Planet formation with ALMA: the summary

AstroTwin Colombia School 2022

Planet formation and ALMA

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Leiden Observatory

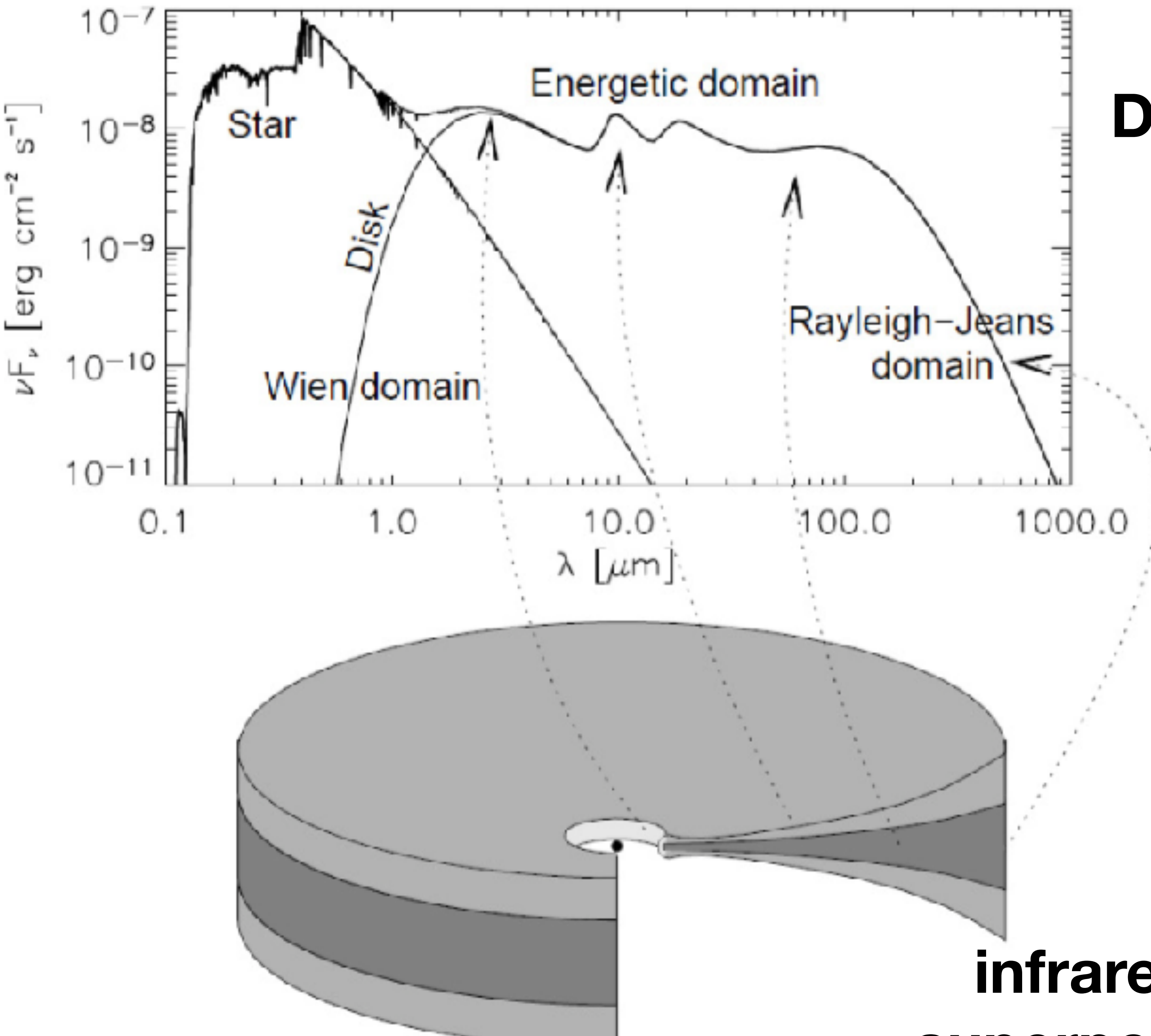
What are the typical densities and temperatures in clouds and disks?

What's it like out there?

- **Conditions very different from Earth!**
- Typical conditions:
    - Diffuse clouds: T_{kin}~100 K, n~100 cm^{-3}
    - Dense clouds: T_{kin}~10-100 K, n~10^4-10^8 cm^{-3}
    - Disk: T_{kin}~10-1000 K, n~10^8-10^{13} cm^{-3}
- In clouds: 100 times more gas than dust!
- Compare atmosphere at sea level:
  T_{kin}~300 K, n~3 10^{19} cm^{-3}

How do dust and gas emit radiation?

SED of a disk

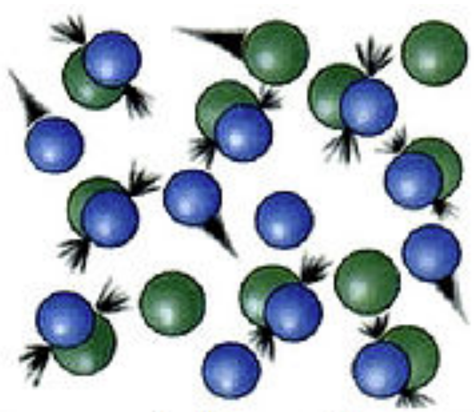


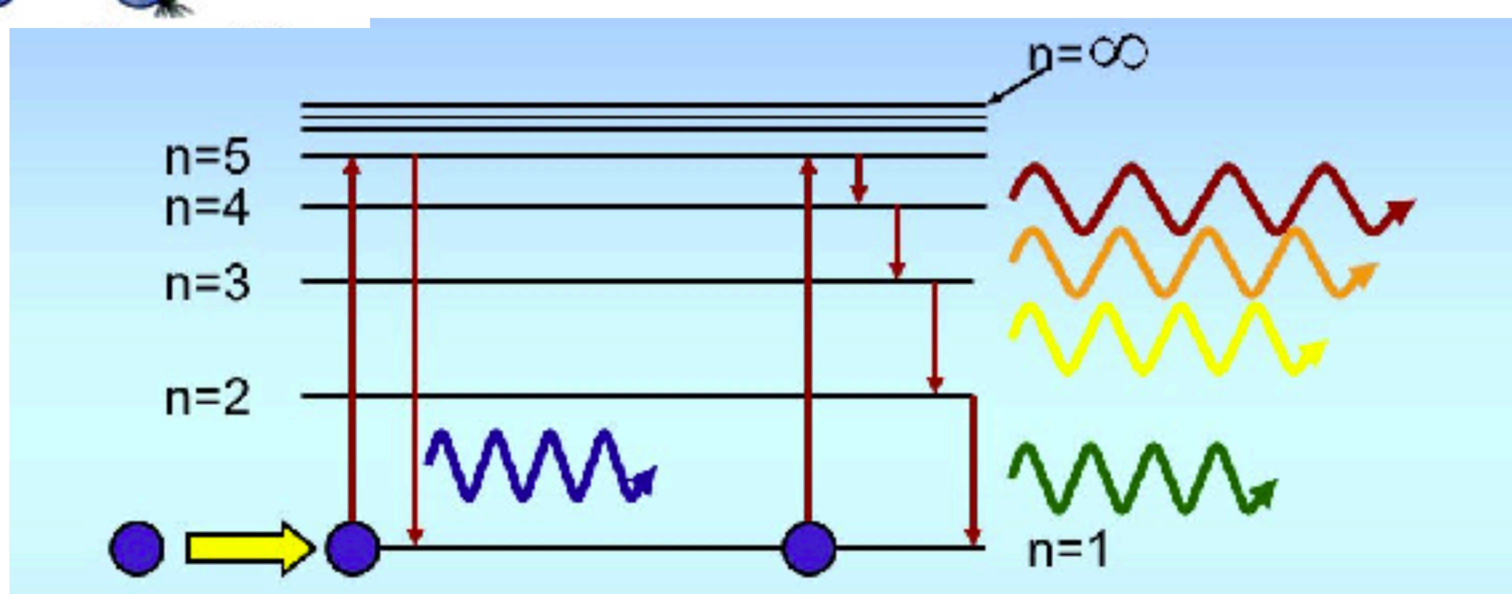
Dust in disk gets heated up by the star: radial temperature gradient

infrared to mm emission: superposition of blackbodies

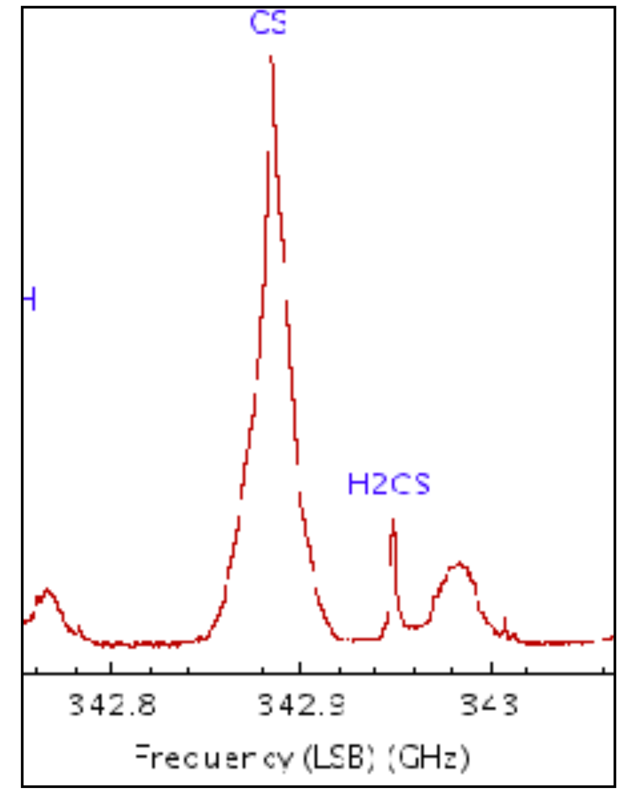
Line excitation

Molecules move around randomly and occasionally collide (more collisions at higher temperature and/or higher density)





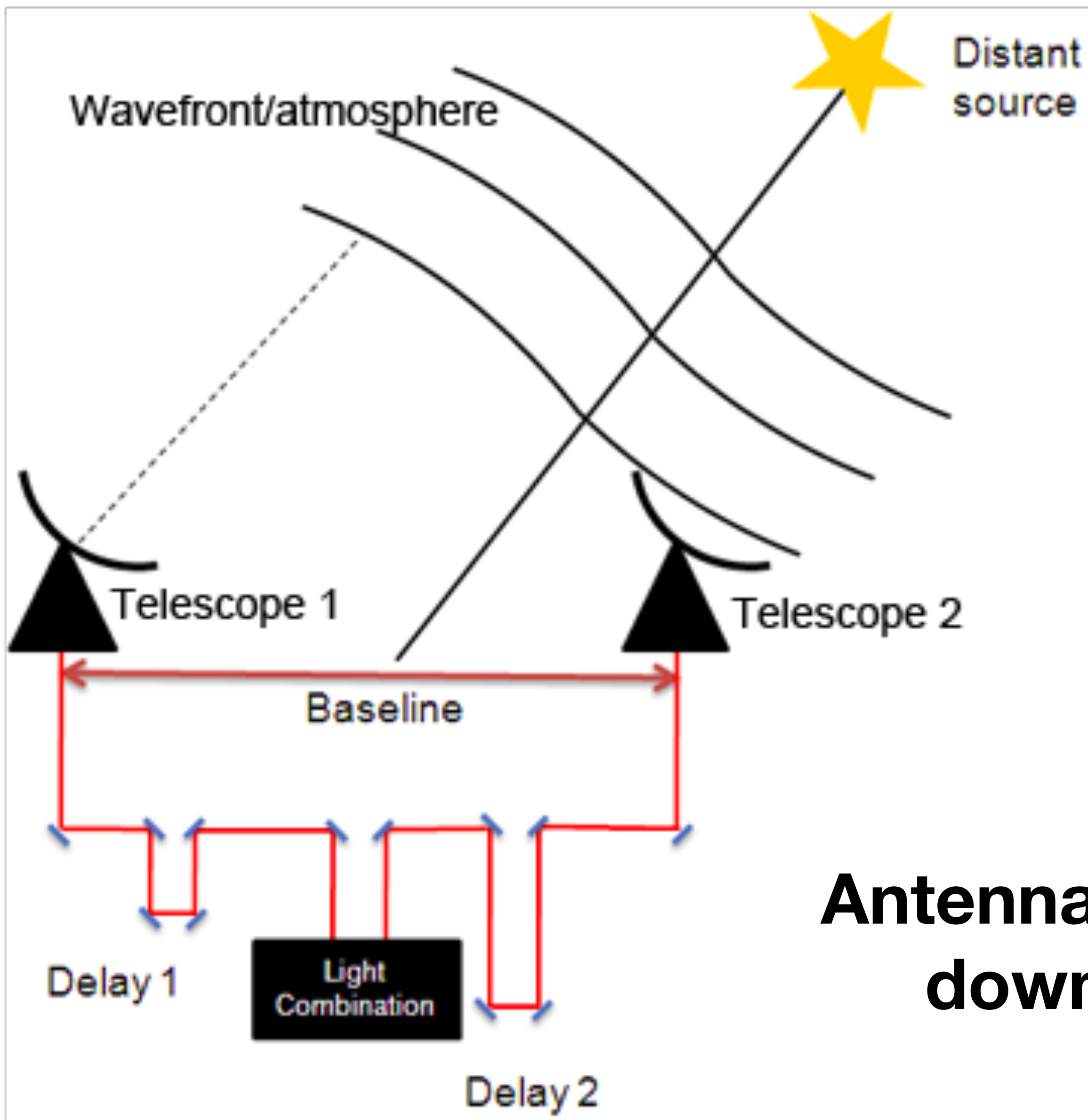
A collision brings a molecule in a higher energetic state



The molecule emits a photon (spontaneous emission) at a specific frequency to get back to lower energy.
The frequency is unique for each molecule and each transition ('fingerprint')

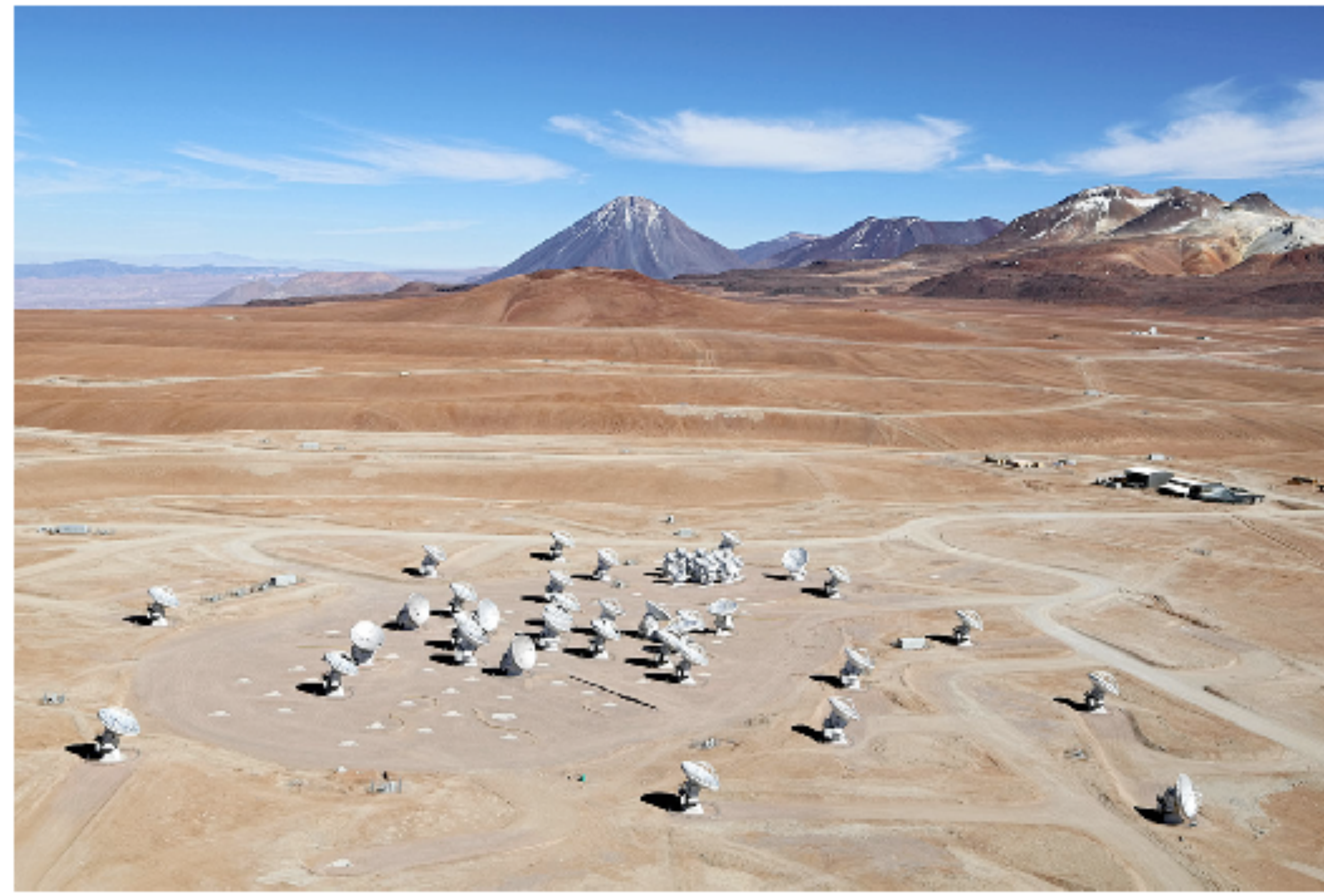
Why is ALMA so much more powerful than Spitzer in disk studies?

Interferometry



Resolution:
λ/baseline length

ALMA: Atacama Large Millimeter/submillimeter Array



Antennas at ~500 m distances:
down to ~0.4” resolution

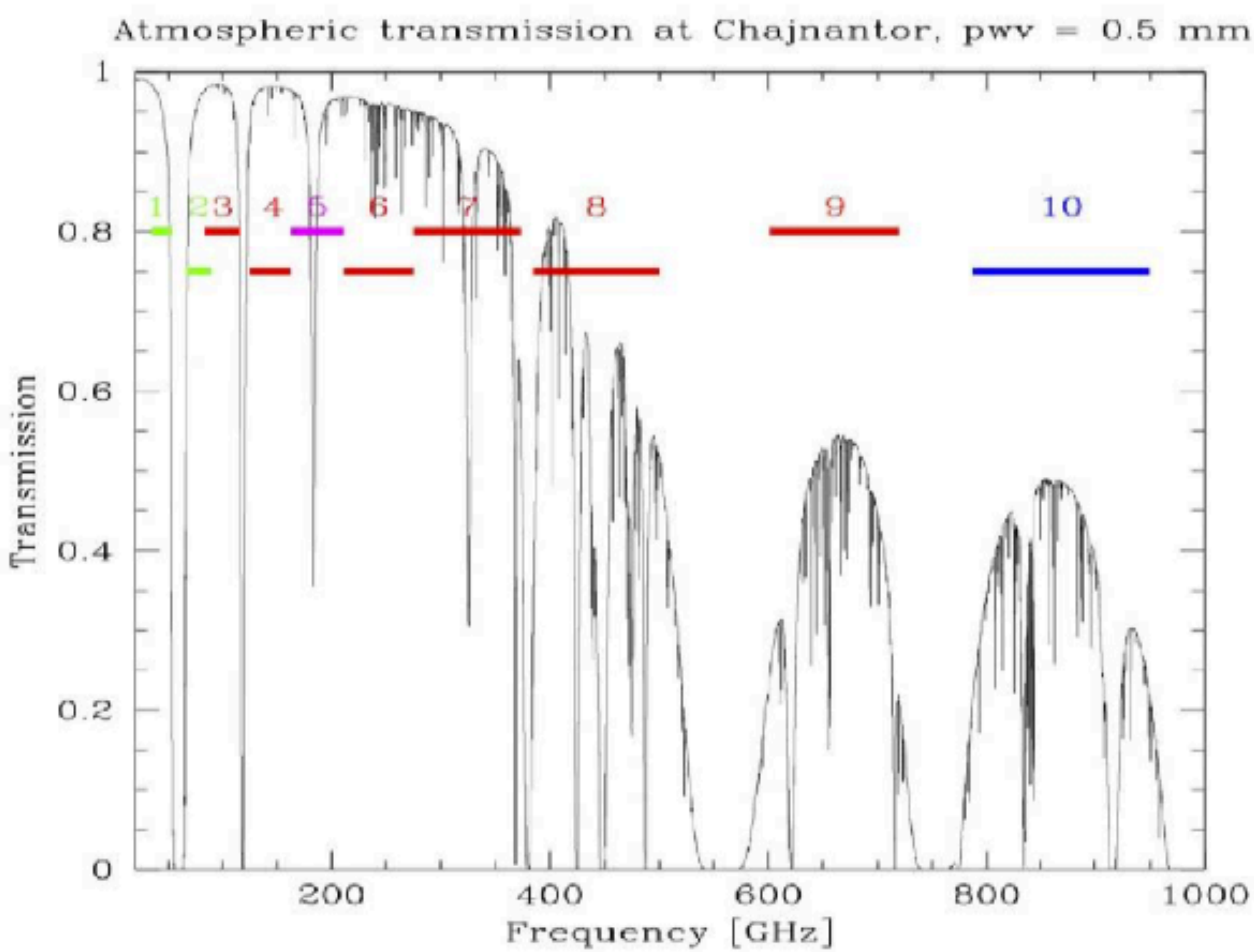
ALMA at 16 km distances:
down to 0.02” resolution

Why is ALMA split up in frequency bands?

ALMA bands

Bands are in between H_2O absorption frequencies

- ALMA Bands: atmosphere

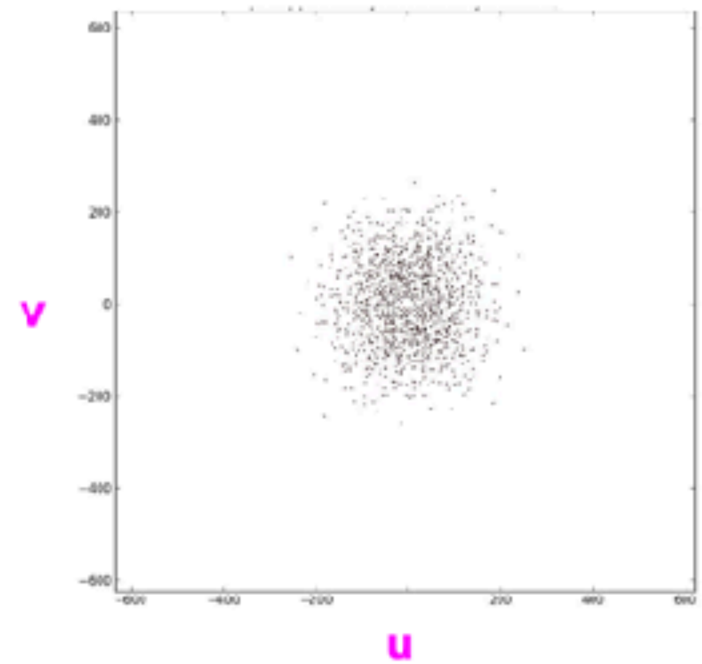


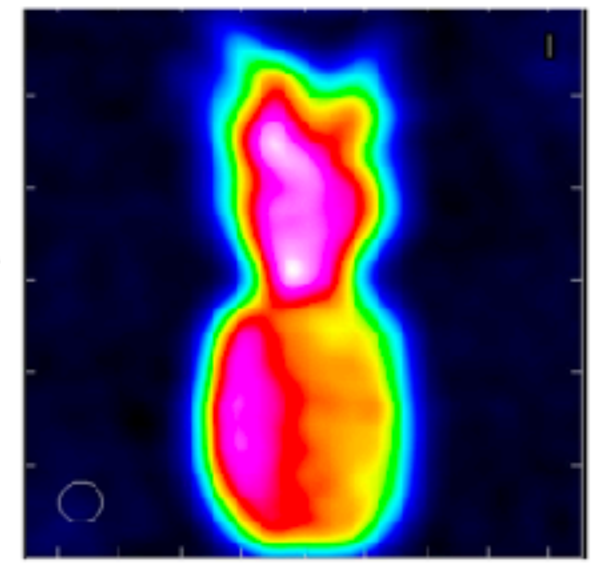
40-900 GHz

What happens if you only measure the emission at long baselines, and not at short baselines?

Demo uv-coverage

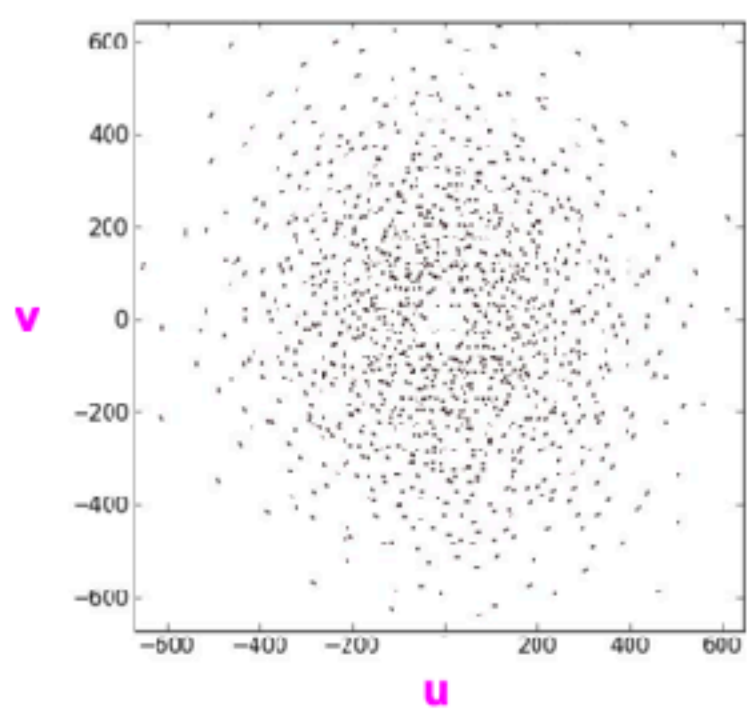
- Interferometers have a **spatial sampling** and **beam shape** determined by their **configuration.**
- **Extended** array configurations (large uv-distances) sample **small scales.**
- **Compact** array configurations (small uv-distances) sample **large scales.**

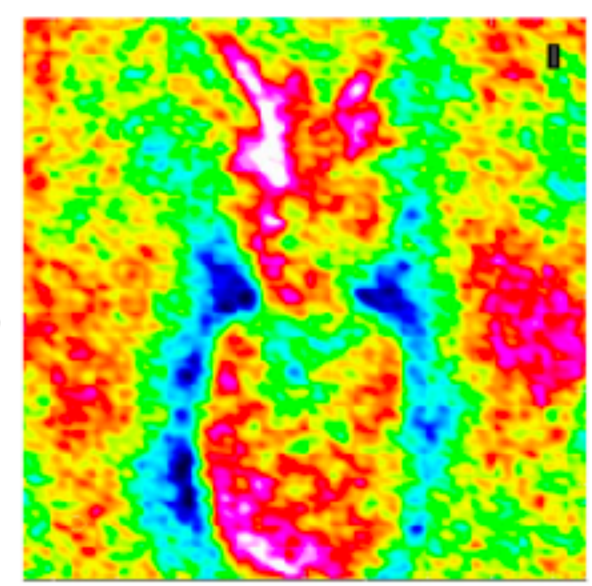




Fourier Domain (uv-plane) Sampling

What ALMA sees:



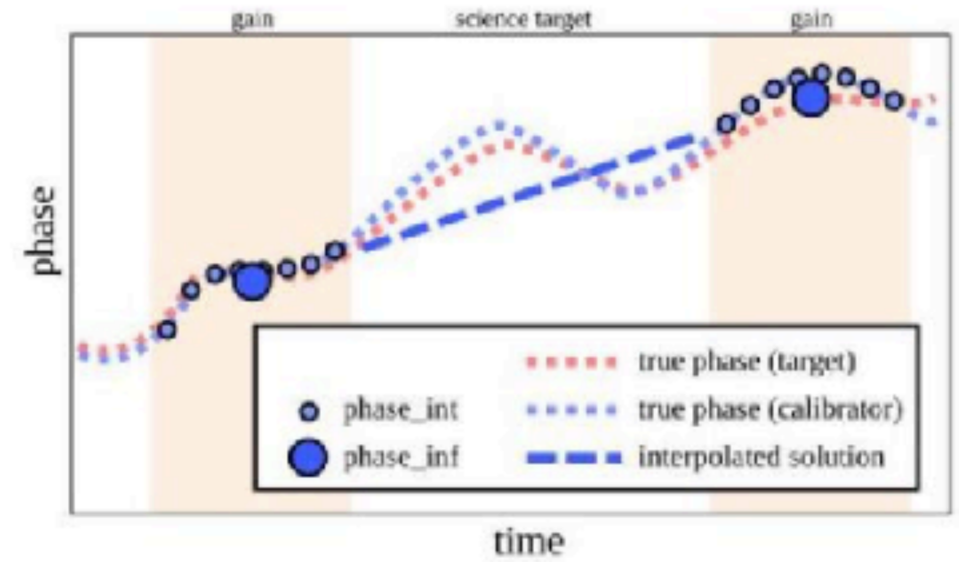


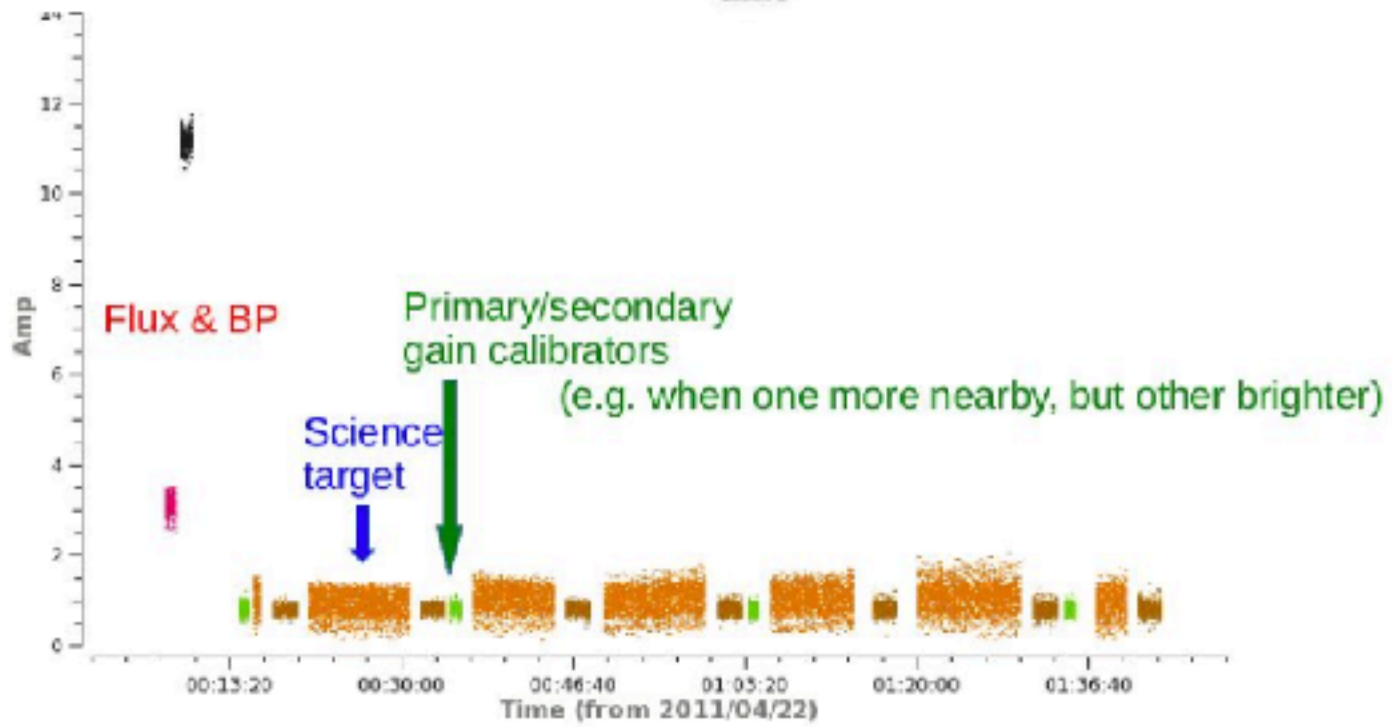
Why is it necessary to do phase calibration during an ALMA observation?

Phase calibration

Phase (gain) Calibration

- Atmospheric turbulence causes large, time variable phase observations **during** an observation.
- Short science target scans are bracketed by observations of a phase calibrator.
- Calibration solutions are interpolated in time to science observations.



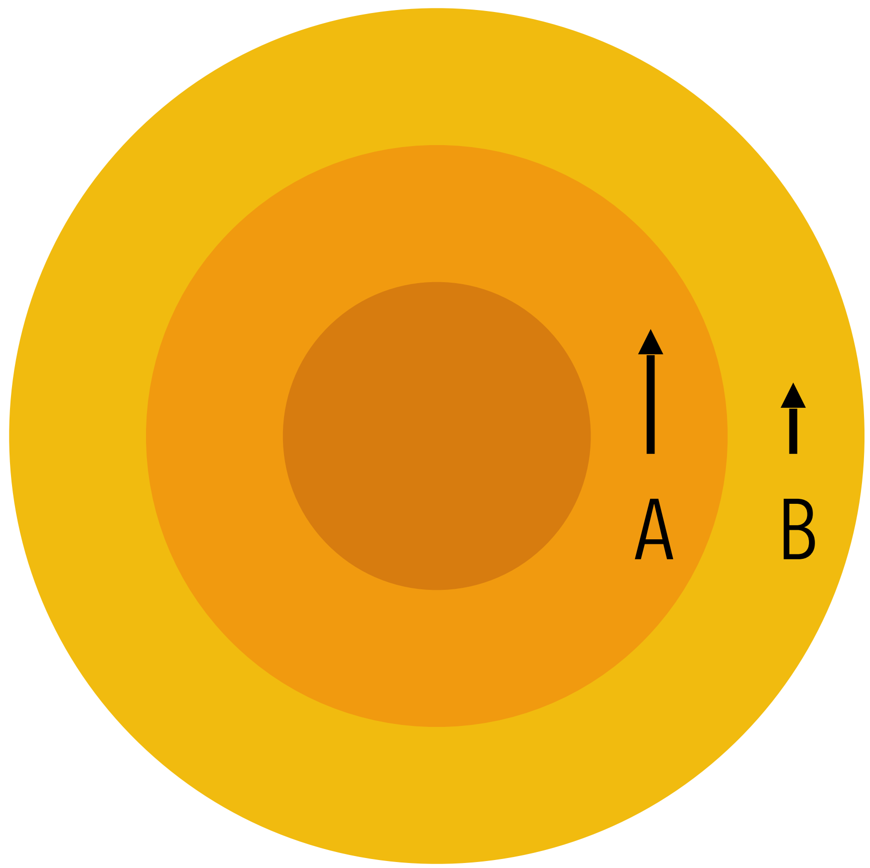


Why does a disk spread in the viscous accretion disk model?

Angular momentum transport

- Ring A moves faster than ring B.

- Friction between A & B slows A down, speeds B up. Therefore ang. mom. transferred from A to B.



- Specific angular momentum for a Keplerian disk:

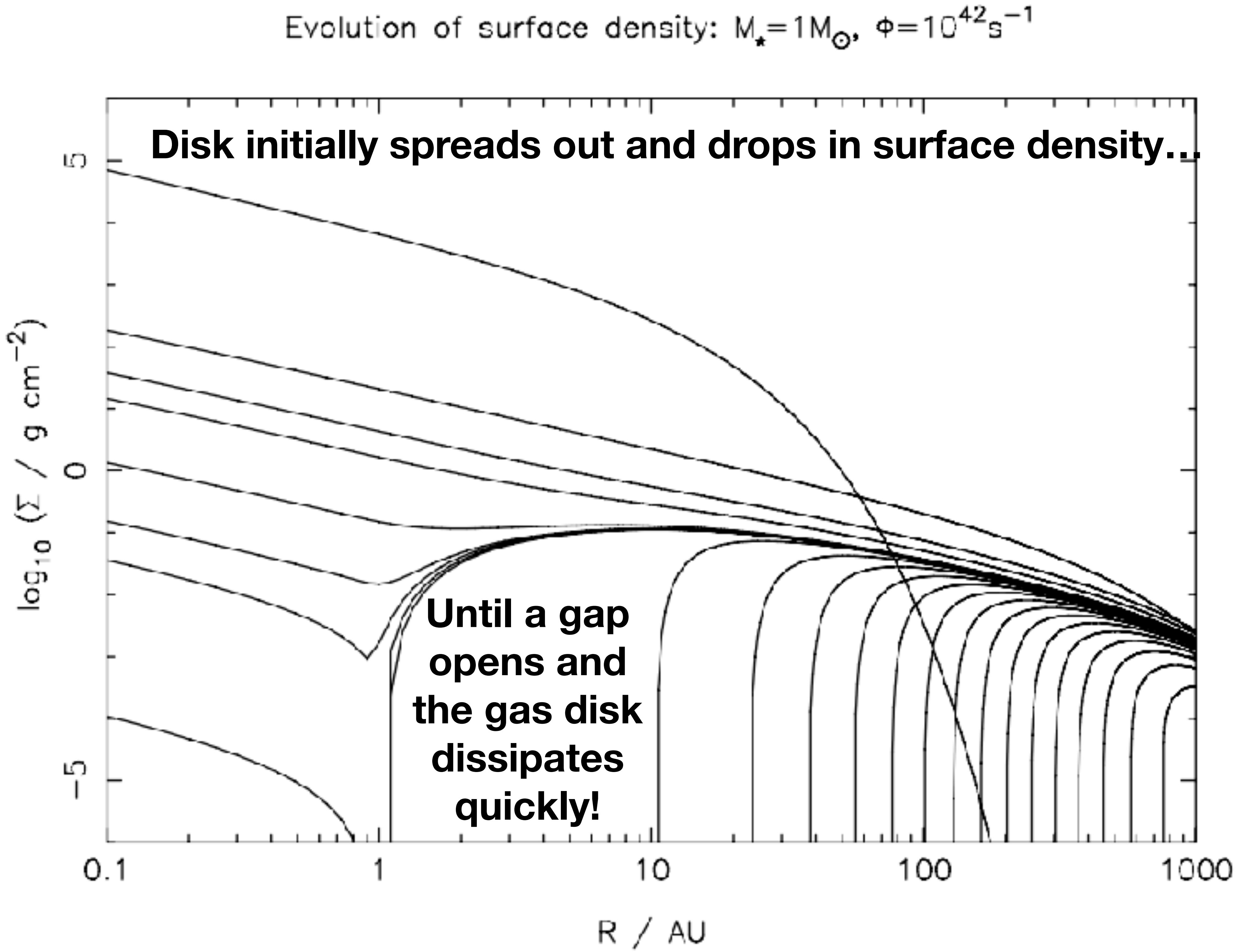
$$l = r\mathrm{v}_\phi = r^2\Omega_K = \sqrt{GM_* r}$$

- So if ring A looses angular momentum (but forced to keep Kepler orbit), it must move inward!

- Ring B moves outward (unless there are additional external rings C, D, etc.).

How does a gas disk dissipate?

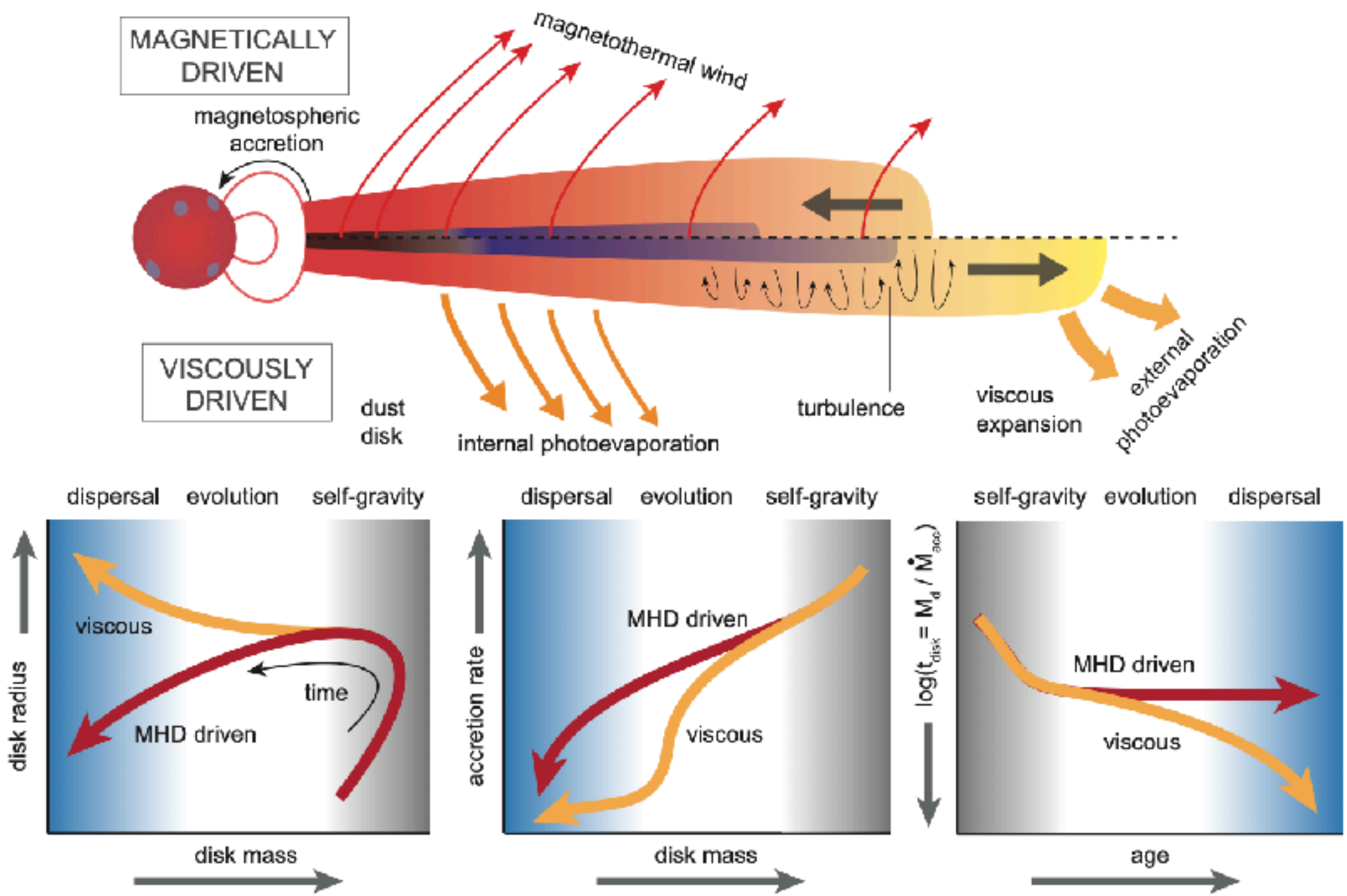
Photoevaporation and disk evolution



Alexander et al. 2013 (PPVI)

What is the alternative evolution scenario instead of the viscous disk model?

MHD disk wind model

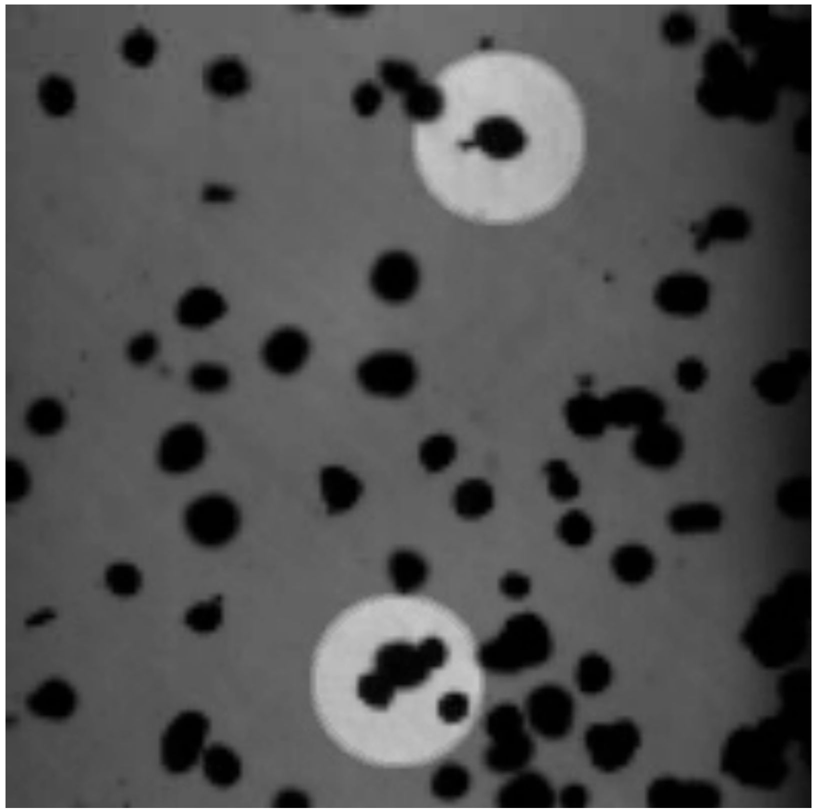


Manara et al. 2022 (PPVII)

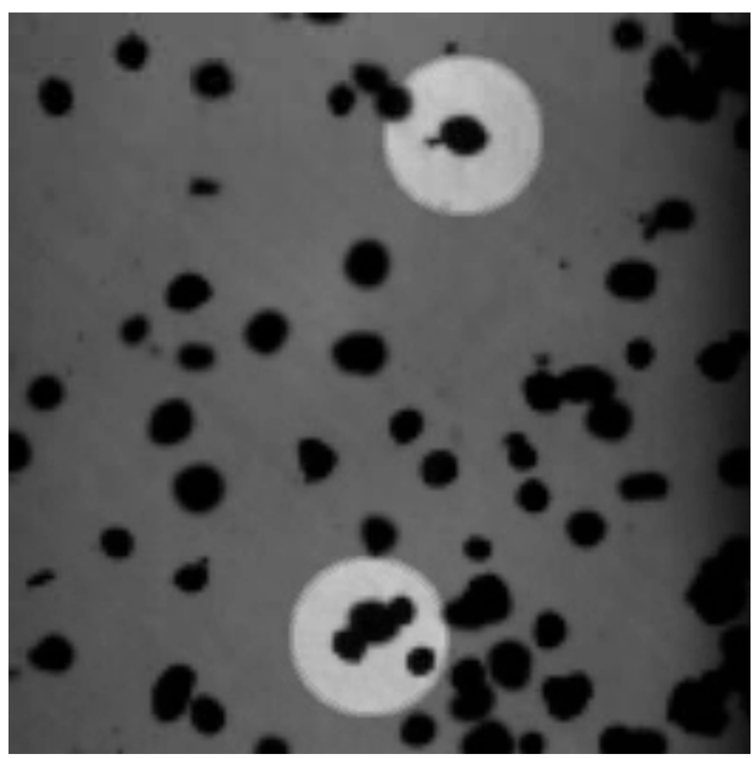
What are the different things that can happen when two grains collide?

Collision outcome

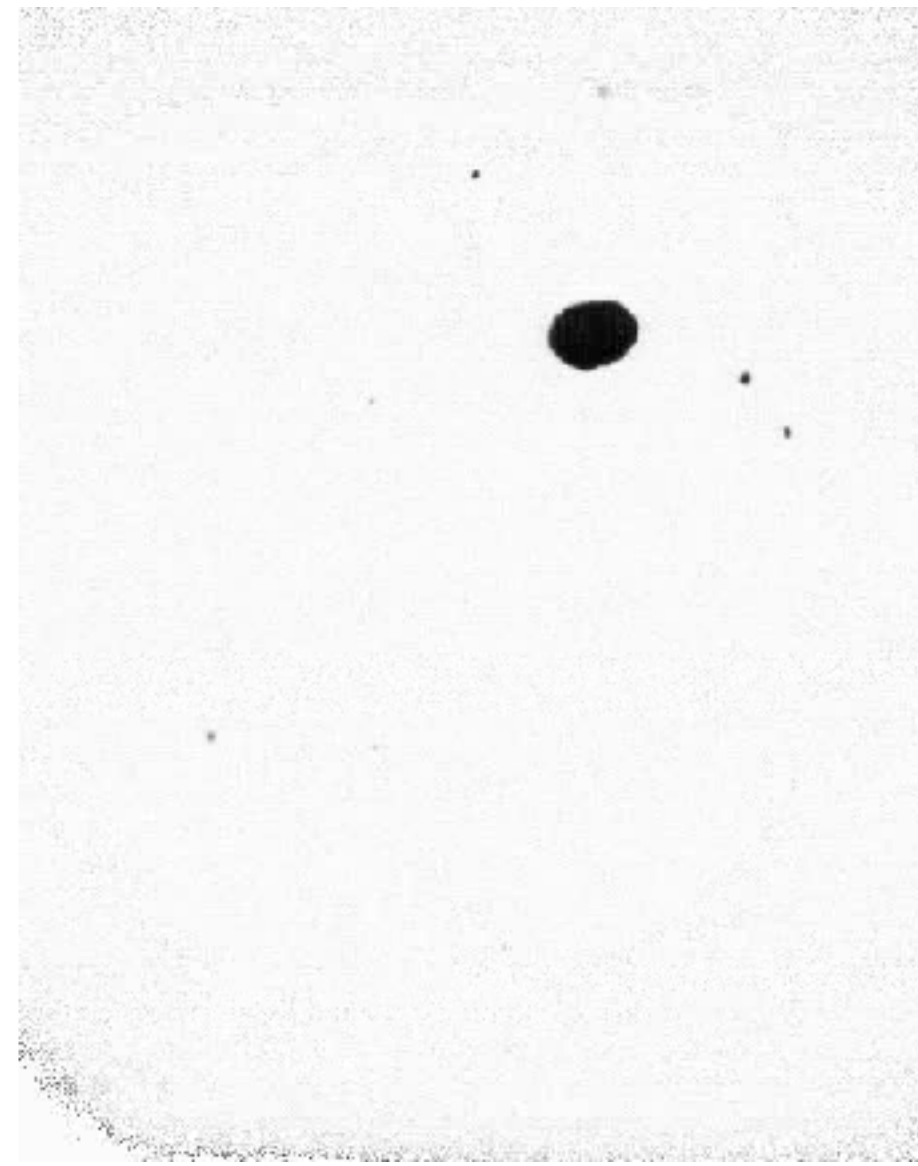
Sticking



Bouncing



Fragmentation



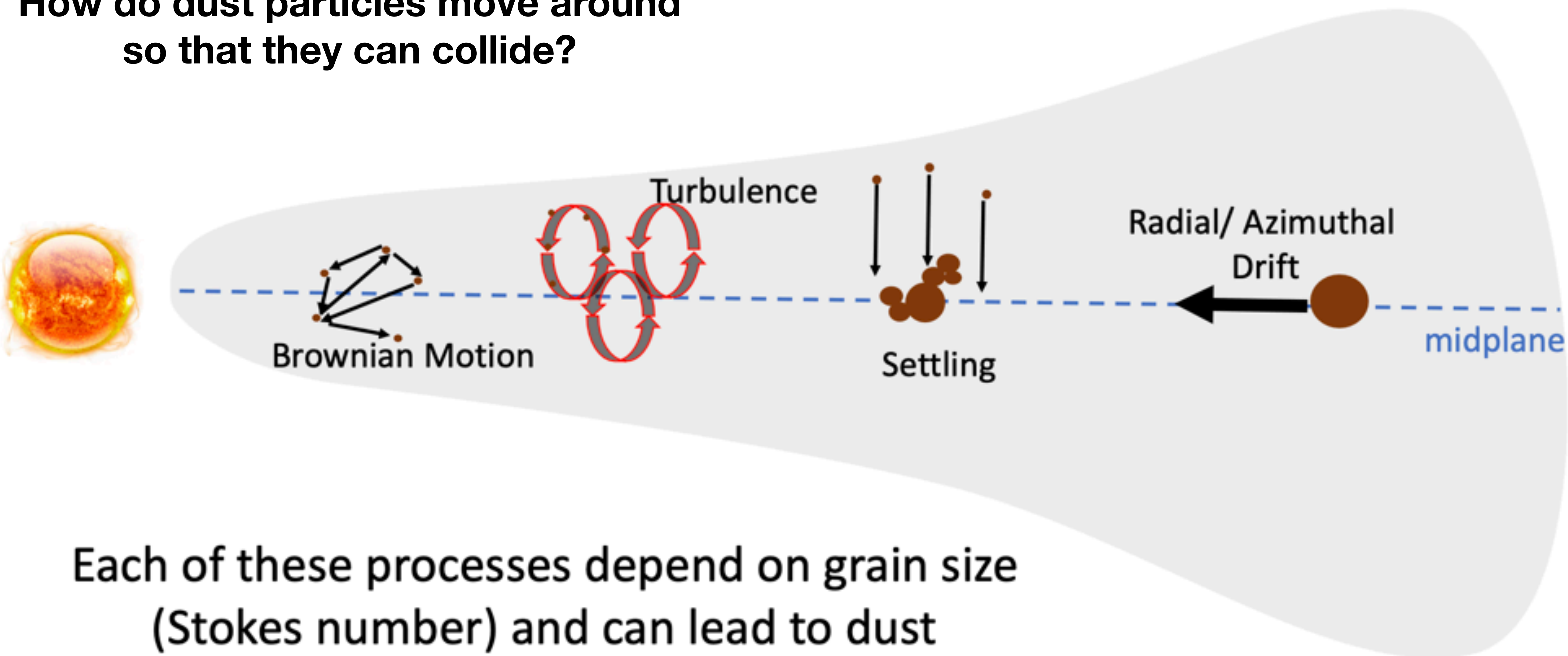
Also: mass transfer and erosion

Courtesy of Paola Pinilla

What mechanisms exist in the disk that cause dust grains to move and collide?

Dust movement in a disk

How do dust particles move around so that they can collide?



Each of these processes depend on grain size (Stokes number) and can lead to dust collisions

What causes the radial drift of a particle?

Radial drift

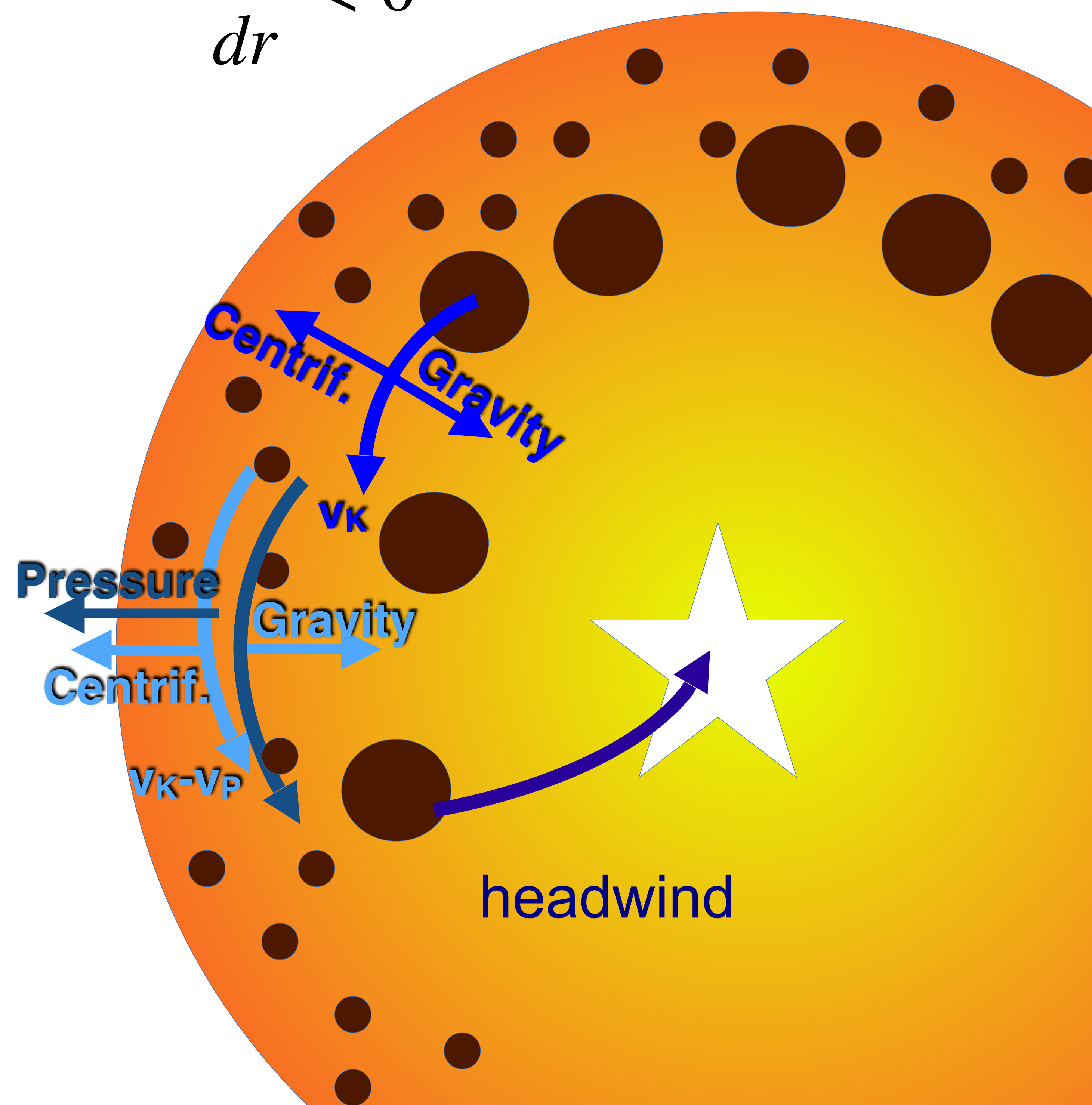
- Gas disk has a pressure gradient $\frac{dp}{dr} < 0$
  - Radial inward <u>drift</u> dust

$$\frac{v_\phi^2}{r} = \frac{GM_\star}{r^2} + \frac{1}{\rho}\frac{dP}{dr}$$

pressure force

$$v_\phi \approx v_K \cdot (1 - \eta)$$

(0.5% slower than Keplerian)



Weidenschilling 1977

What is the Stokes number of a dust particle?

What sets the radial drift?

- **Stokes number: property of particle**

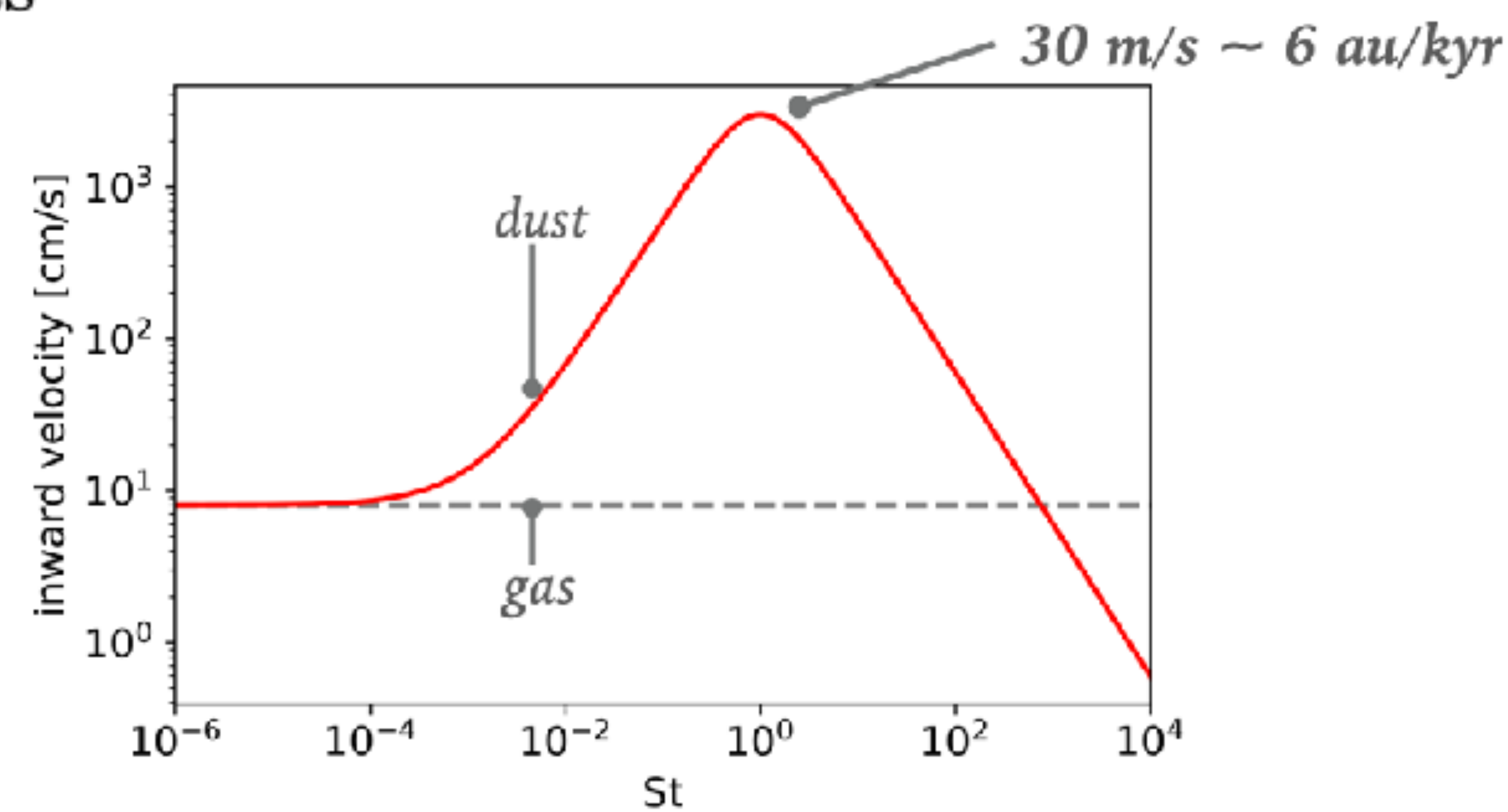
***a* = grain size**

$$\mathrm{St} = \frac{t_{\rm stop}}{t_{\rm orb}} = \frac{\pi}{2}\frac{a\rho_\bullet}{\Sigma_{\rm gas}}$$

(`Epstein regime')

Gas surface density

Drift velocity based on Stokes number

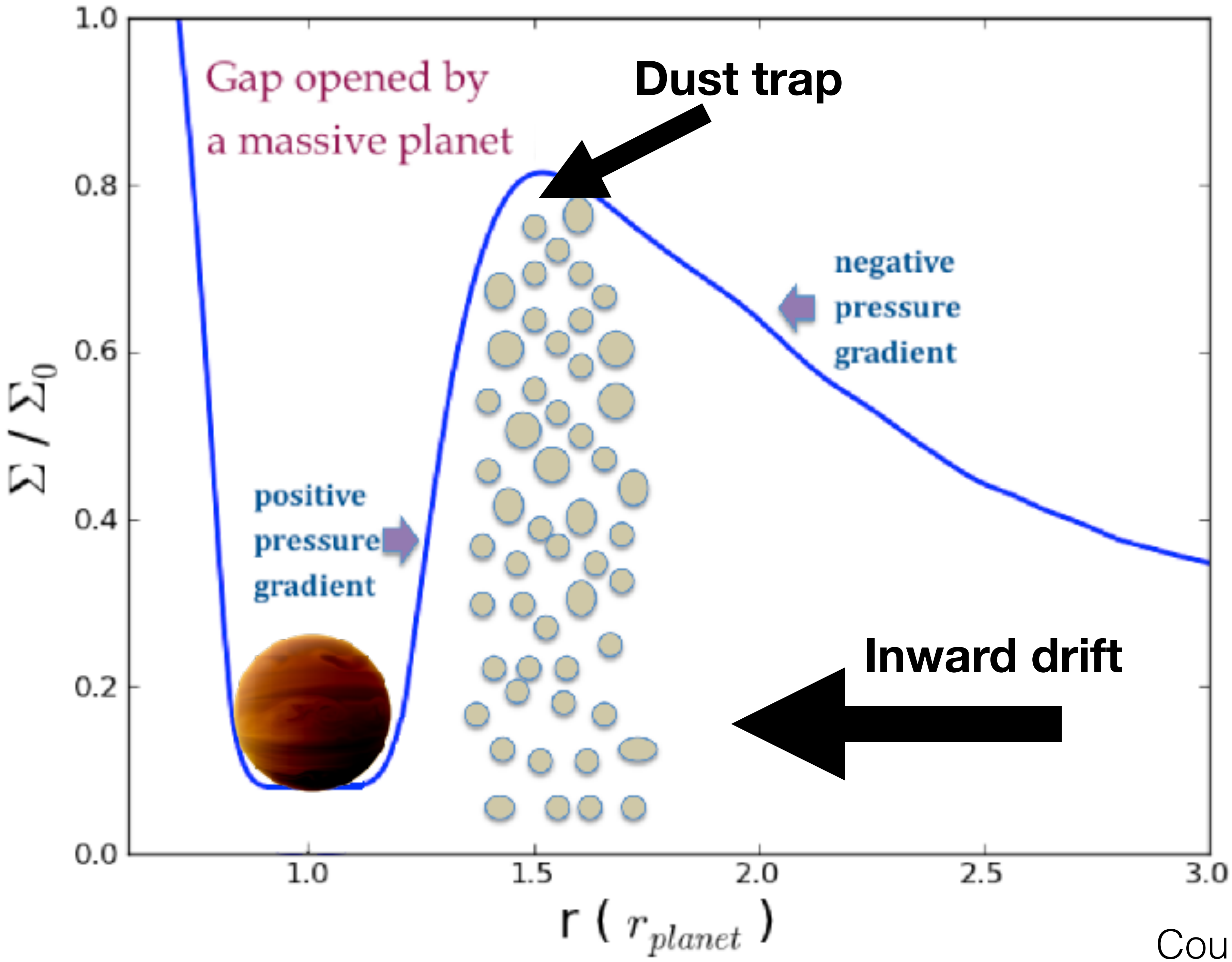


Drazkowska et al. 2022 (PPVII)

How can we prevent radial drift?

Pressure bump/dust trap

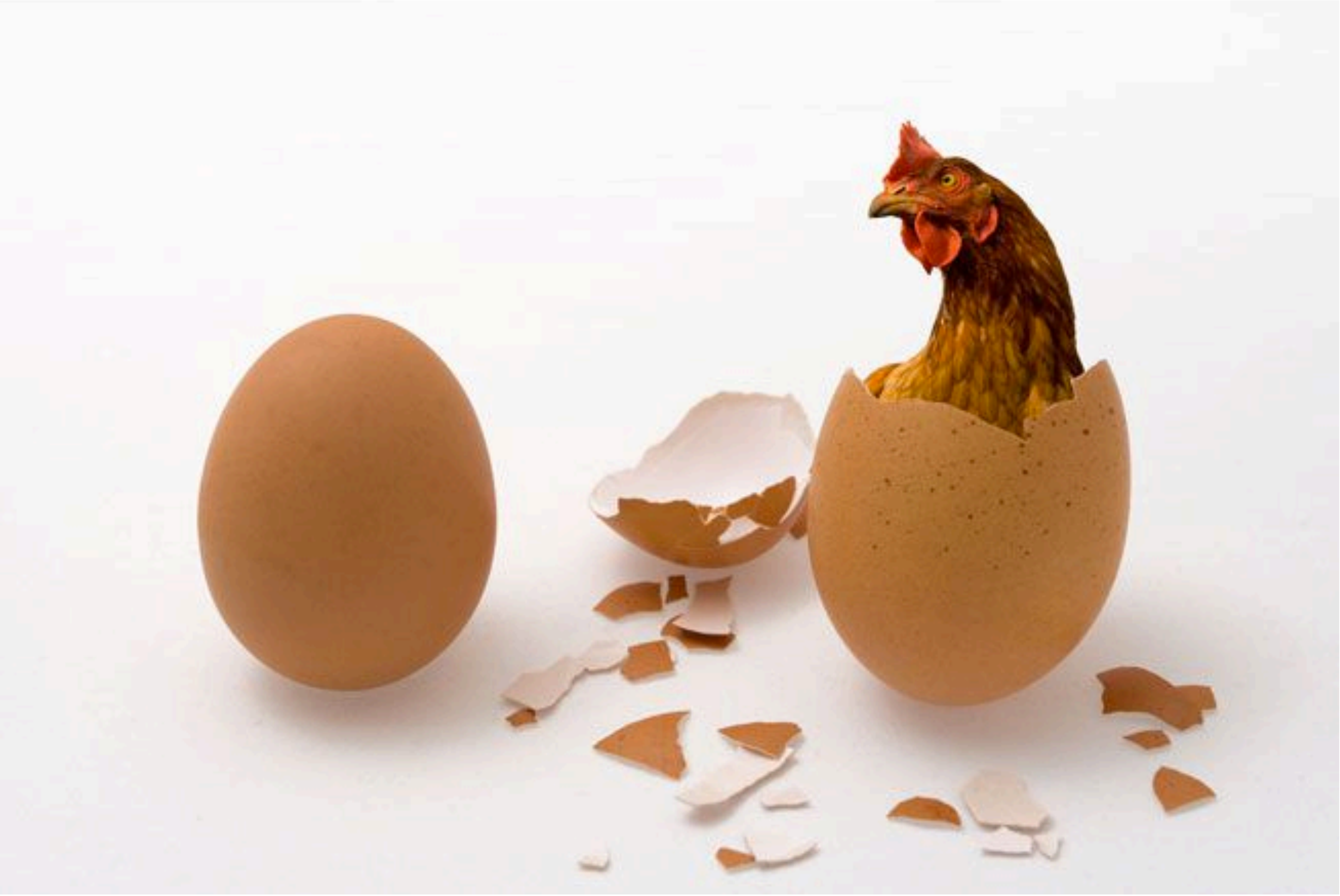
A forming planet will carve a gap in the gas distribution: at the outer edge you naturally get a pressure maximum



Courtesy to Paola Pinilla

Why is such a dust trap not a solution for planet formation?

Problem:
dust traps require planets?



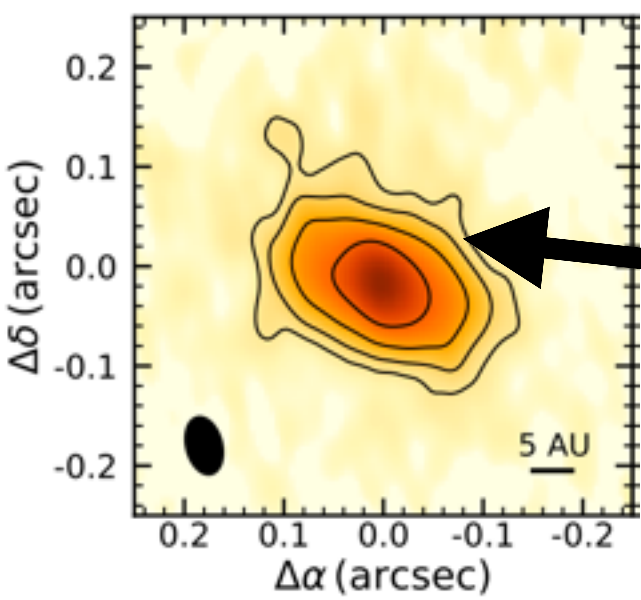
Do we have observational evidence for radial drift?

Gas-to-dust size ratio

<u>Most extreme example</u>

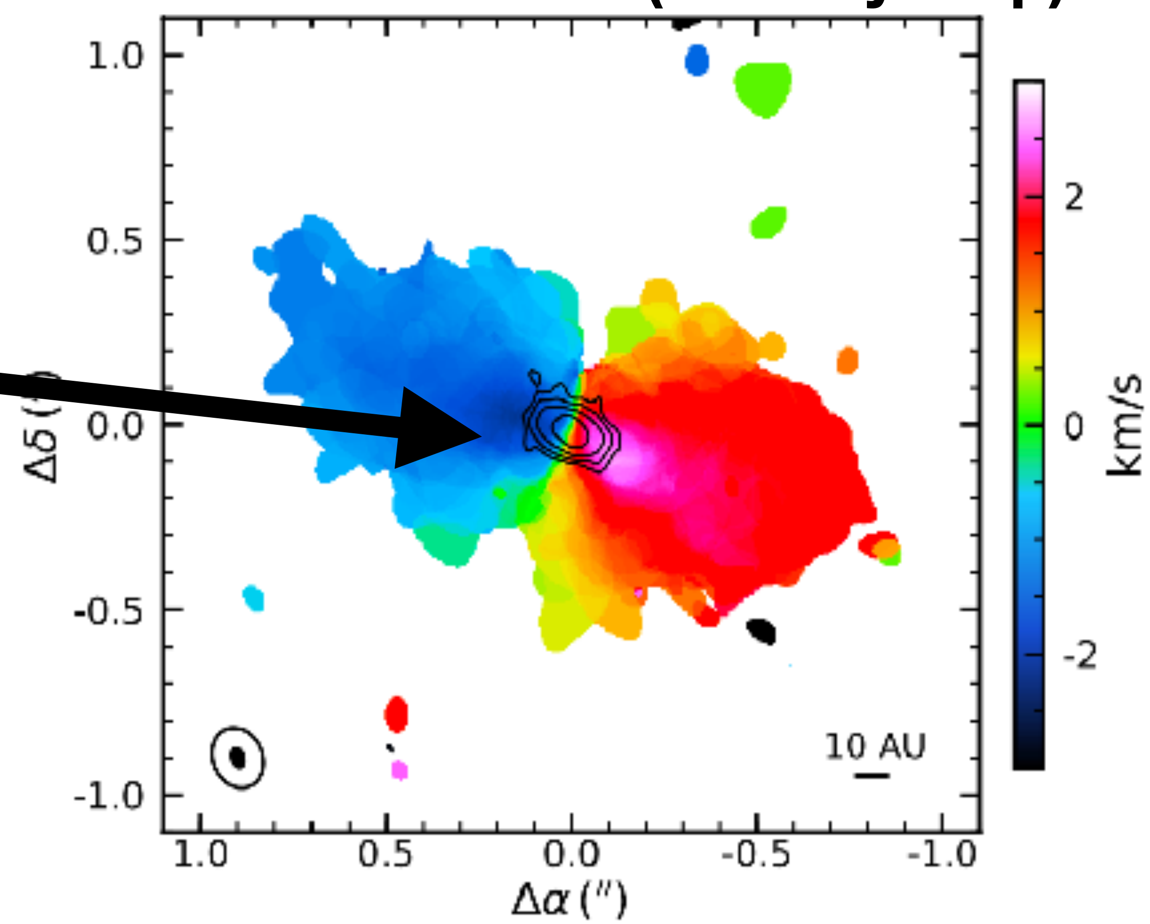
CX Tau (at high resolution of 0.04”!) with a ratio of >6:

Dust continuum



(No gaps seen)

^{12}CO emission (velocity map)



This may be a case of a drift-dominated disk, but very few small disks have been resolved at high spatial resolution

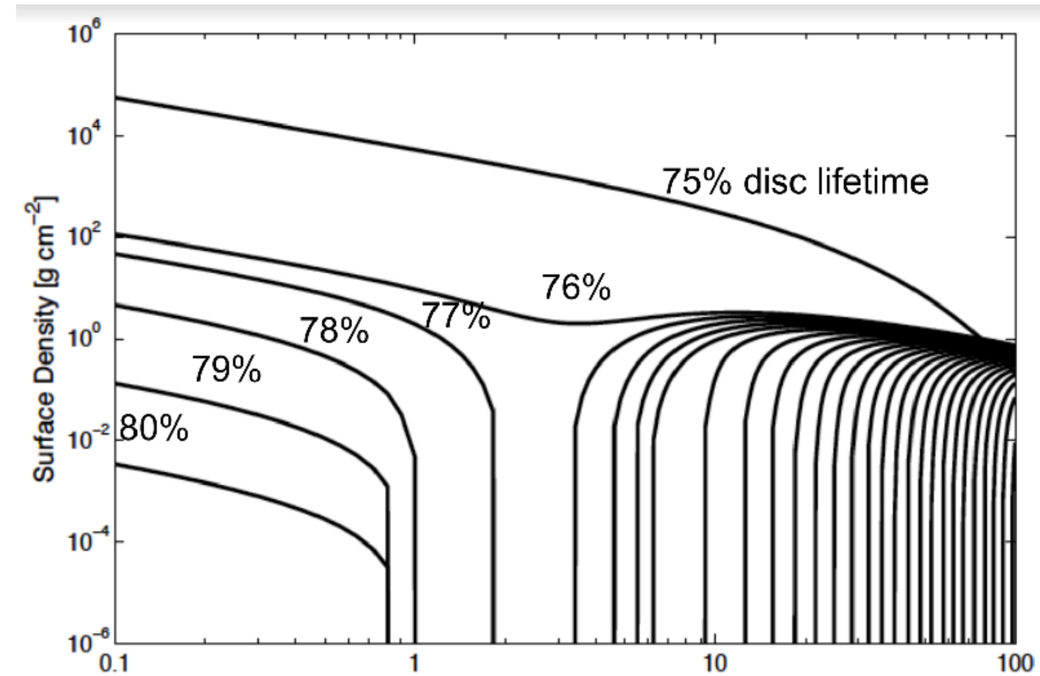
Facchini et al. 2019

What are the four main ways to explain a transition disk cavity?

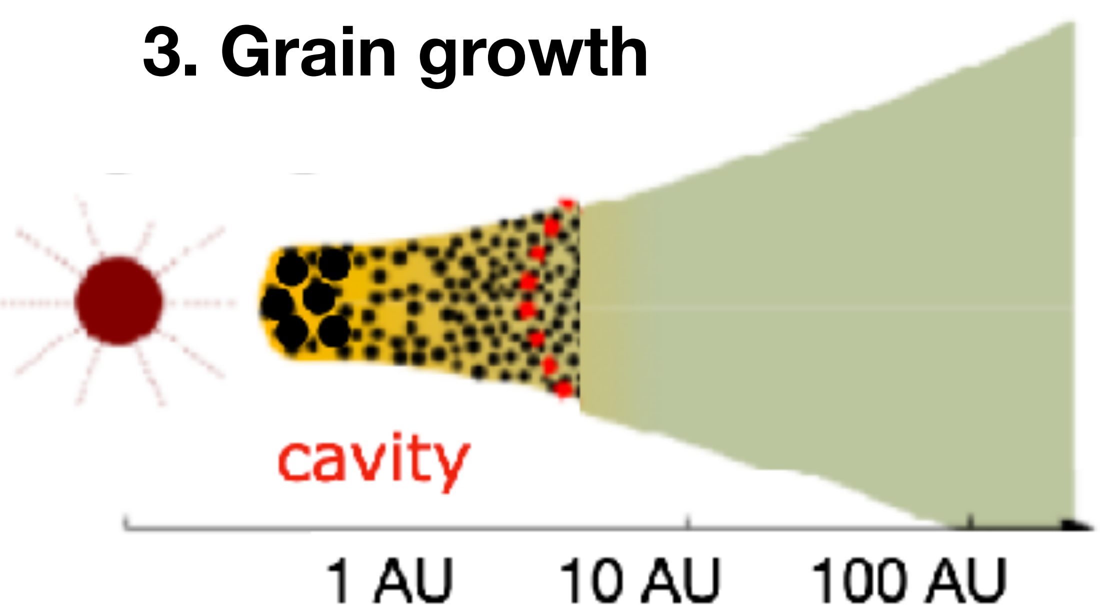
Transition disk cavity clearing

1. Binaries

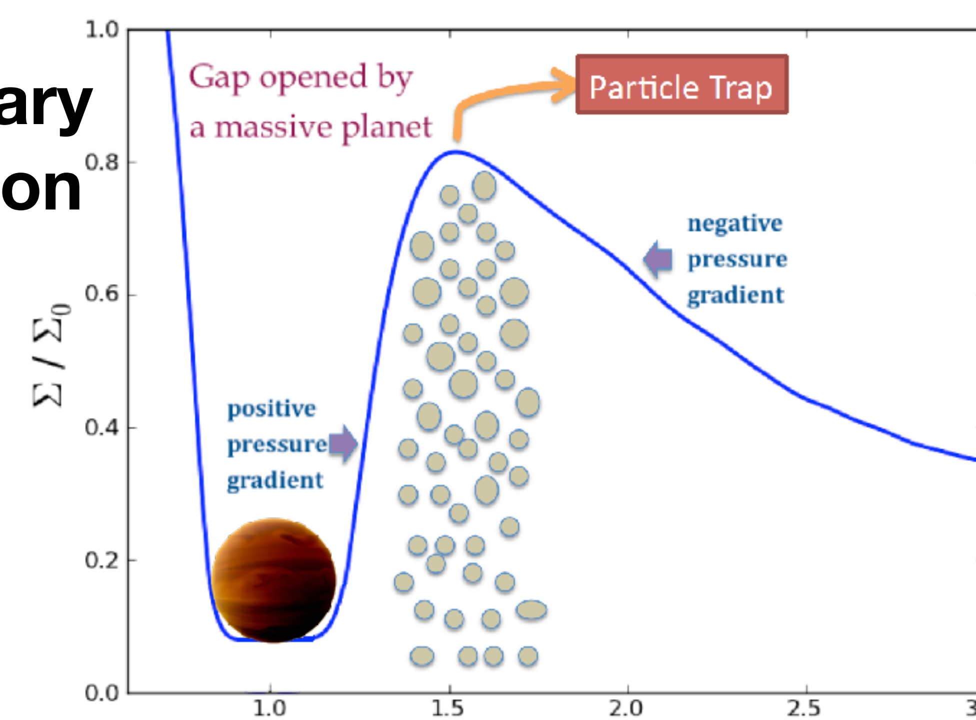
2. Photoevaporation



3. Grain growth

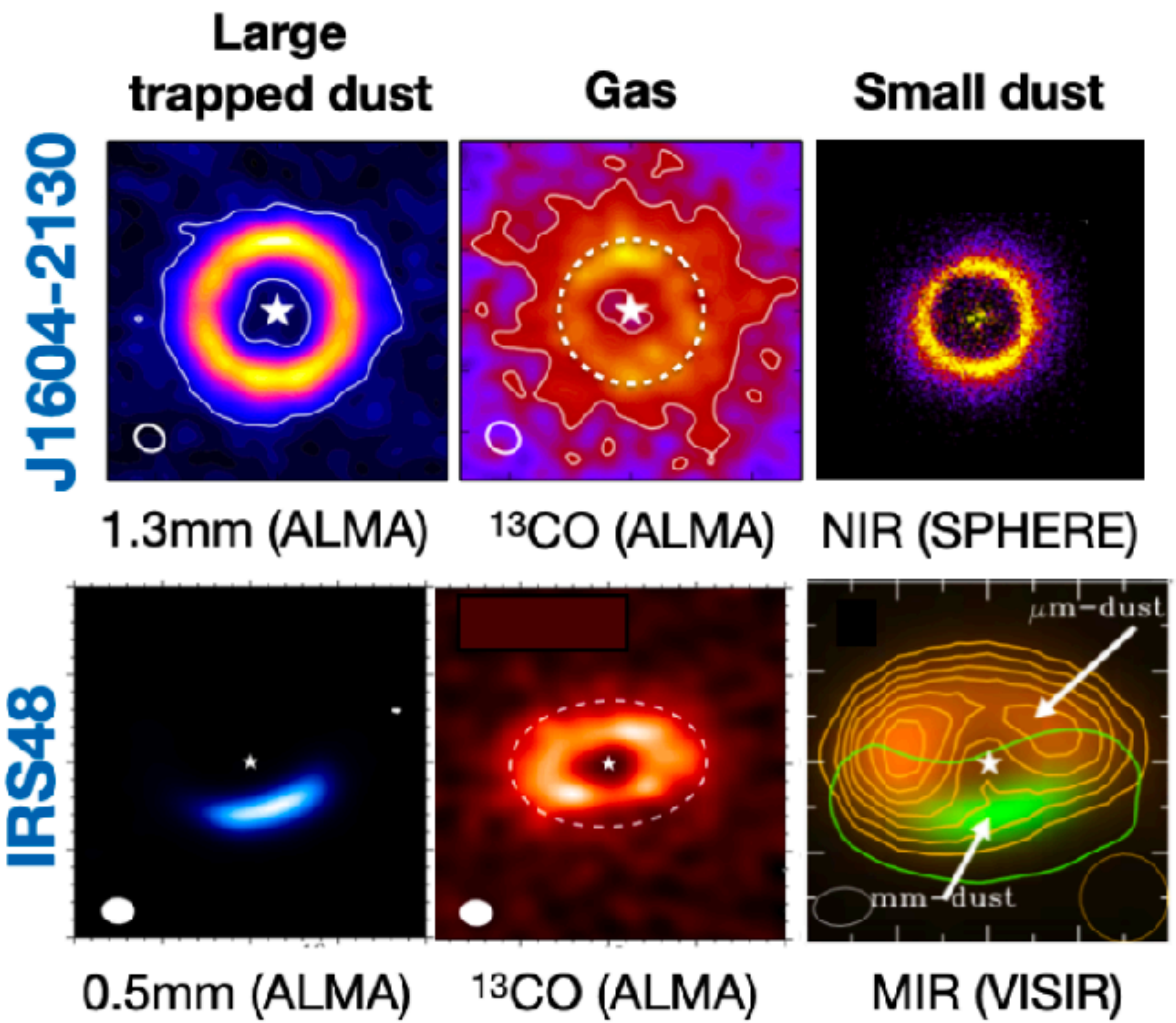


4. Planetary companion



How can we confirm that a dust concentration is caused by trapping?

How do we know that these are dust traps?



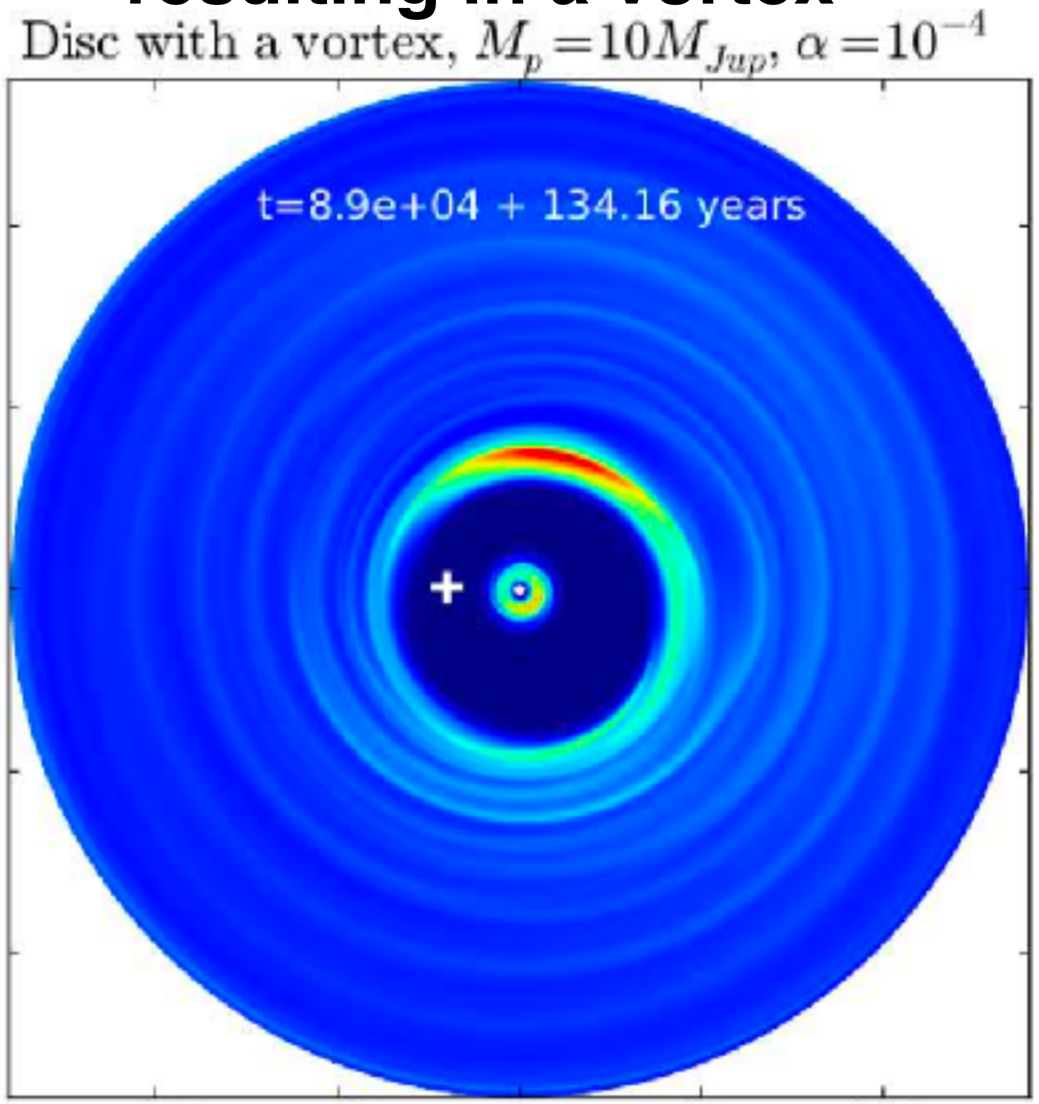
Radial trapping

Azimuthal trapping

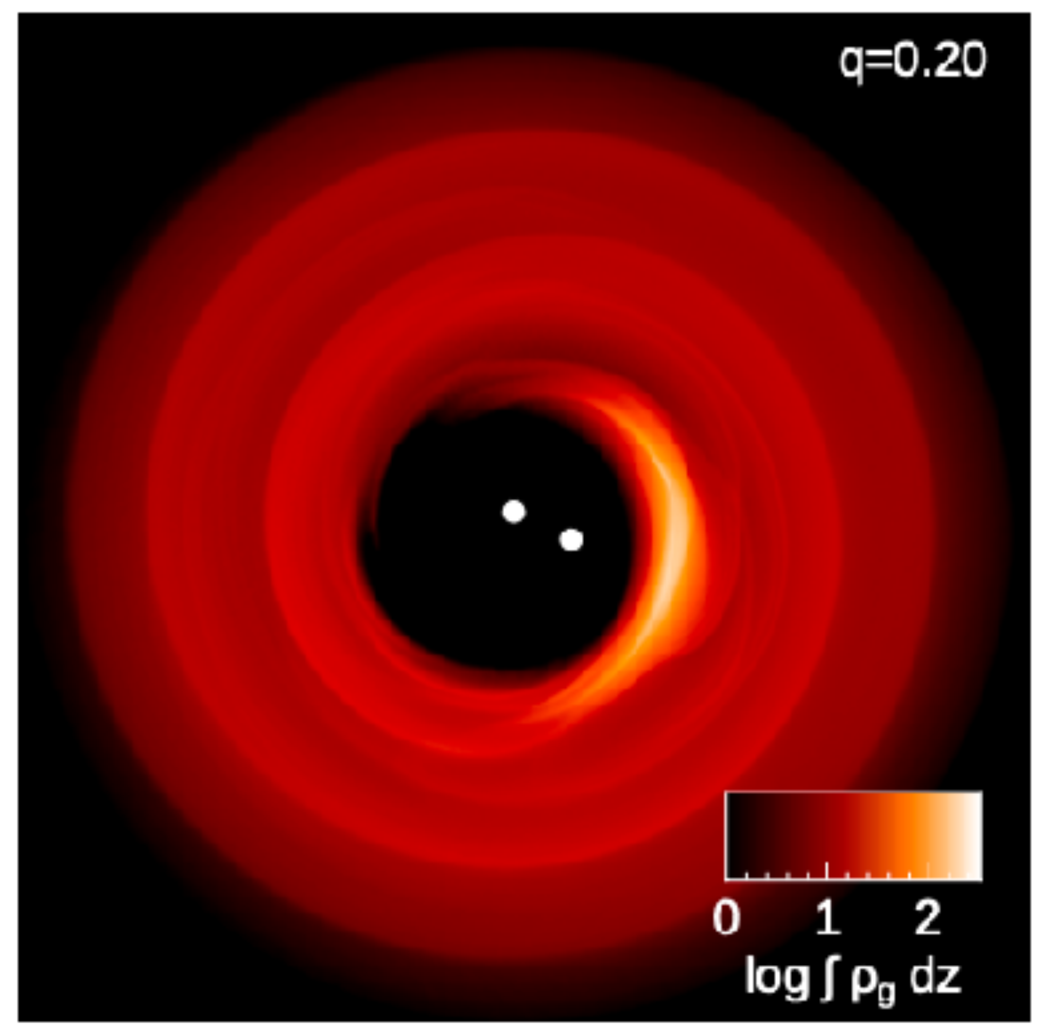
What are the two proposed mechanisms for an azimuthal pressure bump?

Azimuthal pressure bump

Rossby Wave Instability resulting in a vortex



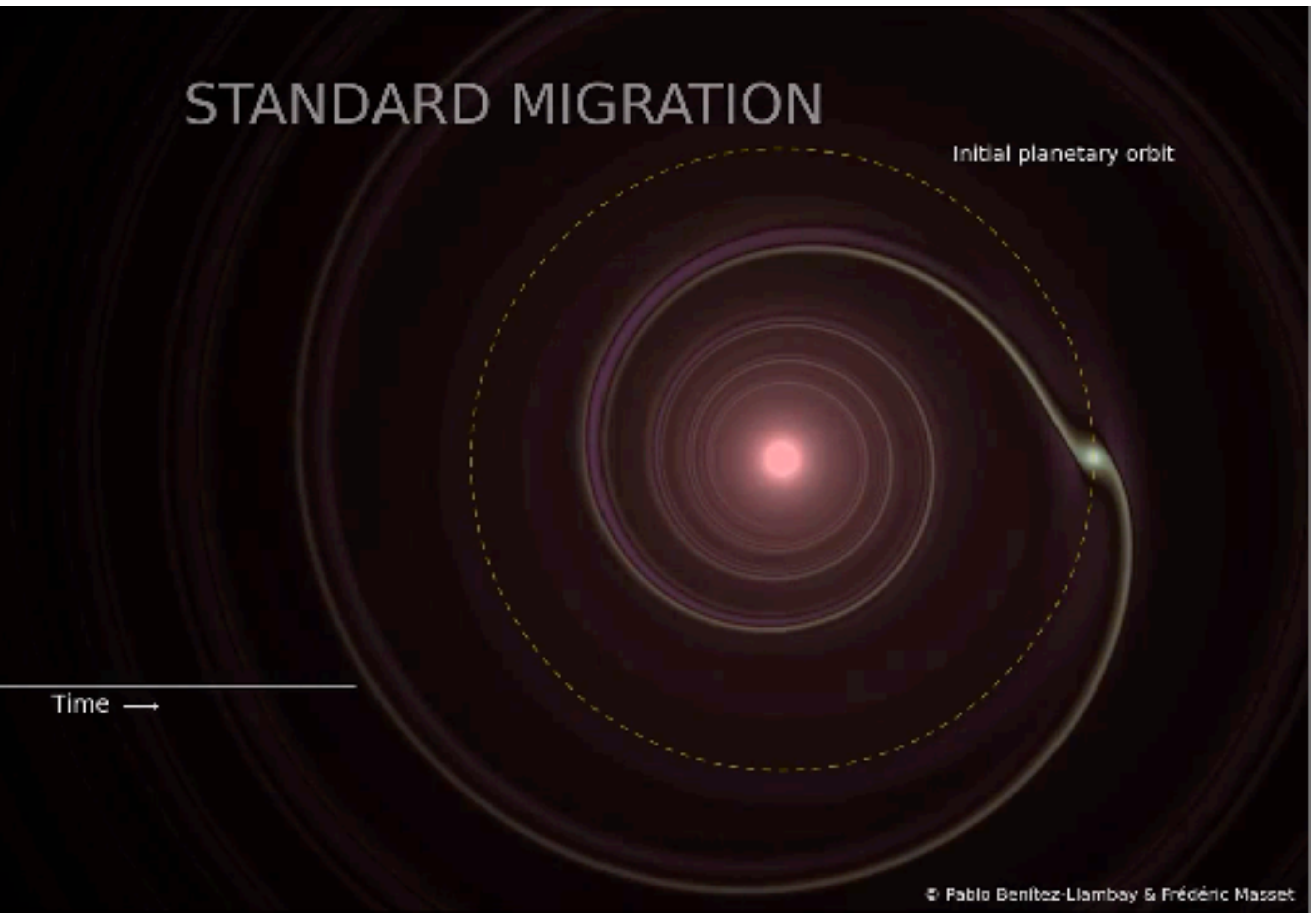
Horseshoe in eccentric circumbinary disk



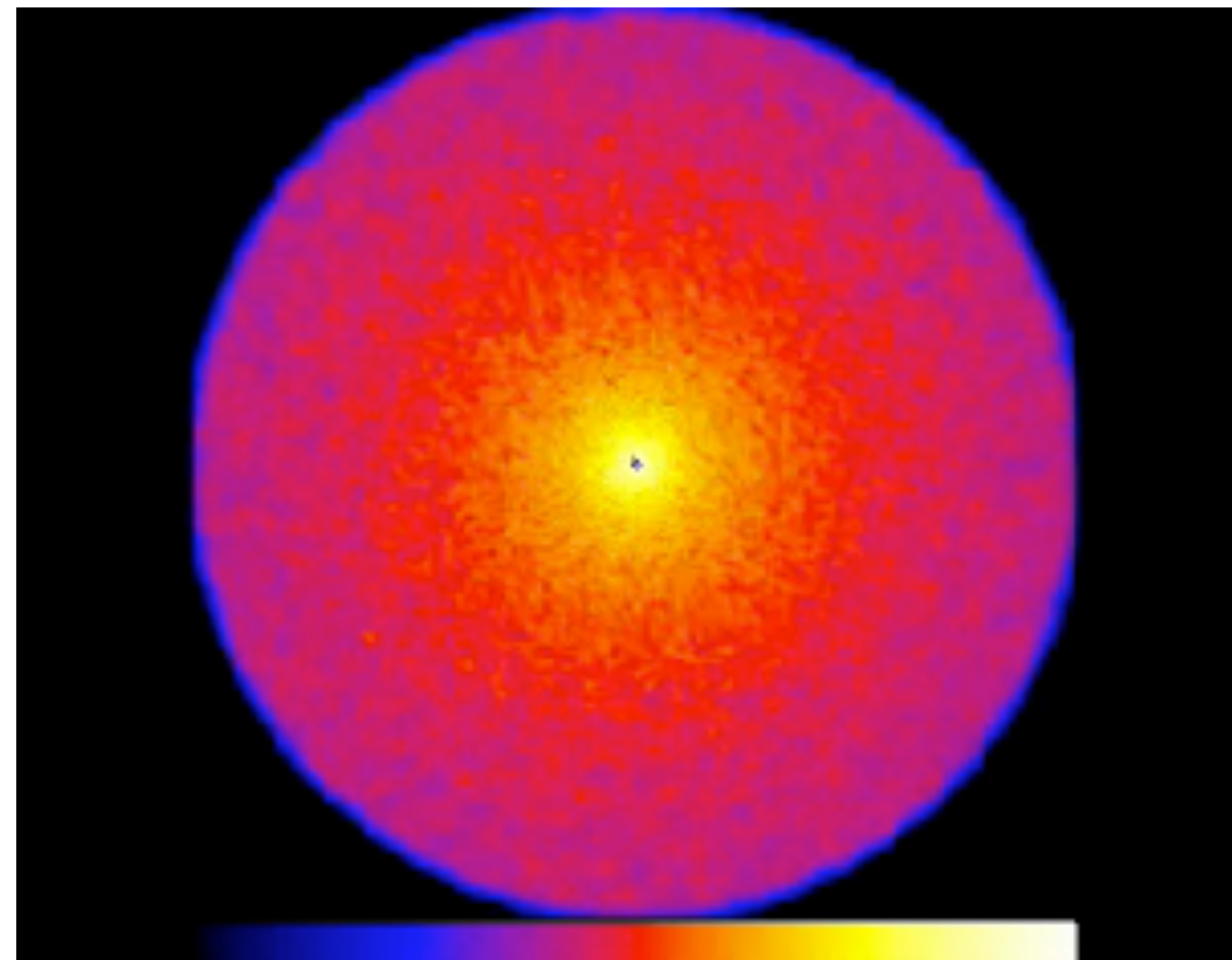
What are two ways to generate a spiral arm in a protoplanetary disk?

Origin spirals?

Planet spiral density waves



Gravitational instability

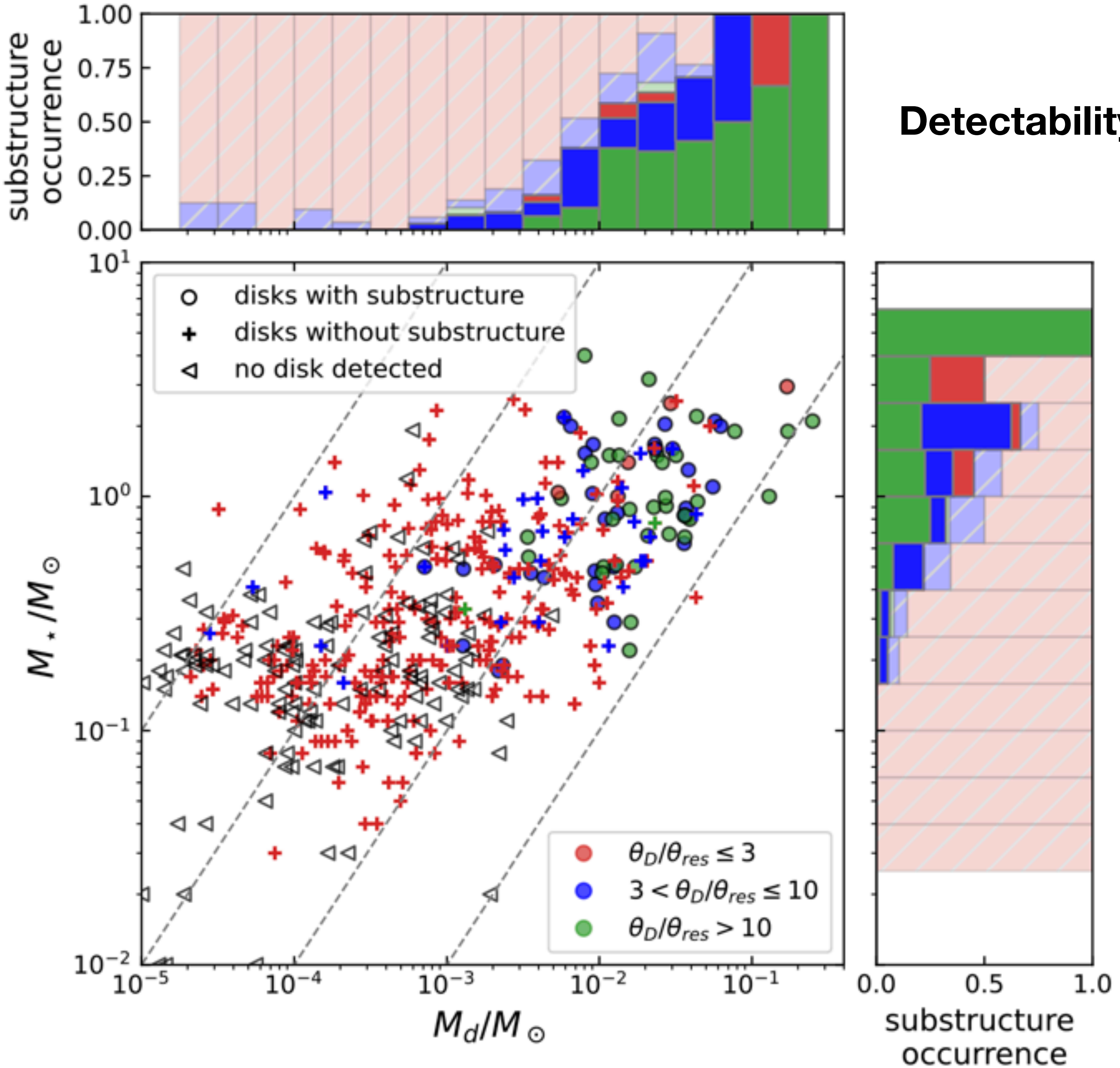


The spirals seen in mm emission are often associated with gravitational instability, as their disk masses are large. The NIR/CO spirals are more scale height/ temperature variations (as the underlying mm disk looks very different) so more likely due to dynamical interaction. Not fully conclusive yet!

Credits:
Pablo Benitez-Llambay, Ken Rice

Why is it so hard to determine the fraction of disks with substructures?

Detectability of substructures



Detectability depends on resolution!

Bae et al. 2022 (PPVII)

Under which assumptions is the grain size related to the observed millimetre spectral index?

Rayleigh-Jeans approximation

Rayleigh-Jeans: $$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT} - 1}$$

Approximation: $h\nu \ll k_\mathrm{B} T$

$$B_\nu(T(r)) = \frac{2\nu^2 k_B T(r)}{c^2} \longrightarrow B_\nu(T) \sim \nu^2$$

Remember: $$\kappa_\nu \sim \nu^\beta$$

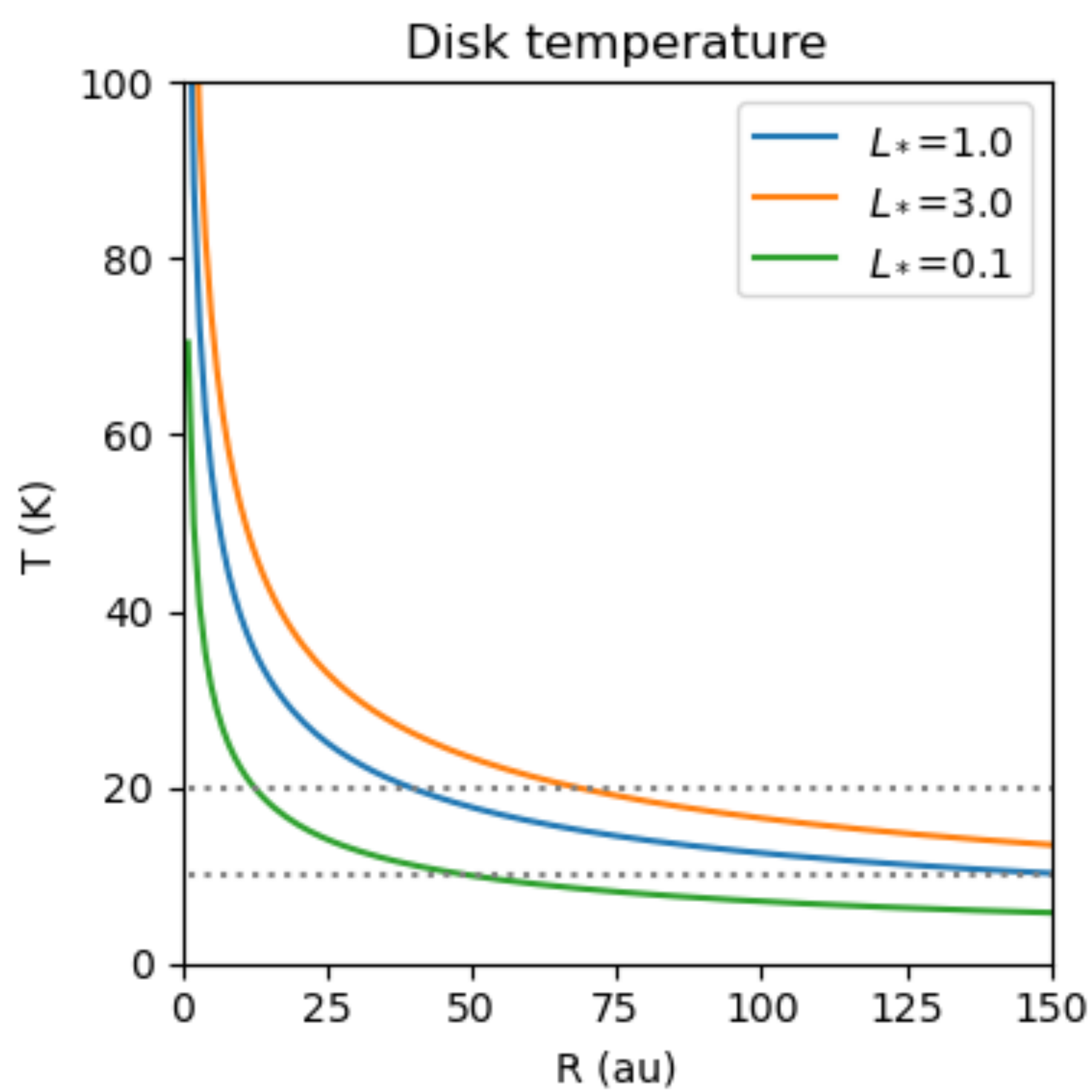
Rayleigh-Jeans + Opt thin regime: $$F_\nu = \frac{B_\nu(T)\kappa_\nu M_{dust}}{d^2} \longrightarrow F_\nu \sim \nu^2 \kappa_\nu \sim \nu^{2+\beta} \sim \nu^\alpha$$

So the spectral index alpha can provide us the dust opacity β in the assumption of opt. thin emission

Why is it OK to assume a constant temperature of 20 K when calculating a disk dust mass from a flux?

Dust temperature

$$T(r) = \left(\frac{\phi L_*}{8\pi\sigma_B r^2}\right)^{1/4} = \sqrt[4]{\frac{\phi L_*}{8\pi\sigma_B}}\frac{1}{\sqrt{r}}$$



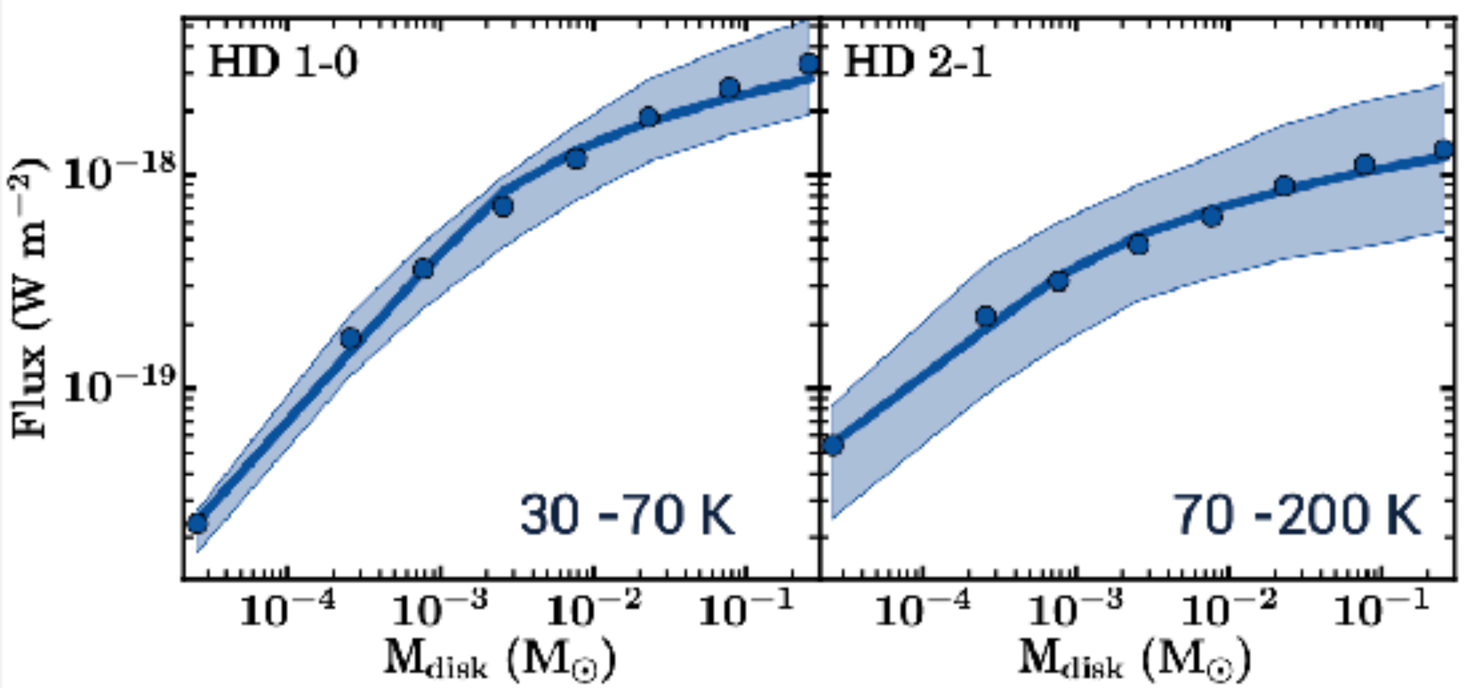
Bulk of the disk (50-150 au, where most of the mass is) is between 10 and 20 K:

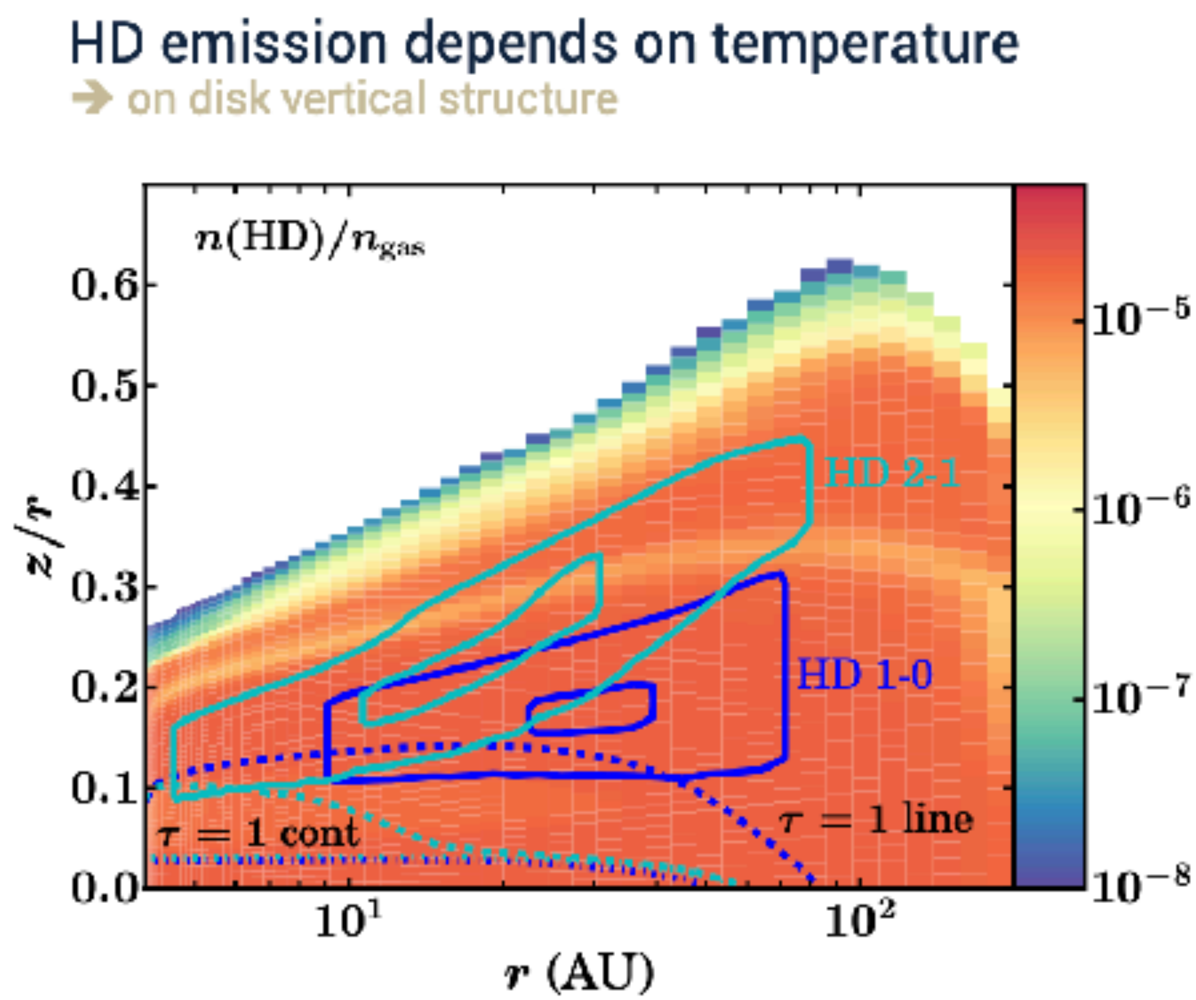
General assumption:
use average temperature to compute dust mass (usually 20 K)

What are the main challenges of using HD as measurement of the disk gas mass?

HD measurements

HD emission depends strongly on disk temperature



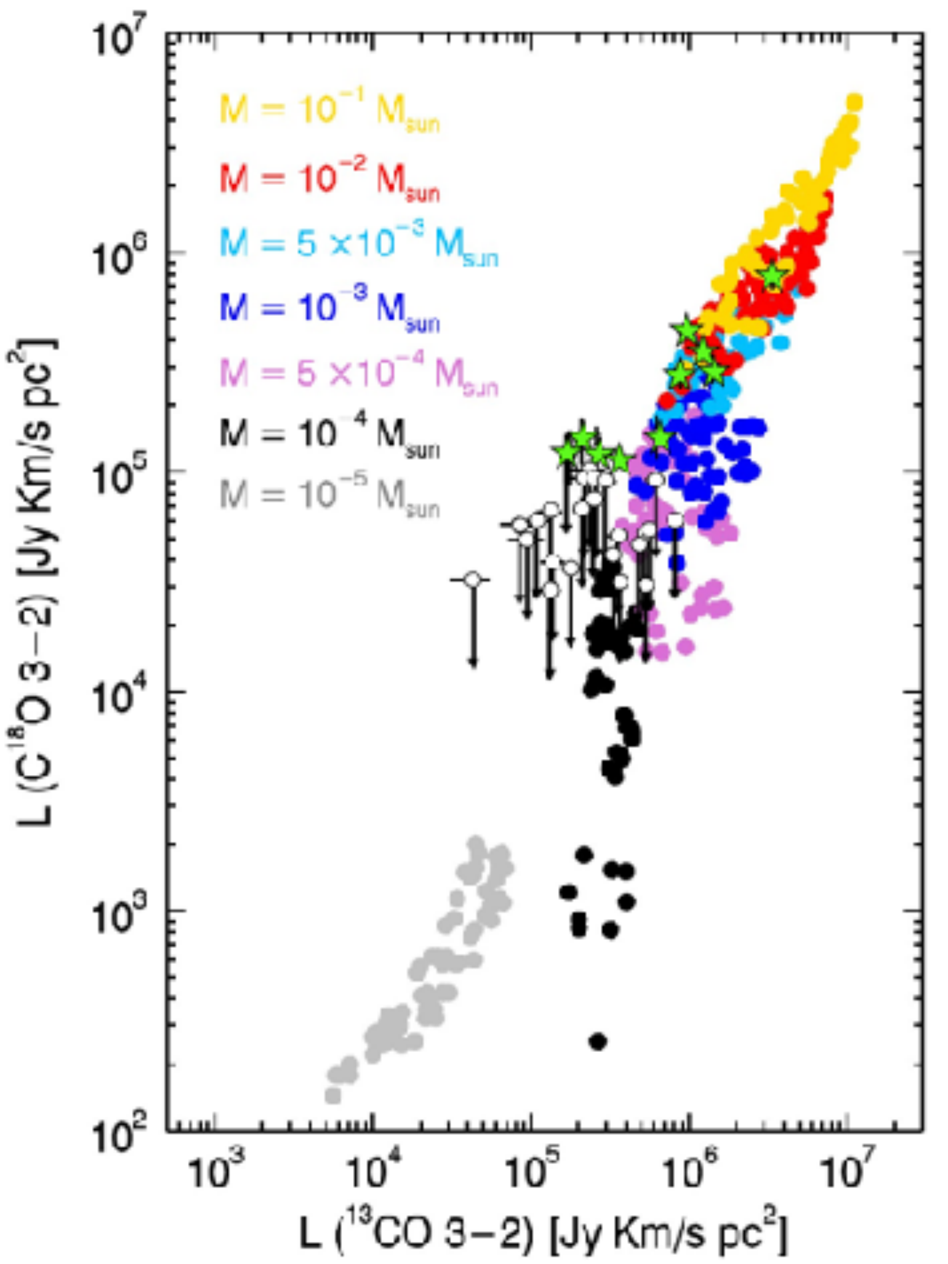


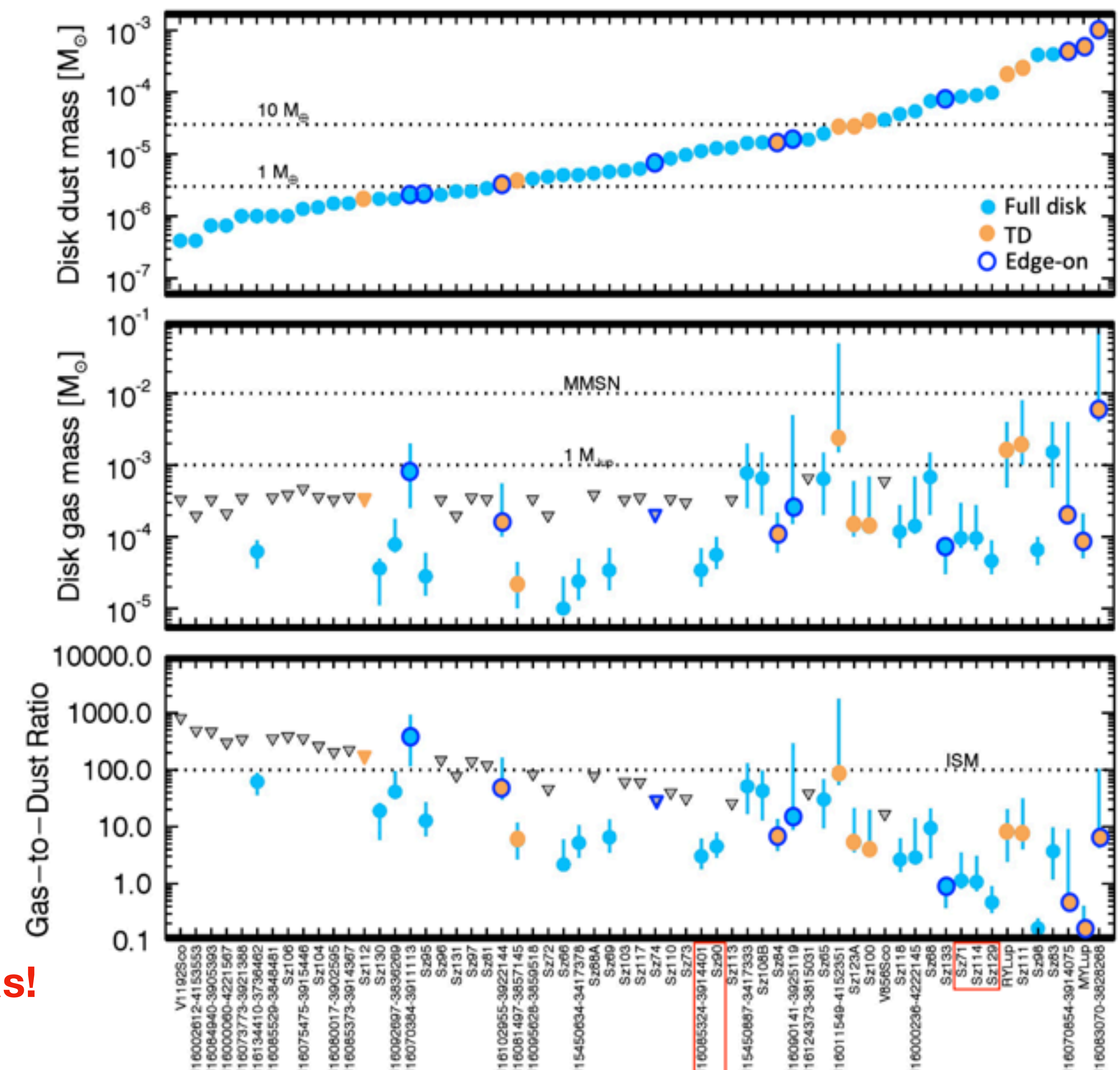
Also: no FIR mission any more in the near future

Trapman et al. 2017

What is the problem with disk gas masses that are derived with CO isotopologue emission?

Gas masses in Lupus





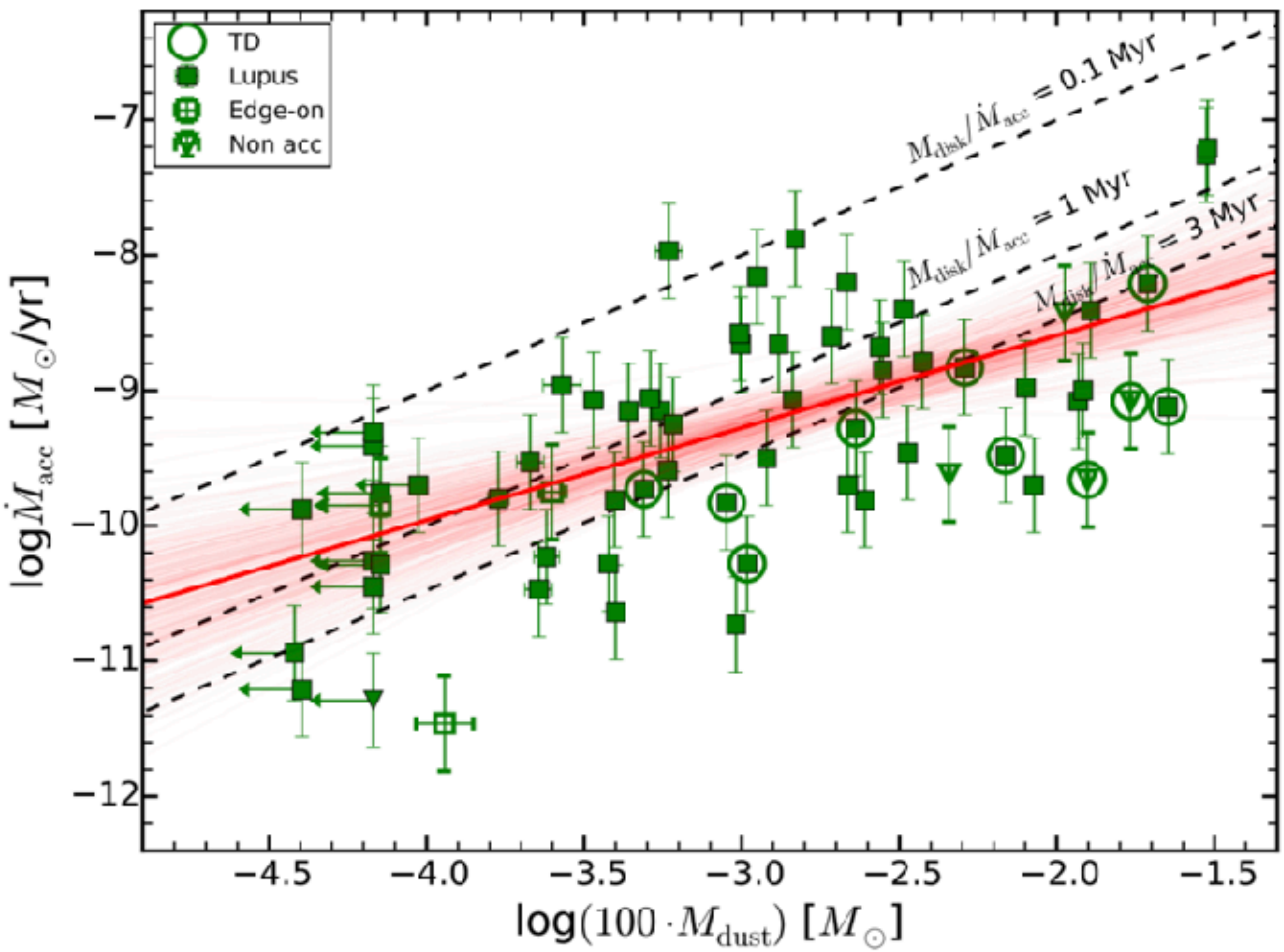
Still low gas masses and GDRs!

Miotello et al. 2017

How do we know that the low GDR is likely not caused by disk dissipation?

Gas dissipation?

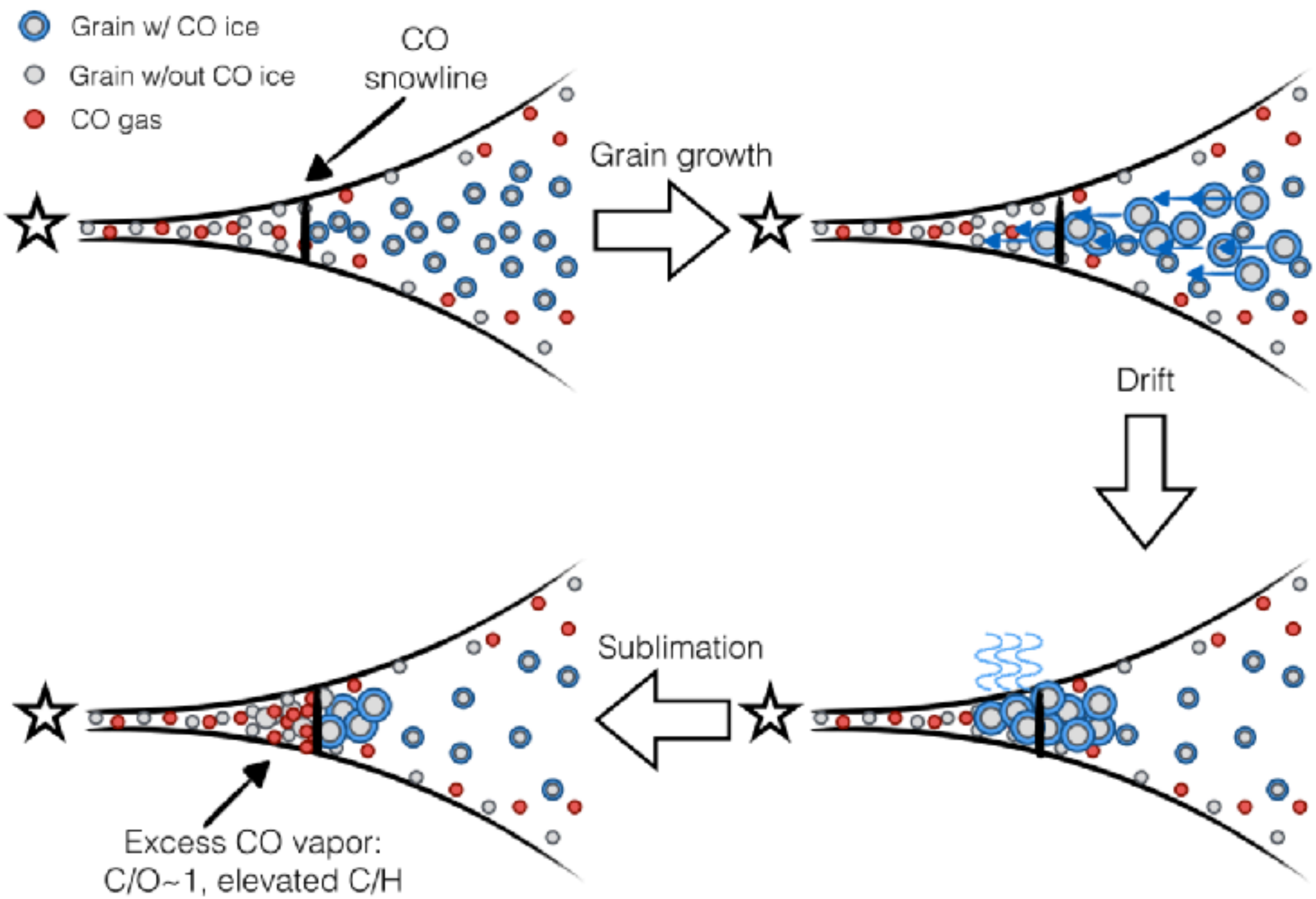
Rapid gas dissipation in Lupus disks is unlikely with the observed accretion rates, which are consistent with a few Myr of evolution



Manara et al. 2016

How can we understand a depletion of CO in a protoplanetary disk?

CO depletion



Dust pebble drift can cause CO depletion as the CO-icy pebbles drift inwards, depleting the outer disk of molecular CO

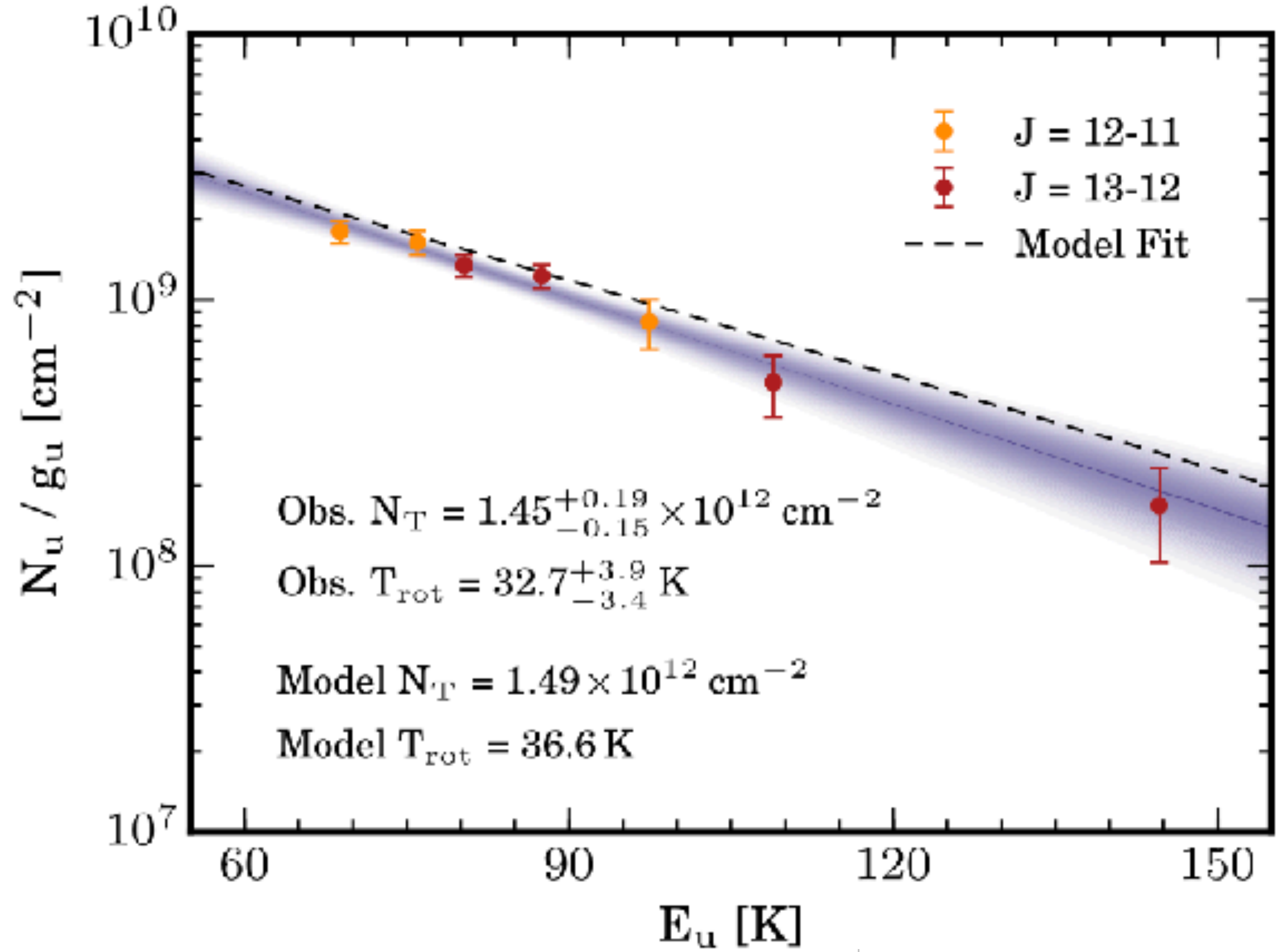
Oberg et al. 2016
Booth & Ilee 2019
Krijt et al. 2018, 2020

How can you determine both gas temperature and density simultaneously from line emission?

Line excitation

If you have multiple transitions of a slab of material, you can calculate a combination of N_T and T_{rot} using a linear fitting procedure, assuming LTE, opt. thin emission and all emission coming from the same region and temperature: <u>a rotational diagram</u>

$$\frac{N_u}{g_u} = \frac{N_T}{Q(T_{rot})} e^{-E_u/kT_{rot}}$$



Take logarithm:

$$\ln\left(\frac{N_u}{g_u}\right) = \ln\left(\frac{N}{Q(T)}\right) - \frac{E_u}{kT} = -\frac{1}{T}\frac{E_u[\mathrm{erg}]}{k} + ln\left(\frac{N}{Q(T)}\right)$$

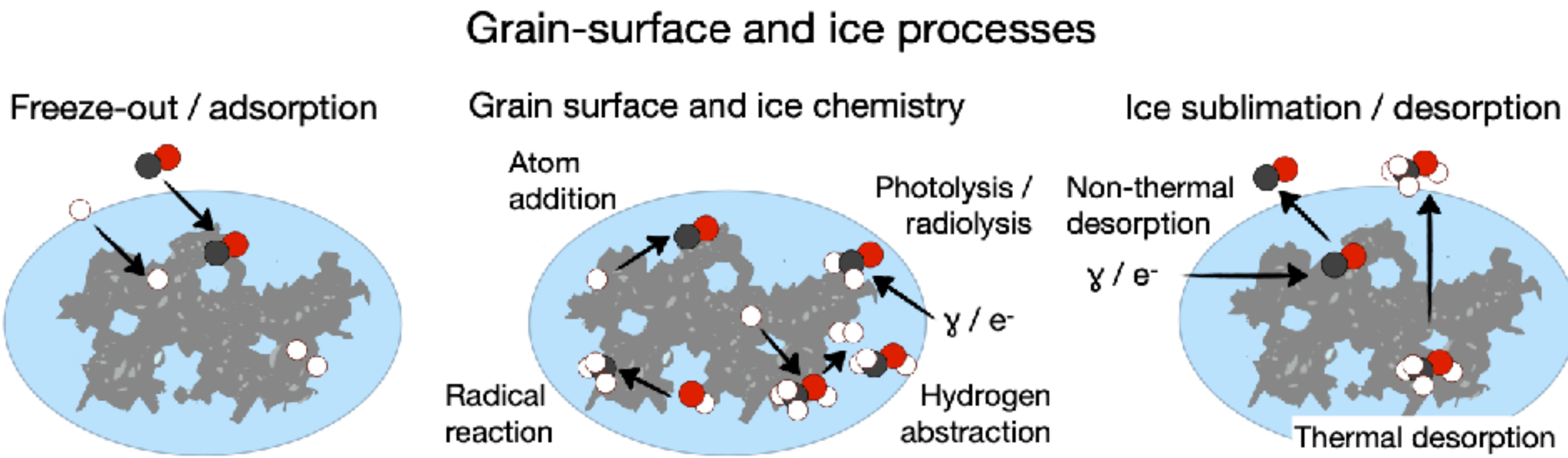
$$\underbrace{\ln\left(\frac{N_u}{g_u}\right)}_{y} = \underbrace{-\frac{1}{T}}_{a}\ \underbrace{E_u[\mathrm{K}]}_{x} + \underbrace{\ln\left(\frac{N}{Q(T)}\right)}_{b}$$

From obs. line flux

So in the end you just do a linear fit and a and b give you column density *N* and temperature *T*

How does ice chemistry contribute to the chemical complexity in a cloud/disk?

Ice chemistry



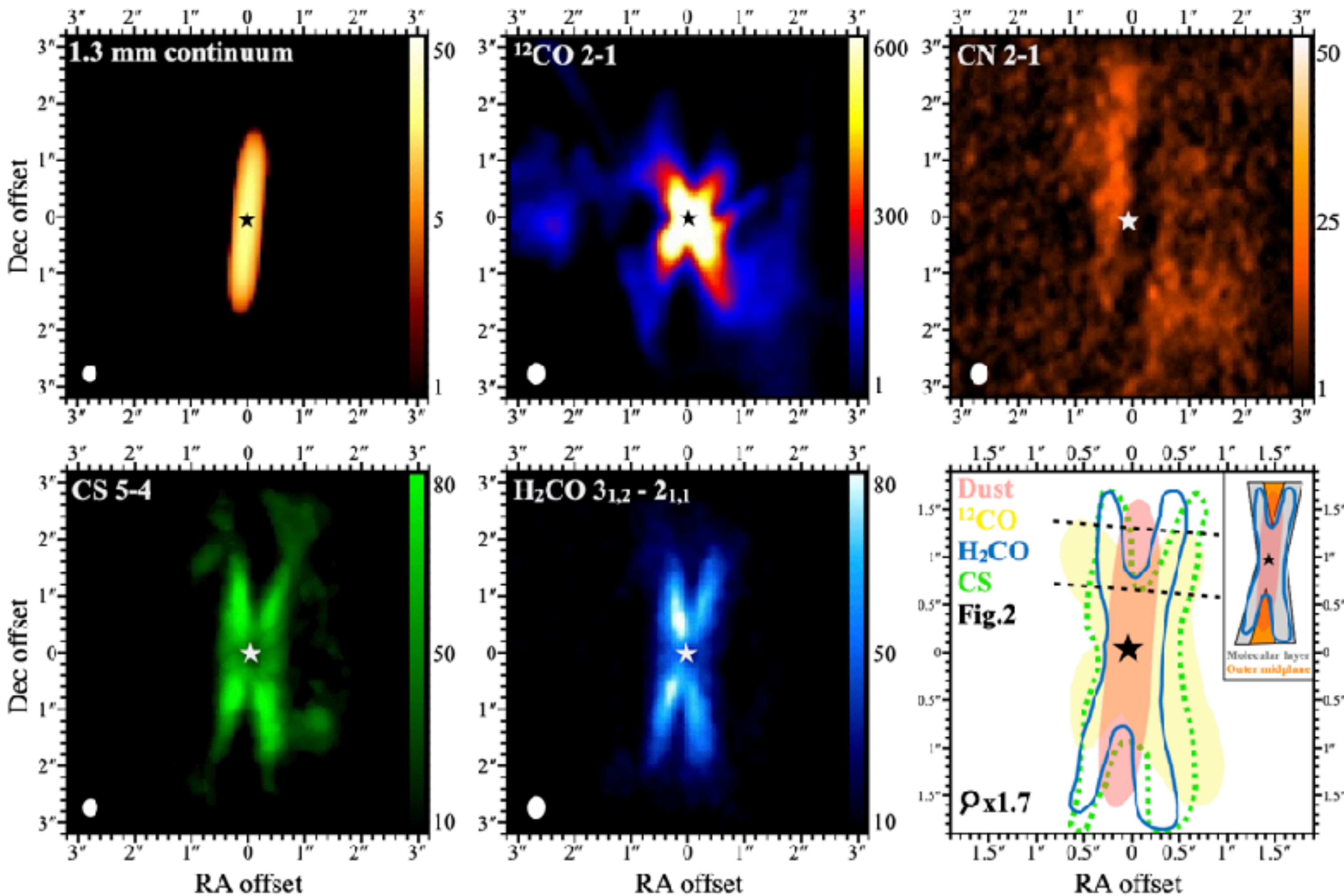
Many possible chemical reactions, followed by ice sublimation

=> more chemical complexity!

Oberg & Bergin 2020

Why are edge-on disks so interesting for studying disk chemistry?

Disk chemistry: vertical structure



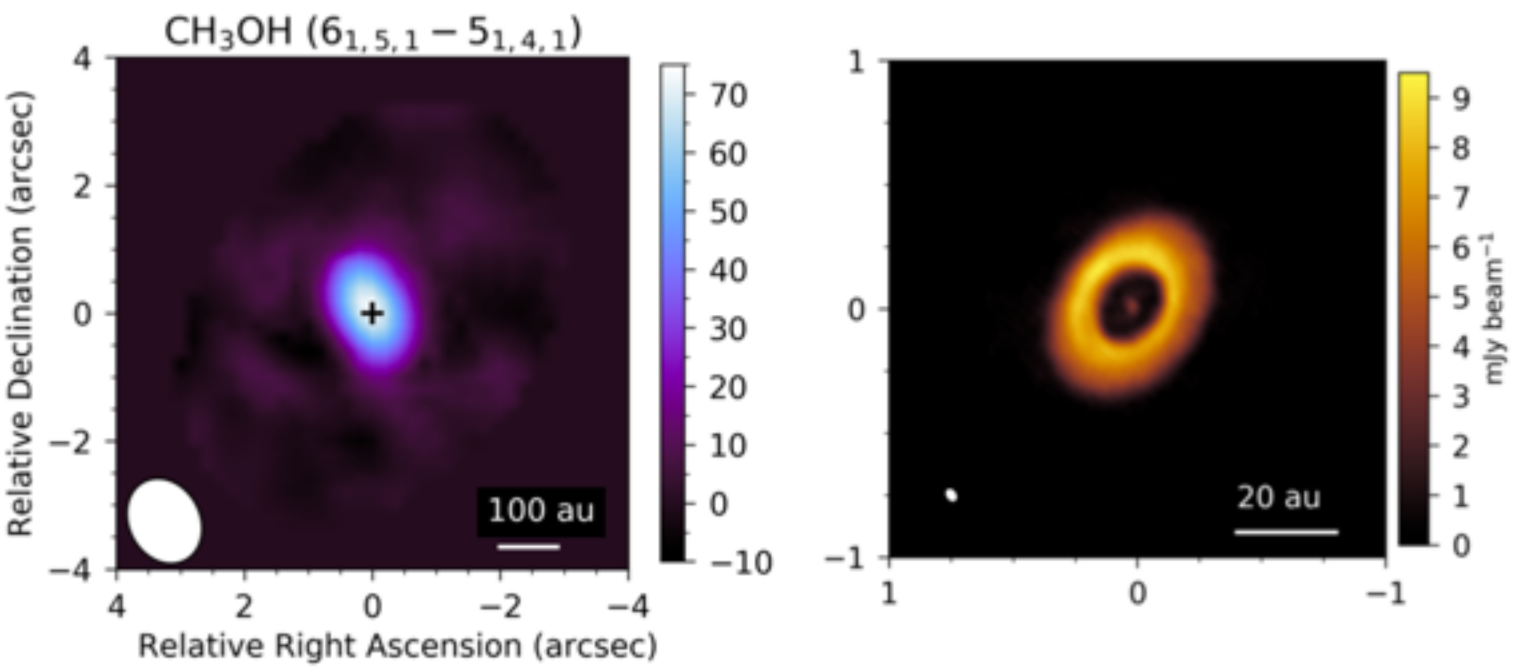
In edge-on disks it is possible to resolve the vertical structure of the molecules: temperature structure

Podio et al. 2020

How can we explain the detection of CH_3OH (an ice product) in a warm Herbig disk?

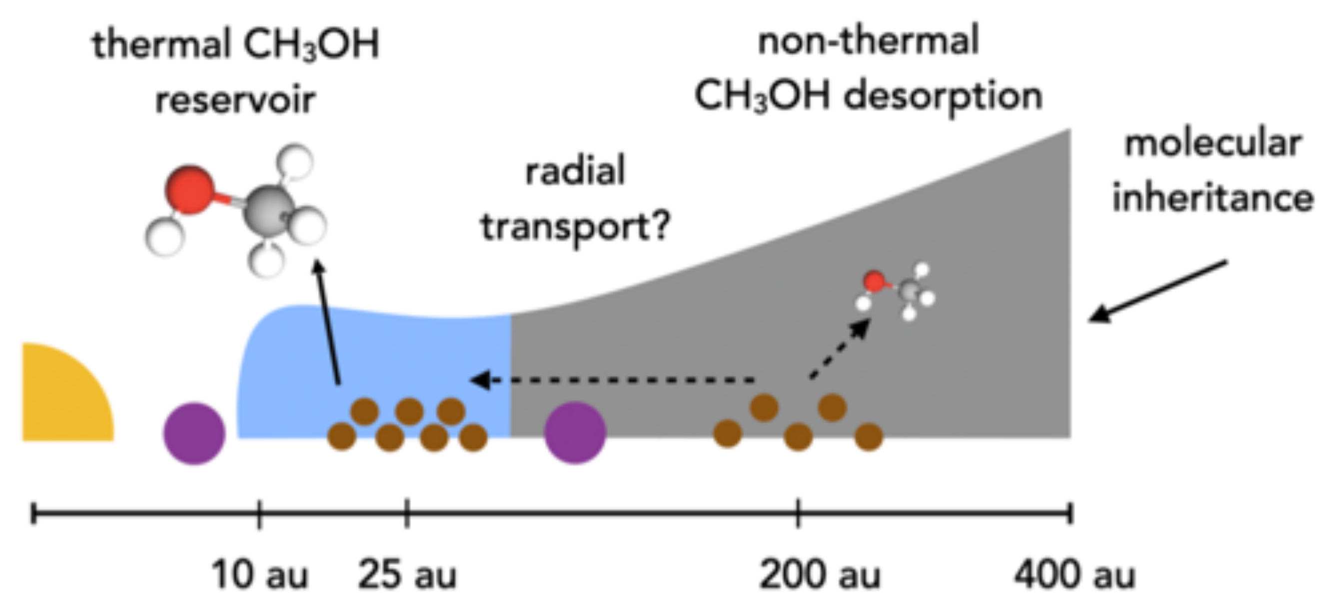
CH_3OH in warm disk?

HD100546: warm disk (hot star) **=> no CO ice reservoir?**



CH_3OH ice must be formed in early cloud phase and inherited, drifted inwards and then sublimated

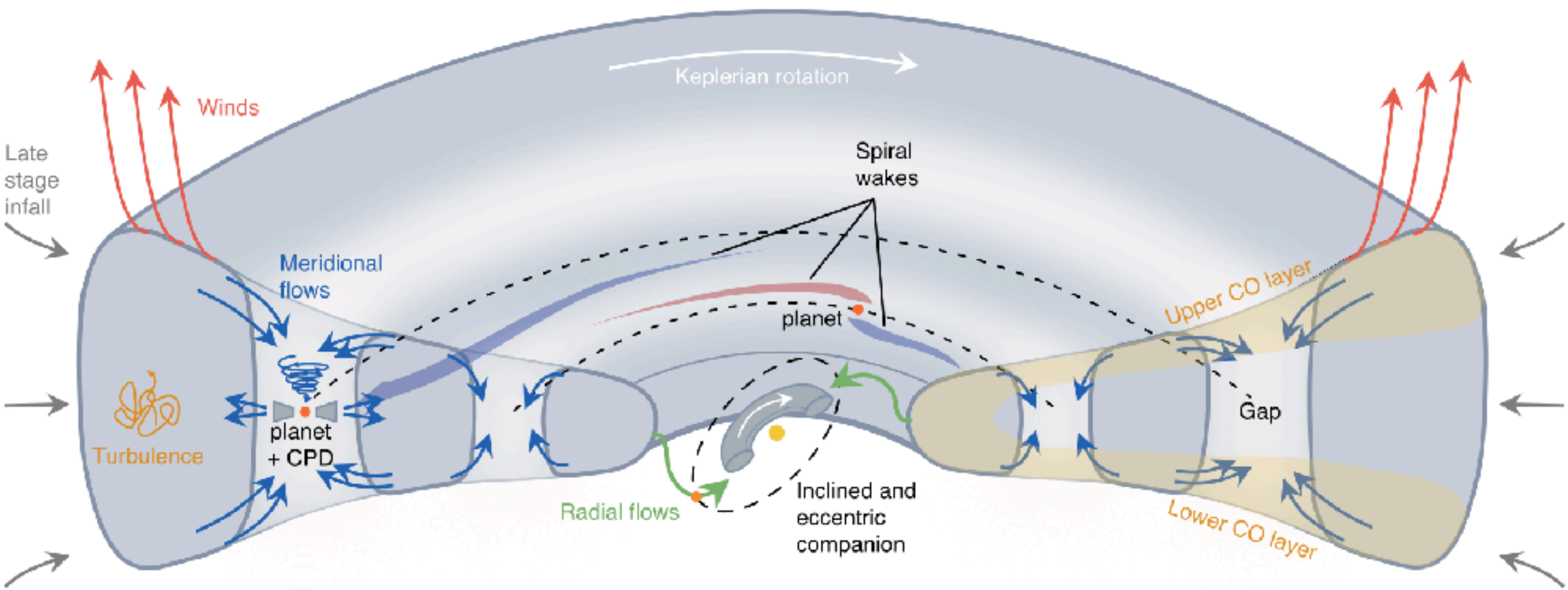
(Also seen in IRS48)



Booth et al. 2021a
van der Marel et al. 2021b

What kind of kinematics have we detected and are we expecting to detect in protoplanetary disks?

Expected kinematics in a disk



Much more than just Keplerian rotation!

Pinte et al. 2022 (PPVII)




Thank you so much!!