Light Scattering and Evolution of Protoplanetary Disks and Planetary Rings

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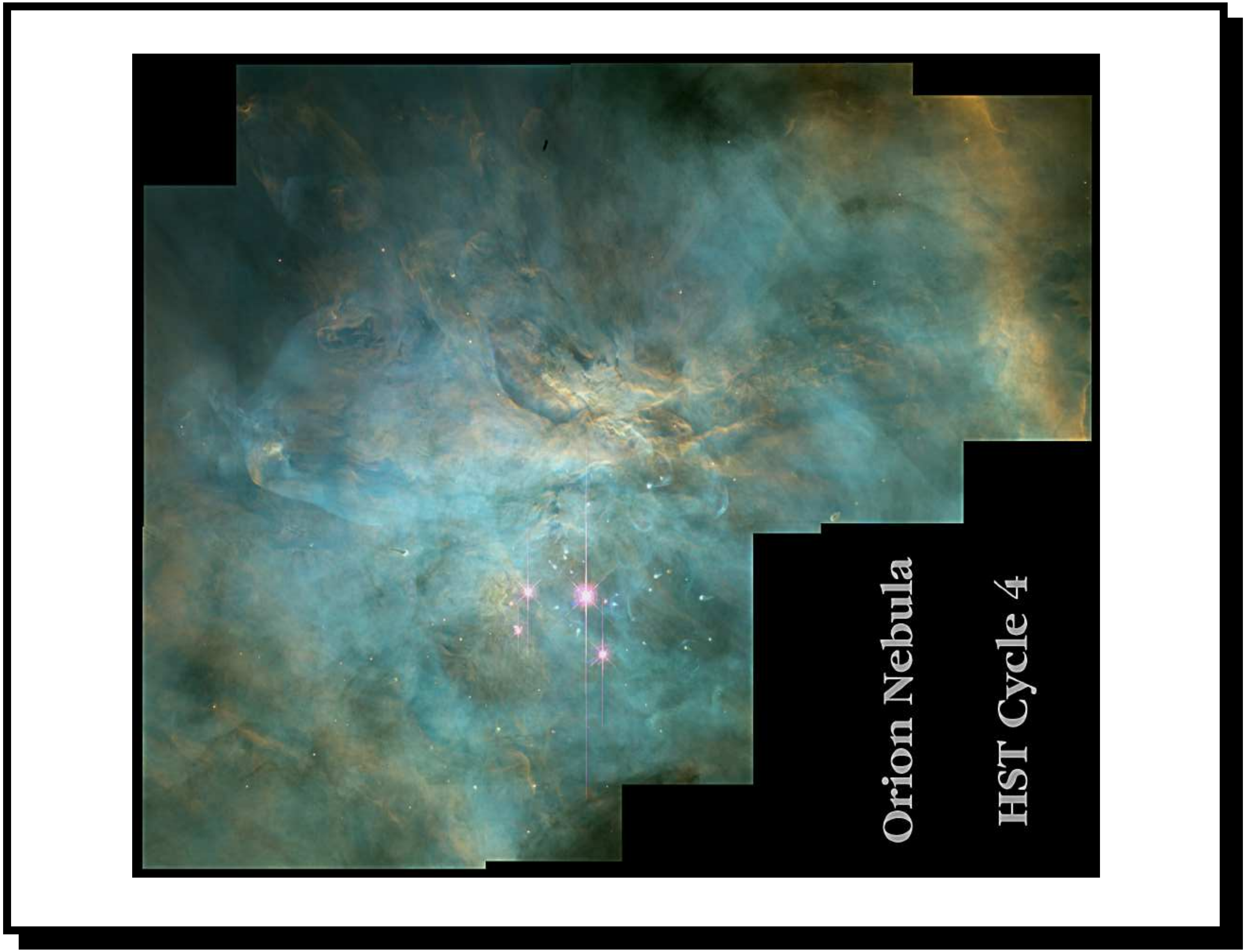
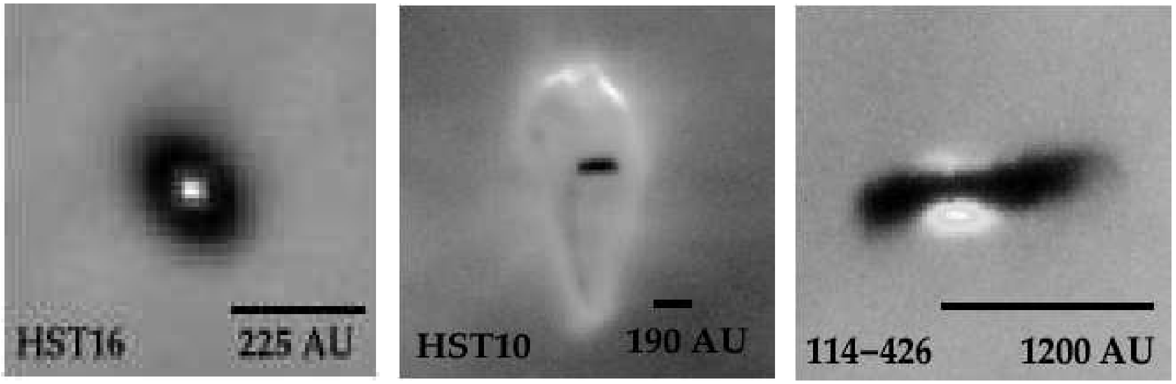
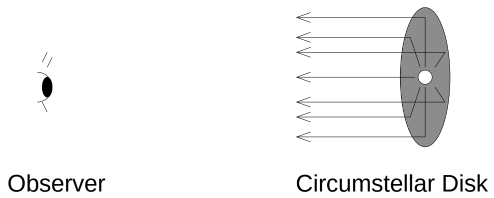
- Observations of young disks in Orion and evidence for grain growth
  - HST
  - OVRO
- Evolutionary modeling of young disks
  - Physical processes in externally-irradiated environments
- Planetary rings
  - Saturn's G ring
- Conclusions & Predictions

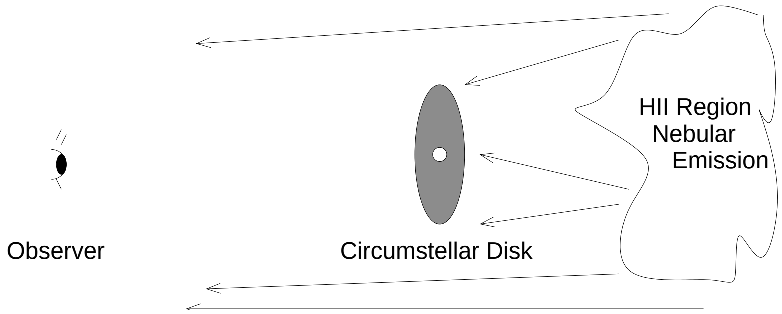

Orion Nebula
HST Cycle 4

Observations





Reflected light
(Taurus, β Pic, rings)

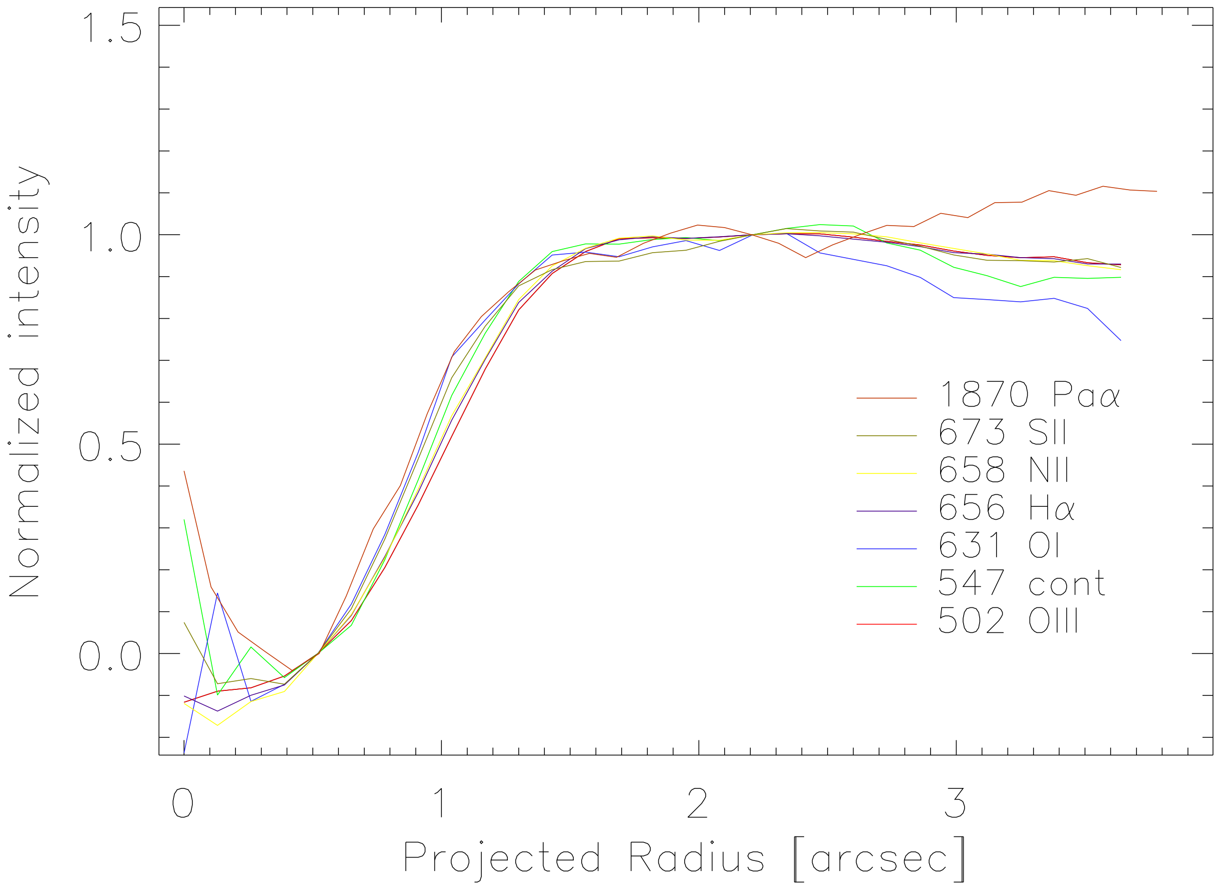


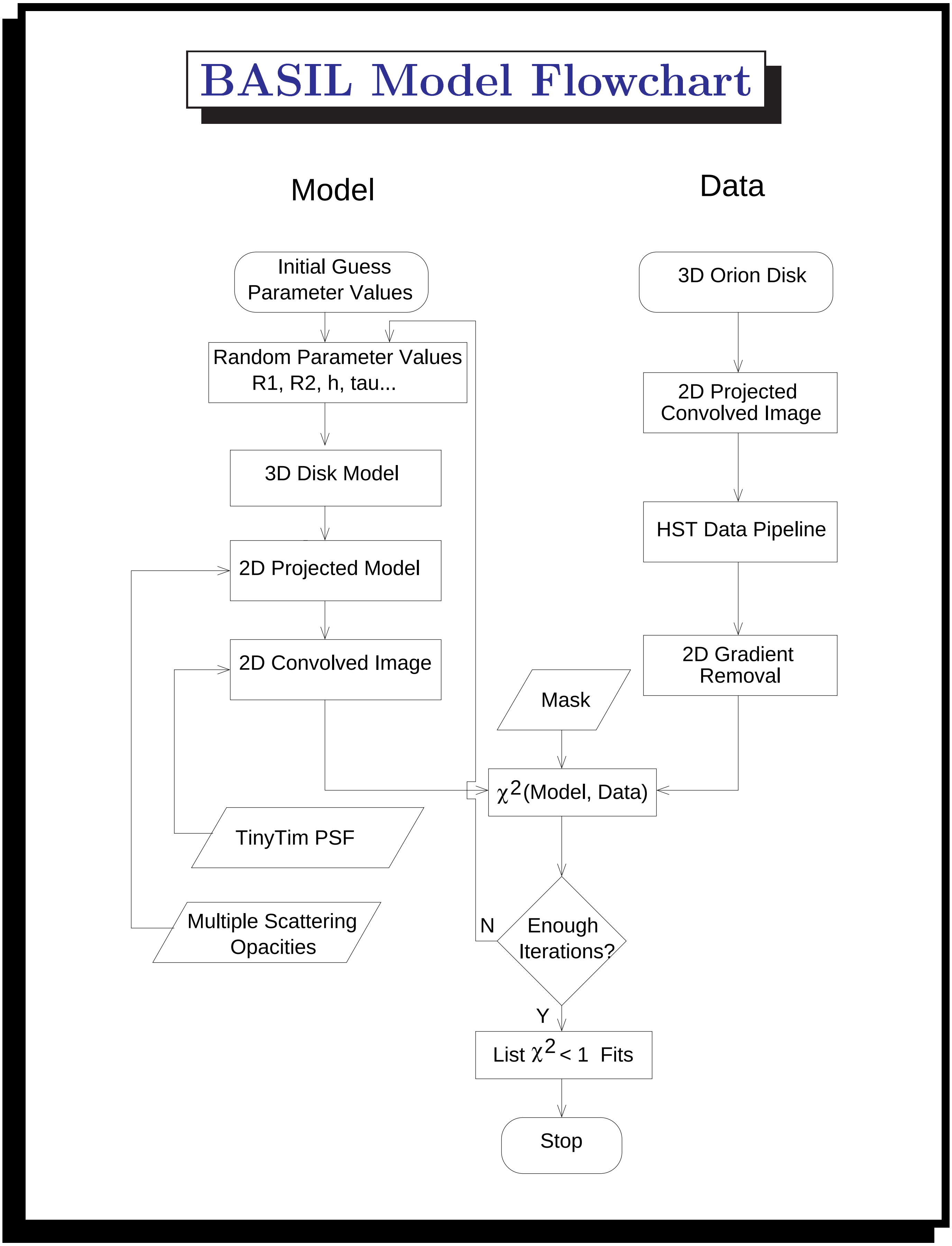
Transmitted light
(Orion)

HST Observations of Orion Disks

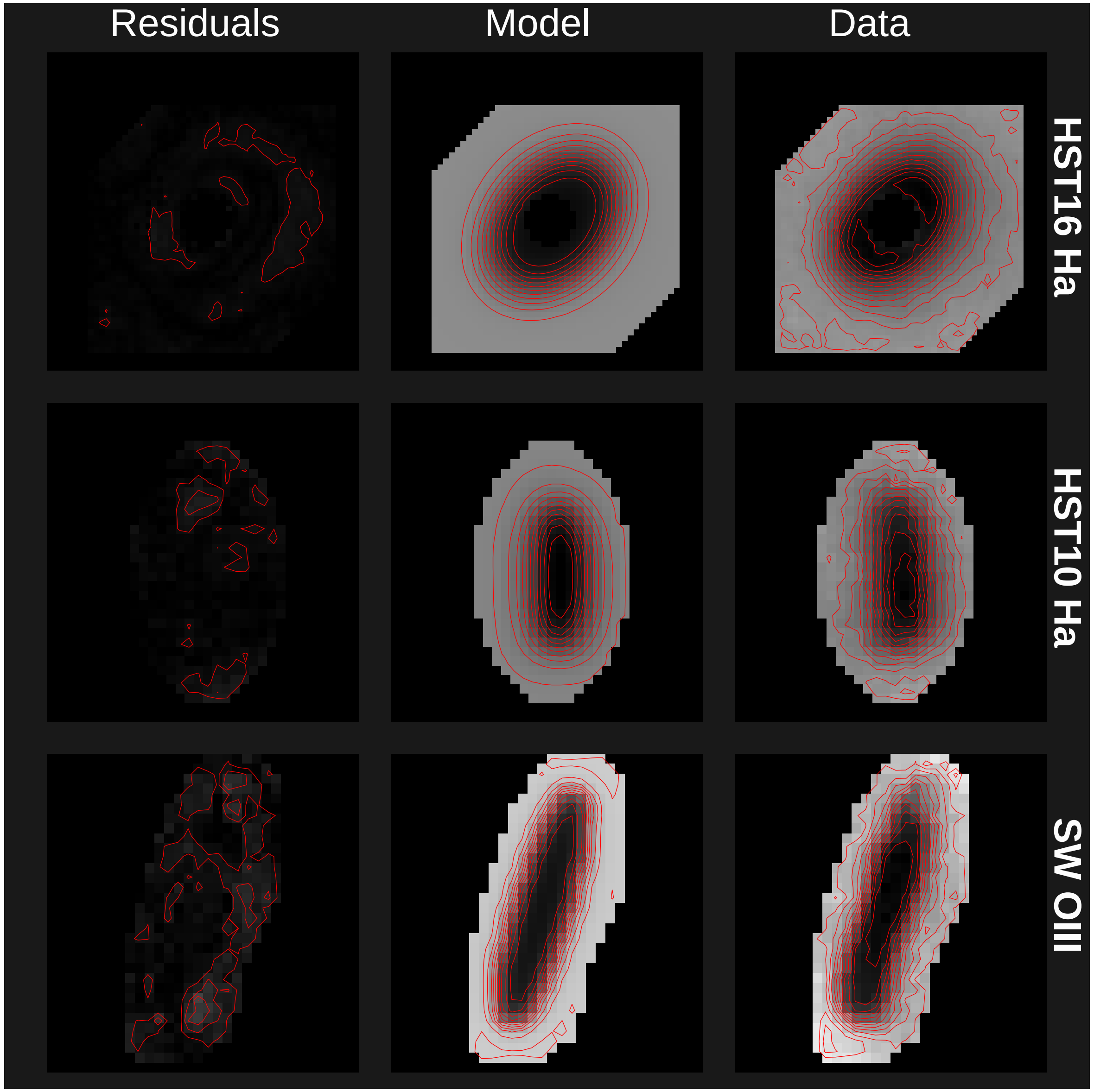
- $\sim$ 50 dark disks, seen in silhouette; $\lambda = 0.2 - 1.9\ \mu$m
- Radial extinction profiles show no measurable reddening!
  - * Disks dominated by large particles?
- Determine particle sizes, disk properties using BASIL model
  - * 9-parameter 3D disk model; forward-convolve to create model 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

Radial Intensity Profiles, SW Disk




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)
Enough Iterations?
N
Y
List χ2 < 1 Fits
Stop

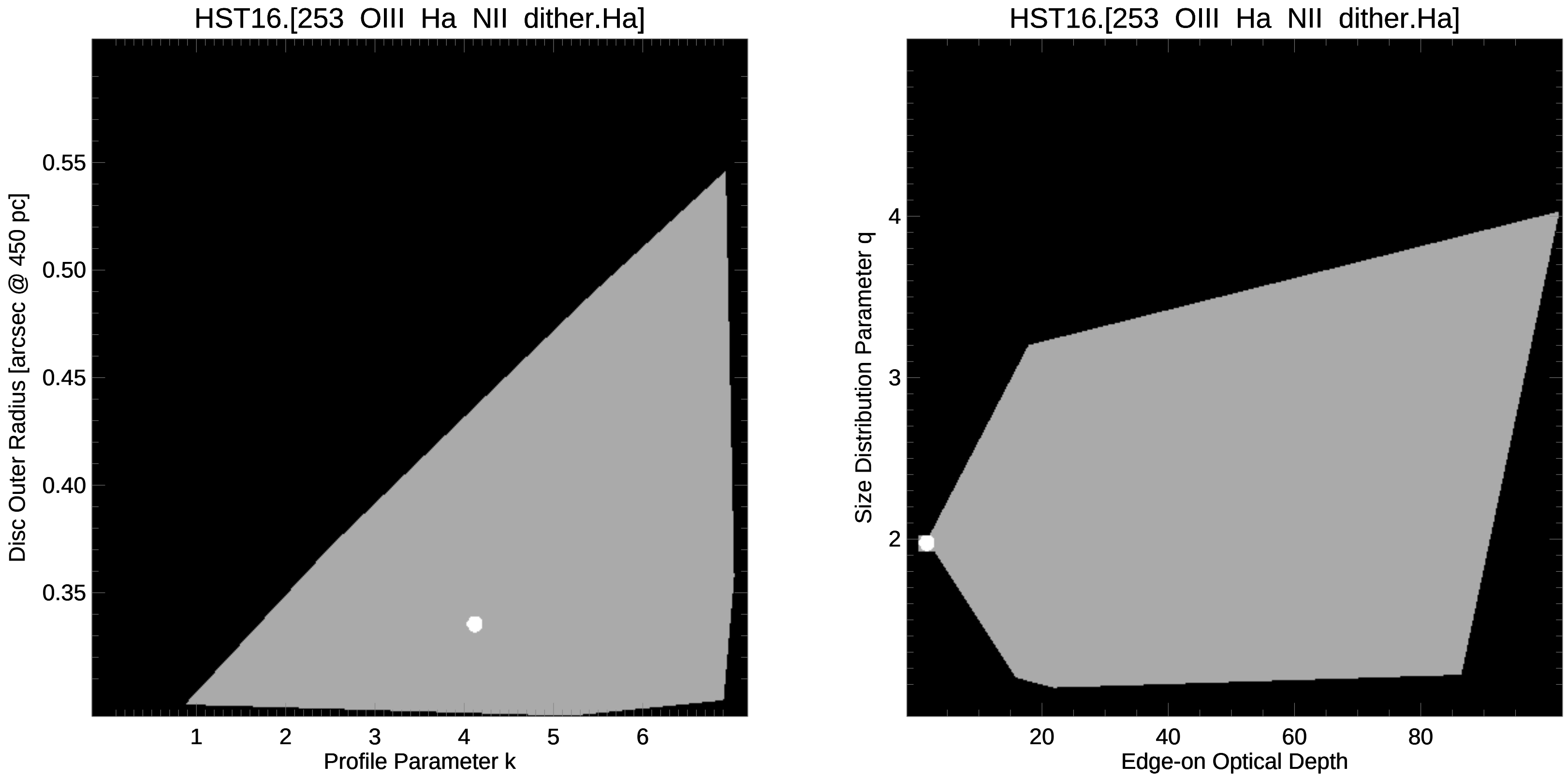
Best Fit Model Results



$\chi^2 < 1$ Best Fit Parameters, HST16

Truncation

Particle Sizes



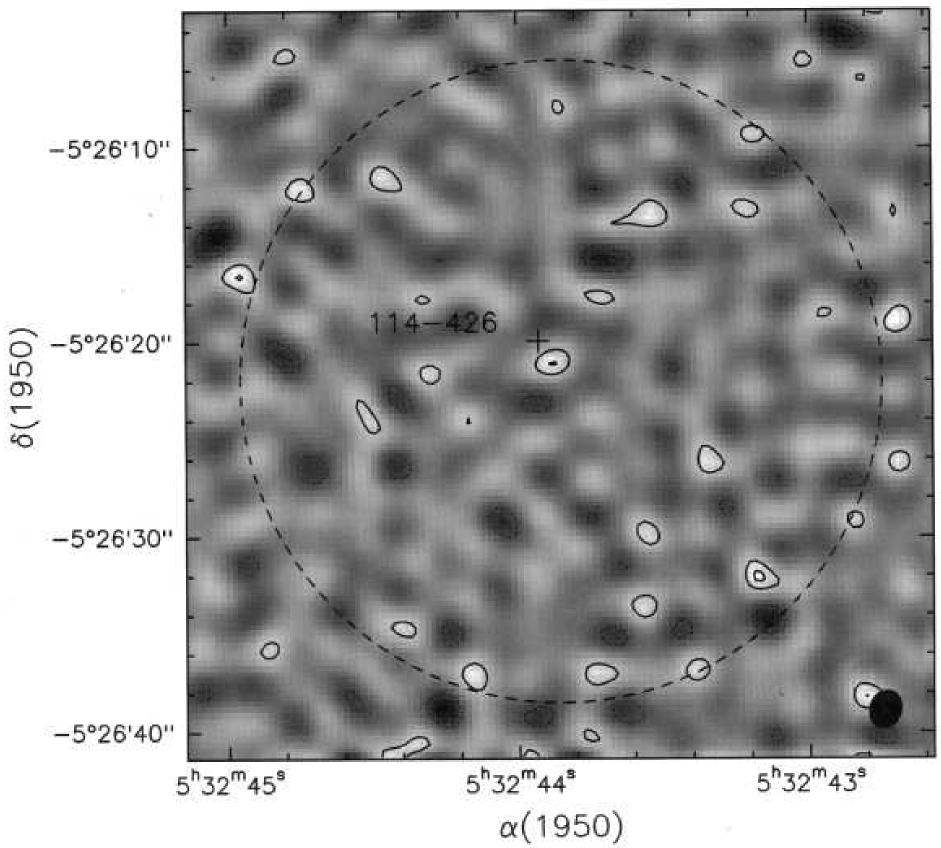
HST Observations of Orion Disks

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
- Constraints ultimately limited by spatial resolution, high optical depth

OVRO Observations of Orion Disks

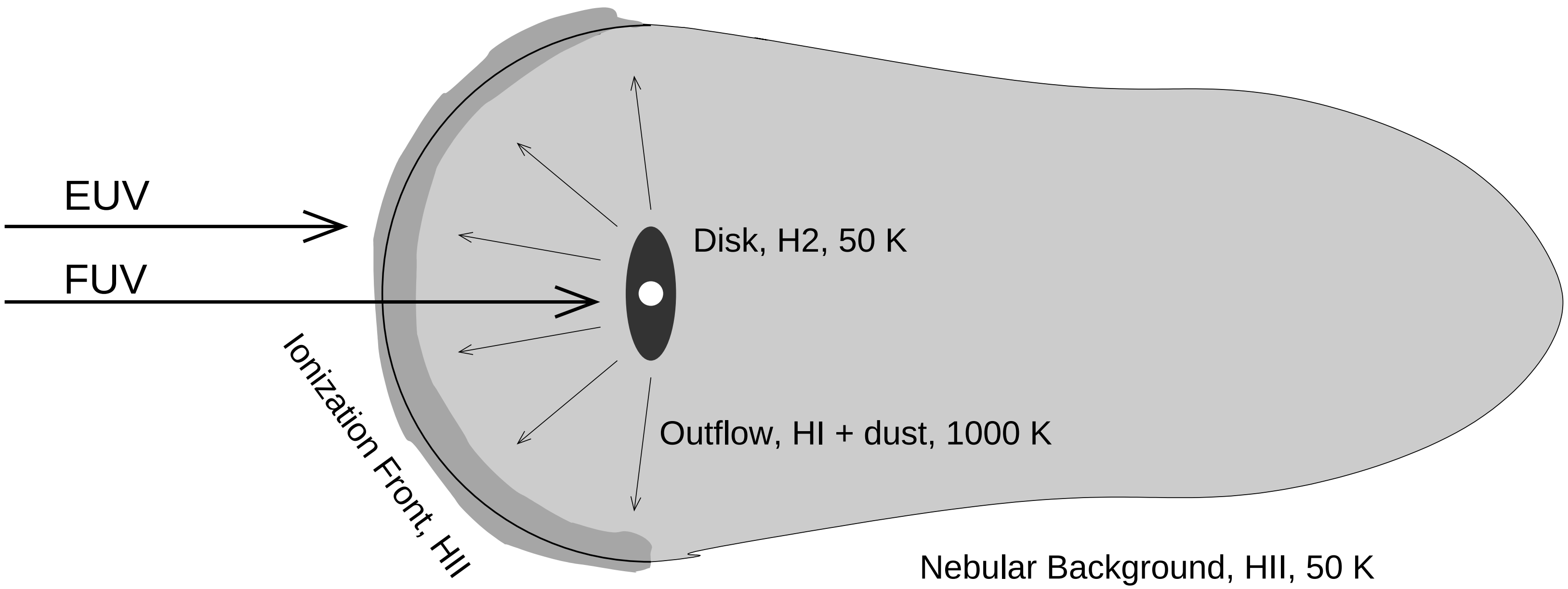
- Observations of Bally *et al.* 1998 of two Orion fields, 1.8” beam
- Continuum, line emission non-detections at 1.3 mm



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: 879 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: $M_{\rm disk} < 0.02 M_\odot$, but requires k_ν inconsistent with modeling results

Photoevaporation of Orion Disks



Evolutionary Modeling of Orion Disks

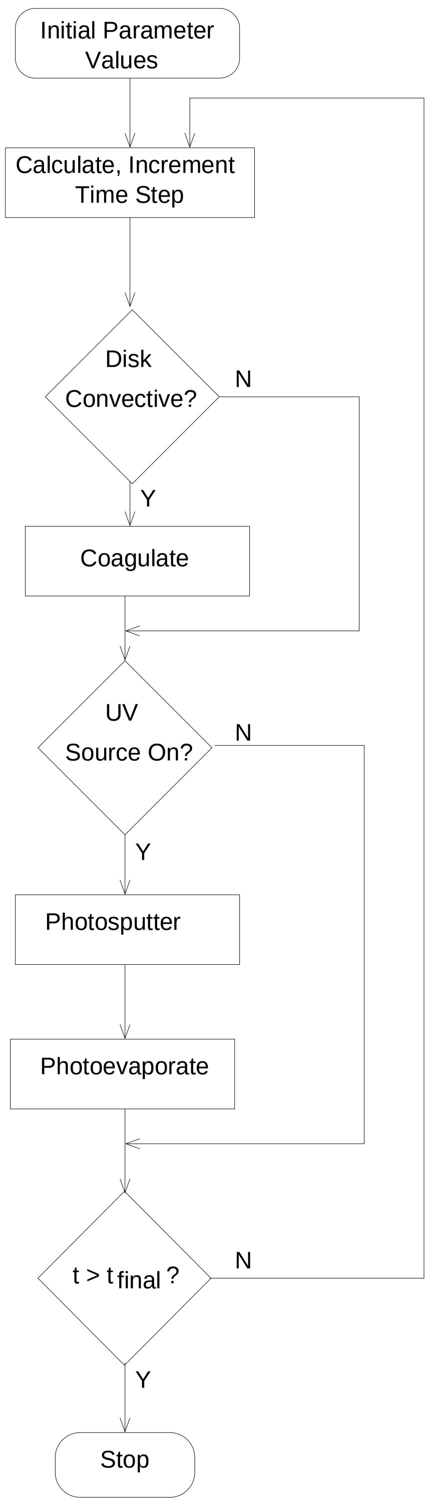
- Orion nebula environment:
  - * Trapezium stars $\rightarrow$ violent place
  - * Disk evolution cannot be modeled in isolation from environment!
  - * Existing Solar Nebula models are not valid for Orion
- Use physical, evolutionary model and knowledge of environment to probe disks deeper than by 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

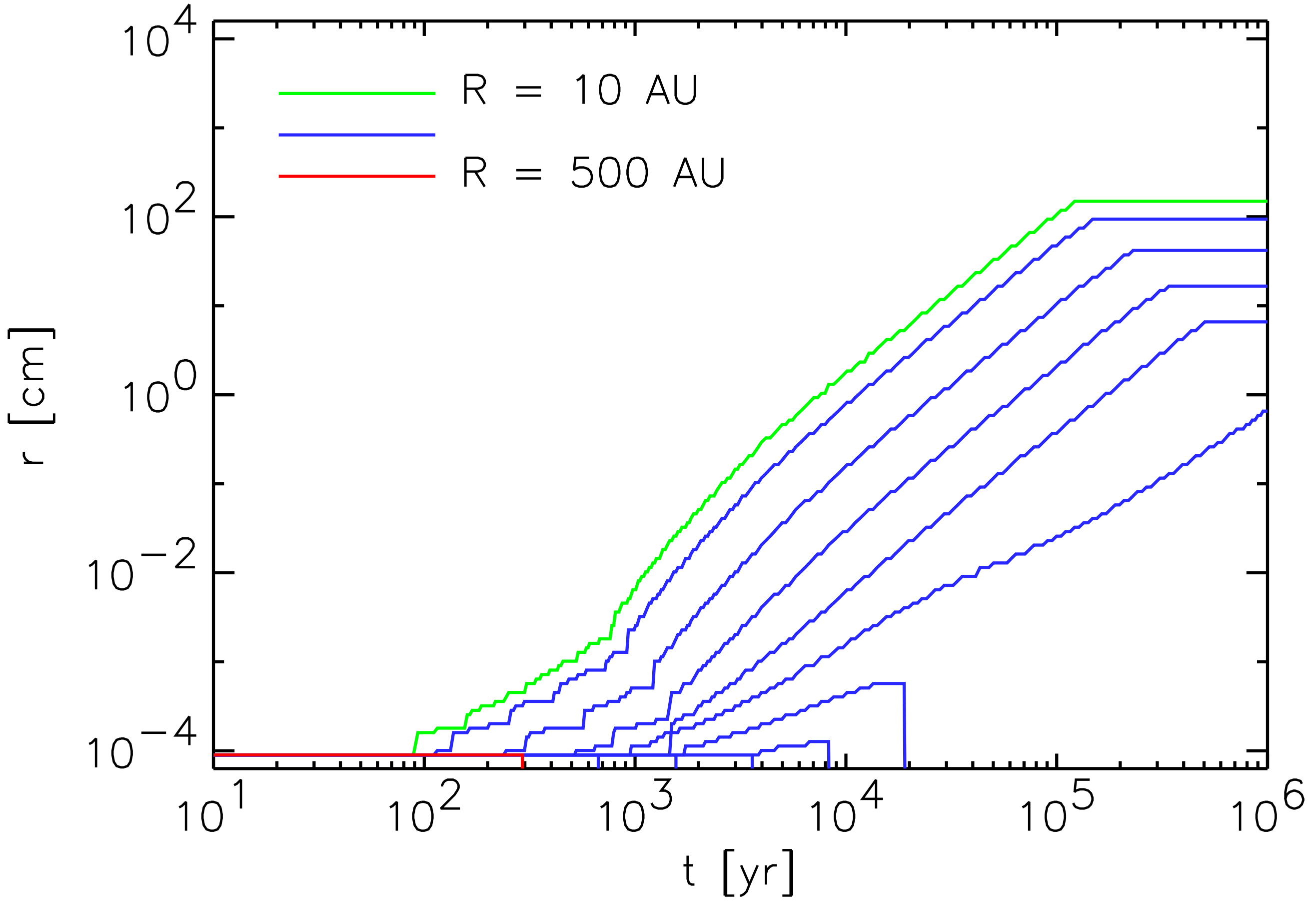
Numerical Model (PAPADUM)

- 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 within externally-irradiated environments
  - ∗ Grain growth
    - – Turbulent collision velocities $\sim$ cm s^{-1}, Mizuno 1988
  - ∗ Photoevaporation of gas and entrainment of small grains
    - – $\dot{M} \simeq 10^{-6} M_\odot$ yr^{-1}; $r_{\rm entrain} \sim v_0^2\, n_0\, R^2$
  - ∗ Photosputtering
    - – $(dr/dt)_{\rm ice} \sim \mu$m yr^{-1}

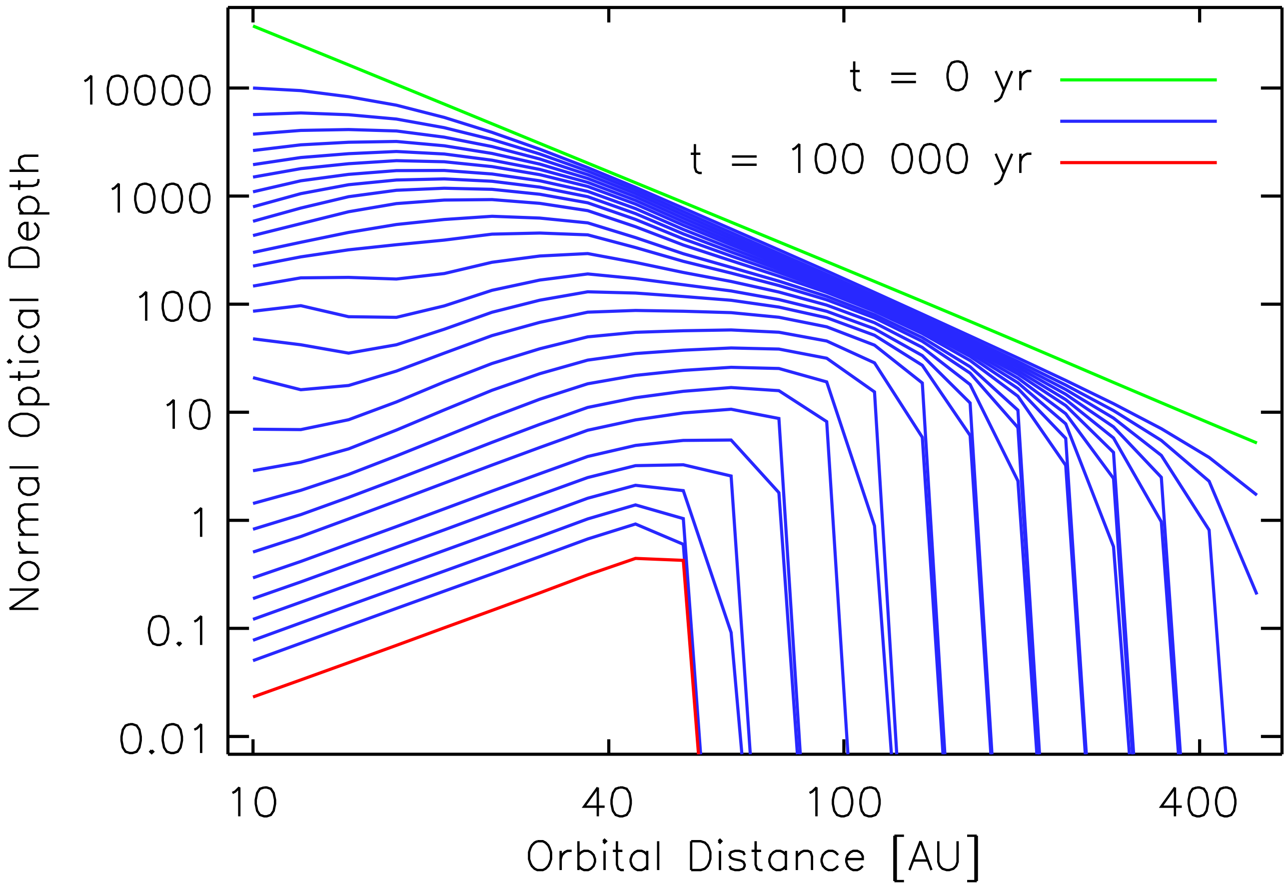
PAPADUM Model Flowchart



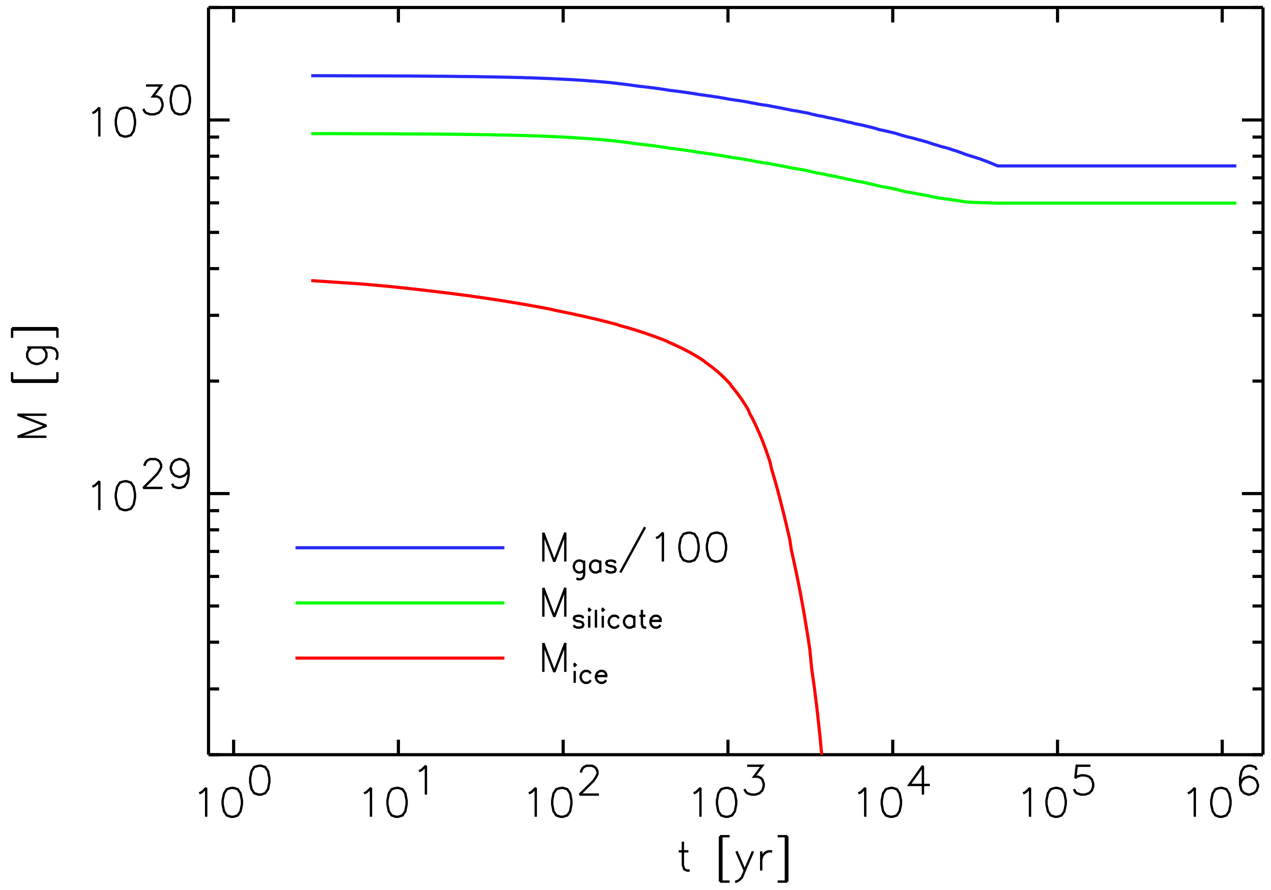
Particle Size Evolution, Steep Case



Optical Depth Profiles, Steep Case



Disk Composition Evolution, Steep Case



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 ~ 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

Planetary Rings – Saturn's G Ring

- Low optical depth: $\tau_{\mathrm{d}} \simeq 10^{-6}$
- Dust sustained in steady-state by small population of 'invisible' km-sized parent bodies
- $R = 2.72 - 2.88 R_{\mathrm{s}}$

Planetary Rings – Saturn's G Ring

Data:

- HST spectra 0.3-2.2 μm
- Voyager phase curves, scattering angle $\theta = 30 - 179°$
- *in situ* plasma, dust measurements

Evolutionary Model:

- Numerical evolution model, state vector n(r,t)
- Processes:
  - Collisional release of dust from parent bodies
  - Sweep-up of dust by parent bodies
  - Inward radial drift and loss
- Integrate forward from satellite break-up to present-day

Conclusions:

- Ring is dominated by micron-sized particles; consistent with steady-state from satellite break-up 10-100 Mya.

Conclusions

- Three lines of evidence suggest large particles in the Orion disks:
  * Lack of color in disks; fits to 3D models are consistent with large particles
  * Non-detection at mm suggest optical depth is low, and thus large particles
  * 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

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 terrestrial/icy **planetesimals; can be detected by absorption signatures** as they infall in onto stars.
- Our Solar System has an anomalously large cometary reservoir, and we should **not expect an extra-solar cometary visit soon**.