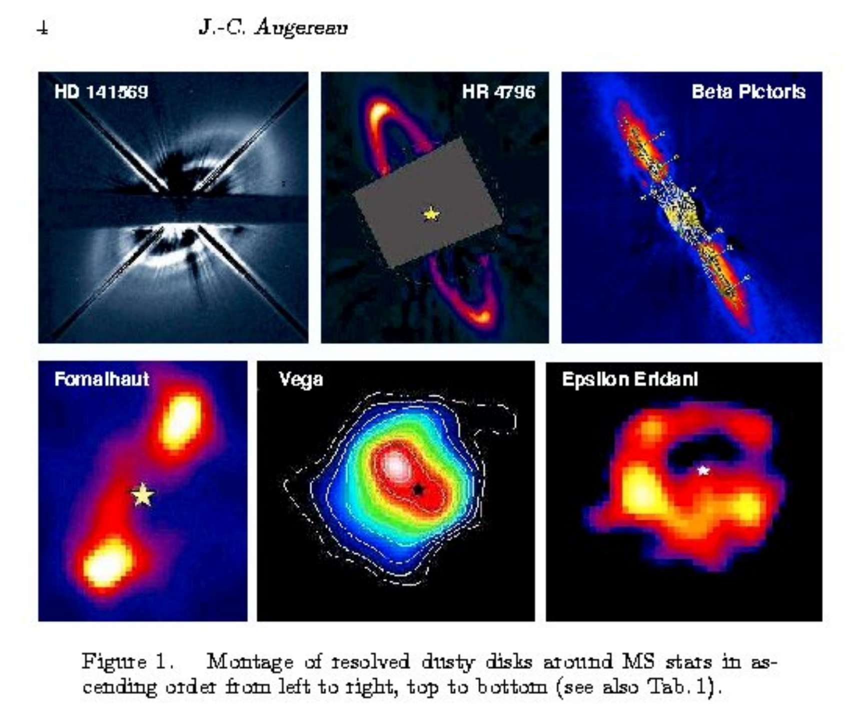


4 J.-C. Augereau

Figure 1. Montage of resolved dusty disks around MS stars in ascending order from left to right, top to bottom (see also Tab. 1).

Lecture L16 & 17

ASTB25

- Beta Pictoris-type dusty disks: extrasolar planetary systems
- Planetary rings

1. **Discovery and study of dusty disks in Vega-type systems**
2. **Evidence of planetesimals and planets in the Beta Pictoris system**
3. **Replenished dust disks: collisions and nature of dust**
4. **Structure in exoplanetary dust disks**
5. **Rings as a laboratory of disk-satellite processes: gap opening**
6. **Physics of dust: temperature, radiation pressure**
7. **Collisions and removal of dust. Rate of mass loss from a disk**
8. **Crystallinity of dust**

Discovery and study of dusty disks:

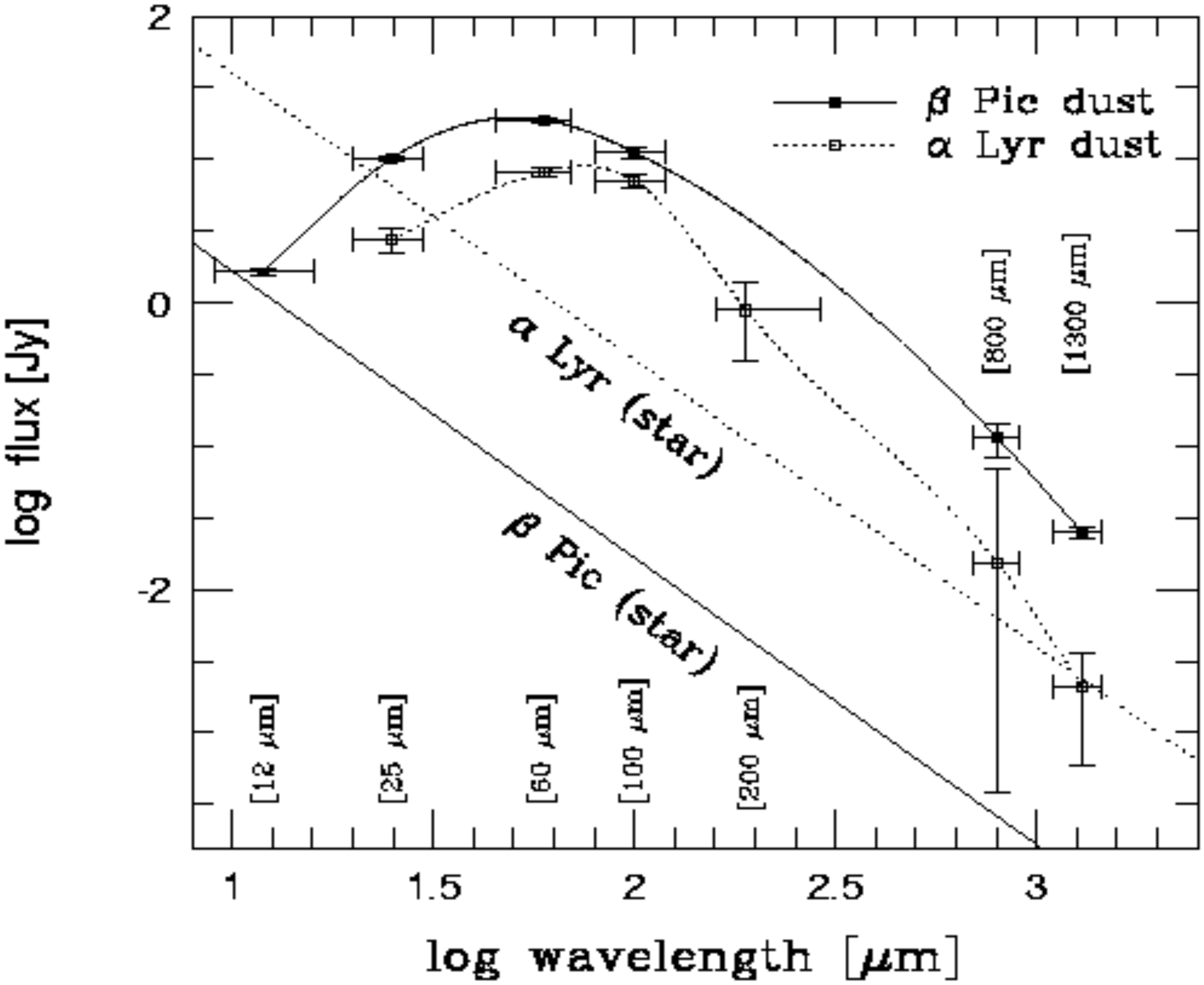
Scattered light tells us how the scattering area is distributed around the star and how reflective particles are

Thermal radiation measurements and images (at wavelengths of 10 microns and larger) tell us how the absorbing and emitting area of particles is distributed around the star and how hot particles are.

Neither the optical nor the mid-infrared images/data alone allow us to separate the contributions of the area and the emissivity (scattering/emission coefficient).

Albedo (A, percentage of light scattered) can only be found by comparing observations done in the visible and mid-infrared (or far-IR) spectral domains.

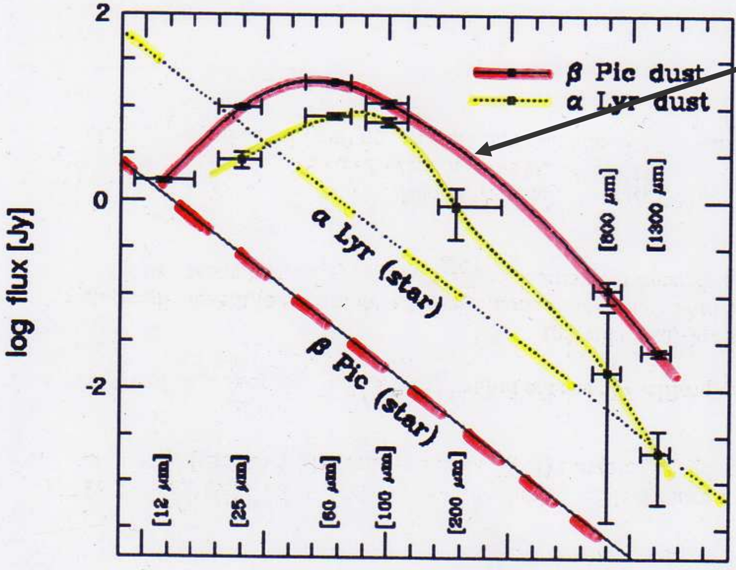
Infrared excess stars (Vega phenomenon)



Artymowicz “Beta Pictoris: An Early Solar System?” Ann. Rev. Planet. Sci. (1997)

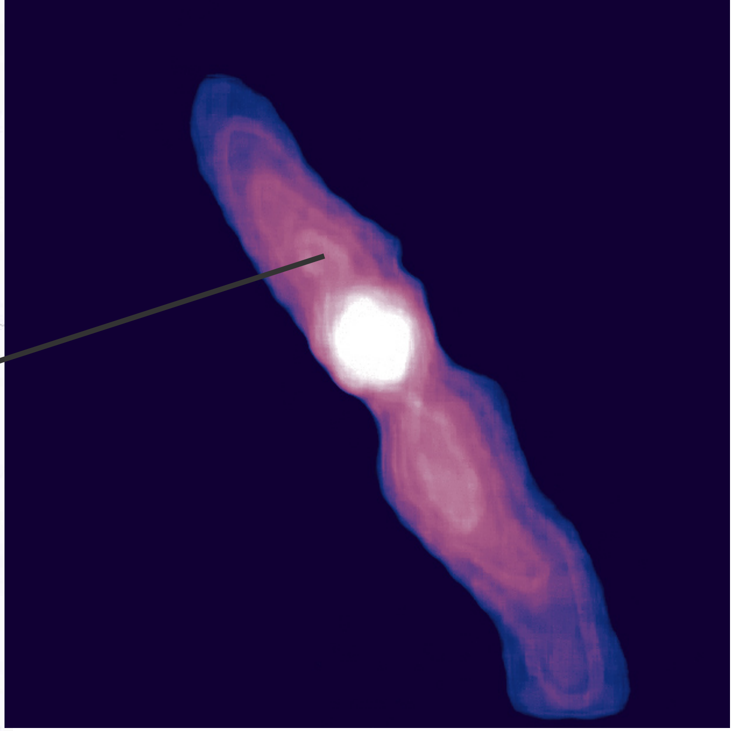
ORDINARY STARS WITH EXTRAORDINARY DISKS - β Pictoris

Artymowicz(1997) Ann. Rev. Earth & Pl. Sci.
collaborators: F Paresce, C Burrows, P-O Lagage, E Pantin, R Liseau, M Clampin, S Heap



IRAS (1983) found 4 prototypes of Vega–type systems:

α Lyr = Vega
β Pic (Pictoris)
ε Eri (Eridani)
α PsA = Fomalhaut

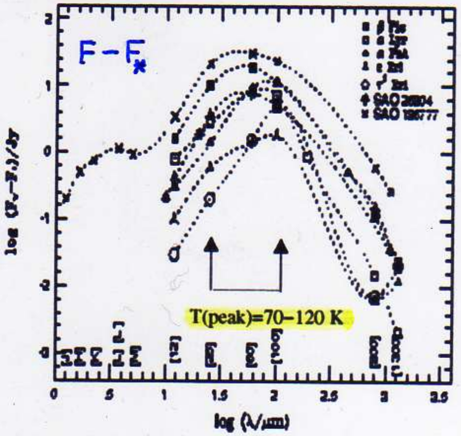


Beta Pictoris

thermal radiation (10 μm)
Lagage & Pantin (1993)

We now know from ISO that >15% of all normal stars have IR excess from cool dust disks, similar to these:

and that they have central clearings with radii ~ Solar System



Vega/β Pic dusty disks. Range of radii established from the temperature of dust coincides with the typical size of a planetary system.

Star	**Spectral Class**	**Distance (ly)**	**Dust orbital range (AU)**
ε Eridani	K2V	10.5	35–75
Tau Ceti	G8V	11.9	35–50
Vega	A0V	25	86–200
Fomalhaut	A3V	25	133–158
AU Microscopii	M1Ve	33	50–150
HD 181327	F5.5V	52	89-110
HD 69830	K0V	41	<1
HD 207129	G0V	52	148–178
HD 139664	F5IV–V	57	60–109
Eta Corvi	F2V	59	100–150
β Pictoris	A6V	63	25–550
Zeta Leporis	A2V	70	2–8
HD 92945	K1V	72	45–175
HD 107146	G2V	88	130
γ Ophiuchi	A0V	95	520
HR 8799	A5V	129	75
51 Ophiuchi	B9	131	0.5–1200
HD 15115	F2V	150	315–550
HR 4796 A	A0V	220	200
HD 141569	B9.5e	320	400
HD 113766A	F4V	430	0.35–5.8

Tutorial Problem:

A dust particle is released on a circular orbit of its parent body (orbital radius r), which is not affected by radiation pressure due to size.

Radiation adds acceleration $+\beta GM/r^2$ to the gravity's acceleration on dust, $-GM/r^2$. Here β is the radiation pressure coefficient, ratio of radiation to gravity forces. M is the star's mass.

Radiation acts purely radially. The new 2-body problem of star+dust particle is equivalent to a standard 2-B problem with central mass $(1-\beta)M$.

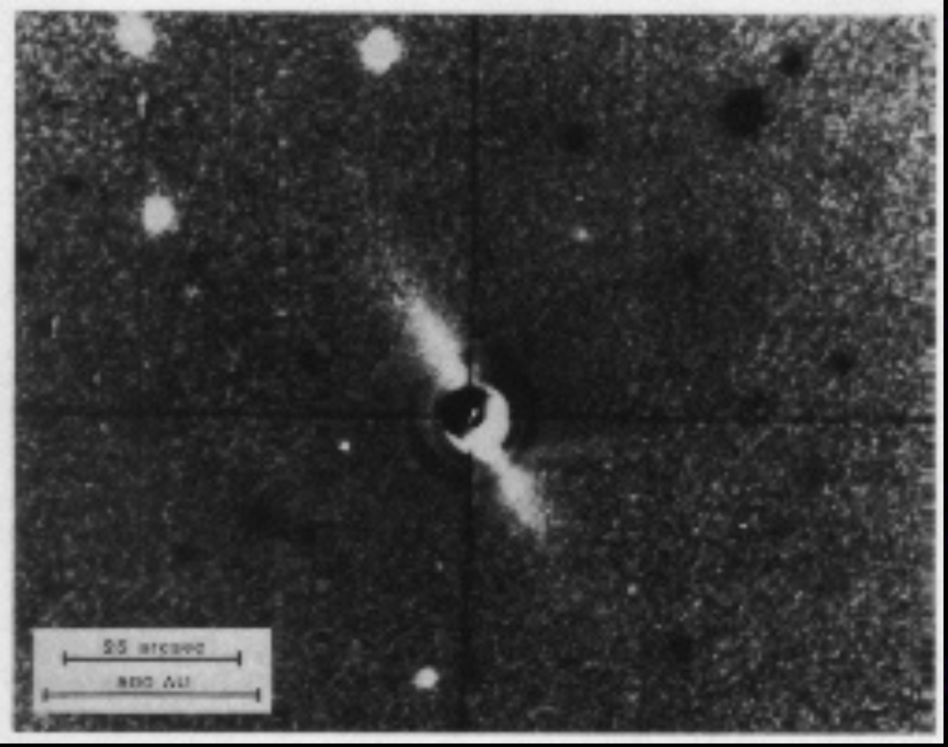
Find the $e(\beta)$ dependence, and a/r ratio as a function of β.

This problem can be solved either using energy or angular momentum.

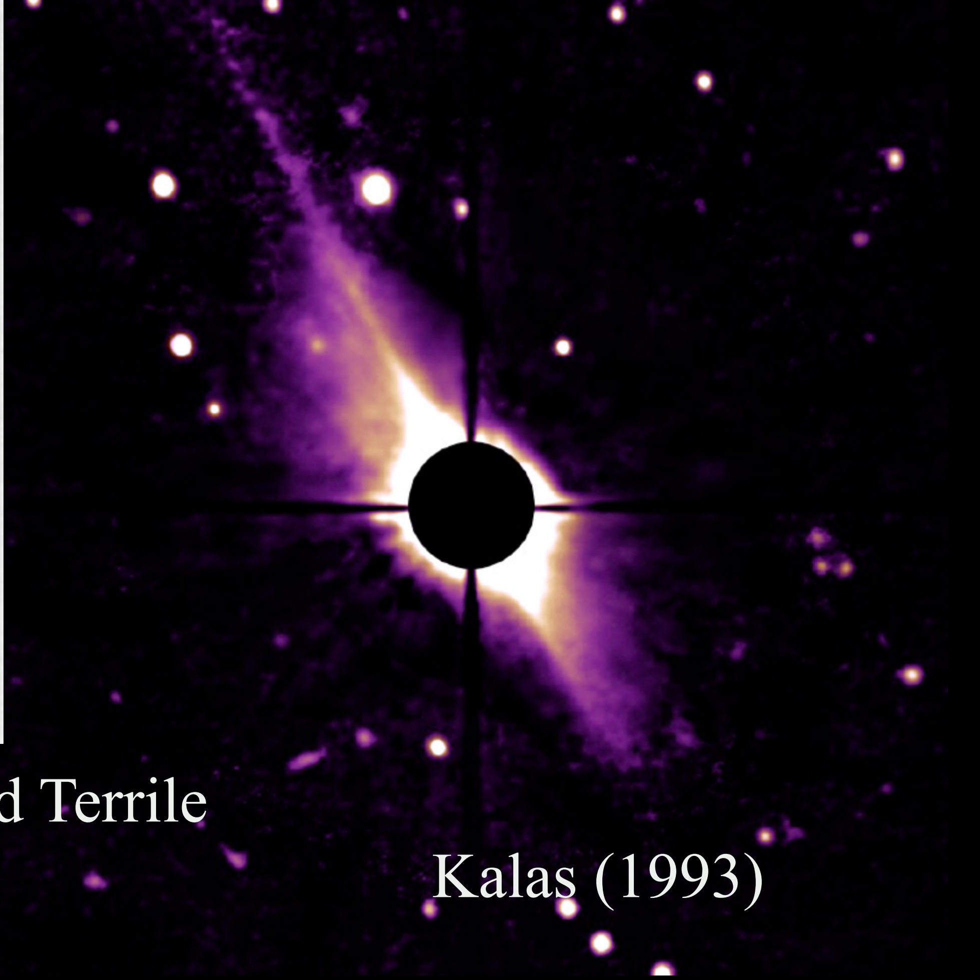
Note that the new pericenter distance is equal to the ord one: $a(1-e) = r$.

1. New energy $E = -G(1-\beta)M/(2a)$, equals old energy $-GM/(2r)$, plus $+\beta GM/r$ (change of potential due to radiation; from the force-potential relationship)
   $(1-\beta)/a == 1/r - 2\beta/r = (1-2\beta)/r \rightarrow r/a = 1- \beta/(1-\beta) == 1-e \rightarrow$
   $e(\beta) = \beta/(1-\beta)$ and $a(\beta) = r(1-\beta)/(1-2\beta)$.
2. $L^2 = GMr == GM(1-\beta)a(1-e^2) == GM(1-\beta)r(1+e) \rightarrow 1 = (1-\beta)(1+e) \rightarrow$
   $e(\beta) = \beta/(1-\beta)$ and $a(\beta) = r(1-\beta)/(1-2\beta)$ again.

What happens with a and e when $\beta=1/2$?

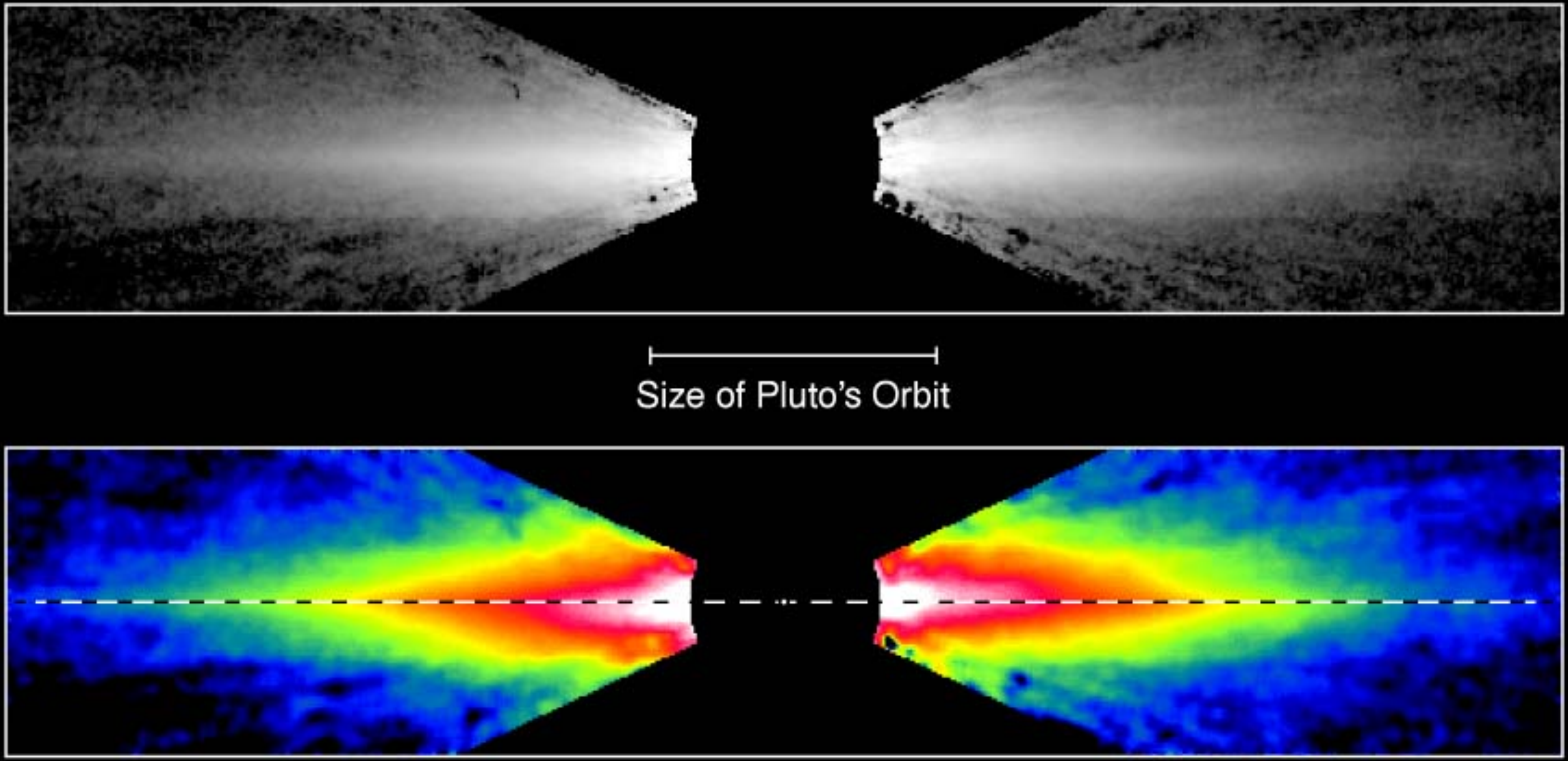


1984, discovery image by Smith and Terrile



Kalas (1993)

β Pictoris seen in the visible, scattered starlight.
Comparison with IR data yields a high albedo, A~0.4-0.5 (like Saturn’s rings but very much unlike the black particles of cometary crust or Uranus rings).

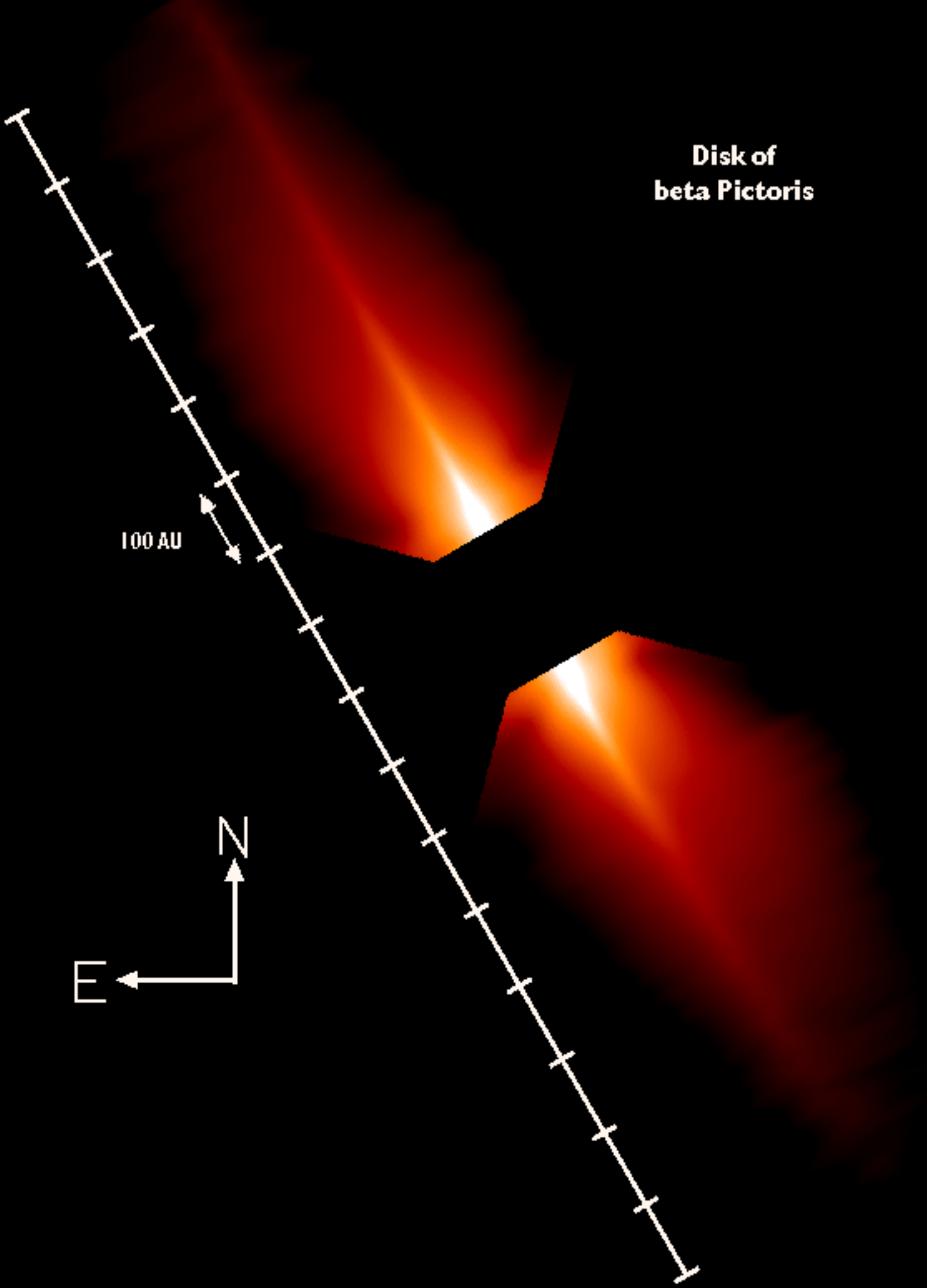


Warped Disk · Beta Pictoris HST · WFPC2

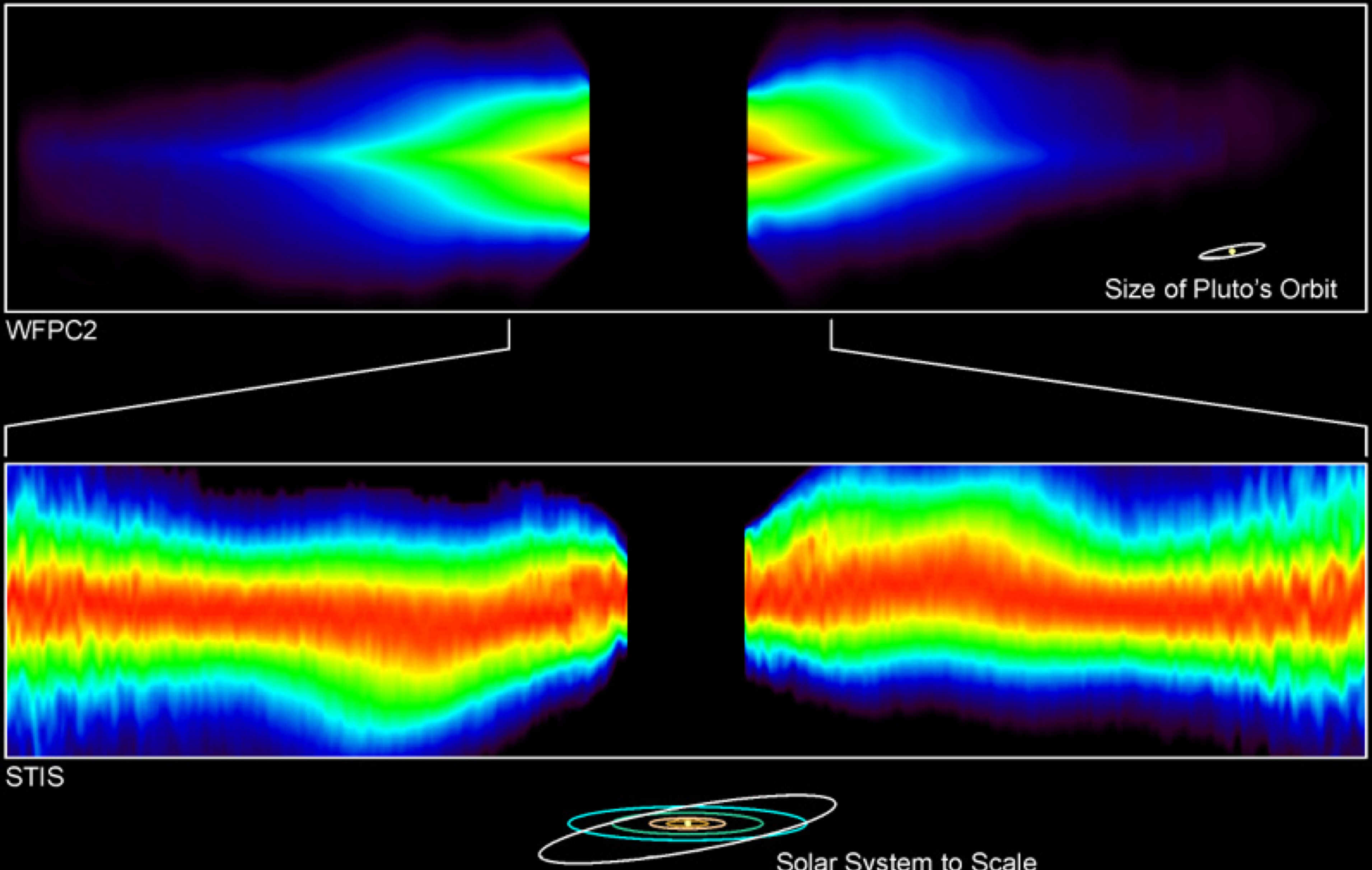
PRC96-02 · ST ScI OPO · January 17, 1995 · C. Burrows and J. Krist (ST ScI), WFPC2 IDT, NASA

The disk a decade after discovery – because of better quality data, image has fewer artifacts, disk appears smoother.

Beta Pictoris
- a prototype of debris disks



scattered light image showing large extent

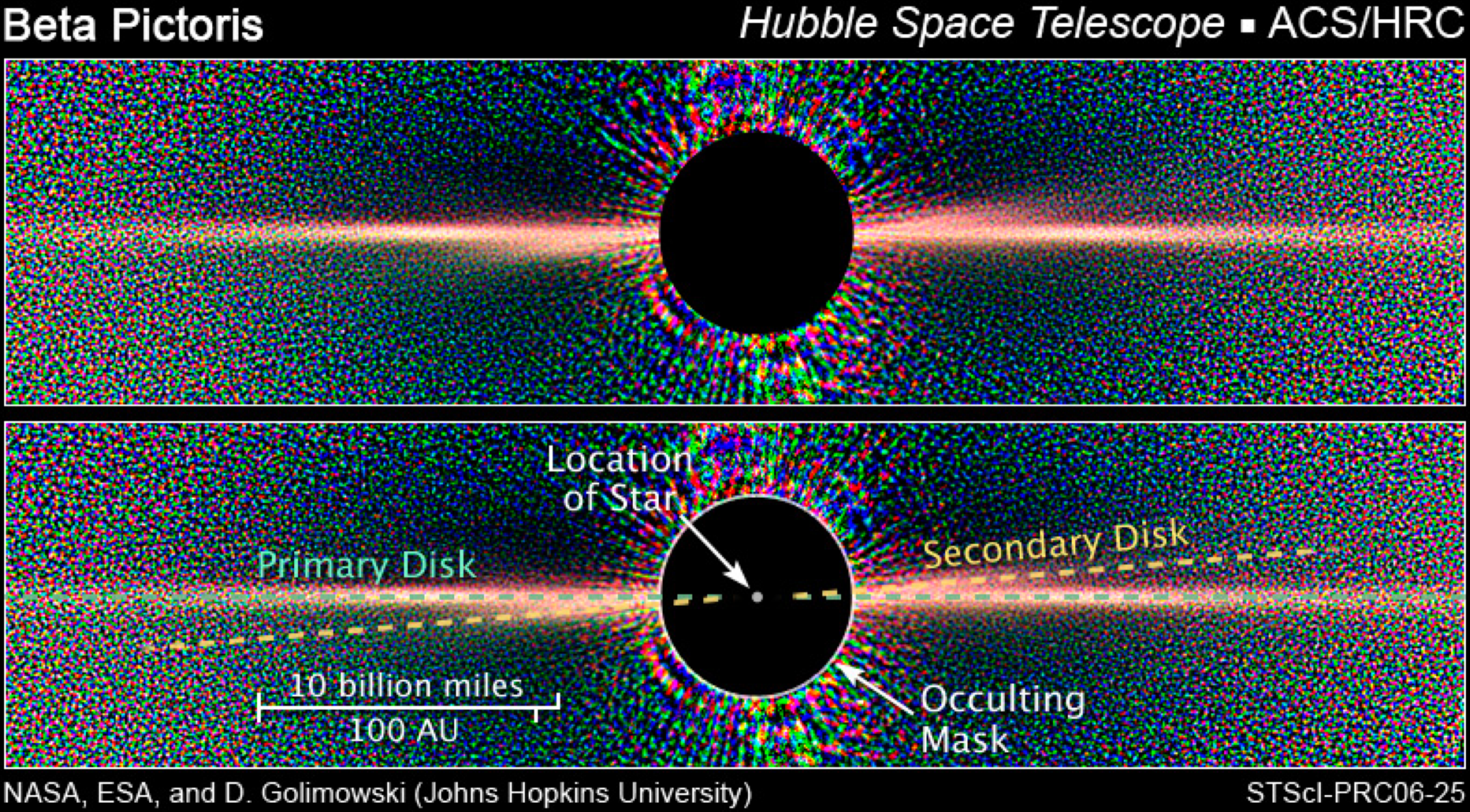


Beta Pictoris

HST • WFPC2 • STIS

PRC98-03 • January 8, 1998 • ST ScI OPO

A. Schultz (Computer Sciences Corp.), S. Heap (NASA Goddard Space Flight Center) and NASA



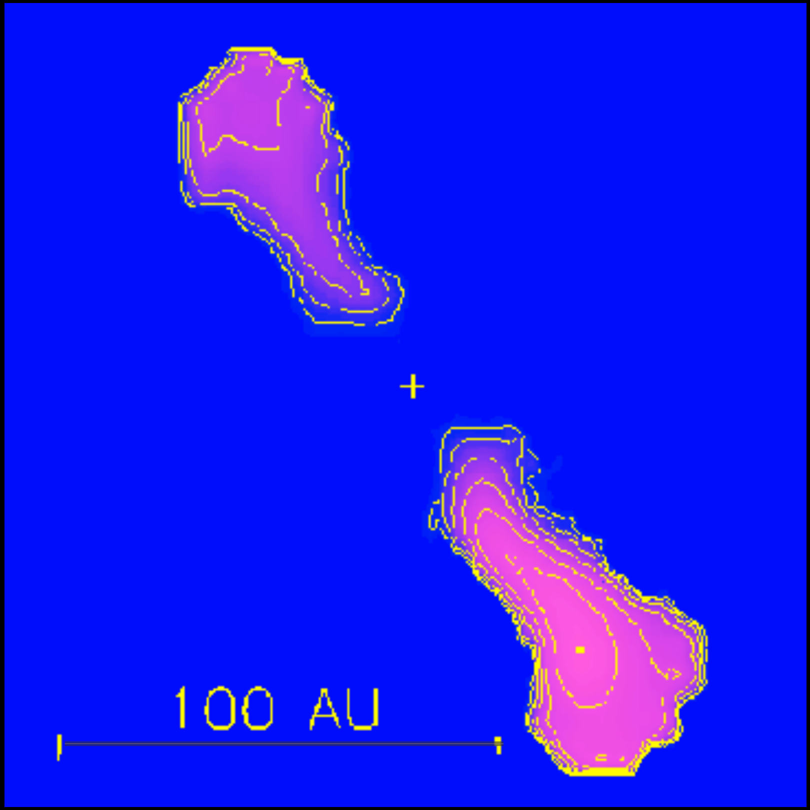
Beta Pictoris disk in Golimowski et al. HST image shows the secondary disk.

Evidence of planetesimals and planets in the vicinity of beta Pictoris:

1. Lack of dust near the star (r<30AU)
2. Spectroscopy => Falling Evaporating Bodies
3. Gravity of a planet is needed to perturb asteroids to produce FEBs
4. The disk is warped or consistes of 2 disks inclined by a few degrees to the plane of the disk (orbit of a planet?)
5. Large reservoir of parent (unseen) bodies of dust needed, of order 100 Earth masses of rock/ice. Otherwise the dust would disappear quickly, on collisional time scale

Beta Pictoris

Not much dust inside ~30 AU



λ=11 μm (thermal) image
(Lagage & Pantin 1994)

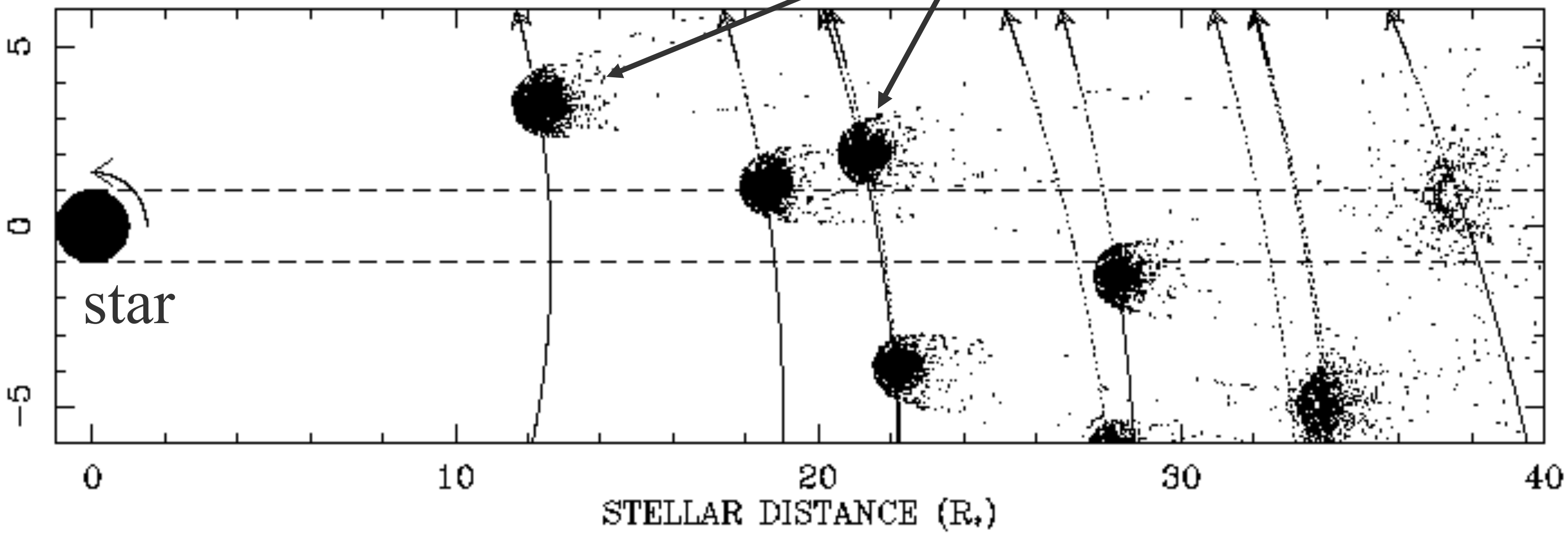
10^4x the number of comets and asteroids in the Solar System

B Pic b sky?

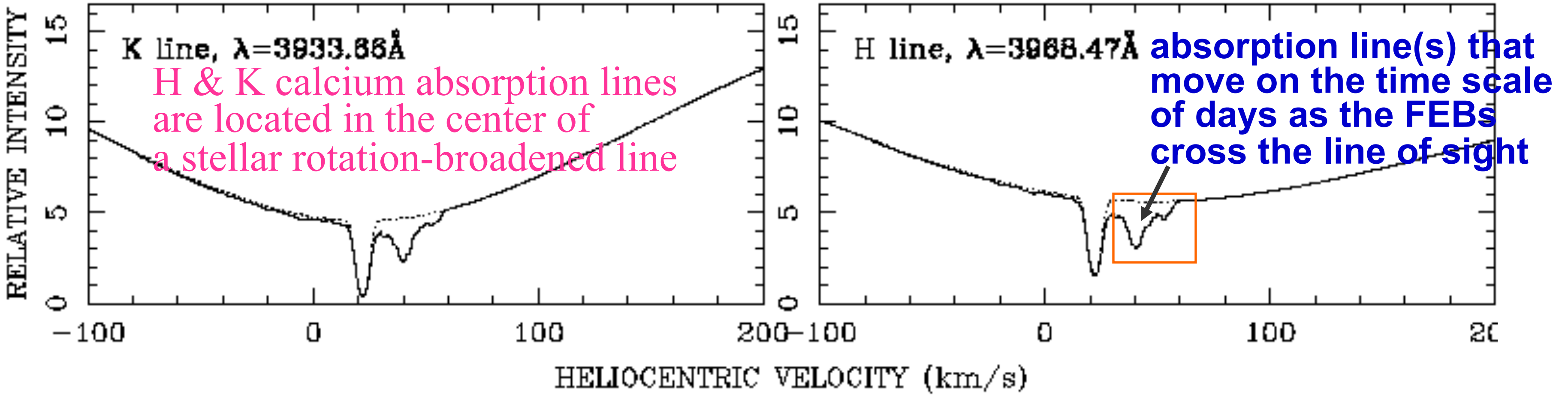
FEB = Falling Evaporating Bodies in Beta Pictoris, evidence from time-variable spectra

Beust et al 1994

FEB

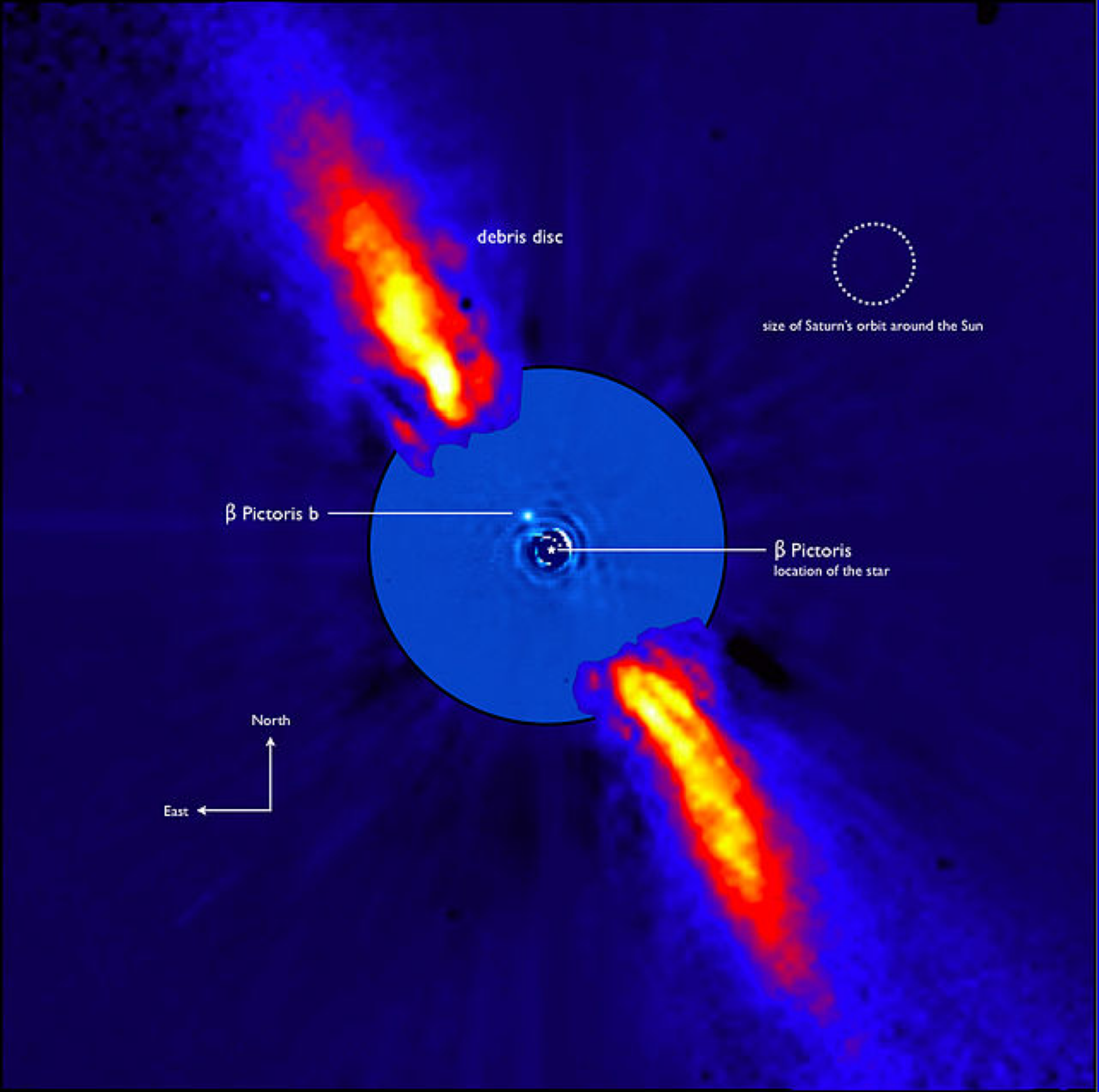


star



H & K calcium absorption lines are located in the center of a stellar rotation-broadened line

absorption line(s) that move on the time scale of days as the FEBs cross the line of sight

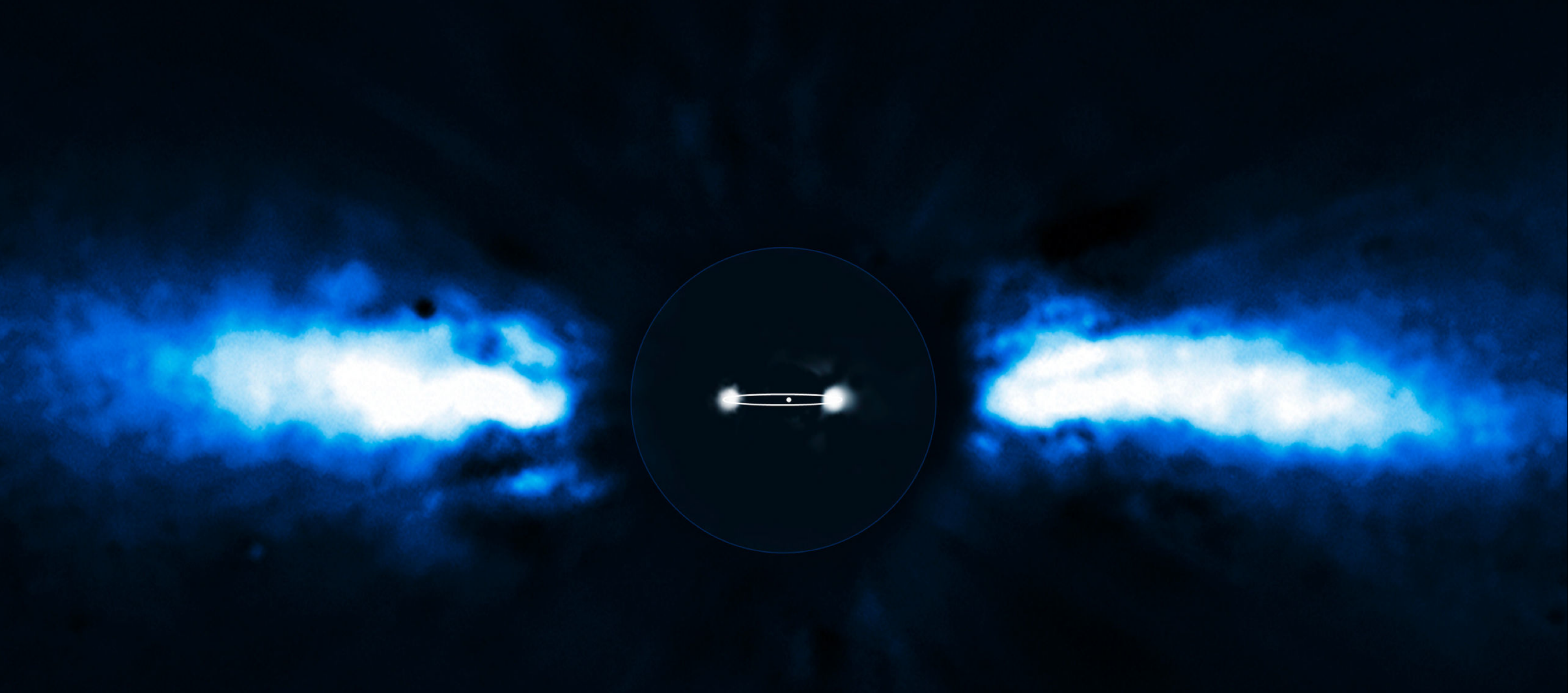


β Pic b

a planet in
the central
clearing

discovered
in 2009

β Pictoris b, an extrasolar planet bigger than Jupiter

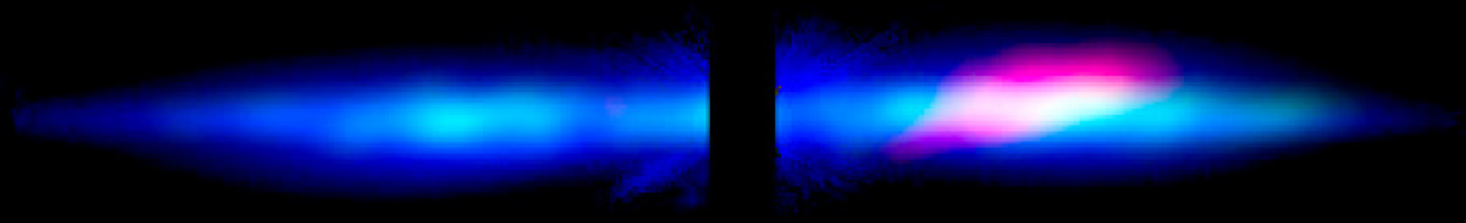


This system for a long time was the only directly imaged debris disk with embedded giant planet (image in the inset).

Beta Pictoris disk has many kinds of asymmetries stable for at lest 15 years of observtions

Here, we see the red light (false-color image of radio emission from CO gas)

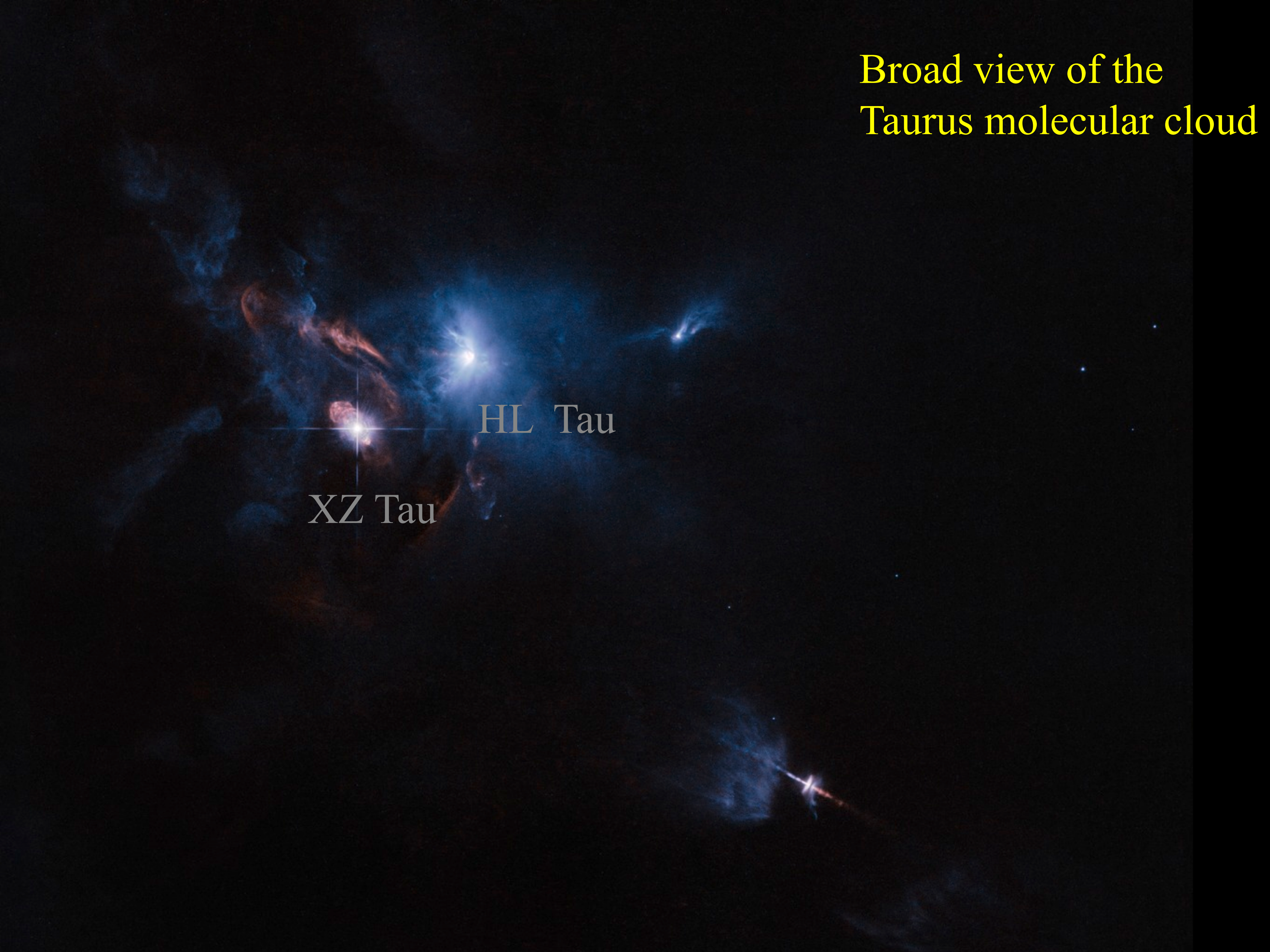
In addition to dust, the disk has many kinds of atoms and ions in it. However, their total mass is < mass of dust, which is very different from the original H+He-dominated protoplanetary disk



ALMA = Atacama Large Millimeter Array

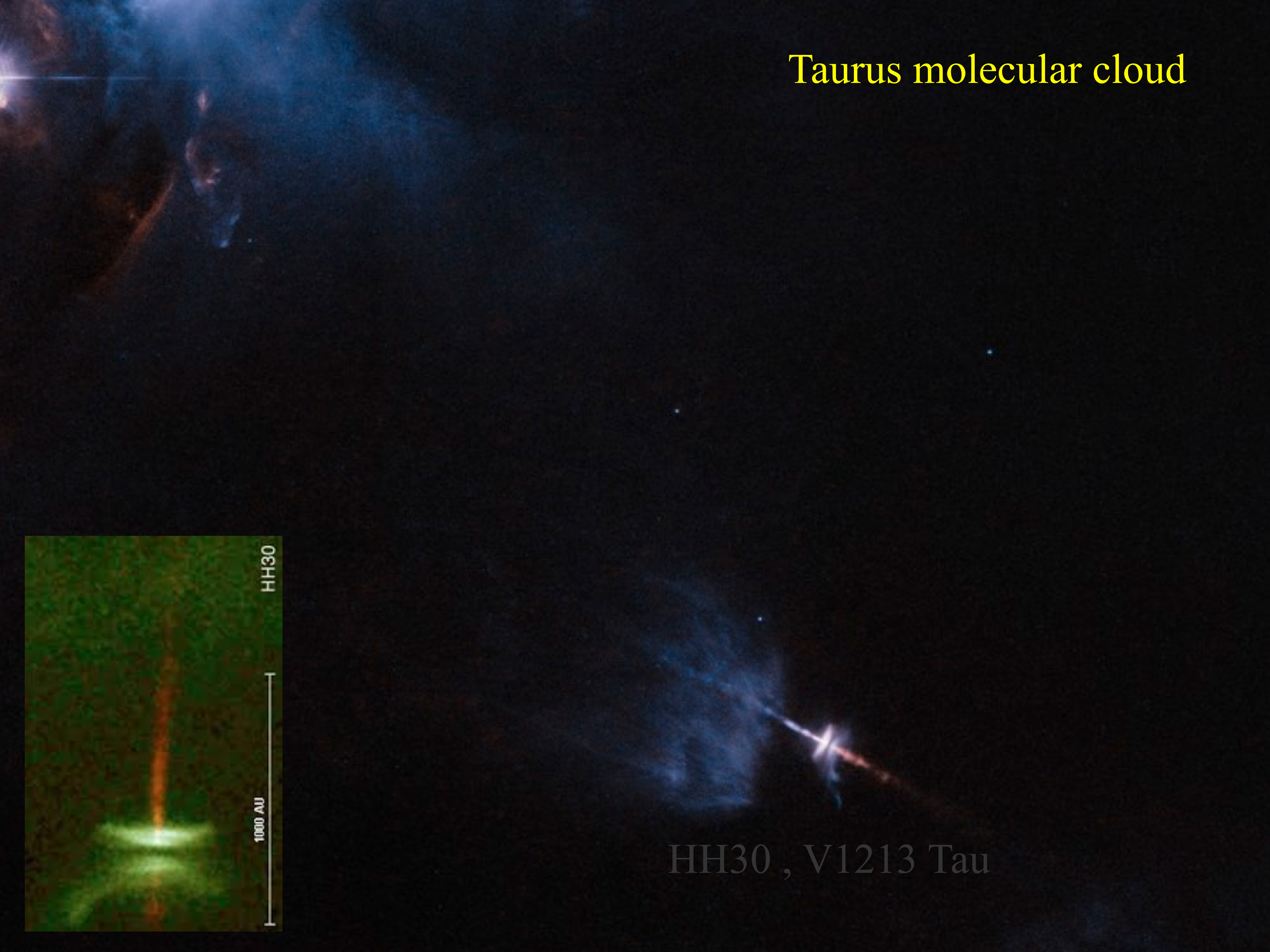
Located on Mt Paranal in Atacama desert in Chile, at 5000 m altitude, not far from VLA (Very Large Telescope = successful European response to the Keck telescopes on Mauna Kea, Hawaii)

ALMA Has 100+ dishes.



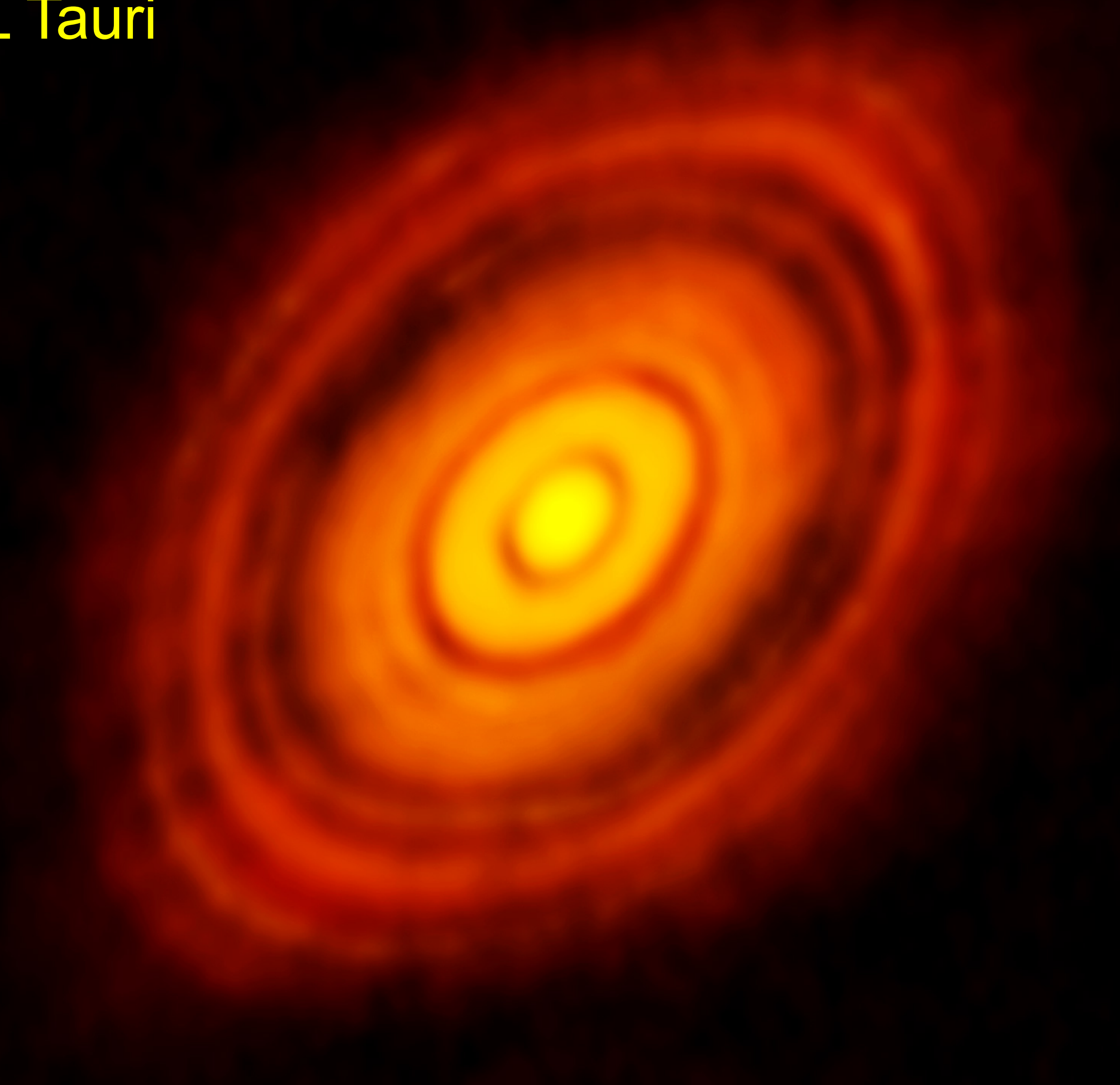
Broad view of the Taurus molecular cloud

Taurus molecular cloud



HH30 , V1213 Tau

On 6 Nov. 2015, engineering tests of ALMA produced this image of HL Tauri



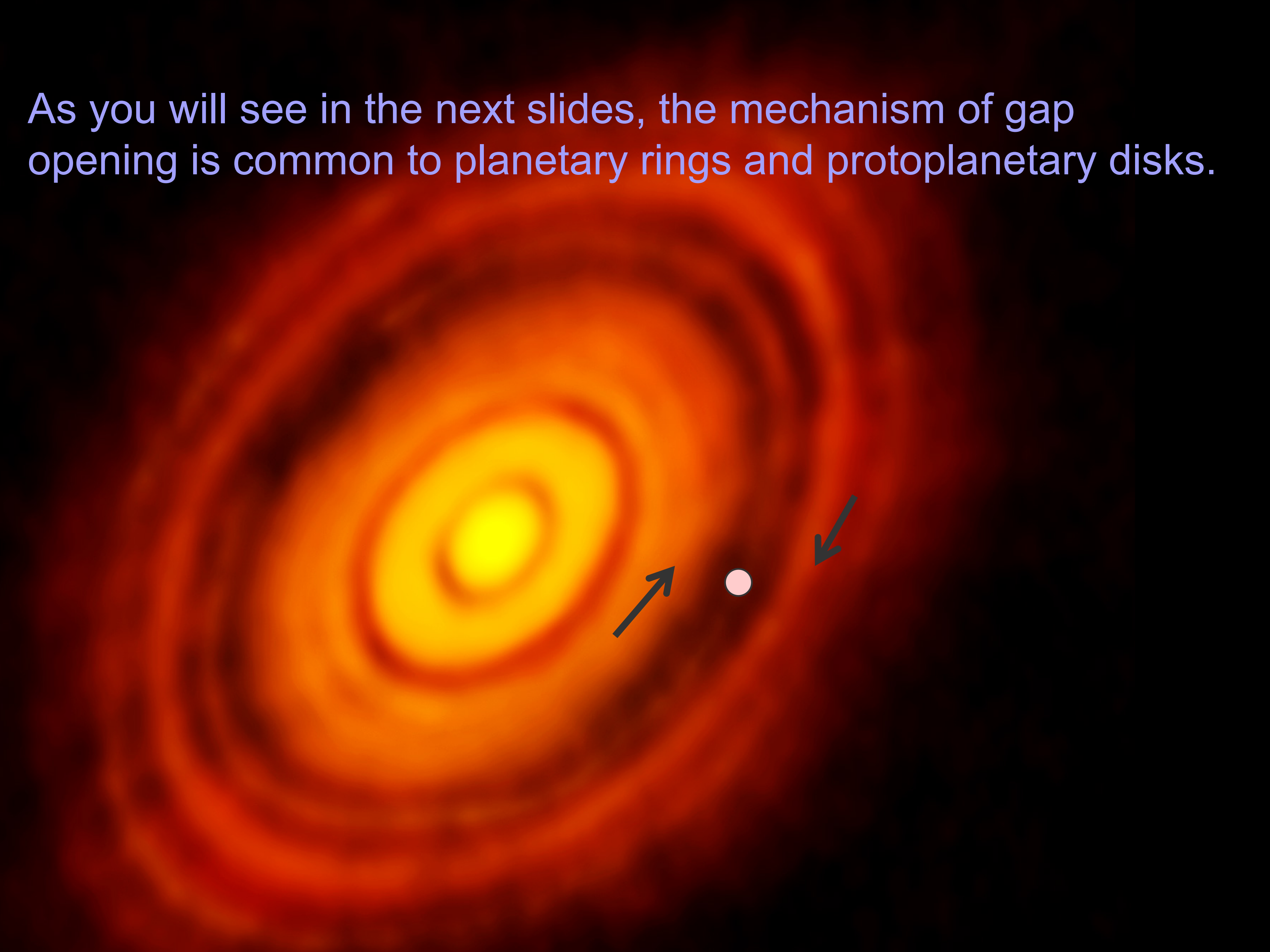
Direct image by ALMA of a young planetary system (0.1 Myr)

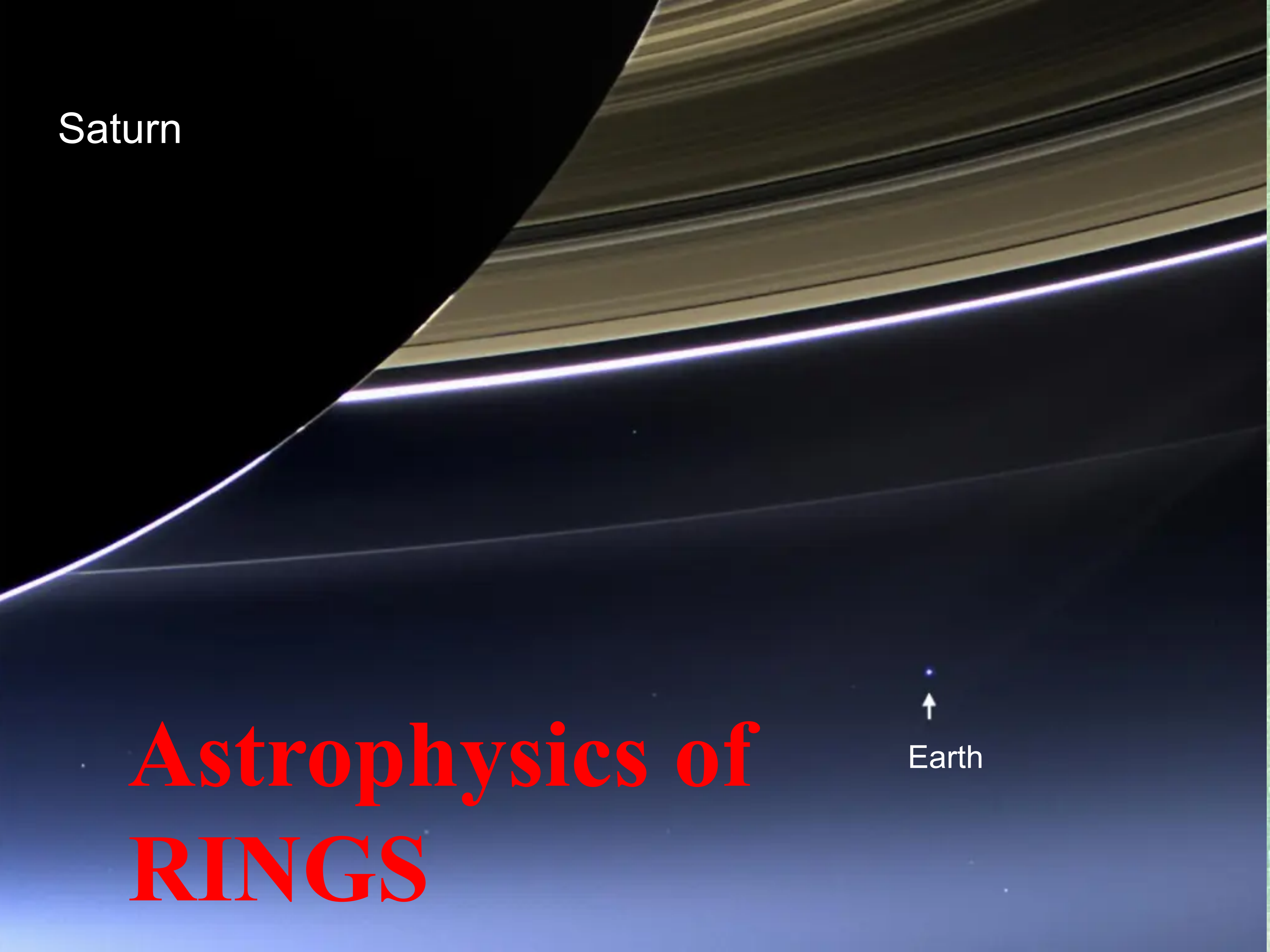
distance 140 pc
size ~200AU
mass 0.05-0.5 $M_\odot$

λ = 1.3 mm

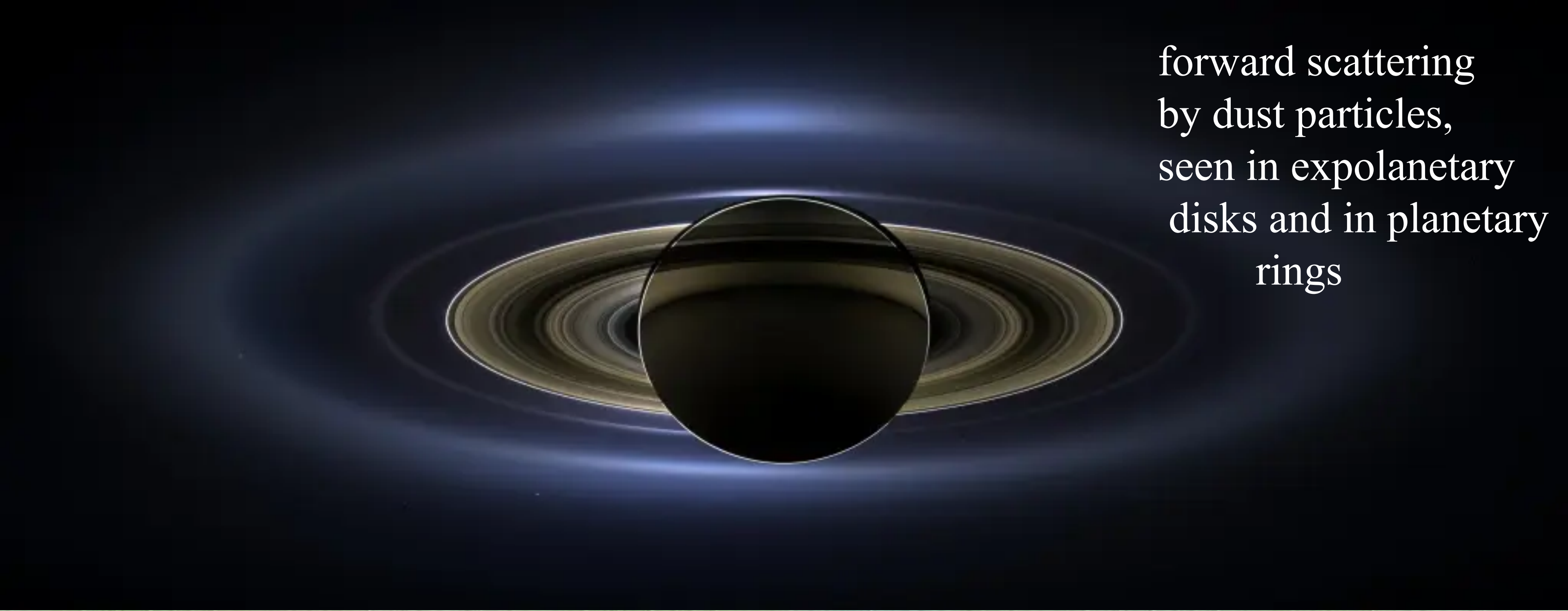
Neptune-class planets creating the many gaps have been proposed, but there are alternatives not involving planets

As you will see in the next slides, the mechanism of gap opening is common to planetary rings and protoplanetary disks.



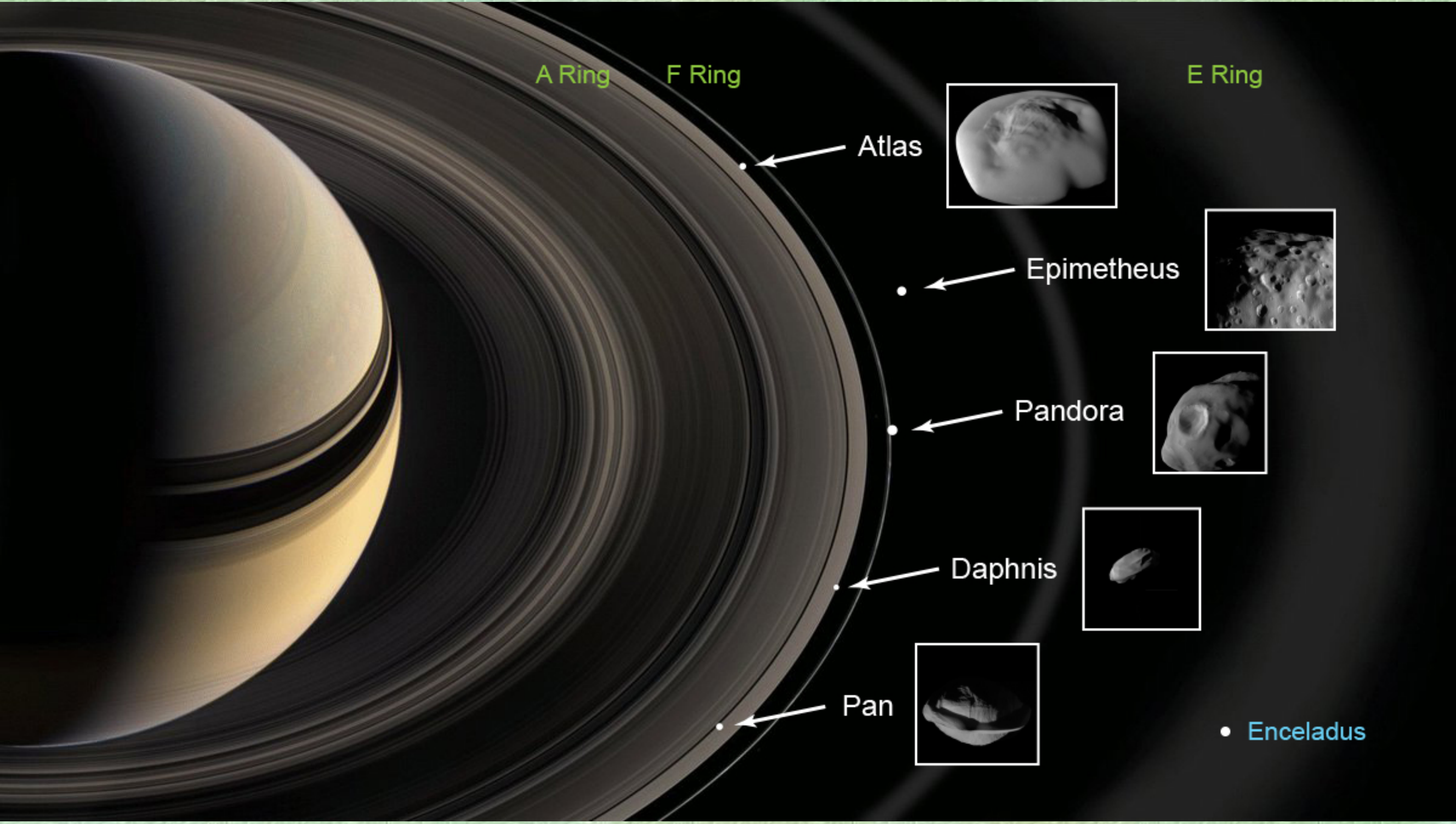


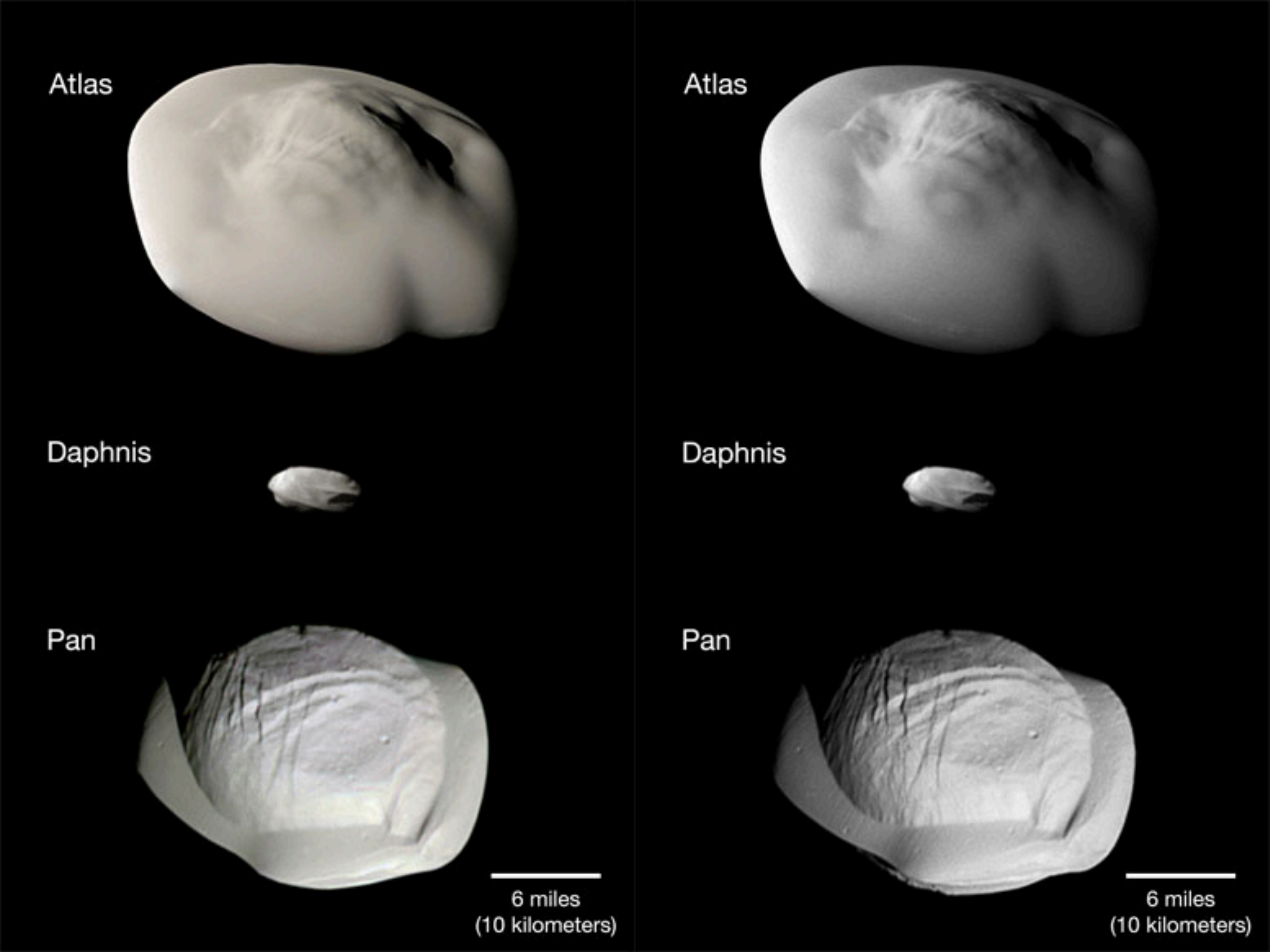
Astrophysics of RINGS

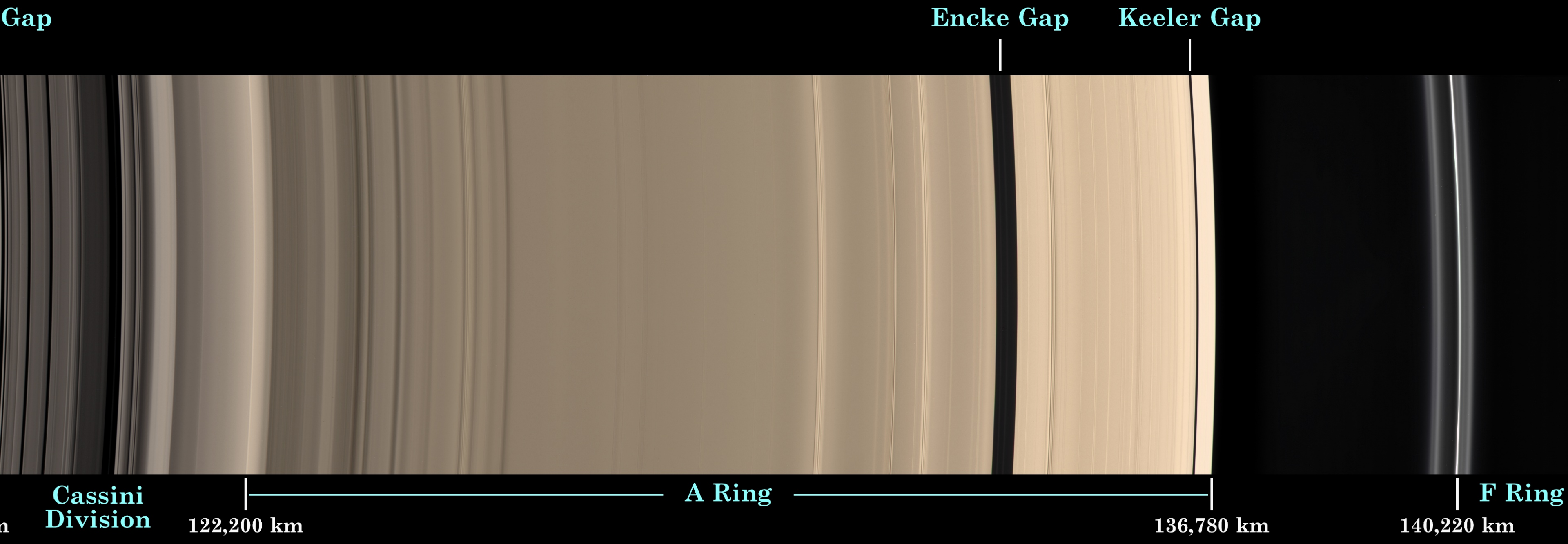


forward scattering
by dust particles,
seen in expolanetary
disks and in planetary
rings

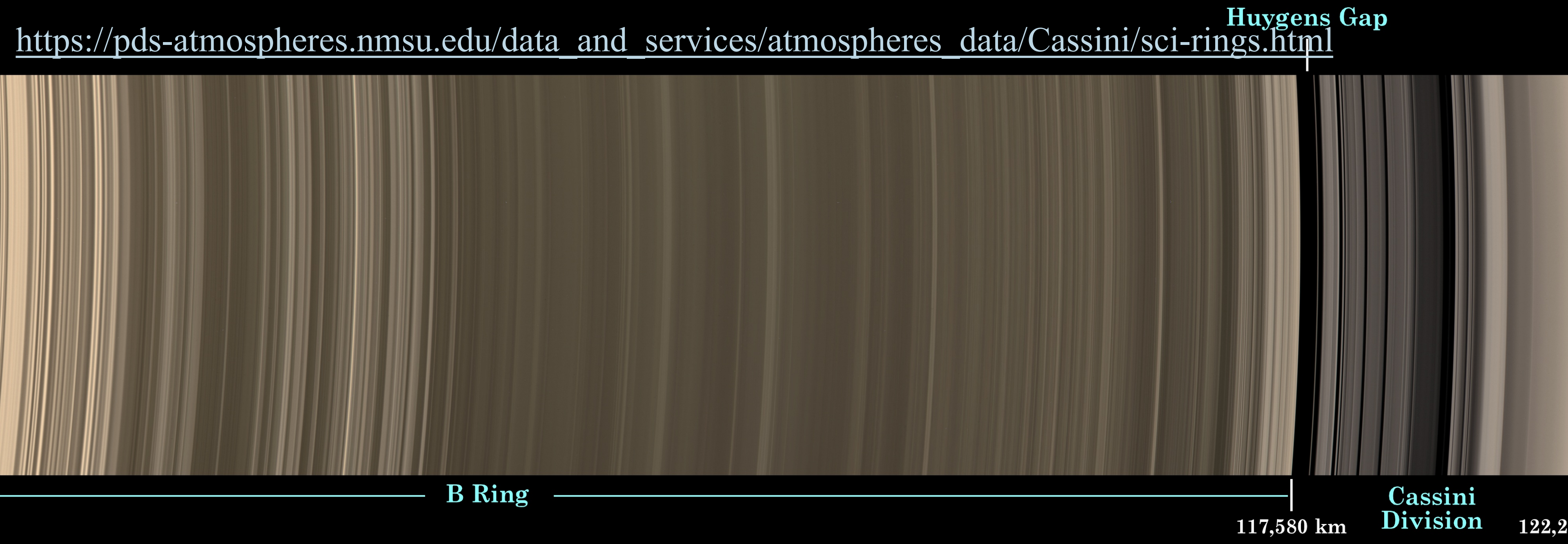
Saturn’s rings as a laboratory for studying disk-satellite (disk-planet) interaction

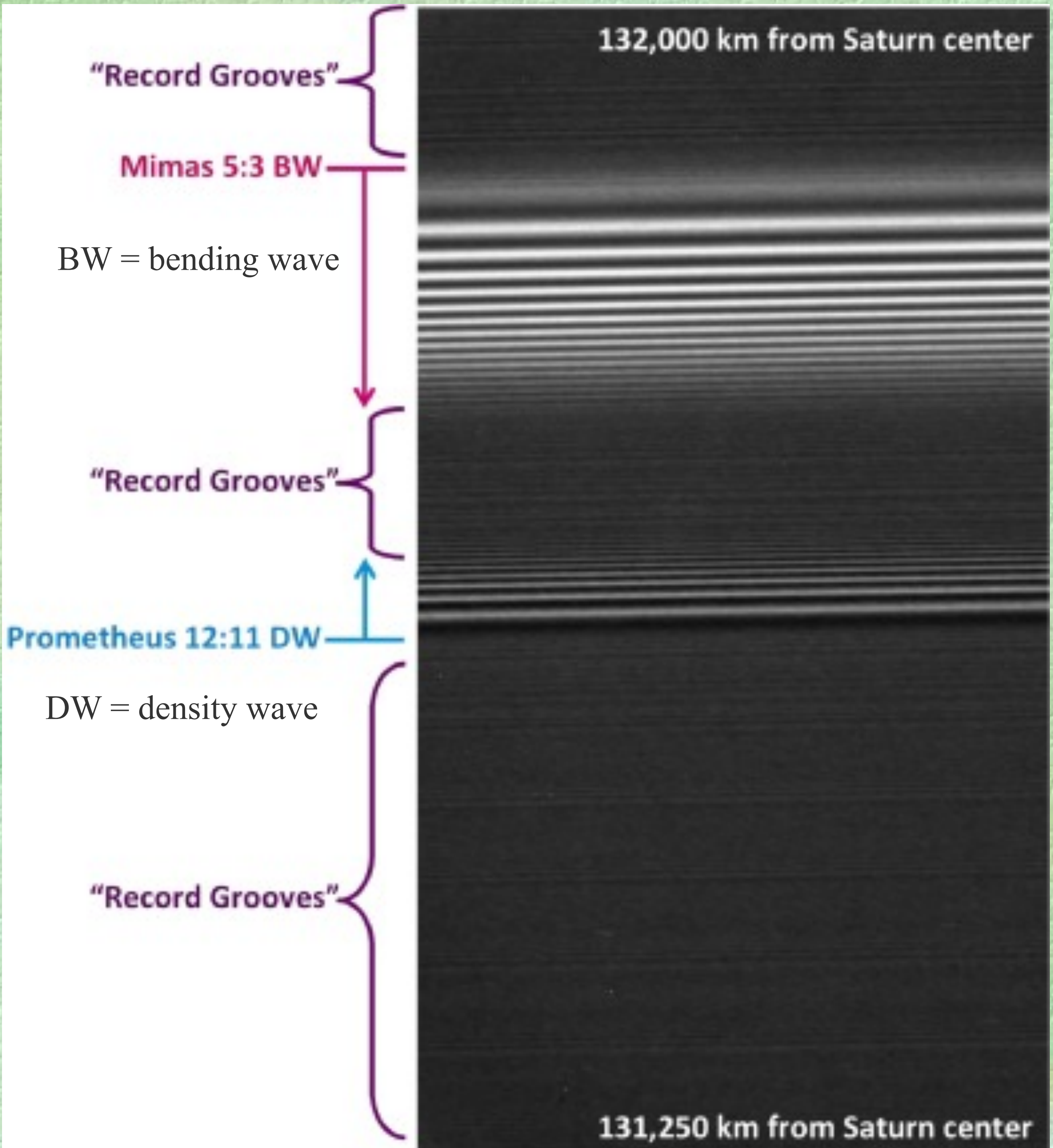



Atlas
Daphnis
Pan
6 miles
(10 kilometers)
Atlas
Daphnis
Pan
6 miles
(10 kilometers)



https://pds-atmospheres.nmsu.edu/data_and_services/atmospheres_data/Cassini/sci-rings.html





BW = bending wave

DW = density wave

Some of the structure in rings is due to long-distance gravitational interaction with moons

bending wave excitation by Mimas (5:3)
&
density wave excitation by Prometheus (12:11)

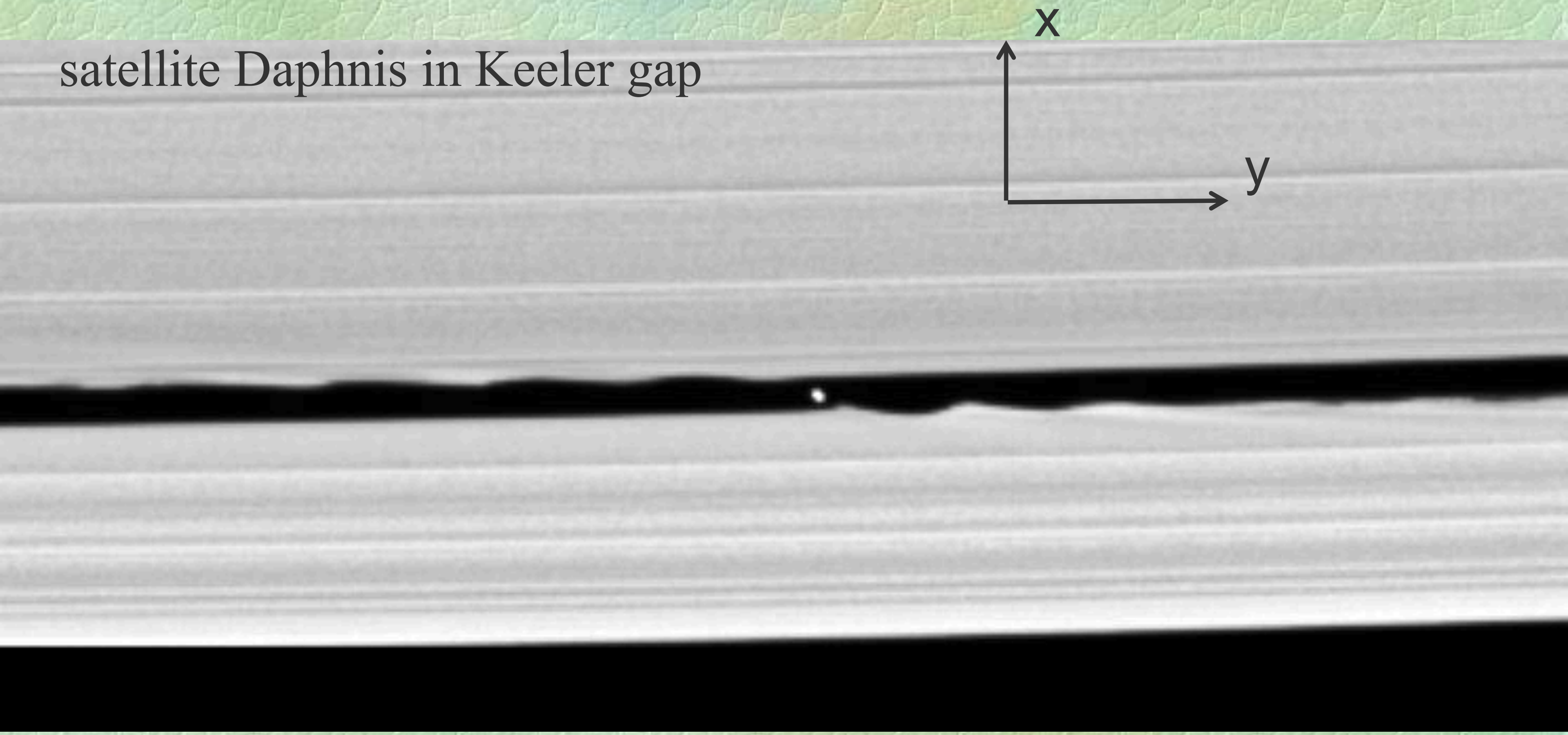
Hills equations describe the motion of ring particles near a satellite:

$d^2x/dt^2 = -Gm\, x/r^3 + 2\, dy/dt + 3\Omega^2 x$ (*gravity, Coriolis, centrif.*)

$d^2y/dt^2 = -Gm\, y/r^3 - 2\, dx/dt$

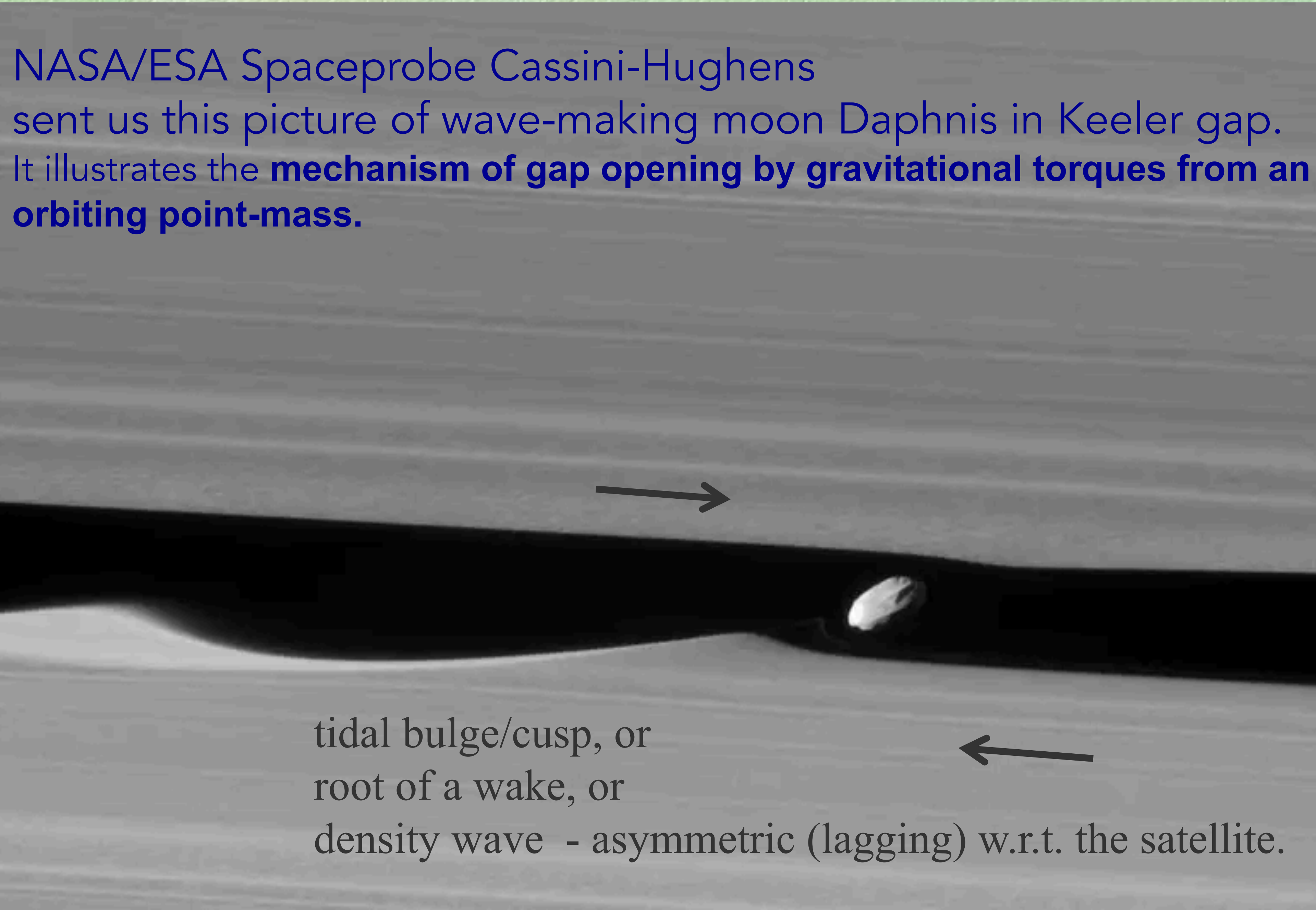
where m = mass of the satellite, $\Omega^2 = GM_*/a^3$,

M_* = mass of the sun, $r^2 = x^2 + y^2$, (x,y) = position of ring particle



Moon Daphnis in Saturn’s rings

NASA/ESA Spaceprobe Cassini-Hughens
sent us this picture of wave-making moon Daphnis in Keeler gap.
It illustrates the **mechanism of gap opening by gravitational torques from an orbiting point-mass.**



tidal bulge/cusp, or
root of a wake, or
density wave - asymmetric (lagging) w.r.t. the satellite.

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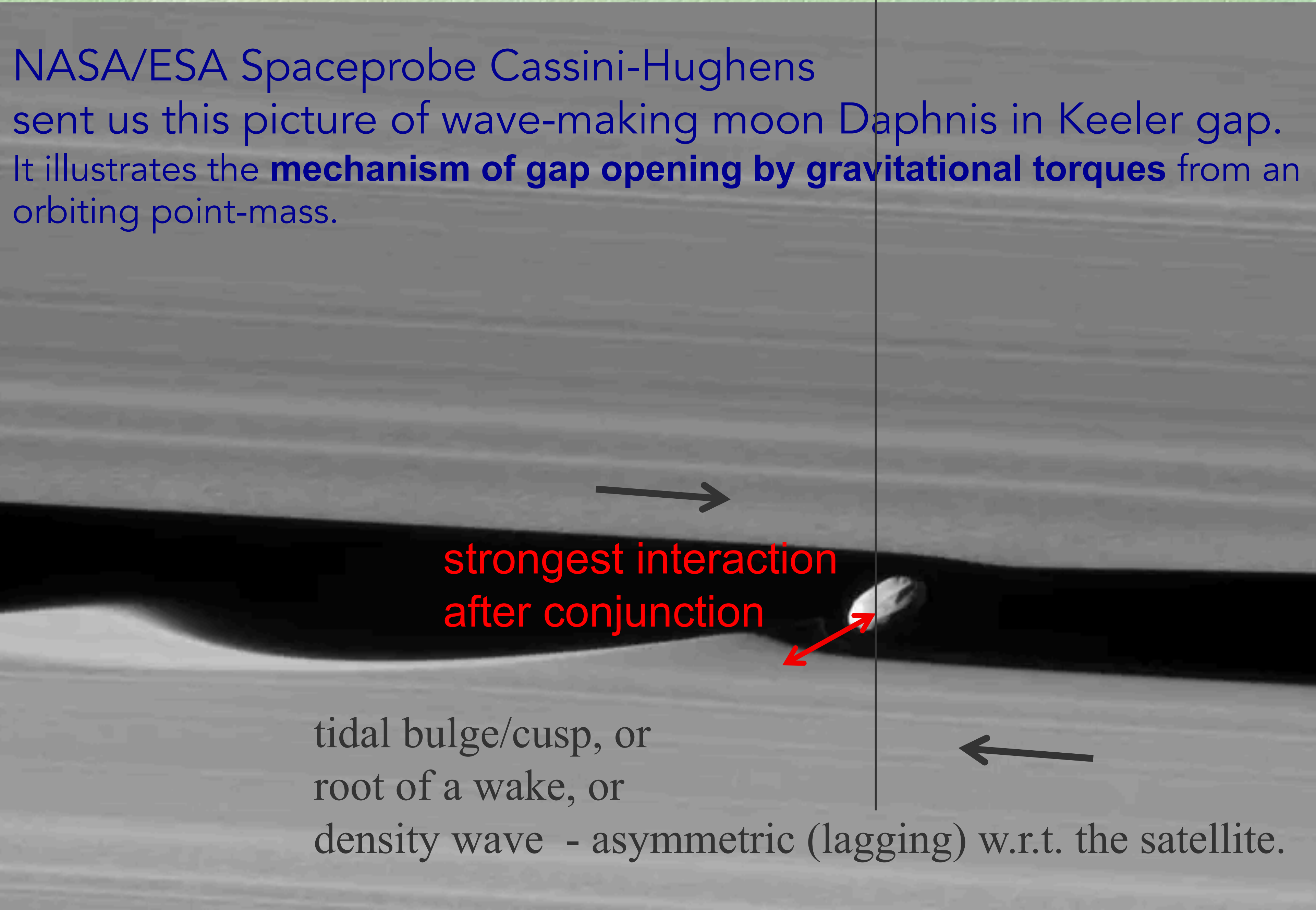
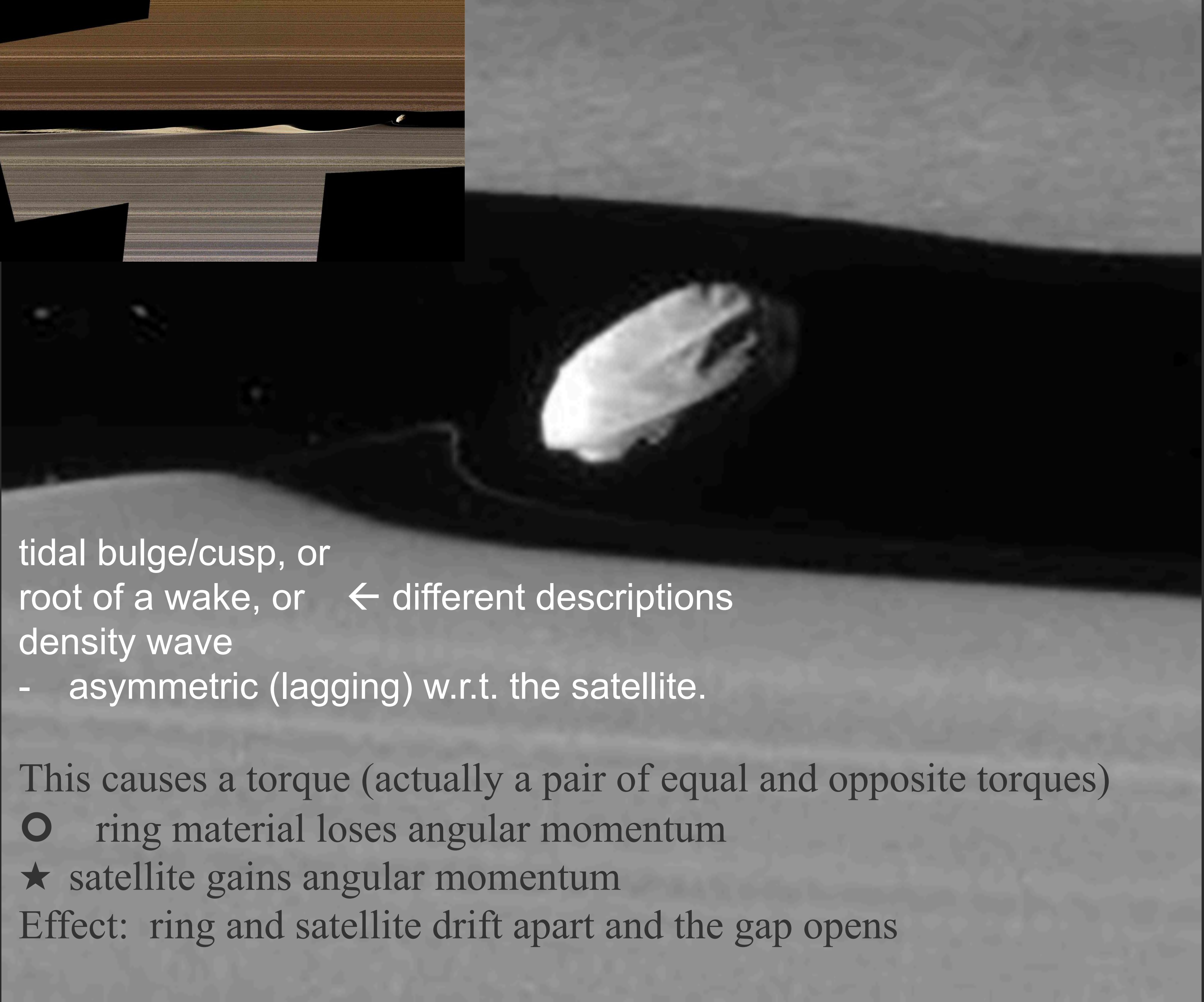


strongest interaction after conjunction

tidal bulge/cusp, or
root of a wake, or
density wave - asymmetric (lagging) w.r.t. the satellite.



tidal bulge/cusp, or
root of a wake, or ← different descriptions
density wave

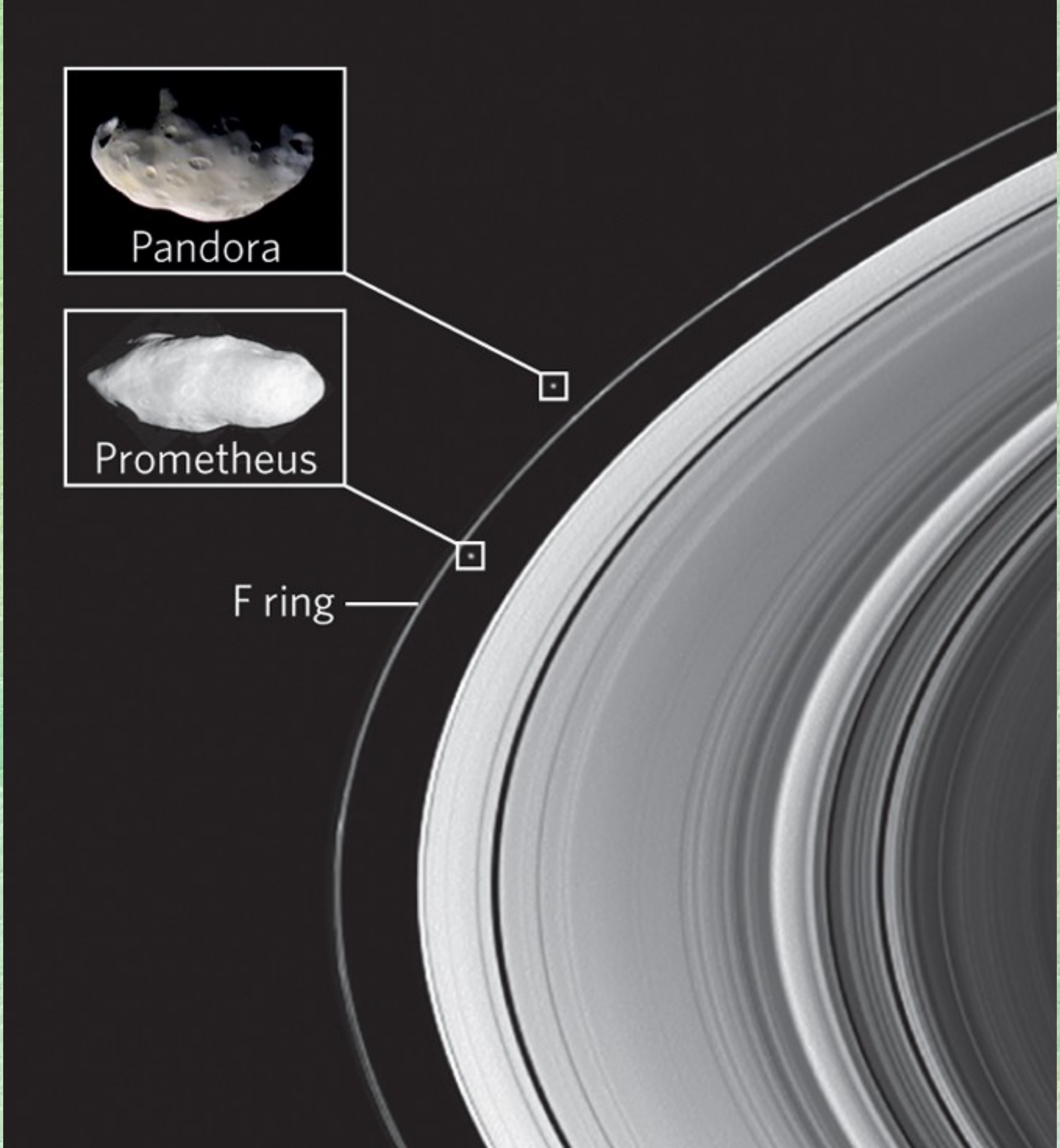
- asymmetric (lagging) w.r.t. the satellite.

This causes a torque (actually a pair of equal and opposite torques)

○ ring material loses angular momentum

★ satellite gains angular momentum

Effect: ring and satellite drift apart and the gap opens



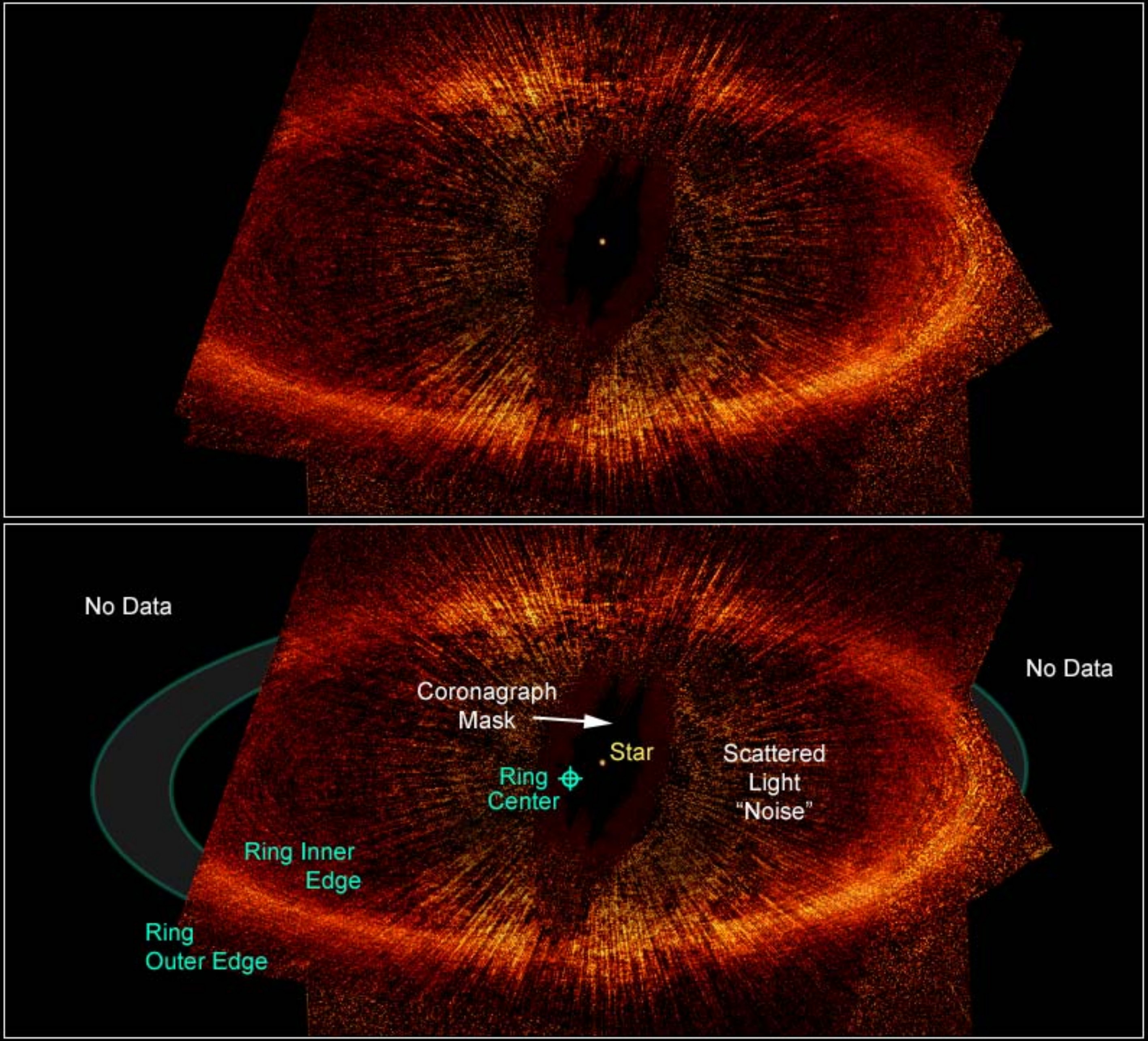
This is also the mechanism of shepherding moons

Gravity + rotation (angular mom. conservation) =

gravity
acts like a repulsion
not attraction

Fomalhaut Debris Ring

Hubble Space Telescope • ACS HRC



NASA, ESA, P. Kalas and J. Graham (University of California, Berkeley) and M. Clampin (NASA/GSFC)

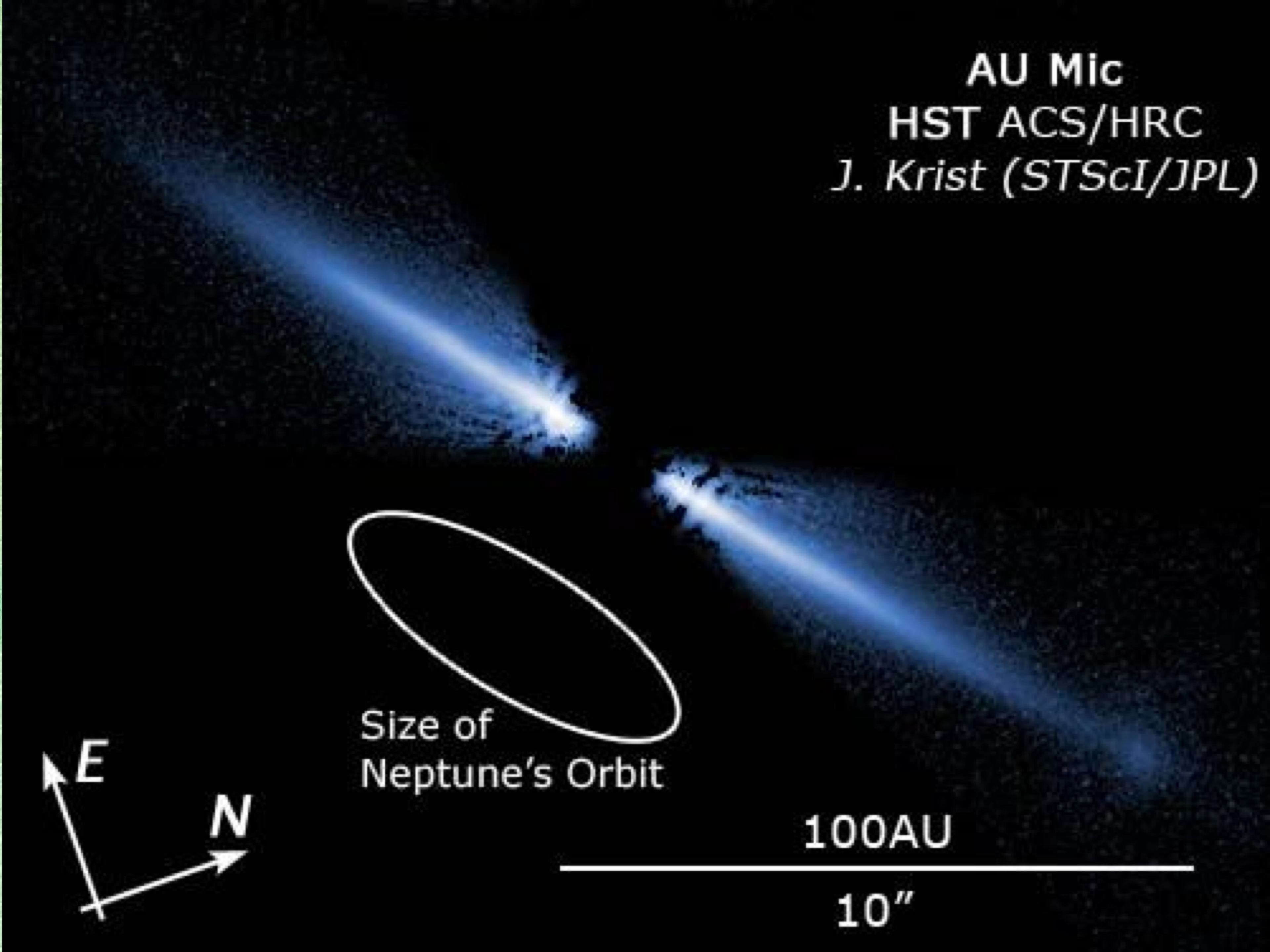
STScI-PRC05-10

Disk of α Pisces Austrini (α PsA)

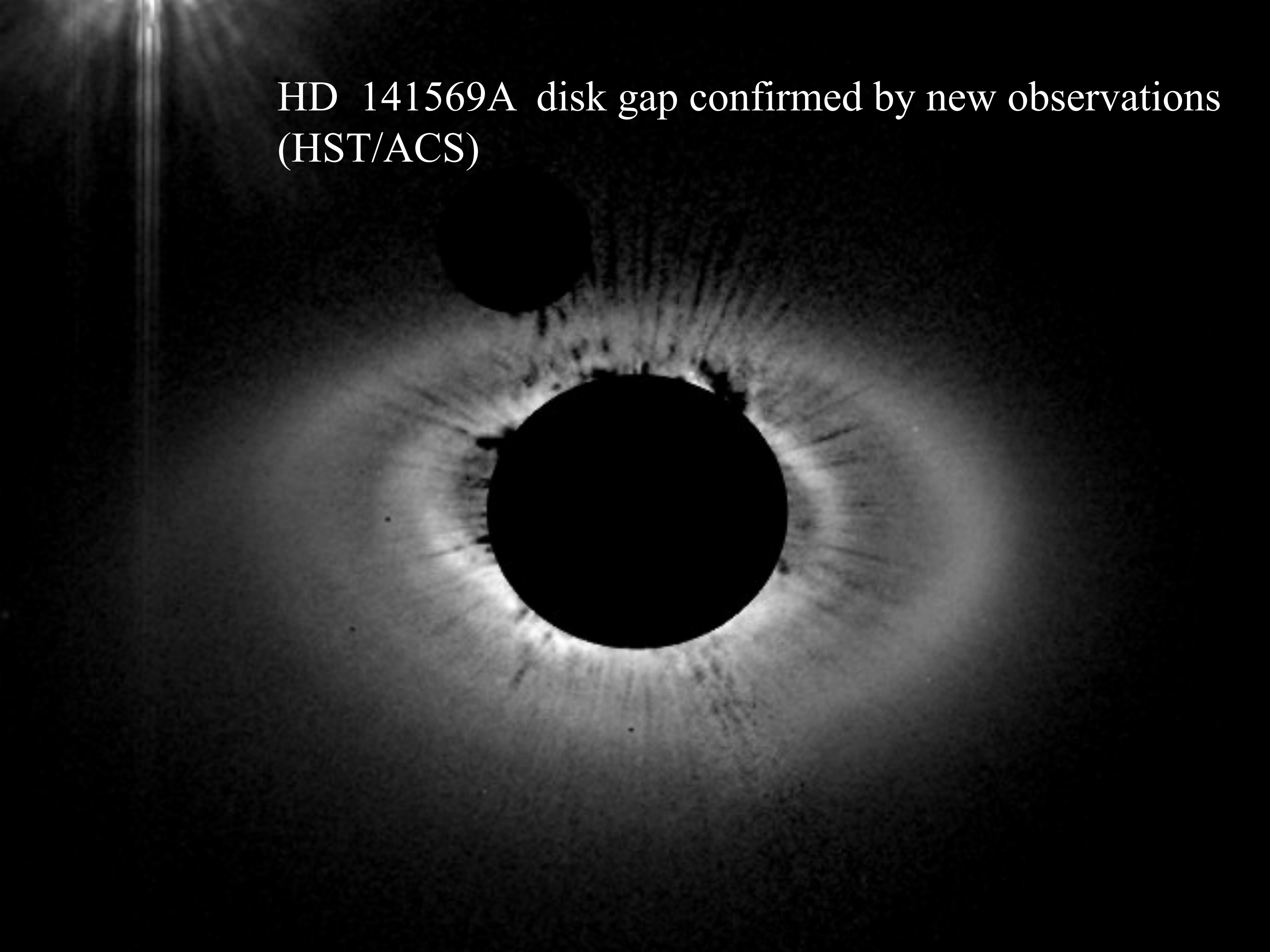
= Fomalhaut

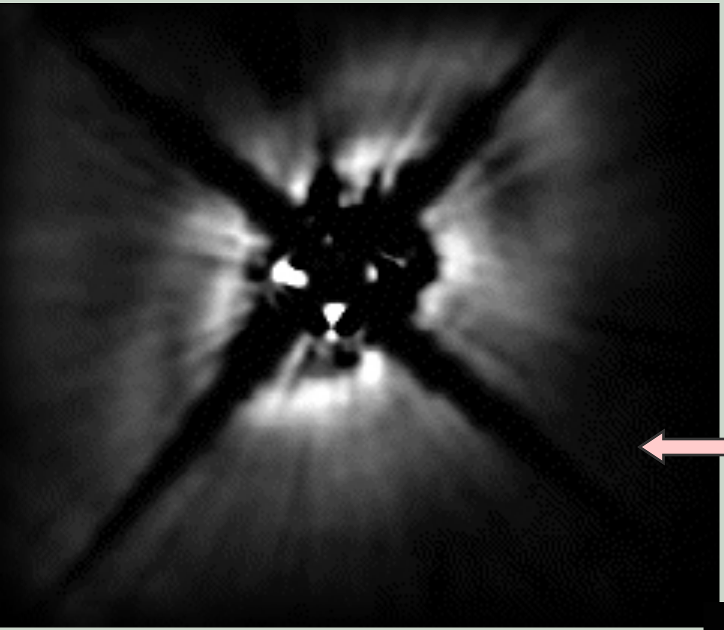
bright southern star of type A5

a narrow ring possibly shepherded by a planets


AU Mic
HST ACS/HRC
J. Krist (STScI/JPL)
Size of
Neptune's Orbit
E
N
100AU
10"

HD 141569A disk gap confirmed by new observations (HST/ACS)



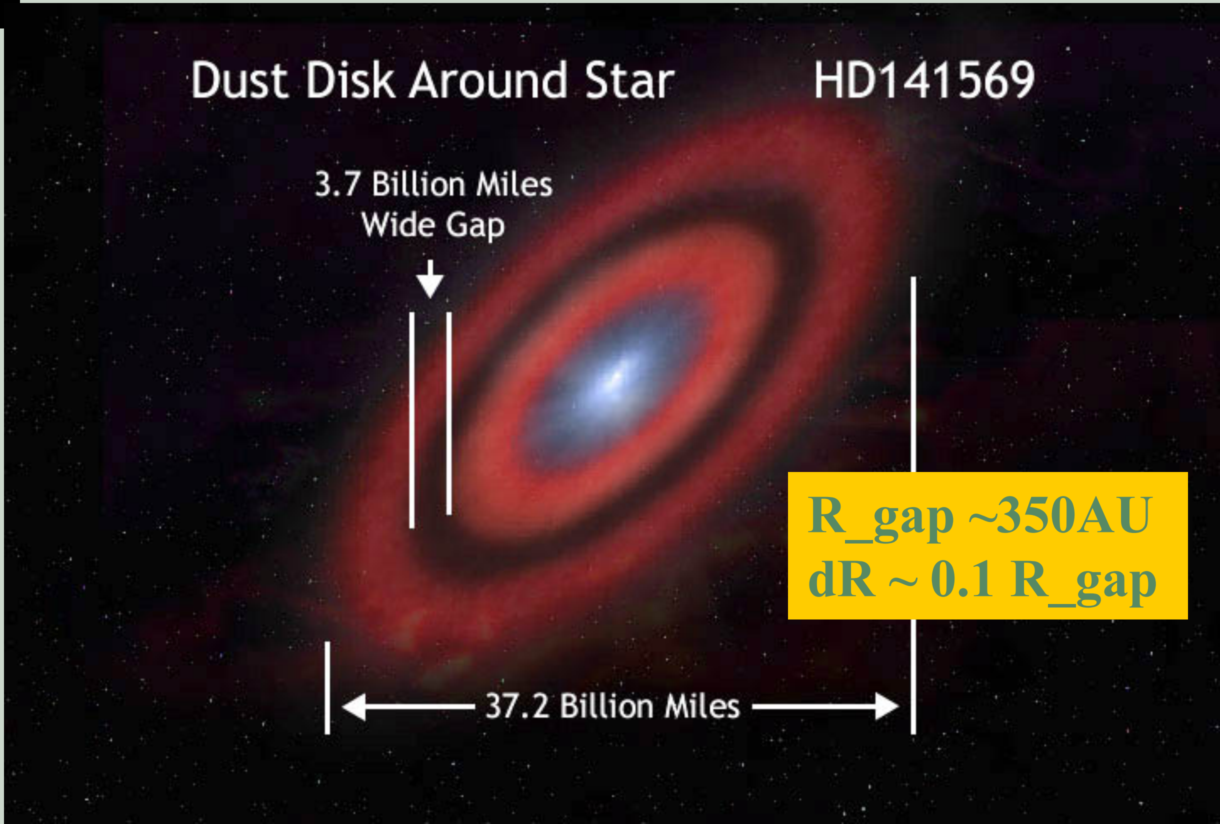


HD 141569A is a Herbig emission star
>2 x solar mass, >10 x solar luminosity, hydrogen emission lines H_α are double, because they come from a rotating inner gas disk.
CO gas has also been found at r = 90 AU.

Observations by Hubble Space Telescope (NICMOS near-IR camera).

Age ~ 5 Myr,
a transitional disk

Gap-opening PLANET ?
So far out??

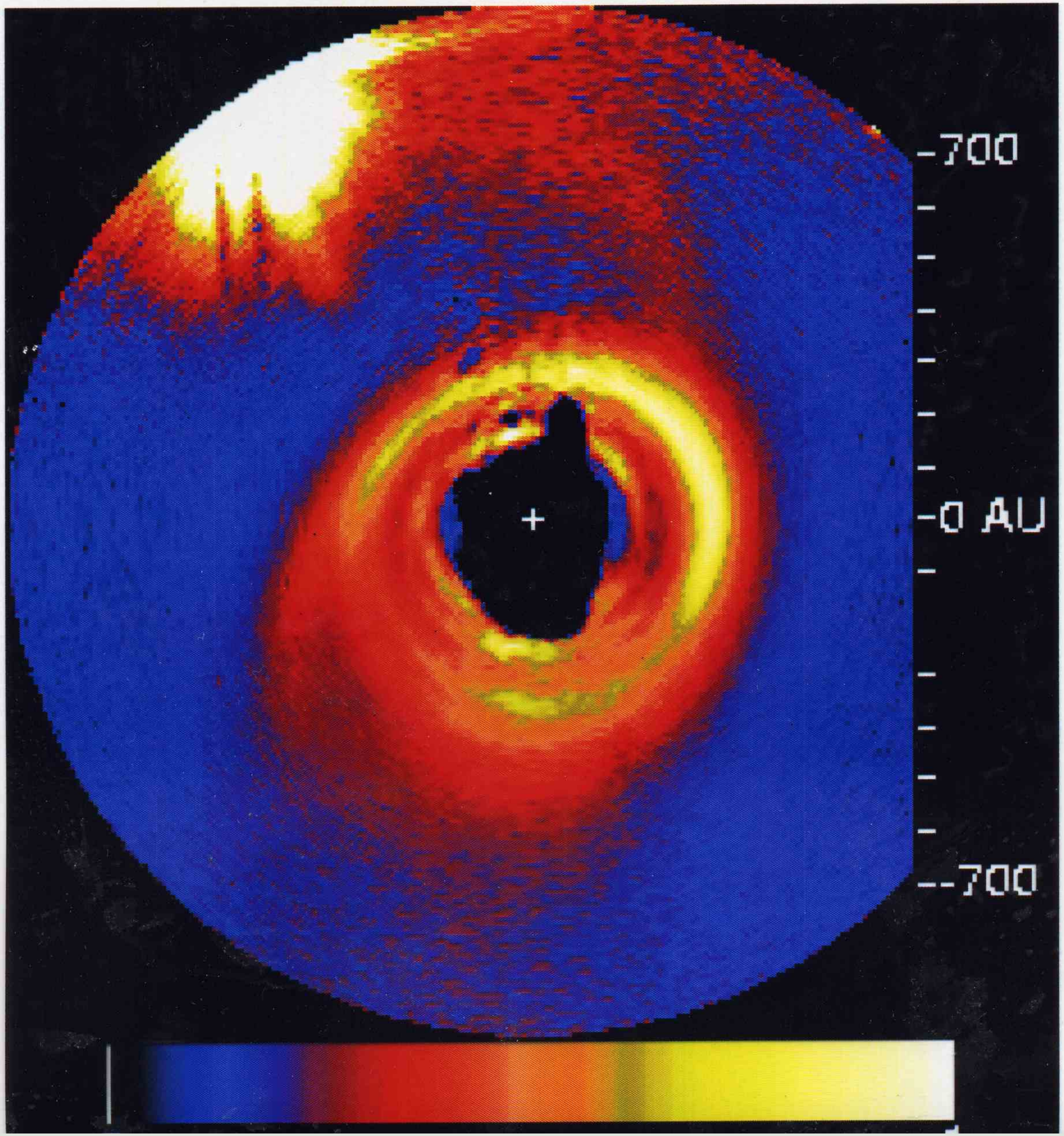


R_gap ~350AU
dR ~ 0.1 R_gap

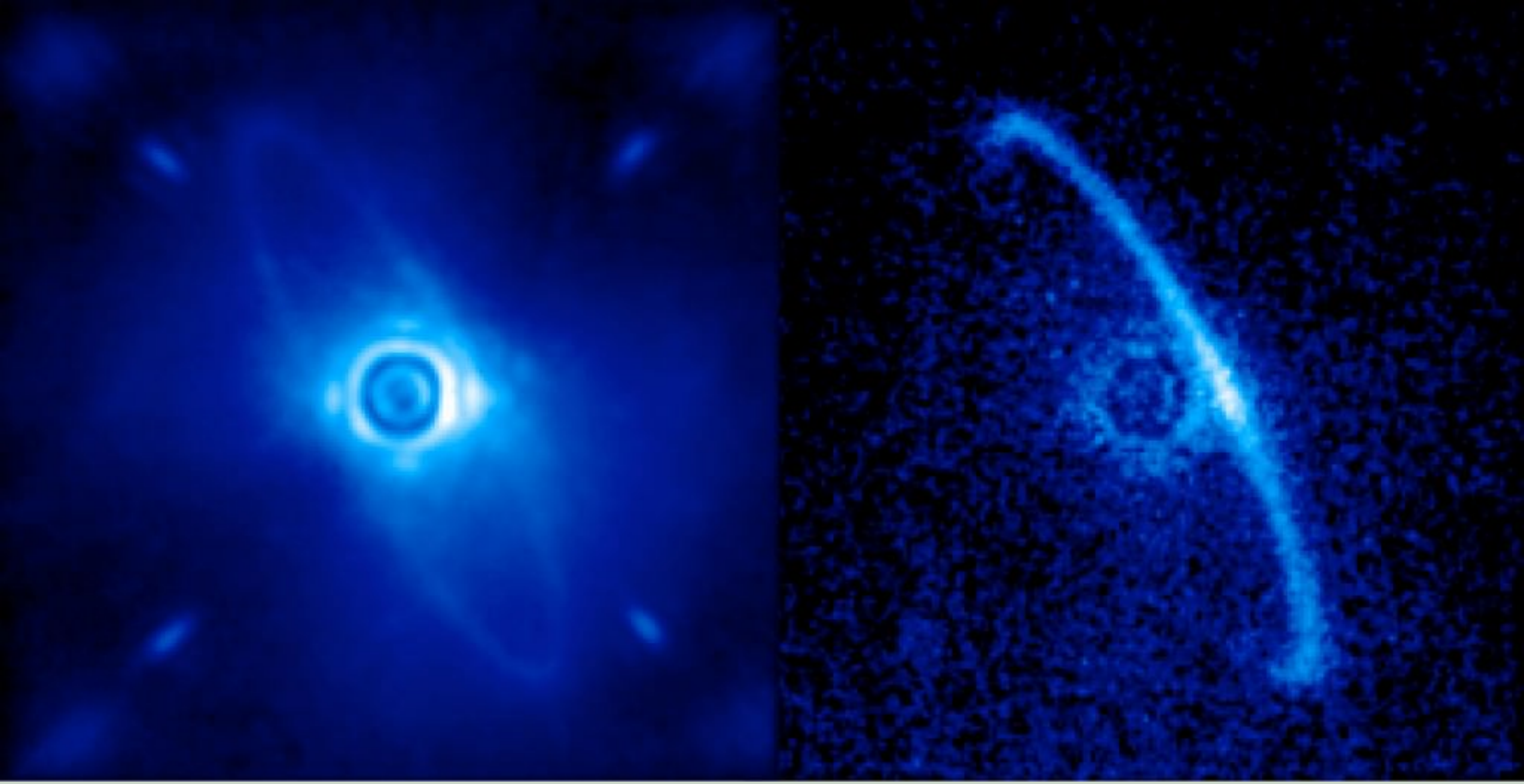
Gas-dust coupling?

Planetary perturbations?

Dust avalanches?



HD 141569A:
Spiral structure detected by (Clampin et al. 2003) with ACS, **A**dvanced **C**amera for **S**urveys onboard Hubble Space Telescope



HR 4796A imaged on the left by Gemini Planet Imager (on 8m telescope Gemini South). The right image is the polarized light – the more polarized side is further from us.

Images:

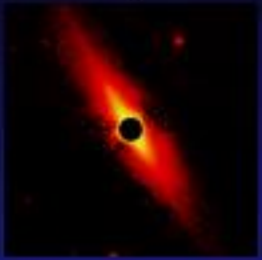
0.5 µm

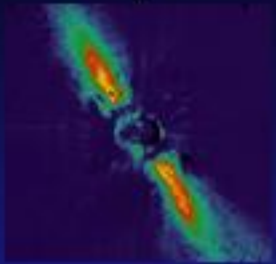
2.2 µm

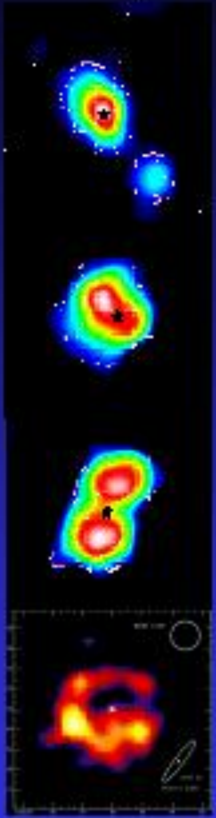
10-20 µm

850 µm

β Pic

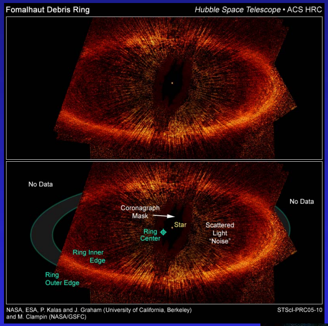






Vega

Fomalhaut



Fomalhaut Debris Ring

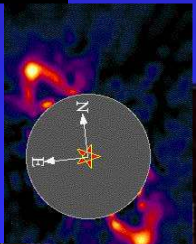
Hubble Space Telescope • ACS HRC

NASA, ESA, P. Kalas and J. Graham (University of California, Berkeley) and M. Clampin (NASA/GSFC)

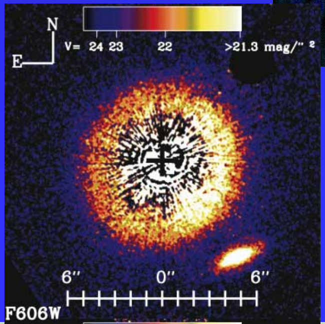
STScI-PRC05-10

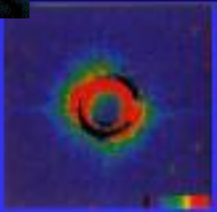
ε Eri

HR 4796A



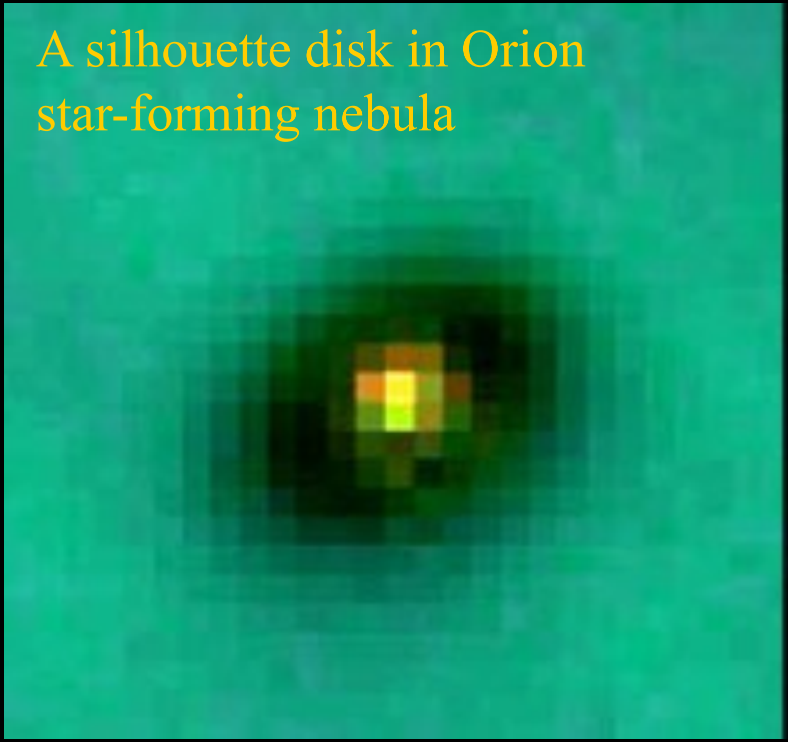
HD107146





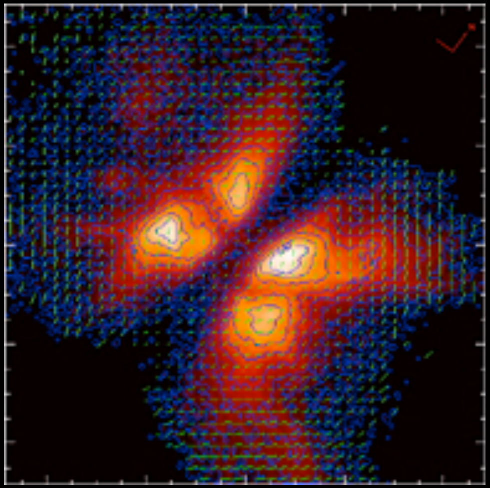
Source: P. Kalas

At the age of 1-10 Myr the primordial solar nebulae = protoplanetary disks = T Tau accretion disks undergo a metamorphosis

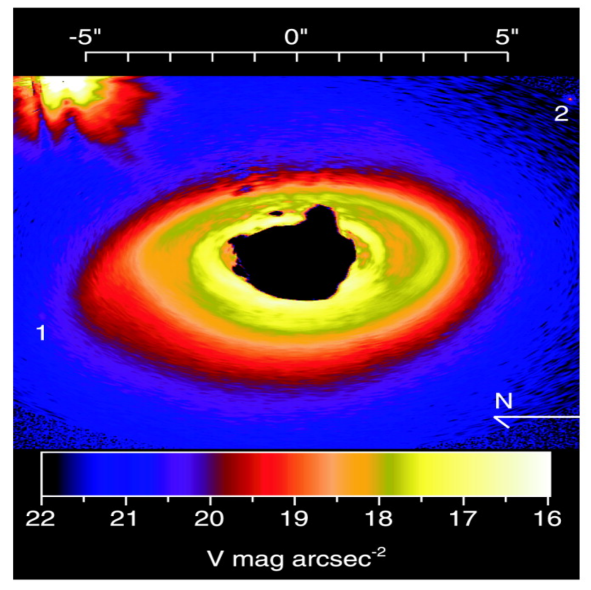

A silhouette disk in Orion star-forming nebula


Beta Pictoris

They lose almost all H and He and after a brief period as transitional disks (such as HD141569) become low-gas, high-dustiness Beta Pictoris systems (Vega systems).

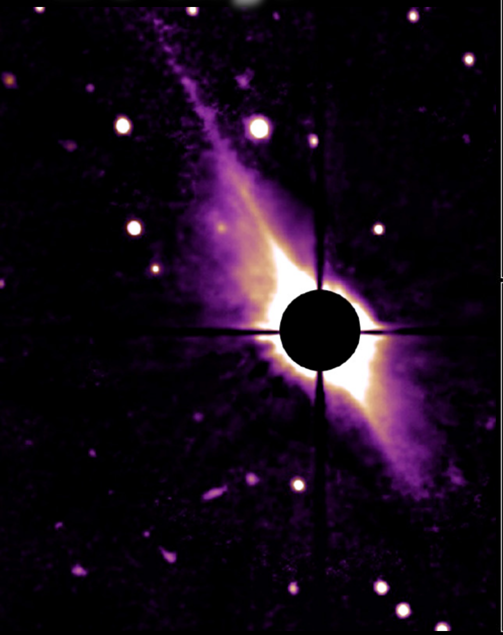


<1 Myr

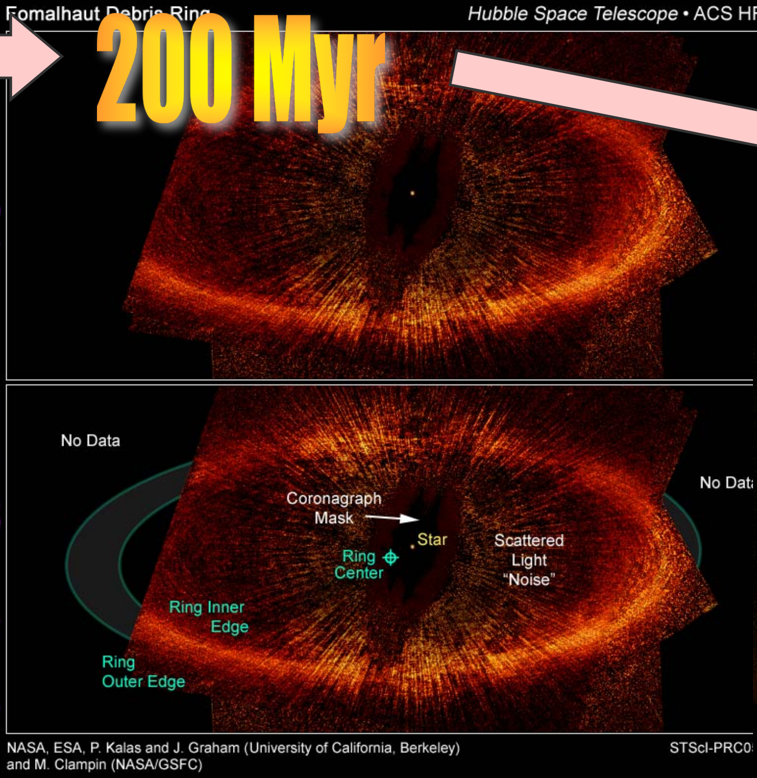


5 Myr

20 Myr



200 Myr



NASA, ESA, P. Kalas and J. Graham (University of California, Berkeley)
and M. Clampin (NASA/GSFC)

STScI-PRC0

4567 Myr

Disk physics

1. Temperature of solid particles around a star

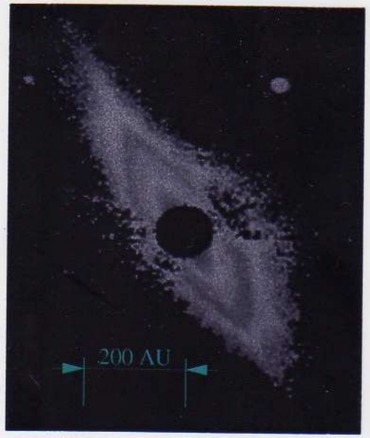
2. Finding out the dust distribution
   (optical thickness)

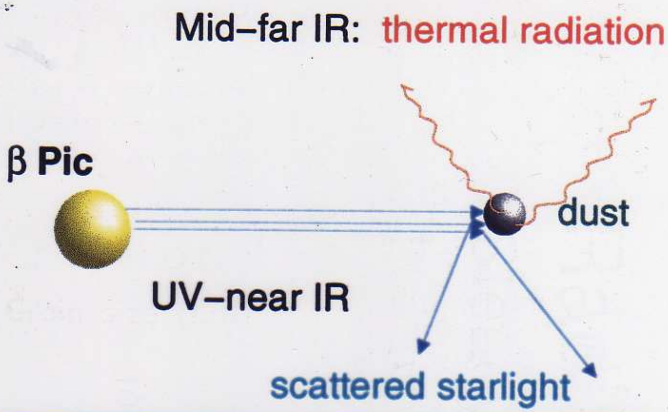
3. Radiation pressure
   - size distribution of particles
   - elliptic orbits of stable particles

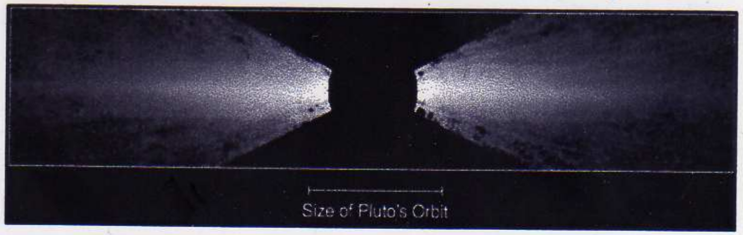
4. Collisional lifetime ~ orbital period / optical thickness

5. Composition and crystallinity of particles

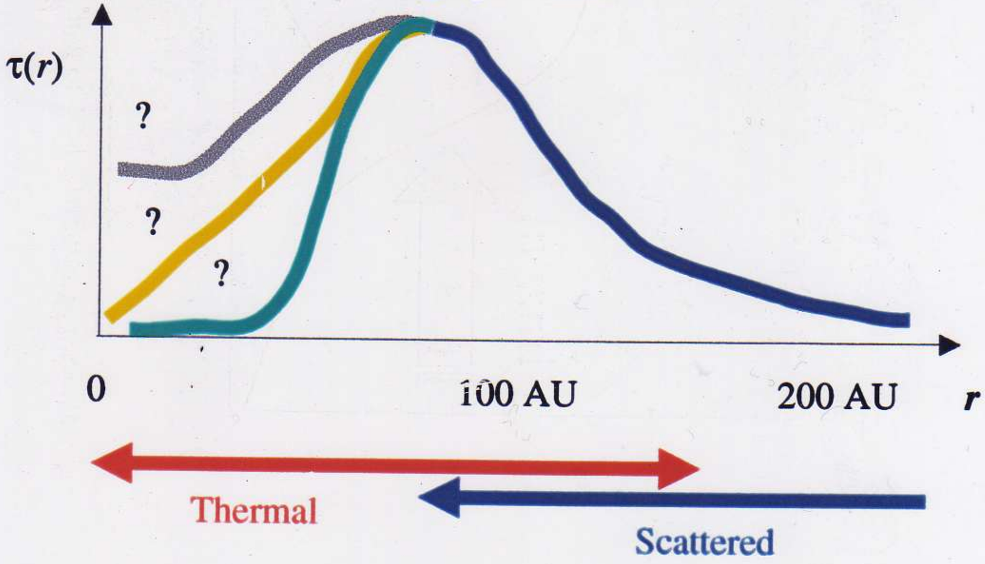
The temperature of dust & larger bodies







1. Geometrical modeling of scattered light disk
2. MEM reconstruction of the missing part of the disk, hidden behind the coronograph mask.



The physics of dust and radiation is very simple

In the past the amount of dust hidden by coronograph mask had to be reconstructed using MEM= maximum entropy method or other models. Today scattered light data often suffice.

τ = optical thickness perpendicular to the disk (vertical optical thicknass)

Equilibrium temperature of solid particles (from dust to planets without atmospheres)

$A = Q_{sca}$ = albedo (percentage of light scattered)

Q_{abs} = absorption coefficient, percentage of light absorbed

$Q_{abs} + Q_{sca} = 1$ (this assumes the size of the body >> wavelength of starlight, otherwise the sum, called extinction coefficient $Q_{ext} = Q_{abs} + Q_{sca}$, might be different)

total absorbing area = $S = \pi r^2$,

total emitting area = $4S$ (in case of a spherical particle, $4\pi r^2$)

Absorbed energy/unit time = Emitted energy /unit time

$$\mathbf{S\ Q_{abs}(vis)\ L/(4\pi r^2) = 4S\ Q_{abs}(IR)\ \sigma T^4}$$

L = stellar luminosity, r = distance to star, $L/4\pi r^2$ = flux of energy,

T = equilibrium temperature of the whole particle, e.g., dust grain,

σ = Stefan-Boltzmann constant (see physical constants table)

T^4 = energy emitted from unit area of a black body in unit time

$Q_{abs}(vis)$ - in the visible/UV range where starlight is emitted/absorbed

$Q_{abs}(IR)$ - emissivity = absorptivity in the infrared, where thermal radiation is emitted (Kirchhoffs law says absorptivity = emissivity!)

Equilibrium temperature

$$T^4 = [Q_{abs}(vis)/\,Q_{abs(IR)}]\;\; L/(16\sigma\pi r^2)$$

$Q_{abs}(vis) = 1\text{-}A,$

$$T = 280\text{ K}\;\; [(1\text{-}A)/Q_{abs(IR)}(L/L_{sun})]^{1/4}\,(r/AU)^{-1/2} \sim r^{-1/2}$$

Theoretical surface temperature T of planets if $Q_{abs}(IR) = 1$, and the actual surface temperature T_p. T and T_p differ due to the **greenhouse effect**.

Body	**Albedo A**	**T(K)**	**T_p(K)**	**greenhouse**
Mercury	0.15	433	433	none
Venus	0.72	240	540	huge
Earth	0.45	235	280	medium
Moon	0.15	270	270	none
Mars	0.25	210	220	weak
typical asteroid	0.15	160	160	none
Ganymede	0.3	112	112	none
Titan	0.2	86	90	some
Pluto	0.5	38	38	none

What is the optical thickness?

definitions:

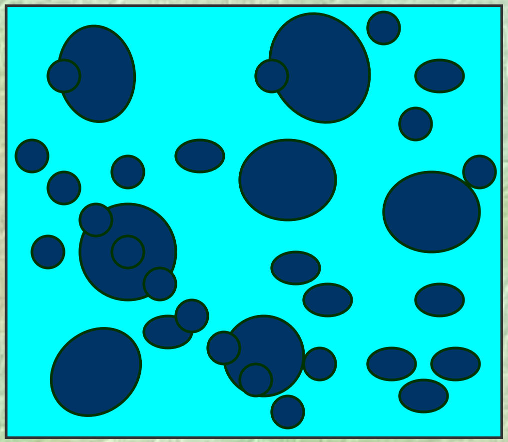
$\tau_{\perp}(r) =$ **perpendicular to the disk**

$\tau_{eq}(r) =$ **in the equatorial plane**

(percentage of starlight scattered and absorbed, as seen by the outside observer looking at the disk edge-on, aproximately like we look through the beta Pictoris disk)

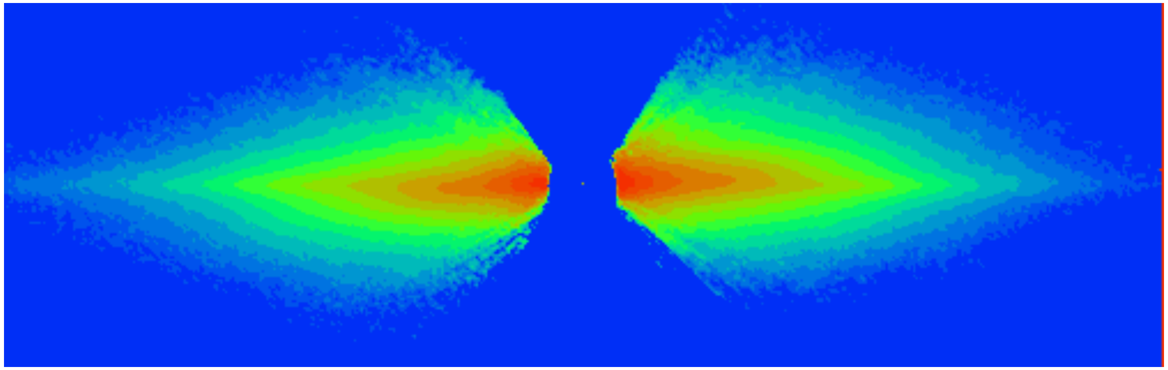
The meaning of optical thickness $\tau_{\perp}(r)$

It is the fraction of the disk surface covered by dust: here I this example it's about 2e-1 (20%) - the disk is optically thin (= transparent, since it blocks only 20% of light)

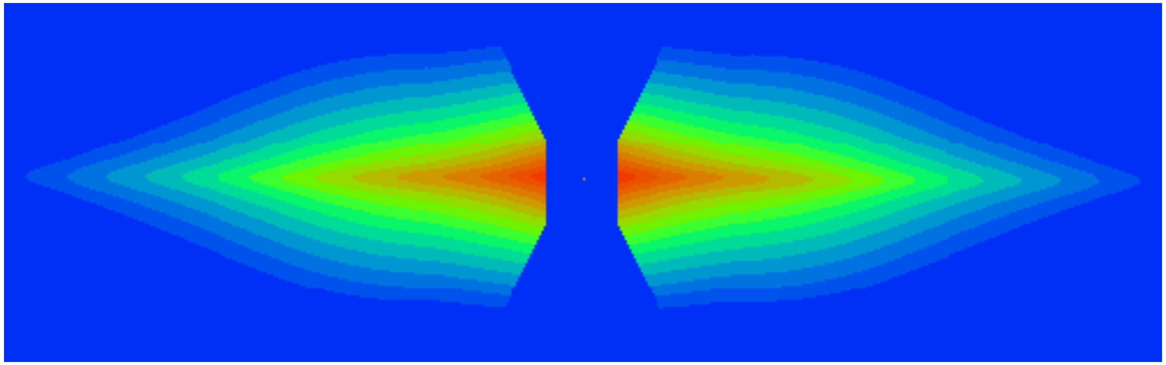


picture of a small portion of the disk seen from above

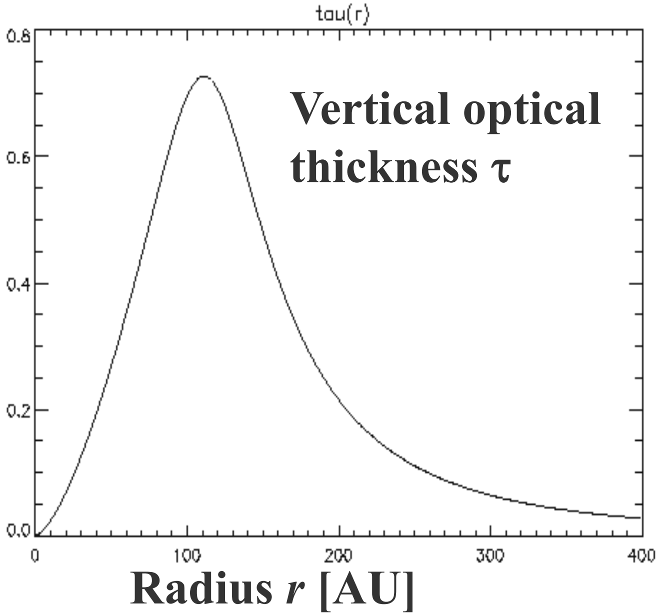
Examples: **beta Pic disk at r = 100 AU, opt.thickness $\tau \sim 3 \cdot 10^{-3}$**
disk around Vega opt.thickness $\tau \sim 10^{-4}$
zodiacal light disk (IDPs) opt.thickness $\tau \sim 10^{-7}$



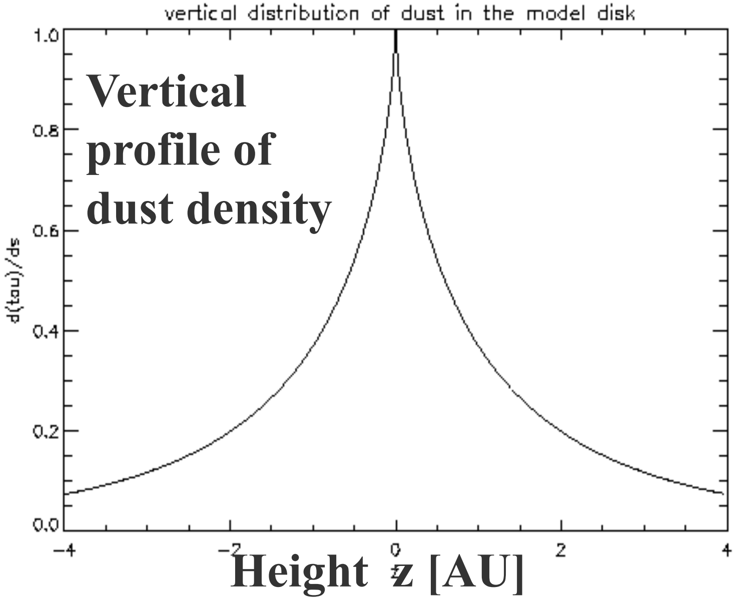
STIS/Hubble imaging
(Heap et al 2000)



Modeling
(Artymowicz 1997):
parametric, axisymmetric disk
cometary dust phase function



Vertical optical thickness τ

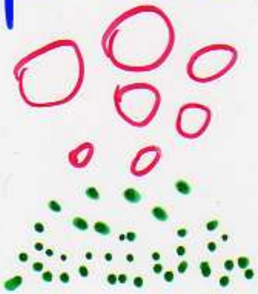


Vertical profile of dust density

How does the Vega-phenomenon relate to our Solar System (Kuiper belt, or TNOs - transneptunian objects)

CONNECTING

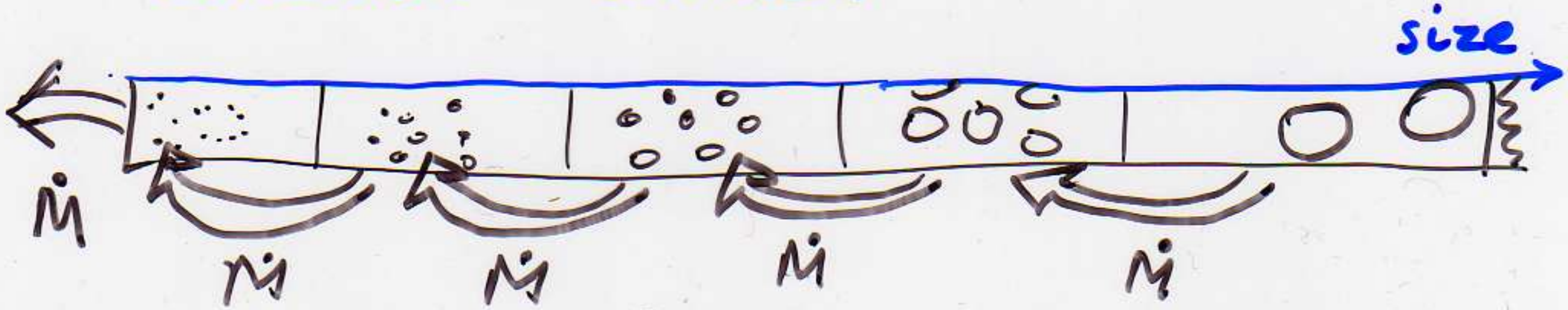
β Pic and early Sol. Sys. TNO's



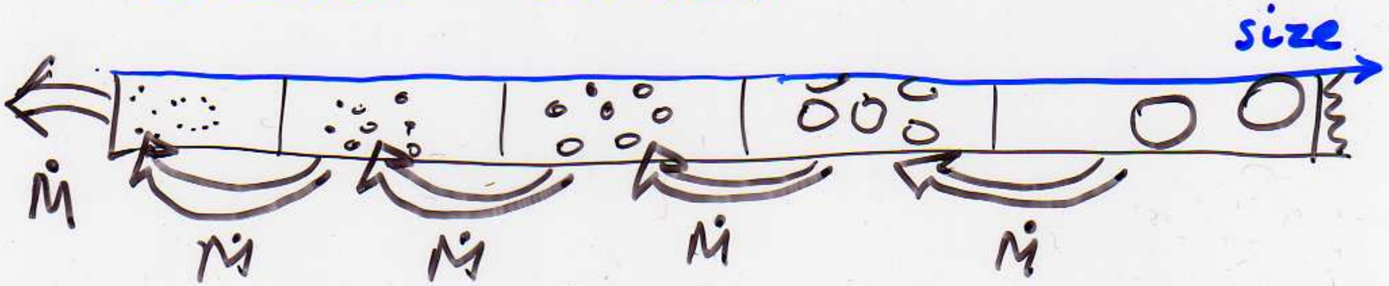
🟩 observed

🟥 invisible (currently)

ASSUMING A STATIONARY COLLISIONAL CASCADE EXISTS:



ASSUMING A STATIONARY COLLISIONAL CASCADE EXISTS:



LOOK AT DUST, INFER LARGE BODY RESERVOIR

Artymowicz et al. ('89 – '97 – ...) β Pic!

$$\dot M \approx \int_{dust} \frac{dM}{t_{coll}} \sim 10^{22}\ g/yr \sim \frac{100\ M_\oplus}{65\ Myr}$$ in β Pic

---

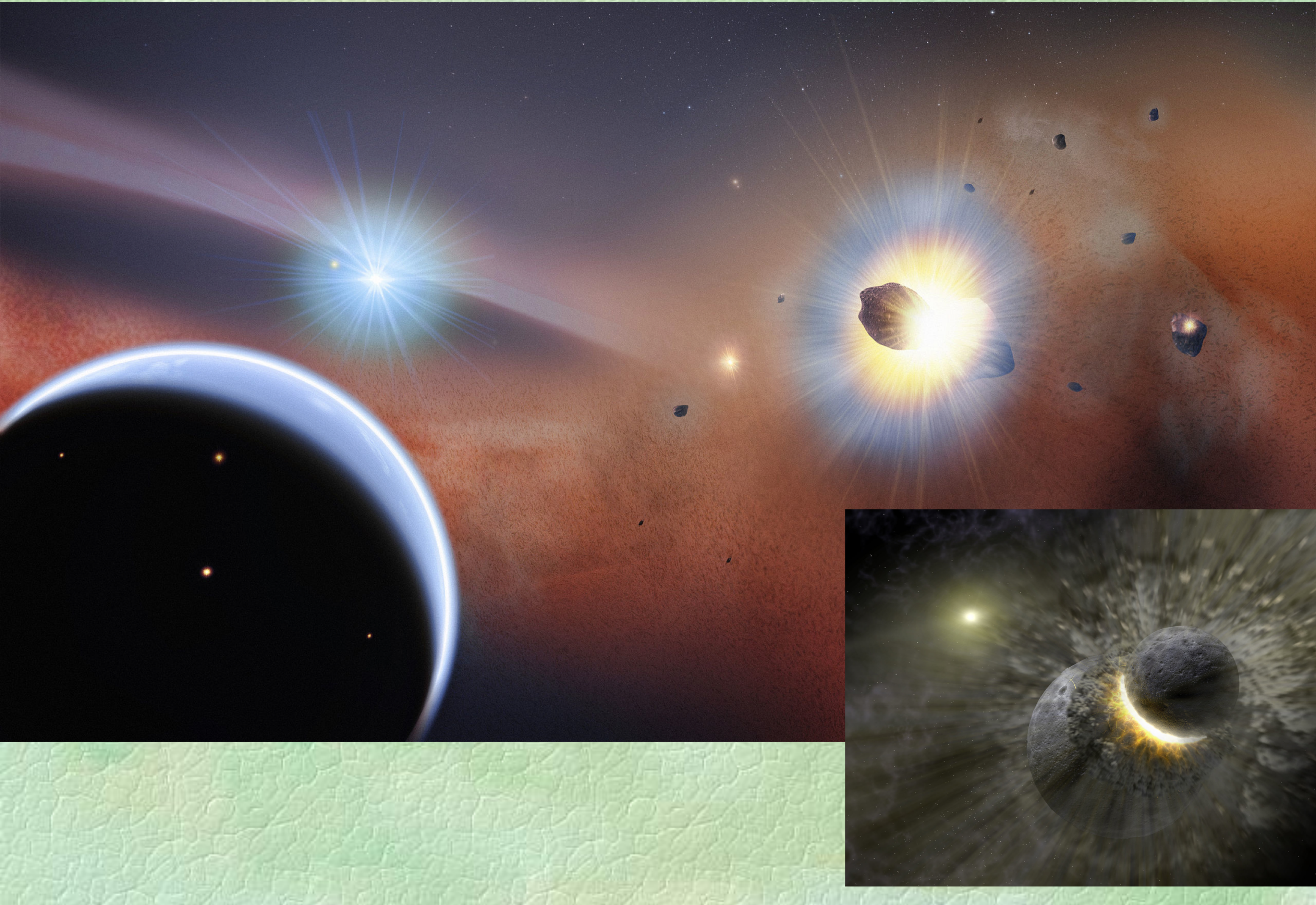
OR LOOK AT (CURRENT OR) (FORMING) KUIPER BELT, INFER DUST DISK

Backman et.al. (1995)
Stern et.al. (1996, 97)
Davis et al. (1997)

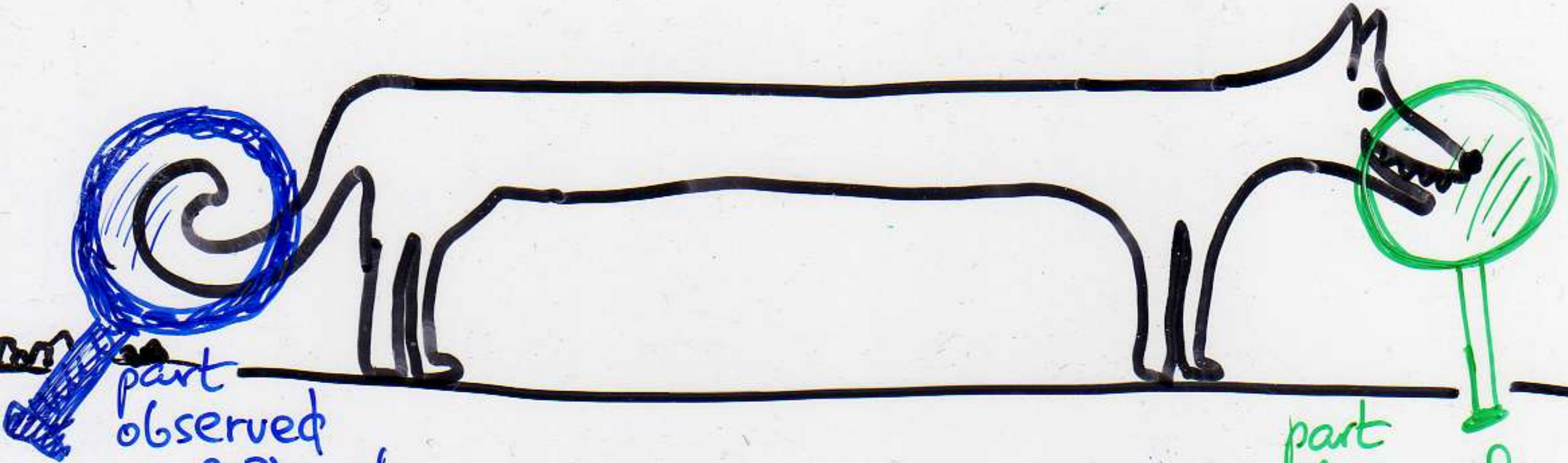
$$\dot M \approx \int_{KB} \frac{dM}{t_{coll}} \sim 10^{20...21}\ g/yr \sim \frac{10 M_\oplus}{10-100\ Myr}$$

in S. Sys.

COLLISIONAL CASCADES IN Vega-type DISKS



WHAT'S THE DOG & WHAT'S THE TAIL?



β-dust

α-dust (micrometeor.) "dust"

meteoroids

planetesim.

large KBOs

---

looking at the tail, reconstructing the dog ⇒ ≥ Solar System!

looking at the tail,
reconstructing the dog ⇒ $\gtrsim$ Solar System!

$$\underset{\dot M}{\Longleftarrow} \qquad \underset{\dot M}{\Longleftarrow} \qquad \underset{\dot M}{\Longleftarrow} \qquad \underset{\dot M}{\Longleftarrow} \qquad \underset{\dot M}{\Longleftarrow} \;\vdots$$

$$\dot M \approx \int_{\text{dust}} \frac{dM}{t_{\text{coll}}(\alpha)} \sim 10^{22}\ \text{g/yr} \sim \frac{10^2\, M_\oplus}{70\ \text{Myr}}$$

Artymowicz et al.
(1989... 97)

---

looking at the tip of the nose*),
predicting the type of tail

⇓

Vega/βPic disk!

*) the nose was bigger in the past!

$$\dot M \approx \int \frac{dM}{t_{\text{coll}}} \sim 10^{20-21}\ \text{g/yr}$$

$\Leftarrow$ (KB)

$$\sim \frac{10^1\, M_\oplus}{10^7 \ldots 10^8\ \text{yr}}$$

Backman et al (1995)
Stern et al (1996, 97)
Davis et al (1997)

Chemistry/mineralogy/crystalinity of dust

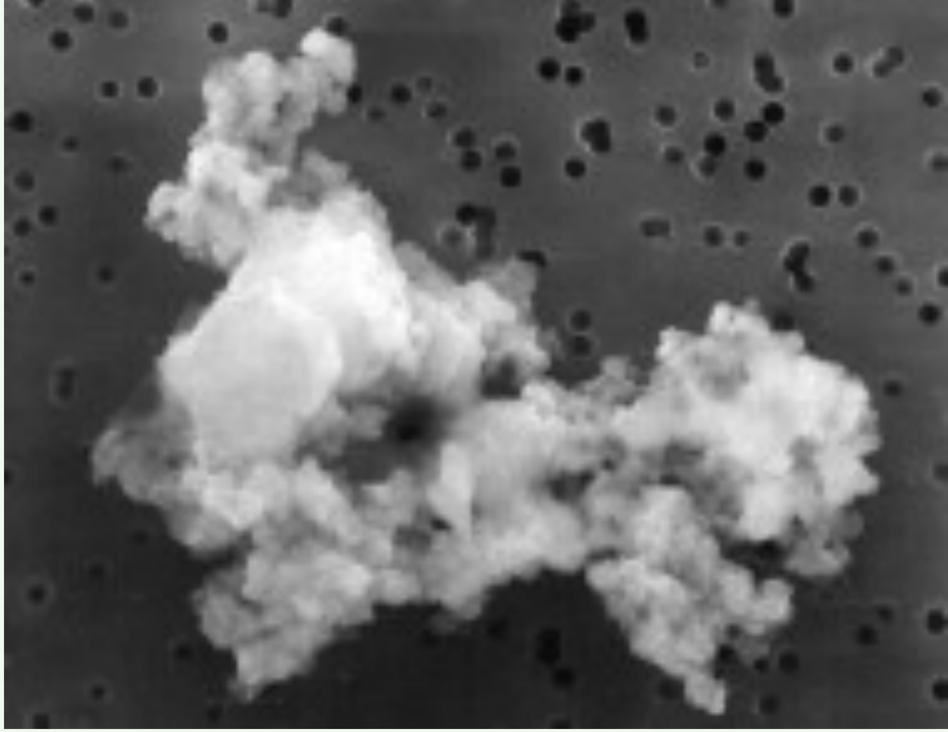
All we see so far is silicate particles similar to the IDPs (interplanetary dust particles from our system)

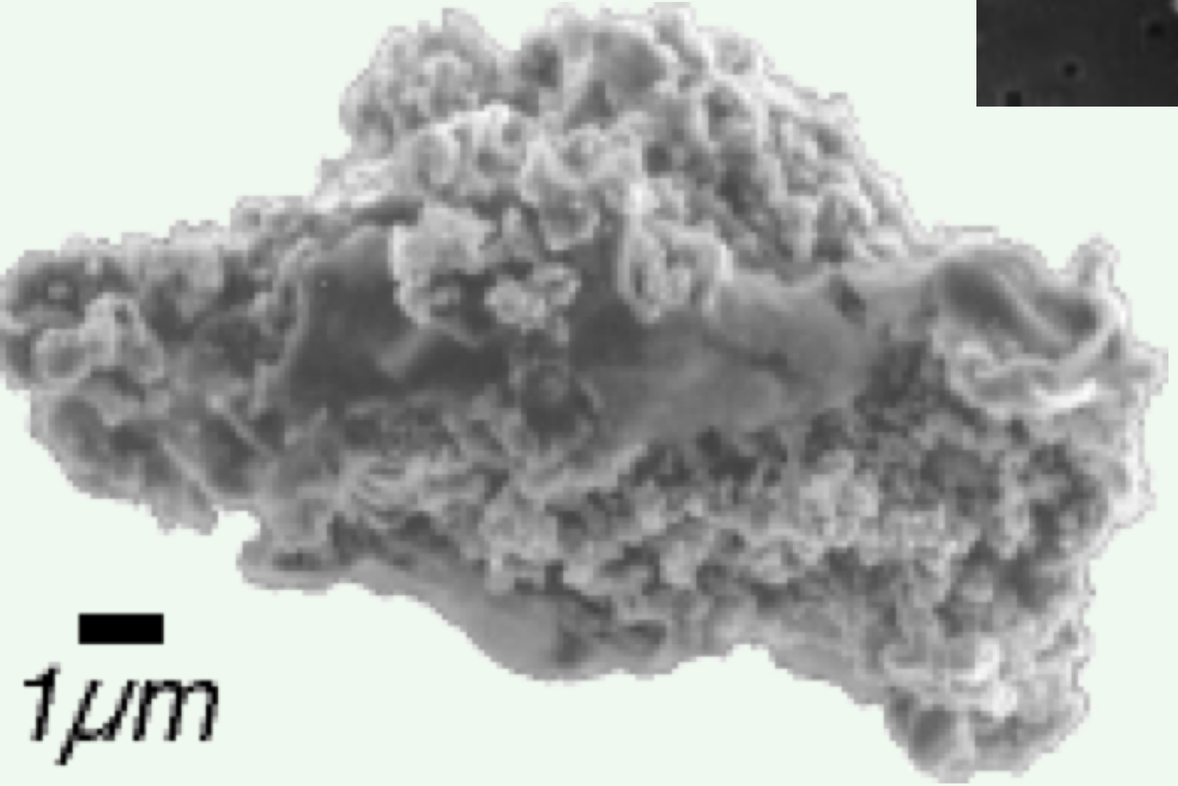
Ice particles are not seen, at least not in the dust size range (that is also true of the IDPs)

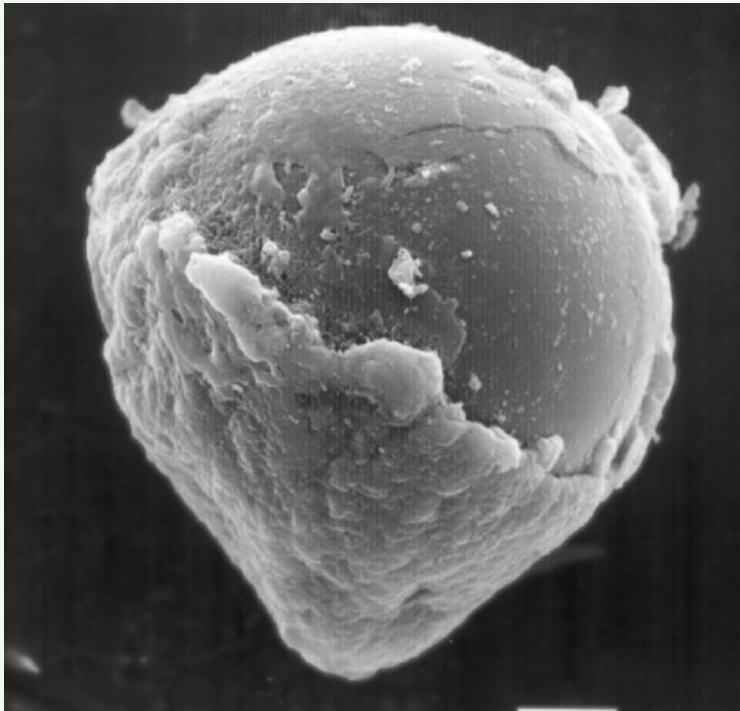
Spectroscopic signatures of amorphous/crystalline silicates differ. The dust we see in other planetary disks is partly amourphous and partly crystalline (which posed some interesting questions)

Microstructure of circumstellar disks: identical with our IDPs (interplanetary dust particles)

mostly Fe+Mg silicates
$(Mg,Fe)SiO_3$
$(Mg,Fe)_2SiO_4$

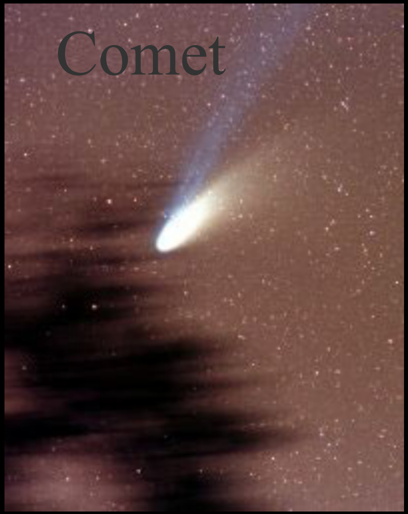


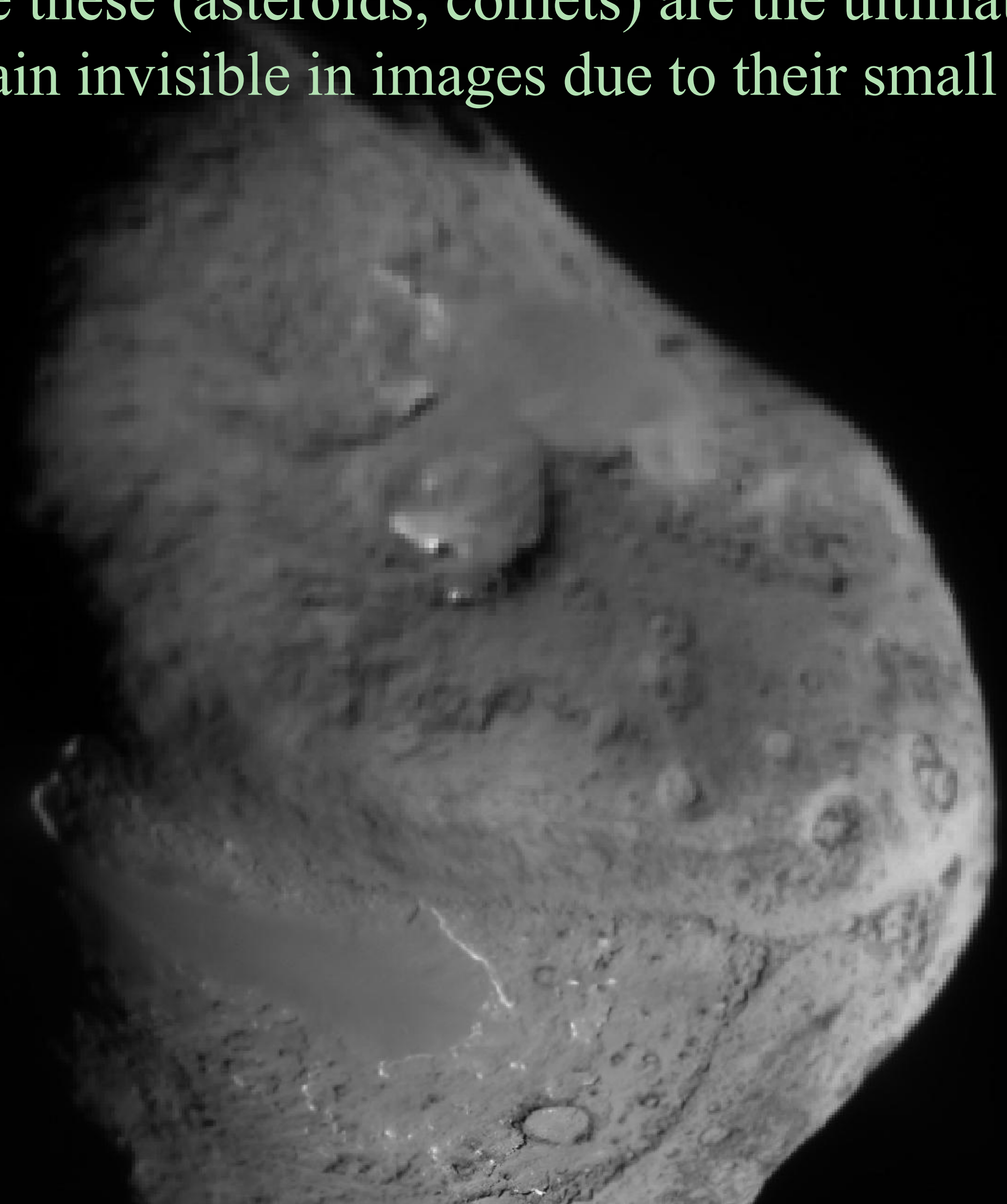




Small dust is observed due to its large total area

Parent bodies like these (asteroids, comets) are the ultimate sources of the dust, but remain invisible in images due to their small combined area





A rock
is a rock
is a rock…

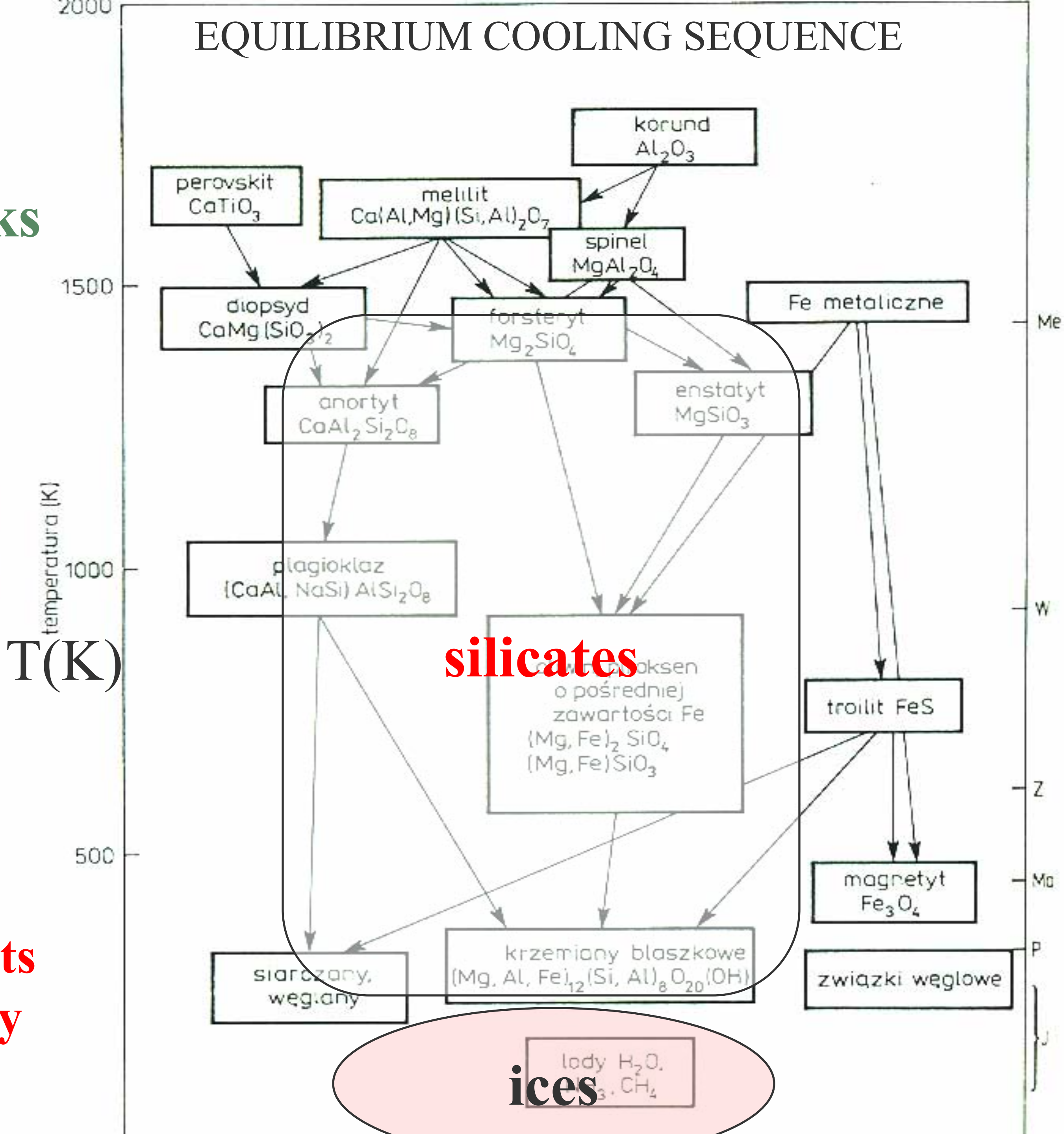
which one is
from the Earth?

from Mars?

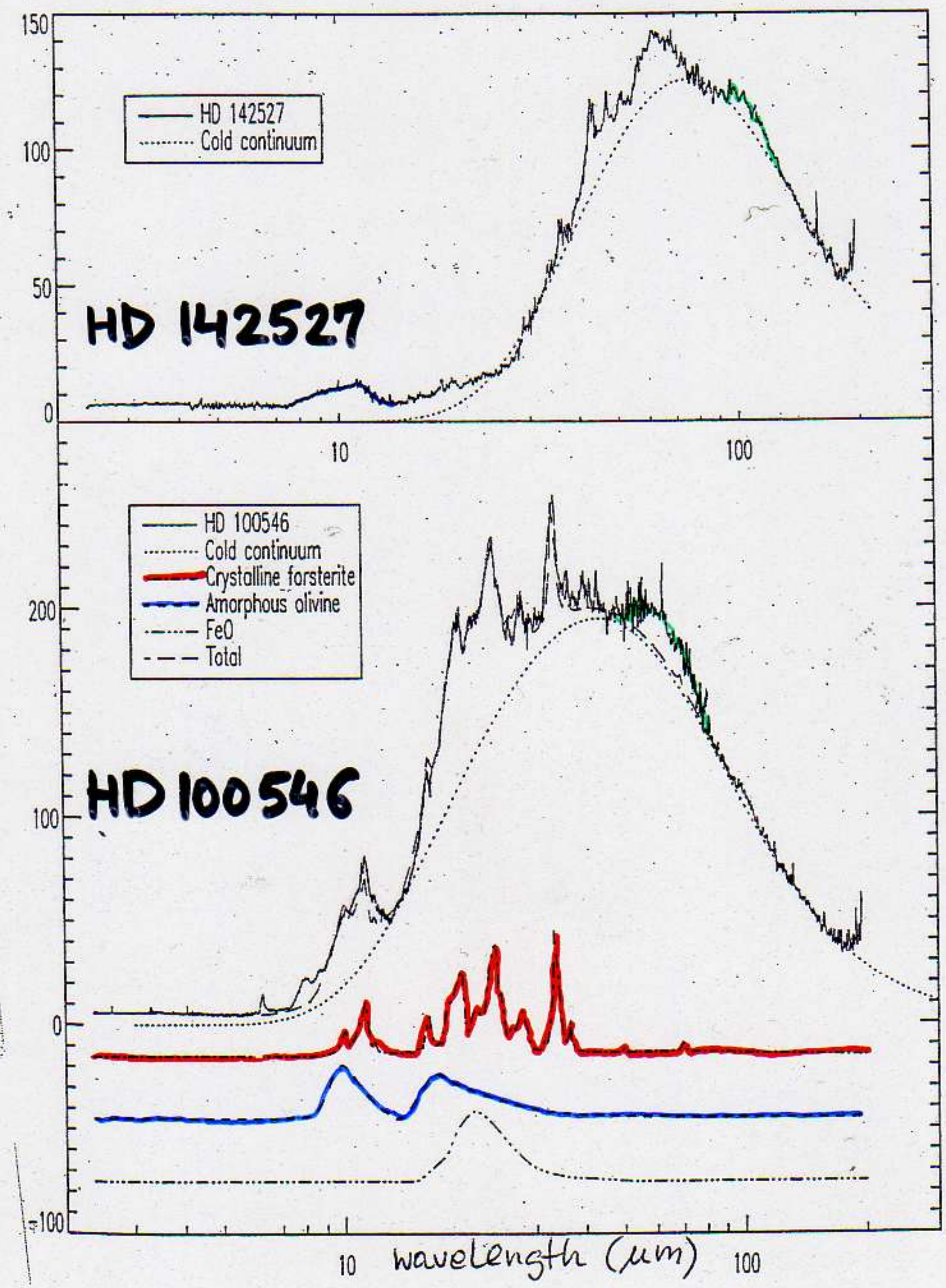
from β Pic?

It is hard to tell from spectroscopy or by looking at a stone.

Chemical unity of nature - thanks to stellar nucleosynthesis!



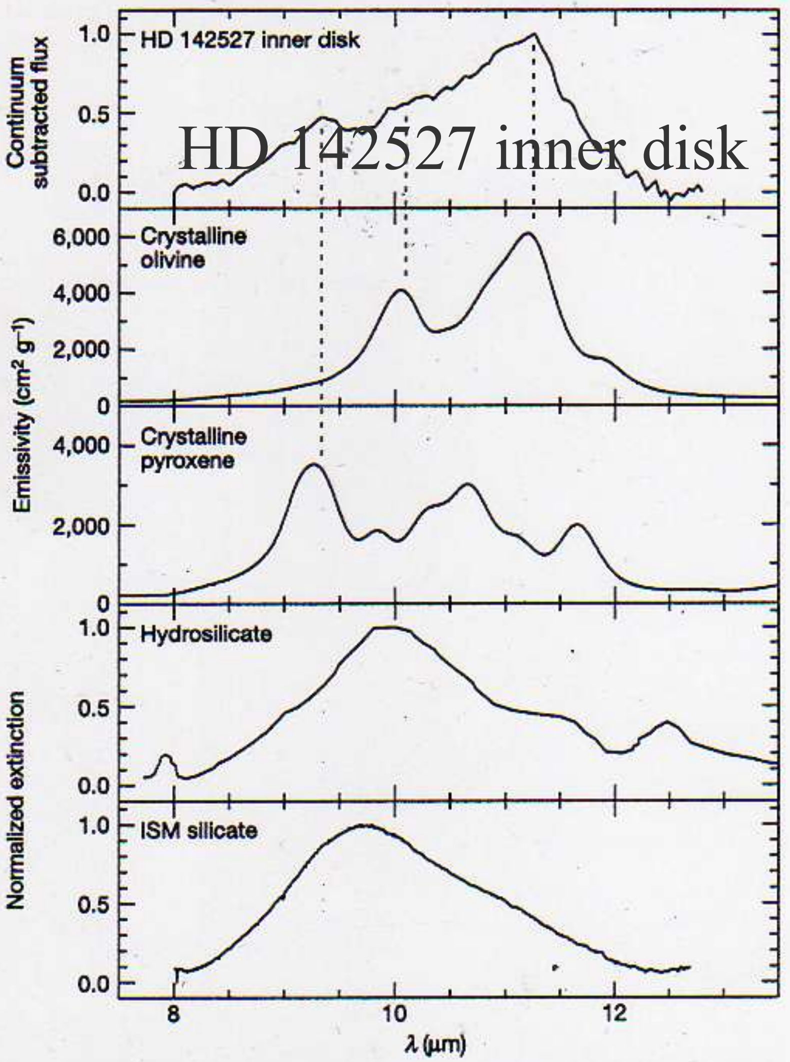
What minerals will precipitate from a solar-composition, cooling gas? Mainly Mg/Fe-rich silicates and water ice. Planets are made of precisely these things.



ISO spectra showing: silicates (amorph. & crystalline), PAHs, crystall. H_2O ice, broad 100μm emiss. (hydrated silic.?)

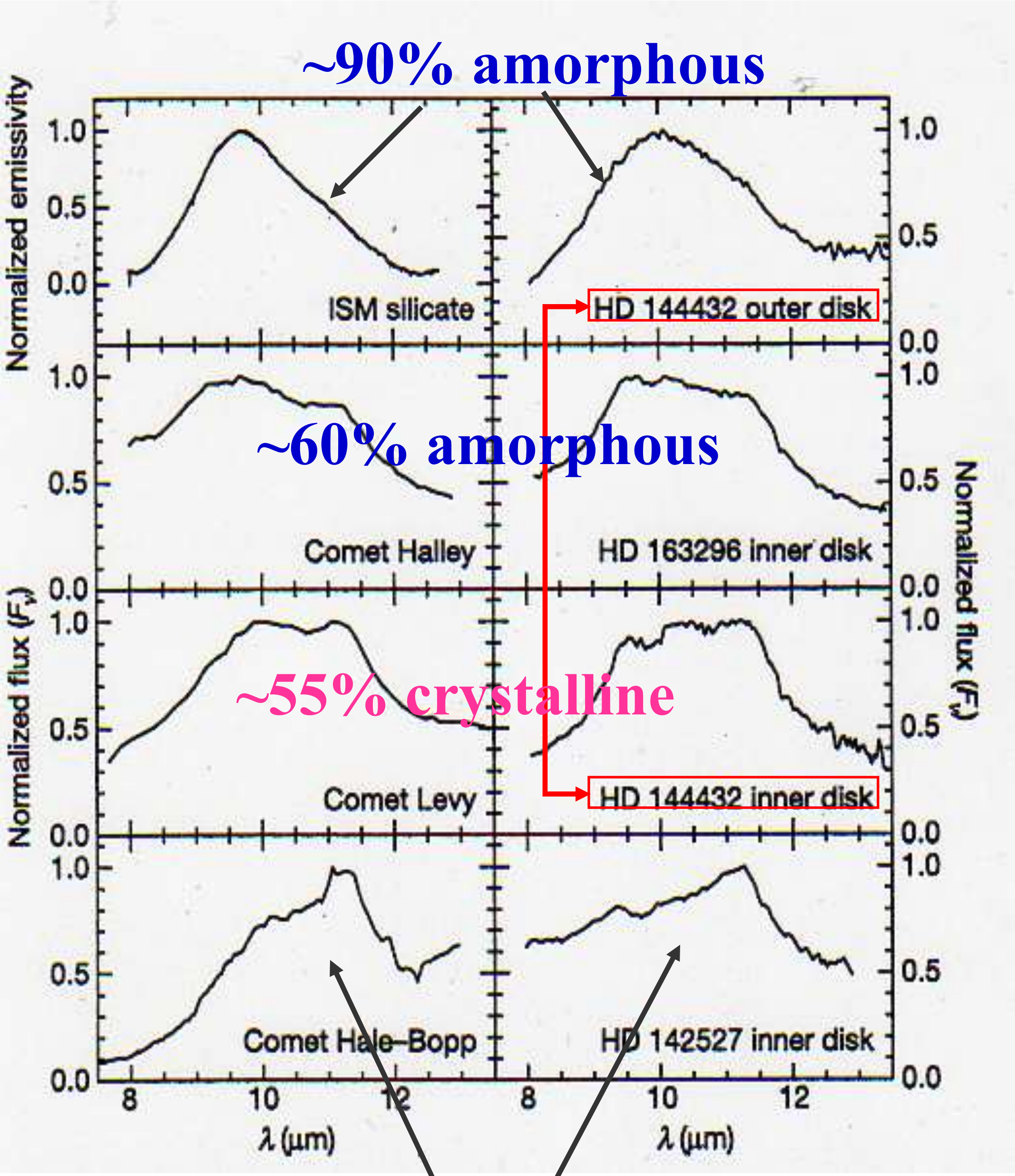
The disk particles are made of the Earth-type minerals!

(olivine, pyroxene, FeO, PAH= Polycyclic Aromatic Hydrocarbons)



HD 142527 inner disk

Figure 1 The spectrum of the innermost disk regions of HD 142527 compared to spectr of typical dust species. From top to bottom we plot the observed inner-disk spectrum c HD 142527, the laboratory spectra of crystalline olivine and pyroxene[29], a laboratory spectrum of an IDP consisting of hydrated silicates[17], and the interstellar medium silicat spectrum[1]. The resolution of the laboratory data is reduced to that of the interferometri spectrum. The main resonances of crystalline pyroxene at 9.2 μm and crystalline olivin at 11.3 μm are clearly seen in the HD 142527 spectrum. We can exclude the possibility c a significant contribution of hydrated silicates to the spectrum in the inner-disk regions of HD 142527, which suggests that we see primary, rather than secondary dust.



~90% amorphous

~60% amorphous

~55% crystalline

~95% crystalline

Lecture L18 ASTB25

Disk processes: Dust avalanches, Irradiation instability

Jeffrey Fung (UTSC u/g → StG gradstudent → Berkeley postdoc, Princeton Fellow → Clemson U. Professor)

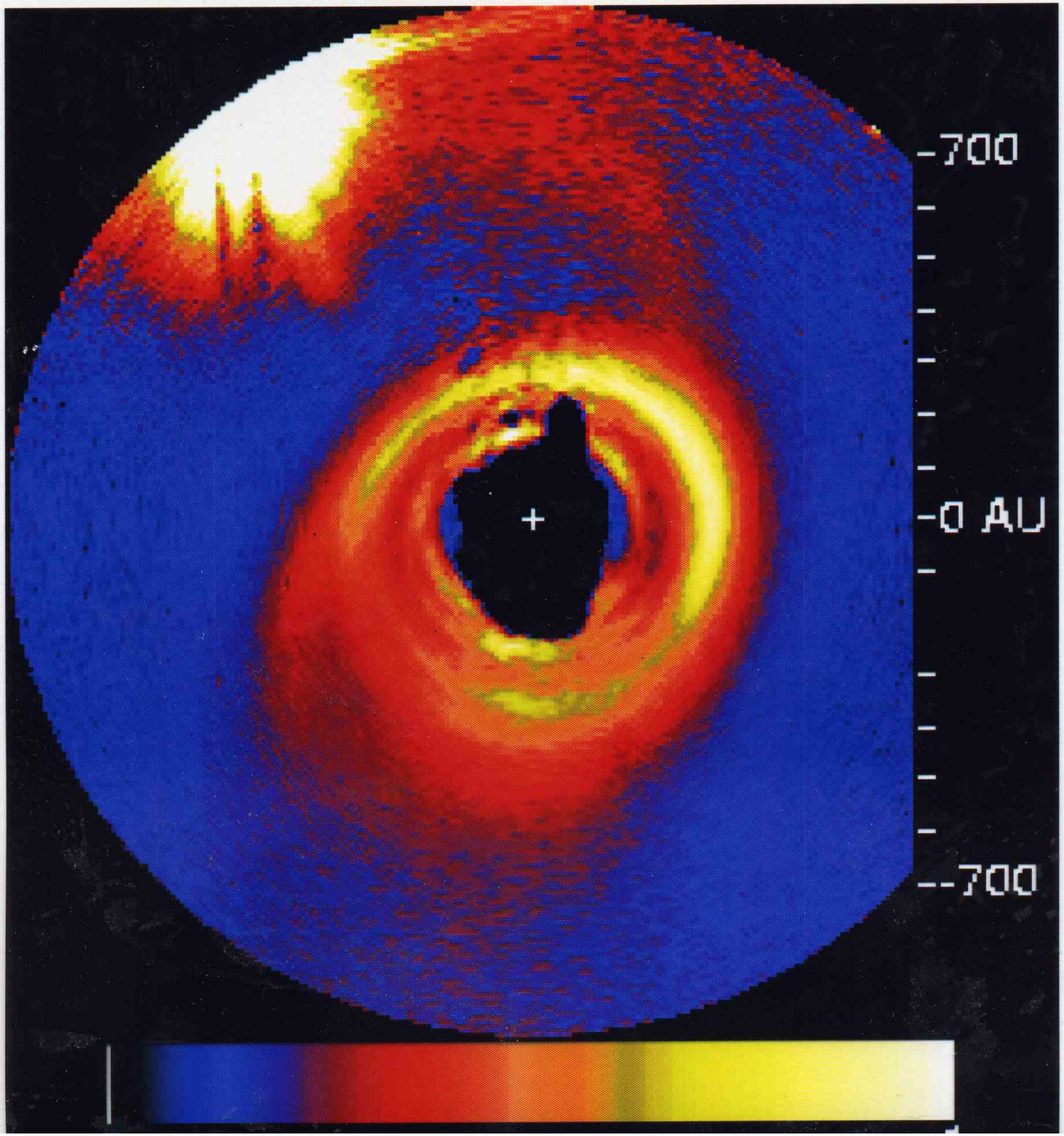
Disks can obtain structure in many ways,
not only due to planets and external perturbations
but also as a result of gas-dust-radiation coupling:
Dust avalanches, dust migration, dust instabilities,
dust_gas instabilities, dust clumping

Gas-dust coupling?

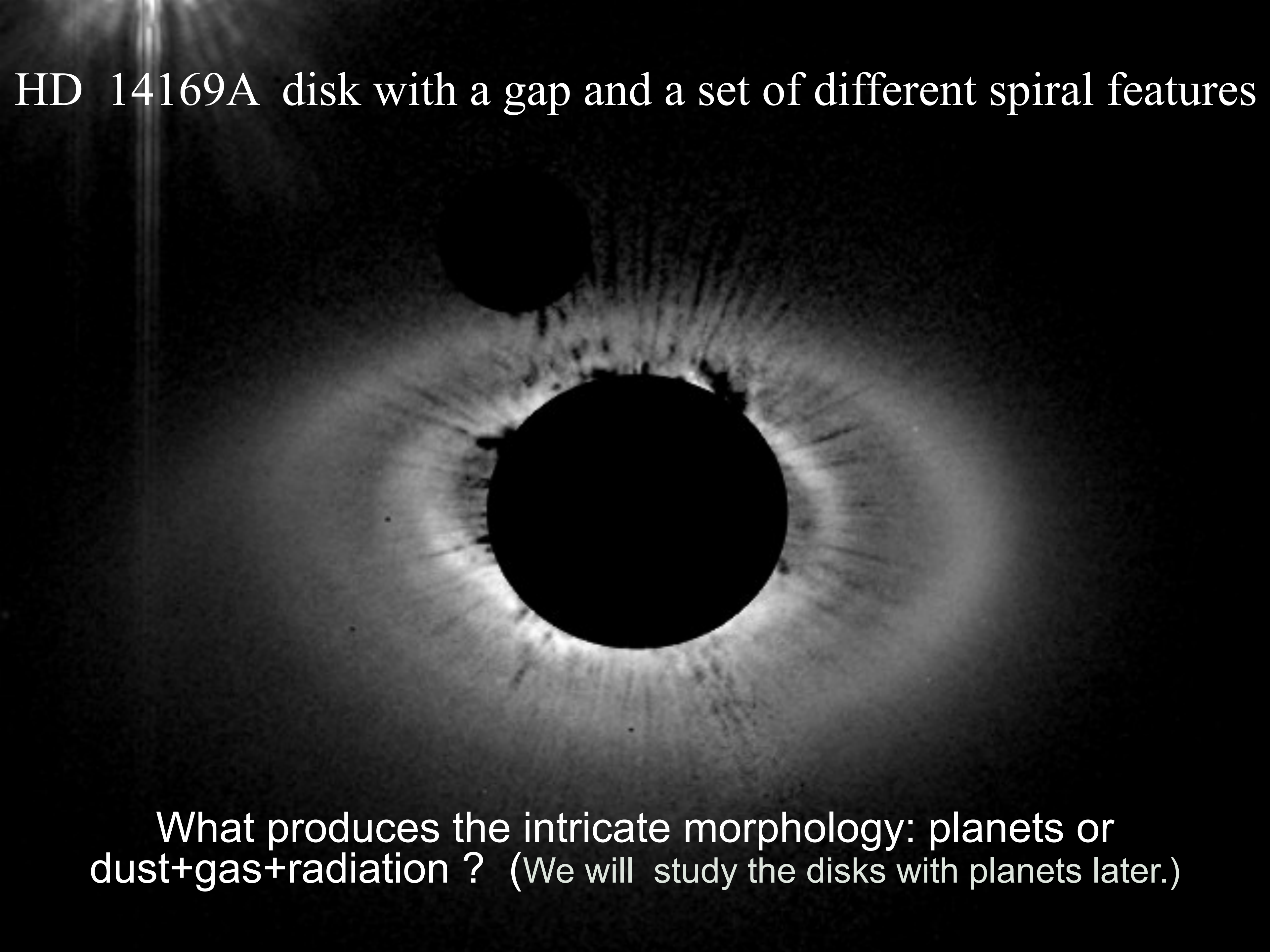
Planetary perturbations?

Dust avalanches?

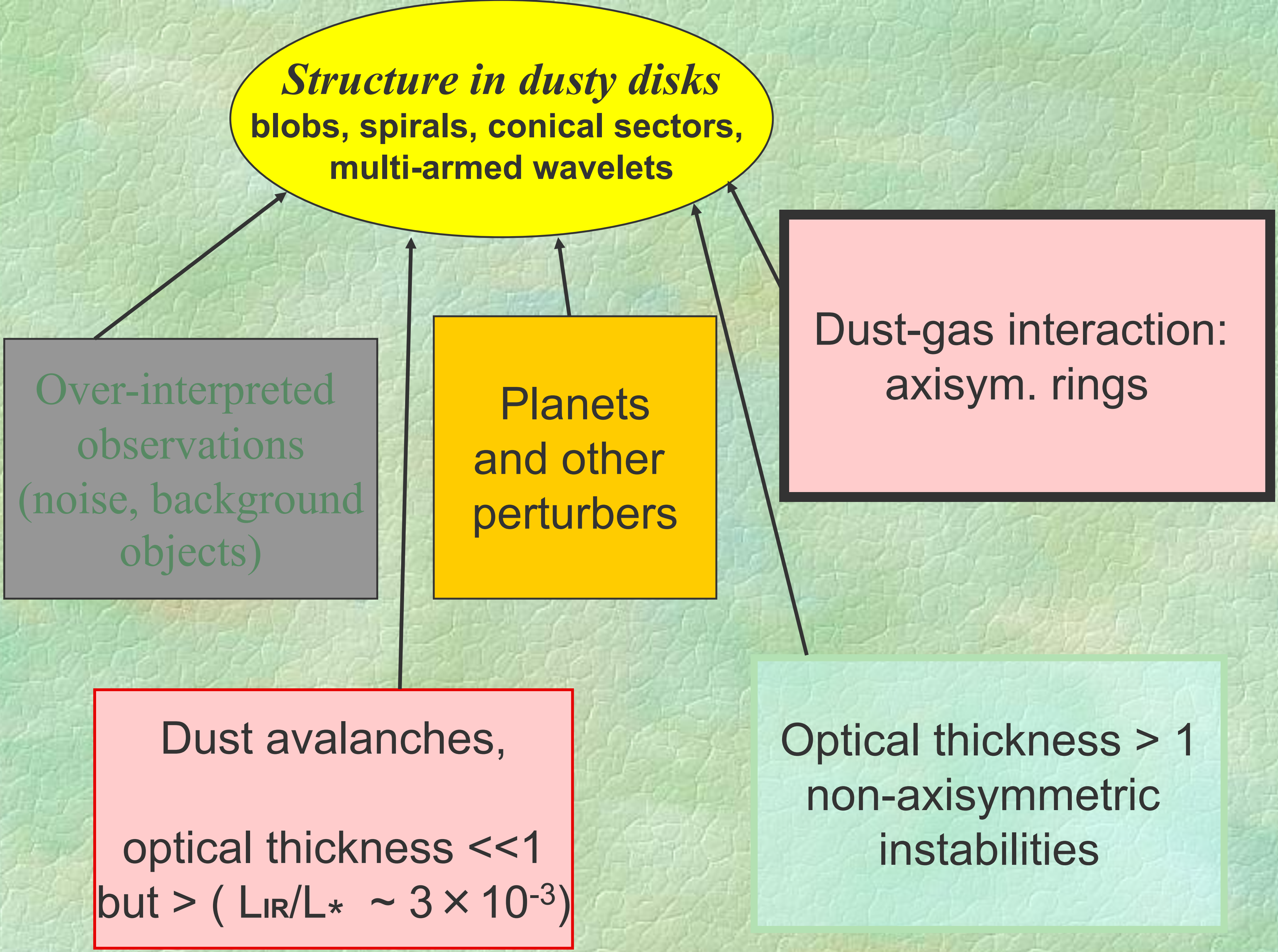
HD 141569A:
Spiral structure detected in 2003 by **A**dvanced **C**amera for **S**urveys onboard the HST (Hubble Space Telescope)



HD 14169A disk with a gap and a set of different spiral features



What produces the intricate morphology: planets or dust+gas+radiation ? (We will study the disks with planets later.)



Structure in dusty disks

blobs, spirals, conical sectors, multi-armed wavelets

Over-interpreted observations (noise, background objects)

Planets and other perturbers

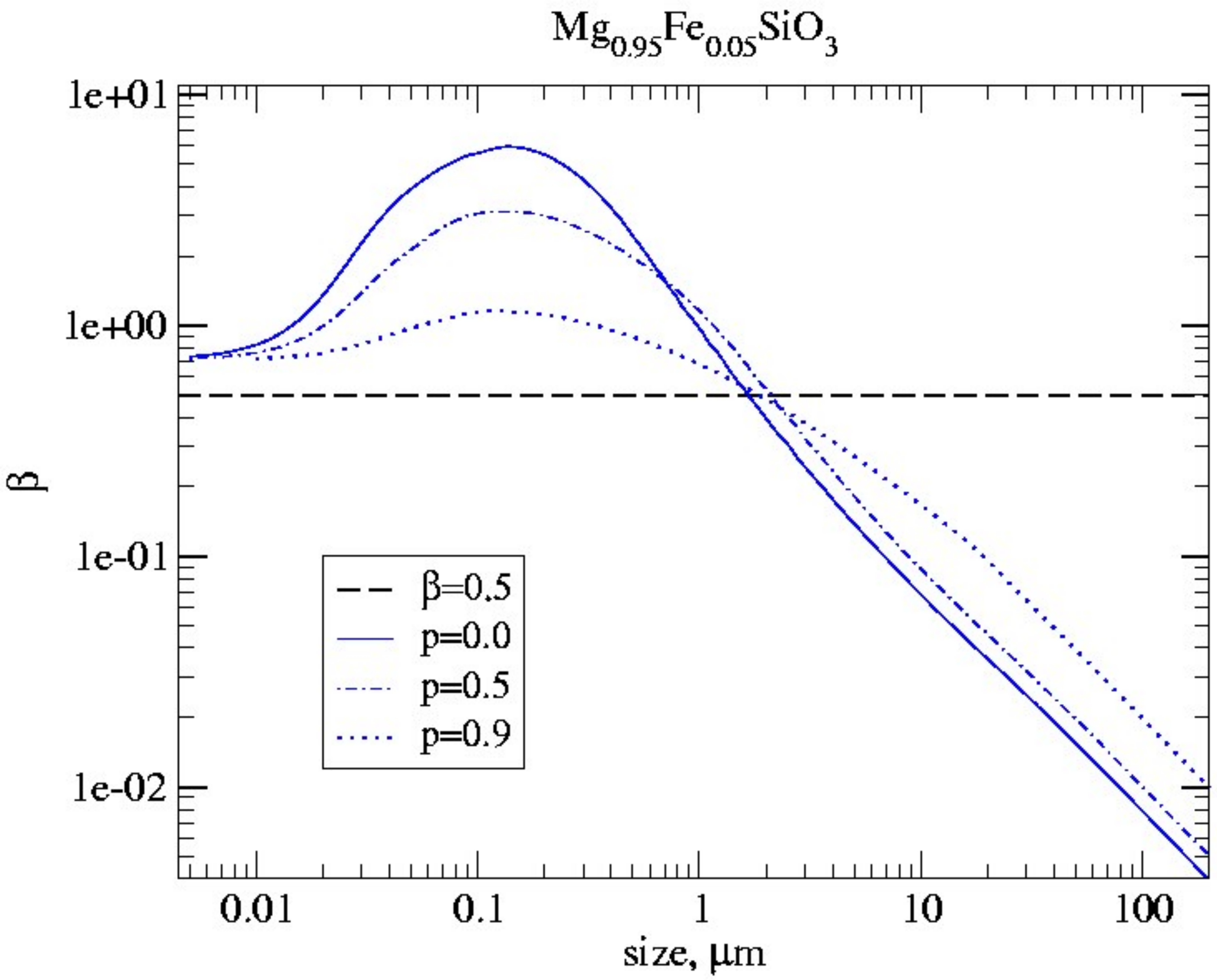
Dust-gas interaction: axisym. rings

Dust avalanches,

optical thickness <<1 but > ($L_{IR}/L_{*} \sim 3 \times 10^{-3}$)

Optical thickness > 1 non-axisymmetric instabilities

Radiation pressure on dust grains in disks: beta Pic disk



Dust + gas interaction: axisym. rings can form because of dust-gas-radiation interaction

gas drag in the presence of radiation pressure (β>0) can result in either inward or outward migration of solids: consider the radial force balance to find the *circular* (e=0) speed of a particle:

$$\ddot{r} = -\frac{GM}{r^2} + \frac{\beta GM}{r^2} + \frac{v^2}{r} = 0$$

$$v^2_{circ} = \frac{GM(1-\beta)}{r} \Rightarrow v_{circ} = \sqrt{1-\beta}\sqrt{\frac{GM}{r}} = \sqrt{1-\beta}\, v_K(r)$$

$$\underline{v_g = (1+\underset{<0}{q})\, v_K(r)}$$

$$f_D = \text{const}(v_g - v_{circ}) = \text{cst}\, v_K(r)\left[1+\overset{<0}{q} - \underset{\approx 1-\beta/2}{\overset{<1}{\sqrt{1-\beta}}}\right]$$

$$\beta << 1 \; ; \; \sqrt{1-\beta} \approx 1 - \frac{\beta}{2}$$

$$\underline{\underline{f_D \sim \left(\overset{>0}{\frac{\beta}{2}} + \overset{<0}{q}\right)}}$$

$q = -0.005$; $\beta \approx 0.01 \rightarrow f_D = 0$ no wind

back-wind

$\beta \approx 0.1 \rightarrow \; > 0$, $\dot{a} > 0$

$\dot{L} > 0$

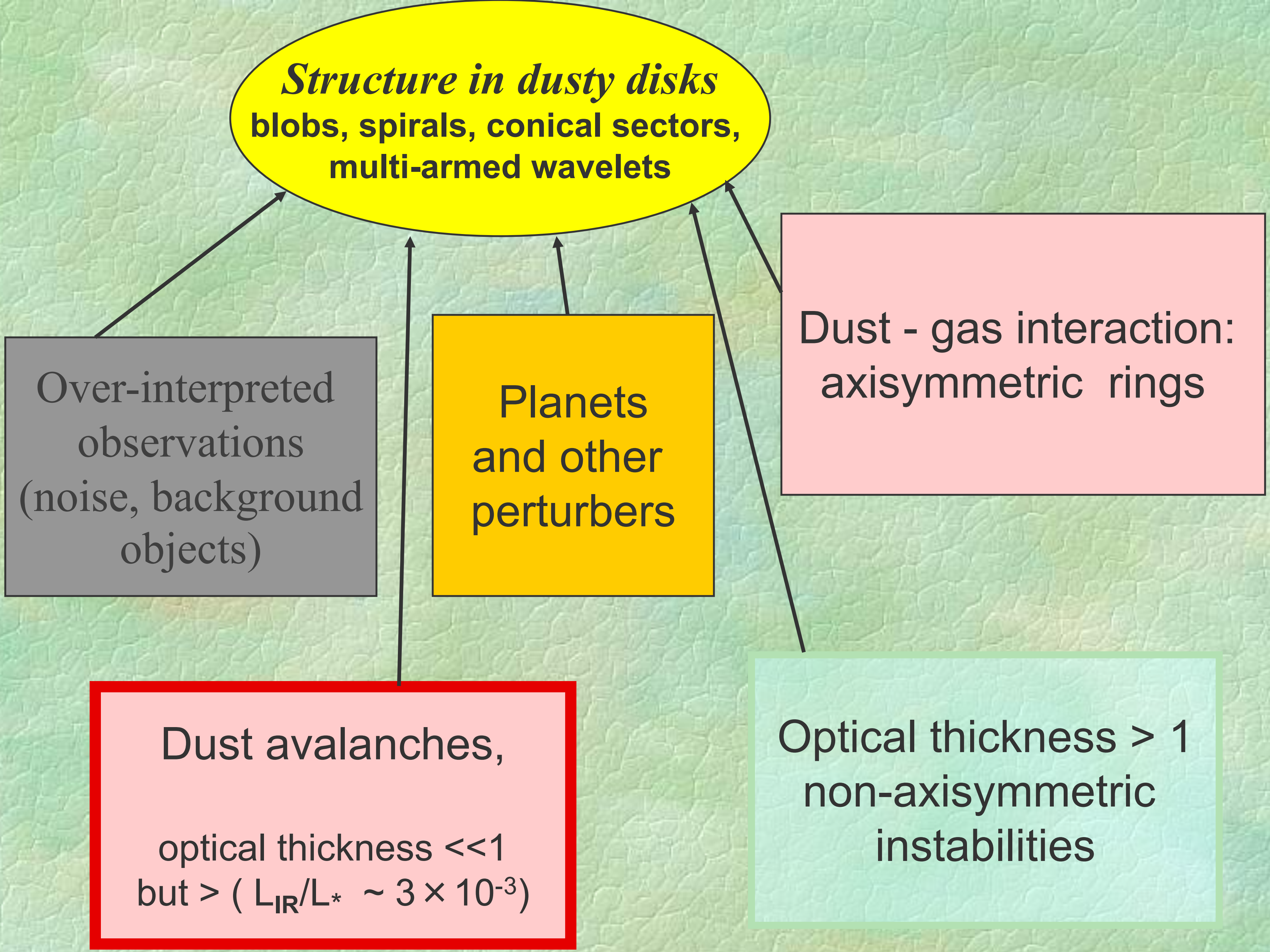
L² = GMa

taking the time derivative:

2L dL/dt = GM da/dt

dL/dt = GM/(2L) da/dt

i.e. if the torque *dL/dt* is positive (particle pushed along the traj.) then the particle drifts away from the star, and vice versa. This happens if there is a back-wind. But if there is a head-wind (gas rotates slower than particle) then the direction of migration is *inward*. The speed of gas is a bit slower, sub-Keplerian, q ~ -0.005



Structure in dusty disks

blobs, spirals, conical sectors, multi-armed wavelets

Over-interpreted observations (noise, background objects)

Planets and other perturbers

Dust - gas interaction: axisymmetric rings

Dust avalanches,

optical thickness <<1
but > ($L_{IR}/L_* \sim 3 \times 10^{-3}$)

Optical thickness > 1
non-axisymmetric instabilities

Grigorieva, Artymowicz and Thebault (2006)

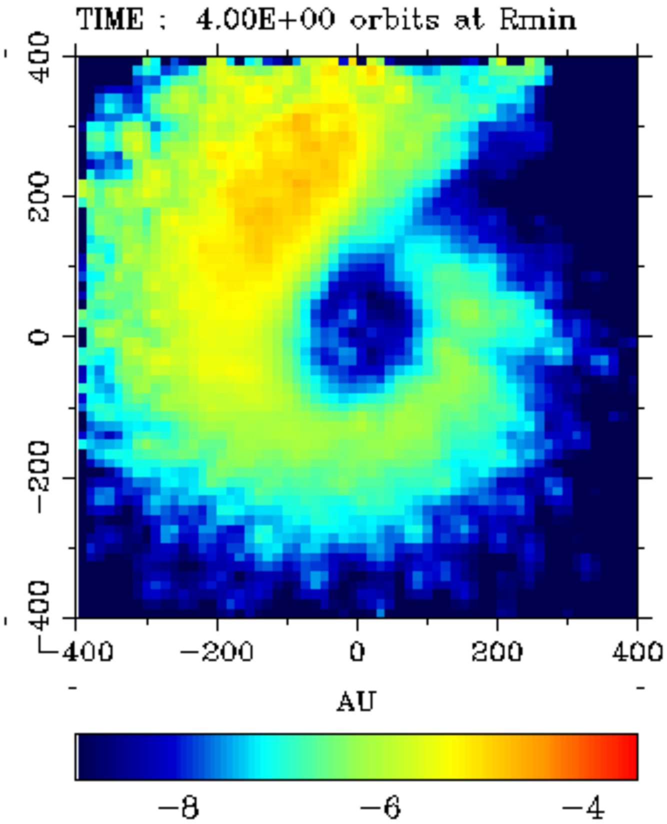
Comprehensive model of dusty debris disk (3D) with full treatment of collisions and particle dynamics.

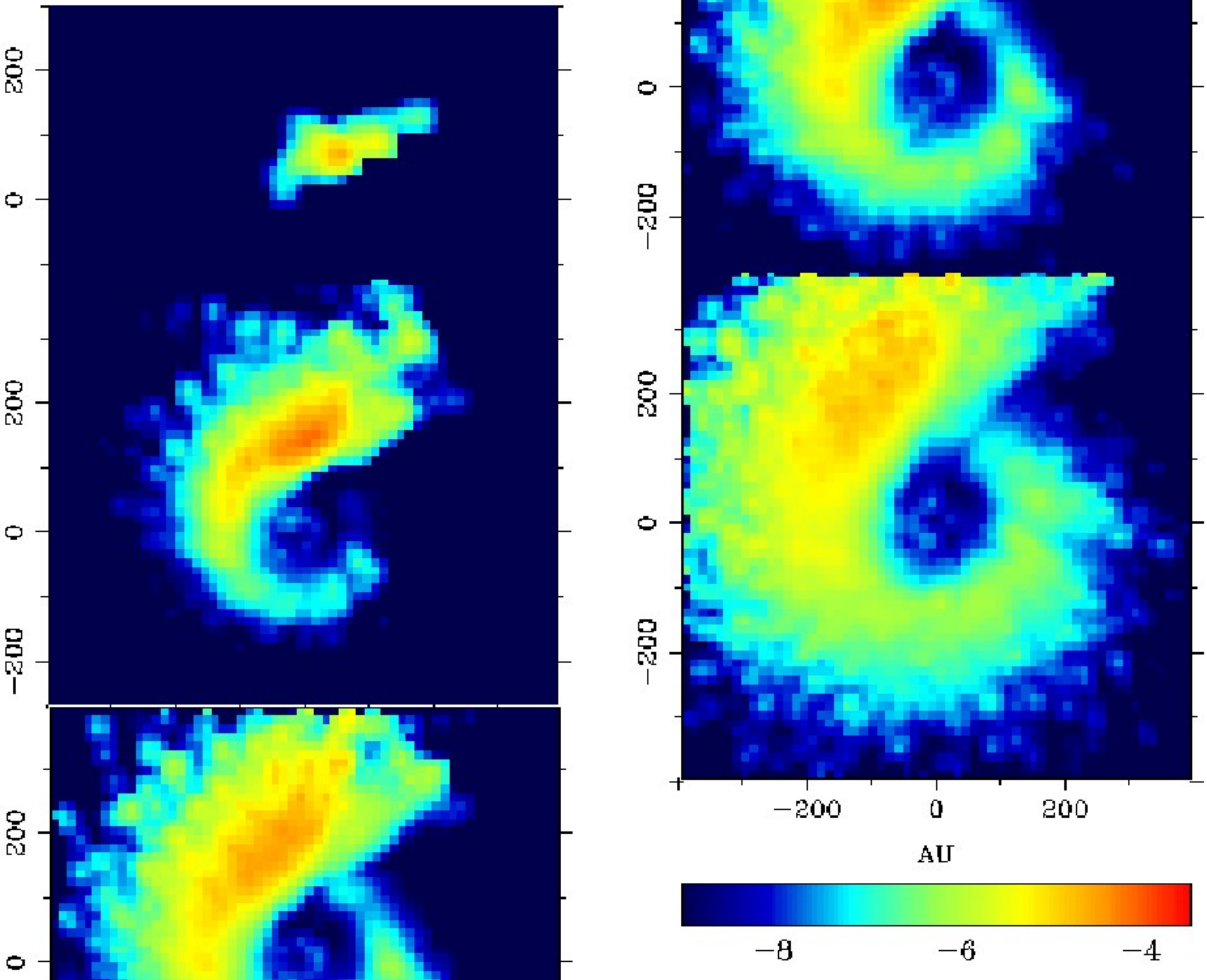
Dust avalanches, optical thickness <<1 but > ($L_{IR}/L_* \sim 3 \times 10^{-3}$)

- especially suitable to denser transitional disks supporting dust avalanches
- detailed treatment of grain-grain colisions, depending on material
- detailed treatment of radiation pressure and optics, depending on material
- localized dust injection (e.g., planetesimal collision)
- dust grains of similar properties and orbits grouped in "superparticles"
- physics: radiation pressure, gas drag, collisions

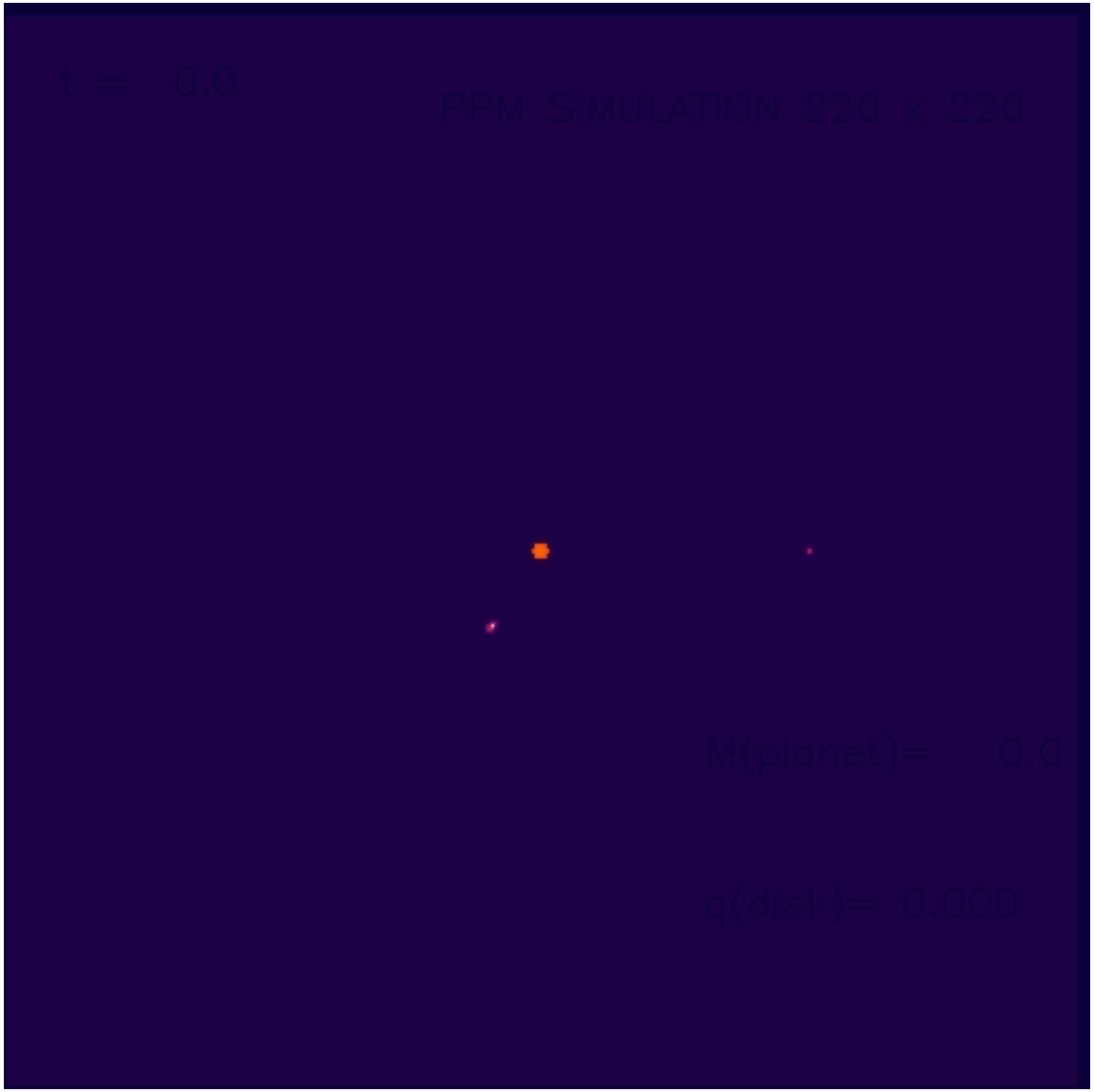
Results:

- beta Pictoris avalanches multiply debris 3-5 x
- more dusty disks can be destroyed by avalanches
- spiral shape of the avalanche robust outcome
- strong dependence on material properties and certain other model assumptions



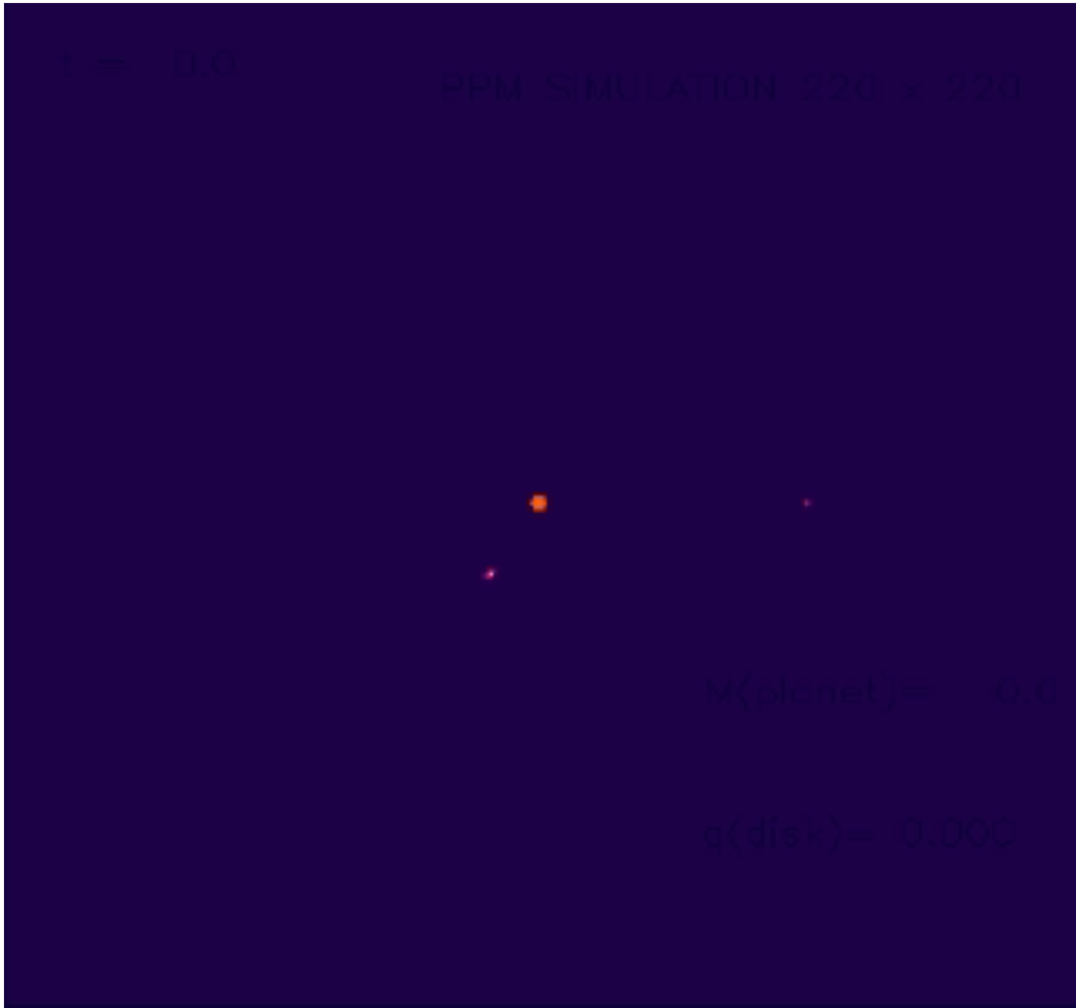

200
0
200
0
−200
200
0
0
−200
200
0
−200
−200
0
200
AU
−8
−6
−4

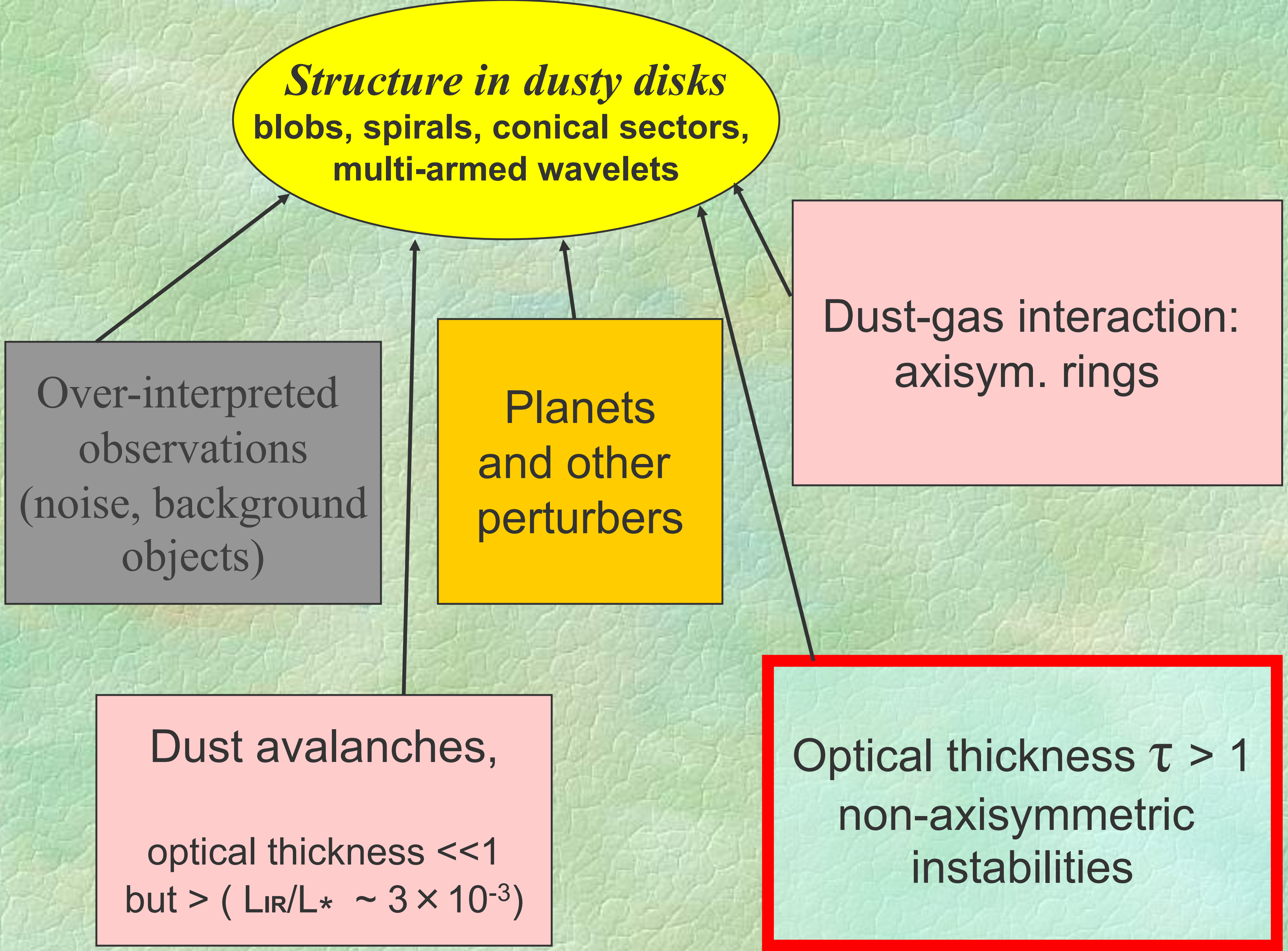
Model of (simplified) collisional avalanche with substantial gas drag, corresponding to 10 Earth masses of gas in disk



Main results of modeling of collisional avalanches:

1. Strongly nonaxisymmetric, growing patterns
2. Substantial exponential multiplication of debris flying out
3. Morphology depends on the amount and distribution of gas, in particular on the presence of an outer disk edge





Structure in dusty disks

blobs, spirals, conical sectors, multi-armed wavelets

Over-interpreted observations (noise, background objects)

Planets and other perturbers

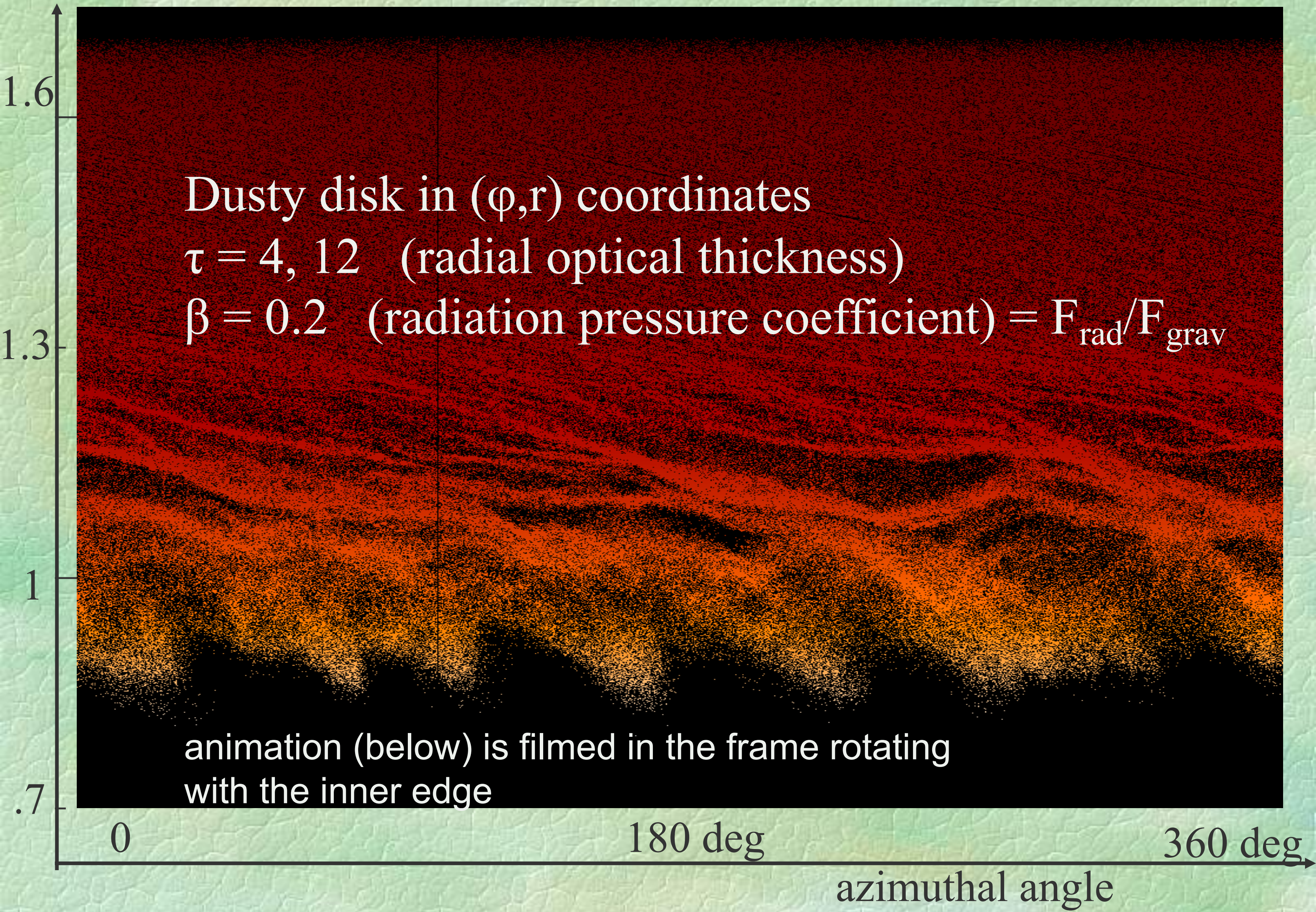
Dust-gas interaction: axisym. rings

Dust avalanches,

optical thickness <<1
but > ($L_{IR}/L_* \sim 3 \times 10^{-3}$)

Optical thickness $\tau > 1$
non-axisymmetric instabilities

Free particles casting shadows



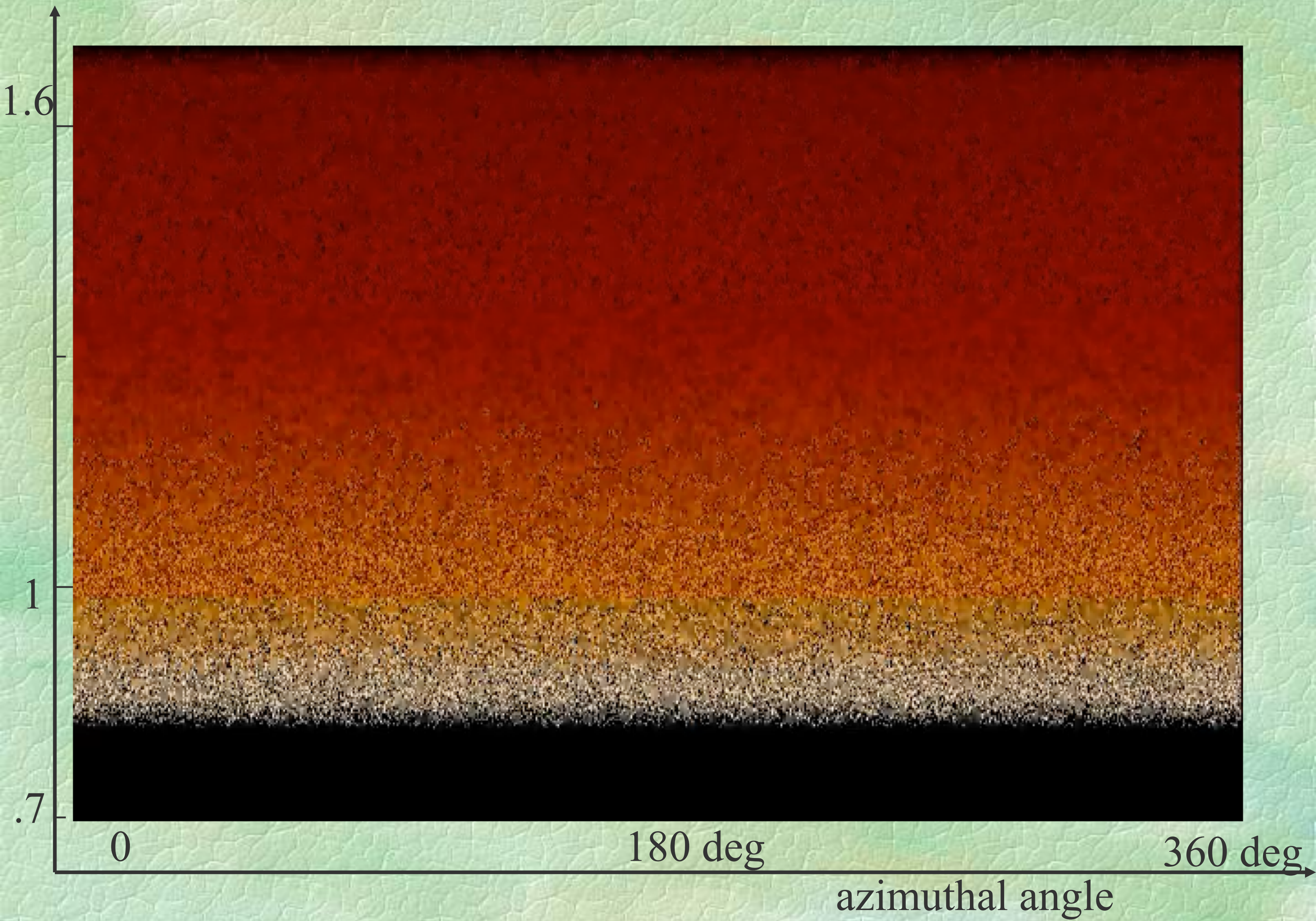
Dusty disk in (φ,r) coordinates

$\tau = 4, 12$ (radial optical thickness)

$\beta = 0.2$ (radiation pressure coefficient) $= F_{rad}/F_{grav}$

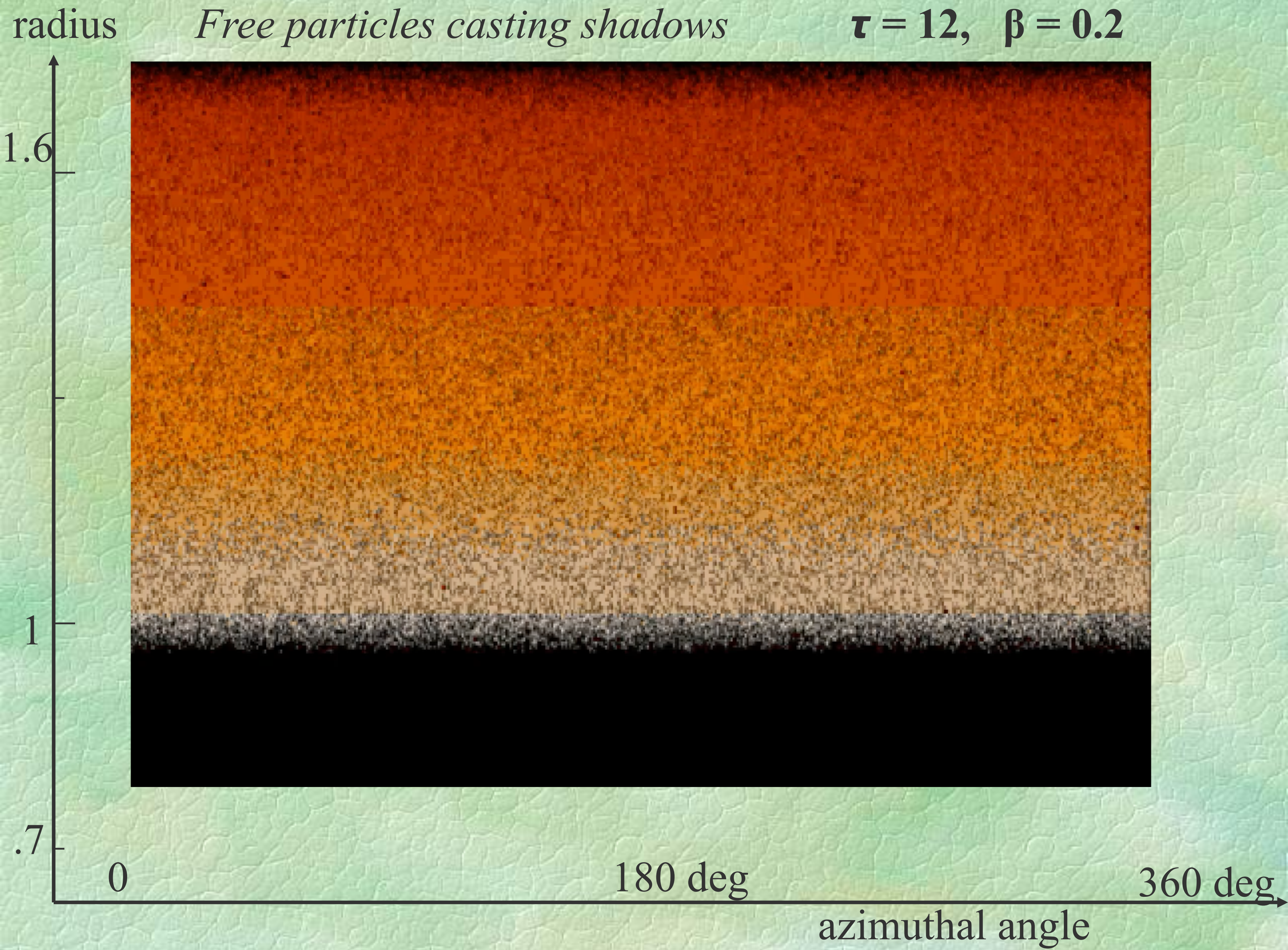
animation (below) is filmed in the frame rotating with the inner edge

Free particles casting shadows video **tau = 4, beta = 0.2**

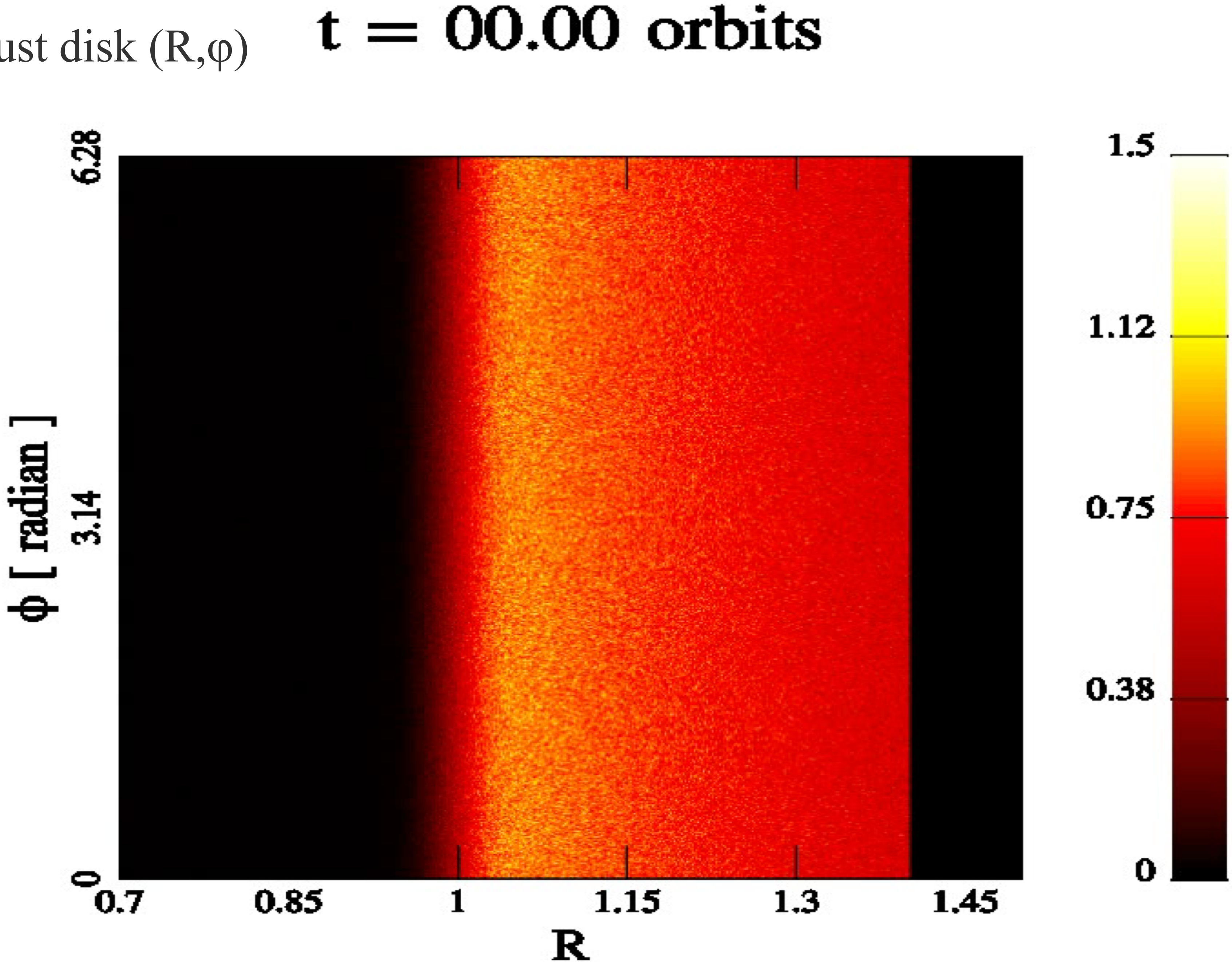


Free particles casting shadows

$\tau = 12$, $\beta = 0.2$

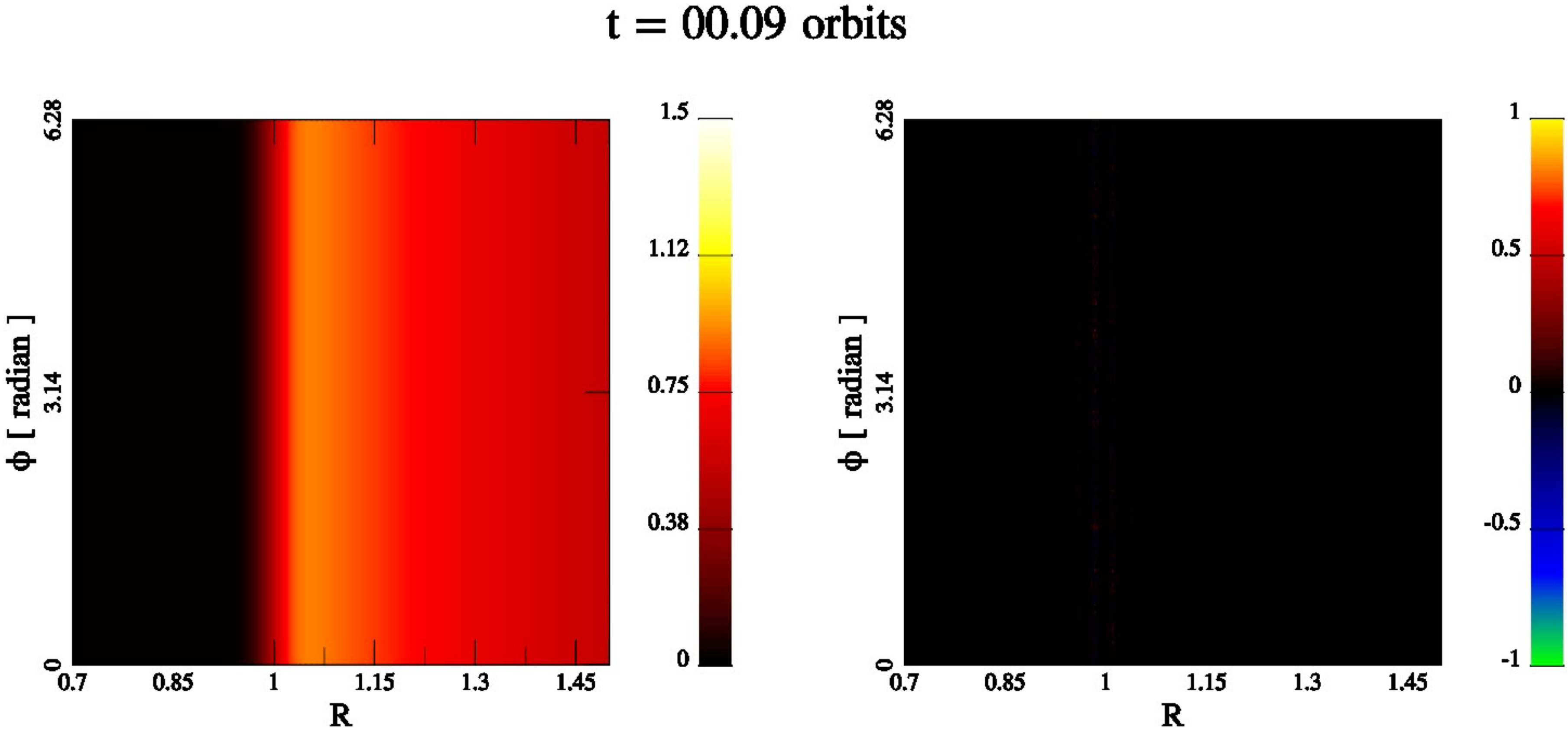


dust disk (R,φ)


t = 00.00 orbits
φ [radian]
6.28
3.14
0
0.7
0.85
1
1.15
1.3
1.45
R
1.5
1.12
0.75
0.38
0

RADIATION PRESSURE-RELATED INSTABILITIES including the IRI = IrRadiation Instability occur in dust and gas disks (Fung & Artymowicz, Astroph. Journal 2015)

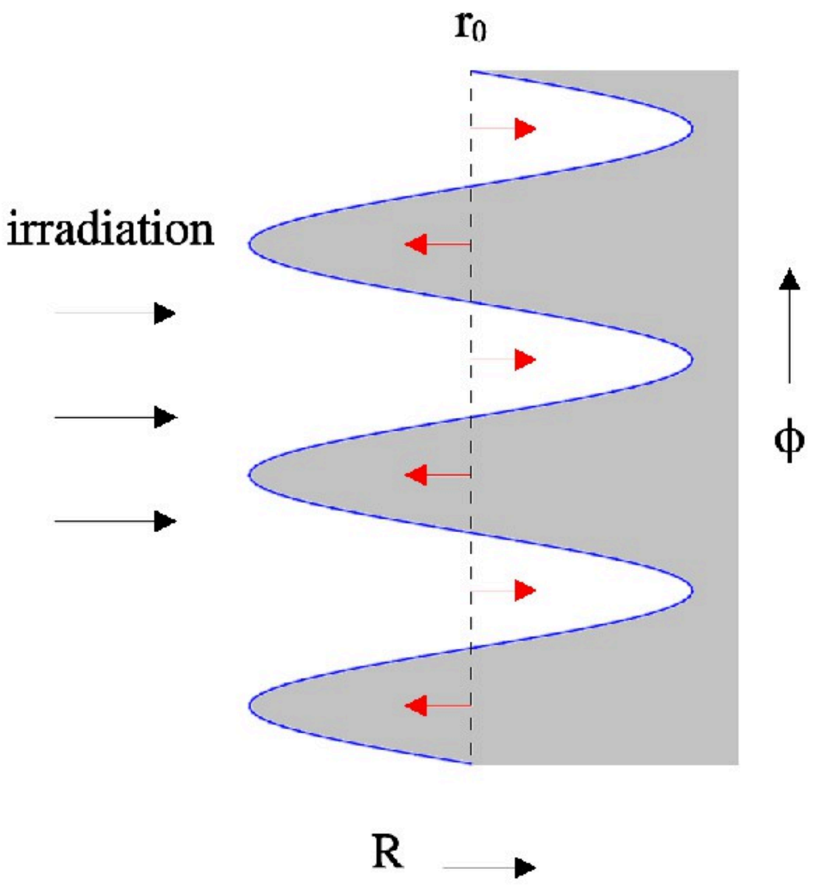
The r.h.s. shows a background-removed picture of density variations in growing modes. Their growth is beautifully predicted semi-analytically.



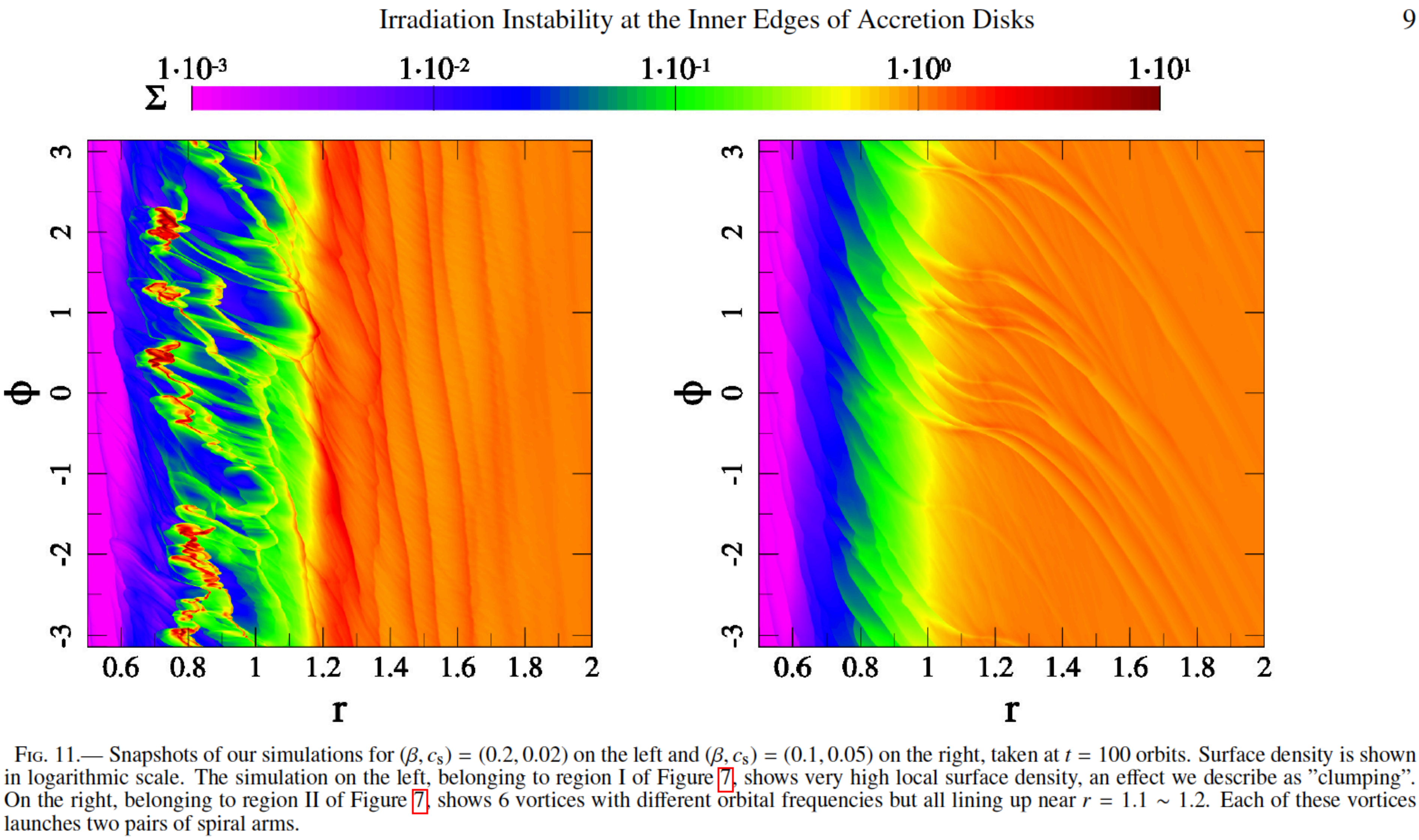
Jeffrey Fung's calculation of modes growing in gas disk

Handwaving explanation of why the IRI happens:
more dust in front → extra inward push
less dust in front → extra outward push (relative to average)

IRI in 2D

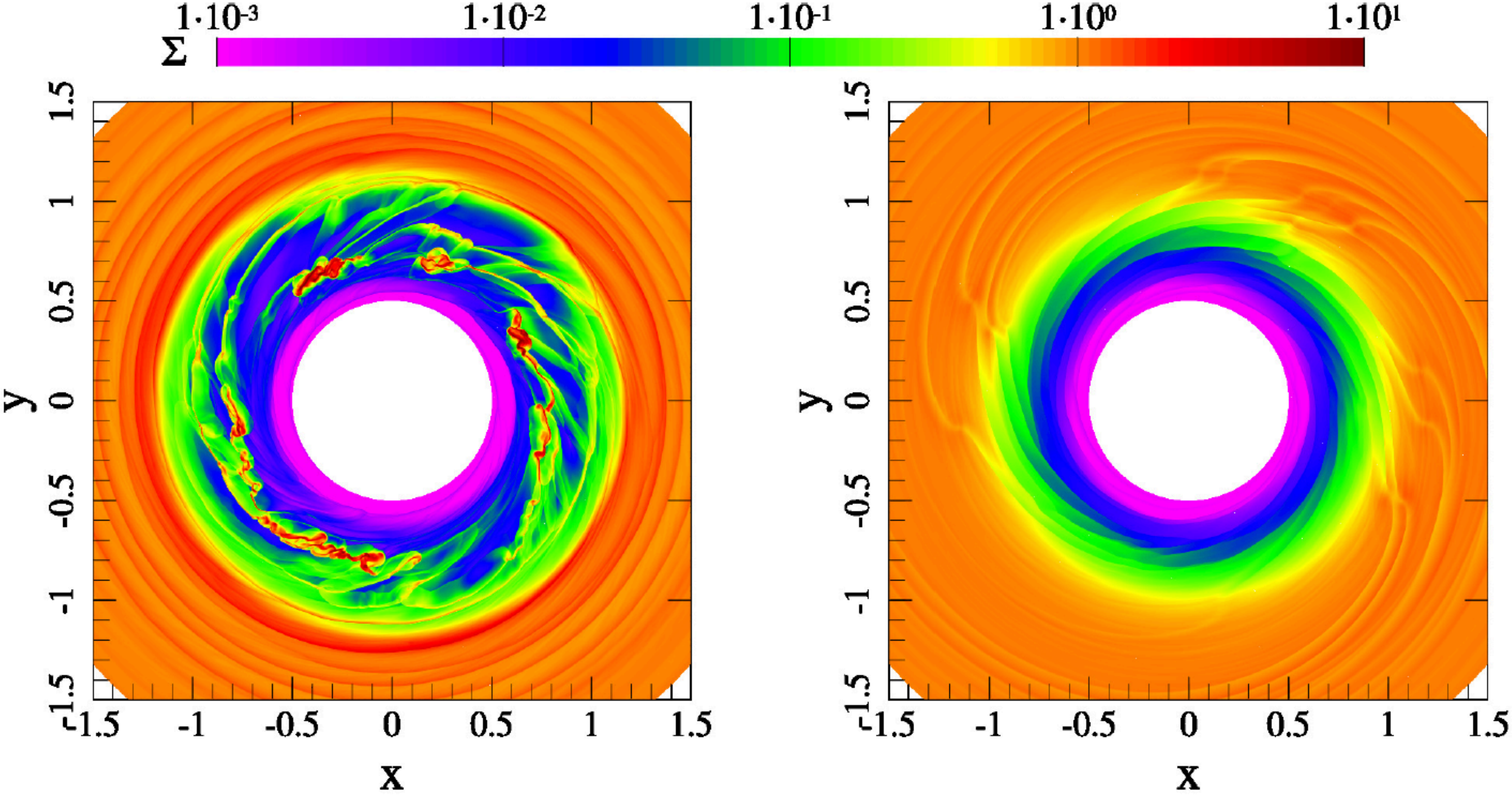


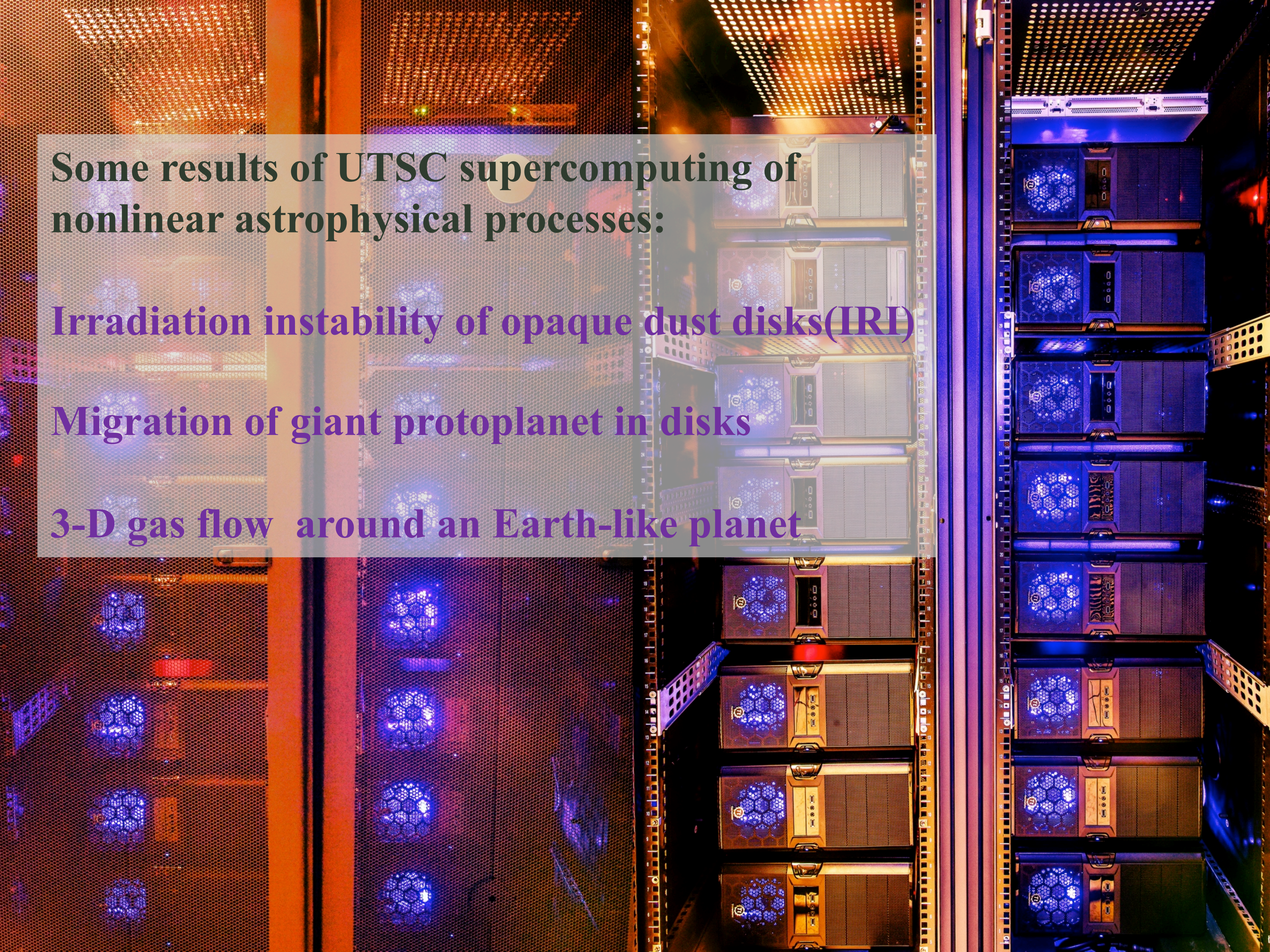
IRI causes morphology similar to the gravitational instability and is goverened by a local criterion that involves gradient of optical thickness



Irradiation Instability at the Inner Edges of Accretion Disks 9

FIG. 11.— Snapshots of our simulations for $(\beta, c_s) = (0.2, 0.02)$ on the left and $(\beta, c_s) = (0.1, 0.05)$ on the right, taken at $t = 100$ orbits. Surface density is shown in logarithmic scale. The simulation on the left, belonging to region I of Figure 7, shows very high local surface density, an effect we describe as ”clumping”. On the right, belonging to region II of Figure 7, shows 6 vortices with different orbital frequencies but all lining up near $r = 1.1 \sim 1.2$. Each of these vortices launches two pairs of spiral arms.


Σ
1·10-3
1·10-2
1·10-1
1·100
1·101
1.5
1
0.5
0
-0.5
-1
-1.5
y
x

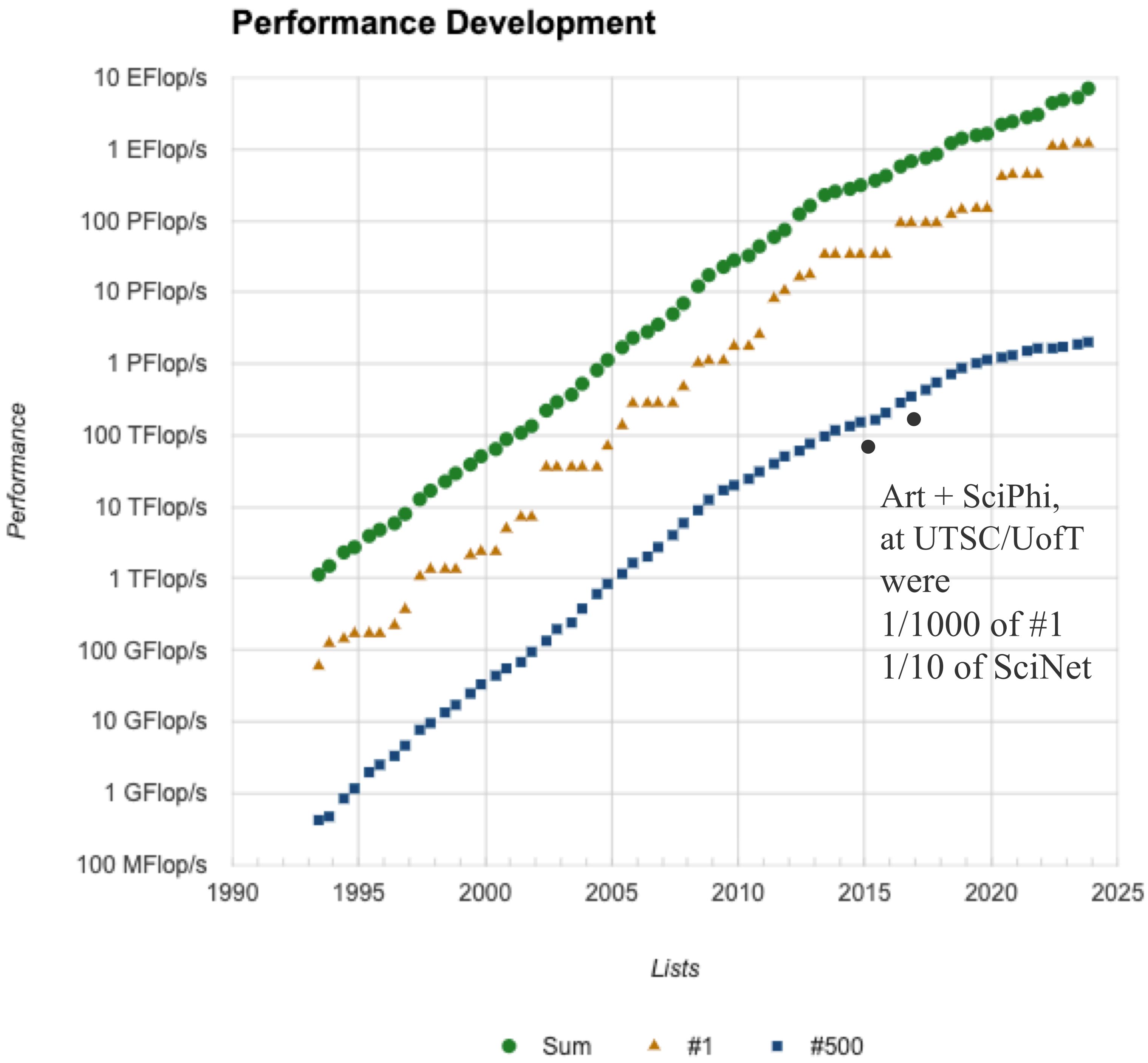


Some results of UTSC supercomputing of nonlinear astrophysical processes:

Irradiation instability of opaque dust disks(IRI)

Migration of giant protoplanet in disks

3-D gas flow around an Earth-like planet



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at UTSC/UofT
were
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1/10 of SciNet