Massive, Embedded, Accreting, Protostellar Disks

Kaitlin Kratter
University of Toronto

Collaborators:

Chris Matzner (U. Toronto)

Mark Krumholz (Princeton/UC Santa Cruz)

November 16th, 2007

KITP

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~~....a theorist’s version of a survey~~

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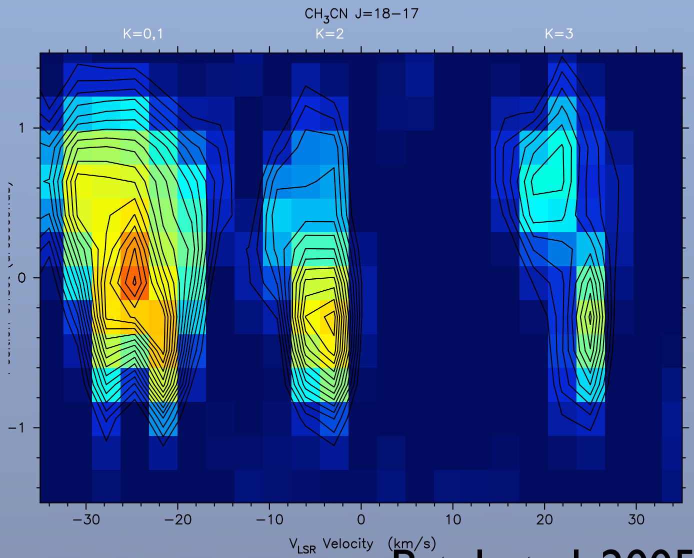
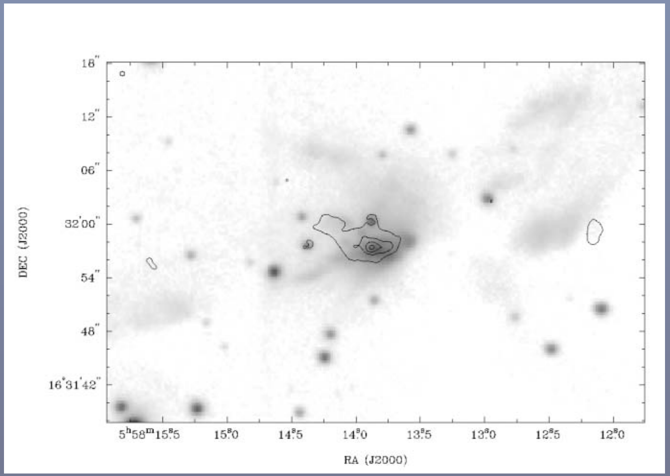
Disks in Massive Star Formation?

- **Theoretically**: existence of disks is a robust result independent of specific formation mechanism
- fundamental in circumventing accretion barrier of radiation pressure (e.g. Wolfire & Cassinelli, 1987, Krumholz et al. 2005)
- may play a role in determining binarity and upper mass cutoff (e.g. Kratter & Matzner, 2006, Moeckel & Bally, 2007)
- **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 do we want to know?

What dominates angular momentum transport?

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

How will these disks appear to ALMA and the EVLA?

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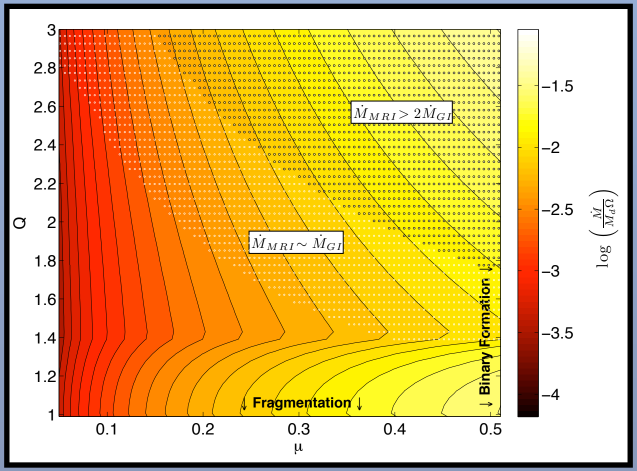

Kratter, Matzner, & Krumholz, 2007 (submitted)

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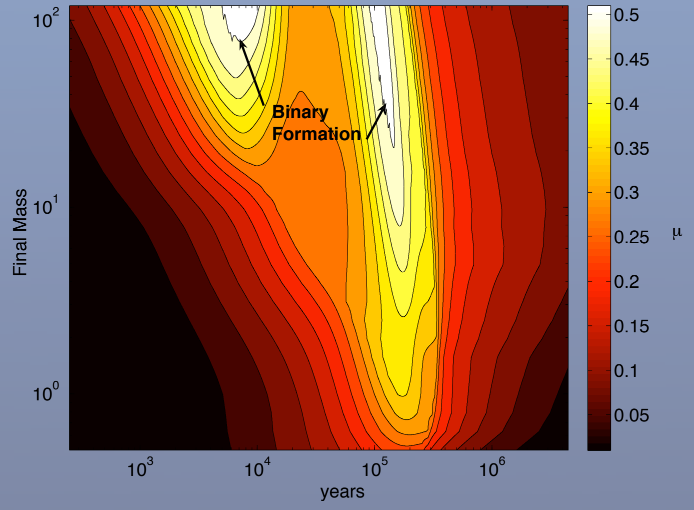
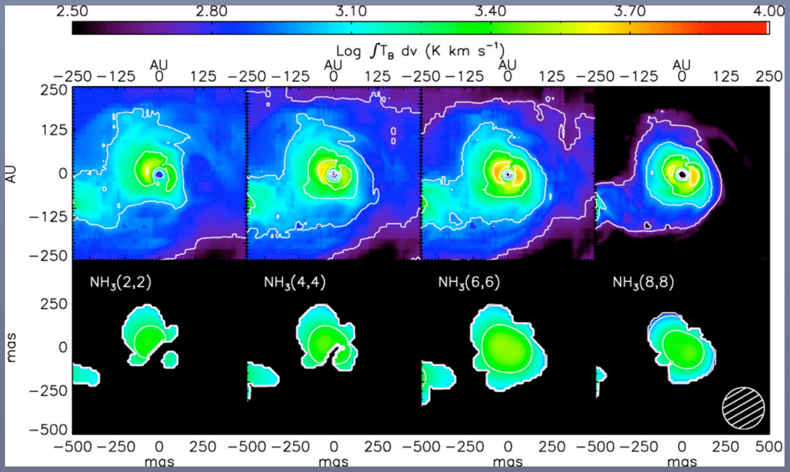
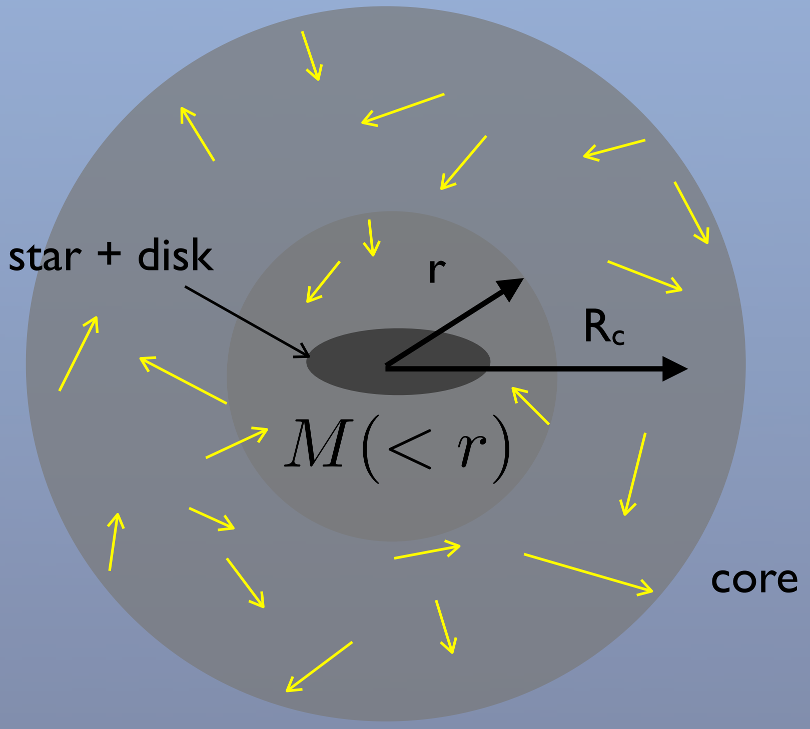




Krumholz, et al. 2007

How will these disks appear to ALMA and the EVLA?

Physical Scenario

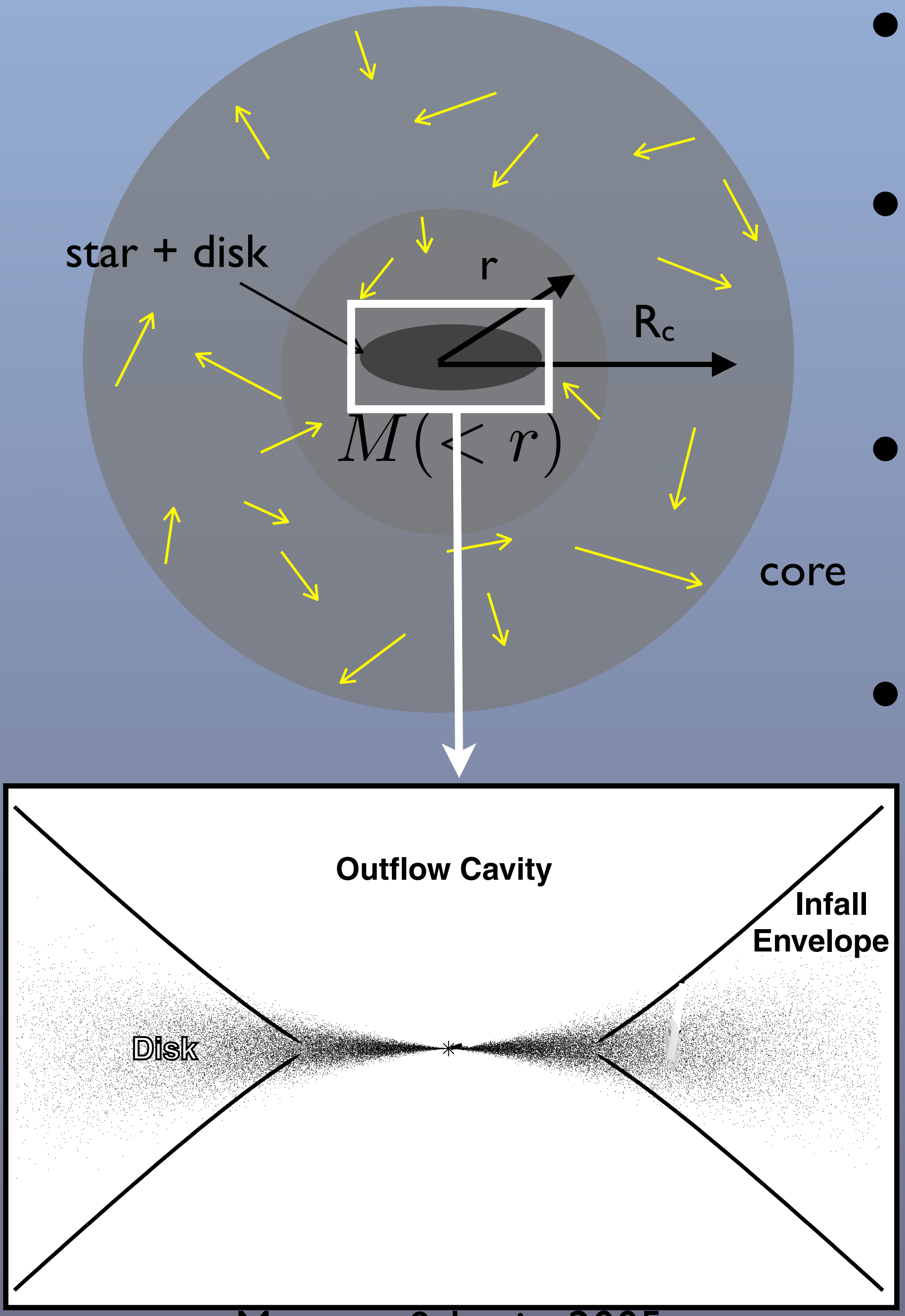


- Turbulent region (core / "entity") begins to collapse
- Cloud pressure and core temperature determine the magnitude of turbulent support
- Net angular momentum determines circularization radius of the infalling material as f(t)
- Magnetic fields?

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

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

Physical Scenario



Matzner & Levin, 2005

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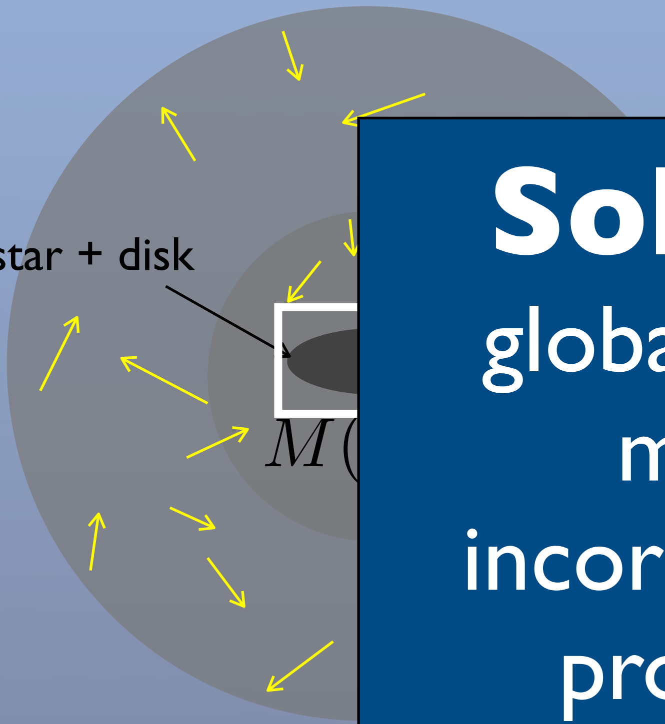

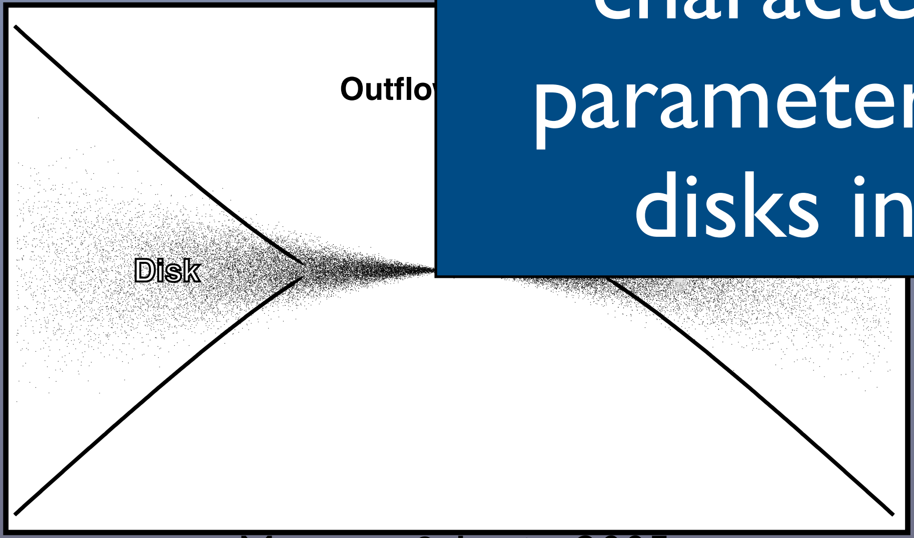

Matzner & Levin, 2005

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

high column cores
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Problem II: large parameter space to explore numerically with MHD + SG + radiation + ...

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

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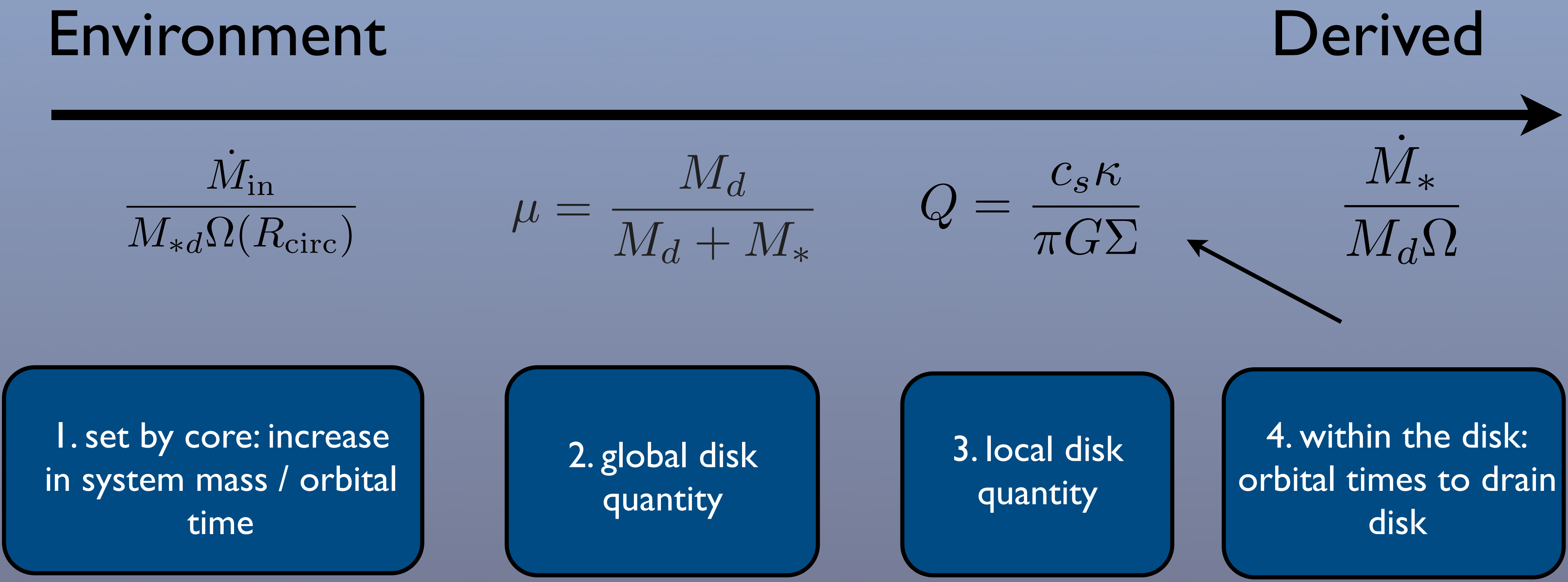

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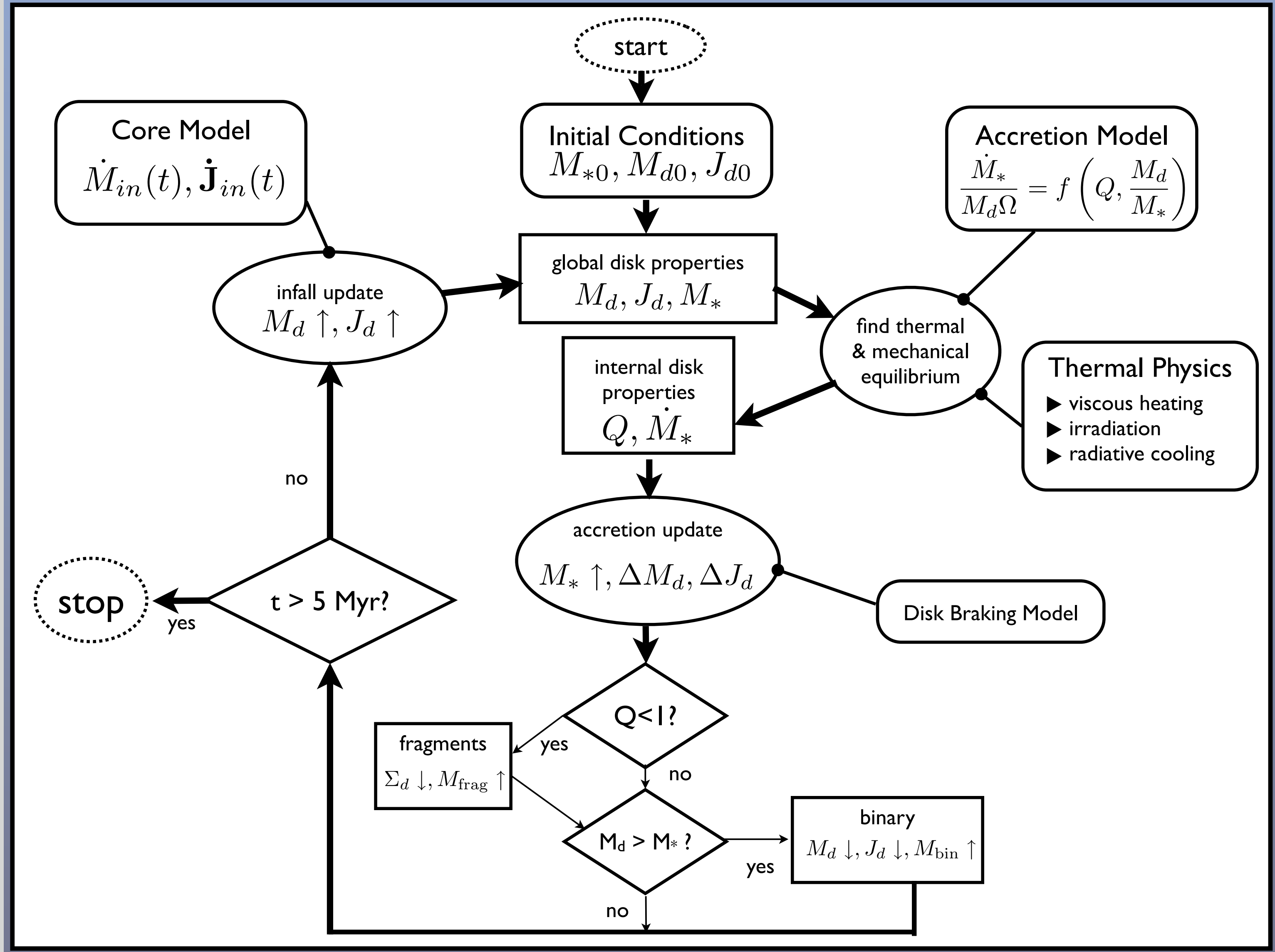

start

Initial Conditions

M_{*0}, M_{d0}, J_{d0}

Core Model

$\dot{M}_{in}(t), \dot{\mathbf{J}}_{in}(t)$

Accretion Model

$\frac{\dot{M}_*}{M_d \Omega} = f\left(Q, \frac{M_d}{M_*}\right)$

global disk properties

M_d, J_d, M_*

infall update

$M_d \uparrow, J_d \uparrow$

find thermal & mechanical equilibrium

Thermal Physics

- viscous heating
- irradiation
- radiative cooling

internal disk properties

$Q, \dot{M}_*$

accretion update

$M_* \uparrow, \Delta M_d, \Delta J_d$

Disk Braking Model

no

stop

yes

t > 5 Myr?

Q<1?

yes

no

fragments

$\Sigma_d \downarrow, M_{\rm frag} \uparrow$

$M_d > M_*$?

yes

binary

$M_d \downarrow, J_d \downarrow, M_{\rm bin} \uparrow$

no

KMK, Matzner, & Krumholz, 2007 (submitted)

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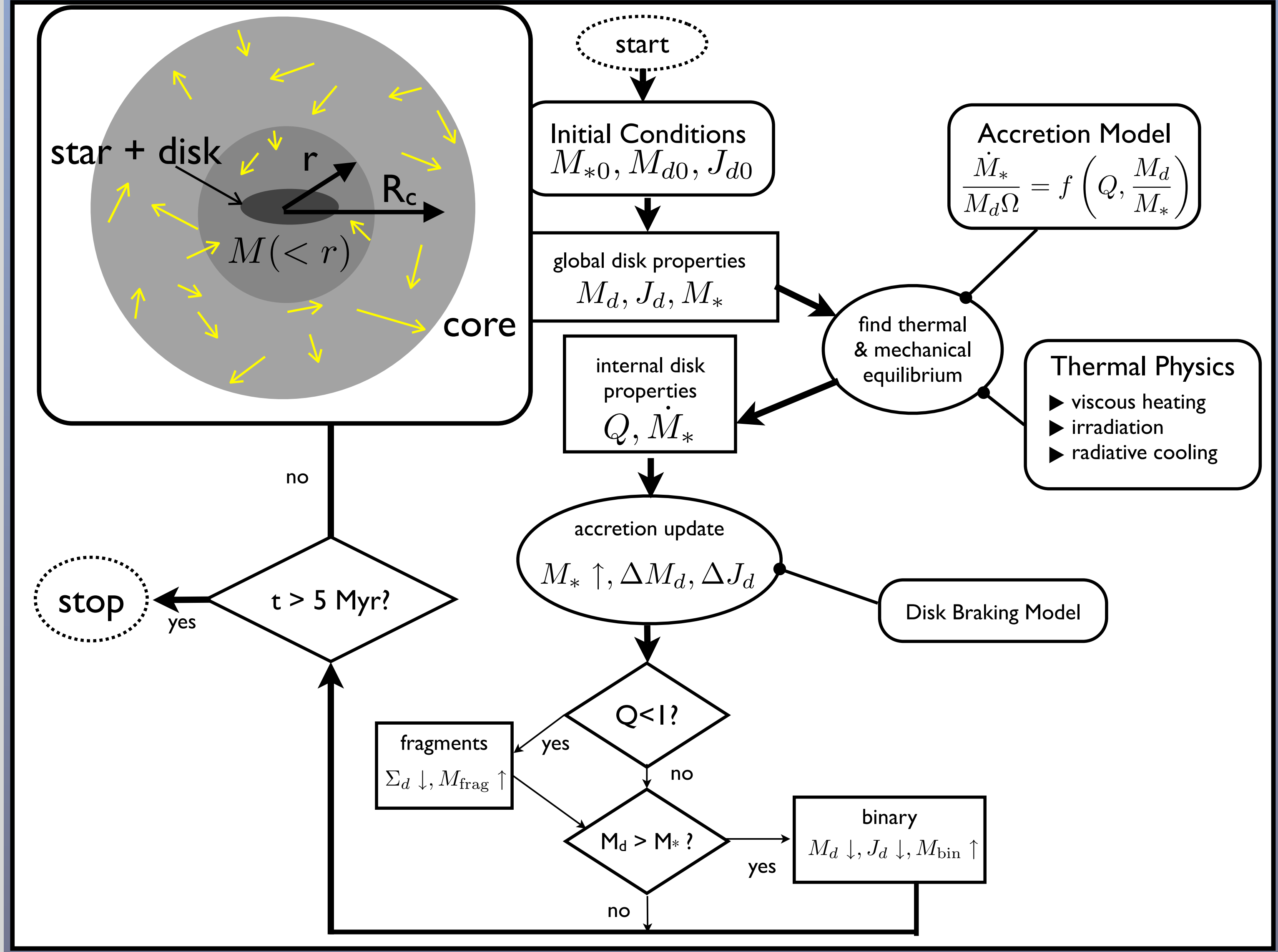

star + disk

r

R_c

$M(<r)$

core

start

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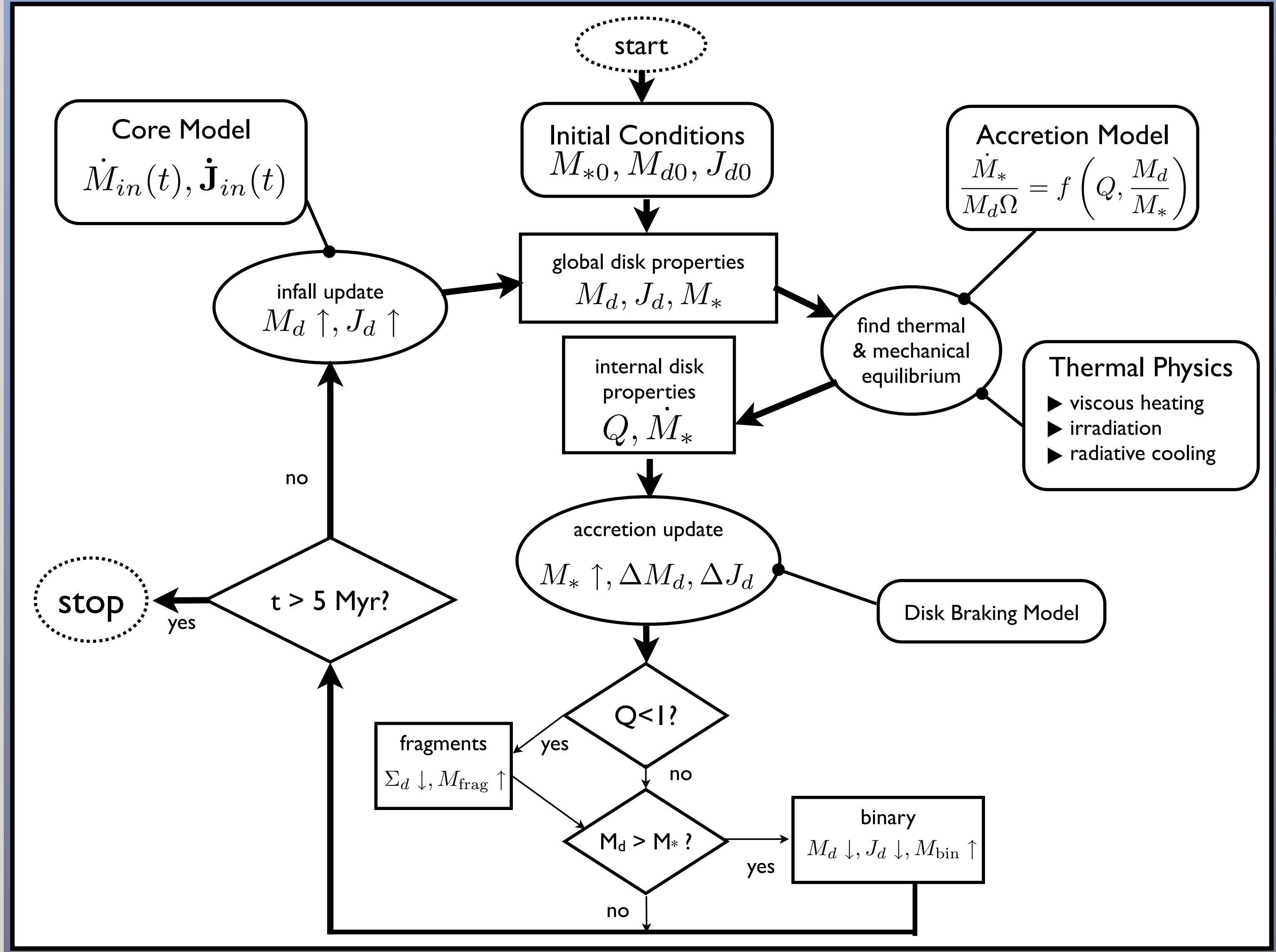

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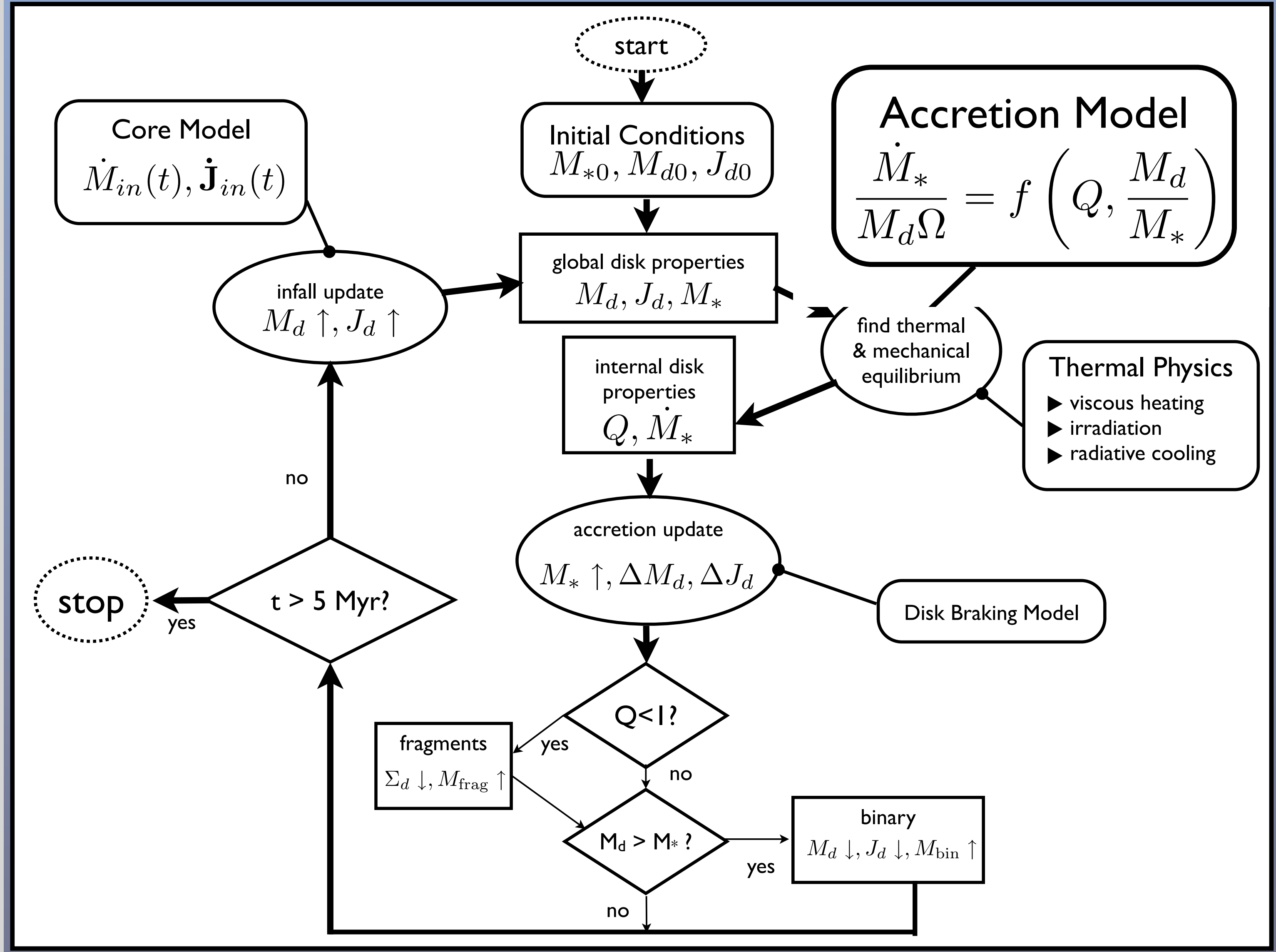

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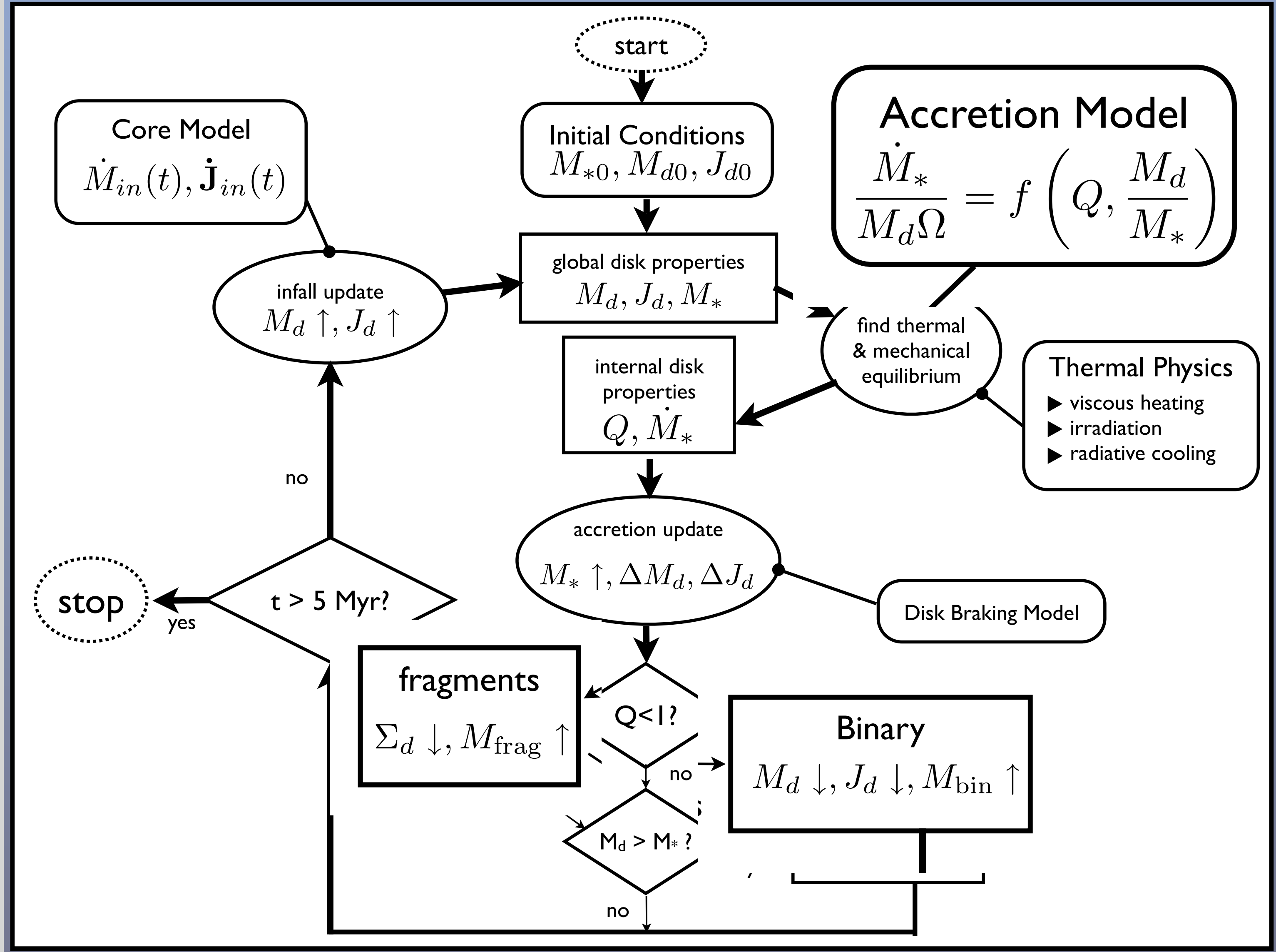

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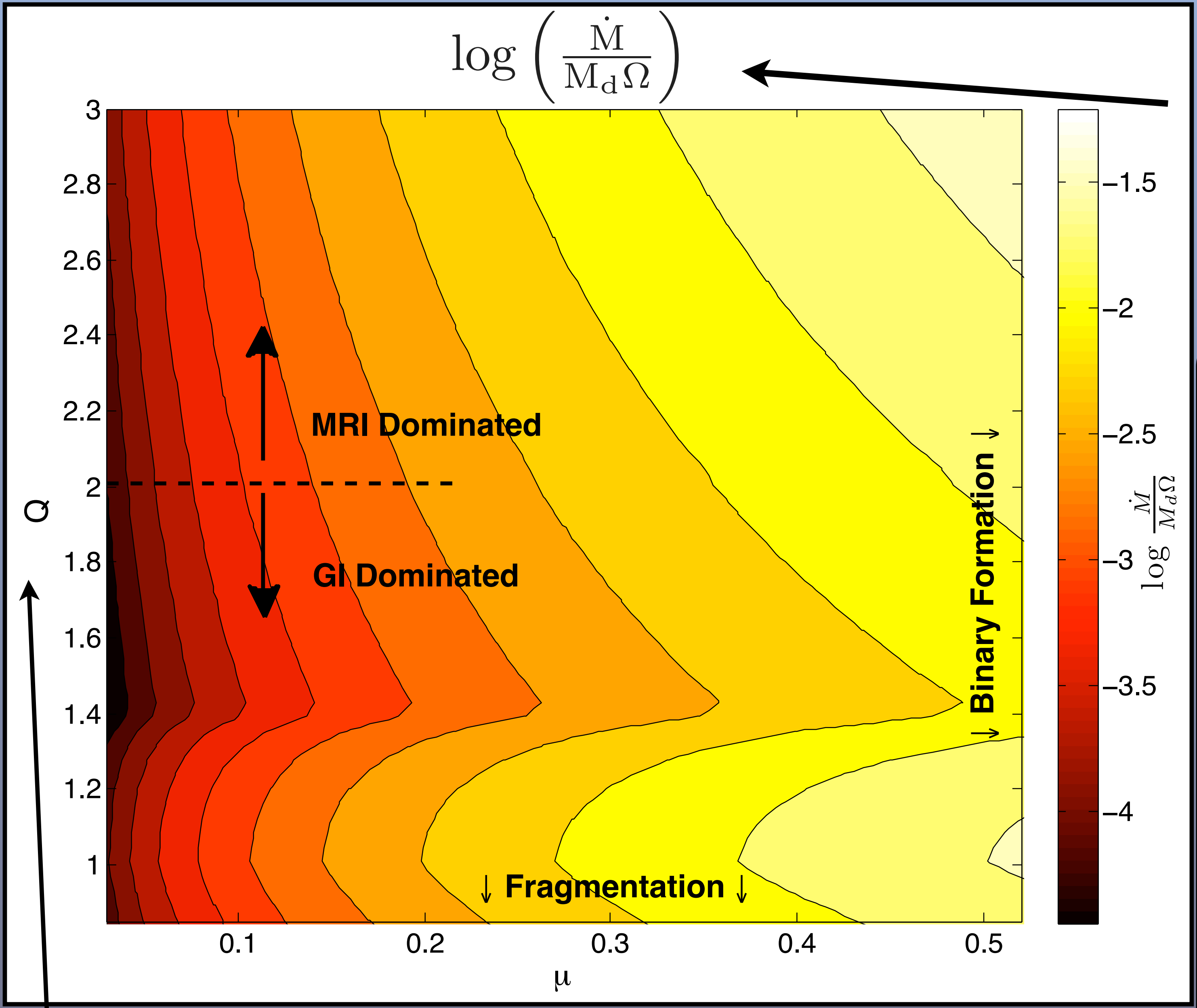
Model Components I: Accretion Model



dynamical times to drain
the disk

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

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

Gammie, 2001

$$\frac{\dot{M}_{*,\rm glob}}{M_d\Omega} = \frac{\mu^2}{100}$$

Laughlin and Rozyczka ,1996

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

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

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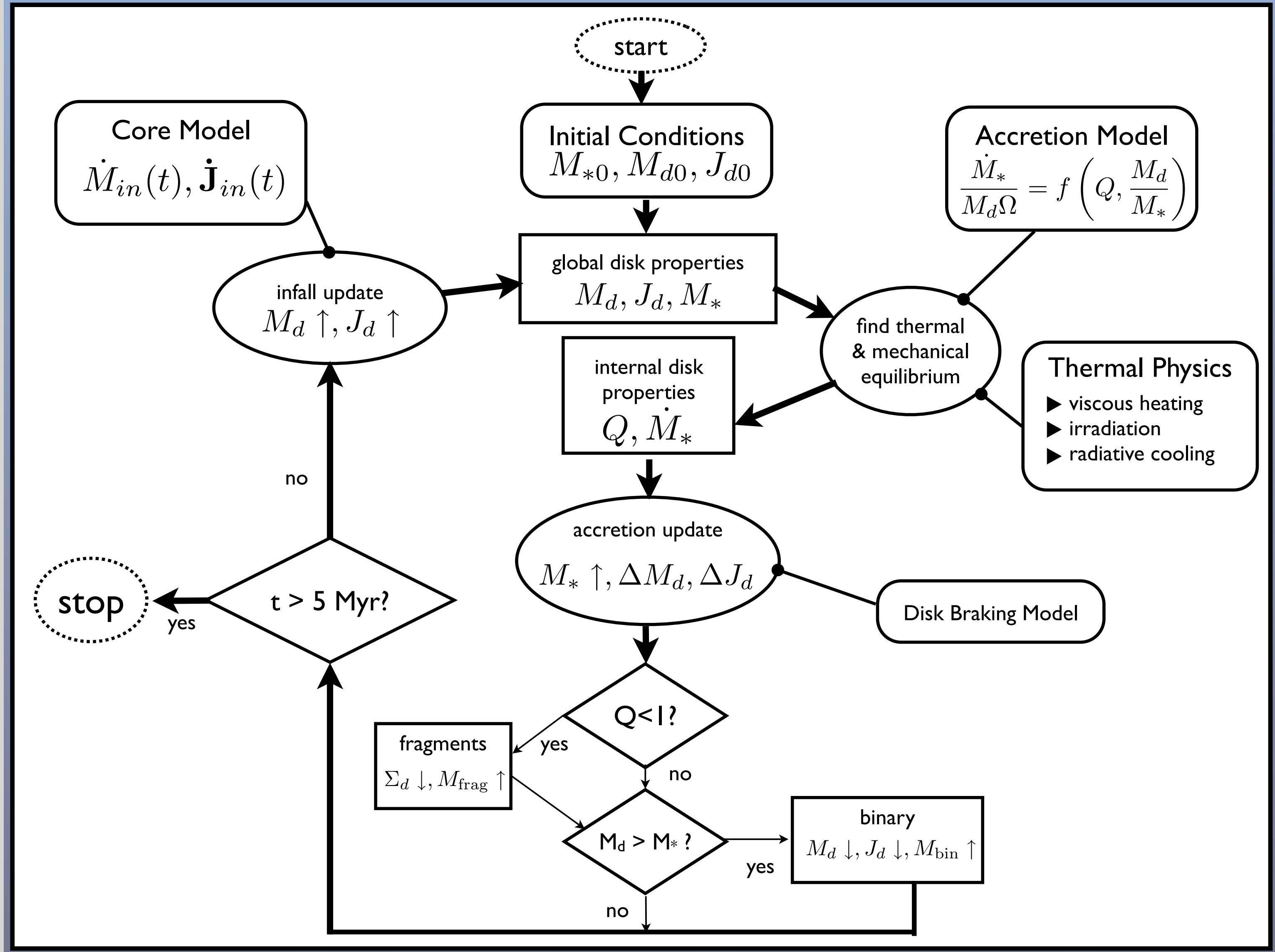

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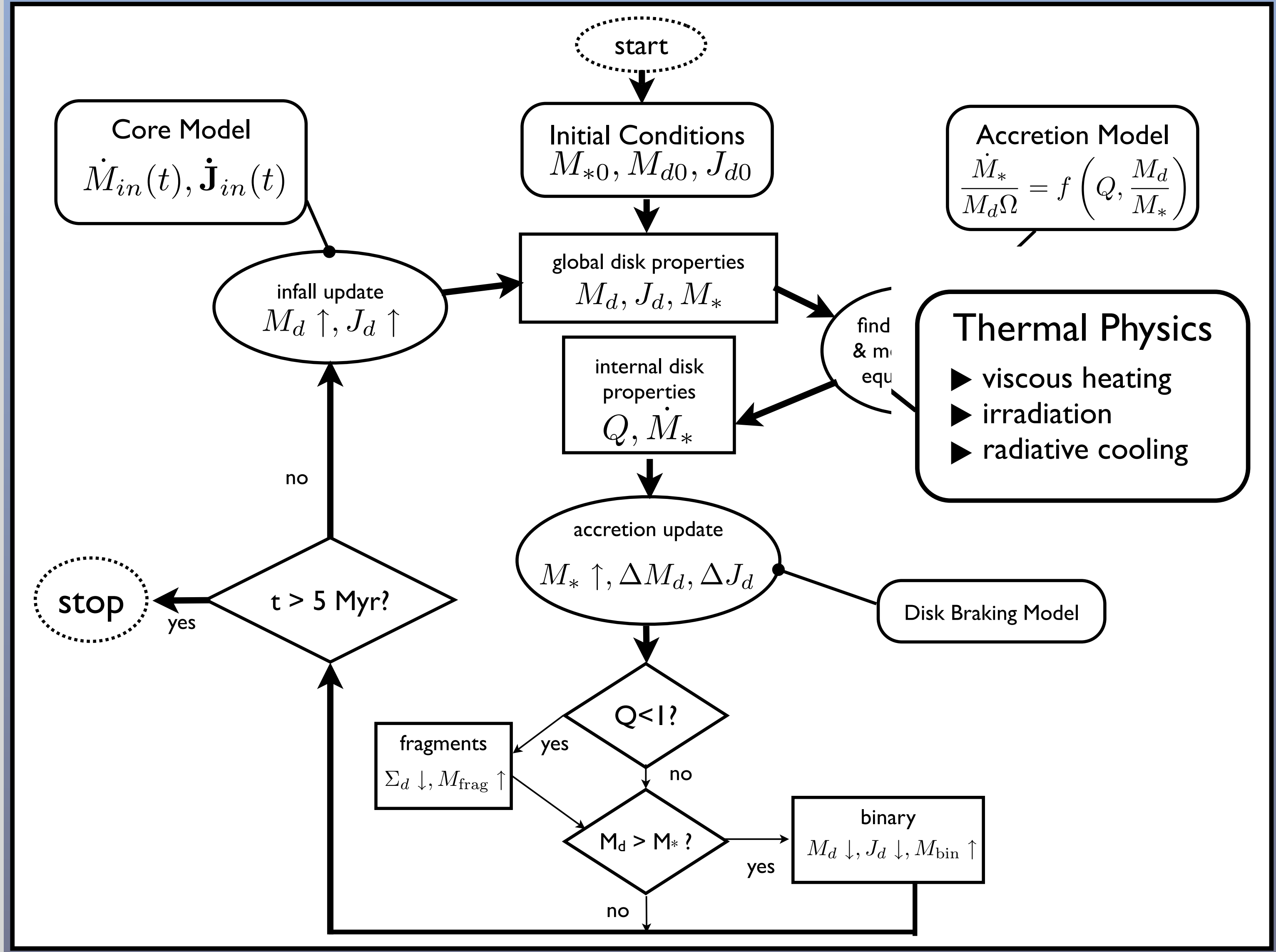

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Model Components II: Heating & Cooling

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

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

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

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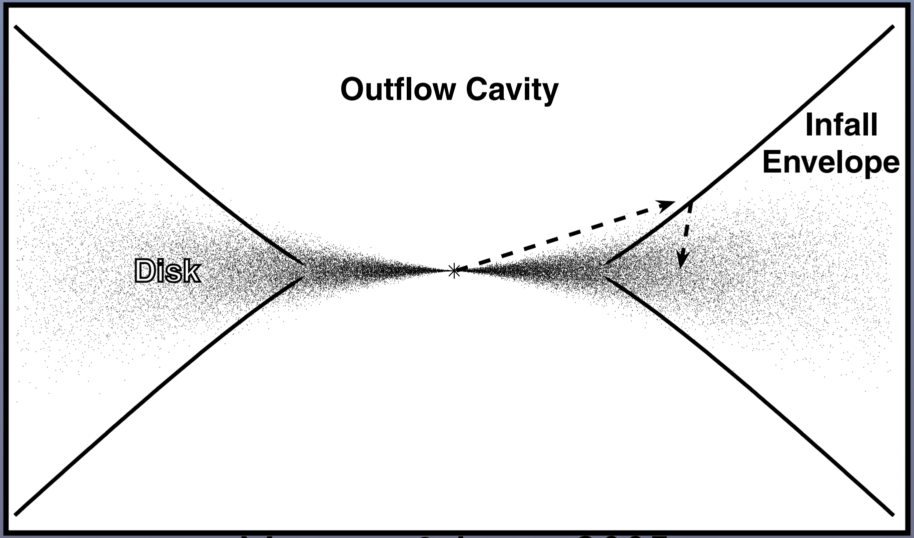
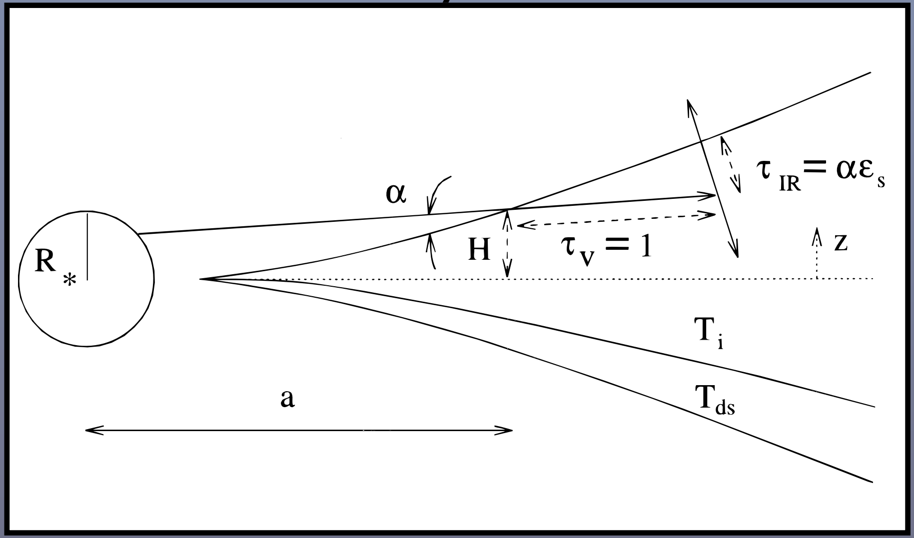
during core accretion -- envelope reprocessing



Matzner & Levin, 2005

after core accretion -- radiating dust layer



Chiang & Goldreich, 1997

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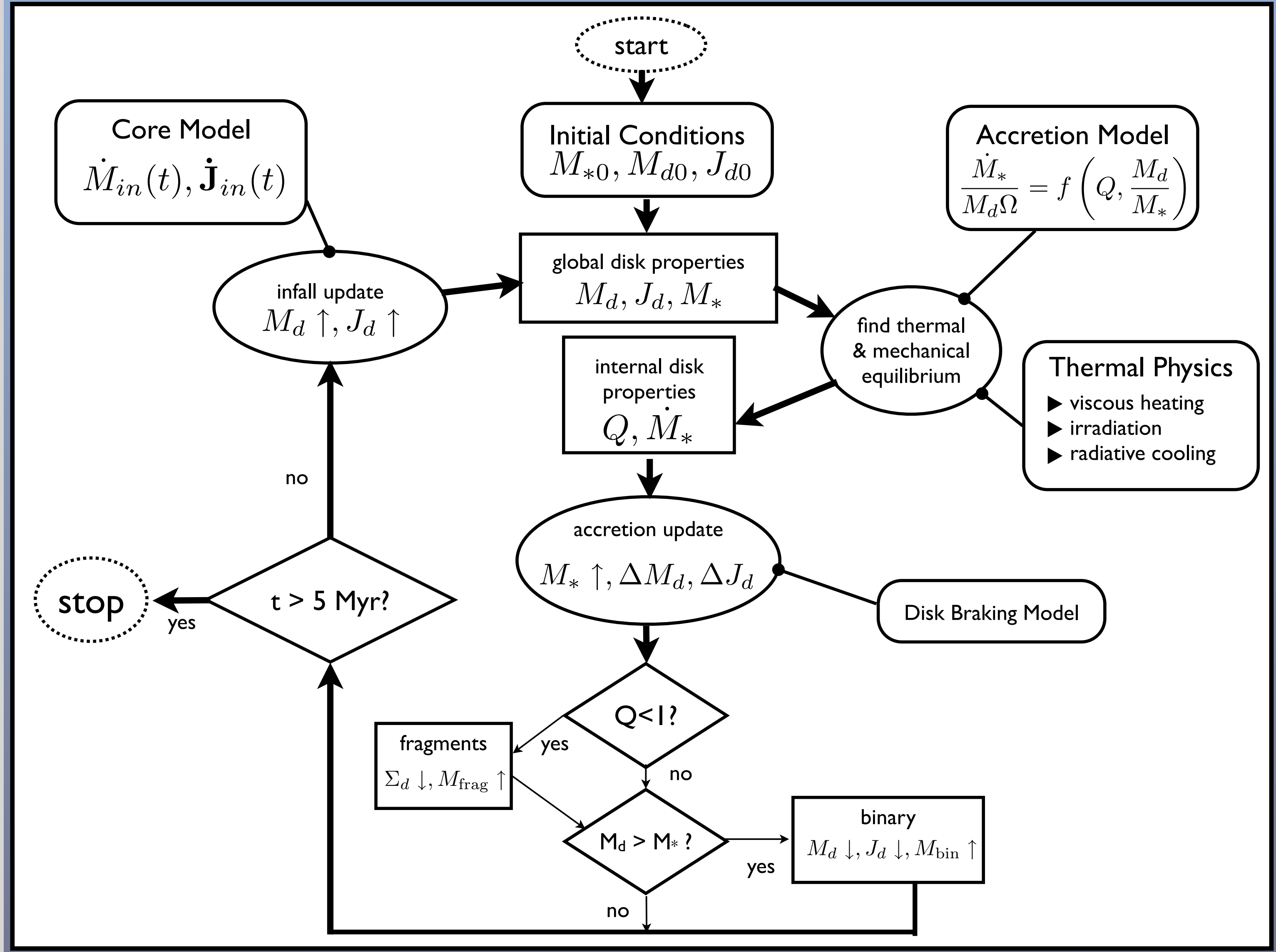

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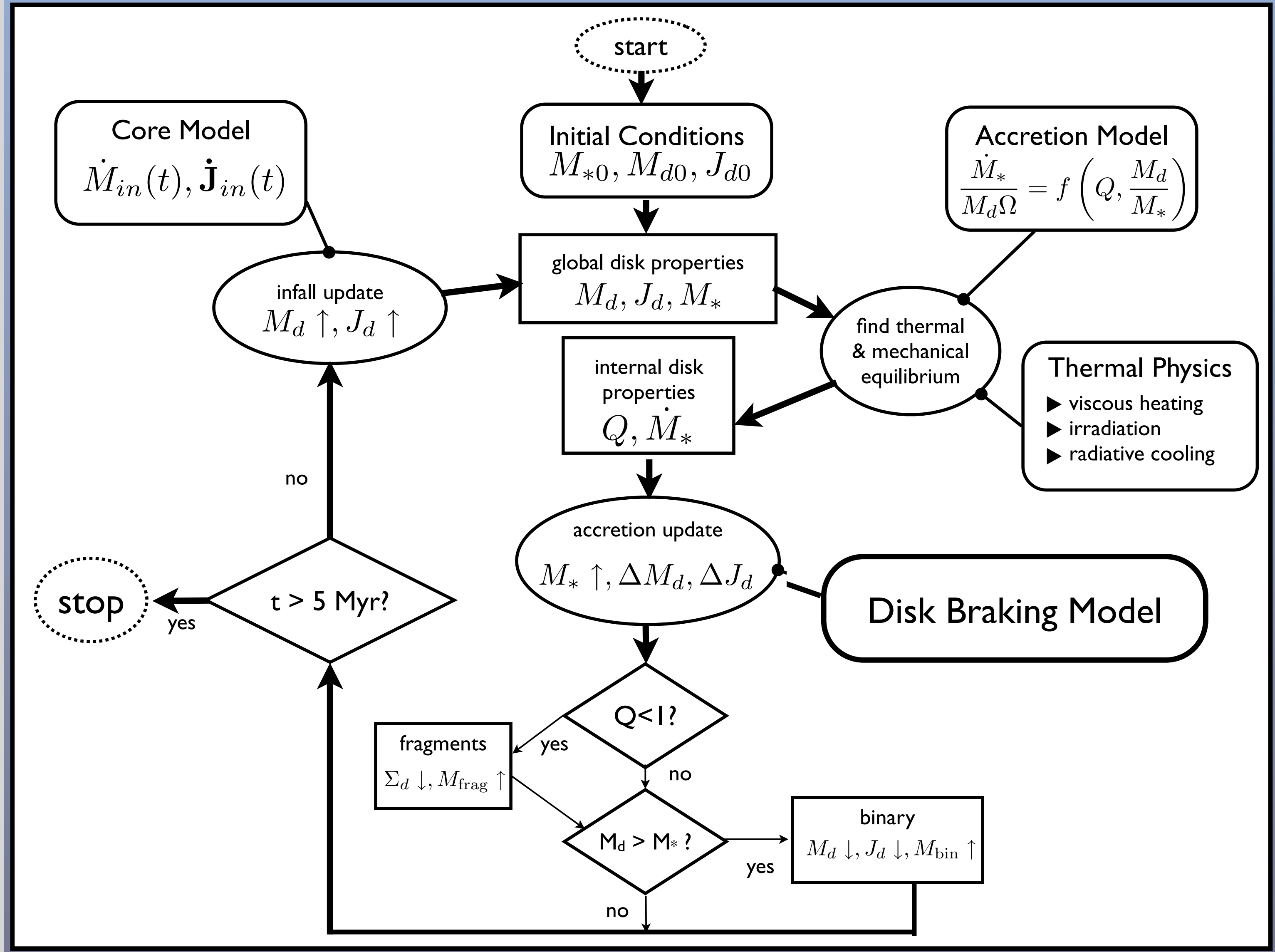

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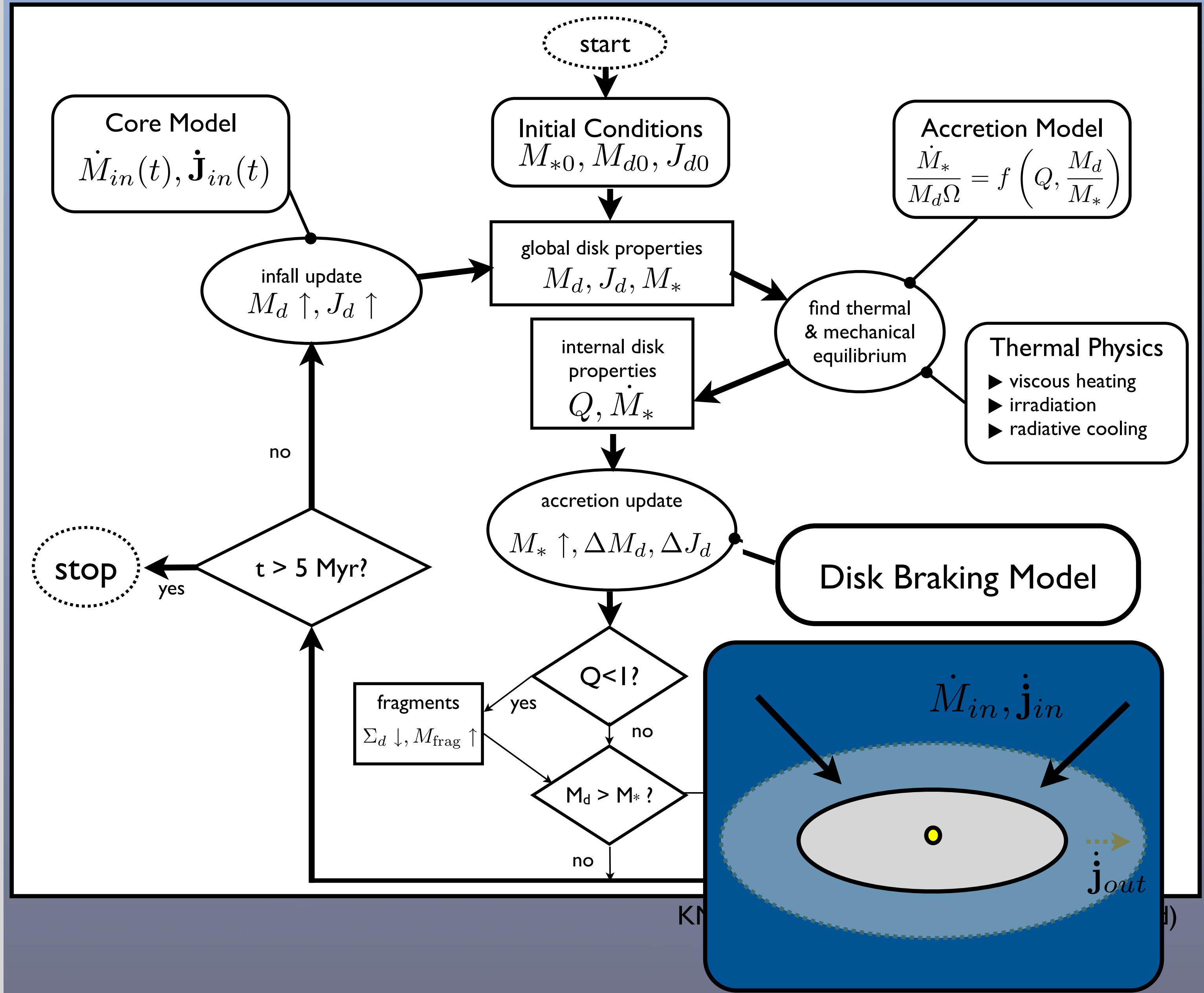
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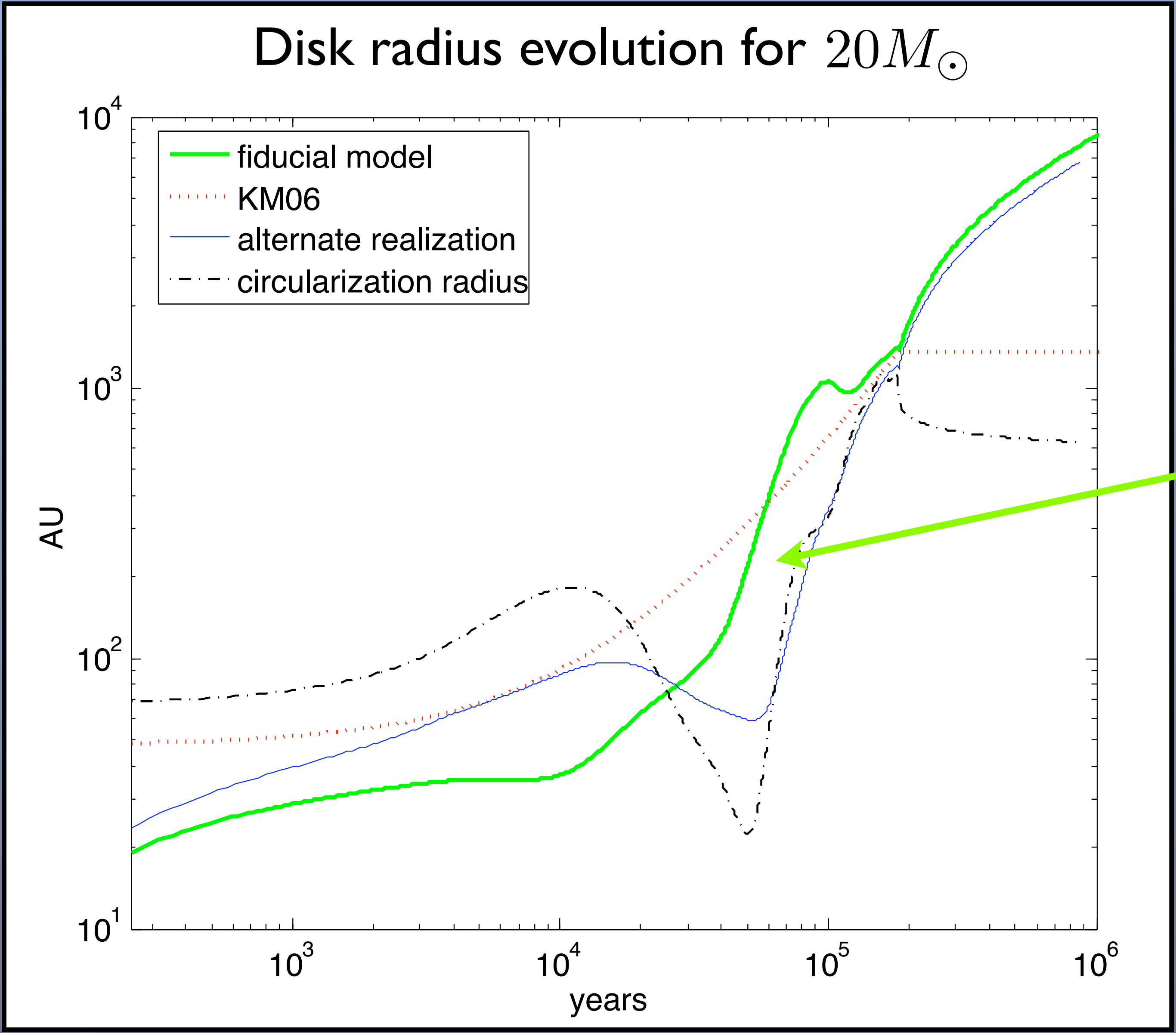
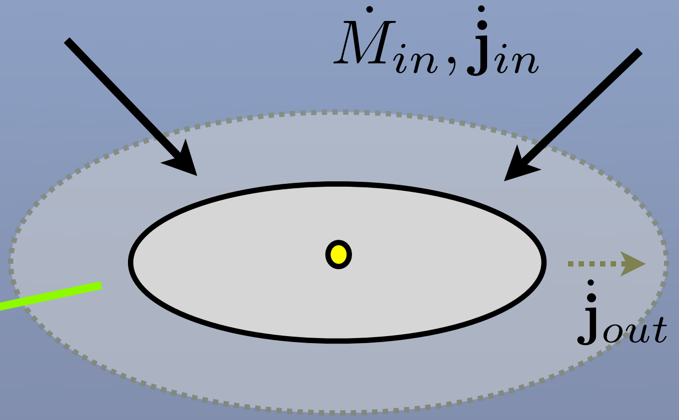
Model Components III: Outer disk braking

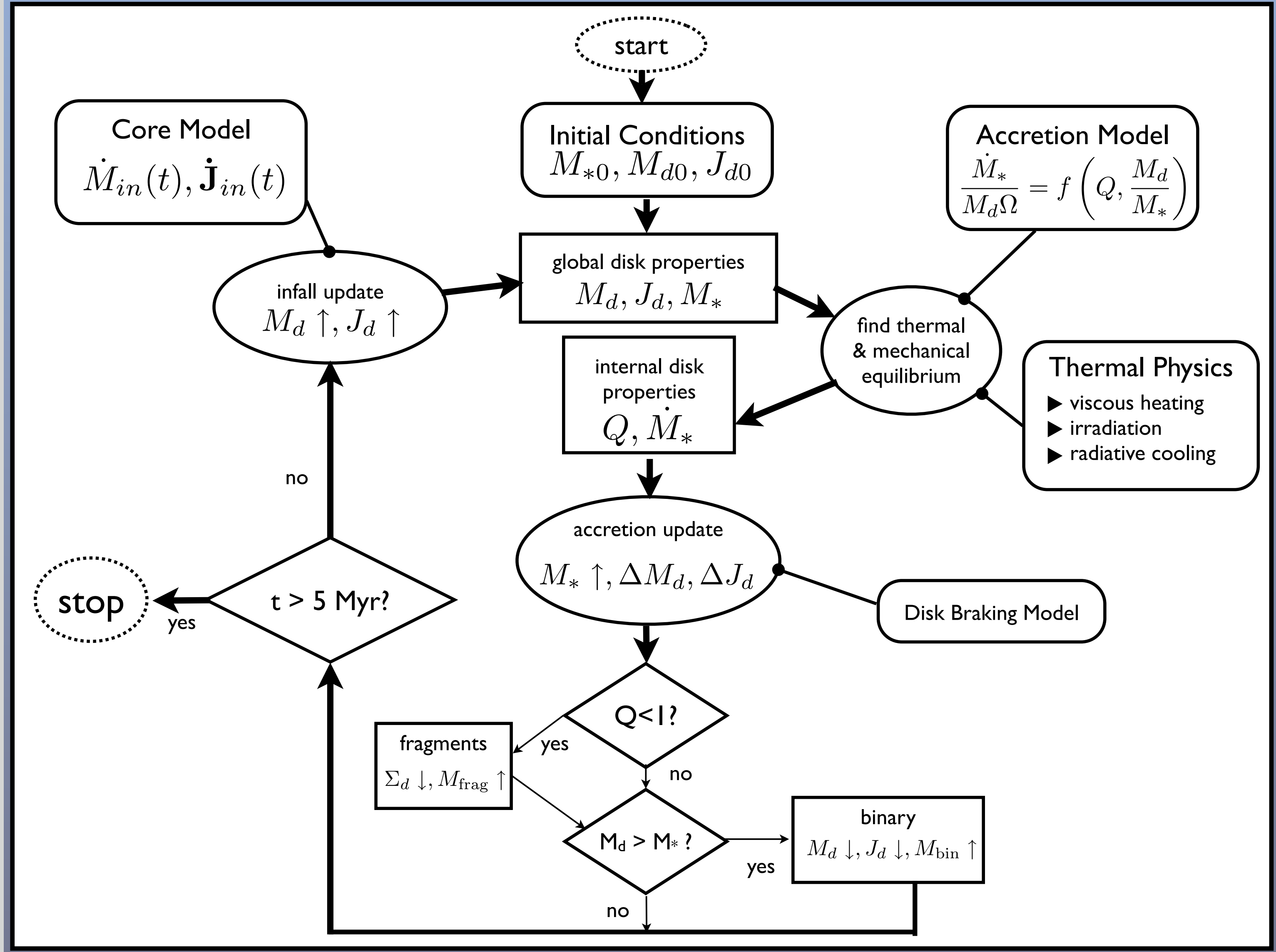




$$\dot{\mathbf{J}}_d = \mathbf{j}_{\rm in}\dot{M}_{\rm in} - b_j\left(\frac{\dot{M}_{\rm in}}{\dot{M}_*}\right)\frac{\dot{M}_{\rm in}}{M_d}\mathbf{J}_d.$$

- 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 and Toomre's **Q**
- consider possibility that disks **fragment** when sufficiently unstable
- employ a realistic model for **irradiation** of the disk midplane

Model Structure



start

Initial Conditions
M_{*0}, M_{d0}, J_{d0}

global disk properties
M_d, J_d, M_*

Accretion Model
$\frac{\dot{M}_*}{M_d \Omega} = f\left(Q, \frac{M_d}{M_*}\right)$

find thermal & mechanical equilibrium

Thermal Physics
- viscous heating
- irradiation
- radiative cooling

internal disk properties
$Q, \dot{M}_*$

accretion update
$M_* \uparrow, \Delta M_d, \Delta J_d$

Disk Braking Model

Q<1?

yes

fragments
$\Sigma_d \downarrow, M_{\rm frag} \uparrow$

no

$M_d > M_*$?

yes

binary
$M_d \downarrow, J_d \downarrow, M_{\rm bin} \uparrow$

no

t > 5 Myr?

yes

stop

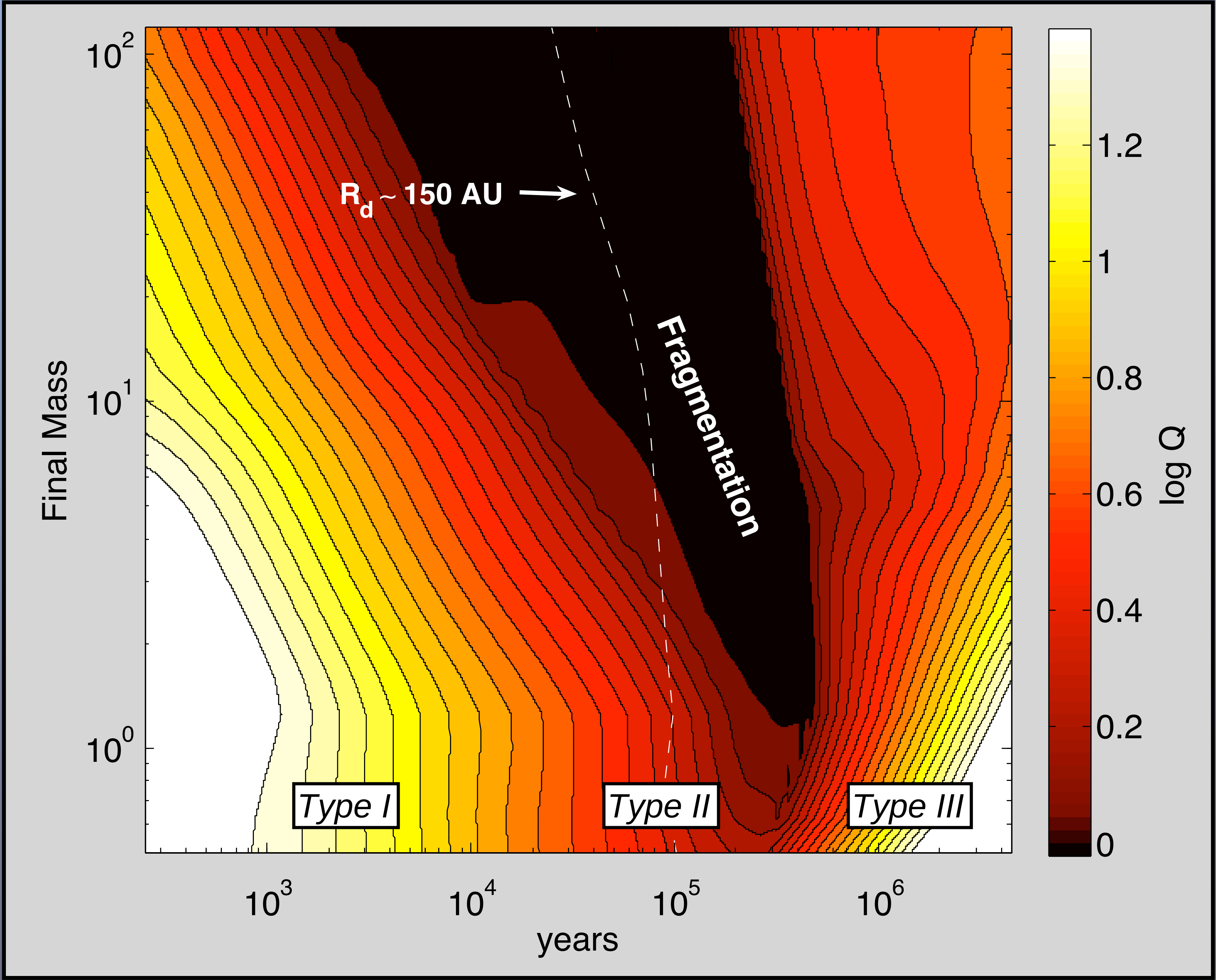
no

infall update
$M_d \uparrow, J_d \uparrow$

Core Model
$\dot{M}_{in}(t), \dot{\mathbf{J}}_{in}(t)$

KMK, Matzner, & Krumholz, 2007 (submitted)

Evolution of Q and μ



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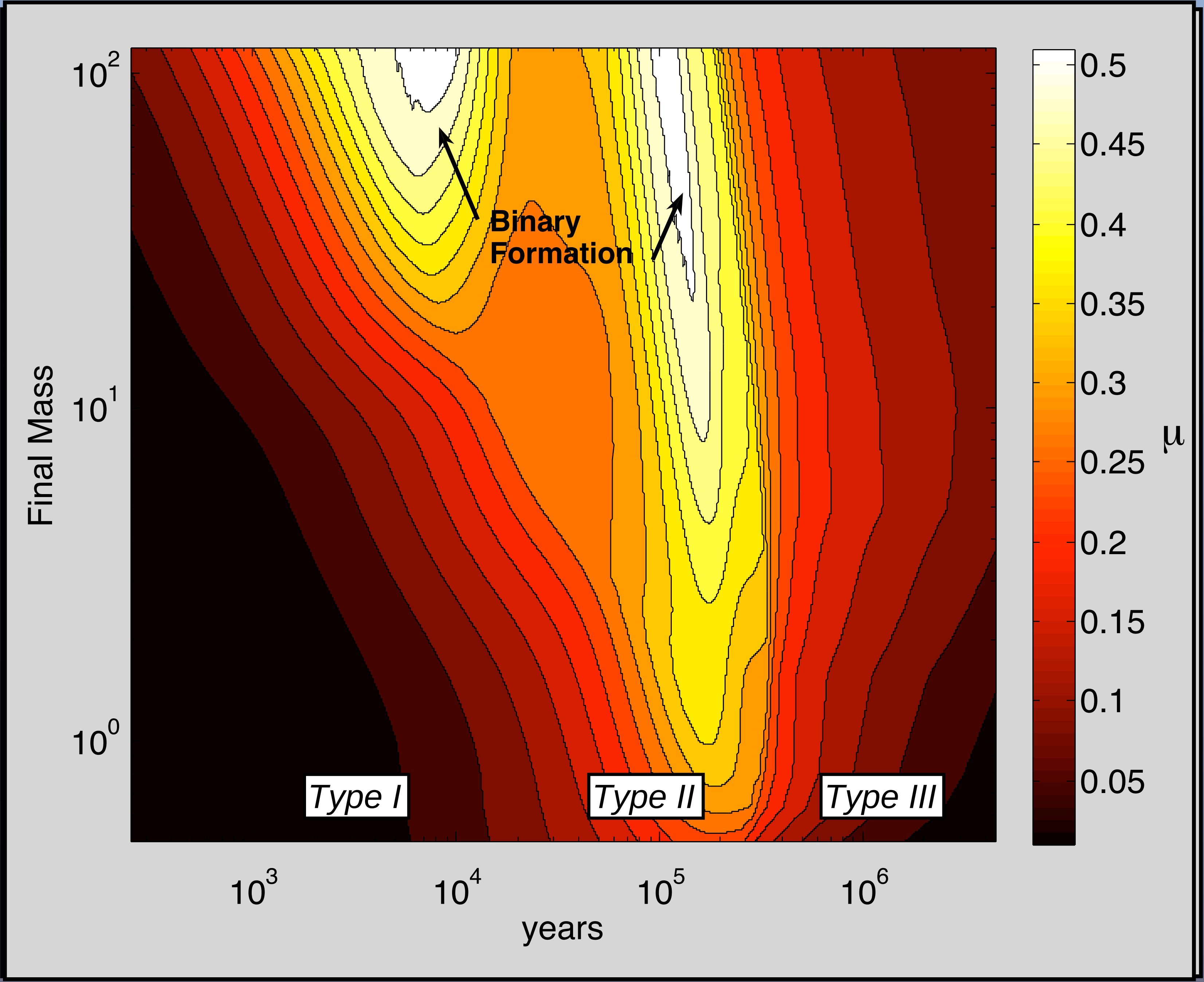
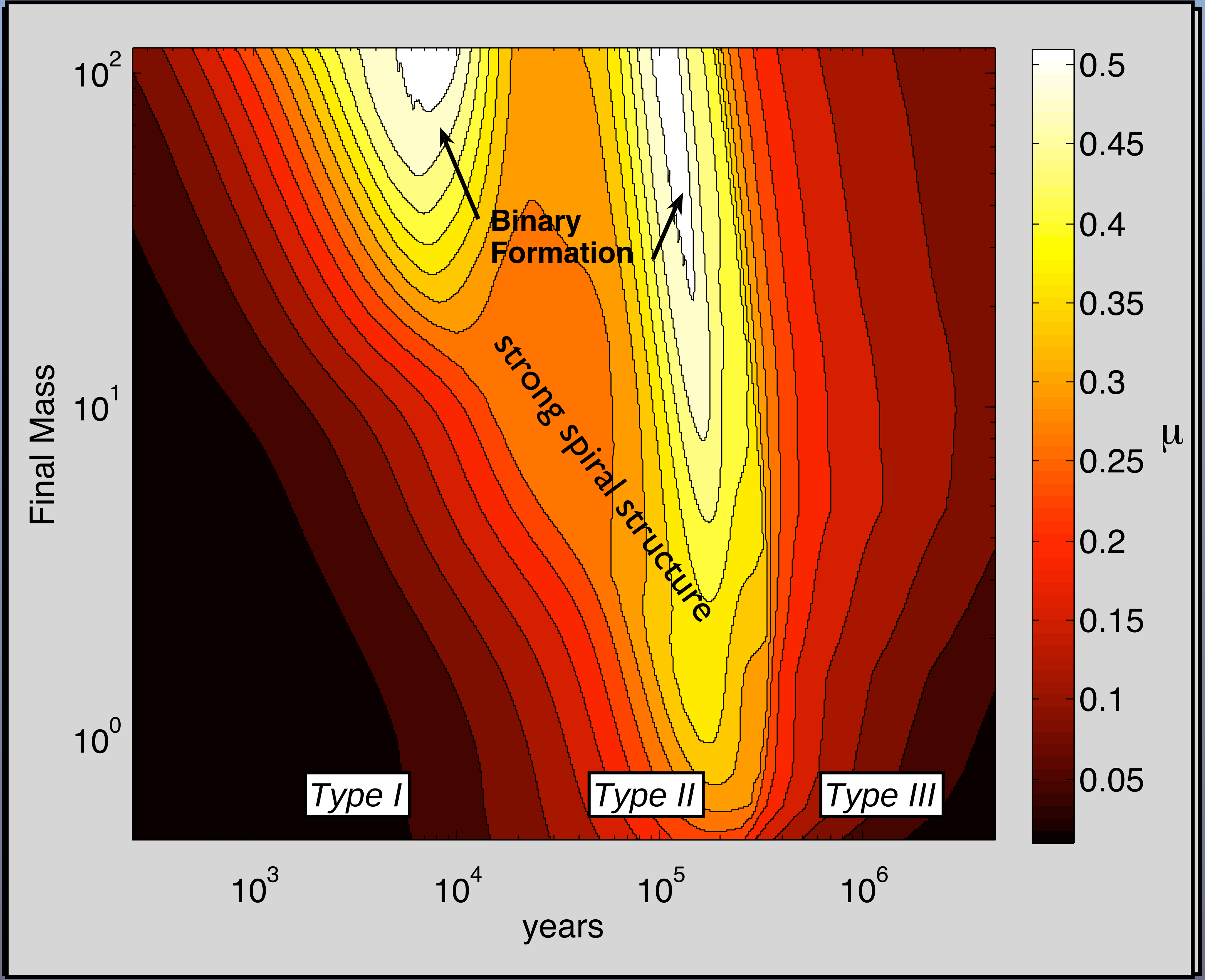
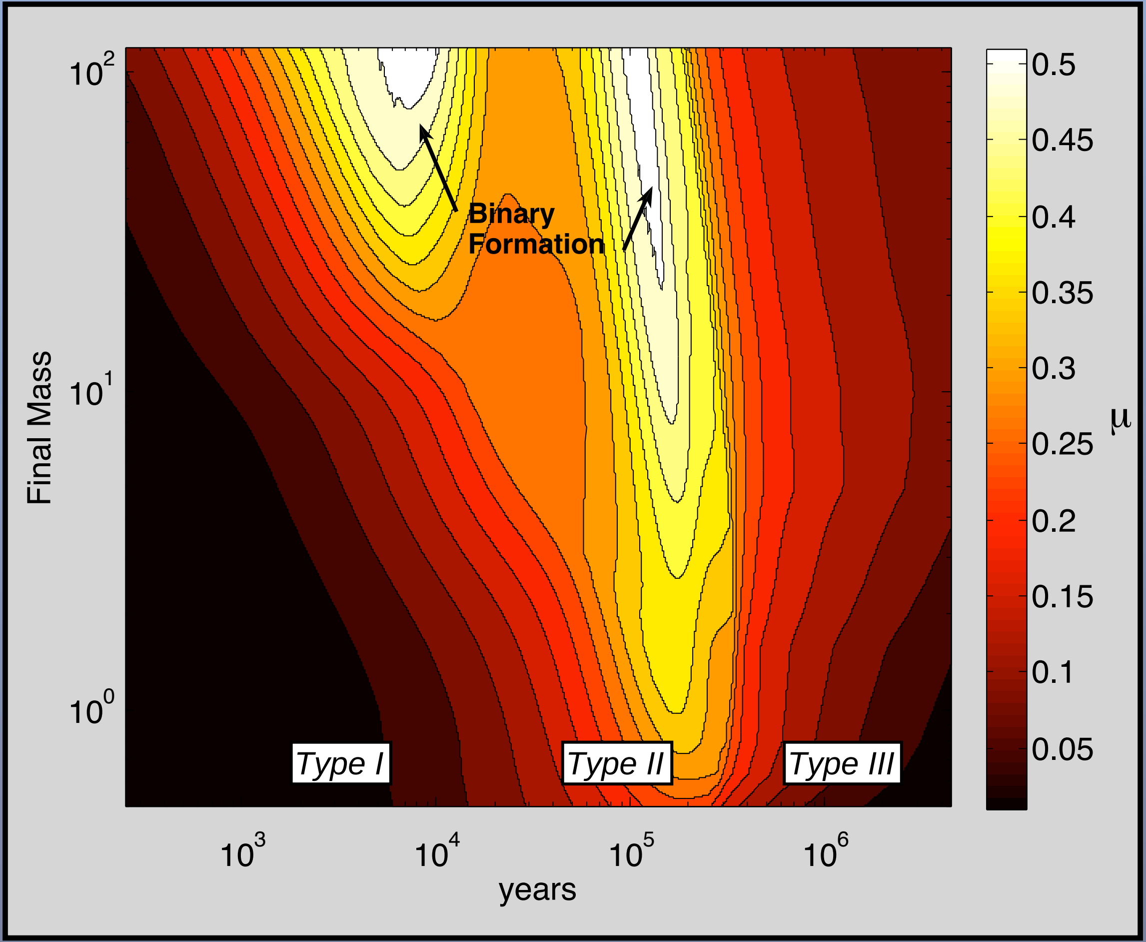


Evolution of Q and μ



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

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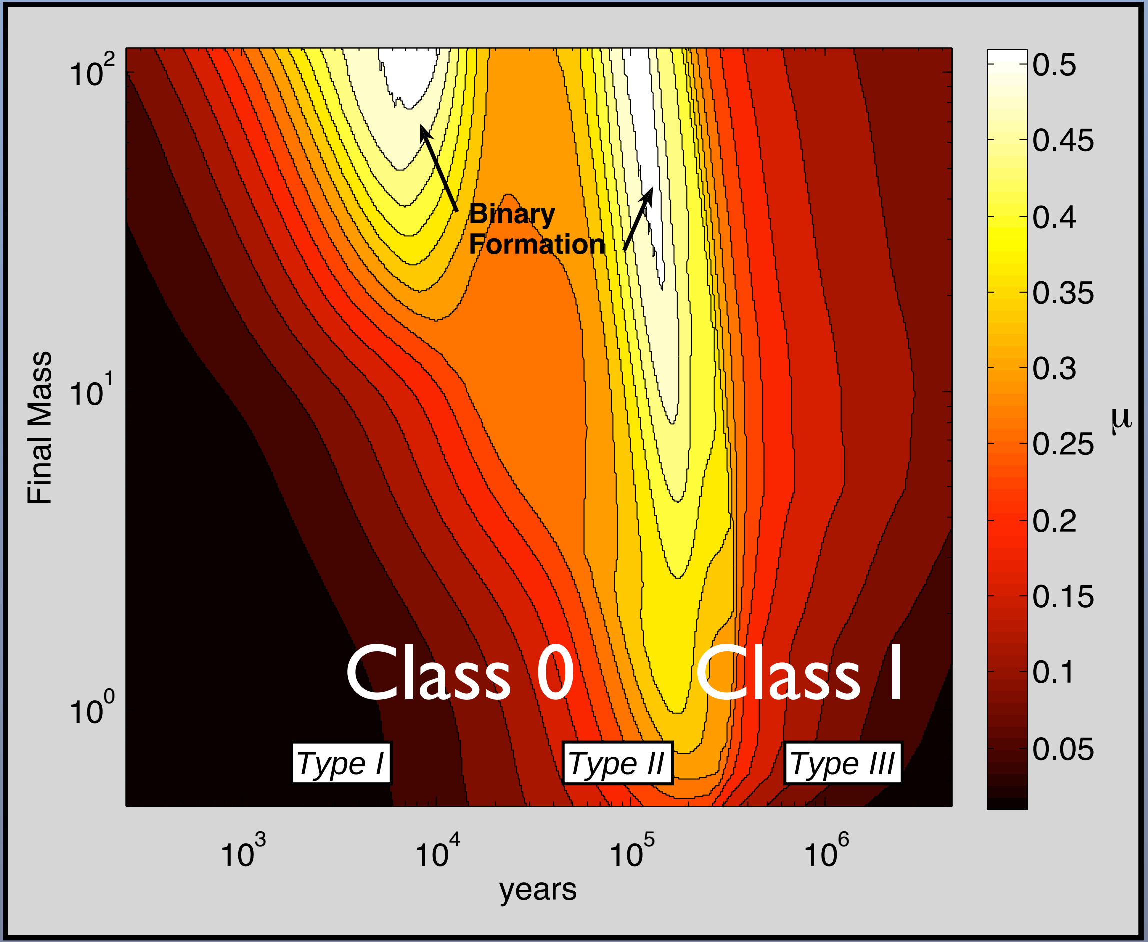

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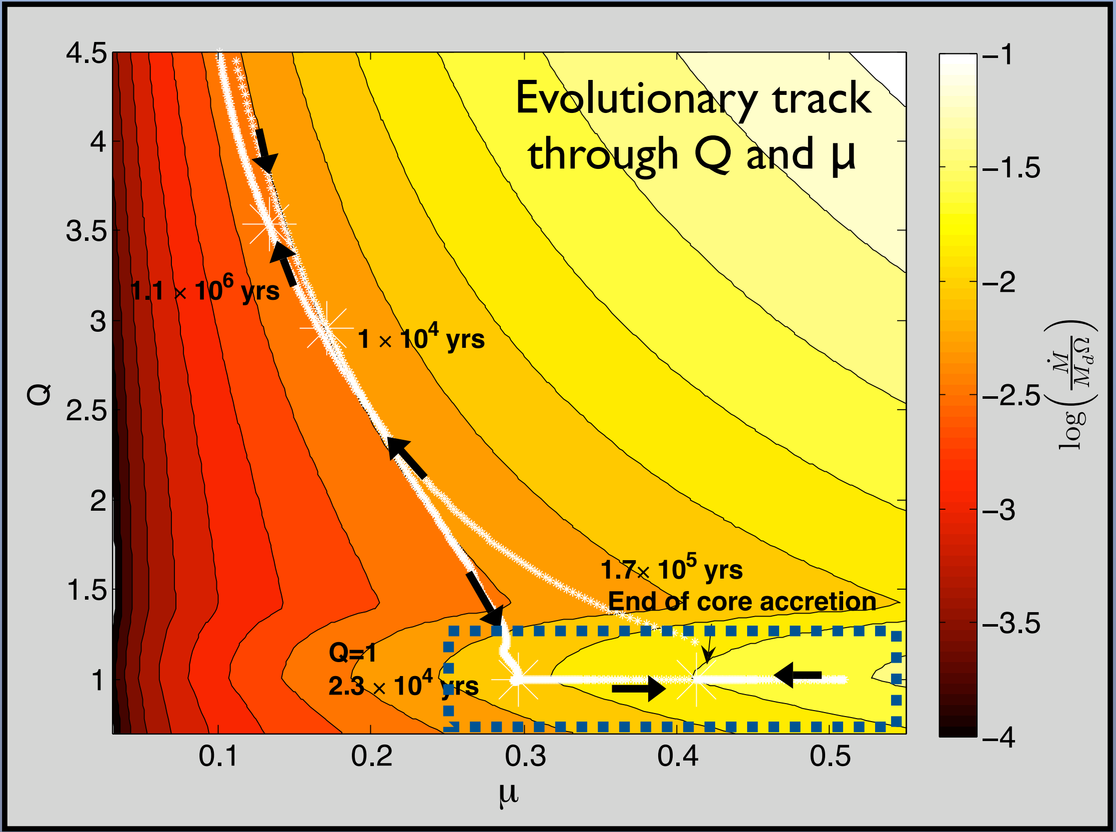
Characteristics of a 15 $M_\odot$ star

- **Disk properties:**

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

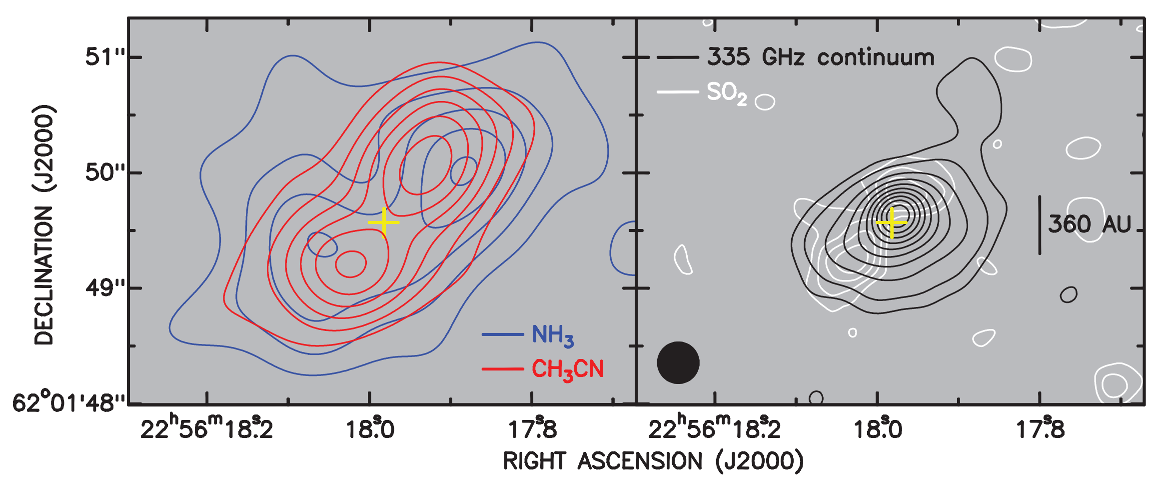
- **Detectable?**
  - ALMA: yes (< 2-3 Kpc)
  - EVLA: yes (< 0.5 Kpc)

(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

Evidence for star - disk velocity offset



Torrelles et al, 2007

Conclusions and Future Directions

- Local instability and fragmentation persists for ~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
- Environmental variables (Σ_c, T_c) do not qualitatively change these conclusions
- Accretion model is uncertain: need simulations
    - **coming**: GI physics numerical experiments
- Beyond a core model for infall:
    - **coming**: plug in semi-analytic model as "sub-grid physics" for SPH simulations