Protoplanetary Disk
* Basics *

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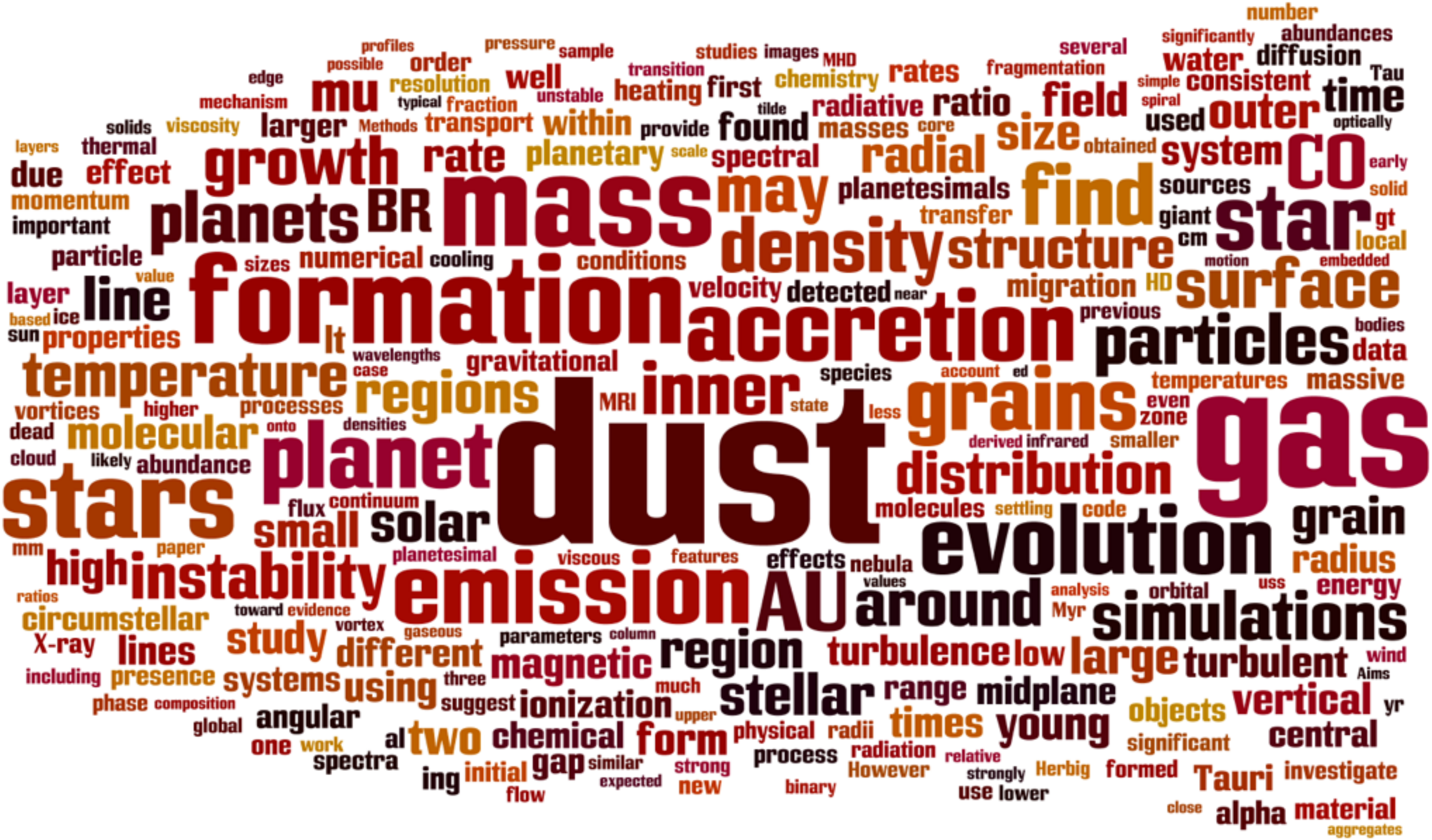
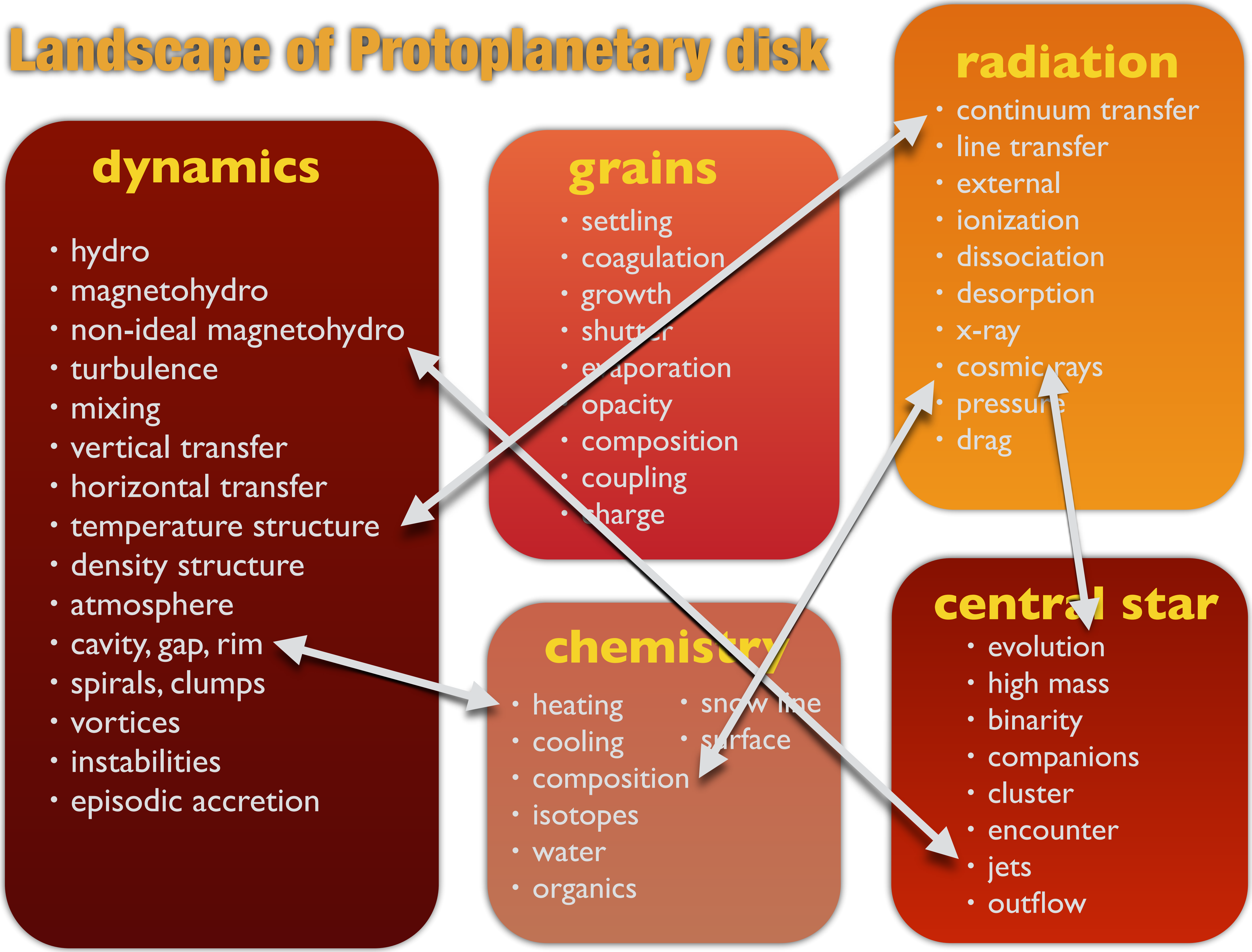
Open questions…

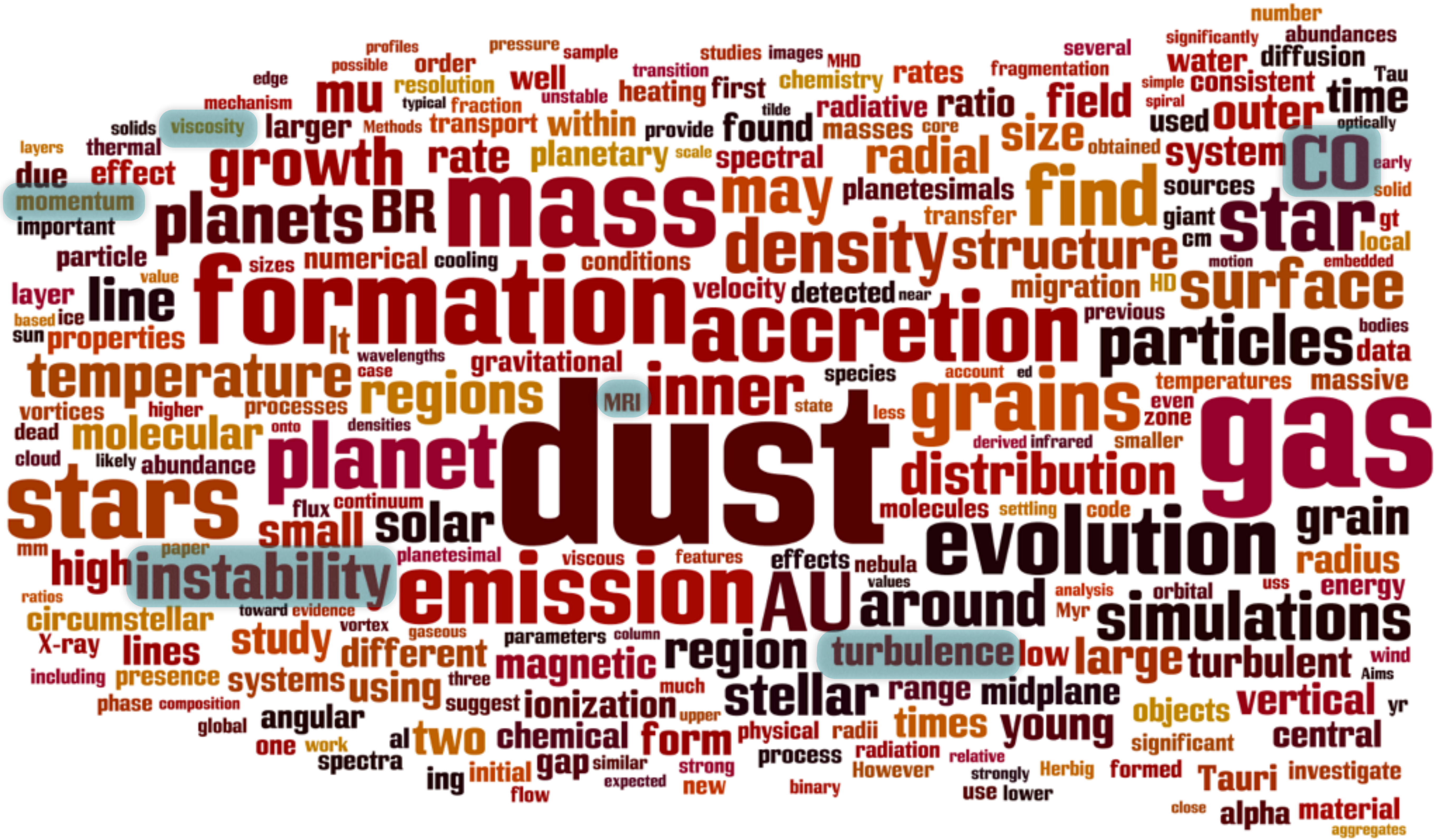
Landscape of Protoplanetary Disk



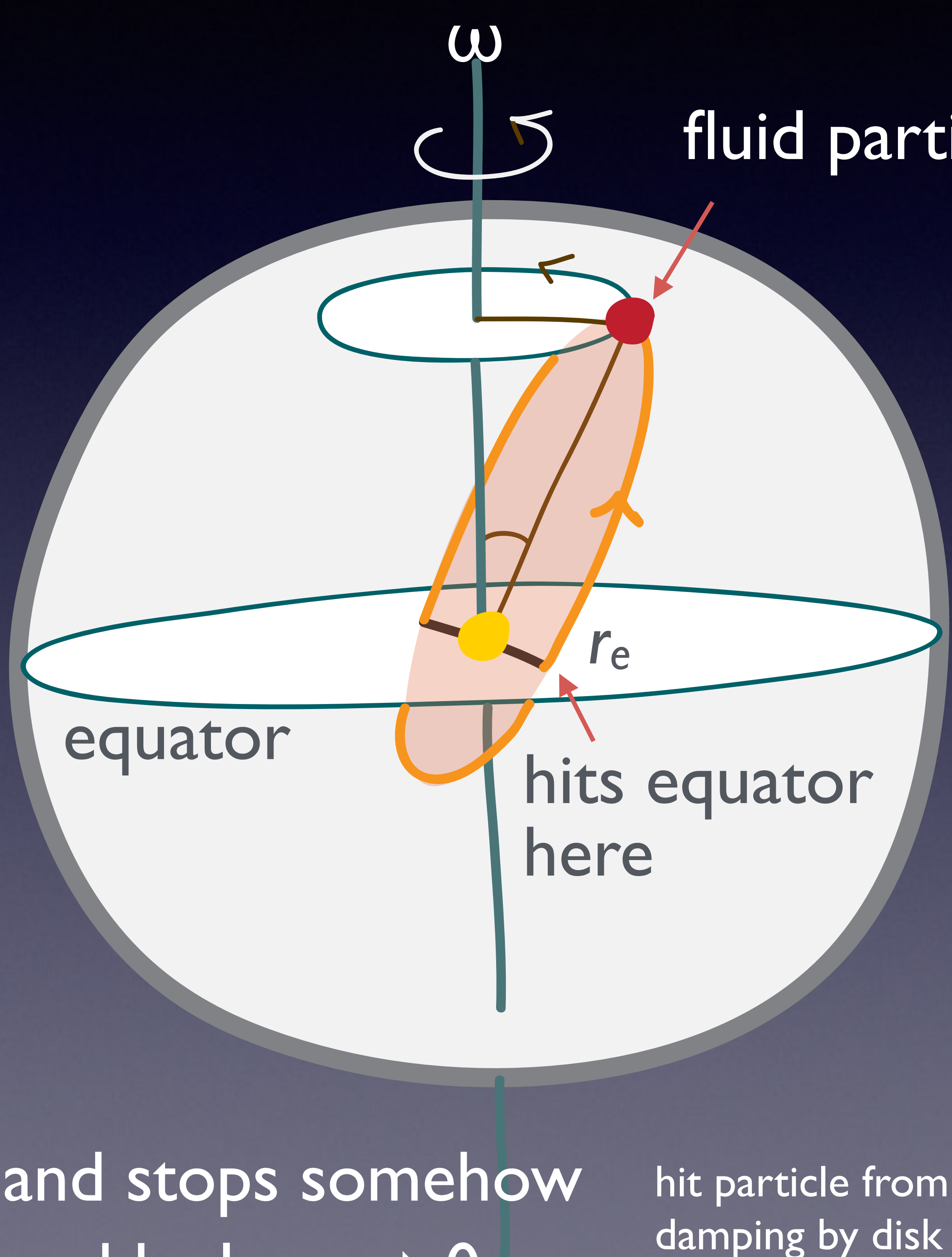
Landscape of Protoplanetary disk

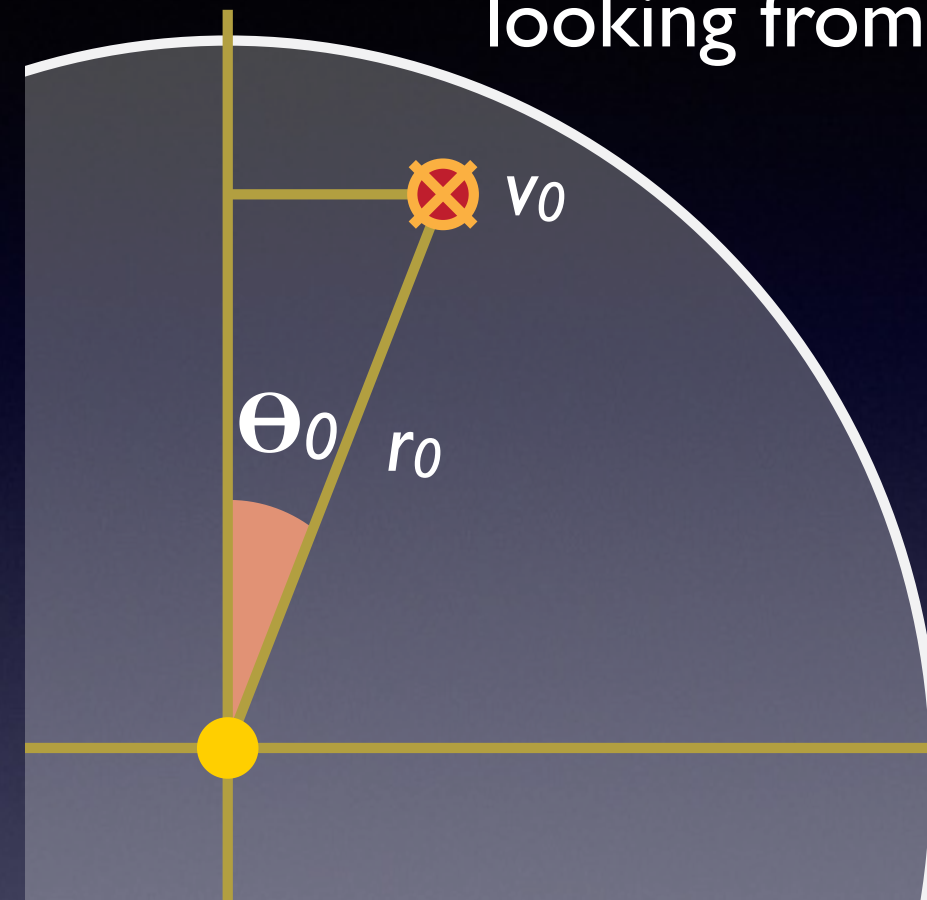


Landscape of Protoplanetary Disk



Why there must be a Disk ?





- particle in elliptical orbit with

$$v_0 = r_0 \omega \sin\theta_0$$

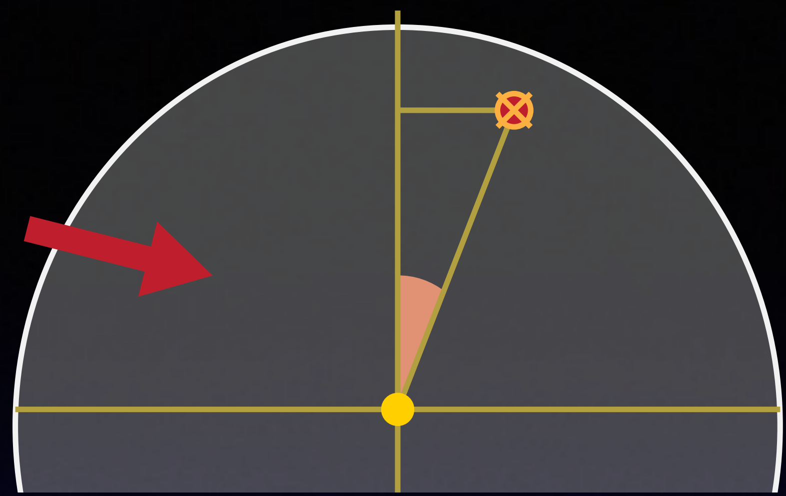
- assume particle barely bound

$$r = \frac{2GM_*}{v^2}$$

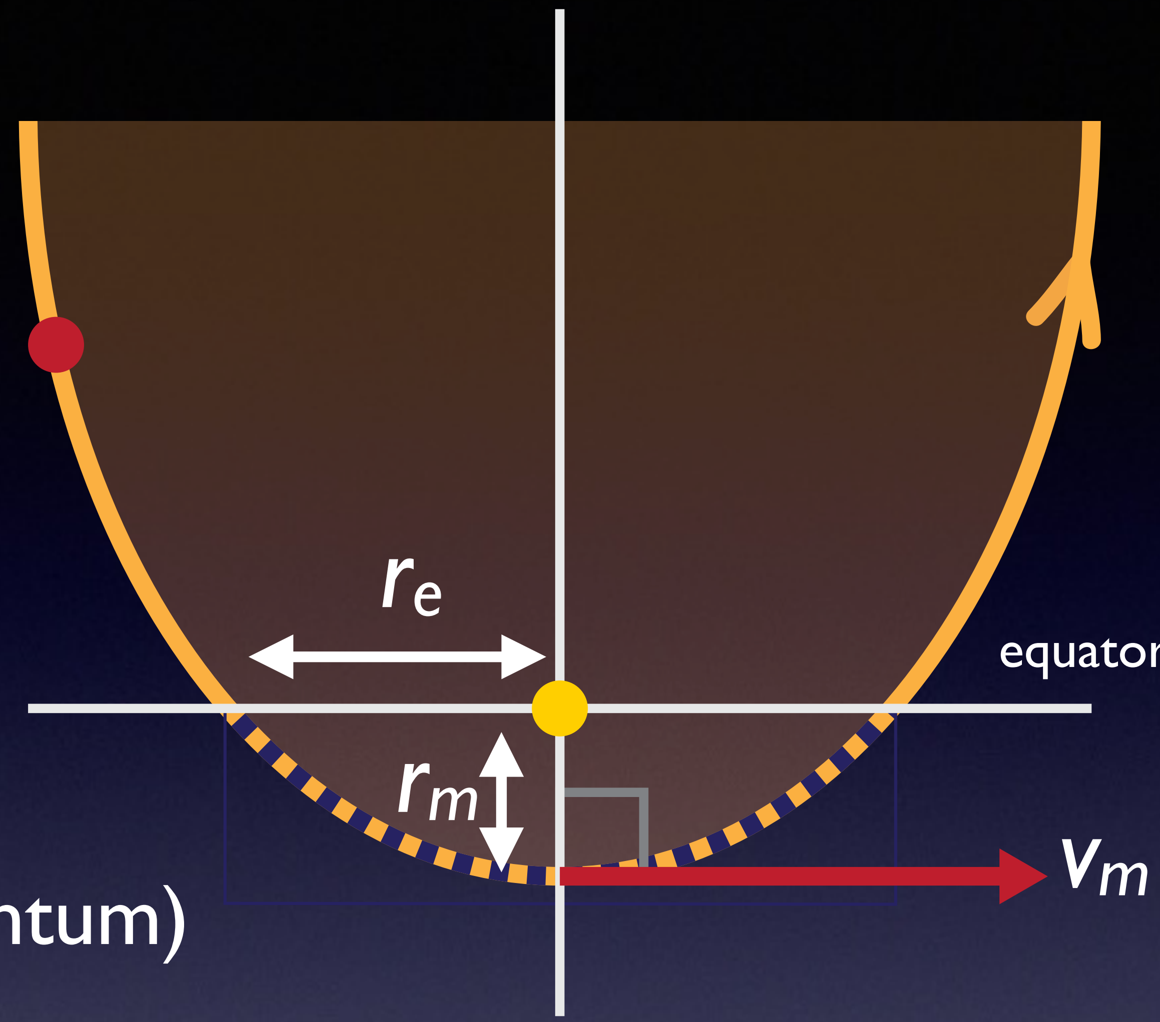
… and stops somehow

suddenly $v_z \to 0$

hit particle from the other side
damping by disk mass



looking at the orbit face on



at $r = r_m$

- orbit vertical to displacement

$\mathbf{v}_m \perp \mathbf{r}_m$

$r_m v_m = r_0 v_0 = j$ (angular momentum)

- energy conservation

$$r_m = \frac{2GM_*}{v_m^2} \longrightarrow r_m v_m^2 = 2GM_*$$

$$r_m = \frac{j^2}{2GM_*}$$

$r_e = 2r_m$ it is almost *parabola*

$$= \frac{j^2}{GM_*} = \frac{r_0^2 v_0^2}{GM_*}$$

$$= \frac{r_0^4 \omega^2 \sin^2\theta_0}{GM_*}$$

because $v_0 = r_0 \omega \sin\theta_0$

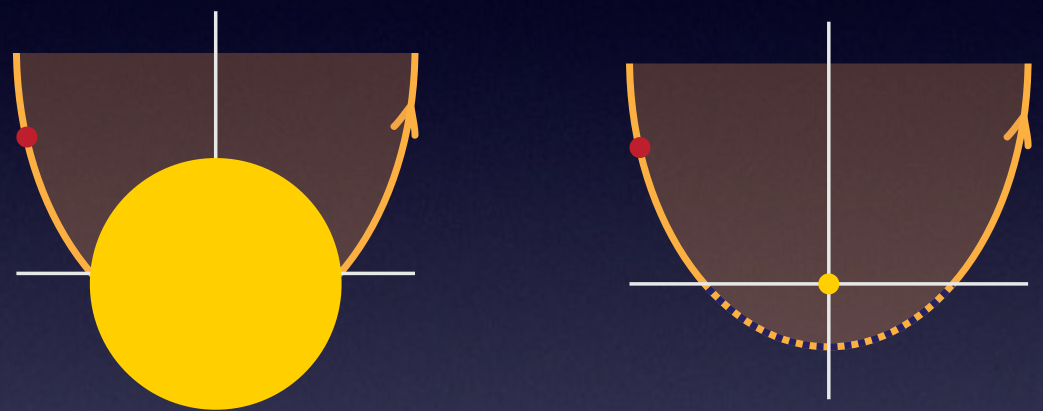
Stahler & Palla

$$r_e = \frac{r_0^4 \omega^2 \sin^2\theta_0}{GM_*}$$

A disk forms only when

$$r_e > R_*$$

Right way of saying is



$r_e < R_*$

disk would not form
particle hits star directly

- angular velocity ω was large enough
- protostar is small enough
- cloud was large enough
  (collection range r_0 large enough)

inside-out collapse of a cloud,
the mass far away reaches to the star later
r_0 becomes larger with time
eventually forms a disk

How to make this disk evolves

$$r_e = \frac{r_0{}^4 \omega^2 \sin^2\theta_0}{GM_*}$$

with fixed r_0

r_e is maximum

$$\xrightarrow{\quad} \qquad \theta_0 = \frac{\pi}{2}$$

$$r_c = \frac{r_0{}^4 \omega^2}{GM_*}$$

centrifugal radius

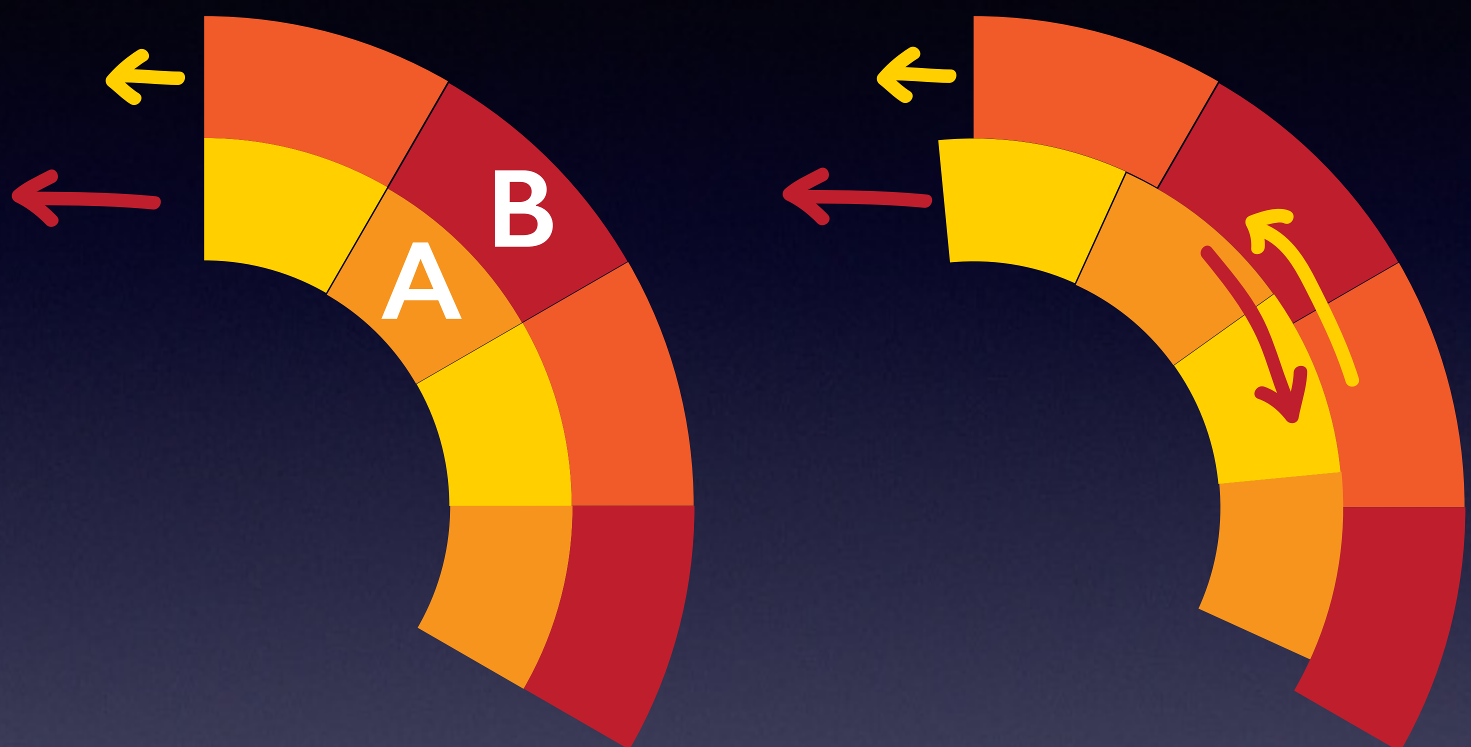
this is as much as the fluid particle come close to the star

- energy can dissipate (gas kinetic energy) → **cooling** radiation

- angular momentum is

only **Transported**

Transport **angular momentum out**



two rings **A** and **B**
in Keplerian rotation

$$v = \sqrt{\frac{GM_*}{r}} \qquad \Omega = \sqrt{\frac{GM_*}{r^3}}$$

orbital velocity
A faster than B

if *viscosity* is present

A : breaking
B : speeding up

angular momentum **transported**

How to have ‘viscosity’ in disk...?

- without viscosity particle in circular orbit forever
  (The Earth is rotating around the Sun for 4 Gyrs)

- gas viscosity is too low

- we will create “effective” viscosity

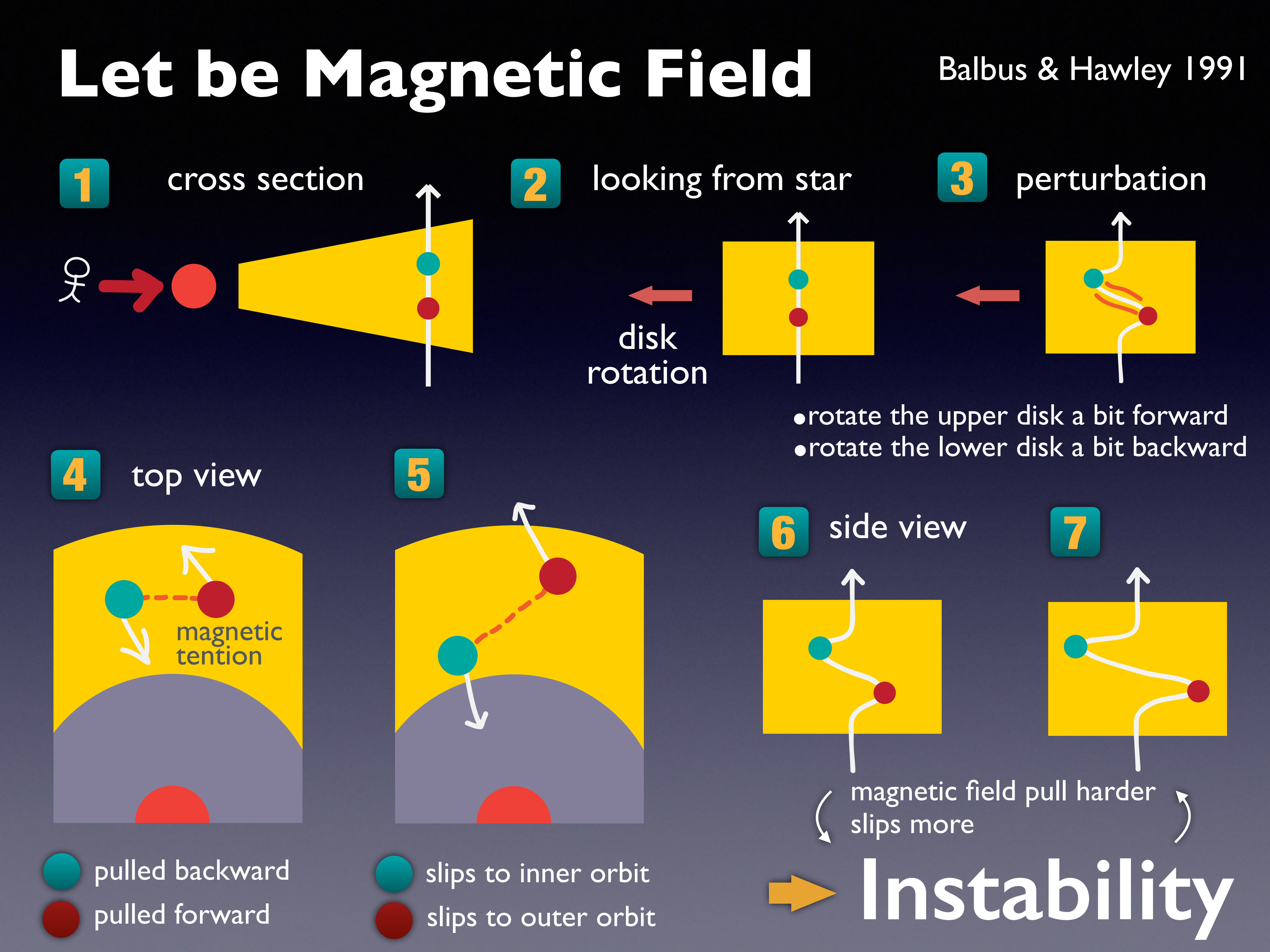
1 Magnetic field

↓

2 Turbulence

↓

3 Effective transport of angular momentum


Let be Magnetic Field
Balbus & Hawley 1991
1
cross section
2
looking from star
disk
rotation
3
perturbation
•rotate the upper disk a bit forward
•rotate the lower disk a bit backward
4
top view
magnetic
tention
5
6
side view
7
magnetic field pull harder
slips more
pulled backward
pulled forward
slips to inner orbit
slips to outer orbit
Instability

Instability → Turbulence

- exchange of mass
- between rings A and B
- A was faster than B

A to B mv_A

>

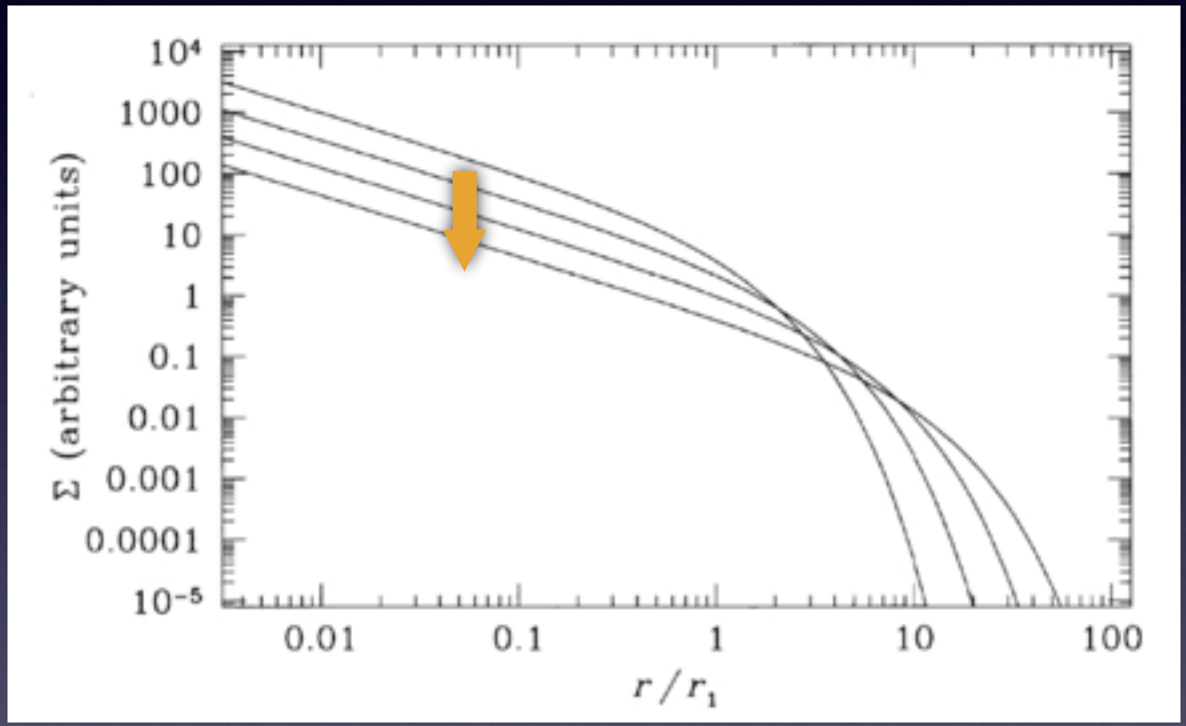
B to A mv_B

Ring A lost more

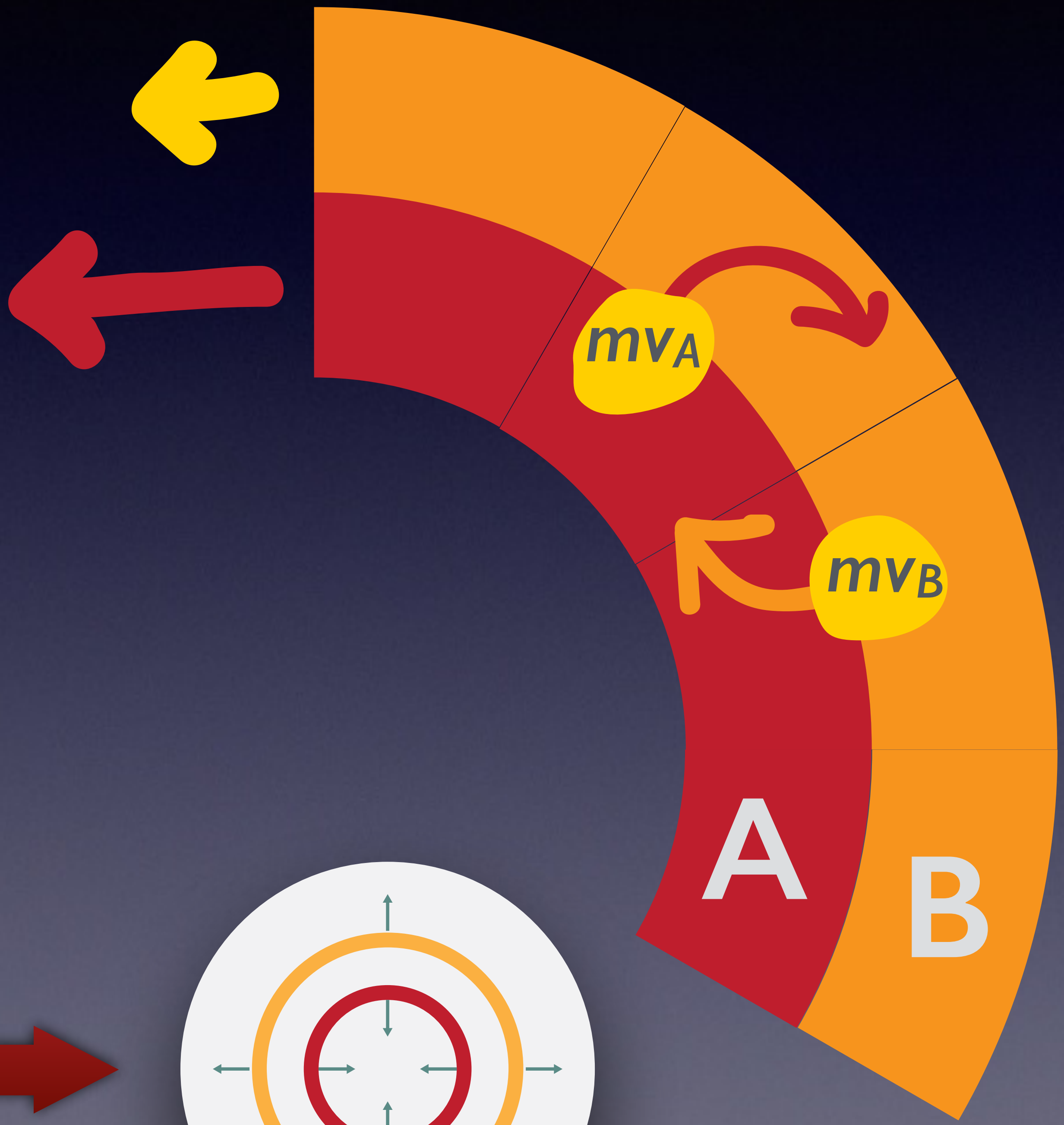
net transport of momentum **A → B**

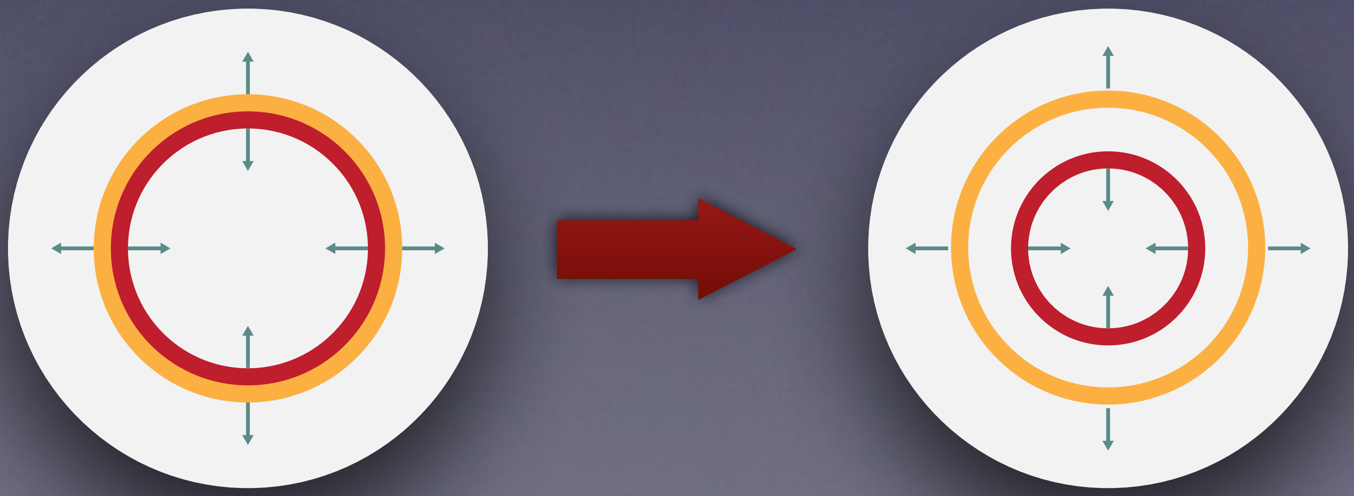
Instability → Turbulence

disk not only accretes inward
spills outward as well

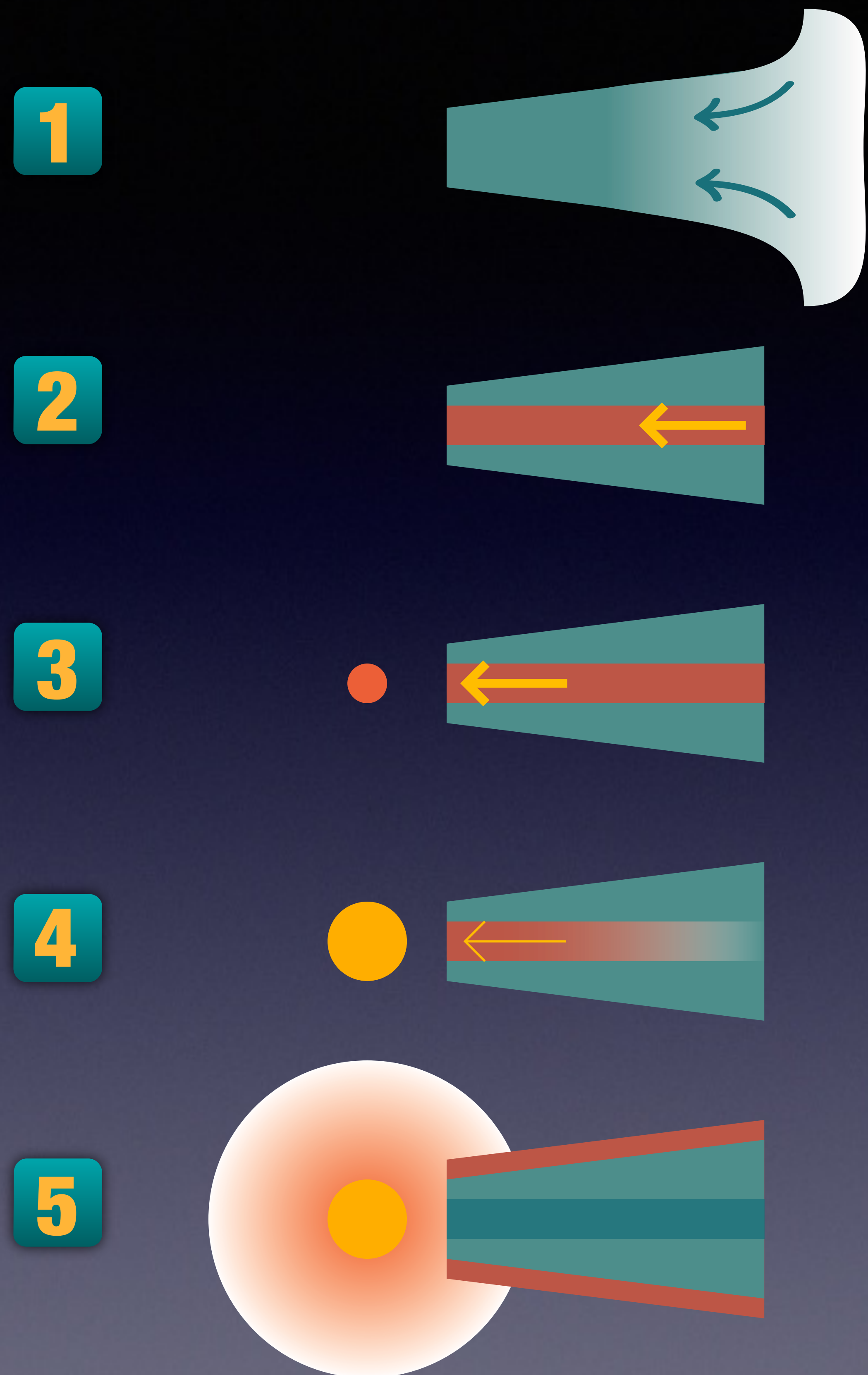


Armitage 2010





disk heated
from inside



- cloud to disk
- mass accretes toward center
- star forms
- disk mass decline
- star mass increase
- disk irradiated
- by the star

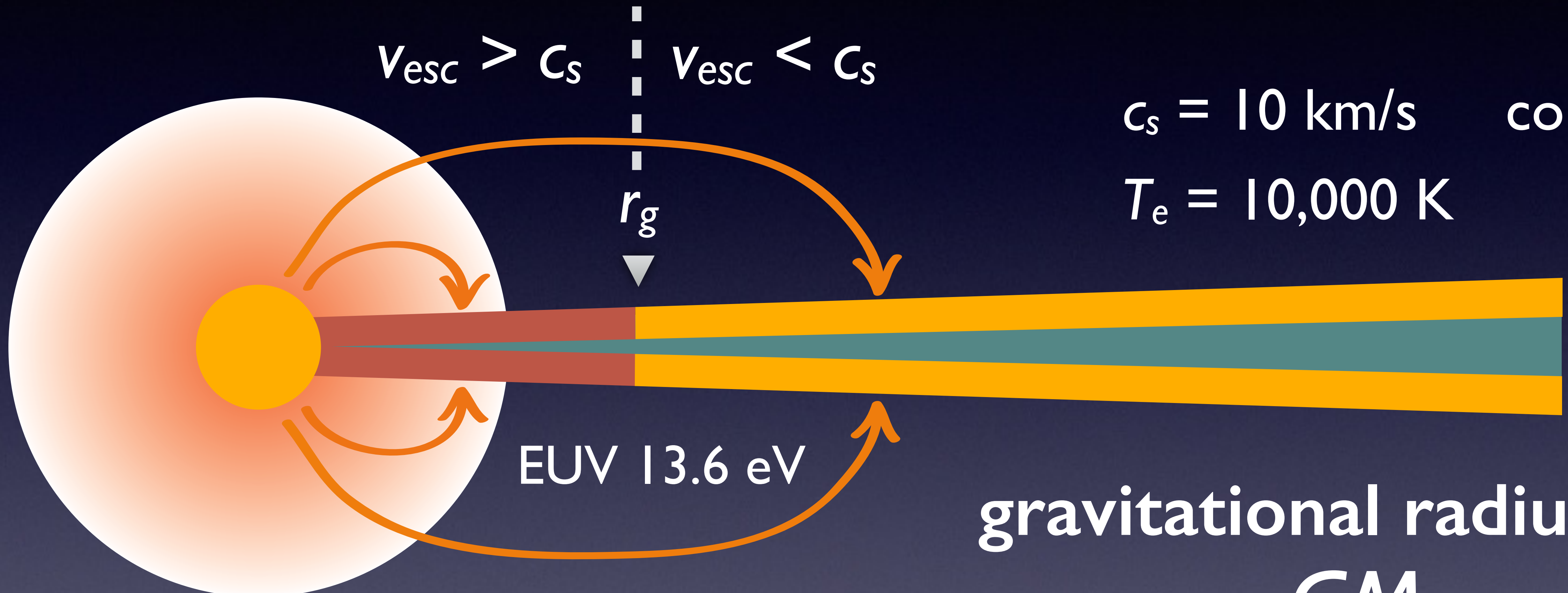
disk heated
from outside

temperature structure flips around

Photoevaporation

is actually photoionization

atomic hydrogen ionized by UV radiation



c_s = 10 km/s constant

T_e = 10,000 K

gravitational radius

$$r_g \sim \frac{GM_*}{c_s^2}$$

escape velocity $\frac{v_{esc}^2}{2} = \frac{GM_*}{r}$

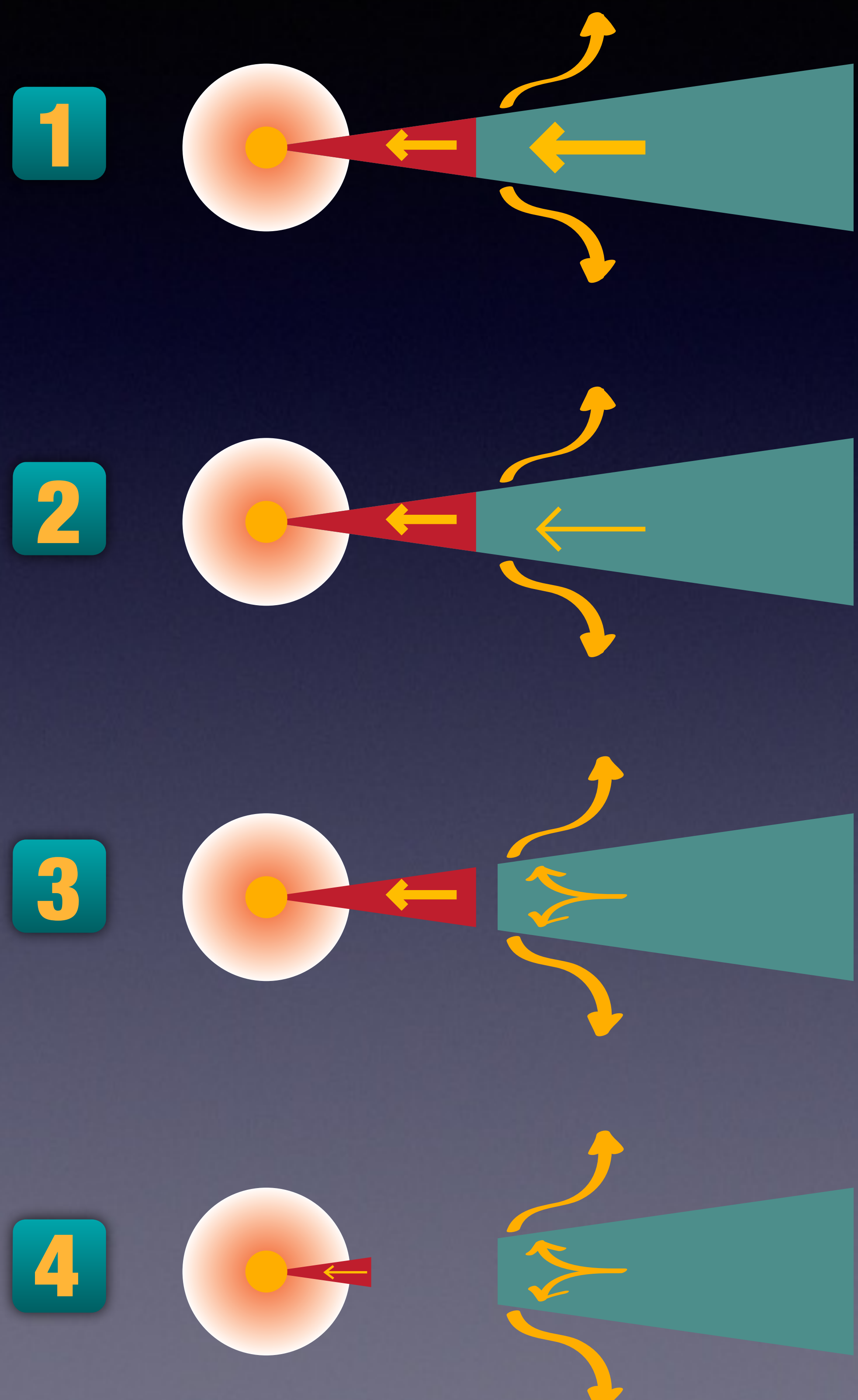
$$v_{esc} \sim \sqrt{\frac{GM_*}{r}} < c_s$$

unbound

- mass removed from surface
- slowly but constantly
- $\dot{M}_{pv} = 10^{-10}\ M_\odot$/yr for solar mass star

UV Switching

Clarke et al. 2001
Owen et al. 2010

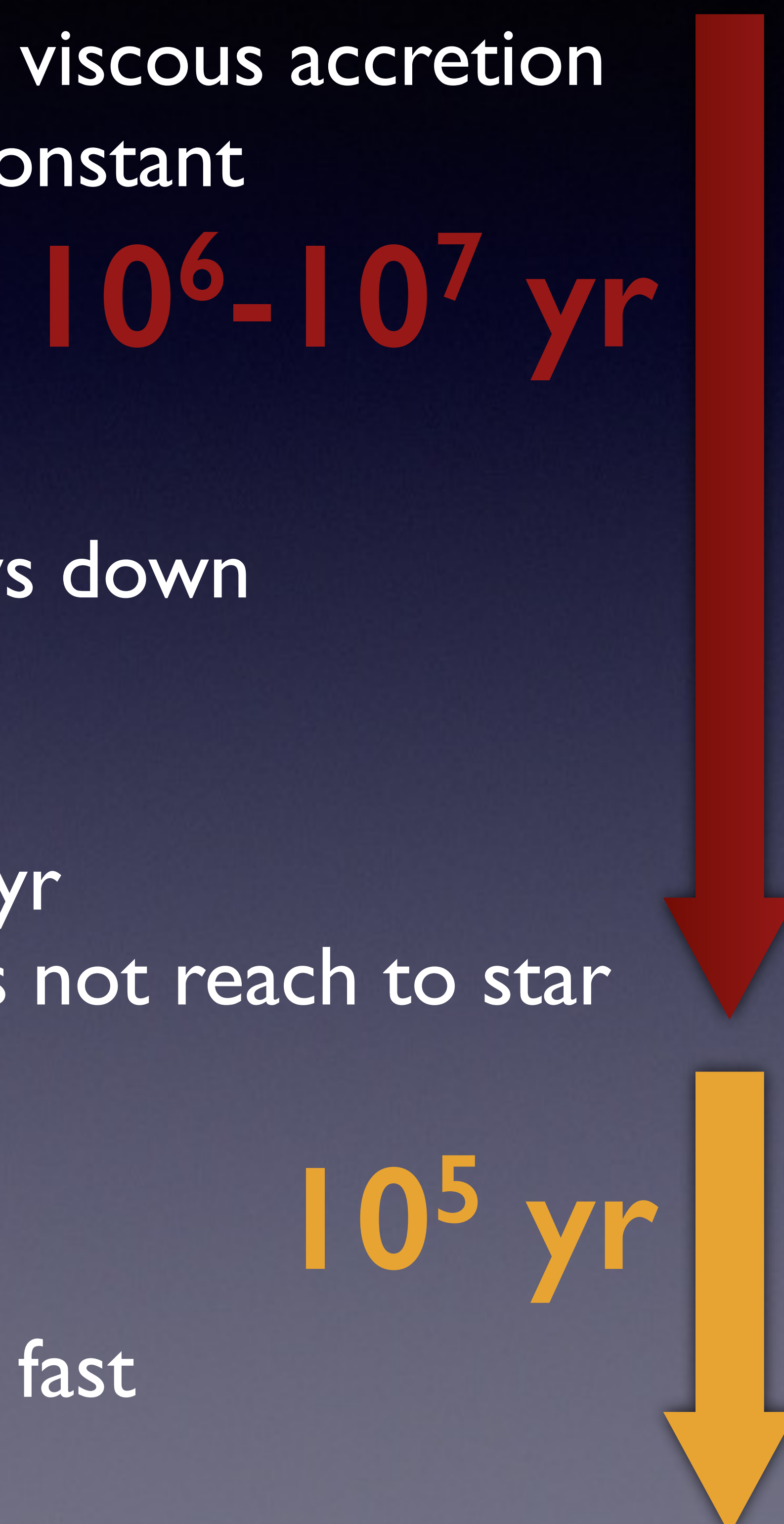


disk evolves mainly via viscous accretion
photoevaporation is constant

as disk mass declines
viscous accretion slows down

$\dot{M}_{vis} < \dot{M}_{pv} \approx 10^{-10}\, M_{\odot}/yr$
viscous accretion does not reach to star
inner part is detached

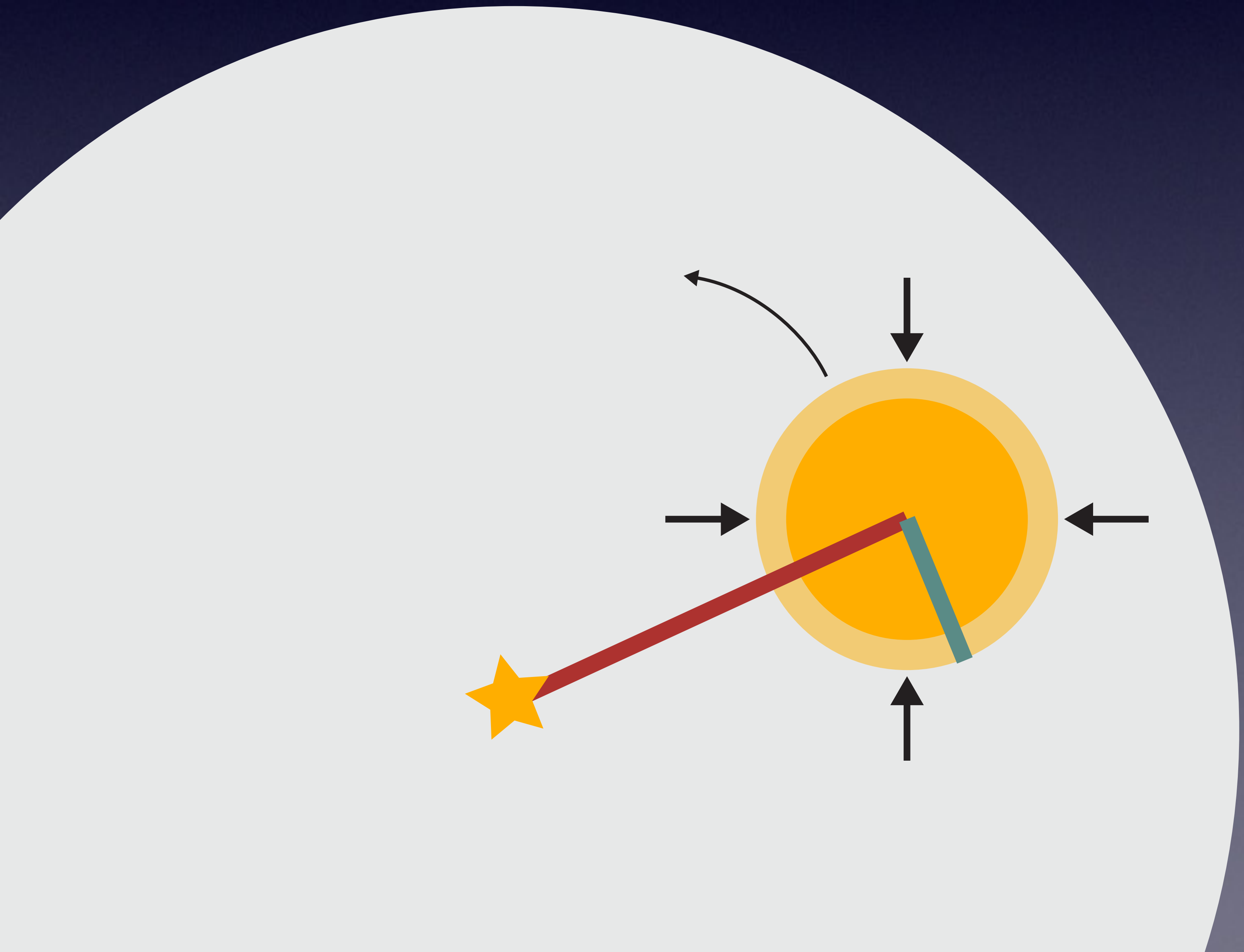
accretion opens cavity fast



When you squeeze a patch of disk in disk

it increases

1	gravitational	pull
2	pressure	push
3	centrifugal force	push



if

1 > 2 + 3

gravitationally unstable

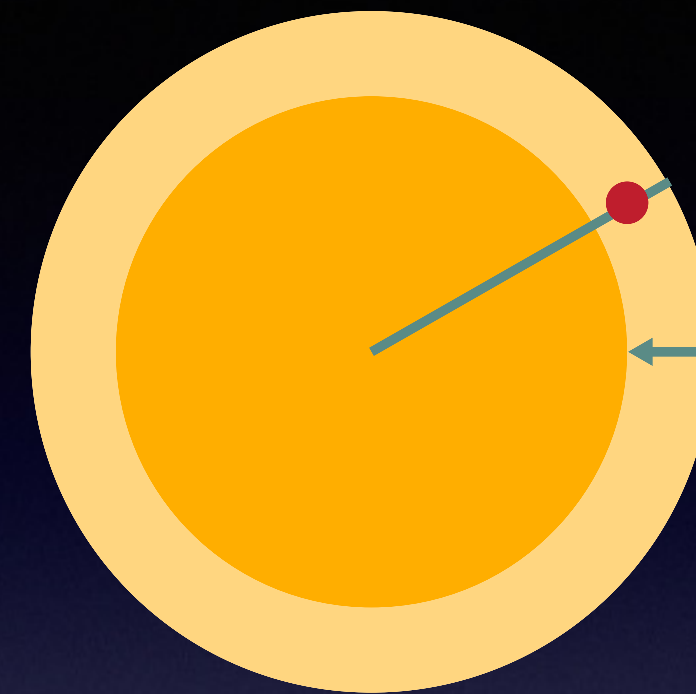
1 gravitational

mass added inside the orbit

$$\Delta M = 2\pi r \Delta r \Sigma$$

$$F_g = \frac{GM}{r^2} \quad \text{(per mass)}$$

$$\varepsilon = \frac{\Delta r}{r}$$



$$\Delta F_g = \frac{G \cdot 2\pi r \Delta r \Sigma}{r^2} = 2\pi\varepsilon G\Sigma$$

$$\approx \varepsilon G \Sigma$$

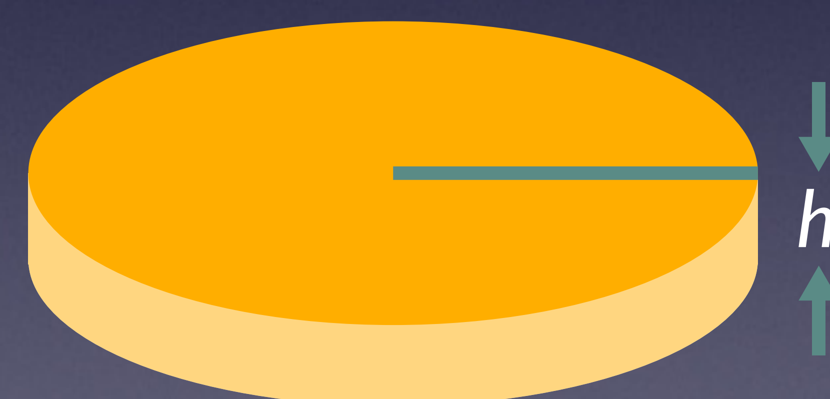
2 pressure

$$p = \frac{\rho}{\mu} kT$$

$$\rho \rightarrow \left(1 + \frac{\Delta r}{r}\right)^2 \rho = (1 + 2\varepsilon)\,\rho$$

$$p \rightarrow (1 + 2\varepsilon)\, p$$

$$c_s^2 = \frac{p}{\rho} = \frac{1}{\mu} kT$$

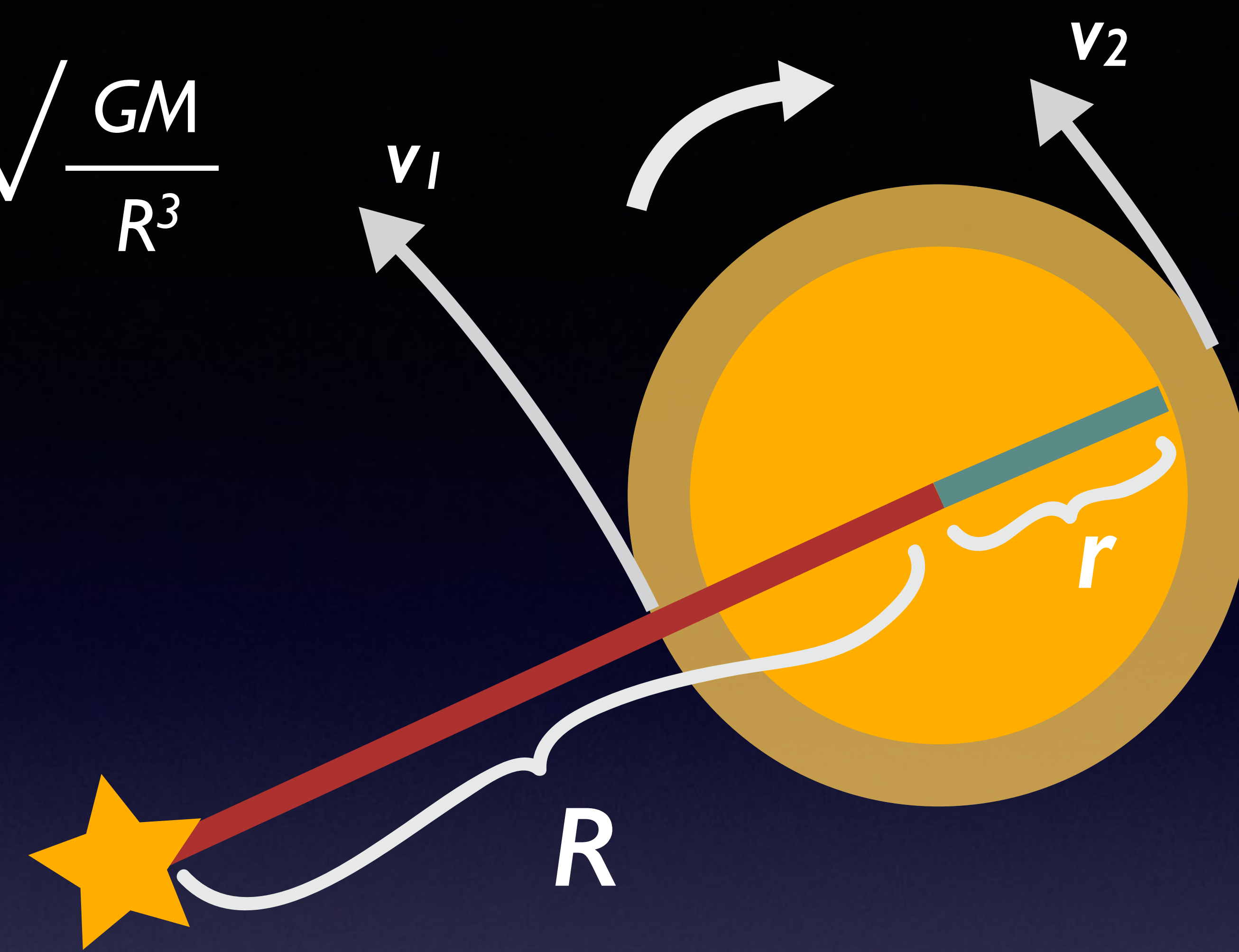


$$\Delta F_p = \frac{2\pi r h \cdot 2\varepsilon p}{\pi r^2 \Sigma} = \frac{4\pi r h c_s^2 \rho}{\pi r^2 \Sigma} = \frac{4\pi\varepsilon r \Sigma c_s^2}{\pi r^2 \Sigma} = \frac{4\pi\varepsilon c_s^2}{r} \approx \frac{\varepsilon c_s^2}{r}$$

(per mass)

3 centrifugal force

$$\Omega_R = \sqrt{\frac{GM}{R^3}}$$



local angular momentum

$$j = mr\,(v_1 - v_2)$$

$$= mr\,R(\Omega_1 - \Omega_2)$$

$$= mr\,R\,\frac{d\Omega_R}{dR} \cdot 2r$$

$$= 2mr^2\Omega_R$$

$$F_c = \frac{v^2}{r}$$

(per mass)

$$r \rightarrow (1 - \varepsilon)\,r$$

$$v \rightarrow (1 - \varepsilon)^{-1}\,v$$

rv const. and j

$$\Delta F_c = 3\varepsilon F_c = 3\varepsilon \cdot \frac{(2r\Omega_R)^2}{r} = 12\varepsilon r\Omega_R^2$$

$$\approx \varepsilon r \Omega_R^2$$

grav. pull		pres. push		cent. push	
1	>	2	+	3	unstable

$$\varepsilon G\Sigma > \frac{\varepsilon {c_s}^2}{r} + \varepsilon r {\Omega_R}^2$$

$$r^2 - \underbrace{\frac{G\Sigma}{{\Omega_R}^2}}_{b} r + \underbrace{\frac{{c_s}^2}{{\Omega_R}^2}}_{c} < 0$$

$$(x - \frac{b}{2})^2 - \frac{b^2}{4} + c < 0$$

$$(\frac{G\Sigma}{{\Omega_R}^2})^2 > \frac{{c_s}^2}{{\Omega_R}^2}$$

$$\frac{\Omega_R c_s}{G\Sigma} < 1$$

unstable

$$r^2 - \underbrace{\frac{G\Sigma}{\Omega_R^2}}_{b} r + \underbrace{\frac{c_s^2}{\Omega_R^2}}_{c} < 0$$

$$(x - \frac{b}{2})^2 - \frac{b^2}{4} + c < 0$$

$$\frac{\Omega_R c_s}{G\Sigma} = 1$$ unstable

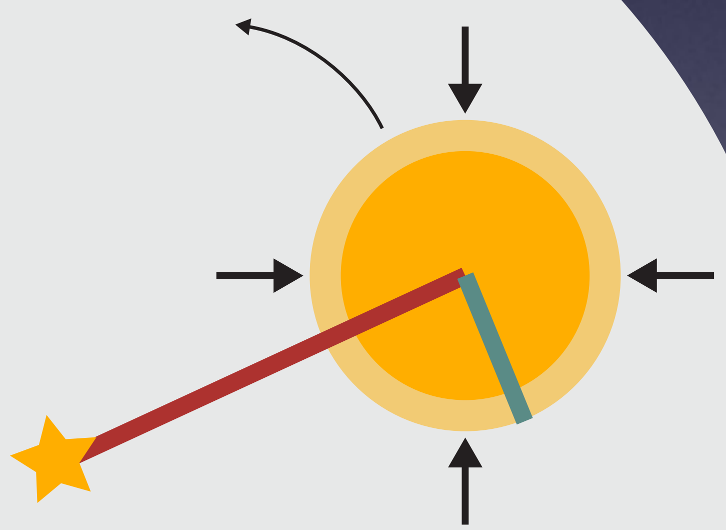
$r \sim b$ scale of instability

$$b = \frac{G\Sigma}{\Omega_R^2}$$

$$M_d = \pi R^2 \Sigma$$

$$\Omega_R = \sqrt{\frac{GM_*}{R^3}}$$

$$= \frac{G\frac{M_d}{\pi R^2}}{\frac{GM_*}{R^3}} = R \cdot \frac{M_d}{M_*} \sim 0.1$$



1/10 of the radius of the disk

We have learned

- how disk is formed
- how disk evolves
- how disk can dissipate
- how disk may become unstable

ELT is an extragalactic telescope

or high-z/cosmological/exoplanetary telescope

- protoplanetary disk is
- not hotter than 1000 K
- exception: jet, outflow, atmosphere

thermal infrared

$\lambda > 3\ \mu m$
where thermal background becomes serious

$$\lambda_{peak} = \frac{3000}{T_{BB}}\ [\mu m]$$

observers rule of thumb

ELT-MOS
ELT-HIRES
ELT-PCS (EPICS)

even after all instrument commissioned

HARMONI	$\lambda < 2.45\ \mu m$
MICADO	$\lambda < 2.45\ \mu m$
* METIS *	$2.9\ \mu m < \lambda < 19\ \mu m$

1000 K < T < 150 K

c.f. *VLT*
CRIRES, VISIR, NACO, ISAAC, MIDI, Matisse

ELT/METIS wrap up

- aperture 39 m

		3 µm	5 µm	8 µm	14 µm
	HD, NH		CO	SO	C
λ/D		16 mas	26 mas	42 mas	74 mas
at 150 pc		2.4 AU	4.0 AU	6.3 AU	11 AU

- METIS = CRIRES + VISIR + NACO + ISAAC

imaging		3-19 µm	coronagraph
low-resolution spectroscopy	*R*=1,000	3-8 µm	
med-resolution spectroscopy	*R*=10,000	8-14 µm	
high-resolution spectroscopy	*R*=100,000	3-5 µm	IFU*

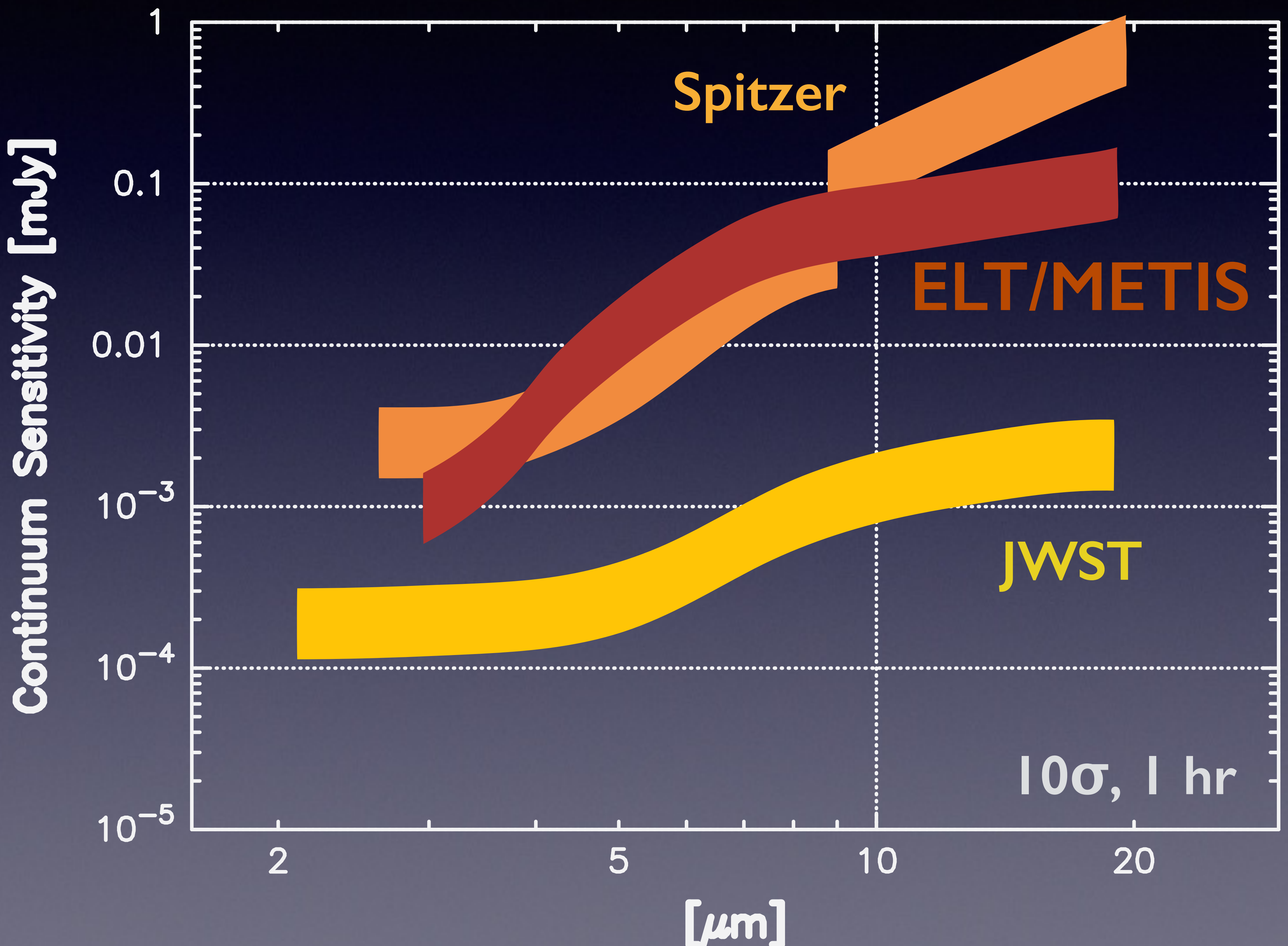
* Integral Field Unit

What you should not do with ELT

	Aperture	Wavelength	Angular Resolution*	Spectral Resolution
ALMA	150-16000 m (1.5 -160 m eqv.)	320 -3600 um (3.2 - 36 um)	4 ~ 1/26	3E+07
JWST	6.5 m	vis-MIR	same ~1/6	3000
SOFIA	2.7 m	NIR-FIR	1/14	100,000
SPICA	2-3 m	NIR-FIR	1/20	< 40,000
TMT	30 m	vis-MIR	same	120,000

* compared with METIS

ELT/METIS sensitivity



Spitzer
JWST
METIS

Sweet Spots

	Aperture	Wavelength	Angular	Spectral
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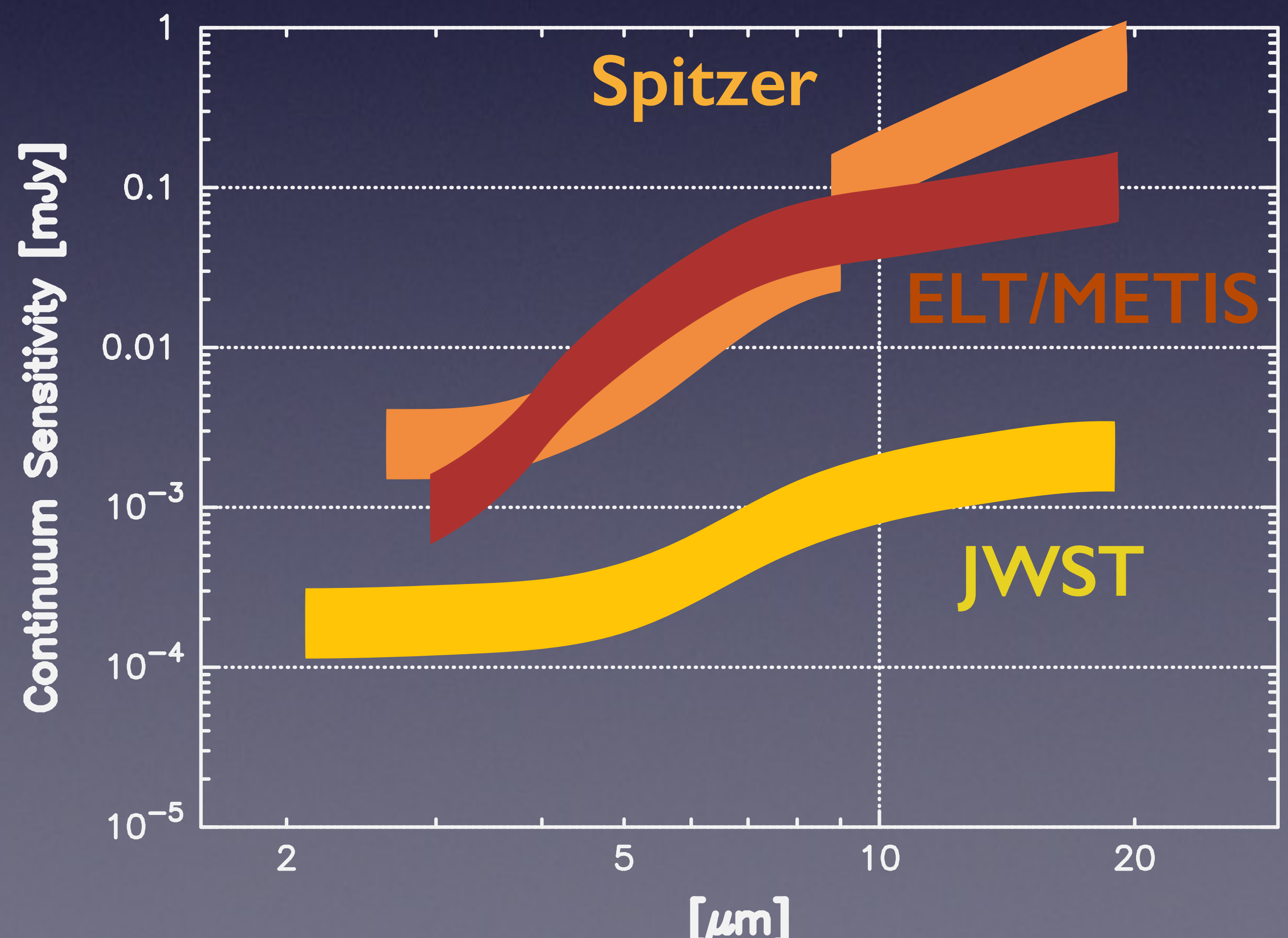


- angular resolution — ALMA
- spectral resolution — ALMA
- NIR-MIR sensitivity — JWST

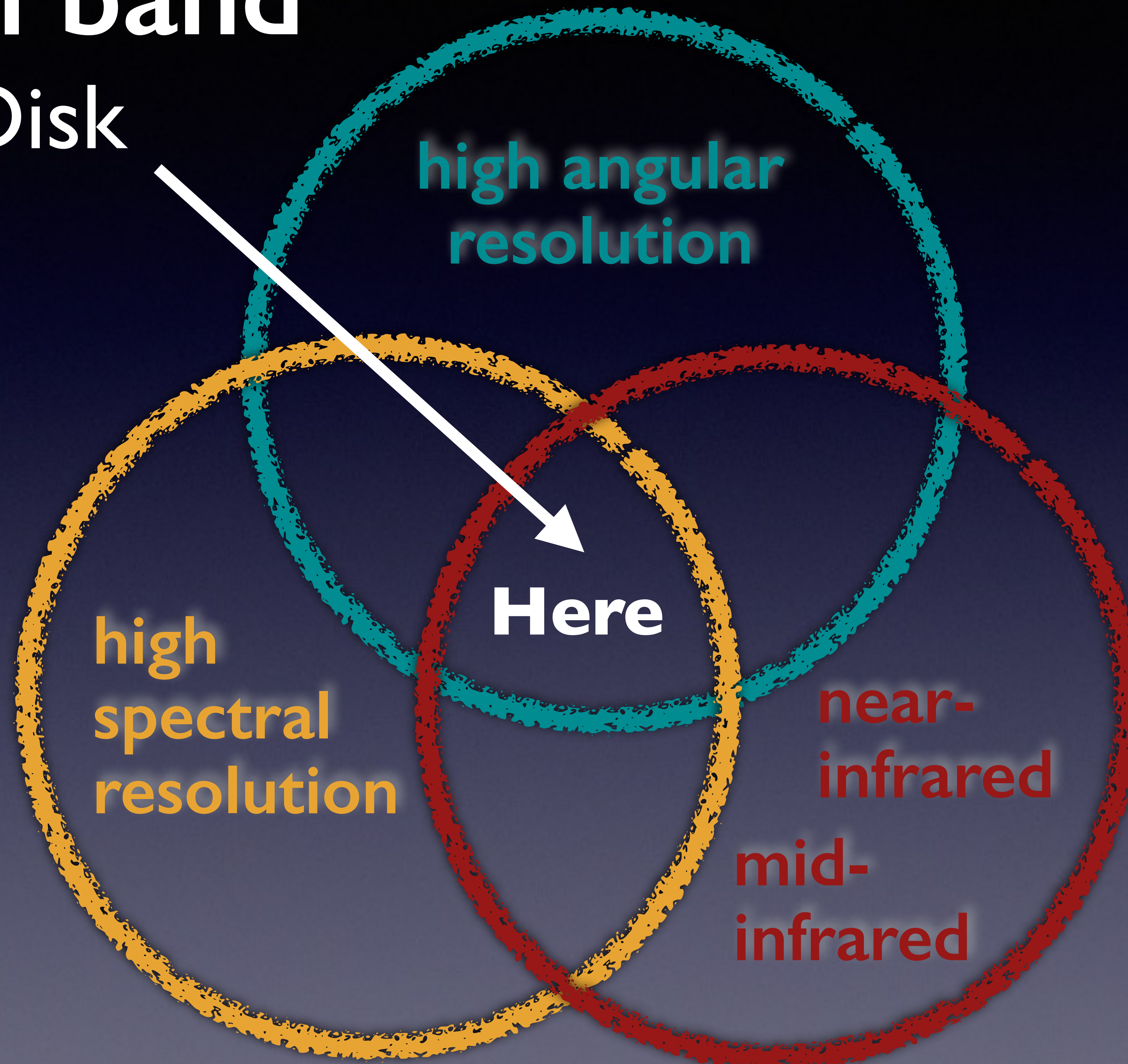
combination

1. angular resolution + IR
2. spectral resolution + IR

Observing

CO vibrational band

in Protoplanetary Disk



1 angular resolution + IR

warm targets that is
barely resolved so far

2 spectral resolution + IR

gas, not ice or dust
molecules
vibrational transitions
kinematics
rotationally quiet molecules even better

H_2, H_3^+, CH_4, C_2H_2 symmetric molecules without permanent dipole moment thank **you** for your **attention**