Massive, Embedded, Accreting, Protostellar Disks

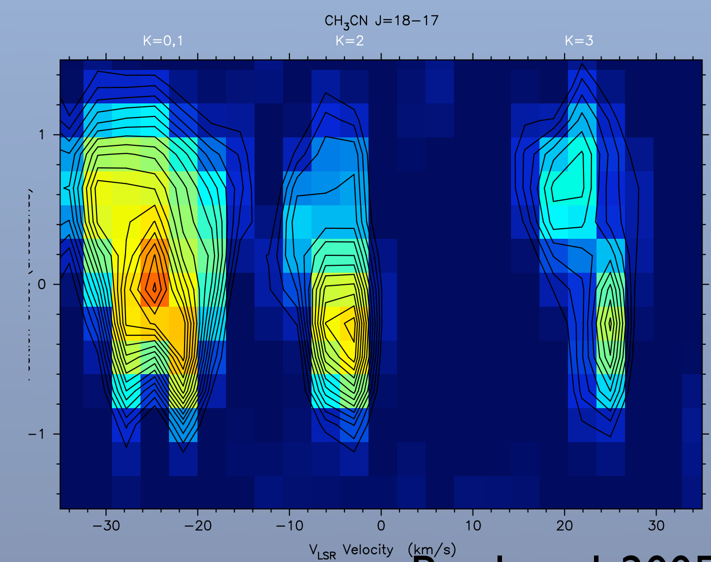
Kaitlin Kratter
University of Toronto

Collaborators: Chris Matzner (U. Toronto)
Mark Krumholz (Princeton/UC Santa Cruz)

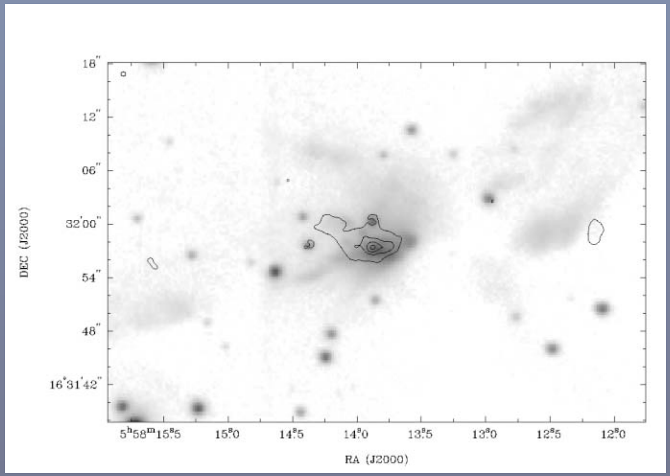
September 12th, 2007
Heidelberg: Massive Star Formation

Disks in Massive Star Formation?

- **Theoretically**: existence of disks is a robust result independent of specific formation mechanism
- fundamental in circumventing accretion barrier of radiation pressure (e.g. Krumholz et al. 2005)
- likely play a role in determining binarity and upper mass cutoff (e.g. Kratter & Matzner, 2006)
- **Observationally**: just beginning to probe proper size and time scales. more soon from ALMA & EVLA



Patel et al, 2005



Indebetouw et al, 2003

How can we make useful predictions for these disks as $f(M_*, t)$?

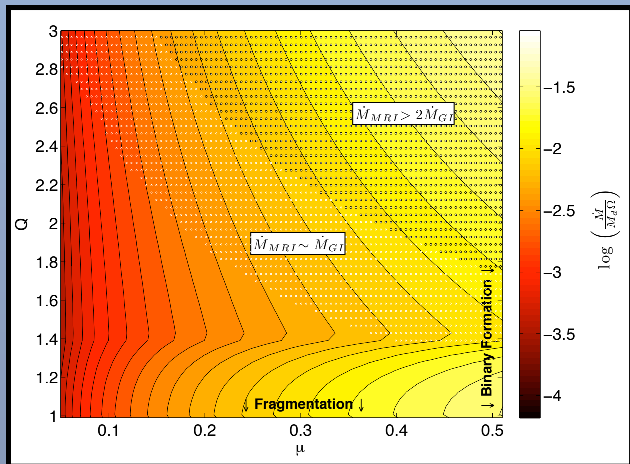
Massive Embedded Disks: what should we expect?

What dominates angular momentum transport?

Do disks fragment? If so, what do they make?

How will these disks appear to ALMA and the EVLA?

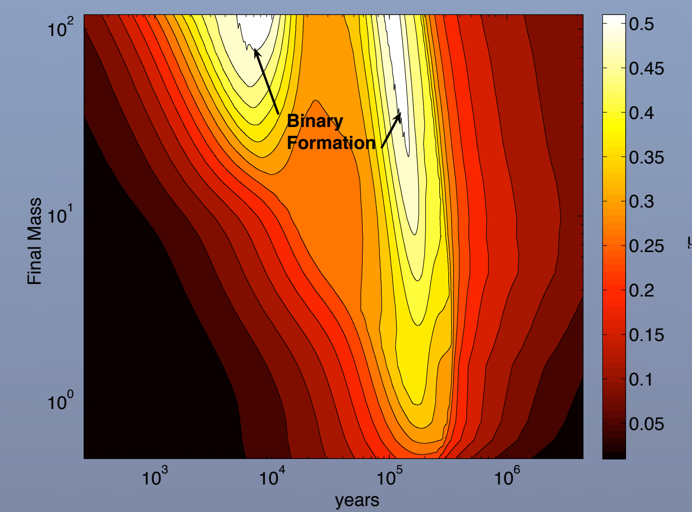
Massive Embedded Disks: what should we expect?

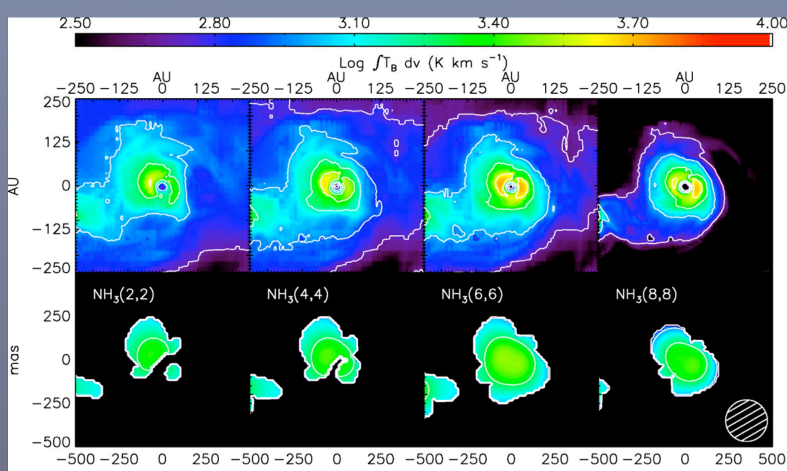


KMK, Matzner, & Krumholz, 2007 (submitted)

What dominates angular momentum transport?

Do disks fragment? If so, what do they make?

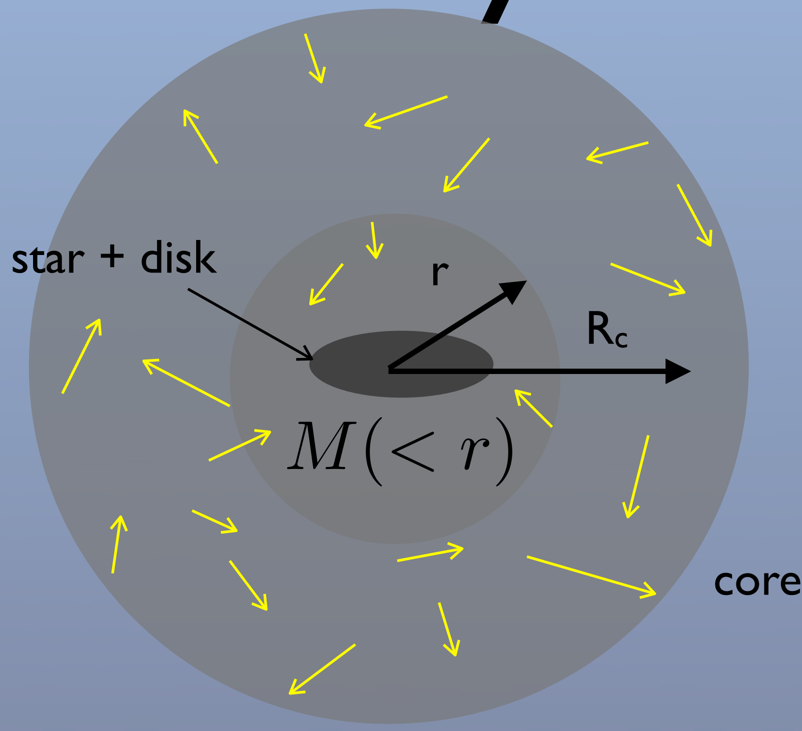




Krumholz, et al. 2007

How will these disks appear to ALMA and the EVLA?

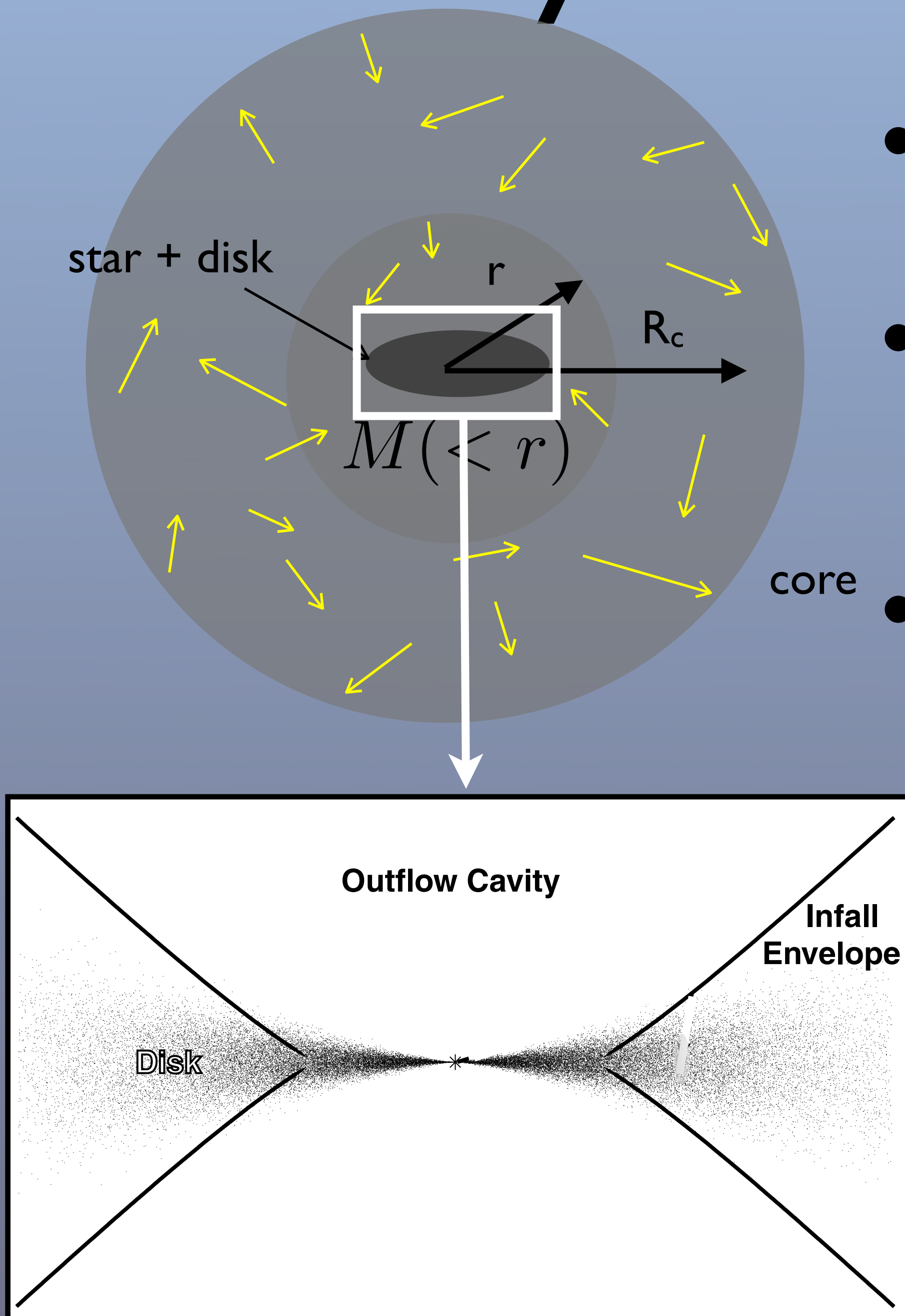
Physical Scenario



- Turbulent region (core) begins to collapse
- Cloud pressure and core temperature determine the magnitude of turbulent support
- Net angular momentum determines circularization radius of the infalling material as f(t)

Problem I: high column cores make these phenomena very difficult to observe

Physical Scenario



Matzner & Levin, 2005

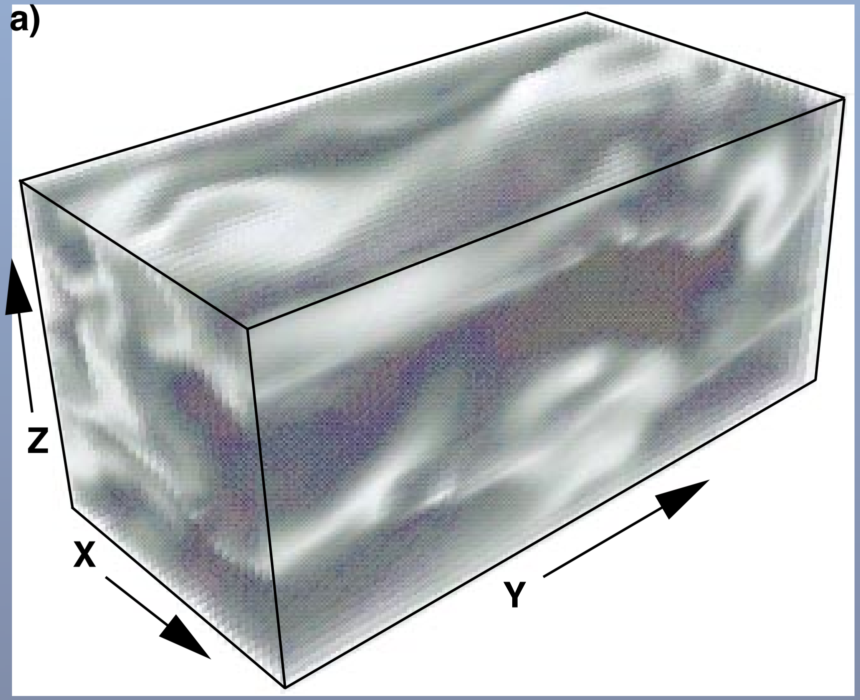
- Turbulent region (core) begins to collapse
- Cloud pressure and core temperature determine the magnitude of turbulent support
- Net angular momentum determines circularization radius of the infalling material as f(t)

Problem I: high column cores make these phenomena very difficult to observe

Problem II: large parameter space to explore numerically with MHD + radiation

Solution: A global, single zone model that incorporates these processes can characterize the parameter space of disks in HMSF

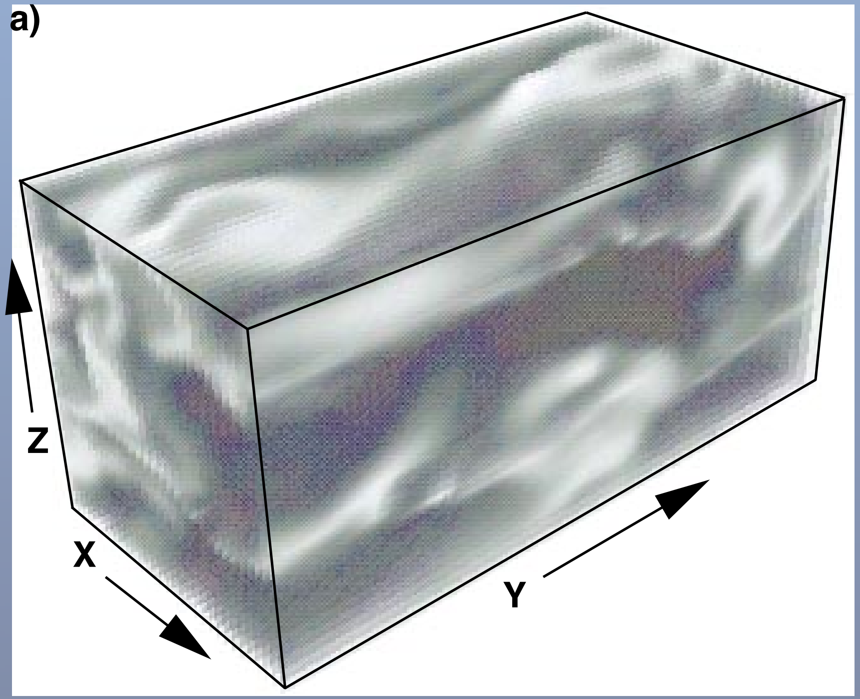
Problem II: large parameter space to explore numerically with MHD + radiation



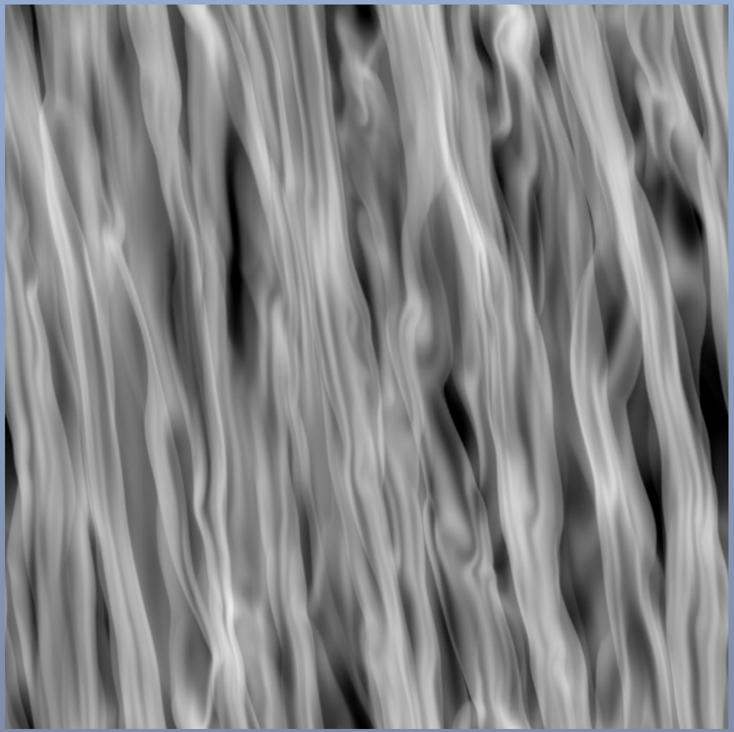
Hawley & Stone, 1998

Solution: A global, single zone model that incorporates these processes can characterize the parameter space of disks in HMSF

Problem II: large parameter space to explore numerically with MHD + radiation



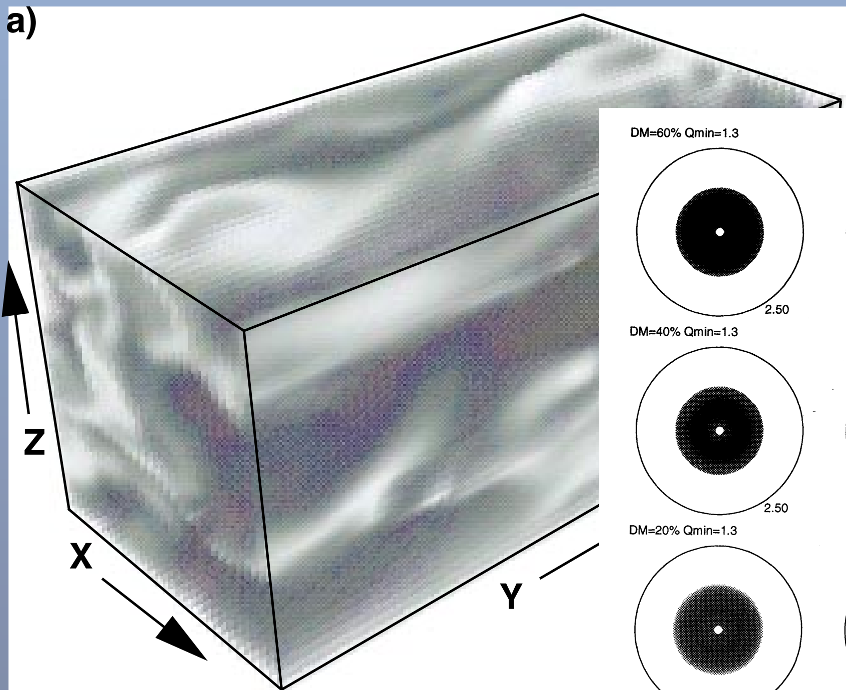
Hawley & Stone, 1998



Gammie, 2001

Solution: A global, single zone model that incorporates these processes can characterize the parameter space of disks in HMSF

Problem II: large parameter space to explore numerically with MHD + radiation



Hawley & Stone, 1998

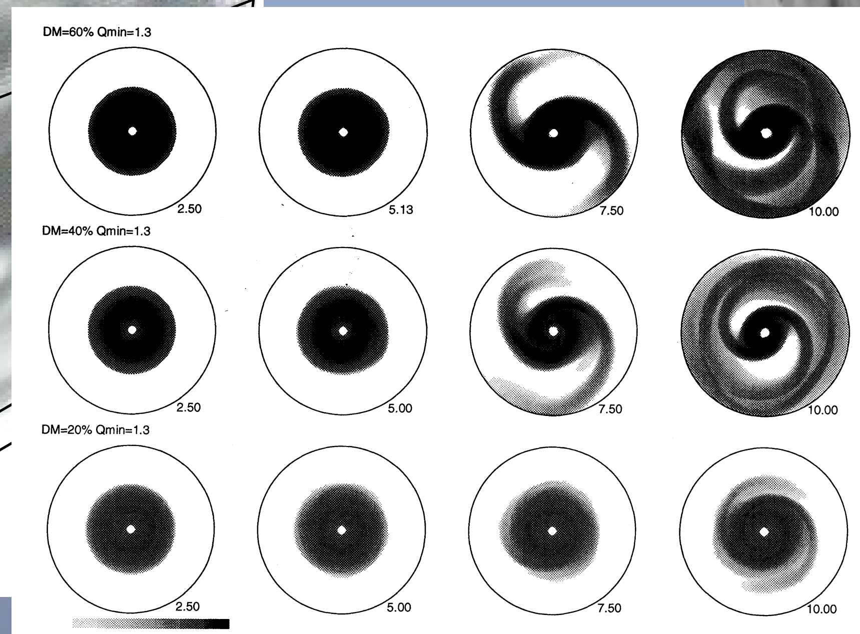
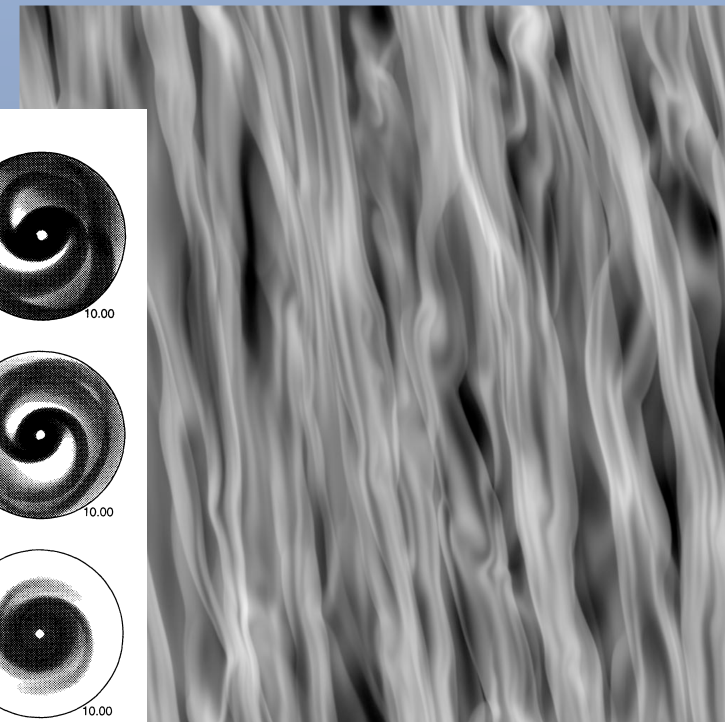


FIG. 1.—Surface density distributions for runs 1, 3, and 5. Gray-scale values are logarithmic and run from log $\sigma(r) = -5$ (*light*) to log $\sigma(r) = 1.5$ (*dark*).

Laughlin & Różyczka, 1996



Gammie, 2001

Solution: A global, single zone model that incorporates these processes can characterize the parameter space of disks in HMSF

Dimensionless Parameters of Accreting Disks

external, imposed quantities vary with environment, while **local** quantities are derived from physical model within the disk

Environment → Derived

$$\frac{\dot{M}_{\rm in}}{M_{*d}\Omega(R_{\rm circ})}$$

$$\mu = \frac{M_d}{M_d + M_*}$$

$$Q = \frac{c_s \kappa}{\pi G \Sigma}$$

$$\frac{\dot{M}_*}{M_d \Omega}$$

1. set by core: increase in system mass / orbital time

2. global disk quantity

3. local disk quantity

4. within the disk: orbital times to drain disk

Dimensionless Parameters of Accreting Disks

external, imposed quantities vary with environment, while **local** quantities are derived from physical model within the disk

Environment → Derived

$$\frac{\dot{M}_{\rm in}}{M_{*d}\Omega(R_{\rm circ})}$$

$$\mu = \frac{M_d}{M_d + M_*}$$

$$Q = \frac{c_s \kappa}{\pi G \Sigma}$$

$$\frac{\dot{M}_*}{M_d \Omega}$$

1. set by core: increase in system mass / orbital time

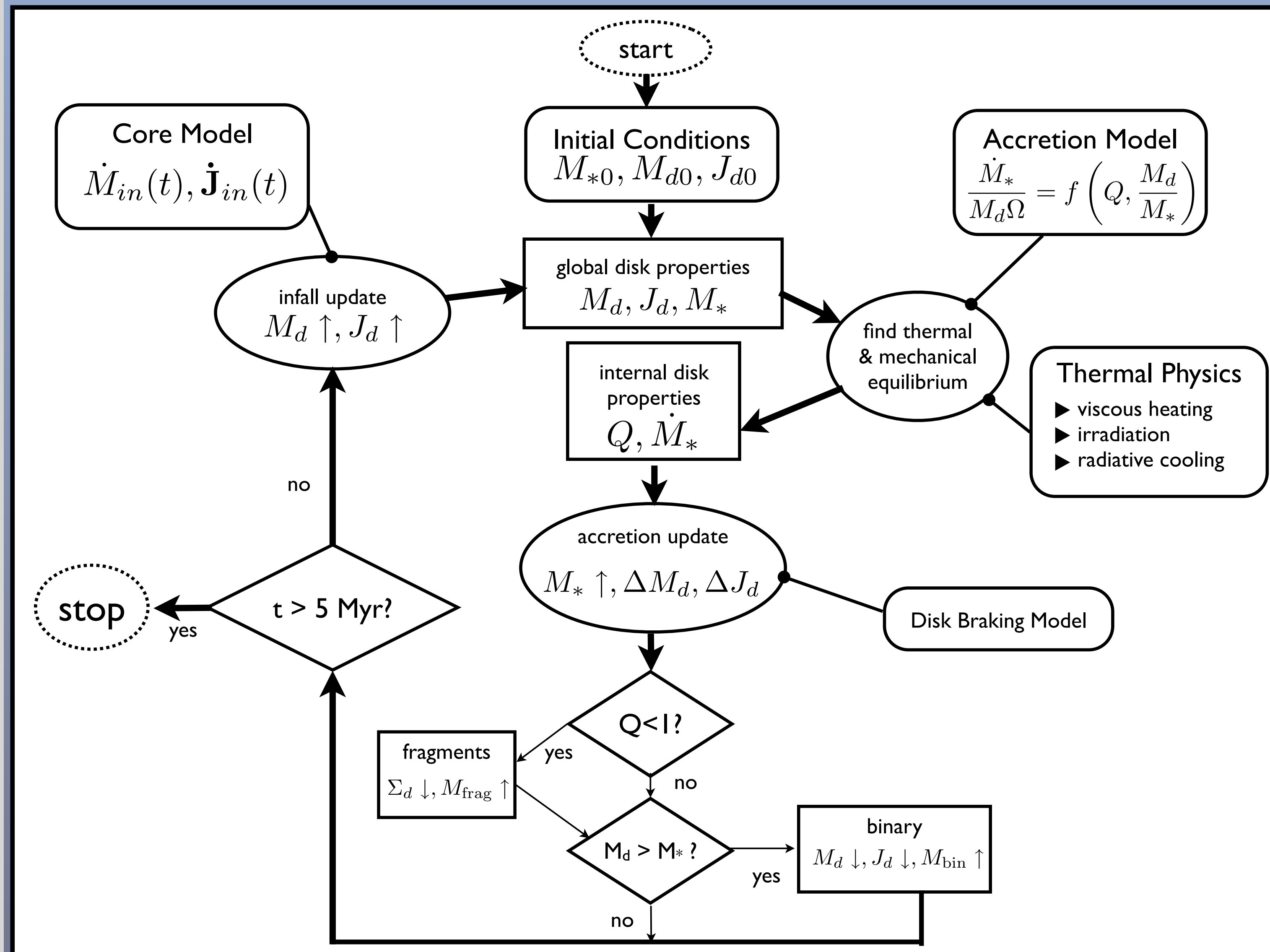
2. global disk quantity

3. local disk quantity

4. within the disk: orbital times to drain disk

- survey the conditions of intermediate-mass and **massive** star formation
- consider fluctuations of the **vector** angular momentum in the infall due to realistic **turbulence** in the collapsing core
- account for dependence of gravitational torques on **disk-to-total mass** ratio Toomre's **Q**
- consider possibility that disks **fragment** when sufficiently unstable
- employ a realistic model for **irradiation** of the disk midplane

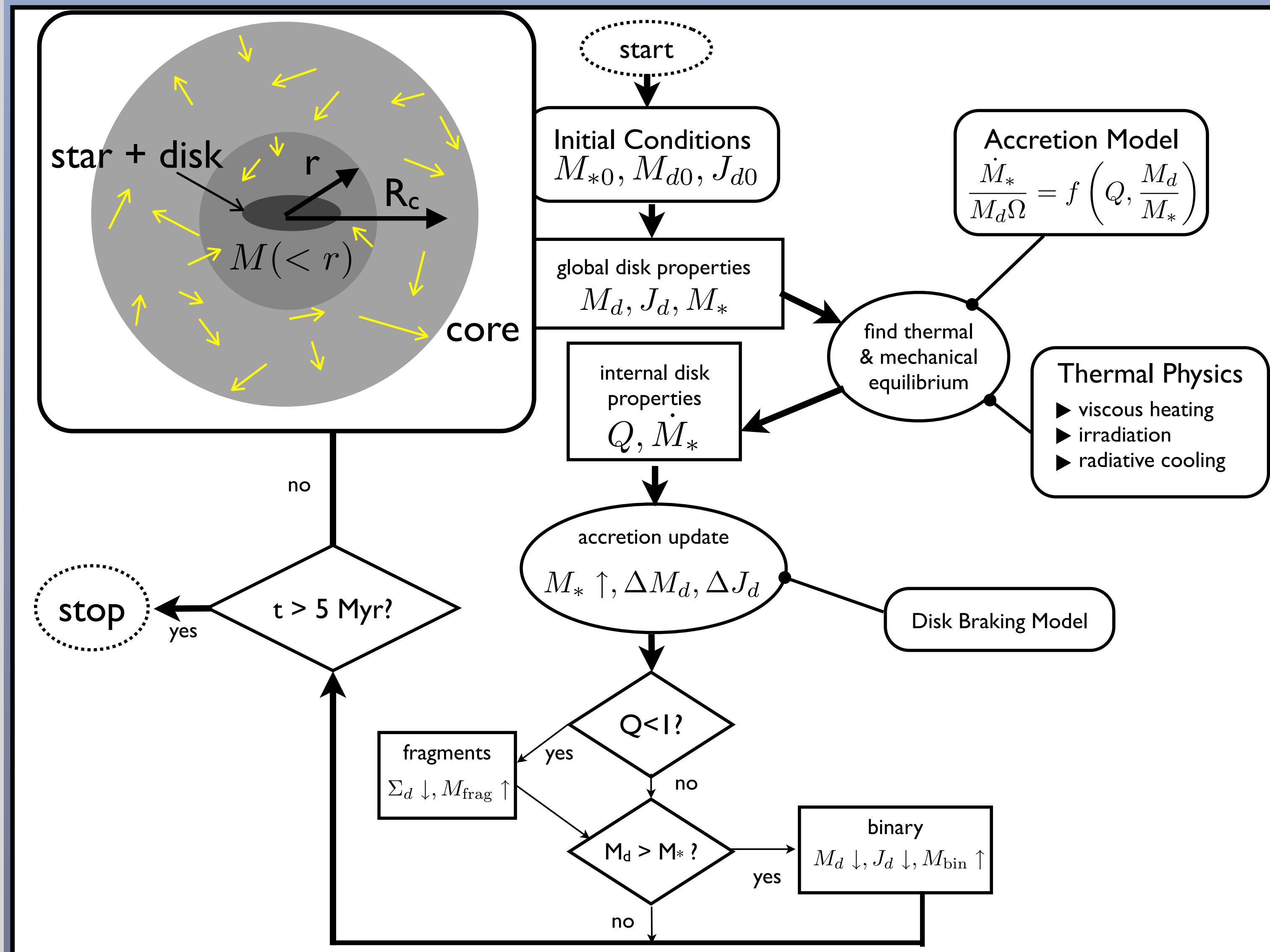
Model Structure



KMK, Matzner, & Krumholz, 2007 (submitted)

Model Structure

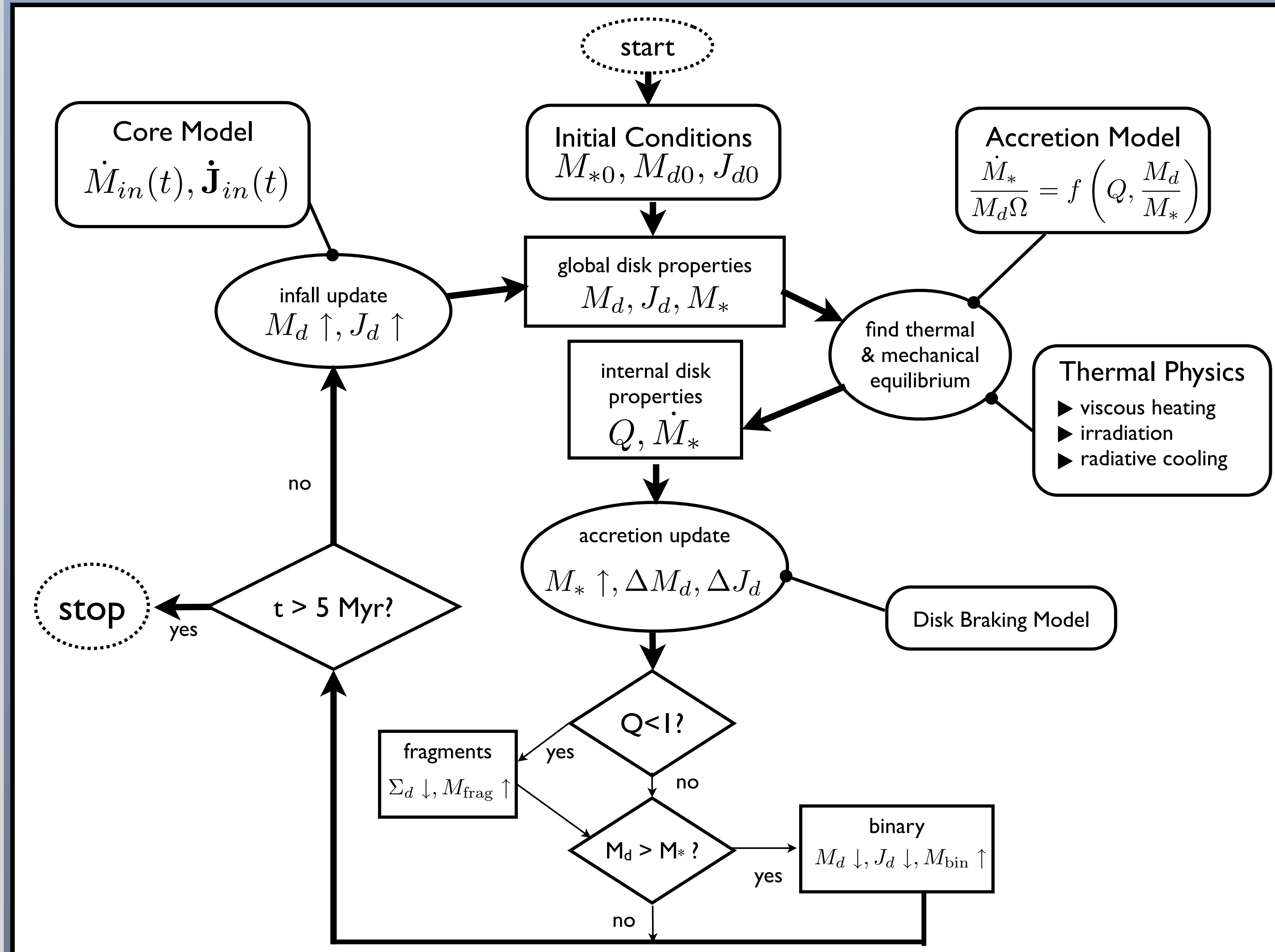
- survey the conditions of intermediate-mass and **massive** star formation
- consider fluctuations of the **vector** angular momentum in the infall due to realistic **turbulence** in the collapsing core
- account for dependence of gravitational torques on **disk-to-total mass** ratio Toomre's **Q**
- consider possibility that disks **fragment** when sufficiently unstable
- employ a realistic model for **irradiation** of the disk midplane



KMK, Matzner, & Krumholz, 2007 (submitted)

- survey the conditions of intermediate-mass and **massive** star formation
- consider fluctuations of the **vector** angular momentum in the infall due to realistic **turbulence** in the collapsing core
- account for dependence of gravitational torques on **disk-to-total mass** ratio Toomre's **Q**
- consider possibility that disks **fragment** when sufficiently unstable
- employ a realistic model for **irradiation** of the disk midplane

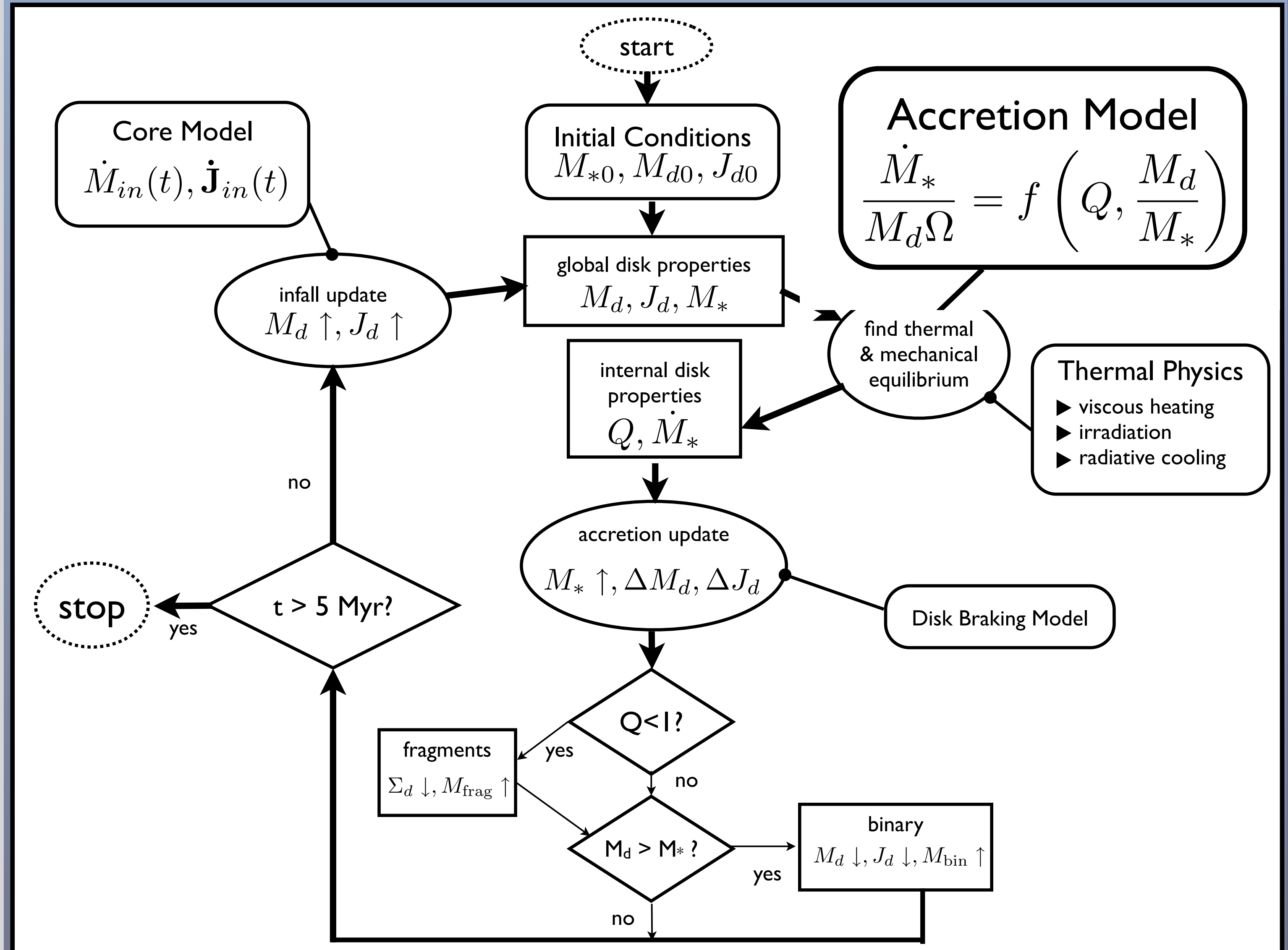
Model Structure



KMK, Matzner, & Krumholz, 2007 (submitted)

Model Structure

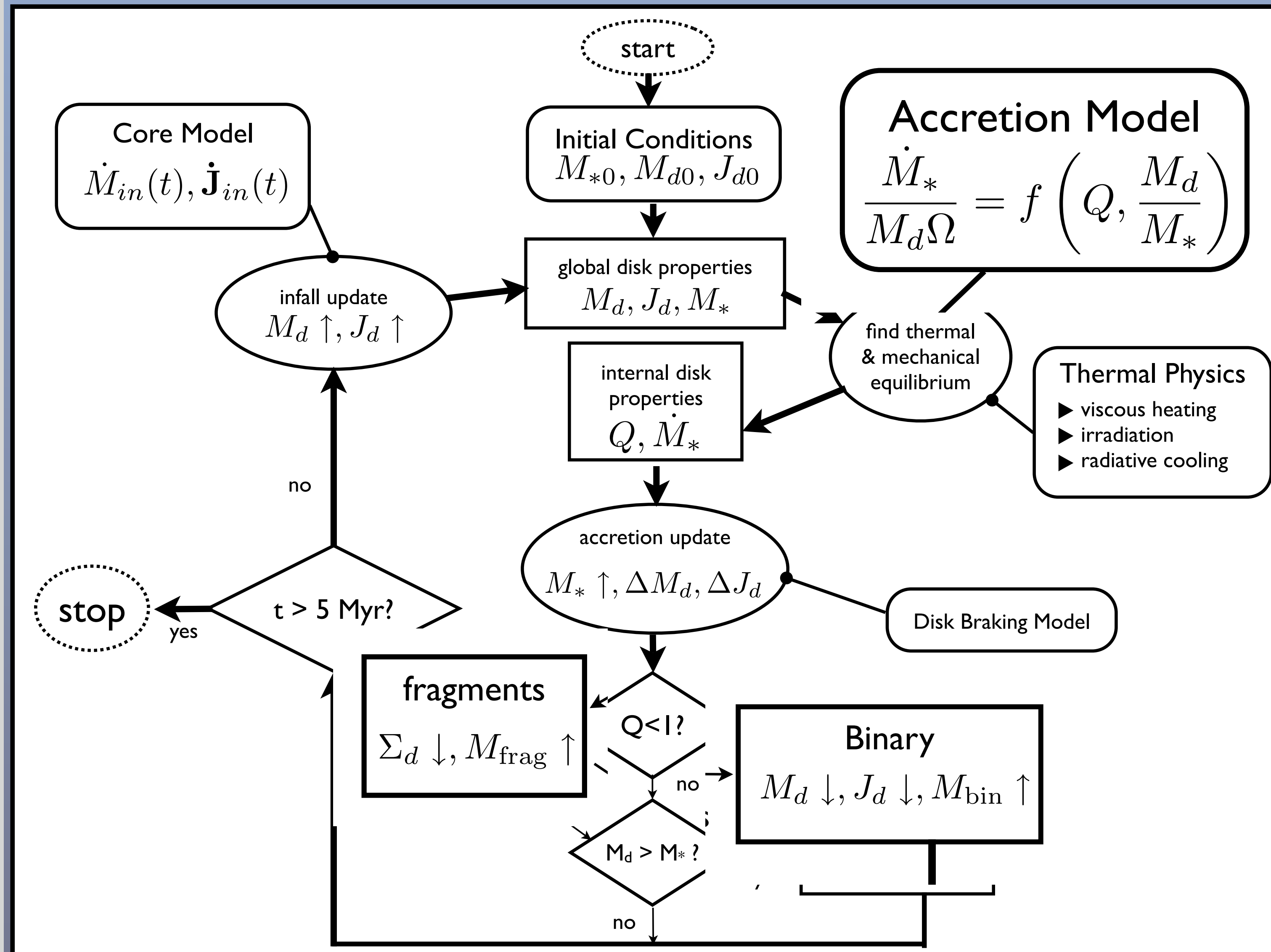
- survey the conditions of intermediate-mass and **massive** star formation
- consider fluctuations of the **vector** angular momentum in the infall due to realistic **turbulence** in the collapsing core
- account for dependence of gravitational torques on **disk-to-total mass** ratio Toomre's **Q**
- consider possibility that disks **fragment** when sufficiently unstable
- employ a realistic model for **irradiation** of the disk midplane



KMK, Matzner, & Krumholz, 2007 (submitted)

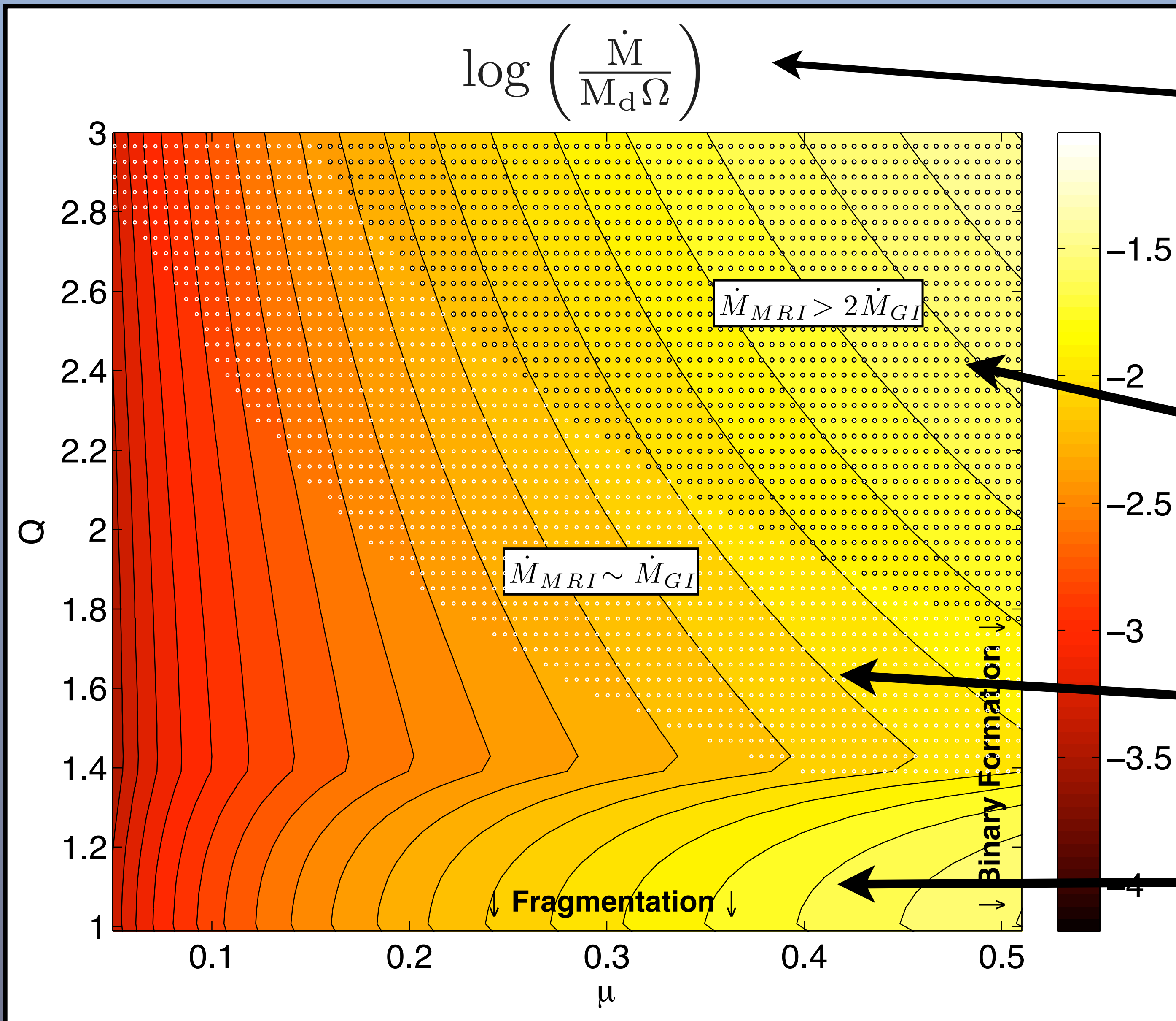
- survey the conditions of intermediate-mass and **massive** star formation
- consider fluctuations of the **vector** angular momentum in the infall due to realistic **turbulence** in the collapsing core
- account for dependence of gravitational torques on **disk-to-total mass** ratio Toomre's **Q**
- consider possibility that disks **fragment** when sufficiently unstable
- employ a realistic model for **irradiation** of the disk midplane

Model Structure



KMK, Matzner, & Krumholz, 2007 (submitted)

Model Components I: Accretion Model



dynamical times to drain the disk

$$\alpha_{\rm MRI} = {\rm const}$$

$$\alpha_{\rm loc} = \begin{cases} 0, & 1.4 < Q; \\ 0.3\frac{1.4-Q}{0.4}, & 1 < Q < 1.4; \\ 0.3 & Q < 1 \end{cases}$$

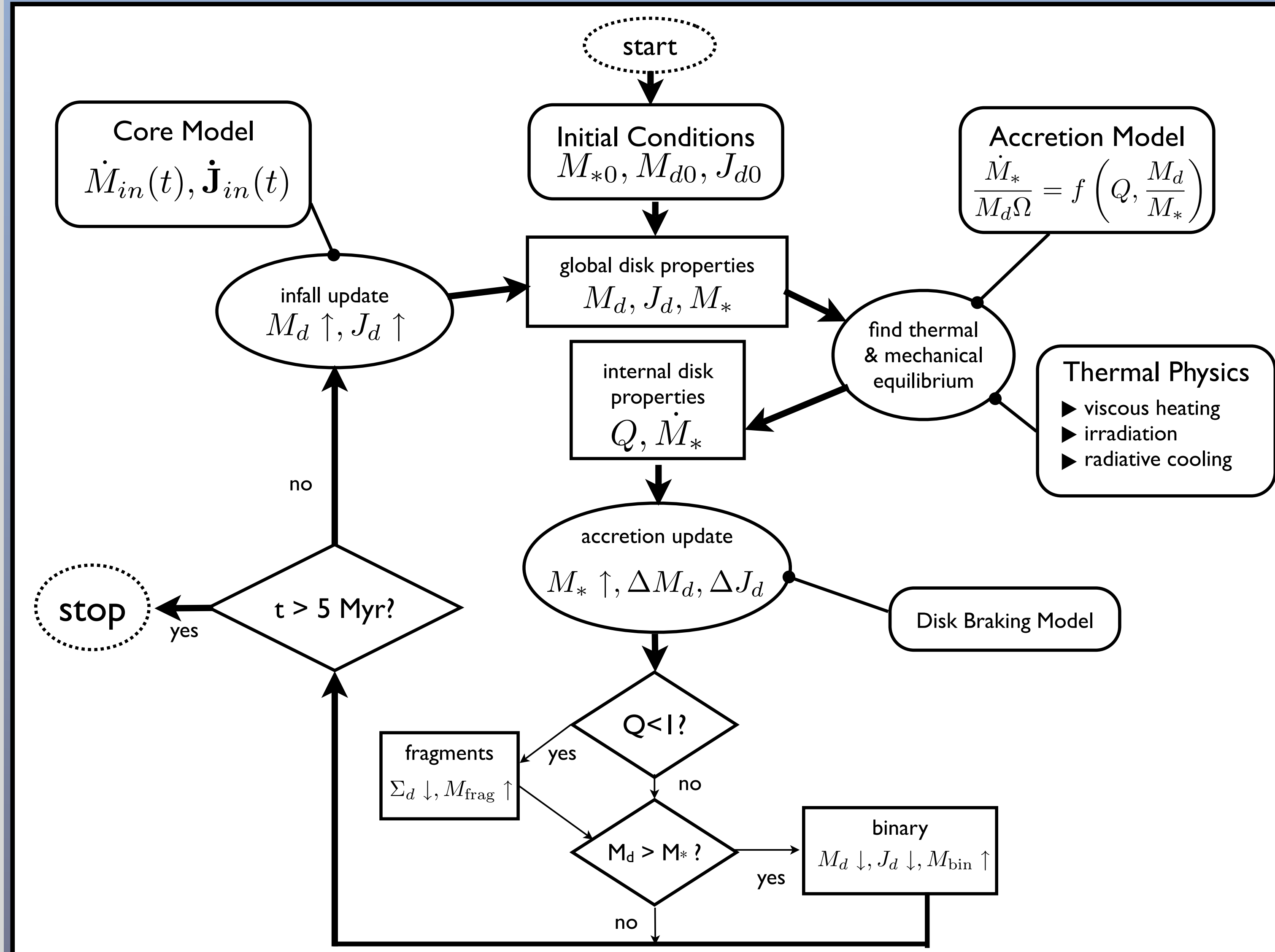
$$\frac{\dot{M}_{*,{\rm glob}}}{M_d \Omega} = .0152\mu - .0004.$$

$$\frac{\dot{M}_{*,{\rm loc}}}{M_d \Omega} = \frac{3\alpha_{\rm loc} Q^2}{8}\left(\frac{M_d}{M_*}\right)^2$$

$$\dot{M}_{*,{\rm tot}} = \left(\dot{M}^2_{*,{\rm loc}} + \dot{M}^2_{*,{\rm glob}} + \dot{M}^2_{*,{\rm MRI}}\right)^{1/2}$$

- survey the conditions of intermediate-mass and **massive** star formation
- consider fluctuations of the **vector** angular momentum in the infall due to realistic **turbulence** in the collapsing core
- account for dependence of gravitational torques on **disk-to-total mass** ratio Toomre's **Q**
- consider possibility that disks **fragment** when sufficiently unstable
- employ a realistic model for **irradiation** of the disk midplane

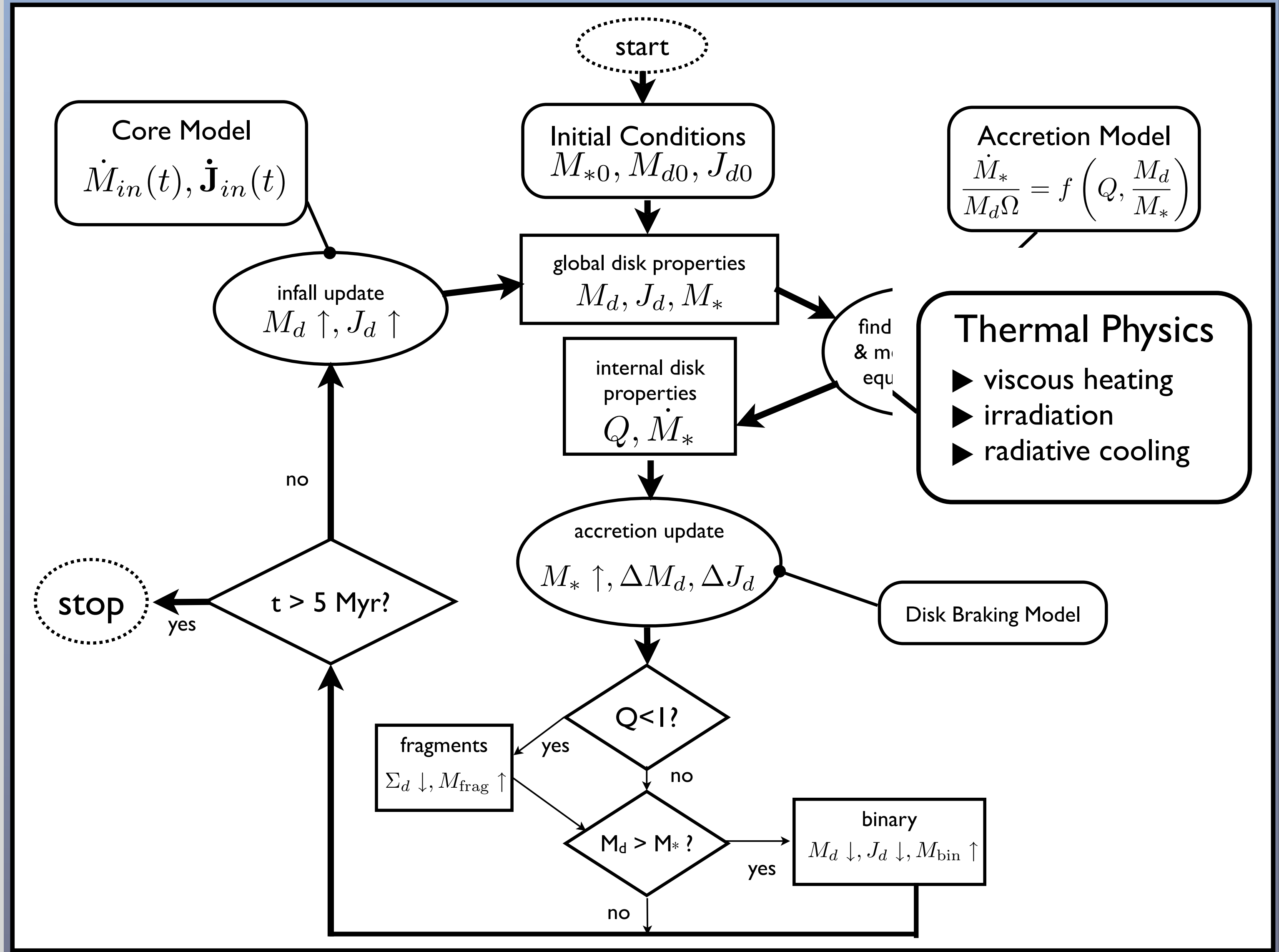
Model Structure



KMK, Matzner, & Krumholz, 2007 (submitted)

Model Structure

- survey the conditions of intermediate-mass and **massive** star formation
- consider fluctuations of the **vector** angular momentum in the infall due to realistic **turbulence** in the collapsing core
- account for dependence of gravitational torques on **disk-to-total mass** ratio Toomre's **Q**
- consider possibility that disks **fragment** when sufficiently unstable
- employ a realistic model for **irradiation** of the disk midplane



KMK, Matzner, & Krumholz, 2007 (submitted)

Model Components II: Heating & Cooling

$$\sigma T^4 = \left(\frac{8}{3}\tau_R + \frac{1}{4\tau_P}\right) F_v + F_{\rm irr}$$

accretion + irradiation contribute *significantly* to disk heating even at high $\dot{M}$

irradiation model accounts for optically thin & thick regimes for two cases:

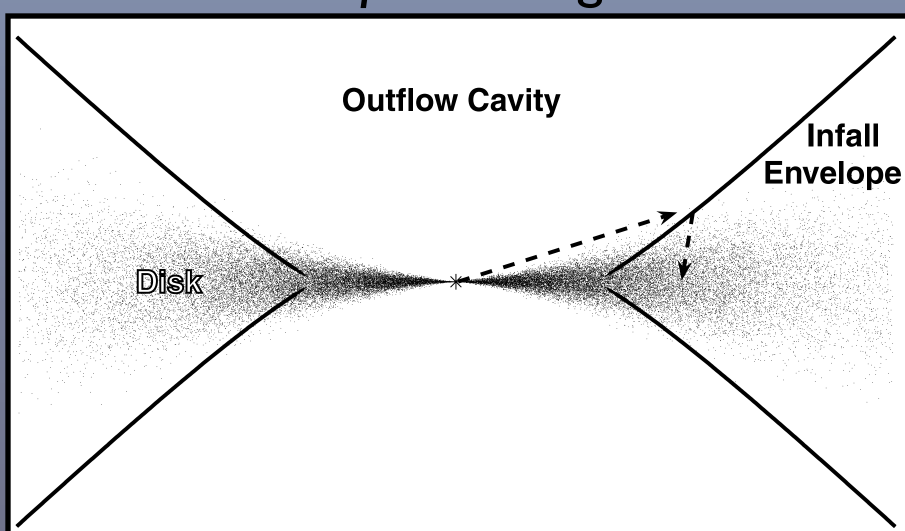
Model Components II: Heating & Cooling

$$\sigma T^4 = \left(\frac{8}{3}\tau_R + \frac{1}{4\tau_P}\right) F_v + F_{\rm irr}$$

accretion + irradiation contribute *significantly* to disk heating even at high $\dot{M}$

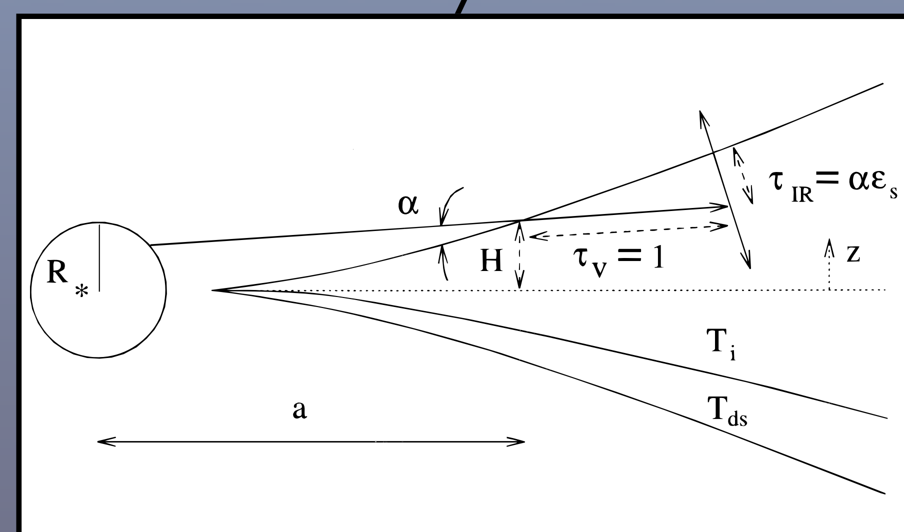
irradiation model accounts for optically thin & thick regimes for two cases:

during core accretion -- envelope reprocessing



Matzner & Levin, 2005

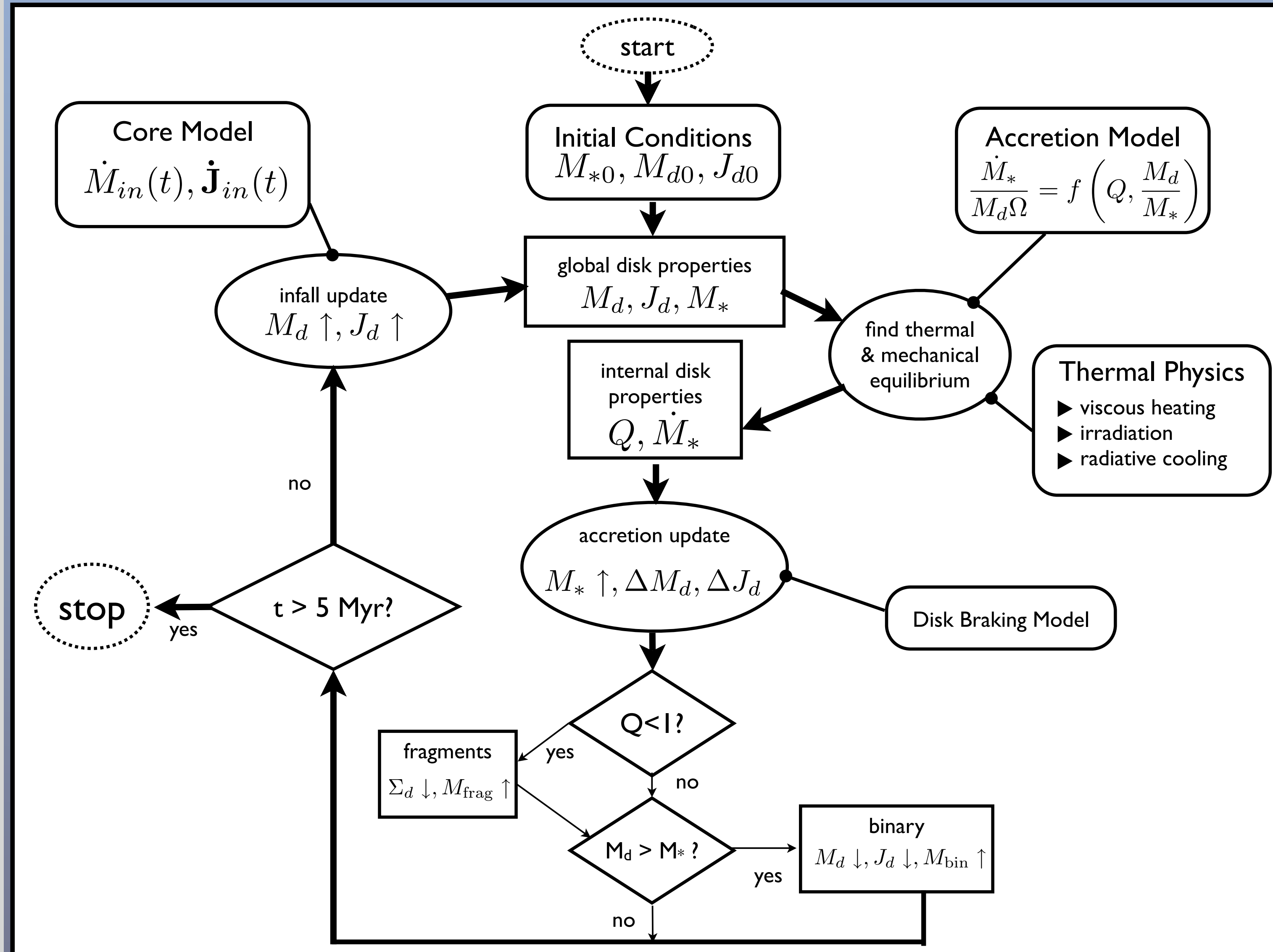
after core accretion -- radiating dust layer



Chiang & Goldreich, 1997

- survey the conditions of intermediate-mass and **massive** star formation
- consider fluctuations of the **vector** angular momentum in the infall due to realistic **turbulence** in the collapsing core
- account for dependence of gravitational torques on **disk-to-total mass** ratio Toomre's **Q**
- consider possibility that disks **fragment** when sufficiently unstable
- employ a realistic model for **irradiation** of the disk midplane

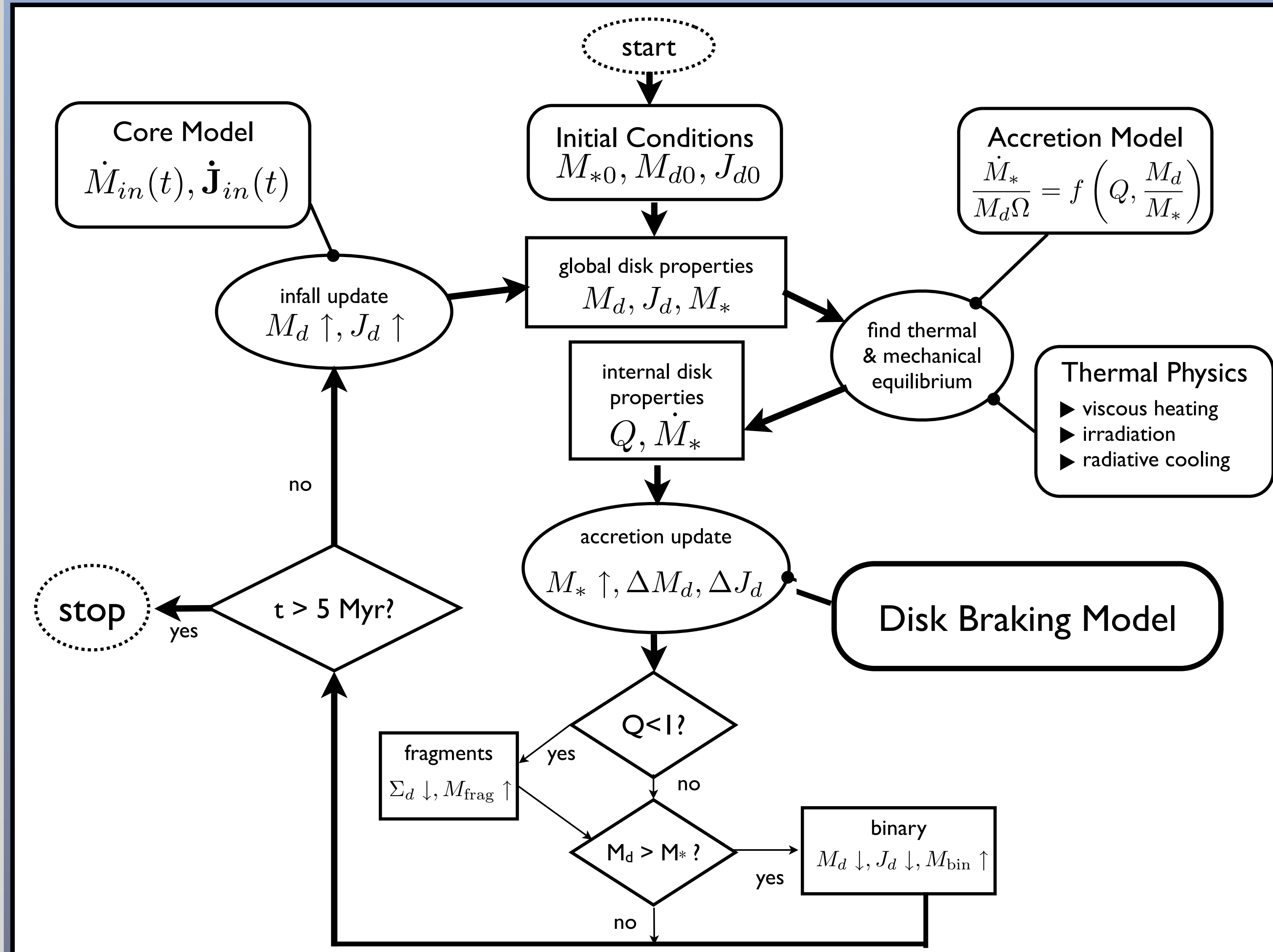
Model Structure



KMK, Matzner, & Krumholz, 2007 (submitted)

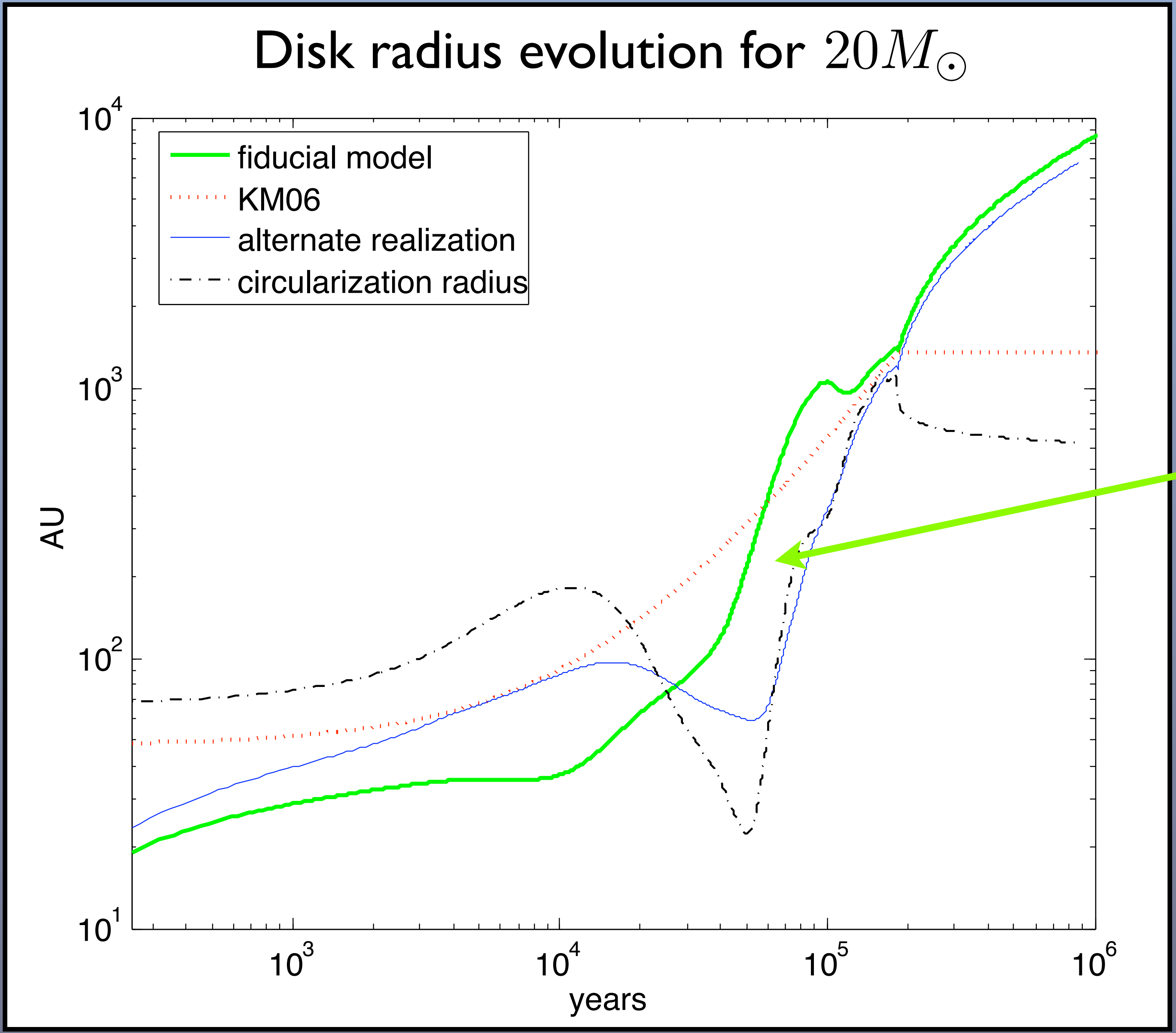
- survey the conditions of intermediate-mass and **massive** star formation
- consider fluctuations of the **vector** angular momentum in the infall due to realistic **turbulence** in the collapsing core
- account for dependence of gravitational torques on **disk-to-total mass** ratio Toomre's **Q**
- consider possibility that disks **fragment** when sufficiently unstable
- employ a realistic model for **irradiation** of the disk midplane

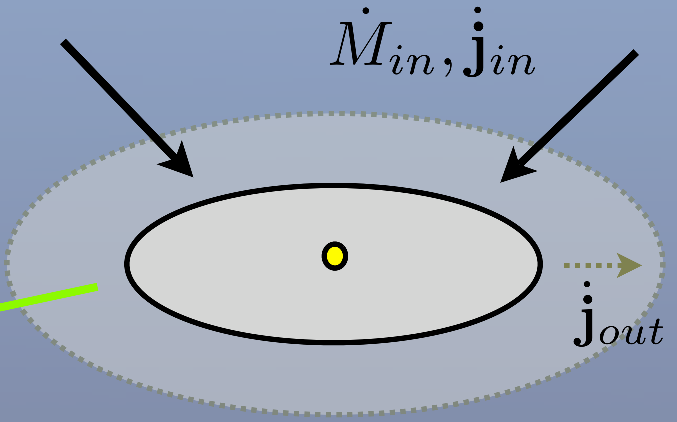
Model Structure



KMK, Matzner, & Krumholz, 2007 (submitted)

Model Components III: Outer disk braking

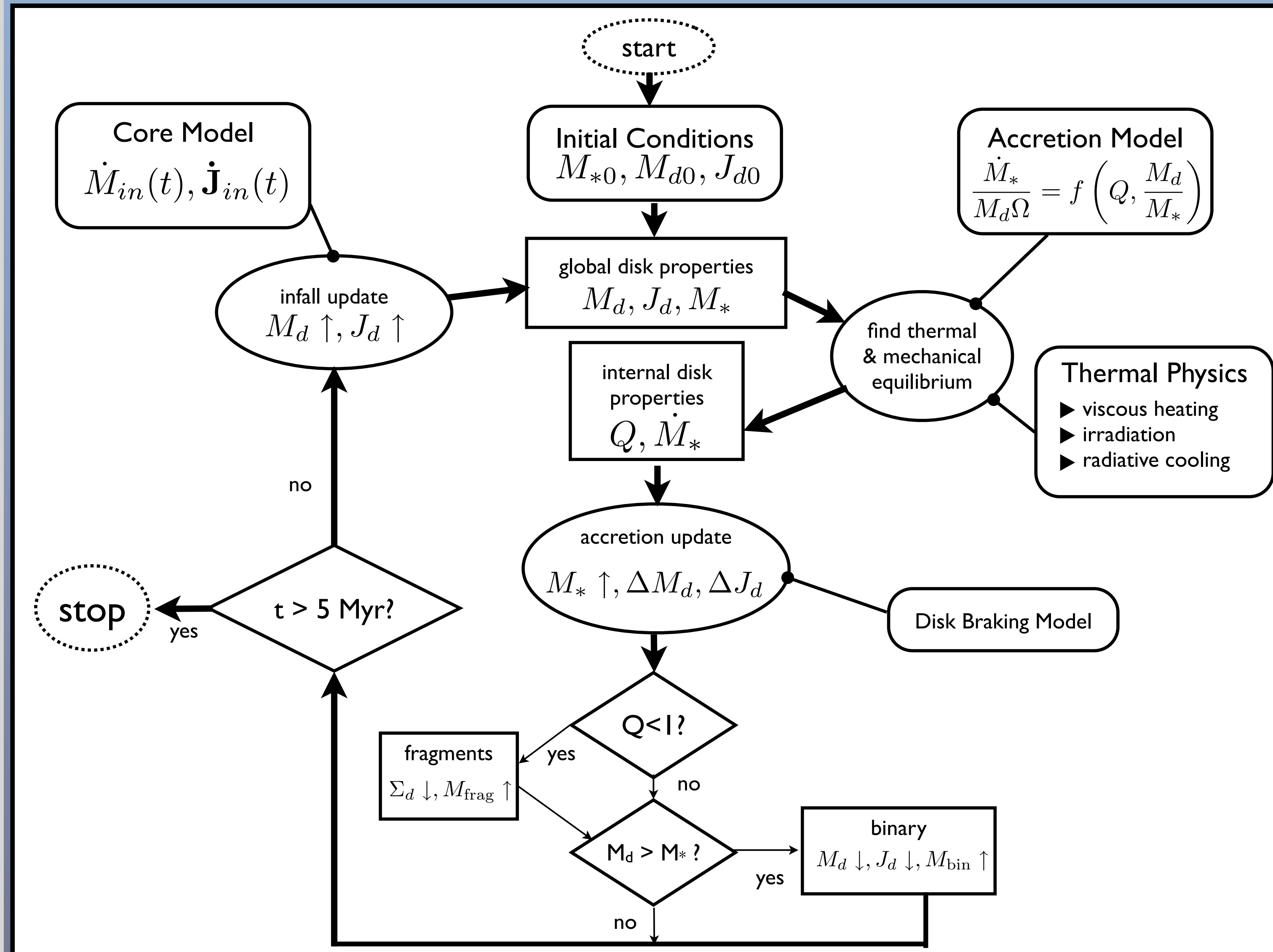




$$\dot{\mathbf{J}}_d = \mathbf{j}_{\rm in}\dot{M}_{\rm in} - b_j \left(\frac{\dot{M}_{\rm in}}{\dot{M}_*}\right)\frac{\dot{M}_{\rm in}}{M_d}\mathbf{J}_d.$$

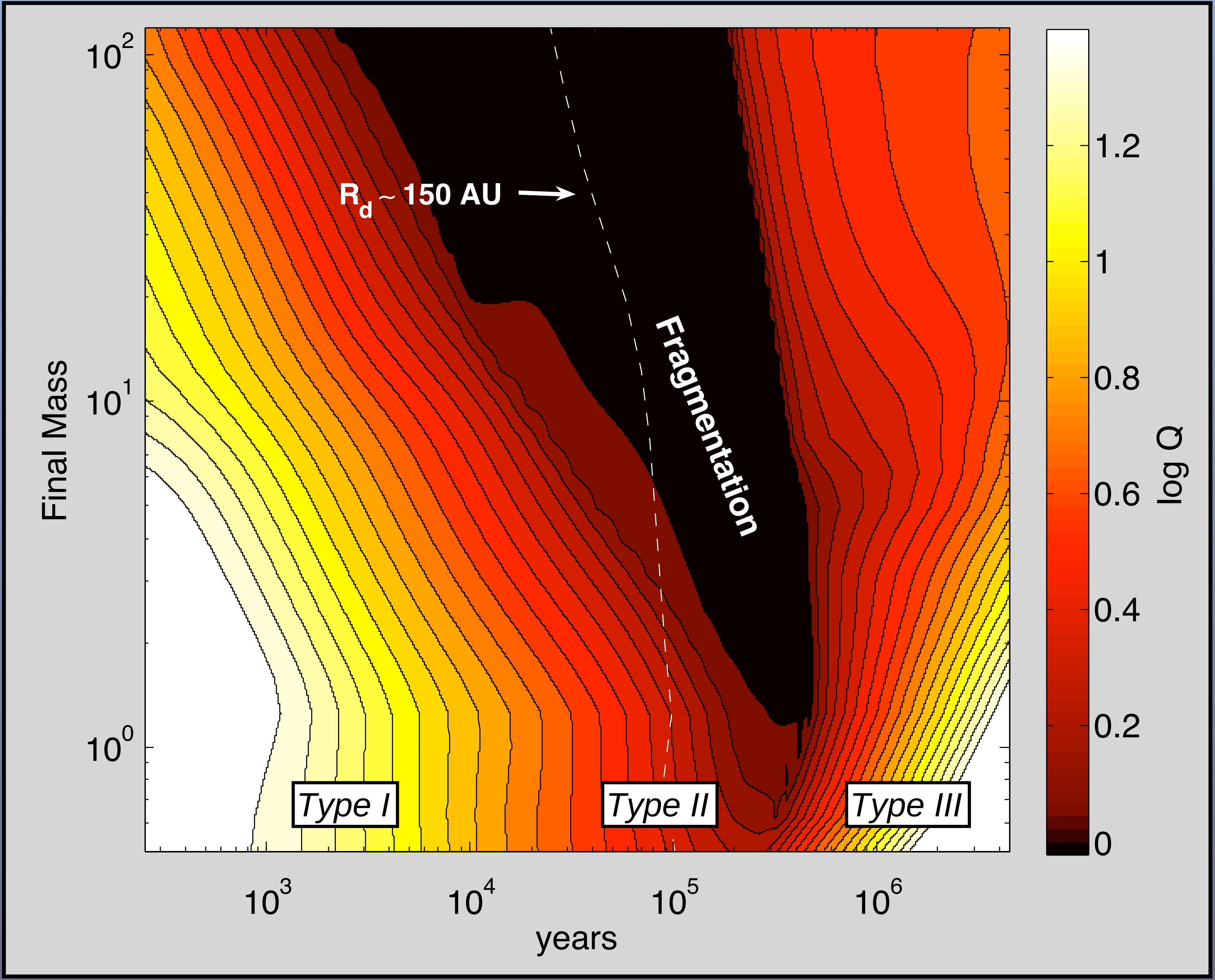
- survey the conditions of intermediate-mass and **massive** star formation
- consider fluctuations of the **vector** angular momentum in the infall due to realistic **turbulence** in the collapsing core
- account for dependence of gravitational torques on **disk-to-total mass** ratio Toomre's **Q**
- consider possibility that disks **fragment** when sufficiently unstable
- employ a realistic model for **irradiation** of the disk midplane

Model Structure

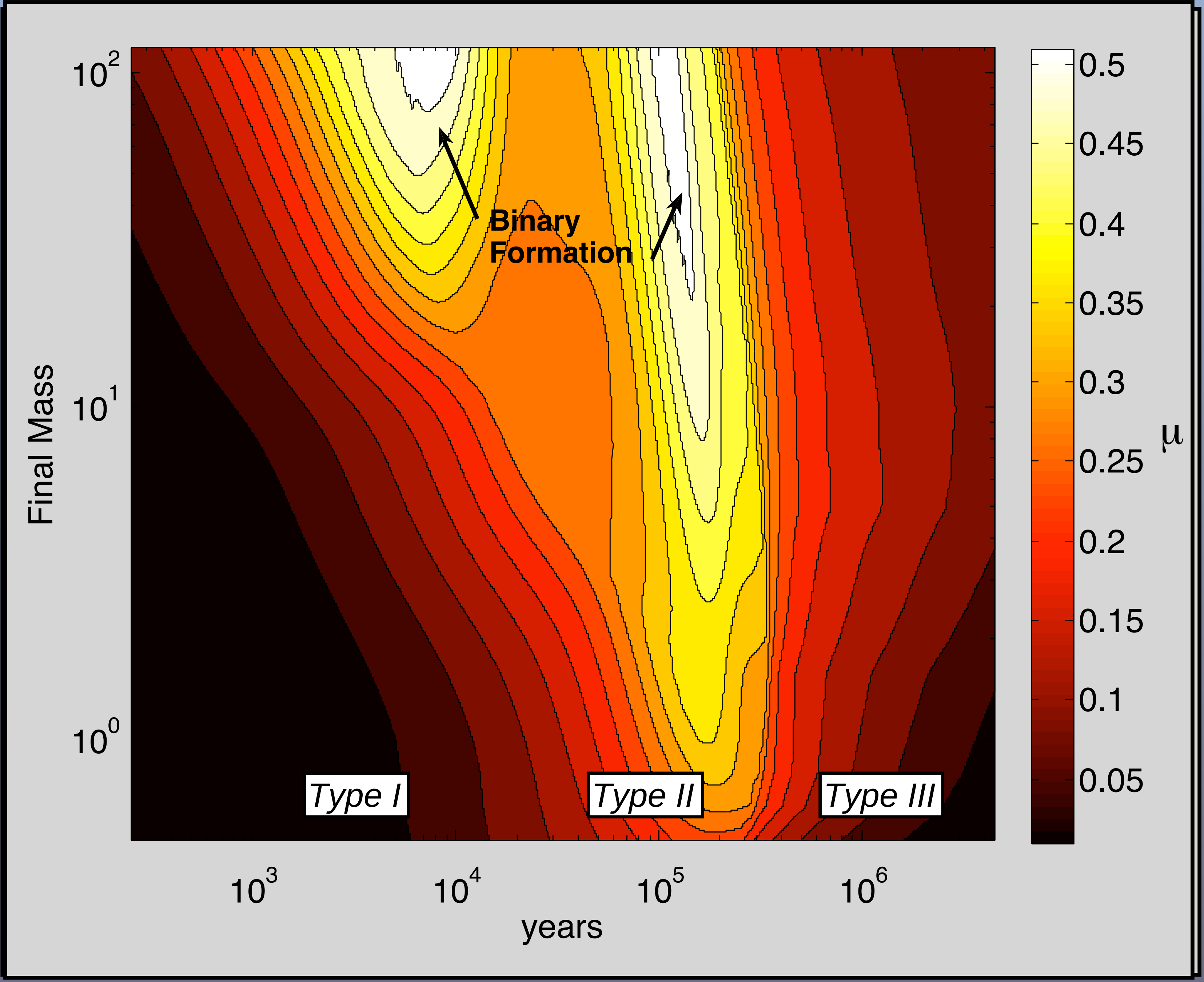


KMK, Matzner, & Krumholz, 2007 (submitted)

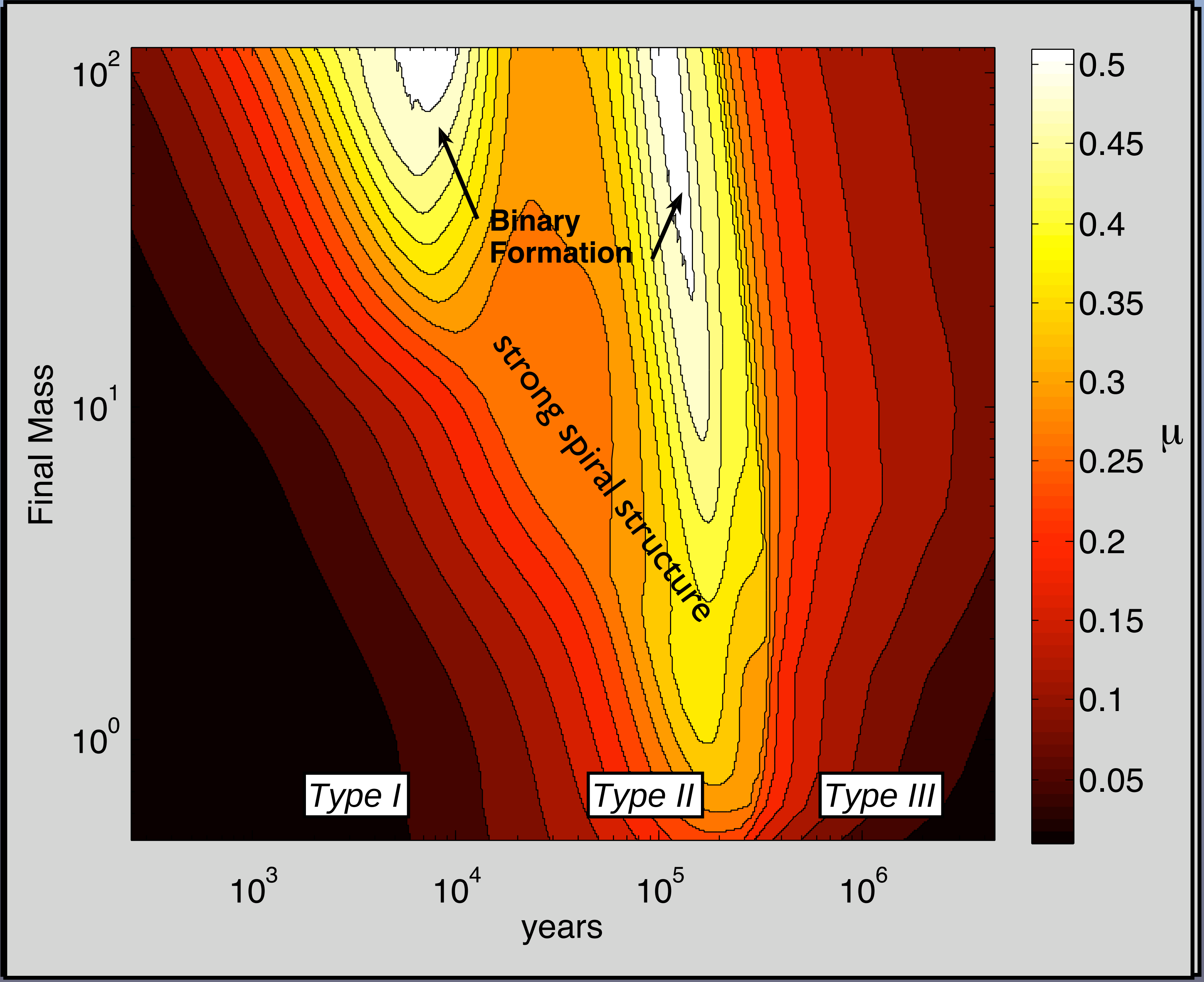
Evolution of Q and μ



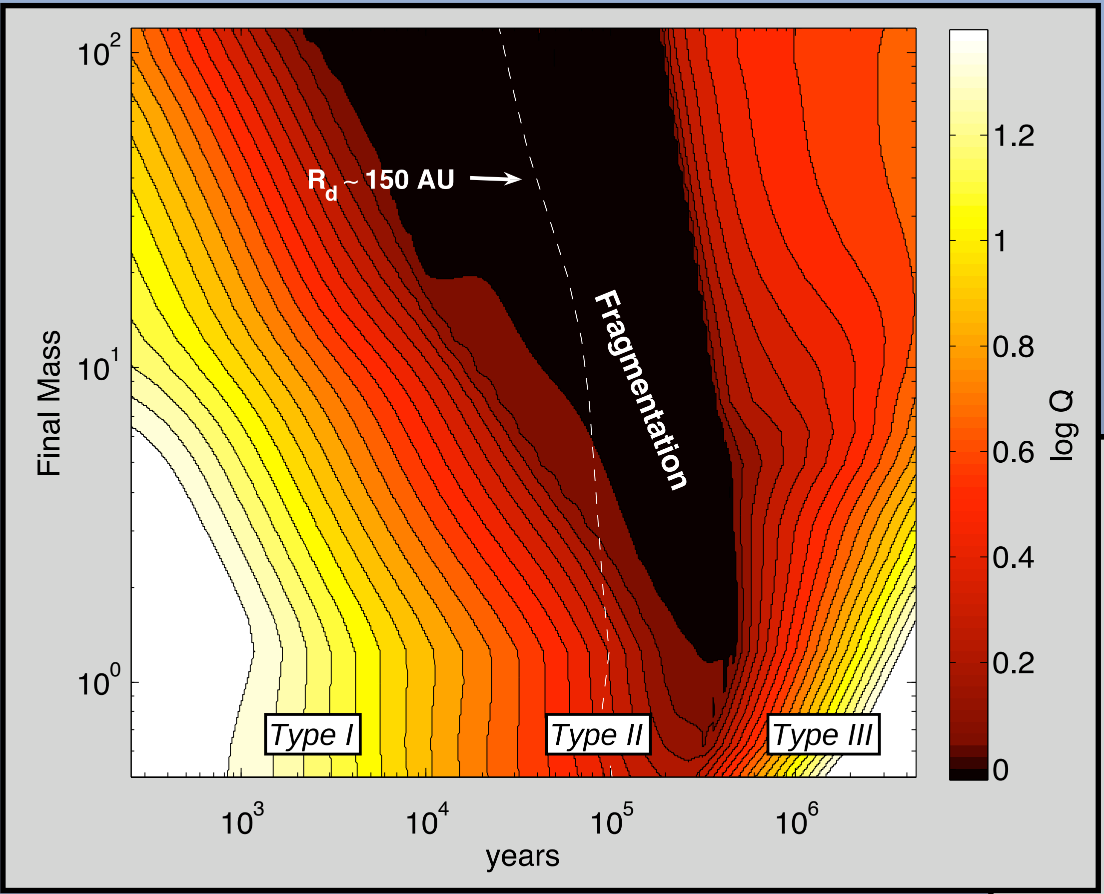
Evolution of Q and μ

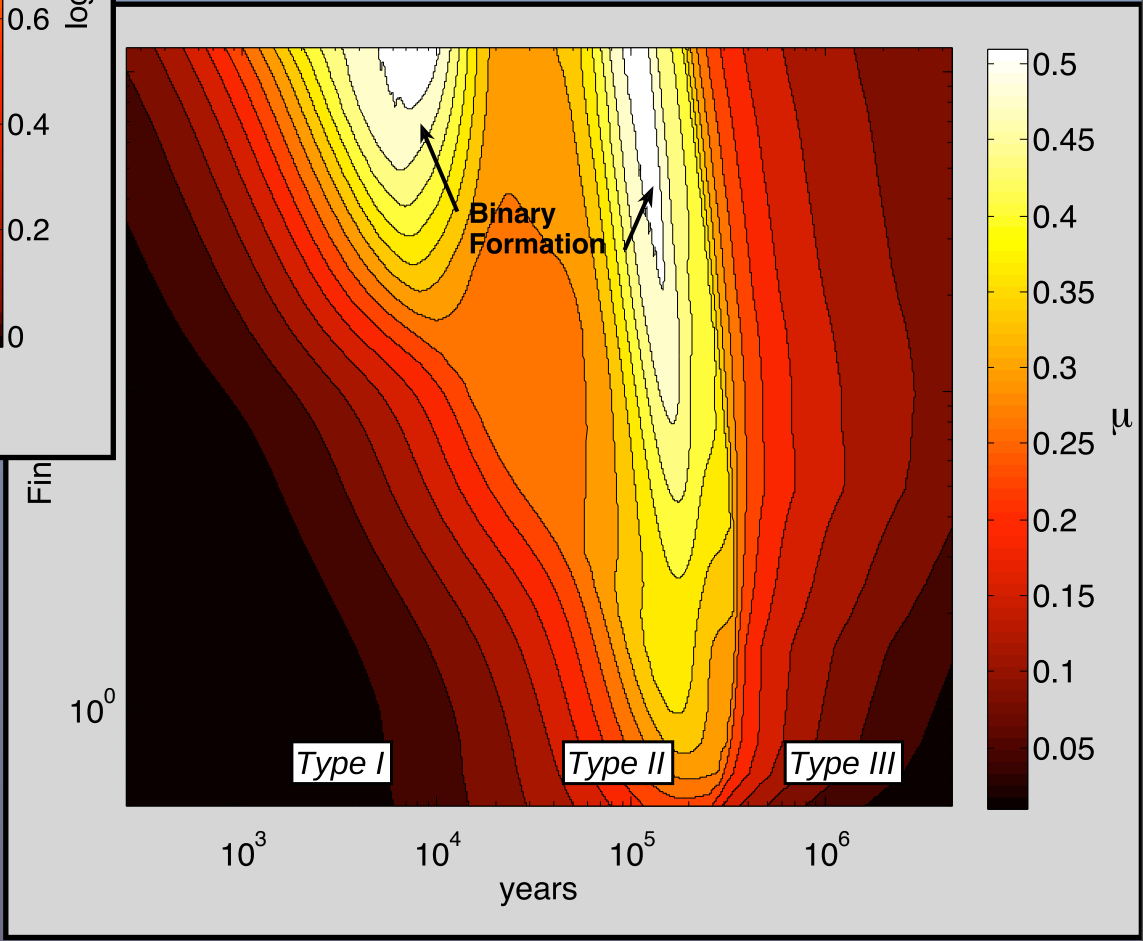


Evolution of Q and μ



Evolution of Q and μ



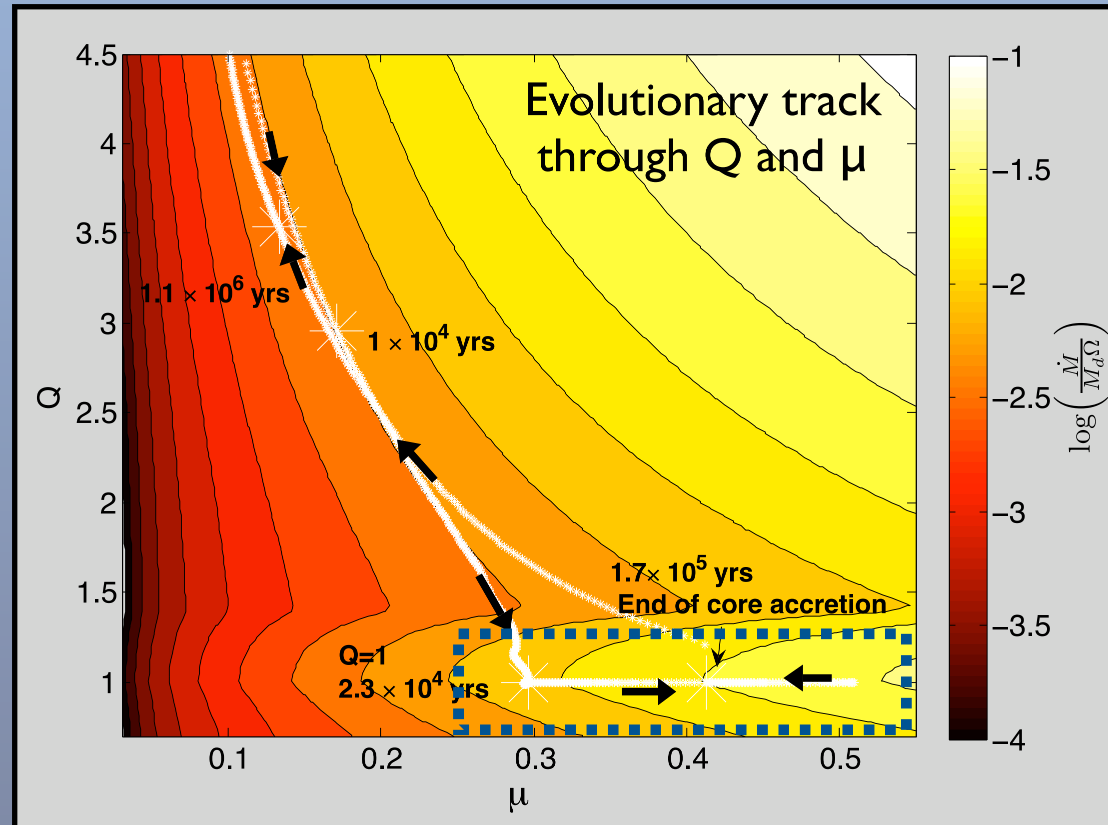


Characteristics of a 15 $M_\odot$ star

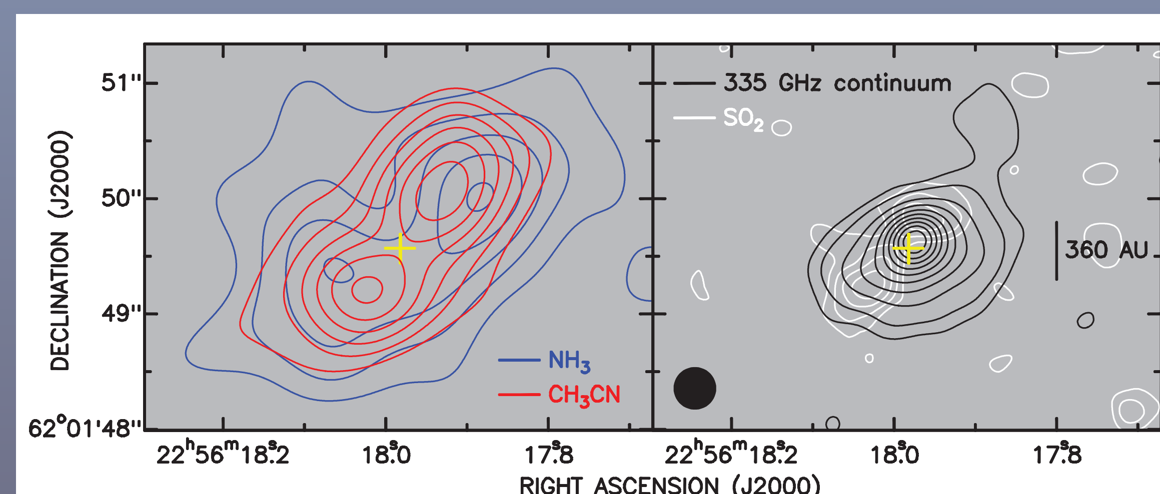
- **Disk properties:**

$$T_d \approx 100\text{K}$$
$$R_d \approx 200\text{AU}$$
$$\Sigma_d \approx 50 \text{ g/cm}^2$$
$$\mu \approx 0.35$$

- **Detectable?**
  - ALMA: yes (< 2-3 Kpc)
  - EVLA: yes (< 0.5 Kpc) (Krumholz et al, 2007)



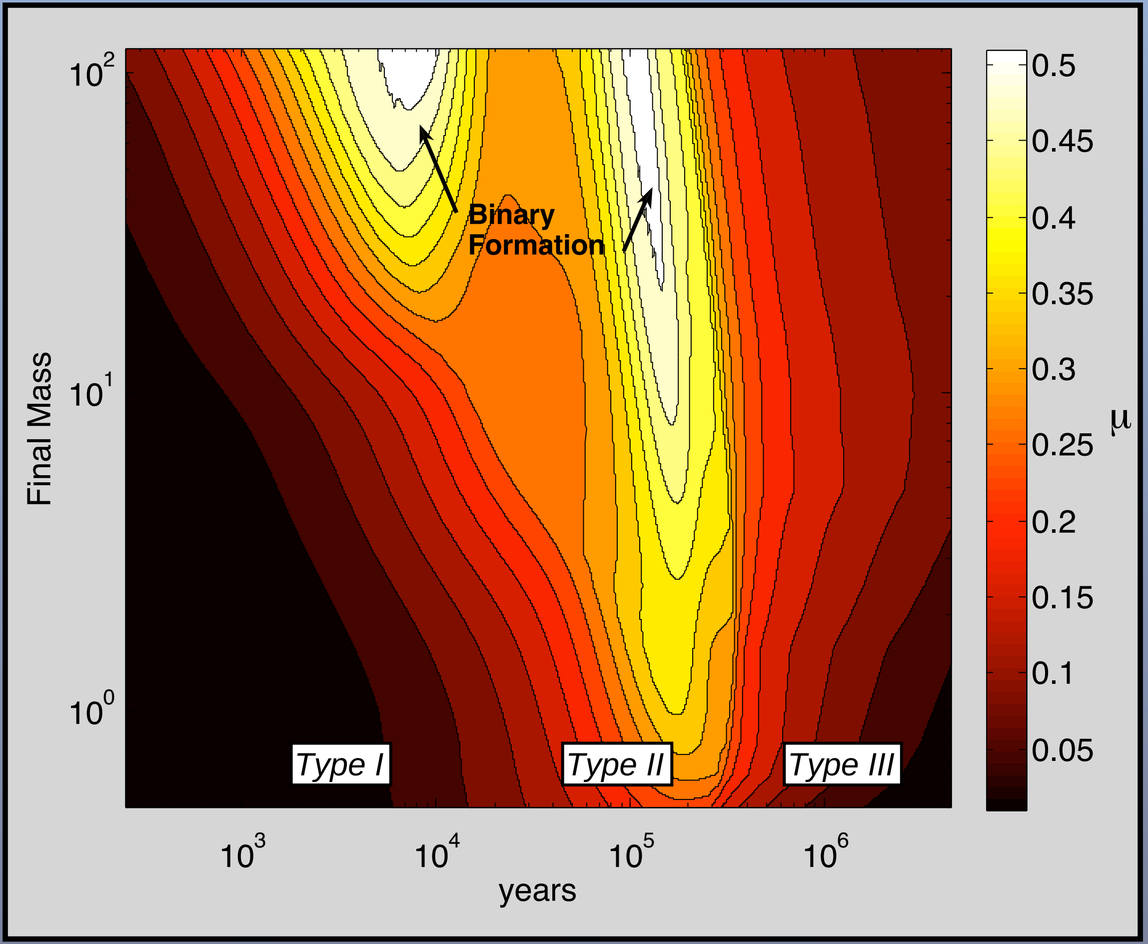
Observed disk around Ceph A HW 2: Patel et al. 2005, Torrelles et al 2007*, & Jimenez-Serra et al 2007 measure similar characteristics



Torrelles et al, 2007

*see poster

Observational Classification

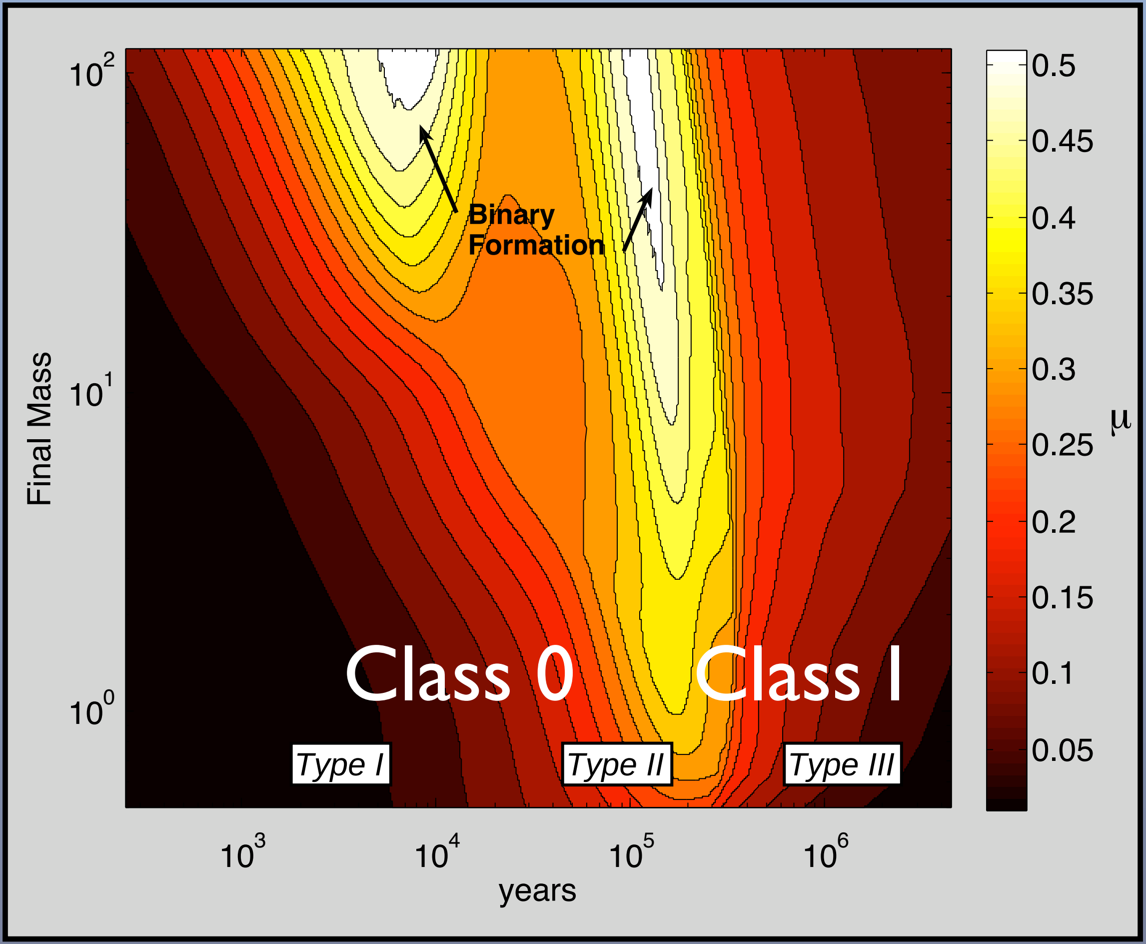


- **Type I**
  - $< 10^4$ yrs
  - stable (local & global)
  - small disk mass
- **Type II**
  - 10^4-$10^{5.5}$ yrs
  - core mass dependence
  - stability:
    - spiral vs fragmentation
  - significant disk mass
- **Type III**
  - $>10^{5.5}$ yrs
  - higher Q
  - small disk mass

Disks with μ > 0.2 around stars with masses $> 8 M_\odot$ should be detectable with ALMA (d ~ few Kpc) and EVLA (d ~0.5 Kpc)

Type II disks should have strong spiral arms (m=1,2) which are easy to find in surveys by observing the disk morphology in the continuum

Observational Classification



- **Type I**
  - < 10^4 yrs
  - stable (local & global)
  - small disk mass
- **Type II**
  - 10^4-$10^{5.5}$ yrs
  - core mass dependence
  - stability:
    - spiral vs fragmentation
  - significant disk mass
- **Type III**
  - >$10^{5.5}$ yrs
  - higher Q
  - small disk mass

Disks with μ > 0.2 around stars with masses $> 8M_{\odot}$ should be detectable with ALMA (d ~ few Kpc) and EVLA (d ~0.5 Kpc)

Type II disks should have strong spiral arms (m=1,2) which are easy to find in surveys by observing the disk morphology in the continuum

Conclusions

- Massive, rapidly accreting disks: Type II
  - Occur during the deeply embedded, Class 0 phase
  - $M_d \sim .3M_*$ for much of accretion, with $R_d \sim$ 200-400 AU
  - Local instability and fragmentation persists for $\sim 10^5$ years
  - Strong spiral arm structure should produce observable, non-Keplerian motion
  - Outer disk temperatures exceed 100K for stars > 10 $M_\odot$
  - Outer disk peak column densities ~50 g/cm^2
- Binary formation through disk fission for cores > 30 $M_\odot$
  - Core angular momentum profile has strong influence
- Environmental variables (Σ_c, T_c) do not qualitatively change these conclusions