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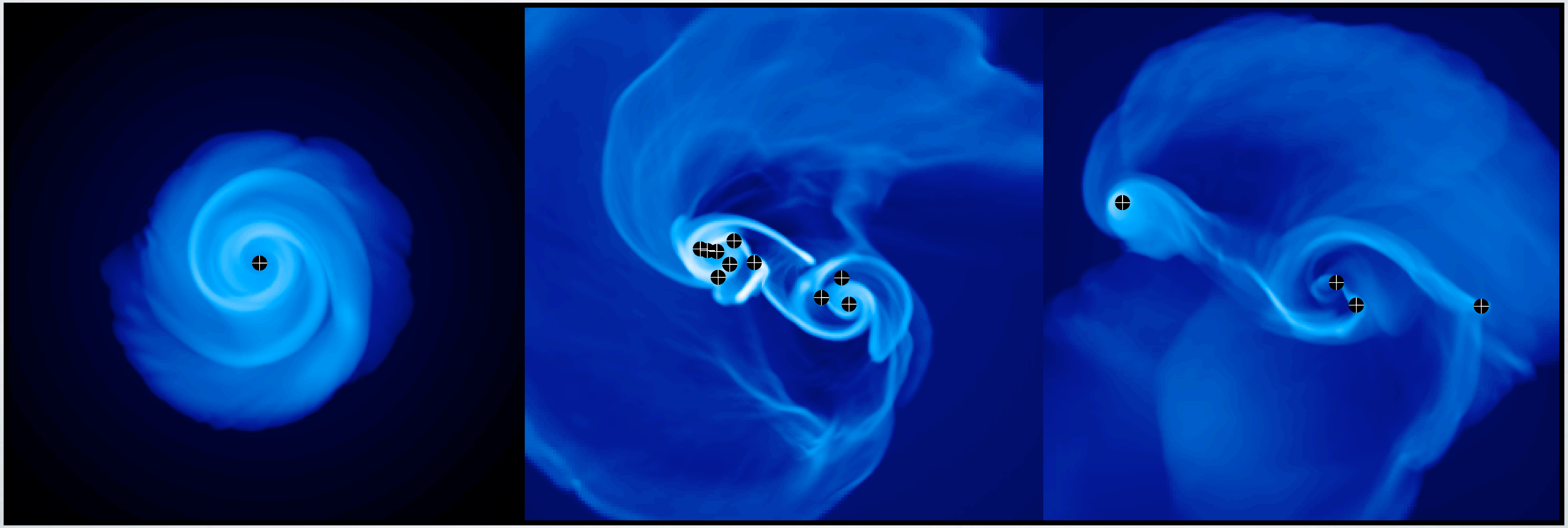
PLANET FORMATION BY GRAVITATIONAL INSTABILITY ?

Kaitlin Kratter
University of Arizona

Sagan Summer Workshop, July 2015



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in GAS!

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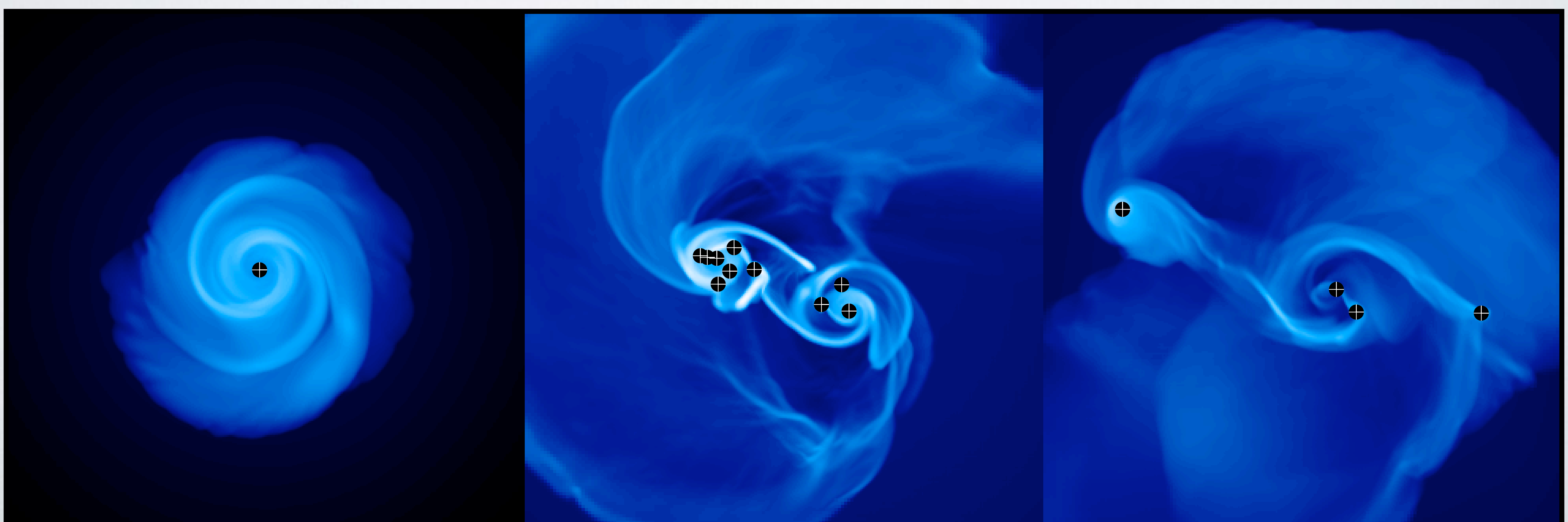


THE BOTTOM LINE

- Few disks appear to be massive enough to fragment (except perhaps at very early times)
- Those that do are more likely to produce more massive objects like brown dwarfs or m-stars
- Inward migration followed by tidal disruption most often leads to complete disruption, rather than mass reduction. But might assist in solid core formation

THE BOTTOM LINE

- Few disks ap… to fragment (except pe…
- Those that … more massive ob… …ars
- Inward mig… …ion most often leads … than mass reduction. … …rmation

accretion disk studies were born in galactic / x-ray binary contexts, some of the standard assumptions made in these contexts are not well suited to protostellar / protoplanetary disks.

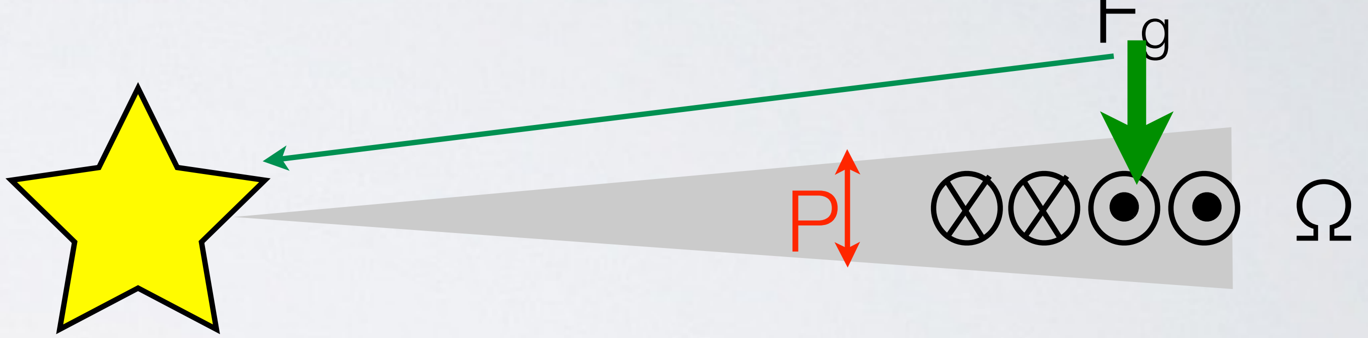
1. Thermodynamics are dominated by stellar irradiation
2. H/R is not <<1

GLOSSARY

- **Self-Gravity:** the gravitational attraction of gas to itself is competitive with the central body
- **Gravitational Instability: (GI)** a linear, hydrodynamic instability that can arise in self-gravitating disks of gas, particles or both
- **Fragment:** a marginally bound gas clump that forms as the non-linear outcome of GI
- **Planet**: depends on whom you ask…

WHAT IS GRAVITATIONAL INSTABILITY?

- A hydrodynamic instability that arises in rotational;y supported disks when **self-gravity** wins out over **pressure** support on small scales, and stabilization due to **shear** on large scales



$$Q = \frac{c_s \Omega}{\pi G \Sigma} = f \frac{M_*}{M_D} \frac{H}{r}$$

Toomre's Q, rewritten this way can point us toward important, order of magnitude arguments

WHAT IS GRAVITATIONAL INSTABILITY? ^WHEN H<<R

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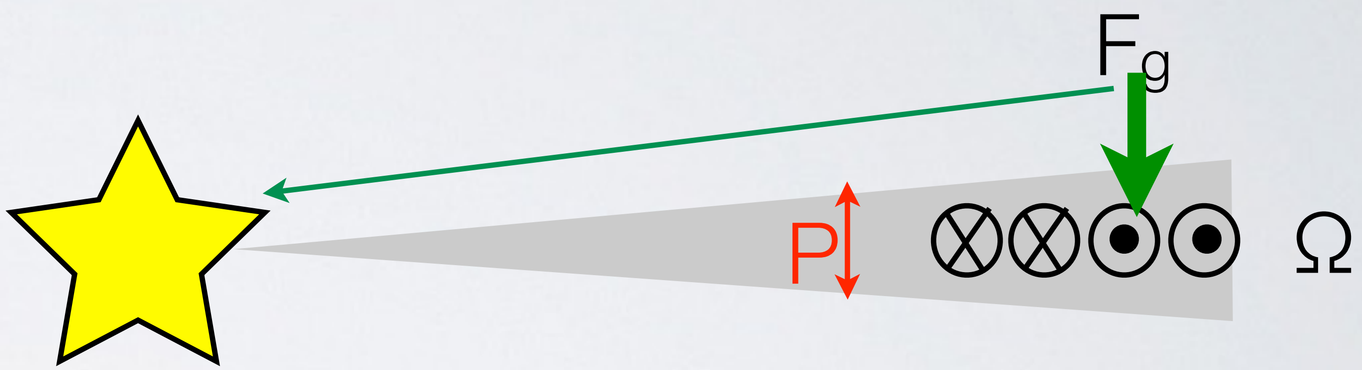


$$(\omega - m\Omega(R))^2 = c_s^2 k^2 - 2\pi G\Sigma|k| + \kappa^2,$$

$$Q = \frac{c_s\Omega}{\pi G\Sigma} = f\frac{M_*}{M_D}\frac{H}{r}$$

Growth begins at Q=1 in the **local** approximation, for axisymmetric modes. since H<<R, Md<<M*

WHAT IS GRAVITATIONAL INSTABILITY? ^WHEN H<R

from Lau & Bertin 1978

$$(\omega - m\Omega)^2 = \kappa^2 + \left(k^2 + \frac{m^2}{r^2}\right)a^2(1+\chi) - 2\pi G\sigma_0\left(k^2 + \frac{m^2}{r^2}\right)^{1/2}(1+\chi)\,, \quad (12)$$

where

$$\chi = \mathscr{J}^2(\lambda/\lambda_c)^2 \quad (13)$$

and $\mathscr{J}$ is defined in equation (6). In equation (13),

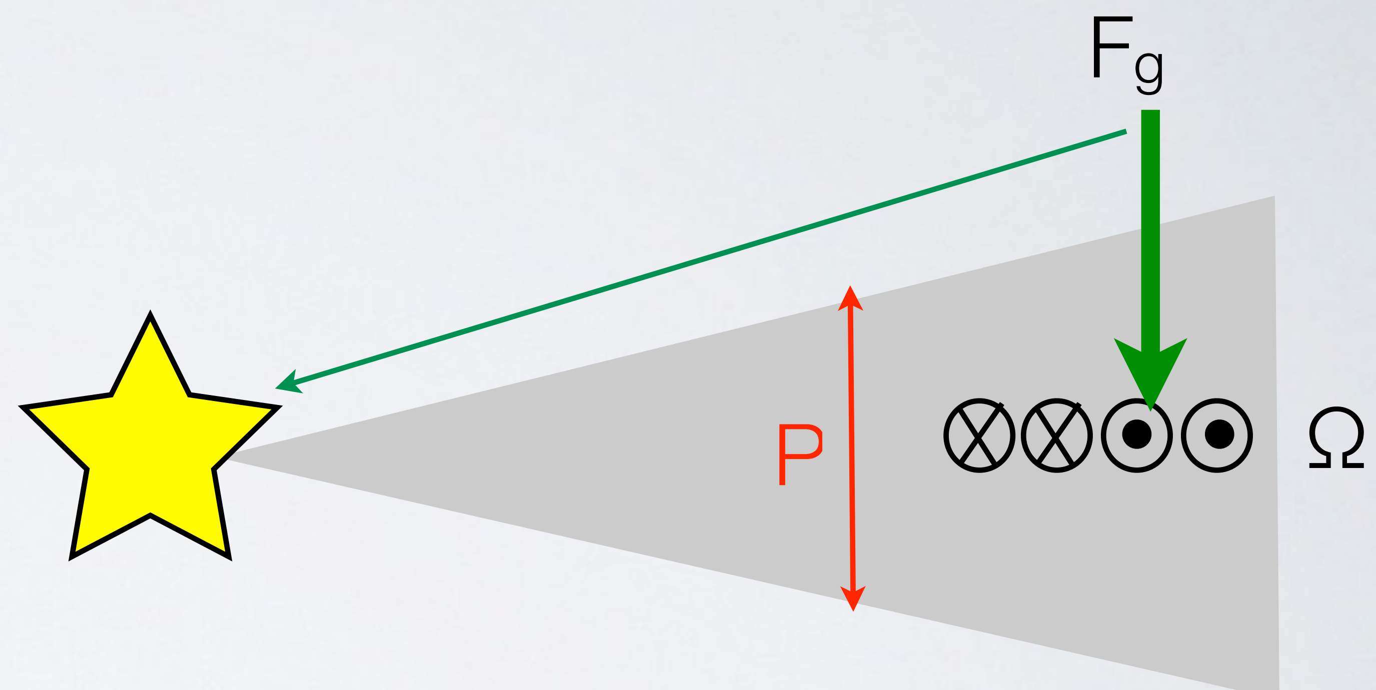
$$\lambda = 2\pi/(k^2 + m^2/r^2)^{1/2} \quad (14a)$$

and

$$\lambda_c = 4\pi^2 G\sigma_0/\kappa^2 \quad (14b)$$

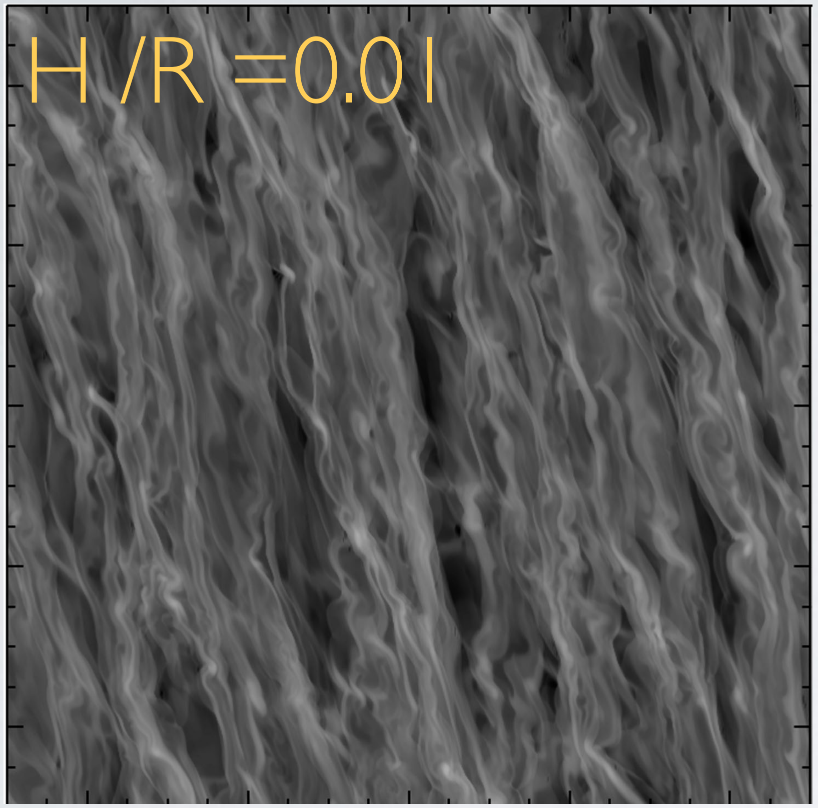
are respectively the local wavelength and the critical wavelengths defined by Toomre (1964). For stability, we obtain the condition

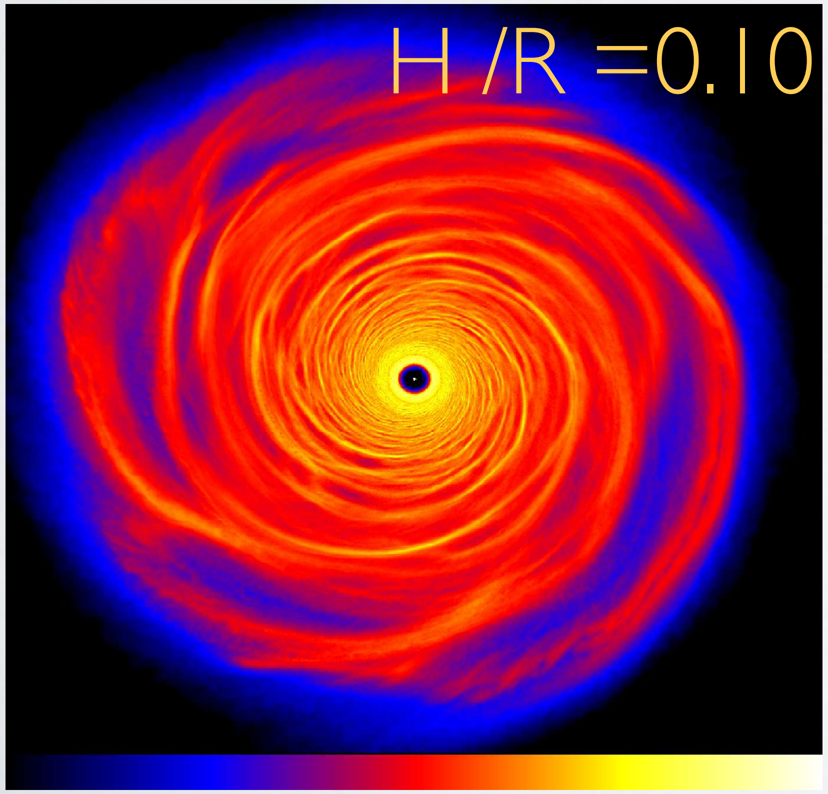
$$Q^2 \geq 4\left[\frac{\lambda}{\lambda_c} - \frac{(\lambda/\lambda_c)^2}{1 + \mathscr{J}^2(\lambda/\lambda_c)^2}\right] \quad (15)$$



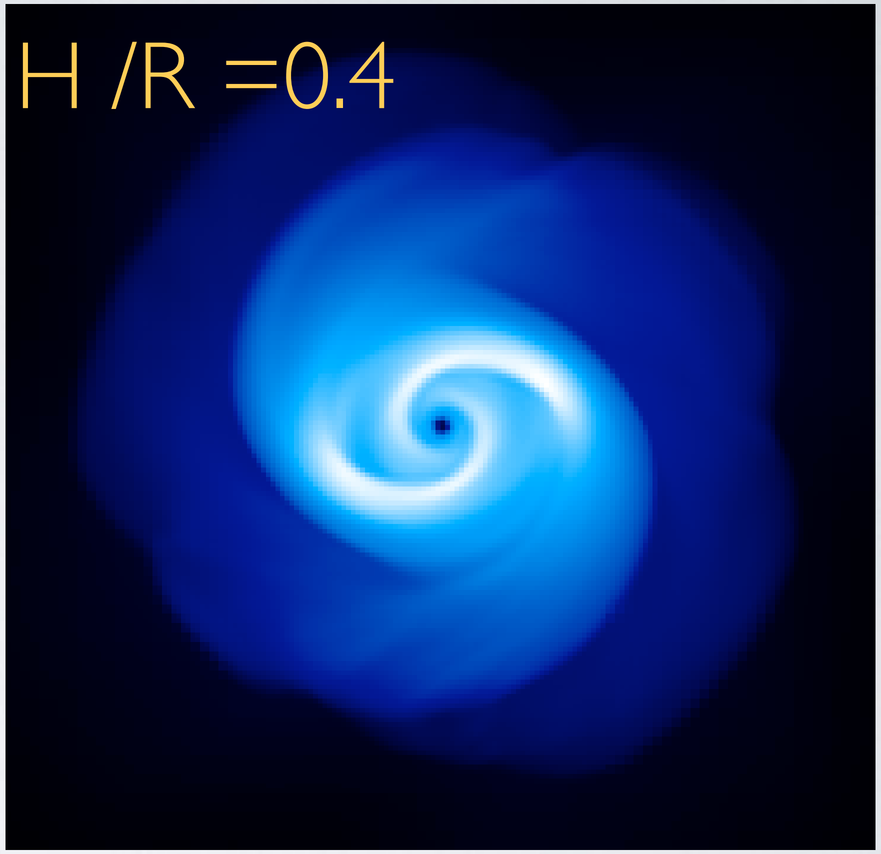
Growth begins at Q>1 in the **"global"** approximation

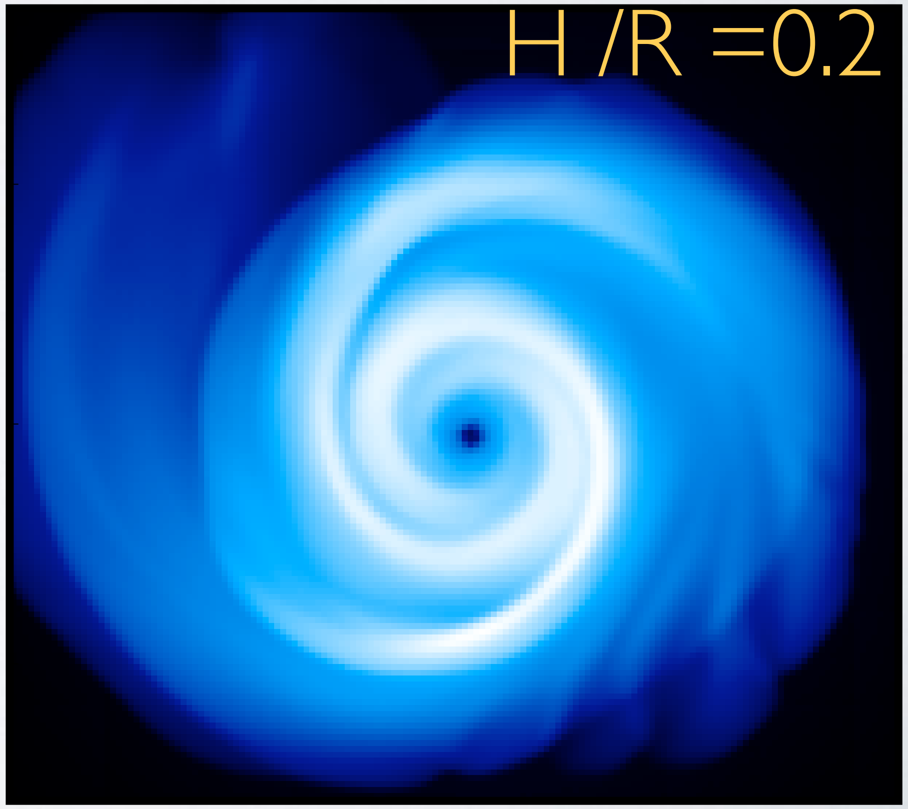
LOCAL VS GLOBAL GI





These two scales are governed by a different dispersion relations, thus different modes grow at different values of Q

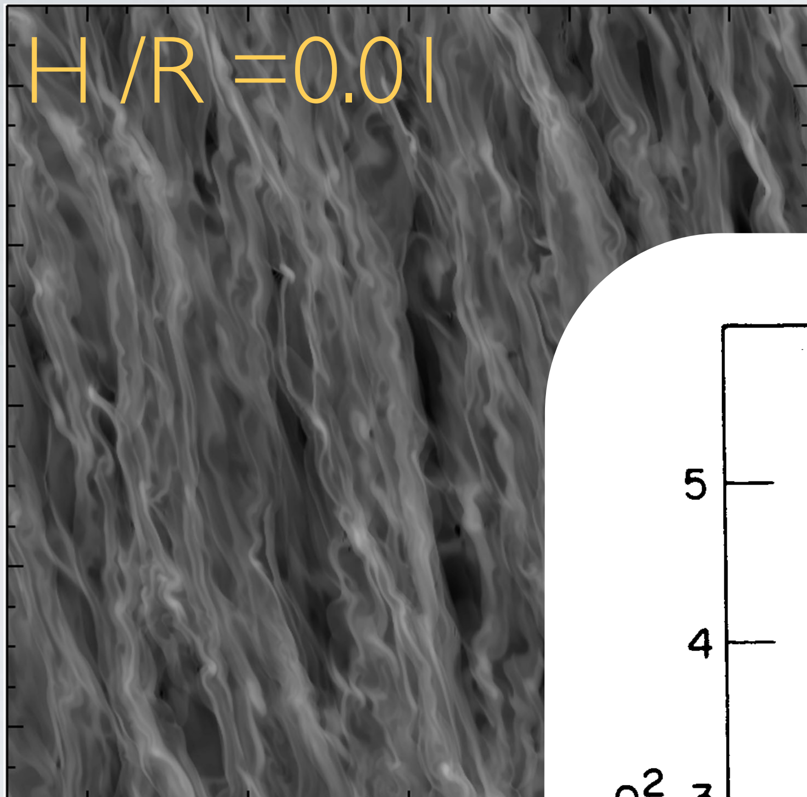




Paardekooper 2012, Rice+2014

Kratter+2010

LOCAL VS GLOBAL GI



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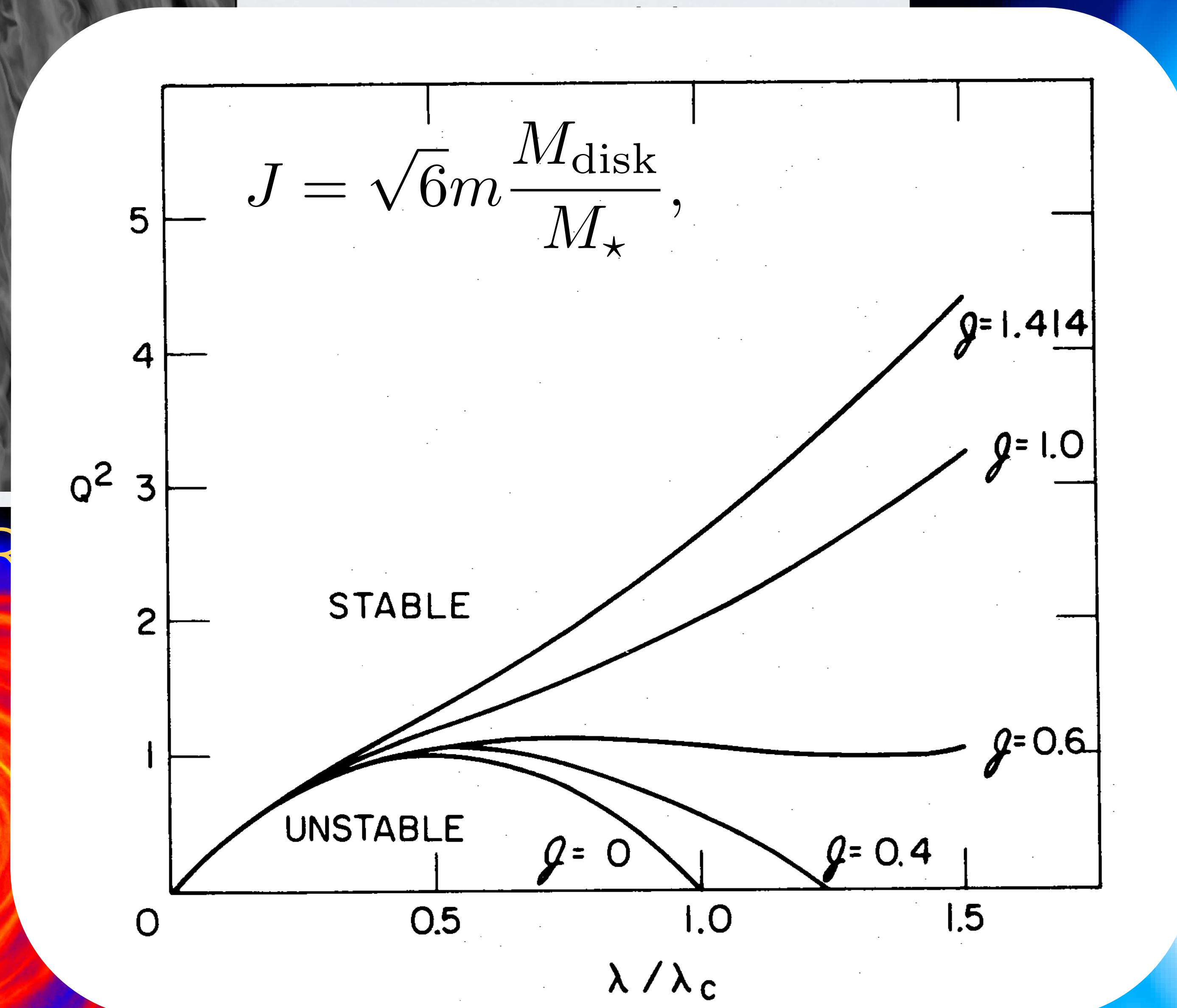
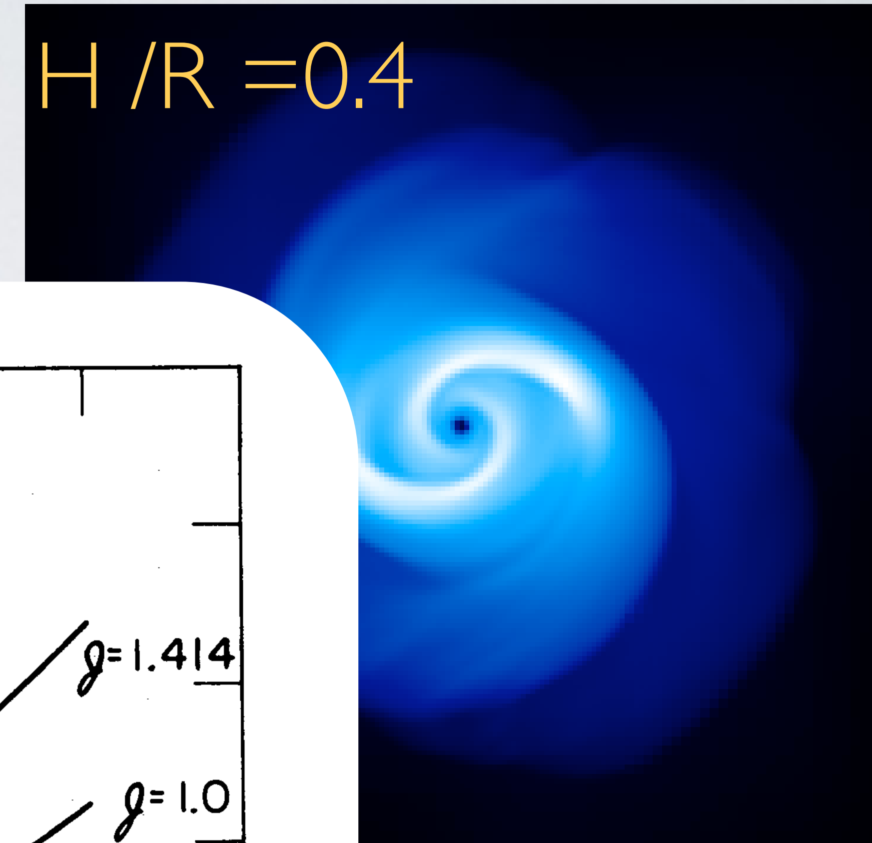
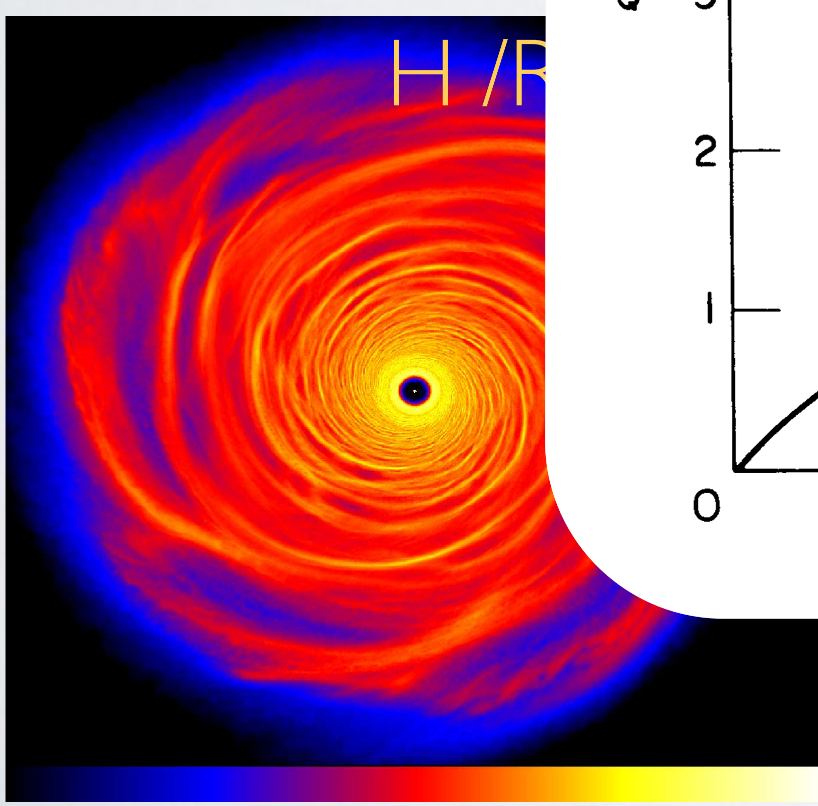
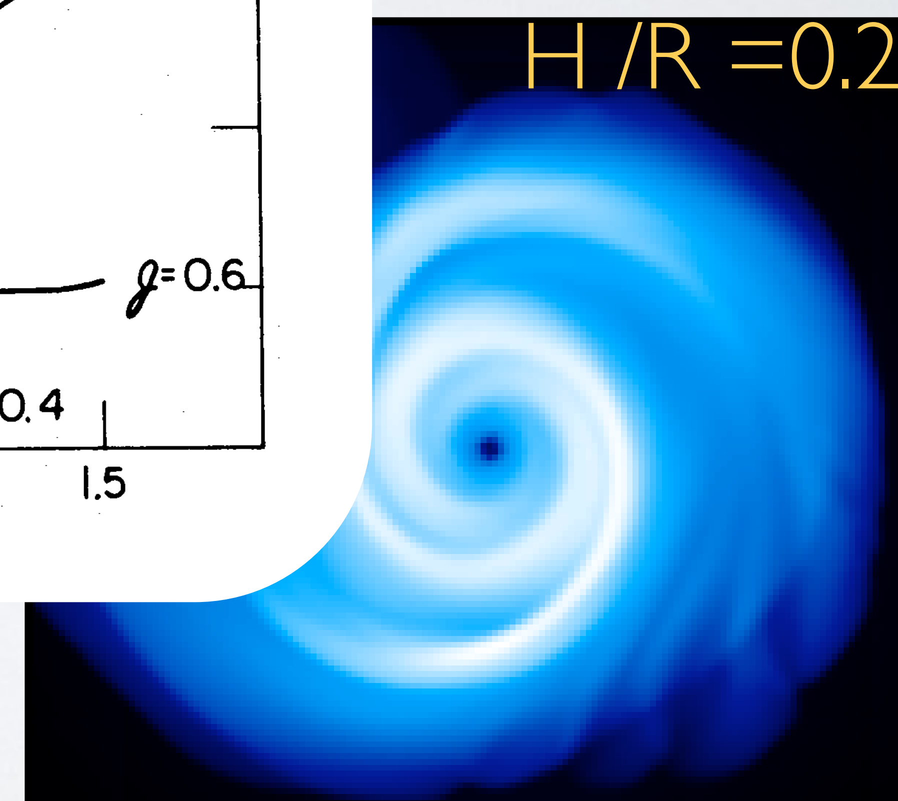








Paardekooper 2012, Rice+2014

Kratter+2010

From GI to Fragmentation

- Fragmentation occurs when the instability does not saturate in the linear phase. Saturation typically occurs in one of two ways:
  - mode-mode coupling
  - thermal feedback

MODE-MODE COUPLING

- Interaction of multiple growing modes saturates the amplitude of density perturbations
- surface density may never get high enough *locally* for collapse, because global modes are triggered at *higher* Q.
- global modes provide very efficient angular momentum transport — may be important where MRI / disk winds fail

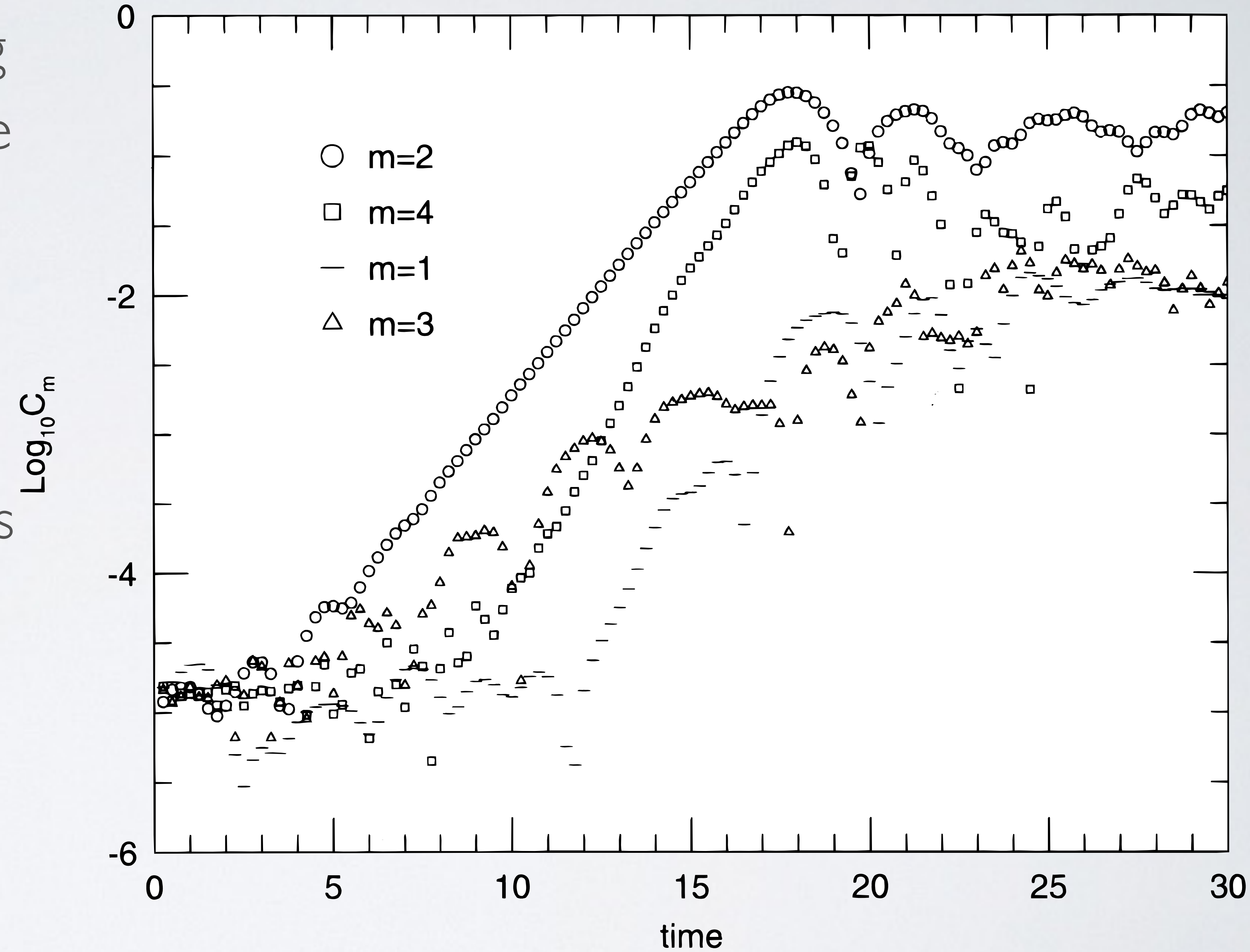


FIG. 6.—Global Fourier amplitudes, C_1–C_4, plotted as a function of time

Laughlin, Korchagin, Adams 1996

THERMAL FEEDBACK: THE COOLING TIME CRITERION

- waves/spiral arms generate subsonic shocks, which heat the gas.

  - too much heating, $Q>1$, self-regulated GI is possible

  - too little heating, $Q<1$, fragmentation

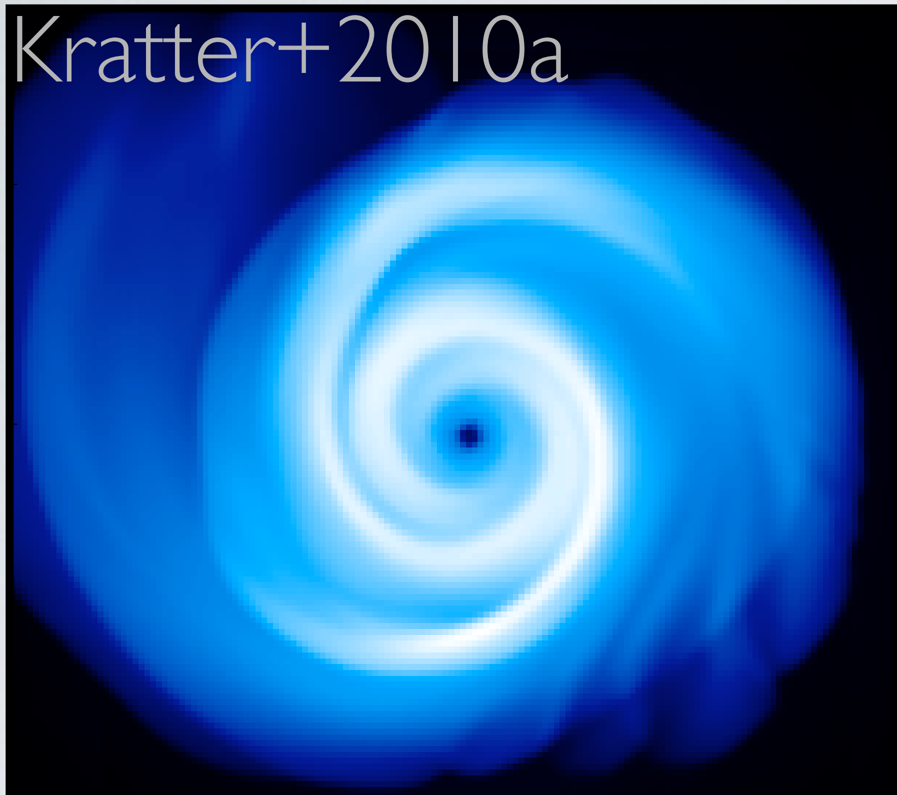
$$\tau_c = \beta\Omega^{-1} \approx \frac{\Sigma c_s^2}{\sigma T^4} f(\tau)$$

since the instability grows on a dynamical time, cooling on a similar timescale is too fast to stave off fragmentation.

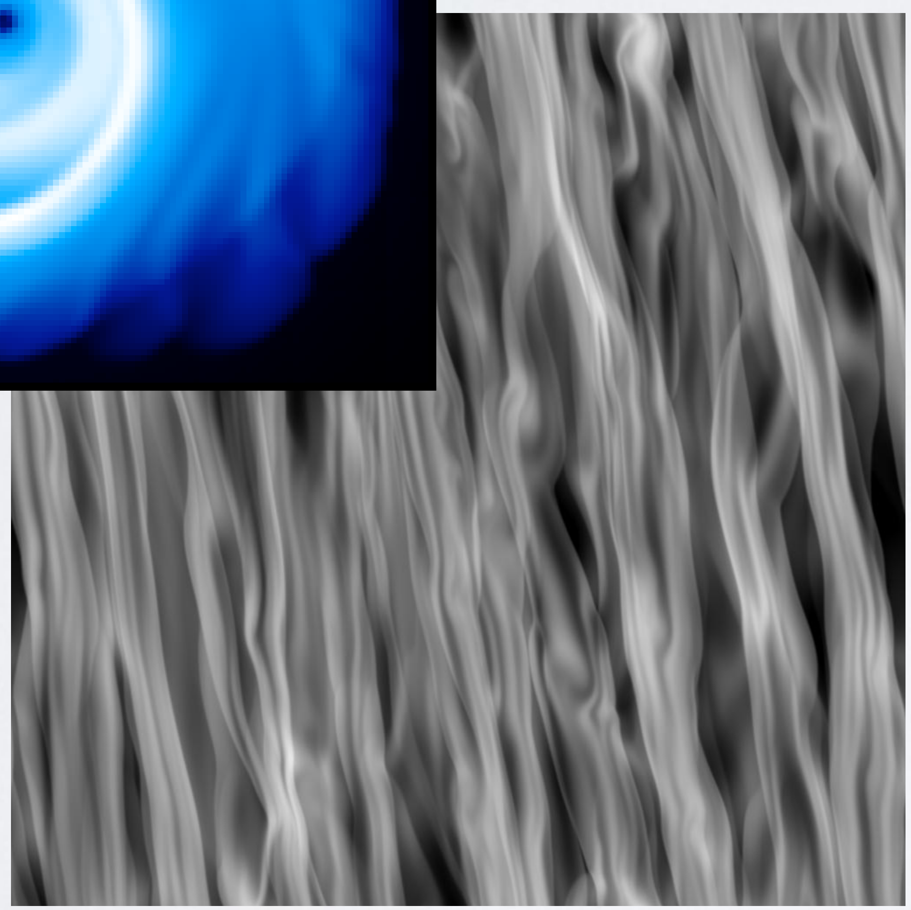
HOW FAST? WHAT IS β

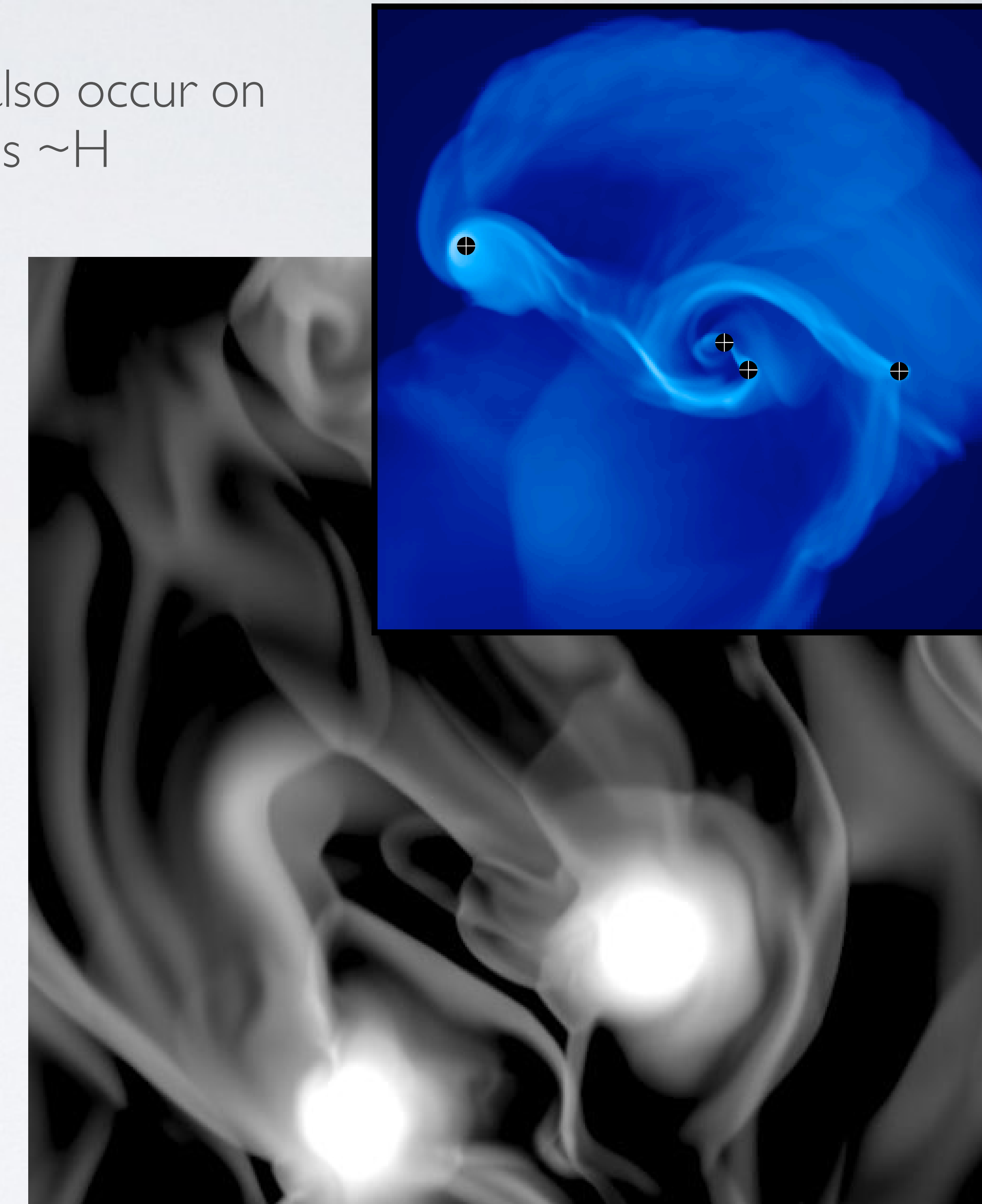
- Physically: set by optical depth due to **dust**.
- It depends on the (effective) EOS (γ)
- Probably between 8-15 for protoplanetary disks with $\gamma = 7/5$
- ***Numerical modelling required***

Saturation vs fragmentation



Fragments also occur on scales ~H





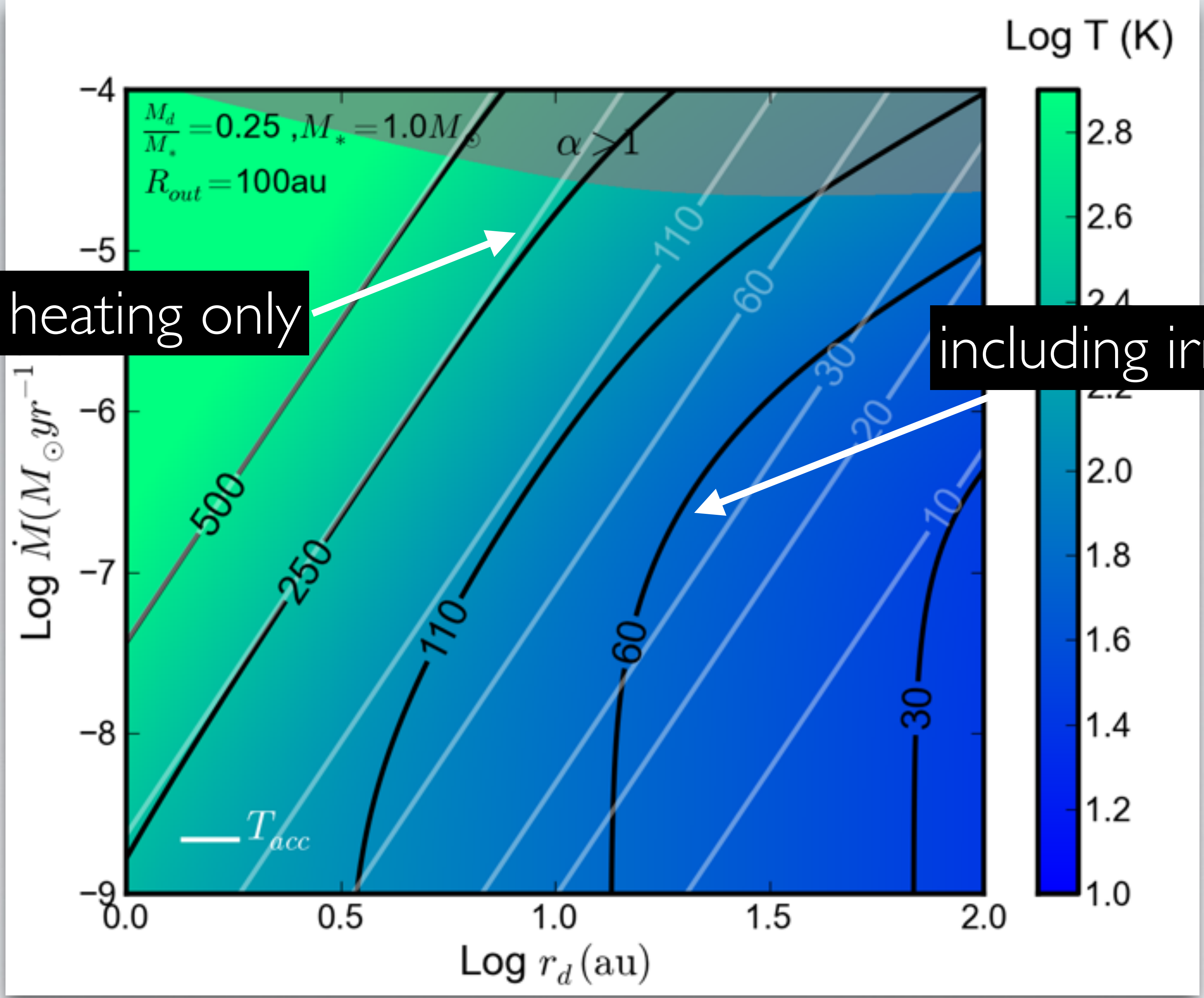
Most power in “gravito-turbulence” occurs on scales 1<H<10

Gammie, 2001

WHAT ARE THE RIGHT PARAMETERS FOR PROTOSTELLAR AND PROTOPLANETARY DISKS?

Kratter & Lodato, in prep

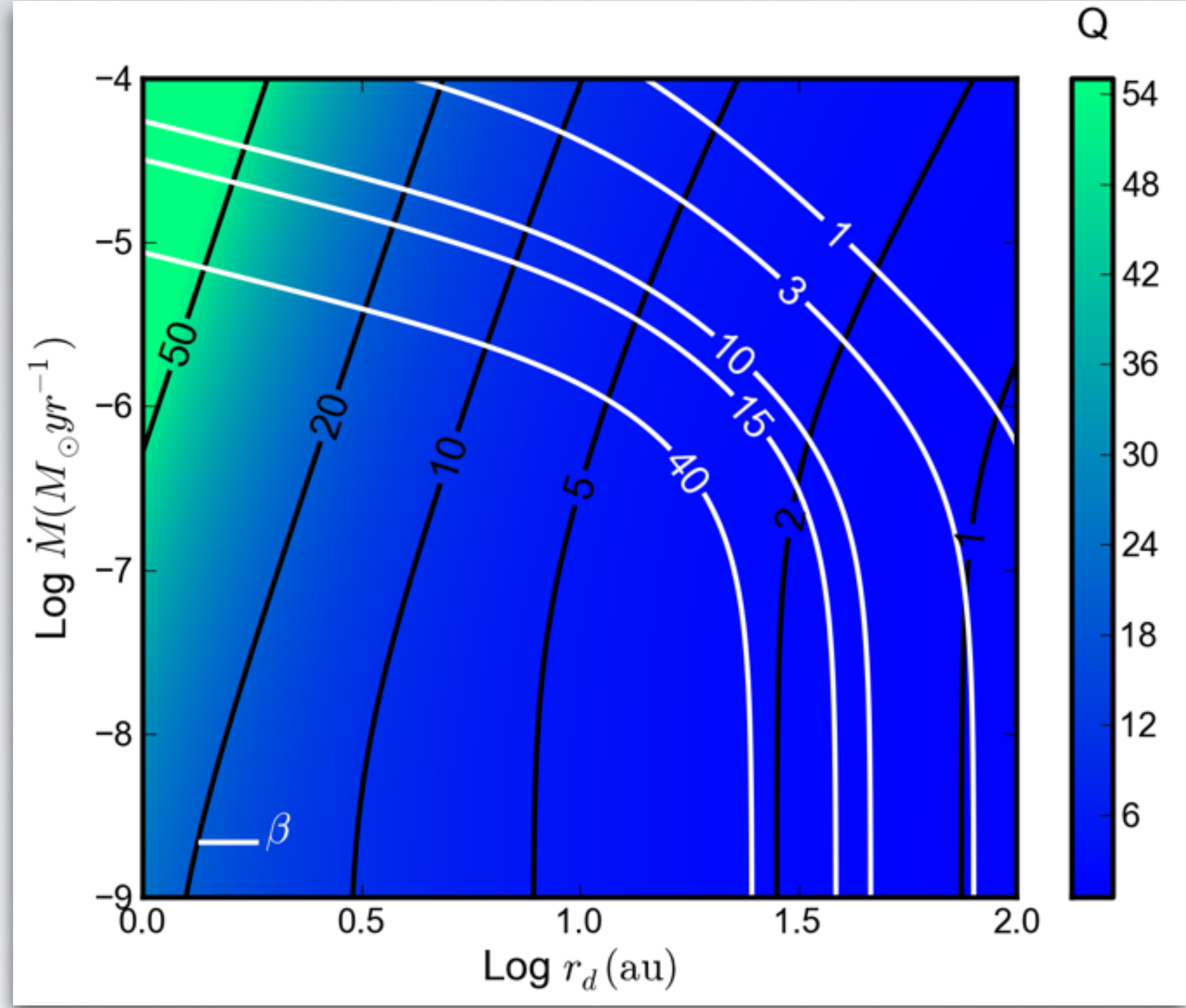
H<R



Conditions in a **massive, protostellar** disk around a sun-like star

$$\sigma T_{\rm mid}^4 = \frac{3}{8} f(\tau_R) F_{\rm acc} + \sigma T_{\rm h,*}^4 + \sigma T_{\rm ex}^4 \qquad F_{\rm acc} = \frac{3}{8\pi} \dot{M} \Omega^2$$

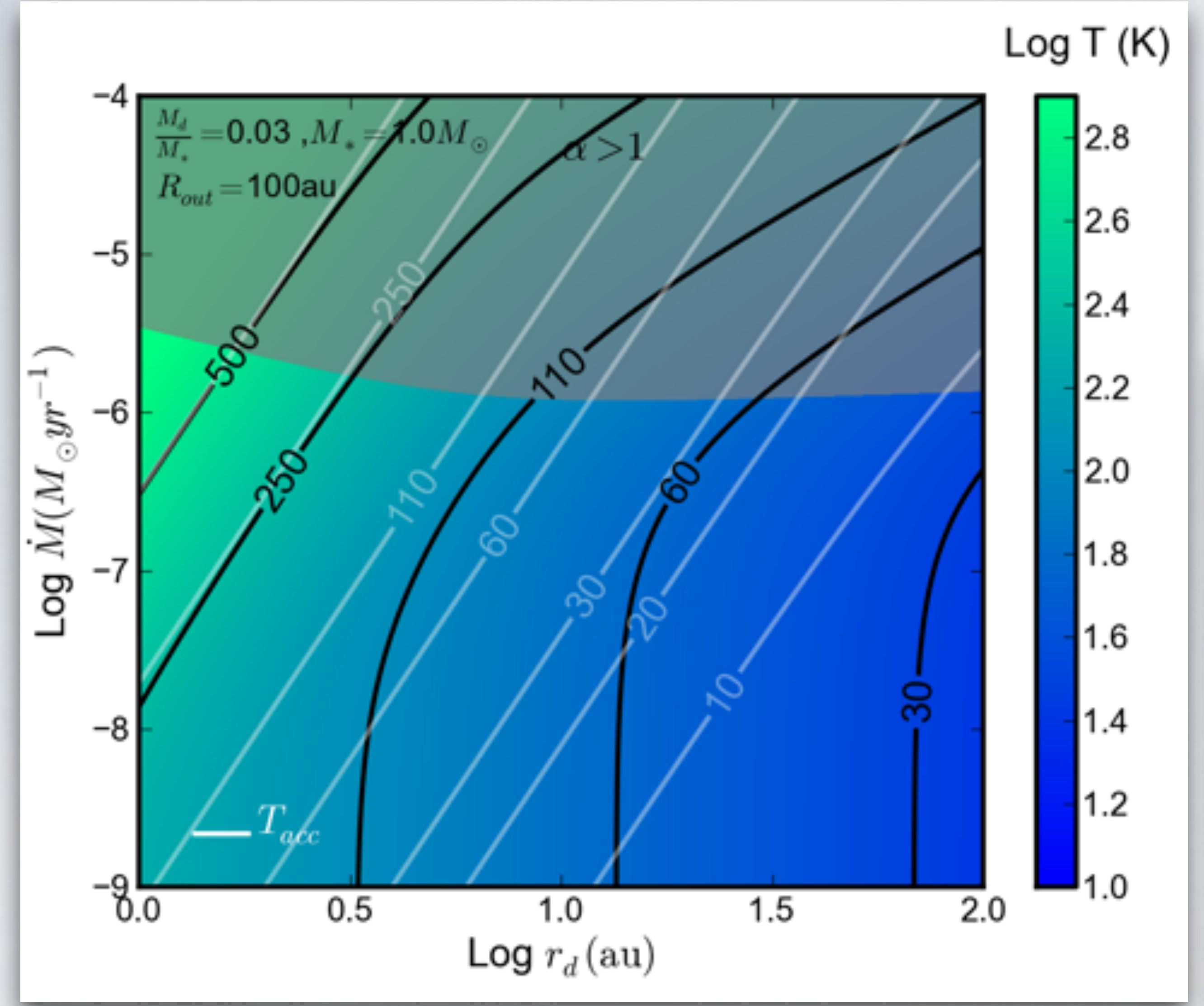
Kratter & Lodato, in prep



H<R

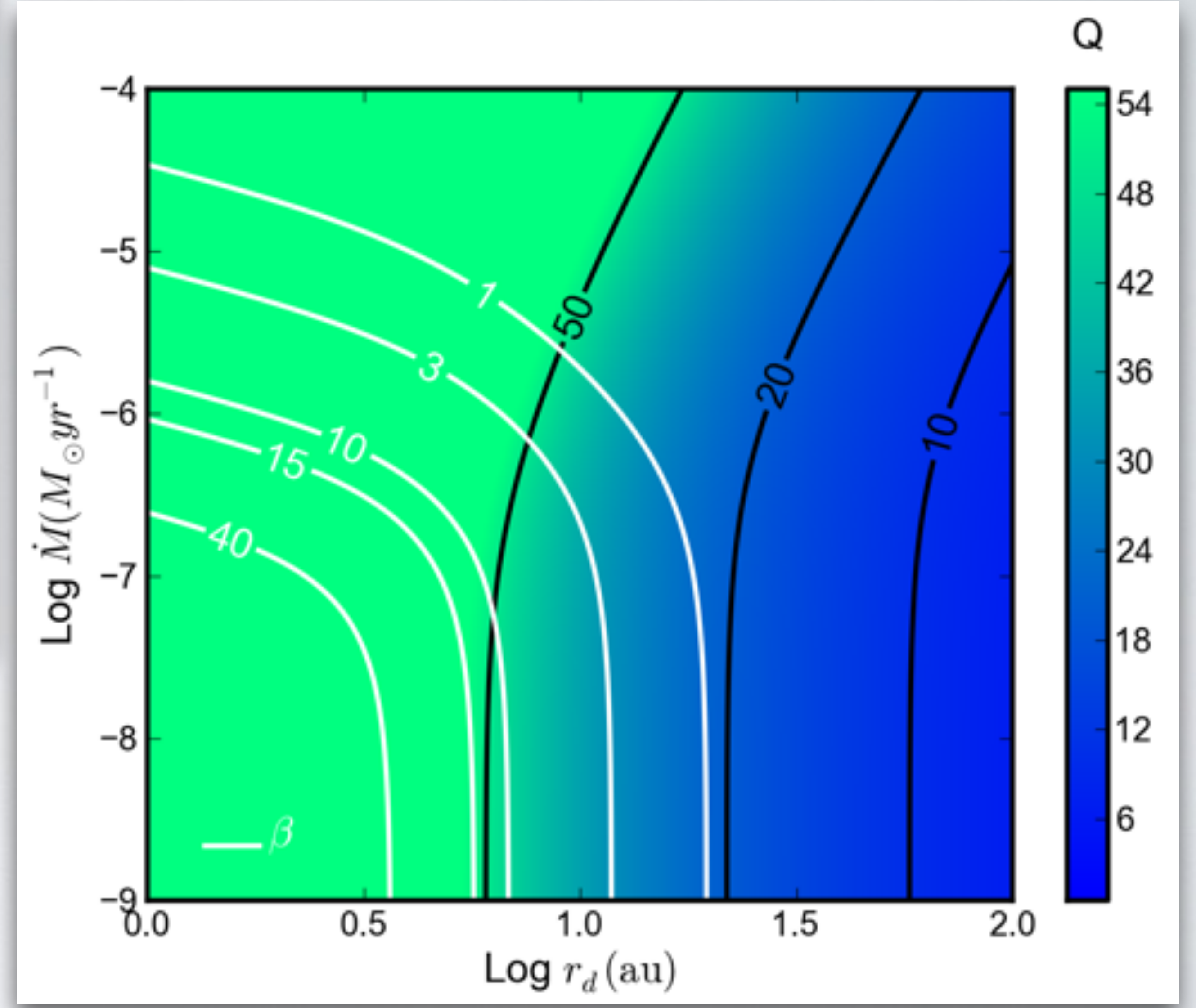
Conditions in a **massive** disk around a sun-like star

corresponding values of Q and cooling time, between 70-100 AU it is close enough to give rise to GI



Kratter & Lodato, in prep

H<<R



Conditions for measured Class I disks around sun-like stars

Disks that are low enough in mass to operate in the local regime are typically too hot to suffer from GI.

HOW DID WE GET HERE?

Disk with Q>1

$$Q = \frac{c_s \Omega}{\pi G \Sigma} = f \frac{M_*}{M_D} \frac{H}{r}$$

- The outer regions of protostellar disks are dominated by stellar irradiation, which fixes the temperature.

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add mass, raise surface density

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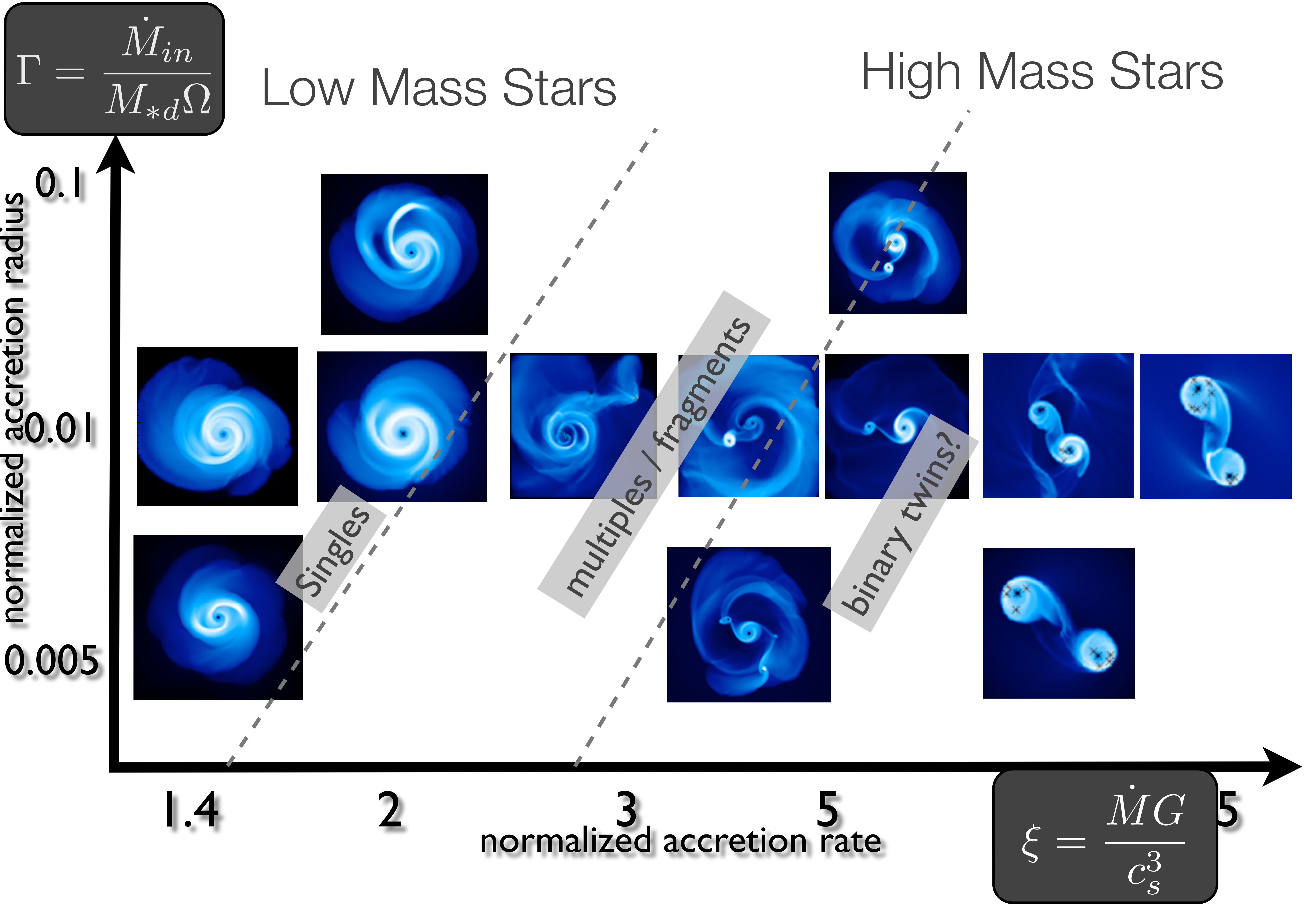
only under very special circumstances can the disk reach instability by getting colder, rather than by adding mass



Kratter et al 2010

Fragment mass, zeroth order

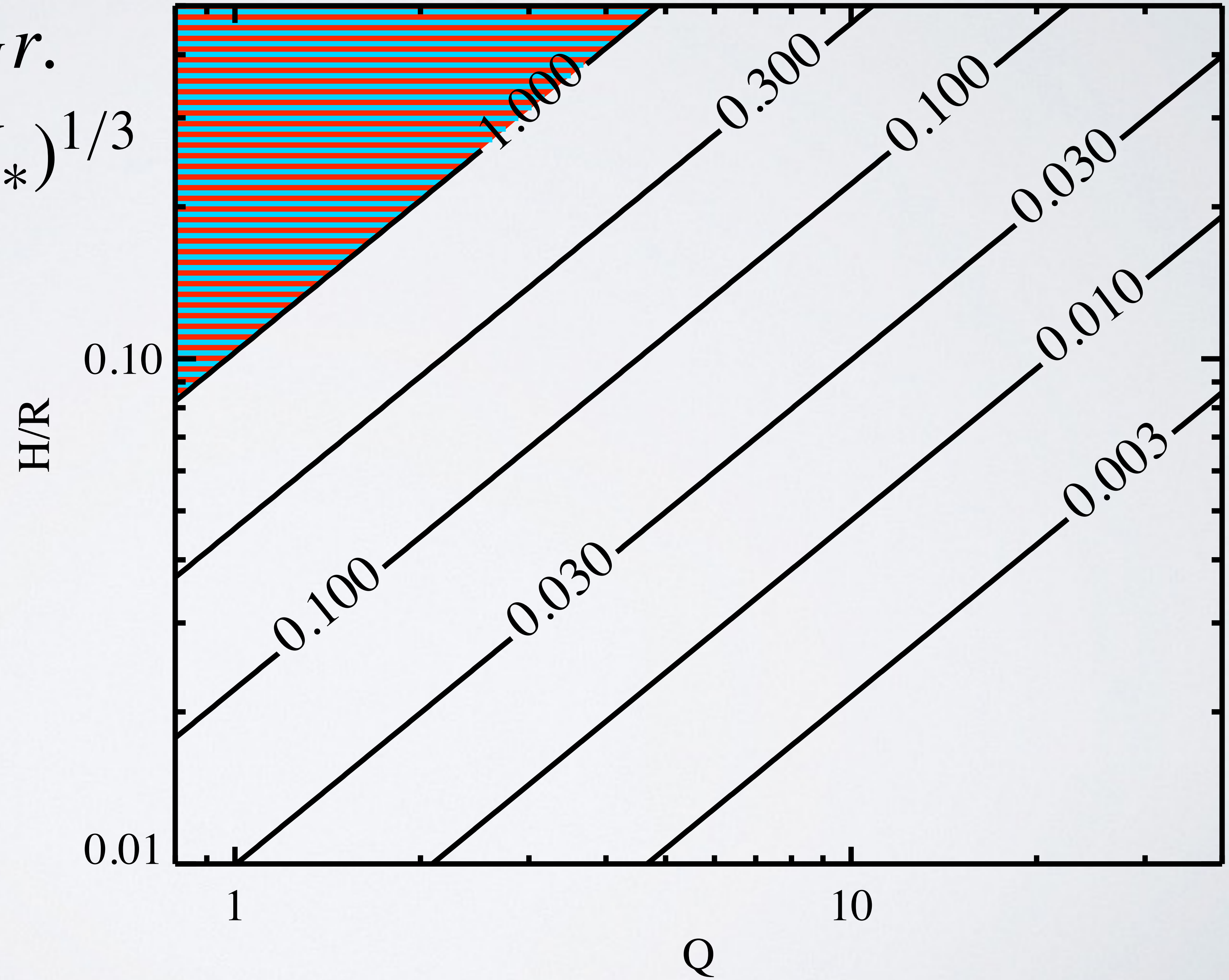
$$M_{frag} = \Sigma\lambda^2 \sim \Sigma H^2$$

$$M_{\rm iso} \approx 4\pi f_H \Sigma R_H r.$$

$$R_H = r(M_{\rm iso}/3M_*)^{1/3}$$

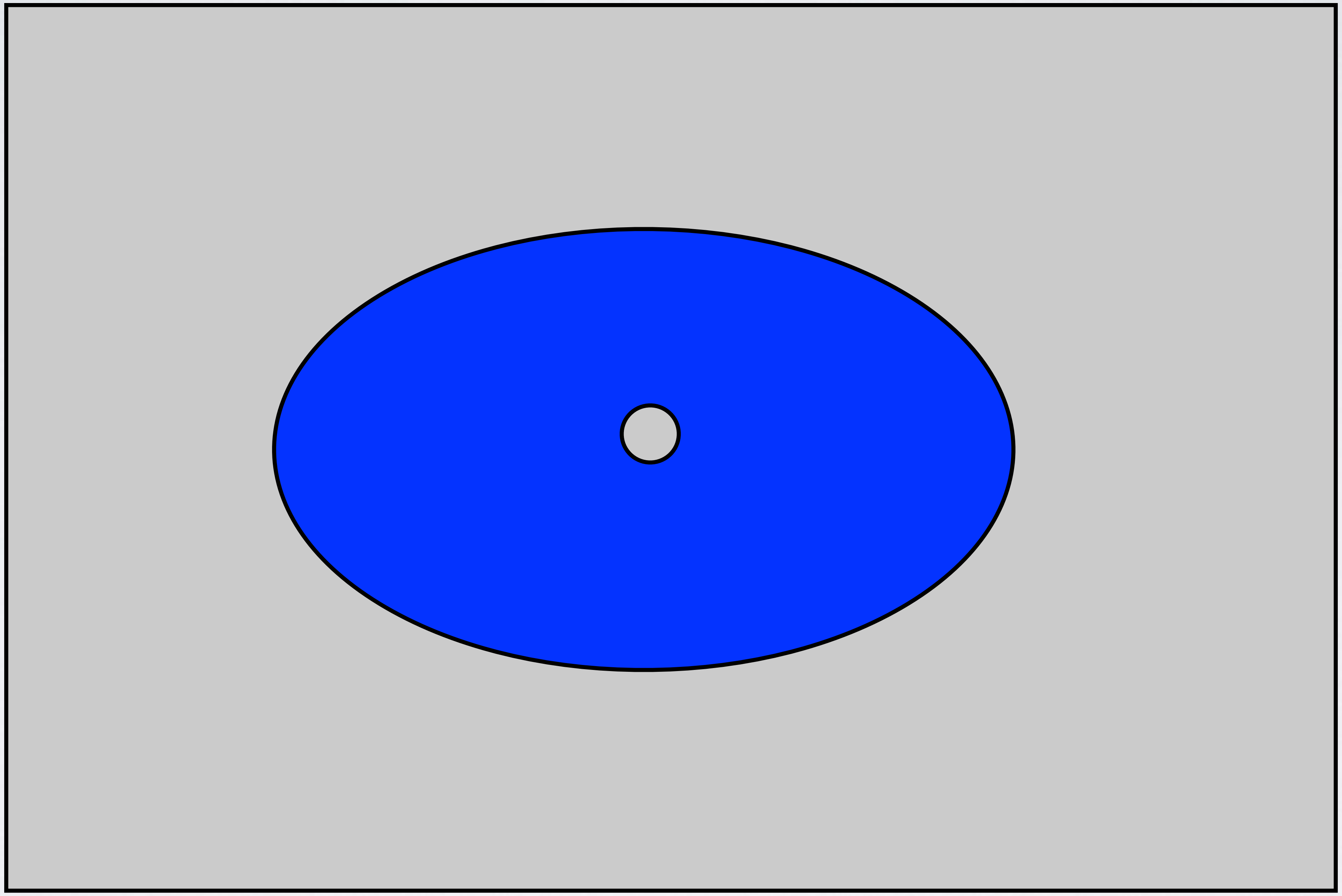
If disks are driven unstable by infall, it can be challenging to avoid isolation mass

M_{iso}/M_*



Kratter et al 2010b

WHY DO FRAGMENTS GROW IN DISKS WITH INFALL?



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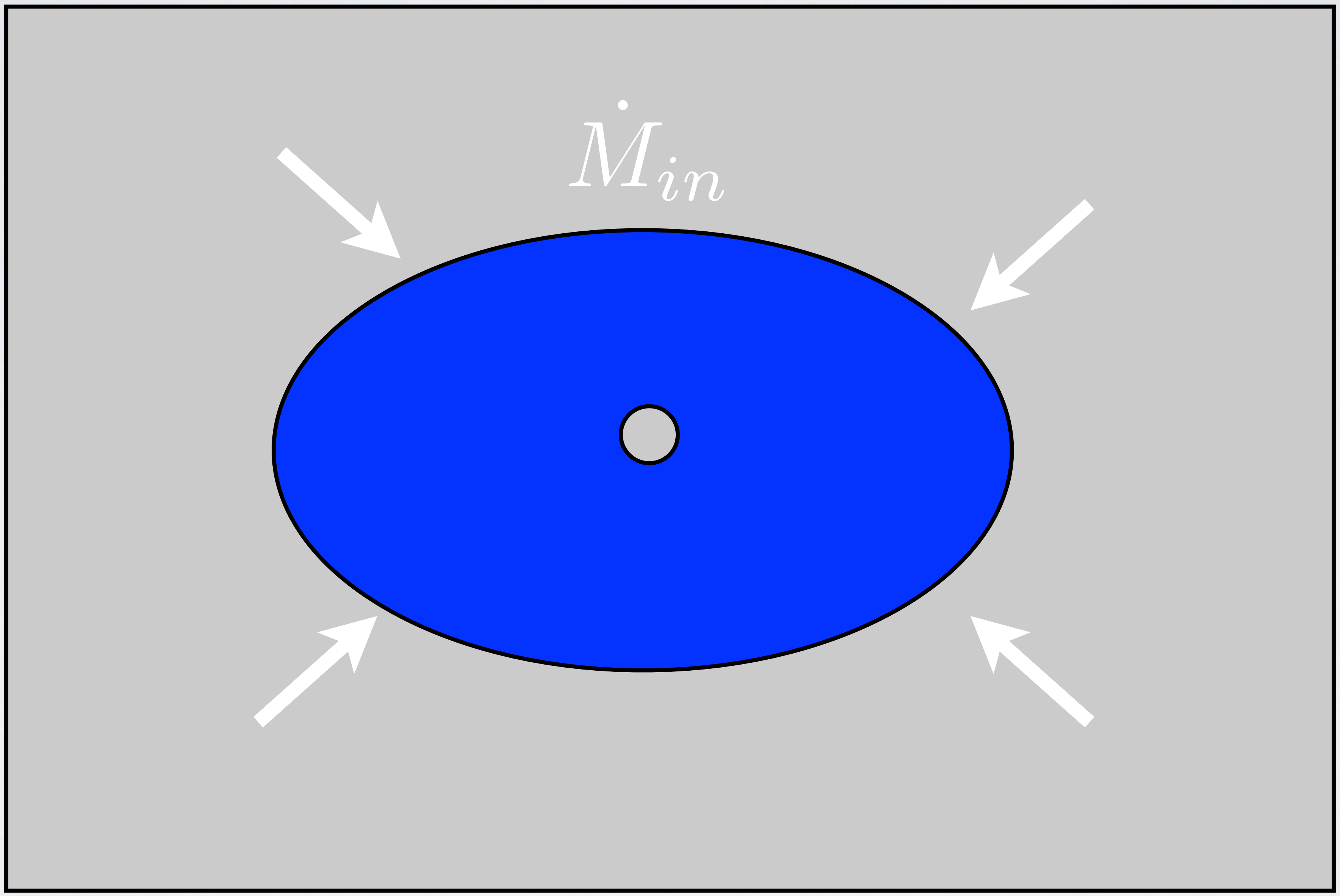

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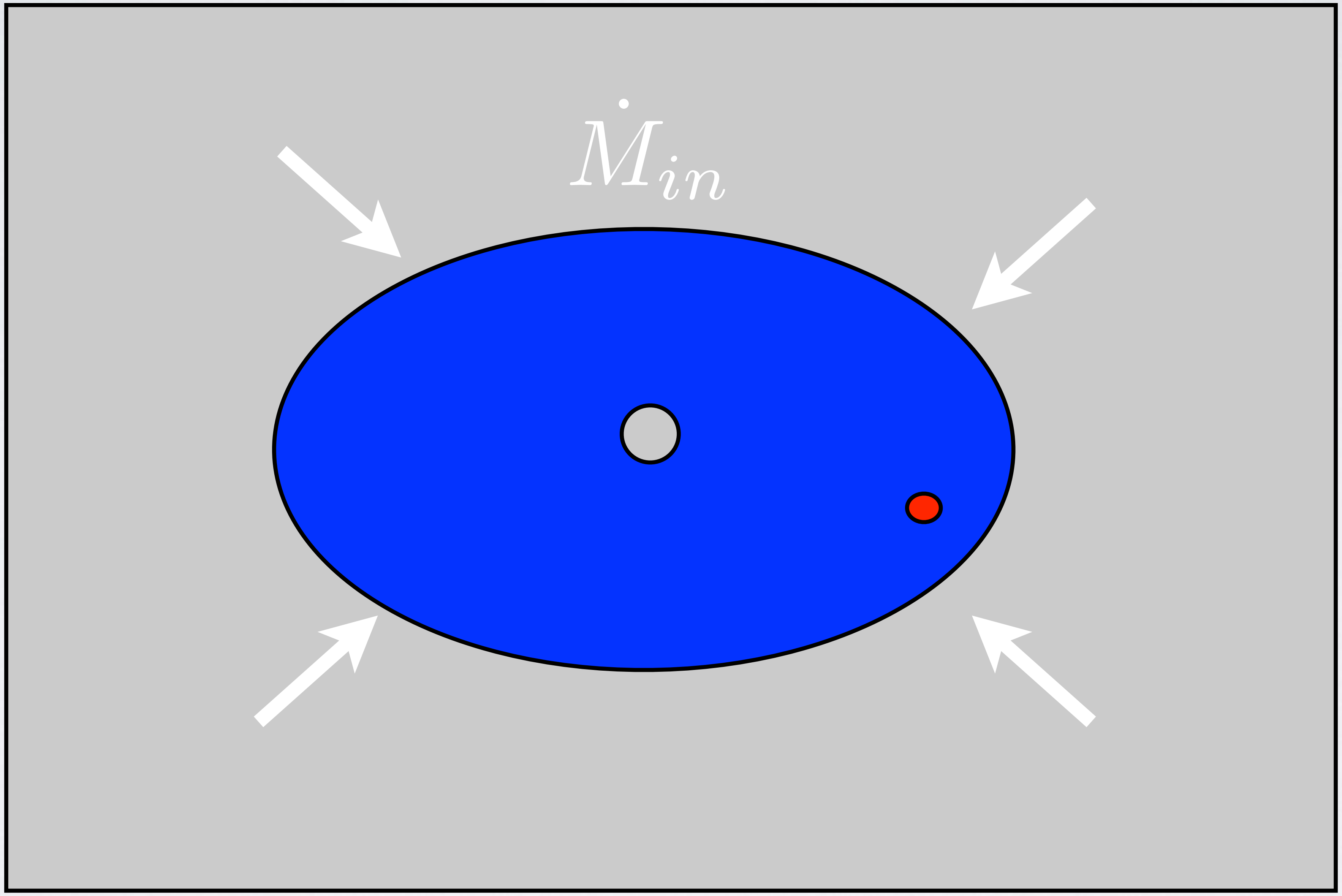

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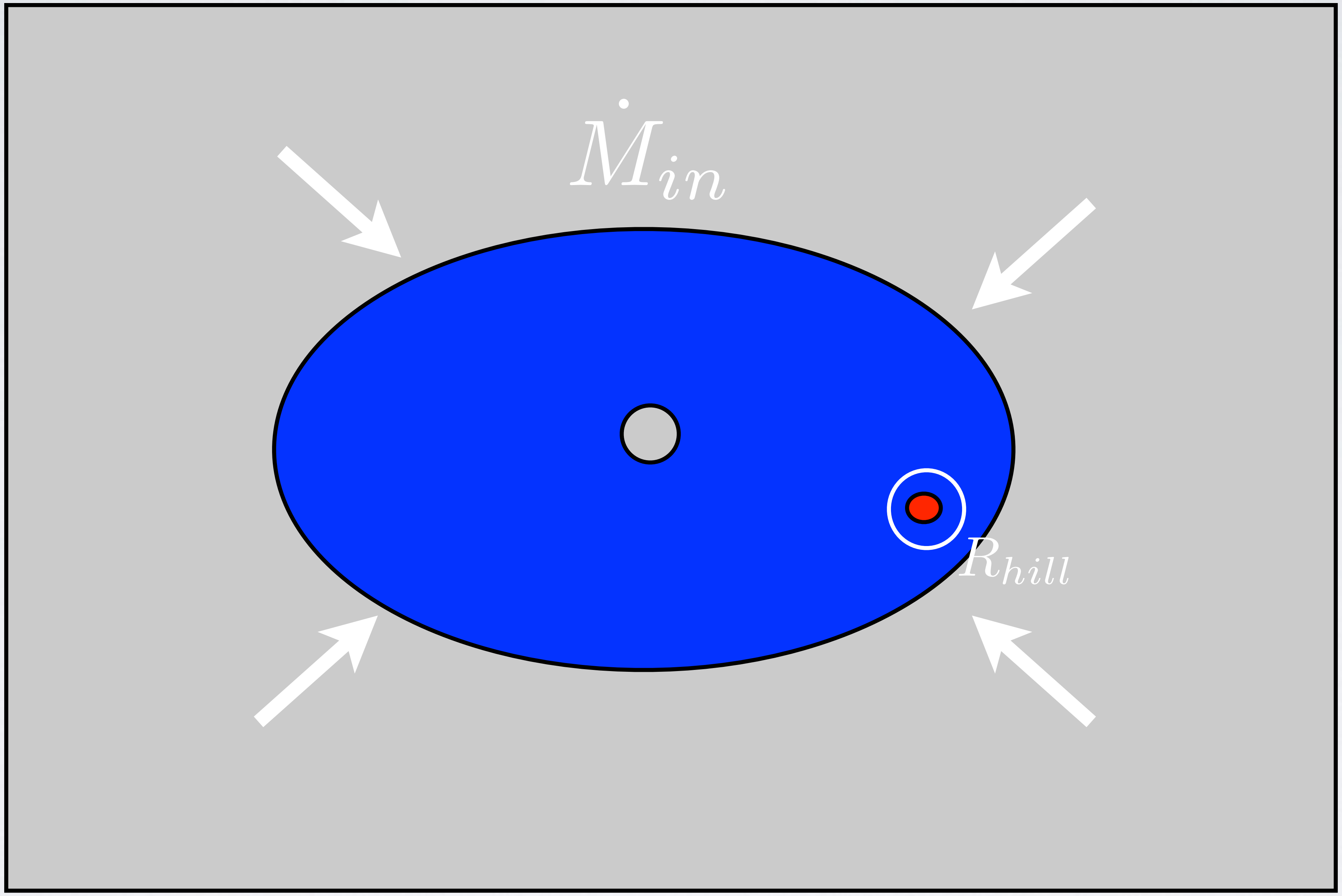

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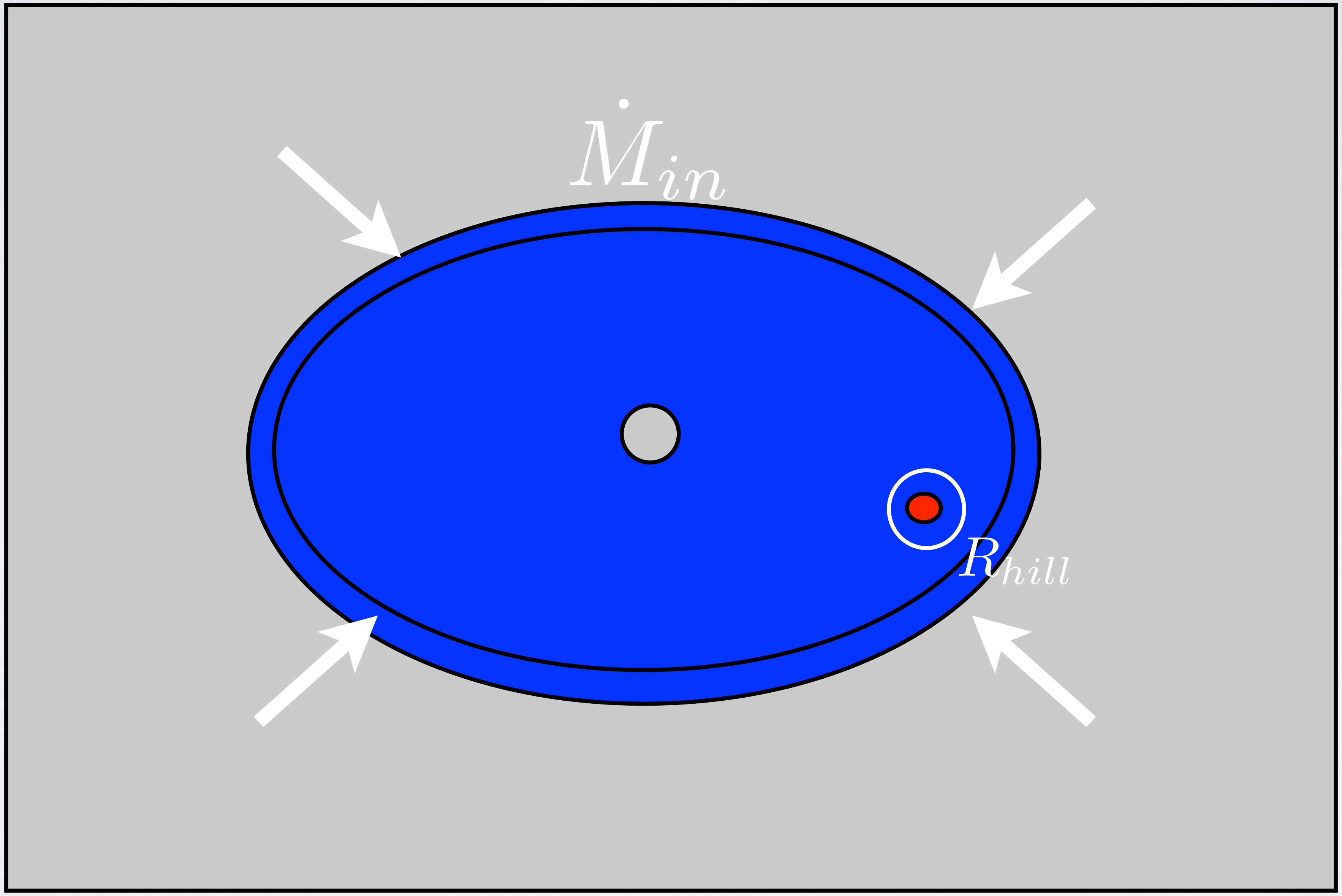

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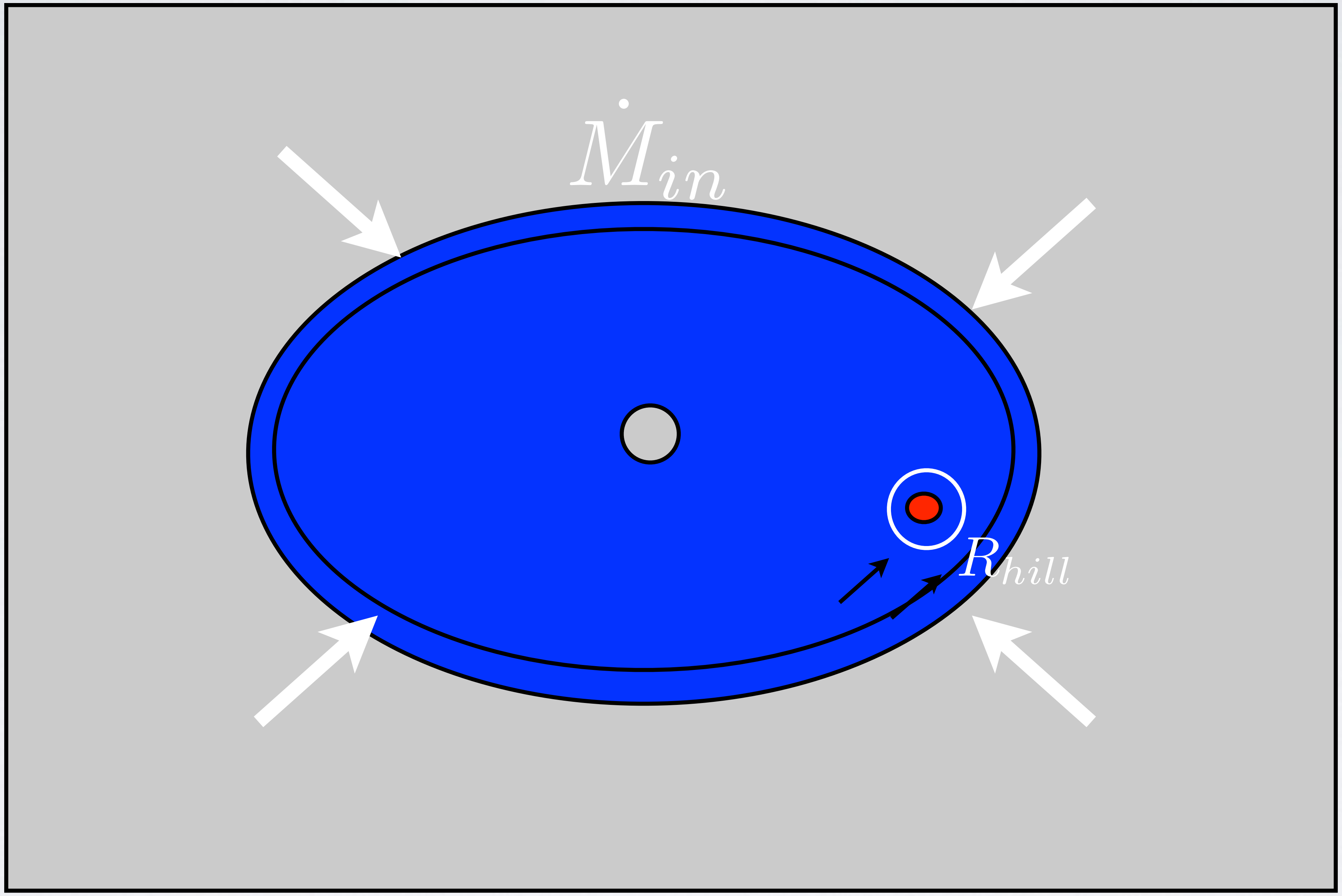

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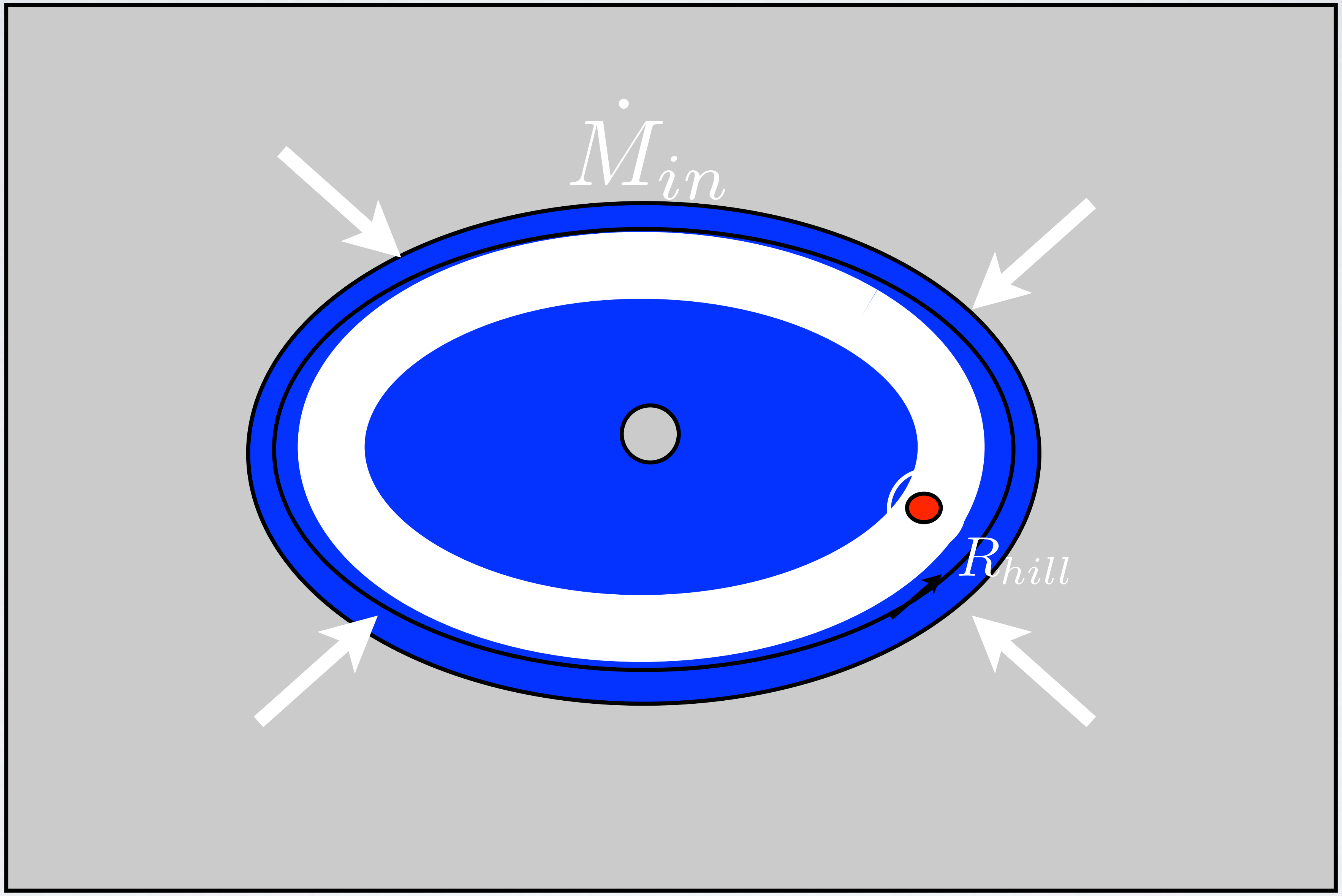


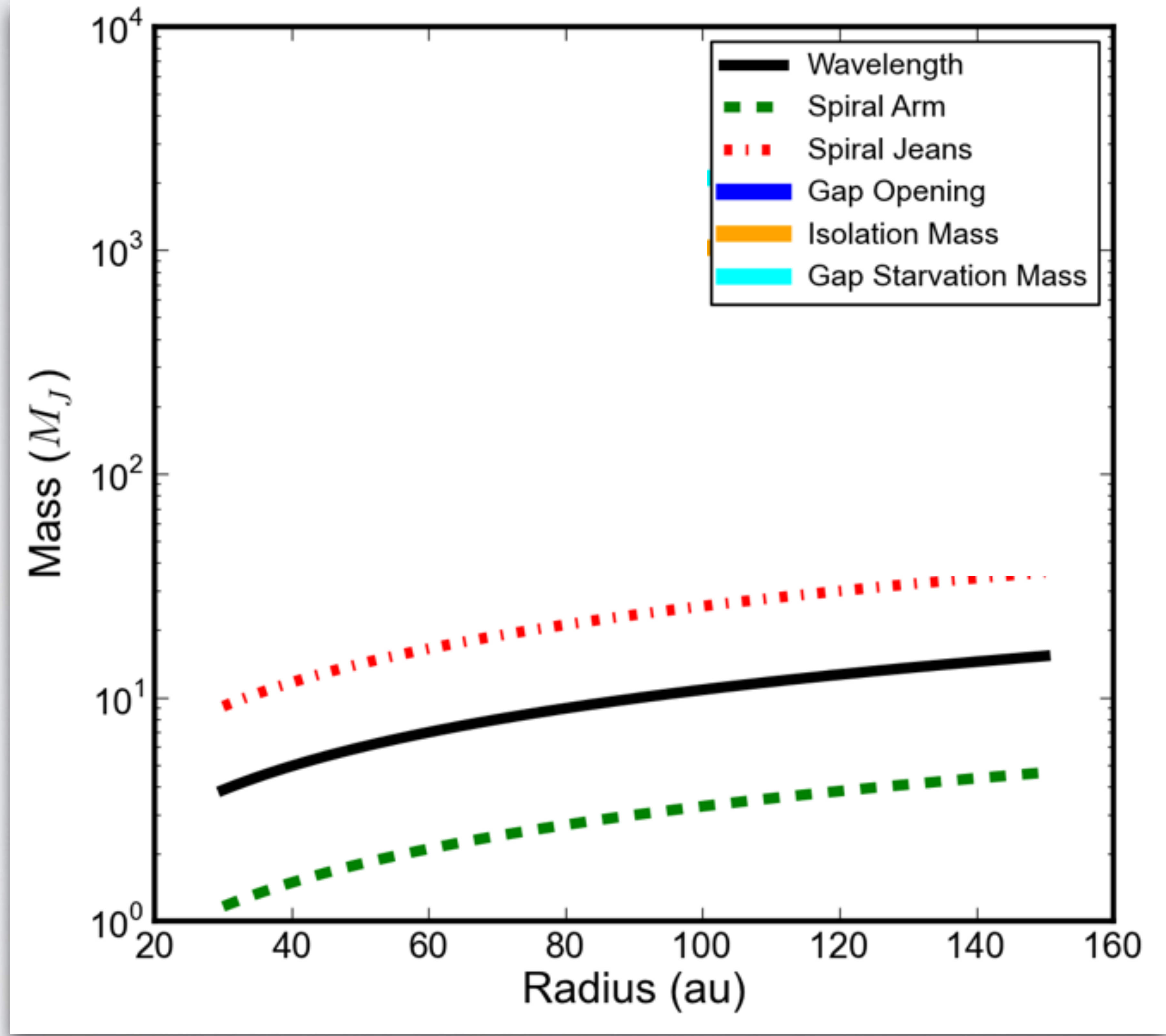
First order: how massive are fragments?

- Initial mass estimates all scale with

$$\Sigma H^2$$

- Fragments that are not disrupted can also easily grow from the parent disk

Kratter & Lodato, in prep, with data from Kratter+2010,Boley +2010,Forgan & Rice 2013,Young & Clarke 2015



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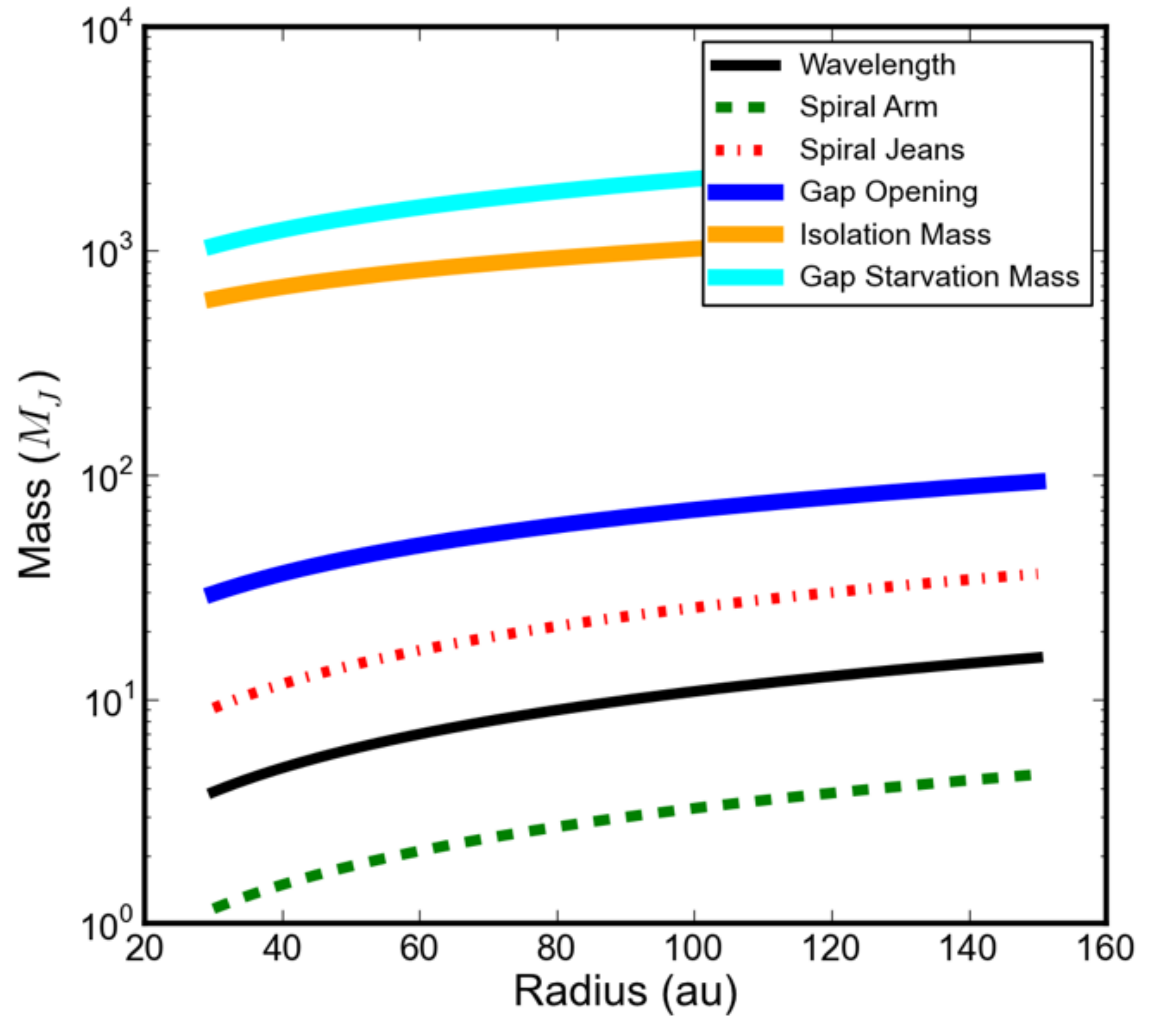

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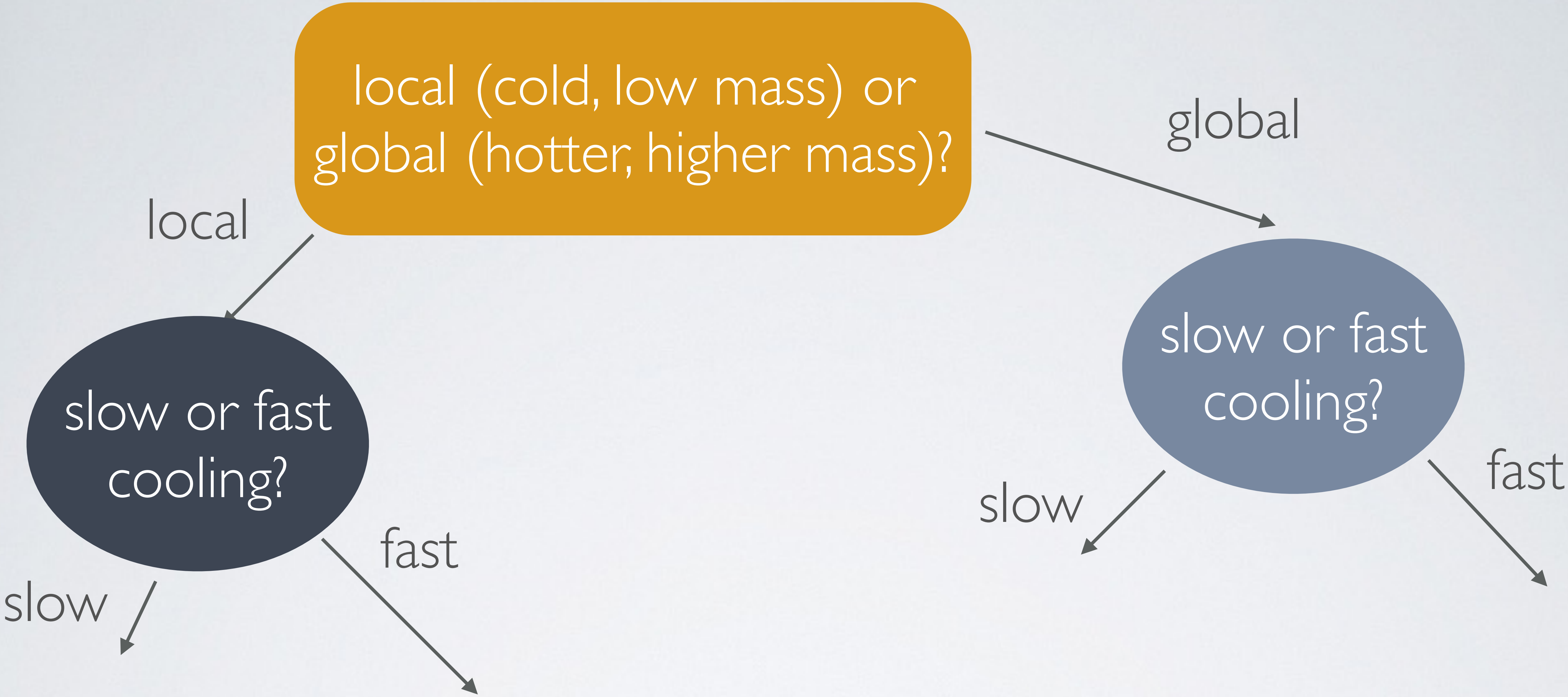
Choose your own GI adventure!



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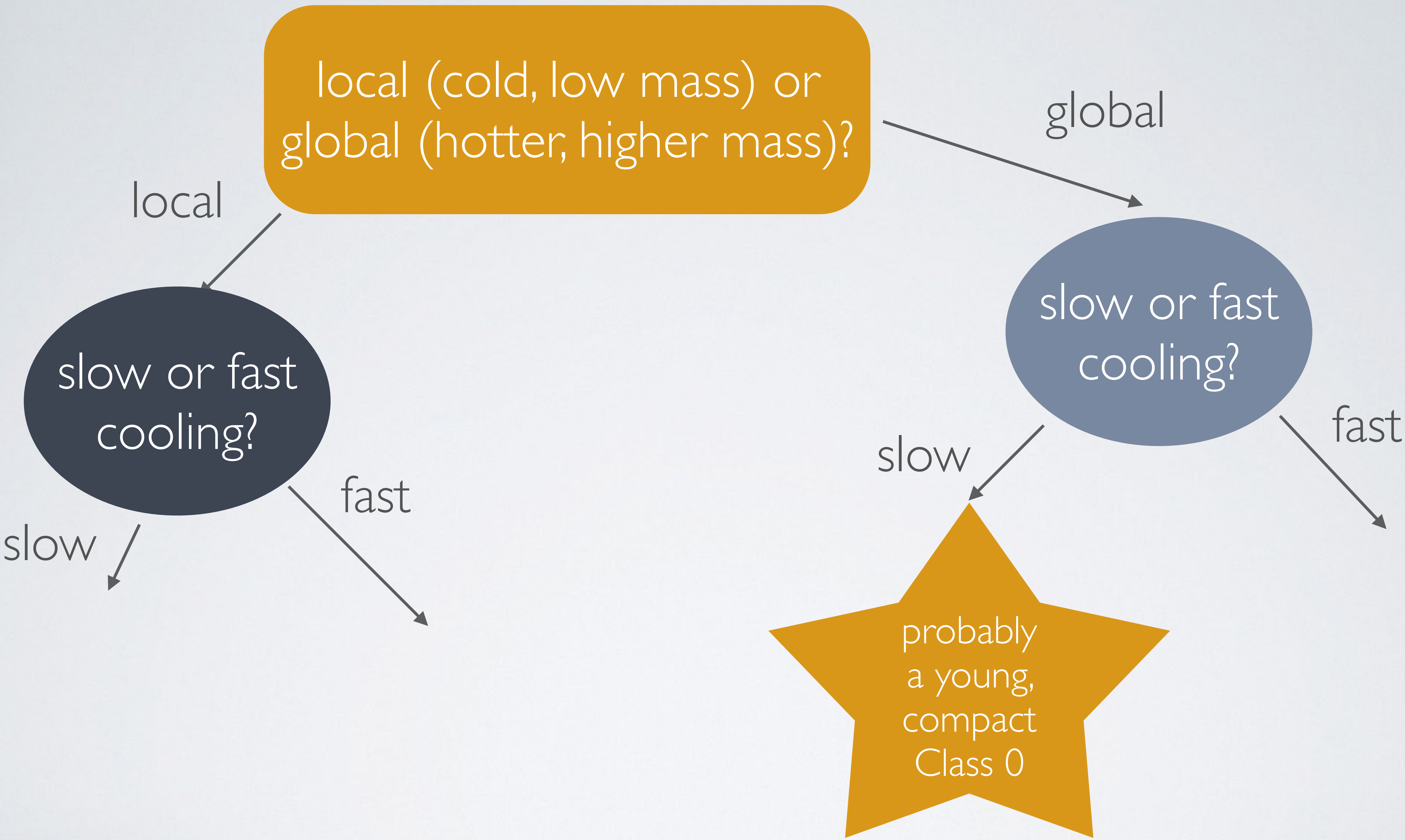

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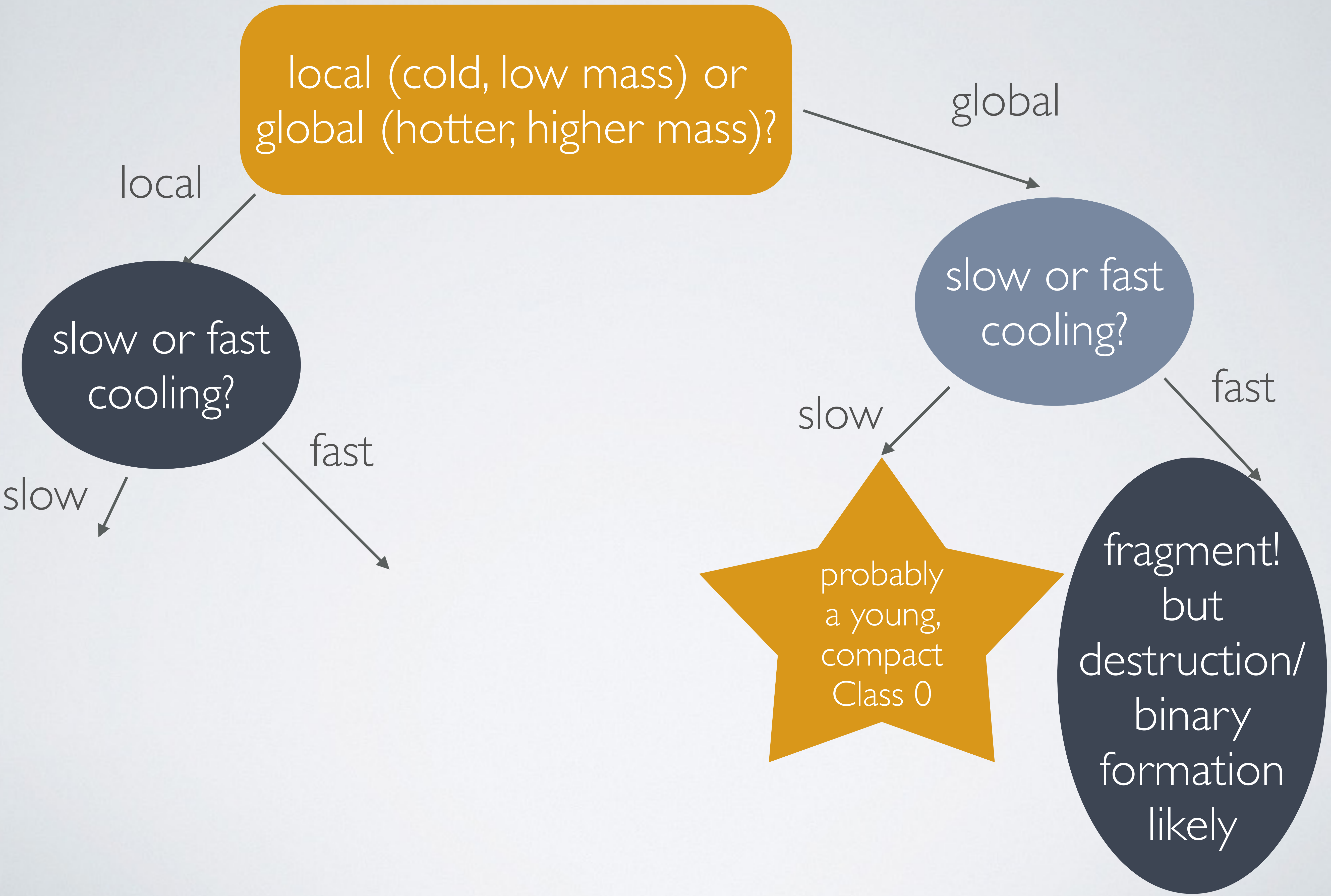

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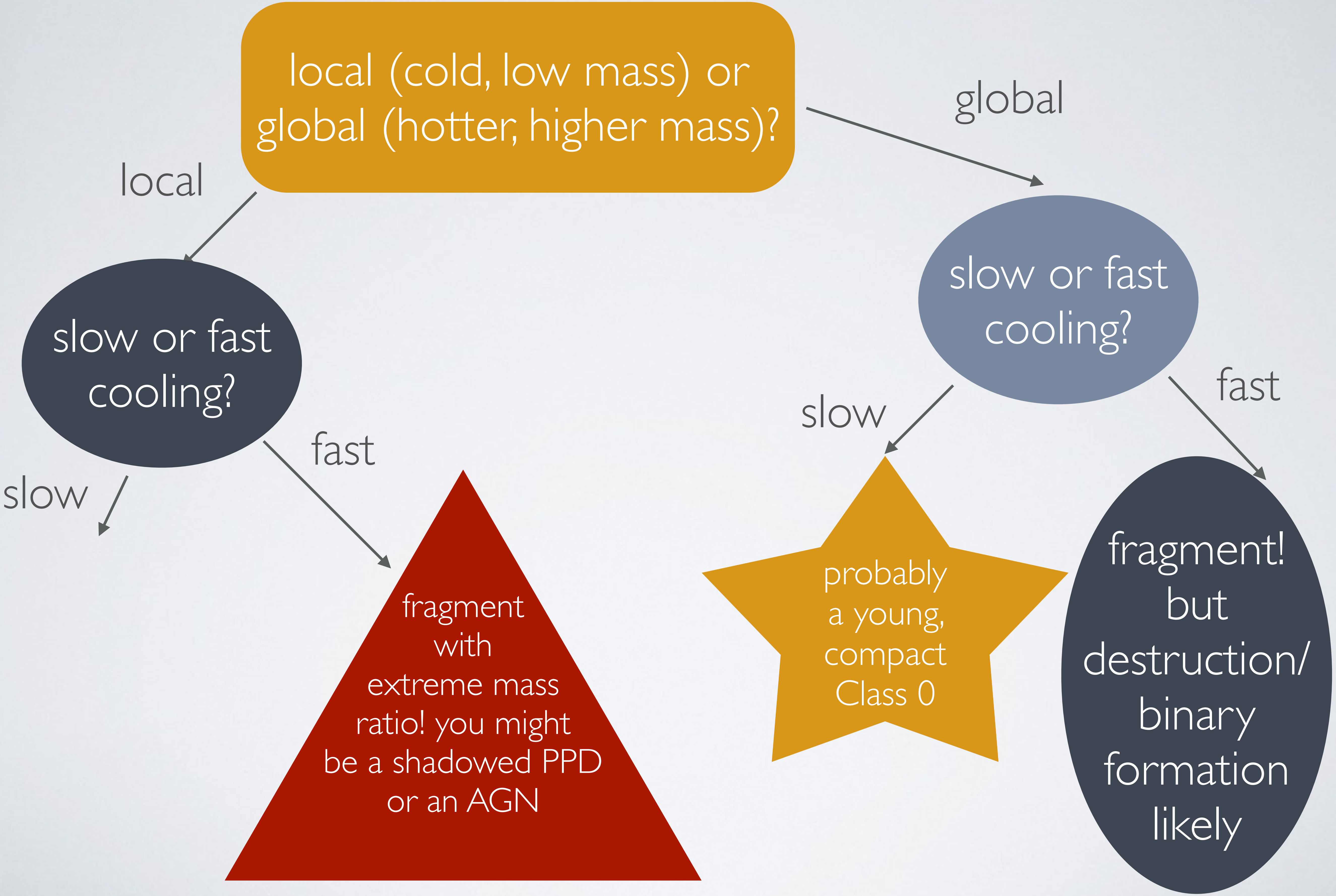

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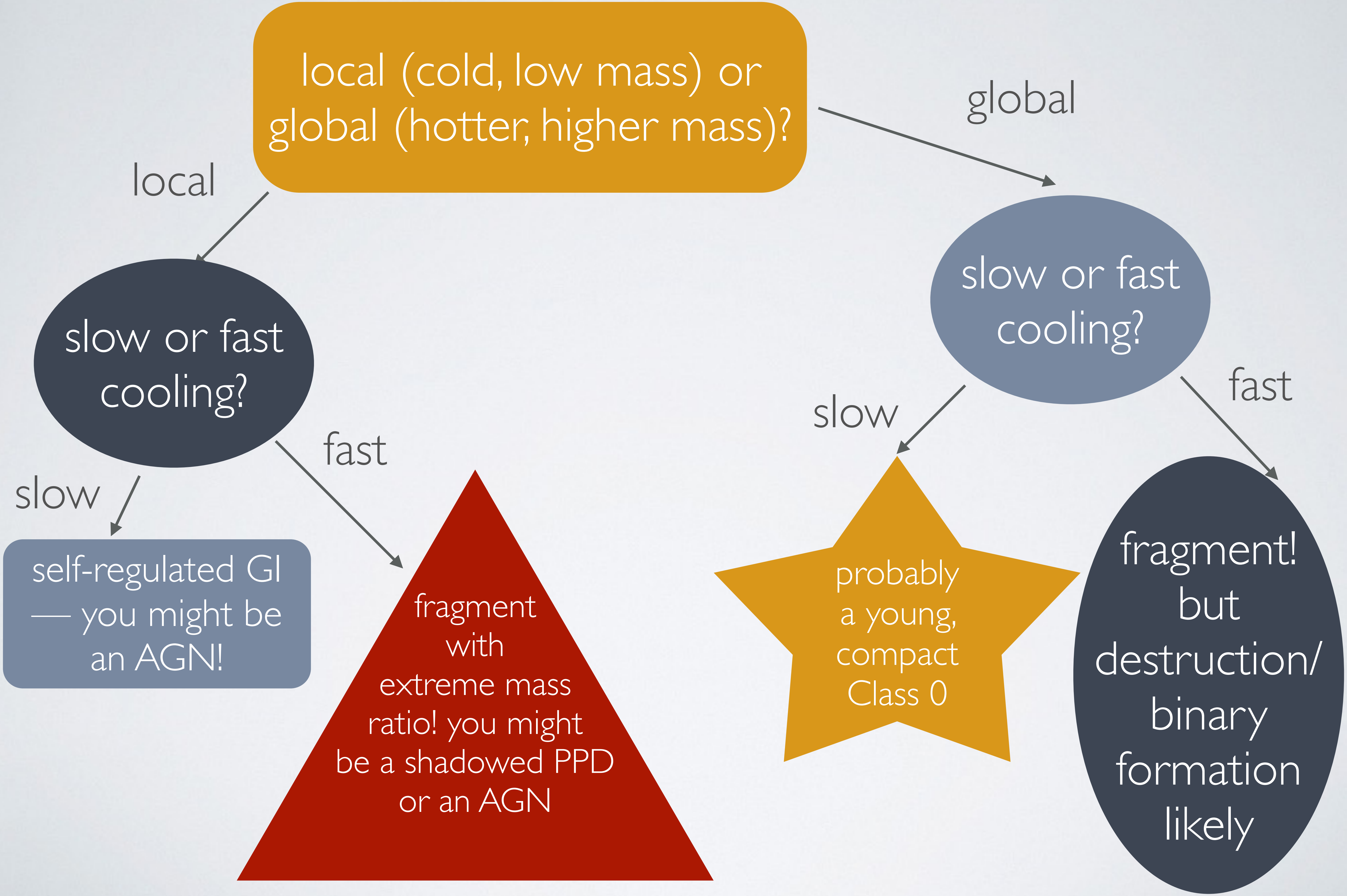

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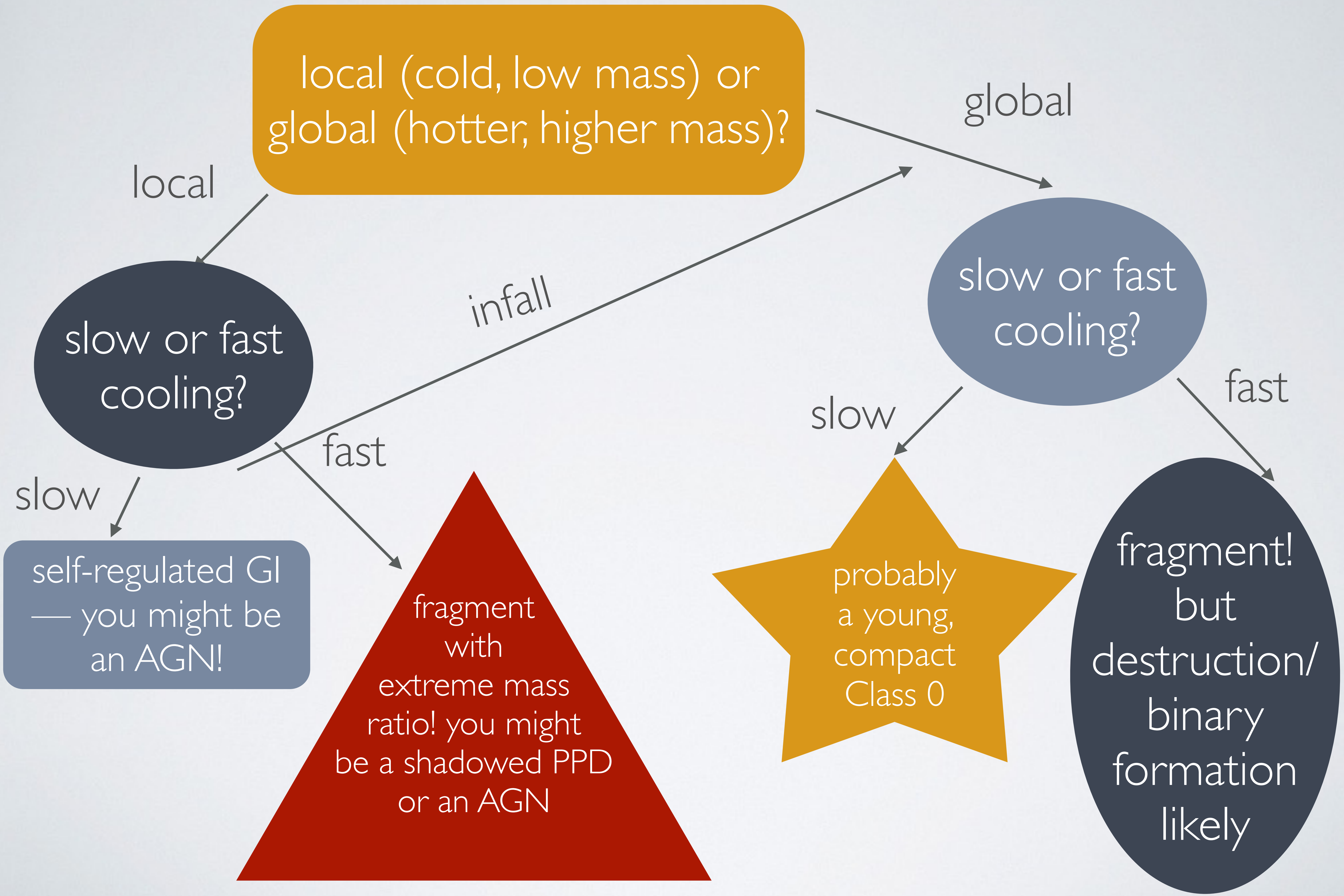

ON THE NEXT INSTALLMENT….FATE OF FRAGMENTS

- Disruption on few dynamical times
- Partial or complete disruption due to inward migration
- Direct collapse / continued growth
- GI population synthesis, and other ways to make wide orbit planets