



Planet Formation

行星形成

南京大学深空探测研究院

2026/9/17

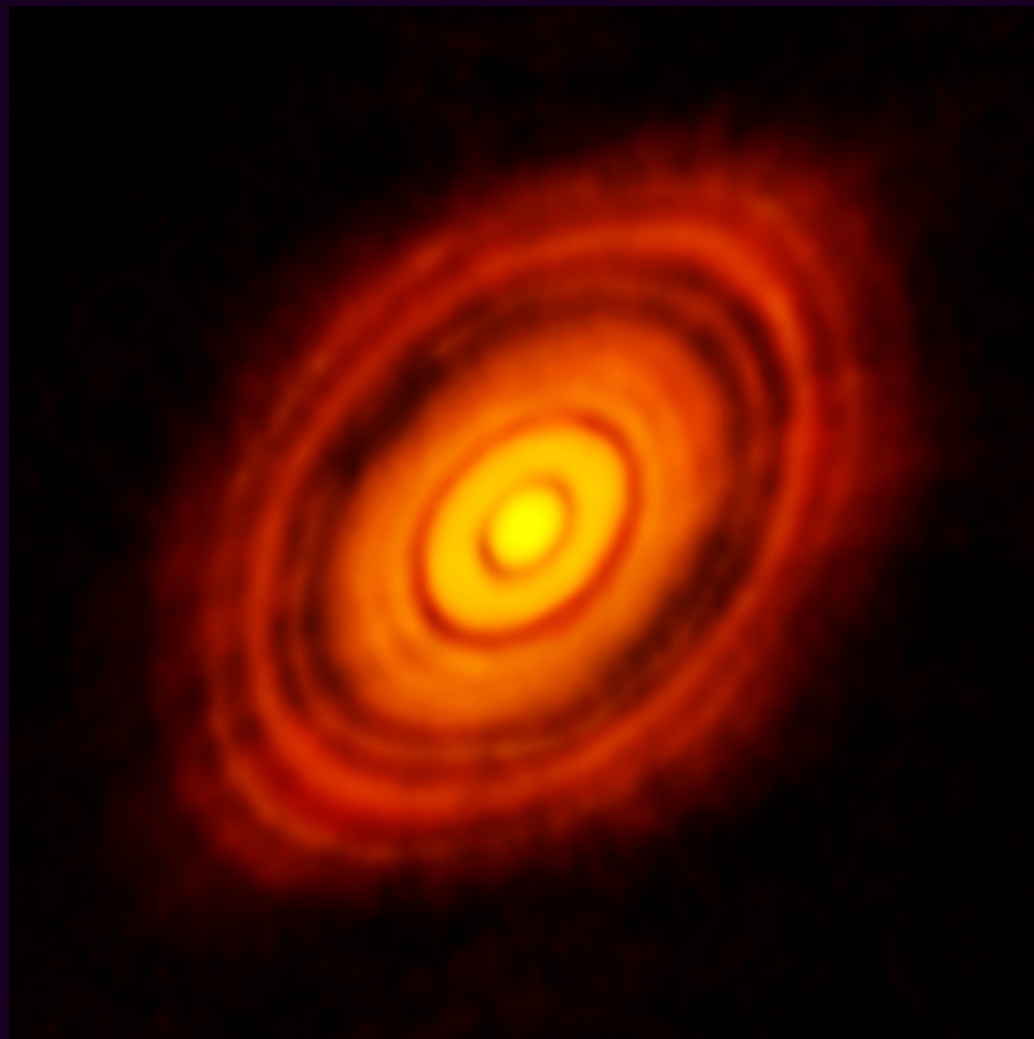
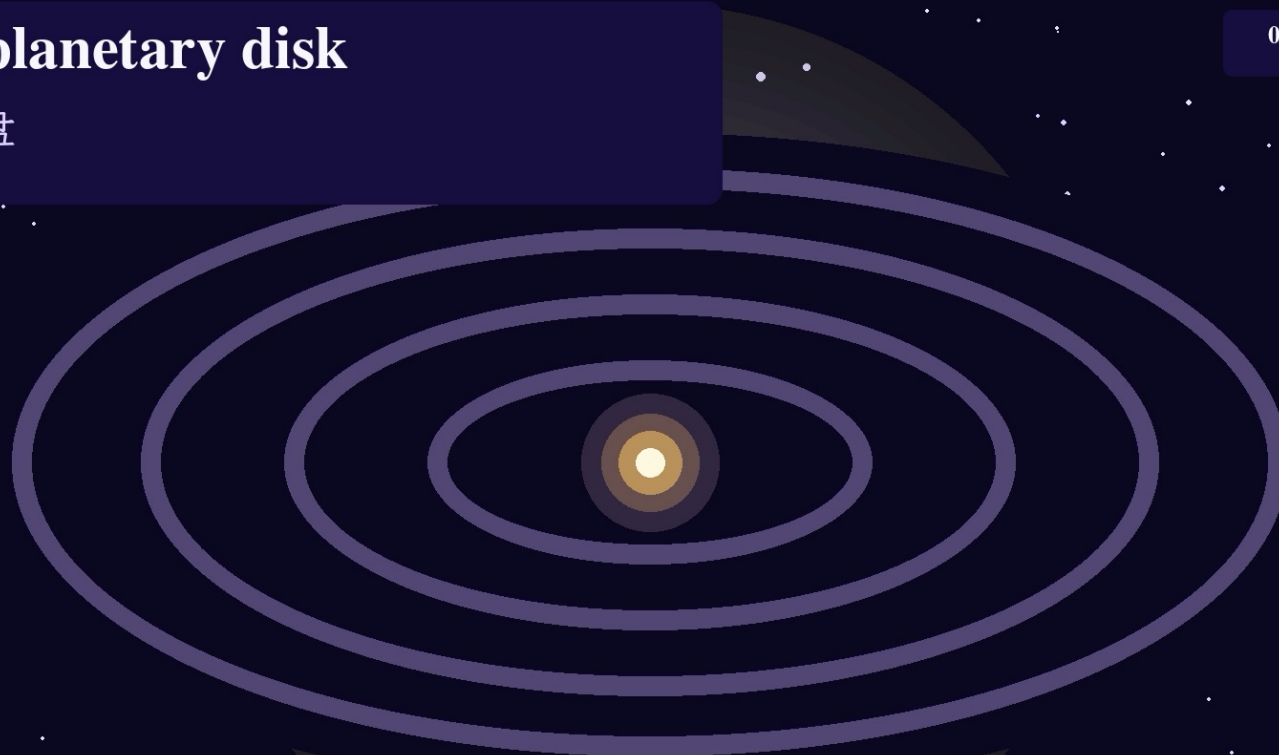


Image credit: ALMA (ESO/NAOJ/NRAO), HL Tauri disk image

Protoplanetary disk

原行星盘

0.10 Myr



A rotating cloud collapses into a star and disk

旋转分子云坍缩，形成恒星与原行星盘

Disk

原行星盘

Planetesimals

星子形成

Pebbles

卵石吸积

Giants

巨行星形成

Migration

轨道迁移

Mature system

成熟系统



Lecture 2

原行星盘

Protoplanetary Disks

原行星盘是行星形成的摇篮

Protoplanetary disks are the birthplaces of planets.

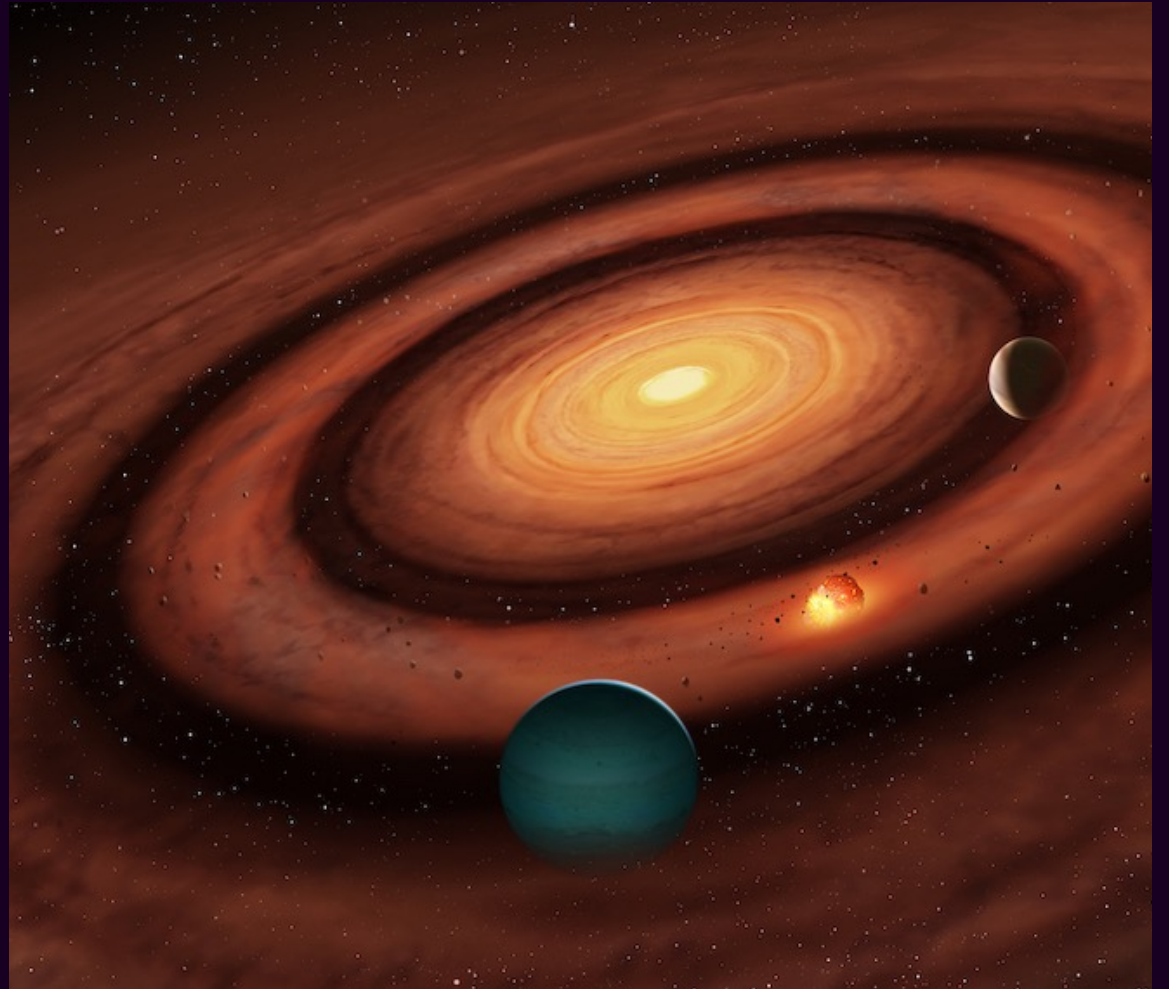


Image credit: Image via University of Warwick/ Mark A. Garlick/ Royal Astronomical Society (CC BY 4.0).

盘的基本参数

PLANET FORMATION - L02

BASIC DISK PROPERTIES: AGE, SIZE, MASS, COMPOSITION

AGE 年龄

1–10 Myr

气体盘寿命限定形成时间

SIZE 尺度

10–100s au

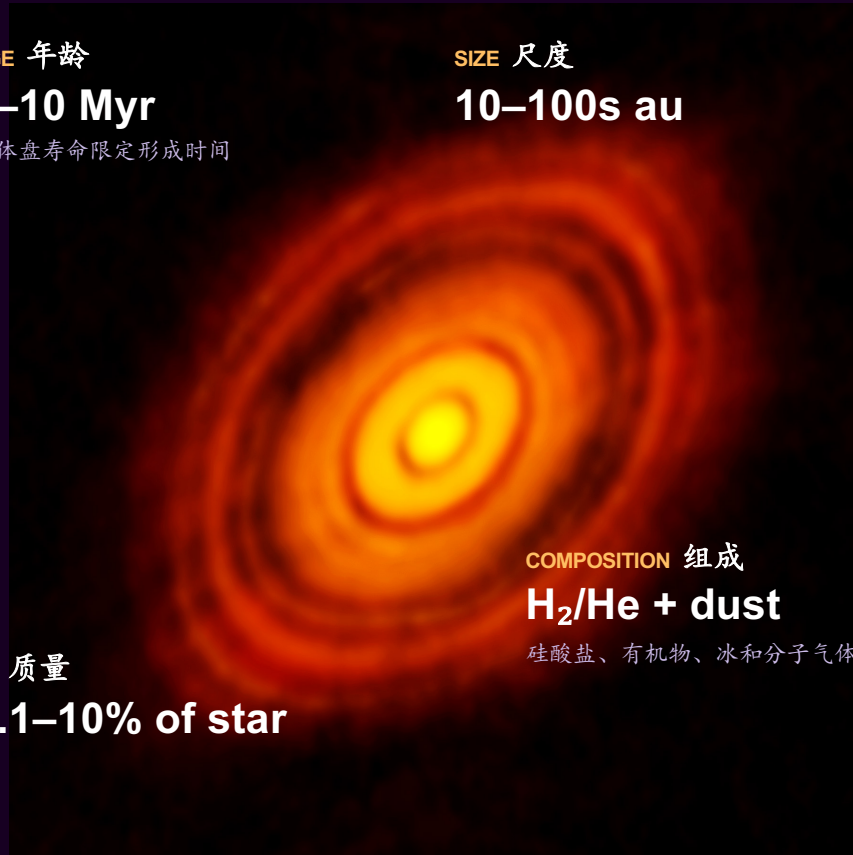
COMPOSITION 组成

H₂/He + dust

硅酸盐、有机物、冰和分子气体

MASS 质量

≈ 0.1–10% of star



ALMA对原行星盘的观测

ALMA IMAGES

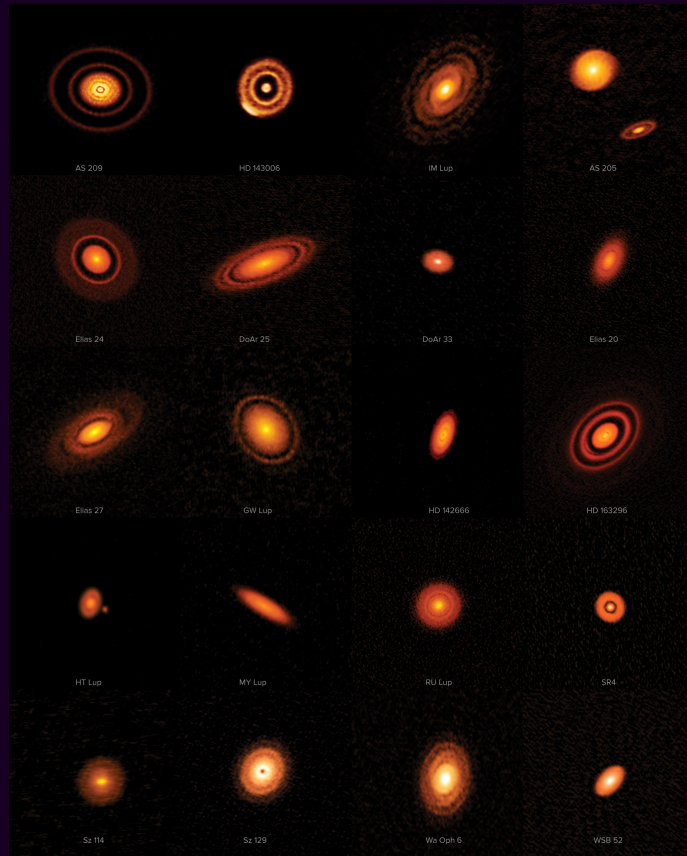
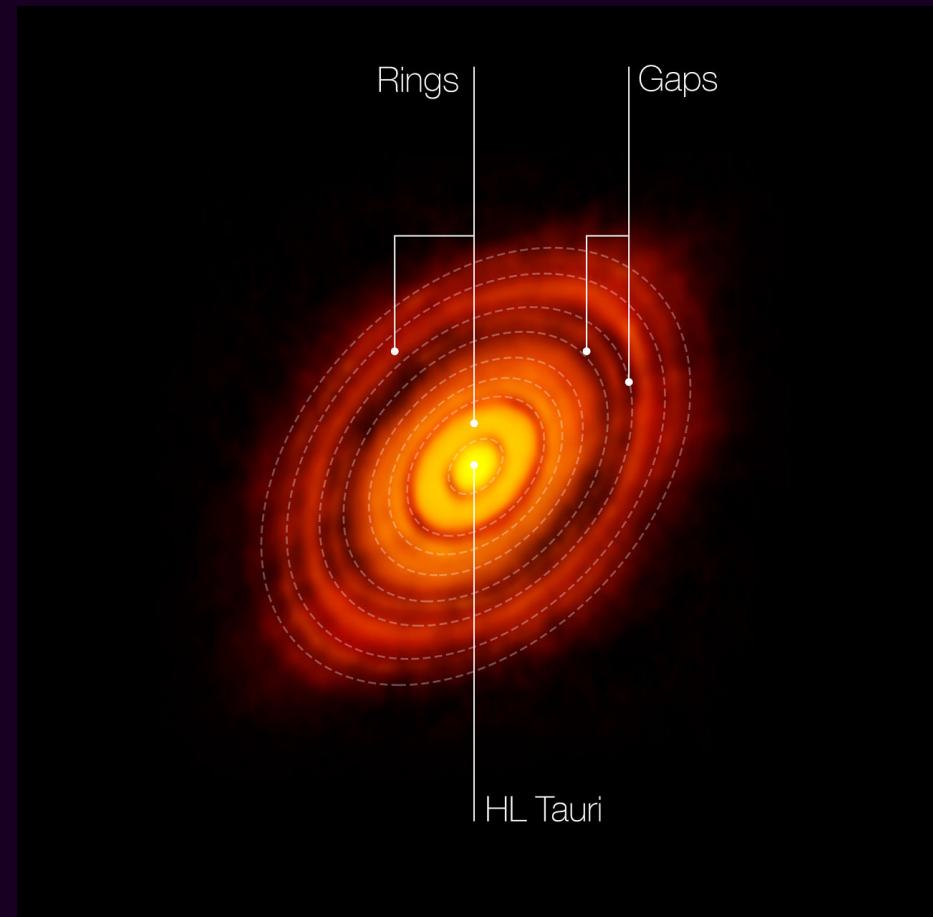


Image credit: ALMA DSHARP survey, Andrews et al.; ALMA (ESO/NAOJ/NRAO)

PLANET FORMATION - L02



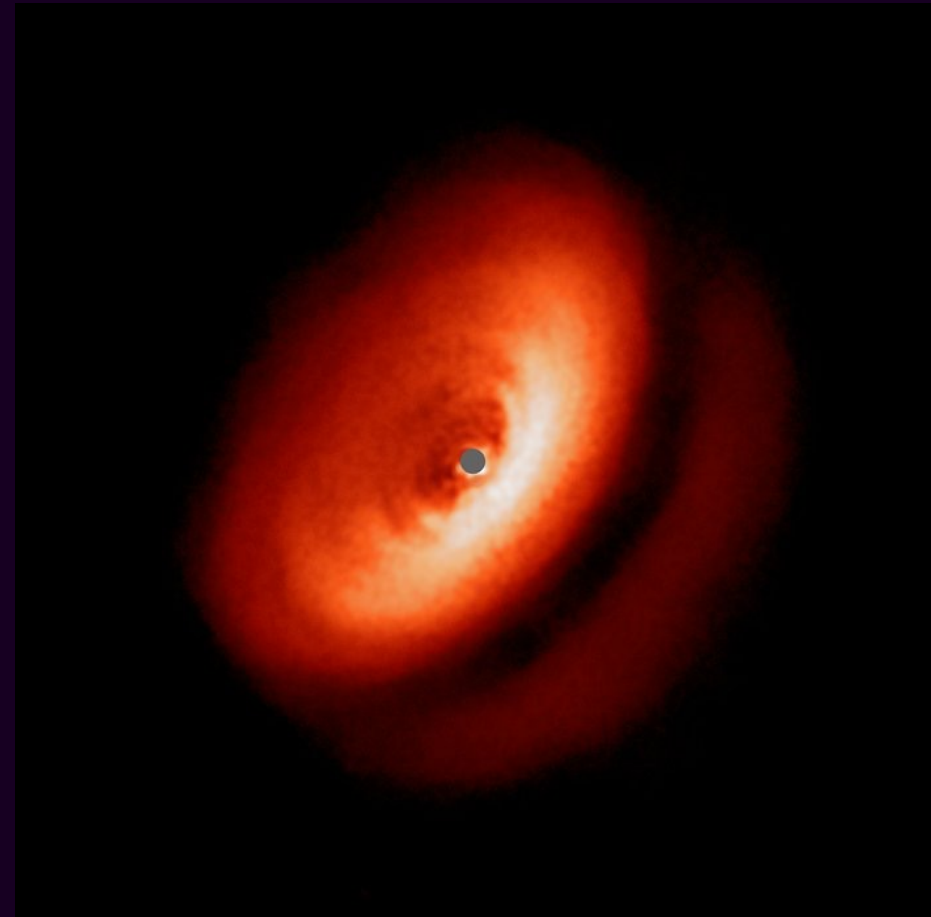
HST和SPHERE对原行星盘的观测

PLANET FORMATION - L02

HST AND SPHERE IMAGES



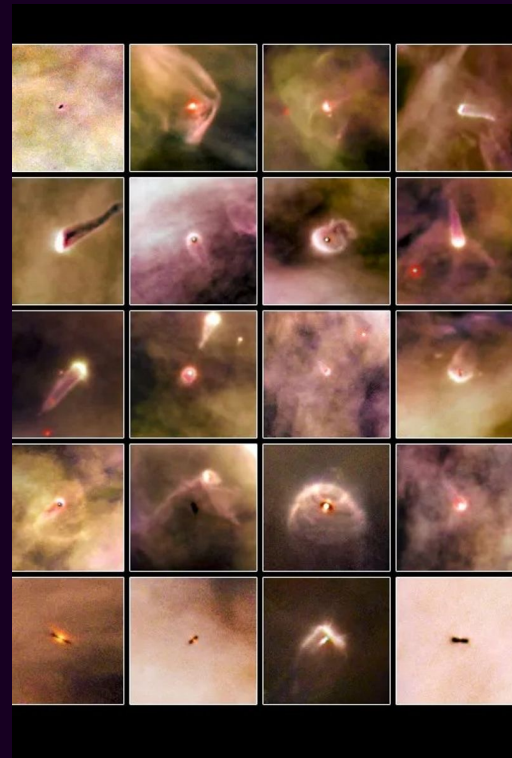
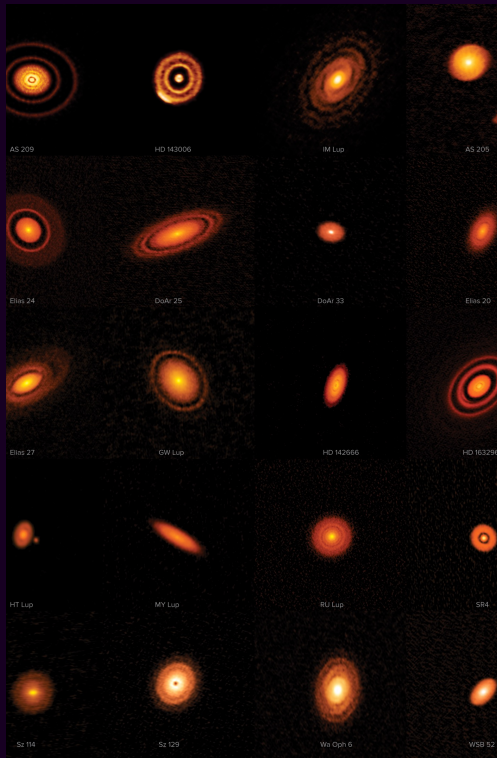
Image credit: Left: ALMA DSHARP survey; right: Hubble/ESA disk gallery public images



测到什么？不能直接测到什么？

WHAT OBS CAN TELL? CANNOT TELL?

PLANET FORMATION - L02



Observables are not identical to physical parameters.

- ALMA continuum measures dust emission
- ALMA molecular lines trace selected species and kinematics.
- Viscosity, turbulence, total solids, and planet properties still require modeling.

区分“直接观测量”与“通过模型反演得到的量”。

盘的结构

DISK STRUCTURE

PLANET FORMATION - L02

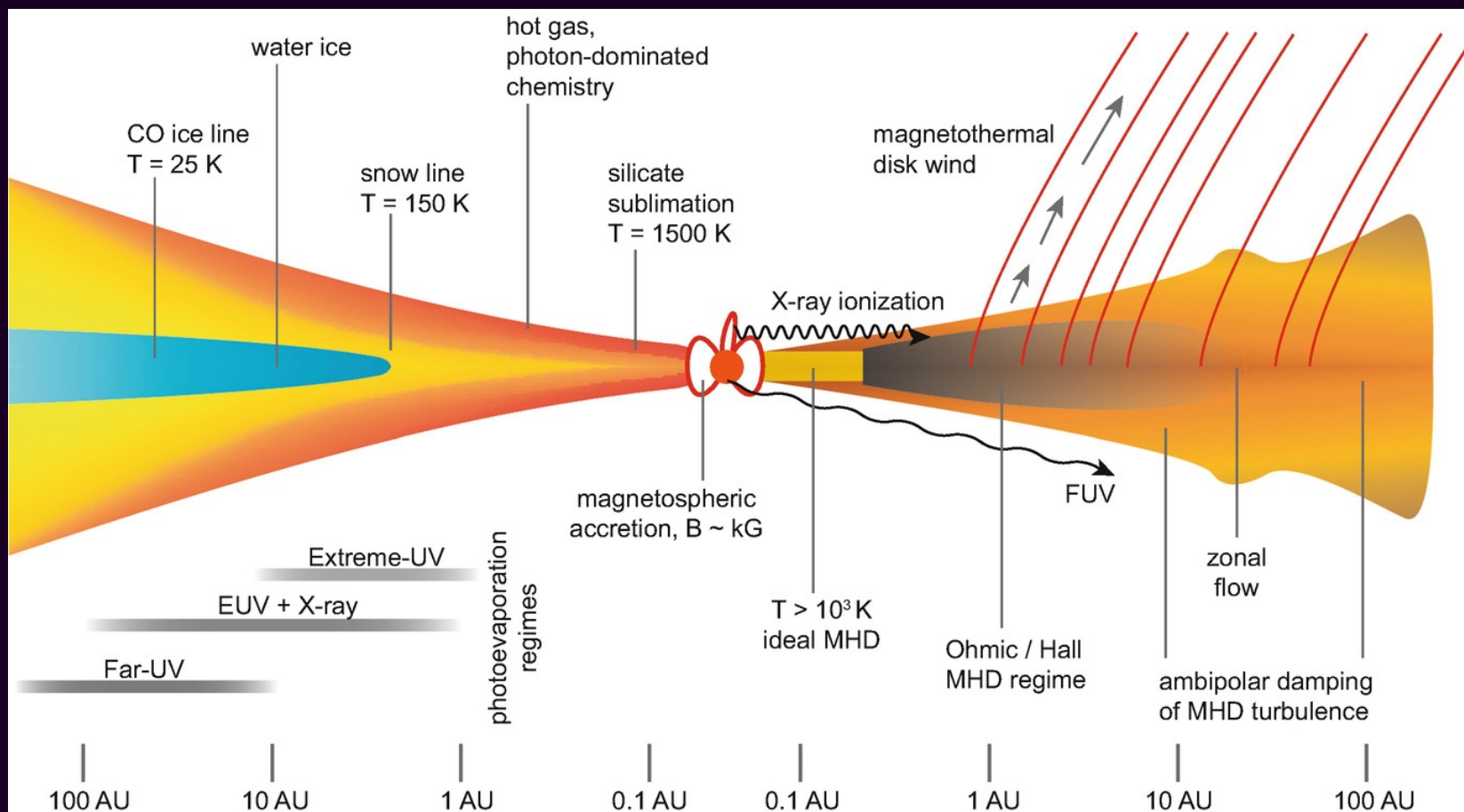
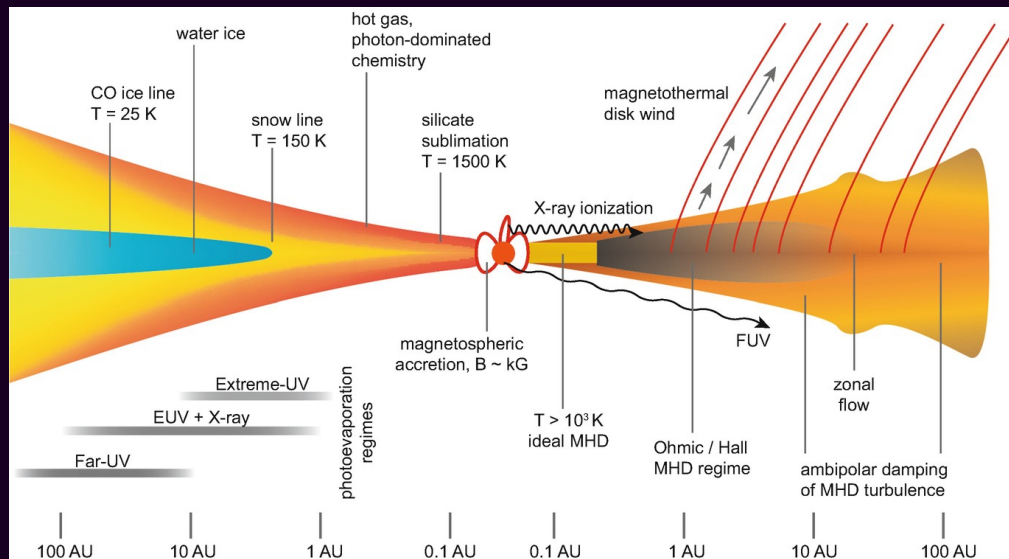


Image credit: A Brief Overview of Planet Formation

被动受照盘

PASSIVE IRRADIATED DISKS

PLANET FORMATION - L02



Starlight controls the thermal structure of the disk.

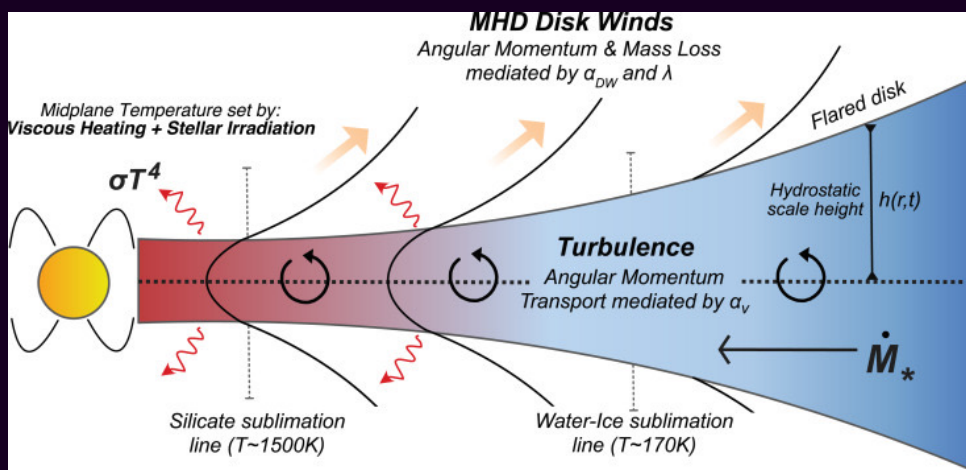
- The disk surface absorbs stellar radiation and re-emits it in the infrared.
- A flared disk intercepts more light at large radius, keeping the outer disk warm.
- The midplane is cooler and more shielded, so vertical temperature gradients are expected.
- Passive heating is especially important when the accretion rate is low.

核心：被动受照盘的温度主要由恒星照射和盘几何决定。

角动量输运与吸积

PLANET FORMATION - L02

ANGULAR MOMENTUM TRANSPORT AND ACCRETION



Gas accretes when angular momentum is removed by turbulence or MHD winds.

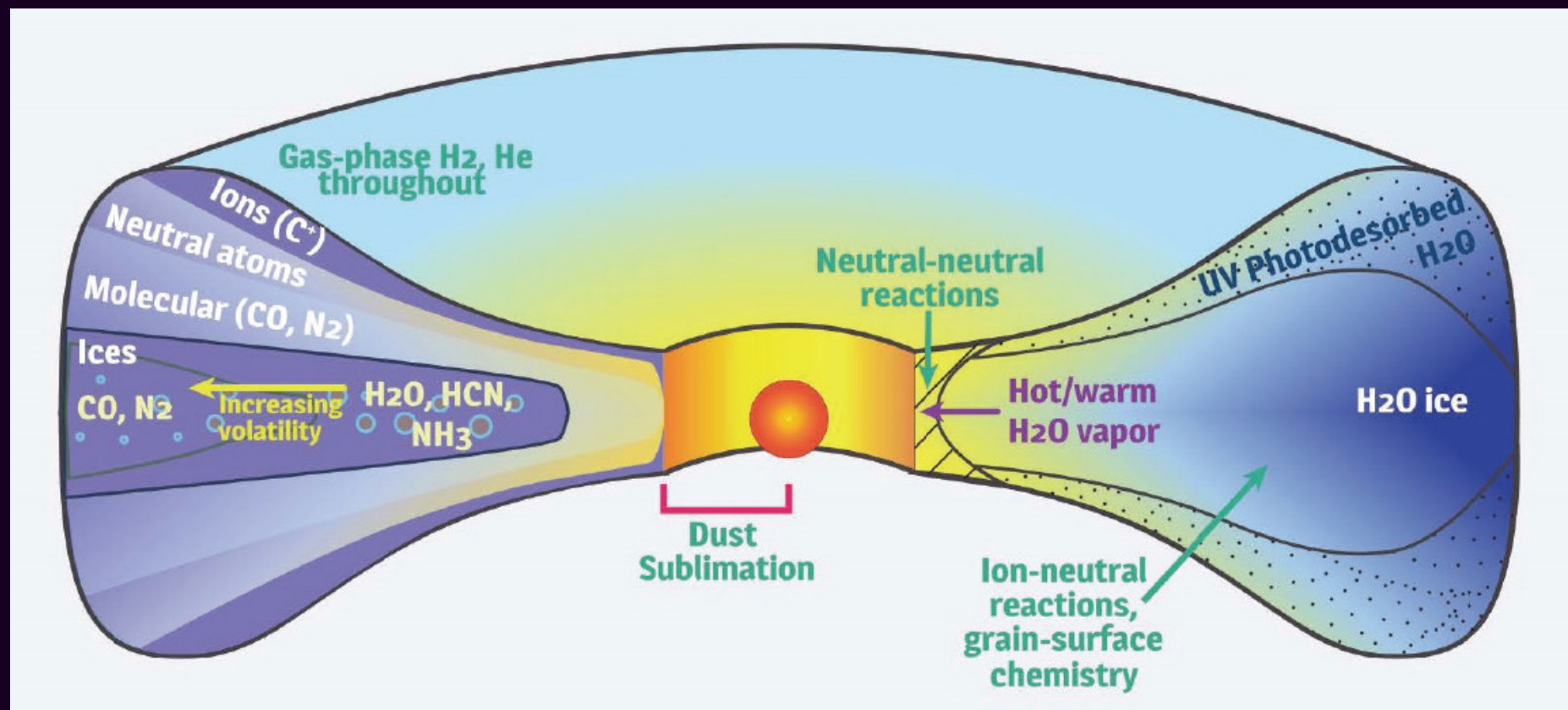
- Turbulent transport redistributes angular momentum radially, often described by an effective viscosity.
- MHD winds remove angular momentum vertically along magnetic field lines.
- The two channels predict different accretion flows, surface-density evolution, and turbulence levels.

径向湍流输运与垂向 MHD wind 输运。

盘化学组成

DISK CHEMISTRY

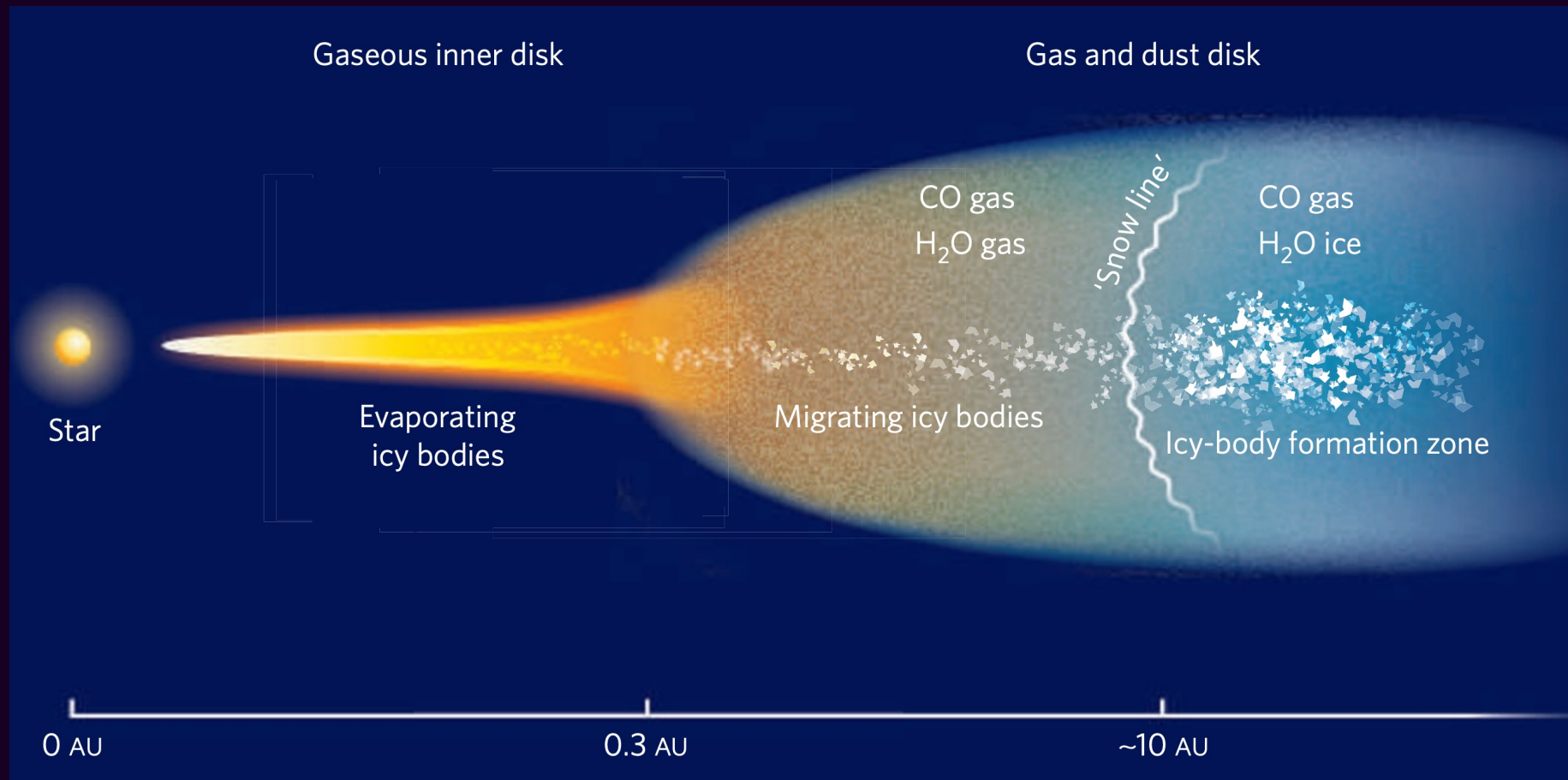
PLANET FORMATION - L02



雪线

SNOWLINE

PLANET FORMATION - L02



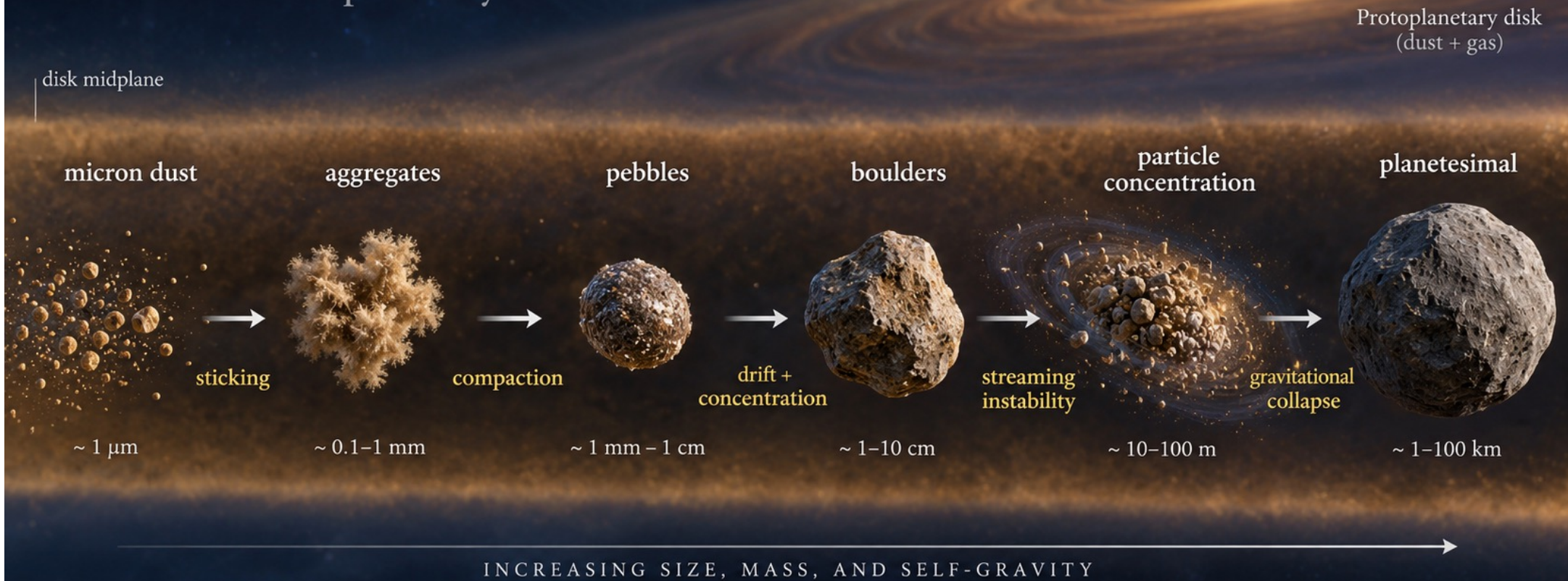
Lecture 3

尘埃动力学与演化

Dust Dynamics and Evolution

From Dust to Planetesimals

Growth in a Protoplanetary Disk



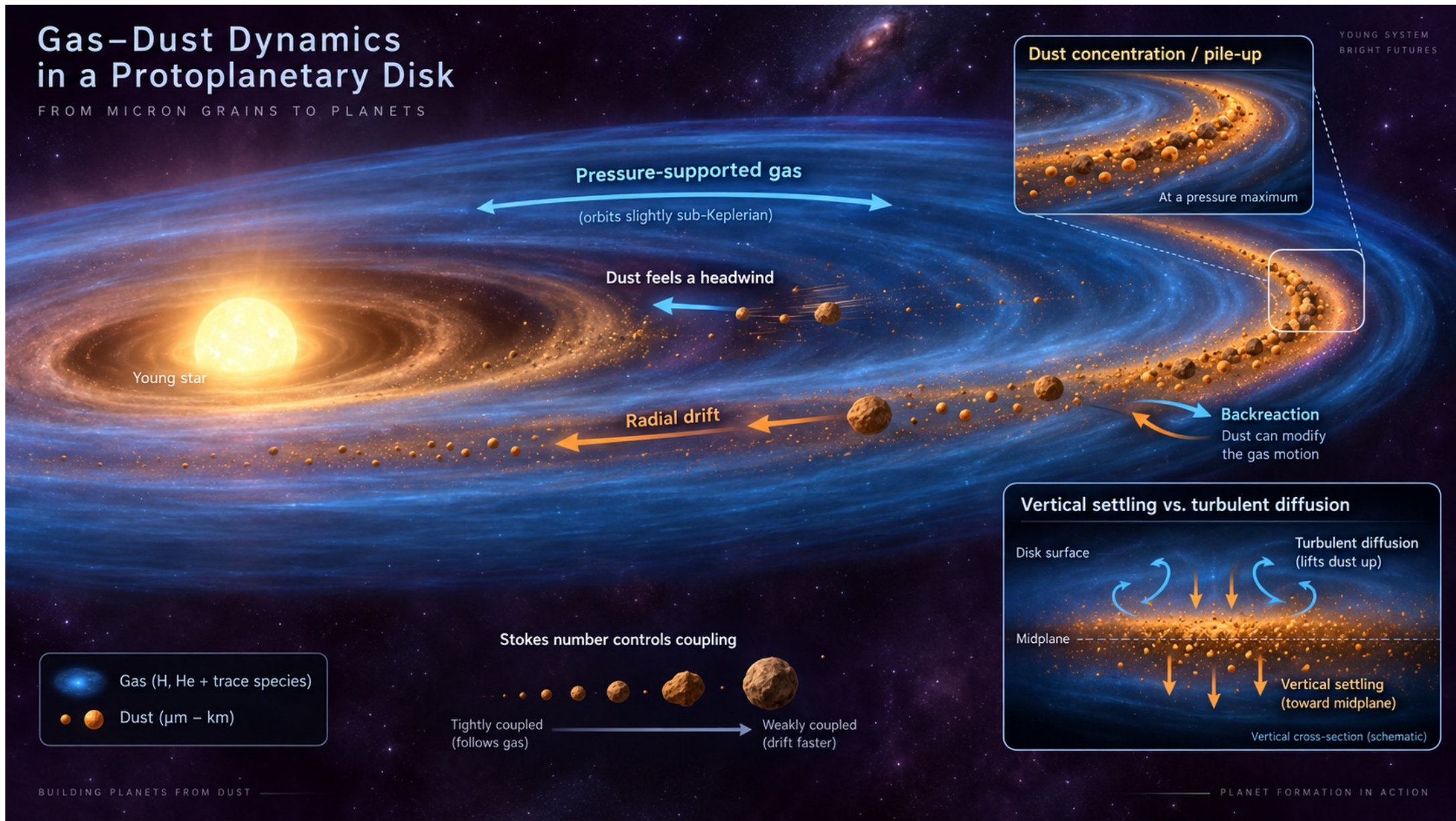
In the midplane of a protoplanetary disk, dust can grow from micron-sized grains to kilometer-sized planetesimals through a combination of sticking, compaction, dynamical concentration, and gravitational collapse.

Building blocks of planets

Gas–Dust Dynamics in a Protoplanetary Disk

FROM MICRON GRAINS TO PLANETS

YOUNG SYSTEM
BRIGHT FUTURES



原行星盘中气体与尘埃的受力

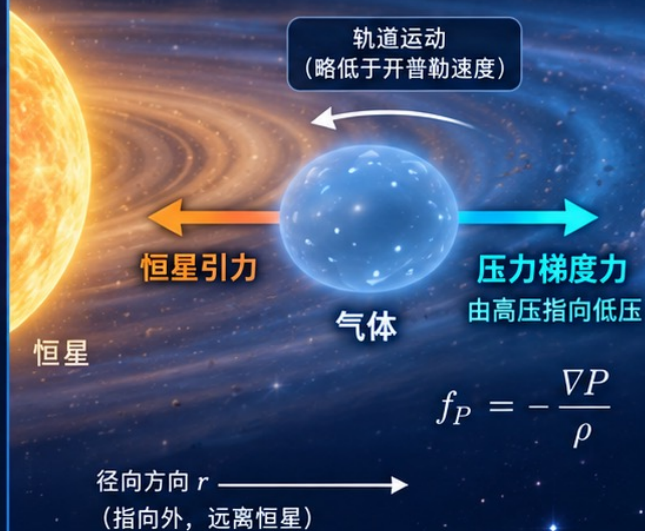
—— 为什么尘埃不直接感受到气体的压力梯度？

行星从星尘中诞生

From dust to planets
in protoplanetary disks

气体受力

气体是连续流体，直接受到压力梯度力



气体是连续流体，直接受到压力梯度力。

尘埃受力

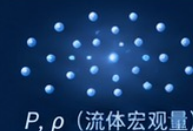
尘埃是离散固体颗粒



尘埃是离散固体颗粒。

为什么尘埃没有直接感受到 pressure?

- 1 压力是气体流体的宏观量，力密度为 $-\nabla P$ 。



- 2 单个尘埃粒子不属于气体连续介质，因此没有显著的直接压力梯度力。



- 3 尘埃与气体的相互作用主要来自表面分子碰撞，因此表现为拖曳力 drag force。



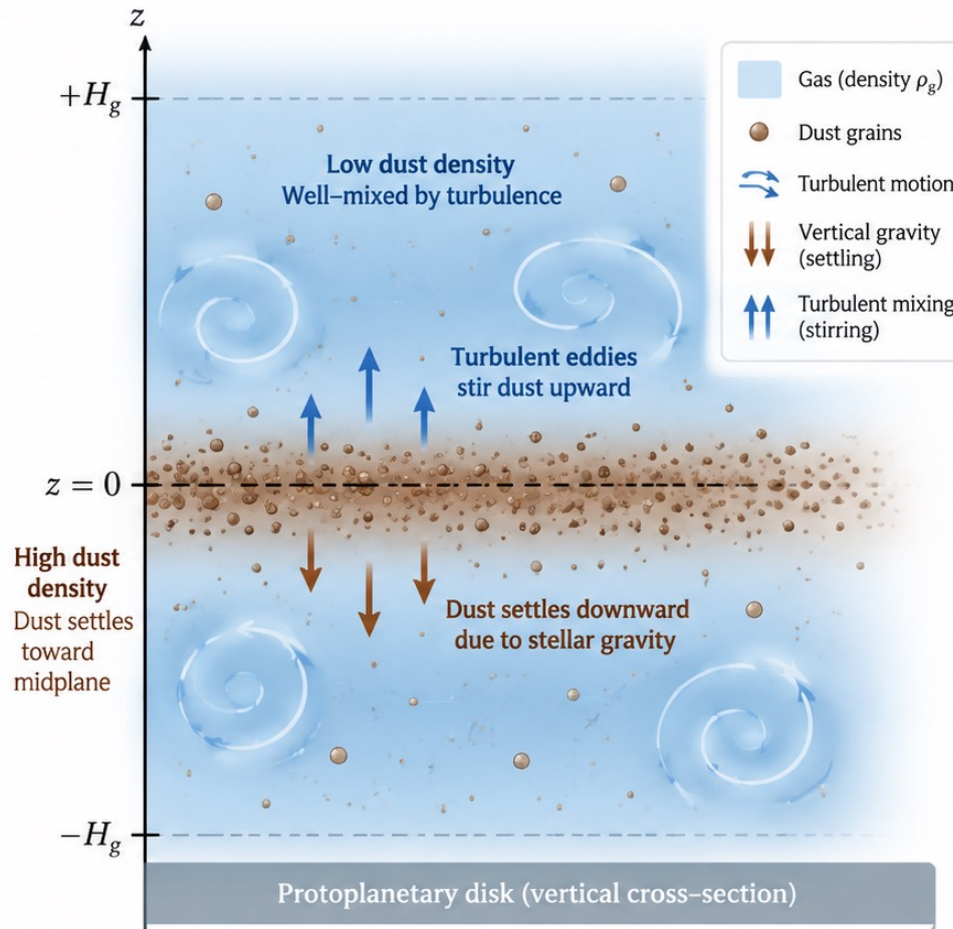
结论： 气体直接受 pressure gradient force；
尘埃只通过 gas drag 间接受到气体影响。

垂向沉降与湍流平衡

DUST SETTLING AND TURBULENT DIFFUSION

PLANET FORMATION · L03

Vertical settling vs. turbulent stirring of dust



Competition between settling and turbulent diffusion

Gravitational settling

$$v_{\text{set}} \approx -\Omega_K^2 t_{\text{stop}} z \quad (\text{for small St})$$

Pulls dust toward the midplane

Turbulent diffusion

$$F_{\text{diff}} = -D_d \frac{\partial \rho_d}{\partial z}$$

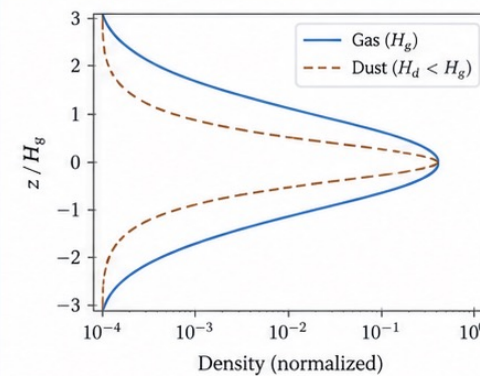
Turbulence mixes dust upward

Equilibrium (settling-stirring balance)

Vertical dust distribution

$$\rho_d(z) = \rho_{d,0} \exp\left(-\frac{z^2}{2H_d^2}\right) \quad H_d = H_g \sqrt{\frac{\alpha}{\alpha + \text{St}}}$$

Vertical profiles (illustration)



- Gas is supported by pressure, so it has a large scale height $H_g = c_s/\Omega_K$.
- Dust feels little pressure force (because the pressure gradient acts on gas; dust feels it only indirectly via gas drag), and thus settles toward the midplane.
- Turbulence counteracts settling, leading to a finite dust scale height H_d .
- Larger St (bigger grains) $\rightarrow$ thinner dust layer.
- Stronger turbulence (larger α) $\rightarrow$ thicker dust layer.

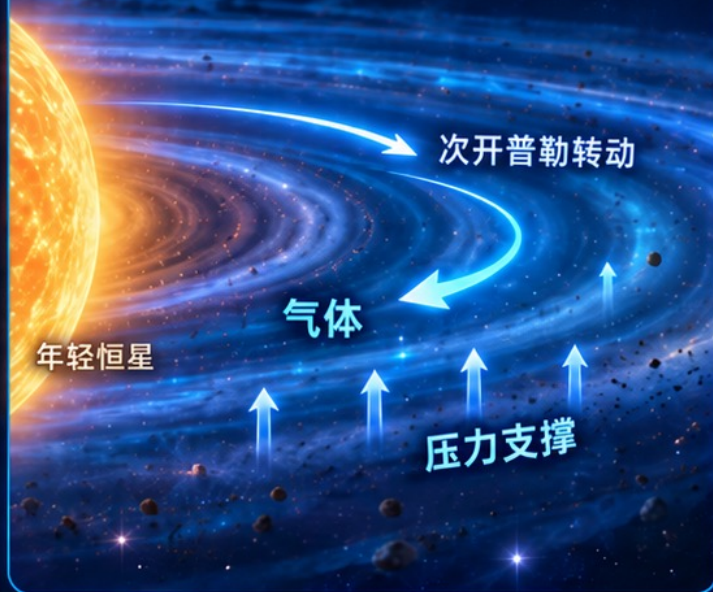
原行星盘中的径向漂移

为什么尘埃会向恒星漂移？

1

气体

气体受压强支撑，转动略慢于开普勒速度



2

尘埃

尘埃本想按开普勒速度运动
但受到气体的迎风阻力



3

结果

尘埃被拖慢，逐渐向恒星靠近



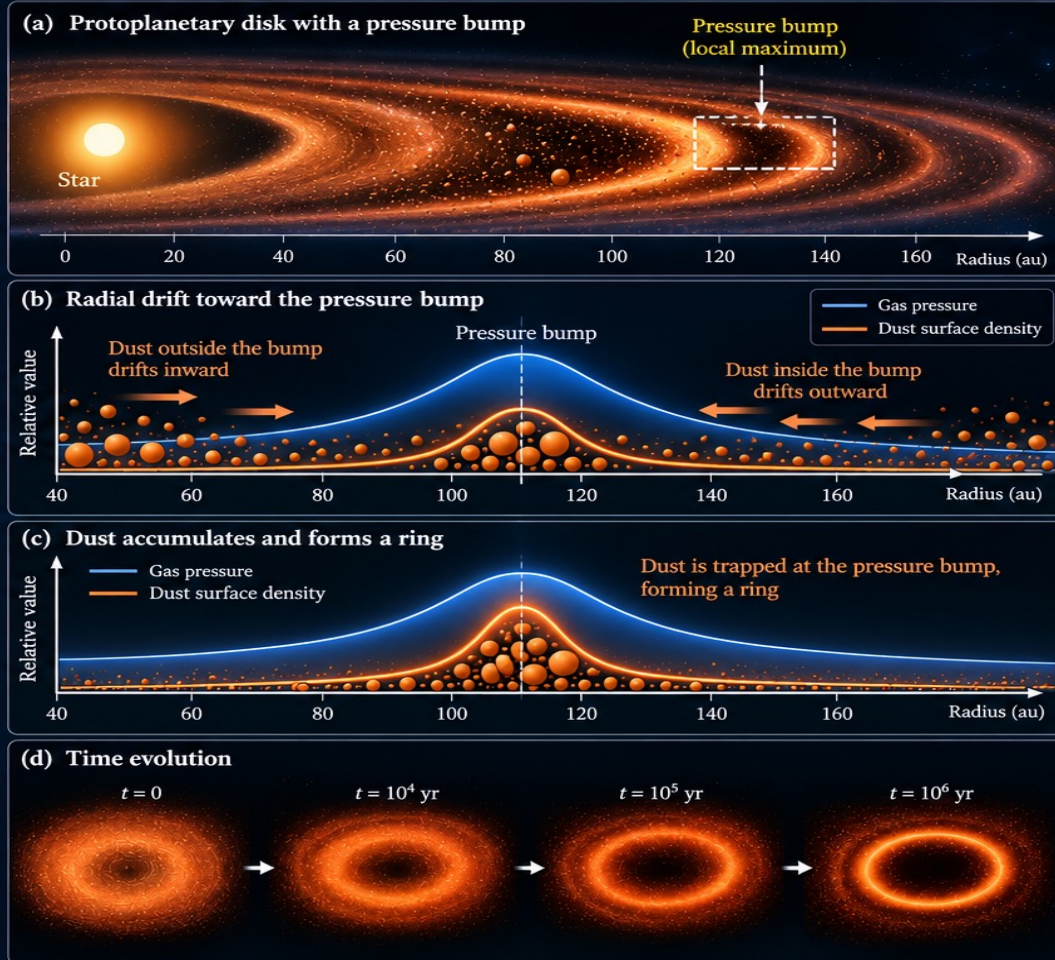
关键结论：压强先改变气体转动；尘埃再通过拖曳力间接受到影响。

观测如何识别漂移与生长？

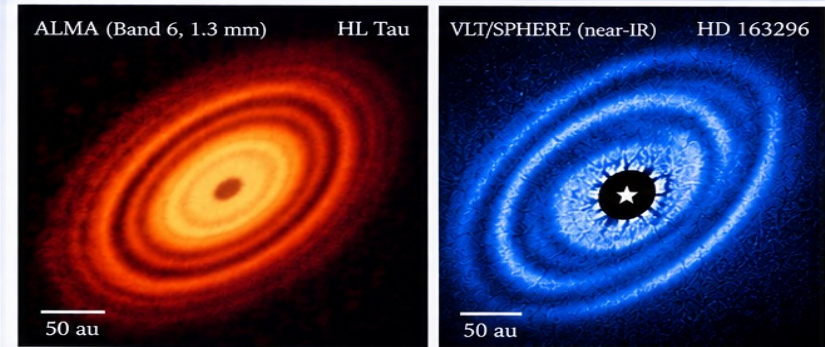
PLANET FORMATION · L03

OBSERVATIONAL SIGNATURES OF DRIFT AND GRAIN GROWTH

Dust Rings from Radial Drift and Pressure Bumps



Observed disks with dust rings



How to distinguish radial drift and dust growth observationally?

Observable	Radial drift signature (redistribution)	Dust growth signature (size evolution)
Ring position vs. wavelength	Rings shift inward at longer wavelengths (larger grains drift more)	Rings at similar locations across wavelengths (if growth is dominant)
Spectral index (α)	Low α in bright rings (large grains accumulate); Usually a global decrease with radius due to drift	Low α specifically in rings due to grain growth
Multi-wavelength morphology	Narrower rings at longer wavelengths (larger grains more confined)	Rings become brighter and more pronounced at longer wavelengths
Time evolution	Rings can form relatively quickly ($\sim 10^4 - 10^5 \text{ yr}$)	Gradual brightening and spectral evolution as grains grow ($\sim 10^5 - 10^6 \text{ yr}$)
Gas vs. dust distribution	Dust rings may be offset from smooth gas (if drift dominates)	Dust and gas rings more well-aligned (if growth dominates)

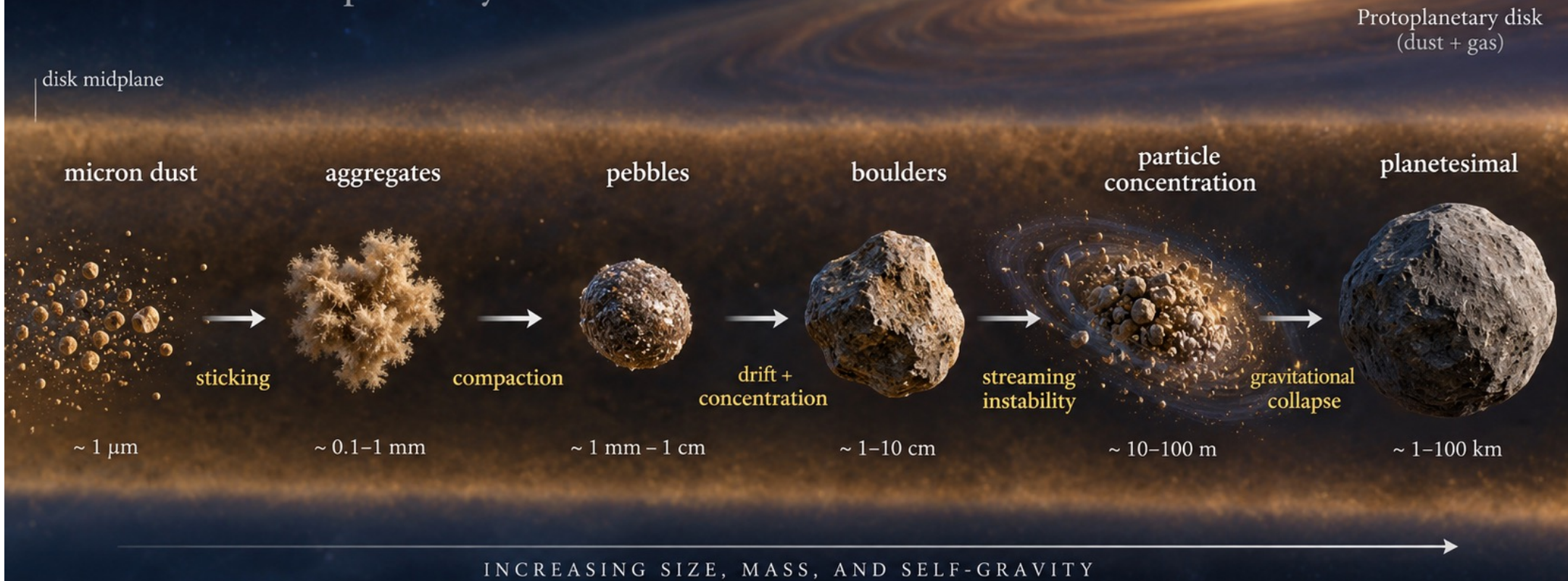
Lecture 4

星子形成

Dust Dynamics and Evolution

From Dust to Planetesimals

Growth in a Protoplanetary Disk



In the midplane of a protoplanetary disk, dust can grow from micron-sized grains to kilometer-sized planetesimals through a combination of sticking, compaction, dynamical concentration, and gravitational collapse.

Building blocks of planets

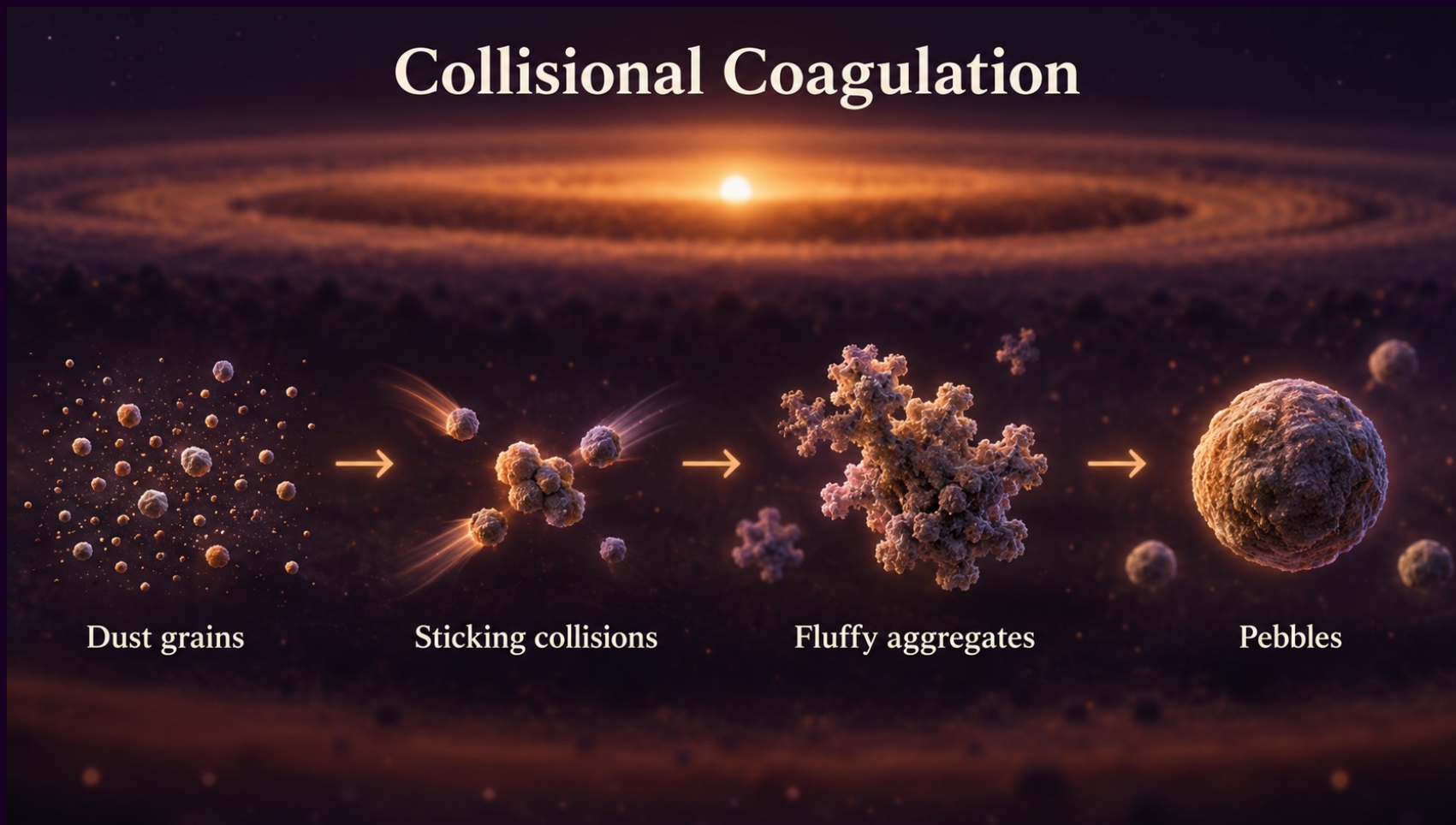
碰撞凝聚

COLLISIONAL COAGULATION

PLANET FORMATION · L04

碰撞凝聚给出起点，但不能保证形成千米级的星子。

Collisional Coagulation



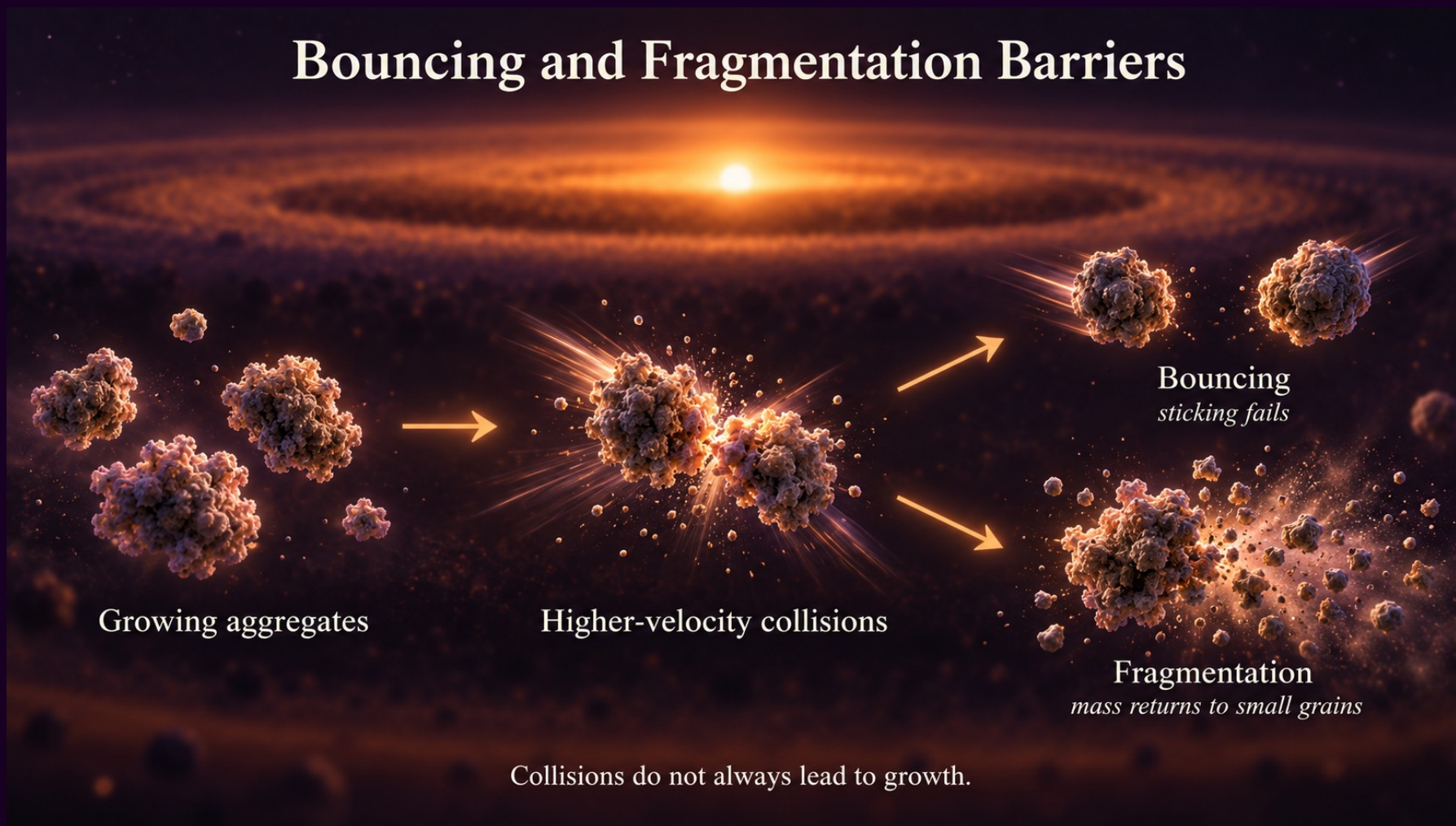
反弹与碎裂障碍

BOUNCING AND FRAGMENTATION BARRIERS

PLANET FORMATION · L04

障碍的本质：碰撞频率增加了，但有效增长效率下降。

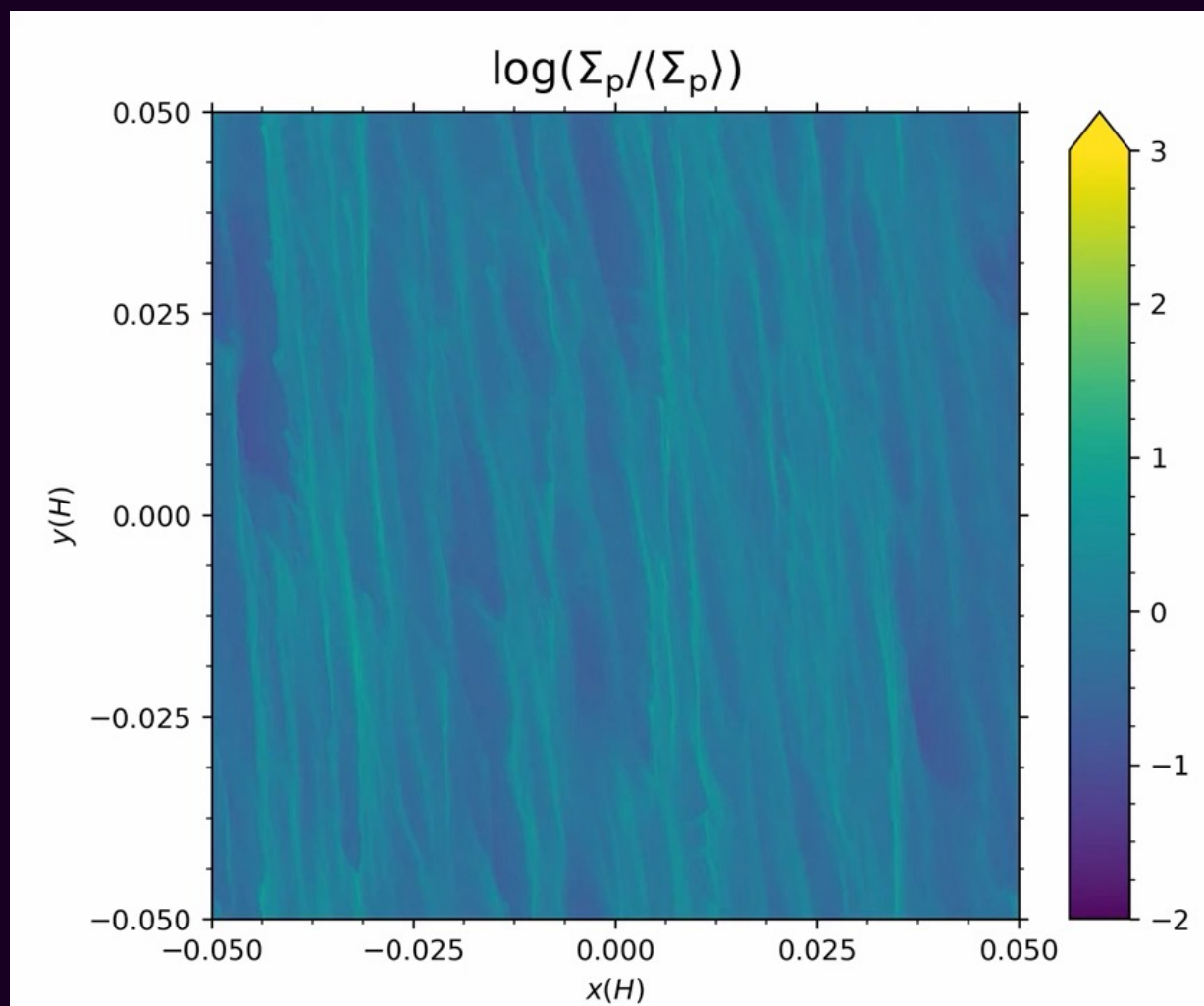
Bouncing and Fragmentation Barriers



流不稳定性

STREAMING INSTABILITY: NUMERICAL RESULTS

PLANET FORMATION · L04

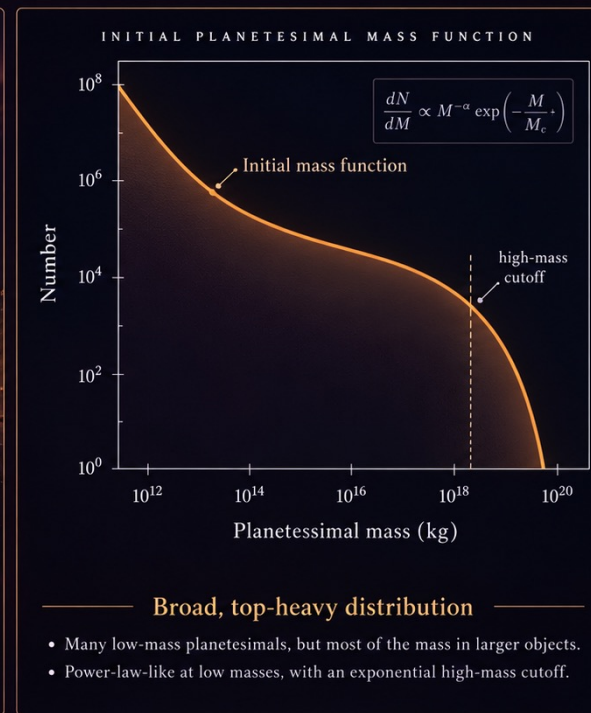


引力坍缩与初始星子质量函数

PLANET FORMATION · L04

GRAVITATIONAL COLLAPSE AND THE INITIAL PLANETESIMAL MASS FUNCTION

Gravitational Collapse and the Initial Planetesimal Mass Function



问题：第一批星子出生时，是小而多，还是已经相当大？

Image credit: NASA/Johns Hopkins APL/Southwest Research Institute; public planet-formation schematic

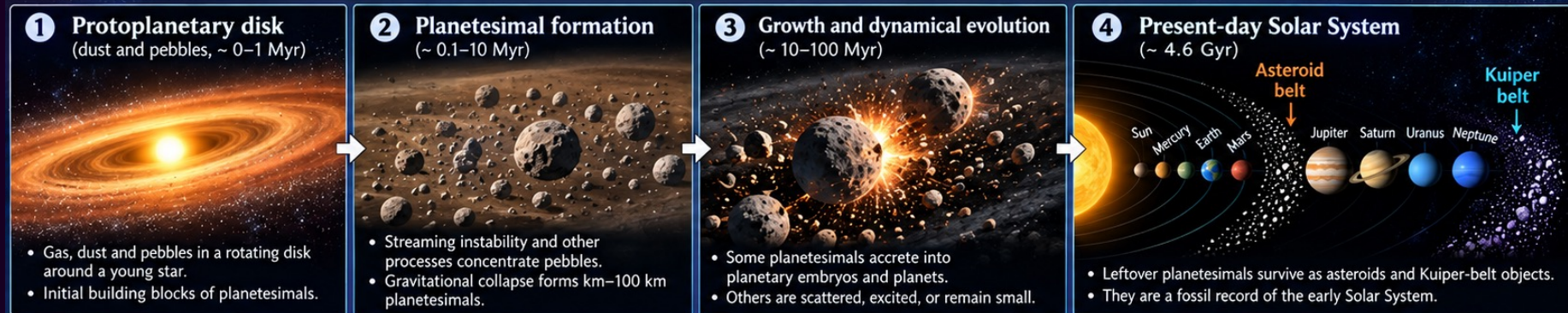
小行星带与柯伊伯带：星子形成的化石记录

PLANET FORMATION · L04

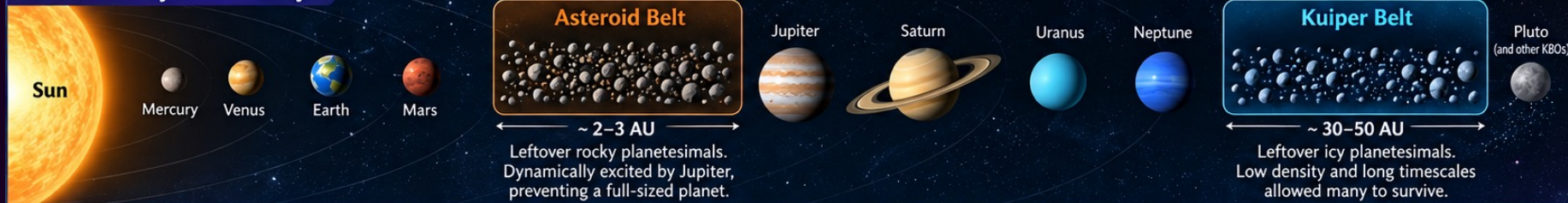
ASTEROID AND KUIPER BELTS AS FOSSIL RECORDS

Asteroid Belt and Kuiper Belt: Fossil Records of Planetsimal Formation

Not all planetesimals became planets — some survived, preserving the early history of our Solar System.



The Solar System Today



Examples of asteroid belt objects (mostly rocky)



Examples of Kuiper belt objects (icy)



What they tell us

- Preserve the primordial composition of the protoplanetary disk.
- Record the size distribution of early planetesimals.
- Constrain models of planetesimal formation and planetary migration.
- Provide clues to the dynamical history of the Solar System.

Asteroid belt and Kuiper belt are time capsules — surviving planetesimals that did not get incorporated into planets.

Lecture 5

卵石吸积

PEBBLE ACCRETION

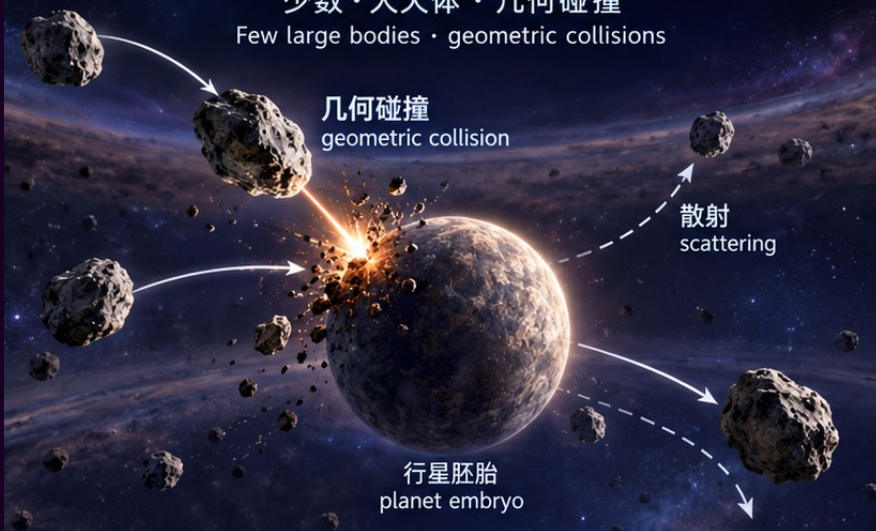
星子吸积和卵石吸积

PLANET FORMATION · L05

PLANETESIMAL AND PEBBLE ACCRETION

星子吸积 Planetesimal accretion

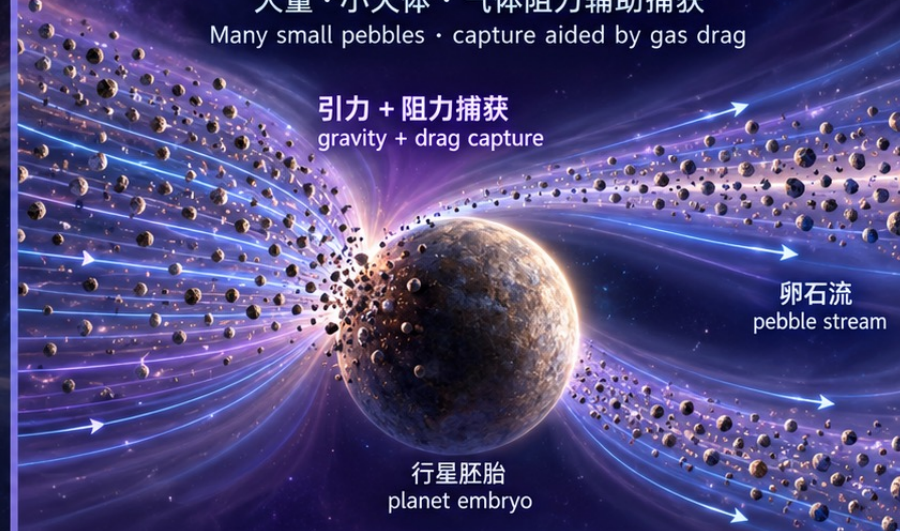
少数 · 大天体 · 几何碰撞
Few large bodies · geometric collisions



- 星子数量少，体积大 Few but large planetesimals
- 以几何碰撞为主 Dominated by geometric collisions
- 碰撞概率低 Low collision probability
- 许多天体被引力散射 Many bodies are gravitationally scattered
- 吸积效率低 Low accretion efficiency

卵石吸积 Pebble accretion

大量 · 小天体 · 气体阻力辅助捕获
Many small pebbles · capture aided by gas drag



- 卵石数量多，尺寸小 Many small pebbles
- 通过引力与气体阻力共同捕获 Captured by gravity and gas drag
- 有效的捕获截面（超越几何） Enhanced capture cross-section (beyond geometric)
- 连续的卵石流 Continuous pebble streams
- 吸积效率高 High accretion efficiency

卵石吸积

PEBBLE ACCRETION

PLANET FORMATION · L05



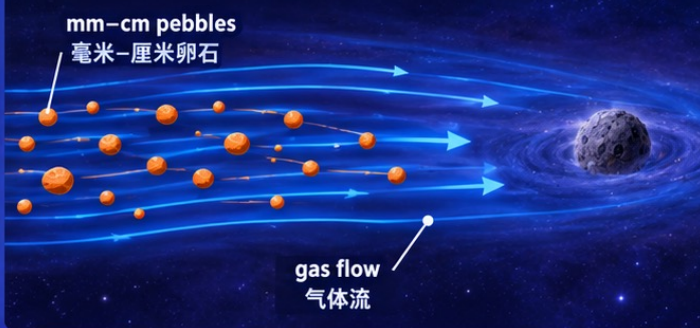
Pebble accretion | 卵石吸积

Small pebbles. Big planets.

Dusty building blocks, gravity and gas, to grow worlds.

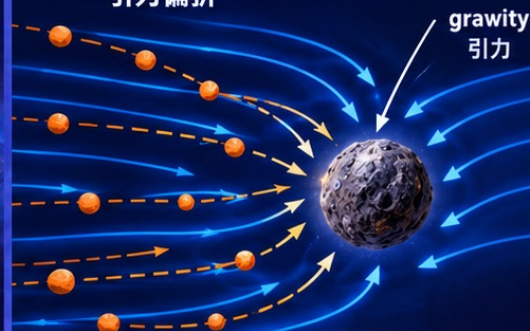
1 Pebbles drift in gas 卵石在气体中漂移

mm-cm pebbles
毫米-厘米卵石



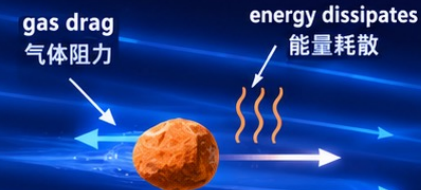
gas flow
气体流

2 gravity deflection 引力偏折



gravity
引力

3 gas drag 气体阻力



gas drag
气体阻力

energy dissipates
能量耗散

4 captured pebble 被捕获



5 Growing planet 逐渐长大的行星胚胎



-  More pebbles
更多卵石 →
-  Bigger core
更大的核心 →
-  Faster growth
更快的生长 →

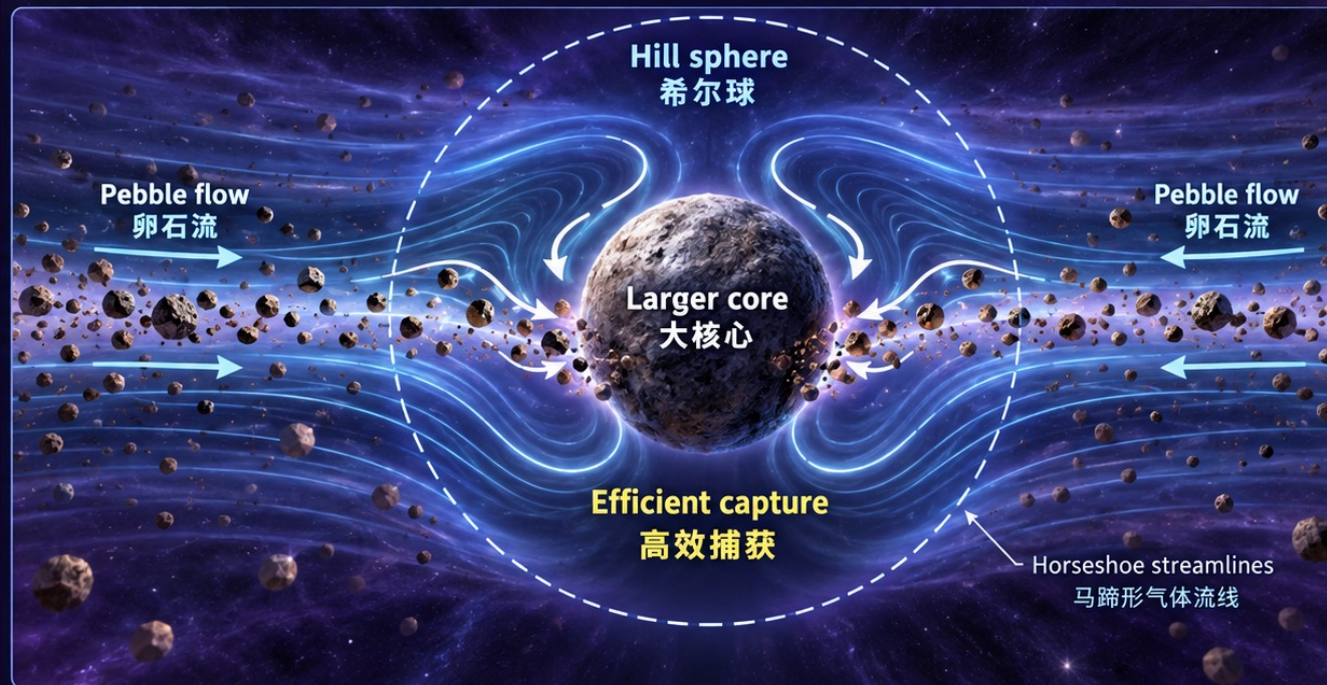
Hill 区域

PLANET FORMATION · L05

THE HILL REGIME: EFFICIENT CAPTURE BY LARGER CORES

Hill regime / Hill 区域

Efficient capture by larger cores 大核心的高效捕获



Hill sphere vs. Bondi sphere 希尔球与邦迪球的比较



For larger cores:
 $R_{\text{Hill}} > R_{\text{Bondi}}$
对于较大的核心:
 $R_{\text{Hill}} > R_{\text{Bondi}}$



Larger core 大核心

Stronger gravity, larger Hill sphere
引力更强，希尔球更大



Horseshoe flow 马蹄形流动

Pebbles from both sides are funneled in
来自两侧的卵石被引导进入



Efficient capture 高效捕获

High probability of accretion
高的吸积概率

卵石流

PEBBLE FLUX

PLANET FORMATION · L05

全局卵石流 Global pebble flux

外盘产生的卵石向内漂移，并在途中被行星胚胎部分吸积，决定了行星核的生长。

Pebbles formed in the outer disk drift inward, are partially accreted by planetary embryos, and control the growth of planetary cores.

中心恒星
Central star

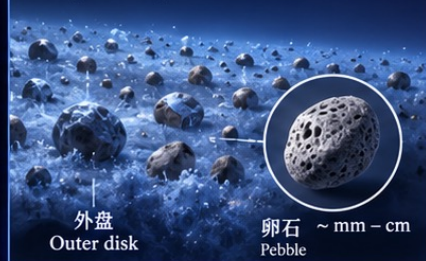
向内 (更高温度)
Inward (higher temperature)

向外 (更低温度)
Outward (lower temperature)

r

1 卵石源 Pebble source

外盘的尘埃在低温下生长并形成卵石。
Dust grows into pebbles in the cold outer disk.



2 径向漂移 Radial drift

卵石在气体盘中因气体阻力向内漂移，形成全局卵石流。
Pebbles experience gas drag and drift inward, forming a global pebble flux.



3 胚胎过滤 Filtering by embryos

沿途的行星胚胎吸积部分卵石，逐步削弱向内的卵石流。
Planetary embryos accrete part of the pebbles en route, gradually reducing the inward flux.



4 漂移限制增长 Drift-limited growth

内盘在多次过滤后卵石流被耗尽，行星核的生长受到漂移供给的限制。
After multiple stages of filtering, the inner disk is starved of pebbles, and core growth is limited by the drift supply.



行星核的生长受限于全局卵石流的供给 — 这就是“漂移限制增长”。
The growth of planetary cores is limited by the global pebble flux — this is drift-limited growth.

卵石隔离质量

PEBBLE ISOLATION MASS

PLANET FORMATION · L05

Pebble isolation 卵石隔离

A growing planet perturbs the gas, creates a pressure bump, blocks inward drifting pebbles, and its core growth slows.

逐渐增大的行星扰动气体，在其轨道外侧形成压强峰，阻断向内漂移的卵石，导致行星核的增长减慢。

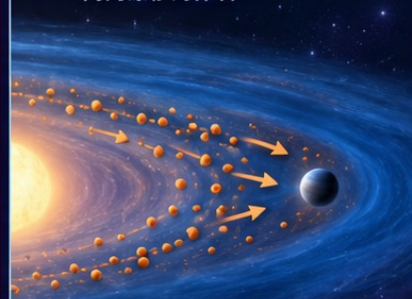
Young star
年轻的恒星

Pebbles (solid particles)
卵石 (固体颗粒)

Gas disk
气体盘

Growing planet
正在成长的行星

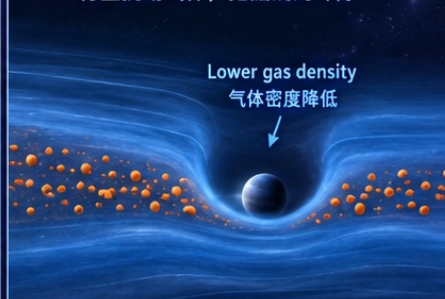
1 Inward drifting pebbles 向内漂移的卵石



Pebbles drift inward through the gas disk due to gas drag and are accreted by the planet, helping its core grow.

在气体阻力作用下，卵石向内漂移，被行星吸积，促进其行星核的增长。

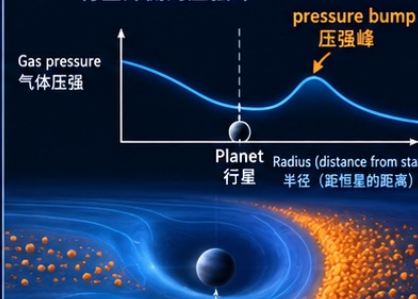
2 Planet perturbs gas and carves a gap 行星扰动气体，挖掘浅的环隙



A sufficiently massive planet (the pebble isolation mass) perturbs the gas and carves a shallow gap in the disk.

当行星质量达到卵石隔离质量时，会显著扰动气体，在盘中挖掘出一个较浅的环隙。

3 Exterior pressure bump 行星外侧的压强峰



The planet's gravity modifies the gas pressure profile, creating a pressure bump outside its orbit, where pebbles accumulate.

行星的引力改变了气体的压强分布，在其轨道外侧形成一个压强峰，卵石在此处堆积。

4 Pebble flow blocked — core growth slows 卵石流被阻断 — 核增长减慢



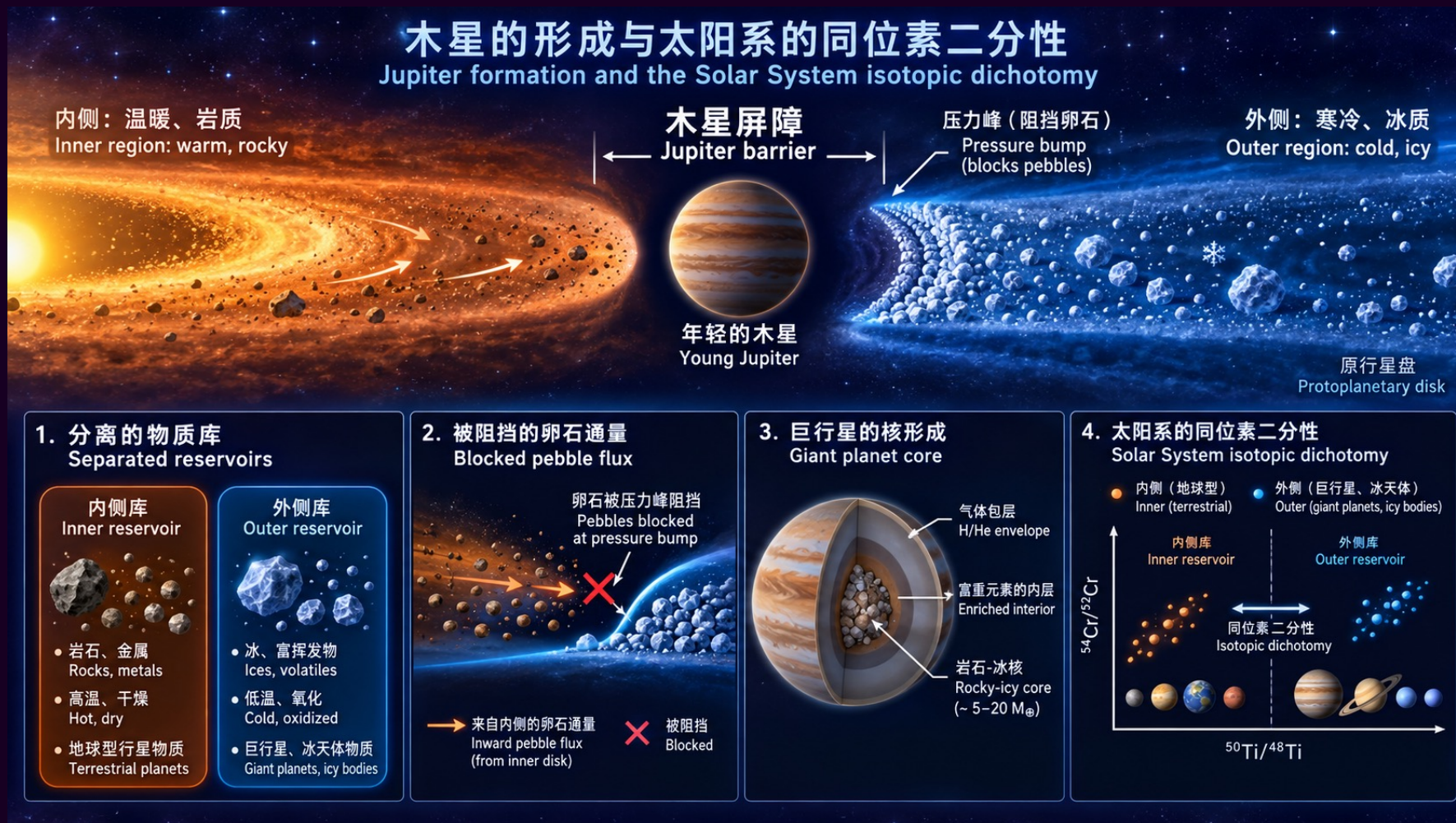
The pressure bump stops further inward pebble drift. With the pebble supply cut off, the planet's core growth slows.

压强峰阻断了进一步向内的卵石流动。由于卵石供给被切断，行星核的增长减慢。

木星形成与太阳系同位素二分性

PLANET FORMATION · L05

JUPITER FORMATION AND THE SOLAR SYSTEM ISOTOPIC DICHOTOMY



Lecture 6

核吸积和引力坍缩

CORE ACCRETION AND GI

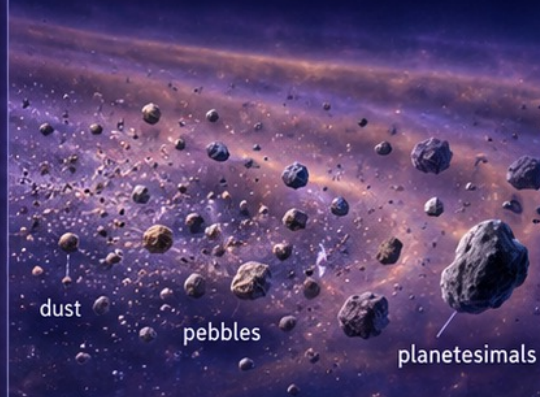
SAME
MATERIALS.
DIFFERENT
WORLDS.

Core Accretion

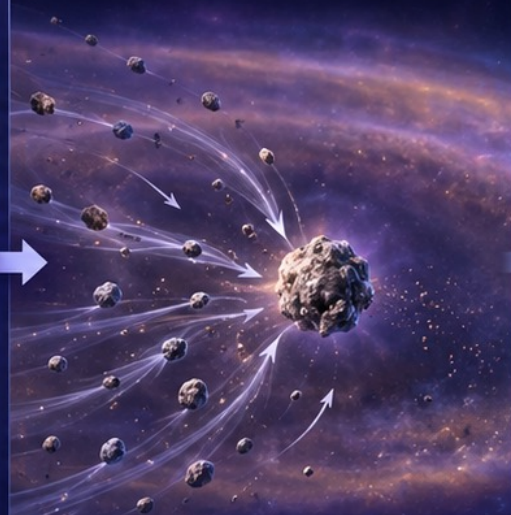
From solids to a giant planet

PLANET FORMATION
IN PROTOPLANETARY DISKS
DUST → CORES → GIANT PLANETS

1. DUST, PEBBLES, PLANETESIMALS SOLID MATERIAL IN A GAS DISK



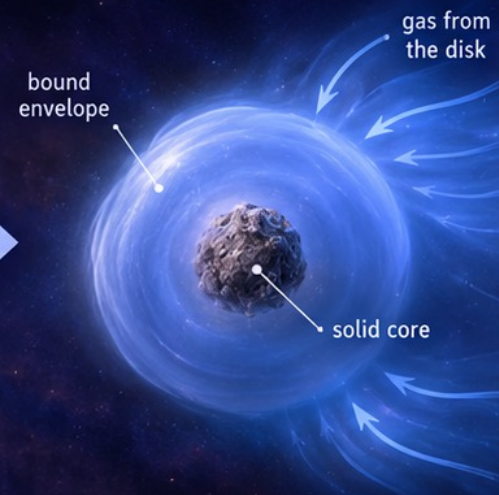
2. PEBBLE ACCRETION RAPID GROWTH BY CAPTURING PEBBLES



3. PLANETESIMAL ACCRETION LATER GROWTH BY LARGER BODIES



4. BOUND GASEOUS ENVELOPE CAPTURING GAS FROM THE DISK



once the core is massive enough, it gravitationally binds a gaseous envelope from the surrounding disk

SOLIDS DOMINATE
building the core

GROWING CORE

GAS ACCRETION BEGINS
toward a giant planet

PLANETS FORM FROM THE BOTTOM UP
Figure: AI-generated instructional illustration

CORES TODAY. GIANT WORLDS TOMORROW.

The Structure of an Accreting Envelope

A protoplanet embedded in a gas disk

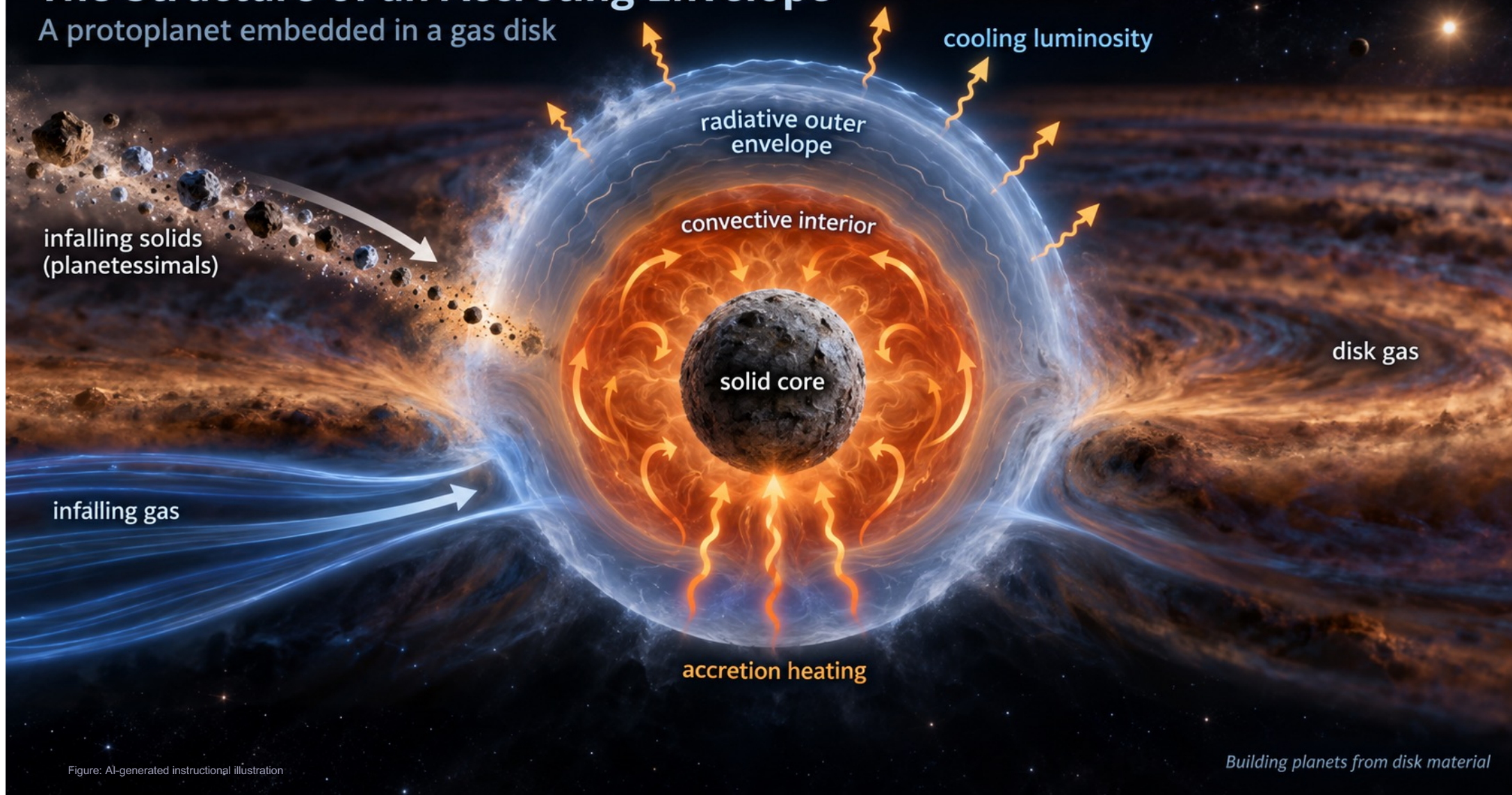


Figure: AI-generated instructional illustration

Building planets from disk material

Gravitational Instability

From a massive, cool disk to self-gravitating clumps

SAME PHYSICS.
NEW WORLDS.

1 MASSIVE, COOL OUTER DISK Early stage



2 SPIRAL INSTABILITY Self-gravity drives spiral arms



3 FRAGMENTATION Clumps condense



4 OUTER DISK Giant planet embryos



KEY INGREDIENTS



Outer disk
Cool, massive disk at large radius.



Toomre $Q \sim 1$
Disk becomes self-gravitating.



Rapid cooling
Heat is radiated away quickly, allowing collapse.



Spiral instability
Self-gravity drives spiral arms.



Fragmentation
Spiral arms break into bound clumps.

Protoplanetary disk around a young star

Increasing radius →

Outer disk
(cool, self-gravitating)

ZOOM: FRAGMENTING SPIRAL ARM



POTENTIAL OUTCOME
Giant planet formed via gravitational instability (at wide orbit).

Figure: AI-generated instructional illustration
COOL DISKS. BIG PLANETS.

FROM DUST TO WORLDS

What Gravitational Instability **Can** and **Cannot** Produce

SAME
PHYSICS.
DIFFERENT
OUTCOMES.

WHAT GI **CAN** PRODUCE



Massive gas giants or brown-dwarf-like companions

Typical masses: a few–tens of Jupiter masses (at the high end, brown-dwarf-like).



Wide orbits

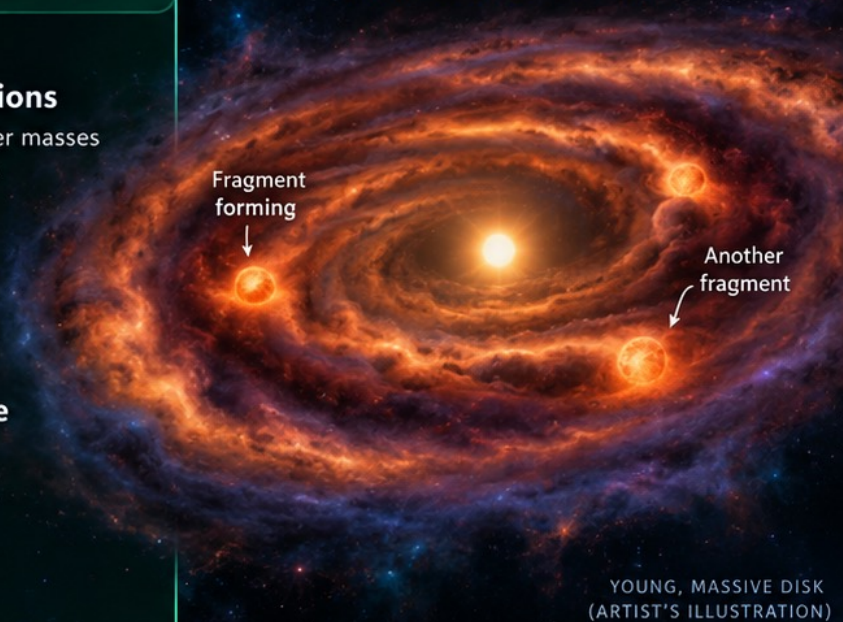
Preferentially at large distances (tens to hundreds of AU).



Rapid formation in massive outer disks

Fragments can form quickly (in ~thousands of years) in cool, massive outer disks.

A DISK FRAGMENTING VIA GRAVITATIONAL INSTABILITY



YOUNG, MASSIVE DISK
(ARTIST'S ILLUSTRATION)

WHAT GI **STRUGGLES** TO PRODUCE



Small cores

GI does not naturally make Earth-mass or super-Earth cores ($\leq 10 M_{\oplus}$).



SMALL CORE
(EARTH-MASS SCALE)



Close-in hot Jupiters (in situ)

Difficult to form giant planets at very small orbital distances (≤ 0.1 AU) by GI.

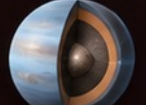


HOT JUPITER
(≤ 0.1 AU)



Metal-rich cores

GI forms gas-rich, metal-poor fragments; high heavy-element cores are not expected.



METAL-RICH CORE
(NOT EXPECTED)



Low-mass ice giants

Producing Uranus/Neptune-mass planets ($\sim 10\text{--}20 M_{\oplus}$) is challenging for GI.



ICE GIANT
($\sim 10\text{--}20 M_{\oplus}$)

EXAMPLE OUTCOMES

GI-FORMED COMPANIONS (TYPICAL)



$\sim 1\text{--}10 M_J$
Wide orbit
($\sim 50\text{--}200$ AU)



$\sim 10\text{--}30 M_J$
Brown-dwarf-like
Wide orbit



Example system
(with star for scale)

Figure: AI-generated instructional illustration

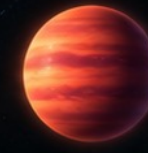
SAME
PROCESS.
DIFFERENT
PLANETS.

GRAVITATIONAL
INSTABILITY EXCELS AT
BIG, COLD, AND FAR —
BUT NOT EVERYTHING.

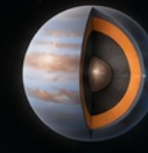
CASES GI STRUGGLES WITH



Small core
($\sim 1 M_{\oplus}$)



Close-in hot Jupiter
(~ 0.05 AU)



Metal-rich giant
(core-dominated)



Low-mass ice giant
($\sim 10\text{--}20 M_{\oplus}$)

Lecture 7

行星-盘的相互作用与迁移

PLANET DISK INTERACTION AND MIGRATION

TYPE I MIGRATION

A SMALL PLANET. A MASSIVE RESPONSE.

LOW-MASS PLANETS EXCHANGE ANGULAR MOMENTUM WITH THE GAS DISK, LEADING TO ORBITAL MIGRATION.

A LOW-MASS PLANET IN A GASEOUS DISK

Spiral waves carry angular momentum, creating a net torque on the planet.

Inner wake
(pushes forward)

Outer wake
(pulls backward)

GAS DISK
DENSITY, TEMPERATURE,
AND PRESSURE GRADIENTS
DRIVE THE TORQUES

Net migration
(toward smaller or larger orbits
depending on torque balance)

LOW-MASS PLANET
($\leq$ a few Earth masses)
opens no deep gape

KEY TORQUE CONTRIBUTIONS

- **Unsaturation torque**
Arises from horseshoe orbits; can be positive.
- **Saturation**
Reduces the corotation torque over time.
- **Thermal torque**
Due to temperature gradients; can enhance outward migration.
- **Dynamical torque (Lindblad)**
From spiral density waves; usually drives inward migration.

MIGRATION DEPENDS ON DISK CONDITIONS

- Local density, temperature, and entropy gradients set the torque strengths.
- The direction (inward or outward) depends on the net torque.
- The speed depends on the planet mass and disk properties.

"Even a small planet can make a big move."

1. CLASSICAL TYPE I MIGRATION

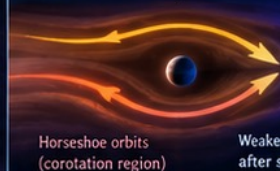
In a smooth, isothermal disk, the dynamical torque dominates.



- Outer wake is stronger than inner wake.
- Net torque is negative (inward).
- Migration is rapid for low-mass planets.

2. COROTATION TORQUE SATURATION

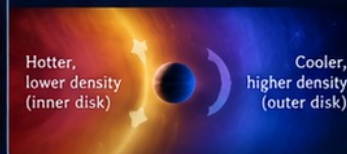
The corotation torque can weaken if gradients are erased.



- Gas on horseshoe orbits exchanges angular momentum.
- If diffusion is weak, the corotation torque saturates (fades).
- Saturation removes a key source of outward migration.

3. ENTROPY / VORTENSITY RELATED TORQUE

Non-isothermal disks can produce a strong corotation torque.



- Entropy and vortensity gradients can drive a positive corotation torque (outward).
- Requires gradients to be maintained (i.e., not saturated).
- Can slow, halt, or reverse migration under the right conditions.

4. THERMAL AND DYNAMICAL TORQUE EFFECTS

Temperature structure and wave dynamics modify the total torque.



- Thermal torque arises from temperature gradients and can add an outward push.
- Dynamical (Lindblad) torque usually drives inward migration.
- The net result depends on the balance of all torques.

THE BOTTOM LINE

Type I migration is rapid for low-mass planets
but can be slowed, halted, or reversed under certain disk conditions.

Gap Opening and Type II Migration

A giant planet can open a gap in a protoplanetary disk and then migrate with the viscous evolution of the disk.

PLANETS CARVE PATHS.
DISKS LEAD THE WAY.

Disk pressure

Pressure tries to smooth out density changes and refill the gap.

Planetary tidal torques

The planet gravitationally pushes material away, clearing a gap.

Giant planet

Disk viscosity

Viscosity transports angular momentum and helps material flow across the gap.

From gap opening to disk-driven migration.

1 Before gap opening

A low-mass planet perturbs the disk, but the disk remains largely continuous.

Low-mass planet

Perturbations are small; no clear gap.

2 Partial gap

A more massive planet creates a noticeable depletion, but material still flows past.

Intermediate mass

Partial gap with significant flow across.

3 Deep gap with circumplanetary flow

A sufficiently massive planet clears a deep gap. A circumplanetary disk forms, fed by material crossing the gap.

Massive planet

Deep gap and circumplanetary disk; limited flow across.

4 Type II migration

The gap-opening planet migrates with the viscous evolution of the disk (usually inward, but outward migration can occur).

Inward migration

Follows disk accretion when the disk flows inward.

Outward migration

Can occur in massive disks or with strong outer disk torques.

Type II migration

The planet is locked to the disk's viscous evolution.



Key Takeaways

- A sufficiently massive planet can open a gap in a protoplanetary disk.
- Gap opening is set by the competition between planetary tidal torques, disk pressure, and viscosity.
- After a deep gap forms, the planet undergoes Type II migration, moving with the viscous evolution of the disk (usually inward, sometimes outward).



When does gap opening occur?

- Occurs when the planet's tidal torques overcome disk pressure and viscosity.
- More likely for massive planets, low disk viscosity, and thin (cold) disks.
- Result is a deep, long-lived gap with a circumplanetary disk.



What controls Type II migration speed?

- Set by the viscous evolution of the disk.
- Inward migration typically follows the disk's inward accretion flow.
- Outward migration can occur in massive disks, with strong outer disk torques or special disk structures.
- Overall speed depends on the disk's viscosity, surface density, and global disk evolution.

Figure: AI-generated Instructional Illustration

PLANETS • DISKS • OTHER WORLDS

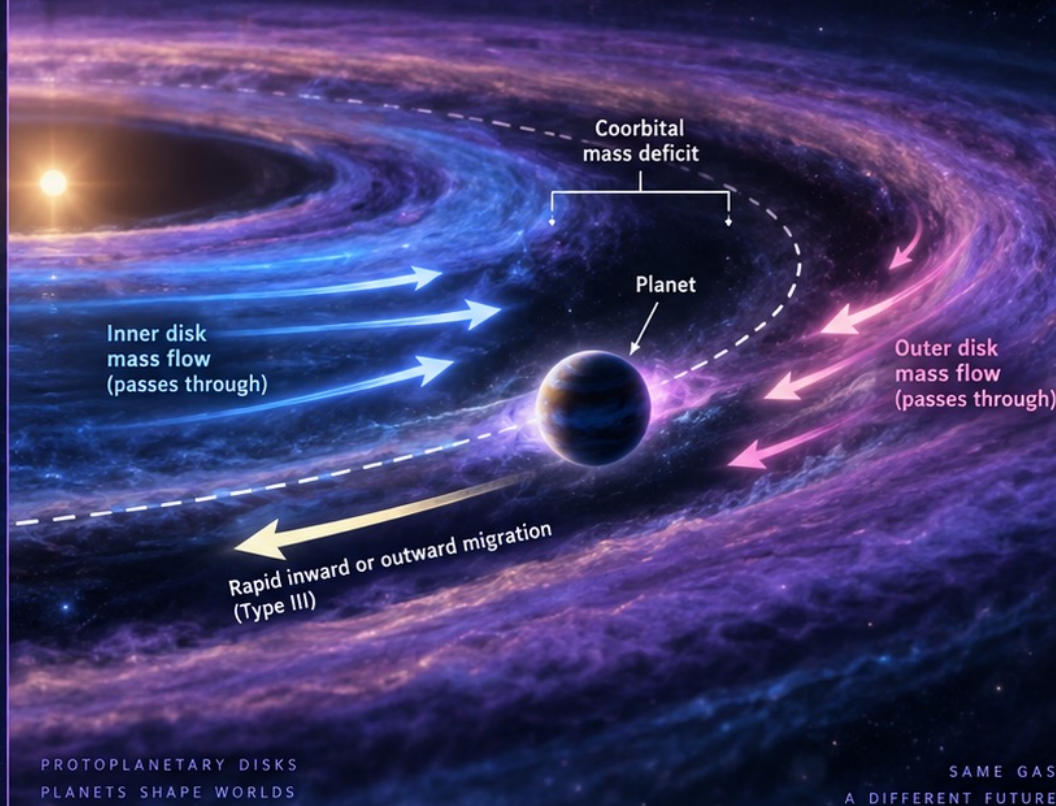
A DEEPER UNIVERSE AWAITS

Type III / Runaway Migration

A PLANET RIDING A FLOOD OF GAS

TYPE III / RUNAWAY MIGRATION

A planet near a coorbital mass deficit experiences strong, asymmetric mass flow through its orbit, leading to very rapid inward or outward migration.



PROTOPLANETARY DISKS
PLANETS SHAPE WORLDS

SAME GAS
A DIFFERENT FUTURE

MASS FLOWS DRIVE PLANETS
RAPID CHANGE IS POSSIBLE

PLANETS
DISKS
EVOLUTION
OUR UNIVERSE

1. COORBITAL MASS DEFICIT



The planet partially opens a gap, creating a deficit of gas in its coorbital region.

2. ASYMMETRY OF GAS FLOW



More gas flows through the orbit on one side than the other, creating a net torque.

3. POSITIVE AND NEGATIVE FEEDBACK

Positive feedback
(runaway)



Migration increases the mass flow, which further accelerates migration.

Negative feedback
(can saturate)



As the coorbital region fills, the torque can weaken and slow the migration.

4. RAPID SEMIMAJOR-AXIS CHANGE



The semimajor axis can change on a very short timescale compared to other migration types.

SUMMARY: TYPE III MIGRATION

- ✓ Very fast migration.
- ✓ Often associated with intermediate-mass planets in massive disks.
- ✓ Can proceed inward or outward.
- ✓ Driven by strong, asymmetric mass flow through a coorbital mass deficit, with runaway behavior possible.



Figure: AI-generated instructional illustration

SAME
MATERIAL.
BRIGHTER
FUTURES.

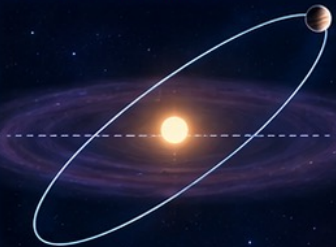
Eccentricity and Inclination Damping

GAS DISKS TEND TO MAKE PLANETS CIRCULAR AND COPLANAR

PLANETS
FORM IN
DISKS
DYNAMICS
WORLDS

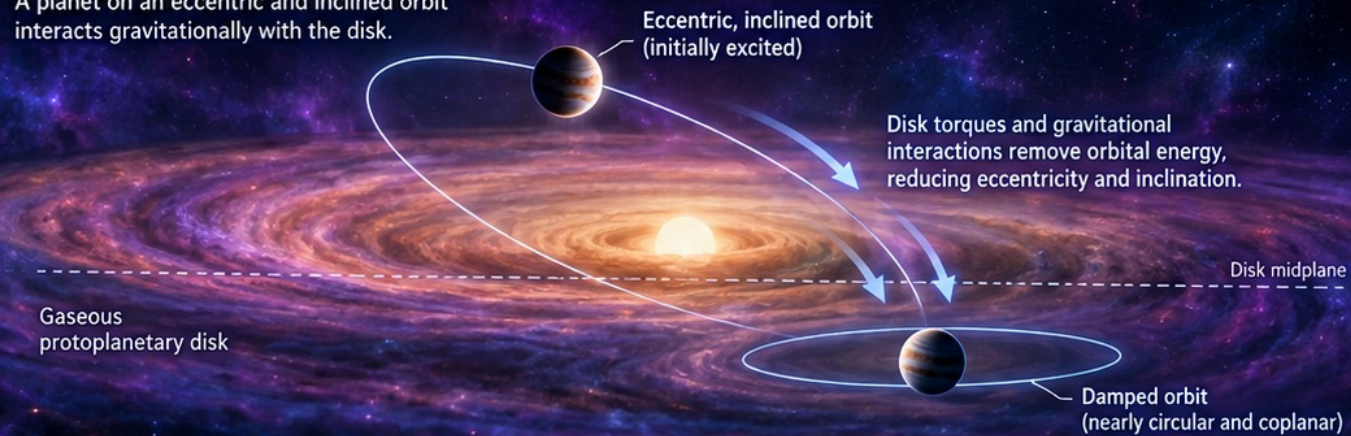
INITIAL EXCITED ORBIT

Eccentric and inclined



- High eccentricity (elongated orbit)
- Significant inclination (tilted)
- Strong interaction with disk gas

A planet on an eccentric and inclined orbit interacts gravitationally with the disk.



FINAL DAMPED ORBIT

Nearly circular and coplanar



- Low eccentricity (nearly circular)
- Low inclination (aligned with disk)
- Reached after exchange of energy and angular momentum with the disk

EXCENTRIC WAKE ASYMMETRY

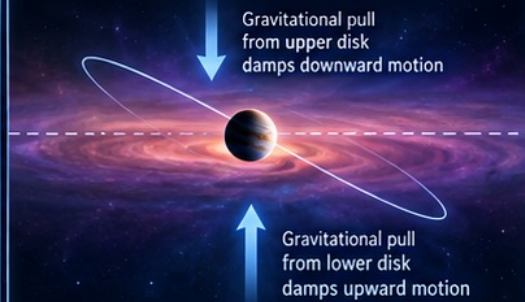
Stronger gravitational pull in front slows the planet



The planet excites spiral density waves in the disk. For an eccentric orbit, the inner (leading) wake is stronger than the outer (trailing) wake, resulting in a net torque that reduces eccentricity.

INCLINATION DAMPING

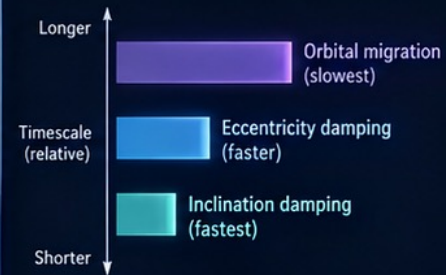
Torques from disk above and below the midplane



When the planet is above or below the midplane, the disk's gravitational pull acts to restore it toward the midplane, reducing inclination.

TIMESCALE HIERARCHY

Eccentricity and inclination damp faster than migration



Typically: inclination damps fastest, eccentricity next, and migration is slowest.

SUMMARY

Disk interactions keep embedded planets well behaved



- Gravitational torques from disk wakes remove orbital energy and angular momentum.
- Eccentricity and inclination are efficiently damped.
- As a result, many embedded planets remain nearly circular and coplanar with the disk.

DISK DAMPING OFTEN KEEPS PLANETS NEARLY CIRCULAR AND COPLANAR.

A QUIETER ORBIT BUILDS BRIGHTER WORLDS.

Resonant Capture and Resonant Chains

Planetary migration in a gas disk naturally brings planets together, where they can become locked in mean-motion resonances — often forming compact resonant chains.

SAME RHYTHM
BRIGHTER WORLDS

*Migration links worlds
to gravitationally dance
together.*

From migration ...

Planets move through the gas disk and converge toward each other ...



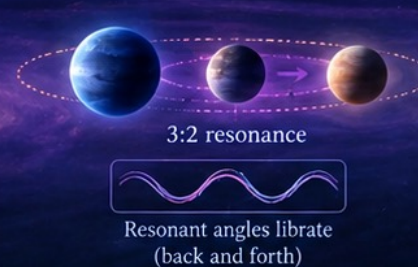
... to resonant capture ...

When close enough, the planets become trapped in a mean-motion resonance.



... to multiple resonances ...

Additional planets can be captured, forming a resonant chain.



... a compact resonant chain

Many close-in planets can end up locked together in a chain of resonances.



1. Convergent migration

Outer planets migrate inward faster than inner planets, so their orbits converge.



2. First resonant capture

The planets become trapped in resonance, with a fixed orbital period ratio.



3. Stable resonant chain

More planets are captured, building a compact, stable chain.



4. After gas dispersal – possible instability

When the gas disk disappears, the system can remain stable — or become unstable over time.



Why migration naturally forms resonant systems

- Disk-planet interactions cause inward migration, often at different rates, leading to convergent orbits.
- When planets get close, they can be captured into mean-motion resonance.
- Continued migration can build chains of resonances, especially for multiple, closely spaced planets.
- Gas damping helps maintain the resonant configuration during the disk phase.
- After the gas disperses, some systems stay intact, while others can become unstable and rearrange.

DIFFERENT ORBITS
A COMMON ORIGIN

Figure: AI-generated instructional illustration

MIGRATION TURNS
ISOLATED WORLDS
INTO ORCHESTRAS.

PLANETS • DISKS • RESONANCES • NEW WORLDS