FROM UNIVERSE

TO PLANETS

LECTURE 2

OUTLINE

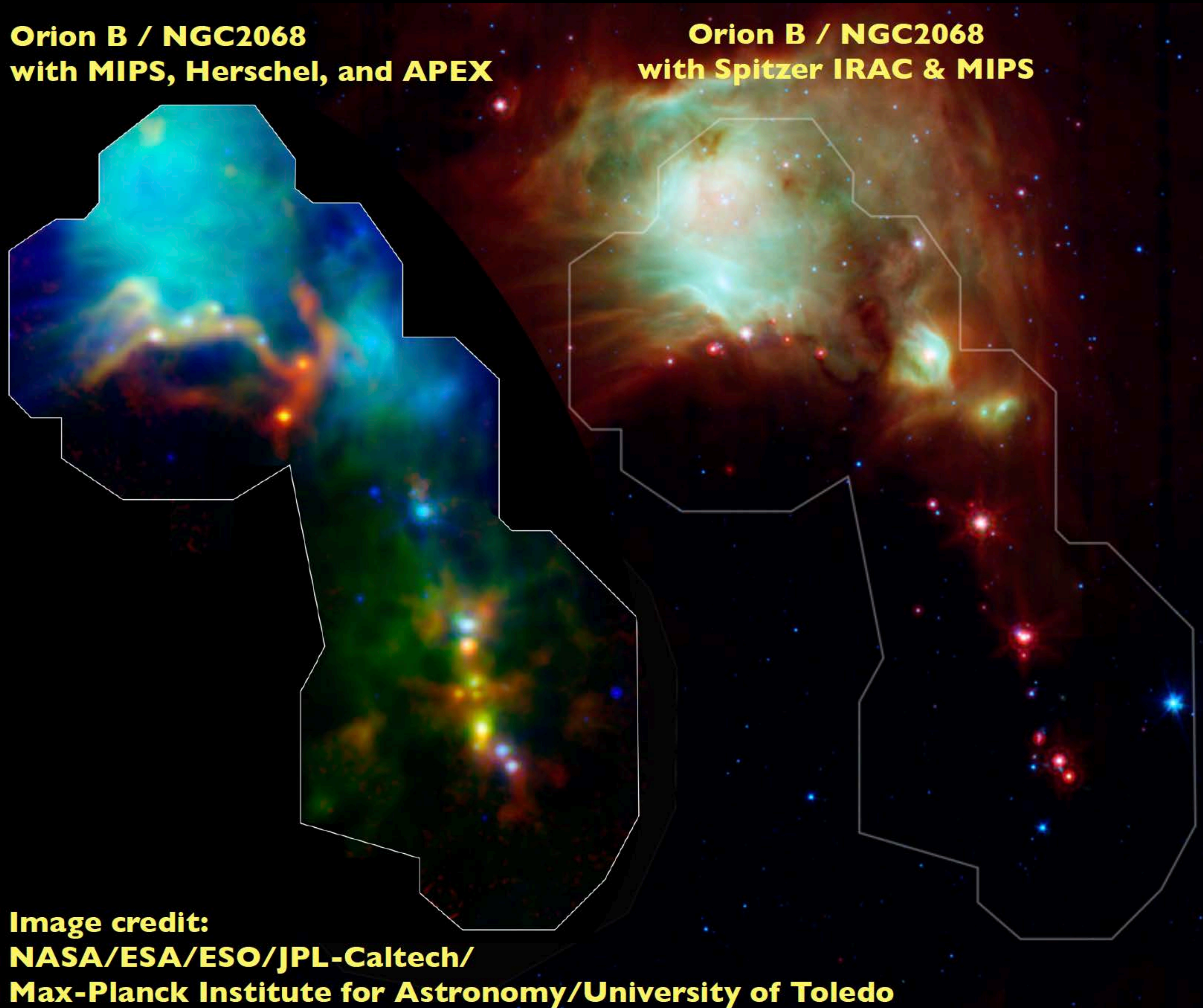
- Review + protoplanetary disc formation:
  - Orbital dynamics
- Disc structure:
  - Observations and composition
- Gas disc evolution/lifetime:
  - Viscous evolution + hint of photoevaporation
- Dust evolution
  - Drag, radial drift, and vertical settling

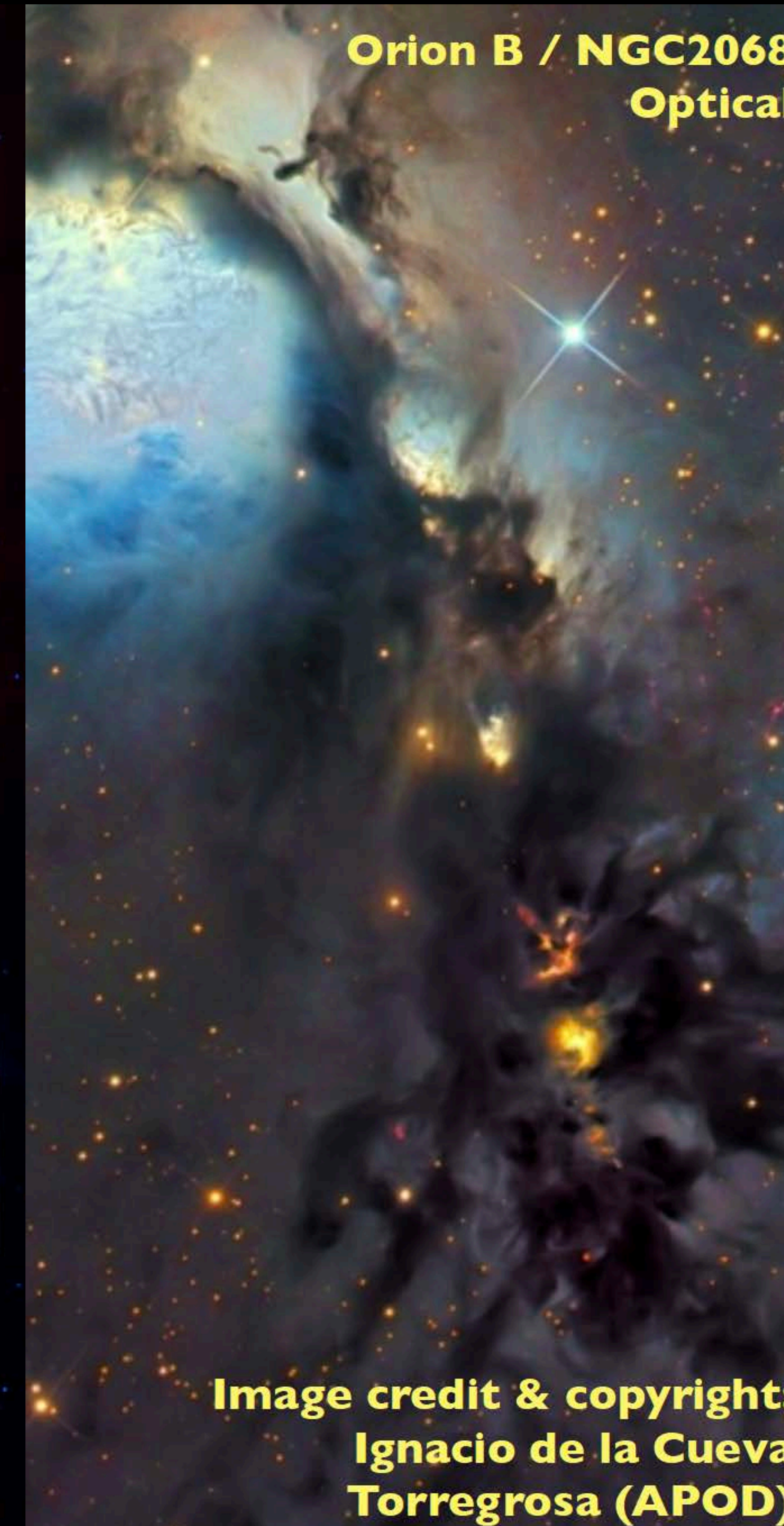
FROM UNIVERSE

TO PLANETS

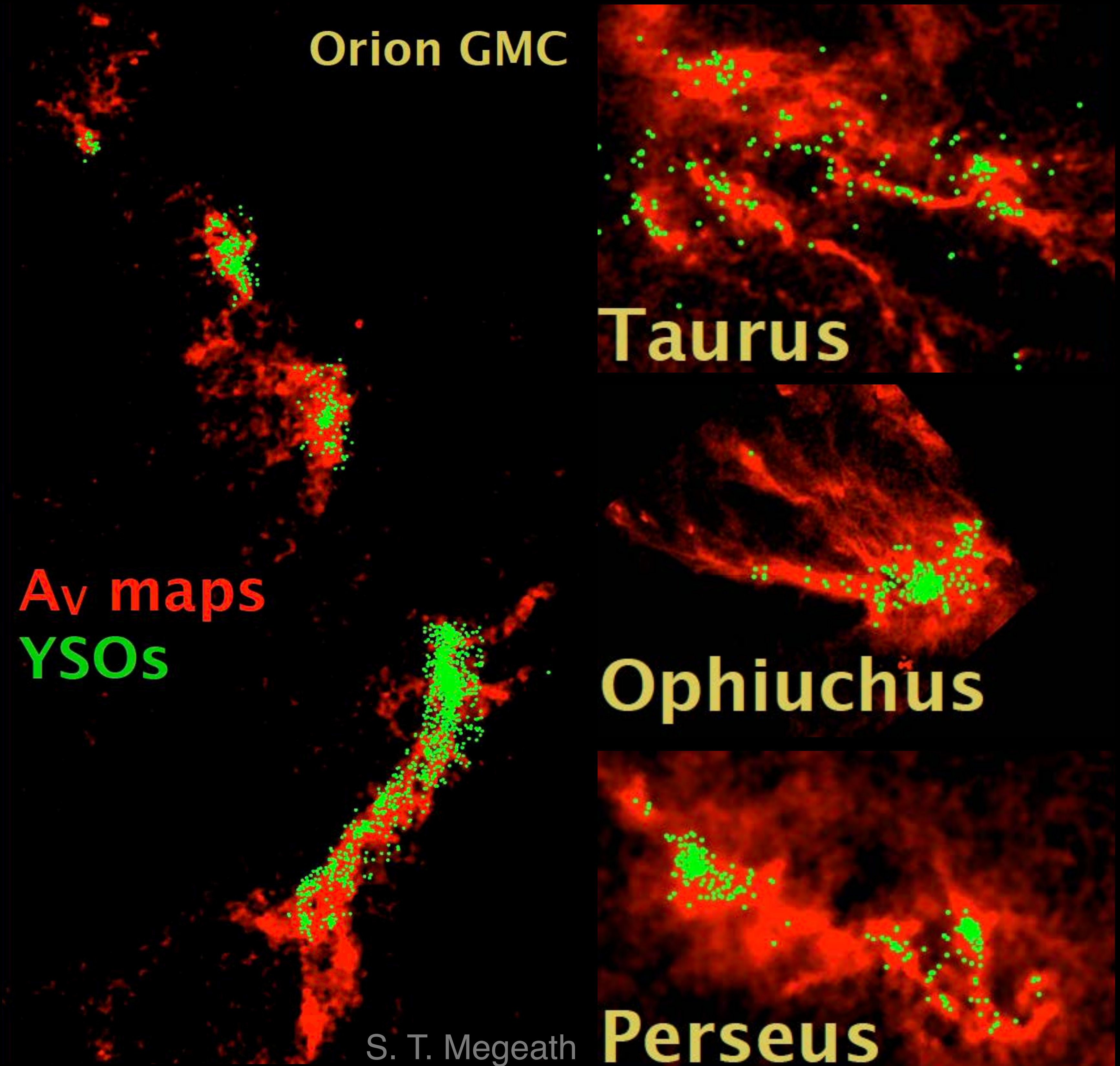
LECTURE 2.1: DISC FORMATION

EMBEDDED SOURCES REVEALED IN INFRARED (NIR AND MIR)

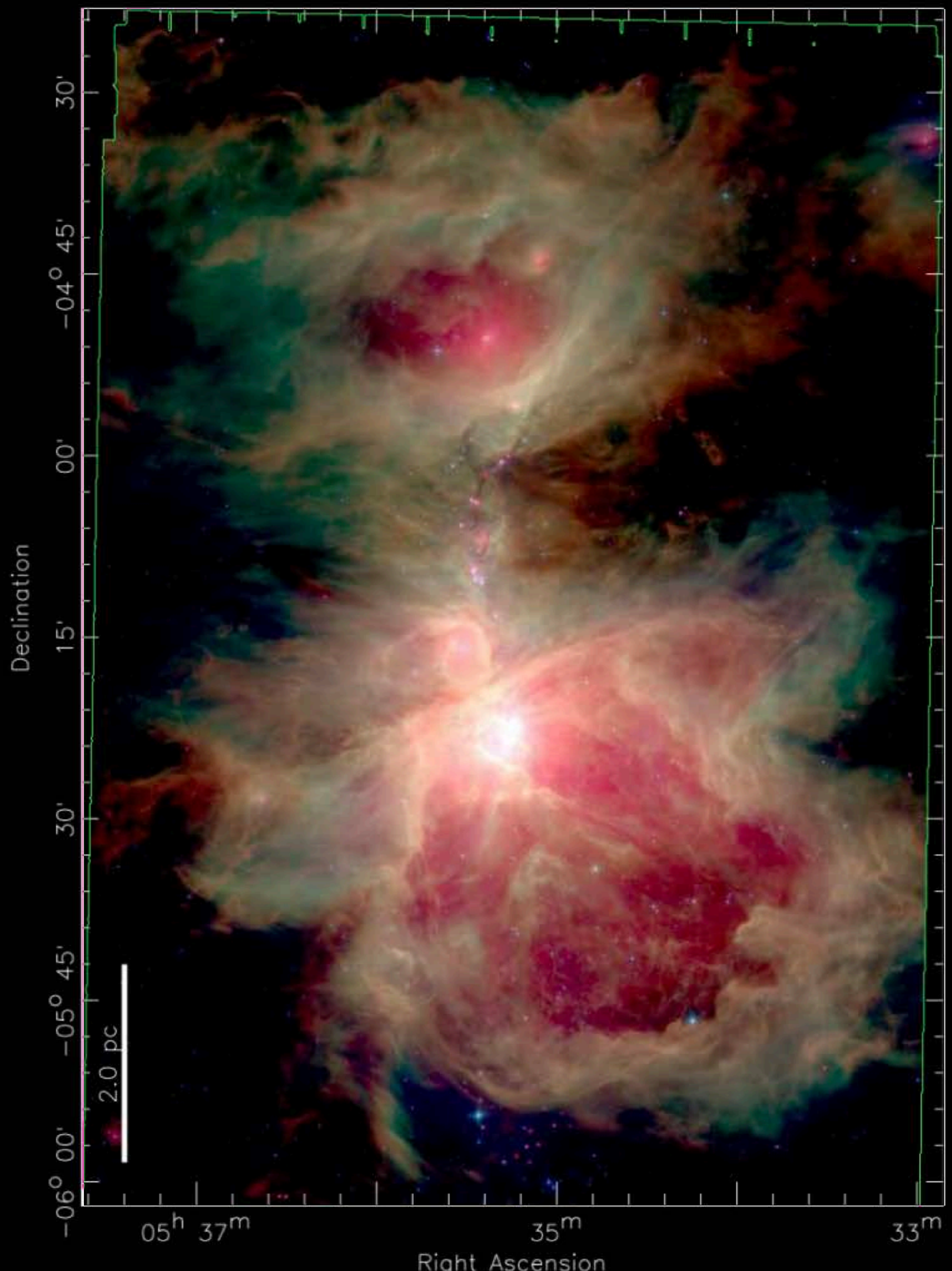




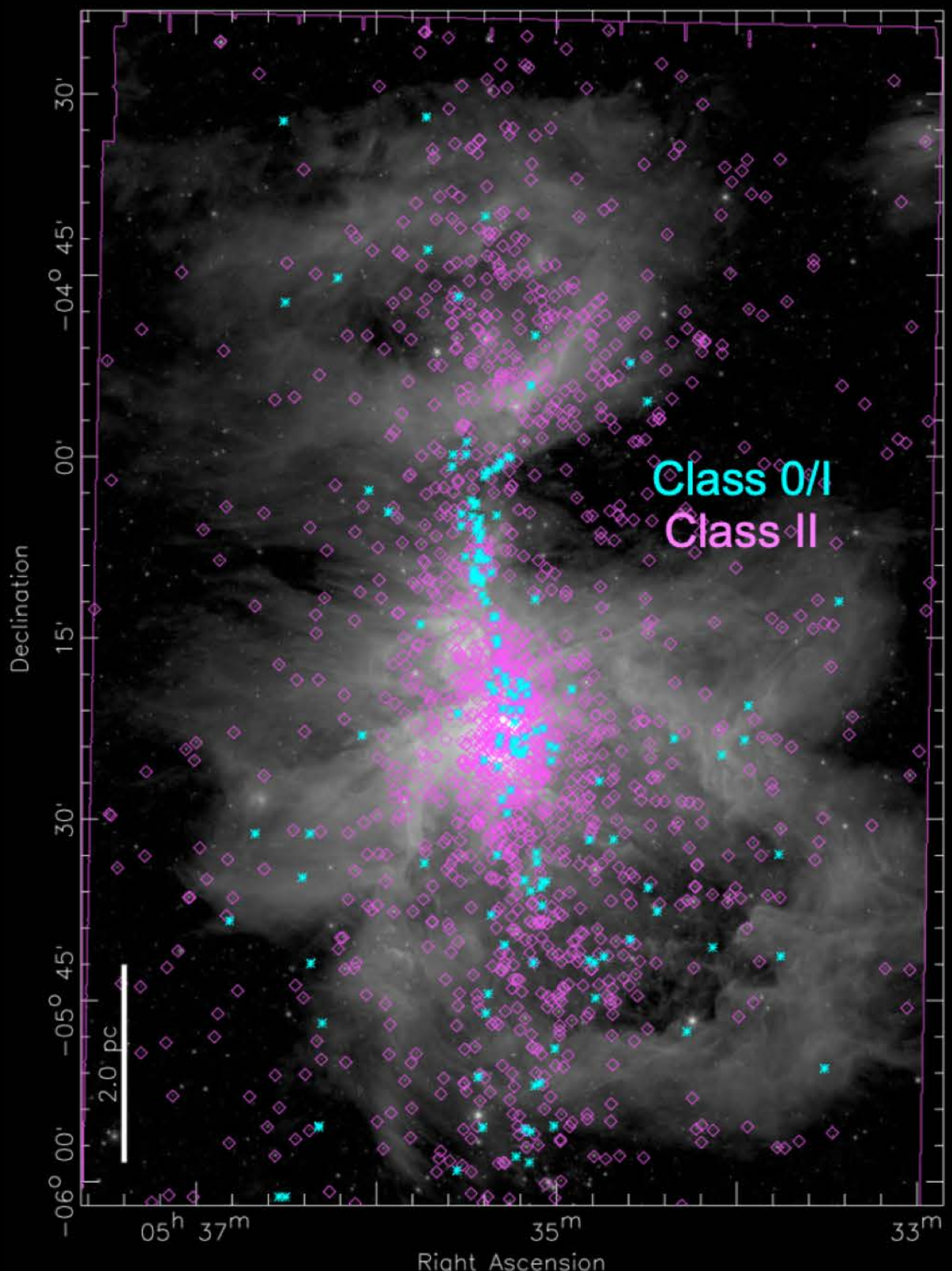
EMBEDDED SOURCES REVEALED IN INFRARED (NIR AND MIR)



THE AGE SPREAD IN STAR FORMING REGIONS



Spitzer 4.5, 5.8, +24 μm image of Northern Orion A



Megeath et al. (2006)

THE AGE SPREAD IN STAR FORMING REGIONS

- Observations of T Tauri (Class II and III) stars show a small age spread:

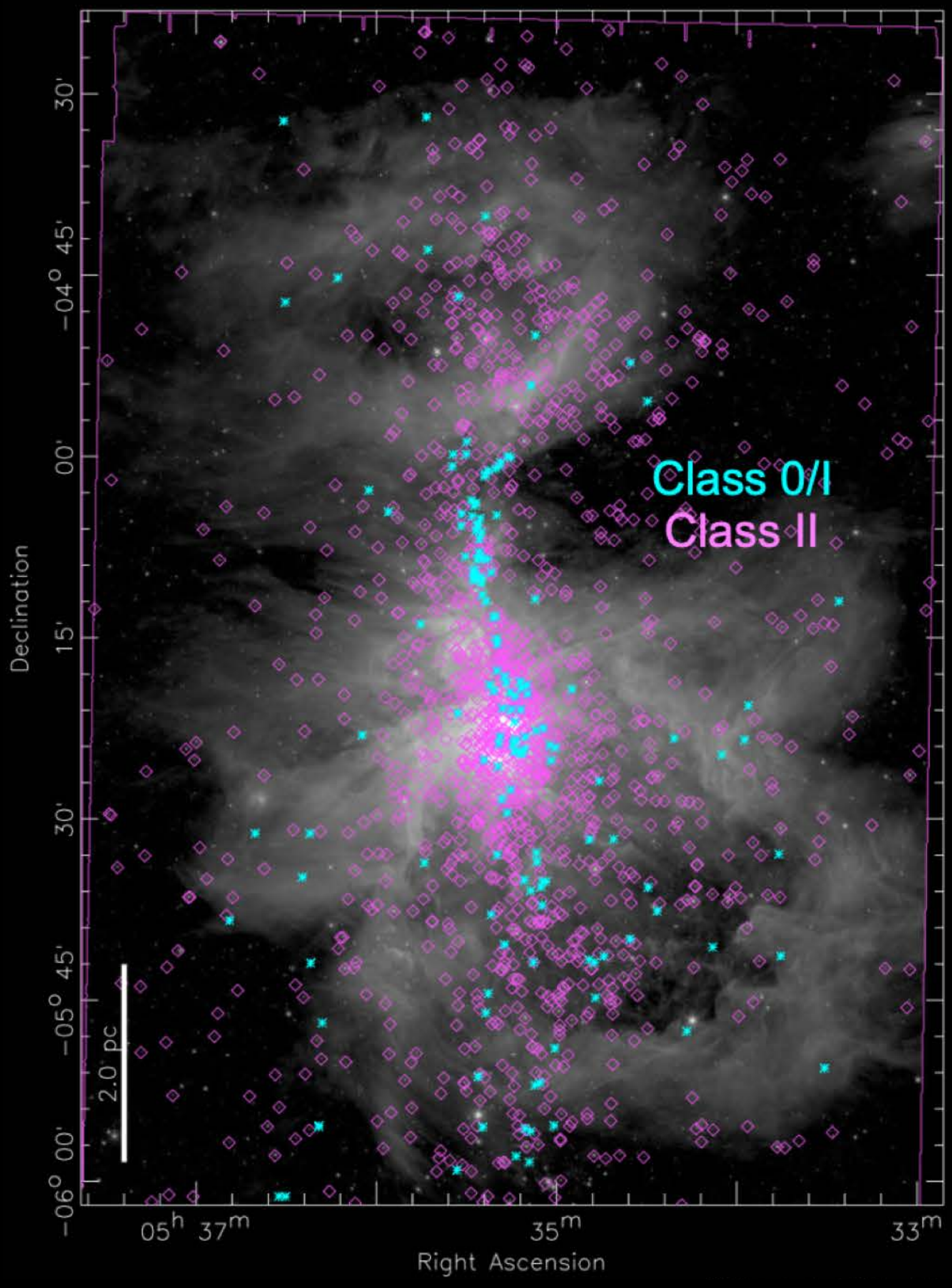
$$\Delta t_{\rm age} \sim 1\text{–}3\ \rm Myr$$

- Compare this to typical crossing times and lifetimes:

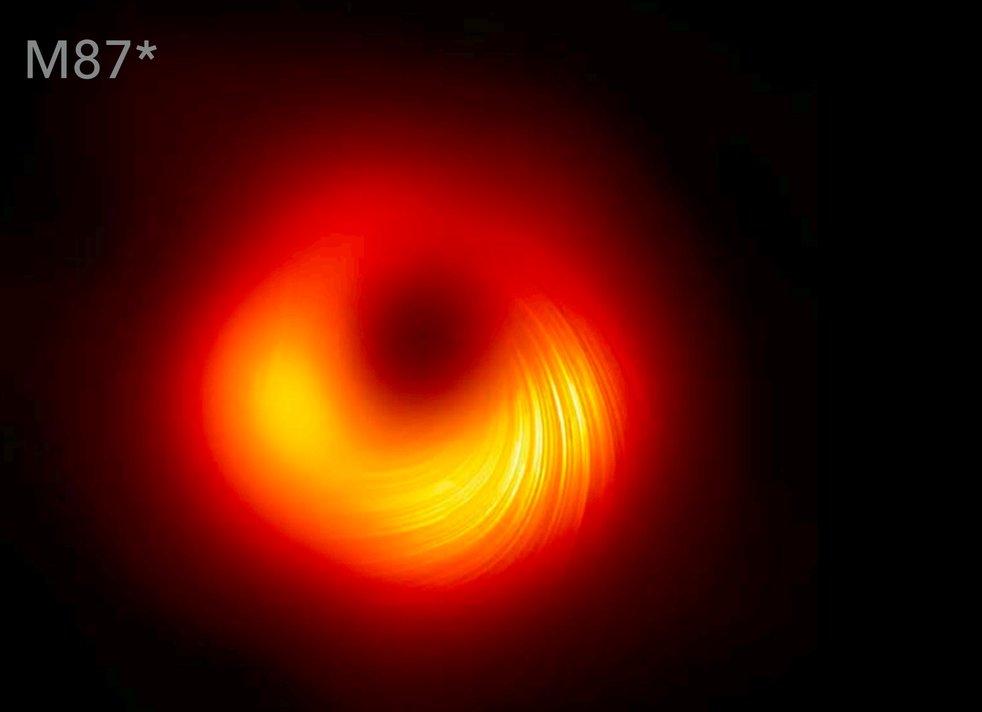
$$t_{\rm cross} = \frac{L}{v} \sim 10\ \rm Myr$$

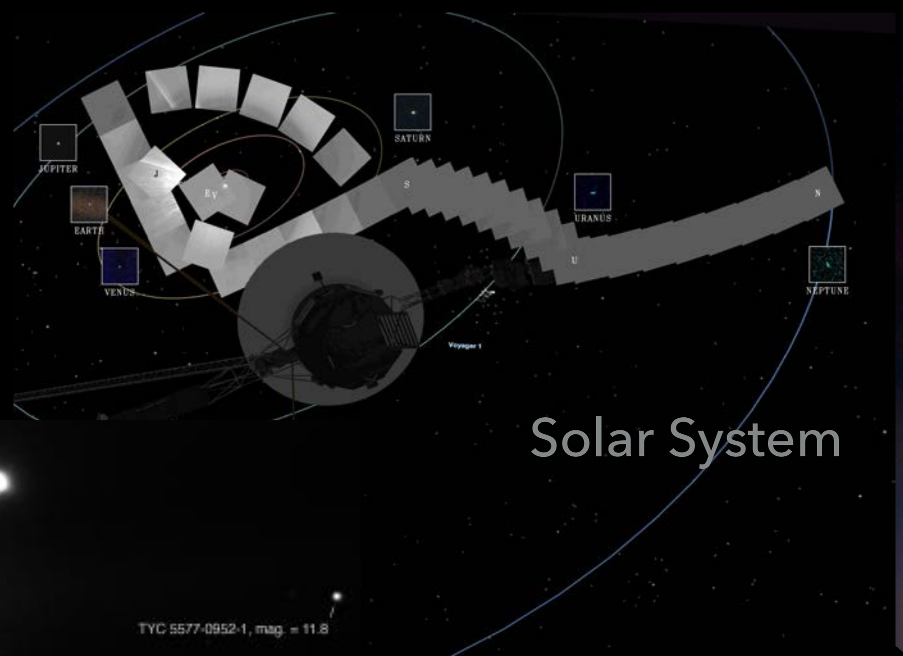
$$t_{\rm life} \sim 10\text{–}30\ \rm Myr$$

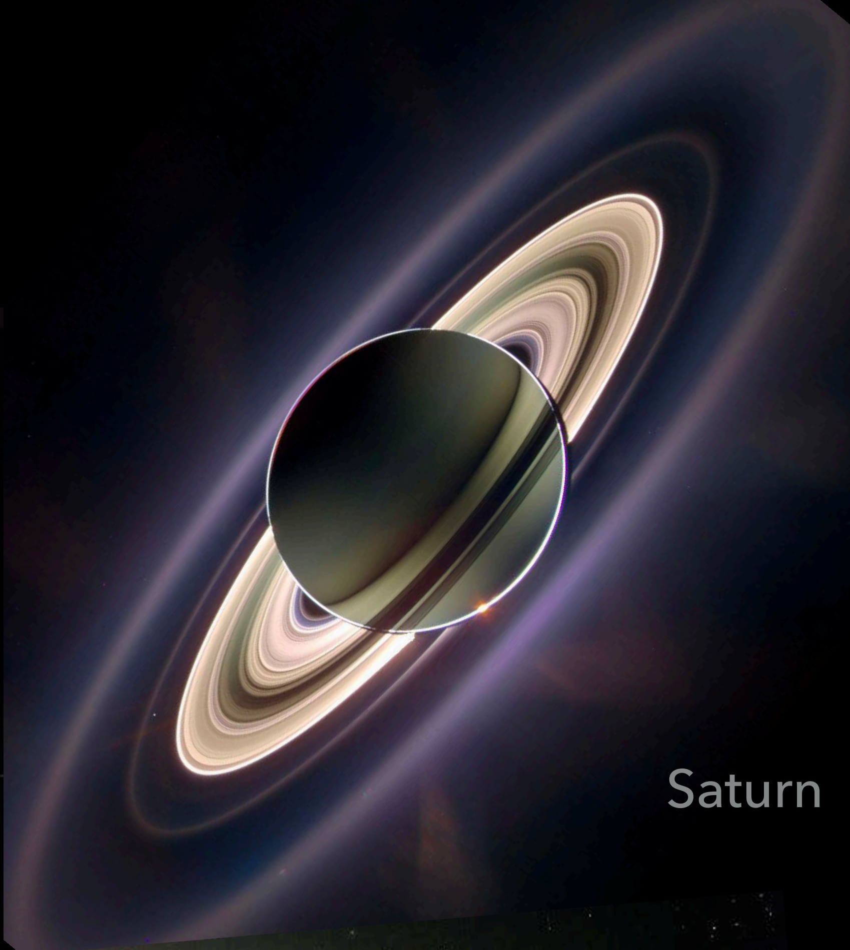
Star Formation must happen fast (i.e. in 1-2 crossing or freefall times) since the global star formation efficiency is low



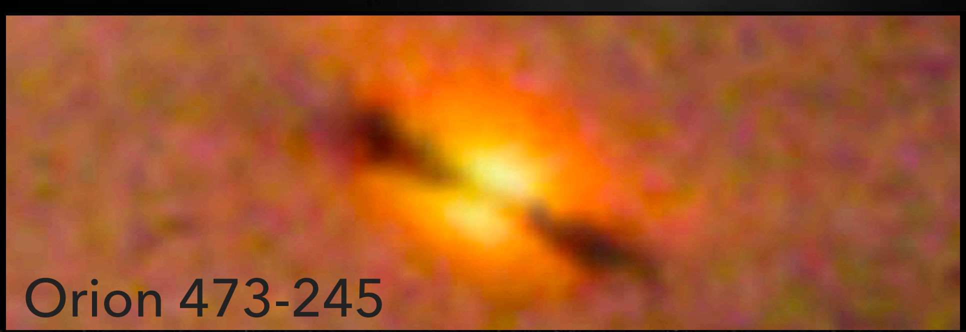
WHY DISCS?

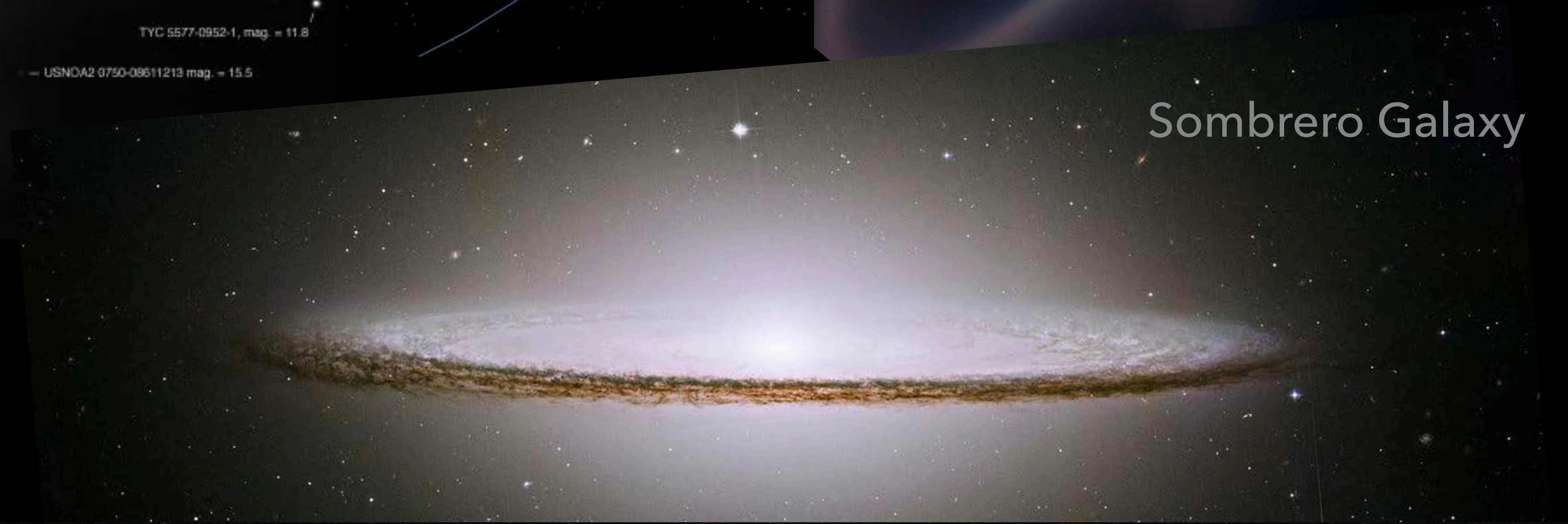

M87*

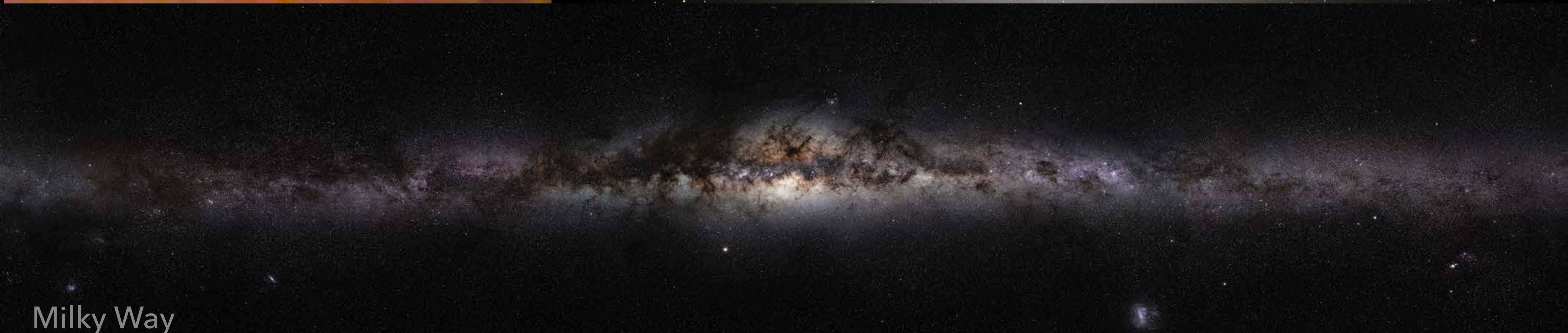

Solar System


Saturn


Jupiter
Europa, mag. = 6.3
Io, mag. = 6.0
Amalthea, mag. = 15.1
Callisto, mag. = 6.6
Ganymede, mag. = 5.6
USNOA2 0750-08613463 mag. = 16.0
GSC 5577-0392, mag. = 13.7
TYC 5577-0952-1, mag. = 11.8
USNOA2 0750-08611213 mag. = 15.5


Orion 473-245

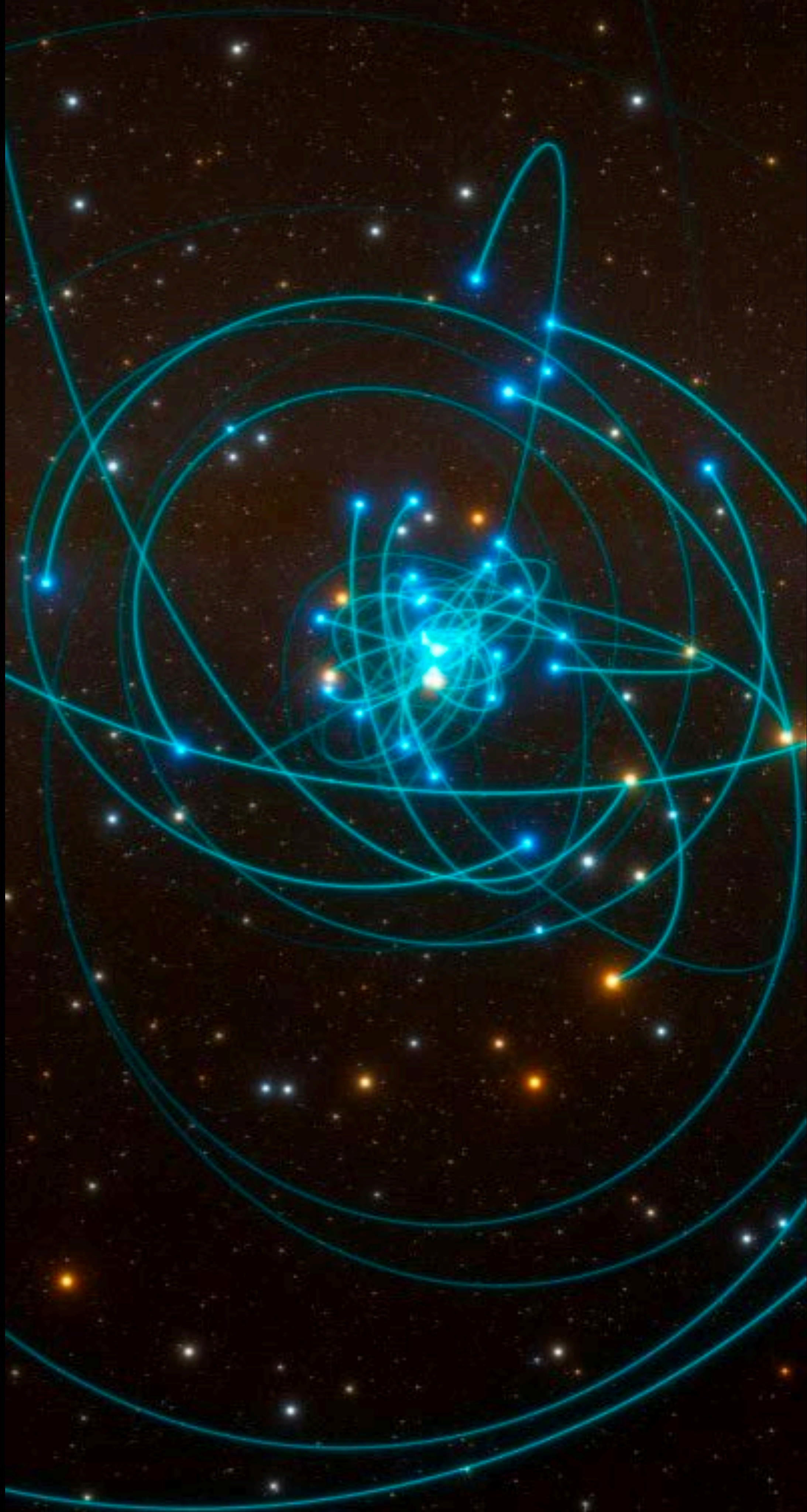

Sombrero Galaxy


Milky Way


M87
NGC 1316
WHY NOT SPHERICAL?
NGC 474
NGC 4365

ORBITAL DYNAMICS

- In a spherically symmetric potential, all objects move on orbital planes
  - Not necessarily in a disc!
- Stars are collisionless and only interact through gravity
  - Structure at time of formation is largely preserved
  - Stars randomly thrown together (e.g. galaxy mergers) create spherical clouds → Elliptical galaxies

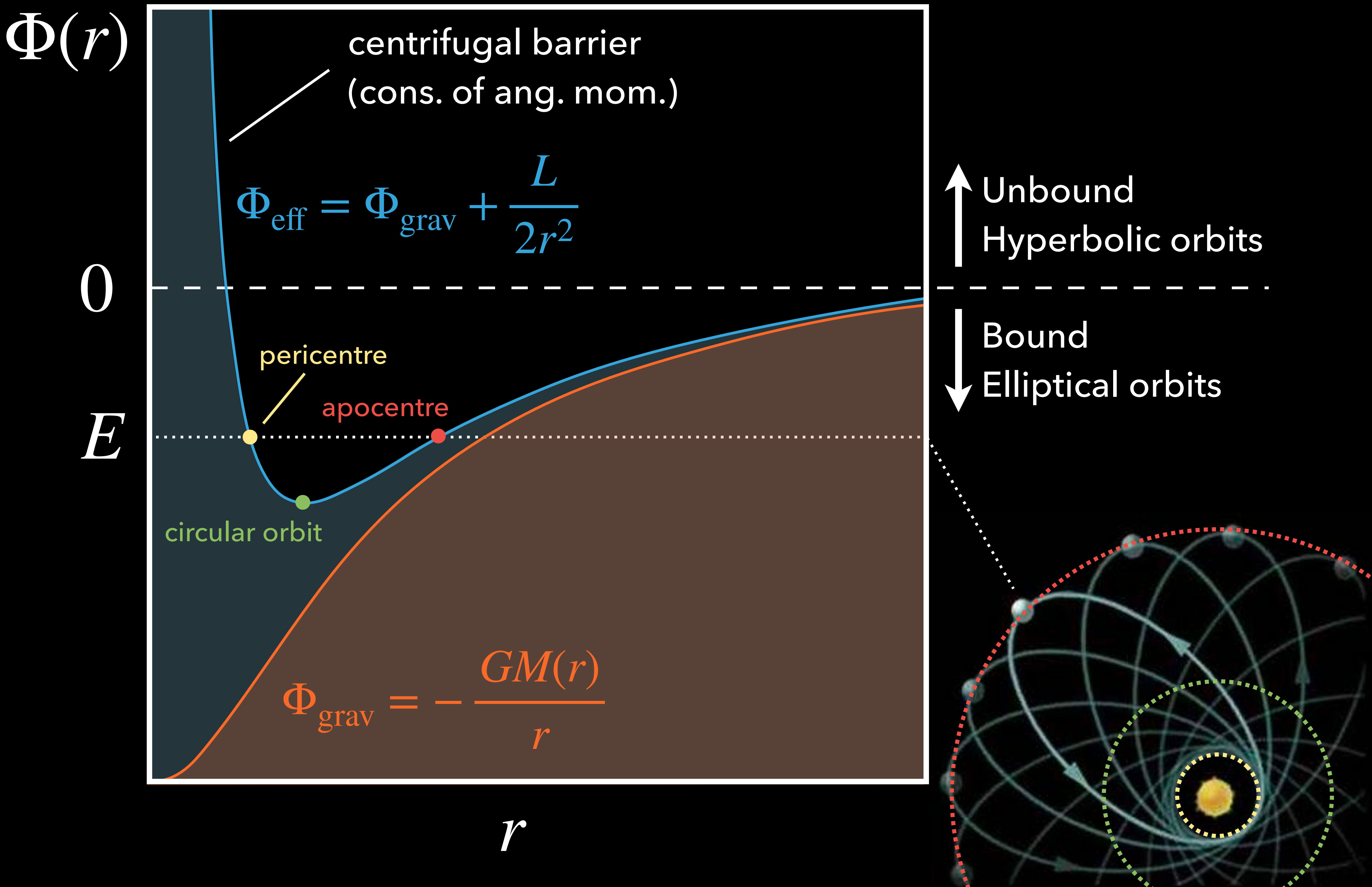


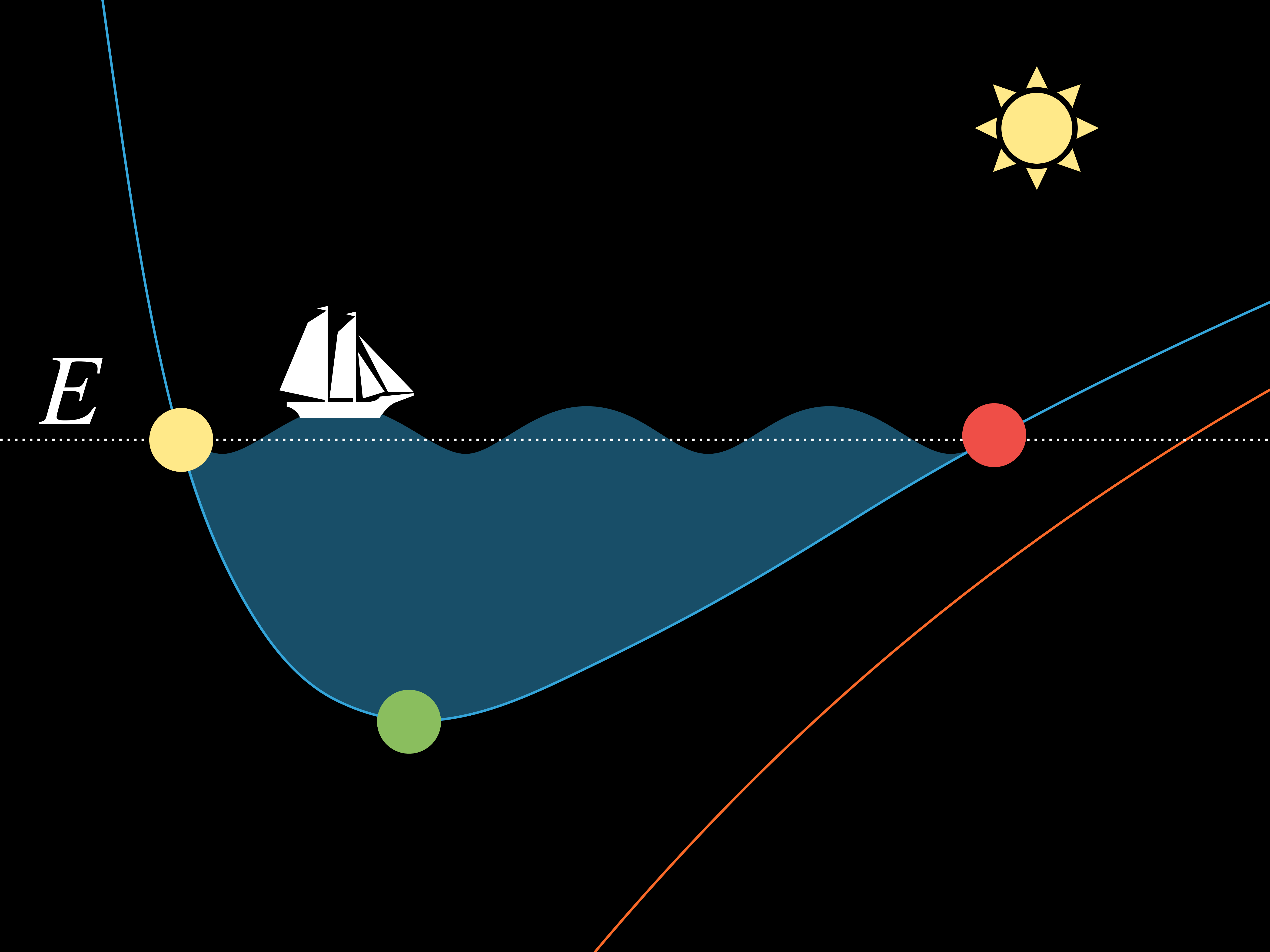
ORBITAL DYNAMICS

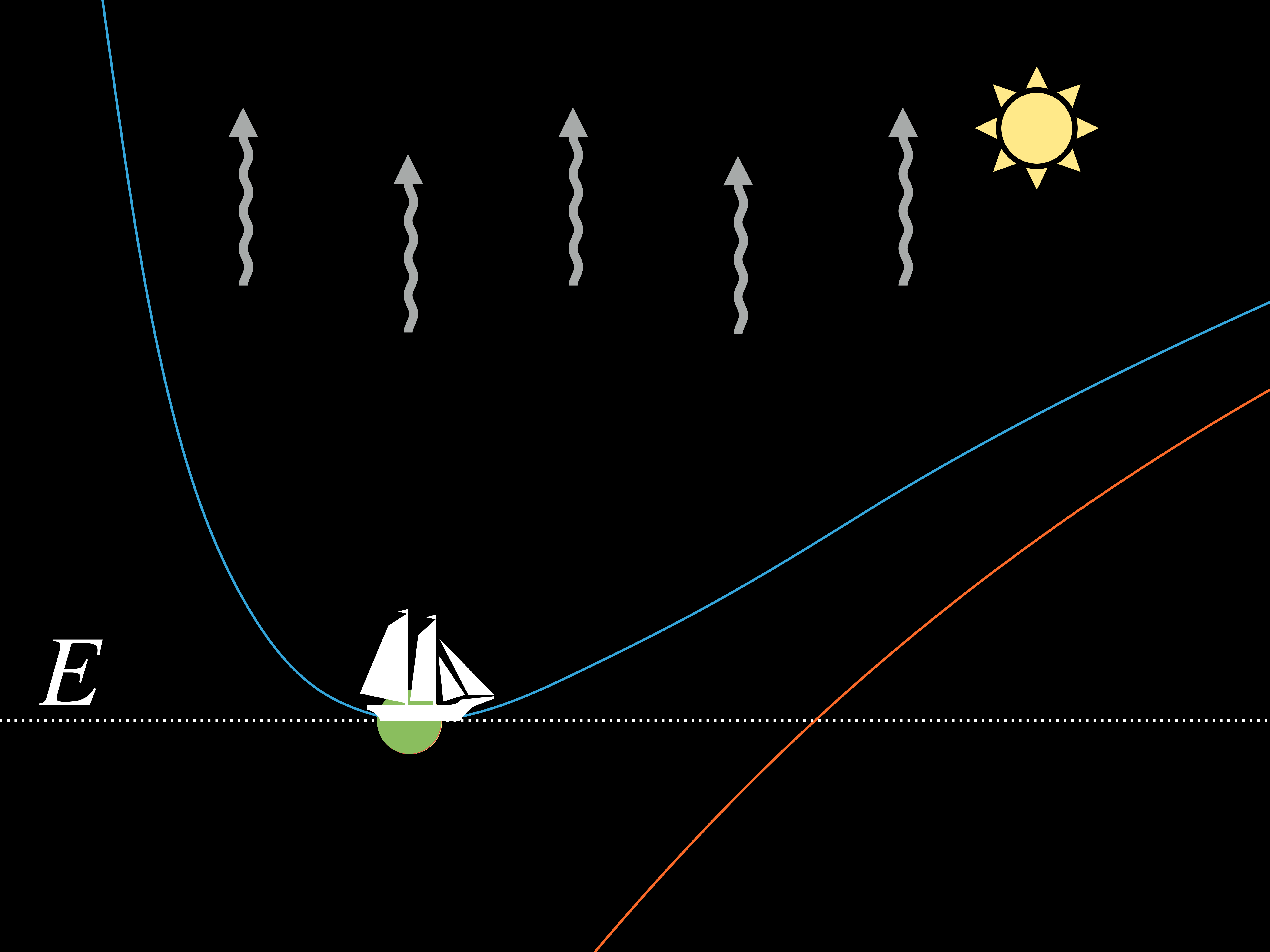
ORBITAL DYNAMICS

- Effective potential is a combination of gravity and angular momentum conservation
- Energy conservation can be violated by dissipative forces (e.g. viscous friction) and radiative cooling
- Angular momentum does not dissipate and cannot be radiated away (although it can be redistributed)
- Unlike stars, gas molecules are constantly colliding
  - Energy loss and relaxation onto circular orbits
  - Gas with low angular momentum accumulates at the centre of the potential well
  - Stars/planets that form in gas disc remain in a disc

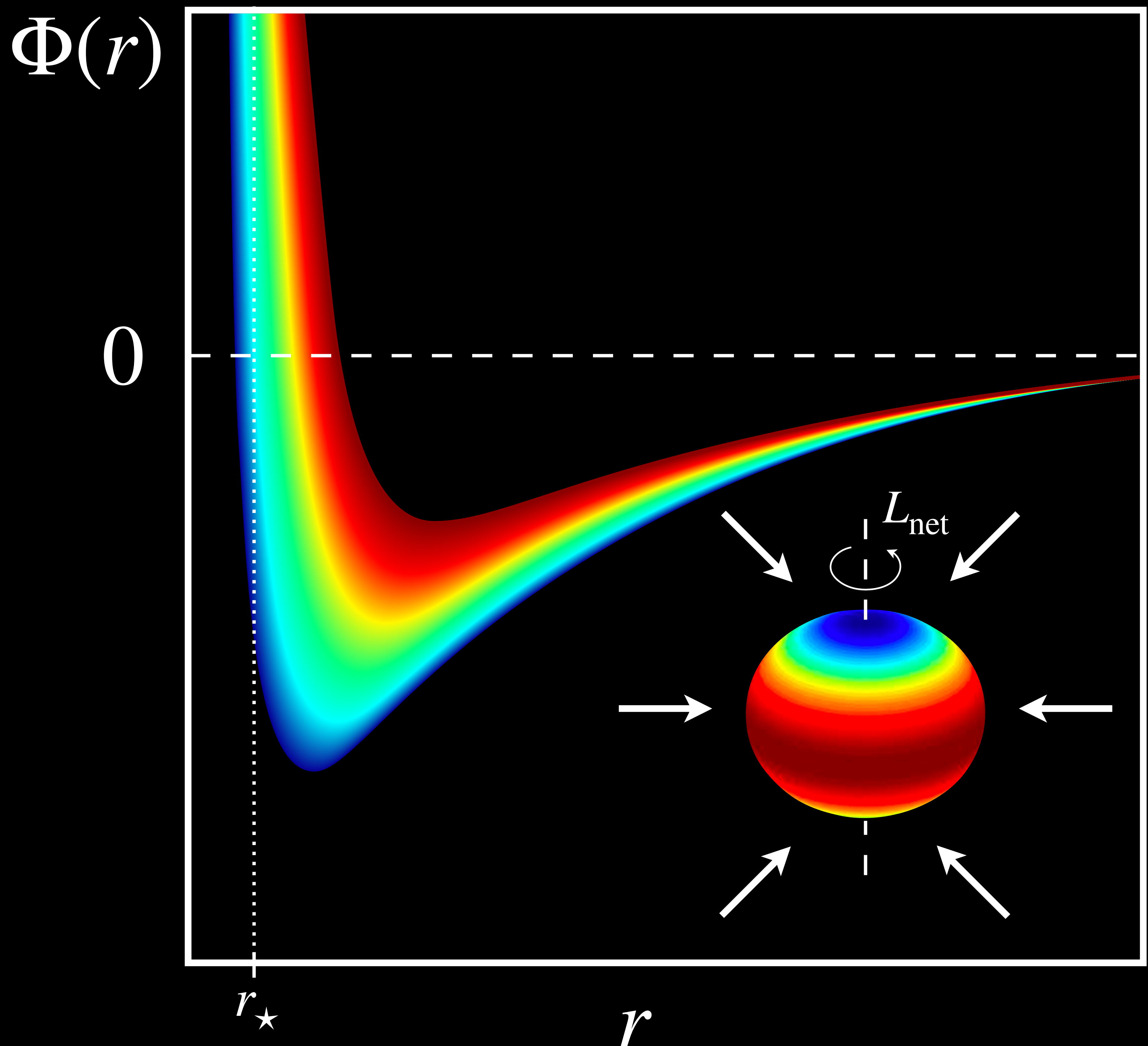
ORBITAL DYNAMICS




E

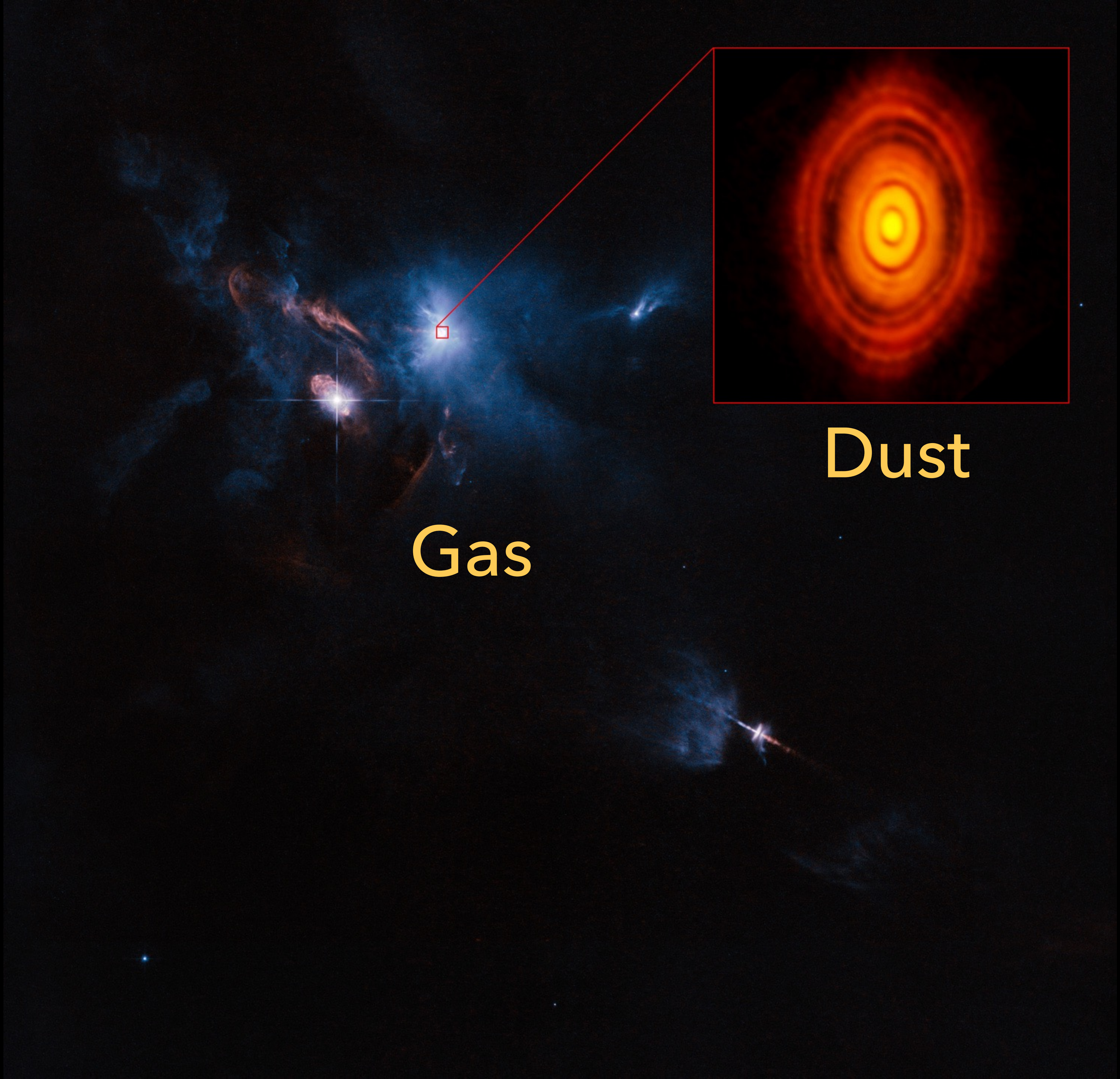

E

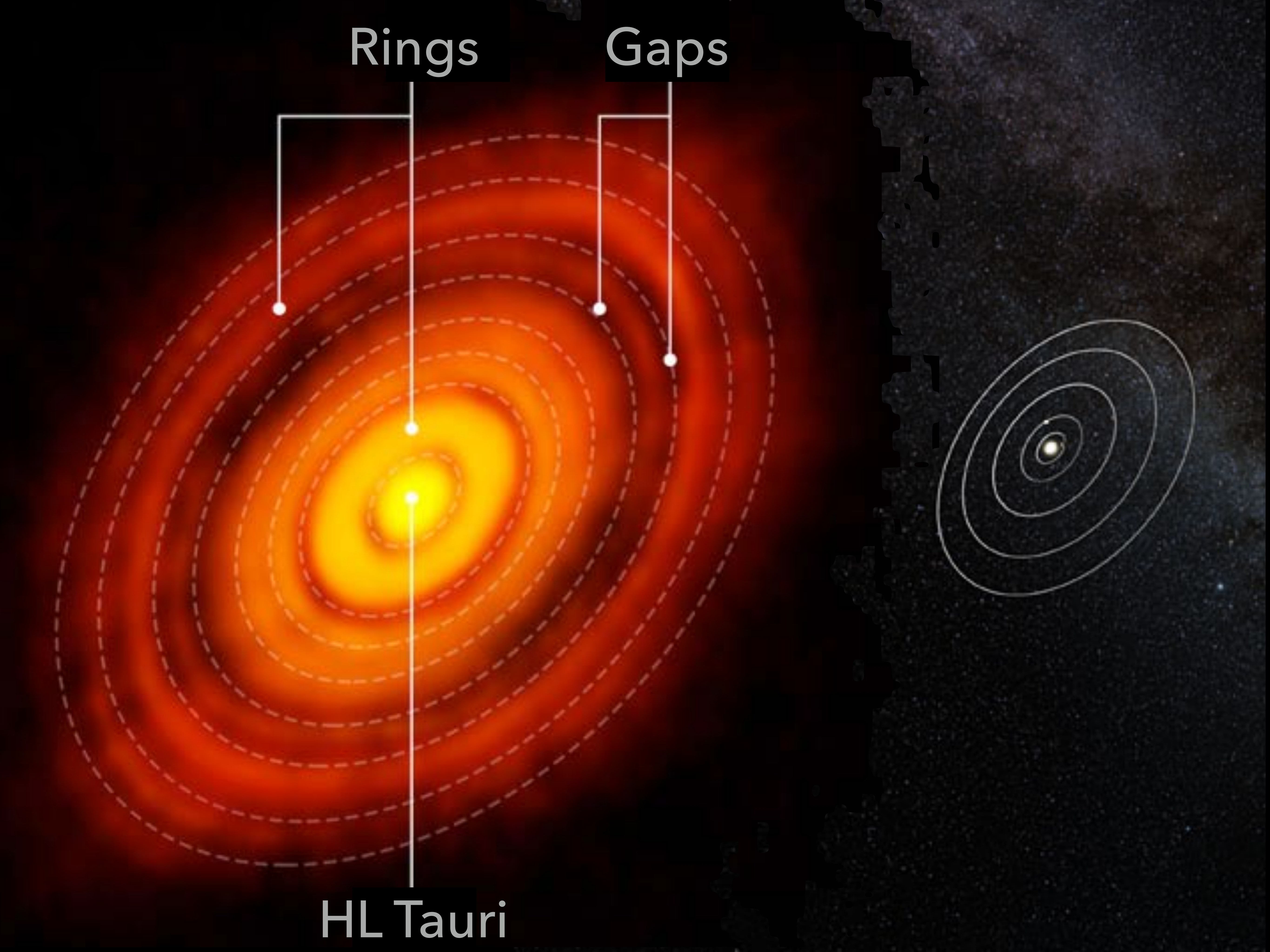
ORBITAL DYNAMICS

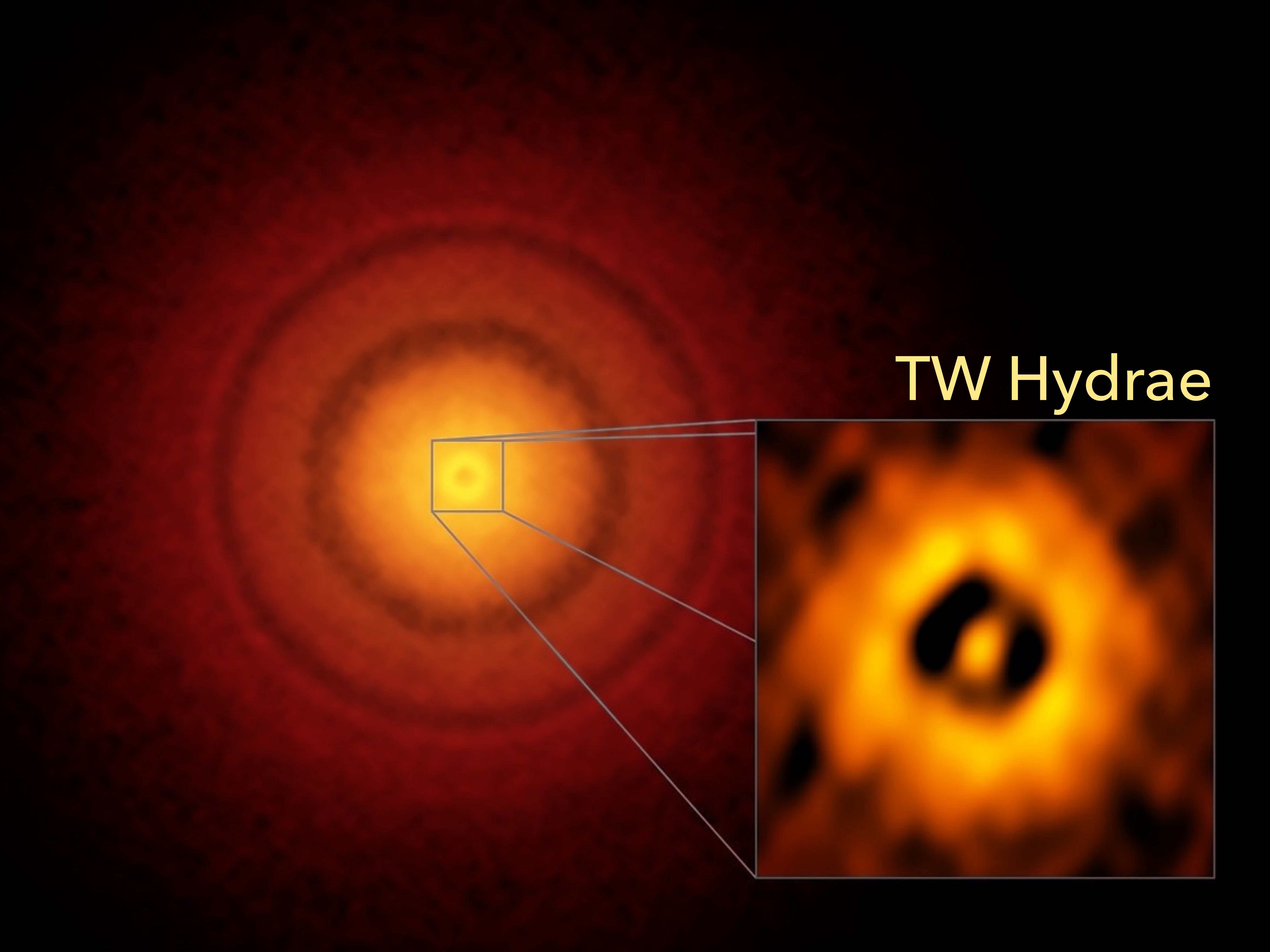


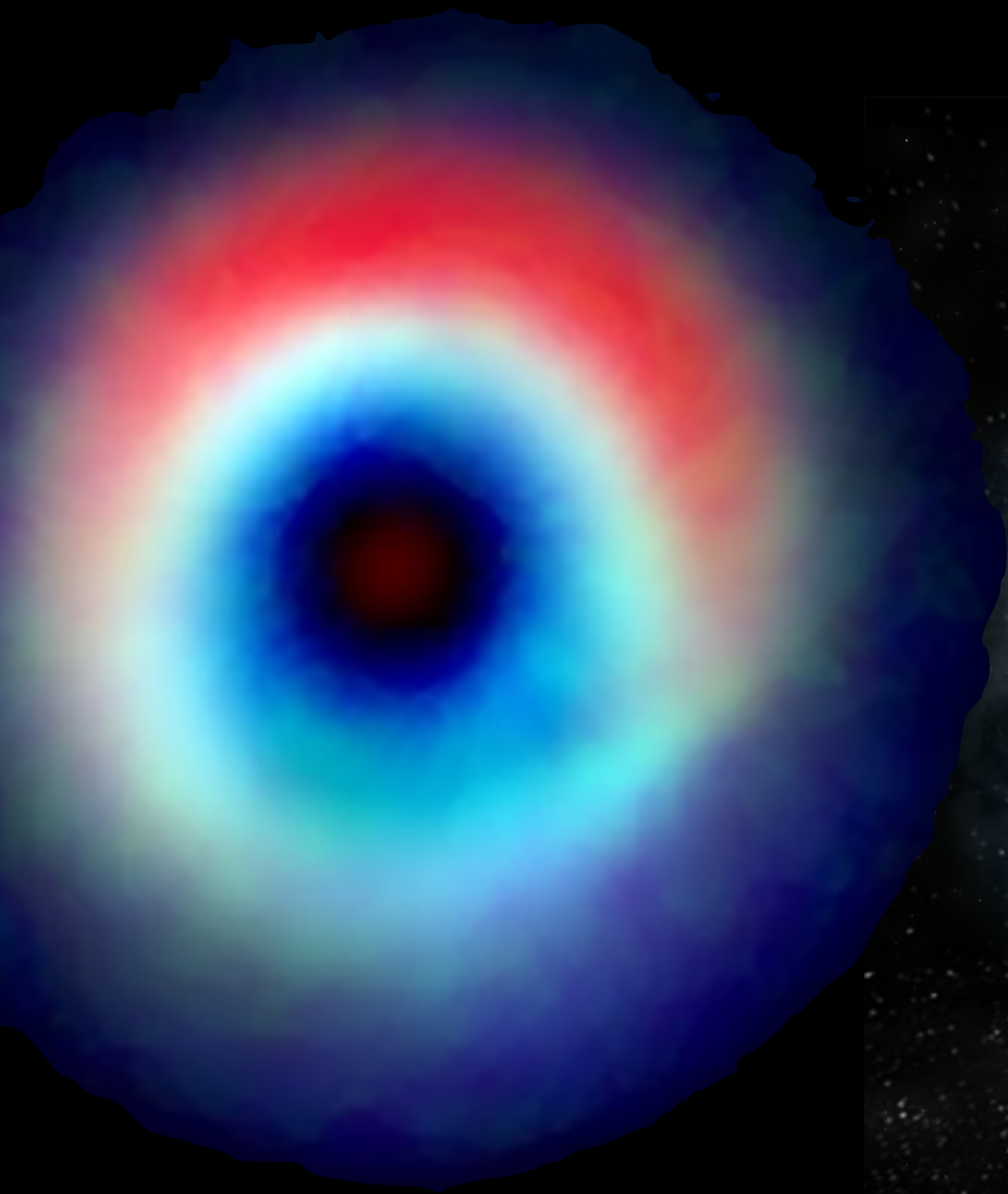
DISC FORMATION

- Stars accumulate angular momentum (spin ~10% of their critical breakup)
- Most of the angular momentum resides with a smaller fraction of the mass in a protostellar disc
- Some is dissipated away through magnetic braking
- Very unlikely to form a prestellar core without forming a disc
- Exceptions may include: massive stars, large magnetic fields, binary/multiple systems

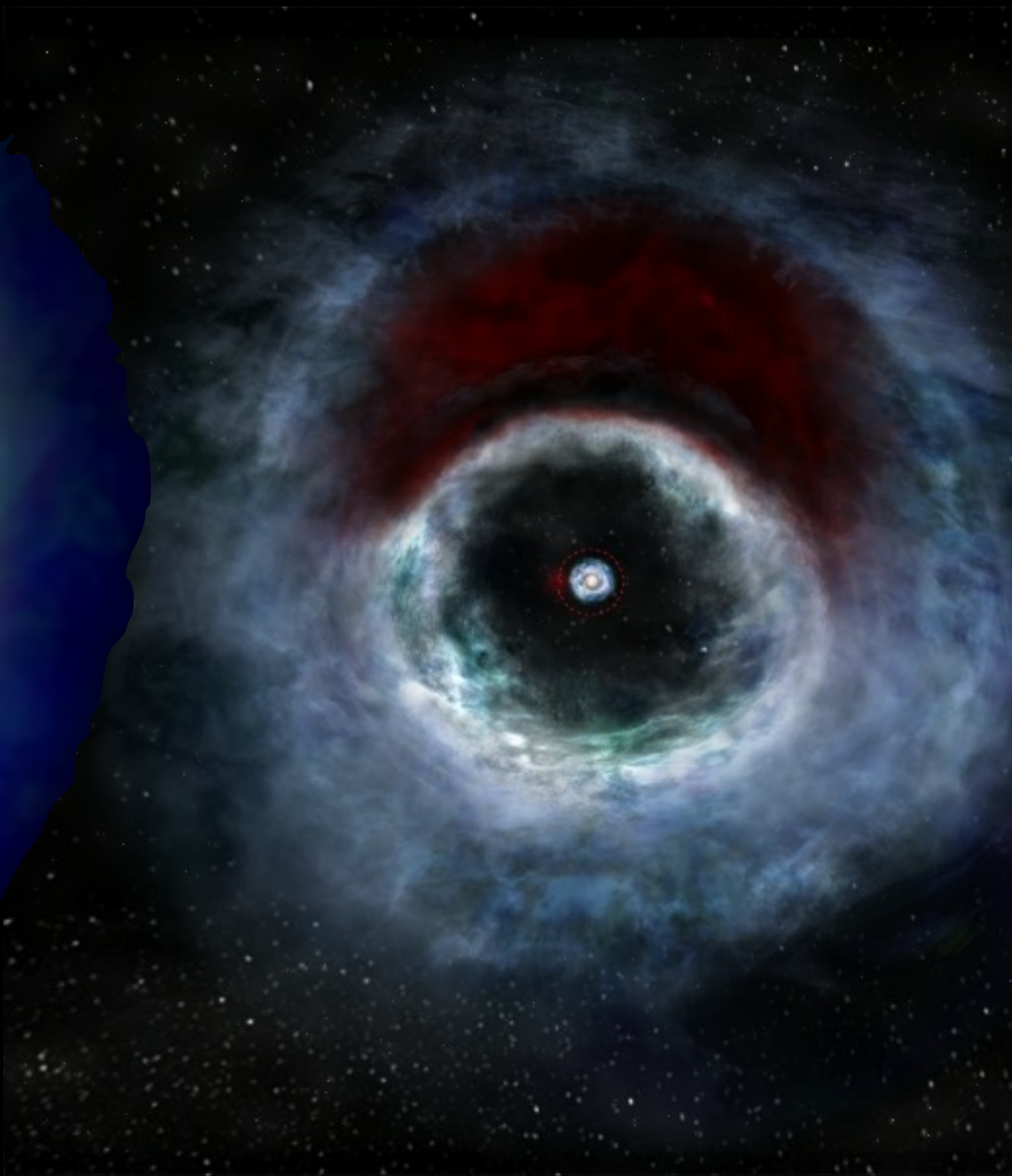

Dust
Gas

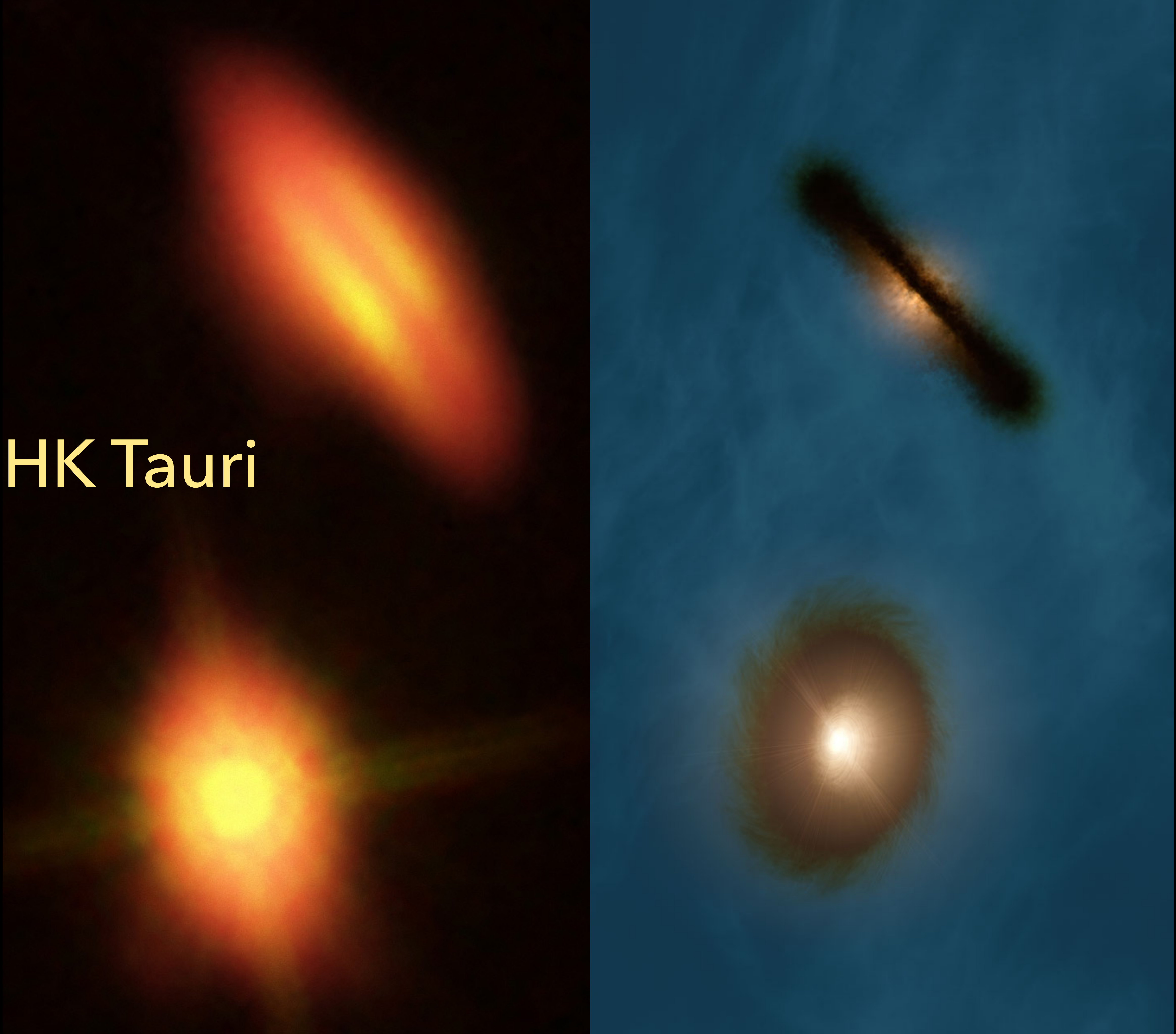

Rings
Gaps
HL Tauri


TW Hydrae

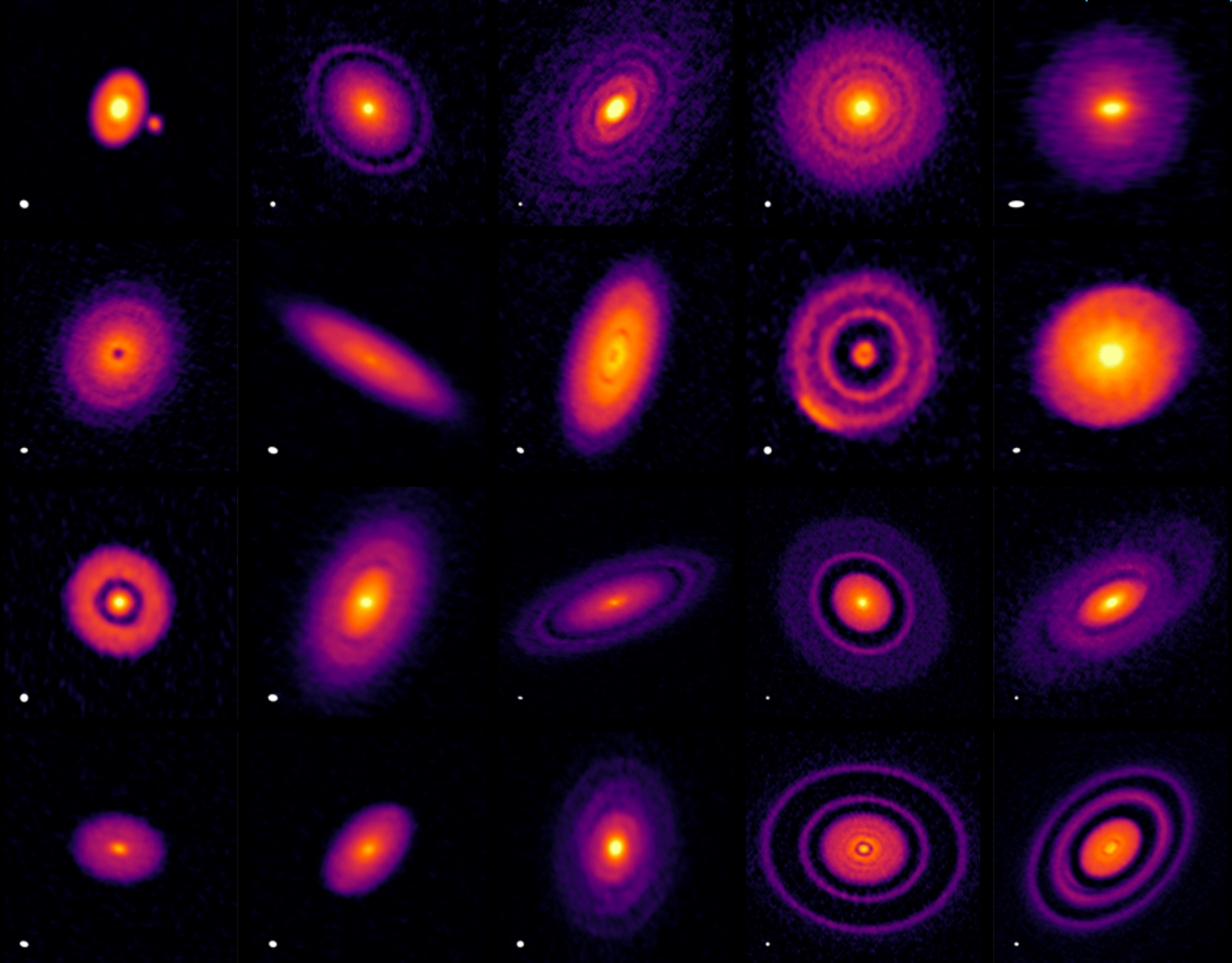


HD 142527



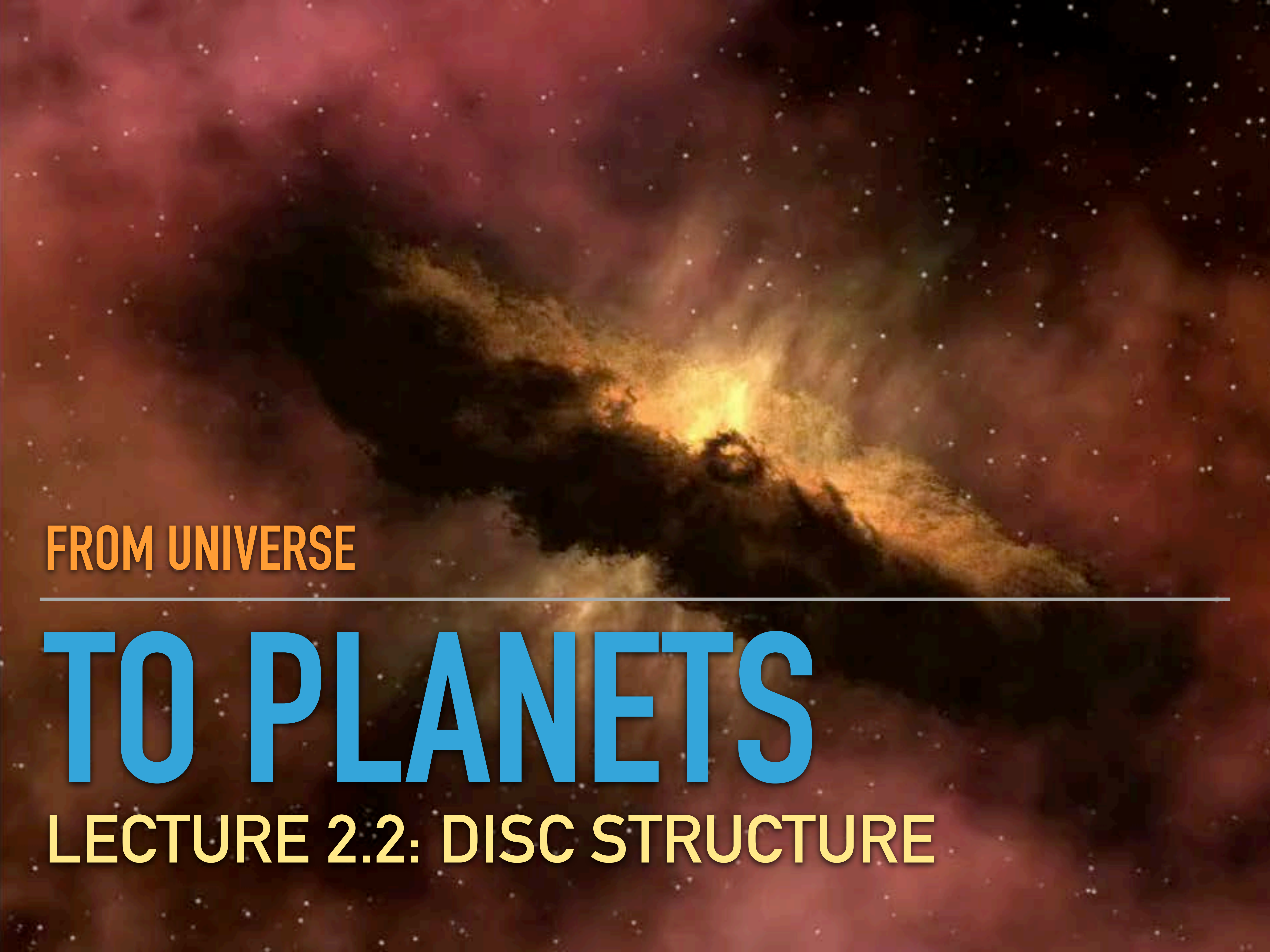

HK Tauri

DISK SUBSTRUCTURES AT HIGH ANGULAR RESOLUTION PROJECT (DSHARP)



BASIC PROPERTIES (UNCERTAIN, BUT IMPROVING)

- Masses: ~ 10^{-3}–10^{-1} $M_\odot$
- Radii: ~ 100 au
- Accretion rates: ~ 10^{-10}–10^{-7} $M_\odot$ / yr
- Lifetimes: ~ 1–15 Myr
- Relevant information for planet formation:
  - Structure – rotation, density, temperature, and chemical composition.
  - Early evolution and disc lifetimes – strength and nature of turbulence.
  - Dust dynamics – radial drift, vertical settling (we'll discuss growth and fragmentation next time).



FROM UNIVERSE

TO PLANETS

LECTURE 2.2: DISC STRUCTURE

ACTIVE VS PASSIVE DISCS

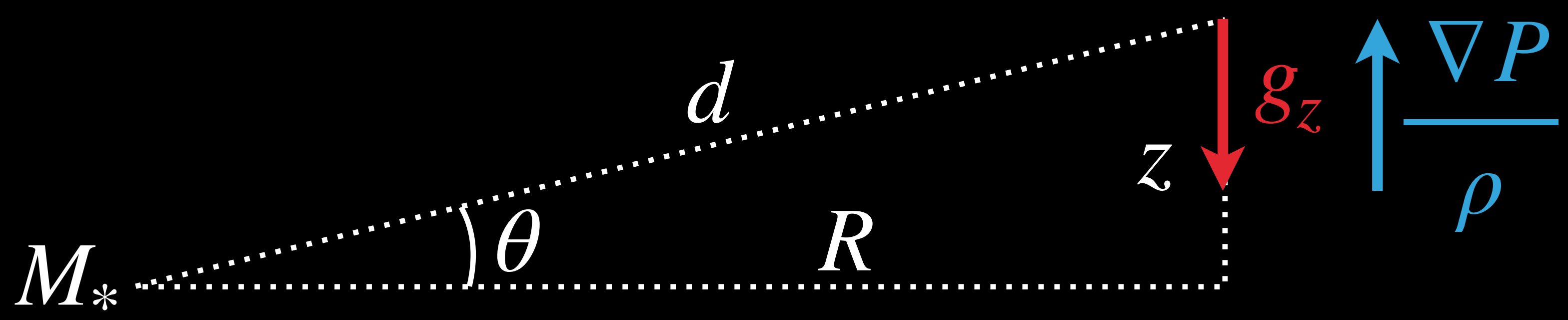
- Active: most of their luminosity comes from the release of gravitational energy as material flows inwards.
- Passive: luminosity comes from reprocessed starlight.
- Critical Accretion rate can be estimated by assuming the disc is flat and intercepts 1/4 of the stellar flux:

$$\frac{1}{4}L_* = \frac{GM_*\dot{M}}{2R_*}$$

  - Solving for $\dot{M}$ we find: $\dot{M} \approx 3 \times 10^{-8} M_\odot \ \mathrm{yr}^{-1}$
- Accretion rates are higher for younger objects, so young disks are generally active, while older object are dominated by reprocessed radiation (passive).

PASSIVE DISCS: VERTICAL STRUCTURE

- Consider hydrostatic equilibrium with pressure gradient:



$$\frac{\nabla P}{\rho} = \frac{1}{\rho}\frac{dP}{dz} = -g_z$$

- For $M_{\rm disc} \ll M_*$ and $z \ll R$: $g_z = \frac{GM_*}{d^2}\sin\theta \approx \Omega_{\rm K}^2 z$
  - Where Keplerian angular frequency: $\Omega_{\rm K} \equiv \sqrt{\frac{GM_*}{R^3}}$
- Equation of state for an isothermal disc: $P = \rho c_{\rm s}^2$
- Equation of hydrostatic equilibrium: $\frac{1}{\rho}\frac{dP}{dz} = c_{\rm s}^2 \frac{d\ln\rho}{dz} = -\Omega_{\rm K}^2 z$

$$\longrightarrow \quad \rho(z) = \rho_0 \exp\left[-\frac{1}{2}\left(\frac{z}{H}\right)^2\right] \quad \text{where} \quad H \equiv c_{\rm s}/\Omega_{\rm K}$$

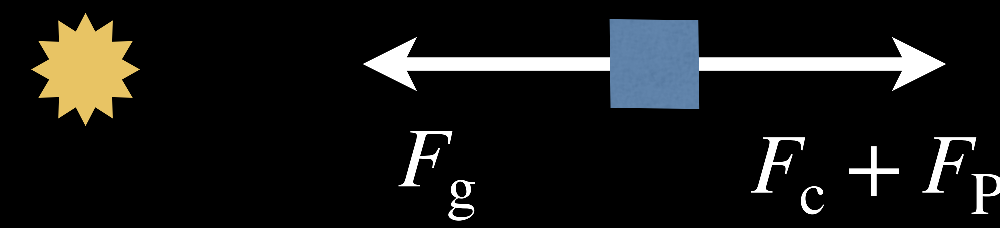
PASSIVE DISCS: VERTICAL STRUCTURE

- Often convenient to use vertically averaged quantities, e.g. surface density:

$$\Sigma = \int_{-\infty}^{\infty} \rho(z)\, dz = \sqrt{2} H \rho_0 \int_{-\infty}^{\infty} \mathrm{e}^{-x^2}\, dx = \sqrt{2\pi} H \rho_0 \quad \longrightarrow \quad \rho_0 = \frac{\Sigma}{\sqrt{2\pi} H}$$

  - Typically assumed to follow: $\Sigma \propto R^{-p}$ with $p \in [0,1.5]$
- Minimum Mass Solar Nebula (MMSN): the minimum amount of solids necessary to build the solar system
  - An aspect ratio $h \equiv H/R \sim 0.05$ gives a mid-plane density (ρ_0) of about 10^{-9} g cm^{-3} at 1 au
- If we assume: $T \propto R^{-q}$ then $c_s \propto R^{-q/2}$ and $h \propto R^{-(q-1)/2}$
  - Flared discs have $q < 1$ (typical values $q \in [0.4,0.8]$)

PASSIVE DISCS: RADIAL STRUCTURE



- In the radial direction a parcel of gas in the disc feels:
  - Gravity from the star (non self-gravitating case)
  - Centrifugal force
  - Pressure force

$$\frac{v^2}{R} = \frac{GM_*}{R^2} + \frac{1}{\rho}\frac{dP}{dR}$$

- Pressure decreases with radius, so gas rotates slightly slower than solids at the same radius (sub-Keplerian).

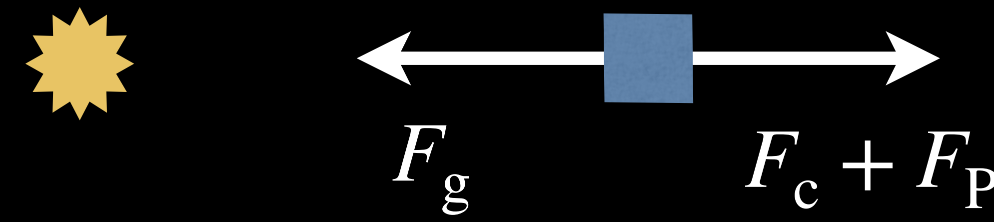
$$f = p + \frac{q}{2} + \frac{3}{2} \sim \mathcal{O}[1]$$

$$\frac{v^2}{R} \approx \Omega_\mathrm{K}^2 R - f\frac{c_\mathrm{s}^2}{R} \sim \Omega_\mathrm{K}^2 R\left(1 - \frac{c_\mathrm{s}^2}{R^2\Omega_\mathrm{K}^2}\right) \quad \rightarrow \quad v = v_\mathrm{K}\left[1 - \mathcal{O}\left(\frac{H}{R}\right)^2\right]$$

- $H/R \ll v_\mathrm{K}$ so we say the disc is in Keplerian motion, but this difference is crucial for understanding dust dynamics.

$$\Sigma \propto R^{-p}$$
$$T \propto R^{-q}$$
$$c_s \propto R^{-q/2}$$
$$\rho \propto R^{-(p-q/2+3/2)}$$
$$H \propto R^{3/2-q/2}$$
$$\Omega_K \propto R^{-3/2}$$
$$P \propto R^{-(p+q/2+3/2)}$$

DIAL STRUCTURE



ction a parcel of gas in the disc feels:

the star (non self-gravitating case)

force

ce

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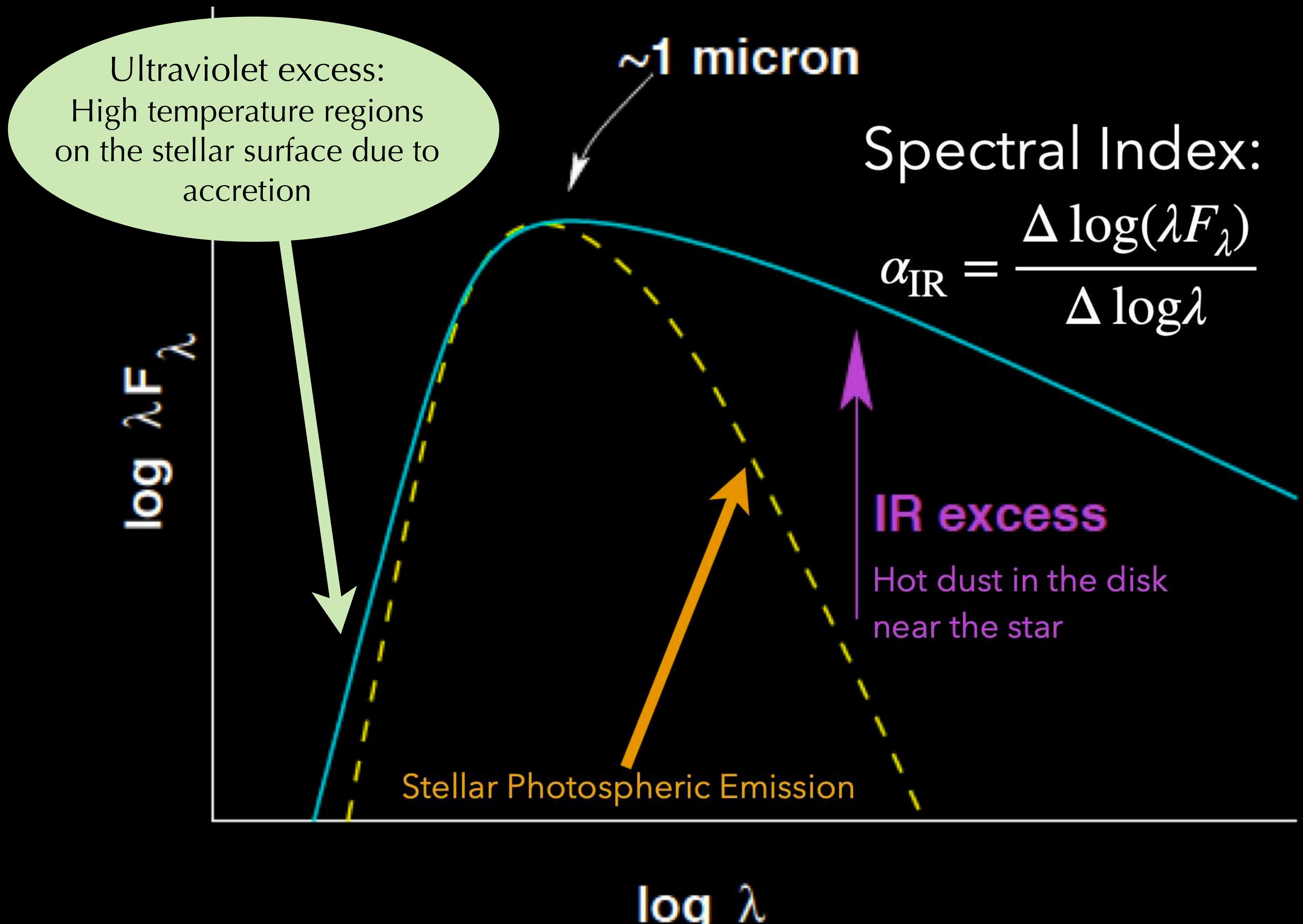
PASSIVE DISCS: SPECTRAL ENERGY DISTRIBUTION (SED)

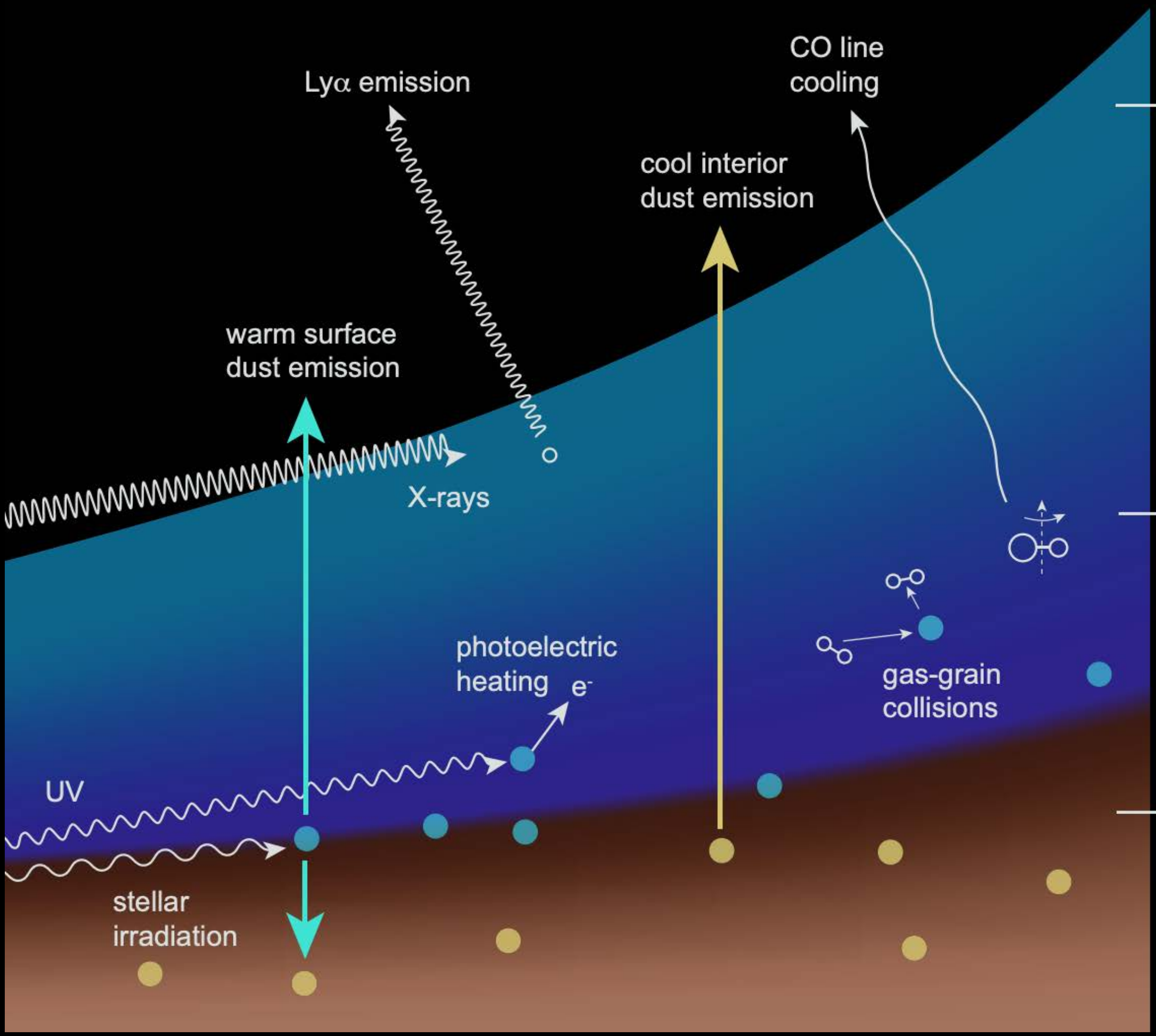


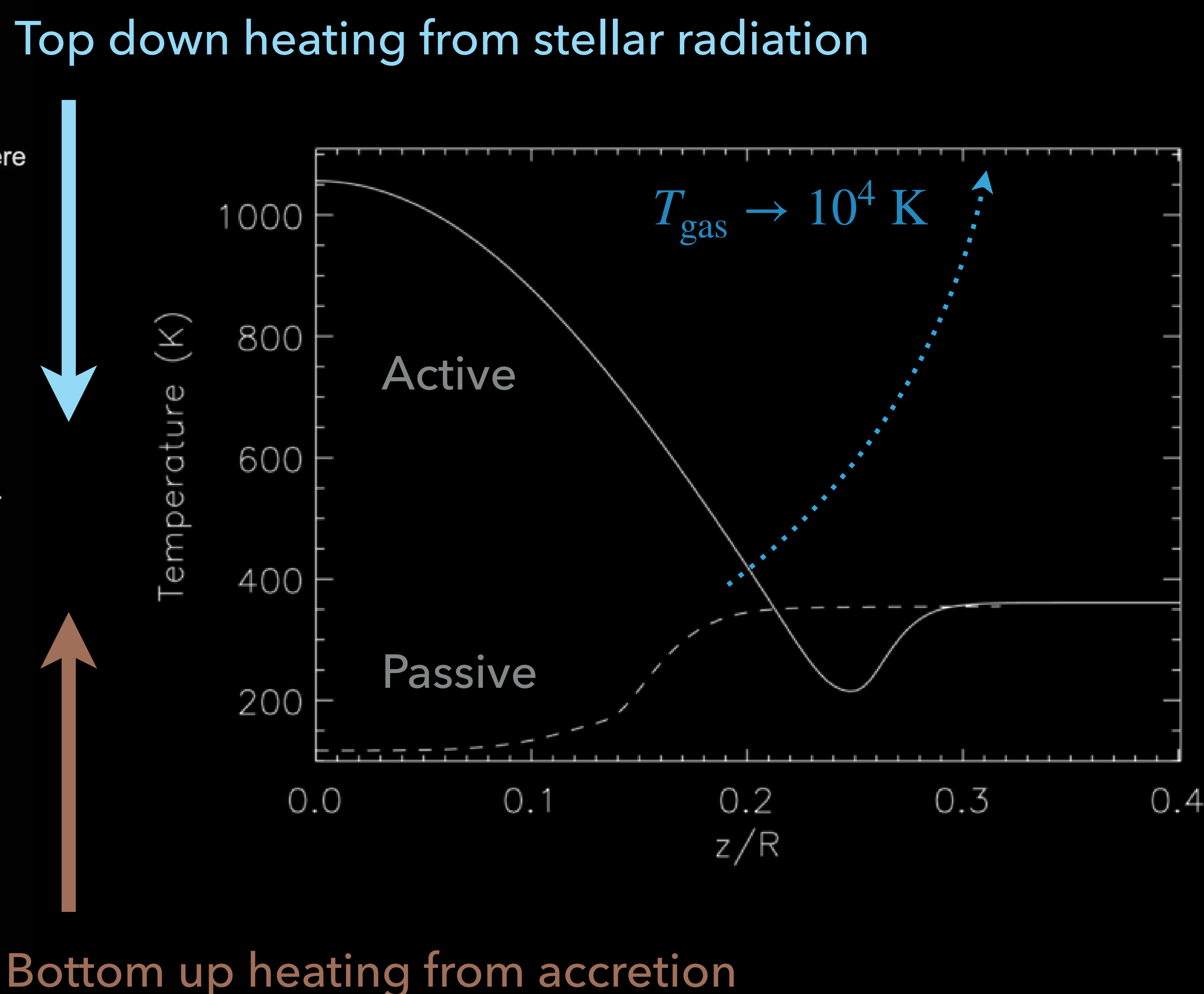
Spectral Index:

$$\alpha_{IR} = \frac{\Delta \log(\lambda F_\lambda)}{\Delta \log \lambda}$$

PASSIVE DISCS: SED

- Of course we are oversimplifying: discs are not single T black bodies
- Dust in the upper layers absorbs stellar radiation more efficiently than it emits IR radiation





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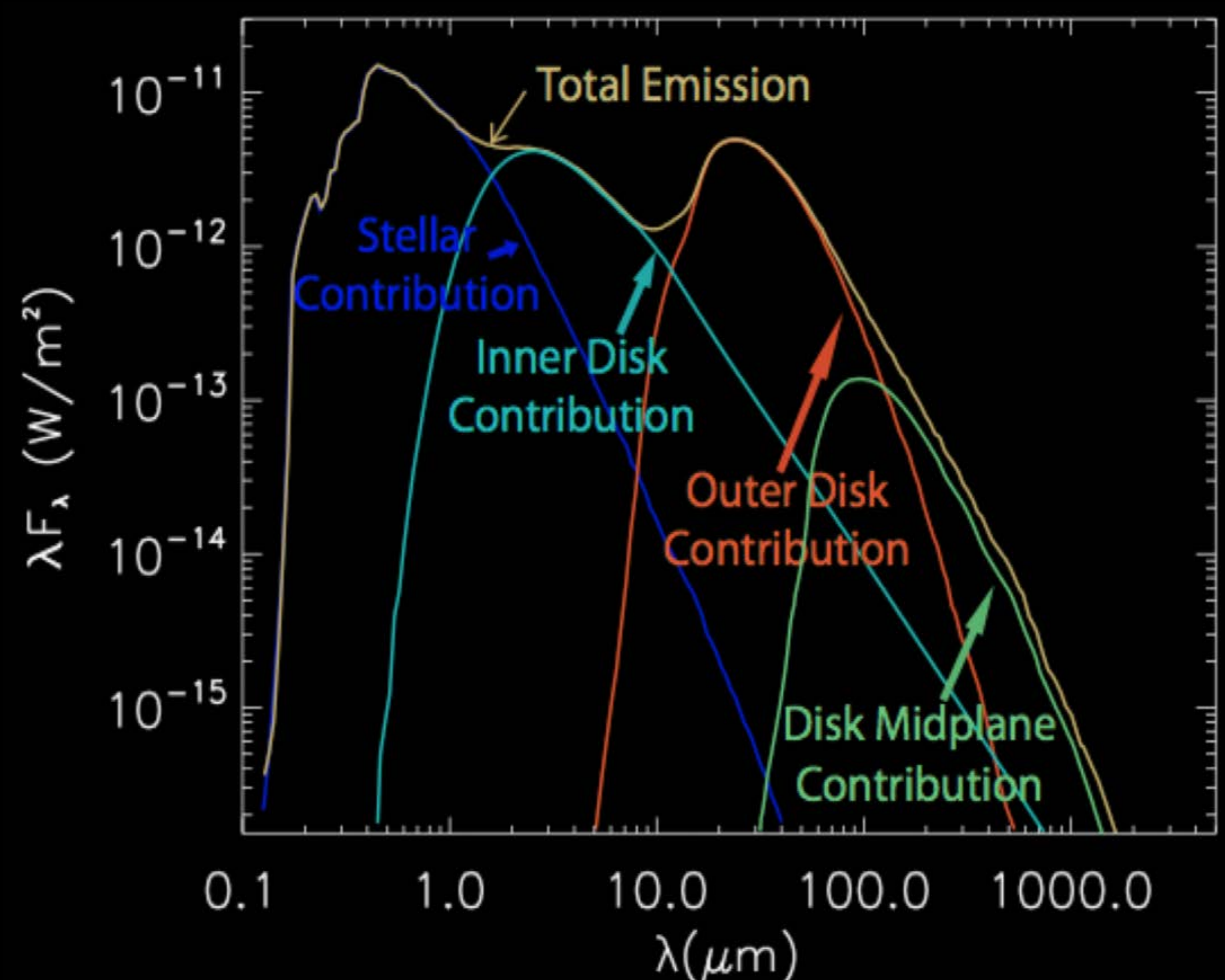
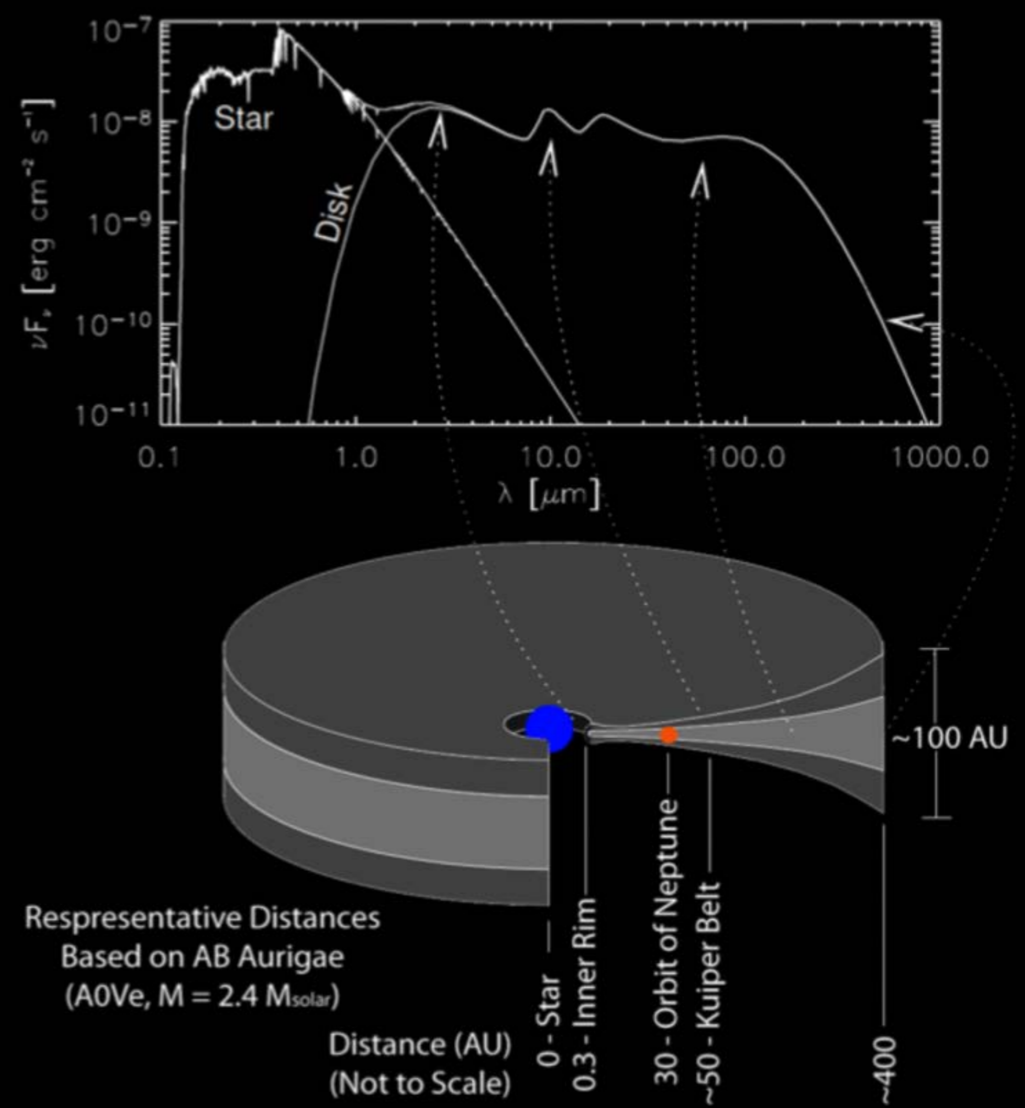
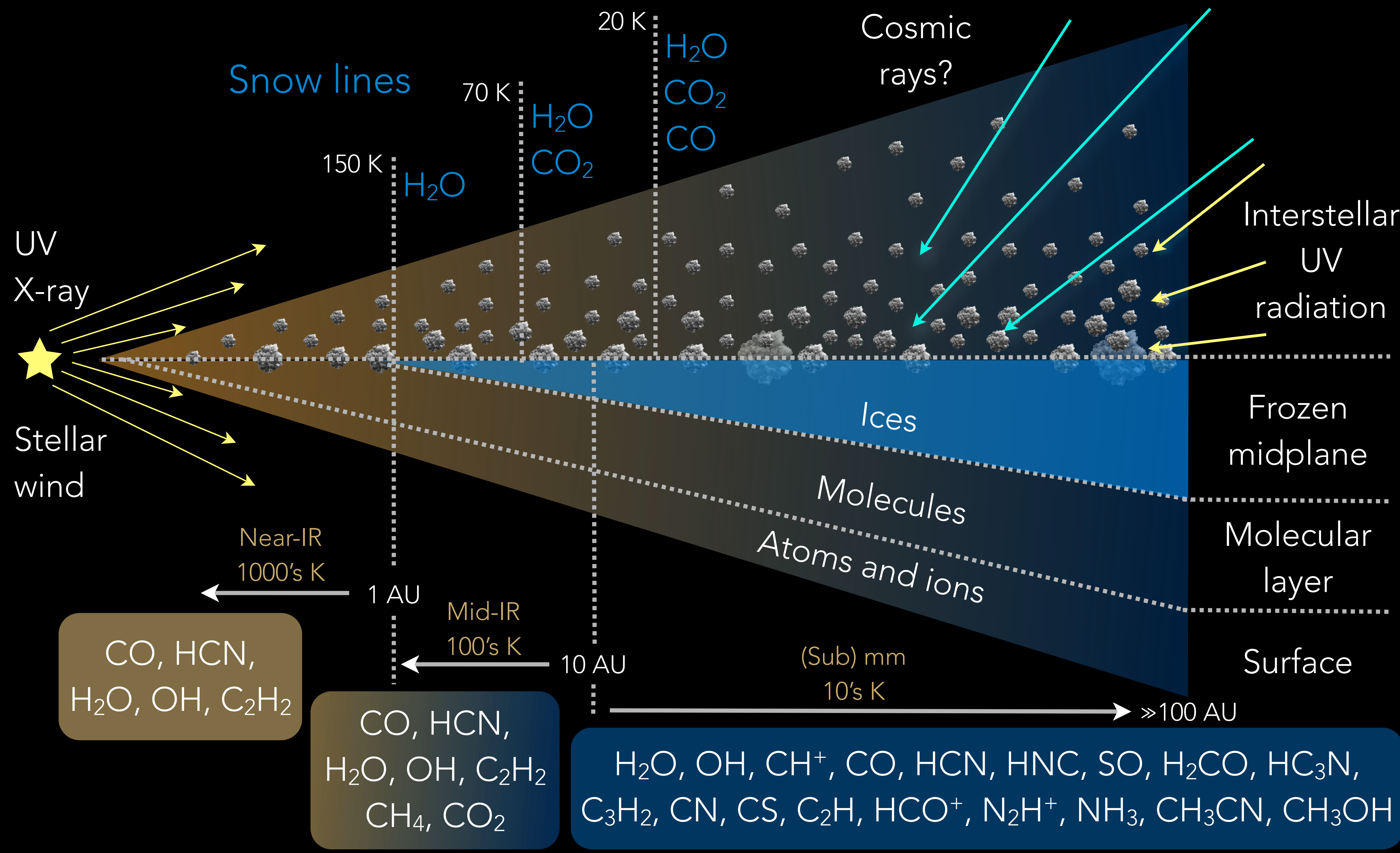




COMPOSITION

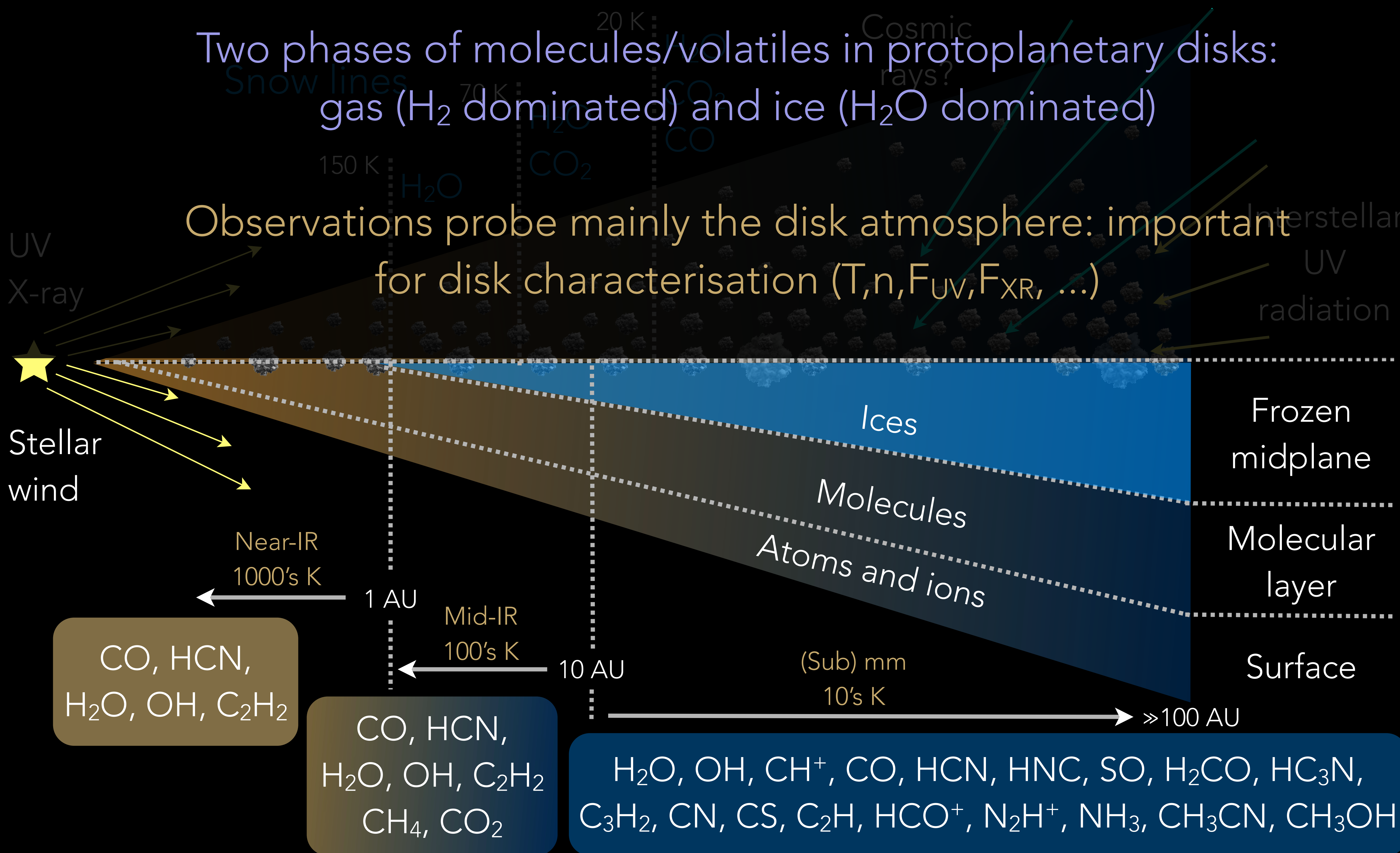


Pontoppidan+, Gibb+, Salyk+, van Dishoeck+, Dutrey+, Chapillon+, Qi+, Oberg+, Kastner+, Thi+, Carr+, Najita+, Hogerheijde+, Fedele+, Meeus+

COMPOSITION

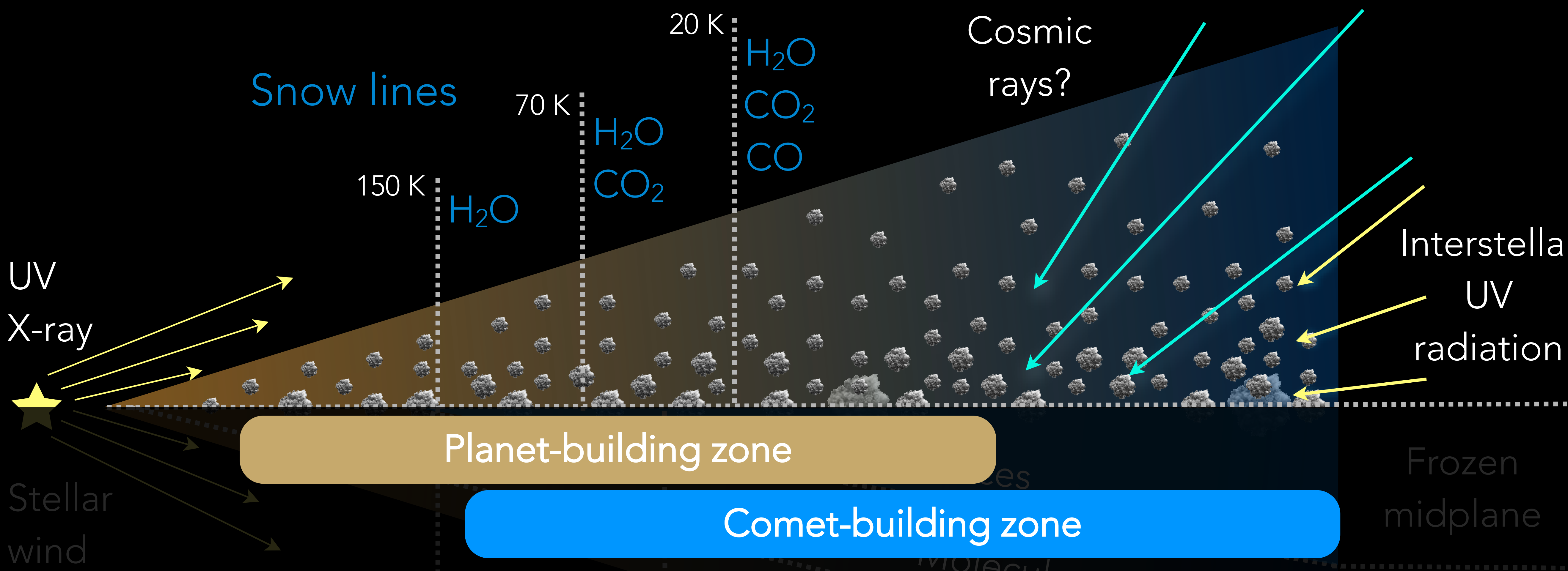
Two phases of molecules/volatiles in protoplanetary disks: gas (H_2 dominated) and ice (H_2O dominated)

Observations probe mainly the disk atmosphere: important for disk characterisation (T, n, F_{UV}, F_{XR}, ...)



Pontoppidan+, Gibb+, Salyk+, van Dishoeck+, Dutrey+, Chapillon+, Qi+, Oberg+, Kastner+, Thi+, Carr+, Najita+, Hogerheijde+, Fedele+, Meeus+

COMPOSITION

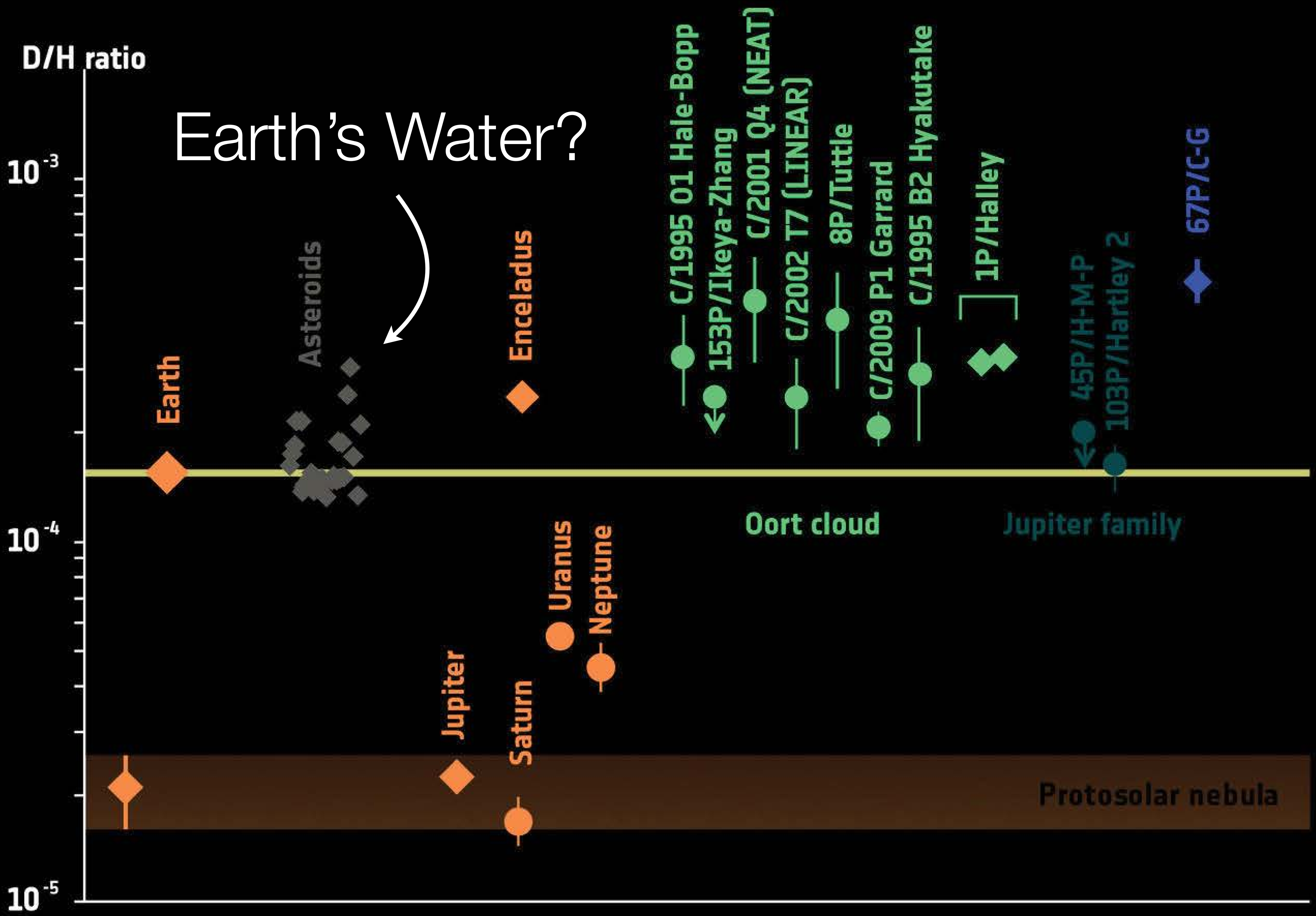


Disk midplane composition will determine the ingredients for planetesimals and comets

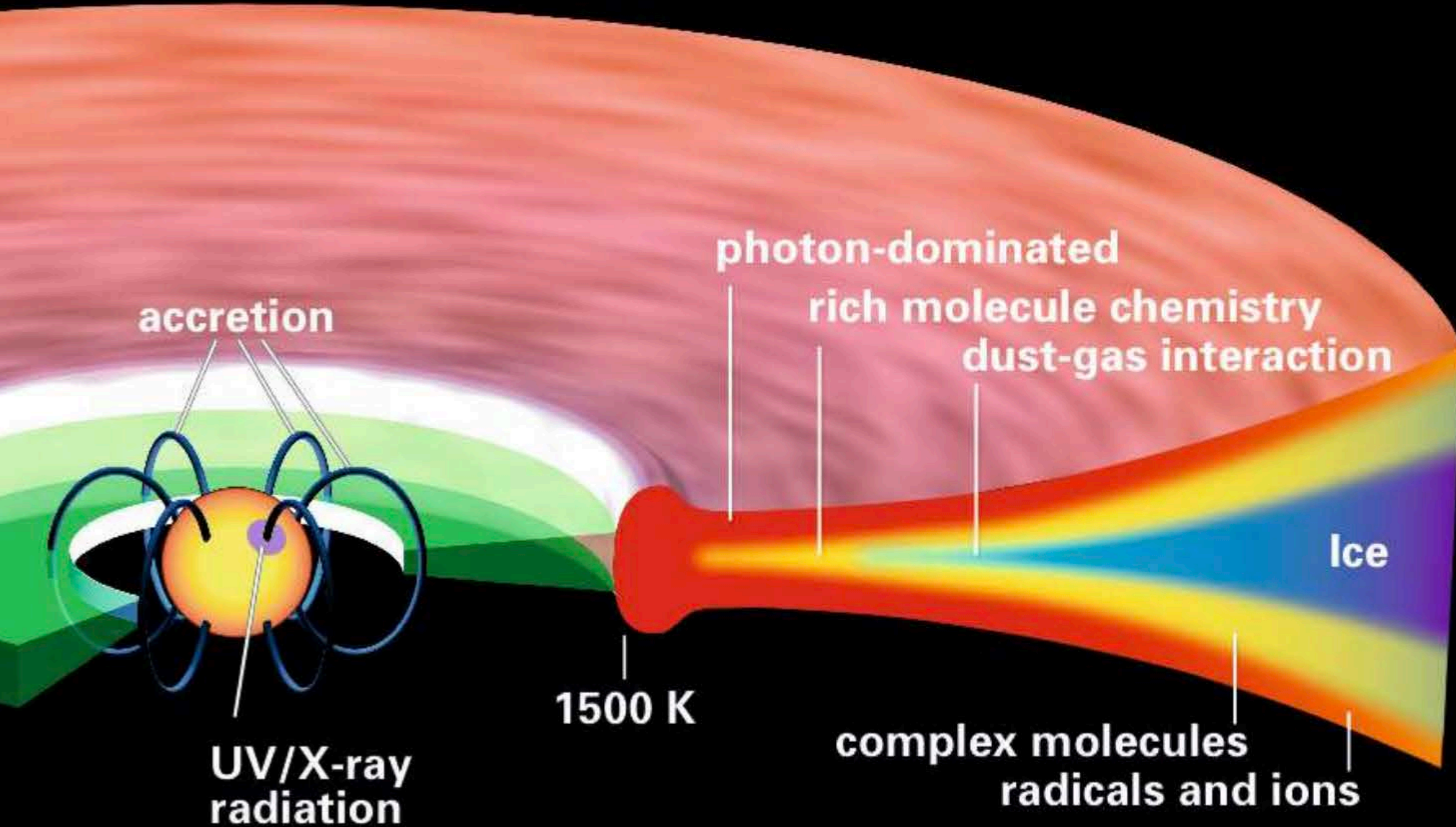
The relative ratios of dominant volatiles will dictate the resulting compositions of planetary atmospheres

Pontoppidan+, Gibb+, Salyk+, van Dishoeck+, Dutrey+, Chapillon+, Qi+, Oberg+, Kastner+, Thi+, Carr+, Najita+, Hogerheijde+, Fedele+, Meeus+

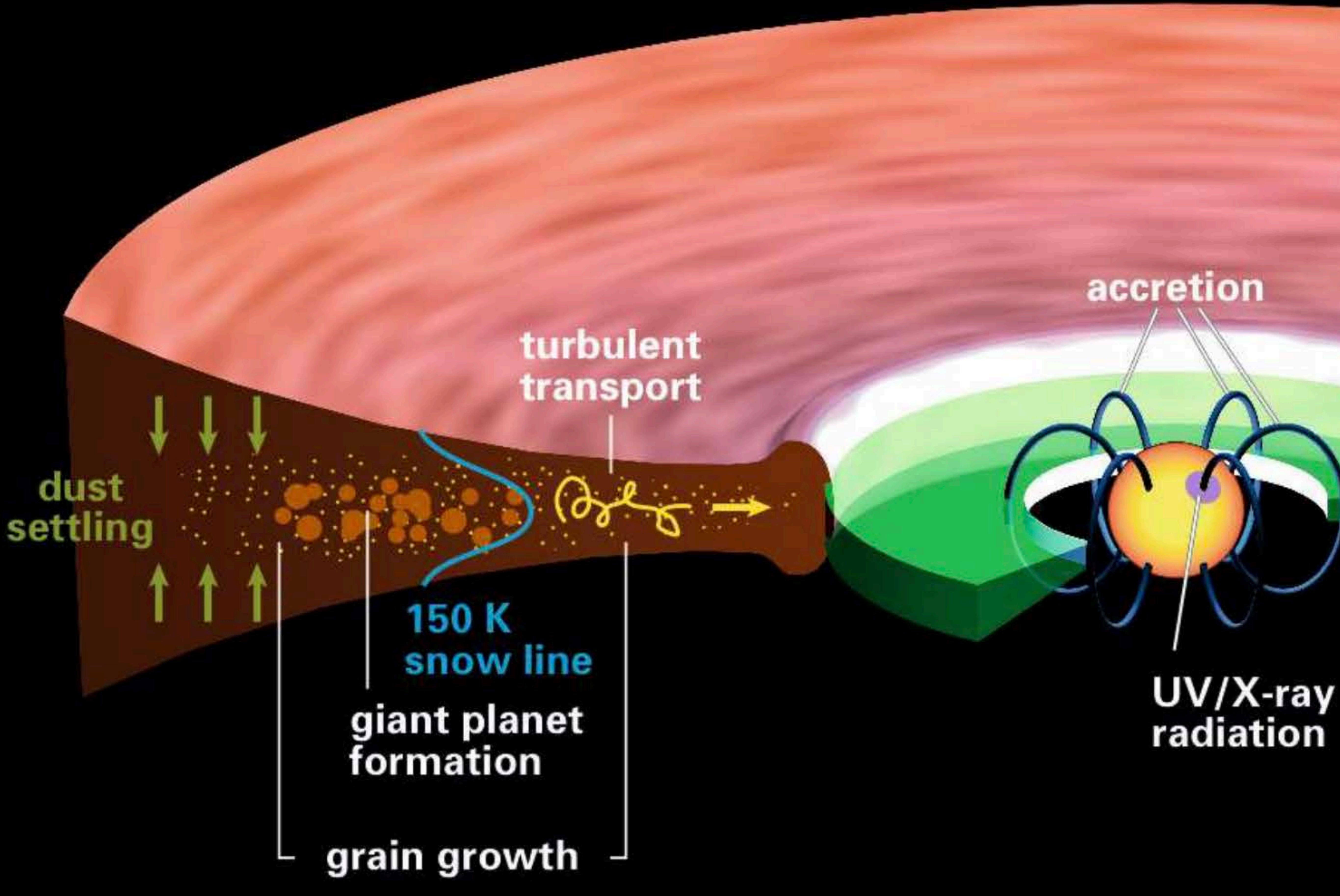
COMPOSITION



STRUCTURE AND COMPOSITION



EVOLUTION AND LIFETIME



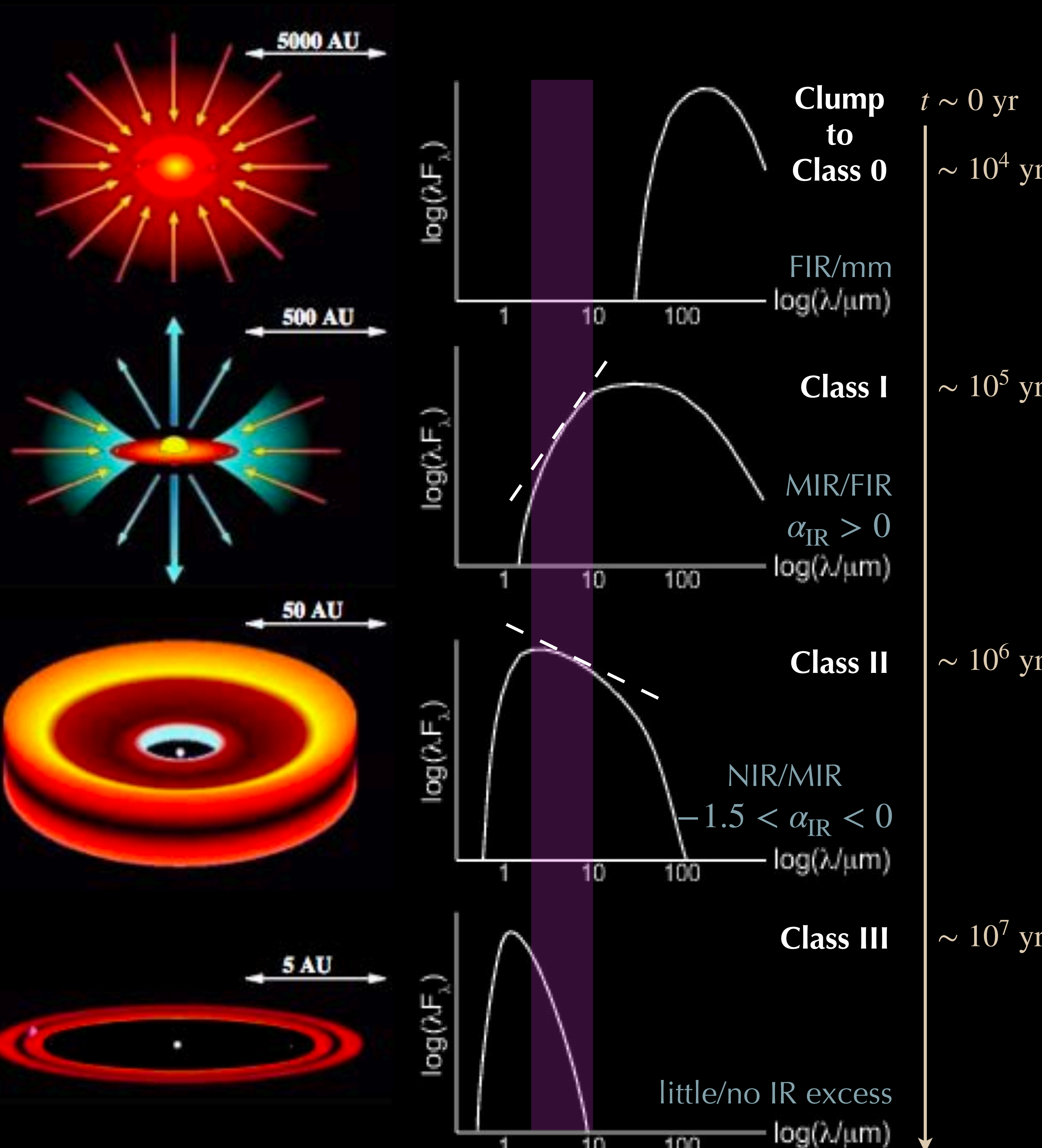
FROM UNIVERSE

TO PLANETS

LECTURE 2.3: DISC EVOLUTION/LIFETIME

STAGES OF EVOLUTION

- Class 0 sources are the youngest stage, here the protostar rapidly accretes the bulk of its mass (main accretion phase) and is surrounded by a massive envelope and a disc.
- Class I sources are slowly accreting the rest of the final stellar mass (late accretion phase). The young stellar object (YSO) is still surrounded by a remnant envelope and massive disc.
- Class II sources no longer have an envelope, but still have an accretion disc producing the observed excess infrared emission. Most T Tauri stars (classical & some weak-line) belong to this class.
- At the Class III stage finally, the star is basically free from circumstellar material, evolving towards the main sequence. Most weak-line, but no classical T Tauri stars.



- Gravitationally bound core
- No central object
- Cold sub-mm dust emission

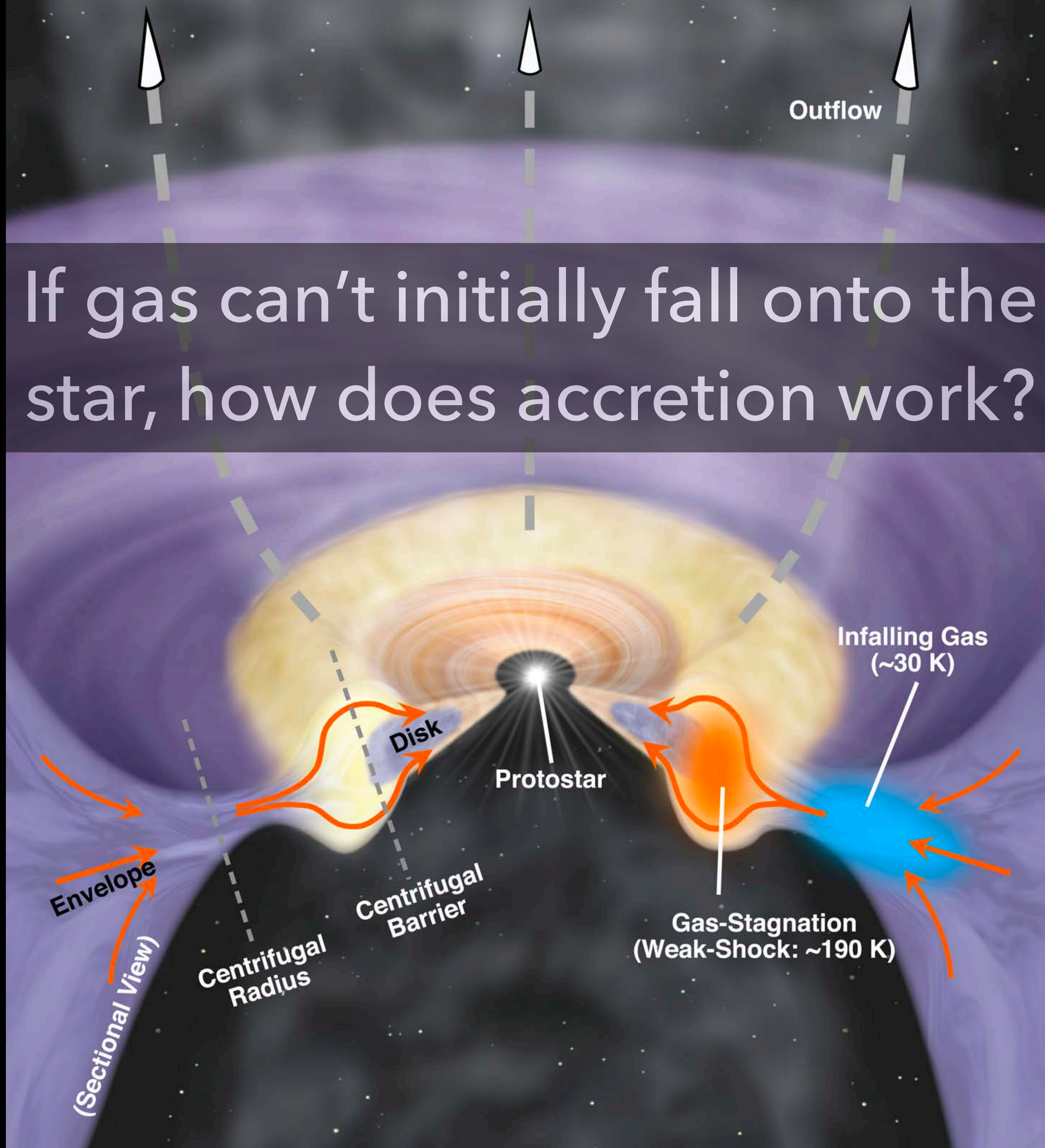
- Formation of central object
- Slightly hotter sub-mm emission (due to heating from grav collapse)

- Majority of mass in central object
- Central emission moves to shorter wavelengths
- Infrared excess due to disc

- Star-disc system fully exposed
- Pre-MS star approaching MS
- Hotter disc emission

- Smaller disc (due to accretion and evaporation) with smaller infrared excess emission
- Star reaches/reaching MS

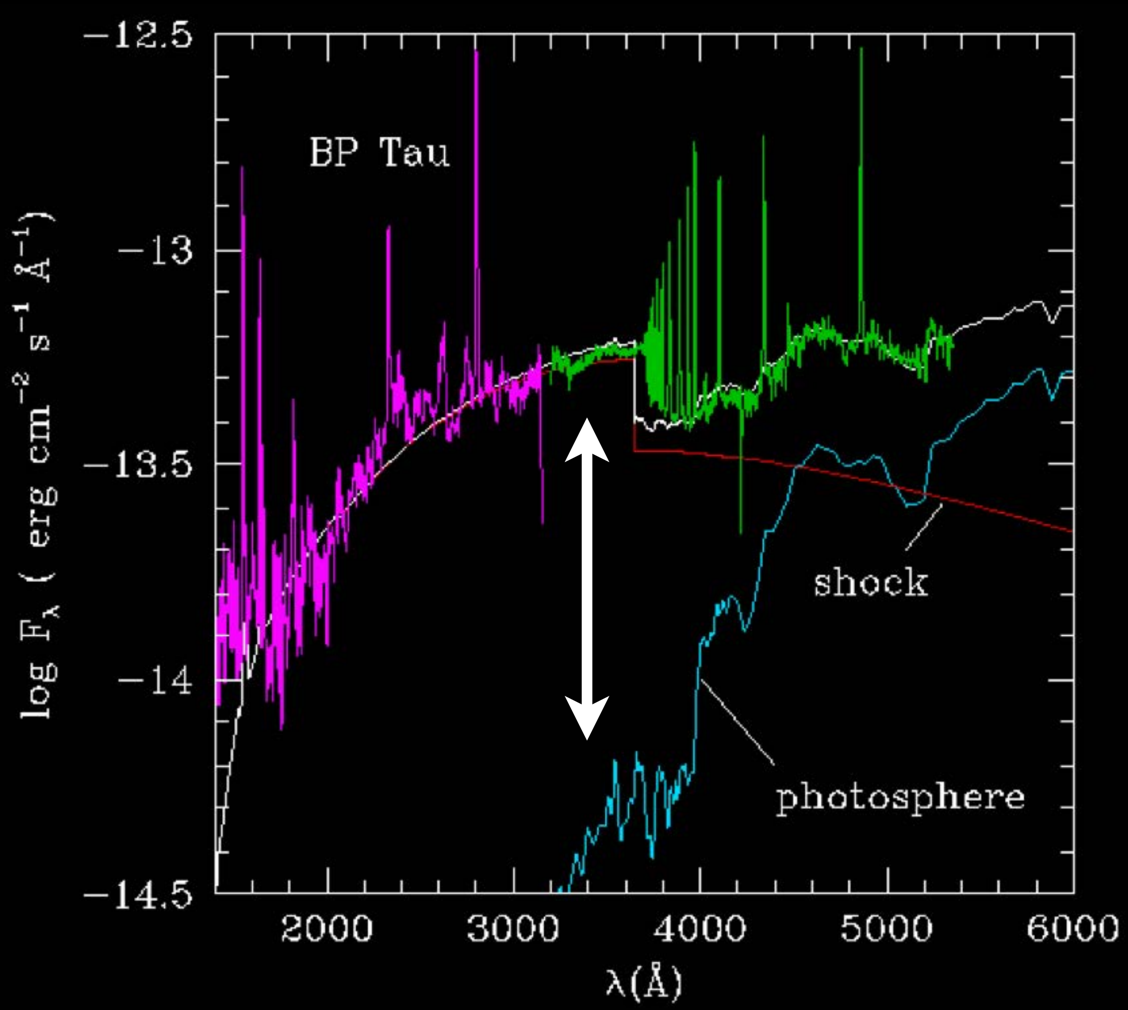
If gas can't initially fall onto the star, how does accretion work?

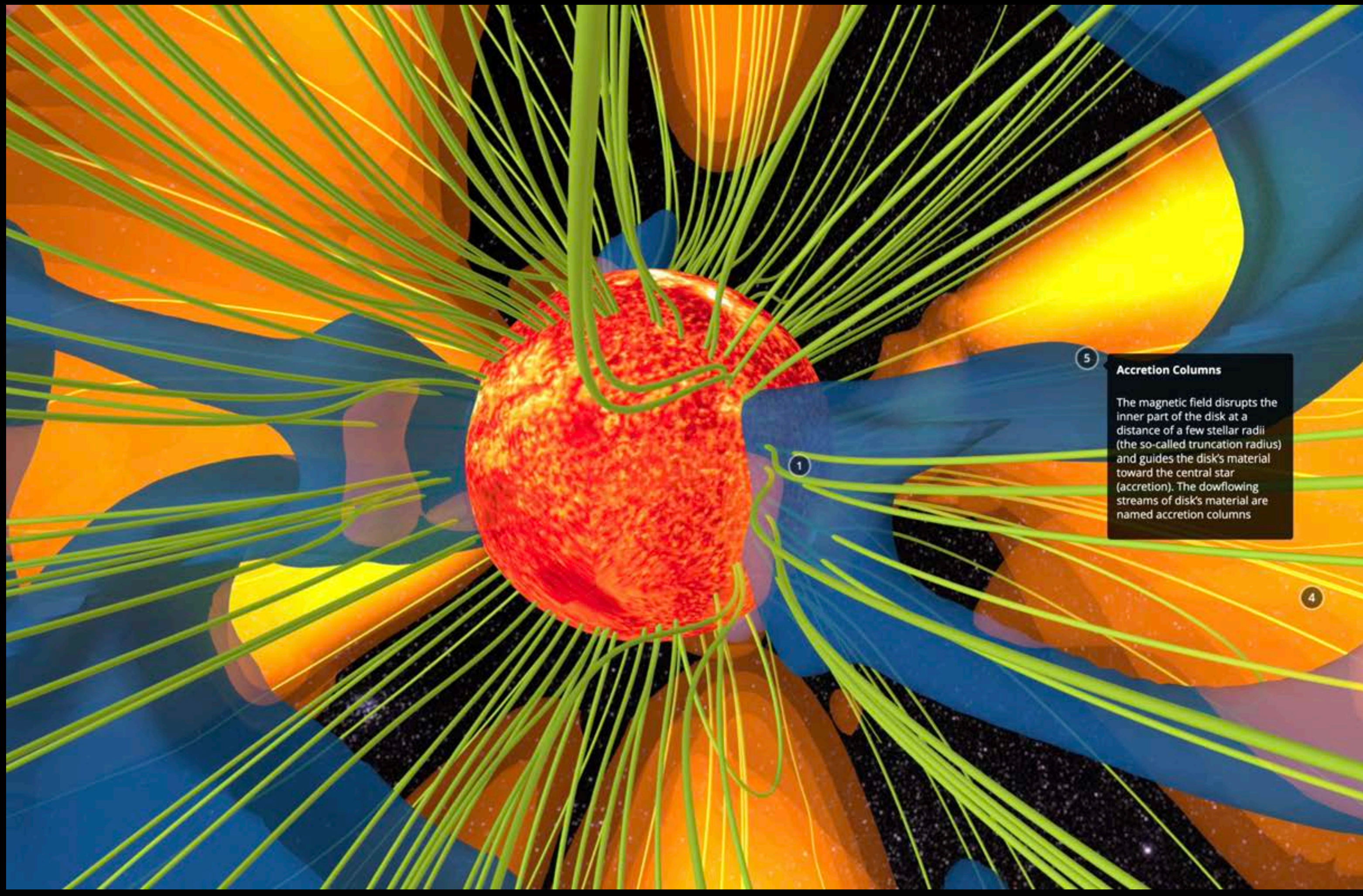


ACCRETION SIGNATURES

ACCRETION SIGNATURES

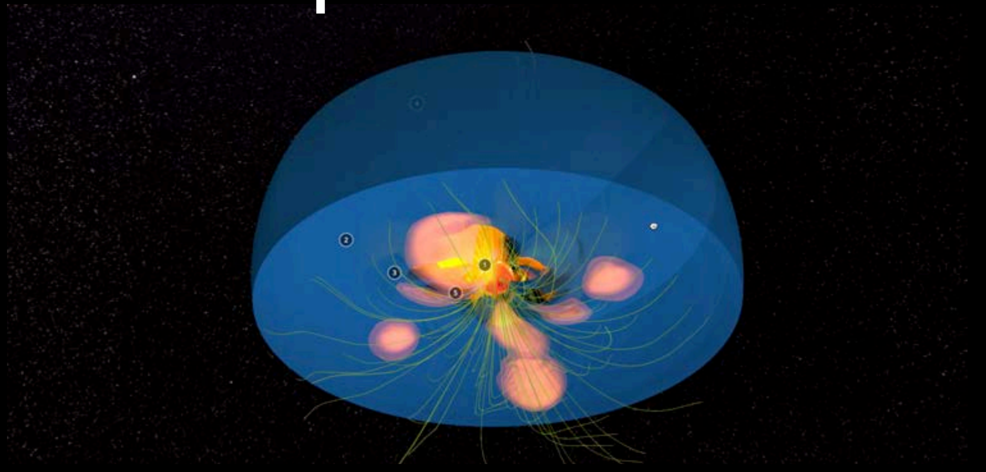
- Excess emission (veiling) over photosphere is strong evidence for accretion: $L_{\rm acc} = GM\dot{M}/R$
- Class II (T Tauri) stars have excess continuum emission arising from the accretion shock on the star, and emission lines from both the magnetosphere and the shock region.

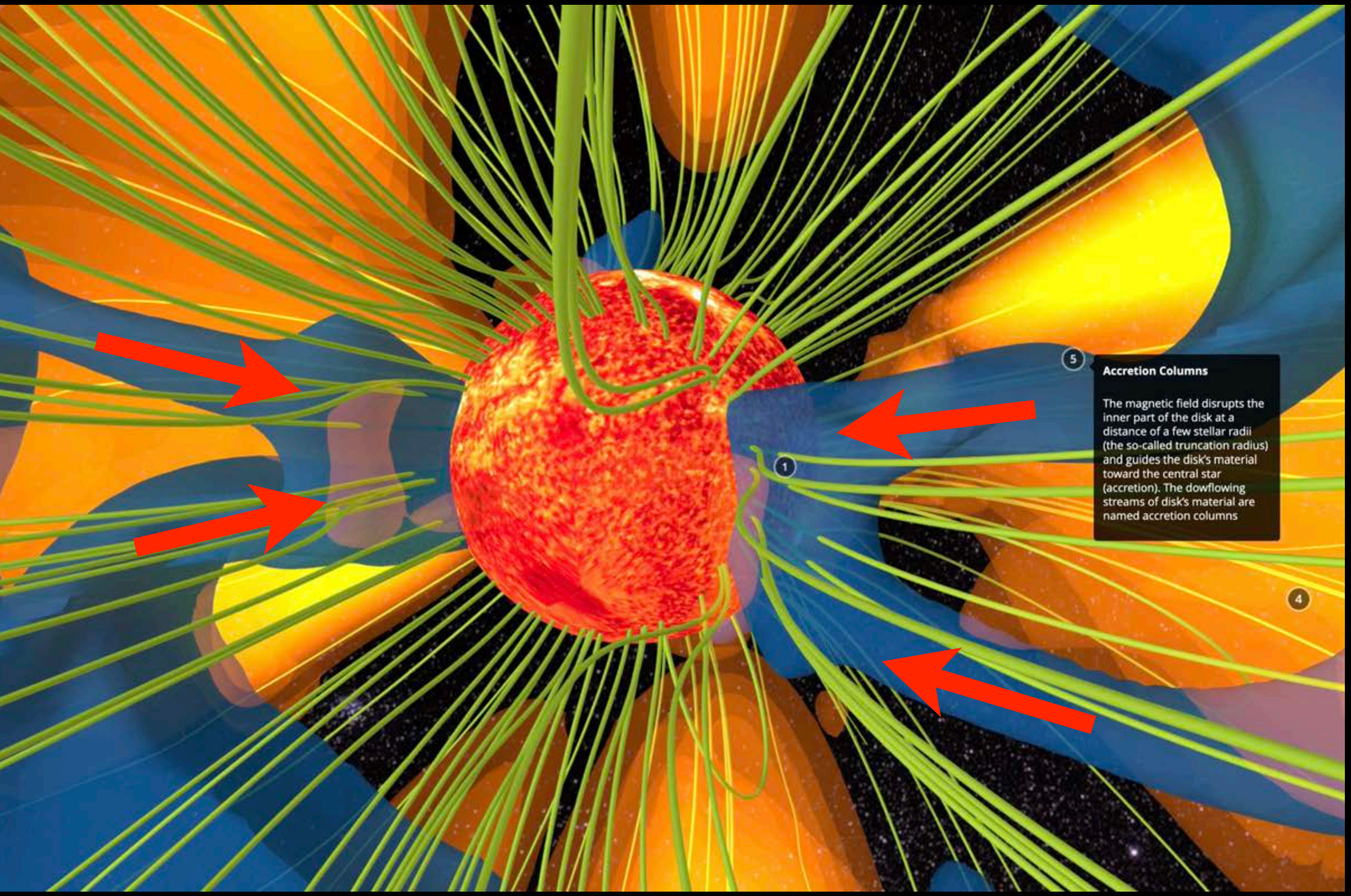


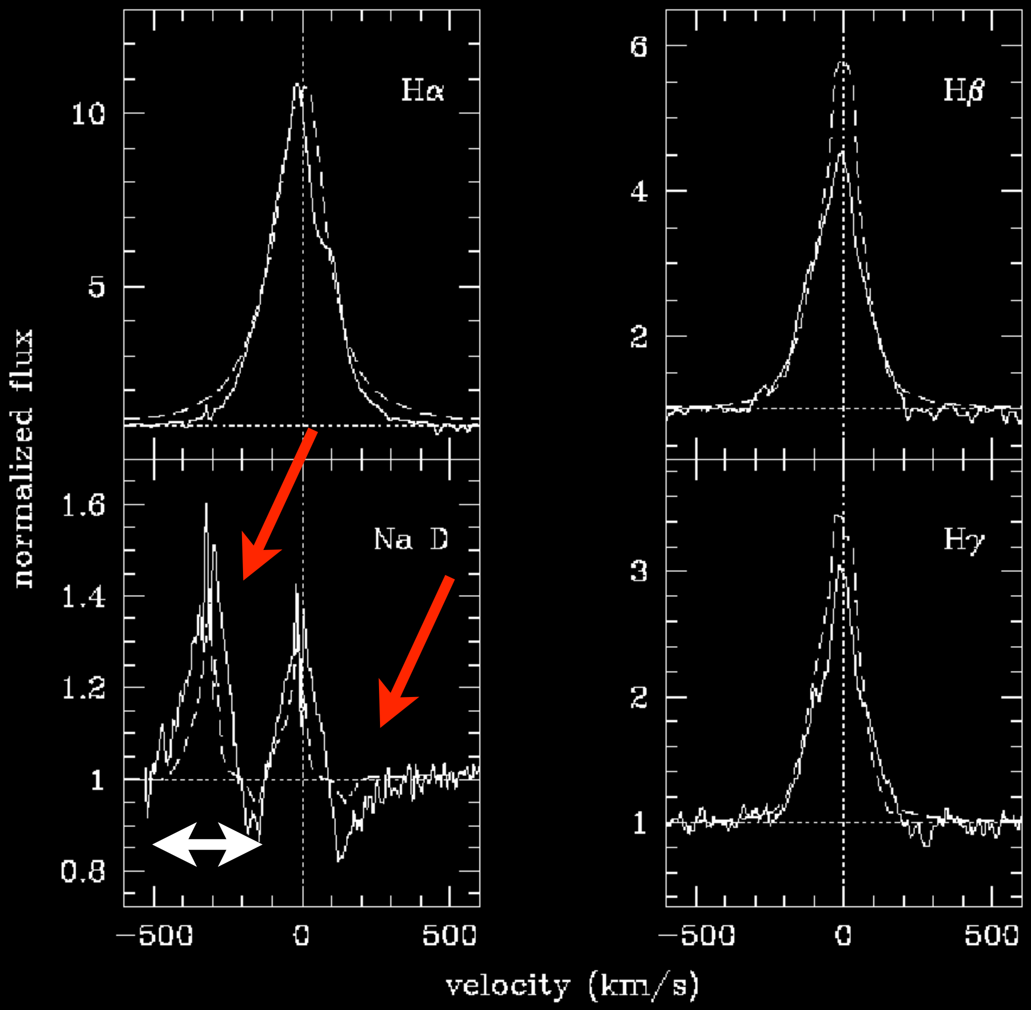


ACCRETION SIGNATURES

- Broad Emission lines ($\Delta v \sim 250$ km/s) from fast moving accretion flows show up as redshifted absorption
- Can only be seen at certain disc inclinations.







ANGULAR MOMENTUM

- Accretion requires angular momentum to be lost or redistributed in the disc.
- Specific angular momentum is approximately that of a Keplerian orbit: $l = \mathbf{R} \times \mathbf{v}_{\mathrm{K}} = R^2\Omega_{\mathrm{K}} = \sqrt{GM_*R}$.
    - Increasing function of radius.
- Two possibilities:
    - Viscous dissipation: predominant theory, but still not clear as to what causes the viscosity (friction).
    - Removed via outflows from the star-disc system.

VISCOUS EVOLUTION

- Within any shearing fluid, momentum is transported in the cross-stream direction because the random motion of molecules leads to collisions between particles that have different velocities.

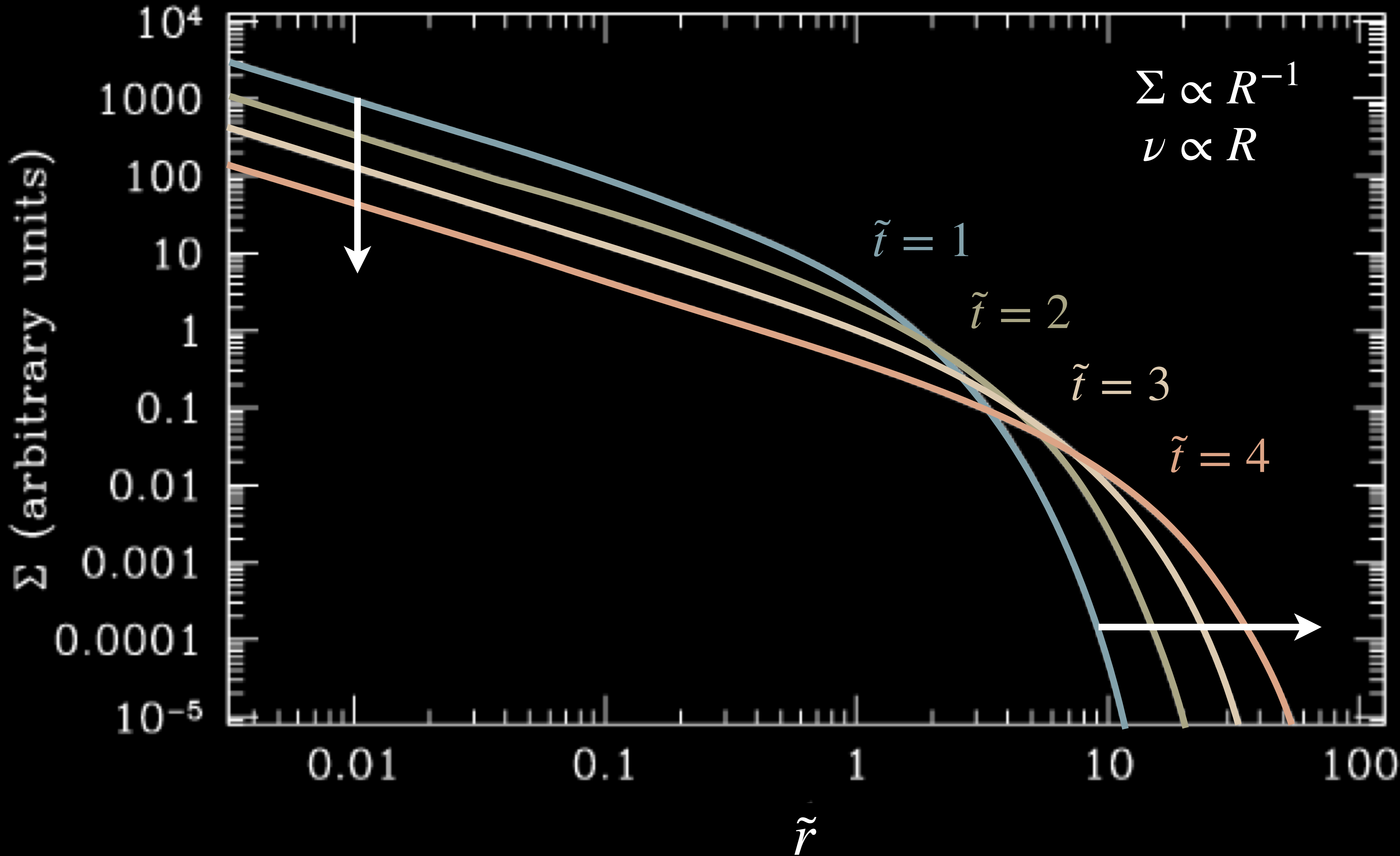
- Assume a vertically thin axisymmetric sheet of viscous fluid to obtain a simple equation for the time evolution of the disk surface density $\Sigma(R, t)$.

- Large caveat: the molecular viscosity of the gas is much too small to lead to any significant dissipation.

    - …but remains approximately valid if the "viscosity" is reinterpreted as the outcome of a turbulent process.

VISCOUS EVOLUTION

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{R}\frac{\partial}{\partial R}\left[\sqrt{R}\frac{\partial}{\partial R}\left(\nu\Sigma\sqrt{R}\right)\right]$$



VISCOUS EVOLUTION

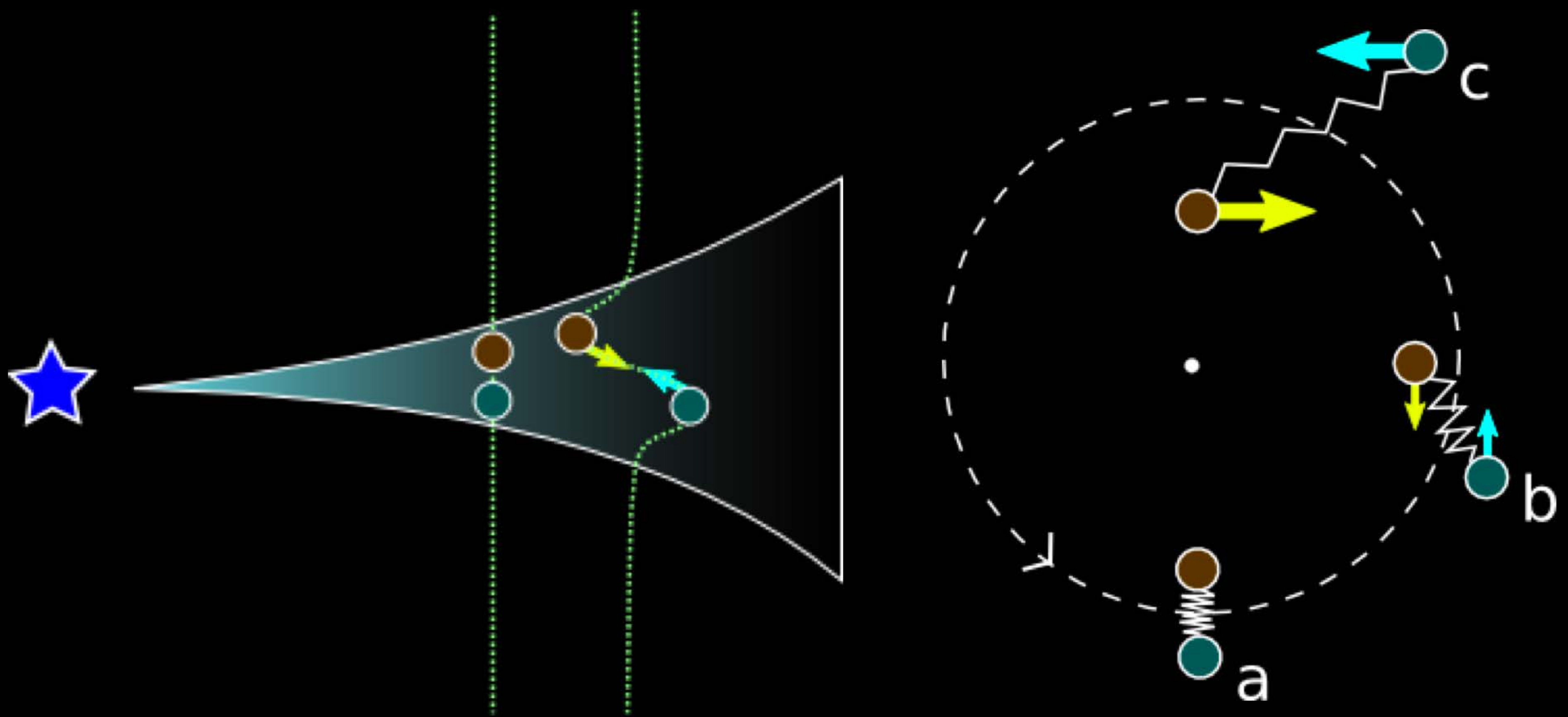
- Molecular viscosity alone yields timescales ~ 10^{13} yrs, longer than the age of the Universe! Instead, we think there is an underlying turbulence that "acts" like an effective viscosity.

- To avoid specifying the source of the turbulence, we often parameterise the viscosity as: $\nu = \alpha c_{\rm s} H$
  - The largest eddy $\lesssim H$
  - Turbulent velocity $\lesssim c_{\rm s}$ (otherwise a shock would form)

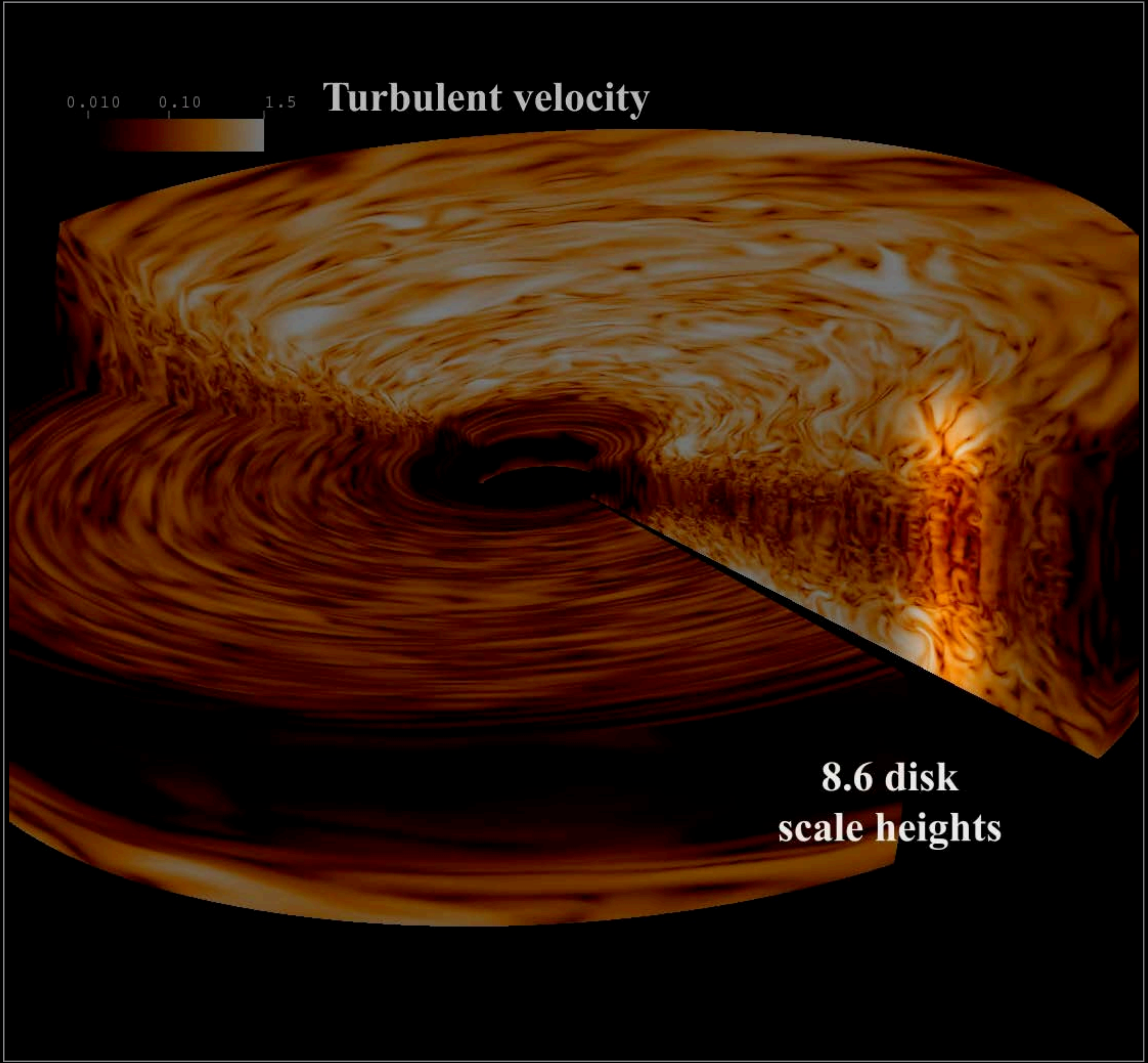
- Describes the leading order scaling expected in disks (so that the dimensionless Shakura-Sunyaev α-parameter varies more slowly with temperature, radius, etc. than ν)

VISCOUS EVOLUTION

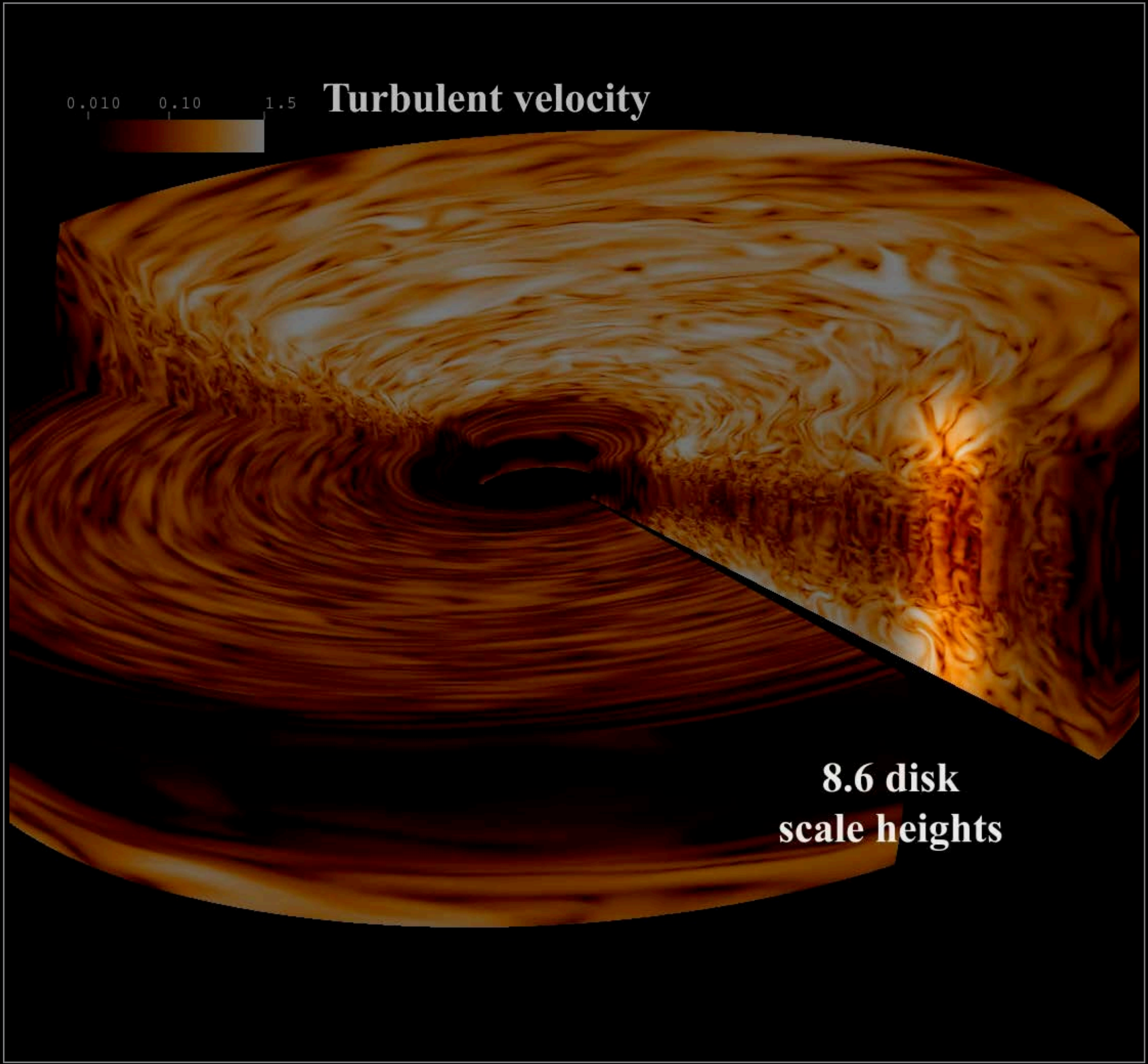
- In ideal MHD, the fluid acts like a perfect conductor and field lines are frozen into the fluid (zero diffusion of magnetic field lines). In this case, even weak magnetic fields will generate a Magnetorotational Instability (MRI).



VISCOUS EVOLUTION



VISCOUS EVOLUTION



$$\beta = \frac{\text{(plasma pressure)}}{\text{magnetic pressure}}$$

$$= \frac{n k_B T}{B^2/2\mu_0}$$

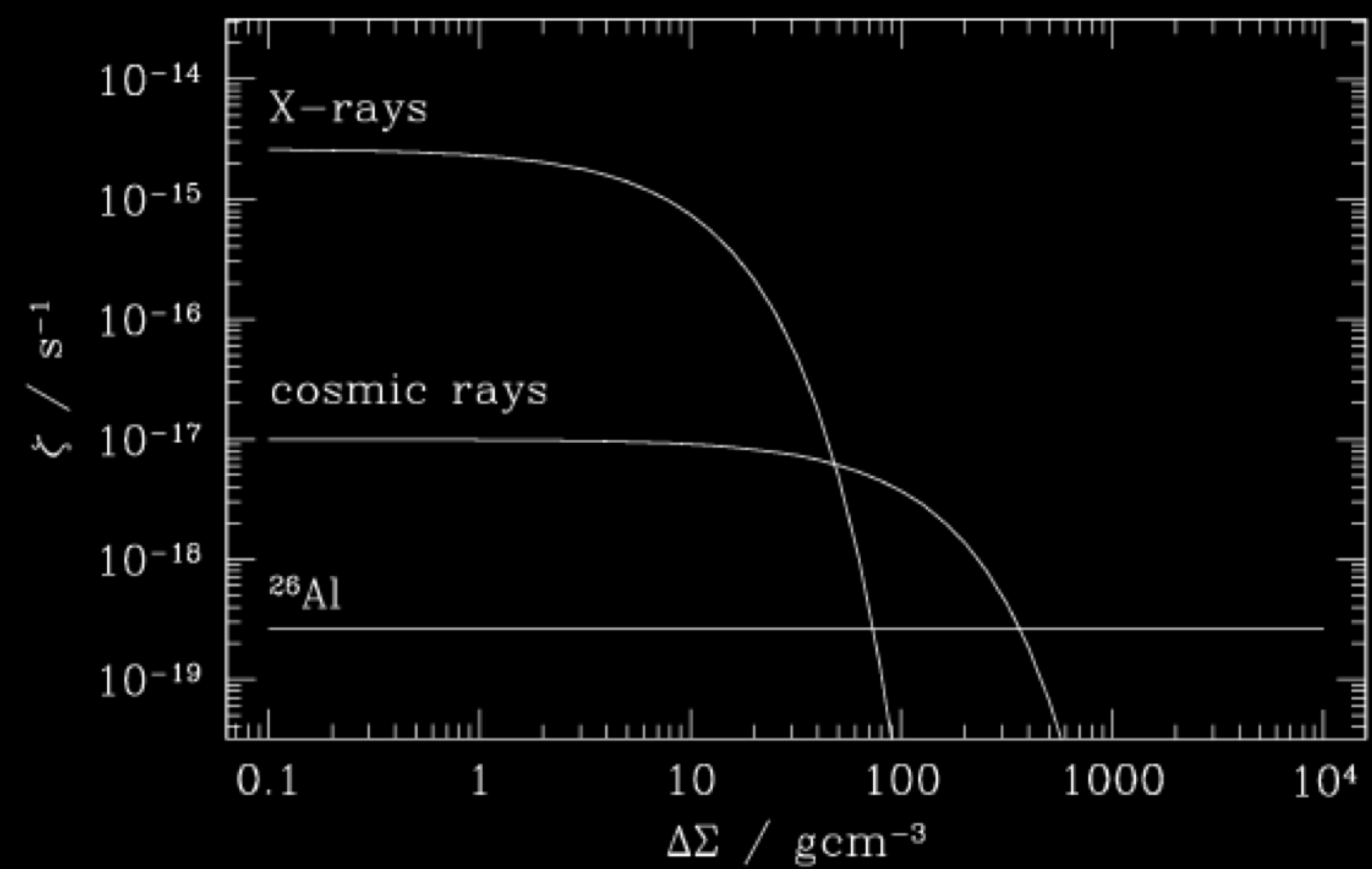
VISCOUS EVOLUTION

- Non-ideal MHD, the disc needs to be sufficiently ionised to overcome the effects of resistivity, which otherwise allows the field lines to diffuse back through the fluid.

- Two processes can ionise the gas in a disc:

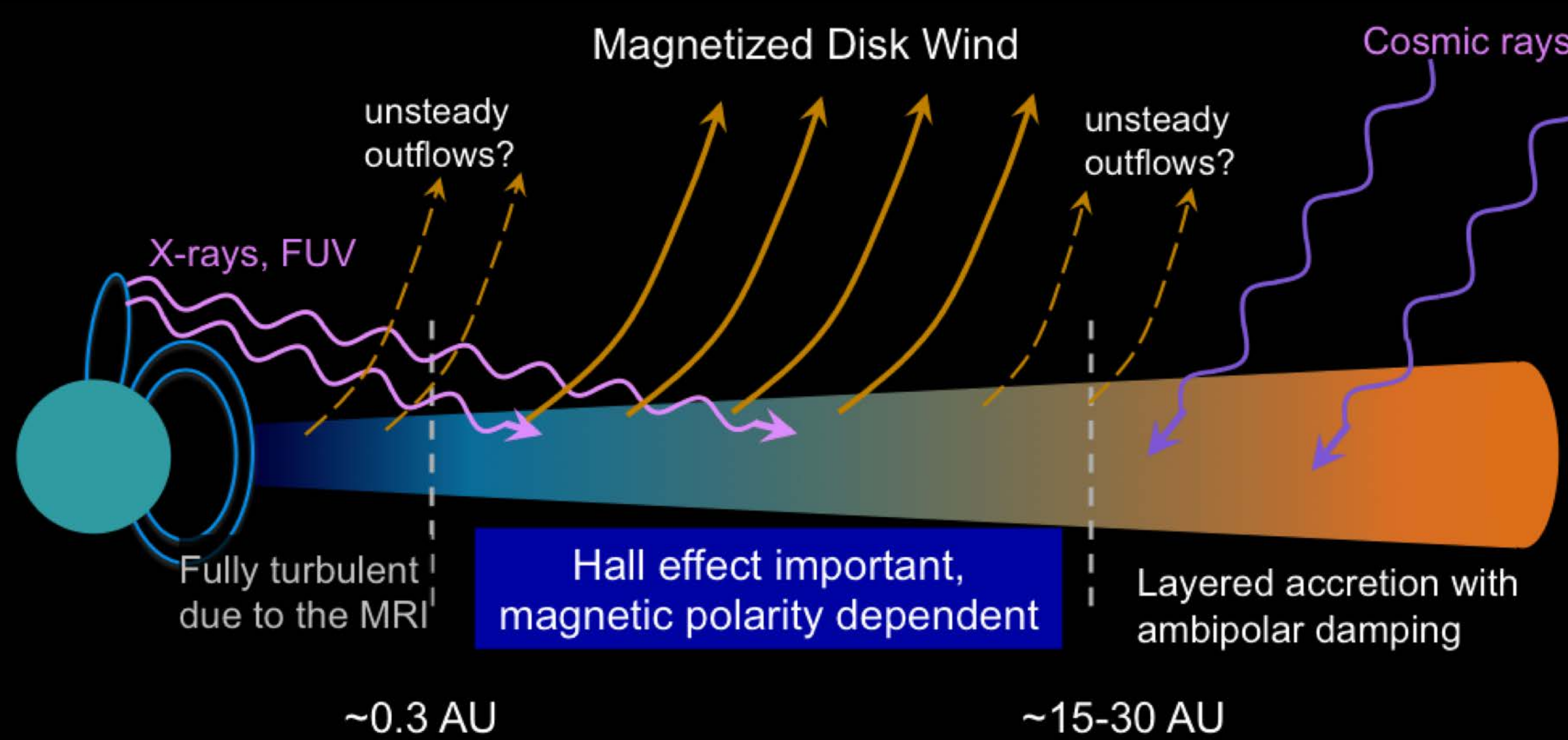
- Thermal (collisional) ionisation: requires $T \gtrsim 1000$ K, only occurs in inner 1 au of disc.

- Non-thermal (photo-) ionisation by UV, X-rays, and/or cosmic rays.

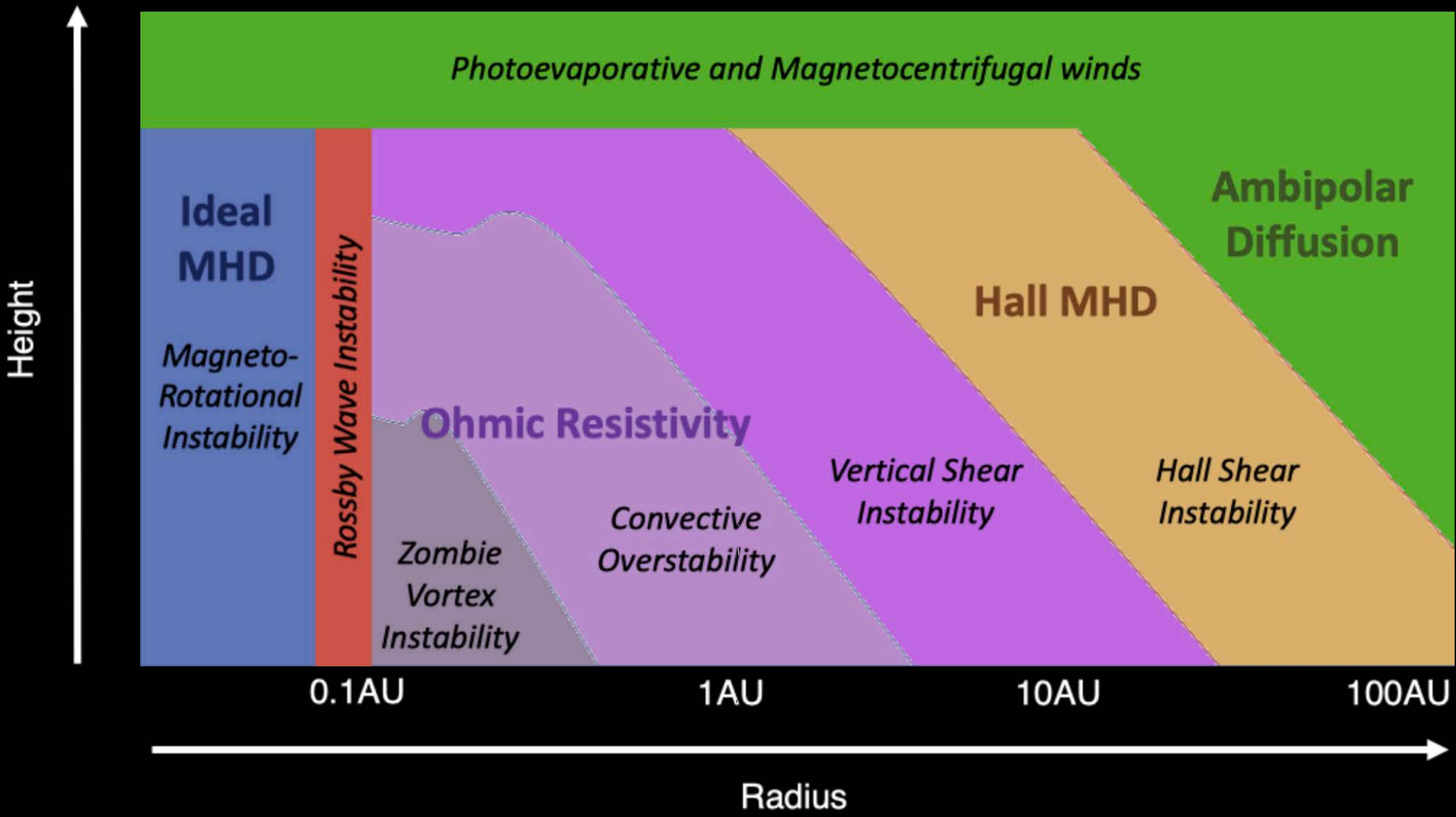


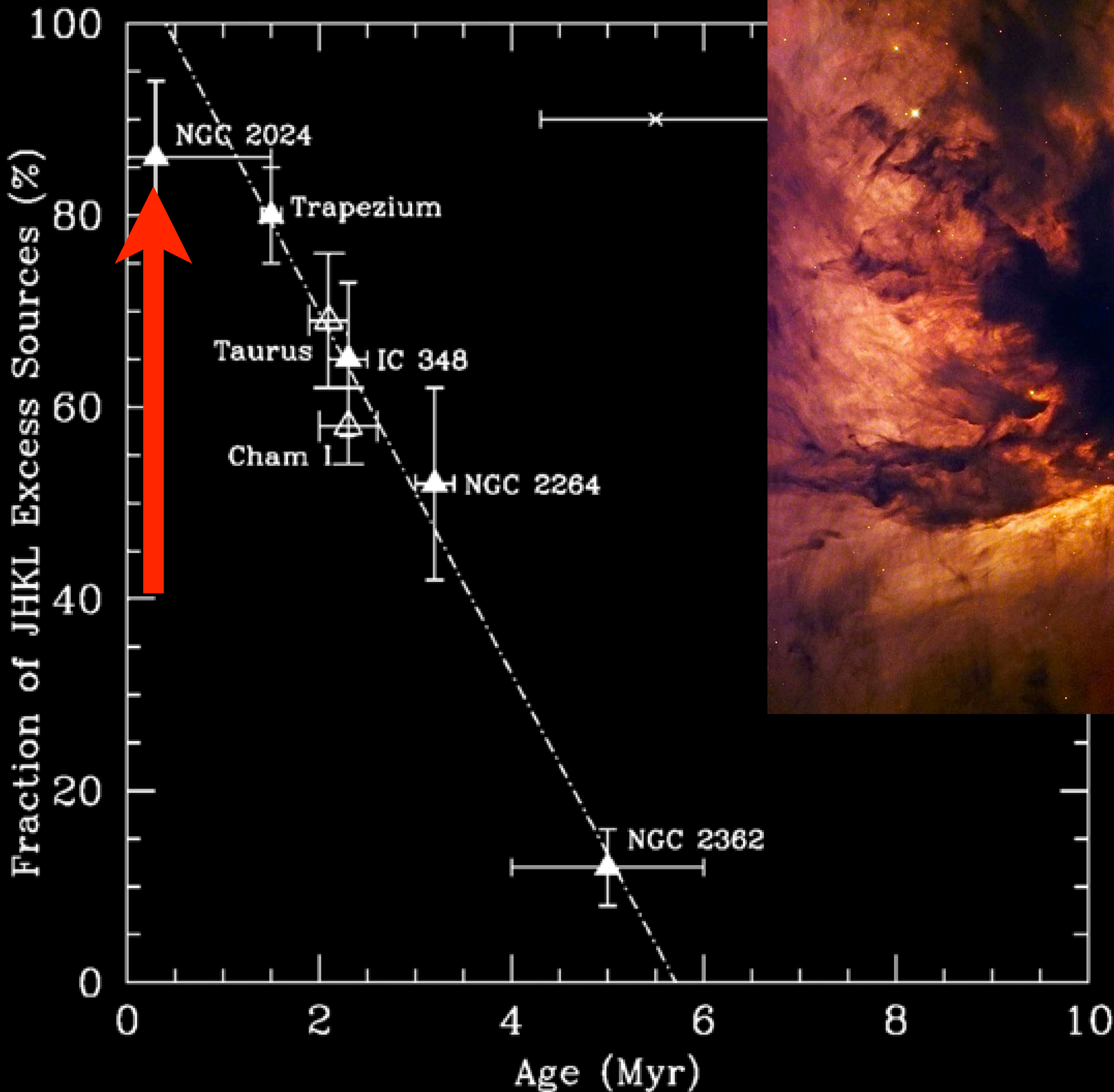
VISCOUS EVOLUTION

- MRI is likely damped between 0.1–10 au (dead zones)
- Important implications for dust dynamics, planetesimal formation, planet migration, and episodic accretion
- Potentially resurrected by hydro instabilities (e.g. zombie vortices)
- Evidence now pointing to influence by magnetised disc winds

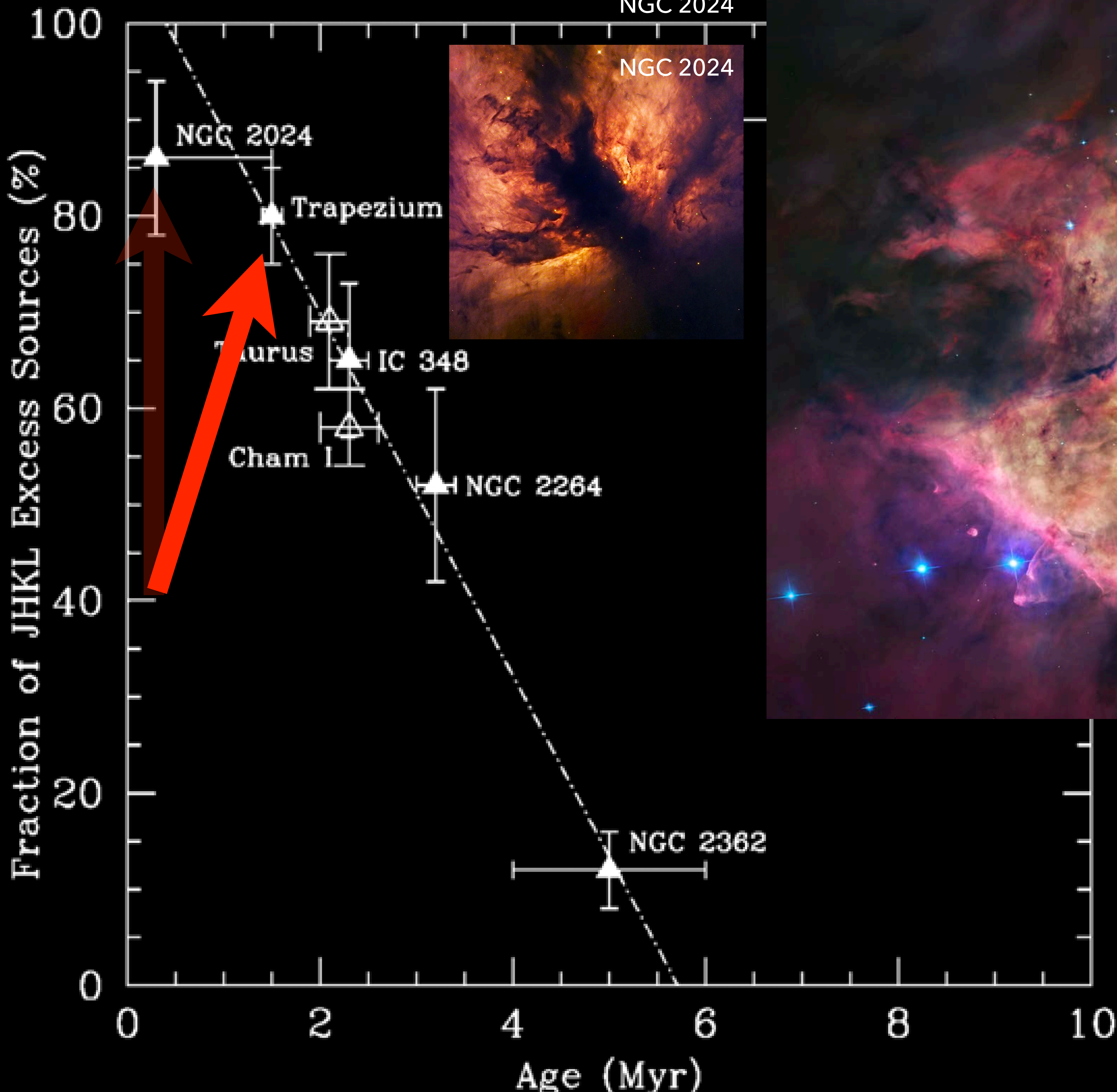


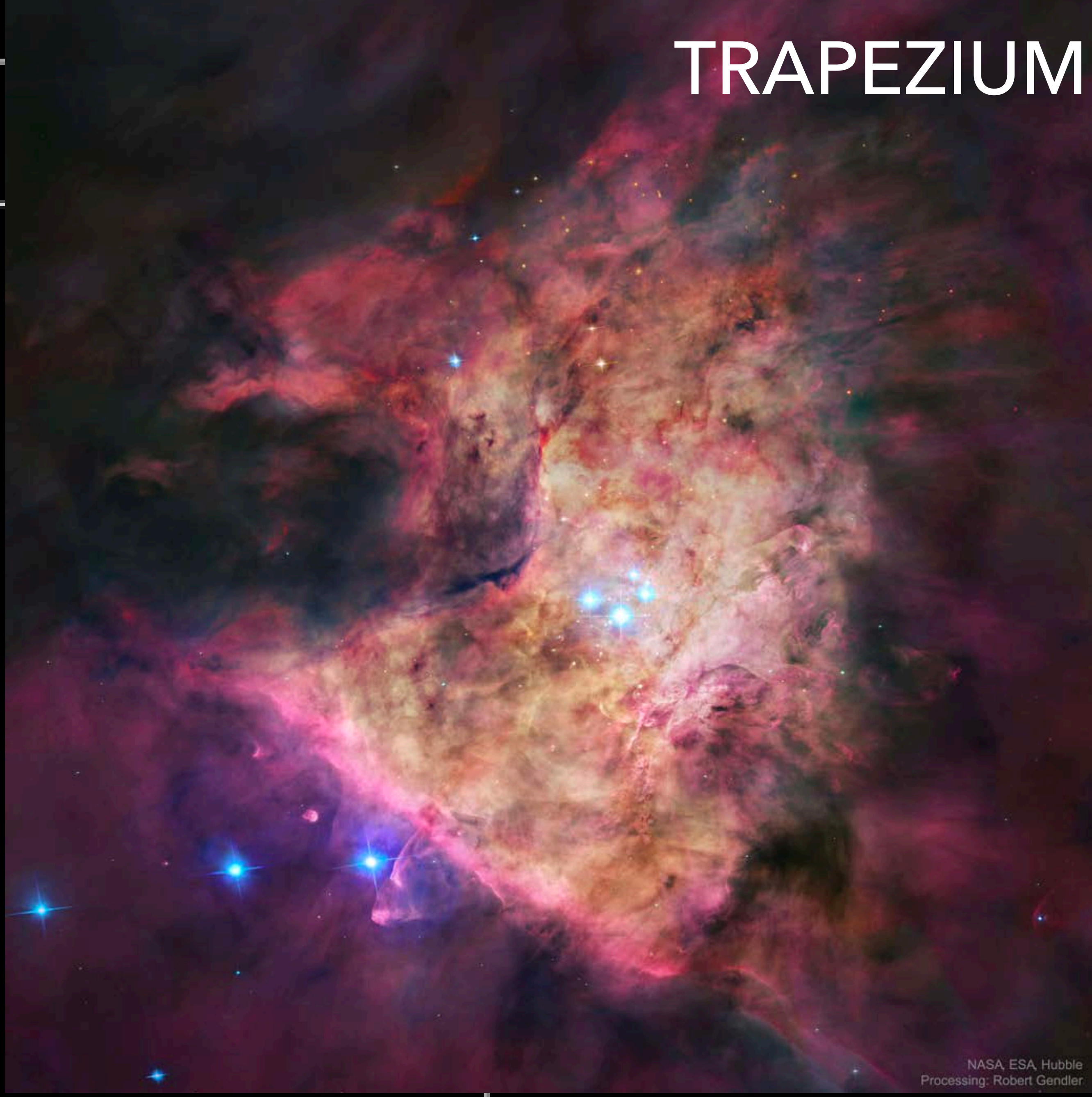
ZOO OF INSTABILITIES



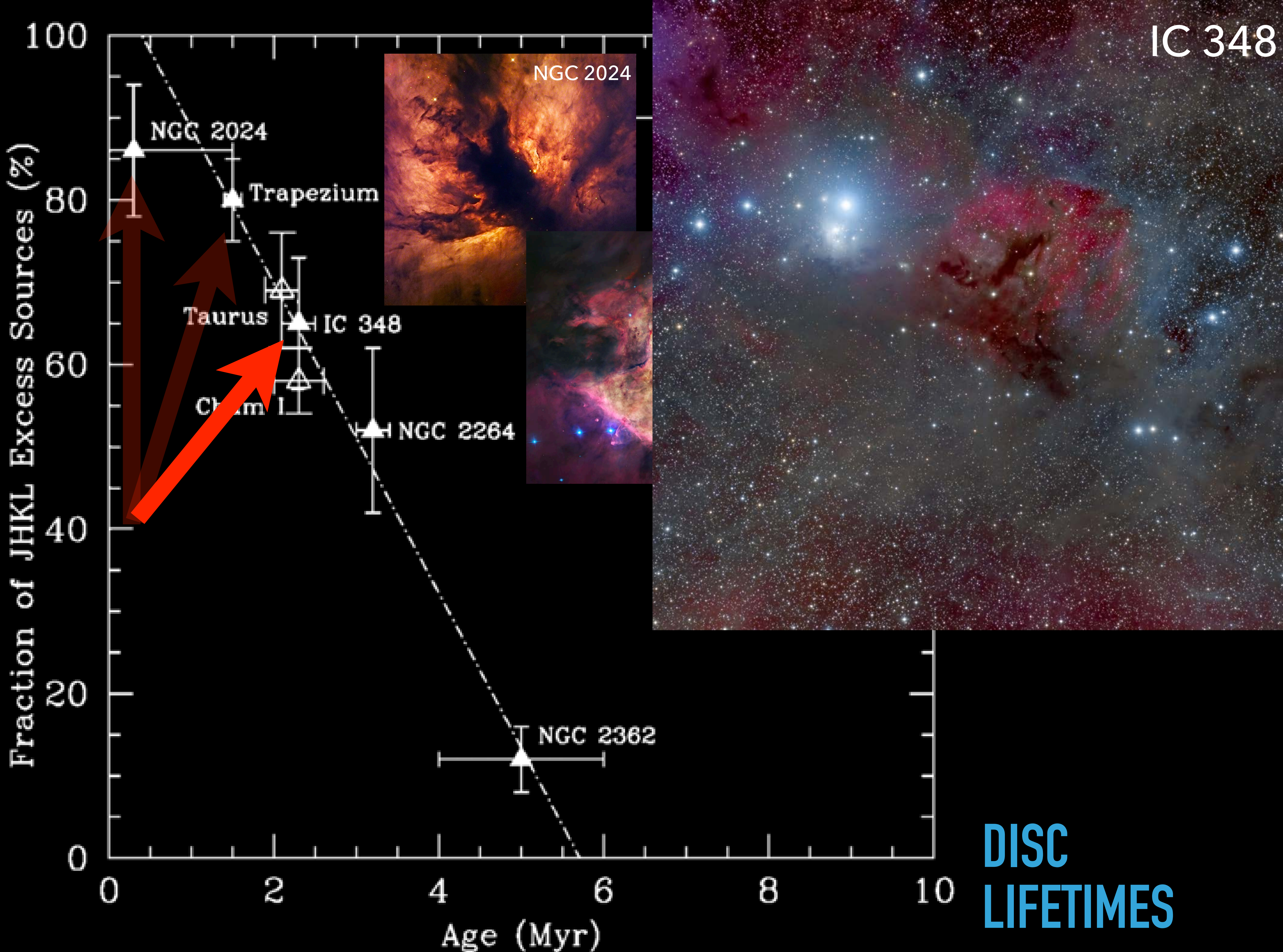


DISC LIFETIMES

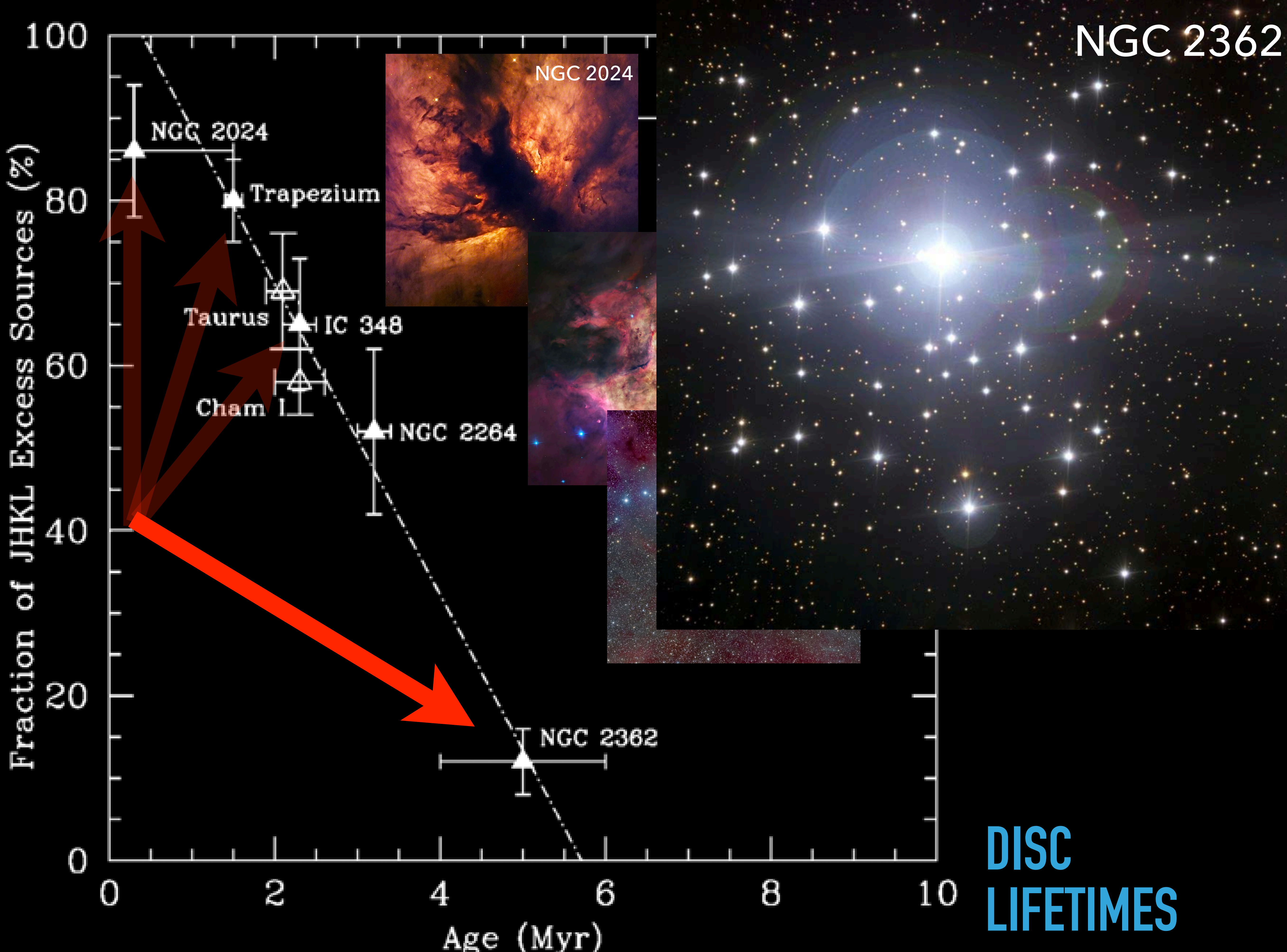




DISC LIFETIMES



DISC LIFETIMES



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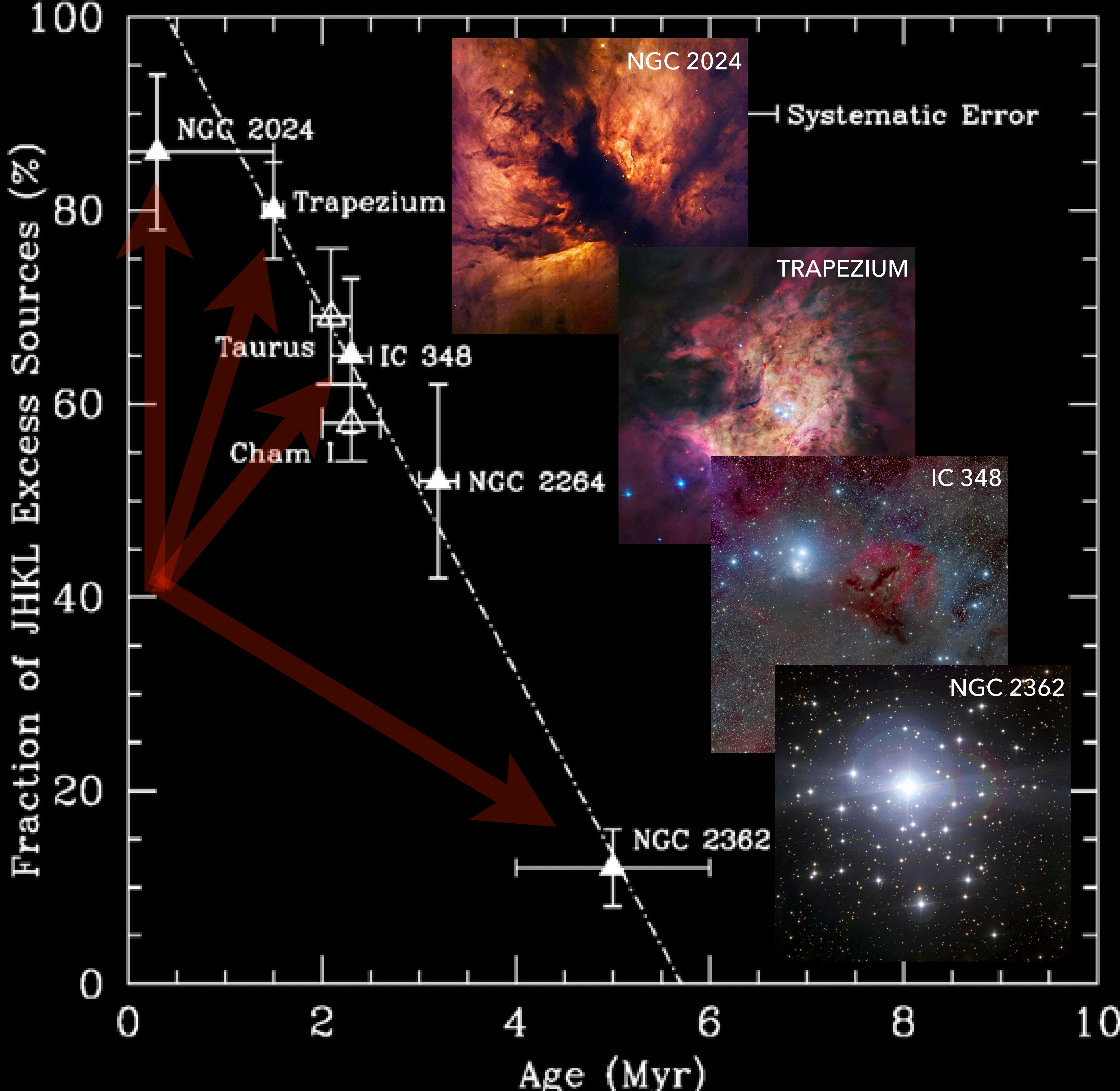

DISC LIFETIMES

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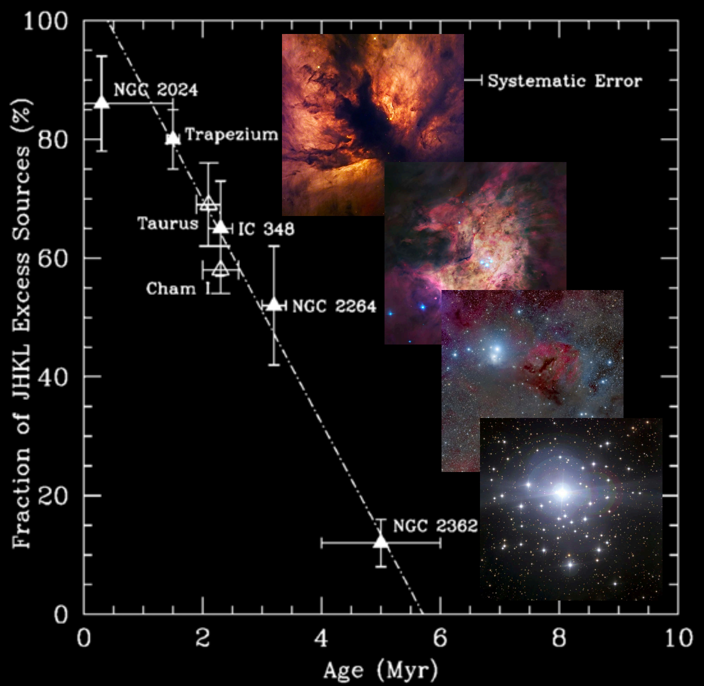
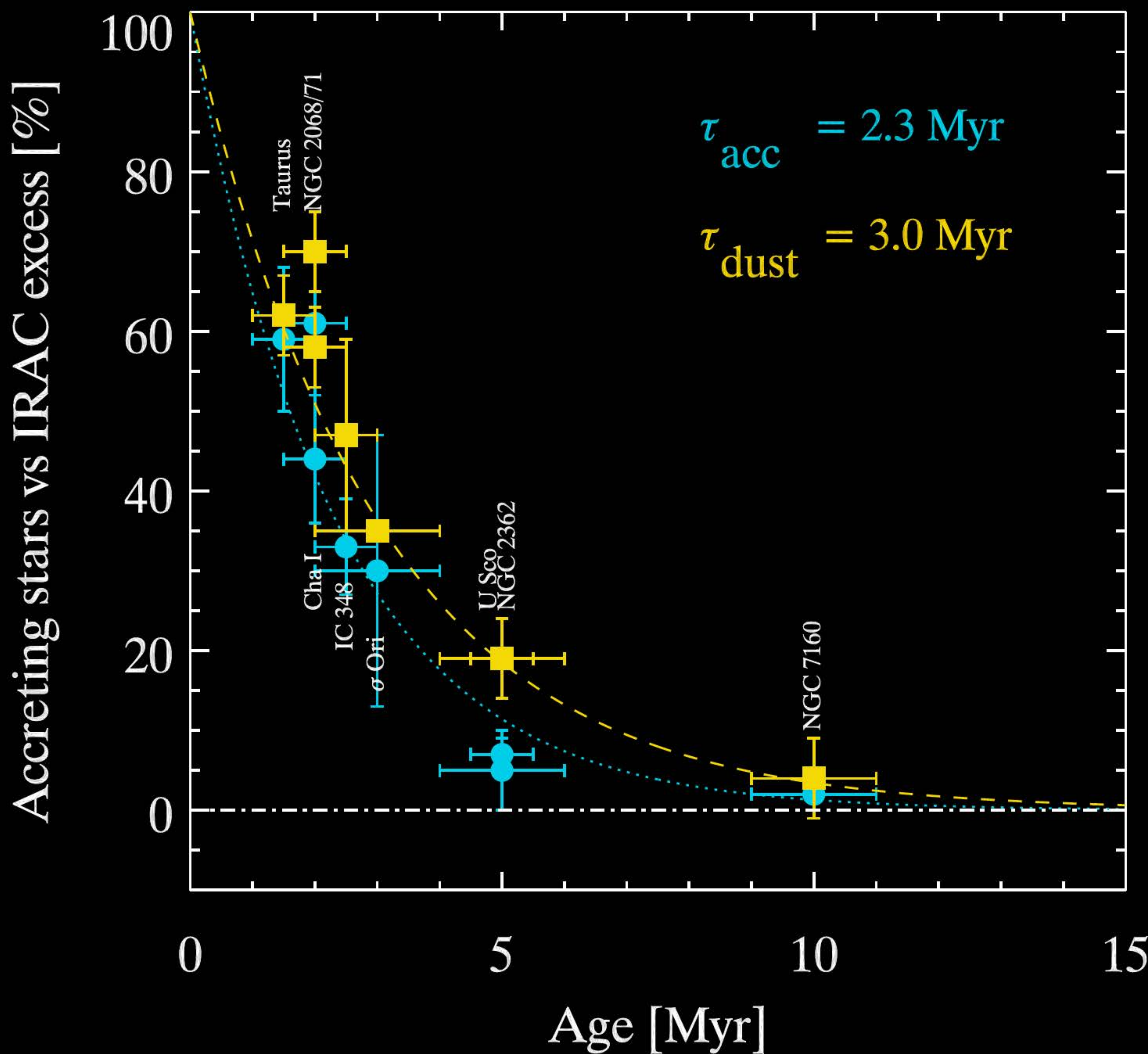
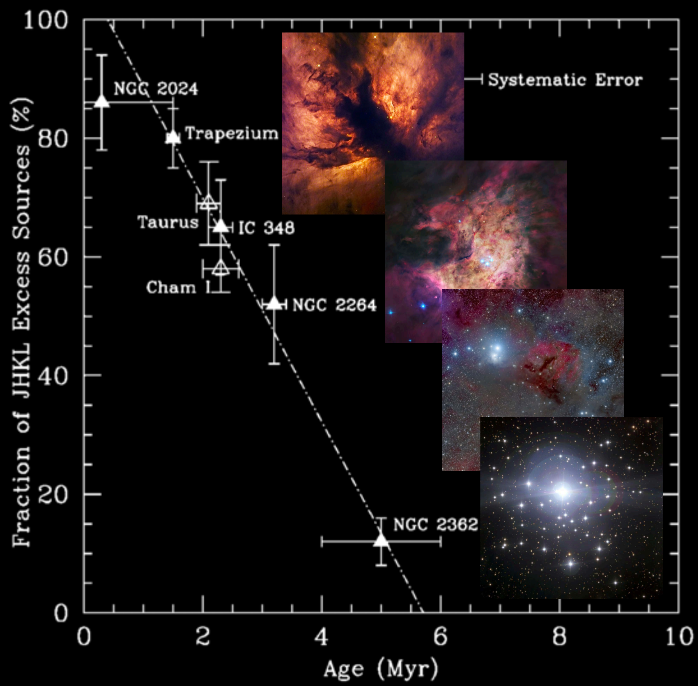
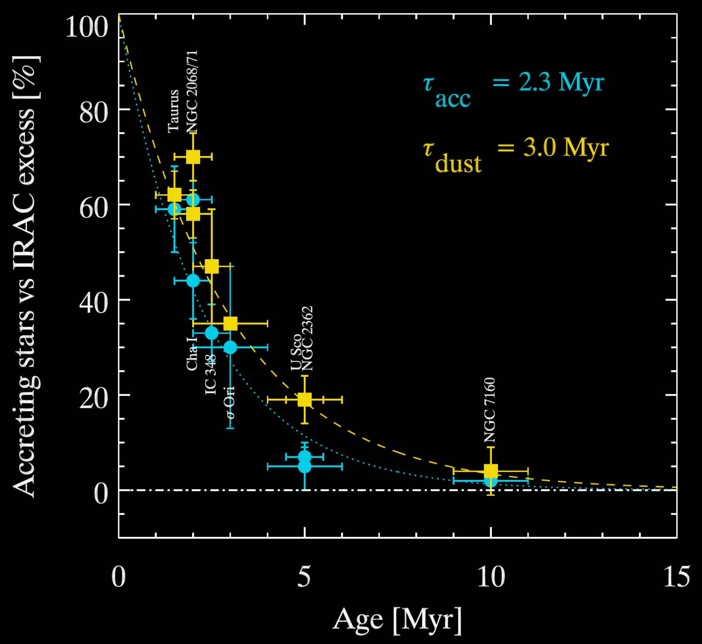
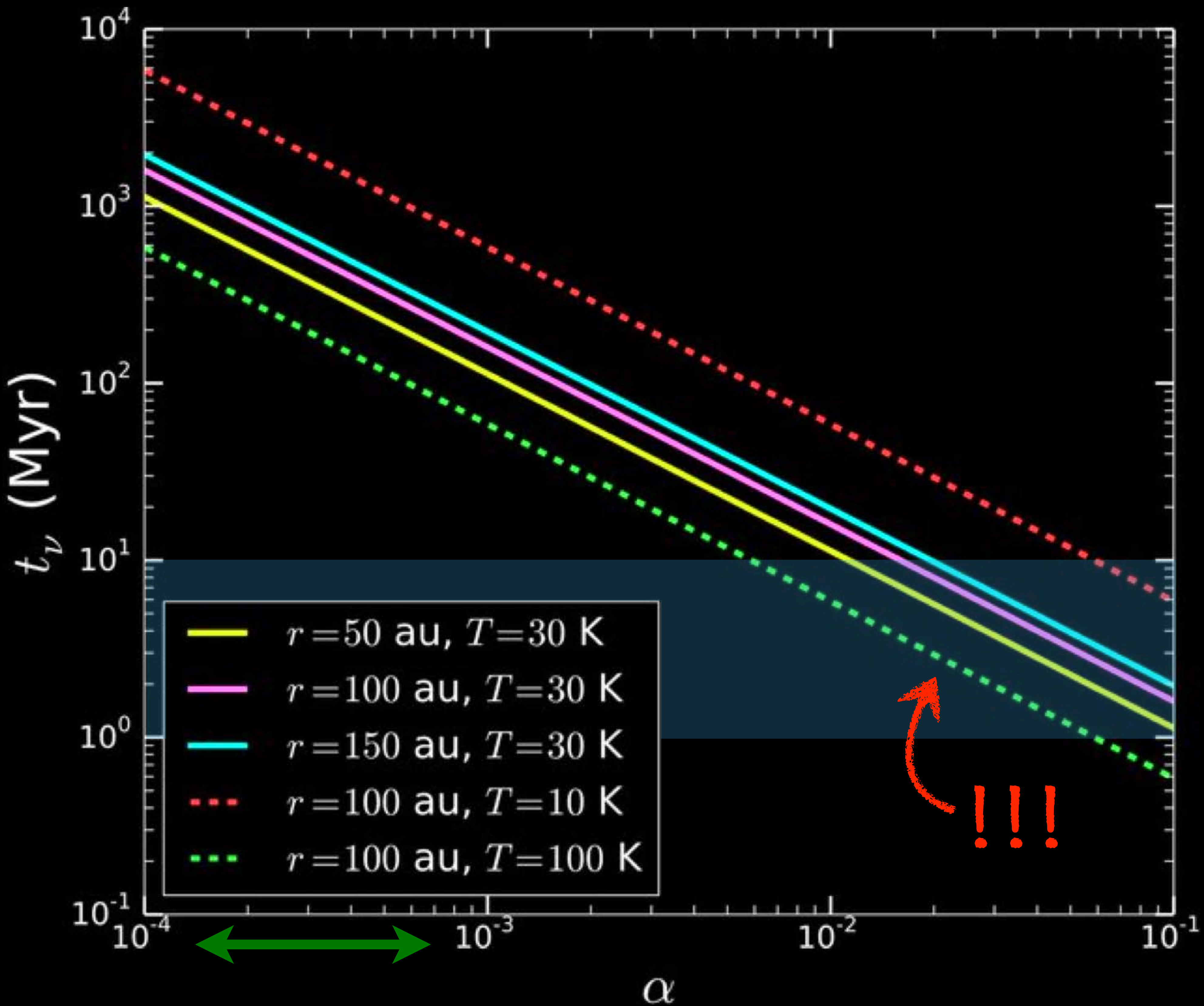




DISC LIFETIMES



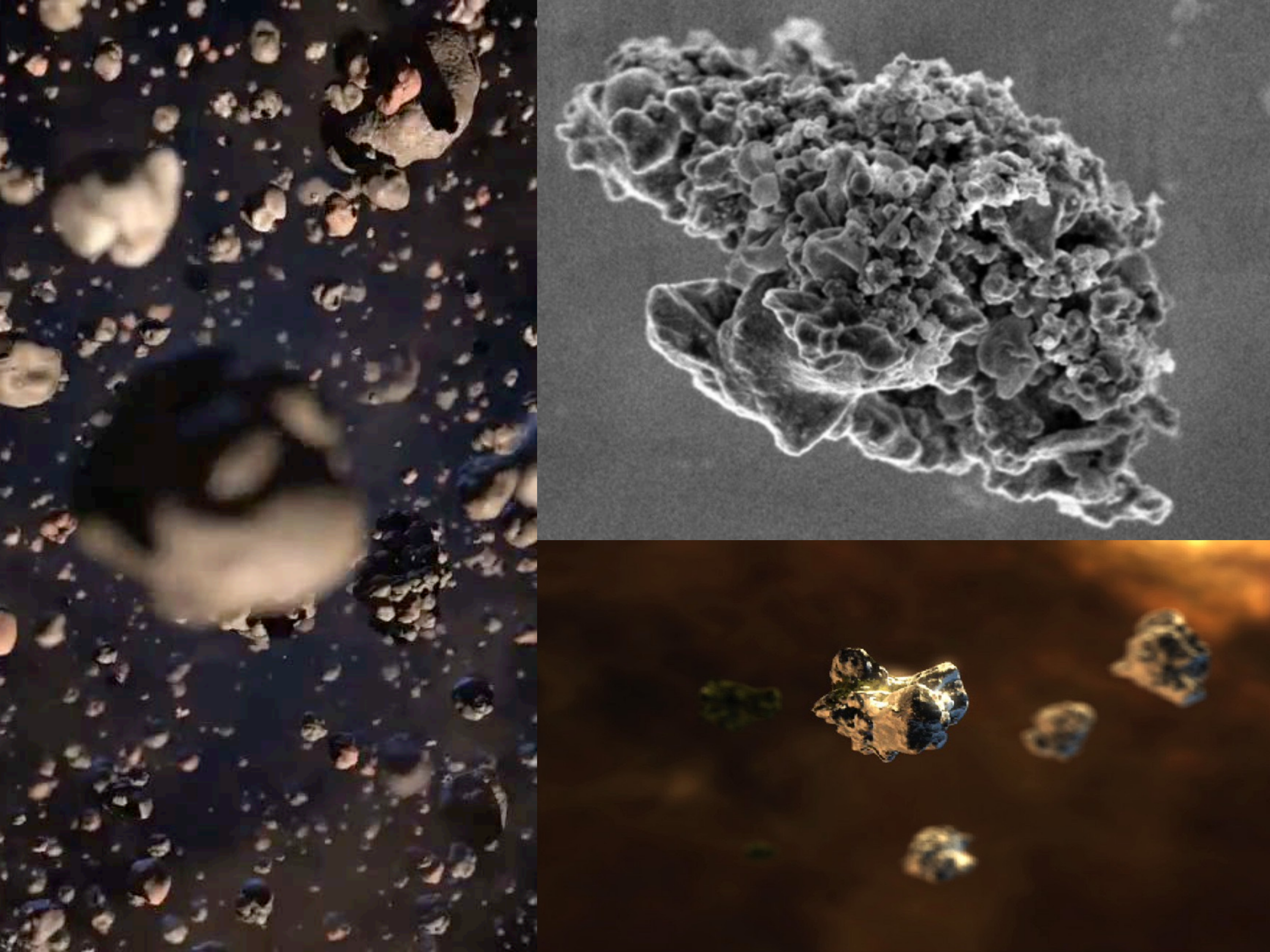




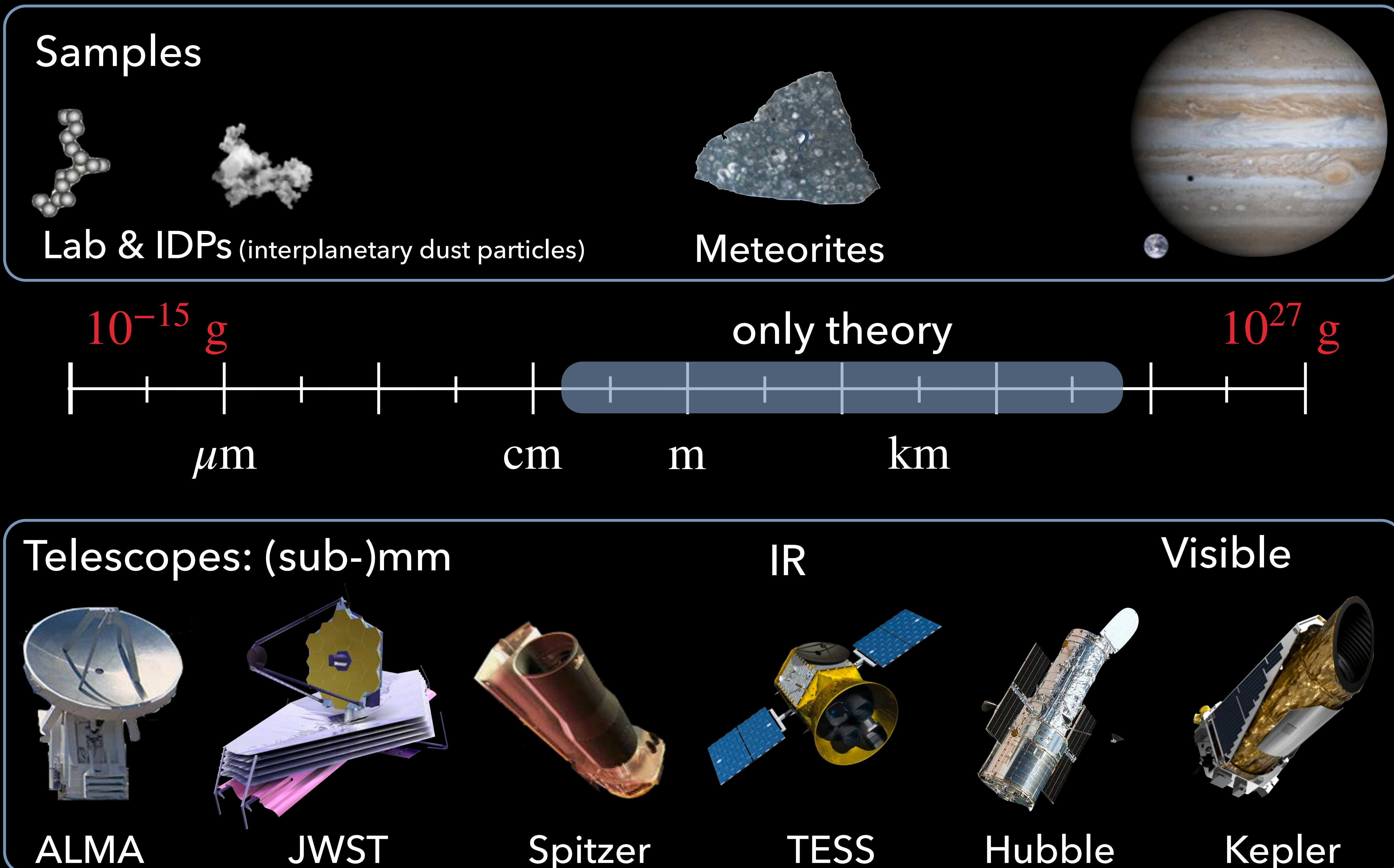
FROM UNIVERSE TO PLANETS

DUST

LECTURE 2.4

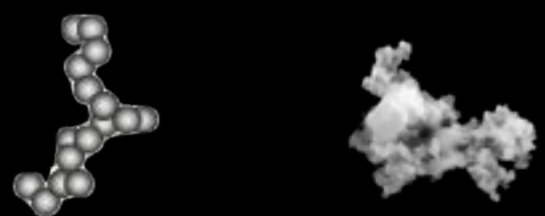


DUST: SIZES AND MASSES

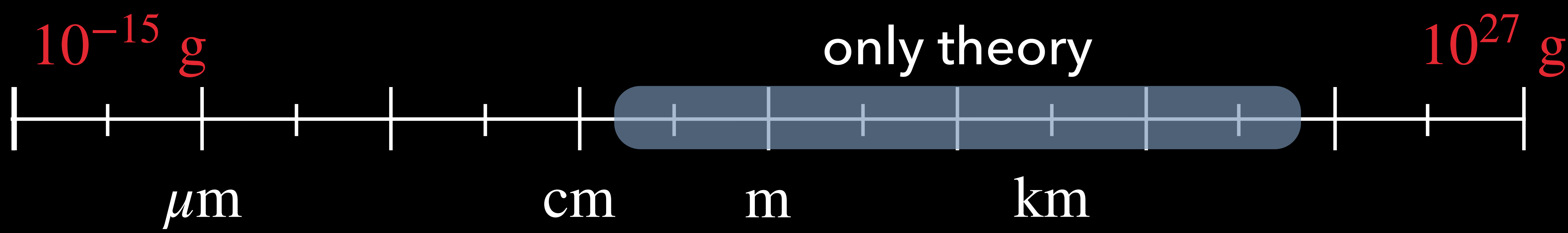


DUST: SIZES AND MASSES

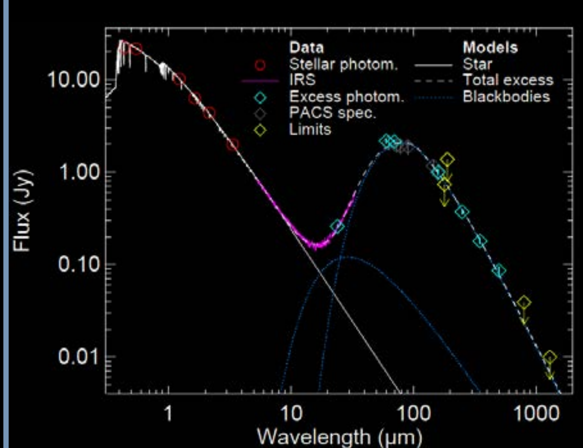
Samples



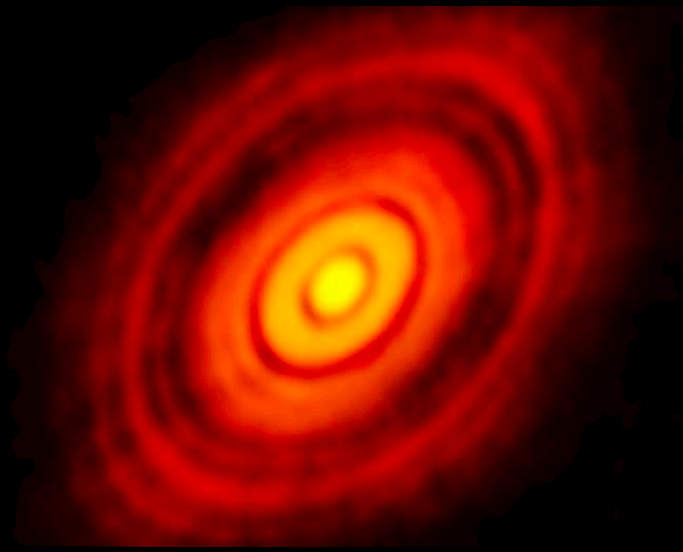
Lab & IDPs (interplanetary dust particles) Meteorites



Observations:

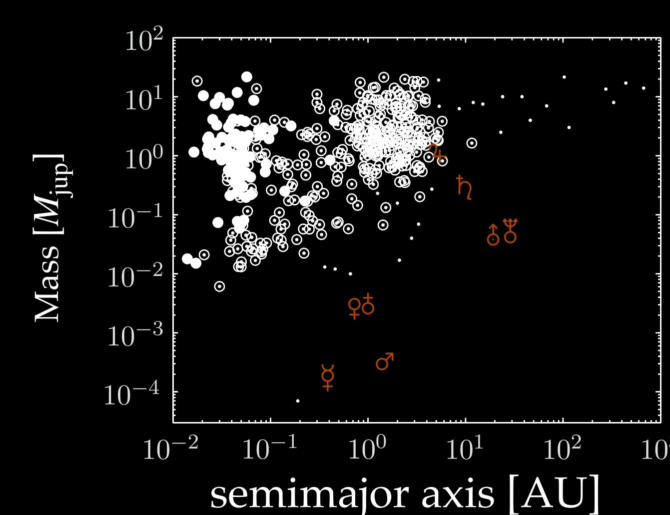


SED



Dust continuum

Direct imaging

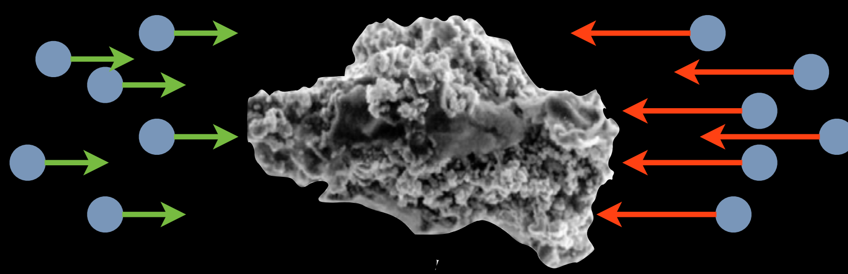


Transit surveys

DUST: DRAG LAWS

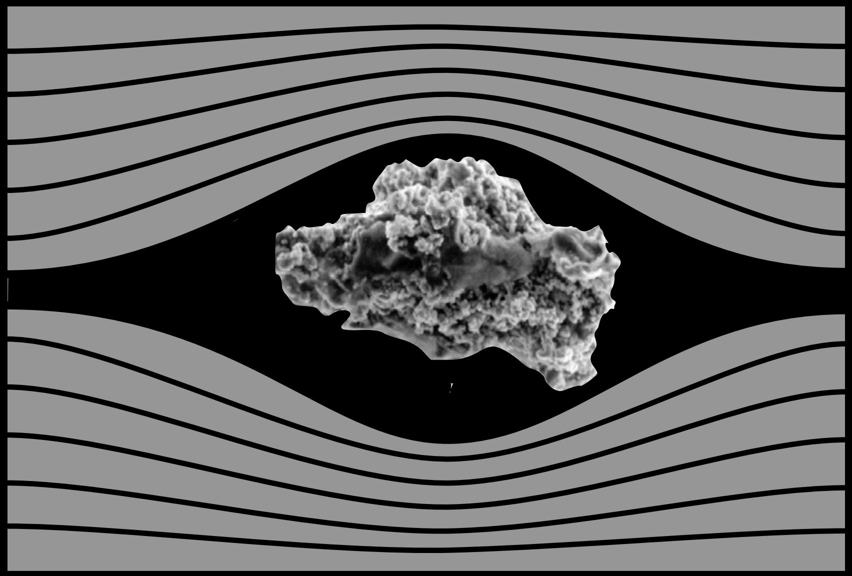
- Epstein regime: if particle size $\lesssim$ mean free path

$$F_{\rm Epstein} = -\frac{4\pi}{3} a^2 \rho_{\rm gas} v_{\rm th} \mathbf{v}$$



- Stokes regime: if particle size $\gtrsim$ mean free path

$$F_{\rm Stokes} = -\frac{C_{\rm D}}{2} \pi a^2 \rho_{\rm gas} v \mathbf{v}$$



  - $C_{\rm D}$ depends on the particle Reynolds number (the ratio of inertial forces to viscous forces).

DUST: RADIAL DRIFT

- Force equation: drag, gravity, and pressure forces:

dust velocity, drag coefficient, gas density

$$\frac{d\mathbf{v}_\mathrm{d}}{dt} = -A\rho_\mathrm{g}(\mathbf{v}_\mathrm{d} - \mathbf{v}_\mathrm{g}) - \frac{GM_*}{R^3}\mathbf{R}$$

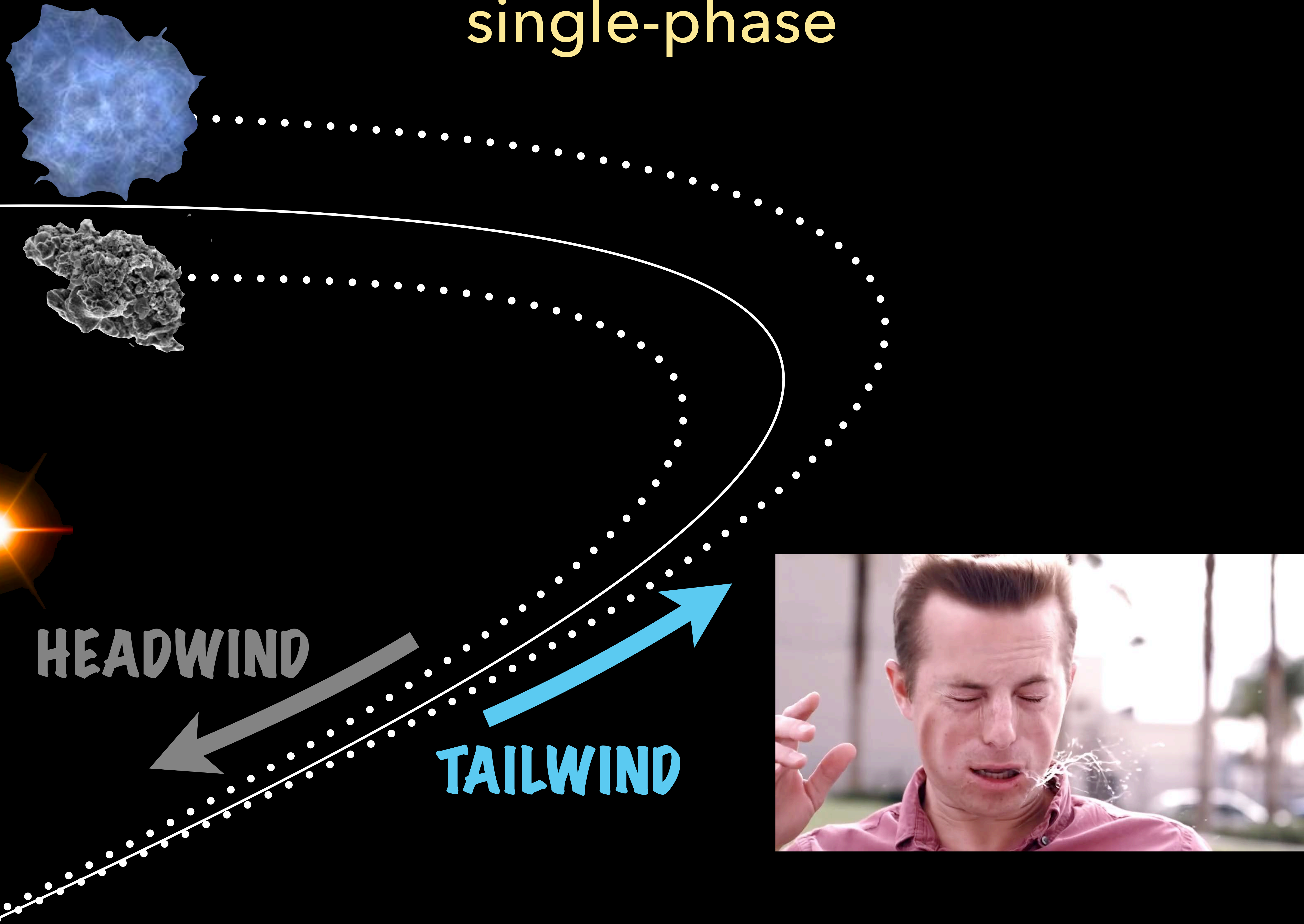
$$\frac{d\mathbf{v}_\mathrm{g}}{dt} = +A\rho_\mathrm{d}(\mathbf{v}_\mathrm{d} - \mathbf{v}_\mathrm{g}) - \frac{GM_*}{R^3}\mathbf{R} - \frac{\nabla P}{\rho_\mathrm{g}}$$

gas velocity, dust density, gas pressure

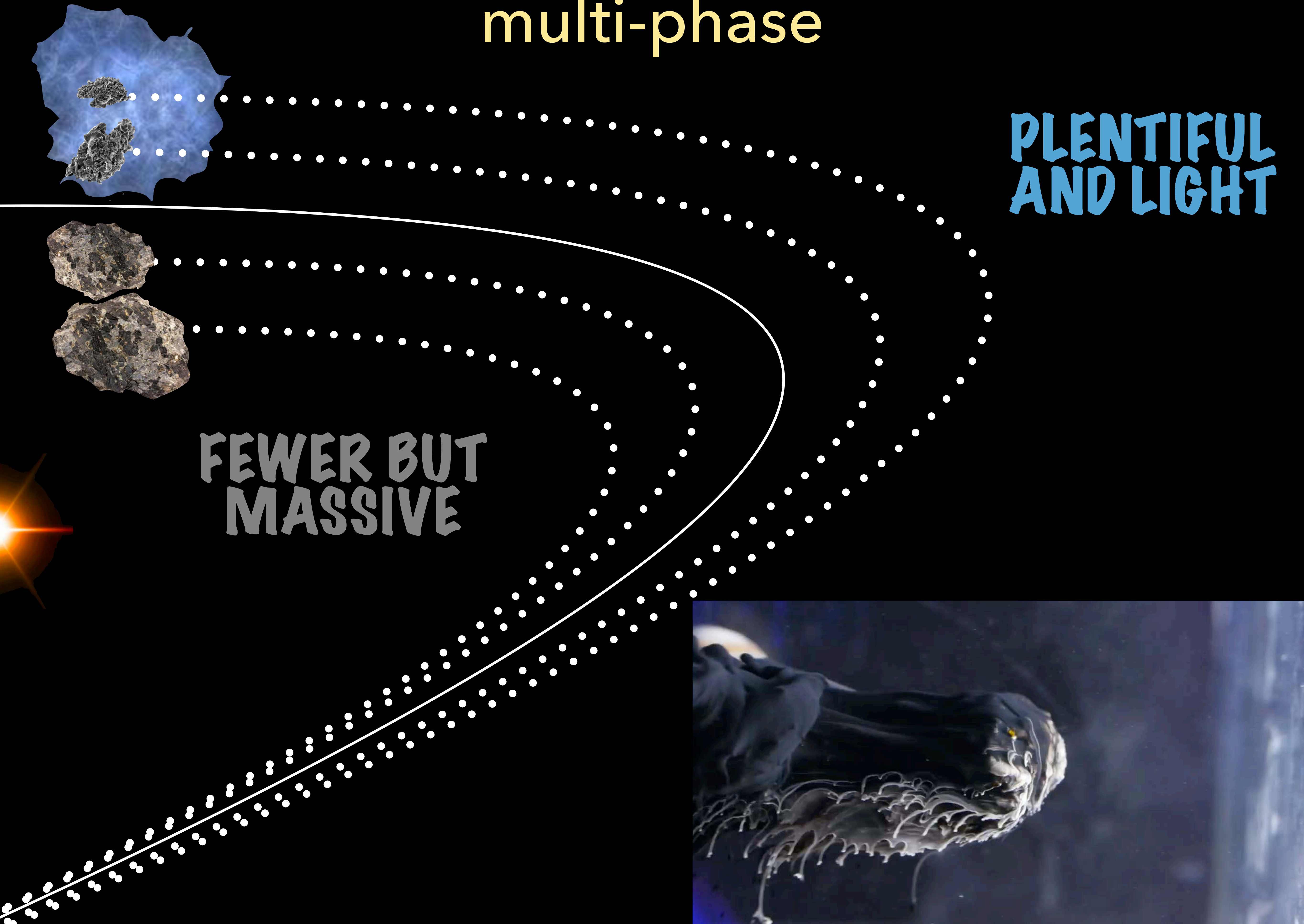
- The drag coefficient is is related to the Stokes number by:

$$A = \frac{v_\mathrm{th}}{\rho_\mathrm{grain} a} \longrightarrow \mathrm{St} = \frac{\Omega_\mathrm{K}}{A\rho_\mathrm{g}}$$

single-phase



multi-phase



DUST: VERTICAL SETTLING

- Now let's consider the vertical component on its own. To simplify things, we'll ignore the back-reaction of the dust onto the gas:

$$\frac{\partial u_{\rm d}^z}{\partial t} = -A\rho_{\rm g}(u_{\rm d}^z - \cancelto{0}{u_{\rm g}^z}) + z\Omega_{\rm K}^2$$

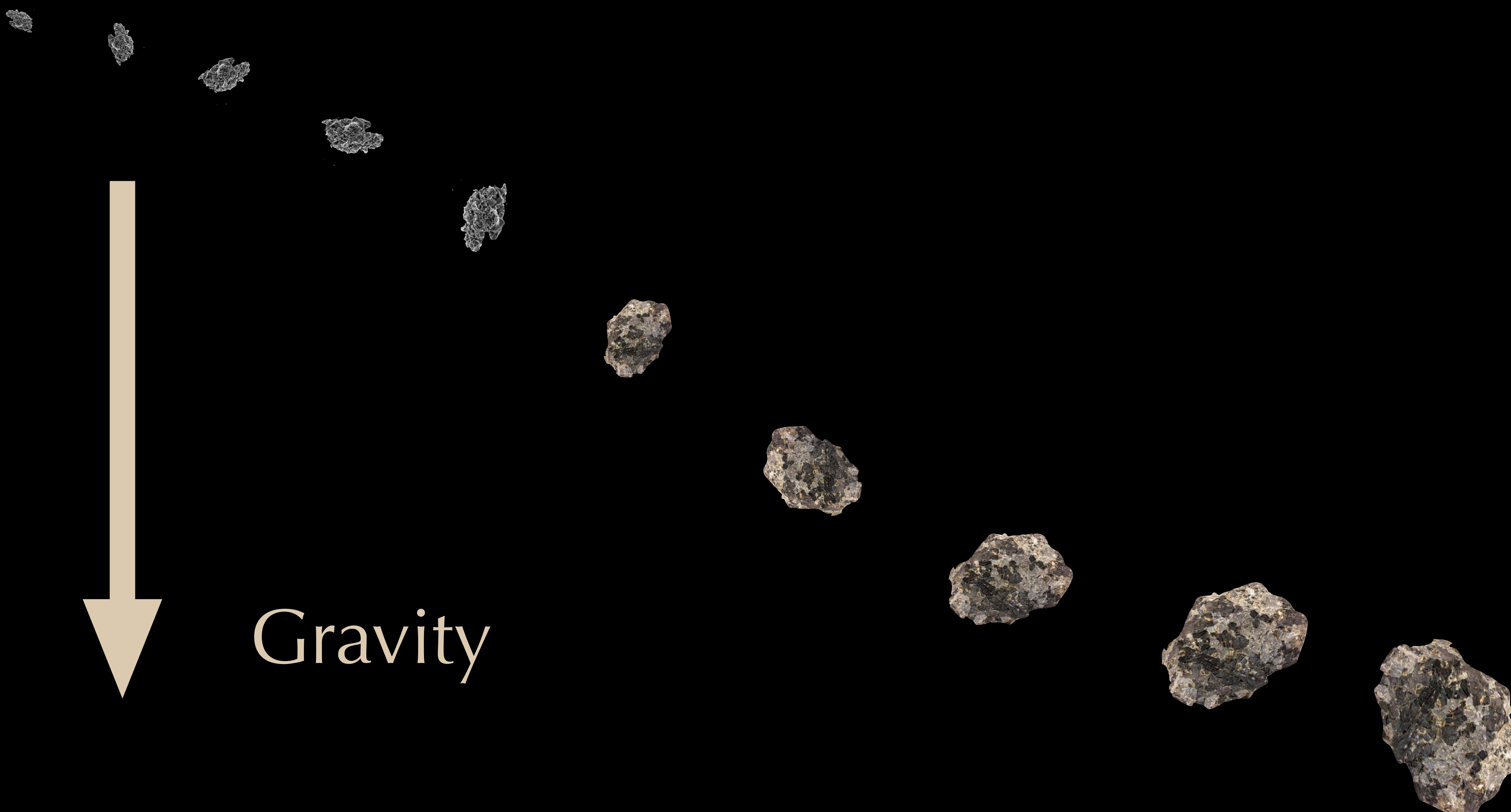
- Which is the equation for a damped harmonic oscillator. The steady state terminal velocity has a simple relation:

$$u_{\rm d}^z = -z\,\Omega_{\rm K}{\rm St} = -z\,t_{\rm stop}$$

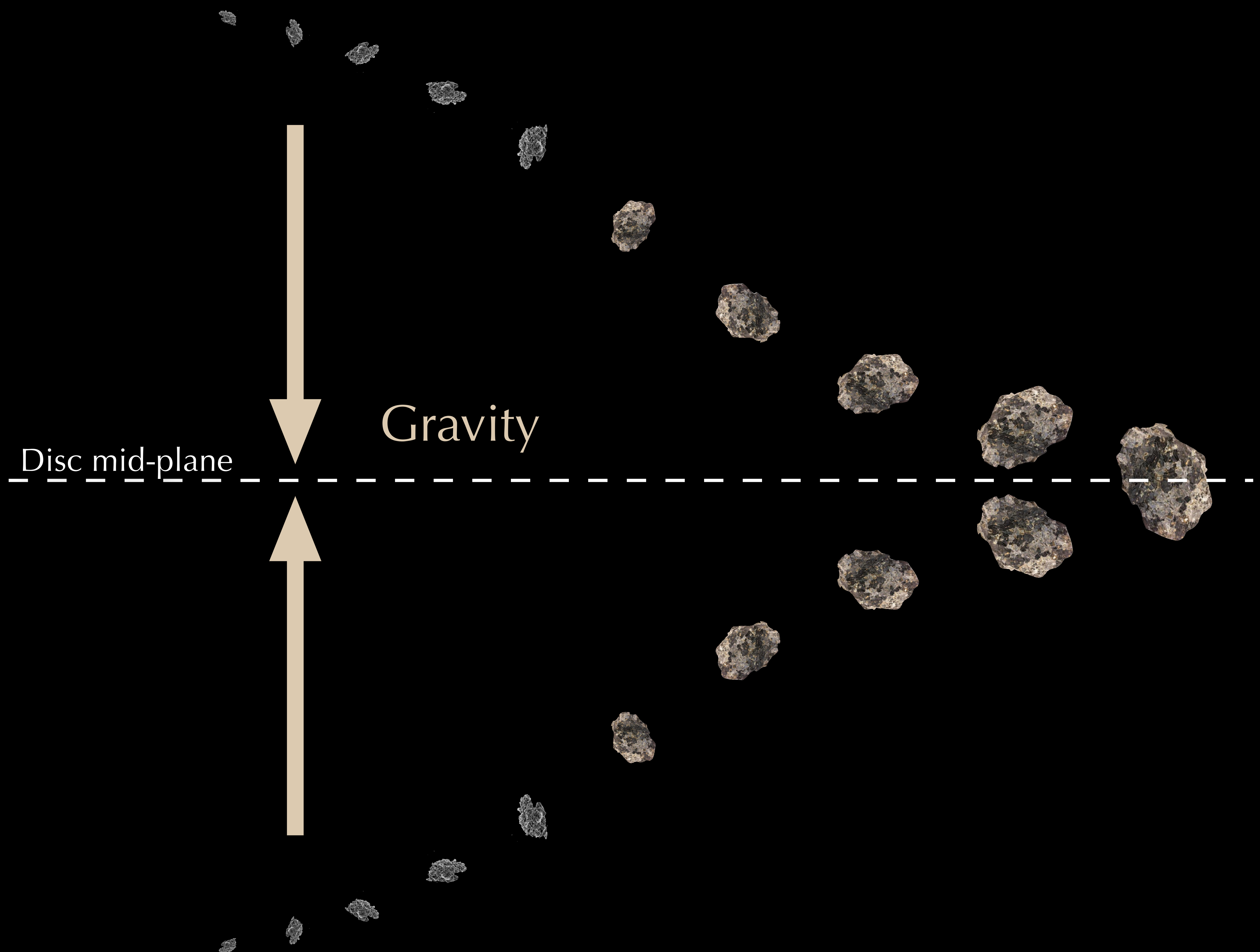
- Importantly, $t_{\rm stop}$ depends on $\rho_{\rm g}$ which increases towards the disc mid-plane. Small grains slowly settle to the mid-plane. Large grains (if lofted up), will oscillate about the disc mid-plane.

DUST: VERTICAL SETTLING

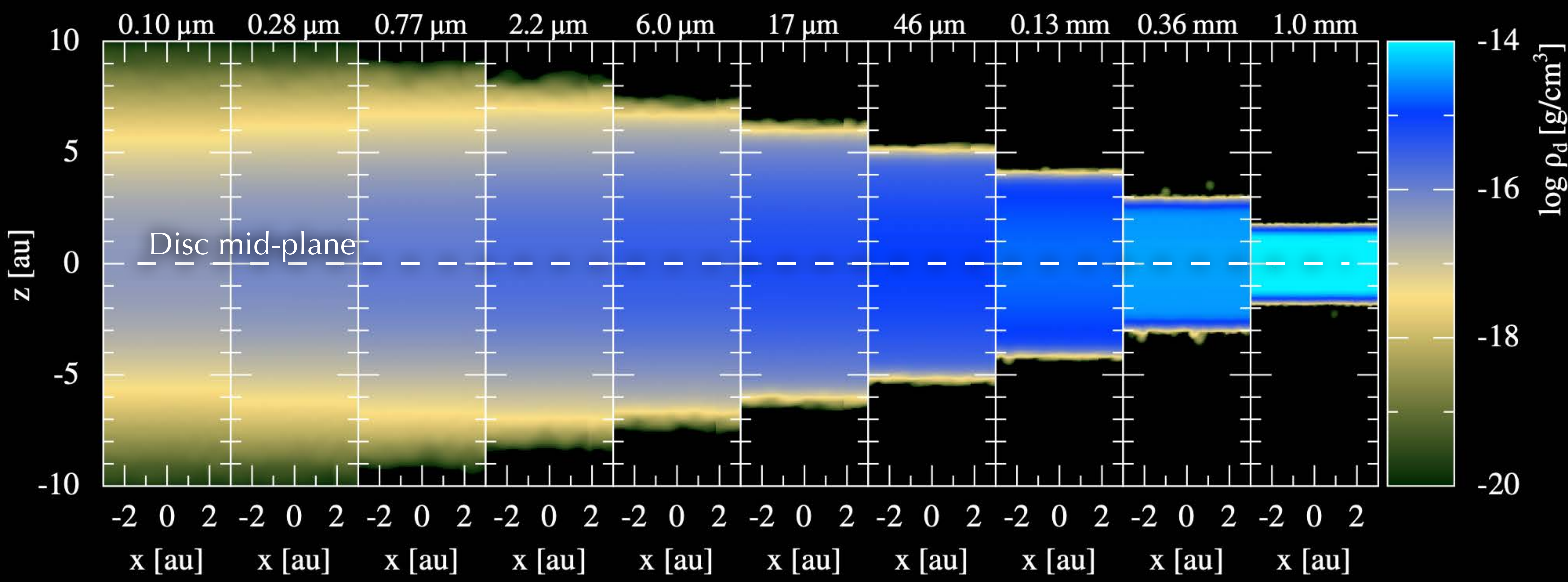
DUST: VERTICAL SETTLING

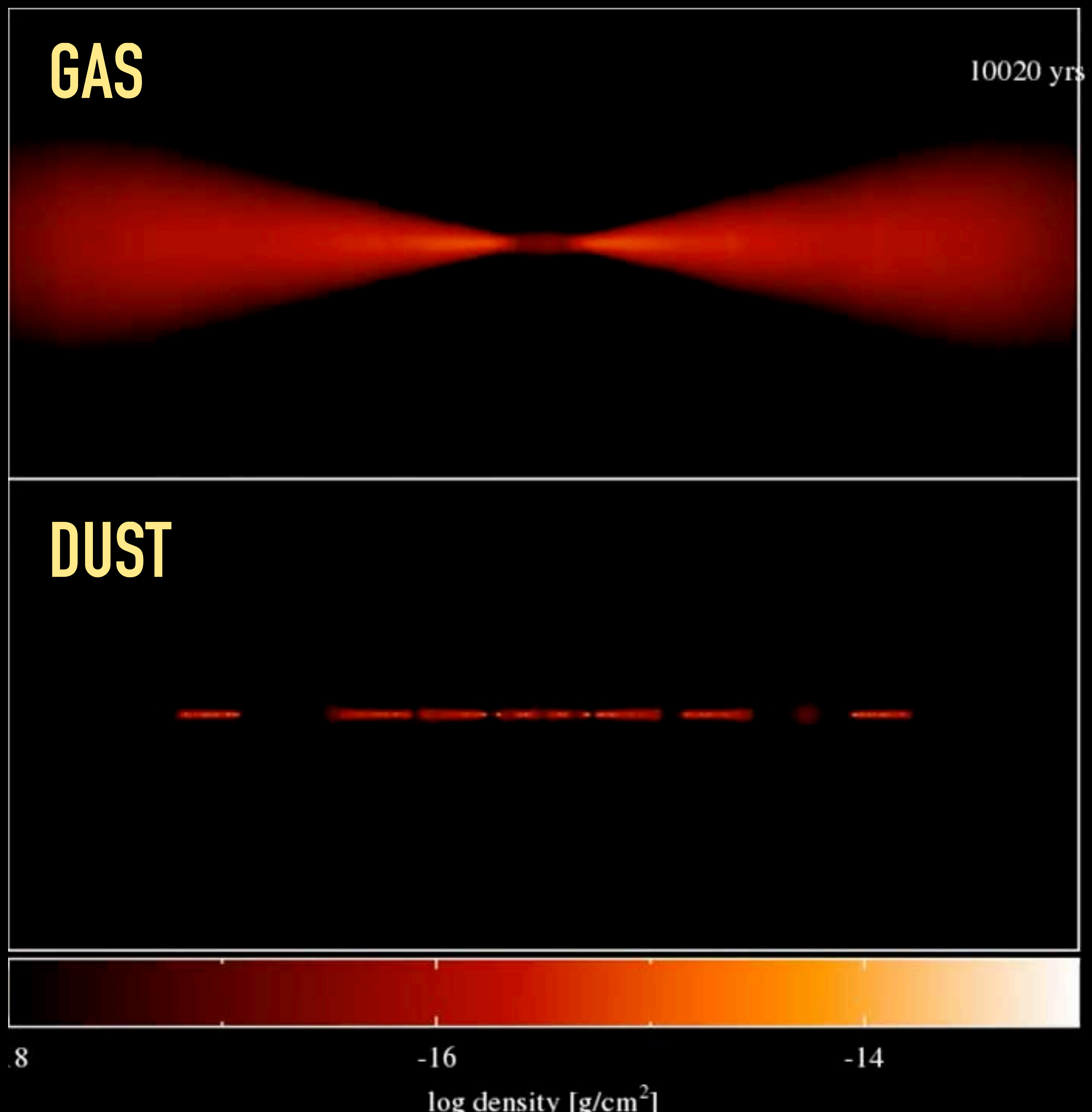


DUST: VERTICAL SETTLING



DUST: VERTICAL SETTLING




GAS
10020 yrs
DUST
.8
-16
-14
log density [g/cm2]

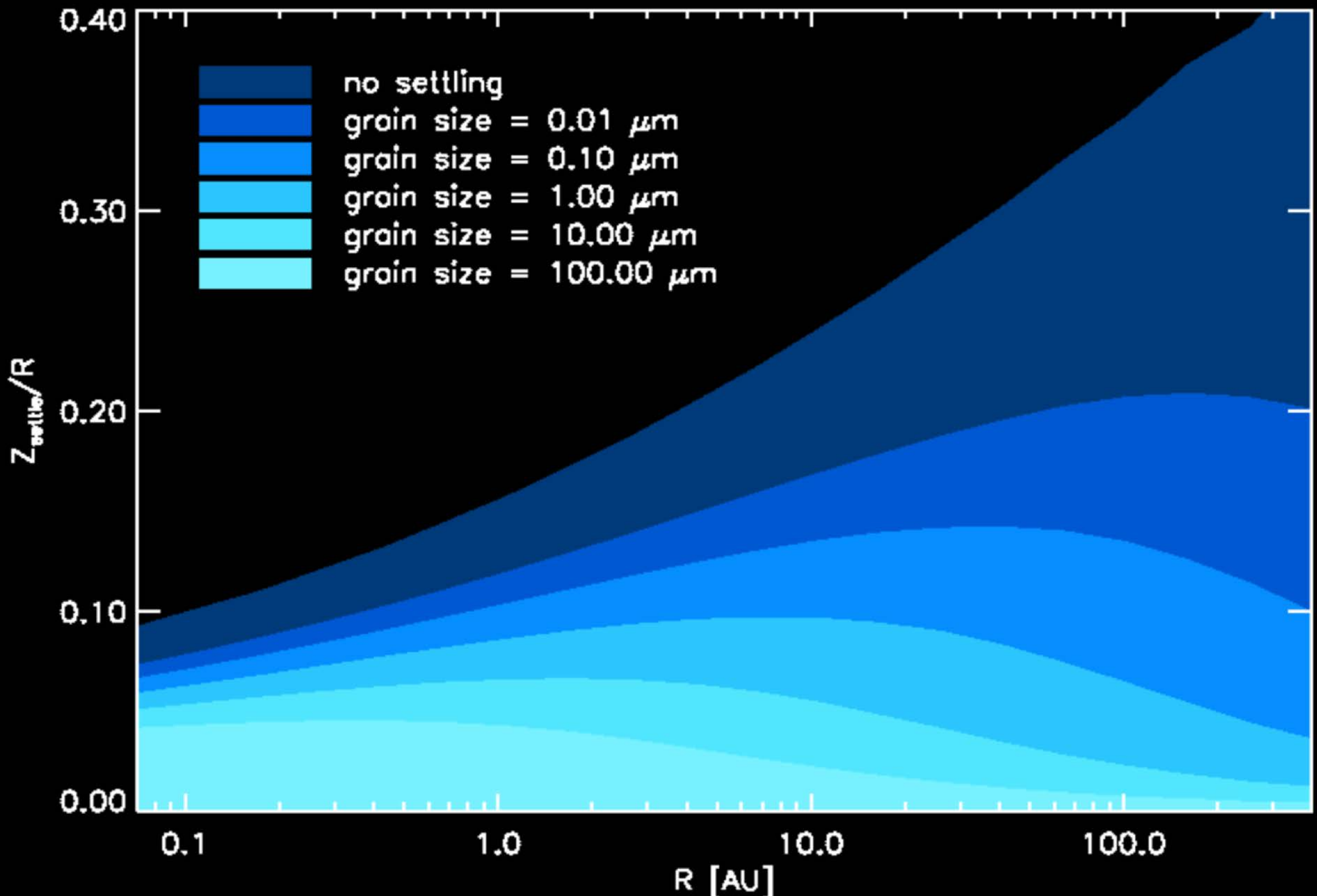
DUST: VERTICAL SETTLING

- In a turbulent disc, turbulent eddies will kick-up dust vertically. Eventually, dust will reach a steady state defined by the following diffusion equation:

$$\frac{\partial \rho_{\rm d}}{\partial t} + \frac{\partial}{\partial z}\left[\rho_{\rm d} v_{\rm d} - \rho_{\rm g} D_{\rm d} \frac{\partial}{\partial z}\left(\frac{\rho_{\rm d}}{\rho_{\rm g}}\right)\right] = 0$$

- Where the diffusion coefficient is defined as: $D_{\rm d} \approx \frac{\alpha c_{\rm s} H}{\rm Sc}$ (${\rm Sc} \sim 1 + {\rm St}$ is the Schmidt Number)

DUST: VERTICAL SETTLING



MAIN POINTS 1

- Discs form naturally when gas collapses
  - Energy is dissipated by friction and radiative cooling
  - Clouds have a net angular momentum spin axis
    - Parallel → small L ; Perpendicular → large L
- Discs are thin, but flared due to incident stellar radiation.
    - Inner disc and disc surfaces are hot (usually ionised). Mid-plane is cold and molecules condense out of the gas onto dust grains.
- Evolutionary stages can be distinguished by their SED.

MAIN POINTS 2

- Discs redistribute angular moment through viscous dissipation, thereby allowing them to accrete.
    - Source of turbulence is still not clear, but likely is related to magnetic fields.
- Gas is pressure supported and rotates at sub-Keplerian velocities.
    - Dust experiences a headwind and drifts radially inwards (important for planet formation)
- Dust settles vertically, increasing the concentration of dust at the mid-plane where planets form.