# Viscous Evolution and Photoevaporation of Circumstellar Disks due to External FUV Radiation Fields

Kassandra Anderson

NSF Graduate Research Fellow
Cornell University

# Viscous Evolution and Photoevaporation of Circumstellar Disks due to External FUV Radiation Fields

Kassandra Anderson

NSF Graduate Research Fellow
Cornell University

In collaboration with Fred Adams & Nuria Calvet

(Anderson, Adams, & Calvet 2013, ApJ)

UNIVERSITY OF MICHIGAN

# Effects of the Cluster Environment on Protoplanetary Disks

- Truncation/disruption due to dynamical interactions
- **Photoevaporation due to FUV/EUV/X-ray radiation fields (from OB stars)**

Most stars are born in groups, rather than in isolation (Lada & Lada 2003), so external effects can be important

# Effects of the Cluster Environment on Protoplanetary Disks

- Truncation/disruption due to dynamical interactions
- **Photoevaporation due to FUV/EUV/X-ray radiation fields (from OB stars)**

Most stars are born in groups, rather than in isolation (Lada & Lada 2003), so external effects can be important

How does this affect disk dispersal?

Is planet formation compromised?

# Outline

- Develop photoevaporation + viscous evolution model due to external FUV fields
- Combine with existing internal photoevaporation model (Owen et al. 2010, 2011, 2012)
- Compare model predictions with observed proplyd masses/radii in the Orion Nebula Cluster (ONC)

External fields = fields from nearby stars
Internal fields = fields from the host star

# Review of disk structure & evolution

- Time evolution for the surface density $\Sigma$ obeys the diffusion equation

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

Specify the disk viscosity ( $\nu$ ) by a dimensionless parameter $\alpha$ (Shakura & Sunyaev 1973)

$$\nu = \alpha \frac{a_s^2}{\Omega}$$

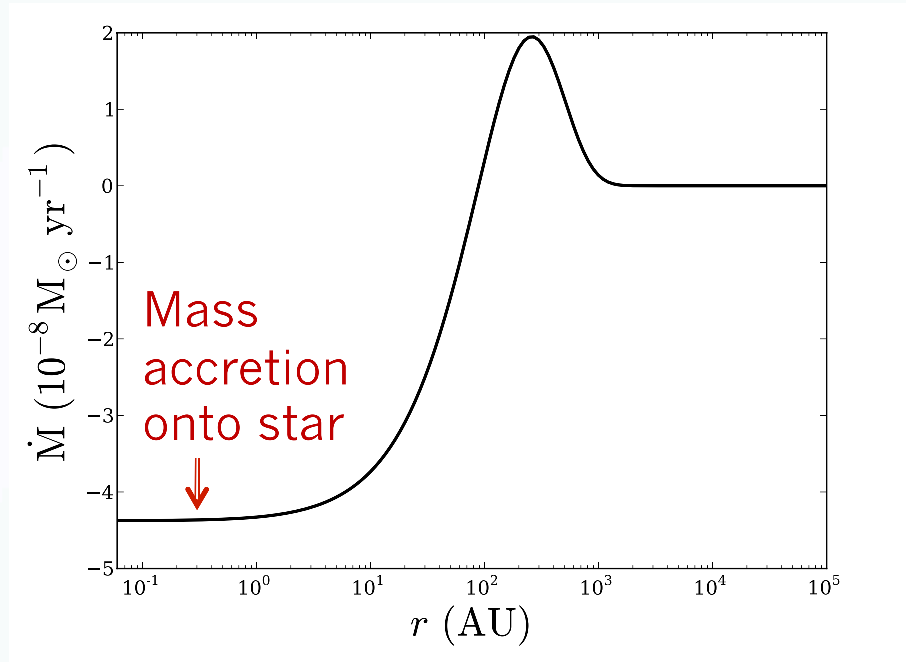
# Viscous disk evolution

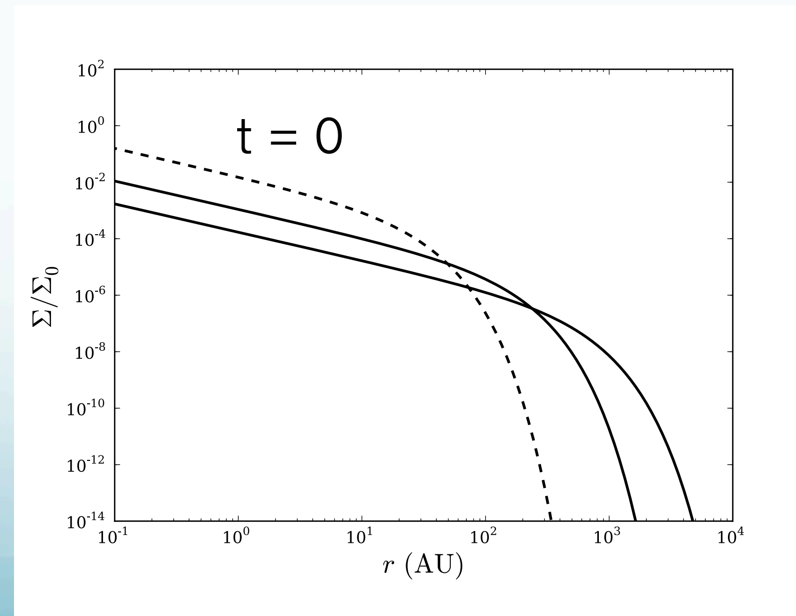
- Mass is transported inward through the disk and accreted onto the host star

- Surface density decreases and disk spreads with time

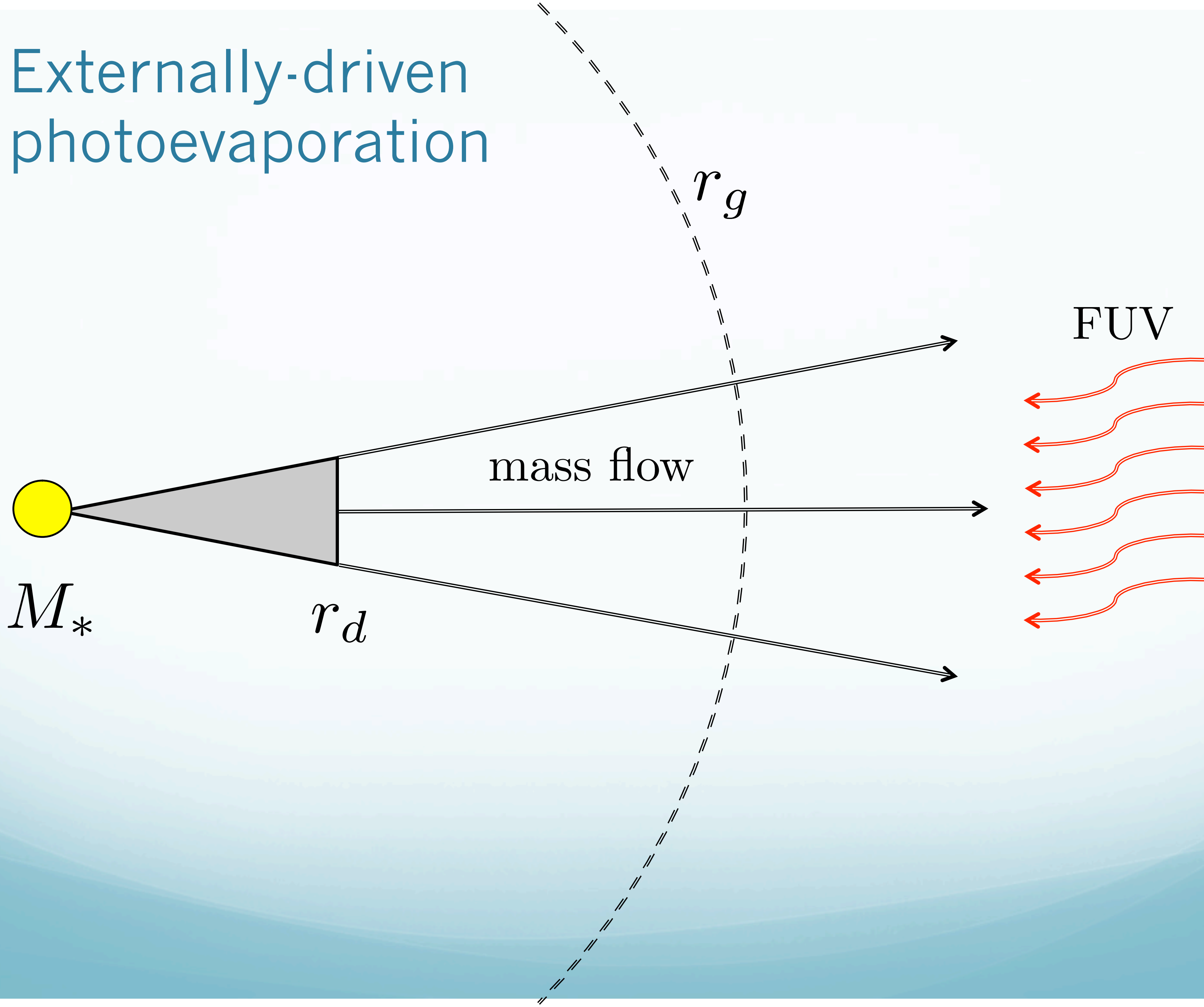
- Disk disperses, but on much longer timescales than observed disk lifetimes of ~ a few Myr

Need additional sources of mass loss

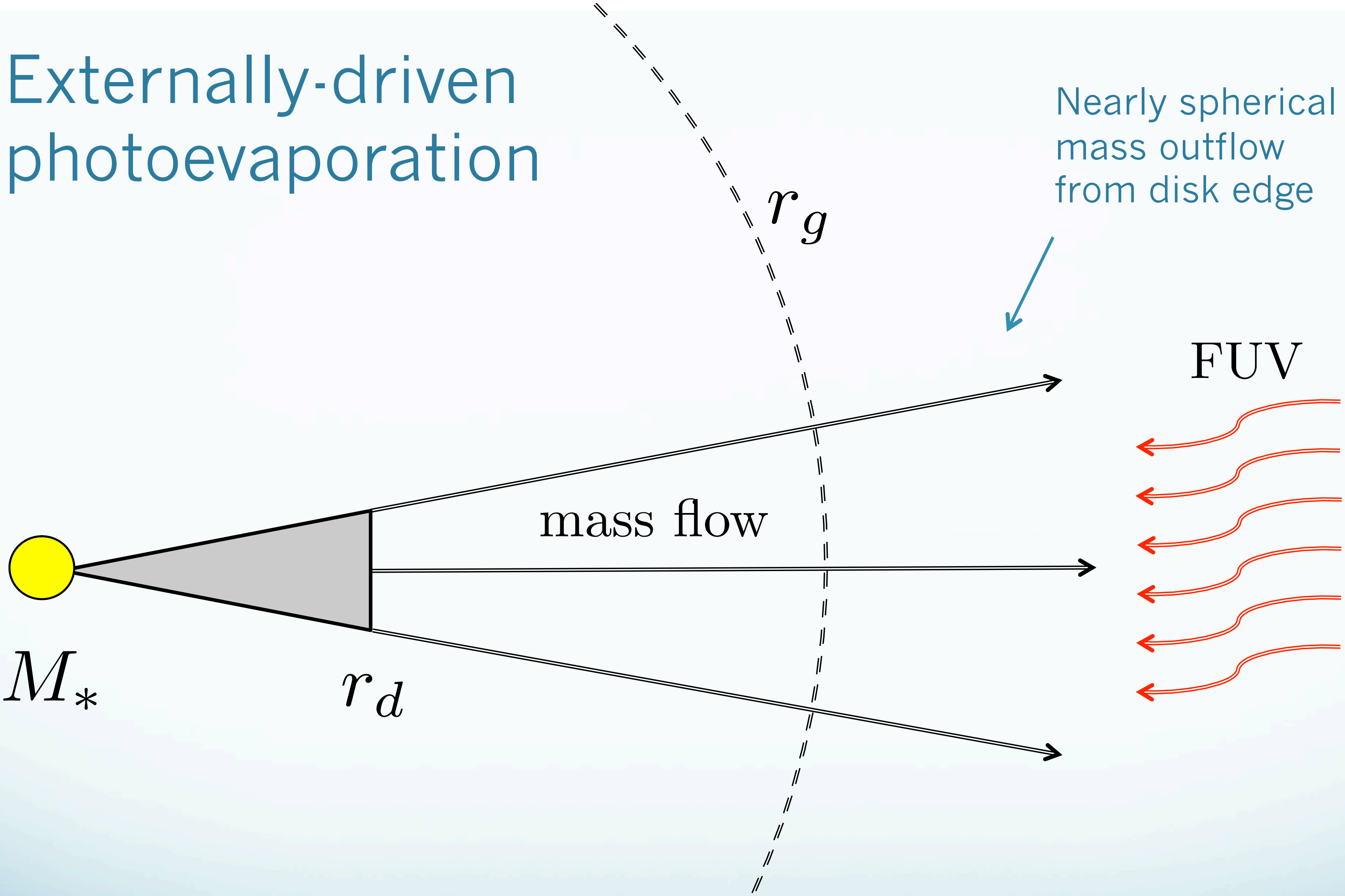


# Externally-driven photoevaporation



# Externally-driven photoevaporation




$$r_g = \frac{GM_*}{a_s^2} \approx 100\ \mathrm{AU} \left(\frac{\mathrm{M}_*}{1\ \mathrm{M}_\odot}\right)\left(\frac{\mathrm{T}}{1000\ \mathrm{K}}\right)^{-1}$$

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

Sink term due to evaporation

Analytic approx for total mass loss rate (Adams et al. 2004)

$$\dot{M}(r) = A r_g^{3/2} r^{1/2} e^{-r_g/2r}$$

$$\dot{\Sigma} = \frac{A}{4\pi}\left(\frac{r_g}{r}\right)^{3/2}\left[1 + \frac{r_g}{r}\right] e^{-r_g/2r}$$

Specify dimensionless external FUV field flux $G_0$

$G_0$ → temperature → evaporation radius $r_g$

# Externally-driven photoevaporation

- Specify dimensionless external FUV field flux $G_0$
- Calculate gas temperature as a function of number density and visual extinction (distance from FUV source)
- temperature → $r_g$ → total mass loss rate

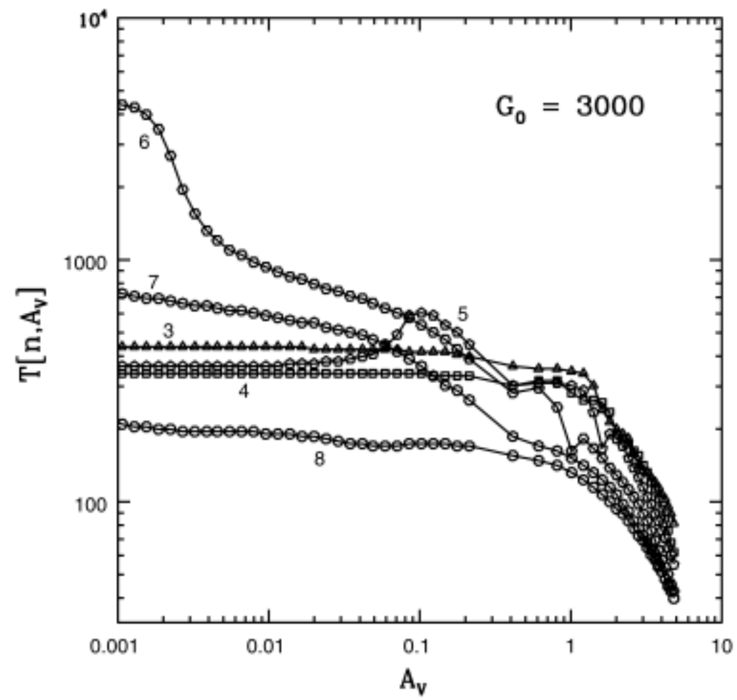



Fig. 2b

Adams et al. 2004

# Summary of externally-driven photoevaporation

- Incident radiation heats the gas near the disk edge, causes mass to flow outward
- Gas flows outward from disk edge where gravitational potential of the host star is shallow, eventually crosses $r_g \sim$ 100 AU and can escape
- Disk is eroded from the outside in

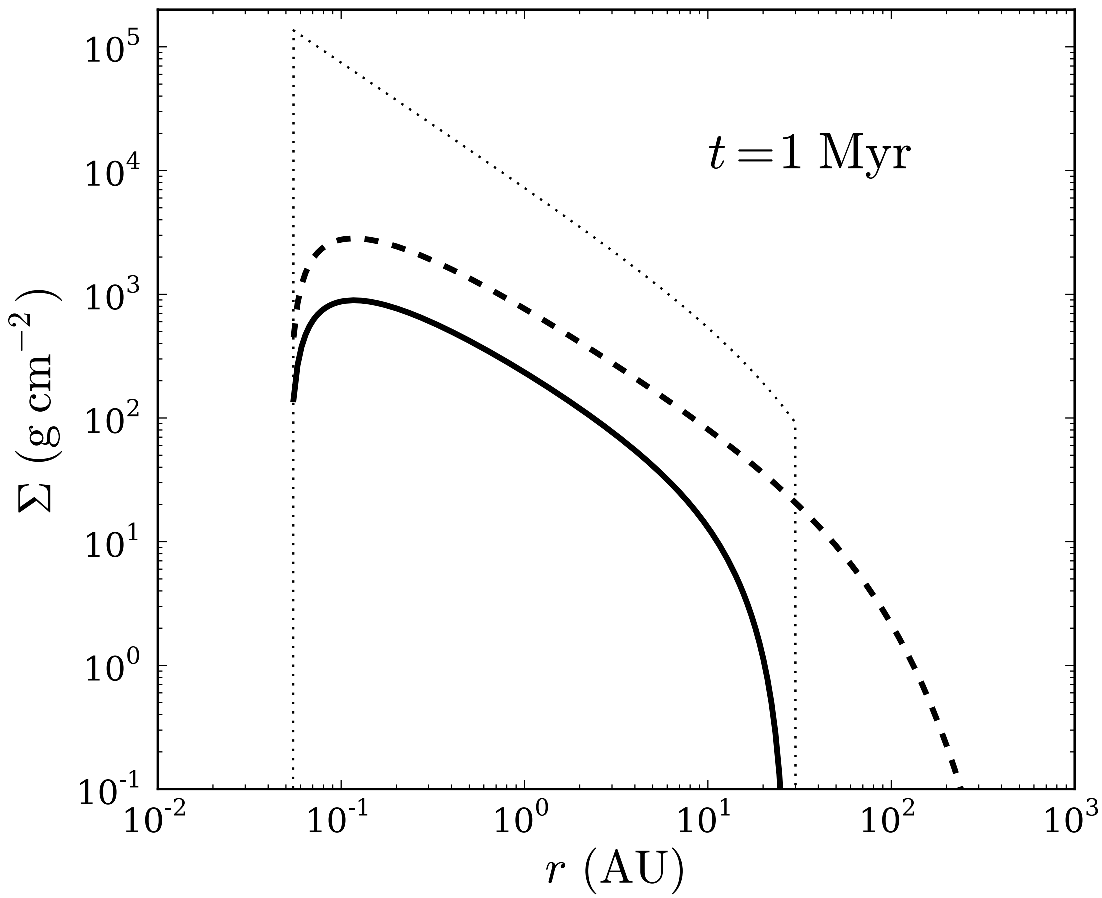
# Parameter Space

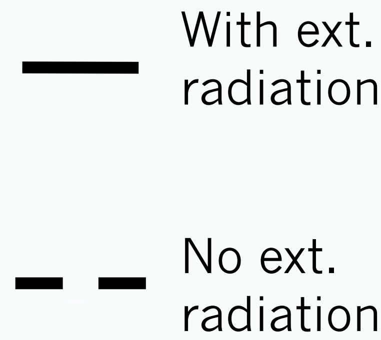
Explore different viscosities ( $\alpha$ ) and FUV flux ($G_0$) to constrain disk masses, evaporation rates, and radii

$G_0$ ~ 300 – 30,000 (local interstellar value $G_0$ ~ 1)

$\alpha$ = $10^{-2}$, $10^{-3}$, $10^{-4}$

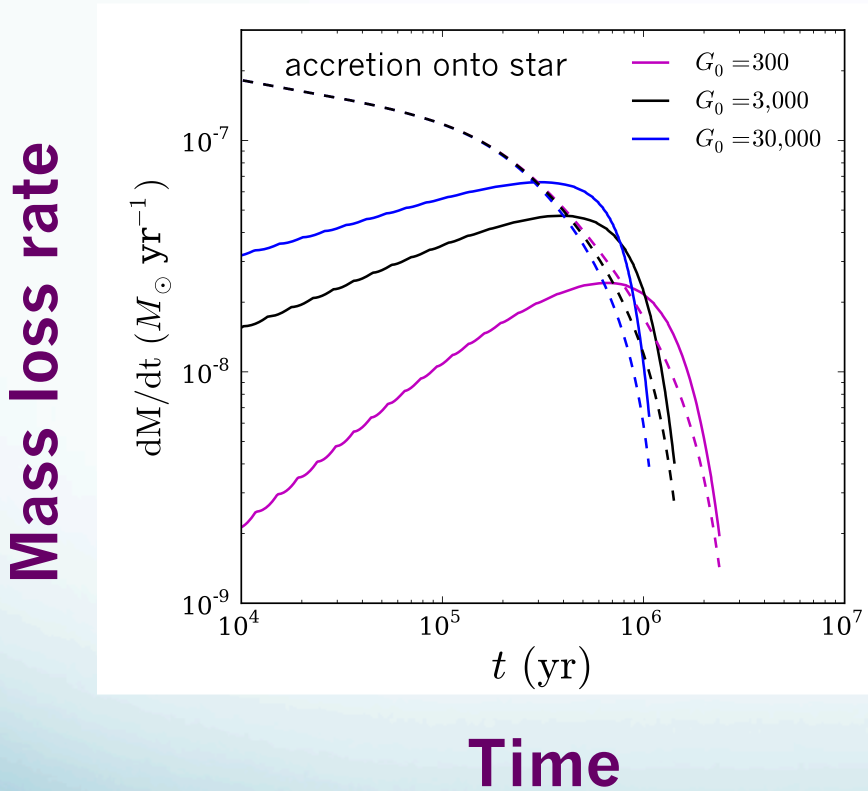
# Disk Evolution

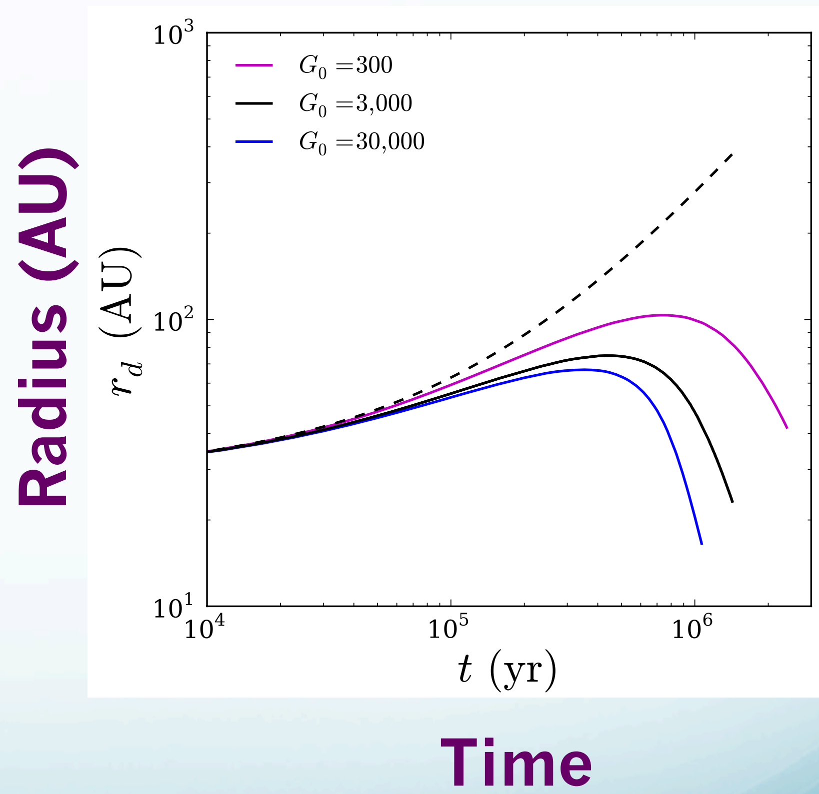


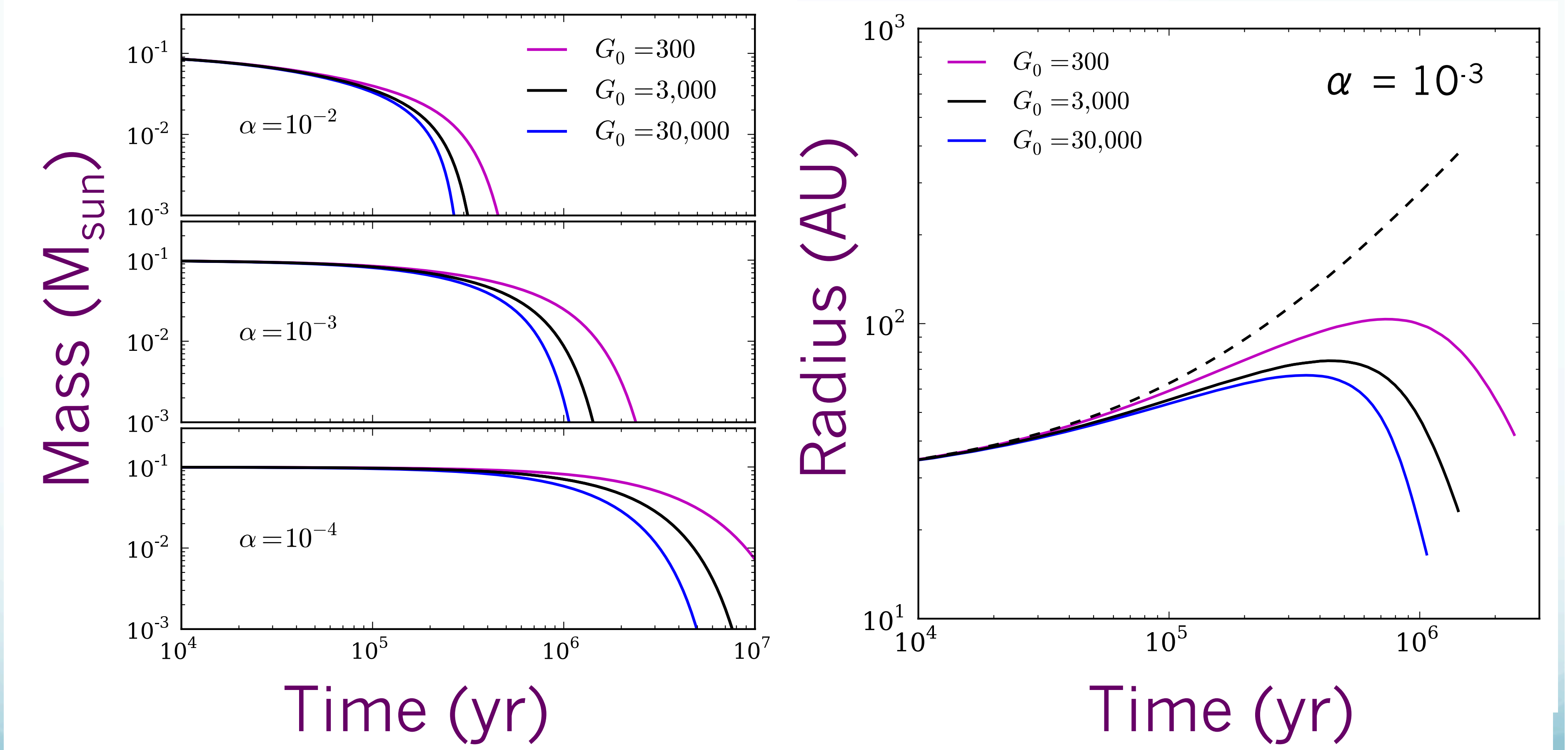

Disk is truncated and mass depleted

# Disk Evolution

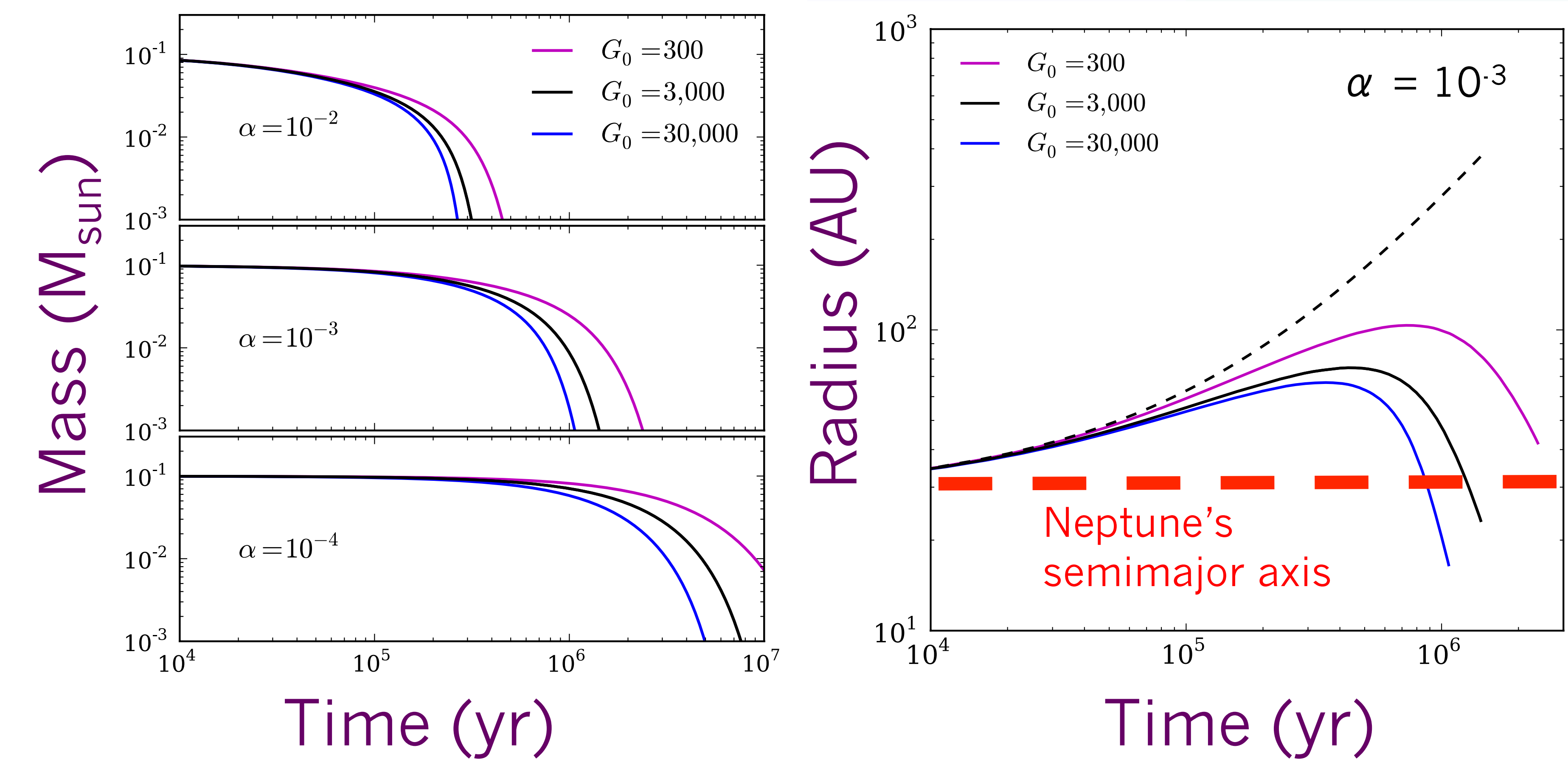


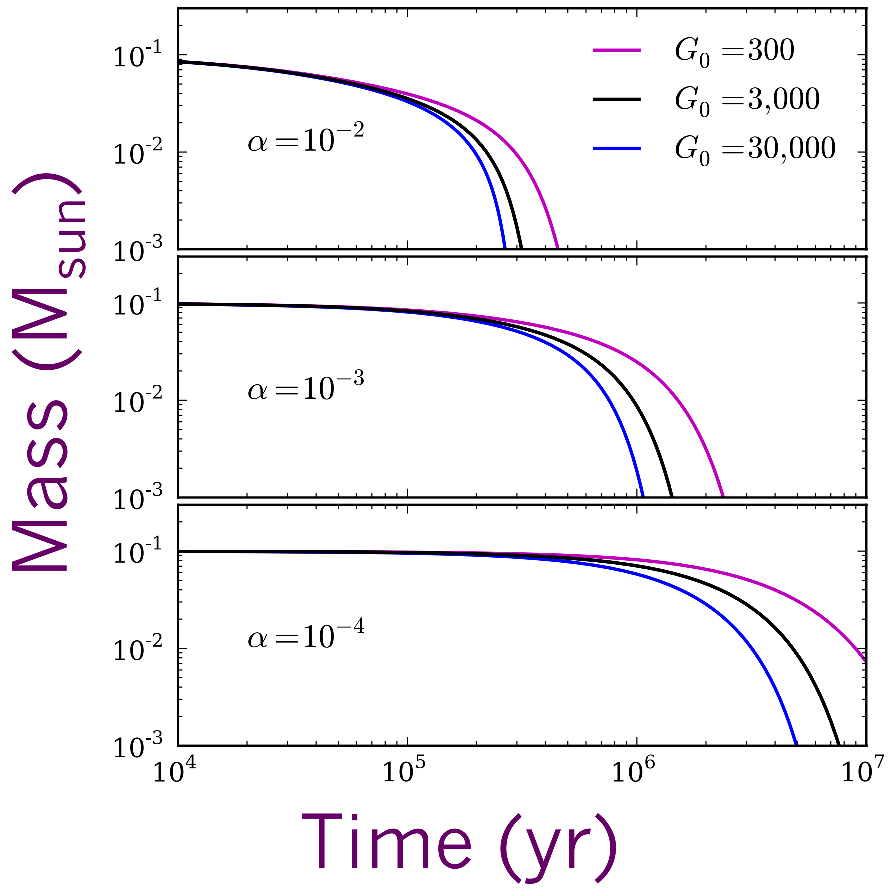
# Disk Evolution

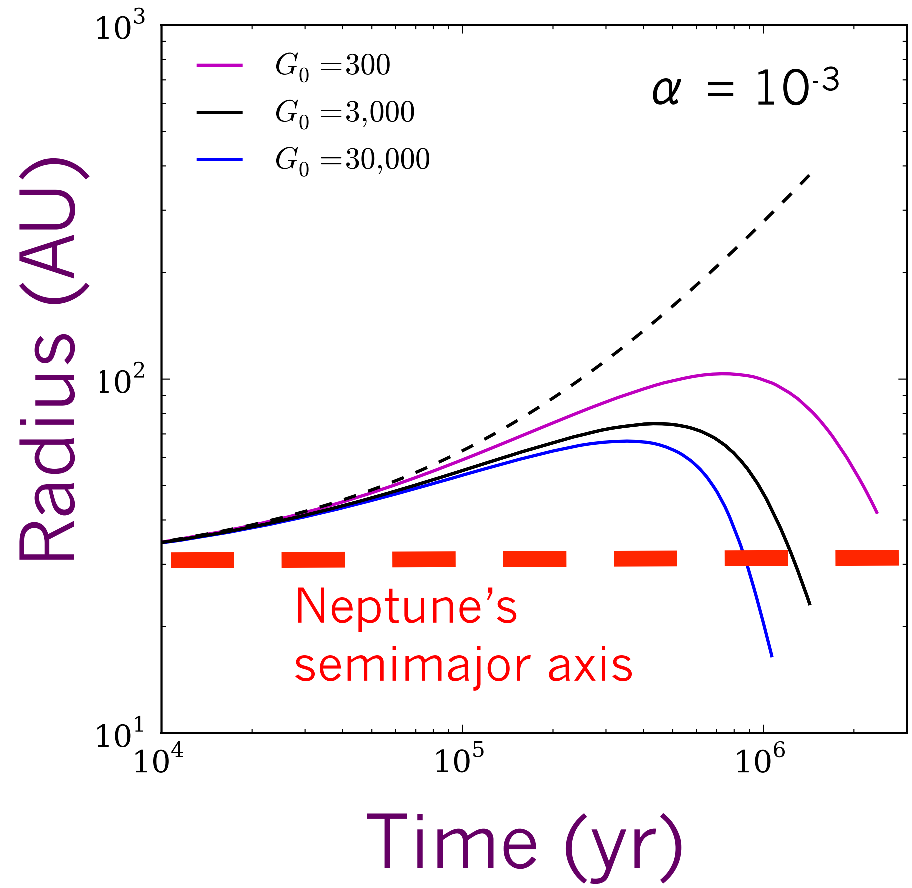


# Disk Evolution



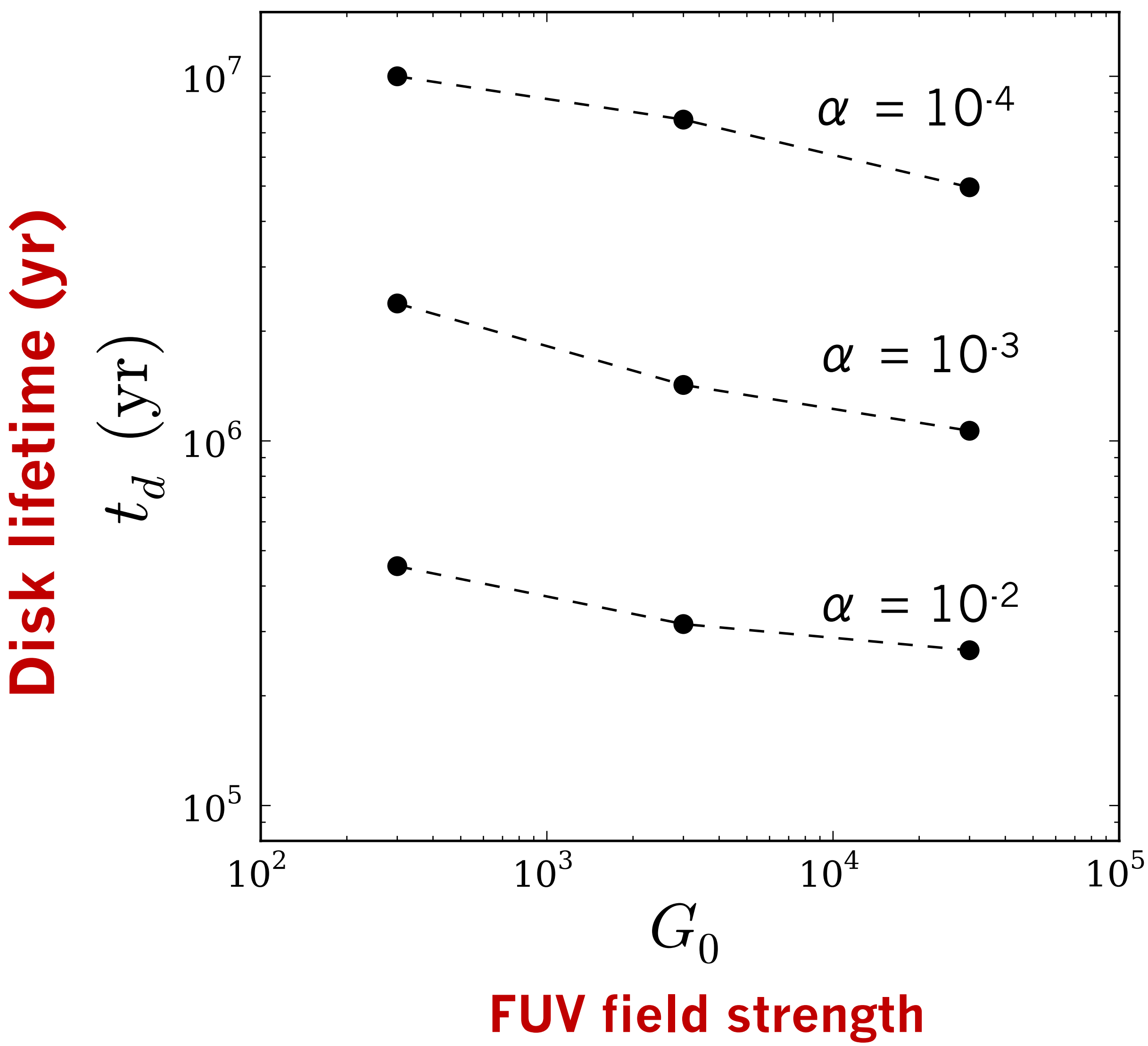
# Disk Evolution




**External FUV fields can efficiently deplete disk masses and truncate the radii, especially disks with high viscosity**

# Disk Lifetimes



# What about photoevaporation from the host star?

Host star generates FUV/EUV/X-rays –
We focus on evaporation due to X-rays

# Internal X-Ray vs External FUV fields

**Qualitatively different!**

Which radiation field wins?

# Internal X-Ray vs External FUV fields

Qualitatively different!

| External FUV | Internal X-rays |
| --- | --- |
| • **Outer** edge affected | • **Inner** edge affected |

Which radiation field wins?

# Internal X-Ray vs External FUV fields

**Qualitatively different!**

| External FUV | Internal X-rays |
| --- | --- |
| • **Outer** edge affected<br>• $r_g \sim$ **100** AU (lower temps) | • **Inner** edge affected<br>• $r_g \sim$ **10** AU (higher temps) |

**Which radiation field wins?**

# Internal X-Ray vs External FUV fields

**Qualitatively different!**

## External FUV

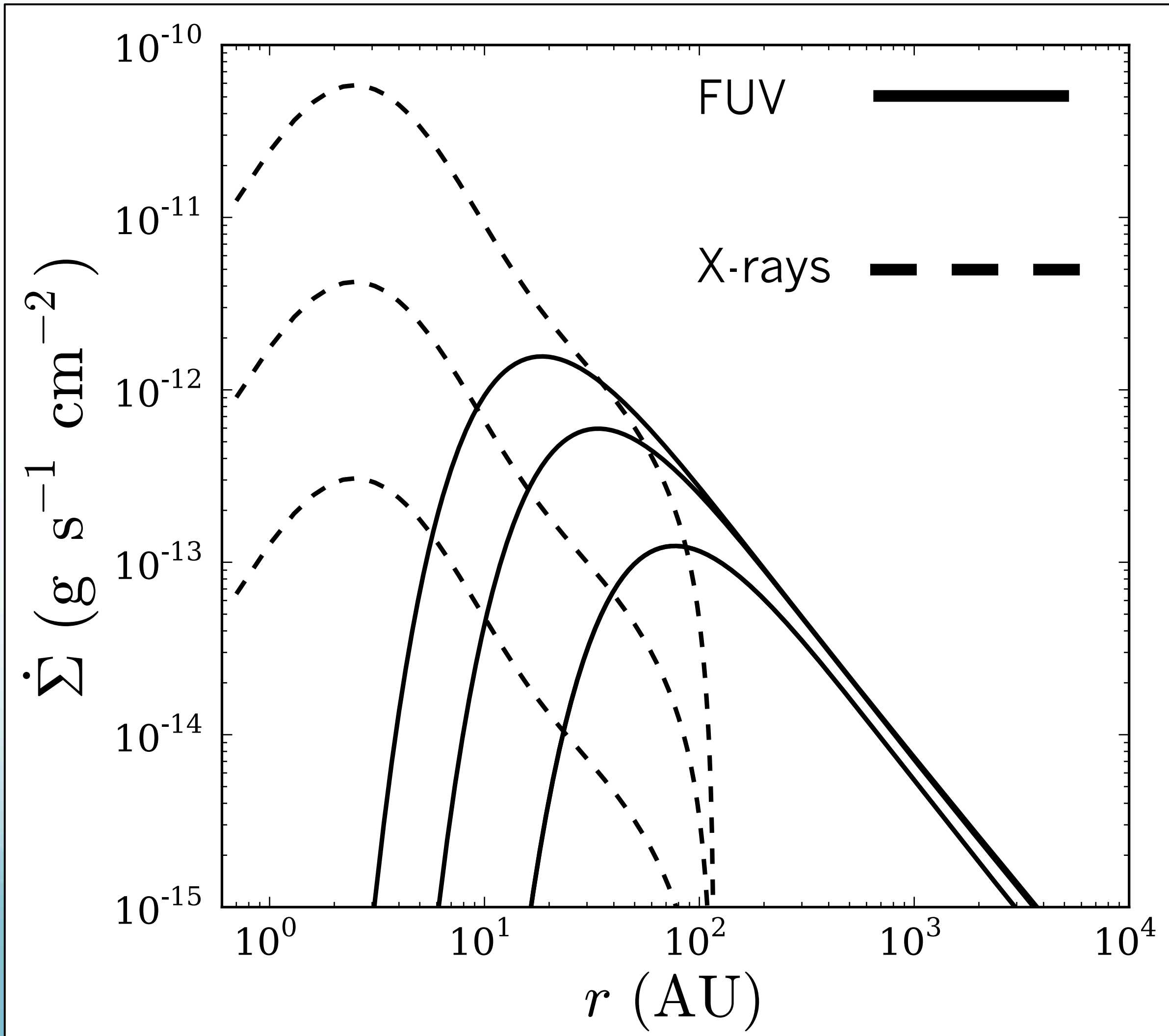
- **Outer** edge affected
- $r_g$ ~ **100** AU (lower temps)
- Disk is eroded from the **outside in**

## Internal X-rays

- **Inner** edge affected
- $r_g$ ~ **10** AU (higher temps)
- Disk is eroded from the **inside out**

**Which radiation field wins?**

# Internal X-Ray Evaporation



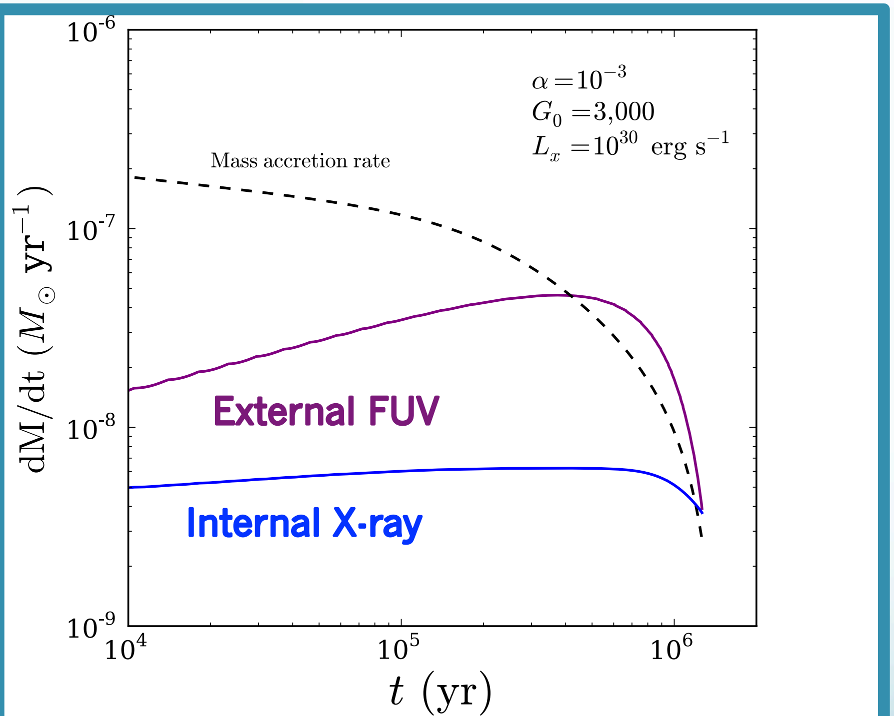

Specify mass loss rate from X-ray luminosity

($L_X \sim 10^{28} - 10^{31}$ erg/s)

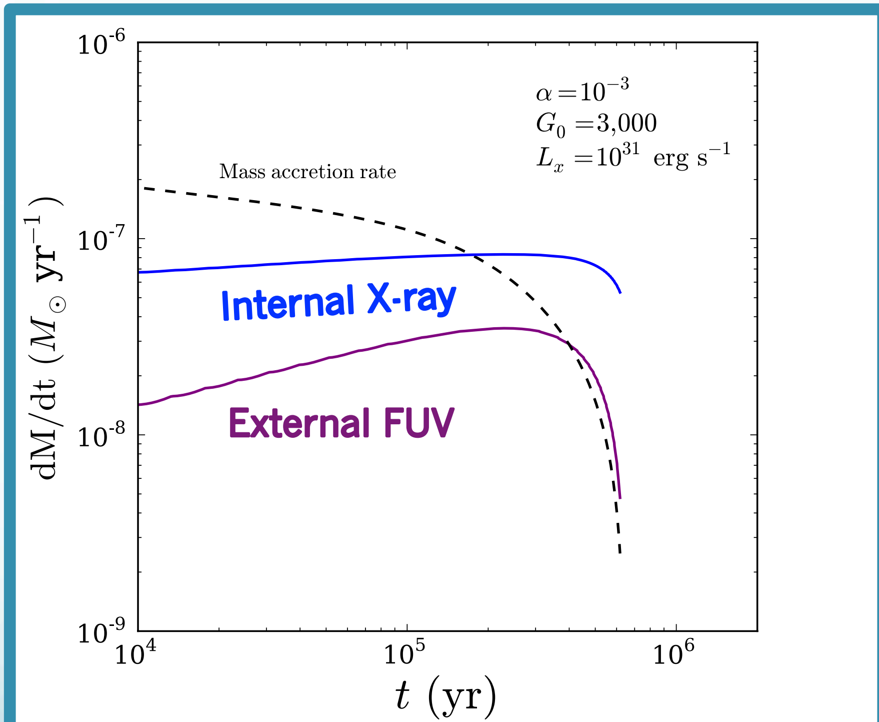
**X-ray evap. model from Owen et al. 2011, 2012**

# Internal X-rays + External FUV

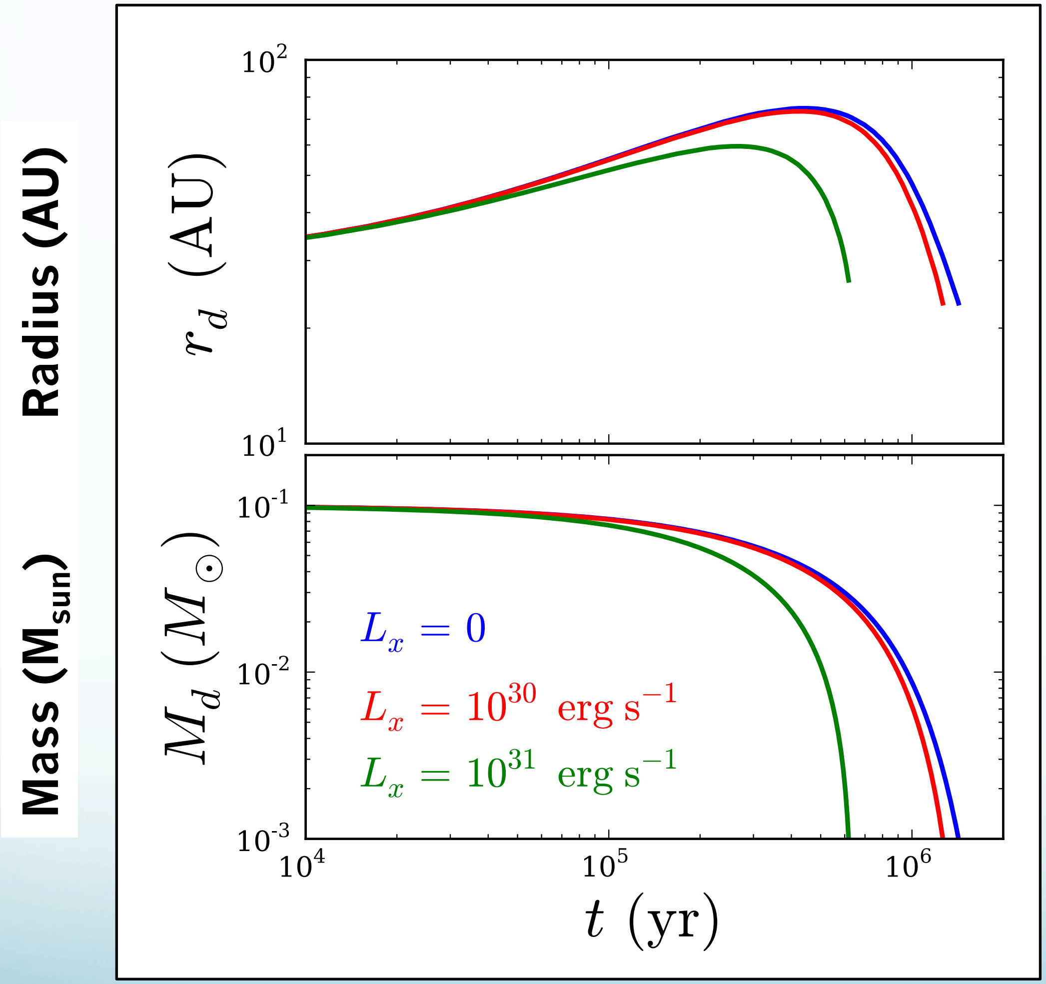
$L_X \sim 10^{30}$ erg/s




$L_X \sim 10^{31}$ erg/s



# Internal X-rays + External FUV




Only highest stellar luminosities ($L_X \sim 10^{31}$ erg/s) can compete with external fields

**External field often wins**

# Application: Proplyds in the Orion Nebula Cluster

NASA/ESA & L. Ricci (ESO)

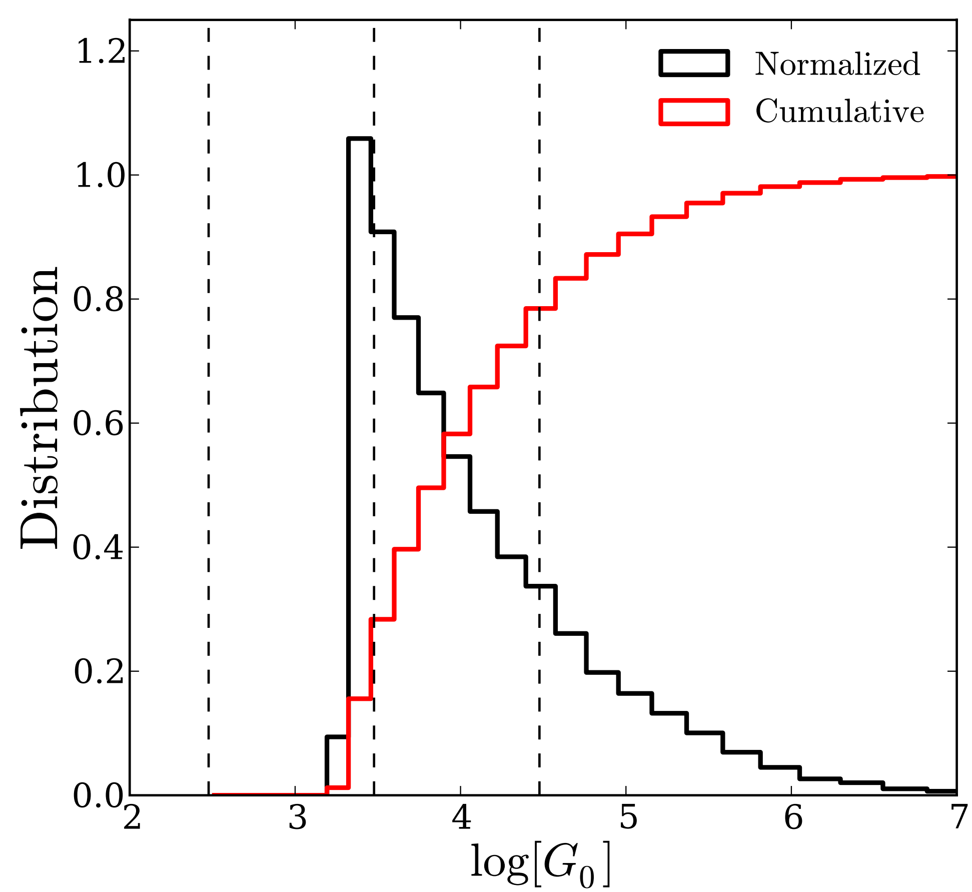
# Application: Proplyds in the Orion Nebula Cluster

NASA/ESA & L. Ricci (ESO)

### Cluster Properties

- ~ 1 – 2 Myr old
- $\theta^1$ Ori C, a 40 $M_{sun}$ O star at center
- Cluster radius ~ 2.5 pc
- 28 proplyds with measured mass + radius, 25 additional systems with mass upper limits

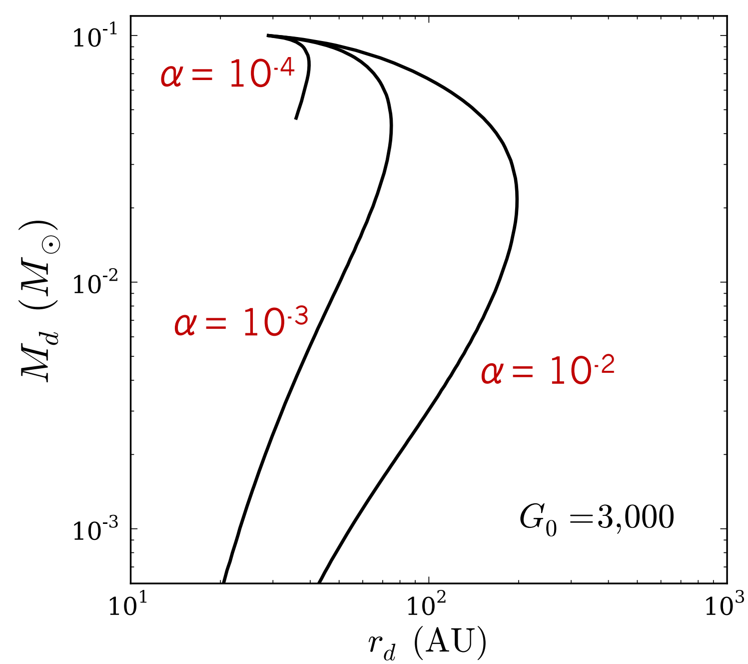
# Estimated flux distribution of observed Proplyds




Expected fluxes $G_0 > 1000$

# Evolutionary Tracks/Isochrones

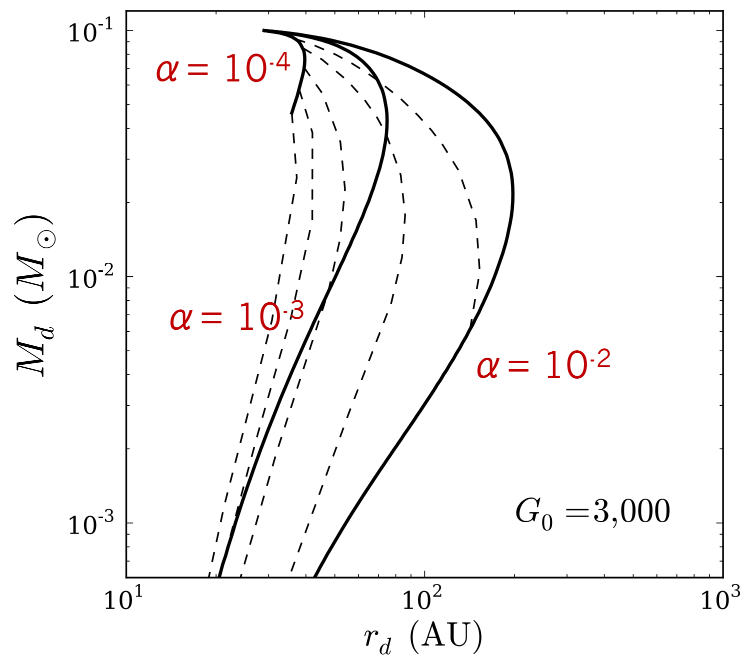
Start with ($M_d$, $r_d$) = (0.1 $M_{sun}$, 30 AU)




**Evolutionary tracks (solid curves)**
($\alpha = 10^{-4}$, $\alpha = 10^{-3}$, $\alpha = 10^{-2}$)

# Evolutionary Tracks/Isochrones

Start with ($M_d$, $r_d$) = (0.1 $M_{sun}$, 30 AU)

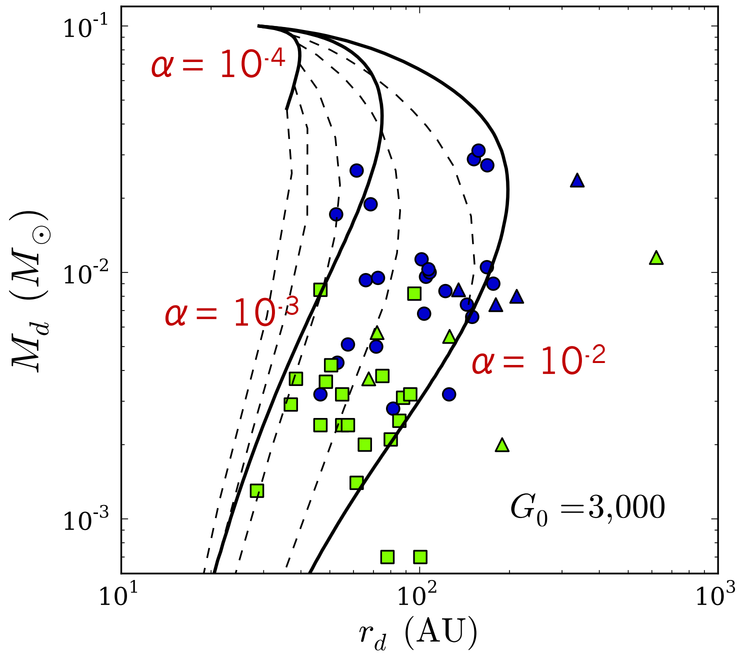



**Evolutionary tracks (solid curves)**
($\alpha = 10^{-4}$, $\alpha = 10^{-3}$, $\alpha = 10^{-2}$)

**Isochrones (dashed curves)**
(t = 0.25, 0.5, 1.0, 1.5, 2.0 Myr)

# Evolutionary Tracks/Isochrones

Start with ($M_d$, $r_d$) = (0.1 $M_{sun}$, 30 AU)

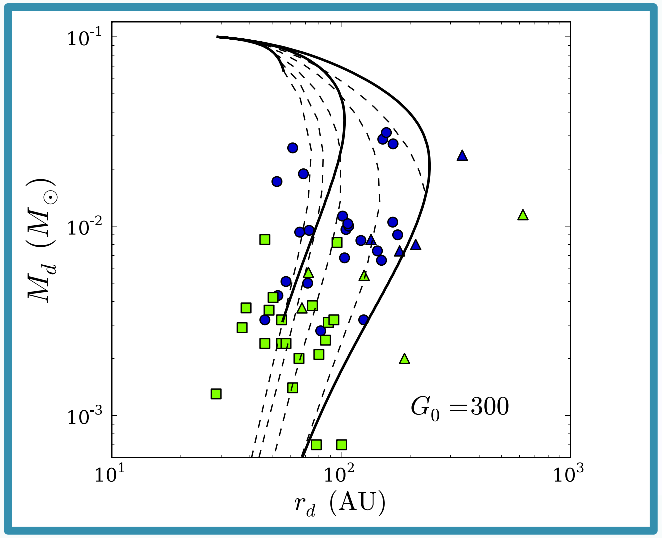


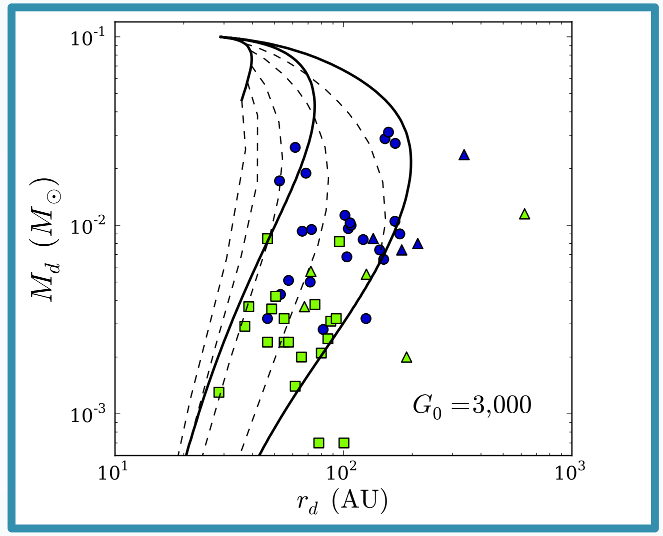

**Evolutionary tracks (solid curves)**
($\alpha = 10^{-4}$, $\alpha = 10^{-3}$, $\alpha = 10^{-2}$)

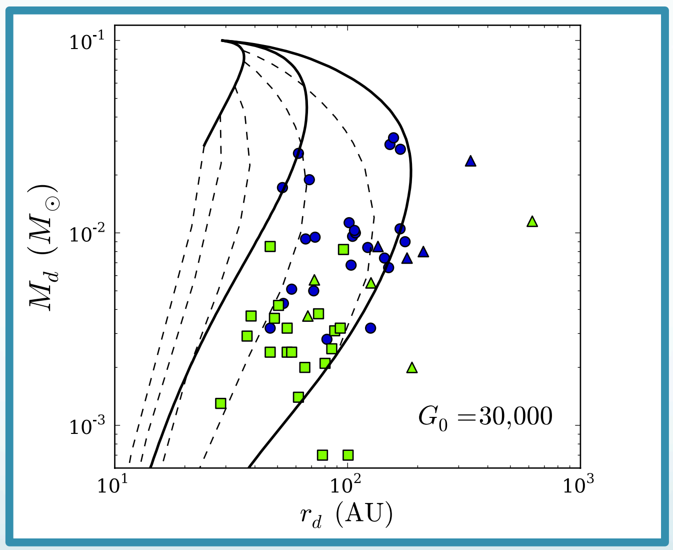
**Isochrones (dashed curves)**
(t = 0.25, 0.5, 1.0, 1.5, 2.0 Myr)

ONC proplyd data from Mann & Williams 2010, Vicente & Alves 2005

**Blue: measured masses**
**Green: mass upper limits**




Most objects well-characterized by $G_0$ = 3,000 – 30,000, $\alpha = 10^{-2}$ - $10^{-3}$, t < 2Myr

# Summary of results

- Viscosity ($\alpha$) most important parameter in governing disk dispersal by external photoevaporation
- X-rays from host star often less important than FUV radiation from external stars
- Useful to analyze disk evolution by looking at ($M_{disk,}$ $R_{disk}$) plane
- Proplyds in the ONC are consistent with evaporation by external field strengths $G_0 \sim 3{,}000 - 30{,}000$ and $\alpha \sim 10^{-2} - 10^{-3}$
- External fields could prohibit planet formation due to short disk lifetimes, and truncated disks