Planetary Formation Near Bright Stars: A Hazardous Process?

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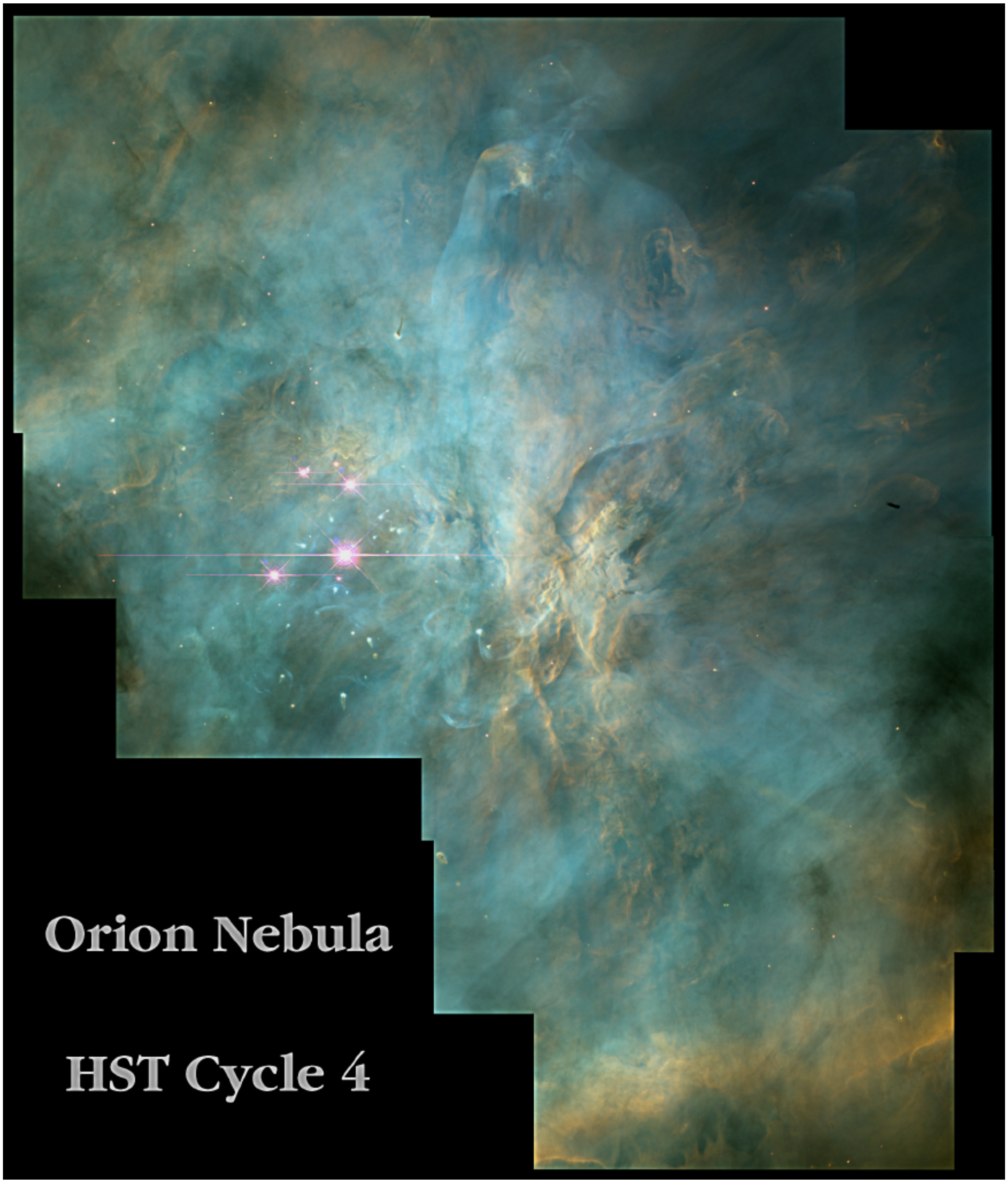
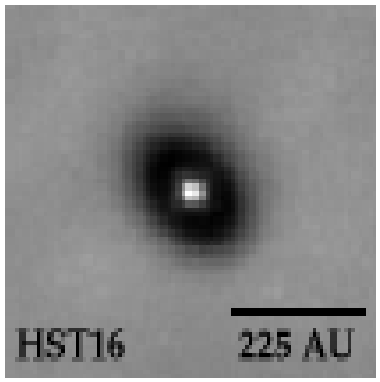
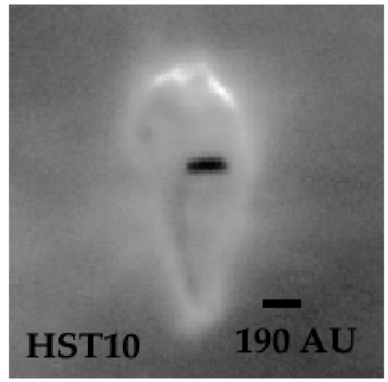
Outline

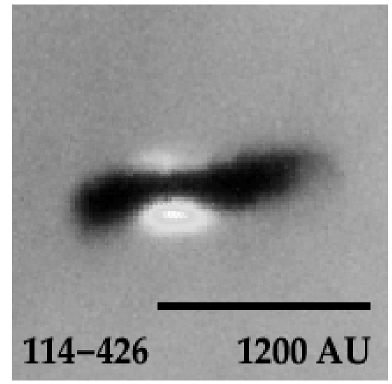
- Where Do Most Stars Form?
- Observations of Young Disks; Evidence for Grain Growth
  - HST
  - OVRO
- Evolutionary Modeling of Young Disks
  - Physical Processes in Externally-Illuminated Environments
- Conclusions & Predictions

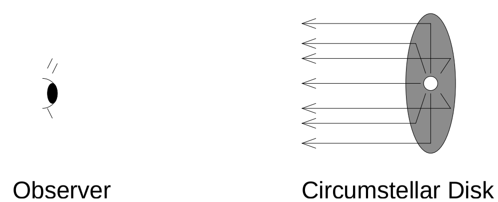

Orion Nebula
HST Cycle 4

Observations

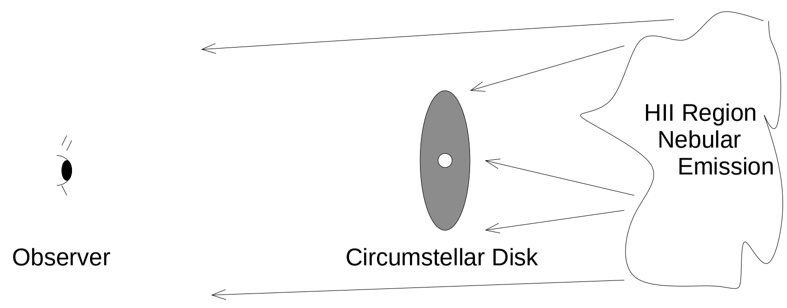








Reflected light
(Taurus, β Pic, rings)

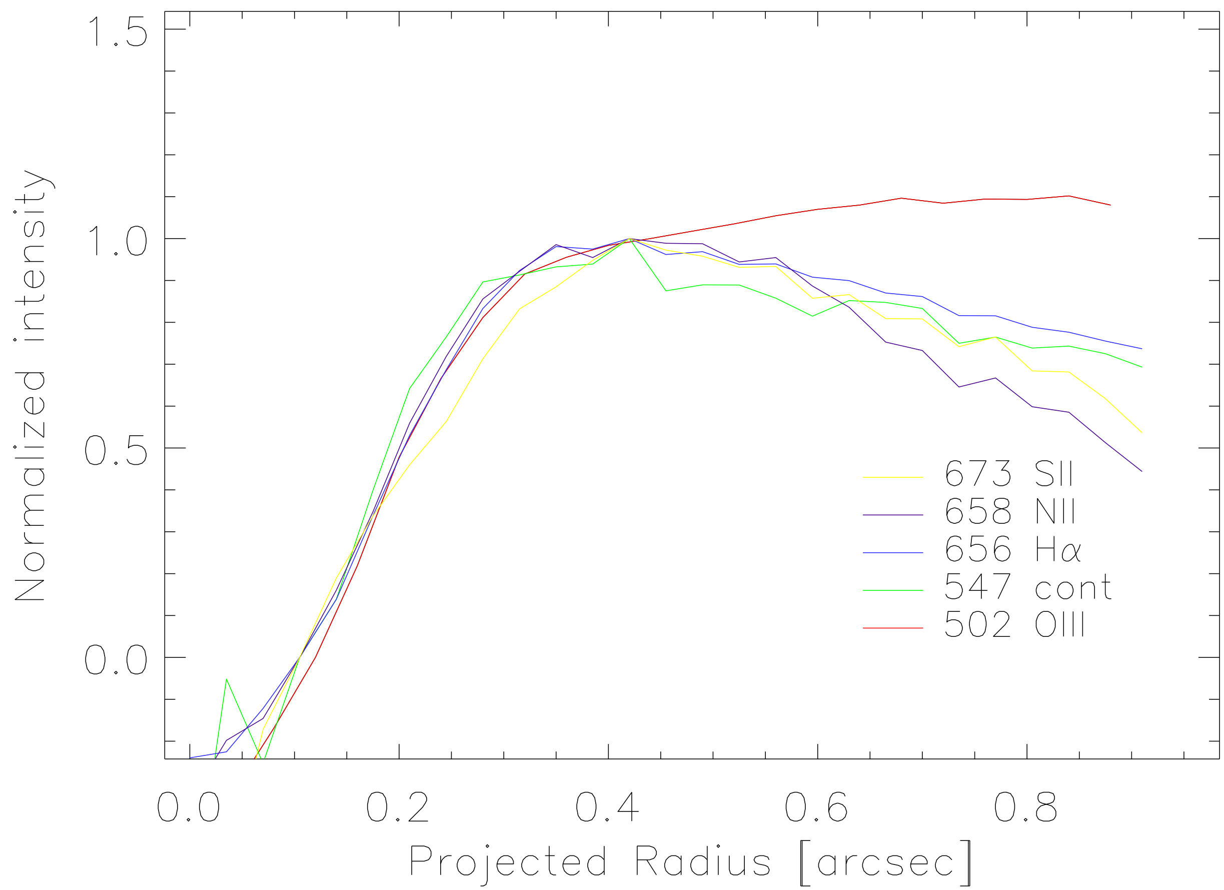


Transmitted light
(Orion Proplyds)

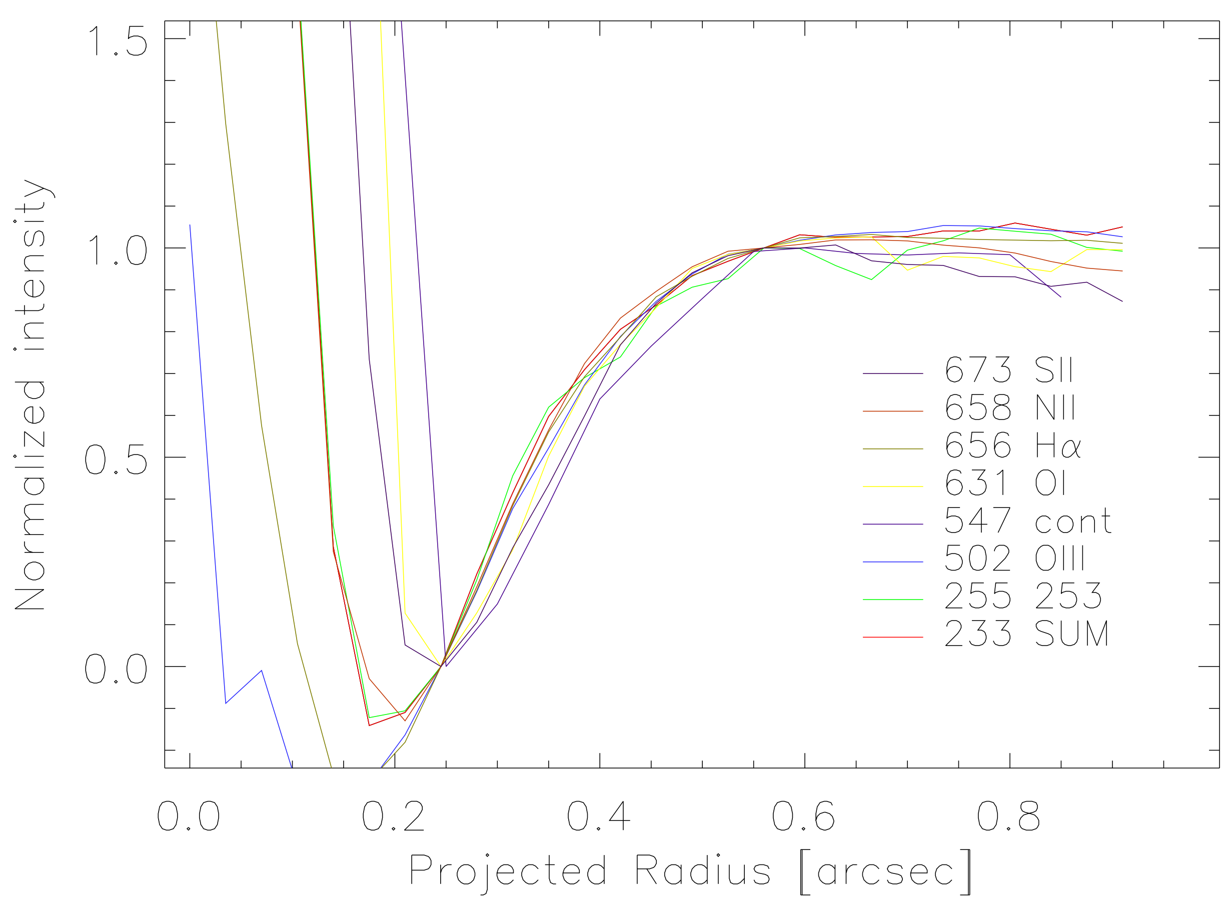
HST Observations of Orion Disks

- ~ 50 dark disks seen in **silhouette**; $\lambda = 0.2 - 1.9\ \mu$m
- Apparent disk size is *independent of wavelength!*
  - * Radial extinction profiles show *no measurable reddening!*
  - * Disks consistent with $R = A_V/E(B-V) \gtrsim 15$, vs $R = 3 - 5$ for ISM.
  - * Disks dominated by large particles?!

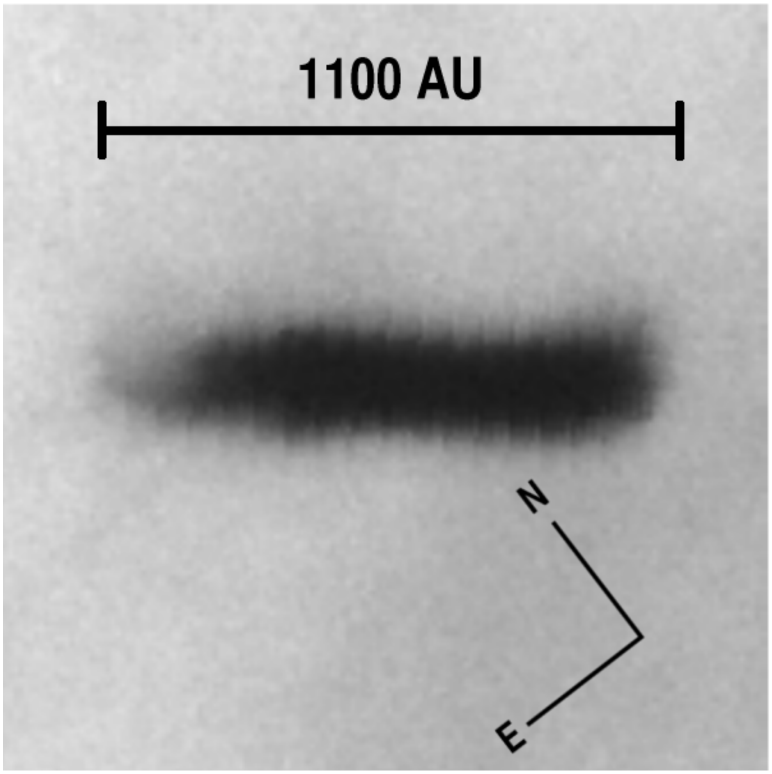
Radial Intensity Profiles, HST 10 Disk



Radial Intensity Profiles, HST 16 Disk



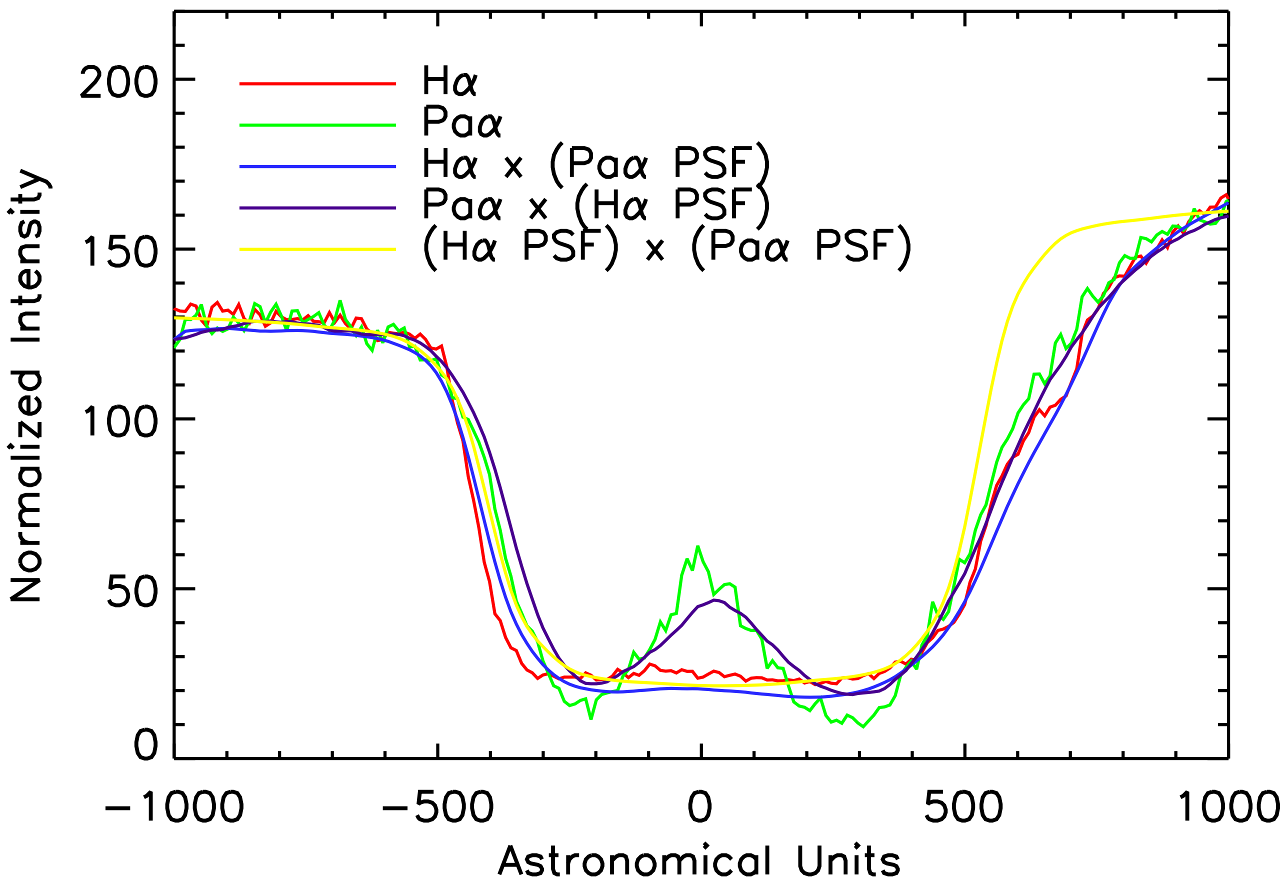
114-426 Disk Images



WFPC2 Hα NICMOS Paα

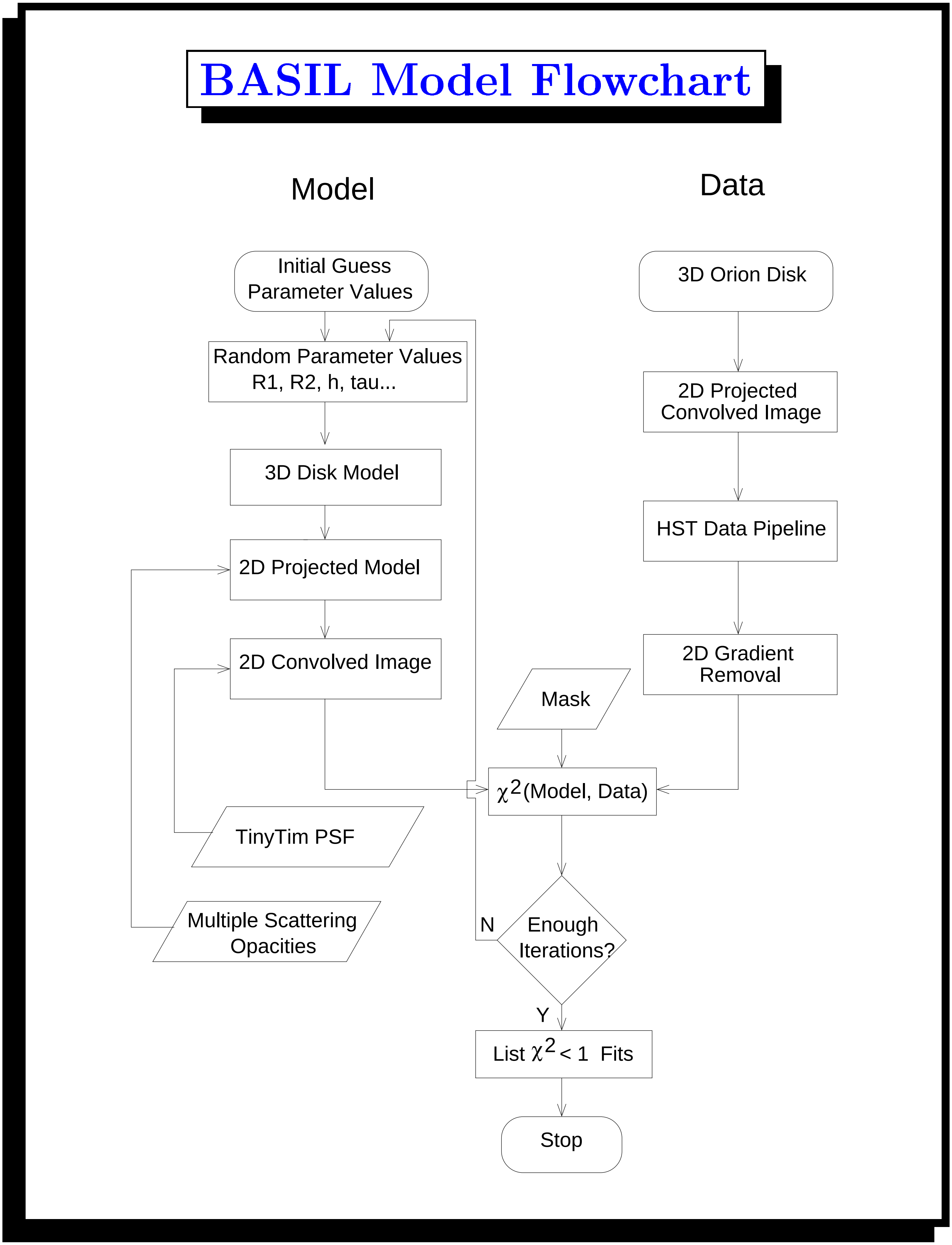
- Translucent NE ansa nearly identical at 0.65 μm, 1.87 μm!
- Polar halos *do* change with wavelength
  * **Large** particles at ansa; **small** particles at poles

114-426 Disk, Linear Slices

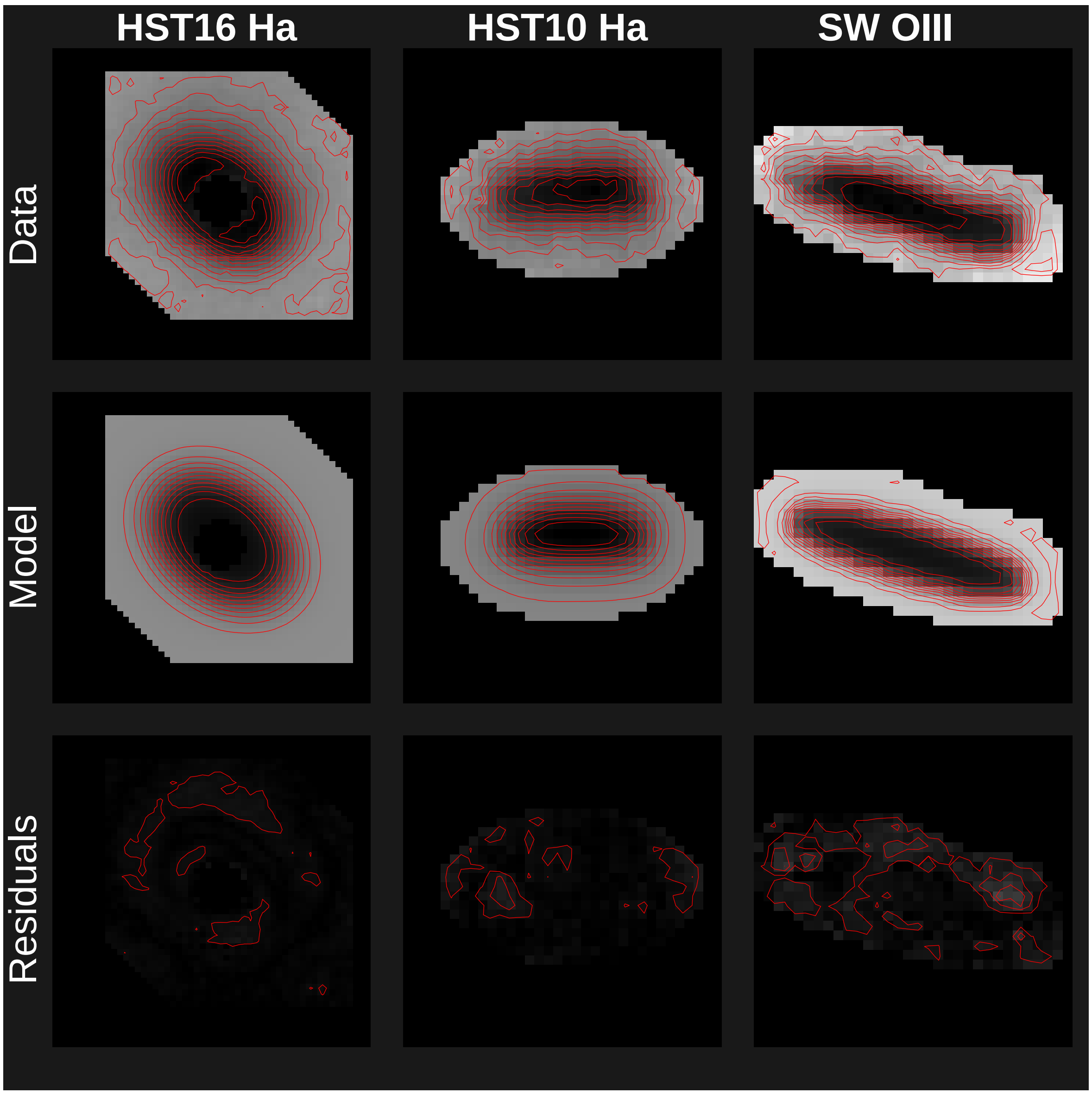


HST Observations of Orion Disks

- Translucent outer edge is $\sim$ PSF scale – need to be careful!
- Determine particle sizes, disk properties using BASIL model
  - 9-parameter 3D disk model; forward-convolve to create model images
  - Consider all wavelengths simultaneously
  - Use Monte Carlo approach: minimize χ^2 over large number of randomly-generated disks
  - Determine best-fit $\chi^2 < 1$ parameter ranges and cross-correlations


BASIL Model Flowchart
Model
Data
Initial Guess Parameter Values
Random Parameter Values R1, R2, h, tau...
3D Disk Model
2D Projected Model
2D Convolved Image
TinyTim PSF
Multiple Scattering Opacities
3D Orion Disk
2D Projected Convolved Image
HST Data Pipeline
2D Gradient Removal
Mask
χ2(Model, Data)
N
Enough Iterations?
Y
List χ2 < 1 Fits
Stop

Best Fit Model Results



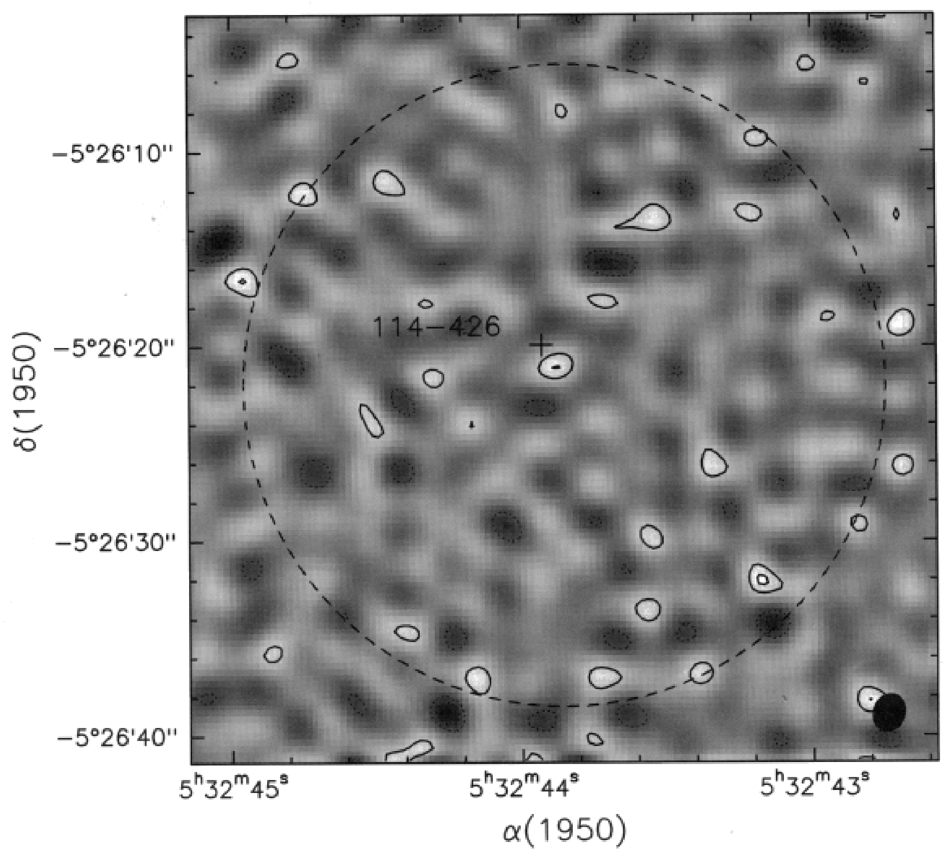
HST Observations of Orion Disks

Results of 3D Monte Carlo disk modeling:

- Disks have **sharply terminated** outer edges
- Disks are consistent with **large particles at outer edges**
- Edge-on, face-on disk structural parameters constrained
- Observational **limitations** are **spatial resolution, optical depth**

OVRO Observations of Orion Disks

- Observations of Bally *et al.* 1998 of two Orion fields, 1.8" beam
- 1.3 mm continuum, line emission not detected, F $<$ 21 mJy



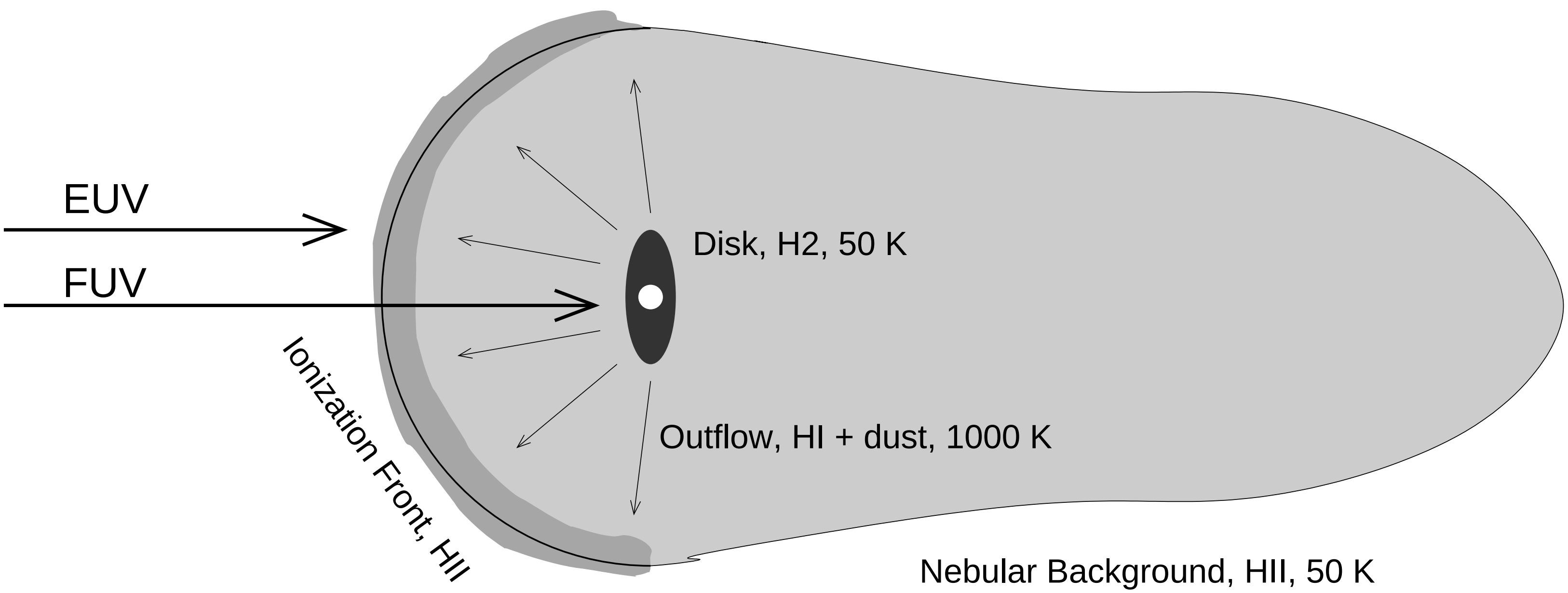
Modeling of OVRO Disk Observations

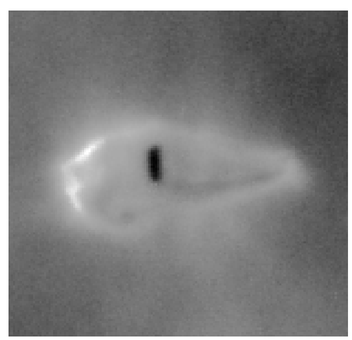
- Optically thick 50K disk *would be visible*
- Non-detection at 21 mJy implies **disk is optically thin**
  - * low τ requires low mass opacity k_ν *i.e.*, large particles
  - * $r \gtrsim$ few cm
- HL Tau: At 450 pc, would detect 100 mJy at 1.3 mm continuum (Beckwith *et al.* 1990)
  - * Orion disks slightly older, more evolved than Taurus?
  - * Orion small particles removed by evaporative flow?
- Non-detection is **difficult to explain without large particles.**
  - * Alternate explanation: Disk masses very low ($M < 0.02M_\odot$)
  - – Requires k_ν inconsistent with modeling results

Disk Scaling Regimes

	Galaxy	Proplyds	β Pic	EKB	Asteroid Belt	Planetary Rings
Optically Thick?		$\surd$				
Dynamically Young?	$\surd$	$\surd$				
Collisionally Active?		$\surd$	$\surd$	$\surd$	$\surd$	$\surd$
Grav. Interactions?	$\surd$			$\surd$	$\surd$	$\surd$
Massive Disk?	$\surd$	$\surd$				
Rapidly Destroyed?		$\surd$				
Light Source?	Intrinsic	External	Central	Central	Central	External

Photoevaporation of Orion Disks





(Johnstone et al. 1998; Störzer & Hollenbach 1999, Henney & O'Dell 1999)

Evolutionary Modeling of Orion Disks

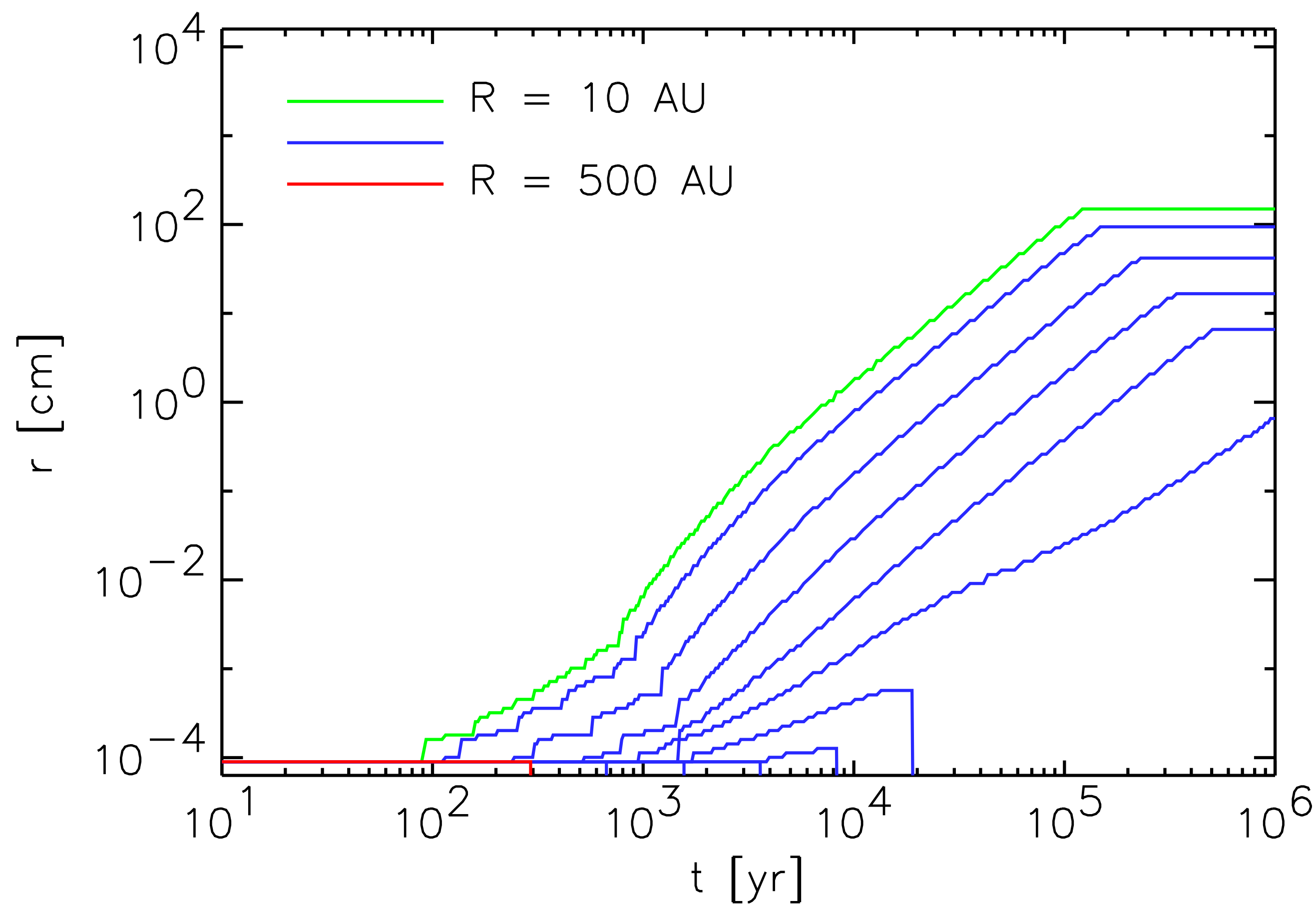
- Orion nebula environment:
  - Trapezium stars $\rightarrow$ violent place
  - Disk evolution cannot be modeled in isolation from environment!
  - Existing Solar Nebula models are not valid for Orion
- Use physical, evolutionary model and knowledge of environment to probe disks deeper than by data alone
- Predict disks' past and future states in addition to present-day
  - Prospects for planetary formation; insight into our own SS

Evolutionary Modeling of Orion Disks

Numerical Model (PAPADUM)

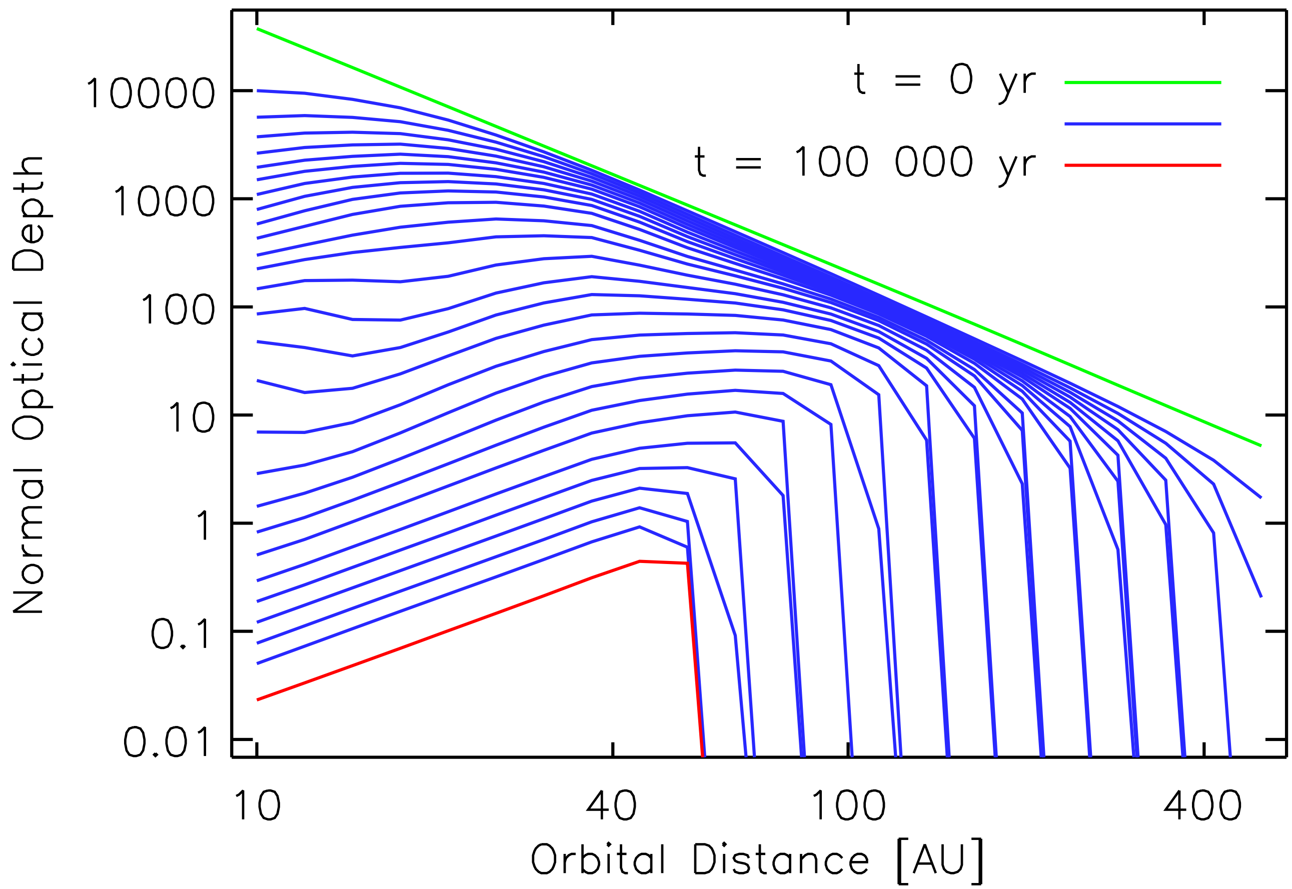
- Tracks state vector $n(r, R, t)$ of ice, silicate, H_2
- Integrate from initial conditions until gas disk is lost or convection stops
- Physical processes in externally-illuminated environments
  * Grain growth
    - Turbulent collision velocities $\sim$ cm s^{-1}, Mizuno 1988
  * Photoevaporation of gas and entrainment of small grains
    - $\dot{M} \simeq 10^{-6} M_\odot \text{ yr}^{-1}$; $r_{\text{entrain}} \sim v_0^2\, n_0\, R^2$
  * Photosputtering
    - $(dr/dt)_{\text{ice}} \sim \mu\text{m yr}^{-1}$

Particle Size Evolution, Steep Case



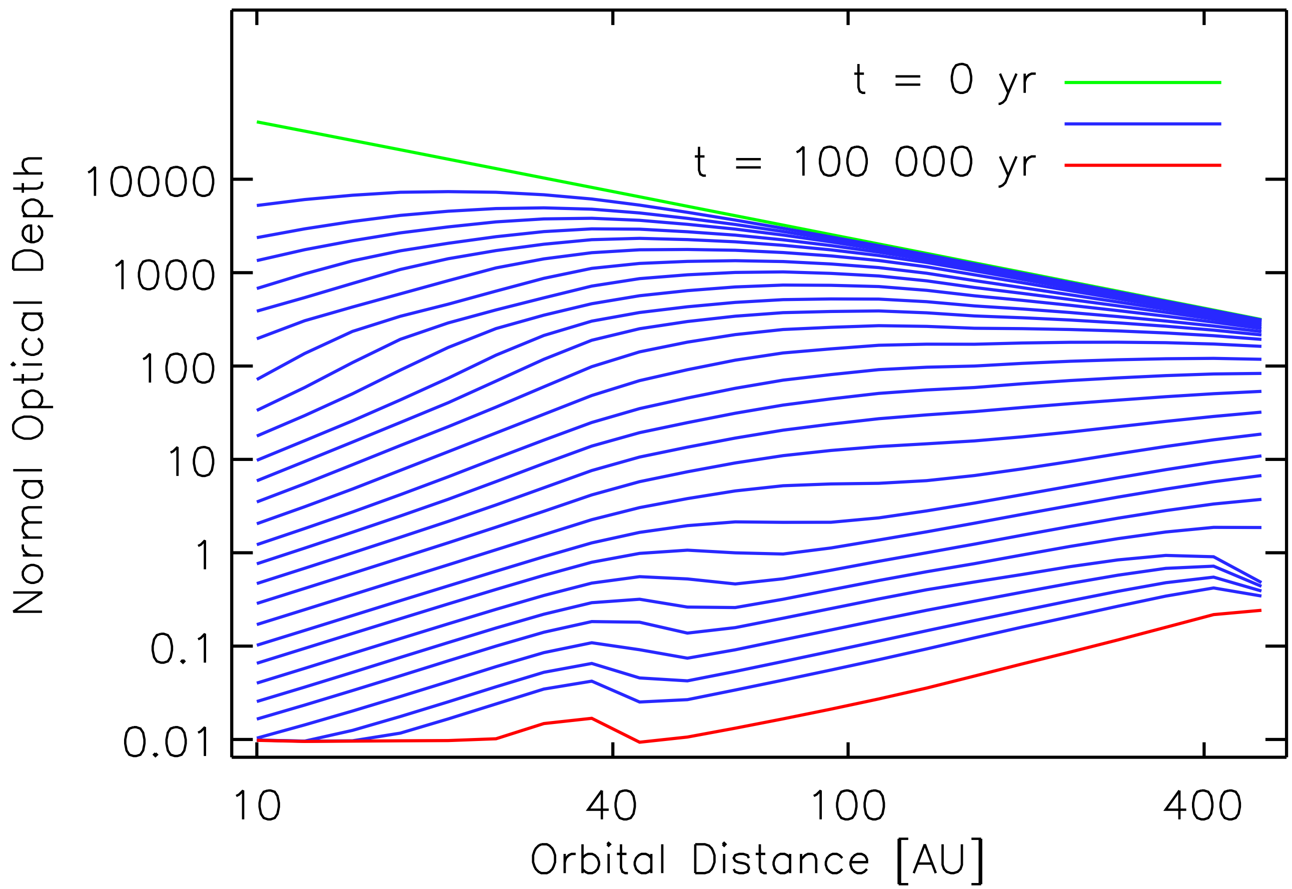
$$\Sigma \sim R^{-3},\ t_{\rm UV} = 0 \text{ yr}$$

Optical Depth Profiles, Steep Case



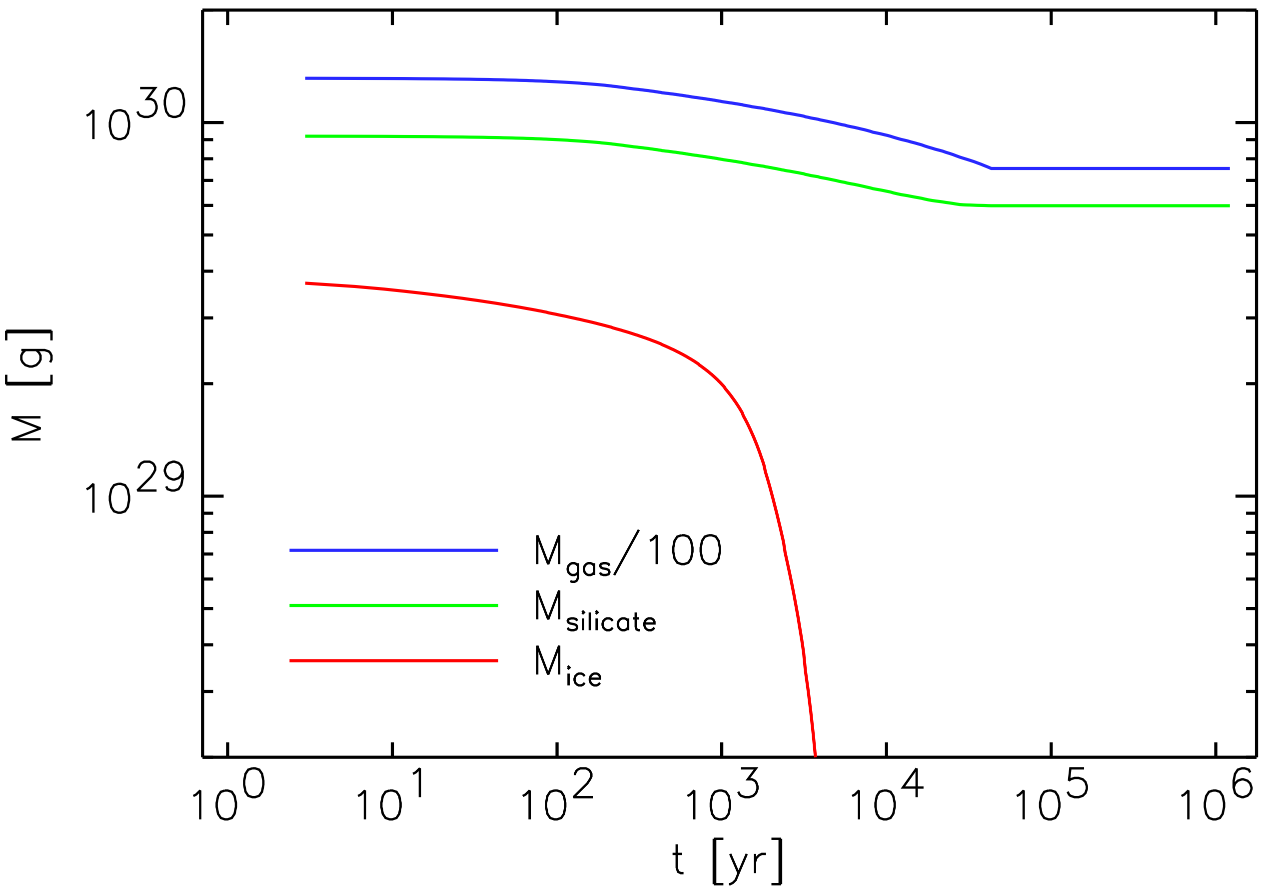
$$\Sigma \sim R^{-3},\ t_{\mathrm{UV}} = 0\ \mathrm{yr}$$

Optical Depth Profiles, Shallow Case



$$\Sigma \sim R^{-1},\ t_{\rm UV} = 10^4\ {\rm yr}$$

Disk Composition Evolution, Steep Case



$$\Sigma \sim R^{-3},\ t_{\mathrm{UV}} = 0\ \mathrm{yr}$$

Evolutionary Modeling of Orion Disks

Results:

- Grain growth is rapid: meter-sized particles in 10^5 yr at 10 AU
- Disk is removed outward of $\sim$ 100 AU
- Disk outer edge is sharp, populated with large particles
- Gas, all small particles lost in $\sim 10^5$ yr
- Formation of planets:
  - Terrestrial planets unaffected
  - Jovian planets difficult
  - Large EKB difficult

Conclusions

- **Three lines of evidence** suggest **large particles** in the Orion disks:
  - Lack of color in disks implies particles $> \mu$m
  - Non-detection at mm implies low optical depth, particles $>$ mm
  - Numerical modeling shows grains grow quickly throughout disks
- We are witnessing very earliest stages of planetary formation (!)
- Difficult to form Jupiters before disks are destroyed
- Terrestrial planet formation only minimally affected
- Results sensitive to initial mass distribution, mass loss rate, sticking properties, UV 'ignition' time
- **Planetary formation is hazardous, but possible and likely!**

But...

A conundrum:

- We see rapid disk destruction (10^5 yr), but we see old disks (10^6 yr)
- We see large particles, in the midst of many hazards

Solutions:

- θ^1 Ori C turned on recently
- Many disks are temporally shielded from radiation as they orbit the Trapezium

If disks have even a small headstart, grain growth will beat out photoevaporation.

Predictions

- **Terrestrial planets** are **common** in OB associations; UV production of **organics** also makes them ideal places for **life**.
- **Jovian planets** are **rare** in OB associations unless they form **rapidly**.
- Jupiter's existence indicates **our Solar System did not form in OB association**; therefore, Kuiper Belt may extend to 100's of AU
- **ISM** is populated with **large, aggregate particles** caused by grain growth followed by photoevaporation.
- Stars in Orion with no visible disks have already formed **giant planets which can be detected by infalling planetesimals** (vsv. β Pic).
- Photoevaporation causes a **positive correlation** between **stellar metallicity** and the **existence of planets** surrounding a star.
- Our Solar System has an anomalously large cometary reservoir, and we should **not expect an extra-solar cometary visit soon**.