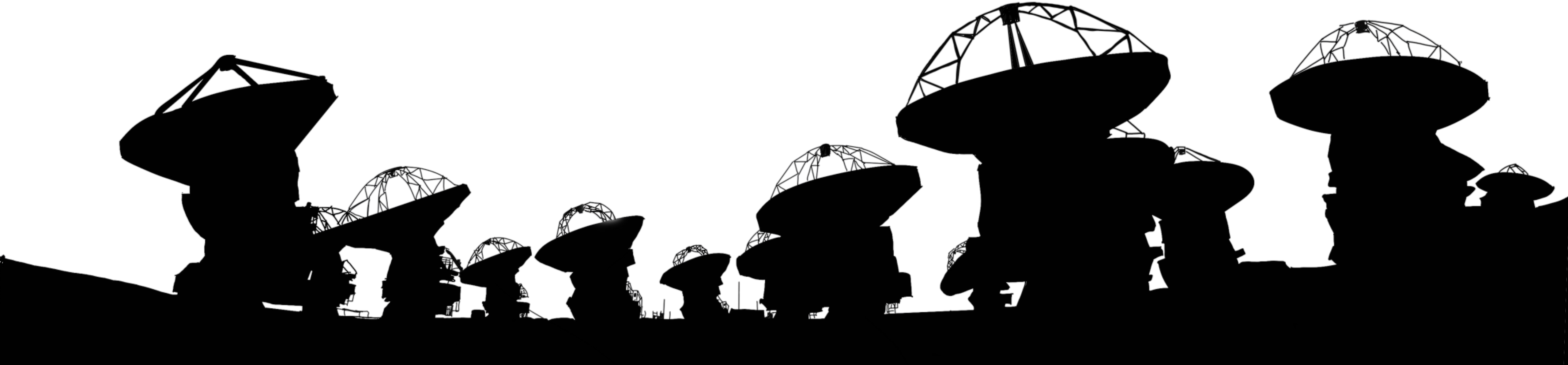
The Disk Exoplanet C/Onnection

Anna Miotello
ARC Astronomer at ESO

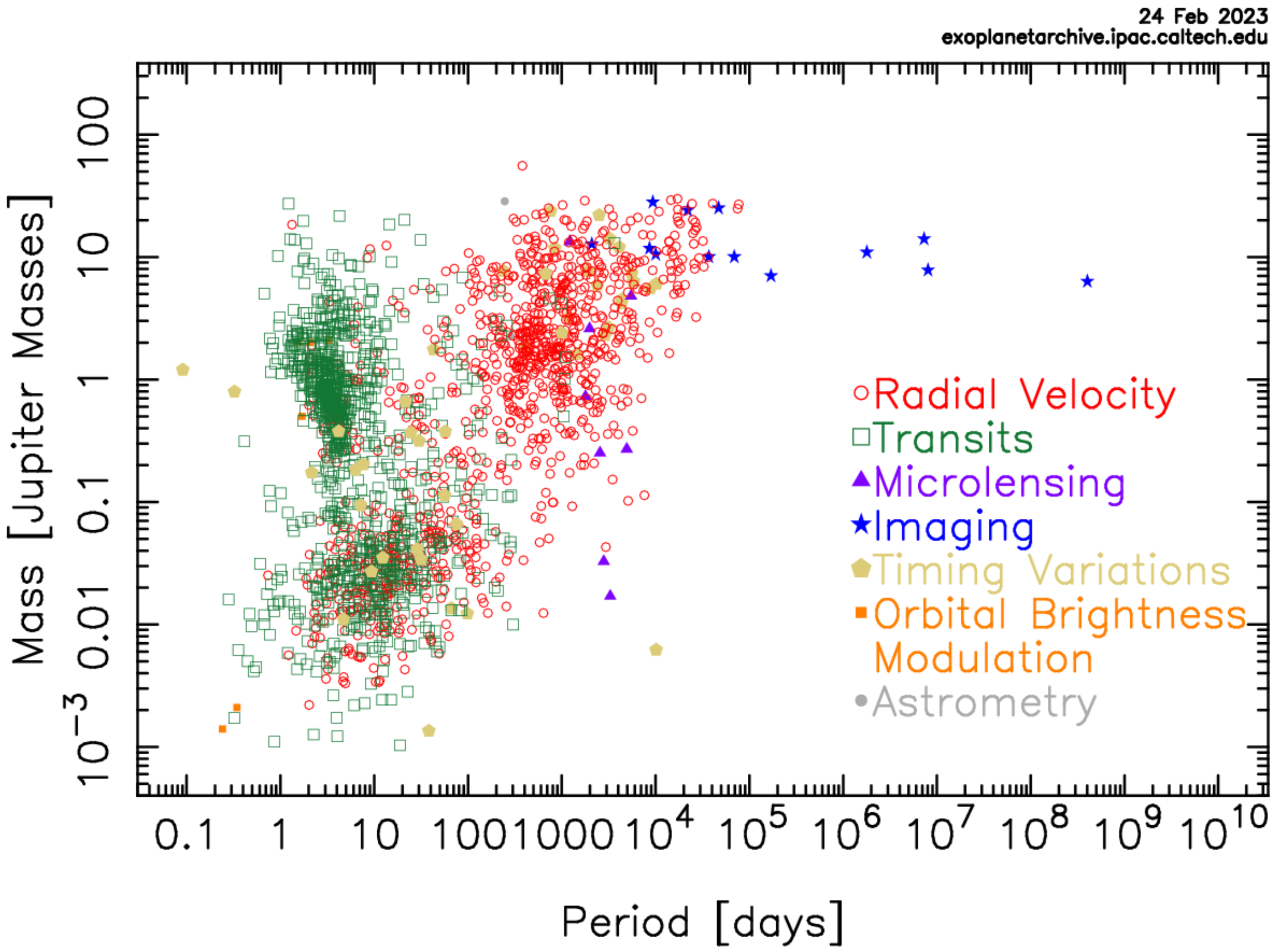
Collaborators: Ilse Cleeves, Yuri Aikawa, Dana Anderson, Viviana Guzman, **Teresa Paneque Carreno, Aashish Gupta,** Giovanni Rosotti, Carlo F. Manara, Francesco Zagaria, Stefano Facchini, Jonathan P. Williams, Ewine F. van Dishoeck, Iinga Kamp, Til Birnstiel, Akimasa Kataoka, & the DECO collaboration



The exoplanet population

>5000

confirmed exoplanets
in the past two decades



Credit: https://exoplanetarchive.ipac.caltech.edu/exoplanetplots/

The exoplanet population

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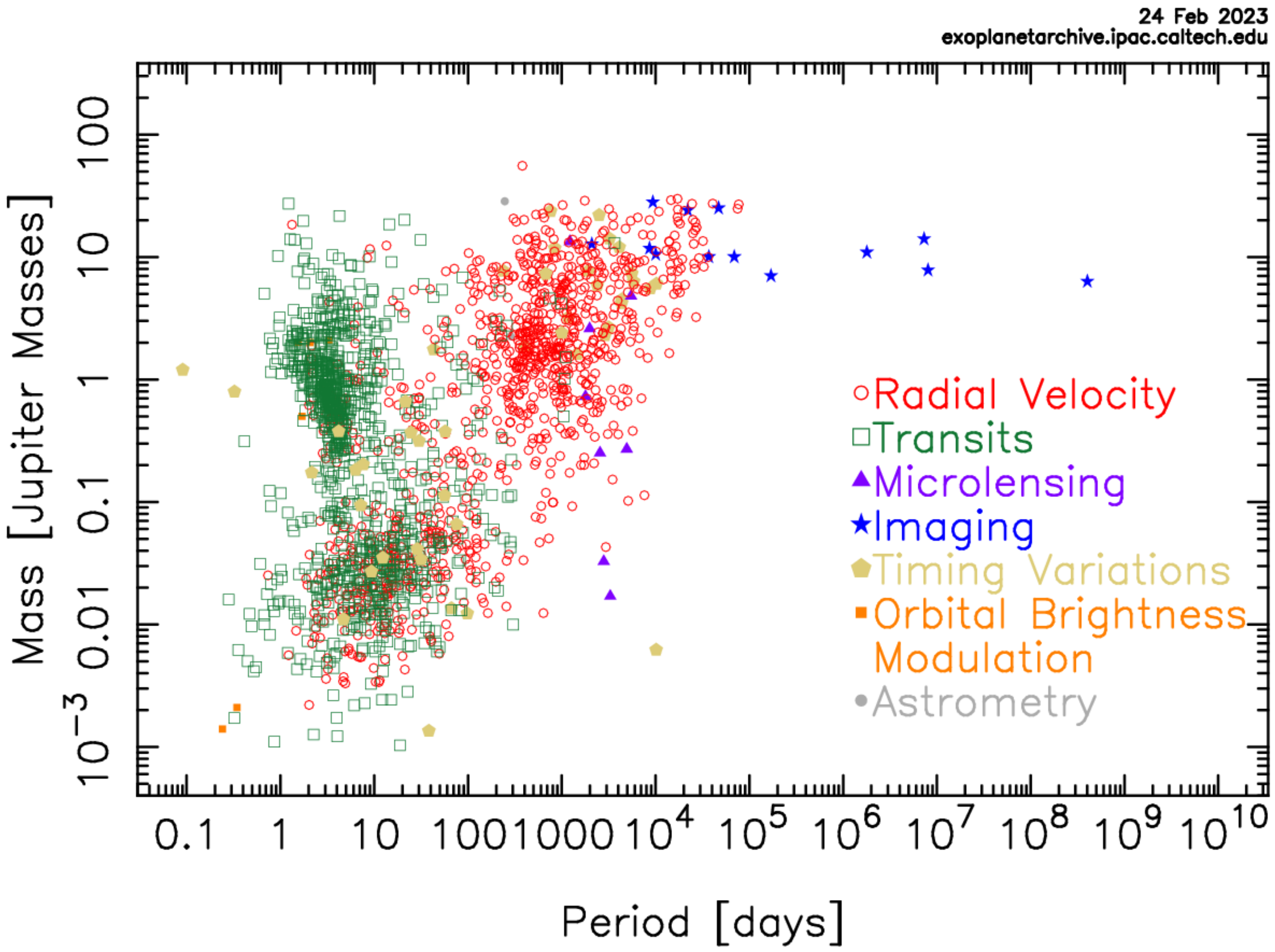
chemical characterization

Is the next frontier

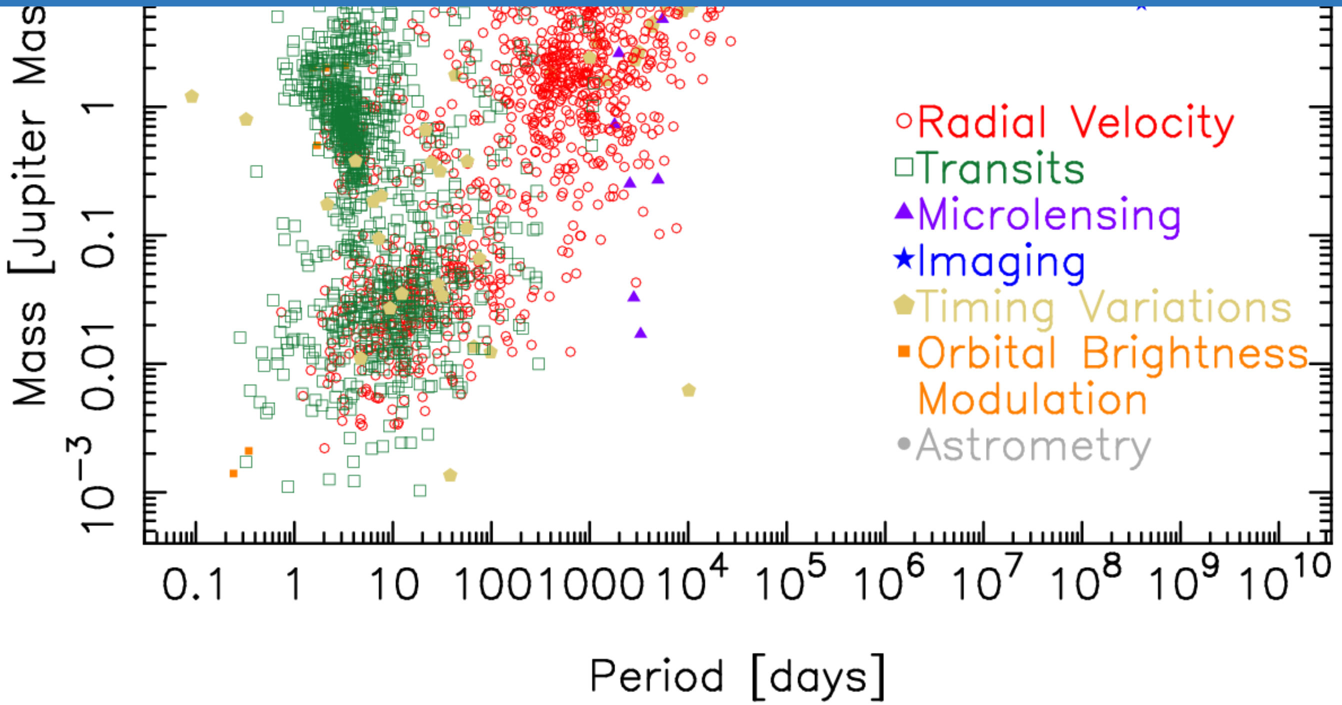
- ~ 19 giant planets with measured atmospheric H_2O abundances
  (Kreidberg et al. 2018; Madhusudhan 2019; Brande et al. 2022)
- 14 giant planets with measured C/O ratios
  (Bonnefoy et al. 2016; Brewer et al. 2017).



Credit: https://exoplanetarchive.ipac.caltech.edu/exoplanetplots/

The exoplanet population

JWST observations targeting an additional 70+ planets' atmospheres in the first cycle, and more anticipated with the launch of missions such as **Ariel**.



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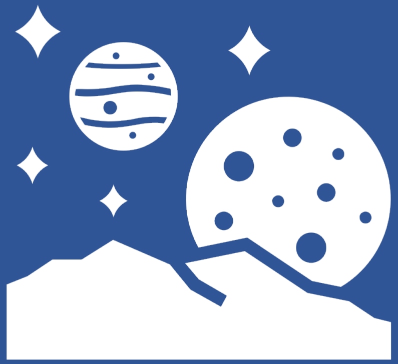
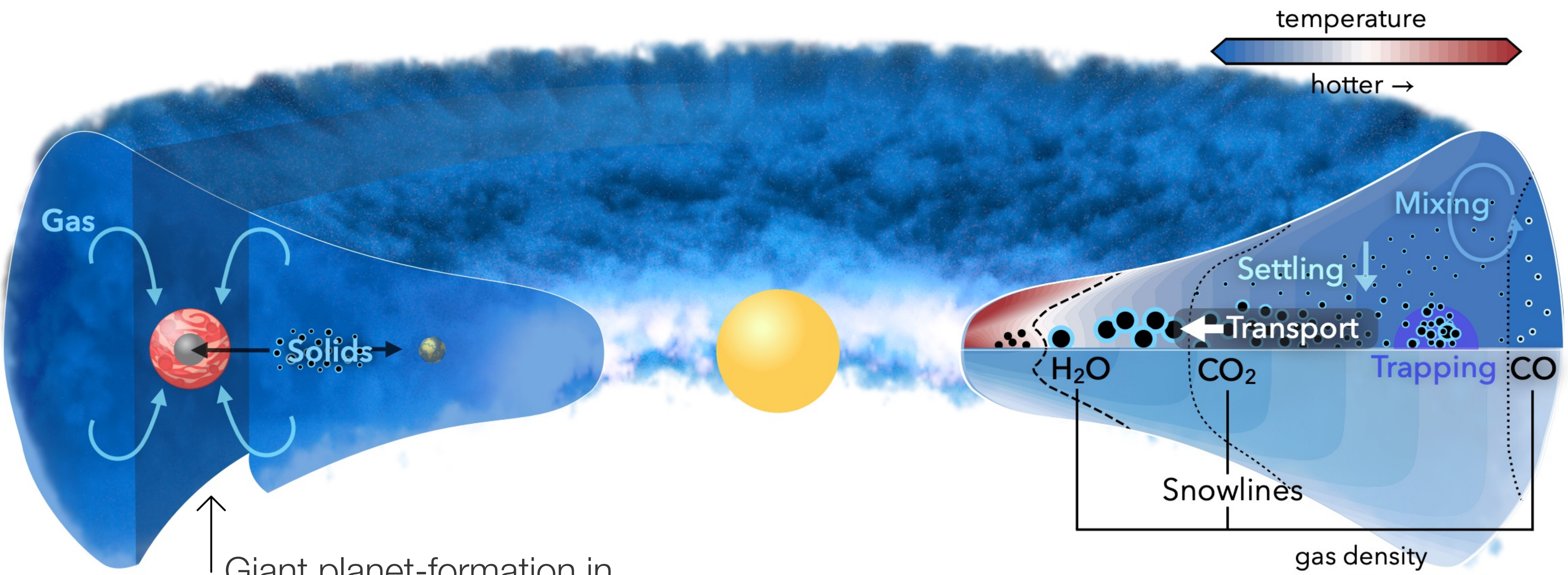


The origin of exoplanets

And of their diversity

The origin of exoplanets

The chemical link between disks and exoplanets

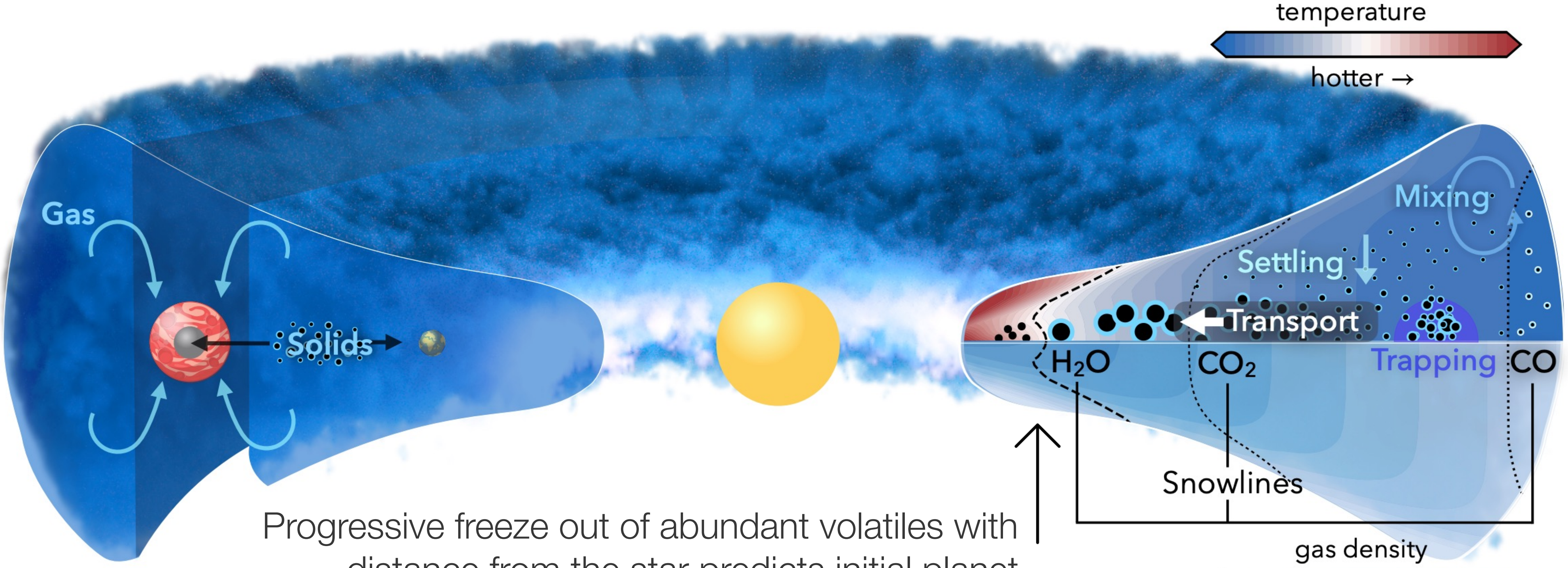


Giant planet-formation in the core accretion scenario (Lissauer 1993)

Edited from Miotello et al. (2022); Credit: T. Birnstiel

The origin of exoplanets

The chemical link between disks and exoplanets

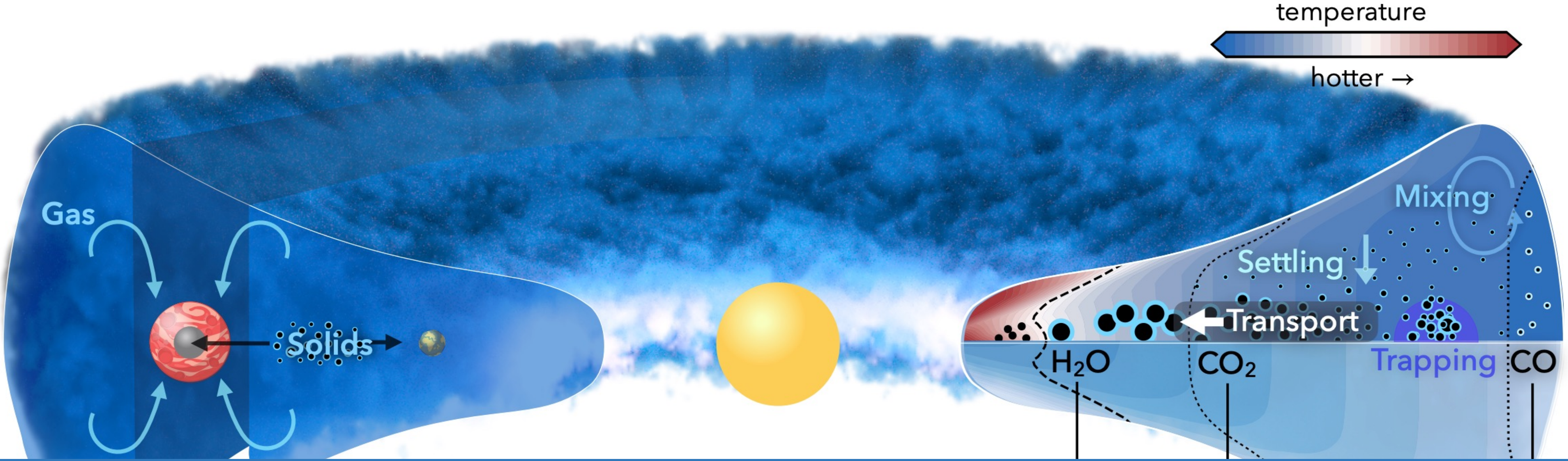


Progressive freeze out of abundant volatiles with distance from the star predicts initial planet compositions in gas and solid-phase C/O, C/H, O/H
(Oberg et al. 2011

Edited from Miotello et al. (2022); Credit: T. Birnstiel

The origin of exoplanets

The chemical link between disks and exoplanets



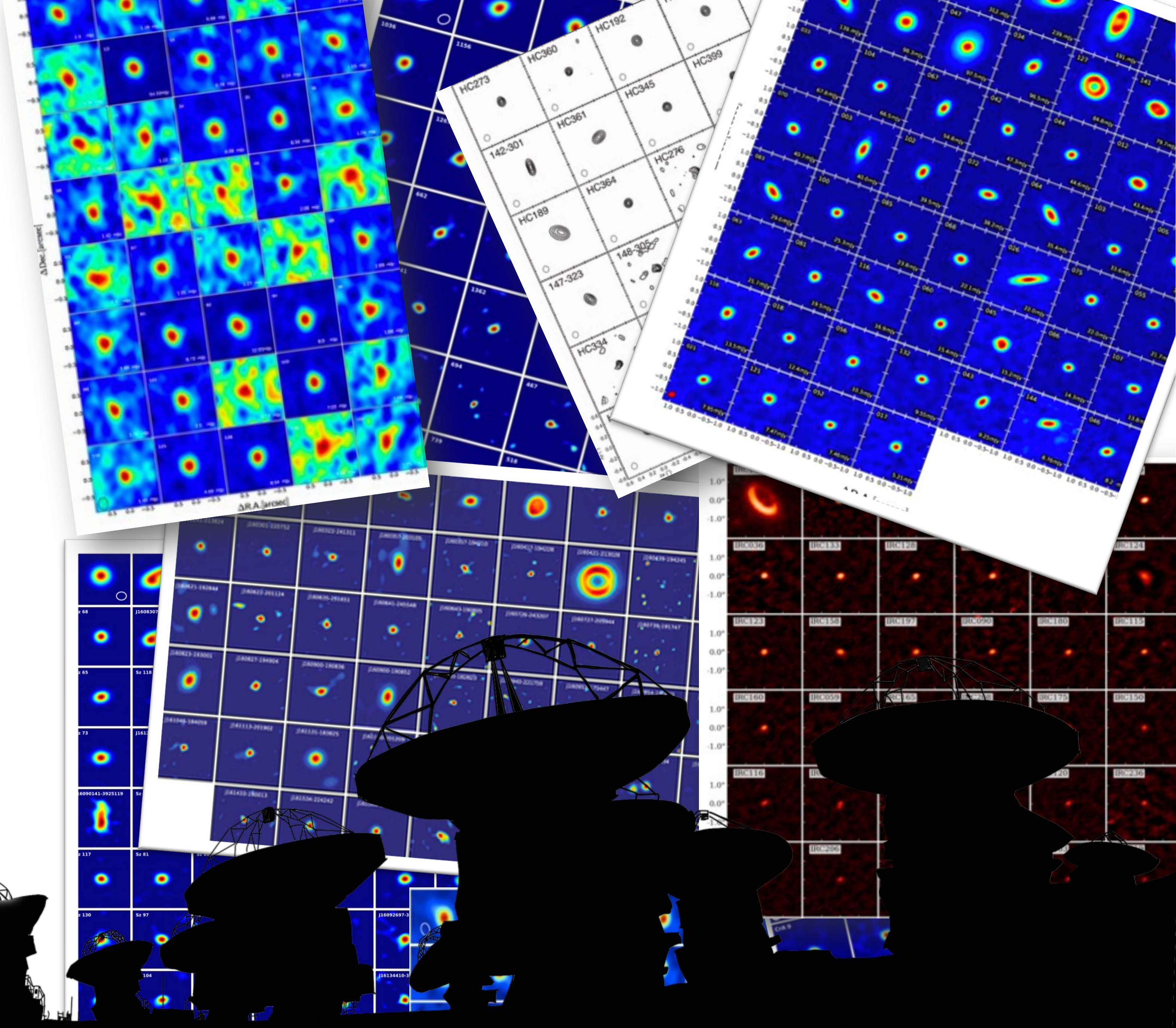
et al. (2022); Credit: T. Birnstiel
Ed

Constraining abundance ratios in disks would be invaluable for understanding how planets form more generally and why there are a variety of planetary system architectures, including many that look nothing like our own

Disk surveys

Mostly shallow and only able to constrain dust properties of disk population

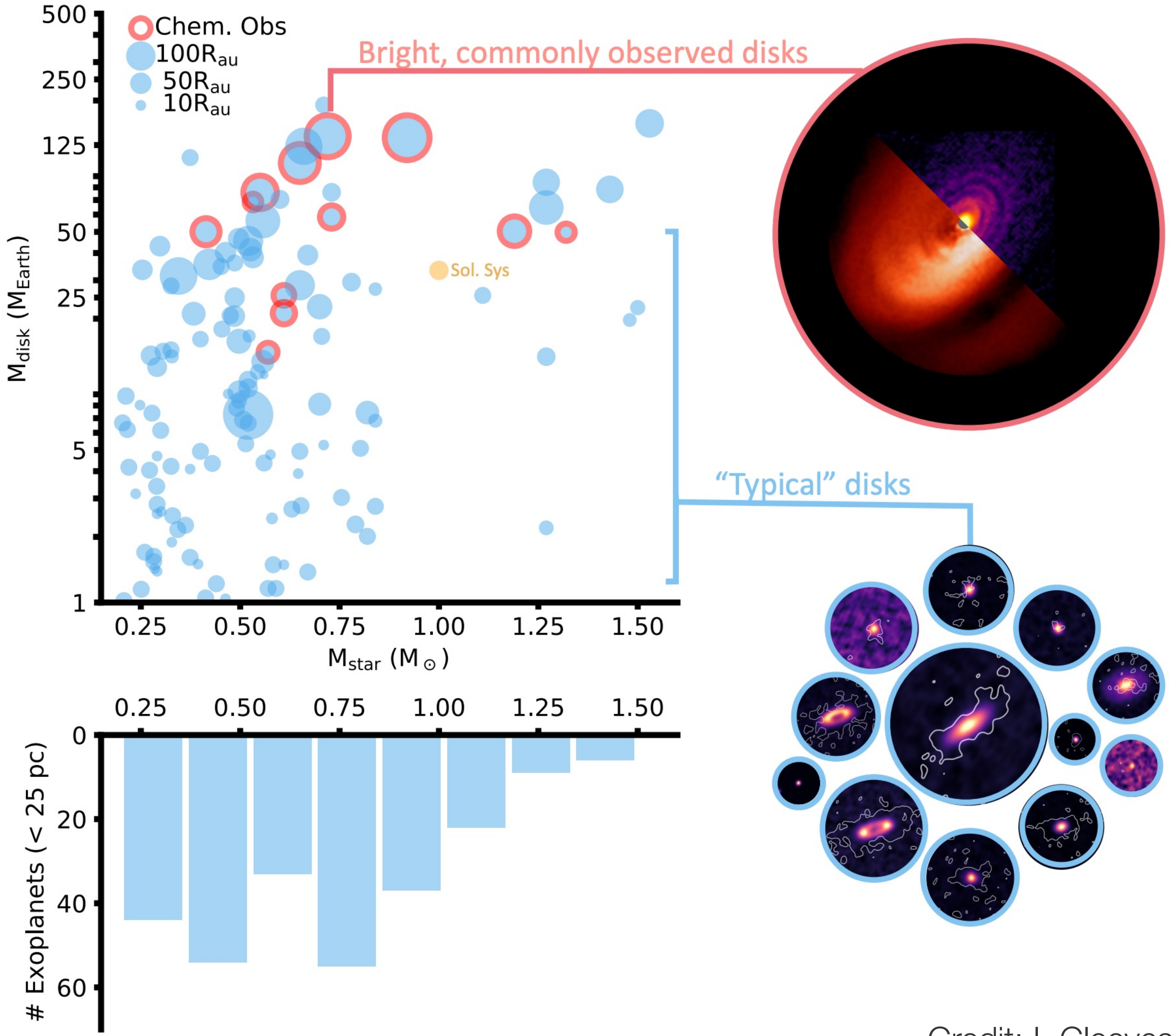
Manara et al. (2022) and references therein



The Atacama Large Millimeter/submillimeter Array (ALMA)

Disk surveys

Mostly shallow and not covering the bulk disk population



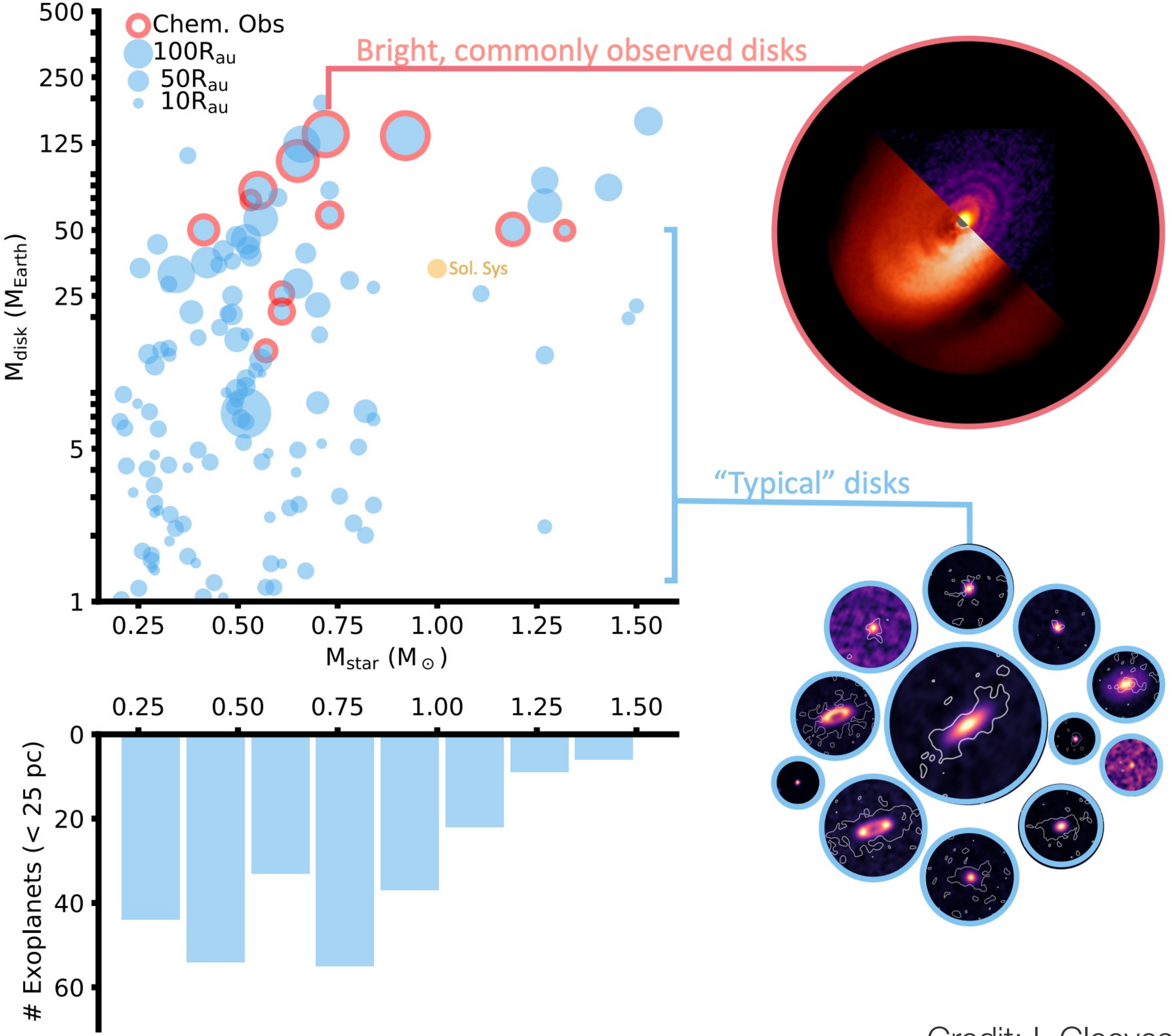
Credit: I. Cleeves

ALMA Large Program

DECO
(Disk Exoplanet C/Onnection)
Cycle 9

PIs: I. Cleeves, A. Miotello, D. Anderson, Y. Aikawa, V. Guzman.

- 80 disks around low mass stars (GKM-type; 0.2-1.5 M_{sun})
- moderate resolution observations of molecules whose abundances track gas-phase C/O and metallicity (C/H and O/H)

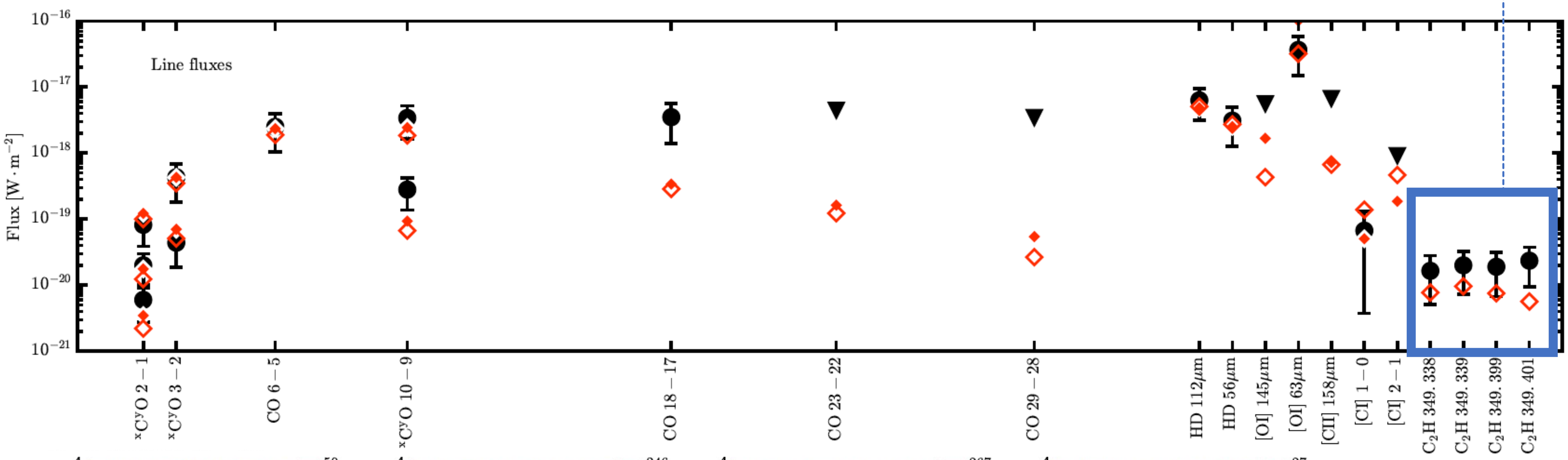


Credit: I. Cleeves

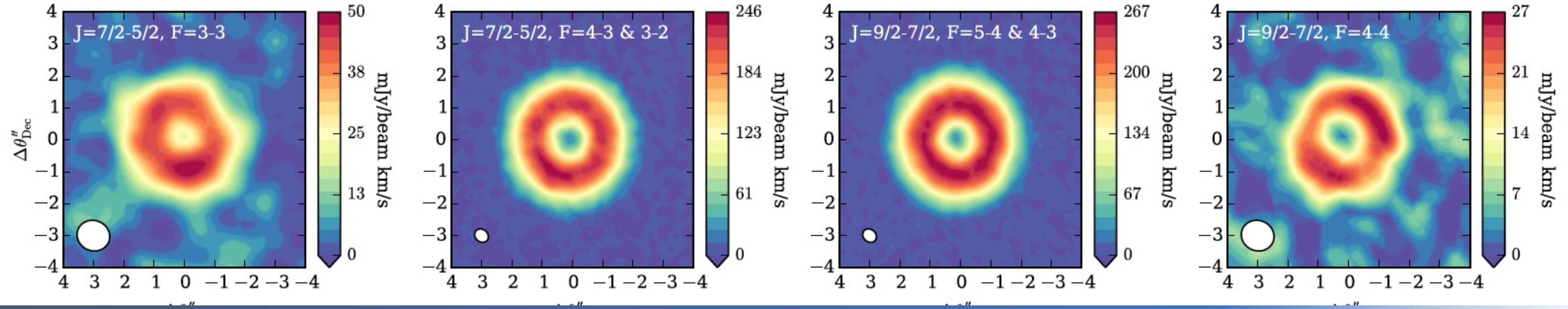
Hydrocarbons

Strong emission lines in TW Hya

- consistent with two orders of magnitude carbon depletion and C/O>1

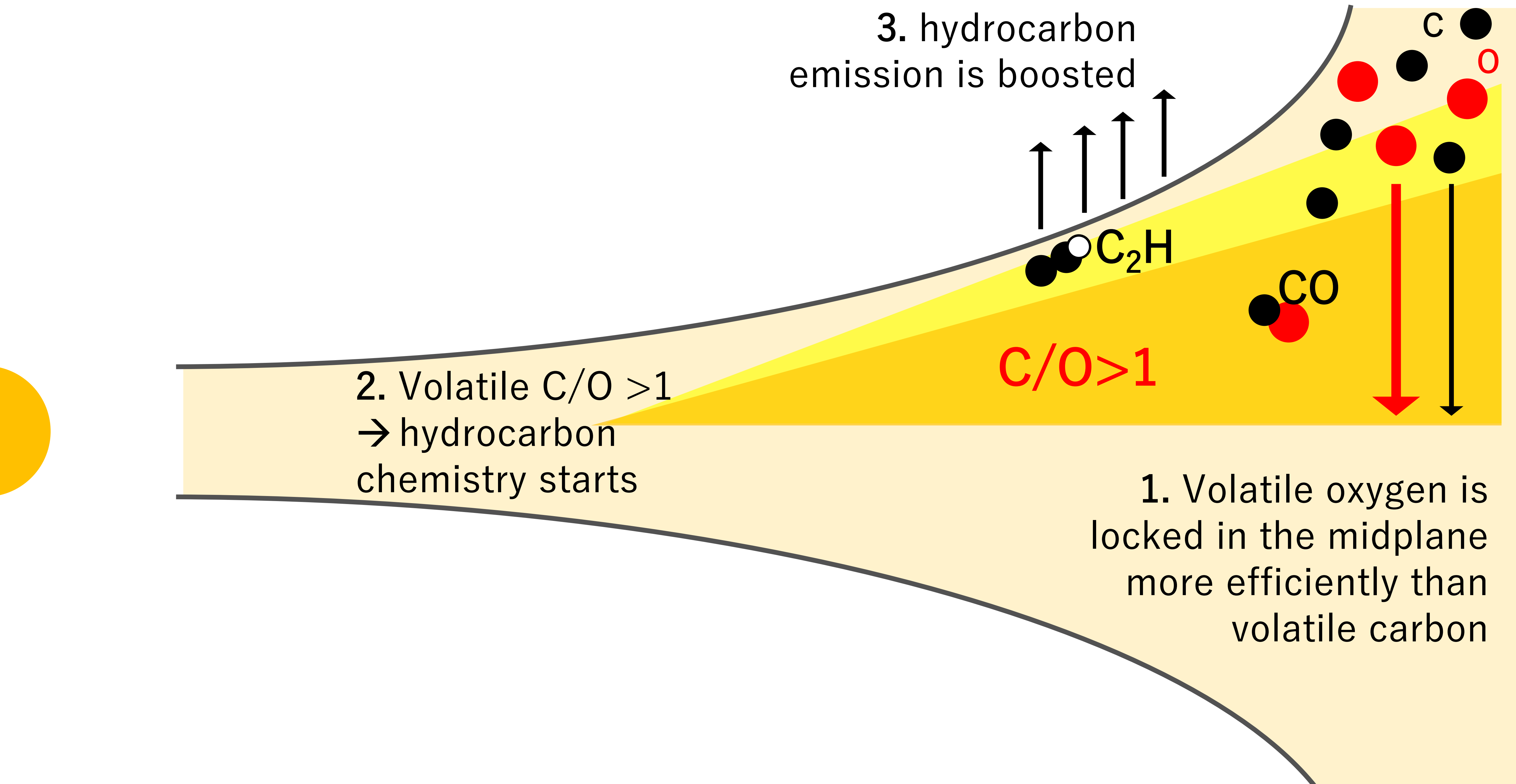


Kama et al. (2016)



Bergin et al. (2016)

C_2H strong emission - CO fainter than expected



Aikawa et al. 1996; Bergin et al. 2014; Du et al. 2015; Eistrup et al. 2016, 2018; Yu et al. 2017a,b; Miotello et al., 2019; Bosman et al. 2017, 2018; Schwarz et al. 2018; Krijt et al. 2018; 2020.

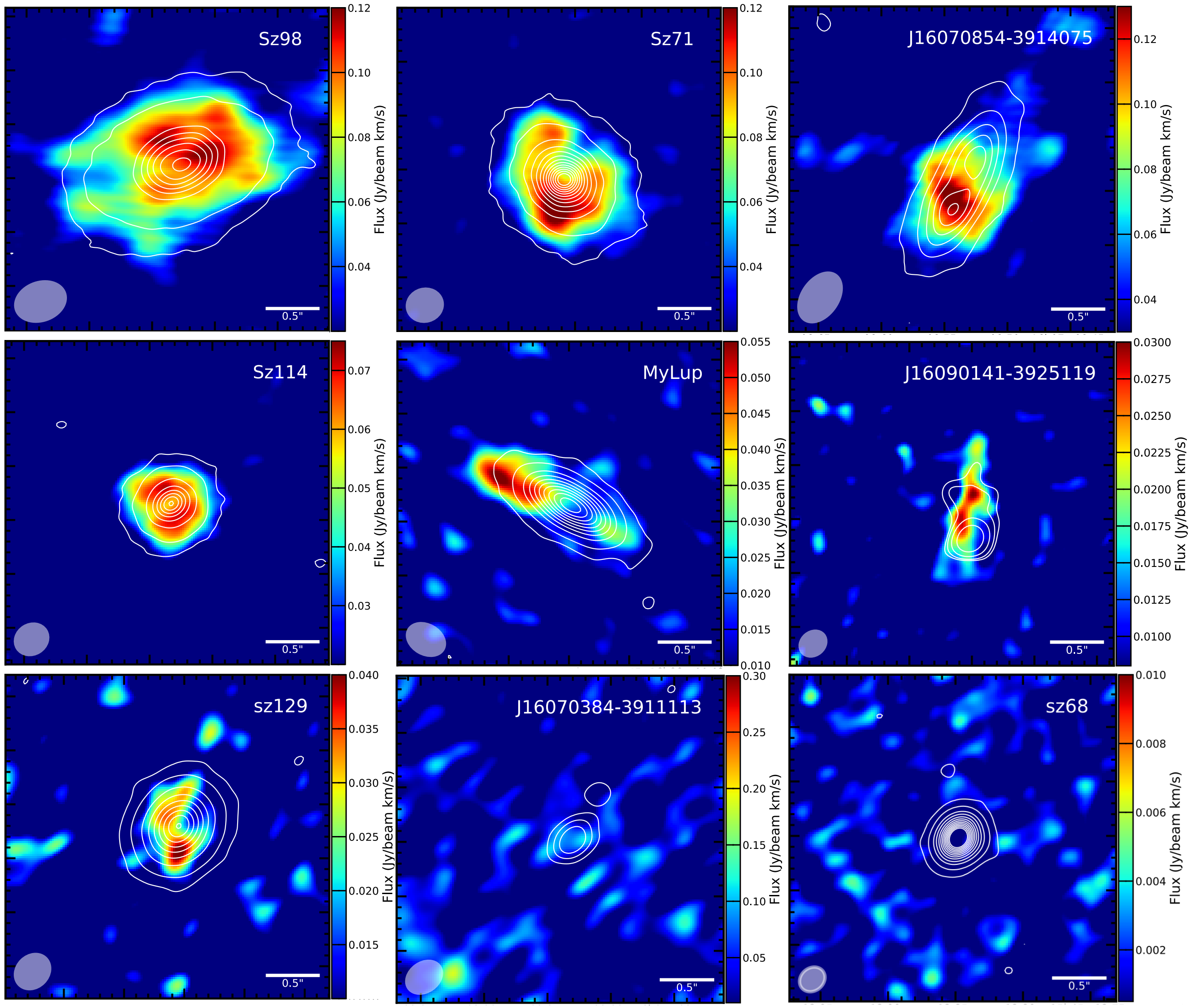
C_2H in Lupus

ALMA Cycle 4
Band 6

C_2H
(N = 3–2, J = 7/2 – 5/2,
F = 4–3 and F = 3–2)

9 Lupus disks
with CO-based
g/d between 1 and 100

Miotello et al. (2019)

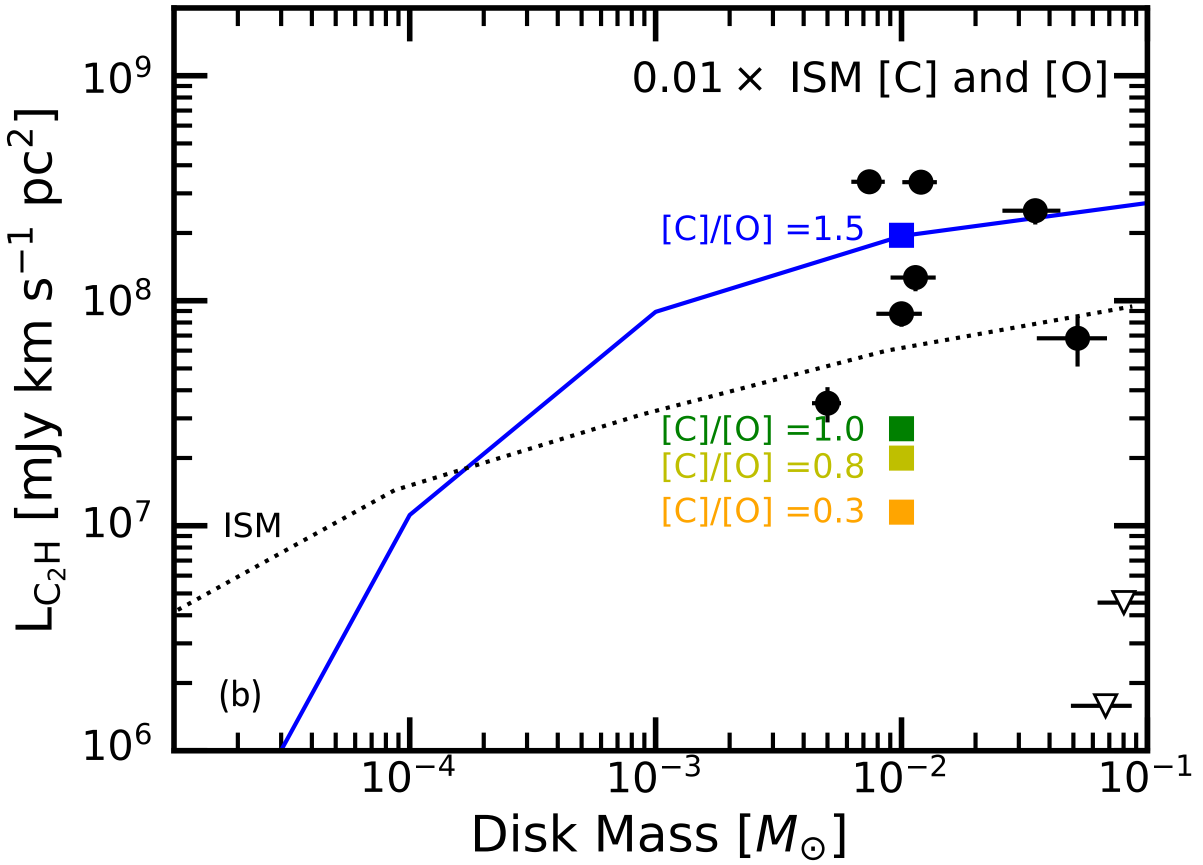


Pre-ALMA C_2H observations: Dutrey et al. 1997 (DM Tau and GG Tau); Henning et al. 2010 (MWC 480, LkCa 15, and DM Tau) Kastner et al. 2015 (TWHya). **ALMA C_2H** data: TWHya, DMTau, IM Lup, and V4046 Sgr (Bergin et al. 2016 ; Cleeves et al. 2018 ; Kastner et al. 2018); Bergner et al. 2019, survey of C_2H observations for 14 discs observed spanning a range of ages, stellar luminosities, and stellar masses.

C_2H

Tracer of [C]/[O]>1 in the gas

C_2H fluxes can be **reproduced** only if volatile carbon and oxygen depletion is allowed and **[C]/[O]>1** in the gas



Miotello et al. (2019)

Cleeves et al. (2018),Cazzoletti et al. (2018)
Anderson et al. (2020),Bosman et al. (2021a)
Bruderer et al. (2012,2013)

GAS
DISK POPULATION
STUDY

Constraints on disk evolution theories

Disk mass

From dust continuum emission

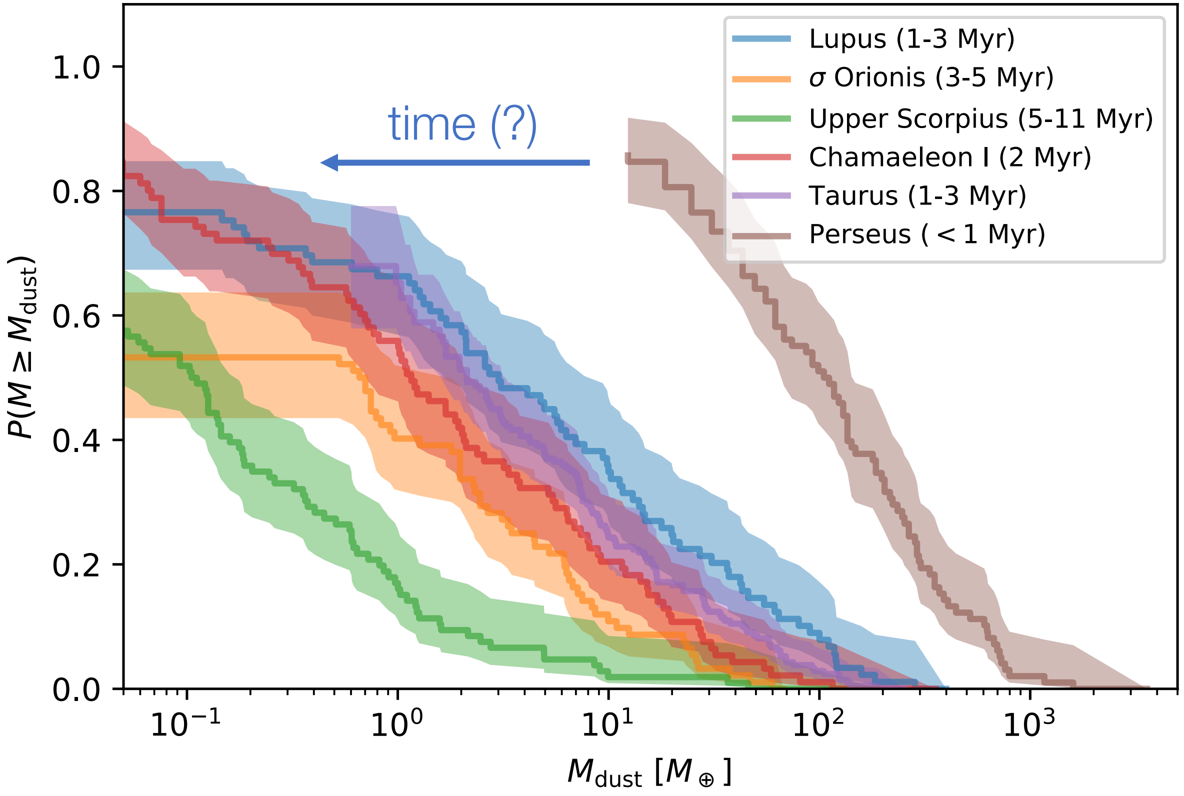
Average disk temperature

Average dust opacity

$$F_\nu = \frac{B_\nu(\bar{T}_\mathrm{d})\,\bar{\kappa}}{d^2} M_\mathrm{dust}$$

$\tau \ll 1$
Optically thin regime

$kT \ll h\nu$
Rayleigh-Jeans regime



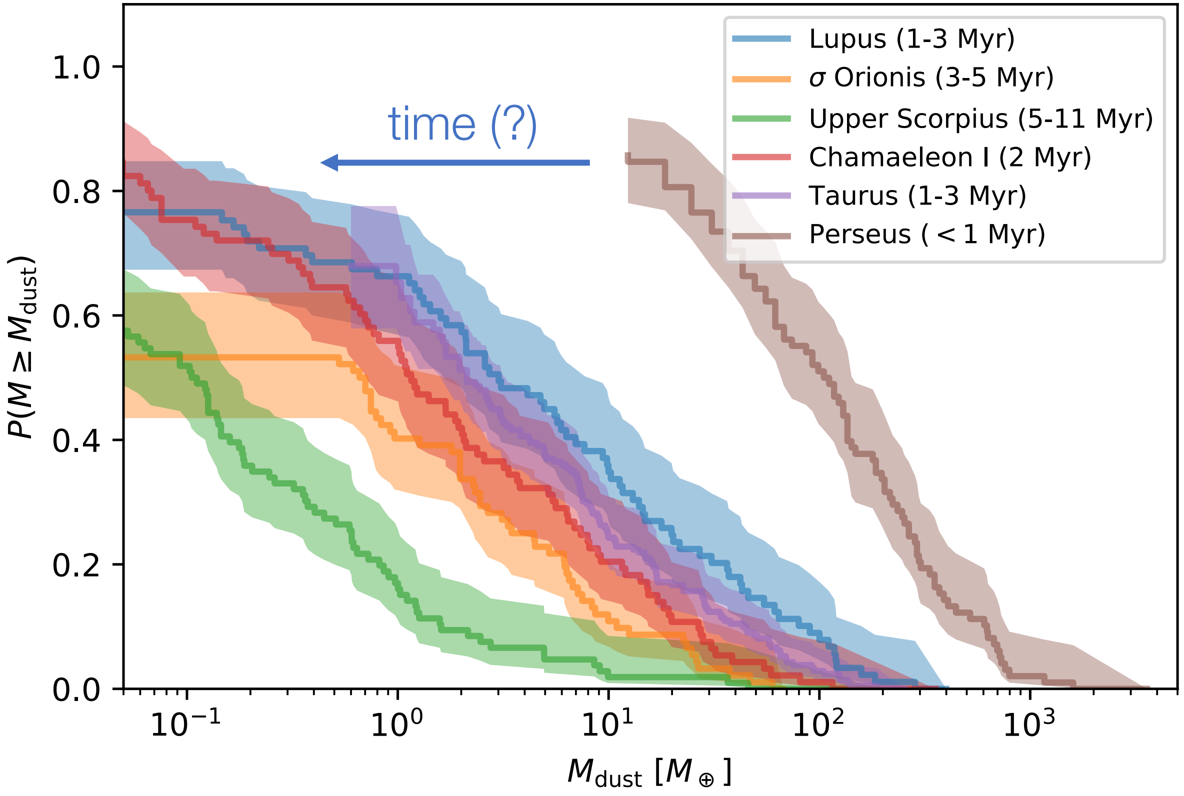
Cumulative disk mass distributions after Tychoniec et al. (2018) for different SFRs.

PPVII Chapter 14 – Miotello et al. (2022)

Disk mass

From dust continuum emission

While significant assumptions are made to derive dust masses from continuum fluxes, there appears to be a mass loss of **two orders of magnitude** from young to old disks – a difference that is difficult to attribute to just uncertainties of the opacities, or the optical depths.

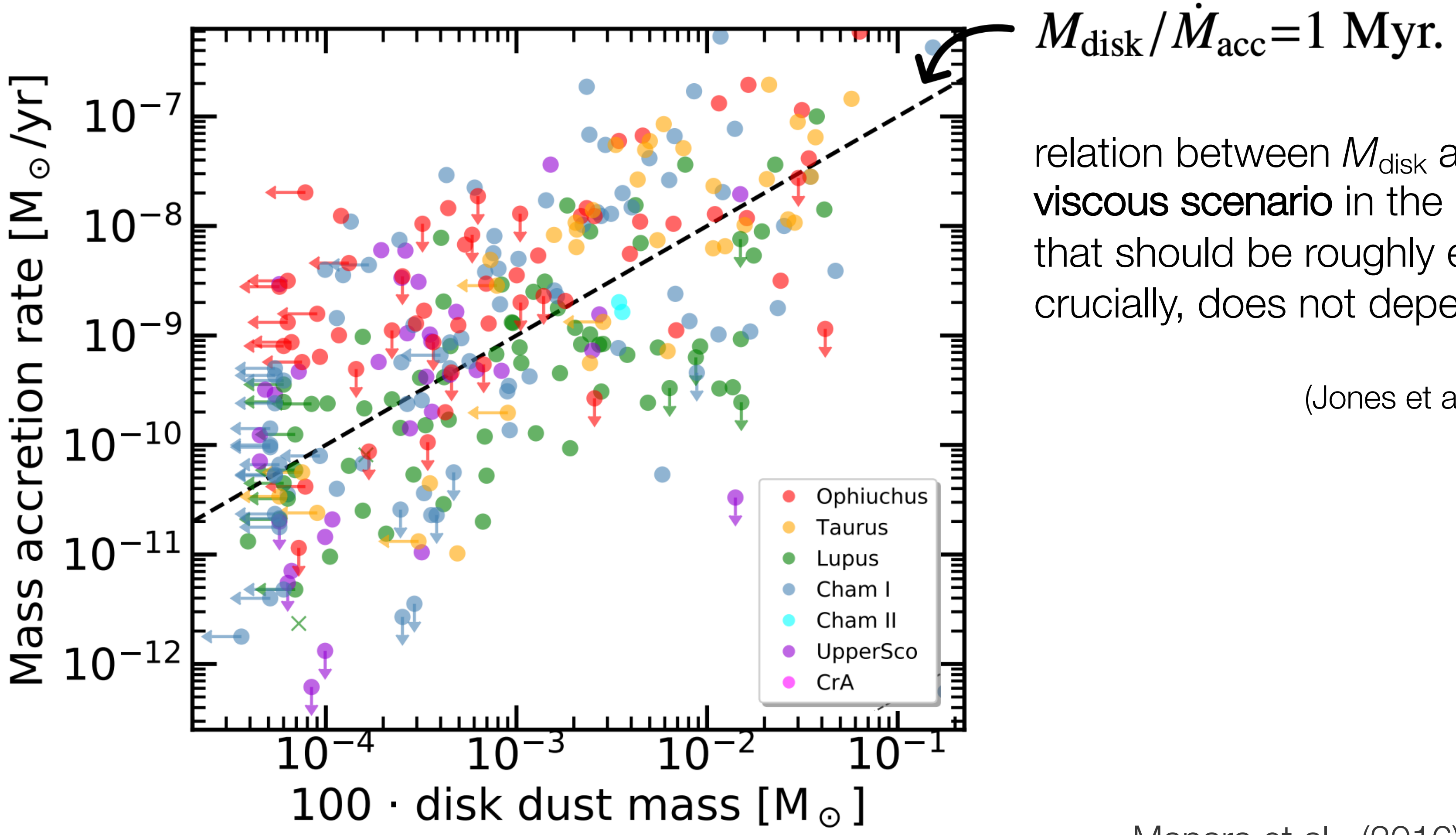


Cumulative disk mass distributions after Tychoniec et al. (2018) for different SFRs.

PPVII Chapter 14 – Miotello et al. (2022)

Dust disk population studies

Try and constrain evolution and planet formation



PPVII Chapter 15 – Manara et al. (2022)

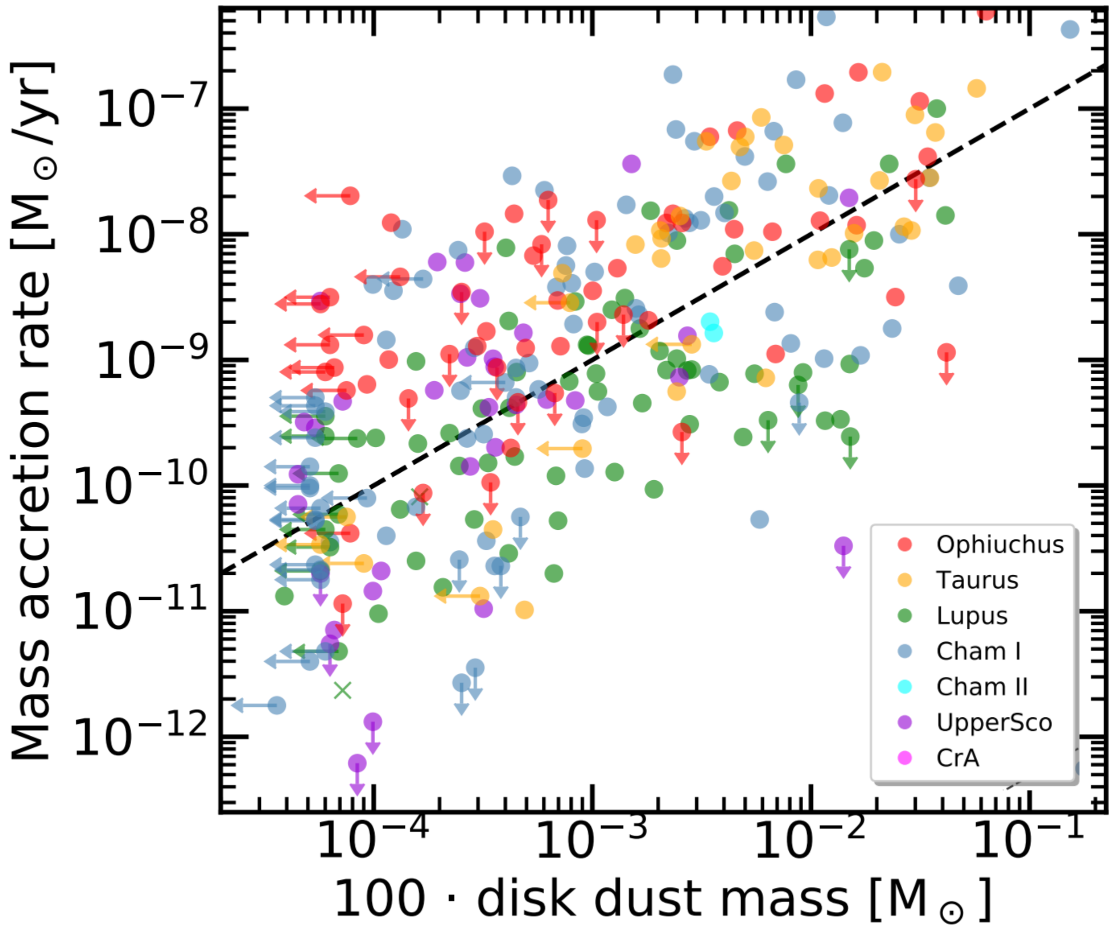
relation between M_{disk} and M_{acc} natural consequence of the **viscous scenario** in the limit of $t \gg t_v$, with a normalisation that should be roughly equal the **age of the region** and that, crucially, does not depend on the value of the viscosity.

(Jones et al. 2012; Rosotti et al. 2017,Manara et al., 2022)

Manara et al., (2016), Mulders et al. (2017), Lodato et al. (2017), Manara et al., (2020), Sellek et al. (2020a)

Dust disk population studies

Try and constrain evolution and planet formation



PPVII Chapter 15 – Manara et al. (2022)

MHD winds

both for the simple model and for a more sophisticated case in which α_{DW} varies with time, the observed correlation is reproduced by choosing a disk population with a relatively narrow distribution of t_{acc}.

Tabone et al. (2021b)

Manara et al., (2016), Mulders et al. (2017), Lodato et al. (2017), Manara et al., (2020), Sellek et al. (2020a), Tabone et al. (2021b)

Gas disk population studies

Try and constrain evolution and planet formation

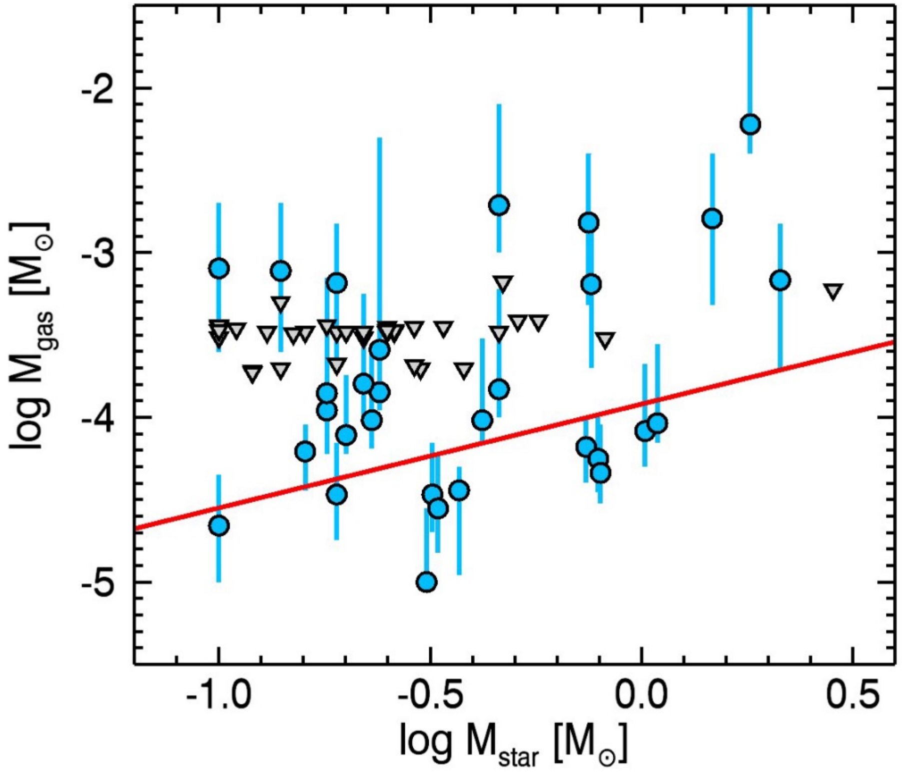


Fig. 9. Disk gas mass as a function of stellar mass for Lupus disks. Gas non-detections are shown as upper limits with gray triangles. For the gas detections the error bars are reported. The red line gives the Bayesian linear regression fit (Kelly 2007).

Miotello et al. (2017)

No correlation between M_{acc} and M_{gas} was found either by Ansdell et al. (2016) or Miotello et al. (2017), due to low number statistics and large error bars.

$M_{\rm disk}/\dot{M}_{\rm acc}$ was found to be **much lower** than the age of Lupus

→ External perturbances or limitation in the gas mass derivation?

Miotello et al. (2017), Ansdell et al. (2016)

Gas disk population studies

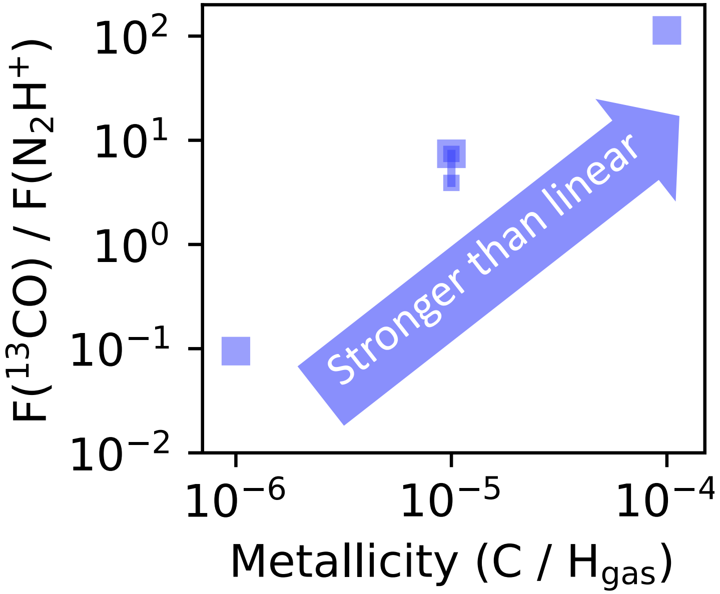
Constrain evolution and planet formation

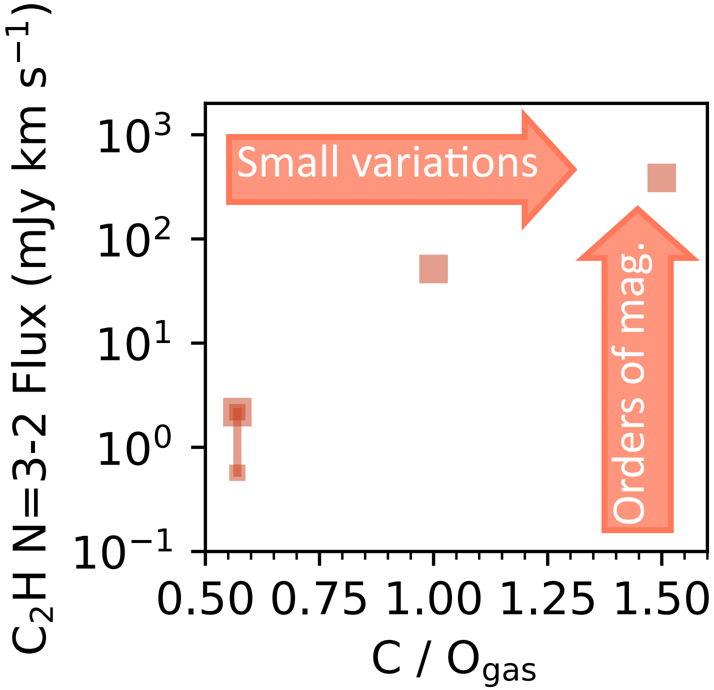
NEEDED FOR THIS PROJECT:

- **M_{gas}** → Obtained from $^{13}CO/C^{18}O+N_2H^+$ analysis of DECO data
- **$M_\star$** → From literature (PPVII Ch., Manara et al. 2023)
- **M_{acc}** → From literature (PPVII Ch., Manara et al. 2023)

POSSIBLE ANCILLARY DATA

- **M_{gas}, $M_\star$, M_{acc}** → from AGE-PRO (& known disks ?)
  - Need to be careful with homogeneity of the sample

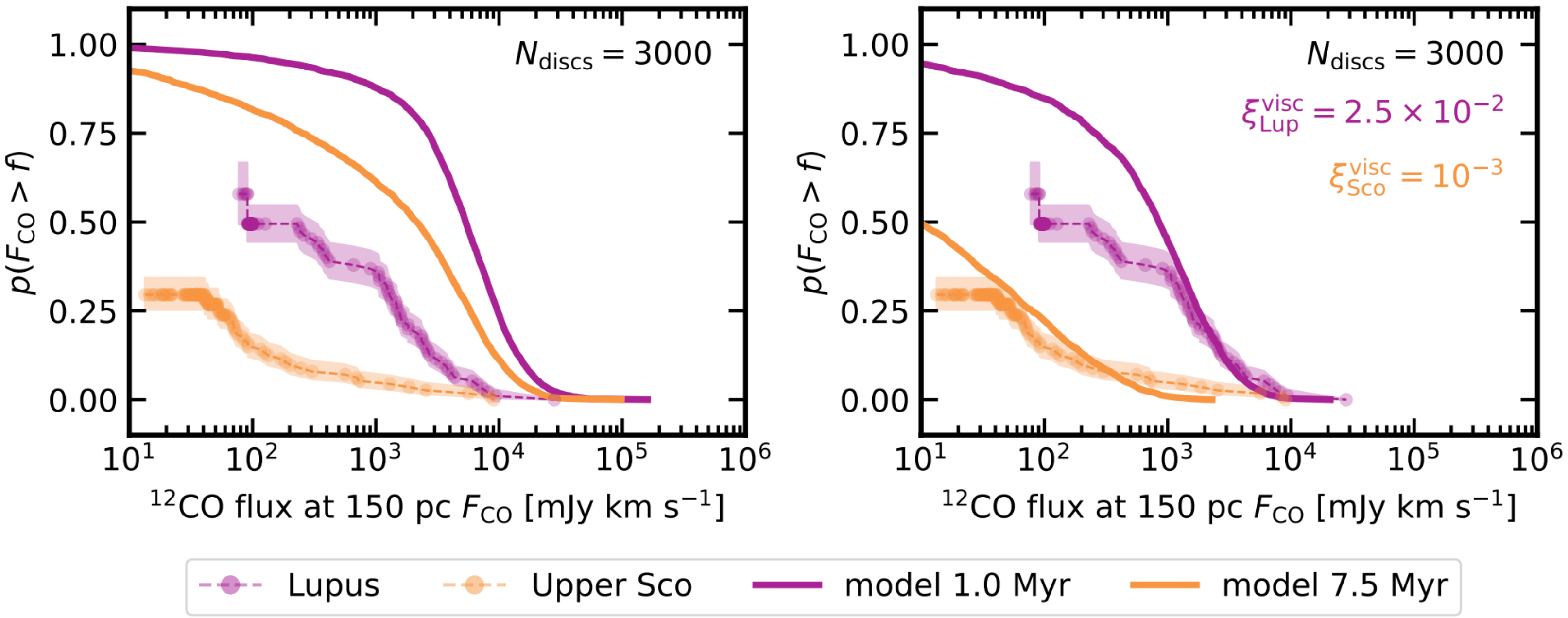




Trapman et al. 2022, Anderson et al. 2022

Disk Radii from CO fluxes

Key for constraining evolution and planet formation

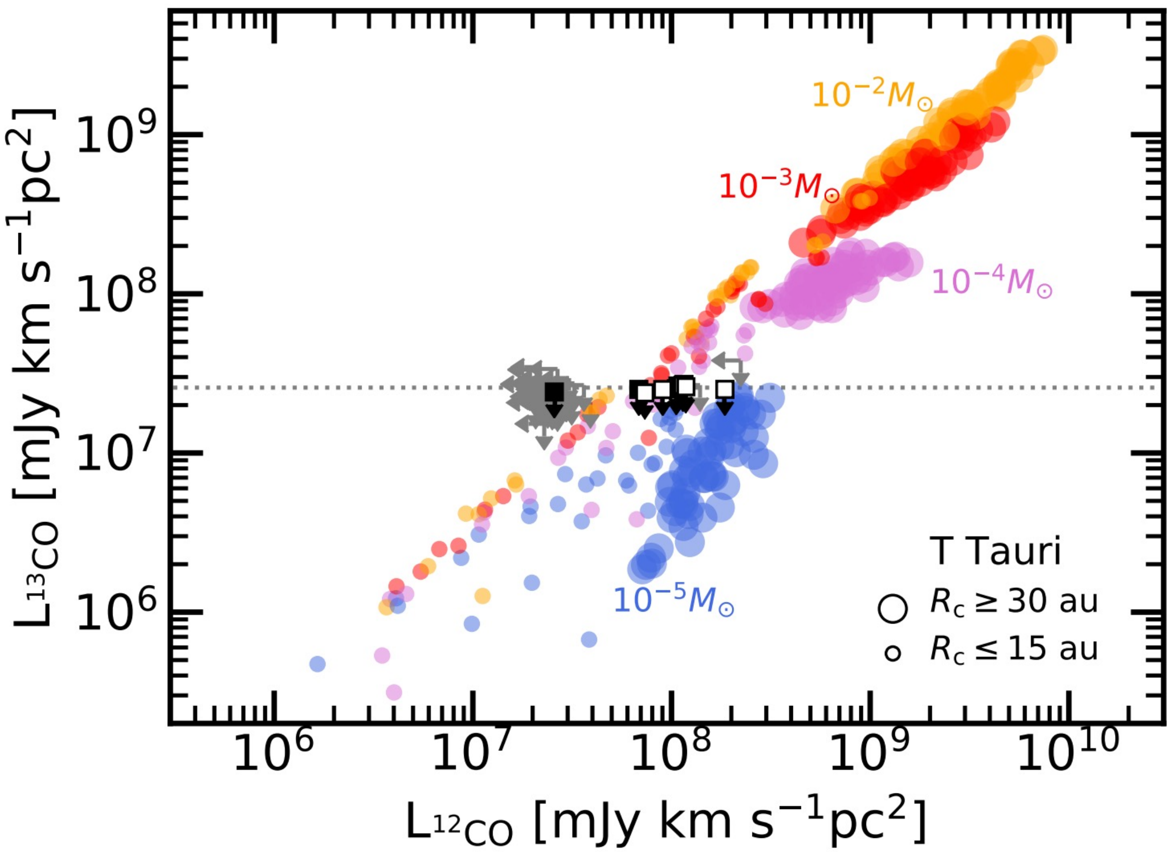


Alternative method based on **^{12}CO fluxes.** Assuming that ^{12}CO fluxes emission is **optically thick**, CO fluxes scale as the disc surface area (i.e., the radius squared), suggesting that modelling fluxes is an indirect way of studying.

Zagaria et al. (2023)

Disk Radii from CO fluxes

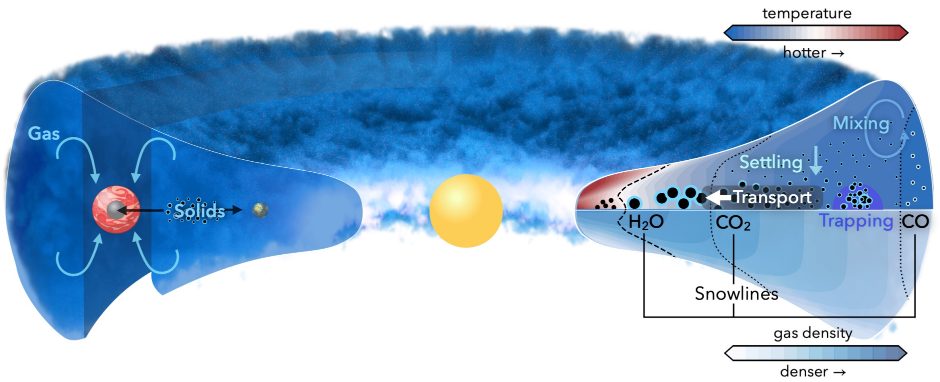
Key for constraining evolution and planet formation



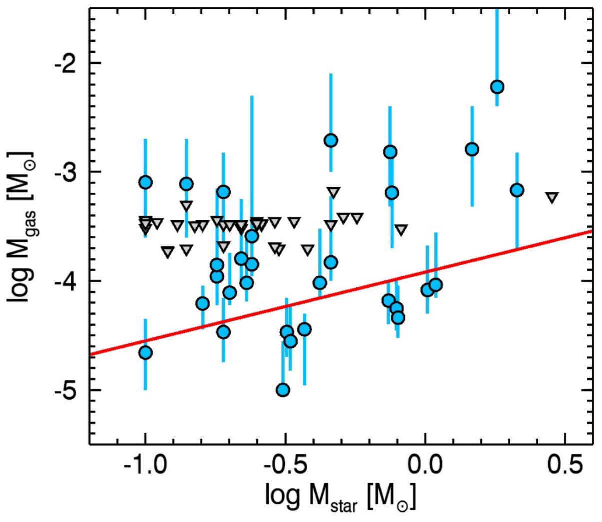
Lupus disks that are not detected in ^{13}CO emission and have faint or undetected ^{12}CO emission are consistent with **compact disk models.** For disks with a limited radial extent, the emission of CO isotopologs is mostly optically thick and scales with the surface area, that is, it is fainter for smaller objects. The fraction of compact disks is potentially between roughly 50% and 60% of the entire Lupus sample.

Miotello et al. (2021)

Take home



Constraining **abundance ratios** in disks is key for constraining how and where the observed exoplanet population formed.



Improved disk **mass and radii measurements** will allow us to perform a gas disk population study for the first time

Ancillary slides

Late accretion

Onto Disks

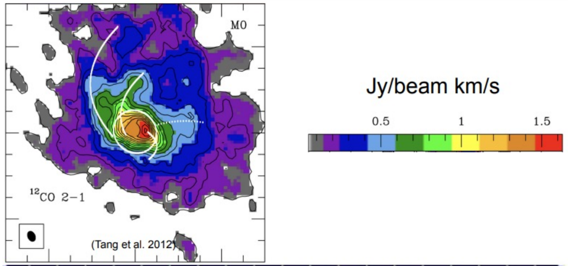
Late accretion

Of material onto Class II disks

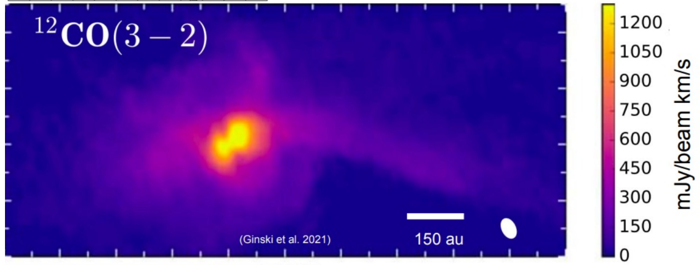
Serendipitous detection of
accretion streamers onto Class II disks.
How frequent and efficient is this a process?

- Sample study
- Characterization of streamers
    - Physical properties (velocity, angular momentum, column density, etc.)
    - Chemical composition

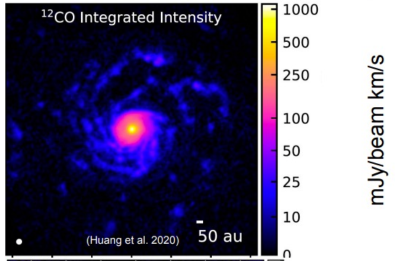
AB Aur
Tang et al., 2012



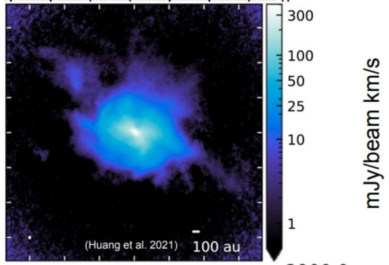
SU Aur
Ginski et al., 2021



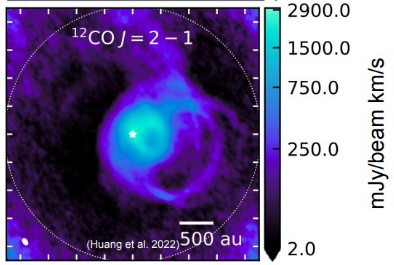
RU Lup
Huang et al., 2020



GM Aur
Huang et al., 2021



DO Tau
Huang et al., 2022



Gupta, et al., 2023

Late accretion

Of material onto Class II disks

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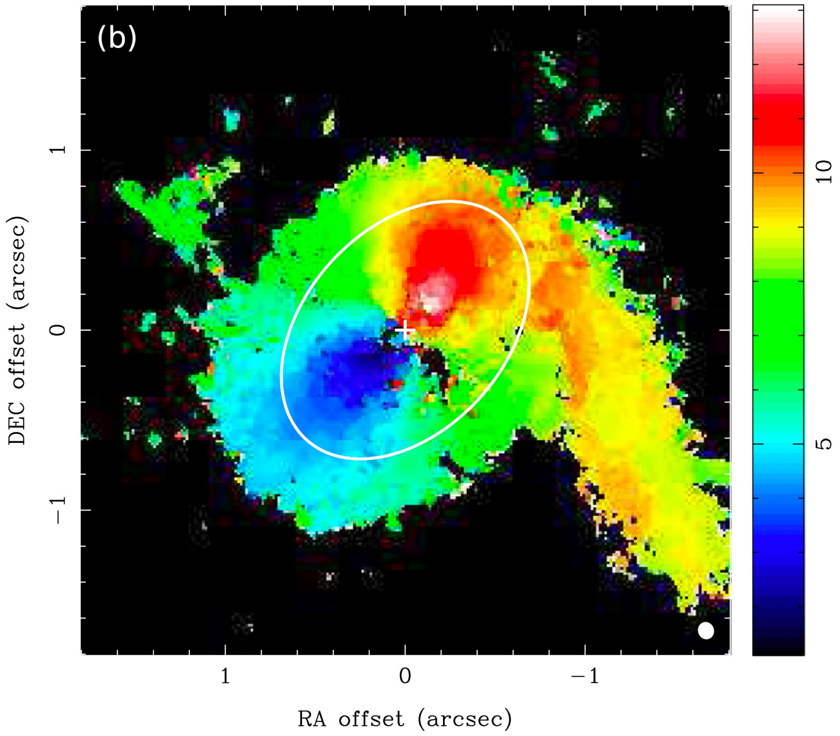
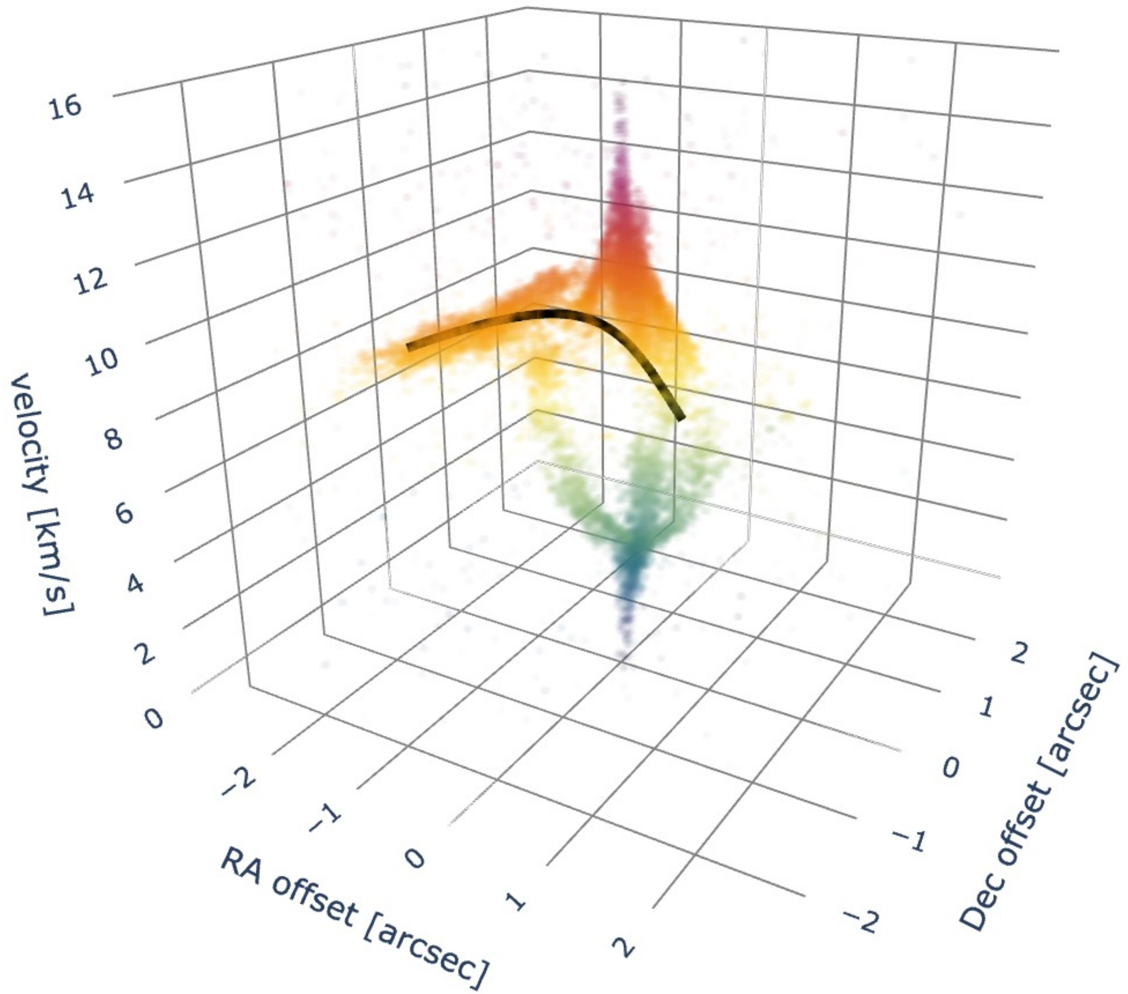
accretion streamers onto Class II disks.
How frequent and efficient is this a process?

HCO$^+$ (3–2) moment 9 map, Yen+ 19



TIPSY
Trajectory of Infalling Particles in Streamers around Young stars



Gupta, et al., in prep.

DISK VERTICAL STRUCTURE

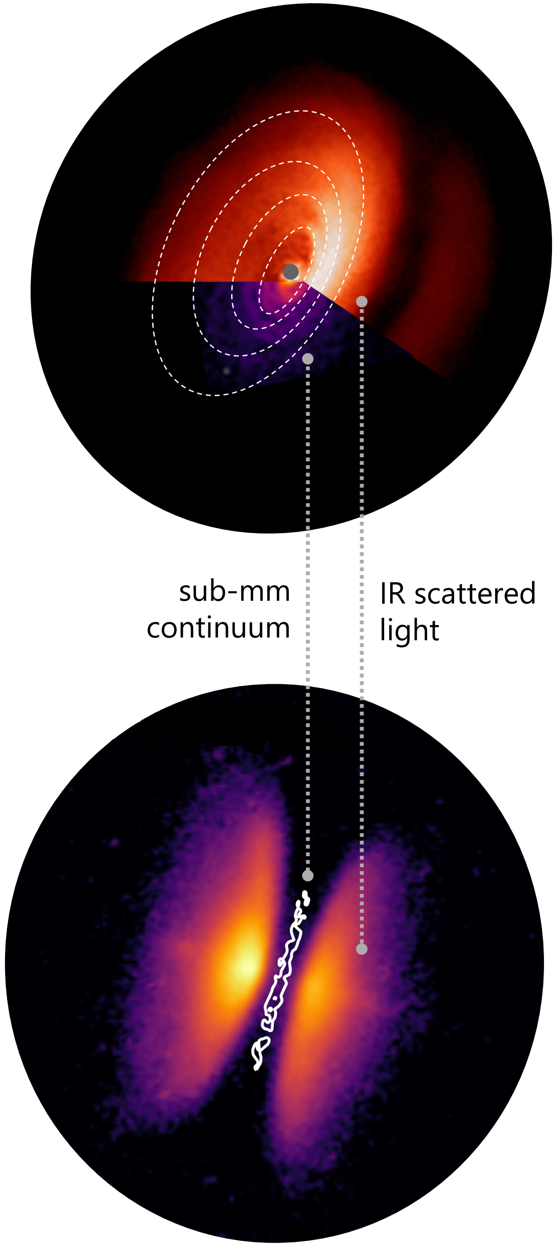
from dust & gas observations

Disk vertical structure

From continuum and scattered light observations

- mm-sized grains are recluse to thin and settled midplanes.
  → turbulence is weak, as found by ALMA gas observations.

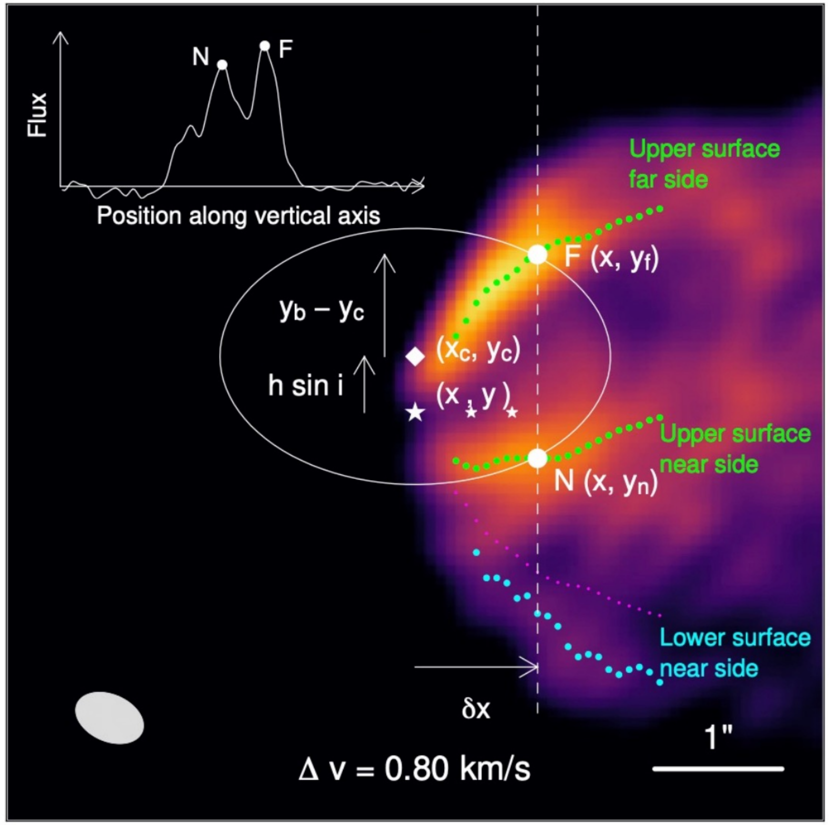
- Highly elevated small grains:
  → long settling times or they are lifted by systematic flows
  → they cannot as easily be treated as tracers of turbulence.

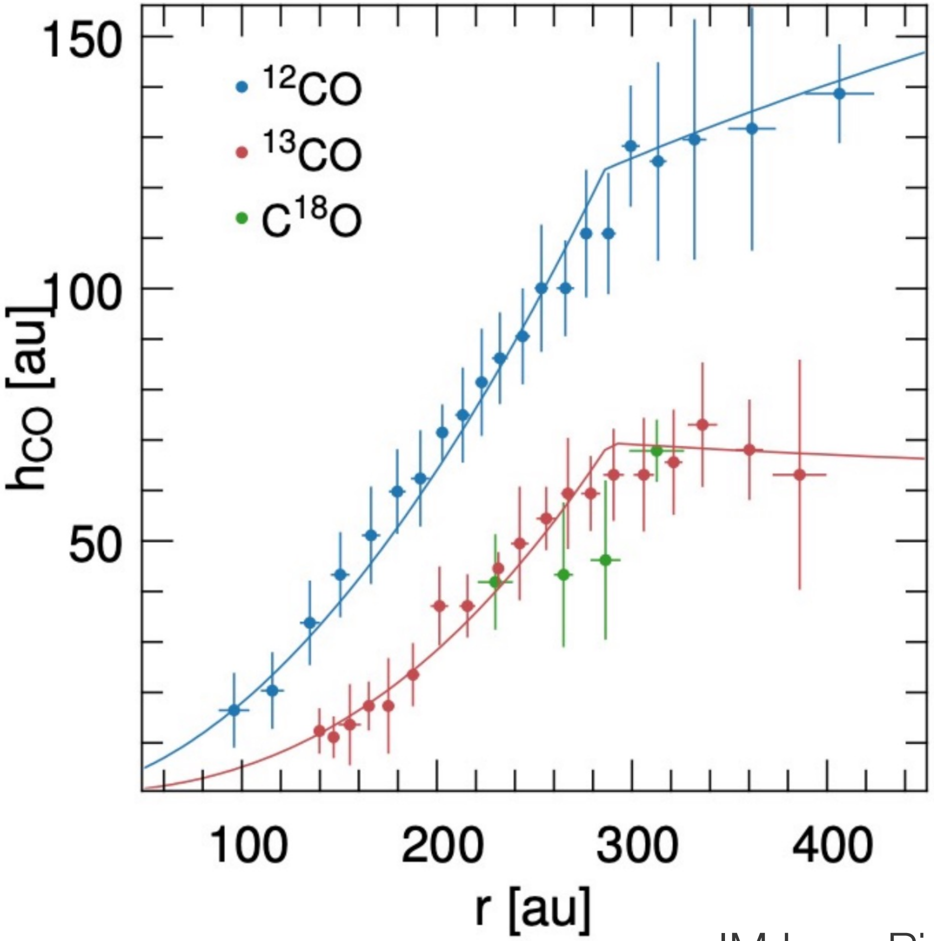


PPVII Chapter 14 – Miotello et al. (2022), Avenhaus et al. (2018), Andrews et al. (2018b), Villenave et al. (2020)

Disk vertical structure

From spatially and spectrally resolved molecular line observations

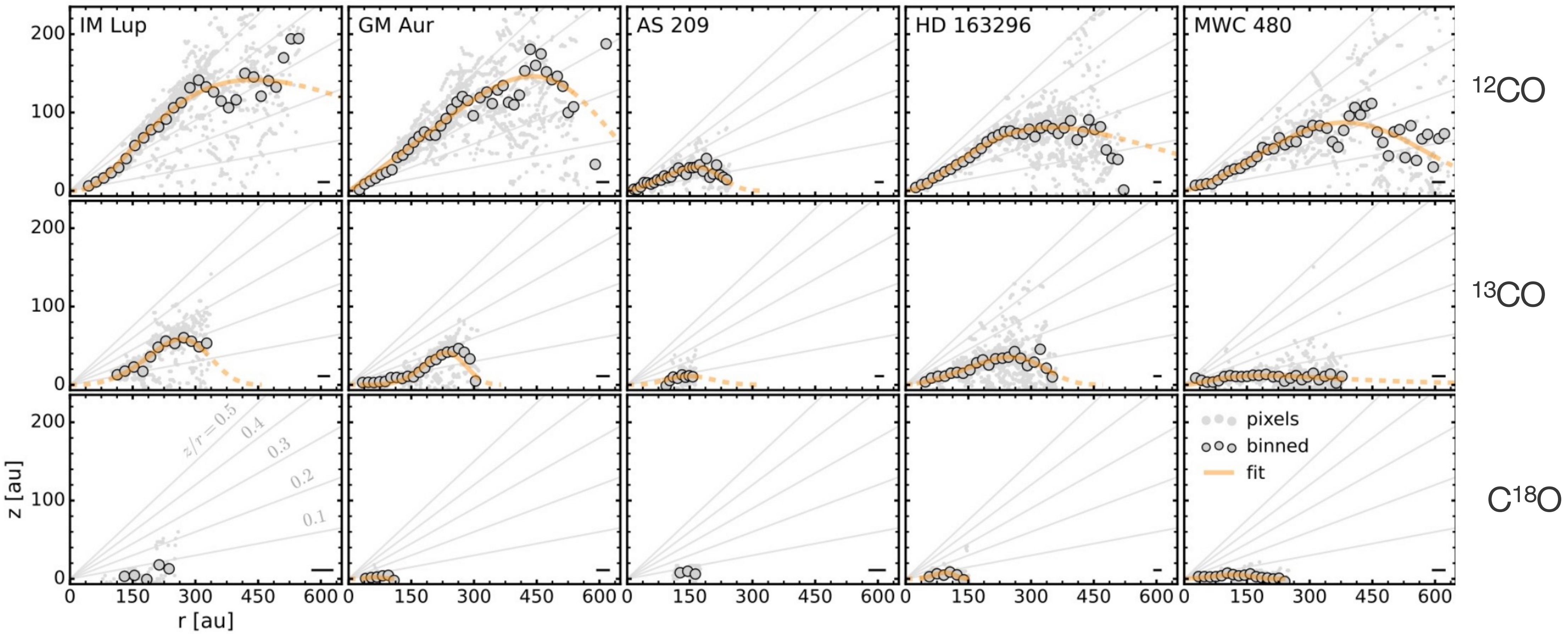




IM Lup, Pinte et al., 2018

Disk vertical structure

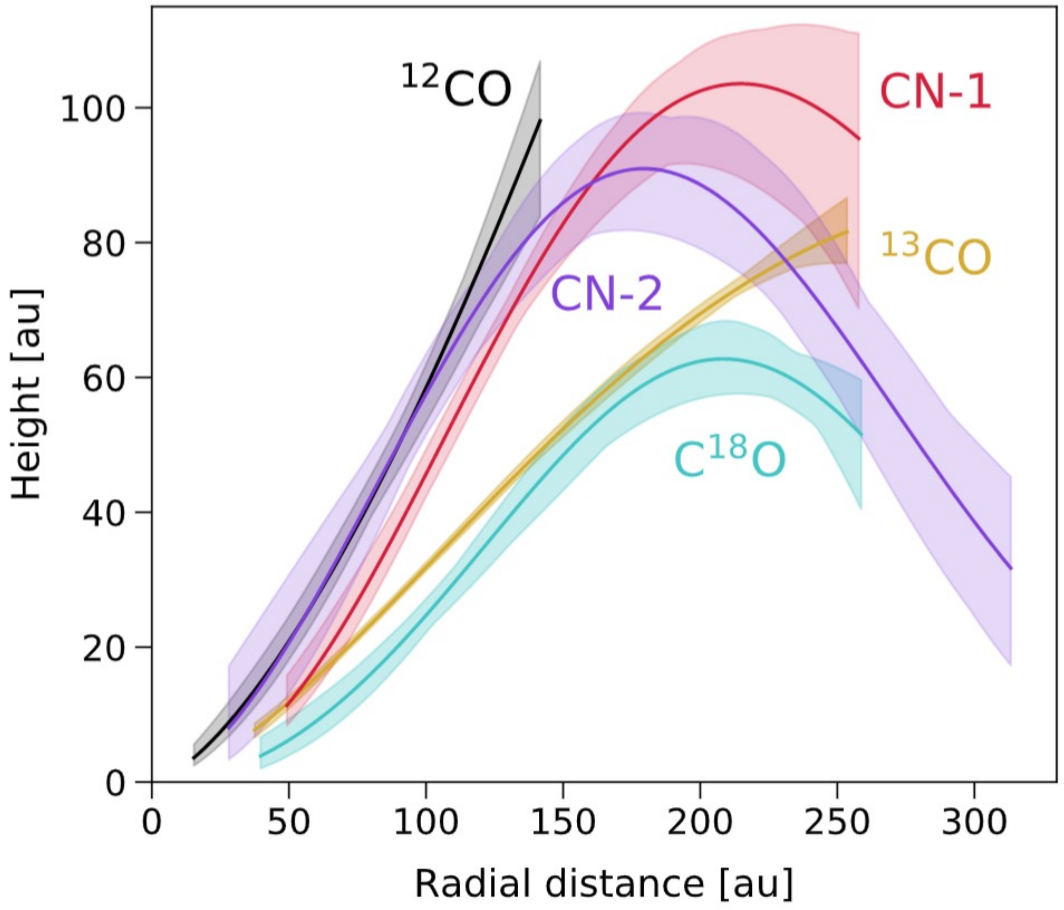
From spatially and spectrally resolved molecular line observations



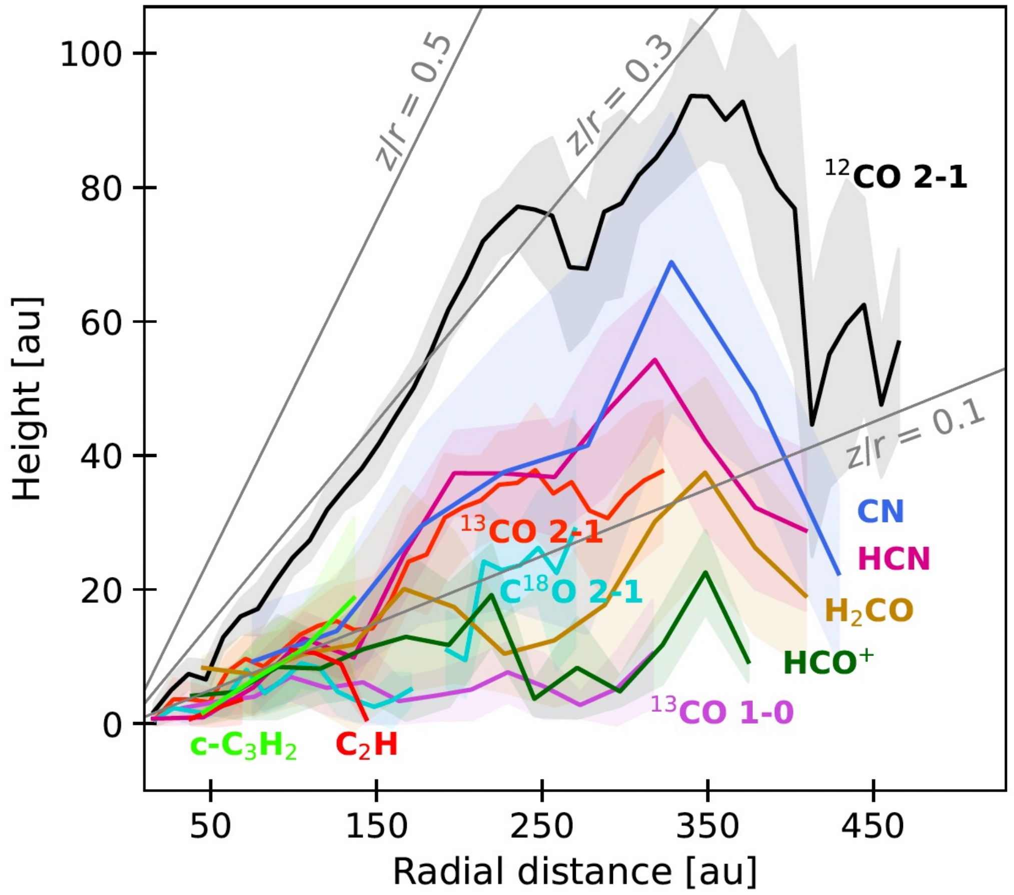
MAPS VI, Law et al. (2021)

Disk vertical structure

From spatially and spectrally resolved molecular line observations



Elias 2-27, Paneque-Carreño et al. (2022a)

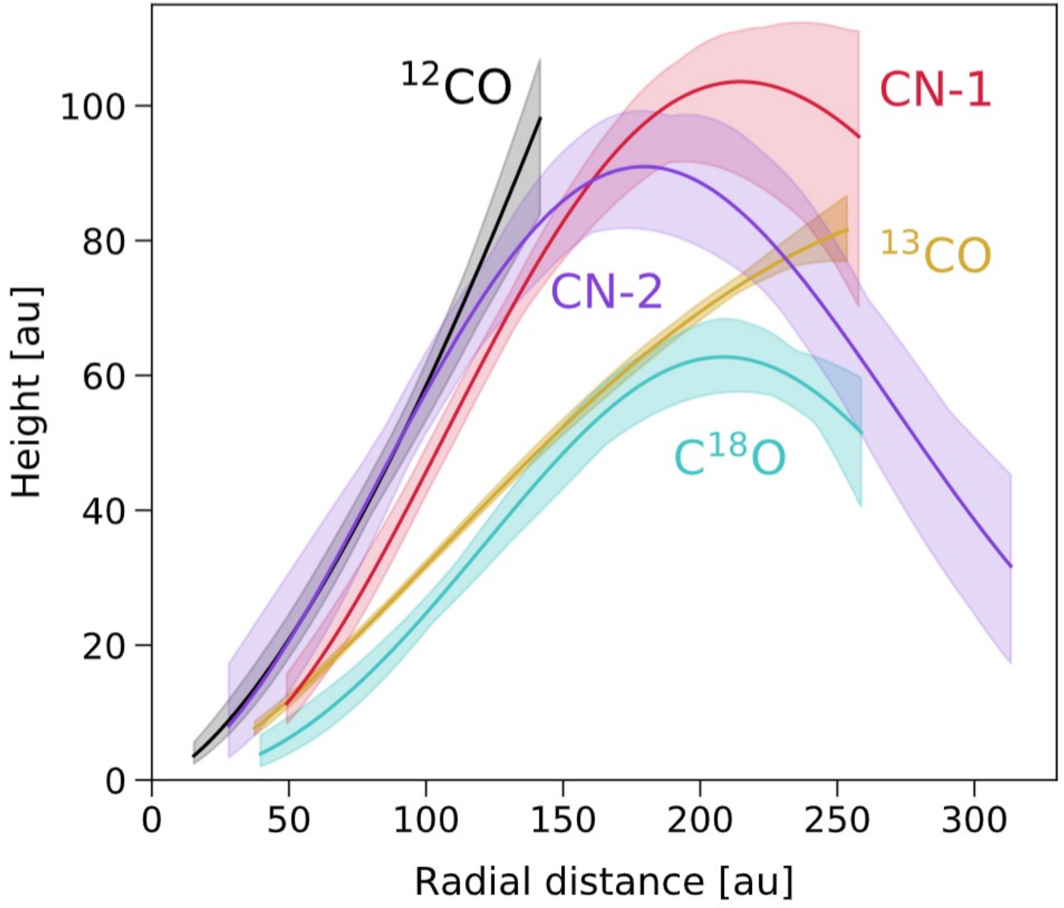


HD 163296, Paneque-Carreño et al. (2022b)

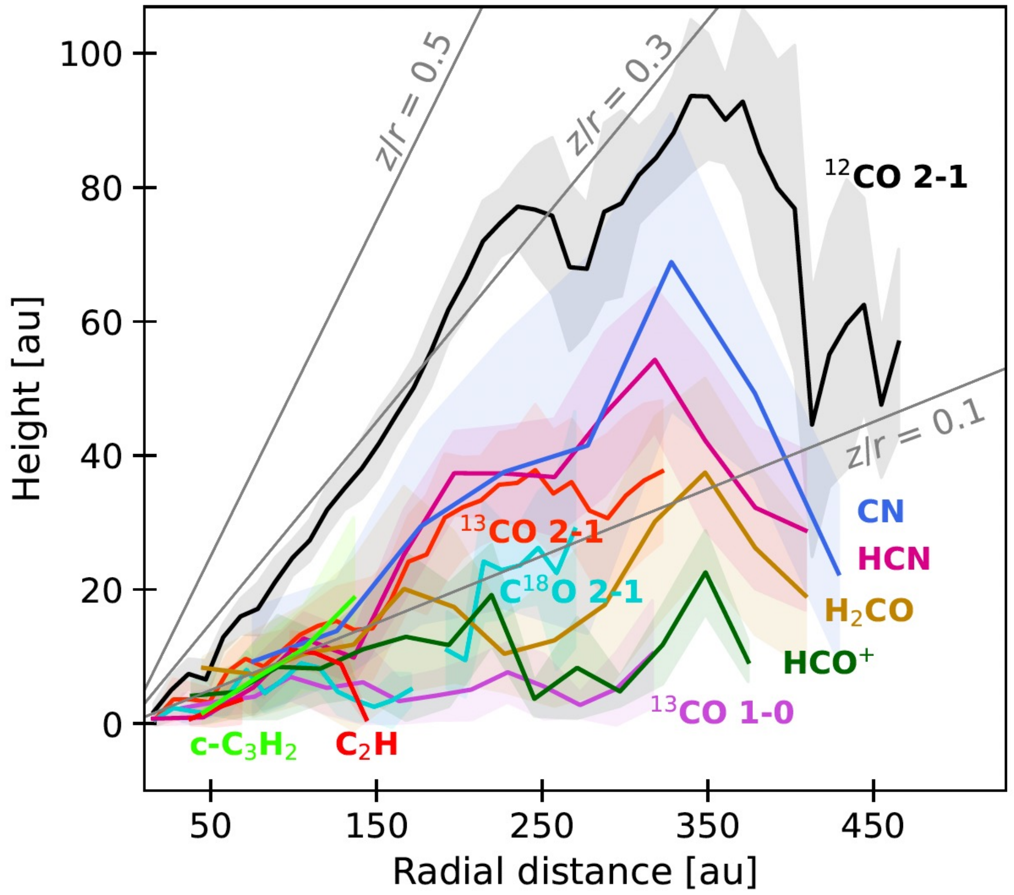
Disk vertical structure

From spatially and spectrally resolved molecular line observations

If the emission is **optically thick** and good approximations for the **surface density** and **CO abundance** are available, the ^{12}CO emission surface can be used to obtain the **gas pressure scale height**



Elias 2-27, Paneque-Carreño et al. (2022a)



HD 163296, Paneque-Carreño et al. (2022b)

Late accretion

Of material onto Class II disks

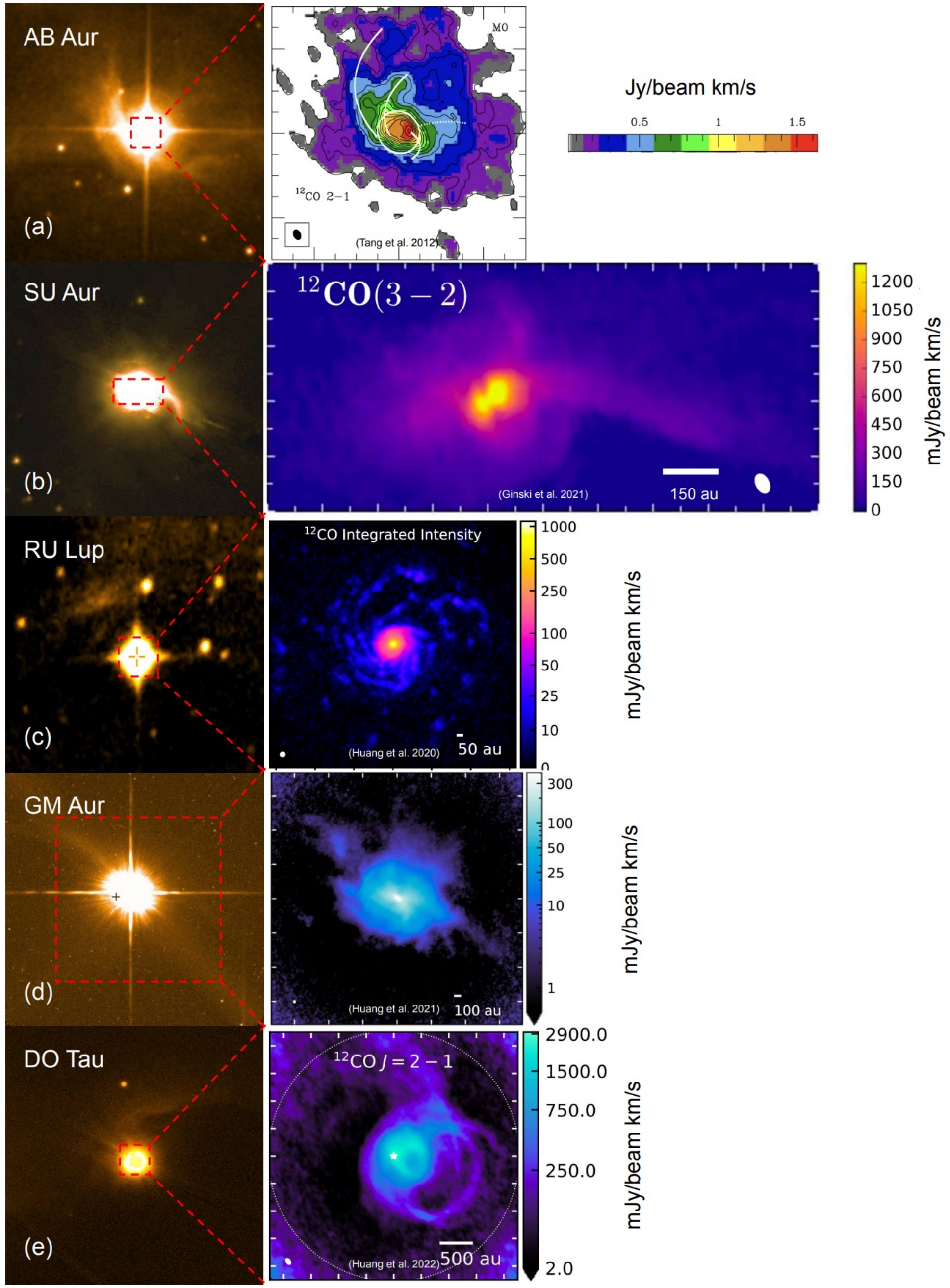
Serendipitous detection of
accretion streamers onto Class II disks.
How frequent and efficient is this a process?

Reflection Nebulae close to Class II stars can be used to identify late-infall candidates.

Main limitations:

- Incompleteness of the RNe catalogues
- Find best observational strategy.
- Characterization of the streamers.

Stay tuned…



Gupta, et al., 2023