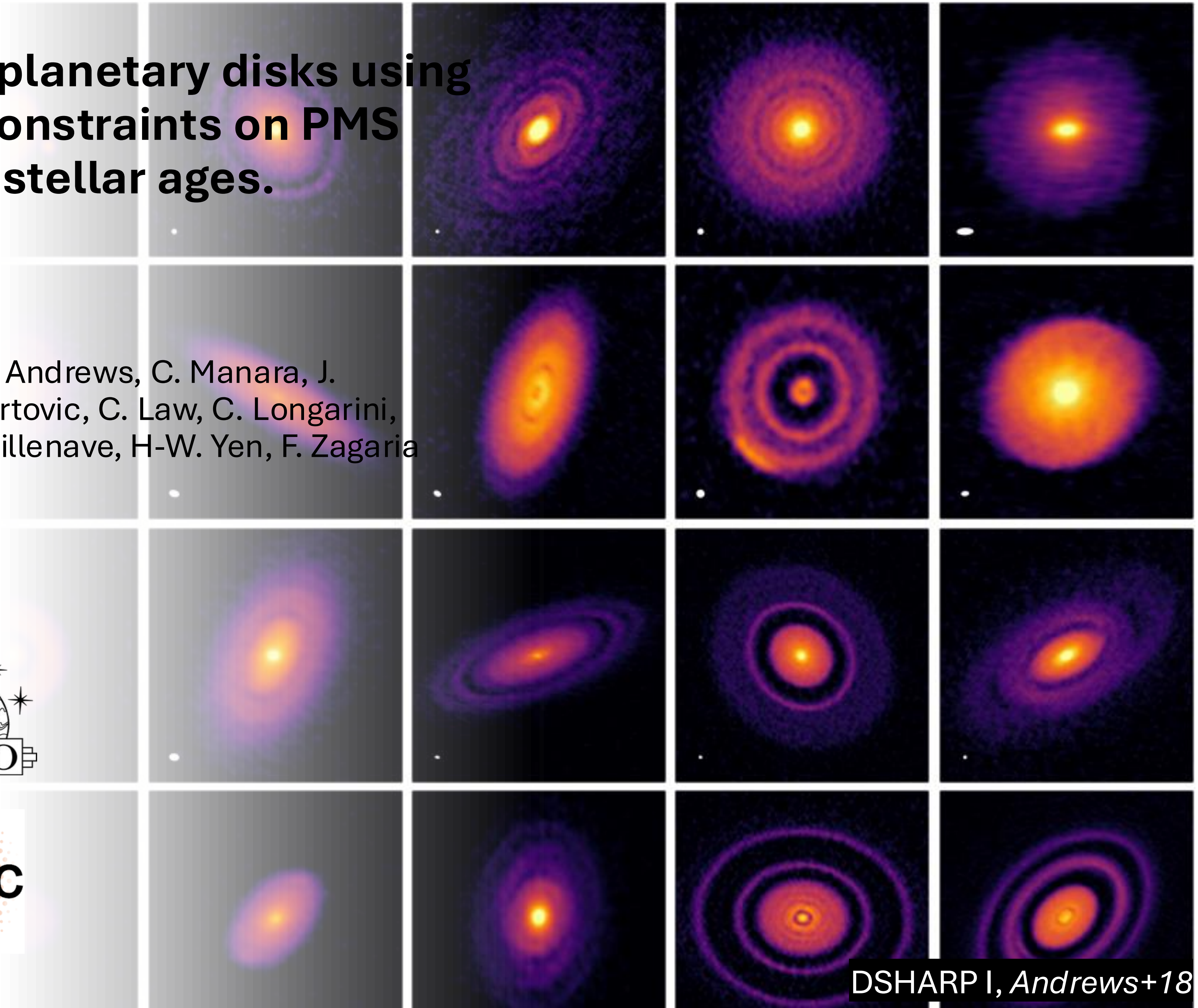
Bulk properties of protoplanetary disks using ALMA visibilities. New constraints on PMS evolutionary tracks and stellar ages.

Luigi Zallio

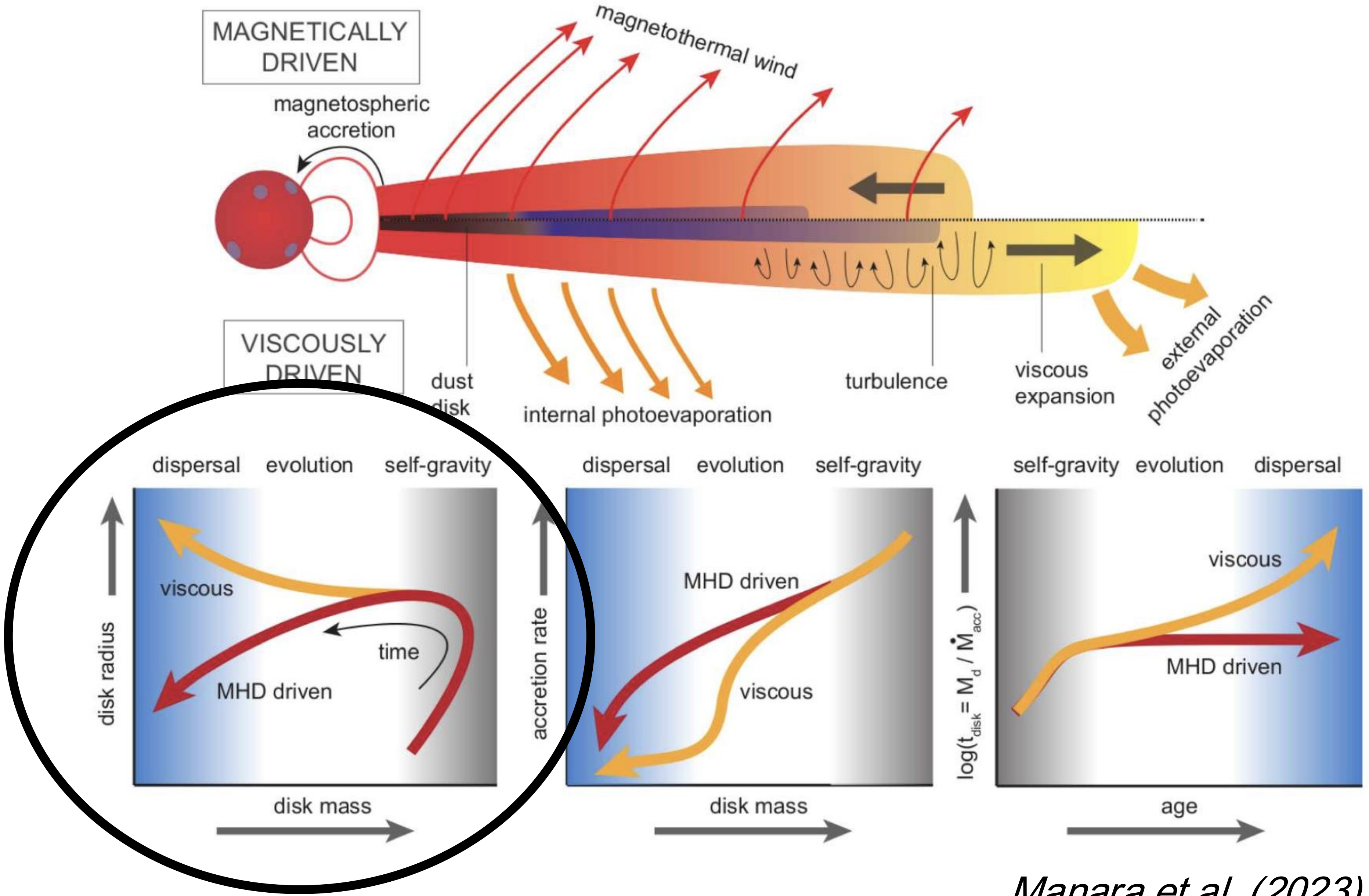
G. Rosotti, M. Vioque, A. Miotello, S. Andrews, C. Manara, J. Carpenter, D. Deng, A. Empey, N. Kurtovic, C. Law, C. Longarini, T. Paneque-Carreno, R. Teague, M. Villenave, H-W. Yen, F. Zagaria
+ DEC/O collaboration

Università degli Studi di Milano (IT)



DSHARP I, *Andrews+18*

Extracting bulk disk properties from moderate angular resolution ALMA line observations



Manara et al. (2023)

Extracting bulk disk properties from moderate angular resolution ALMA line observations

Putting empirical constraint on the accretion scenarios: gas radii

RECIPE:

1. **Statistics**.
   Accurate CO radii are difficult to extract on a population – base.

   - *Ansdell et al., 2018:* 22 gas disk sizes
   - *Sanchis et al., 2021:* 42 gas disk sizes
   - *Long et al., 2022:* 44 gas disk sizes

overlap of some disks.

Extracting bulk disk properties from moderate angular resolution ALMA line observations

Putting empirical constraint on the accretion scenarios: gas radii

RECIPE:

1. **Statistics**.
   <u>*Accurate*</u> CO radii are difficult to extract on a population – base.

   - *Ansdell et al., 2018:* 22 gas disk sizes
   - *Sanchis et al., 2021:* 42 gas disk sizes
   - *Long et al., 2022:* 44 gas disk sizes

   overlap of some disks.

2. **Wide range of ages (hence SFRs).**
   We are mostly biased towards Lupus and Taurus.
   AGE-PRO is out! *(Zhang et al., 2025; Trapman et al., 2025)*

Extracting bulk disk properties from moderate angular resolution ALMA line observations

Putting empirical constraint on the accretion scenarios: gas radii

RECIPE:

1. **Statistics**.
   Accurate CO radii are difficult to extract on a population – base.

   - *Ansdell et al., 2018:* 22 gas disk sizes
   - *Sanchis et al., 2021:* 42 gas disk sizes
   - *Long et al., 2022:* 44 gas disk sizes

   overlap of some disks.

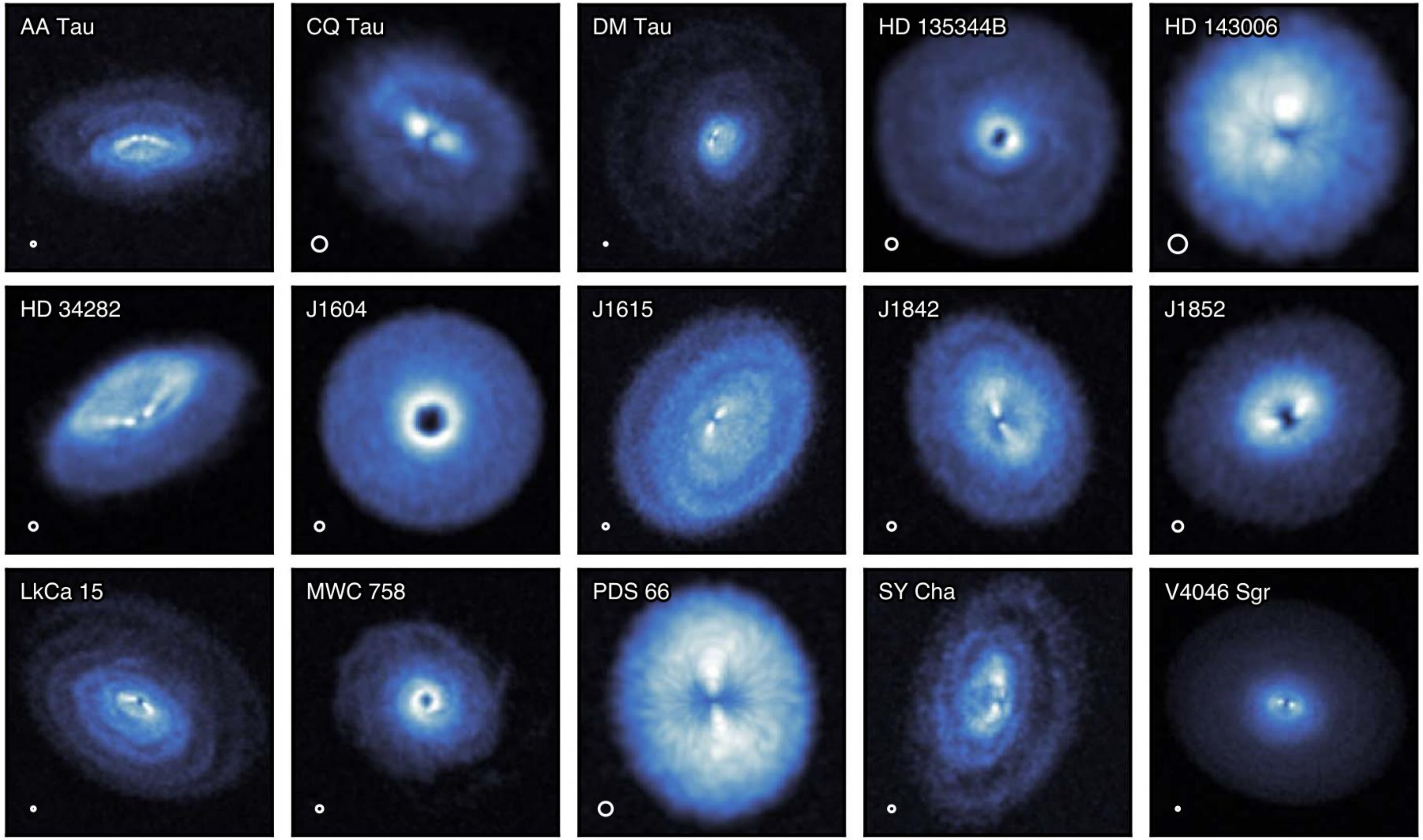
2. **Wide range of ages (hence SFRs).**
   We are mostly biased towards Lupus and Taurus.
   AGE-PRO is out! *(Zhang et al., 2025; Trapman et al., 2025)*

3. **'Common' disks.**
   Most reliable size measurements come from very extended and bright disks (e.g., *Öberg et al., 2021; Teague et al., 2025*)

What about compact and/or faint disks?

Extracting bulk disk properties from moderate angular resolution ALMA line observations

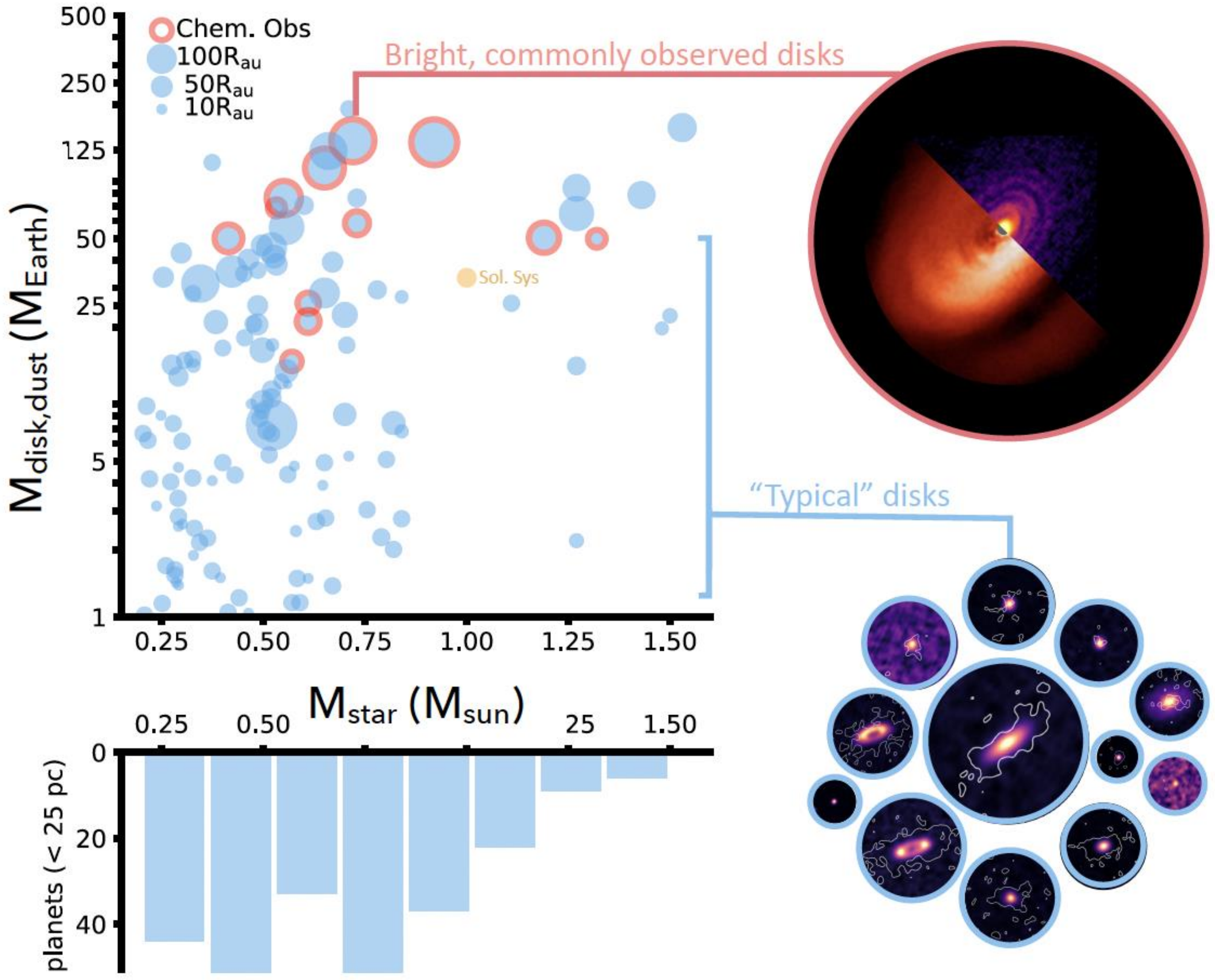
Typical disk galleries you probably have seen
12CO collection of some bright (and large!) protoplanetary disks



Teague et al. (2025)

Extracting bulk disk properties from moderate angular resolution ALMA line observations

However, the compact ones are fundamental!

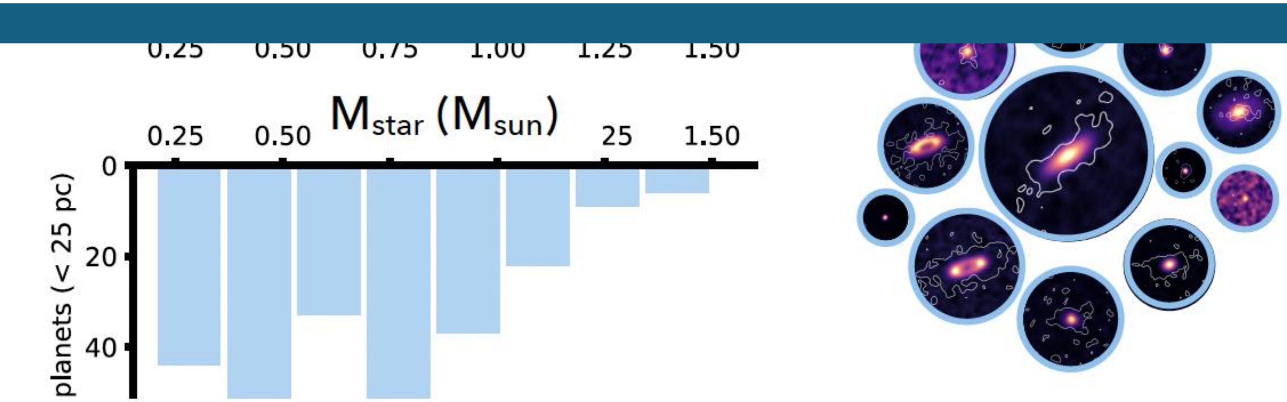


Adapted from a slide of L. I. Cleeves

Extracting bulk disk properties from moderate angular resolution ALMA line observations

However, the compact ones are fundamental!

How can we derive accurate disk properties from compact molecular line disk emission ?



Adapted from a slide of L. I. Cleeves

Extracting bulk disk properties from moderate angular resolution ALMA line observations

GAS VISIBILITY FITTING

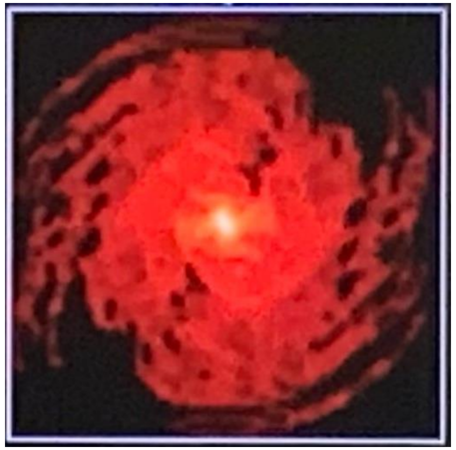
Squeezing water from stone

Extracting bulk disk properties from moderate angular resolution ALMA line observations

GAS VISIBILITY FITTING

Squeezing water from stone

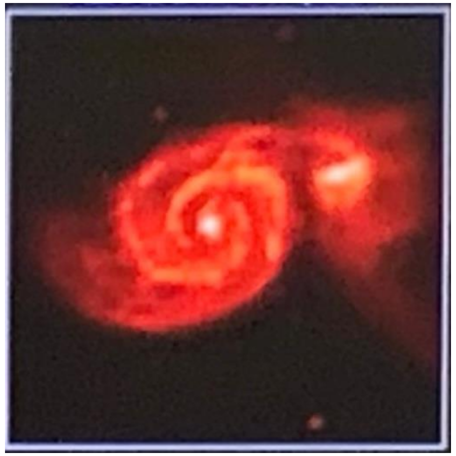
V



FFT-1

'cleaning'

I

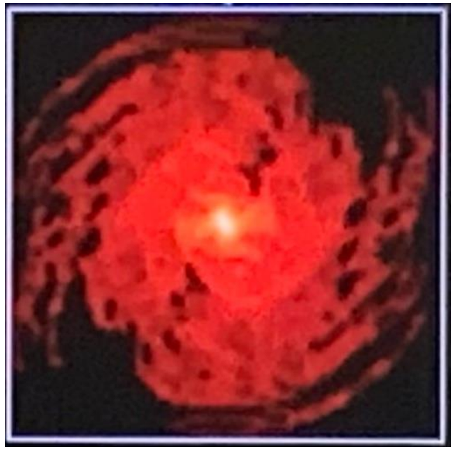


Extracting bulk disk properties from moderate angular resolution ALMA line observations

GAS VISIBILITY FITTING

Squeezing water from stone

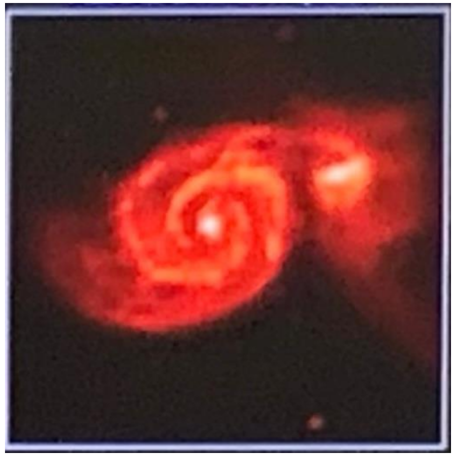
V



FFT-1

‘cleaning’

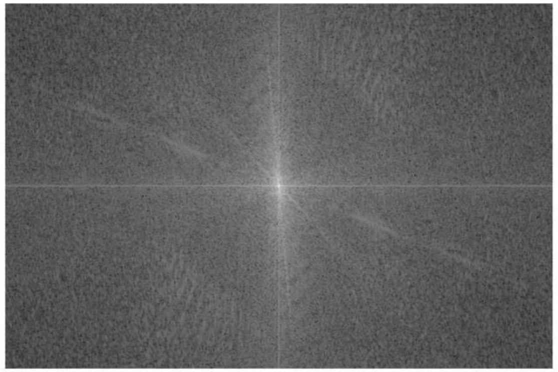
I



This procedure is ***amazing***, **BUT:**

- Relies on deconvolution algorithms (**tclean**)
- Needs thresholds to stop
- Can give different results based on the weights
- Introduces *systematics* to the final products (e.g., non-gaussian thermal noise)

Extracting bulk disk properties from moderate angular resolution ALMA line observations



What do **I** do?

1. I take the raw data (the **visibilities V**)

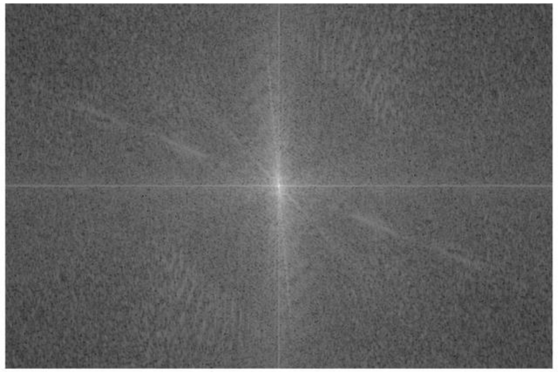
2. I *try* to do science **without further processing them**

Is this easy?

- Not at all

- Can **you** think in complex space? (Fourier space)

Extracting bulk disk properties from moderate angular resolution ALMA line observations



What do **I** do?

1. I take the raw data (the **visibilities V**)

2. I *try* to do science **without further processing them**

Is this easy?

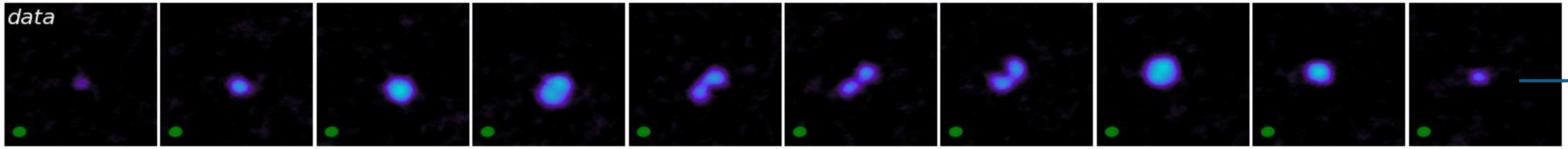
- Not at all

- Can **you** think in complex space? (Fourier space)

Extracting bulk disk properties from moderate angular resolution ALMA line observations

GAS VISIBILITY FITTING

'Circumstellar Spectral Analysis with Line Tomography' (`csalt`)
Andrews et al., in prep. (including **L. Zallio**)

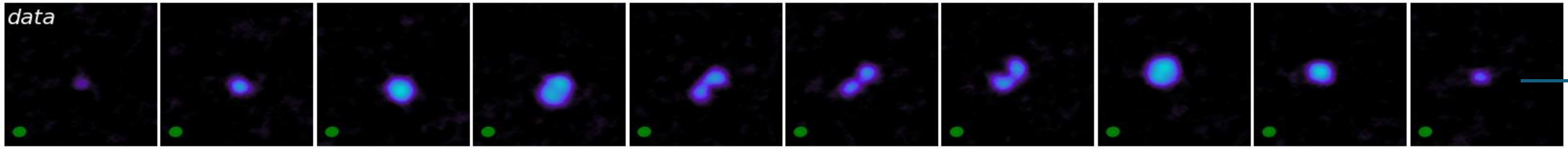


Channel maps of the datacube

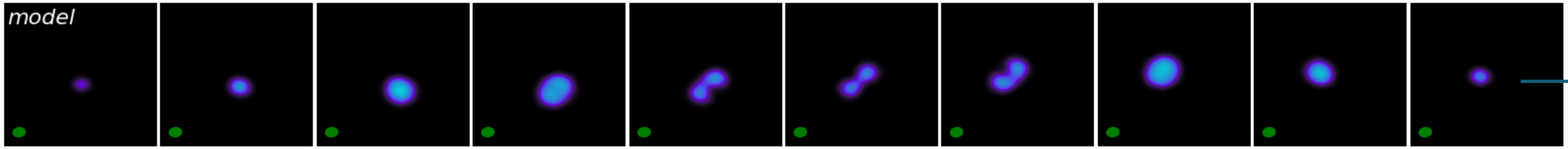
Extracting bulk disk properties from moderate angular resolution ALMA line observations

GAS VISIBILITY FITTING

'Circumstellar Spectral Analysis with Line Tomography' (`csalt`)
Andrews et al., in prep. (including **L. Zallio**)



Channel maps of the datacube

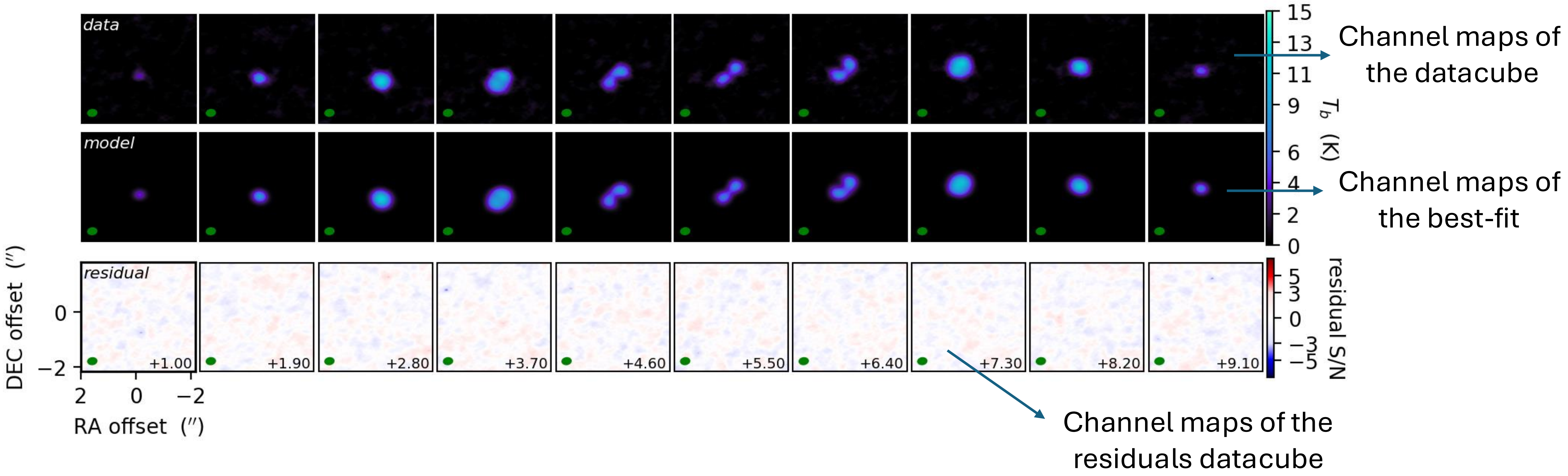


Channel maps of the best-fit

Extracting bulk disk properties from moderate angular resolution ALMA line observations

GAS VISIBILITY FITTING

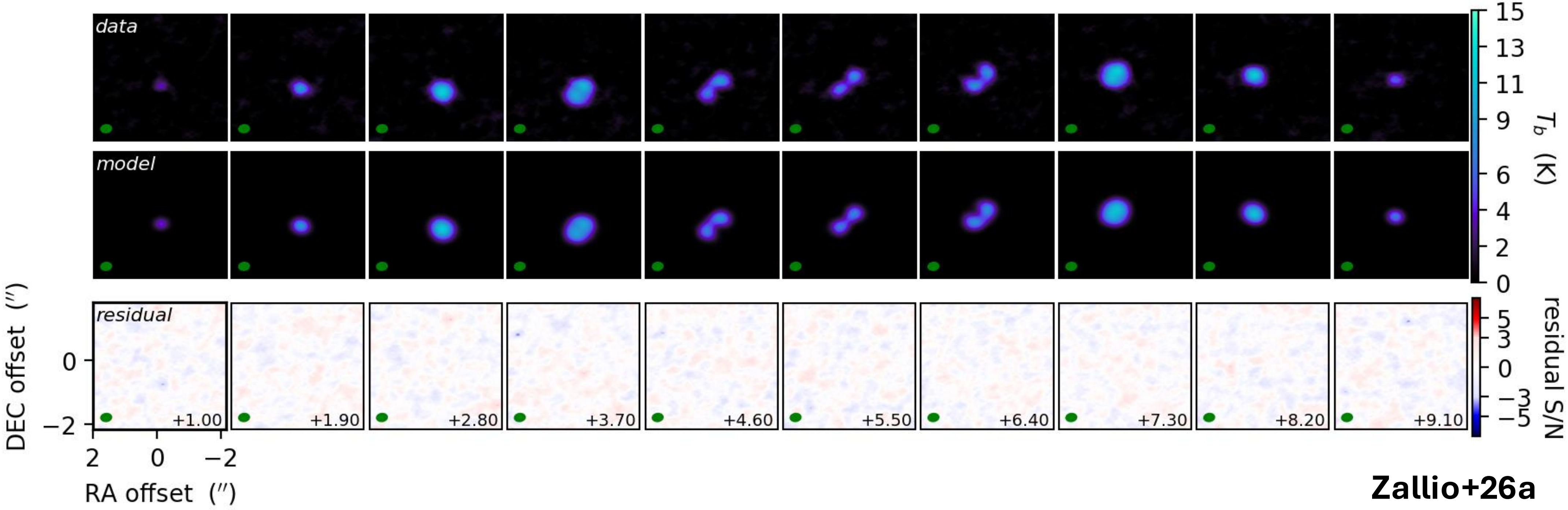
'Circumstellar Spectral Analysis with Line Tomography' (`csalt`)
Andrews et al., in prep. (including **L. Zallio**)



For a similar approach, see *Kurtovic et al., 2024*

Extracting bulk disk properties from moderate angular resolution ALMA line observations

GAS VISIBILITY FITTING



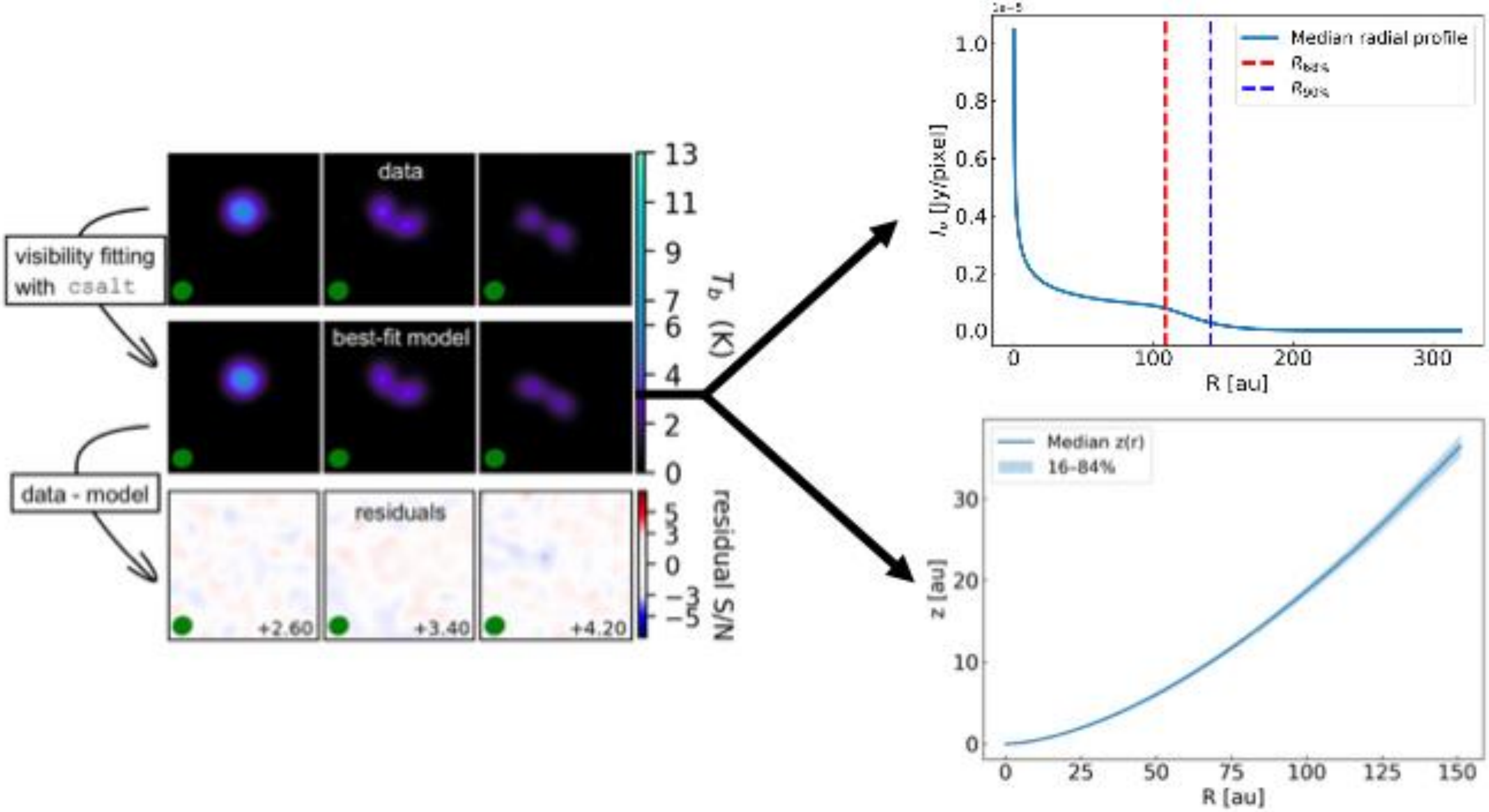
Zallio+26a

In my model I fit for:

- Disk geometry (inc, PA, dRA, dDEC, vsys)
- Stellar mass (**<u>Keplerian – with contribution from vertical height</u>**)
- Temperature profile (power-law)
- Optical depth profile (exp tapered power-law)
- z(r) (exp tapered power-law)

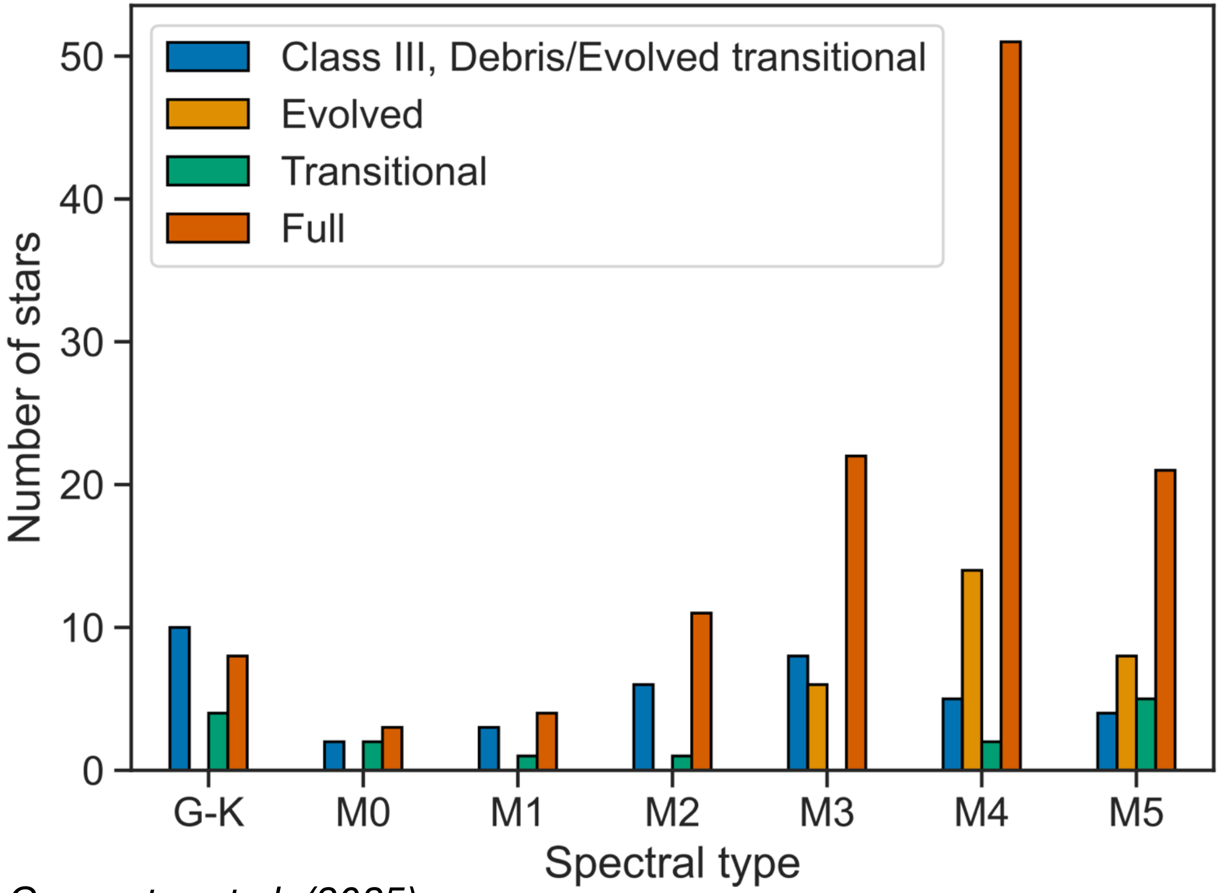
Extracting bulk disk properties from moderate angular resolution ALMA line observations

GAS VISIBILITY FITTING



The 12CO Gas Structures of Protoplanetary Disks in the Upper Scorpius Region

Zallio+26a



Carpenter et al. (2025)

Sample:

- Collection of ALMA cycle 0,2,6 Band 7 continuum+12CO observations at ~0.3’’ in Upper Scorpius

- 202 sources
  - 120 (56%) continuum detections (see *Pinilla+25* for dust analysis)
  - 83 (41%) 12CO detections

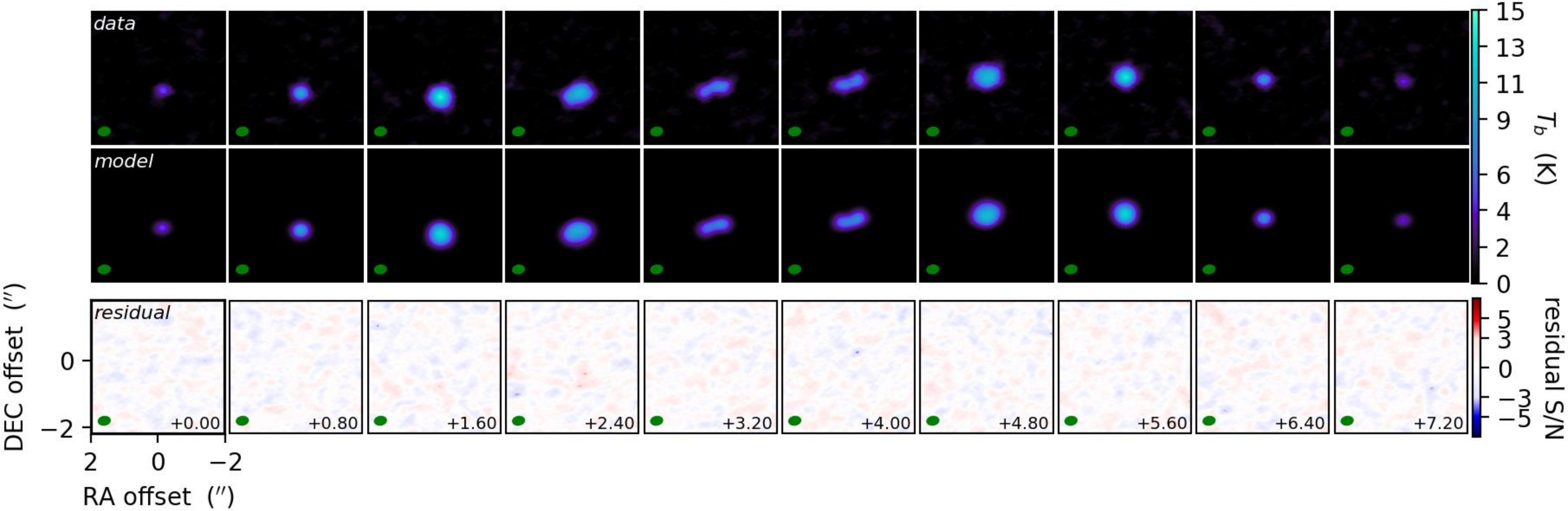
- Upper Sco is old (4-14 Myr) and mildly irradiated (FUV ~ 5-40 G0, *Anania et al., 2025*)

The 12CO Gas Structures of Protoplanetary Disks in the Upper Scorpius Region

Zallio+26a

Upper Scorpius analysis – 37 new disks modeled!

Data from *Carpenter et al. (2025)*



The 12CO Gas Structures of Protoplanetary Disks in the Upper Scorpius Region

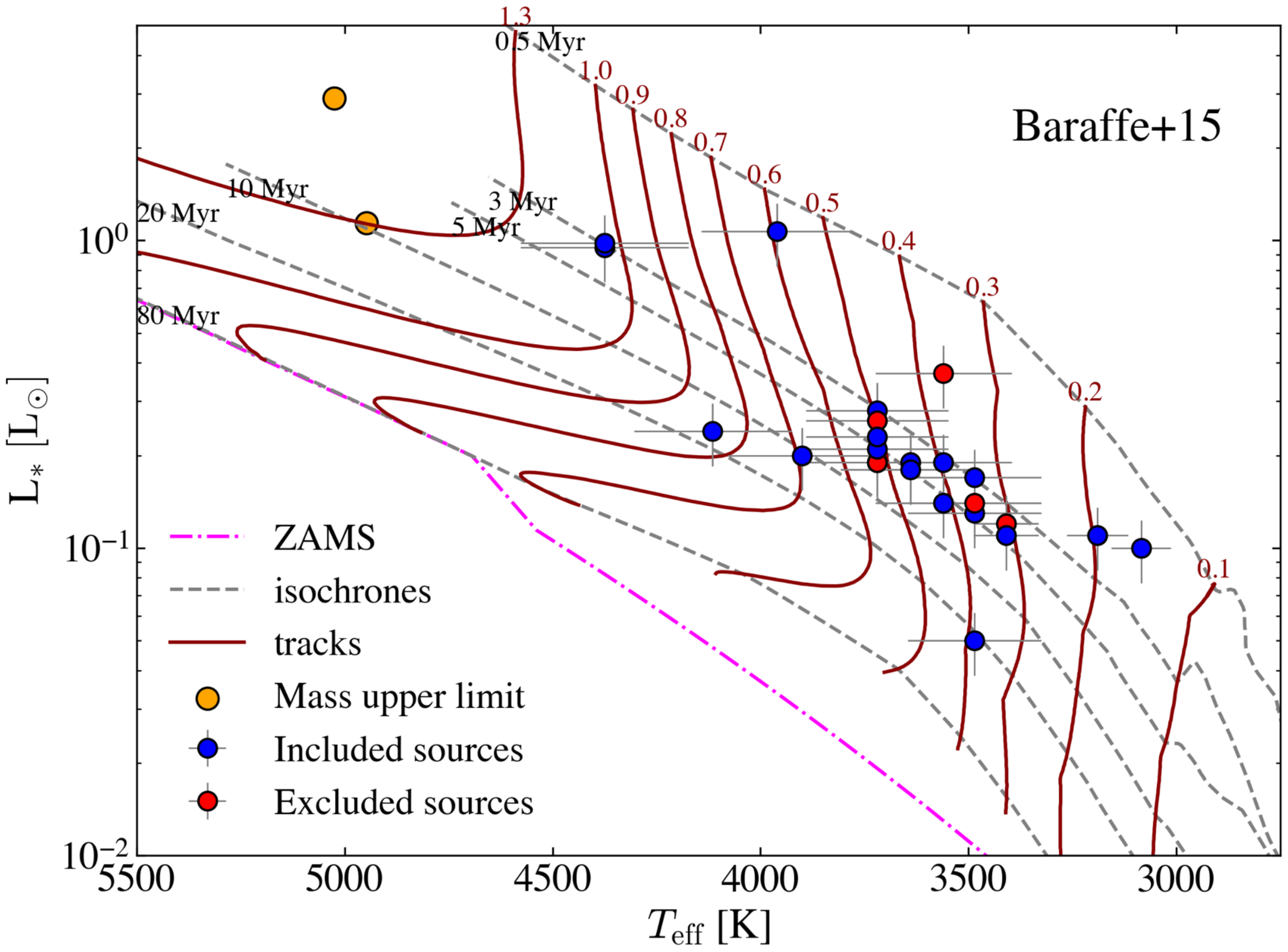
Zallio+26a

One of the most important products:
DISK-BASED DYNAMICAL STELLAR MASSES

Benchmarking pre-main sequence tracks using dynamical stellar masses

Zallio+26b

HR-diagrams to derive stellar masses and ages



4 variables:

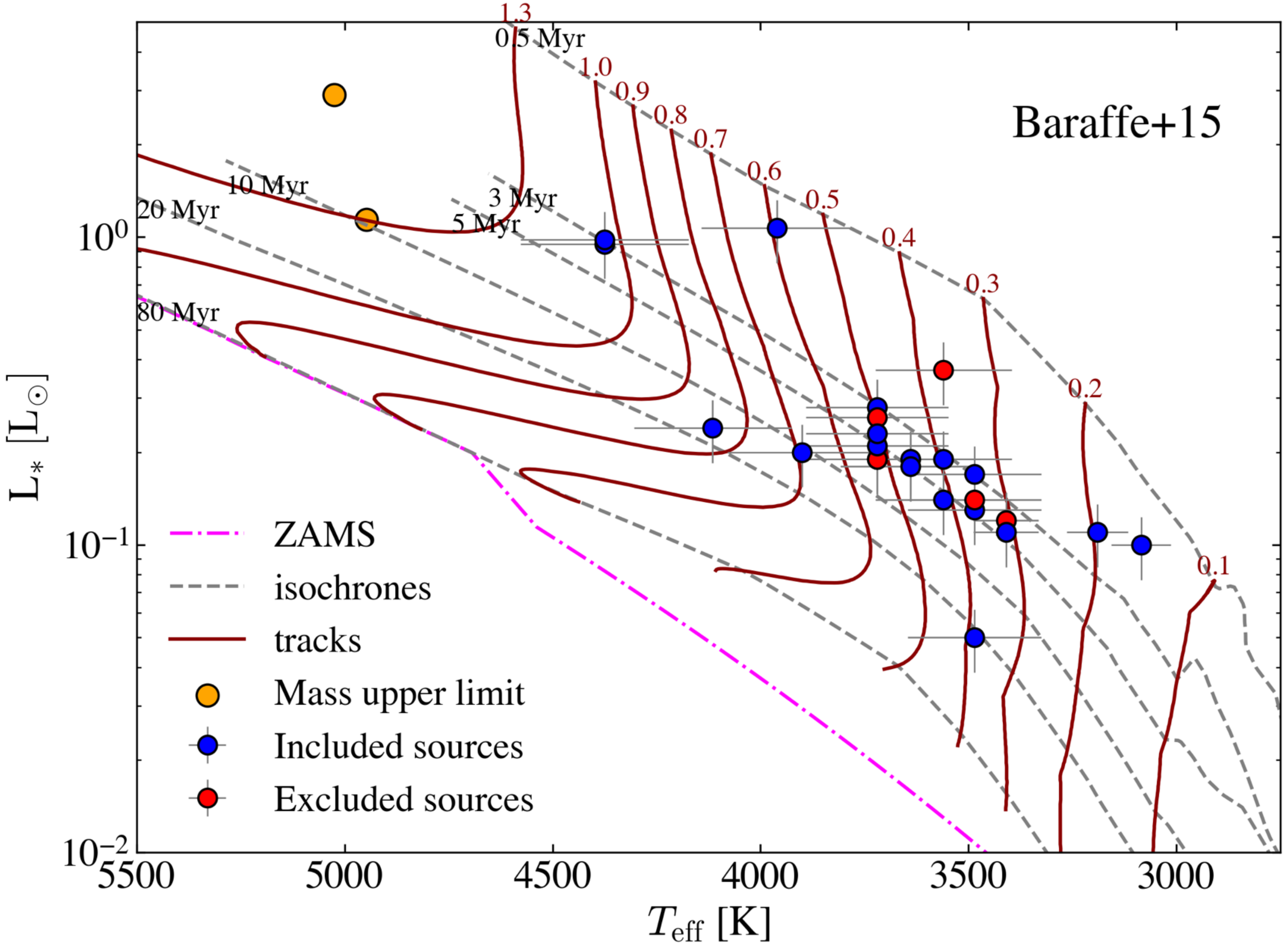
- Stellar luminosity
- Effective temperature

- Stellar mass
- Stellar ages

Benchmarking pre-main sequence tracks using dynamical stellar masses

Zallio+26b

HR-diagrams to derive stellar masses and ages



4 variables:

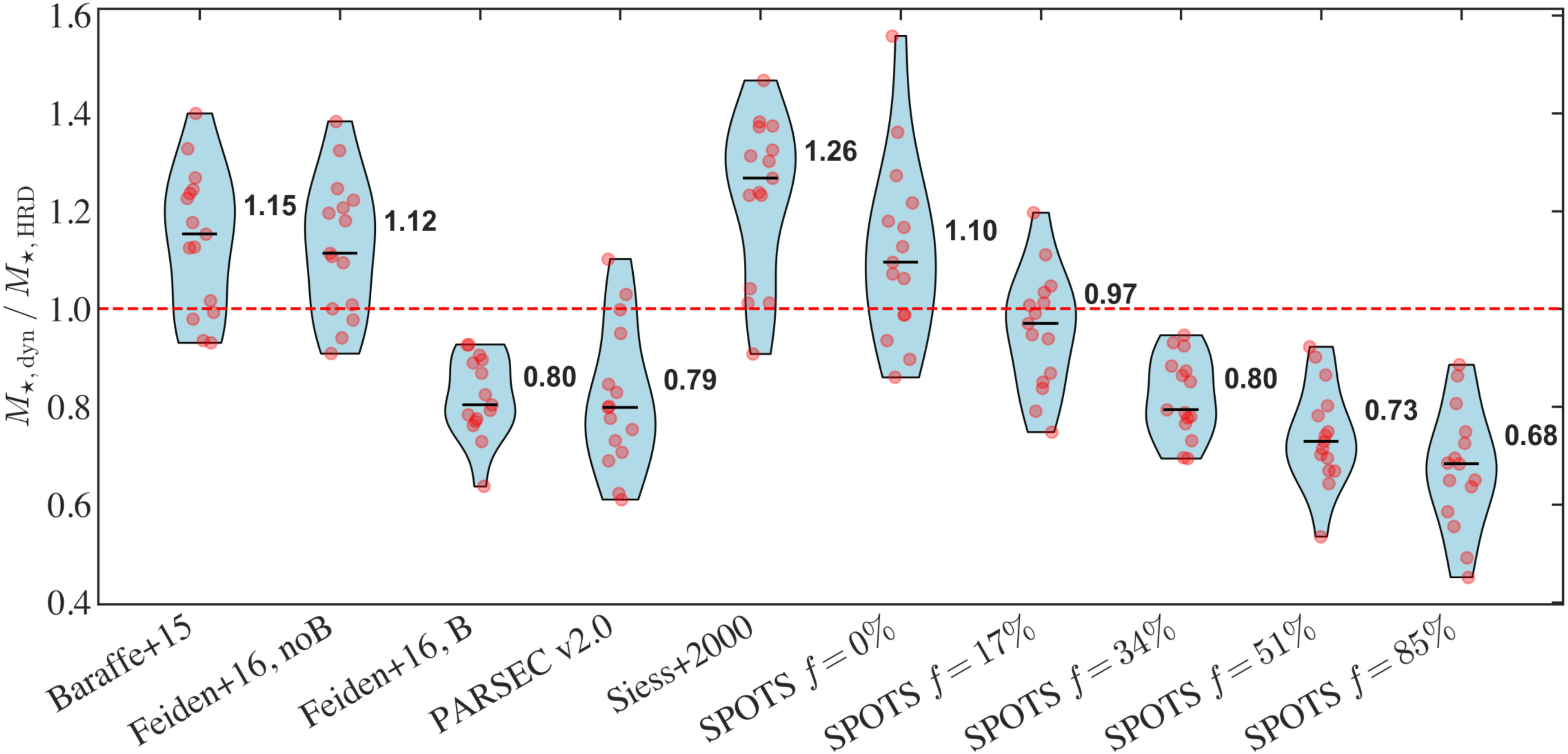
- Stellar luminosity
- Effective temperature

- Stellar mass
- Stellar ages

Constraints on these variables are highly uncertain and **model dependent**!

Benchmarking pre-main sequence tracks using dynamical stellar masses
Zallio+26b

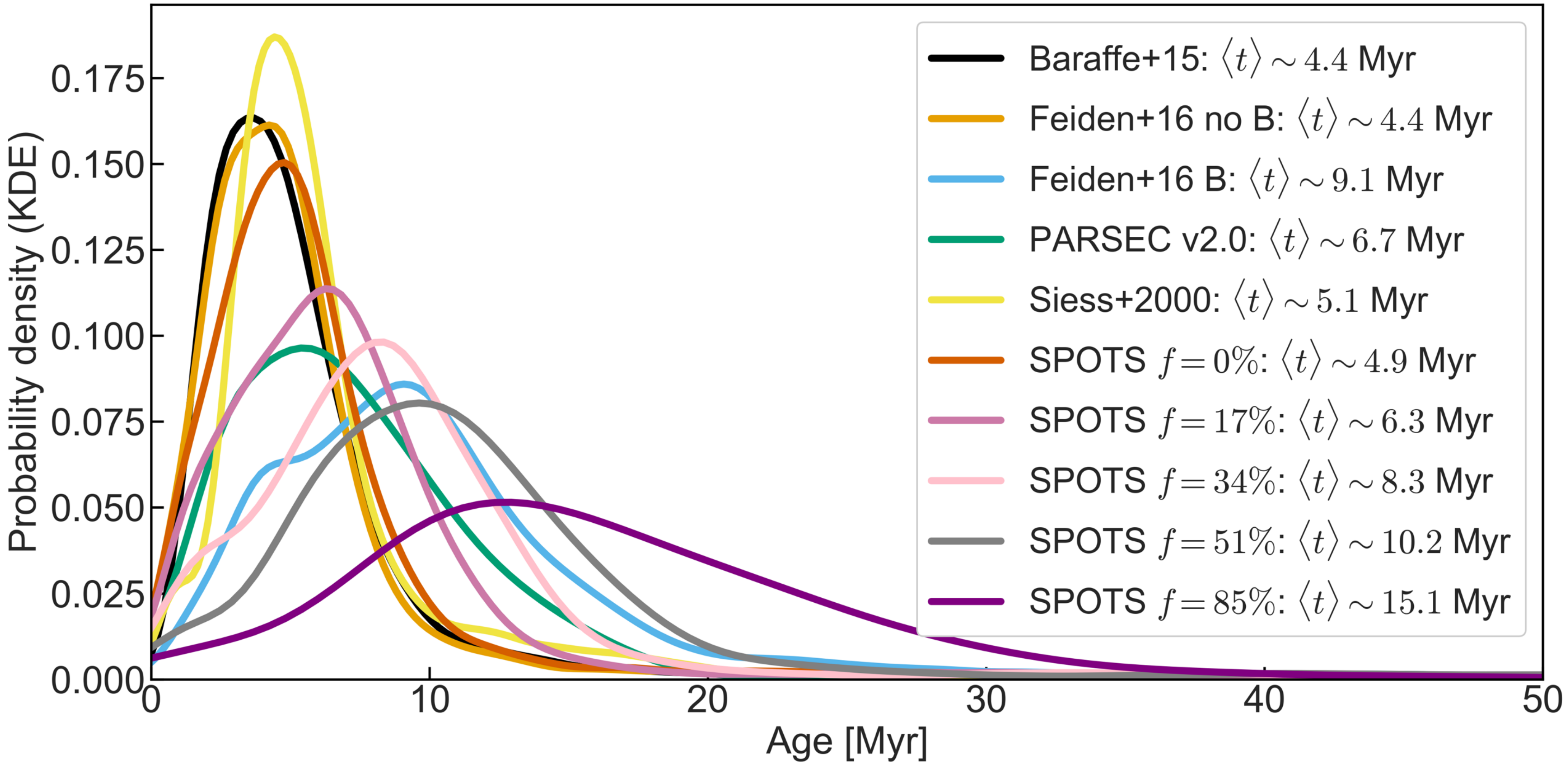
Disk-based Stellar Masses -> benchmarking PMS tracks



Benchmarking pre-main sequence tracks using dynamical stellar masses

Zallio+26b

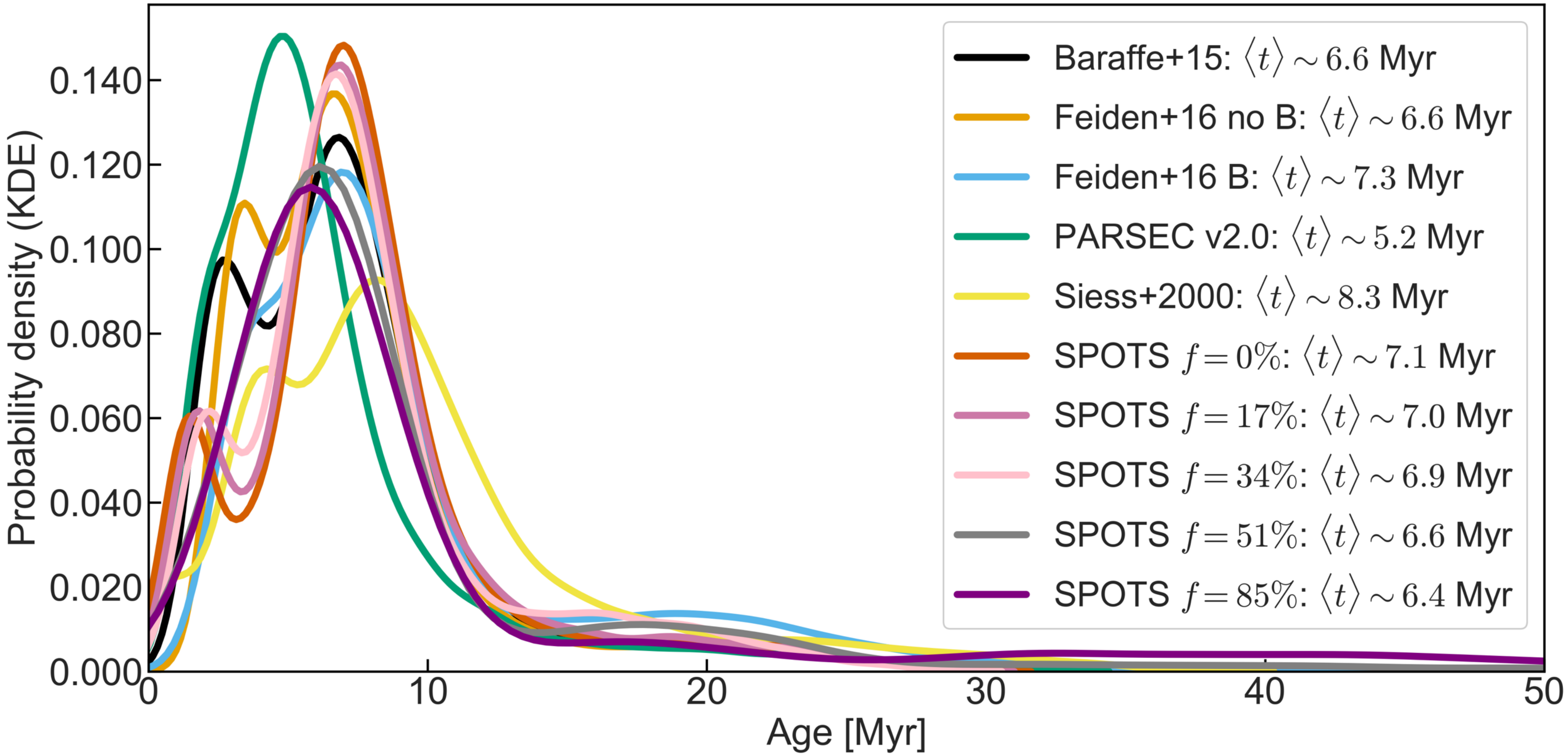
Keplerian Stellar Masses -> Precise stellar ages



Benchmarking pre-main sequence tracks using dynamical stellar masses

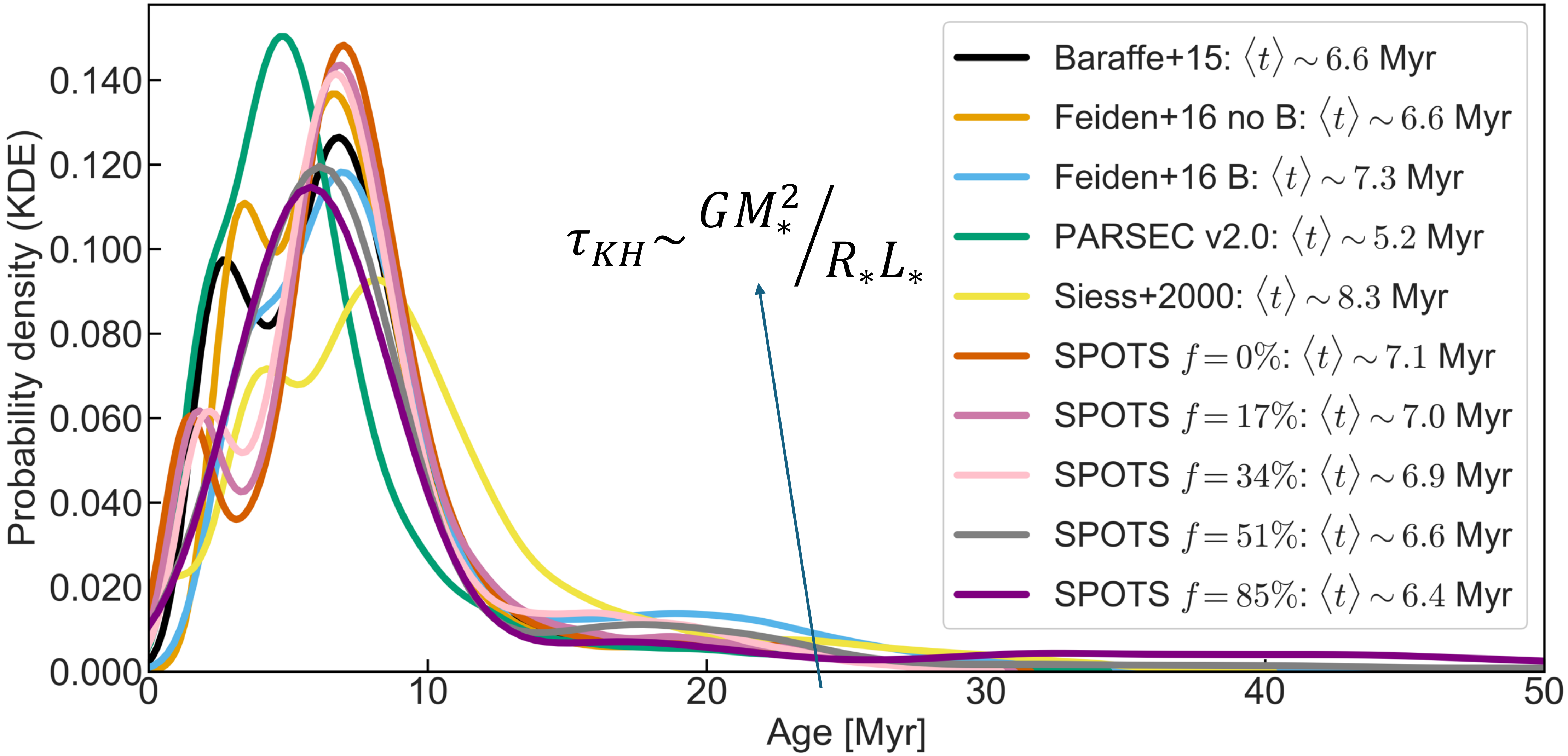
Zallio+26b

Keplerian Stellar Masses -> Precise stellar ages

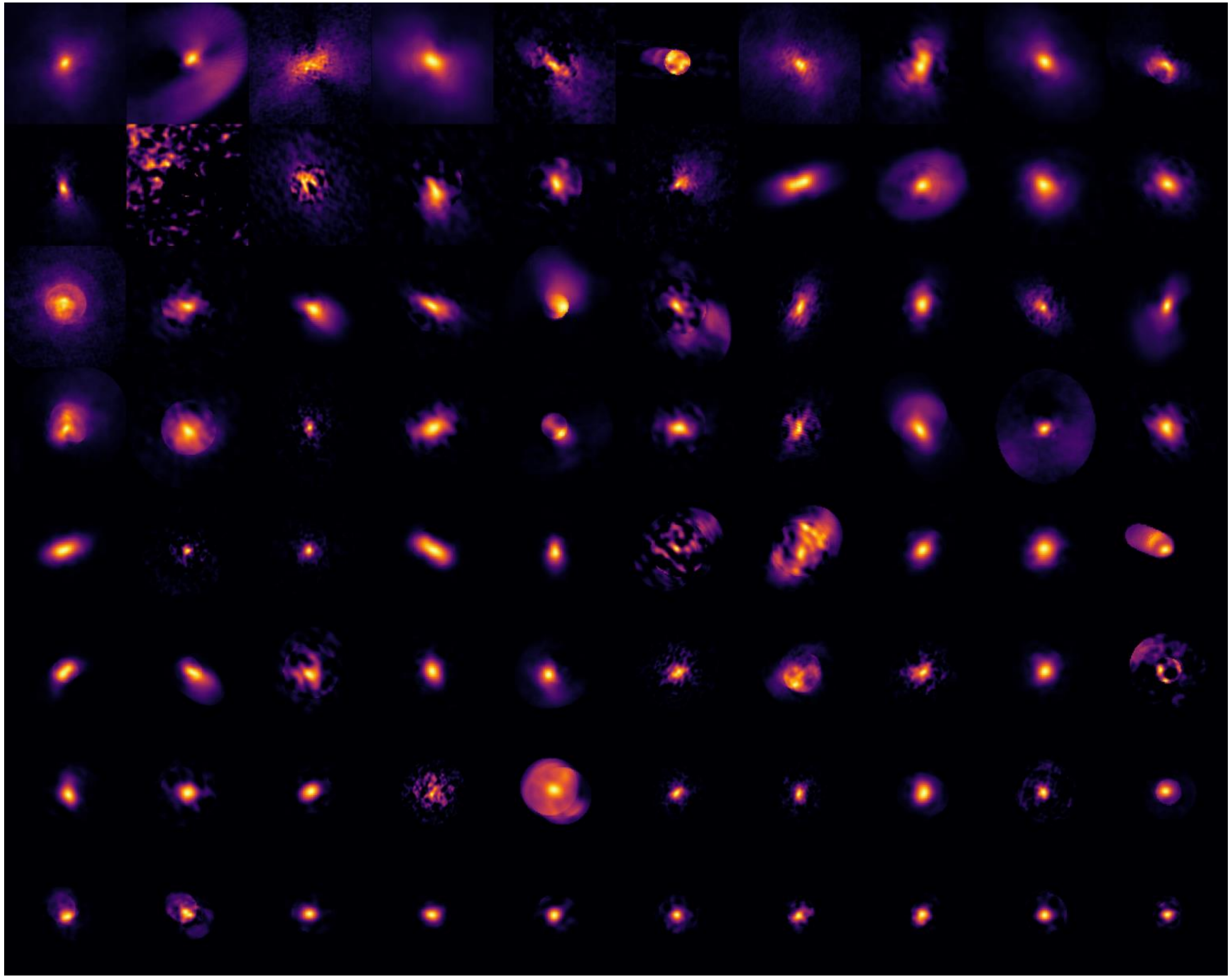


Benchmarking pre-main sequence tracks using dynamical stellar masses
Zallio+26b

Keplerian Stellar Masses -> Precise stellar ages



Moving to novel data.
The ALMA Disk-Exoplanet C/Onnection (PI: L. I. Cleeves)



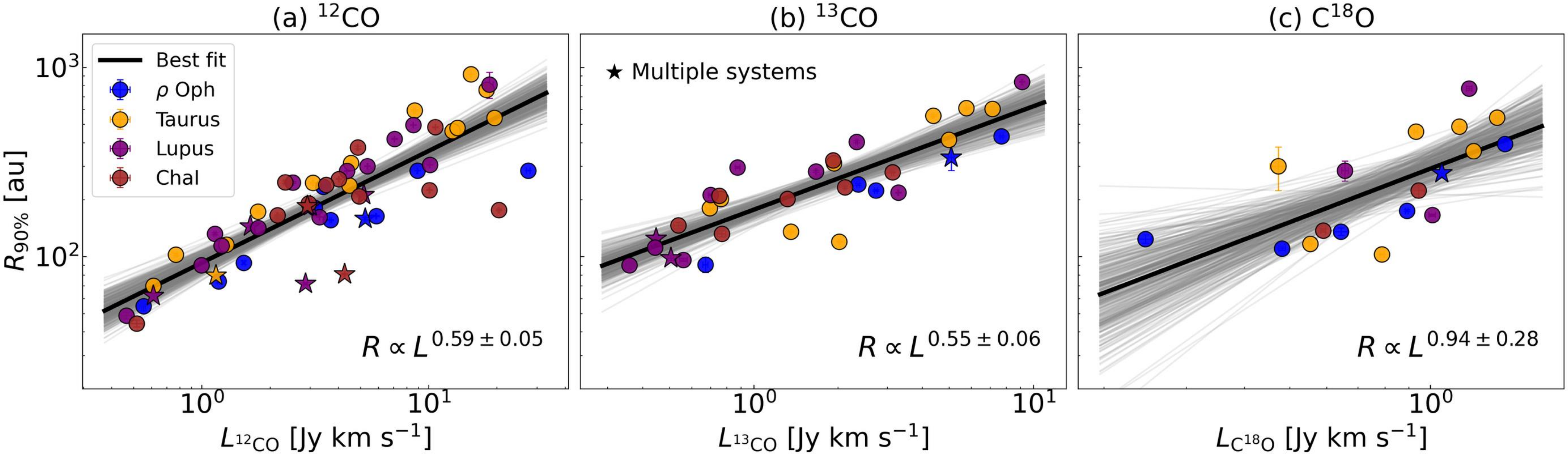
- **80 disks** in 12 molecular lines, divided in Rho Ophiucus, Taurus, Lupus and Chamaeleon I
- **0.2** $M_{\odot}$ **<** $\boldsymbol{M_{\star}}$ **< 1.5** $M_{\odot}$, GKM stars -> ‘typical disks’
- Half of the sample has PPVII $R_{dust} \leq 40$ au and half with $R_{dust} > 40$ au
- I analyzed 12CO, 13CO and C18O

Zallio et al. ***(in prep)***

The ALMA Disk-Exoplanet C/Onnection (PI: L. I. Cleeves)

Zallio et al. *(in prep.)*

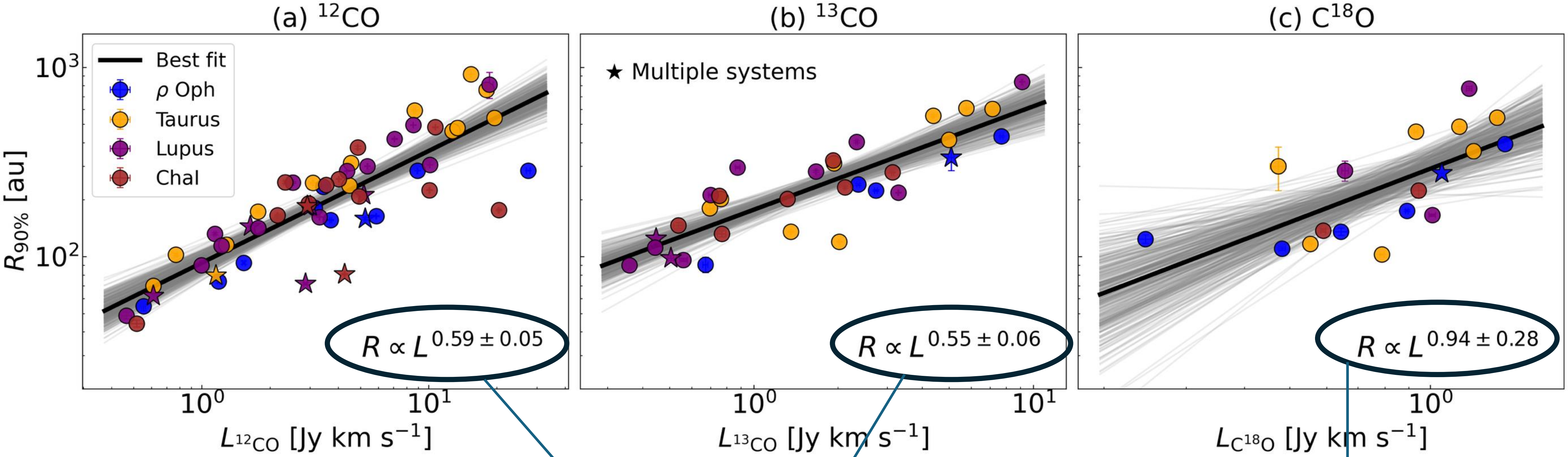
Radius – luminosity plane



The ALMA Disk-Exoplanet C/Onnection (PI: L. I. Cleeves)

Zallio et al. *(in prep.)*

Radius – luminosity plane



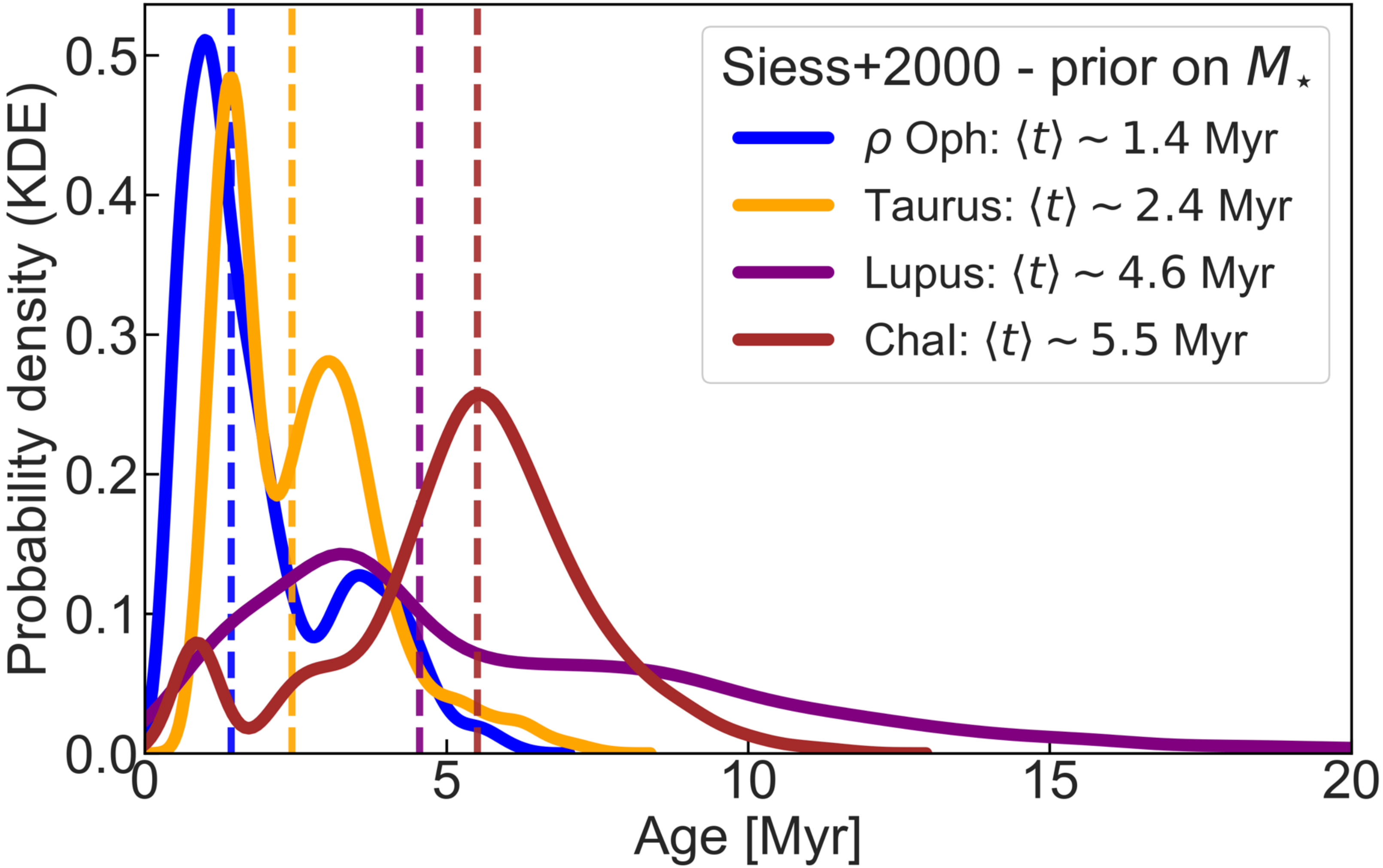
Optically **thick** emission

Optically **thinner** emission

The ALMA Disk-Exoplanet C/Onnection (PI: L. I. Cleeves)

Zallio et al. *(in prep.)*

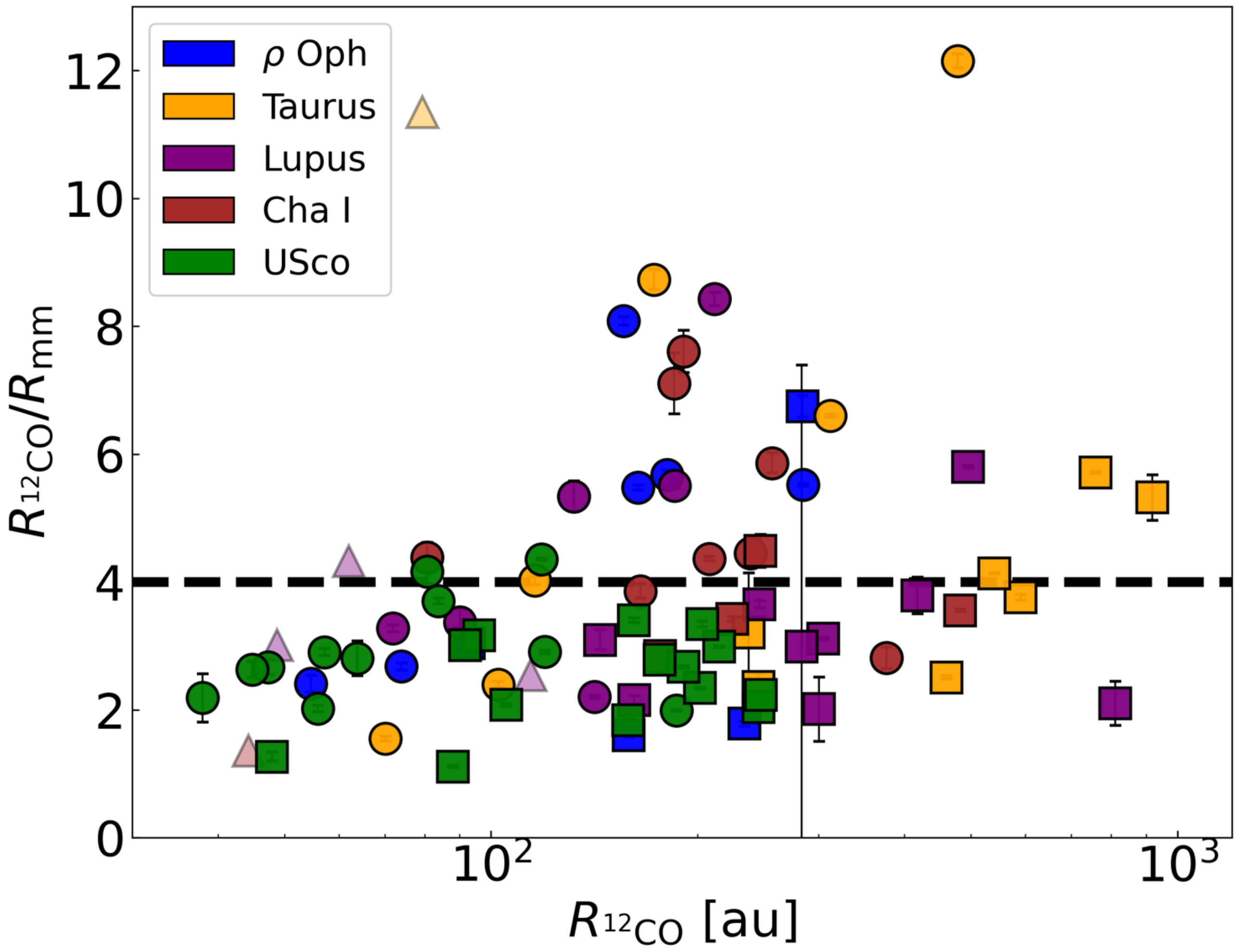
Now, the ages.



The ALMA Disk-Exoplanet C/Onnection (PI: L. I. Cleeves)

Zallio et al. *(in prep.)*

Gas-to-dust size ratios



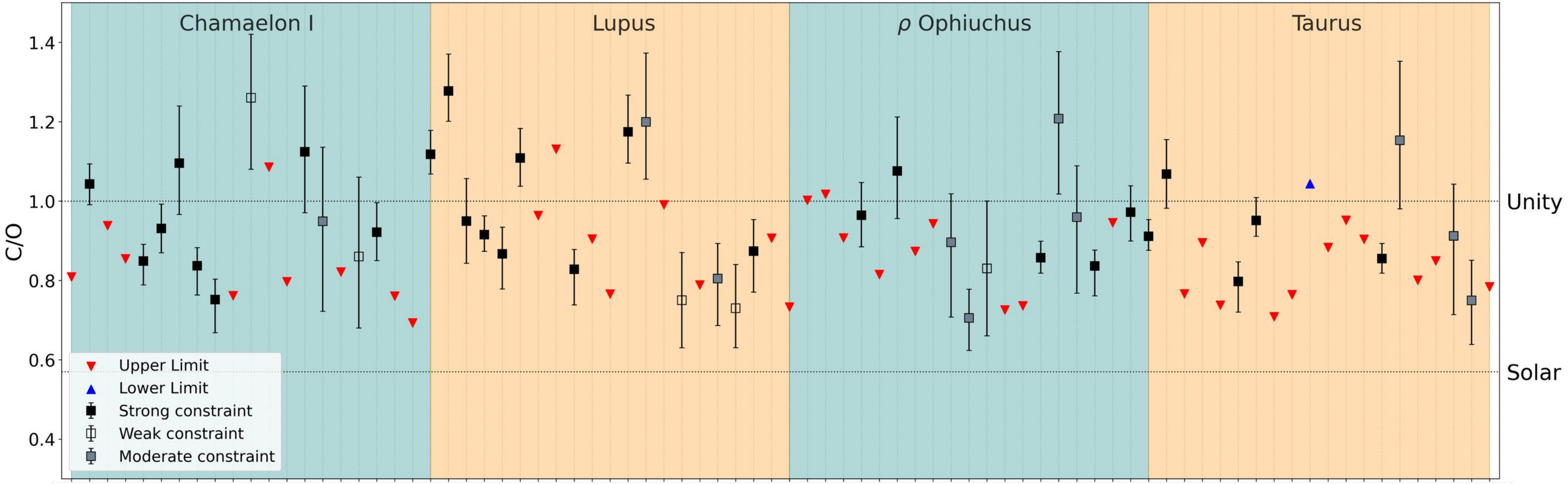
- $^{R_{12CO}}/_{R_{mm}} \geq 4$ in ~42% of the DEC/O sample
- $^{R_{12CO}}/_{R_{mm}} \geq 4$ in ~13% of the **dust-substructured** DEC/O sample

Are dust substructures slowing radial drift?

Why does Upper Scorpius have lower values?

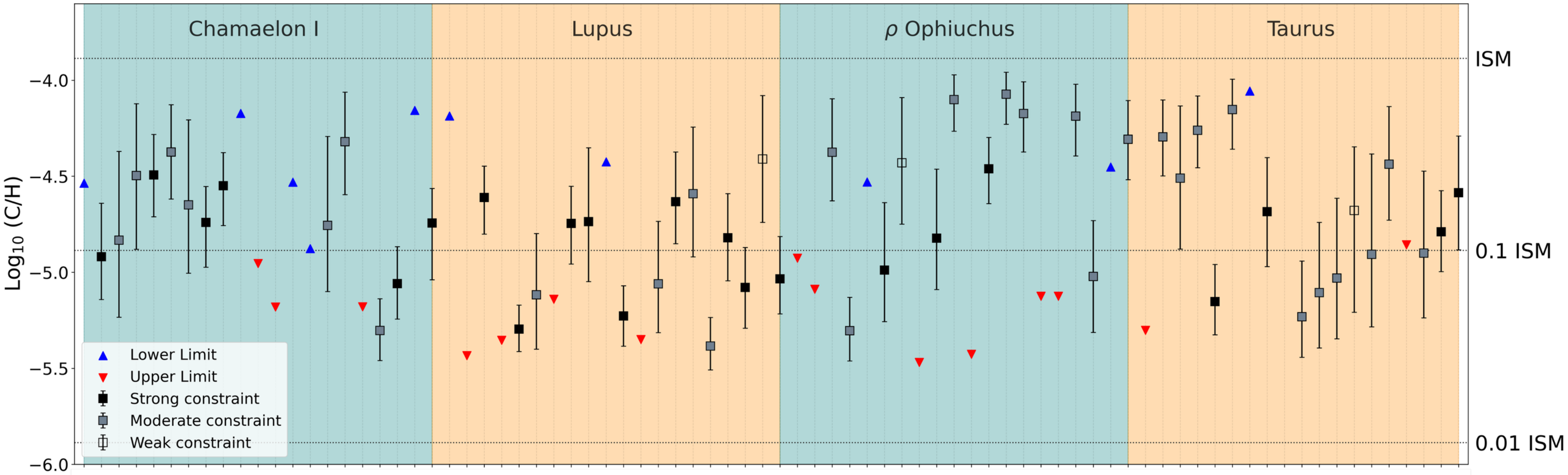
The ALMA Disk-Exoplanet C/Onnection (PI: L. I. Cleeves)

Diop et al. *(in prep.)*



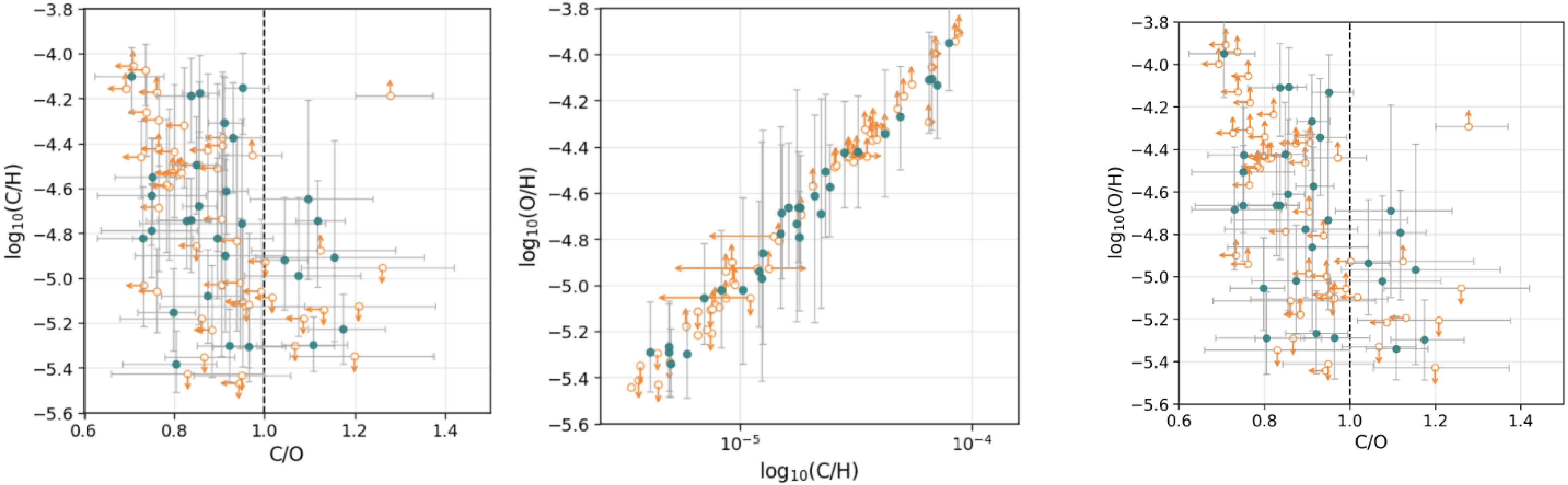
The ALMA Disk-Exoplanet C/Onnection (PI: L. I. Cleeves)

Diop et al. *(in prep.)*



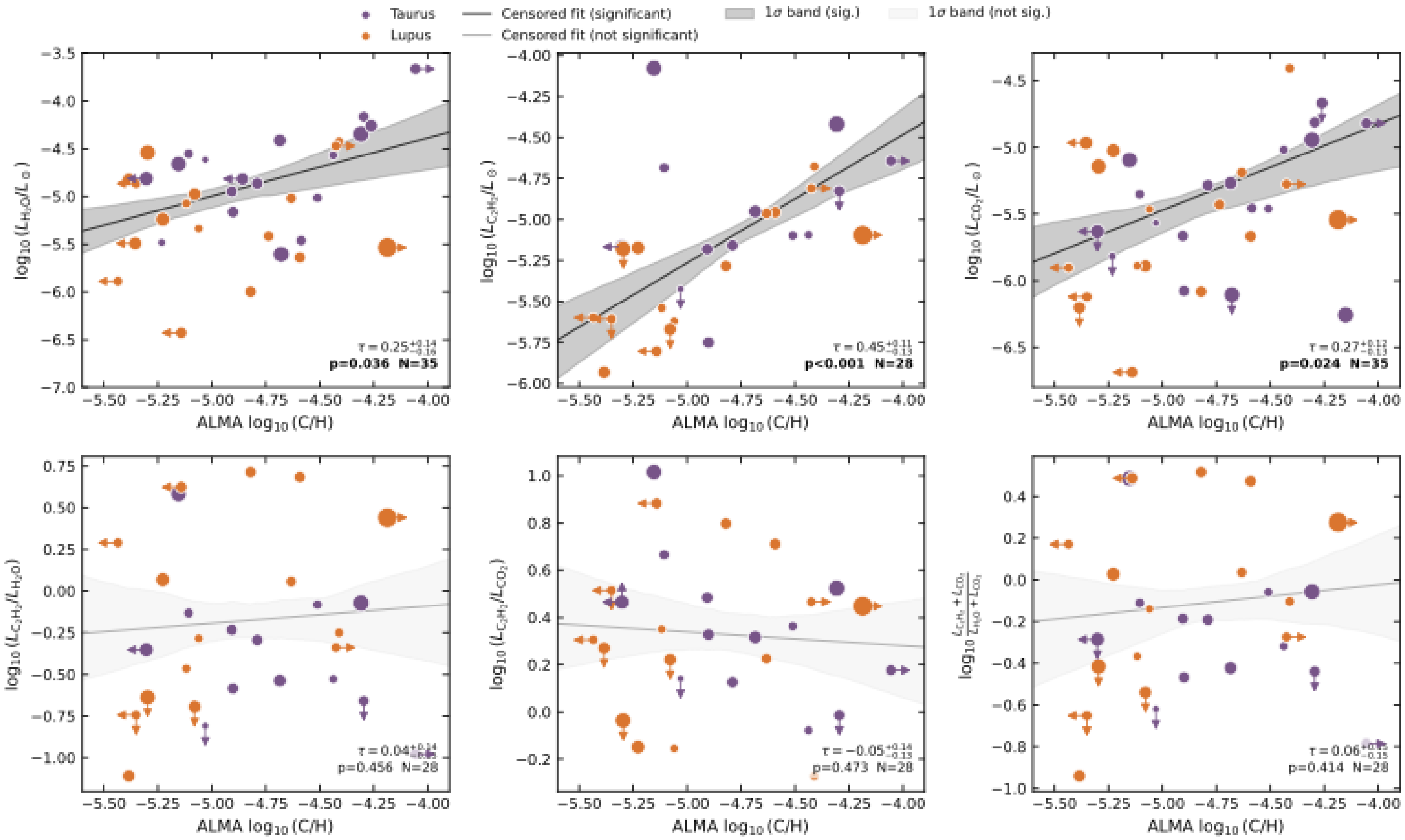
The ALMA Disk-Exoplanet C/Onnection (PI: L. I. Cleeves)

Diop et al. *(in prep.)*



The ALMA Disk-Exoplanet C/Onnection (PI: L. I. Cleeves)

Colmenares et al. *(in prep.)* – *synergy with JWST*



Extracting bulk disk properties from moderate angular resolution ALMA line observations

Conclusions

1. **Visibility fitting rocks □ □ .**
   - Robust parametric inference.
   - Avoids *tclean*.
   - Is the most complete way to analyze spectral lines data.

2. **37 new Upper Scorpius 12CO radii, aspect ratios, brightness temp profiles published** *(Zallio+26a)*

3. **Benchmarking pms tracks** *(Zallio+26b)*
   - Beware the power of the Kelvin-Helmholtz timescale…

4. **`csalt` will be submitted** *(Andrews+, in prep., including **L. Zallio**)*

5. **DEC/O Large Program results incoming…** *(Zallio+, in prep.), etc.!*