Disk Dynamics & Signatures of Embedded Planets

Phil Armitage, University of Colorado

with:

Richard Alexander, Leiden
Ken Rice, Edinburgh

Disk Dynamics & Signature of Embedded Planets

- Disk evolution framework (review)
- Minimal models motivated by observations
- "Physics first" models based on *ab initio* angular momentum transport simulations

"Giant Planet Migration, Disk Evolution, and the Origin of Transitional Disks", Alexander & Armitage (2009)

"Time-dependent models of the structure and stability of self-gravitating protoplanetary discs", Rice & Armitage (2009)

Disk Dynamics

Surface density of a geometrically thin / low mass / planar and circular disk evolves as:

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{r}\frac{\partial}{\partial r}\left[r^{1/2}\frac{\partial}{\partial r}\left(\nu \Sigma r^{1/2}\right)\right] + \dot{\Sigma}(r,t)$$

…if no external torques act

mass loss with $l = l_{disk}$ (e.g. photoevaporation)

$\nu = \nu(r, \Sigma, t, x_e \ldots)$ has dimensions of viscosity [$cm^2\, s^{-1}$], with initial conditions + model for mass loss determines evolution

Complementary approaches:

- regard ν as fundamental quantity, constrain with observations
- calculate from first principles (MRI, self-gravity etc), observations still needed to constrain microphysics (e.g. saturation level for Hall MRI turbulence?)

Observational options…

Equivalently, write $\nu = \alpha c_s h$ → now α is the parameter **or function** to be determined… sensible as plausibly removes leading order scaling

In a turbulent, magnetized flow: $$\alpha = \left\langle \frac{\delta v_r \delta v_\phi}{c_s^2} - \frac{B_r B_\phi}{4\pi\rho c_s^2} \right\rangle$$

Three related (but not equivalent) observational targets:

(1) Identify a characteristic timescale with a given radius

$\tau \sim 1$ Myr for disks of scale ~20 AU

$$\tau \sim \frac{R^2}{\nu}$$ → $\nu \sim 3 \times 10^{15}$ cm^2 s^{-1}, or $\alpha \sim 6 \times 10^{-3}$ assuming $h / r = 0.05$

Essence of diagnostics based on population studies

Observational options…

Equivalently, write $\nu = \alpha c_s h$ → now α is the parameter **or function** to be determined… sensible as plausibly removes leading order scaling

In a turbulent, magnetized flow: $$\alpha = \left\langle \frac{\delta v_r \delta v_\phi}{c_s^2} - \frac{B_r B_\phi}{4\pi\rho c_s^2} \right\rangle$$

Three related (but not equivalent) observational targets:

(2) Measure Maxwell and / or Reynolds stresses

Expect: $$\delta v \sim \alpha^{1/2} c_s = 0.15 \left(\frac{\alpha}{10^{-2}} \right)^{1/2} \left(\frac{h/r}{0.05} \right) \left(\frac{r}{1 \text{ AU}} \right)^{-1/2} \text{ km s}^{-1}$$

$$B \sim 1 \left(\frac{\alpha}{10^{-2}} \right)^{1/2} \left(\frac{r}{1 \text{ AU}} \right)^{-7/4} \text{ G}$$

MMSN with $h/r = 0.05$

c.f. Meredith Hughes' talk yesterday…

Observational options…

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{r}\frac{\partial}{\partial r}\left[r^{1/2}\frac{\partial}{\partial r}\left(\nu \Sigma r^{1/2}\right)\right] + \dot{\Sigma}(r,t)$$

Three related (but not equivalent) observational targets:

(3) Measure surface density profile + accretion rate

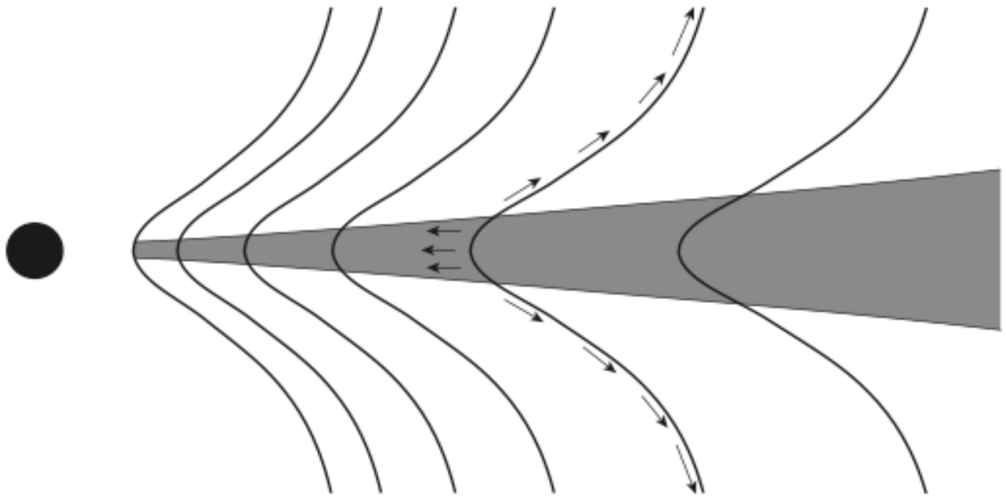
In steady state: $\nu \Sigma = \frac{\dot{M}}{3\pi}$

assumption will be safer on smaller spatial scales, less safe if mass loss rate very high

e.g. Andrews et al. (2009); Isella et al. (2009)

Consistency among all three measures would be a good sign we're on basically the right track!

Might this framework be wrong?



Magnetized disk winds as important as internal Maxwell stress when:

$$B_z^s B_\phi^s > \left(\frac{h}{r}\right)\langle B_r B_\phi \rangle$$

Need observational constraints… could magnetic wind torques destroy disks early in a fraction of sources?

Disks formed from turbulent collapse might *not* be flat or circular… warped / eccentric disks evolve differently (usually faster) than simple disks.

ν might not be deterministic (fluctuating quantity that does not converge in t_{disk}), or local - possible but does not seem likely…

Minimal models for protoplanetary disks

Consider simplest theoretical model for population study of planets and transitional disks:

- viscous disk evolution (constant α for passive disk)
- dispersion in initial disk mass (needed to generate a smooth CTTS / WTTS transition)
- giant planet formation + Type II migration
- photoevaporation

yields "transitional disks" via inside-out photoevaporative disk clearing

yields gaps and inner cavities that *may* appear "transitional"

Other processes may produce disks that look transitional too… not considered in this model

Minimal models for protoplanetary disks

Consider simplest theoretical model for population study of planets and transitional disks:

DISK

- viscosity $\nu = \nu_0 r$, $\alpha = 10^{-2}$
- mean disk mass 0.03 M_*, 3σ dispersion 0.5 dex
- initial accretion rate 4 x 10^{-7} M_{Sun} / yr
- similarity solution initial conditions, R_s = 10 AU

WIND

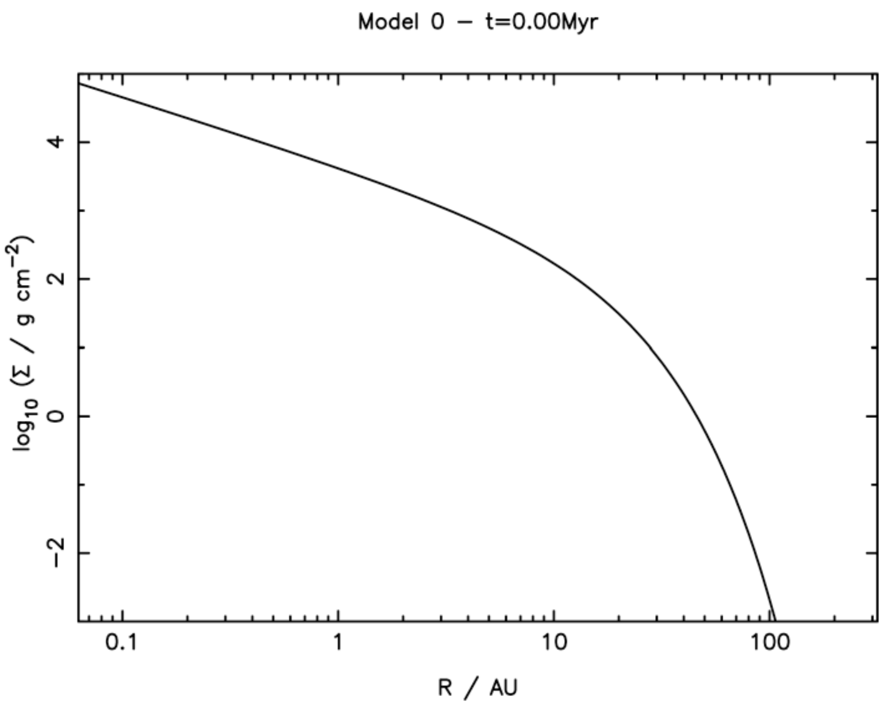
- EUV photoevaporation model (diffuse + direct, $\Phi = 10^{42}$ s^{-1})

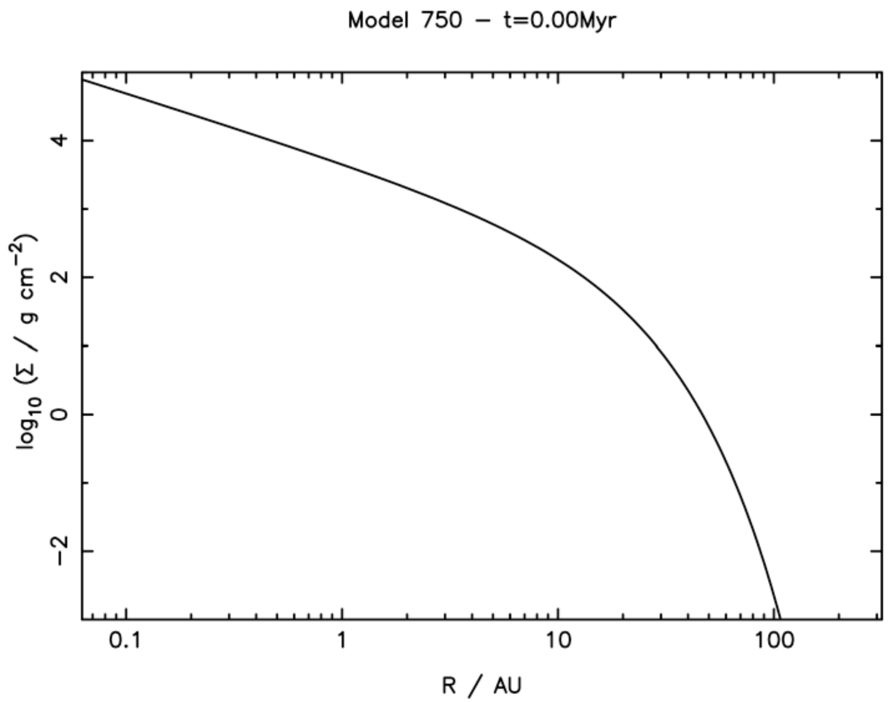
PLANETS

- form planets $0.5_J < M_p < 5\ M_J$ at 5AU, uniform rate
- accretion and flow across gap adopted to match simulations

Evolve disk (and planet, when present) with 1D radial model

Minimal models for protoplanetary disks



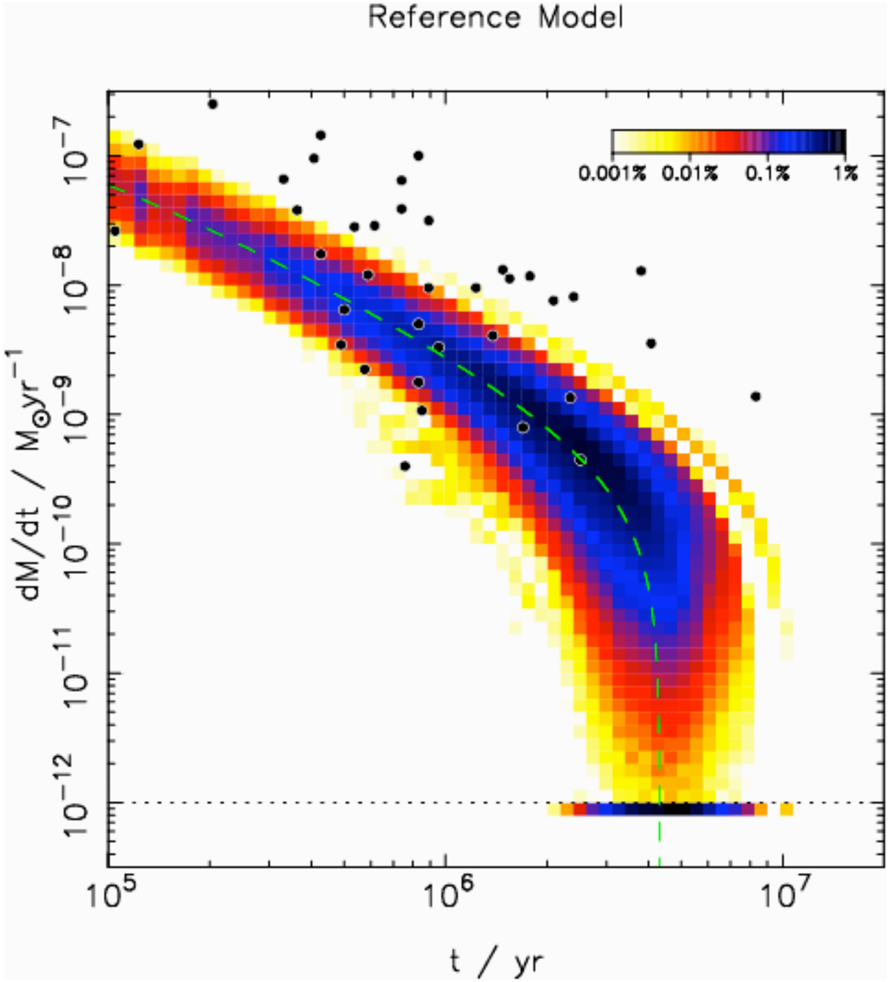


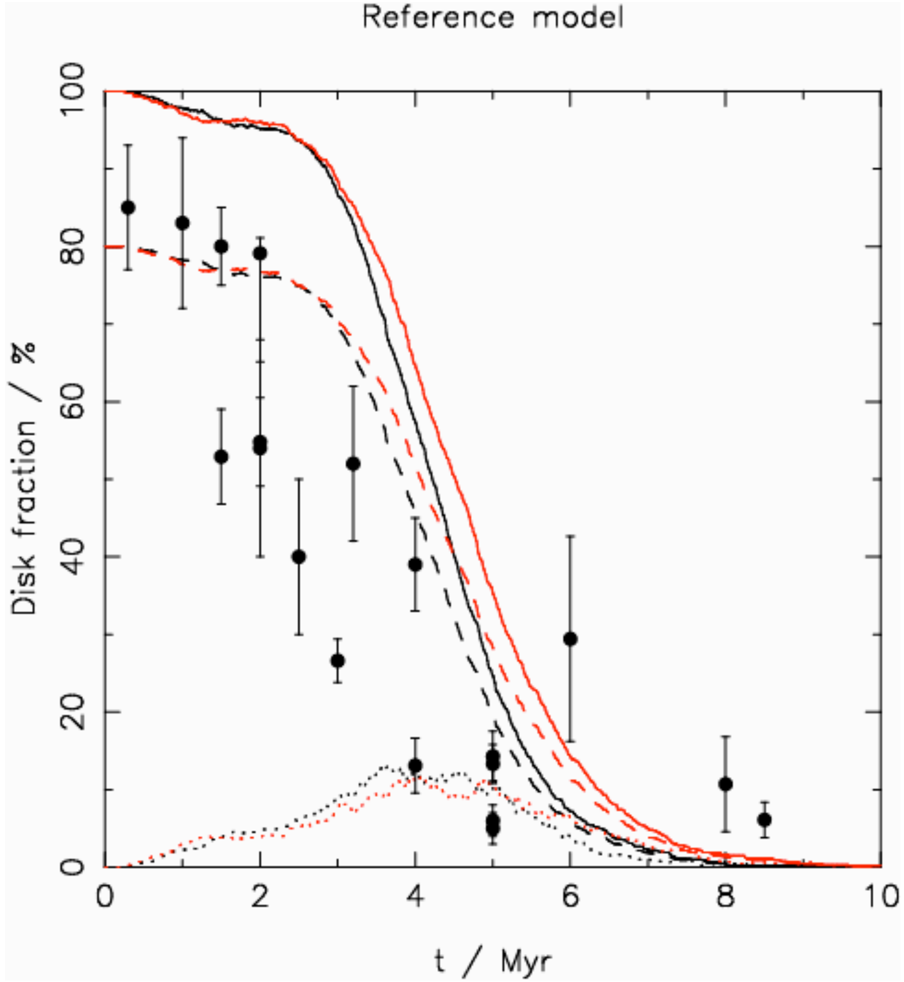
Disk evolution

Planet migration

Disk evolution is coupled to migration: when planet forms gap alters the photoevaporative radiation field seen by disk

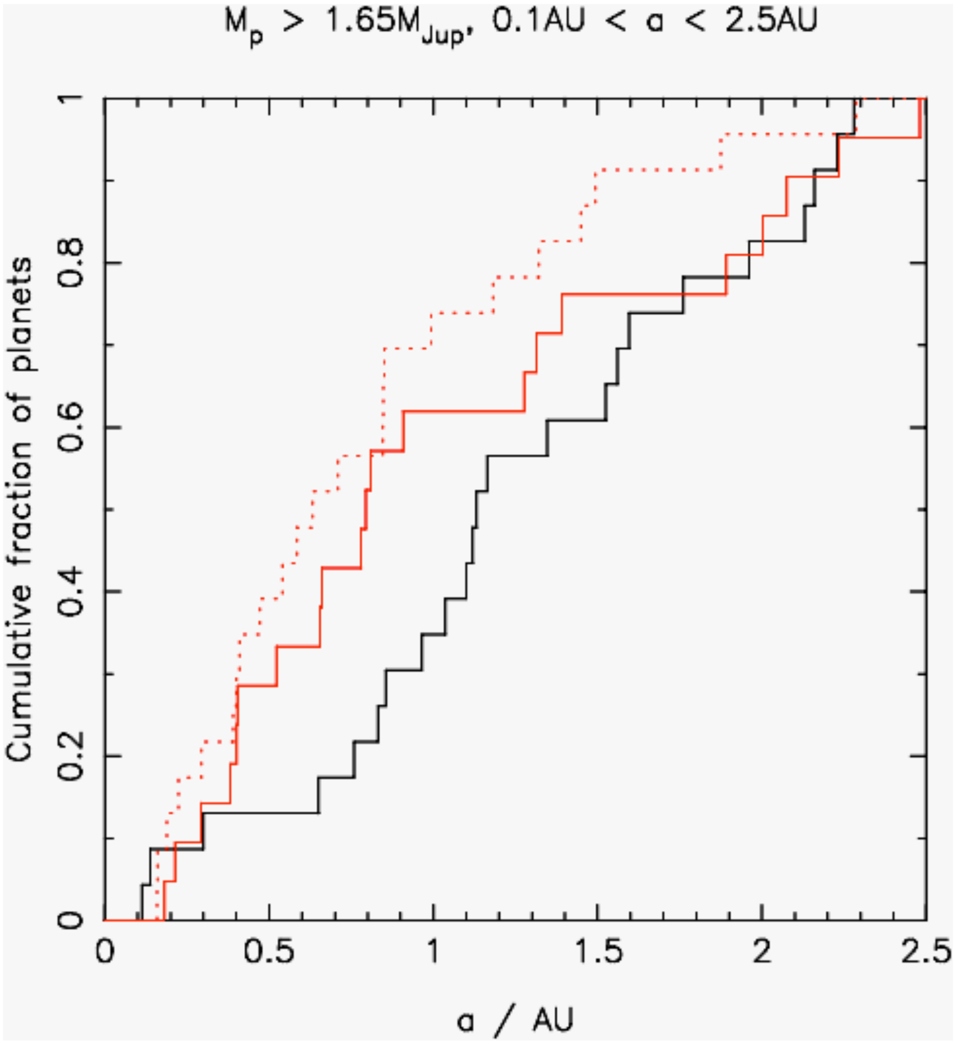
Minimal models for protoplanetary disks





Simple model of this type can match the decline in accretion rate / IR disk fraction data reasonably, though hard to disperse disk at $t < 2$ Myr (binaries? c.f. Adam Kraus' talk)

Minimal models for protoplanetary disks

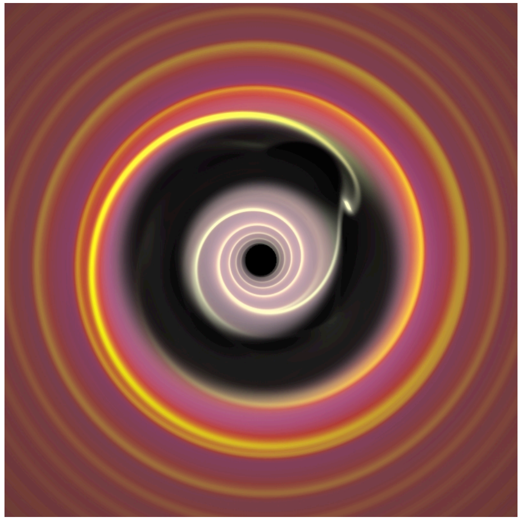


Type II migration in a viscous disk yields observed radial distribution of massive planets (e.g. Armitage et al. 2002; Trilling et al . 2002)

Adjust the normalization (i.e. probability that a disk forms planets at all) to match observed frequency

Up to metallicity uncertainties, our disks have the “right” number of embedded planets

Do planetary gaps = transitional disks?



Even massive (gap opening) planets allow some **gas** flow across gap: ~10% (Lubow & D'Angelo 2006)

Dust is filtered from the gas by pressure gradient at gap edge (Rice et al. 2006; Paardekooper & Mellema 2006)

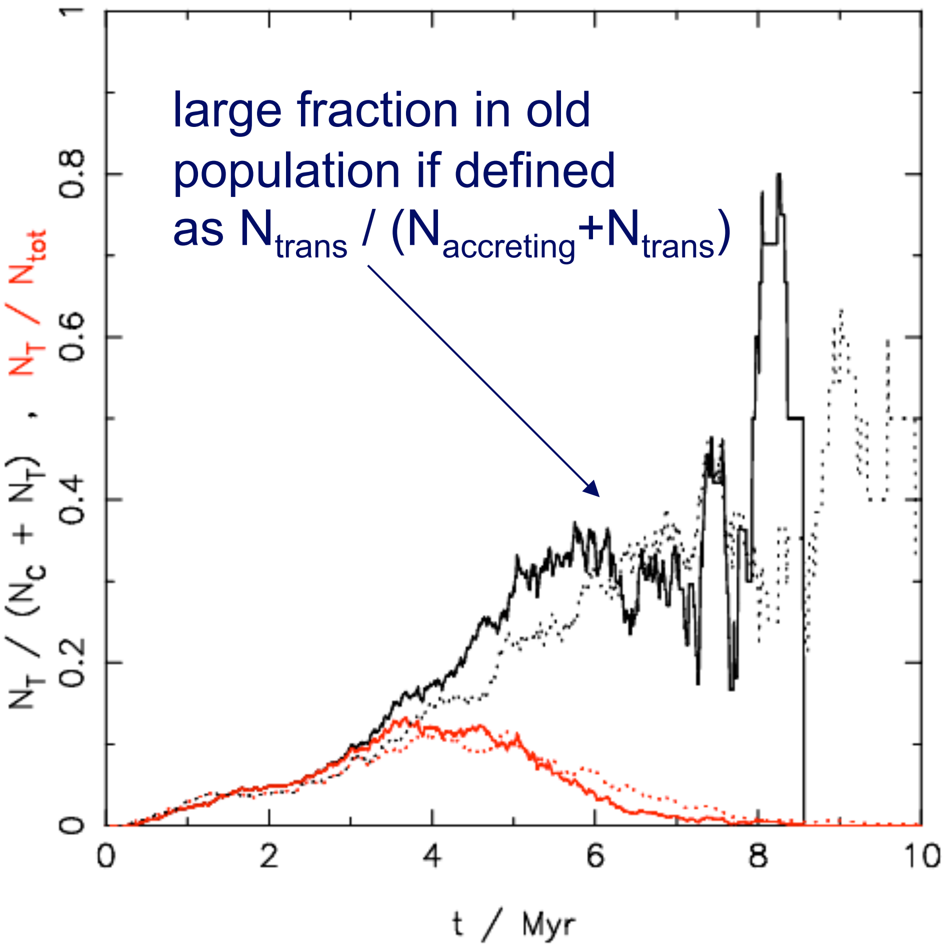
Argue that massive planets *do* produce transitional disks

Irrespective of whether these look like transitional disks, exoplanet statistics imply some fraction of disks must harbor migrating massive planets.

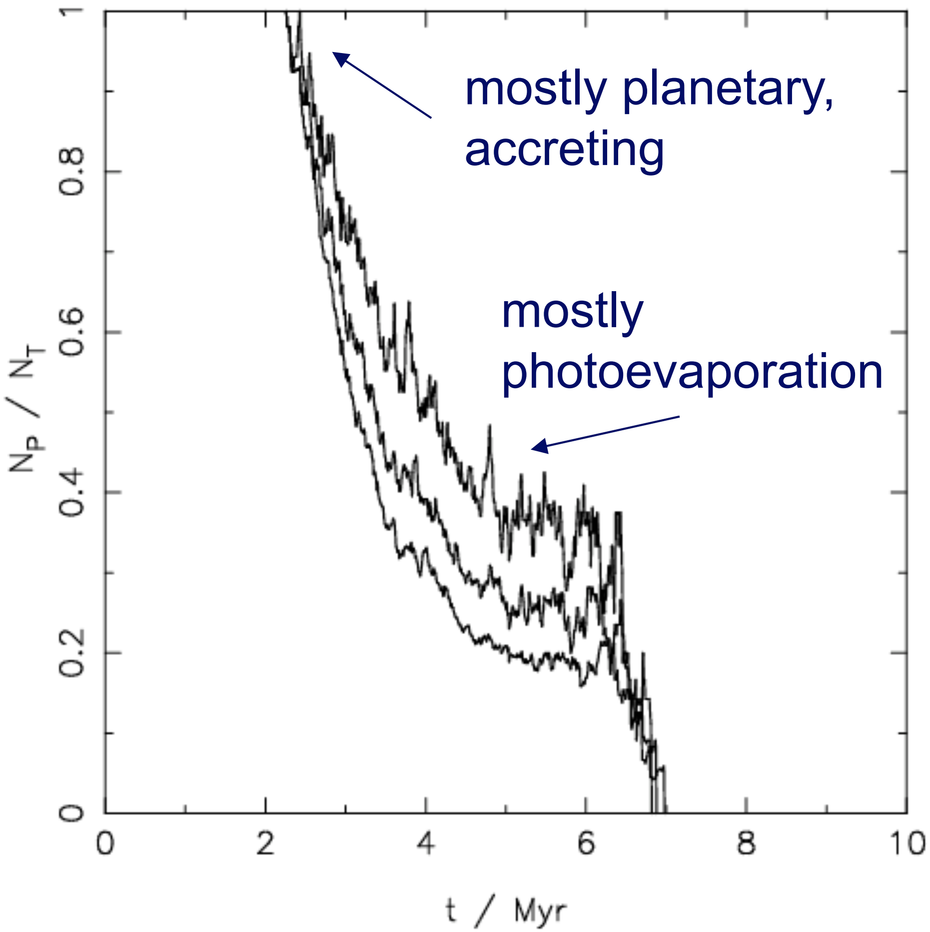
Define disks as transitional if they exhibit optically thin / thick transition with radius, or if they harbor a planet.

Predicted population of transitional disks

Transition disk fraction



Fraction of transitional disks caused by planets



Note: trends / fractions are more robust than absolute ages…

Ab initio disk models

Alternative approach: build disk model *starting* from physics of identified angular momentum transport mechanisms

- self-gravity: can compute $\alpha = f(Q_T, t_{cool})$

  if dominant process results in rapid accumulation of mass on ~10 AU scales: $\Sigma = \Sigma_0 r^{-\beta}$ with β = 2-3 (Rice & Armitage 2009; Clarke 2009)

- MRI: Ohmic damping suppresses linear modes when:

  $$\mathrm{Re}_M = \frac{c_s^2}{\eta\Omega} < \mathrm{Re}_{M,\mathrm{crit}}$$

  …or electron fraction $x_e < 10^{-13}$

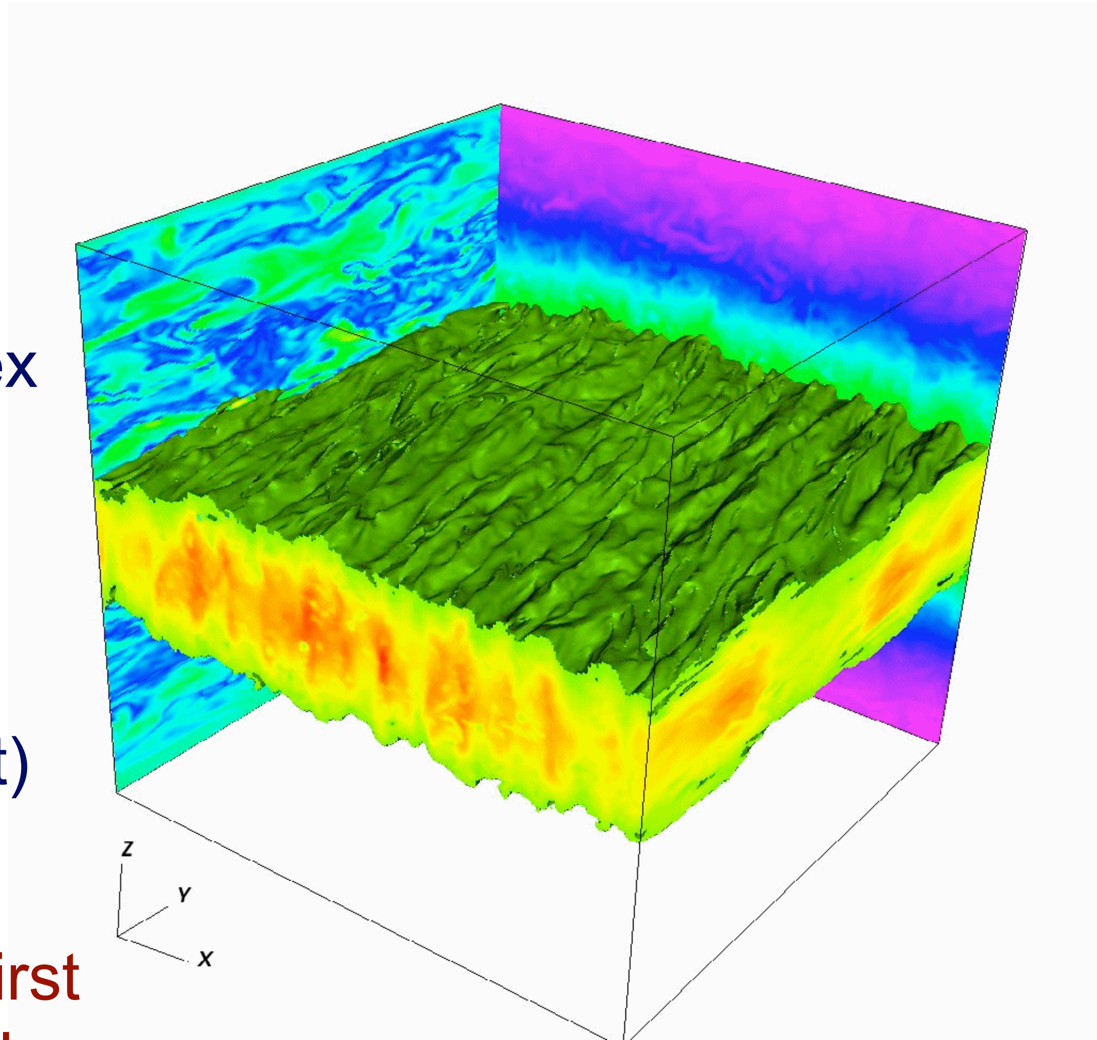
- hydrodynamic instabilities - work continues on Klahr's baroclinic instability (Lesur & Papaloizou, astro-ph) but transport levels seem low

Ab initio disk models

Non-linear behavior and saturation of the MRI is **not** well understood…

- appears to be a complex dependence on the magnetic Prandtl number Pm = ν / η

- role of strong (dominant) Hall term not clear



Davis, Stone & Pessah (2009)

Forseeable future: even “first principles” disk models will involve parameters that must be constrained observationally

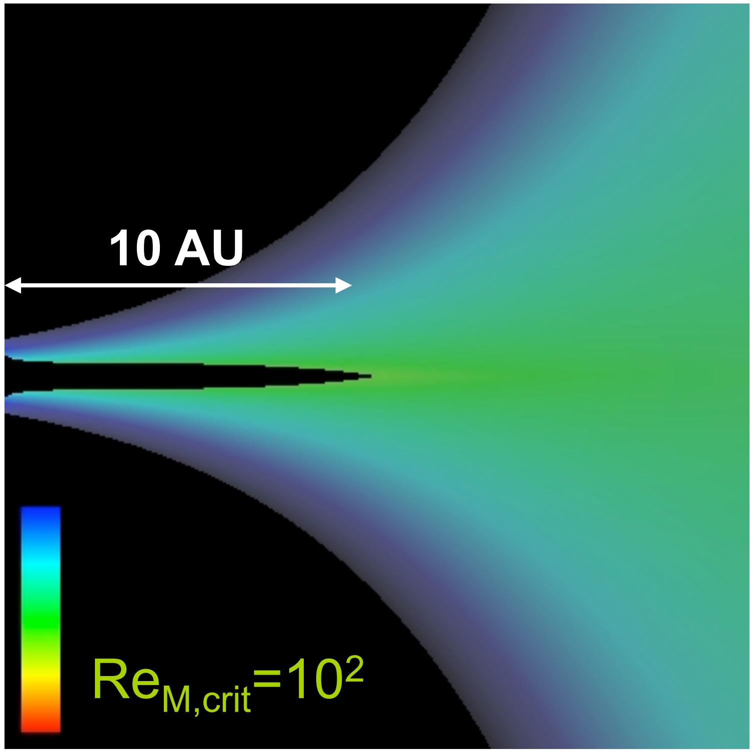
Ab initio disk models

Toy model: MRI *only* - how different is it?

X-ray ionization (5 keV, $L_X = 2 \times 10^{30}$ erg / s, fit to Igea & Glassgold 1999)

Dissociative recombination

Same initial conditions / photoevaporation as previous models



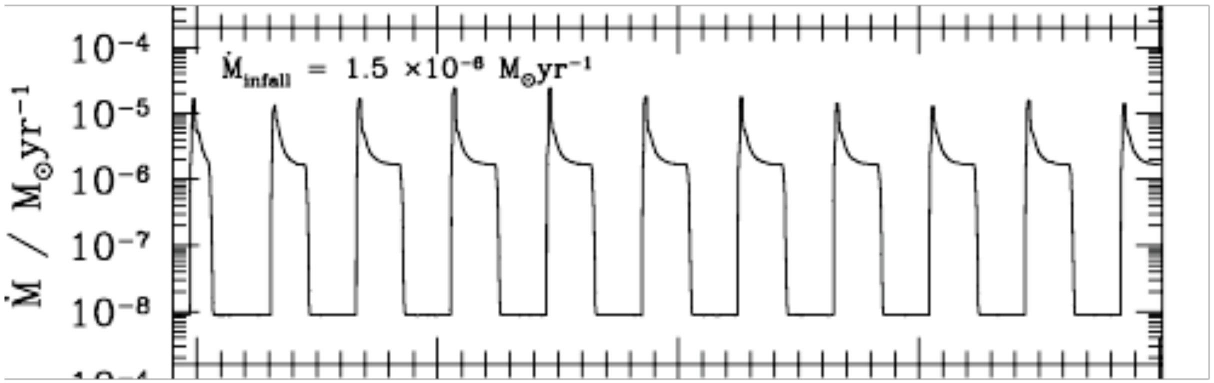
Dead zone in initial disk model out to about 10AU, mass accumulates here as the disk evolves

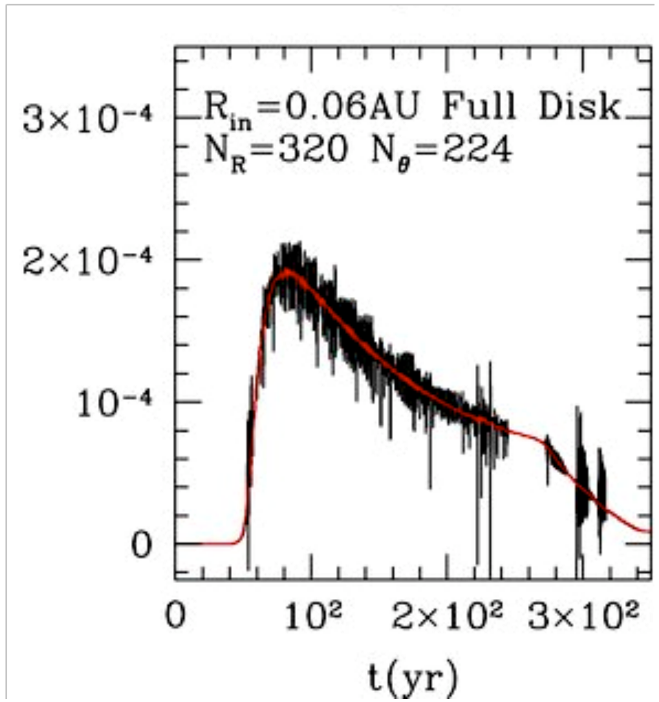
Ab initio disk models

X-ray flares probably *not* important for variability: flare time scale << MRI growth time ($\sim\Omega^{-1}$, see Ilgner & Nelson 2006)

BUT, at early times dead zone vulnerable to thermal instability with two states:

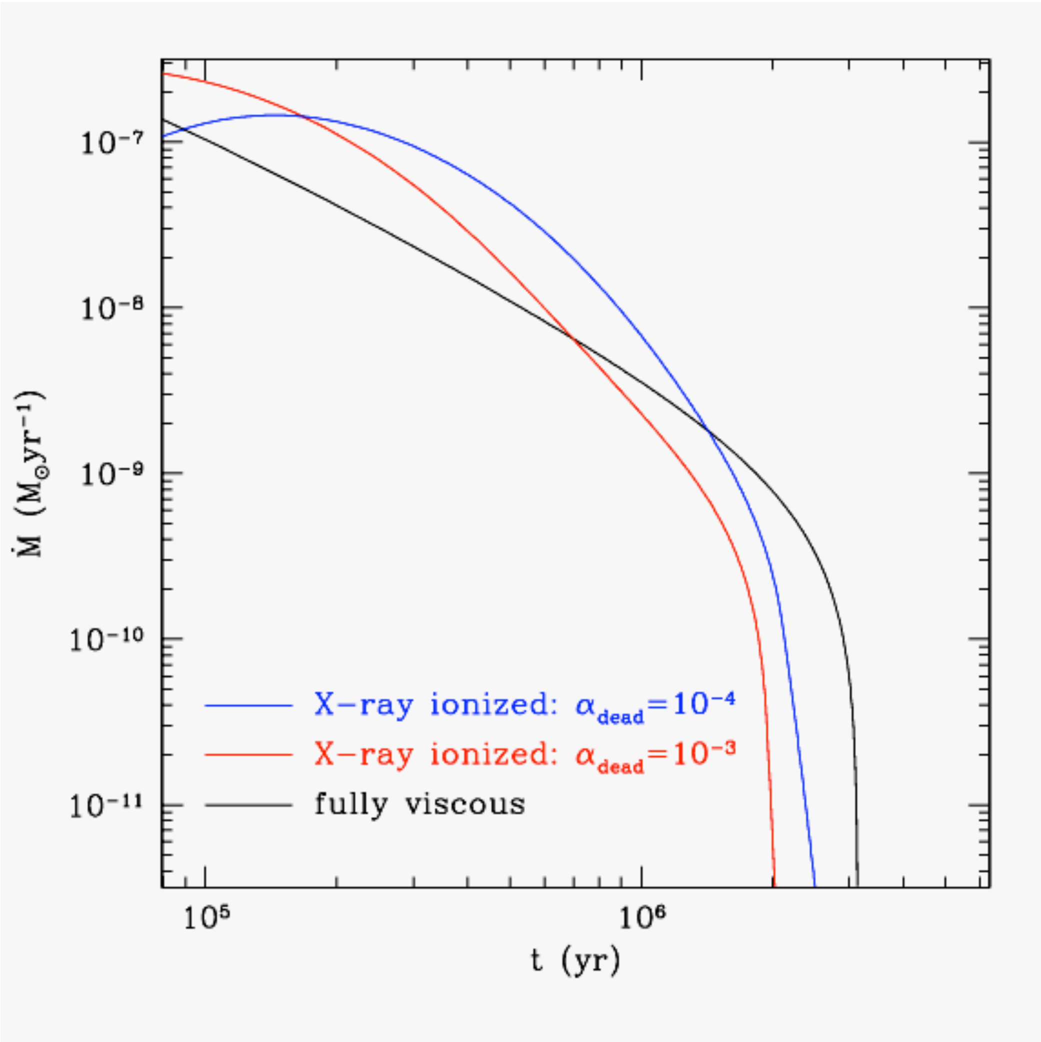
- low accretion rate: non-thermal ionization, dead
- very high accretion rate: thermal ionization





Armitage, Livio & Pringle (2001, 1D), Zhu et al. (2009a,2009b, 2D). New calculations promising for FU Orionis

Ab initio disk models



At late times, model with α_{MRI} (in active zone) = 0.1 evolves and disperses very similarly to the minimal viscous model with $\alpha \sim 10^{-2}$

Note: $\alpha \sim 0.1$ more consistent with other disk systems (King et al. 2007)

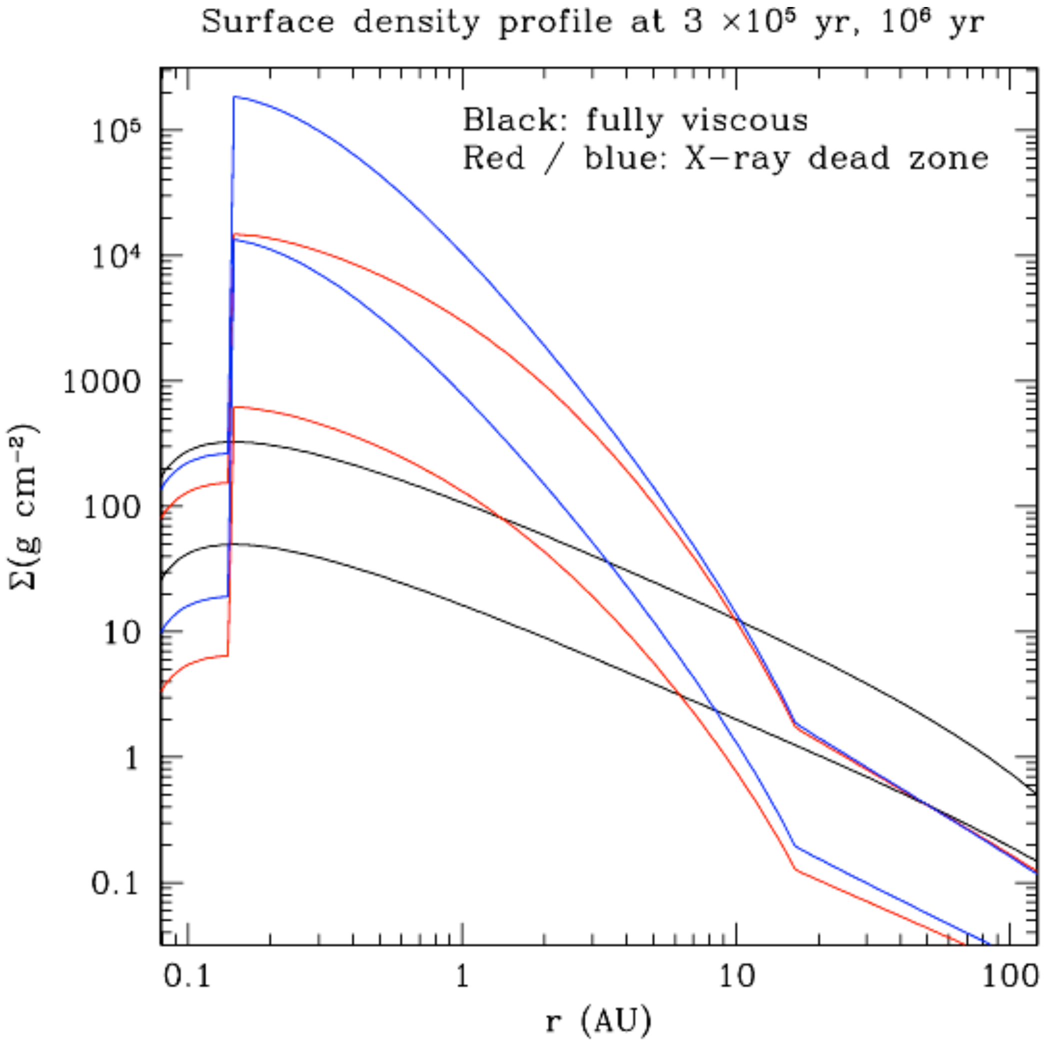
Success of simple models may not reflect *any* fundamental understanding of disk physics

Ab initio disk models

Surface density profiles are very different (much steeper, with higher normalization), but only at r ~ 0.5 - 3 AU

Significant consequences for planetesimal formation, if true…

Developing better (but still simple) models with Eric Feigelson, Barbara Ercolano



Are there observational probes?

Summary

- (over)-simple α disk models consistent with basic evolution of disks, can be used to predict planet population and nature of transitional disks
- progress in understanding physics input (self-gravity, MRI, photoevaporation) needed to construct ab initio disk models
- very likely that even “ab initio” models will involve free parameters that need to be constrained observationally
- single most valuable gas disk observation: measure of Σ near 1 AU where the dead zone (if it exists) is dominant