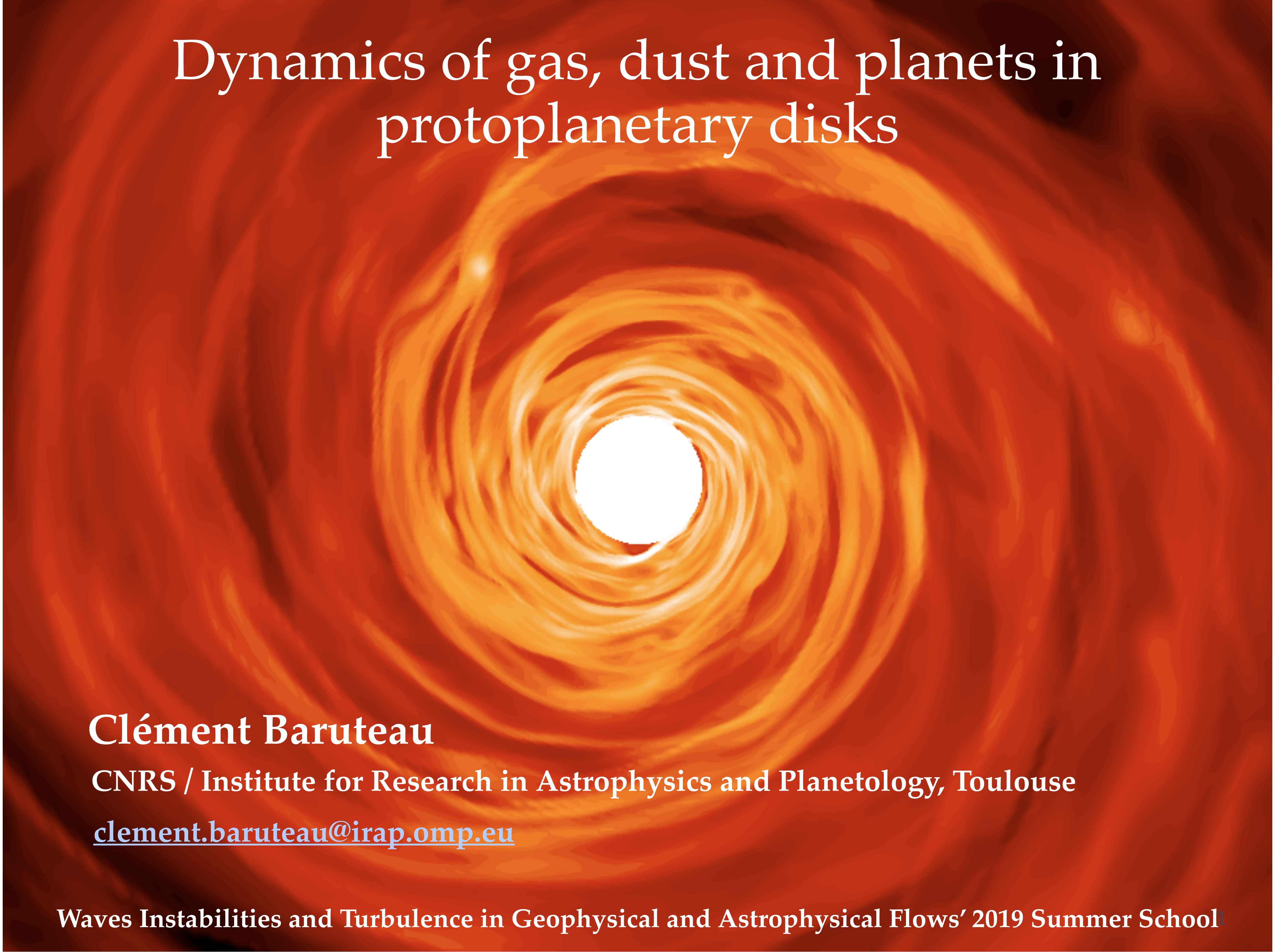

Dynamics of gas, dust and planets in protoplanetary disks

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Waves Instabilities and Turbulence in Geophysical and Astrophysical Flows' 2019 Summer School

Objectives and outline

- Give a **practical** overview of the **physical** processes that drive the dynamics of protoplanetary disks

    ❶ disks **observations**

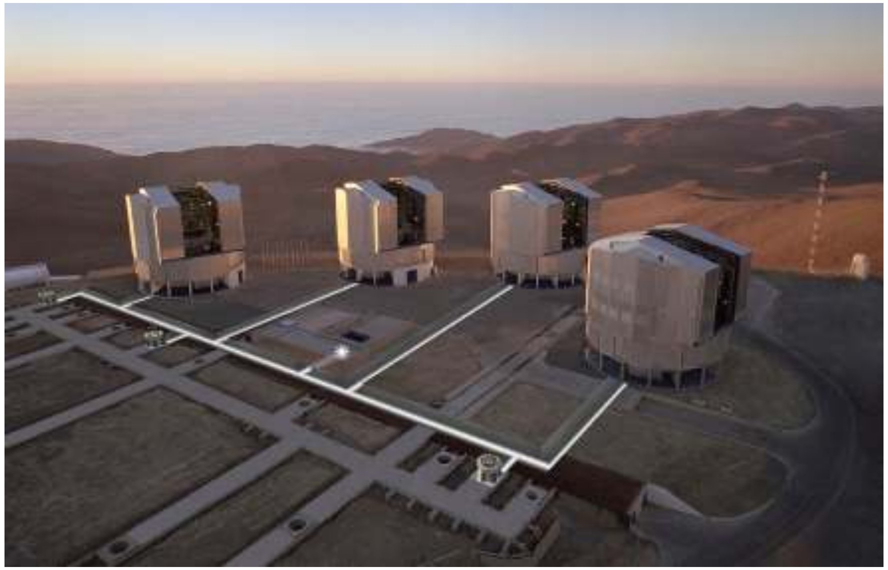
    ❷ **gas**: base flow, MHD instabilities, turbulence - we'll try to draw **analogies** with instabilities in planetary / stellar dynamics

    ❸ **dust**: drift relative to gas, growth, streaming instability

    ❹ **planet**: wakes and orbital evolution (low-mass planets)

- Discuss whether these processes can account for the **evolution** of disks and their **observed** features (spirals, vortices, rings…)

Lecture 1: Observations of gas and dust in protoplanetary disks



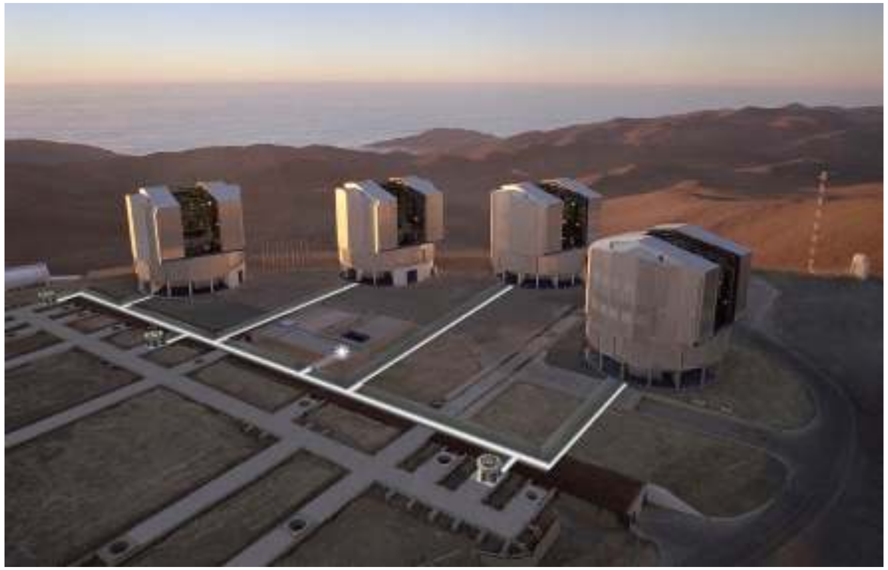
VLT telescopes (optical/near-infrared) @Atacama desert, Chile

ALMA array of 66 radio antennas @Atacama desert, Chile

Suggested references:

- Williams & Cieza 2011, ***Protoplanetary Disks and their Evolution*** arxiv.org/abs/1103.0556
- Andrews 2015, ***Observations of solids in protoplanetary disks*** arxiv.org/abs/1507.04758

Lecture 1: Observations of gas and dust in protoplanetary disks



VLT telescopes (optical/near-infrared) @Atacama desert, Chile

ALMA array of 66 radio antennas @Atacama desert, Chile

typical **size** of a protoplanetary disk ~100 au
(1 au = 1 astronomical unit = Sun-Earth mean distance ≈ 1.5×10^{11} m)

typical **distance** of nearby disks ~150 pc
(1 pc = 1 parsec ≈ 206265 au)

→ typical **angular size** ~ 0.66″
(1″ = 1 arcsecond = 1/3600 degree ≈ 1/206265 radian)

best angular **resolution** of a telescope
(diffraction limit):

wavelength

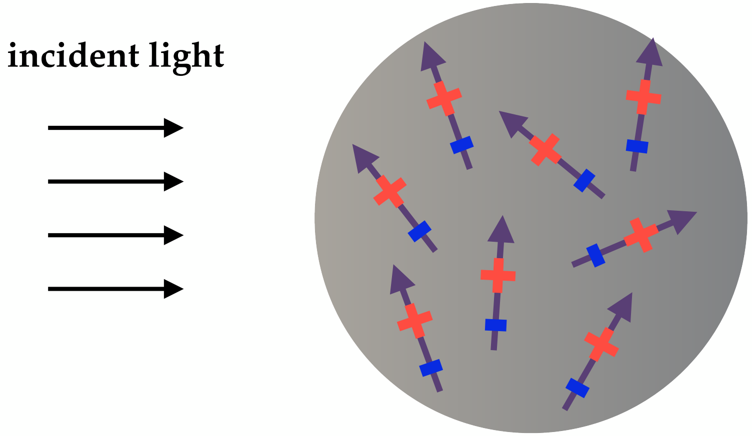
$$\Delta\theta \sim \frac{\lambda}{D} \sim 0.03'' \times \left(\frac{\lambda}{1\,\mu\mathrm{m}}\right)\left(\frac{D}{10\,\mathrm{m}}\right)^{-1}$$

telescope diametre

→ use of **interferometry** at **radio λ**, where
D becomes the distance between antennas

How do protoplanetary disks emit light?

- by **scattering** and **thermal** re-**emission** of starlight by **dust** grains



dust grain conceptually subdivided into discrete electric charges, with dipole moments induced by incident light

- electric field of incident light sets the electric **charges** in the **dust** into **oscillatory** motion. The electromagnetic energy radiated by these **accelerated** charges is known as **scattered light**
- the excited charges also transform part of the incident electromagnetic energy into **thermal energy**, which is re-emitted at **all wavelengths** as a **continuum emission**
- scattered light and thermal emission depend on the **size**, **shape** and **chemical composition** of dust grains, the **wavelength** of incident radiation etc.

→ **scattered light** dominates the disks emission at $\lambda \lesssim$ **1μm**, and arises from **sub-μm dust** grains near the disks **surface**

→ **thermal emission** dominates at $\lambda >$ **a few μm**, and mostly arises from **dust** with **size** $\approx \lambda$. The longer λ, the colder the dust that primarily contributes to thermal emission

How do protoplanetary disks emit light?

- by **scattering** and **thermal** re-**emission** of starlight by **dust** grains
- by collisions / excitations of **gas atoms** or **molecules**
  - disk gas **heats up** in several ways: **collisions** with other gas molecules / atoms, with dust grains, and via **photoelectric heating** (electrons **ejected** from dust grains **collide** with gas)

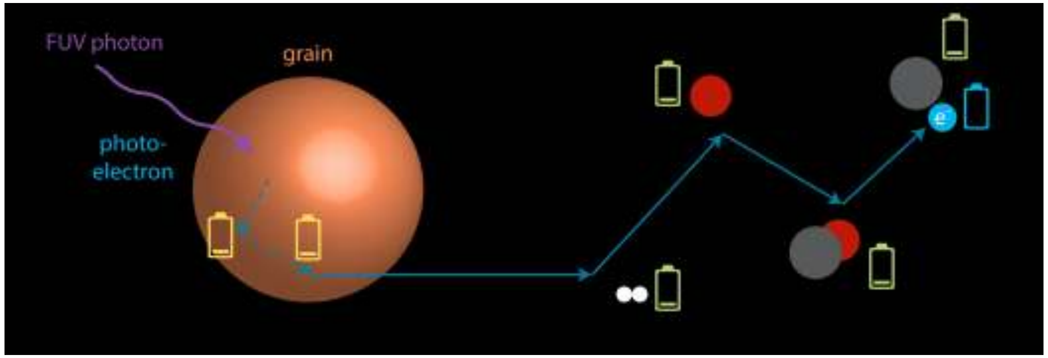
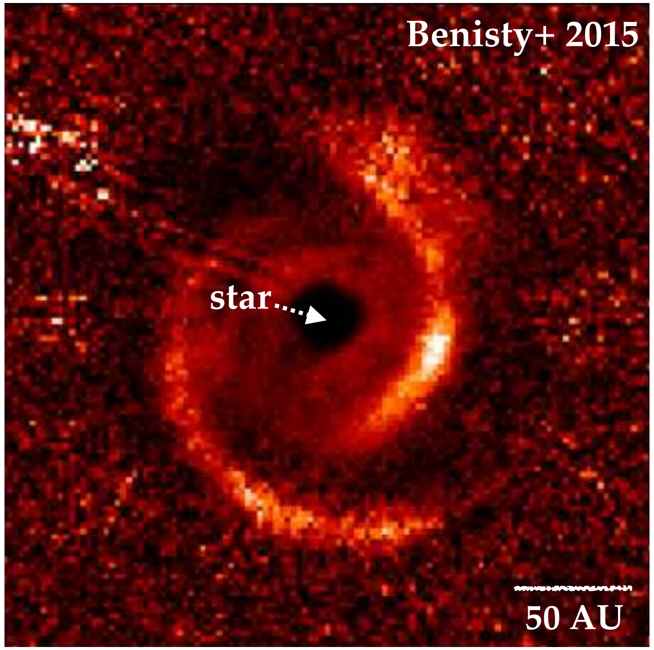


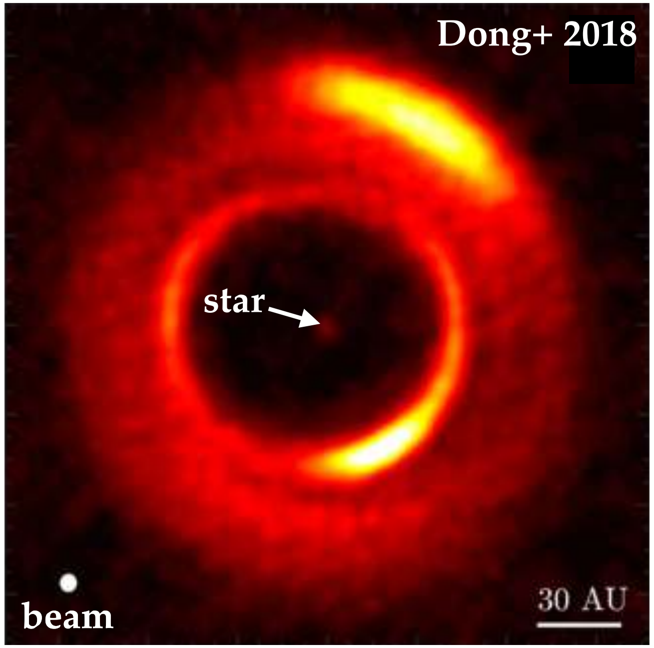
illustration of photoelectric heating by Jason Champion

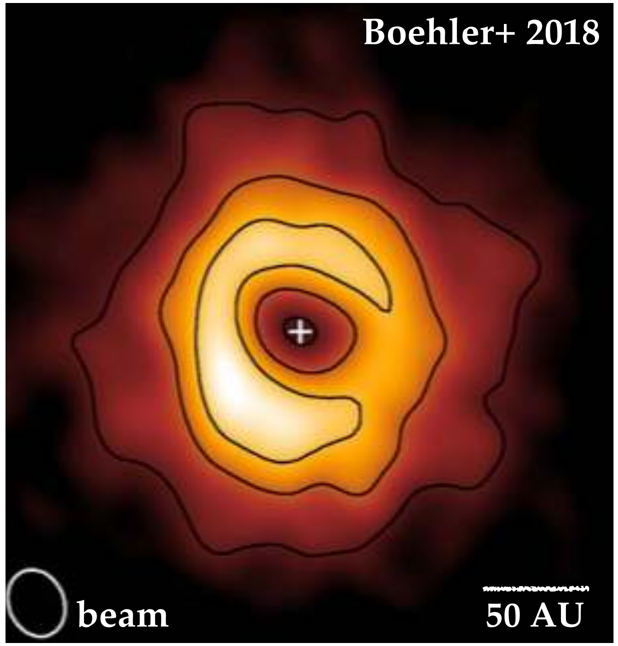
  - gas **cools down** and thus **radiates** by emission of photons at very **specific** wavelengths
  - gas emission is sensitive to temperature, to chemistry

How do protoplanetary disks emit light?

- by **scattering** and **thermal** re-**emission** of starlight by **dust** grains
- by collisions/excitations of **gas atoms** or **molecules**
- protoplanetary disks may look very **different** when seen in the **dust** or the **gas**, and when observed at different λ - this is well illustrated by the disk around the star MWC 758:







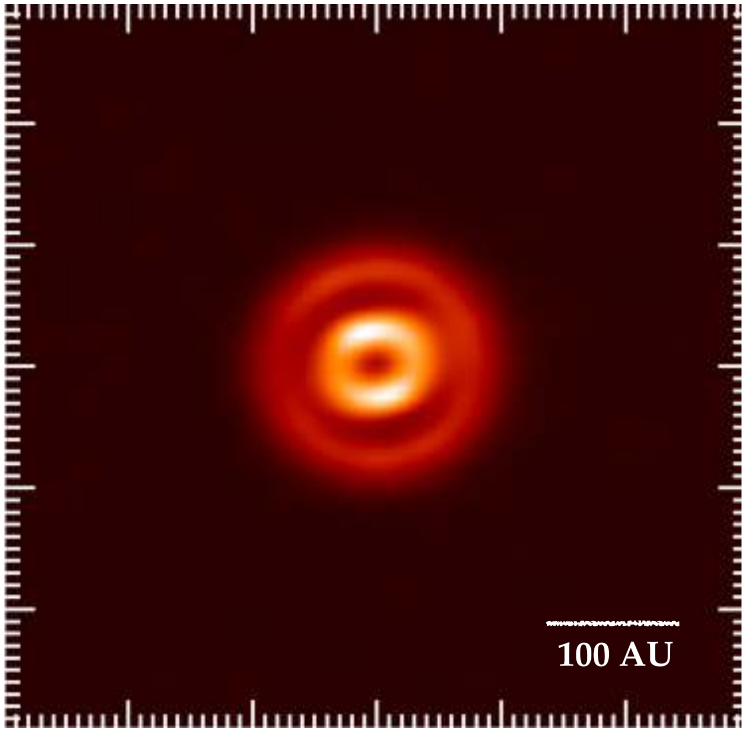
near-IR scattered light (λ~1.0μm) | **dust continuum emission (λ~0.9mm)** | **gas ^{13}CO emission (λ~0.9mm)**

→ **spirals?**

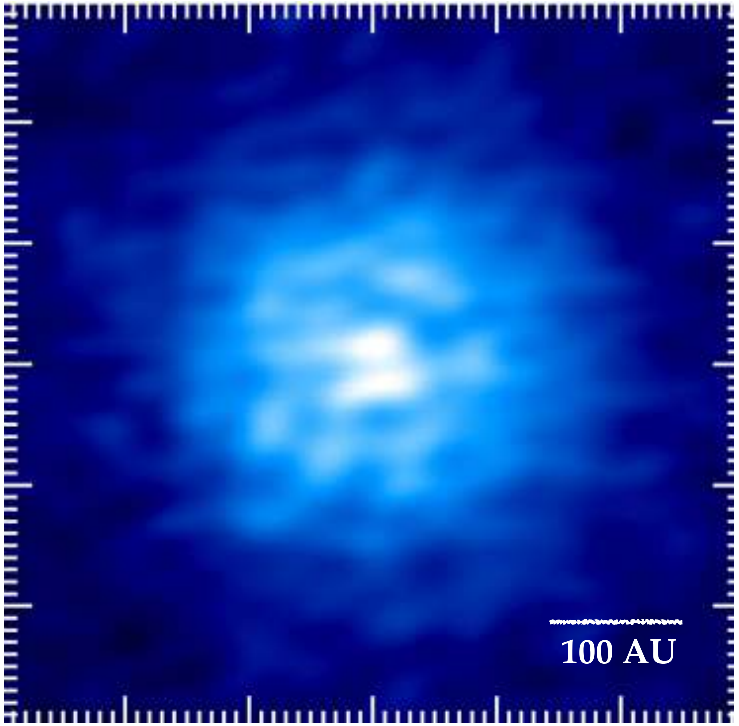
→ **asymmetric rings? vortices?**

Size of protoplanetary disks

- Disks have a **radius** (R) of typically **~100 au**
  - disks very often look **smaller** when observed in the **dust** than in the gas



dust continuum emission (λ~1.3mm)

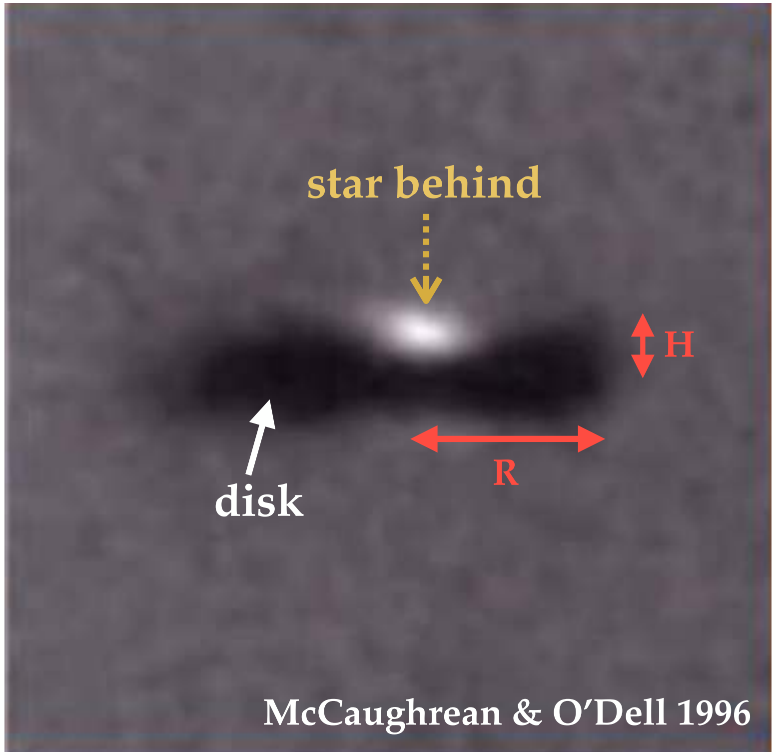


gas ^{13}CO emission (λ~1.36mm)

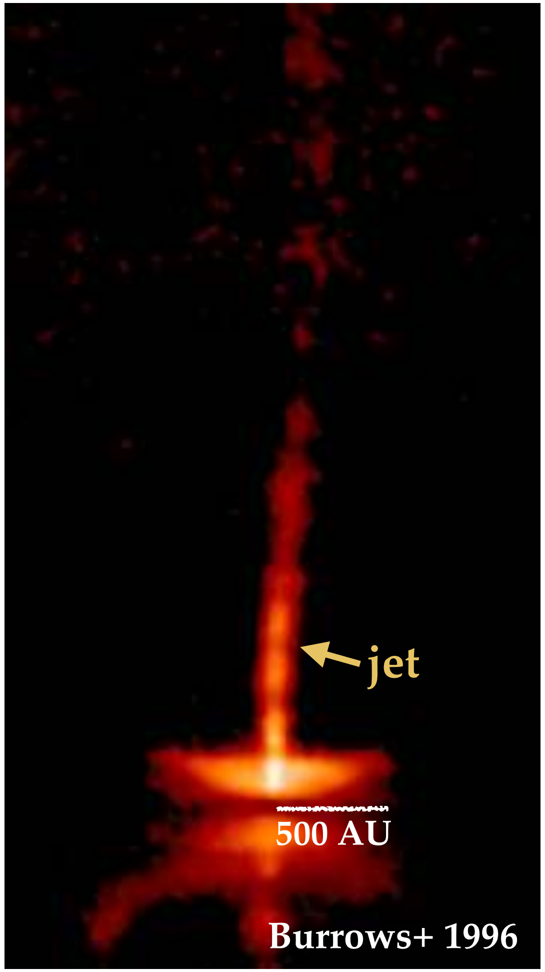
Fedele+ 2017 (HD 169142 disk)

Size of protoplanetary disks

- Disks have a **radius** (R) of typically **~100 au**
  - disks very often look **smaller** when observed in the **dust** than in the gas
- Edge-on disks have a vertical height H ≪ R
  - H/R~0.1 at R~100 au



disk in the *Orion* star-forming region
(gas emission line composite in the optical)

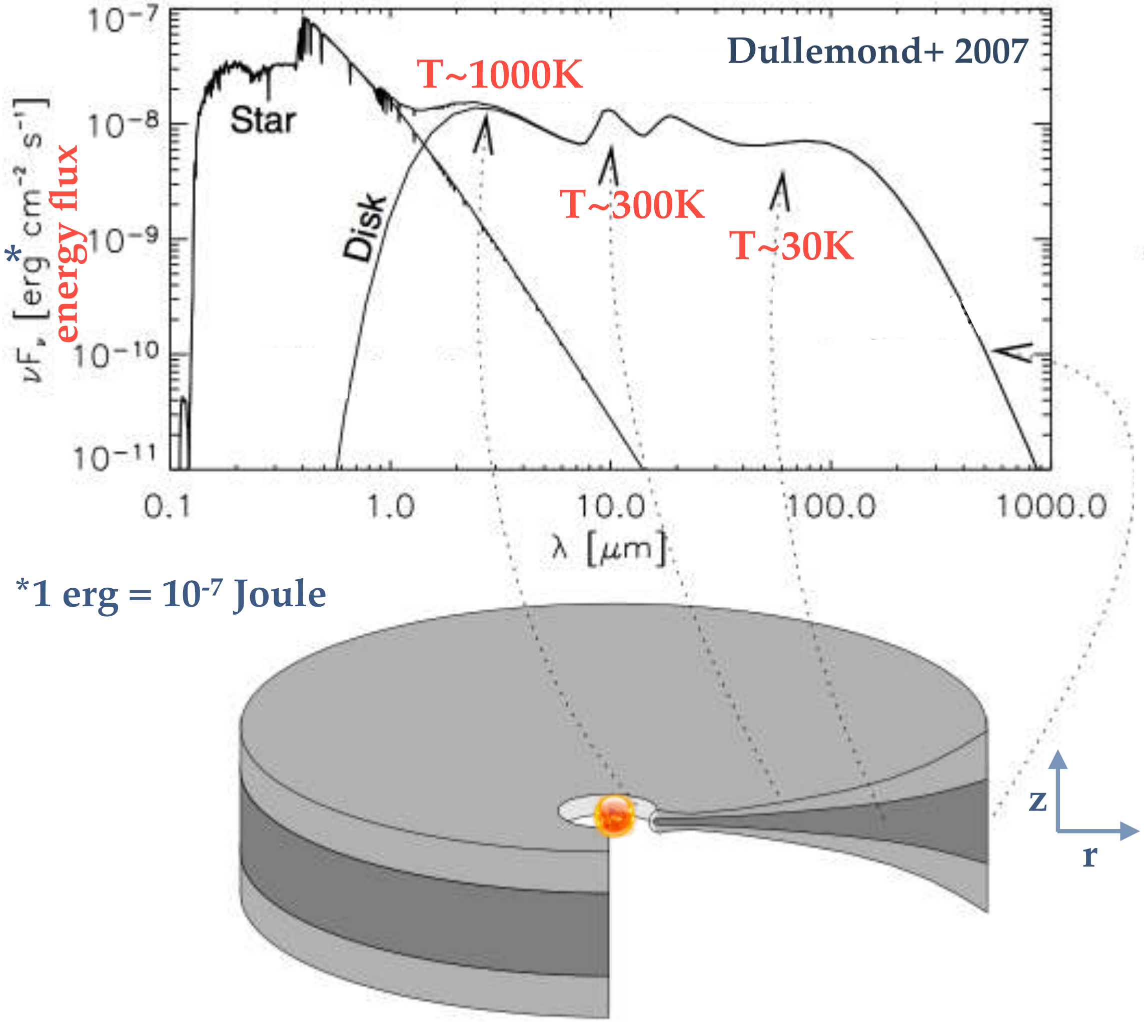


disk and jet around star HH 30 in the
Taurus star-forming region (optical)

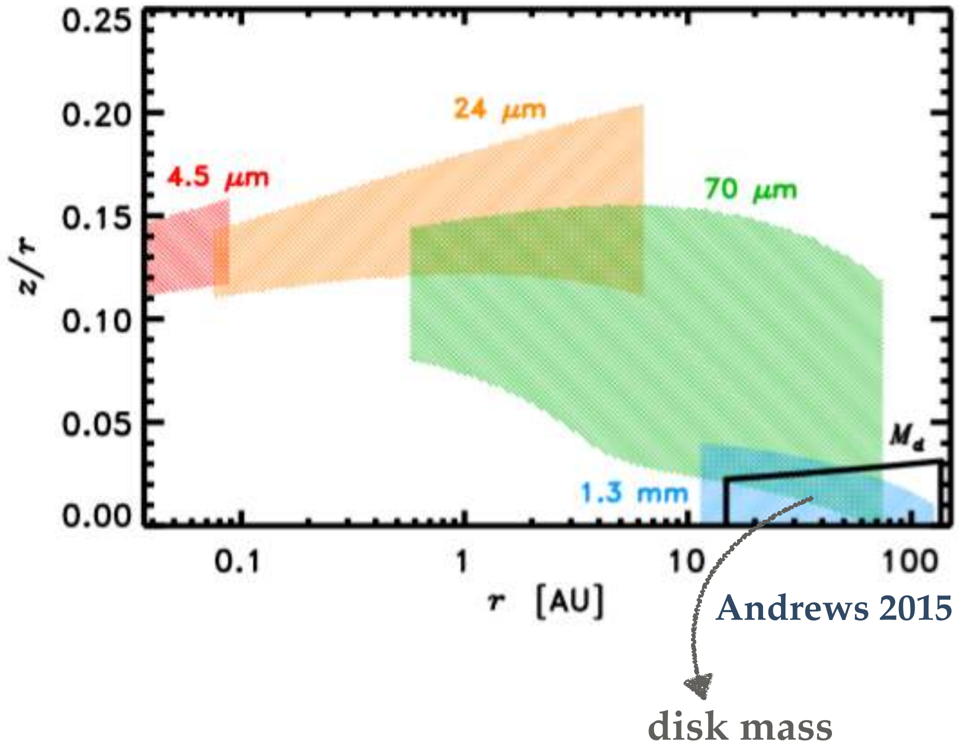
Mass of protoplanetary disks

- The mass of **dust** can be **estimated** via the **flux** of the **continuum** emission at **radio λ**

Spectral Energy Distribution (SED):



*1 erg = 10^{-7} Joule



Mass of protoplanetary disks

- The mass of **dust** can be **estimated** via the **flux** of the **continuum** emission at **radio λ**

  - By solving the dust radiative transfer equation, it can be shown that the **specific intensity** of dust thermal emission reads

$$I_\nu = B_\nu(T_{\rm dust})(1 - e^{-\tau}) \qquad \text{with} \qquad \tau \sim \kappa_\nu \Sigma_{\rm dust} \quad \text{the optical depth}$$

Planck function (B_ν); dust temperature ($T_{\rm dust}$); dust's absorption opacity (κ_ν); dust's surface density ($\Sigma_{\rm dust}$)

<u>N.B.</u> **specific intensity I_ν :** **energy flux** (energy per unit time, per unit area of the object) **per unit solid angle** that the radiation is measured over, **per unit frequency** of the radiation

  - **optically thick** (**$\tau \gg 1$**) thermal emission only probes **dust temperature**
  - **optically thin** (**$\tau \lesssim 1$**) thermal emission probes both **dust temperature <u>and</u> density**

  - If dust emission is optically **thin**, which turns out to be more likely at **radio λ**, we get

see, e.g., Andrews 2015

$$M_{\rm dust} \approx \frac{d^2 F_\nu}{\kappa_\nu B_\nu(T_{\rm dust})}$$

d: disk distance

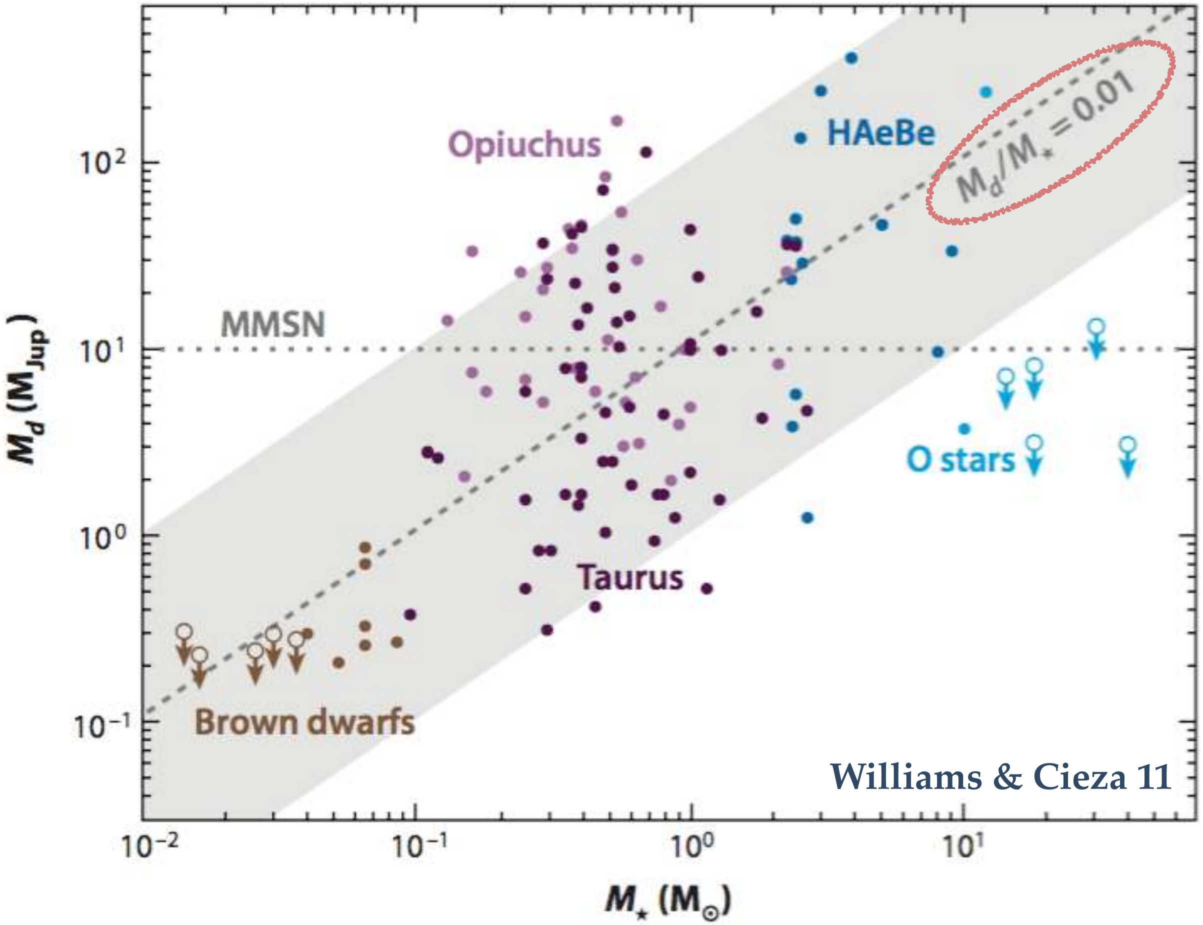
F_ν : energy flux per unit frequency (directly measured by <u>observations</u>)

Mass of protoplanetary disks

- The mass of **dust** can be **estimated** via the **flux** of the **continuum** emission at **radio λ**

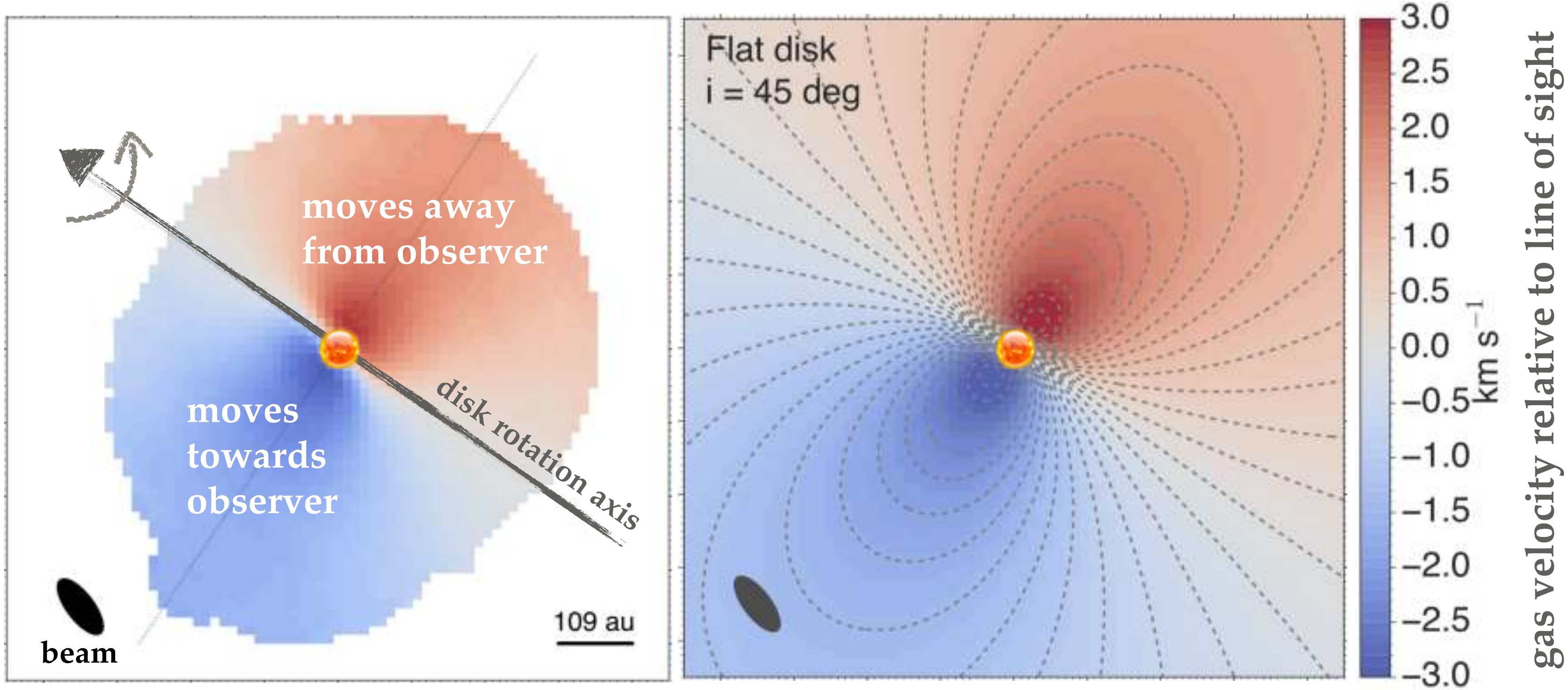
- The **total** mass of the disk (gas+dust) is commonly inferred assuming a **gas-to-dust mass ratio of 100**, an ***educated guess*** inherited from studies of the interstellar medium. But **it's highly uncertain!**

  → $M_{disk} \sim 0.01 M_\star$ over a **wide range of stellar masses**, but with a large **scatter**



Rotation of protoplanetary disks

- Gas **kinematics** as a **probe** of **Keplerian rotation**
  - gas **emission** lines observed in **narrow frequency bands** around expected line frequency allows to measure **gas velocity** relative to line of sight via the **Doppler effect**



ALMA observations (λ~0.87mm) of the ^{12}CO gas kinematics in the disk around HD 100546

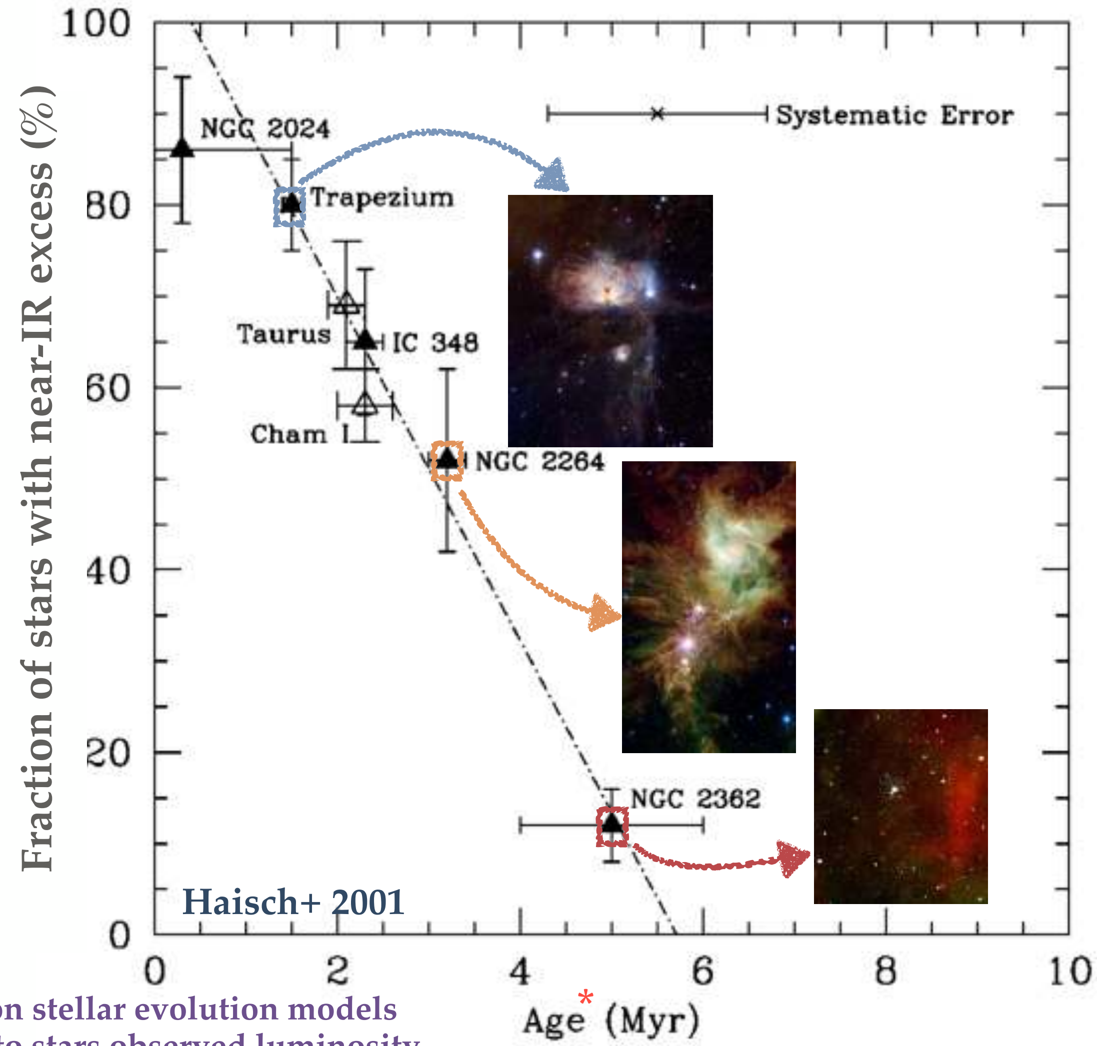
Keplerian disk model that best fits these observations

Walsh+ 2017

  - method can estimate the **mass** of the **star**!
  - some disks show **departure** from Keplerian rotation (inflows? sub-stellar/planet companions?)

Lifetime of protoplanetary disks

- can be estimated as the typical age of stars from which the **IR excess** in the SED **disappears**
  - **hard** to estimate **age** of individual **young stars** accurately
  - in practice: take **star-forming regions** (coeval stars) and find for each the **fraction of stars with near-IR excess**



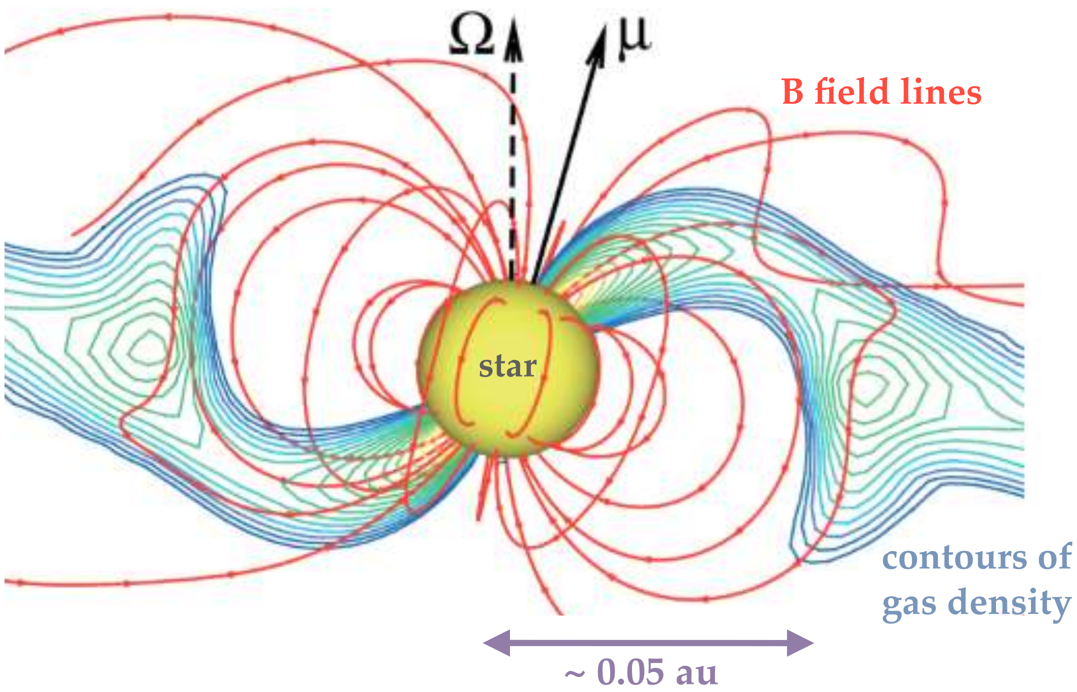
→ **lifetime ~ a few Myr**

NB: this traces the **lifetime of hot dust close to the star** (not that of the disk gas, nor that of the cold dust far from the star)

*based on stellar evolution models applied to stars observed luminosity and surface temperature

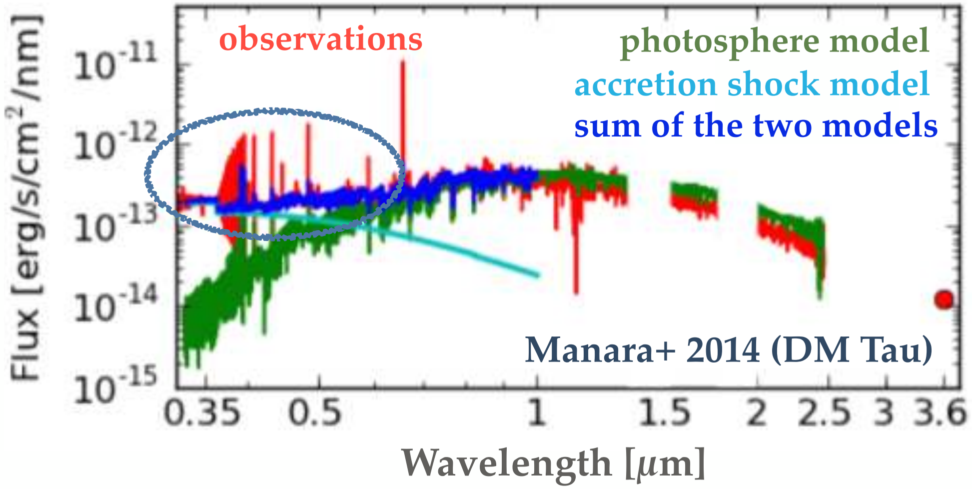
Disks accretion rate on the star

- **accretion shock** on the stellar surface induces many **gas lines** in emission that blend and form an **UV excess** in the SED
- Modeling of the shock gives quantitative estimate of **stellar accretion rate $\dot{M}$**



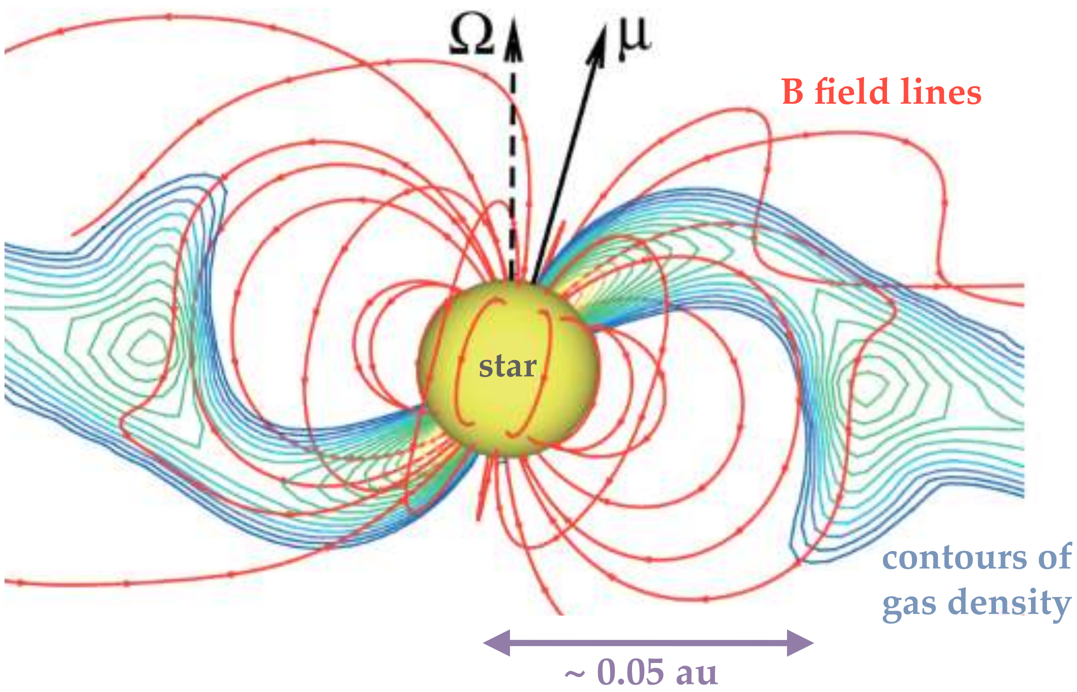
Ω: spin angular momentum
μ: magnetic moment

Romanova+ 2004



Disks accretion rate on the star

- **accretion shock** on the stellar surface induces many **gas lines** in emission that blend and form an **UV excess** in the SED
- Modeling of the shock gives quantitative estimate of **stellar accretion rate $\dot{M}$**
- Protoplanetary disks typically have $\dot{M} \sim 10^{-8}\, M_\odot\, yr^{-1}$ with a large scatter and age dependence



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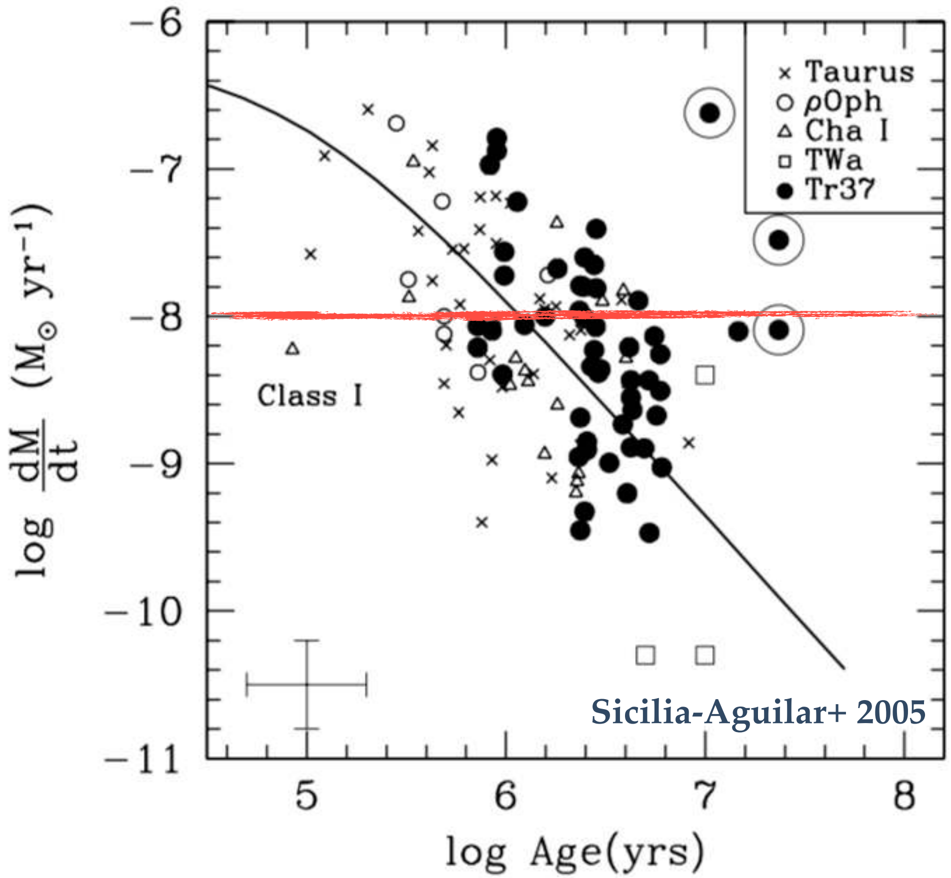

A few summary points

- Protoplanetary disks are geometrically **thin** ($H \ll R$), **rotationally-supported** structures of gas and dust around newly born stars

- They have a typical radius **~100 AU**, a total mass (gas+dust) of **~10^{-2} M_{star},** and a lifetime of a few **10^6 yr** at most

- Stellar accretion rates are typically **~10^{-8} $M_\odot$ yr^{-1}** which, along with the rather short lifetime, implies that gas mass must be efficiently **transported** through or **removed** from disks

- Gas and dust behave **differently** in protoplanetary disks

- **Radial discontinuities** and (large-scale) **asymmetries** may be **common** features of the dust's continuum **emission**