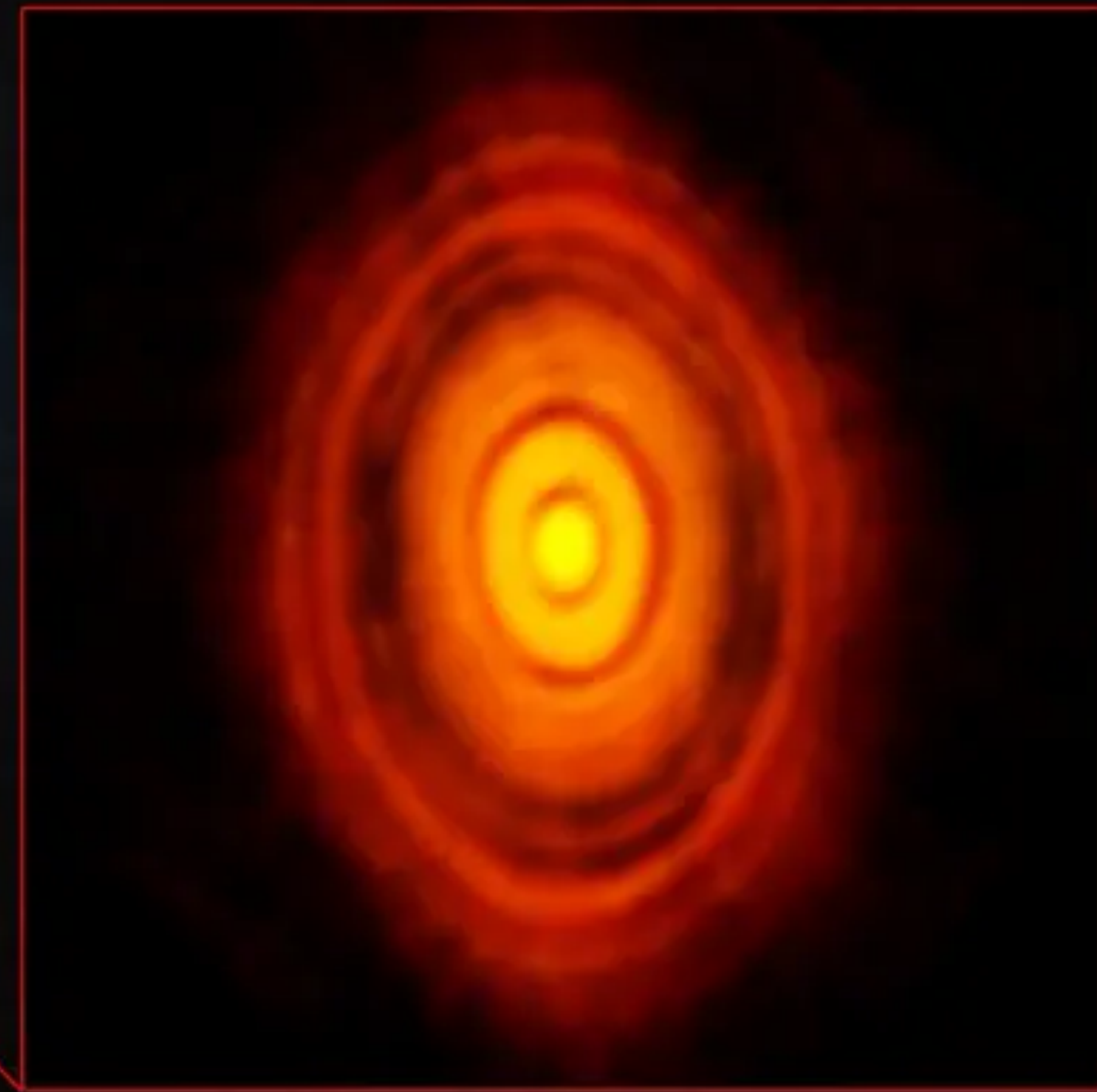


# Microphysics in Disk Formation and Evolution

Hsi-Wei Yen (ASIAA)





# Accretion and Feedback - Stellar properties

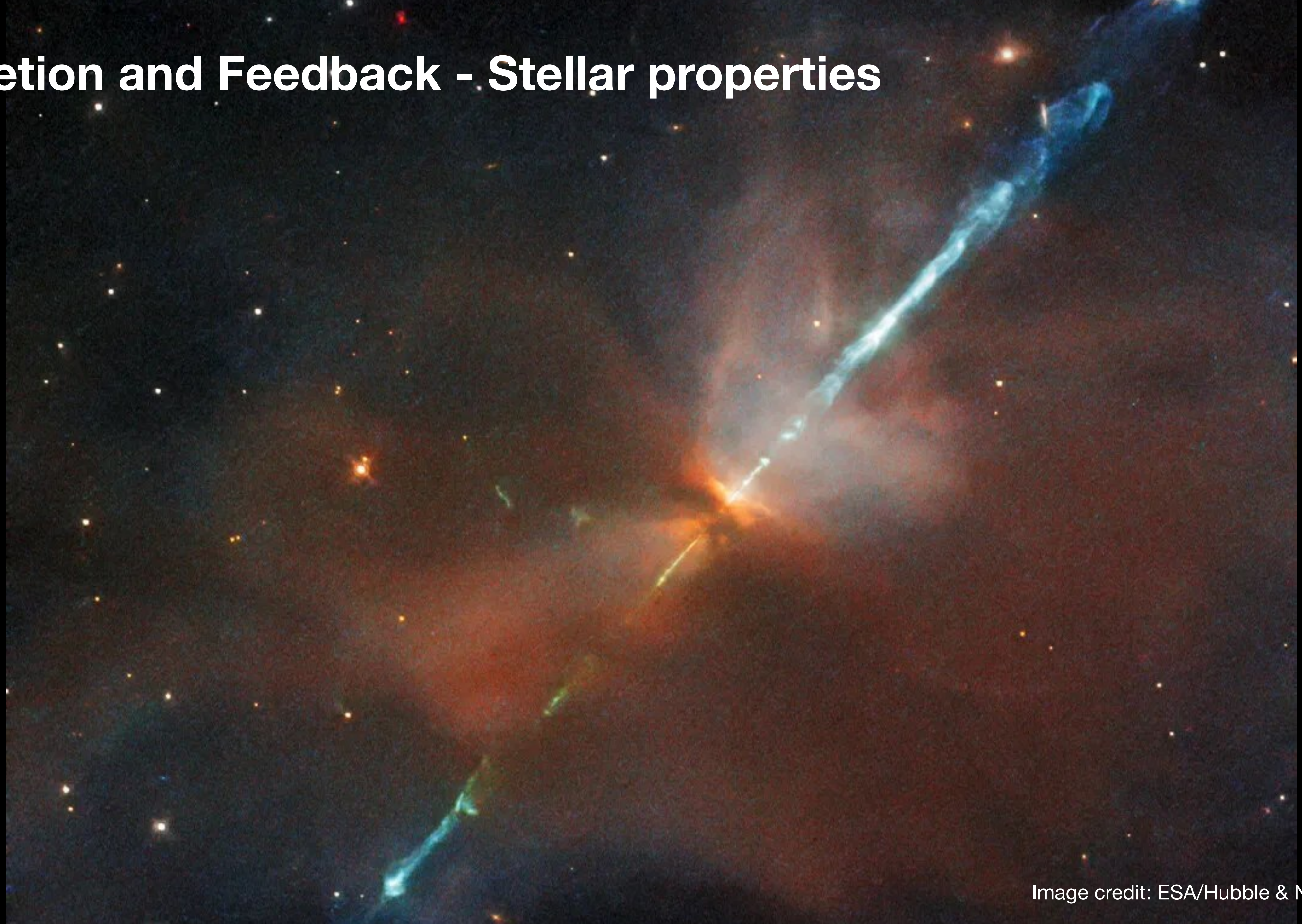
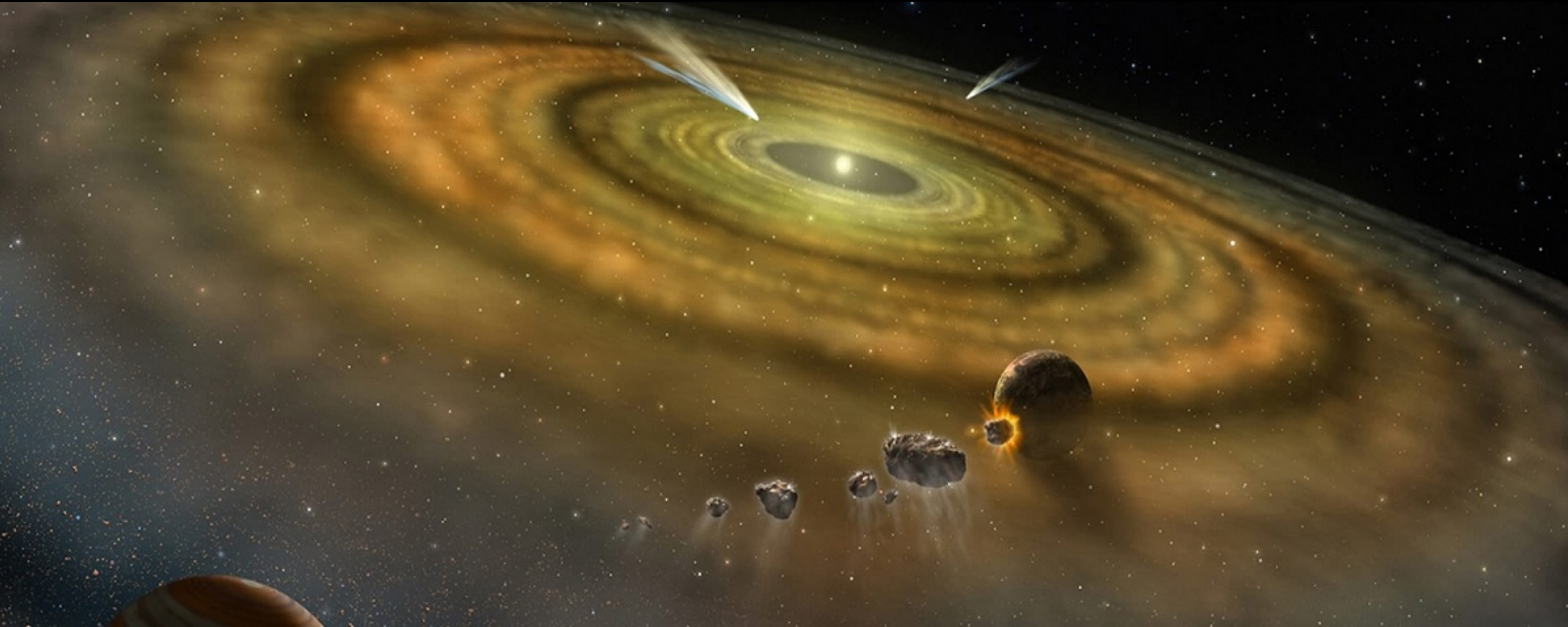


Image credit: ESA/Hubble & NASA, B. Nisini



# Planet Formation - Initial conditions

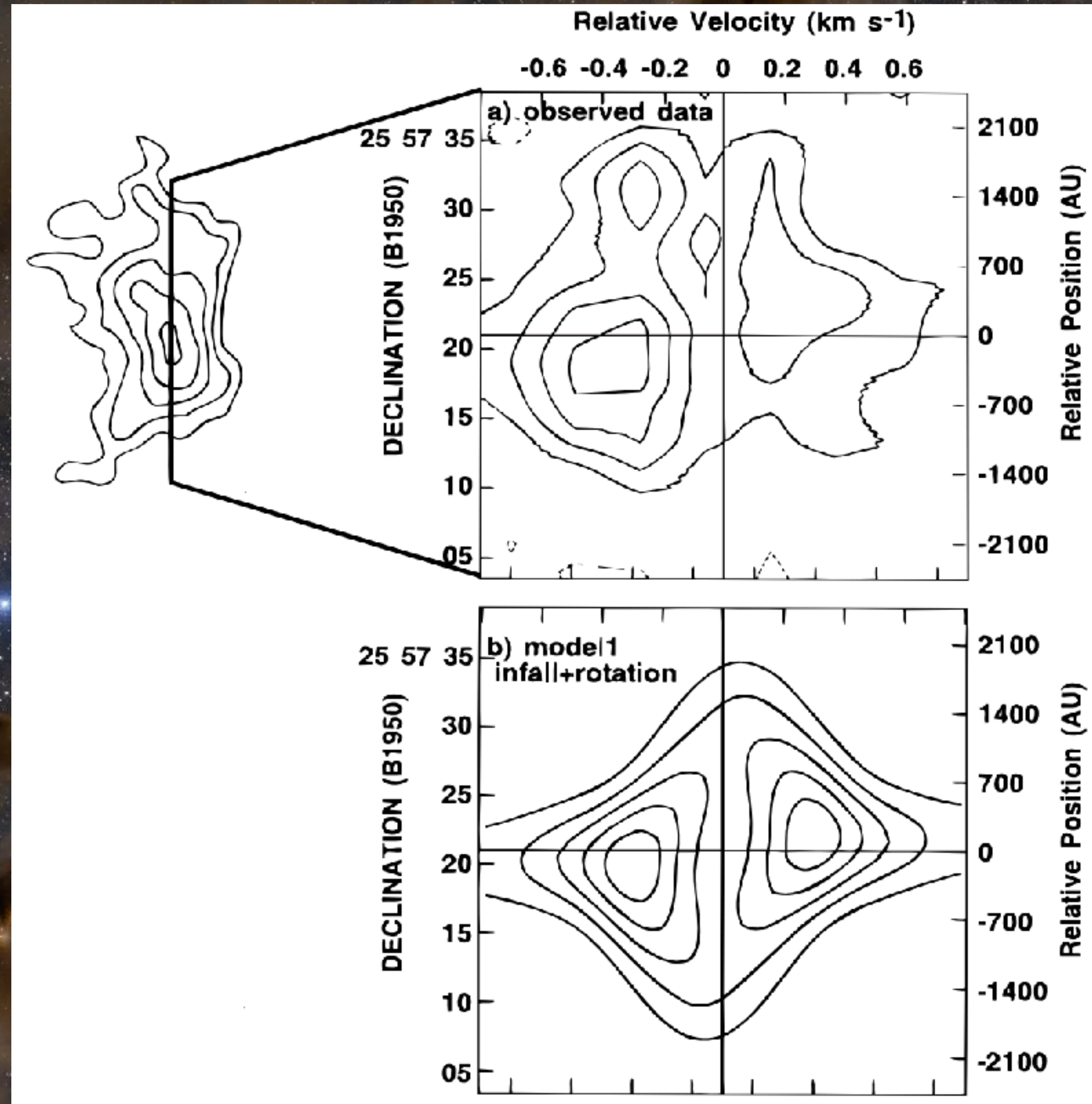
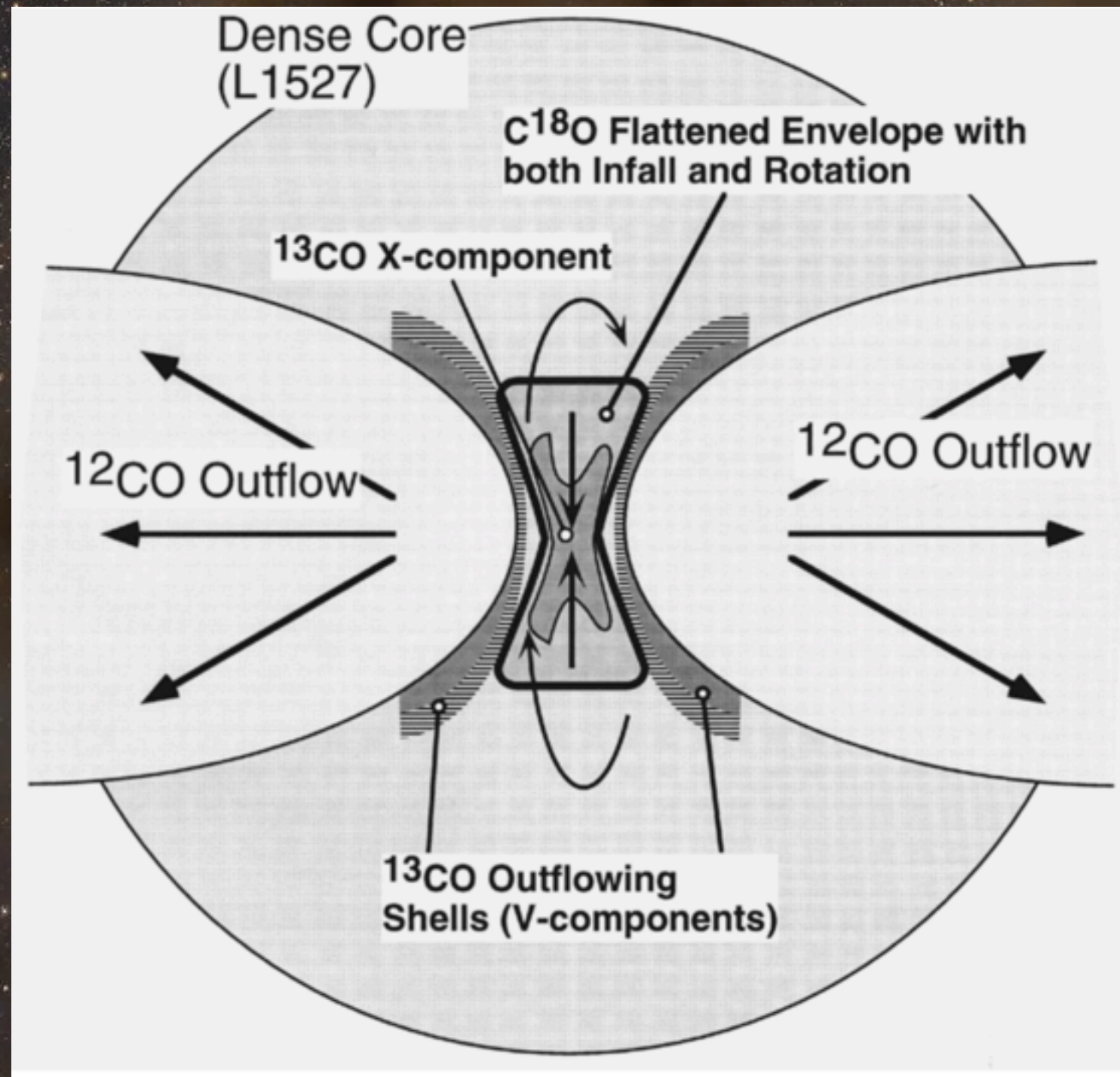




**Disks are embedded in molecular clouds  
at the early stage of star formation**



# Millimeter observations probe structures and kinematics around protostars

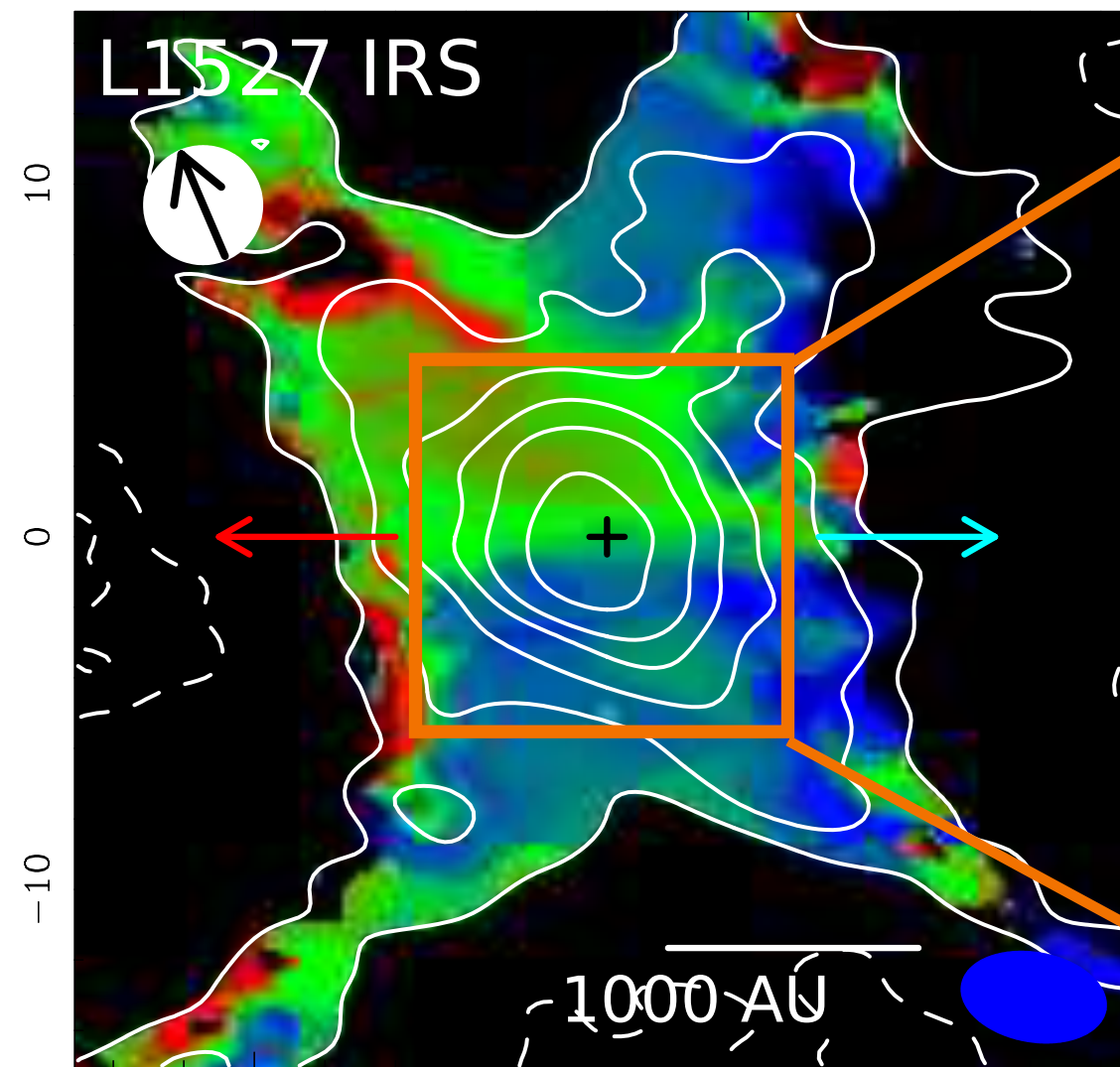


Ohashi et al. (1997)

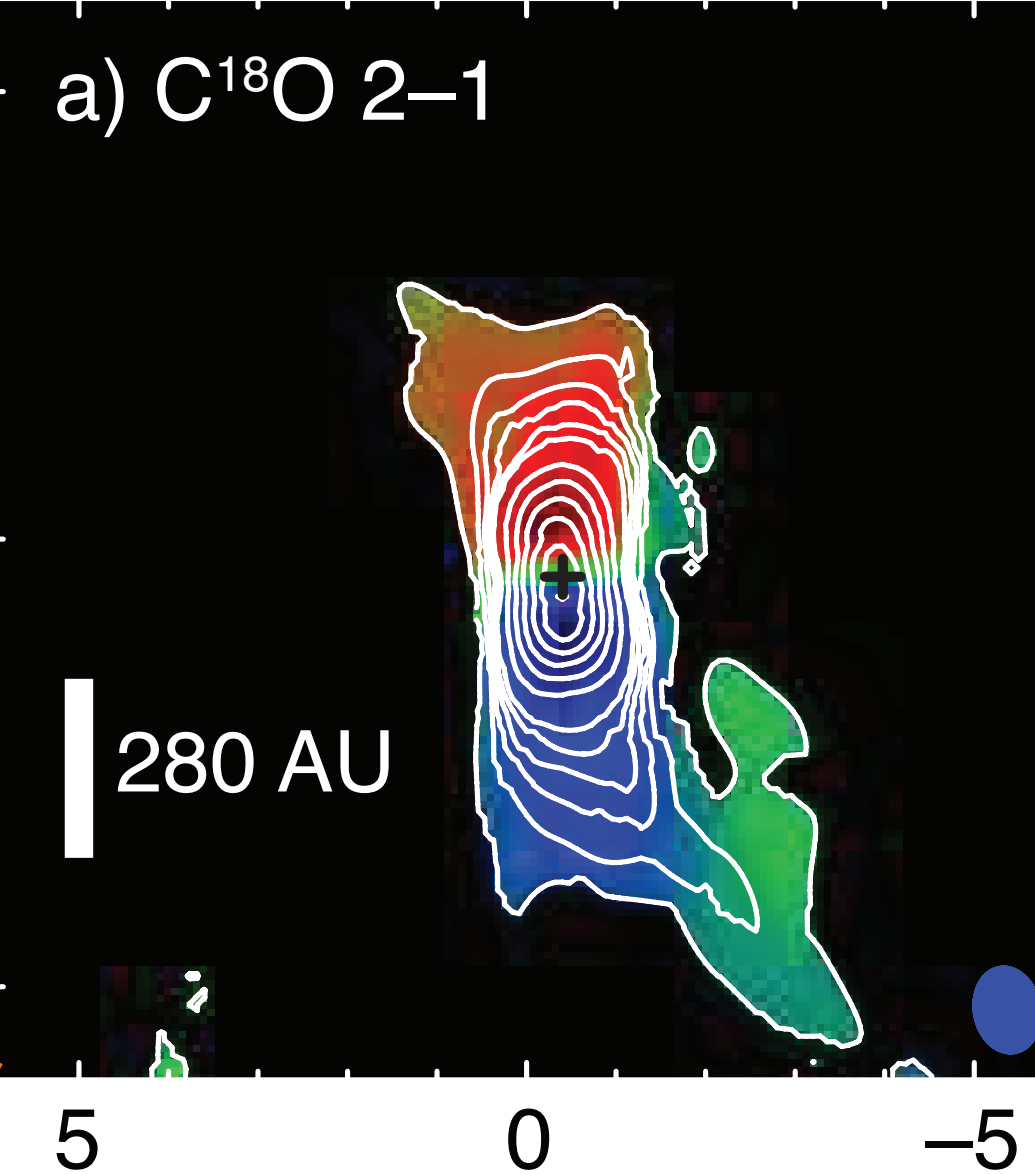


# Improvement in resolution and sensitivity

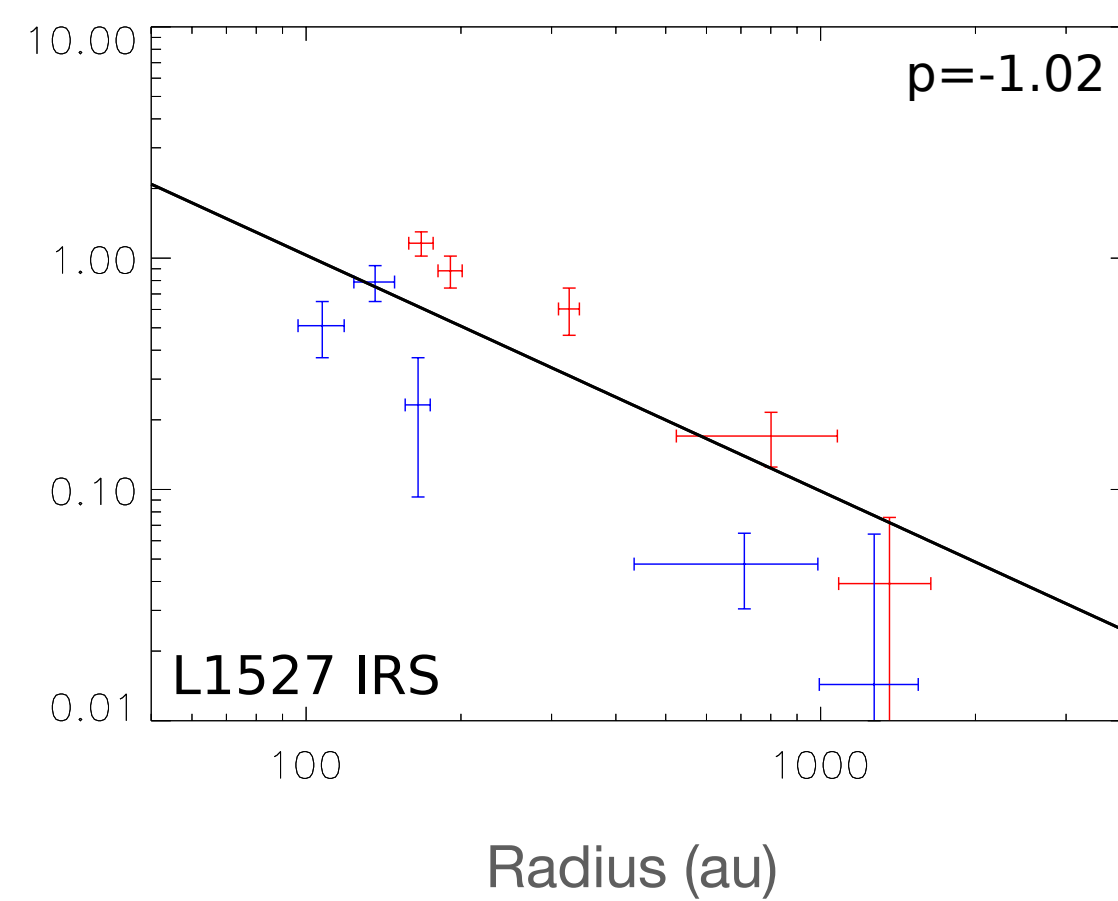
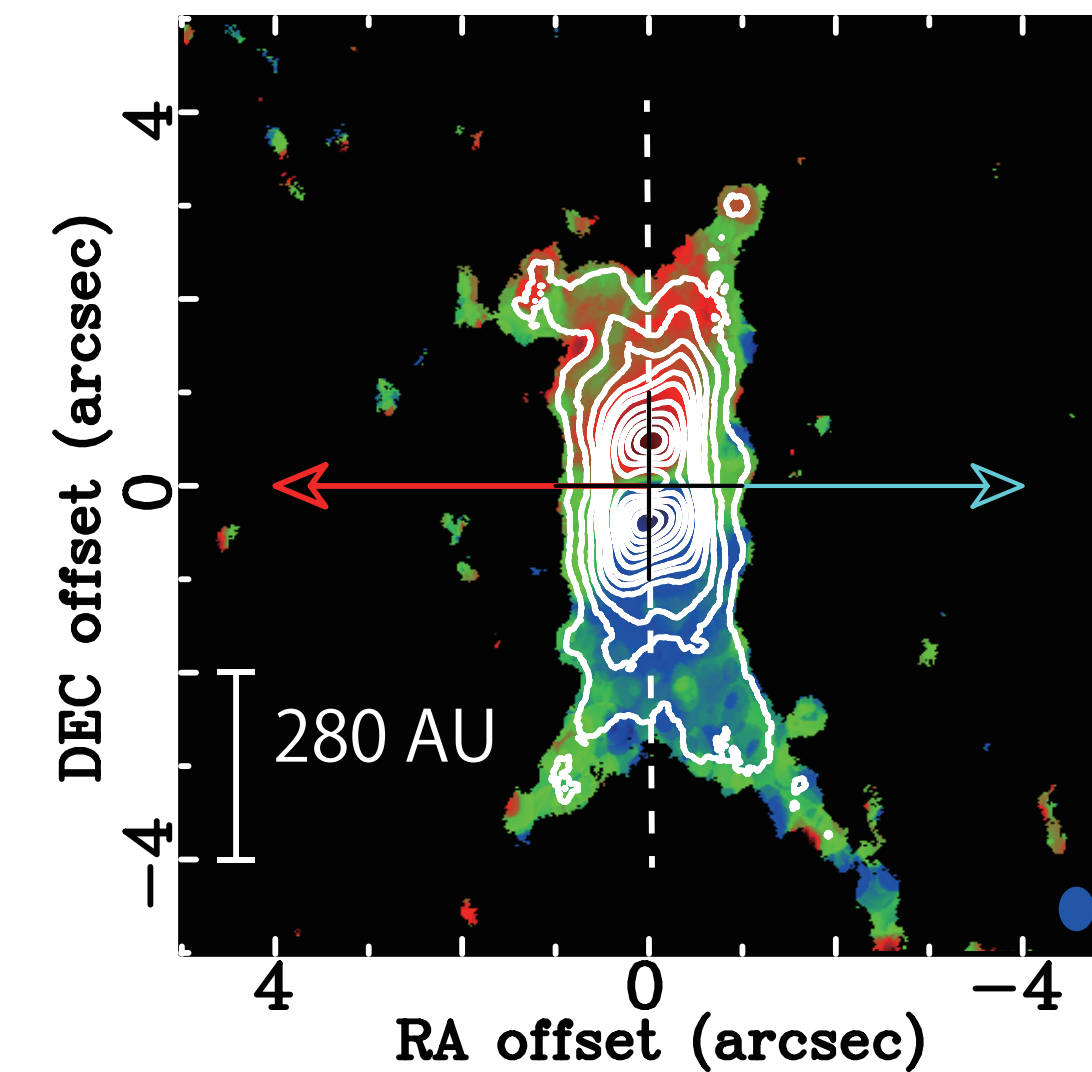
SMA — Resolution  $\sim 500$  au



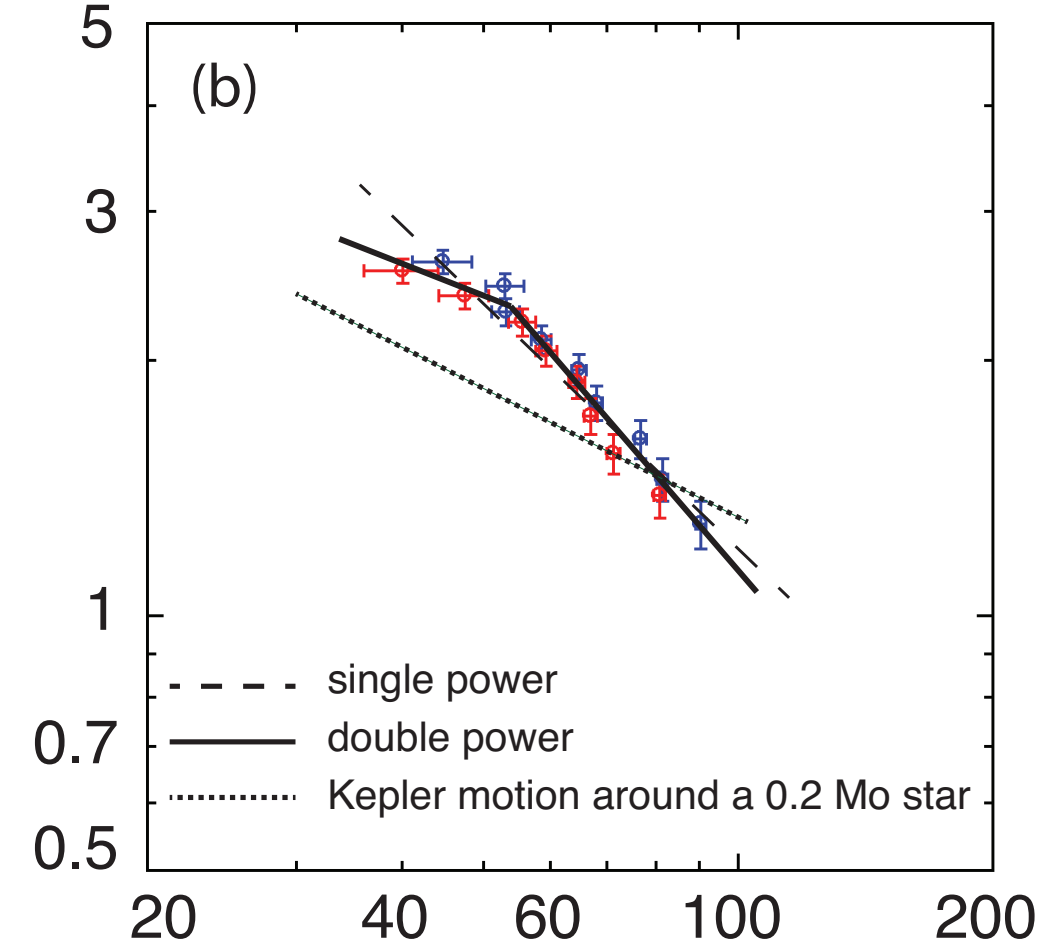
ALMA — Resolution  $\sim 100$  au



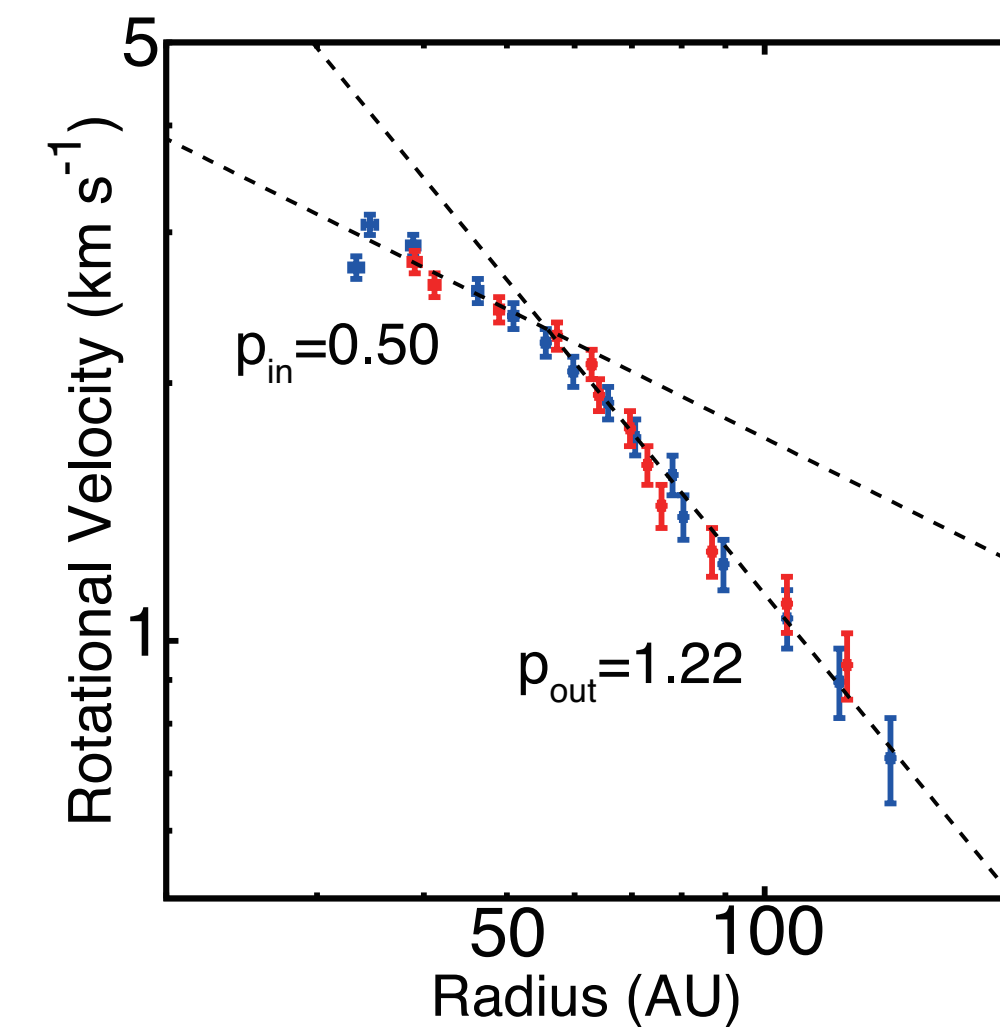
& Resolution  $\sim 50$  au



Yen et al. 2013



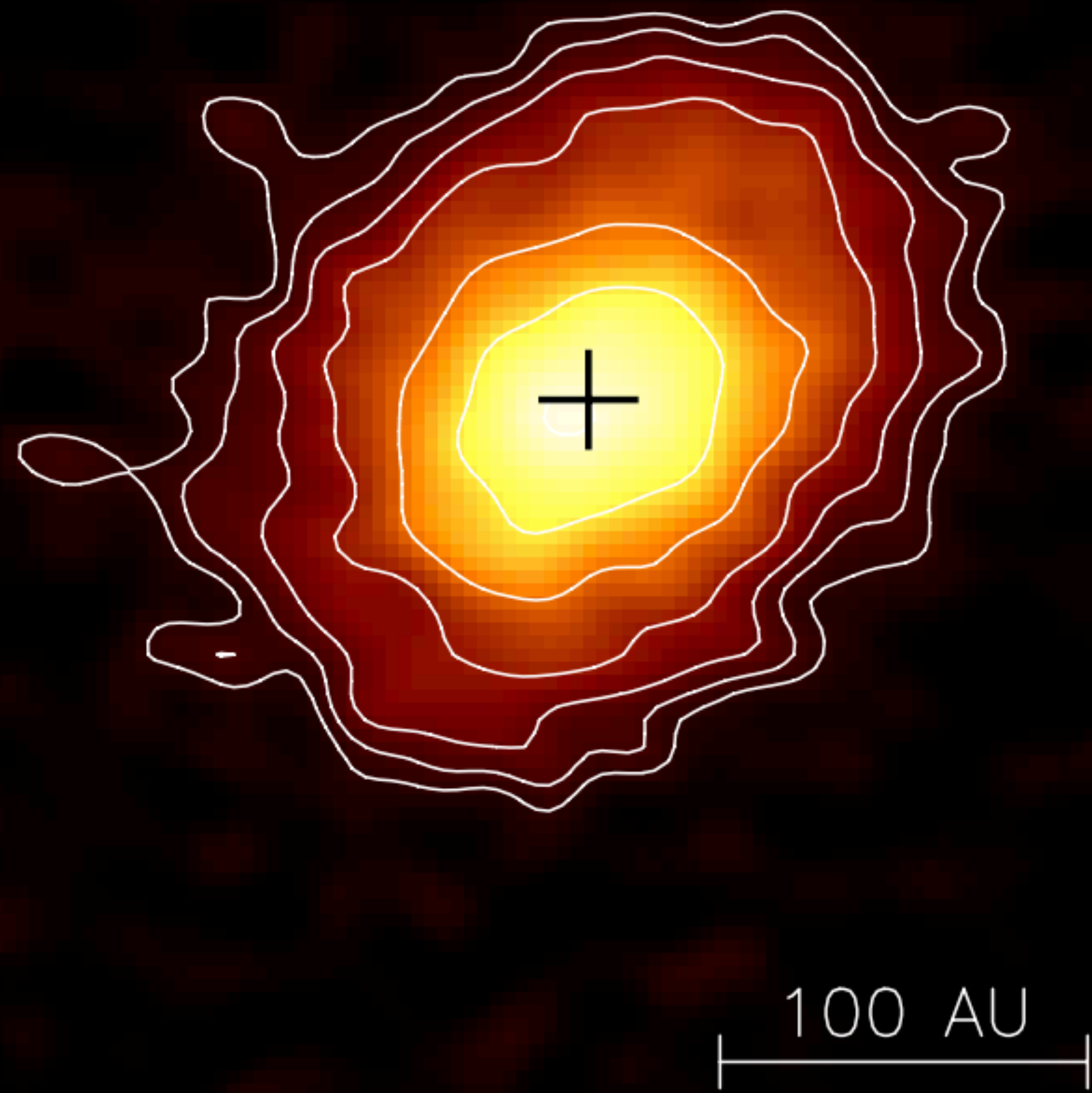
Ohashi et al. 2014



Aso et al. 2017



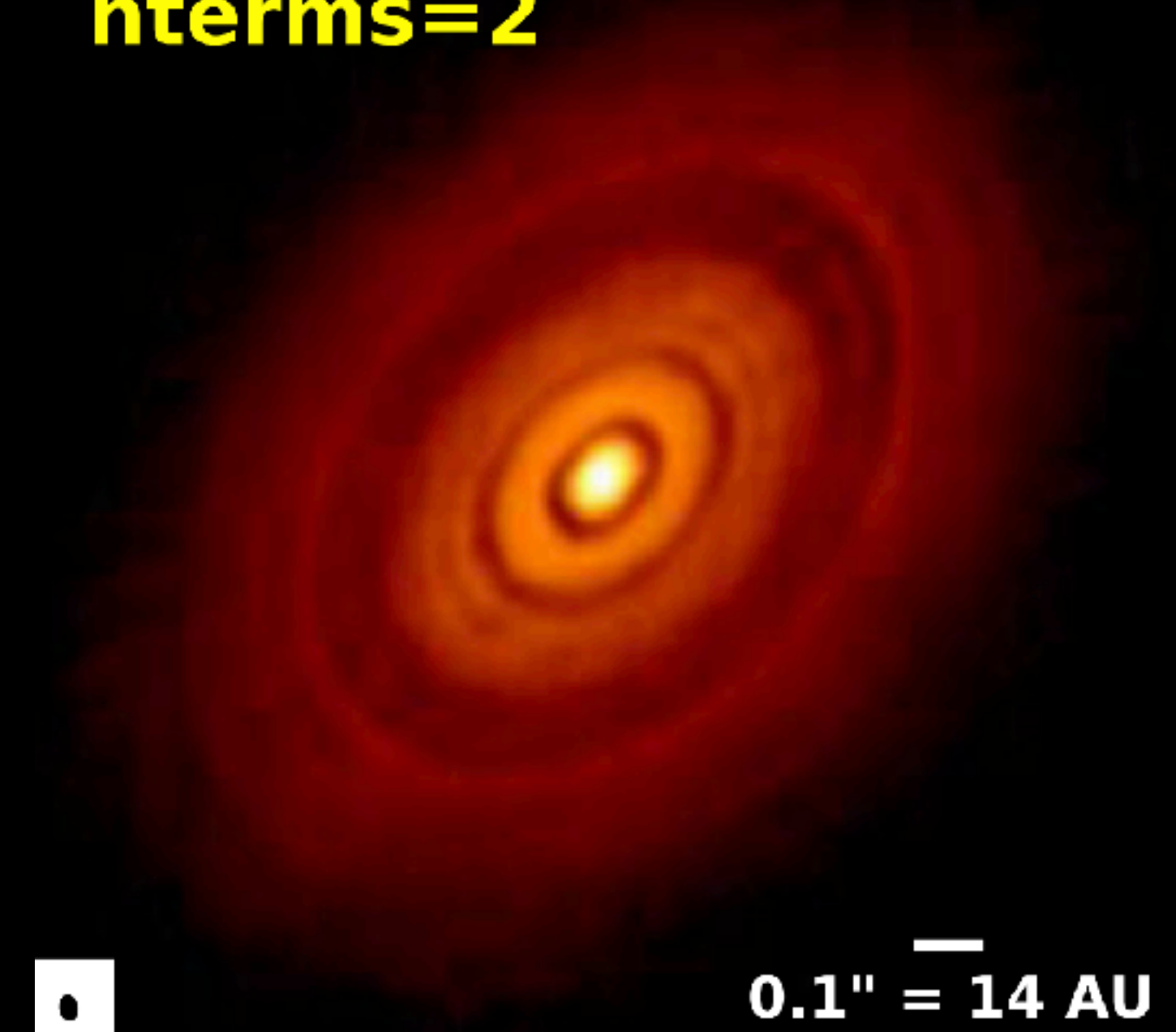
HL Tau



Kwon et al. (2011)

Five times higher resolution

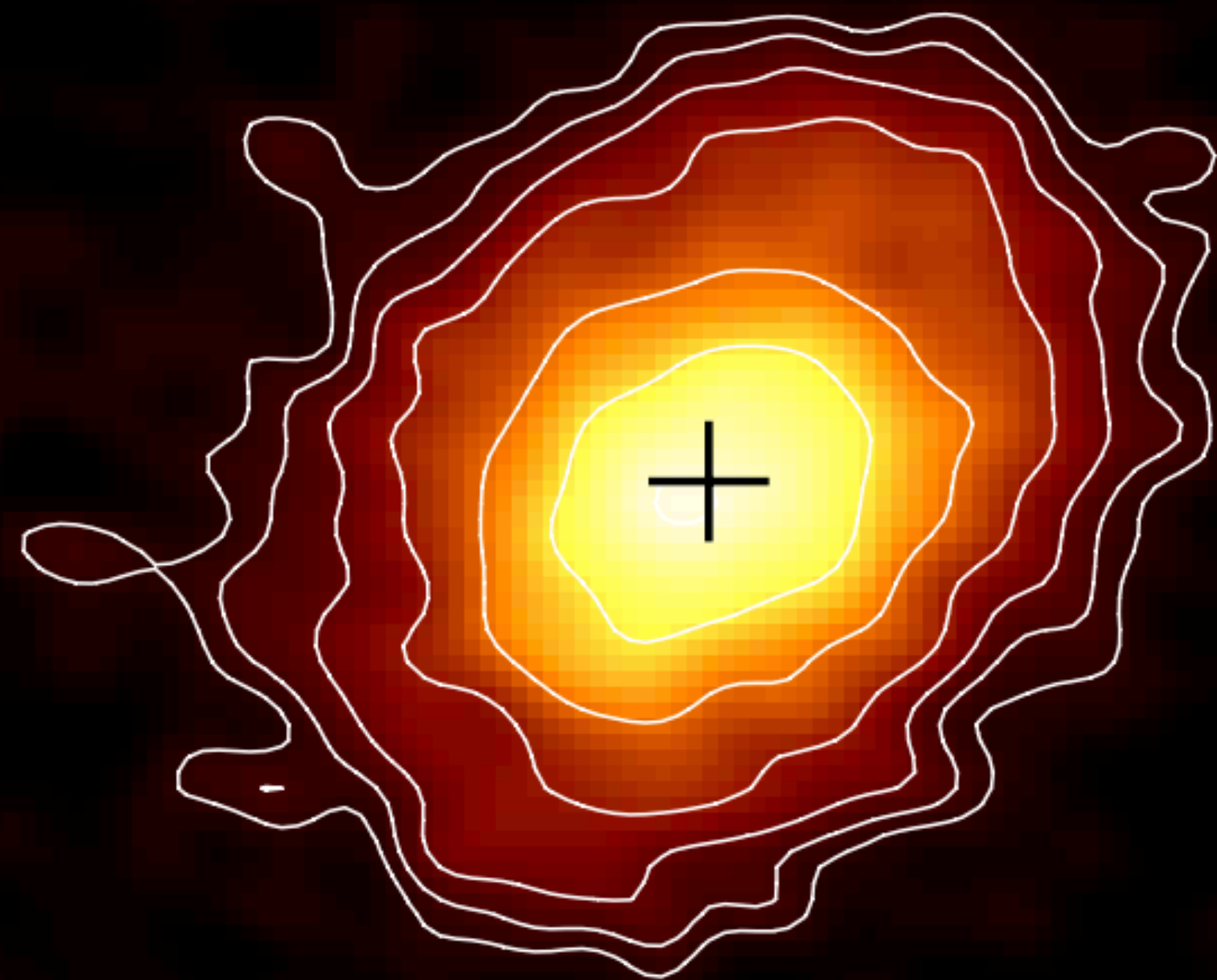
(e) 1.0 mm (B6+B7)  
nterms=2



ALMA partnership et al. (2015)



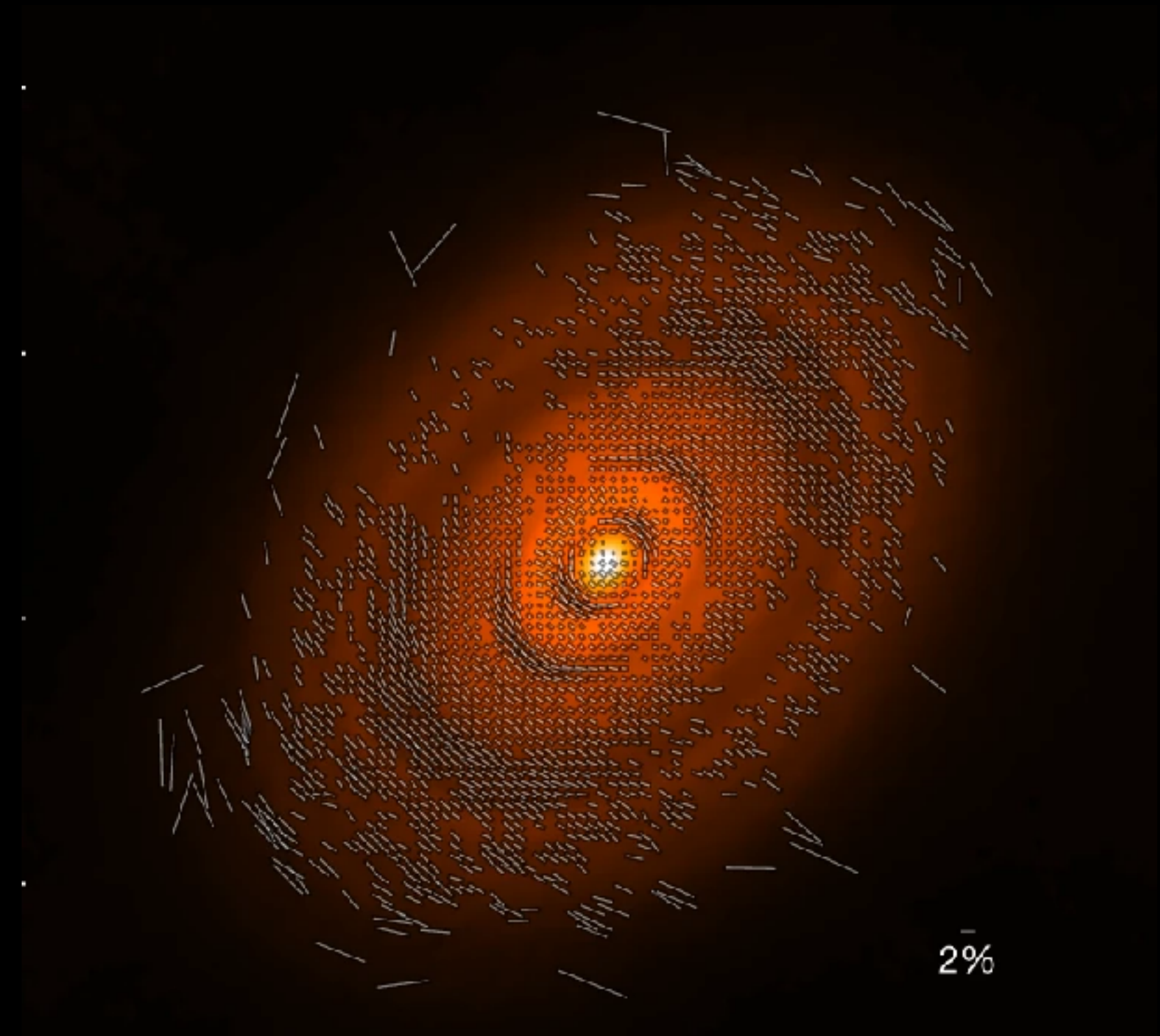
HL Tau



100 AU



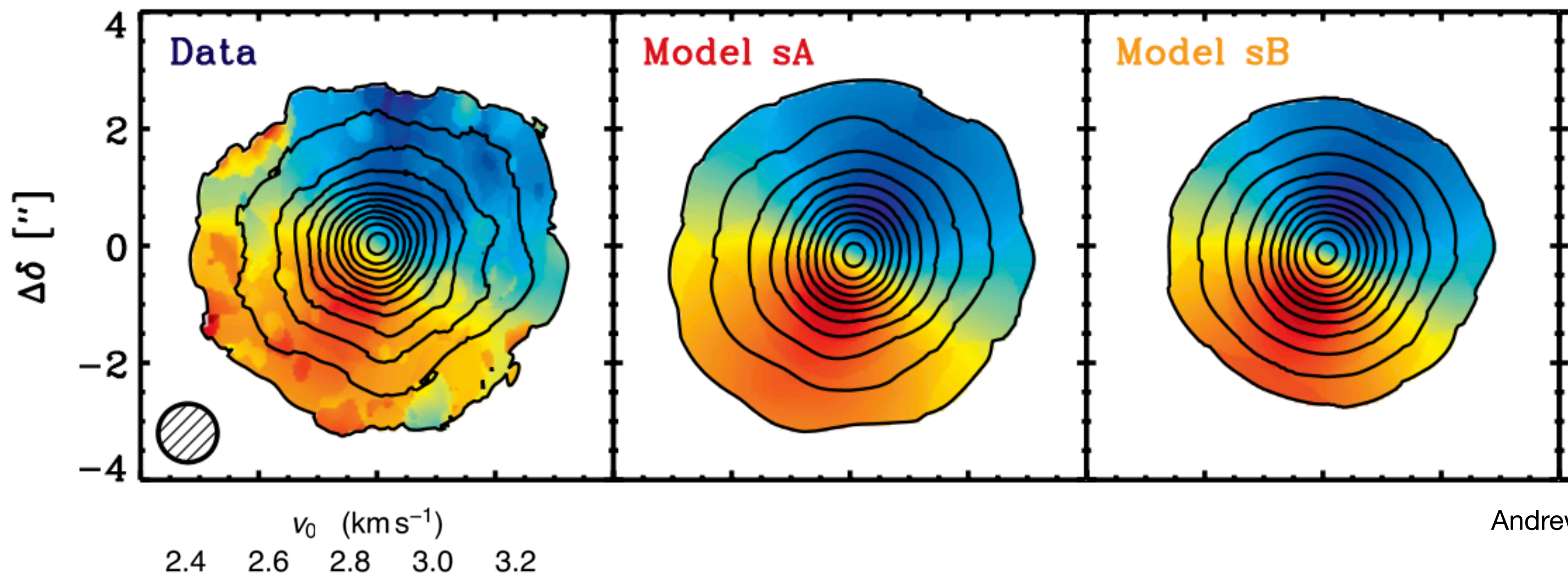
**Five times higher resolution**  
**Detailed polarization pattern**



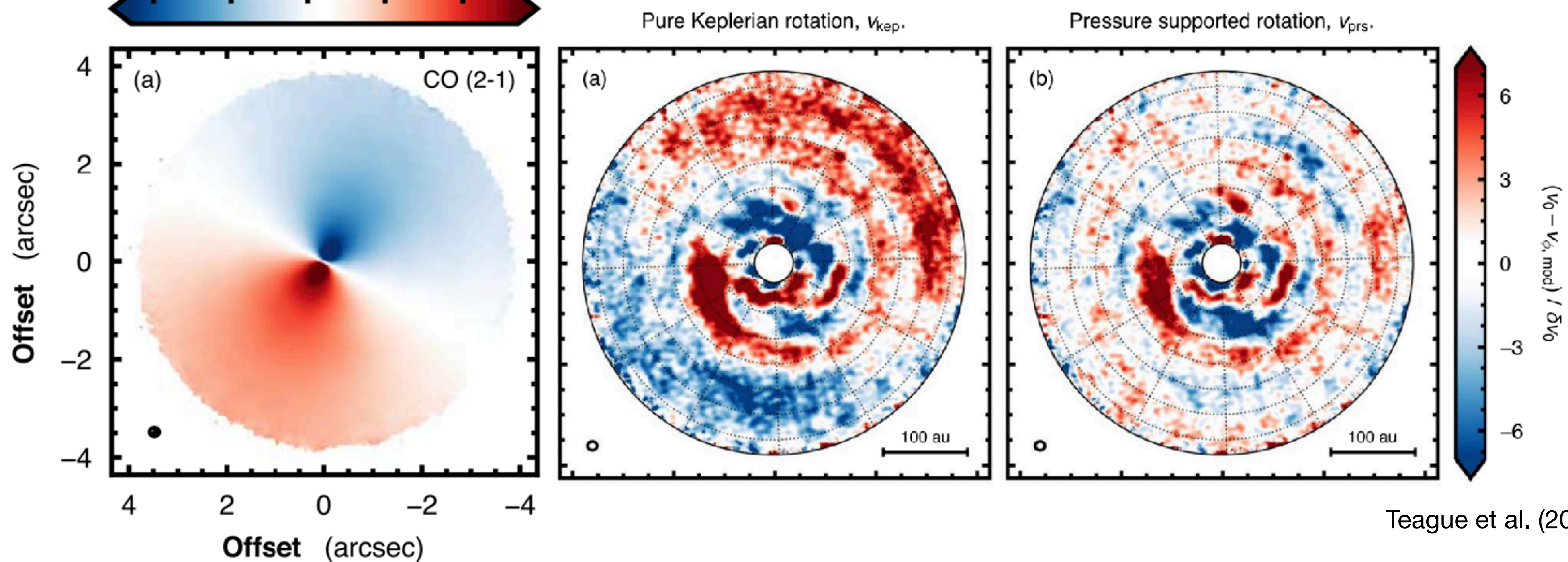
2%



# Detailed Dynamics



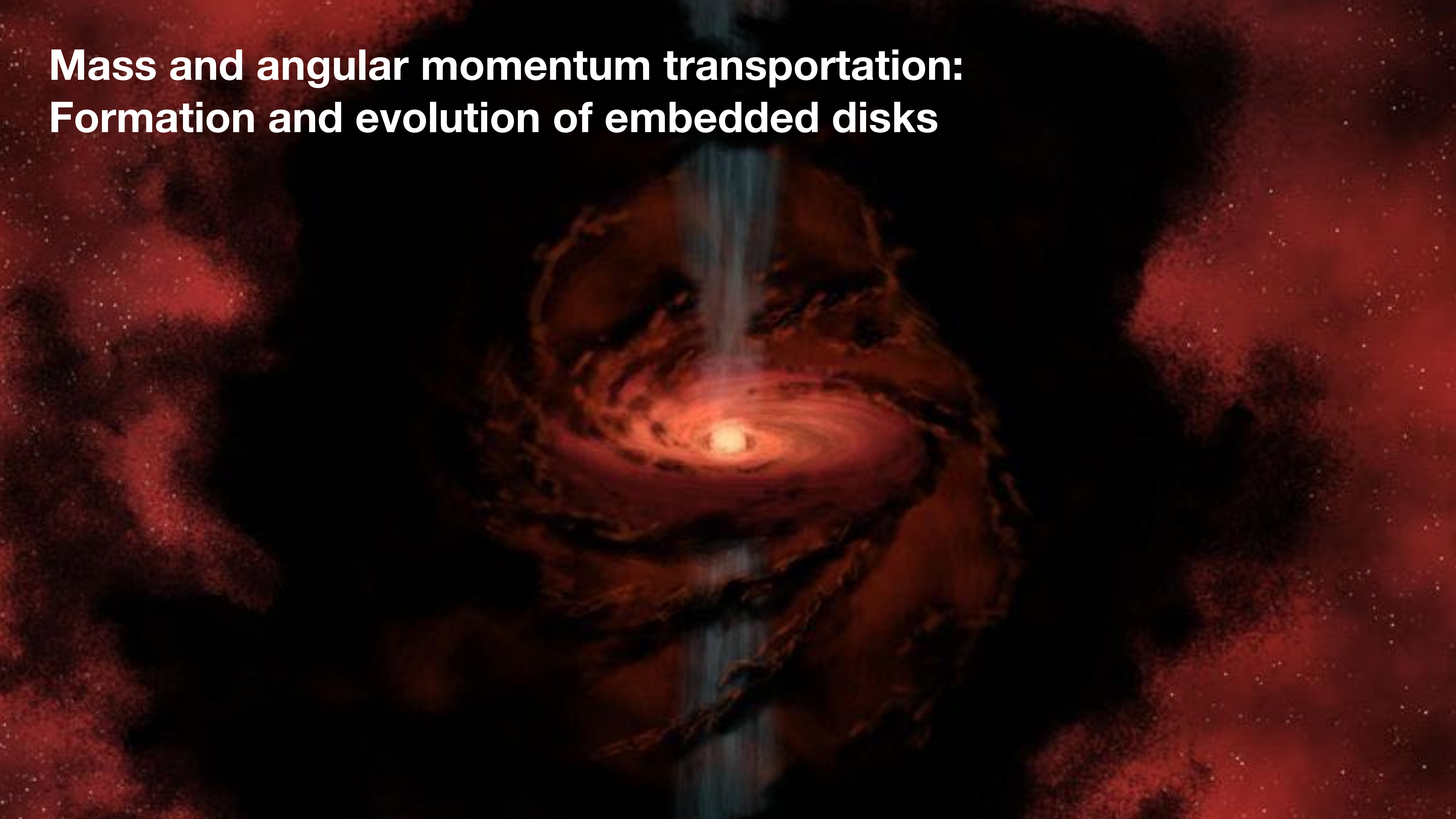
Andrews et al. (2012)



Teague et al. (2022)



# **Mass and angular momentum transportation: Formation and evolution of embedded disks**





# Mass and angular momentum transportation: Formation and evolution of embedded disks

## Hydrodynamics

Angular momentum conservations

Disks tend to be big



# Star-forming regions are magnetized

Herschel & Planck polarization maps

Lazarian (2007)

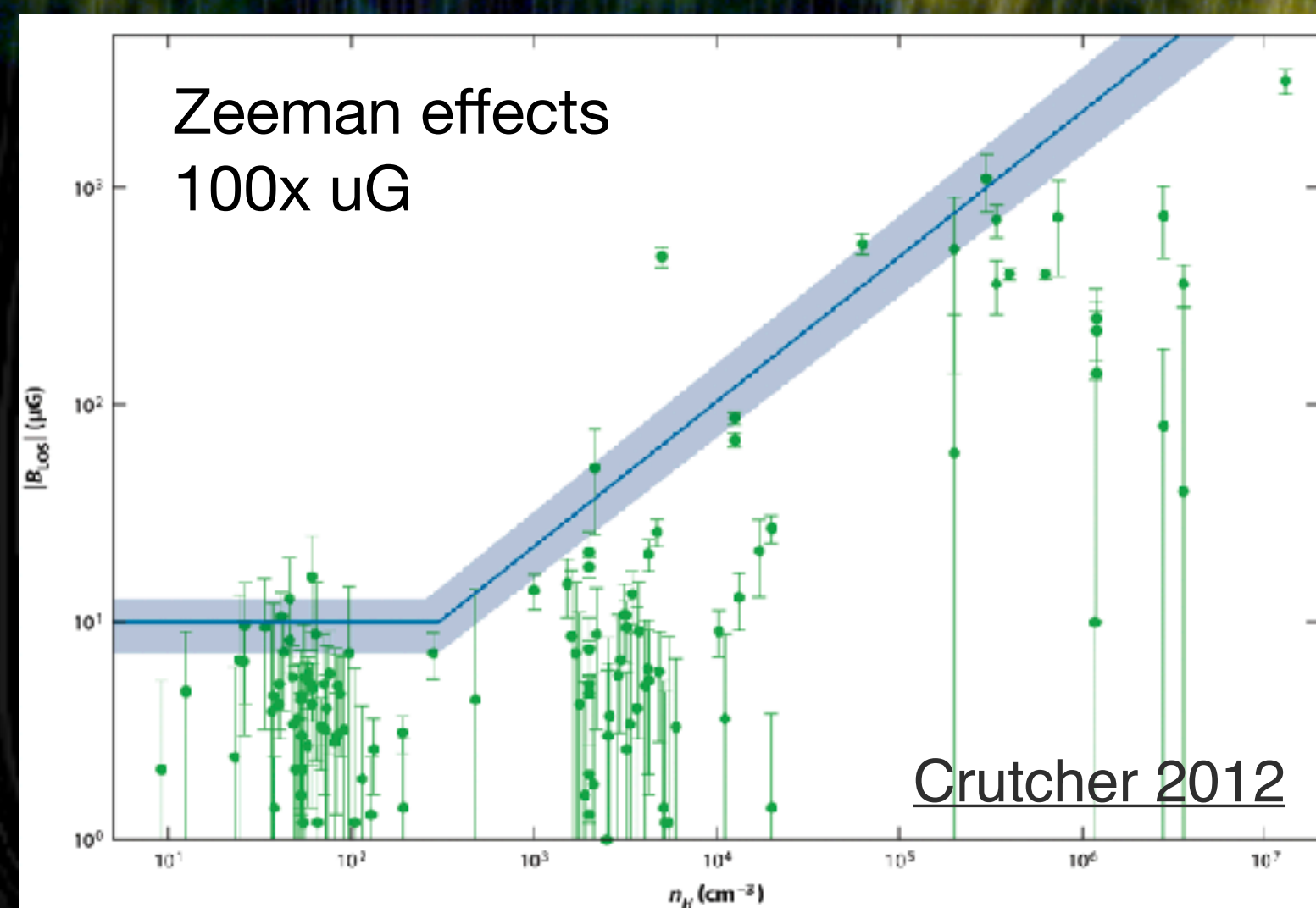


Image credit:  
ESA/Herschel/Planck; J. D. Soler, MPIA



# Star-forming regions are magnetized

Herschel & Planck polarization maps

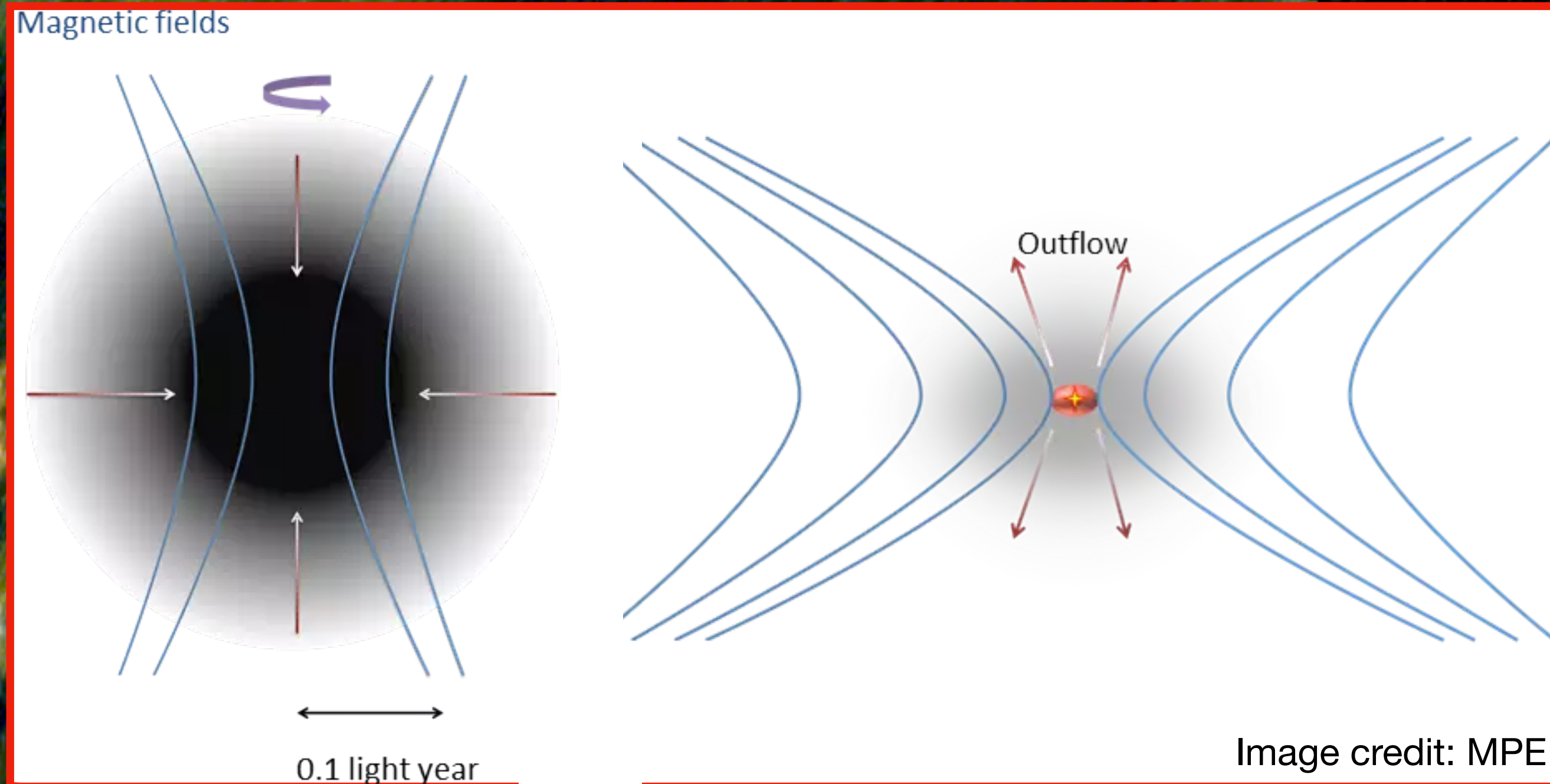
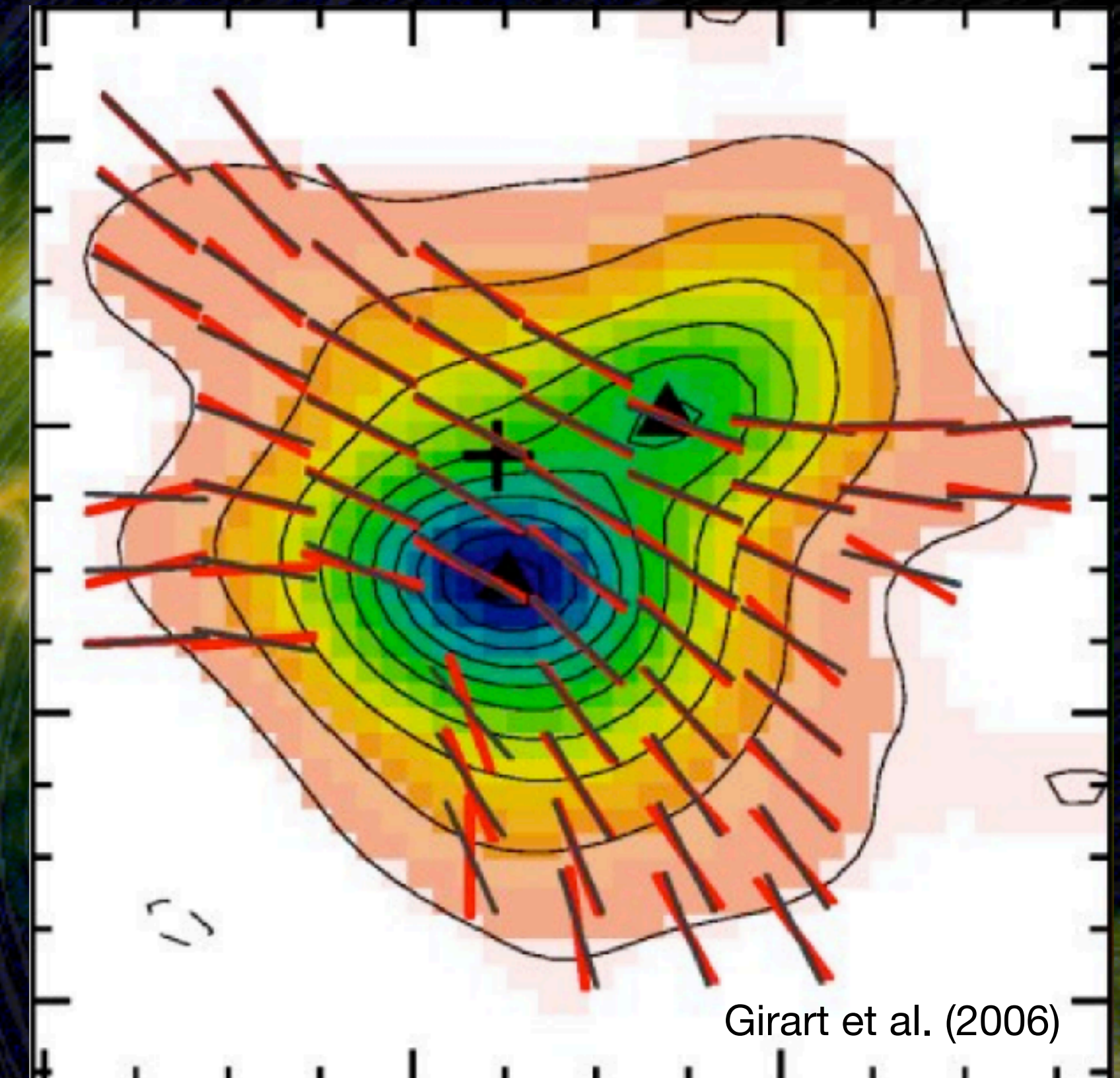
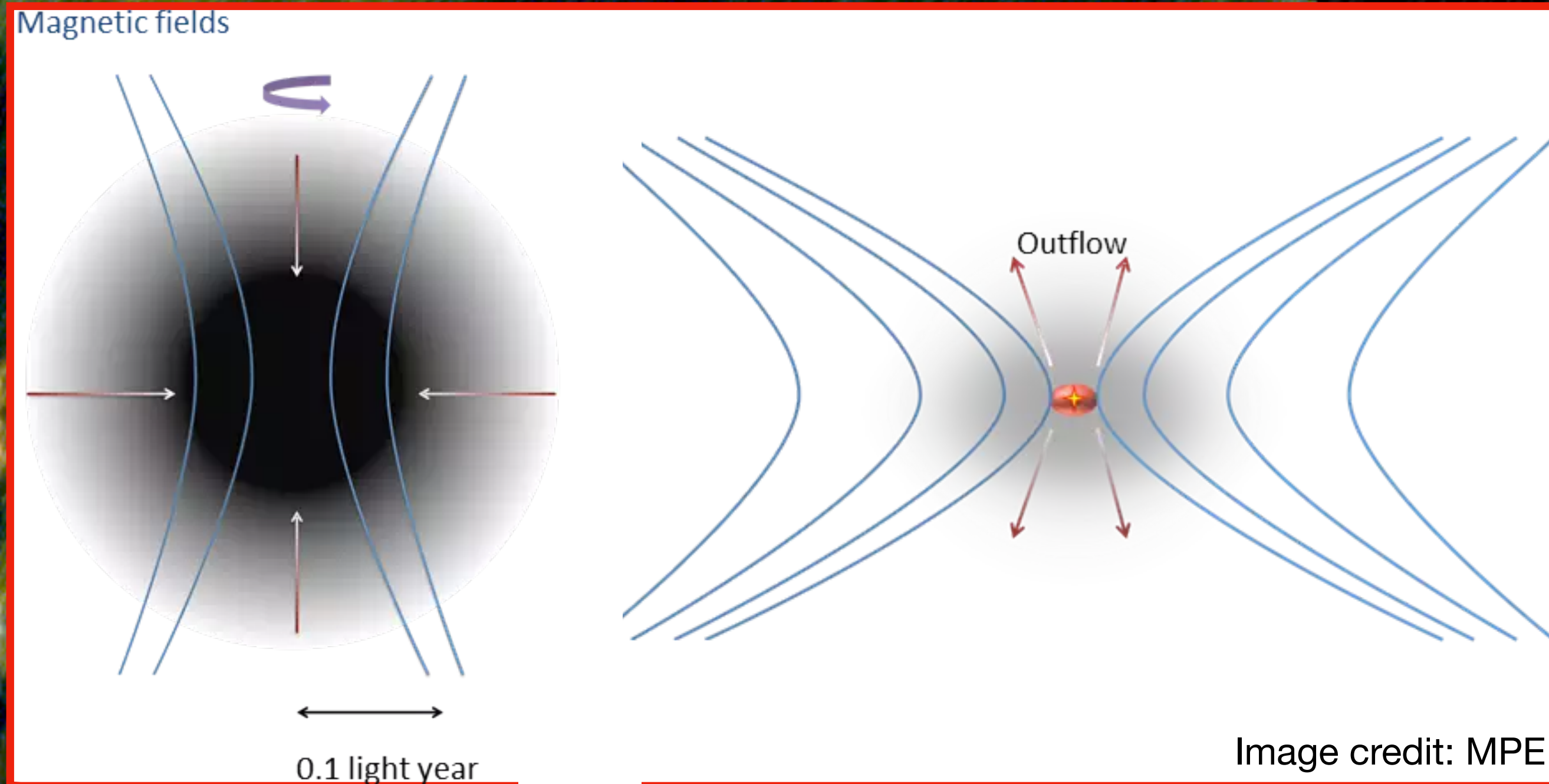


Image credit:  
ESA/Herschel/Planck; J. D. Soler, MPIA



# Star-forming regions are magnetized

Herschel & Planck polarization maps



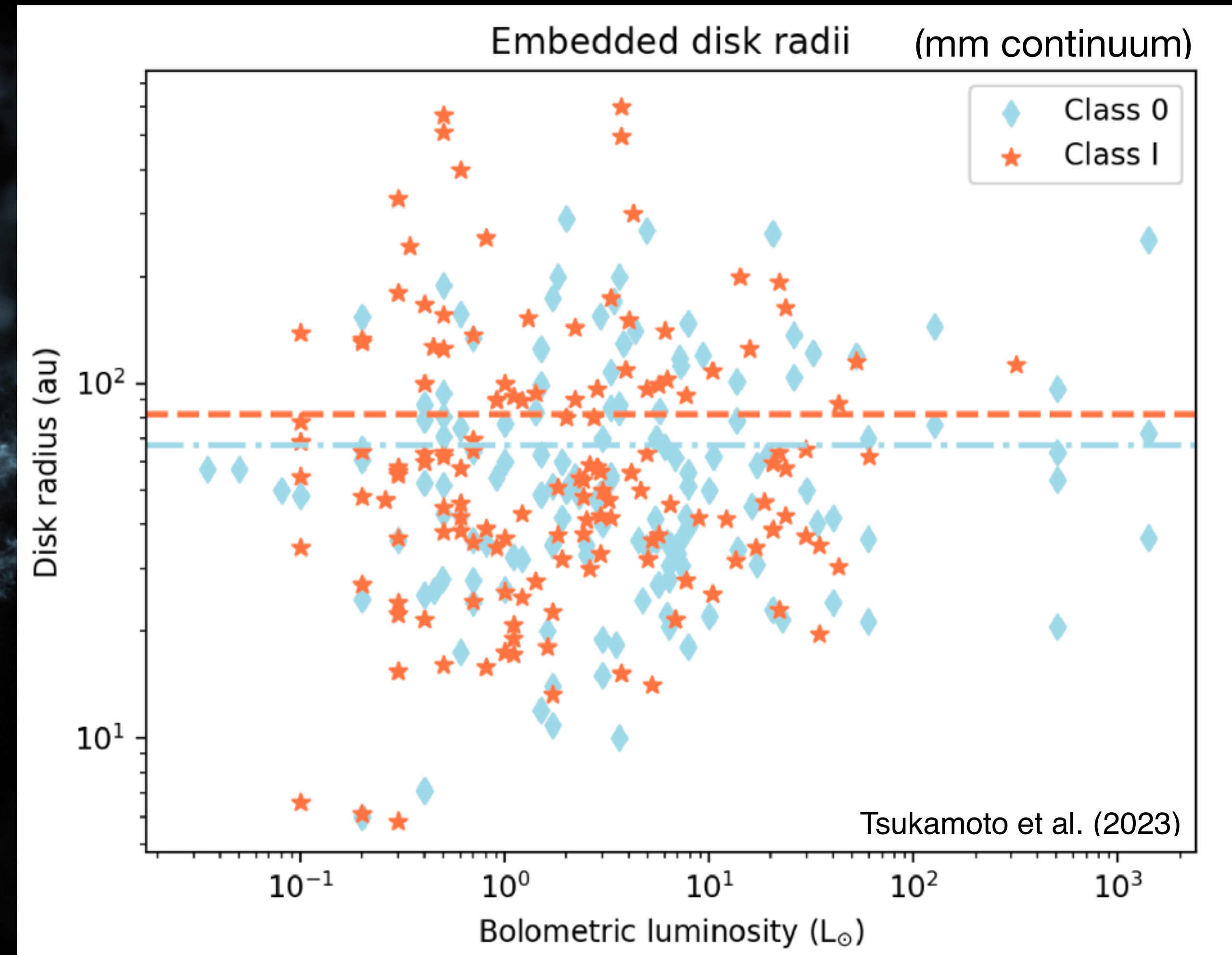
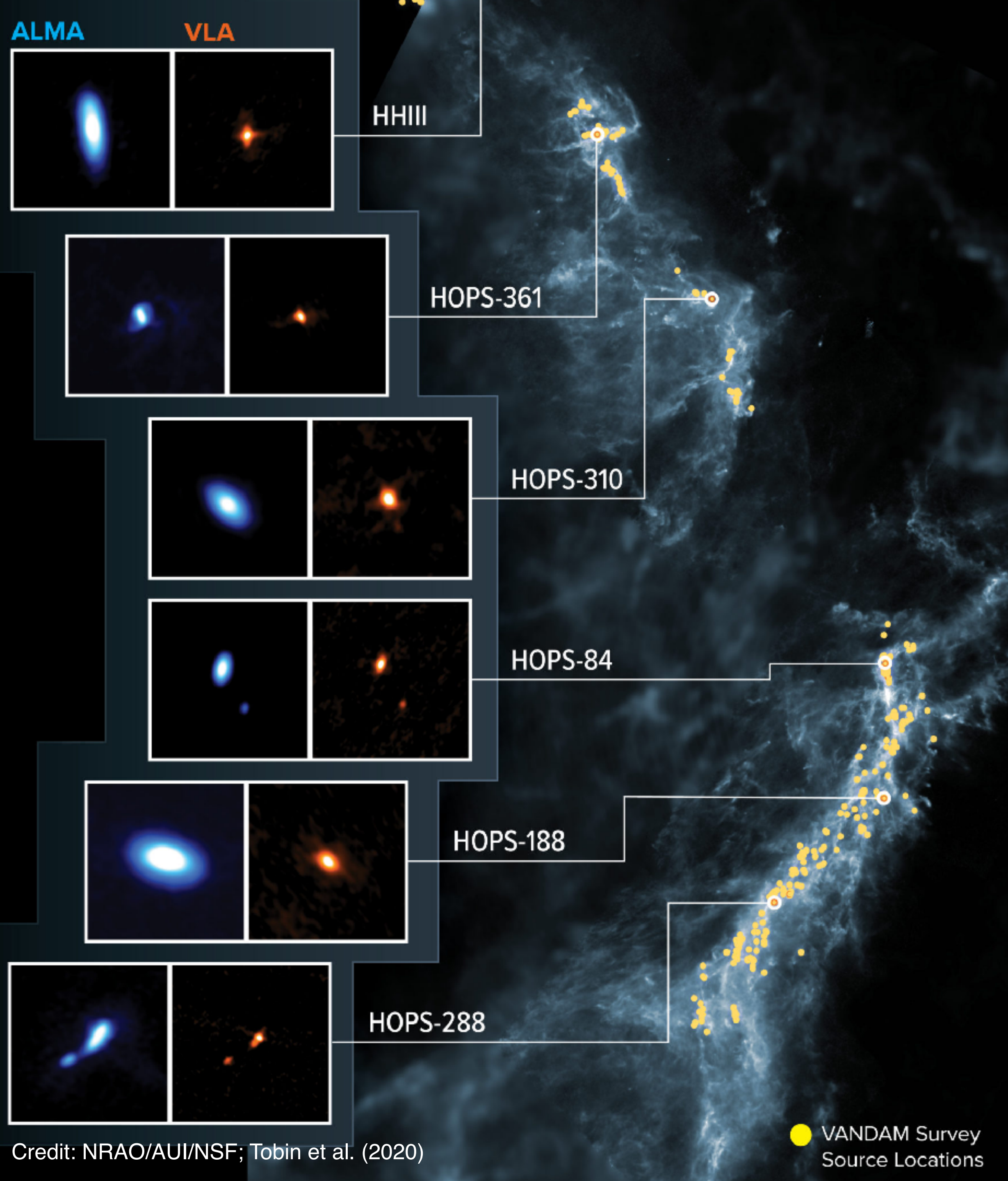
**Ideal Magnetohydrodynamics**

**Efficient magnetic braking**

**Disks tend to be very small**

Image credit:  
ESA/Herschel/Planck; J. D. Soler, MPA





**Disks with radii of 10x au are common**





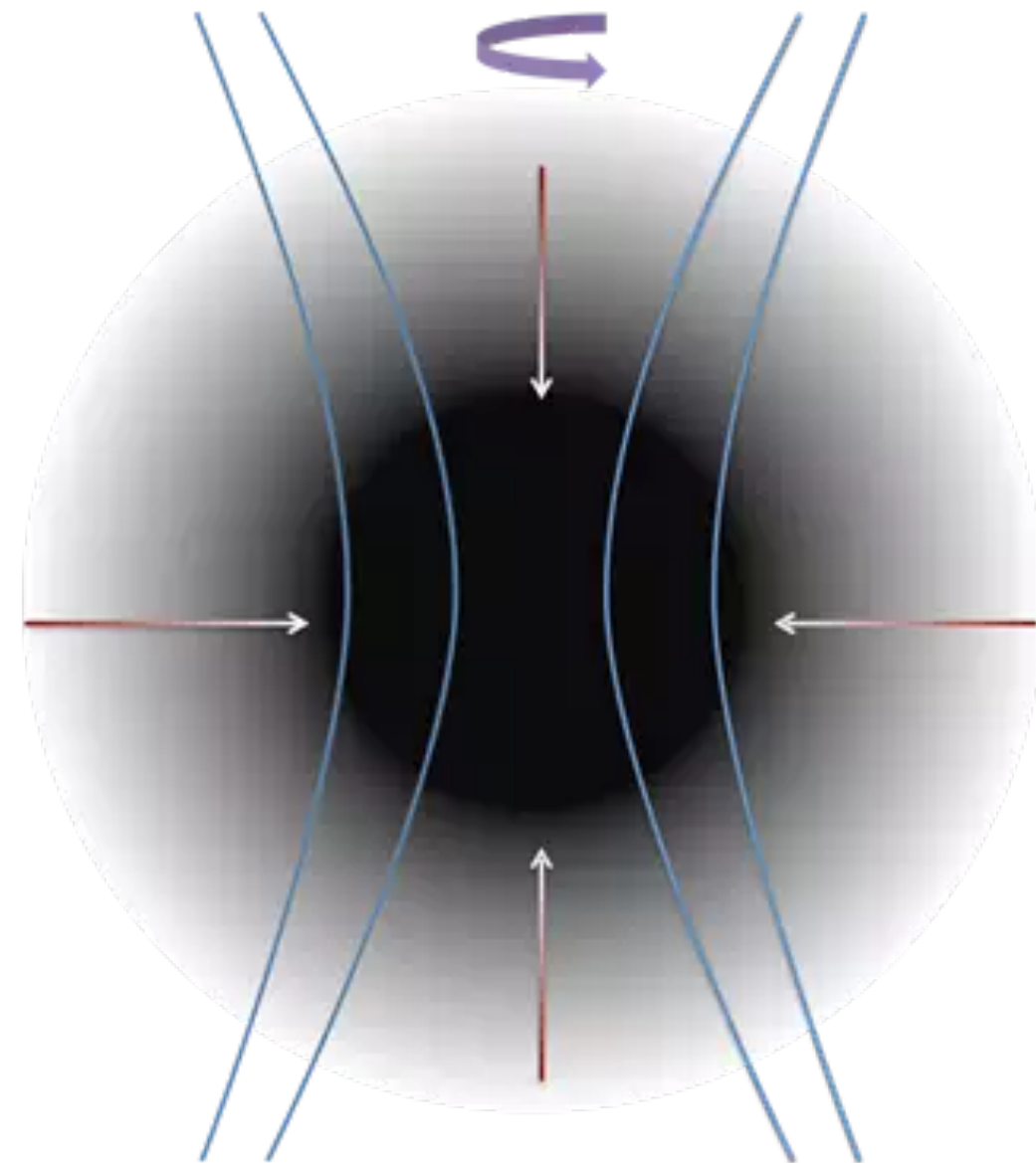
Image credit:  
NASA/JPL-Caltech

## Hydrodynamics

**Angular momentum conservations**

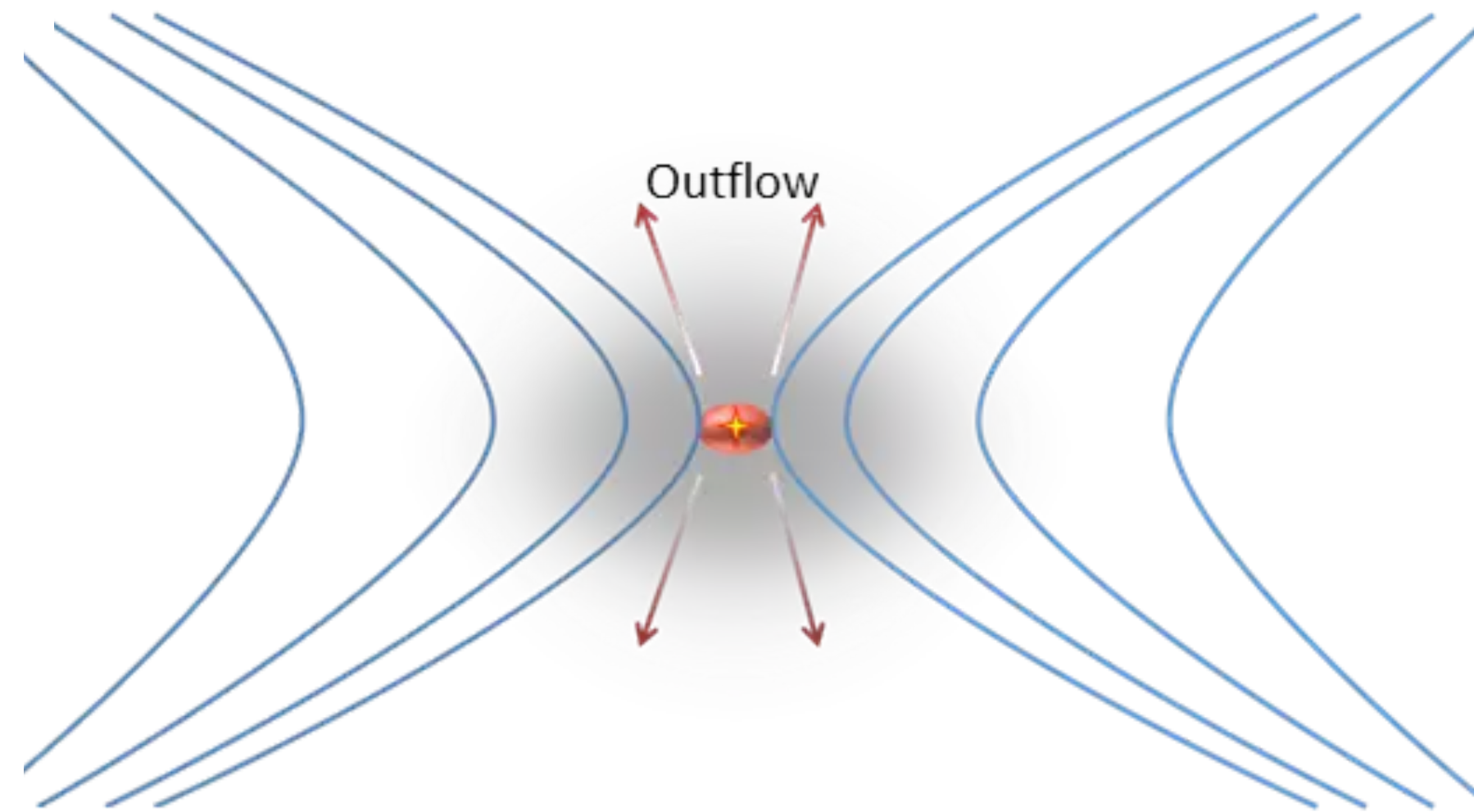
**Disks tend to be big**

Magnetic fields



0.1 light year

Image credit: MPE



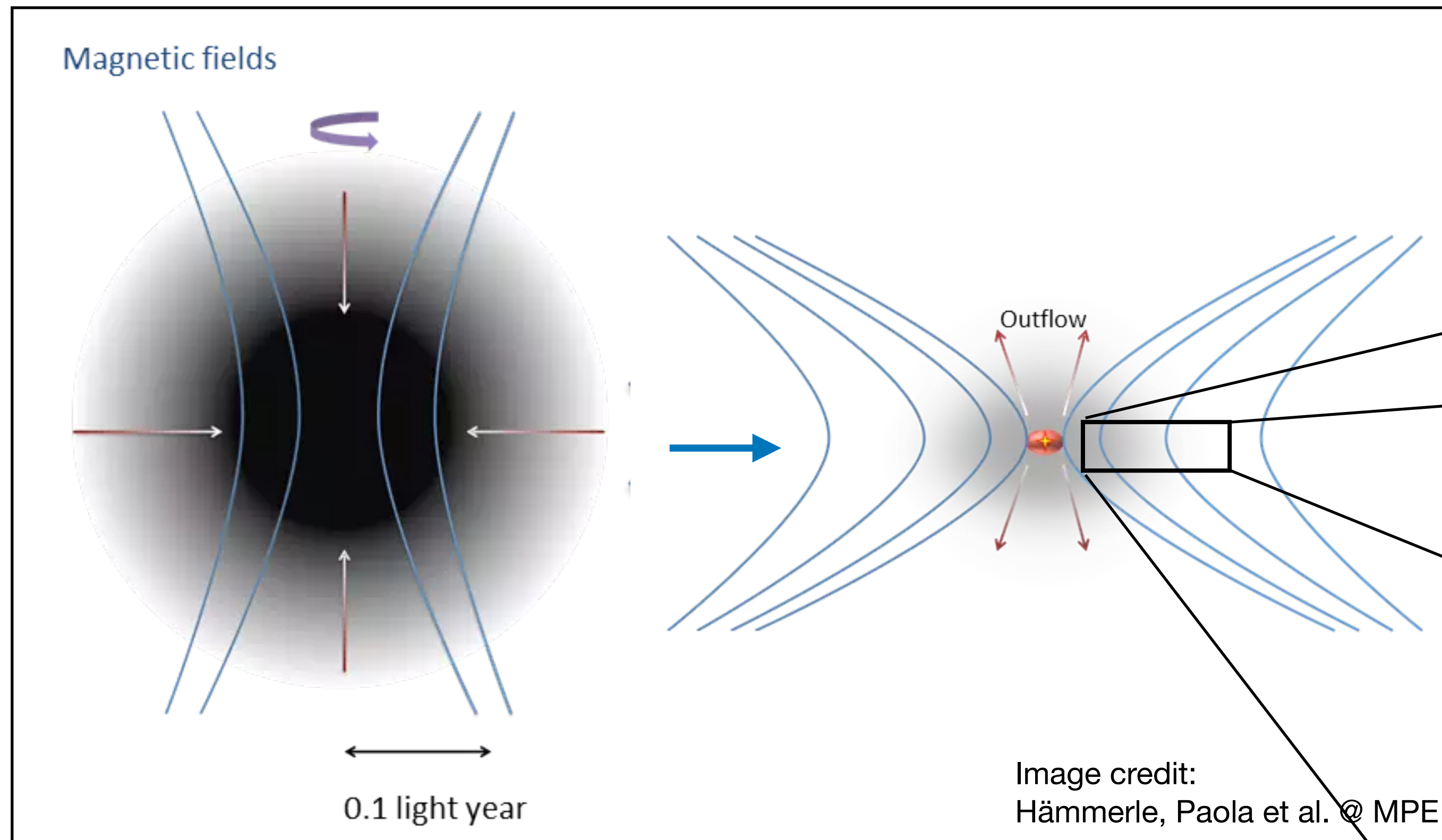
## Ideal Magnetohydrodynamics

**Efficient magnetic braking**

**Disks tend to be too small**

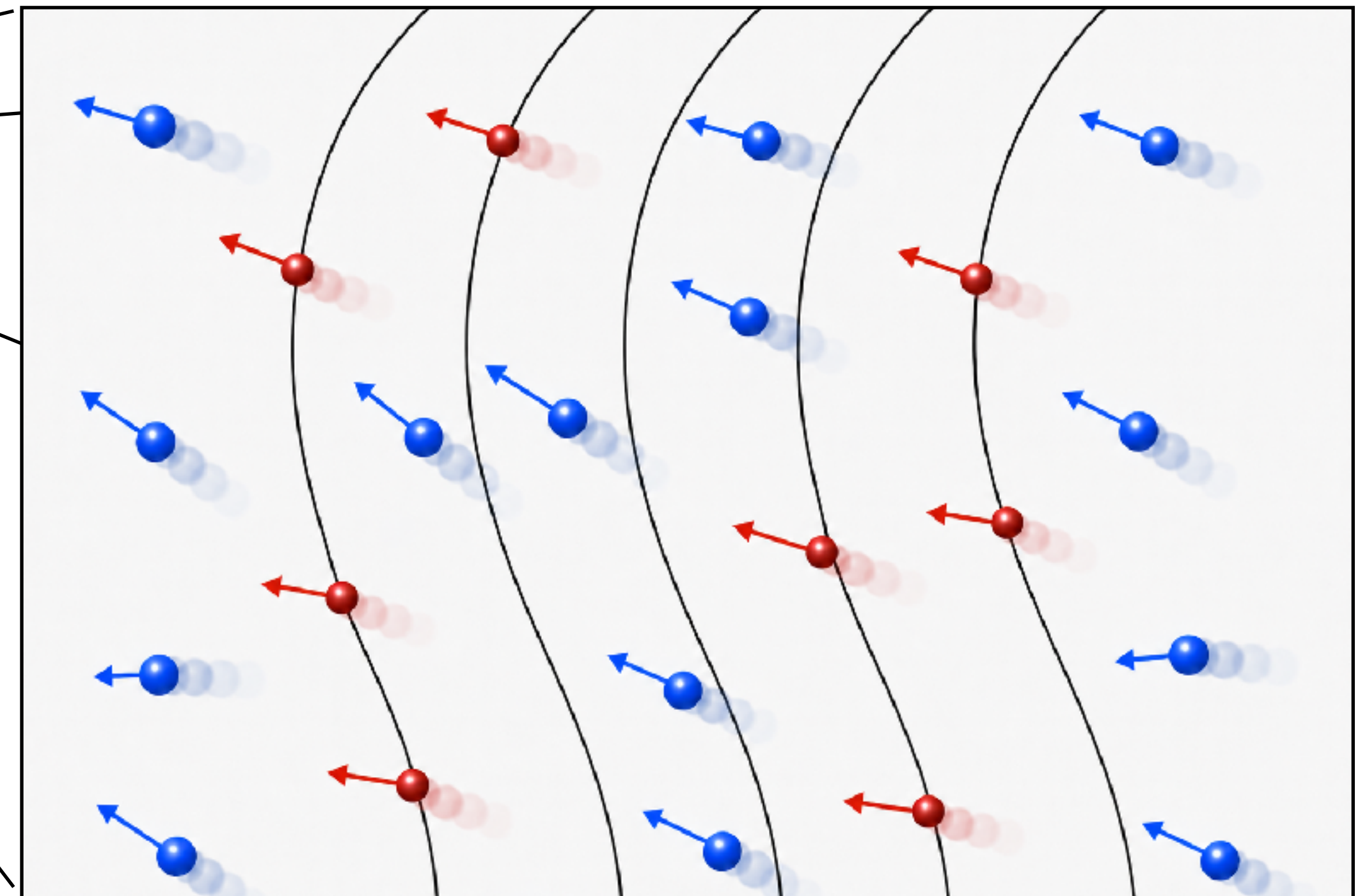


# To regulate the efficiency of magnetic braking: Non-ideal MHD effect (Ambipolar Diffusion)



**Ionized particles** are coupled to the magnetic fields

**Neutral particles** do not.

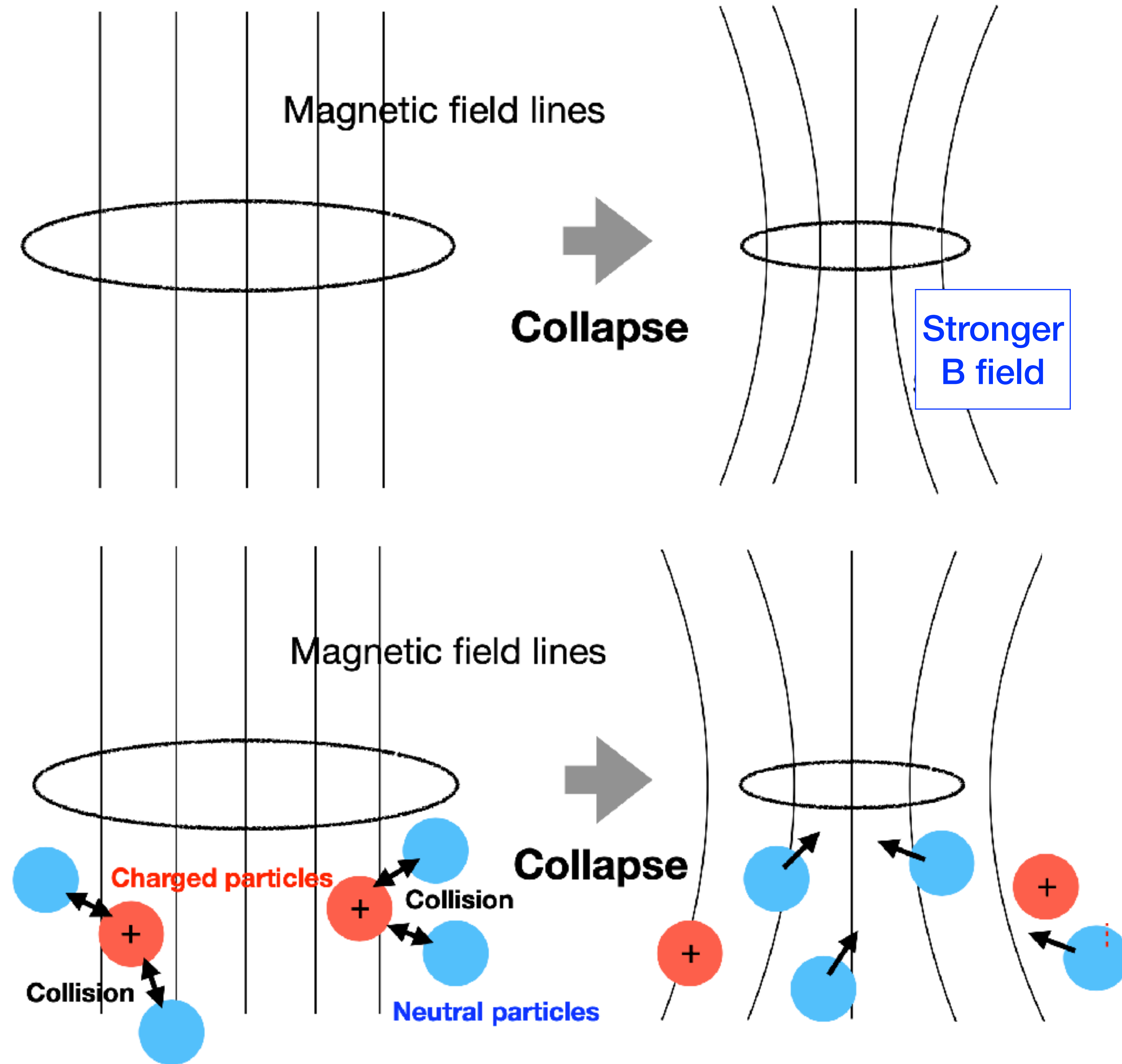


**B fields are left behind**



## Key parameters:

- Ionization fraction
- Ion – neutral Interaction
- Observables:  
ion – neutral drift

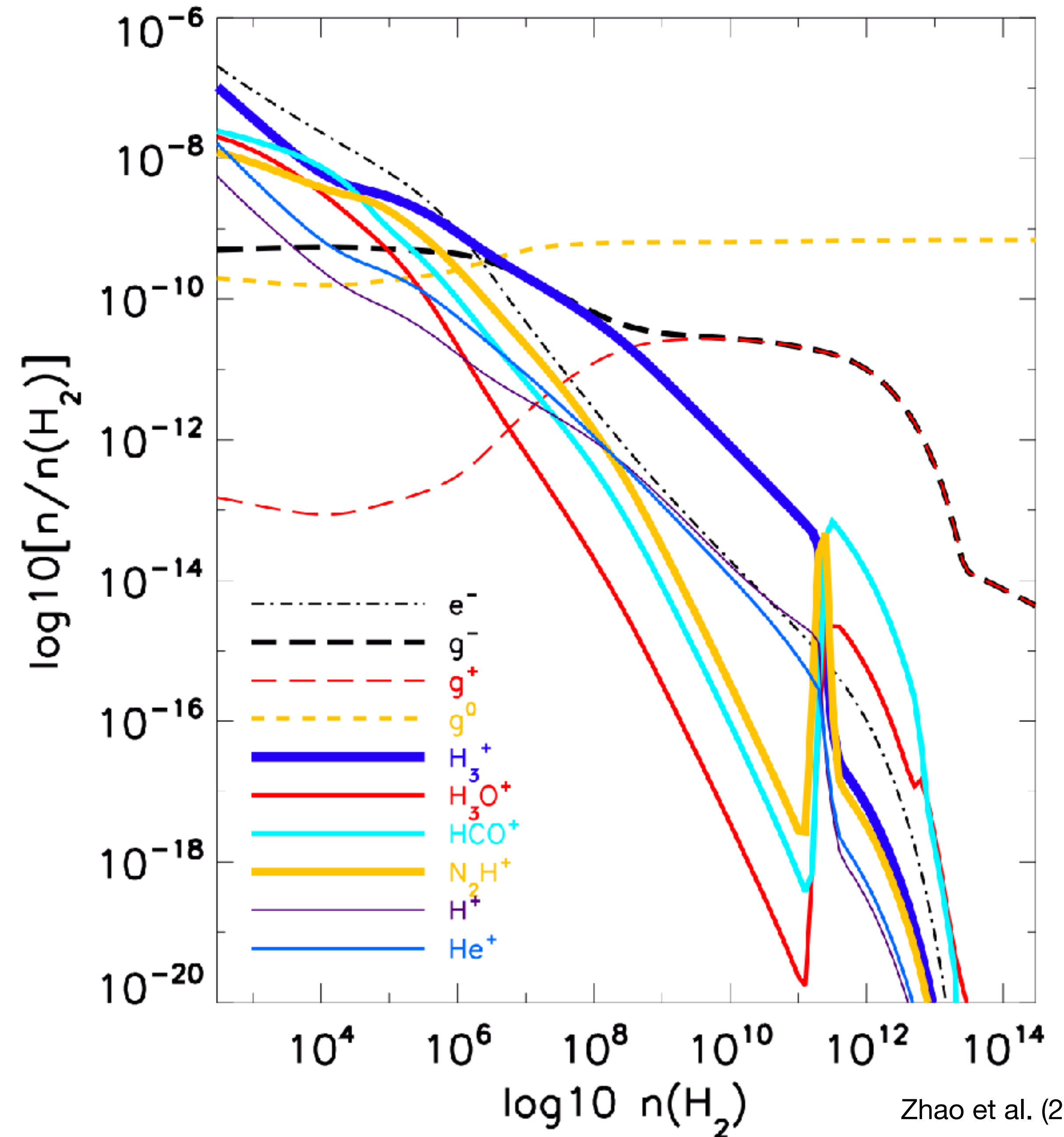




# Dust grains are mostly charged

## Key parameters:

- Ionization fraction
- Ion — neutral Interaction
- Observables:  
ion — neutral drift

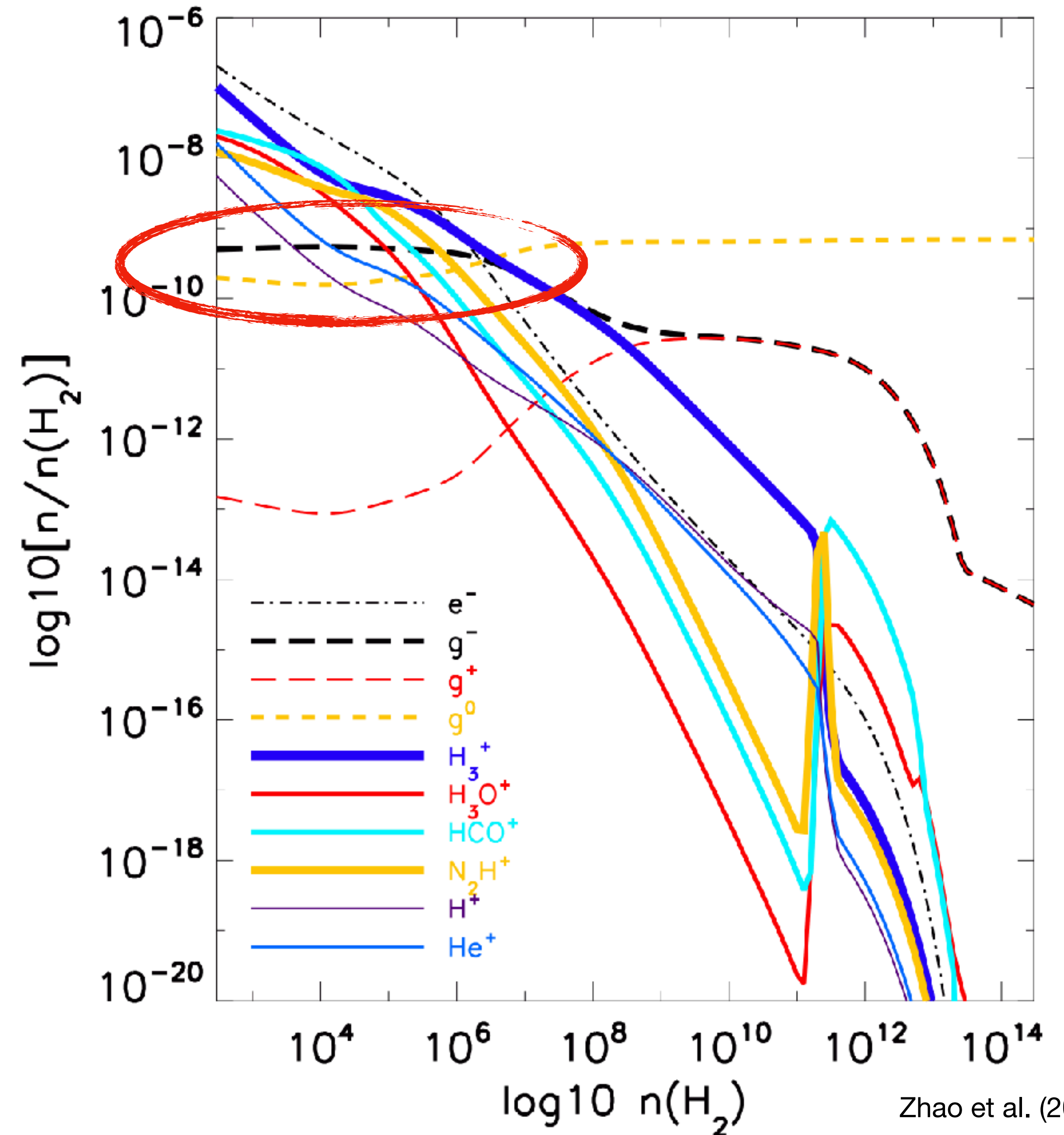




# Dust grains are mostly charged

## Key parameters:

- Ionization fraction
- Ion — neutral Interaction
- Observables:  
ion — neutral drift

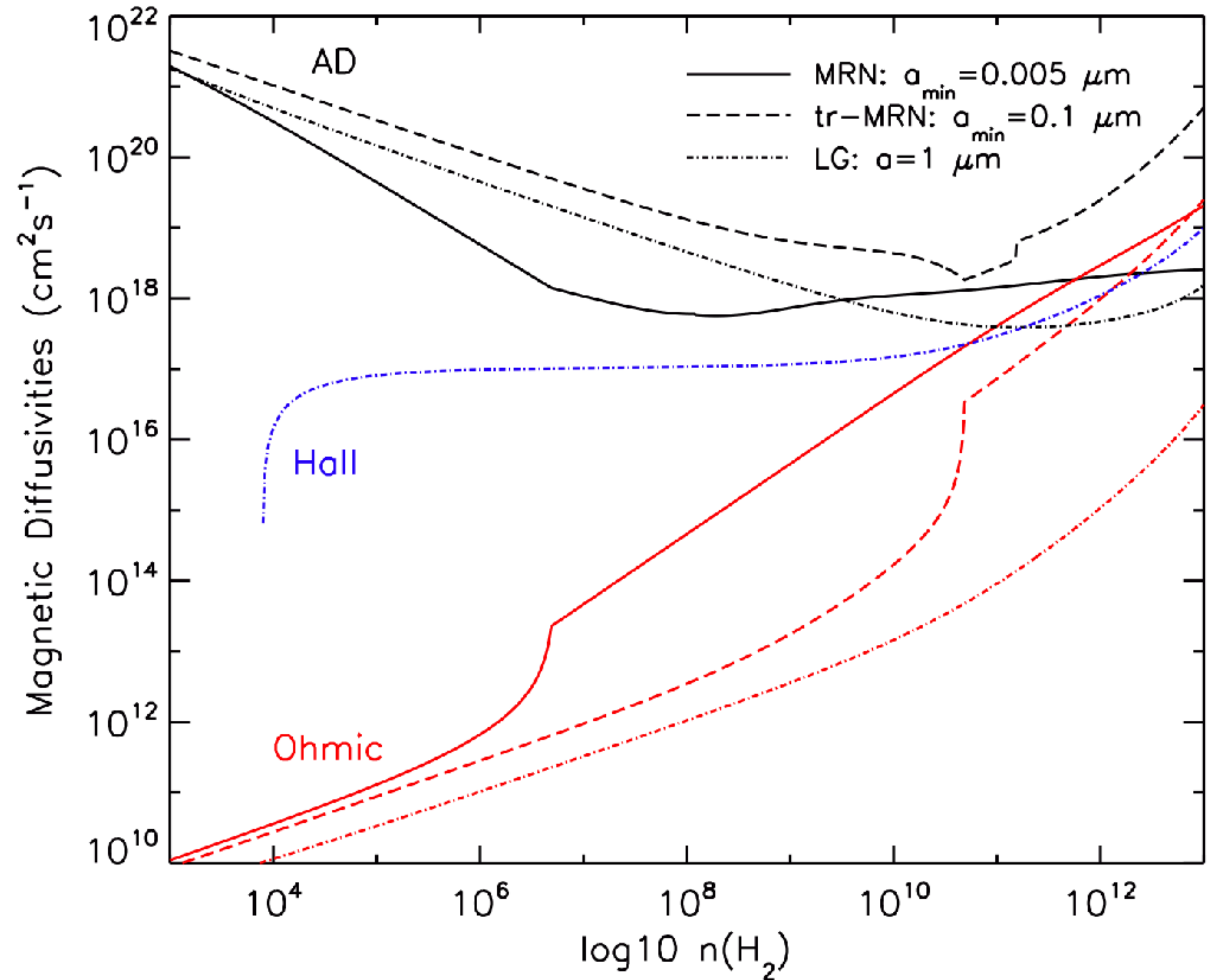
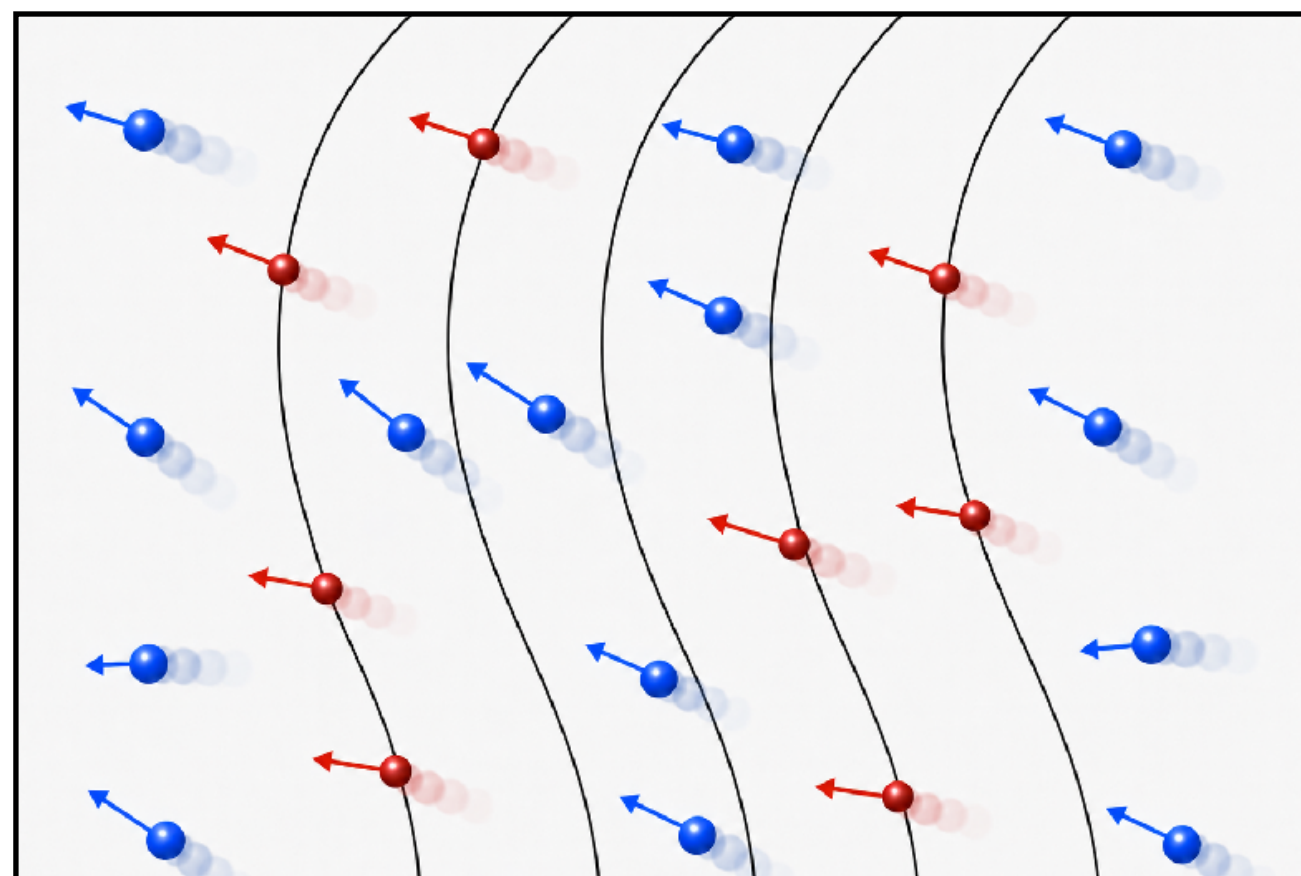




## Dust grain size matters

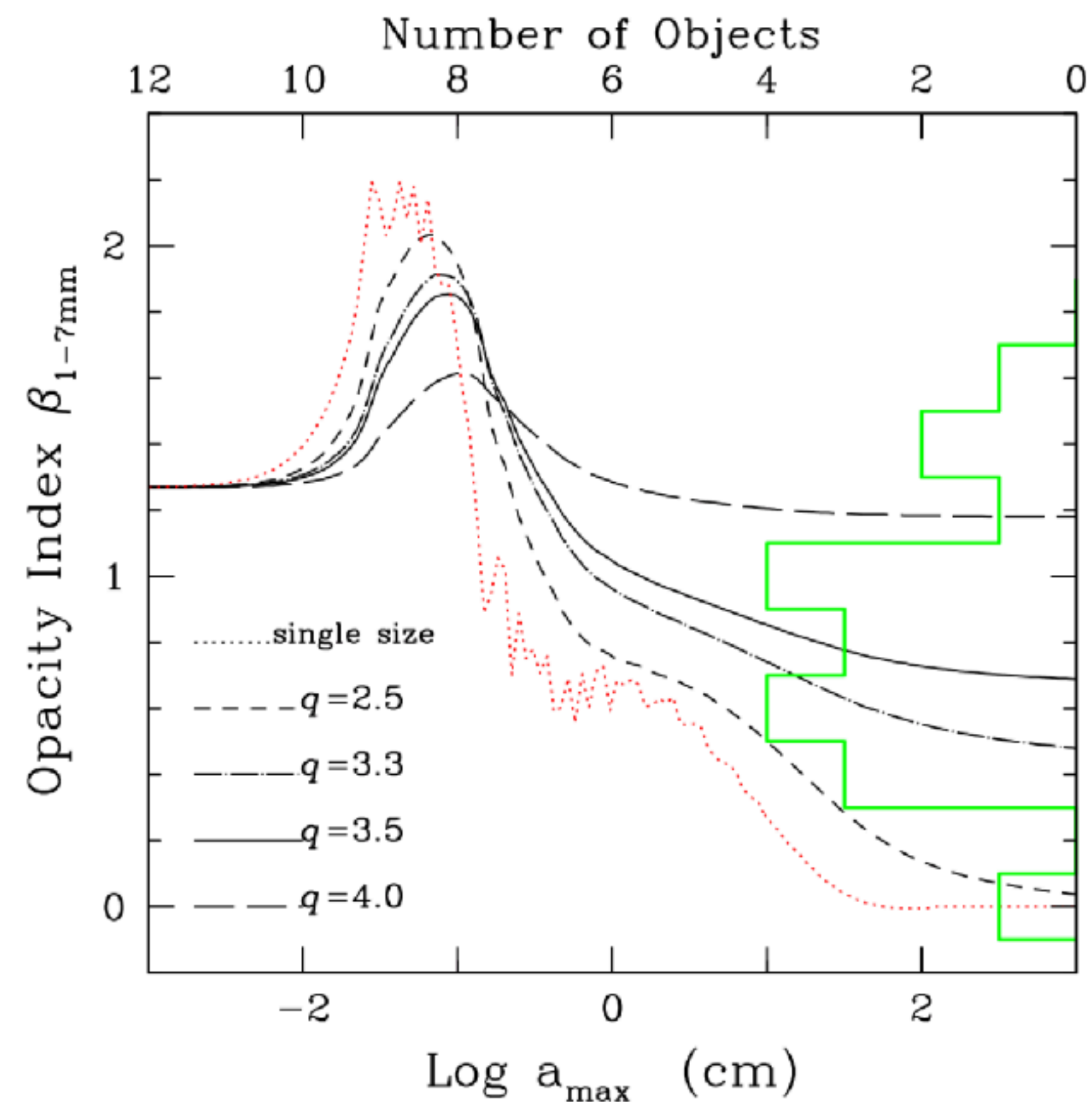
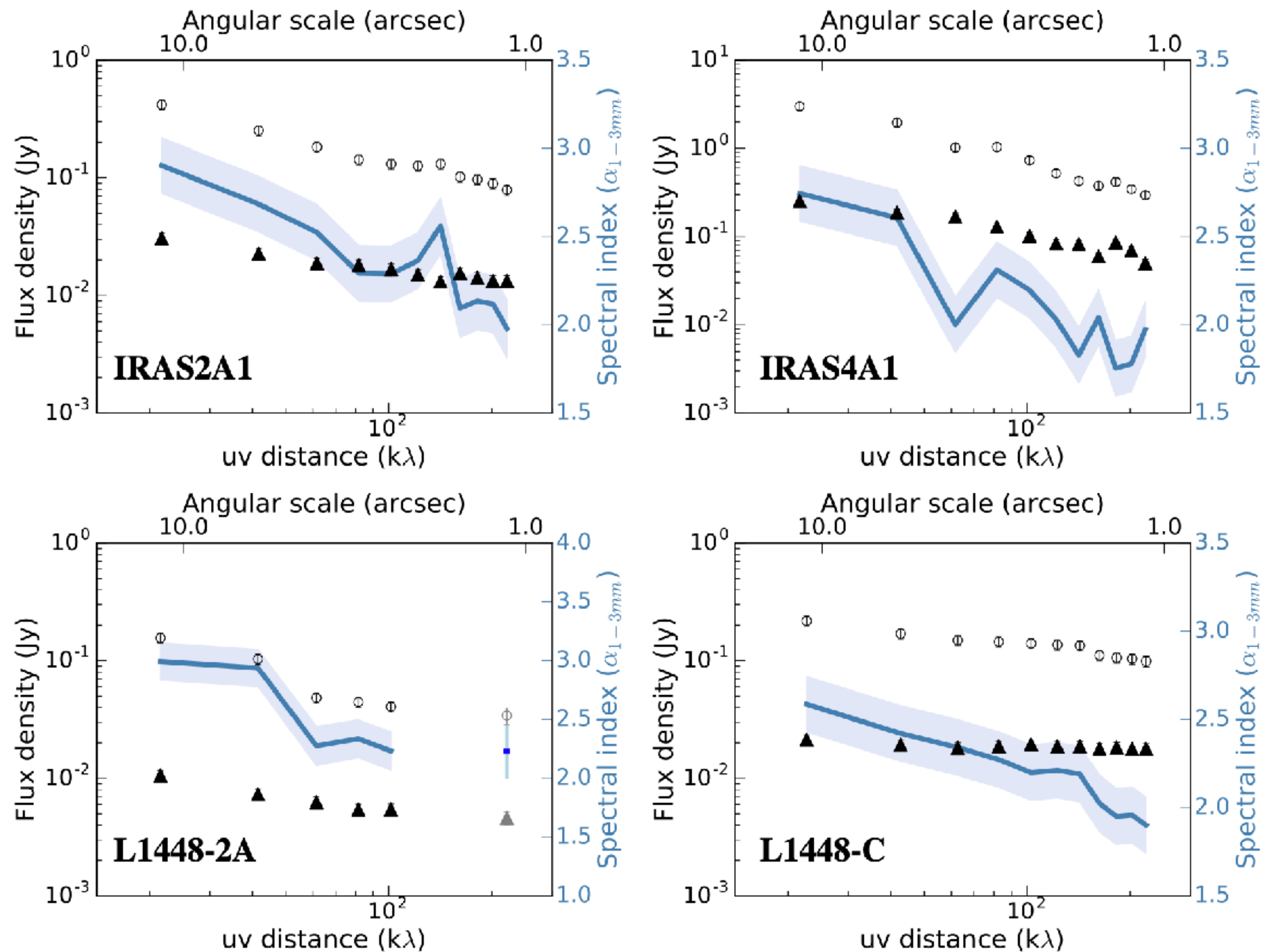
### Key parameters:

- Ionization fraction
- Ion – neutral Interaction
- Observables:  
ion – neutral drift





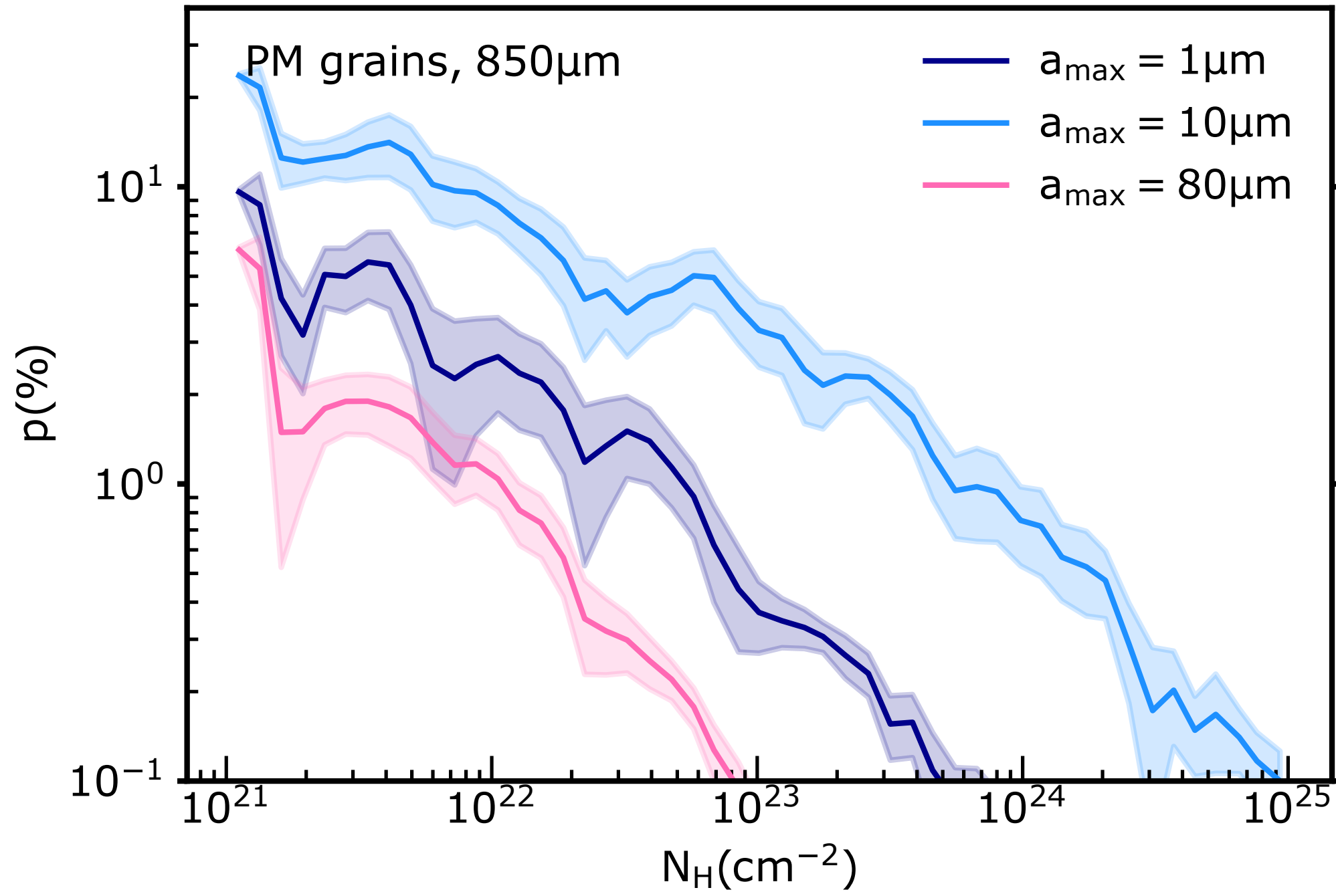
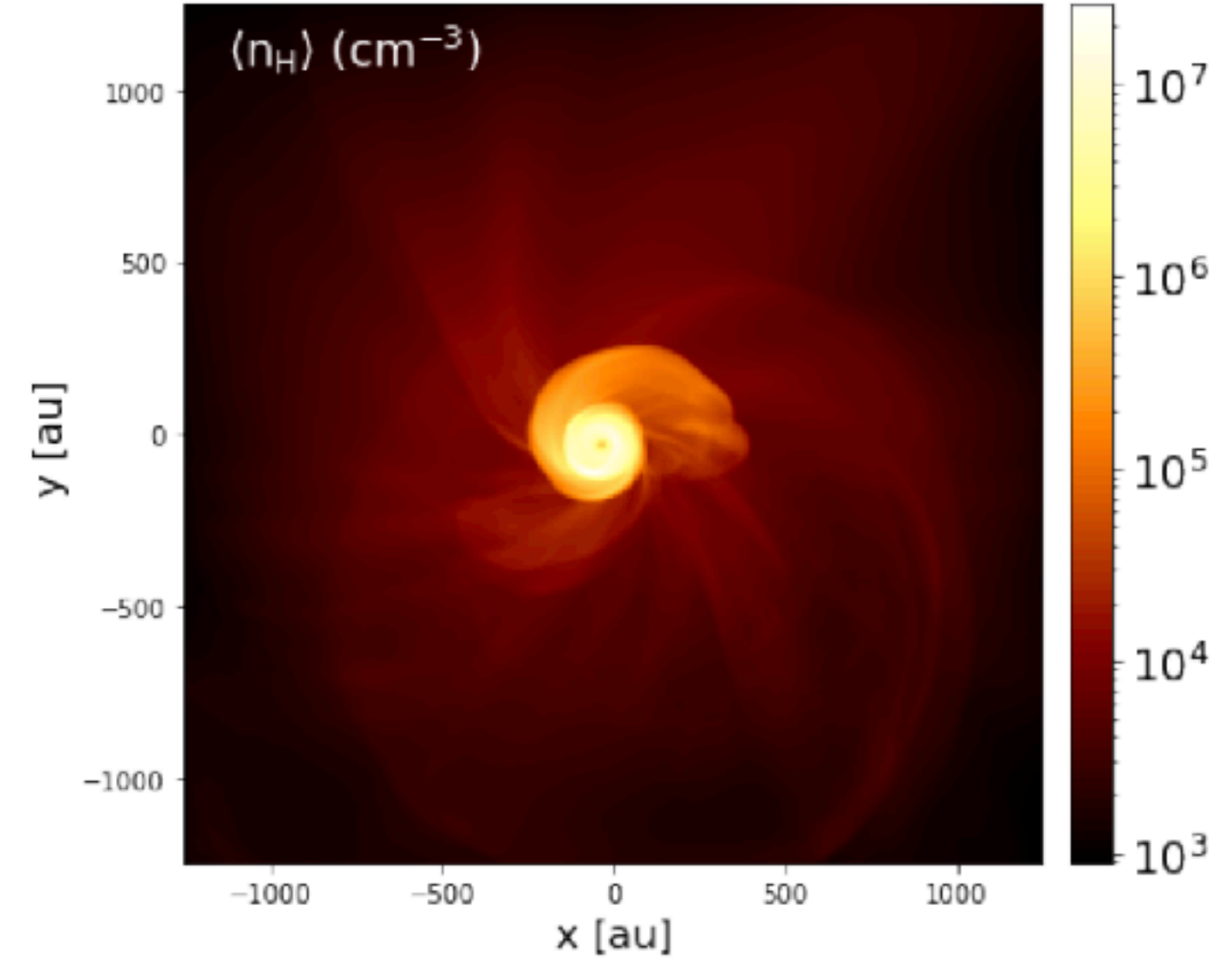
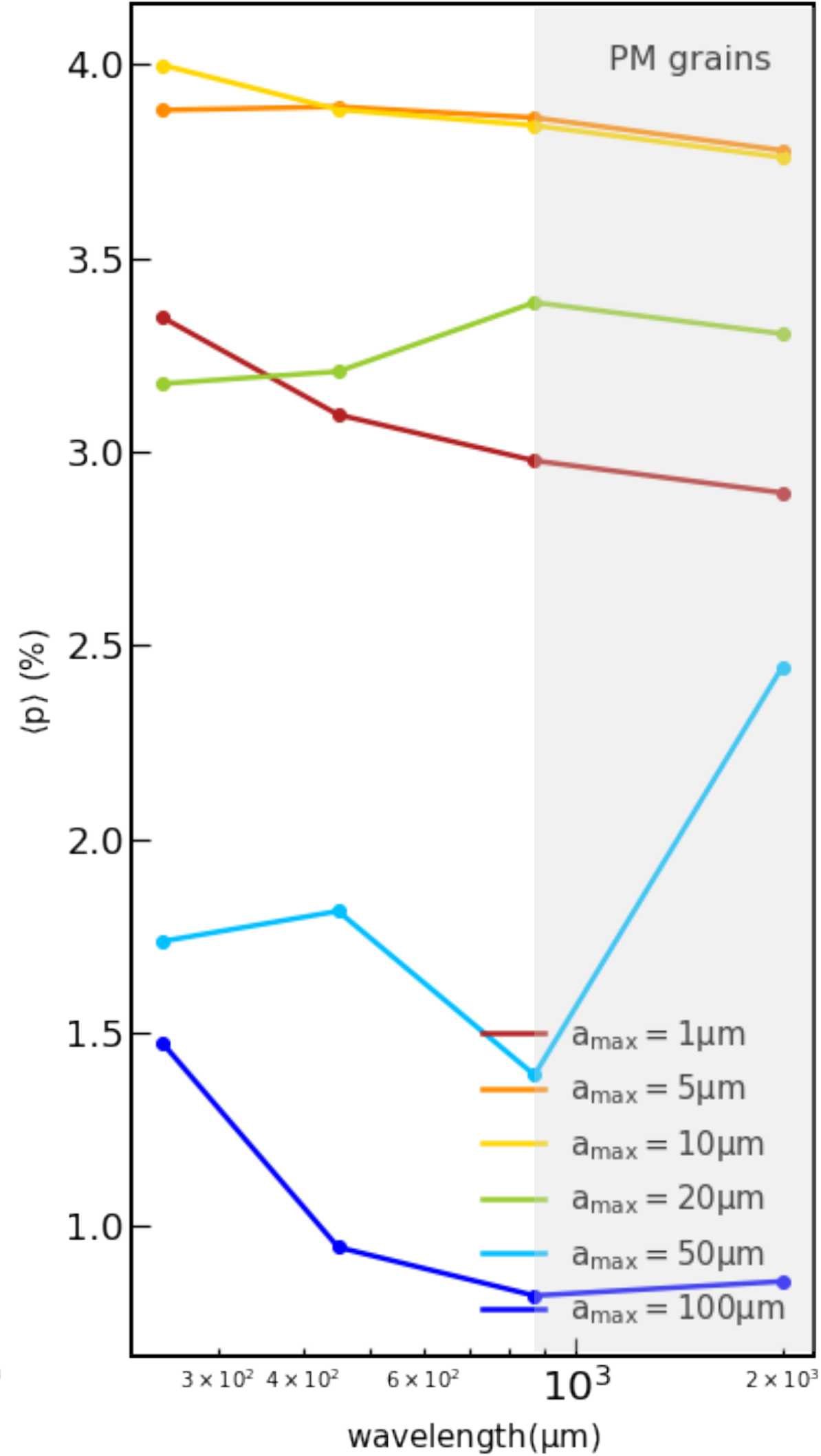
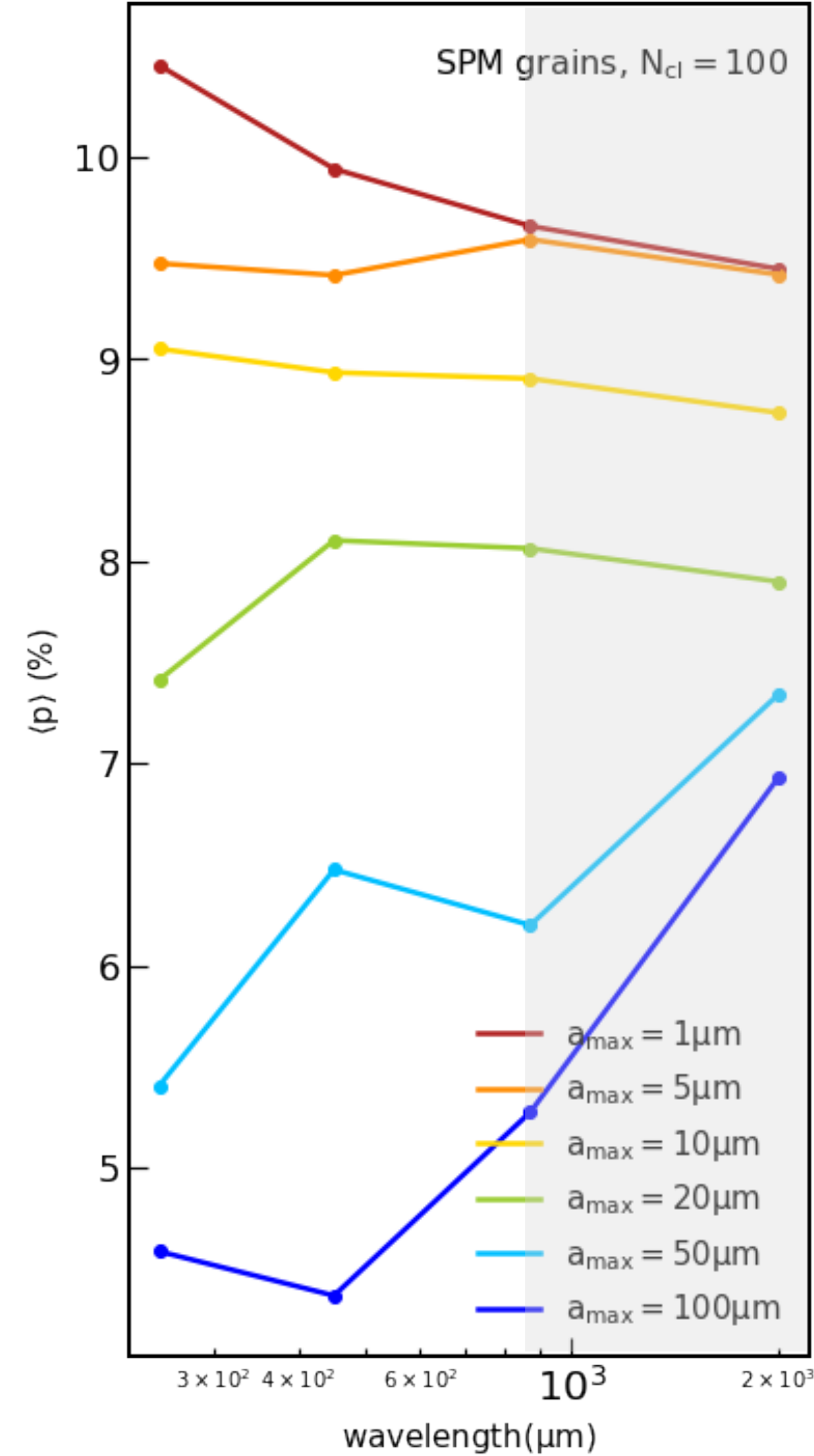
# Multi-wavelength dust continuum: Spectral index



Banzatti (2009)

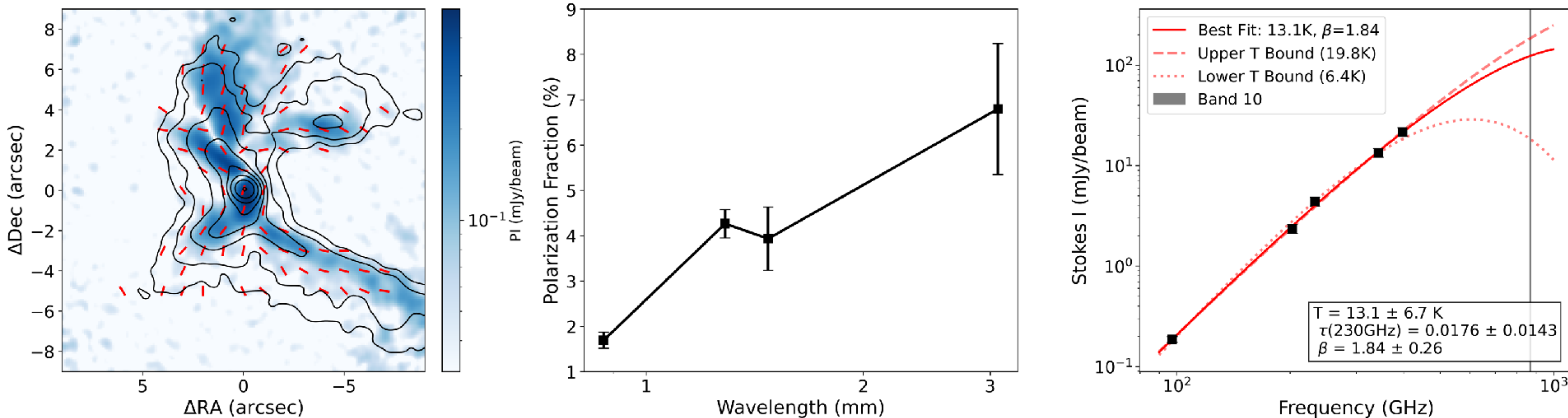


# Multi-wavelength dust polarized continuum





# Multi-wavelength dust (**polarized**) continuum: Dust grain size distribution

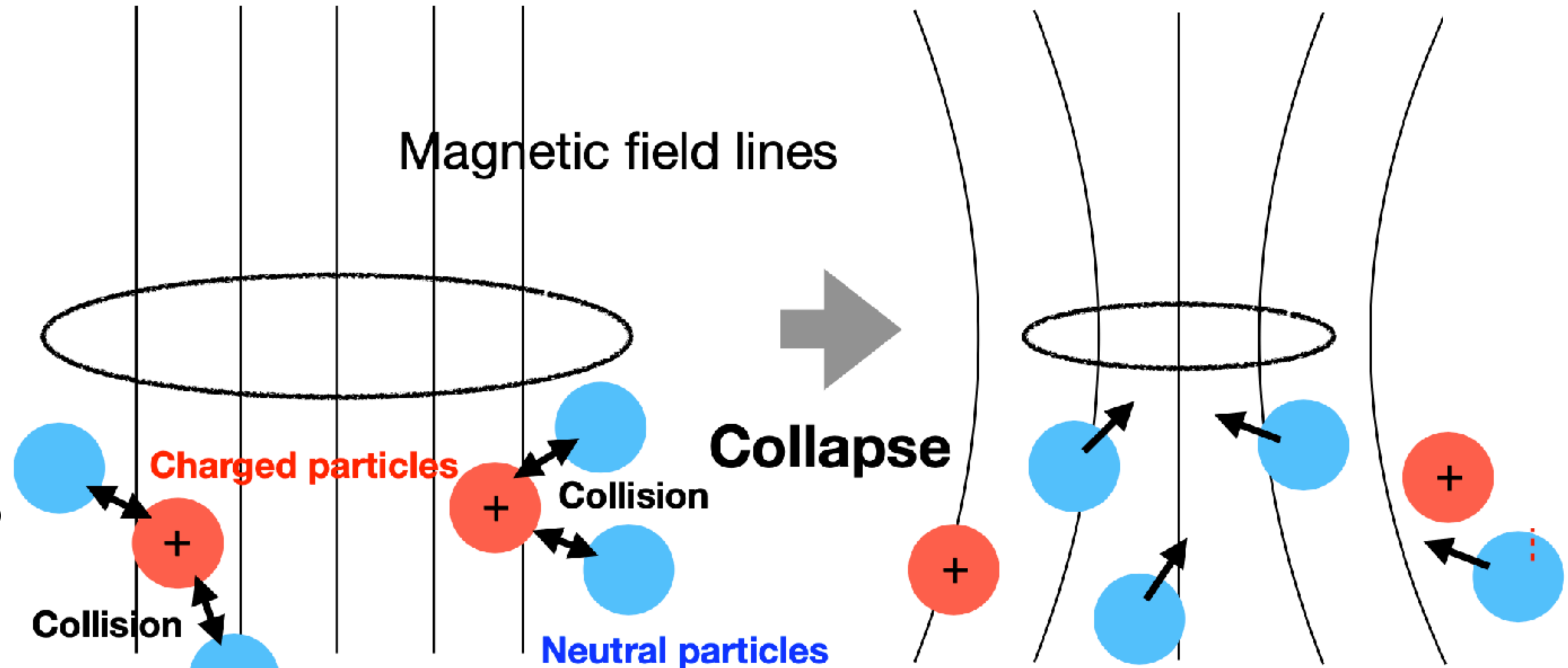
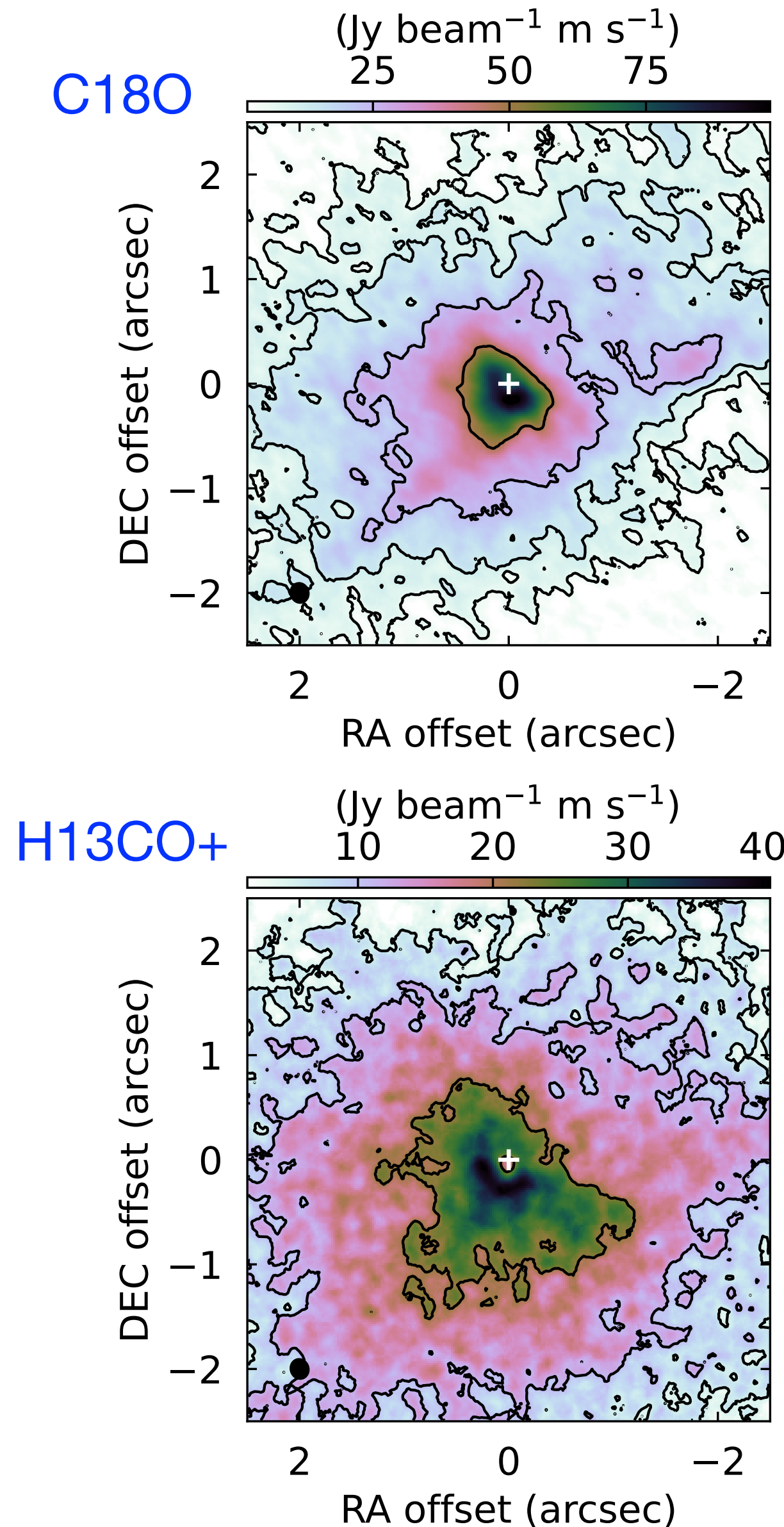


- Higher frequencies: to constrain temperature and density
- Polarization at higher frequencies

- Ionization fraction
- Ion—neutral Interaction
- Observables:  
ion—neutral drift



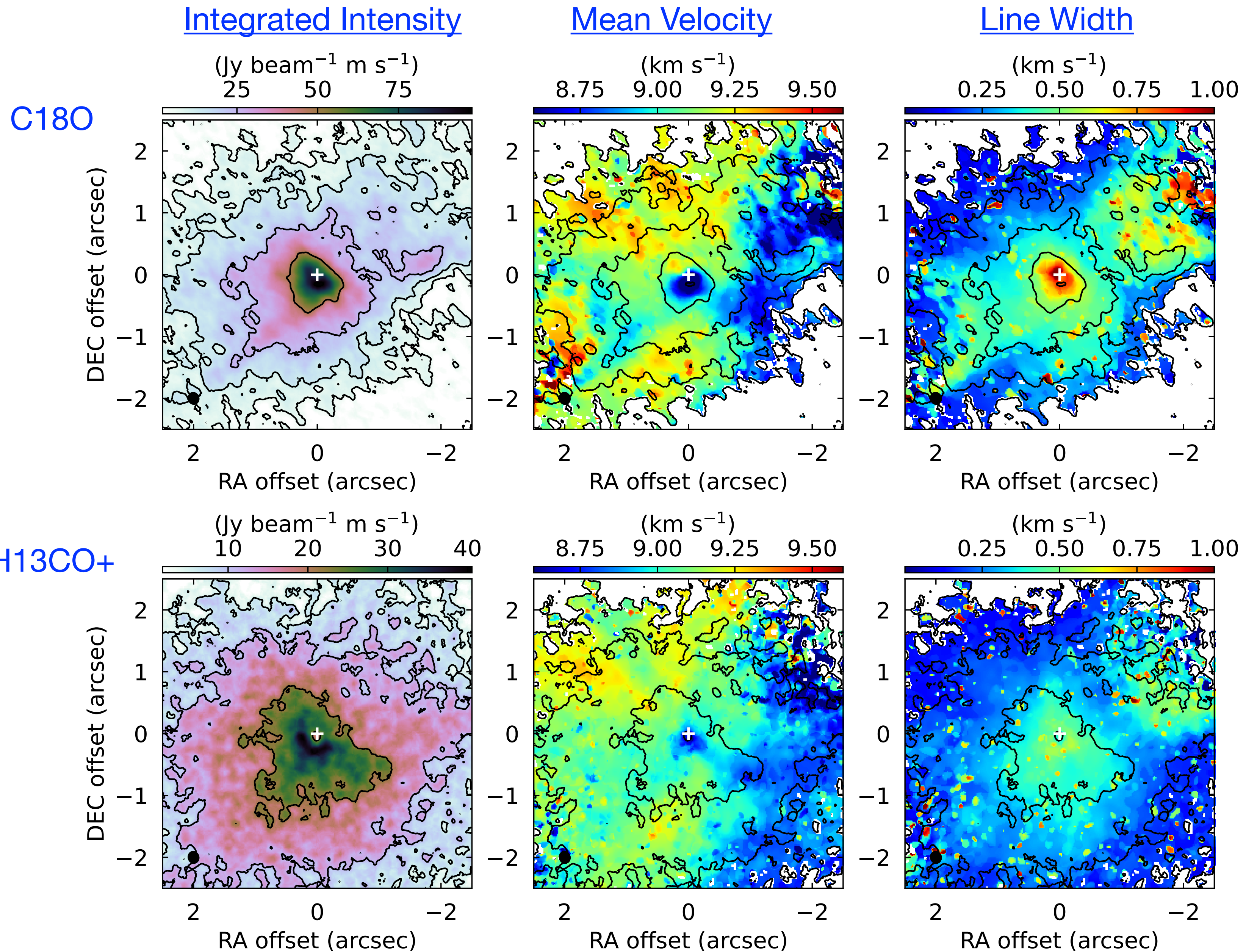
# To trace how B fields move relatively to matter



- Ionization fraction
- Ion – neutral Interaction
- Observables:  
ion – neutral drift



# Ambipolar diffusion: ion-neutral drift velocity

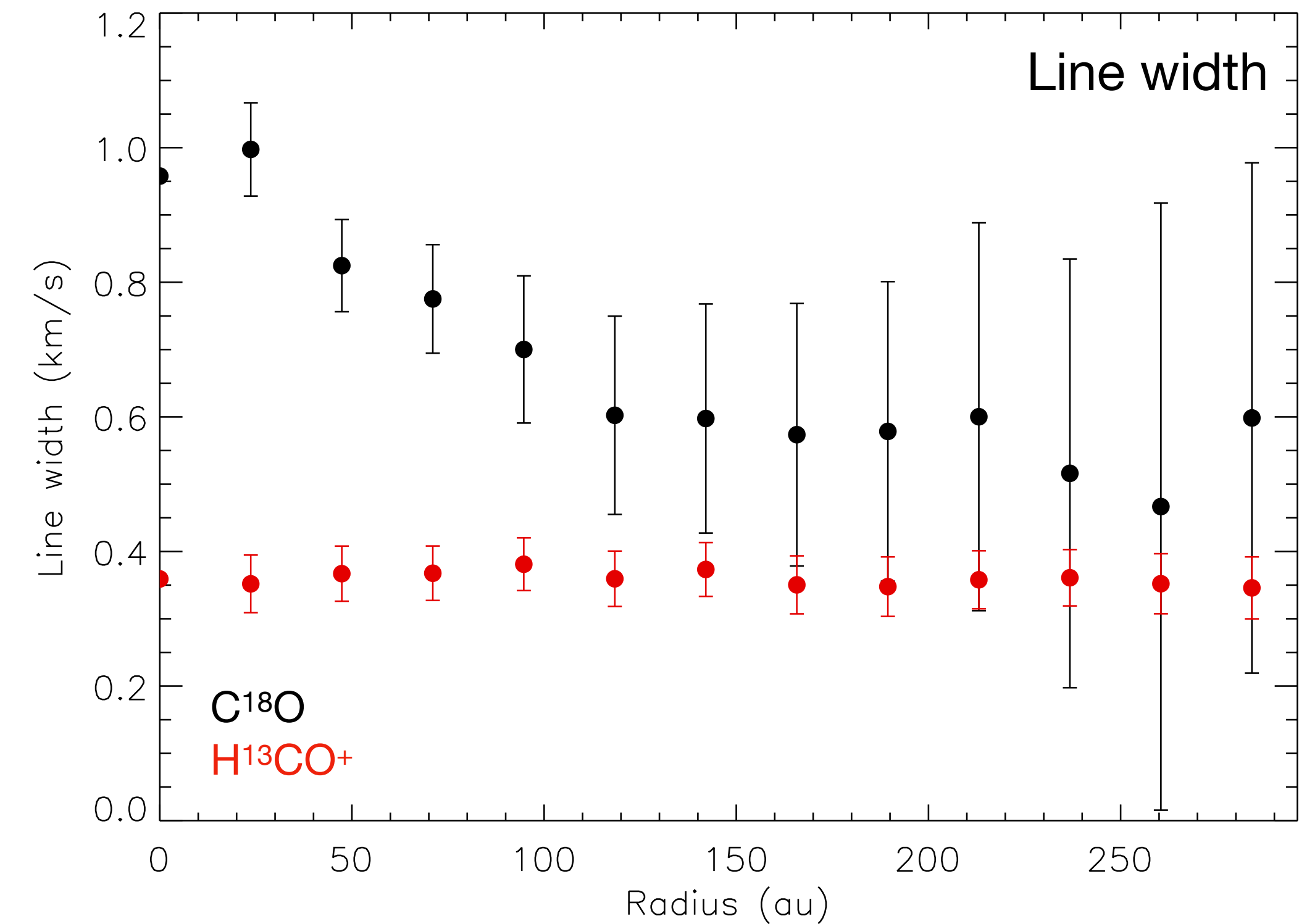
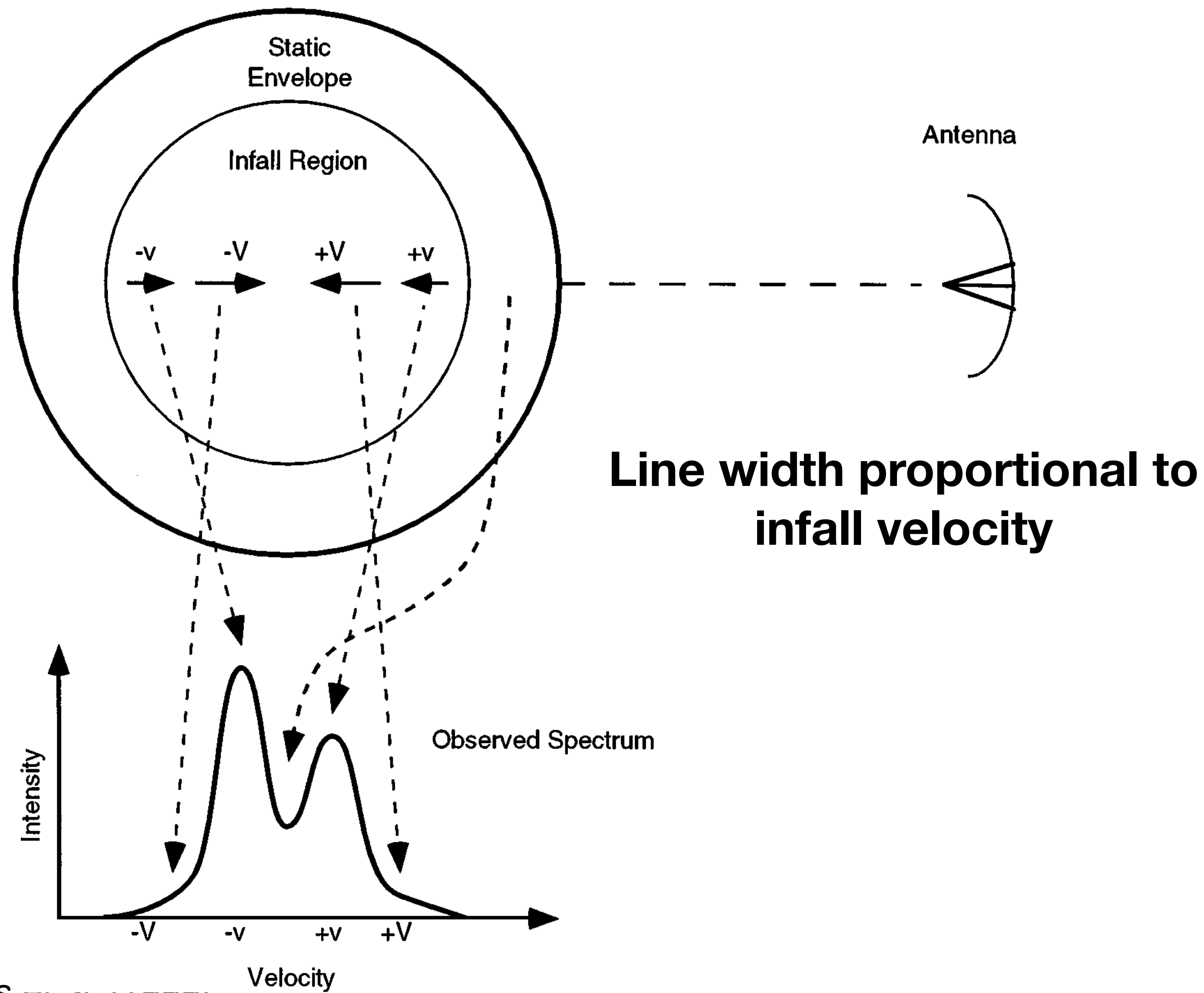


Edge-on Class 0 Protostars  
With a 20 au disk



# Ambipolar diffusion: ion-neutral drift velocity

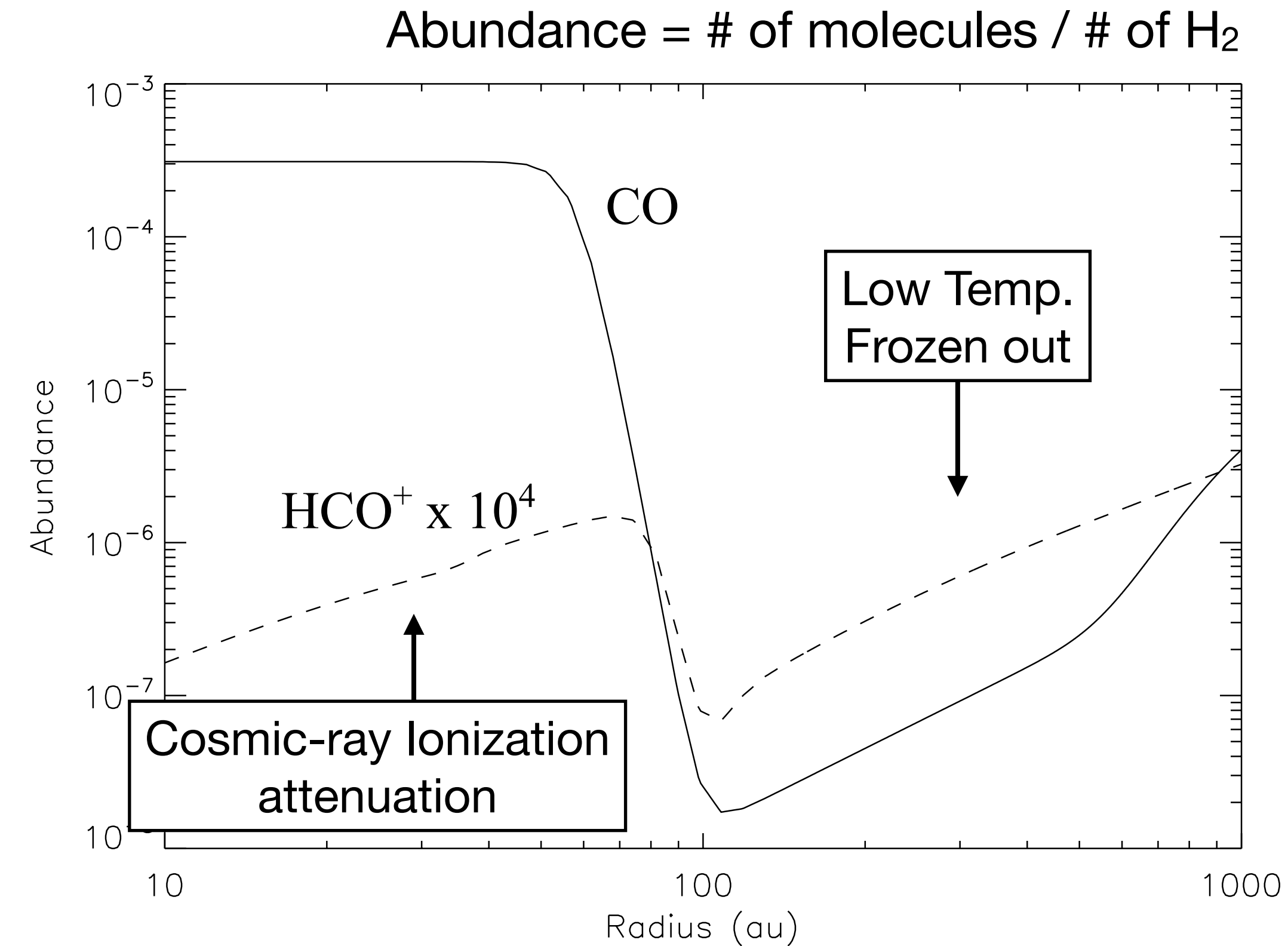
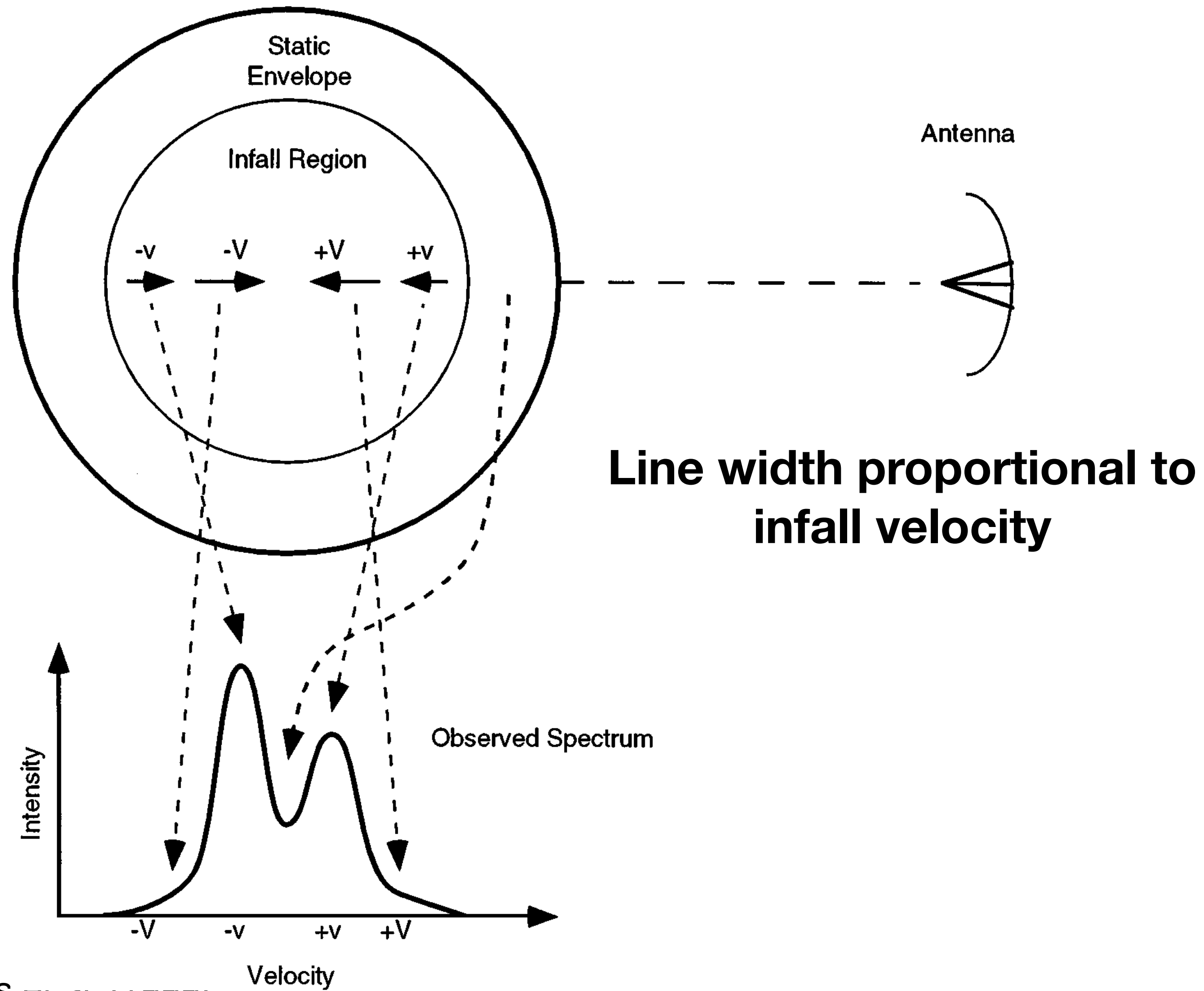
Edge-on object





# Ambipolar diffusion: ion-neutral drift velocity

Edge-on object





# Ambipolar diffusion: ion-neutral drift velocity

Spectrum

Radiative transfer modeling using the SPARX code

Model Input :

Density ( $x$ )  
Temperature ( $x$ )  
Velocity ( $x$ )  
Molecular abundance ( $x$ )

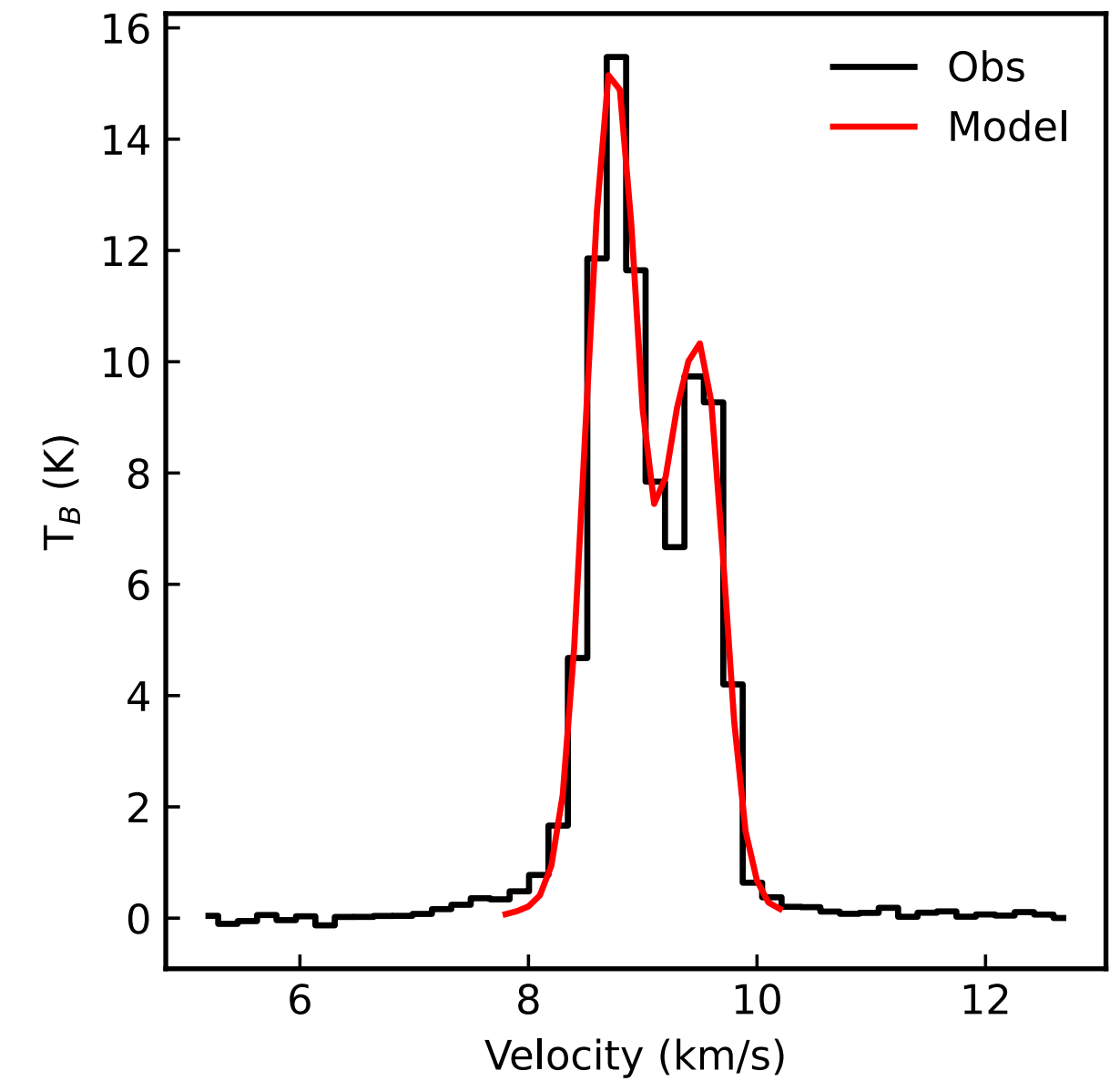
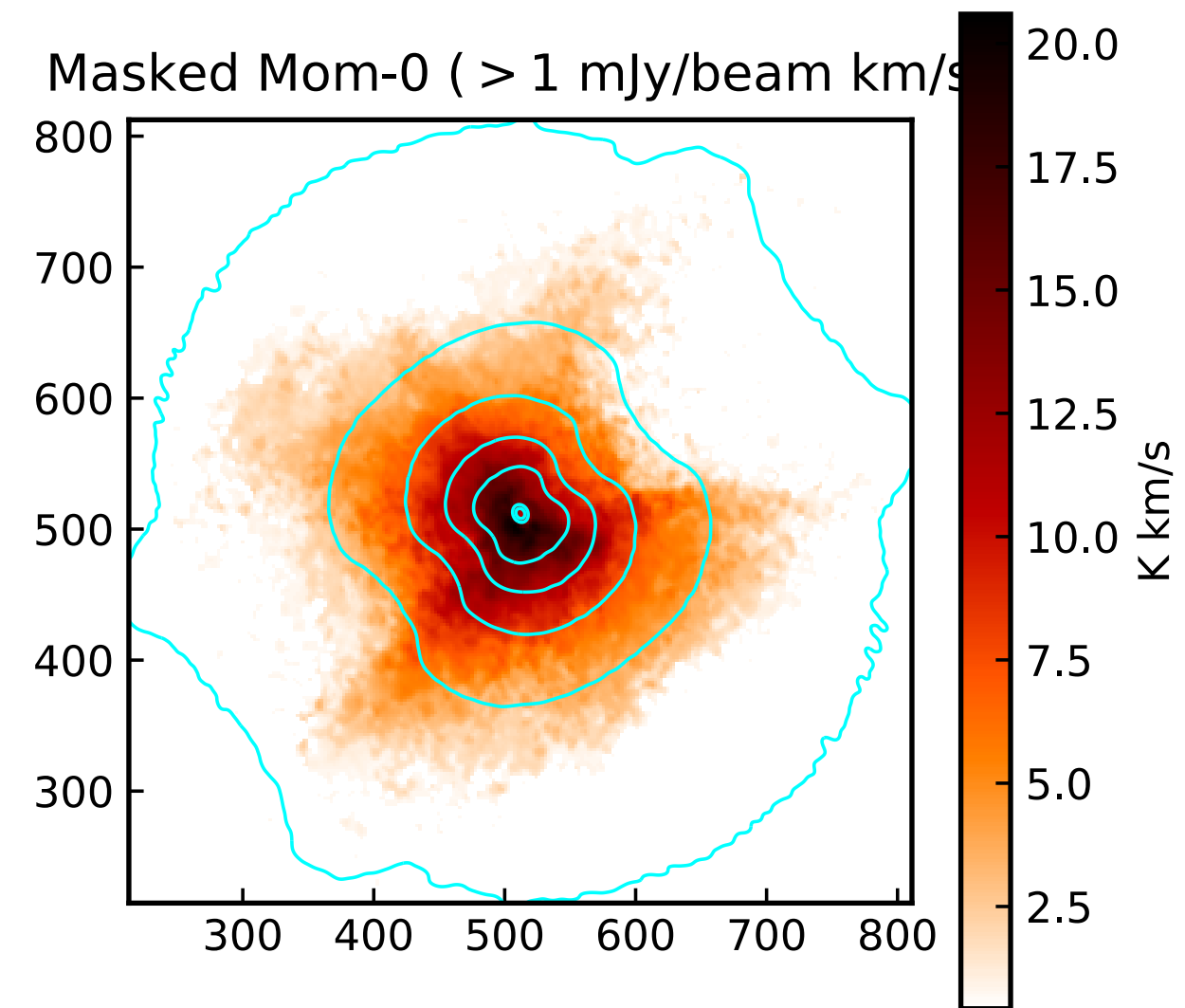
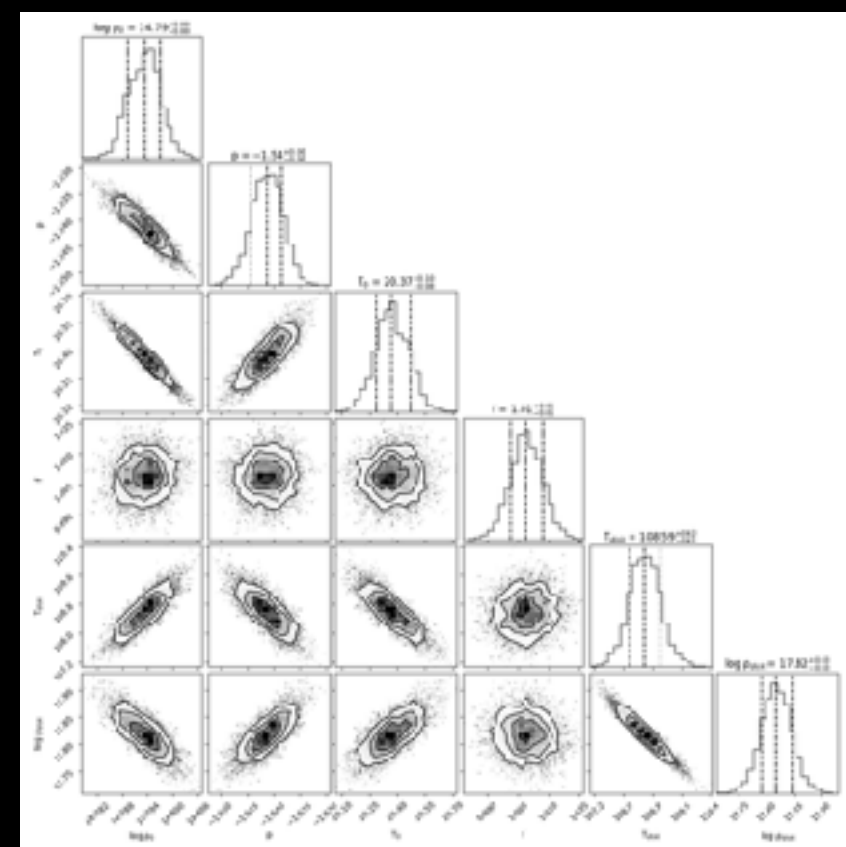
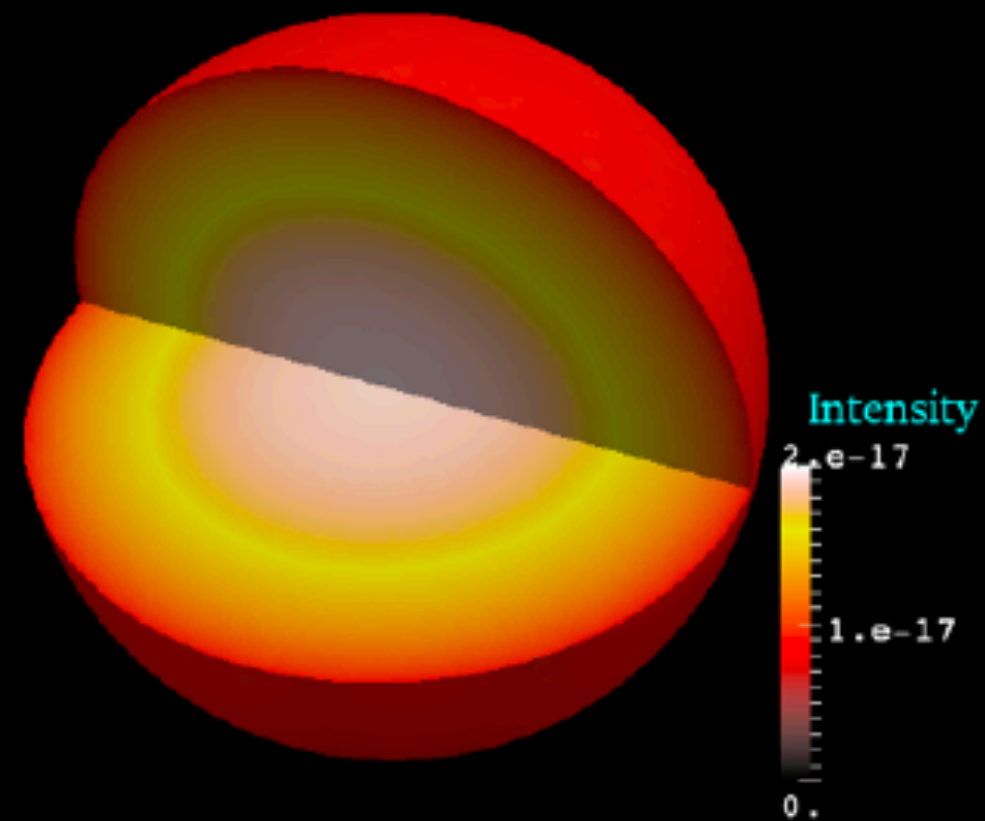
Axisymmetric infalling and rotating envelope with an embedded disk

+ Velocity profile  
+ Abundance profile

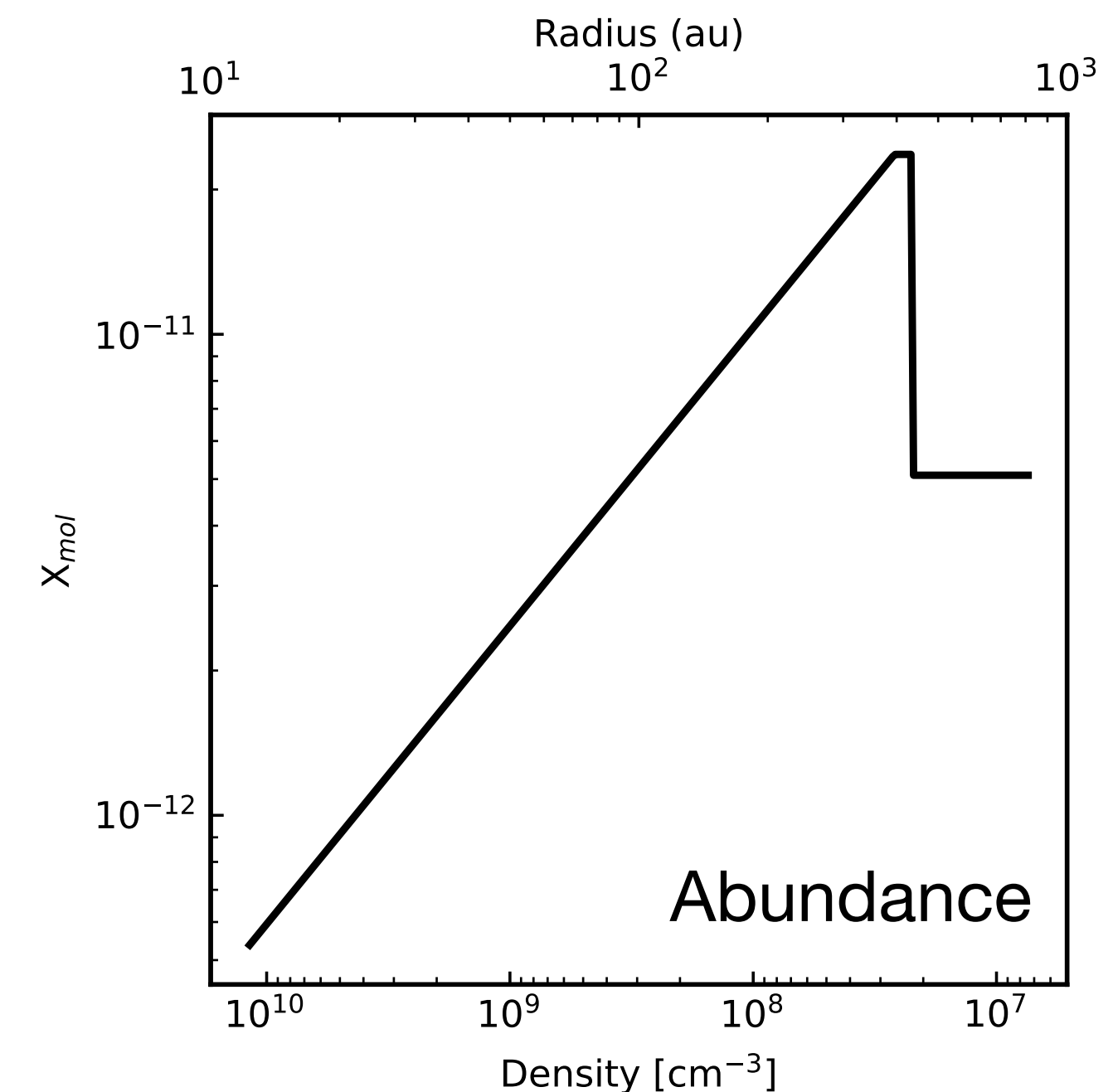
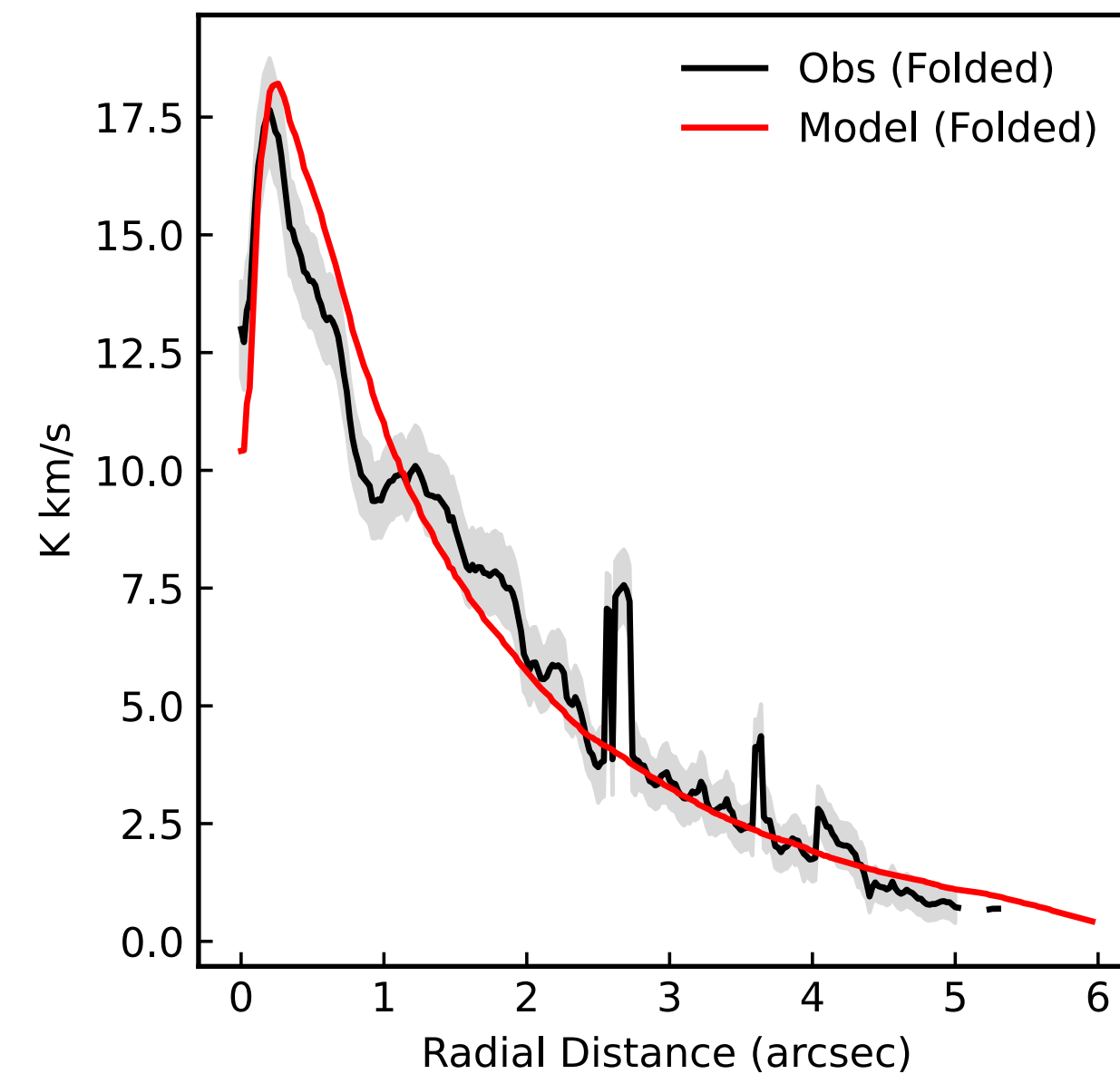
Model Output:

Radiation field ( $x$ )  
Level population ( $x$ )

-> Visibility  
-> MCMC fitting



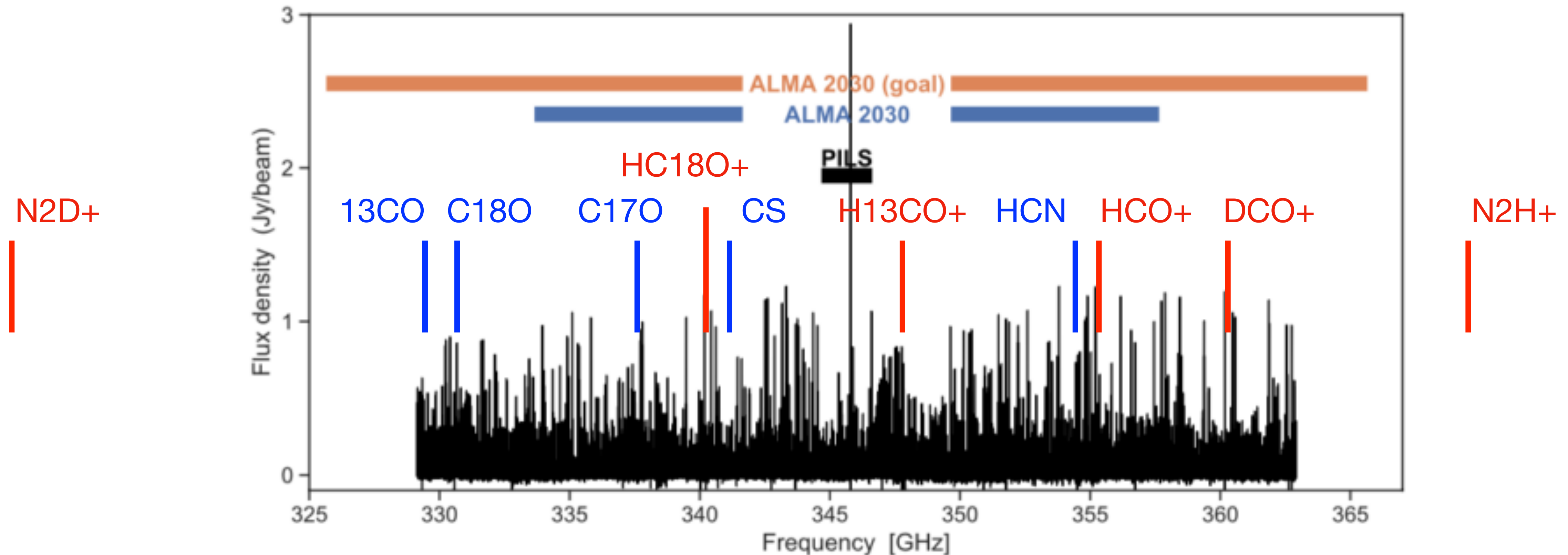
Intensity profile





# More species: general behavior of neutrals and ions

different regions, different layers

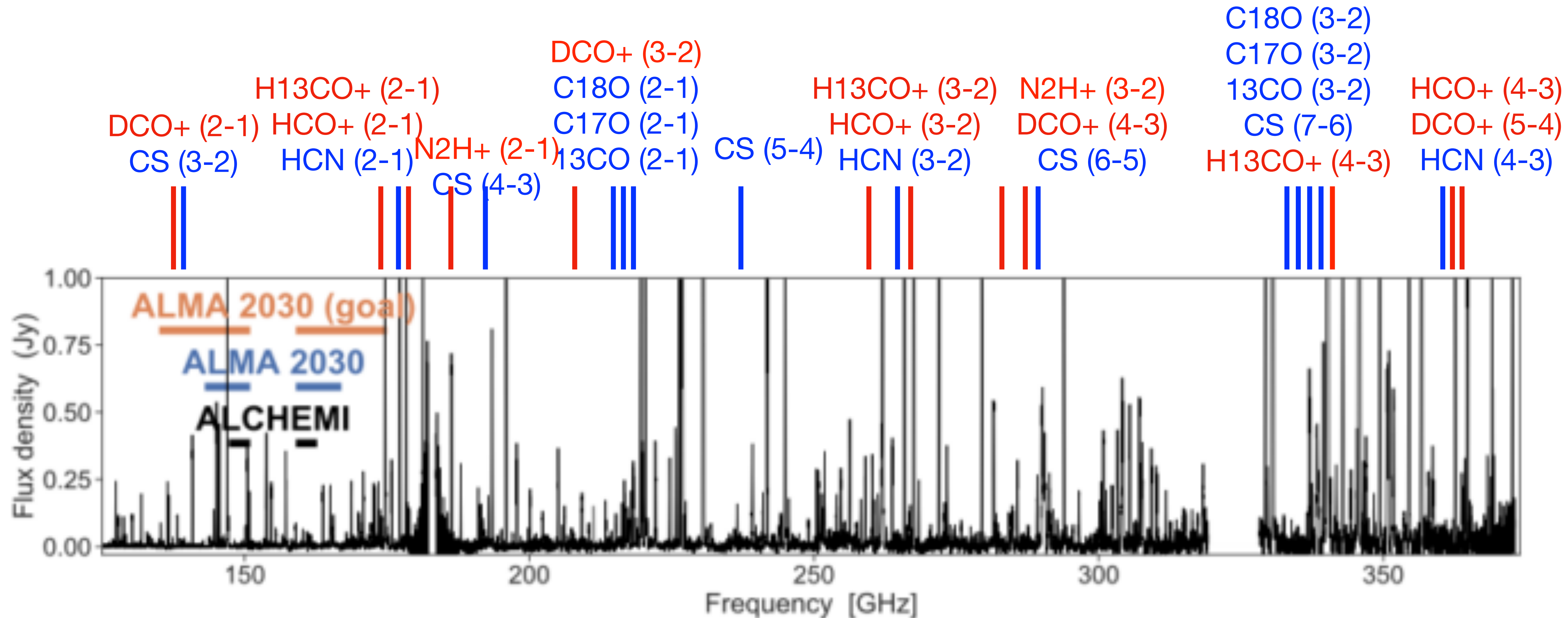


-Wide bandwidth

-High sensitivity (1 K @ 0.1"?)

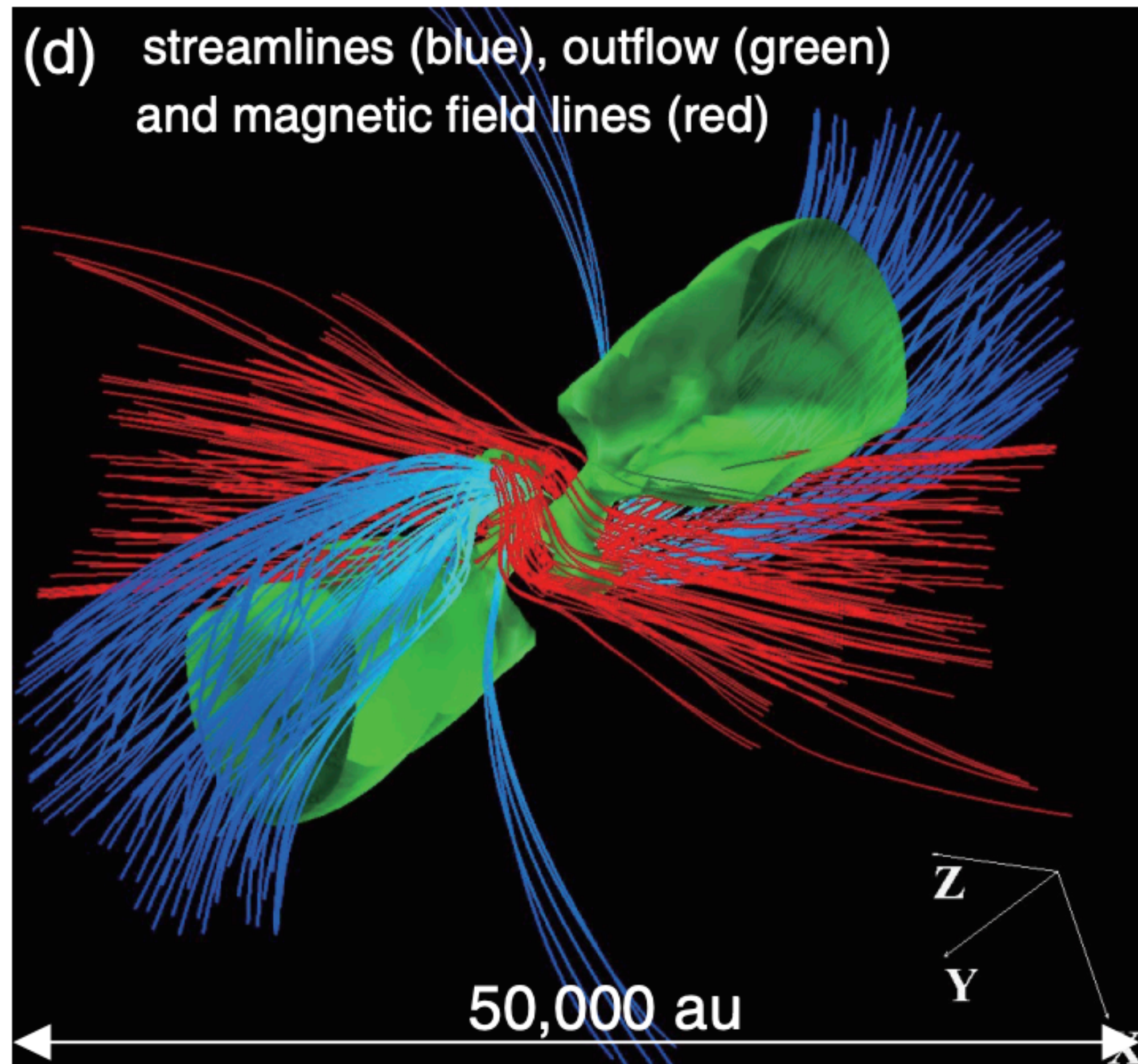


# More transitions: density and temperature to locate the traced regions or layers





# Mass and angular momentum transportation to disks



Machida et al. (2026)

Inside the disk

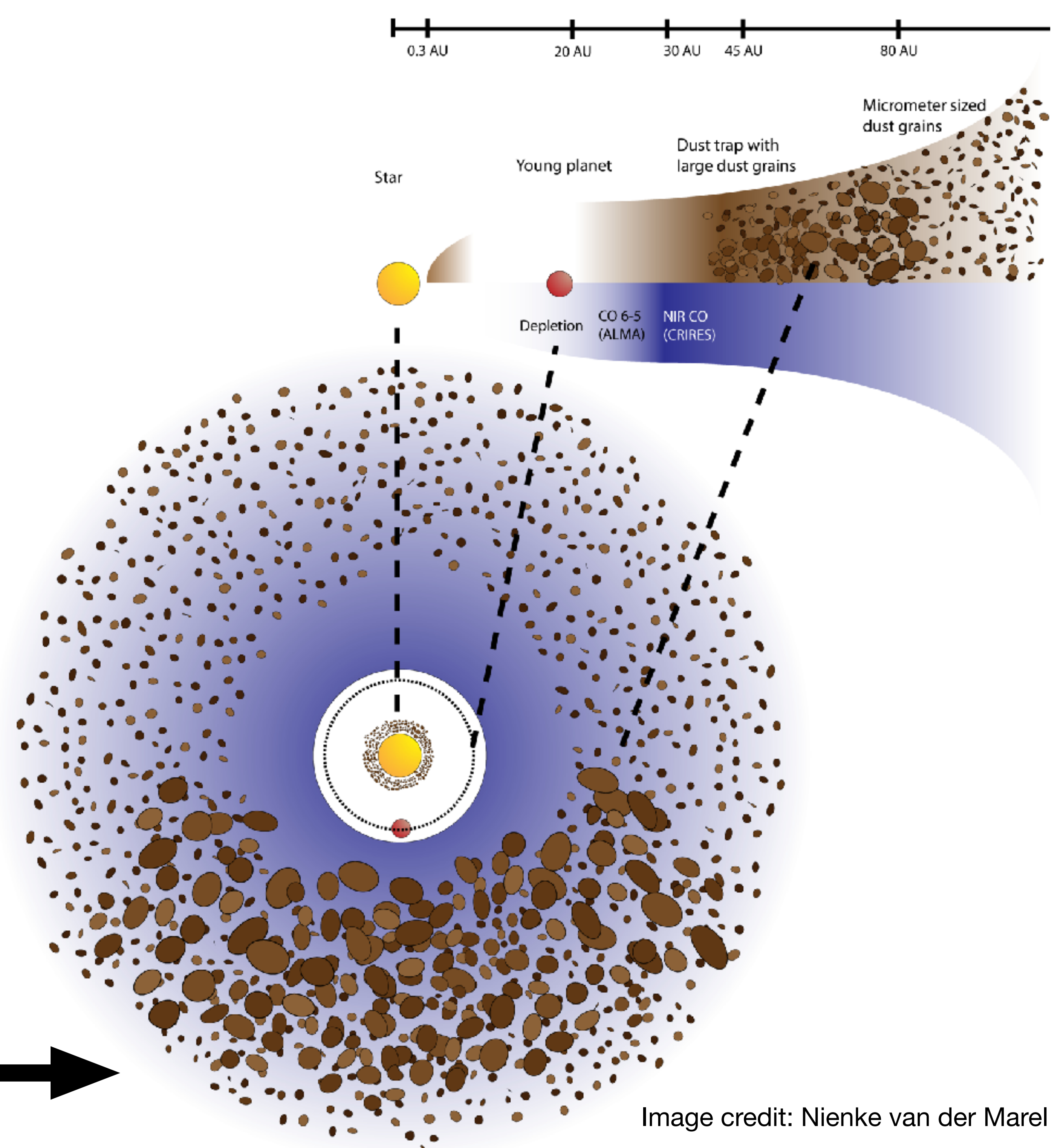
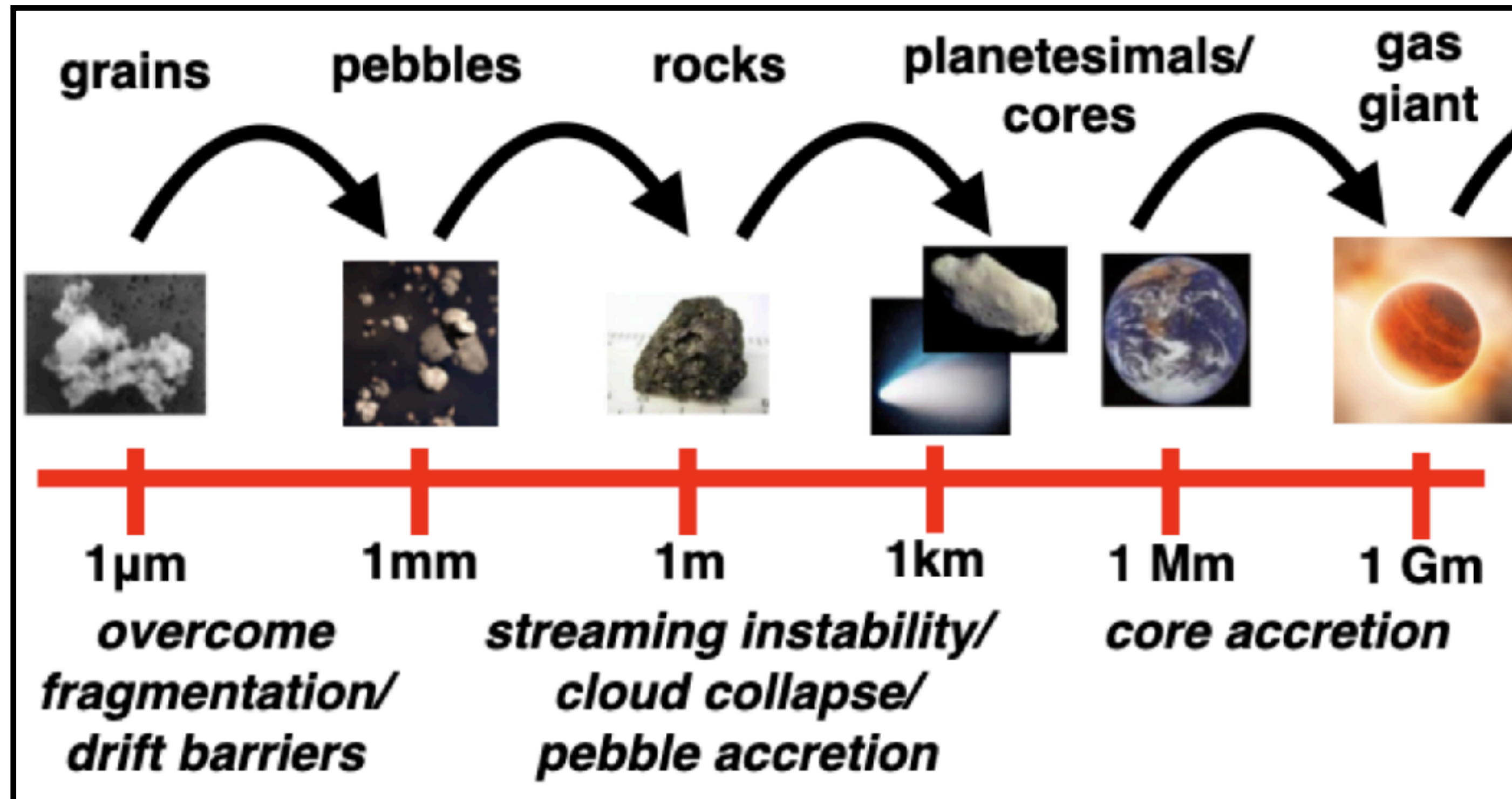


Image credit: Nienke van der Marel



# Dust evolution



van der Marel & Pinilla (2024)

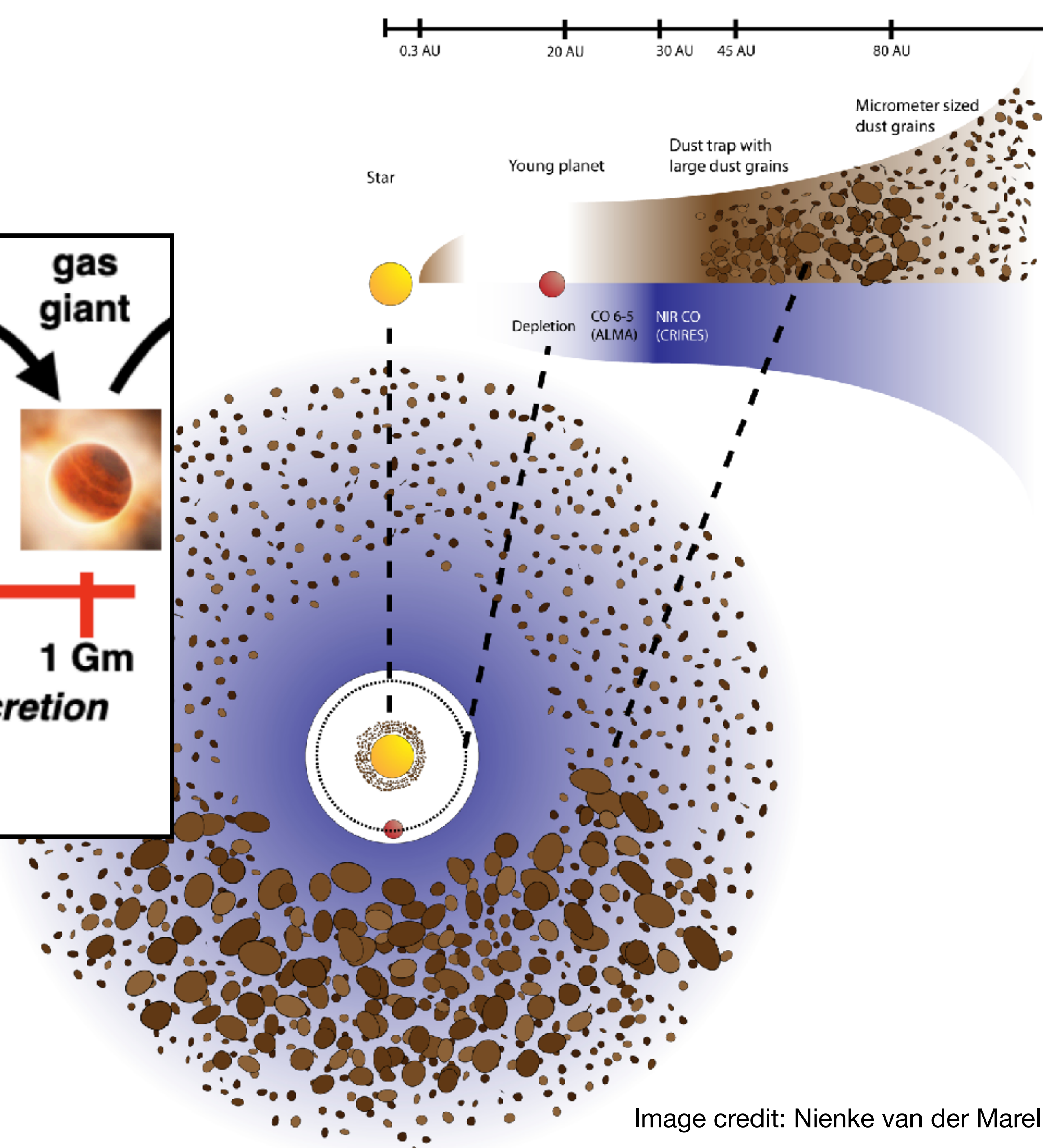


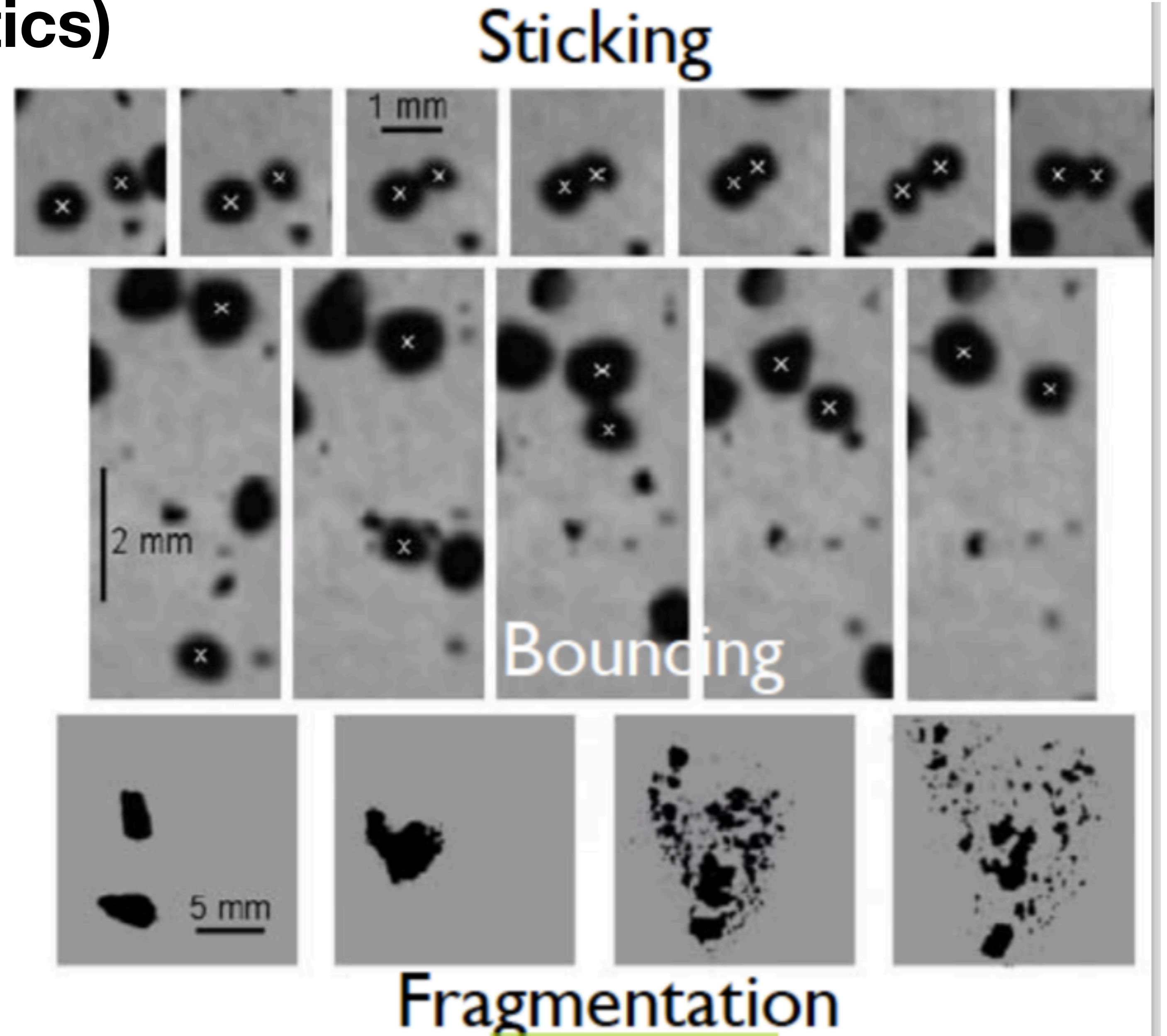
Image credit: Nienke van der Marel



# Dust motion (or kinematics)

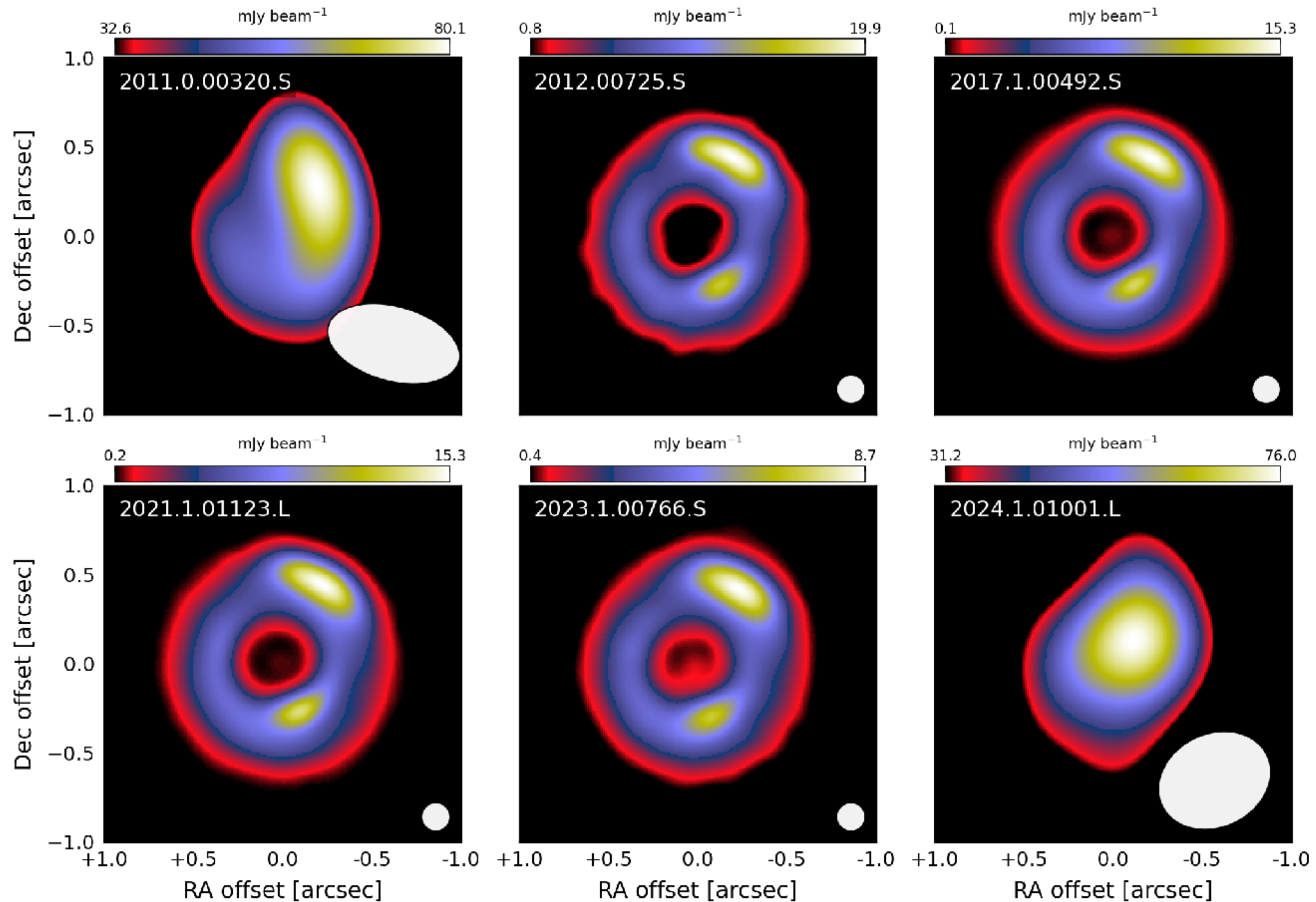
Different from line observations

No velocity information





# Time domain observations





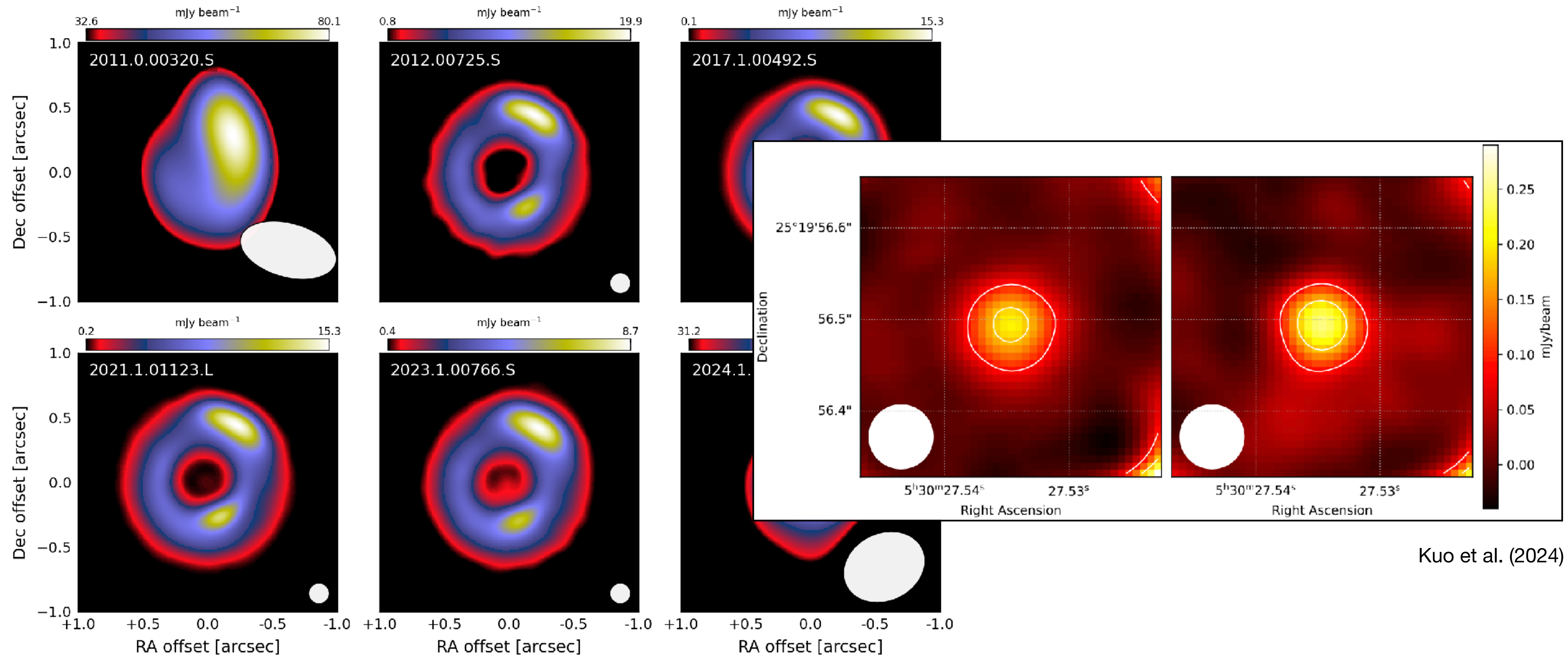
# Need for a common uv coverage: Image fidelity

| Project ID     | Frequency<br>(GHz) | Observing period      | Baseline length<br>(k $\lambda$ ) | Flux<br>(mJy) | Robust | Synthesized beam                       | Noise<br>(mJy) |
|----------------|--------------------|-----------------------|-----------------------------------|---------------|--------|----------------------------------------|----------------|
| 2011.0.00320.S | 337                | 2012/08/15–2012/10/19 | 15–432                            | 237 $\pm$ 2   | 0.5    | 0''.76 $\times$ 0''.41 (15 $^\circ$ )  | 0.52           |
| 2012.1.00725.S | 342                | 2015/09/01–2015/09/24 | 21–1766                           | 269 $\pm$ 2   | –0.5   | 0''.16 $\times$ 0''.1 (26 $^\circ$ )   | 0.17           |
| 2017.1.00492.S | 343                | 2017/11/12–2018/09/20 | 13–13902                          | 210 $\pm$ 1   | 0.9    | 0''.16 $\times$ 0''.13 (–21 $^\circ$ ) | 0.02           |
| 2021.1.01123.L | 334                | 2021/11/25–2022/09/15 | 13–3386                           | 210 $\pm$ 1   | 0.5    | 0''.16 $\times$ 0''.11 (–49 $^\circ$ ) | 0.03           |
| 2023.1.00766.S | 322                | 2024/07/04–2024/07/24 | 21–2465                           | 138 $\pm$ 1   | 0.3    | 0''.15 $\times$ 0''.1 (–44 $^\circ$ )  | 0.03           |
| 2024.1.01001.L | 354                | 2024/10/23            | 14–461                            | 206 $\pm$ 1   | 0.5    | 0''.65 $\times$ 0''.52 (–26 $^\circ$ ) | 0.04           |

-Dense uv sampling (many antennas?)

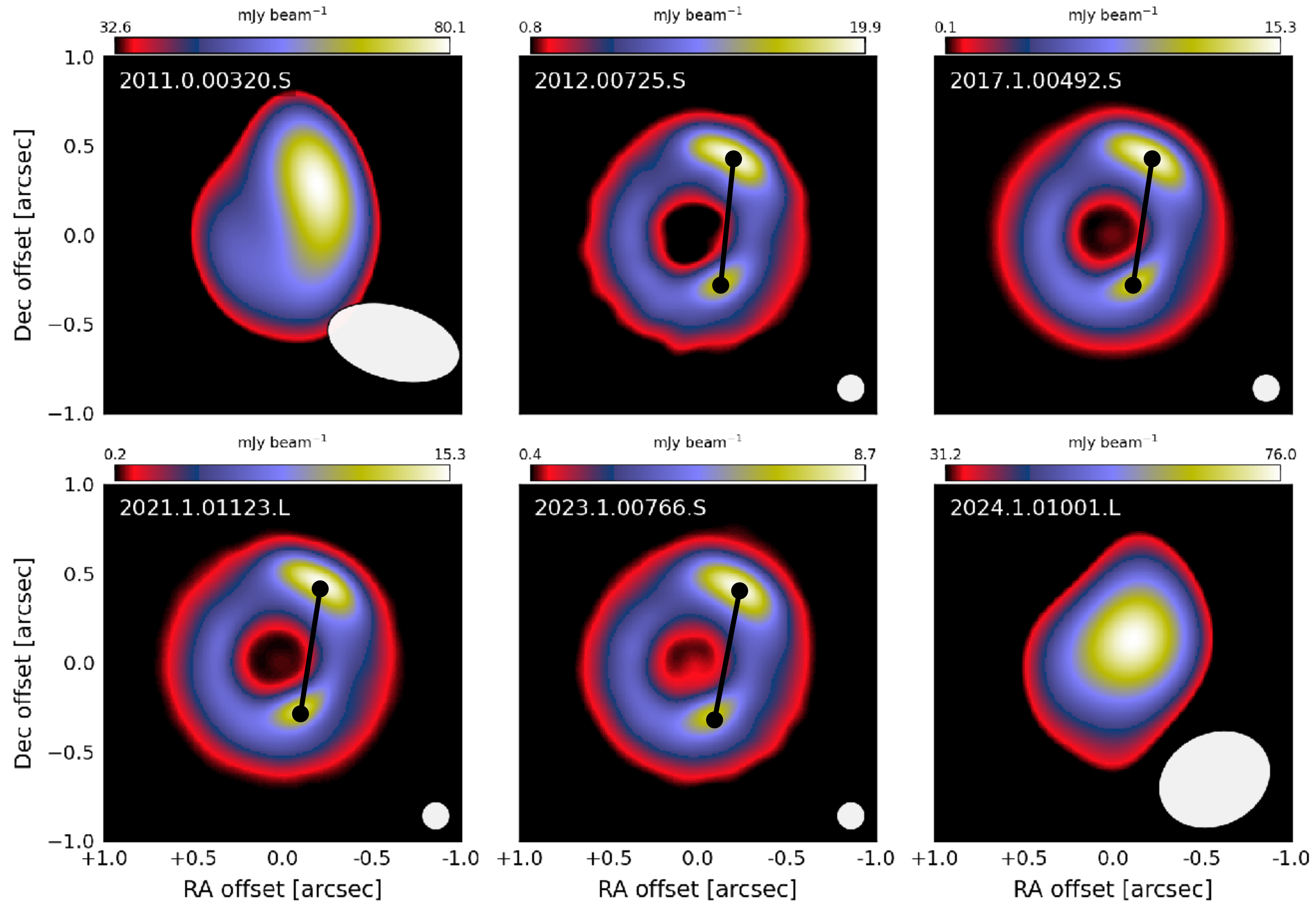


# Need for accurate absolute position: Trace temporal changes in structures



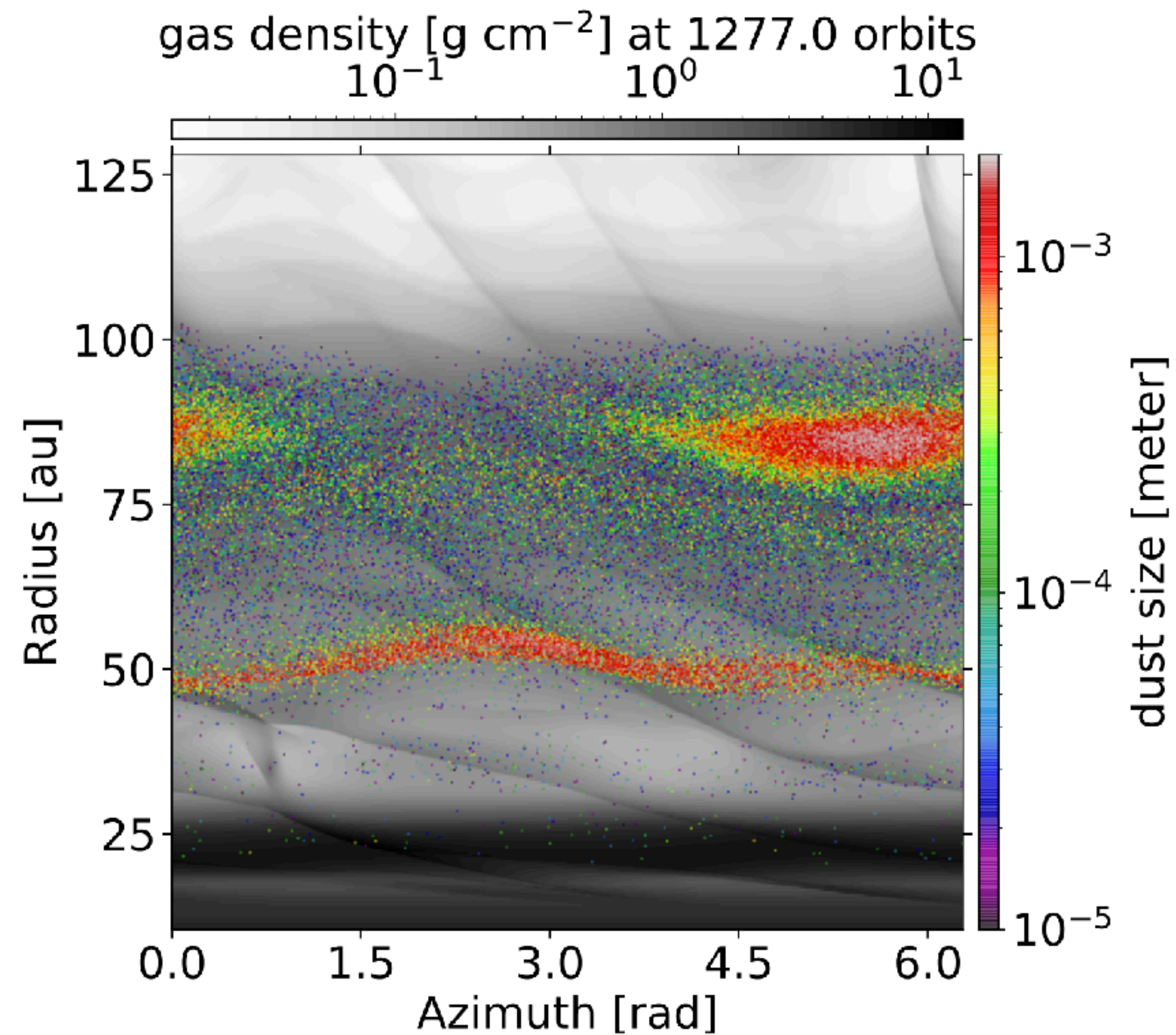
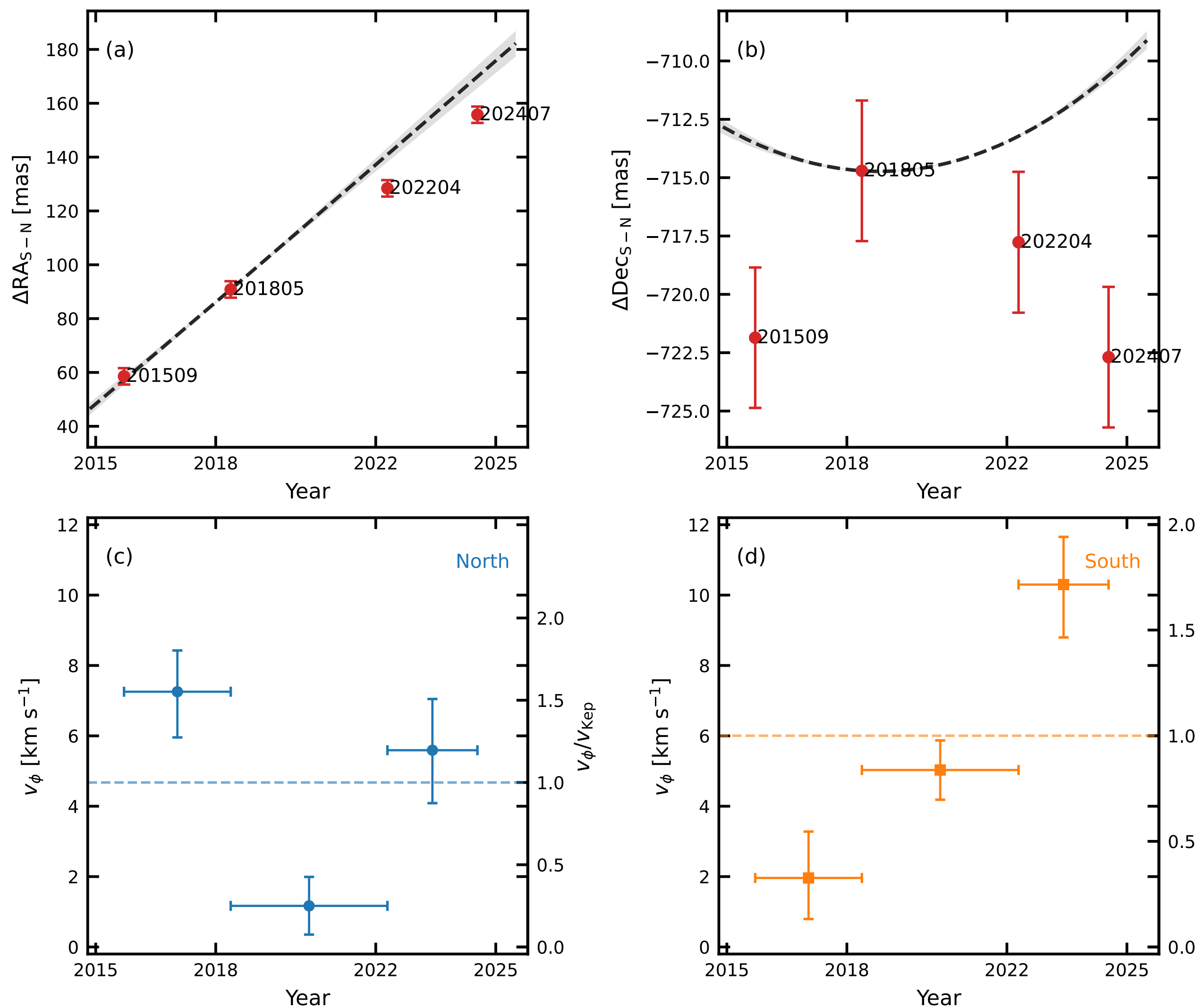


# Time domain observations





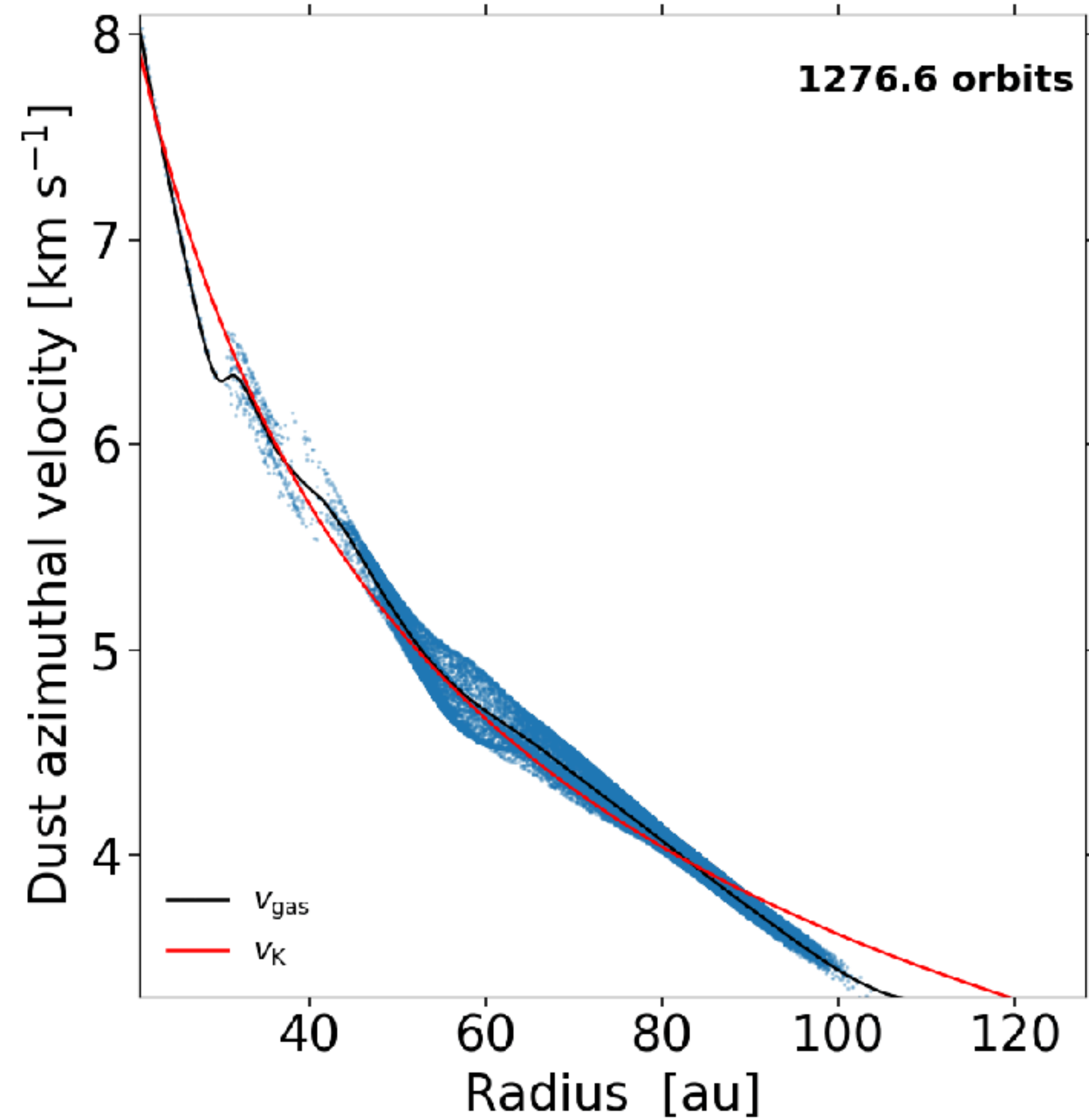
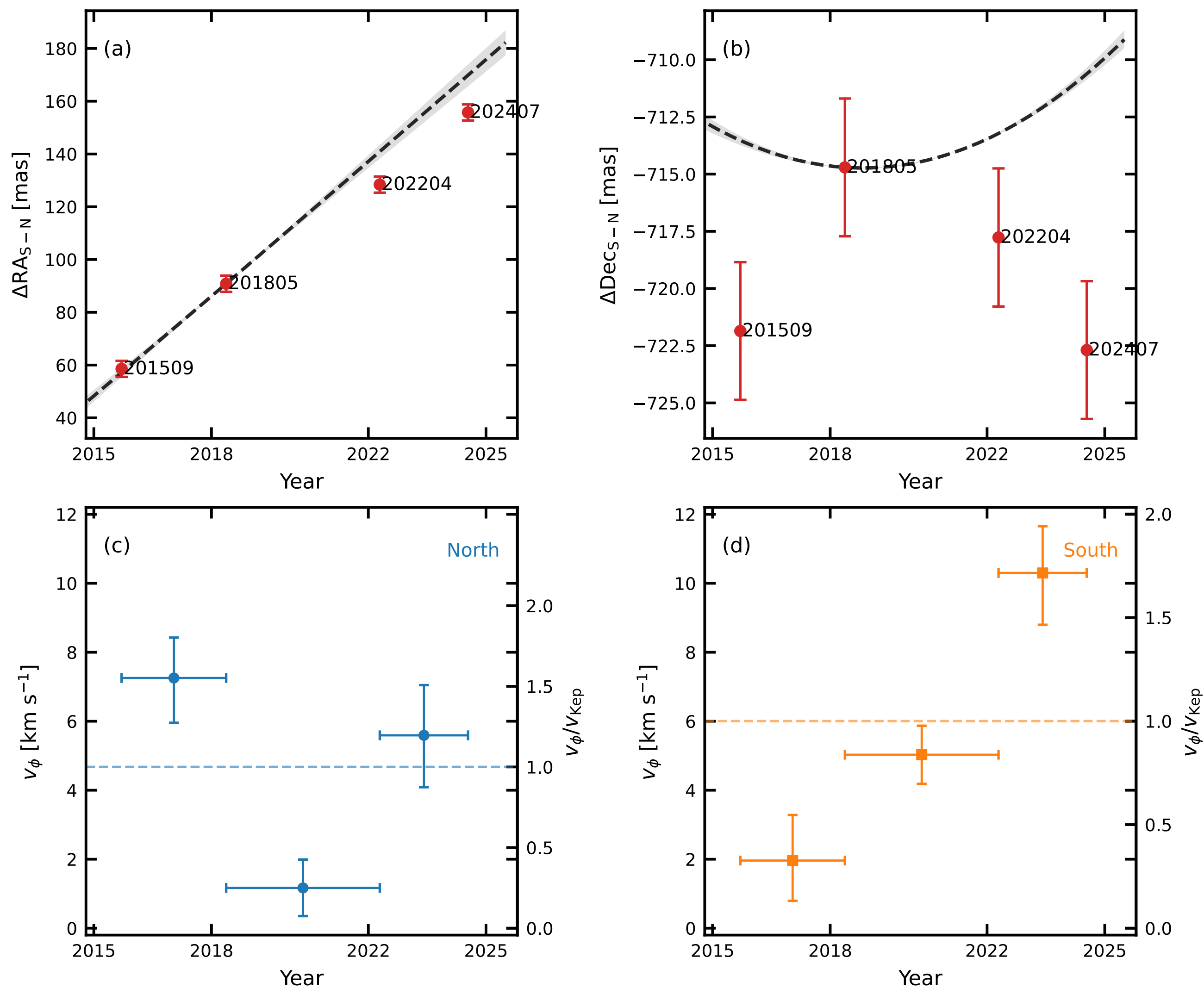
# Change in relative peak position with time



Baruteau et al. (2019)



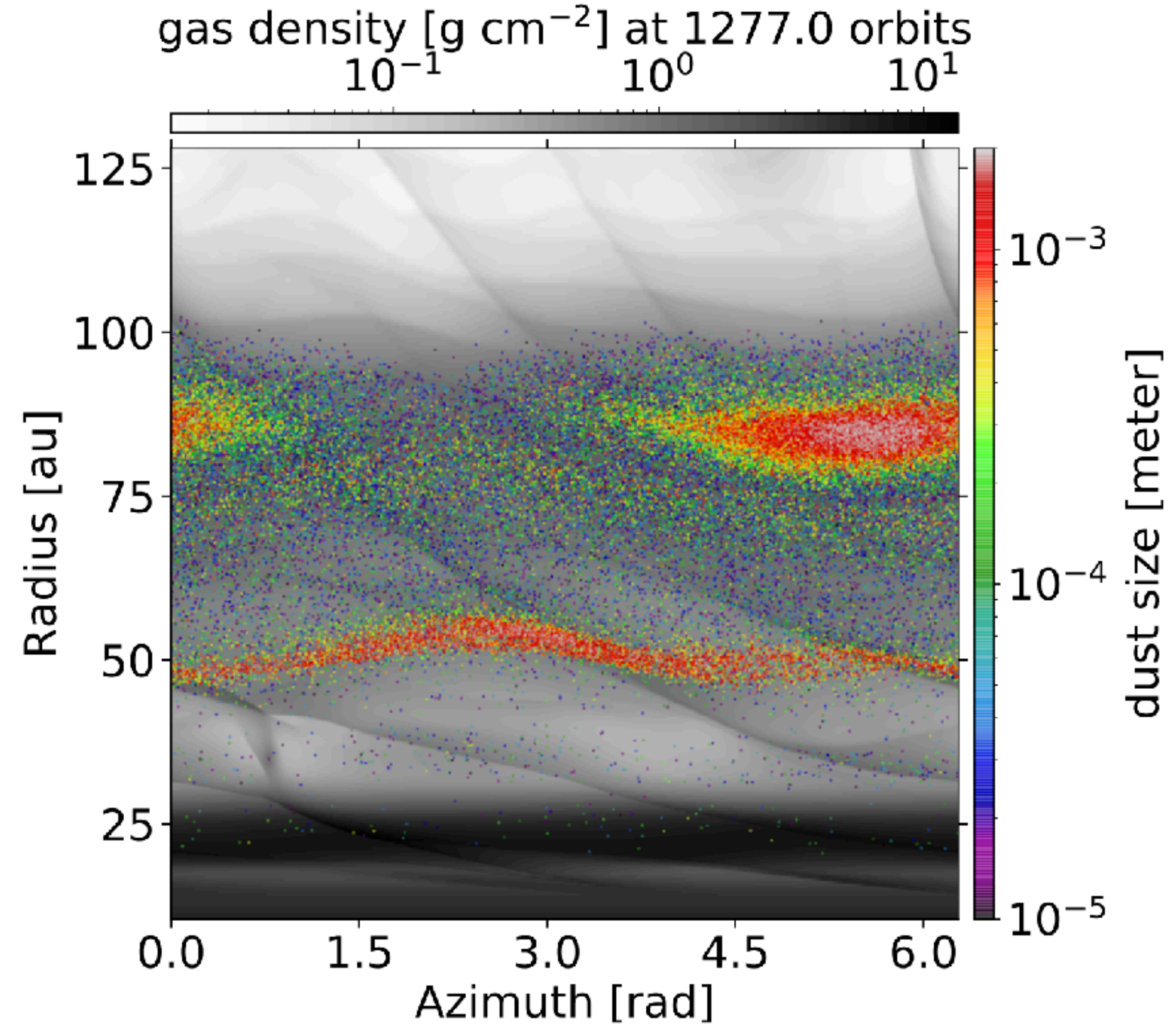
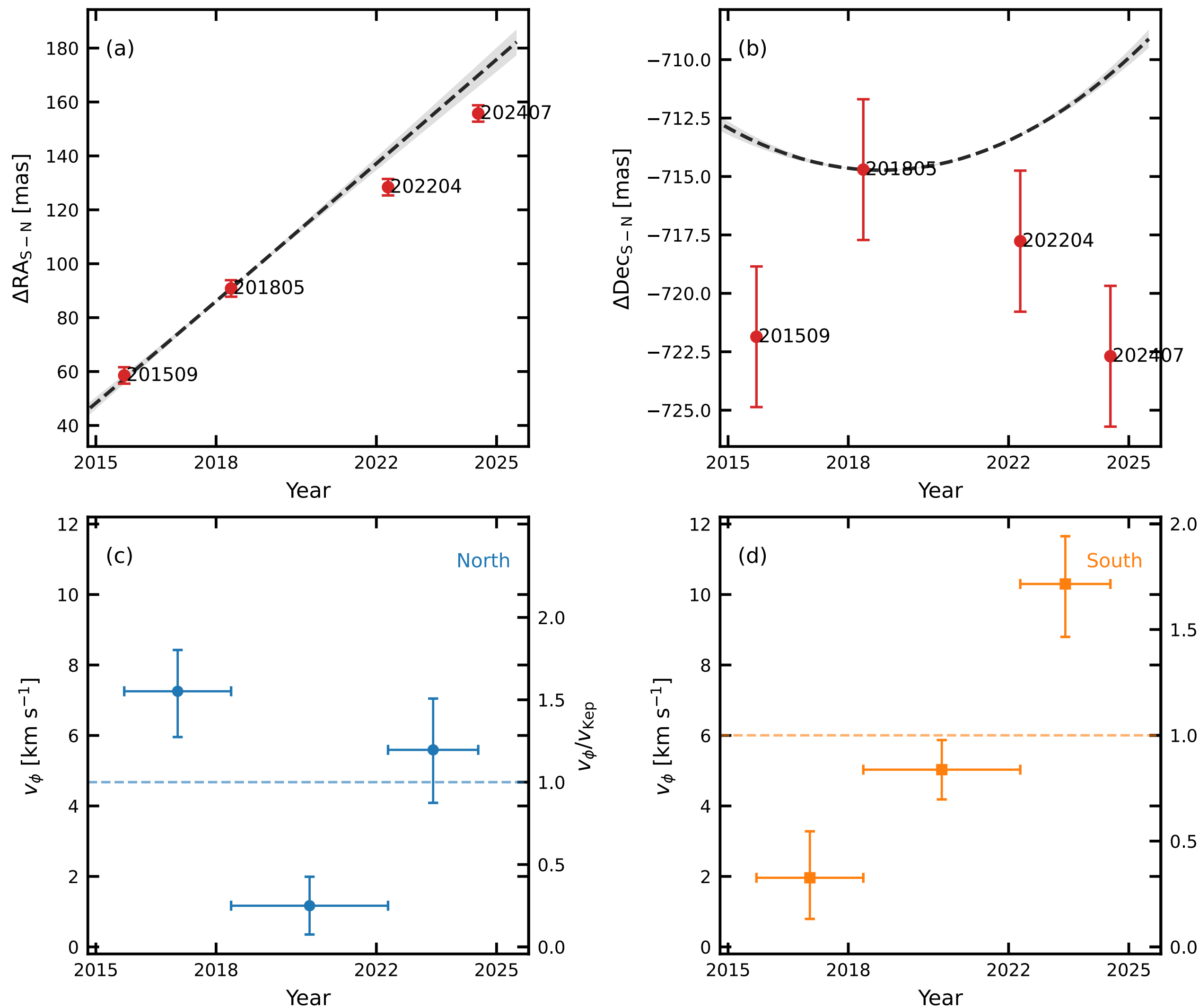
# Change in relative peak position with time



Baruteau et al. (2019)



# Change in relative peak position with time

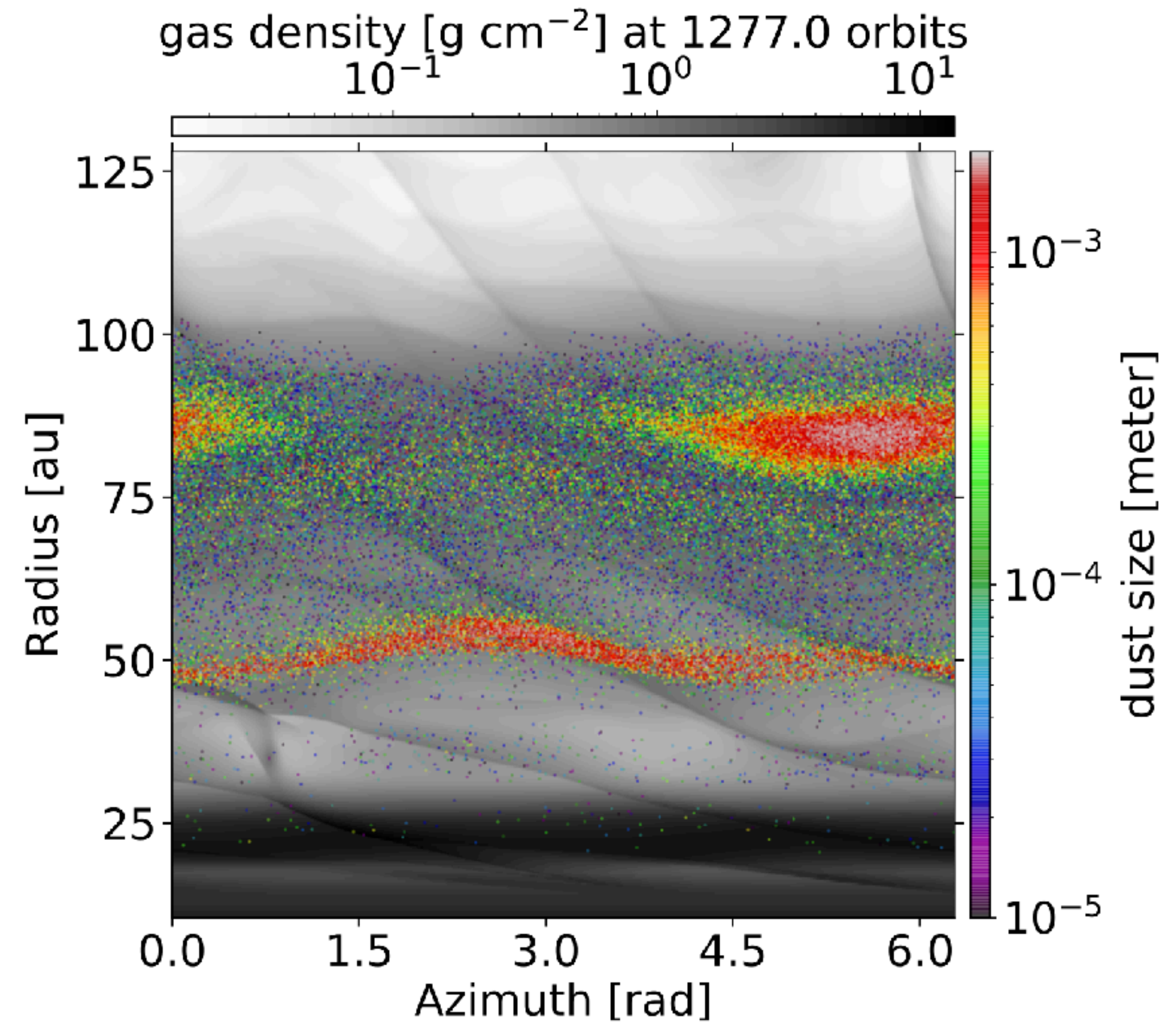
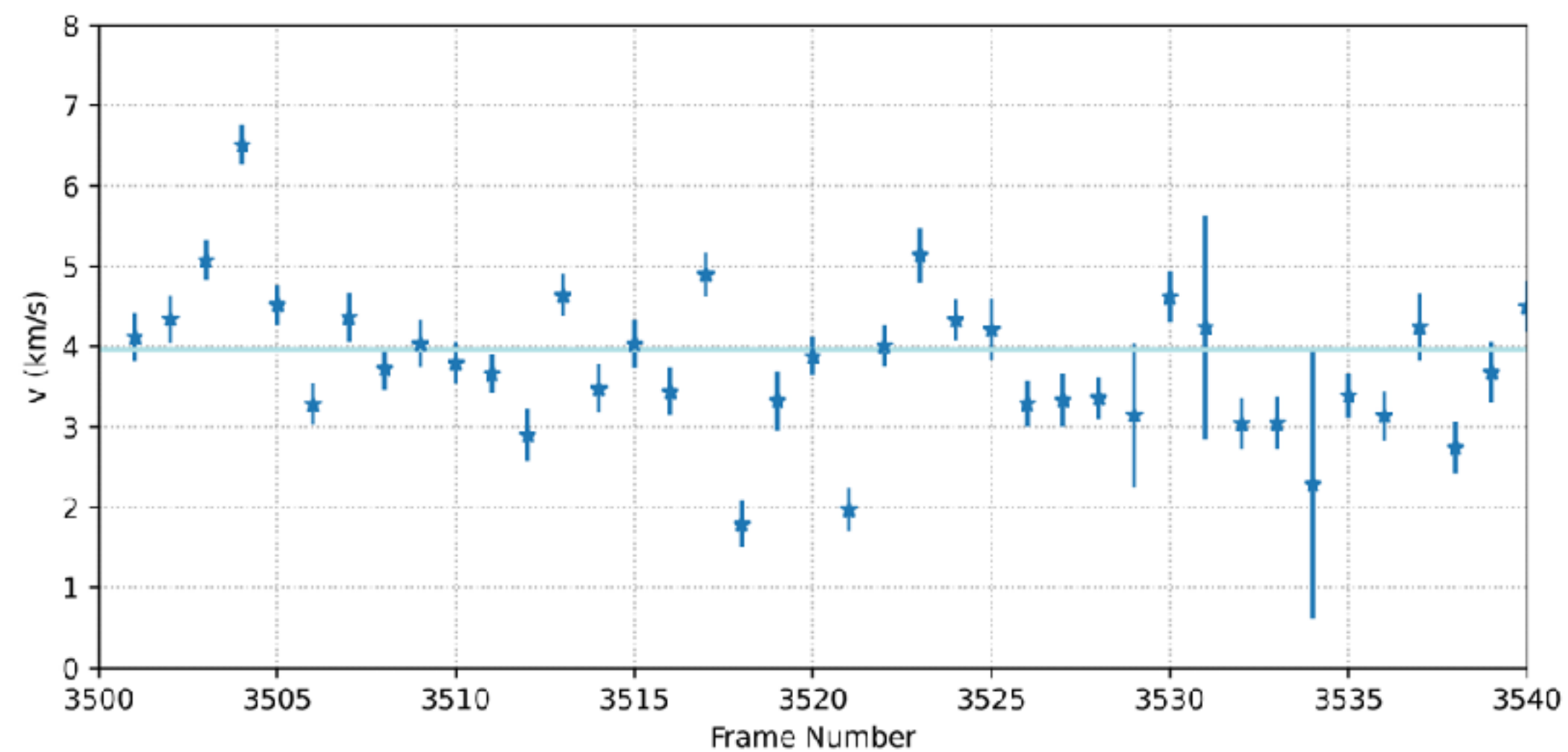
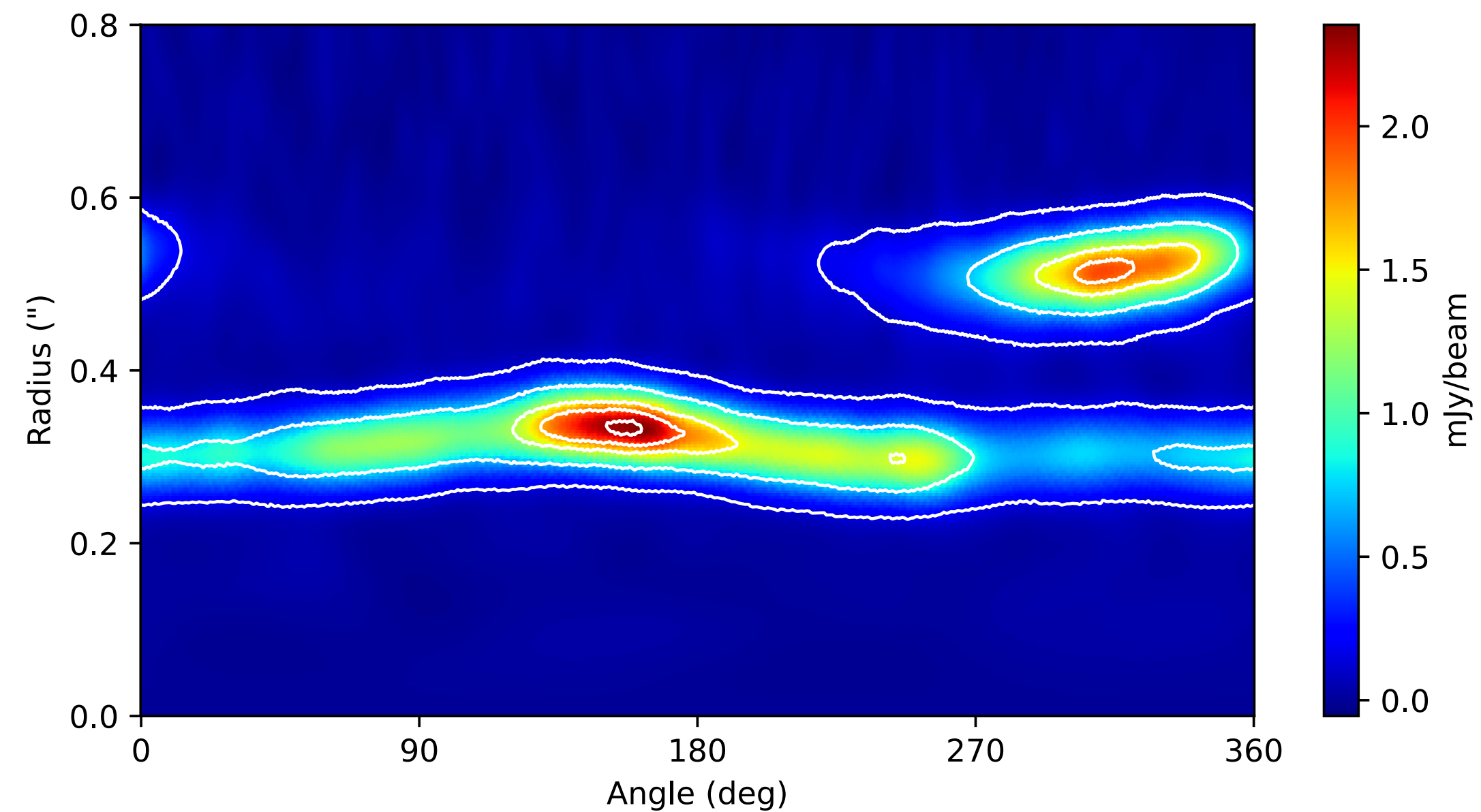


Baruteau et al. (2019)

Fluctuation in dust distribution



# Change in relative peak position with time

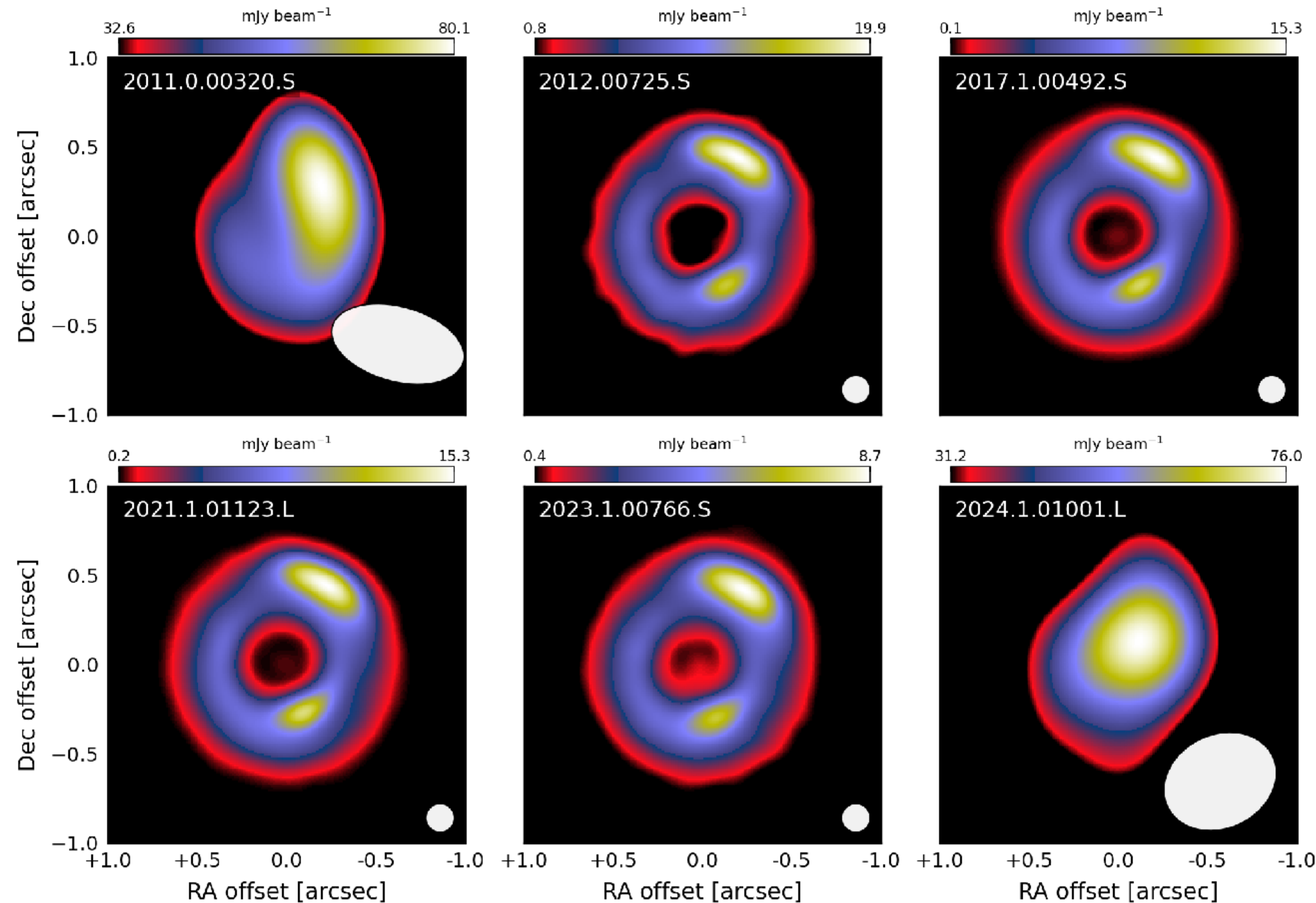


Baruteau et al. (2019)

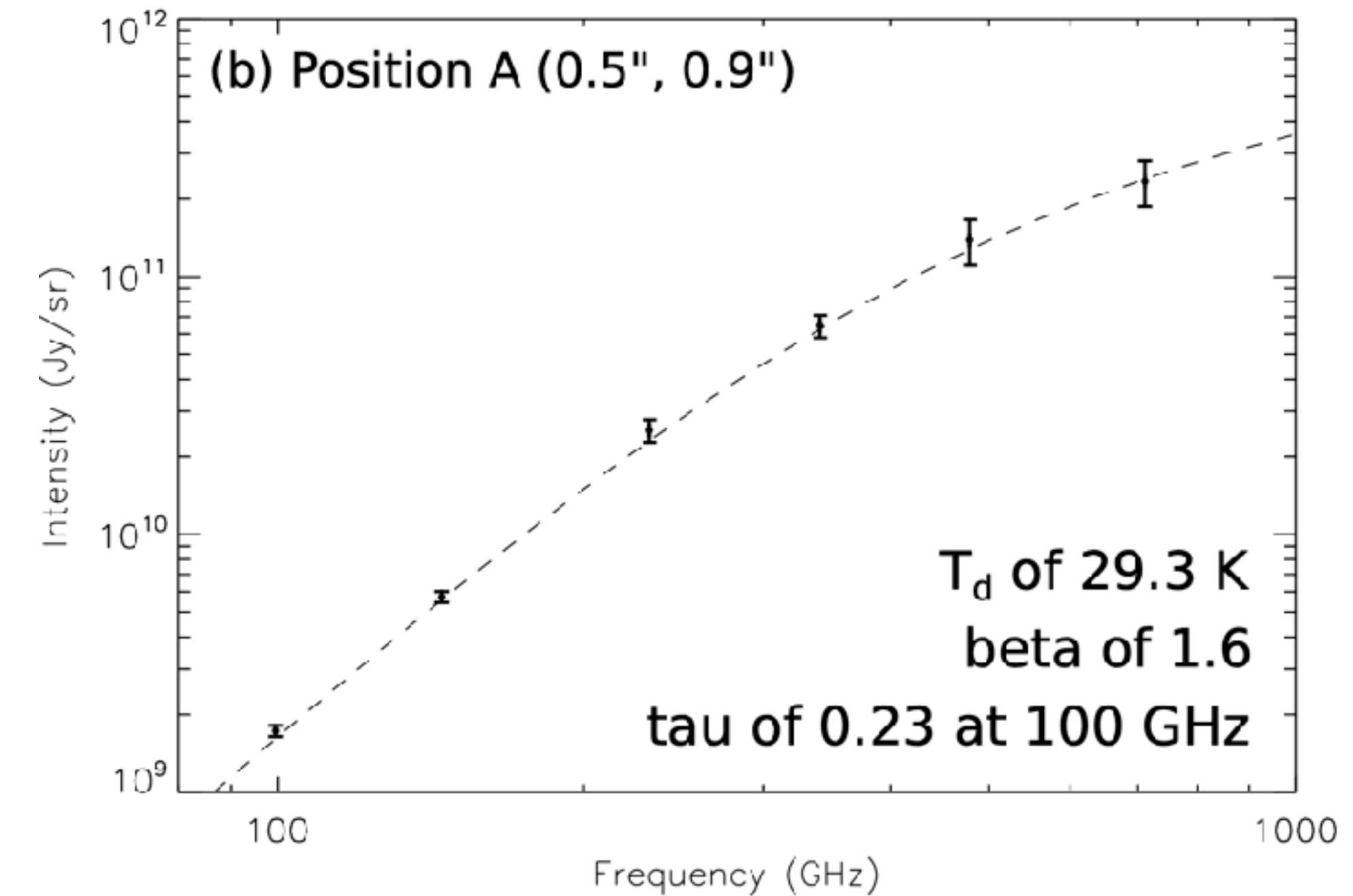
Wavelength dependent!



# Need for multi band observations: Disentangle density, temperature, grain size



For example:



Yen et al. (2020)

- Common uv range (many antennas?)
- Absolute flux accuracy



# Microphysics in Disk Formation and Evolution

To constrain:

Magnetic field—matter coupling (dust properties)

Motion of magnetic fields (ion—neutral drift)

To observe:

Dust kinematics

(multi-band time domain)

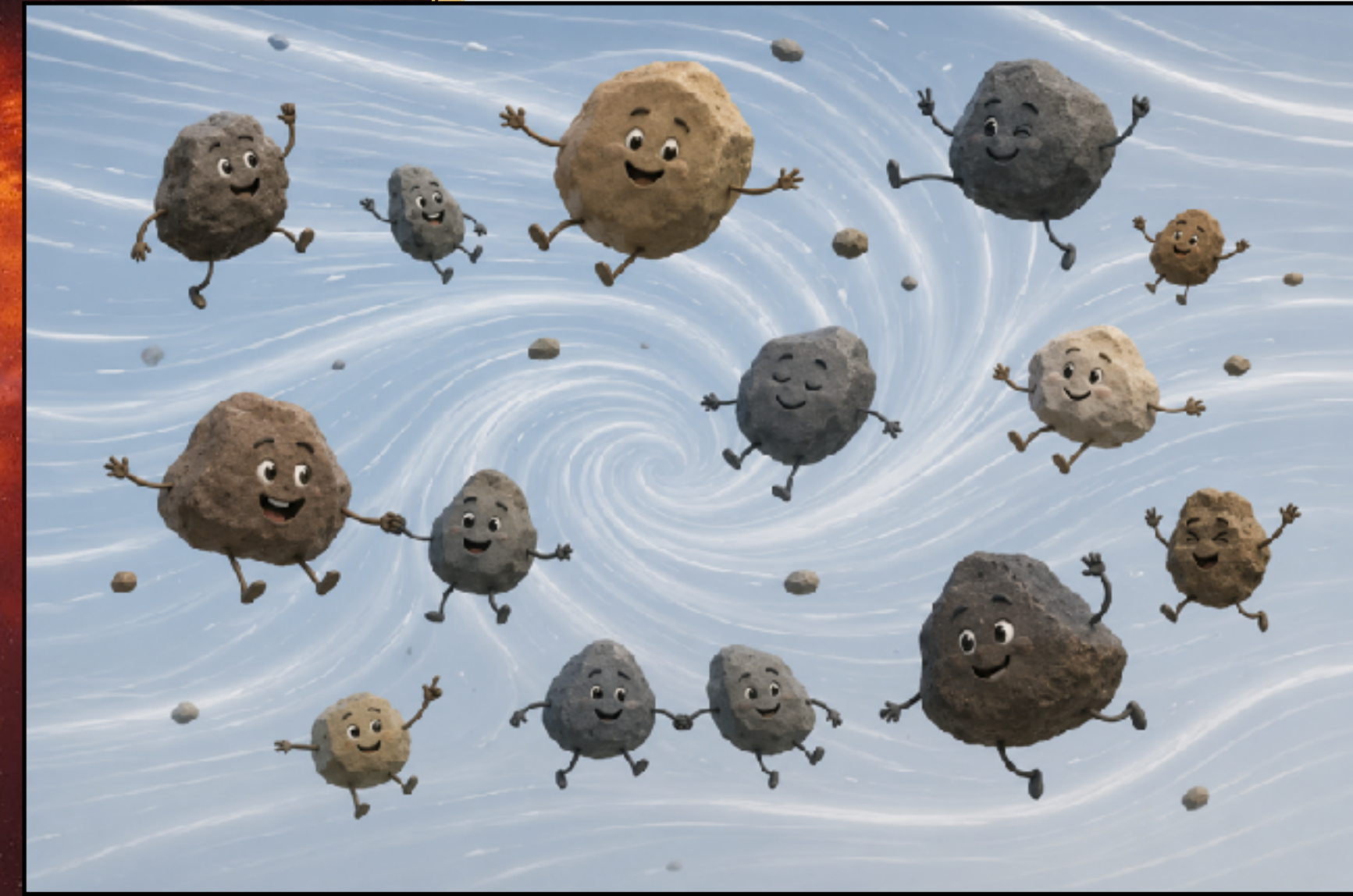
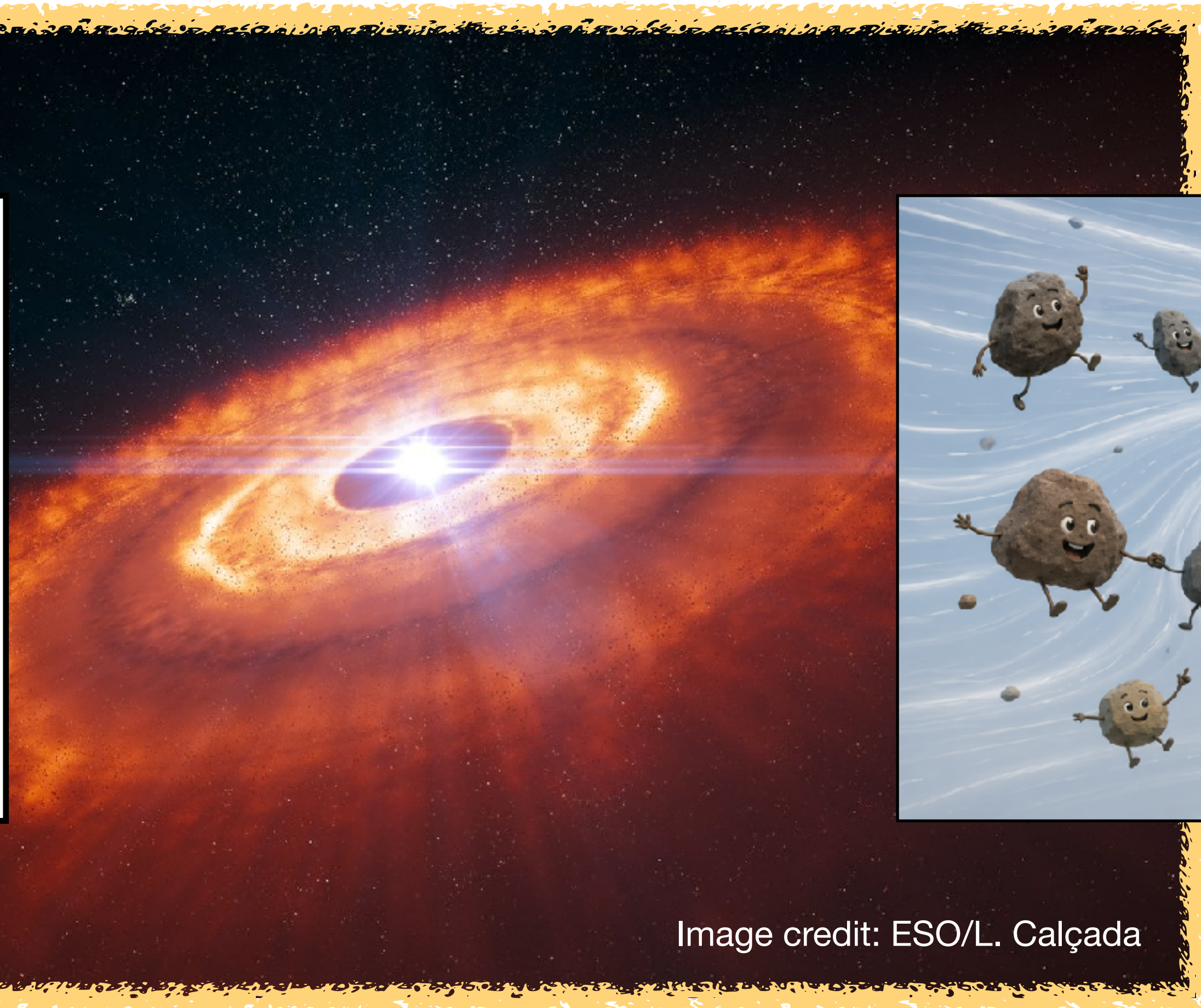
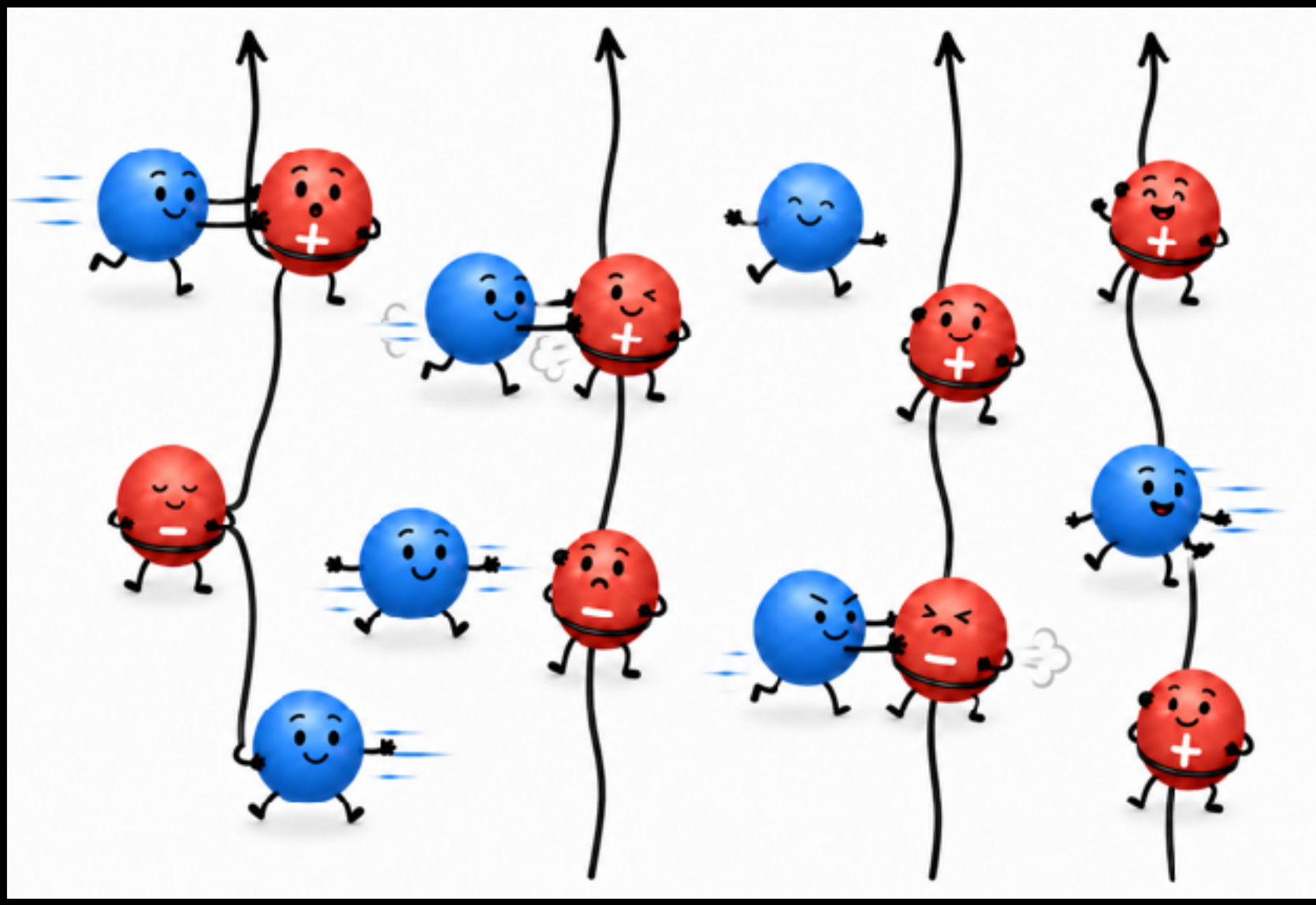


Image credit: ESO/L. Calçada



# Looking ahead

- **Wide frequency band**  
Extend to higher frequency (B9, B10 & THz?)  
in continuum, lines, and polarization
  - Density & temperature
  - Dust properties
  - Locate different species
- **Absolute flux accuracy**
  - SED, excitation
- **All bands simultaneously**
  - Time domain
- **UV coverage (or image fidelity)**
  - Comparing images at different freq.
- **Absolute position accuracy**  
1 mas level?
  - Temporal variation in structures

