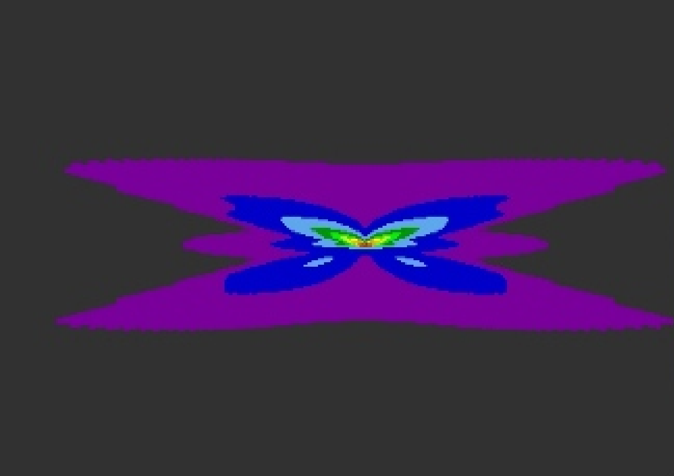
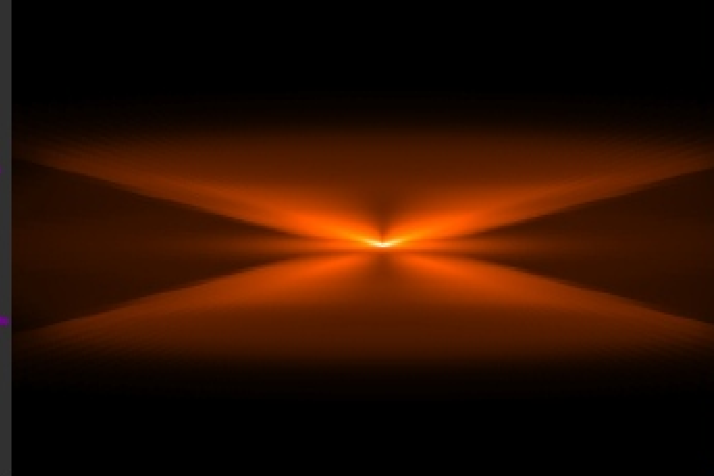
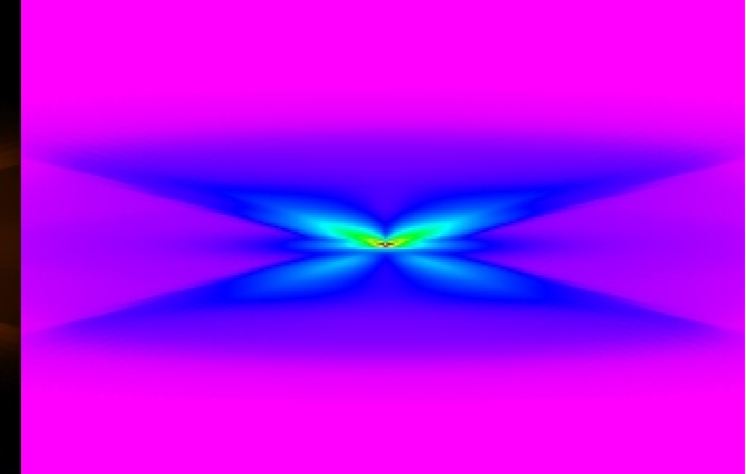
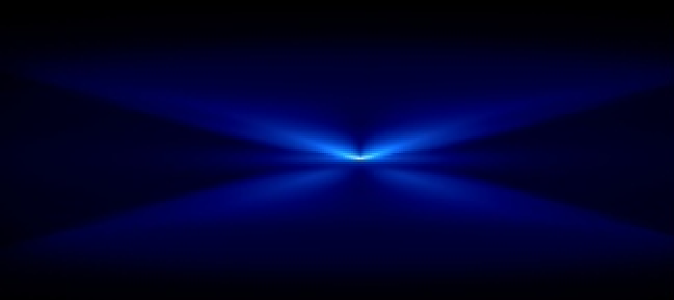
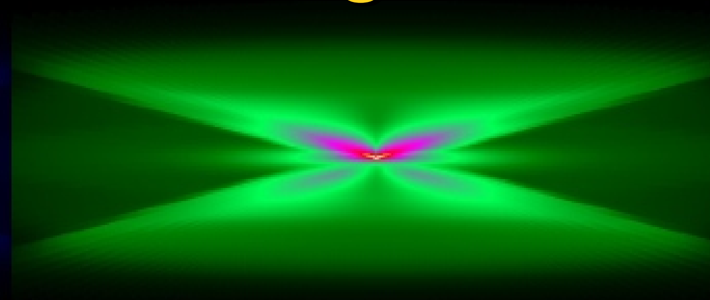
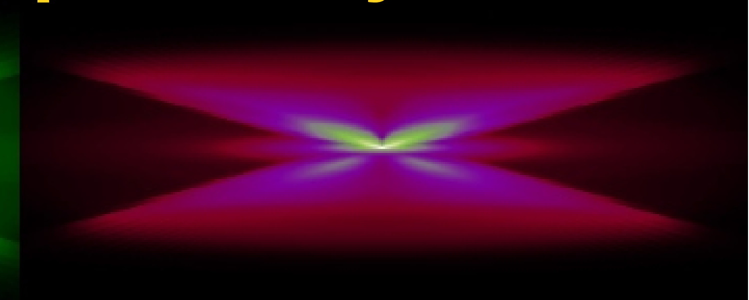
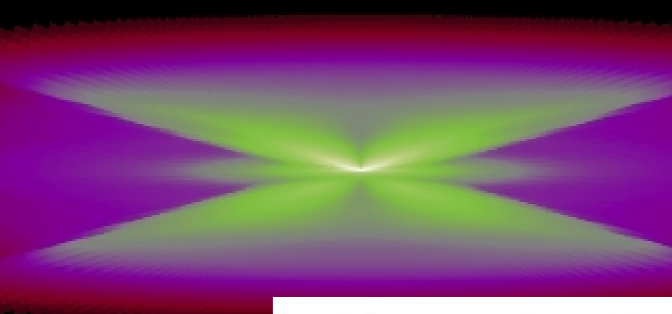
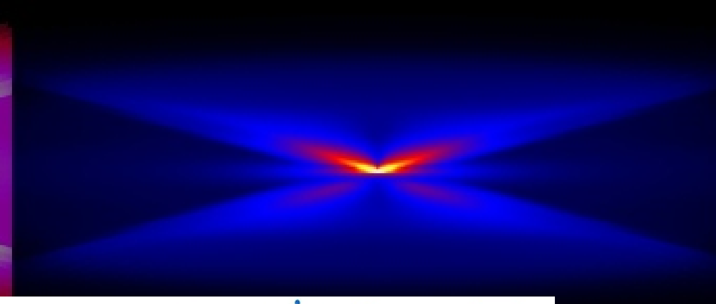




Gas and Dust Modelling in Protoplanetary Disks

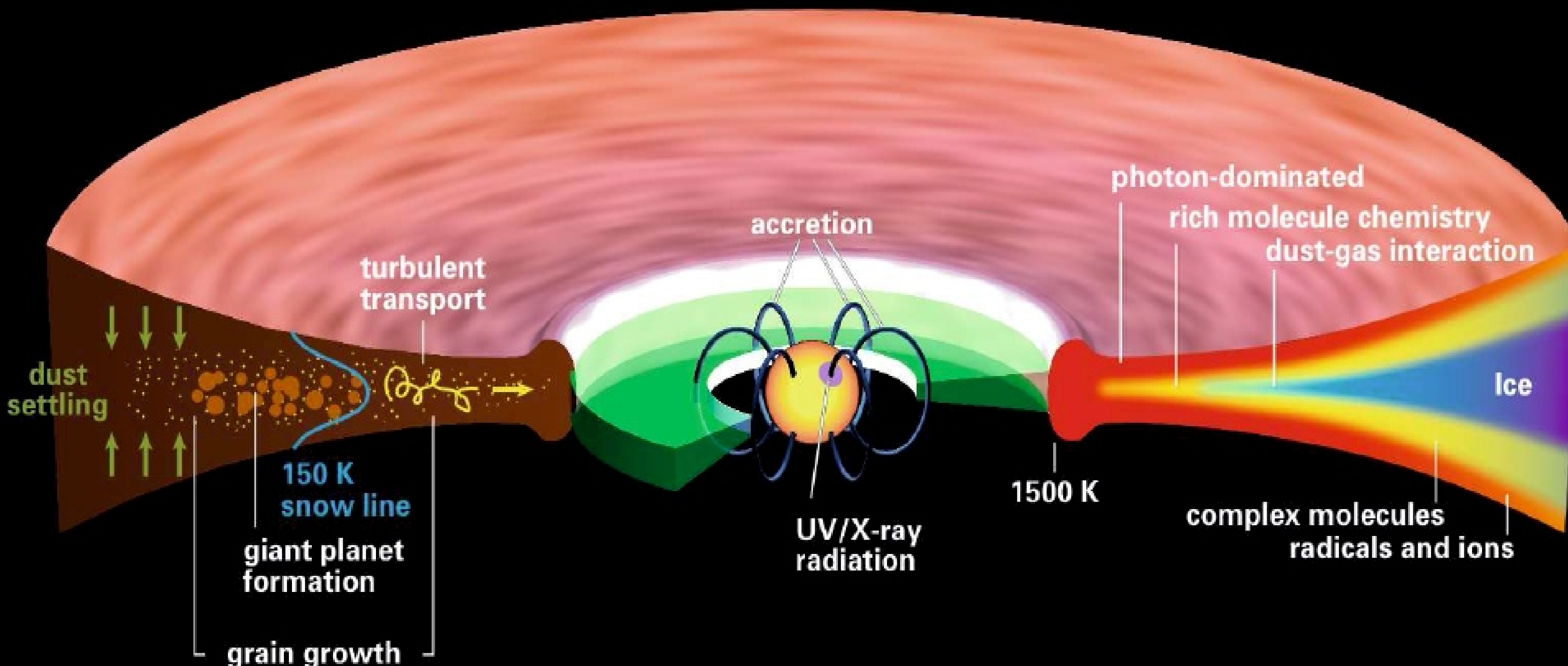




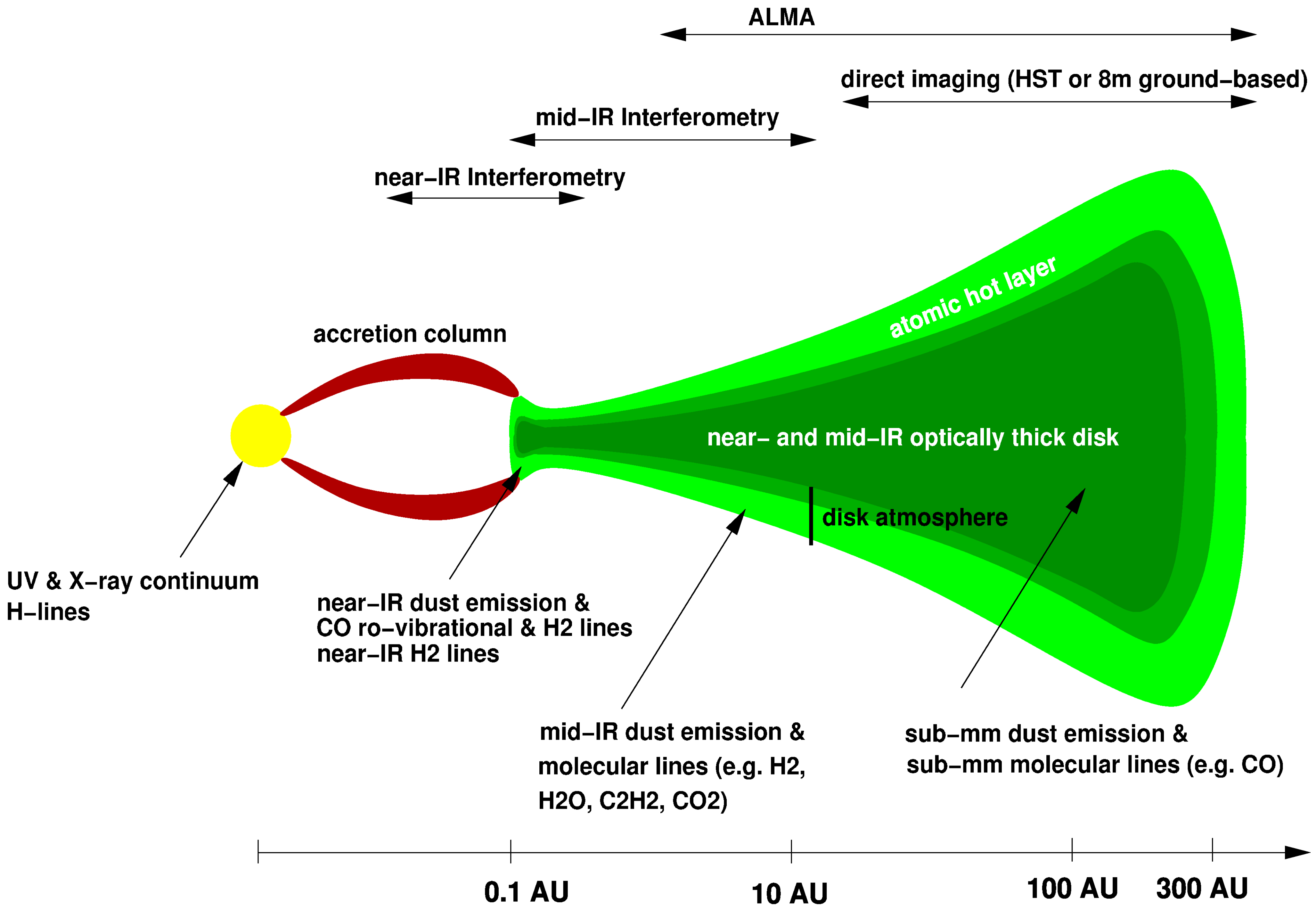
Peter Woitke, St Andrews, Scotland, UK


Kiel, Planet Formation & Evolution, Sept 8, 2014

Protoplanetary Disks



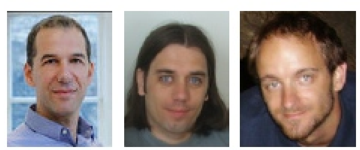
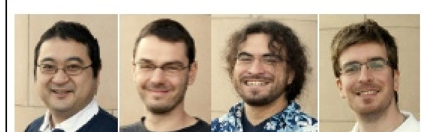


ALMA
direct imaging (HST or 8m ground-based)
mid-IR Interferometry
near-IR Interferometry
atomic hot layer
accretion column
near- and mid-IR optically thick disk
disk atmosphere
UV & X-ray continuum
H-lines
near-IR dust emission &
CO ro-vibrational & H2 lines
near-IR H2 lines
mid-IR dust emission &
molecular lines (e.g. H2,
H2O, C2H2, CO2)
sub-mm dust emission &
sub-mm molecular lines (e.g. CO)
0.1 AU
10 AU
100 AU
300 AU

DiscAnalysis DIANA

FP7-SPACE 2011 collaboration

Analysis and Modelling of Multi-wavelength Observational Data from Protoplanetary Discs

St Andrews	**Vienna**	**Amsterdam**	**Grenoble**	**Groningen**
				
P. Woitke	*M. Güdel*	*R. Waters*	*F. Ménard*	*I. Kamp*
				
Greaves Ilee Rigon	*Dionatos Rab Liebhart*	*Min Dominik*	*Thi Pinte Carmona Anthonioz*	*Antonellini*
sub-mm to cm	**X-rays**	**near-mid IR**	**near-far IR**	**near IR - mm**
coordination	obs./mod.	mod./obs.	obs./mod.	mod./obs.
JCMT, eMERLIN	XMM, Herschel	VLT, JWST	HST, Herschel	Herschel, JWST
astrobiology	high energy	dust mod.	interferometry	gas mod.

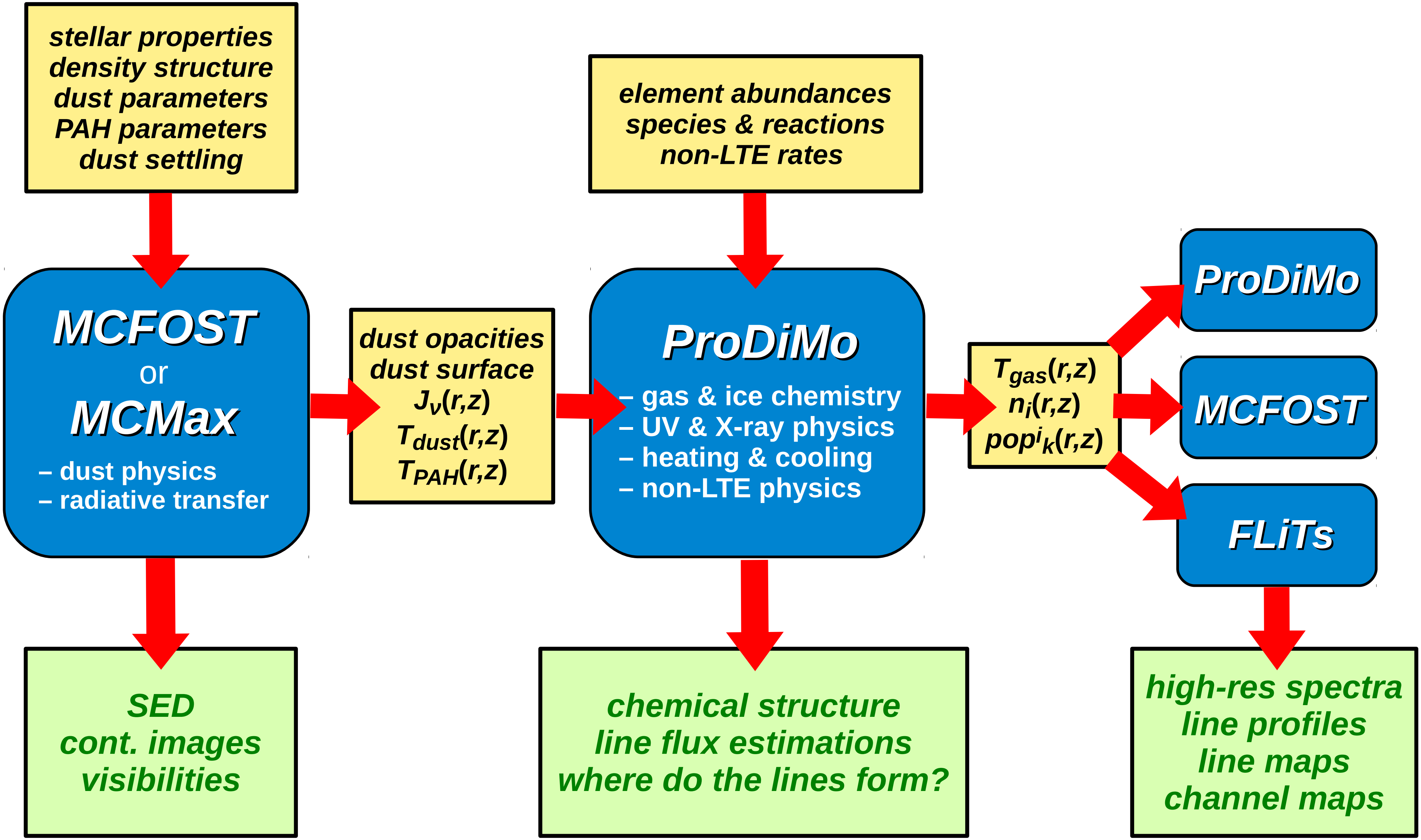
multi-λ data collection X-ray to cm (archival and proprietary)

coherent, detailed modelling of gas & dust throughout the disc

using disk modelling software ProDiMo, MCMax, MCFOST

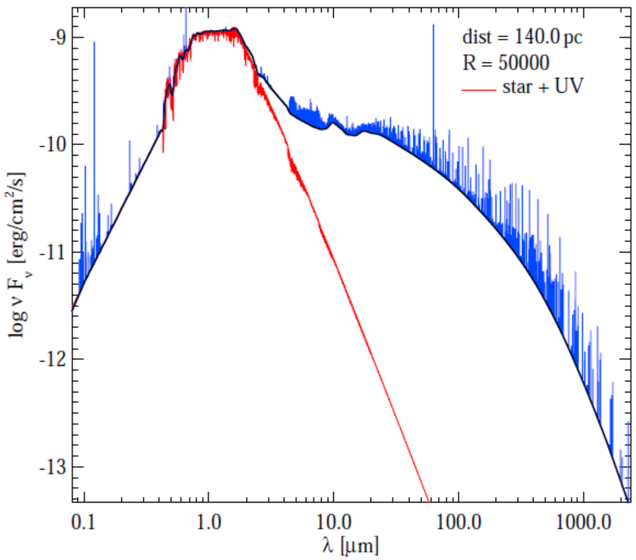
aim: disc shape, temperatures, dust properties, chemistry in the birth-places of exoplanets

“*holistic*” modelling approach

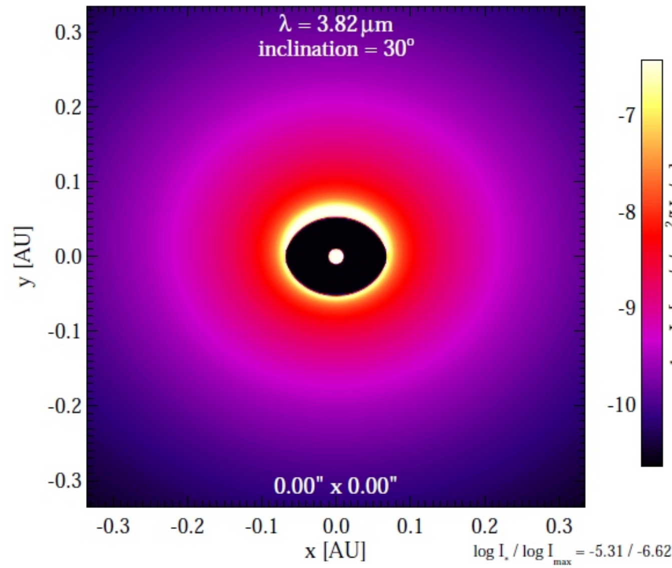


simulated observations

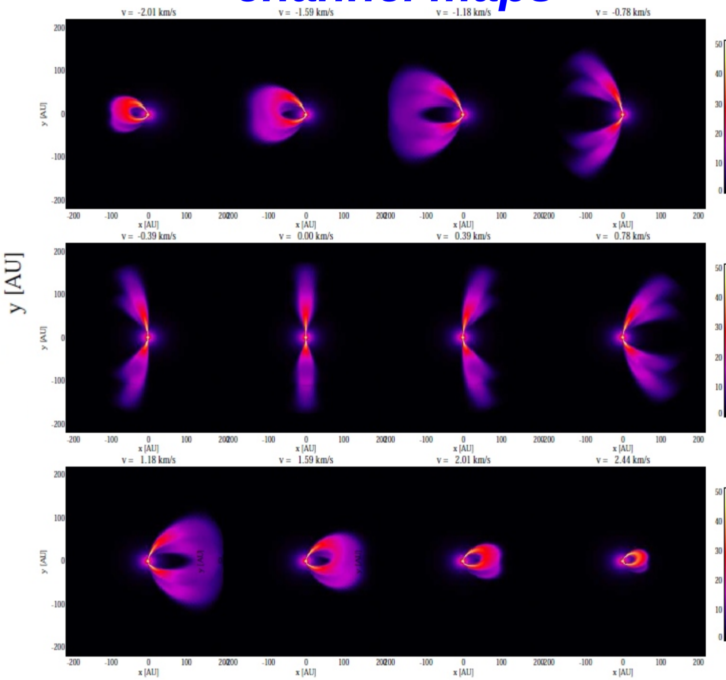
SED and line fluxes



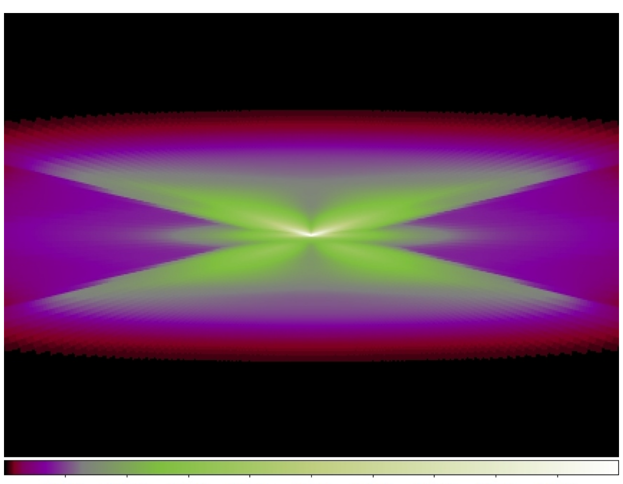
continnum images



channel maps

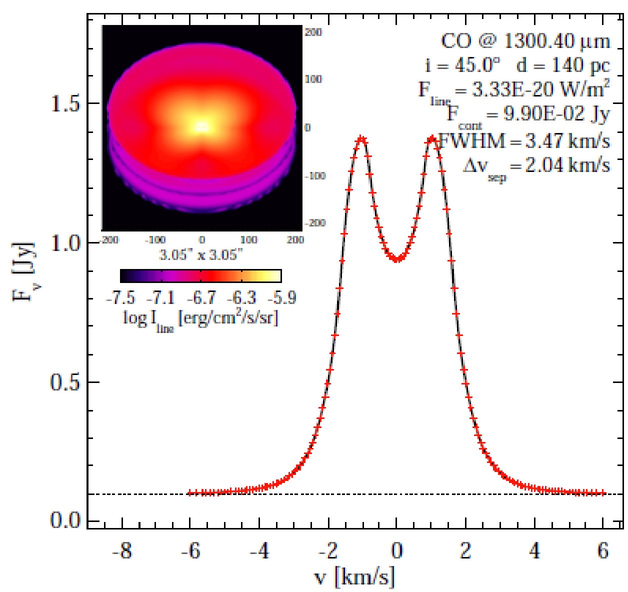


emission line maps



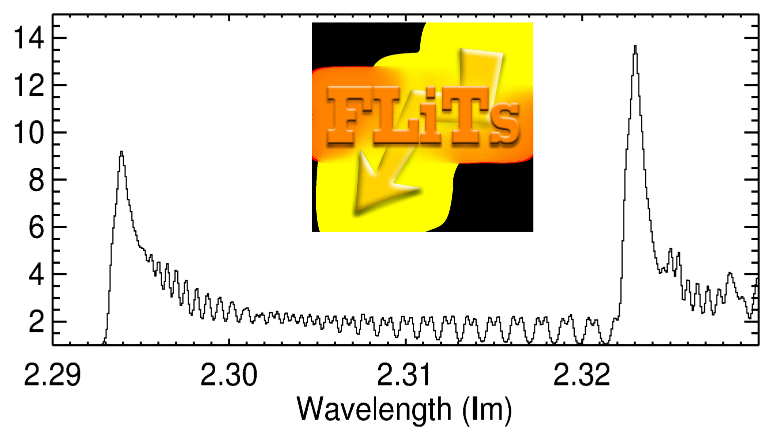
^{13}CO line @ 220.399 GHz from an edge-on disk

velocity profile

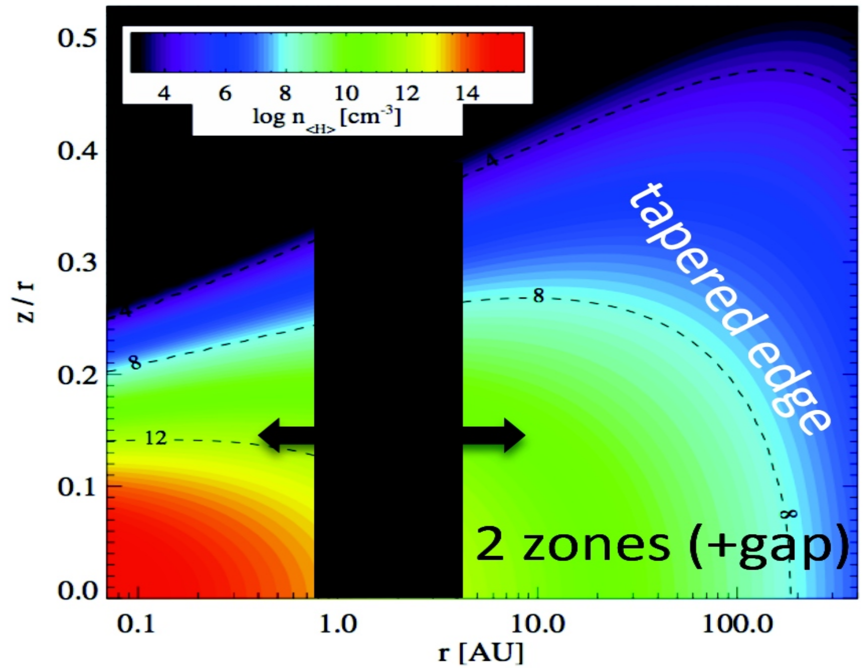


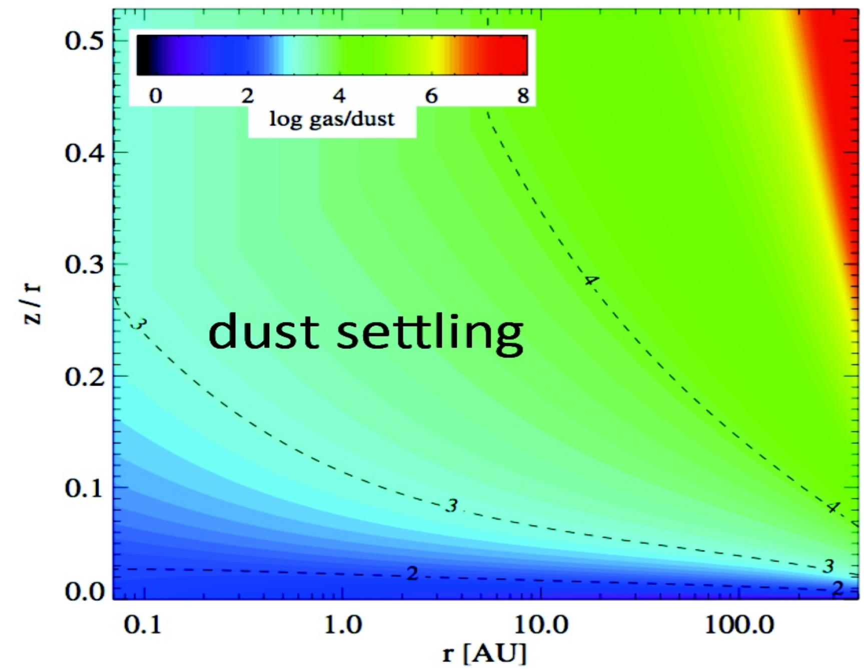
new: *high-res IR spectrum*

ProDiMo model + FLiTs



“standards” for disk modelling

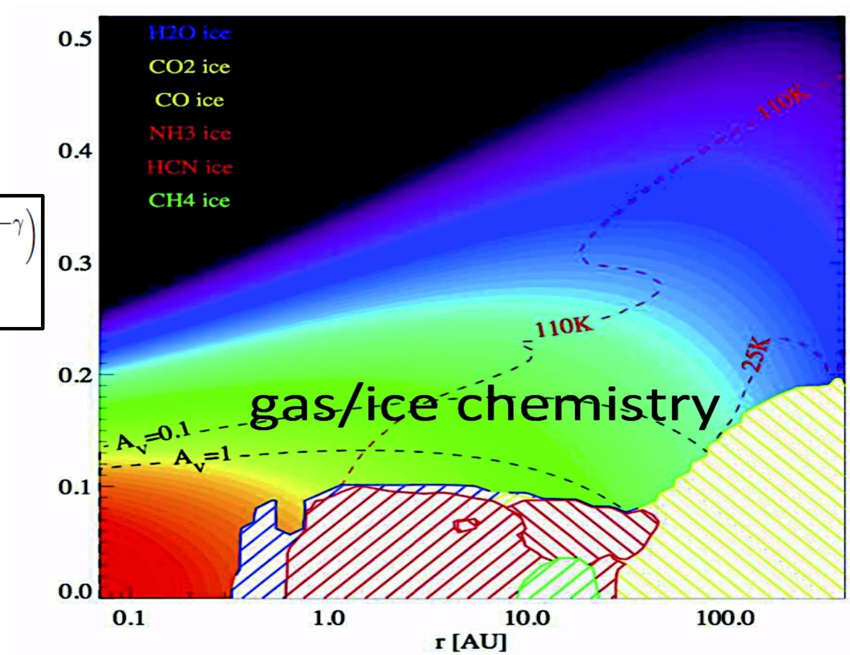




Disk modelling standards missing in the community!

- ≤ 2 parametric radial zones
- tapered outer edge
- dust settling → Dubrulle et al. (1995)
- standard dust opacities
- standard chemical species, reactions, element abundances

$$\Sigma(r) \propto r^{-\epsilon} \exp\left(-(r/R_{\rm tap})^{2-\gamma}\right)$$
$$H(r) = H_0 (r/r_0)^{\beta}$$

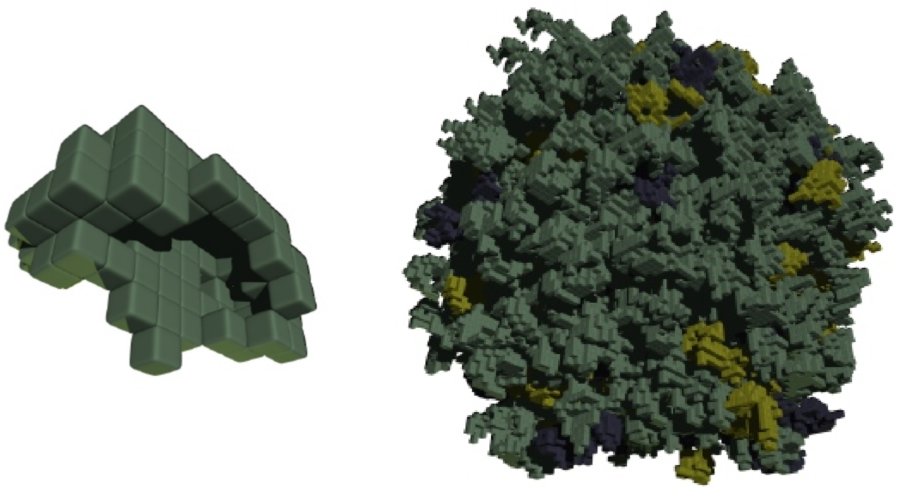


"Standard" dust opacities for disks

→ *Michiel Min, University of Amsterdam, NL, 2014 in prep.*

Opacities of aggregates

– DDA, 100 dipoles/GRF, up to 8000 GRFs (4μm)
– results include phase function, polarisation, ...



DIANA dust opacity standard

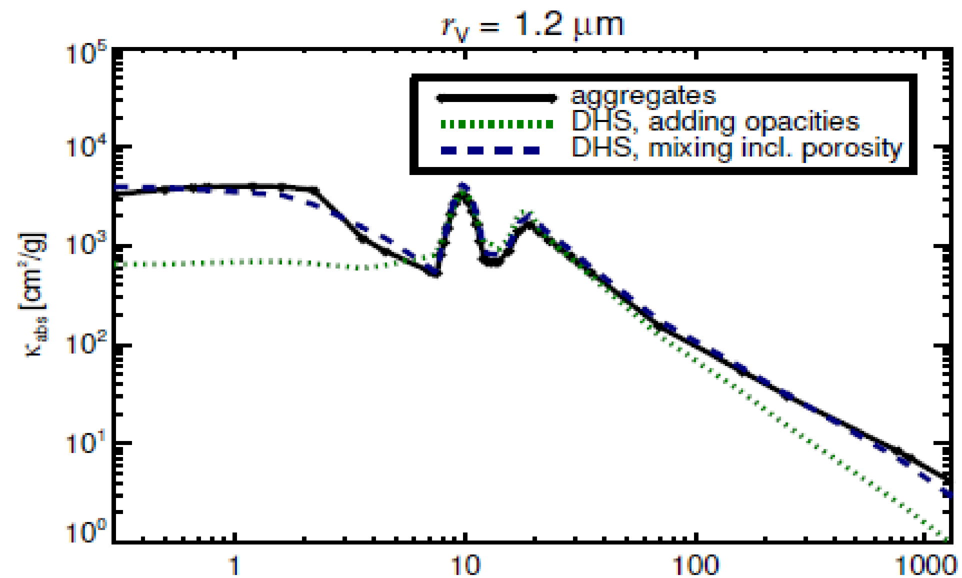
- ***effective mixture of***
  ~60% laboratory amorphous silicates
  ($Mg_{0.7}Fe_{0.3}SiO_3$, Jena)

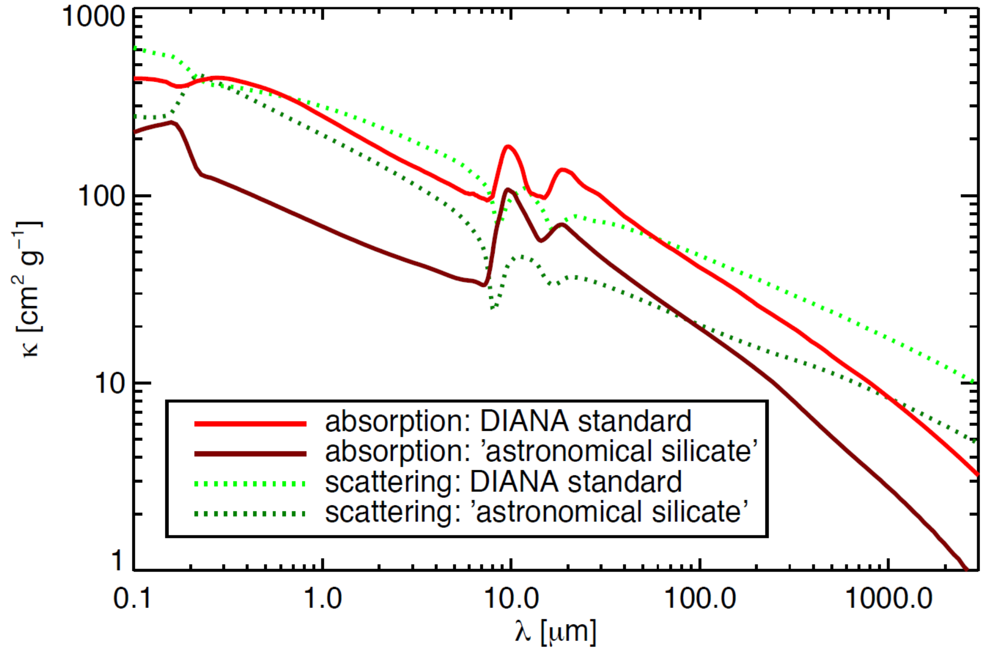
  ~15% amorphous carbon
  (Zubko 1996, BE-sample)

  ~25% porosity
- ***powerlaw size distribution*** f(a) ~ a^{-pow}
  (a_{min} = ***0.05 μm***, a_{max} = ***3 mm***, a_{pow} ~ ***3...4***)
- ***distribution of hollow spheres***
  (hollow volume ratio ***0 … 0.8***)

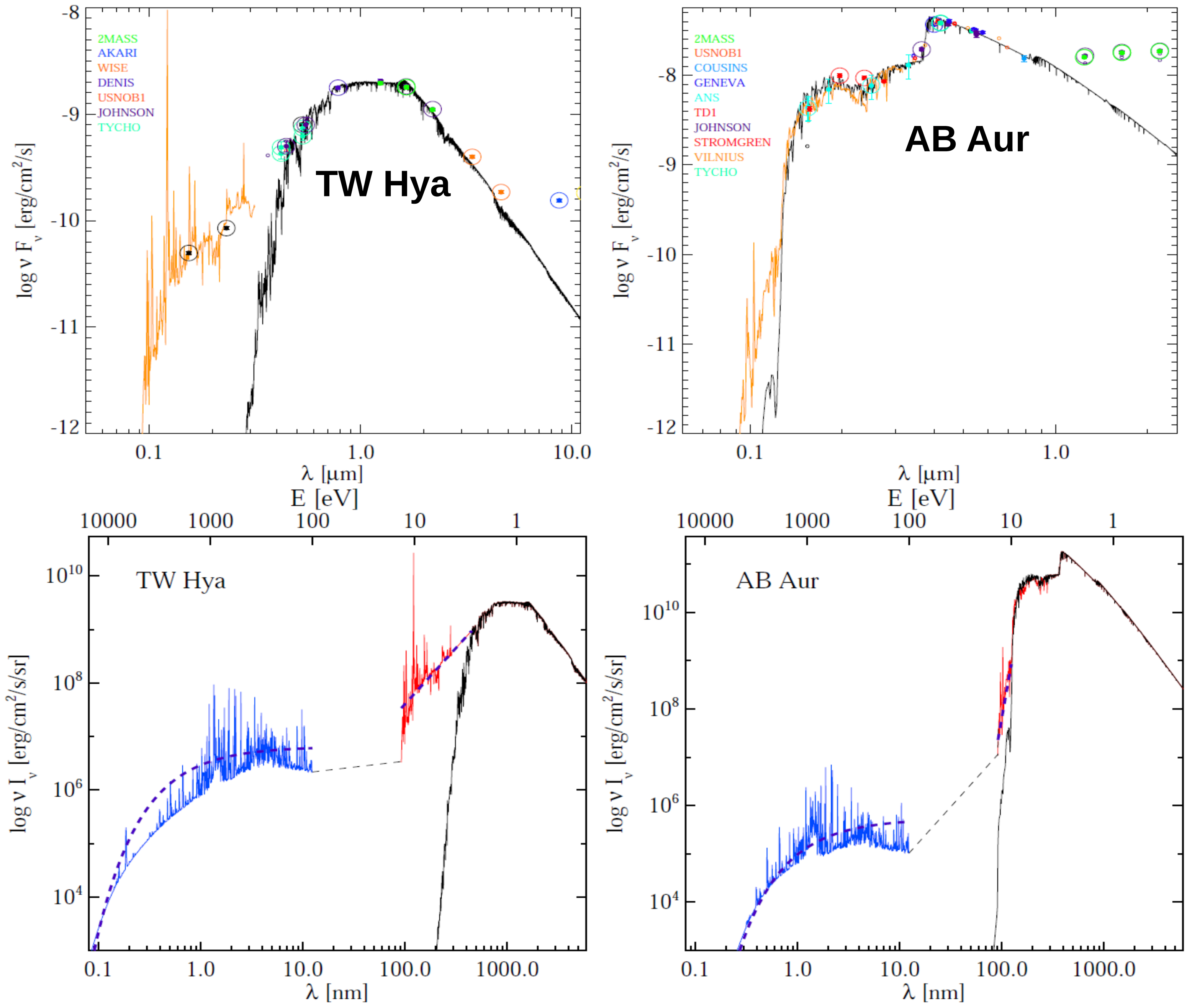
Fit with "simple" methods

(effective medium, porosity, DHS)





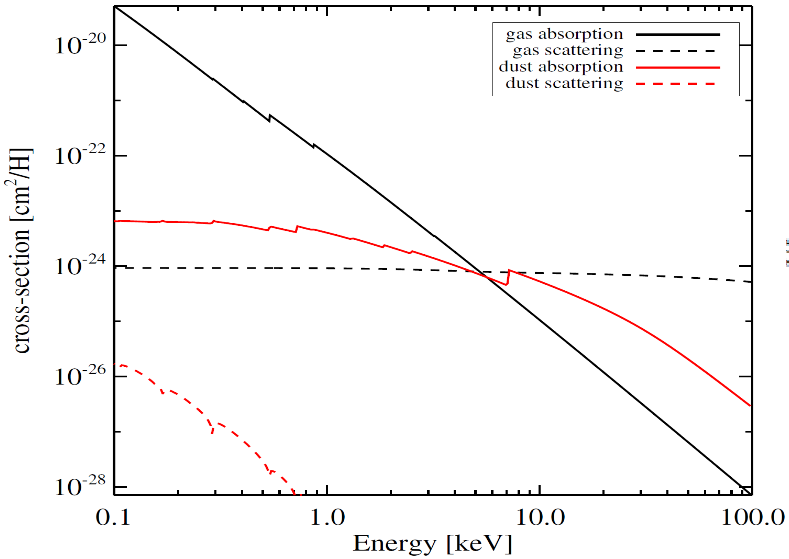
usage of UV and X-ray data



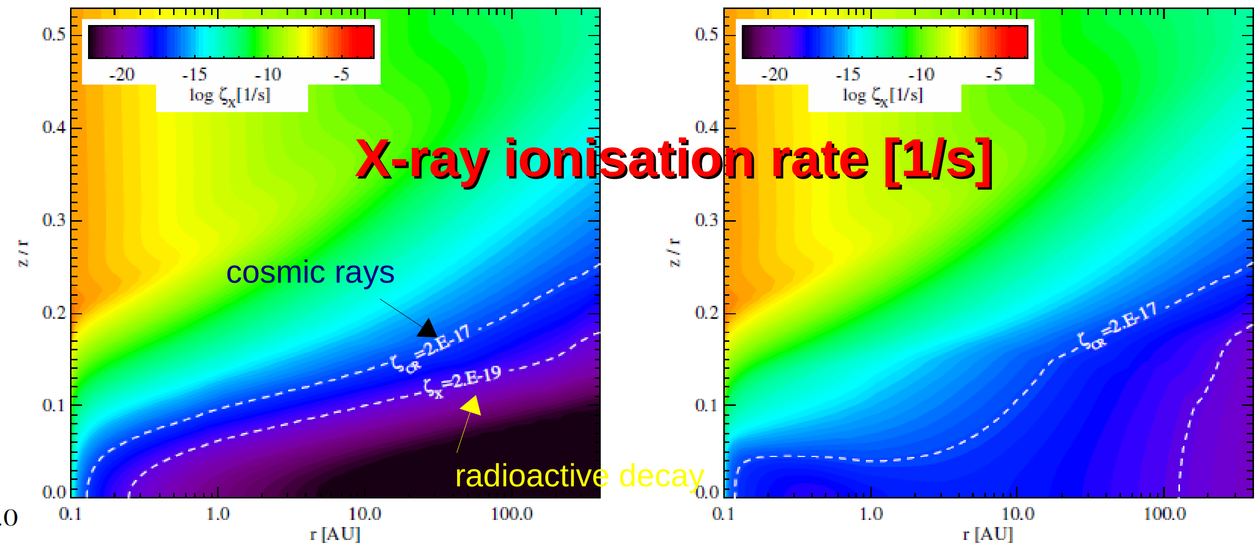
X-ray radiative transfer

→ Christian Rab, University of Vienna, Austria, 2014 in prep

X-ray gas & dust opacities

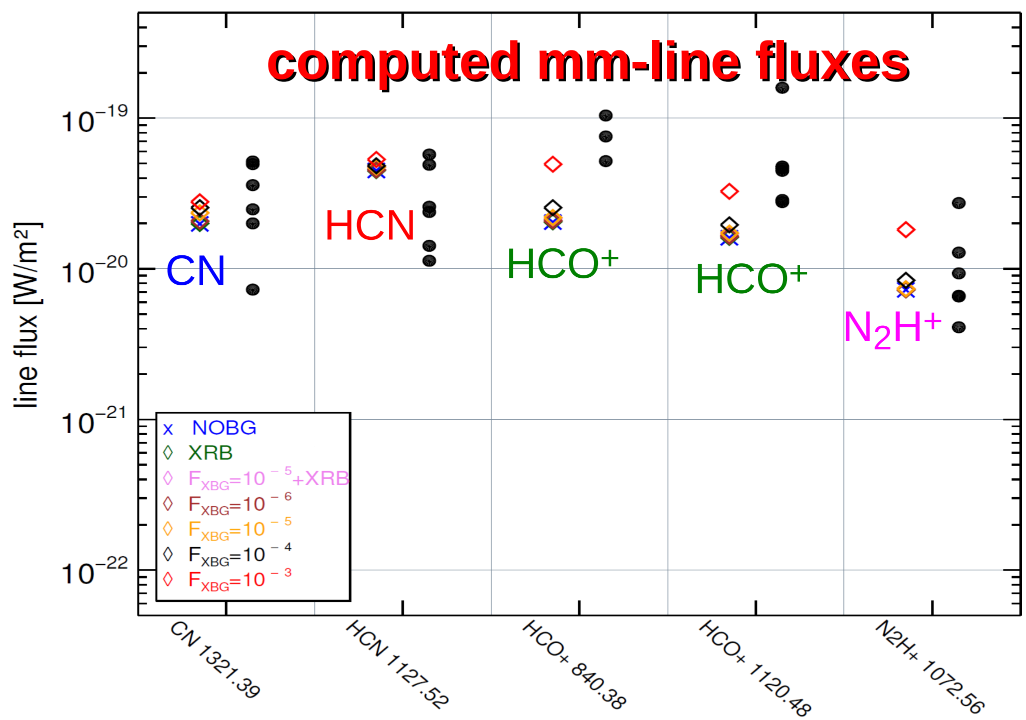


absorption only / absorption & scattering



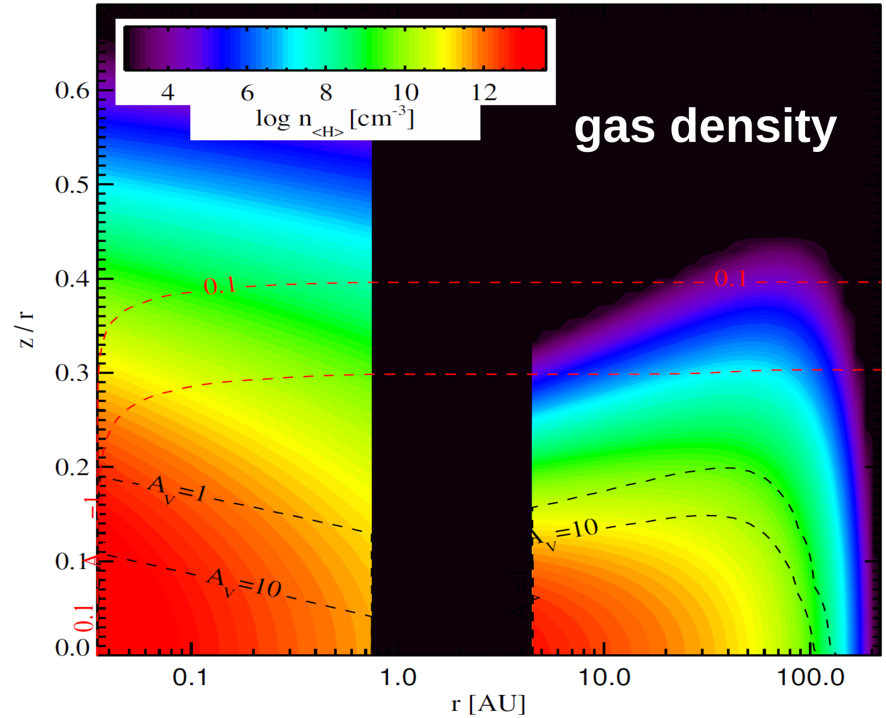
DIANA chemical standards

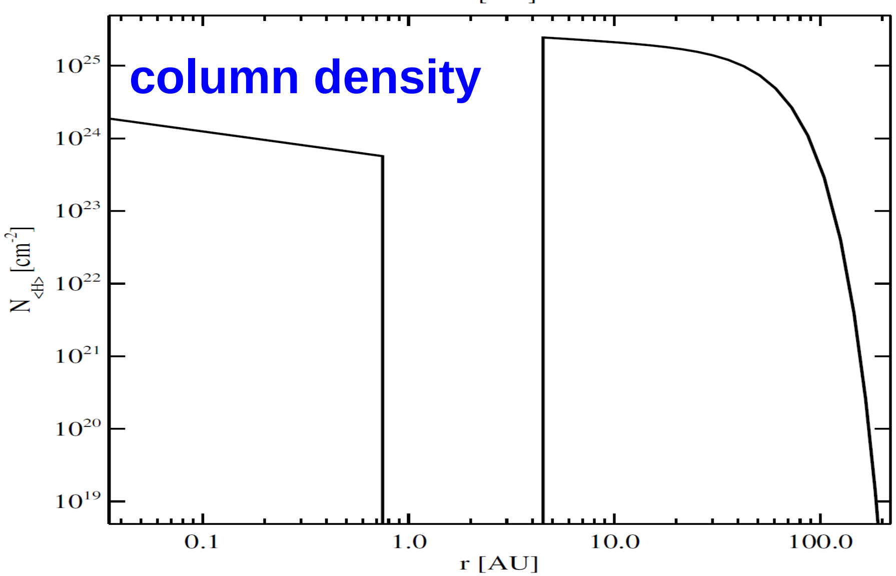
- *element abundances*
- *choice of chemical species*
  - "small" / "large"
- *chemical reaction network*
  - ice absorption energies
  - vibrationally excited H_2
  - treatment of PAHs
  - X-ray and UV-reactions



one example: CY Tau

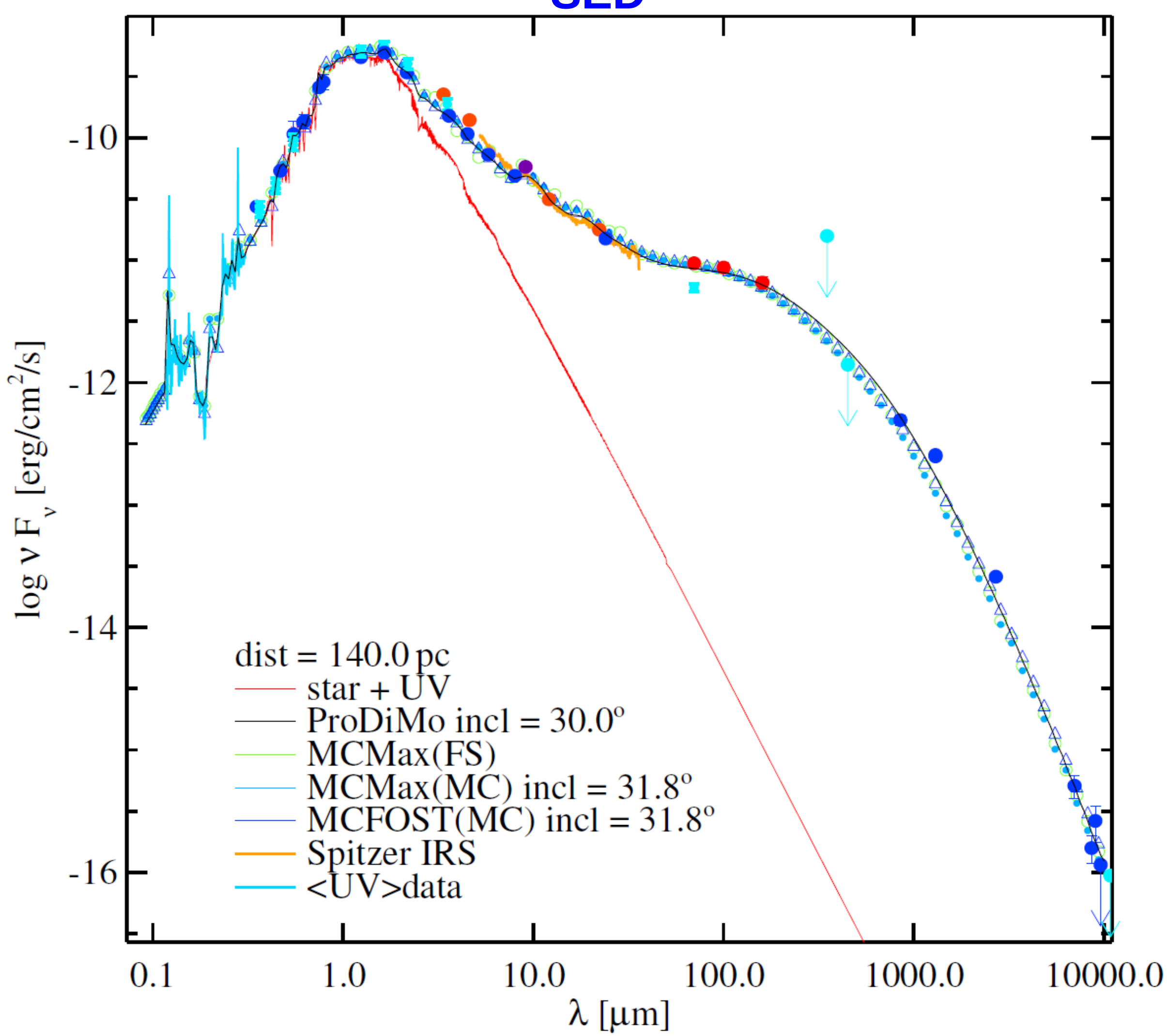
→ *Peter Woitke, St Andrews, UK, 2014 in prep*





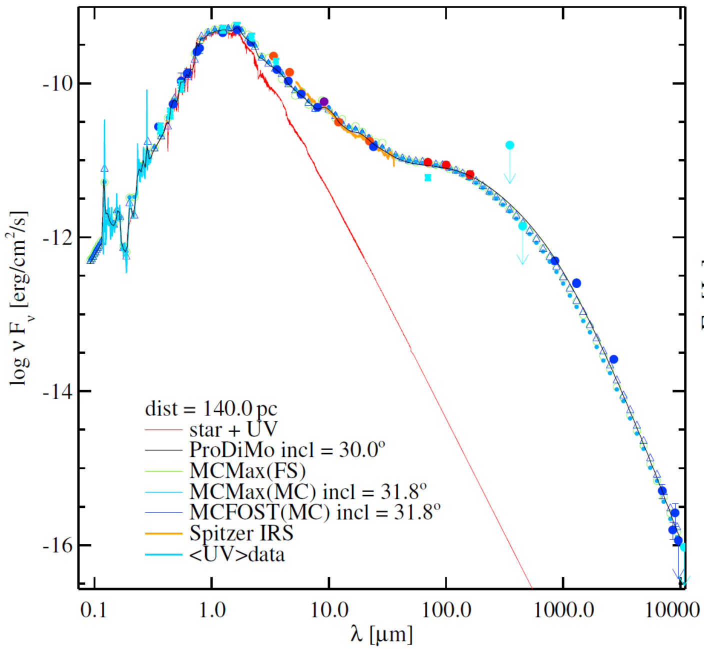
CTTS, M1, A_V = 0.1, T_{eff} = 3640 K, L_* = 0.36 L_{sun}, M_* = 0.42 M_{sun}, M_{acc} ~ 7 x 10^{-9} M_{sun}/yr, age ~ 2.2 Myr

SED

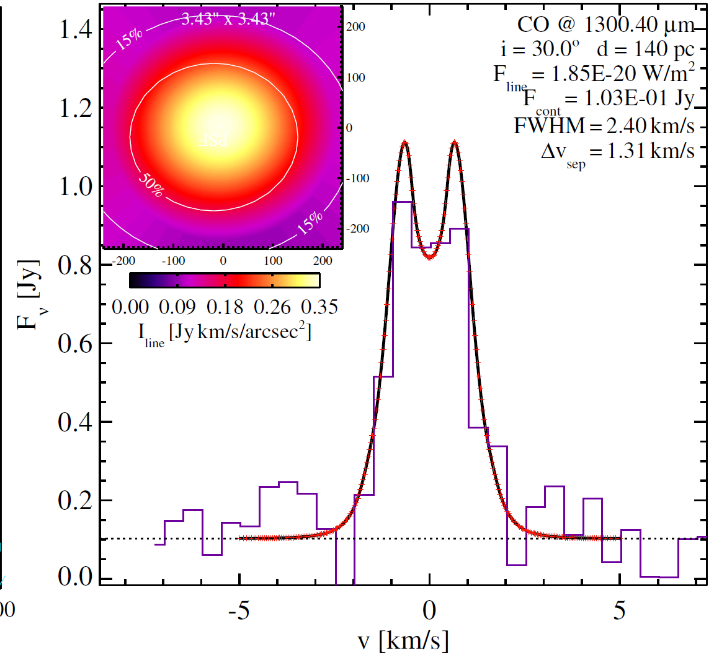


CY Tau: line & image results

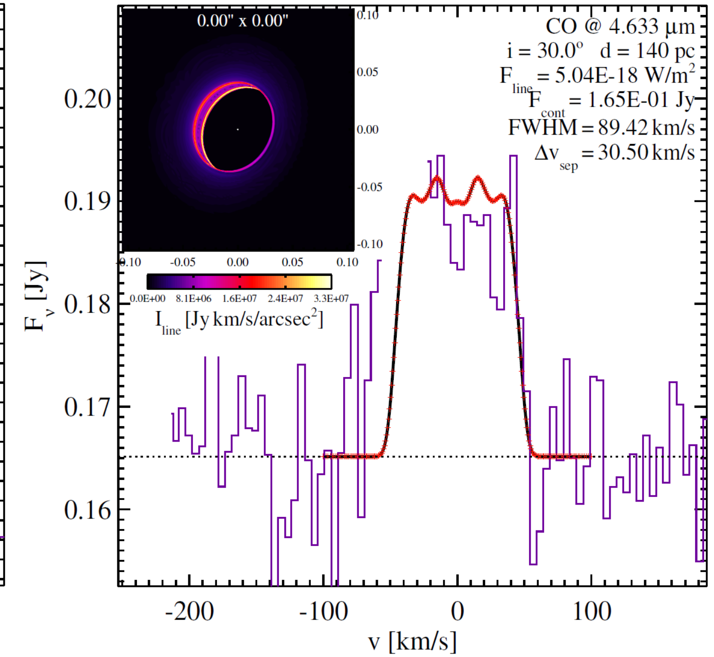
SED



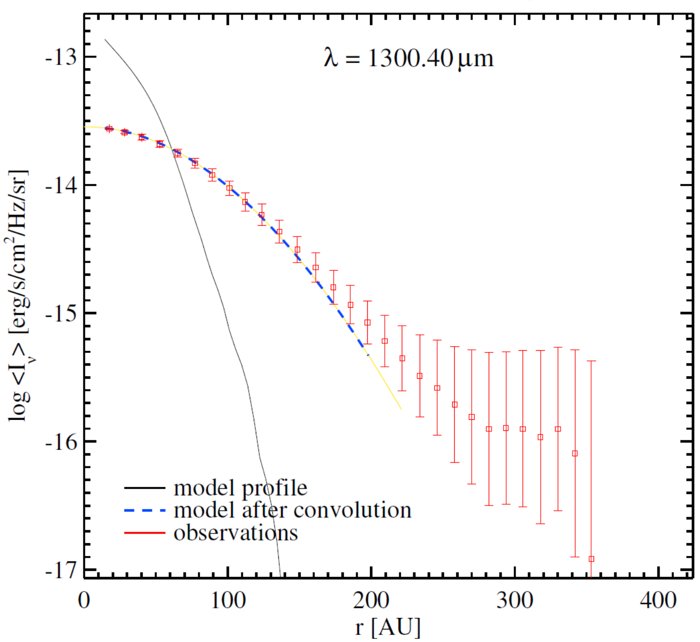
^{12}CO J=2-1



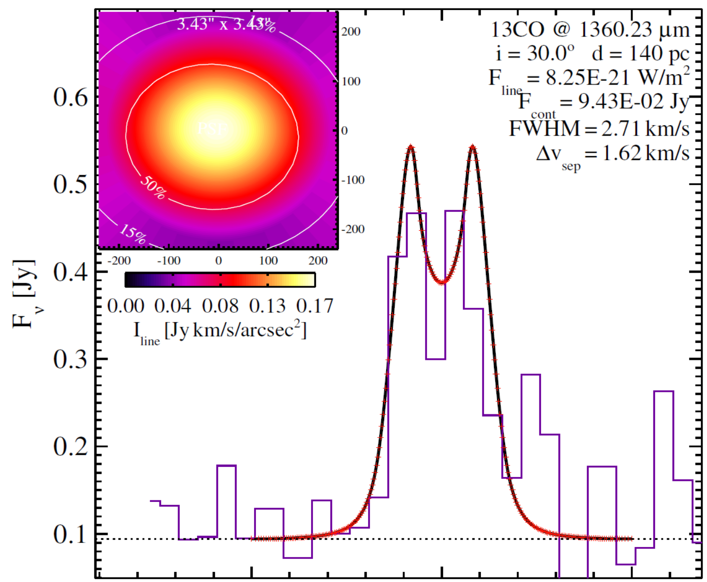
^{12}CO v=1-0 R(3)



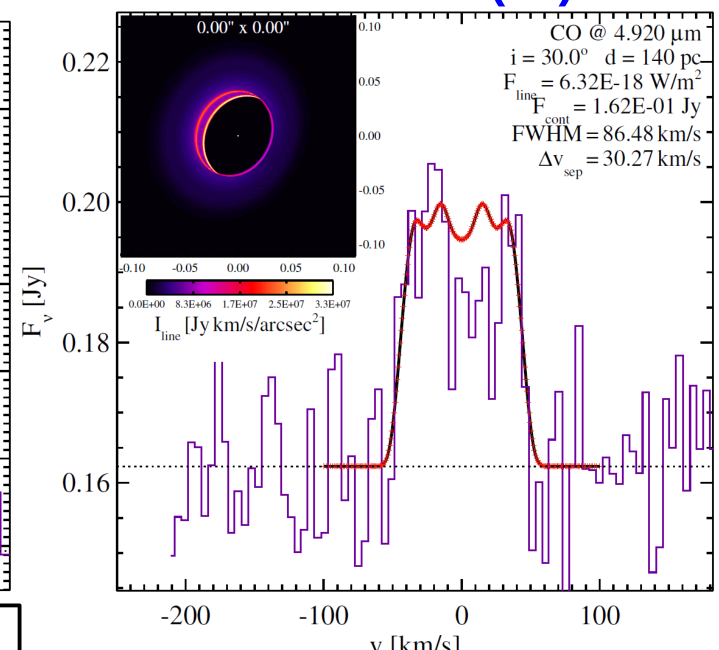
1.3mm intensity profile



^{13}CO J=2-1

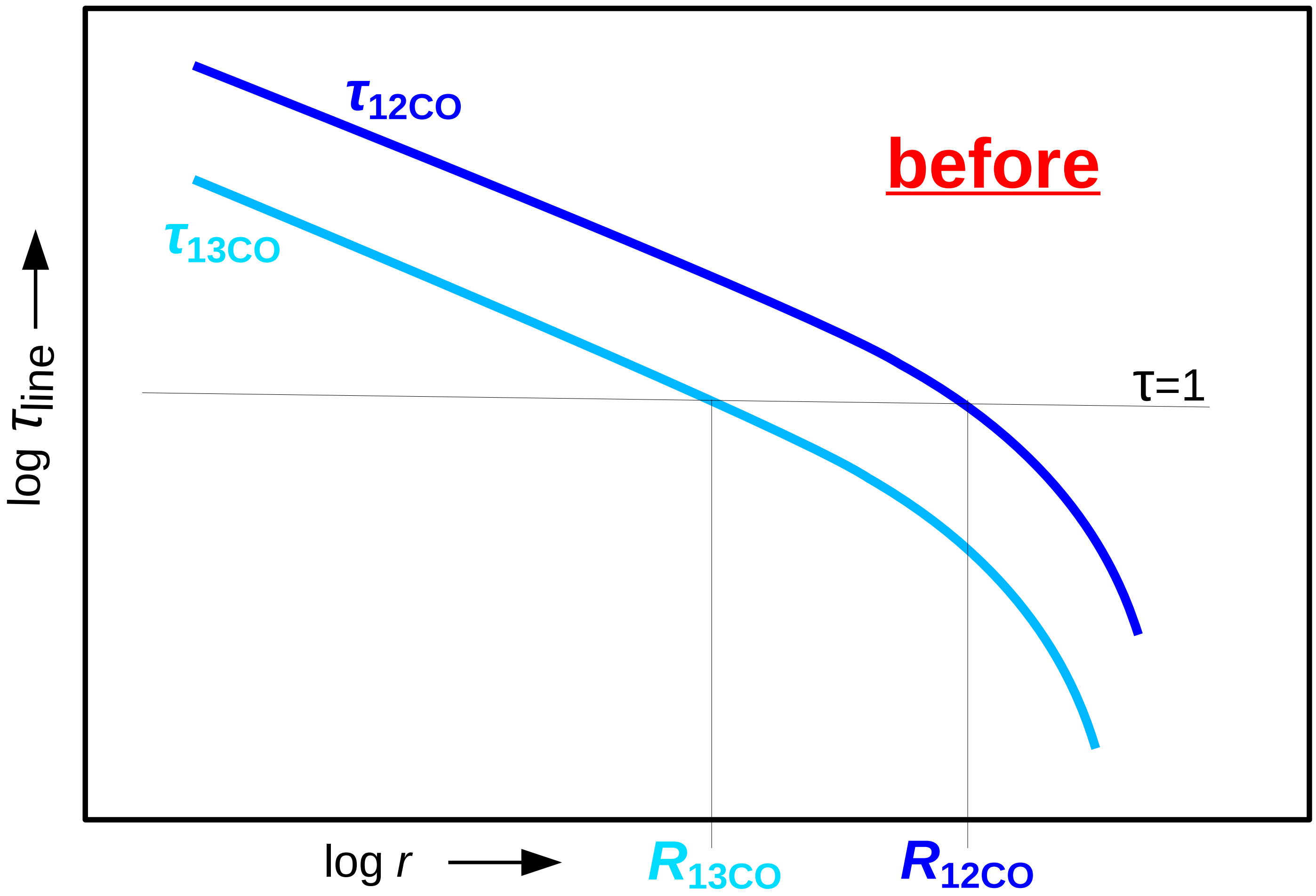


^{12}CO v=1-0 P(26)



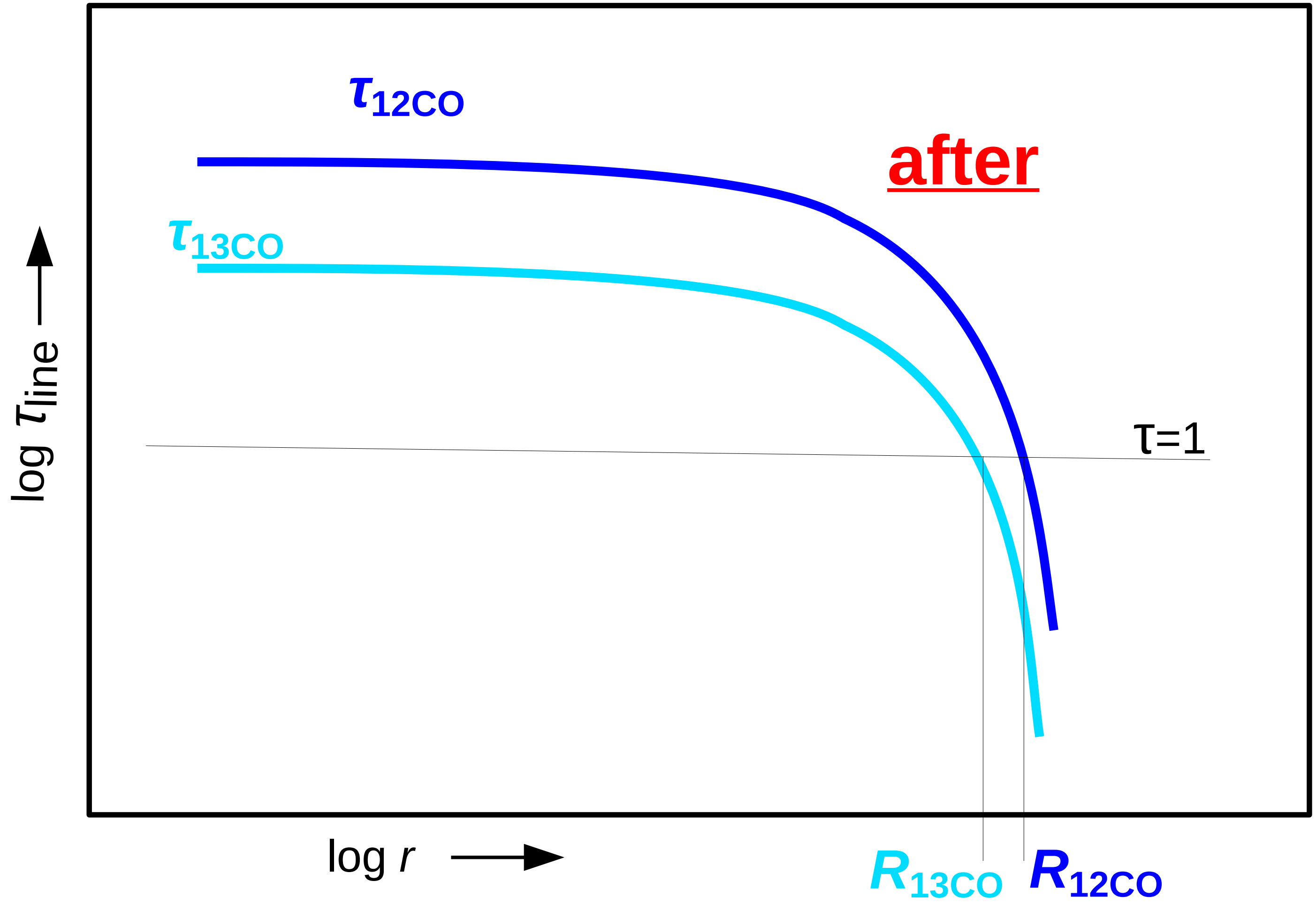
also [OI] 63µm, [OI] 6300A

How to decrease $^{12}CO/^{13}CO$ flux ratio?



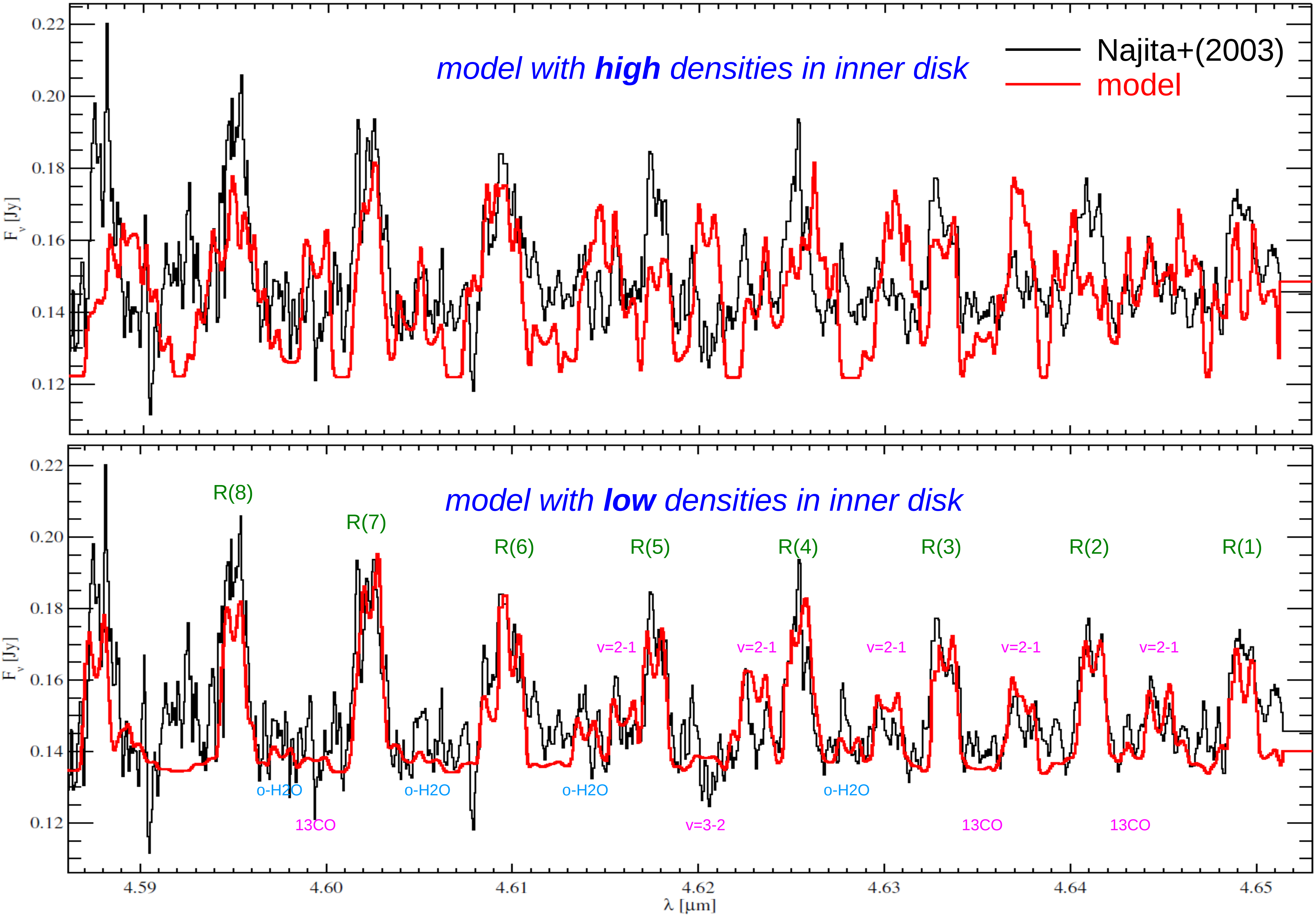
$F_{line} \sim R_{CO}^2 \; T_{CO}(\tau=1)$

How to decrease $^{12}CO/^{13}CO$ flux ratio?



=> $^{12}CO/^{13}CO$ is *not* necessarily a good M_{disk} tracer !

The R-branch CO fundamental with FLiTs ...



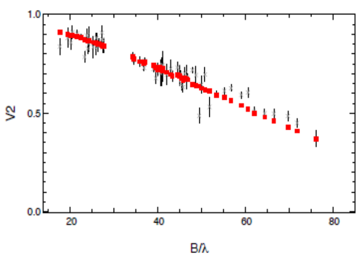
Conclusions CY Tau ...

- steep **Spitzer-slope** and **PACS photometry** suggests that **CYTau** has a ***"pre-transitional" disk with a hole at ~ (1-5) AU***
- **cm-data** implies that the ***outer zone is massive ~ 0.05*** M_{sun}
- **SMA continuum** and **^{12}CO data** are consistent with a ***small disk*** R_{taper} ***~ 50 AU***
- observed **^{12}CO/^{13}CO ratio ~2** suggests that ***outer edge is sharp*** $\gamma \sim -0.2$
- **[OI]63 flux** suggests that the ***outer disk is flared and settled***
- **SED** and **CO ro-vib** can be fitted only if ***the inner wall of the outer zone is situated in the shadow of the inner disk***
- **CO ro-vib data** is characterized by ***LTE emission of a warm low-density gas***, possibly powered by viscous heating
- last two points require a ***tenuous high inner zone*** with a ***break in surface density*** between inner and outer zone

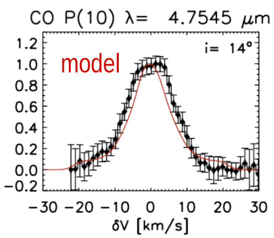
HD 135344B

→ *Andres Carmona (Madrid) et al. (2014, A&A 567, 23)*

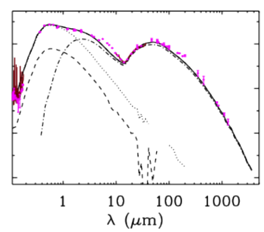
PIONIER H-band visibilities
(hot dust at R<0.2 AU)



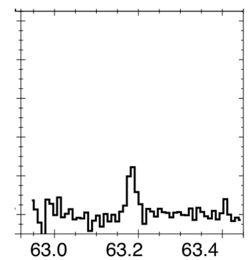
VLT/CRIRES CO 4.7μm
(warm gas 0.2<R<30 AU)



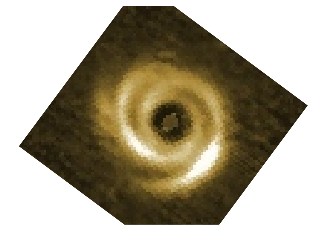
SED



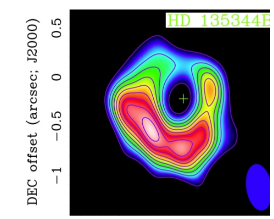
Herschel
[OI] 63 μm



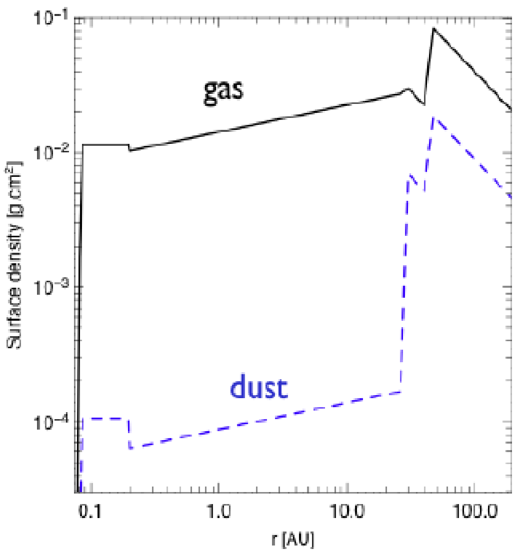
NACO near-IR
(small dust R>30 AU)

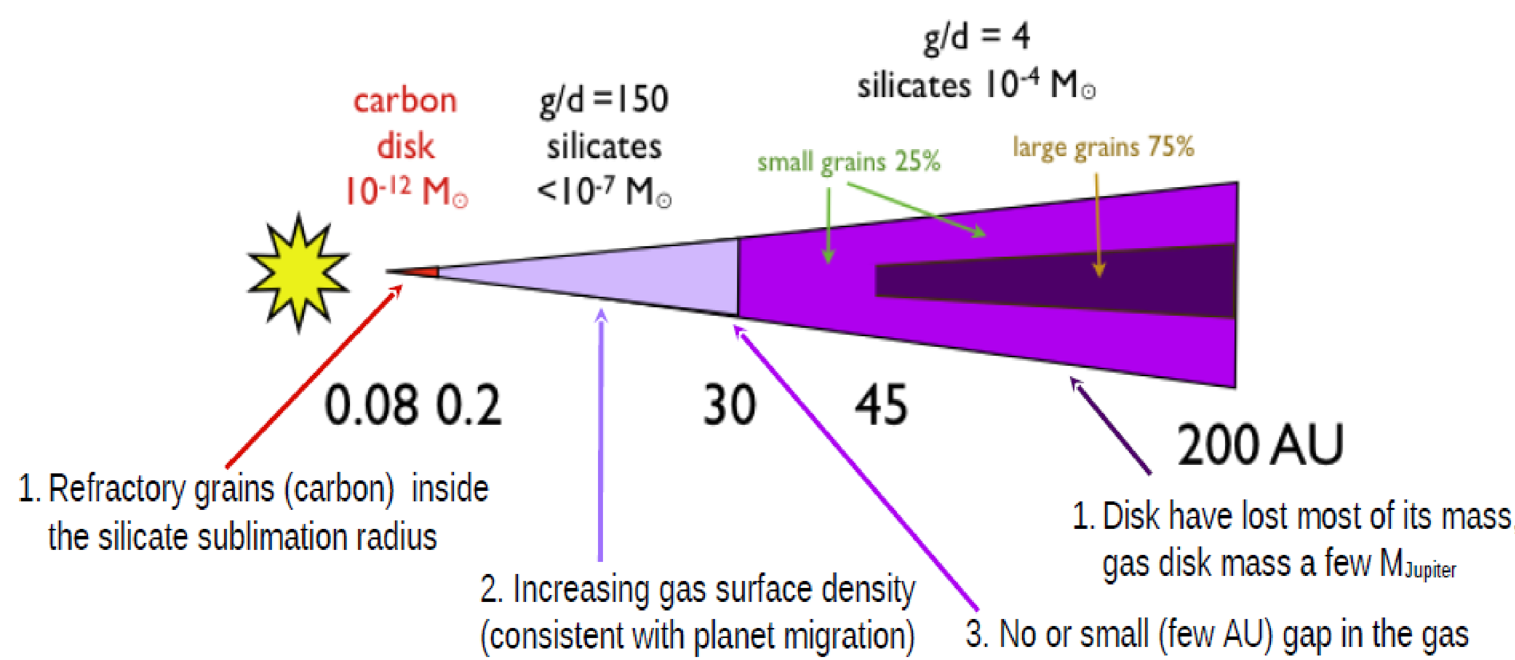


SMA 830 μm
(cold dust R>45 AU)



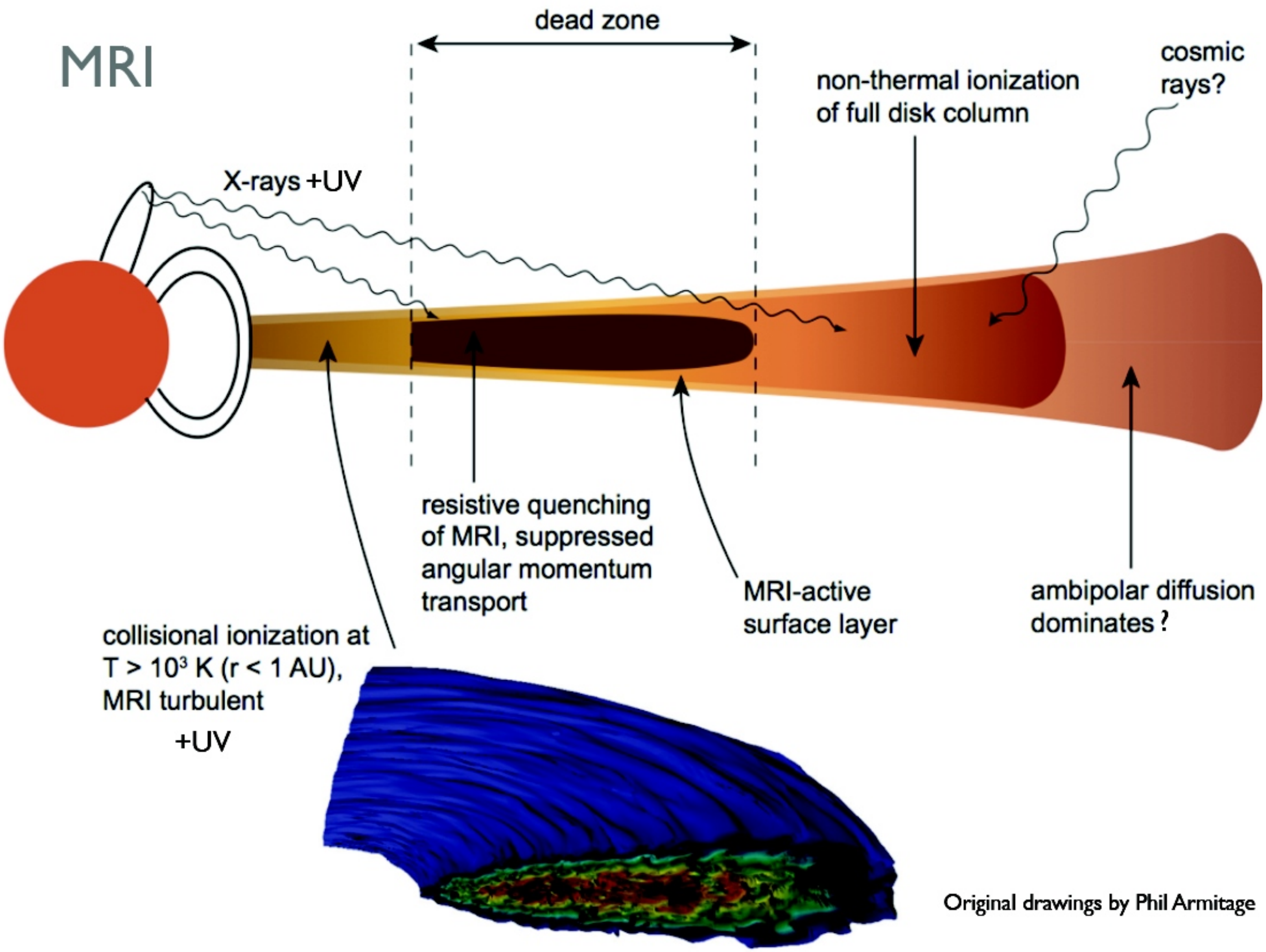
disk structure deduced from multi-λ continuum & line observations





MRI with chemistry & ionisation

→ *Wing-Fai Thi, Garching, Germany*



MRI instability

- creates viscosity, causes accretion, causes heating
- requires low resistivity, low ambipolar diffusion
- requires to know electron concentration, temperature

Disk chemistry

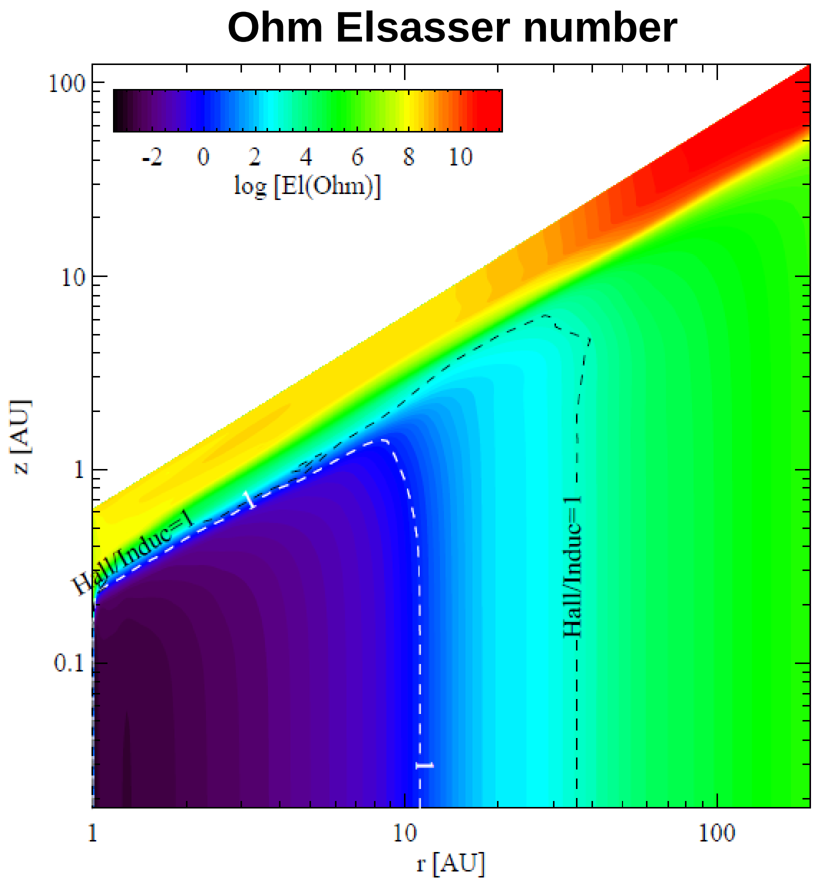
- takes into account additional heating
- predicts electron concentration, temperature

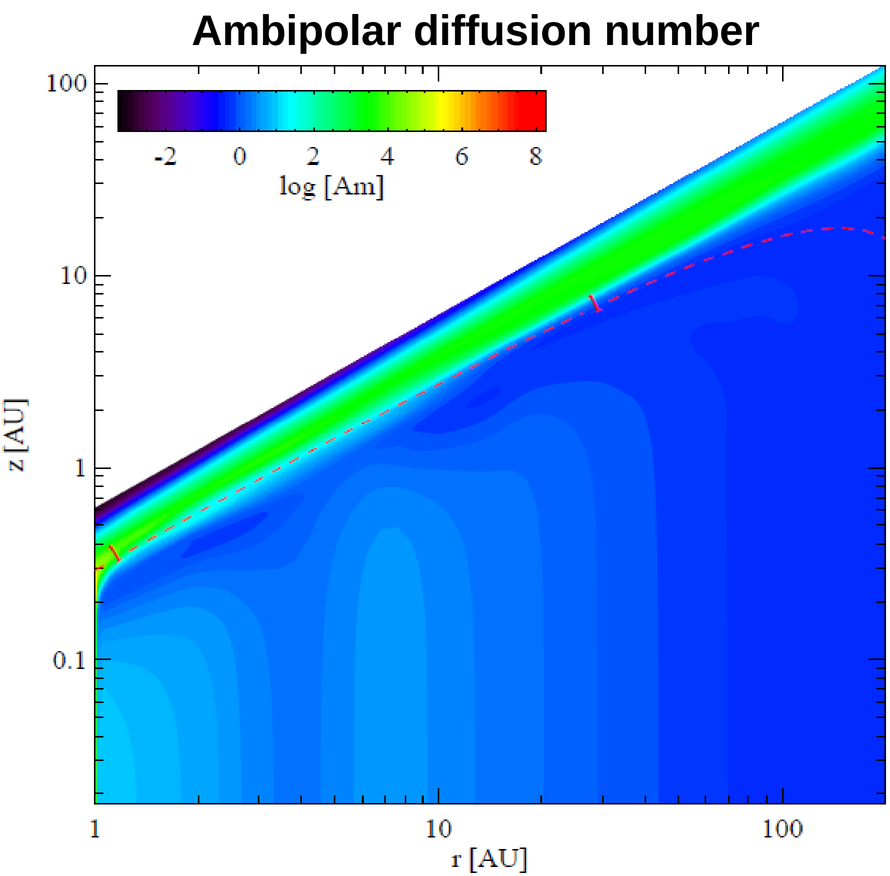
Our approach

- make a consistent model !
  - → predict $\alpha_{vis}(r,z)$
  - → predict $v_{turb}(r,z)$

MRI with chemistry & ionisation

→ *Wing-Fai Thi, Garching, Germany*

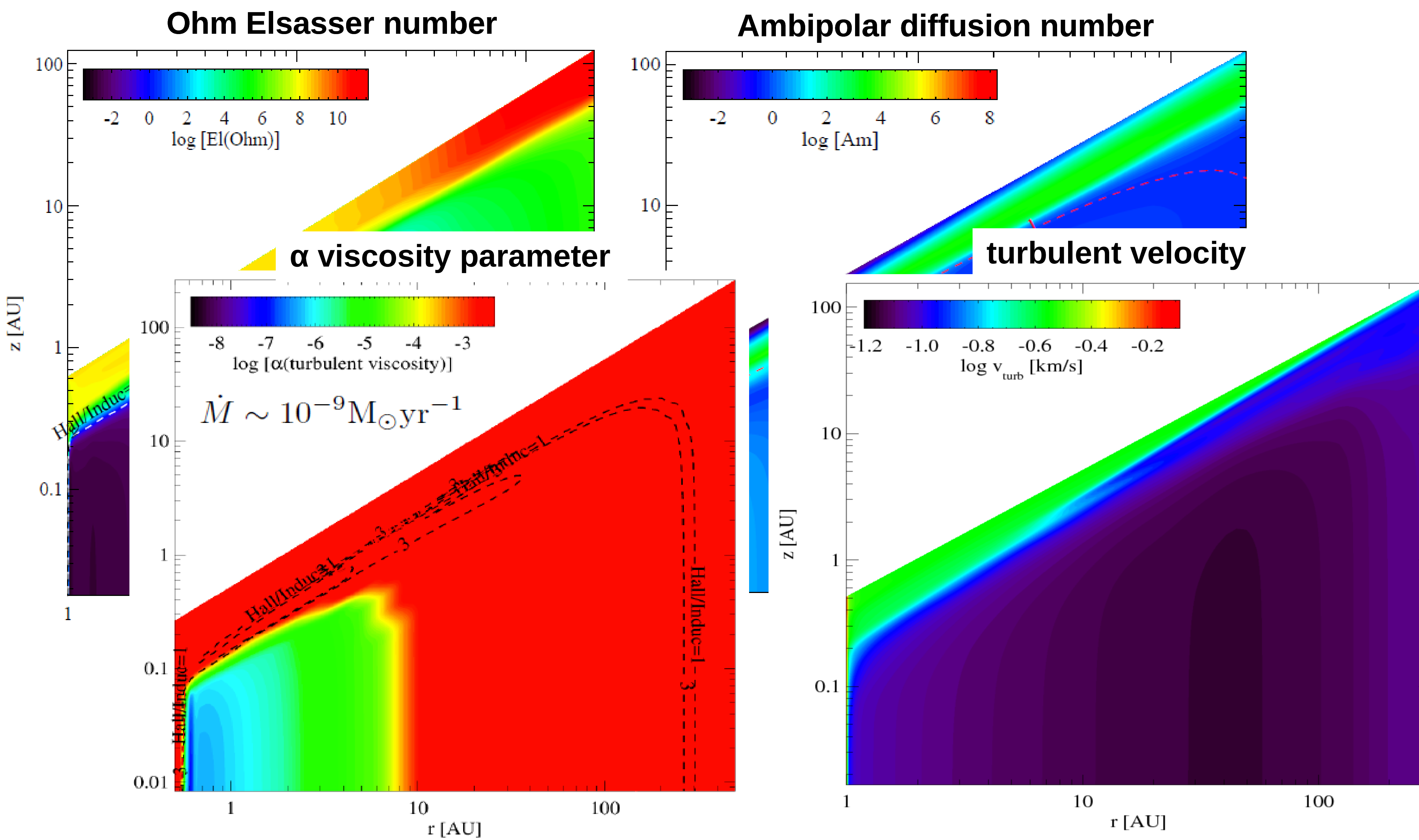




W.F.-Thi, G. Lesur, et al. 2014, A&A in prep.

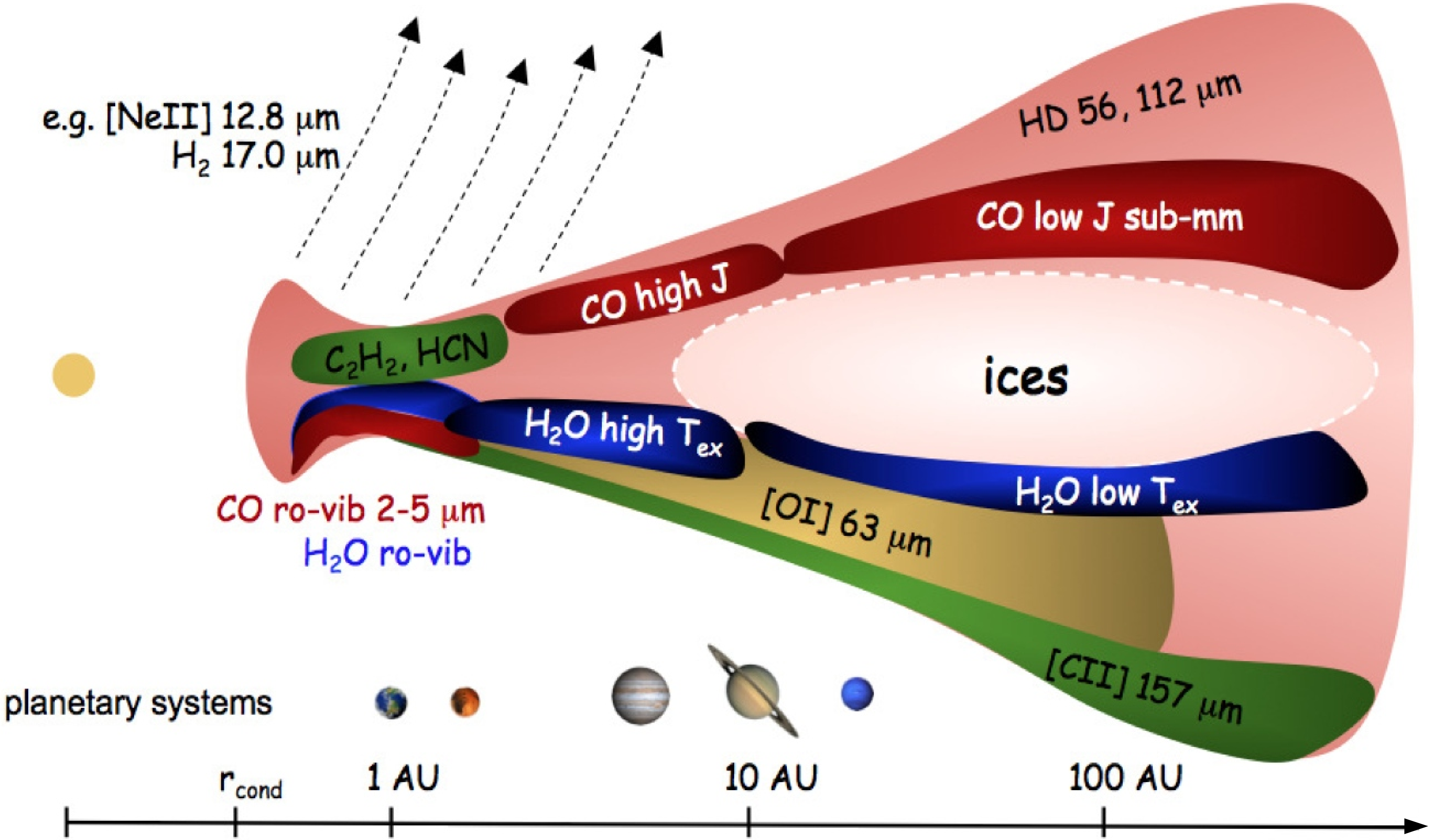
MRI with chemistry & ionisation

→ *Wing-Fai Thi, Garching, Germany*



W.F.-Thi, G. Lesur, et al. 2014, A&A in prep.

Understanding, Analysis, Observers' Tools ...



Summary

- ***EU FP7 project DIANA ...***
  - collects ***multi-λ observational datasets*** for ~80 T Tauri & Herbig Ae disks (continuum & line data)
  - sets ***"standards" for disk modelling*** (dust opacities, chemistry, disk shape, …)
  - provides detailed, high-quality, ***individual models of ~ 30 disks***
  - performs ***analysis & cross-comparison*** of data & modelling results

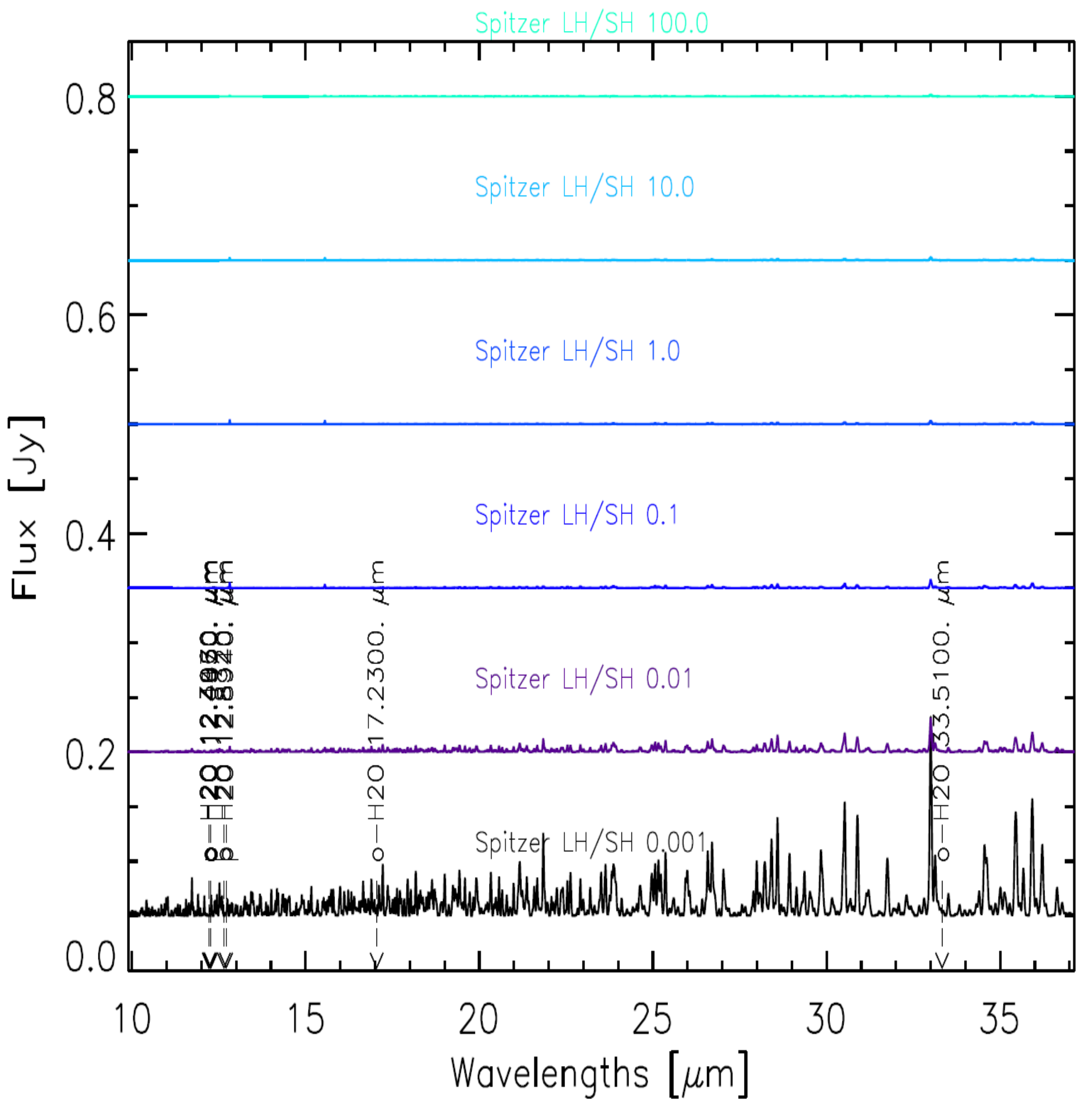
- ***EU FP7 project DIANA*** attacks some basic physio-chemical processes
  - ***X-ray scattering***
  - coupling between ***MRI*** and chemistry
  - gas inside ***inner rim***

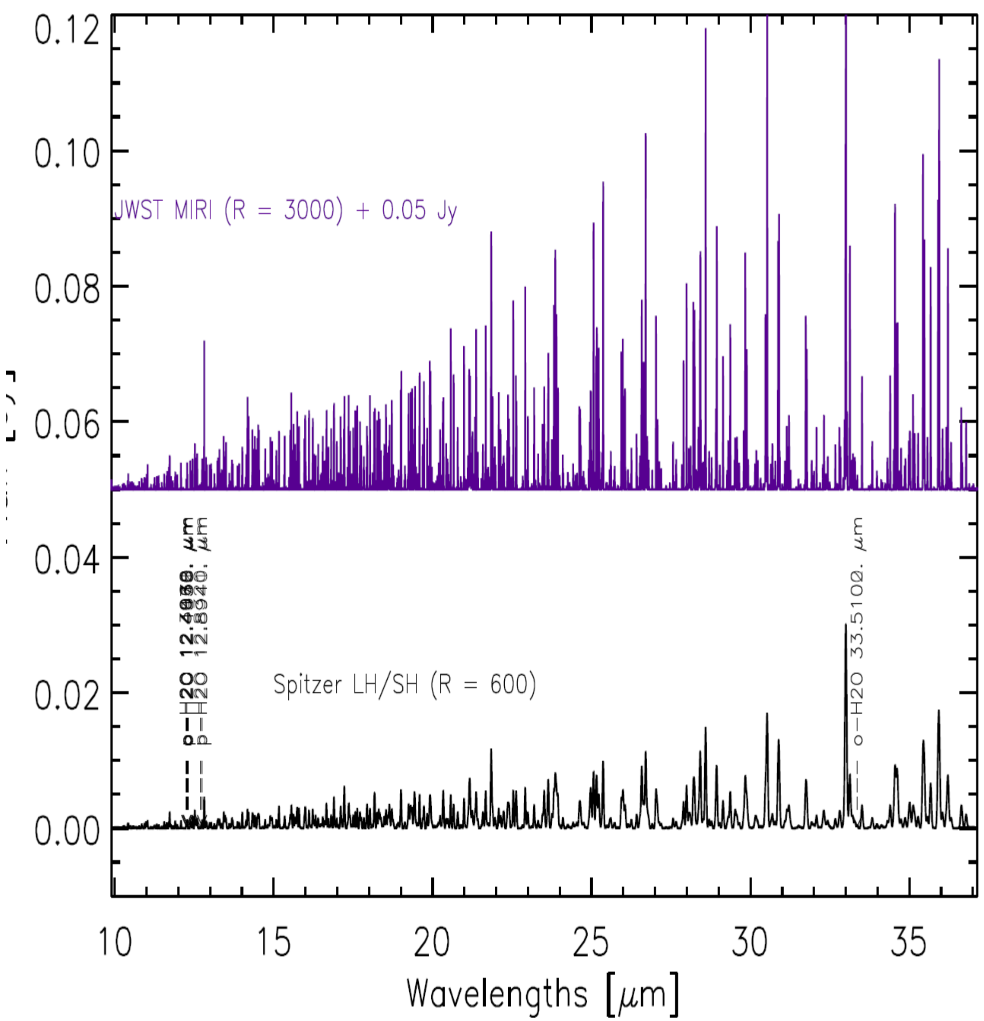
- ***EU FP7 project DIANA*** aims at
  - studying multi-λ ***emission lines: Where do they form? What do they tell us?***
  - providing continuum and line ***analysis tools for observers***

- see ***http://www.diana-project.com***
  - → ***all modelling software available against co-author right***
  - → ***observational data and modelling results will be available online ~ spring 2016***

mid-IR water

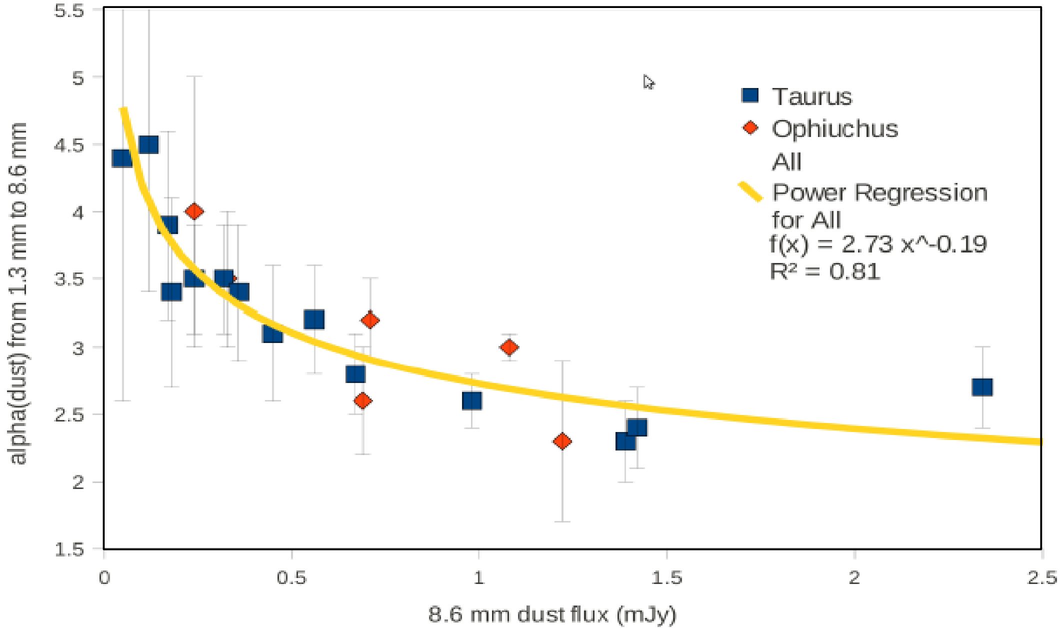
→ *Stefano Antonellini (Groningen, NL), 2014 in prep.*

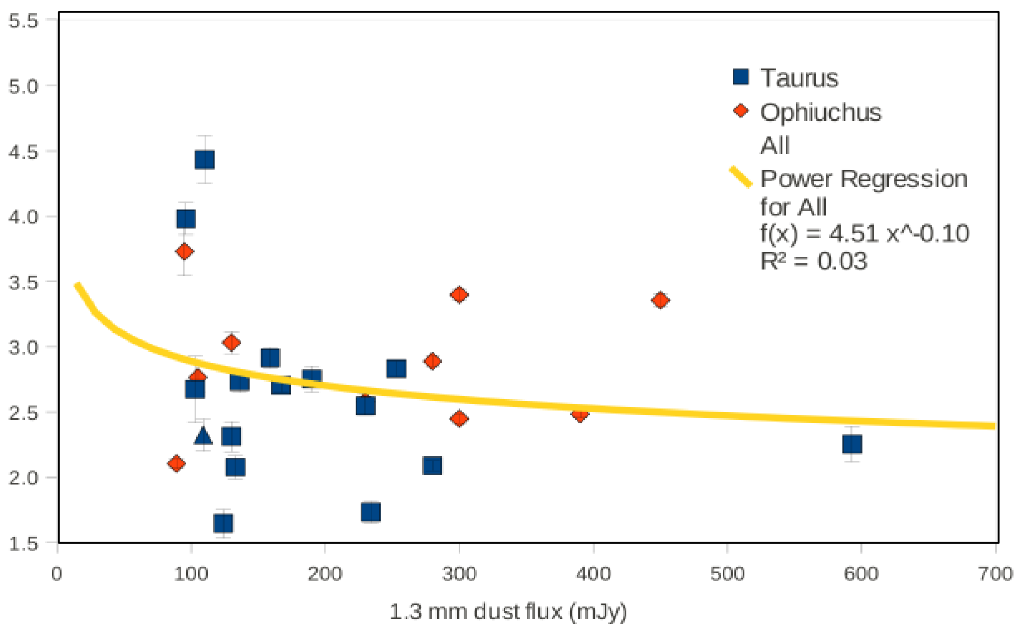


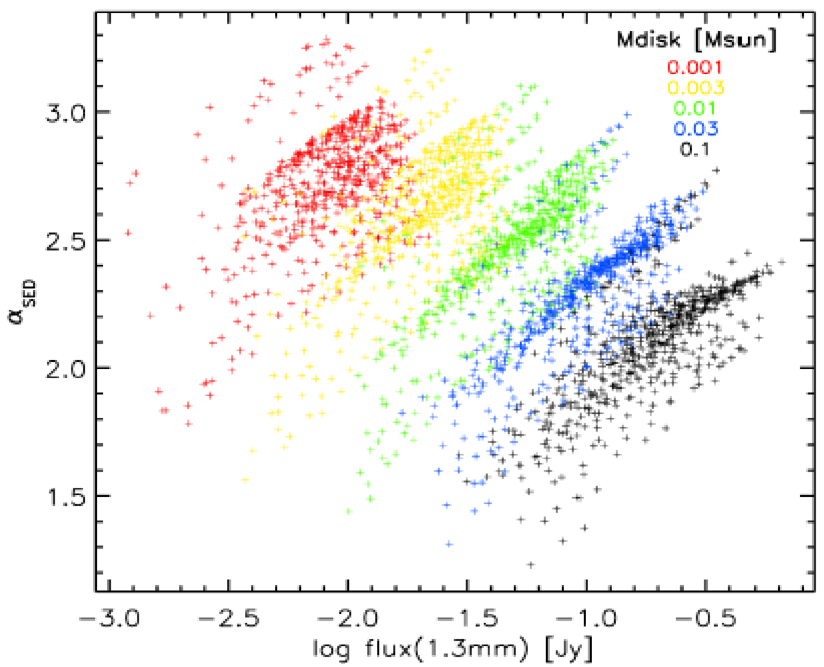


mm-cm SED slope

→ *J. Greaves, L. Rigon, P. Woitke, St Andrews University, UK, 2014, in prep*







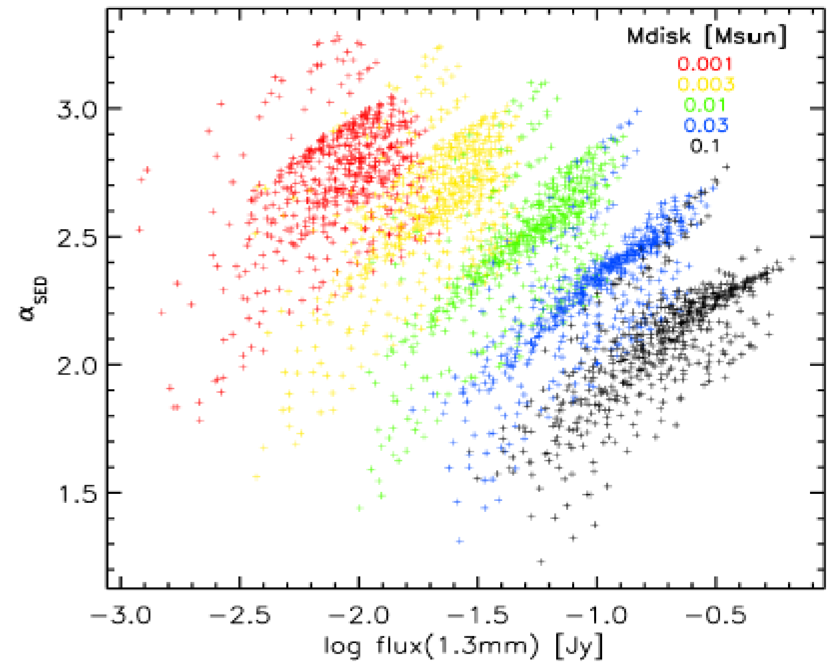
SED and mm-slope

→ *Peter Woitke & Laura Rigon, St Andrews University, UK*

Parameters of the betaGRID

stellar parameter			
	fixed: T Tauri (K7), $T_{\rm eff}=4000\,$K, $L_\star=1\,L_\odot$, $M_\star=0.7\,M_\odot$, $L_{\rm UV}/L_\star=0.01$, $L_X=10^{30}L_\odot$		
disk shape parameter			
1.	$M_{\rm dust}$	disk mass $[M_\odot]$	0.001, 0.003, 0.01, 0.03, 0.1
2.	$R_{\rm out}$	outer disk radius $[AU]$	100, 200, 400
3.	ϵ	column density power index using $\Sigma(r)\propto r^{-\epsilon}\exp\left(-r/R_{\rm tap}\right)$	0.5, 0.75, 1.0, 1.25, 1.5
4.	H_0	scale height [AU] at $R_0=3\,$AU	0.1, 0.14, 0.2, 0.28, 0.4
5.	β	flaring power $H(r)=H_0(\frac{r}{R_0})^\beta$	1.04, 1.08, 1.12, 1.16, 1.2
	fixed: gas/dust$\,=100$, $R_{\rm in}=0.07\,$AU, $R_{\rm tap}=R_{\rm out}/4$		
dust parameter			
6.	$a_{\rm pow}$	size power index $f(a)\propto a^{-a_{\rm pow}}$	3.35, 3.5, 3.65, 3.8, 4.05
7.	α	turbulent mixing for settling	10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}, 10^{-1}
	fixed: $a_{\rm min}=0.05\,\mu$m, $a_{\rm max}=1\,$mm, Dubrulle(1995)-settling (45% $MgFeSiO_4$, 35% $Mg_{0.5}Fe_{0.5}SiO_3$, 15% AC, 5% FeS)		

- 1000 disk models, $T_{\rm dust}(r,z)$ & SEDs computed with MCMax (Min et al. 2009)
- $T_{\rm gas}(r,z)$, chemistry & emission lines computed with ProDiMo (Woitke et al. 2009)

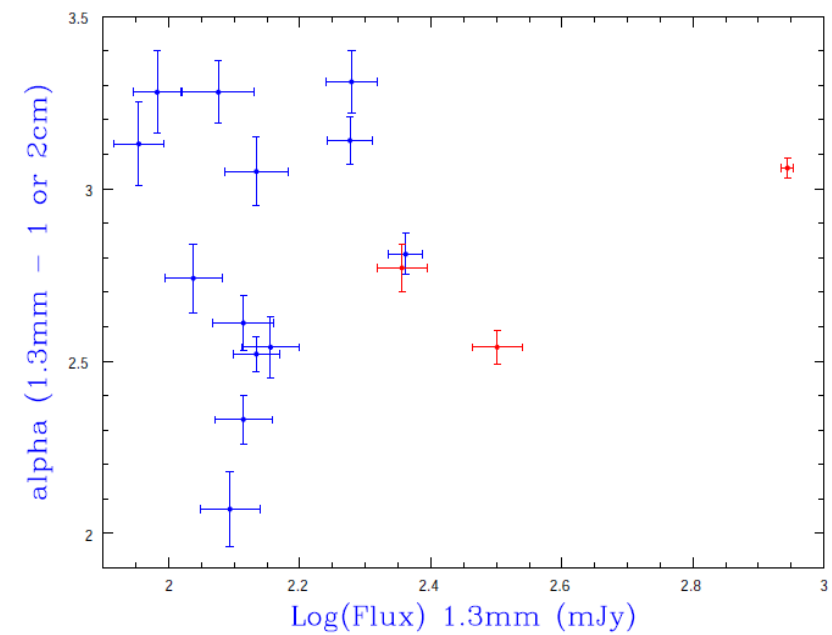


Grid of models

- **large variety of SED mm-fluxes (and slopes) for constant dust mass** (→ dust settling!)
- **observing mm-flux and slope may improve $M_{\rm dust}$ - determination**

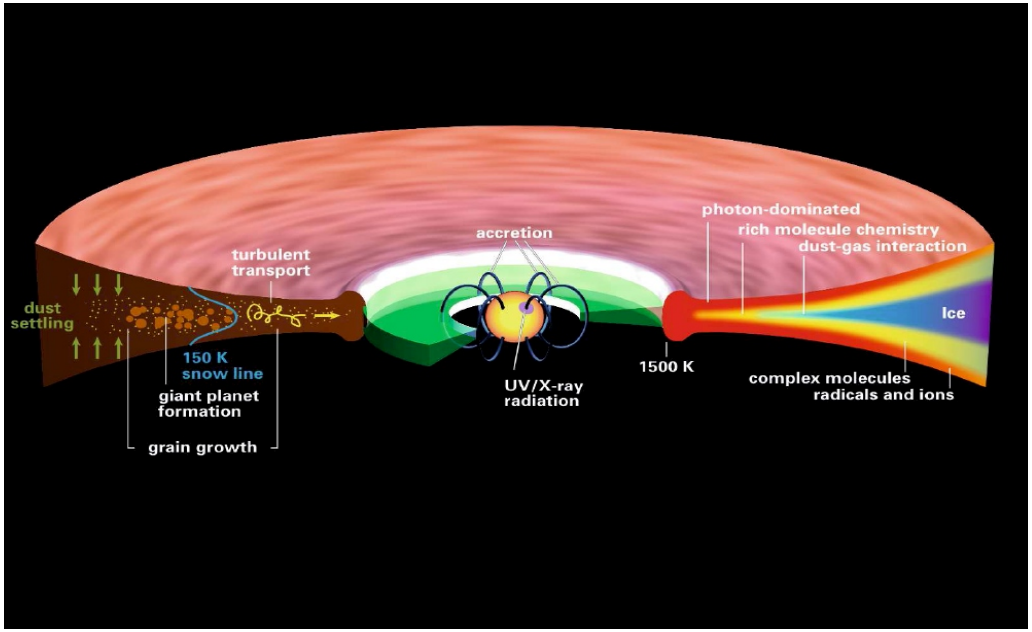
Real stars (with new GBT cm-data!)

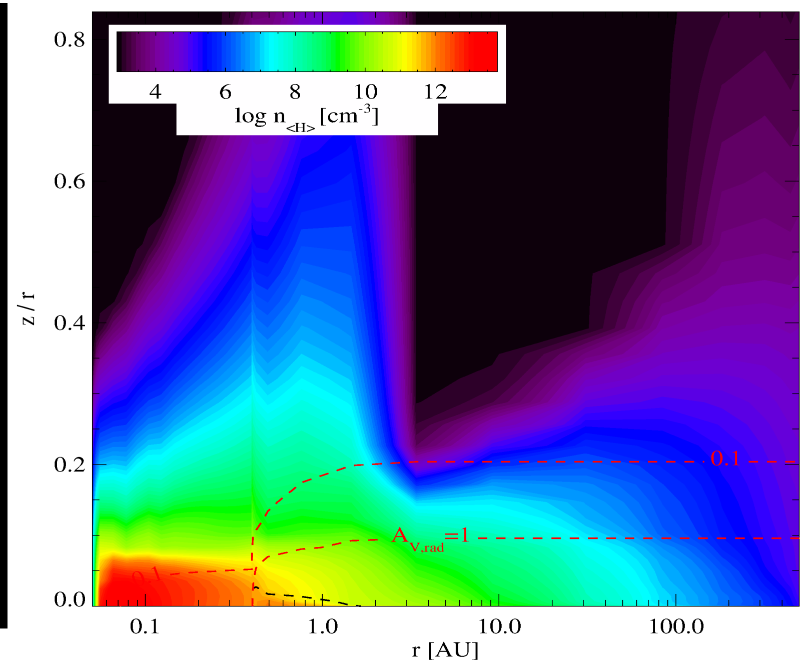
- **only when including cm-data, large variety becomes obvious**

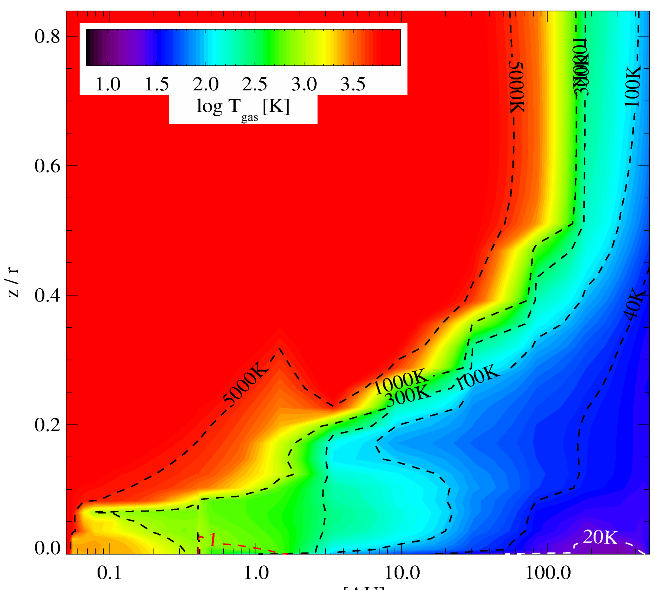


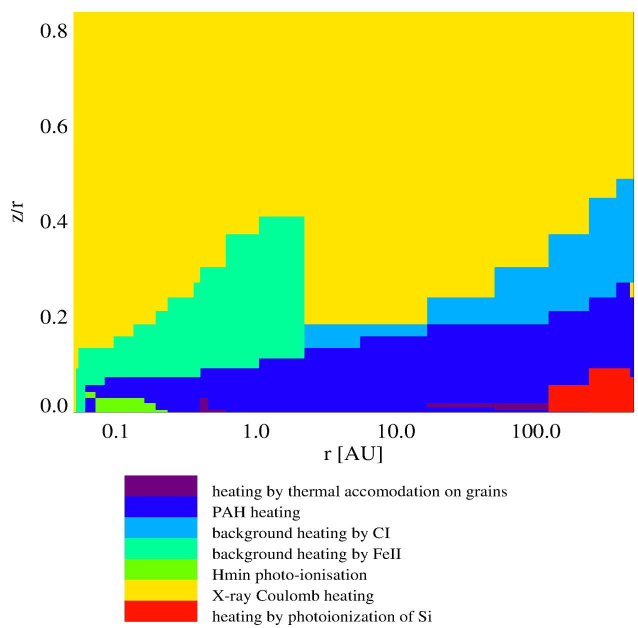
Gas inside of the dust inner rim?

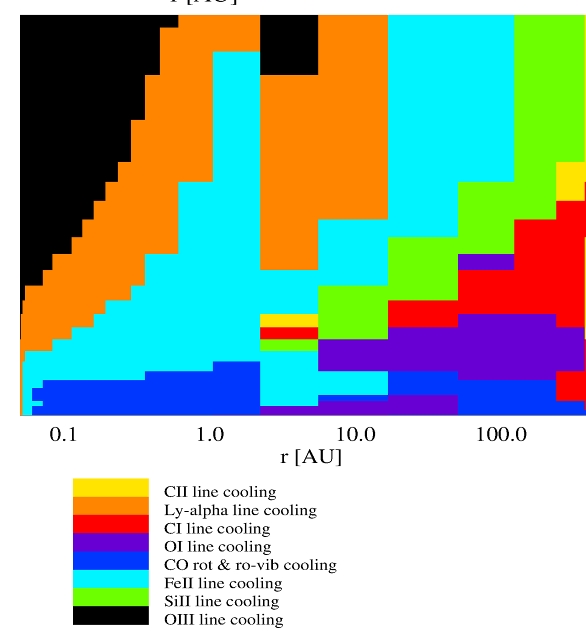
→ *John Ilee, St Andrews University, UK*



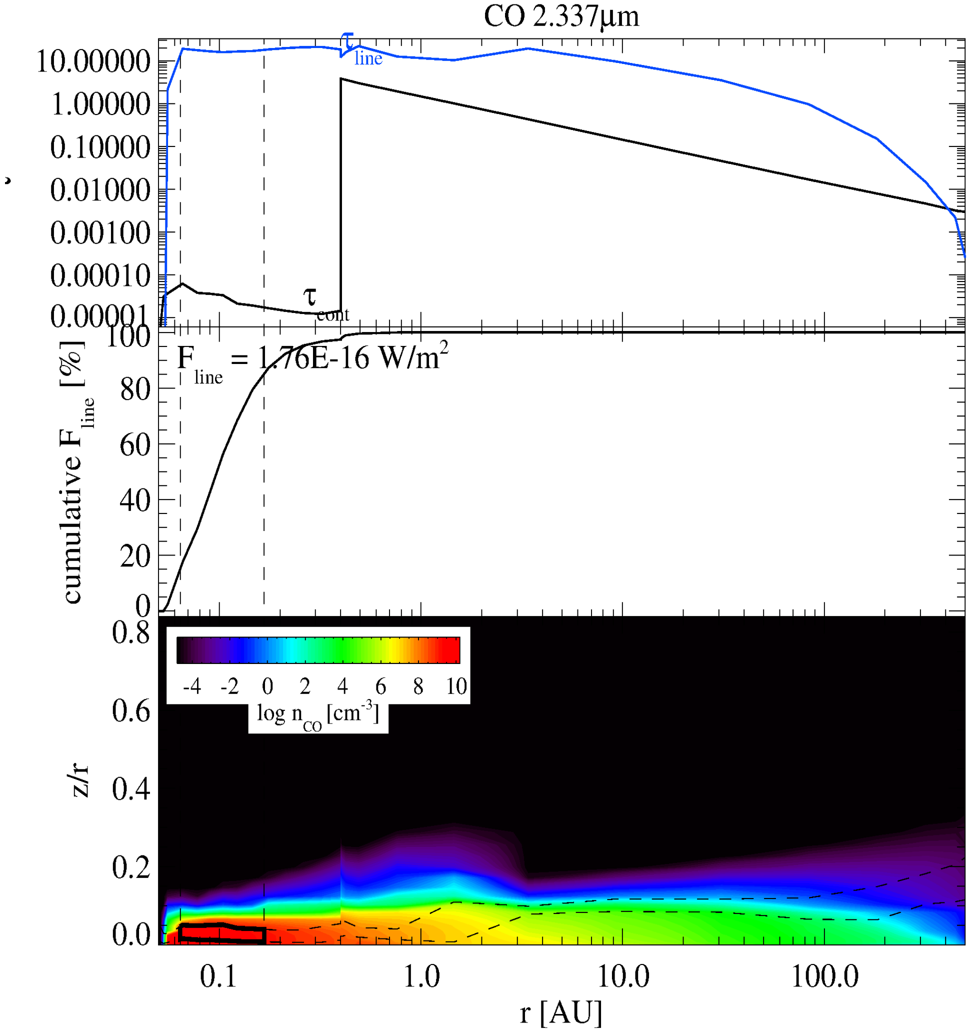


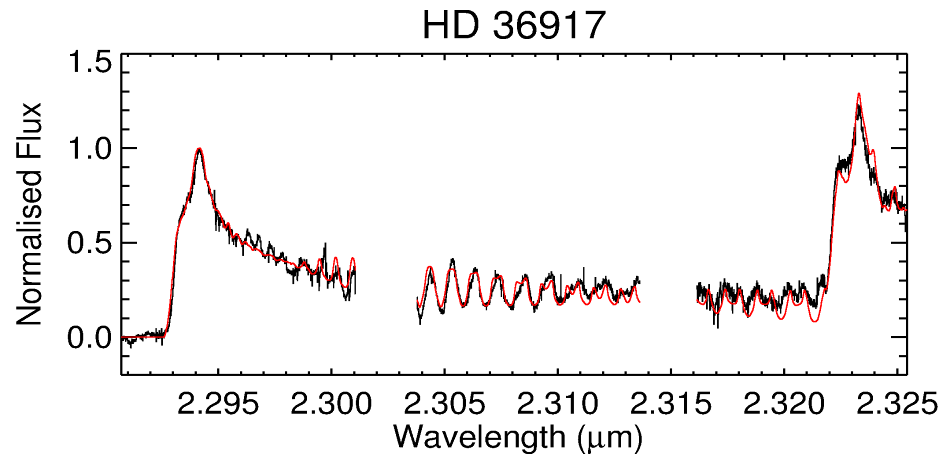


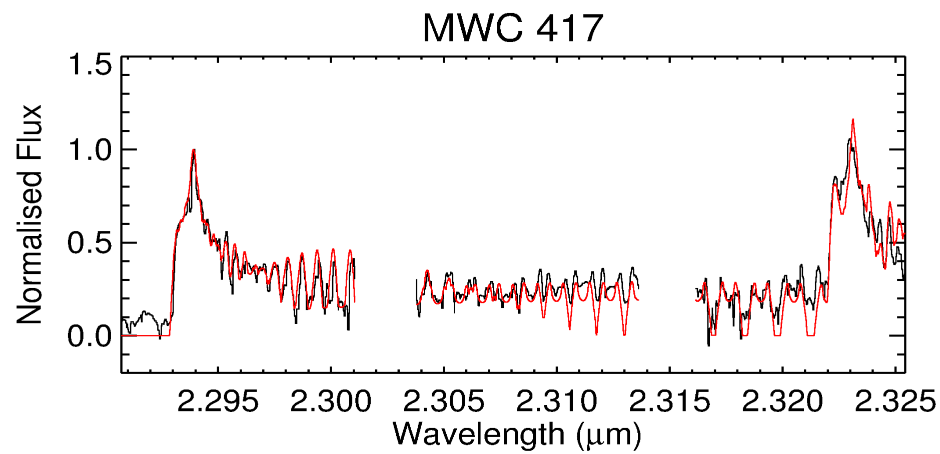




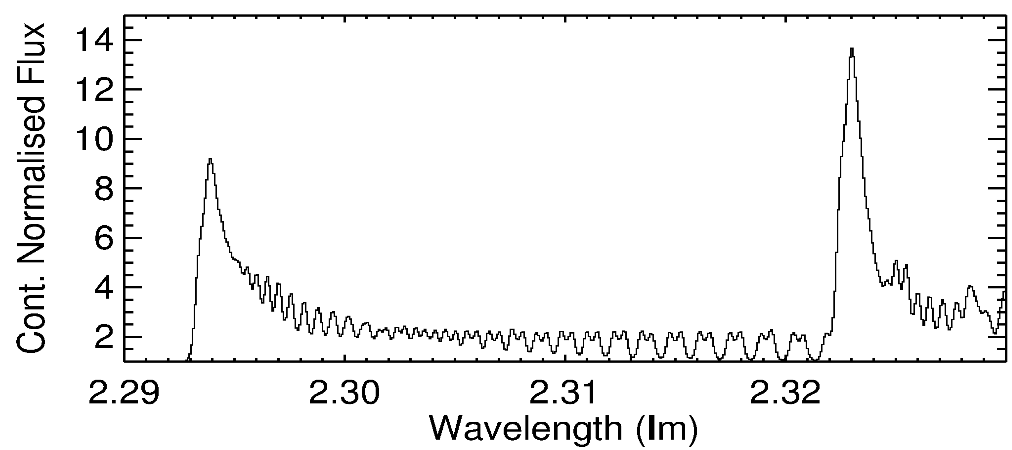
Gas inside of the dust inner rim?





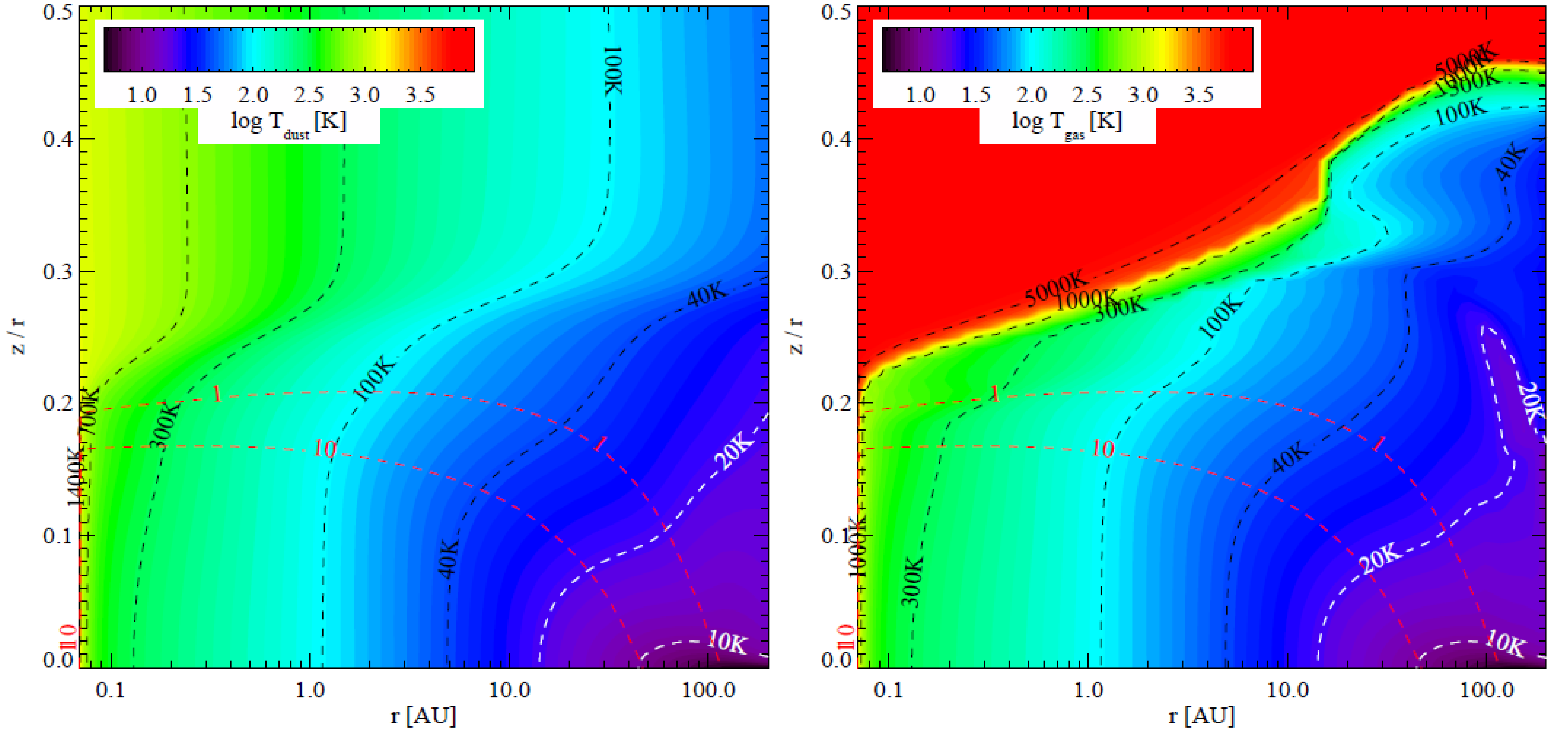


New: ProDiMo model + FLiTs

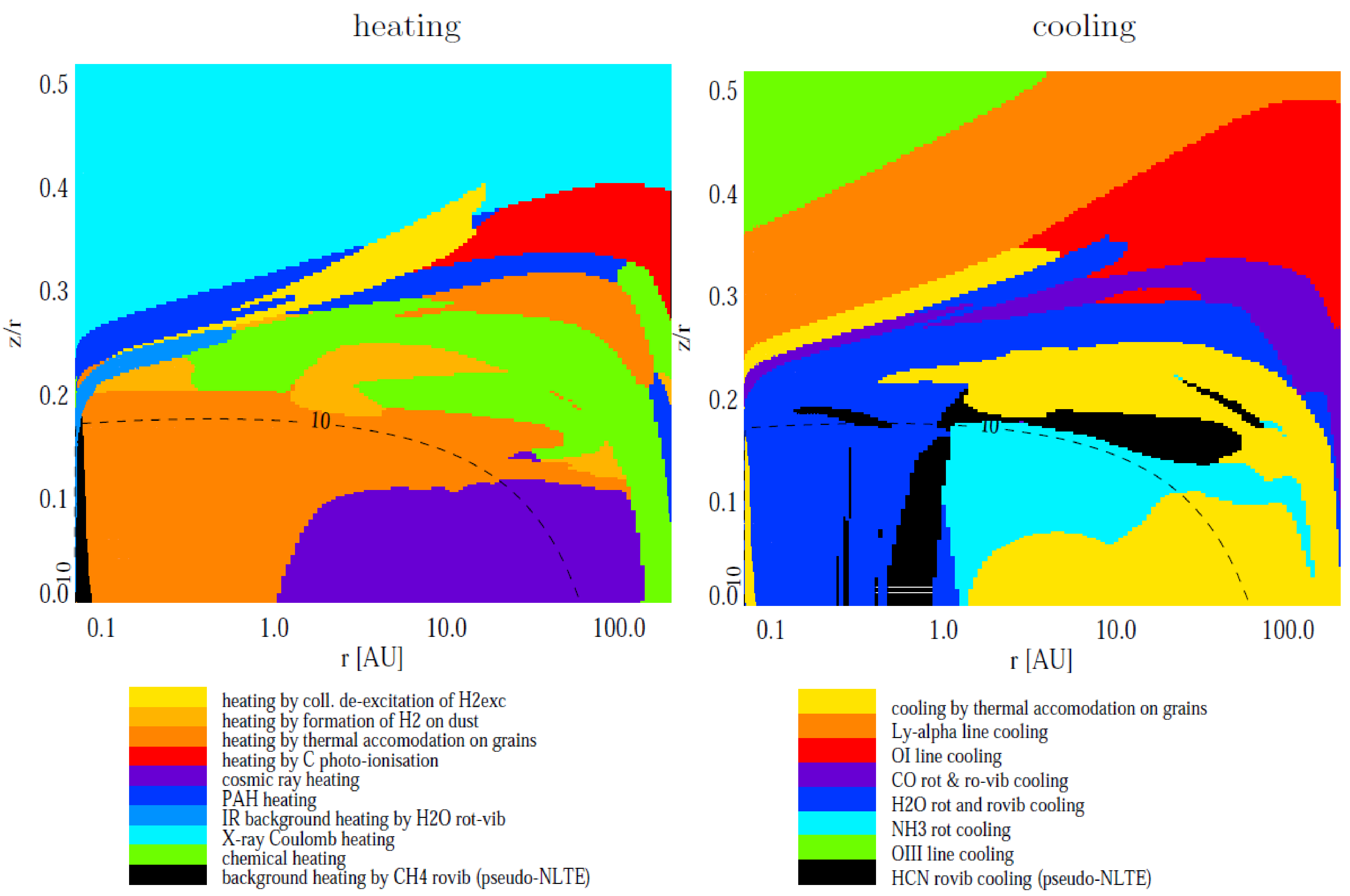


- ***CO overtone emission*** *probes gas inside of inner dust rim*
- ***ProDiMo can be used to characterize that gas*** *(temperature, vertical structure, chemistry ...)*
- *non-detection implies lower limit for the* ***amount of such gas***

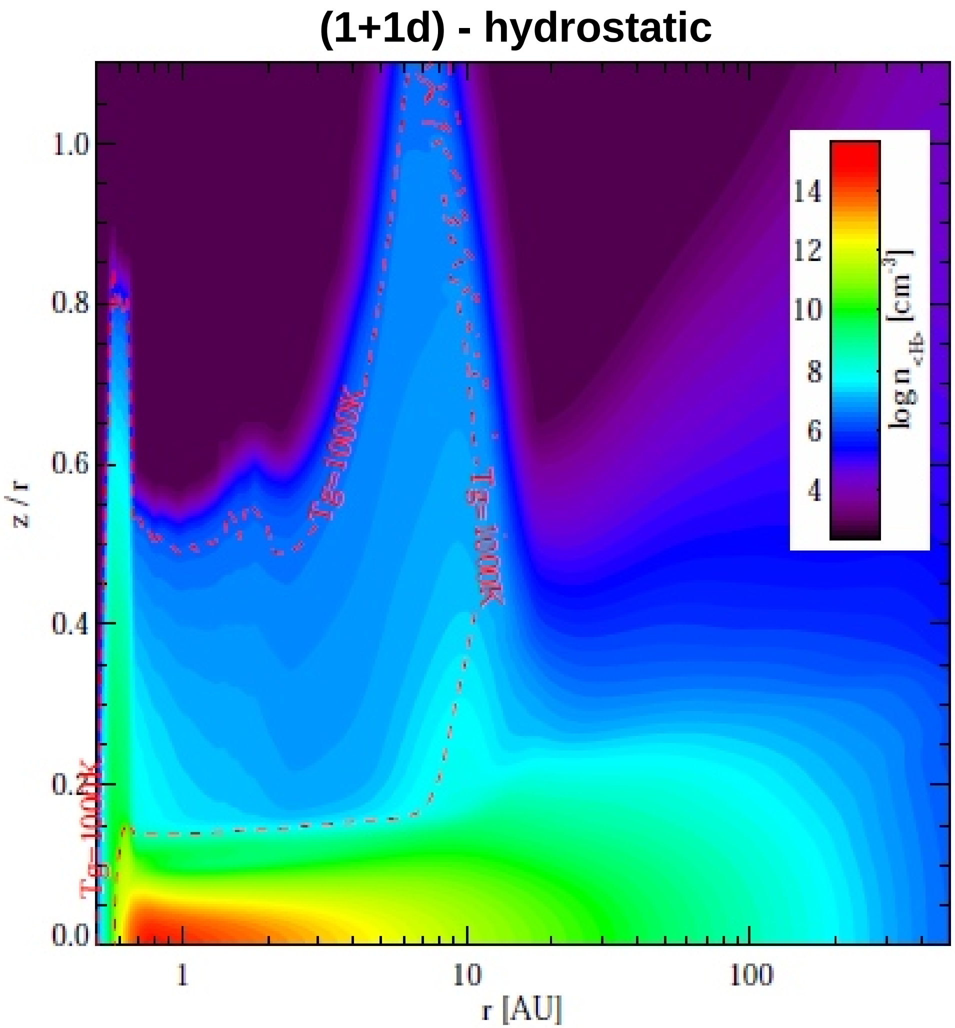
Gas and Dust Temperatures

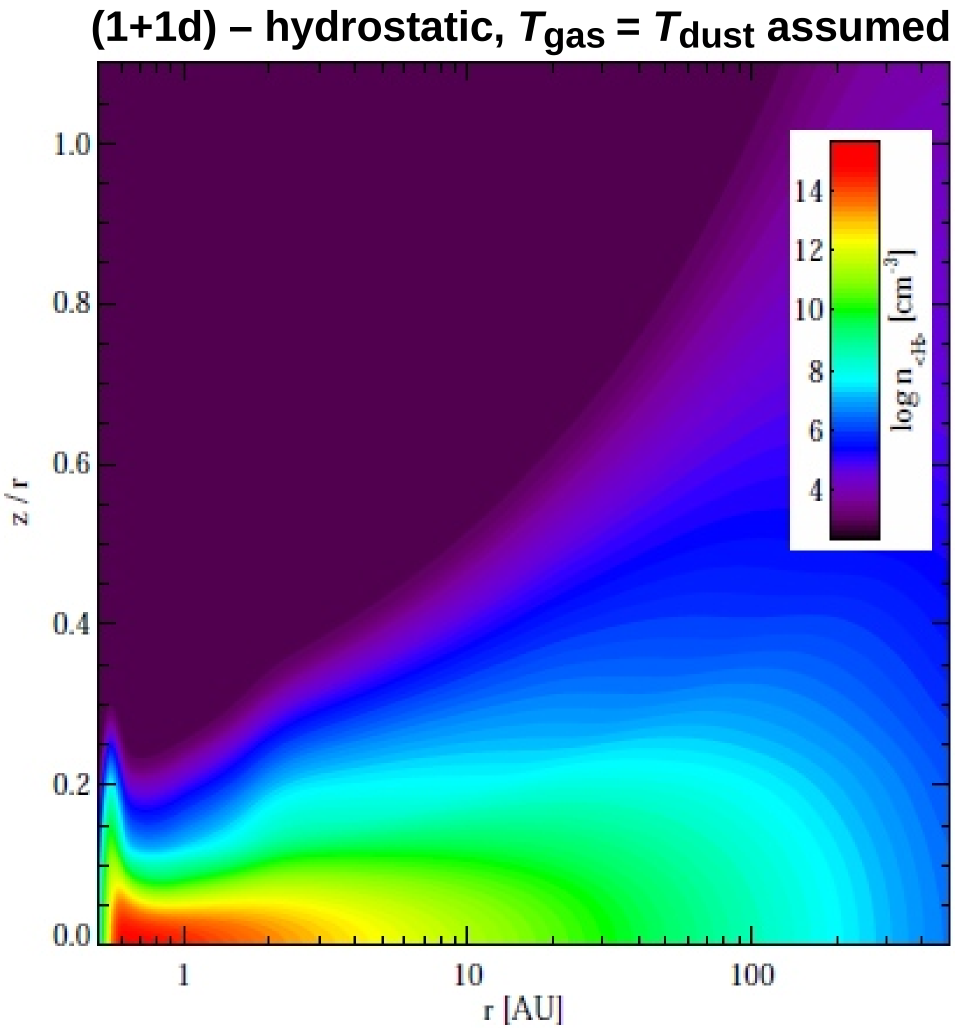


Gas Heating & Cooling



Density Structure

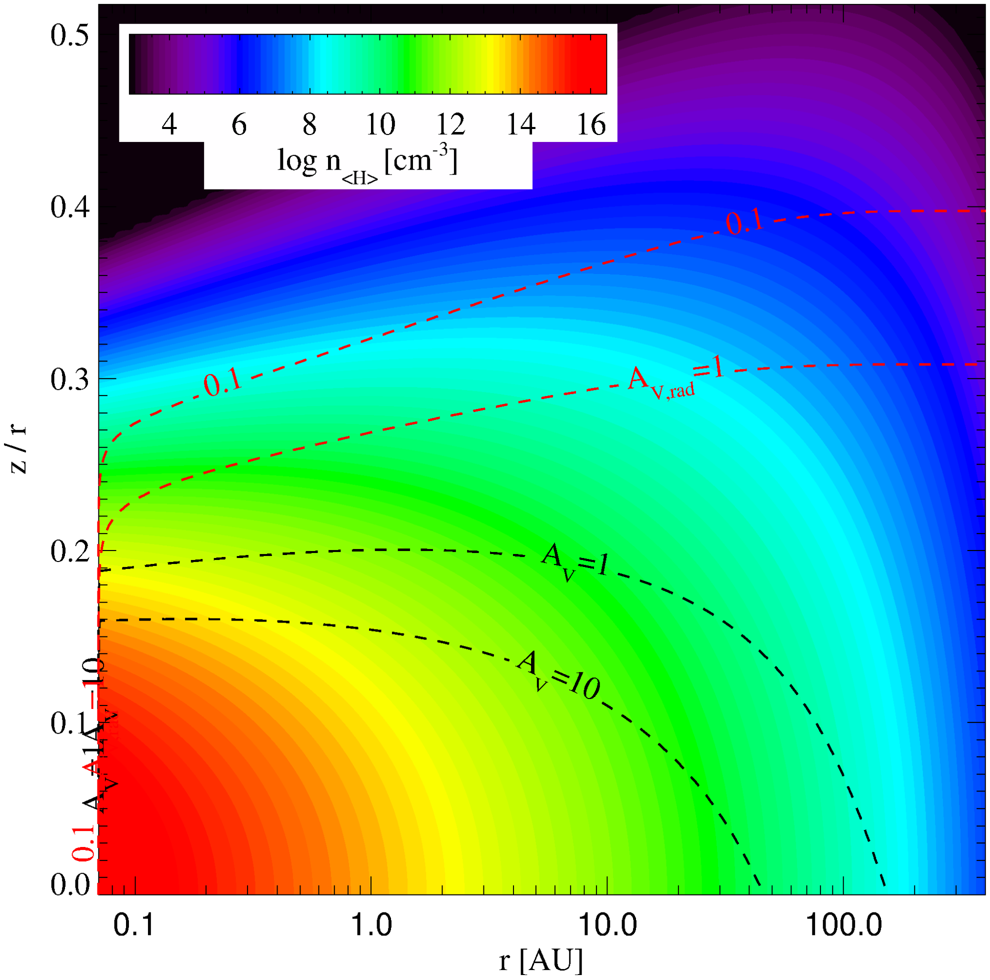




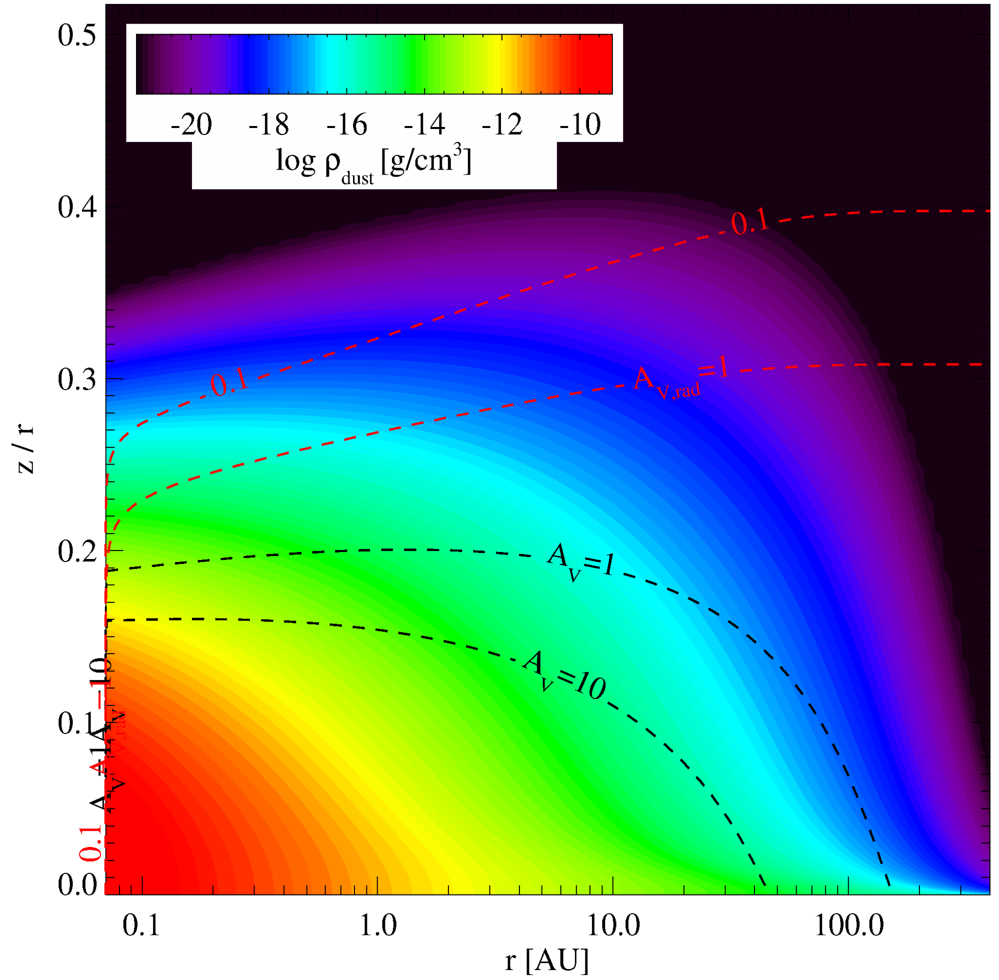
Woitke, Kamp & Thi (2009, A&A 501, 383);
Thi, Woitke, Kamp (2011, MNRAS 412, 711)

Dust settling

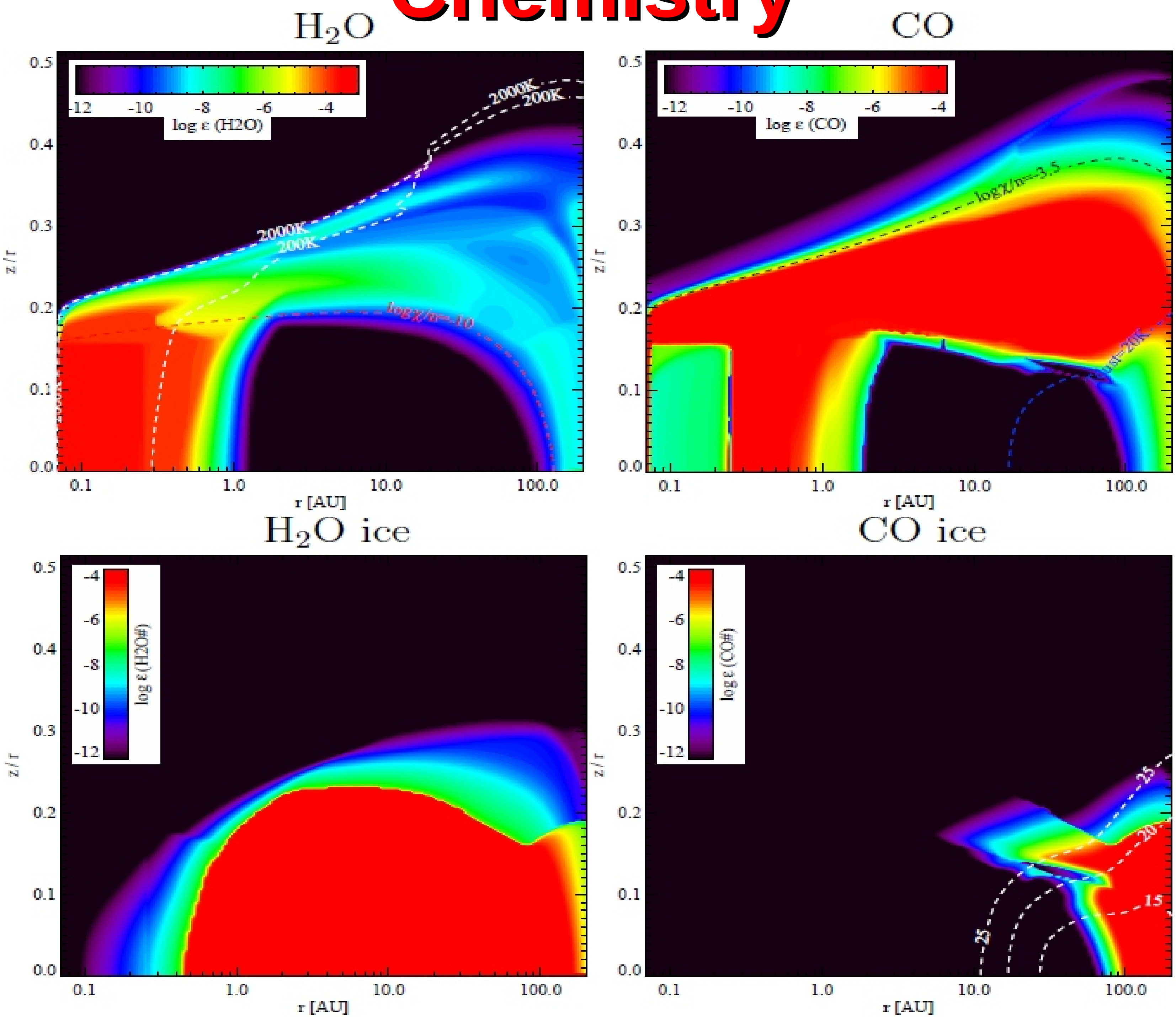
gas (assumed): exponential tapering-off



dust (calculated): Dubrulle-settling $\alpha = 10^{-3}$



Chemistry


H2O
CO
log ε (H2O)
log ε (CO)
2000K
200K
logχ/n=-10
logχ/n=-3.5
Tdust=20K
z / r
r [AU]
H2O ice
CO ice
log ε (H2O#)
log ε (CO#)
25
20
15

Overview of thermo-chemical models

	RT	chemistry	X-rays	heat & cool	vert. struc.	transport & mixing
Gorti, Hollenbach et al.	*	**	✓	**	***	-
Heinzeller, Normura et al.	*	***	✓	**	***	*
Bruderer et al.	***	**	✓	**	(fixed)	-
Semenov, Bergin et al.	*	****	✓	$(T_g = T_d)$	(fixed)	***
ProDiMo	**	**	✓	***	***	-
ProDiMo & MCFOST	***	**	✓	***	(fixed)	-

Gorti, Hollenbach, Najita, Pascucci (2011, ApJ 735, 90)
Heinzeller, Nomura, Walsh, Millar (2011, ApJ 731, 115)
Bruderer, van Dishoeck, Doty, Herczeg (2012, A&A in press)
Fogel, Bethell, Bergin, Calvet, Semenov (2011, ApJ 726, 29)
Woitke, Thi, Kamp, Aresu, Meijerink, Spaans (various papers 2009–2012)
Pinte, Ménard, Duchêne (2006, A&A 459, 797)