Circumstellar disks as observed at millimeter wavelegths

Leonardo Testi (European Southern Observatory)

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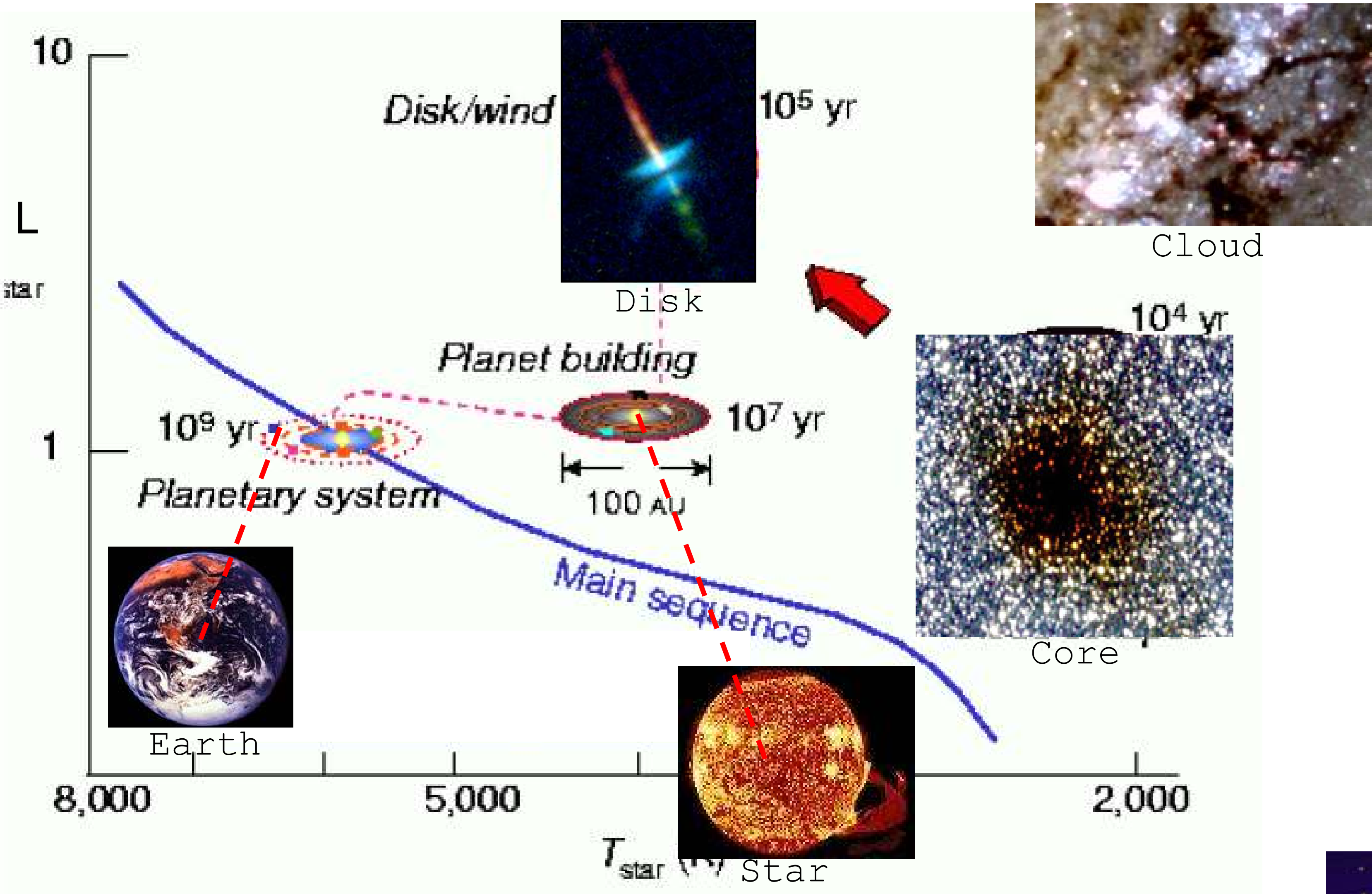
- Introduction - LT
- Disks and Star Formation @ mm-λ - SL
- Disk Evolution & Planet Formation - LT
- Present and Future of mm observations - SL

Introduction: Observing Circumstellar Disks @ mm-λ

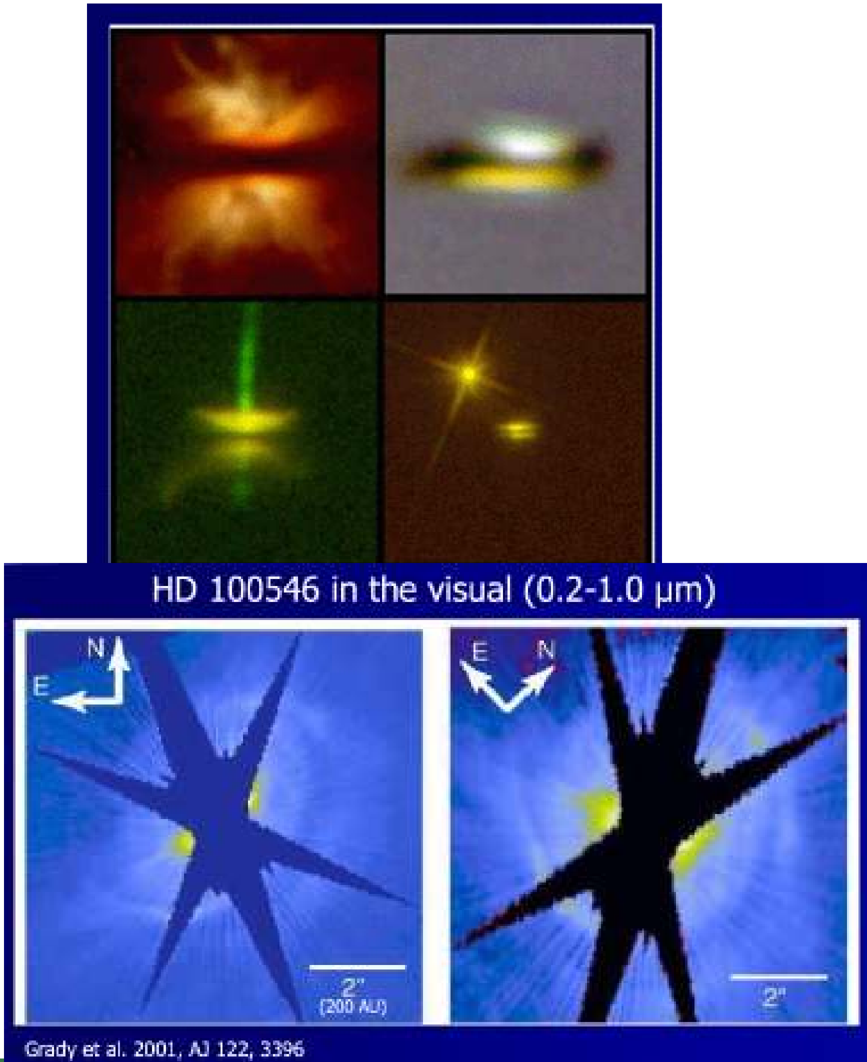
Leonardo Testi (European Southern Observatory)

- Structure of Circumstellar Disks
- Millimeter Continuum Emission from Disks
- Molecular Lines Emission from Disks

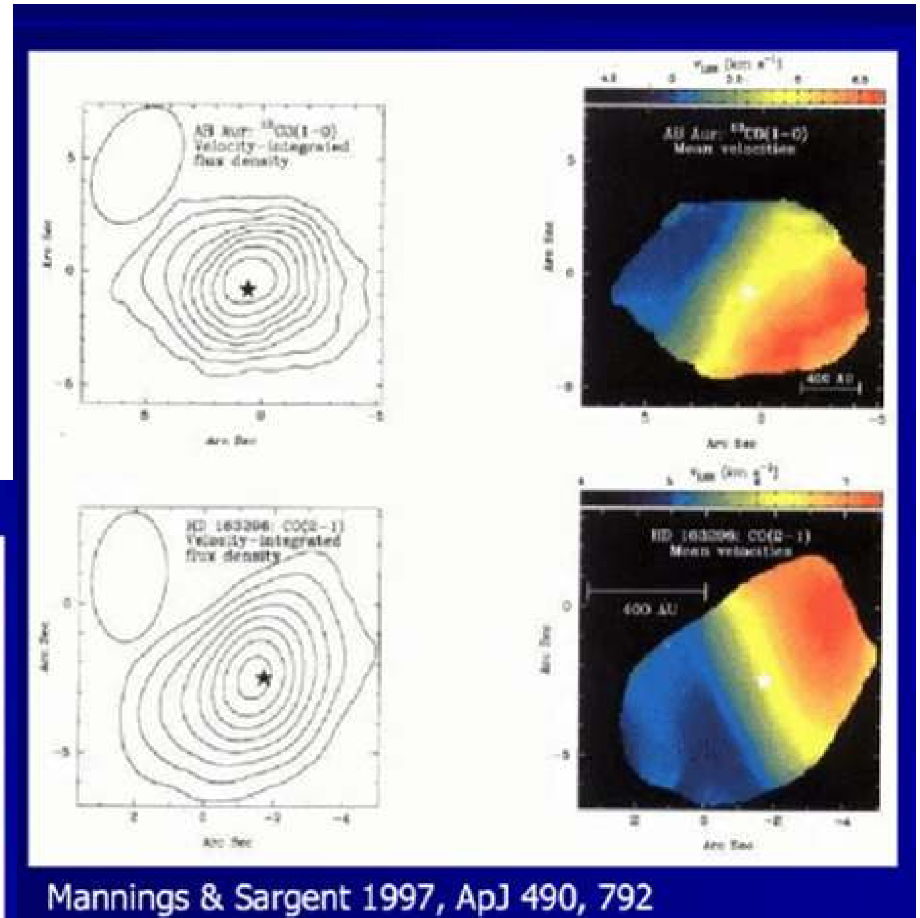
From Cores to Stars and Planetary Systems



Disks at different wavelengths



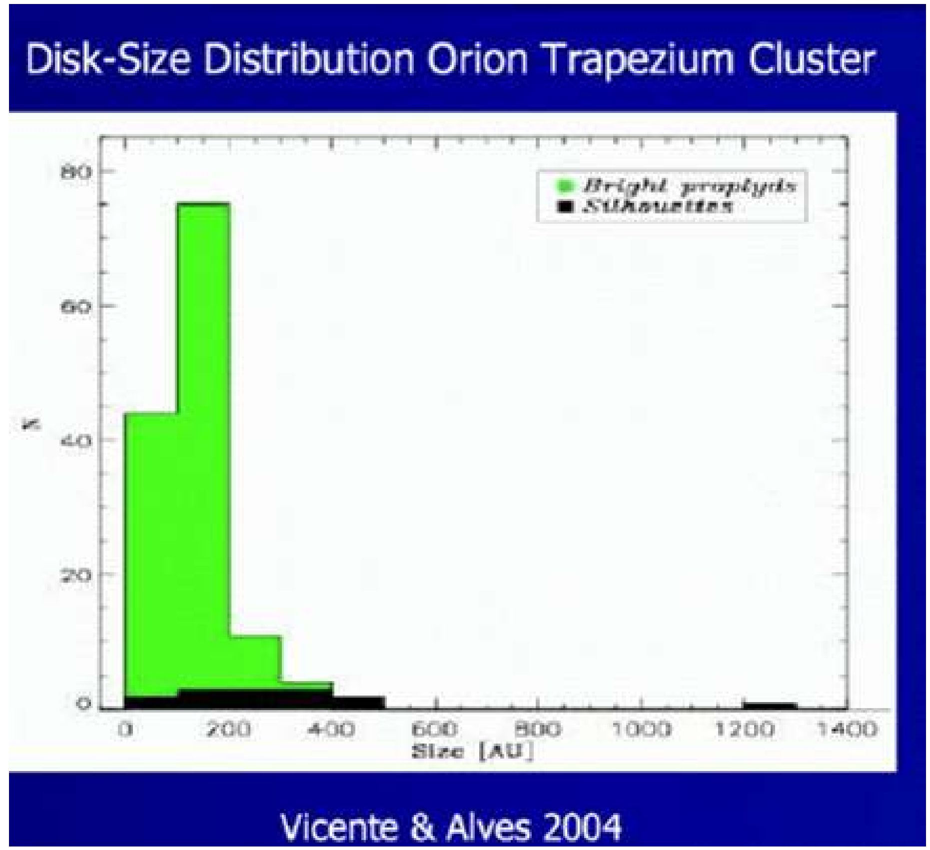
Grady et al. 2001, AJ 122, 3396



Mannings & Sargent 1997, ApJ 490, 792

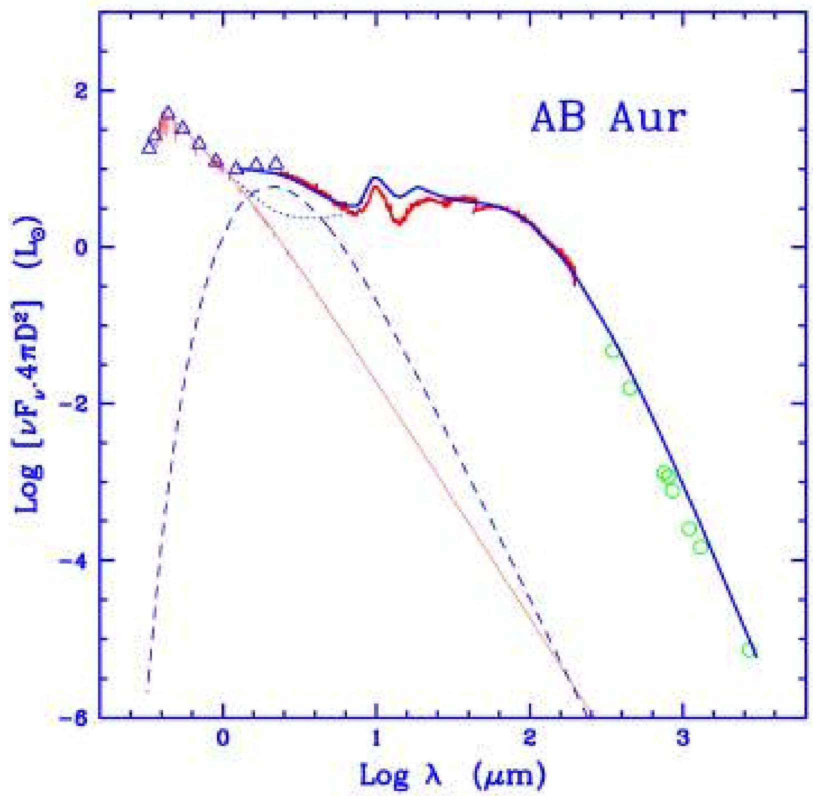
Physical sizes

- Few hundred AUs
  - From scattered light
  - Mm continuum
  - CO mm lines

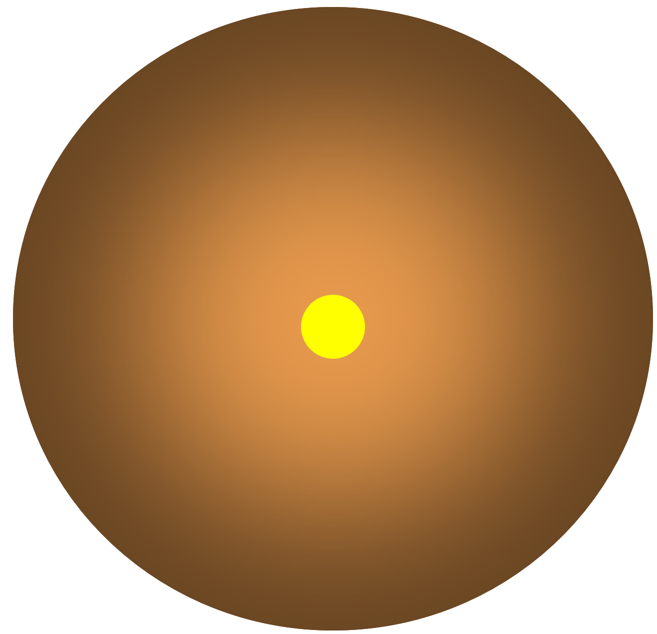


SED and Infrared Excess

- Cirsumstellar disks in the PMS phase are optically thick (except at λ≥mm)
- Disks dominate the emission beyond 1-2μm
- The shape of the SED depends on the disk structure



(sub)mm continuum emission



$$F_\nu = \frac{cos\theta}{D^2} \int_{r_i}^{r_o} B_\nu(T_d)(1 - e^{-\tau_\nu}) 2\pi r dr$$

$$\mathrm{T}_d \sim r^{-q}$$

$\tau_\nu \propto \Sigma(r)\kappa_\nu$ $\Sigma(r) \propto r^{-p}$ $\kappa_\nu \propto \kappa_o \nu^\beta$

Masses: (sub)mm continuum emission

- $M_D \sim 0.01\text{-}0.1$ Msun
- M_D/Mstar ~ 0.03

- $F_{1mm} \sim B_n(T)\, k_{1mm}\, M_D$

$$F_\nu = \frac{cos\theta}{D^2} \int_{r_i}^{r_o} B_\nu(T_d)(1 - e^{-\tau_\nu}) 2\pi r dr$$

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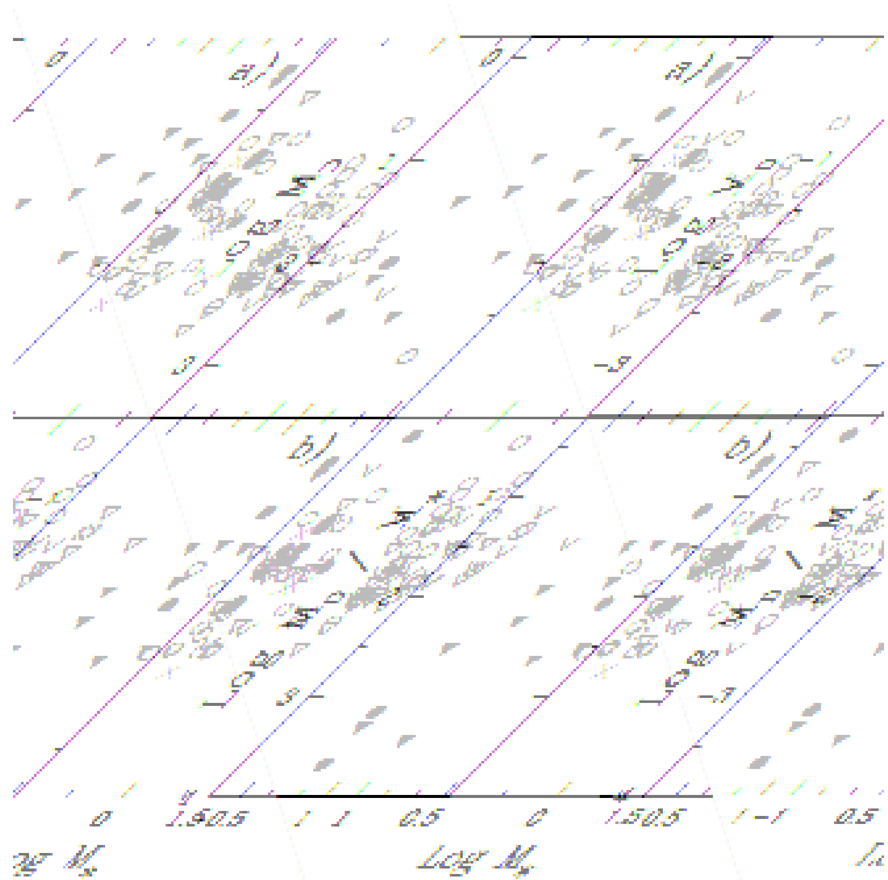
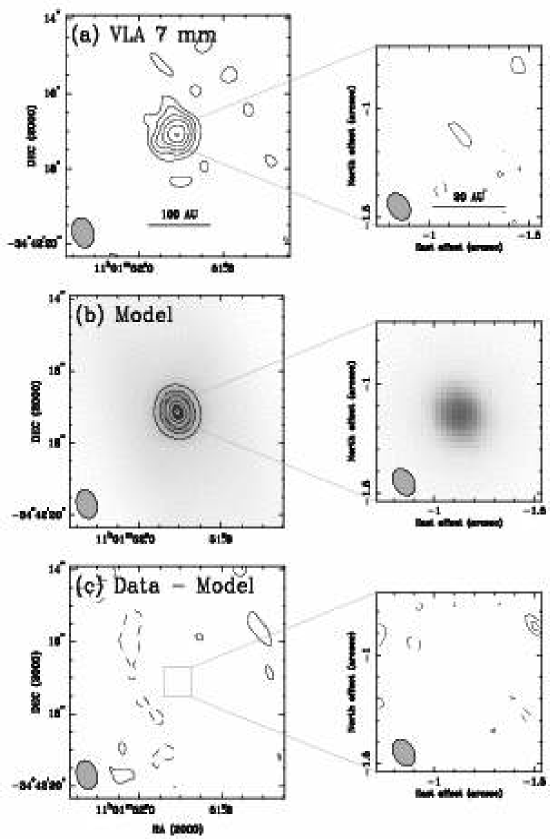


Radial density profiles

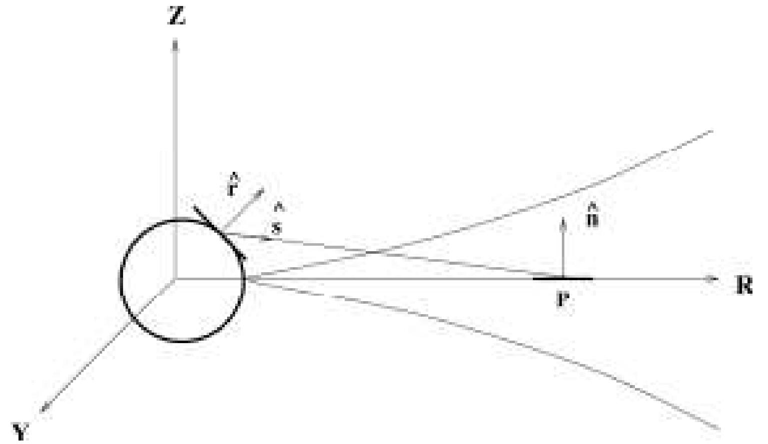
- High resolution mm continuum observations allow to derive the dust column density as a function of radius

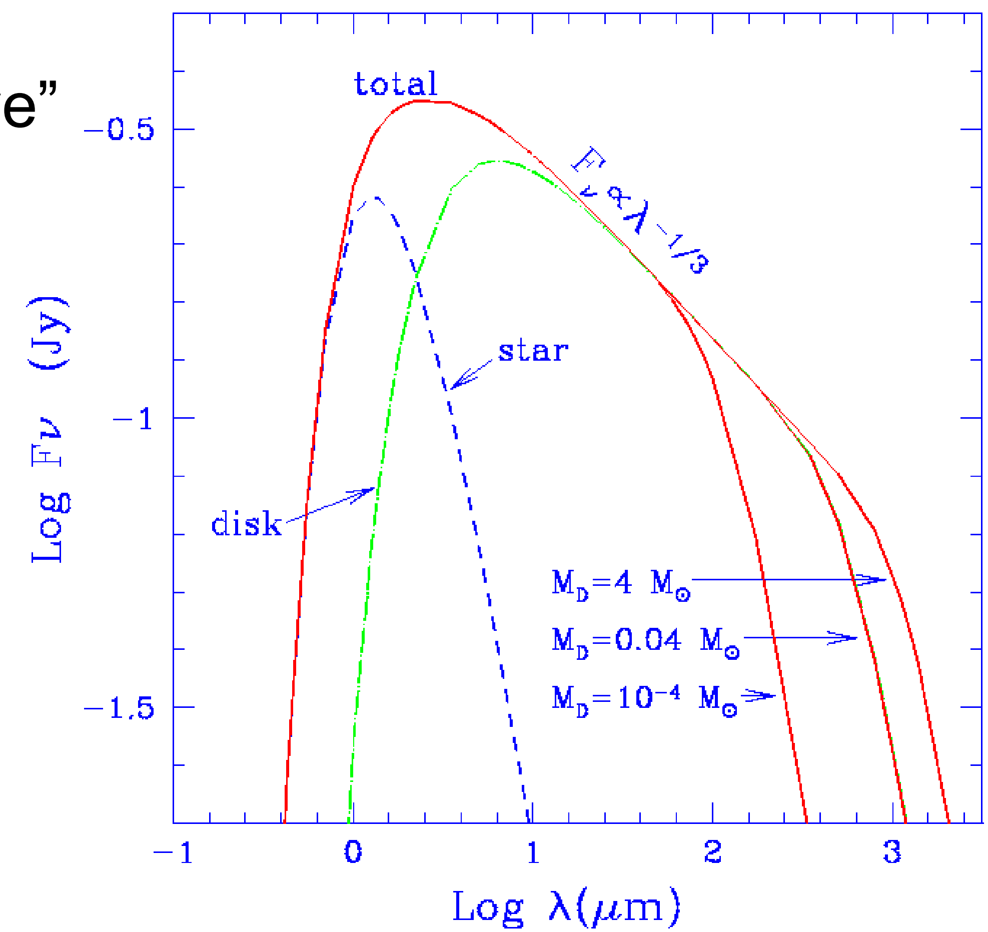


VLA 7mm
$T \sim r^{-q}$; $q \sim 0.5$
$\Sigma \sim r^{-p}$; $p \sim 1.0$
(Wilner et al. 2000)

Fflat accretion disk

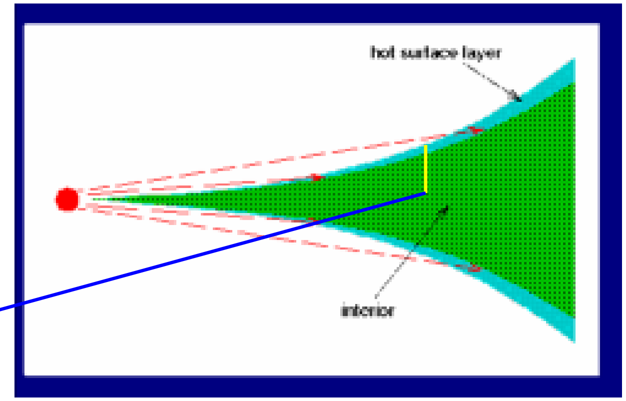
- Geometrically thin disks (in z):
  - Too cool to be "passive"
  - Too "active" to be consistent with measured accretion rates

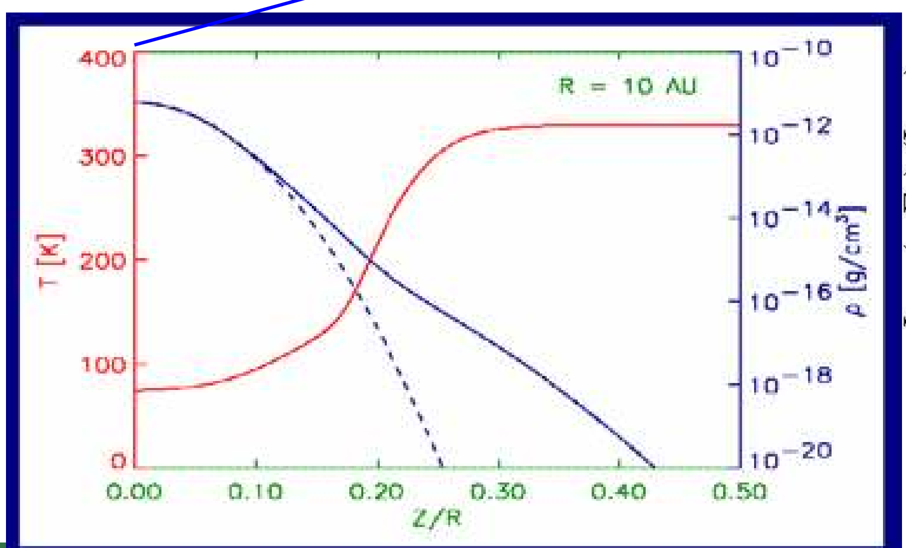


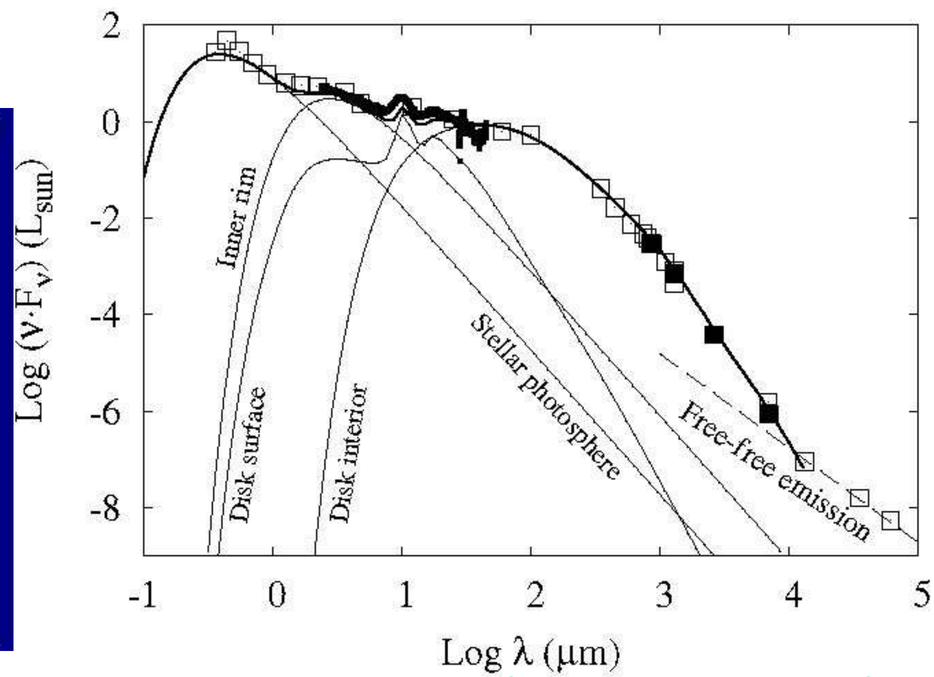


"Flared" disks

- Two components:
  - An optically thin surface layer (atmosphere)
  - A cool, optically thick inner layer which contains most of (~all) the mass

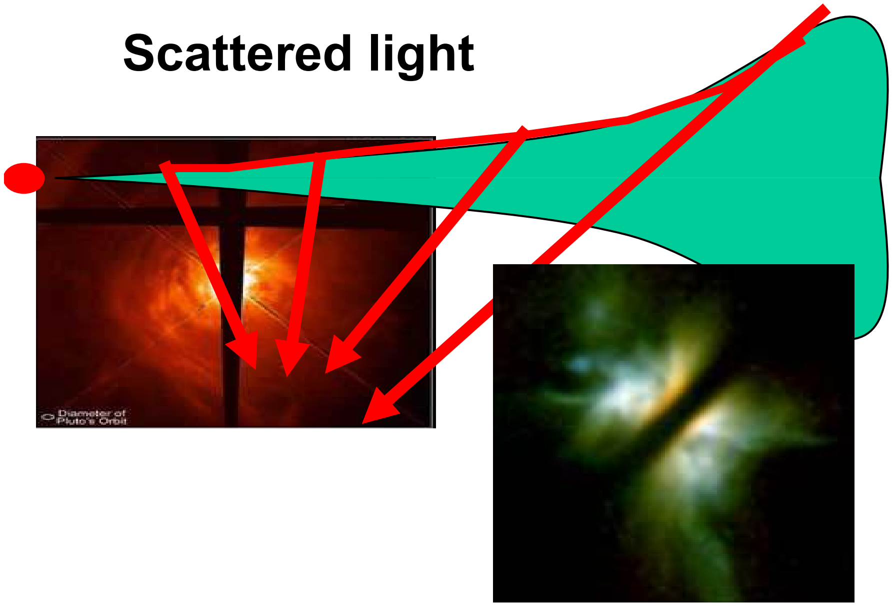


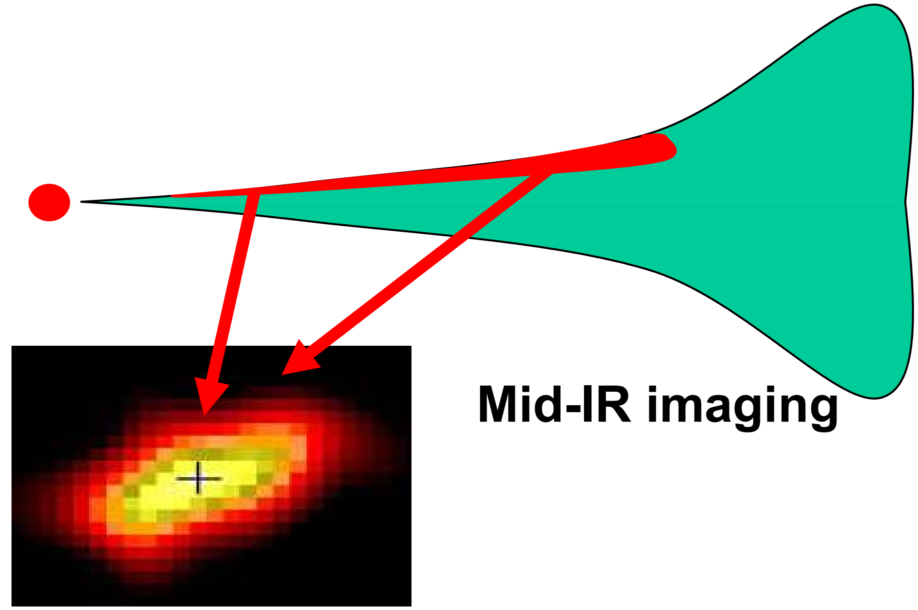


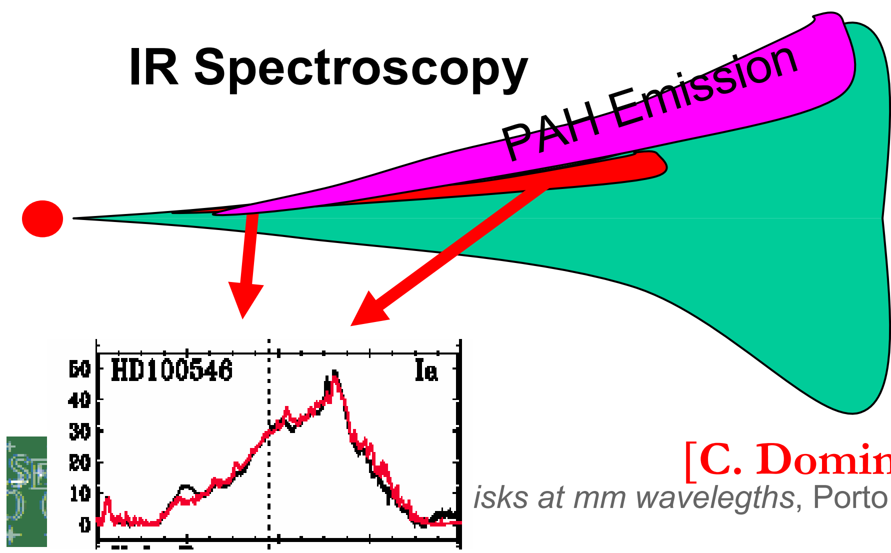


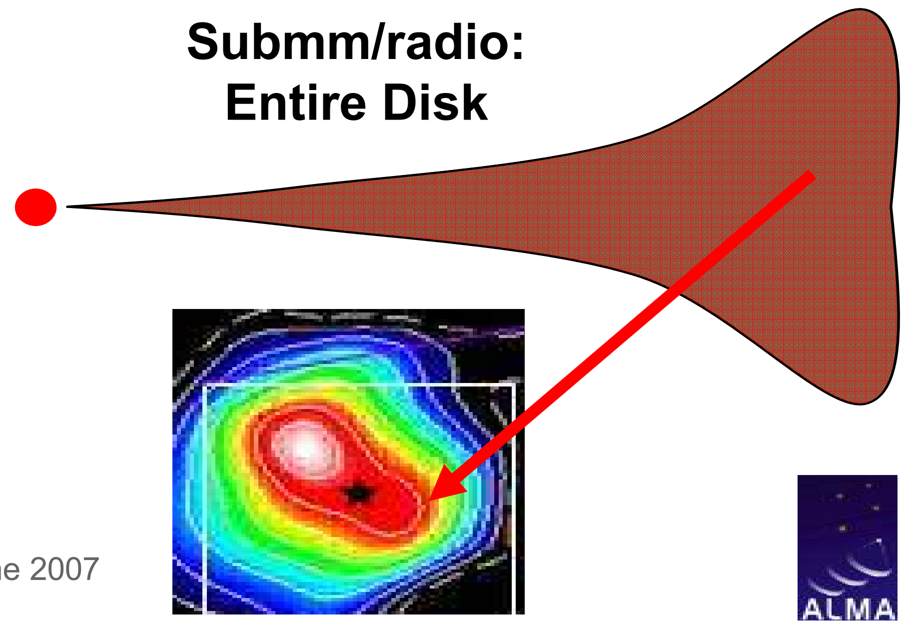
(Isella et al. 2007)

Which observations probe what?









[C. Dominic]

Molecular gas

- Gas has to dominate the disk mass
  - From geometry : **H/R ~ 0.1 at 1 AU**

$$\frac{1}{\rho}\,\frac{\partial p}{\partial z} \sim \frac{p}{\rho z} = -\frac{GM_* z}{R^3}$$

$$\rho(z) = \rho(0)\ exp(-z^2/2H^2)$$

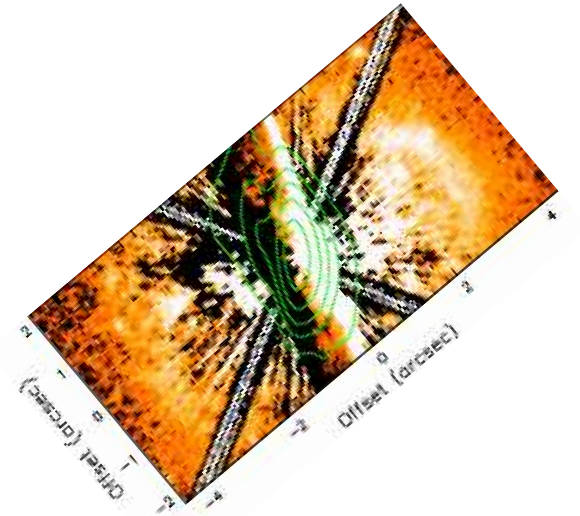
$$H/R = (T_d/T_g)^{1/2}\ (R/R_*)^{1/2}$$

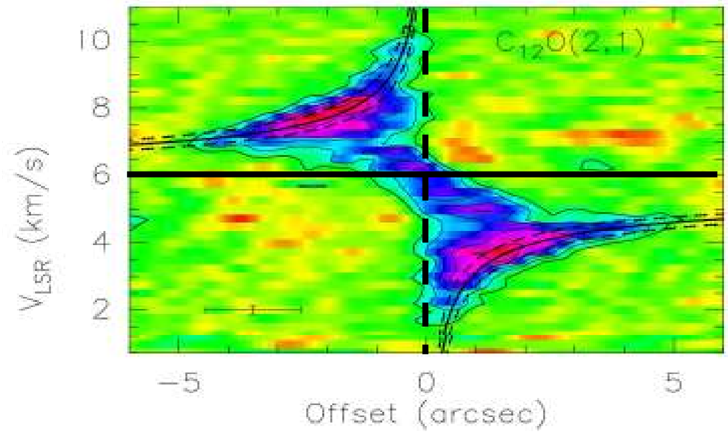
$$T_g = \frac{GM_*\mu}{kR_*}$$

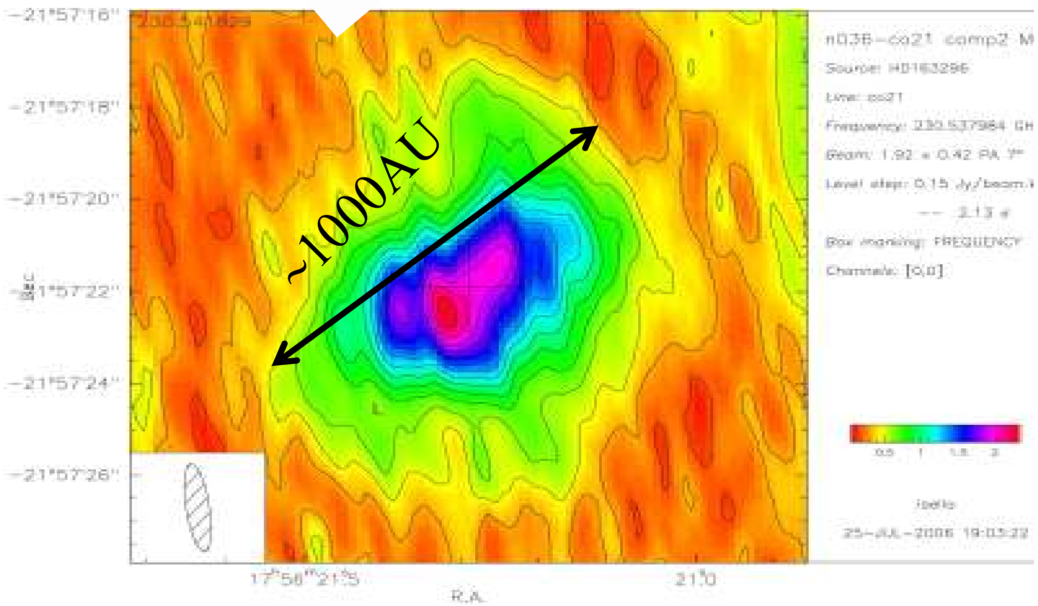
- Direct measurements:
  - Cold gas CO, … (outer disk)
  - Warm gas H_2, CO, H_2O(?) (inner disk)
  - Indirect: Accretion and Jets

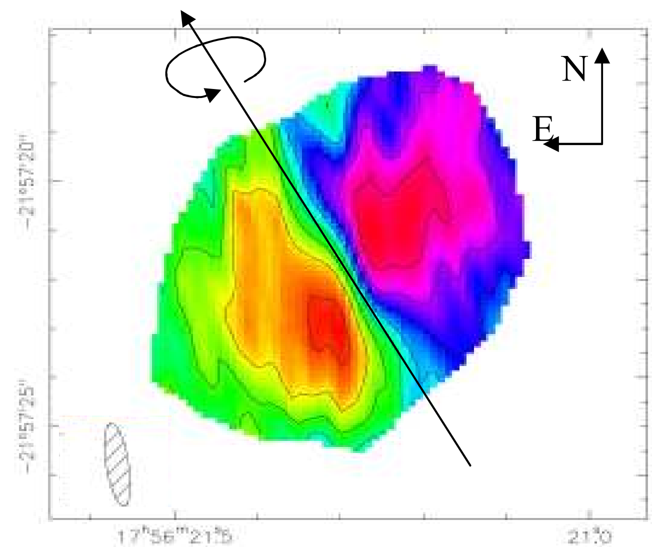
Outer disks structure and kinematics

HD163296





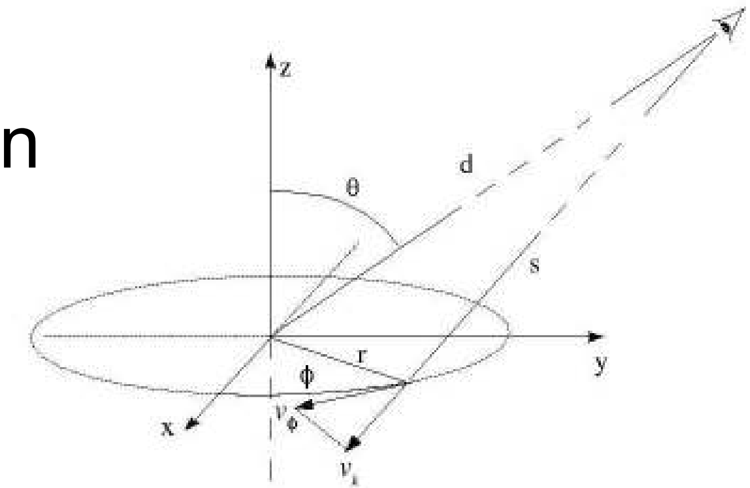




(Isella et al 2007)

Molecular gas

- Calculation of the CO emission assuming thermalised gas



$$I_\nu = \int_0^\infty S_\nu(s) e^{-\tau_\nu}(s) K_\nu(s) ds$$

$$\tau_\nu(s) = \int_0^s K_\nu(s') ds' \qquad K_\nu^d(s) = \rho(s) \cdot k_\nu \qquad K_\nu^{CO}(s) = n_l(s) \cdot \sigma_\nu(s)$$

$$n_l(s) = \chi_{CO} \frac{\rho(s)}{m_0} \cdot \frac{g_l\, e^{-E_l/\mathrm{k}T_{CO}(s)}}{Z(T_{CO}(s))}$$

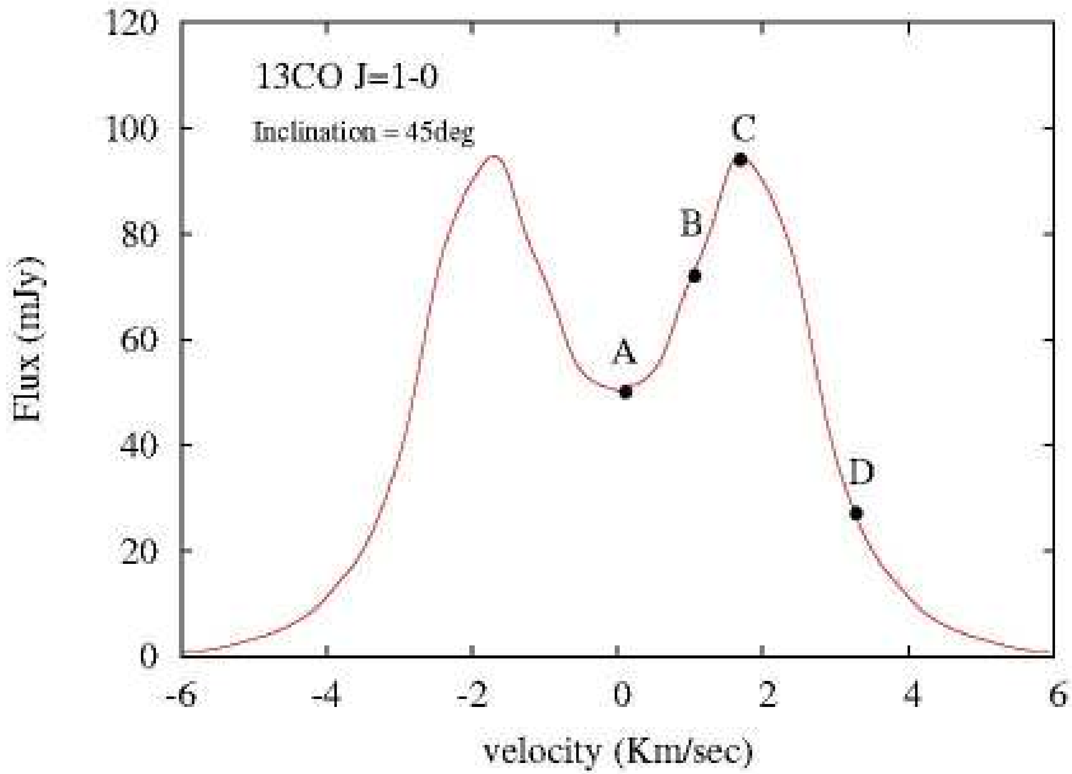
$$S_\nu(s) = B_\nu(T_{CO}(s)) = \frac{2\mathrm{h}\nu^3}{\mathrm{c}^2} \frac{1}{\exp(\mathrm{h}\nu/\mathrm{k}T_{CO}(s)) - 1}$$

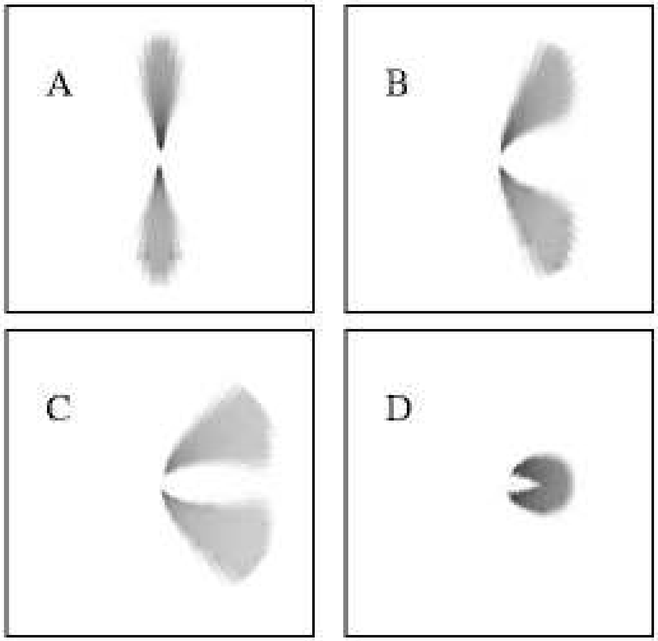
$$T_{CO}(r) = T_{CO}(r_0)(r/r_0)^{-q}$$

(Isella et al. 2007)

Molecular gas

- Simulated CO profiles and maps

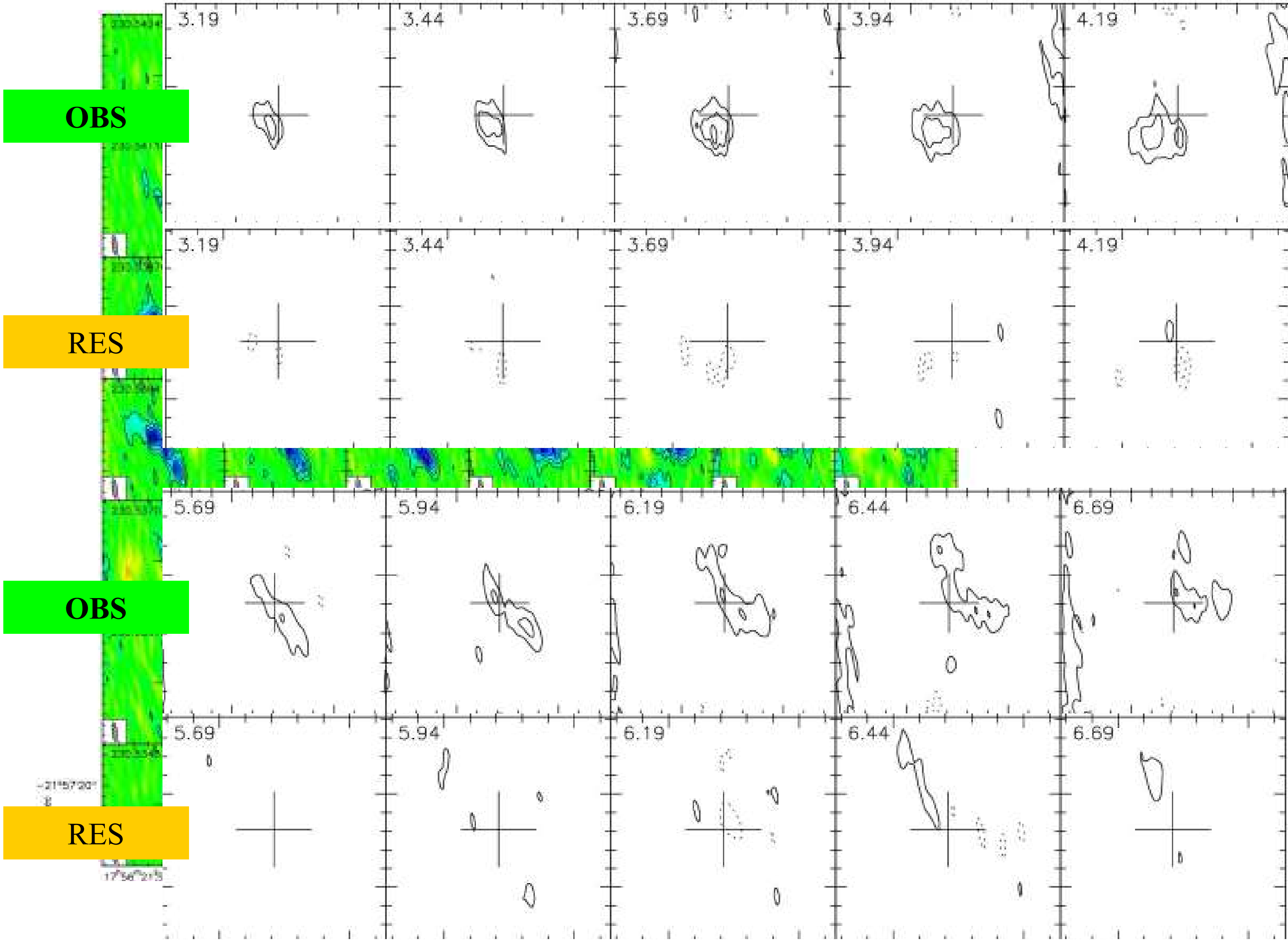




(Isella et al. 2007)

Outer disks structure and kinematics

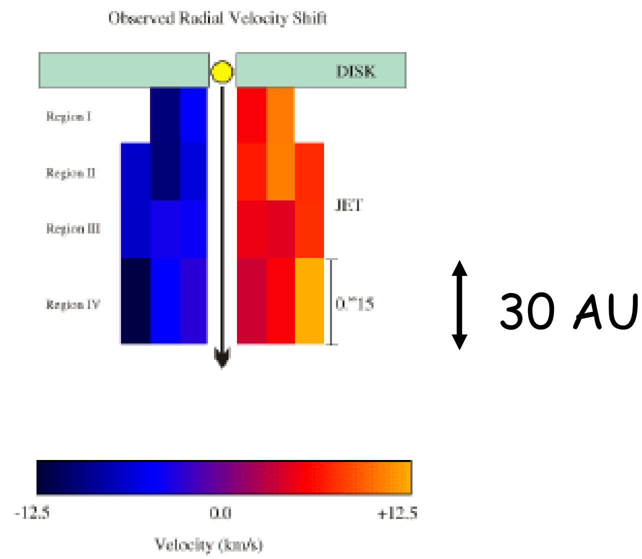
HD163296



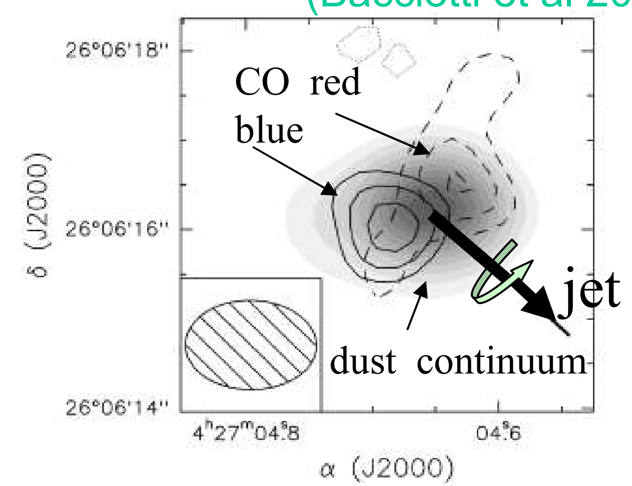
(Isella et al. 2007)

Gas properties and evolution

- Kinematics
  - Disk-outflow interaction
  - Possible evidence for non keplerian motions
- Physical properties
  - Temperature, density structure
  - Abundance, gas to dust ratio
- Chemical properties
  - Formation of complex molecules
  - Chemical differentiation in different regions of the disk



(Bacciotti et al 2002)



(Testi et al.2002)

Gas properties and evolution

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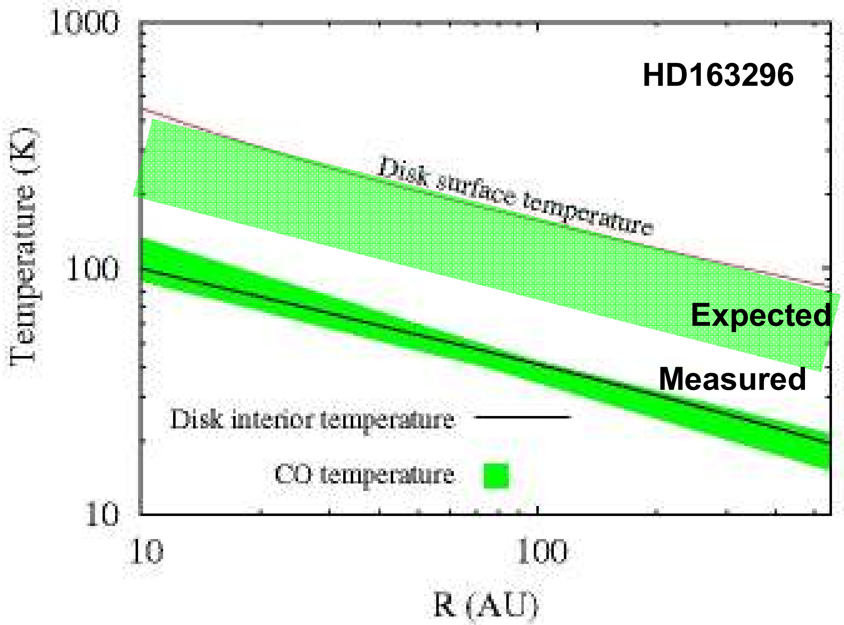


CO isotopes depletion factors:
$^{13}CO \Rightarrow \sim 10$ ($[^{13}CO]/[H_2] \sim 10^{-7}$)
$C^{18}O \Rightarrow >60$

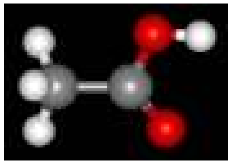
ISM Molecules

H_2	HD	H_3+	H_2D+				
CH	CH^+	C_2	CH_2	C_2H	*C_3		
CH_3	C_2H_2	C_3H(lin)	c-C_3H	*CH_4	C_4		
c-C_3H_2	H_2CCC(lin)		C_4H	*C_5	*C_2H_4	C_5H	
H_2C_4(lin)	*HC_4H	CH_3C_2H	C_6H	*HC_6H	H_2C_6		
*C_7H	CH_3C_4H	C_8H	*C_6H_6				
OH	CO	CO+	H_2O	HCO	HCO+		
HOC+	C_2O	CO_2	H_3O+	HOCO+	H_2CO		
C_3O	CH_2CO	HCOOH	H_2COH+	CH_3OH	CH_2CHO		
CH_2CHOH	CH_2CHCHO		HC_2CHO	C_5O	CH_3CHO	c-C_2H_4O	
CH_3OCHO	CH_2OHCHO		CH_3COOH	CH_3OCH_3	CH_3CH_2OH	CH_3CH_2CHO	
$(CH_3)_2$CO	$HOCH_2CH_2$OH		$C_2H_5OCH_3$	$(CH_2OH)_2$CO			
NH	CN	N_2	NH_2	HCN	HNC		
N_2H^+	NH_3	$HCNH^+$	H_2CN	HCCN	C_3N		
CH_2CN	CH_2NH	HC_2CN	HC_2NC	NH_2CN	C_3NH		
CH_3CN	CH_3NC	HC_3NH^+	*HC_4N	C_5N	CH_3NH_2		
CH_2CHCN	HC_5N	CH_3C_3N	CH_3CH_2CN	HC_7N	CH_3C_5N?	HC_9N	HC_{11}N
NO	HNO	N2O	HNCO	NH2CHO			
SH	CS	SO	SO+	NS	SiH		
*SiC	SiN	SiO	SiS	HCl	*NaCl		
*AlCl	*KCl	HF	*AlF	*CP	PN		
H_2S	C_2S	SO_2	OCS	HCS+	c-SiC_2		
*SiCN	*SiNC	*NaCN	*MgCN	*MgNC	*AlNC		
H_2CS	HNCS	C_3S	c-SiC_3	*SiH_4	*SiC_4		
CH_3SH	C_5S	FeO					

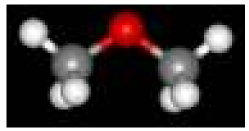
DEMIRM

Complex Organic Molecules

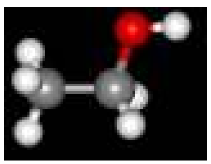
Detected



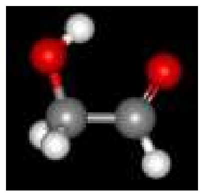
Acetic acid



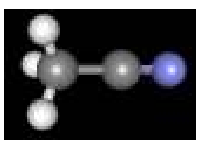
Di-methyl ether



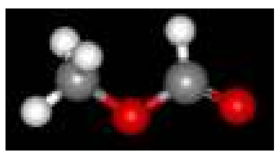
Ethanol



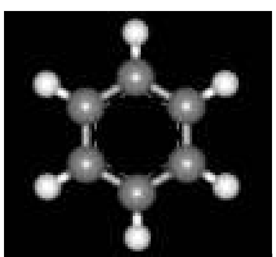
Sugar



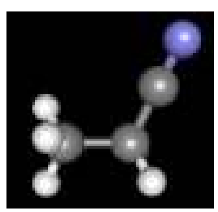
Methyl cyanide



Methyl formate

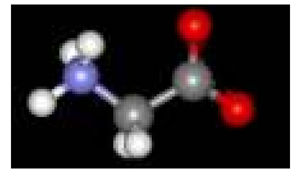


Benzene

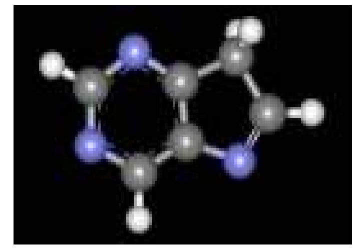


Ethyl cyanide

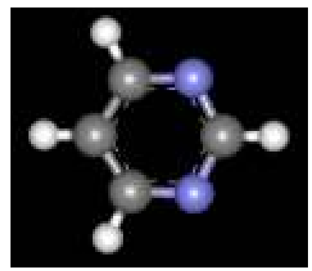
Not (yet) detected



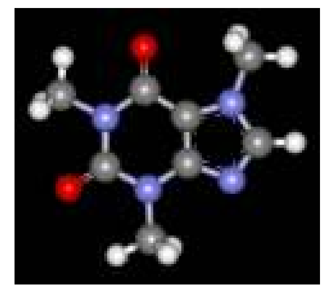
Glycine



Purine



Pyrimidine



Caffeine

How far does chemical complexity go?
Can we find pre-biotic molecules in Disks?

Based on Ehrenfreund 2003

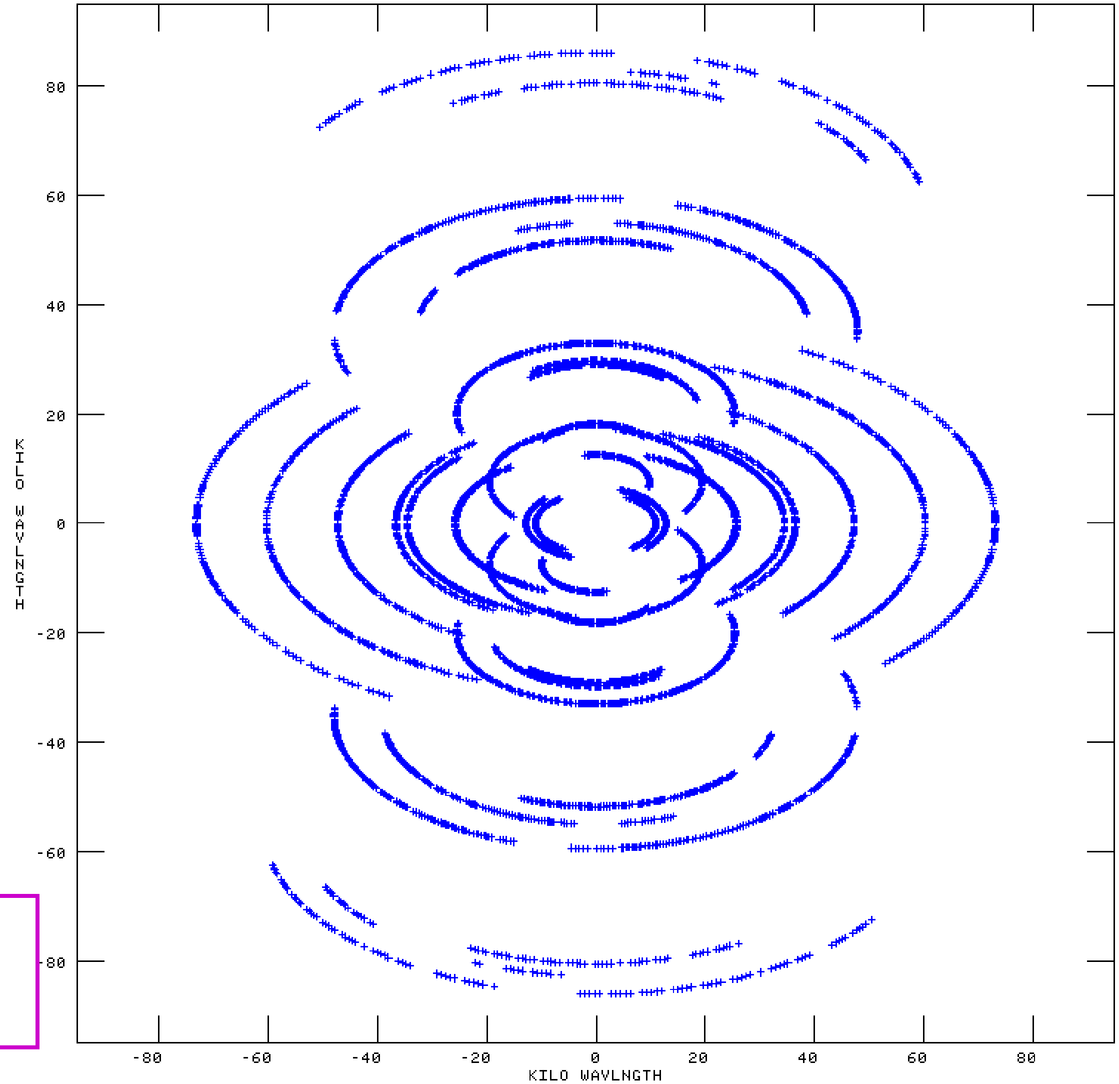
mm Interferometers (u,v) coverage

OVRO mm Array,
6 Antennas

L-configuration
single integration

L-Configuration few
hrs of observations

Final coverage: a
few hrs in both the
L and H
configurations



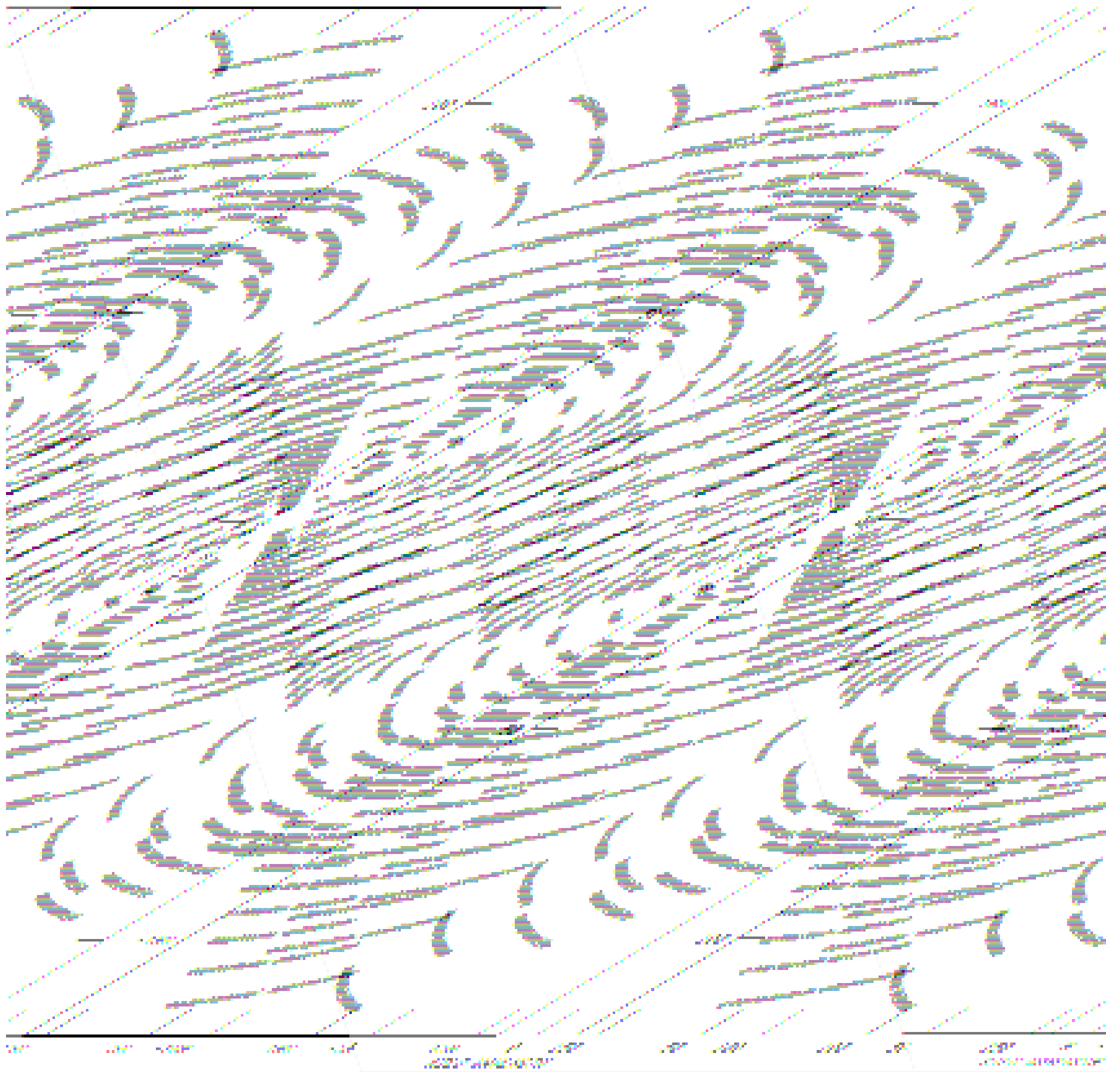
N.B. (u,v) coverage
is not uniform

mm Interferometers (u,v) coverage

Very Large Array,
27 Antennas,
1.5h of observing time!

N.B. (u,v) coverage is still not uniform.

Critical parameters:
- Long baselines
- Short baselines
- Number of (u,v) points
- (u,v) coverage distribution



mm Interferometers (u,v) coverage

- Current mm interferometers offer typically ~10^4 visibility measurements in several hours, the VLA delivers ~10^5 visibilities per hour
- ALMA will improve by almost two orders of magnitude