The Evolution of Circumplanetary Disks around Planets in Wide Orbits:

Implications for Formation Theory, Observations, and Moon Systems

Masters Presentation
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Introduction

- T-Tauri class 0, or 1 disks
- Gravitational instability, H_2 dissociation
- Previous planet formation studies focus on the interaction between the circumstellar disk and the planet. (Quillen & Trilling 1998, Ayliffe & Bate 2009)
- Circumplanetary disk (subdisk) mass evolution
- 1. Ice desorption 2. Grain emission -> ALMA!

Science Questions

- How fast do subdisks evolve away from their initially massive state?
- How do subdisks affect the growth of the host planet?
- How do non-axisymmetric instabilities such as bore shocks and spiral arm instabilities affect the processing of subdisk material?
- What are the observables of extended subdisks?
- What is the resulting size and mass of the subdisk and what does this imply about moon formation?
- How does circumstellar material effect the growth of the host planet (isolated vs. embedded subdisks)?

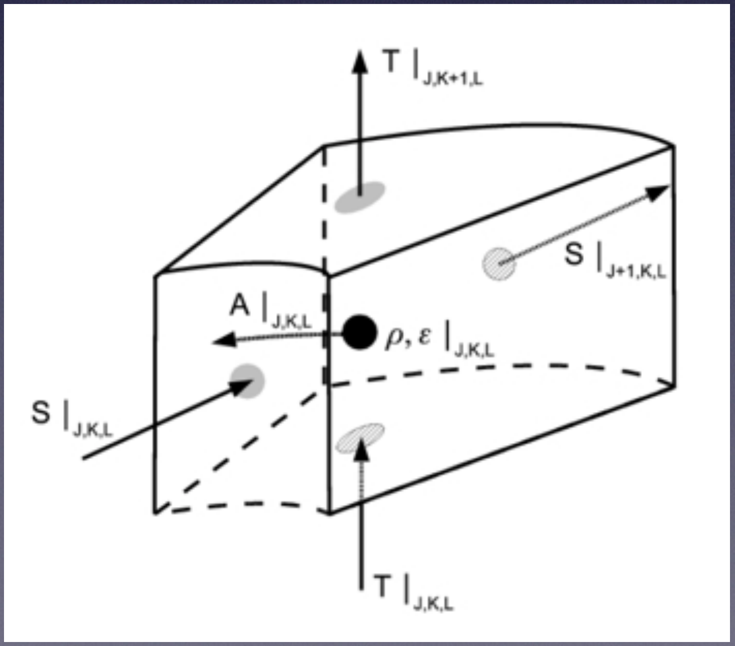
Methods

Overview:

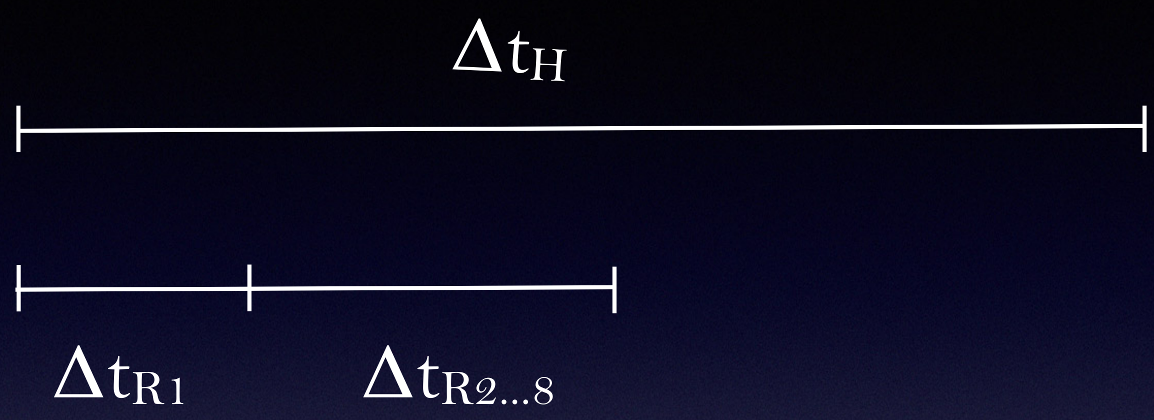
- CHYMERA: radiation hydrodynamics code
- Cooling routine
- Tidal potential
- Luminosity feedback
- Fluxing mass onto the grid

CHYMERA

- Computational HYdrodynamics with MultiplE Radiation Algorithms (Boley 2007).
- Fixed cylindrical grid centered on the planet
- Eularian method -> S, A, T, are momentum density in radial, azimuthal, and vertical directions. ε (internal energy density), ρ(gas density)



Cooling Routine



- 8 subcycles of cooling/heating (Δt_{Ri})
- Cooling/Heating boundaries:
    - Heat gas to 10% (determined numerically) of final iteration value
    - Or cool gas to as low as the background temperature

Tidal Potential

- Subtract off l=1 term to eliminate the motion towards the gravitating object (Boss 2006)
- This allows us to work in the frame of the subdisk
- Higher order terms effect the local dispersion of the material

$$\Phi_{\mathrm{tide}}(\boldsymbol{r}) = -\frac{GM_b}{|\boldsymbol{r} - \boldsymbol{r}_b|}$$

$$\Phi_{\mathrm{tide}}(\boldsymbol{r}) = -\frac{GM_b}{r_b}\sum_{l=0}^{\infty}\left(\frac{r}{r_b}\right)^l P_l(\cos S)$$

$$\bar{\Phi}_{\mathrm{tide}}(\boldsymbol{r}) = -\frac{GM_b}{|\boldsymbol{r} - \boldsymbol{r}_b|} + \frac{GM_b r}{r_b^2}\cos S$$

Luminosity Feedback

- Mass accretion luminosity is accounted for in our simulations
- The radial temperature of the subdisk is updated each hydrodynamical step

$$T_{irr}^4 = \left(\frac{1}{2}\right)\left(T_e^4 + T_{acc}^4\right) \quad \left(\frac{R_p}{D}\right)^3 + T_B^4$$

Fluxing mass onto the grid

- For the embedded disk simulation we add 10^{-13} g/cm^3 of mass to the grid at the escape speed of the planet/subdisk system
- The mass enters the system counter clockwise between 3 and 6 o'clock and 9 and 12 o'clock based on global simulations models.

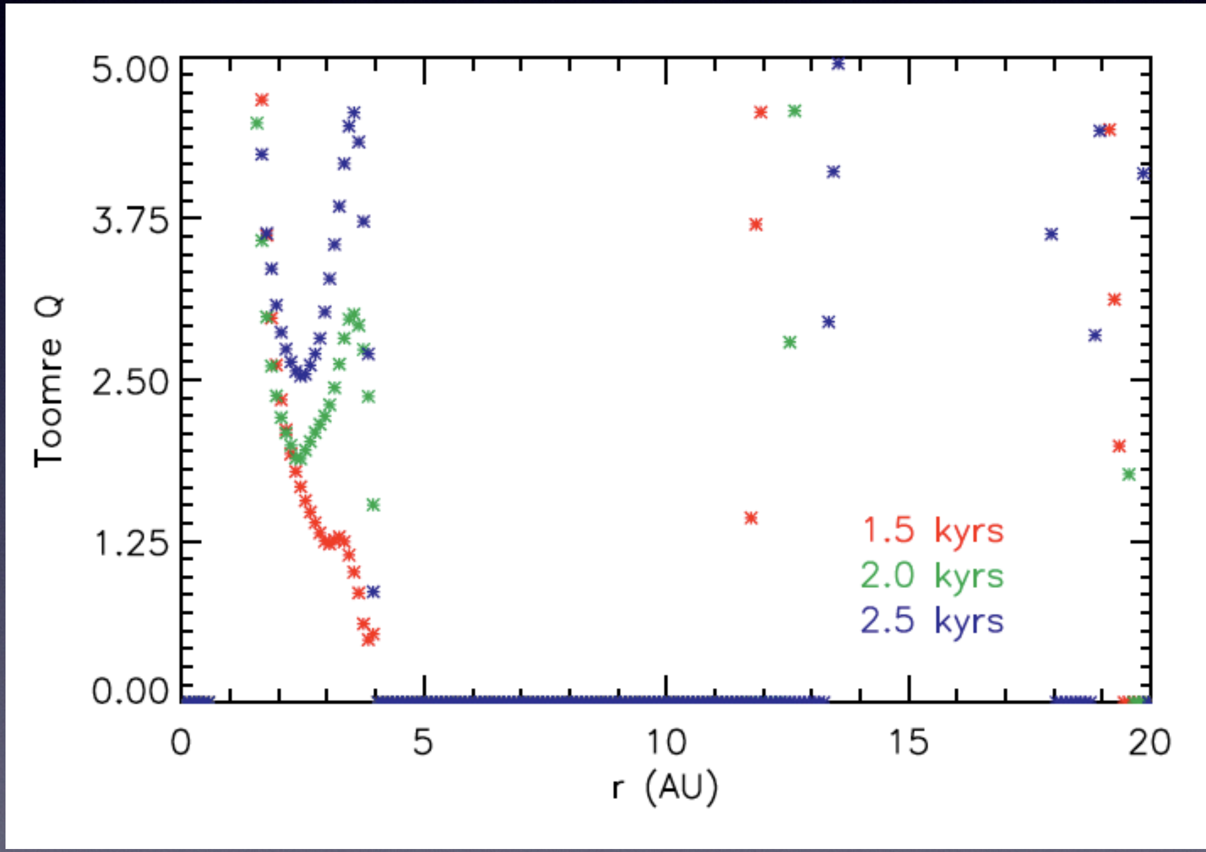
Initial Conditions

- **Isolated subdisk:** circumstellar gas has dissapated
- **Embedded subdisk:** mass from the circumstellar disk is accreting onto the circumplanetary disk

Disk mass	$3M_J$
Host planet mass	$3M_J$
Barycenter of subdisk orbit	$100AU$
Disk radius	$10AU$
Initial Toomre Q	~1.1
Host star mass	$1M_\odot$

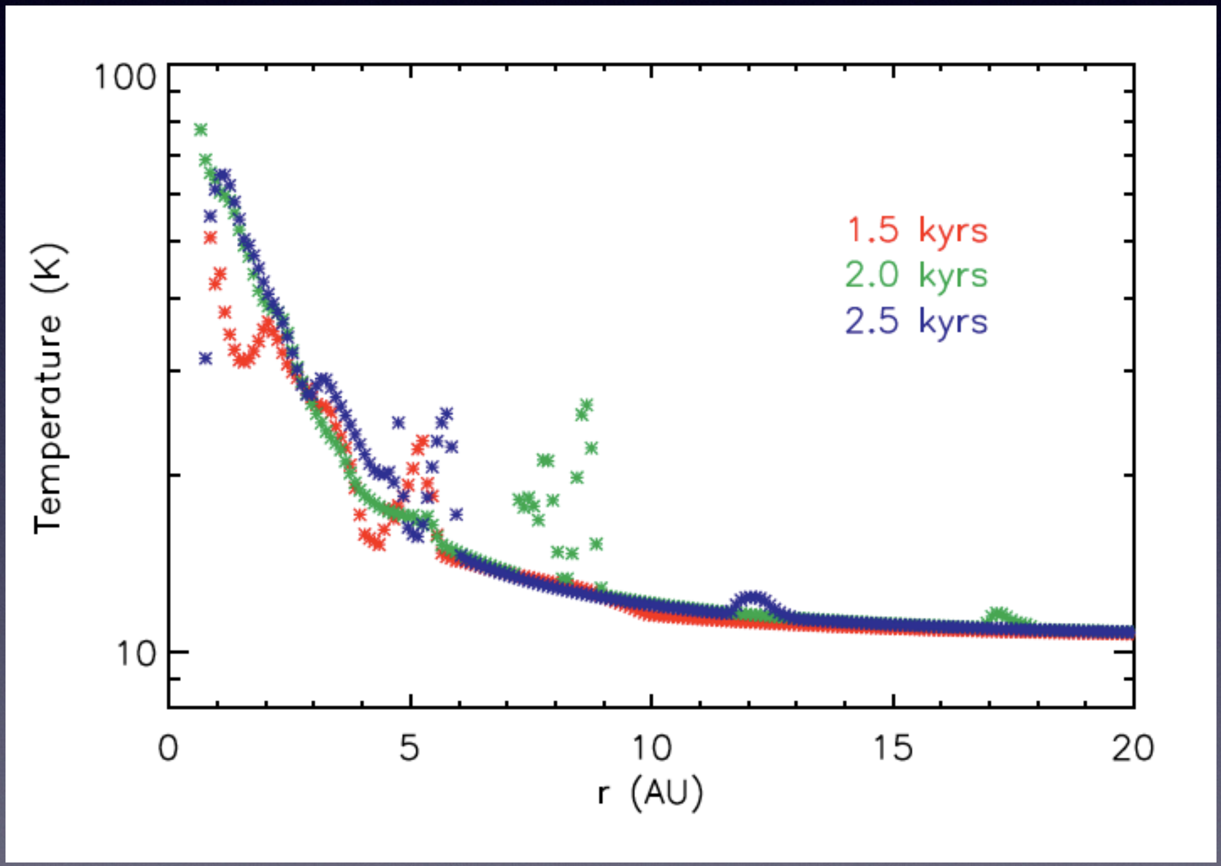
Toomre Q Instability Criterion

- Radial profiles of the azimuthally averaged Toomre Q instability crierion
- The disk is rapidly evolving away from an initially unstable state of Q~1
- $Q = C_s \varkappa / \pi G \Sigma$



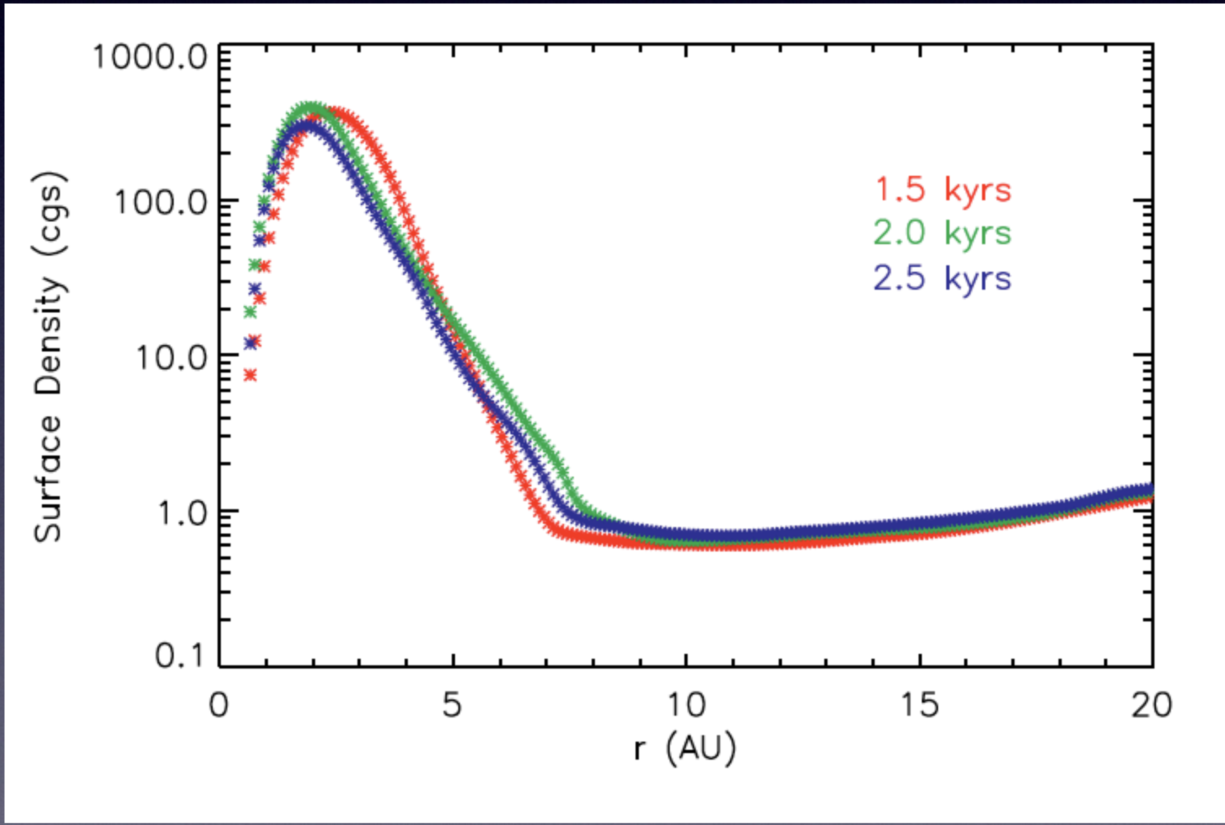
Midplane Temperature

- Radial Profiles of azimuthally averaged midplane temerature
- Shocks heating causes temperature variation throughout evolution
- Outburst events cause subdisk temperatures to rise at 2kyrs
- CO desorption into the gas phase -> Observable with ALMA!

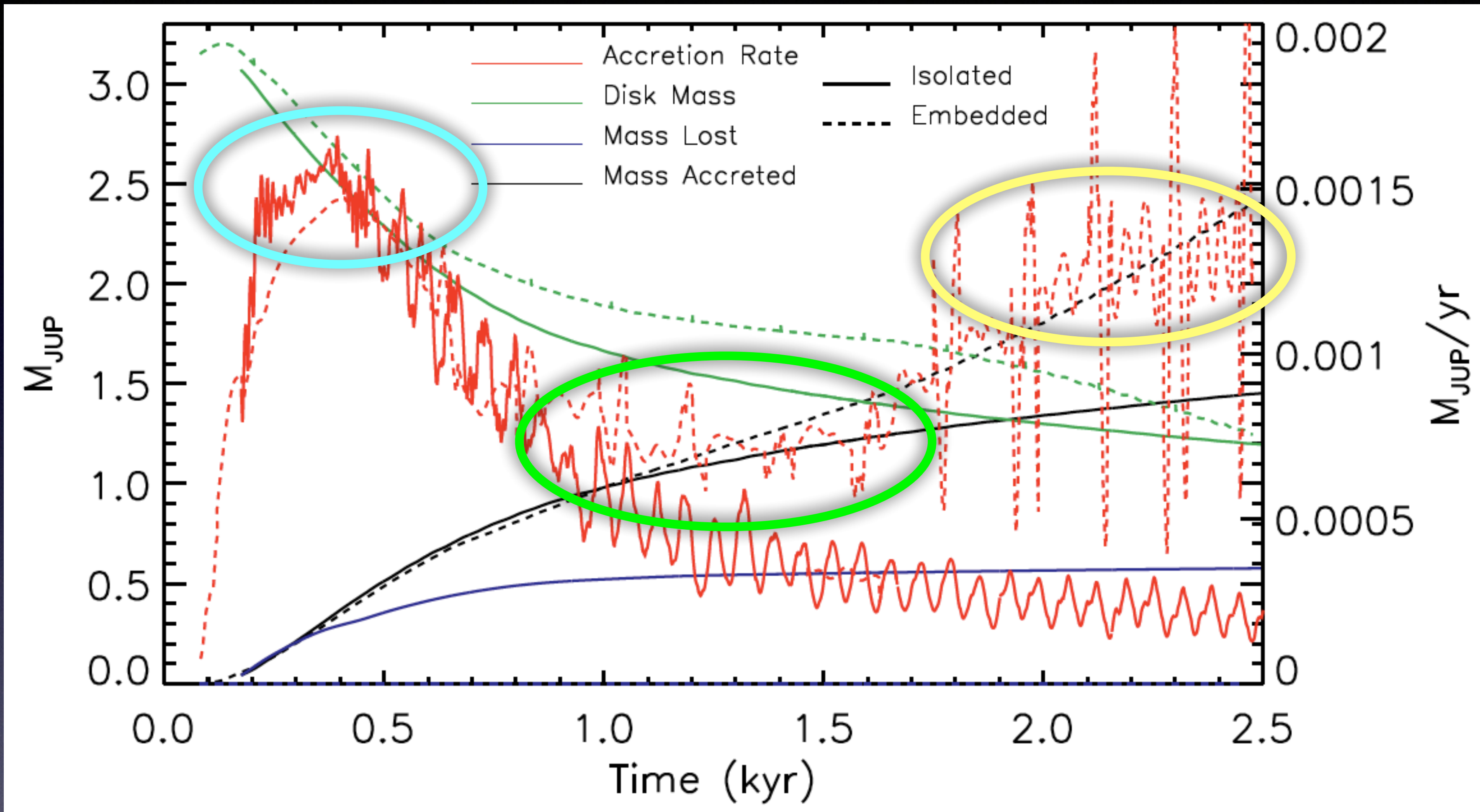


Surface Density

- Radial profiles of azimuthally averaged surface density
- Mass is transfered from the subdisk onto the planet and outside the stable region of the Hill sphere.
- The high-density region moves closer to the inner subdisk boundary -> subdisk mass is becoming depleted



Mass Evolution



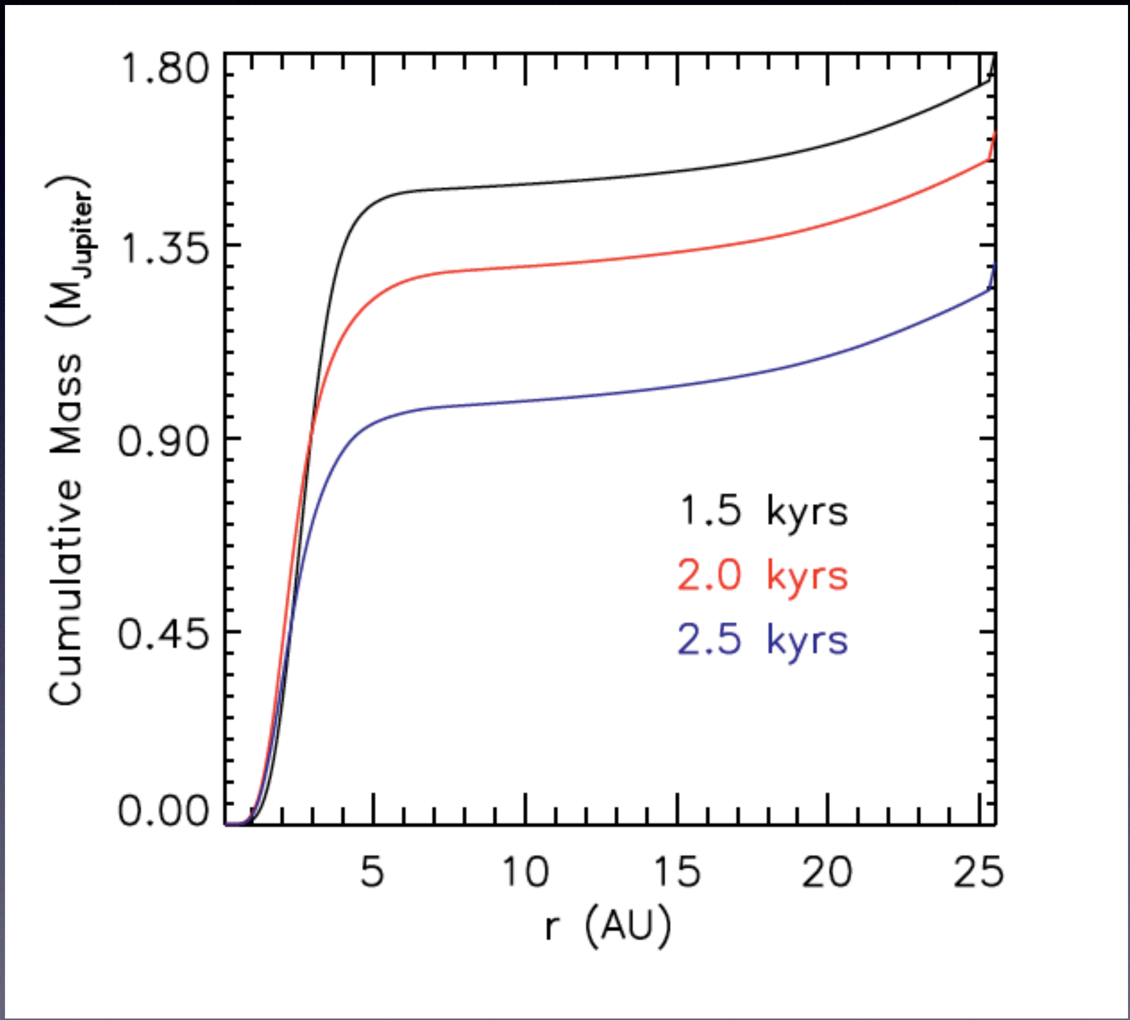
1 Strong torque reshapes disk initially. Disk evolves rapidly away from our guessed initial condition based on physics.

2 Accretion rate goes down due to 'self-limiting'. Tides and gravity effects allow it to evolve more slowly. Still fairly rapid on absolute time scales.

3 Set by mass flow onto the grid. Circumstellar disk is a huge driver for mass accretion rate.

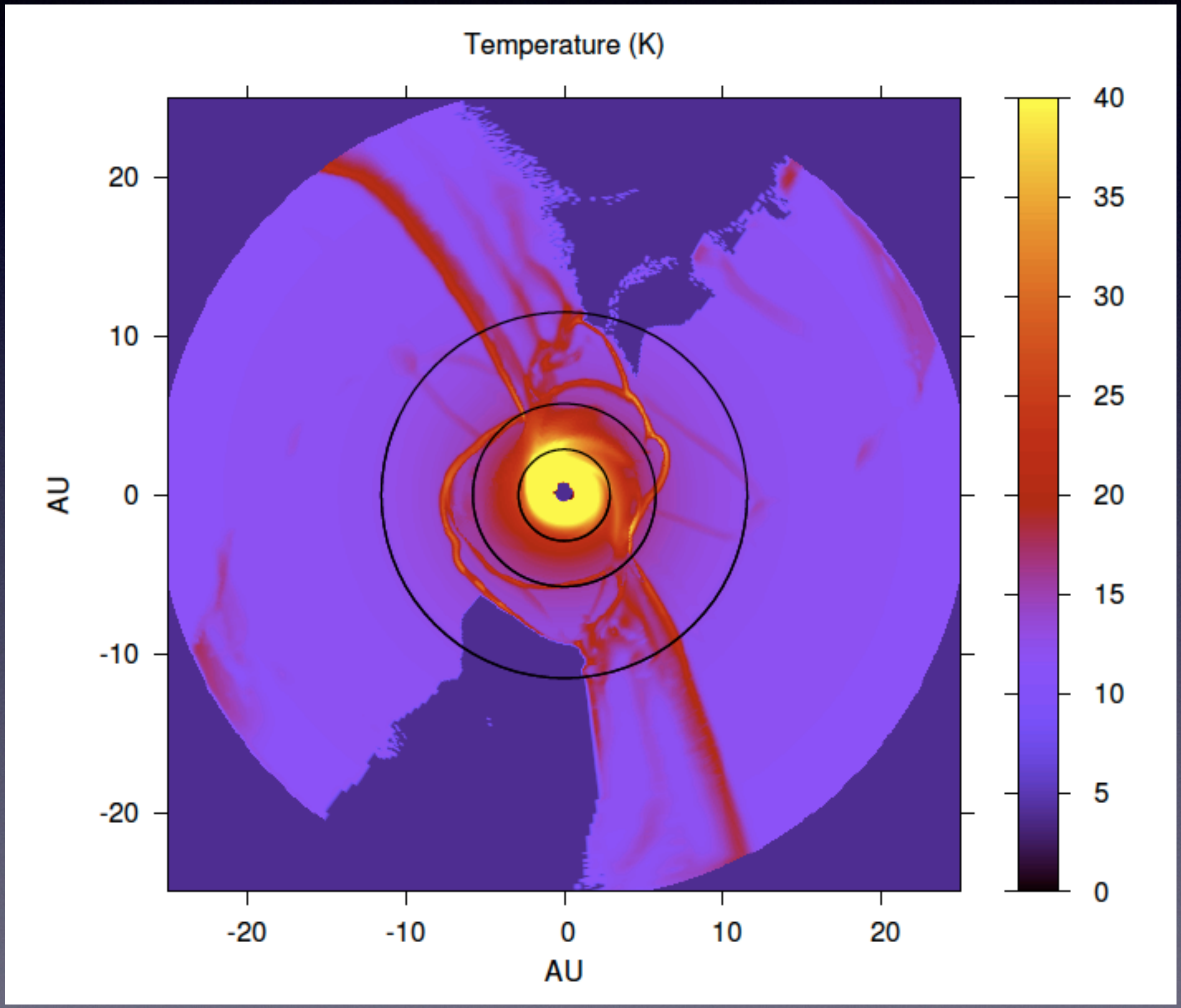
Cumulative Mass Radial Profiles

- As disk evolves, the largest fraction of the mass remains within 5 AU
- This is $\sim 2/5$ the hill sphere of the host planet



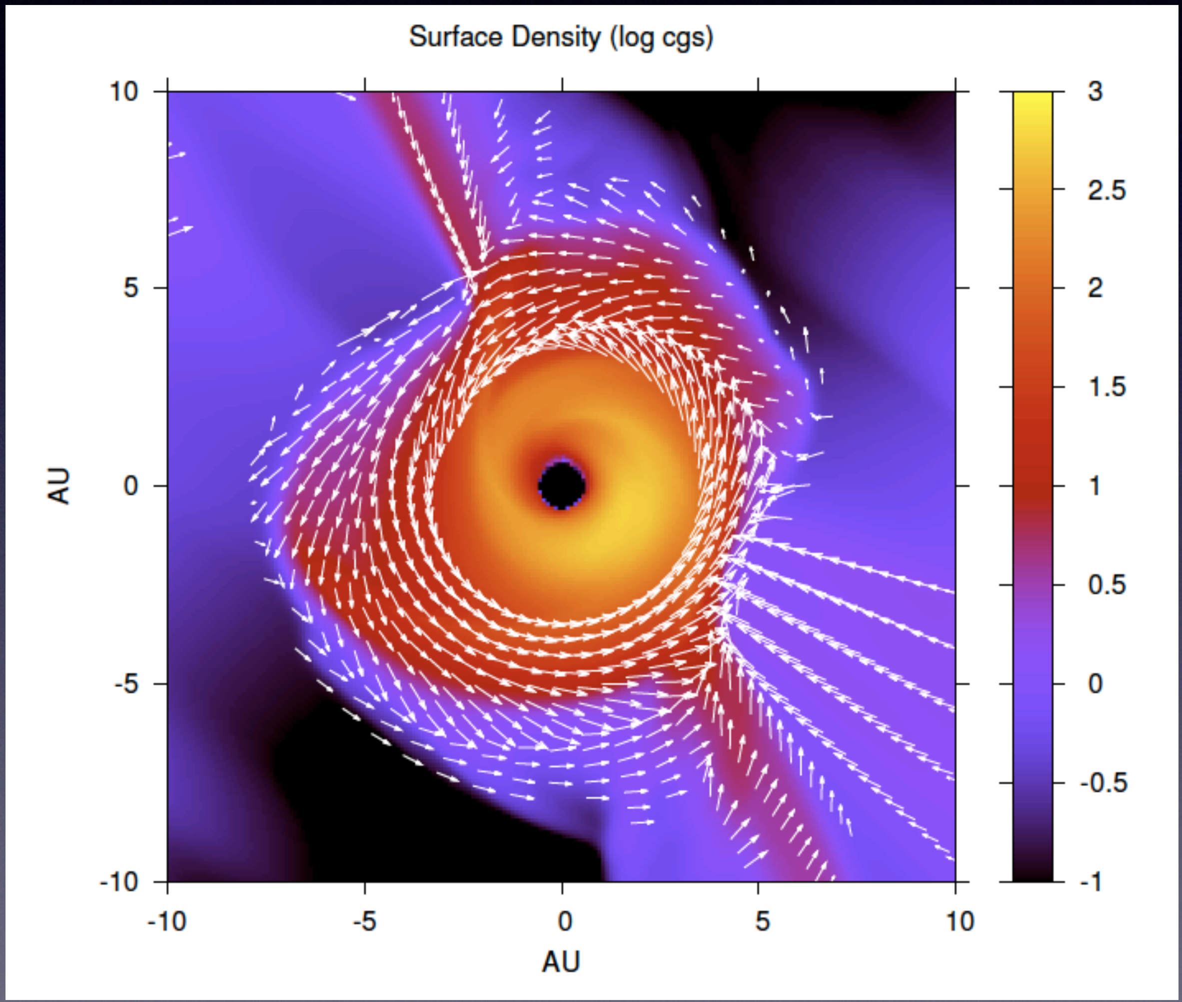
Midplane Temperature

- End state -> 2.5 kyrs
- Disk is truncated between $R_{Hill}/2$ and $R_{Hill}/3$
- Region of subdisk where material is flowing onto the grid produce high temperature that could lead to emission from gas phase molecules -> ALMA observables!



Surface Density

- End state -> 2.5 kyrs
- velocity vectors trace the flow of mass into the subdisk from the surrounding circumstellar material
- inside 5AU, velocity and density rapidly increase as the gravitational effects of the host planet begin to dominate



Conclusions

- Subdisks take 0.9 kyrs to evolve away from their initially massive state
- During this phase, ~ 1 Jupiter mass material is added to the embedded subdisk host planet, and 0.5 a Jupiter mass is added to the isolated disk simulation's host planet
- Shock heating phenomena cause temperatures to reach values high enough for CO disorption off of ice grains (~30K) -> Observable! -> gas phase CO molecules emit in ALMA band 6
- Disks are truncated between $R_{Hill}/2$ and $R_{Hill}/3$ -> Observable! -> large surface area favorable for ALMA. Eventually be able to detect and perhaps resolve structure

Future Work

- Estimate duration of luminous subdisk -> statistical analysis of how many objects we expect to find to get probability for actaully detecting them
- Measuring size of subdisk at its particular orbital distance can constrain migration history
- ALMA cycle 1 proposals to try to observe these systems -> indirectly detect planets in early stages of formation
- Further analysis and publication