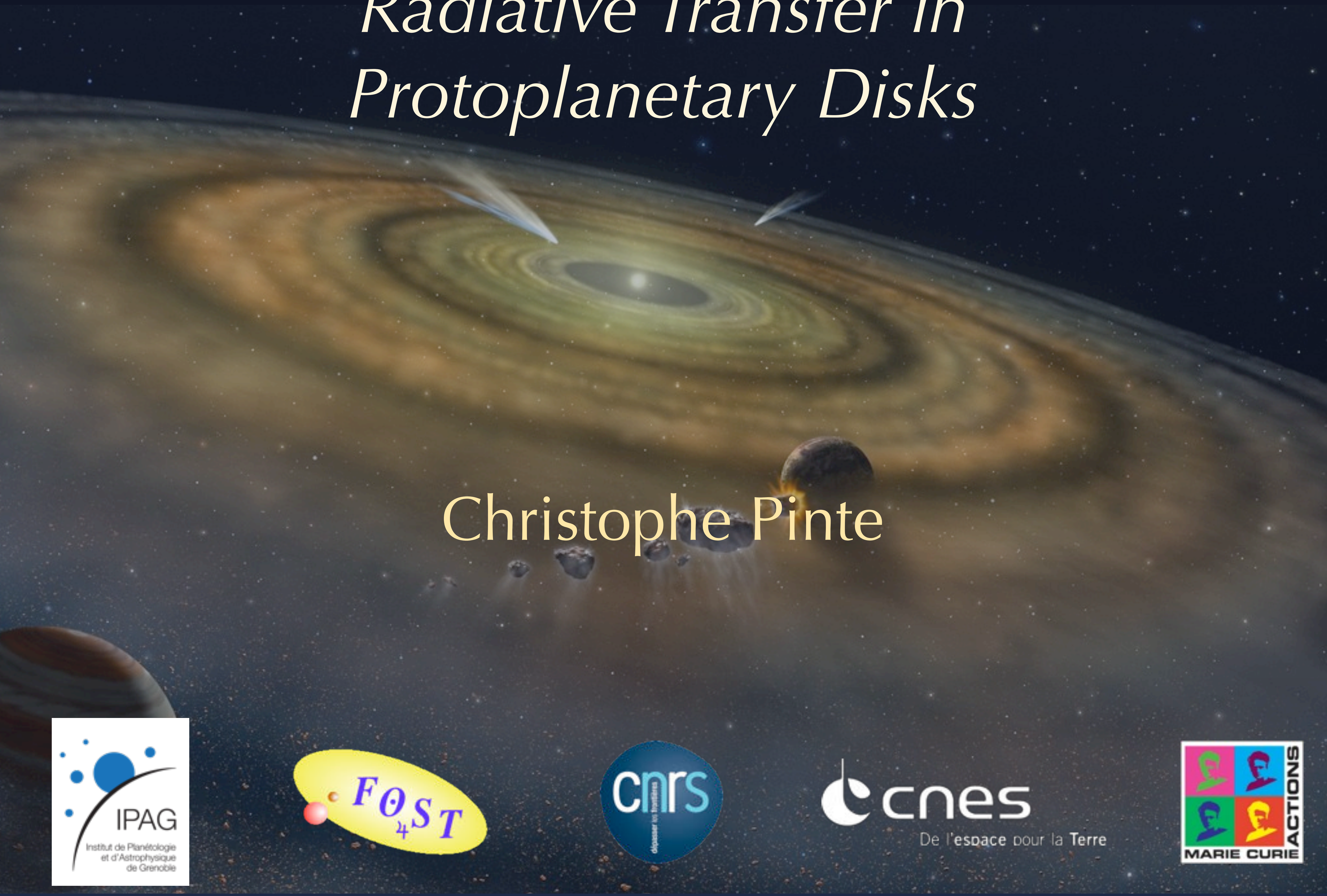
Radiative Transfer in Protoplanetary Disks

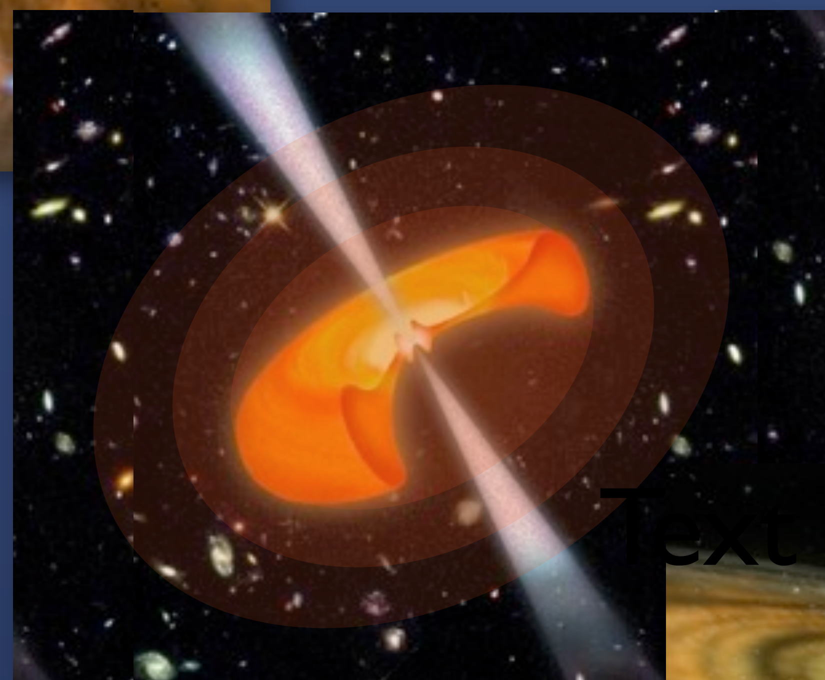


Christophe Pinte

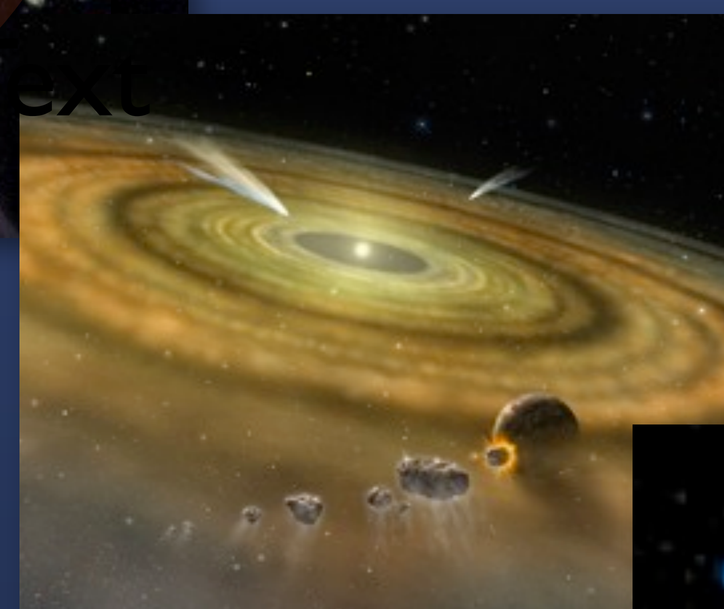
Outline

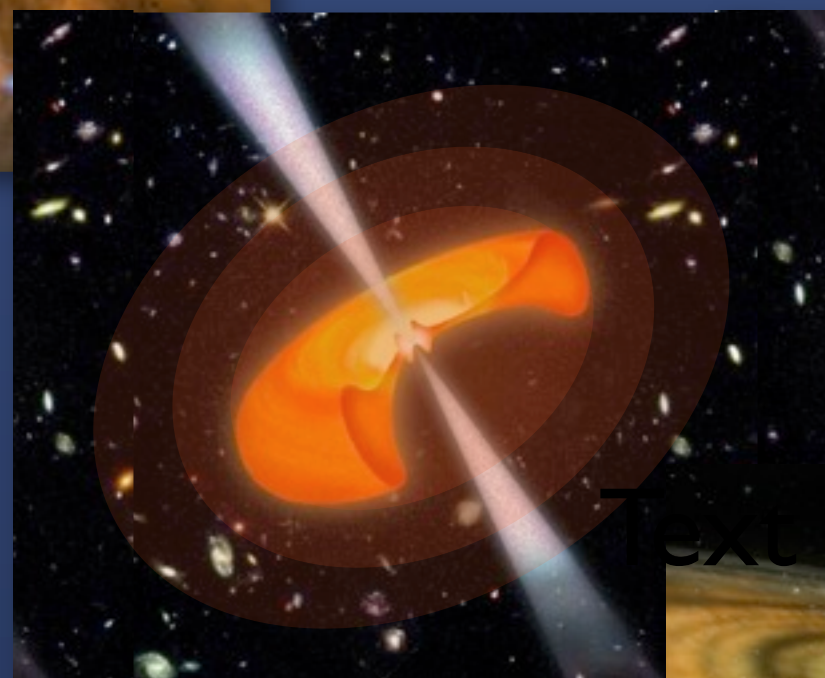
- Context: Circumstellar Disks around Young Stars
- Elements of continuum radiative transfer
- Constraints from various techniques:
  - thermal emission & spectroscopy,
  - light scattering,
  - polarization,
  - infrared interferometry
- Multi-technique modelling
- Observation & modelling of Gas in disks

From clouds
to envelopes,
to disks,
to planets



Text





From clouds
to envelopes,
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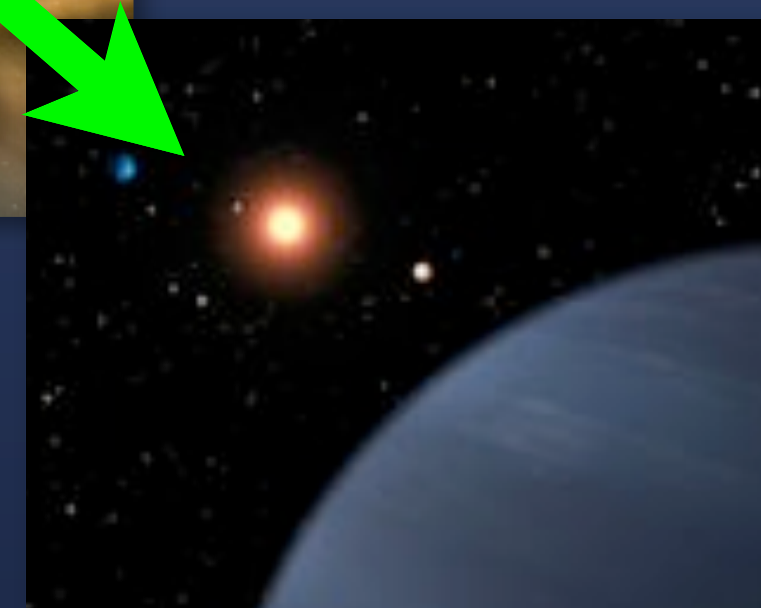
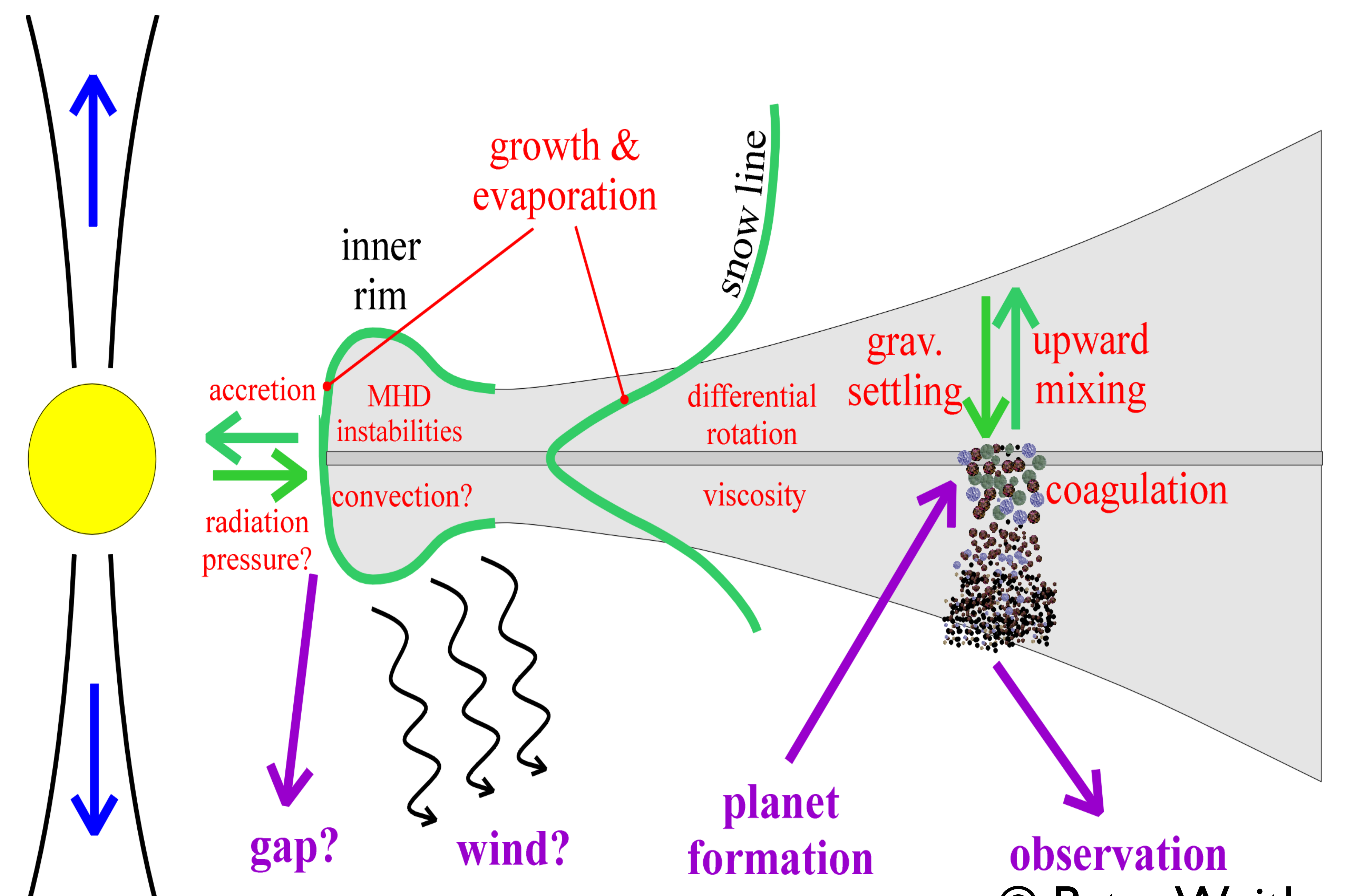
to planets



- *Timescale for gas dispersal and planet formation?*
- *Grain growth and settling ?*
- *Relative evolution of dust and gas ?*

Processes in Protoplanetary disks



Dust in Protoplanetary disks

- Dust grains are expected to grow by coagulation and to settle by gravity
  - Disks should have a stratified structure
- Physical models predict extremely short timescales ($<10^5$ yrs) for both phenomena
  - Disks around 10^6 yr-old T Tauri stars could already show evidence for these effects

The search for stratified disks is on !

A variety of observations

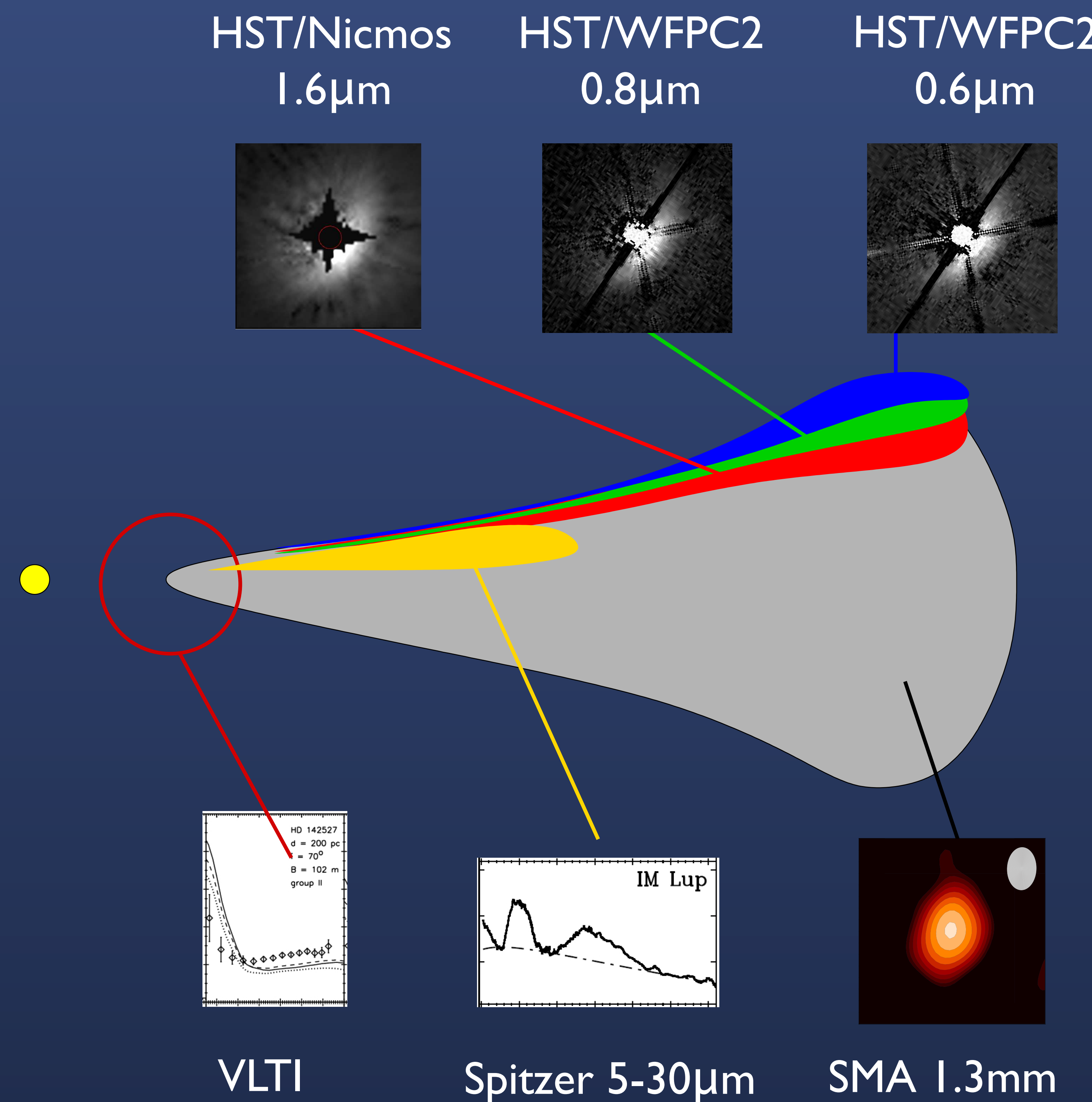
Each approach probes a different part of the disk

Disk modelling must consider as many observations as possible *at once*

Multi-λ modelling

Not so frequent

… but necessary!

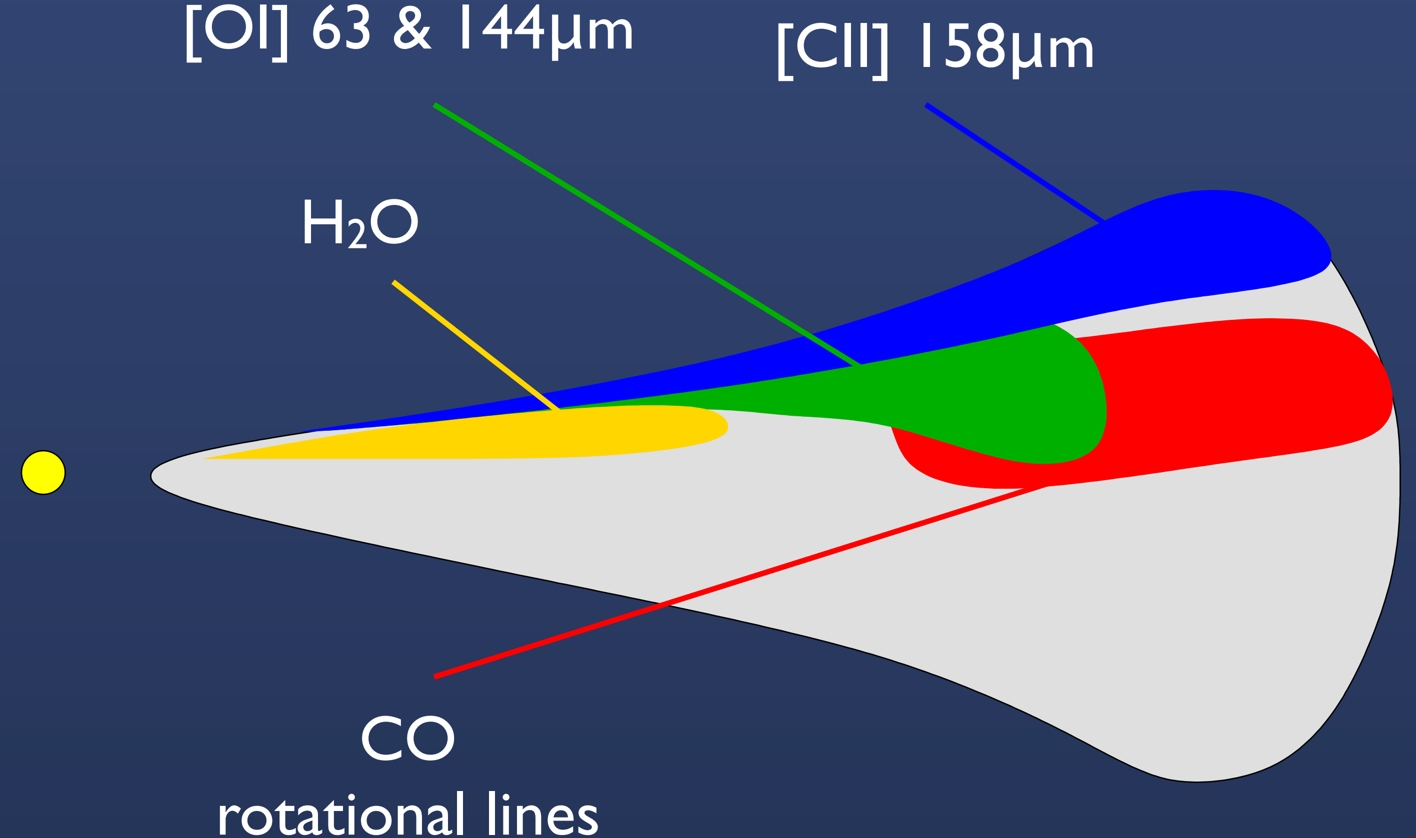


⇒ Radiative transfer code (MCFOST)

A variety of observations

Each approach probes a different part of the disk

The same is now true for the gas phase



Disk modelling must consider as many observations as possible *at once*

Multi-λ modelling
Not so frequent
... but necessary!

⇒ Radiative transfer code (MCFOST)

How to extract information from observations?

1) **Goal: obtain simple, parametric fit to as wide a set of observations as possible**

- A few simplistic asumptions:
  - parametric description of disk structure
  - Mie theory
- exact radiative transfer: **MCFOST**
- systematic exploration of the parameter space
- $\chi 2$ fitting, Bayesian estimates

⇒ Quantify parameters AND their validity range

2) **Link with models of the physics of disks**

Radiative transfer in dust

$$\frac{dI_\lambda(\overrightarrow{r},\overrightarrow{n})}{ds} = -\,\kappa_\lambda^{\text{ext}}(\overrightarrow{r})\,I_\lambda(\overrightarrow{r},\overrightarrow{n})$$
$$+\,\kappa_\lambda^{\text{abs}}(\overrightarrow{r})\,B_\lambda(T(\overrightarrow{r}))$$
$$+\,\kappa_\lambda^{\text{scatt}}(\overrightarrow{r})\,\frac{1}{4\pi}\int_\Omega \psi_\lambda(\overrightarrow{r},\overrightarrow{n}',\overrightarrow{n})\,I_\lambda(\overrightarrow{r},\overrightarrow{n}')\,d\Omega'$$

and

$$4\pi\,M(\overrightarrow{r})\,\int_0^\infty \kappa^{\text{abs}}(\lambda,\overrightarrow{r})B_\lambda(T(\overrightarrow{r}))\,d\lambda = \Gamma^{\text{abs}}(\overrightarrow{r})$$

Radiative transfer in dust

$$\frac{dI_\lambda(\overrightarrow{r},\overrightarrow{n})}{ds} = -\,\kappa_\lambda^{\rm ext}(\overrightarrow{r})\,I_\lambda(\overrightarrow{r},\overrightarrow{n}) + \kappa_\lambda^{\rm abs}(\overrightarrow{r})\,B_\lambda(T(\overrightarrow{r})) + \kappa_\lambda^{\rm scatt}(\overrightarrow{r})\,\frac{1}{4\pi}\int_\Omega \psi_\lambda(\overrightarrow{r},\overrightarrow{n}',\overrightarrow{n})\,I_\lambda(\overrightarrow{r},\overrightarrow{n}')\,d\Omega'$$

Phase function

and

$$4\pi\,M(\overrightarrow{r})\,\int_0^\infty \kappa^{\rm abs}(\lambda,\overrightarrow{r})B_\lambda(T(\overrightarrow{r}))\,d\lambda = \Gamma^{\rm abs}(\overrightarrow{r})$$

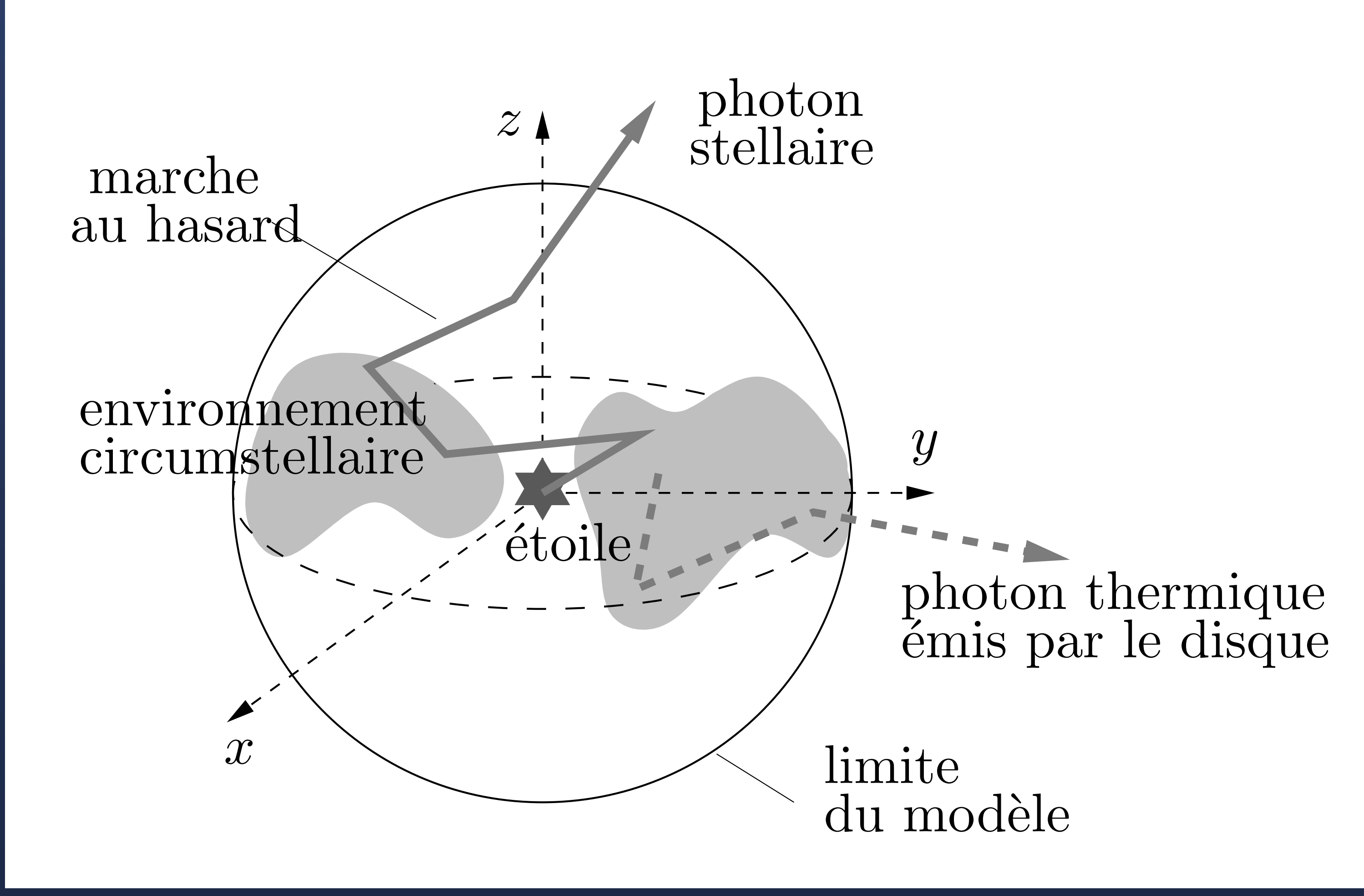
Why the need for Monte Carlo?

- multiple-scattering
- anisotropic scattering (+ polarisation)
- complex 3D structure

- benchmark: tested up to very high optical depths (10^6)
- Fast: variance reduction techniques, MC + diffusion approx., MC + ray-tracing

Lefevre et al 1982, 1983

Bjorkman & Wood, 2001
Wolf, 2003
Niccolini, 2003
Juvela, 2005
Pinte et al, 2006, 2009



MCFOST

MCFOST?
- 3D radiative transfer Monte Carlo method
- radiative transfer in dust and gas

Physical processes:
- multiple scattering and polarisation
- dust heating
- NLTE molecular pop.

Code specificities:
- Spatial differentiation (radial/vertical)
- No limits on opacity: $\tau_V = 0 \rightarrow 10^9$
- Non-equilibrium grains: PAHs, VSGs
- consistent modeling of dust and gas phases

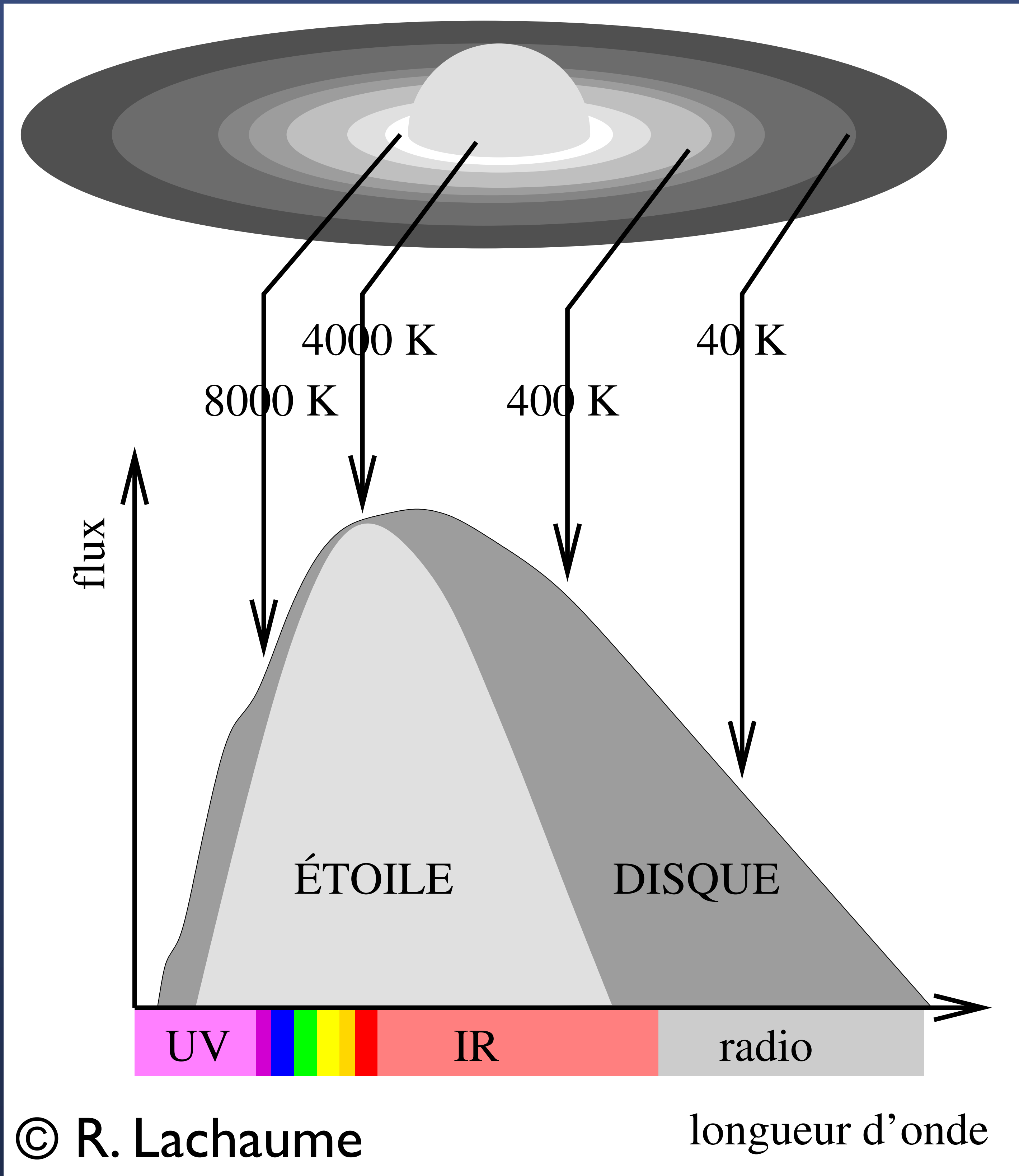
⇒ scattered light (+ pola) & thermal emission maps + SEDs

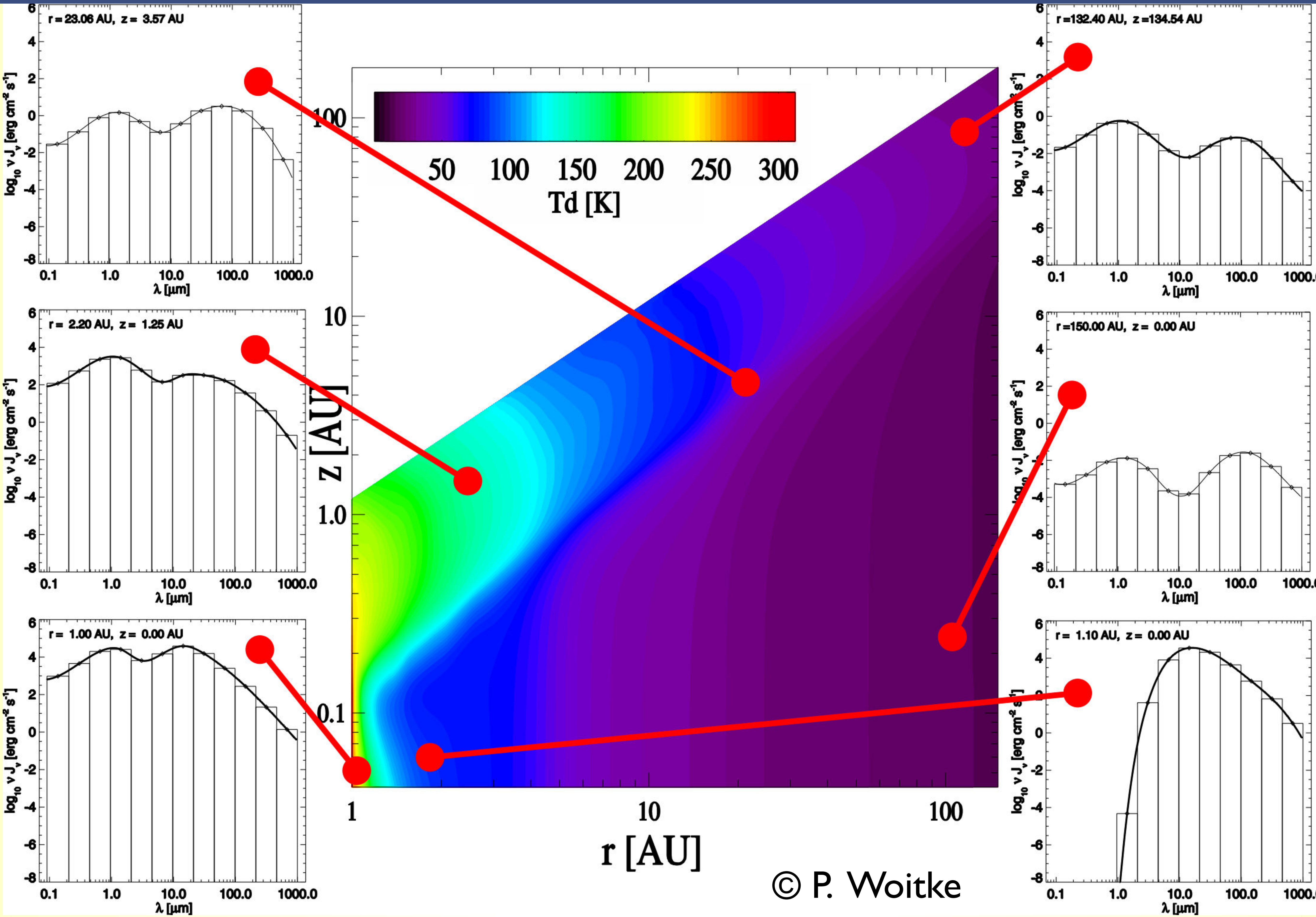
+ visibilities + molecular emission maps & line profiles

Disk Emission

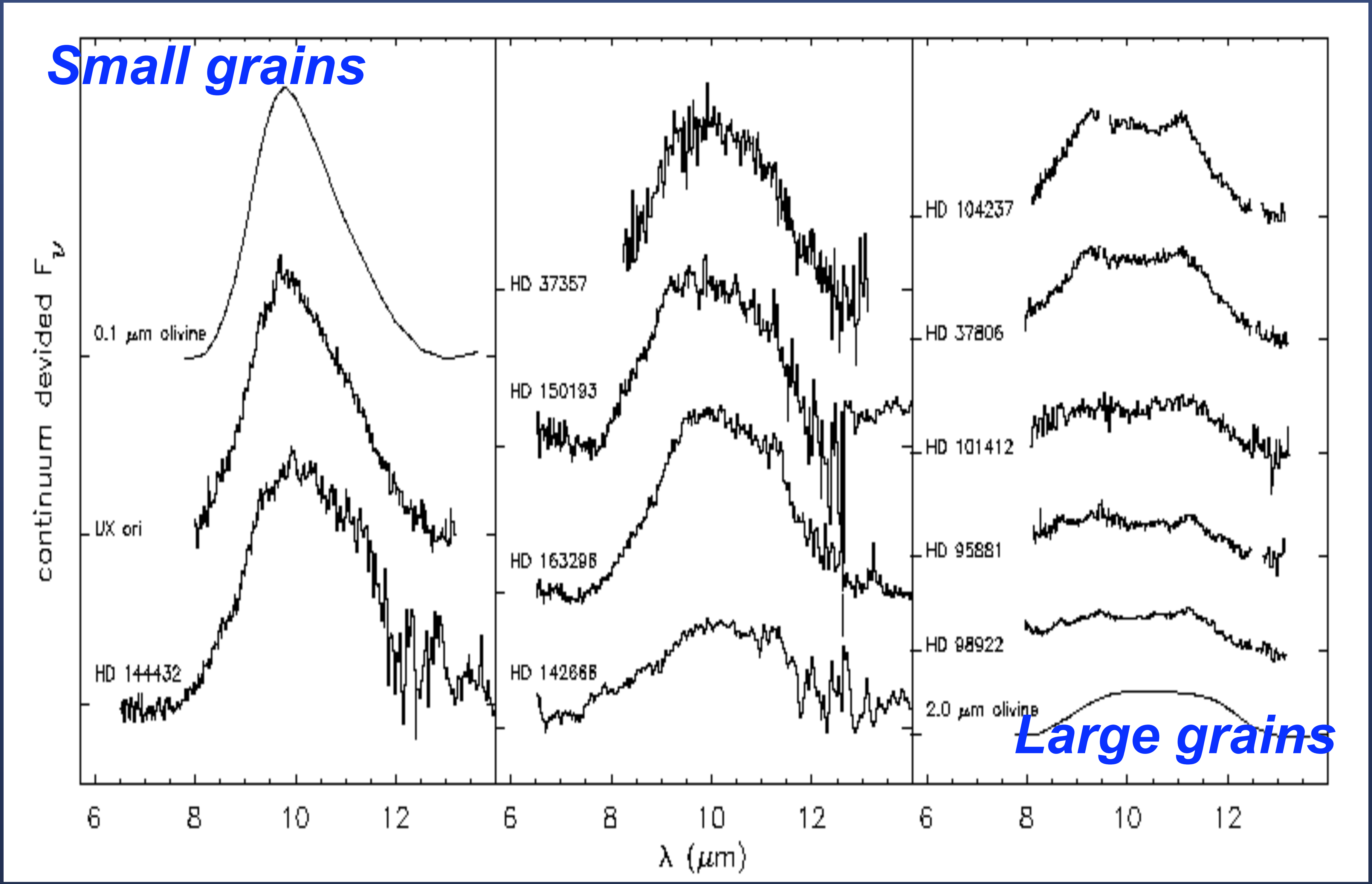
- The disk is reprocessing the stellar light
- hot surface + warm/cool midplane
- T ranges from 1500K (Rin) to 30K (Rout, midplane)

⇒ disk radiates from NIR to mm/cm regime




r = 23.06 AU, z = 3.57 AU
r = 2.20 AU, z = 1.25 AU
r = 1.00 AU, z = 0.00 AU
r = 132.40 AU, z = 134.54 AU
r = 150.00 AU, z = 0.00 AU
r = 1.10 AU, z = 0.00 AU
λ [μm]
Td [K]
50 100 150 200 250 300
z [AU]
r [AU]
© P. Woitke

IR spectroscopy with Spitzer



Grains grow to μm sizes in the surface

v. Boekel et al 2003

Thermal emission at mm wavelengths

Emission from a pole-on disk:

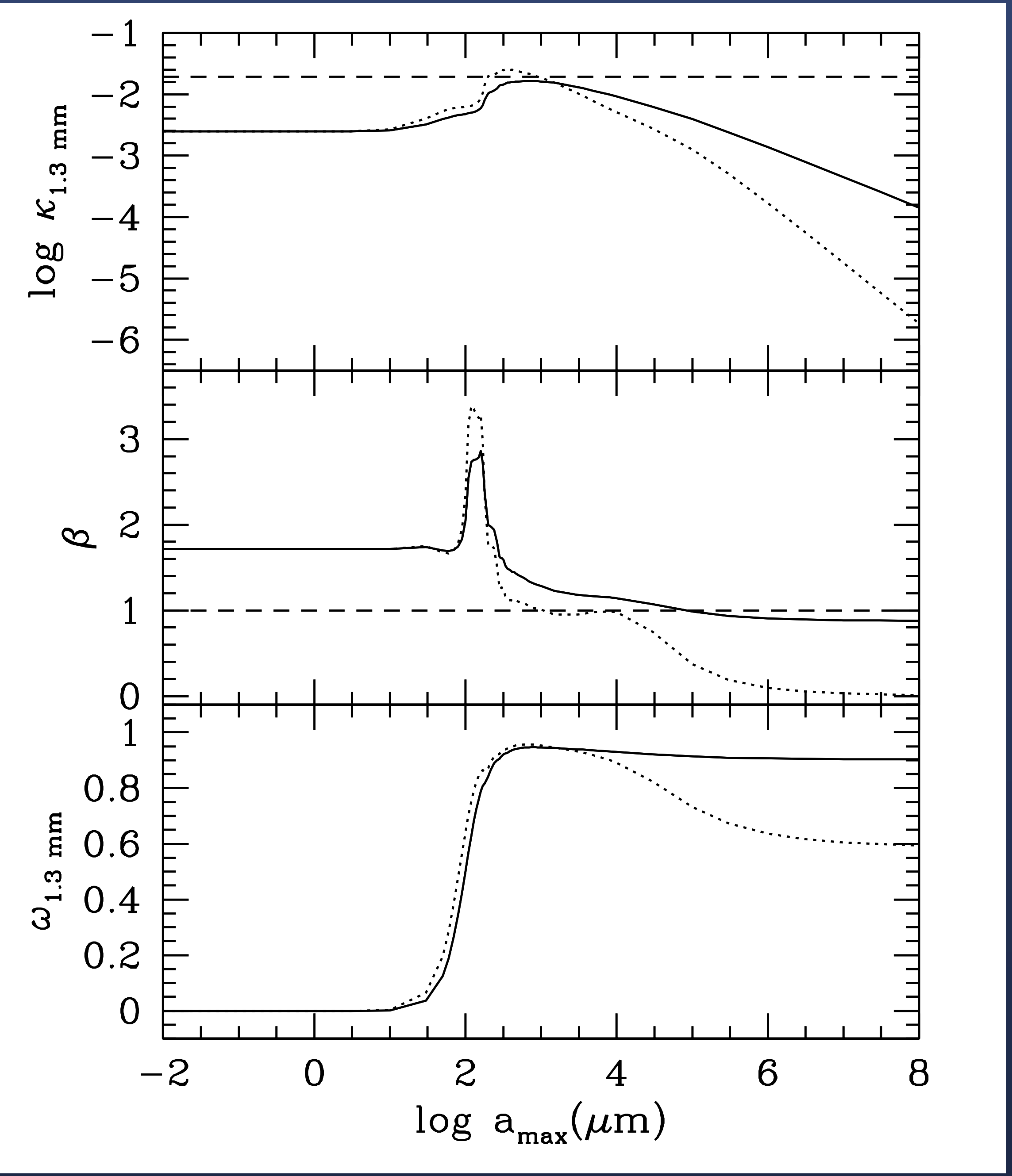
$$F_\nu = \frac{1}{D^2}\int_{R_{in}}^{R_{out}} B_\nu(T(r))(1-e^{-\tau(\nu,r)})2\pi r dr$$

Dust opacity strongly dependent on grain size

$\tau(\nu) \propto \kappa(\nu) \propto \nu^\beta$

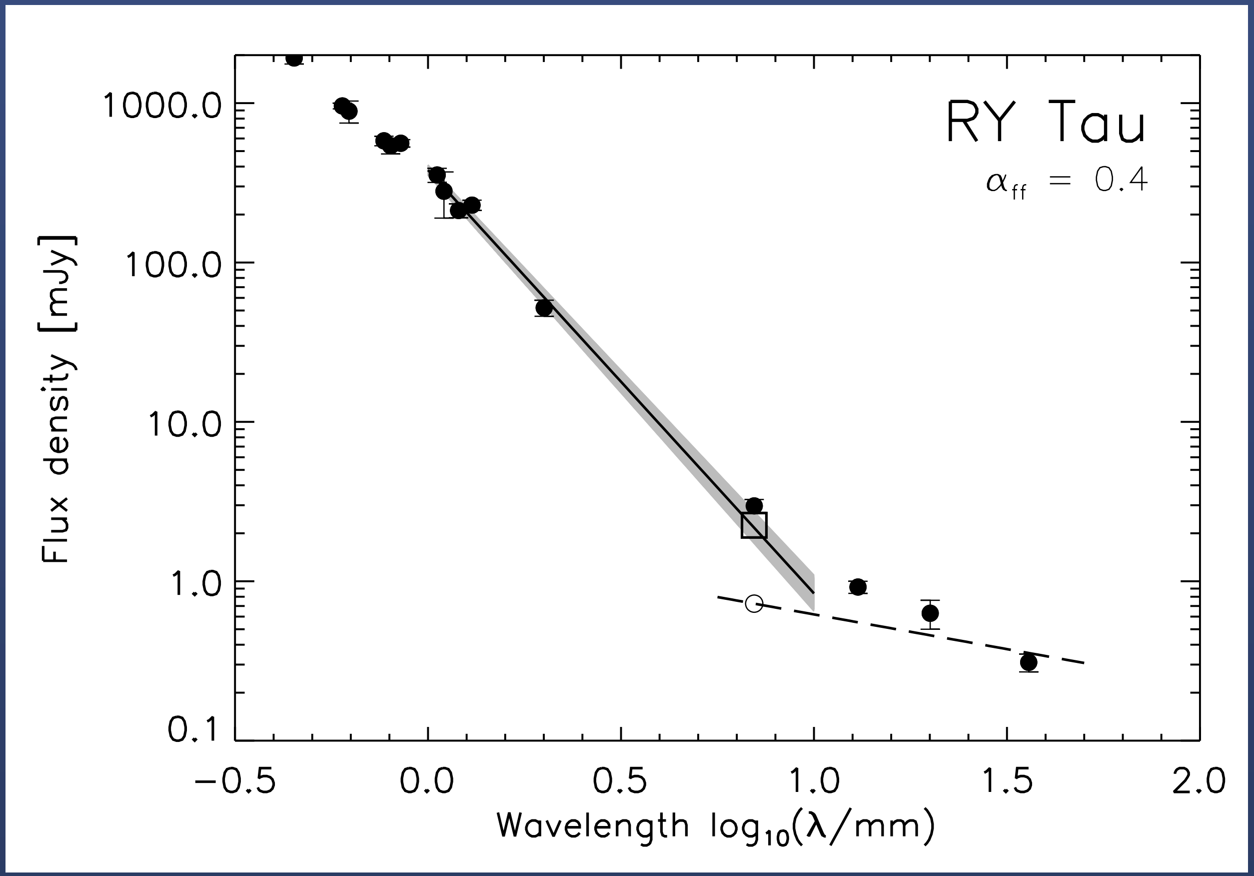
Optically thin regime:

$F_\nu \propto \nu^2\tau(\nu) \propto \nu^2\kappa(\nu) \propto \nu^{(2+\beta)}$



D'Alessio et al 2001

Dust opacity indices



Measure of β

Korner et al 1995
Calvet et al 2002
Testi et al 2003
Natta et al 2004
Wilner et al 2005
Rodmann et al 2006
Lommen et al 2009

Opacity indices < 2

⇒ Grains grow to

centimeter size boulders

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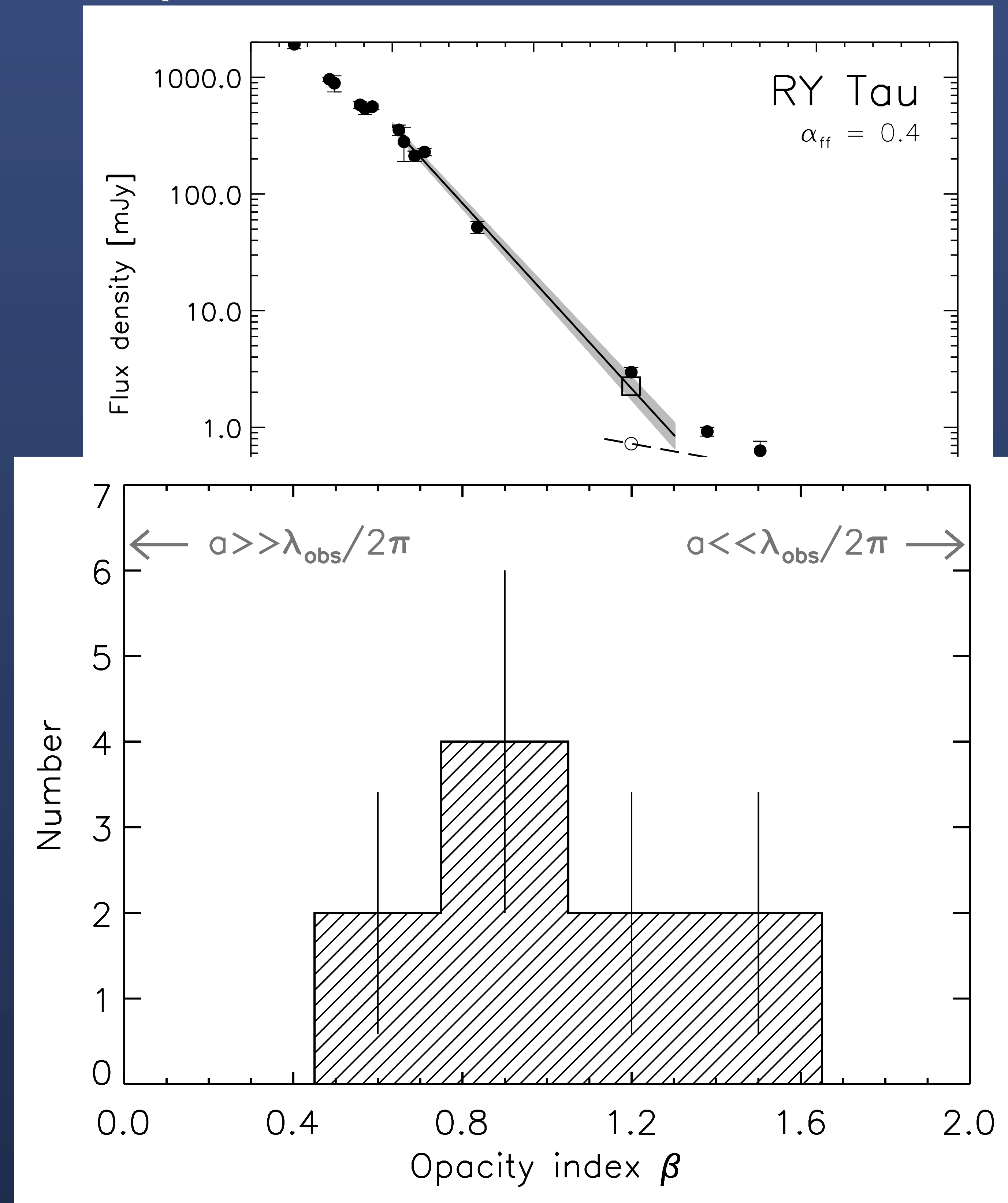
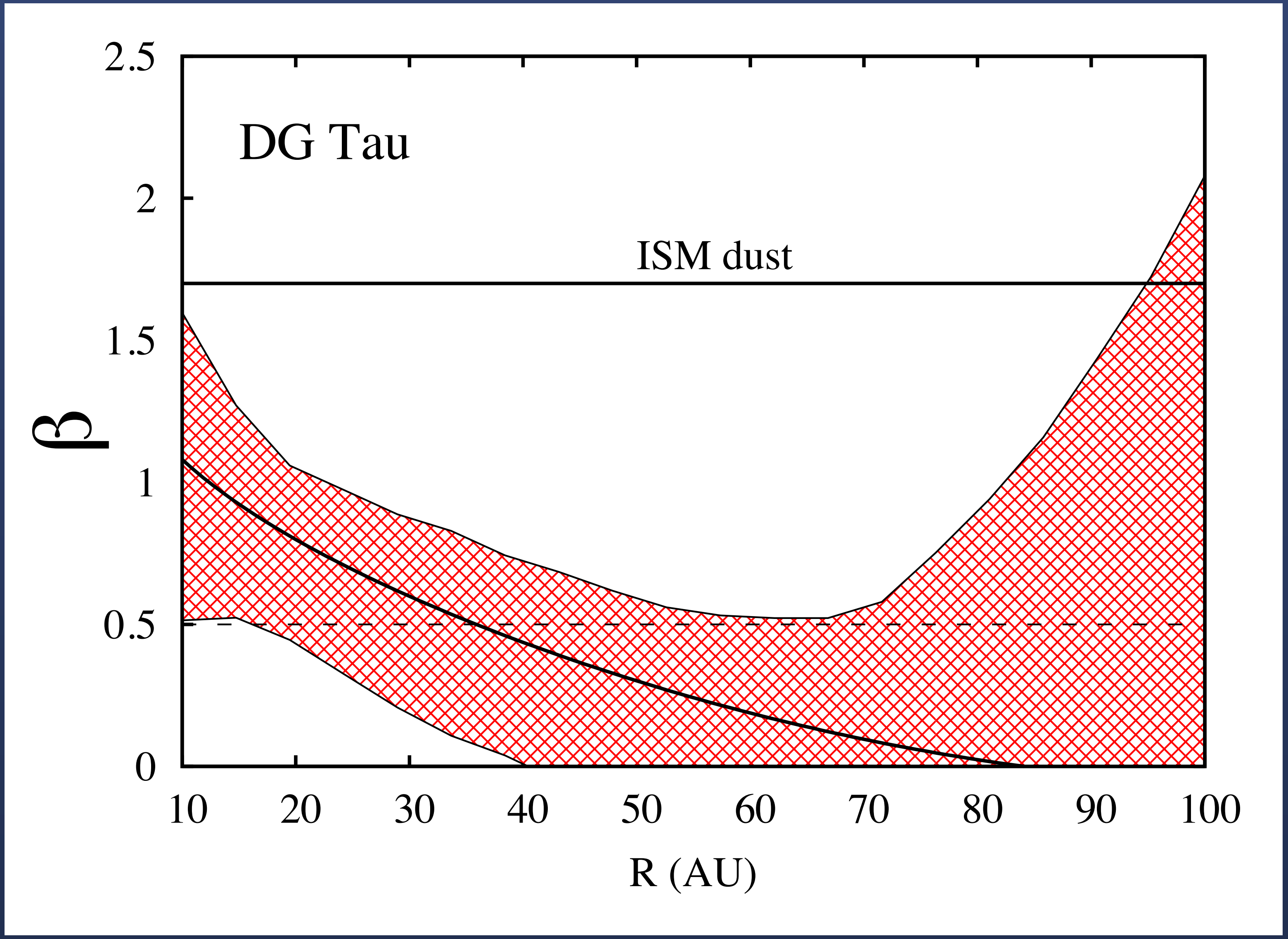


Rodman et al 2006

First evidence of differential grain growth ?

β might be larger in central parts of the disk
→ ALMA

See also Guilloteau et al 2010



Isella et al 2010

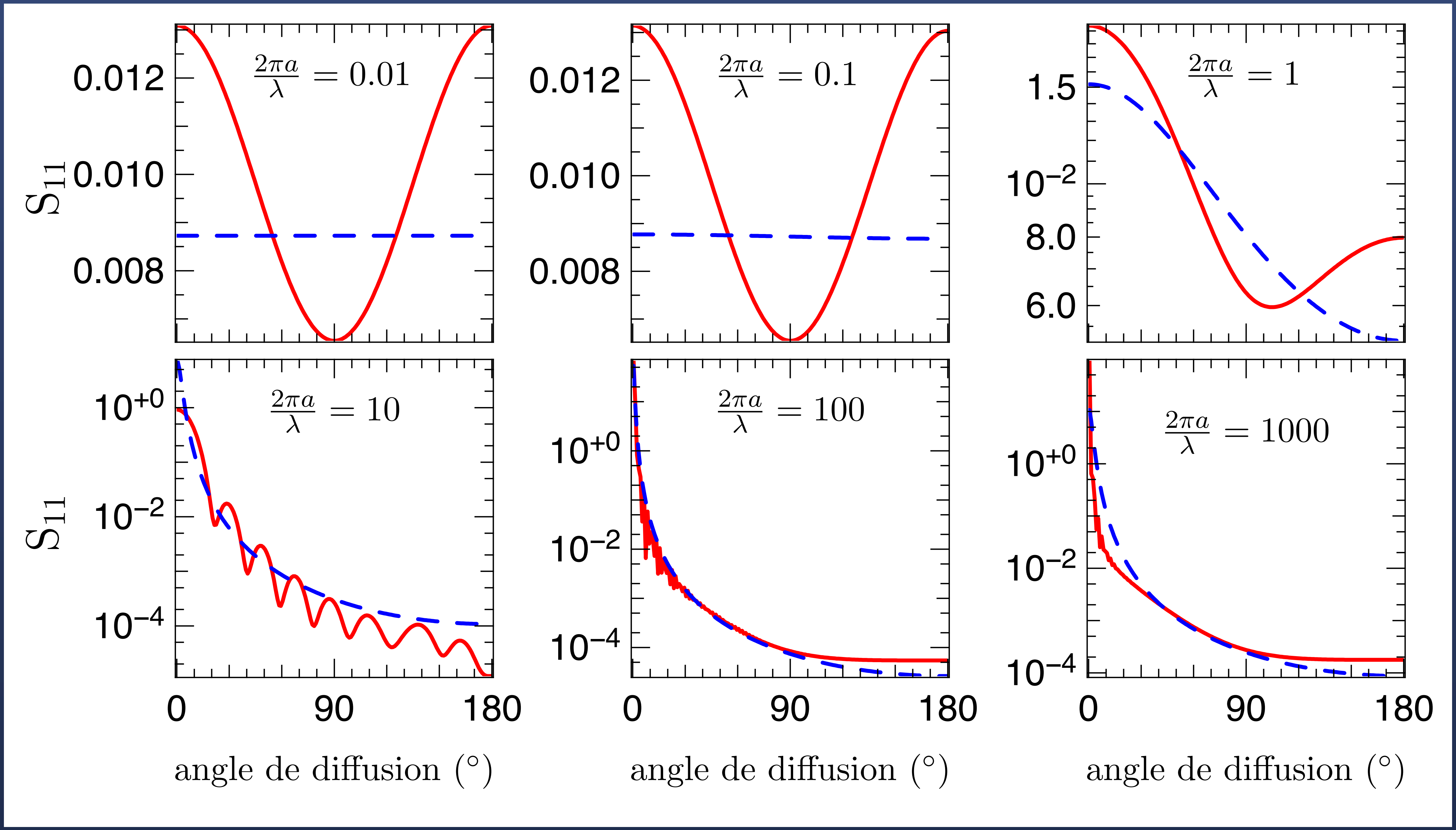
Multi-λ scattered light images

- Dust opacity decreases with increasing λ
  - Images in the thermal IR probe deeper into the disks than optical/NIR images
- Scattering depends on grain size and , and is most sensitive to $2\pi a \approx \lambda$ grains
  - Optical/NIR ⇔ 0.1-0.5 μm dust grains
  - Thermal IR ⇔ 1-5 μm dust grains

A powerful tool to probe stratification

Light scattering: anisotropy

Polarisability depends on grain size

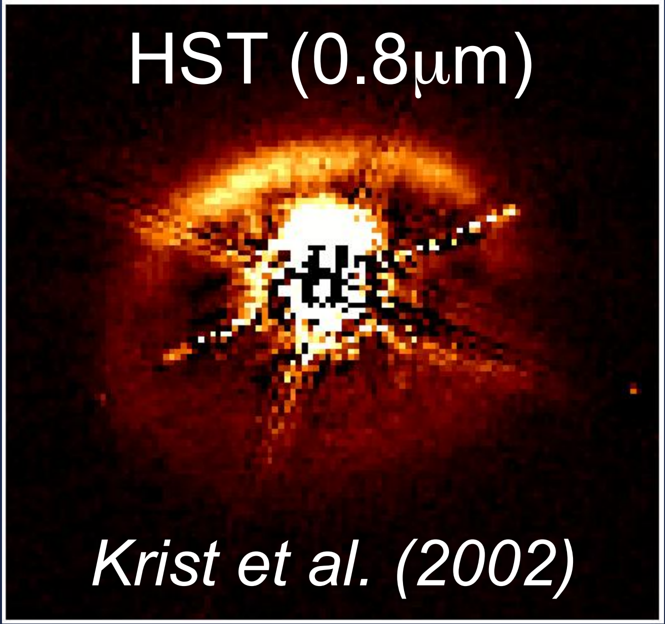


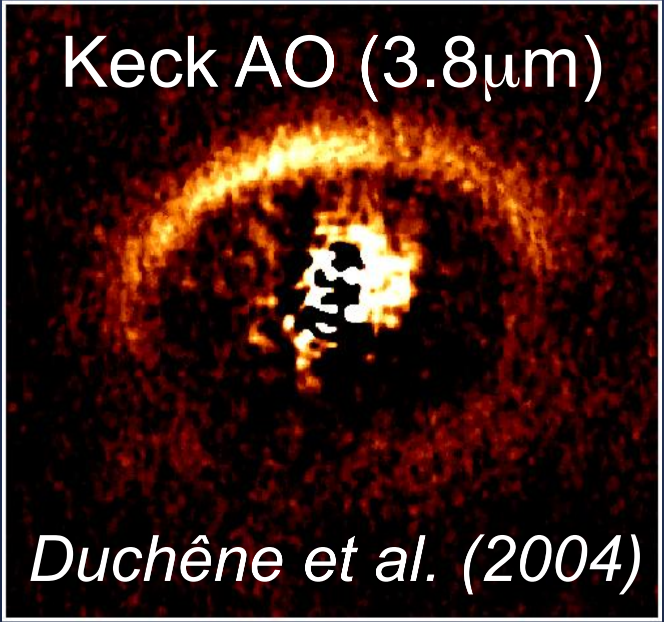
Mie theory grain size distribution $dn(a) \propto a^{-3.5} da$

The case of GG Tau

- A 0.13M, 180AU-radius circumbinary ring
- Clear detection of the ring in scattered light
- Morphology extremely similar to visible image

ISM dust models match the visible Image with i ≈ 40°





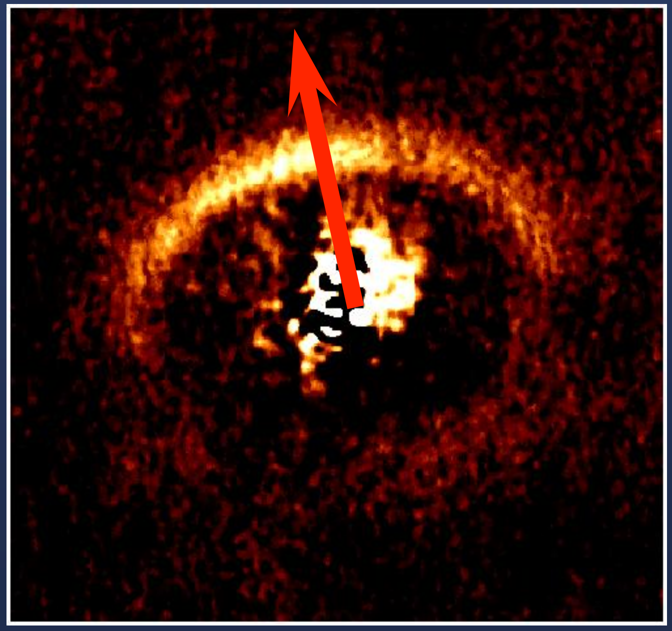
1”

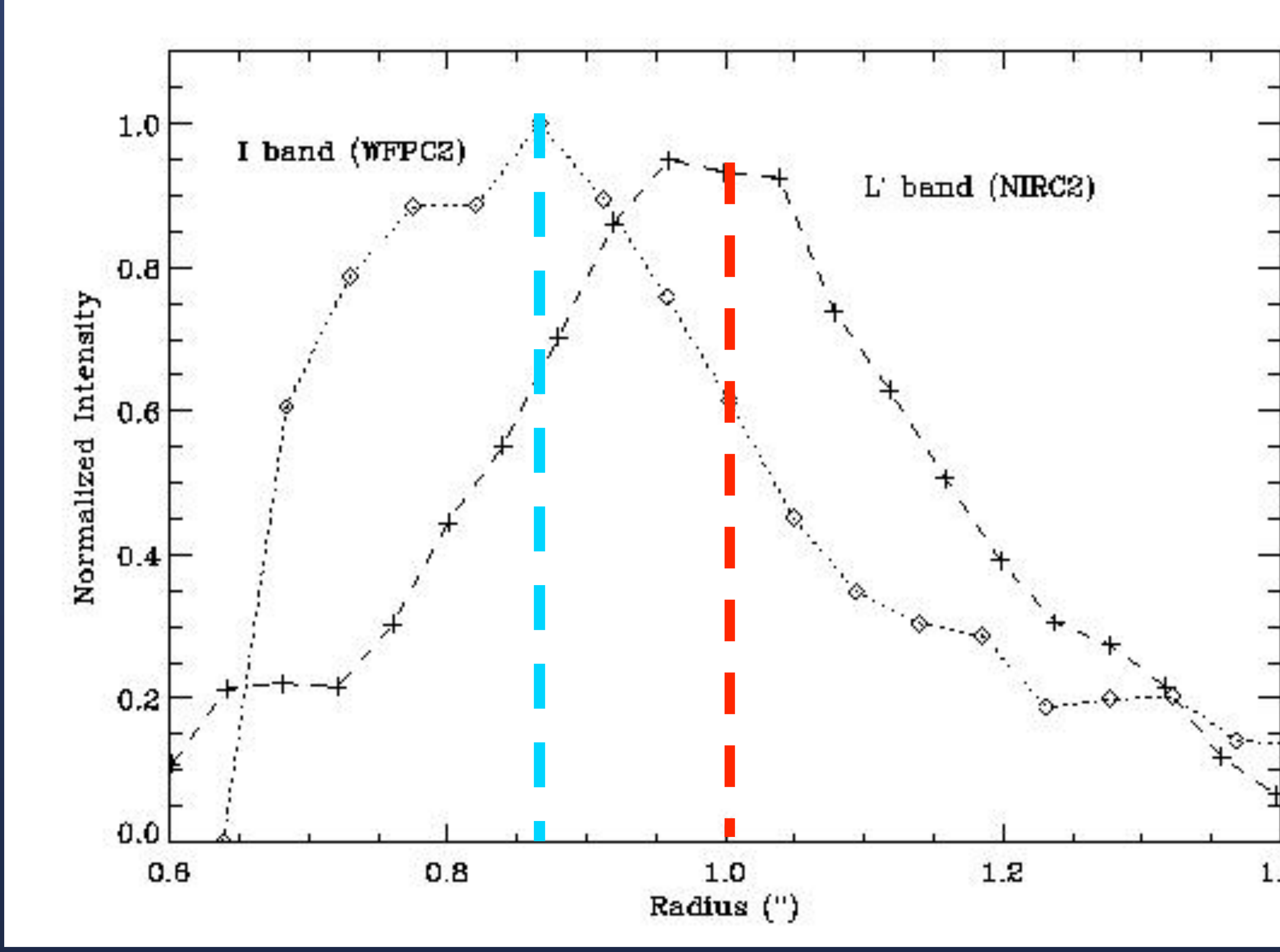
A first direct evidence

Scattered light at L’ comes from 25AU above the midplane; I band, 50AU above

- Arguably the most direct evidence of dust stratification to date

Settling and/or growth?



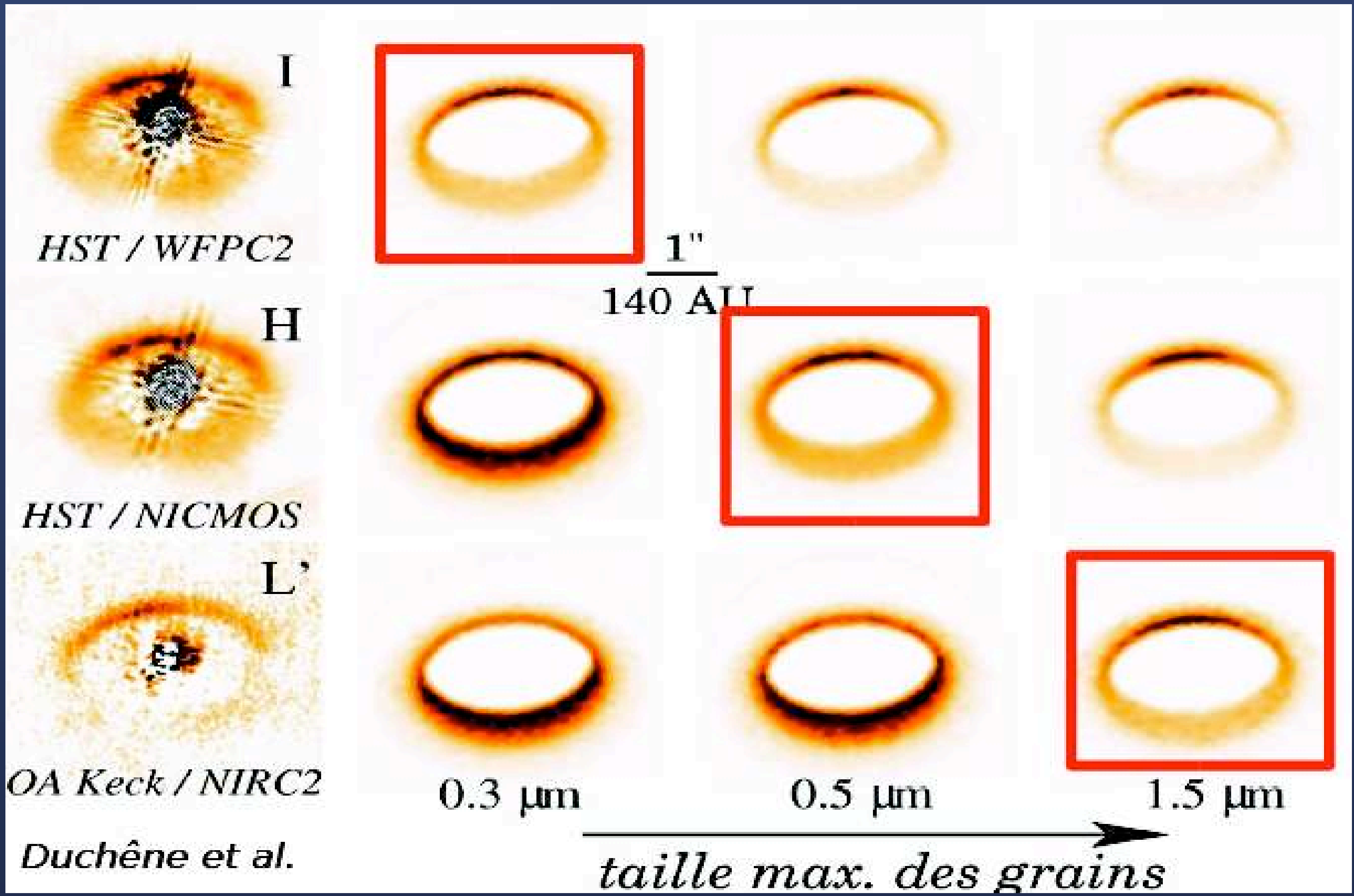


The GG Tau ring

0.5 - 3.8 μm scattered light images

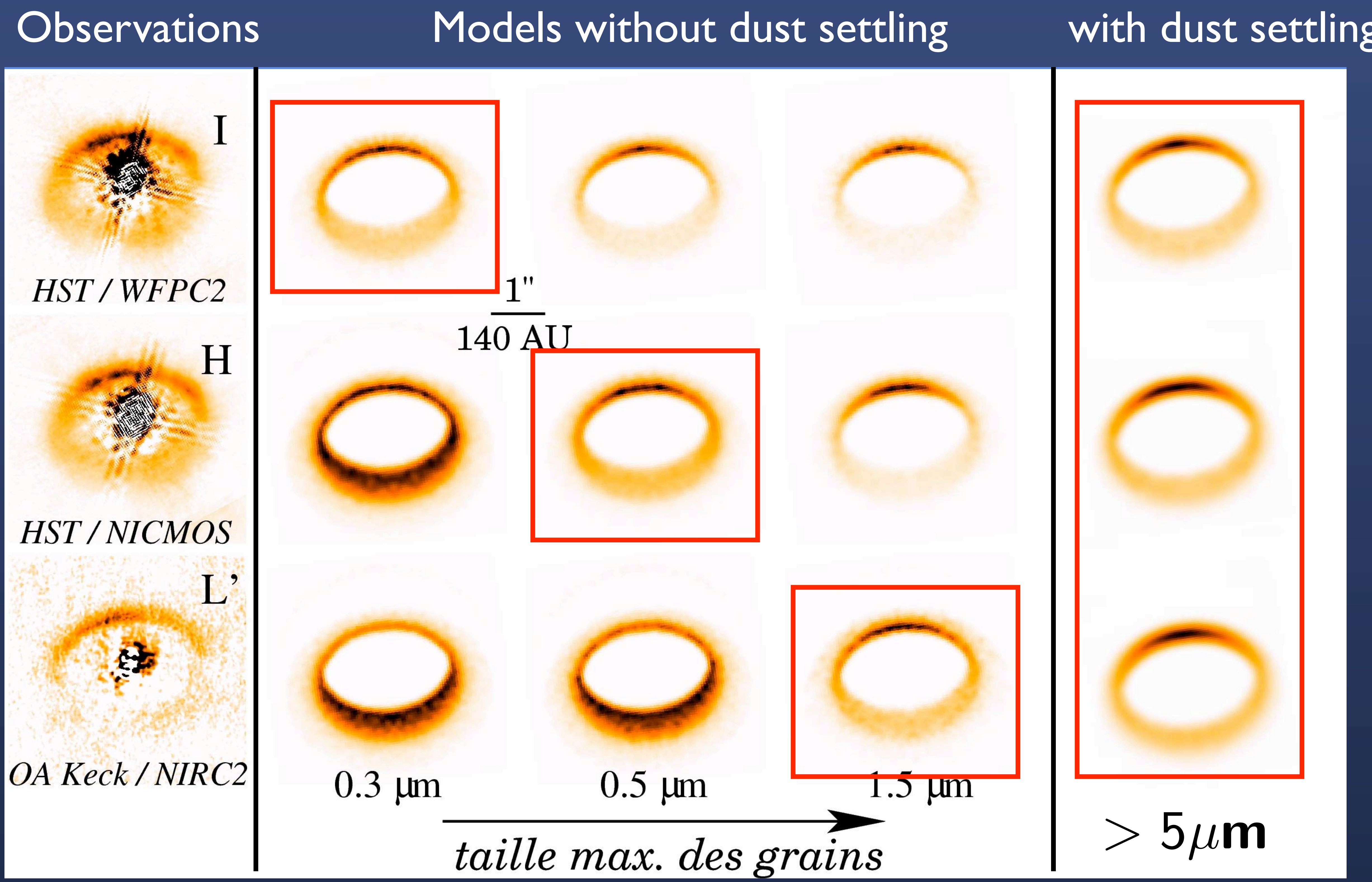
- Large grains (>1μm) are present in the disk
- The larger the deeper

⇒ Disk stratification



Duchêne et al 2004

GG Tau: models with dust stratification

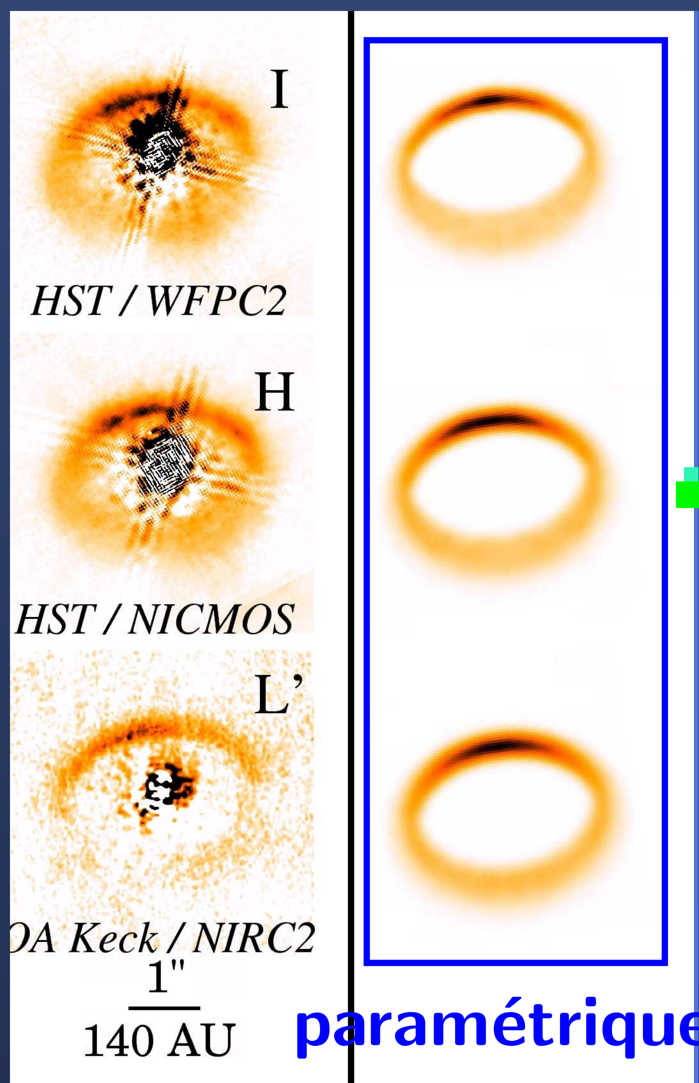


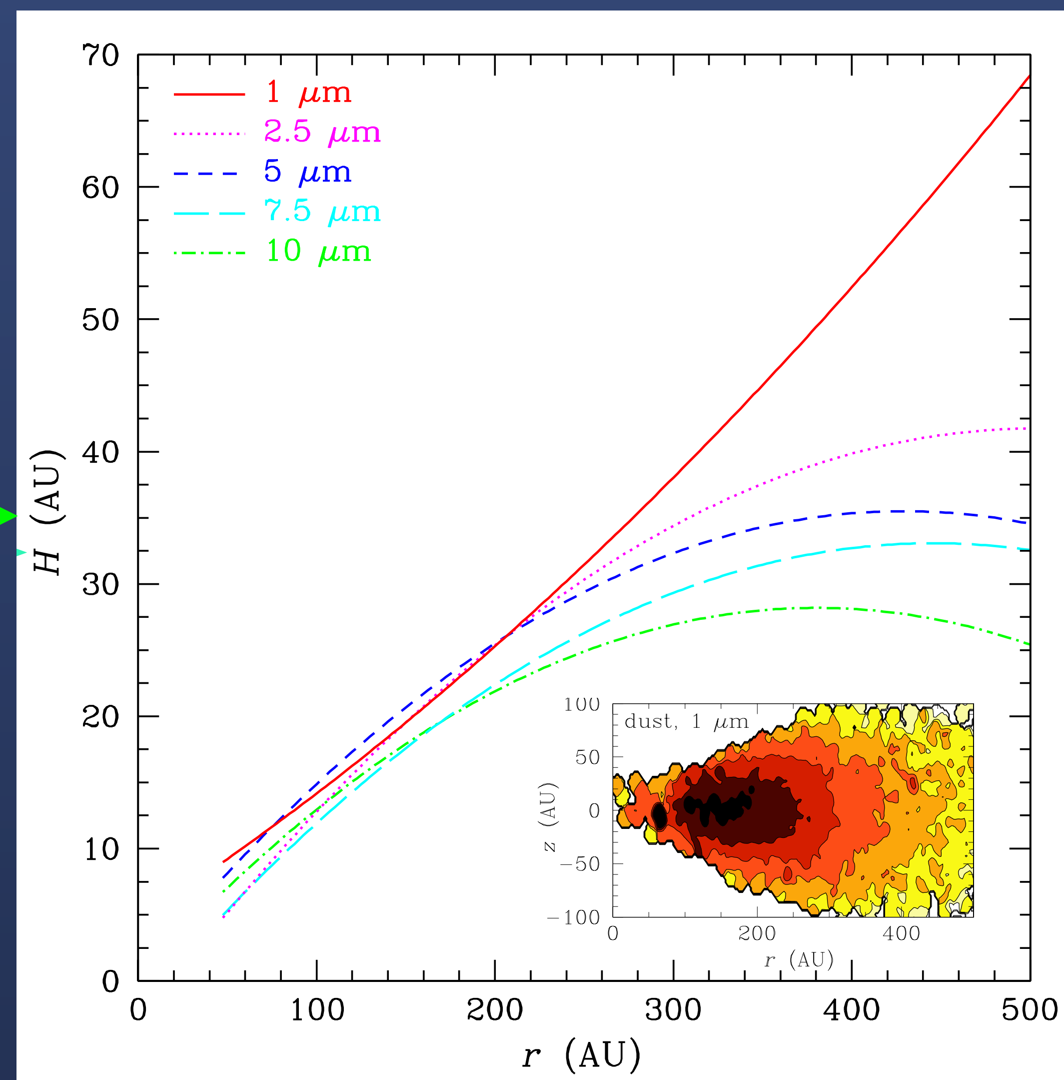
Pinte et al. (2007)

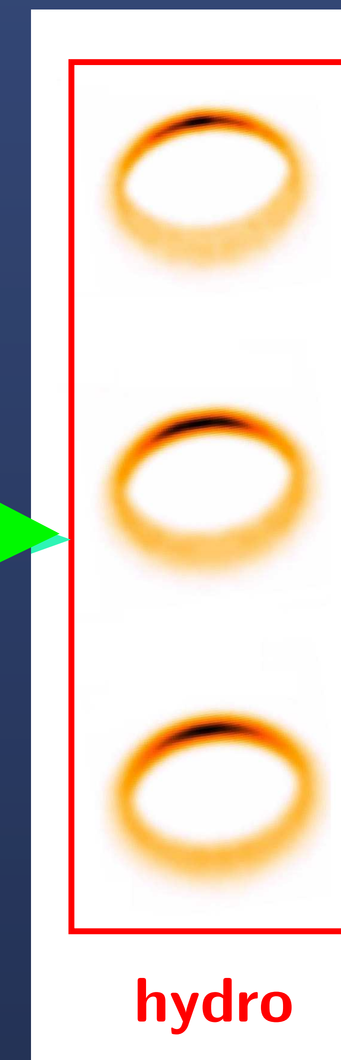
GG Tau: a stratified ring

Model with stratification reproduces images from 0.5 to 3.8μm

Obs Models



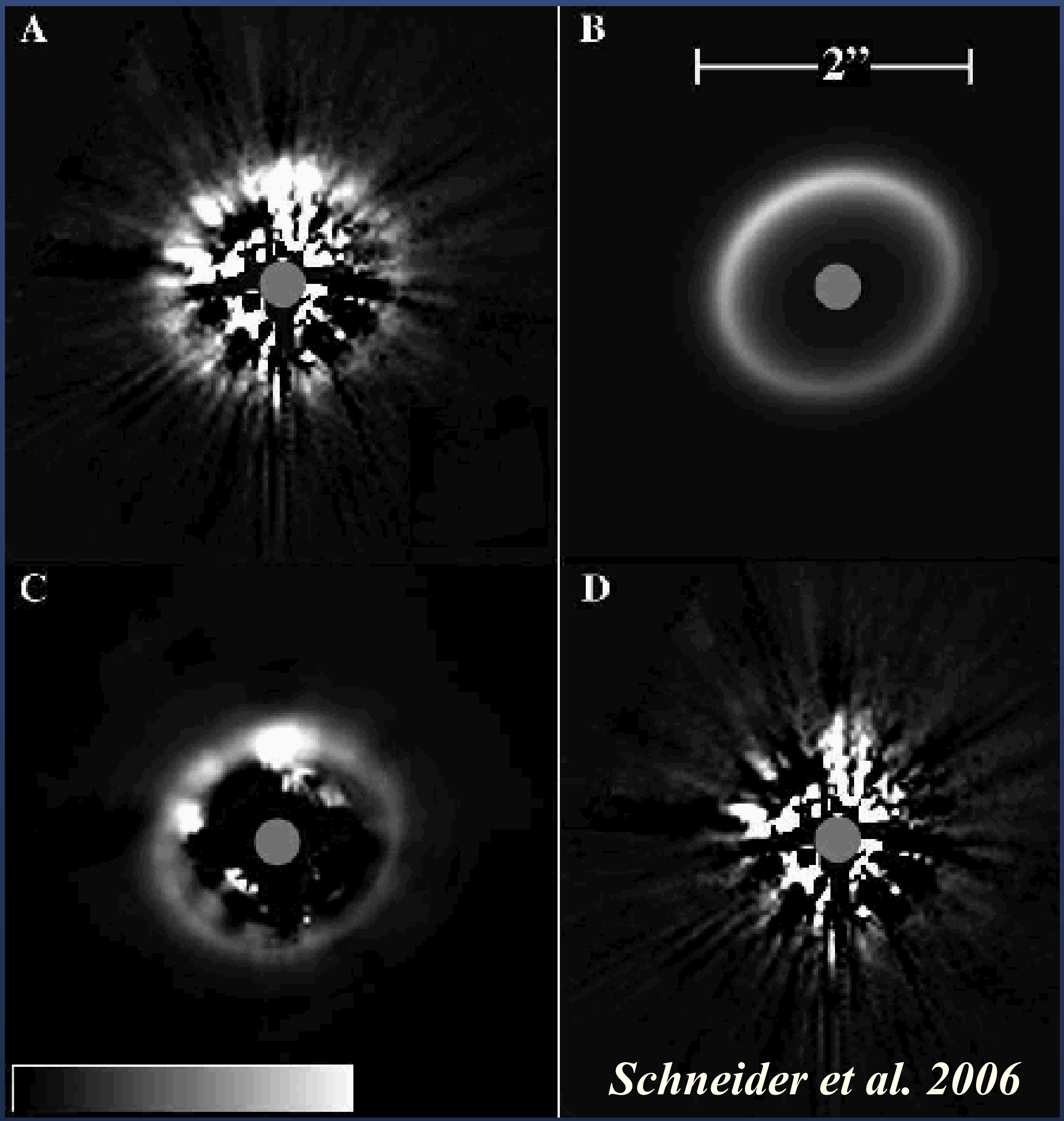




SPH simulations (Fouchet, Gonzalez, Lyon) + **radiative transfer**

Pinte et al 2007

Dust grains properties

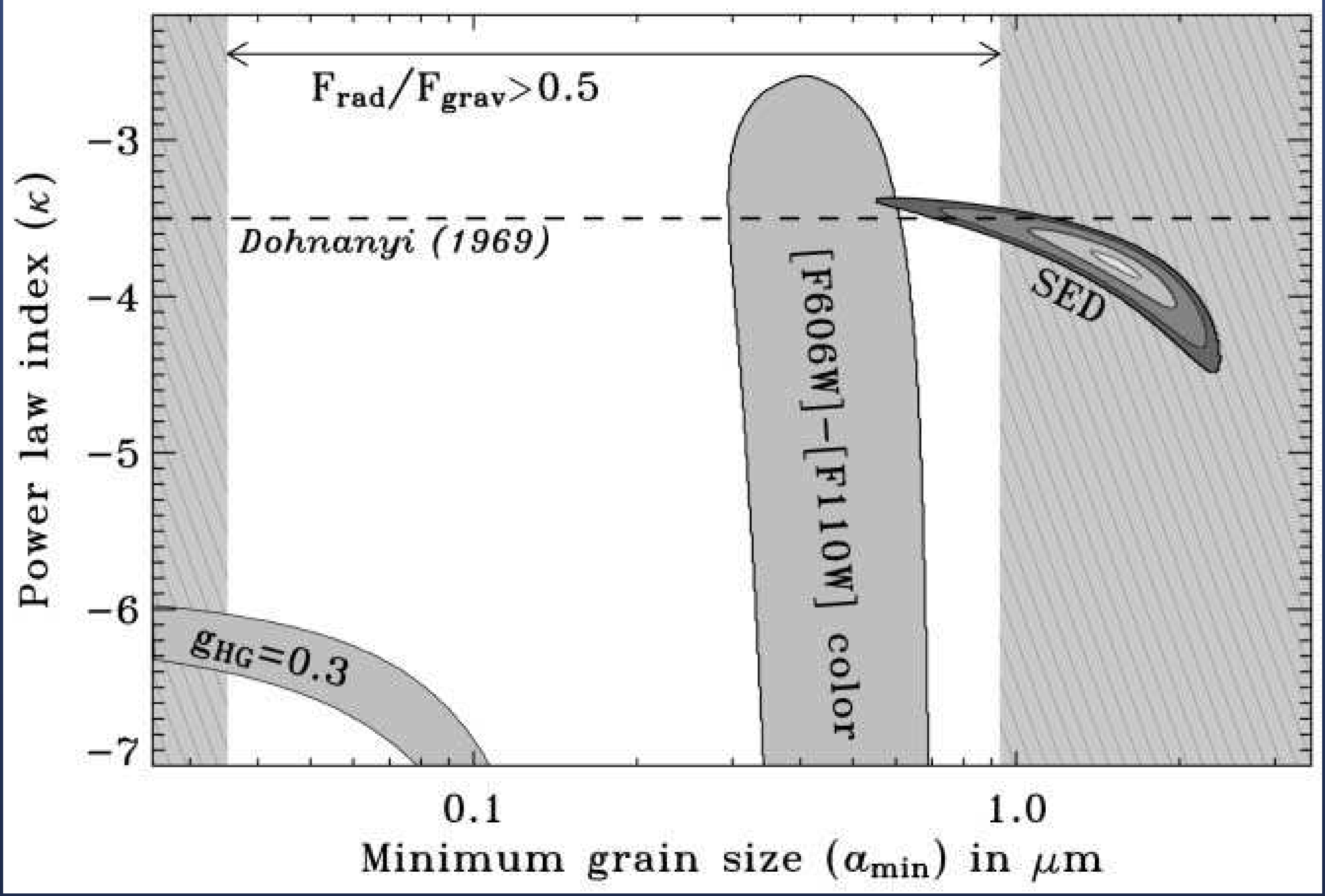


HD 181327 (debris disk).

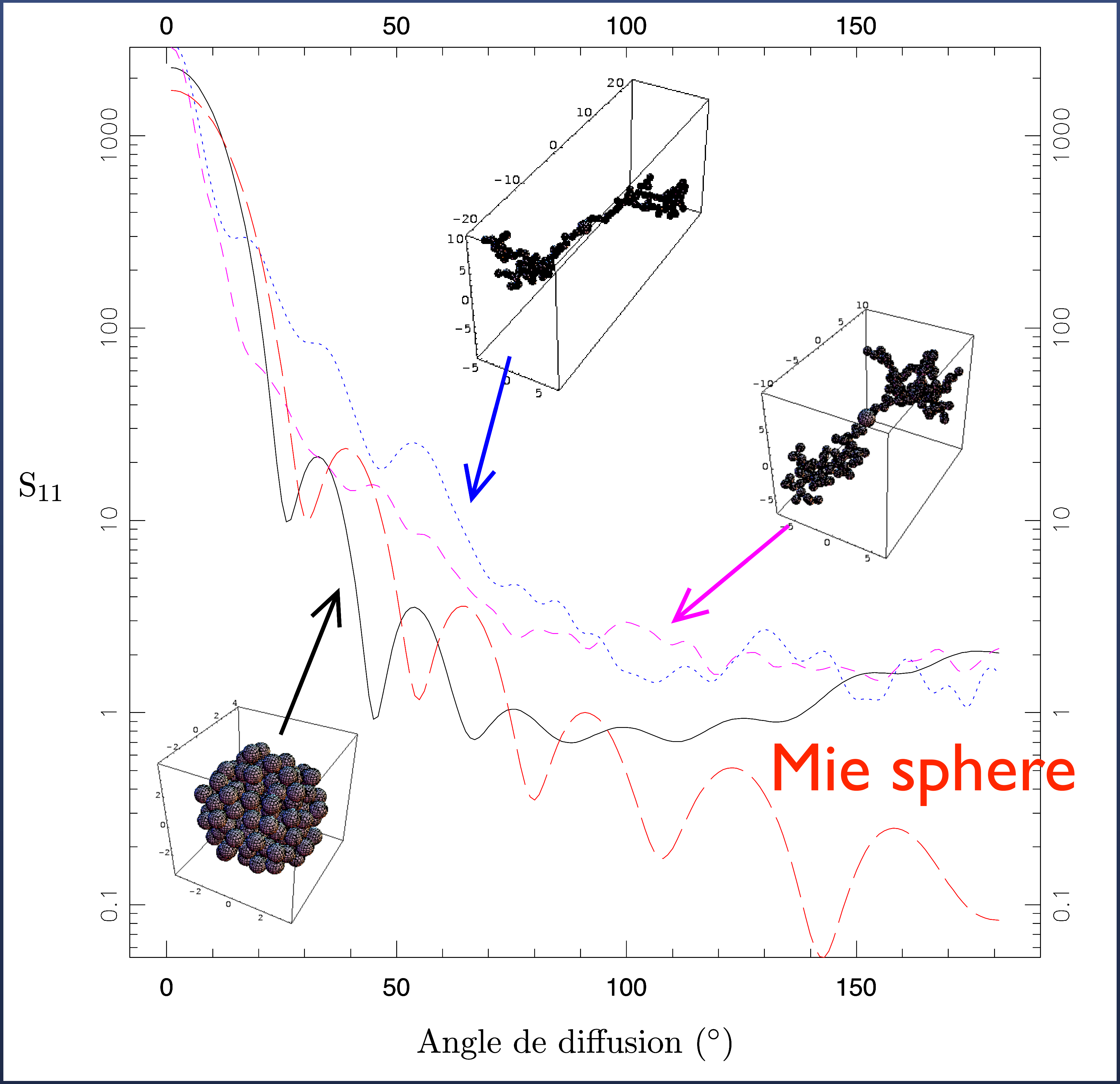
The dust is more evolved (2nd generation)

Inclinaison: 32°

Evidence of non spherical grains



Signatures of agregates ?



Polarisation

Polarisation by scattering very sensitive to dust properties

Mueller matrix (Mie theory)

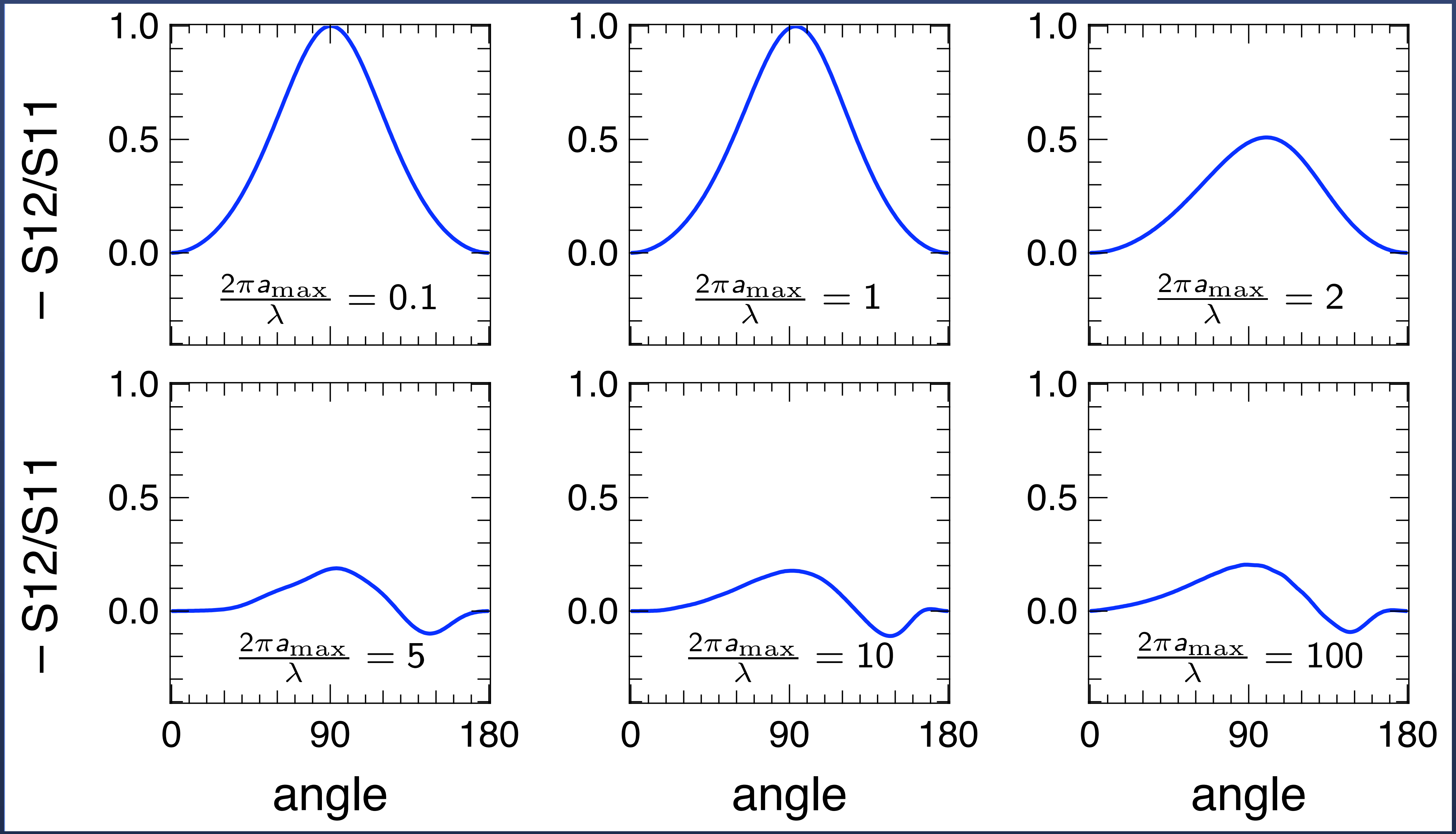
$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}_d = \begin{pmatrix} S_{11} & S_{12} & 0 & 0 \\ S_{12} & S_{11} & 0 & 0 \\ 0 & 0 & S_{33} & S_{34} \\ 0 & 0 & -S_{34} & S_{33} \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}_i$$

Circular polarisation in case of multiple scattering

$$\begin{pmatrix} I = 1 \\ Q = 0 \\ U = 0 \\ V = 0 \end{pmatrix} \overbrace{\longrightarrow}^{1^{\text{ère}}\text{diff}} \begin{pmatrix} I = 1 \\ Q \neq 0 \\ U = 0 \\ V = 0 \end{pmatrix} \overbrace{\longrightarrow}^{2^{\text{ème}}\text{diff}} \begin{pmatrix} I = 1 \\ Q \neq 0 \\ U \neq 0 \\ V \neq 0 \end{pmatrix}$$

Polarisability of dust grains

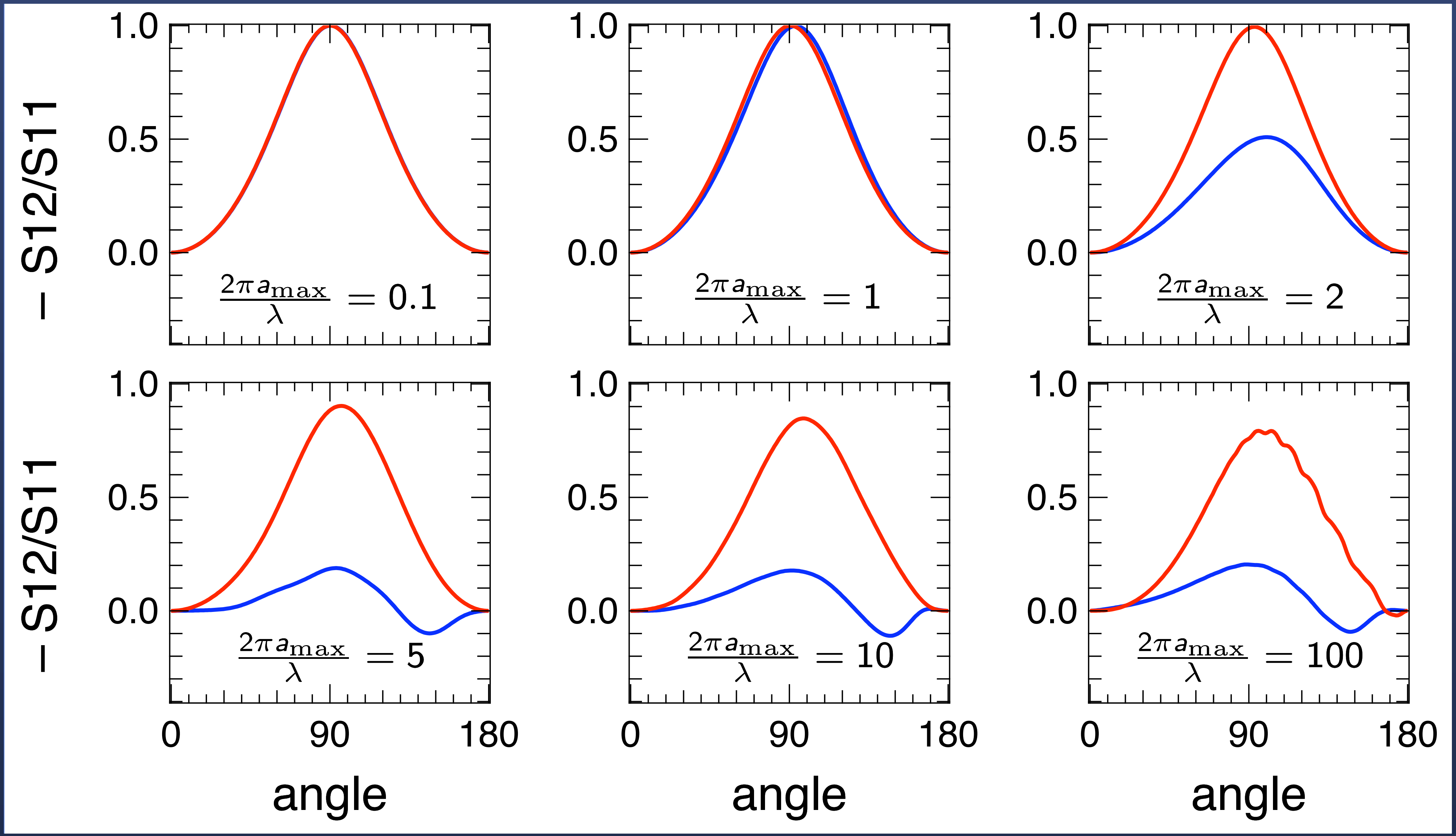
Polarisability depends on grain size



Mie theory   grain size distribution $dn(a) \propto a^{-3.5}\, da$

Polarisability of dust grains

Polarisability depends on grain size
& composition/porosity (real part of refractive index)



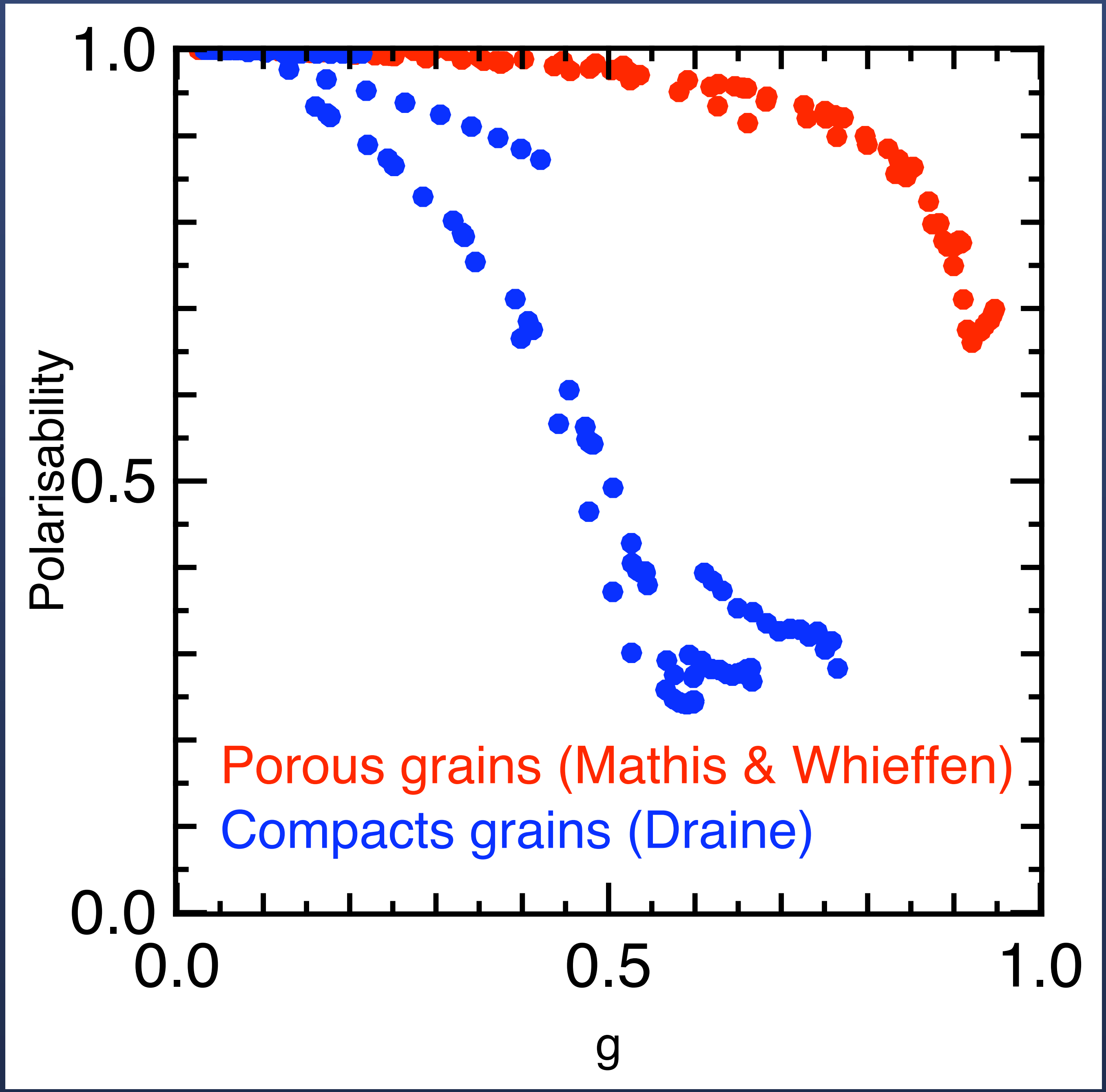
Mie theory grain size distribution dn(a) α $a^{-3.5}$ da

Effect of chemical composition/porosity

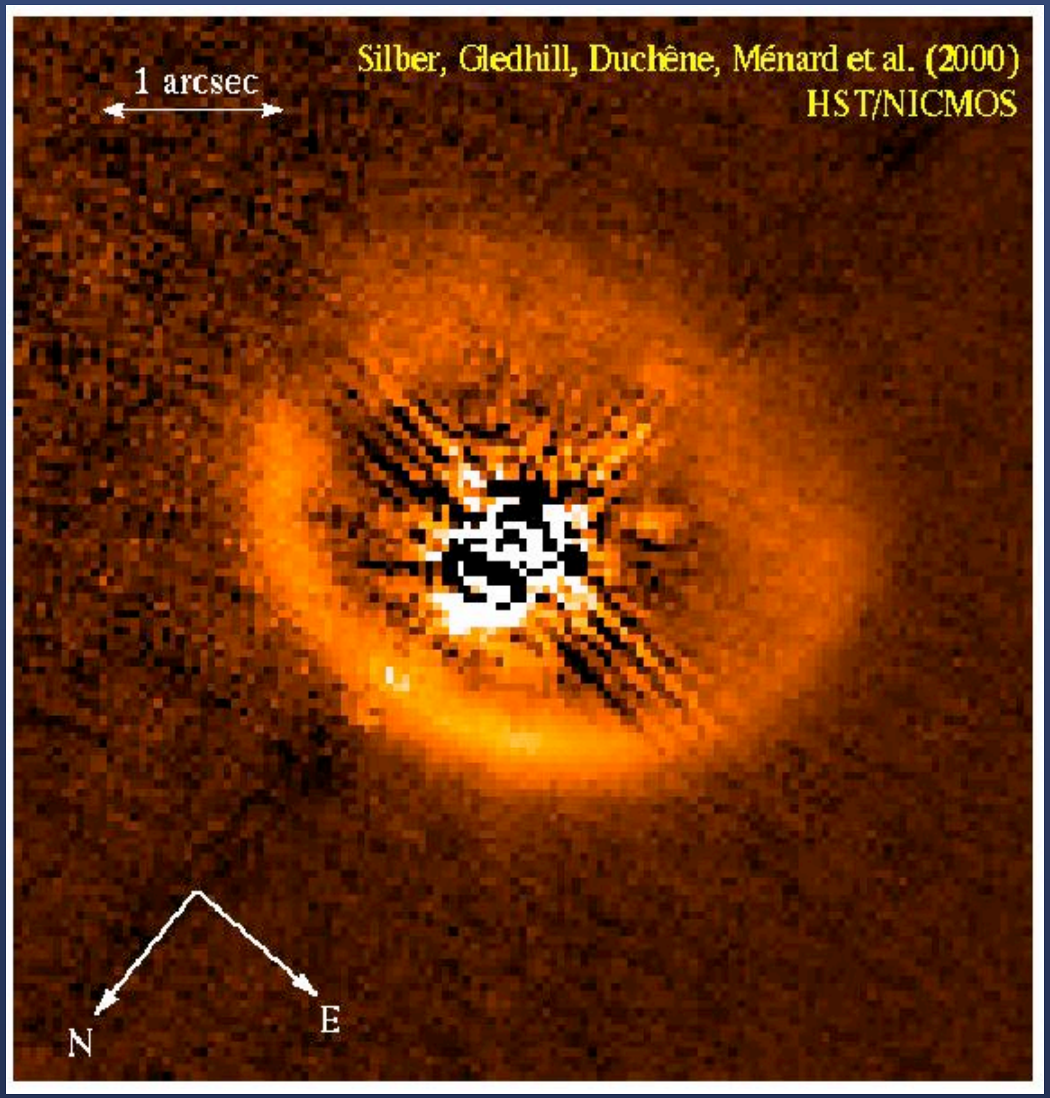
Scattering phase function & polarisability both depend on grain composition & porosity

Porous grains produce larger polarization for same asymmetry parameter

need to constrain g
→ multi-technique analysis



The GG Tau ring



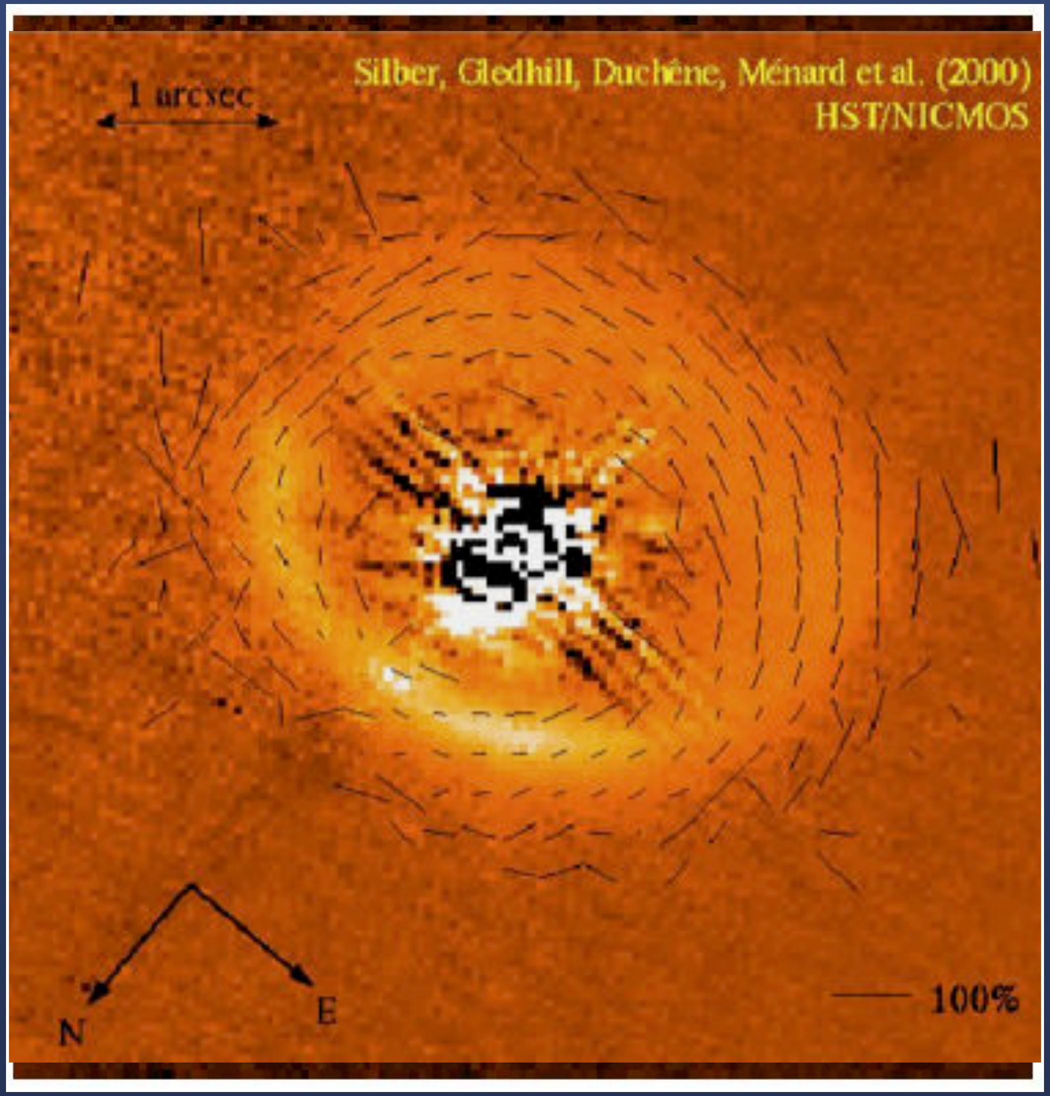
- Intensity map:

effect of anisotropic scattering clearly visible

$g \approx 0.6$

$\Rightarrow$ grains with size $\approx \lambda$

The GG Tau ring



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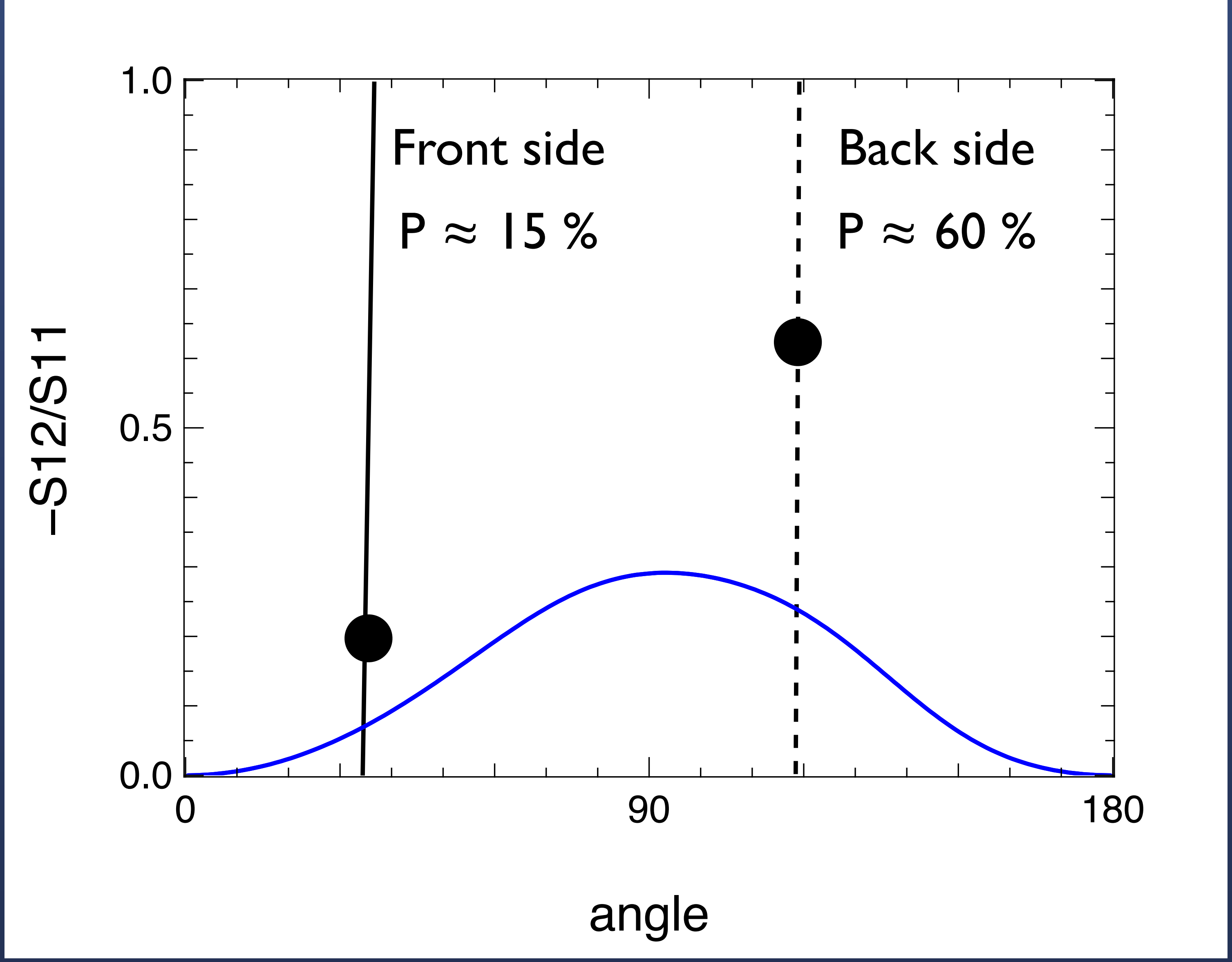
- Polarization map:

high polarisation
$\Rightarrow$ “Rayleigh” scattering

Not reproduced by compact silicates

The GG Tau ring



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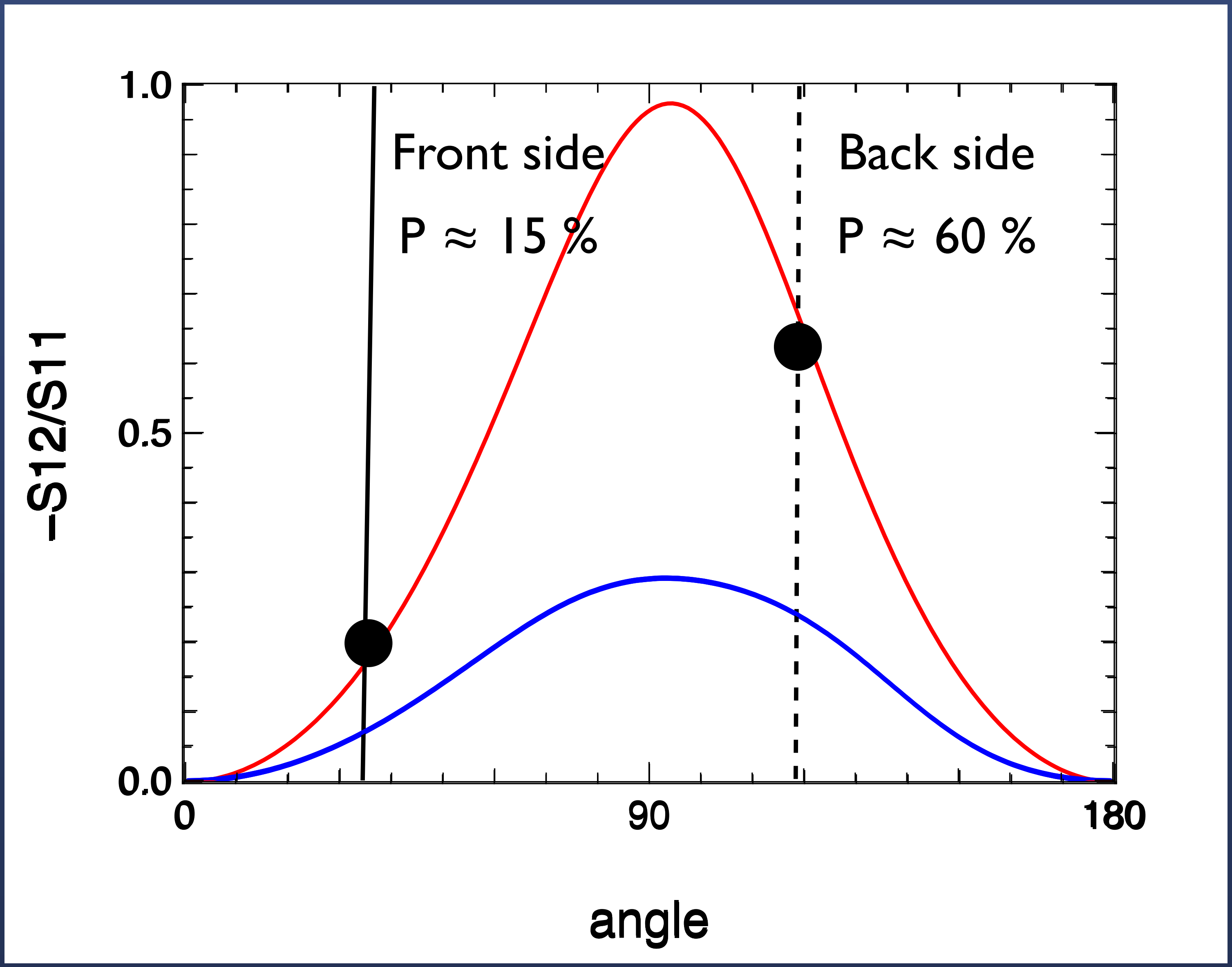

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effect of anisotropic scattering clearly visible
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high polarisation
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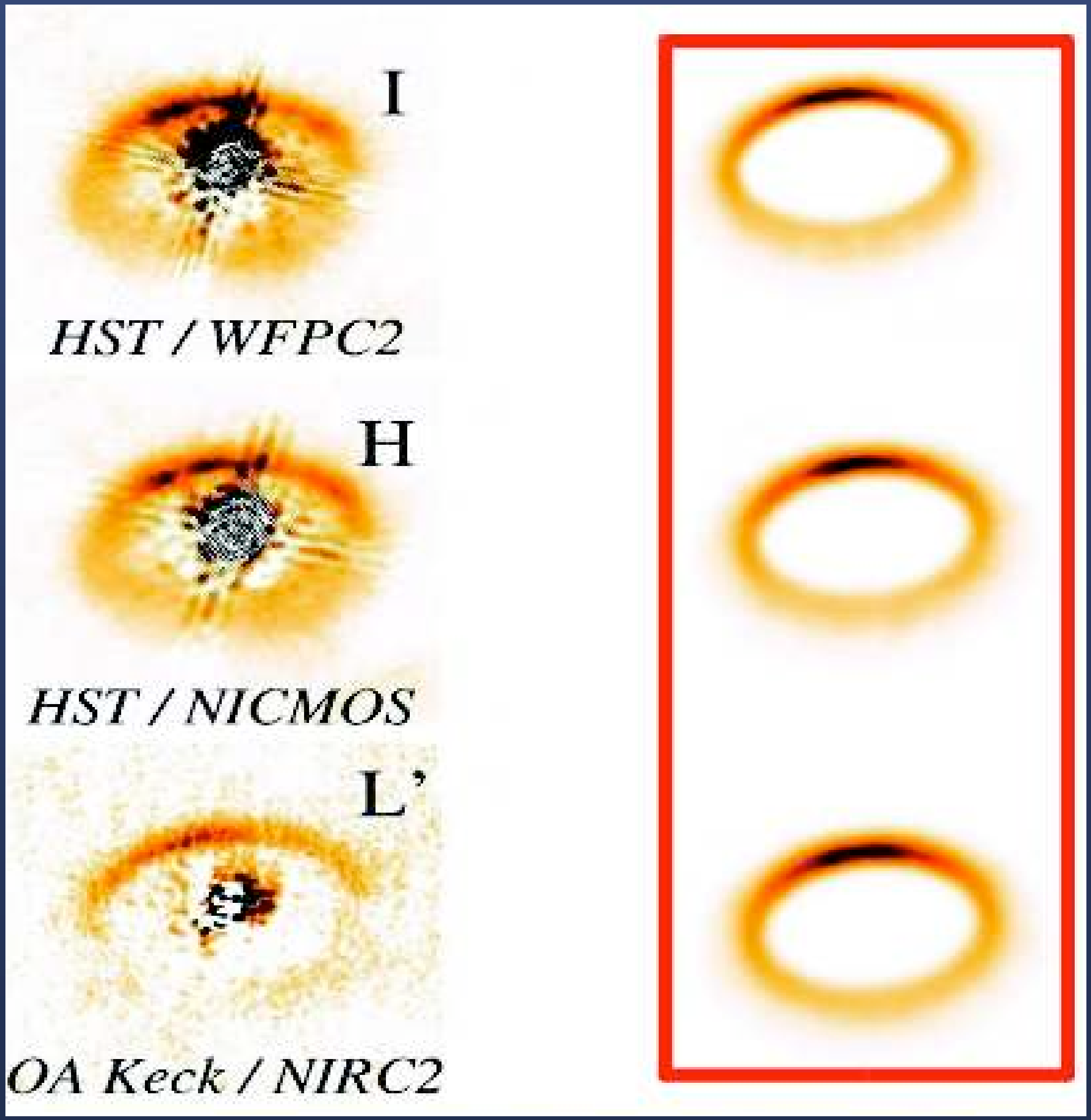
Not reproduced by compact silicates

Suggests grains with low refractive index:
porous grains or ices

Solution is not unique !!!

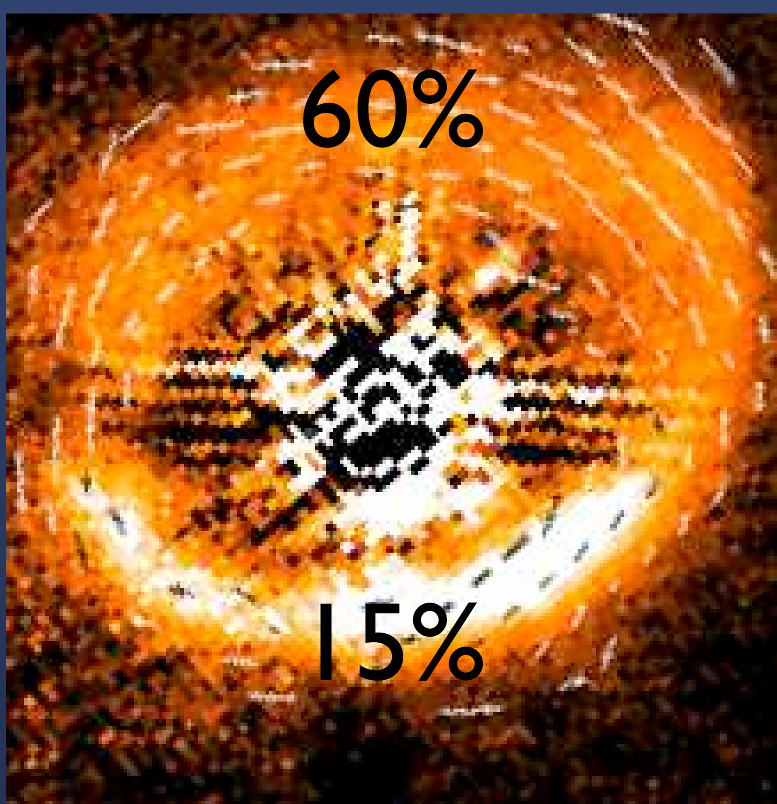
Models with well-mixed dust population can also reproduce but this requires an "exotic" dust size distribution

$$dn(a) \propto a^{-5.5}\, da$$

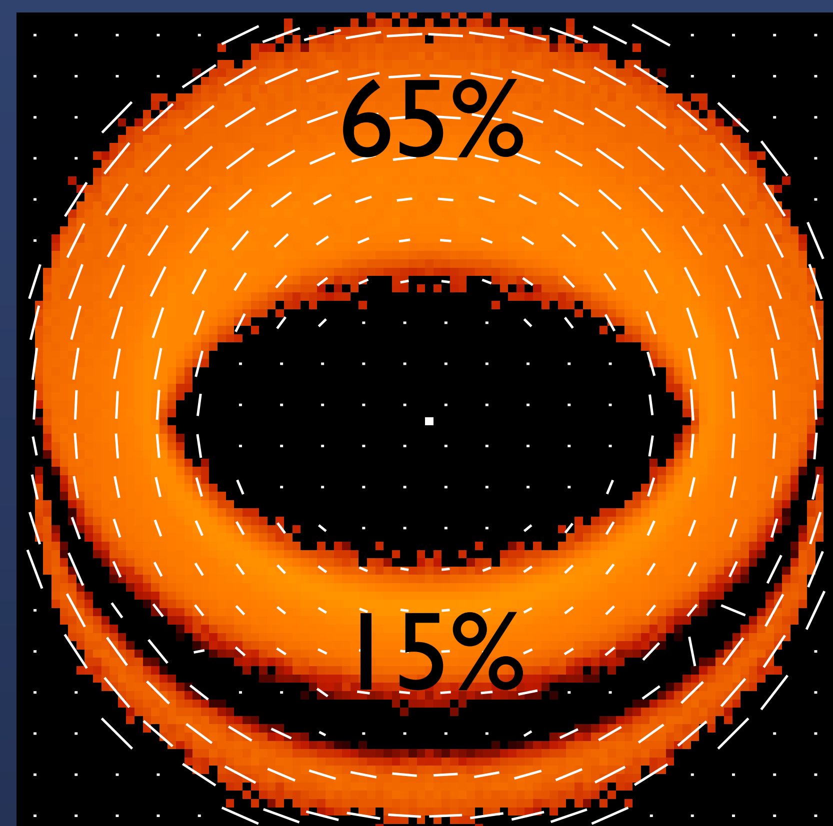


… polarization can help !!!

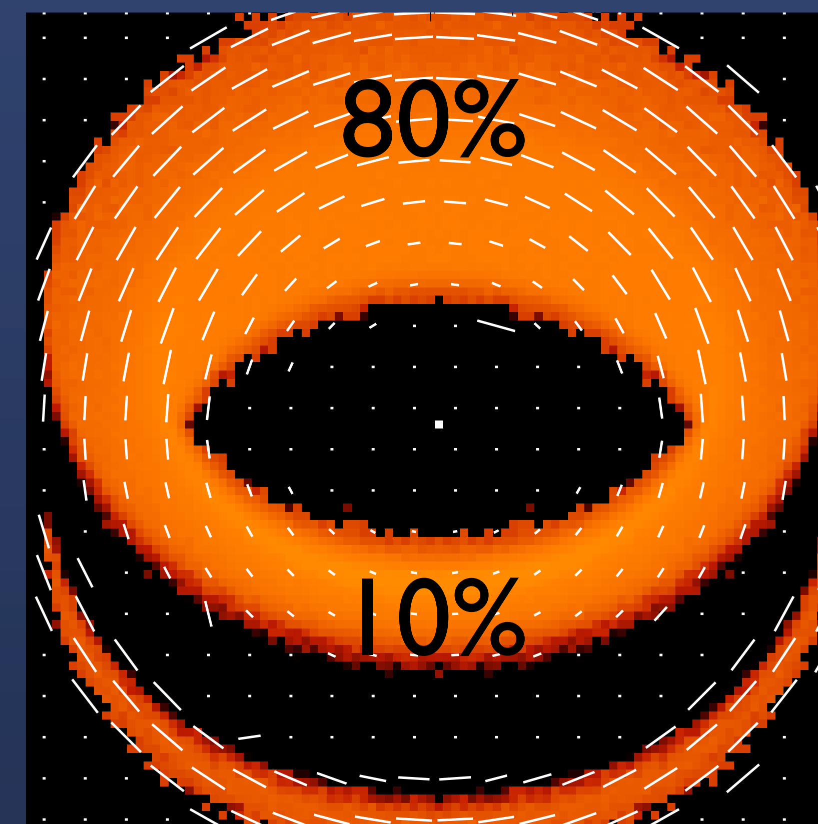
Using polarimetry to refine the model



Observations

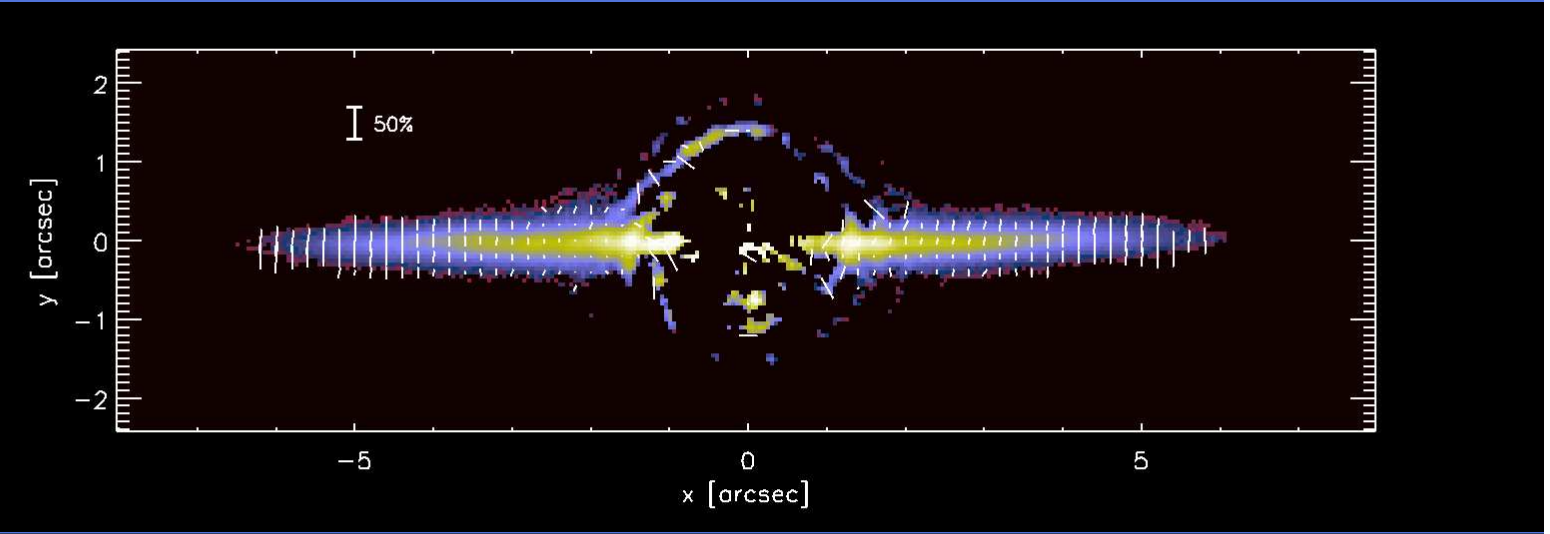


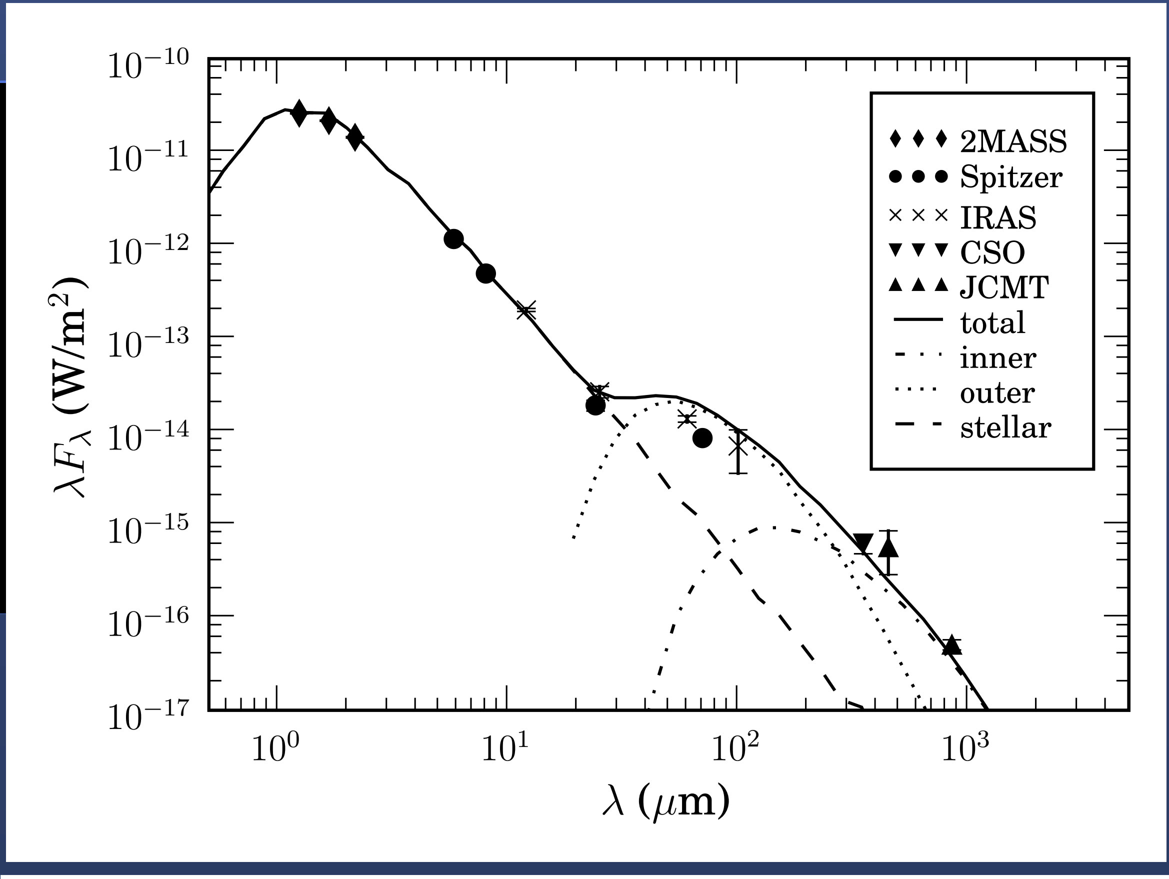
Model with strat



without strat

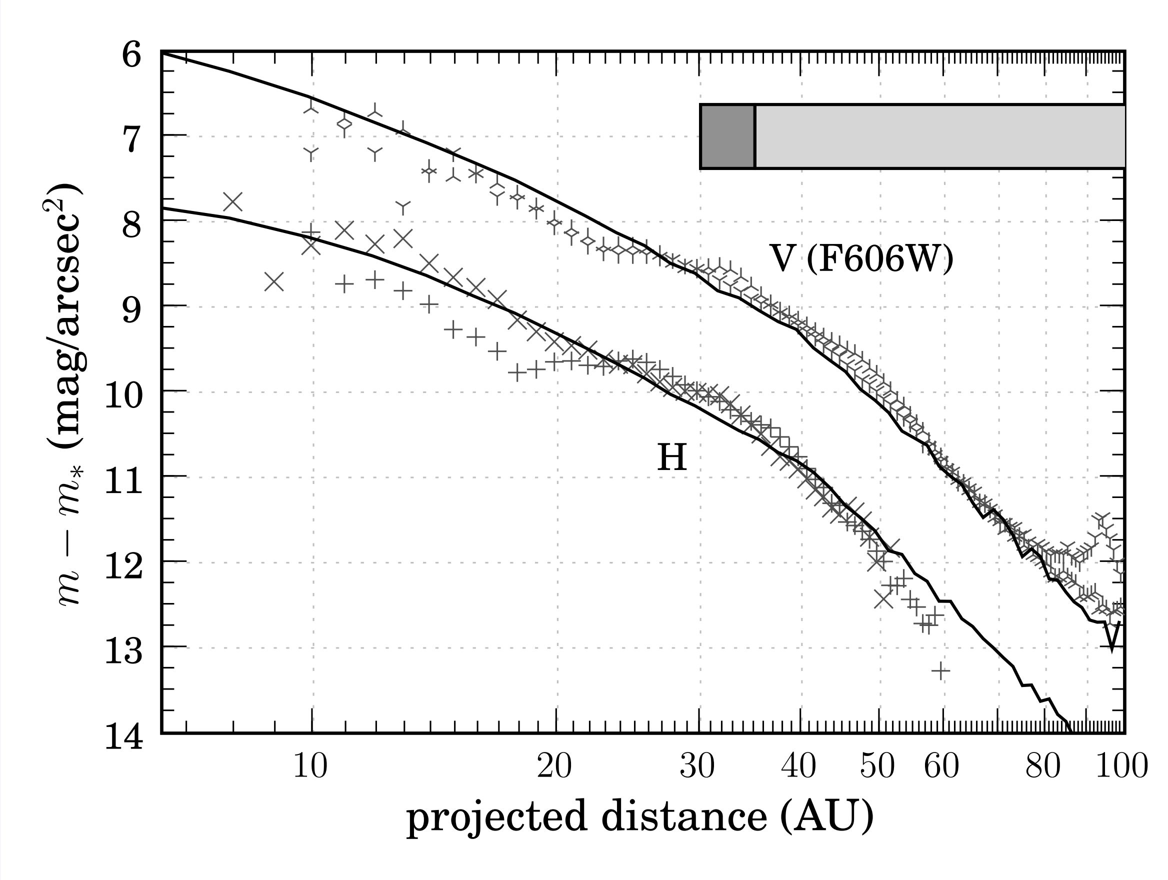
Another example: AU Mic





SED and images can be reproduced both with compact and porous dust grains

Large polarisation → porous grains (ices)



Fitzgerald et al 2007

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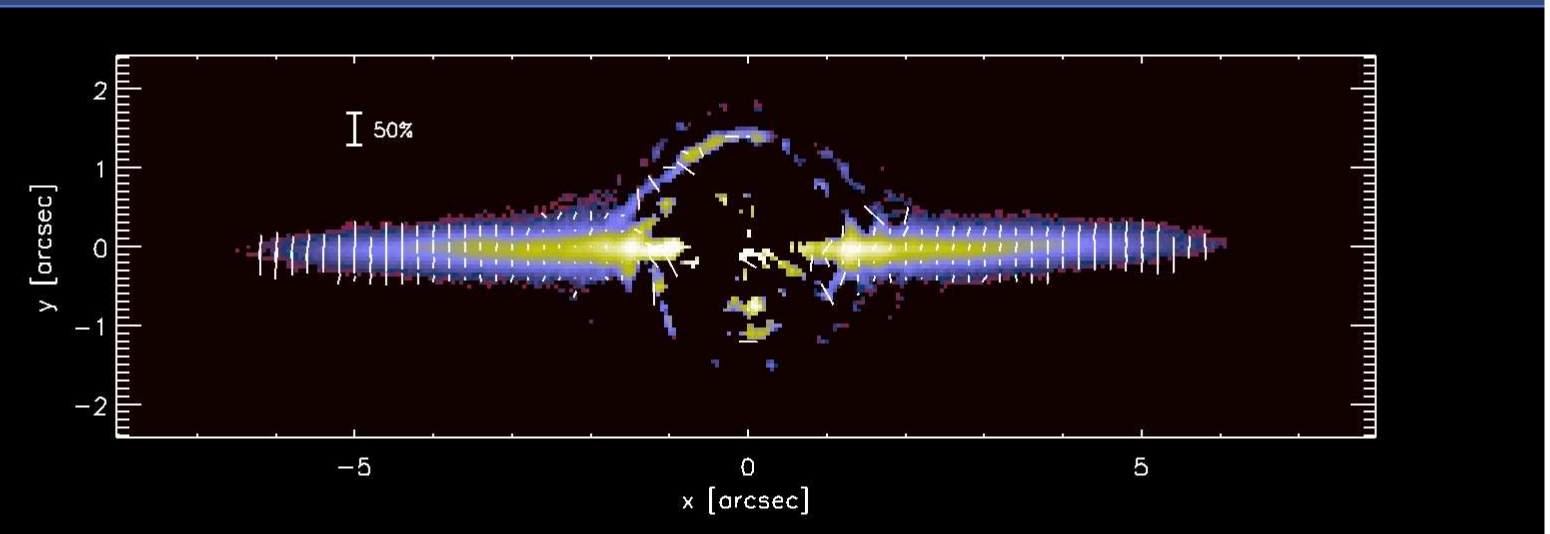

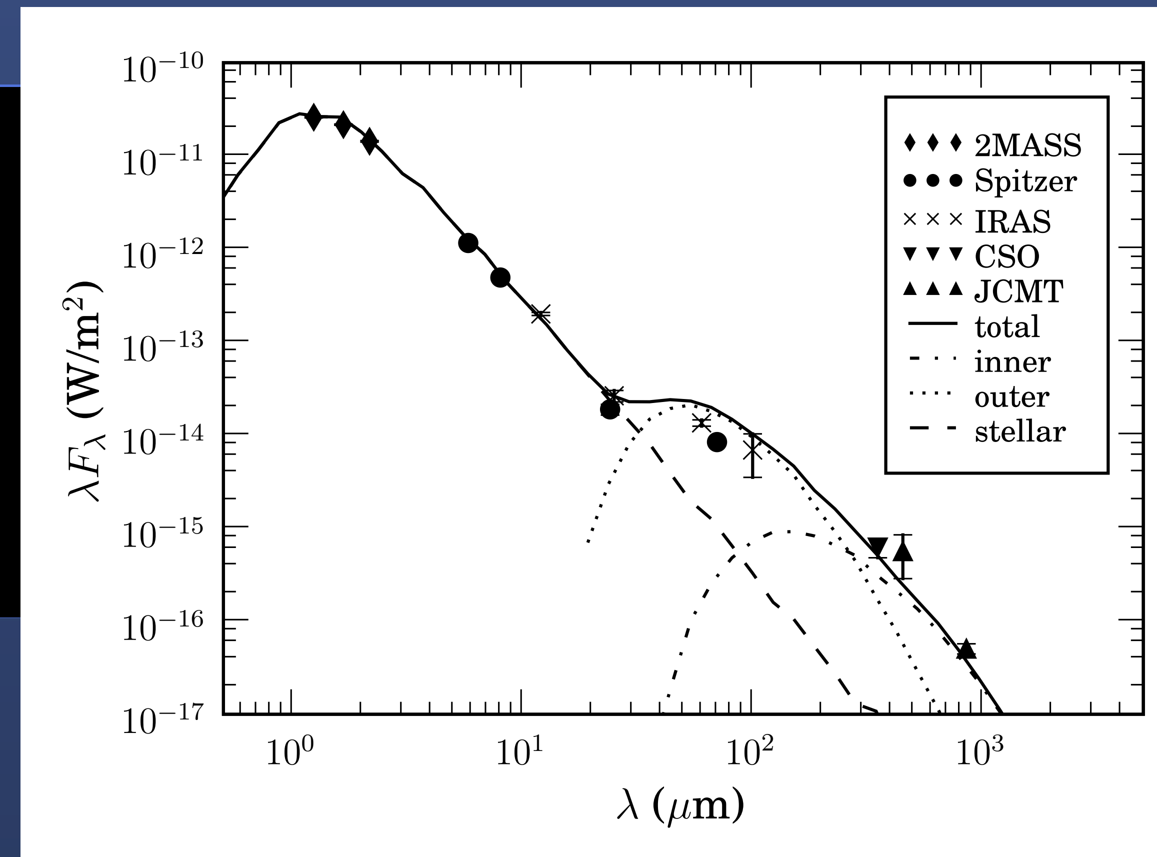

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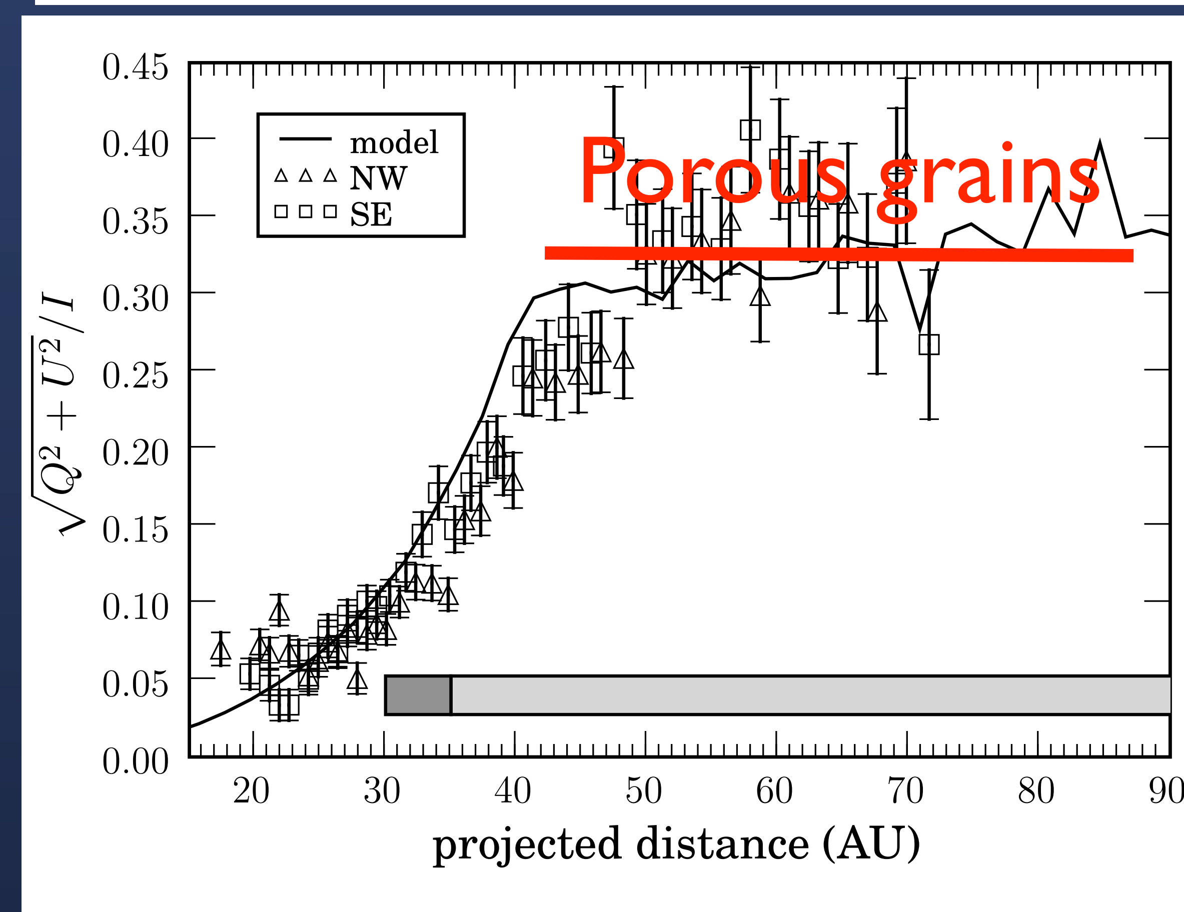

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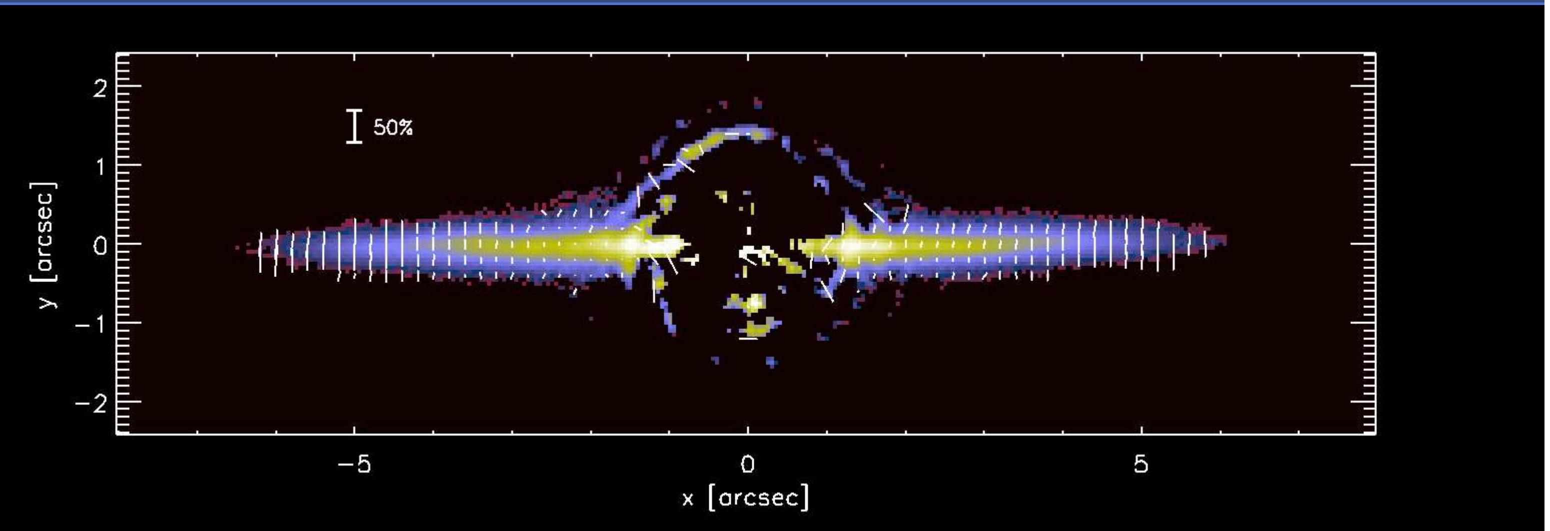
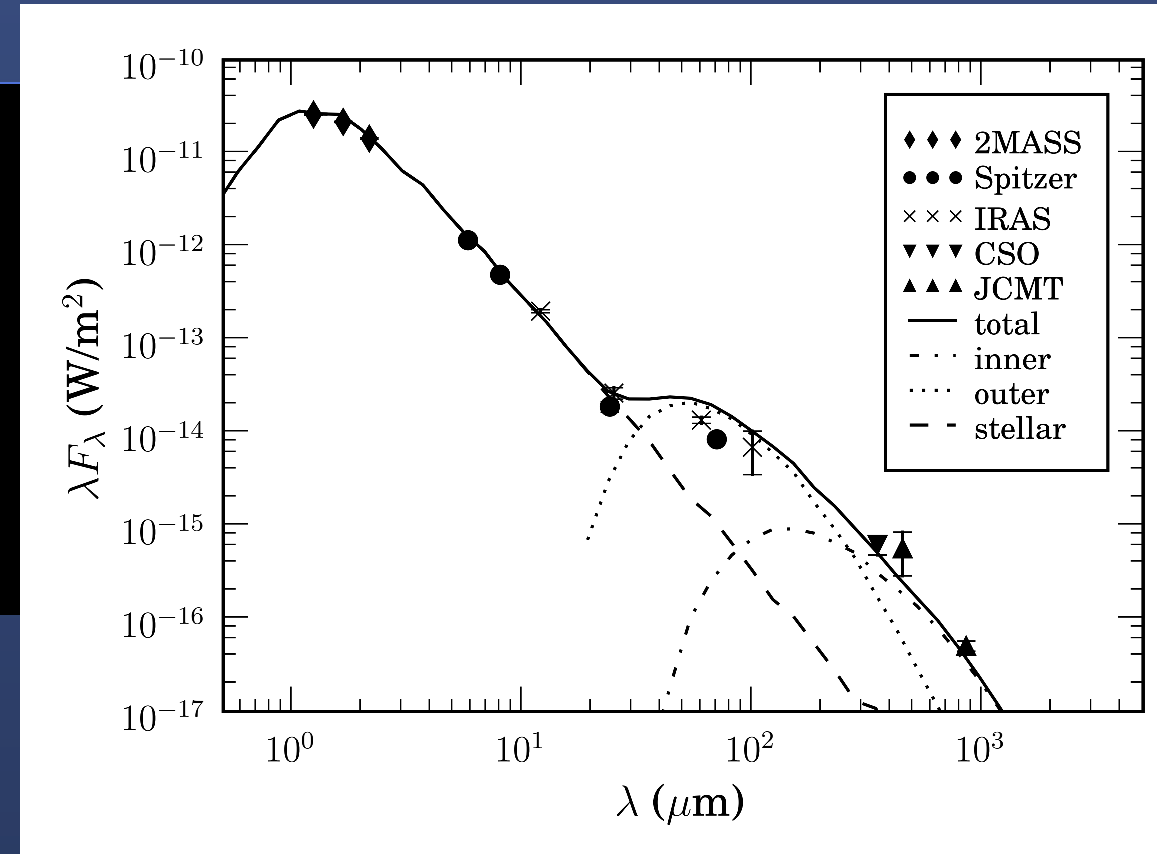
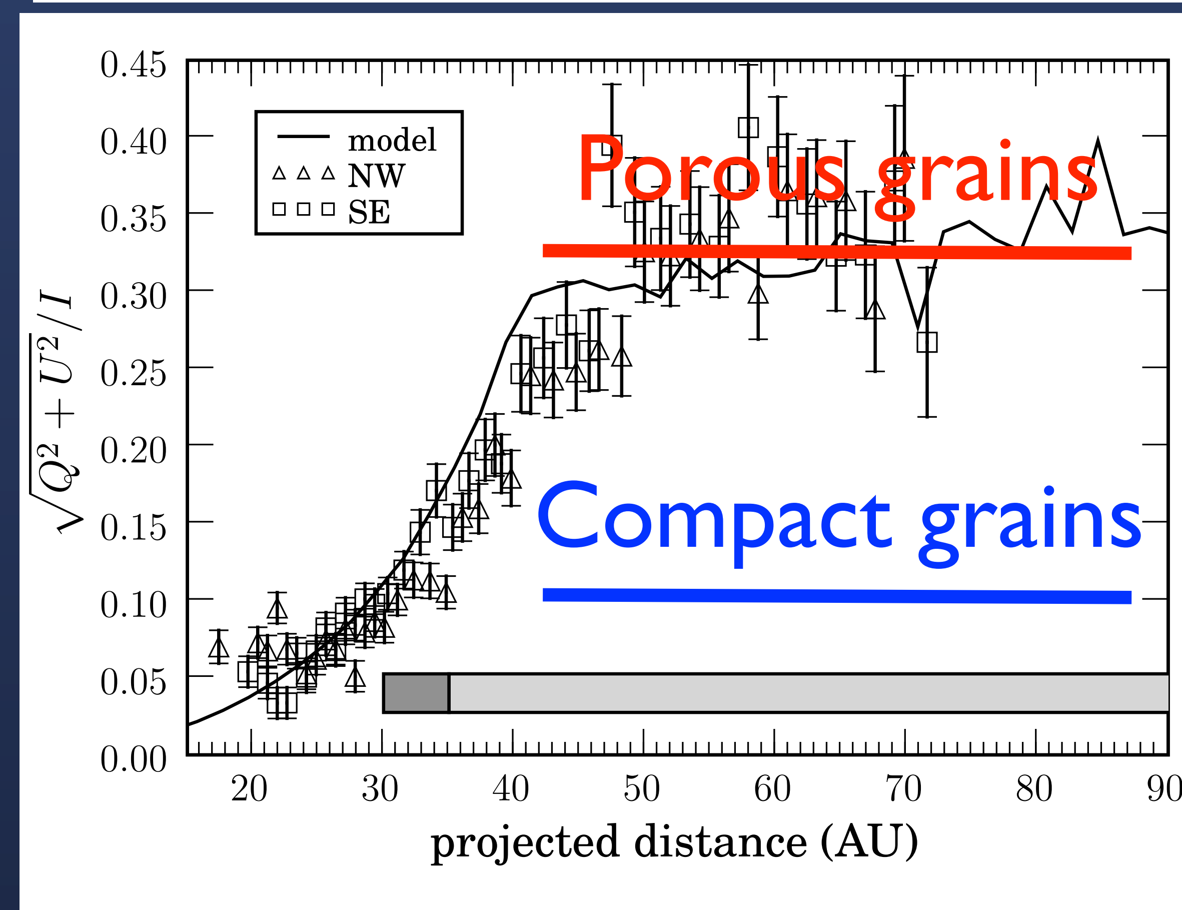




SED and images can be reproduced both with compact and porous dust grains

Large polarisation → porous grains (ices)



Fitzgerald et al 2007

Unresolved polarimetry: tomography of inner disk

Tool to probe the disk-star interface

The magnetospheric accretion predicts formation of warp at the inner edge

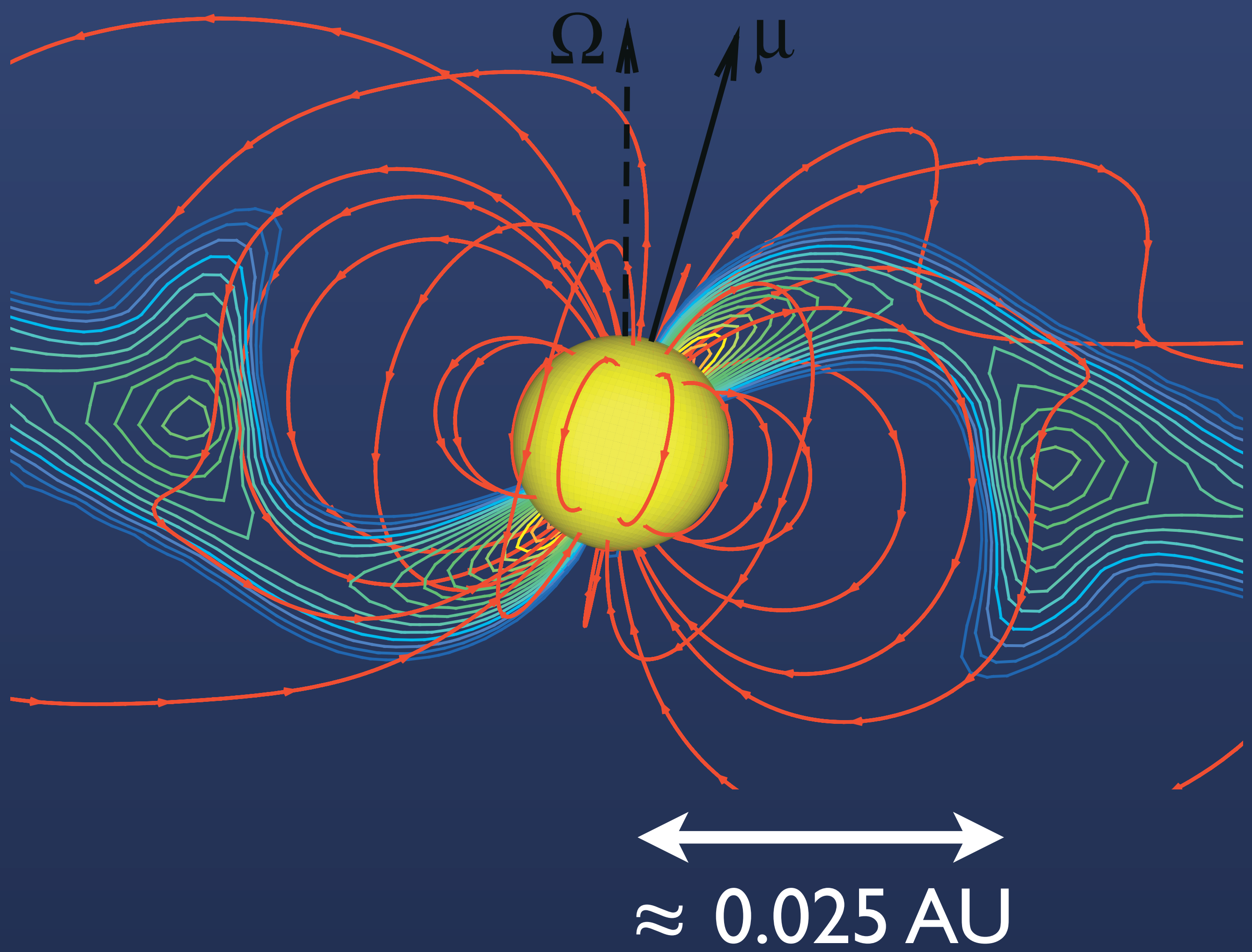


Figure from Romanova et al 2004

Unresolved polarimetry: tomography of inner disk

Tool to probe the disk-star interface

The magnetospheric accretion predicts formation of warp at the inner edge

⇒ can eclipse the star

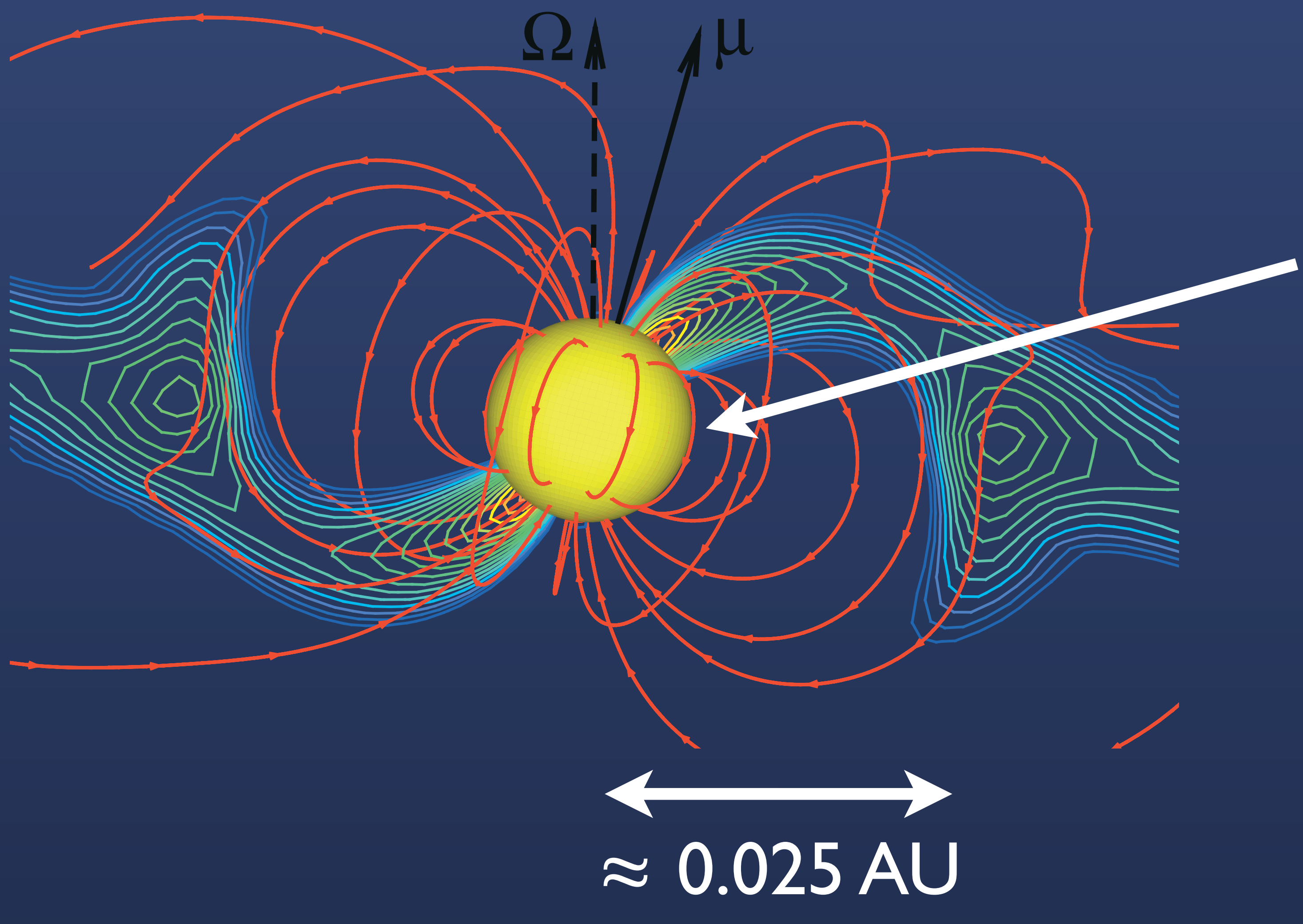
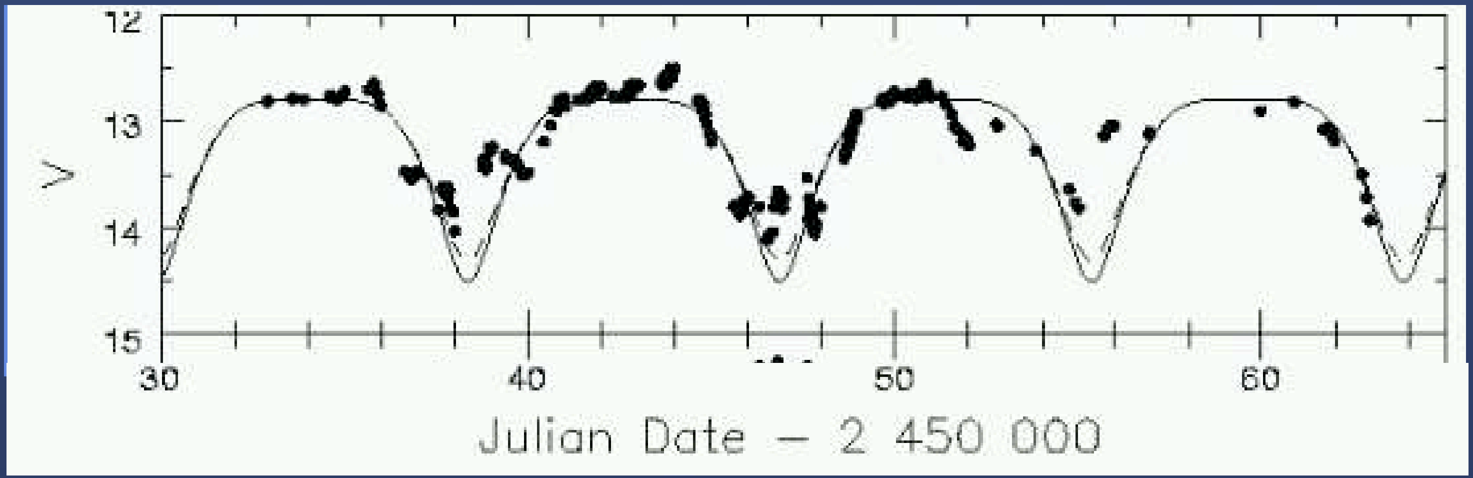


Figure from Romanova et al 2004

Tomography of the inner disk

Wood et al 1996
Ménard et al 2003
O'Sullivan et al 2005



AA Tau

synoptic monitoring
Many rotation periods

Quick summary:

Need variable achromatic extinction → occultation by a "deformed" disk

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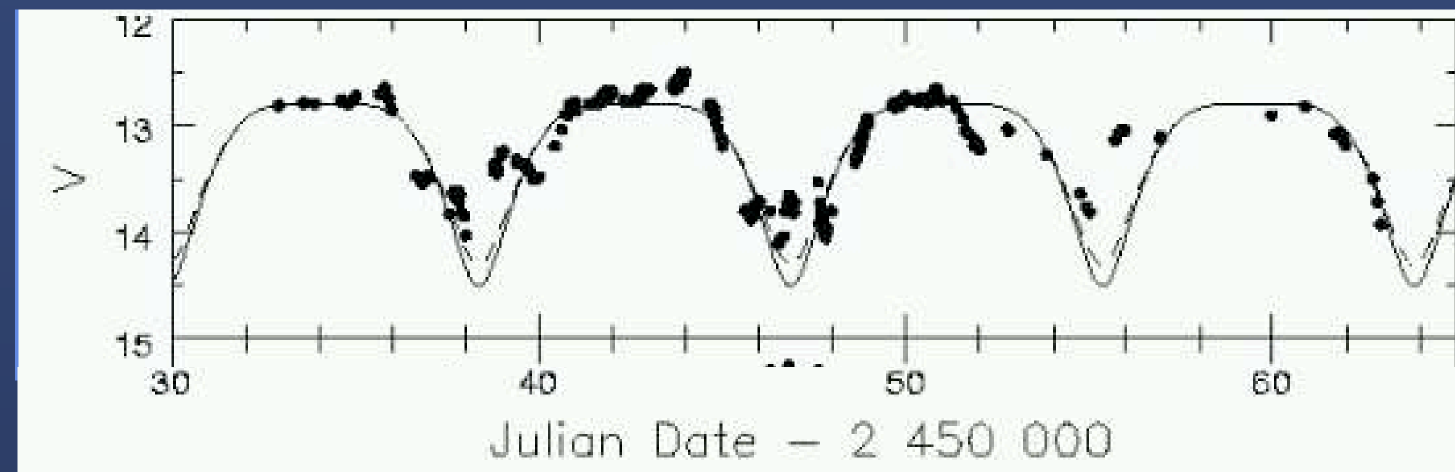

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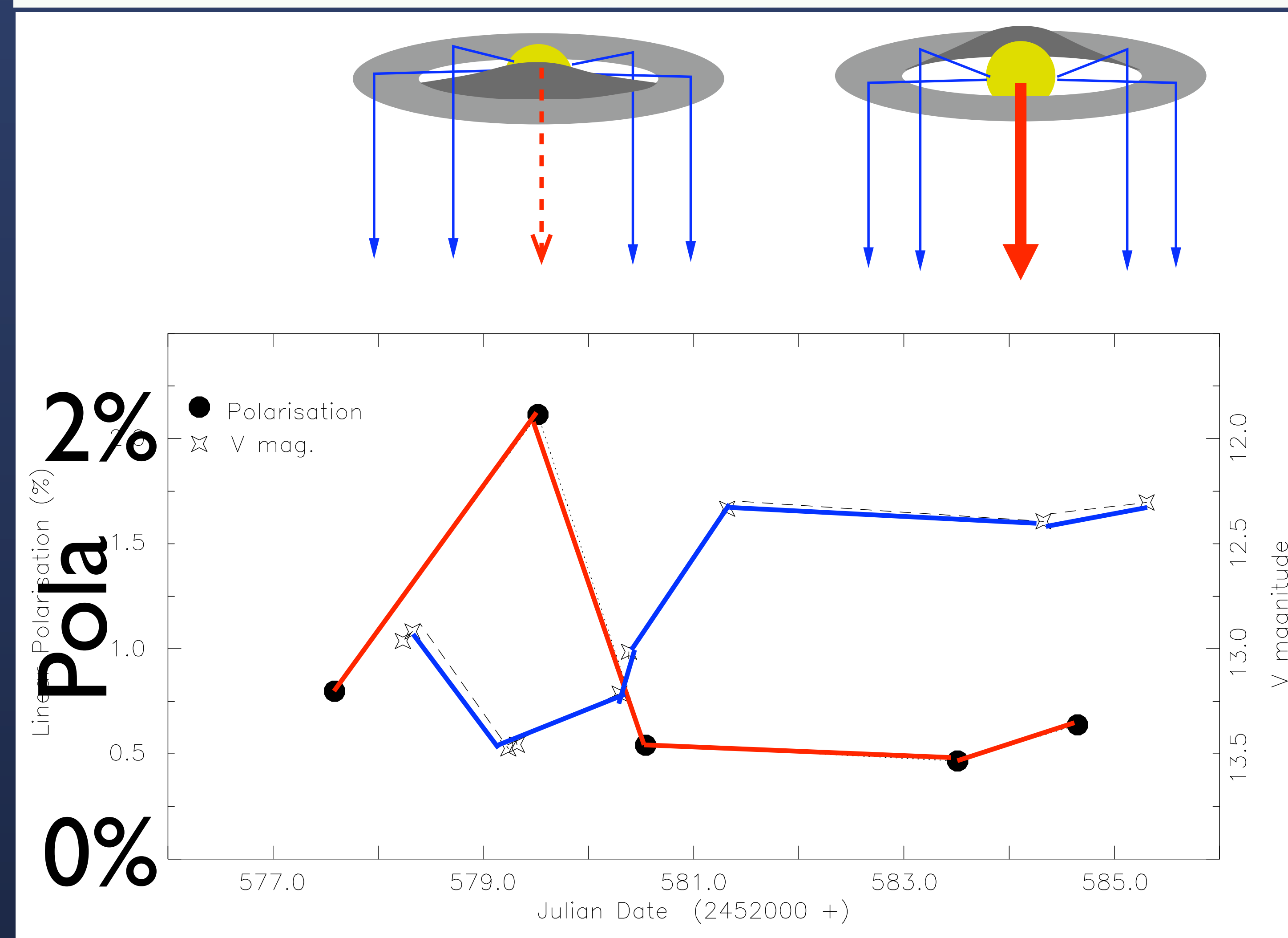
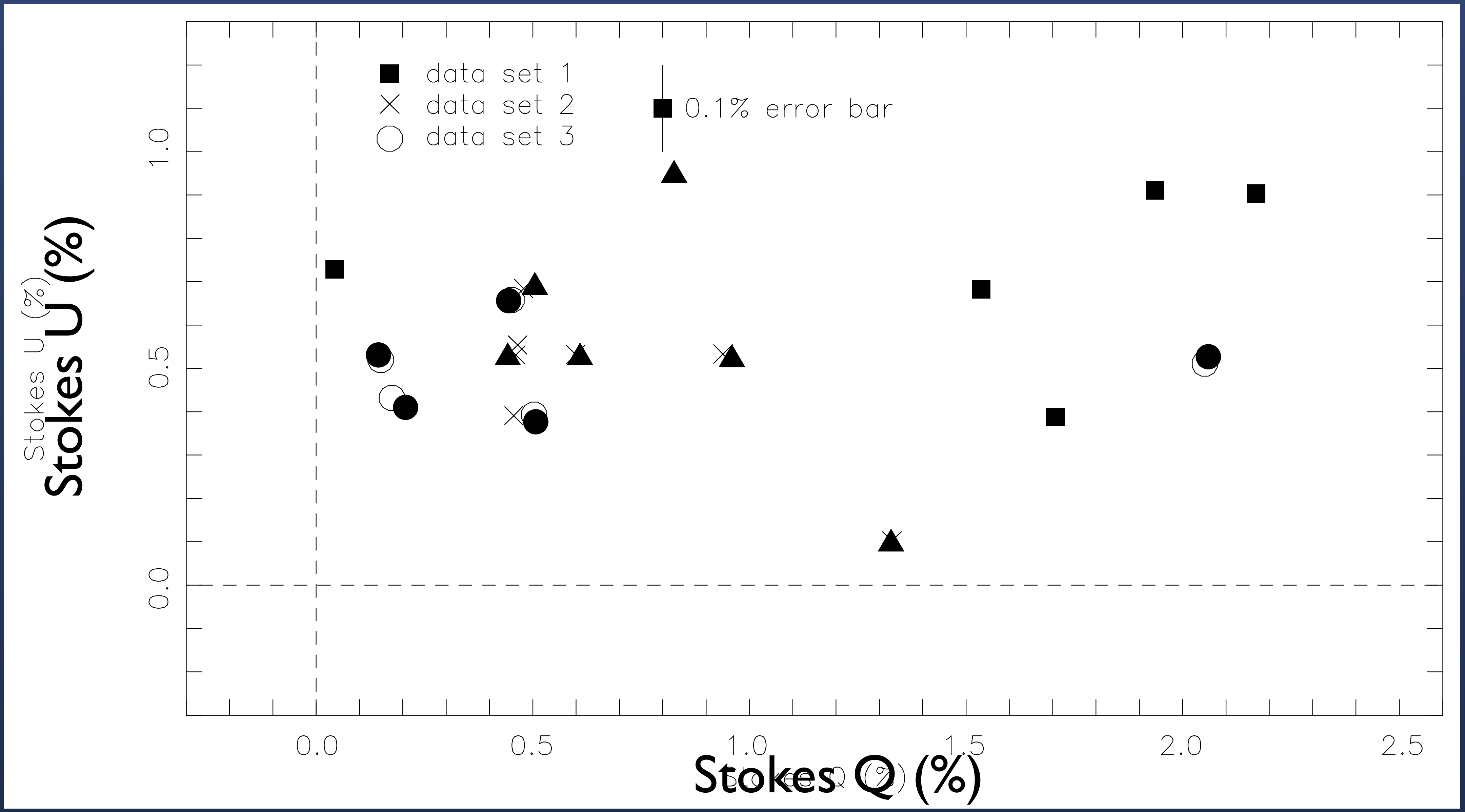


Photo-polarimetric variation

Disk orientation and inclination

Variations along Q axis

⇒ disk oriented east-west & disk inclination $\approx 70^\circ$



Ménard et al 2003

Disk orientation and inclination

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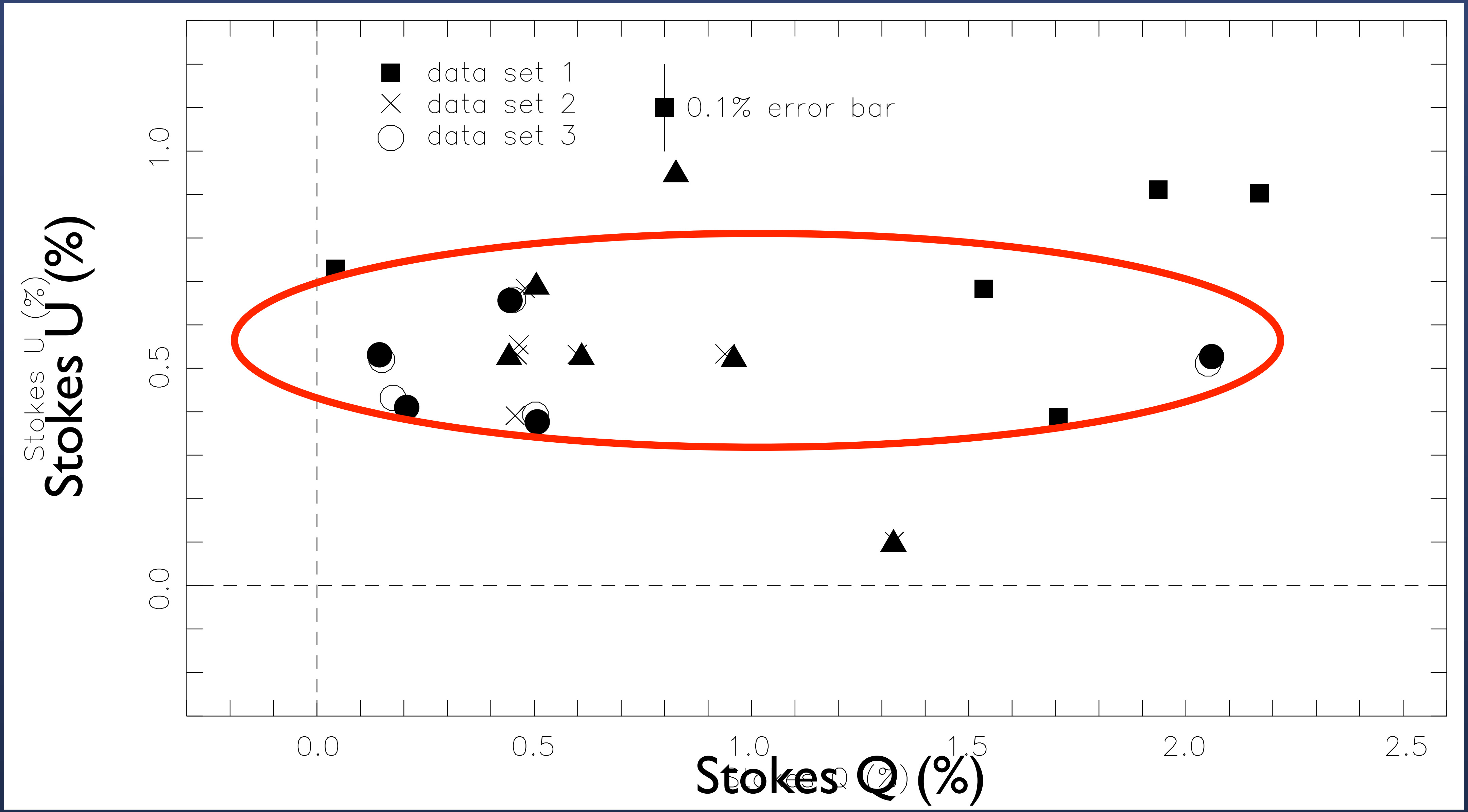
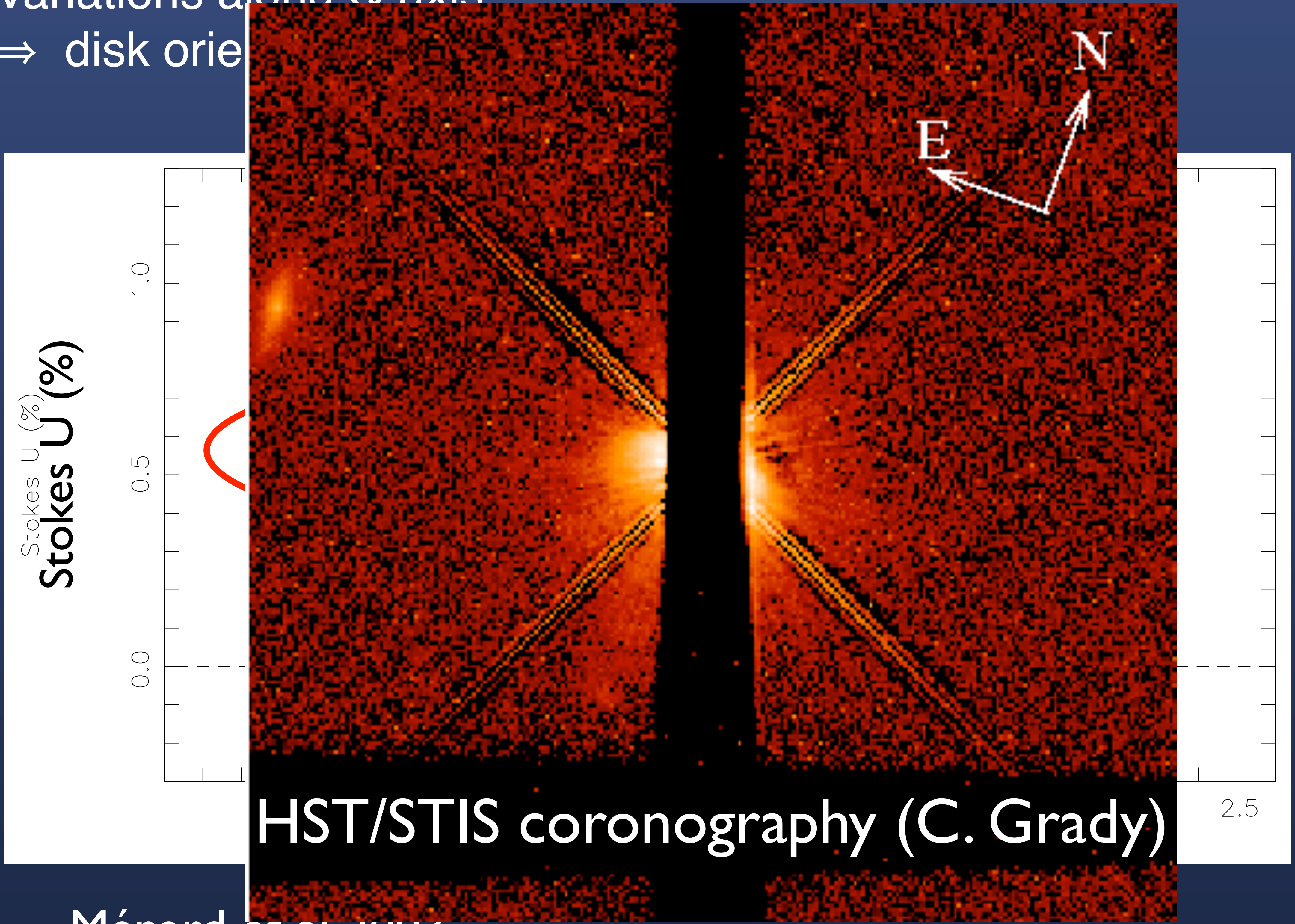


Ménard et al 2003

Disk orientation and inclination

Variations along Q axis
⇒ disk orie

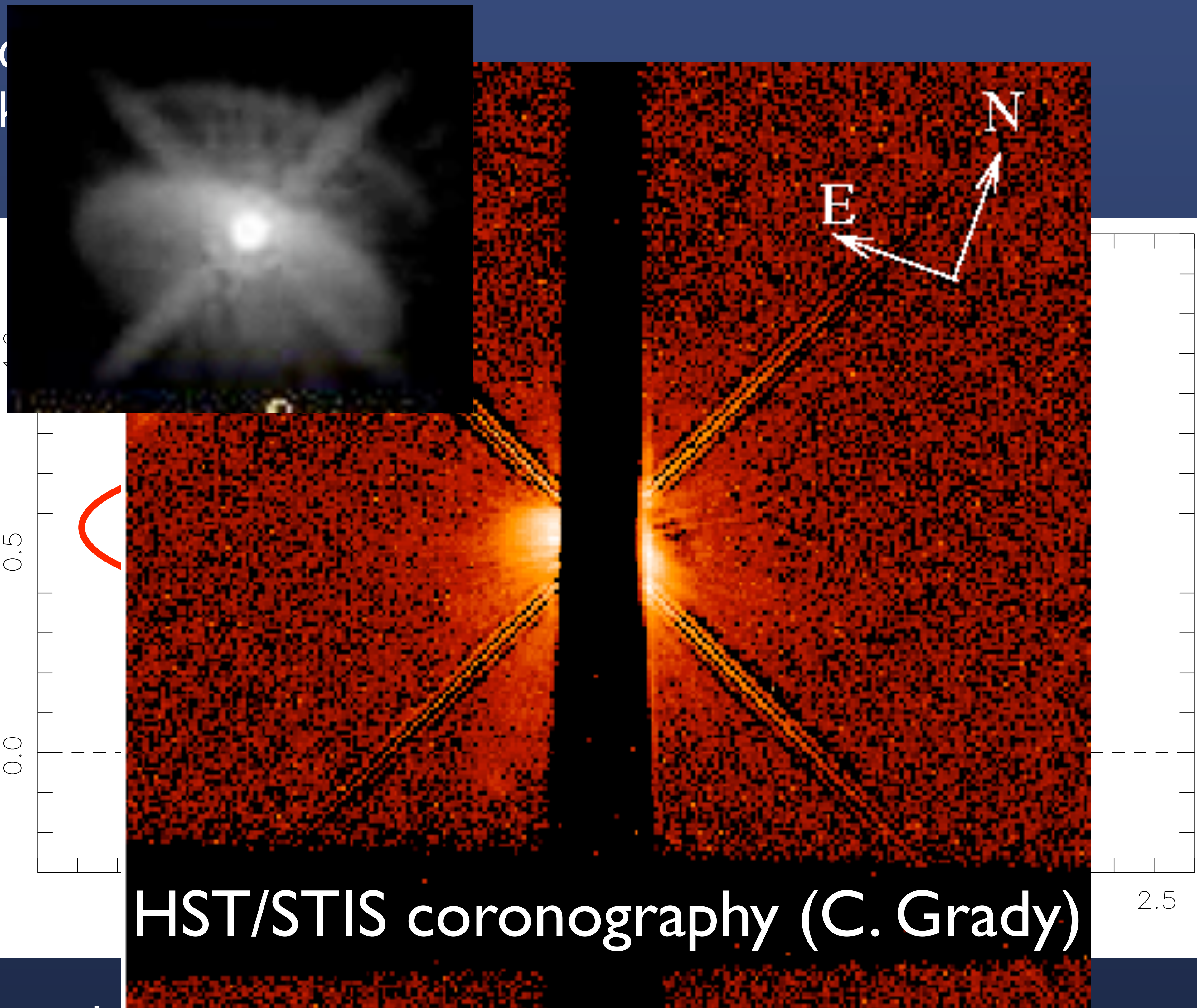


Ménard et al 2003

Disk orientation and inclination

Variati

⇒ disk



Ménard et al 2003

Disk orientation and inclination

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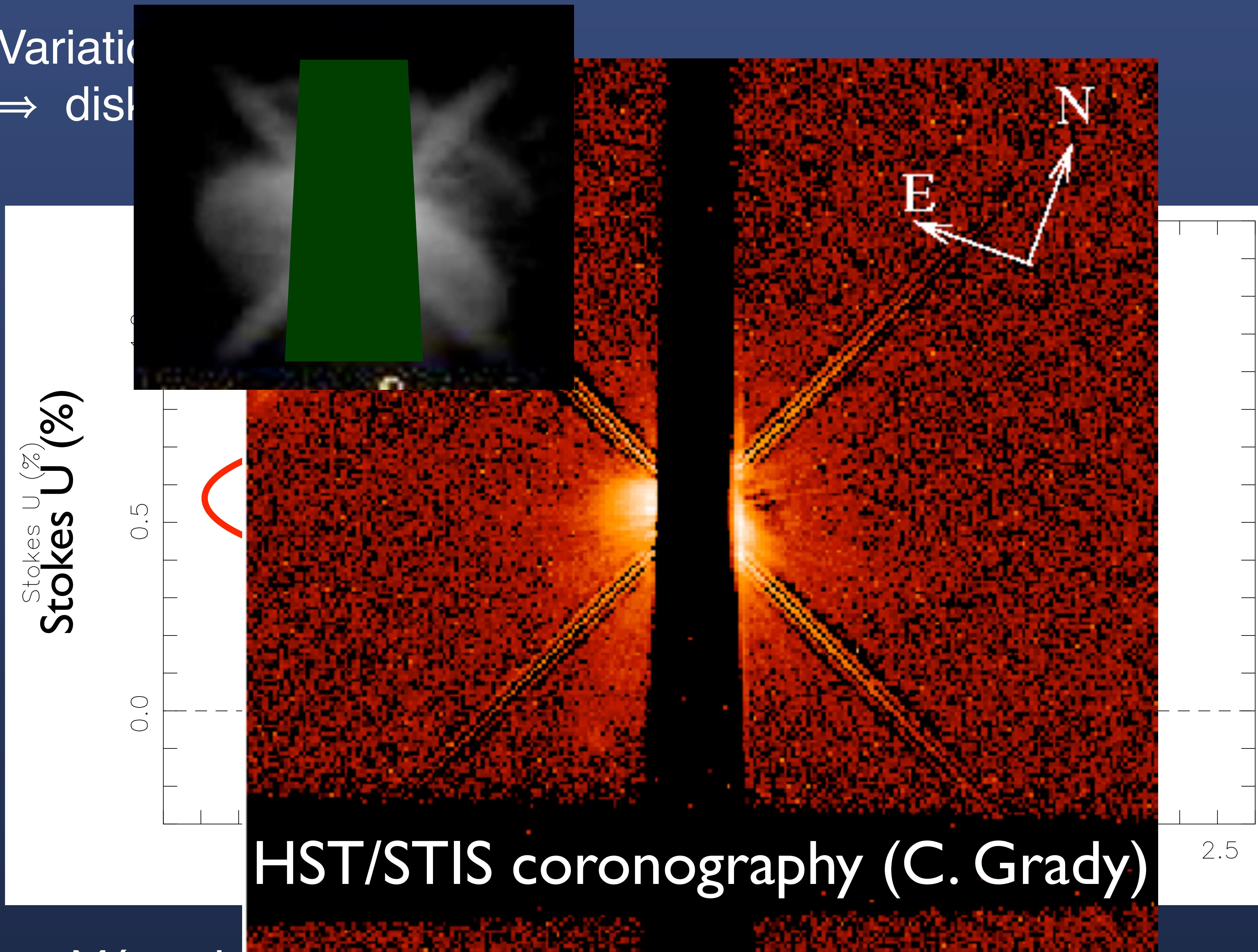
⇒ disk



Ménard et al 2003

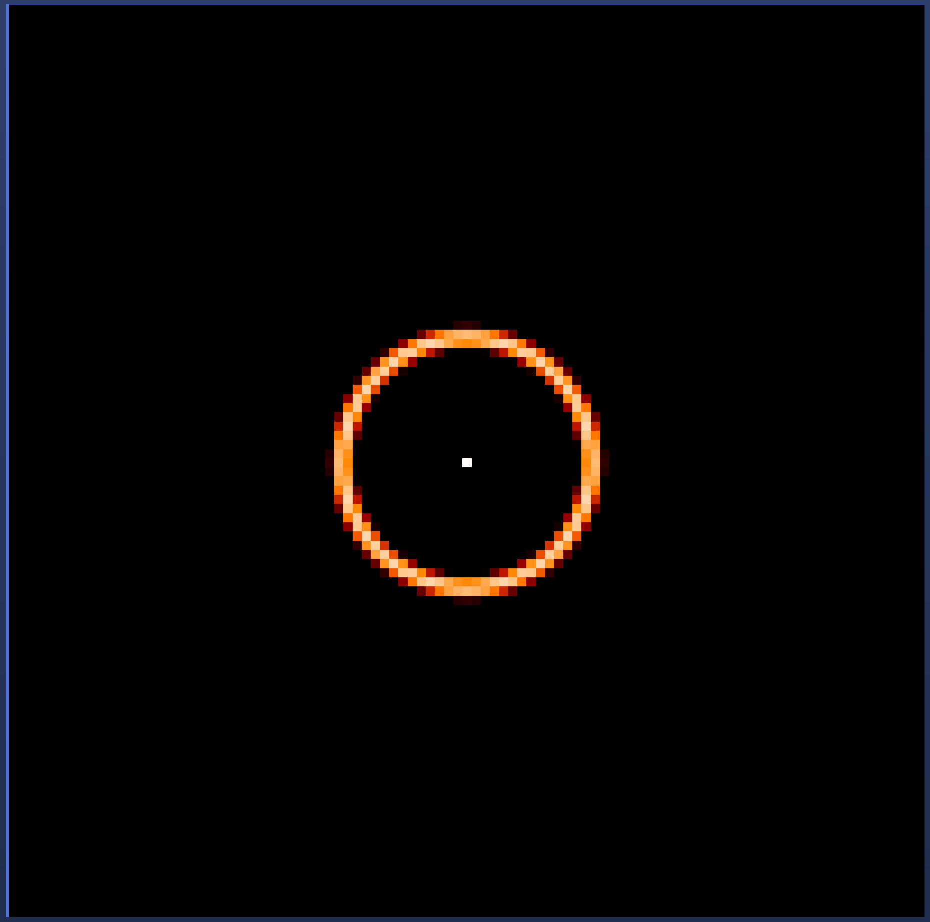
Measuring the inner radius of disks

Characteristic NIR size measured by interferometers < 1 AU: comparable to the location of terrestrial planets in more evolved systems

Ring model:

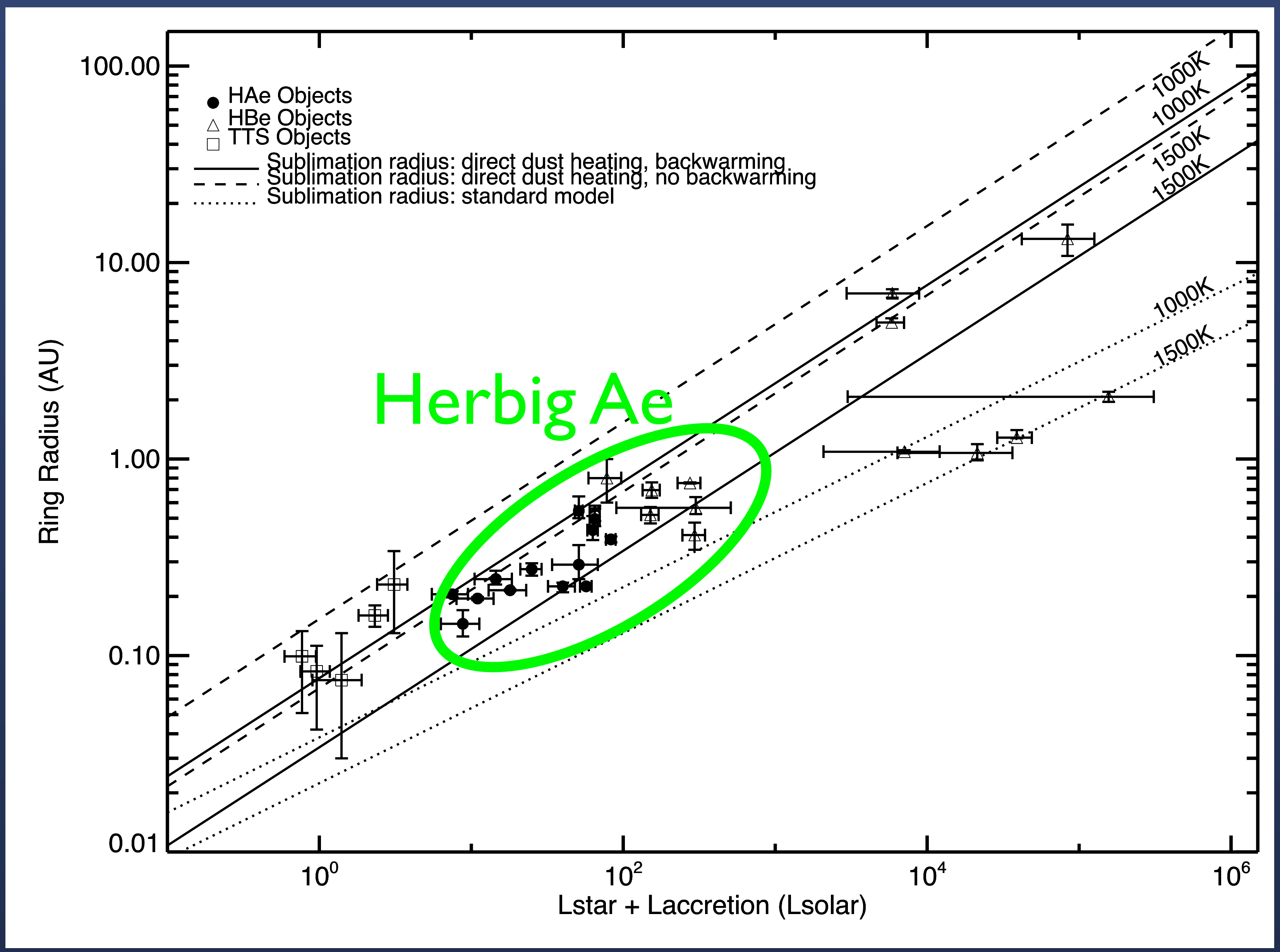
simple emission model: unresolved central star + narrow ring

relative contribution from star & disk estimated from SED



Inner radius ot T Tauri stars

Radii inferred from interferometry larger than predicted



Millan-Gabet et al 2006

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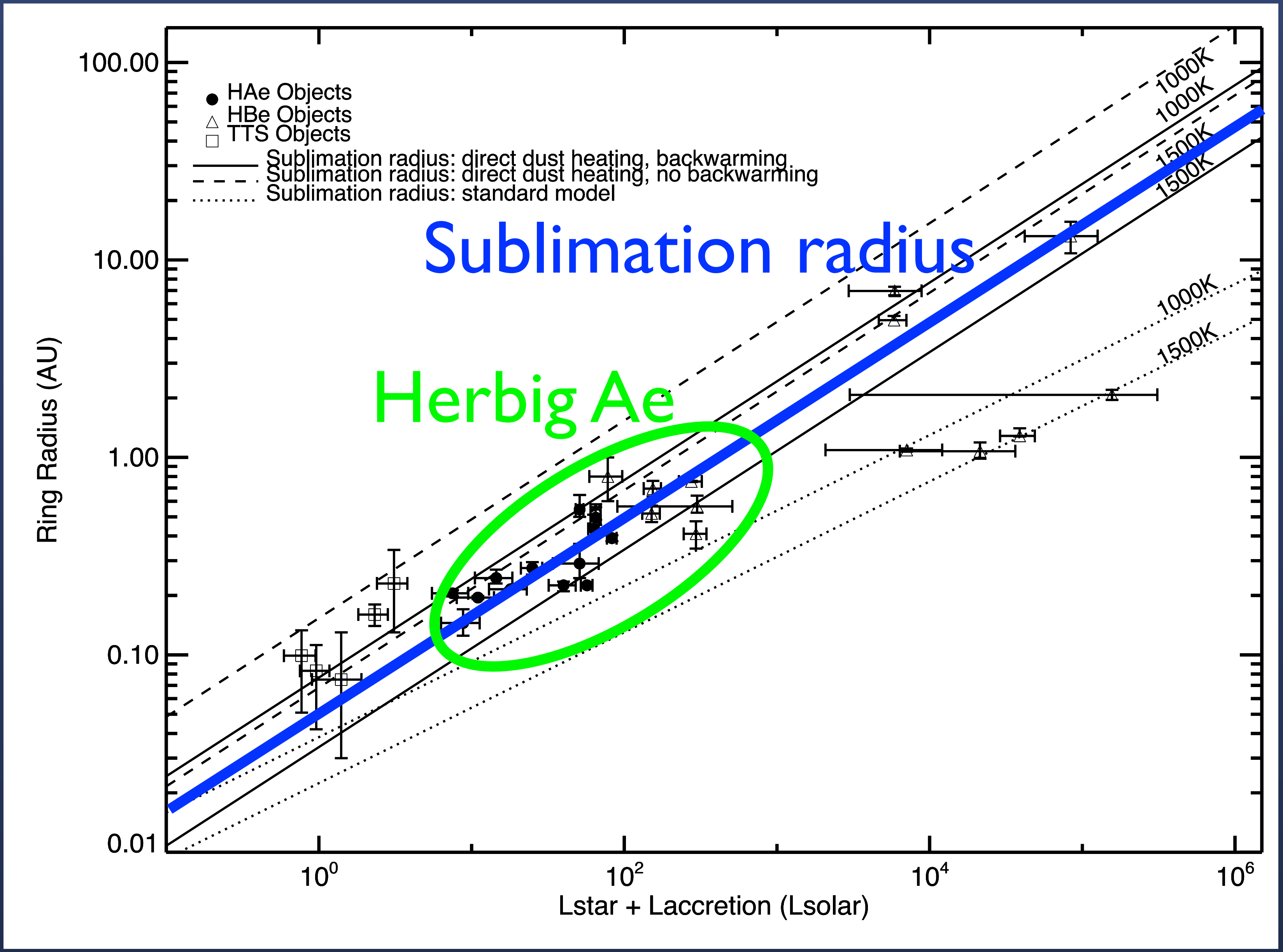

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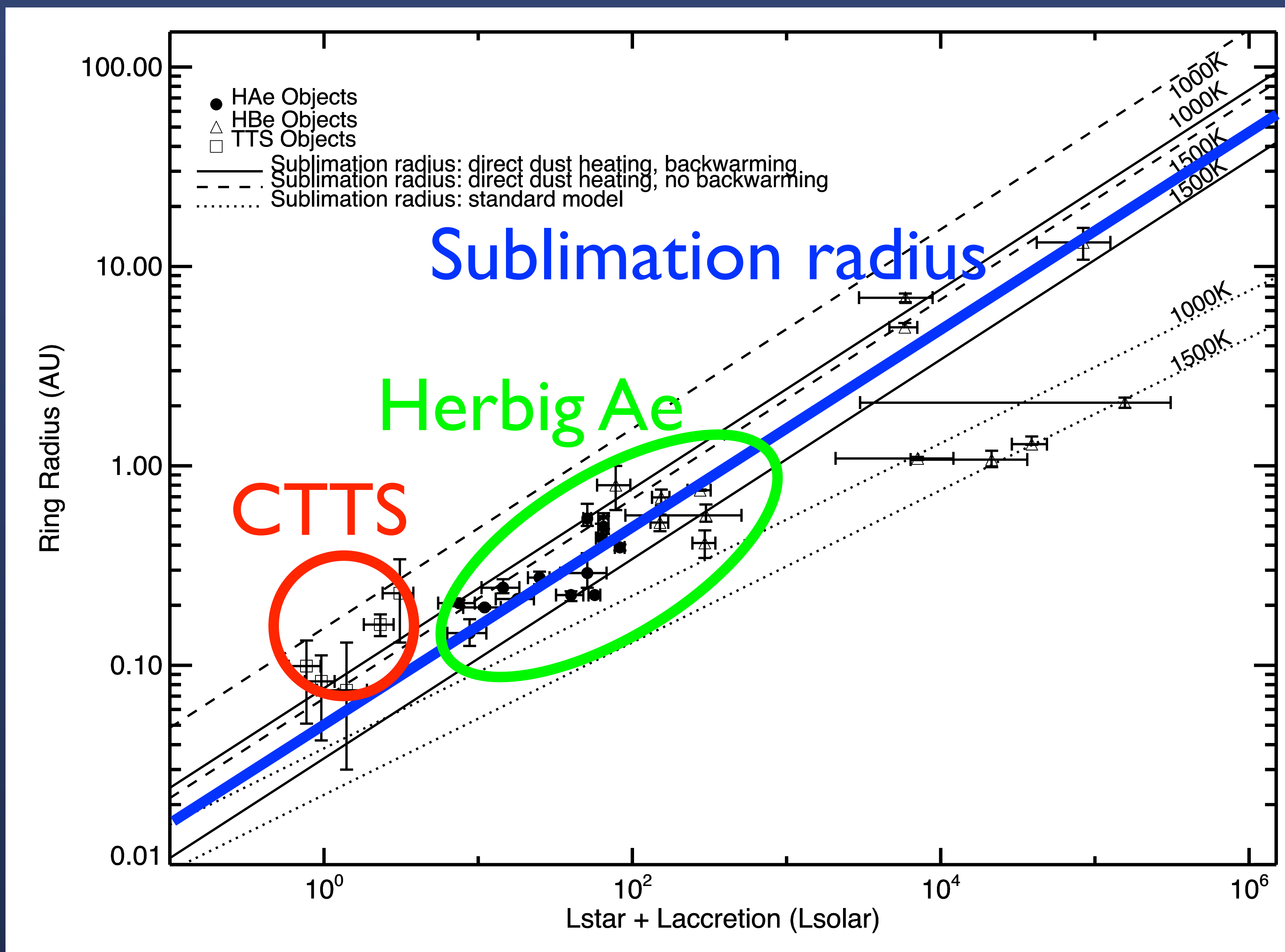

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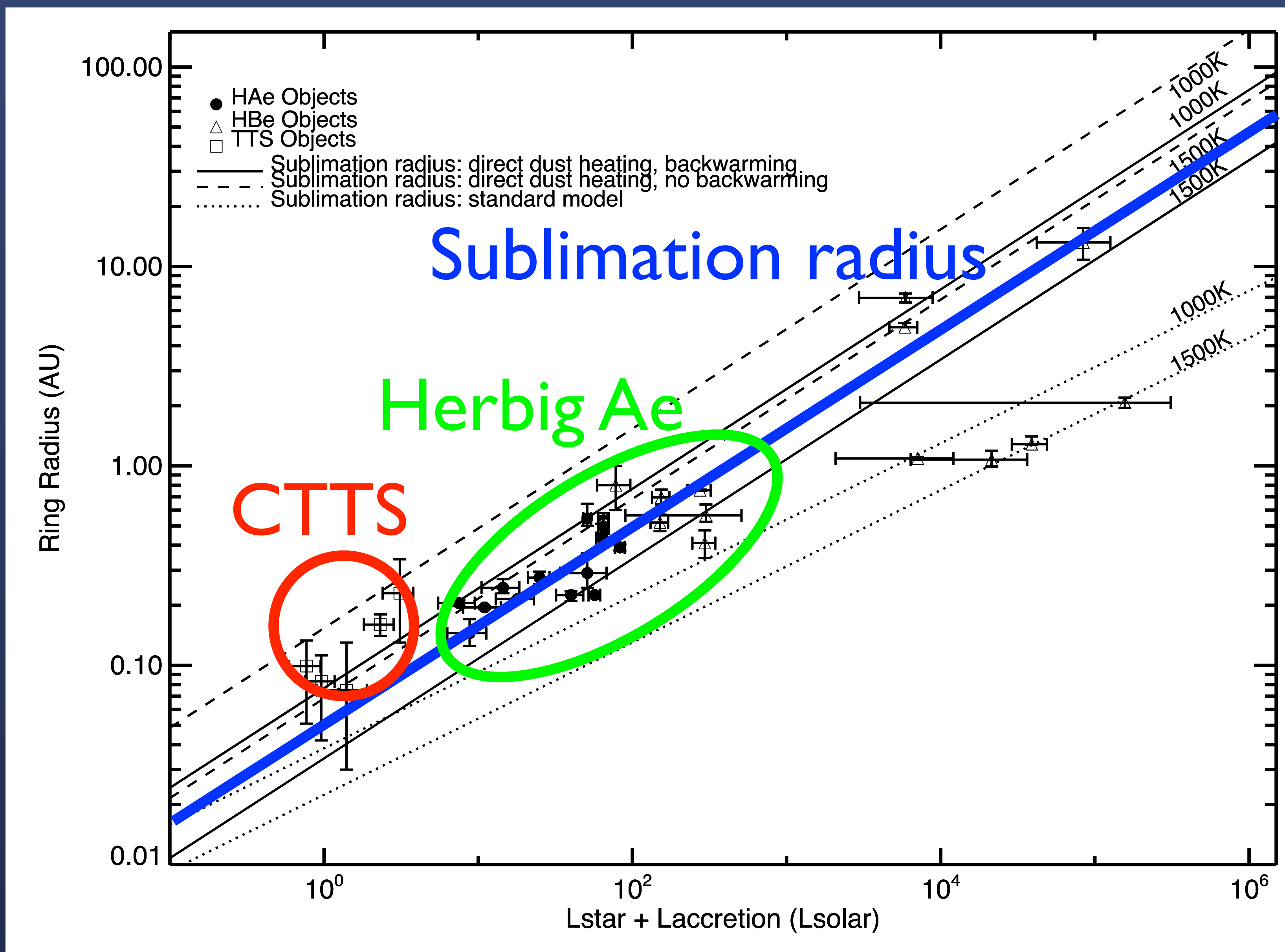


accretional heating? lower sublimation temperature? smaller dust grains? photoevaporation? magnetospheric truncation? scattered light?

Millan-Gabet et al 2006

Measuring the inner radius of disks

Ring model justification
NIR emission only comes from the hottest dust disk are optically thick : shielding by the inner disk → further drop in dust temperature scattered light from inner disk is negligible

Introduced at the beginning to study Herbig Ae/Be stars (Tuthill et al. 2001)

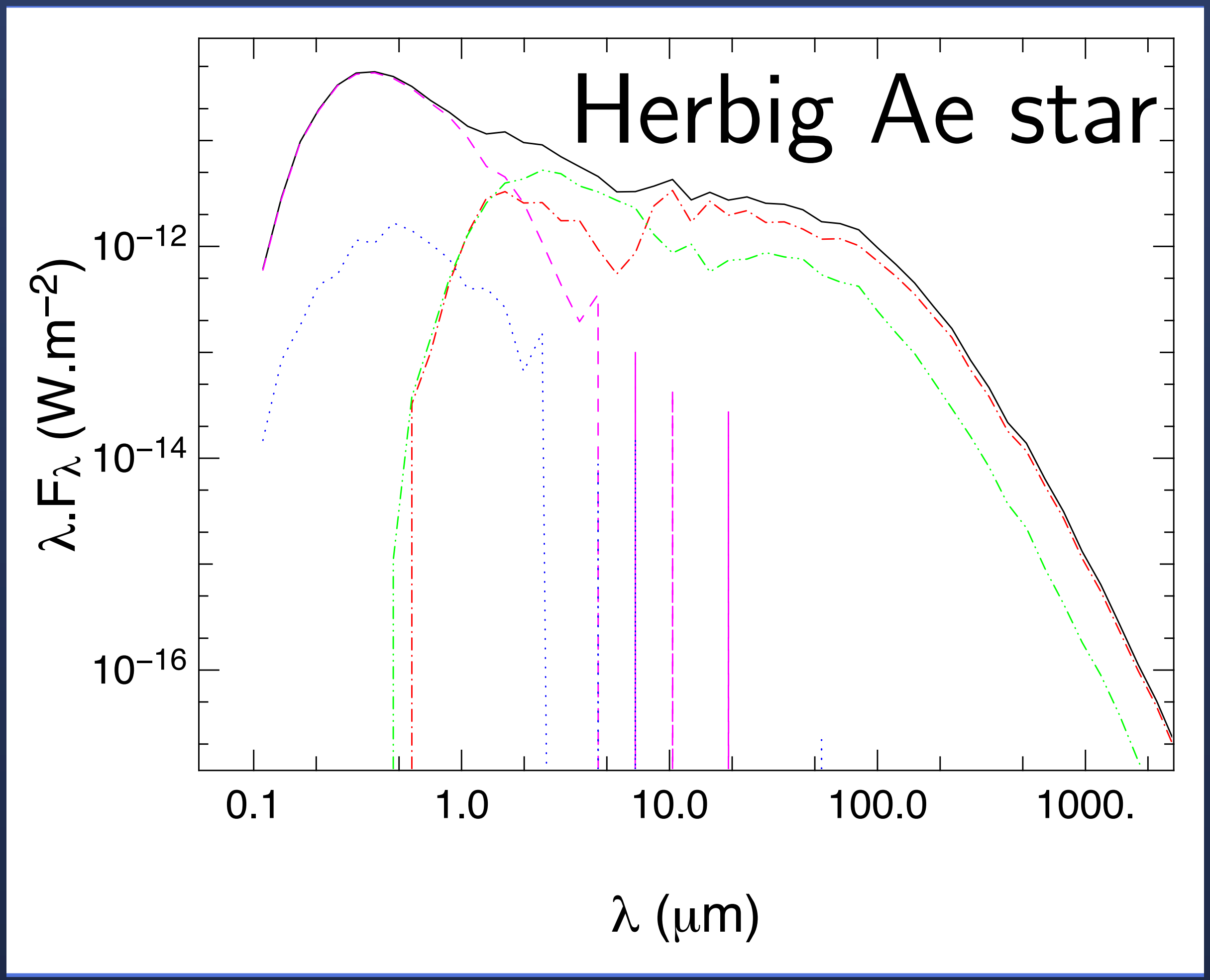
Improved sensibility: T Tauri stars can now be studied (Akeson et al 2005 ; Eisner et al 2007)

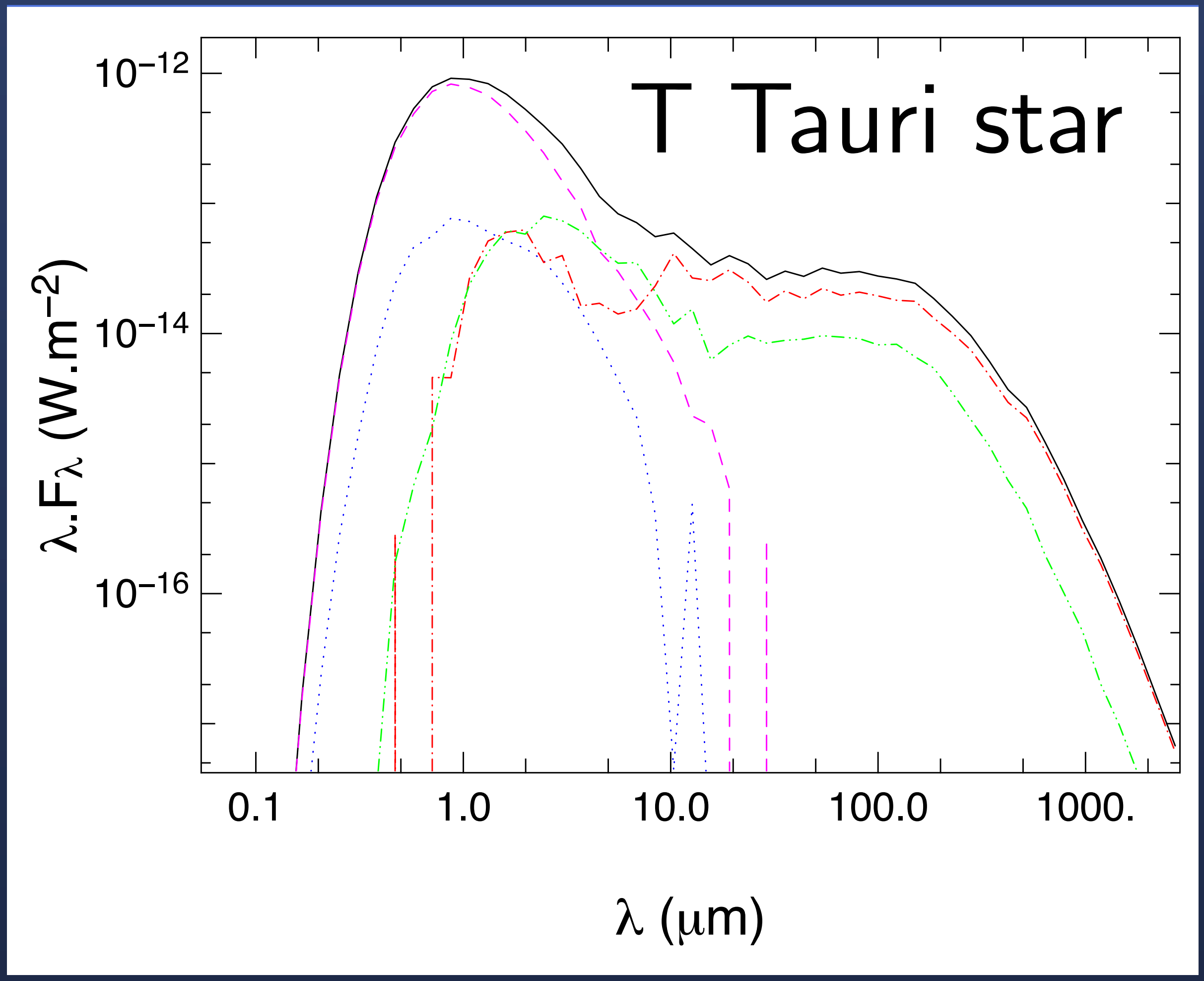
⇒ Is the assumption on scattered light still valid for T Tauri stars ?

Why should we care about scattered light?

Peak of the photosphere moving towards longer λ
Fraction of stellar (and then also scattered) light is larger

Albedo can be large in the NIR ! between 0.4 and 0.9 at 2.2 μm, depending on grain sizes and dust composition





Inner radius of T Tauri stars

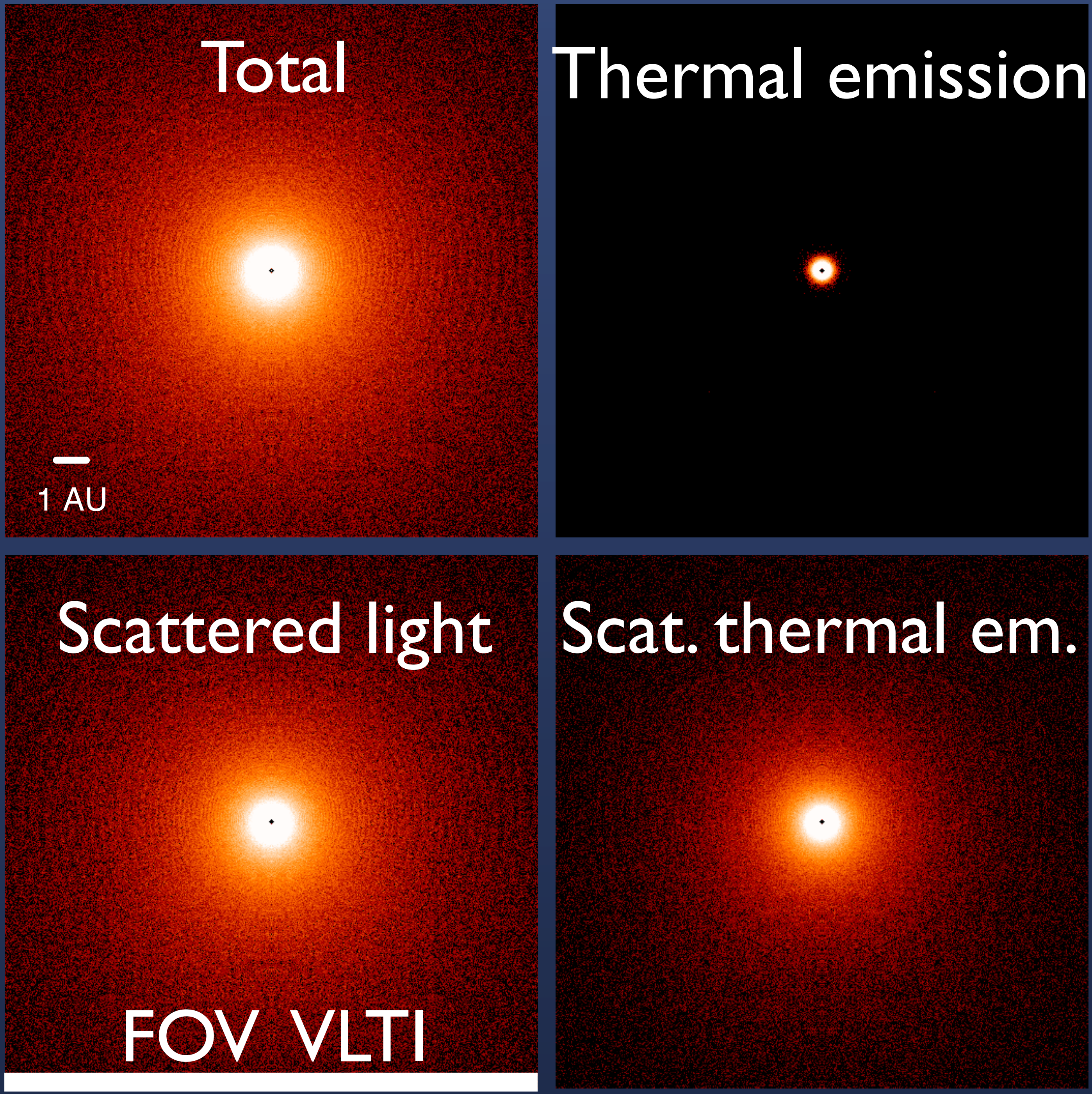
Inner radius measured by IR interferometry apparently larger than sublimation radius for T Tauri stars

But models were **neglecting scattered light**, which is the **dominant contribution**

→ over-estimation by factor 2

Need for detailed RT codes like MCFOST

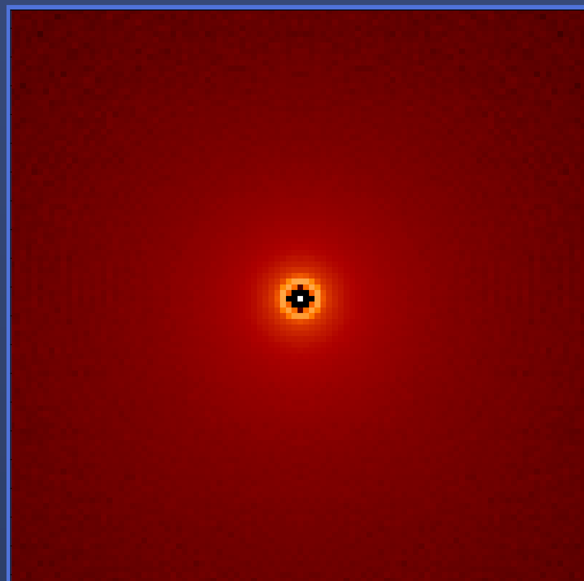
Interpretation of AMBER data:
Tatulli et al 2008
Benisty et al 2010
Olofsson et al 2010
Tatulli et al 2010



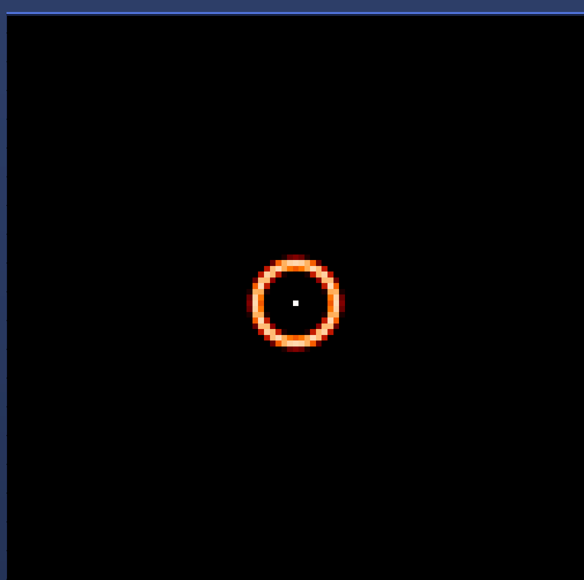
Pinte et al 2008

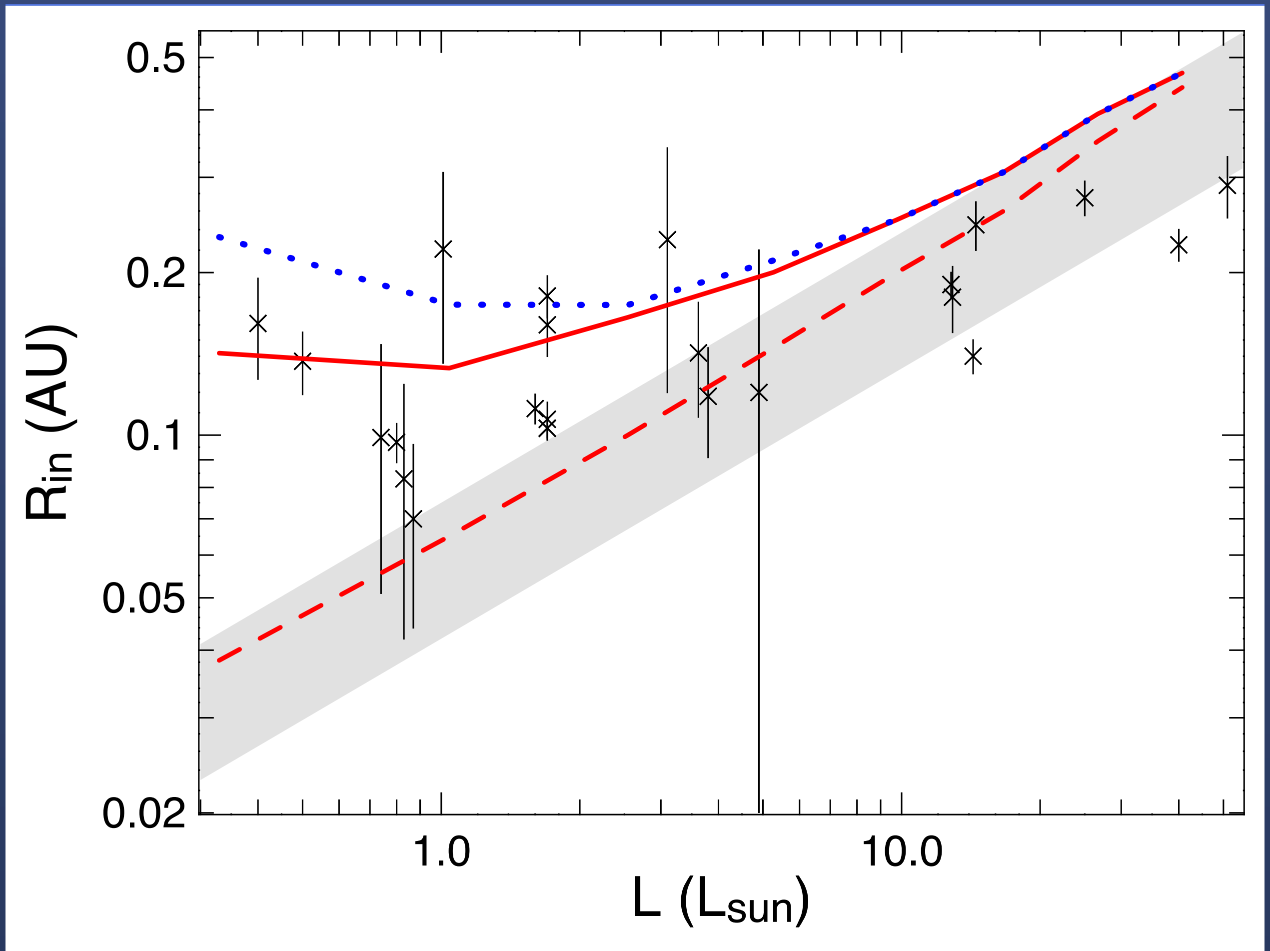
What radius would have been measured ?

Disk model



Fitted ring



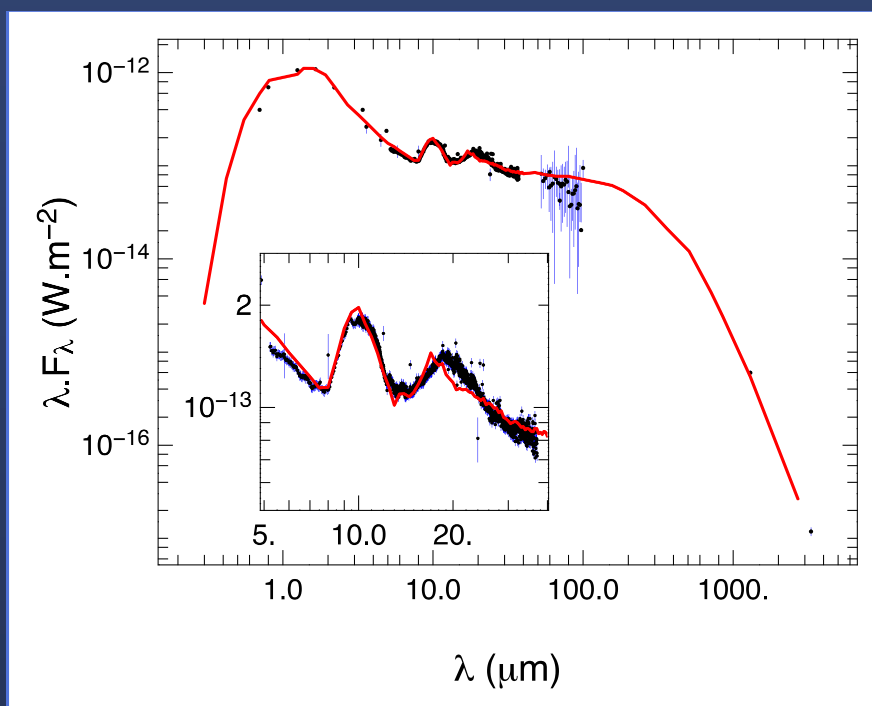


Scattered light is a sufficient explanation

The location of fitted inner radii mimics very well the distribution of data points

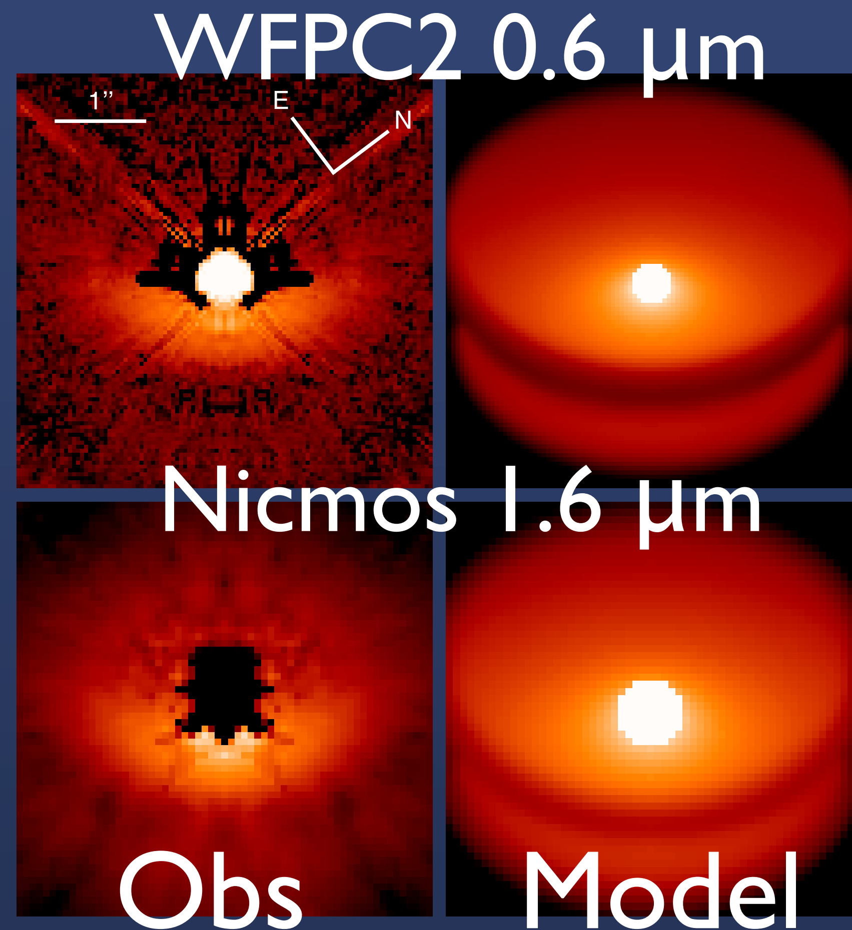
Multi-λ modelling of IM Lupi

A single model with **mild stratification** remarkably reproduces all observations: H(1mm) ≈ 0.5 H(1µm)



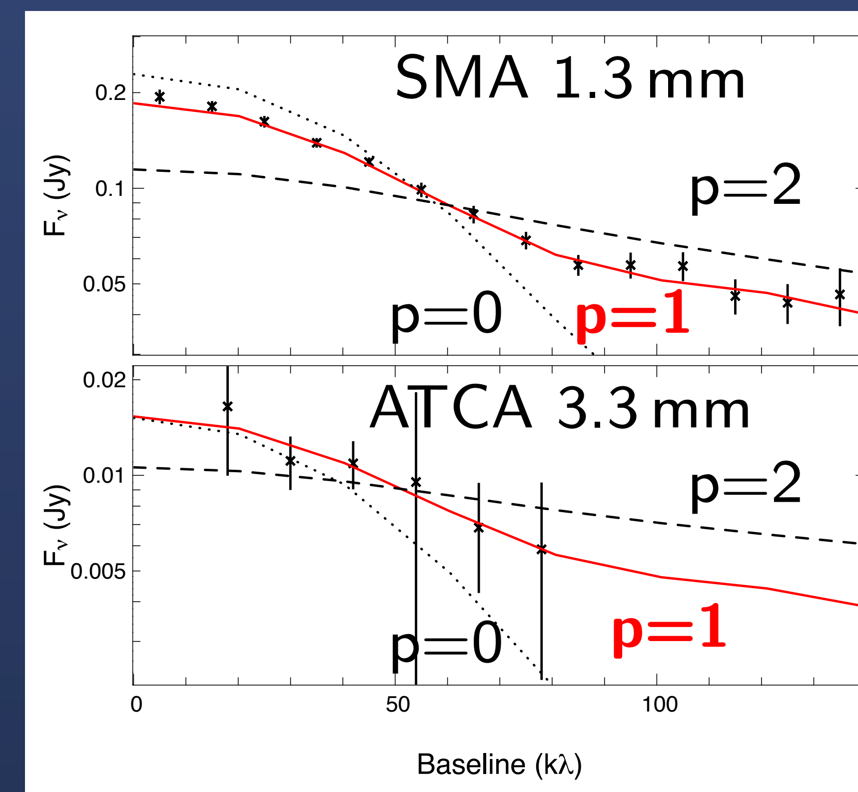
↓

M_{dust}, grain growth & settling



↓

R_{out}, i, H_o, grain size, composition



↓

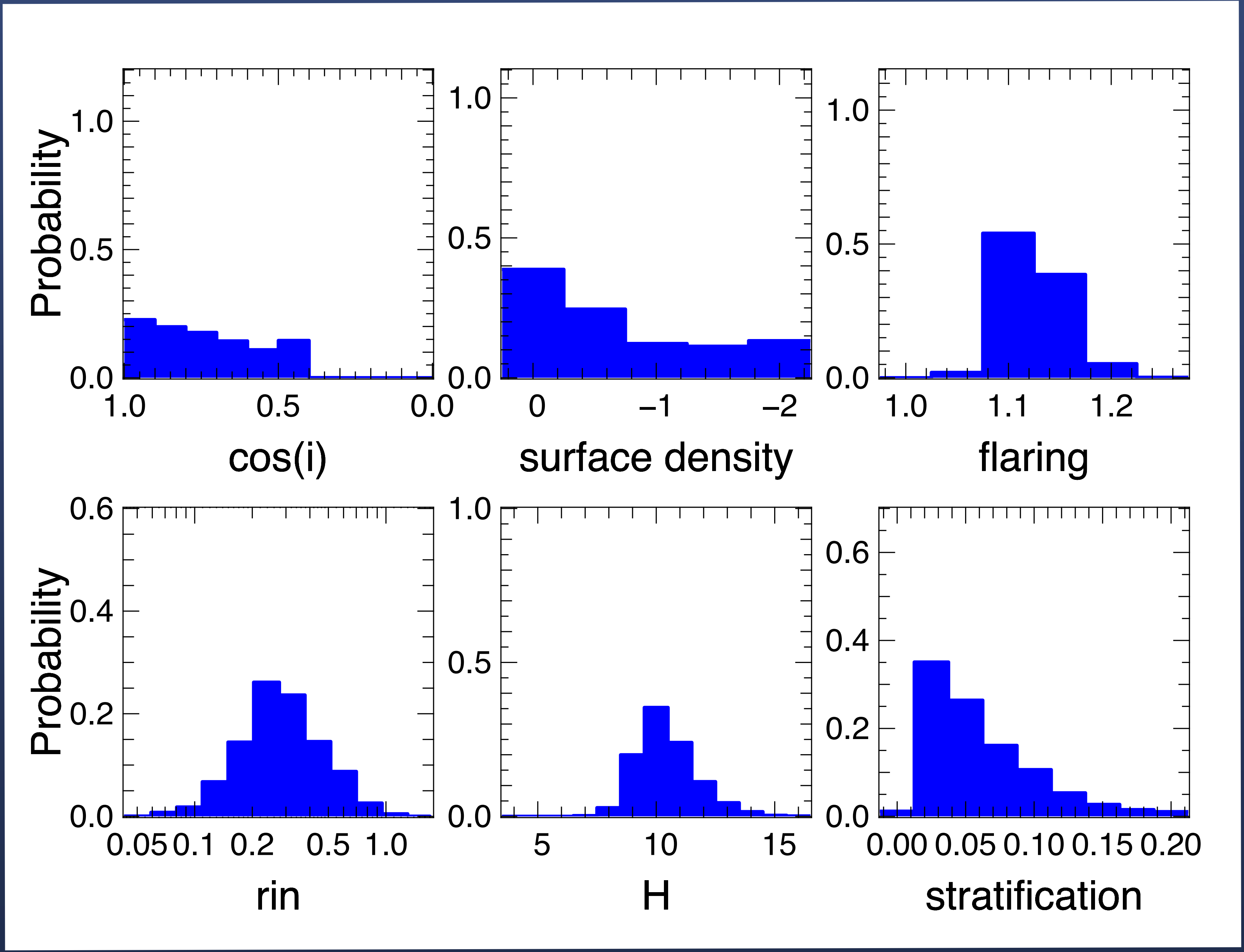
Surface density $\Sigma(r) \propto r^{-p}$

Pinte et al 2008

IM Lupi: quantitative constraints

Bayesian method to estimate model parameters:
for SED

≈ 400 000 models
Some parameters fixed from data (a_{max}, M_{dust}, R_{out})
→Fitting for 6 parameters



Pinte et al 2008

See also Glauser et al 2008, Bouy et al 2008, Duchêne et al 2010

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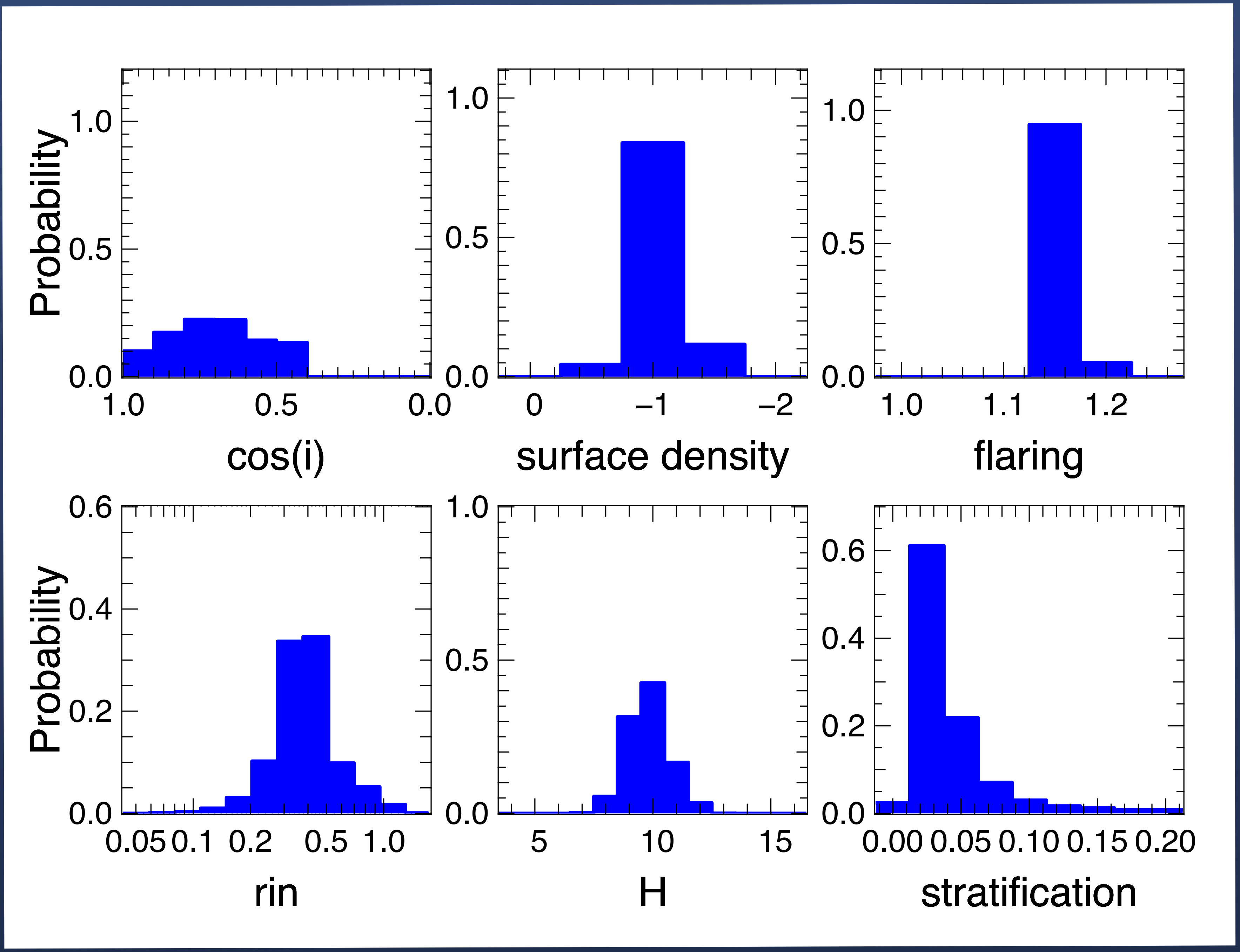

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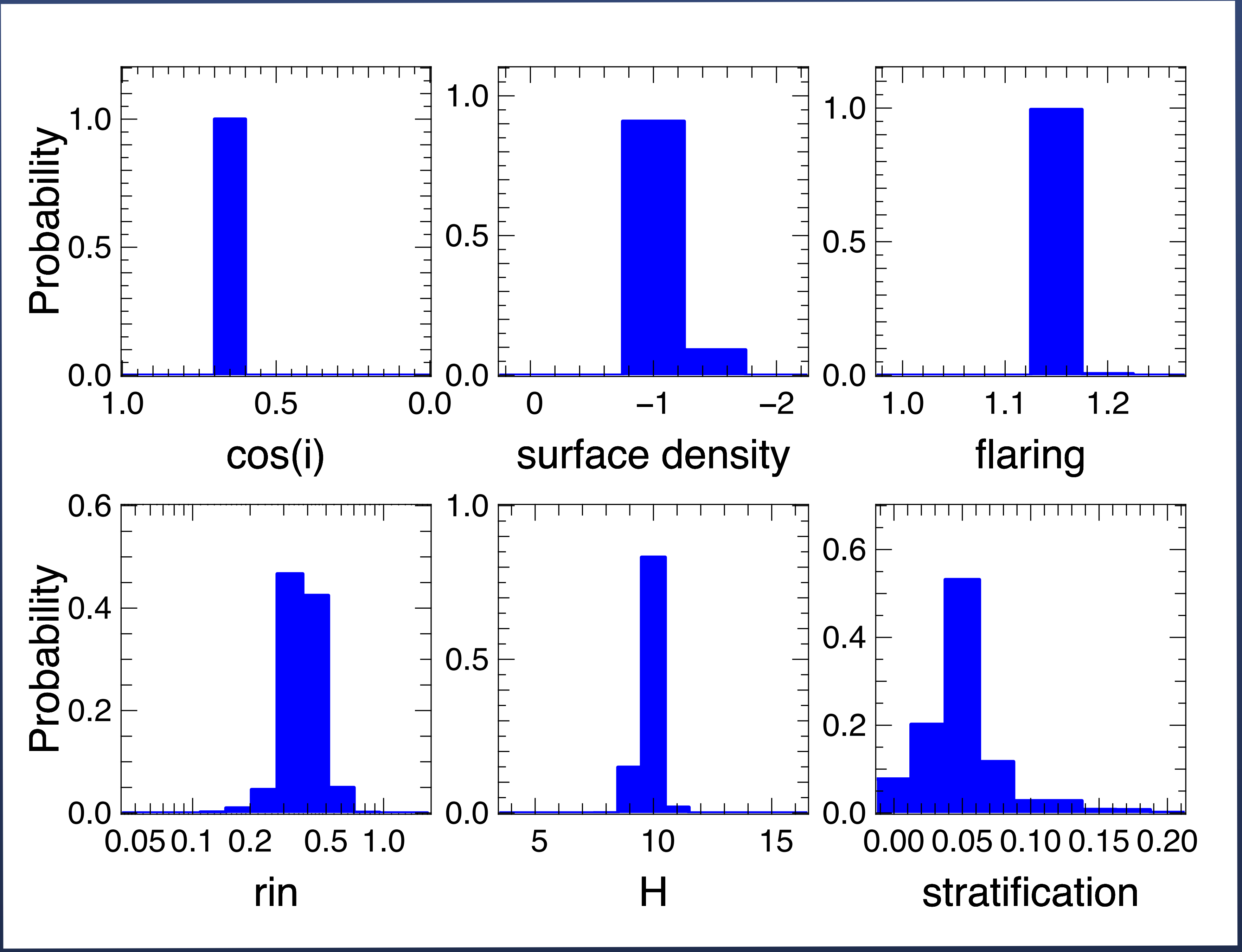

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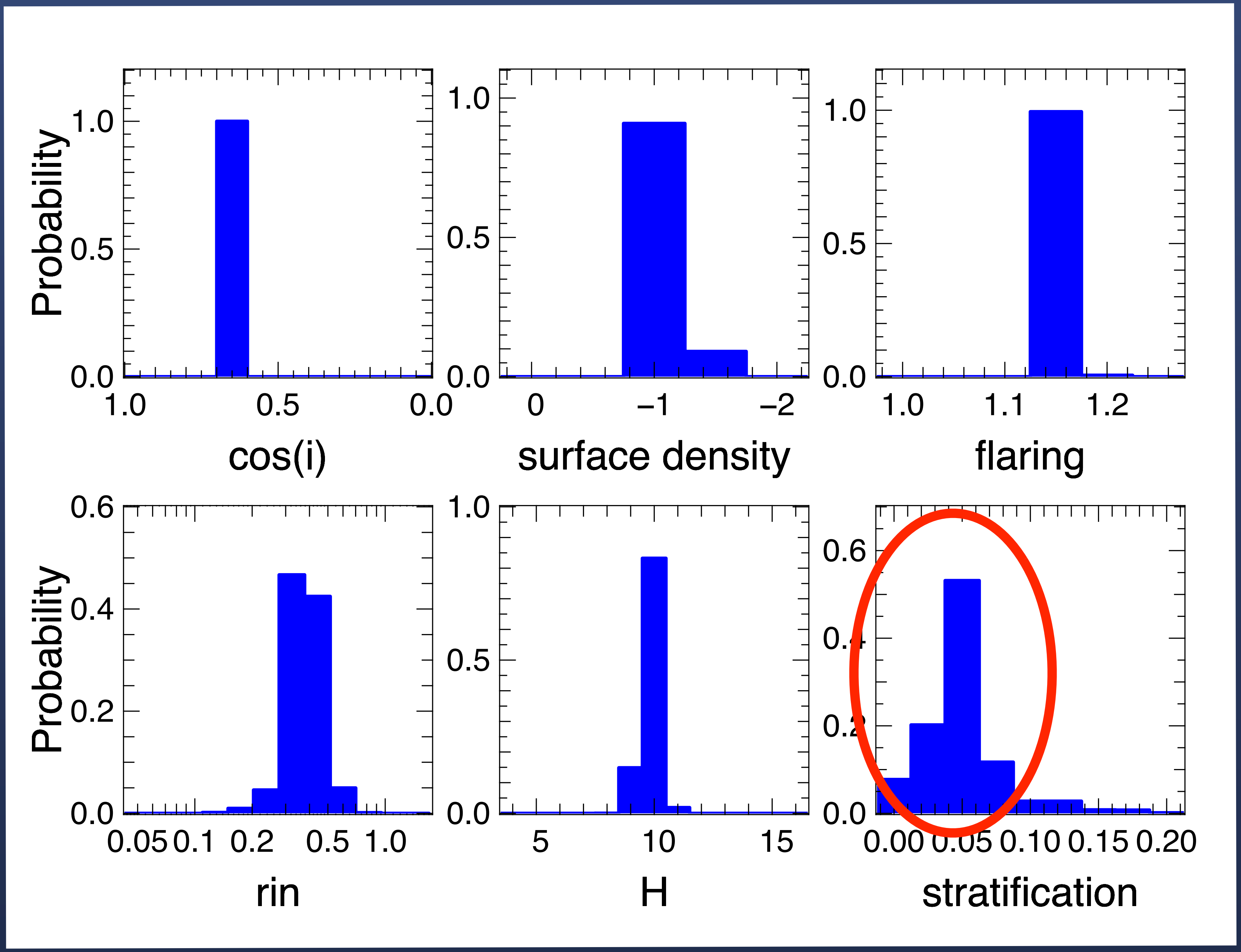
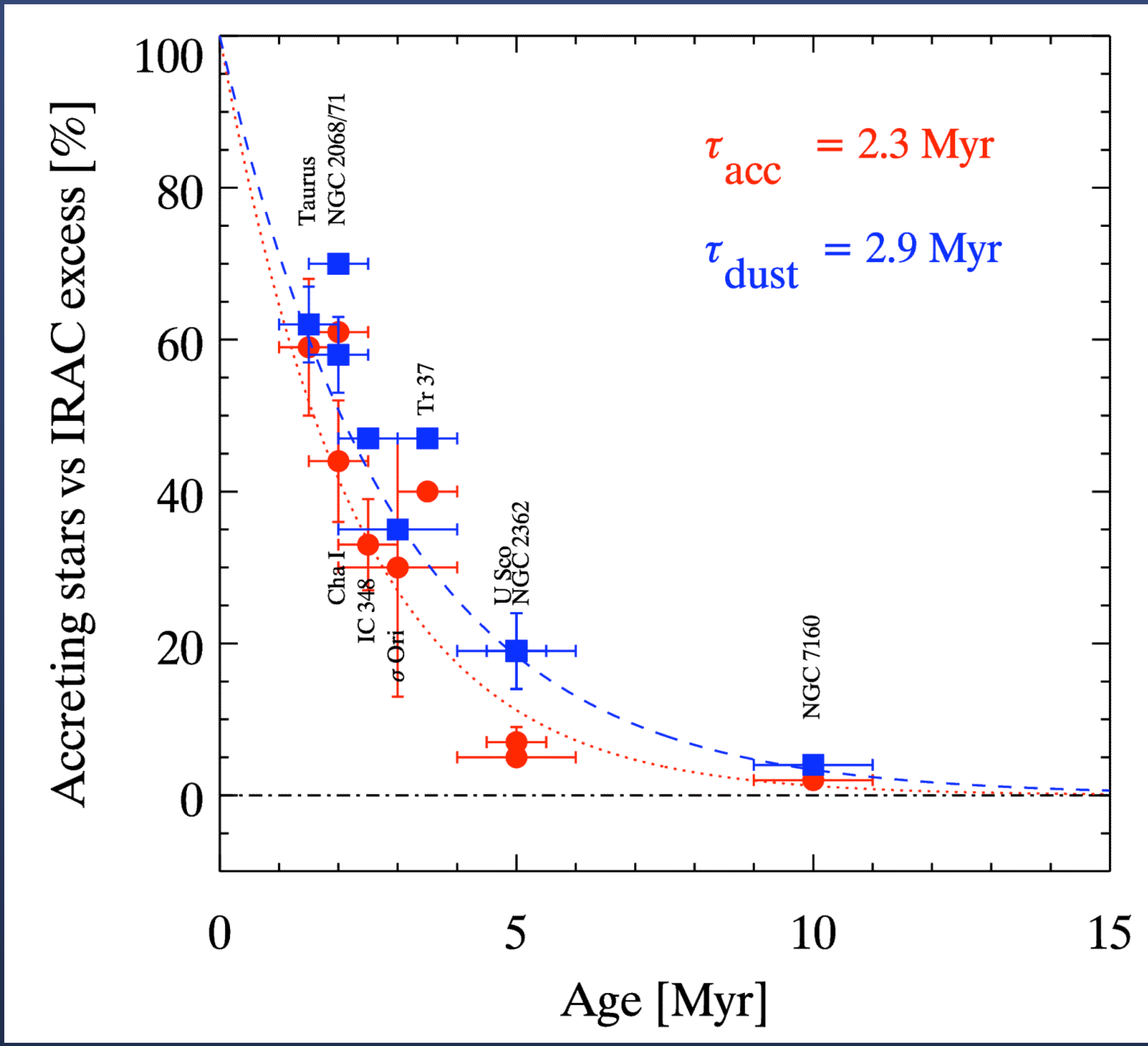


Pinte et al 2008

See also Glauser et al 2008, Bouy et al 2008, Duchêne et al 2010

Gas & Dust evolution

- Gas represents 99% of the disk mass
- Difficult to observe but Herschel is opening the far-IR window
- Gas & dust evolution strongly coupled

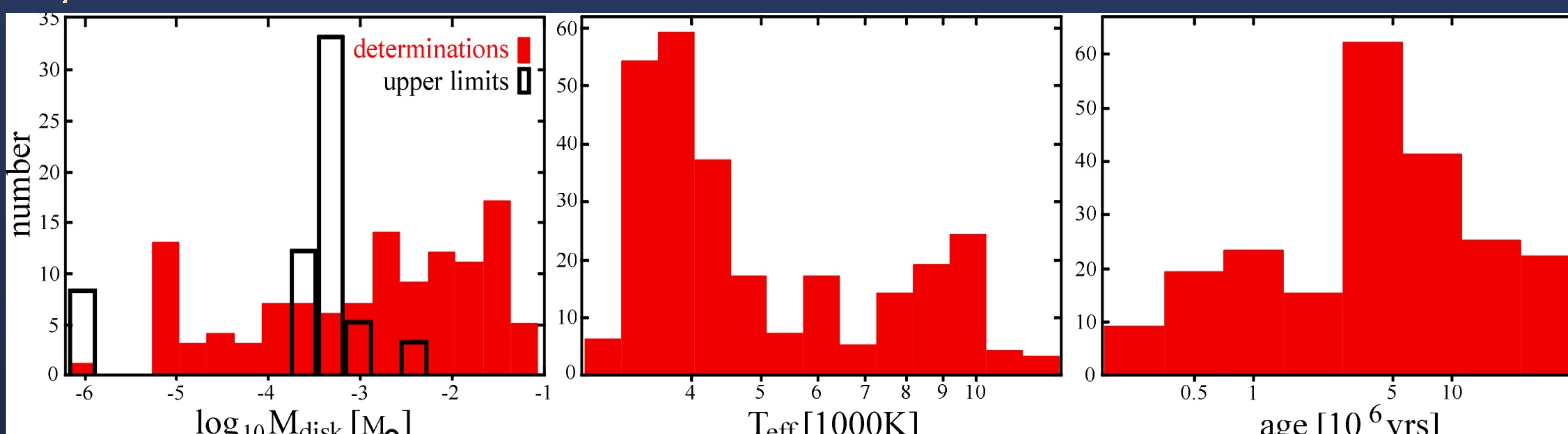


Fedele et al. 2009

Gas in Protoplanetary Systems

Statistical survey (≈ 250 disks) : evolution of gas and dust from young gas-rich protoplanetary disks, to old “dry” debris disks:

- Ages 1 – 30Myr, M to A stars, disk dust mass (10^{-2} - 10^{-5}Mo)
- Well-known star-forming regions (Taurus, TW Hydra, η Cha, β Pic, Tuc Hor, Upper Sco, Herbig Ae/Be)
- Key far-IR tracers: [OI], [CII], H_2O, CO + Phot. at 70 & 160μm



Modelling tools: MCFOST + ProDiMo

Interpretation of line observations is complex !
→ need for detailed modelling.

MCFOST: 3D continuum & line radiative transfer (Pinte et al 2006, 2009)

+ **ProDiMo**: thermal balance & chemistry (Woitke et 2009, Kamp et al 2010)

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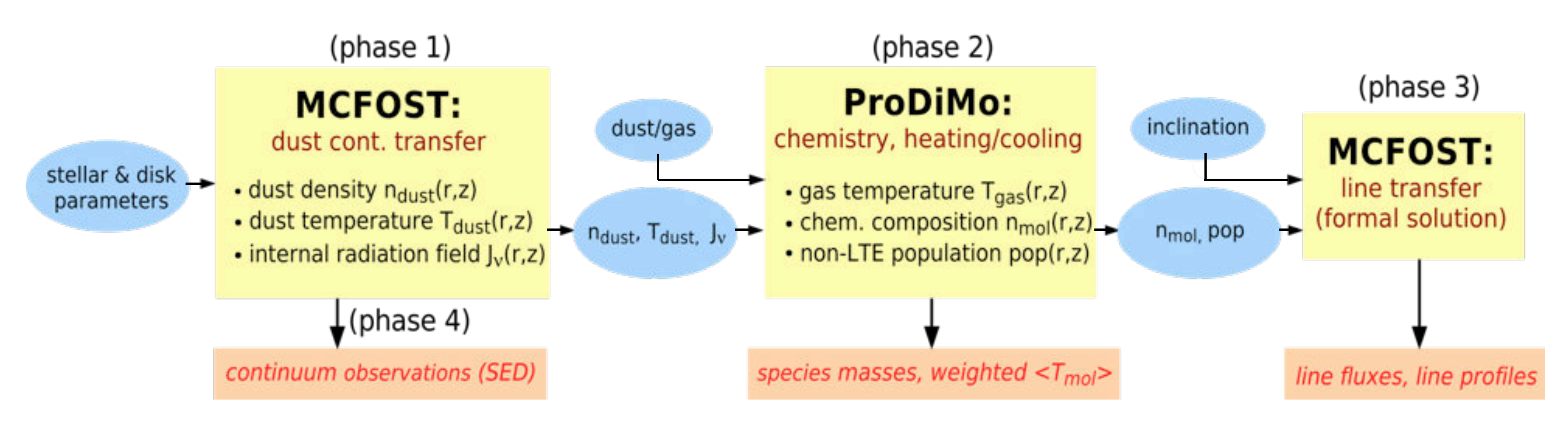


Modelling tools: the DENT grid

Grid of ≈ 300 000 disk models:

Woitke et al 2010
Kamp et al, in prep.
Ménard et al, in prep.

- sample the disk parameters observed by GASPS
- thermo-chemical structure: T_{dust}, T_{gas}, abundances
- SEDs
- 29 line fluxes and profiles: [OI], [CII], ^{12}CO, o-H_2O, p-H_2O

stellar parameter		
$M_\star$	stellar mass [$M_\odot$]	0.5, 1.0, 1.5, 2.0, 2.5
age	age [Myr]	1, 3, 10, 100
f_{UV}	excess UV $f_{UV} = L_{UV}/L_\star$	0.001, 0.1
disc parameter		
M_d	disc dust mass [$M_\odot$]	$10^{-7}, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}$
$\delta = \rho_d/\rho_g$	dust/gas mass ratio	0.001, 0.01, 0.1, 1, 10
R_{in}	inner disc radius [R_{subli}]	1, 10, 100
R_{out}	outer disc radius [AU]	100, 300, 500
ϵ	column density $N_H(r) \propto r^{-\epsilon}$	0.5, 1.0, 1.5
β	flaring $H(r) = H_0\left(\frac{r}{r_0}\right)^\beta$	0.8, 1.0, 1.2
dust parameter		
s	settling $H(r,a) \propto H(r)\,a^{-s/2}$	0, 0.5
a_{min}	minimum grain size [μm]	0.05, 1
radiative transfer parameter		
i	inclination	$0^o, 41.41^o, 60^o, 75.52^o, 90^o$ (edge-on)

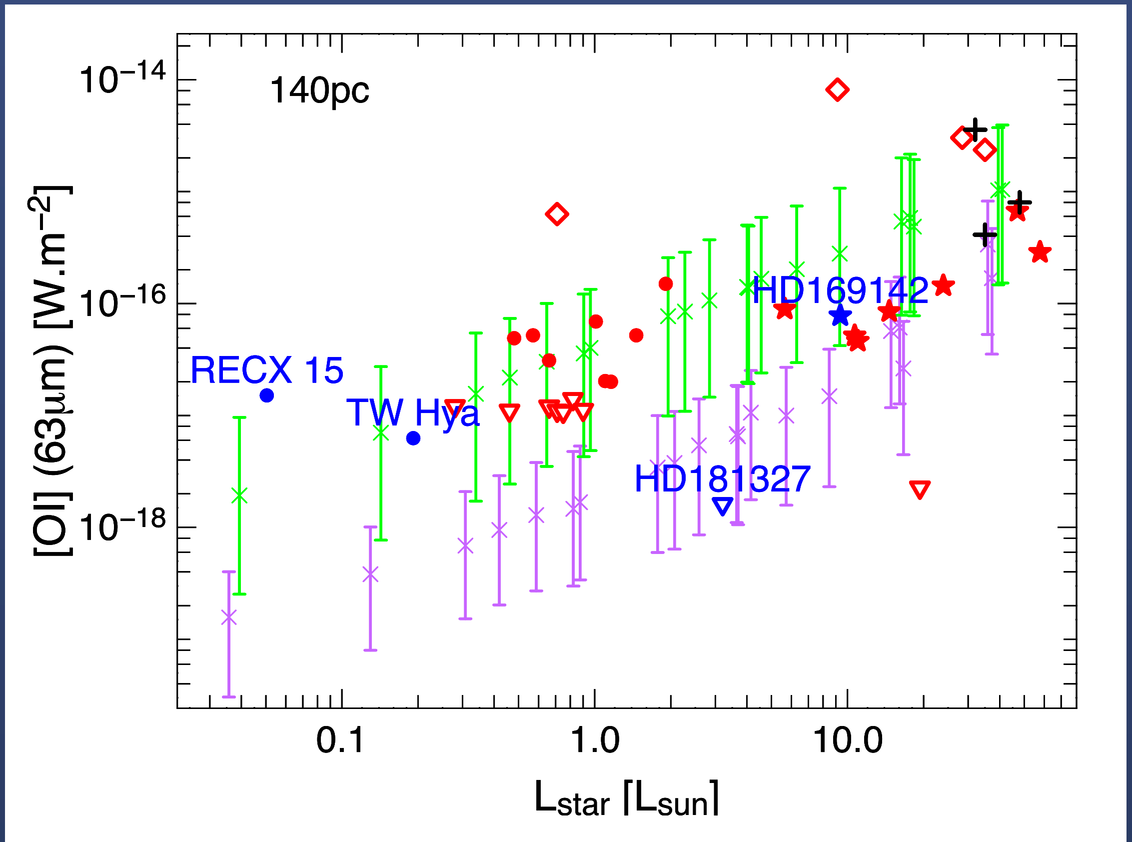
→ **Statistical tool**

200 000 cpu-hours (ANR "Dusty Disk" supercomputer, PI: F. Ménard)

Main heating mechanisms

Pinte et al 2010

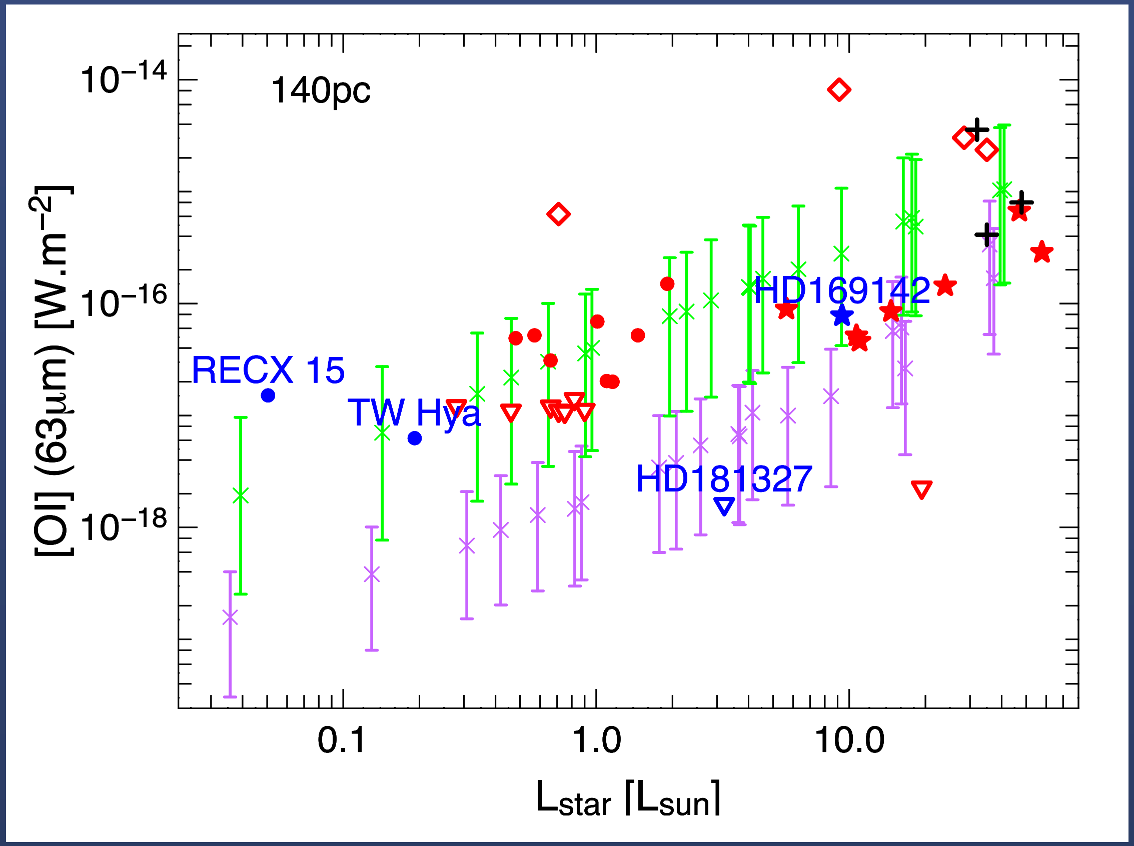
- Herbig Ae/Be stars: line flux correlates with L★
- T Tauri stars: UV excess required to interpret line flux

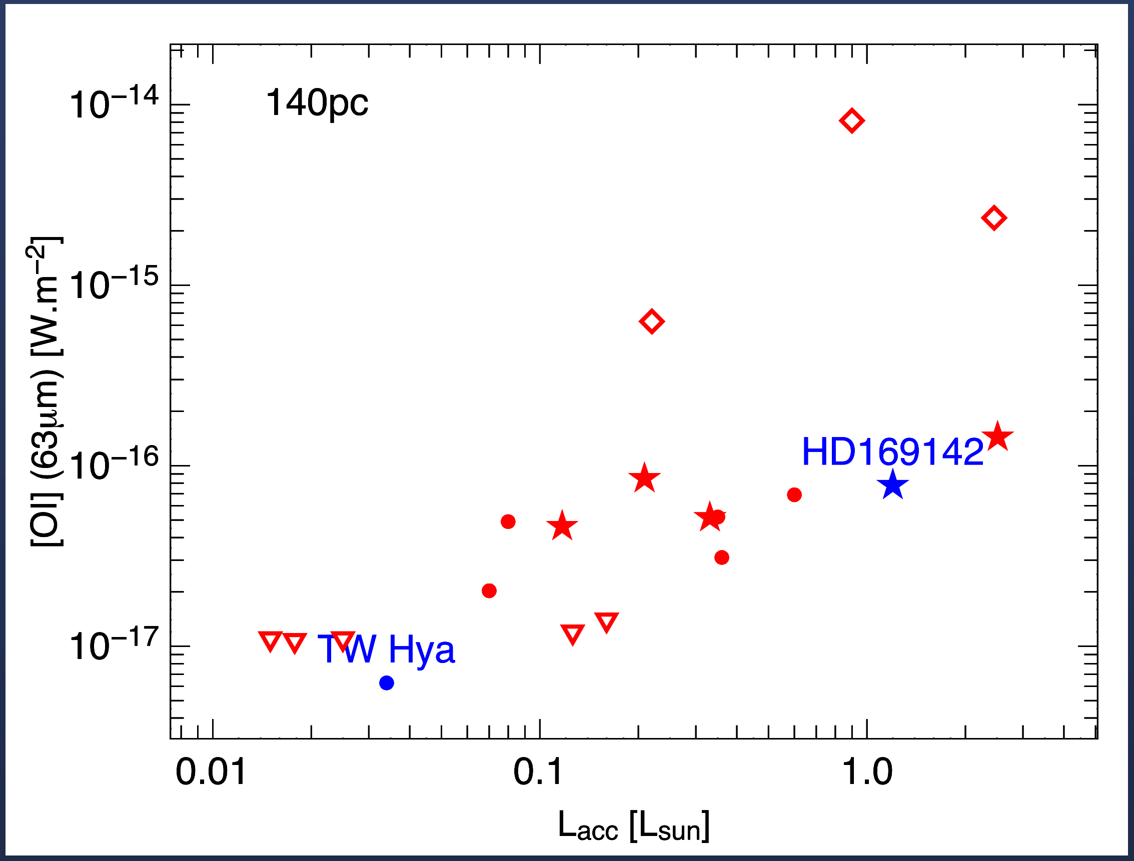


Main heating mechanisms

Pinte et al 2010

- Herbig Ae/Be stars: line flux correlates with $L_\star$
- T Tauri stars: UV excess required to interpret line flux
- suggestion that L_{acc} could play a role
- No apparent correlation with L_X





HD 169142

Dust modelling (SED + images) to constrain the disk structure and dust properties

→ geometry, gap at 10 AU

→ amount of PAHs: $f_{PAH}=0.03$

Input for gas modelling

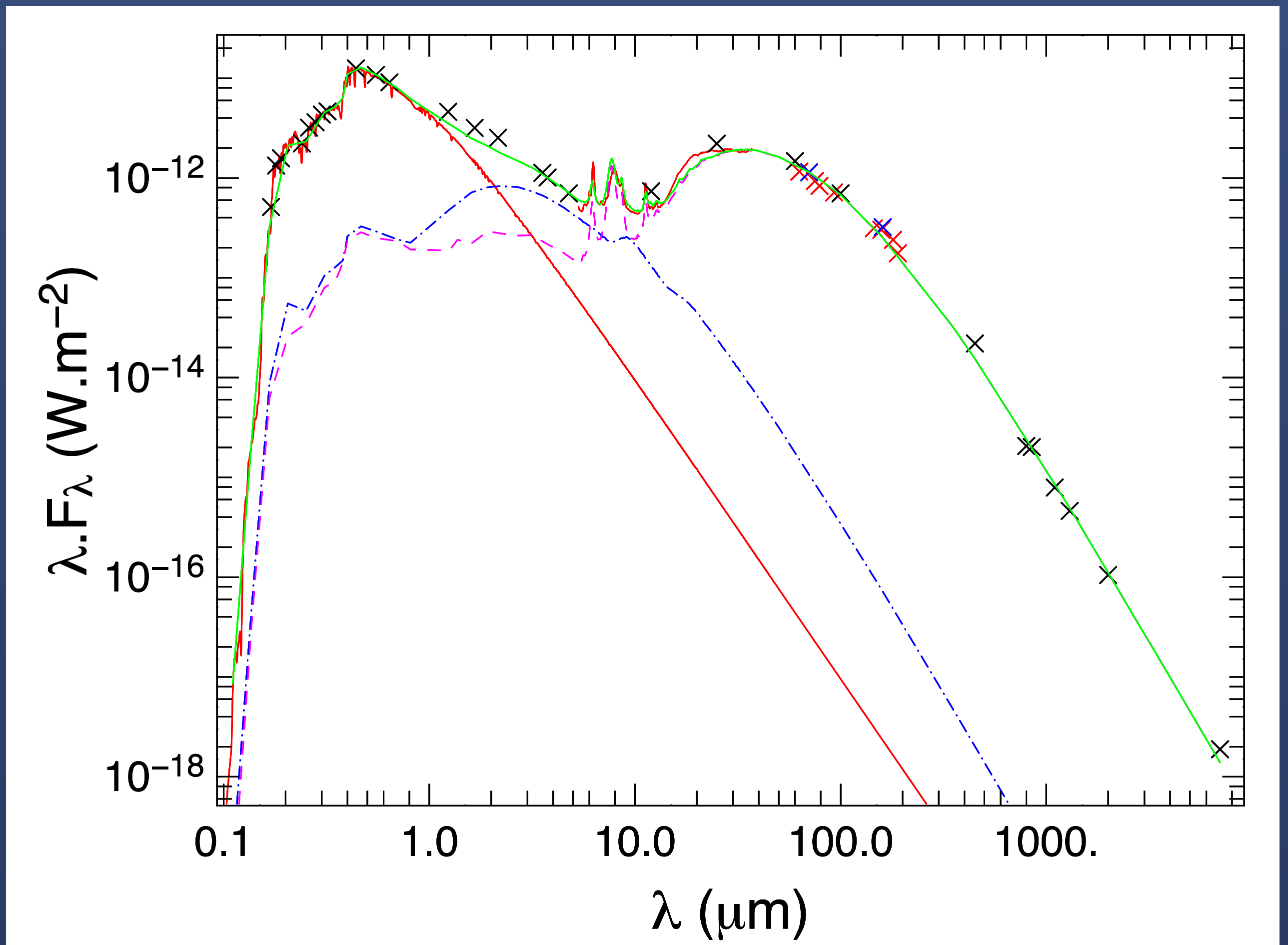
→ low UV excess

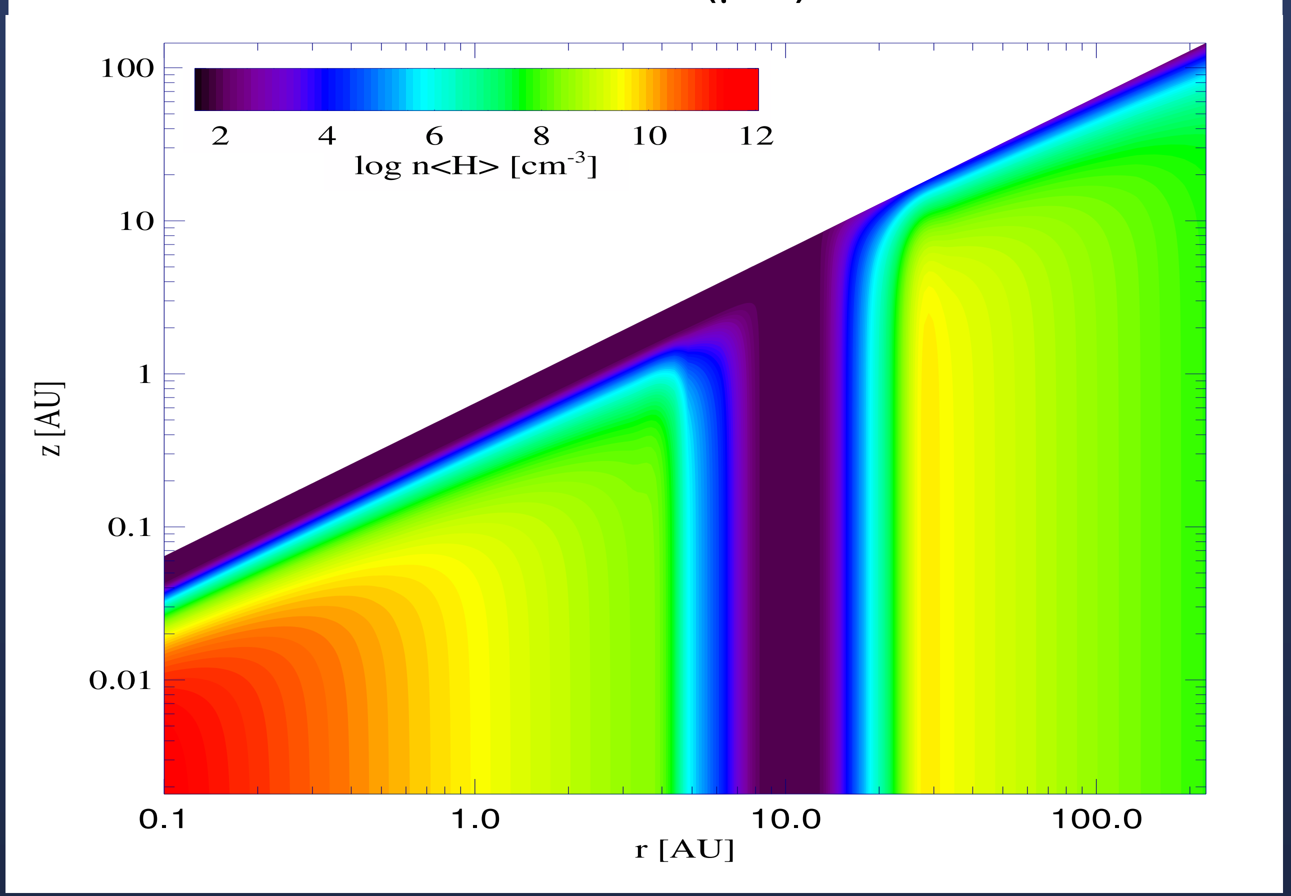
→ PAH = main gas heating source

→ gas dust ratio ≈ 20-50

Meeus et al 2010

Similar work for the T Tauri star TW Hydra, see Thi et al 2010





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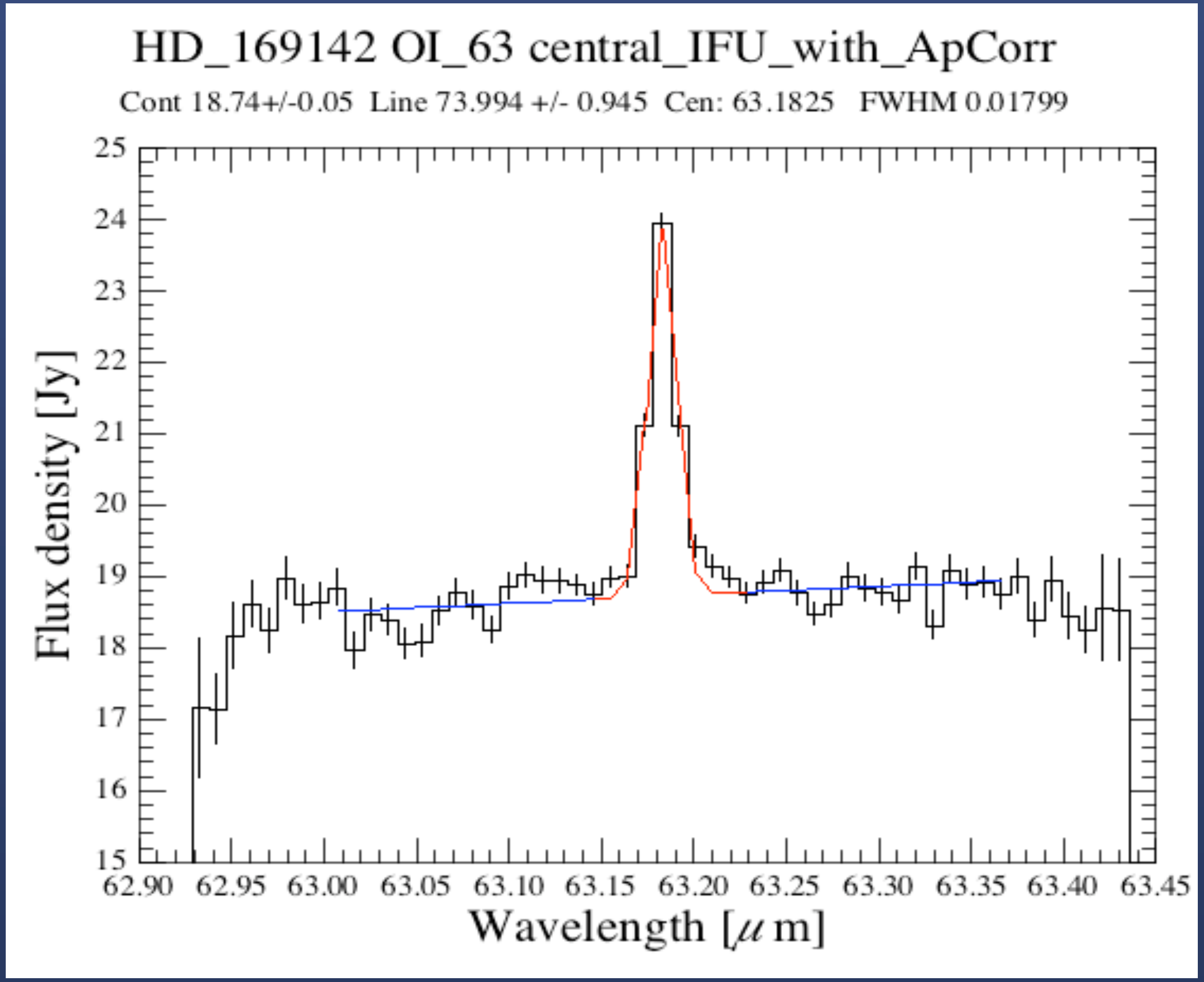


	observed	model
[OI] 63 μm	71.7	71.6
CO 2 → 1	0.093	0.092
^{13}CO 2 → 1	0.048	0.048

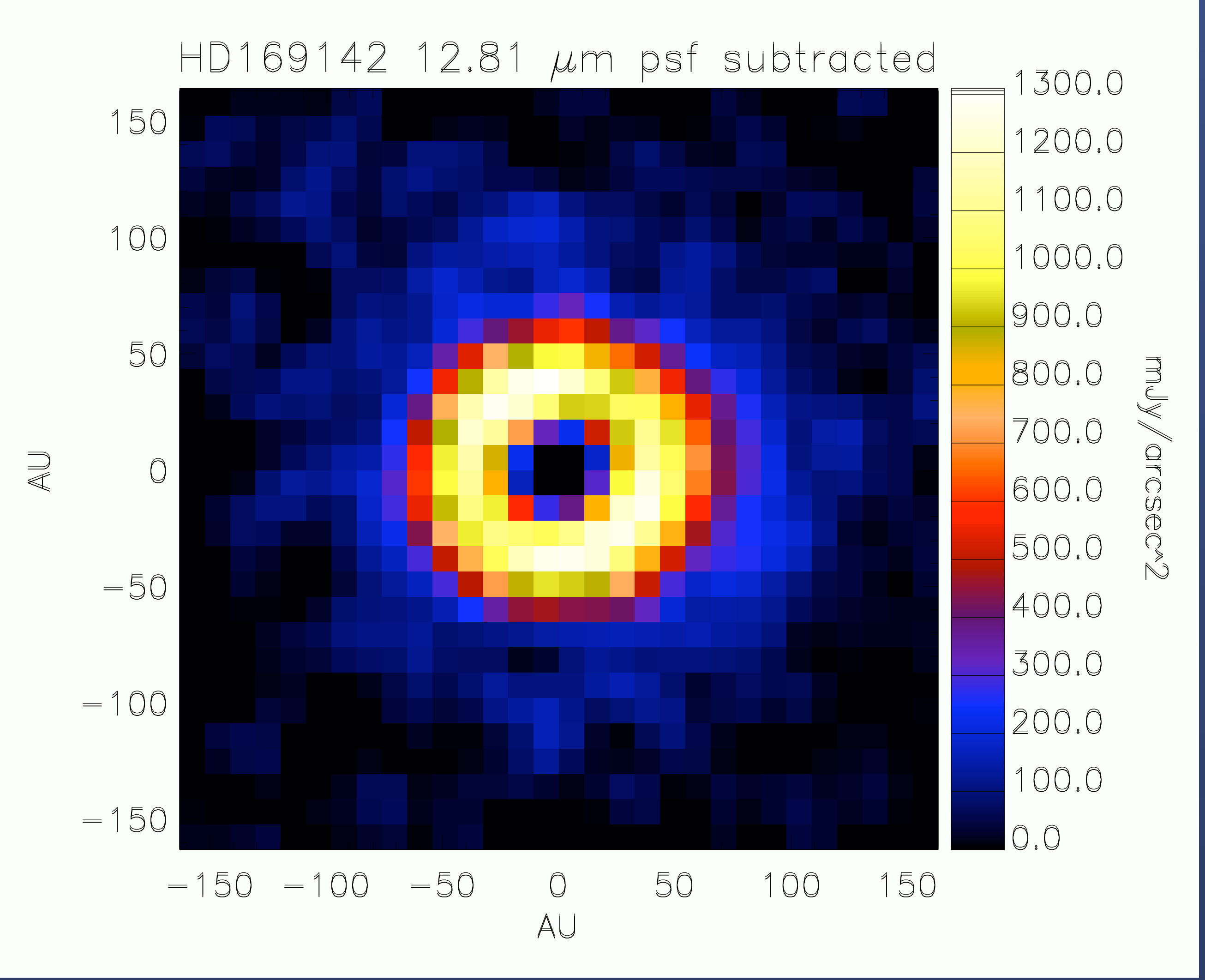
line fluxes in $[10^{-18}\,W/m^2]$

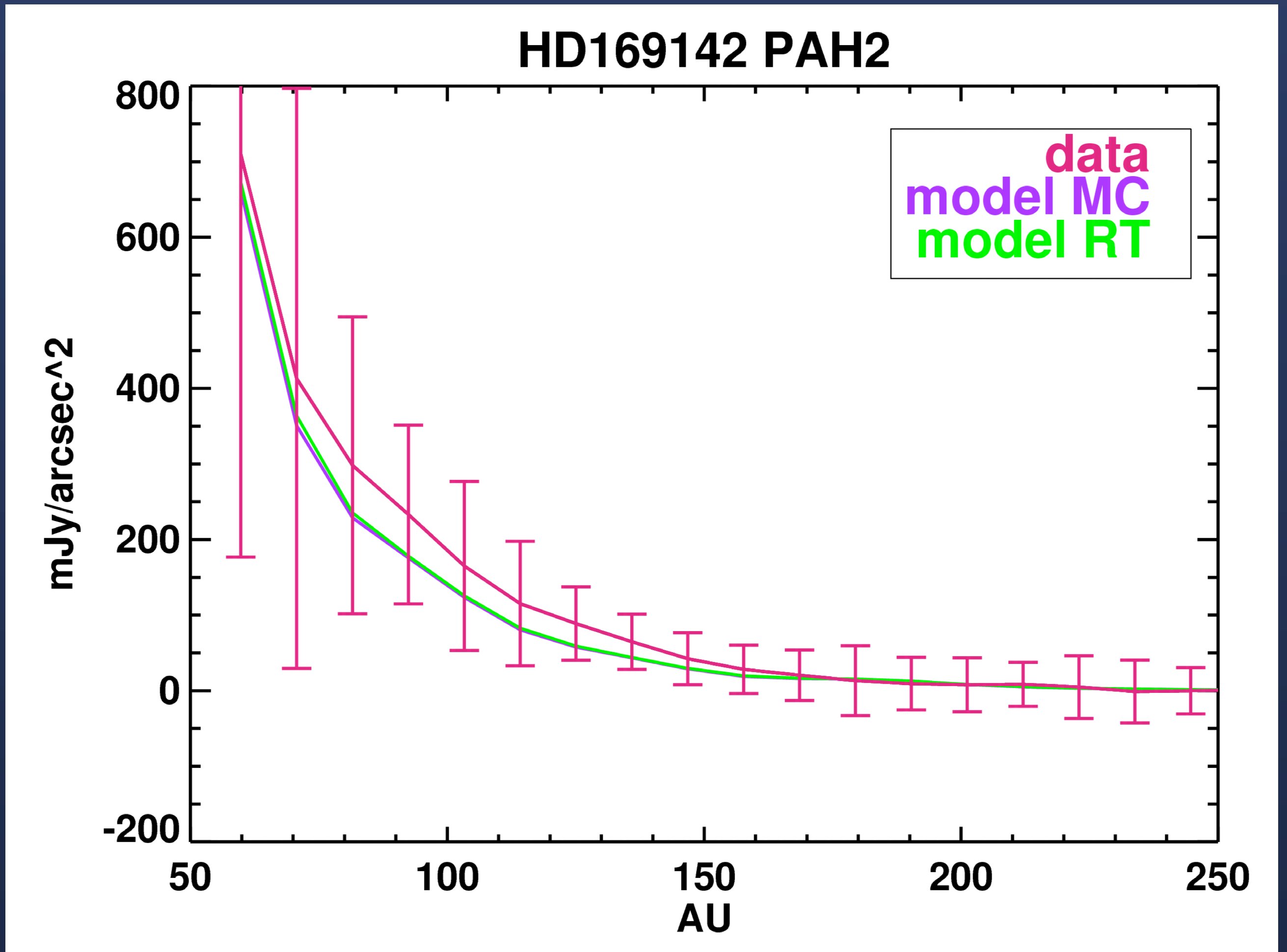
HD169142 in PAHs

Imaging in Mid-IR
VISIR observations
→ disk resolved in continuum and PAHs bands

Model consistent with observations
→ **confirms amount of PAHs and geometry of the disk surface**

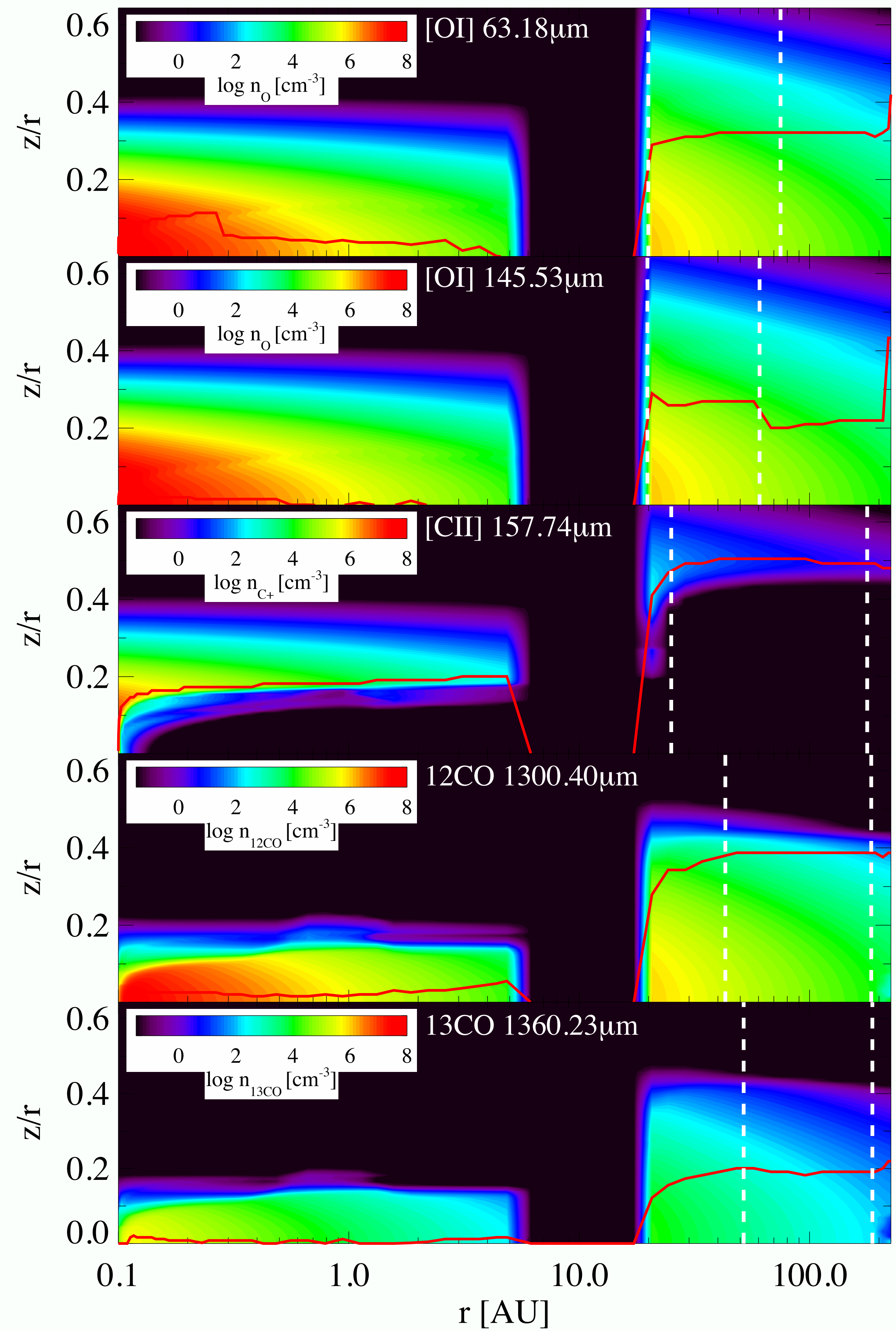
See also Lagage et al, 2006 and Doucet et al, 2007



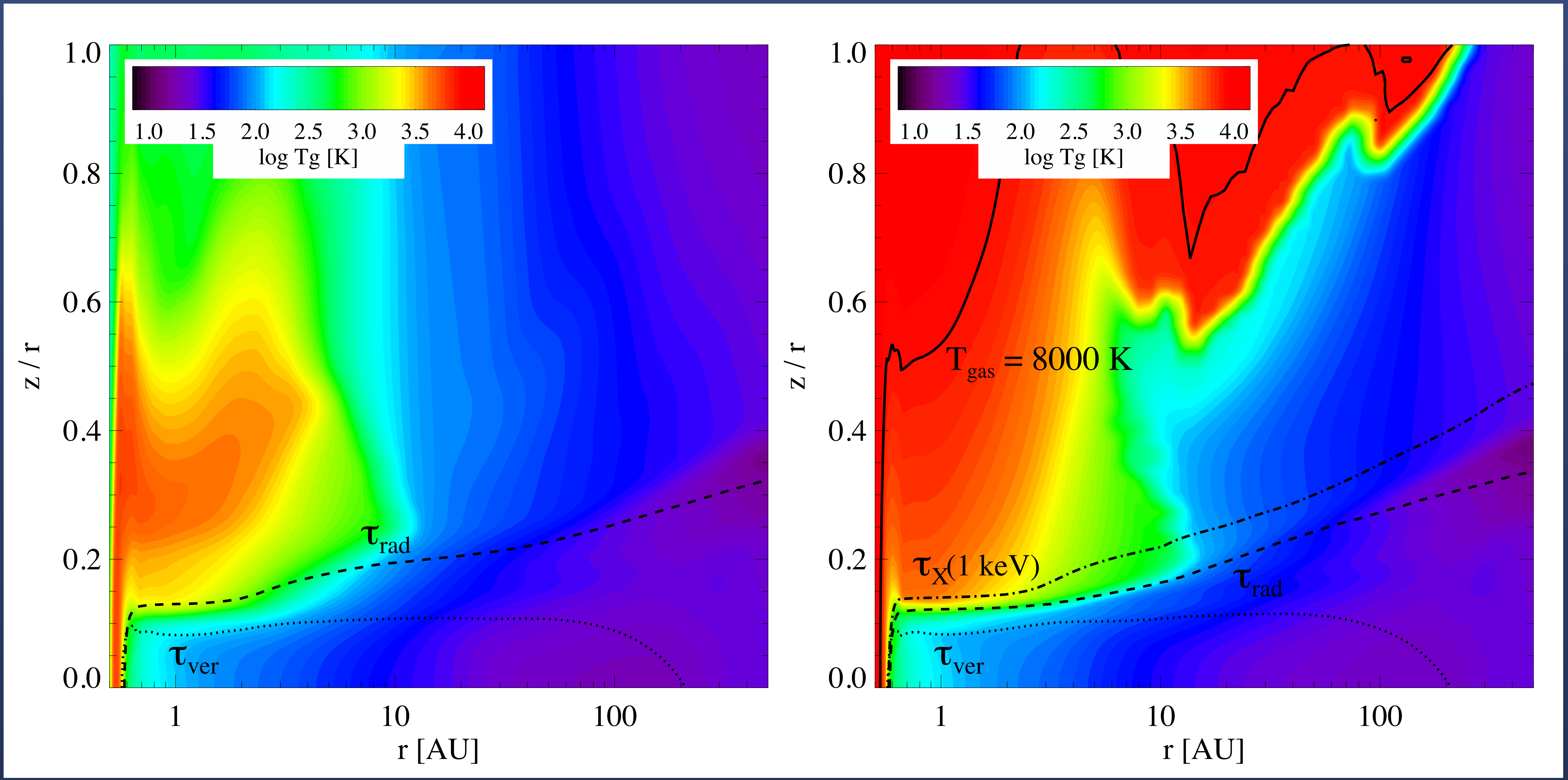


Spatial origin of the lines

HD 169142



Effect of X-ray irradiation



G. Aresu et al, 2010

Far-IR lines significantly affected only if $L_X \geq 10^{31}$ erg/s

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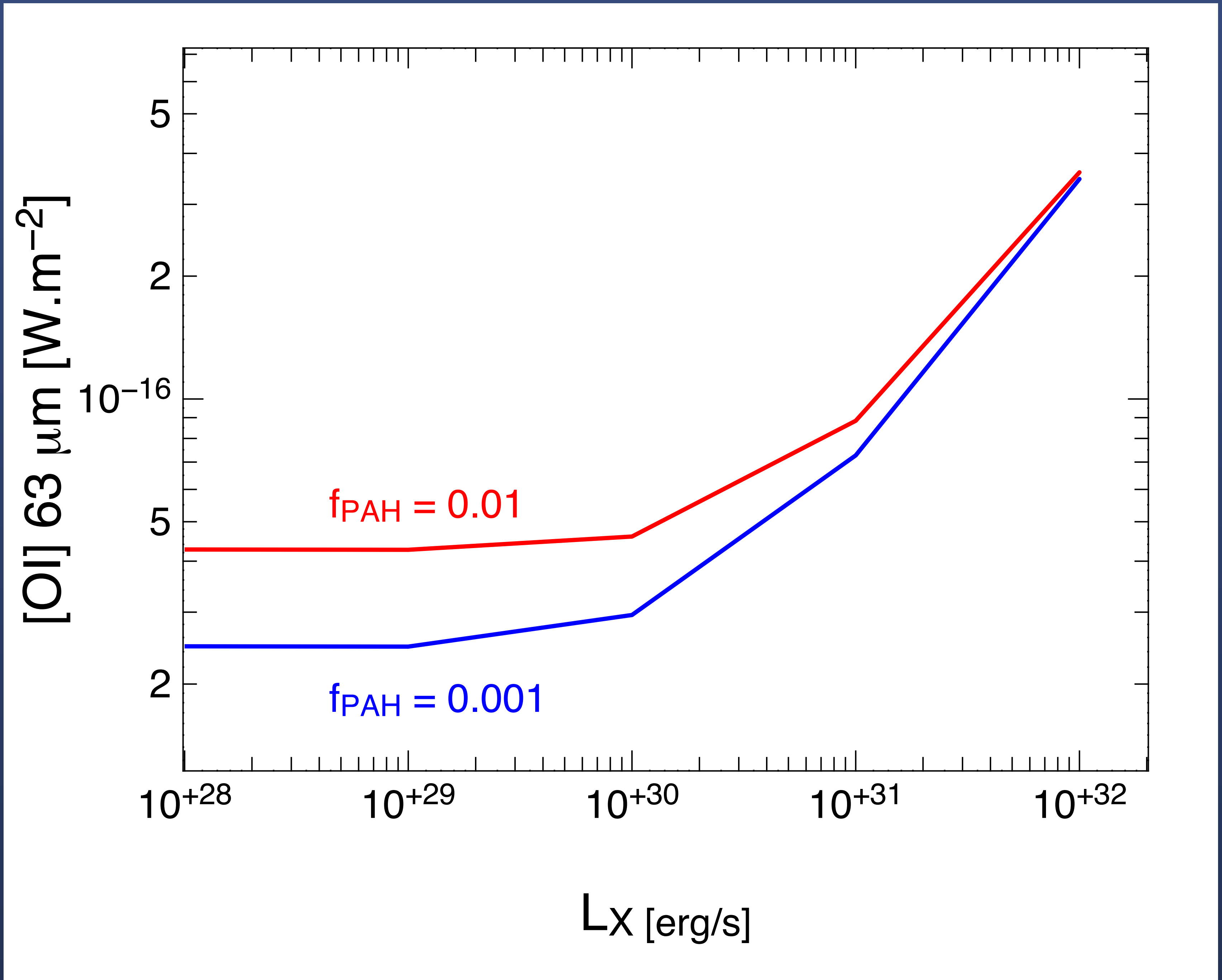

G. Aresu et al, 2010

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Concluding remarks

A variety of datasets = finer disk models

- Spatial differentiation is frequent in disks around T Tauri stars
- Similar studies in Herbig Ae disks, disks around brown dwarfs and debris disks are now possible
- **Testing the physics of dust grains towards planet formation:** separate dust populations, non-spherical aggregates?
- Combining fine-structure lines, CO sub-mm lines and dust observations + detailed modelling is a powerful diagnosis: main gas heating mechanism, dust-to-gas ratios, ...