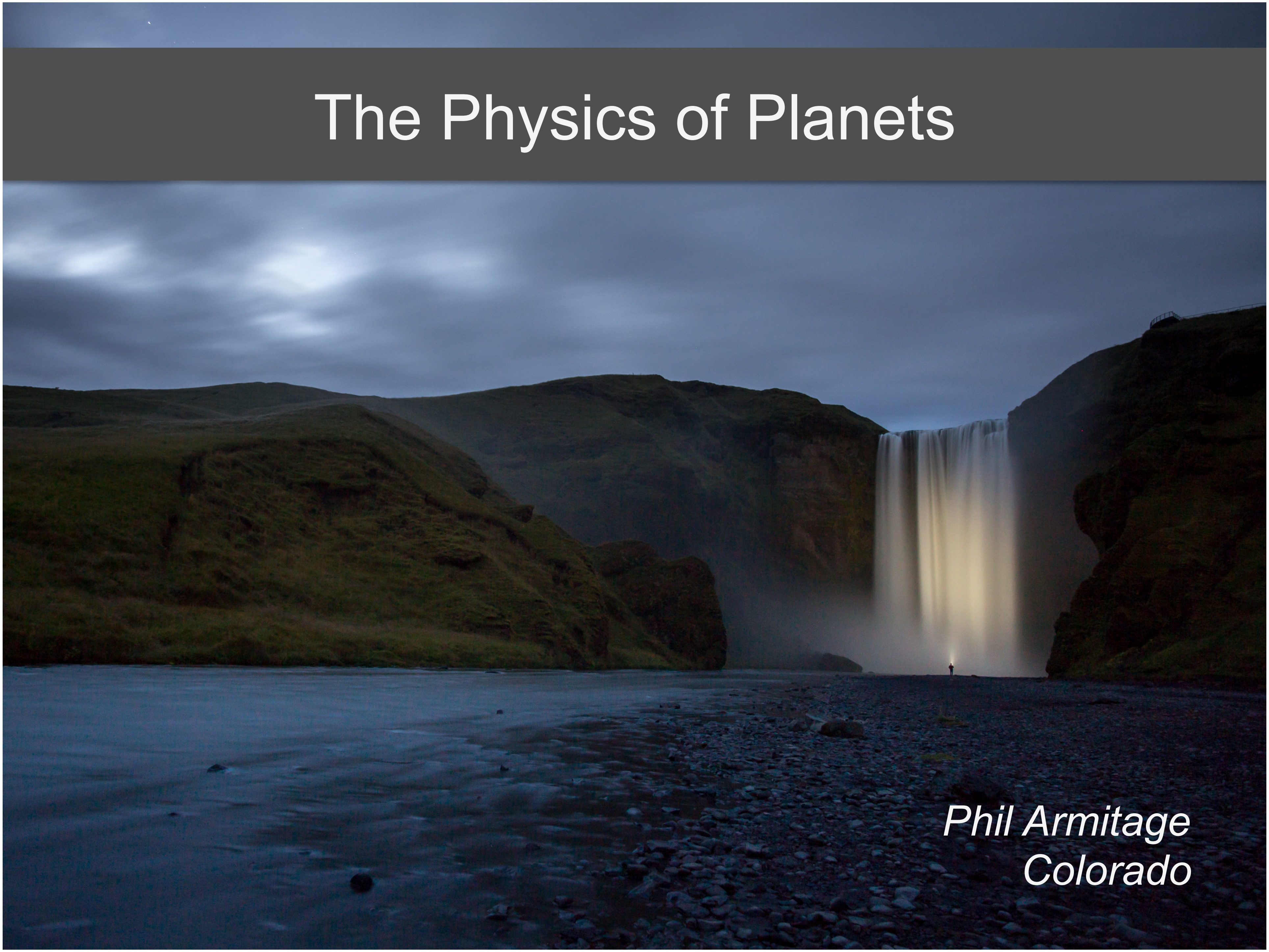
The Physics of Planets



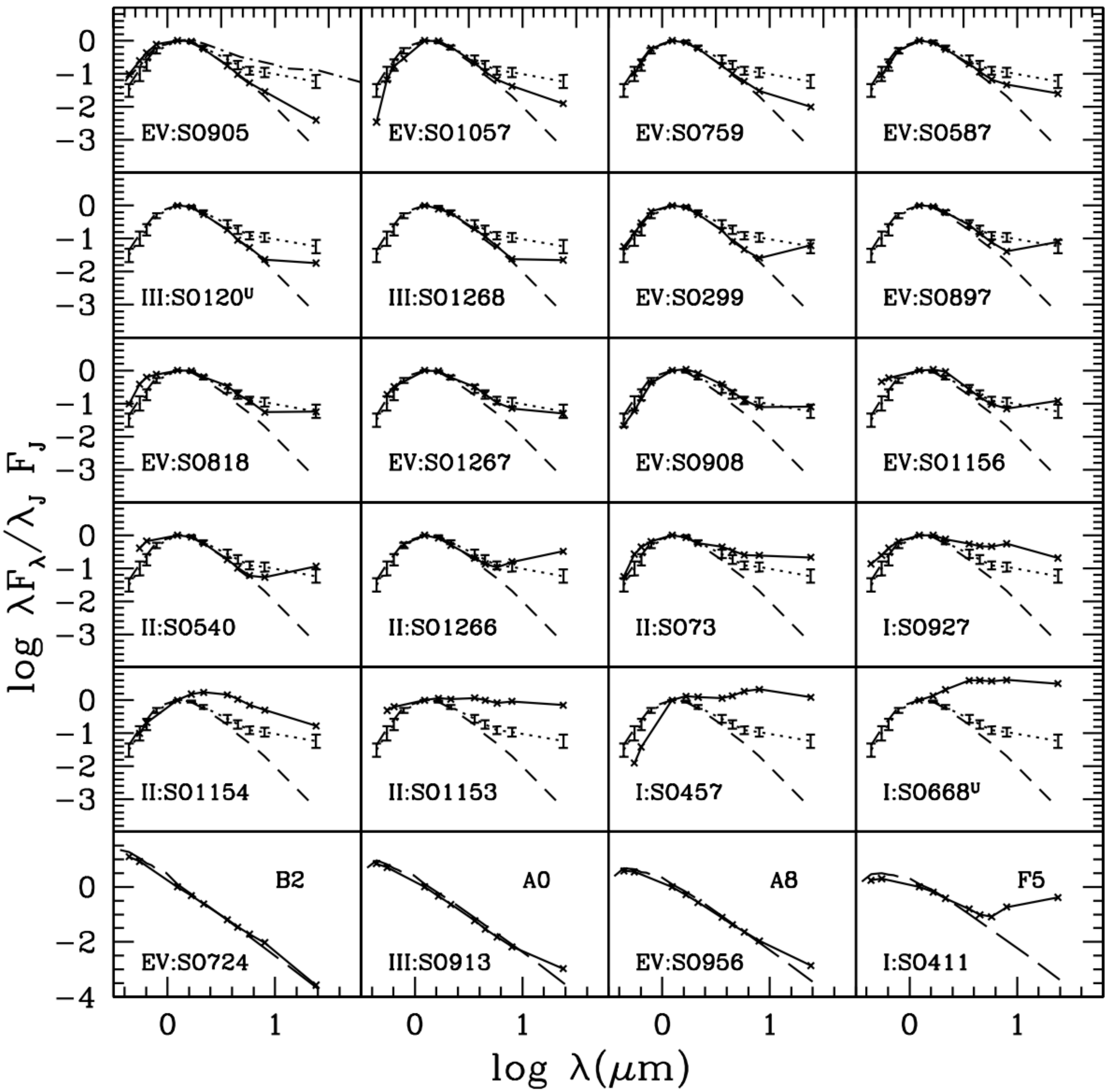
Phil Armitage
Colorado

Disk structure

Basic principles: disks are long-lived and (usually) well approximated by -

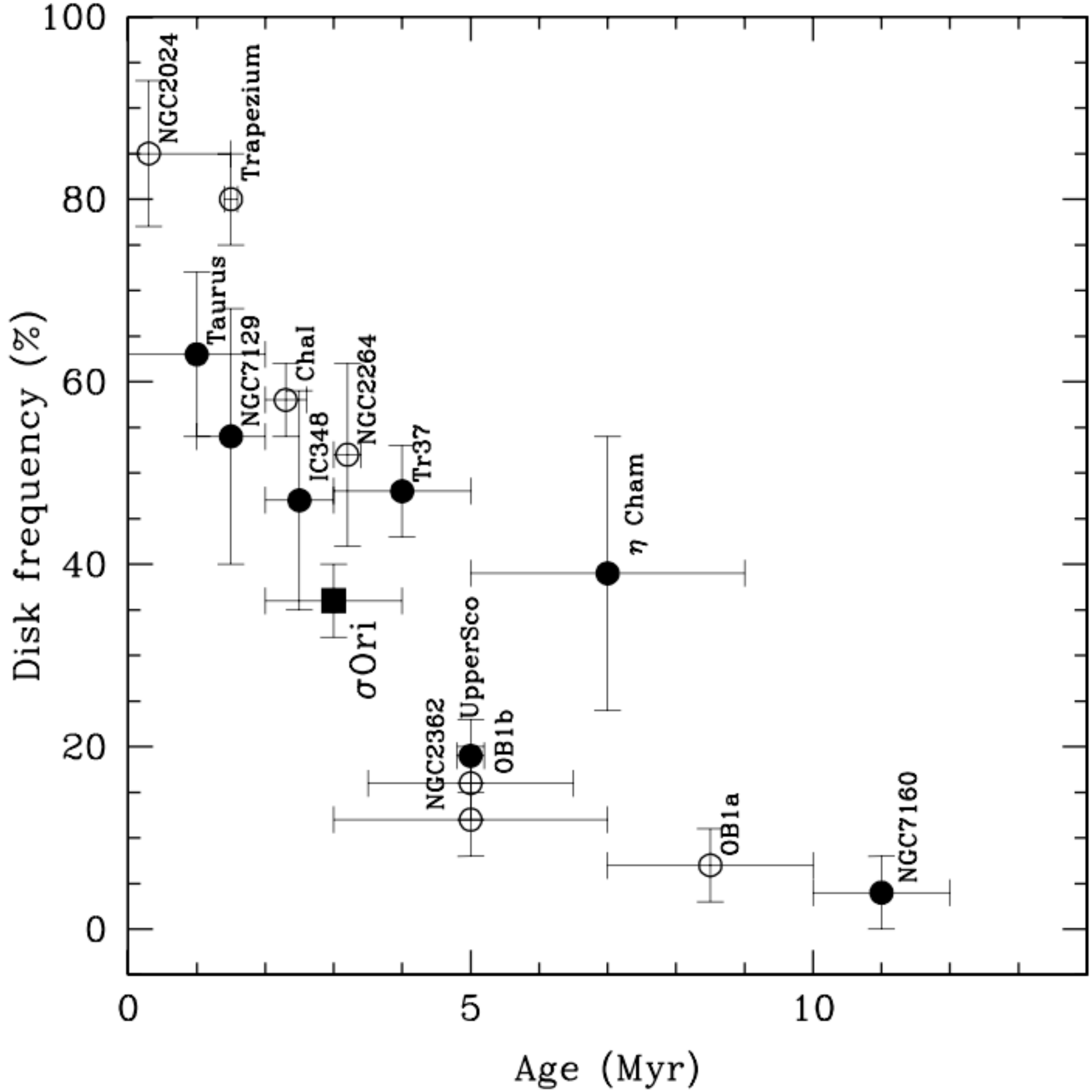
- hydrostatic equilibrium
- thermal equilibrium
- local ionization equilibrium

In many cases chemistry is *not* necessarily in equilibrium



Disk lifetimes

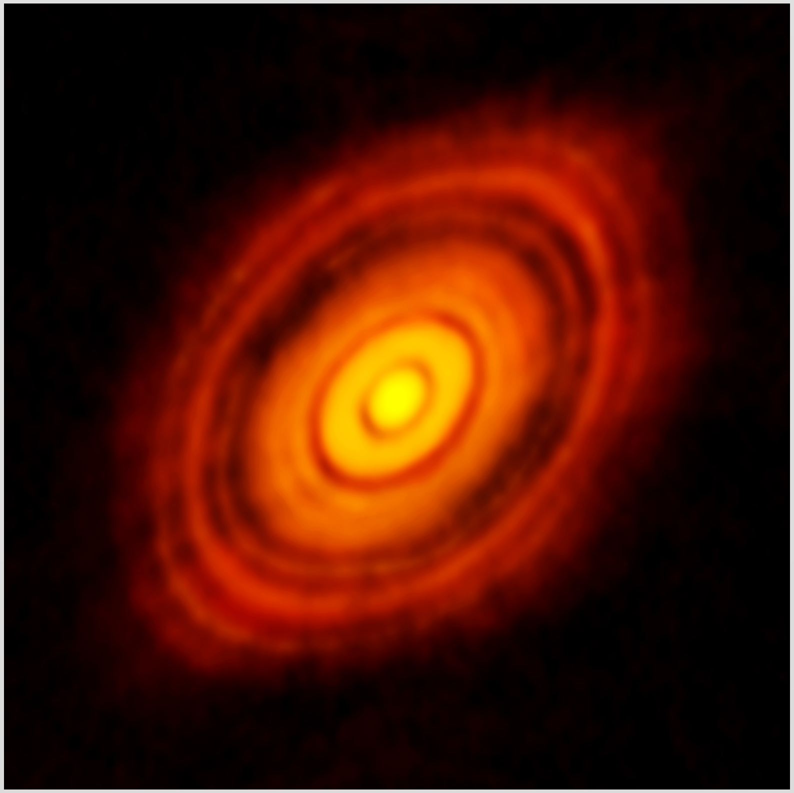
Hernandez et al. 07



Disk lifetimes

Hernandez et al. 07

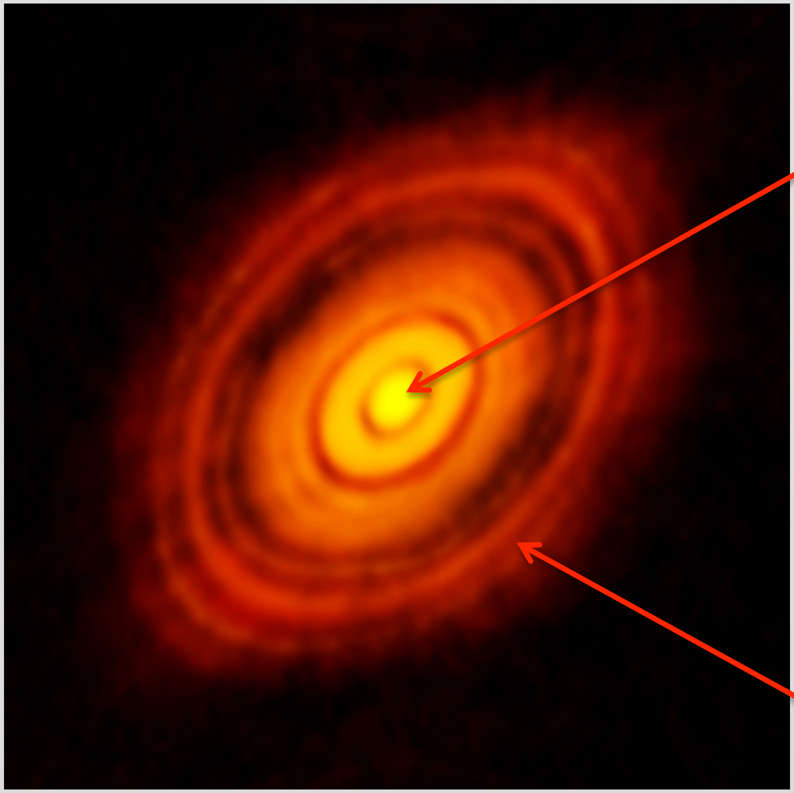
Best / easiest observations of protoplanetary disks are in **mm / sub-mm dust continuum emission**



Also observe in:

- molecular line emission
  (CO, other species)
- scattered light at optical /
- near-IR
- ~cm wavelength radio

What does the dust emission tell us?



optically thick: black body emission, f(T) only

disk atmosphere may impact spectral features

optically thin

$$I_\nu \simeq B_\nu(T)\tau_\nu$$

- τ proportional to mass, emission probes $\Sigma(r)$
- spectral dependence probes dust size distribution

Good review: Woitke (2015)

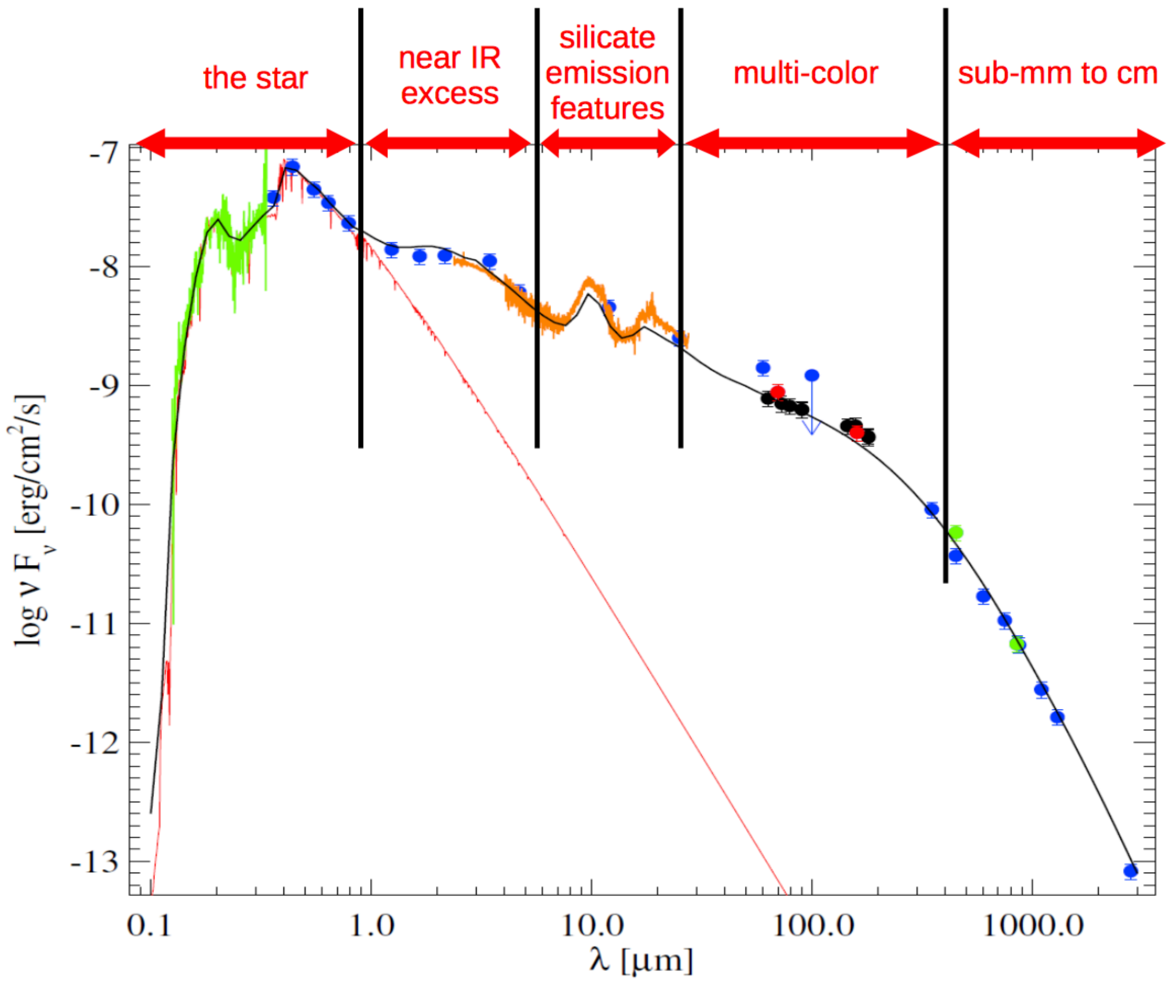


Figure 1. The SED of the Herbig Ae star HD 163296 (Tilling et al. 2012, reproduced with permission © ESO). The blue, red, black and green circles with errorbars are photometric measurement points from different instruments, the green line shows a de-reddened observed UV spectrum, and the orange line shows an ISO/SWS spectrum. The full black line is the disk model, and the thin red line indicates the photospheric model. The SED can be roughly sub-divided into 5 different spectral regions, as discussed in the text.

Good review: Woitke (2015)

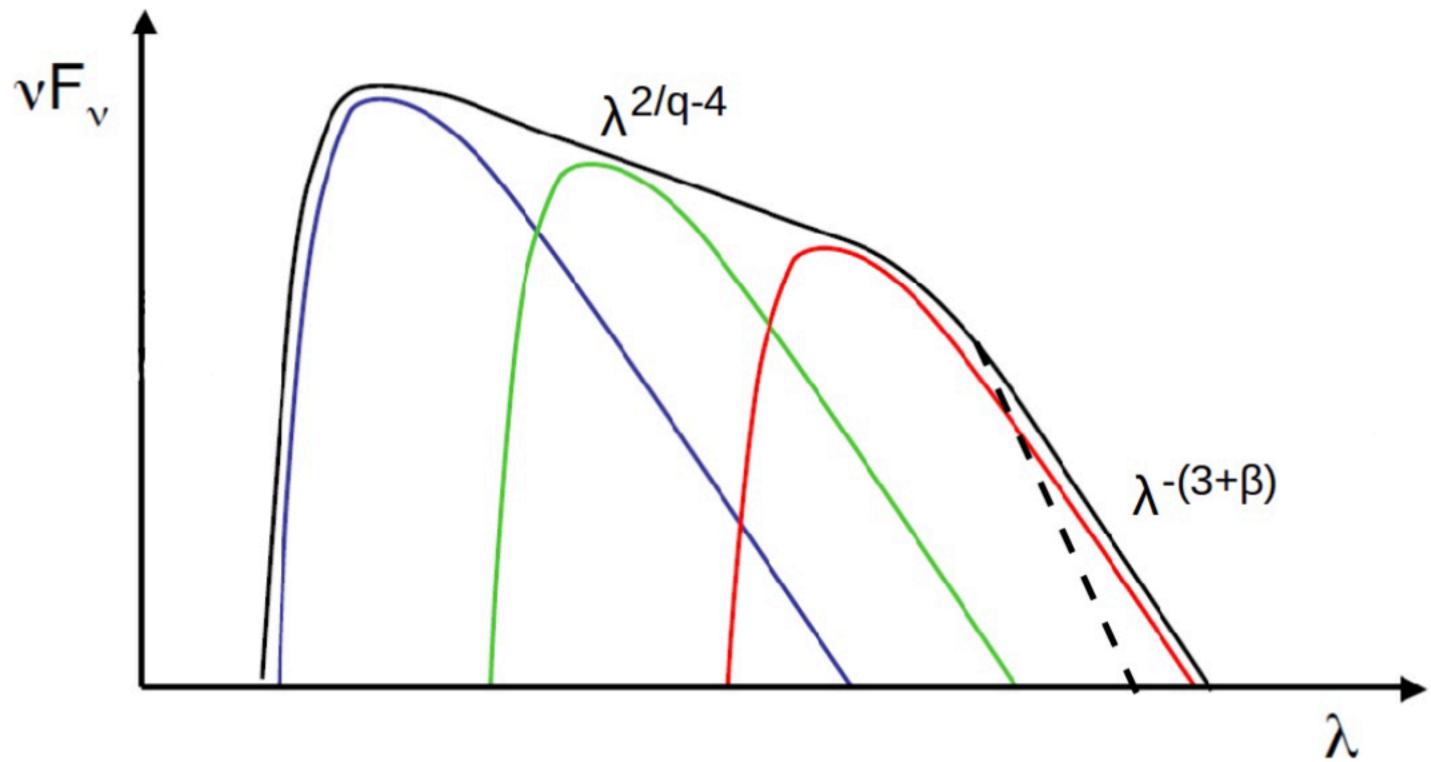


Figure 4. Steeper SEDs in the mm-region because the dust becomes increasingly optically thin.

$$T(r) \propto r^{-q}$$
$$\kappa_\nu \propto \lambda^{-\beta}$$

Example of state-of-the-art constraints: *Tazzari et al. (2016)*

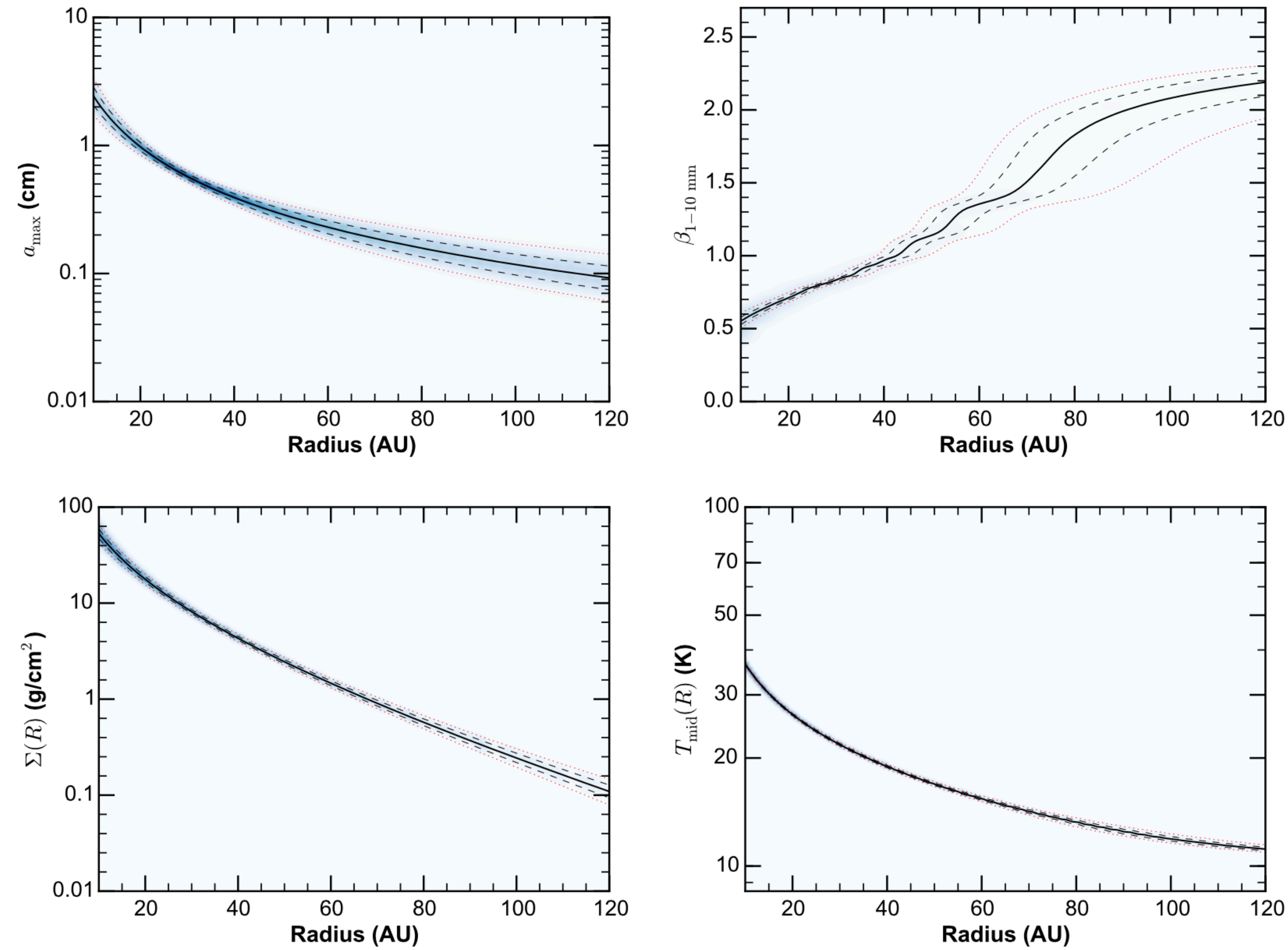


Fig. 5. Results of the FT Tau fit. *Top:* in the left panel, the posterior PDF of the maximum dust grain size $a_{\max}$ as a function of the disk radius; in the right panel, the posterior PDF of the dust spectral radial profile $\beta(R)$ between 1 and 10 mm. *Bottom:* in the left panel, the posterior PDF of the gas surface density; in the right panel, the posterior PDF of the midplane temperature. Line conventions are the same as those in Fig. 4.

Example of state-of-the-art constraints: *Tazzari et al. (2016)*

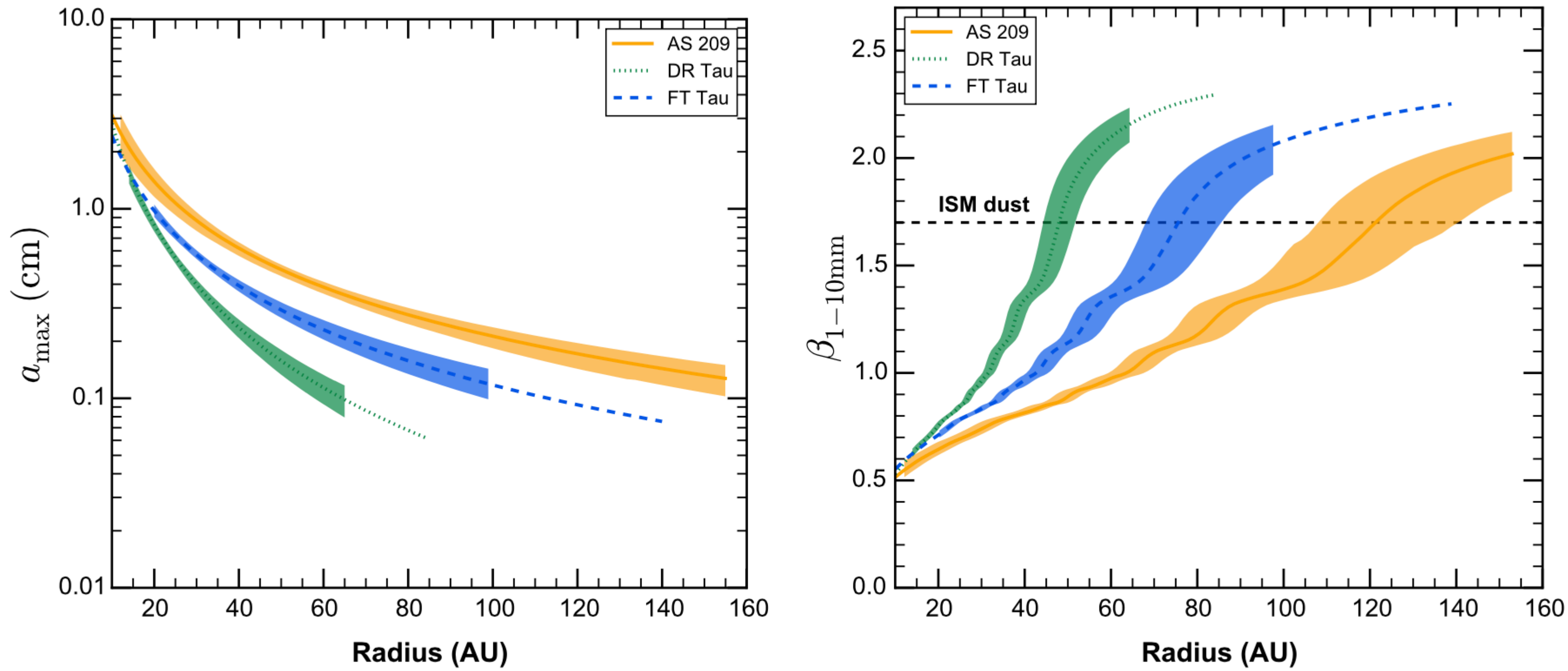
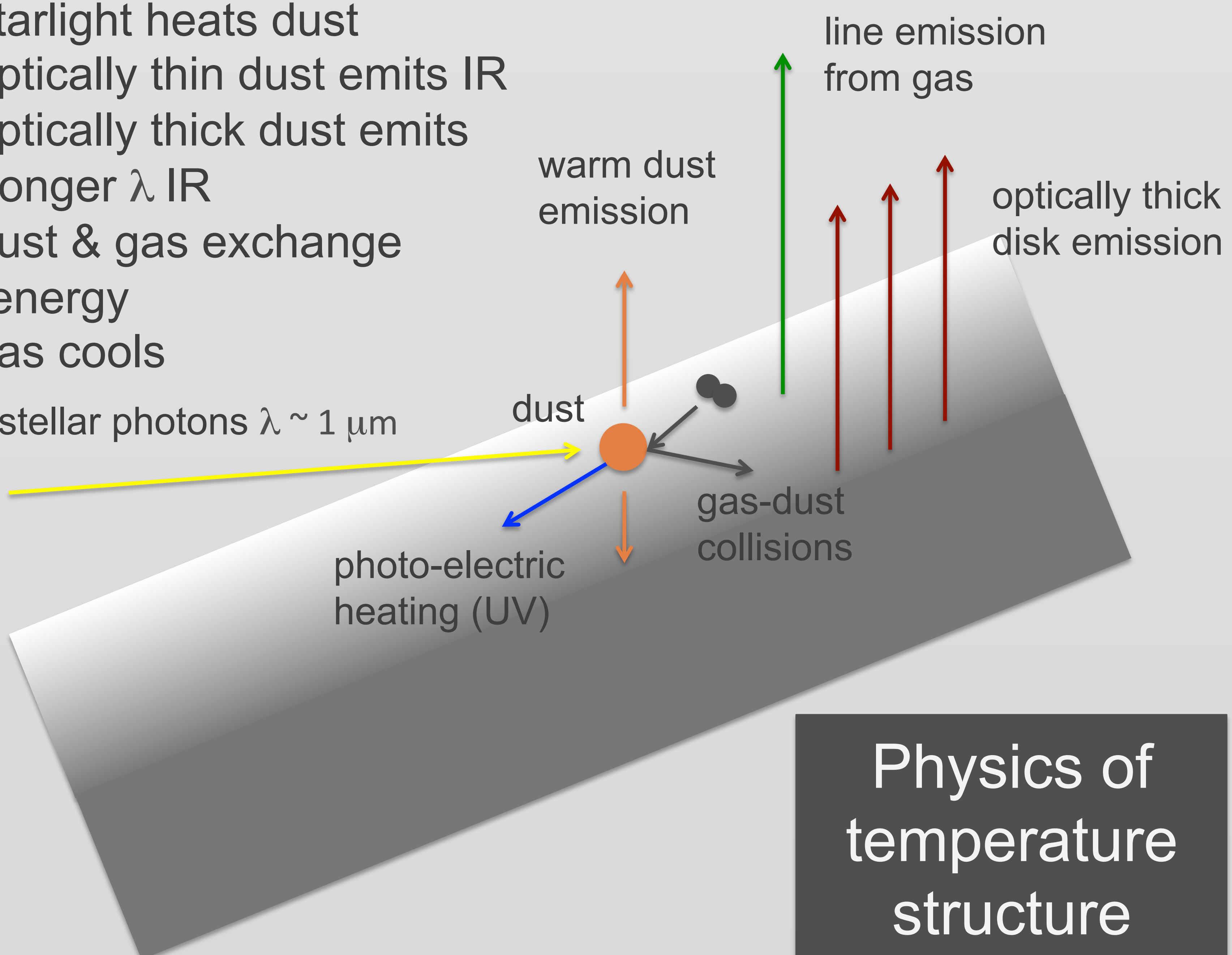


Fig. 6. *Left panel:* radial profile of the maximum dust grain size $a_{\rm max}$ constrained from the multi-wavelength fits. *Right panel:* radial profile of the dust opacity spectral slope $\beta(R)$ between 1 mm and 10 mm. The dashed black horizontal line at $\beta_{\rm ISM} = 1.7$ represents the typical value of β for small ISM dust grains. *In both panels:* the thick lines represent the median (i.e., the best-fit) model, and the shaded areas represent the 1σ credibility intervals. The best-fit model lines are plotted wherever the signal-to-noise ratio is larger than 3 (computed for the observation displaying the most extended disk emission); the shaded areas are truncated at half the average beam size (inner regions) and at $R = \overline{R}$ (outer regions).

Physics of temperature structure

- starlight heats dust
- optically thin dust emits IR
- optically thick dust emits longer λ IR
- dust & gas exchange energy
- gas cools



Additional physics for **dust** emission

1) Disk flares, intercepts more flux at large r than flat disk *(Kenyon & Hartmann 1987)*

2) Surface dust radiates inefficiently (size smaller than the wavelength of re-emitted IR radiation)

thermal equilibrium for dust, radius s

$$\frac{L_*}{4\pi r^2}\pi s^2 = \sigma T_{\rm s}^4 \epsilon\left(T_{\rm s}\right) 4\pi s^2$$

absorption *re-radiation*

$$\epsilon = (T/T_*)^\beta$$

emissivity, with $\beta \sim 1$

warm optically thin emission from surface dust layer

$$T_{\rm s} = \frac{1}{\epsilon^{1/4}}\left(\frac{R_*}{2r}\right)^{1/2} T_*$$

Approximate analytic models:

$$T_{\rm i} \approx 150 \left(\frac{r}{1\ {\rm AU}} \right)^{-3/7}\ {\rm K}$$

50% of disk L in blackbody interior emission

$$T_{\rm s} \approx 550 \left(\frac{r}{1\ {\rm AU}} \right)^{-2/5}\ {\rm K}$$

50% in emission from a warmer surface dust layer

Chiang & Goldreich '97 – $\Sigma = 10^3\ (r / \mathrm{AU})^{-3/2}$ g cm^{-2}, $M = 0.5\ M_{Sun}$, $T = 4000$ K, $R_* = 2.5\ R_{Sun}$

Garaud & Lin '07 for version including accretion heating

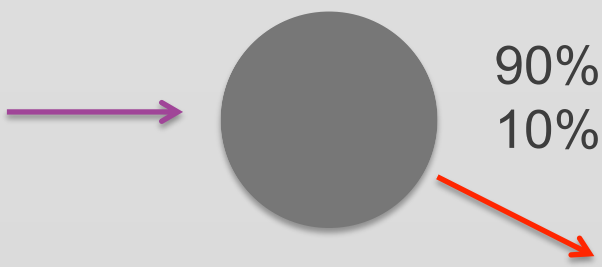
Passive disks have $T \sim r^{-0.5}$, flare to large r, any contribution from accretion heating greater at small r

What about the **gas** temperature?

Heating

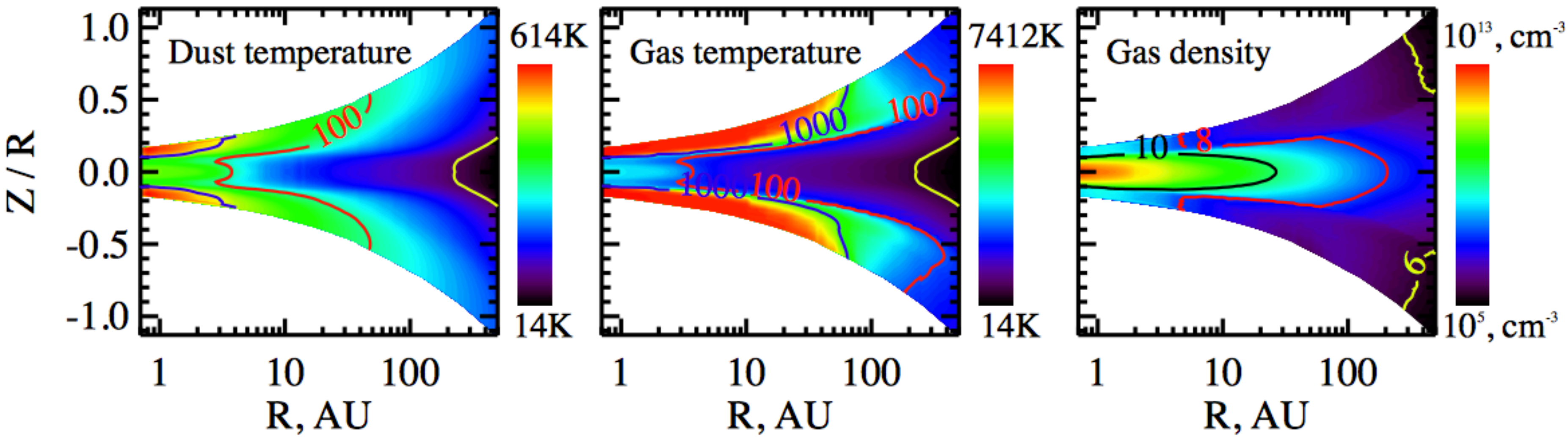
- collisions between molecules and dust particles
  - efficient equilibration at high density: $T_{gas} = T_{dust}$

- *photoelectric* heating near surface



~5% of incident UV flux goes into gas heating

Cooling – rotational transitions (e.g. CO), atomic fine structure lines



Henning & Semenov '13, from Akimkin et al. '13

General structure:

- optically thick, vertically isothermal structure near disk mid-plane
- warmer dust at surface
- still warmer molecular layer of gas

Need numerical codes to compute gas + dust models

Ionization

Ionization fraction $x_e = n_e / n_H$ affects:

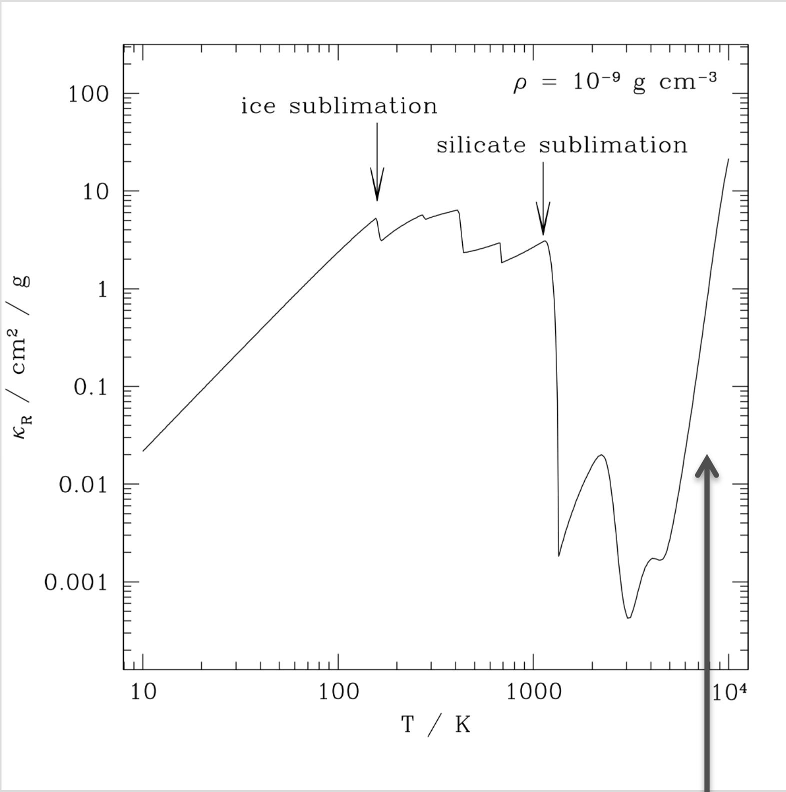
- chemistry
- coupling of gas to magnetic fields

Thermal ionization

Gas becomes fully ionized only at T ~ 10^4 K

These temperatures attained only in very high accretion rate states

Change in *opacity* when H is ionized is important for episodic accretion models

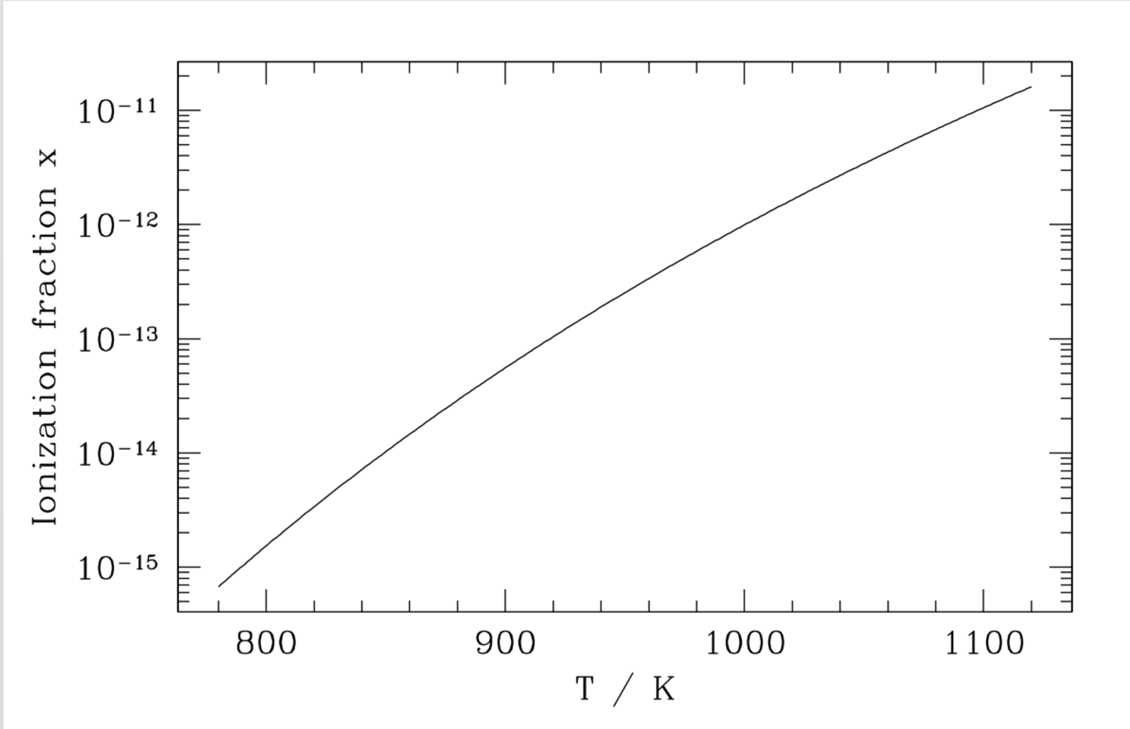


ionization of hydrogen
(opacity from *Semenov et al. '03)*

Thermal ionization

Ionization of the alkali metals occurs at $T \sim 10^3$ K

Yields an electron fraction $x_e \sim 10^{-12}$



Very low ionization degree, **but** comparable to the ionization needed to couple magnetic fields to gas

Calculation: use Saha equation, answer just $f(T,\rho)$

Non-thermal ionization – this is *much nastier!*

Need to know and balance:

- explicit ionization rates ζ from non-thermal processes
- specific reactions that lead to recombination

e.g. if dominant reaction is recombination with molecular ions ("dissociative recombination"), such as

$$e^- + HCO^+ \longrightarrow H + CO$$

rate equation

$$\frac{\mathrm{d}n_e}{\mathrm{d}t} = \zeta n_n - \beta n_e n_{HCO^+} = 0$$

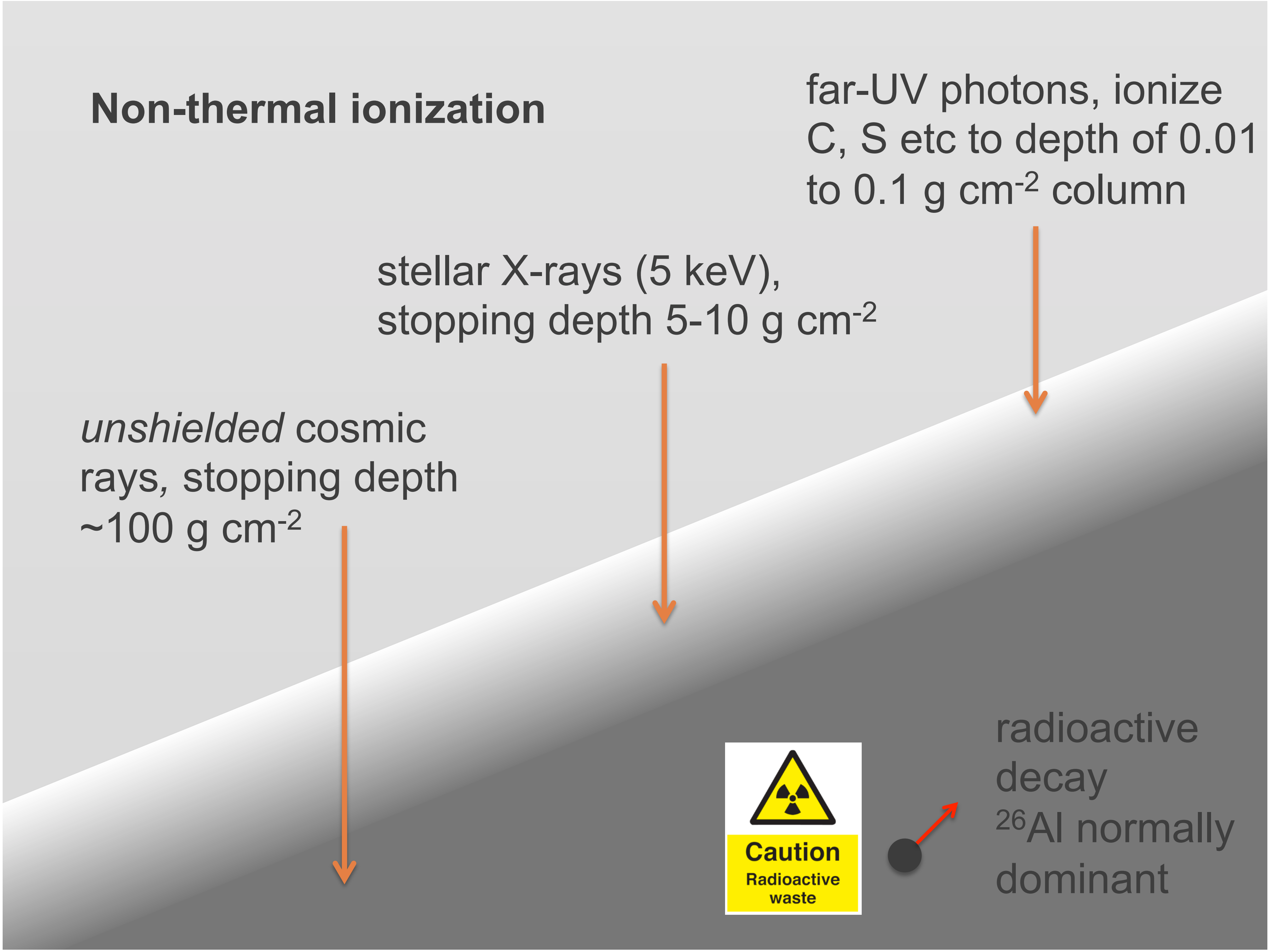
in ionization equilibrium

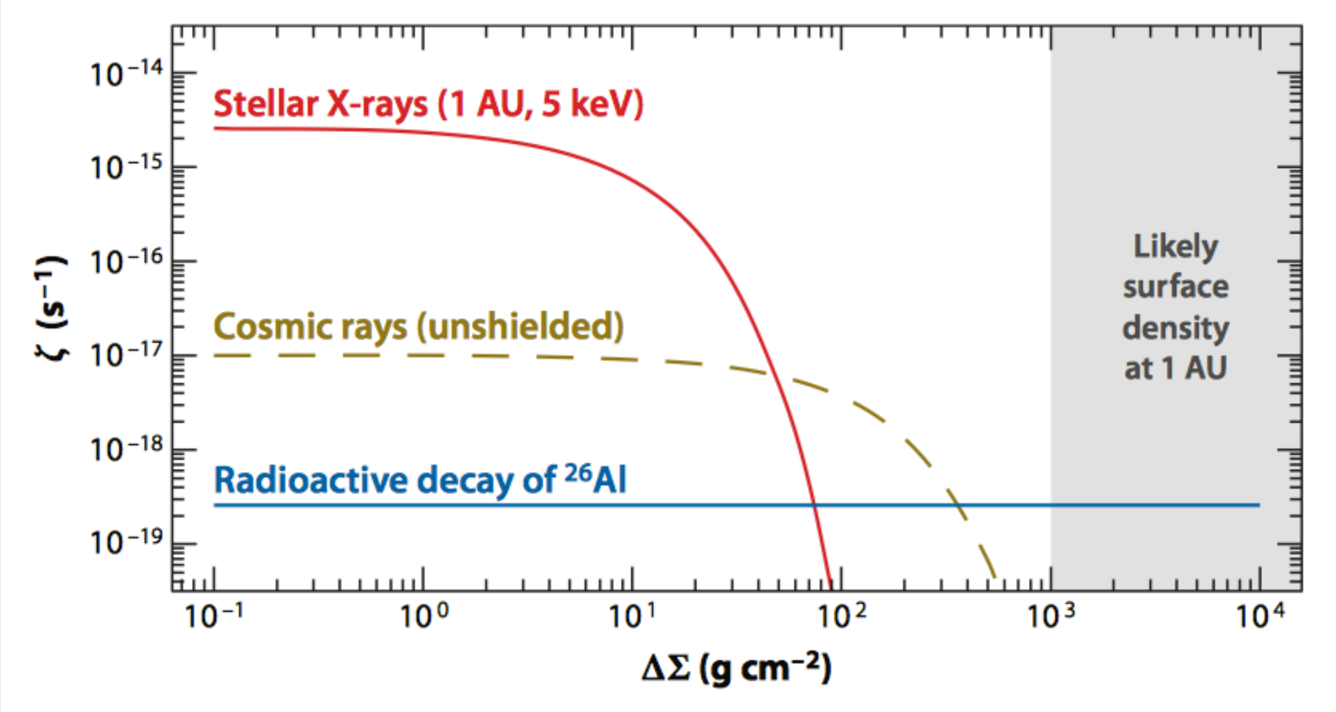
neutrals (n_n)

rate coefficient (function of T) (β)

Solution assuming overall neutrality

$$x_e = \sqrt{\frac{\zeta}{\beta n_n}}$$


Non-thermal ionization
far-UV photons, ionize C, S etc to depth of 0.01 to 0.1 g cm^{-2} column
stellar X-rays (5 keV), stopping depth 5-10 g cm^{-2}
unshielded cosmic rays, stopping depth ~100 g cm^{-2}
Caution
Radioactive waste
radioactive decay
^{26}Al normally dominant



Simplified model for ionization rates after Turner & Sano '08

Mid-plane of the inner disk is too cold to be thermally ionized, dense enough to be shielded from external sources of ionizing radiation… very low x_e

Stellar X-ray ionization from *Ercolano & Glassgold '13*

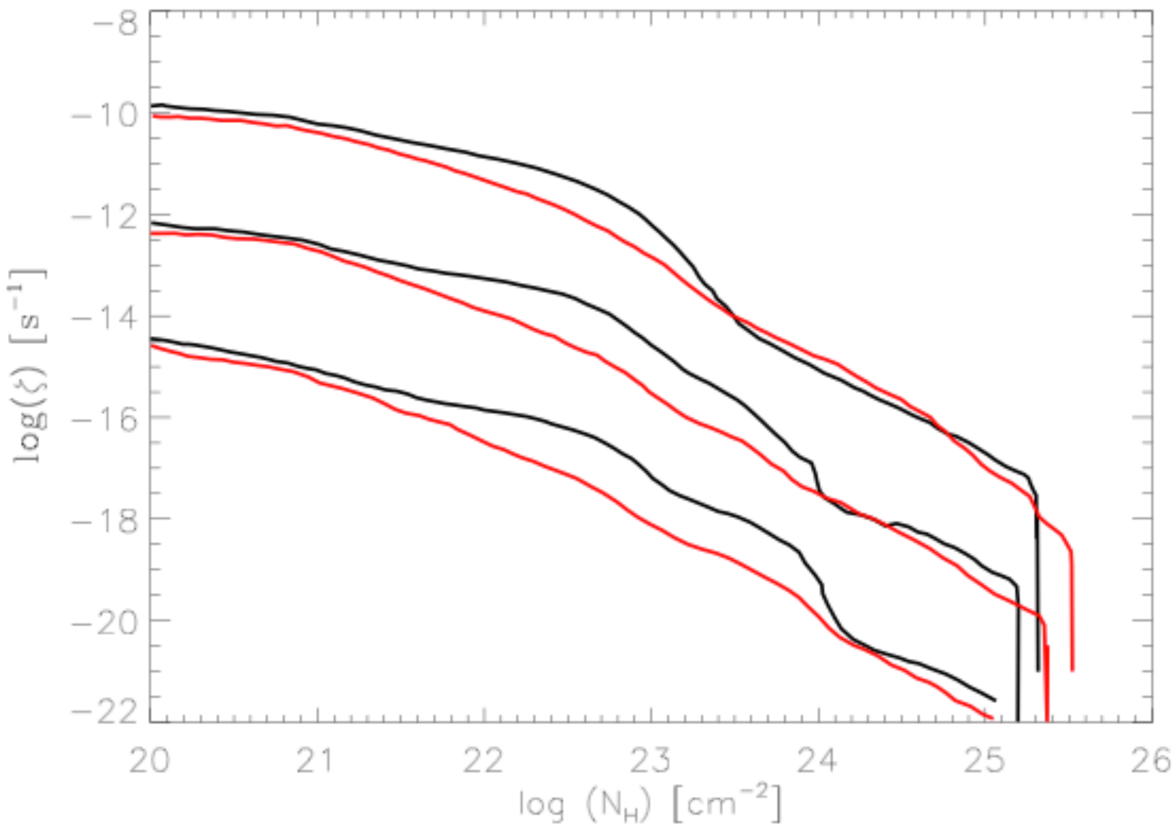


Figure 3. Ionization rates plotted vs. vertical column density for a two-temperature average representation of the COUP X-ray observations (Wolk et al. 2005) of the Orion Nebula Custer at 1 AU, 5 AU and 10 AU for solar abundances (black) and depleted interstellar abundances (red) given in Table 1. The X-ray luminosity is $L_X = 2 \times 10^{30} \mathrm{erg\,s^{-1}}$, and the other spectrum parameters are given in Table 2. For ease of viewing, the 5 AU and 10 AU curves have been shifted down by factors of 10 and 1,000 relative to those for 1 AU.

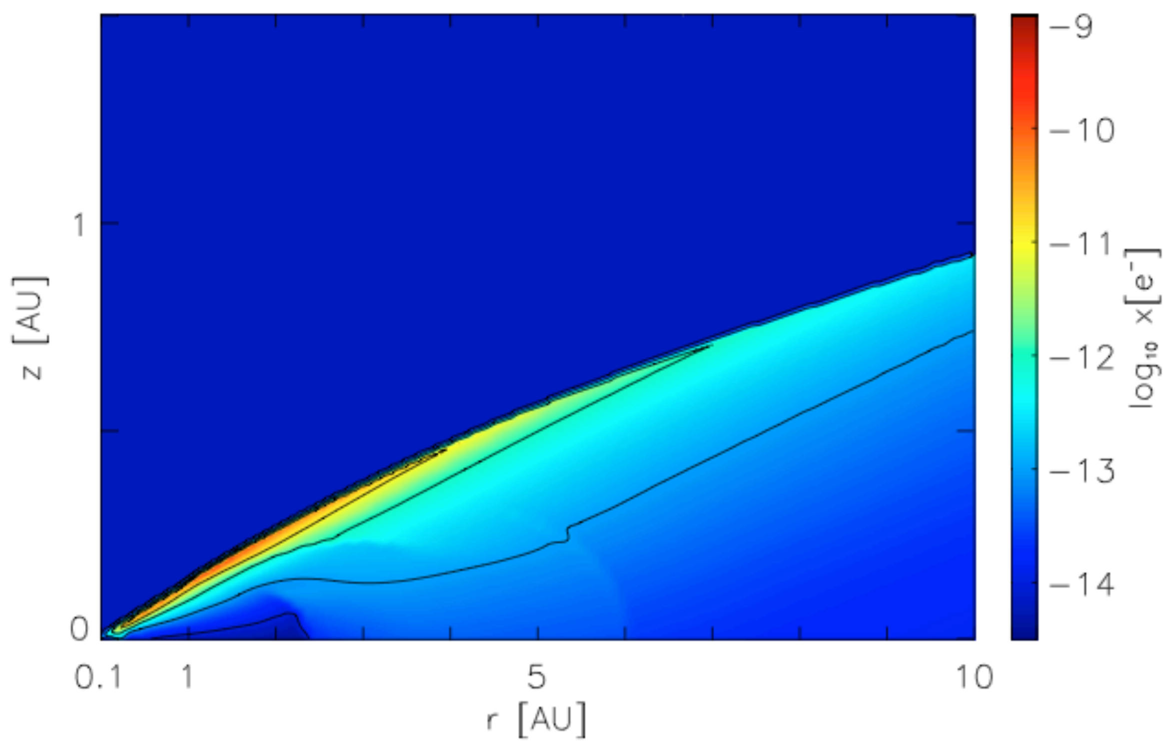


Fig. 20. This contour plot shows the electron distribution at $t = 10^5$ yrs for our $\alpha = 10^{-2}$, $\dot{M} = 10^{-7}\ M_\odot\,\mathrm{yr}^{-1}$ disk model by applying the UMIST model (`model3`) with $x_{\mathrm{Mg}} = 10^{-12}$. The contour lines refer to values $x[\mathrm{e}^-]$ of 10^{-14}, 10^{-13}, 10^{-12}, and 10^{-11}.

Calculation of ionization fraction from *Ilgner & Nelson '06*

Metal ions and dust grain reactions are both important factors determining ionization degree

Are cosmic rays shielded from disk? Solar wind modulates local flux of cosmic rays, do T Tauri stellar or disk winds have similar effect? *(Cleeves et al. '13)*

Is the microphysics of ionization balance fully understood? Ionization by electrons accelerated in MHD turbulence, non-linear relation between current and electric field strength… *(Inutsuka & Sano '05; Okuzumi & Inutsuka '15)*