Spiral arms in the disk of HD 142527 with ALMA

Quartet

(~~Triptych~~ on HD 142527 - part III)

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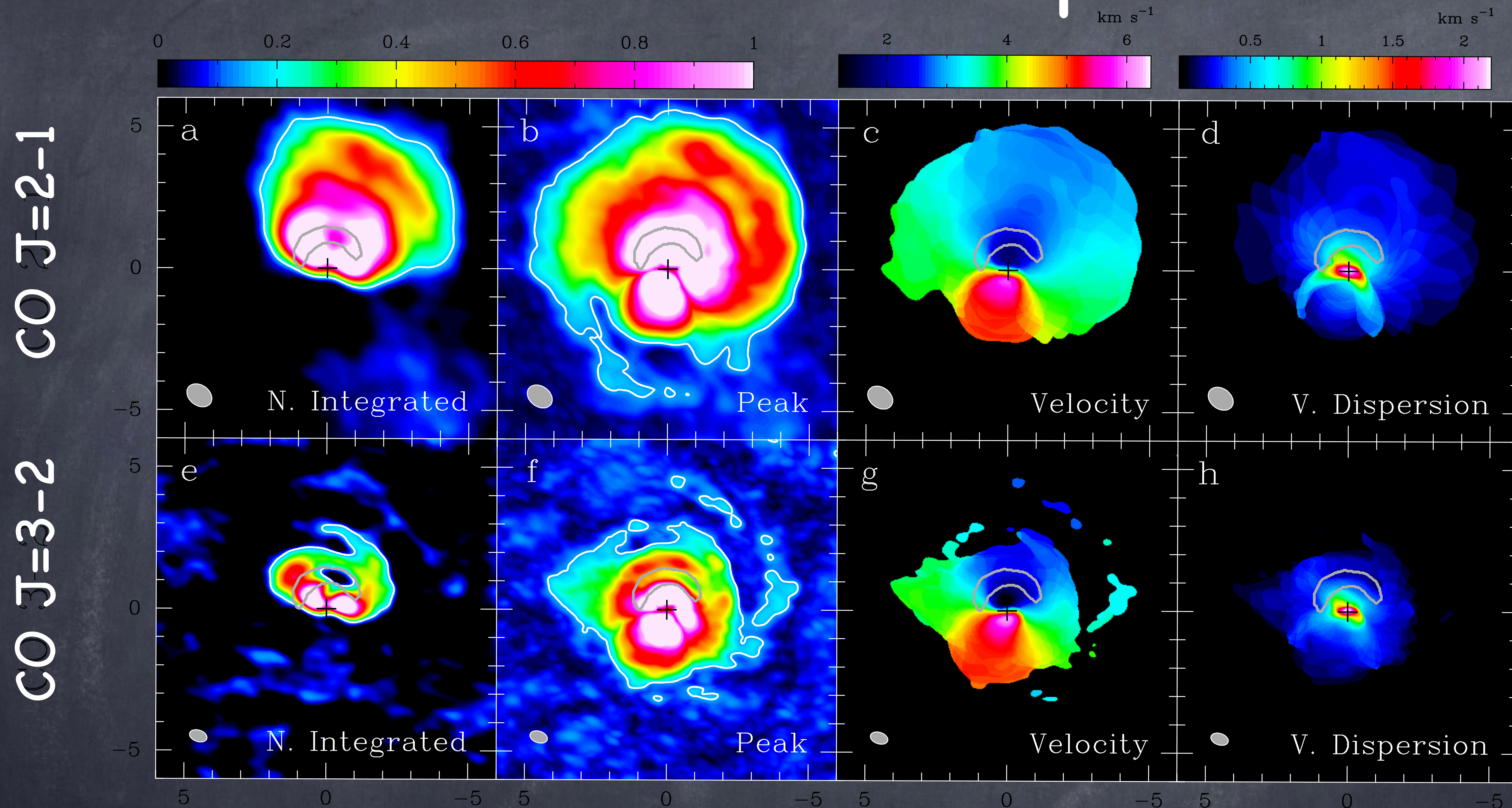
Outline

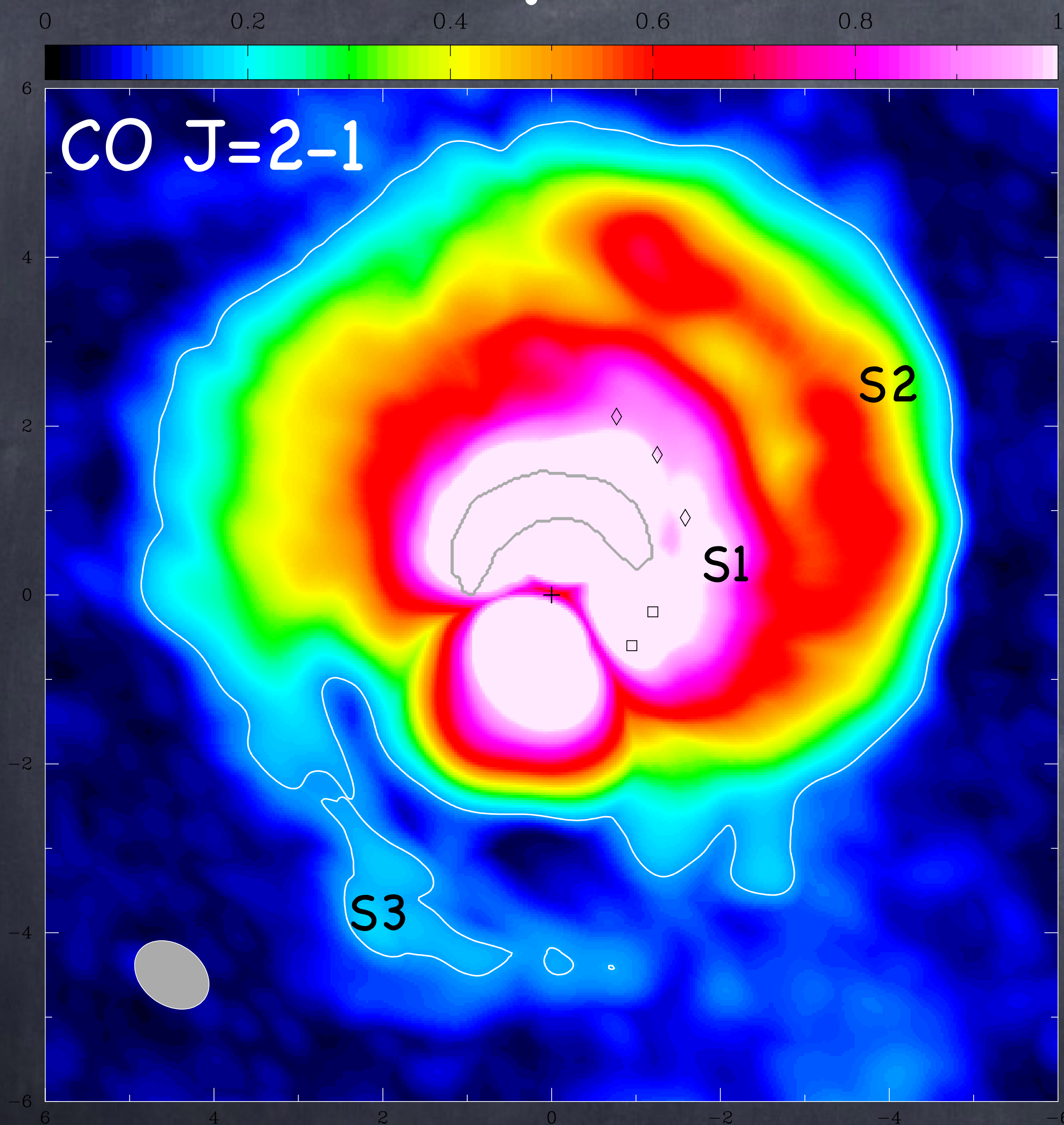
1. Moment maps and detection of spiral arms
2. Description of the spiral arms
3. Geometrical modelling
4. Discussion on their origin

1. Moment maps



- Extended diffuse cloud absorbs signal in the South (Casassus et al. 2013)
- Spiral structures in I_{int} and I_{peak} maps; best seen in CO J=2-1 I_{peak} map
- Keplerian vel. + no significant vel. dispersion under the spirals
- Outer disk too faint to reveal structures in ^{13}CO J=2-1

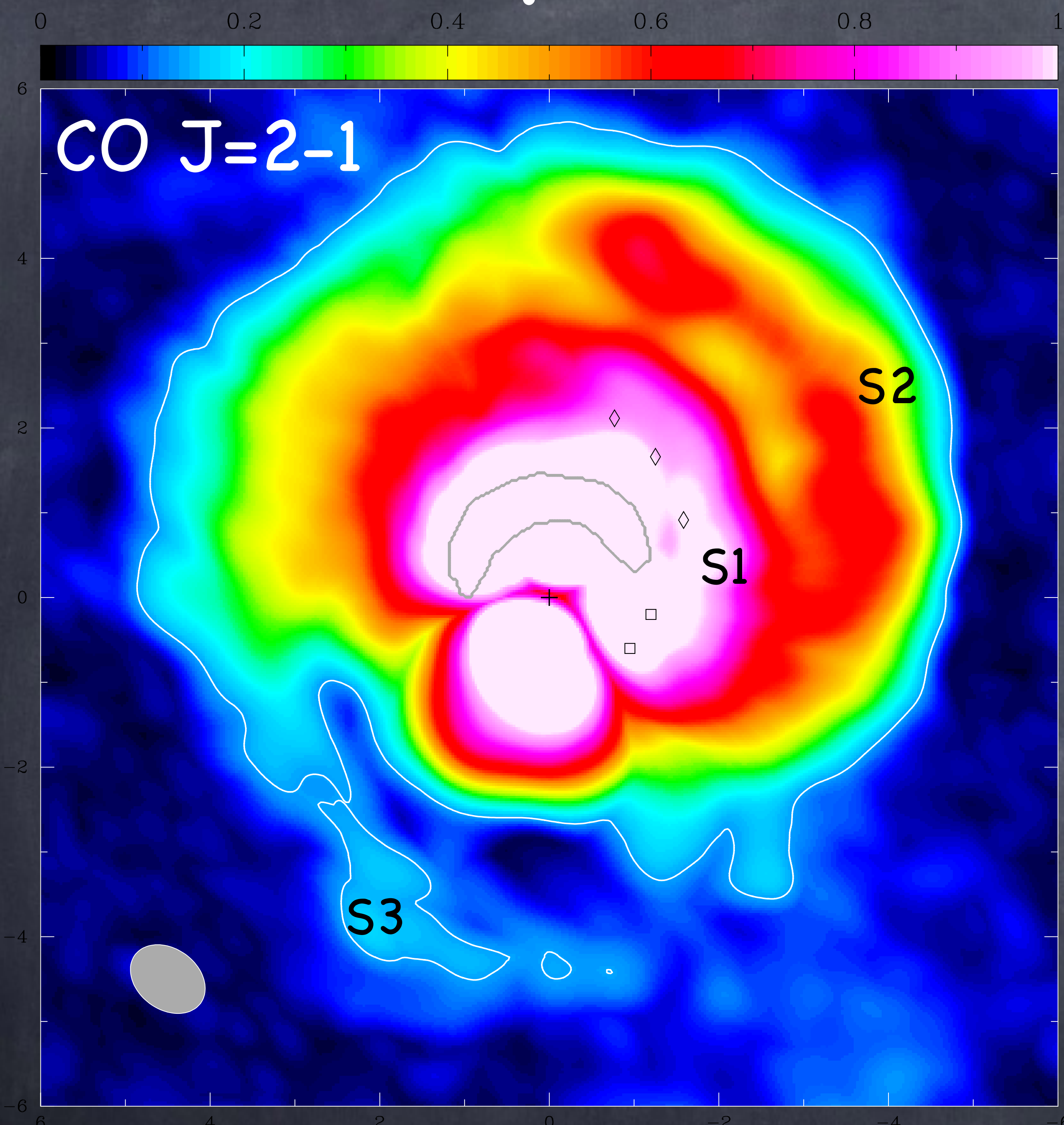
2. Spiral arms description



	S1	S2	S3
R (")	1.9-2.8	3.0-4.2	3.2-4.4
R (au)	290-380	520-640	520-670
PA (º)	-110 - 0	-100 - 0	100-190

- S1 in NIR: diamonds (Fukagawa+ 06) and squares (e.g. Casassus+ 12)
- Very large scale: R>300 au for S1, R>500 au for S2 and △PA ~100º
- S3 signal absorbed by an intervening cloud (Casassus+ 13)

2. Spiral arms description



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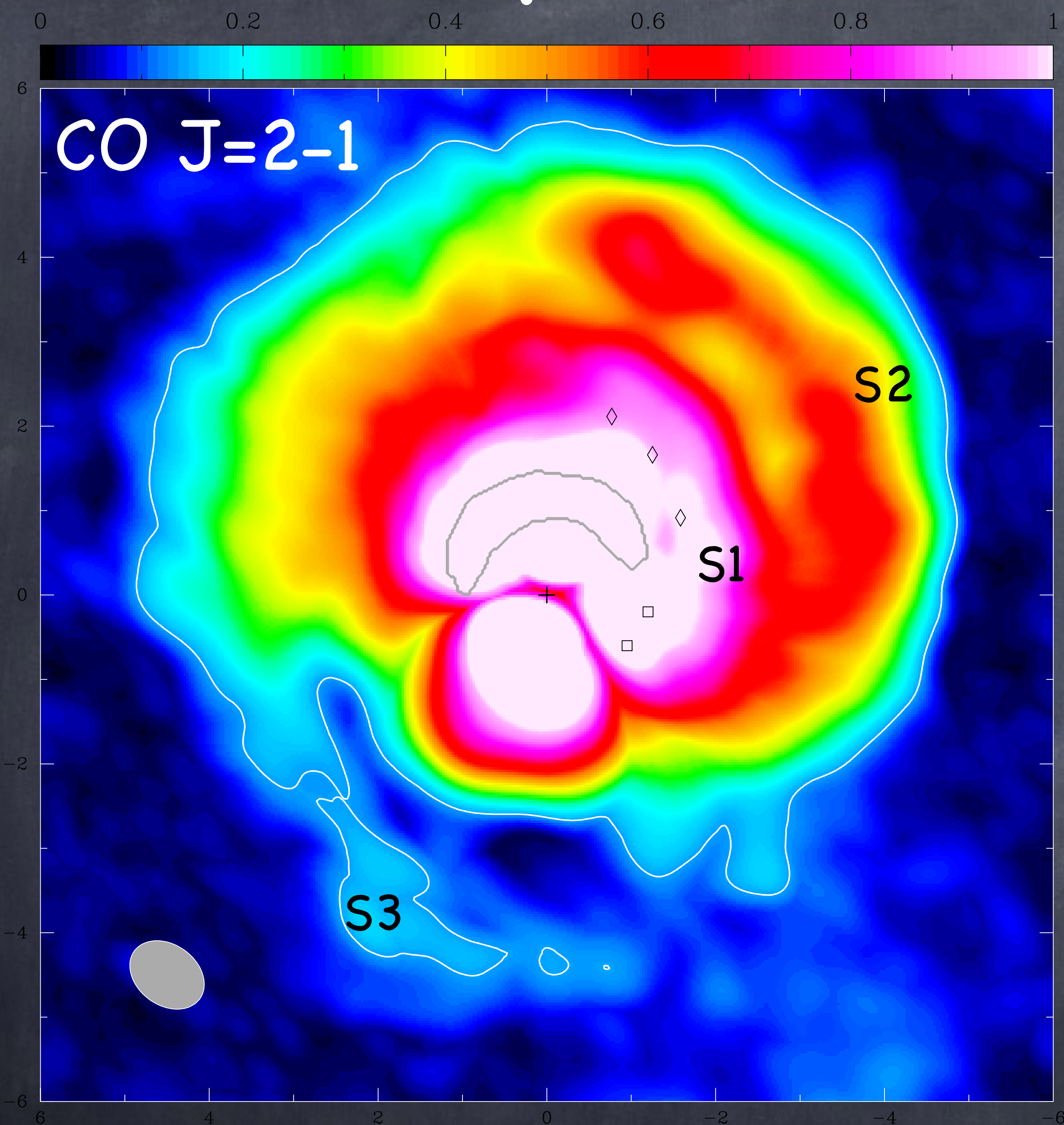
T_b (K)	20-20	11-15	?
T_{ex} (K)	22-27	13-15	?

- ⋆ T(S2) < 18K => CO should freeze-out (e.g. Leger 83; Qi+ 11)

=> dust depleted or settled (e.g. Dubrulle+ 95; Dullemond & Dominik 04)
and/or CO desorbed (e.g. Hersant 09)

- ⋆ T(gap)~42K (Fukagawa+ 13; Perez+ 14 submitted) => $T \propto r^{-q}$ with T_b(CO2-1): q~0.5

2. Spiral arms description



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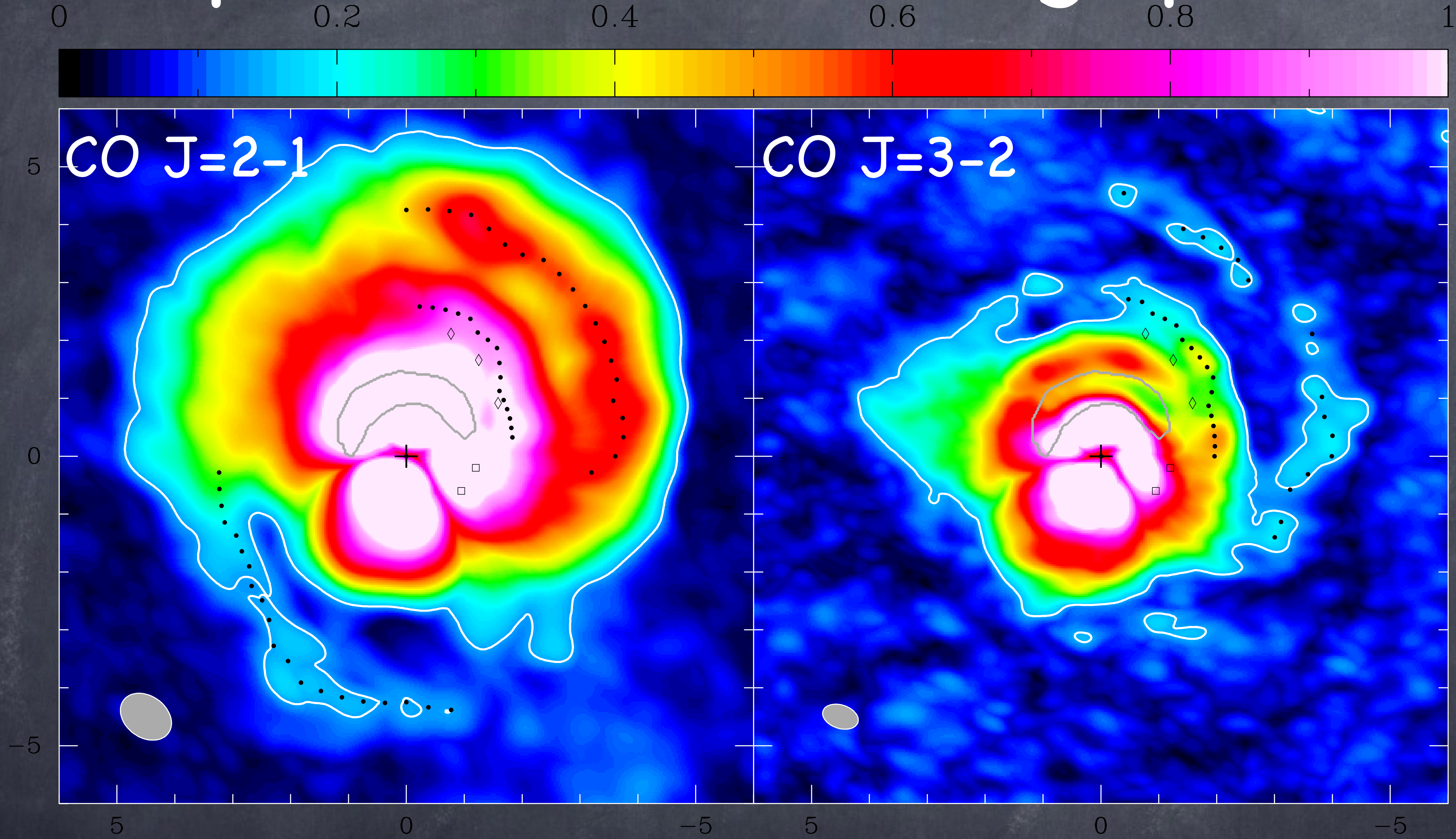
T_b (K)	20-20	11-15	?
T_{ex}(K)	22-27	13-15	?
H (au)	38-44	66-76	?
h	0.11-0.13	0.11-0.13	?

★ If i~28º (Perez+ 14, submitted) => H~20au at the wall (h~0.10-0.15; Avenhaus+ 14)

3. Spiral arm modelling (points)



- 20 Points with: 1st derivative null (S2,S3) in radial I_{peak} profile
  OR 2nd derivative null (S1)

3. Spiral arm modelling (Muto+ 12)

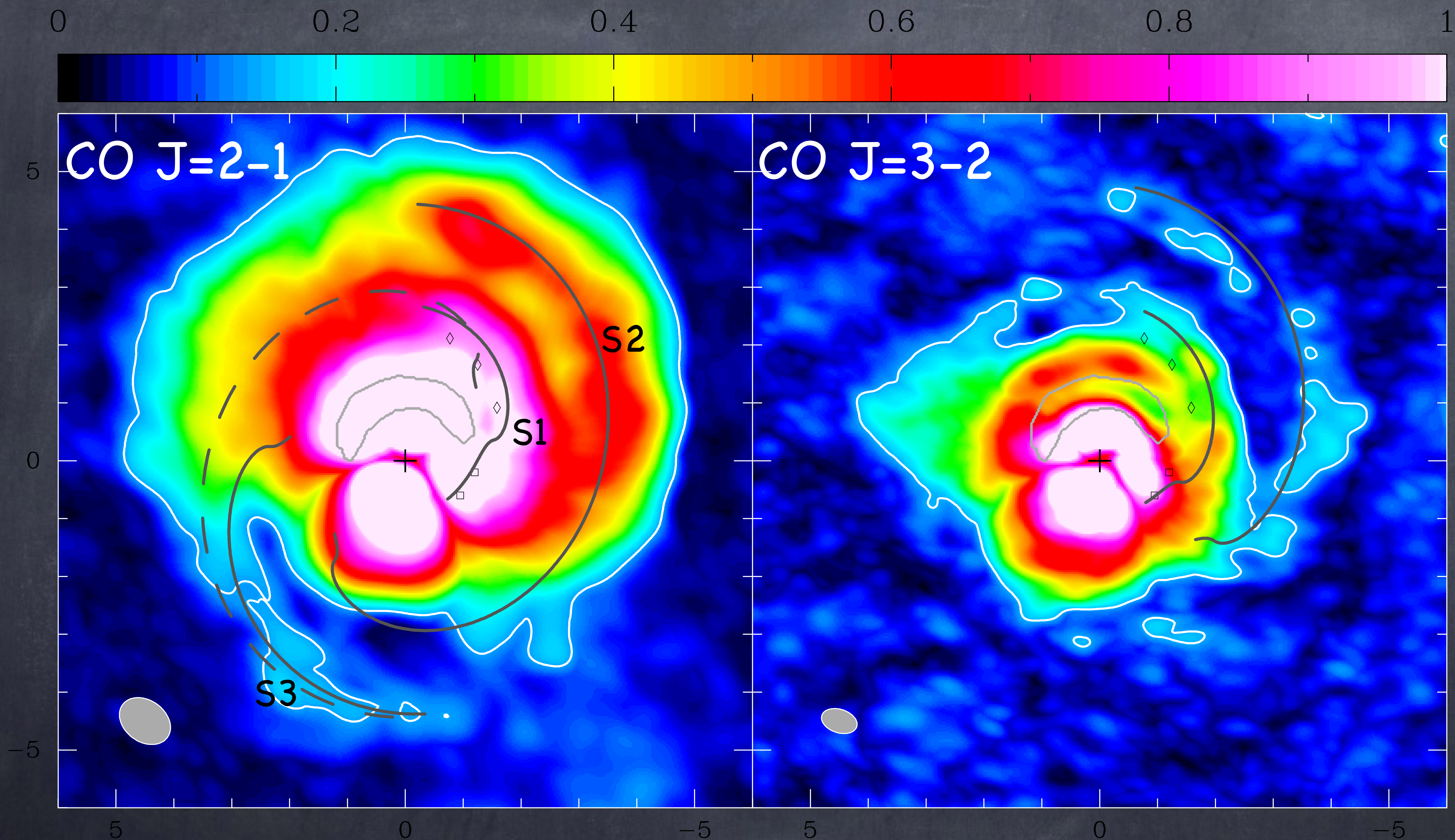
$$\theta(r) = \theta_c + \frac{\mathrm{sgn}(r - r_c)}{h_c} \times \left\{ \left(\frac{r}{r_c}\right)^{1+\beta} \left[\frac{1}{1+\beta} - \frac{1}{1-\alpha+\beta}\left(\frac{r}{r_c}\right)^{-\alpha}\right] - \left(\frac{1}{1+\beta} - \frac{1}{1-\alpha+\beta}\right) \right\}$$

- 5 parameters: θ_c, r_c, h_c, α and β (with $\Omega \propto r^{-\alpha}$ and $c_s \propto r^{-\beta}$)
- The parameters are degenerate (also noted by Muto+ 12, Grady+ 13, Boccaletti+ 13).
- α := 1.5 (Keplerian rotation)
  β := 0.25 ($T \propto r^{-0.5}$)
  h_c := 0.14 (best fit value for S1 if set as free parameter)

χ^2	S1	S2	S3
CO 2-1	2.38	18.0	4.67
CO 3-2	2.06	36.0	/

- σ not independently determined => S1 is better fit than S2 and S3

3. Spiral arm modelling (Muto+ 12)



- Inflection point in the curves: best fit location of the planet
- S1 + S3 ~ Point-symmetric of S2

3. Spiral arm modelling (Kim 11)

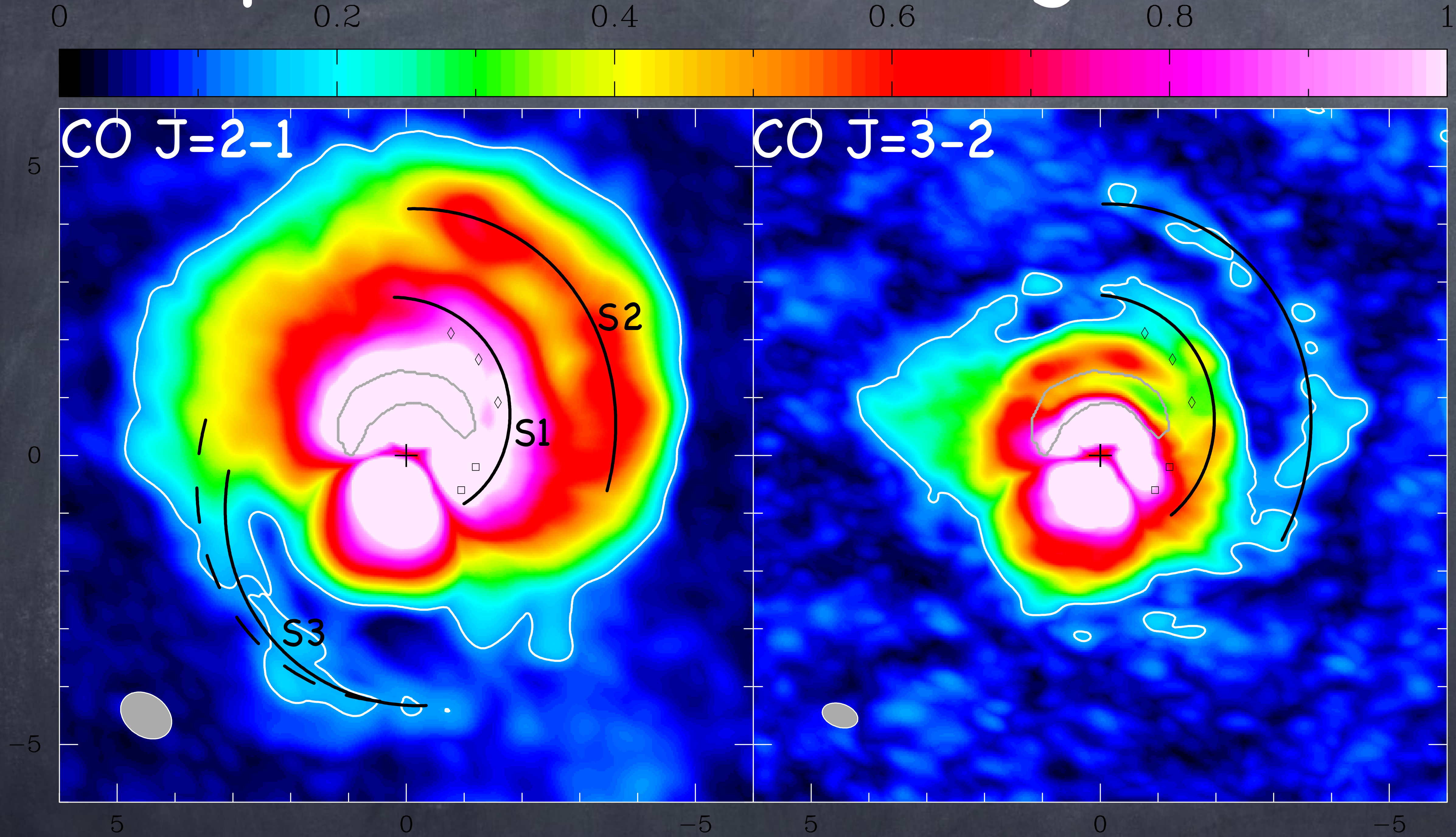
$$r = a\theta + b$$

- 2 parameters: a and b (Archimedean spiral)
- $\begin{cases} a = r_p/M_p \\ b = cte \end{cases}$ with r_p = planet's orbital distance; M_p = planet's Mach number

χ^2	S1	S2	S3
CO 2-1	0.16	0.30	0.40
CO 3-2	0.18	2.94	/

=> S1 is also better fit than S2 and S3.

3. Spiral arm modelling (Kim 11)

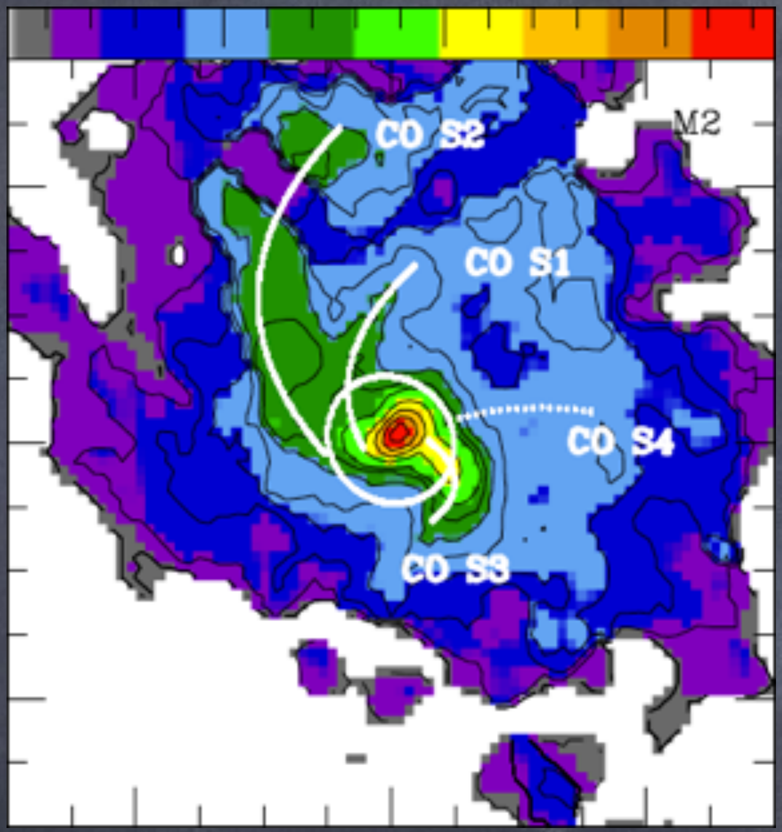


- NIR H-band spiral (diamonds, Fukagawa+ 06), Ks-band spiral root (squares, Casassus+ 12), and S1 => trace the same spiral structure?
- S3 ~ point-symmetric of S2 => two-armed spiral structure?

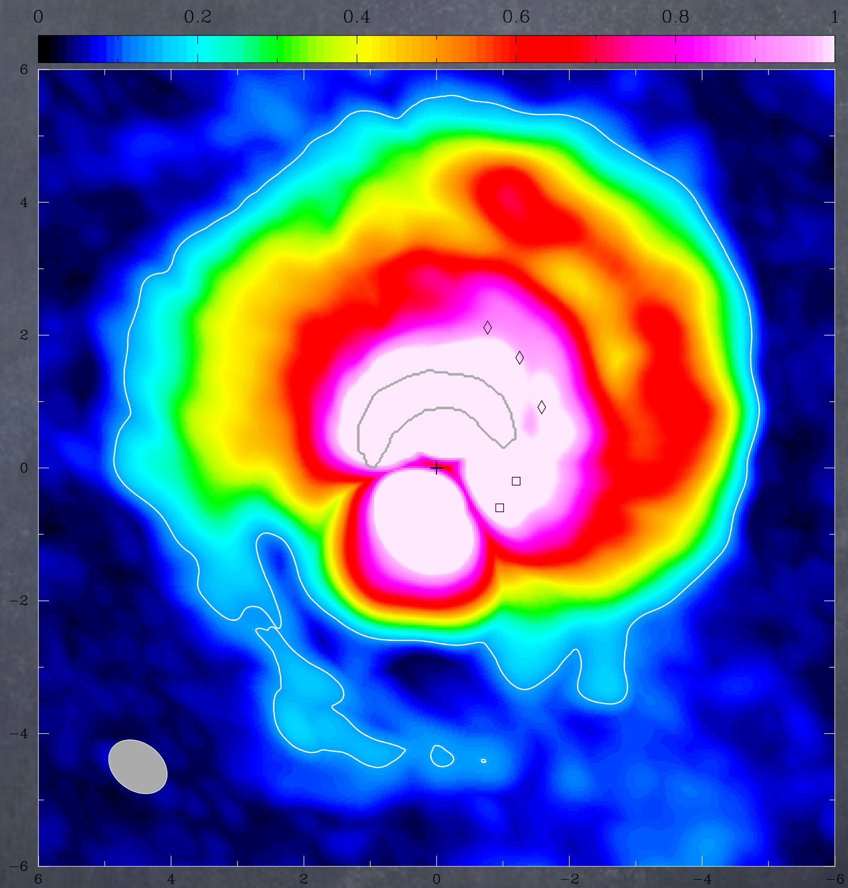
4. Discussion: Origin of the spirals

1/ Late envelope infall? (Tang+ 12)

- AB Aur: Herbig star, large gap, only TD with known sub-mm spirals



Tang+ 12



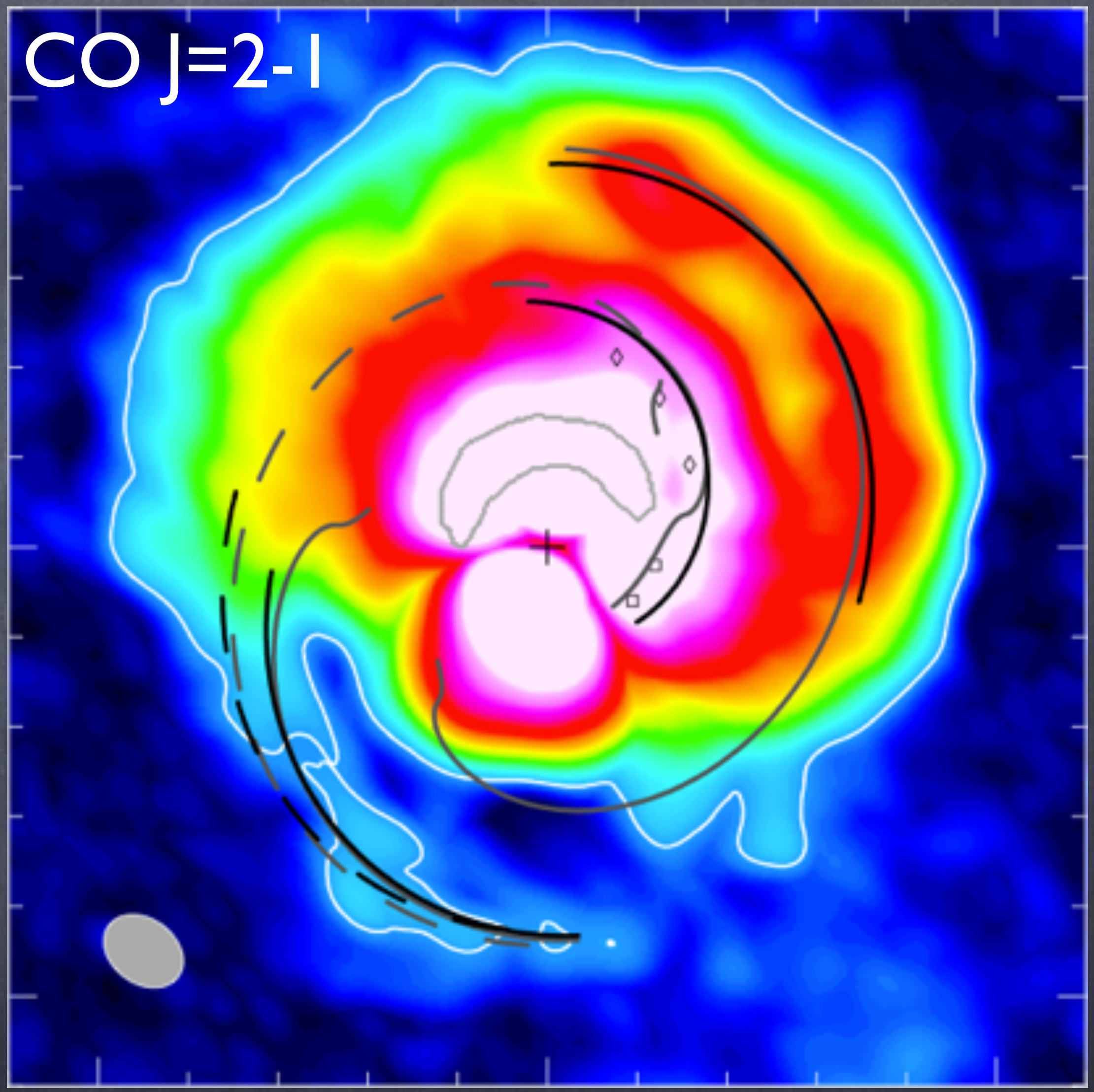
- AB Aur spiral arms have a larger pitch angle.
- AB Aur spiral arms seem to counter-rotate with the disk (vel. disp.).

=> Late envelope infall above or below the mid-plane of the disk.

For HD 142527? NO

4. Discussion: Origin of the spirals

2/ Planetary companion?



- ⋆ S1 is better fit with Muto and Kim equations than S2 and S3.
- ⋆ The very large scale of S2 and S3 argue against a planetary origin.
- ⋆ Object (stellar companion?) detected at ∼12 au (Biller+ 12, Close+ 14)

Companion origin? Maybe for S1, less likely for S2 and S3

4. Discussion: Origin of the spirals

3/ Tidal interaction? (e.g. Larwood & Kalas 01, Quillen+ 05)

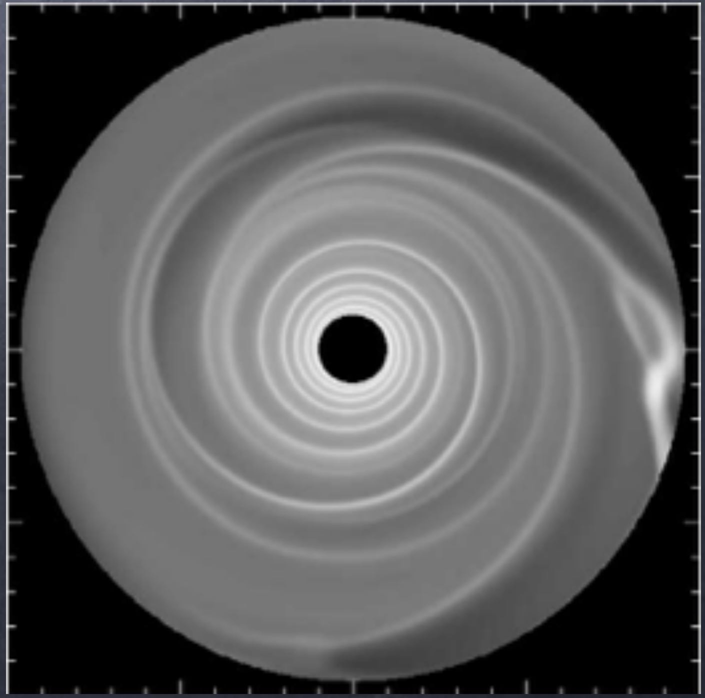
a) Past stellar encounter

★ Galaxy encounters are able to create m=2 spiral structures (Toomre 1972)

★ Stellar encounters with pp. disks too (Larwood & Kalas 01, Quillen+ 05)

★ Transient (~10^3 yrs) => very recent encounter => culpit still in the neighbourhood.
No such object in a FOV of 20" (Fukagawa+ 06).

Past stellar encounter?
Requires larger FOV; cannot be ruled out.



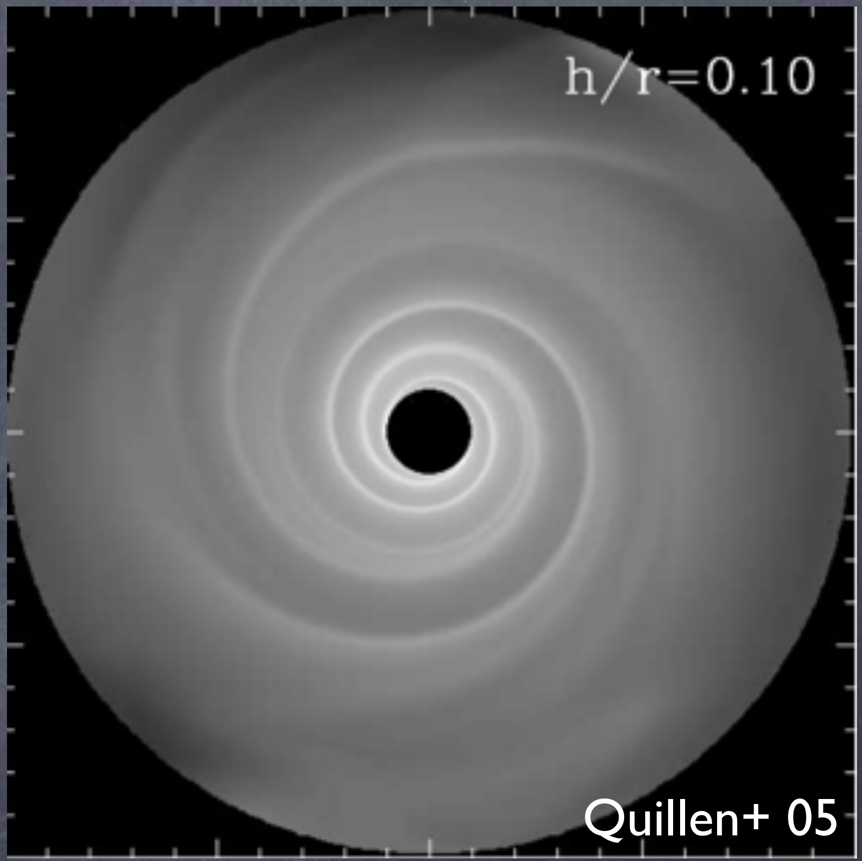
Quillen+ 05

4. Discussion: Origin of the spirals

3/ Tidal interaction? (e.g. Augereau & Papaloizou 04, Quillen+ 05)

b) Bound external companion

★ Large scale (~325 au) tightly wound spiral in the disk of HD 141569A due to one of its M-dwarf companions (Augereau & Papaloizou 04, Quillen+ 05)



★ For HD 142527, no external companion of M > $4M_J$ (Casassus+ 13)

Bound external companion? Not likely

4. Discussion: Origin of the spirals

4/ Gravitational instability (GI)? (e.g. Boss 1998, talk by G. Lodato)

- Disk self-gravity can lead to multi-arm spiral pattern (with perhaps some unresolved modes here)

- The stability of a disk against self-gravity is characterized by:

$$Q = \frac{c_s \Omega}{\pi G \Sigma} \qquad \text{(Toomre 1964)}$$

$$\approx \frac{M_*}{M_d} h \qquad \text{(Gammie 2001)}$$

- If Q $\lesssim$ 1 : disk instability

- $\begin{cases} M_* \sim 2^{+0.2}_{-0.1}\, M_\odot & \text{(Fukagawa+ 06, Verhoeff+ 2011)} \\ M_d \sim 0.1\, M_\odot & \text{(Verhoeff+ 2011)} \\ h = h_s \sim 0.1 & \end{cases}$ => Q $\sim$ 2 (similar to Fukagawa+ 13)

GI? Marginal stability, but very rough estimated

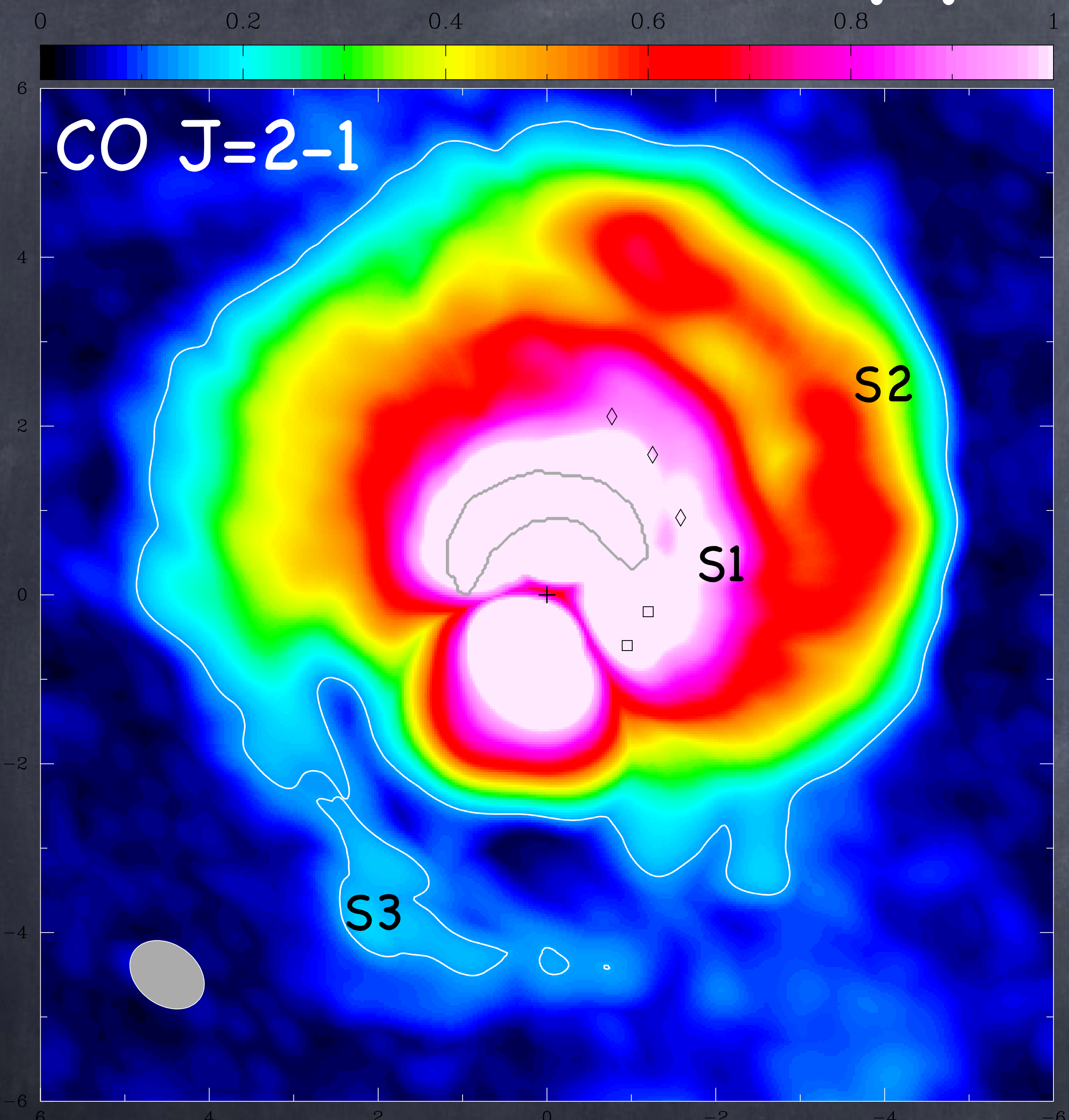
Summary

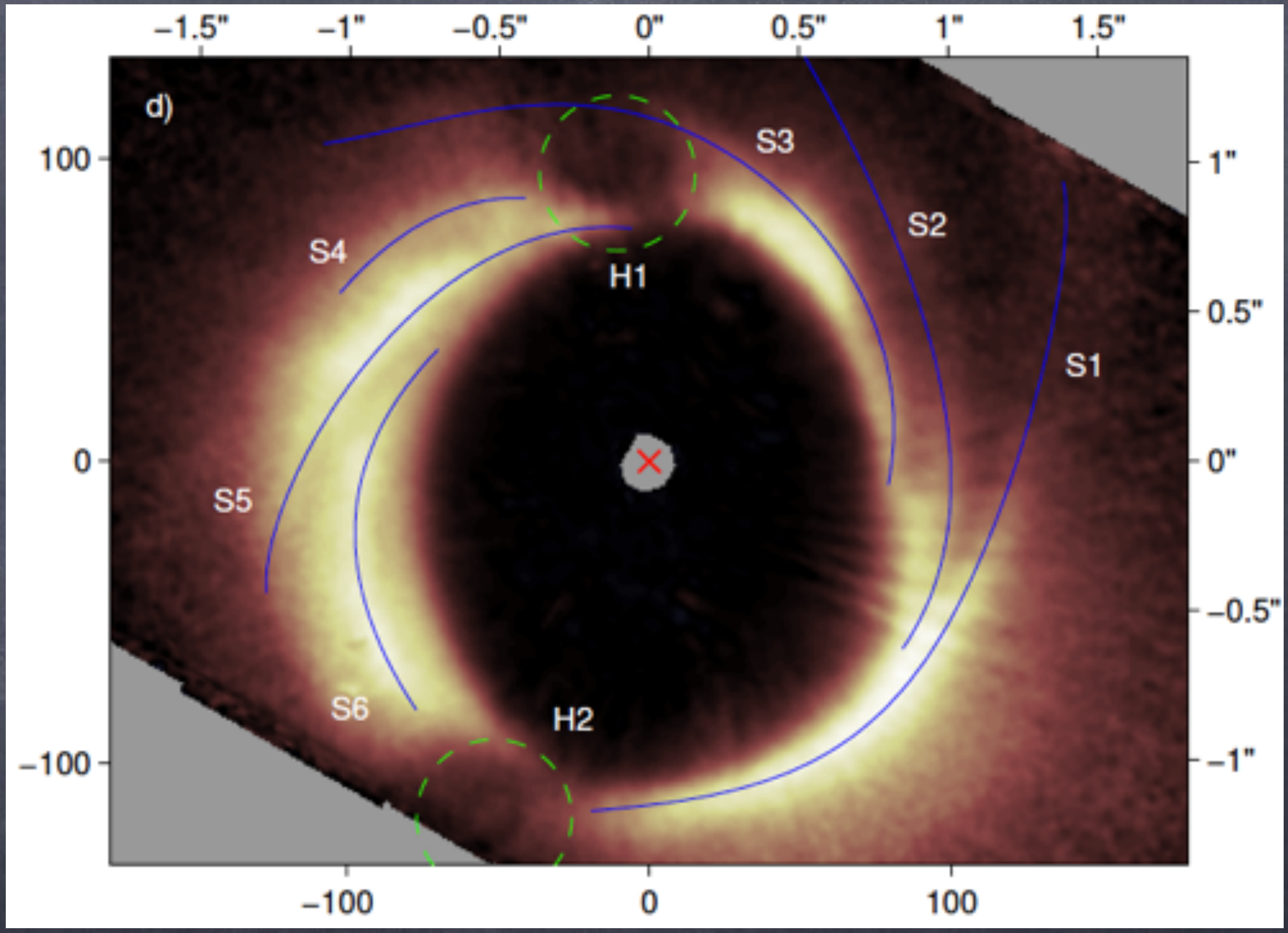
- Three CO spiral arms in the disk of HD 142527:
  - S1 is radially shifted outward w.r.t. NIR spirals
  - S2 and S3 are new and at larger scale (> 500au)
- S2 has T $\lesssim$ 18K: dust is depleted or settled or CO is desorbed.
- h $\sim$ 0.11-0.13 in the outer disk
- S1 better fit than S2 and S3 to eqs. assuming embedded companion.
- Other possible origins: { past stellar encounter / gravitational instability }

- Paper: Christiaens, Casassus, Perez, van der Plas & Menard 2014, ApJL, 785, L12


Thank you for your attention!

Appendix





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