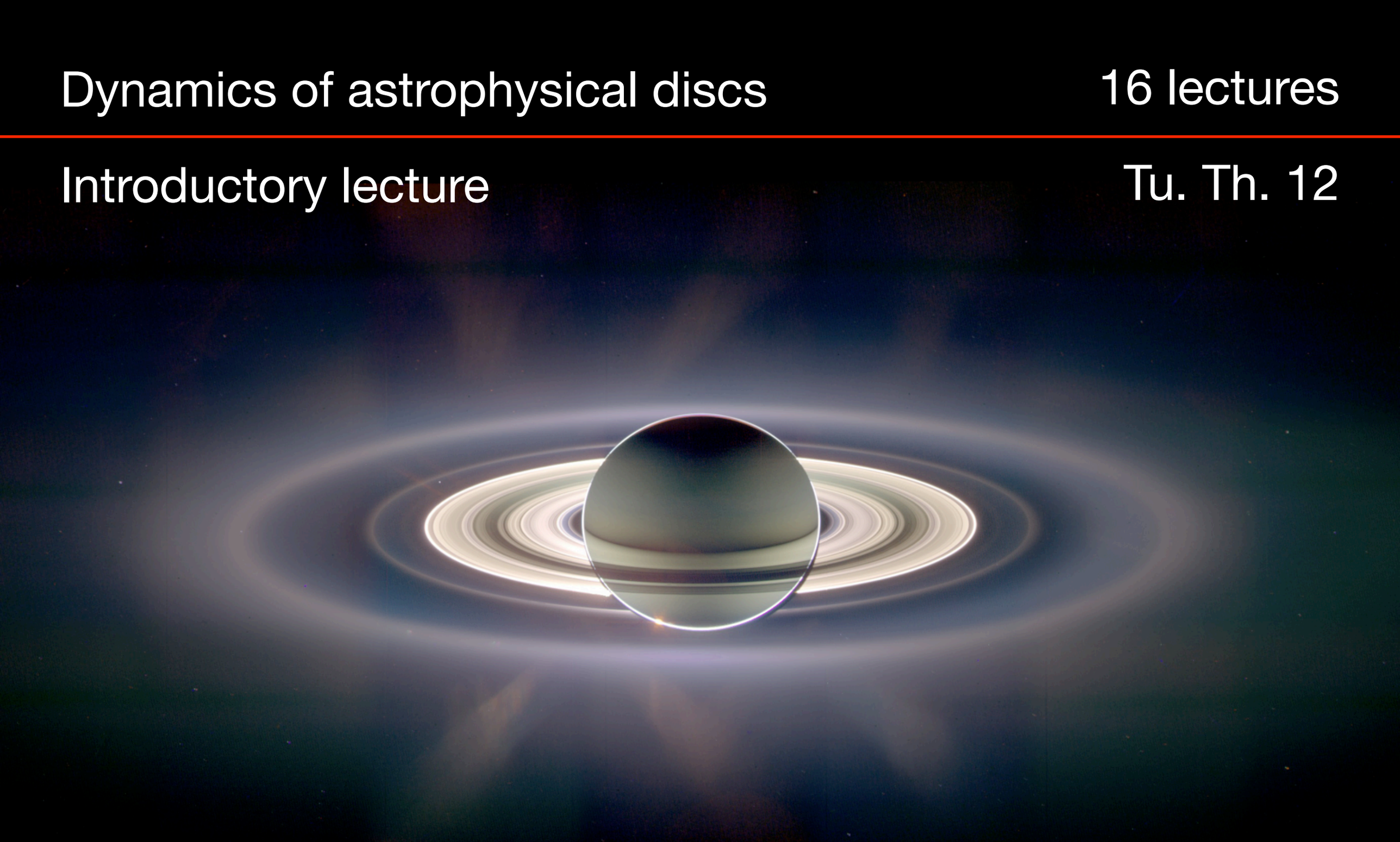
Dynamics of astrophysical discs

16 lectures

Introductory lecture

Tu. Th. 12



Professor Gordon Ogilvie

DAMTP F1.02

Part III Mathematics 2019–20

gio10@cam

Provisional synopsis

- Occurrence of discs, physical and observational properties
- Orbital dynamics, mechanics of accretion
- Global and local views
- Evolution of an accretion disc
- Vertical disc structure, timescales
- Thermal / viscous instability and outbursts
- Hydrodynamic waves and instabilities
- Vortices, zonal flows and dust dynamics
- Satellite–disc interaction
- Magnetic fields and magnetorotational instability

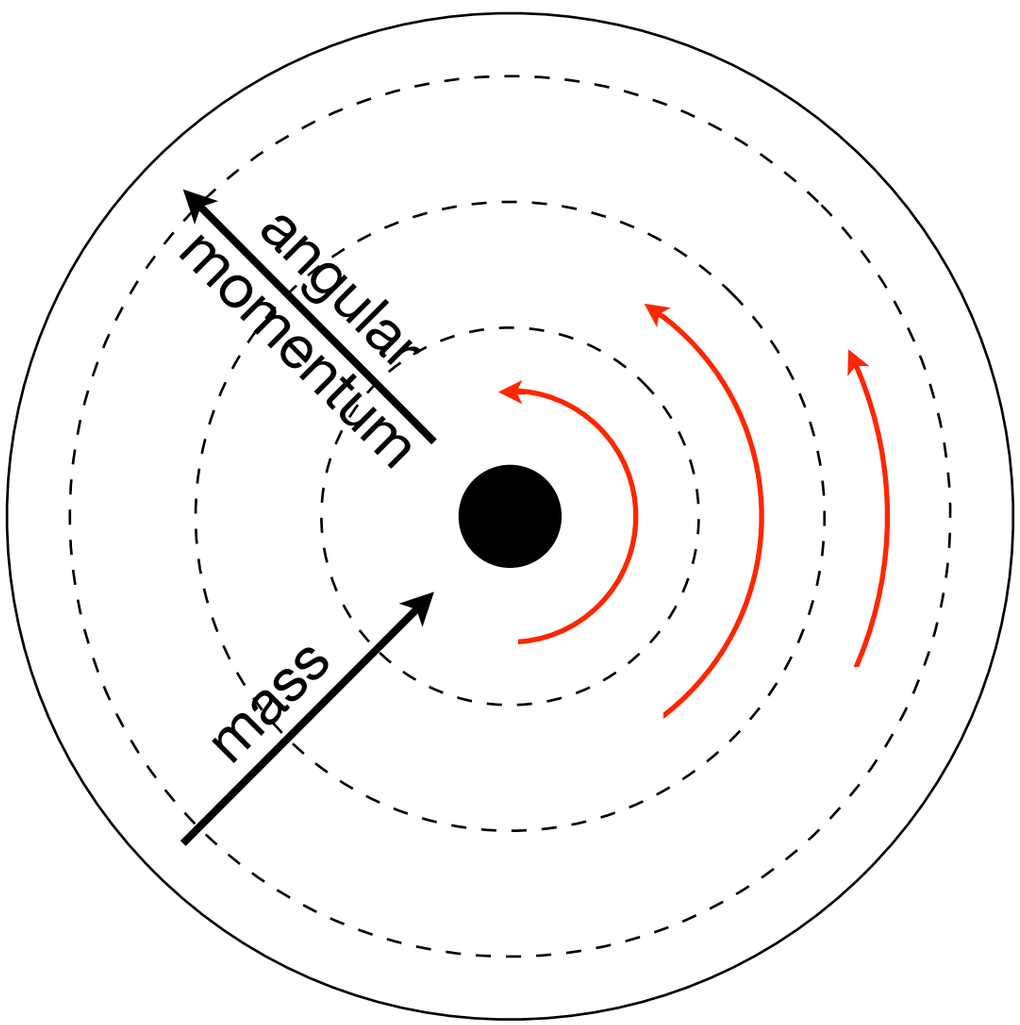
Plus 3 example sheets and classes

(Wed 12 Feb, 26 Feb, 11 Mar, 2:00–3:30 pm, room TBC)

Astrophysical discs

Continuous medium in orbital motion around a massive central body

orbital dynamics / celestial mechanics ⇔ fluid dynamics / continuum mechanics



- Usually circular, coplanar and thin
- Usually Keplerian (dominated by gravity of central mass)

$$\Omega = \left(\frac{GM}{r^3}\right)^{1/2}$$

- Shearing, dissipative systems
- Accretion disc (angular momentum out, mass in, energy liberated)

Occurrence of discs

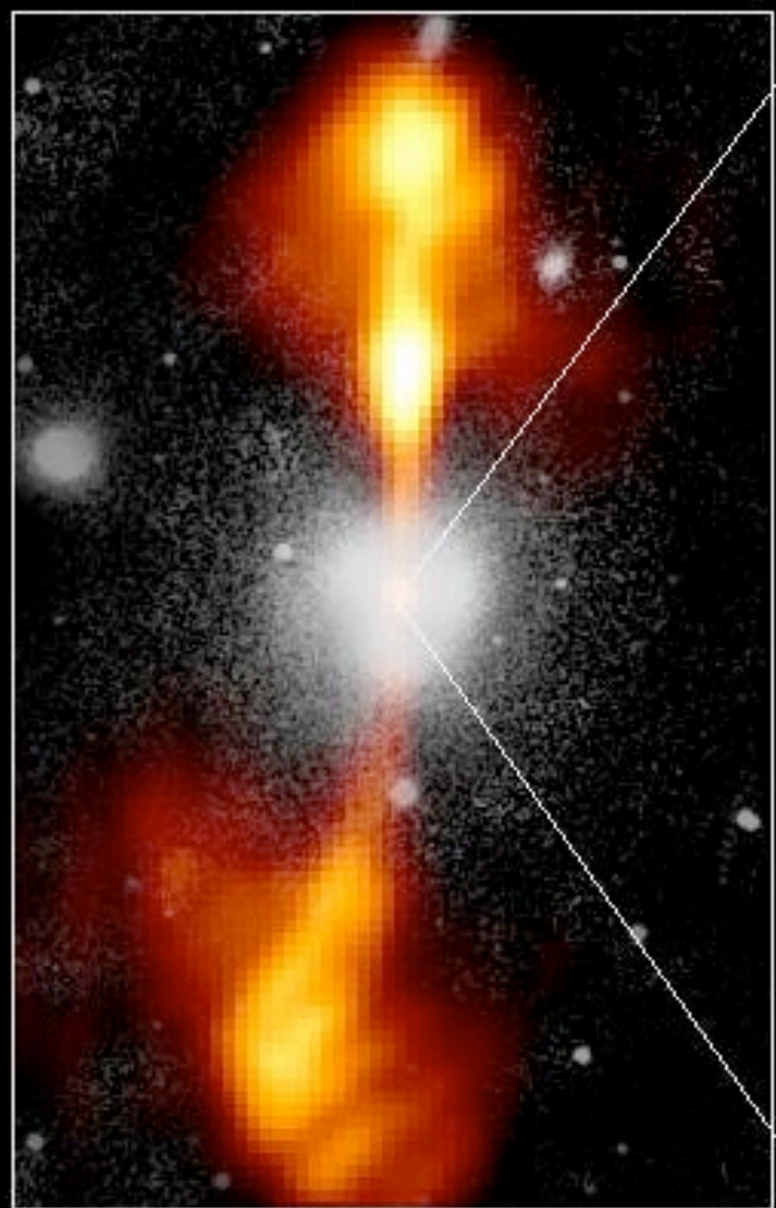
- Spiral galaxies (different : dark matter, stars, time-scales)
- Active galactic nuclei, quasars
- Interacting binary stars
- Protostellar / protoplanetary discs, solar nebula
- Planetary rings, circumplanetary discs
- Debris discs (main-sequence stars and white dwarfs)
- Very rapidly rotating stars (Be stars)
- Exotica : supernovae, kilonovae, ...

Core of Galaxy NGC 4261

Hubble Space Telescope

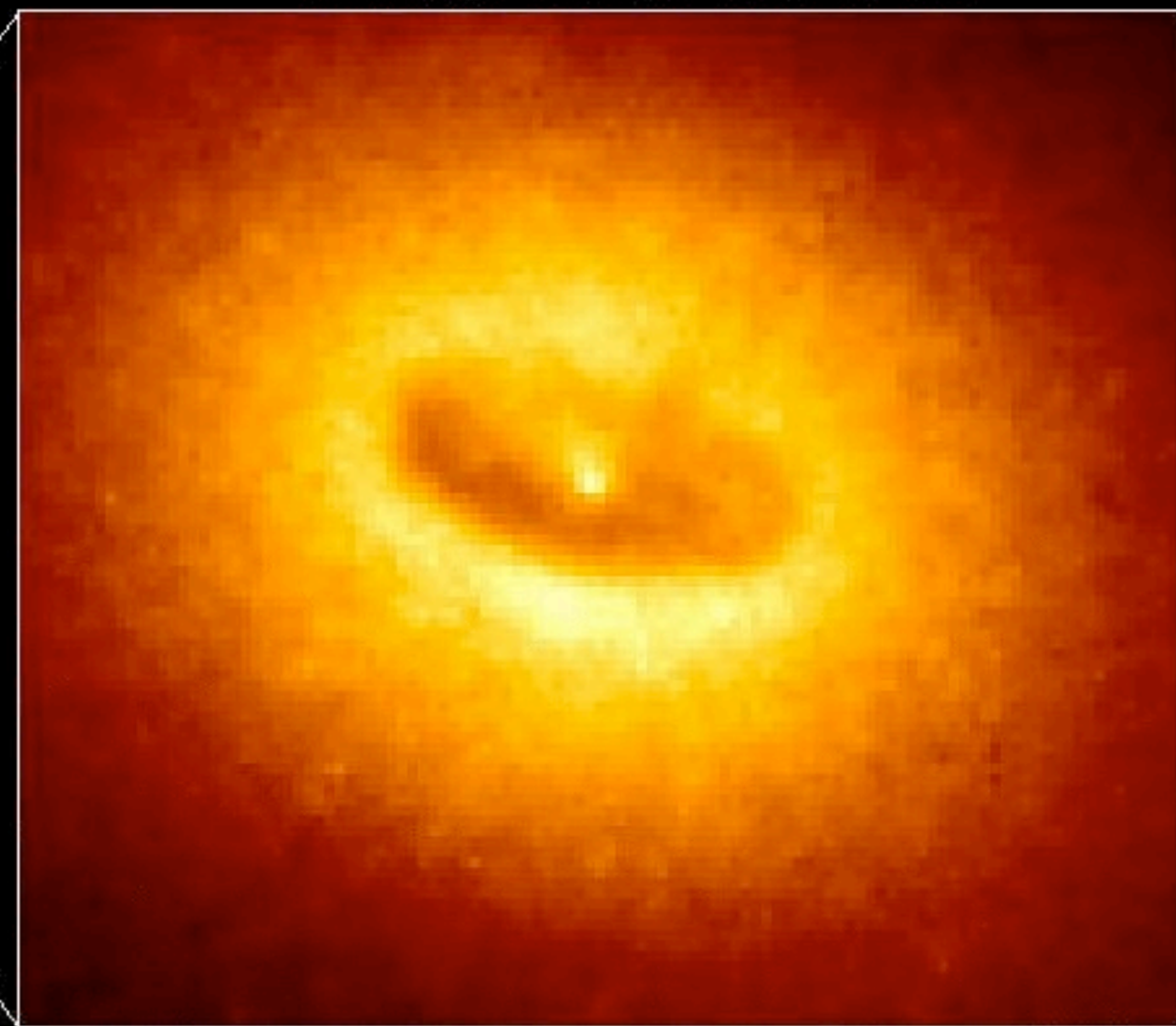
Wide Field / Planetary Camera

Ground-Based Optical/Radio Image

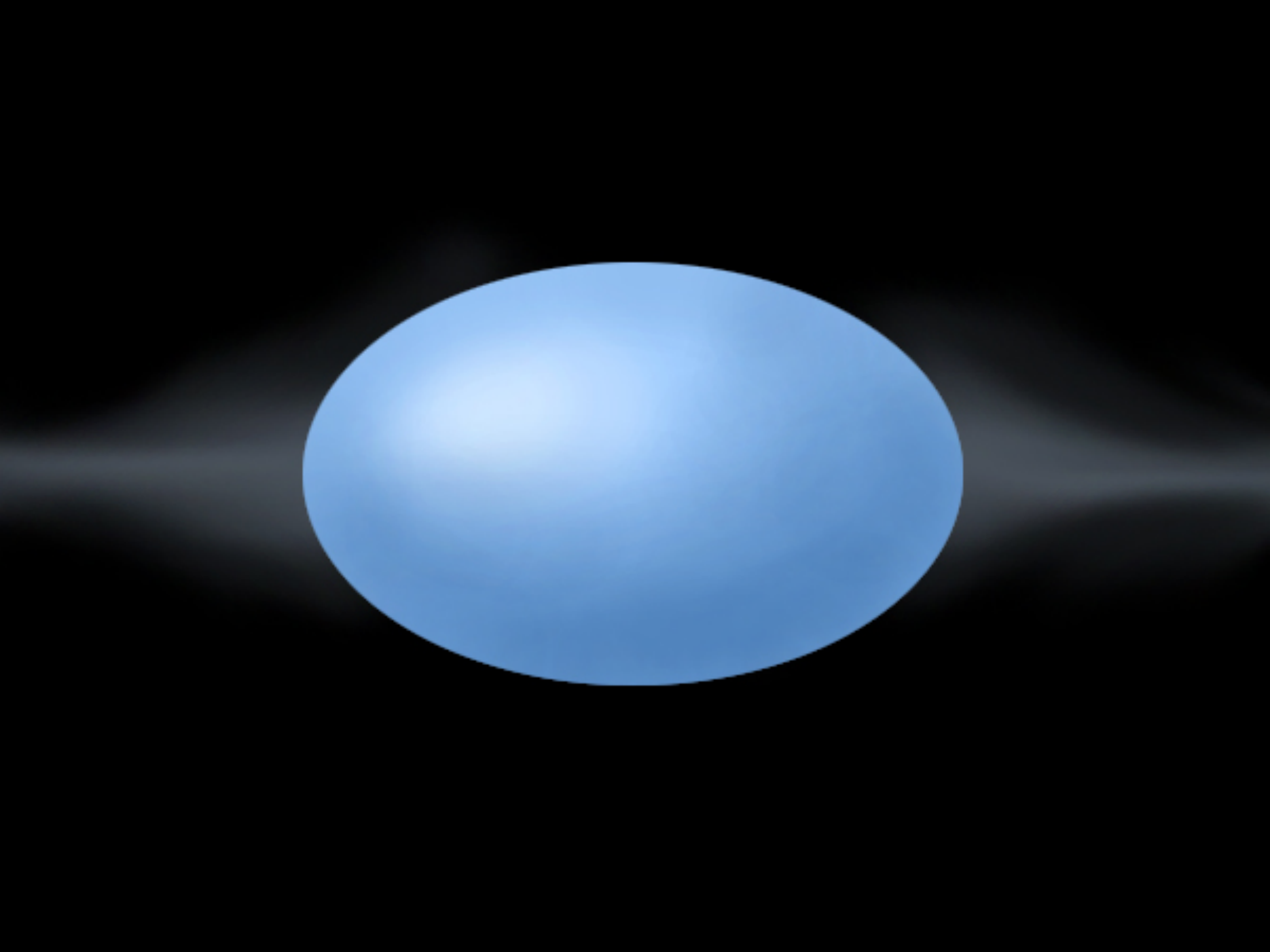


380 Arc Seconds
88,000 LIGHT-YEARS

HST Image of a Gas and Dust Disk

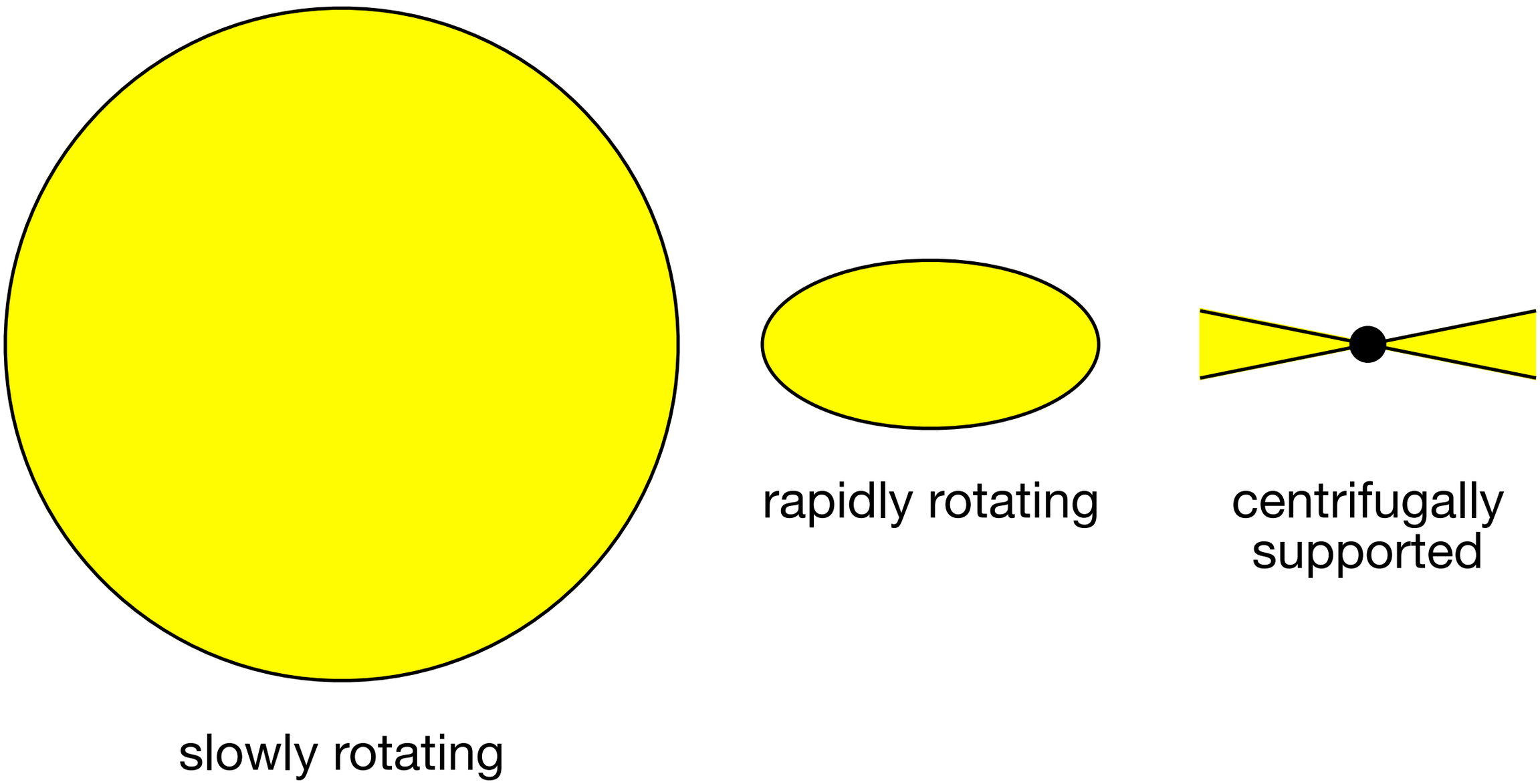


1.7 Arc Seconds
400 LIGHT-YEARS



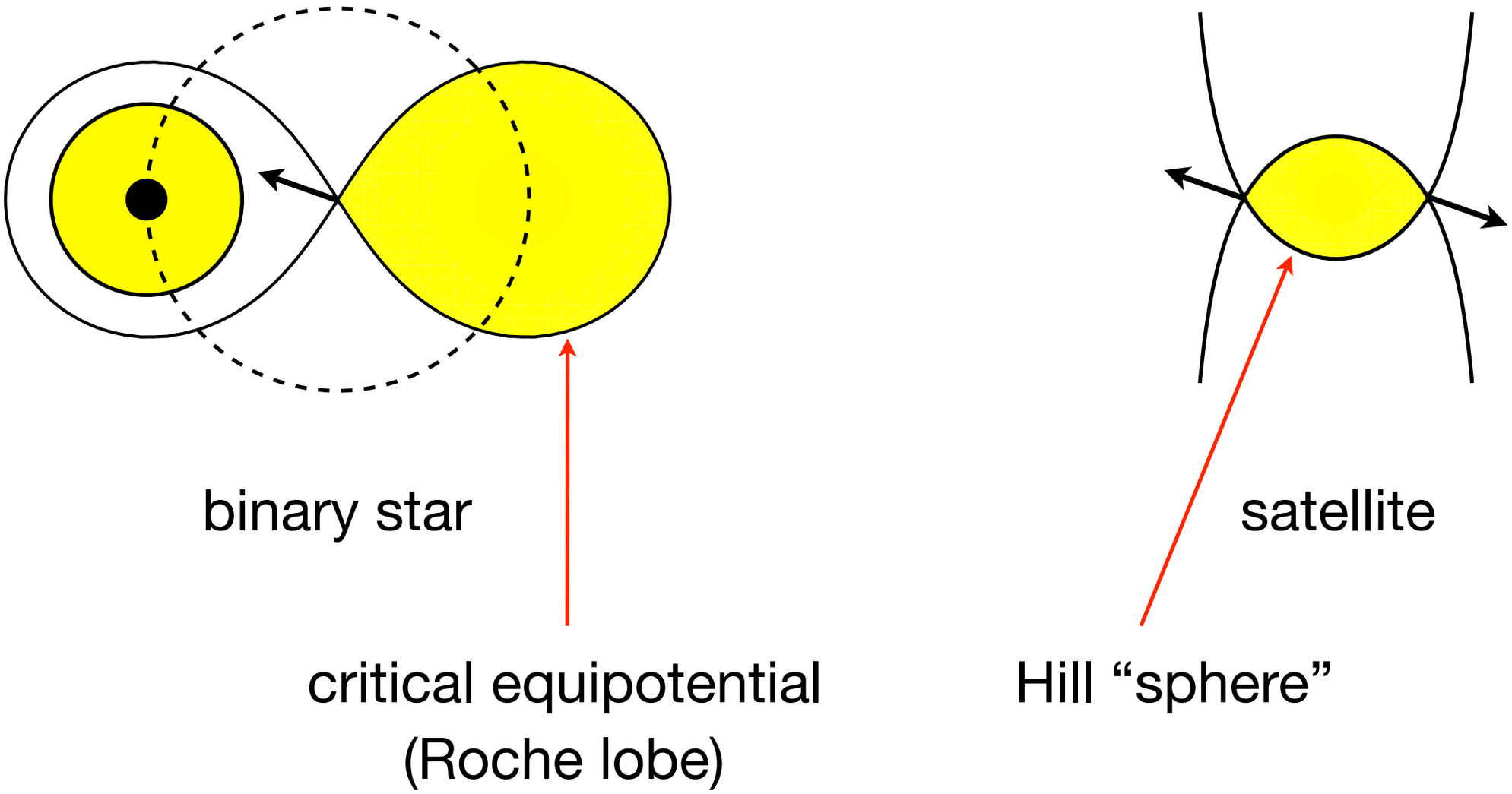
Formation of discs

- Collapse of rotating cloud (e.g. star formation)



Formation of discs

- Mass transfer / tidal disruption / merger



- Other scenarios : captured stellar winds, stellar pulsations, ...

Physical composition

- Weakly ionized H / H_2 gas + solid particles (protoplanetary discs)
  aspect ratio $H/R \lesssim 0.1$, temperature $10\,\mathrm{K} \lesssim T \lesssim 10^3\,\mathrm{K}$
- Dense H / He plasma (interacting binary stars, AGN)
  aspect ratio $H/R \lesssim 0.03$, temperature $10^3\,\mathrm{K} \lesssim T \lesssim 10^7\,\mathrm{K}$
- Nuclear matter (exotica)
- Metre-sized iceballs (dense planetary rings)
  aspect ratio $H/R \sim 10^{-7}$, random velocity $\sim \mathrm{mm\,s^{-1}}$
- Dilute plasma (some cases of black-hole accretion flows)

Relevant descriptions :

- Gas dynamics
- Magnetohydrodynamics
- Kinetic theory

[+ relativity
+ radiation forces
where needed]

Characteristic length-scales and orbital periods

- Planetary ring : $r \sim 10^5\,\mathrm{km},\ t \sim 10\,\mathrm{hr}$
- Protoplanetary disc : $r_{\mathrm{out}} \sim 100\,\mathrm{AU},\ t_{\mathrm{out}} \sim 1000\,\mathrm{yr}$

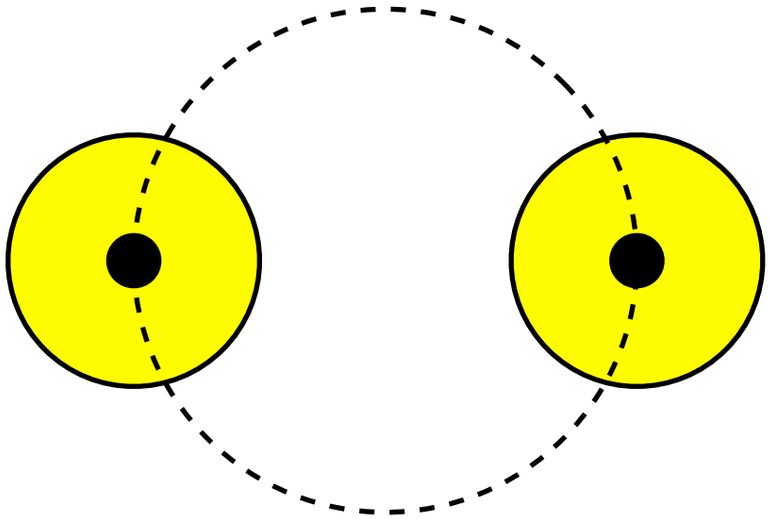
  $r_{\mathrm{in}} \sim 0.1\,\mathrm{AU},\ t_{\mathrm{in}} \sim 10\,\mathrm{day}$
- X-ray binary star : $r_{\mathrm{out}} \sim R_\odot,\ t_{\mathrm{out}} \sim \mathrm{hr} - \mathrm{day}$

  $r_{\mathrm{in}} \sim 10\,\mathrm{km},\ t_{\mathrm{in}} \sim 10^{-3}\,\mathrm{s}$
- AGN : $r_{\mathrm{out}} \sim 0.1\,\mathrm{pc},\ t_{\mathrm{out}} \sim 1000\,\mathrm{yr}$

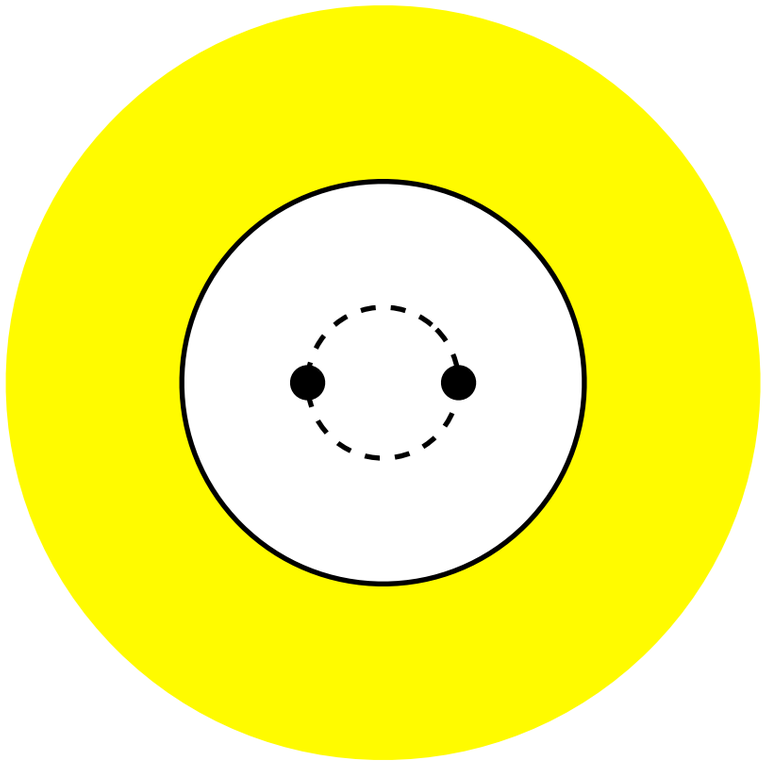
  $r_{\mathrm{in}} \sim \mathrm{AU},\ t_{\mathrm{in}} \sim \mathrm{hr}$

- Parsec $\mathrm{pc} = 3.086 \times 10^{18}\,\mathrm{cm}$
- Astronomical unit $\mathrm{AU} = 1.496 \times 10^{13}\,\mathrm{cm}$
- Solar radius $R_\odot = 6.960 \times 10^{10}\,\mathrm{cm}$

Configurations : binary stars

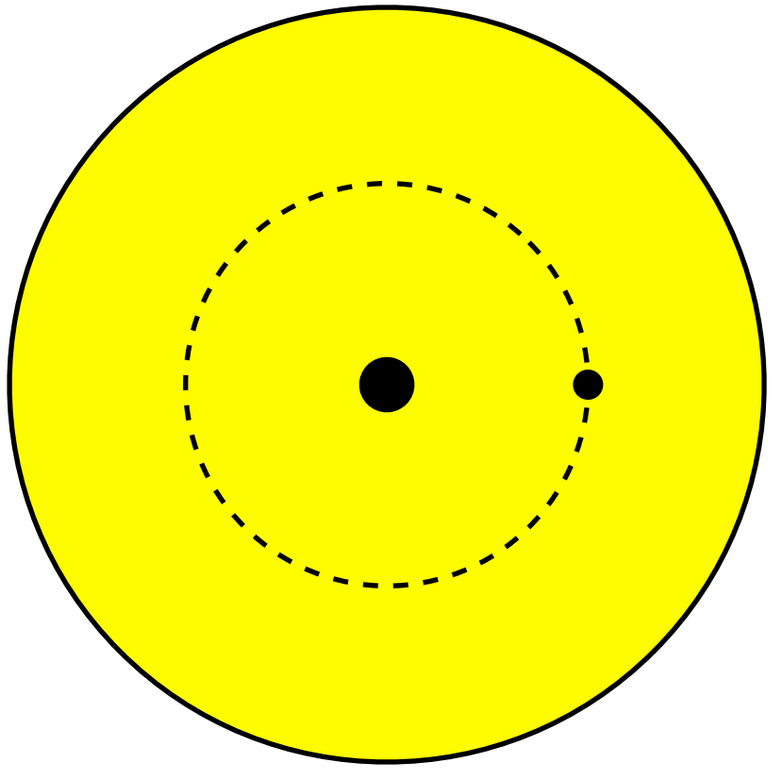


circumstellar disc(s)

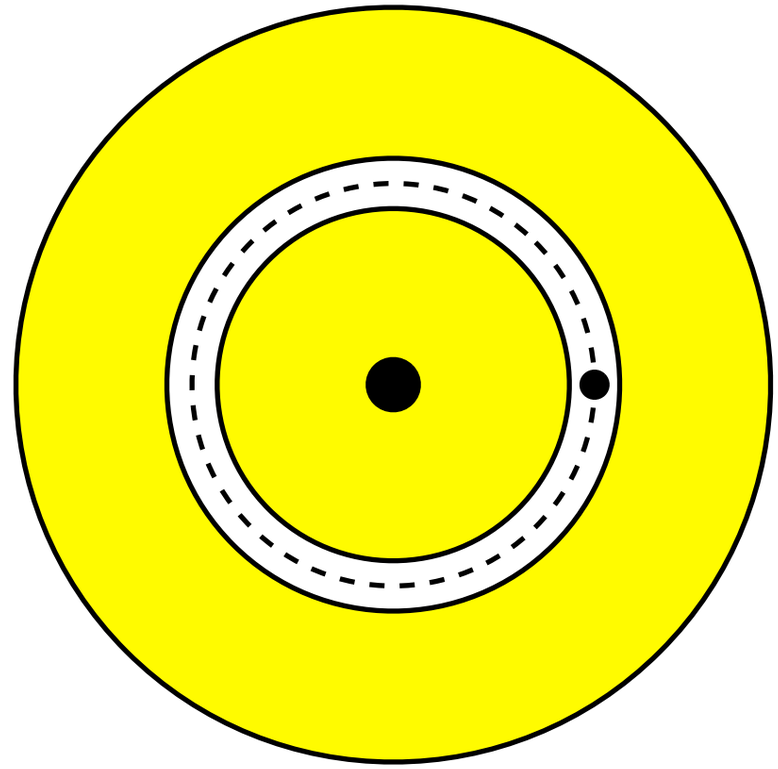


circumbinary disc

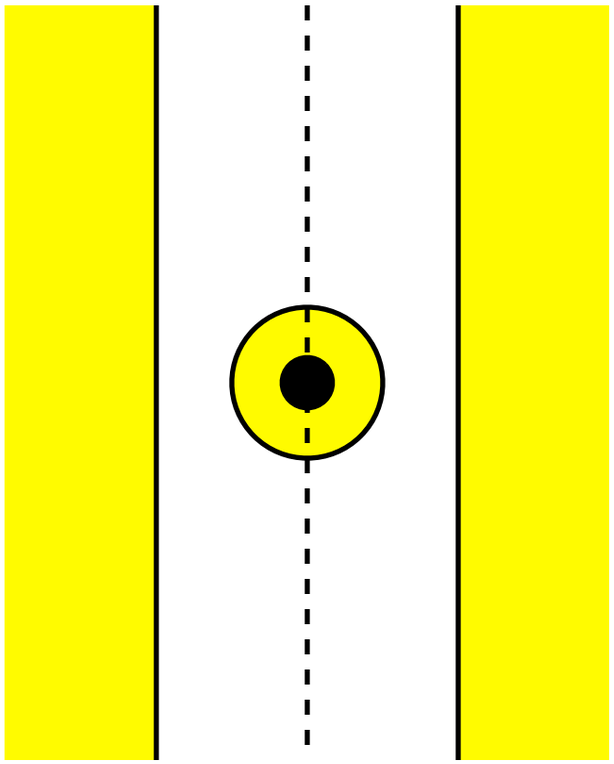
Configurations : protoplanetary systems



embedded planet



gap-opening planet
interior + exterior discs

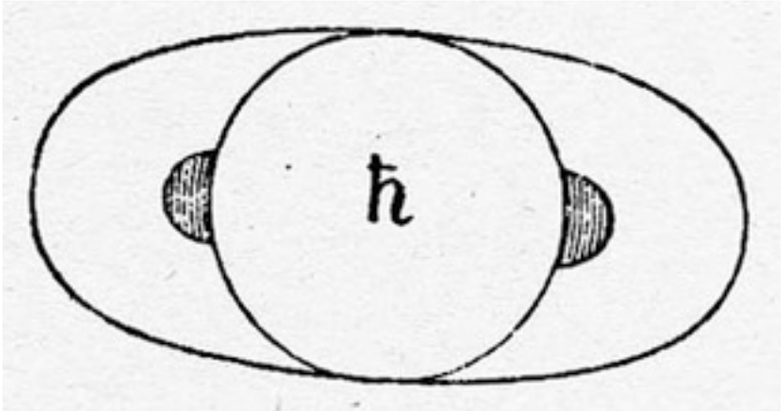


circumplanetary disc

Observations : Saturn's rings

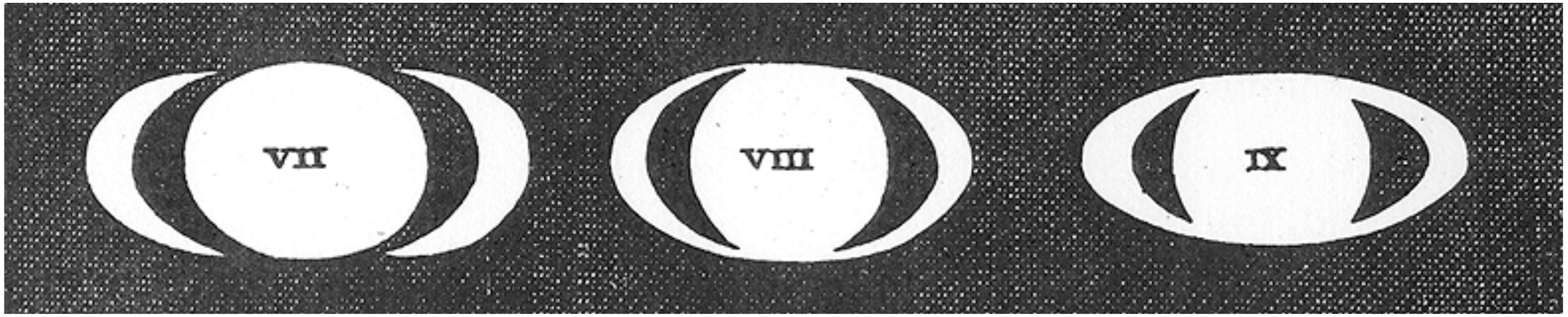
- Galileo (1610)

SMAISMRMILMEPOETALEUMIBUNENUGTTAUIRAS
ALTISSIMUM PLANETAM TERGEMINUM OBSERVAVI
I have observed the most distant planet to have a triple form



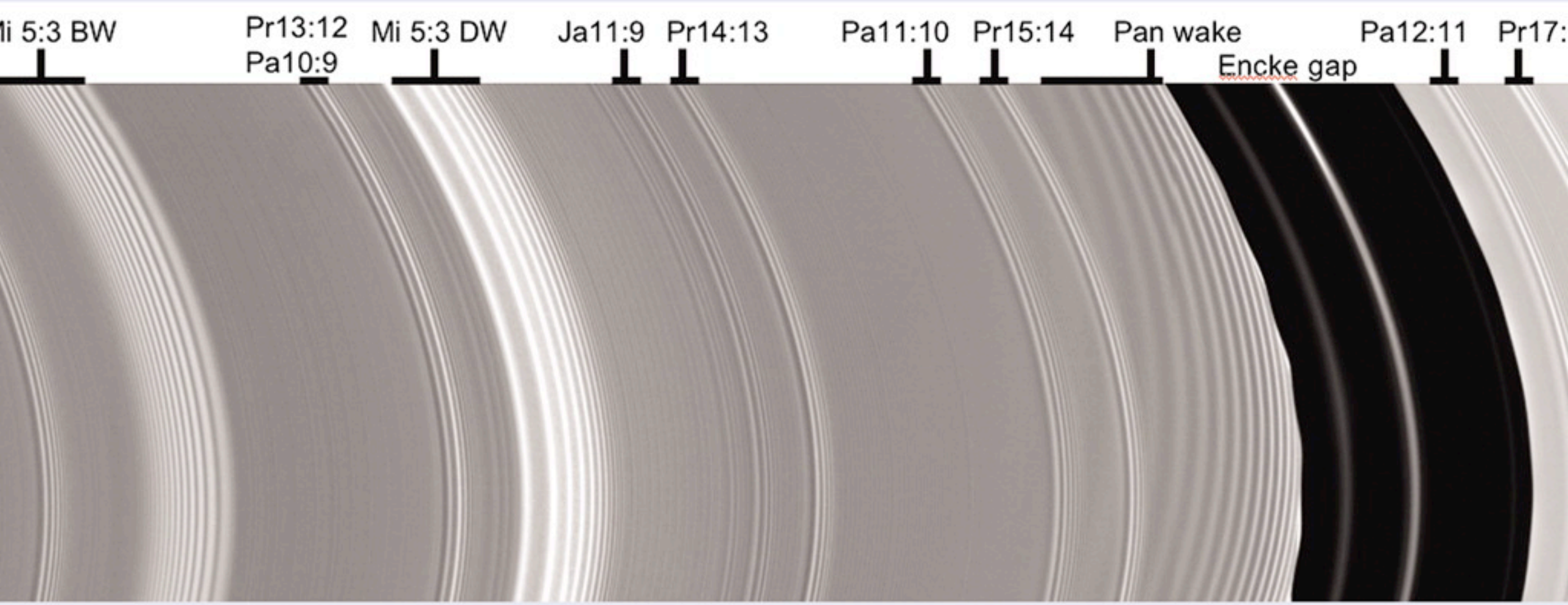
- Huygens (1656)

AAAAAACCCCCDEEEEEHIIIIIIIILLLLMMNNNNNNNNNNOOOOPPQRRSTTTTTUUUUU
ANNULO CINGITUR TENUI PLANO NUSQUAM COHAERENTE AD ECLIPTICAM INCLINATO
It is surrounded by a thin flat ring, nowhere touching, and inclined to the ecliptic



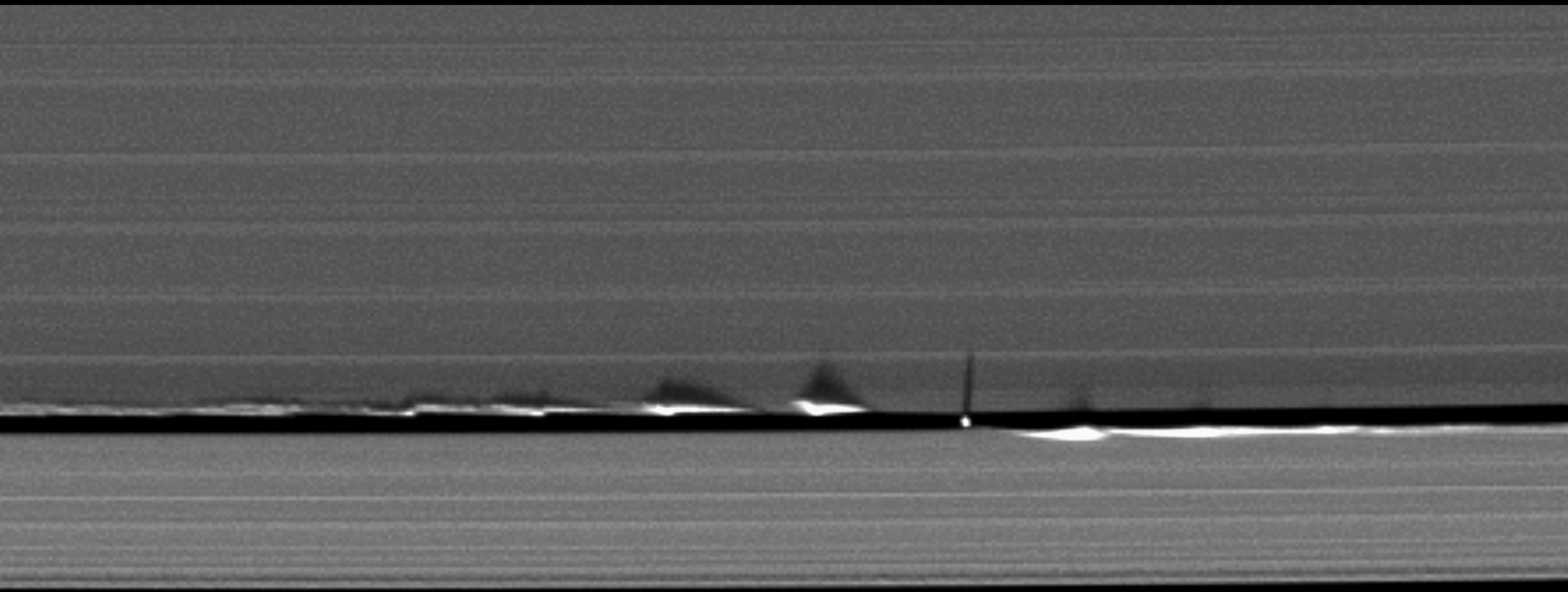
- Hooke, Cassini, ..., Laplace, Maxwell, ...
- *Voyager 1* and *2* flybys (1980–1)
- *Cassini* in orbit (2004–17)

Observations : Saturn's rings

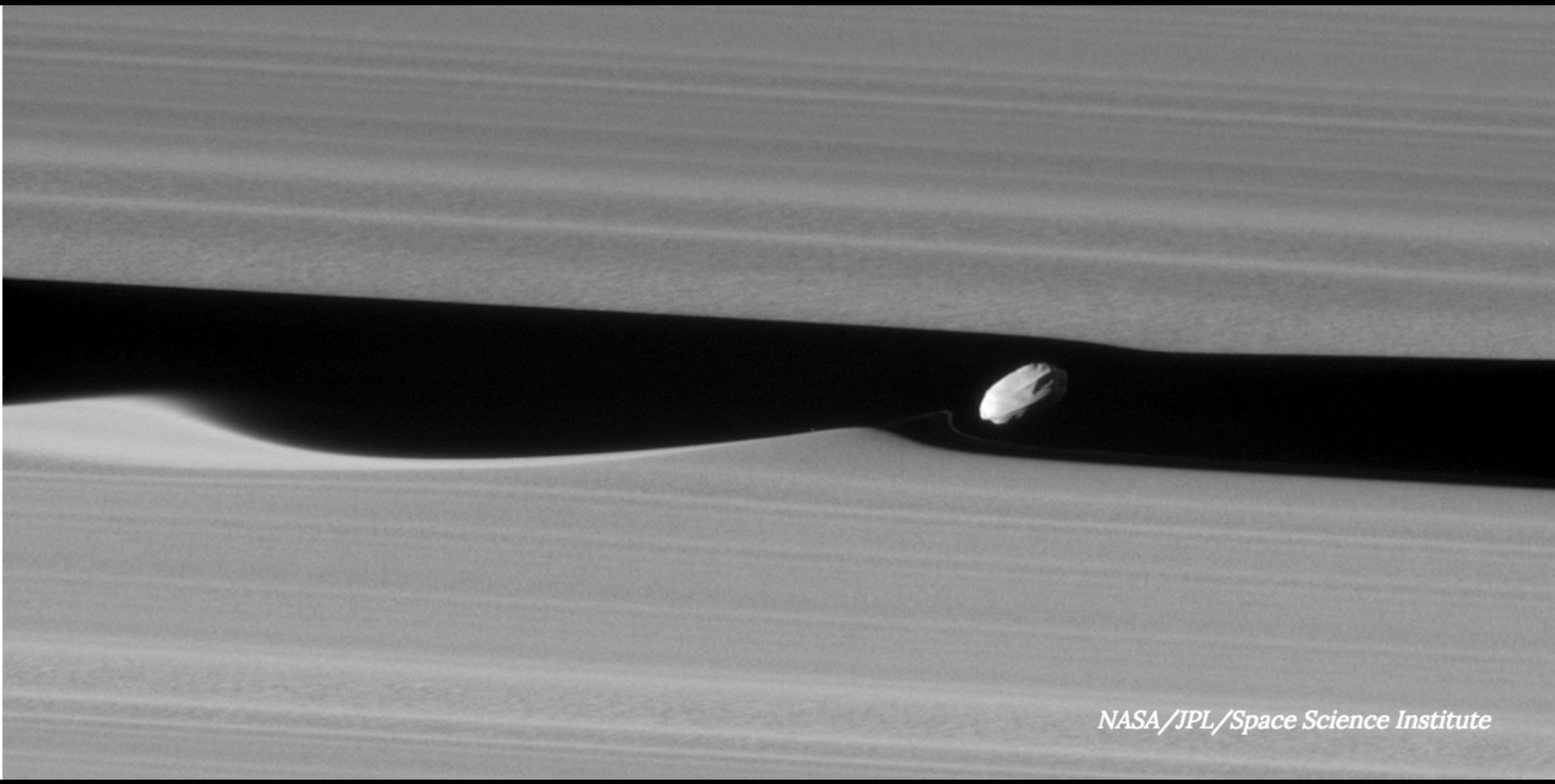


- waves, wakes, gaps, ringlets, braids, shepherds, propellers, ...
- `ciclops.org`

Observations : satellite-disc interaction



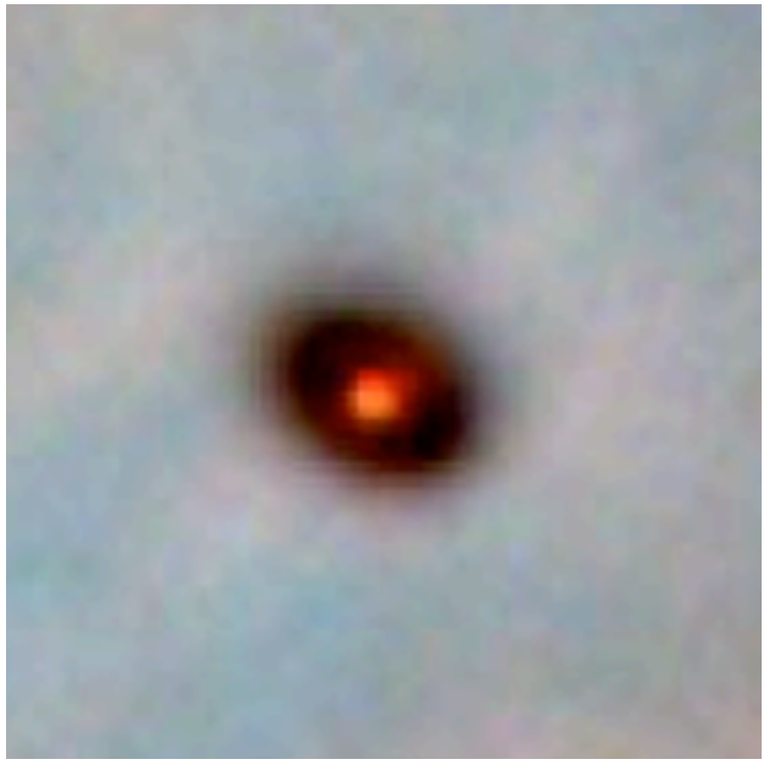
Observations : satellite-disc interaction

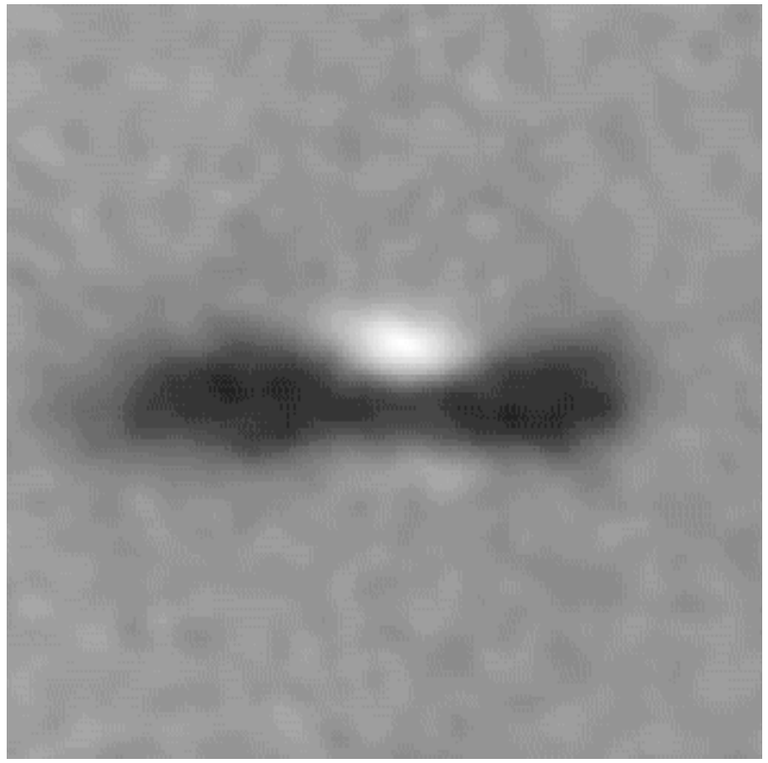


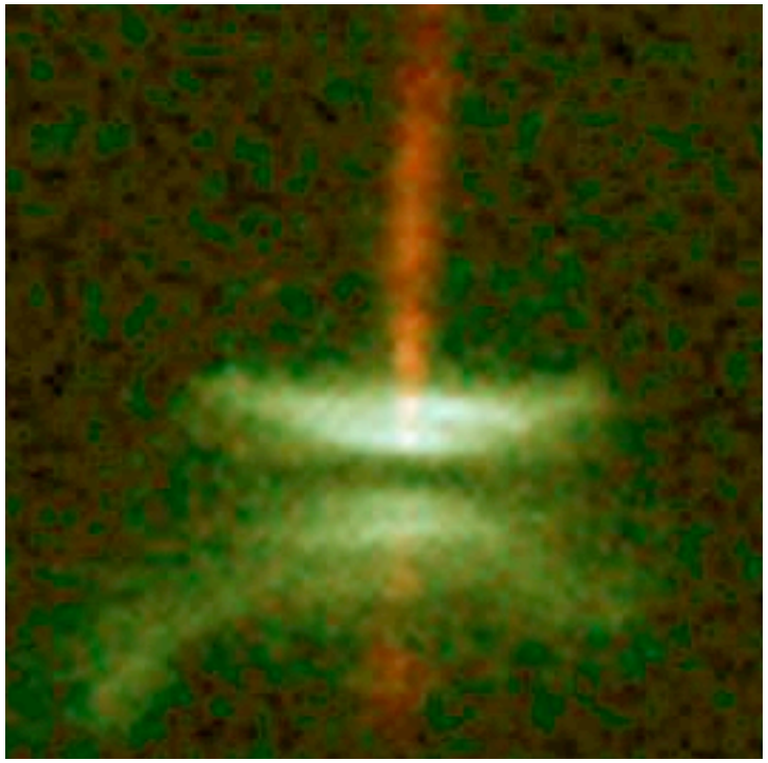
Observations : protoplanetary discs

- Nebular hypothesis (solar nebula) :
  Swedenborg, Kant, Laplace (18th century)

- Direct observations of protoplanetary discs (Hubble ST, 1995–)

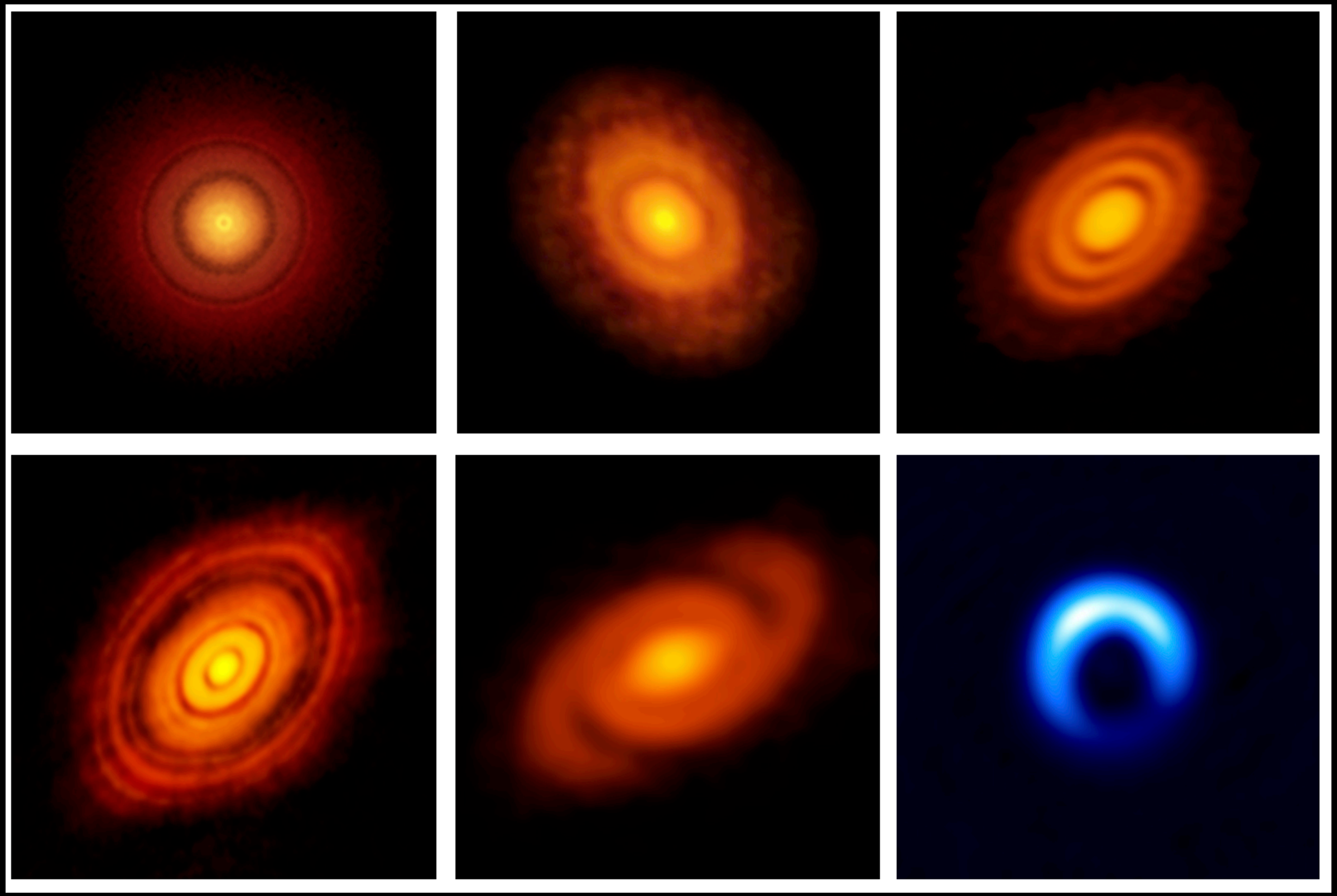




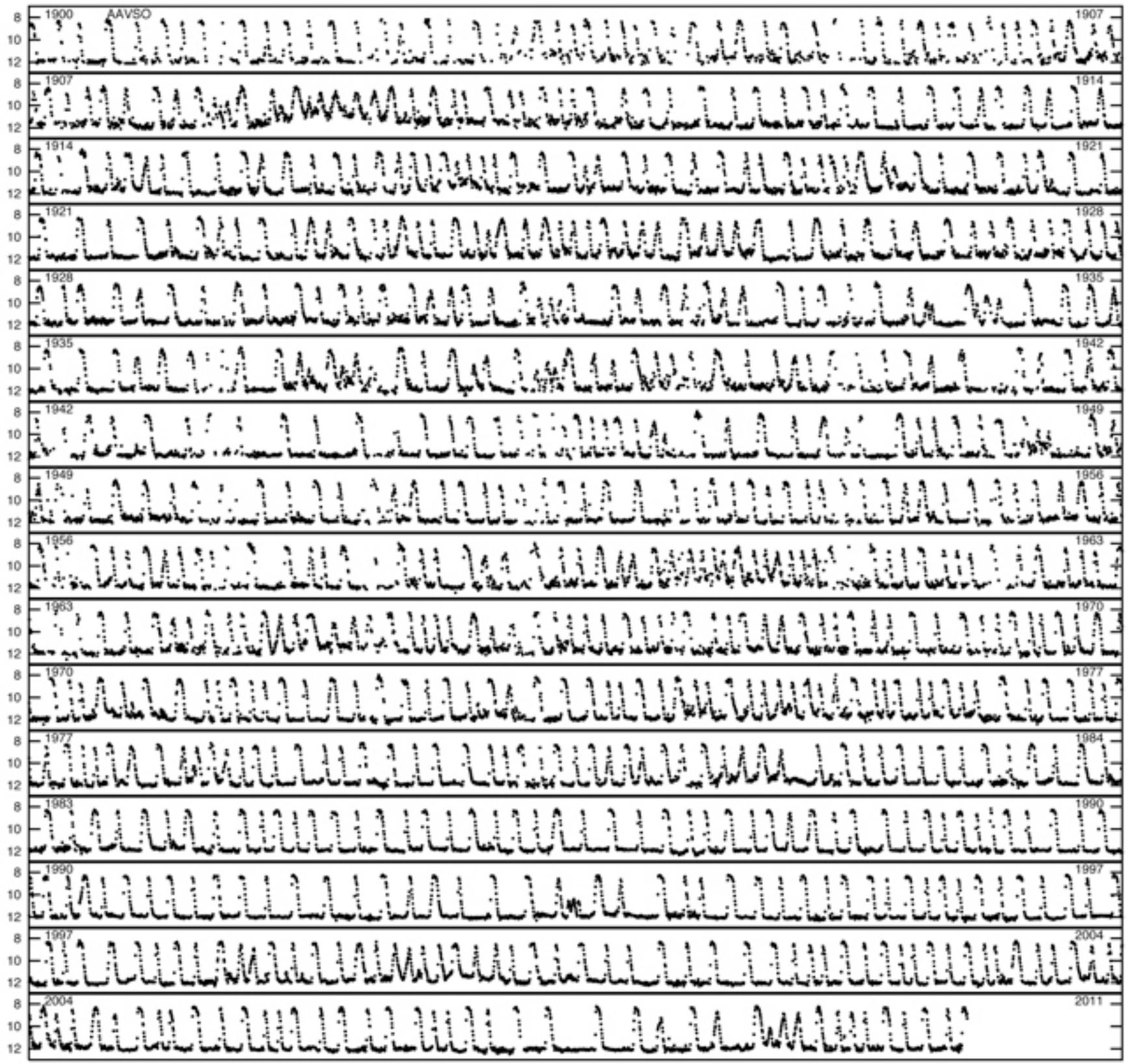


- Extrasolar planets around main-sequence stars (1995–)
- Dust structures in protoplanetary discs
  SPHERE (micron-size grains), ALMA (larger grains)

Observations : protoplanetary discs (ALMA, 2011–)



Observations : cataclysmic variable stars



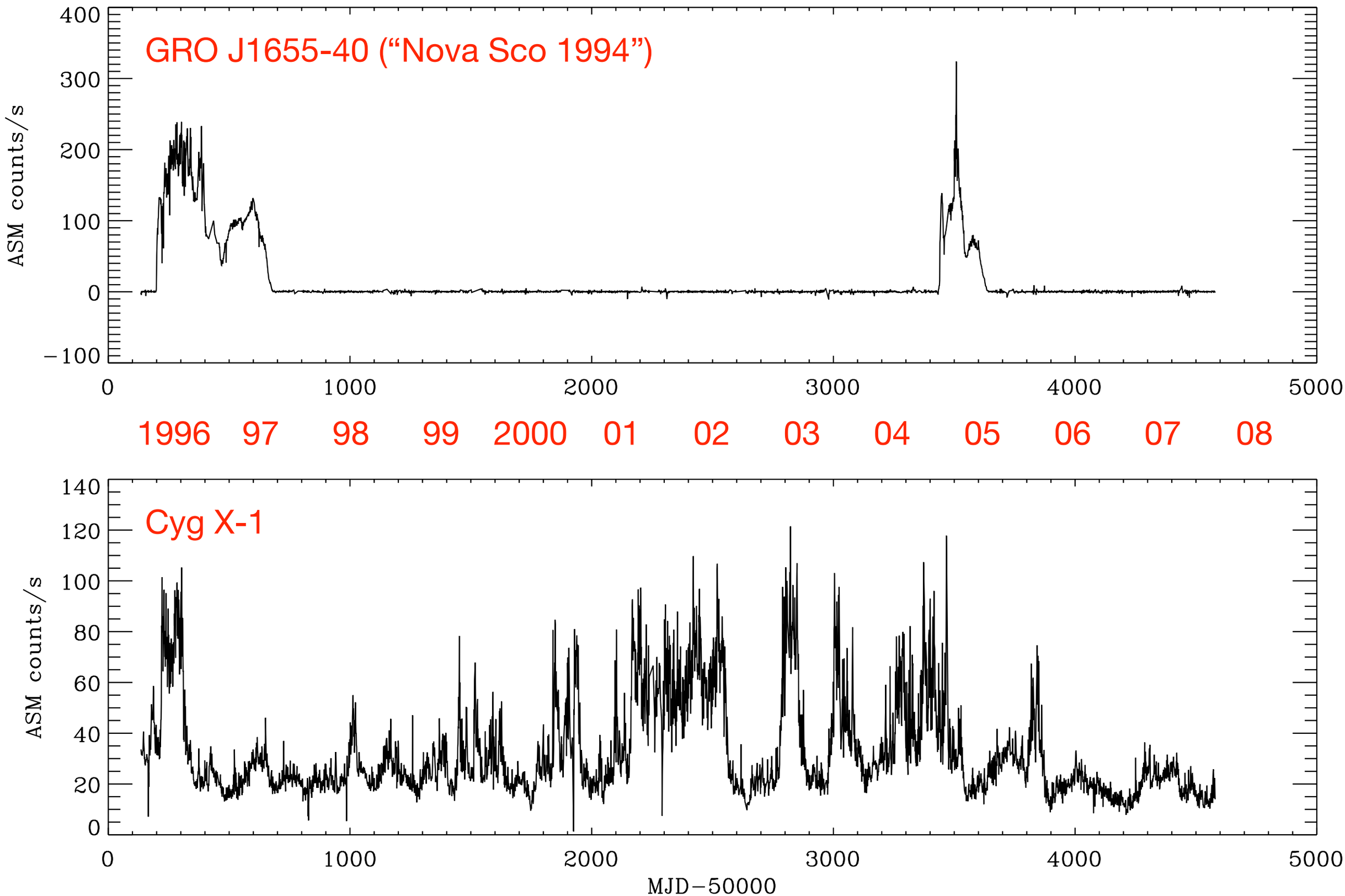
SS Cygni
dwarf nova

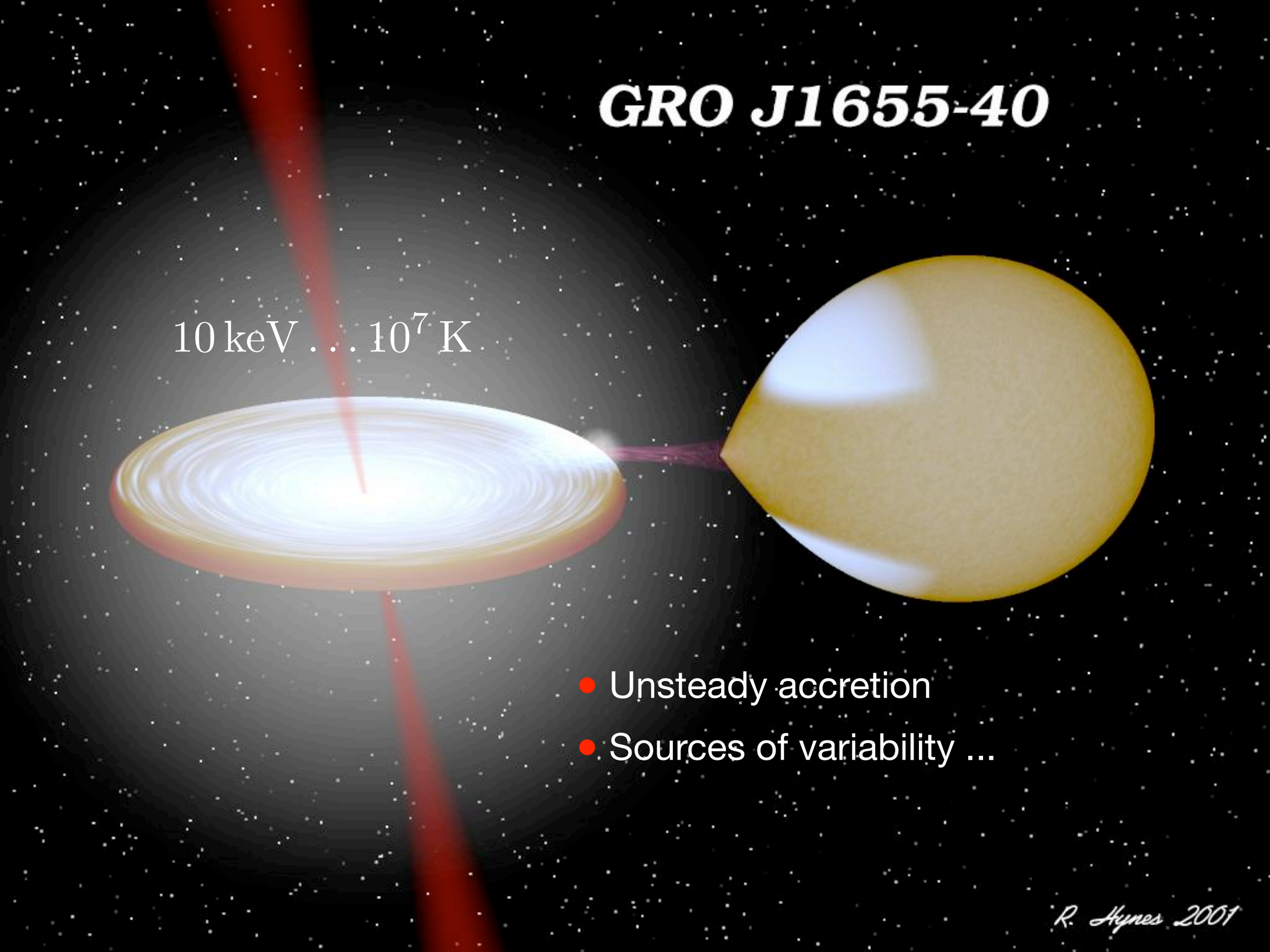
V magnitude
(range 12–8)
1900–2010

`aavso.org`

Also UV and
soft X-rays

Observations : X-ray binary stars (1960s–)





- Unsteady accretion
- Sources of variability ...

Observations : shadow of black hole in M87 (EHT, 2019)