Physics of Accretion Disks

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Quick Bio

Wladimir Lyra

B.Sc. in Astronomy, Federal University of Rio de Janeiro (UFRJ, **Brazil**), 1999-2003.

Research Assistant 2003-2004

Space Telescope Science Institute (*STScI*, Baltimore **MD**)
Cerro Tololo Interamerican Observatory (*CTIO*, La Serena – **Chile**)
European Southern Observatory (*ESO*, Munich – **Germany**)
Lisbon Observatory, **Portugal**.

Ph.D. in Astronomy, Uppsala University (Uppsala, **Sweden**), 2004-2009.

Nordic Institute for Theoretical Physics (*NORDITA*, Stockholm, **Sweden**)
Max-Planck Institute for Astronomy (*MPIA*, Heidelberg, **Germany**)

Postdoctoral Researcher

American Museum of Natural History (*AMNH*, New York **NY**), 2009-2011.
Jet Propulsion Laboratory (NASA-JPL/Caltech, Pasadena **CA**), 2011-2015.

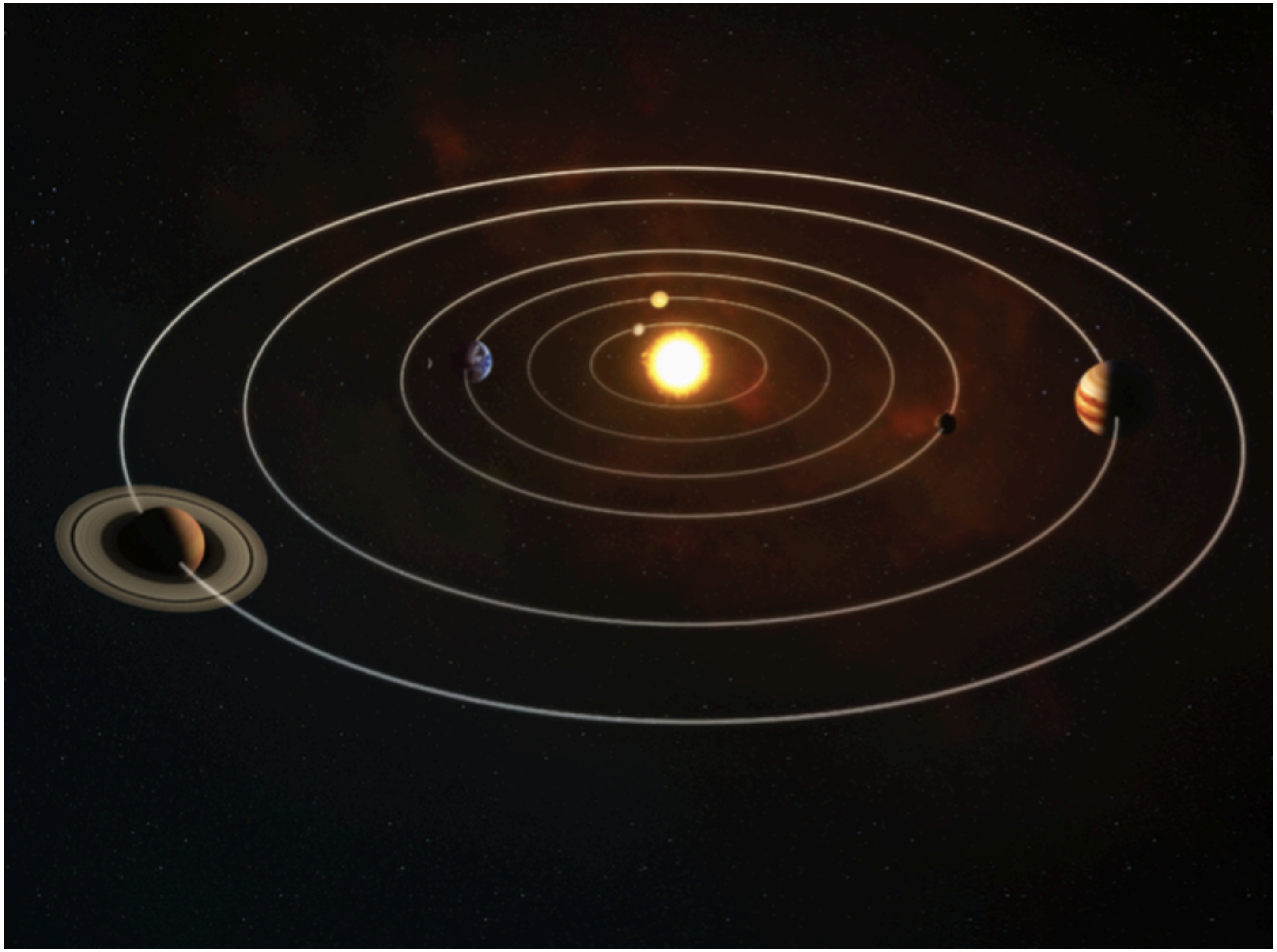
Stellar Astrophysics, Planetary Sciences

Solar-type stars, extrasolar planets, star formation, *circumstellar disks and planet formation*.
Hydrodynamics, plasma physics, turbulence, life in the universe, *icy moons and Europa*.

Question #1

The Earth exists. Why?

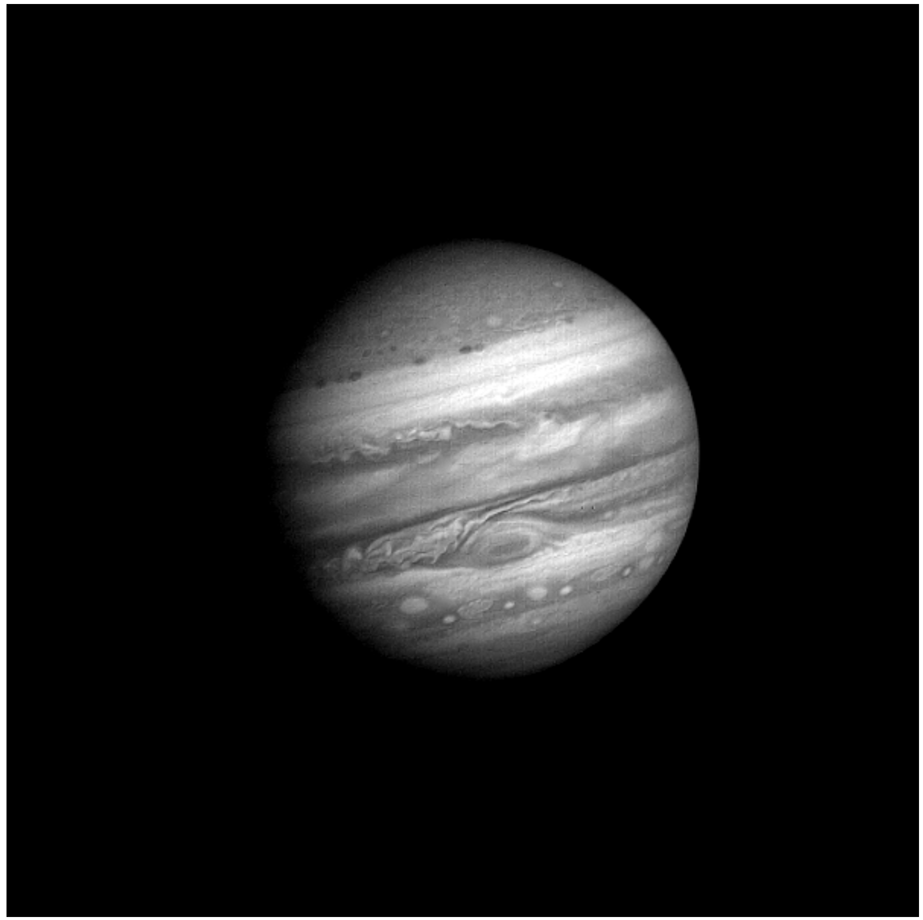
Clues from the Solar System



All planets orbit the Sun in approximately the same plane.

The easiest way to obtain this configuration is to suppose they formed in **a disk!**

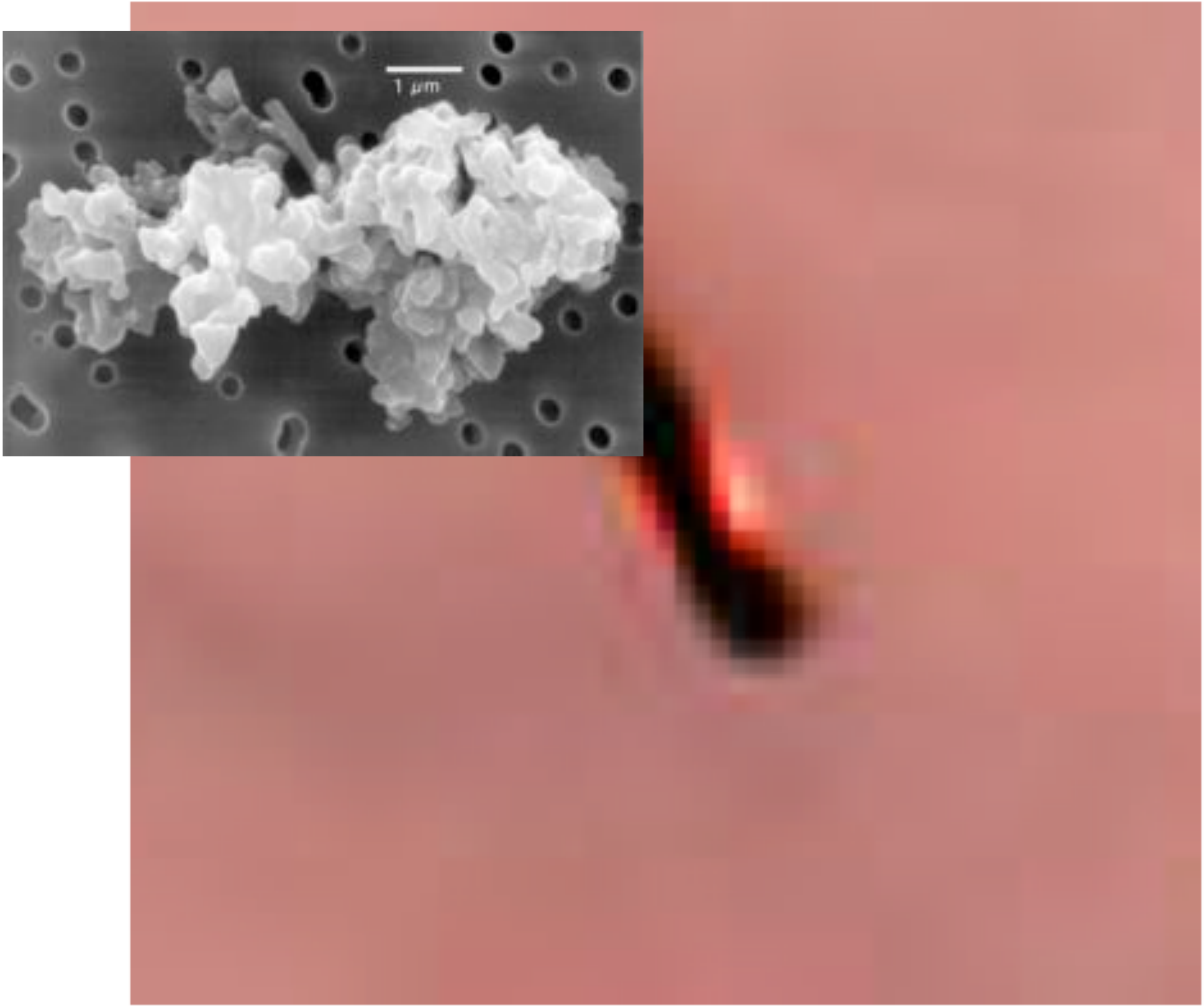
Clues from the Solar System



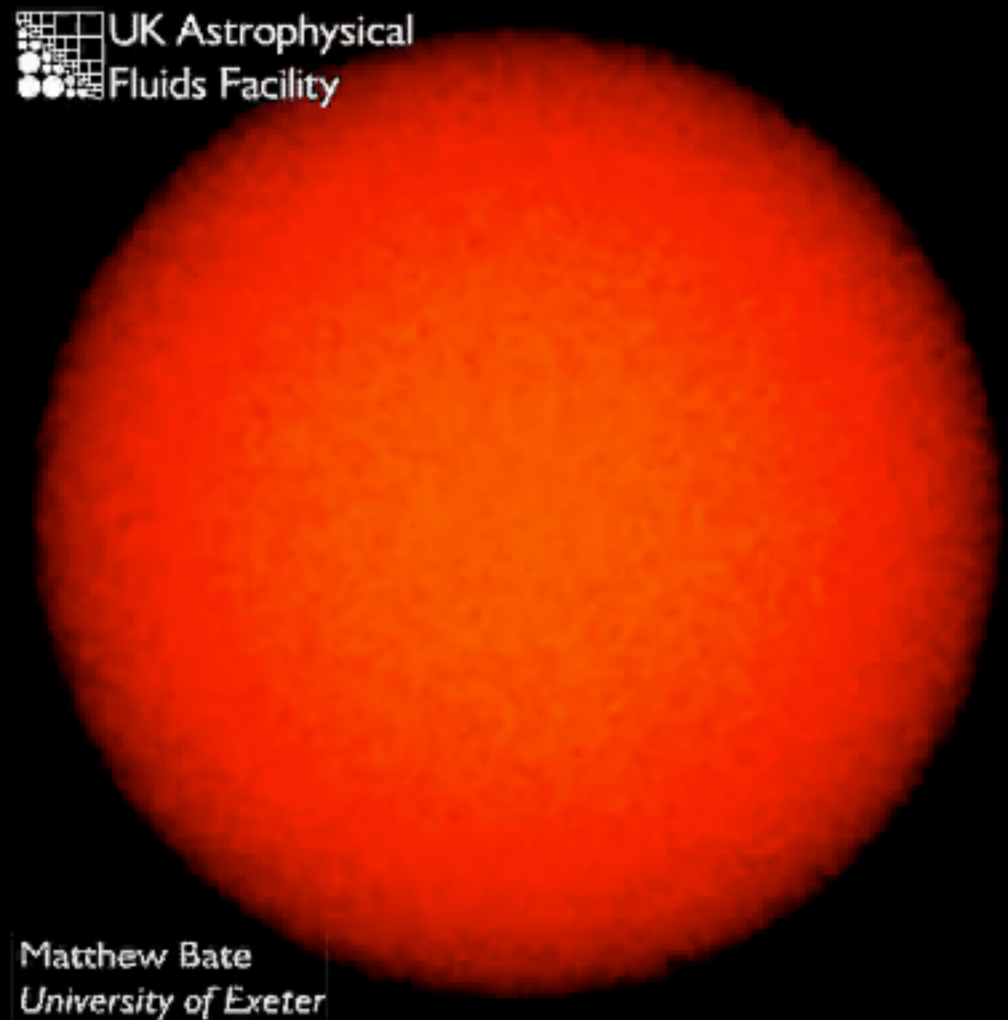
Because Jupiter is a gas giant, this disk must have been a disk of **gas**.

Clues from outside the Solar System. Looking for disks around young stars.

The Orion Nebula


1 μm

Star Formation



Stars are born with gas around them

Protoplanetary Disks

PP disk fact sheet

Density: $10^{13} – 10^{15}$ cm^{-3}
(Air: 10^{21} cm^{-3})

Temperature: 10-1000 K

Scale: 0.1-100AU
(1 AU = 1.49 x 10^{13} cm)

Mass: $10^{-3} – 10^{-1}$ M_{sun}
(1 M_{sun} = 2 x 10^{33} g)

The Minimum Mass Solar Nebula

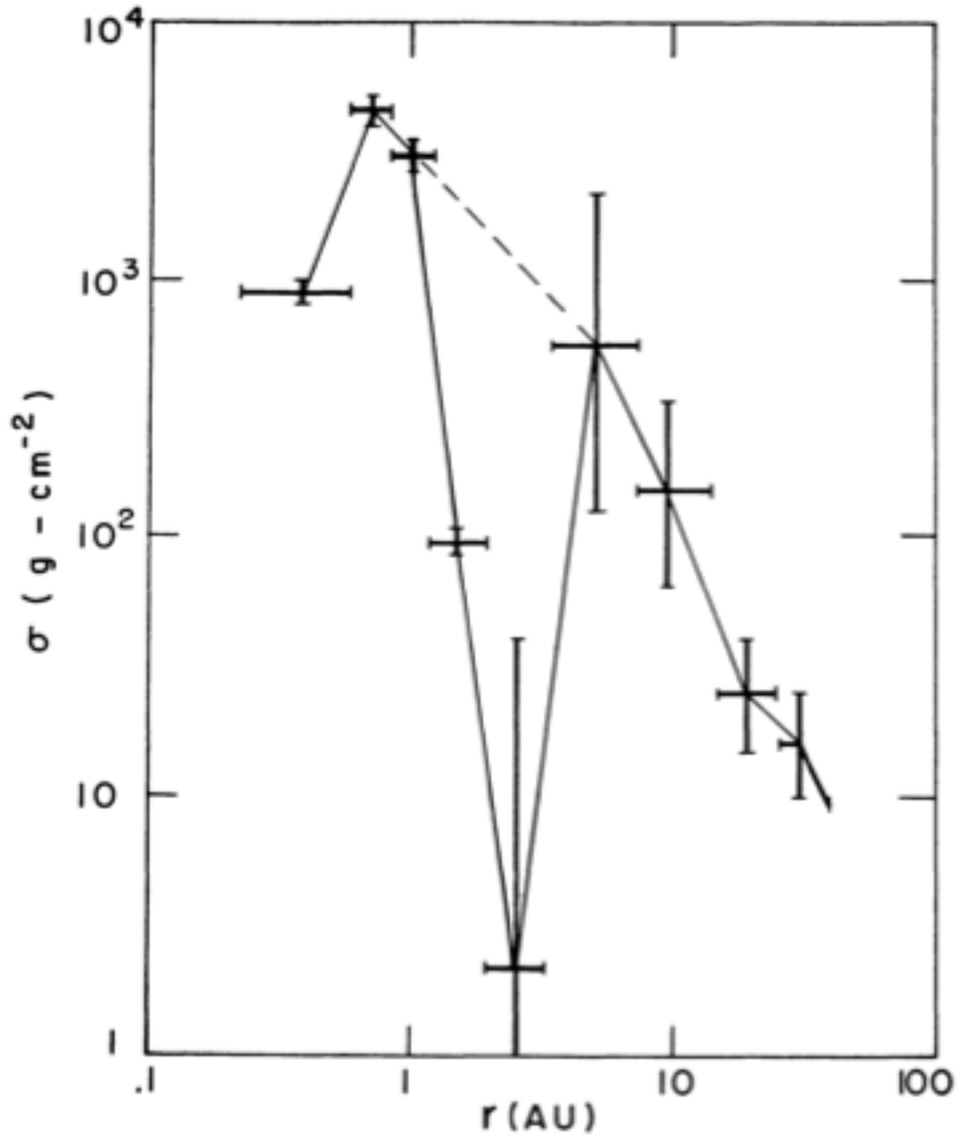


Fig. 1. Surface densities, σ, obtained by restoring the planets to solar composition and spreading the resulting masses through contiguous zones surrounding their orbits. The meaning of the 'error bars' is discussed in the text.

Distribute the mass of each planet in a ring around its orbit, then add hydrogen and helium until solar composition is reached.

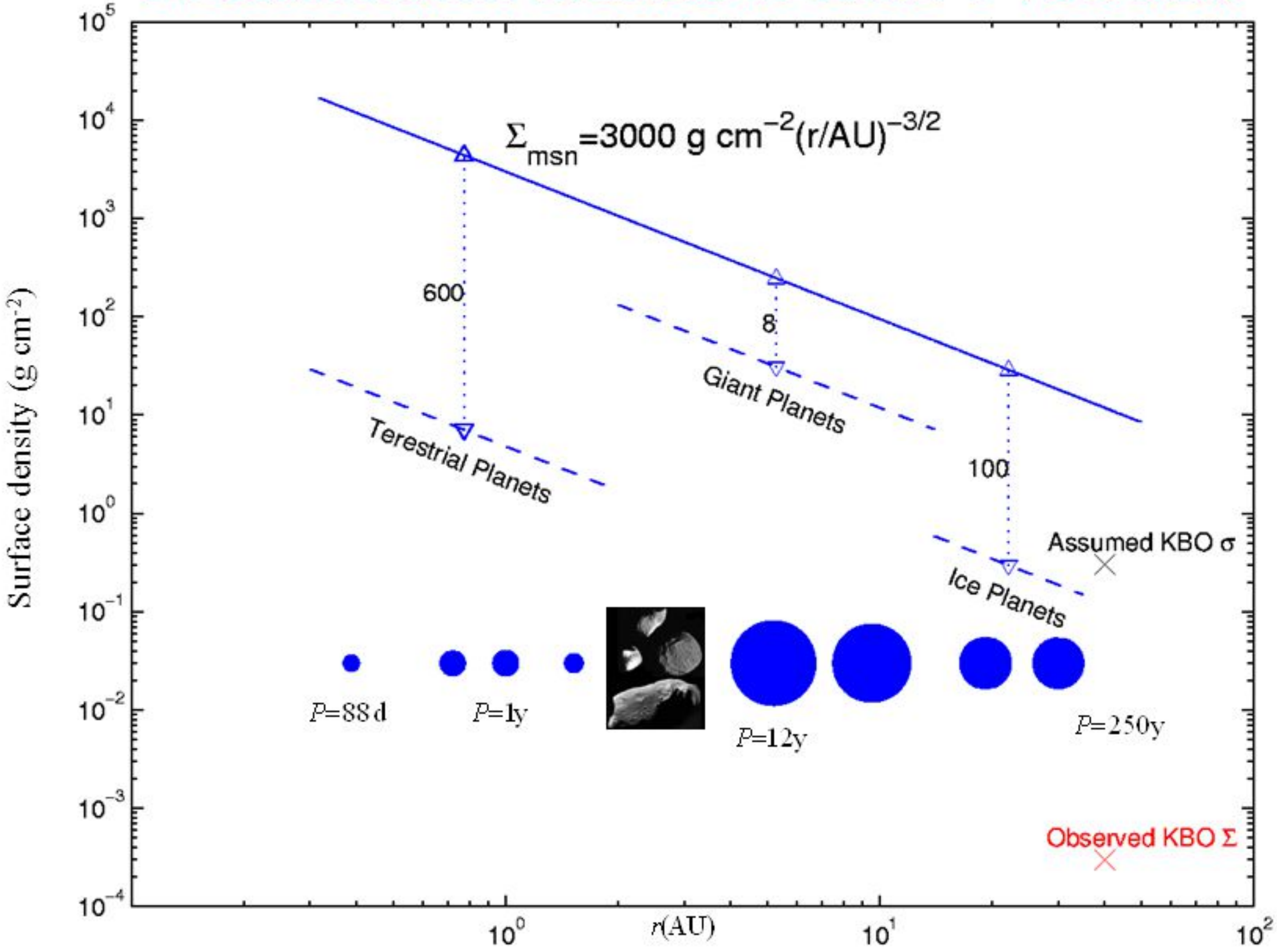
This creates a gas disk with a radial density gradient as shown in the plot.

This is the very minimum mass that the Solar Nebula must have had to form the planets.

We call it the Minimum Mass Solar Nebula.

(Weidenschilling 1977)

Minimum Mass Solar Nebula

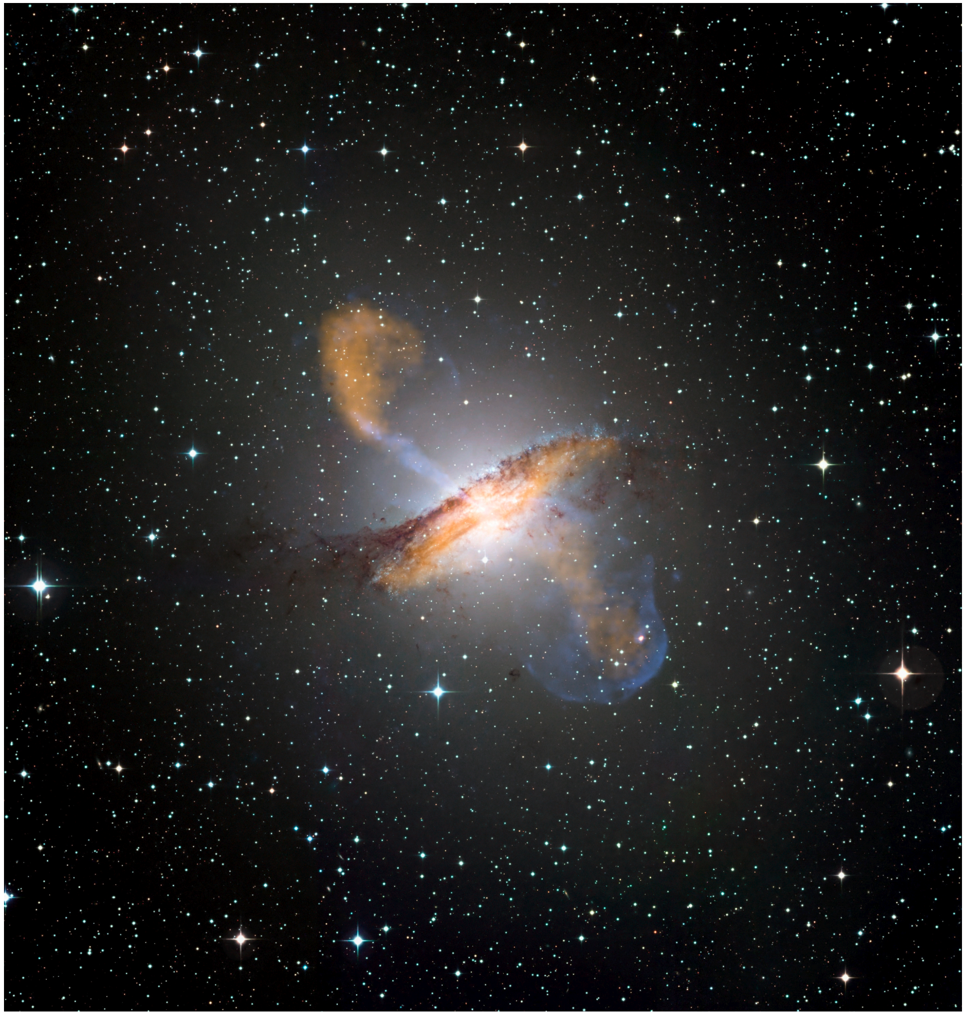


A more modern version of the same plot.
The numbers give the factor by which the mass has to be multiplied to achieve solar composition.

Scale invariance (nearly)

Disks are common in the Universe. The physics of protoplanetary disks shares similarities with **galaxies.**

Scale invariance (nearly)



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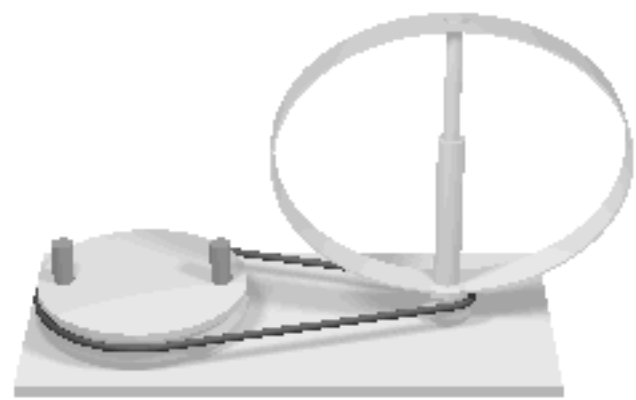
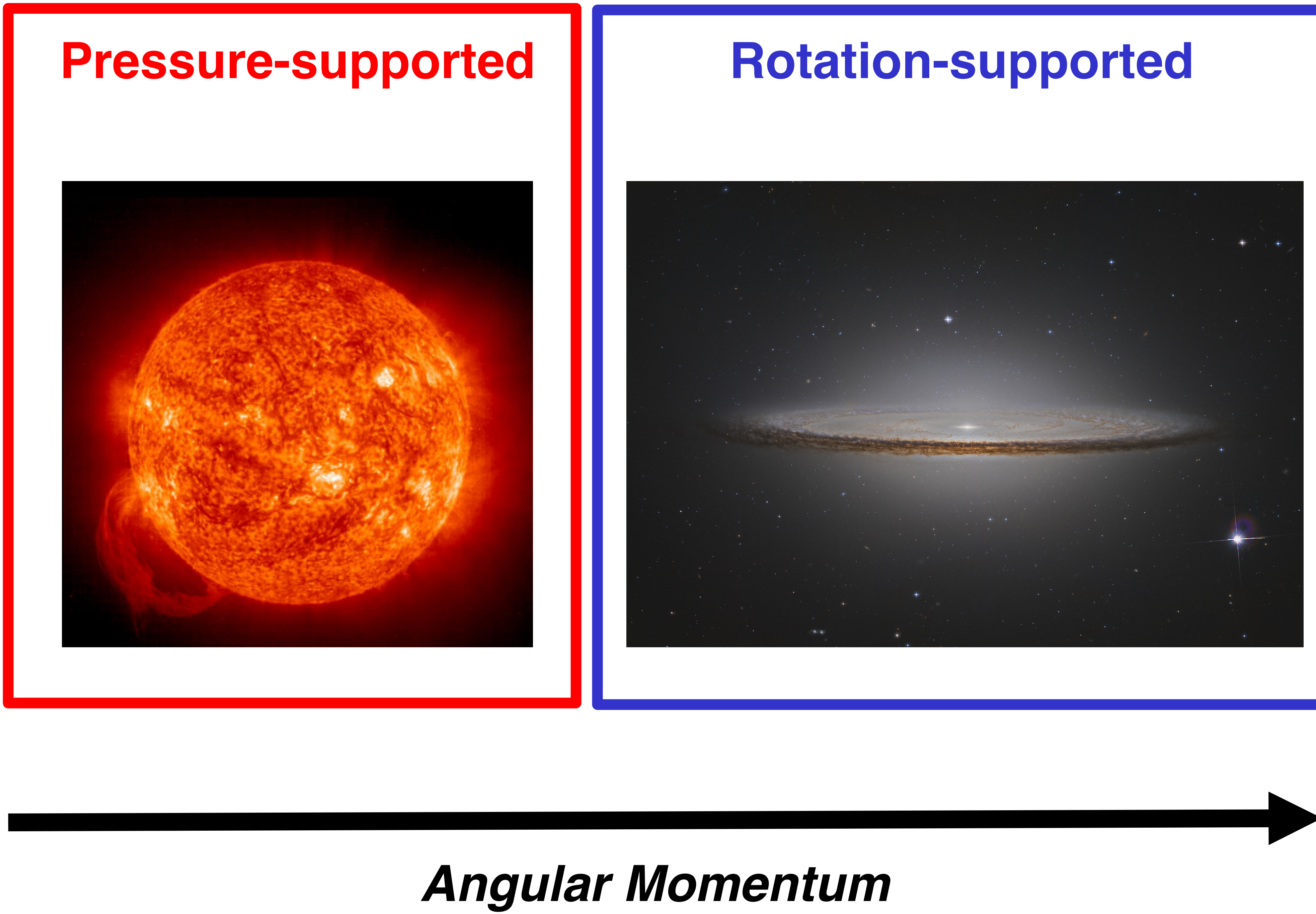
Centrifugal flattening



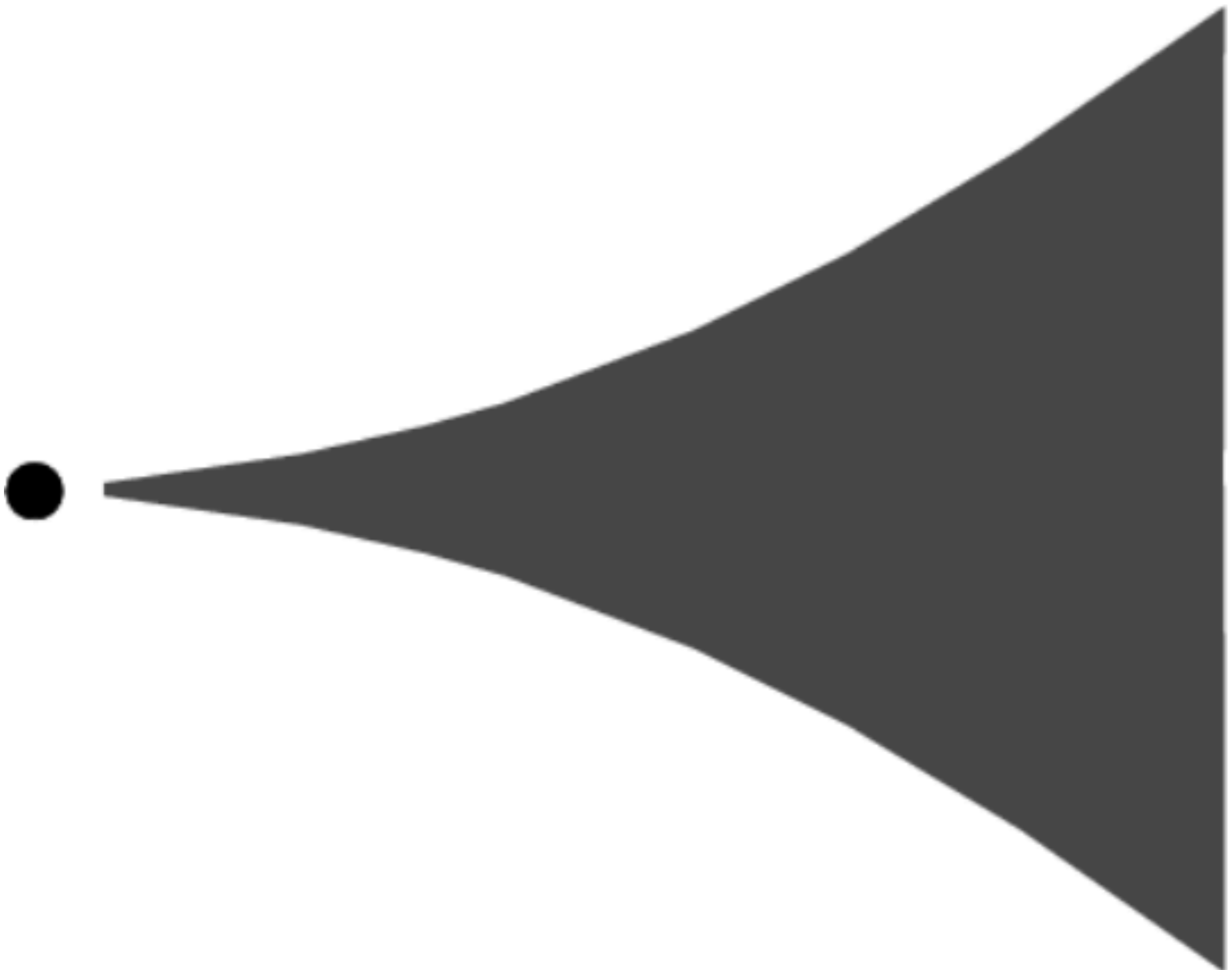
Gravity makes things spherical.
So what makes them “disky”?

The centrifugal force! (see notes)


Pressure-supported
Rotation-supported
Angular Momentum

Vertical structure: Hydrostatic Equilibrium

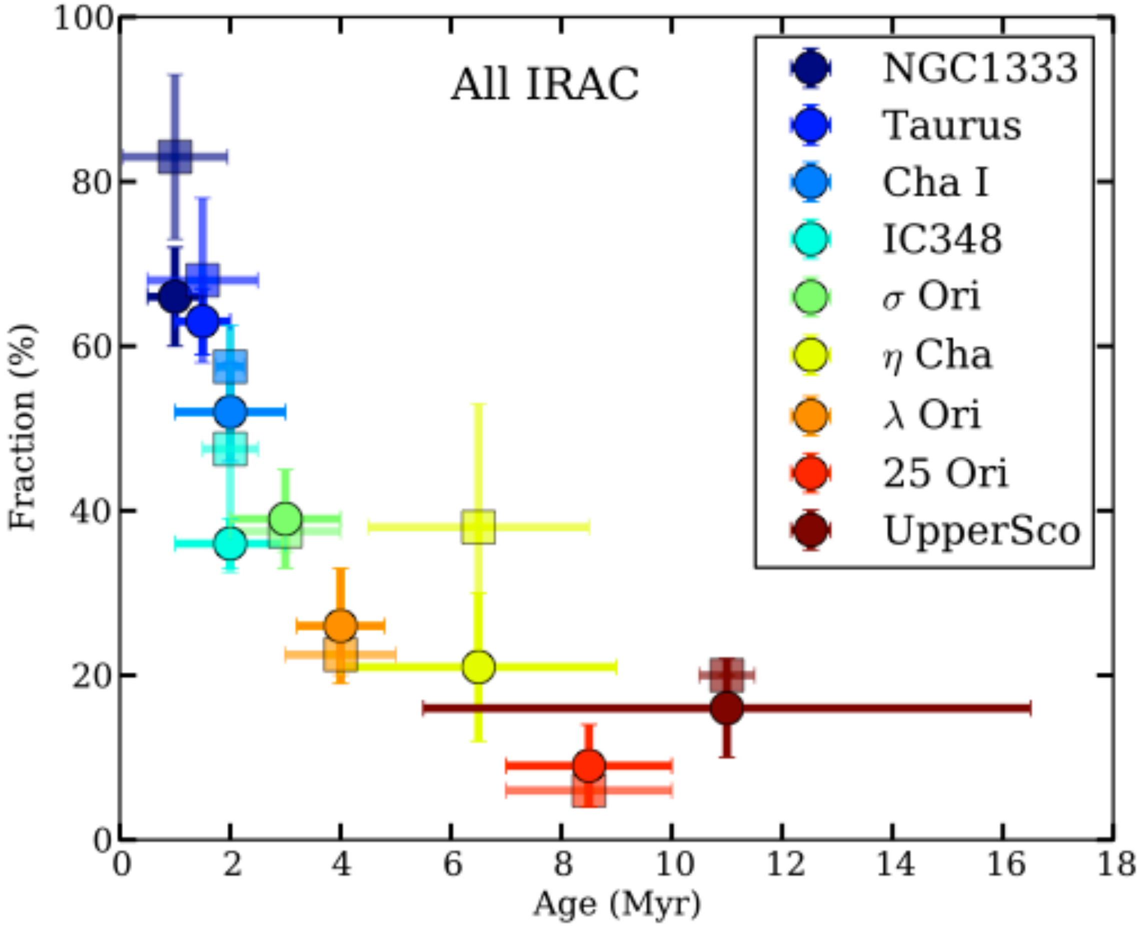
Disks are "flared"



$h \propto r^b; \quad b > 0$

The aspect ratio
H(R)/R
increases with
distance, giving the
disk a flared appearance.

Disk lifetime



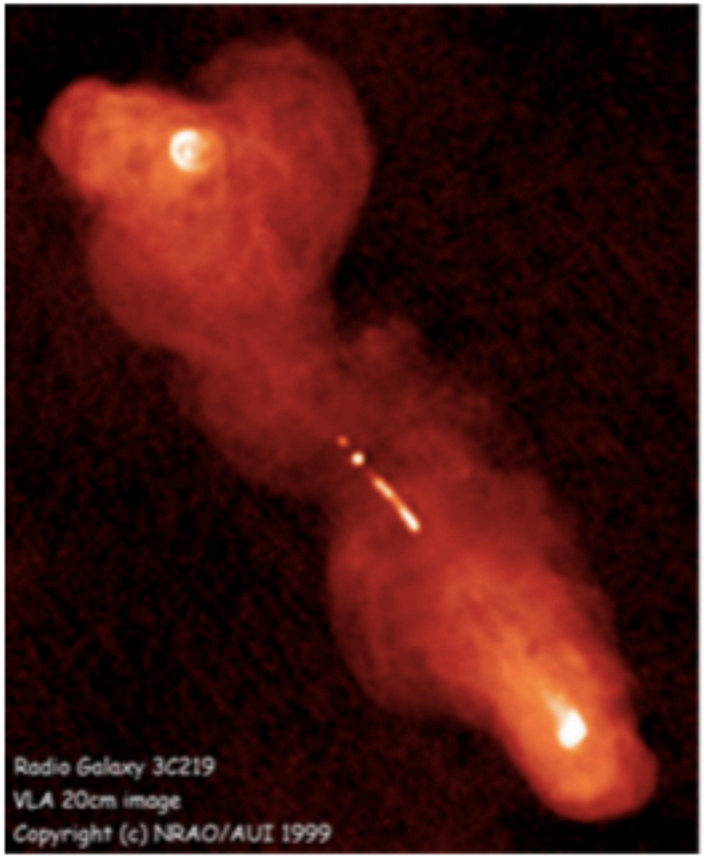
(Ribas et al. 2014)

Protoplanetary disks dissipate within ~10Myr.
A static description cannot be the full picture.
Disks must evolve in time.

Accretion

- The Royal Society for Putting Things on Top of Other Things

Accretion



300 Kp

Accretion onto a central compact object is believed to power some of the most energetic phenomena in the universe

Black hole accretion
(Lynden-Bell 1969)

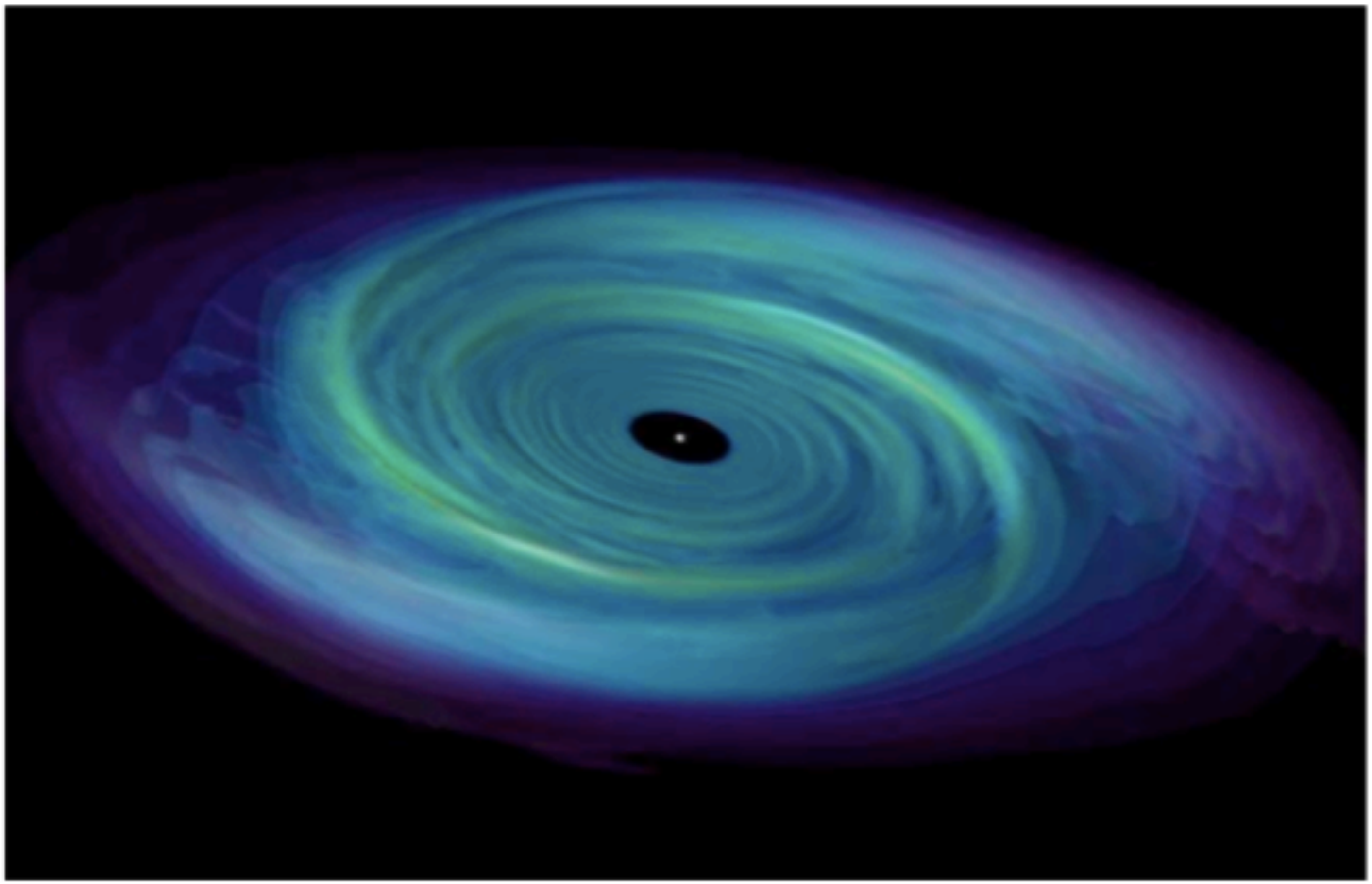
- **Central mass ~10^8-10^{10} M_{sun}**
- **Accretion rate ~1 M_{sun}/yr**
- **Total luminosity ~10^{47} L_{sun}**

"The central problem of nearly 30 years of accretion disk theory has been to understand how they accrete."

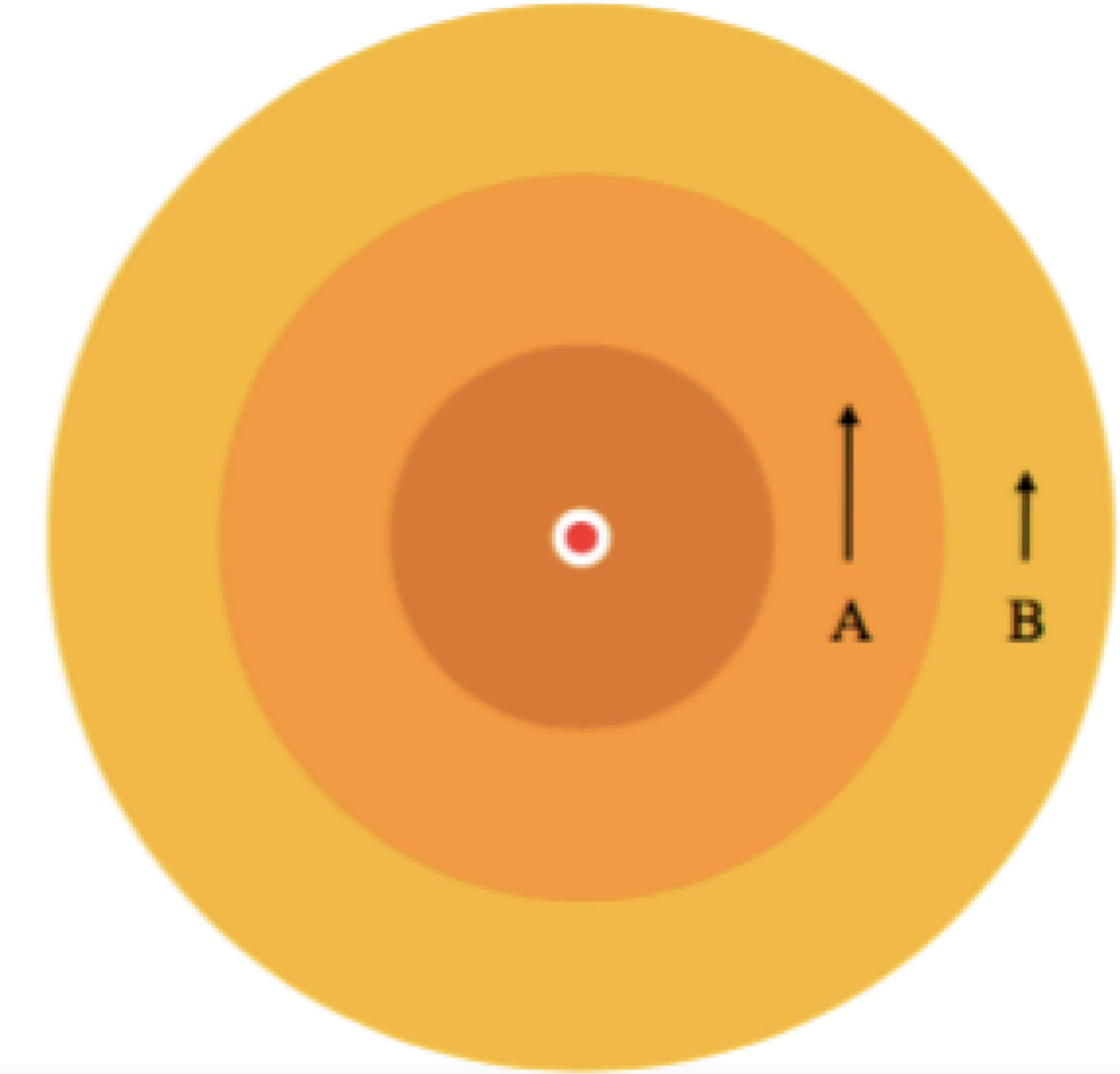
Balbus & Hawley (1998)

Angular momentum transport

- If angular momentum is conserved matter just orbits the central object
- Accretion rate is determined by the <u>outward</u> transport of angular momentum



Viscous friction:
Outward transport of angular momentum



Consider the disk as a series of concentric disks.

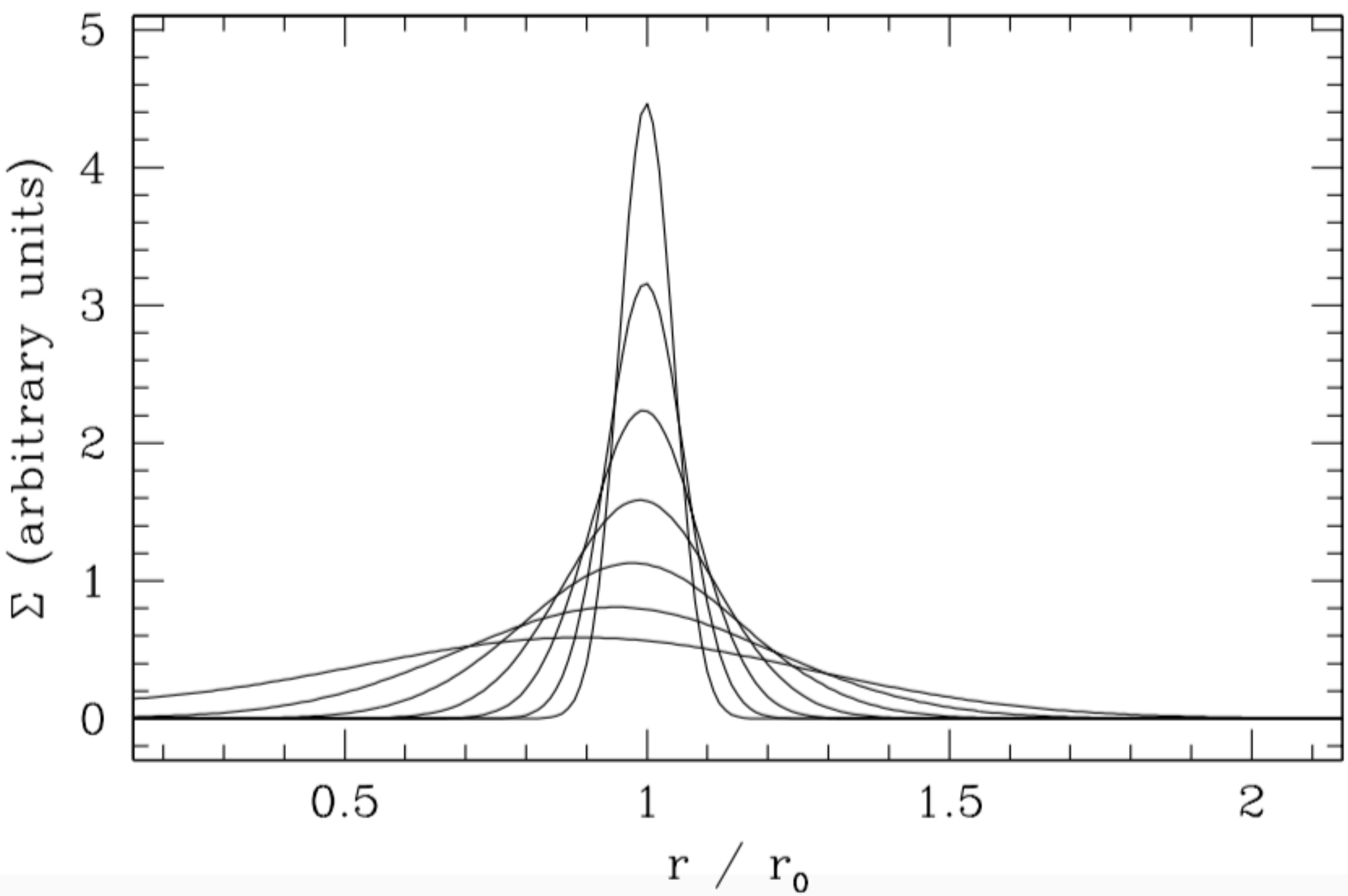
If there is friction between them, then ring A, that rotates faster than B, is slowed down.

As angular momentum is conserved, this momentum is transferred to B.

B would likewise transfer its momentum to a ring C. Eventually the outermost ring receives all the angular momentum, and all other rings move inwards.

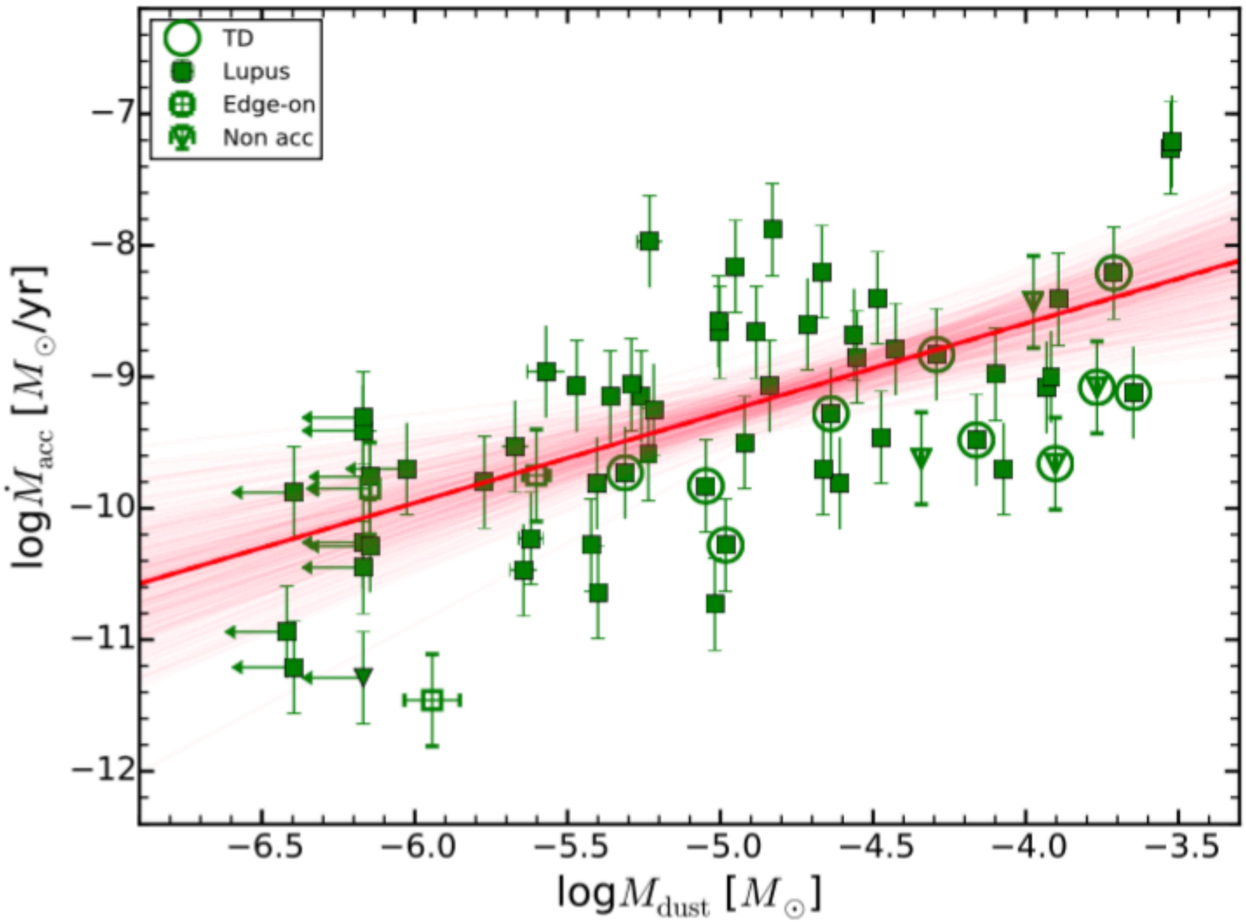
Analytical solution

$$\Sigma(x,\tau) = \frac{m}{\pi r_0^2}\frac{1}{\tau}x^{-1/4}\exp\left[-\frac{(1+x^2)}{\tau}\right]I_{1/4}\left(\frac{2x}{\tau}\right)$$



Initial condition: Dirac Delta.
A negligible amount of matter flows outwards, carrying the angular momentum.

Mass Accretion Rates



We can compare the viscous solution

$$dM/dt = 3\,\pi\,\nu\,\Sigma$$

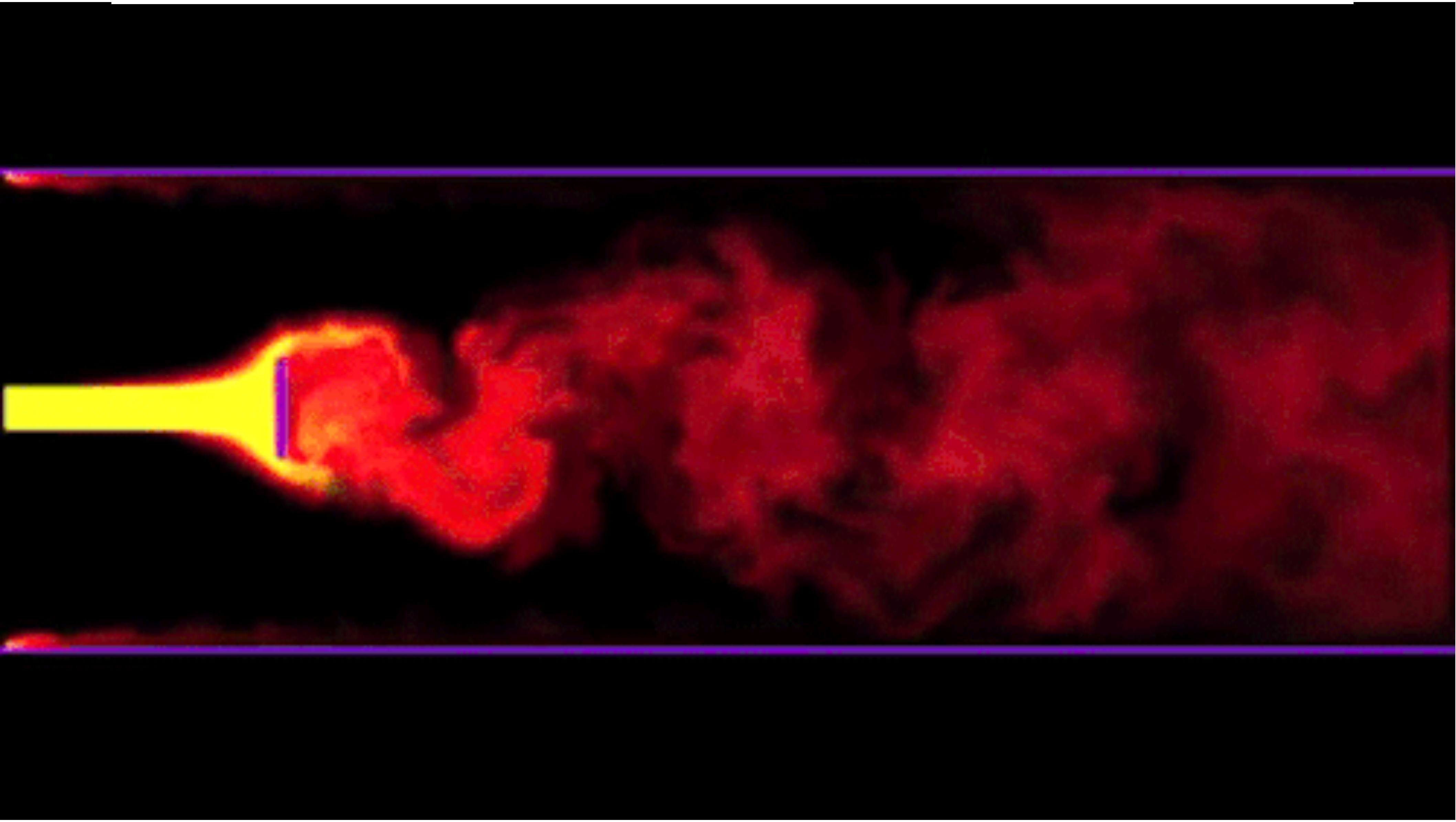
with observations. A young disk Of mass $M_{dust}=10^{-4}$-10^{-3} ($M_{gas} \sim 10^{-2}$-10^{-1}) should accrete at the rate of 10^{-8} Msun/yr, which for MMSN densities means a viscosity of $10^{14} - 10^{15}$ cm^2/s.

Molecular viscosity only yields about 10^7 cm^2/s.

Discrepancy of seven orders of magnitude!!

The Shakura-Sunyaev model 1973

Next class: Turbulence leads to viscous-like behavior



State Prize of the Russian Federation in Science and Technology 2017