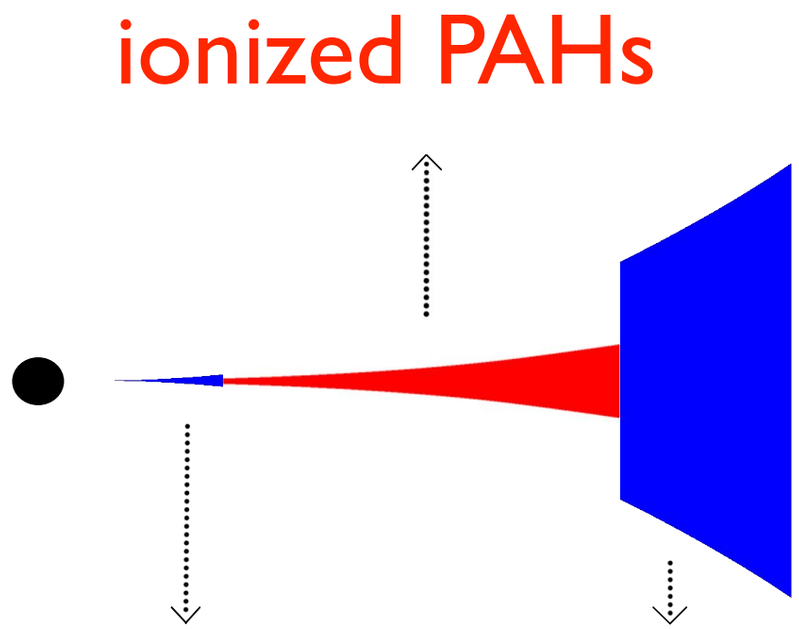
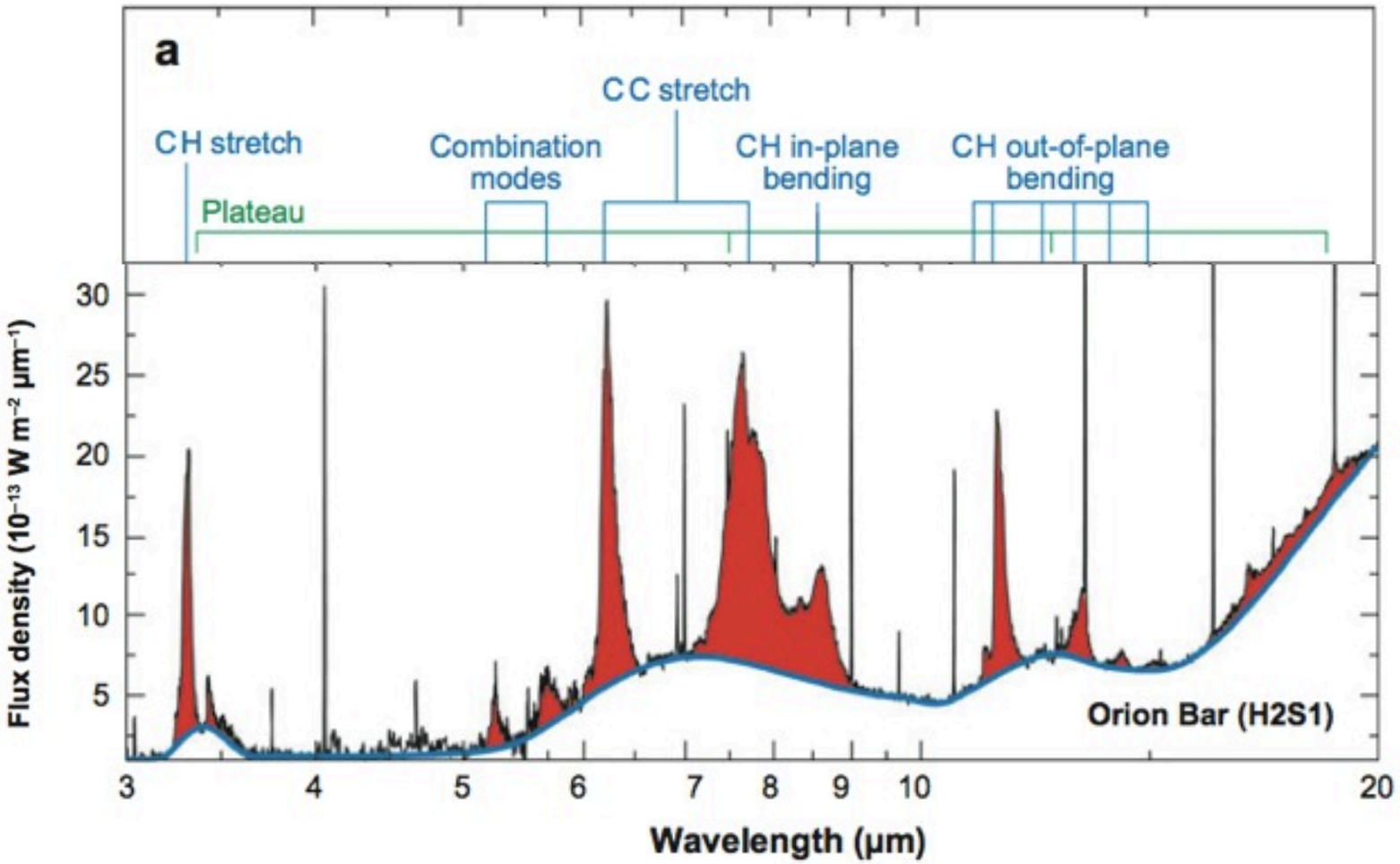
PAH ionization as a tracer of gas flows through disk gaps

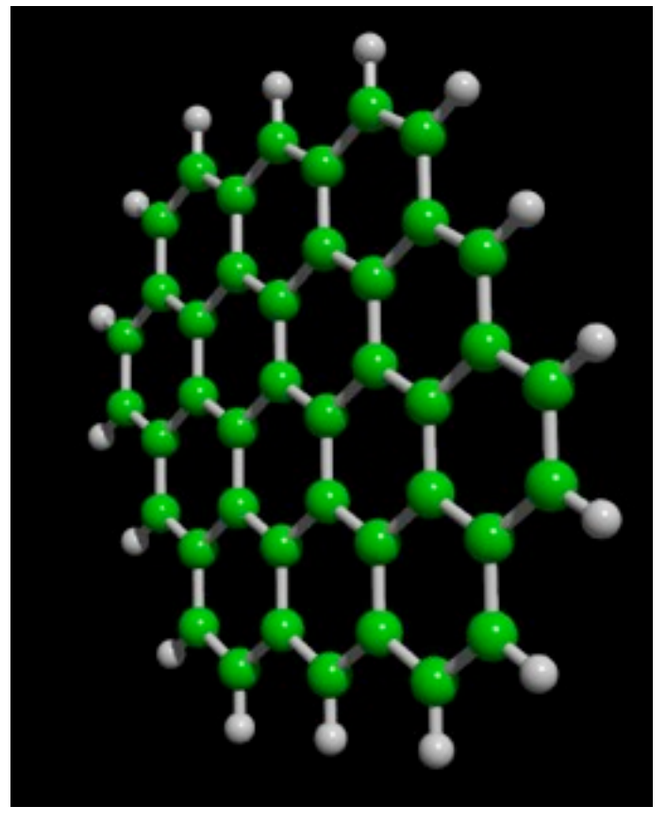


Koen Maaskant
(PhD student Leiden Observatory)

Collaborators: *Xander Tielens, Rens Waters, Michiel Min, Carsten Dominik*

PAHs probe the physical conditions of a region (density, temperature, radiation field)
(e.g.: Hudgins & Allamandola 1999, Allamandola et al. 1999, Galliano 2008, Tielens 2008, Bauschlicher et al 2009, Ricca et al 2012).





Peeters et al. 2002

PAHs in disks:

Why important?

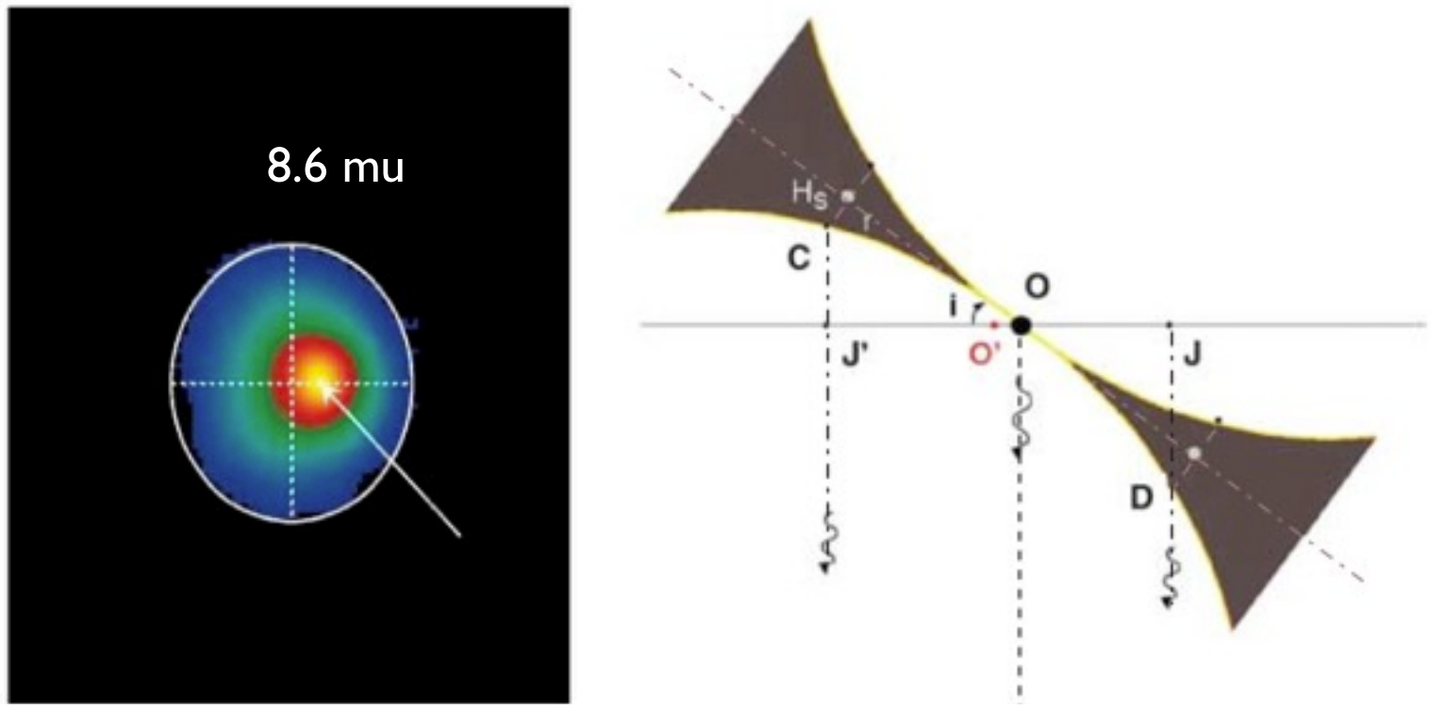
- **PAHs are observed in Herbig and T tauri disks**
  (e.g.: Meeus et al. 2001, Acke & Ancker 2004, Geers et al 2007, Bouwman 2008, Keller et al 2008, Acke 2010).

- **PAHs important for the chemistry and heating of the gas in disks**
  (e.g.: Jonkheid 2006, Woitke et al 2009, Kamp 2011).

- **PAHs can be used to probe the disk structure**
  (e.g.: Habart 2006, Doucet 2006, Lagage 2006).

PAHs and the disk structure

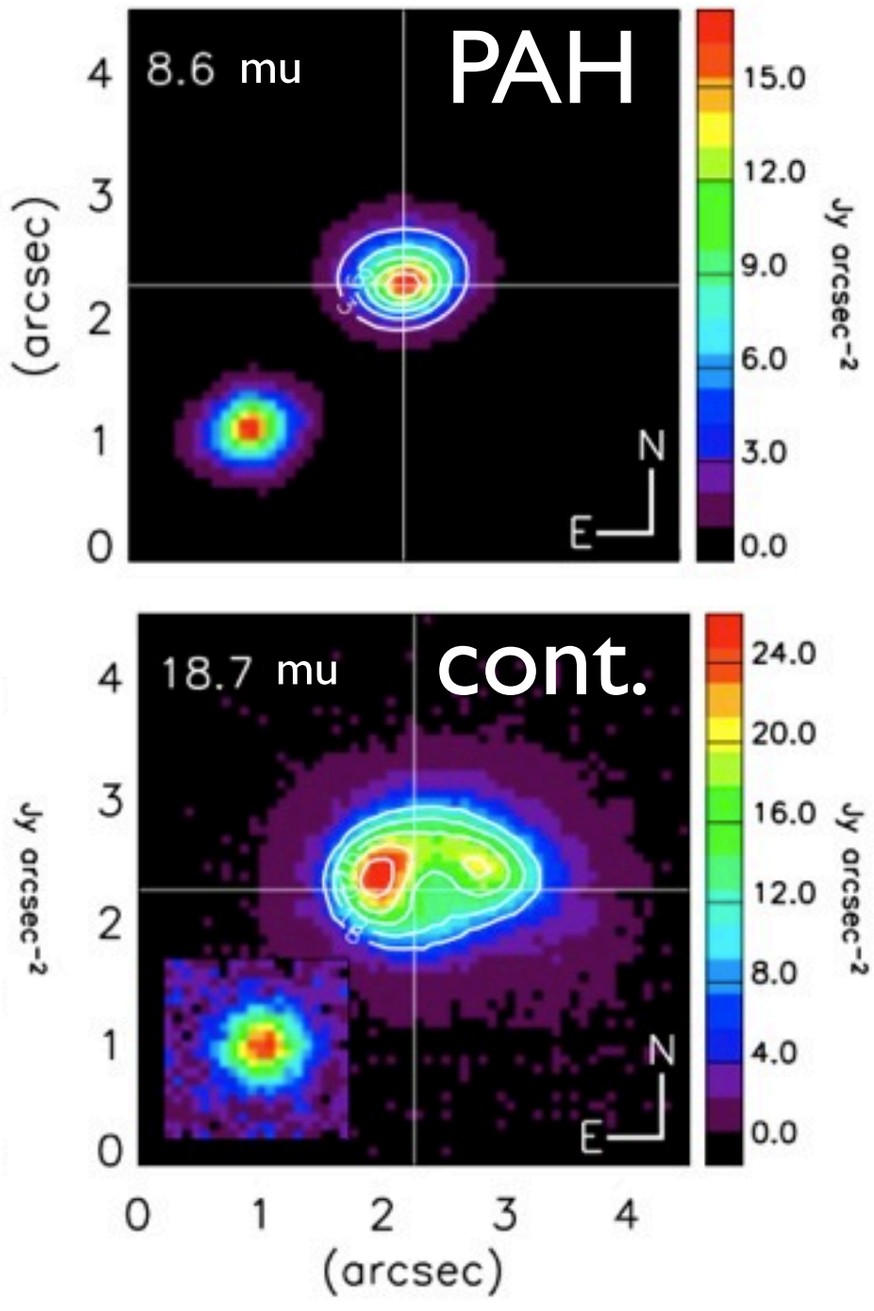
Tracing the flaring disk structure



HD97048, Lagage et al 2006, Doucet et al 2006

PAHs and the disk structure

PAHs (and other gas) in dust gaps



IRS 48, Geers et al. 2007

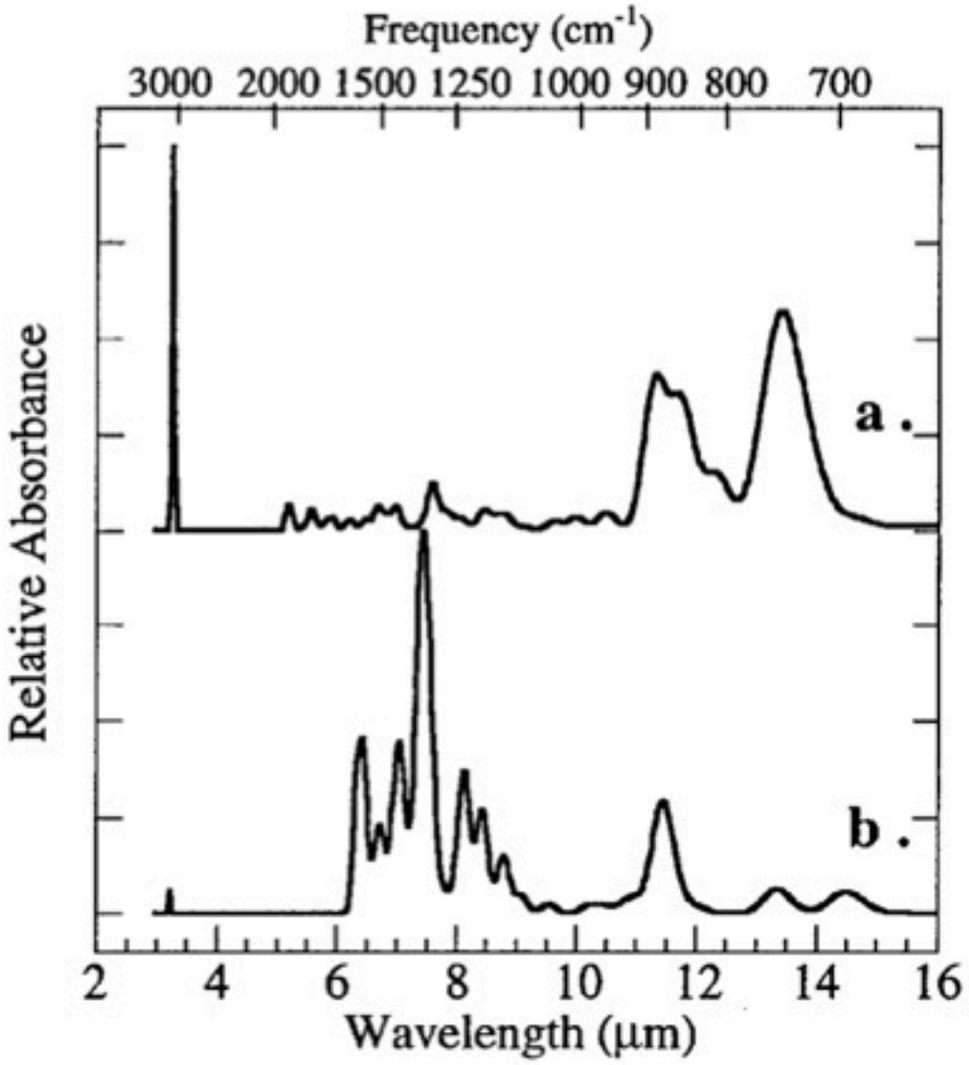
Other examples: **CO emission** in inner disks(-gaps):

- **T Tauri stars** (Salyk et al. 2007, 2009)
- **HD 135344 B** (Pontoppidan et al. 2008, Carmona 2014)
- **HD 142527** (Casassus et al. 2013, Valentin et al. 2014)
- **Oph IRS 48** (Brown et al. 2012, Bruderer 2014)

key question:

How can we use PAHs to trace disk structures?

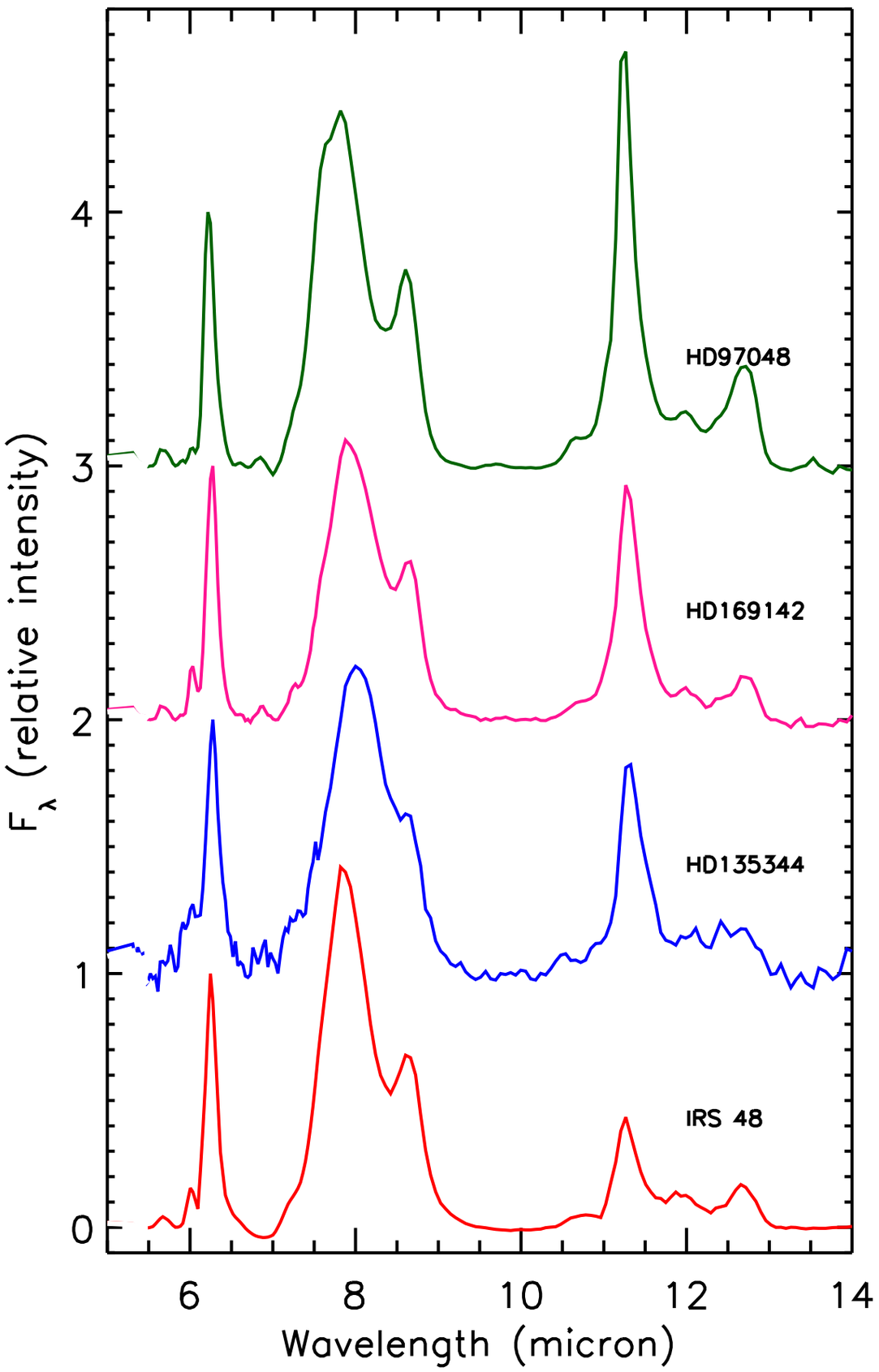
neutral and ionized PAH spectra:



Neutral

ionized

Allamandola et al 1999



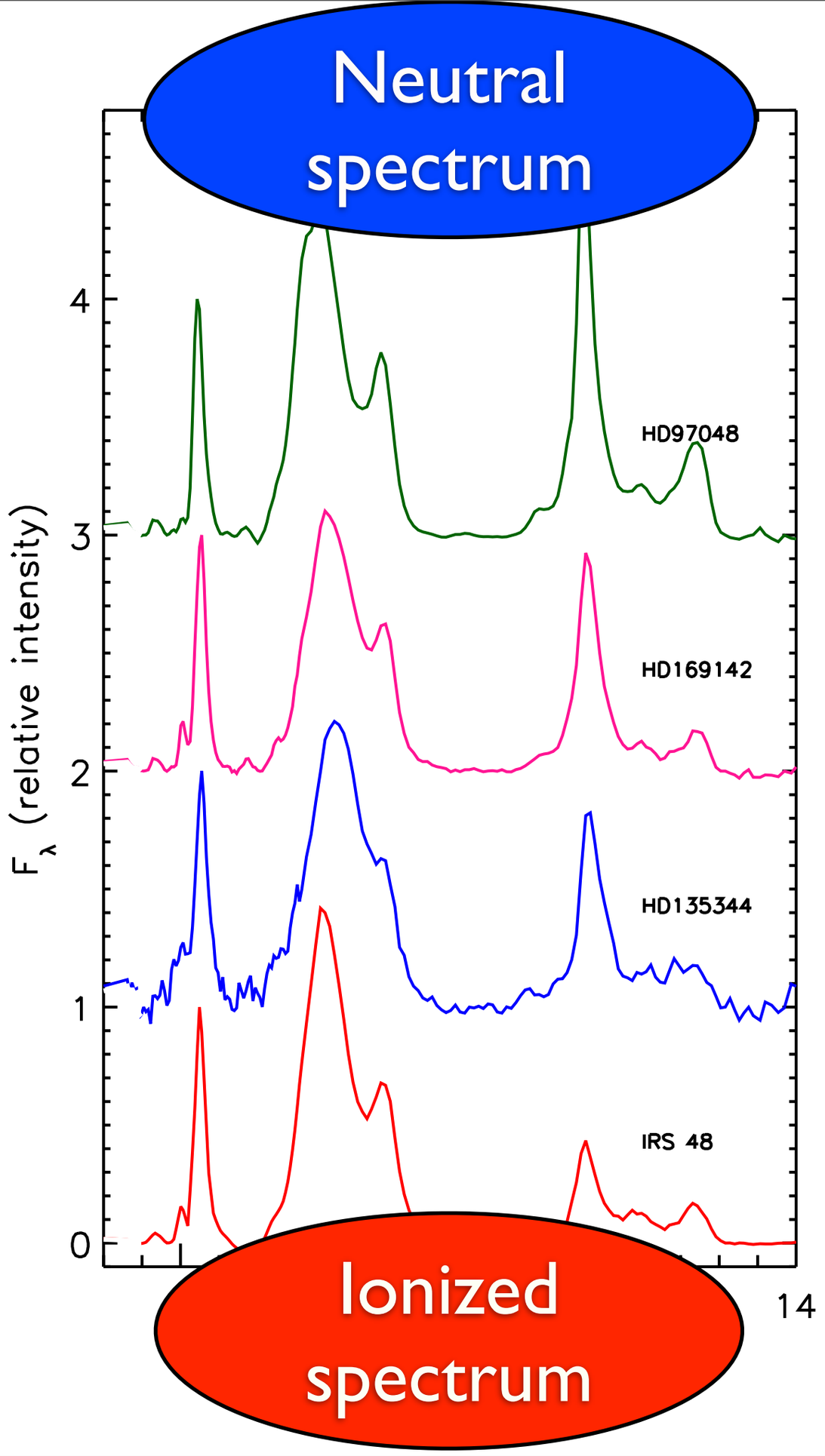
HD97048

HD169142

HD135344B

Oph IRS 48

Maaskant et al 2013, 2014



HD97048

HD169142

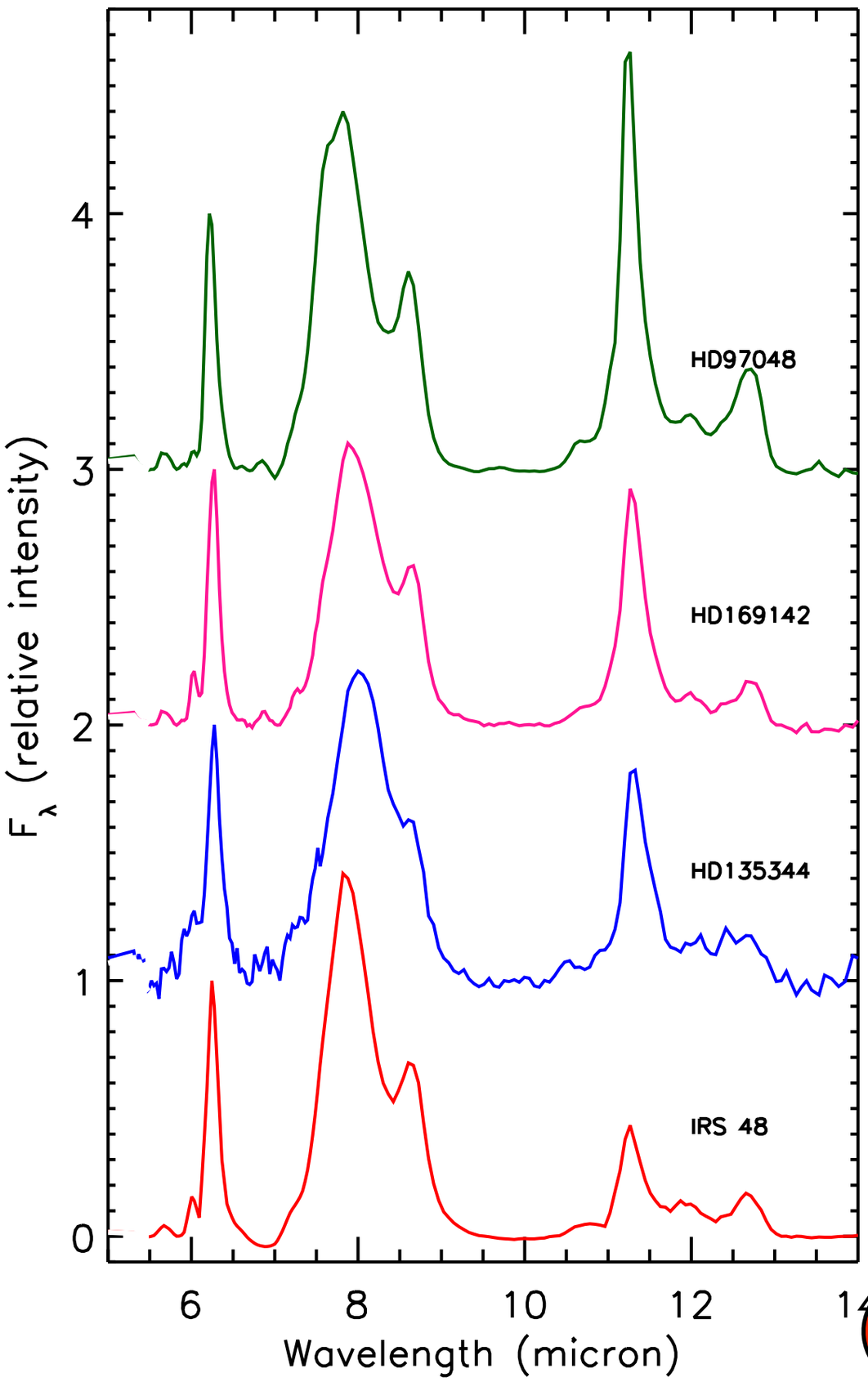
HD135344B

Oph IRS 48

Maaskant et al 2013, 2014

outer disk

Lagage 2006
Doucet 2006



HD97048

HD169142

HD135344B

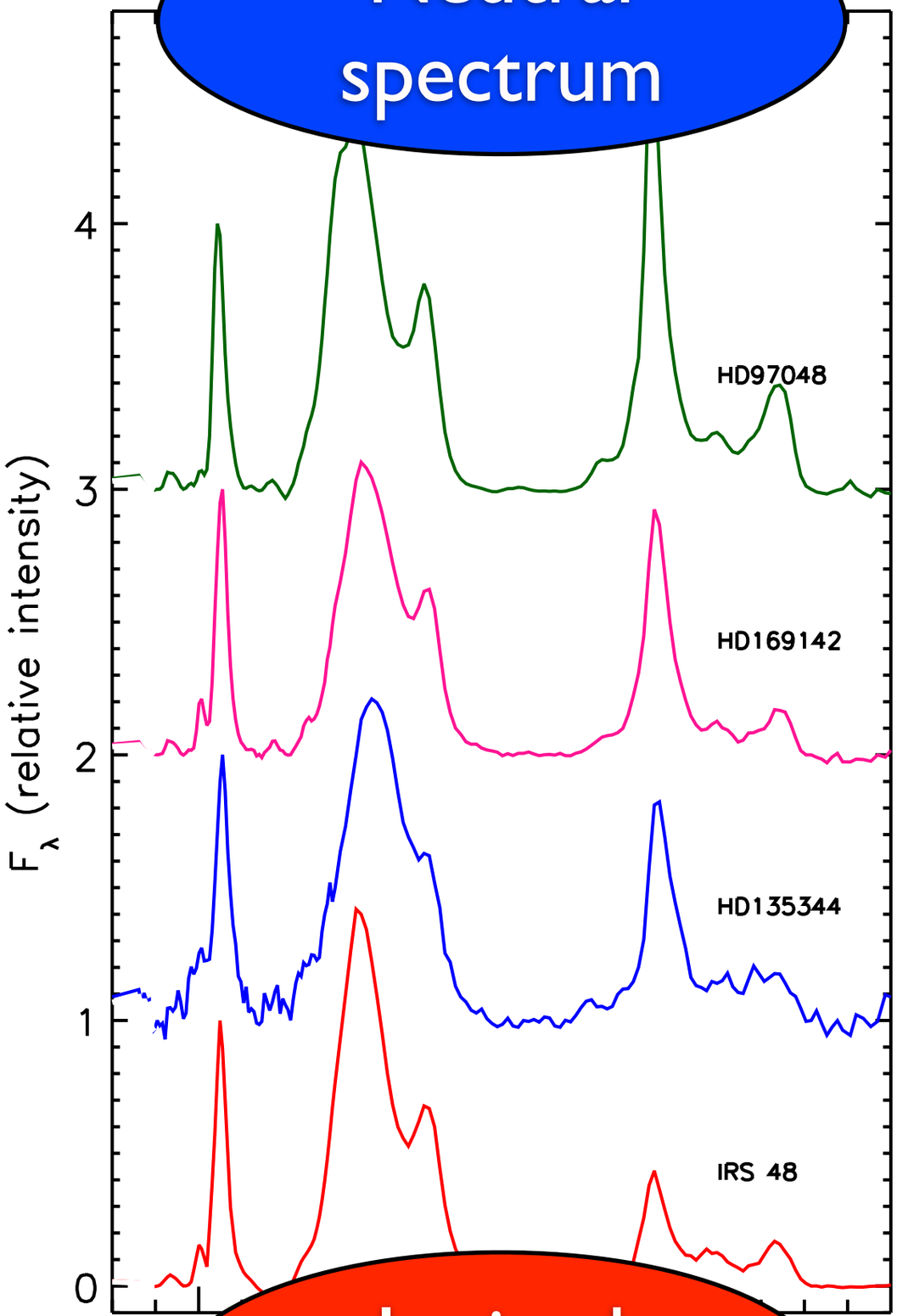
Oph IRS 48

Geers 2007

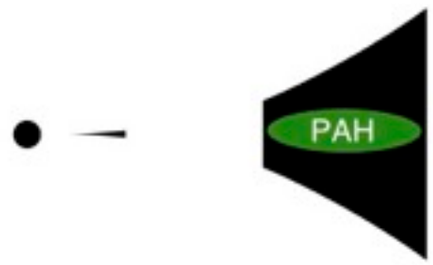
gap

Neutral spectrum

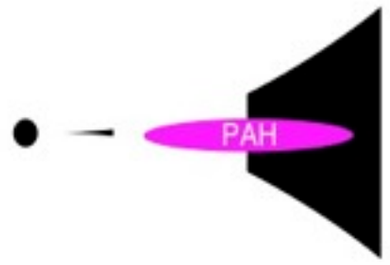
outer disk



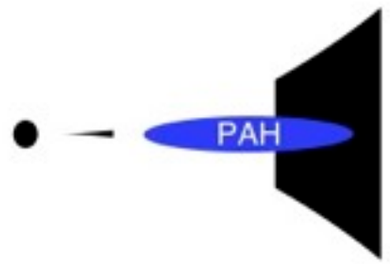
HD97048



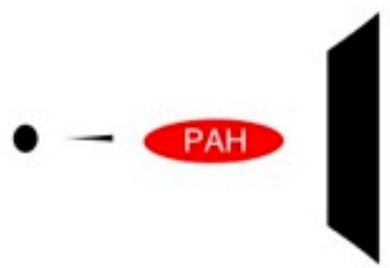
HD169142



HD135344B



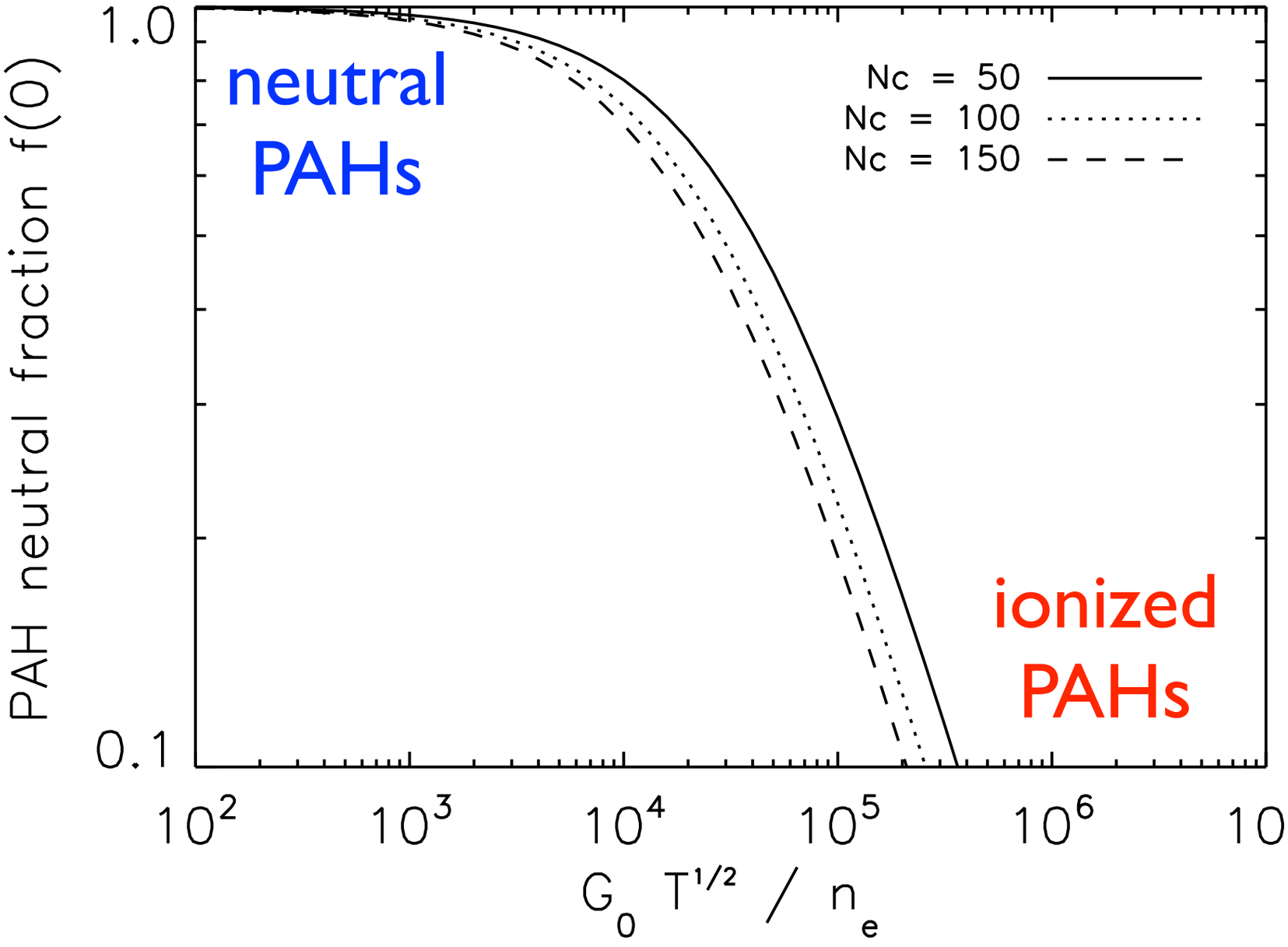
Oph IRS 48



Ionized spectrum

gap

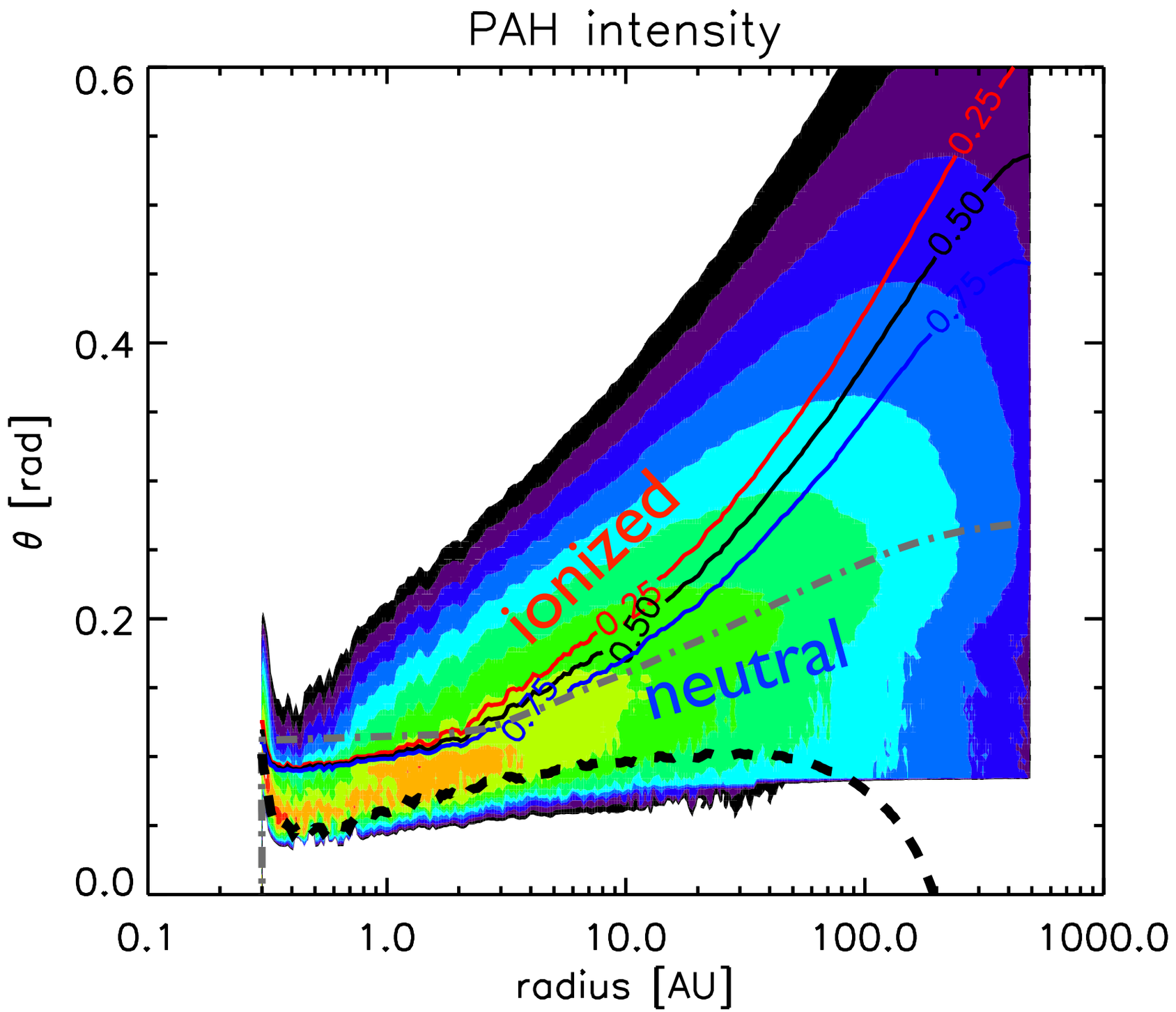
PAH model in RT code MCMax (Min et al 2009)



Bakes & Tielens 1994
Tielens 2005
Galliano 2008

Benchmark model

~90 %
neutral
at all radii

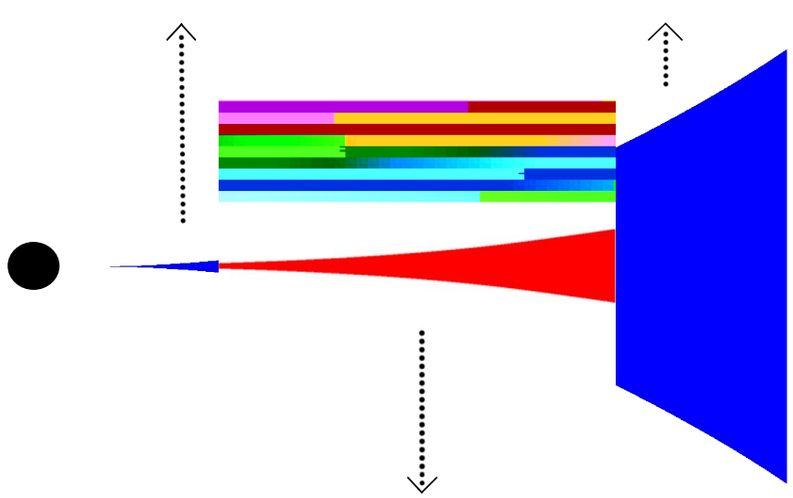


How to get ionized PAHs in disks?

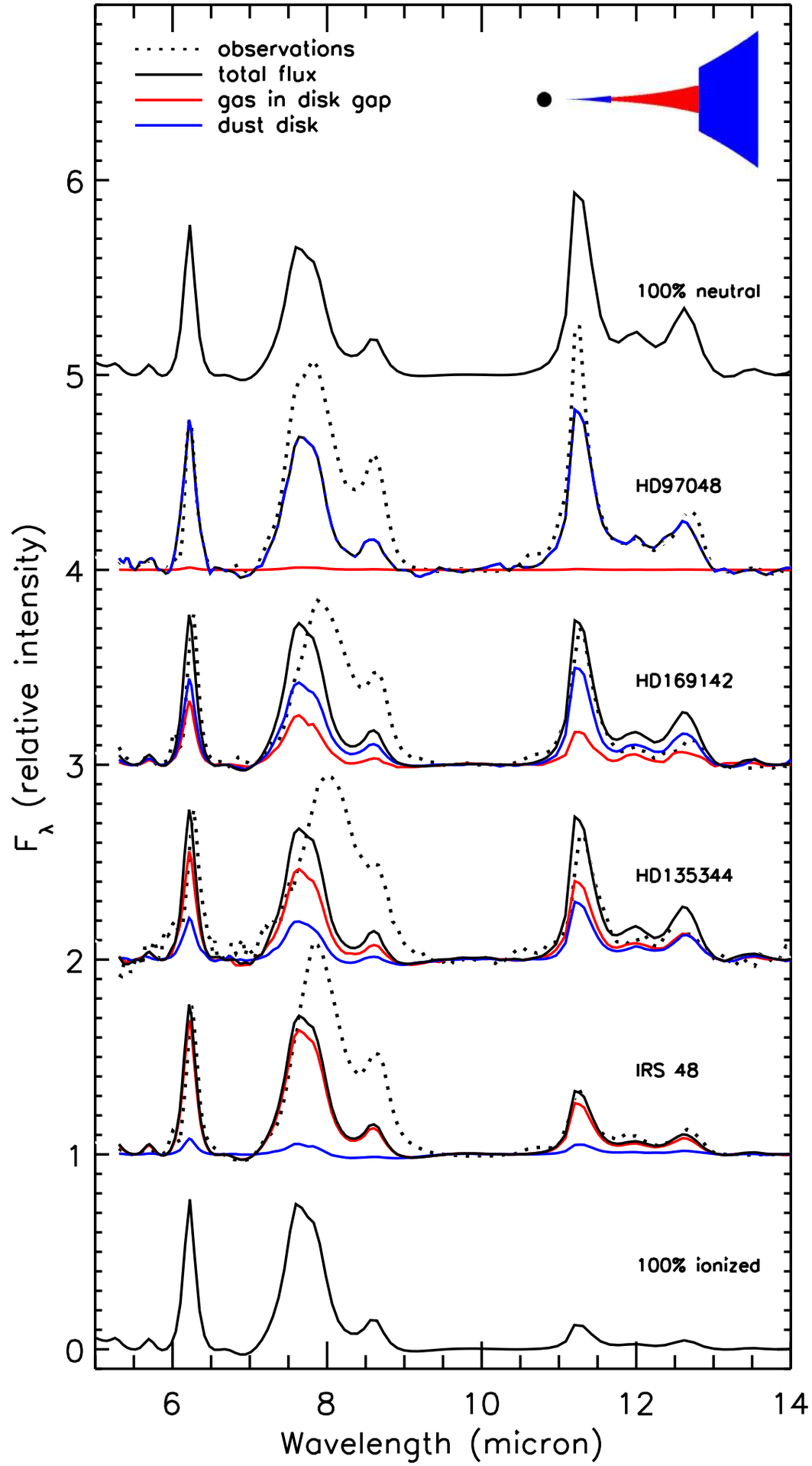
Optically thin gaps!

Demonstration: RT models of four transitional disks

neutral PAHs

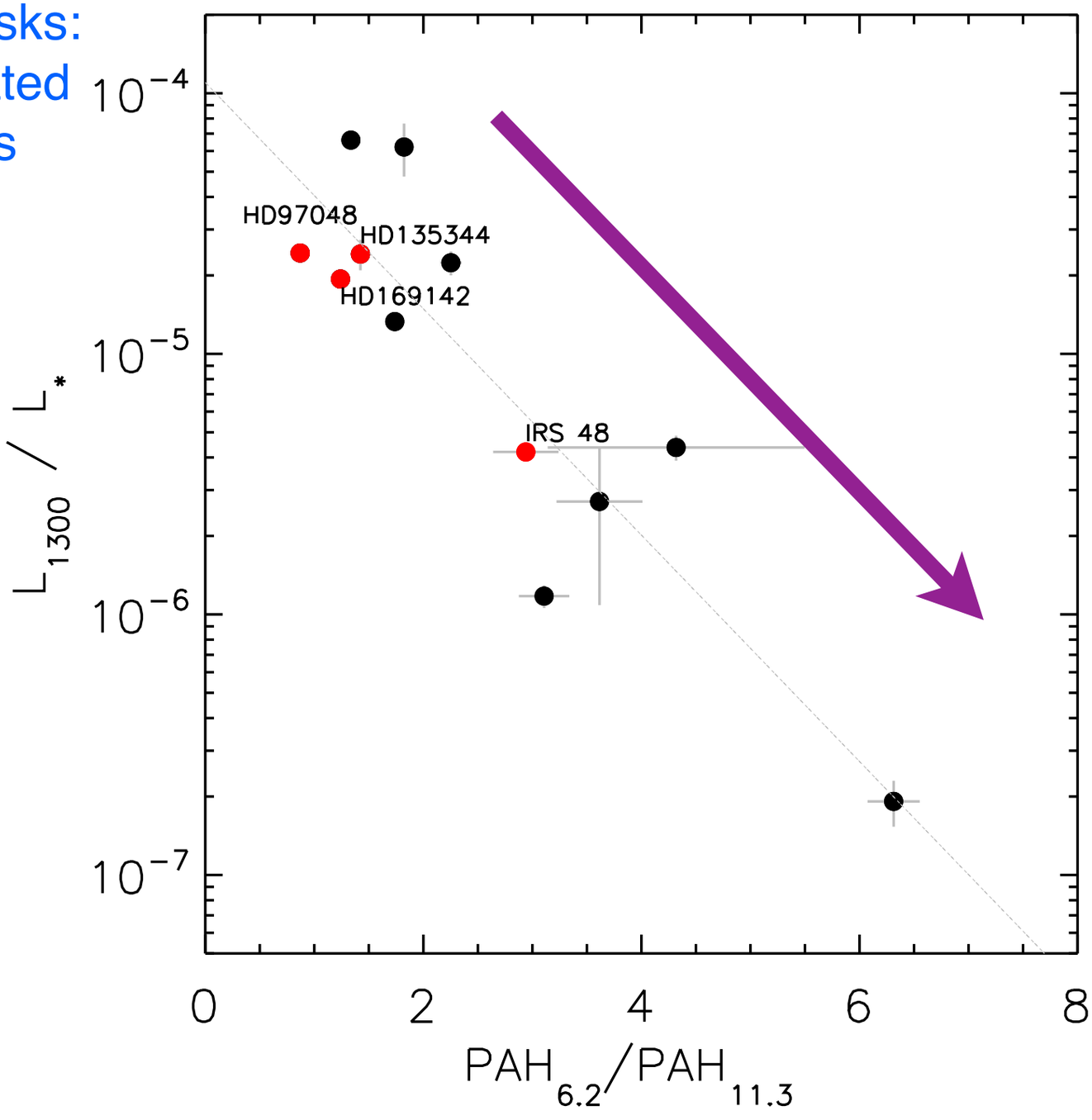


ionized PAHs



Trend:
mm luminosity (disk mass) vs PAH ionization

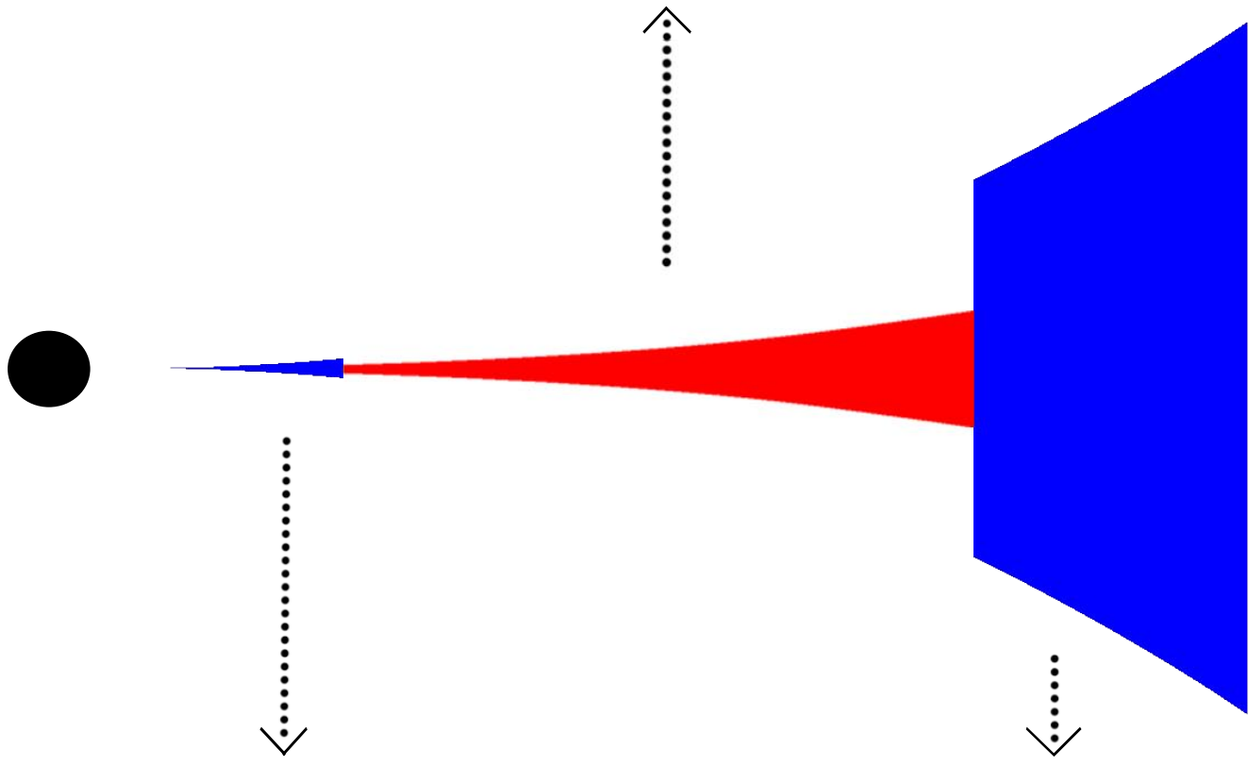
Higher mass disks:
spectra dominated
by neutral PAHs



Lower mass disks:
spectra dominated by
ionized PAHs in gaps

Conclusion

Ionized PAHs in low density, optically thin gas flows through the gap (high UV field, low electron density)



Neutral PAHs in optically thick disk (low UV field, high electron density)

Future:

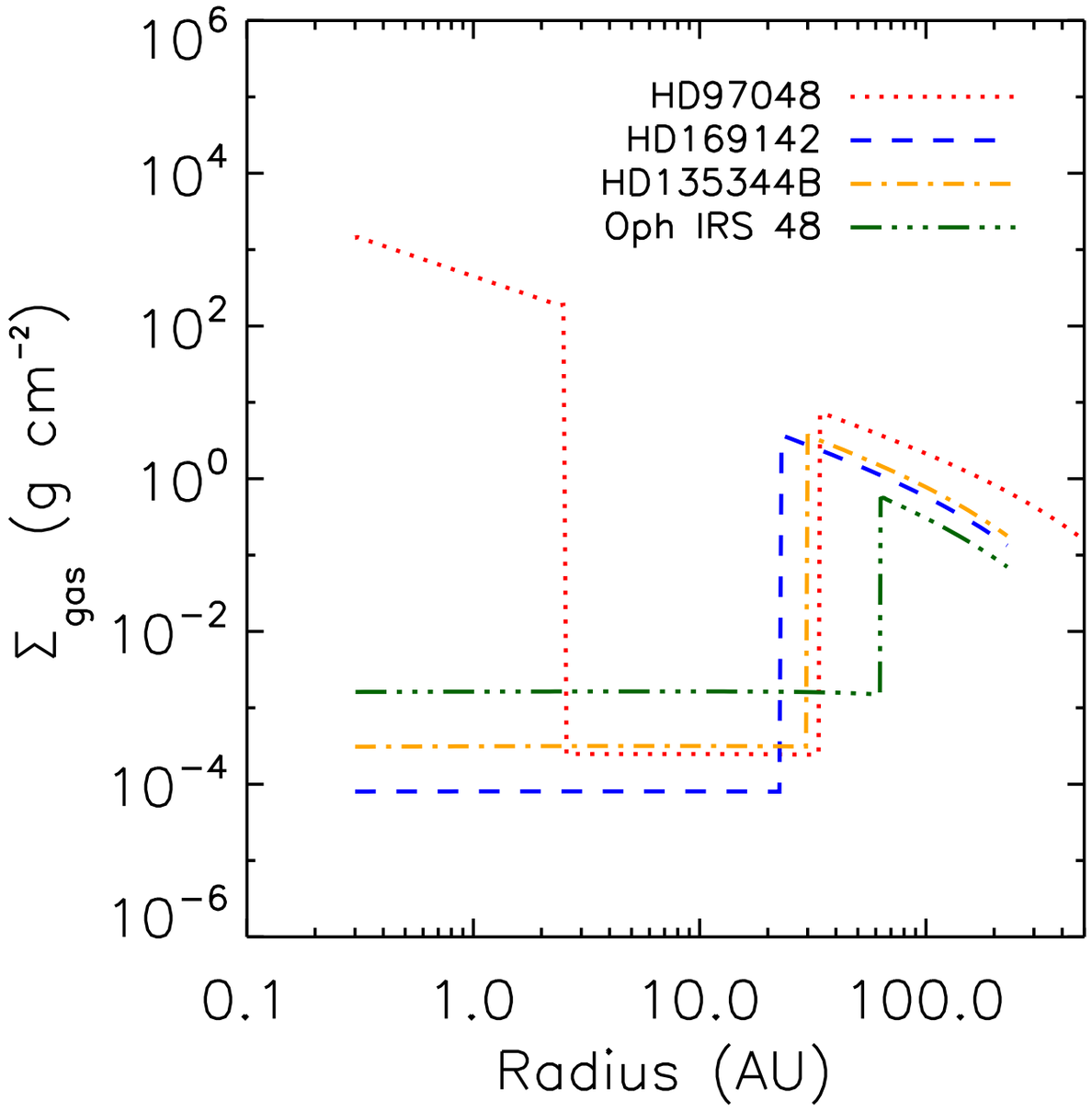
- Low abundance of PAHs in gap can give strong features, is that also true for other gas tracers?

- **Observational**: imaging of ionized versus neutral PAH bands (E-ELT/METIS, JWST/MIRI)

- **Modeling**: what is the influence of PAHs on gas and dust in the disk (and gap).

back-up slides

Demonstration: PAH models of four transitional disks



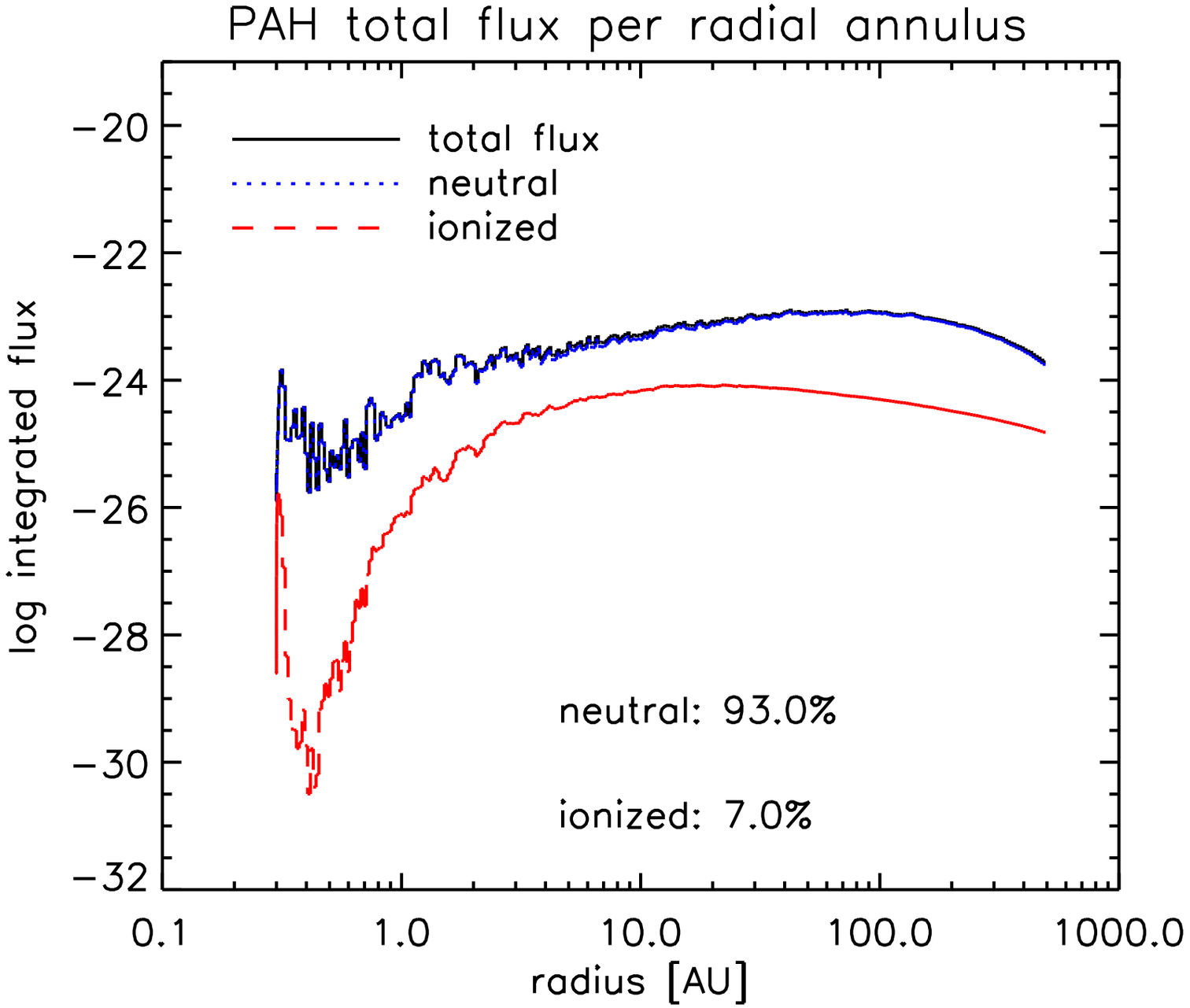
Benchmark model

Table 2: Parameters of benchmark model

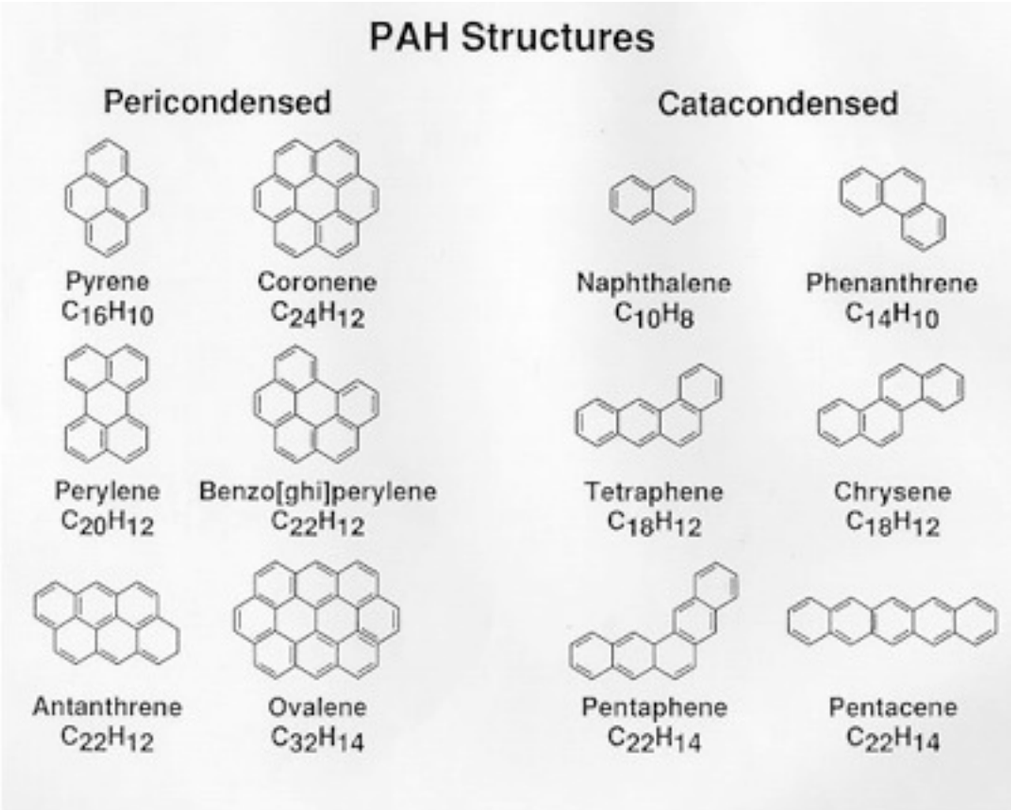
Parameter			value
Stellar temperature	T_*	=	10 000 K
Stellar luminosity	L_*	=	40 $L_\odot$
Stellar radius	R_*	=	2.12 $R_\odot$
Stellar mass	M_*	=	2.5 $M_\odot$
Distance	d	=	158 pc
Inner disk radius	R_{in}	=	0.3 AU
Outer disk radius	R_{out}	=	500 AU
Disk mass	M_{disk}	=	5×10^{-2} $M_\odot$
Dust mass	M_{dust}	=	5×10^{-4} $M_\odot$
Silicate mass	M_{Si}	=	0.8 M_{dust}
Carbon mass	M_C	=	0.2 M_{dust}
PAH mass	M_{PAH}	=	10^{-3} M_{dust}
Carbon atoms in PAH	N_C	=	100
Min dust size	a_{min}	=	1 μm
Max dust size	a_{max}	=	1 mm
Dust-size powerlaw index	a_{pow}	=	-3.5
Surface density powerlaw	p	=	-1

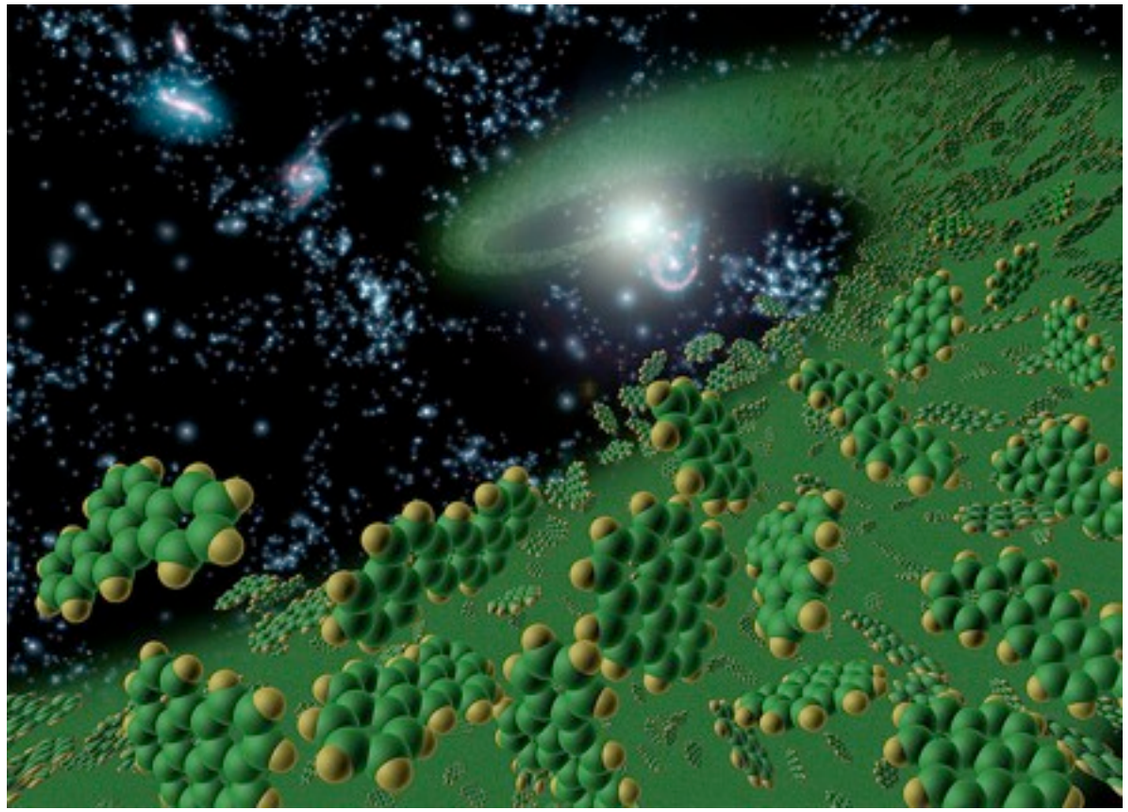
Benchmark model

In an optically thick disk, PAHs are neutral



Polycyclic Aromatic Hydrocarbon molecules





gas in dust depleted gaps

evidence of planet formation?

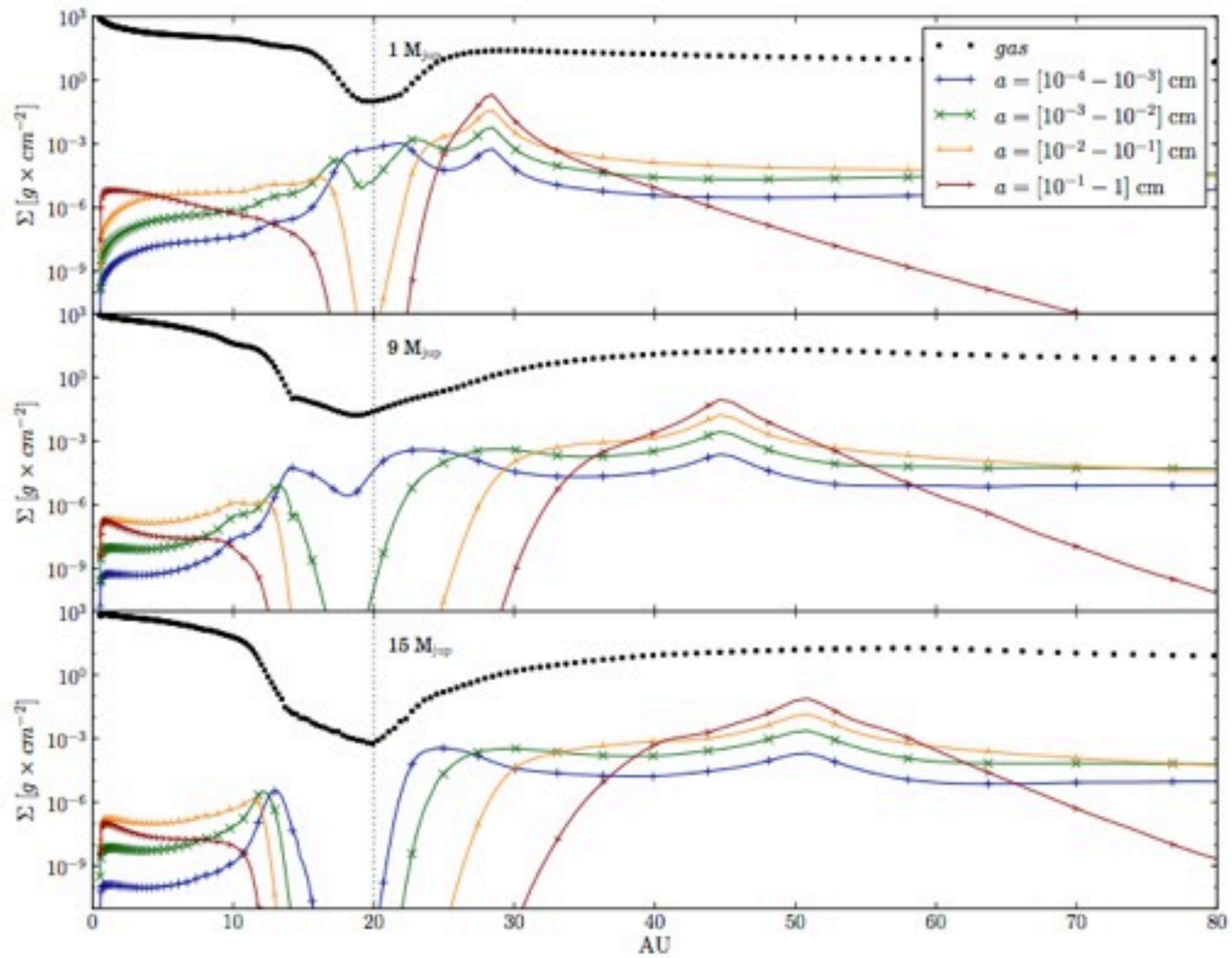
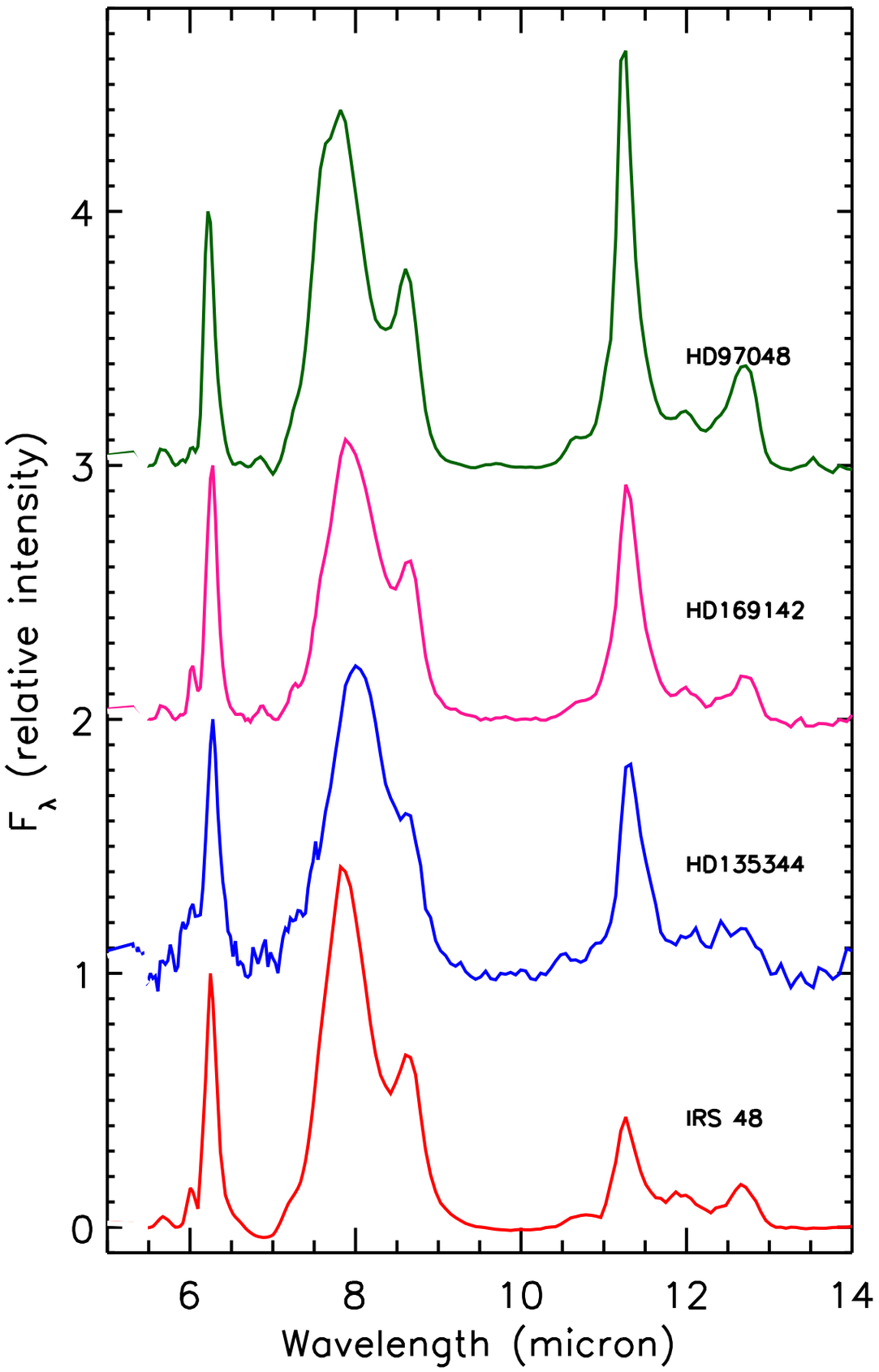
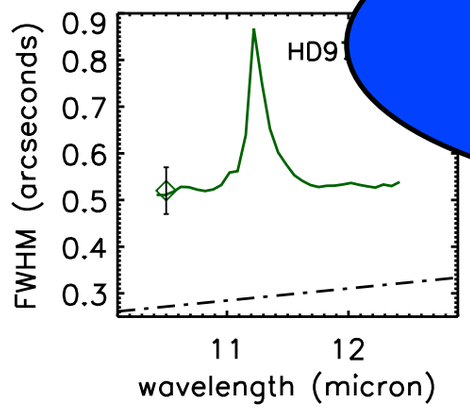
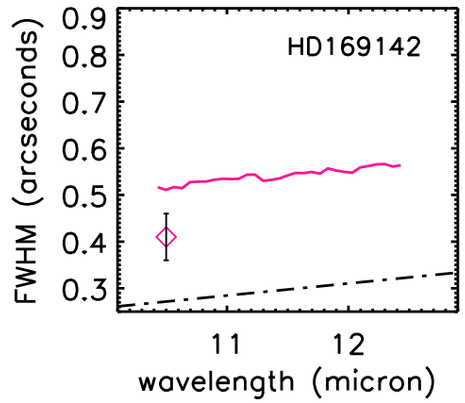


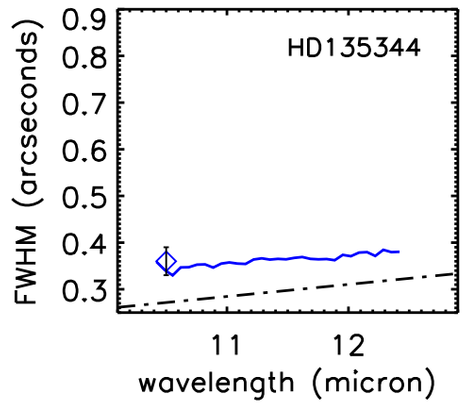
Fig. 7: Surface density profiles for gas and different dust particle size ranges for the three planet mass cases, i.e. $M_p = [1, 9, 15]\, M_{\rm Jup}$. The vertical dotted line indicates the position of the planet at 20 AU.

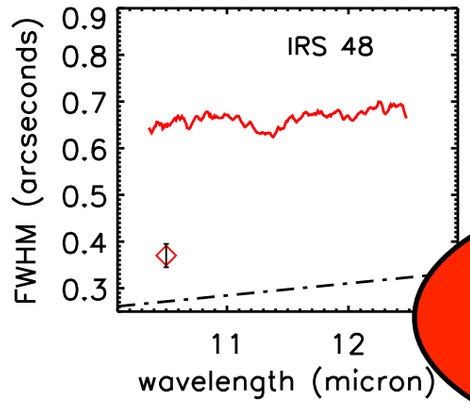
Pinilla 2013, de Juan Ovelar 2013







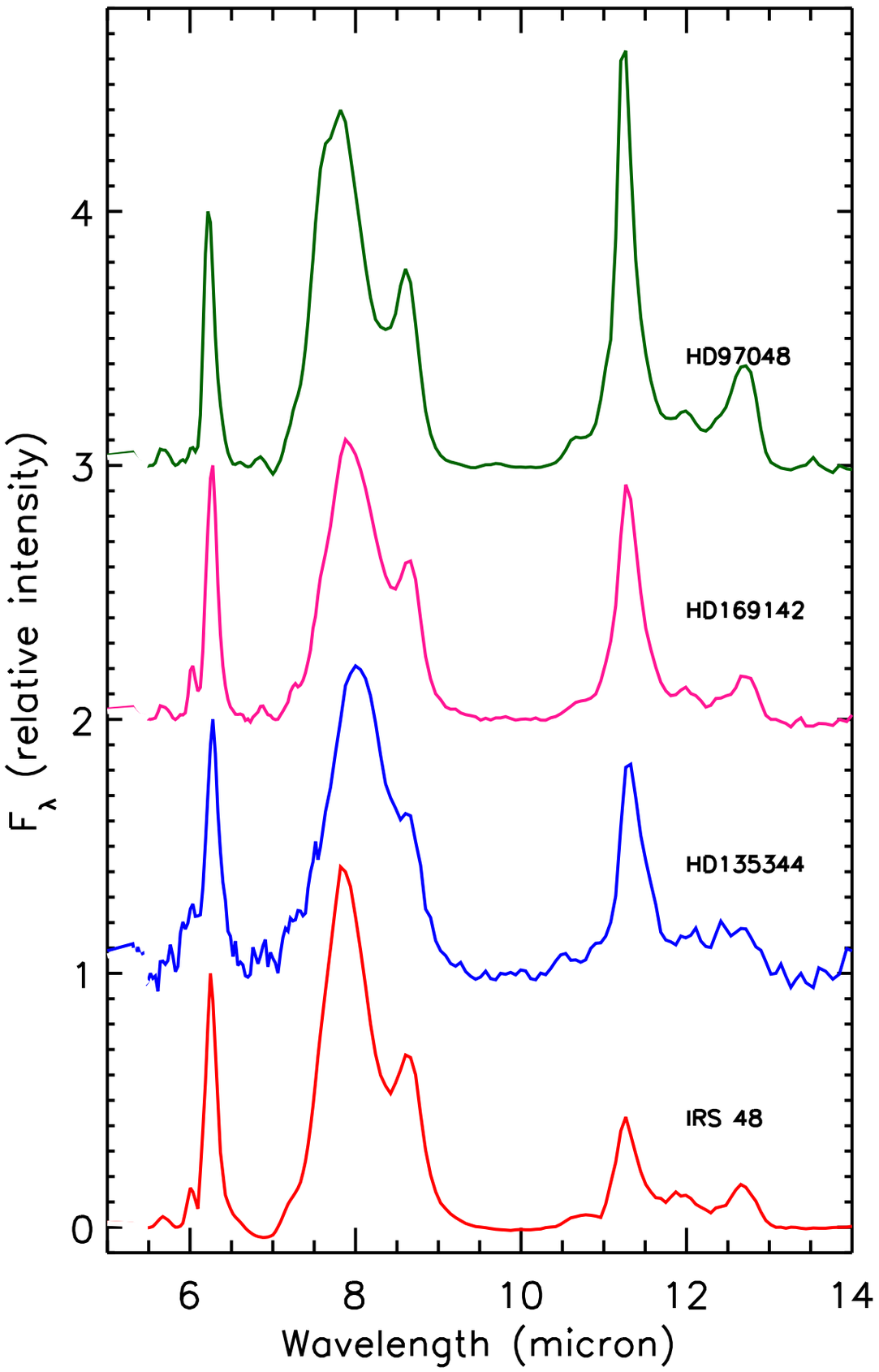


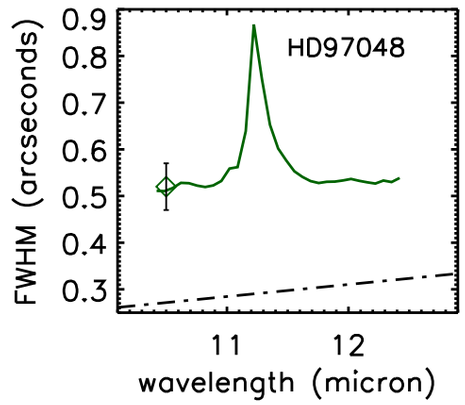


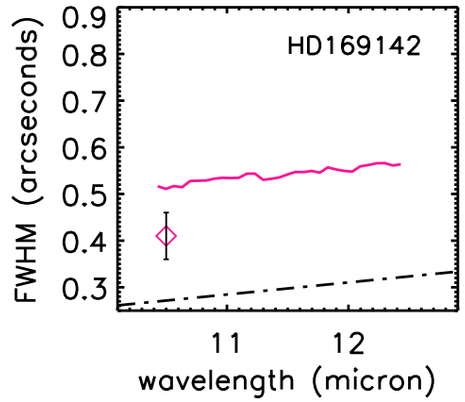
outer disk

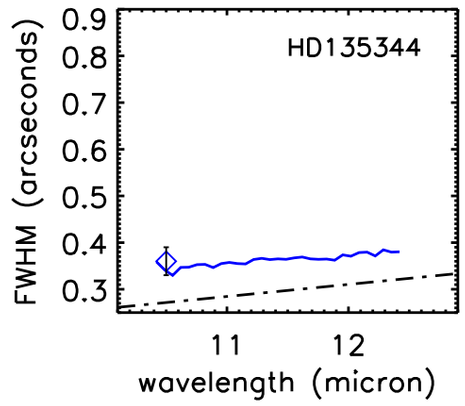
gap

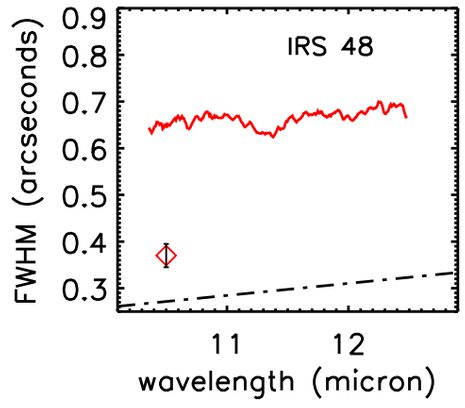
al 2013, 2014

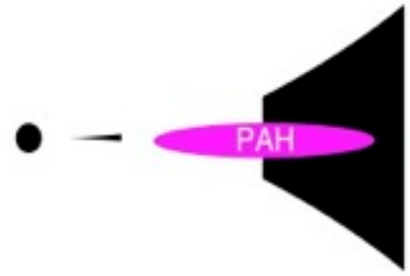


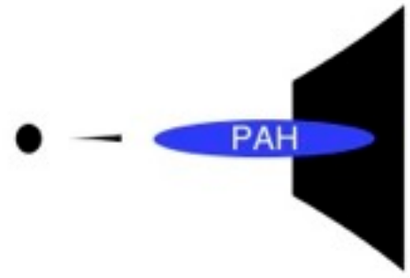






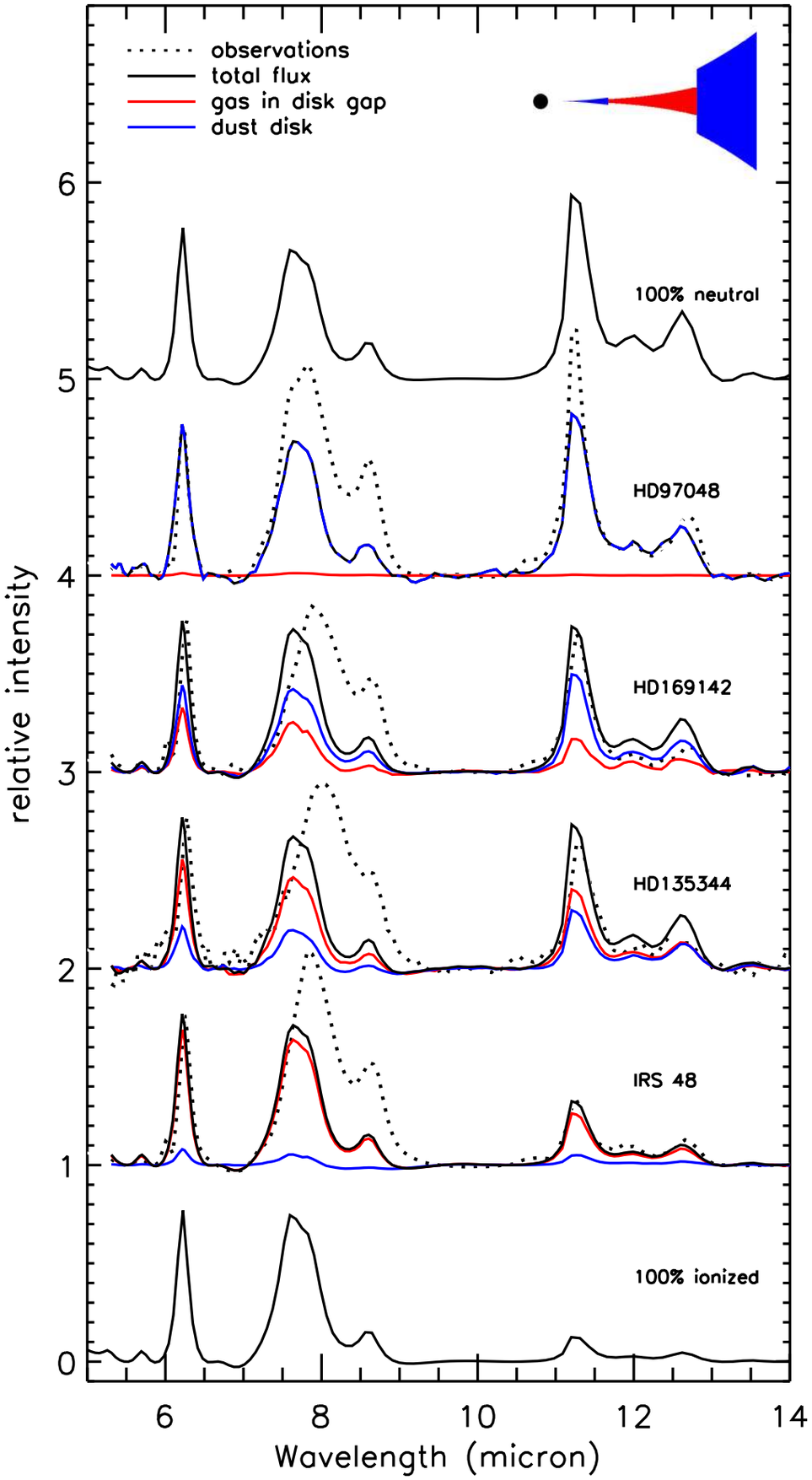






Geers et al 2007, Maaskant et al 2013, 2014

Demonstration: PAH models of four transitional disks

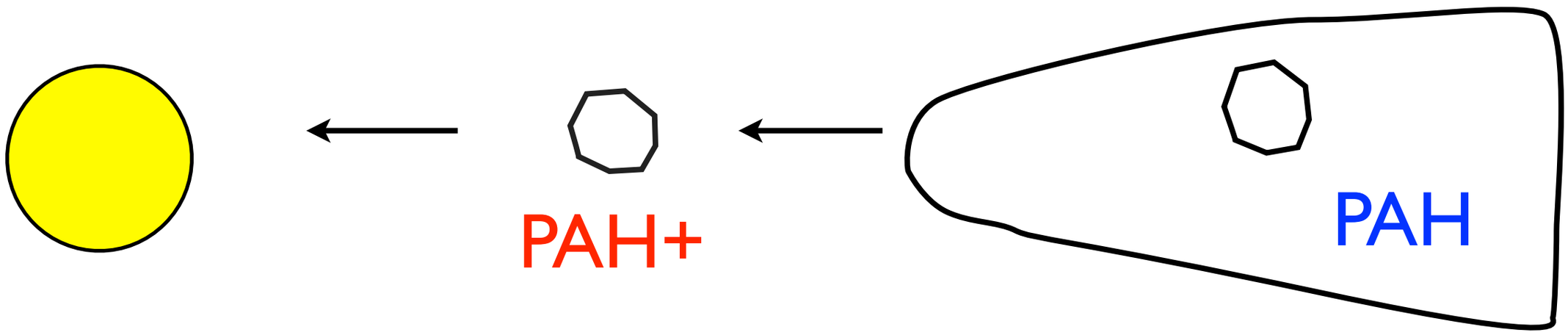


Conclusion

- Ionized PAHs trace low density, optically thin regions.

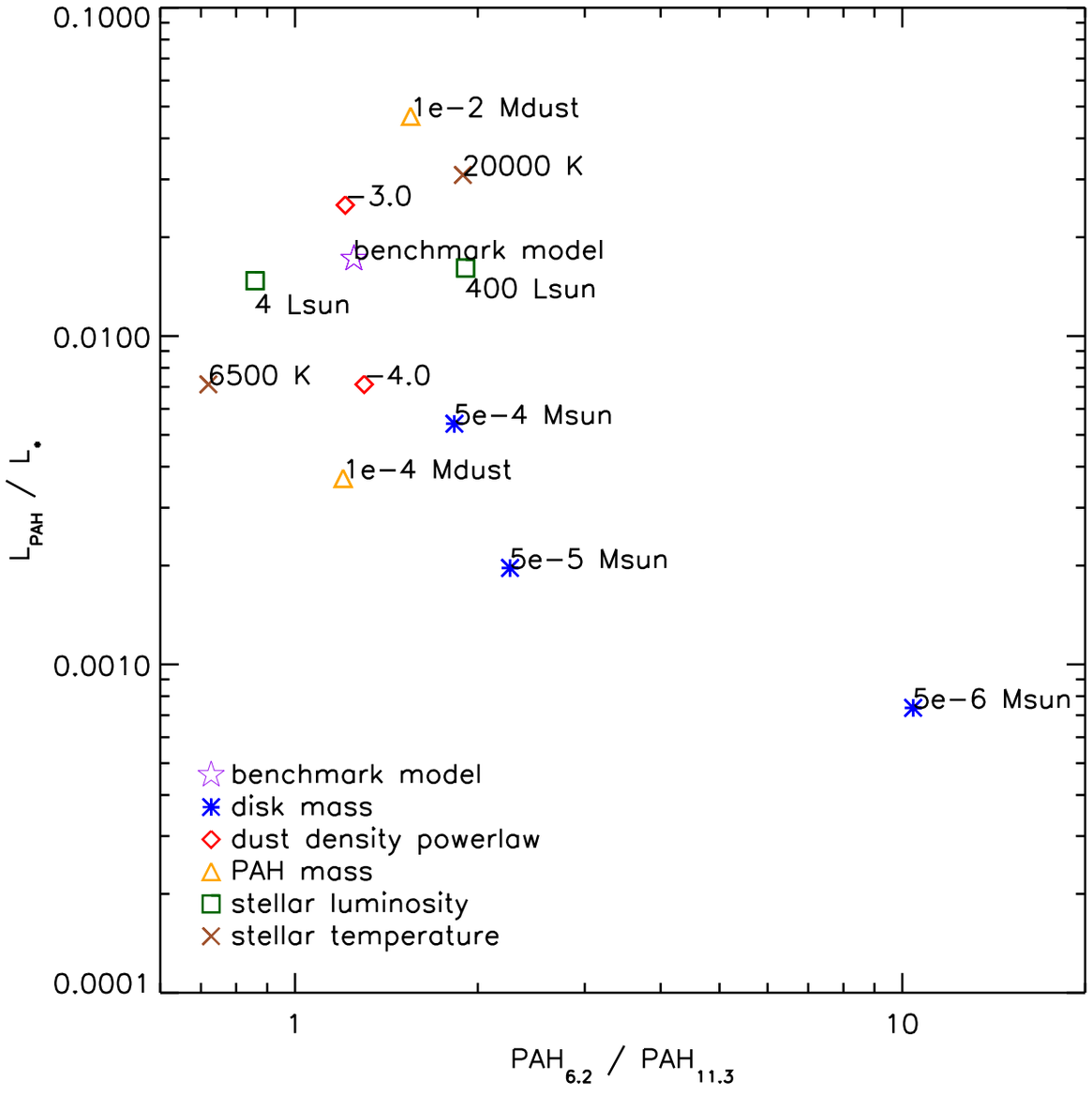
↓

- Ionized PAHs trace gas flows through proto-planetary disk gaps

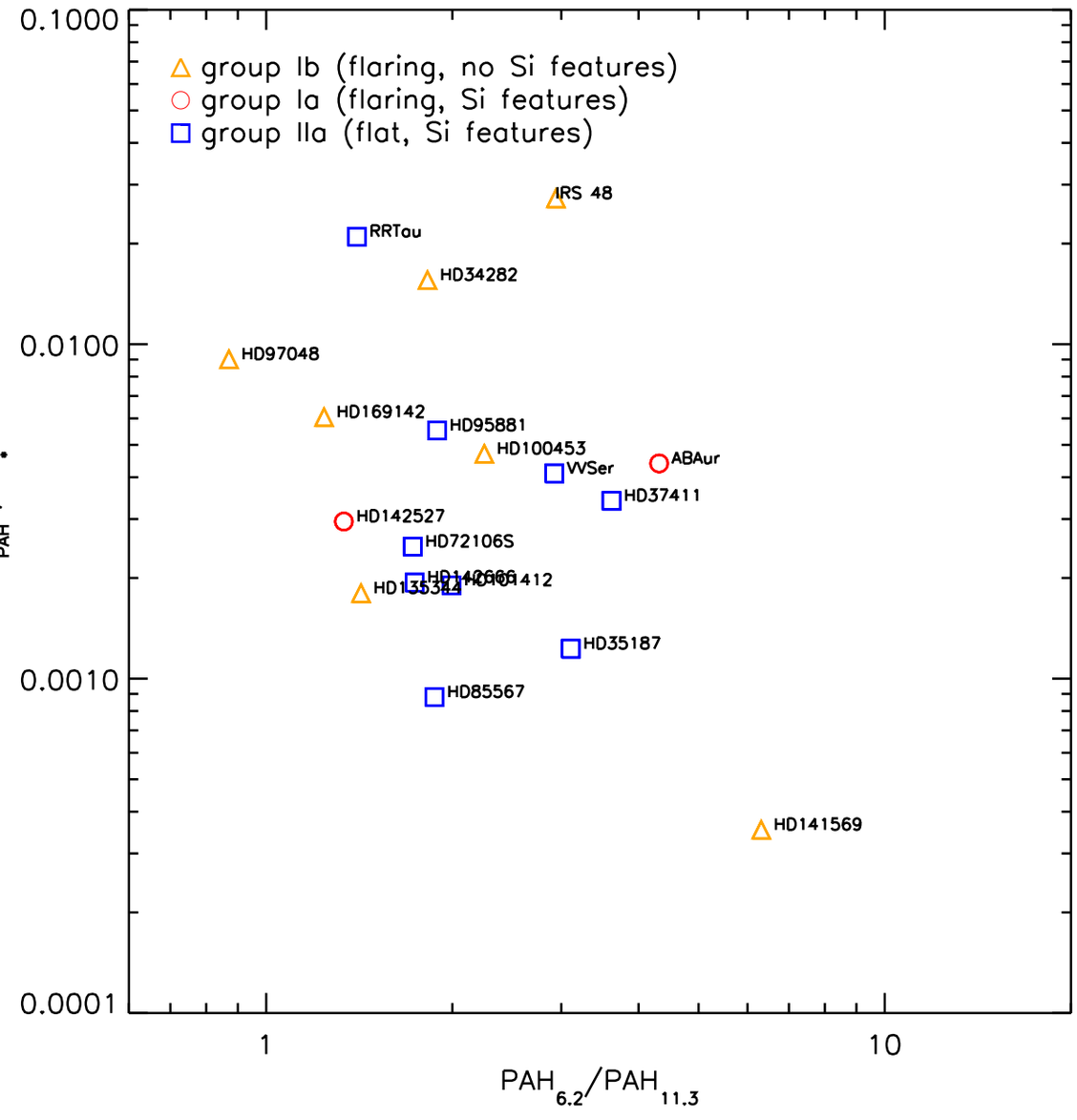


Benchmark parameter study

models



observations



gas in dust depleted gaps

evidence of planet formation?

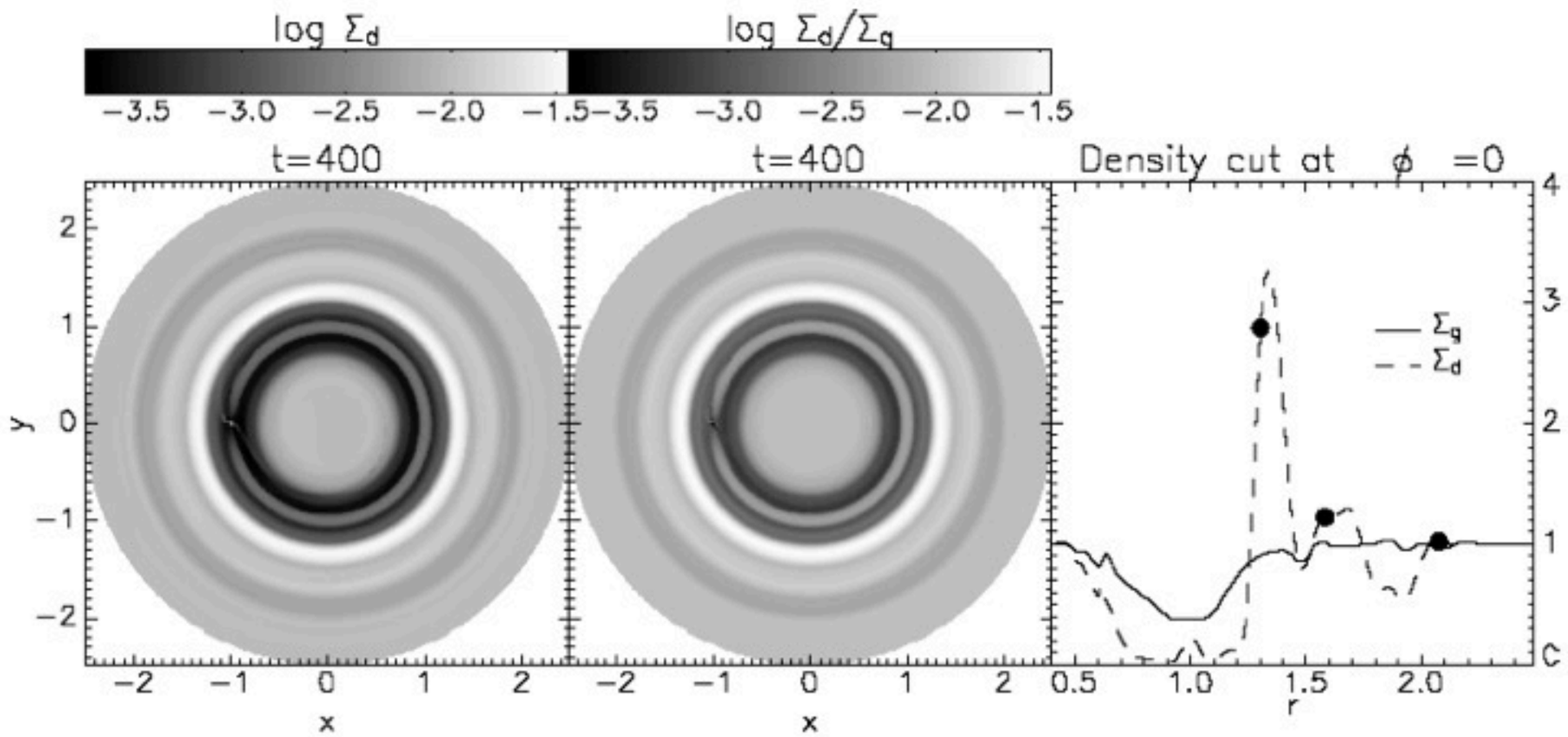
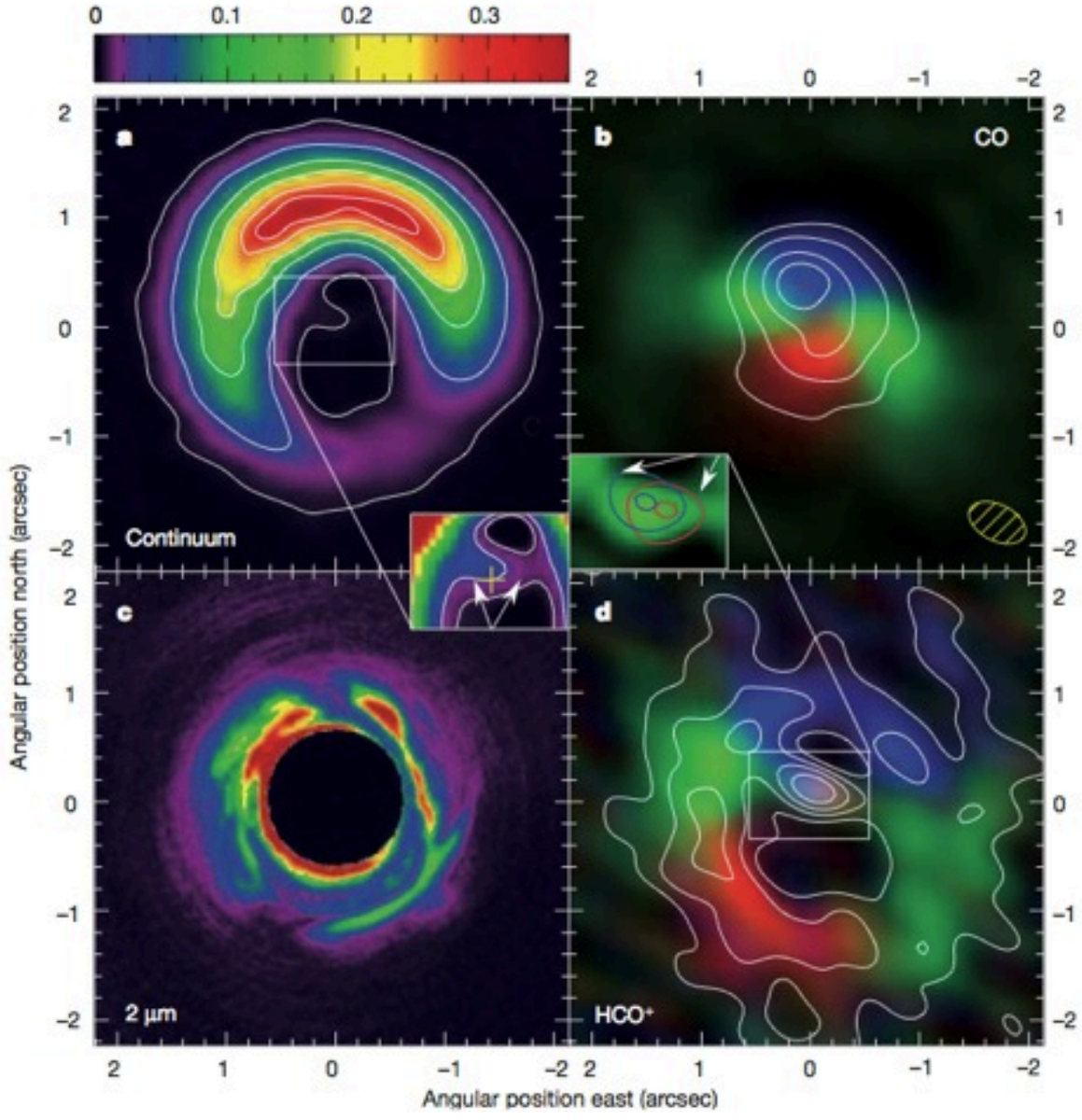


Fig. 1. Dust flow near a 0.1 M_J planet. *Left panel*: grey-scale plot of the logarithm of the dust surface density after 400 planetary orbits. *Middle panel*: logarithm of the dust-to-gas ratio. *Right panel*: radial cut at $\phi = 0$ (opposite to the planet). Solid line: gas surface density, dashed line: dust surface density ×100. The filled circles indicate the 3:2, the 2:1 and the 3:1 mean motion resonances.

Paardekoper & Mellema 2004

Transitional disks:

Gas in dust depleted gaps

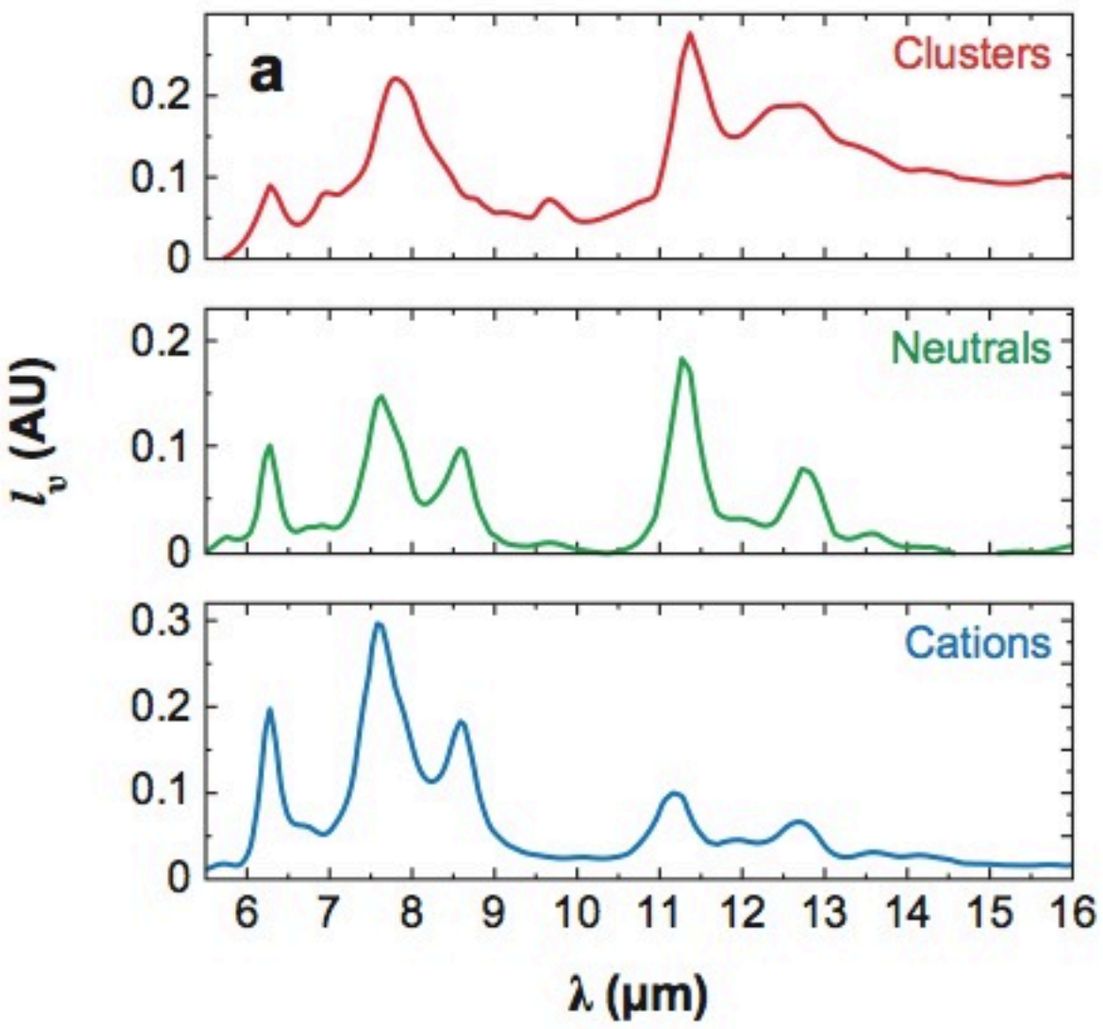


(HD142527, Casassus et al 2013)

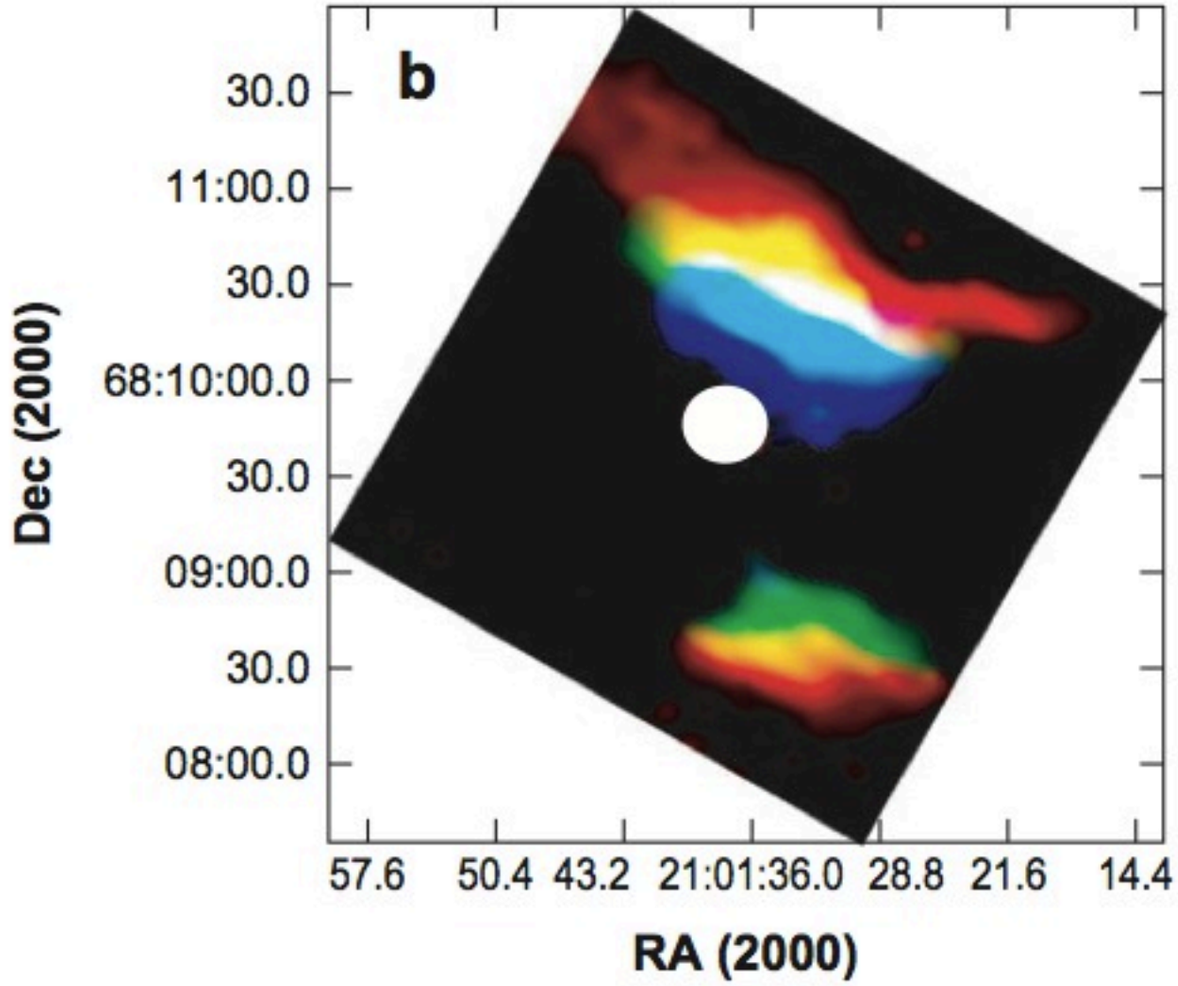
examples of **CO emission** in inner disks(-gaps):

- **T Tauri stars** (Salyk et al. 2007, 2009)
- **HD 135344 B** (Pontoppidan et al. 2008, Carmona 2014)
- **Oph IRS 48** (Brown et al. 2012, Bruderer 2014)
- **HD 142527** (Casassus et al. 2013, Valentin et al. 2014)

Ionization of PAHs



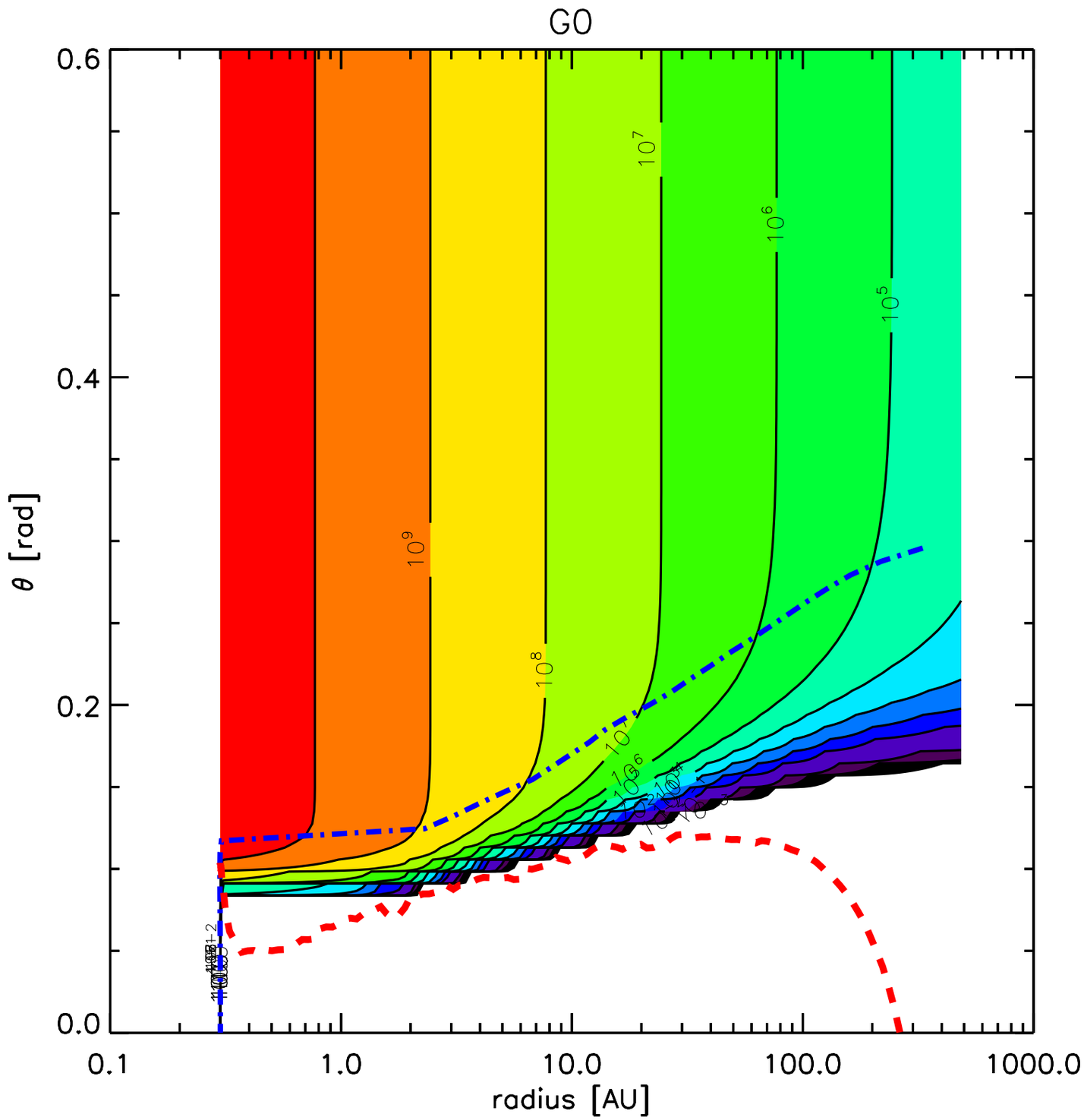
NGC 7023



Rapacioli, Joblin & Boissel 2005

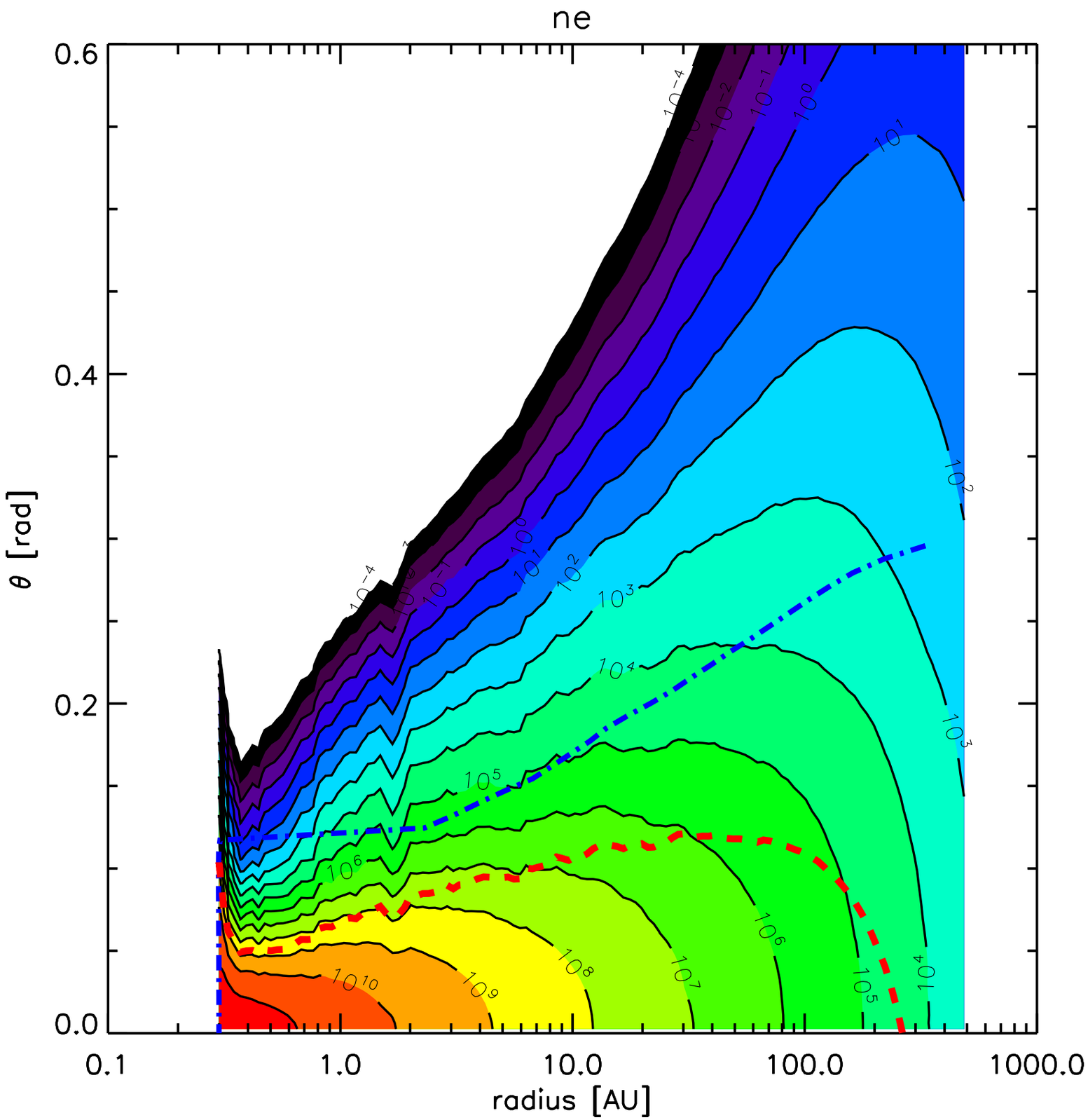
Benchmark model

G0 = UV field strength

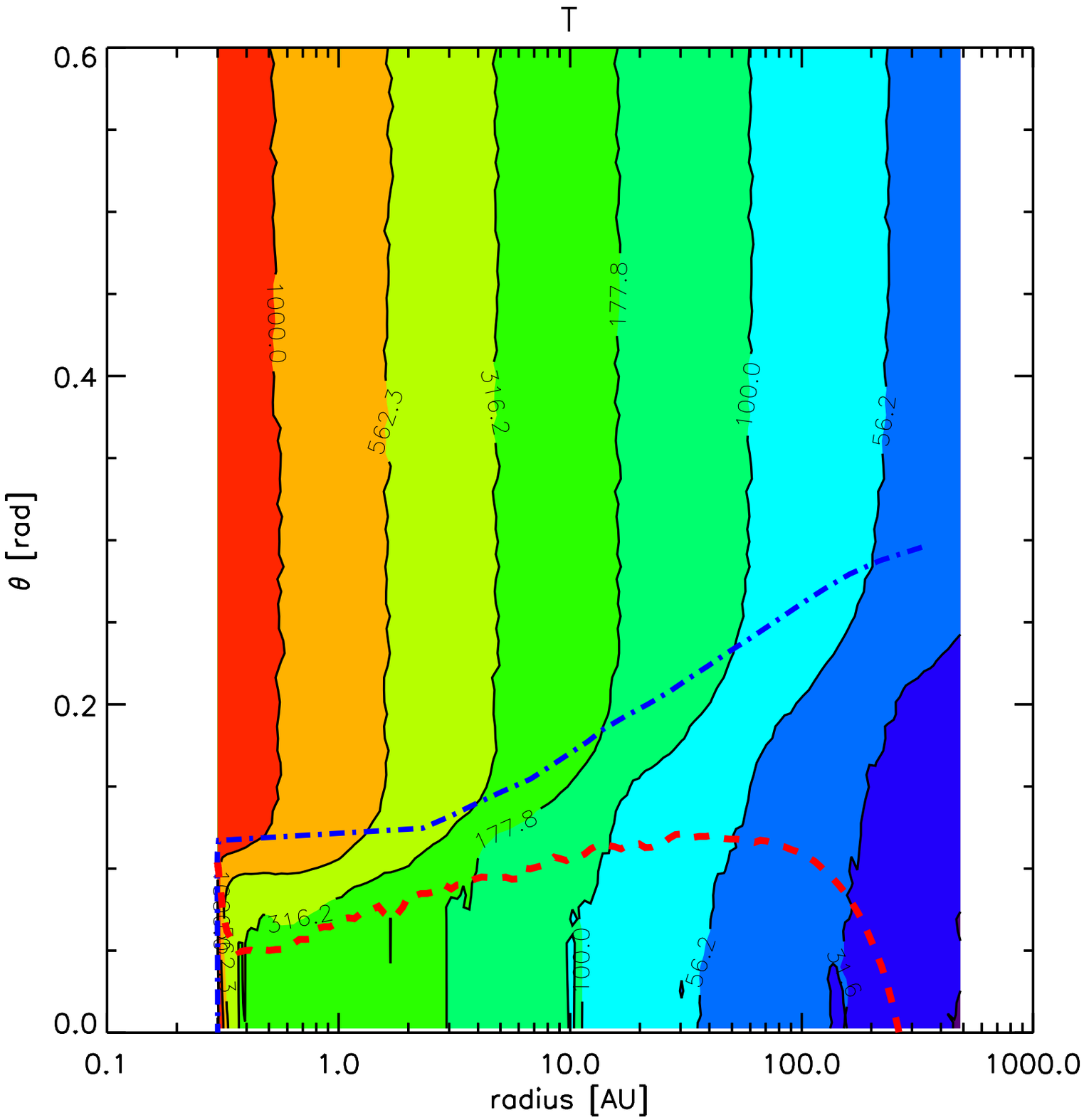


ne = electron density

Benchmark model



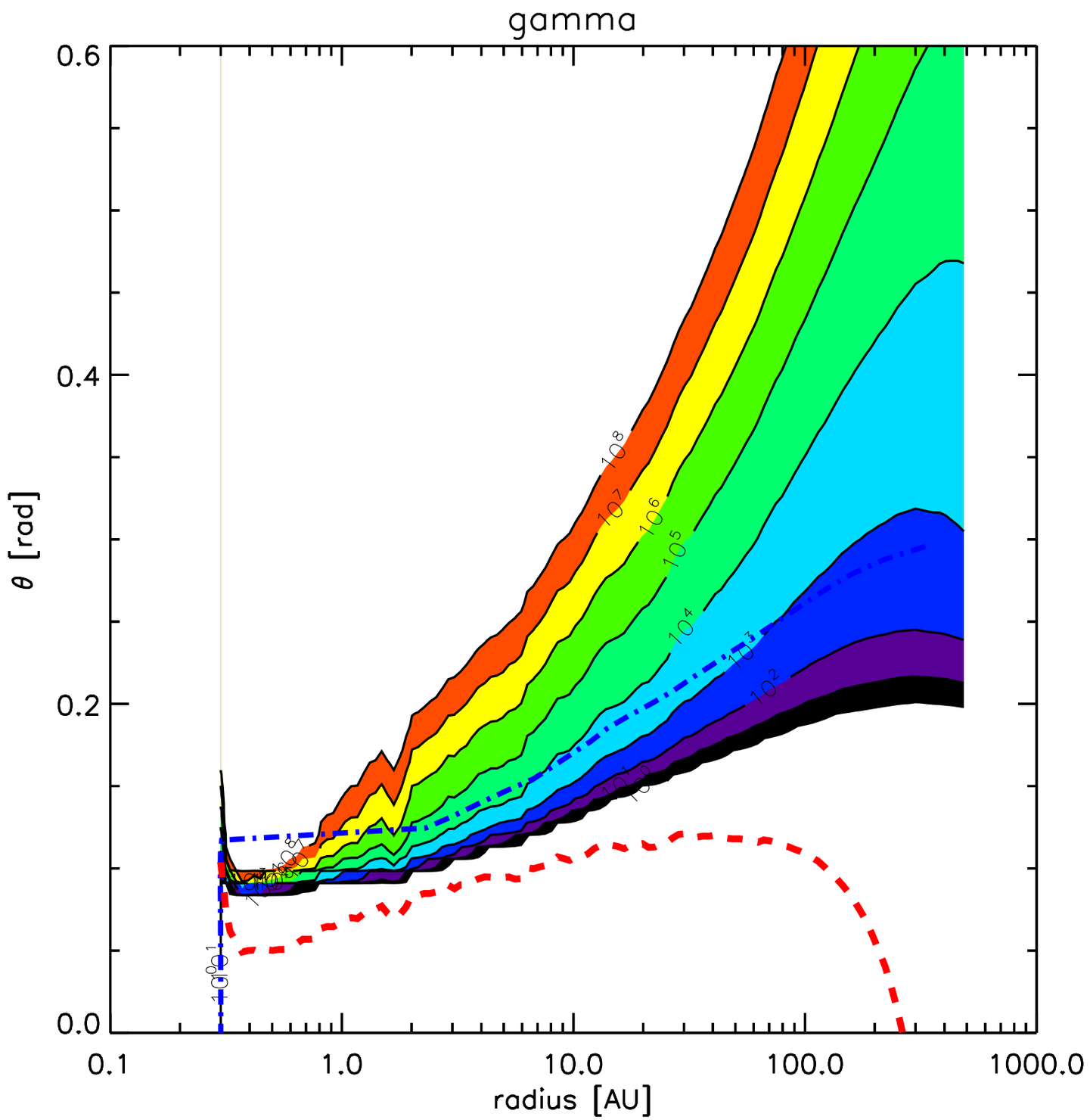
Benchmark model



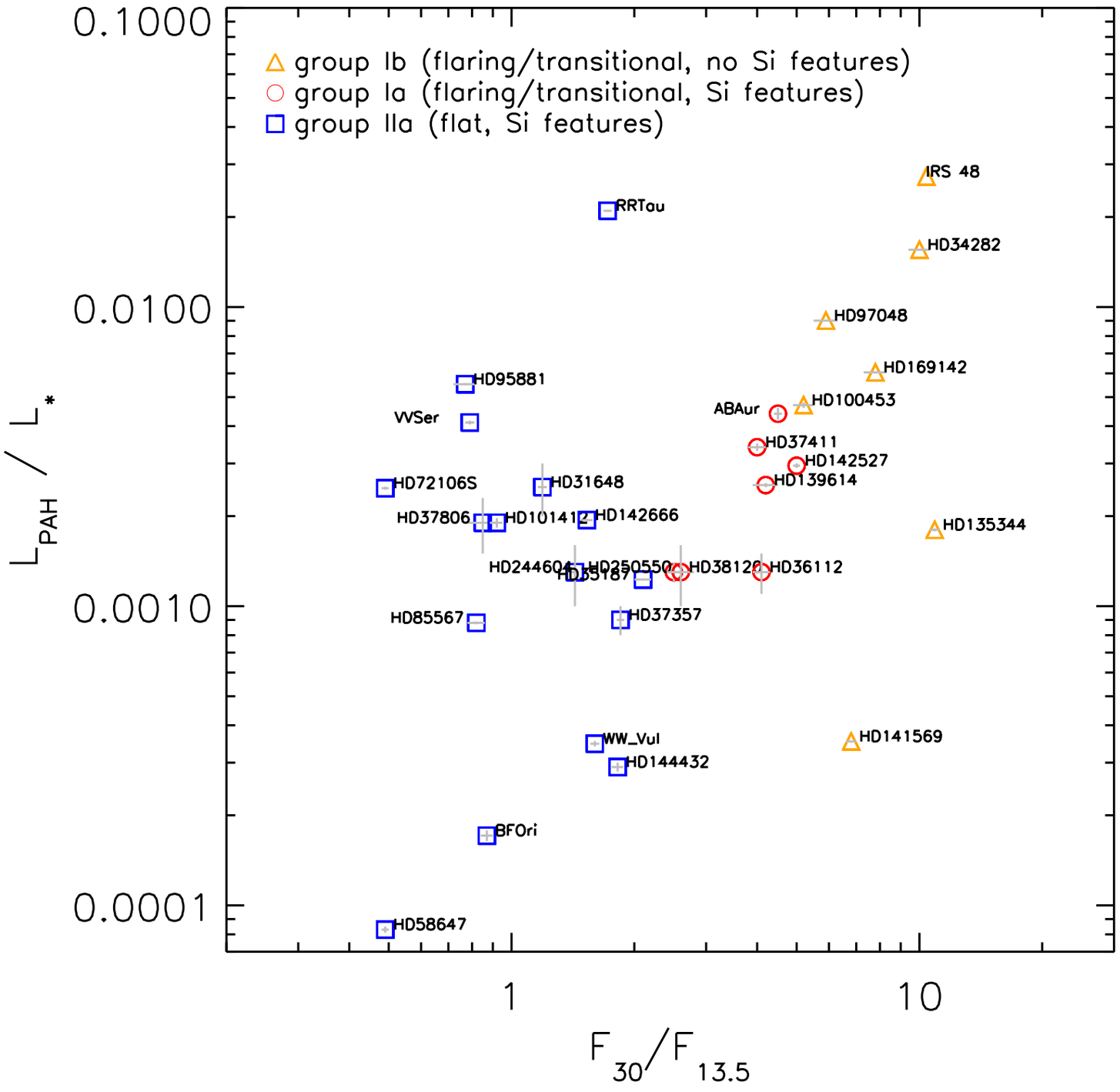
Benchmark model

$$\gamma_0 = 3.5 \times 10^{-6} N_c^{1/2} \frac{G_0 T^{1/2}}{n_e}$$

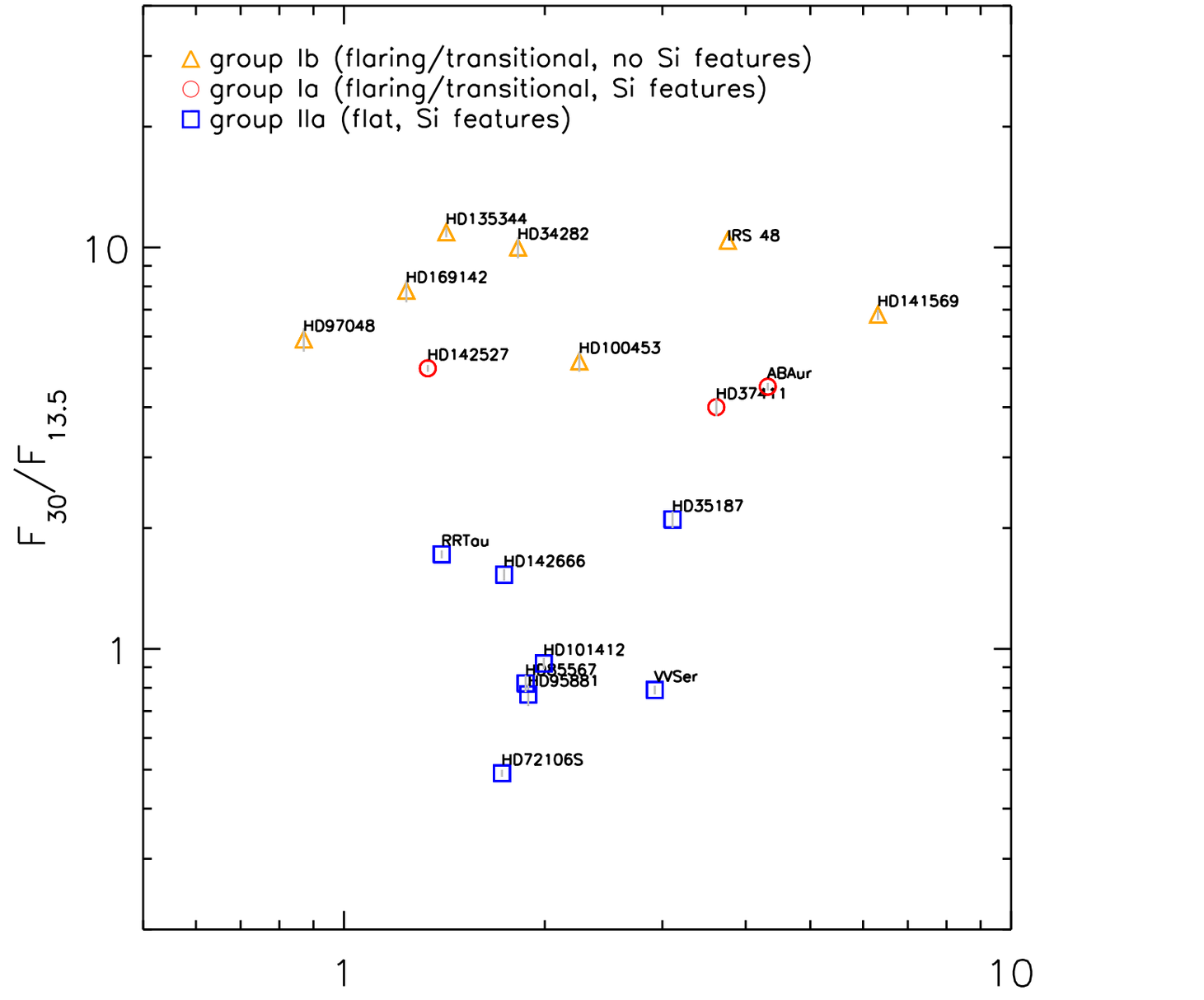
Bakes & Tielens 1994



PAH luminosity not very sensitive to disk geometry



However, PAH ionization higher in flaring/transitional objects



neutral ⟶ Ionized

IR emission components

Table 2 Abundances of the carriers of infrared (IR) emission components

Carrier	IR emission component	N_c	a (Å)	f_C[a] (ppm)[b]
PAHs	IR emission features	20–100	4–10[c]	14
PAH clusters	Plateaus	100–1000	10–20	8
Very small grains	25-μm cirrus	10^3–10^4	20–30	7
Small grains	60-μm cirrus	$\sim 10^5$	50	16
Classical grains	$\lambda > 100$ μm		>100	35[d]?
C chains[e]	IR emission	>3		$<3 \times 10^{-1}$
C_{60}[f]	Far-red absorption bands			2

gas in dust depleted gaps

evidence of planet formation?

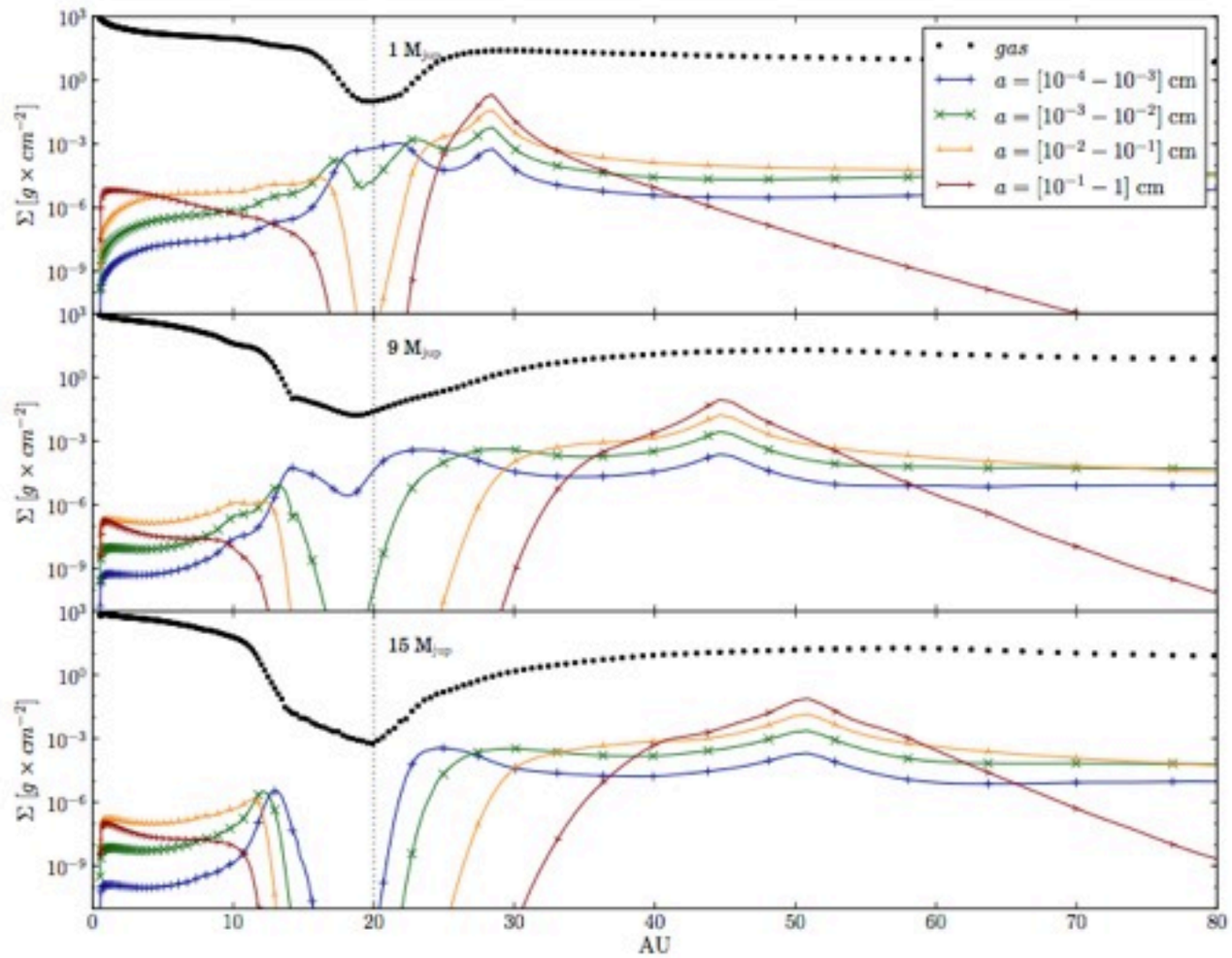
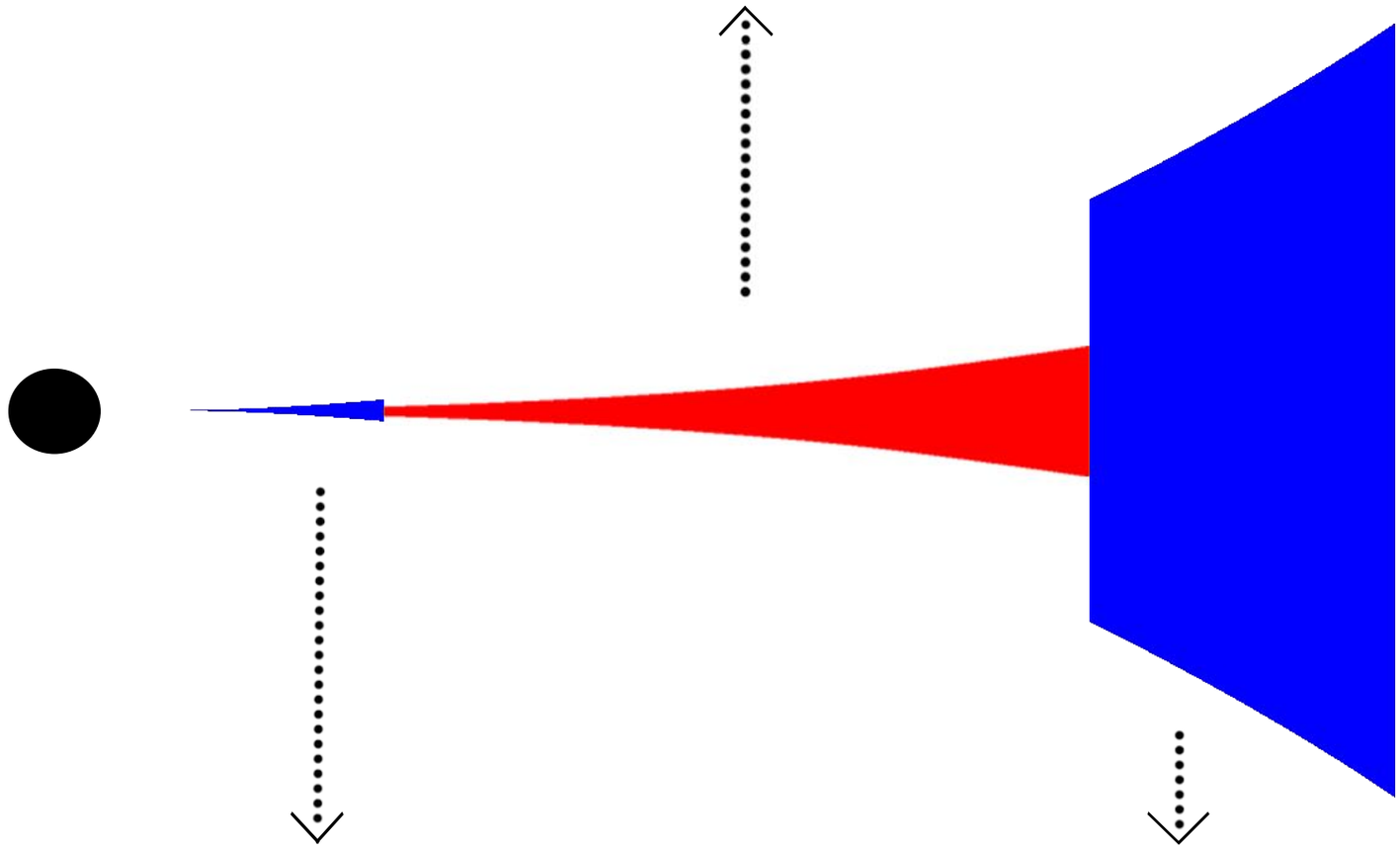


Fig. 7: Surface density profiles for gas and different dust particle size ranges for the three planet mass cases, i.e. $M_p = [1, 9, 15]\, M_{\rm Jup}$. The vertical dotted line indicates the position of the planet at 20 AU.

Pinilla 2013, de Juan Ovelar 2013

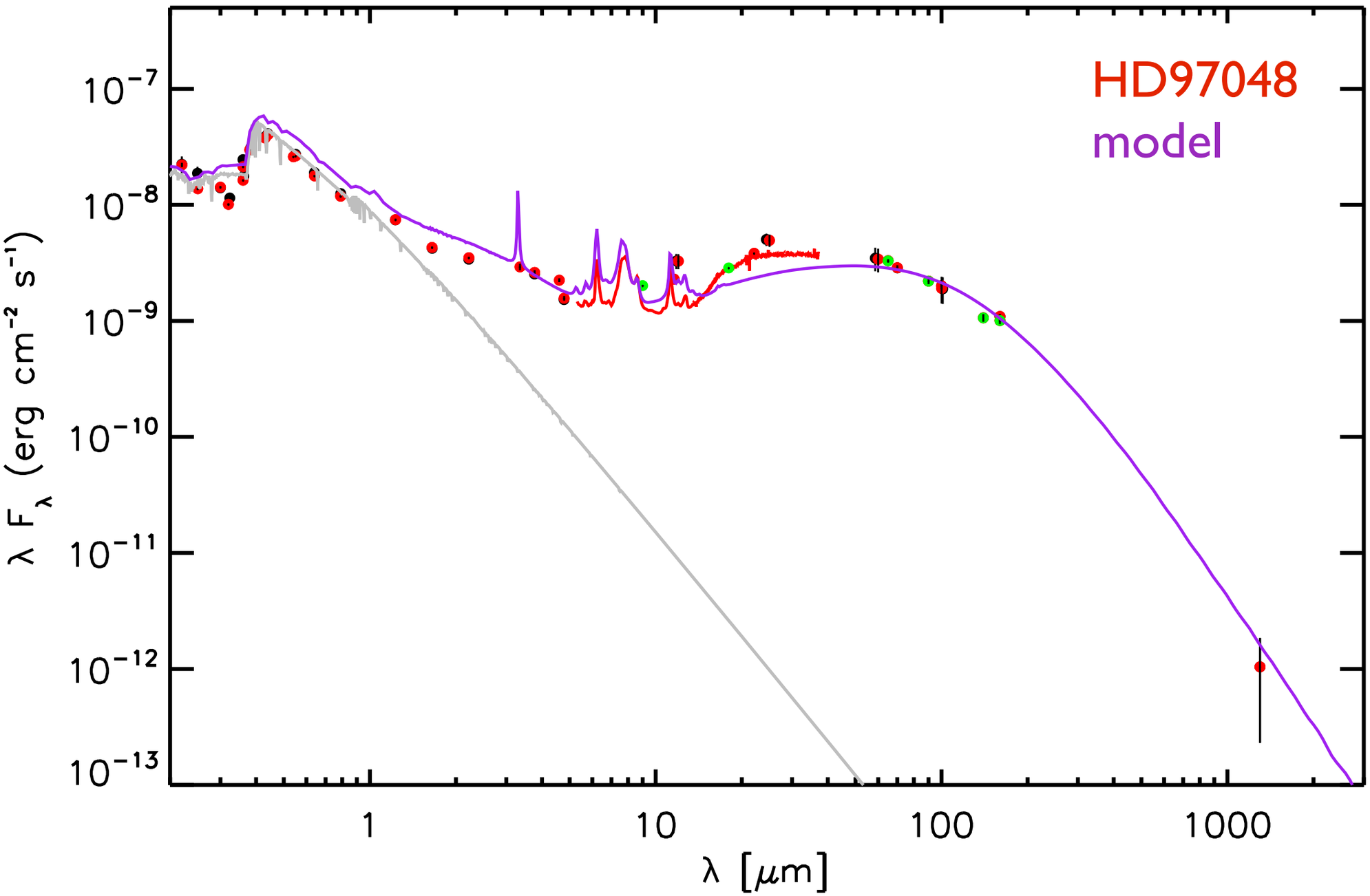
Ionized PAHs in low density, optically thin gas flows through the gap (high UV field, low electron density)



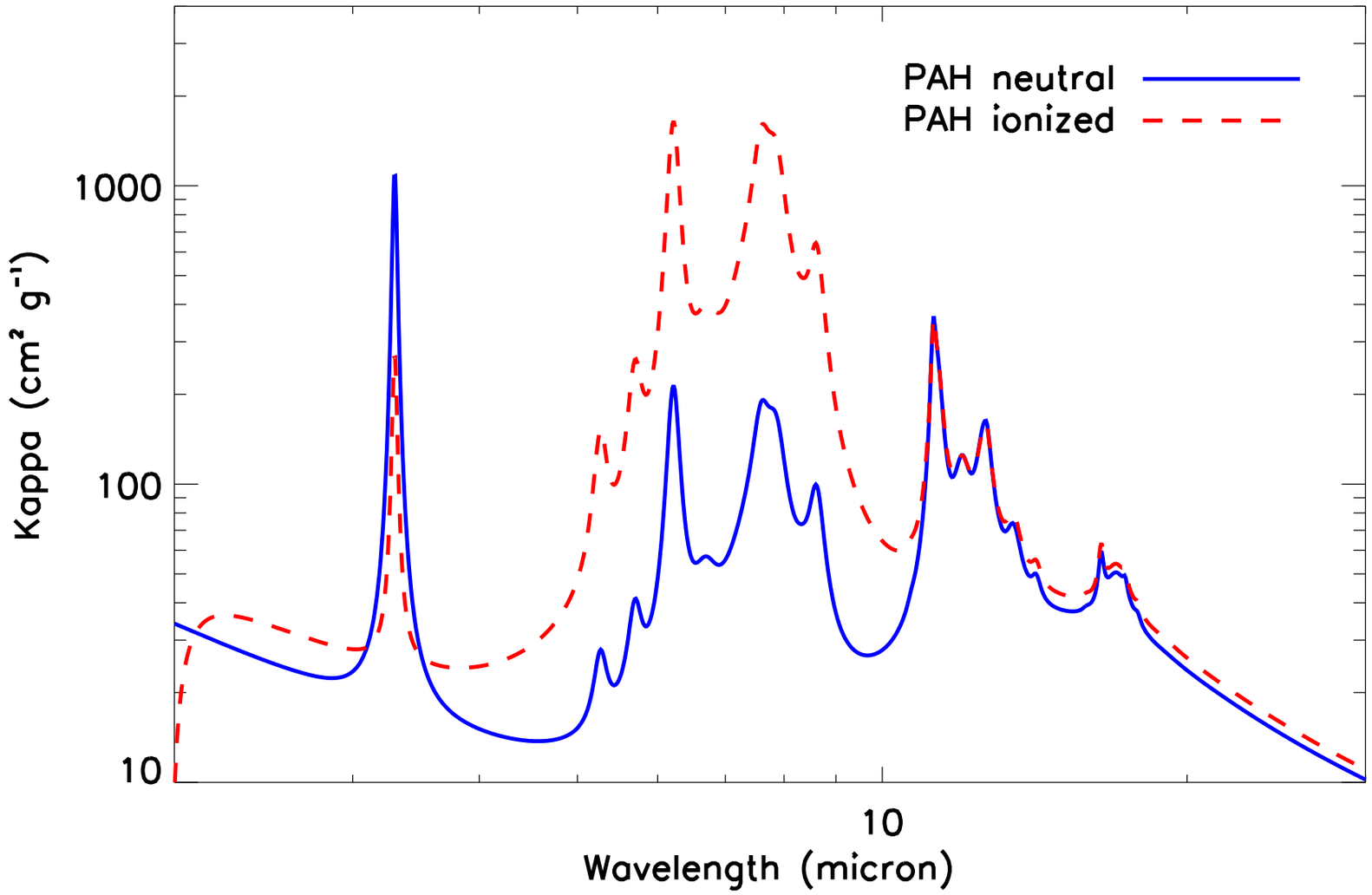
Neutral PAHs in optically thick disk (low UV field, high electron density)

Maaskant et al 2014

Benchmark model



PAHs in RT code MCMax



Draine 2001, 2007
Min 2009