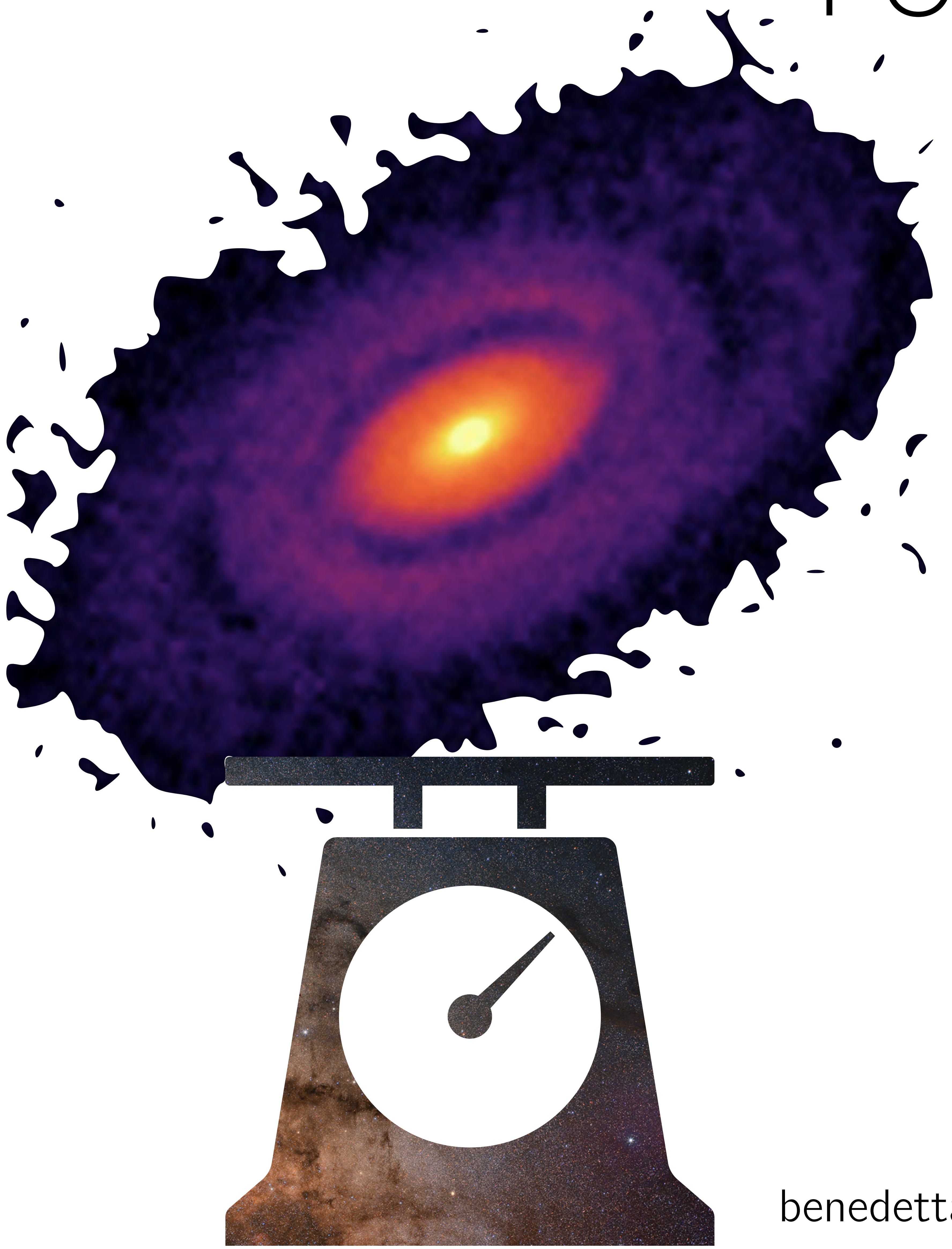
DISC SELF GRAVITY AS A DYNAMICAL SCALE FOR THE DISC MASS



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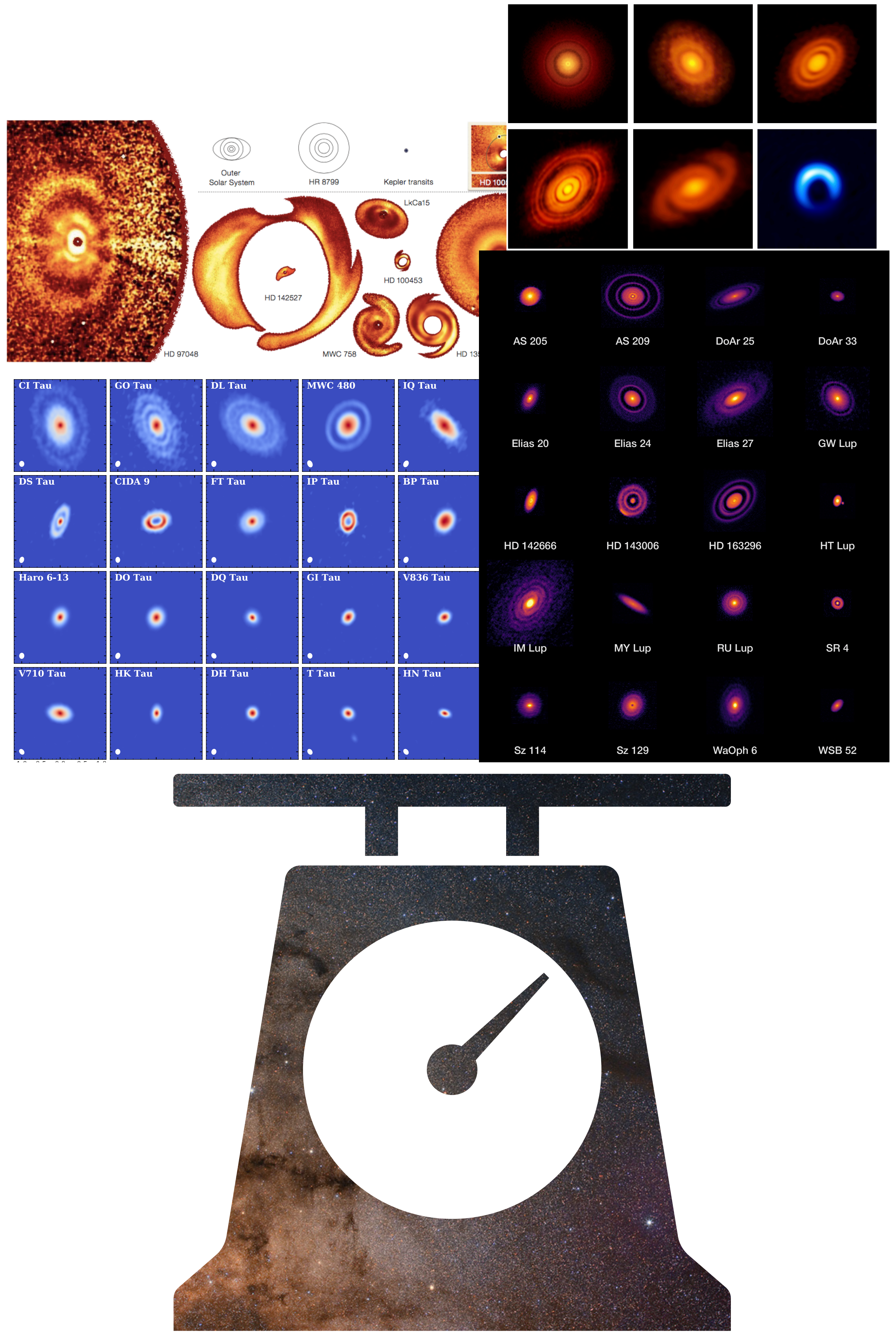
October 12, 2021 MIAPP

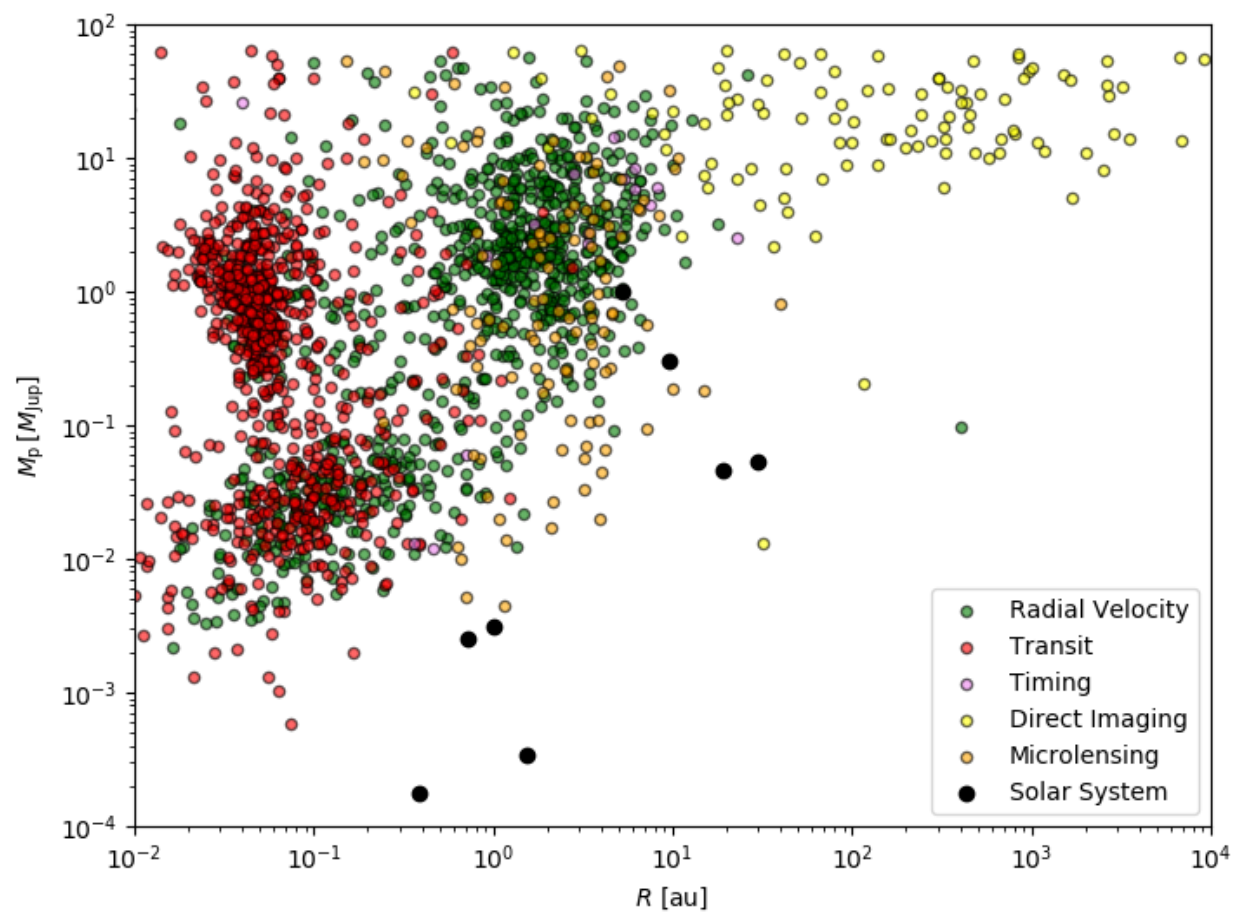
HOW MASSIVE ARE PROTOPLANETARY DISCS?

$$M_{\mathrm{disc}} = ?\, M_{\odot}$$



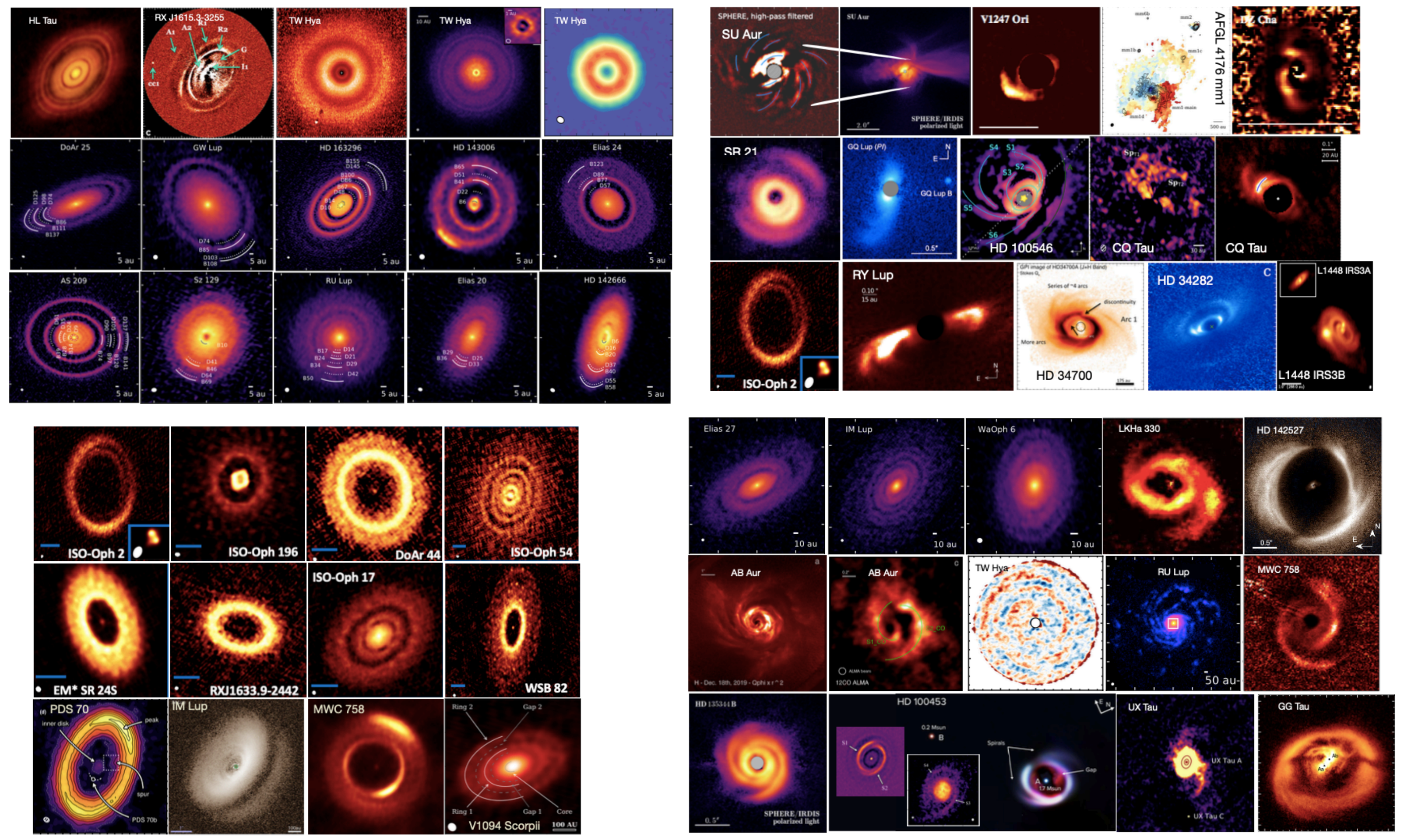
HOW MASSIVE ARE PROTOPLANETARY DISCS?

Reservoir for planets: exoplanets distribution



$$M_{\rm disc} = \,?\, M_\odot$$

$\mathrm{St} \propto \Sigma^{-1}$: dust and gas evolution (also, substructures...)

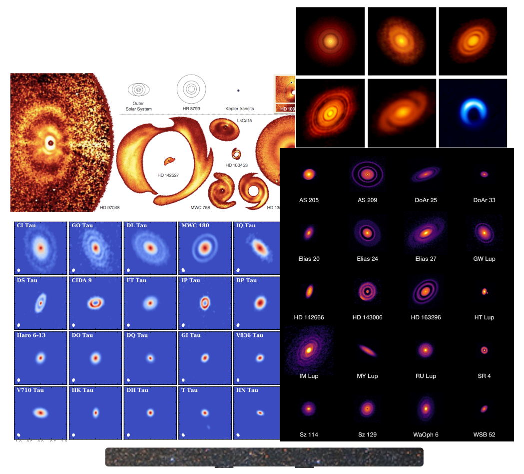


Planet evolution: migration, accretion...

Ionization rate (MRI,....)

Chemistry

HOW TO WEIGH PROTOPLANETARY DISCS?



From the dust mass....

Optically thin mm flux (e.g. from ALMA)

Distance to disk (e.g. from Gaia)

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

Single grain **opacity** (large uncertainty)

Dust temperature (e.g. **isothermal** 20 K)

Dust mass primarily in (sub)mm grains

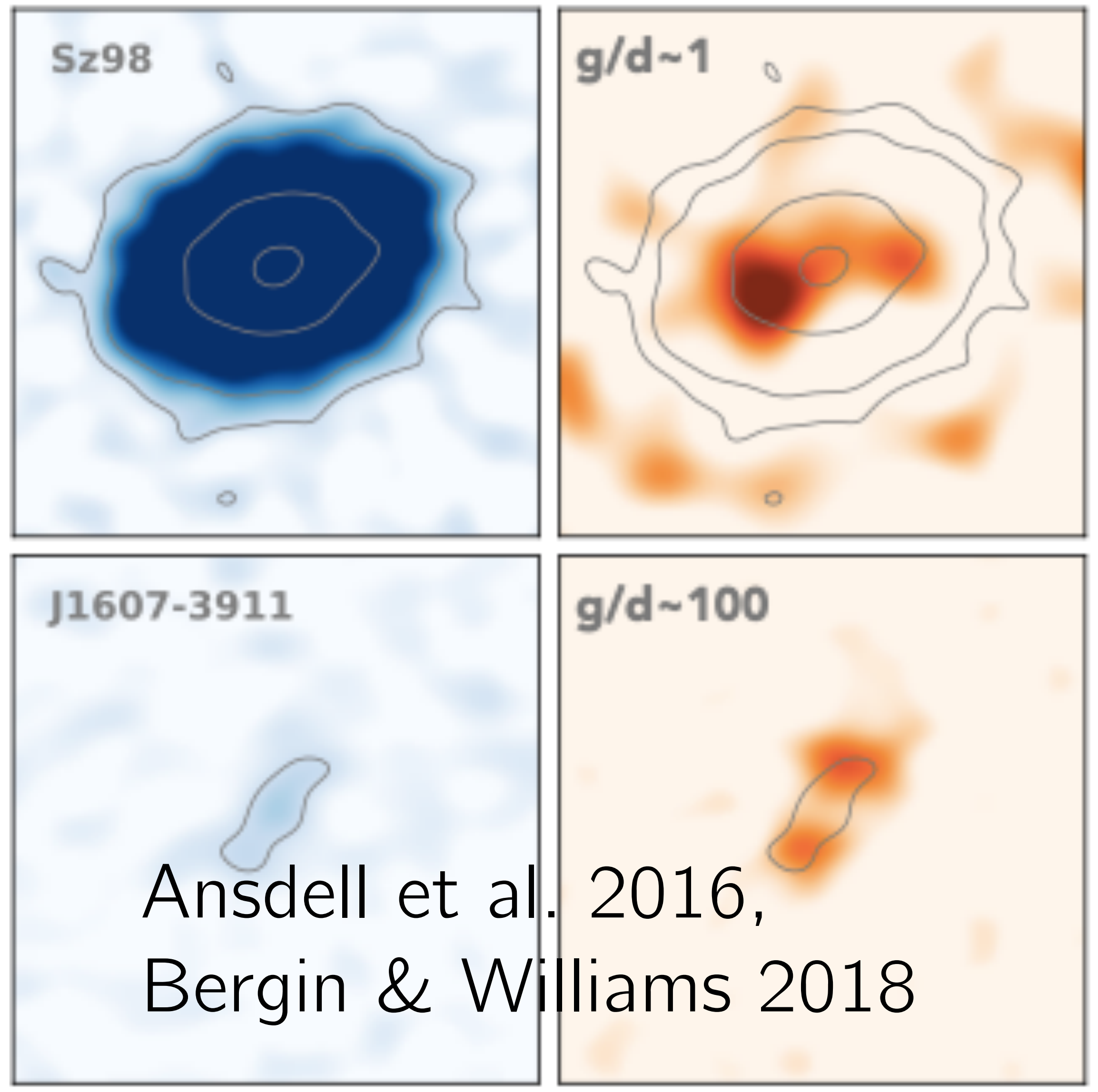
$$M_{\rm disk} \approx 100 \times M_{\rm dust}$$

ISM gas-to-dust ratio (gas is 99% of disk mass)

(From Megan Ansdell slides')

Continuum

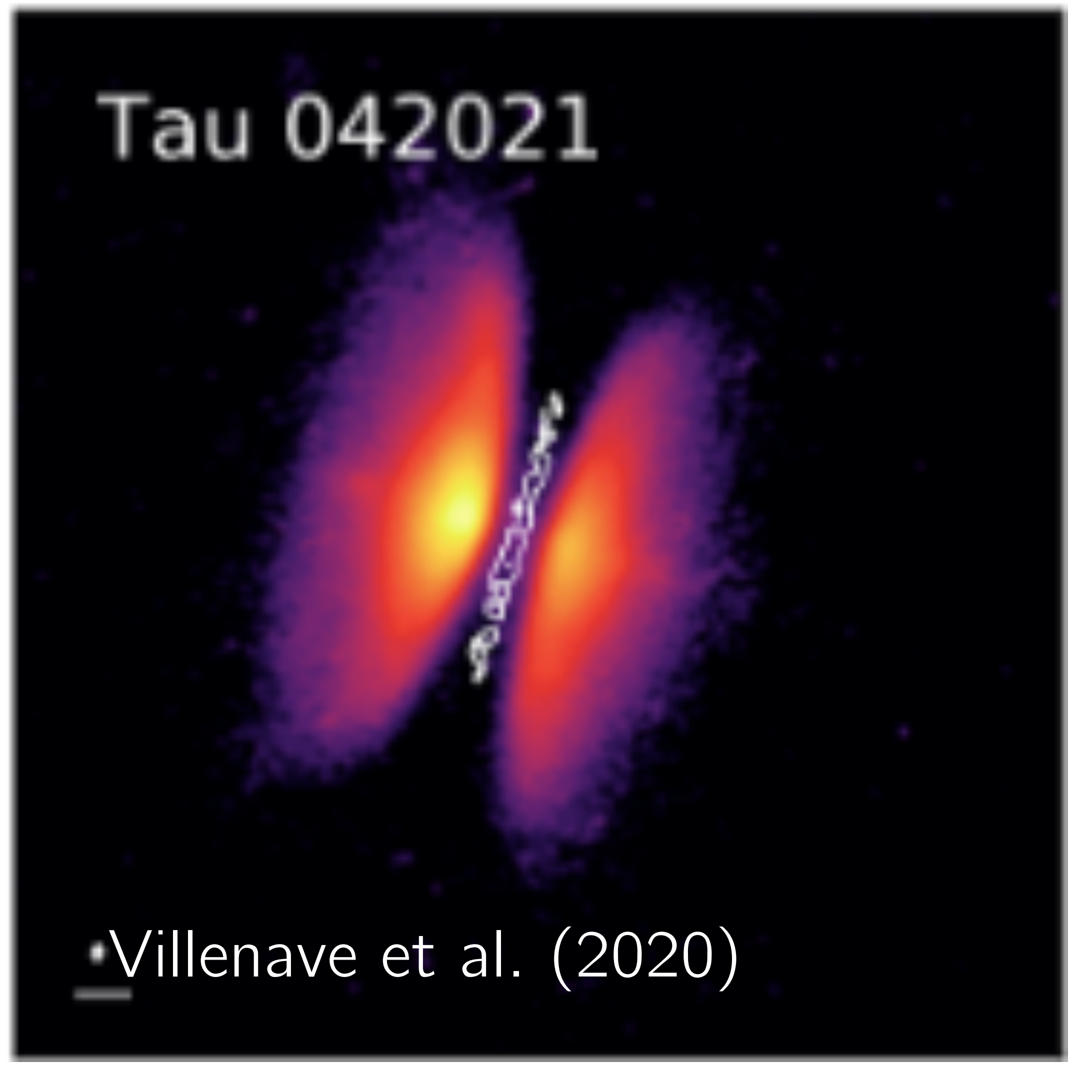
Line



Ansdell et al. 2016, Bergin & Williams 2018

Uncertainties:

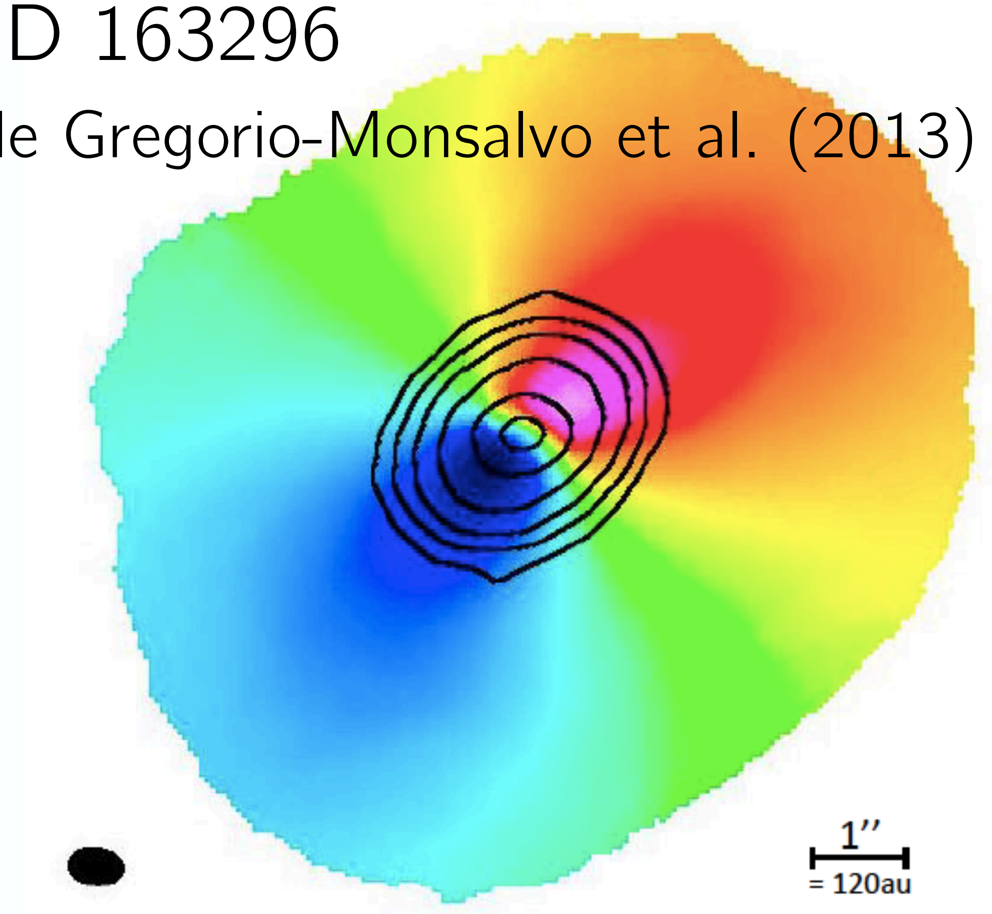
- Gas/dust ISM value = 100 ?? (Draine 2003)
- $R_{\rm gas} \neq R_{\rm dust}$, $H_{\rm gas} \neq H_{\rm dust}$ (drift, settling, viscous evolution of the gas, initial conditions?...)
- Mdust (Manara et al. 2018, Kuffmeier et al. 2017, Tychoniec et al. 2020)



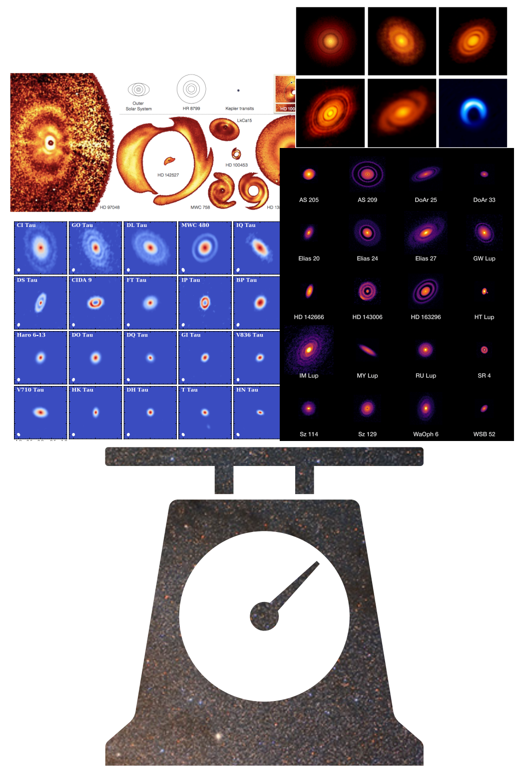
Villenave et al. (2020)

HD 163296

de Gregorio-Monsalvo et al. (2013)



HOW TO WEIGH PROTOPLANETARY DISCS?

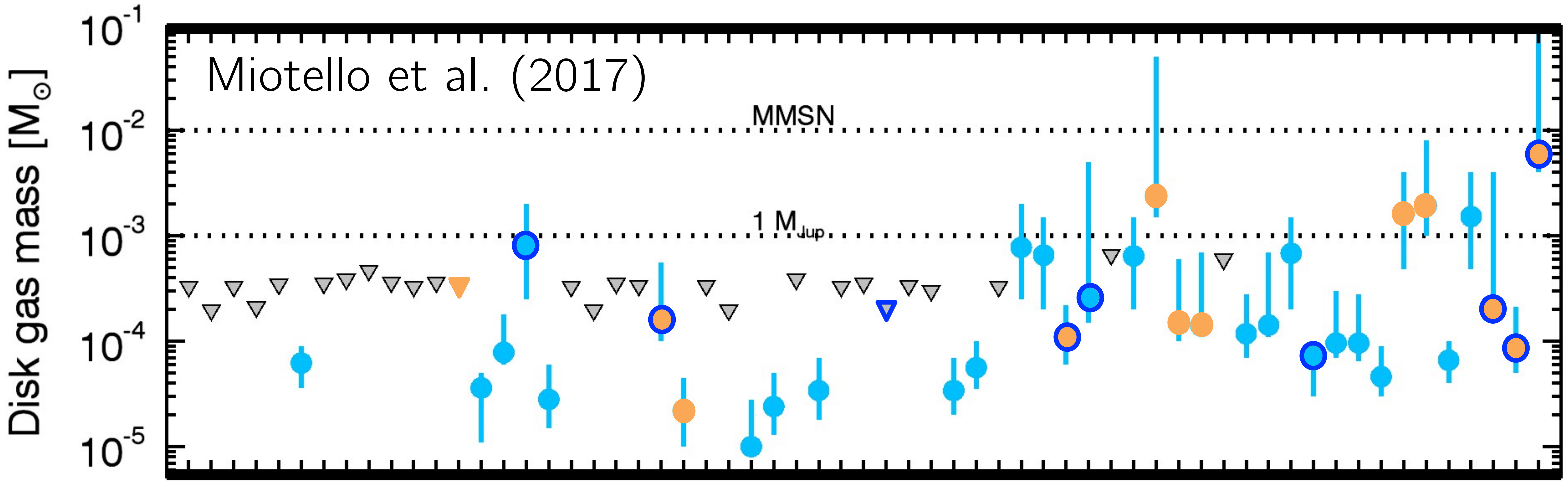


From the gas mass….it's even more difficult!

H_2 not directly detectable: CO isotopologues

Conversion between CO-isotopolgues and H_2 (large uncertainty)

lower limit estimate: low CO-based gas masses and gas-to-dust ratios (Ansdell et al. 2016, Miotello et al. 2017)



WHY? CO-depletion (Favre et al. 2013, Miotello et al. 2017):

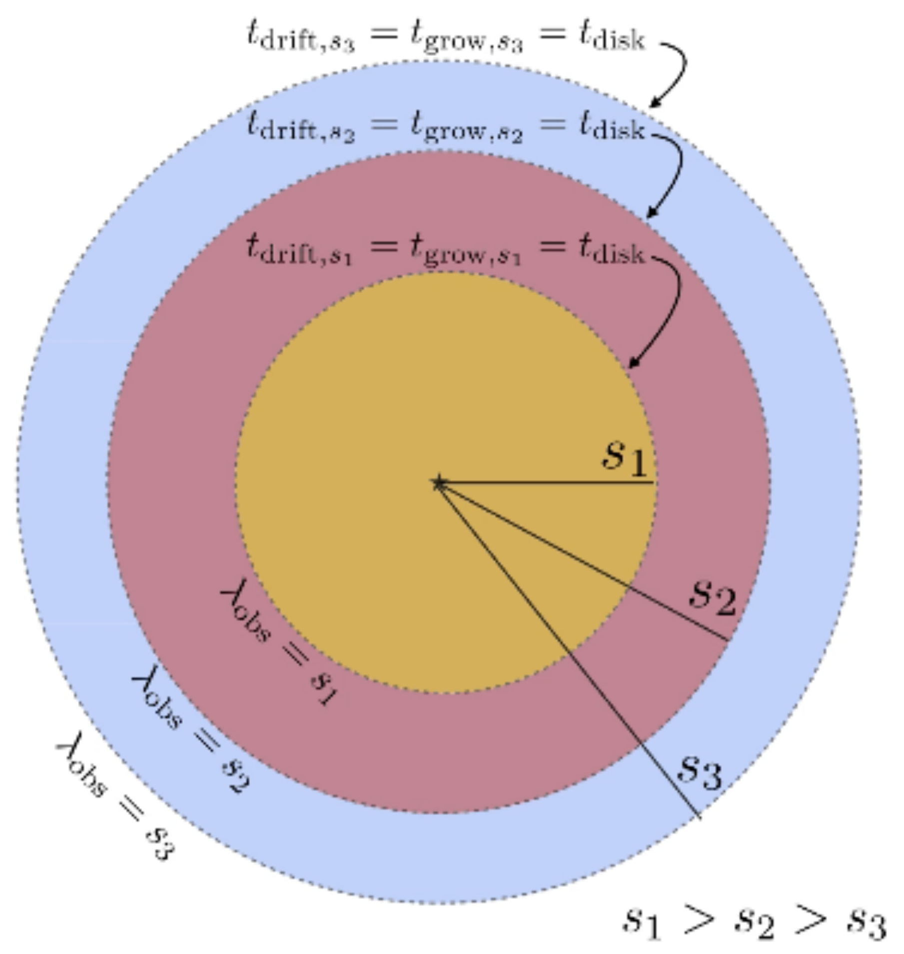
e.g., freeze-out onto dust grains

ALTERNATIVE DISC SCALE

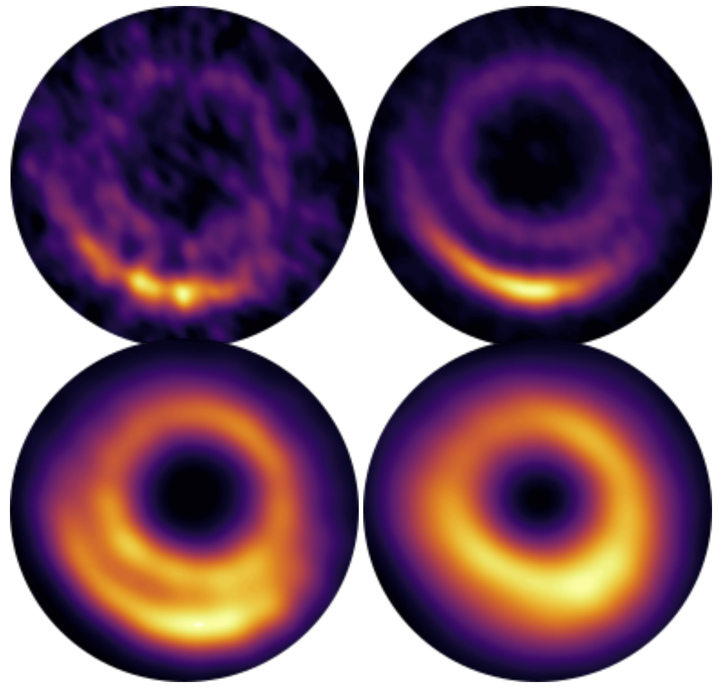
Is there a method to estimate the disc mass which is independent of CO/dust to H_2 conversion factor?

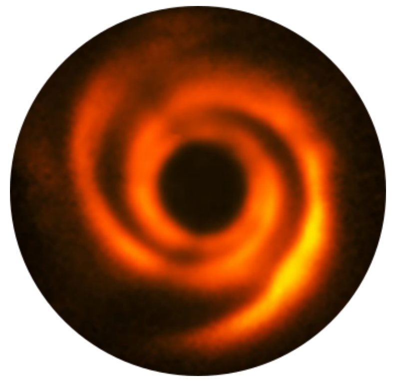
HD measurements → HD does not freeze-out! T vertical structure needed (Trapman et al. 2017) e.g., TWHya (Bergin et al. 2013), DM Tau and GM Aur (McClure et al. 2016)

Disc dust lines at different λ, R_{mm} (Powell et al. 2017,2019) → Total gas surface density estimate
Hyp: $t_{\mathrm{drift,s}} = t_{\mathrm{growth,s}} = t_{\mathrm{disc}}$

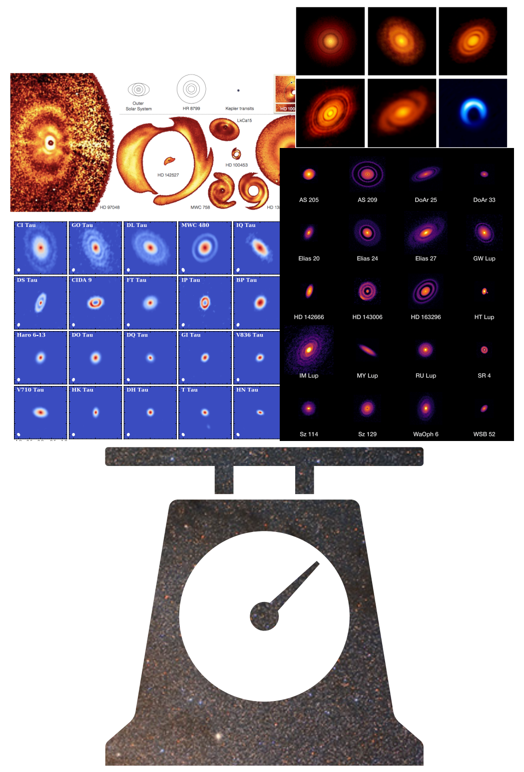


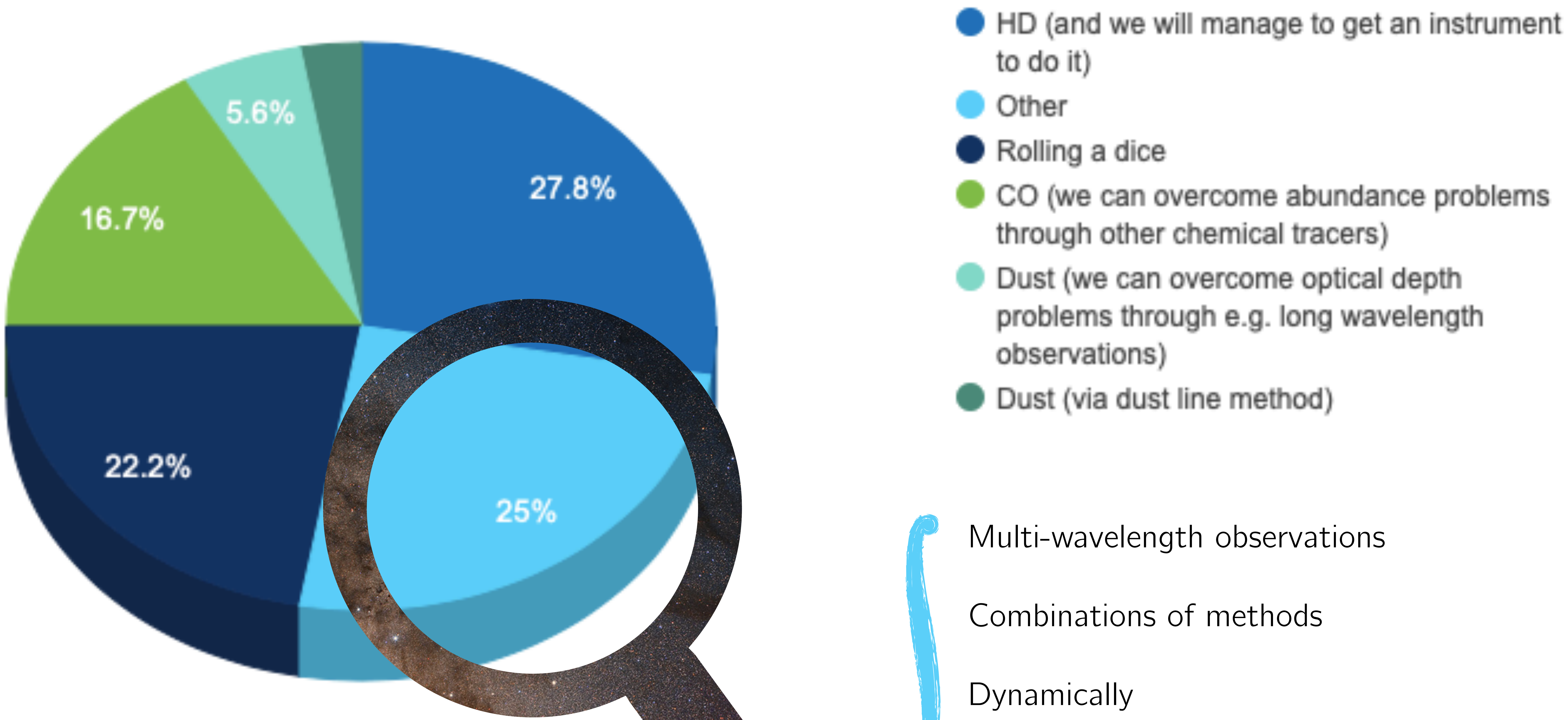
Scattered light vs continuum features Veronesi et al. (2019) → **Dust/gas interaction** as disc **scale** (local surface density estimate)





HOW SHOULD WE WEIGH PROTOPLANETARY DISCS?

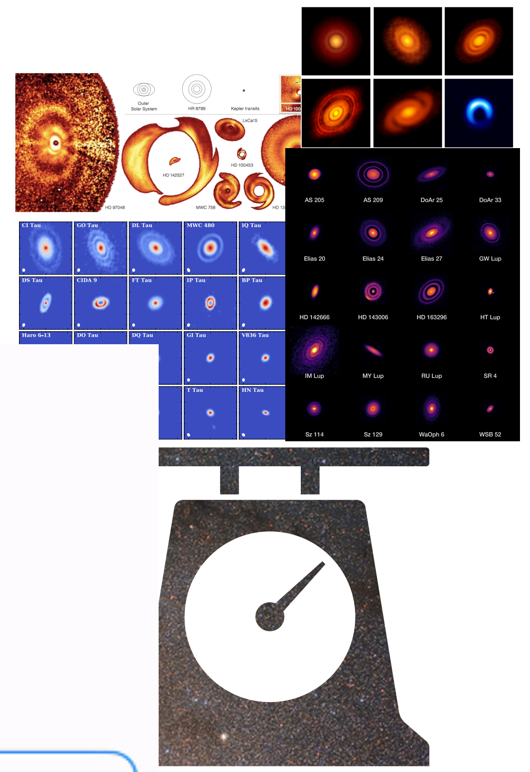


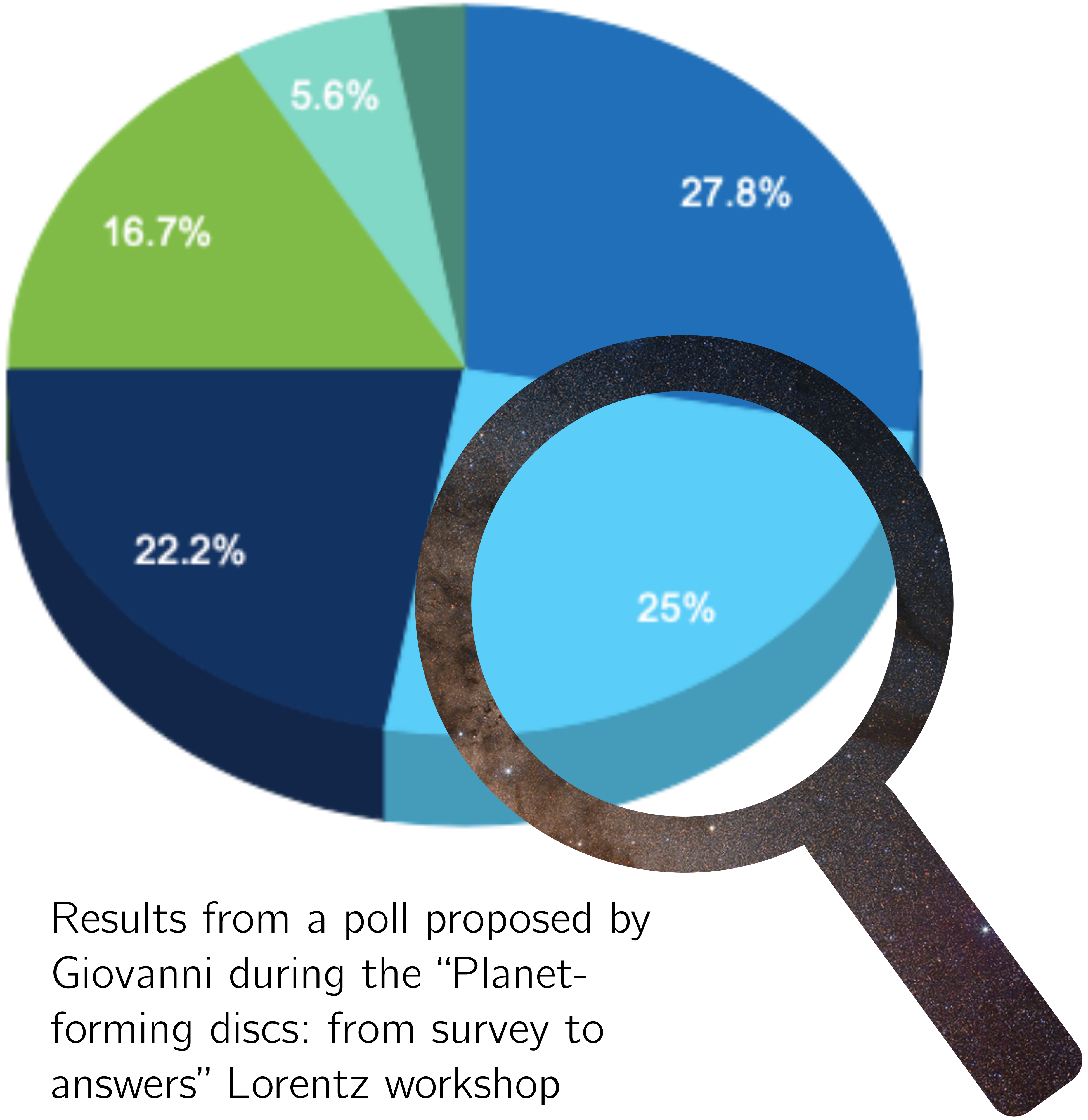


Results from a poll proposed by Giovanni during the “Planet-forming discs: from survey to answers” Lorentz workshop

- Multi-wavelength observations
- Combinations of methods
- Dynamically
- CO + effects of pebble transport in order to interpret CO abundance outside CO snowline
- Dust by long wavelengths / gas by HD (hopefully)
- Combination of dust and gas (e.g. CO and/or HD) after careful calibration

HOW SHOULD WE WEIGH PROTOPLANETARY DISCS?





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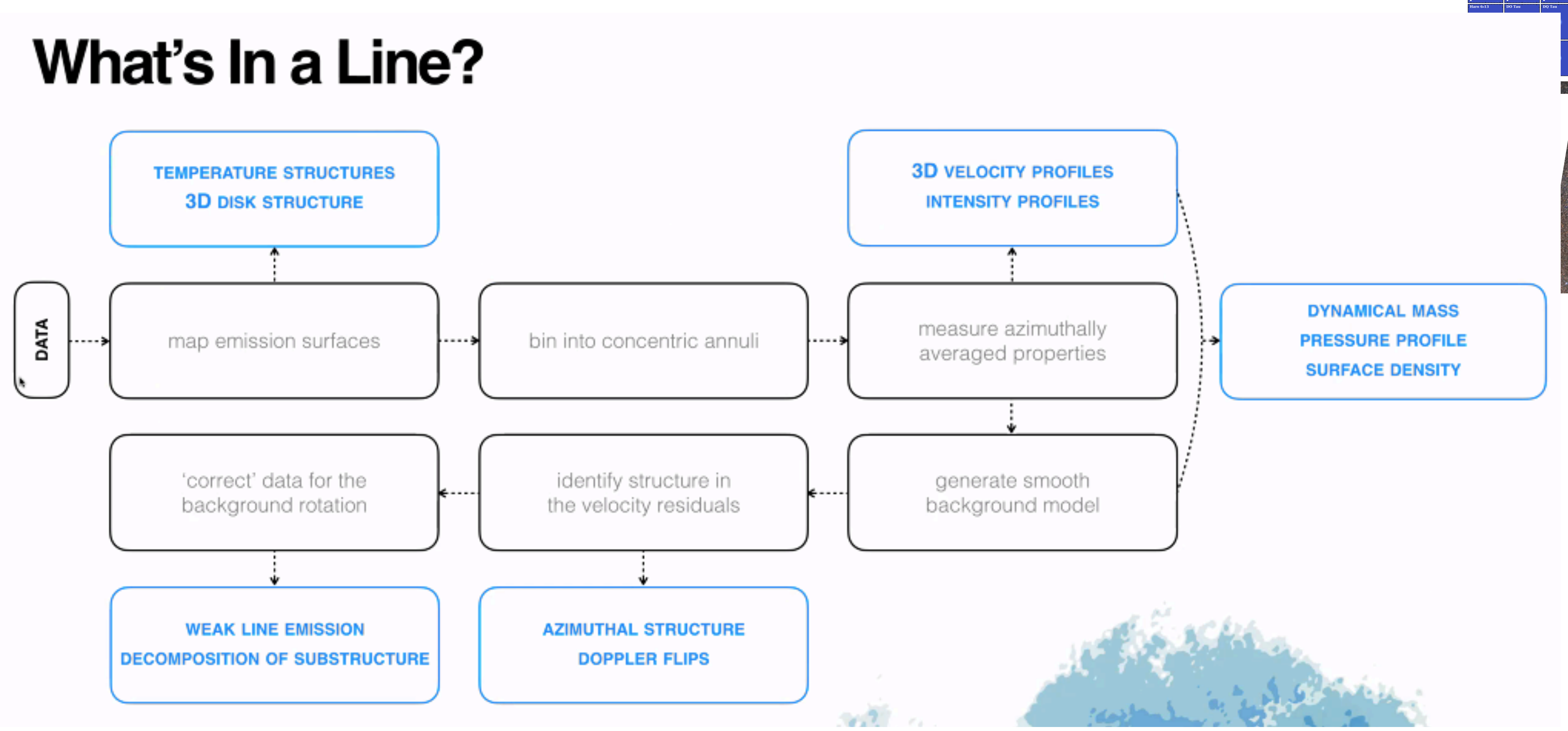
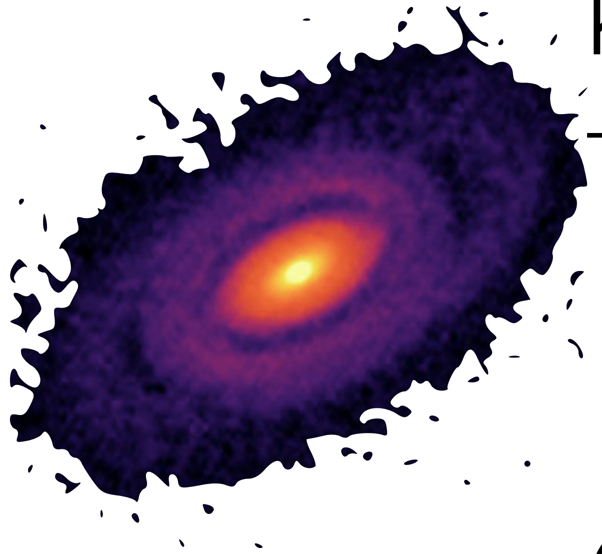


Rich Teague's talk: what we can extract from the kinematics

Dynamically → Searching for **SG** deviation from Keplerianity in the disc rotation curve

This talk, Veronesi et al. (2021), ApJL, 914, 27



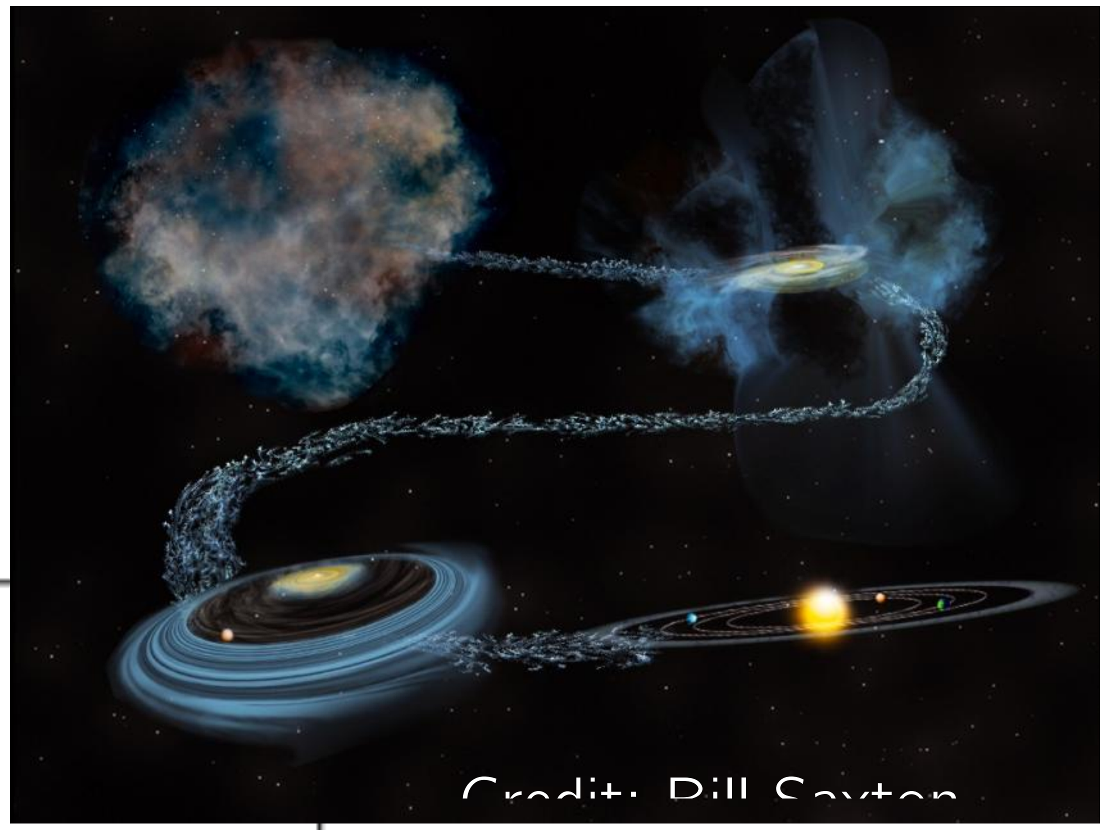
(but also, Mdisc from the GI wiggle, look at Terry et al., subm.)

DISC SELF-GRAVITY IN A NUTSHELL

$$Q = \frac{c_s \kappa}{\pi \mathcal{G} \Sigma} \simeq \frac{M_*}{M_\mathrm{d}} \frac{H}{r} \leq 1 \longrightarrow \frac{M_\mathrm{d}}{M_*} \approx \frac{H}{R} \geq 0.06 - 0.1$$

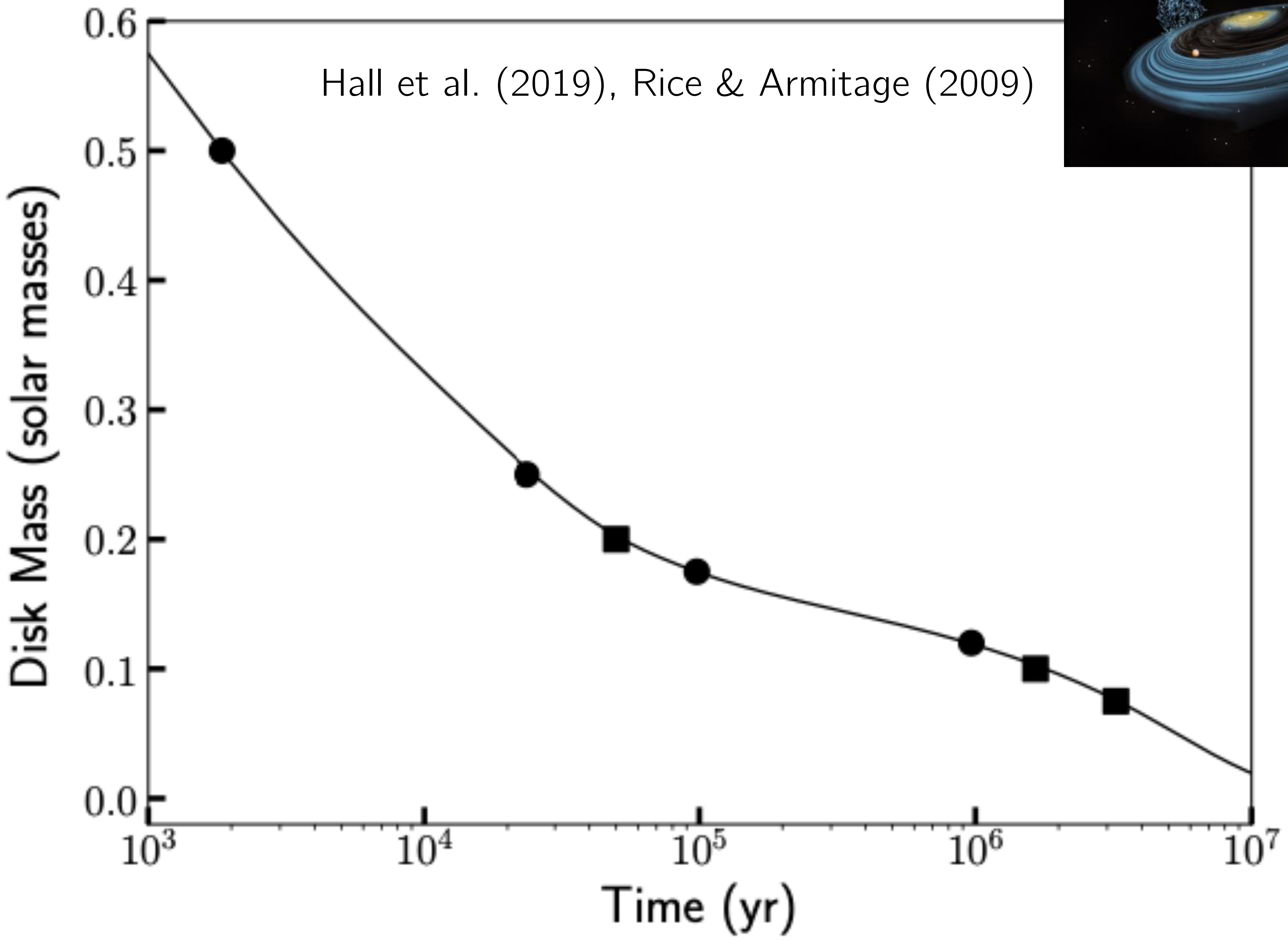
Toomre (1964)

DISC IS SELF-GRAVITATING
UNSTABLE!



Disc self gravity >> thermal pressure + other stabilizing effect, e.g rotation

SG fundamental to understand the entire planet formation process



When?

Initial evolutionary stages, after formation from the parental molecular cloud

→ GI from rapid accretion (see Kaitlin Kratter's tutorial talk) -> stellar companion

Late episode of infall accretion from the MC (e.g. Elias 2-27?)

DISC SELF-GRAVITY IN A NUTSHELL

$$Q = \frac{c_s \kappa}{\pi \mathcal{G} \Sigma} \simeq \frac{M_*}{M_\mathrm{d}} \frac{H}{r} \leq 1 \longrightarrow \frac{M_\mathrm{d}}{M_*} \approx \frac{H}{R} \geq 0.06 - 0.1$$

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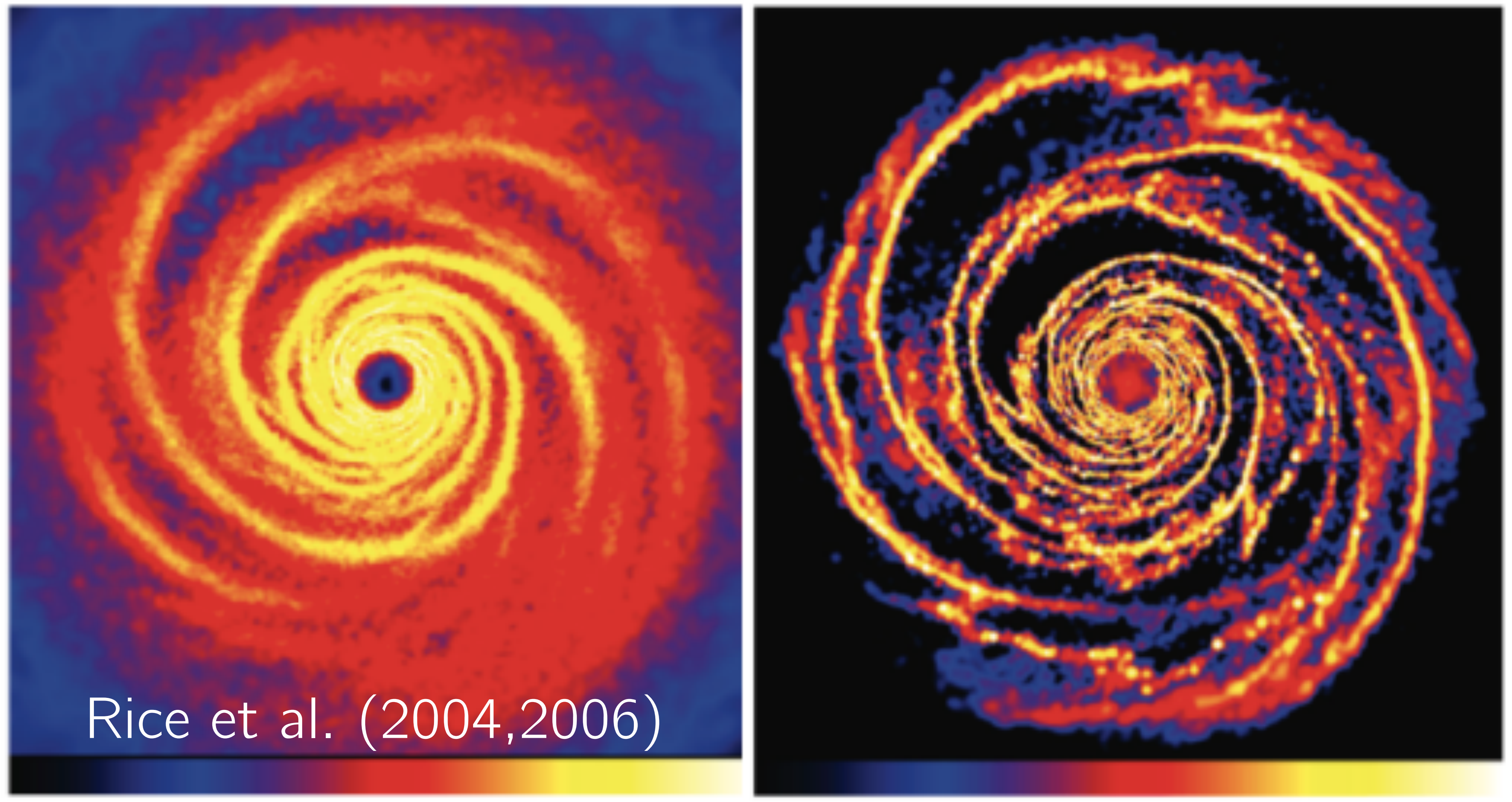


Dust concentration and fragmentation in GI spirals:

Possible starting mechanism of planet formation

(Rice et al. 2004,2006; Longarini et al. in prep, see Giuseppe's talk)

Planet survival in a self-gravitating disc:

- Unlikely with constant cooling β: e.g., Baruteau et al. (2011), Malik et al. (2015)

- Possible with variable cooling $\beta(R)$: e.g., Rowther et al. (2020)

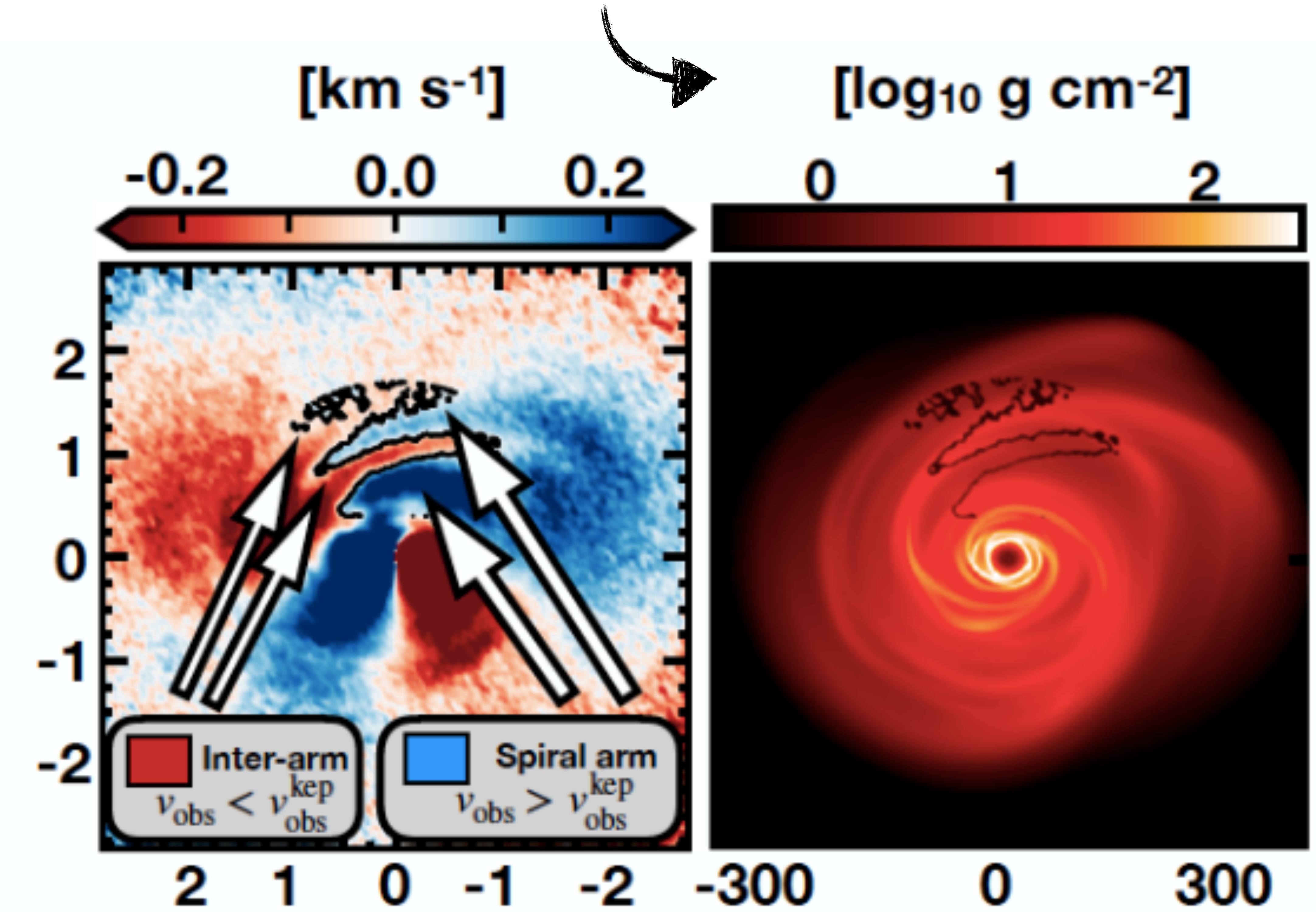
DISC SELF-GRAVITY IN A NUTSHELL

$$Q = \frac{c_s \kappa}{\pi \mathcal{G} \Sigma} \simeq \frac{M_*}{M_\mathrm{d}} \frac{H}{r} \leq 1 \longrightarrow \frac{M_\mathrm{d}}{M_*} \approx \frac{H}{R} \geq 0.06 - 0.1$$

DISC IS SELF-GRAVITATING UNSTABLE!

Toomre (1964)

SG fundamental to understand the entire planet formation process



Hall et al., including Veronesi B. (2020)

Self-gravity contributes to the gravitational potential:

- **basic state**: **super-Keplerian rotation curve**

(e.g., Lodato & Bertin 2003; Veronesi et al. 2021)

- **non axisymmetric perturbation: GI spirals** -> wiggle

(Hall et al. 2020, Terry et al. 2021, Longarini et al. 2021)

DISC SELF-GRAVITY IN A NUTSHELL

$$Q = \frac{c_s \kappa}{\pi \mathcal{G} \Sigma} \simeq \frac{M_*}{M_\mathrm{d}} \frac{H}{r} \leq 1 \rightarrow \frac{M_\mathrm{d}}{M_*} \approx \frac{H}{R} \geq 0.06 - 0.1$$

Morphological difference between planets or by GI spiral arms (e.g., Dong et al. 2018, Jaehan's talk):

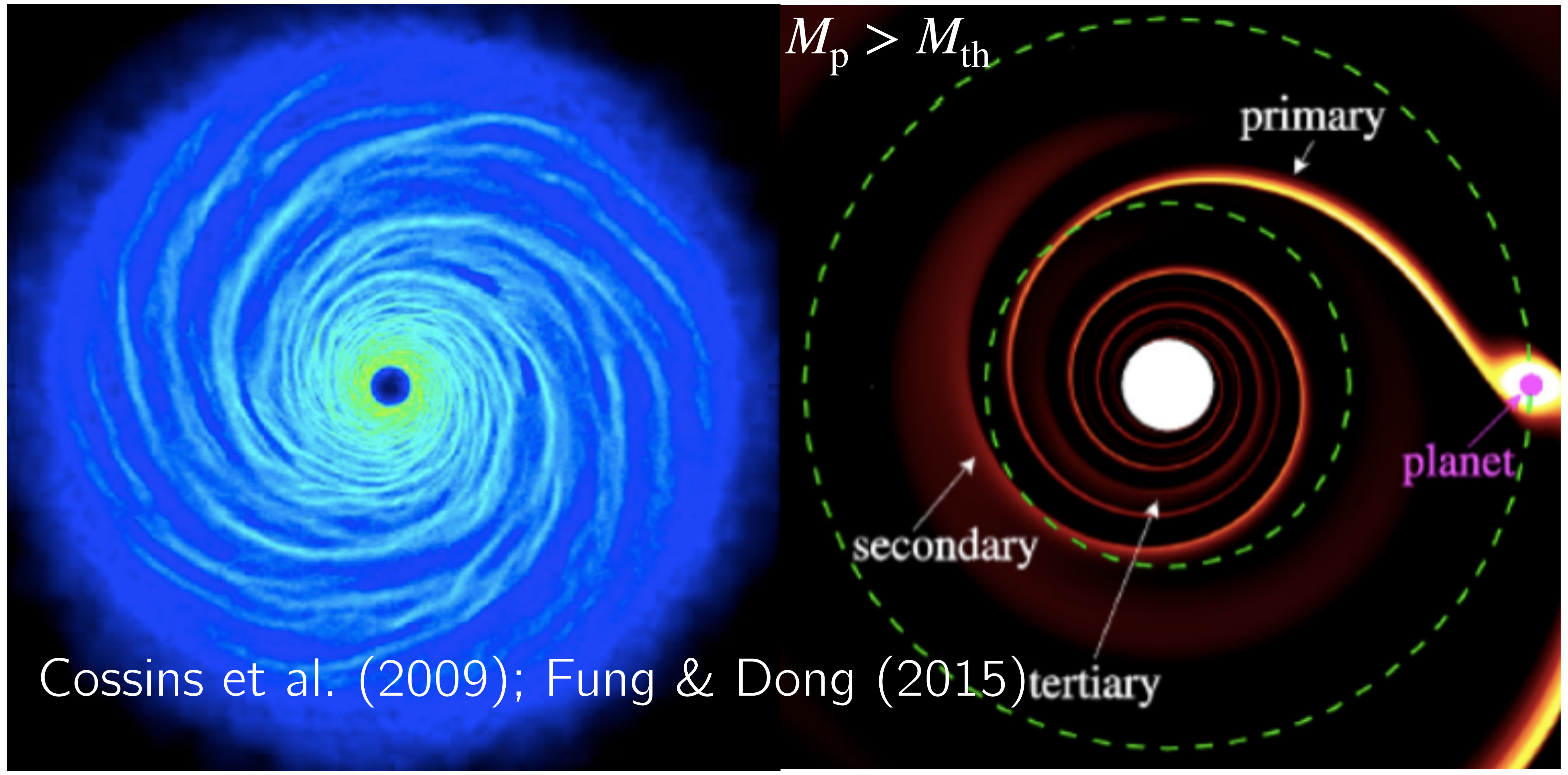
- Pitch angle (constant for GI, e.g., Forgan et al. 2018)

- Number of modes m ($m \leq 3$ for planets, more for GI, **but Dipierro et al. 2014**)

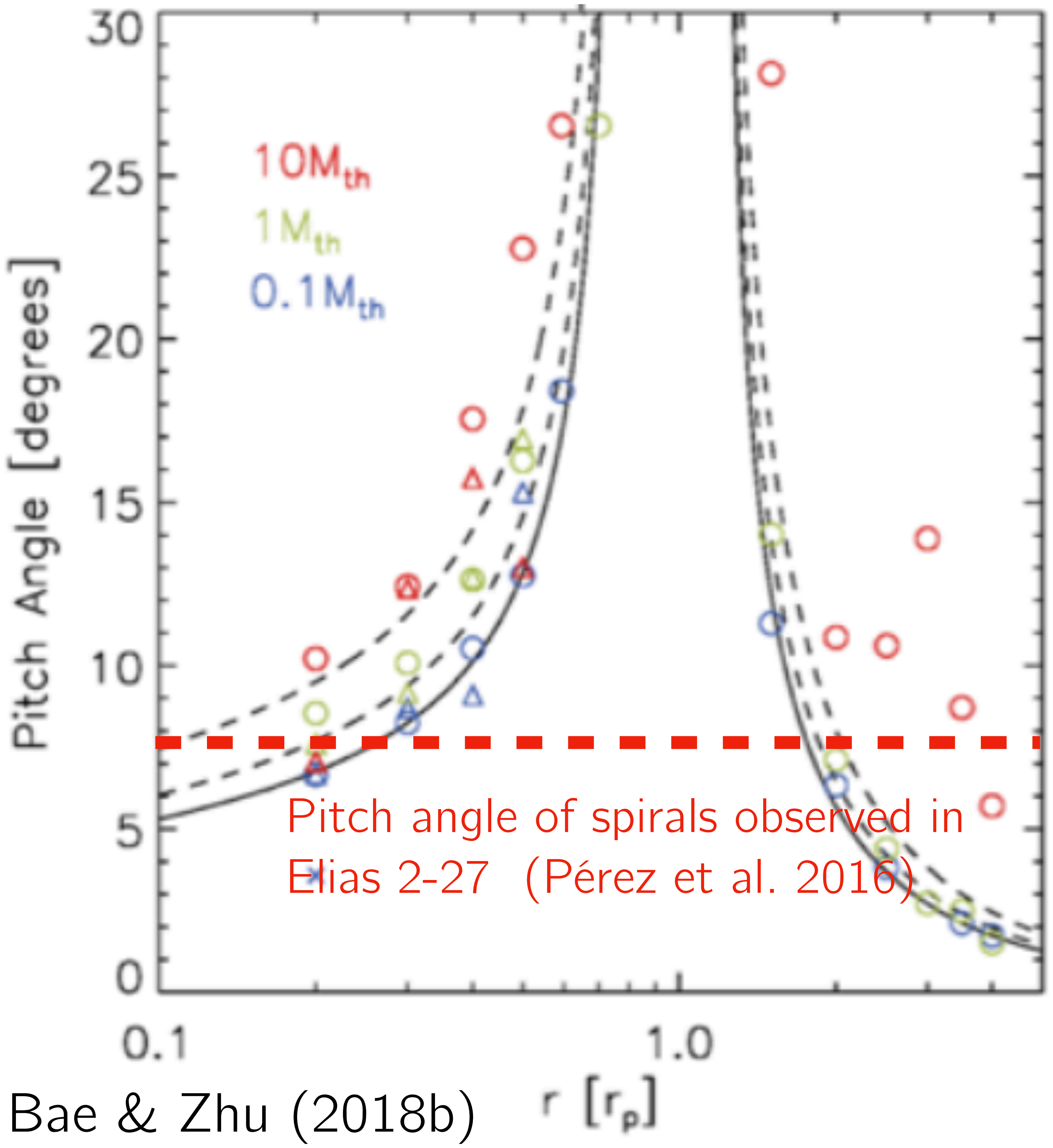
- Velocity of the spiral arm (GI spirals can trap dust, Rice et al. 2004,2006)

$$i \approx \tan^{-1}\left(\frac{c_s}{[r\left|\Omega_\mathrm{k} - \Omega_p\right|]}\right)$$

Planet induced spirals pitch angle



Cossins et al. (2009); Fung & Dong (2015)



Bae & Zhu (2018b)

A DYNAMICAL MASS ESTIMATE: WHO?

Is there a method to estimate the disc mass which is independent of CO/dust to H_2 conversion factor?

THE CANDIDATE: ELIAS 2-27

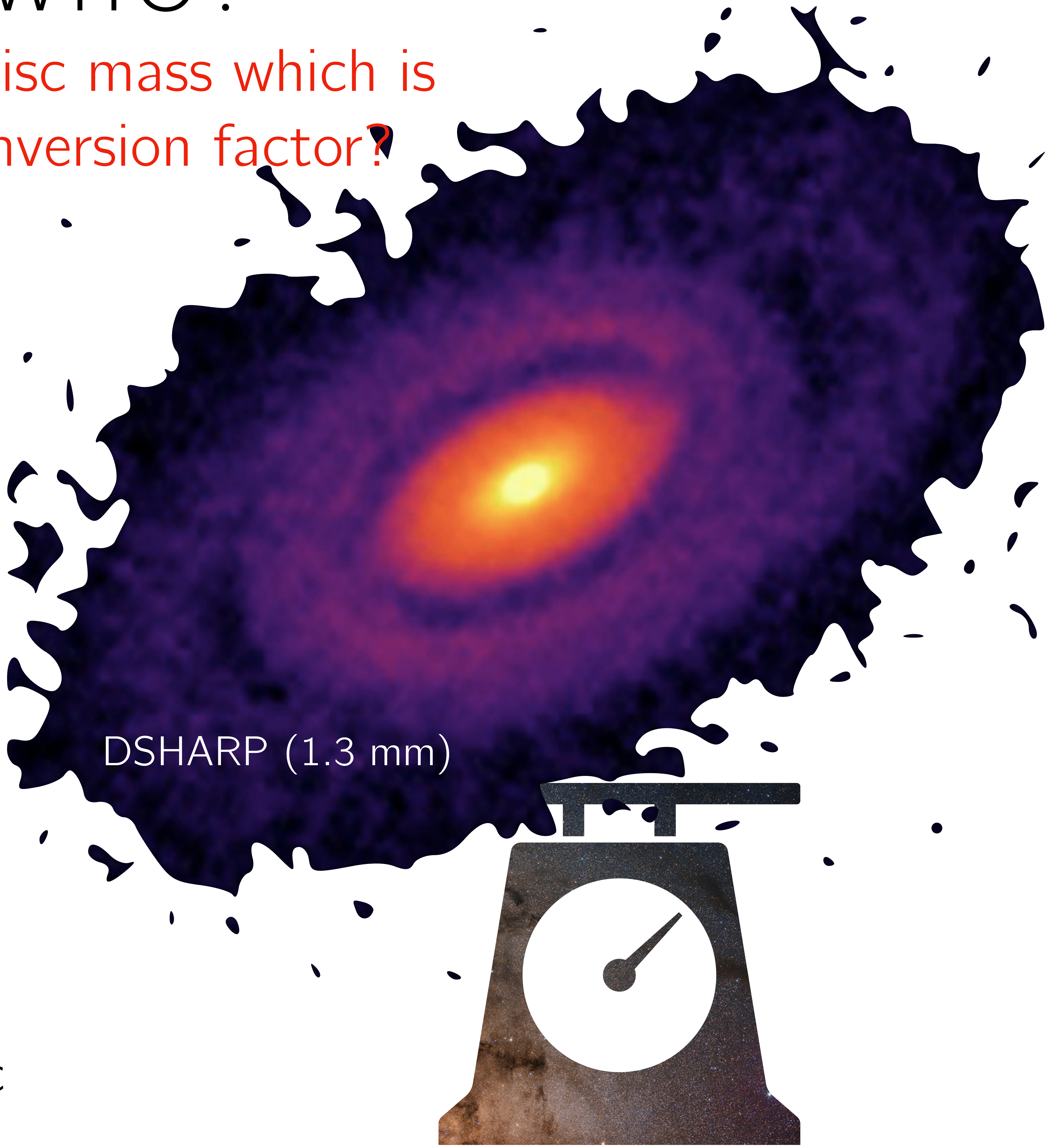
Elias 2-27: 0.8 Myr, M0 star, d=140 pc

Two large-scale spiral arms
(Pérez et al. 2016a; Andrews et al. 2018, Paneque-Carreno et al. 2021)

Disc-to-star ≈ 0.3, considering gas/dust=100
(Andrews et al. 2009; Pérez et al. 2016; Meru et al. 2017; Hall et al. 2018; Cadman et al. 2020; Paneque-Carreno et al. 2021)

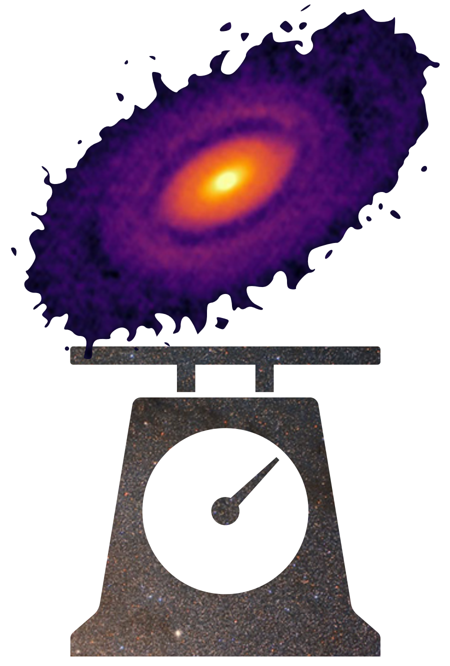
Possible origin for the spiral arms: gravitational instabilities
(Meru et al. 2017, Hall et al. 2018, Paneque-Carreno et al. 2021)

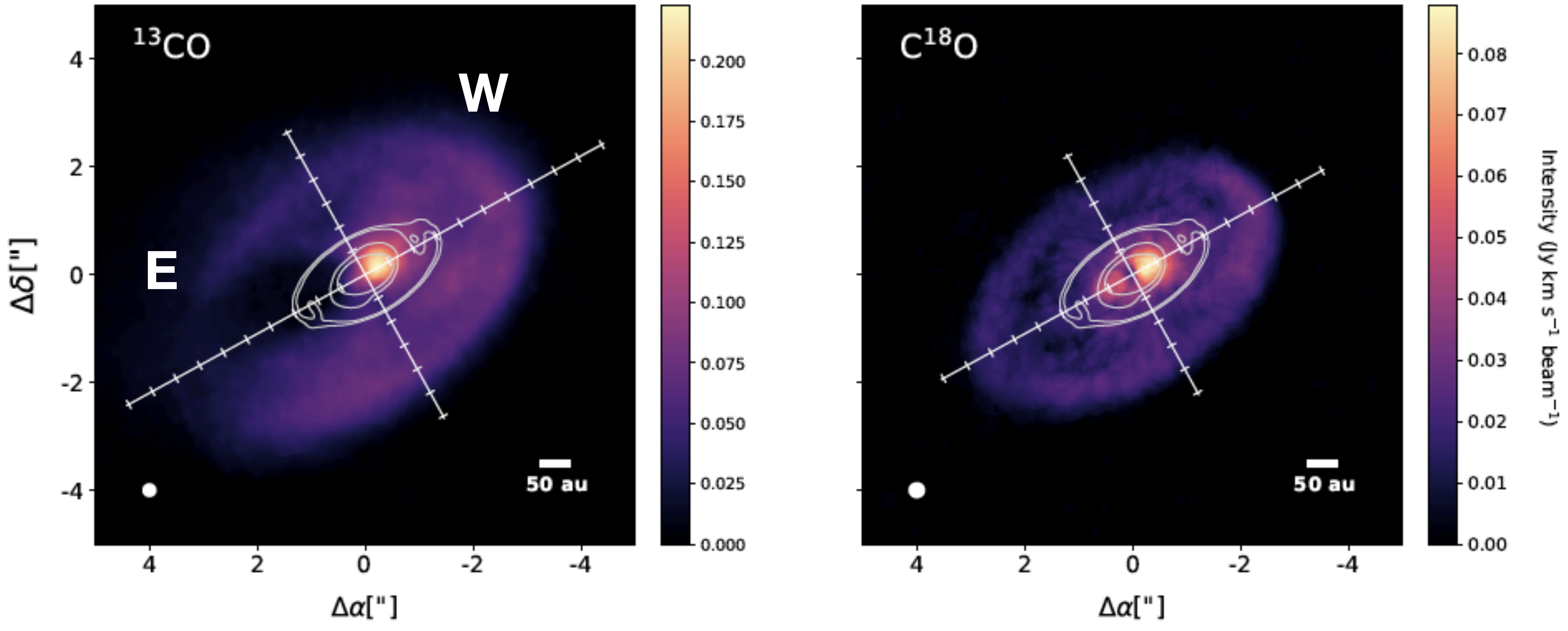
Inner gap at ~ 60 au: possible companion formed after disc fragmentation? (Huang et al. 2018)



Observations from: Peréz et al. (2016), Huang at al. (2018), Paneque-Carreno et al. including **Veronesi B.** (2021)

A DYNAMICAL MASS ESTIMATE: THE DATA



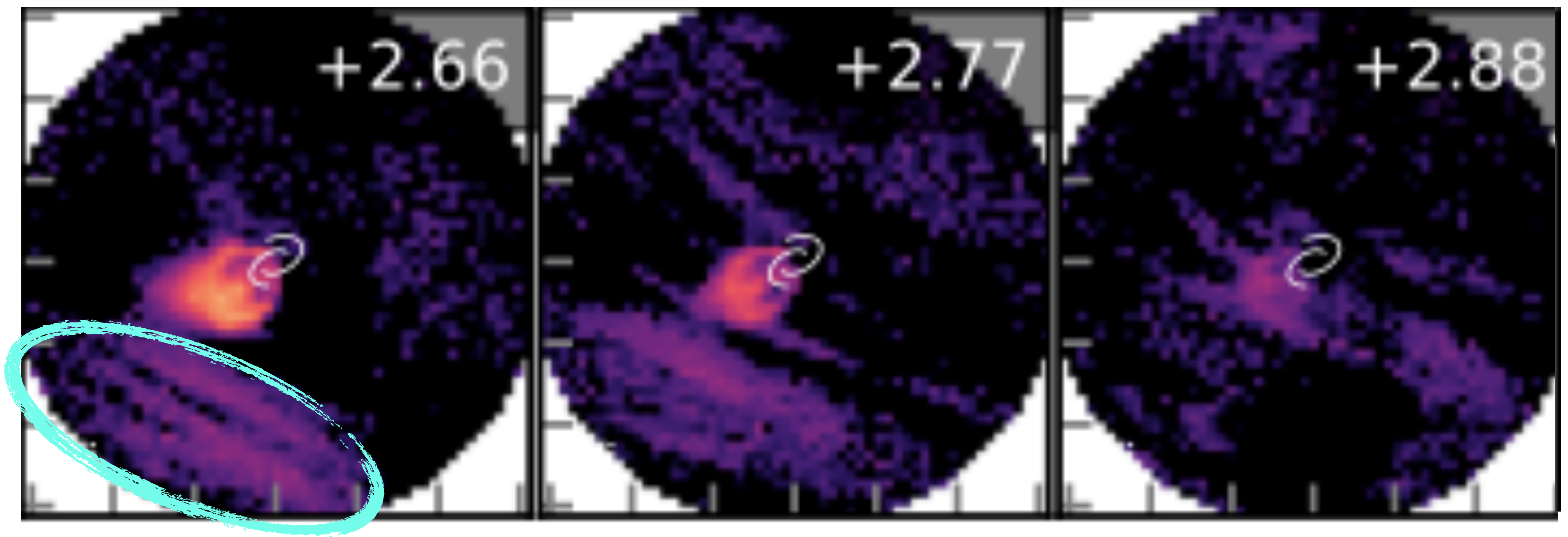


Asymmetry between East and West side

East side: more extended and cloud-contaminated.

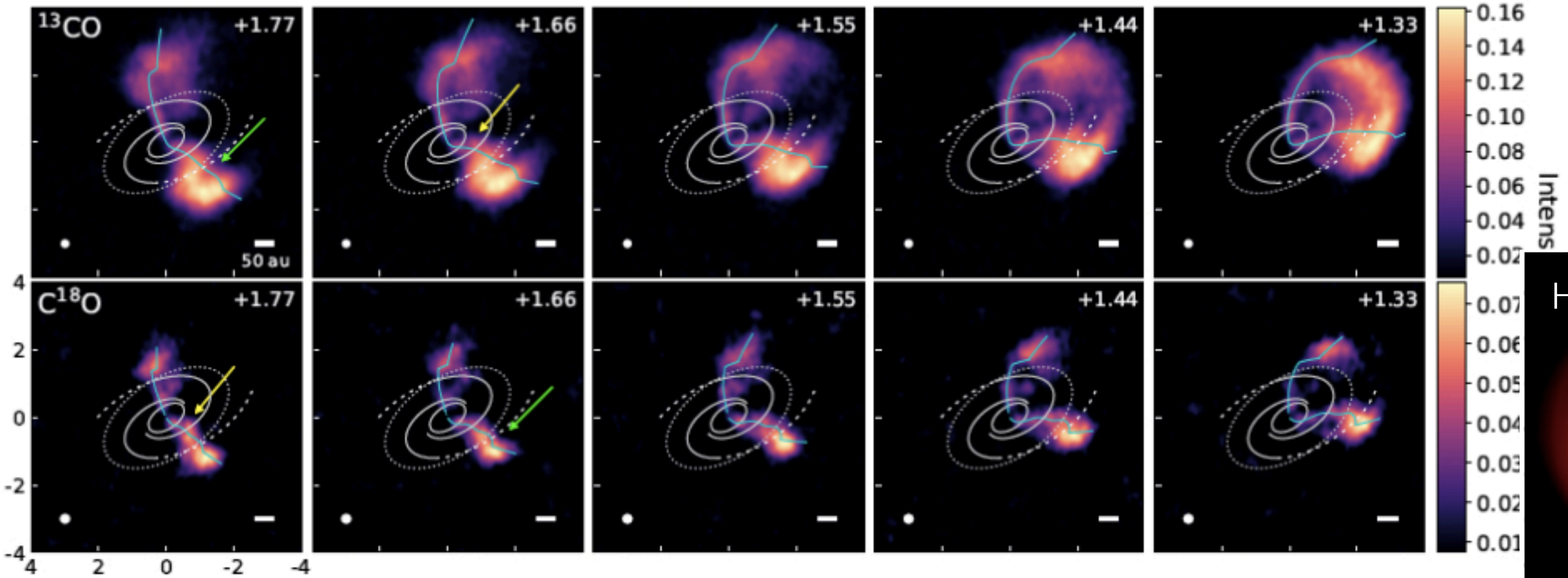
Infall? Chaotic accretion? Connection with large-scale structures?

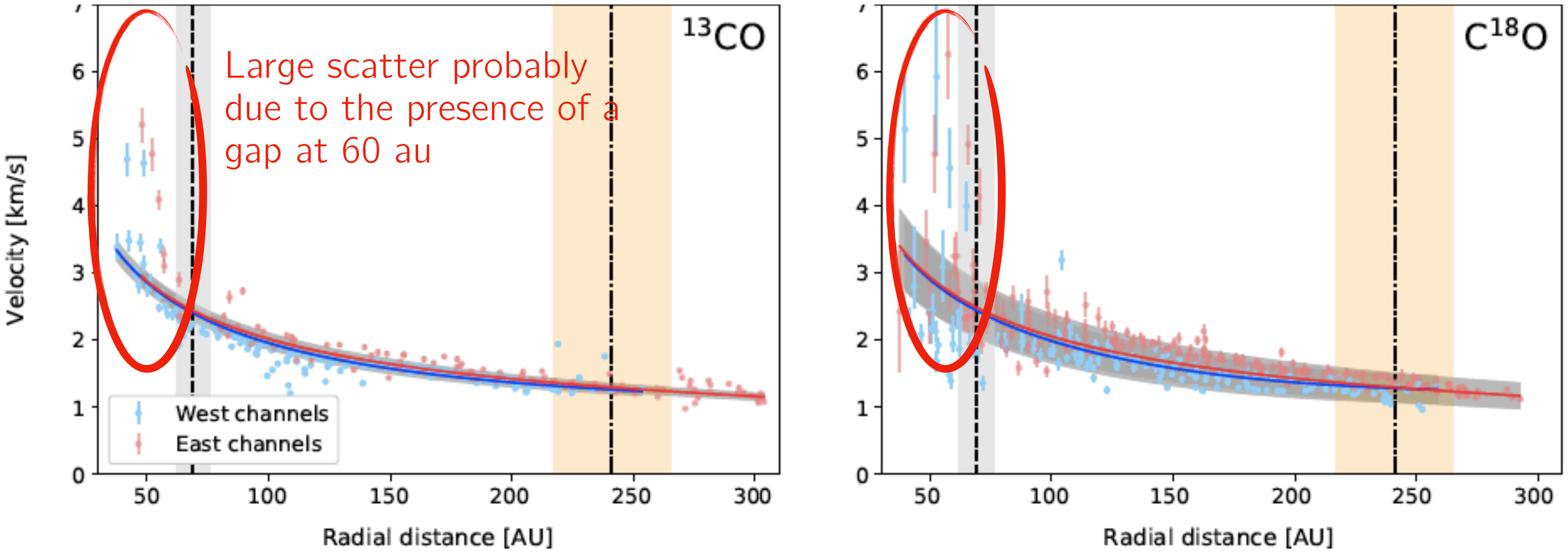
Zoom in...

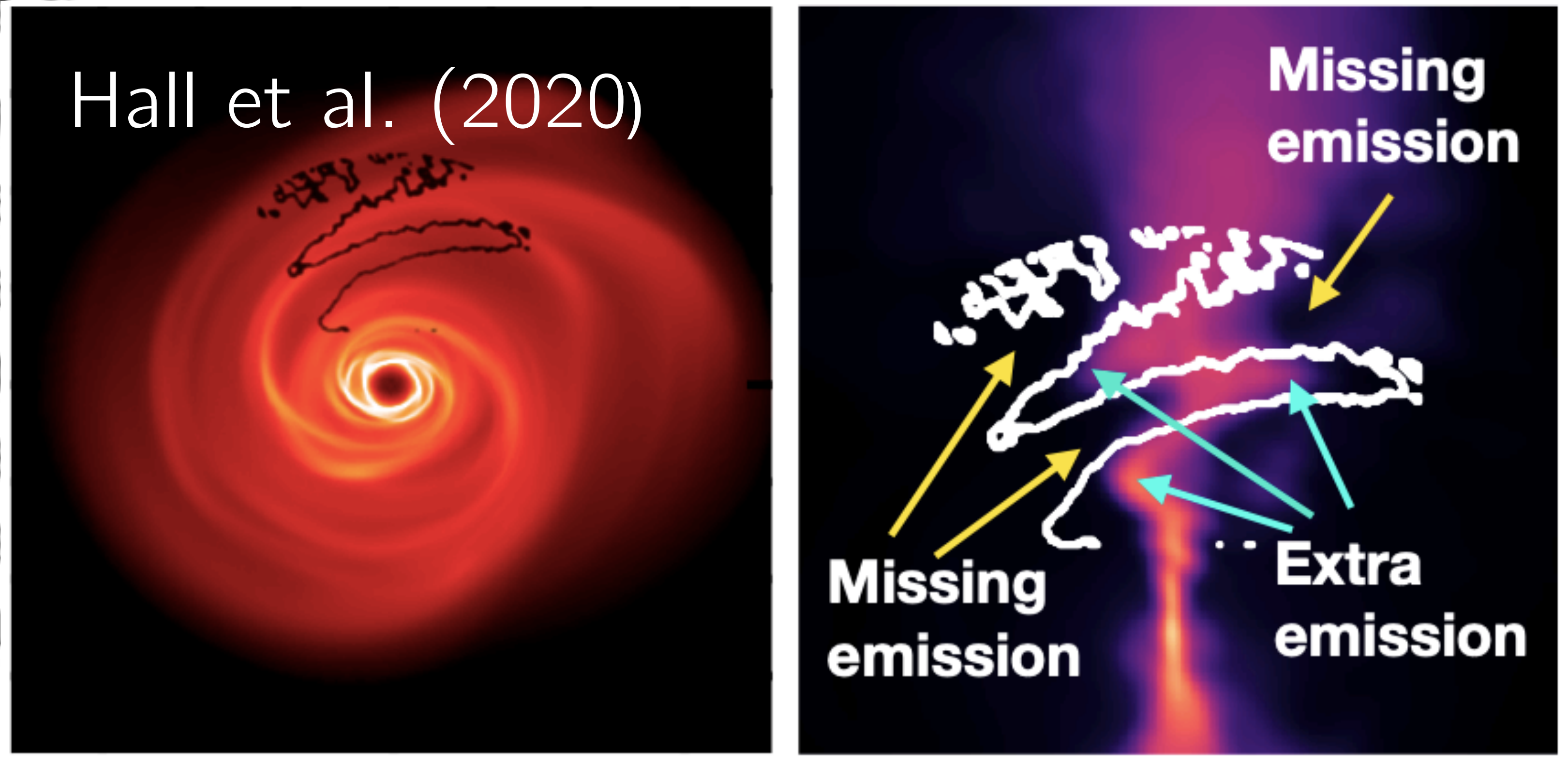


Paneque-Carreno et al., including **Veronesi B.** (2021)

A DYNAMICAL MASS ESTIMATE: THE DATA



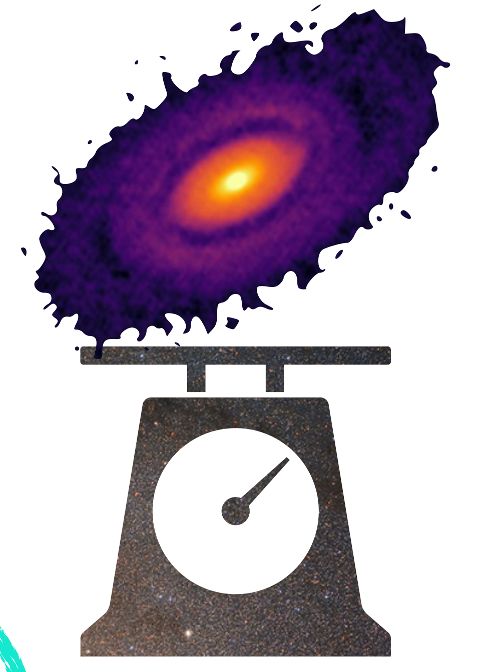




Derivation of the **gas emitting layer height z(r),** and of the **rotation curve** with geometrical method described in Pinte et al. (2018)

Paneque-Carreno et al., including **Veronesi B.** (2021)

IDEA: A DYNAMICAL MASS ESTIMATE



$M_{\rm disc} \ll M_\star$ Keplerian disc

mass of the central object

$$\Omega^2 \sim \frac{\mathcal{G} M_\star}{\left(R^2 + z(R)^2\right)^{3/2}} \quad \xrightarrow{\text{BUT!}} \quad \Omega^2 \sim \frac{1}{R}\frac{\mathrm{d}\Phi_{\rm disc}}{\mathrm{d}R}(R,z) + \frac{\mathcal{G} M_\star}{\left(R^2 + z(R)^2\right)^{3/2}} + \frac{1}{R}\frac{1}{\rho}\frac{\mathrm{d}P}{\mathrm{d}R}$$

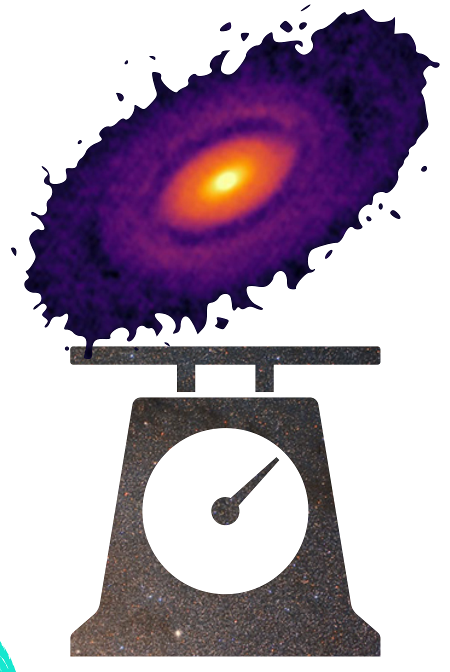
disc self-gravity → For a MASSIVE disc this term MATTERS

$$O\left(\frac{M_{\rm disc}}{M_\star}\right) \sim O\left(\frac{H}{R}\right)$$

pressure term

$$O\left(\frac{H^2}{R^2}\right)$$

IDEA: A DYNAMICAL MASS ESTIMATE



$$\Sigma(R) = \Sigma_c \left(\frac{R}{R_c}\right)^{-p} \exp\left[-\left(\frac{R}{R_c}\right)^{2-p}\right]$$

$T(R) \propto R^{-0.5}$

Pérez et al. (2016), Paneque-Carreño et al. (2021)

$$z(R) = z_0 \left(\frac{R}{R_0}\right)^{\psi} + z_1 \left(\frac{R}{R_0}\right)^{\varphi}$$

Paneque-Carreño et al. (2021)

mass of the central object

$$\Omega^2 \sim \frac{1}{R}\frac{\mathrm{d}\Phi_{\mathrm{disc}}}{\mathrm{d}R}(R, z) + \frac{\mathcal{G}M_\star}{\left(R^2 + z(R)^2\right)^{3/2}} + \frac{1}{R}\frac{1}{\rho}\frac{\mathrm{d}P}{\mathrm{d}R}$$

pressure term

For a MASSIVE disc this term MATTERS

$$\frac{\partial \Phi_{\mathrm{disc}}}{\partial r}(r, z) = \frac{G}{r}\int_0^\infty \left[K(k) - \frac{1}{4}\left(\frac{k^2}{1-k^2}\right) \times \left(\frac{r'}{r} - \frac{r}{r'} + \frac{z^2}{rr'}\right) E(k)\right] \sqrt{\frac{r'}{r}} k \Sigma(r')\, dr'$$

$$k^2 = \frac{4RR'}{\left[(R+R')^2 + z^2\right]}$$

Lodato & Bertin (1999,2003)

deviations from Keplerian rotation in protoplanetary disc with a self-gravitating model → Infer simultaneously the disc and star mass

POWER-LAW FIT

Power-law with free index

$$v(R) = v_0 \cdot R^{-p} \longrightarrow \begin{cases} p < 0.5 & \text{Flatter: hints of SG disc} \\ p = 0.5 & \text{Keplerian disc} \\ p > 0.5 & \text{Steeper: Warp geometry, other processes} \end{cases}$$

p	Combined	Individual isotopologues	West side
Both	0.43 ± 0.03		0.44 ± 0.04
^{13}CO		0.43 ± 0.03	0.42 ± 0.05
C^{18}O		$0.54^{+0.09}_{-0.10}$	$0.58^{+0.12}_{-0.13}$

There are hints that the disc self-gravity is important

Larger uncertainties on p:
C^{18}O data less constrained

Two analytical competing models:

SG model

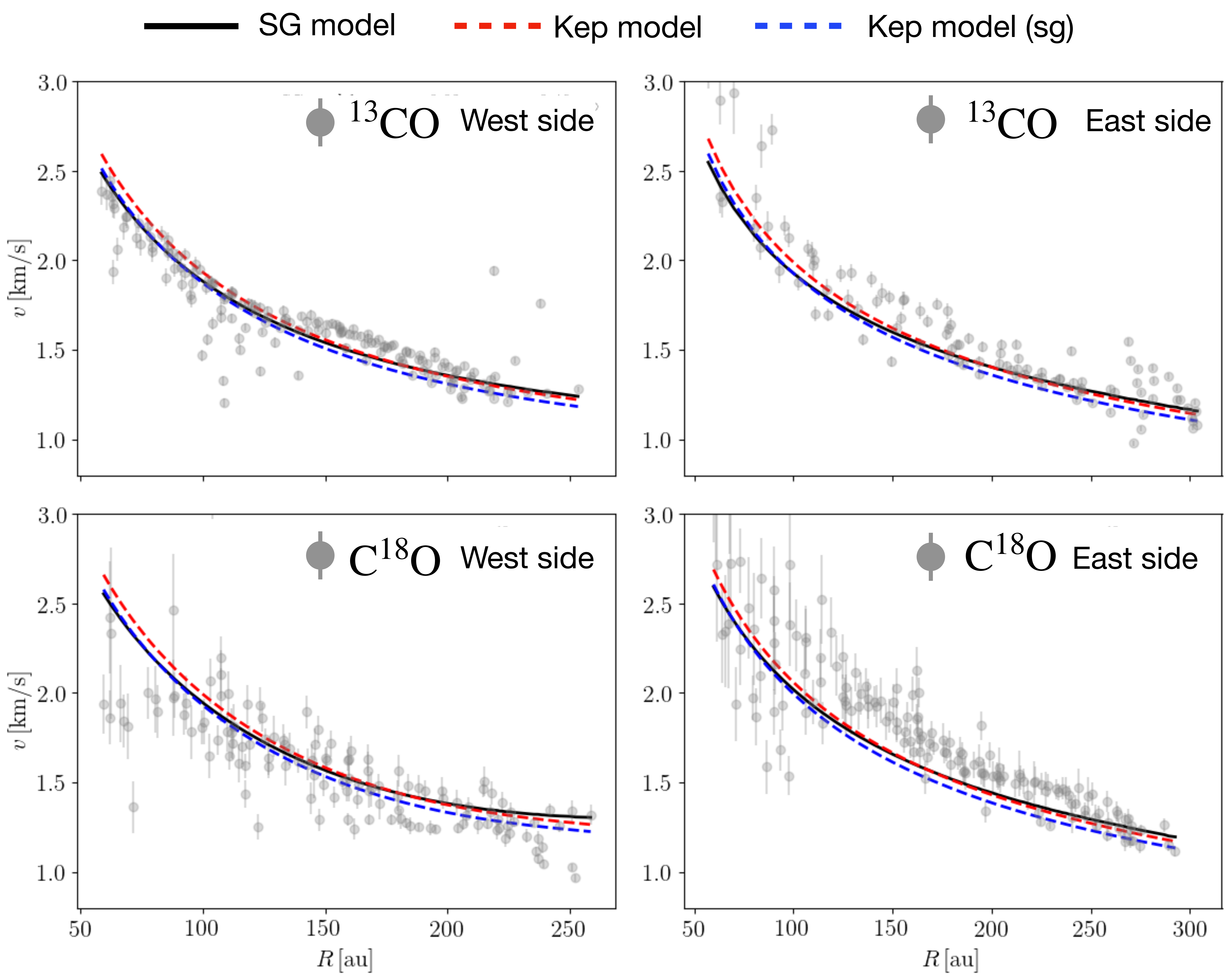
$$\Omega^2 \sim \frac{1}{R}\frac{\mathrm{d}\Phi_{\mathrm{disc}}}{\mathrm{d}R}(R,z) + \frac{\mathcal{G}M_\star}{\left(R^2 + z(R)^2\right)^{3/2}} + \frac{1}{R}\frac{1}{\rho}\frac{\mathrm{d}P}{\mathrm{d}R}$$

VS

Kep model

$$\Omega^2 \sim \frac{\mathcal{G}M_\star}{\left(R^2 + z(R)^2\right)^{3/2}}$$

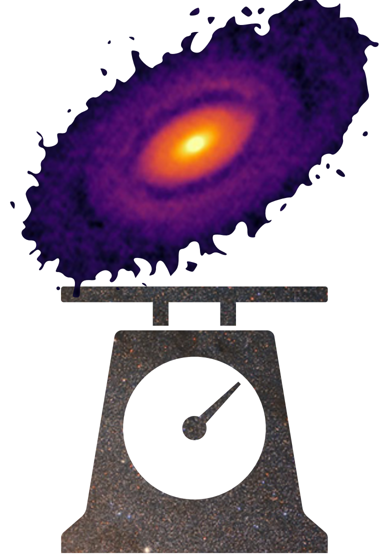
FITS RESULTS

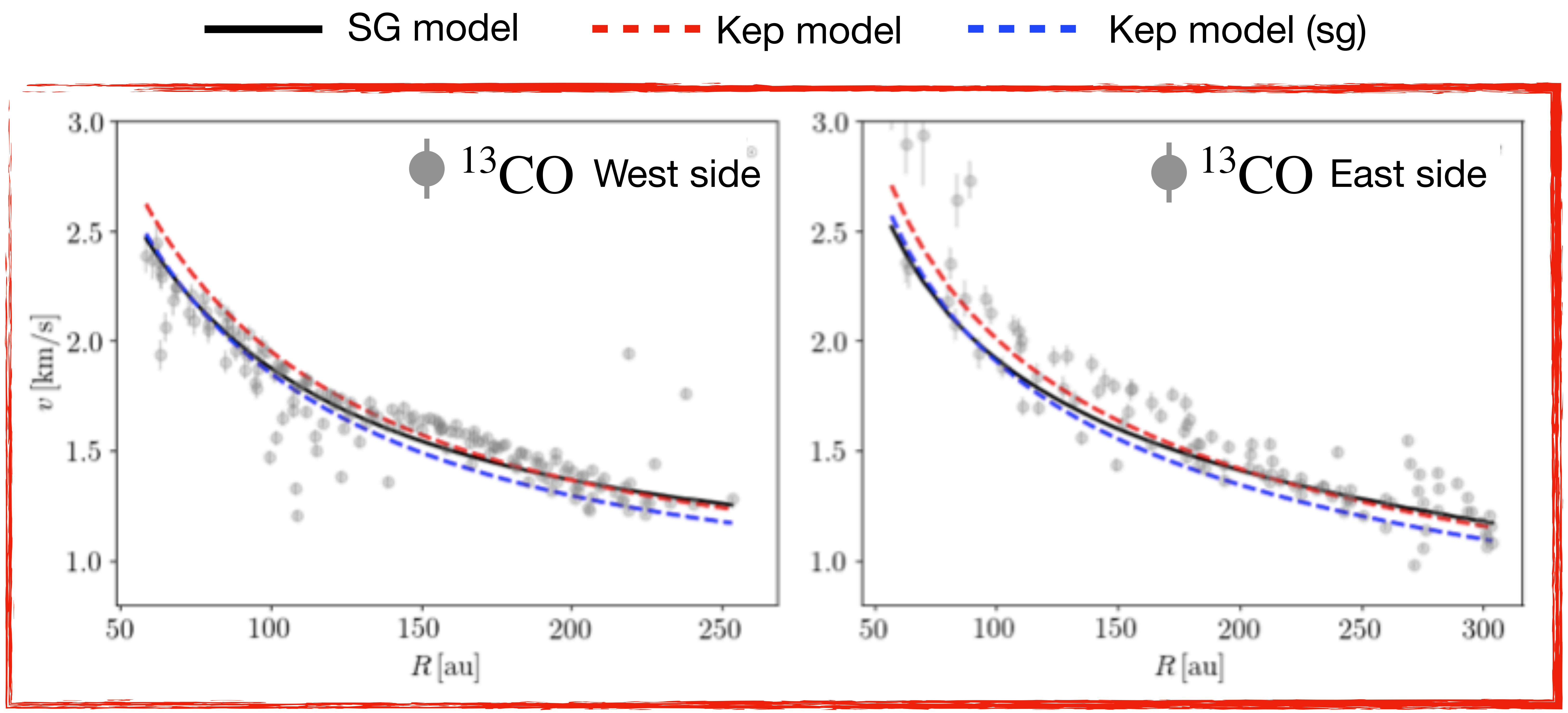


Fitting procedure: both sides, both isotopologues (combined fit)

	^{13}CO	C^{18}O	Combined fit
Keplerian fit			
$M_\star\,[M_\odot]$	$0.50^{+0.01}_{-0.01}$	$0.46^{+0.03}_{-0.03}$	$0.49^{+0.01}_{-0.01}$
Self-gravitating fit			
$M_\star\,[M_\odot]$	$0.45^{+0.03}_{-0.03}$	$0.43^{+0.05}_{-0.07}$	$0.46^{+0.03}_{-0.03}$
$M_{\rm disk}\,[M_\odot]$	$0.1^{+0.05}_{-0.04}$	$0.08^{+0.08}_{-0.05}$	$0.08^{+0.04}_{-0.04}$
$\lambda = \Delta$(red-χ^2)	2.16	-0.19	1.38

FITS RESULTS





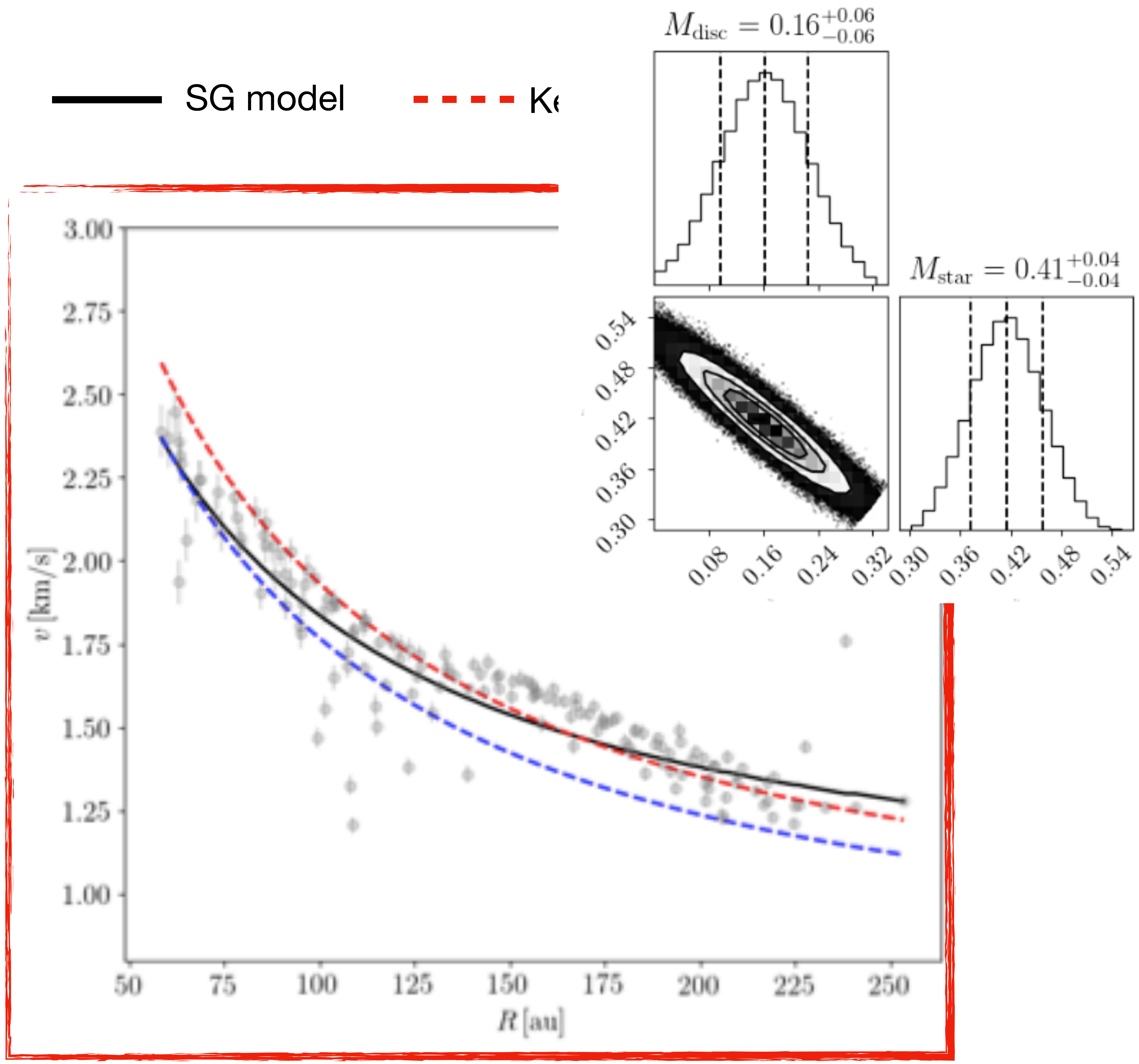
^{13}CO fit: both sides

	^{13}CO	C^{18}O	Combined fit
Keplerian fit			
$M_\star\,[M_\odot]$	$0.50^{+0.01}_{-0.01}$	$0.46^{+0.03}_{-0.03}$	$0.49^{+0.01}_{-0.01}$
Self-gravitating fit			
$M_\star\,[M_\odot]$	$0.45^{+0.03}_{-0.03}$	$0.43^{+0.05}_{-0.07}$	$0.46^{+0.03}_{-0.03}$
$M_{\rm disk}\,[M_\odot]$	$0.1^{+0.05}_{-0.04}$	$0.08^{+0.08}_{-0.05}$	$0.08^{+0.04}_{-0.04}$
$\lambda = \Delta(\textbf{red-}\chi^2)$	2.16	-0.19	1.38

self-gravitating disc model

Models not distinguishable (errorbars too wide)

FITS RESULTS



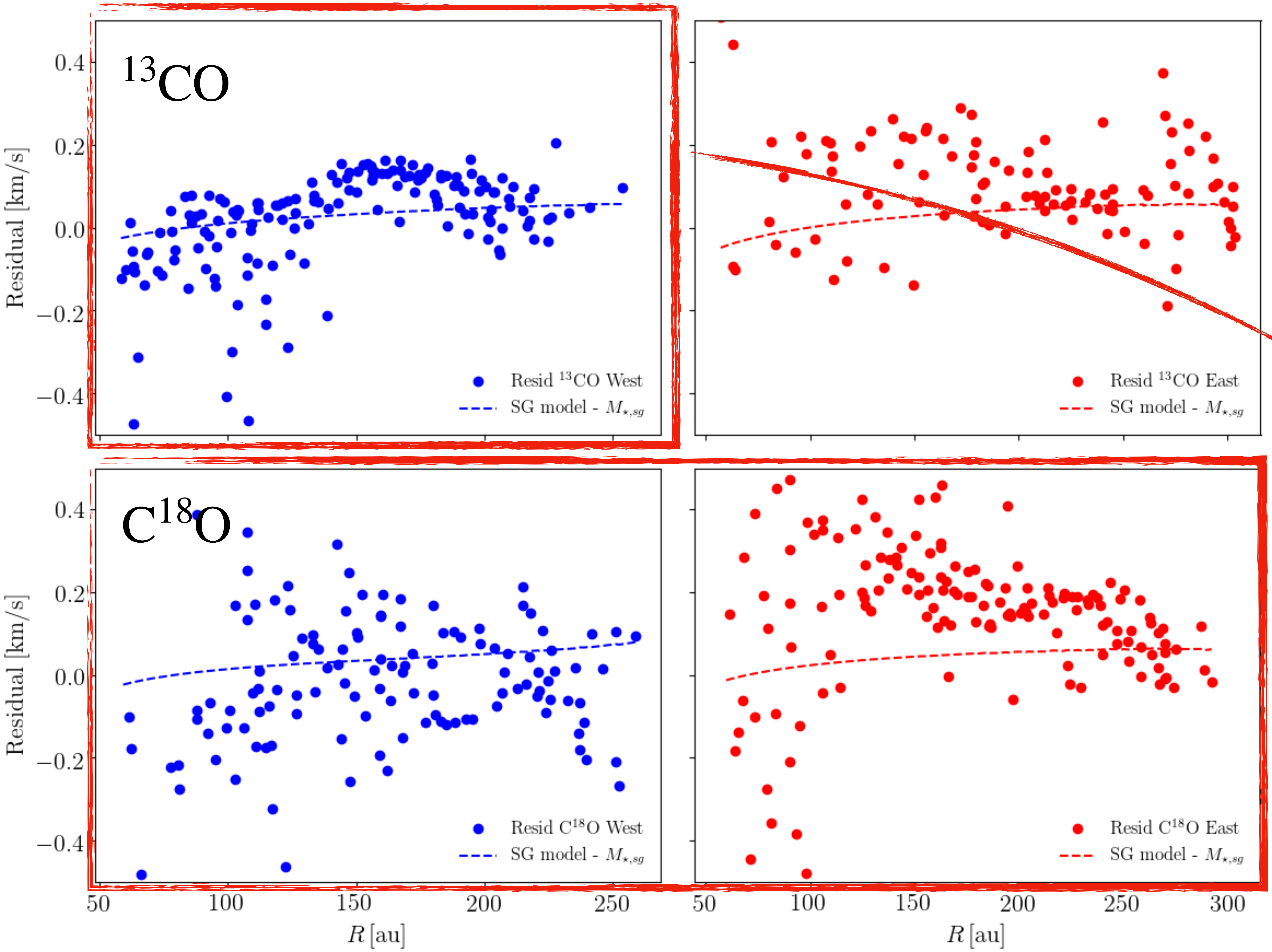
^{13}CO fit West side

	^{13}CO	$C^{18}O$
Keplerian fit		
$M_\star\ [M_\odot]$	$0.49^{0.01}_{-0.01}$	$0.42^{0.03}_{-0.03}$
Self-gravitating fit		
$M_\star\ [M_\odot]$	$0.41^{+0.04}_{-0.04}$	$0.38^{+0.06}_{-0.07}$
$M_{\rm disk}\ [M_\odot]$	$0.16^{+0.06}_{-0.06}$	$0.08^{+0.08}_{-0.06}$
$\lambda = \Delta$(**red**-χ^2)	4.57	-0.51

self-gravitating
disc model

WEST SIDE: not cloud-contaminated
(better data, better estimate)

FITS RESULTS



● $v_{\rm data} - v_{\rm Kep,M_{(\star,sg)}}$

- - - $v_{\rm sg} - v_{\rm Kep,(M_\star,sg)}$

Disc contribution to the gravitational potential

$C^{18}O$ large scatter in both directions (larger error bars in the dataset)

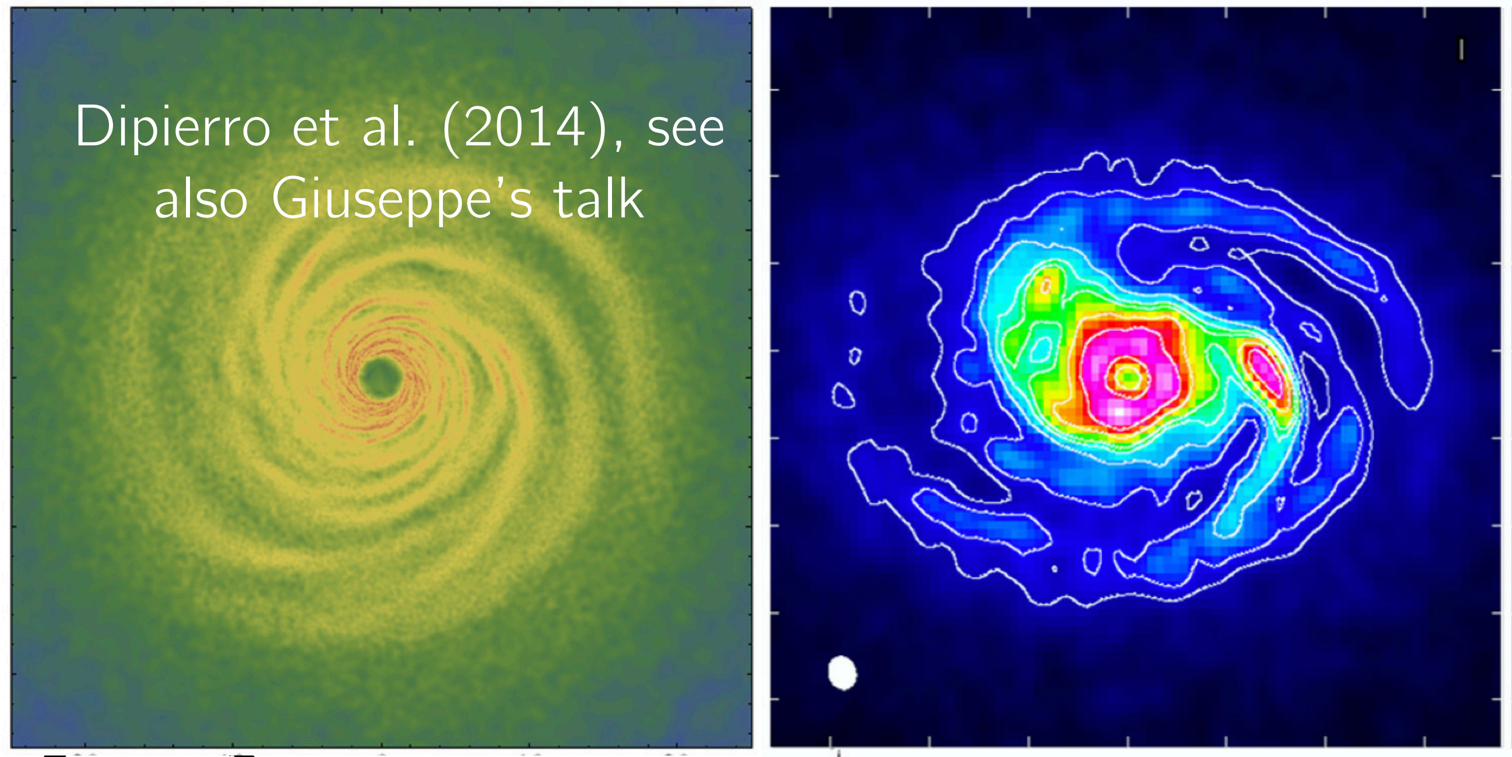
DISC MASS RESULTS AND GI

$$Q = \frac{c_s \Omega}{\pi G \Sigma} = f \frac{M_*}{M_{\rm disc}} \frac{H}{r}$$

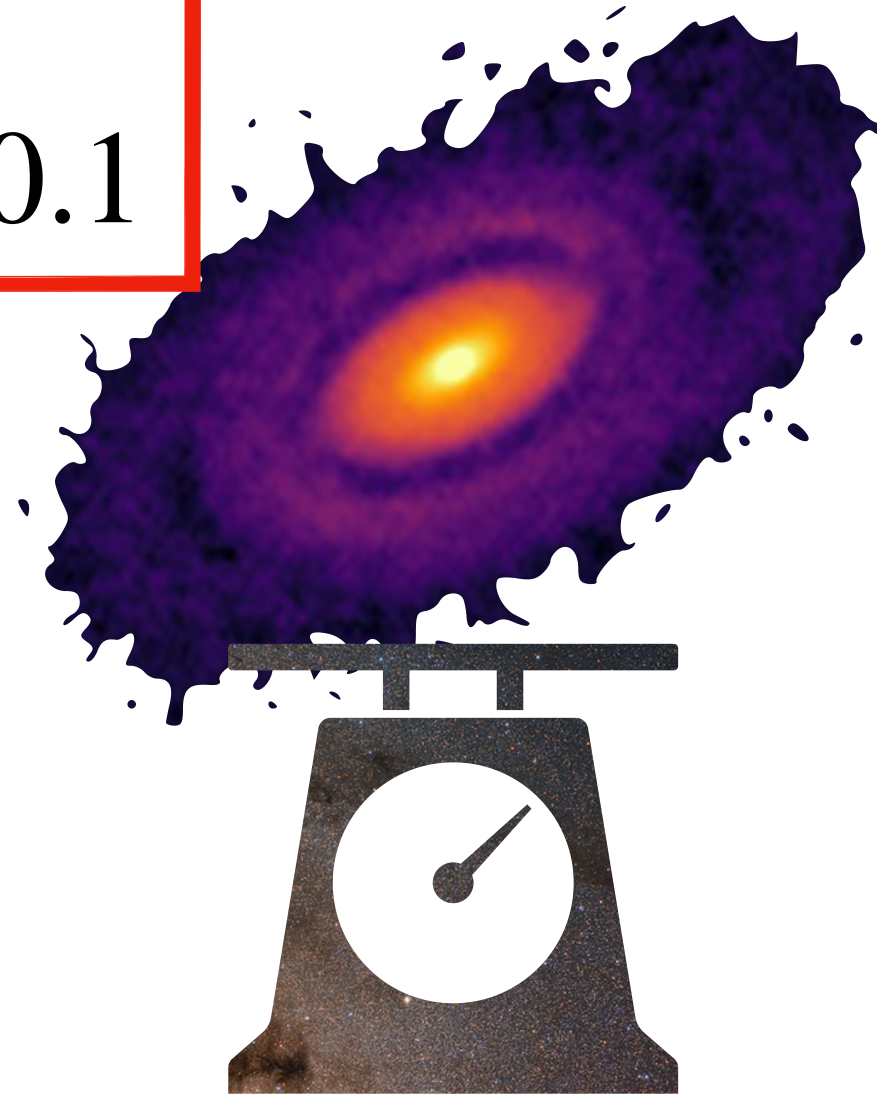
	Combined	^{13}CO	^{13}CO **West side**
$M_{\rm disc}\,[M_\odot]$	0.08 ± 0.04	$0.1^{+0.05}_{-0.04}$	0.16 ± 0.06
$M_\star\,[M_\odot]$	0.46 ± 0.03	0.45 ± 0.03	0.41 ± 0.04
$q = M_{\rm disc}/M_\star$	0.17	0.22	0.40

Correct range to produce gravitational instabilities and the observed spiral structure

Previous estimates: **q=0.24, 0.16, 0.15** (Meru et al. 2017, Hall et al. 2018, Paneque-Carreño et al. 2020)



$$\boxed{\begin{array}{c}\text{disc/star} \approx \text{H/R} \\ \text{for protostellar disc} \approx 0.1\end{array}}$$



Also:

$$M_{\rm disc} = 0.08 \pm 0.04\, M_\odot$$
$$M_{\rm dust} \approx 10^{-3}\, M_\odot$$

Pérez et al. (2016)

$$\text{gas/dust} \approx 80$$

20% < ISM value of 100 (Draine 2003)

TAKE HOME MESSAGES: A DYNAMICAL SCALE

Is there a method to estimate the disc mass which is independent of CO/dust to H_2 conversion factor?

We searched for deviation from Keplerianity in the disc rotation curve of Elias 2-27

Best fit: SG model

$$\frac{M_{\mathrm{disc}}}{M_\star} \approx 0.17 - 0.22$$

GI regime: spirals Elias 2-27

From the disc mass it is possible to infer also the gas/dust ratio: $\approx 80 - 100$

FURTHER INVESTIGATIONS NEEDED…

1. **Asymmetry** between West and East side needs to be further investigated (maybe **infall**?)

2. Consider also the **vertical** contribution to the **pressure gradients** (super-Keplerian contribution, see Giuseppe's talk)

3. How does this method apply to **other protoplanetary discs** showing **spiral structures** or a **high disc-to-star mass ratio**?
   e.g.: IM Lup, WaOph 6 (see Giuseppe's talk), AB Aur (proposal Robin Dong)…
   Name your favourite (potentially) massive and SG disc and we'll weigh it for you!
   https://www.supersurvey.com/Q7Y4WXXCS

4. Try different **methods to derive the disc rotation curve** (as for WaOph 6, see Giuseppe's talk)
   e.g. with the Eddy tool by Teague et al. 2018, DiscMiner code by Izquierdo et al. 2021

5. Parametric study: down to which disc mass value (and with what ALMA resolution) we would be able to detect the deviation from Keplerianity induced by the disc SG? (Work in progress…)

THANKS FOR THE ATTENTION!

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