Accretion Discs and Planet Formation

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Petnica Summer School on Astrophysics

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About me

- Researcher at Institute of Physics Belgrade

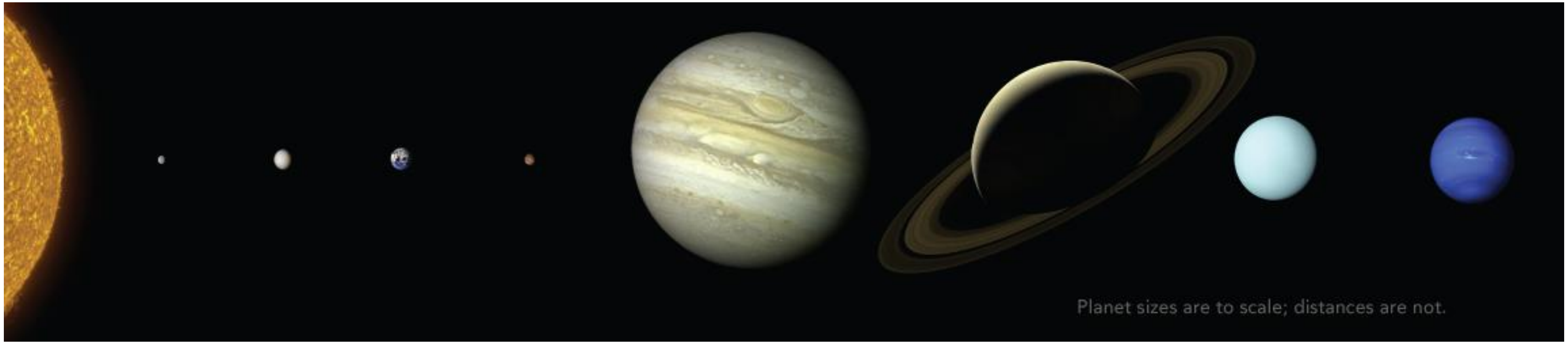
- My research interests:
  - Numerical models of protoplanetary discs and planet formation
  - Simulations of debris discs and dynamics of small dust grains

Overview of the lectures

- Lecture 1
  - (Exo)planets
  - Protoplanetary discs
  - Protoplanetary discs as accretion discs
  - Evolution of dust in protoplanetary discs
- Lecture 2
  - Dust growth
  - Planetesimal formation
  - Formation of planet cores
  - Accretion of planet envelopes
  - How do (exo)planets form?

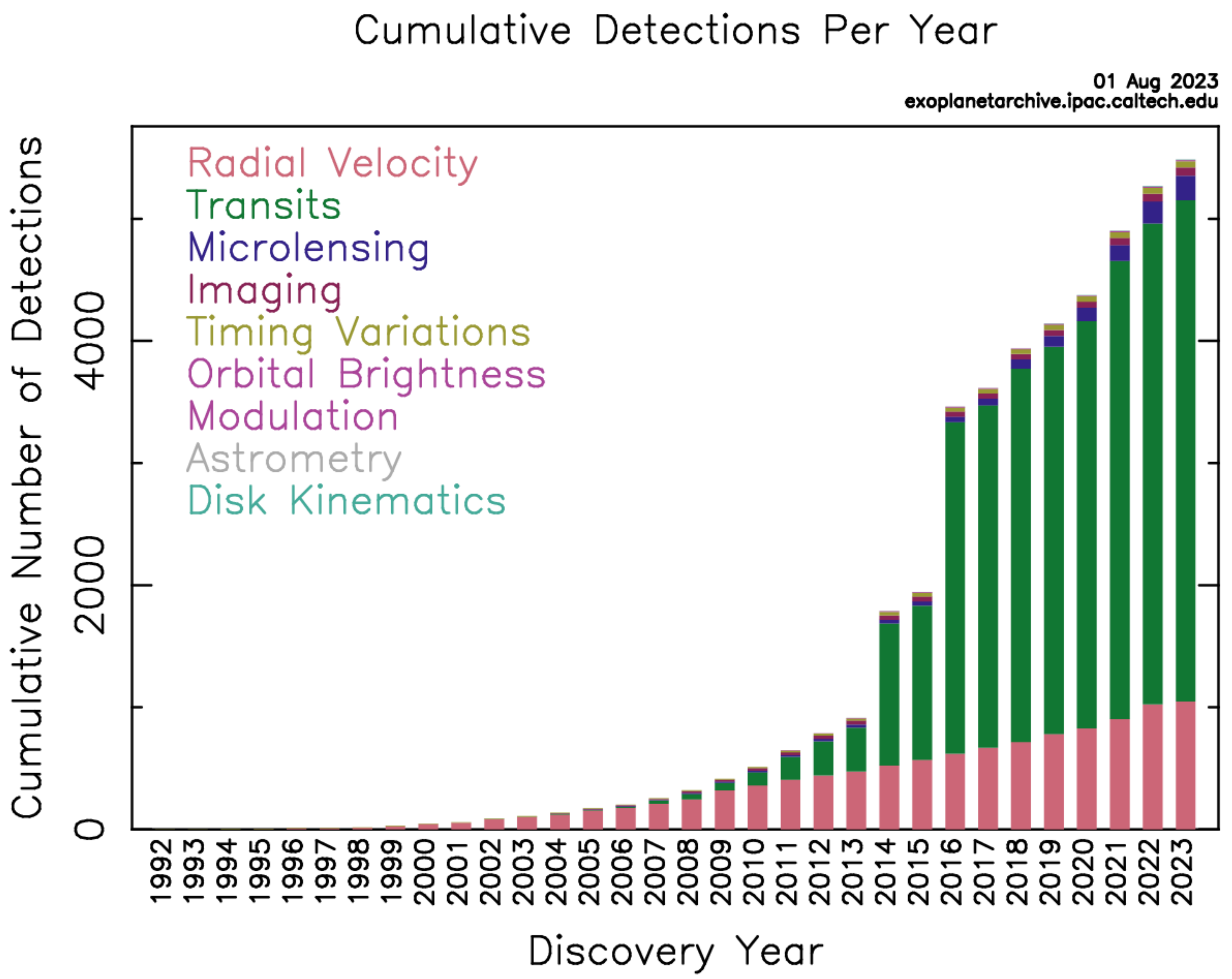
(Exo)planets

Solar system

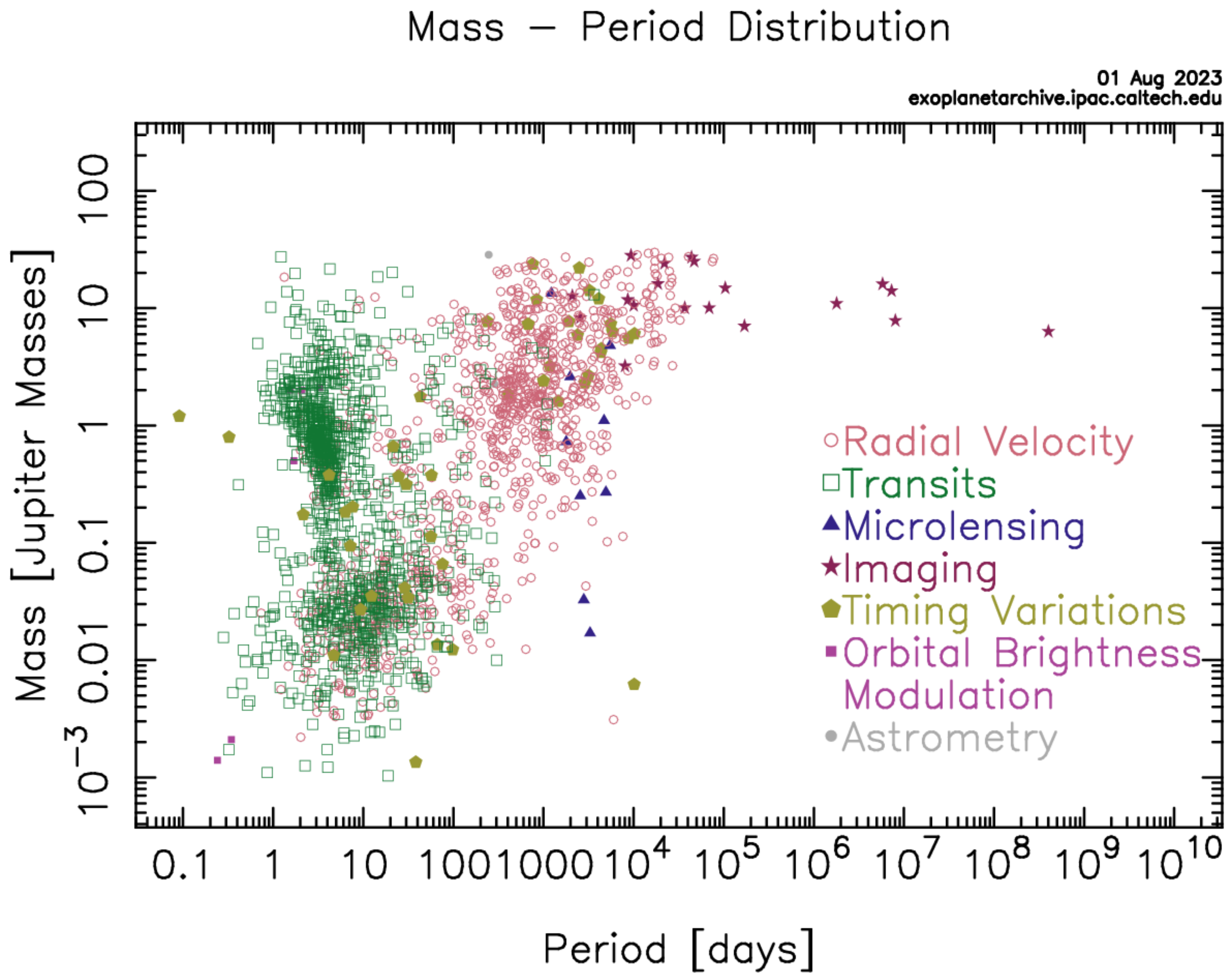


Credits: NASA/Ames Research Center/Wendy Stenzel

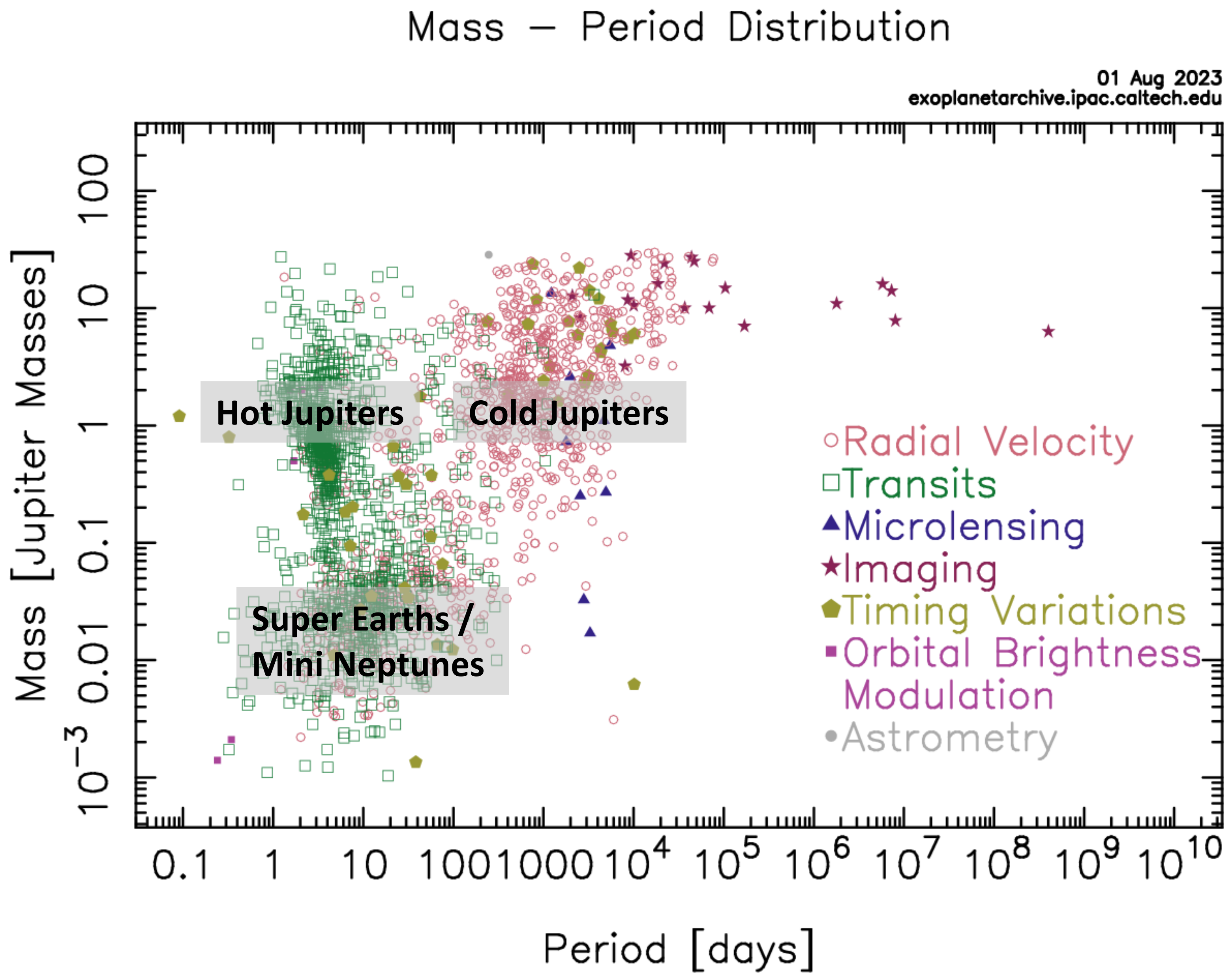
- 1 star
- 8 planets (or more?)
- 9 dwarf planets (or more?)
- 2 planetesimal belts + Oort cloud + other small bodies…



Cumulative Detections Per Year
01 Aug 2023
exoplanetarchive.ipac.caltech.edu
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness
Modulation
Astrometry
Disk Kinematics
Cumulative Number of Detections
0
2000
4000
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
Discovery Year

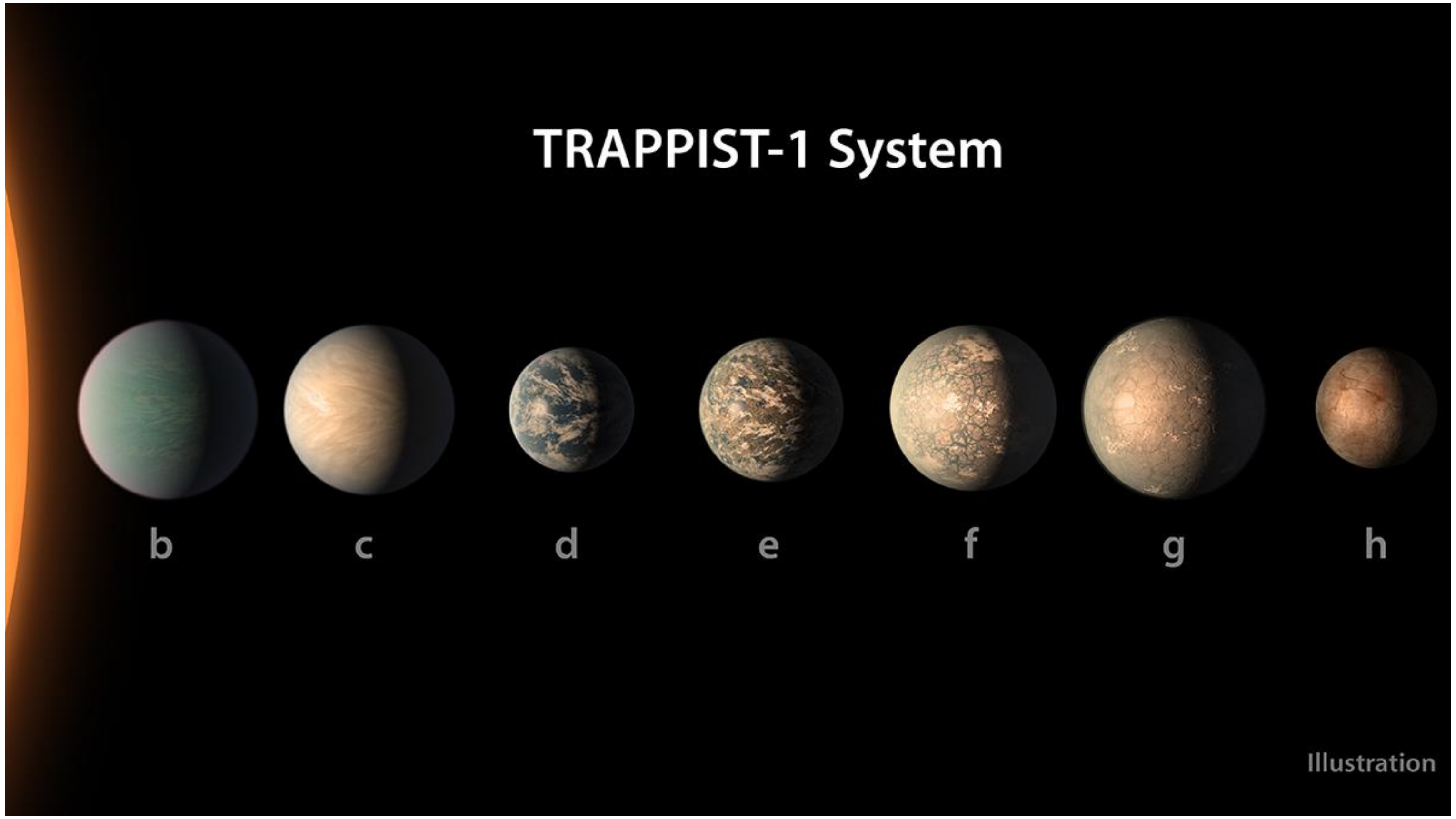


Mass – Period Distribution
01 Aug 2023
exoplanetarchive.ipac.caltech.edu
Mass [Jupiter Masses]
100
10
1
0.1
0.01
10^{-3}
0.1
1
10
100
1000
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
Period [days]
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness Modulation
Astrometry

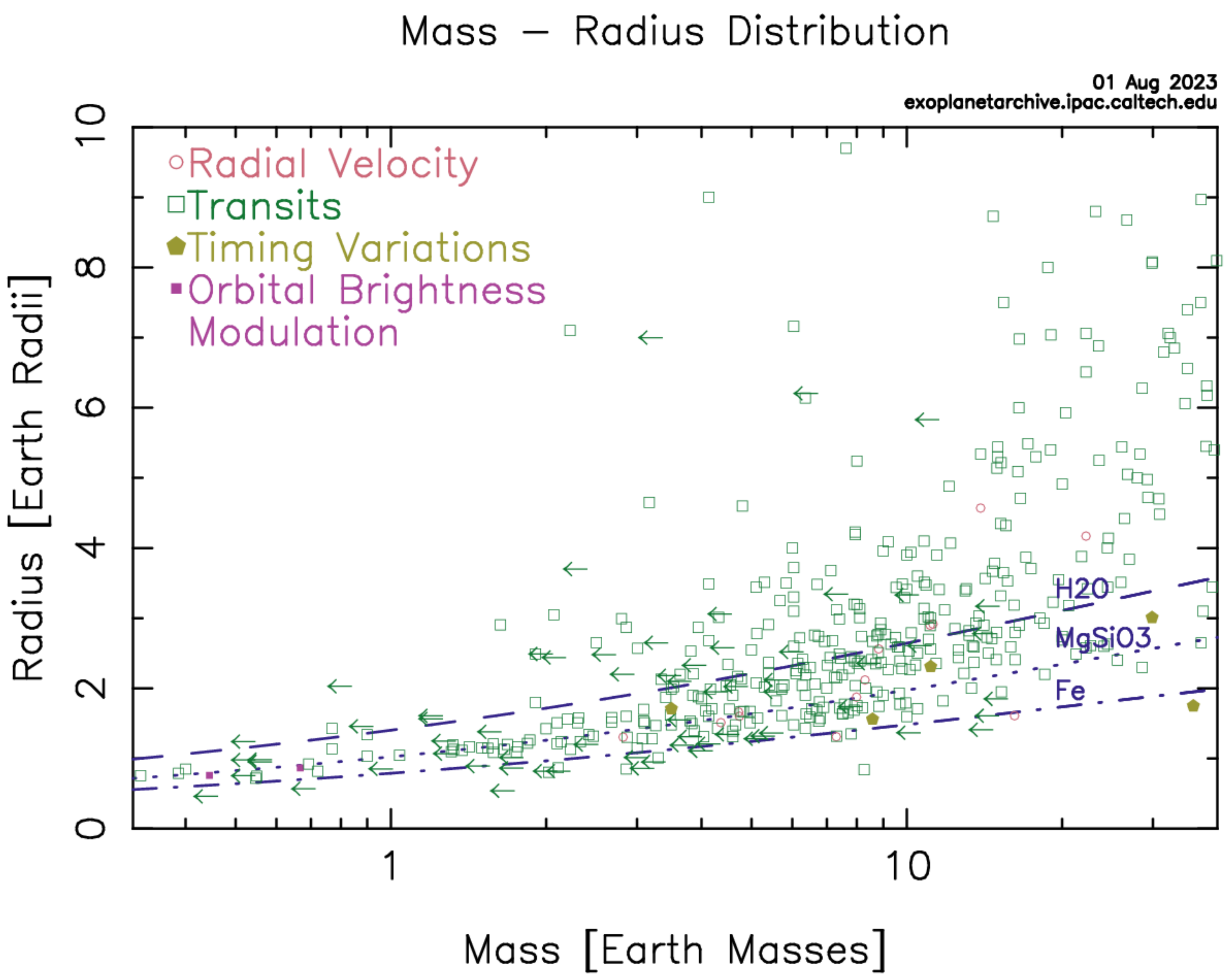


Mass – Period Distribution
01 Aug 2023
exoplanetarchive.ipac.caltech.edu
Hot Jupiters
Cold Jupiters
Super Earths /
Mini Neptunes
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness
Modulation
Astrometry
Mass [Jupiter Masses]
100
10
1
0.1
0.01
10^{-3}
Period [days]
0.1
1
10
100
1000
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}

Extra-solar systems

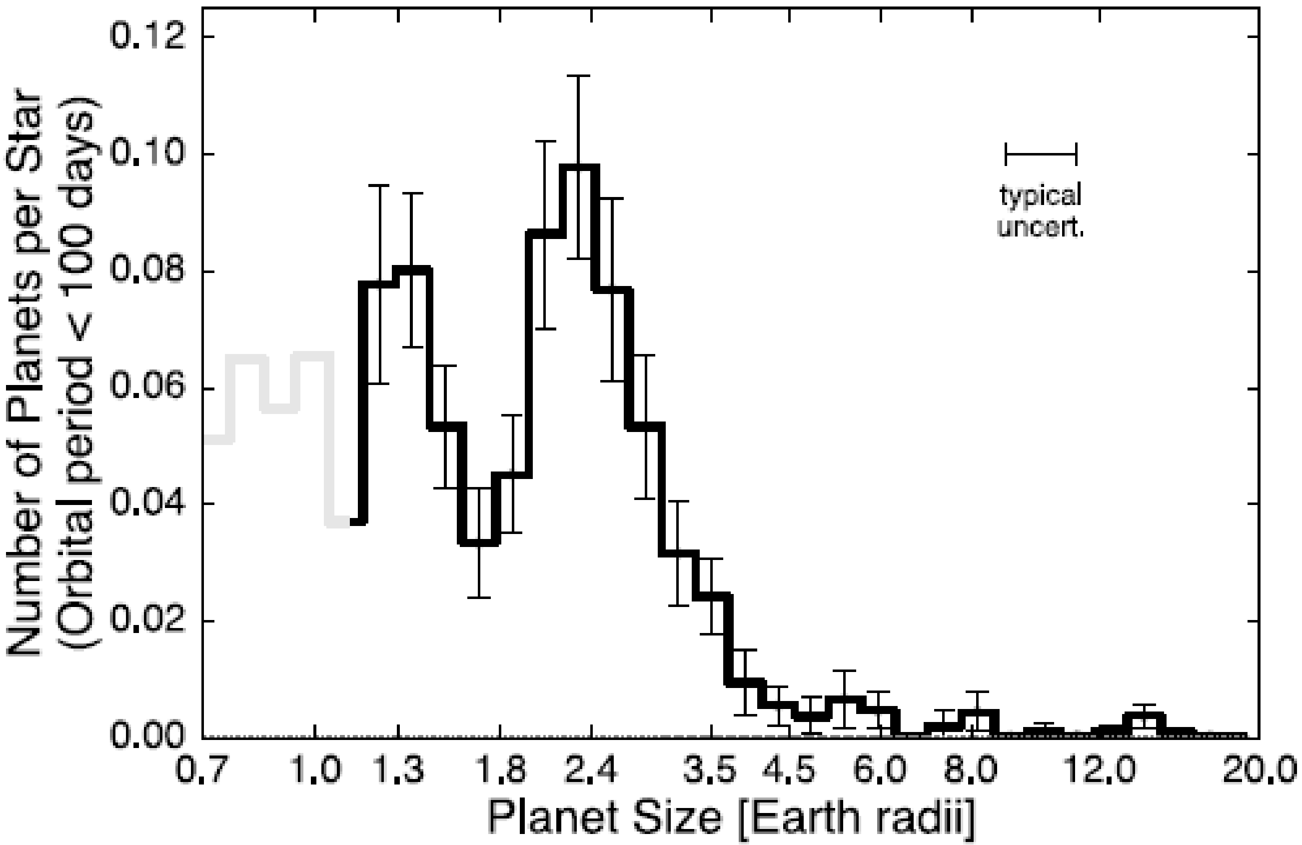


Credits: NASA/JPL-Caltech



Mass – Radius Distribution
01 Aug 2023
exoplanetarchive.ipac.caltech.edu
Radial Velocity
Transits
Timing Variations
Orbital Brightness Modulation
H2O
MgSiO3
Fe
Radius [Earth Radii]
0
2
4
6
8
10
1
10
Mass [Earth Masses]

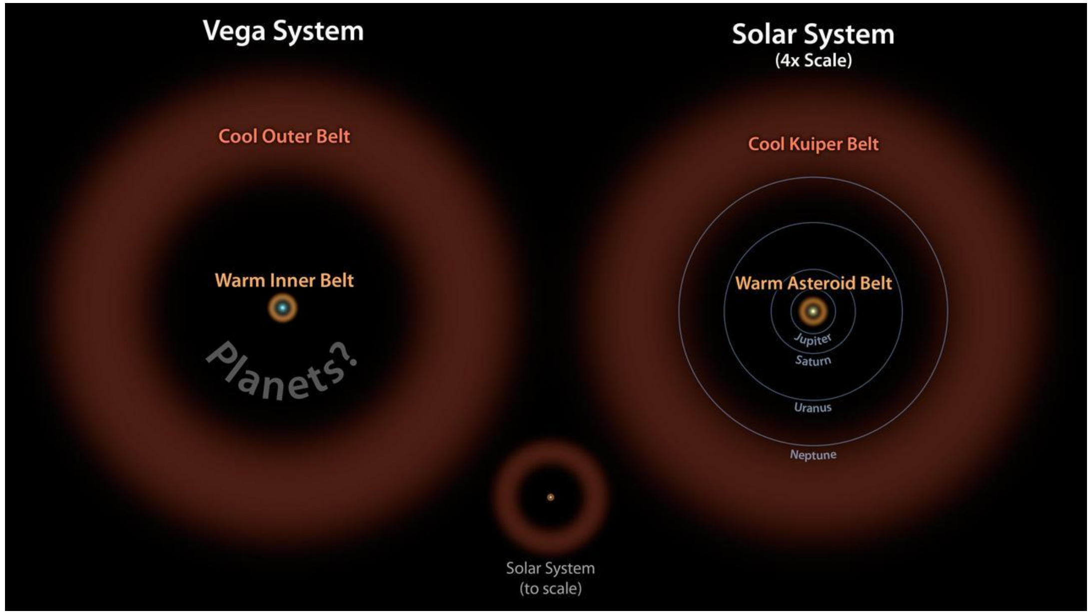
Super Earths & Mini Neptunes



Fulton et al. (2017)

Extrasolar planetesimal belts

- One cannot directly detect a dwarf planet or a planetesimal, but…
- Planetesimals collide and produce small dust grains
- These belts are debris leftover from planet formation (thus also known as *debris discs*)



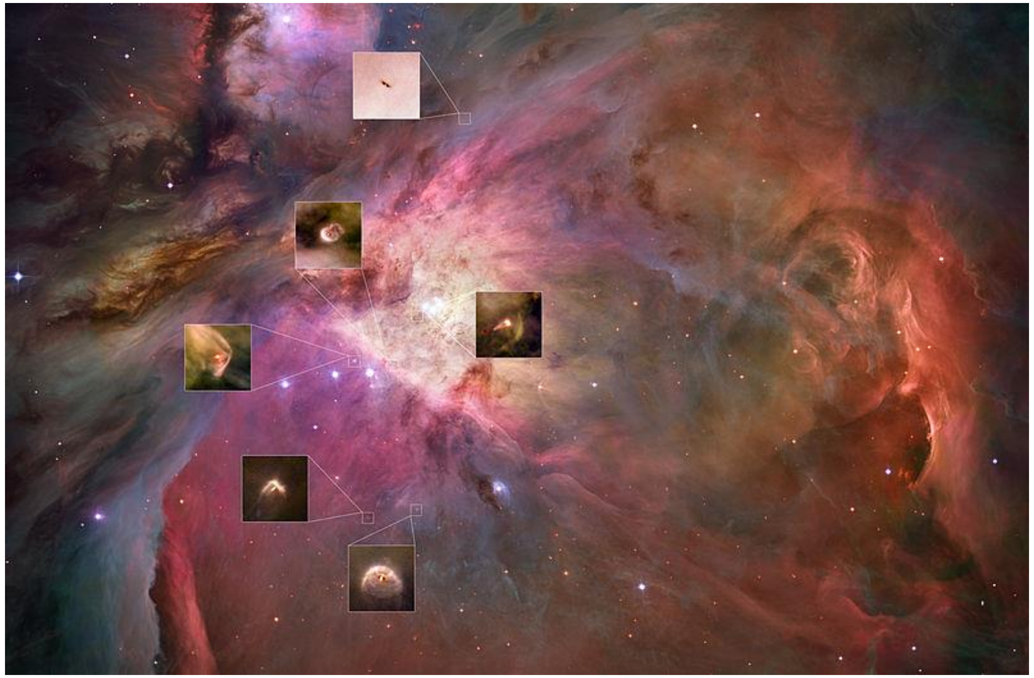
Credits: NASA/JPL-Caltech

How and where do planetary systems form?

Stars form in fragments of giant cold clouds

Orion nebula. Credit: NASA/ESA/M. Robberto (Space Telescope Science Institute/ESA)/Hubble Space Telescope

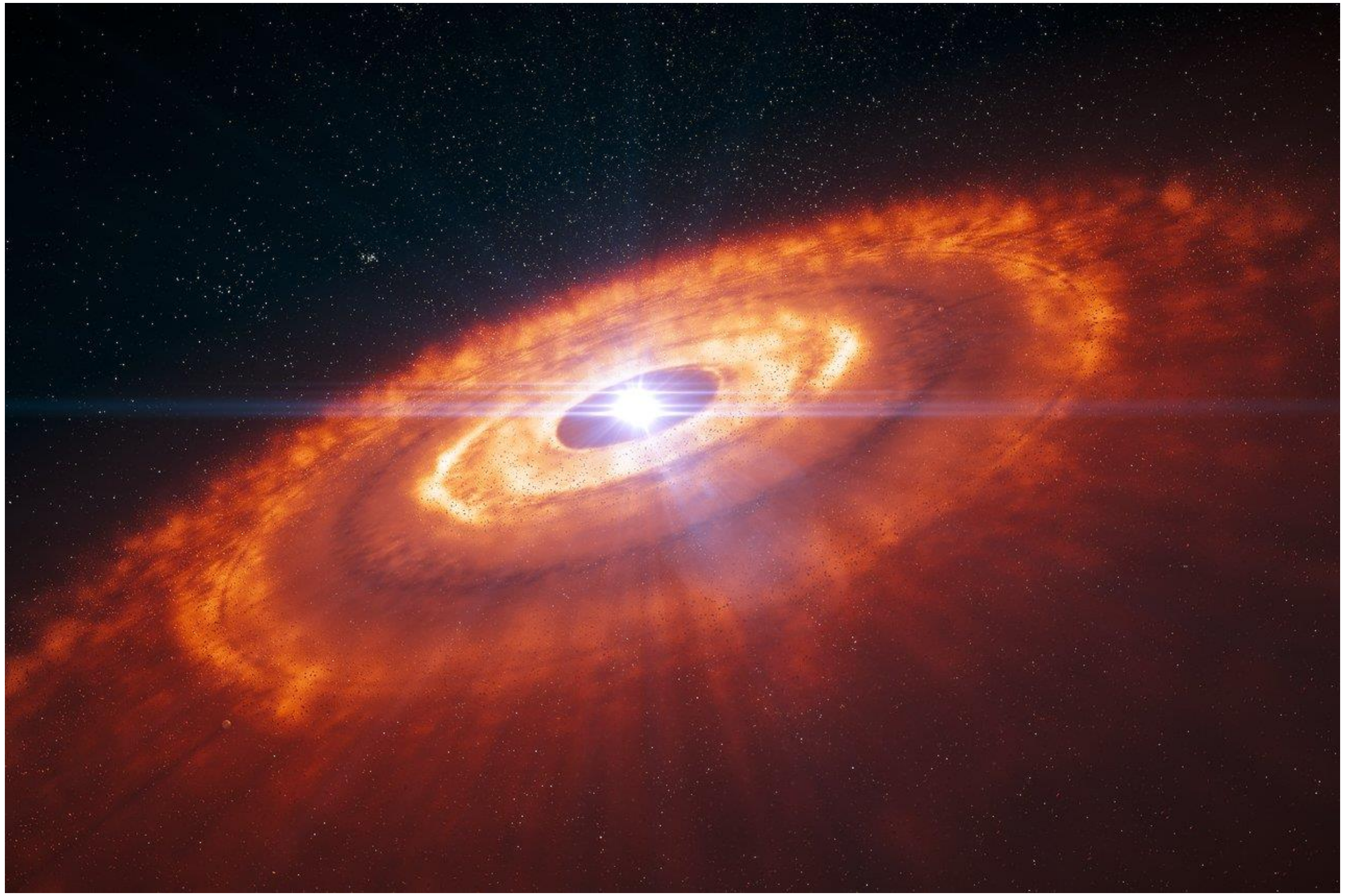
Stars form surrounded by discs of gas and dust



Orion nebula with proplyds.
Credit: ESA/Hubble Space Telescope

(but most star-forming regions aren't this violent)

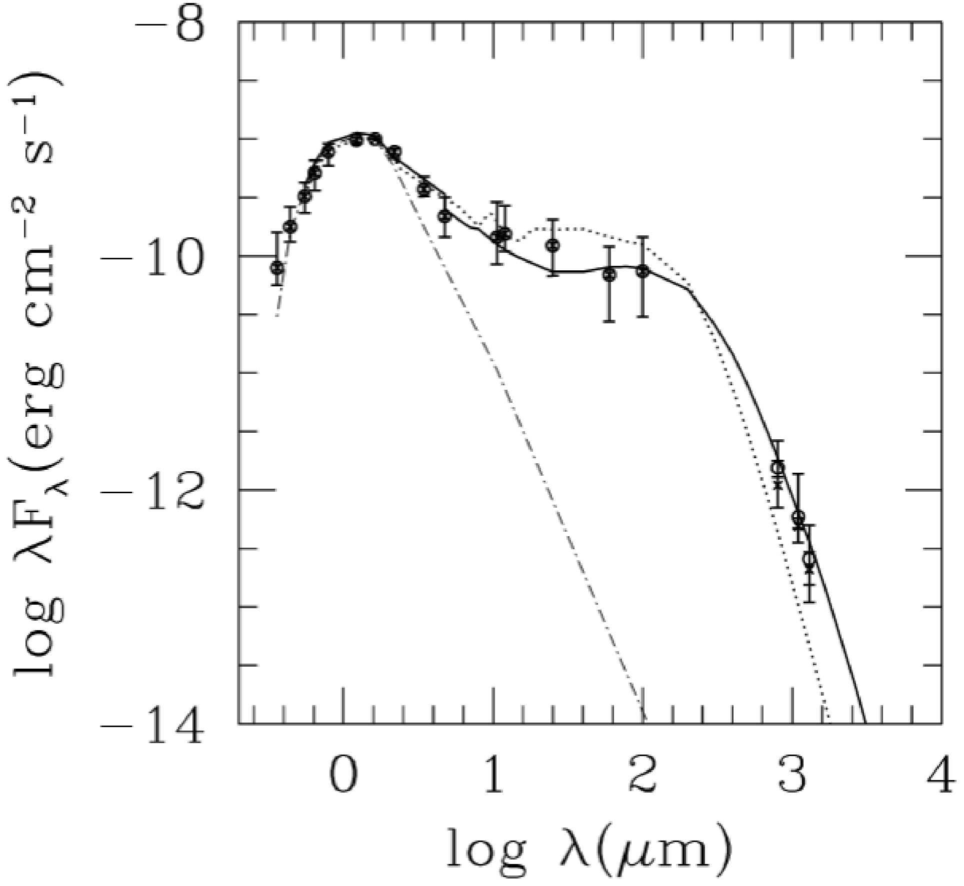
These are protoplanetary discs



Artist’s impression of a young star surrounded by a protoplanetary disc. Credit: ESO/L. Calçada

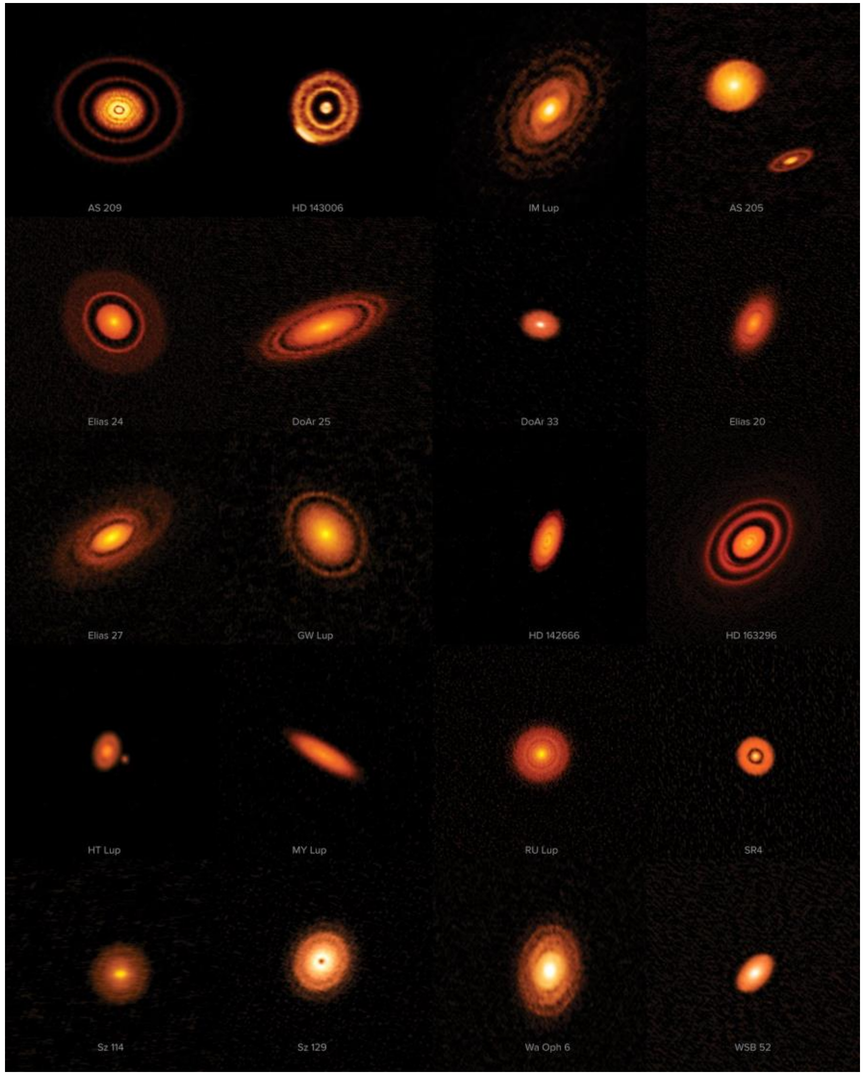
Protoplanetary discs

Spectral Energy Distribution (SED)



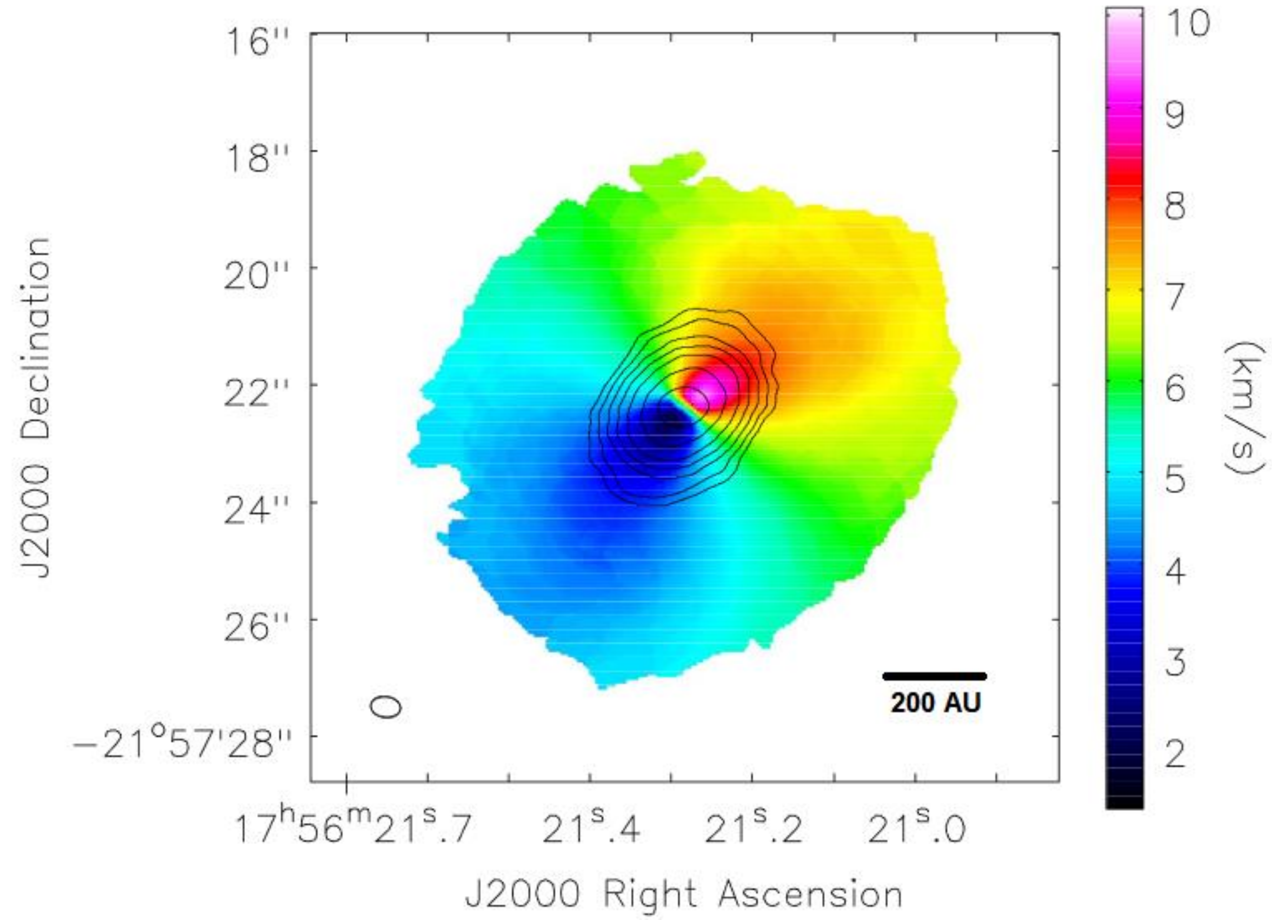
D'Alessio et al. 2001

Resolved observations of dust continuum



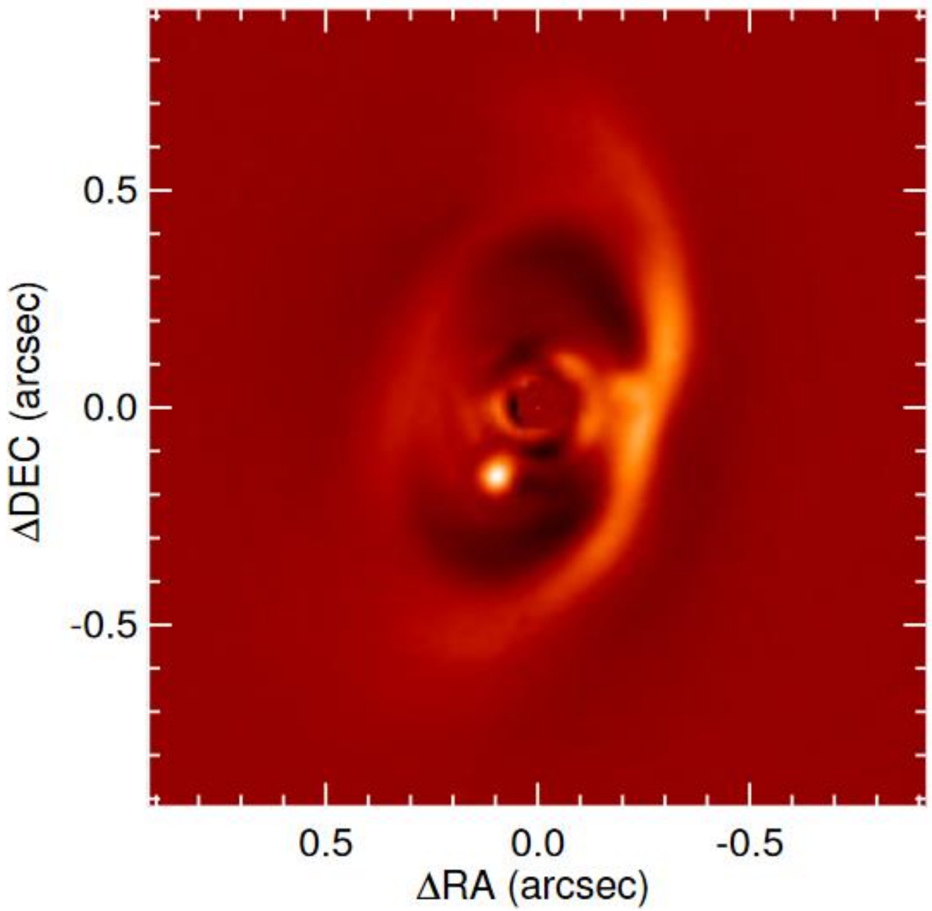
Dust continuum emission gallery from DSHARP program. Credit: ALMA (ESO/NAOJ/NRAO), S. Andrews et al.; NRAO/AUI/NSF, S. Dagnello

Gas structure probed through tracer species



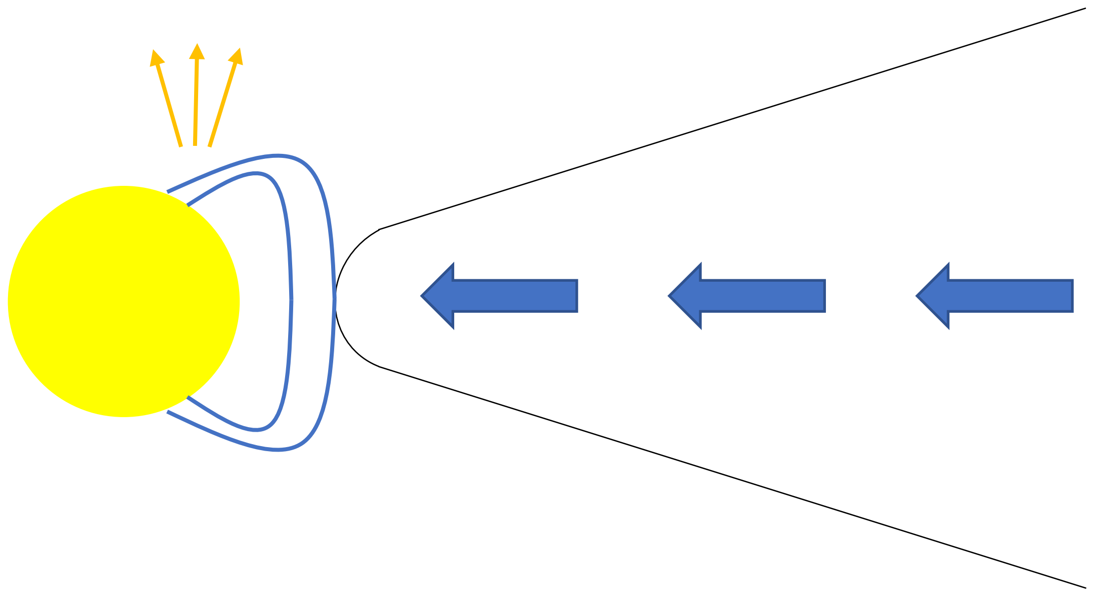
CO line and dust continuum emission (de Gregorio-Monsalvo et al. 2013)

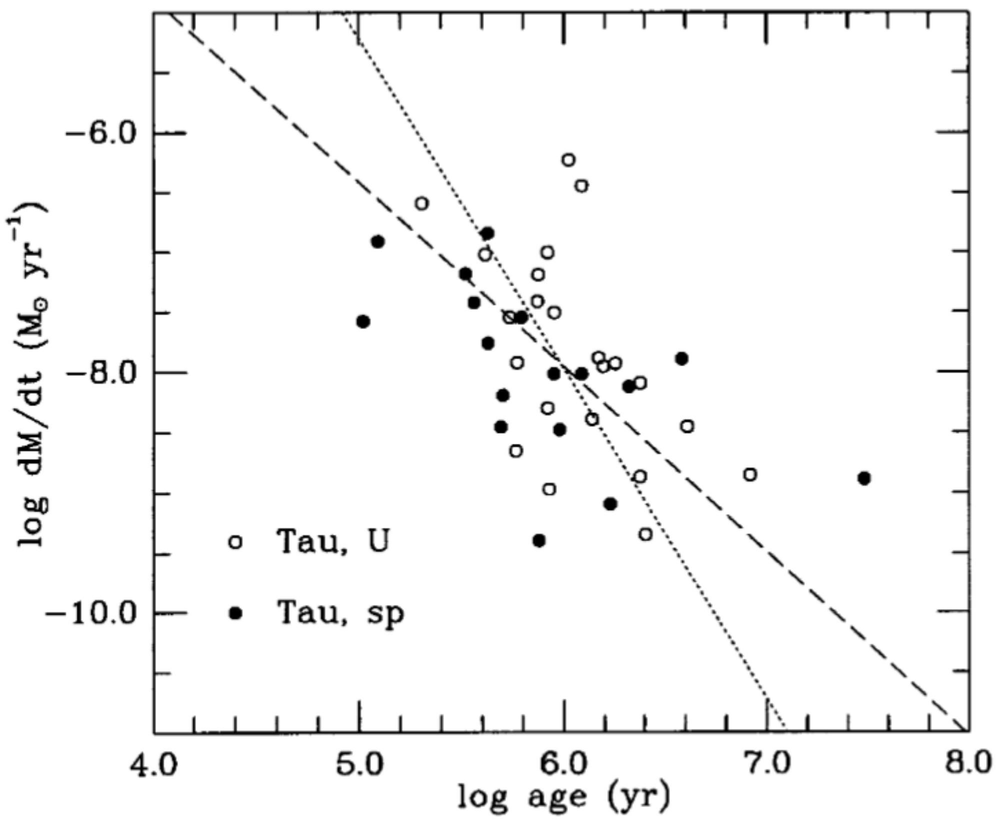
A planet has been detected in one disc!



PDS 70b (Muller et al. 2018)

Protoplanetary discs are accretion discs





Hartmann et al. 1998

Protoplanetary disc lifetime

- Young stars lose their discs after a few million years
- Gaseous giants must form within this time!

Main points so far

- Planets form in discs of gas and dust surrounding young stars
- These protoplanetary discs last for a few million years
- During this time material accretes onto the star
- Observations of dust continuum emission and gas tracer species probe the structure and evolution of protoplanetary discs

Protoplanetary discs as accretion discs

Thin circumstellar disc

Vertical direction: thermal pressure balances stellar gravity

$$\frac{\partial P}{\partial z} = -\rho \frac{GM_* z}{(r^2 + z^2)^{3/2}}$$

Radial direction: pressure gradient leads to sub-Keplerian rotation

$$r\Omega^2 = r\Omega_{\mathsf{K}}^2 + \frac{1}{\rho}\frac{\partial P}{\partial r}$$

Viscous accretion disc

Viscous disc accretes onto the star: angular momentum is transported outwards, mass is transported inwards.

Viscous accretion disc

Viscous disc accretes onto the star: angular momentum is transported outwards, mass is transported inwards.

Viscosity is produced by turbulence!

Viscous accretion disc

Consider a differentially rotating disc as a series of infinitesimal rings and a Newtonian shear stress of the form:

$$W_{r\phi} = \rho \nu r \frac{\partial \Omega}{\partial r}$$

Conservation of angular momentum:

$$\rho u_r \frac{1}{r} \frac{\partial (r^2 \Omega)}{\partial r} = (\nabla W)_\phi$$

Mass continuity:

$$\frac{\partial \rho}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} (r \rho u_r) = 0$$

Viscous accretion disc

Vertically integrated:

$$\frac{\partial \Sigma}{\partial t} - \frac{1}{2\pi r}\frac{\partial \dot{M}}{\partial r} = 0$$

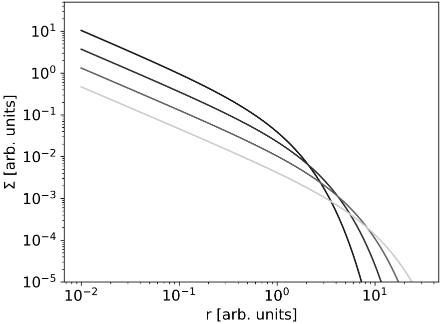
$$-\frac{1}{2\pi}\dot{M}\frac{\partial}{\partial r}\left(r^2\Omega\right) = \frac{\partial}{\partial r}\left(r^2\Sigma\bar{\nu}r\frac{\partial \Omega}{\partial r}\right)$$

where $\dot{M} = -2\pi r \int_{-\infty}^{\infty} dz \rho u_r$ is the inwards gas accretion rate, $\Sigma = \int_{-\infty}^{\infty} dz \rho$ is the gas surface density.

Viscous accretion disc

Evolution of the surface density is given by a diffusion equation:

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{r}\frac{\partial}{\partial r}\left(r^{1/2}\frac{\partial}{\partial r}\left(r^{1/2}\bar{\nu}\Sigma\right)\right)$$



Self-similar solution of Lynden-Bell & Pringle (1974)

Viscous accretion disc

Parametrization of viscosity, Shakura and Sunyaev (1973) α parameter:

$$\nu = \alpha \frac{c_s^2}{\Omega}$$

Viscous accretion disc

Steady-state solution:

$$\dot{M} = 3\pi\bar{\nu}\Sigma f_r^{-1}$$

Viscous accretion disc

Thermal balance:

$$F = \frac{9}{8}\Sigma\bar{\nu}\Omega^2 = \frac{3}{8\pi}\Omega^2\dot{M}f_r$$

Midplane temperature:

$$\sigma T_{\text{mid}}^4 = \frac{3}{8}\tau_{\text{mid}}F$$

where $\tau_{\text{mid}} = \frac{1}{2}\Sigma\kappa$

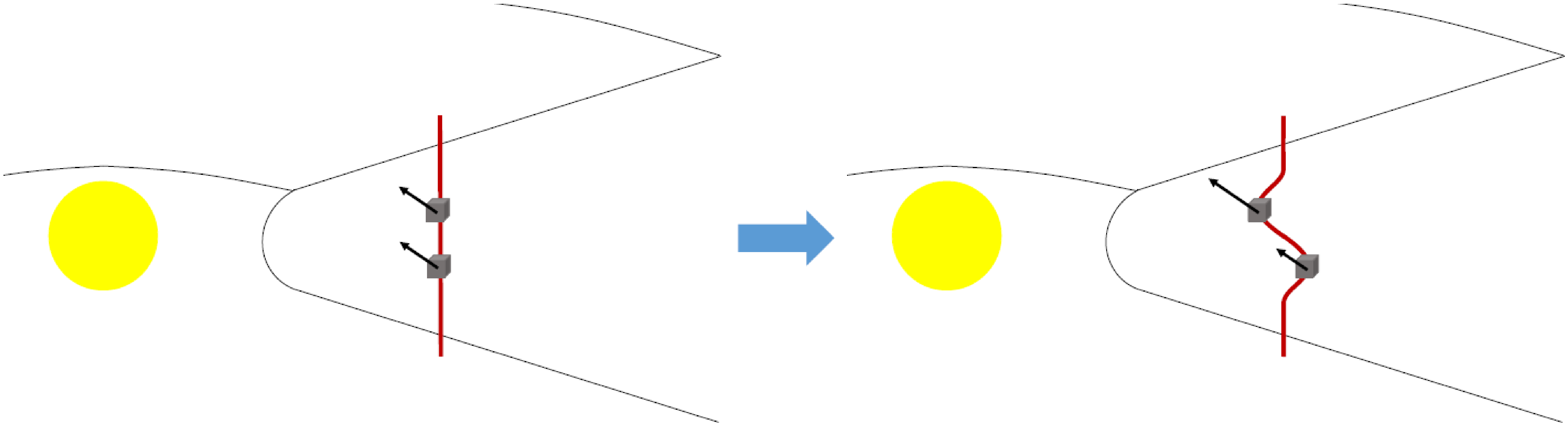
Viscous accretion disc

Standard α-disc model:

$$\Sigma \propto \kappa^{-1/5}\bar{\alpha}^{-4/5}M_*^{1/5}(f_r\dot{M})^{3/5}r^{-3/5}$$
$$\rho_{\text{mid}} \propto \kappa^{-3/10}\bar{\alpha}^{-7/10}M_*^{11/20}(f_r\dot{M})^{2/5}r^{-33/20}$$
$$T_{\text{mid}} \propto \kappa^{1/5}\bar{\alpha}^{-1/5}M_*^{3/10}(f_r\dot{M})^{2/5}r^{-9/10}$$
$$P_{\text{mid}} \propto \kappa^{-1/10}\bar{\alpha}^{-9/10}M_*^{17/20}(f_r\dot{M})^{4/5}r^{-51/20}$$

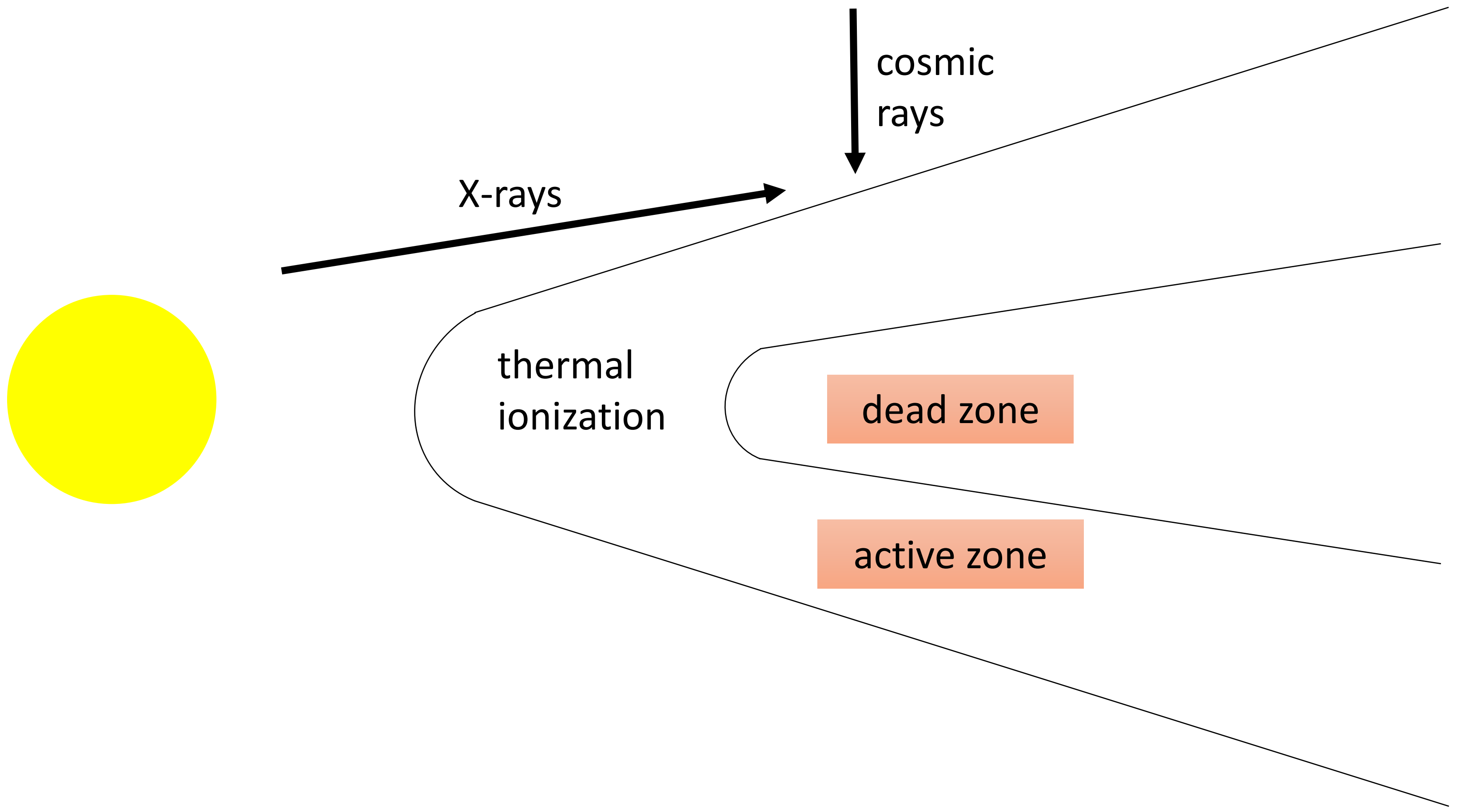
What is the source of the viscosity/turbulence?

Magneto-rotational instability (MRI) (Balbus & Hawley 1991)



Difficulties with MRI

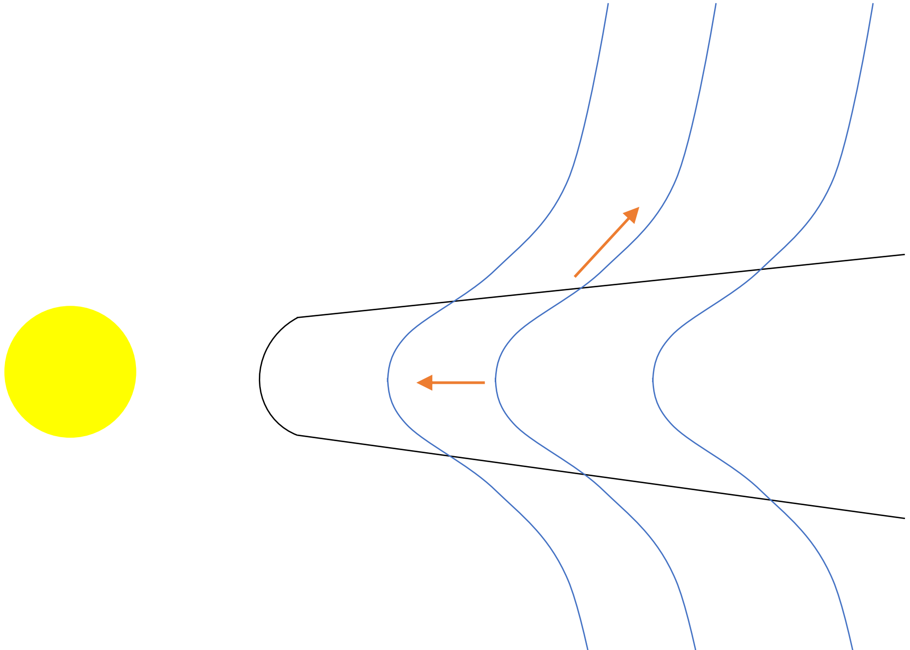
Protoplanetary discs are weakly ionized



Are there other candidates?

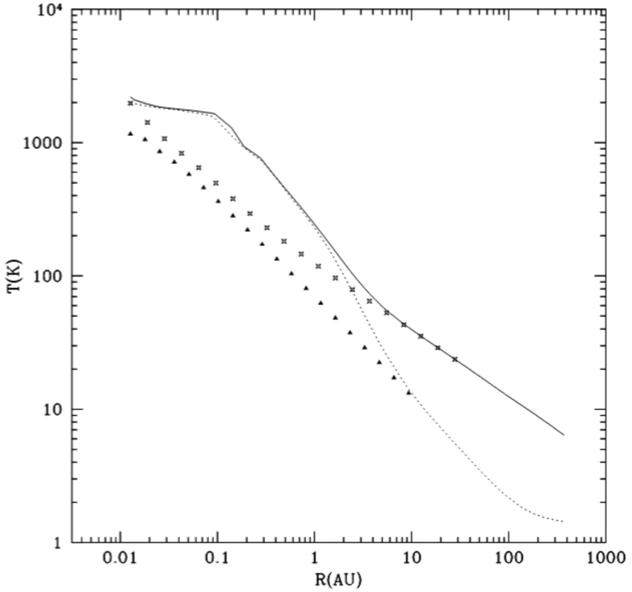
- Under the right conditions, some hydrodynamic instabilities (e.g. vertical shear instability) also produce turbulence which can transport angular momentum…
- Non-viscous accretion! Angular momentum may be lost via

  magnetic winds.

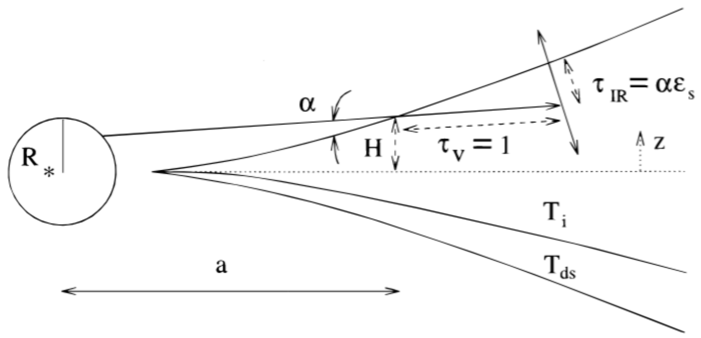


Protoplanetary discs are also heated by stellar irradiation

- Disc surface is hit by stellar irradiation
- Dust absorbs and re-emits stellar light
- Upper layers and outer disc are primarily heated by stellar irradiation, not viscous dissipation



D'Alessio et al. (1998)



Chiang & Goldreich (1997)

Evolution of dust in protoplanetary discs

Dust grains are subject to gas drag

- Epstein drag regime (but may also enter Stokes regime!)

$$F_{drag} = -\frac{4\pi}{3}\rho s^2 v_{th} v$$

- Friction time scale

$$t_{fric} = \frac{mv}{|F_{drag}|}$$

- Dimensionless friction time scale (Stokes number)

$$\tau_{fric} = t_{fric}\Omega_K$$

Vertical settling

- Gas is stationary in the vertical direction
- Dust grains tend towards Keplerian orbits

  => dust grains feel gas drag

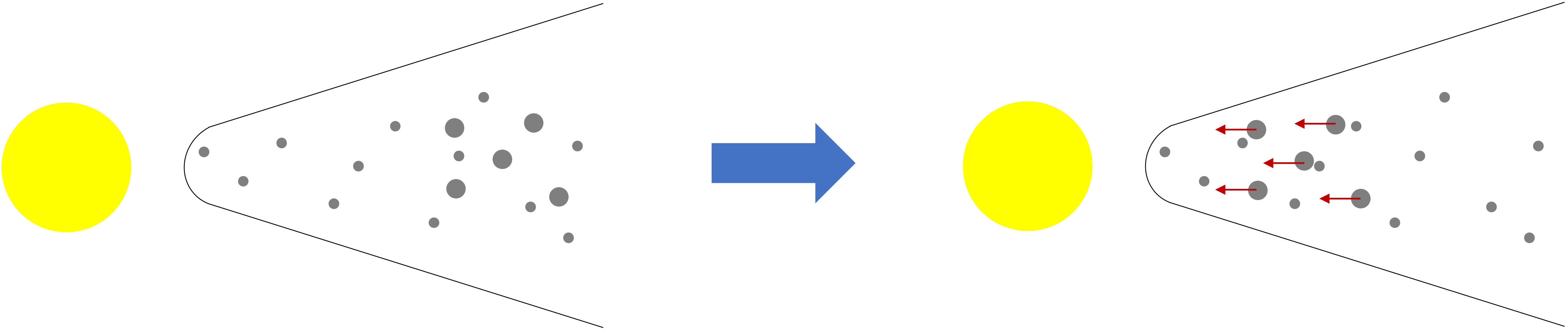
  => dust grains settle towards disc midplane
- Dust also vertically mixed by turbulence
- Mathematically described by an advection-diffusion equation

Radial drift of dust

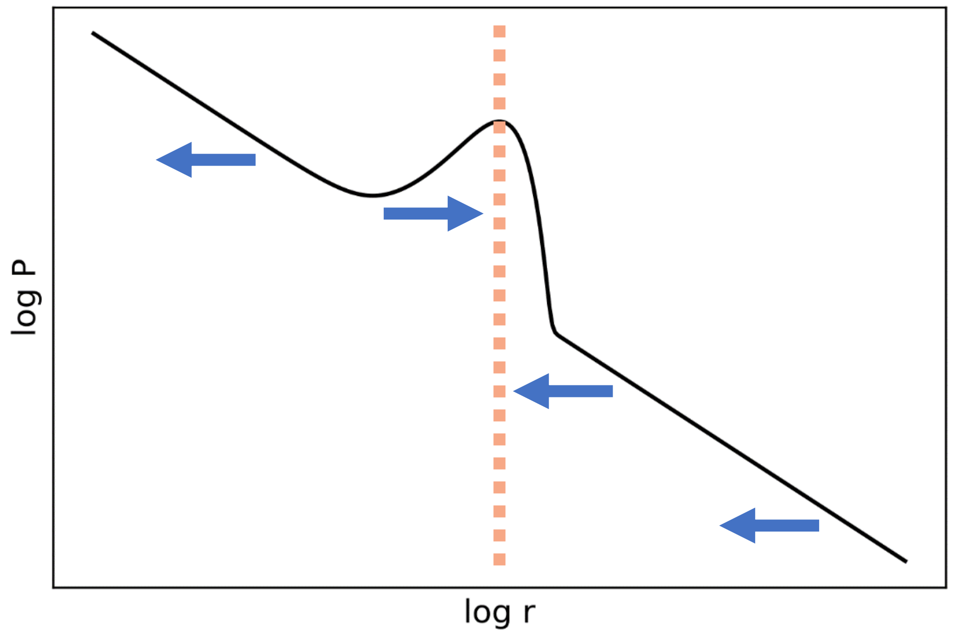
- Recall that gas revolves around the star at sub-Keplerian velocities
- Dust grains tend towards Keplerian velocities

  => dust grains feel gas drag

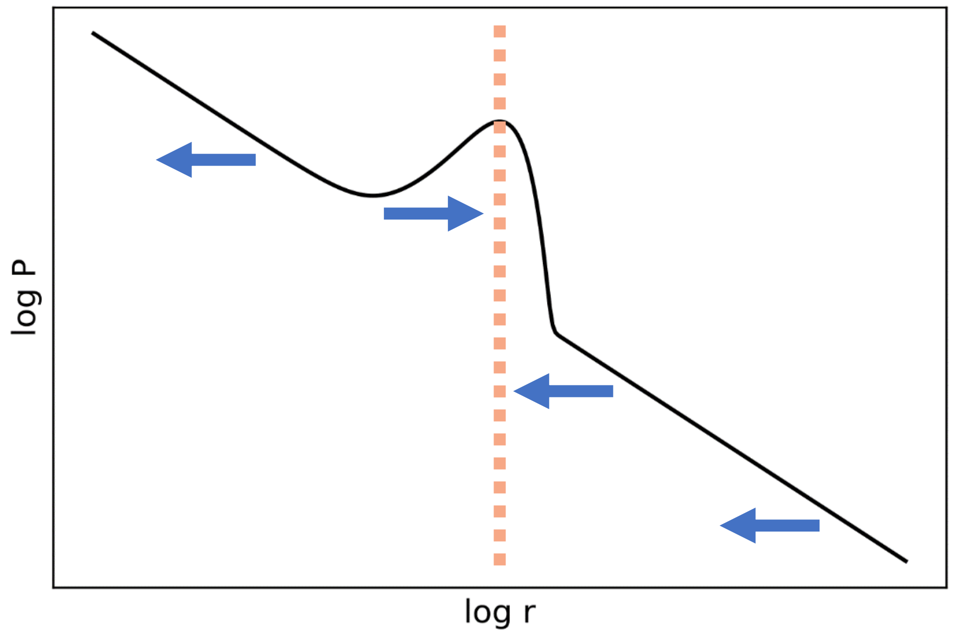
  => dust grains spiral towards the star

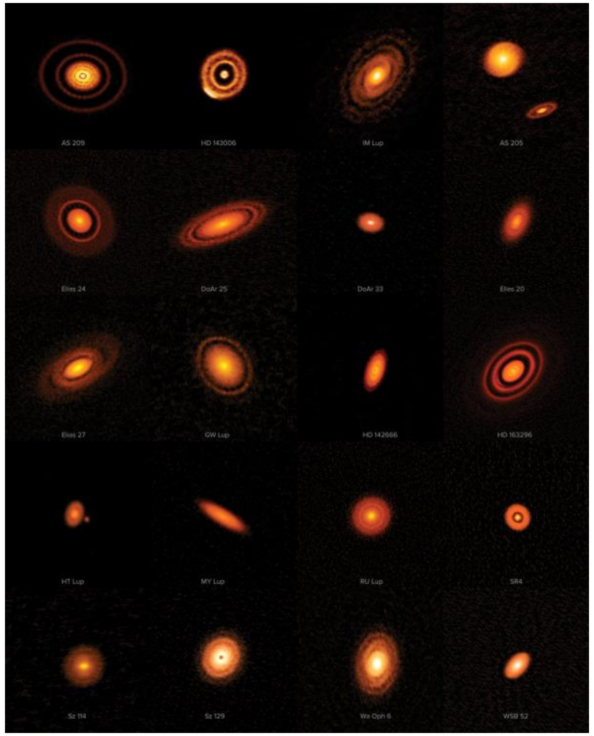


Radial drift of dust leads to concentration of dust in local pressure maxima



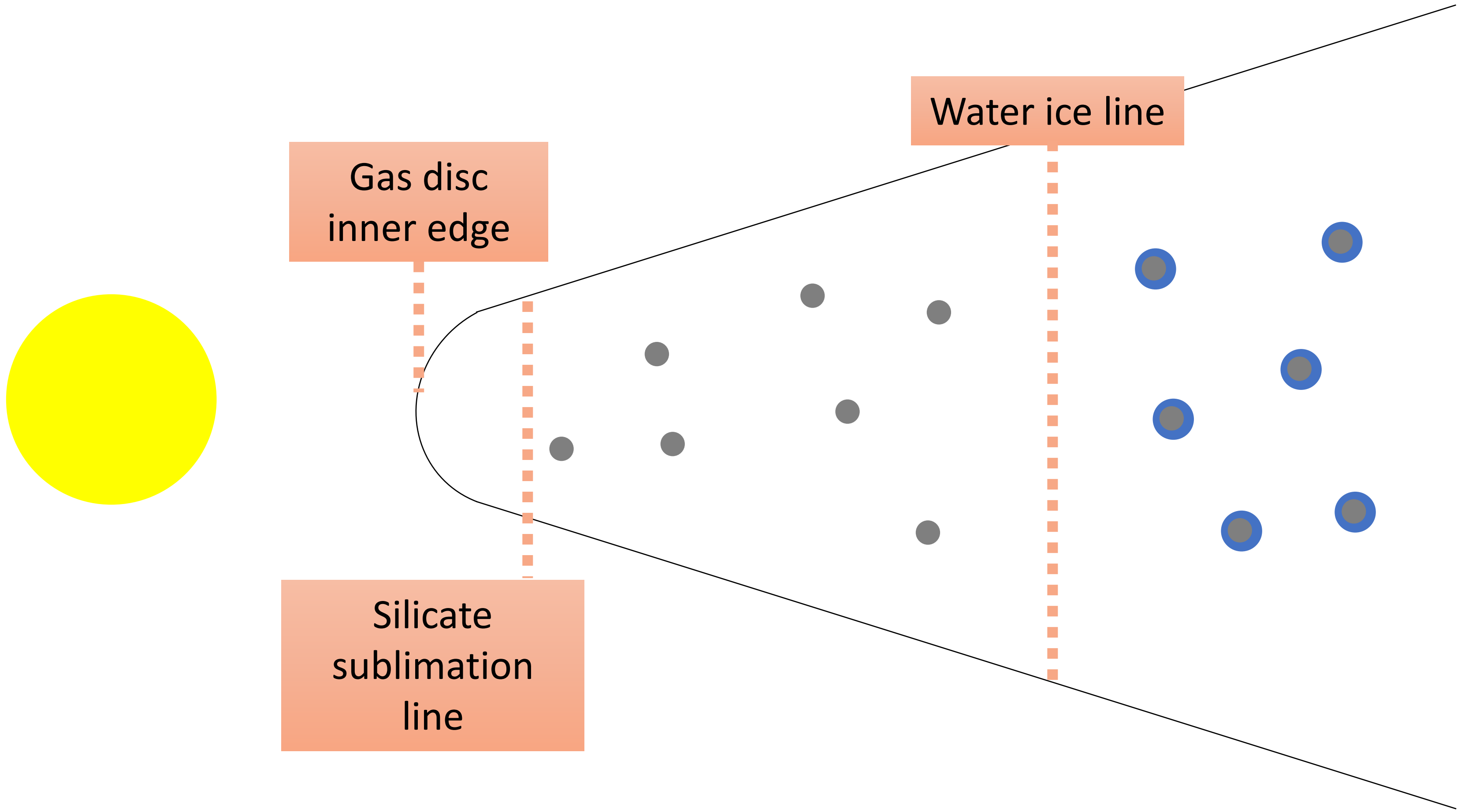
Radial drift of dust leads to concentration of dust in local pressure maxima





Dust continuum emission gallery from DSHARP program. Credit: ALMA (ESO/NAOJ/NRAO), S. Andrews et al.; NRAO/AUI/NSF, S. Dagnello

Dust sublimation lines



Summary of today's lecture

- Planets around other stars are numerous and diverse
- Planets form in discs of gas and dust surrounding newly-born stars
- These protoplanetary discs last a few million years, and during that time they accrete onto the star
- Protoplanetary discs are likely turbulent, which may or may not be driving accretion onto the star
- Evolution of dust is driven by gas drag
- Dust grains settle vertically and migrate radially in the disc

End of Lecture 1