3D dust modeling of circumplanetary disks

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July 11, 2019

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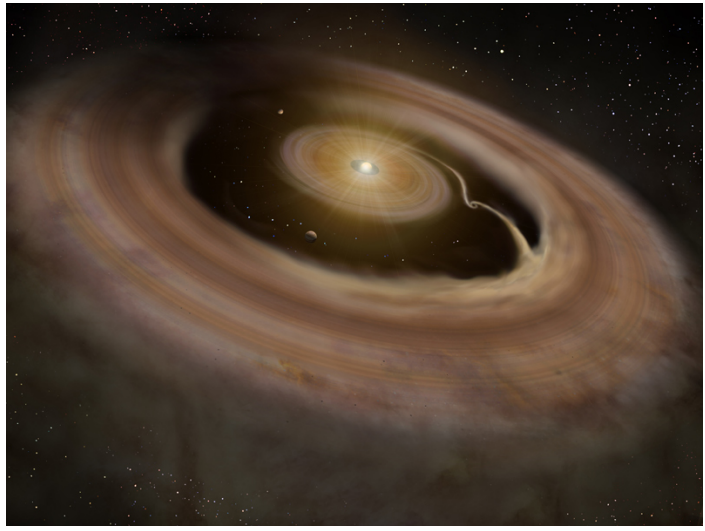
Motivation

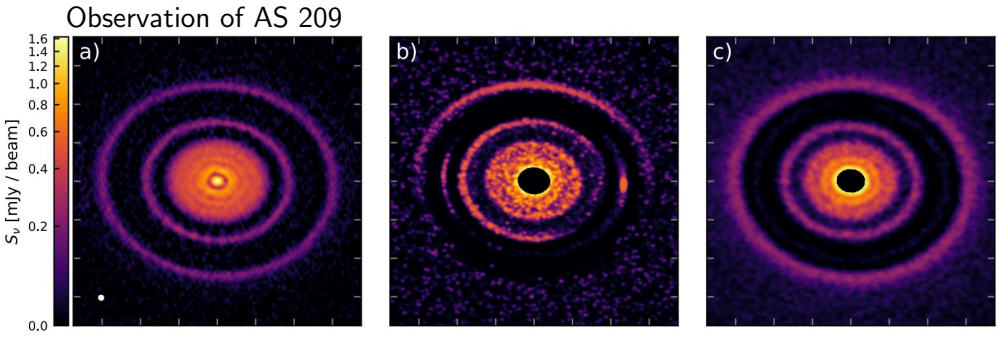
- Giant planets in solar system have moons
- These moons are regular satellites
- Possibly formed in circumplanetary disks (CPD)
- Candidates have only recently been observed



(Credit: The Graduate University for Advanced Studies/NAOJ)

Formation

- Planets form in protoplanetary disks via agglomeration
- Gaps form due to planet-disk interactions
- Planet forms circumplanetary disk in gap due to non-vanishing gas accretion



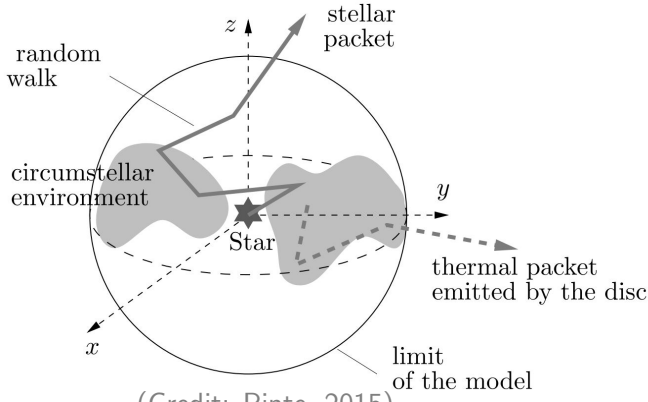
(Credit: Zhang et al., 2018)

Scientific goal

- Study impact of star on temperature and radiation field of circumplanetary disk
- Important for chemistry and thus observations
- Also study impact of circumplanetary disk/planet on protoplanetary disk
- Investigate the limits of the modelling program for this new set-up

Monte Carlo

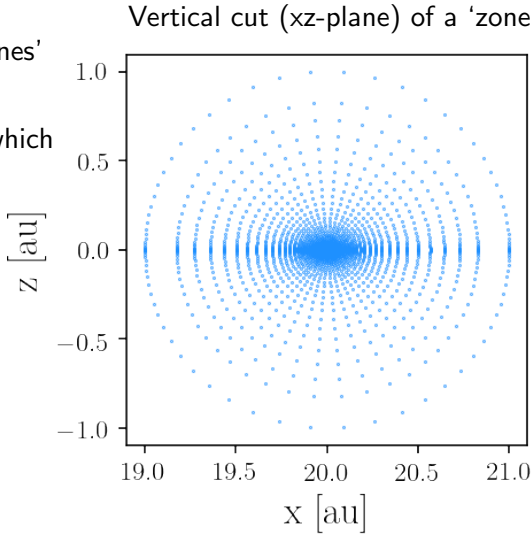
- Solves continuum radiative transfer process by following photons individually
- Calculates the temperature of the system via the photon packets
- Relies on randomness which leads to noise
- Mimics 3D propagation of photons



(Credit: Pinte, 2015)

MCMax3D

- Simulates RT process using Monte Carlo method
- Flexible in building up structure via 'zones'
- Generates a 'static' model in 3D
- Grid points are volume elements with which the photon packet interact

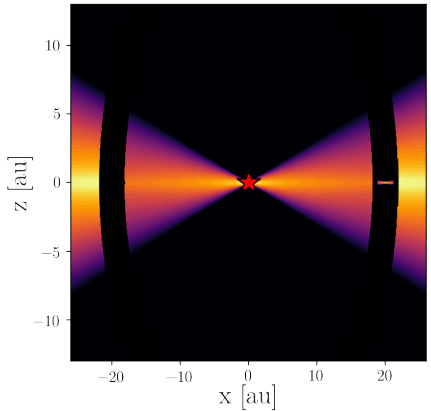


Model set-up (Dust density of system)

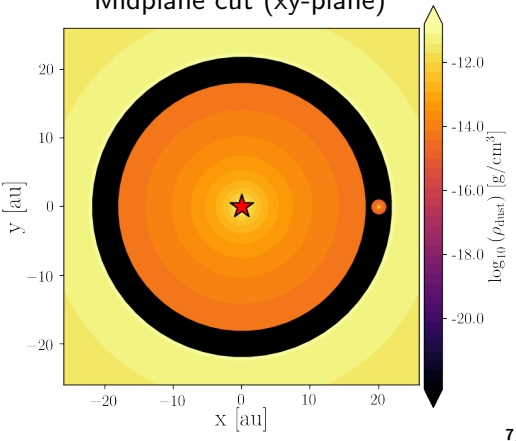
- T Tauri star with $L_* = 1.01\,\mathrm{L}_\odot$
- Default planet luminosity of $L_\mathrm{p} = 1.01 \times 10^{-2}\,\mathrm{L}_\odot$

Quantity	Inner disk	Outer disk	CPD
Inner radius	0.4 au	22 au	3×10^{-3} au
Outer radius	18 au	500 au	1 au
Dust mass	$2 \times 10^{-5}\,\mathrm{M}_\odot$	$1 \times 10^{-4}\,\mathrm{M}_\odot$	$10^{-10}\,\mathrm{M}_\odot$
Optical depth	4.7×10^4	2.3×10^2	9.1×10^2
Position	(0,0,0) au	(0,0,0) au	(20,0,0) au

Vertical cut (xz-plane)



Midplane cut (xy-plane)



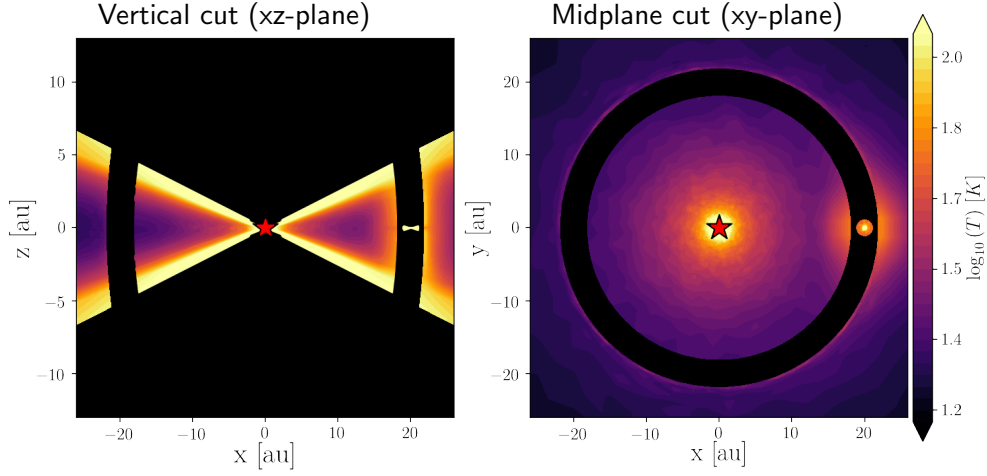
2 Main models

1. Full system (i.e., inner disk, outer disk and CPD)
2. Inner disk removed and CPD + planet placed at 10 au distance from the star

Tested for two planetary luminosities: $L_{\rm p} = 1.01 \times 10^{-2}\,{\rm L}_{\odot}$ and $L_{\rm p} = 1.01 \times 10^{-3}\,{\rm L}_{\odot}$

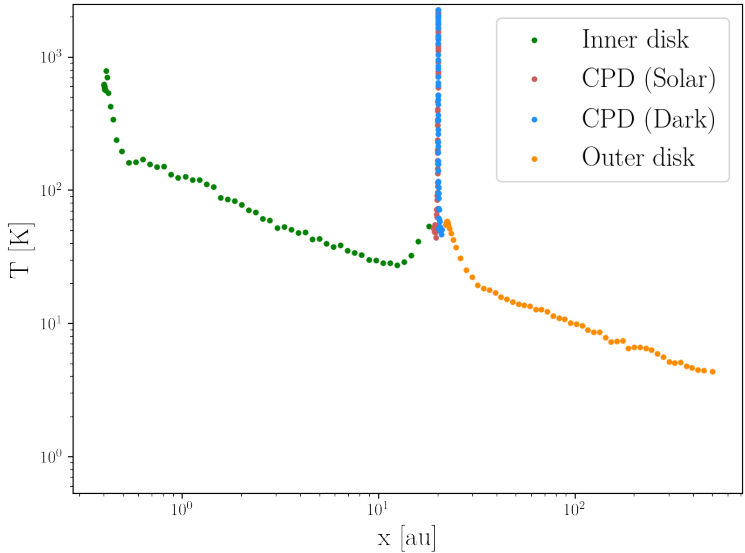
Dust temperature full system for $L_{\mathrm{p}} = 1.01 \times 10^{-2}\,\mathrm{L}_{\odot}$

- 3D model shows temperature asymmetry in midplane
- Interested in 'Solar' and 'Dark' side of circumplanetary disk

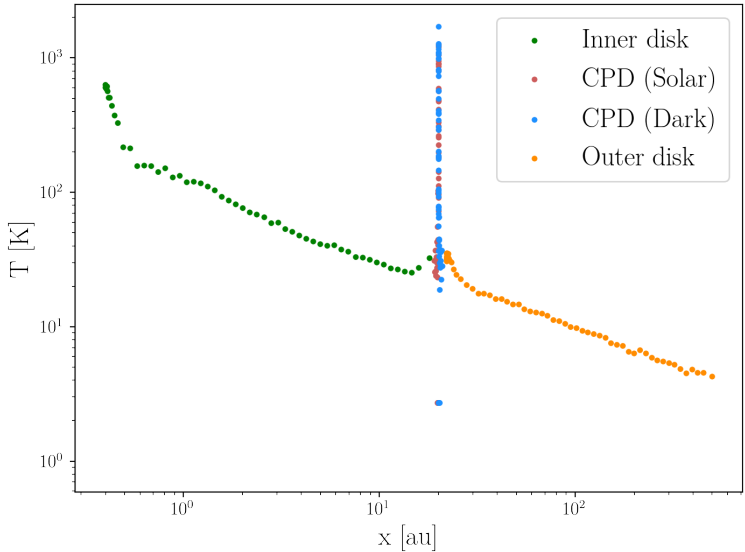


Dust temperature in midplane ($L_p = 1.01 \times 10^{-2}\,L_\odot$)

- Planet heats up surrounding inner and outer disk

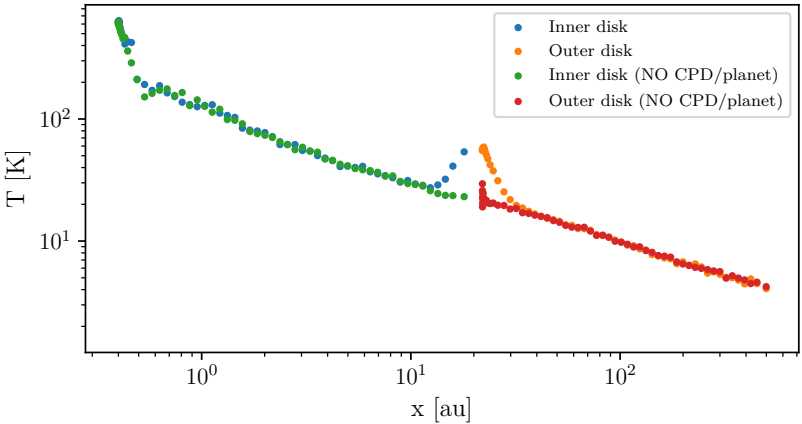


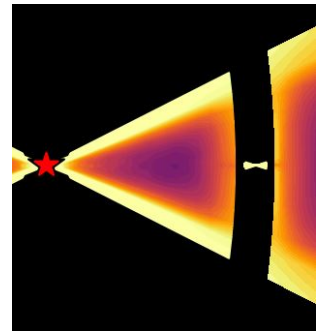
Dust temperature in midplane ($L_p = 1.01 \times 10^{-3}\,L_\odot$)



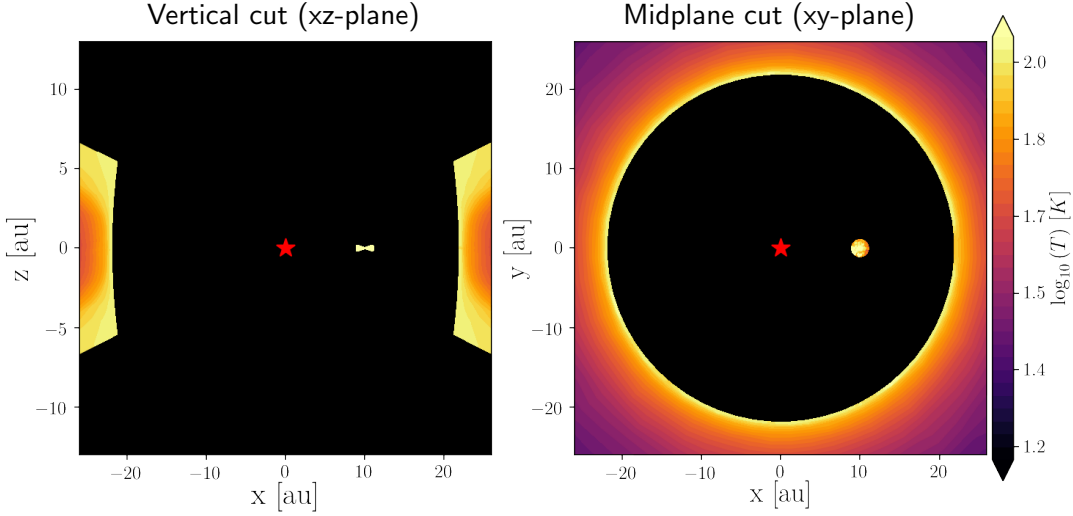
Impact of CPD/planet on protoplanetary disk for $L_{\rm p} = 1.01 \times 10^{-2}\,{\rm L}_{\odot}$

- Stellar photons heat up midplane of outer disk via gap



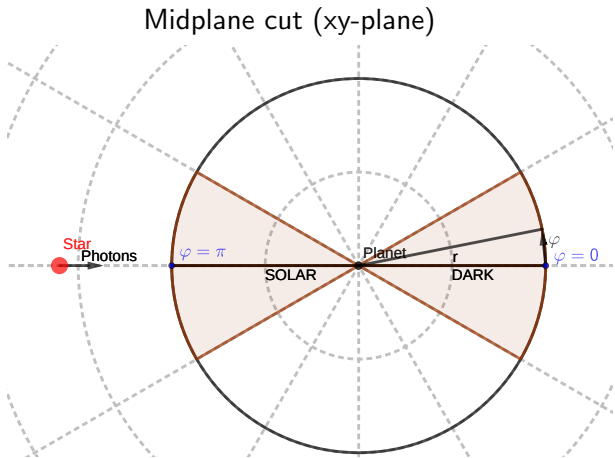


Inner disk removed and CPD/planet closer to star for $L_{\rm p} = 1.01 \times 10^{-2}\,{\rm L}_{\odot}$



Monte Carlo Noise reduction for temperature and radiation field

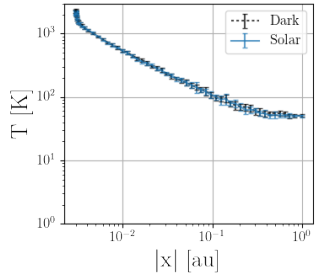
- Averaging procedure for temperature
- Sextants in order to maintain difference between Solar and Dark side
- Radiation field will be averaged over complete semi circles

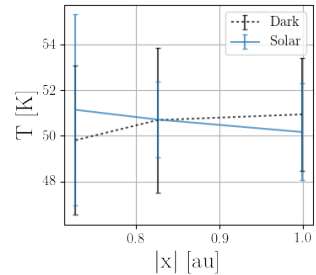


Temperature CPD full system

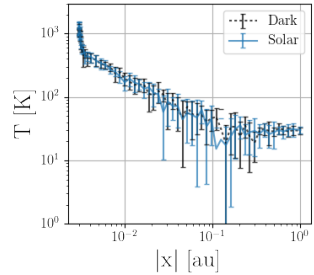
- Average temperature of Dark and Solar side as function of distance to planet
- 1σ error bars is Monte Carlo noise
- Large errors are due to lack of photons
- Interested in outer edge to see maximal possible difference
- Star does not heat the circumplanetary disk

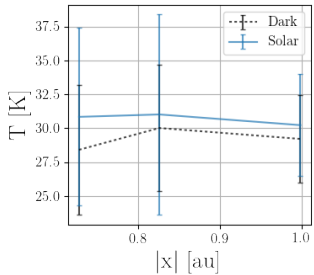
$L_\mathrm{p} = 1.01 \times 10^{-2}\,\mathrm{L}_\odot$





$L_\mathrm{p} = 1.01 \times 10^{-3}\,\mathrm{L}_\odot$

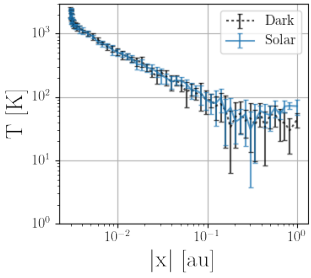


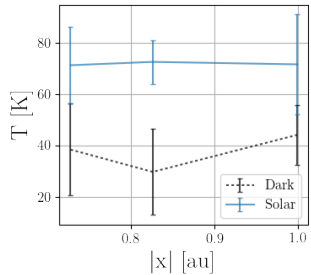


Temperature CPD reduced system

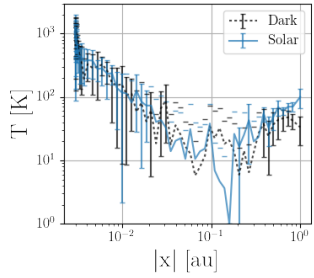
- Inner disk removed and planet/CPD placed at 10 au
- Solar side is clearly heated by star at the outer edge

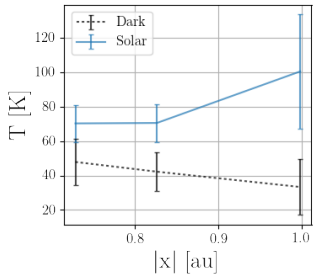
$L_p = 1.01 \times 10^{-2}\, L_\odot$





$L_p = 1.01 \times 10^{-3}\, L_\odot$

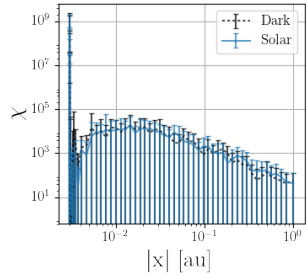


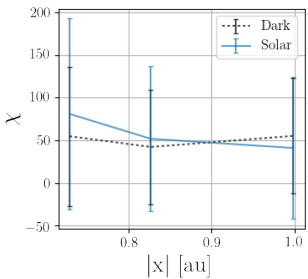


Radiation field only for $L_{\mathrm{p}} = 1.01 \times 10^{-2}\,\mathrm{L}_{\odot}$

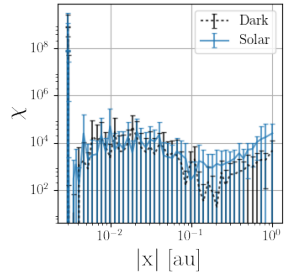
- Far-UV ($0.1\,\mu\mathrm{m} < \lambda < 0.2\,\mu\mathrm{m}$)
- Radiation field (χ) is normalized to Draine field
- Monte Carlo noise is very strong here
- Due to lack of radiation field photons
- Still a trend emerges

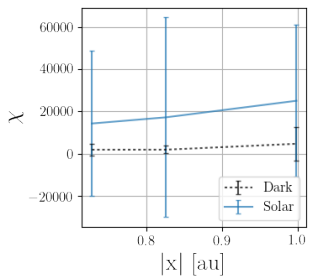
Full system





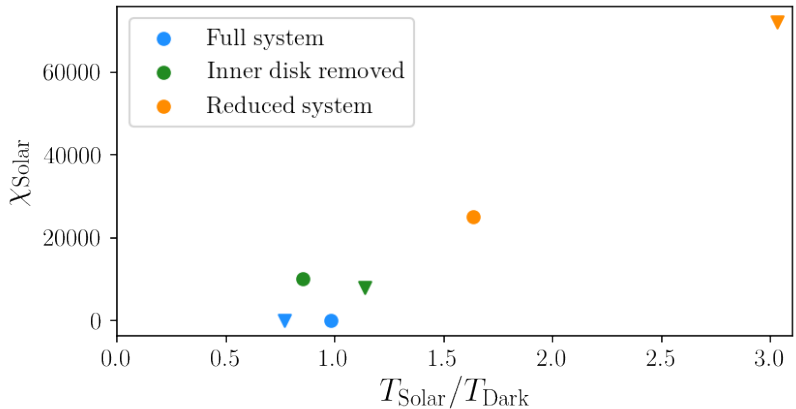
Reduced system





Comparing the differences

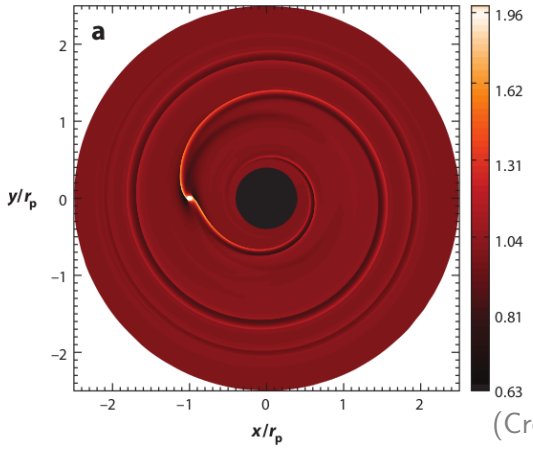
- Ratio of temperature at outer edge indicates asymmetry
- Correlation between χ_{Solar} and T_{Solar}



Concluding remarks and future prospects

- The inner disk can make stellar radiation extinct, interesting to test for lower density
- MCMax3D could be improved by better control over selecting number of photon packets per source
- To properly study a circumplanetary disk model, more photon packets are required to account for its small size

Planet-disk interaction

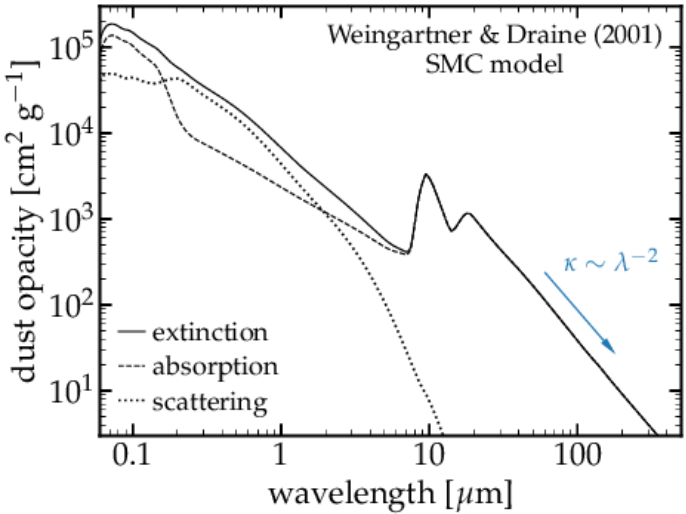


(Credit: W. Kley and R.P. Nelson, 2012)

$$l = rv_{\phi,gas} = \sqrt{GM_* r}$$

Dust grain opacity law

- Far-UV ($0.1\,\mu\text{m} < \lambda < 0.2\,\mu\text{m}$) has very high dust opacity
- Meaning it interacts easier with medium and thus propagates less far



(Credit: Weingartner and B. T. Draine, 2001)