Planet Formation

行星形成

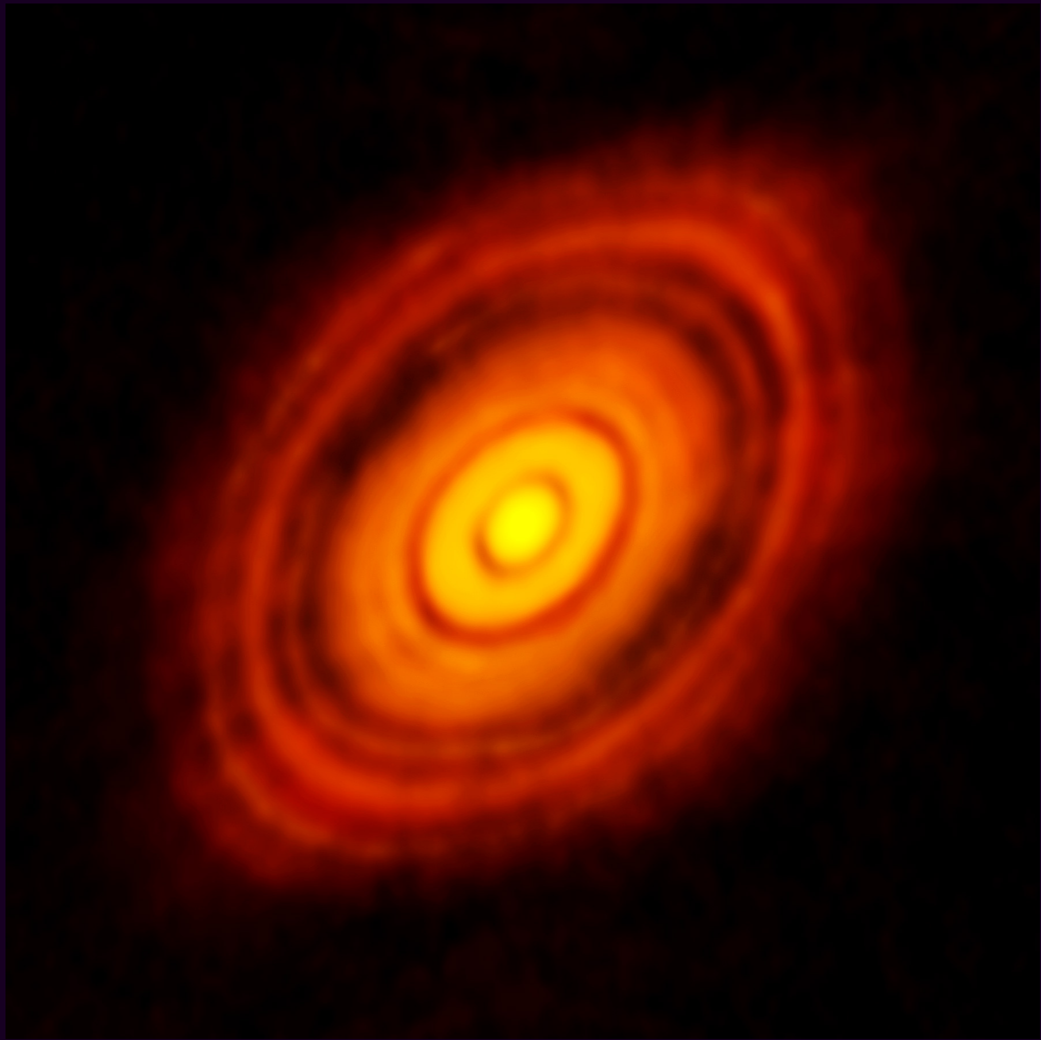


Image credit: ALMA (ESO/NAOJ/NRAO), HL Tauri disk image

南京大学深空探测研究院

2026/9/17

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

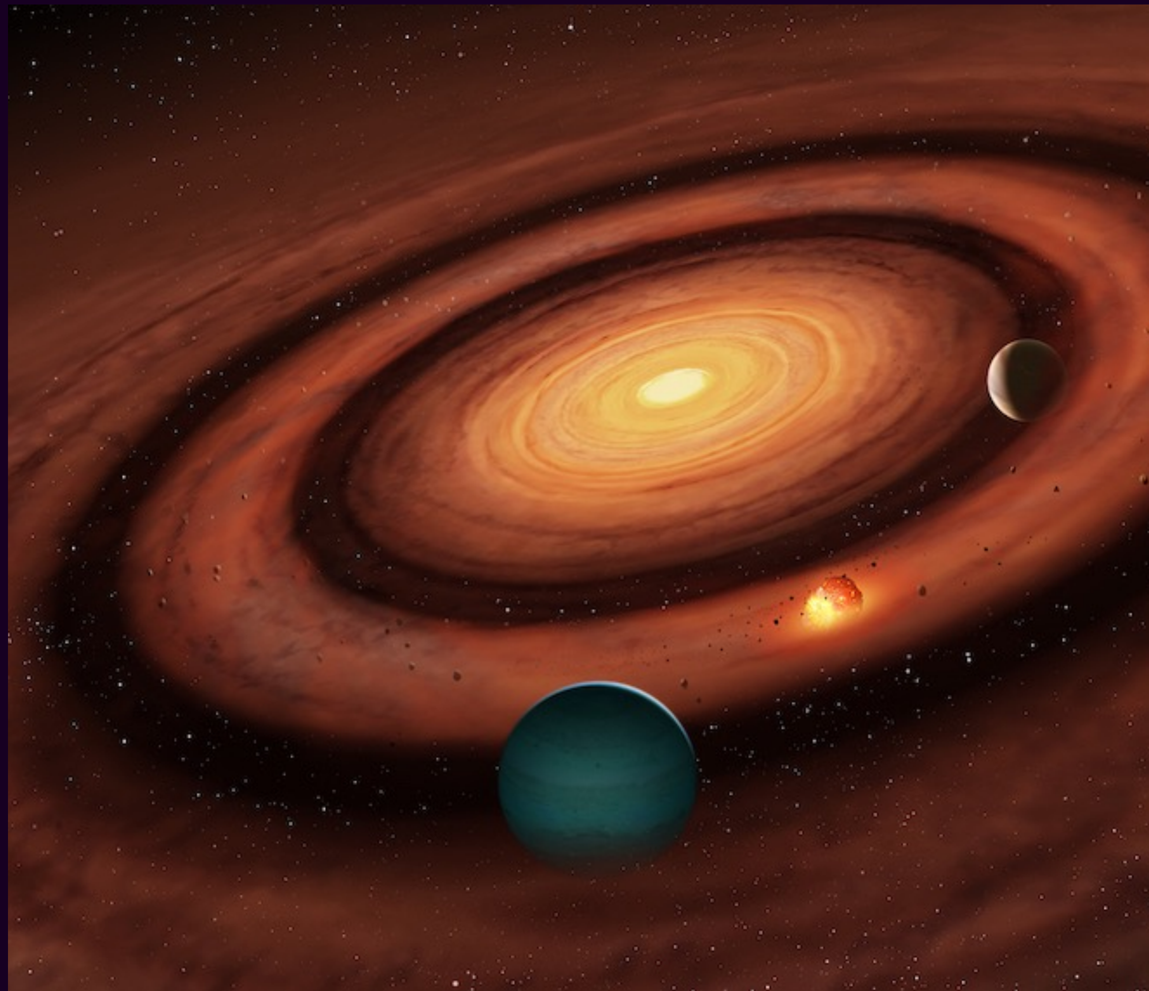
Lecture 2

原行星盘

Protoplanetary Disks

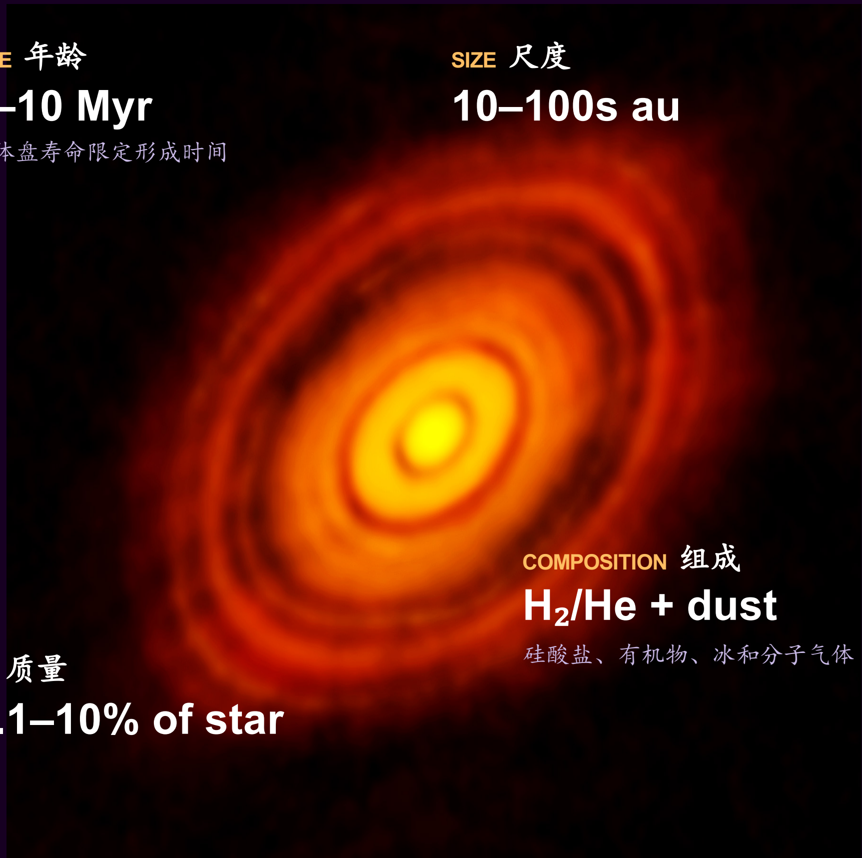
原行星盘是行星形成的摇篮

Protoplanetary disks are the birthplaces of planets.



盘的基本参数

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

H_2/He + dust

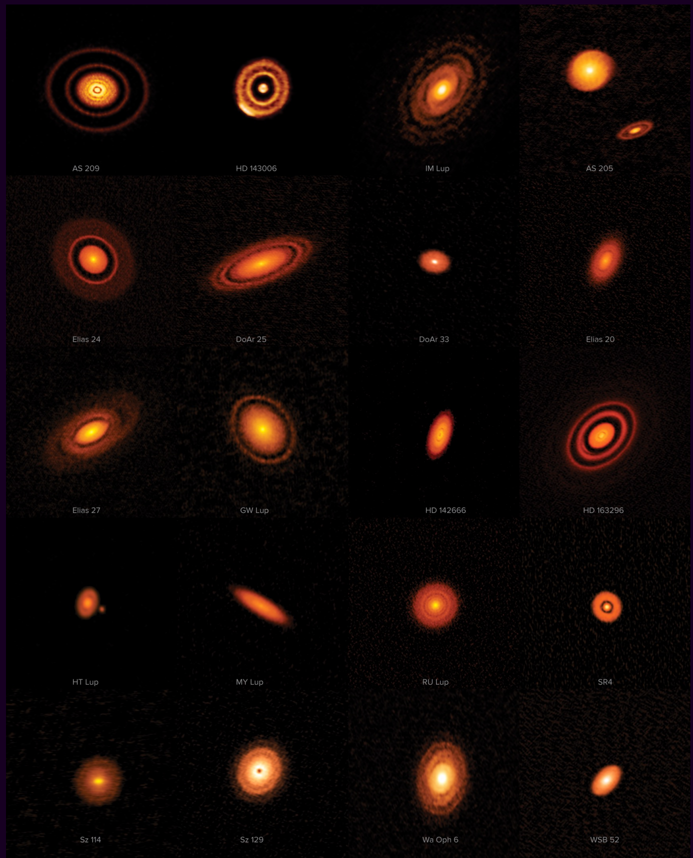
硅酸盐、有机物、冰和分子气体

MASS 质量

≈ 0.1–10% of star

ALMA对原行星盘的观测

ALMA IMAGES



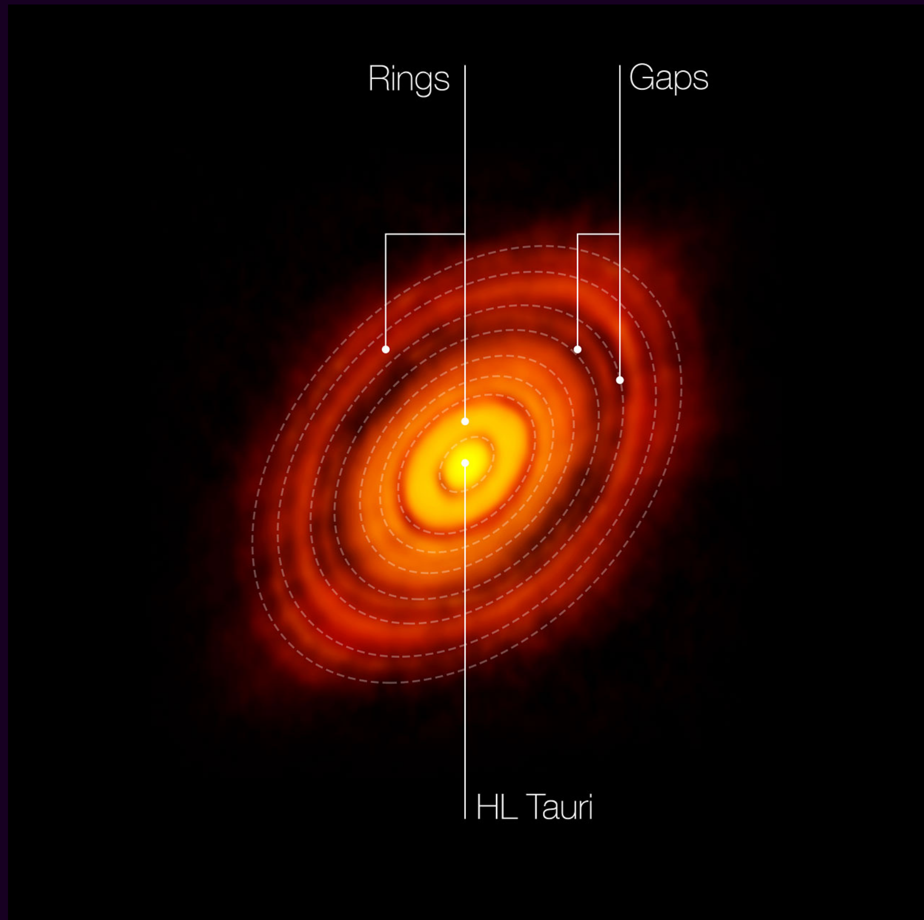


Image credit: ALMA DSHARP survey, Andrews et al.; ALMA (ESO/NAOJ/NRAO)

HST和SPHERE对原行星盘的观测

HST AND SPHERE IMAGES

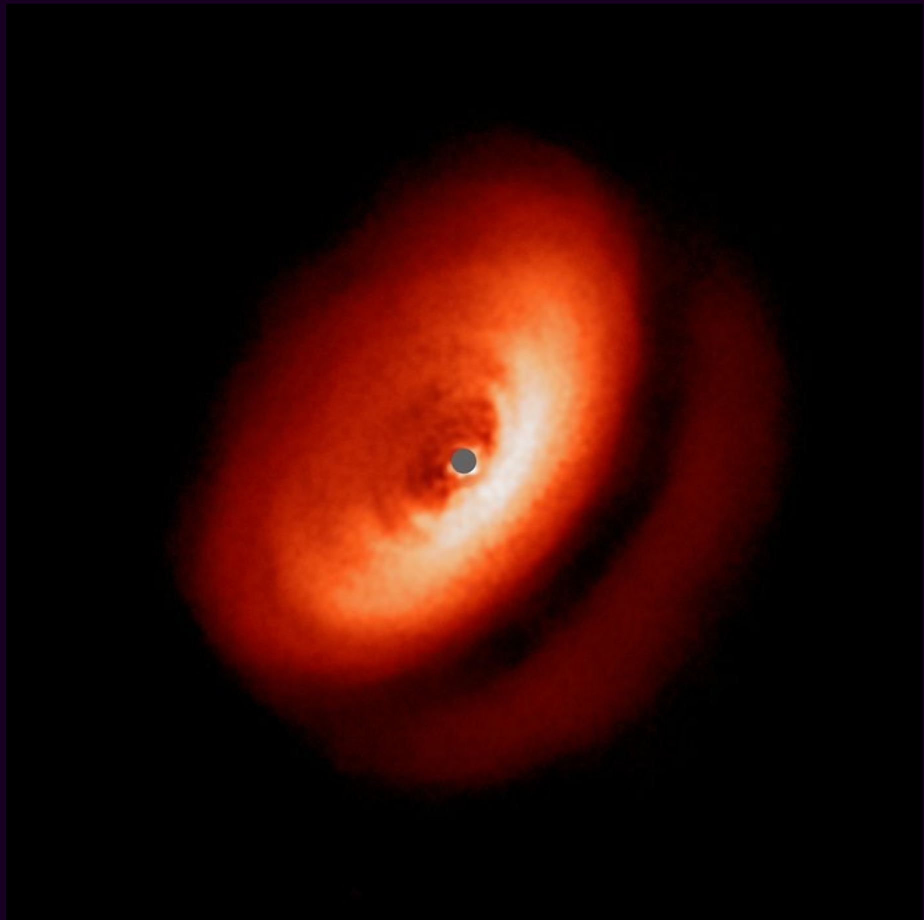
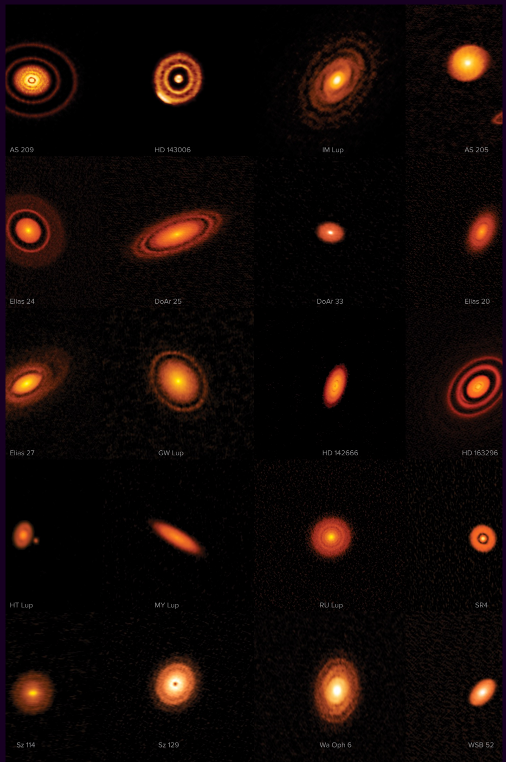
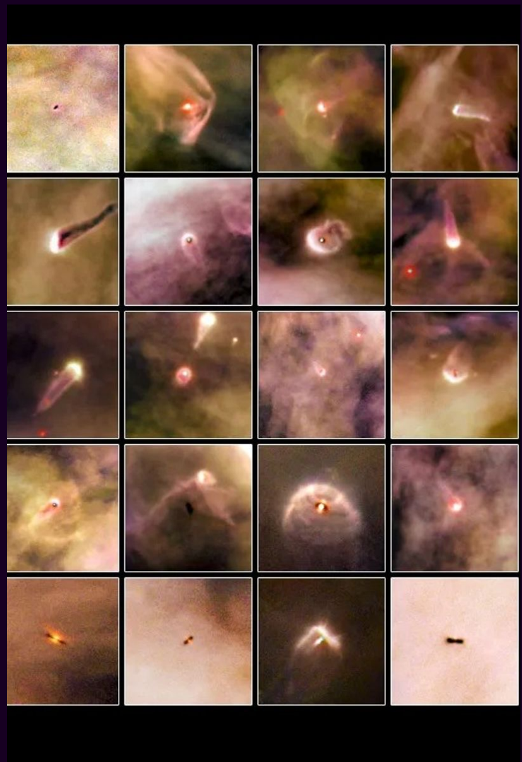


Image credit: Left: ALMA DSHARP survey; right: Hubble/ESA disk gallery public images

测到什么？不能直接测到什么？

WHAT OBS CAN TELL? CANNOT TELL?





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

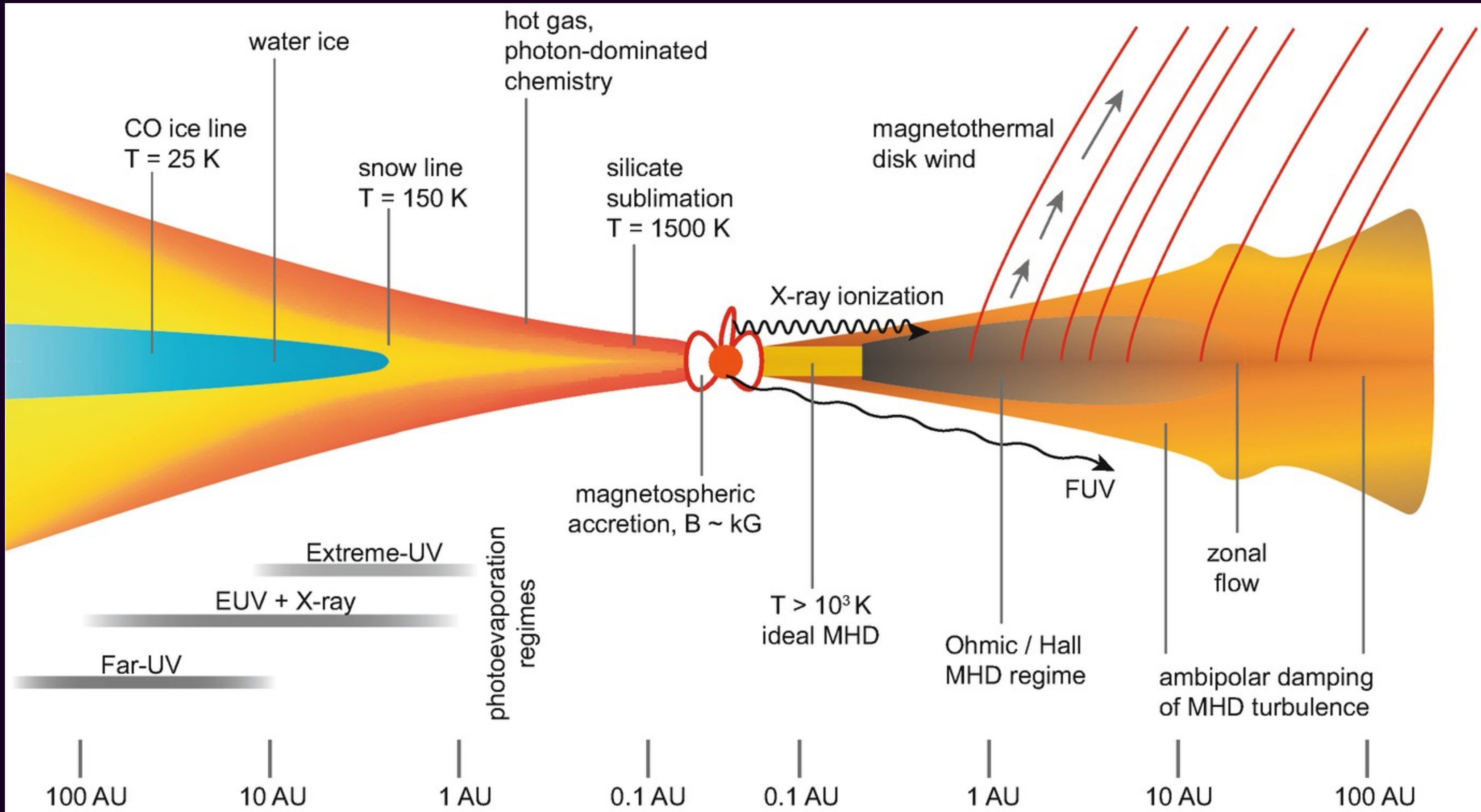
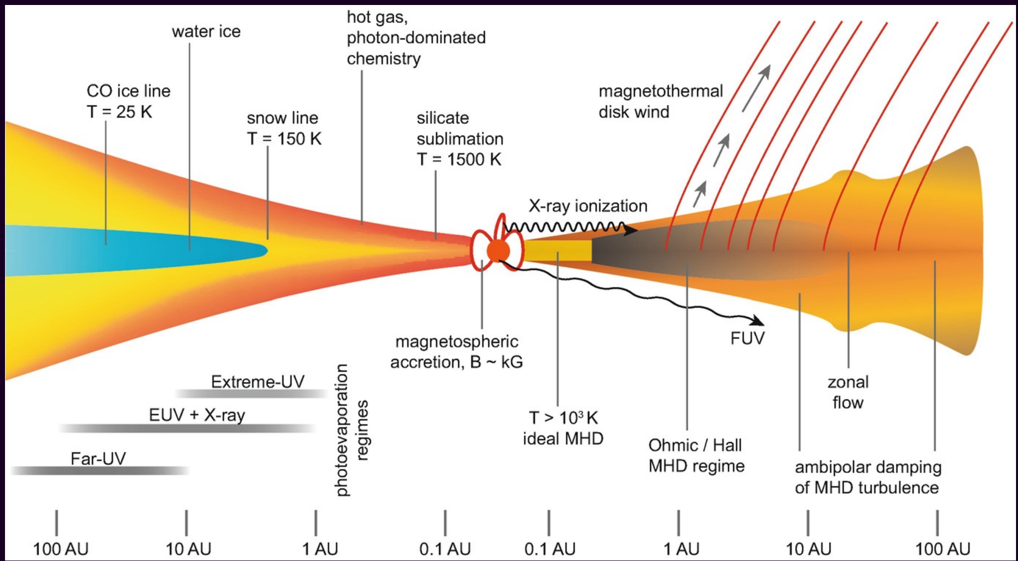


Image credit: A Brief Overview of Planet Formation

被动受照盘

PASSIVE IRRADIATED DISKS



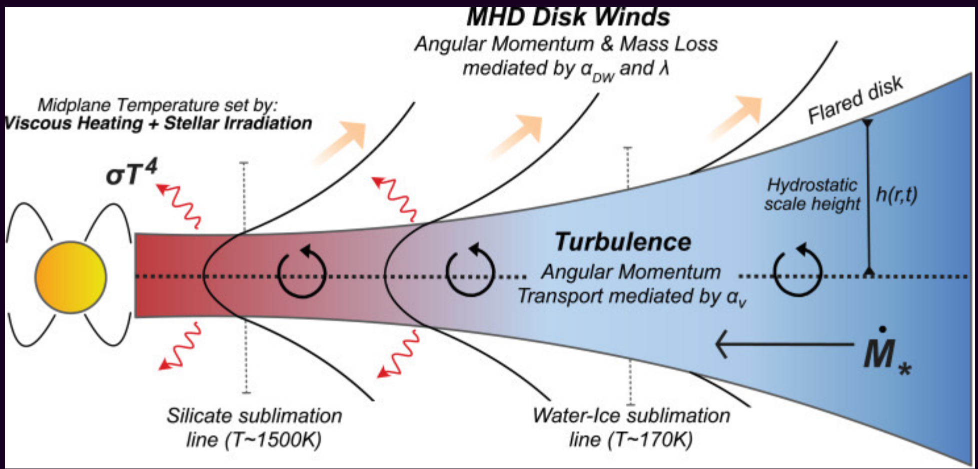
Starlight controls the thermal structure of the disk.

- 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

ANGULAR MOMENTUM TRANSPORT AND ACCRETION



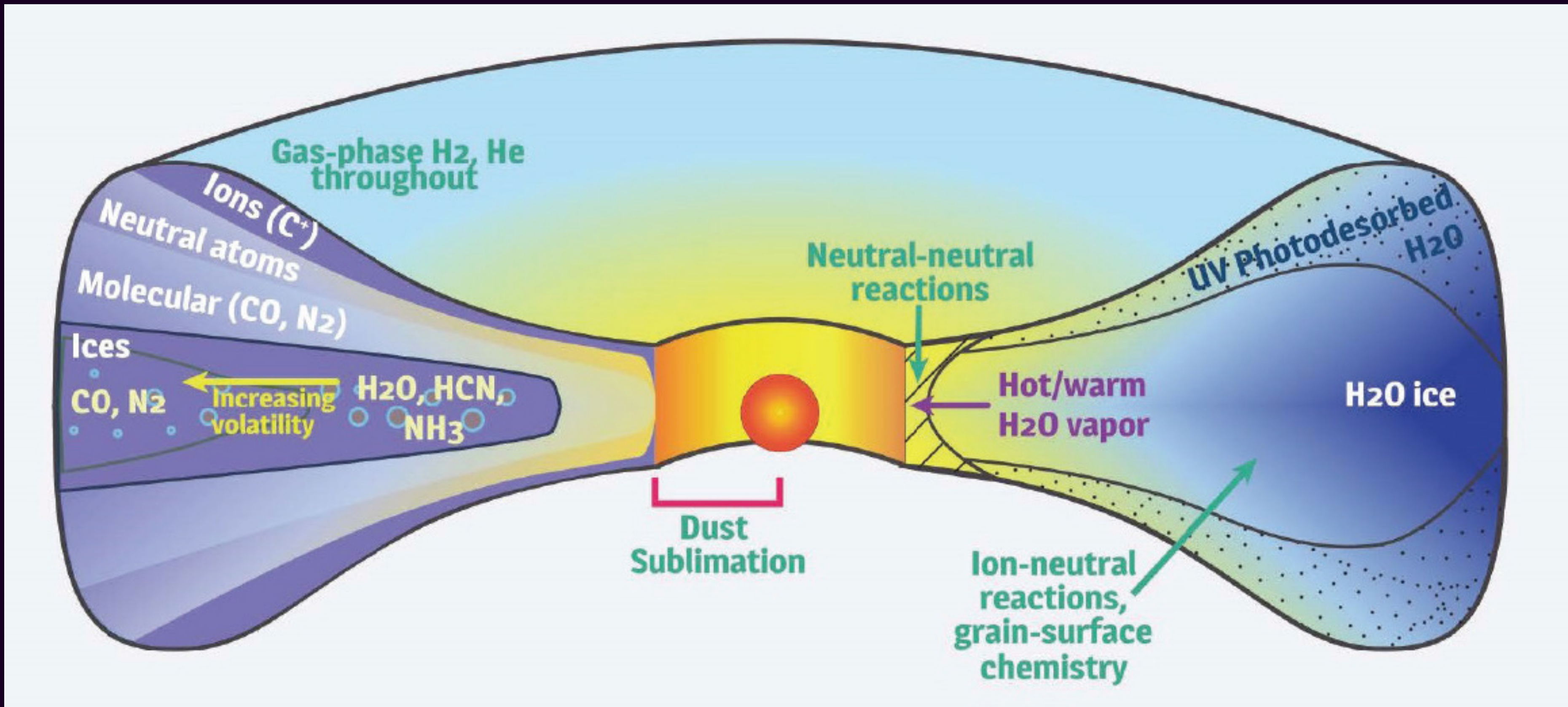
Gas accretes when angular momentum is removed by turbulence or MHD winds.

- 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.

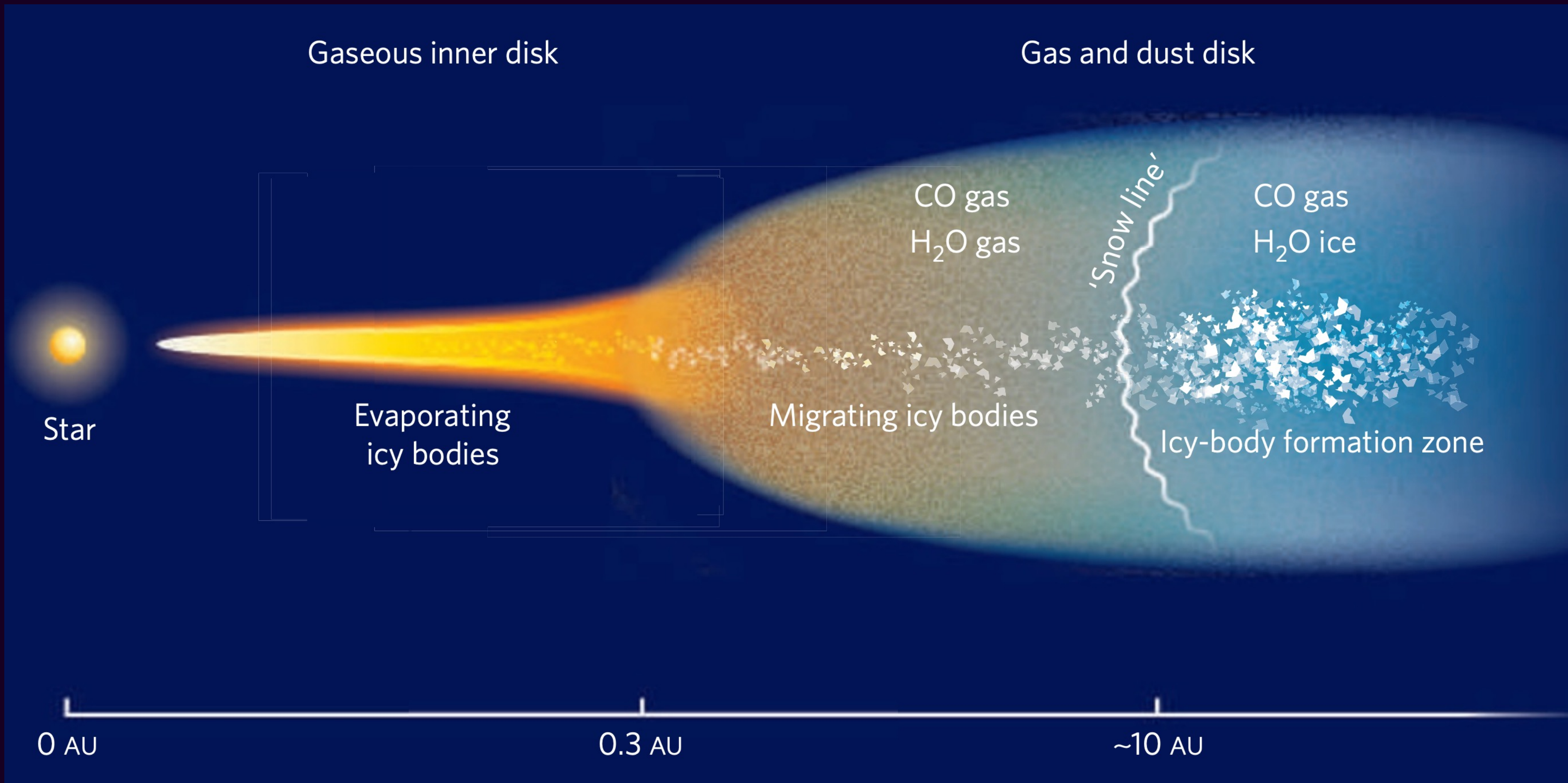
径向湍流输运与垂向 MHD wind 输运。

盘化学组成

DISK CHEMISTRY



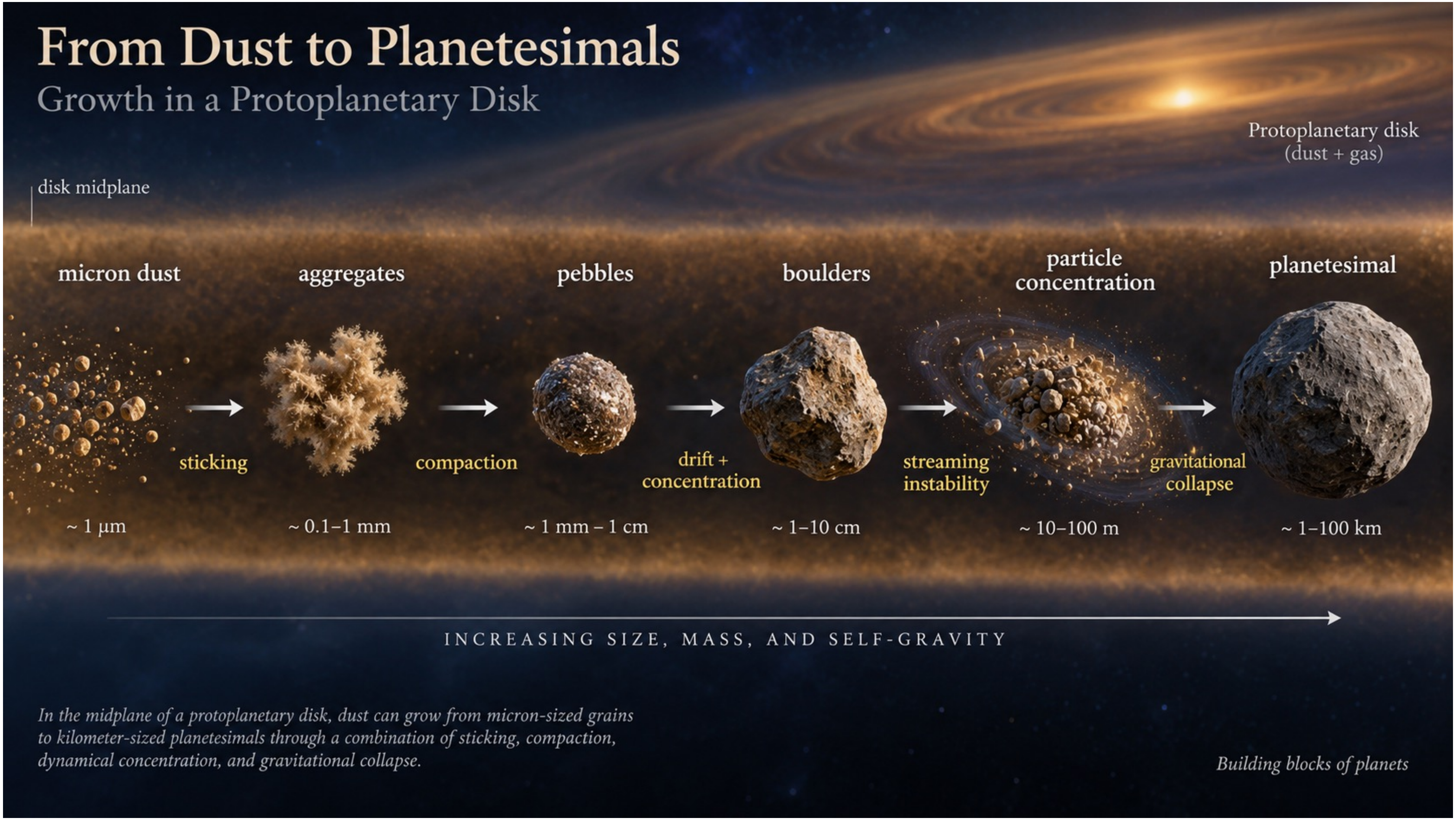
雪线
SNOWLINE

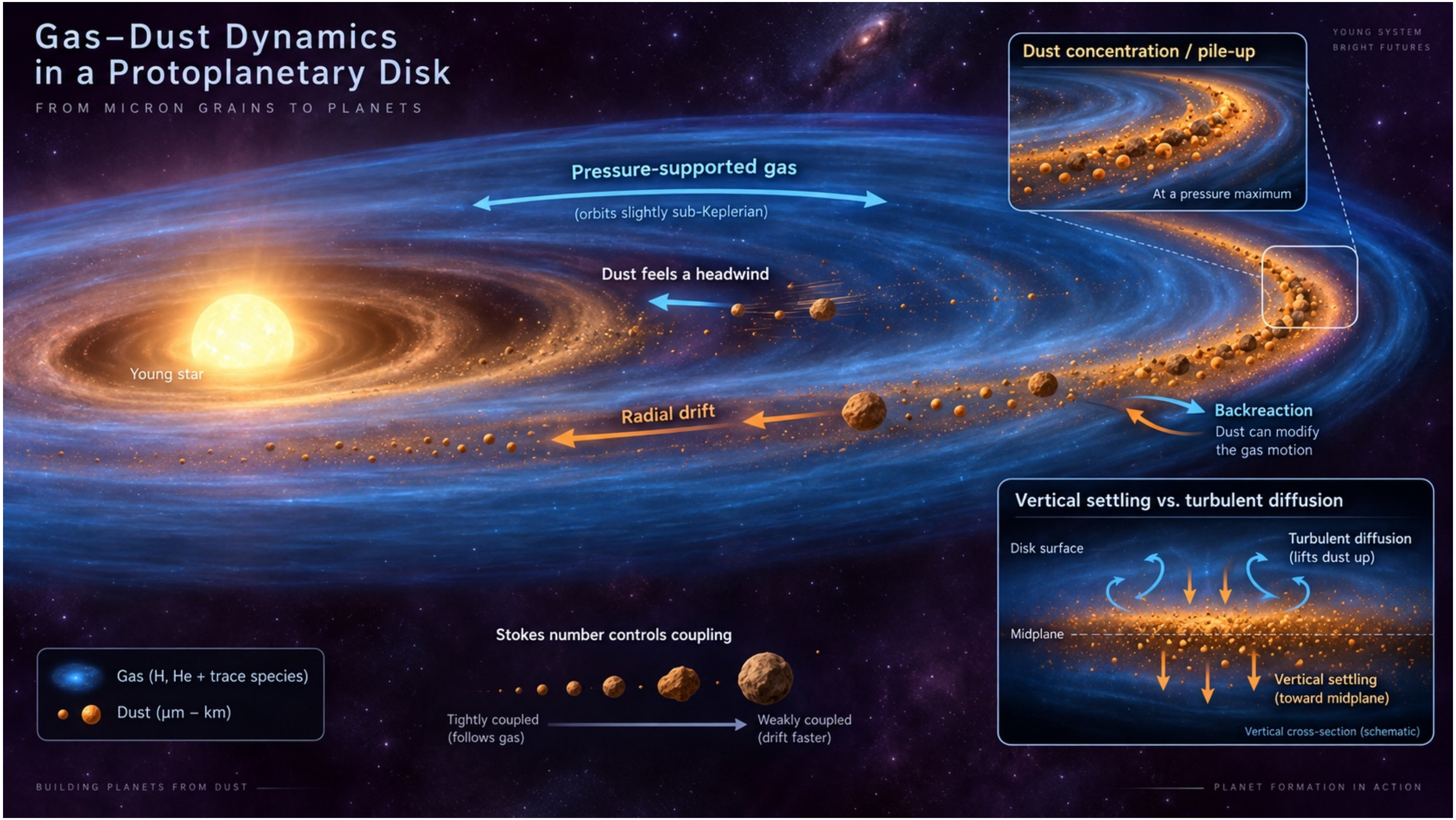

Gaseous inner disk
Gas and dust disk
CO gas
H_2O gas
'Snow line'
CO gas
H_2O ice
Star
Evaporating icy bodies
Migrating icy bodies
Icy-body formation zone
0 AU
0.3 AU
~10 AU

Lecture 3

尘埃动力学与演化

Dust Dynamics and Evolution


From Dust to Planetesimals
Growth in a Protoplanetary Disk
Protoplanetary disk
(dust + gas)
disk midplane
micron dust
aggregates
pebbles
boulders
particle concentration
planetesimal
sticking
compaction
drift + concentration
streaming instability
gravitational collapse
~ 1 µm
~ 0.1–1 mm
~ 1 mm – 1 cm
~ 1–10 cm
~ 10–100 m
~ 1–100 km
INCREASING SIZE, MASS, AND SELF-GRAVITY
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



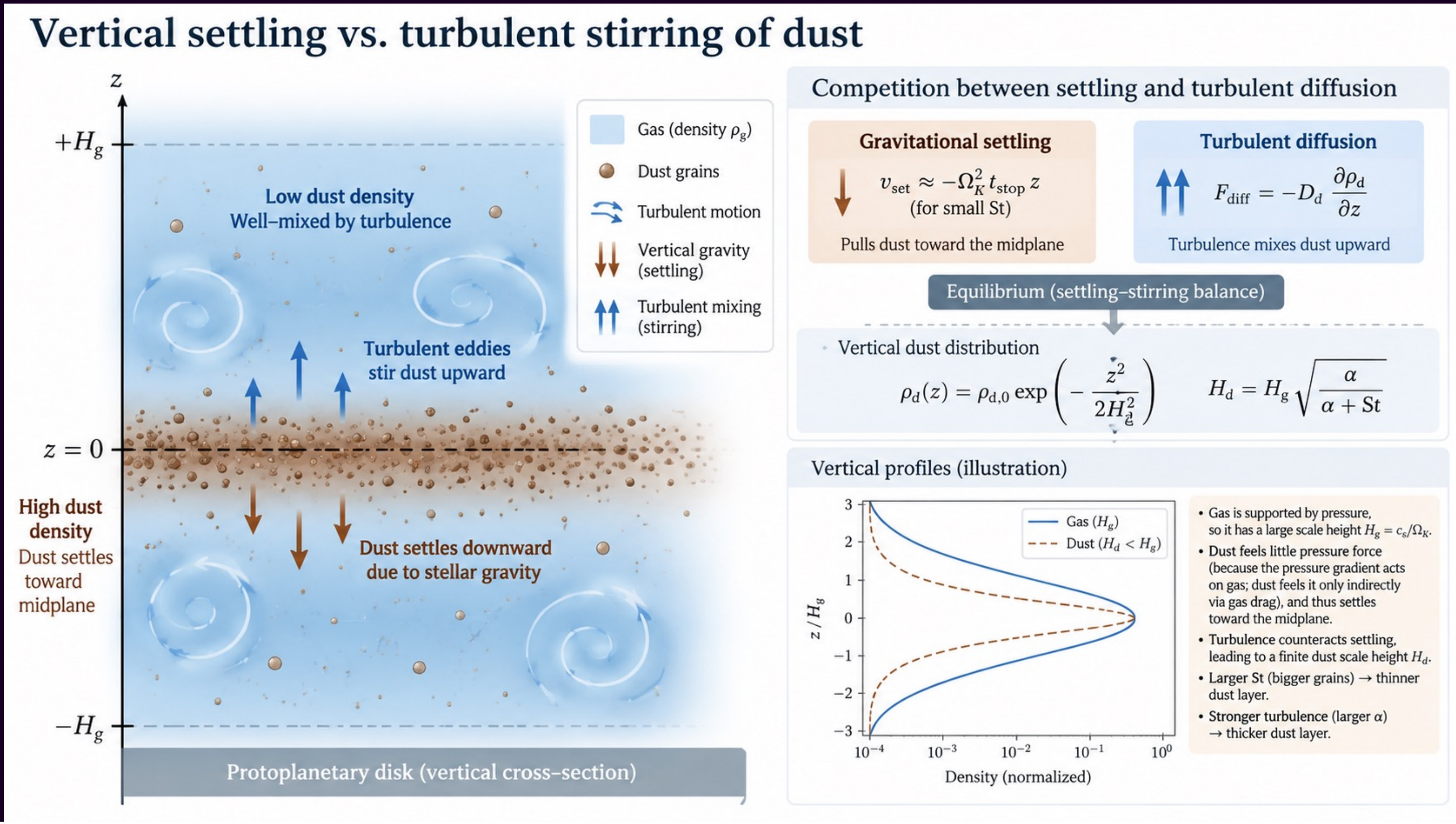
Gas–Dust Dynamics in a Protoplanetary Disk
FROM MICRON GRAINS TO PLANETS
YOUNG SYSTEM
BRIGHT FUTURES
Dust concentration / pile-up
At a pressure maximum
Pressure-supported gas
(orbits slightly sub-Keplerian)
Dust feels a headwind
Young star
Radial drift
Backreaction
Dust can modify the gas motion
Vertical settling vs. turbulent diffusion
Disk surface
Turbulent diffusion (lifts dust up)
Midplane
Vertical settling (toward midplane)
Vertical cross-section (schematic)
Stokes number controls coupling
Tightly coupled (follows gas)
Weakly coupled (drift faster)
Gas (H, He + trace species)
Dust (μm – km)
BUILDING PLANETS FROM DUST
PLANET FORMATION IN ACTION

气尘动力学

DUST AND GAS AERODYNAMICS

垂向沉降与湍流平衡

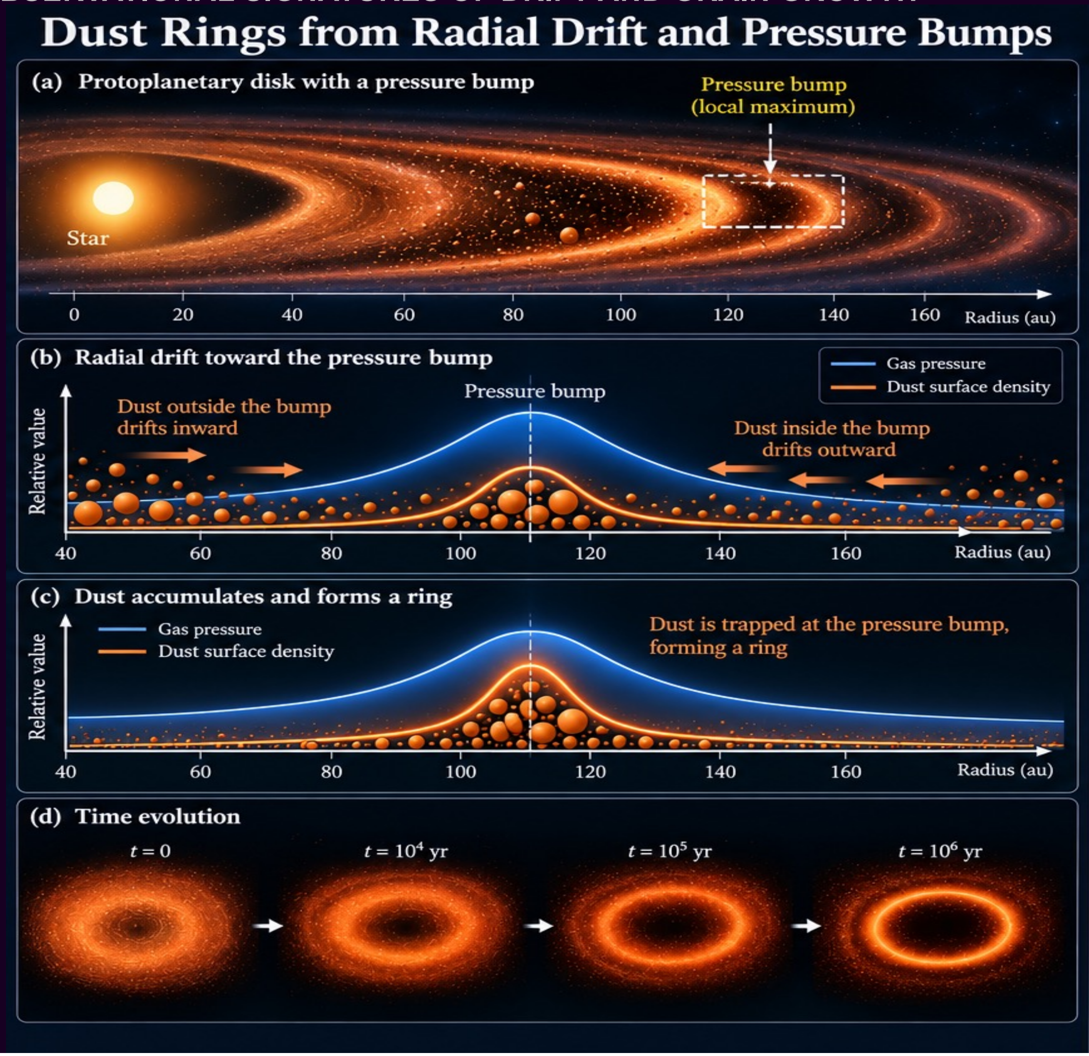
DUST SETTLING AND TURBULENT DIFFUSION



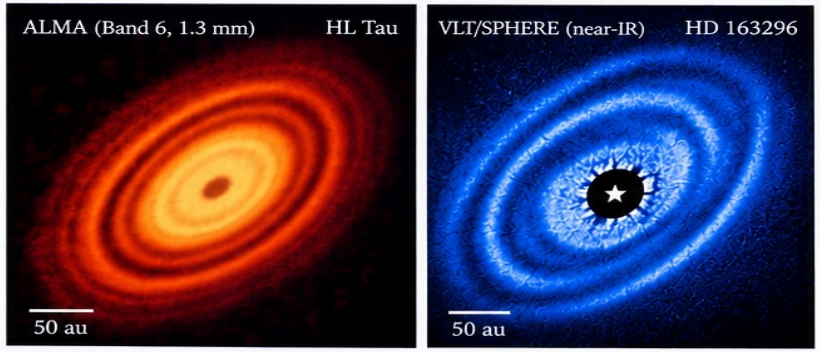

原行星盘中的径向漂移
为什么尘埃会向恒星漂移？
1
气 体
气体受压强支撑，转动略慢于开普勒速度
次开普勒转动
气体
年轻恒星
压力支撑
2
尘 埃
尘埃本想按开普勒速度运动
但受到气体的迎风阻力
尘埃本想按
开普勒速度运动
迎风 / 拖曳力
（来自较慢的气体）
失去角动量
3
结 果
尘埃被拖慢，逐渐向恒星靠近
向内漂移
尘埃被拖慢
逐渐向恒星靠近
关键结论：压强先改变气体转动；尘埃再通过拖曳力间接受到影响。

观测如何识别漂移与生长？

OBSERVATIONAL SIGNATURES OF DRIFT AND GRAIN GROWTH



Observed disks with dust rings



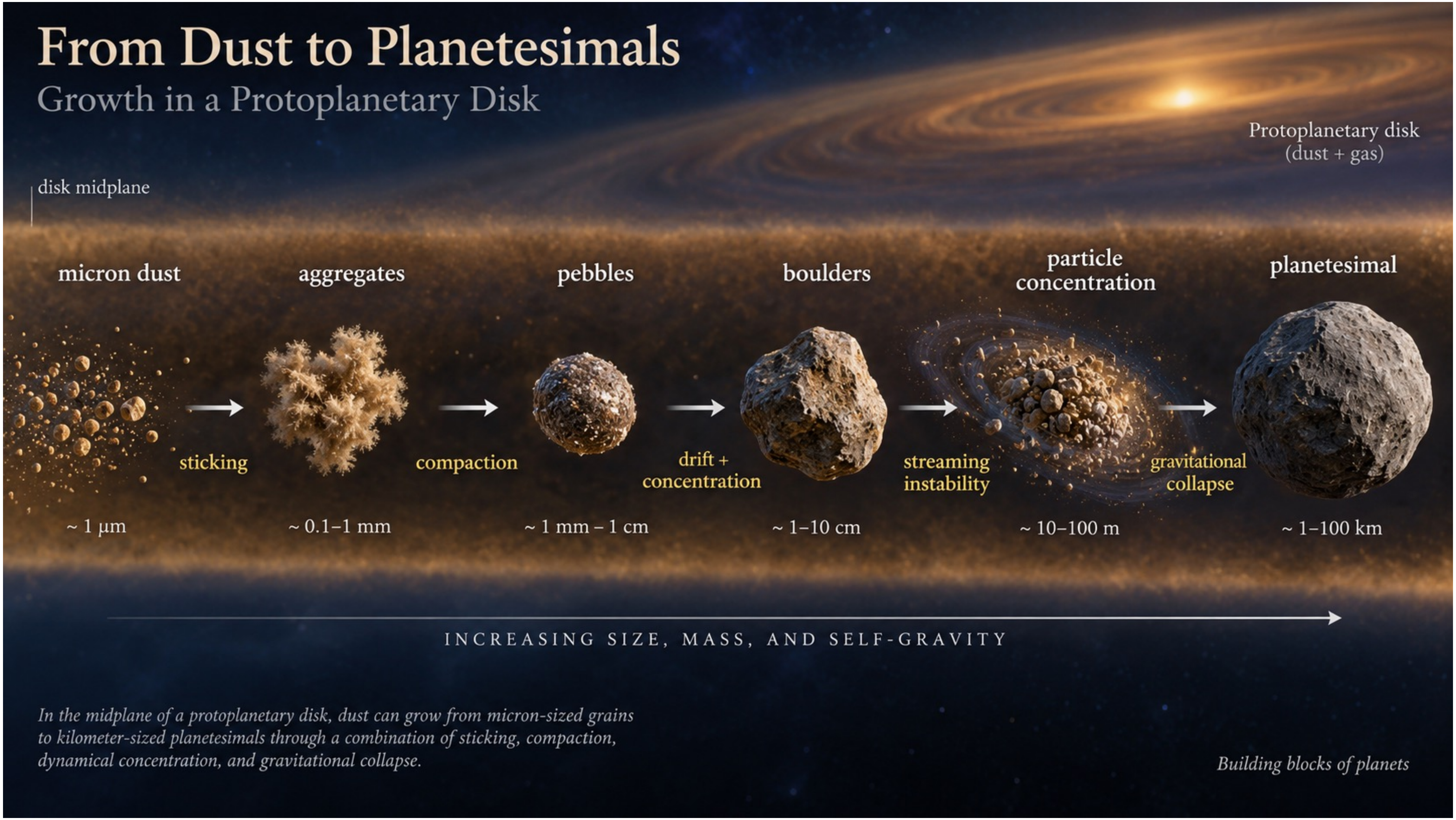
How to distinguish radial drift and dust growth observationally?

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 ($\sim 10^4 - 10^5$ yr)	Gradual brightening and spectral evolution as grains grow ($\sim 10^5 - 10^6$ 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

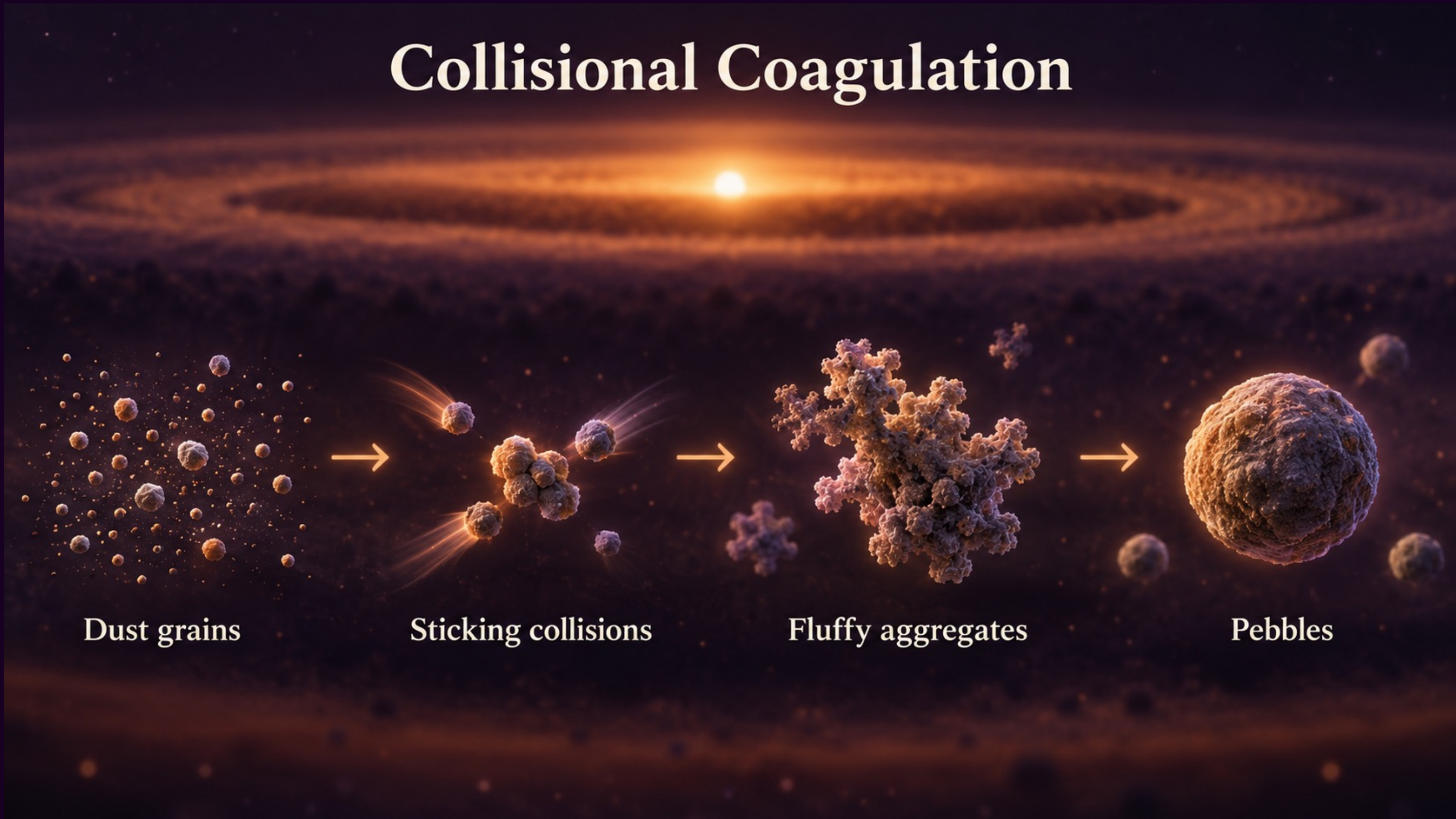
Dust Dynamics and Evolution


From Dust to Planetesimals
Growth in a Protoplanetary Disk
Protoplanetary disk
(dust + gas)
disk midplane
micron dust
aggregates
pebbles
boulders
particle
concentration
planetesimal
sticking
compaction
drift +
concentration
streaming
instability
gravitational
collapse
~ 1 µm
~ 0.1–1 mm
~ 1 mm – 1 cm
~ 1–10 cm
~ 10–100 m
~ 1–100 km
INCREASING SIZE, MASS, AND SELF-GRAVITY
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

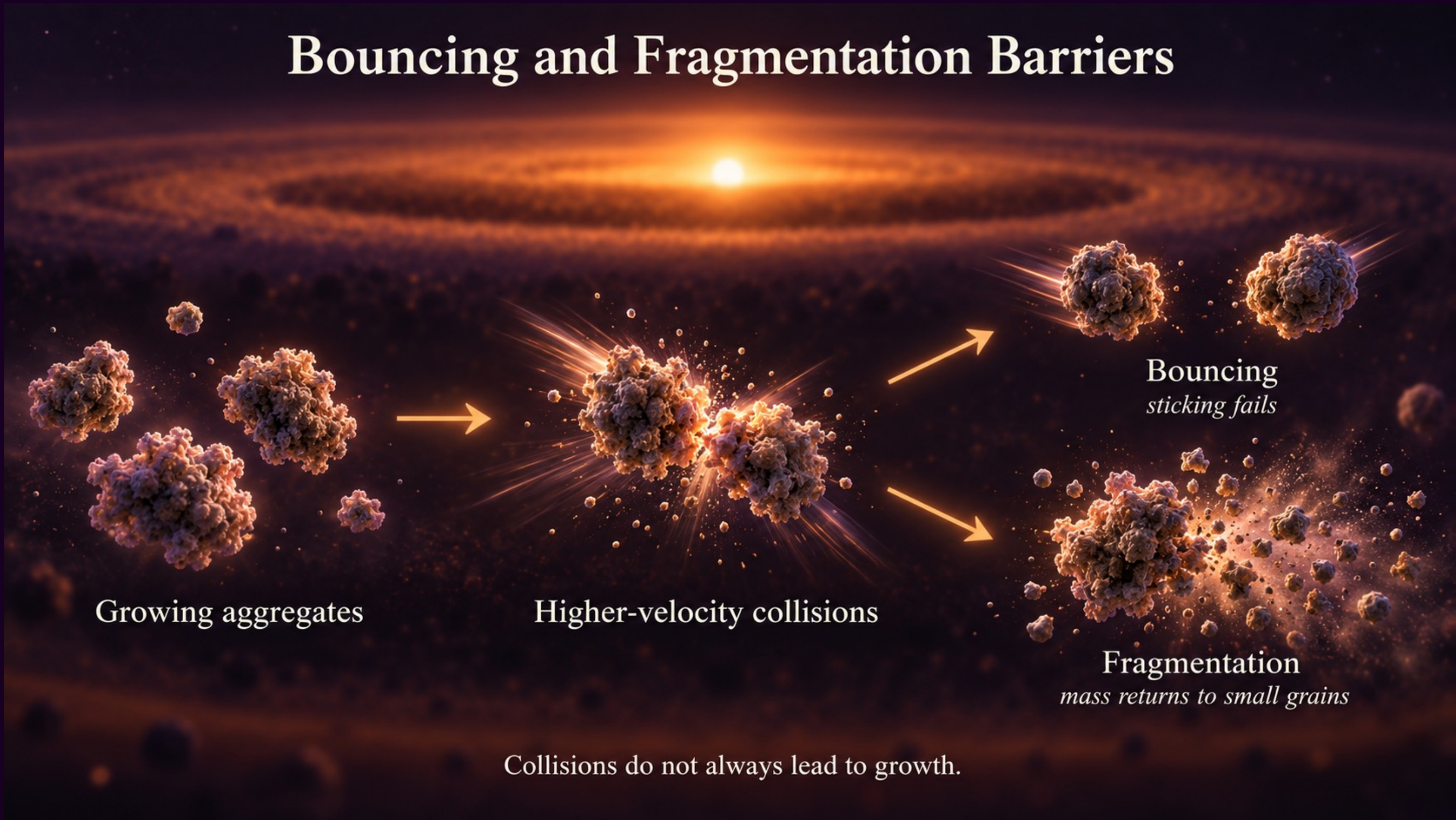
碰撞凝聚给出起点，但不能保证形成千米级的星子。



反弹与碎裂障碍

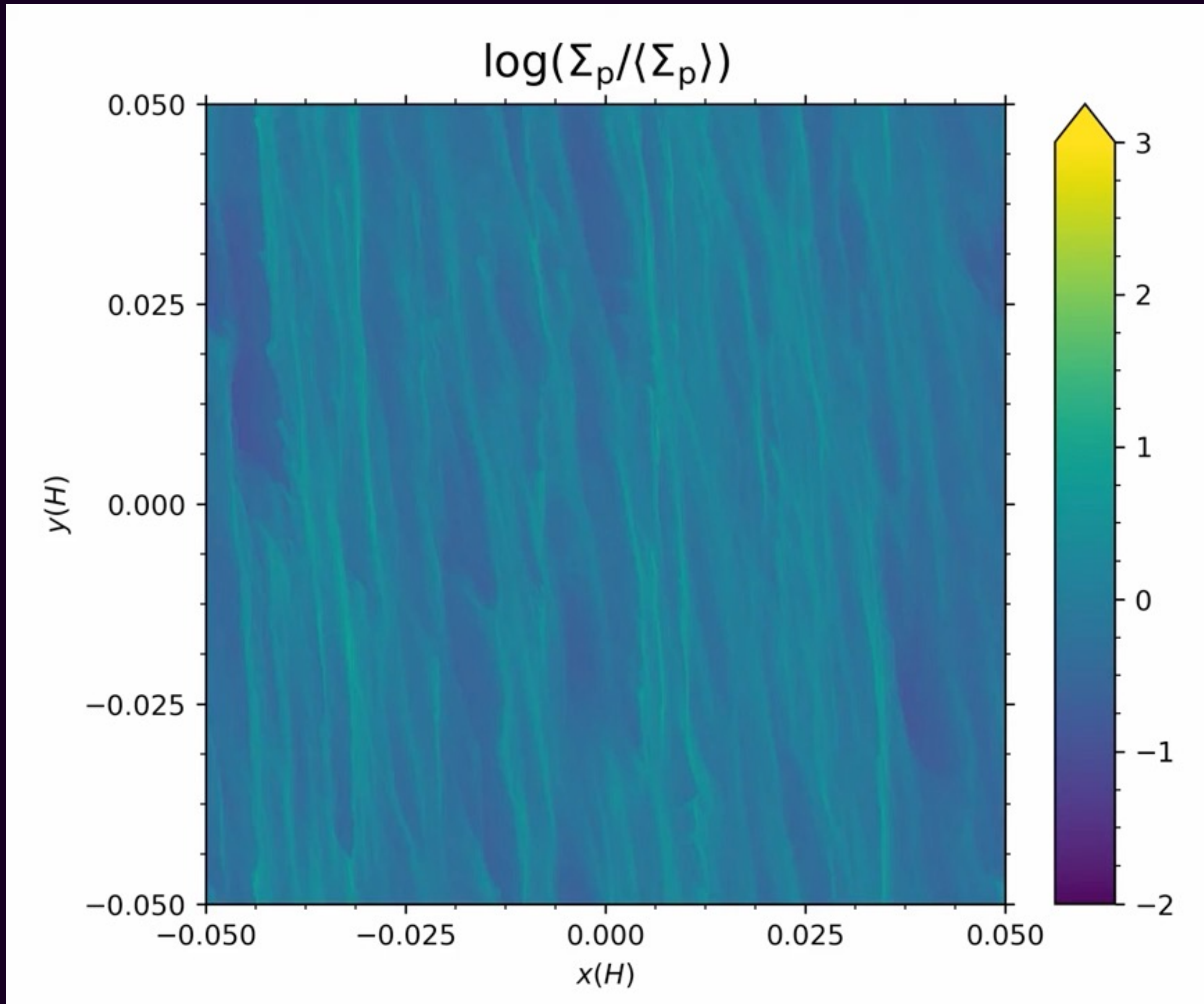
BOUNCING AND FRAGMENTATION BARRIERS

障碍的本质：碰撞频率增加了，但有效增长效率下降。



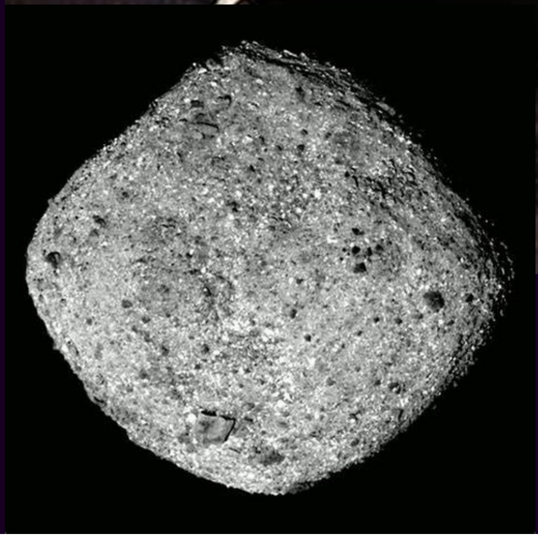
流不稳定性

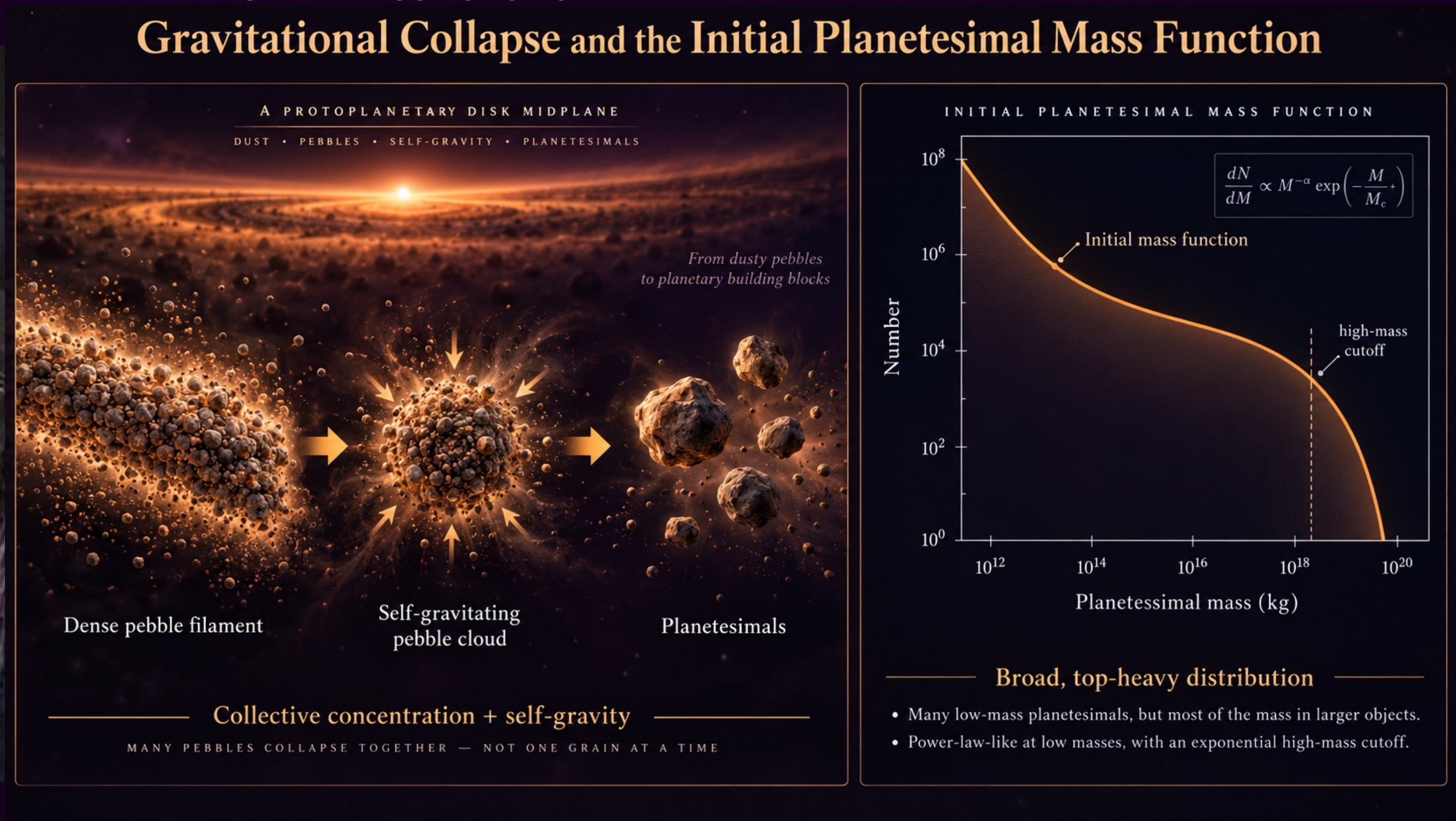
STREAMING INSTABILITY: NUMERICAL RESULTS



引力坍缩与初始星子质量函数

GRAVITATIONAL COLLAPSE AND THE INITIAL PLANETESIMAL MASS FUNCTION



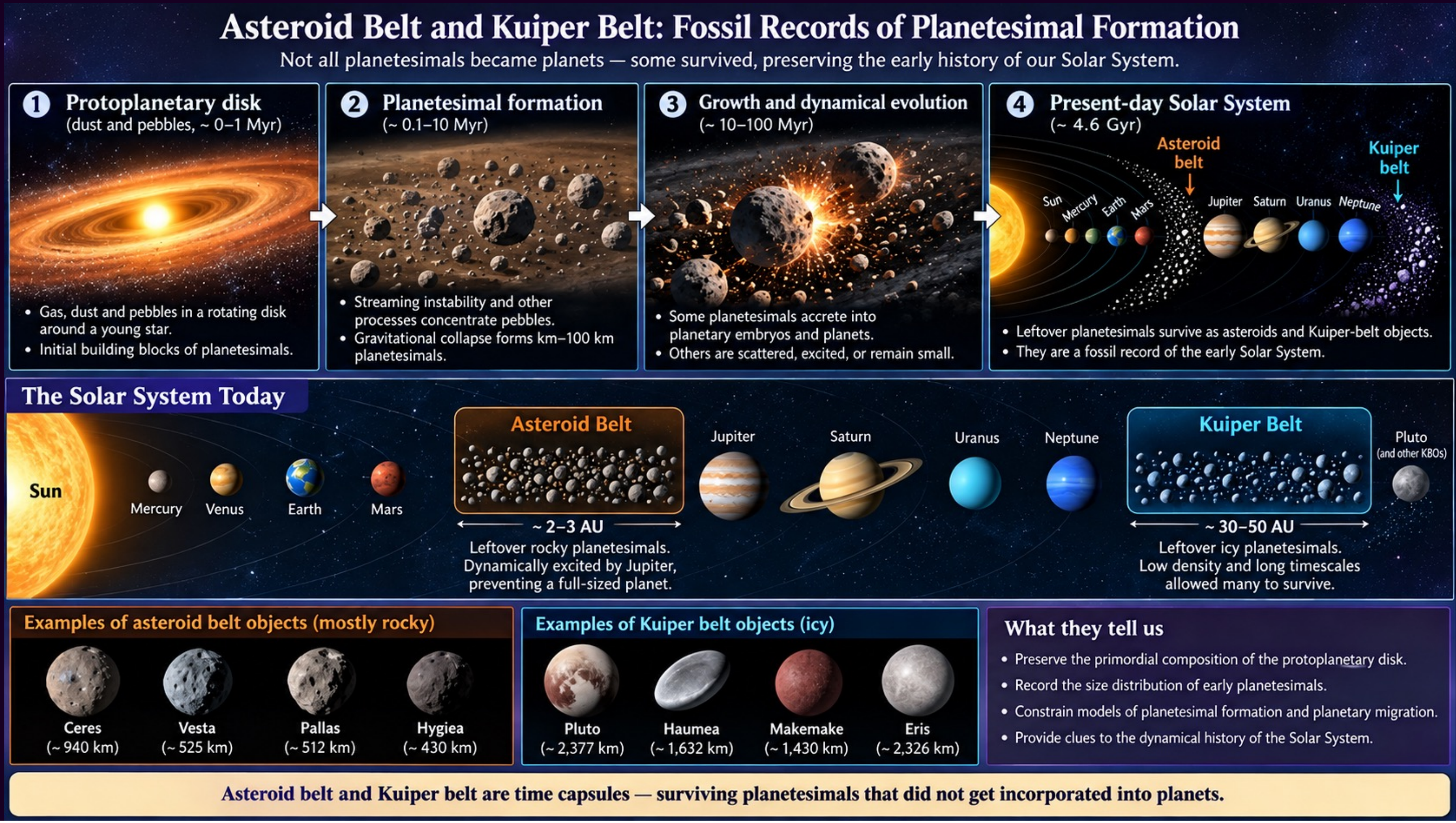


问题：第一批星子出生时，是小而多，还是已经相当大？

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

ASTEROID AND KUIPER BELTS AS FOSSIL RECORDS



Lecture 5

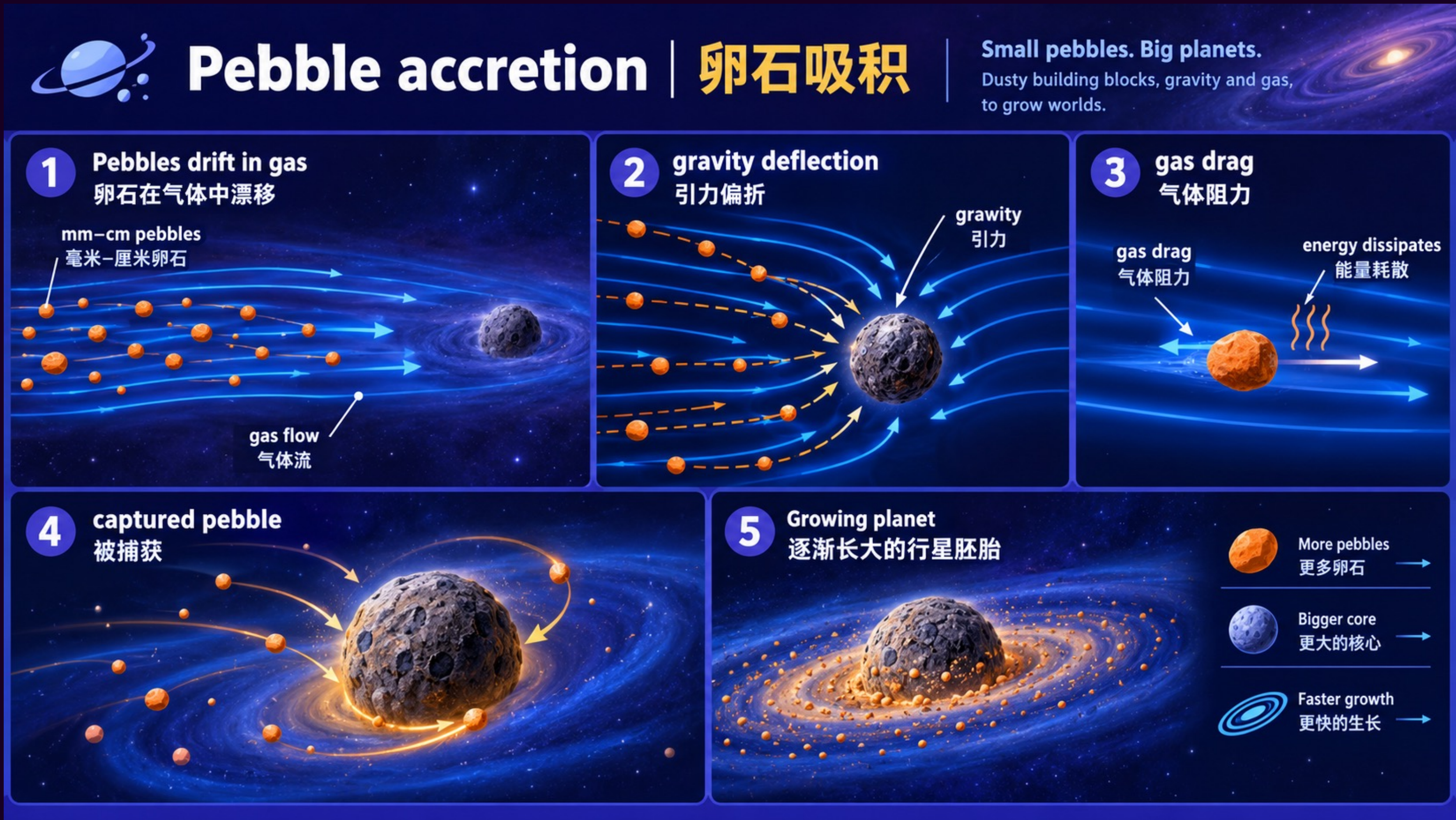
卵石吸积

PEBBLE ACCRETION

星子吸积和卵石吸积

PLANETESIMAL AND PEBBLE ACCRETION

卵石吸积
PEBBLE ACCRETION



Hill 区域

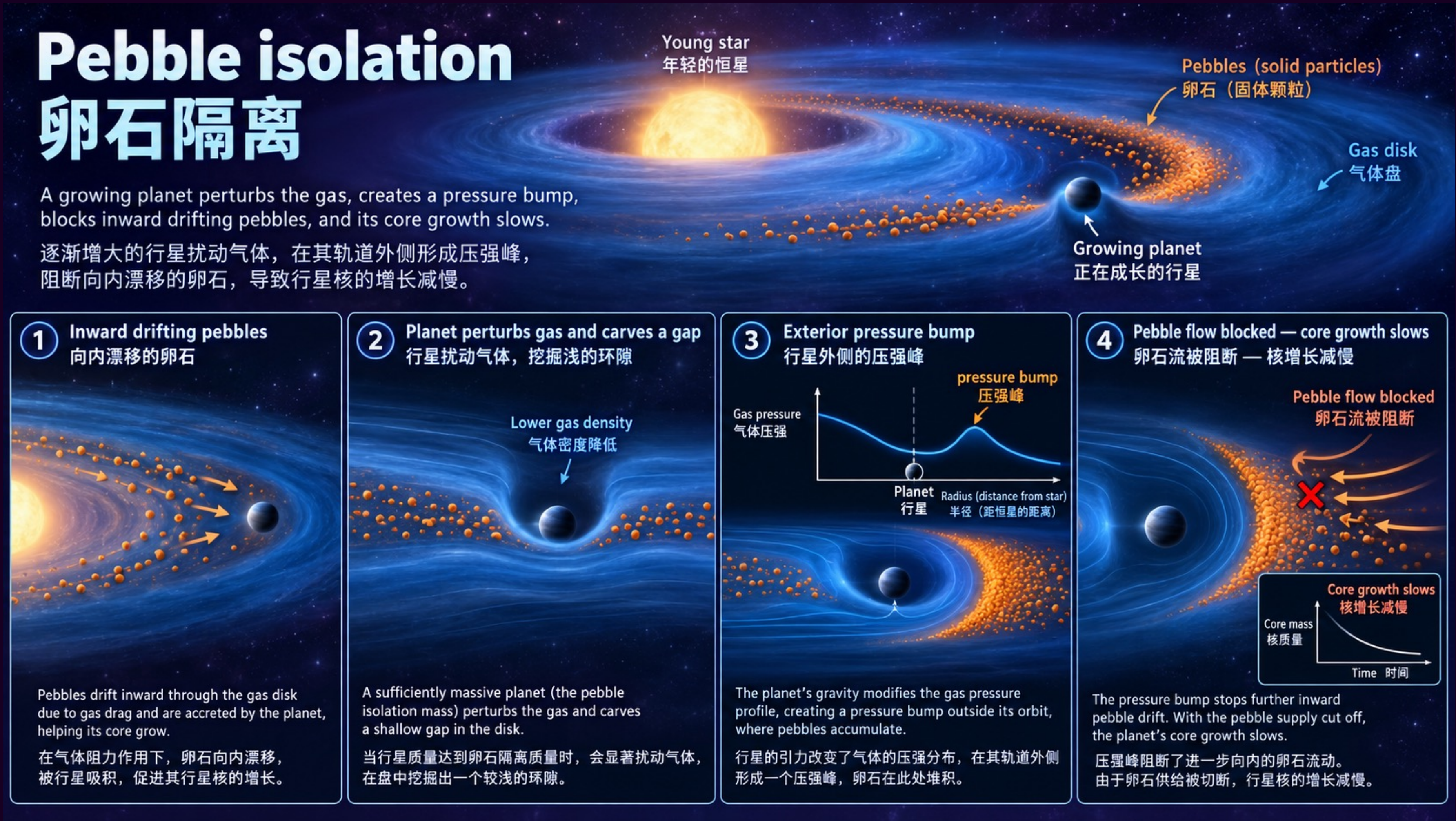
THE HILL REGIME: EFFICIENT CAPTURE BY LARGER CORES

卵石流

PEBBLE FLUX

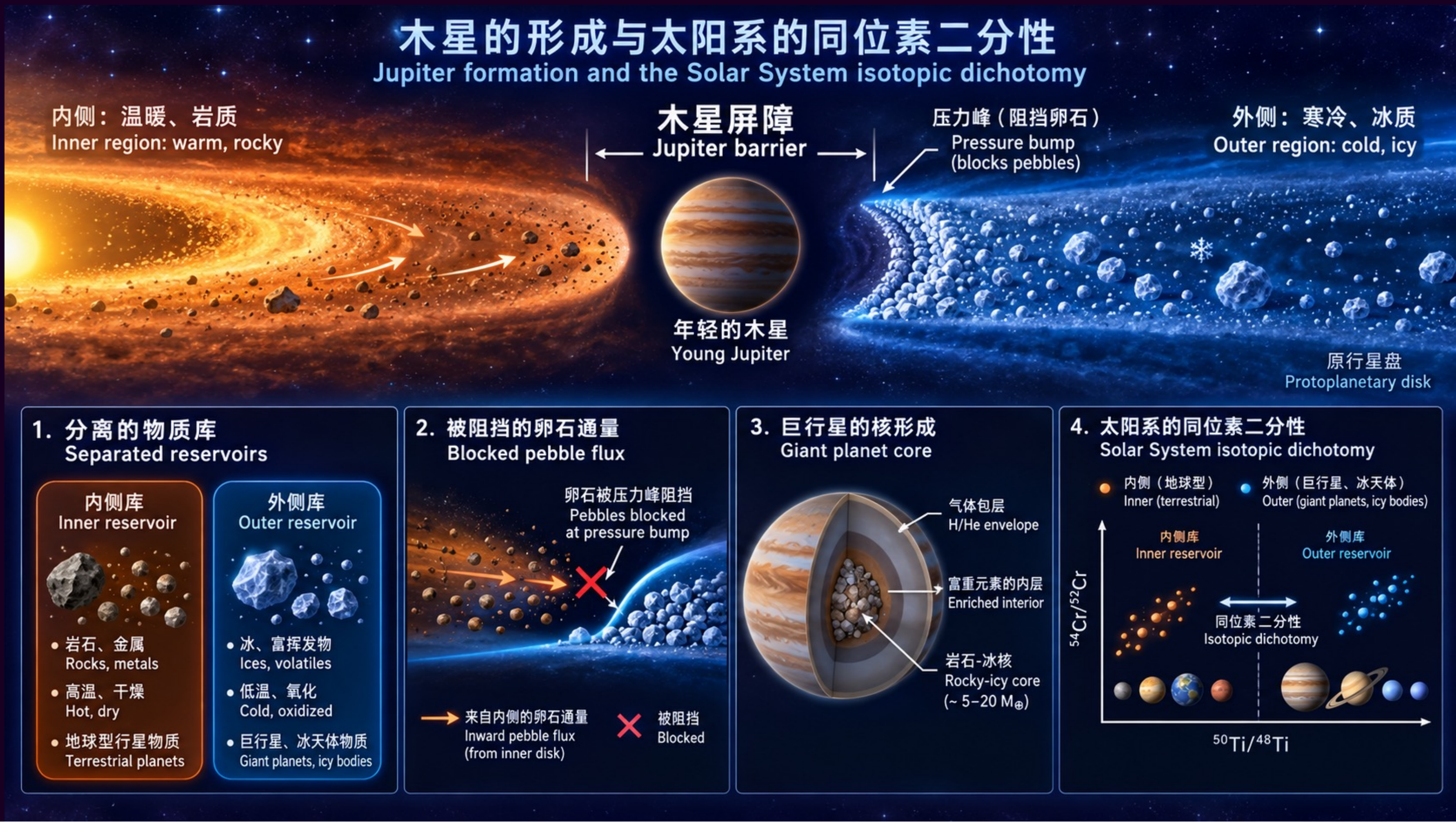
卵石隔离质量

PEBBLE ISOLATION MASS



木星形成与太阳系同位素二分性

JUPITER FORMATION AND THE SOLAR SYSTEM ISOTOPIC DICHOTOMY

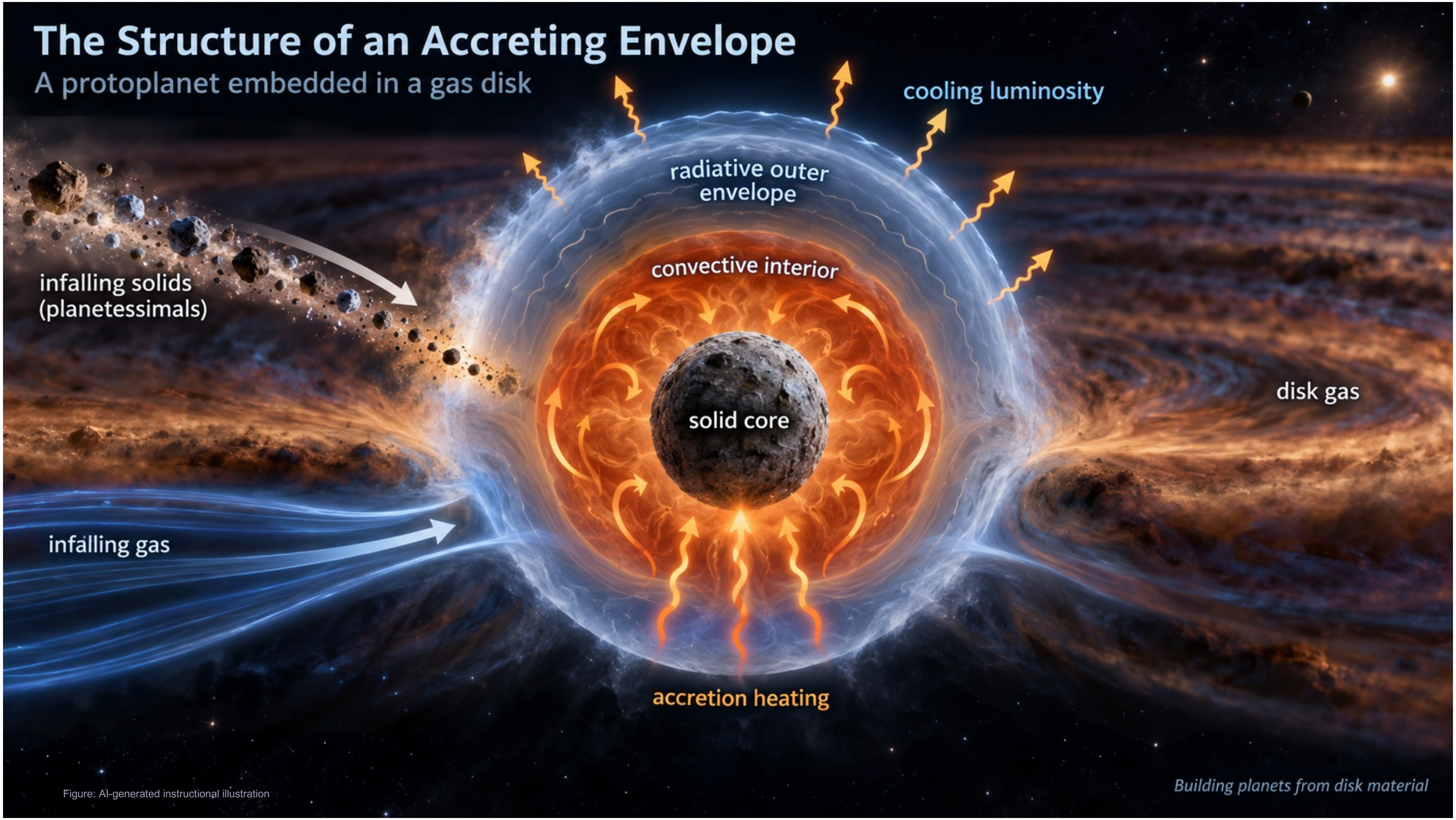


Lecture 6

核吸积和引力坍缩

CORE ACCRETION AND GI

Figure: AI-generated instructional illustration


The Structure of an Accreting Envelope
A protoplanet embedded in a gas disk
cooling luminosity
radiative outer envelope
convective interior
infalling solids (planetessimals)
solid core
disk gas
infalling gas
accretion heating
Figure: AI-generated instructional illustration
Building planets from disk material

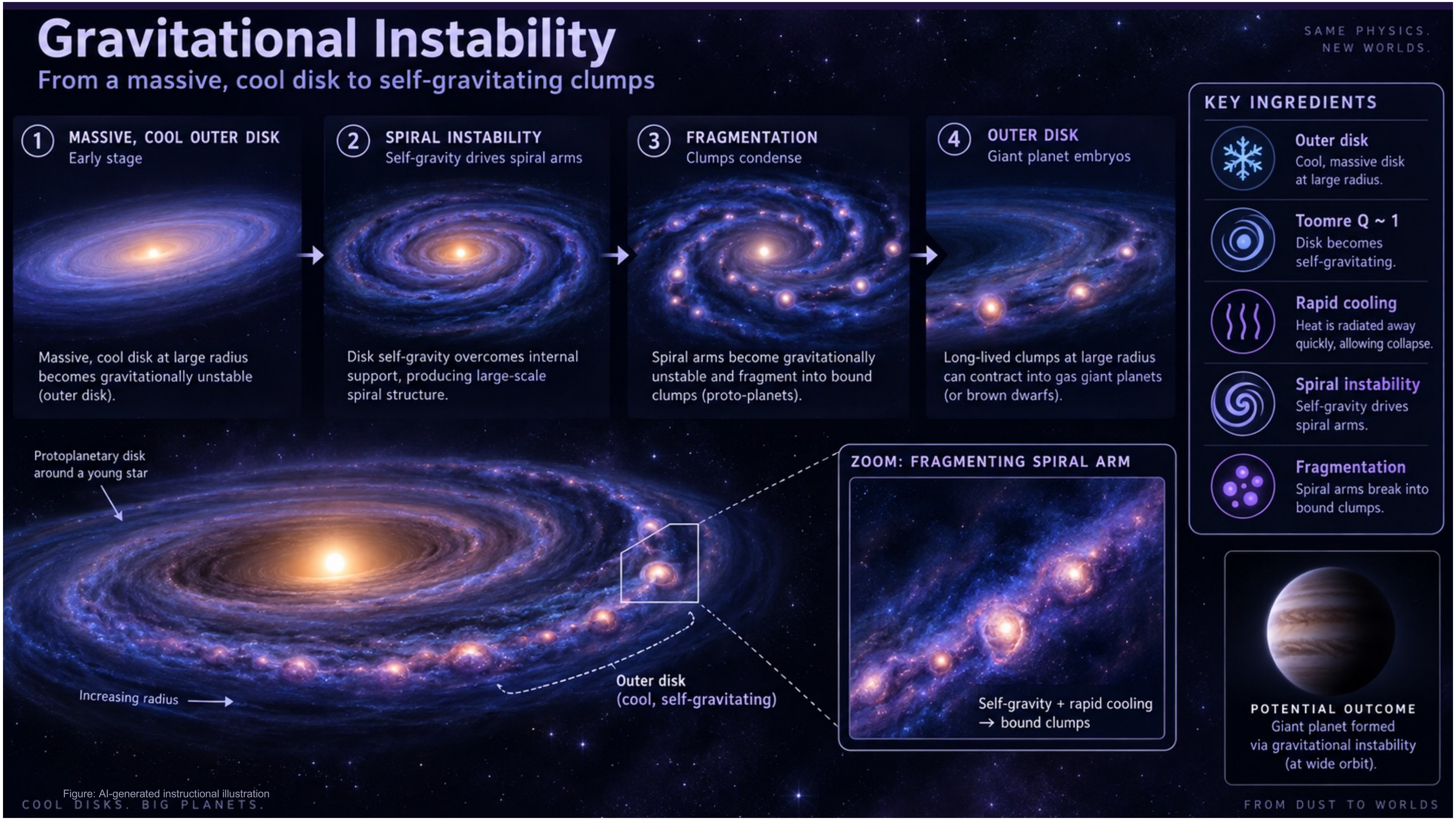


Figure: AI-generated instructional illustration

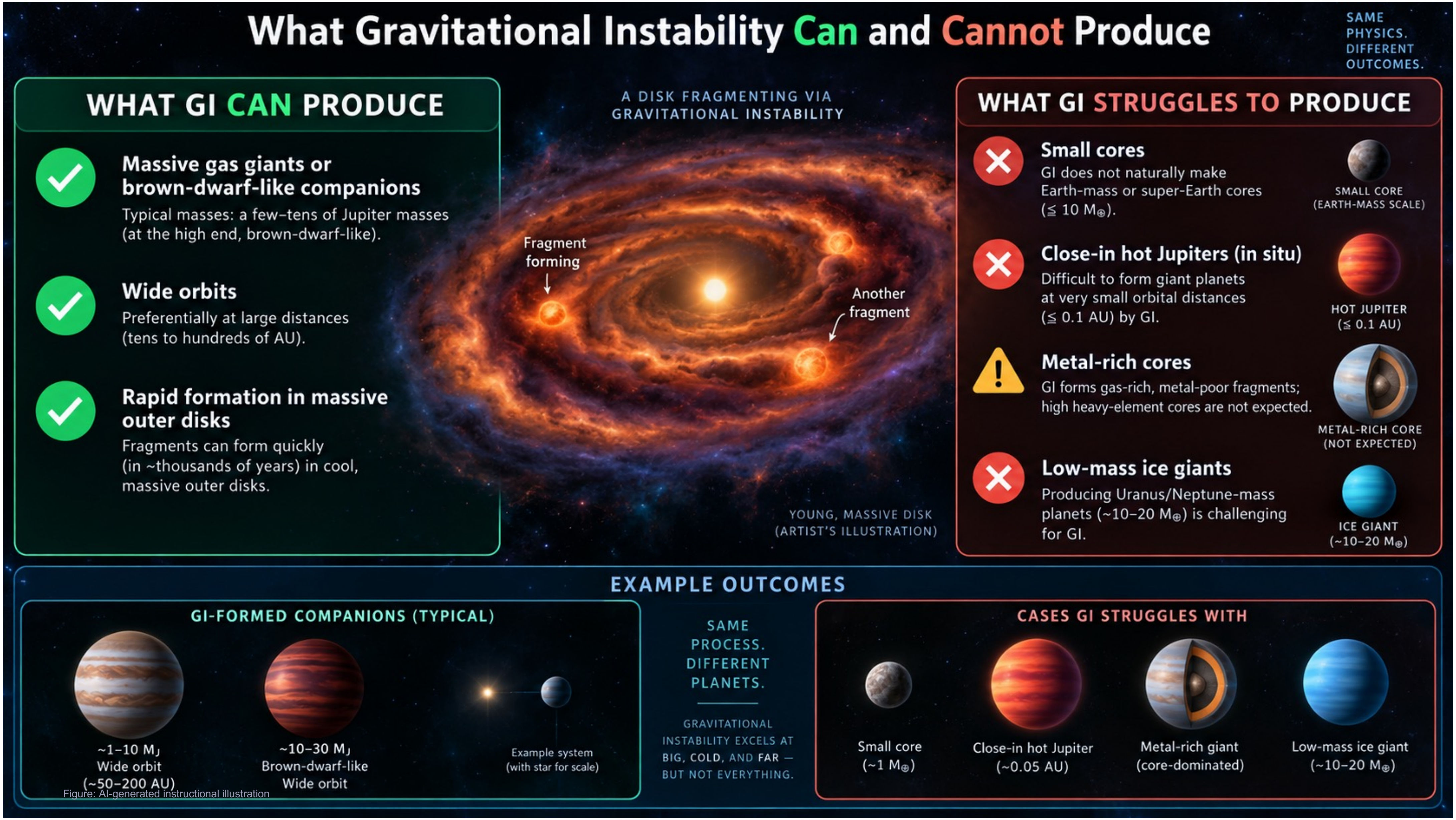


Figure: AI-generated instructional illustration

Lecture 7

行星-盘的相互作用与迁移

PLANET DISK INTERACTION AND MIGRATION

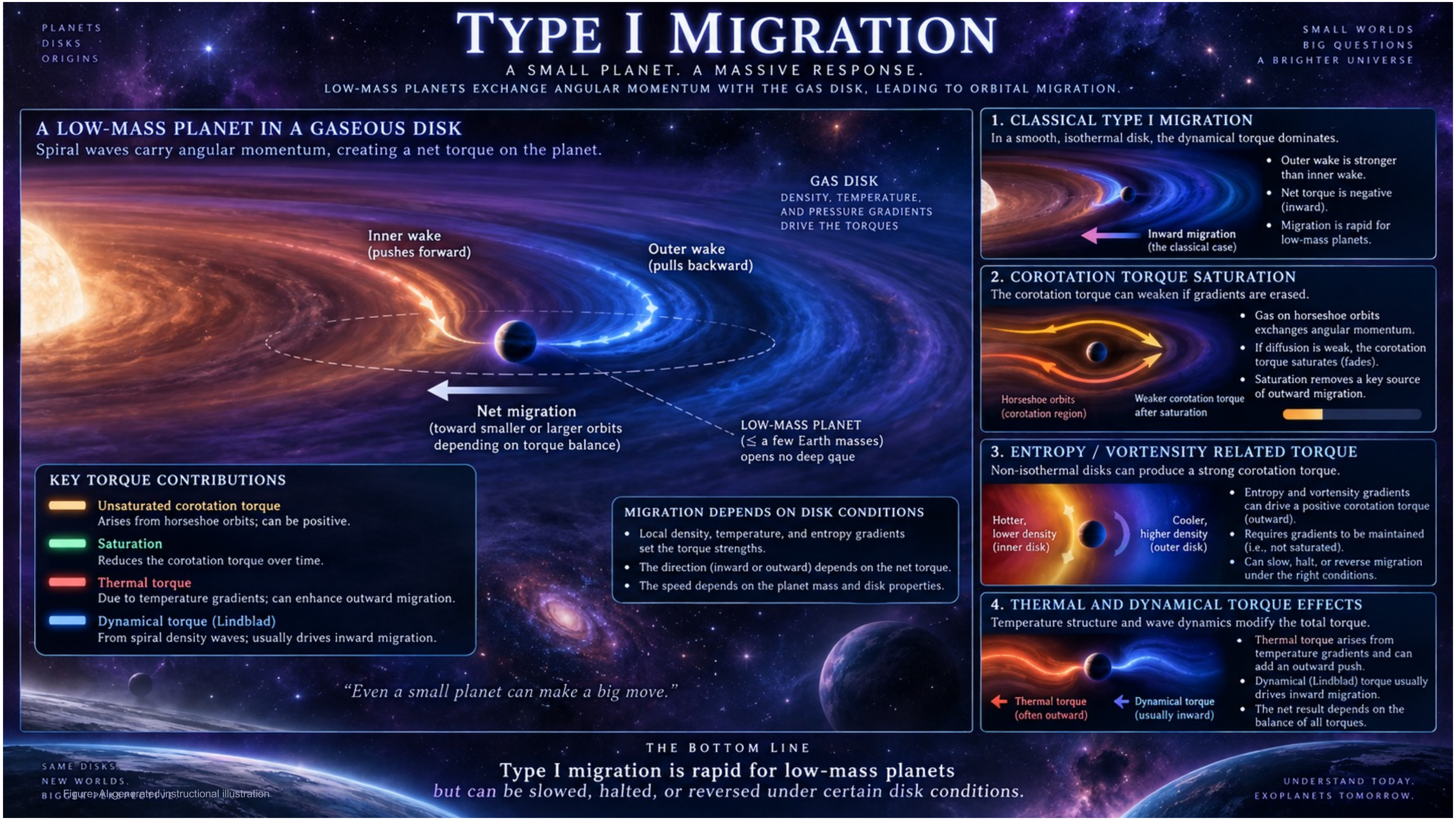
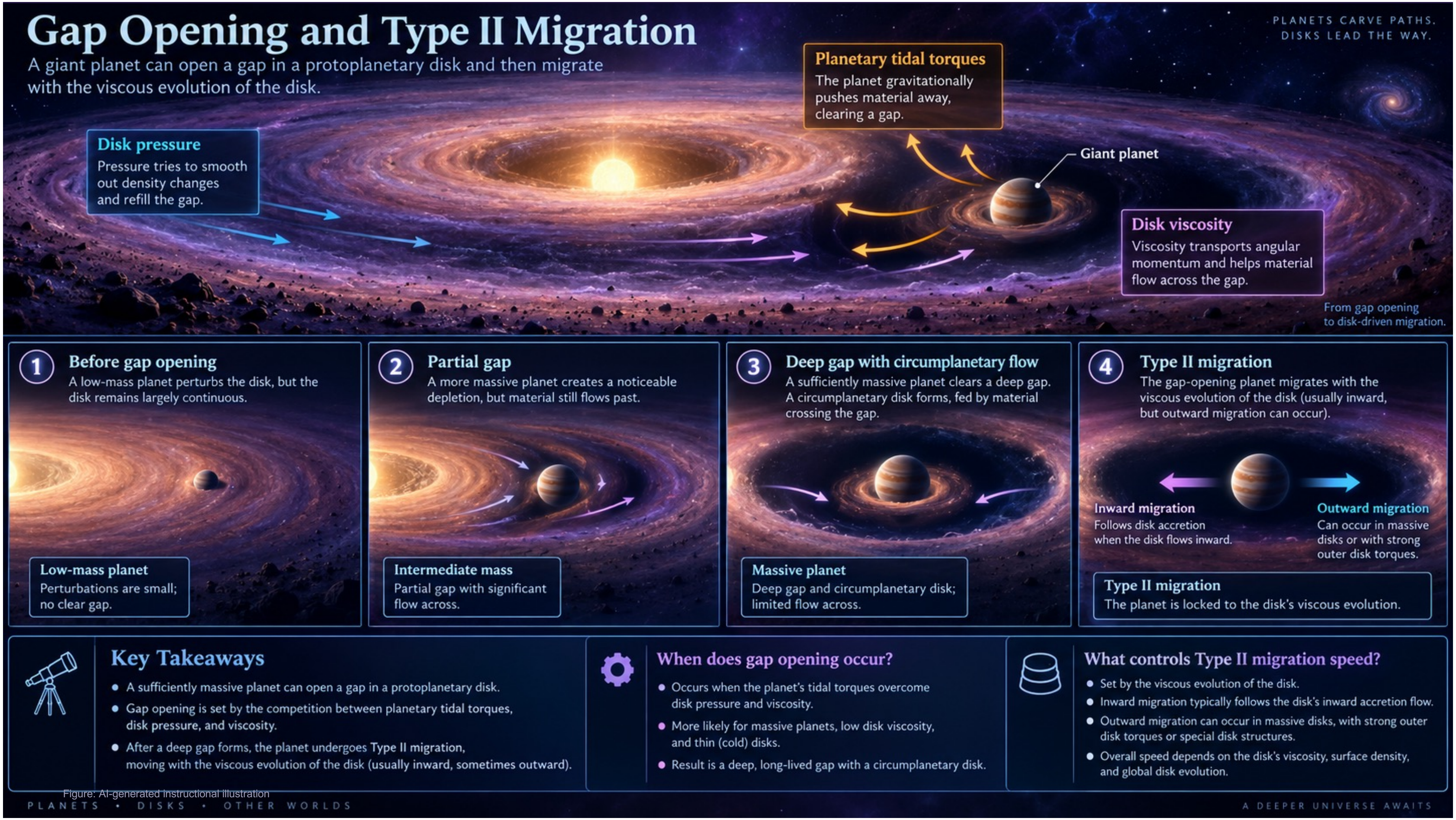


Figure: AI-generated instructional illustration



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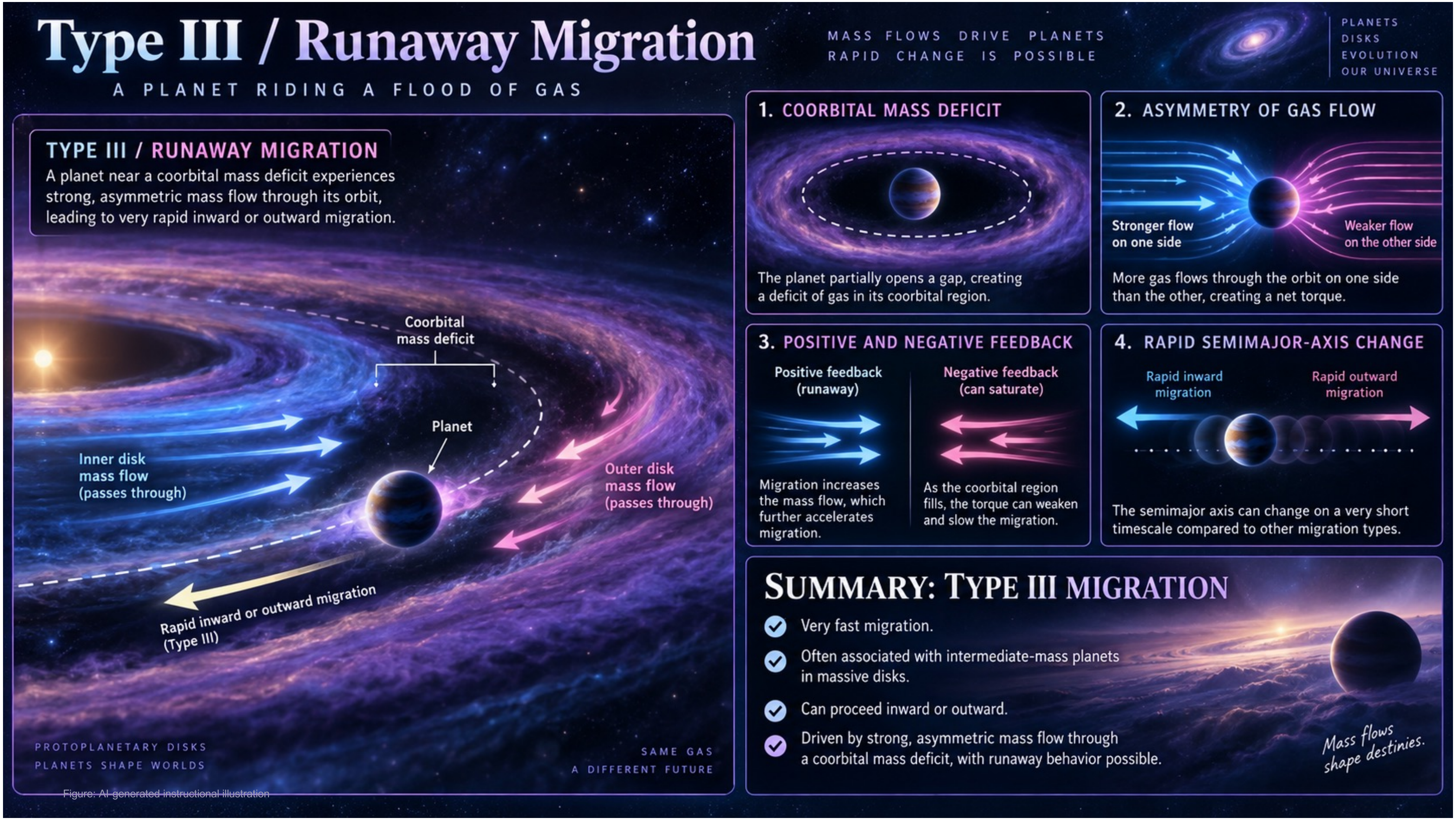

Figure: AI-generated instructional illustration

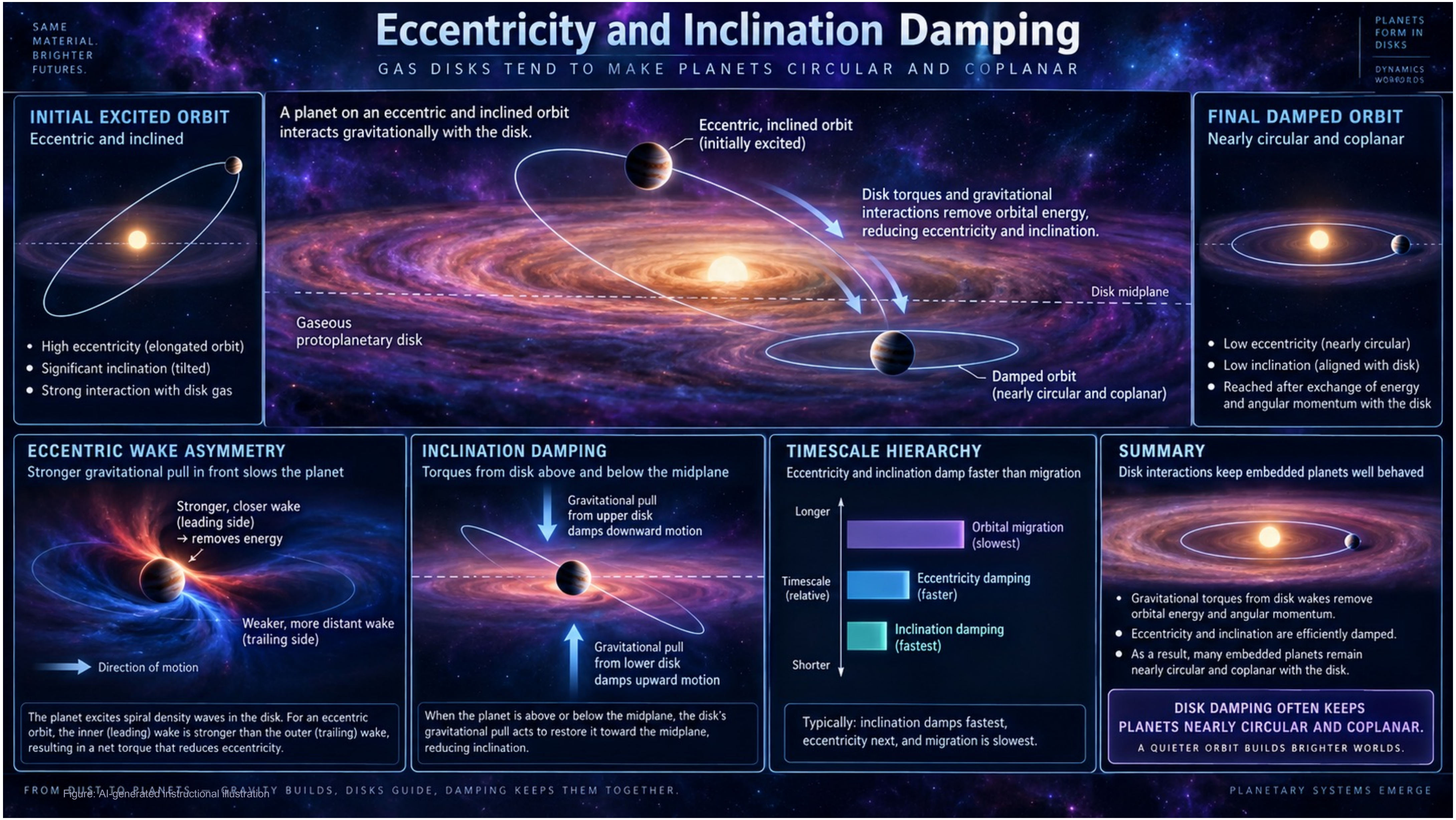

Figure: AI-generated instructional illustration

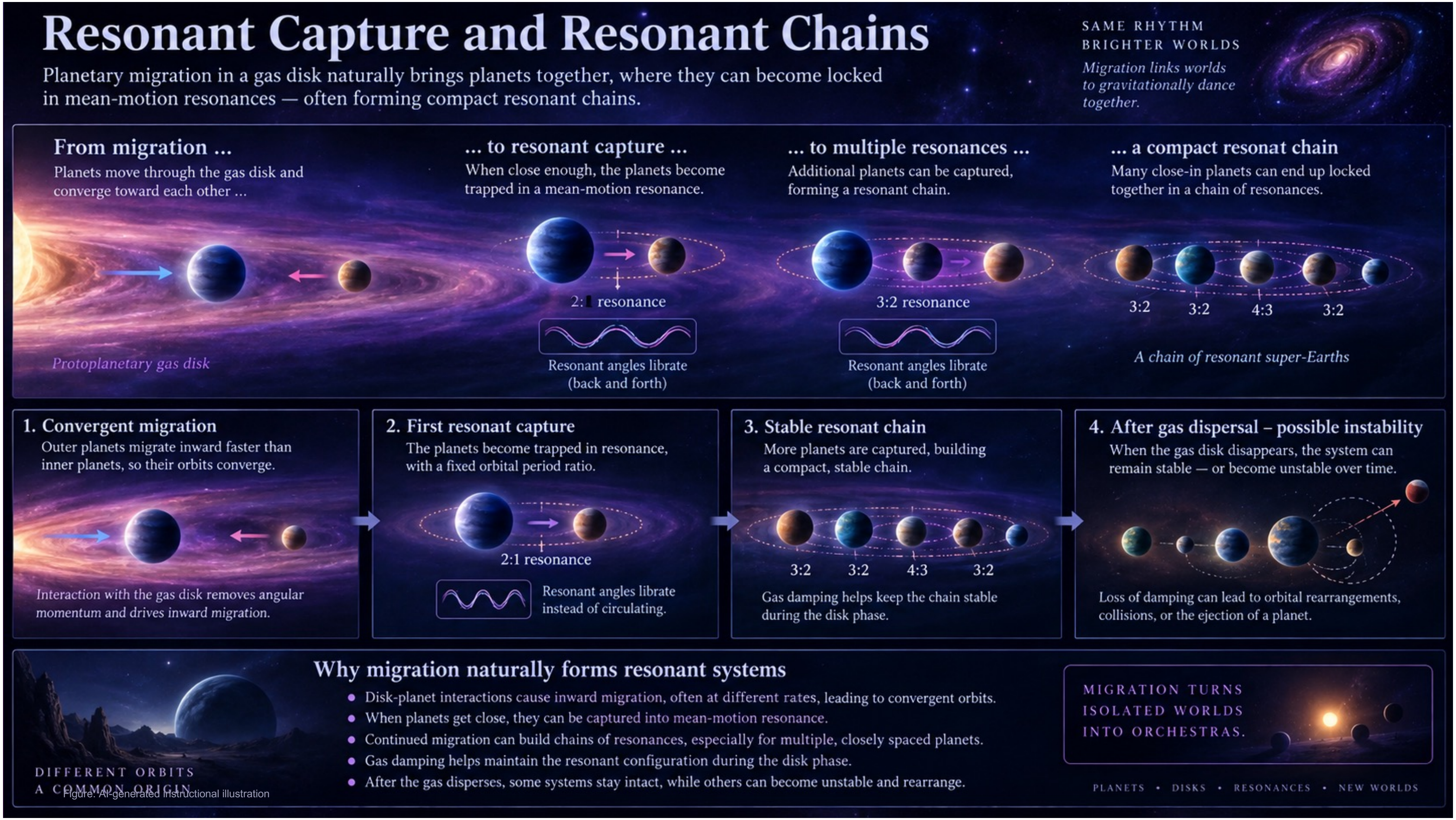

Figure: AI-generated instructional illustration