Unsolved problem #1:

How much mass is available for planet formation?

Measuring the mass of planet forming discs

- Important, because

1. It determines how much mass is available for planets (both in the solid and in the gaseous component)

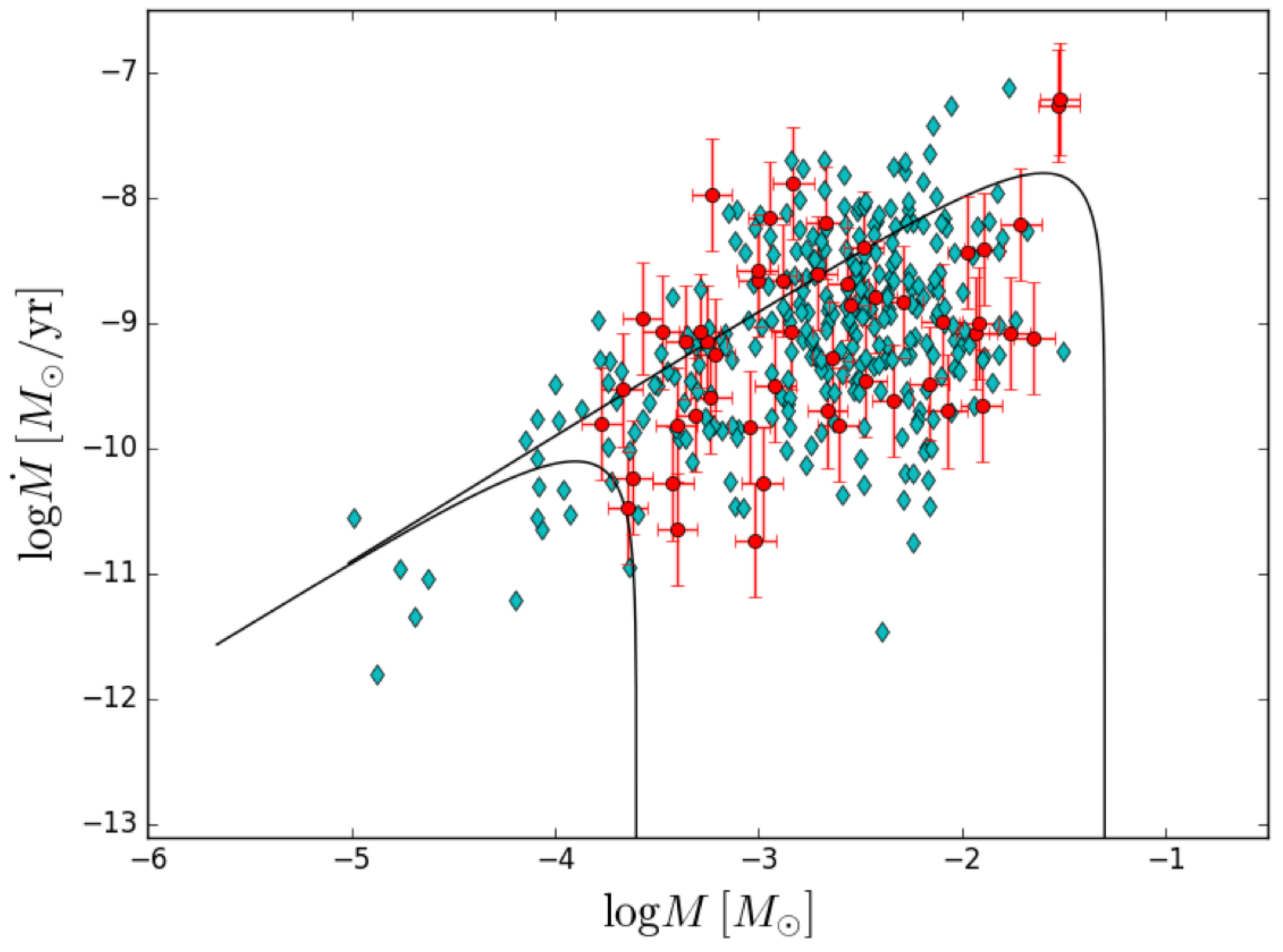
2. It determines the level of coupling between gas and dust and hence influences dust dynamics (a process essential to planet formation)

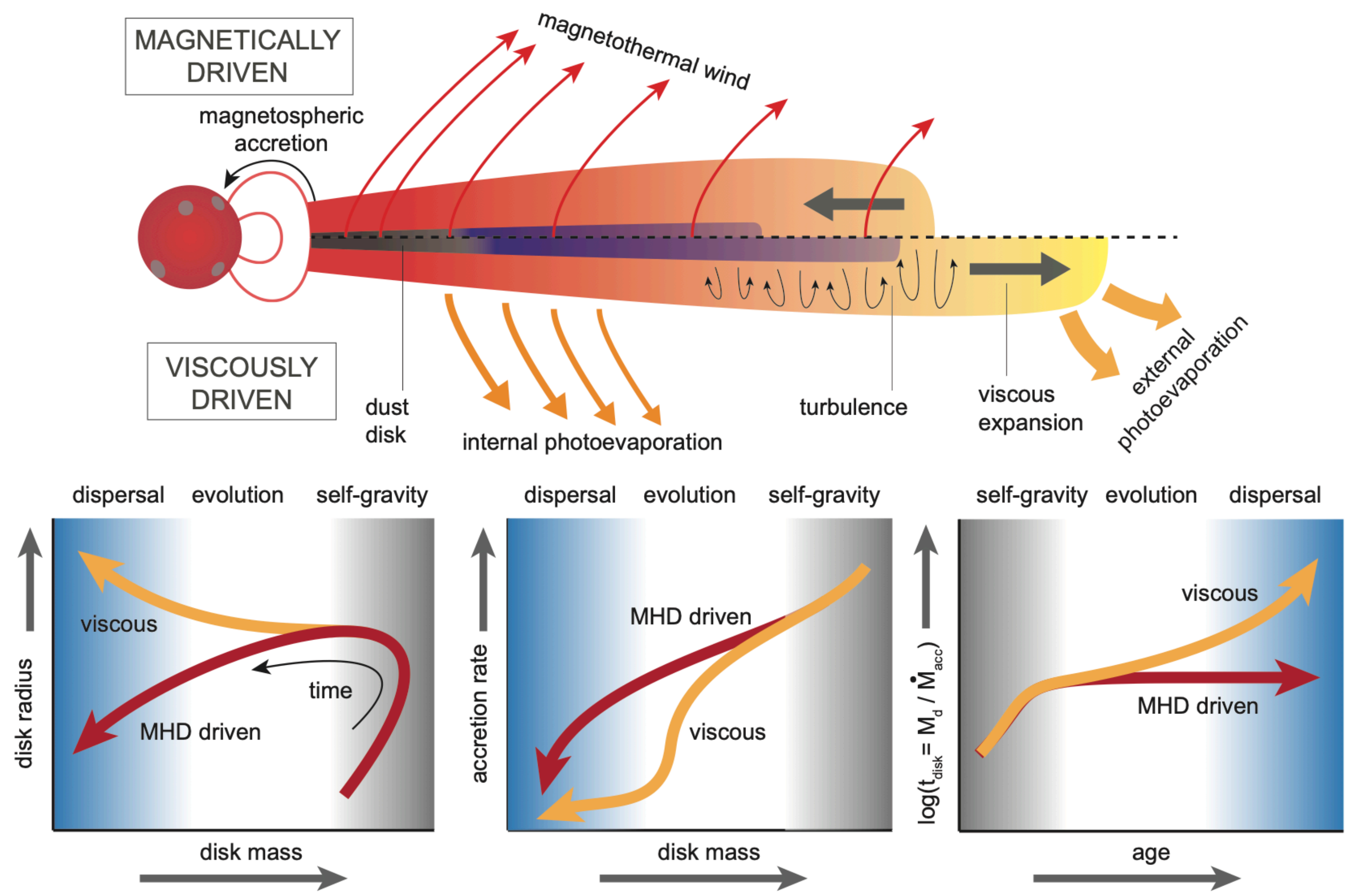
$$St \approx \frac{\rho_0 a}{\Sigma}$$

4. It's a key quantity to validate disc evolutionary models (Manara et al 2022)

5. If disc mass is high, the disc becomes unstable

$$Q(R) = \frac{c_s \kappa}{\pi G \Sigma} \approx 1 \qquad \frac{M_{\rm disc}}{M_\star} \approx \frac{H}{R}$$



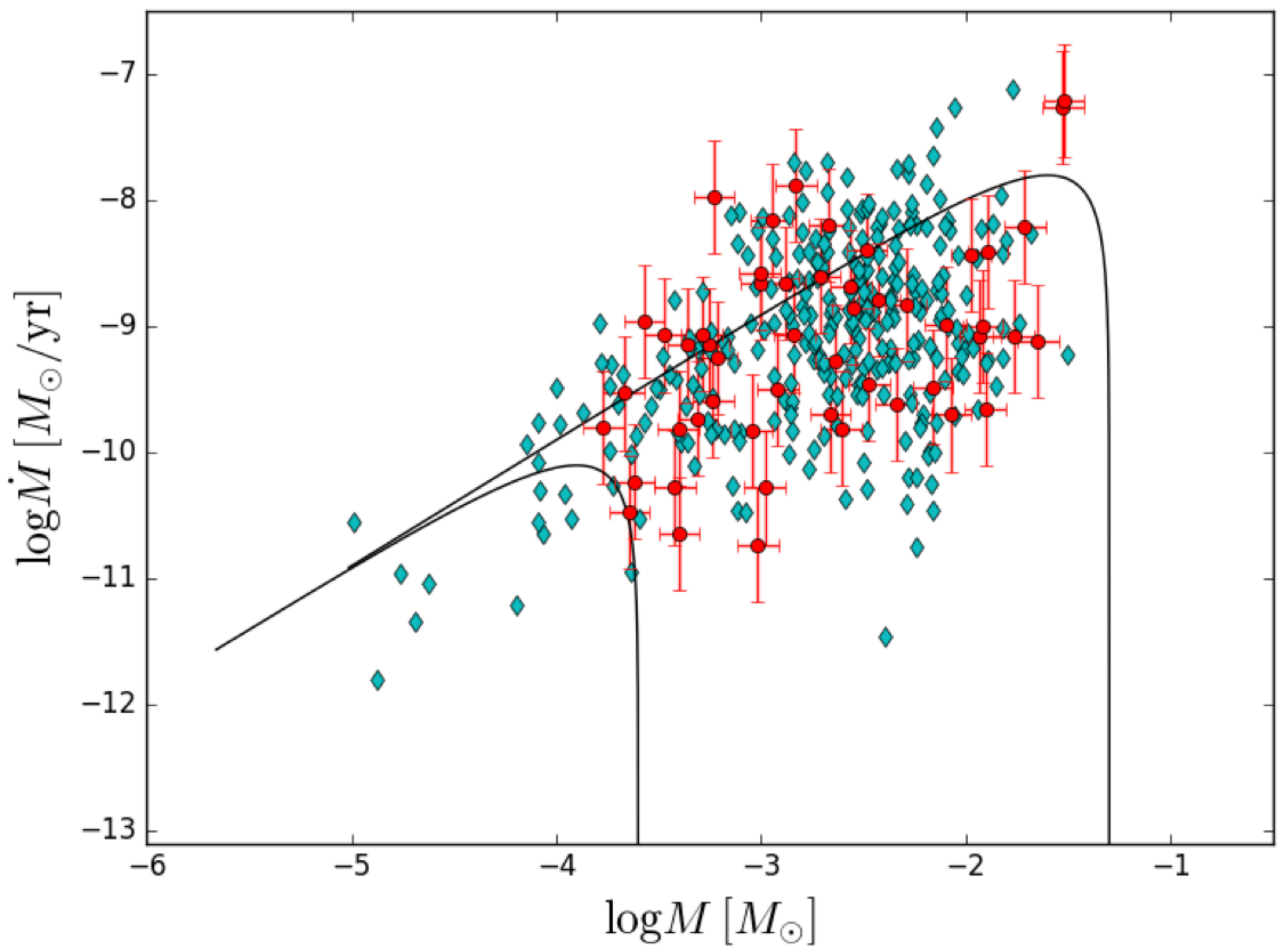


Measuring the mass of planet forming discs

- **Hard**, because the main constituent, H_2 has little emission.
- Use proxies instead:
    - Dust mass relatively easy from mm-continuum emission with ALMA, but requires knowledge of dust opacity, optical thickness and especially dust/gas ratio, usually assumed to be 1%

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

    - Note: dust mass correlates with accretion rate onto the star (Manara et al 2022)



Measuring the mass of planet forming discs

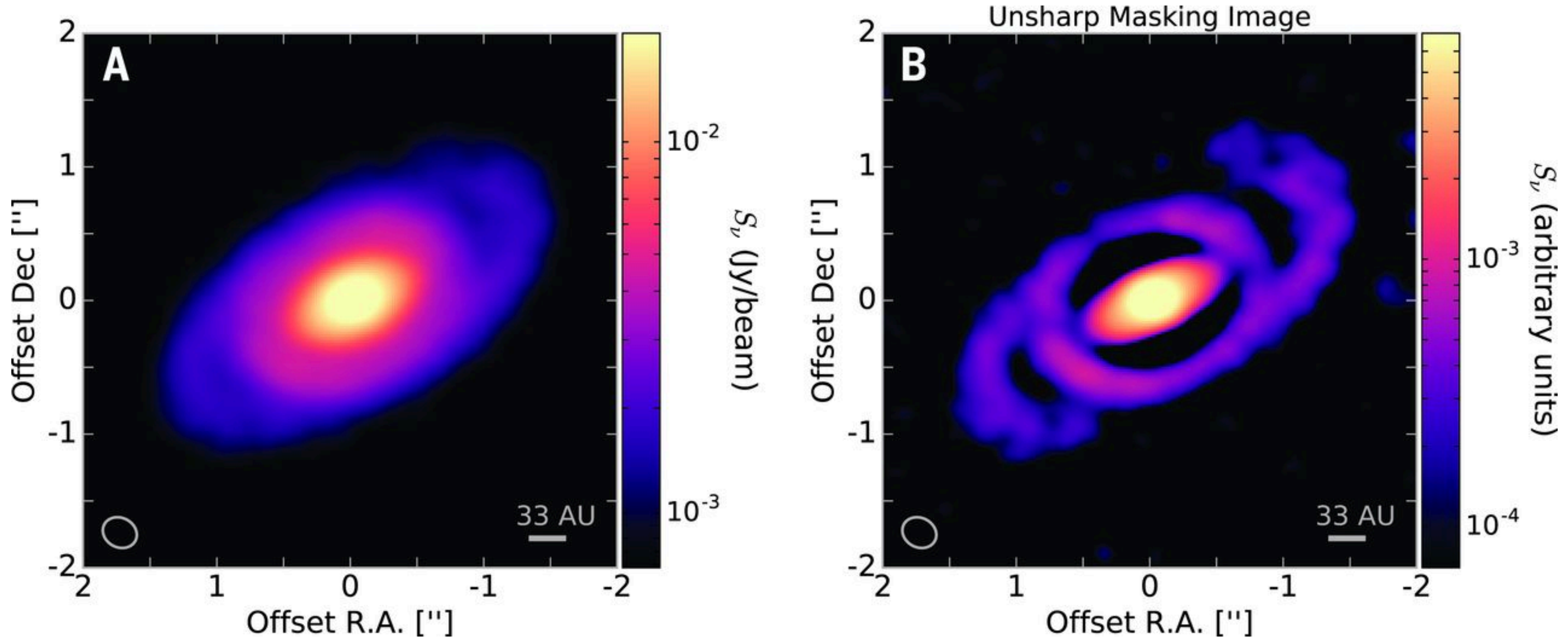
- **Hard**, because the main constituent, H_2 has little emission.
- Use proxies instead:
  - Gas tracers also difficult to use
  - **CO** and its isotopologues might work, but CO chemistry is complex and carbon depletion is known to be at work (Miotello et al 2016, 2017) —> disc masses much lower than estimated from dust
  - **HD** might be a good alternative:
    - only available for a handful of objects, usually indicating very high disc masses (e.g. for TW Hya, $M_{disc} \gtrsim 0.06\ M_{sun}$ (Bergin et al 2013)

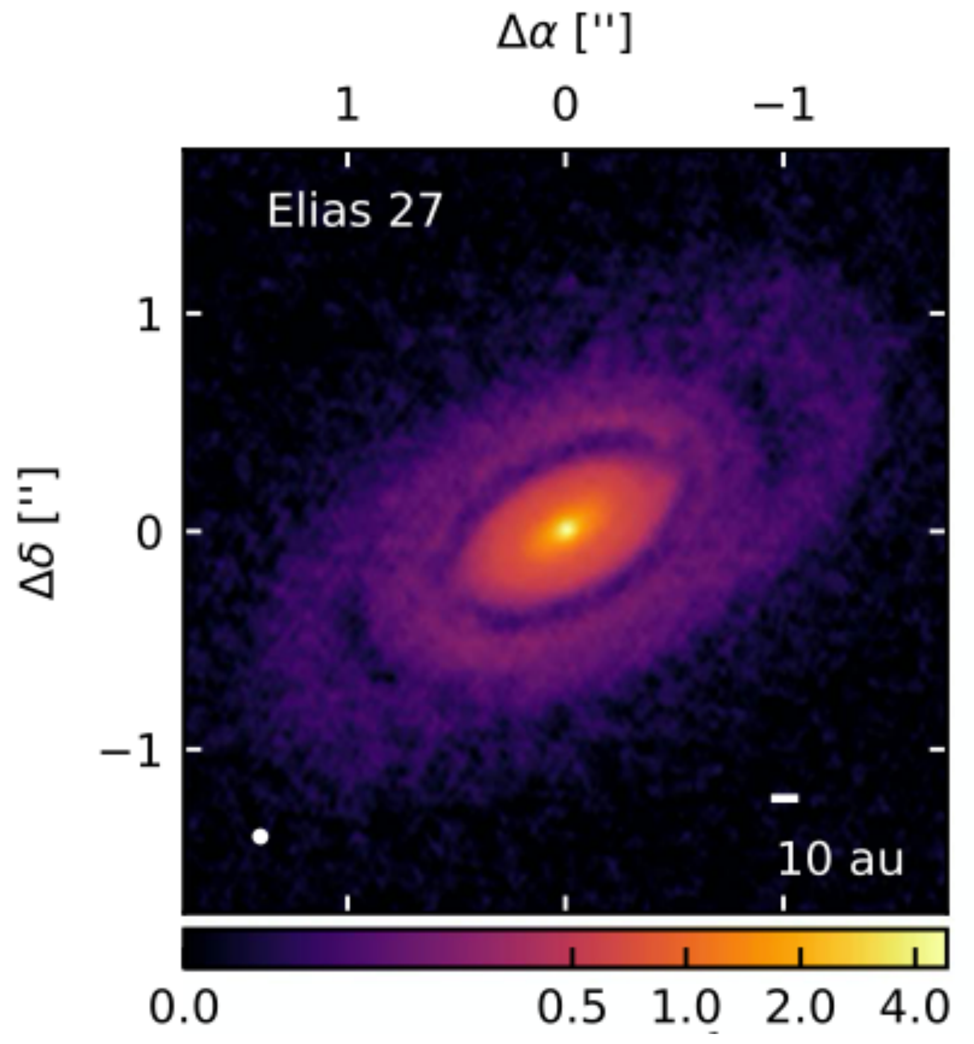
Dynamical mass measurements

- ALMA kinematics is reaching an accuracy (~ 20 m/sec) that allows to probe small deviations from Keplerian motion
  - Localised perturbations due to a planet (Pinte et al, 2019, 2020)
  - Pressure gradient effects at the edge of the disc (Dullemond et al 2020)
  - The "GI wiggle" (Hall et al 2020, Longarini et al 2021)
- Can we use such high precision kinematics to measure the disc mass dynamically from deviations from Keplerianity?
  - Answer: yes! We have done this for three sources: **Elias 2-27** (Veronesi et al 2021), **IM Lup** and **GM Aur** (Lodato et al, 2022)

The case of Elias 2-27

- A disc that is strongly suspected of being gravitationally unstable, based on the large scale spiral and the high dust flux (Perez et al 2016, DSHARP 2018)





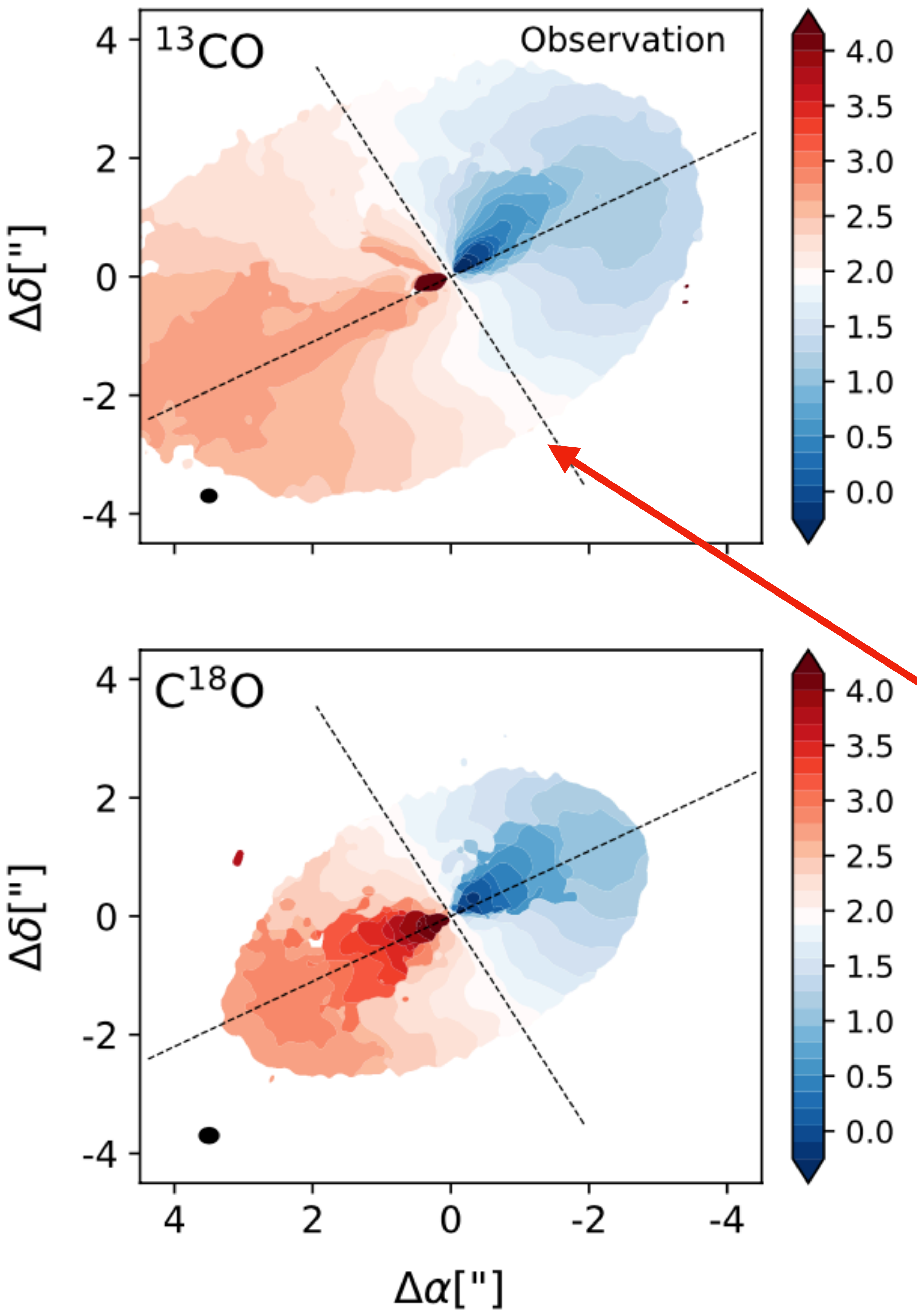
M_{star} ~ 0.5 M_{sun}

- Disc mass estimate from dust continuum (assuming the standard 100 gas/dust ratio): ~ 0.1Msun
- Origin of the spiral has been attributed either to a planet or to GI (Meru et al 2017, Hall et al 2018, Forgan et al 2018)
- To reproduce the spiral morphology, a disc mass ~ 0.15-0.24 Msun was needed (Meru et al, Hall et al)

New multi-wavelength data in gas and dust

Paneque-Carreno et al (2021)

- CO line observations



- Strong absoprtion to the East side of the disc
- Asymmetric shape (East side more extended)
- Gas disc extends much further than dust
- Moment 1 maps show “wiggling” channels

Constrain total disc mass dynamically from rotation curve

Veronesi et al (2021)

- If disc mass is ~0.3-0.5 M_{star}, sizable deviations from Keplerian rotation are expected
- Fit with a "complete" model including stellar and disc potential and pressure gradients

$$\Omega^2 = \frac{1}{R}\frac{d\Phi_\sigma}{dR}(R,z) + \frac{\mathcal{G}M_\star}{(R^2+z(R)^2)^{3/2}} + \frac{1}{R}\frac{1}{\rho}\frac{dP}{dR}$$

super-Keplerian

~ Keplerian

sub-Keplerian

$$\frac{\partial \Phi_\sigma}{\partial R}(R,z) = \frac{\mathcal{G}}{R}\int_0^\infty \left[K(k) - \frac{1}{\dots}\left(\frac{k^2}{\dots}\right)\left(\frac{R'}{\dots} - \frac{R}{\dots}\dots\right)E(k)\right]\sqrt{\frac{R'}{R}}\,k\sigma(R')\,dR'$$

Remember: disc contribution can be dominant even if the disc is GI stable!

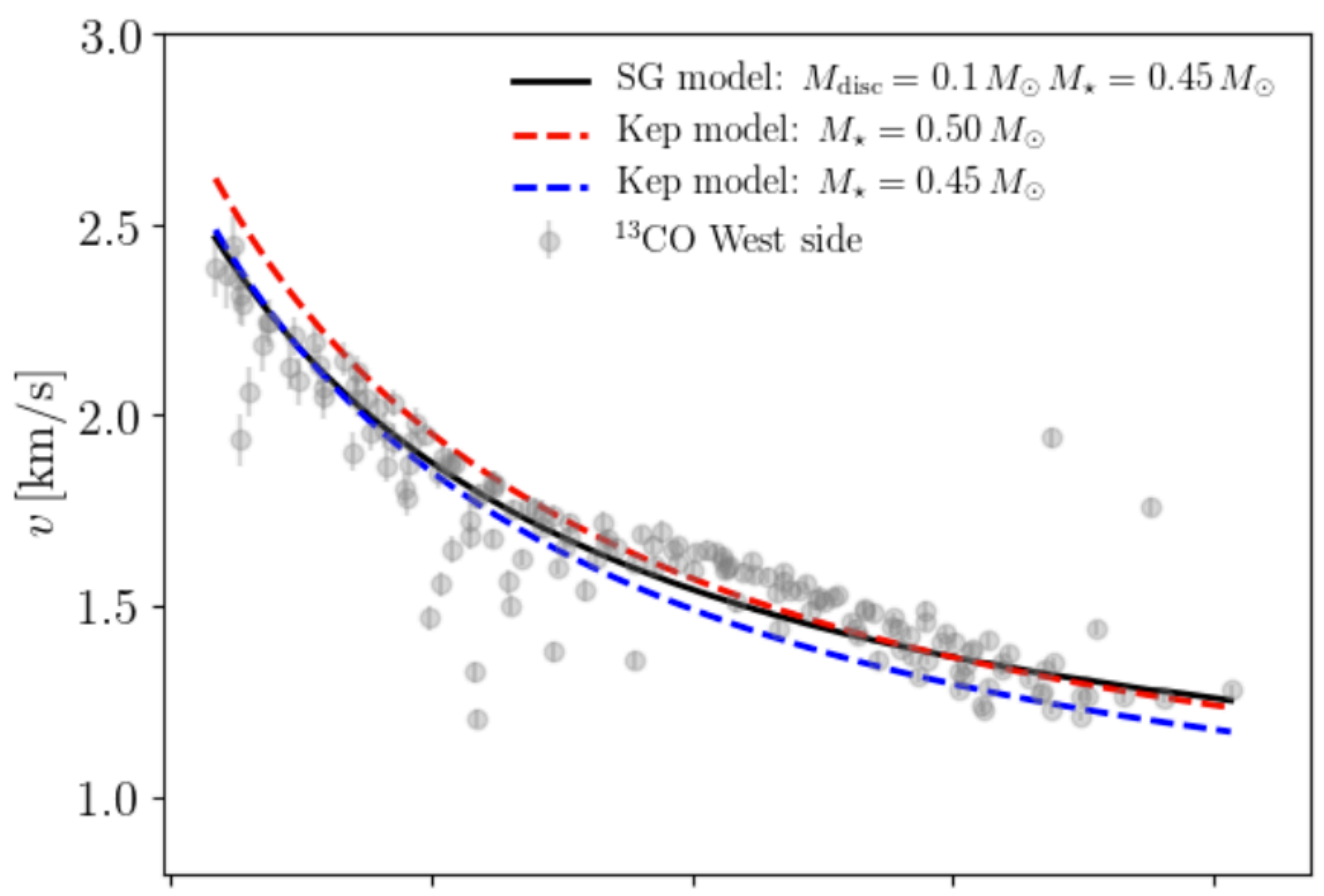
Self-gravity contribution: ~ M_{disc}/M_*

Pressure contribution: ~ $(H/R)^2$

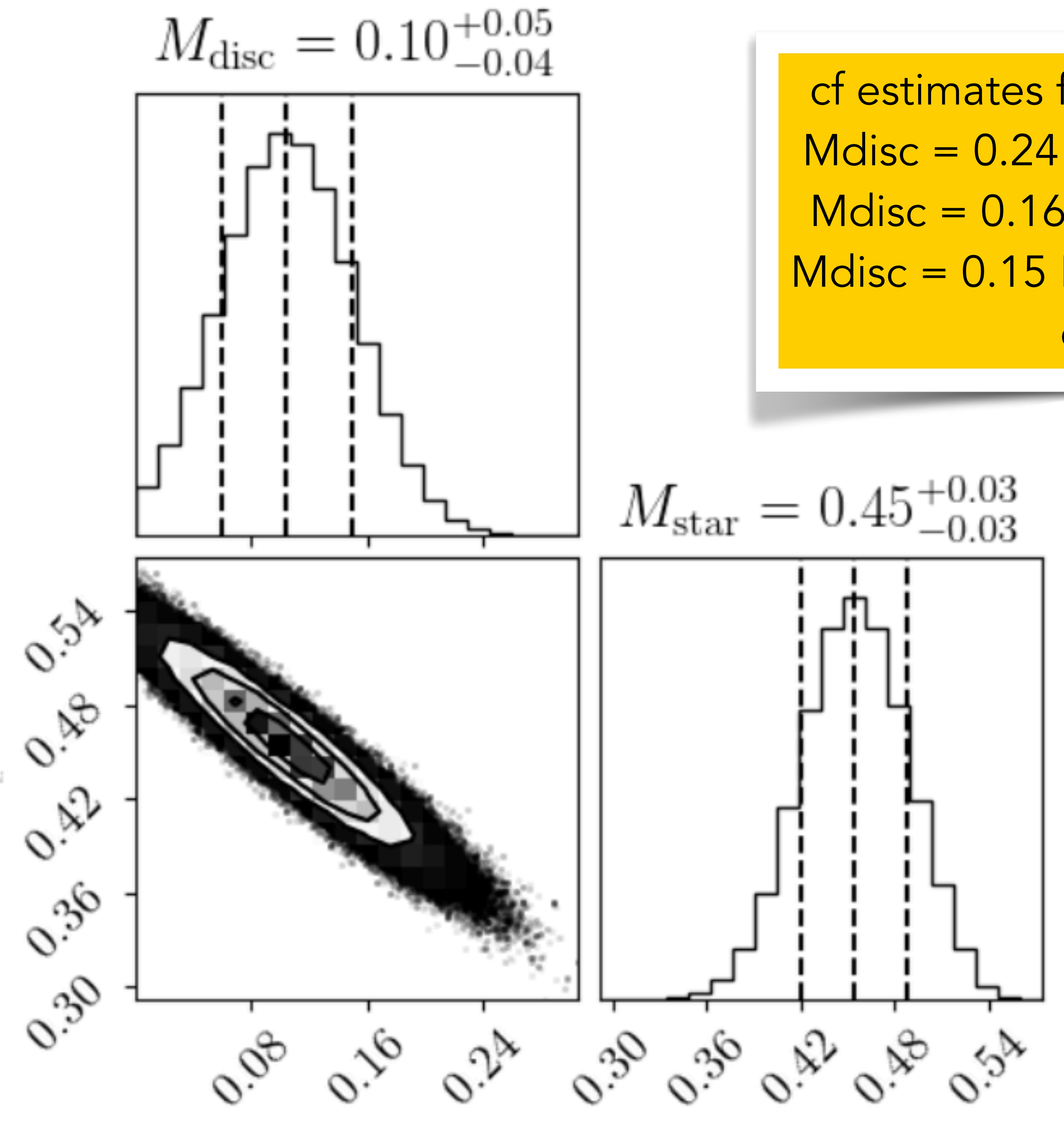
Constrain total disc mass dynamically from rotation curve

Veronesi et al (2021)

- Results slightly depend on which data we fit. Here results for ^{13}CO are shown



data shown for West side, but fit made on both sides

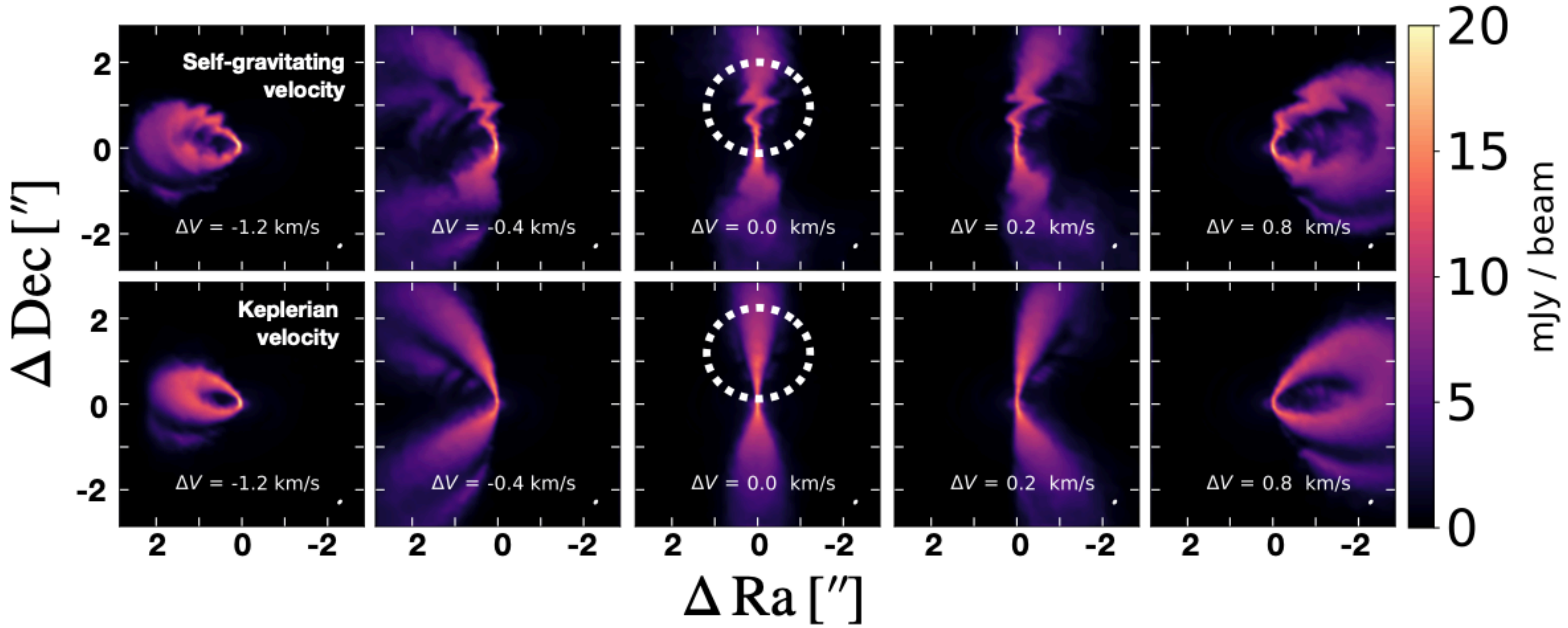


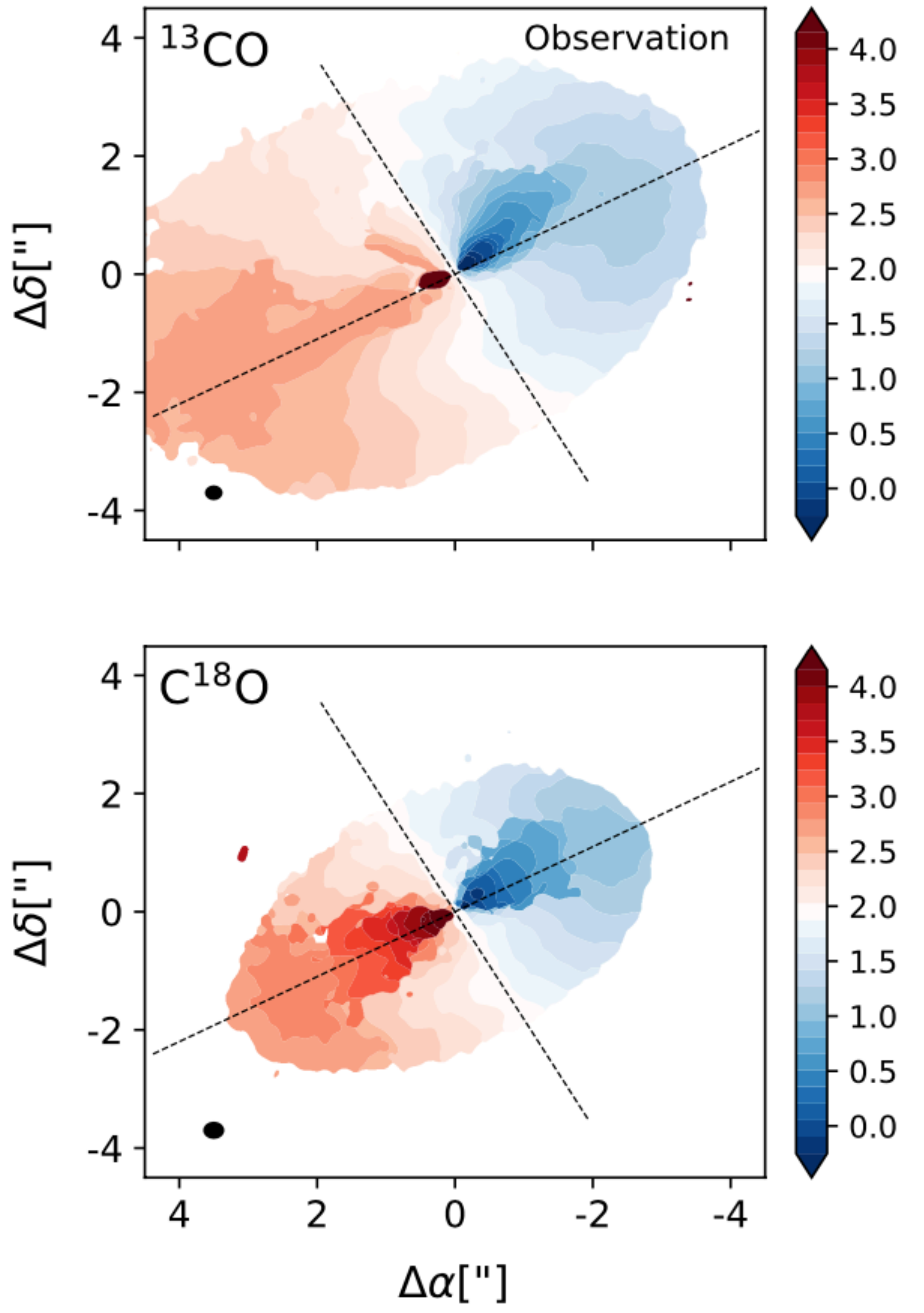
cf estimates from spiral morphology
Mdisc = 0.24 Msun (Meru et al 2017)
Mdisc = 0.16 Msun (Hall et al 2018)
Mdisc = 0.15 Msun (Paneque-Carreno et al 2020)

Looking at GI perturbations: the “wiggle”

Longarini, GL et al (2021)

- Hall et al. (2020) show that the spiral structure induced by GI has characteristic wiggles in the channel maps, as observed in Elias 2-27





Paneque Carreno et al 2021

- Compute analytically the velocity perturbations due to the spiral in a self-gravitating discs (in the same way as can be done for a planet, see Bollati et al, 2021)

Constrain dynamically the cooling rate from the GI-wiggle

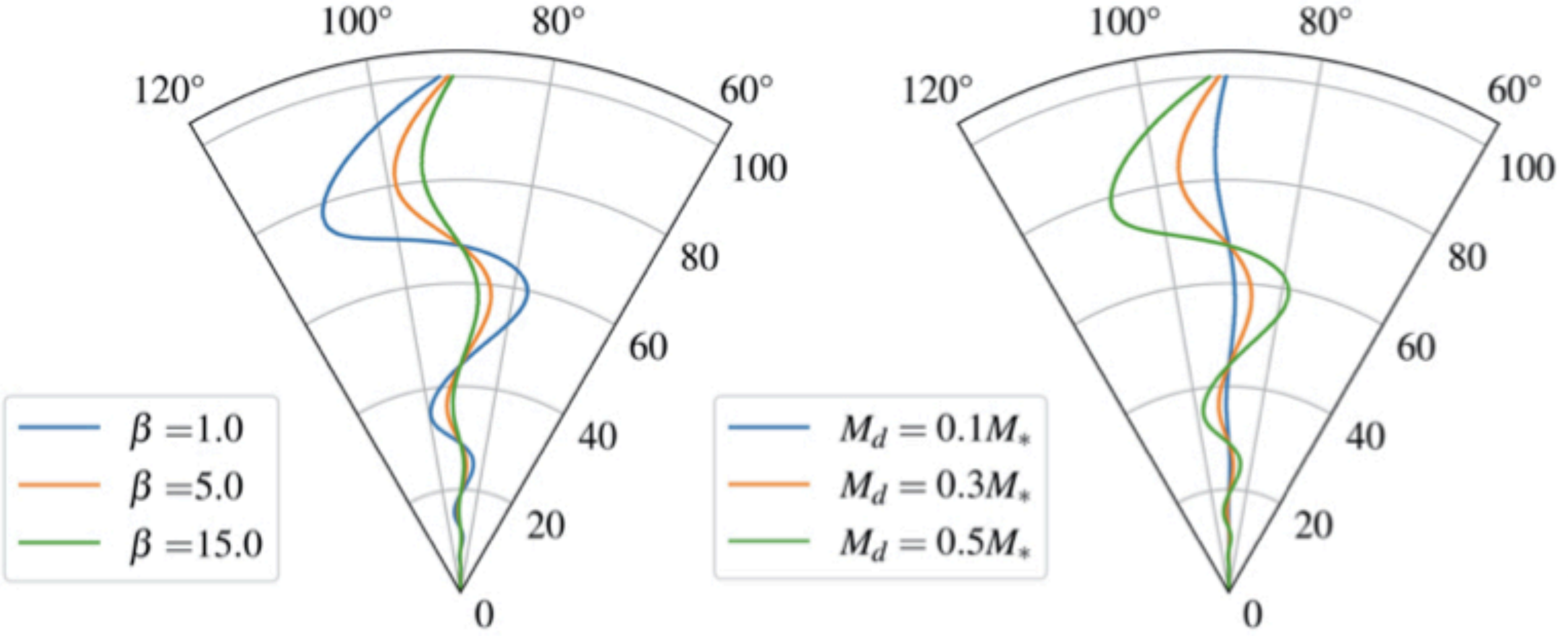
Longarini, GL et al (2021) - see also Terry et al (2021)

- Use the standard WKB approximation, for nearly Keplerian discs
- Assume that the density perturbation scales with the cooling rate (Cossins et al 2009)
- Obtain velocity perturbations (after some maths!) and wiggle

$$\frac{\delta\Sigma}{\Sigma} = \chi\beta^{-1/2}$$

$$\delta u_r = 2im\chi\beta^{-1/2}\left(\frac{M_d(r)}{M_\star}\right)^2 u_k$$

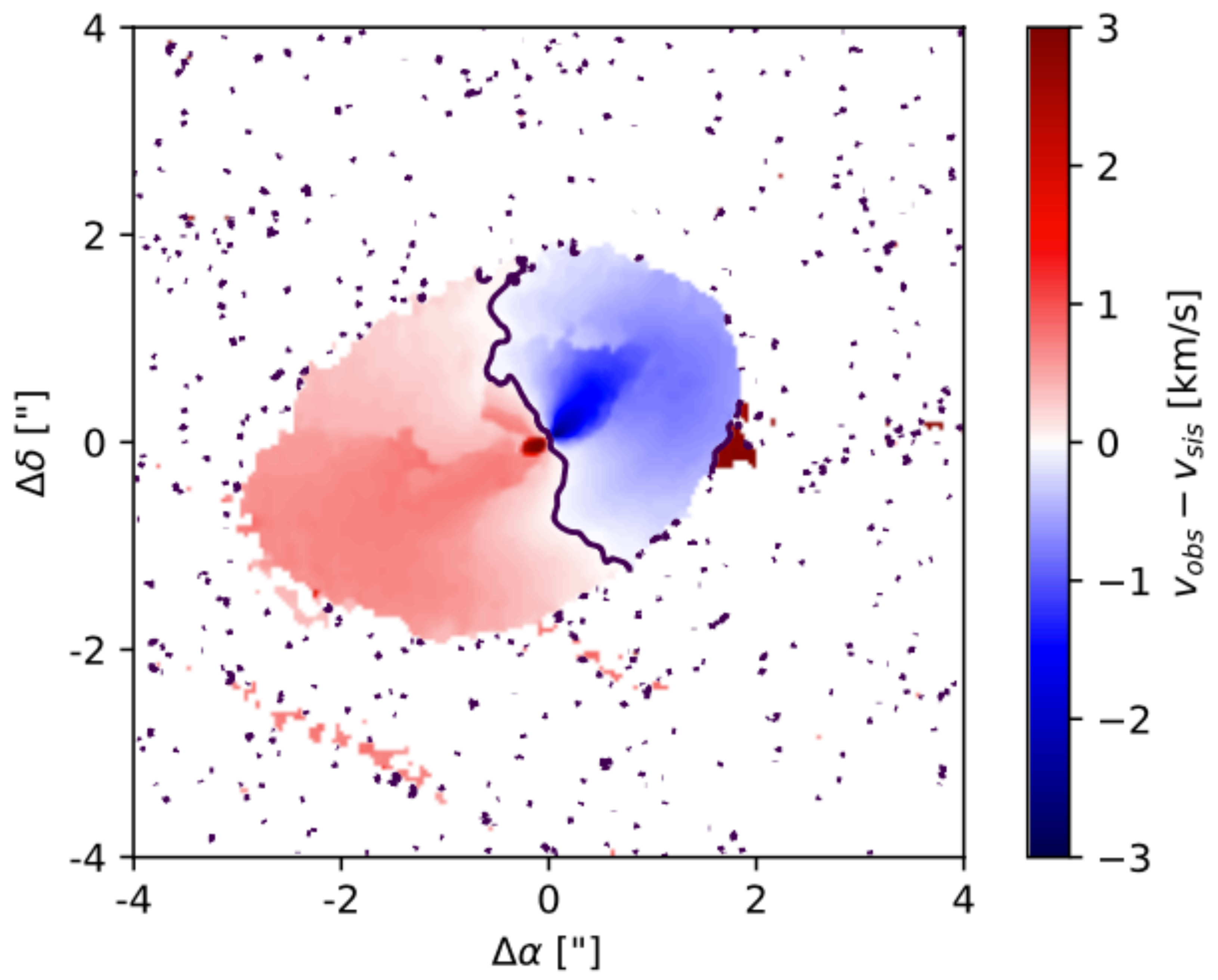
$$\delta u_\phi = -\frac{i\chi\beta^{-1/2}}{2}\left(\frac{M_d(r)}{M_\star}\right) u_k,$$

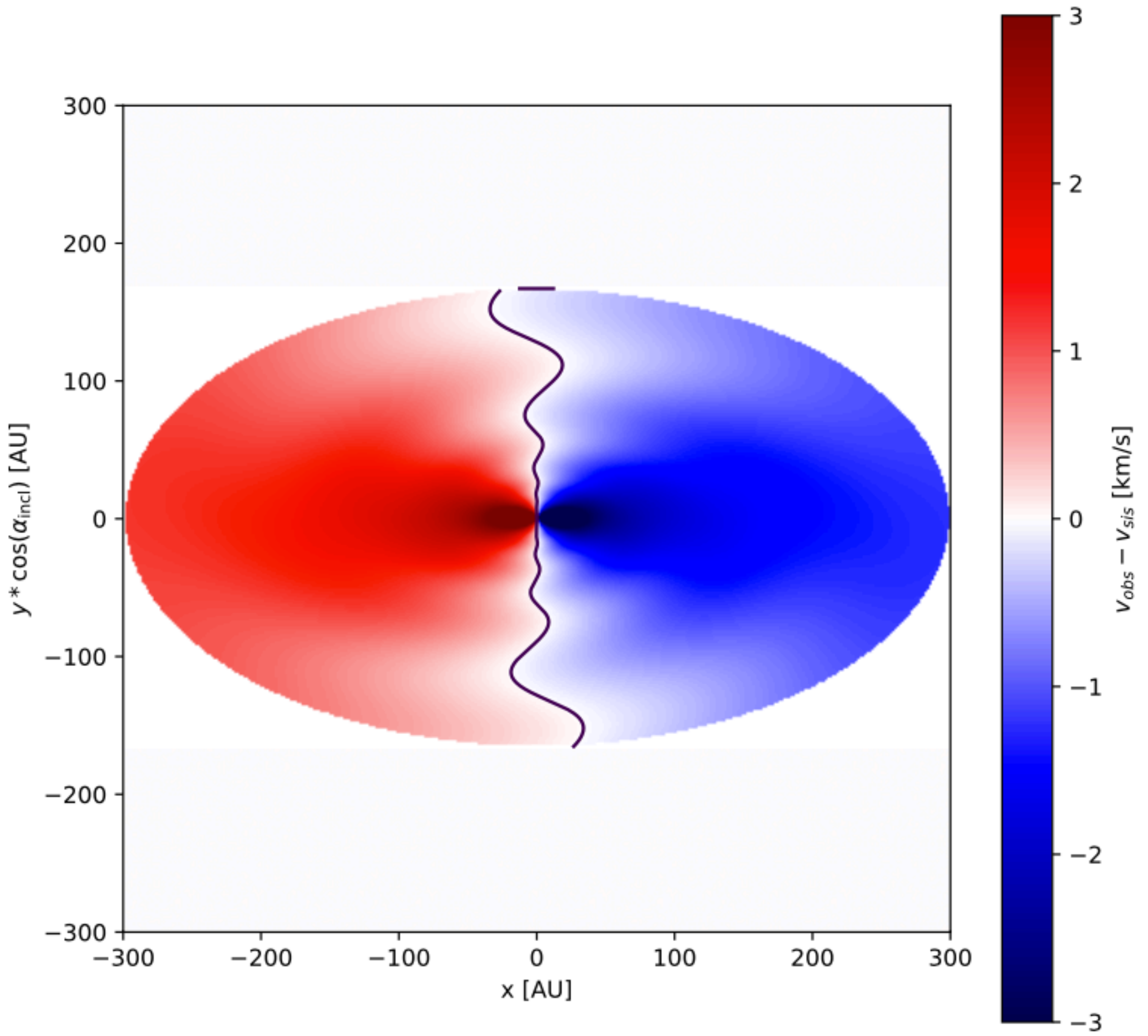


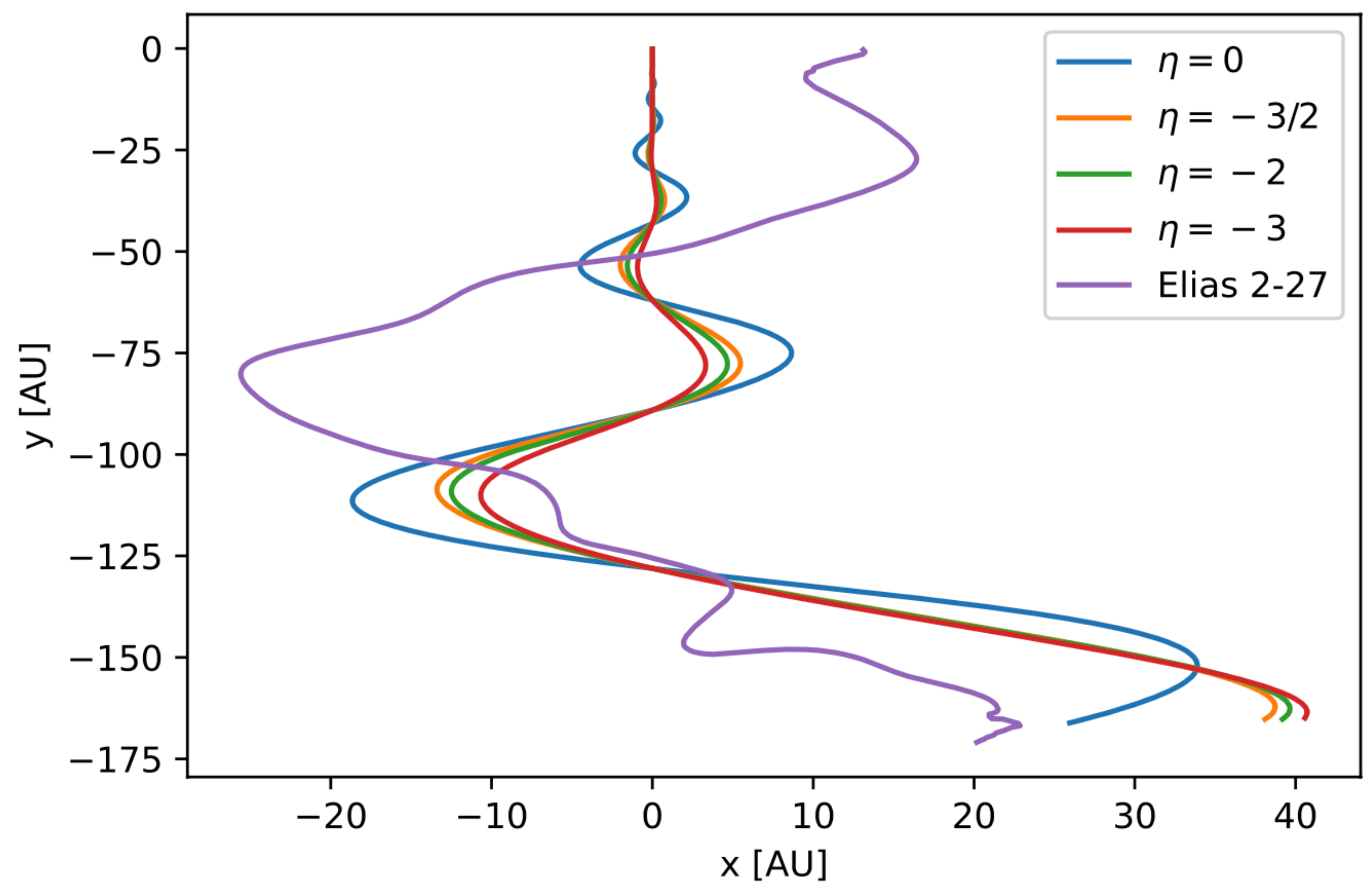
Constraining the outer cooling time in Elias 2-27

Longarini, GL et al, in prep - Bachelor Thesis of E. Arrigoni in Milano

- Apply model to Elias 2-27
- Match wiggle amplitude (std. dev. of zero velocity channel)
- Best match with β ~ 6.7-8.3



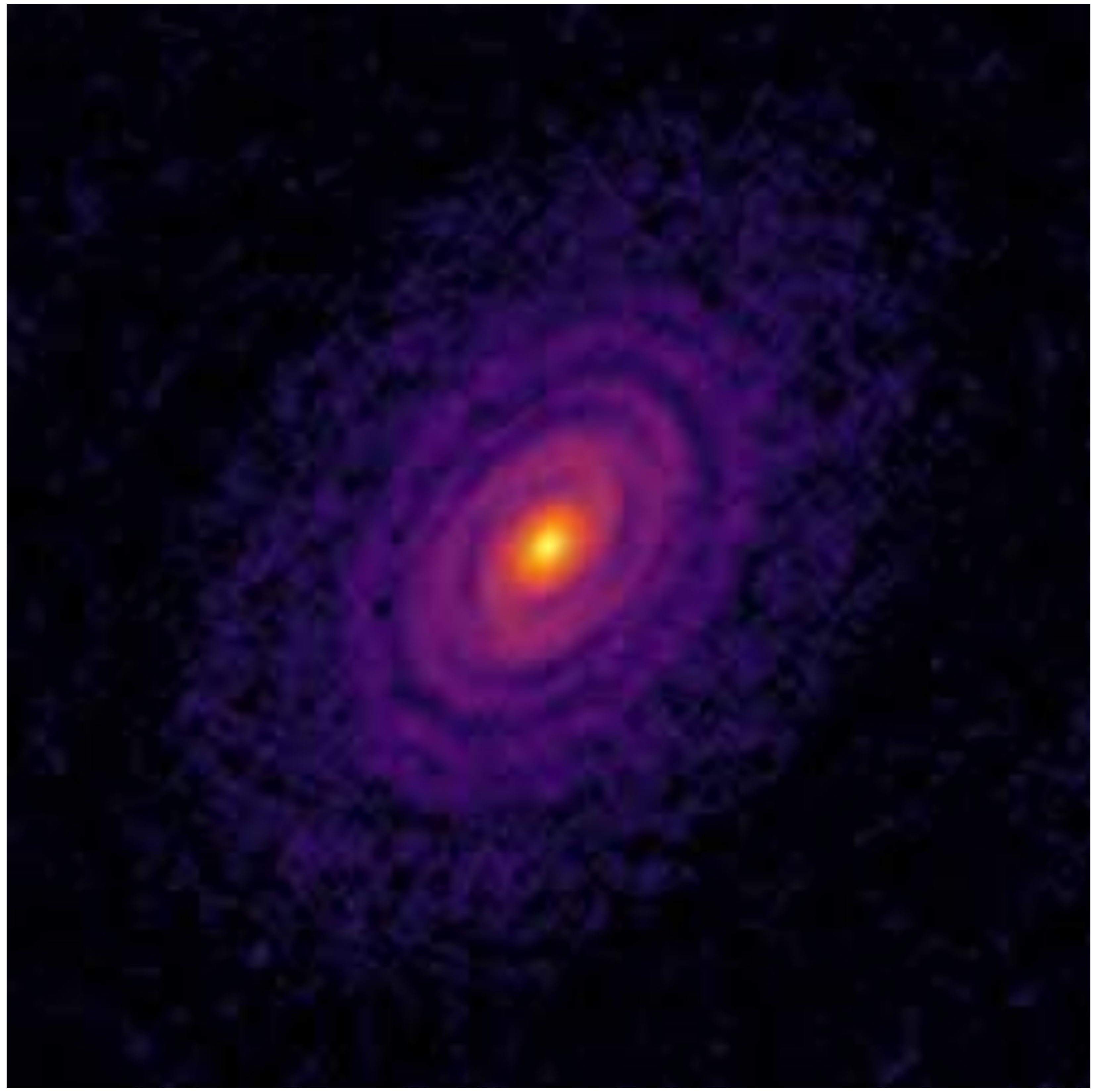




The disc mass in IM Lup

Lodato et al, 2022, MNRAS, in press

- IM Lup is one of the DSHARP sources
- Shows a prominent spiral structure
- Stellar mass ~ 1Msun
- Dust mass: 0.0017 Msun
- With a d/g ratio of 100, would translate into 0.17 Msun



The disc mass in IM

- High quality data exist from the MAPS survey (C
- We wish to improve in several ways on what done
  1. Include pressure gradient (as a function of height)

Additional parameters that we fix to literaure values

1. Pressure scale height H(R)
2. Power law index of surface density, γ
3. Height of the emitting layer, z(R)

$$\Sigma(R) = \frac{(2-\gamma)M_{\rm d}}{2\pi R_{\rm c}^2}\left(\frac{R}{R_{\rm c}}\right)^{-\gamma}\exp\left[-\left(\frac{R}{R_{\rm c}}\right)^{2-\gamma}\right]$$

Assume self-similar solution a la Lynden-Bell & Pringle (1974)

$$\rho(R,z) = \rho_0(R)\exp\left[-\frac{R^2}{H^2}\left(1-\frac{1}{\sqrt{1+z^2/R^2}}\right)\right]$$

Important: go beyond the simple Gaussian vertical profile

$$v_{\rm rot}^2 = v_{\rm K}^2\left\{1-\left[\gamma'+(2-\gamma)\left(\frac{R}{R_{\rm c}}\right)^{2-\gamma}\right]\left(\frac{H}{R}\right)^2 - q\left(1-\frac{1}{\sqrt{1+(z/R)^2}}\right)\right\}$$

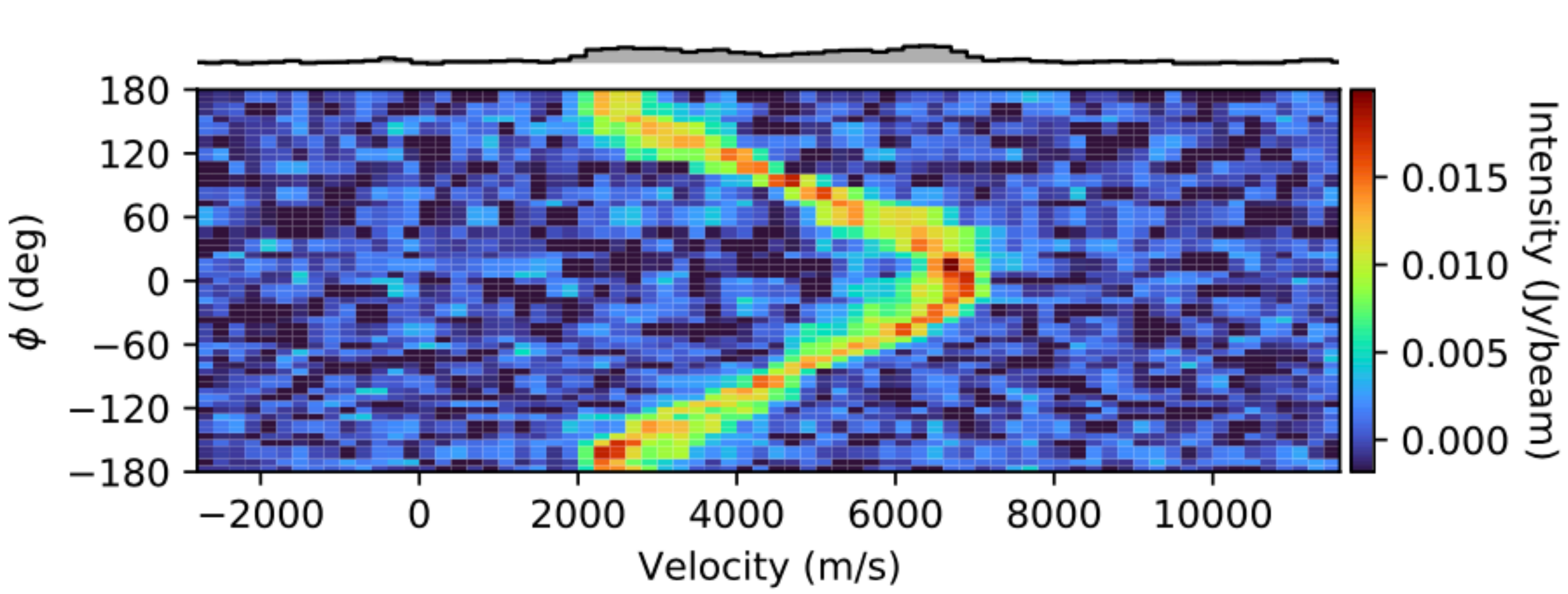
Pressure contribution to rotation assuming vertical isothermal disc (Nelson et al 2013)

Three free parameters to fit: disc mass, star mass and density scale radius

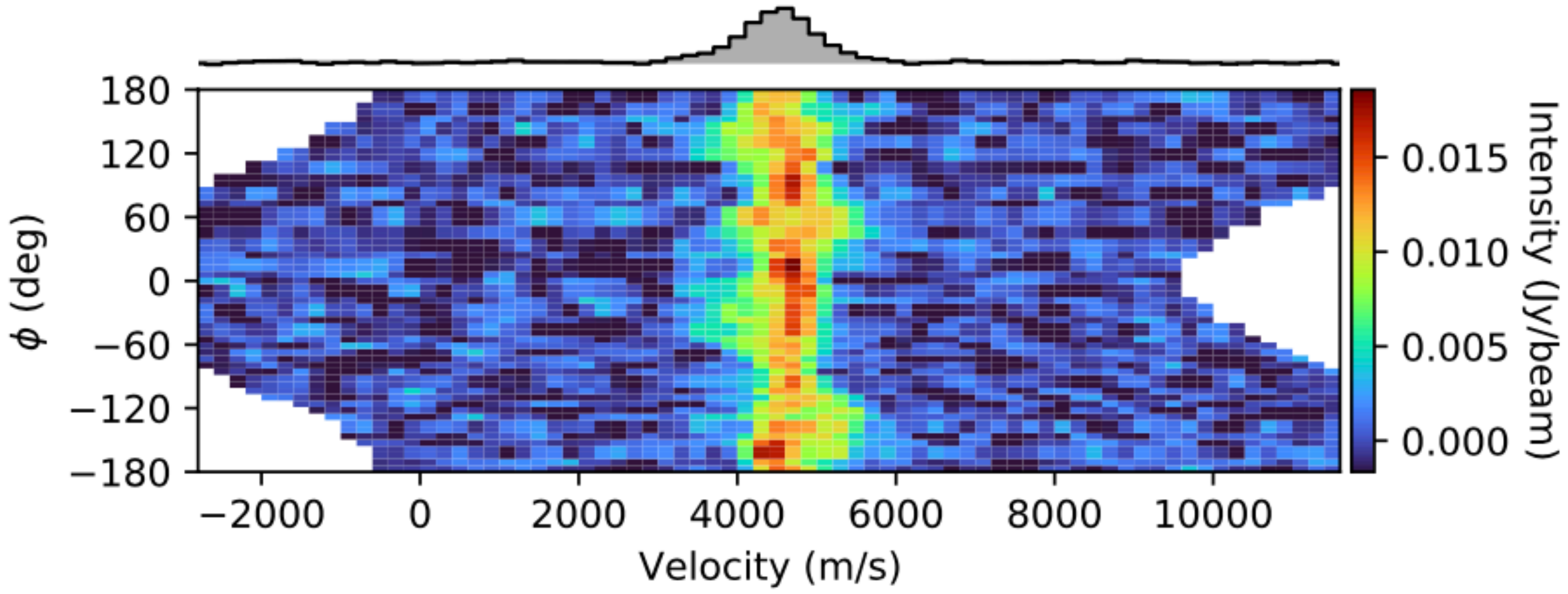
The disc mass in IM Lupi

- High quality data exist from the MAPS survey (Oberg et al 2021)
- We wish to improve in several ways on what done by Veronesi et al (2021)
    1. Include pressure gradient (as a function of height)
    2. Improved method for retrieving the rotation curve
        a. Use Eddy (Teague 2020)
        b. Use discminer (Izquierdo et al, 2021)

Intermezzo: using Eddy to derive rotation curve

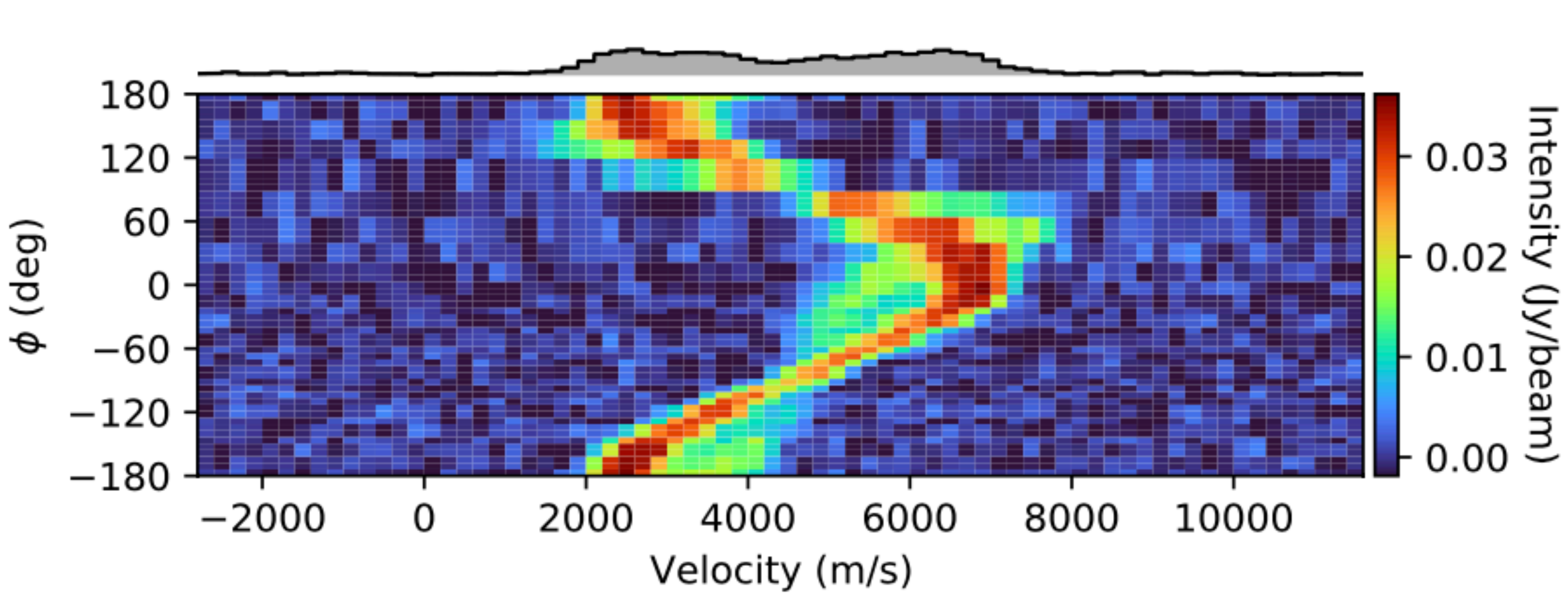


(a) Not aligned spectra.

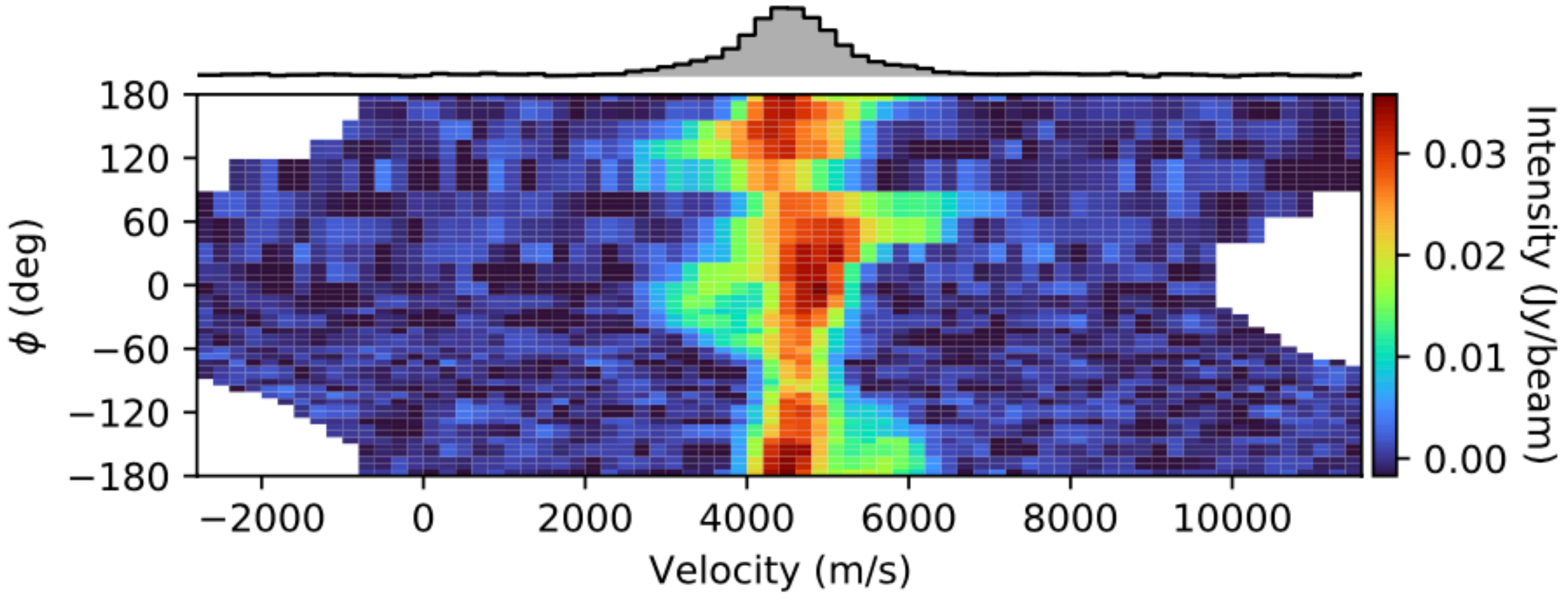


(b) Aligned spectra.

13CO



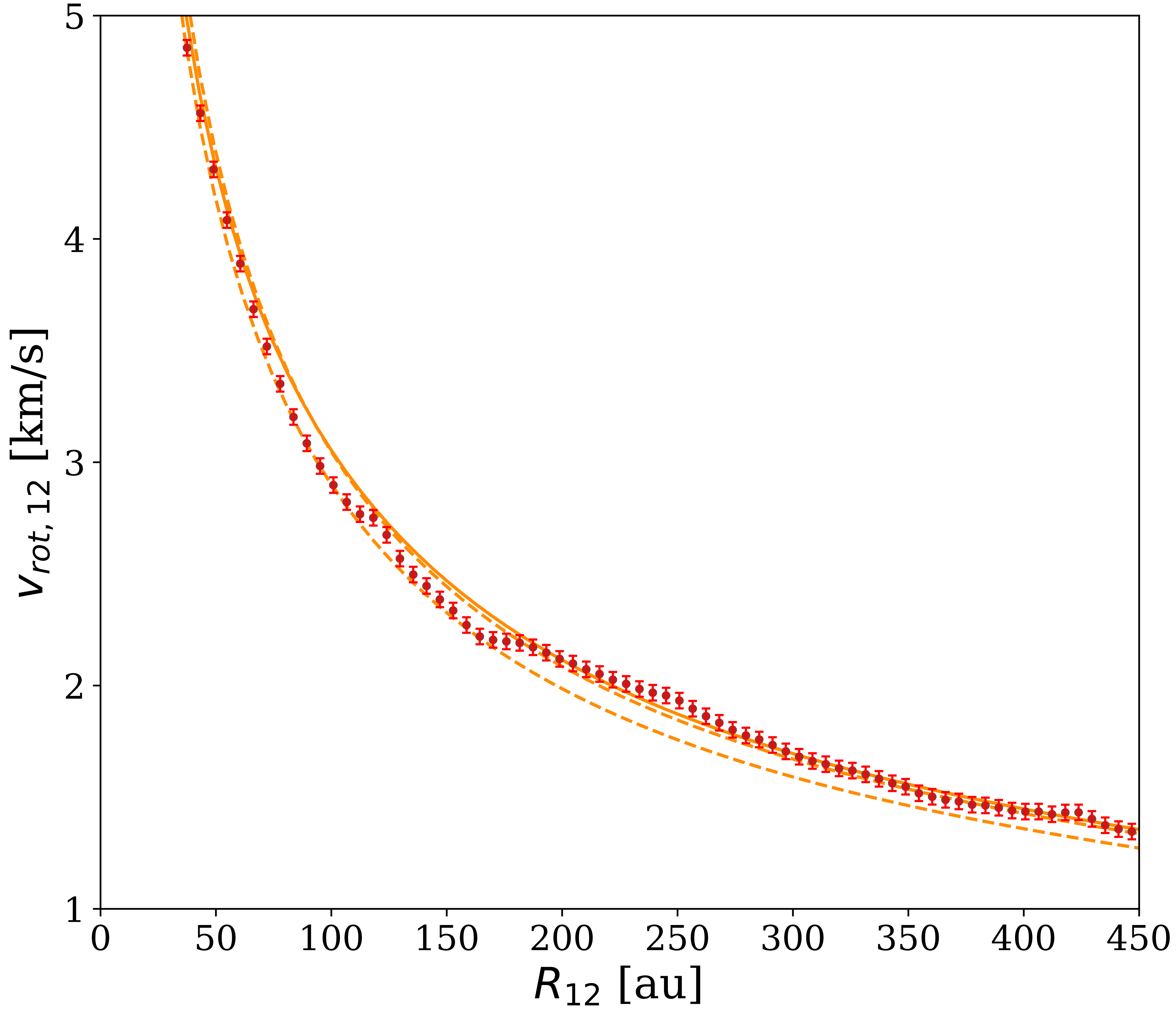
(d) Not aligned spectra.

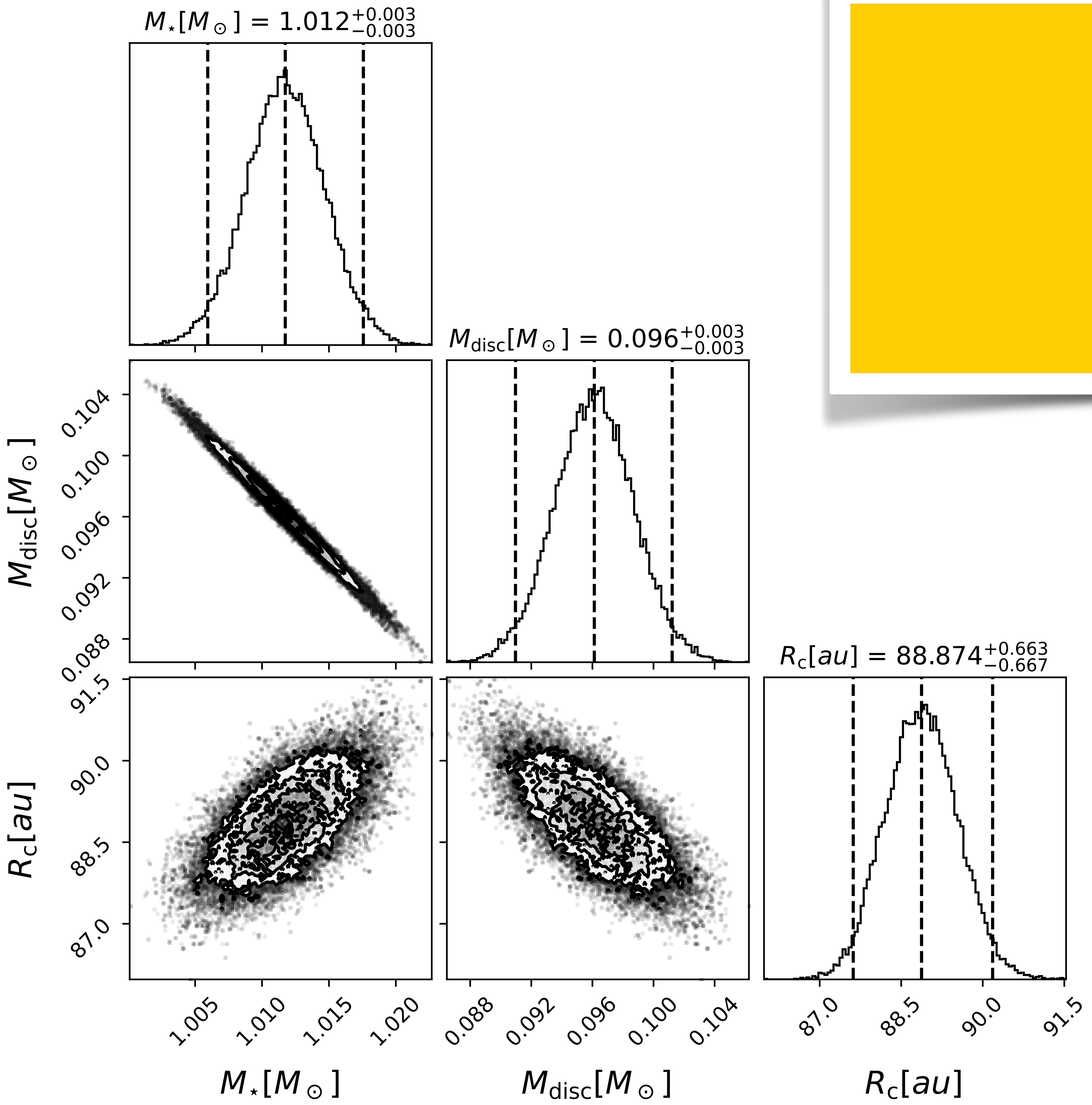


(e) Aligned spectra.

12CO

The rotation curve of IM Lupi





Best fit values:

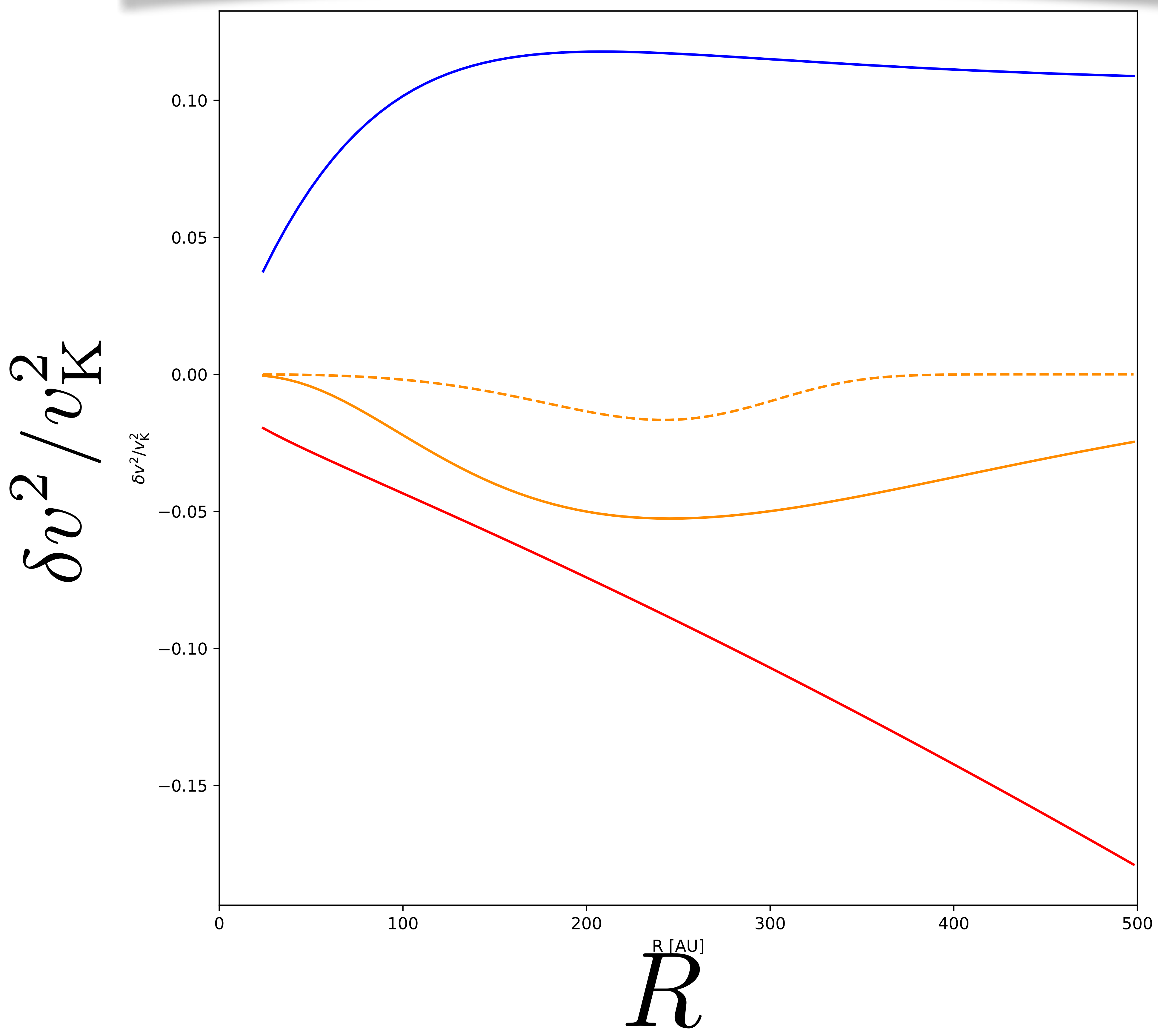
M_{star} ~ 1.01 M_{sun}

M_{disc} ~ 0.1 M_{sun}

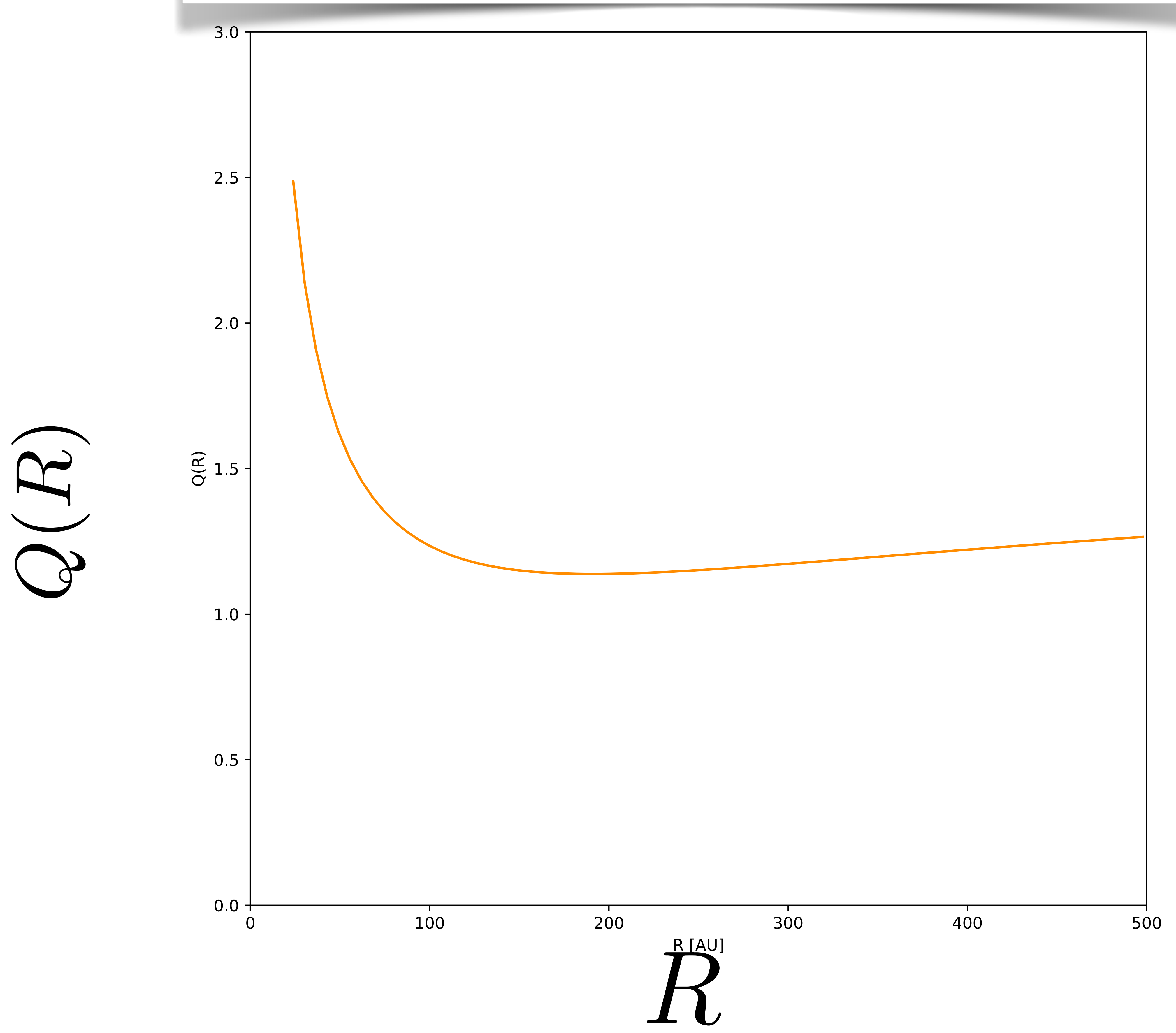
R_c ~ 88 au

IM Lupi fit

Contributions to non-Keplerianity



Q profile



Conclusions

- ALMA kinematics has reached a precision such that we can measure dynamically disc masses within a factor ~ 2 (including systematics)
- Typically the dust/gas ratio that we obtain from these measurements are compatible with the standard assumption of 100 (namely: ~ 80 for Elias, ~ 60 for IM Lup)
- In both Elias and IM Lup the resulting disc mass is high enough to make the disc marginally stable (relation to observed spiral?)
- Disc kinematics in GI unstable disc can give hints on the cooling rate in the outer disc
- Further work:
    - Test the lowest disc mass that we can measure in this way
    - Apply to other sources (work in progress on Wa Oph 6)