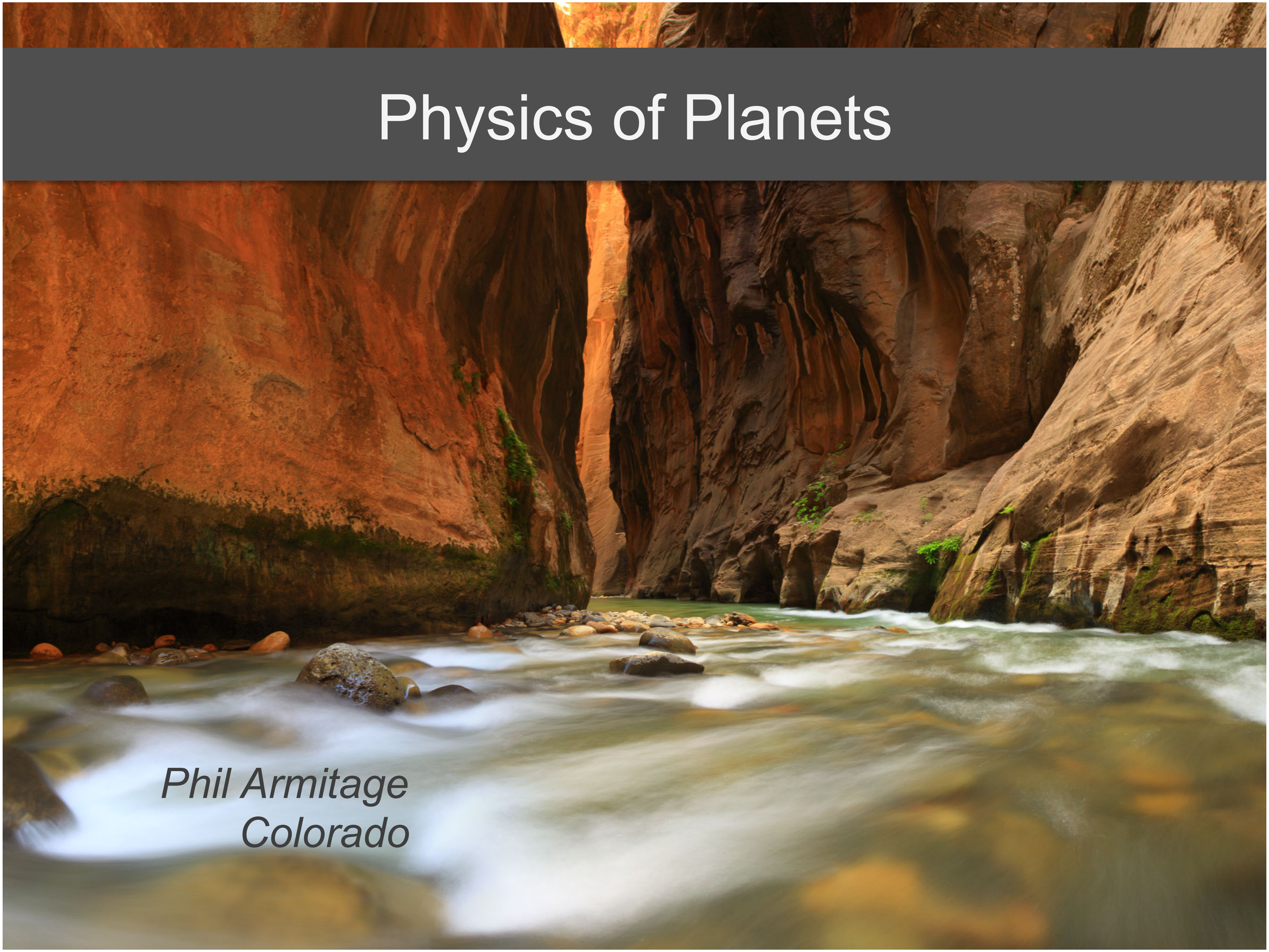
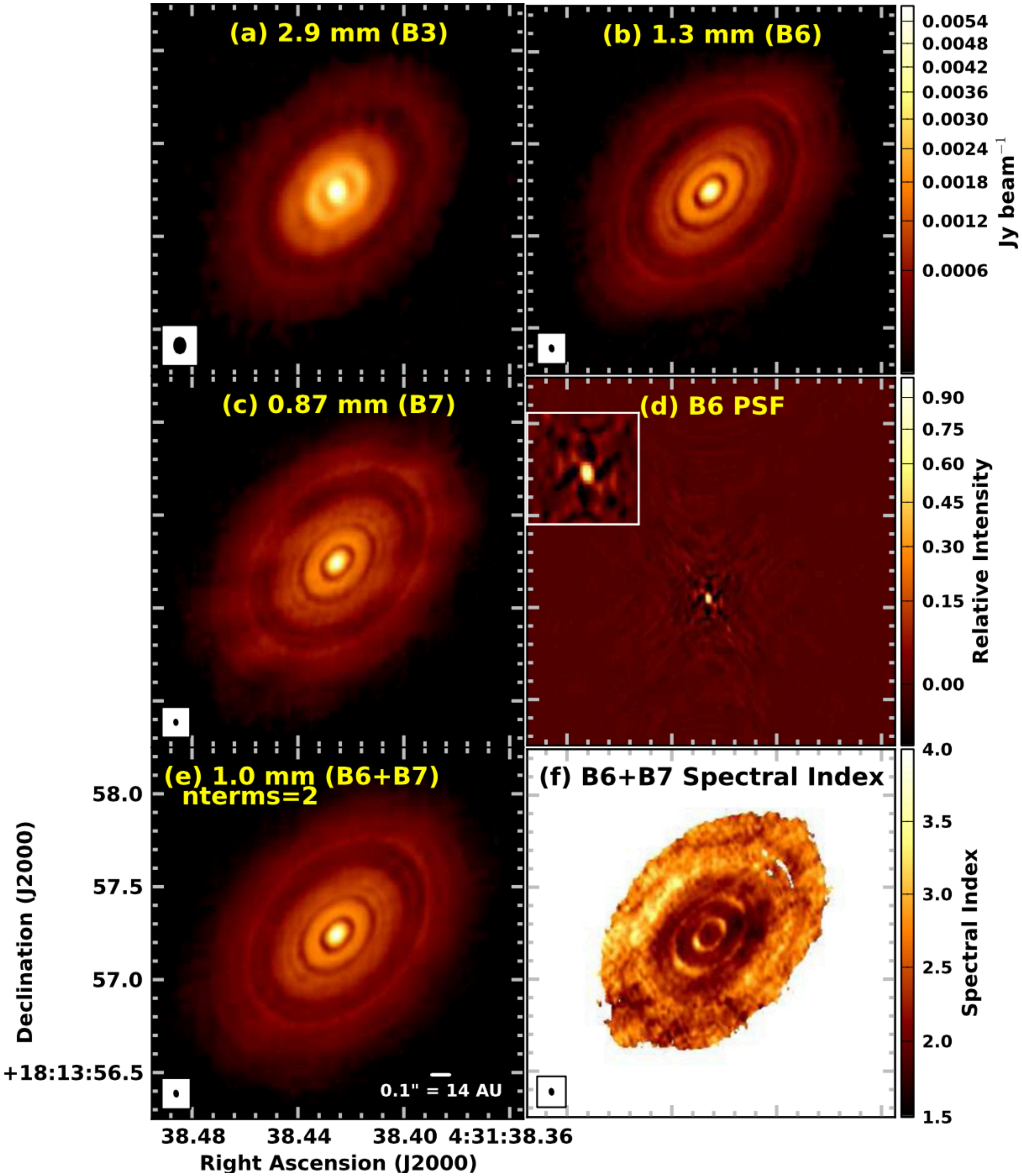
Physics of Planets

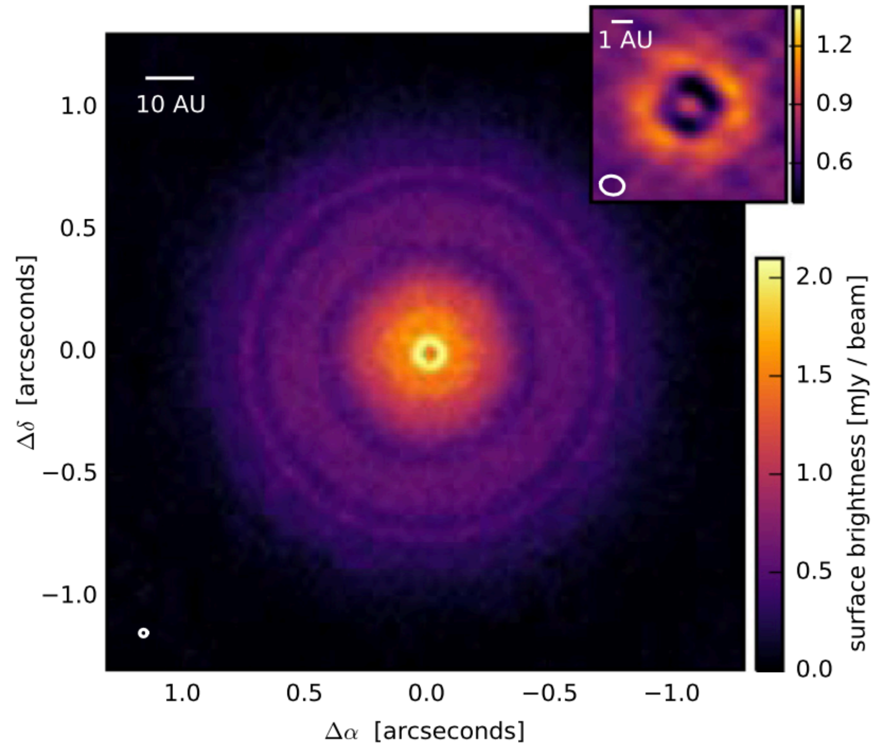


Phil Armitage
Colorado



HL Tau

ALMA Partnership (2015)



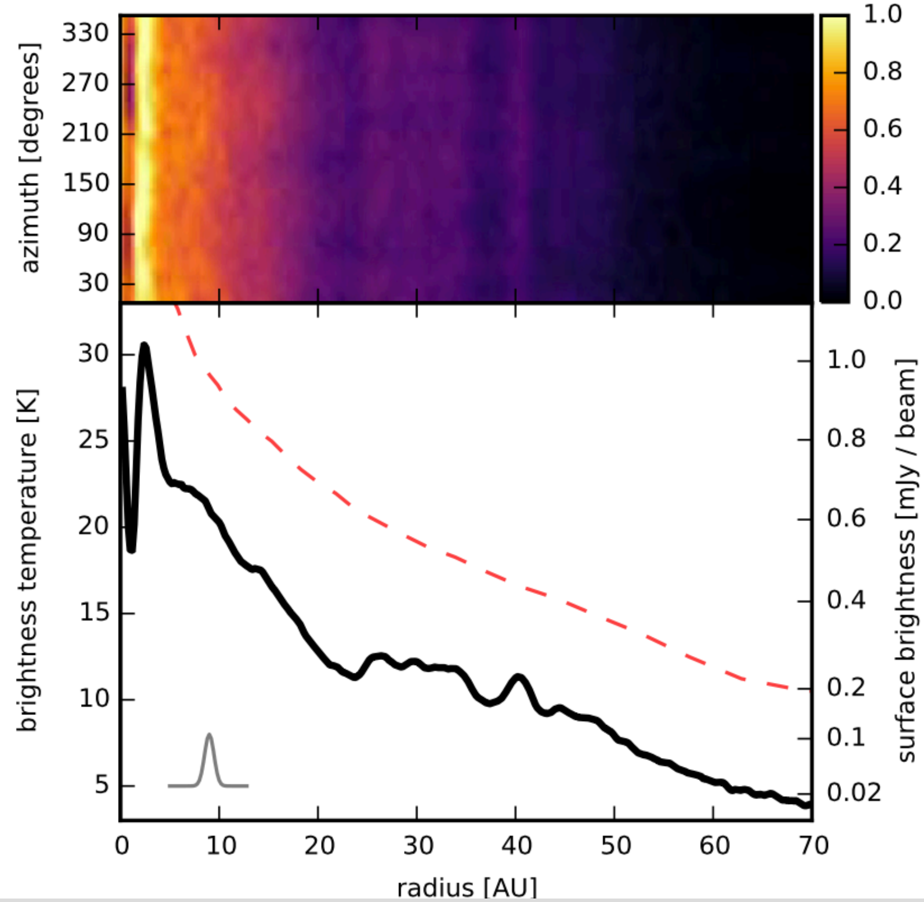
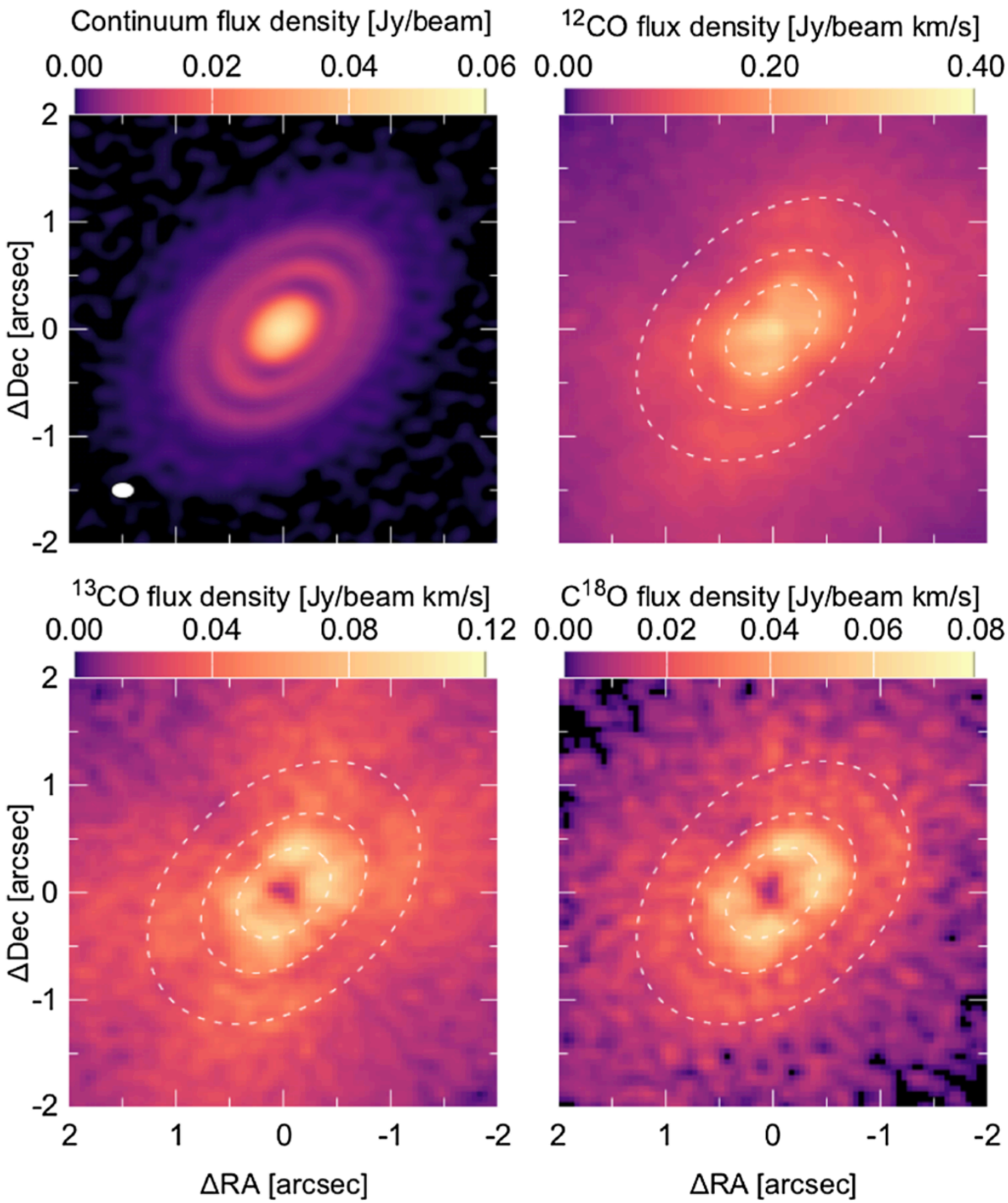


Figure 1. Synthesized image of the 870 μm continuum emission from the TW Hya disk with a 30 mas FWHM (1.6 au) circular beam. The rms noise level is $\sim$35 μJy beam^{-1}. The inset shows a $0\farcs2$ wide (10.8 au) zoom using an image with finer resolution (24 $\times$ 18 mas, or 1.3 $\times$ 1.0 au, FWHM beam).

TW Hya

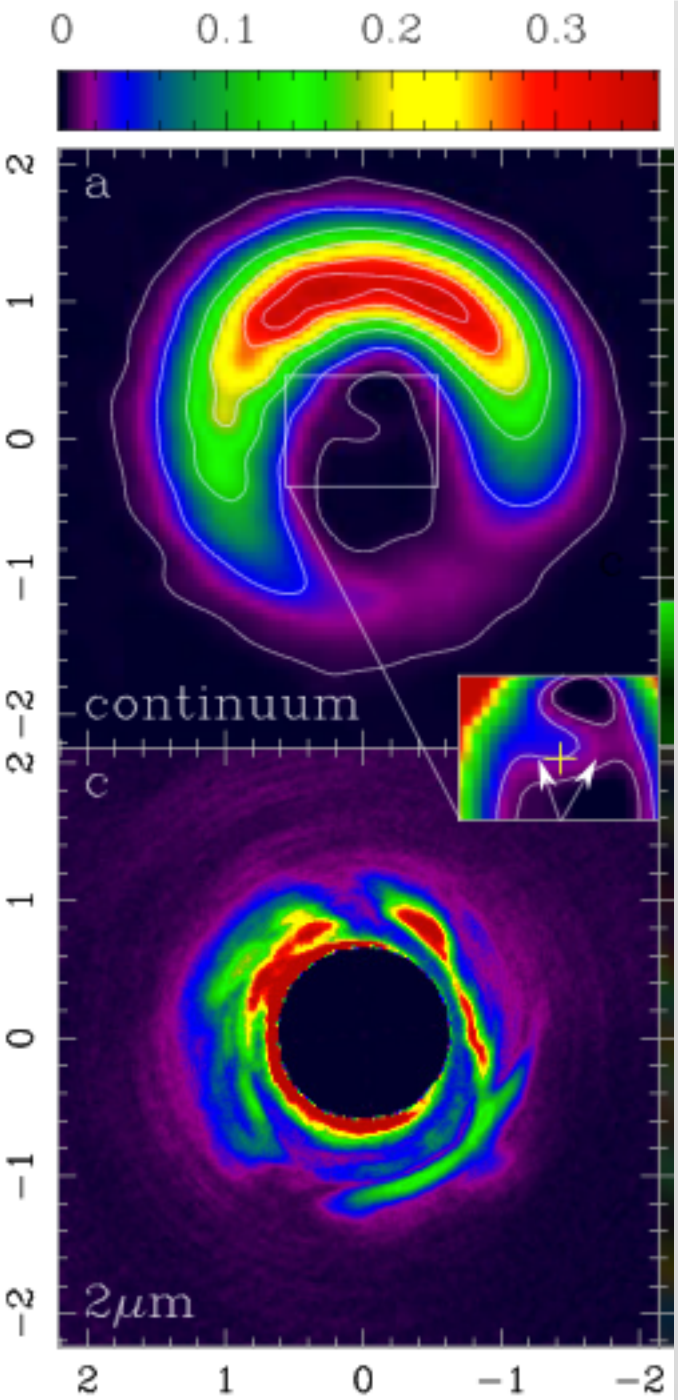
Andrews et al. (2016)

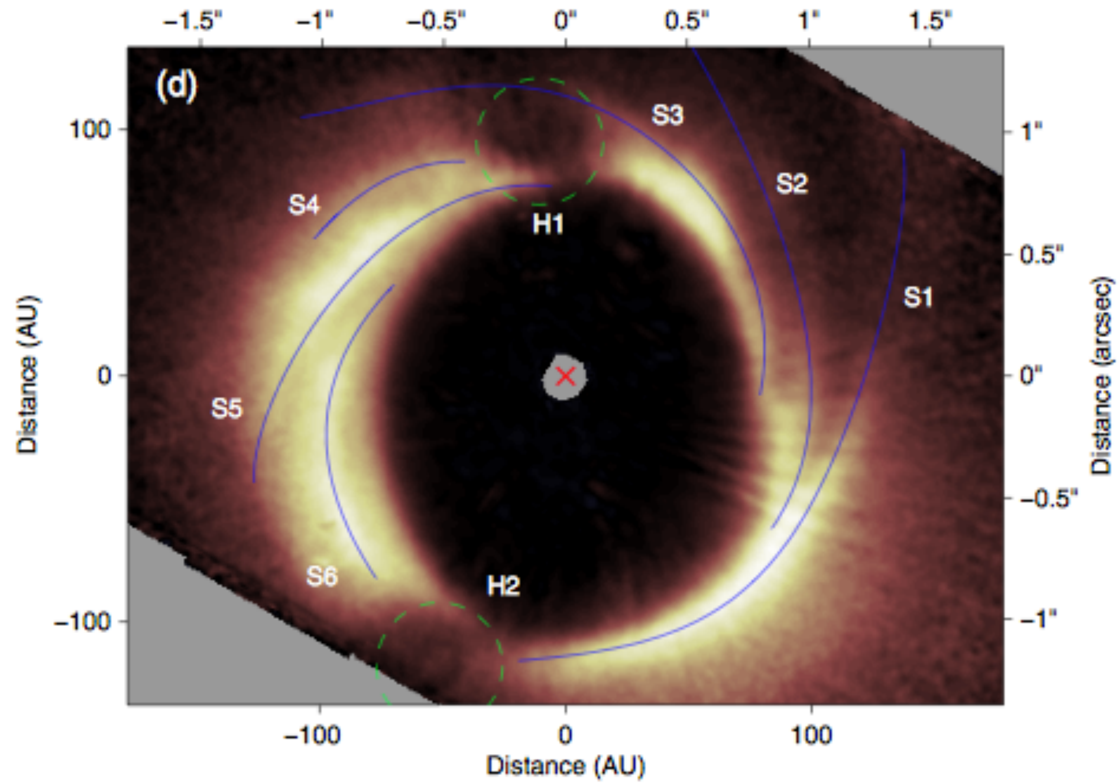


HD 163296

Isella et al. (2016)

Axisymmetric large-scale structure (rings) may be common in disks observed at high resolution

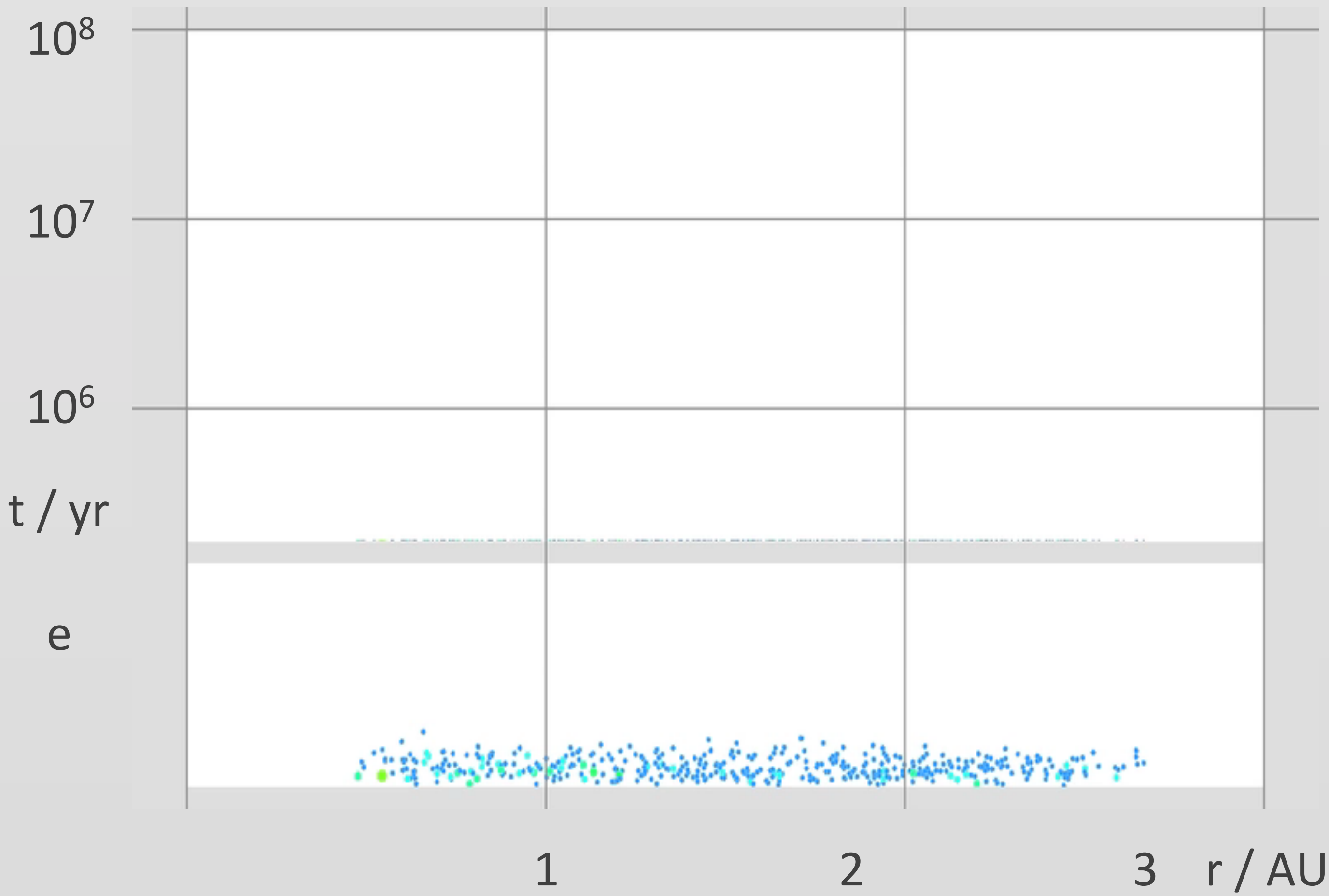




Avenhaus et al. '14

Also observe spiral arms, other non-axisymmetric structure in disks. What planetary and non-planetary processes responsible?

Casassus et al. '13



Often assume a smooth radial distribution of planetesimals as an effective initial condition for subsequent growth – is that a reasonable assumption?

Two possible types of structure:

- **persistent** structures caused by physical changes in the disk tied to specific temperatures, changes in ionization level, planetary perturbations
  - ice lines, edges of dead zones, planetary gaps
- **transient** structures that could form anywhere in the disk
  - vortices, zonal flows
  …might be thought of as “inverse cascade” consequences of turbulence

Ice lines

Water snow line: T = 150-170 K, signature in the asteroid belt at r ~ 2.7 AU

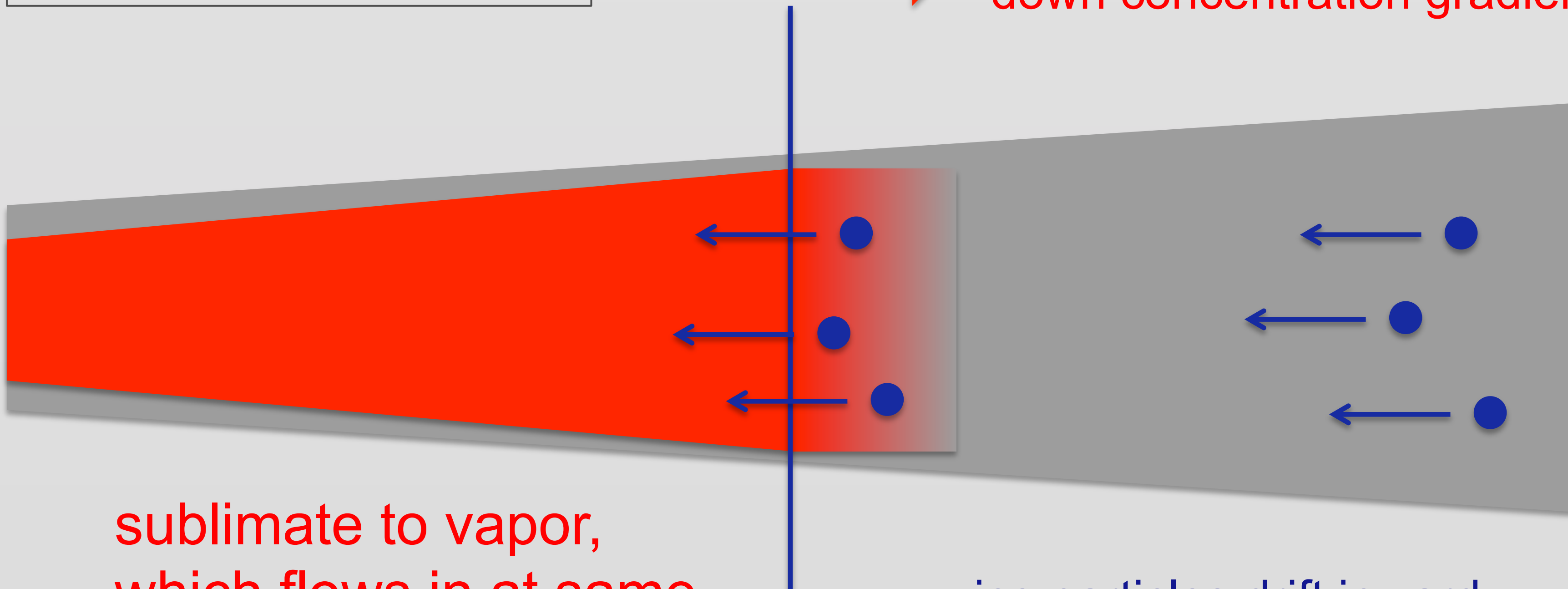
CO snow line: T = 20 K, around 30 AU corresponding to the Solar System Kuiper Belt

Multiple physical processes:

- diffusive outward flux of vapor *(Stevenson & Lunine ‘88)*
- feedback on ionization state *(Kretke & Lin ‘07)*
- opacity feedback on thermal structure *(Hasegawa & Pudritz ‘11)*

Physics at an ice line

vapor diffuses upstream
down concentration gradient

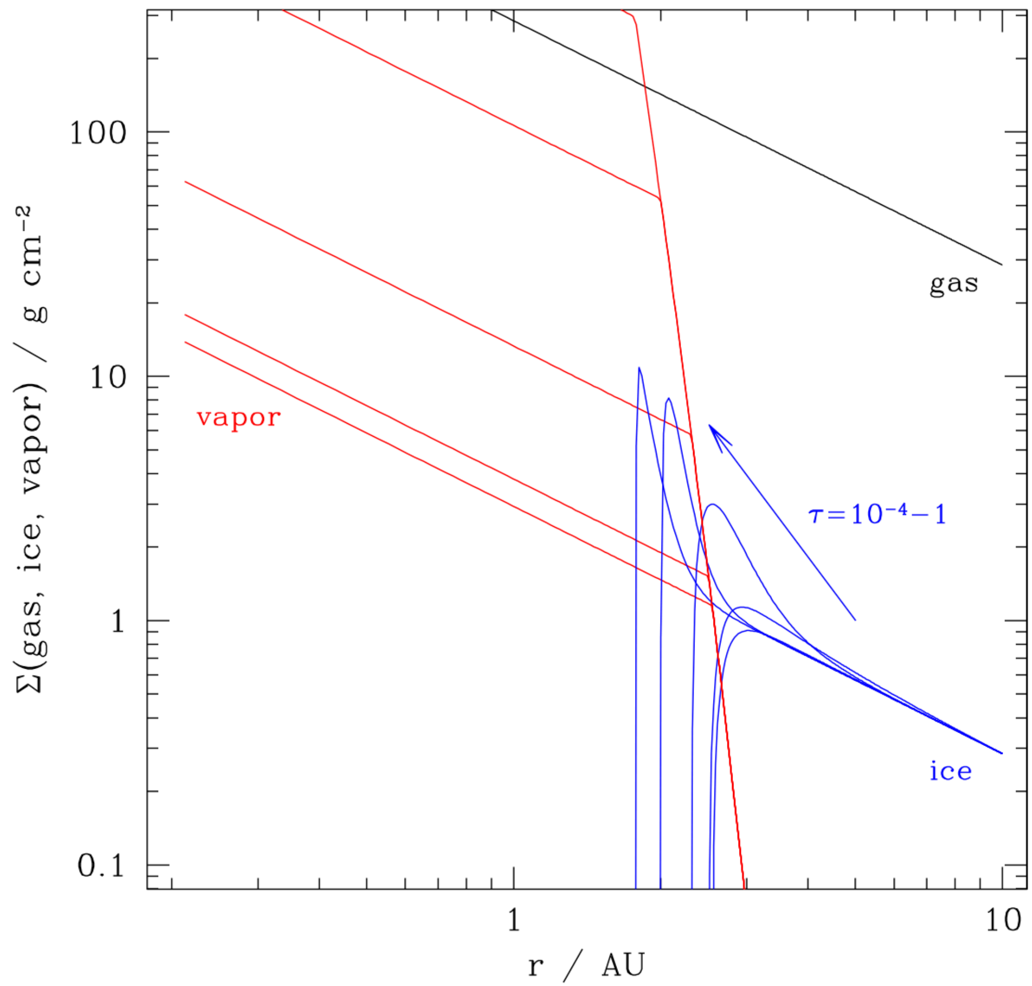


sublimate to vapor,
which flows in at same
speed as gas (it *is* gas!)

ice particles drift inward
at **faster** than gas inflow
speed (radial drift problem)

…and recondenses into (or onto)
ice particles just outside snow line

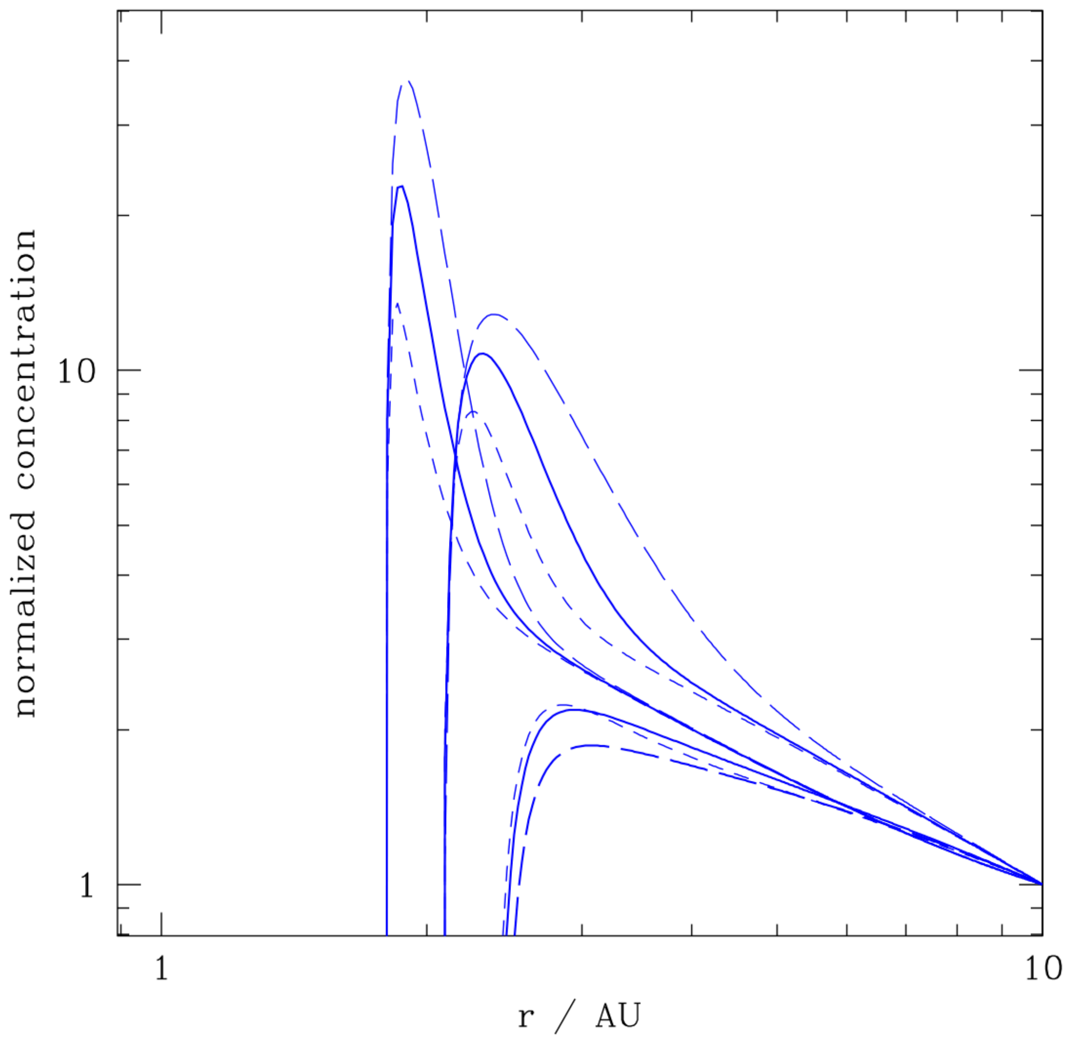
Net effect: vapor diffusion leads to an overdensity of solids in the vicinity of the ice line *(Stevenson & Lunine '88)*



For icy particles that drift in rapidly:

- can have high vapor density inside snow line (continuity)
- overdensity of solids outside from diffusion + re-condensation

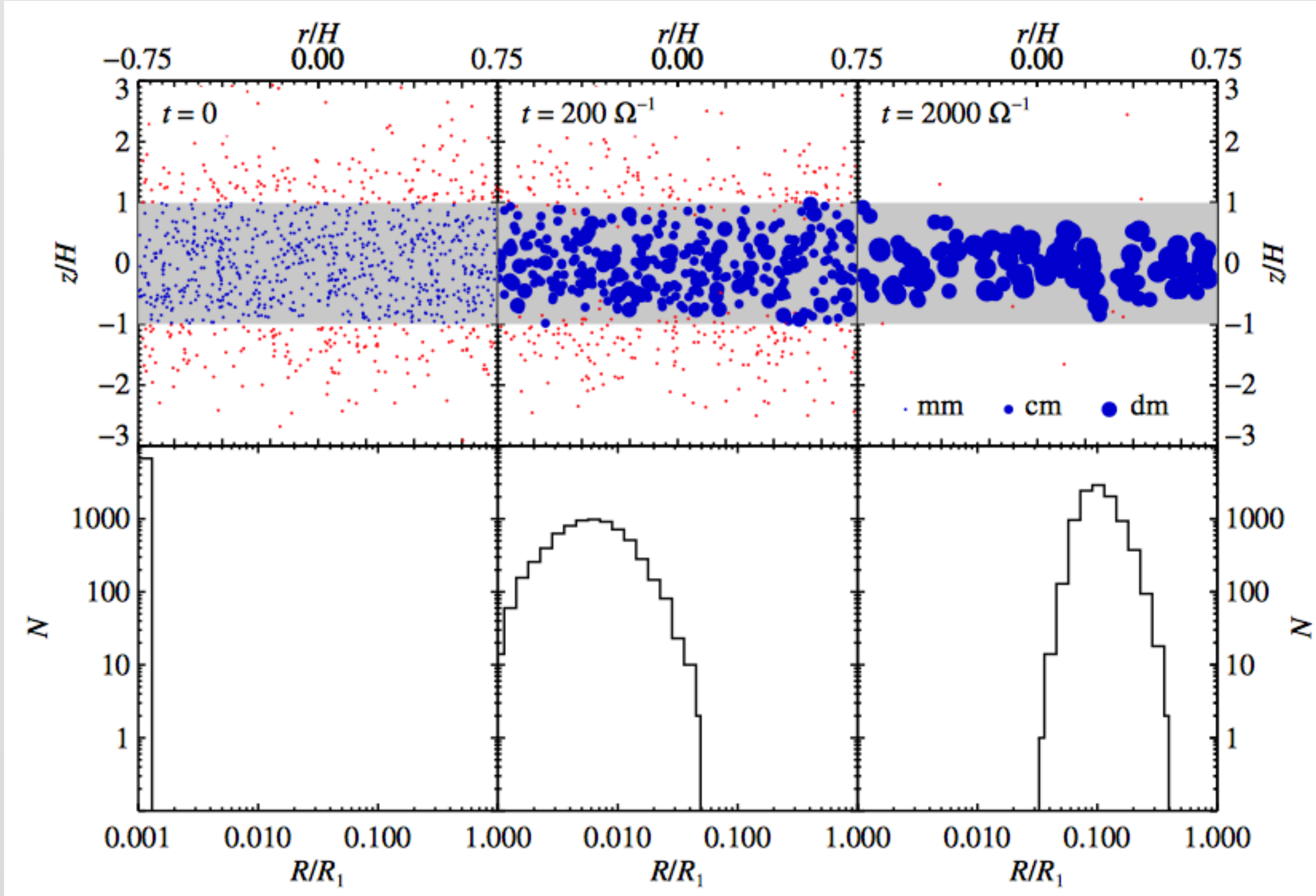
1D model with radial drift, sublimation / recondensation, turbulent radial diffusion



Stevenson & Lunine '88 and Ciesla & Cuzzi '06 argue that solid over-density outside snow line ought to promote planetesimal formation there

Possibly a stronger effect in "threshold" planetesimal formation models based on the streaming instability

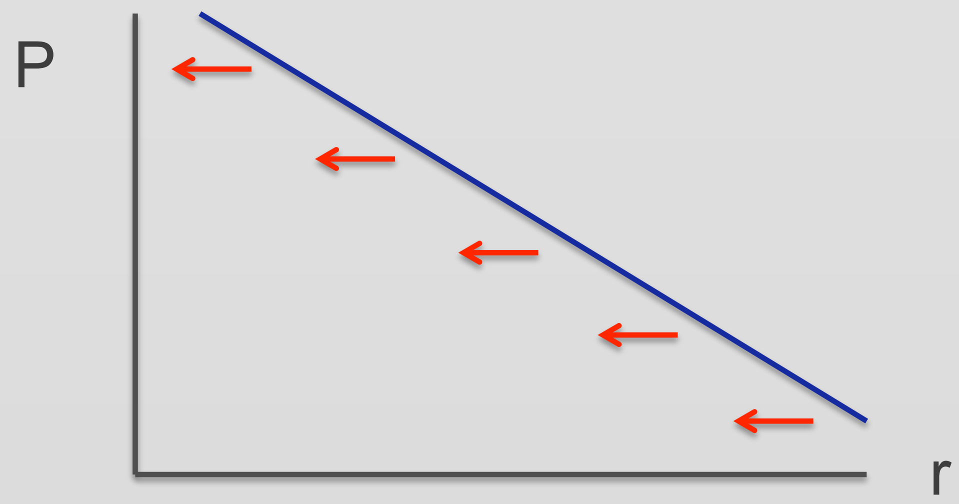
Ros & Johansen '13



Condensation of vapor on pre-existing particles could lead to rapid growth of particle size in same region

Particle traps

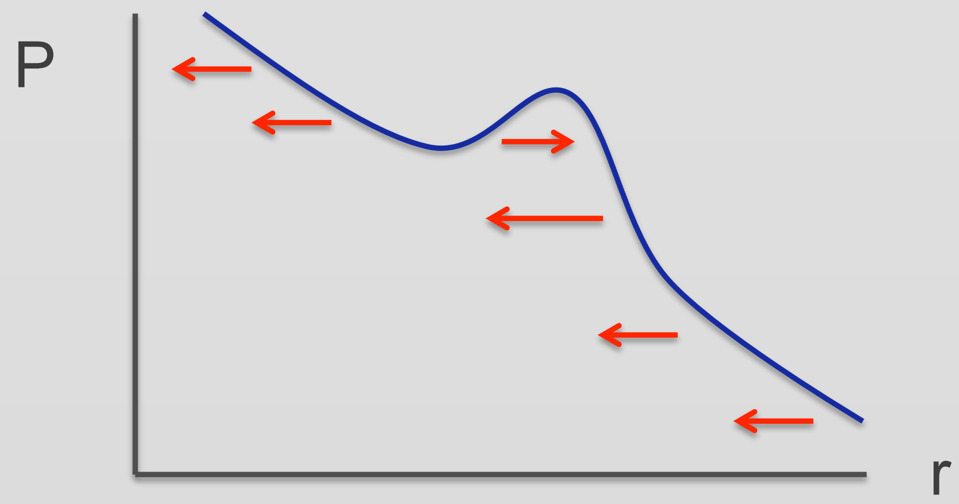
Radial drift – particle flow is toward pressure maxima



- inward in a smoothly varying disk model
- unaffected by diffusive snow line physics

Particle traps

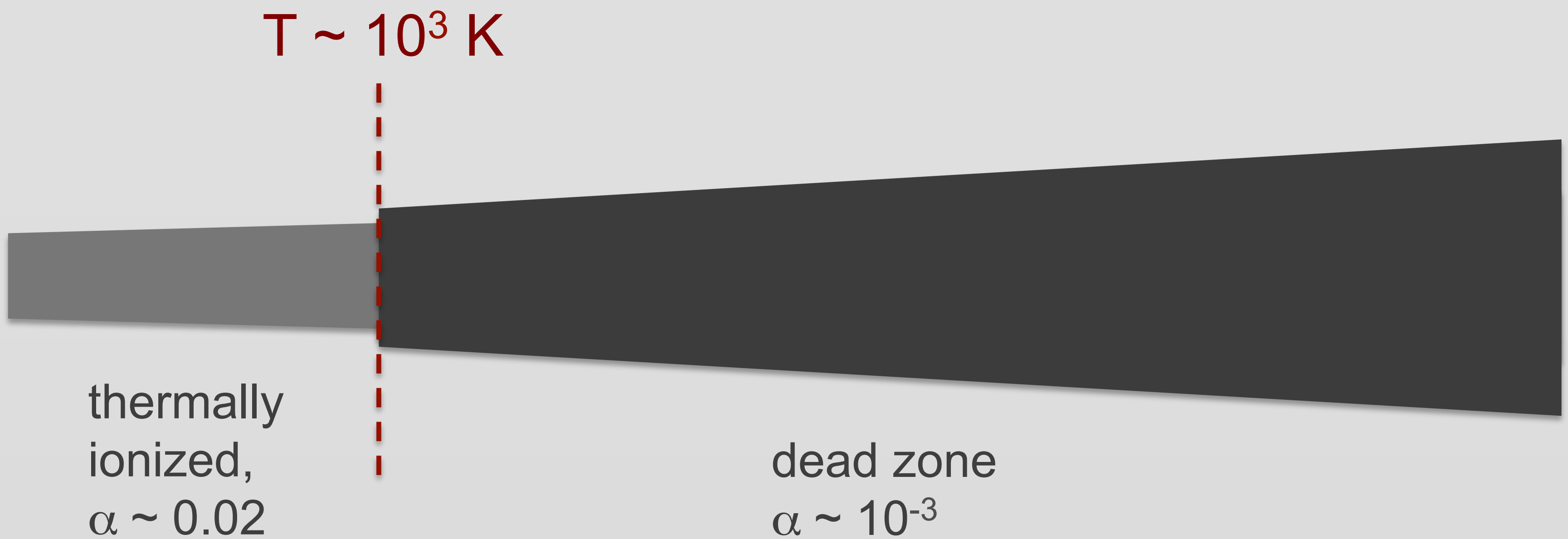
Radial drift – particle flow is toward pressure maxima



Introduce axisymmetric local pressure maximum in disk – convergent radial drift toward the location of peak pressure… a “particle trap”

Where might traps form in disks?

Inner edge of a dead zone…



- in steady state $\nu\Sigma = \dot{M}/3\pi$

  surface density scales as α^{-1}

- thermal ionization exponential f(T), so expect sharp transition

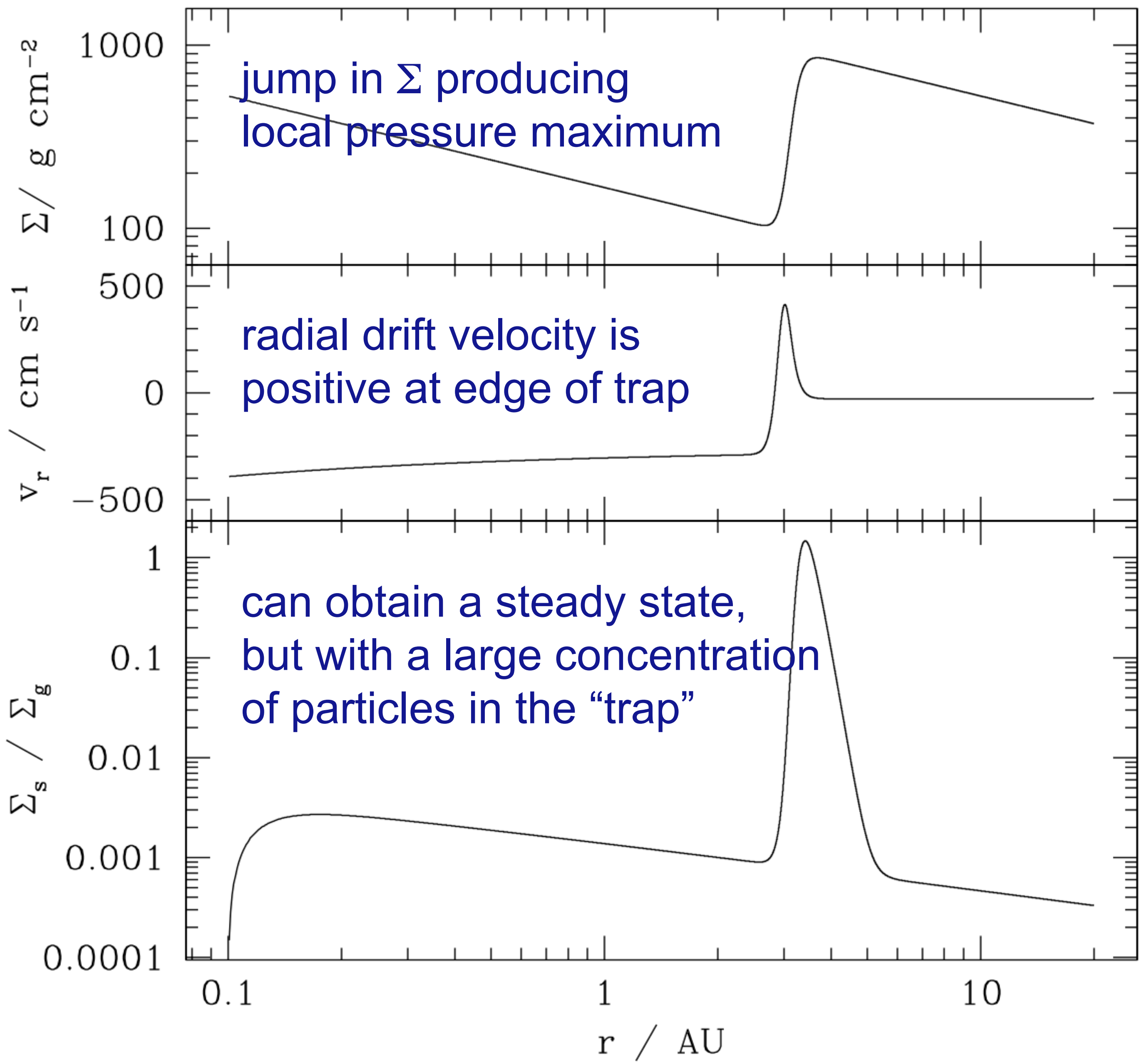
Can model in 1D using equation for particle drift + turbulent diffusion:

$$\frac{\partial C}{\partial t} = \frac{1}{r\Sigma}\frac{\partial}{\partial r}\left(Dr\Sigma\frac{\partial C}{\partial r}\right) - v_r\frac{\partial C}{\partial r}$$

radial drift term, now
not a monotonic f(r)

if diffusion is present, term “particle trap” is a misnomer

for any P(r) can find steady-state solution… particle density builds up in “trap” until dC / dr large enough for particles to diffuse through the trap and into inner disk



Example for a hypothetical trap at the snow line