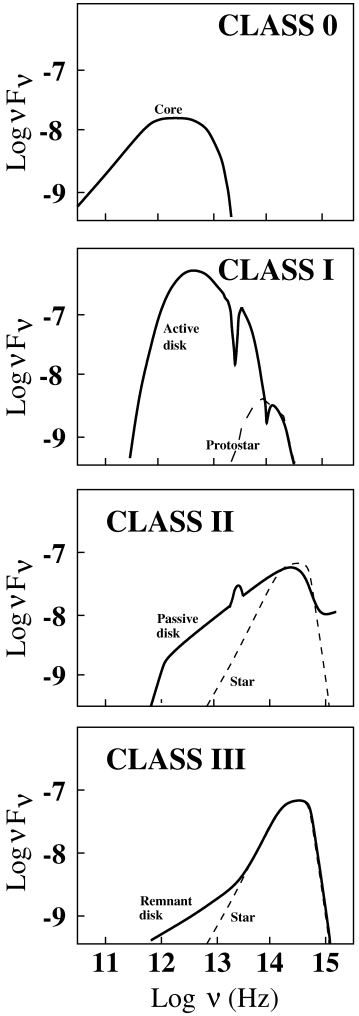
From cores to disks to planets

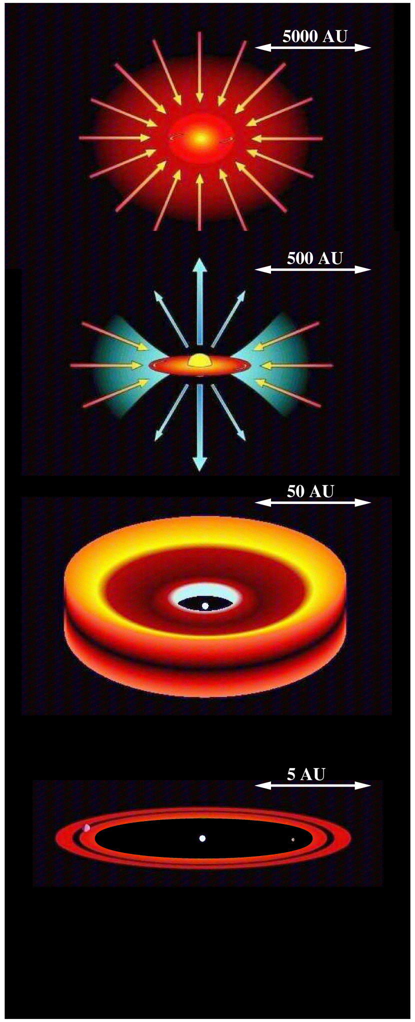




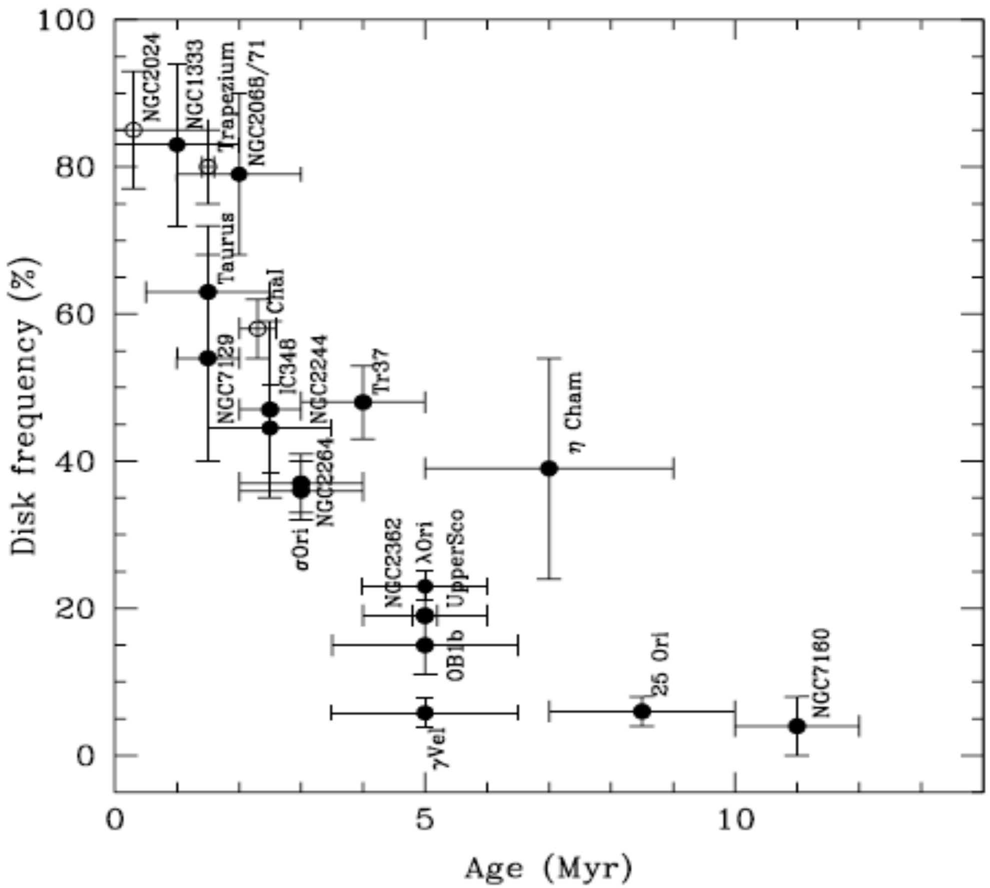


Inner disk dispersal time scale

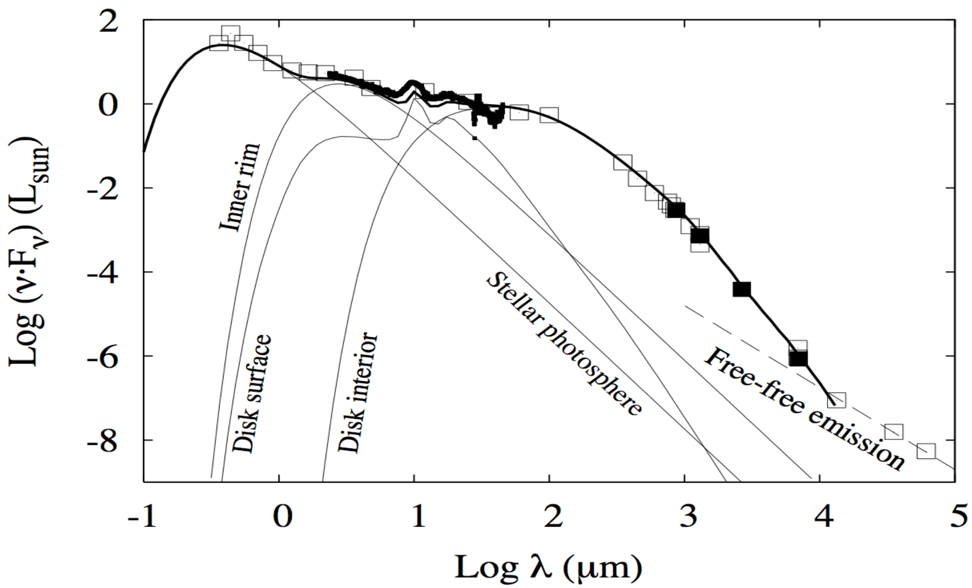


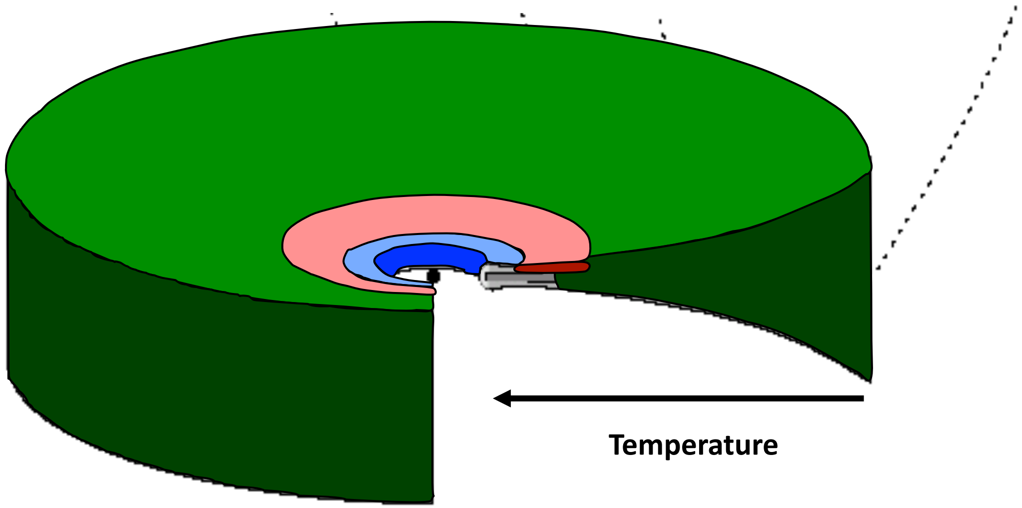


Hernandez et al. (2008)



Thermal disk emission





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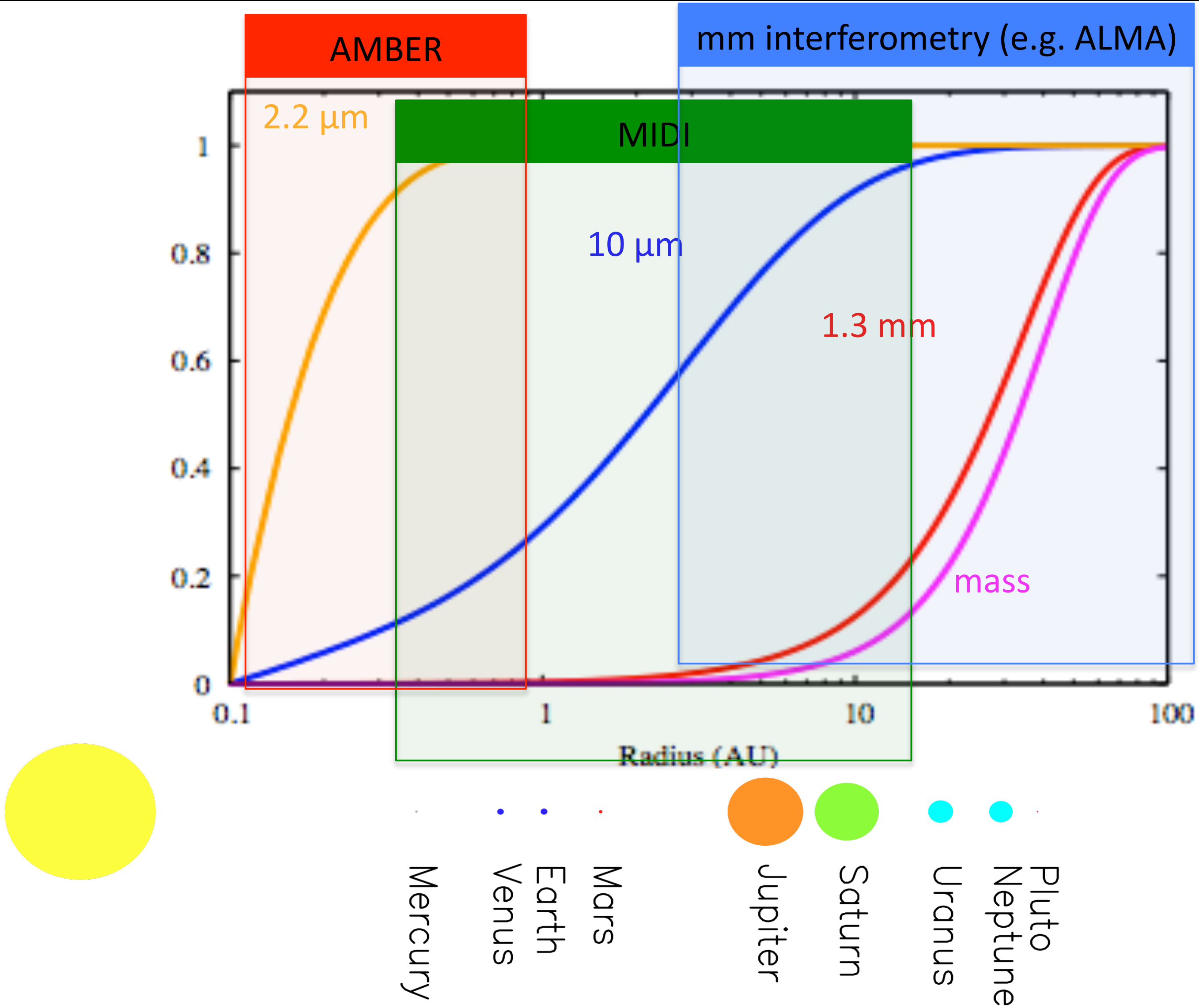
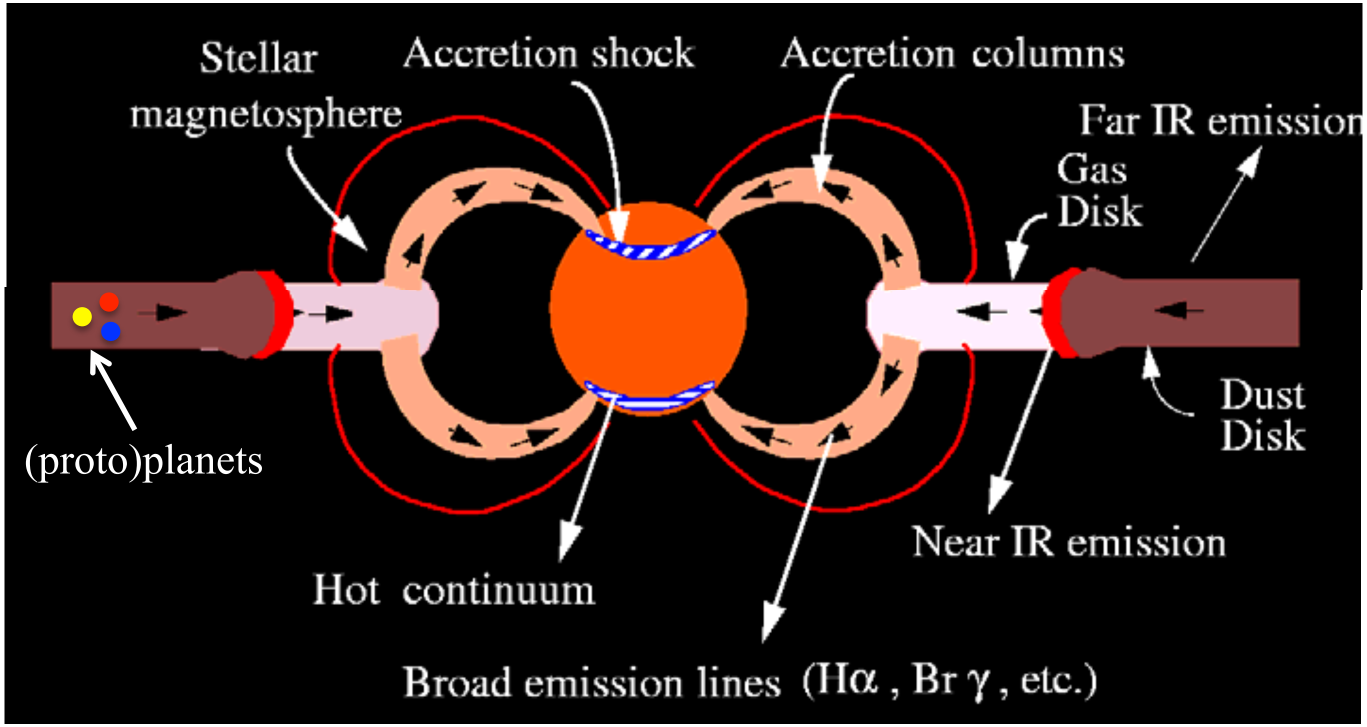


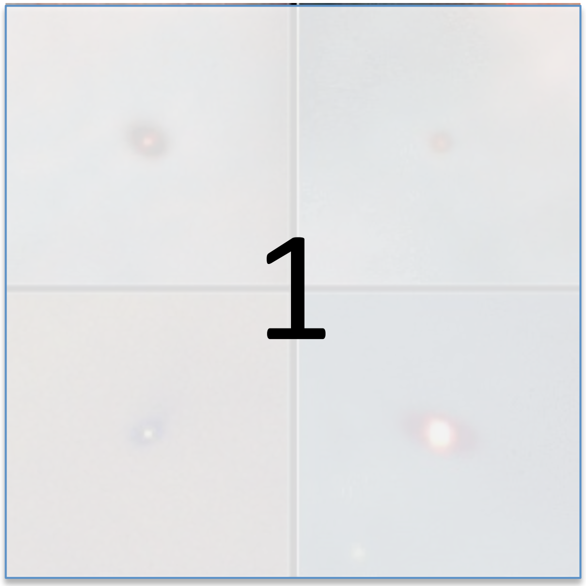
Physics in the inner disk



- planet formation and planet-disk interaction
- crystallization of dust and composition of meteorites (e.g. CAI) Acke
- dust sublimation (effects the global disk structure, the formation and migration of planets)
- disk-star connection, jets and winds (regulate the angular momentum of the disk and star)
- accretion (regulate the final stellar mass, depends on the magnetic field and disk viscosity)

Planet formation

Age < a few Myr	Age of about 60 Myr
Silhouette disks in Orion	Planets around HR 8799



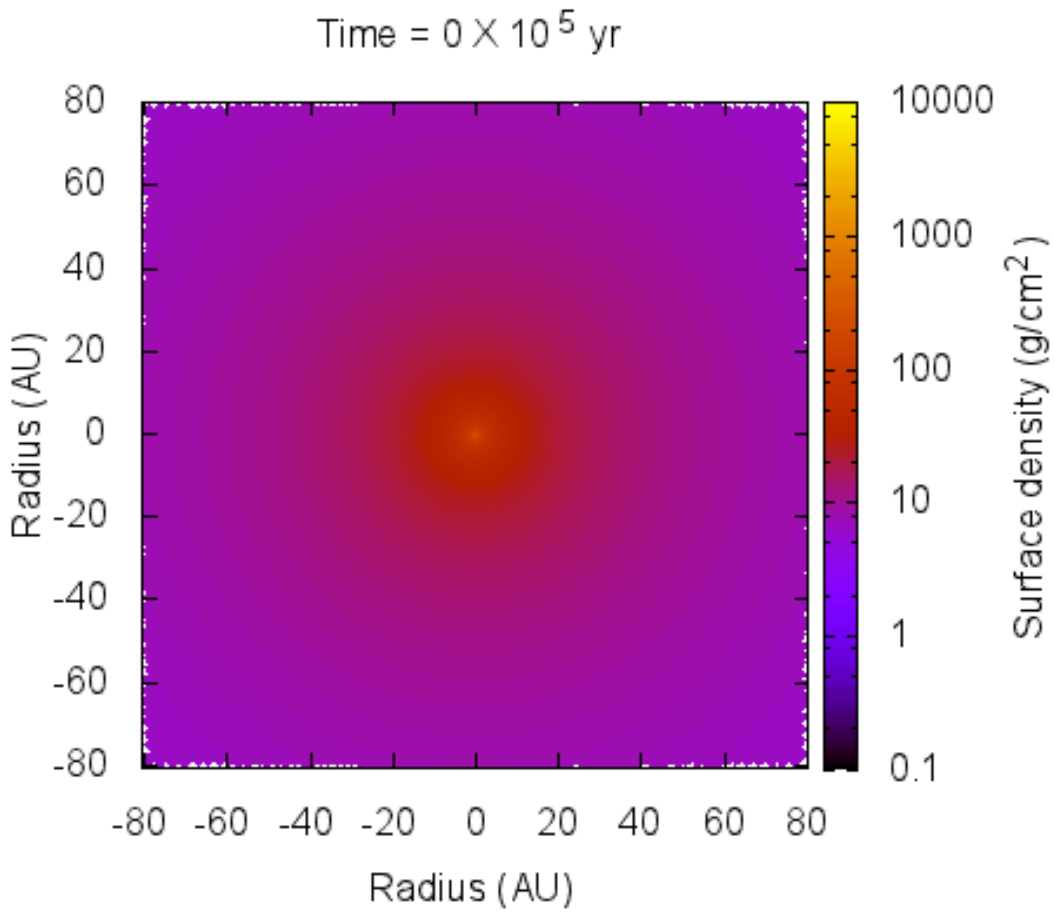
McCaughrean & O’Dell (1995)

Marois et al. (2010)

How much material is available to form planets? What is its composition and kinematics? How this material is radially distributed?
Where in the disk do planets form? When do planets form?

➡ Observe the location and evolution of the gas and dust

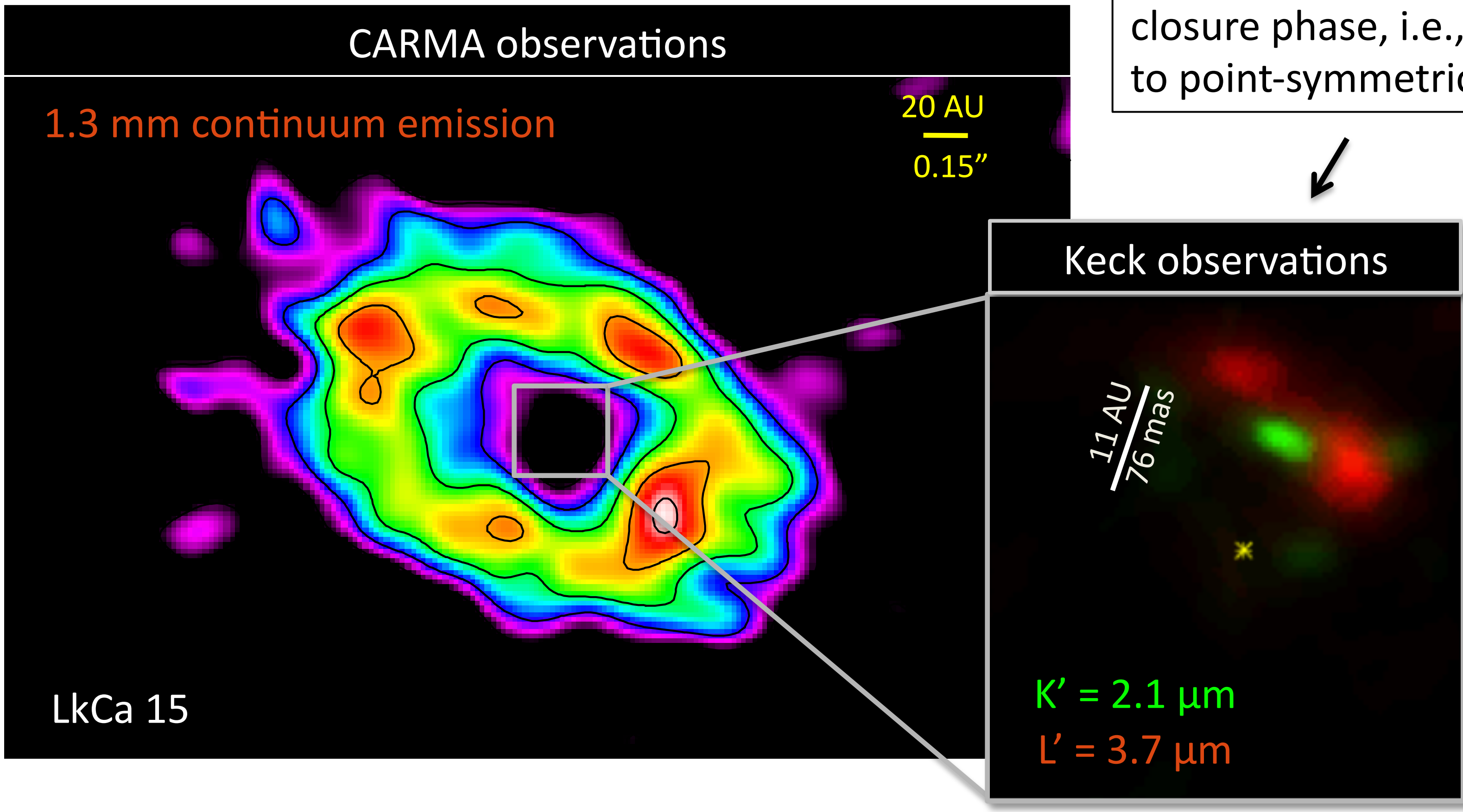
LkCa15: a planetary system in formation



LkCa15: a planetary system in formation

K5 – 1 Msun – 2-5 Myr in the Taurus Molecular Cloud

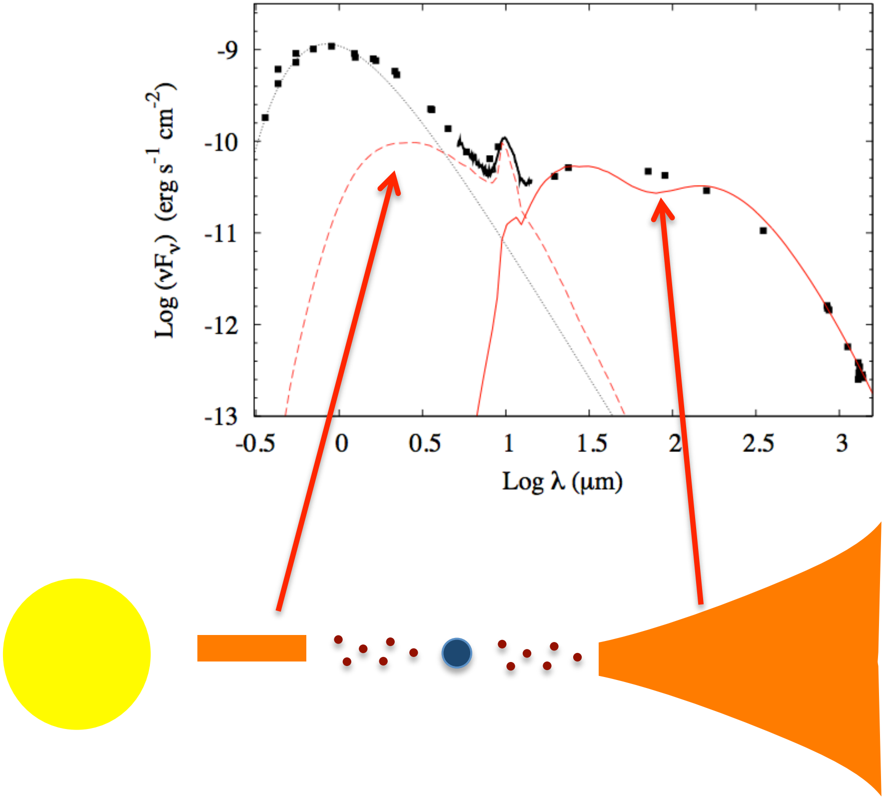
Image reconstructed using the closure phase, i.e., insensitive to point-symmetric emission



Isella et al., ApJ, submitted

Krauss & Ireland (2011)

LkCa15: a planetary system in formation



the inner disk can be investigate using the VLTI

HD100546

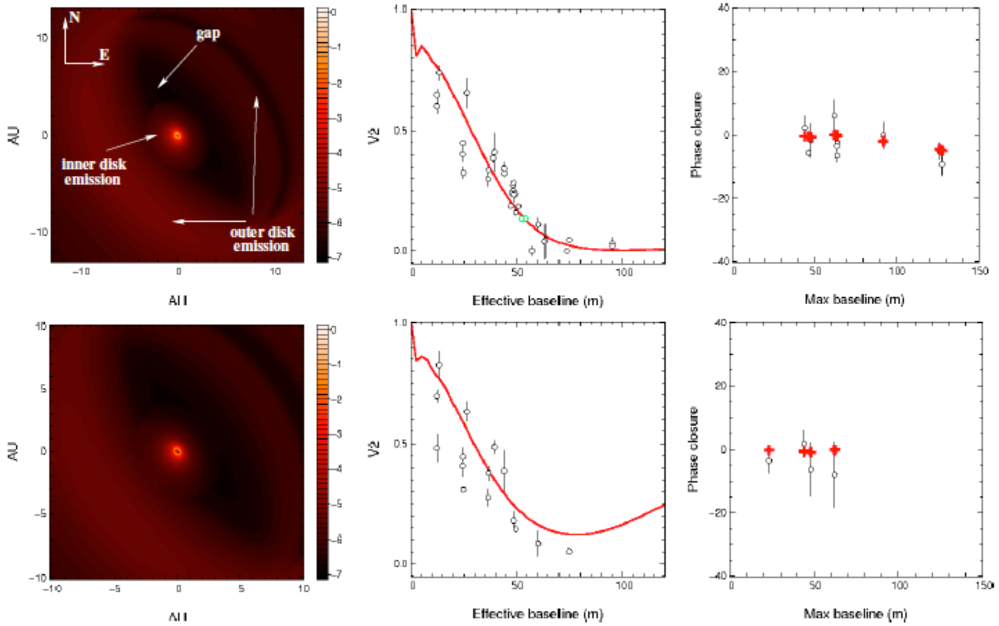


Fig. 3. K-band (top) and H-band (bottom) MCFOST modeling of HD 100546. From left to right: NIR images (normalized intensity to one at maximum, in logarithmic scale), visibility (red solid lines) and closure phase (red crosses), compared with the interferometric observations (black circles and error bars). In the middle panels, the "kink" in the model visibility curves at B∼10 m is a real feature caused by the sharp inner edge of the outer disk.

Tatulli et al. (2011)

Inner disk from 0.2-4 AU

Gap from 4-13 AU

Giant planet at 8 AU?

Benz, Benisty, Panic

Investigation the dust structure

Van Boekel (2004)

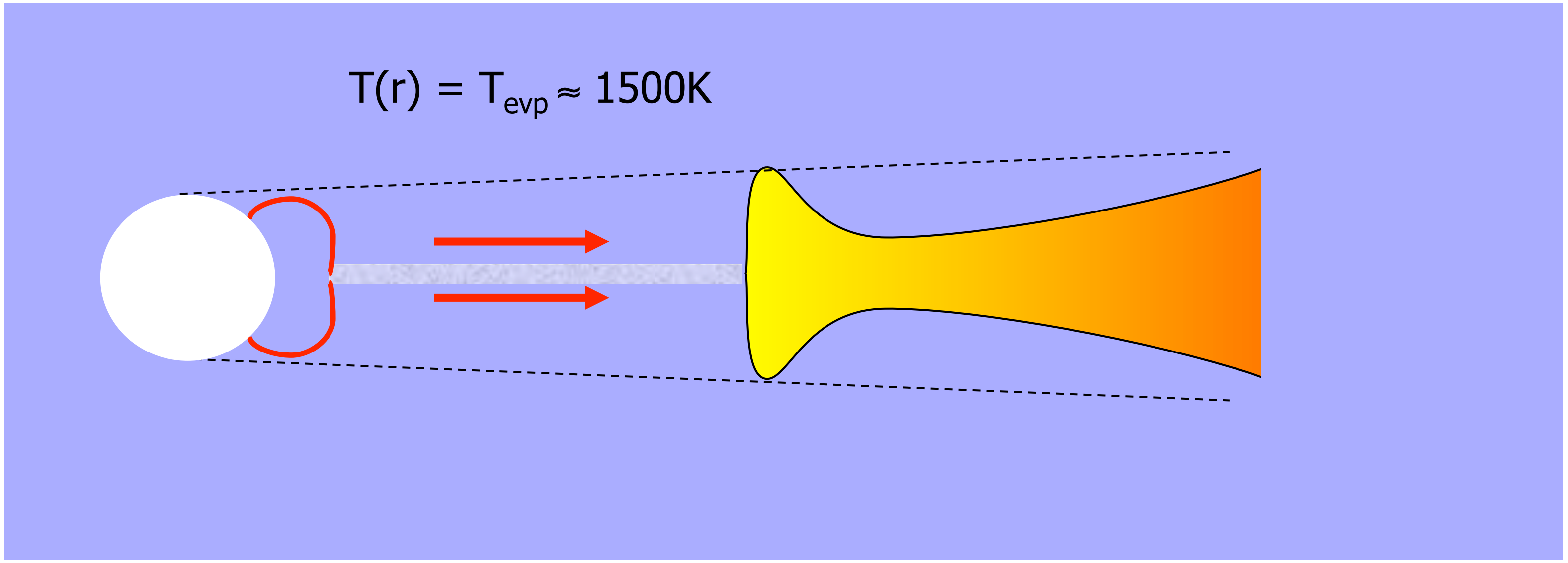
Dust in the inner disk is similar to comets ... But comets are found in the outer Solar system .. A process to circulate the dust is required

this requires temperature > 900 K, which naturally occurs in the innermost part

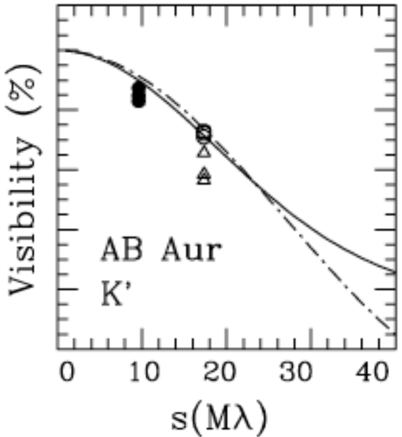
Eventually, the dust may sublimate ... Strong opacity discontinuity .. Nex slide

Acke

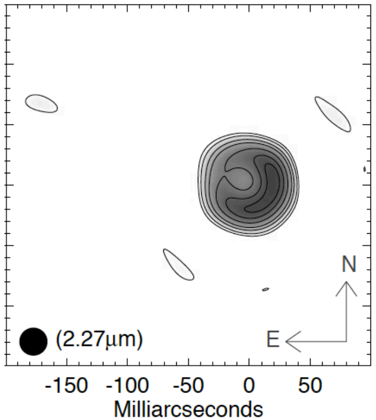
Dust sublimation: the inner rim of the dusty disk



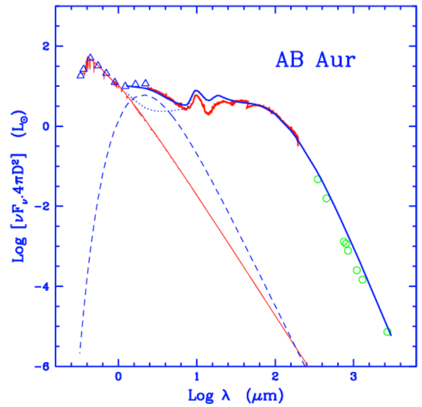
Millan-Gabet et al. (2001)



Tuthill et al. (2001)

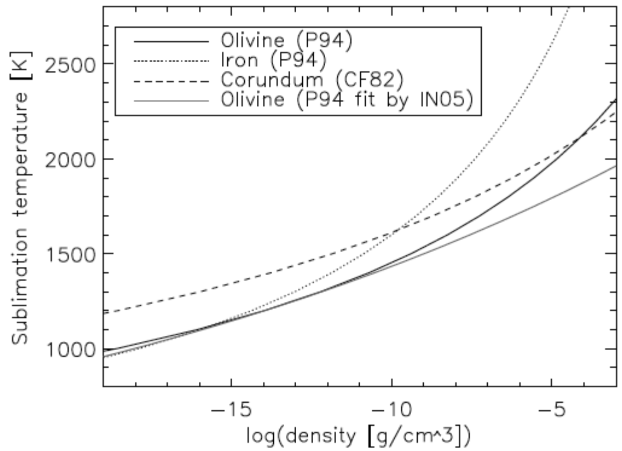


Natta et al. (2001)



The "puffed-up" inner rim model

Dullemond, Dominick & Natta (2001)
Isella & Natta (2005)
Vinkovic et al. (2006)
Tannirkulam et al. (2007)
Kama et al. (2009)

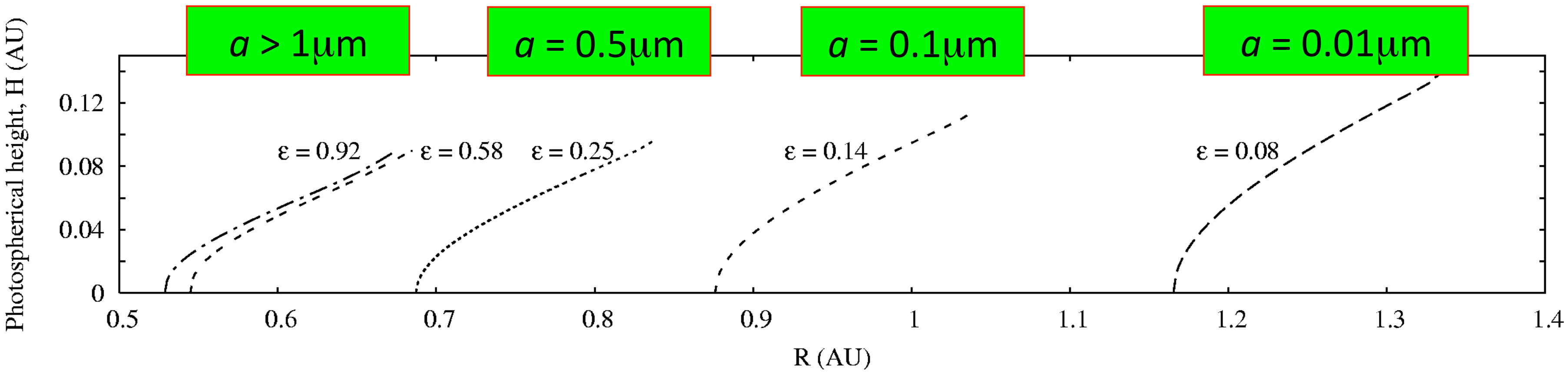


Kama et al. (2009)
Pollack et al. (1994)

SINGLE GRAIN SIZE and COMPOSITION, NEGLIGIBLE GAS OPACITY

Isella & Natta (2005)

$$R_{\rm evp}[{\rm AU}] = 0.034 \cdot \left(\frac{1500}{T_{\rm evp}}\right)^2 \sqrt{\frac{L_\star}{L_\odot}\left(2+\frac{1}{\epsilon}\right)}, \qquad \rho(z) \propto \exp(-z^2/2h^2)$$



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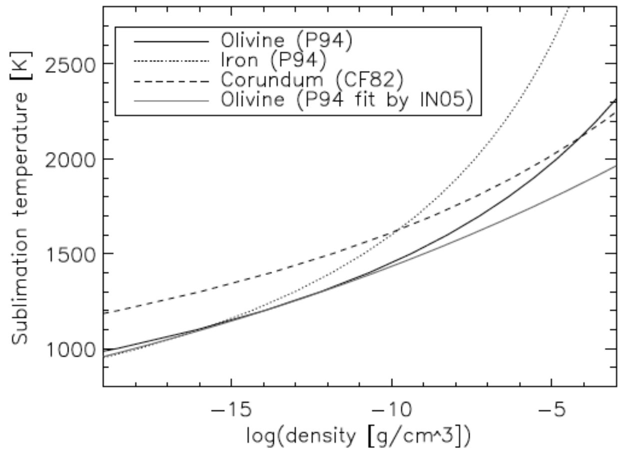

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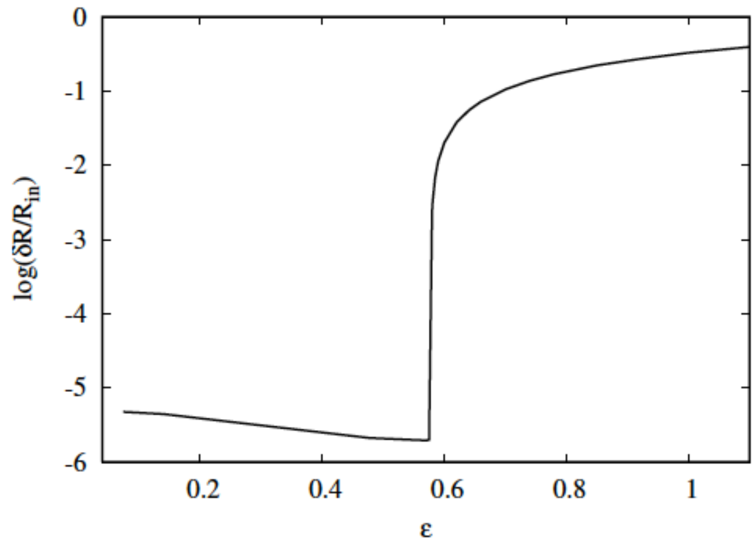
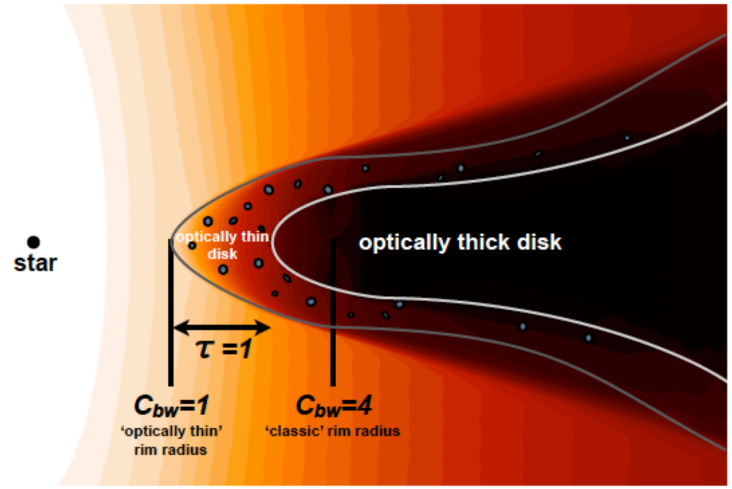


Isella & Natta (2005)



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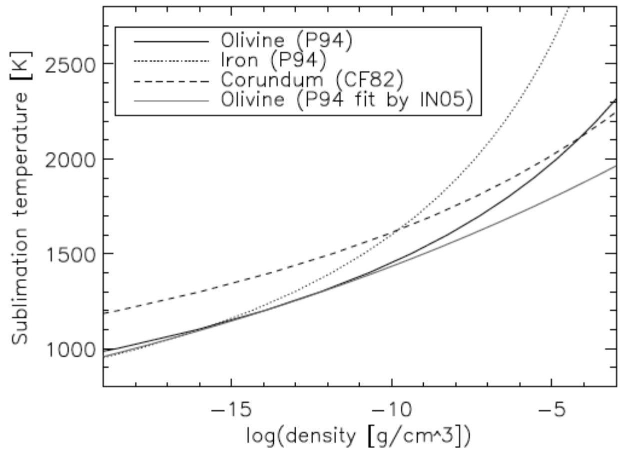
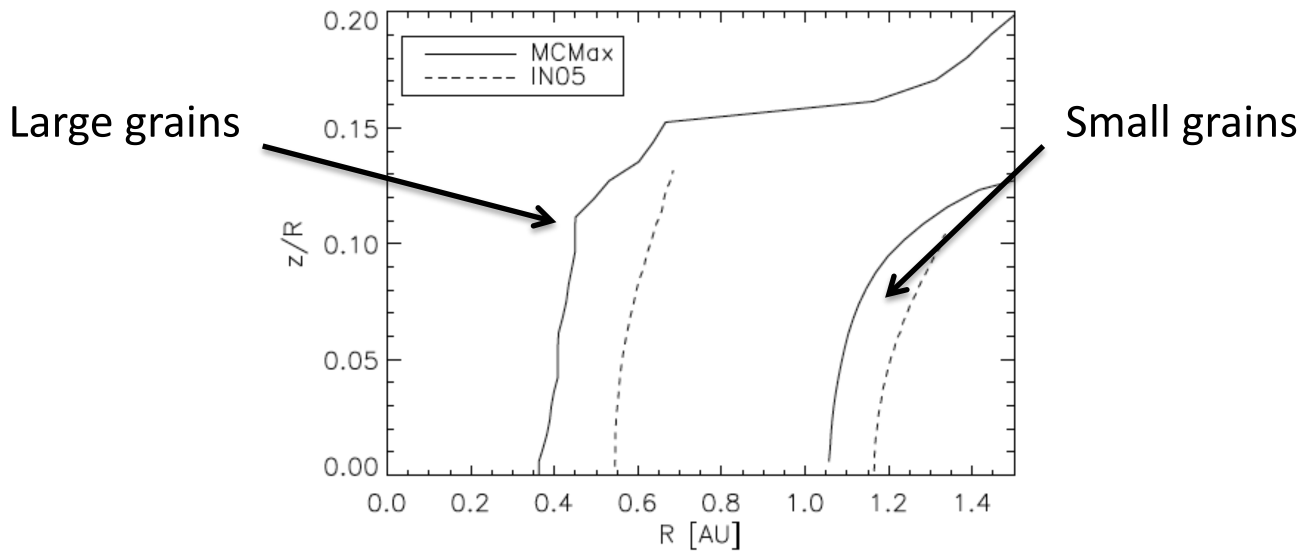


Kama et al. (2009)
Pollack et al. (1994)

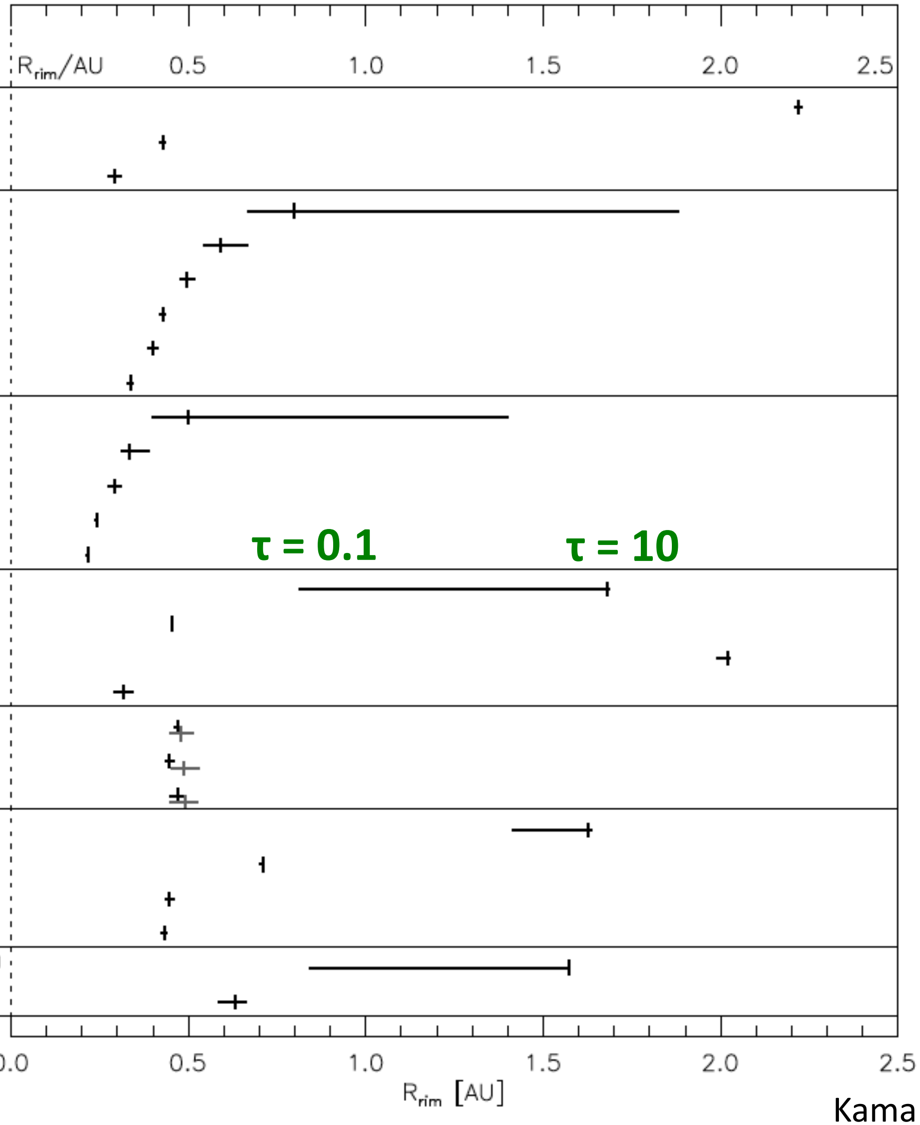
MULTI SIZE and COMPOSITION DUST GRAINS, NEGLIGIBLE GAS OPACITY



Kama et al. (2009)

The "puffed-up" inner rim model

N_{mod}	log Σ_0	Olivine 0.1	Olivine 10	Olivine 100	Fors 10	Iron 0.1	Iron 10	Cor 0.1
0	0	1.0						
1	0		1.0					
2	0			1.0				
3	−3		1.0					
4	−2		1.0					
5	−1		1.0					
6	0		1.0					
7	1		1.0					
8	2		1.0					
9	−2			1.0				
10	−1			1.0				
11	0			1.0				
12	1			1.0				
13	2			1.0				
14	0	0.9999	0.0001					
15	0	0.9	0.1					
16	0	0.9999		0.0001				
17	0	0.9		0.1				
18	0		0.9999		0.0001			
19	0		0.9		0.1			
20	0		0.1		0.9			
21	0	0.9999				0.0001		
22	0	0.9				0.1		
23	0		0.9			0.1		
24	0		0.9				0.1	
25	0	0.9999						0.0001
26	0	0.99						0.01



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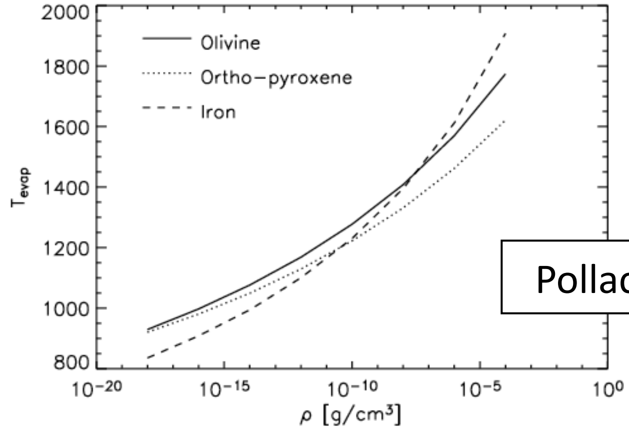
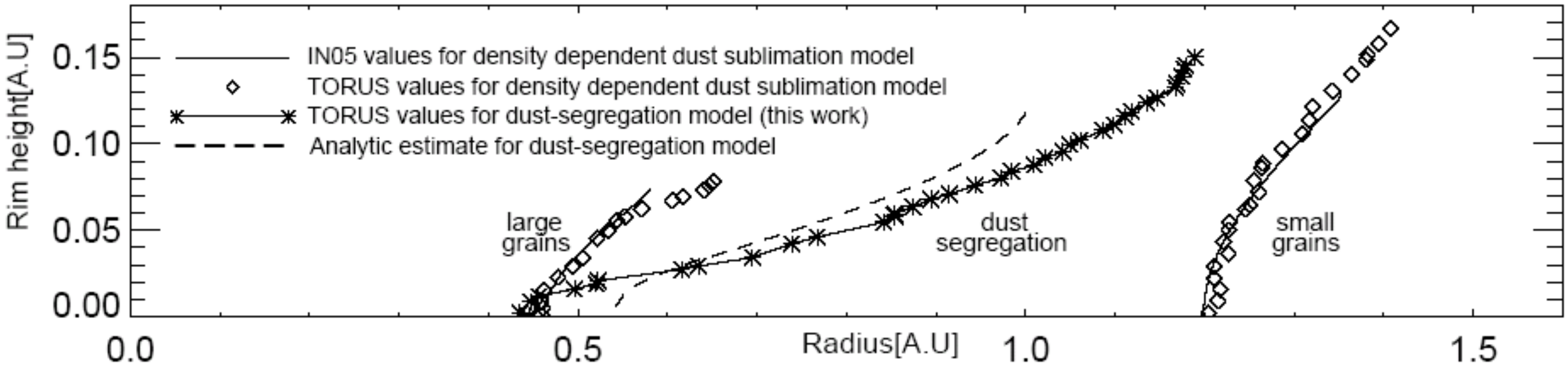


Pollack et al. (1994)

MULTI SIZE DUST GRAINS + SETTLING, NEGLIGIBLE GAS OPACITY

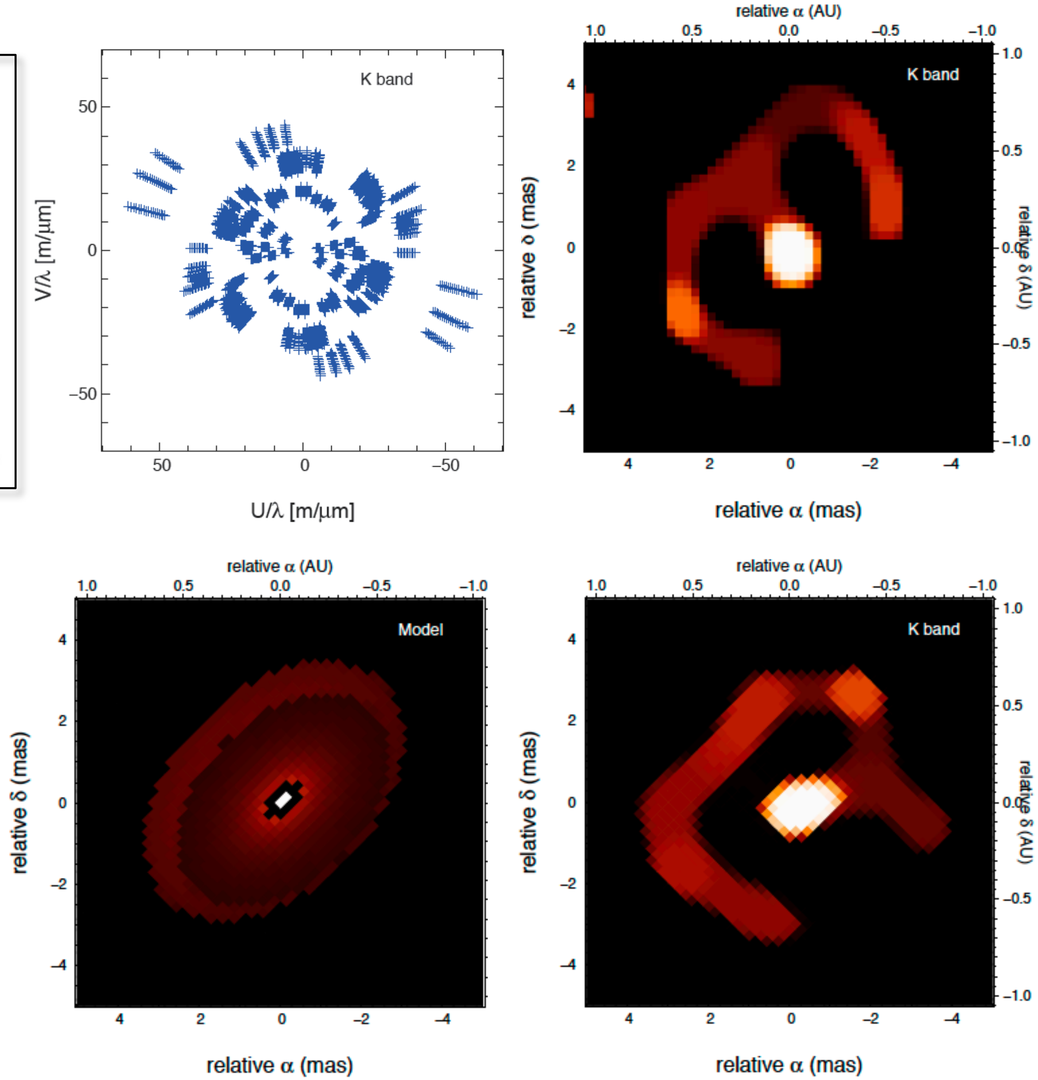


Tannirkulam et al. (2007)

Observations the "puffed up" inner rim

Akeson et al. (2005)
Isella et al. (2006)
Monnier et al. (2006)
Tatulli et al. (2007, VLTI/AMBER)
Eisner et al. (2007, 2009, 2010)
Isella et al. (2008, VLTI/AMBER)
Krauss et al. (2008, VLTI/AMBER)
Benisty et al. (2010,2011, VLTI/AMBER)

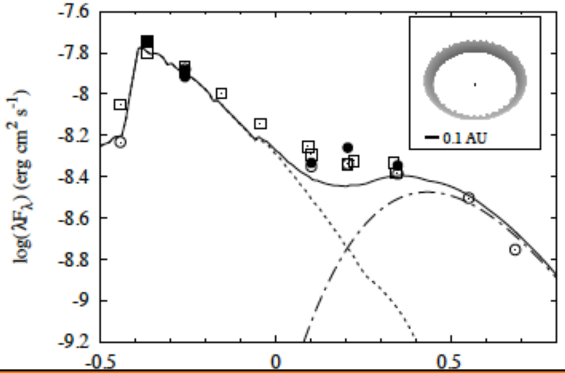
Akeson



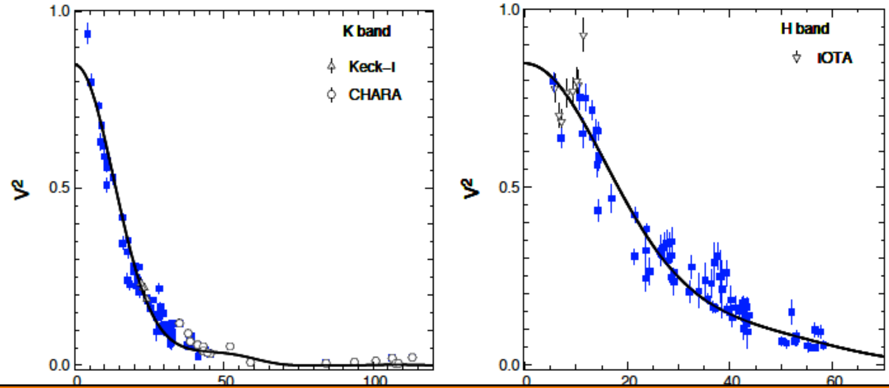
Benisty et al. (2011)

The rim is not enough

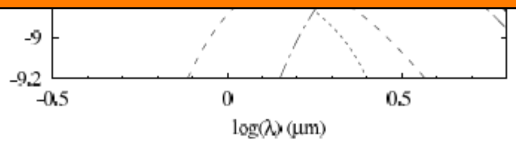
MWC 758



HD 163296 – A1

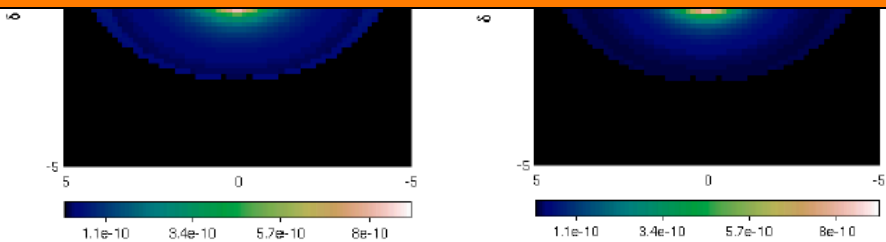


A full treatment of the dust and gas opacity in needed!



Isella et al. (2008)

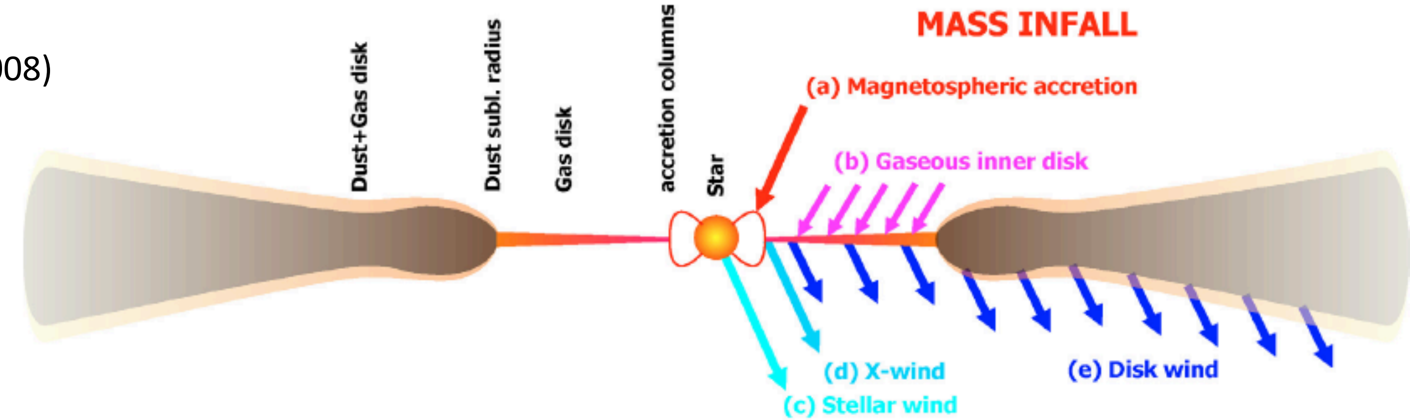
see also Akeson et al. (2005)

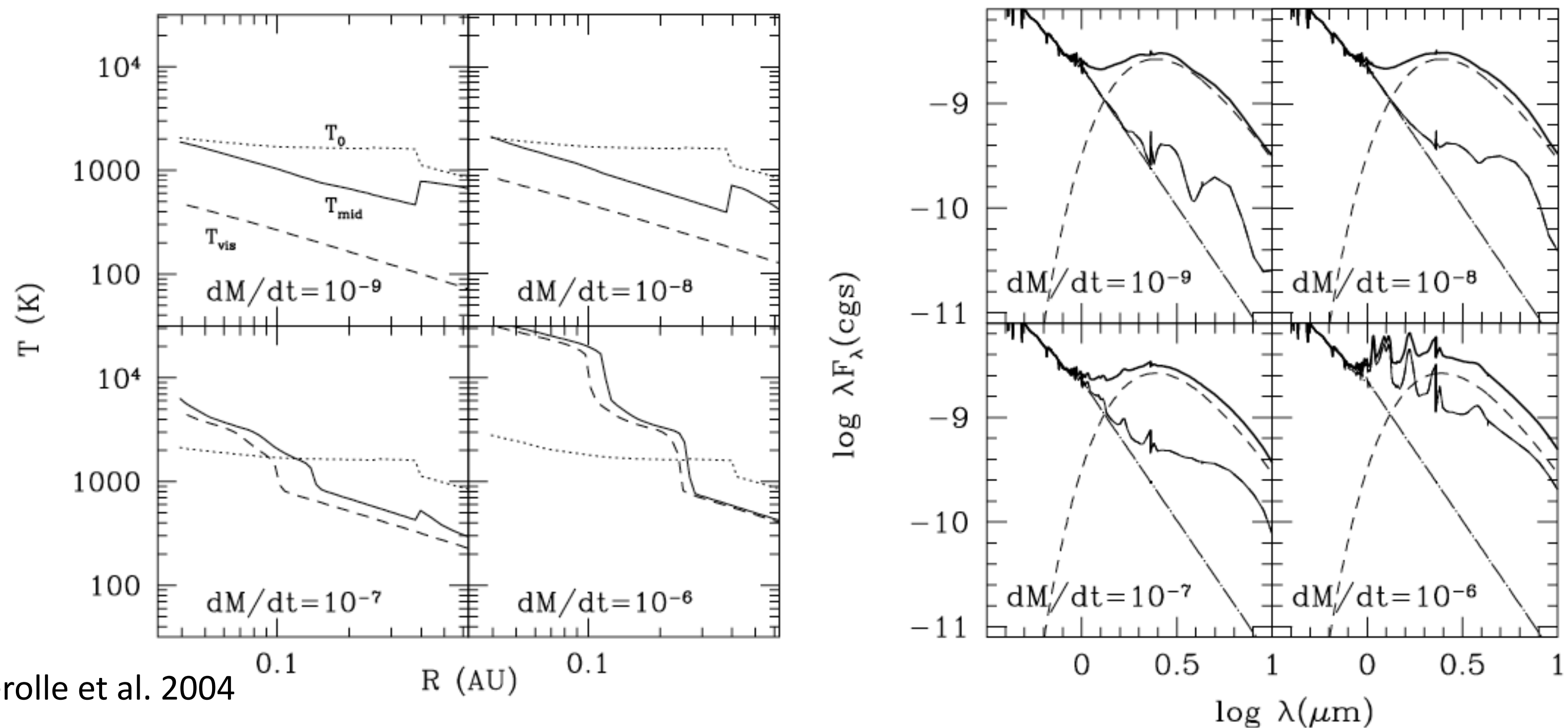


Benisty et al. (2010)

The gaseous inner disk

Kraus et al. (2008)

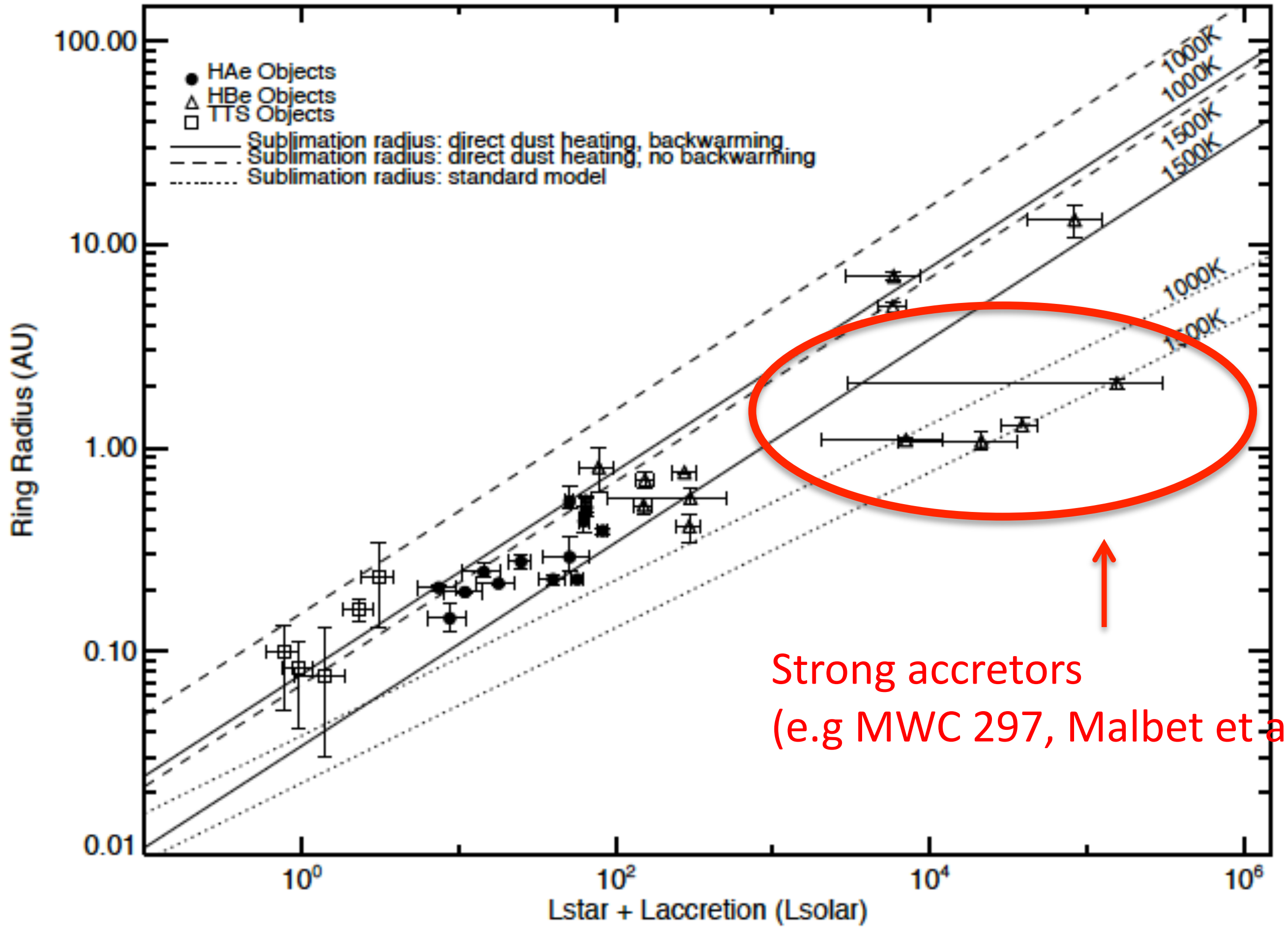




Muzerolle et al. 2004

The gaseous inner disk

Millan-Gabet et al. (PPV)



Strong accretors
(e.g MWC 297, Malbet et al. 2007)

Probing the gaseous inner disk with spectro-interferometry

Overtone CO emission (V=2-0) observed with AMBER/Medium Resolution toward 51 Oph (B9, Macc=10^{-7} Msun/yr)

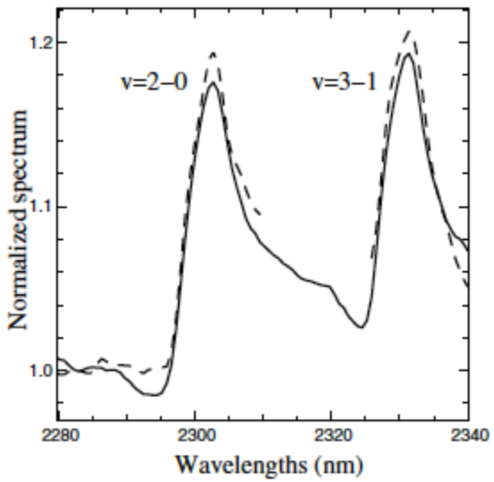
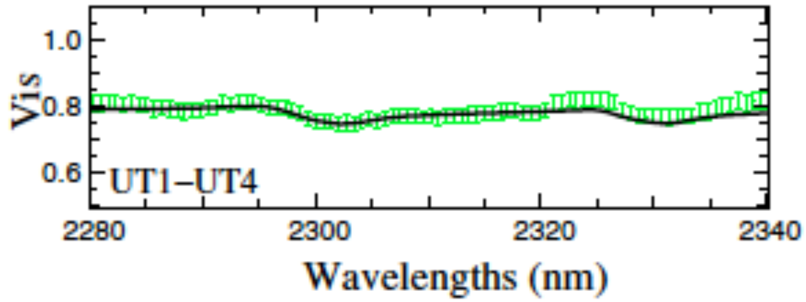
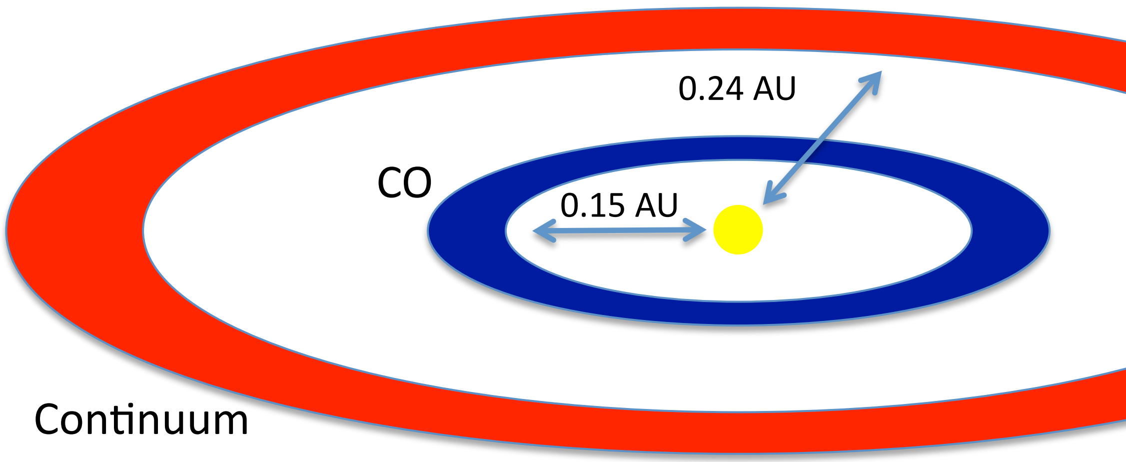


Fig. 1. AMBER calibrated spectrum of 51 Oph around the 2-0 and 3-1 bands of the CO overtone at 2.3 microns. For comparison purposes is plotted (dashed line) the same spectrum measured with the TNG spectrograph (L. Testi, private communication). Note that we did not plot the TNG spectrum between the two bandheads because of irrelevant instrumental artifact.

Tatulli et al. (2008)





Magnetospheric accretion

e.g., Camenzind (1990), Konigl (1991), Shu et al. (1994)

From $R_\star$ to a few $R_\star$ (< 0.1 AU) ::: <1 mas resolution

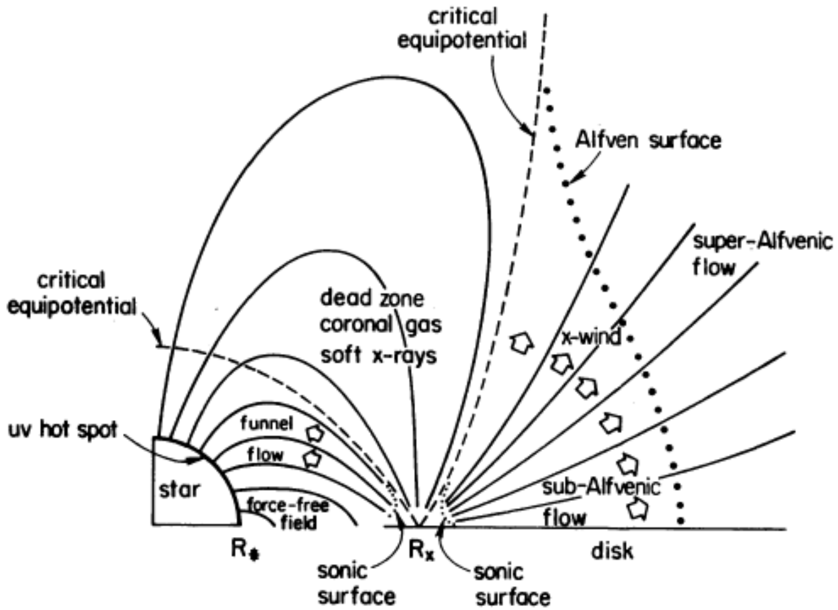
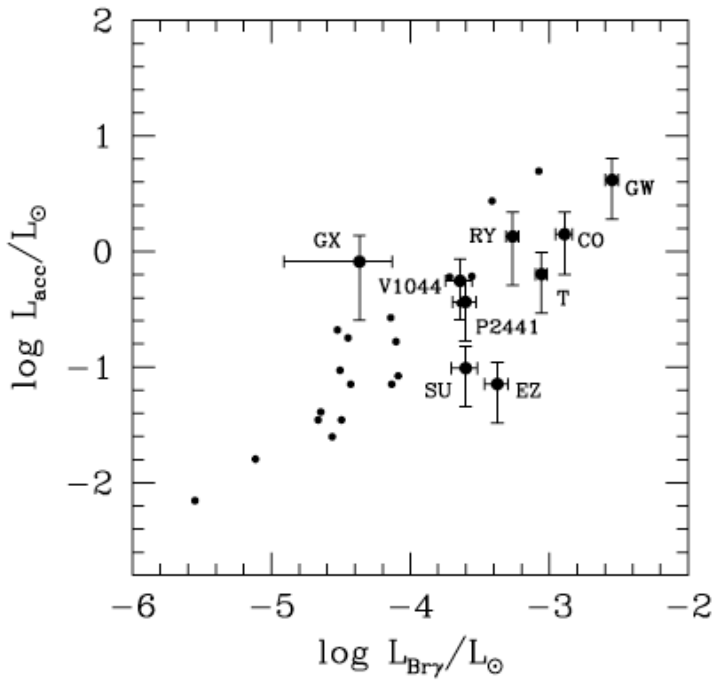


FIG. 4.—Schematic diagram of principal components in a typical CTTS system.

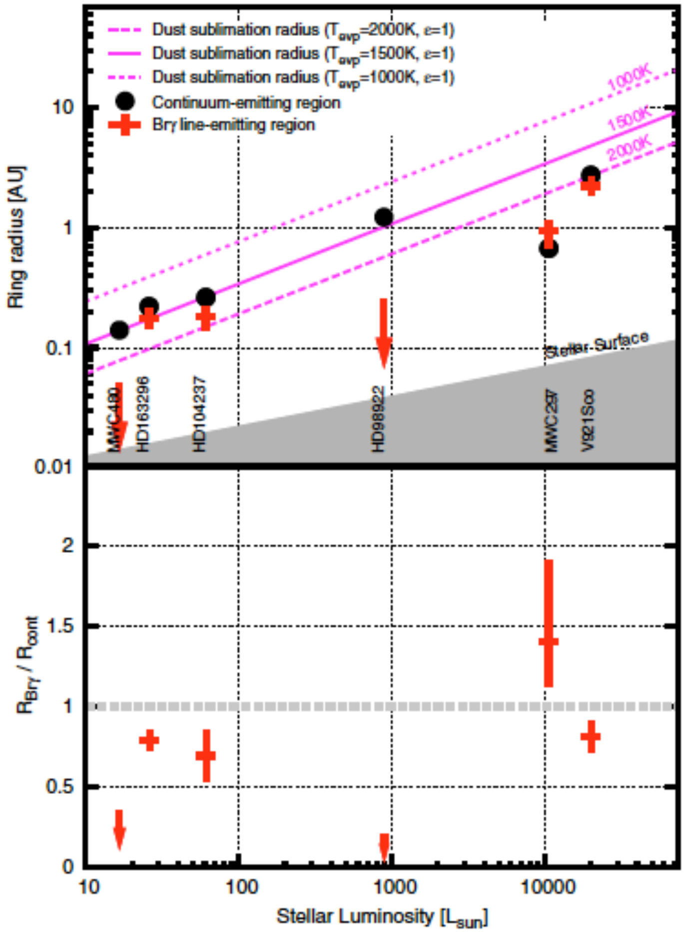


Measured from the UV veiling and the Hα line profile (e.g. Muzerolle et al. 2004), but also from infrared H lines such as Brγ and Phβ

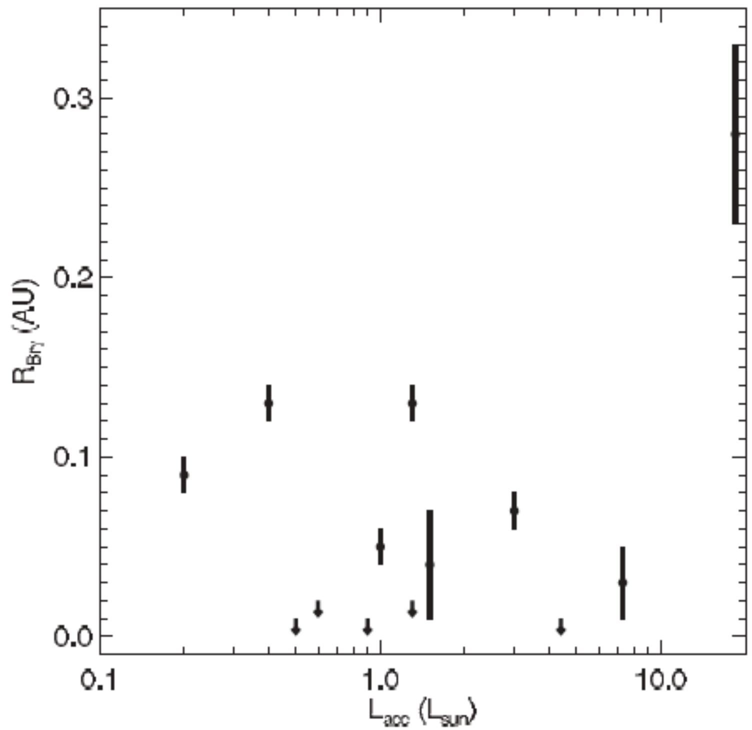
Calvet et al. (2004)
Natta et al. (2004)

Brγ: accretion or outflow?

Malbet et al. (2007)
Tatulli et al. (2007)
Kraus et al. (2008)

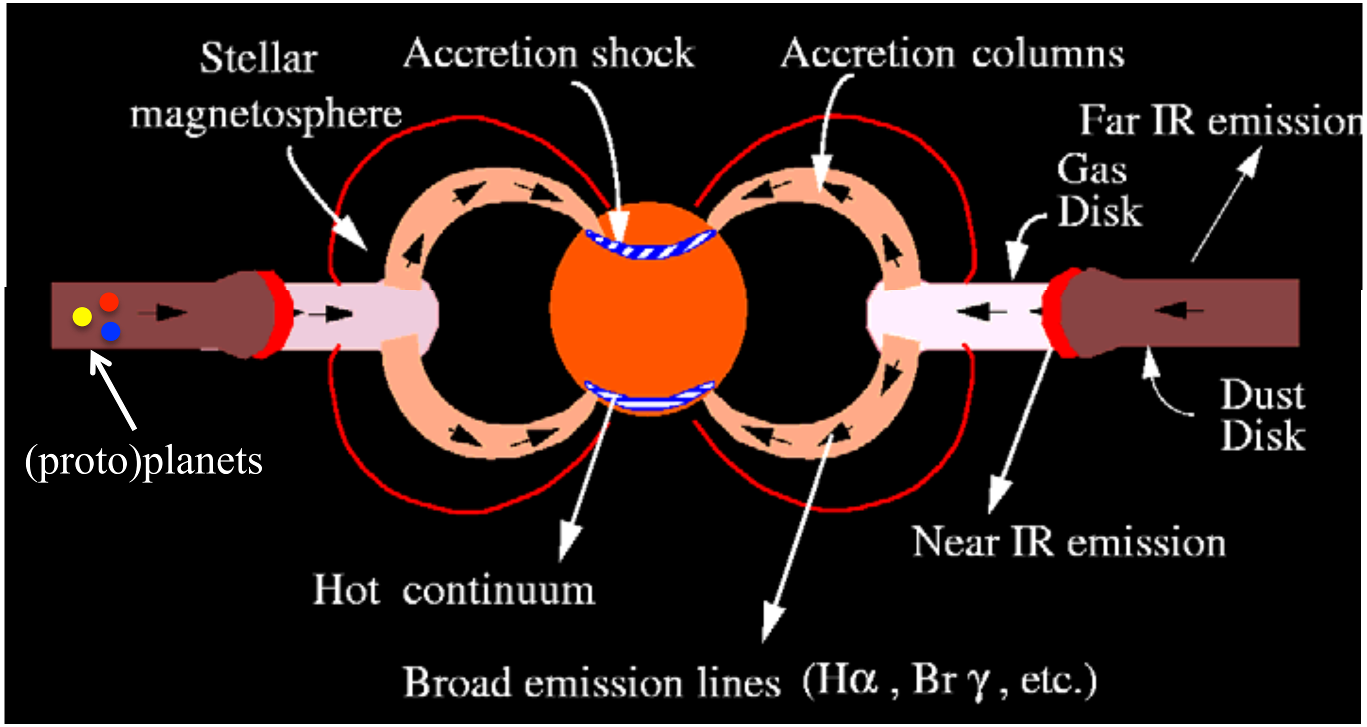


Eisner et al. (2010)



Akeson

Conclusions & Final remarks



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