# A Prototype Protoplanetary Disk for Modelling: HD 163296

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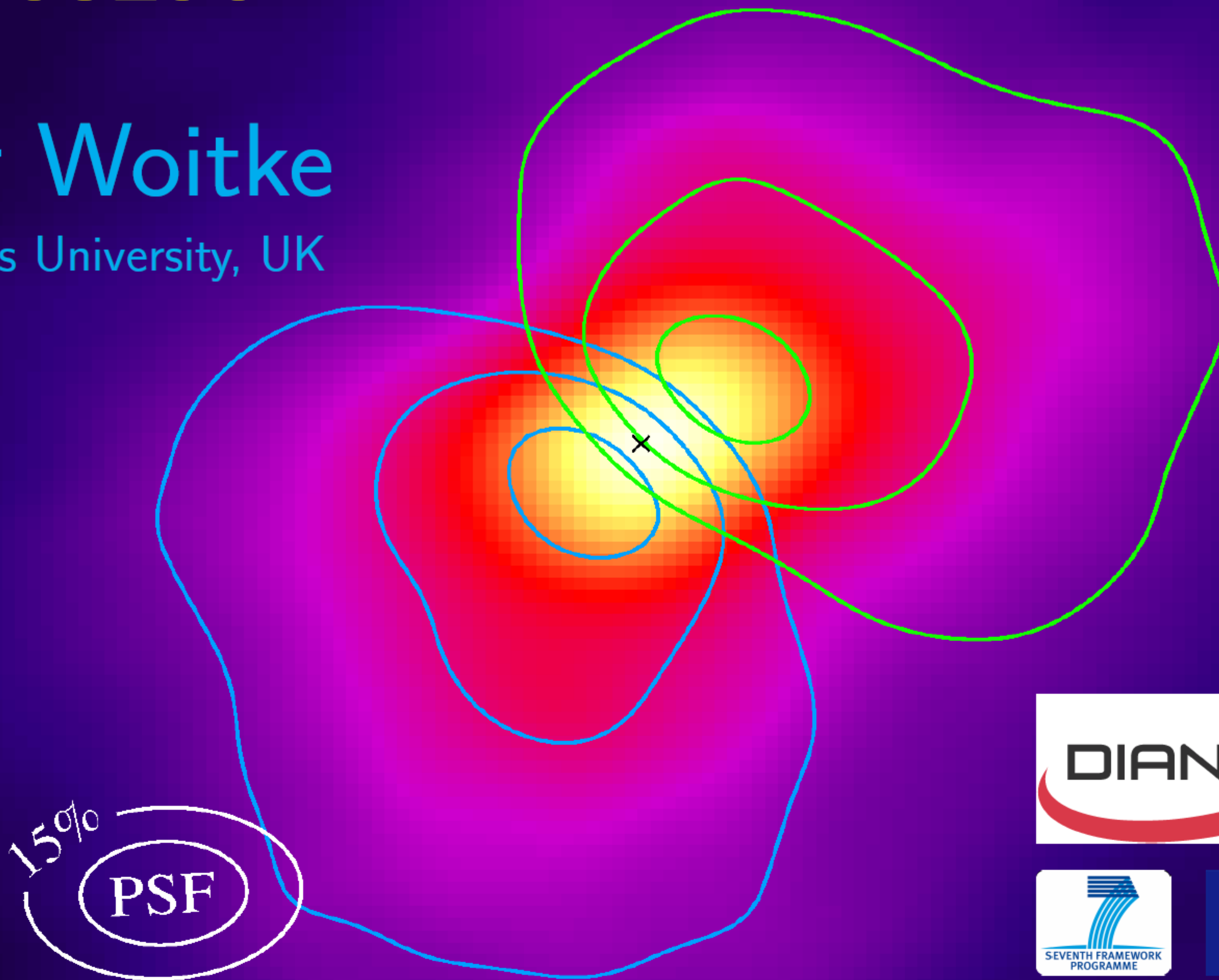
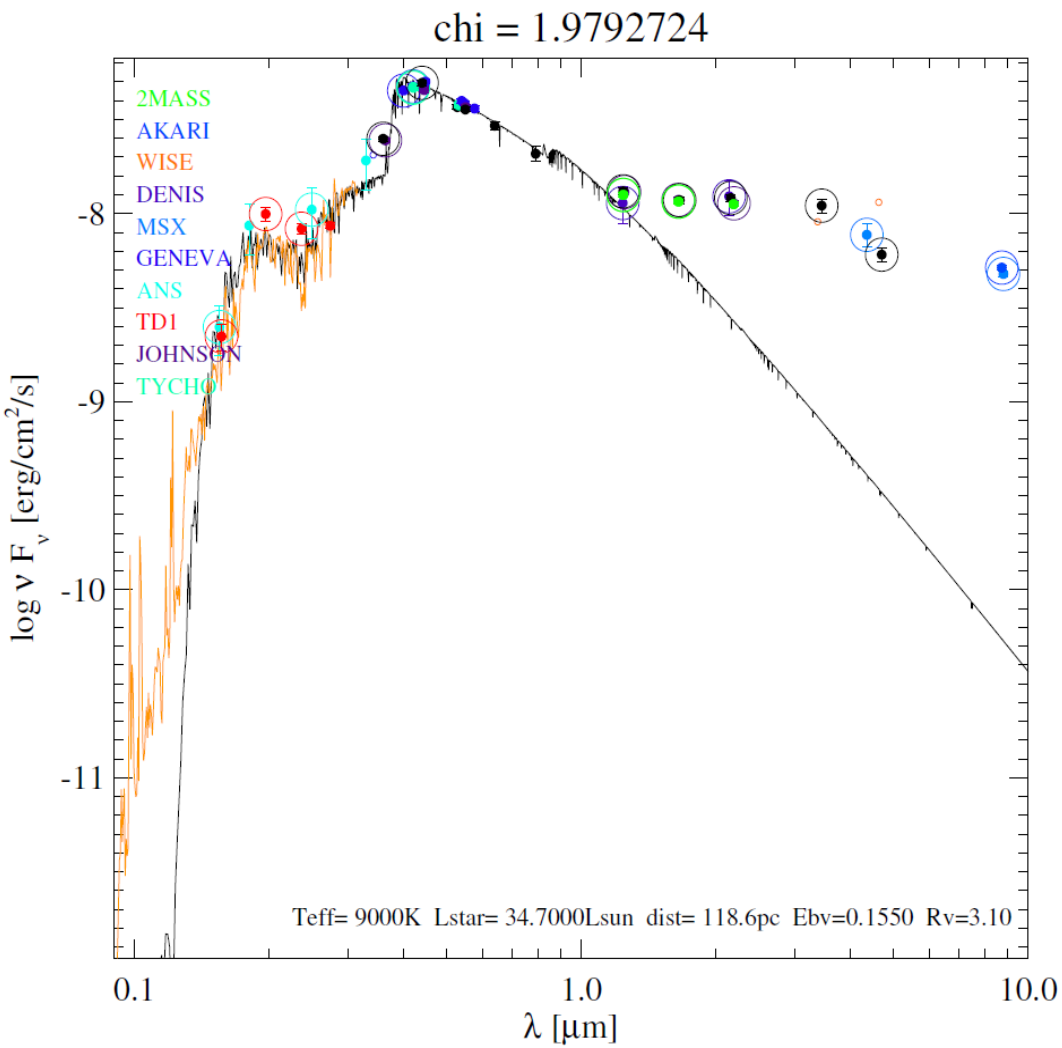
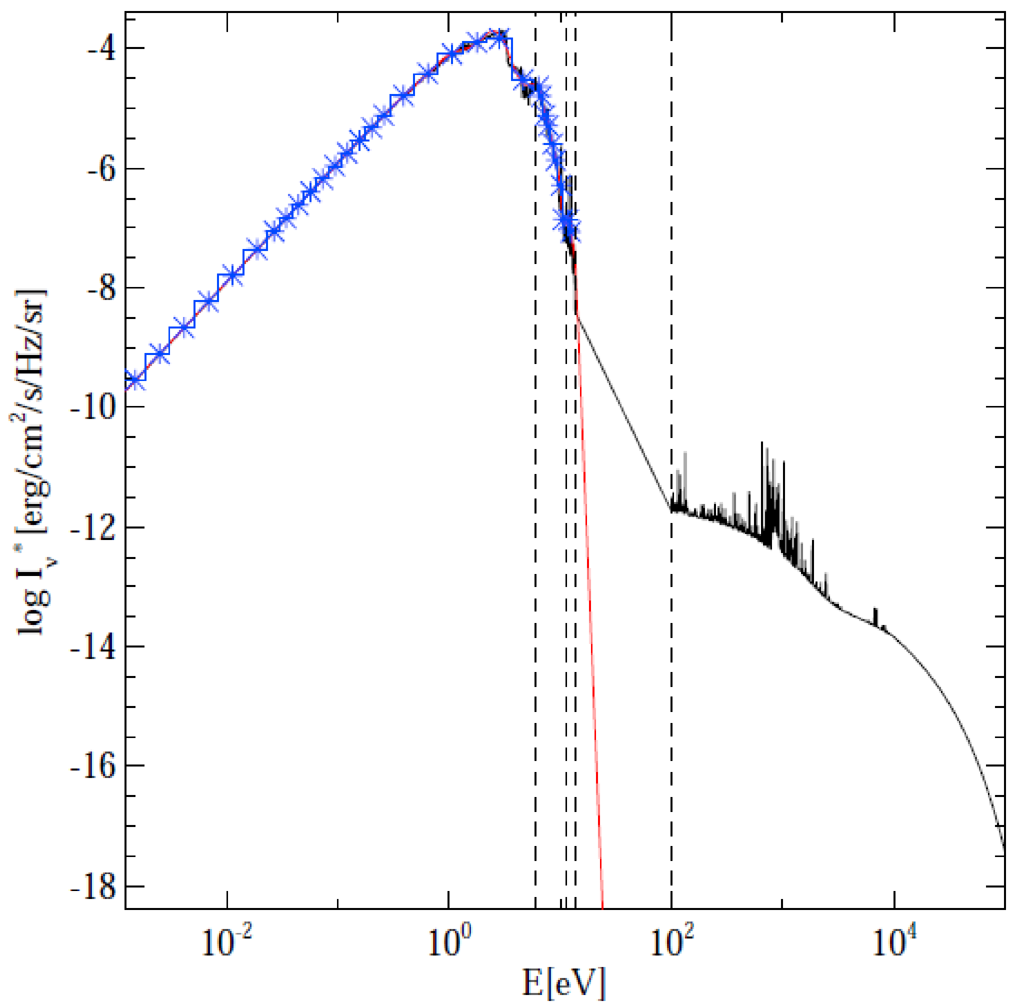


# UV and X-ray data



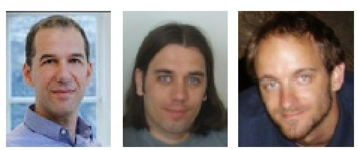
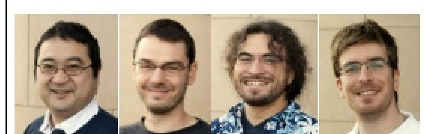
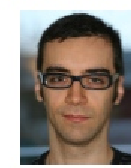




- **photometry** from automated catalog search
- **<UV>-data** from FUSE, STIS & IUE
- **UV → non-photospheric** λ < 150 nm
- **IR → non-photospheric** λ > 2 μm

- **X-ray data** from Chandra, XMM/Newton
- $L_X \approx 10^{29.8}$ **erg/s**
- fitted and extinction-corrected with two-component X-ray emission model

FP7-SPACE 2011 collaboration

# Analysis and Modelling of Multi-wavelength Observational Data from Protoplanetary Discs

| St Andrews | Vienna | Amsterdam | Grenoble | Groningen |
|---|---|---|---|---|
| <br>*P. Woitke*<br><br>*Greaves Ilee Rigon* | <br>*M. Güdel*<br><br>*Dionatos Rab Liebhart* | <br>*R. Waters*<br><br>*Min Dominik* | <br>*F. Ménard*<br><br>*Thi Pinte Carmona Anthonioz* | <br>*I. Kamp*<br><br>*Antonellini* |
| **sub-mm to cm** | **X-rays** | **near-mid IR** | **near-far IR** | **near IR - mm** |
| **coordination**<br>JCMT, eMERLIN<br>astrobiology | obs./mod.<br>XMM, Herschel<br>high energy | mod./obs.<br>VLT, JWST<br>dust mod. | obs./mod.<br>HST, Herschel<br>interferometry | mod./obs.<br>Herschel, JWST<br>gas mod. |

multi-$\lambda$ data collection X-ray to cm (archival and proprietary)

coherent, detailed modelling of gas & dust throughout the disc

using disk modelling software ProDiMo, MCMax, MCFOST

**aim:** disc shape, temperatures, dust properties, chemistry in the birth-places of exoplanets

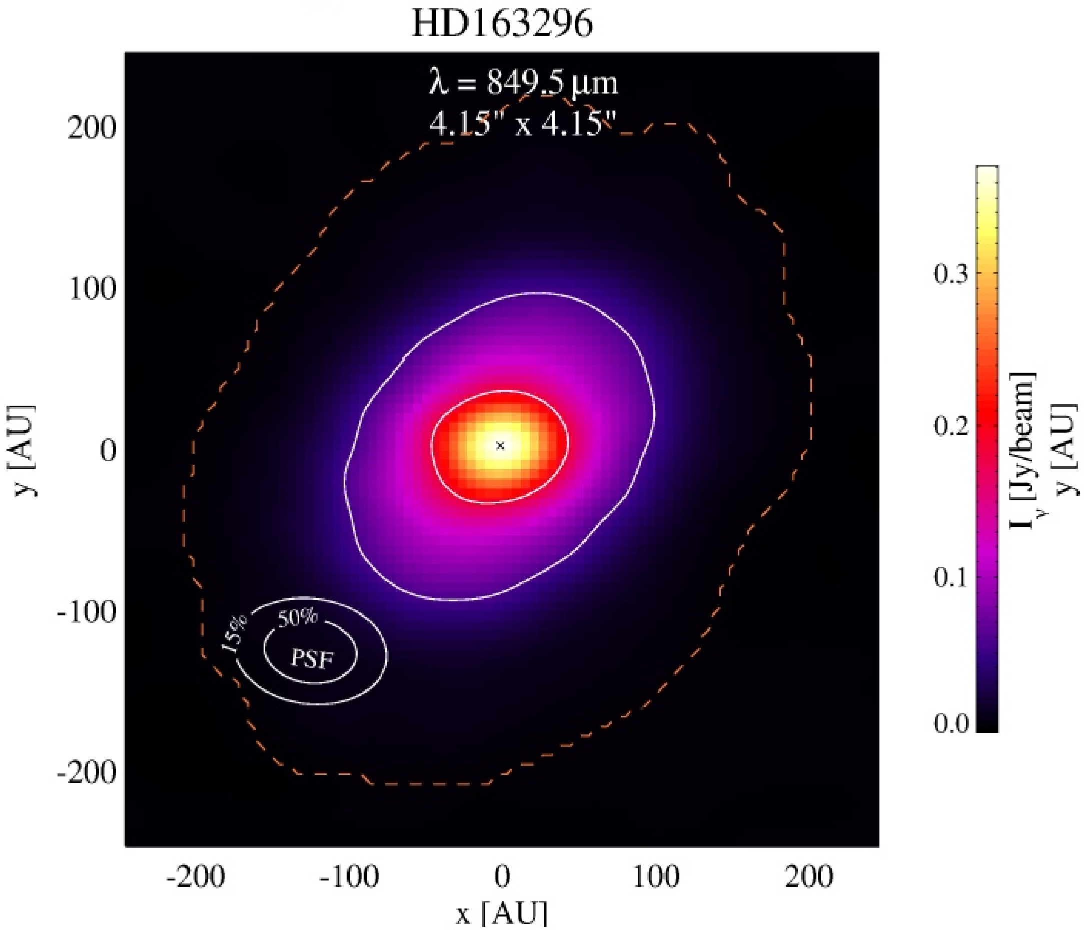
# The DiscAnalysis DIANA modelling approach

- use detailed **UV** and **X-ray** data for input spectrum
- "standard" **dust opacities**, and dust **radiative transfer** ***(MCFOST, MCMax)***
- simple "standard" **gas & ice chemistry** *(kinetic chemical eq.)*
- **gas heating & cooling** ***(ProDiMo)***
- simple **2D parametric disk shape** *(tapered outer edge)*
- **dust settling** → *Dubrulle et al. (1995)*
- fit all continuum observations **(SED, images, interferometry)**
- simultaneously, fit all line observations like CO ro-vib, Spitzer, Herschel, sub-mm **(line flux, velocity profile, radial profile)**
- … with one model (!)

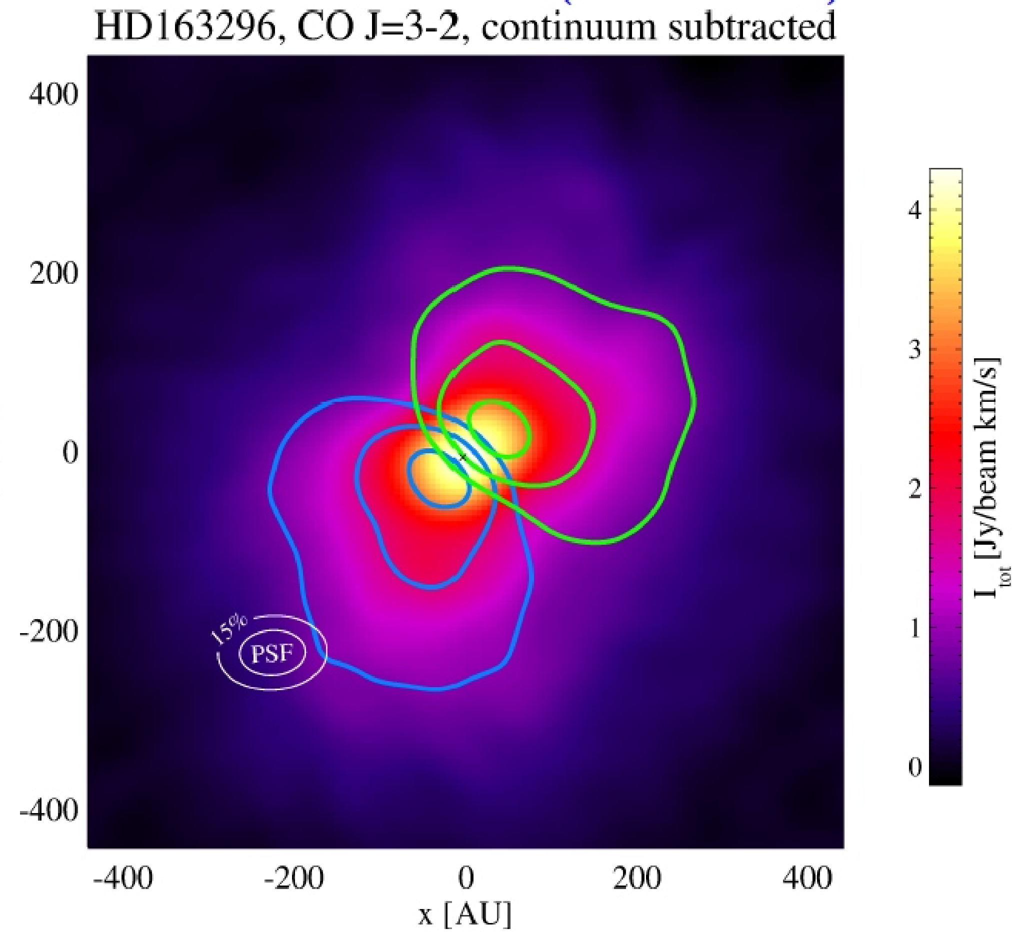
# The perfectly symmetric disk of HD 163296

(( A1.5, $T_{\rm eff} \approx 9000\,{\rm K}$, $L_\star \approx 35\,L_\odot$, $M_\star \approx 2.3\,M_\odot$, $d \approx 119\,{\rm pc}$, age $\approx$ 4 Myr, $\dot{M}_{\rm outflow} \approx 10^{-8} M_\odot/{\rm yr}$ ))

**850 $\mu$m cont. ALMA**




**CO $J = 3 \rightarrow 2$ (ALMA)**

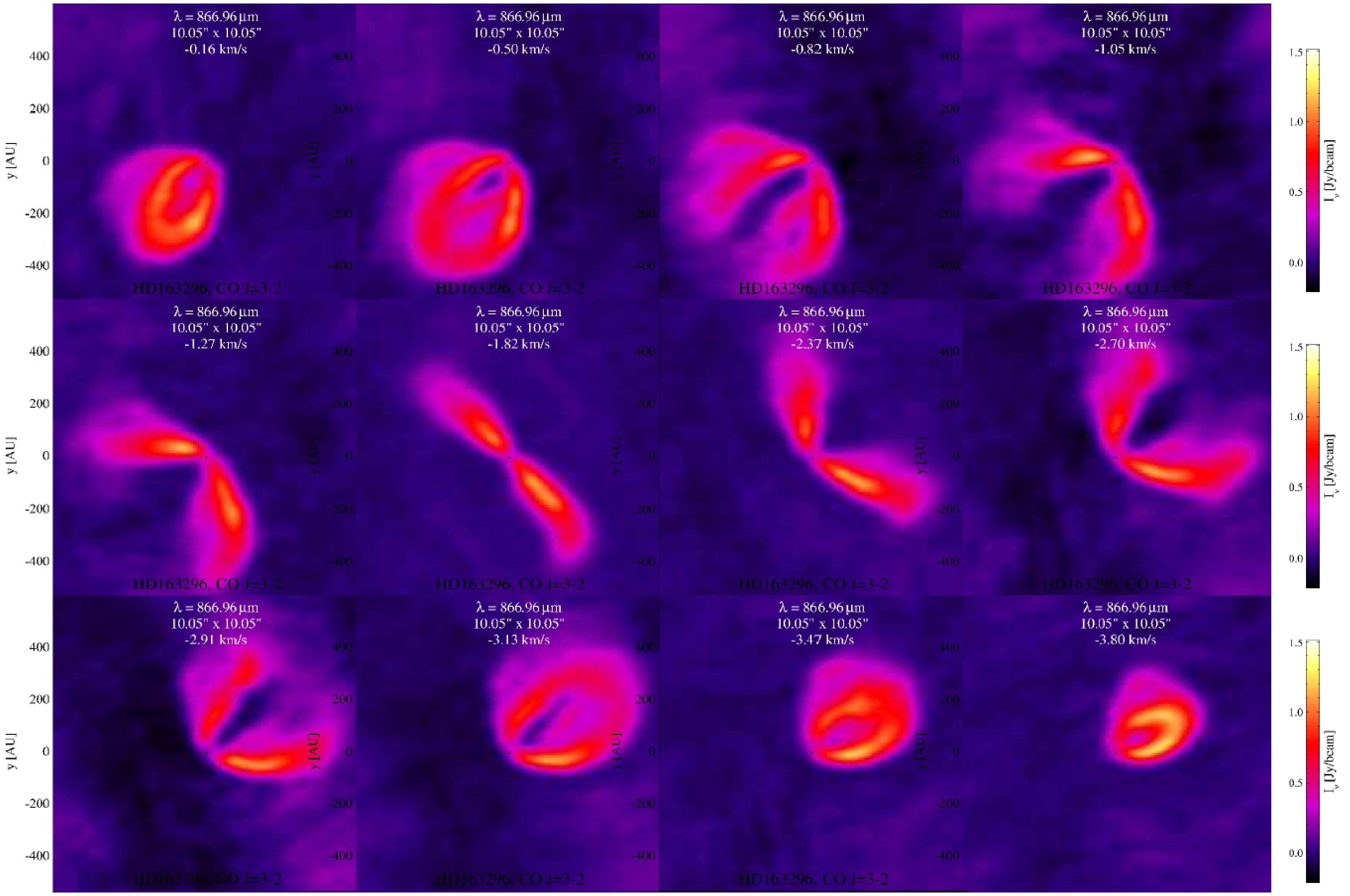



http://almascience.eso.org/alma-data/science-verification

de Gregorio-Monsalvo et al. (2013, A&A 557, 133)

Rosenfeld et al. (2013, ApJ 774, 16)

# The HD 163296 CO 3→2 channel maps



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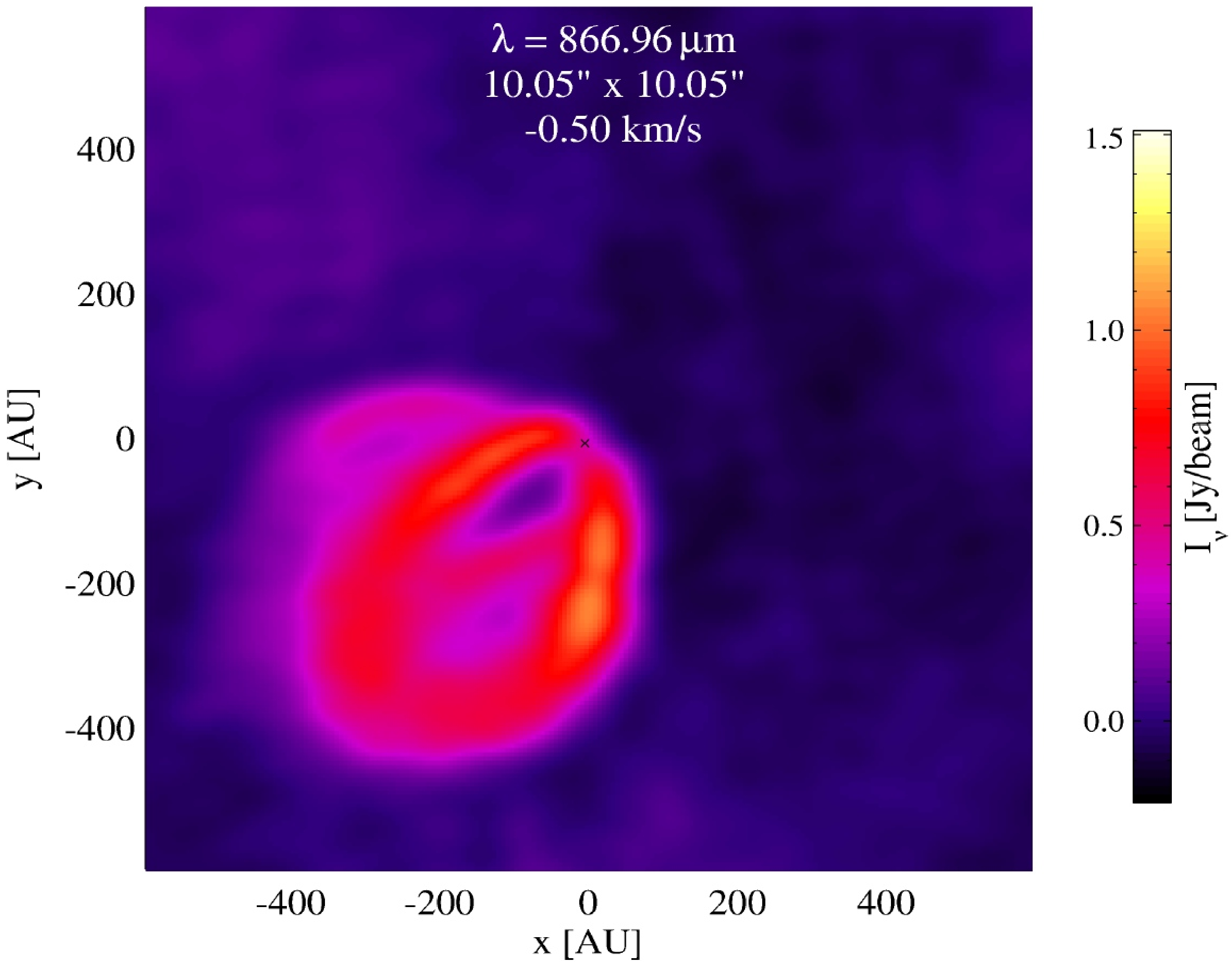

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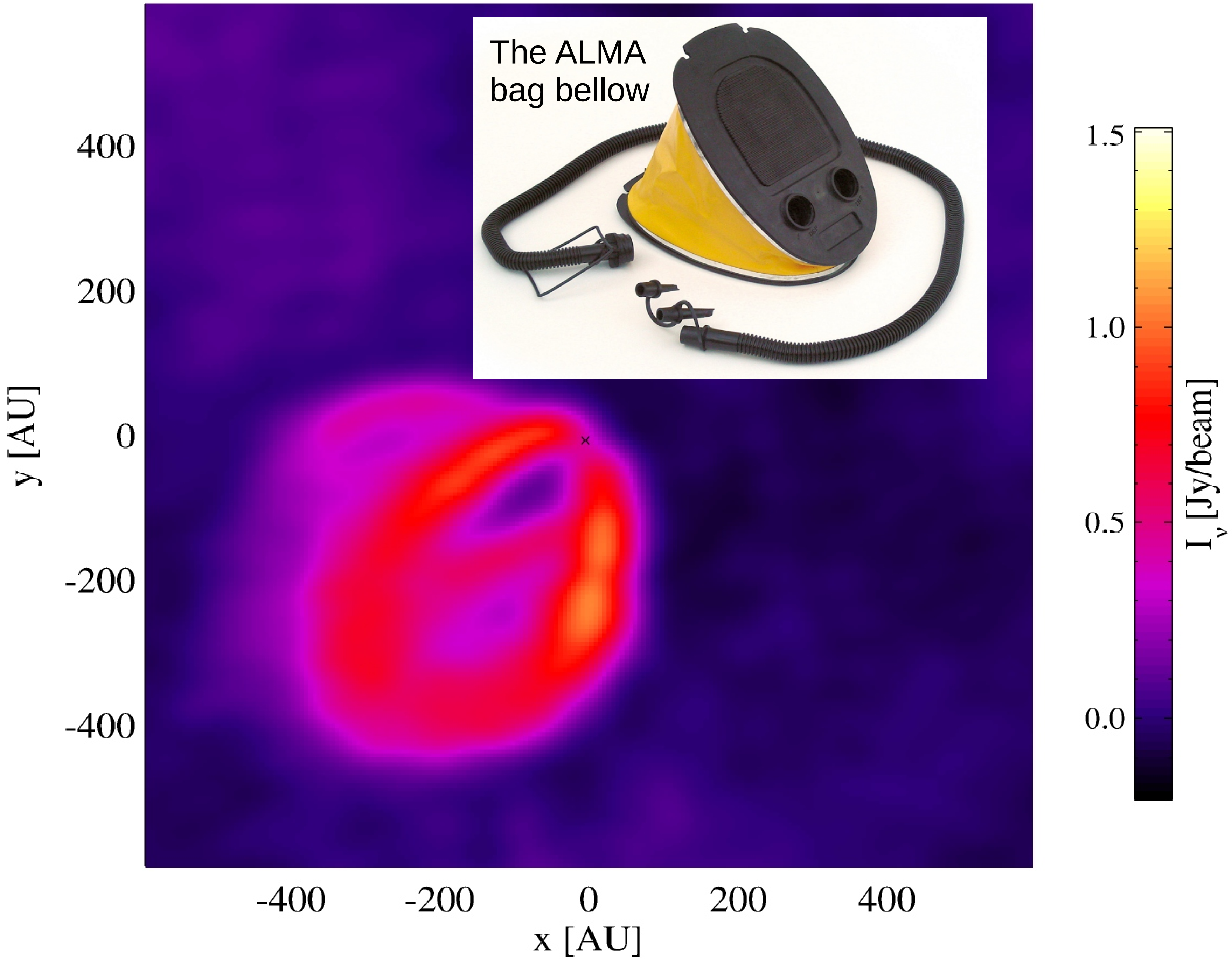

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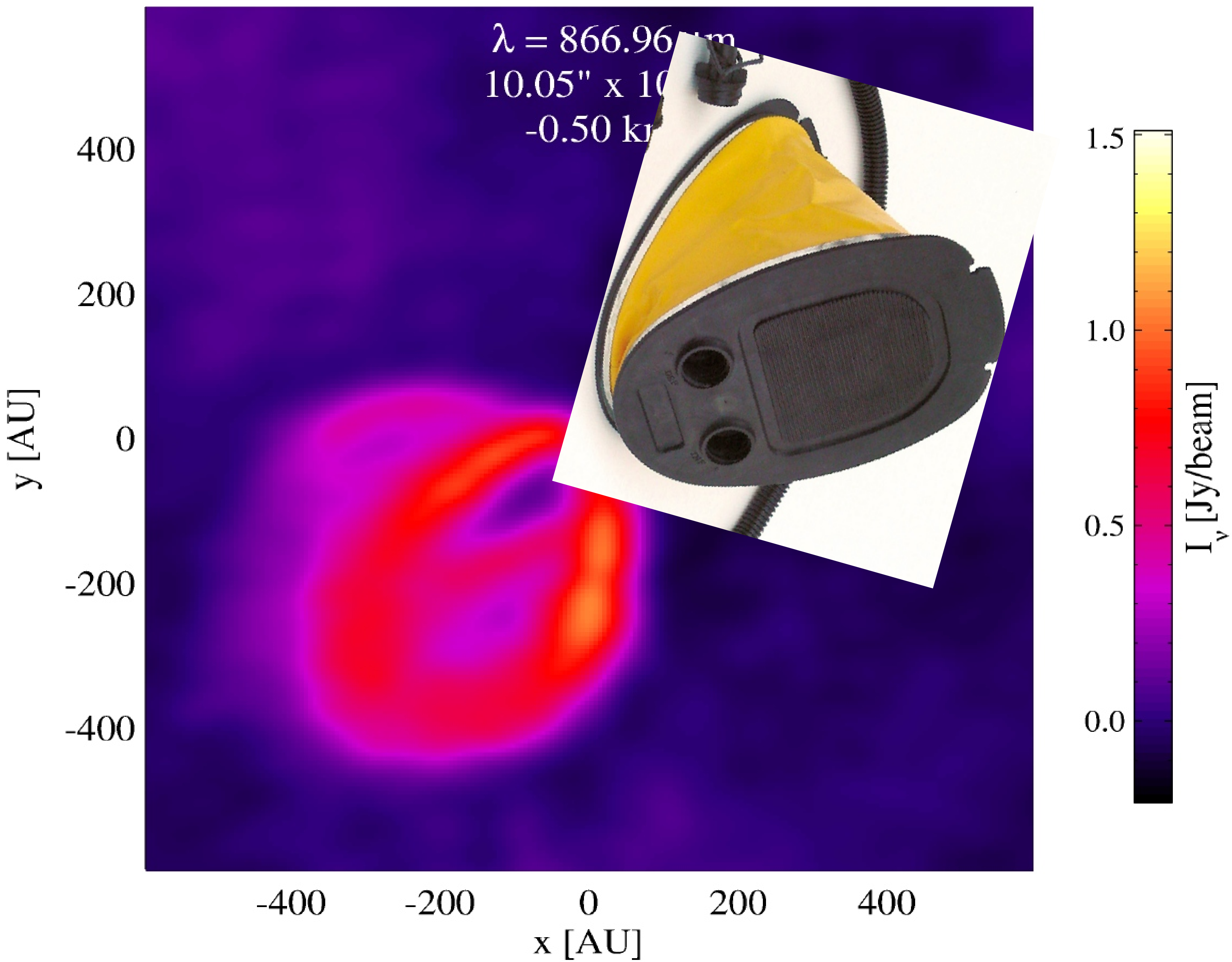
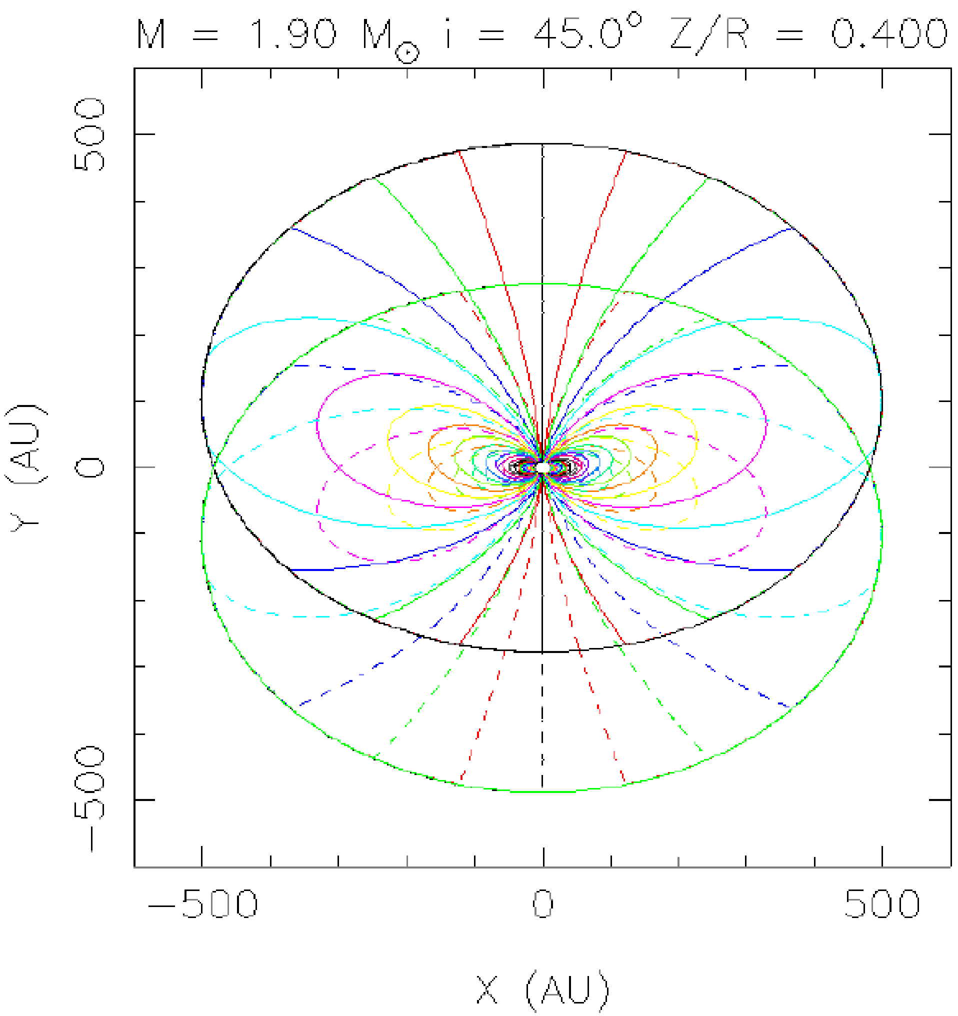
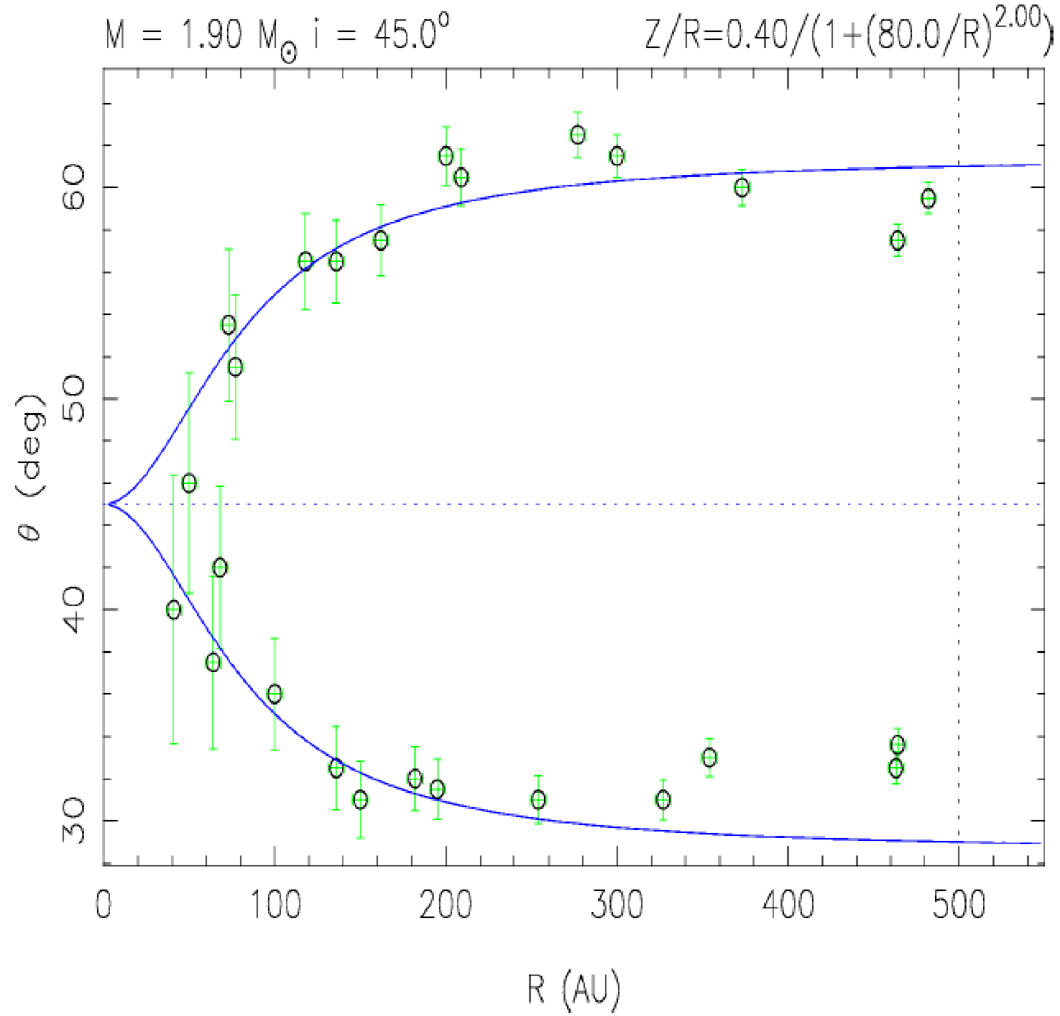


## CO emission geometry




$$r(\theta) = \frac{G\,M_\star}{v^2}\left(\sin i\,\sin\theta\right)^2$$

## derived height of CO emission

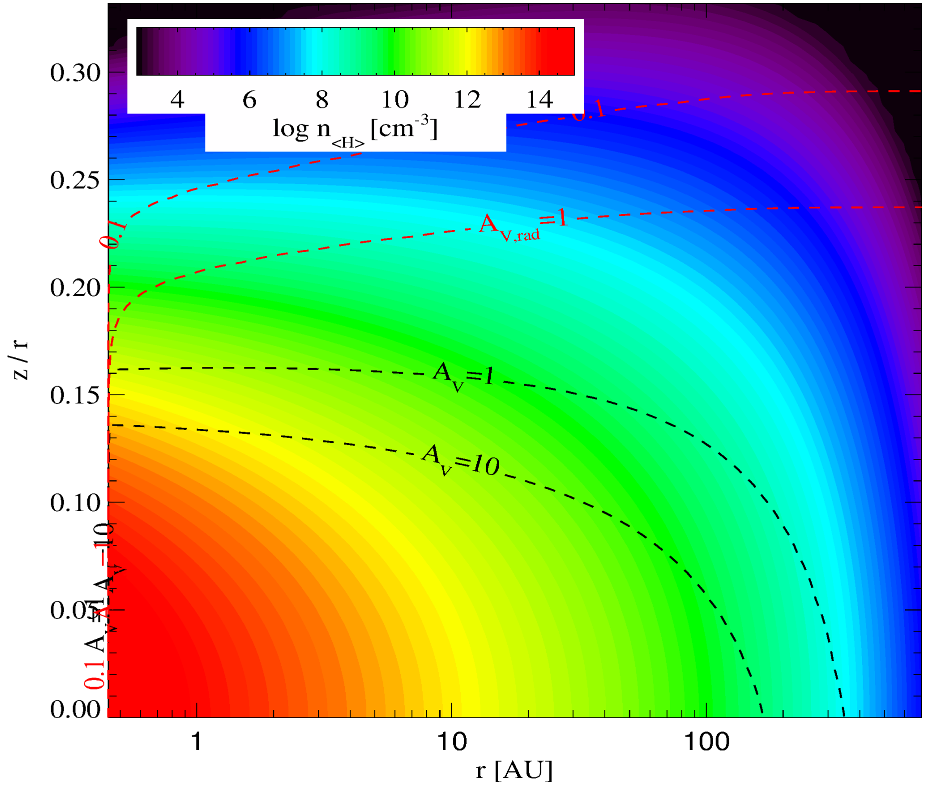


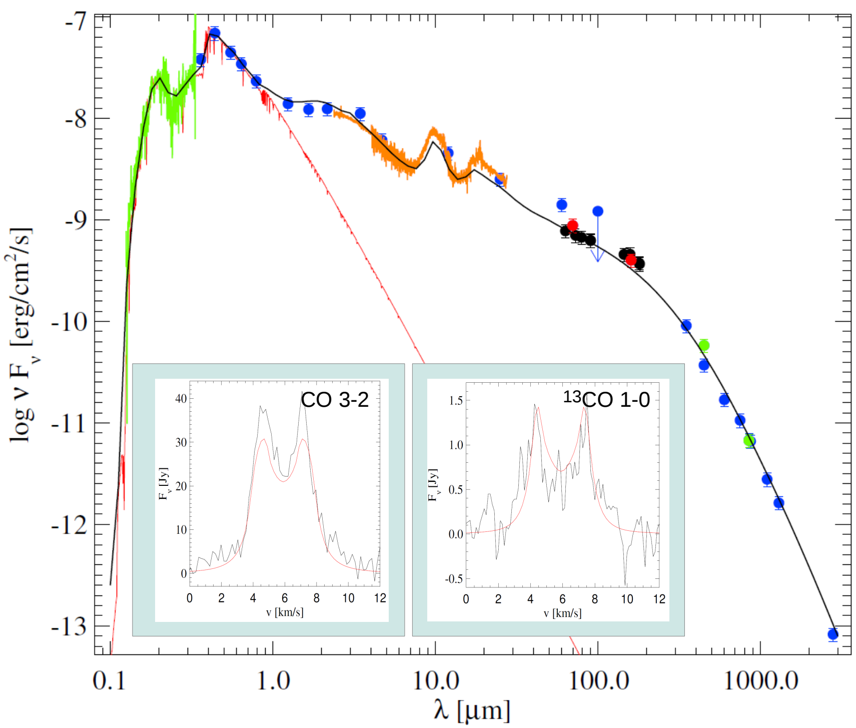

$$\frac{z}{r} \approx \frac{0.4}{1 + (80\,\mathrm{AU}/r)^2}$$

Horne & Woitke (2013, unpublished)

Rosenfeld et al. (2013, ApJ 774, 16) **← z/r = tan(15°) = 0.27 !?**

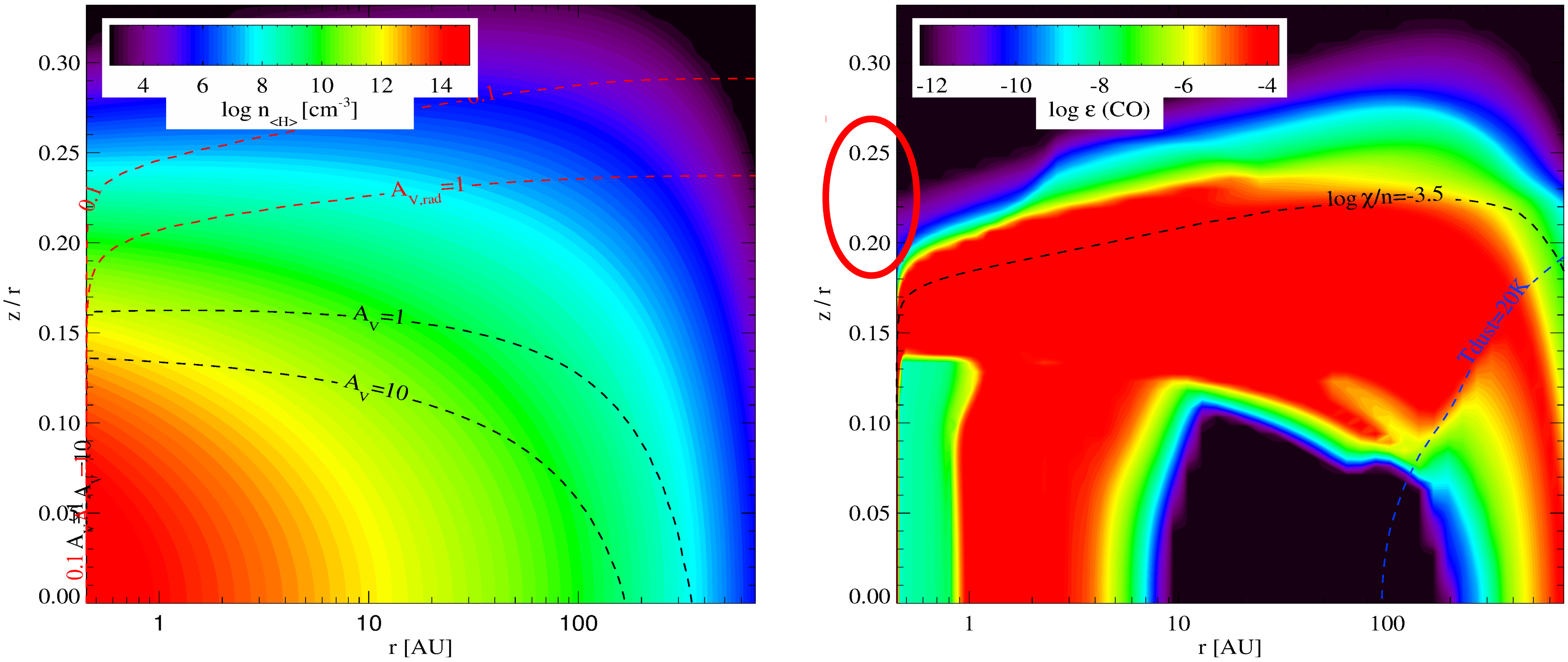
# Tilling et at. 2012 (A&A 538, 20)




| quantity | symbol | Tilling+2012 |
|---|---|---|
| stellar mass | $M_\star$ [$M_\odot$] | 2.47 |
| effective temp. | $T_{\rm eff}$ [K] | 9250 |
| ISM extinction | $A_V$ | 0.47 |
| stellar luminosity | $L_\star$ [$L_\odot$] | 37.7 |
| FUV luminosity | $L_{\rm FUV}$ [$L_\odot$] | 3.1 |
| X-ray luminosity | $L_X$ [erg/s] | - |
| disk inclination | $i$ [°] | 50 |
| distance | $d$ [pc] | 119 |
| disk gas mass | $M_{\rm gas}$ [$M_\odot$] | 0.071 |
| disk dust mass | $M_{\rm dust}$ [$M_\odot$] | 6.8(-4) |
| inner disk radius | $R_{\rm in}$ [AU] | 0.45 |
| tapering-off radius | $R_{\rm taper}$ [AU] | 125 |
| column density power | $\epsilon$ | 0.9 |
| tapering power index | $g_{\rm taper}$ | 0.9 |
| reference scale height | $H_0$ [AU] | 0.019 |
| reference radius | $r_0$ [AU] | 0.45 |
| flaring power index | $\beta$ | 1.07 |
| minimum dust radius | $a_{\rm min}$ [$\mu$m] | 0.0096 |
| maximum dust radius | $a_{\rm max}$ [$\mu$m] | 2041 |
| dust size p-index | $a_{\rm pow}$ | 3.68 |
| dust settling | $\alpha_{\rm vis}$ | – |
| dust composition | silicates | 74.5% |
| (volume fractions) | amorph. carbon | 15% |
| | porosity | – |
| hollow-spheres | $V_{\rm max}$-ratio | – |

Tilling et at. 2012 (A&A 538, 20)



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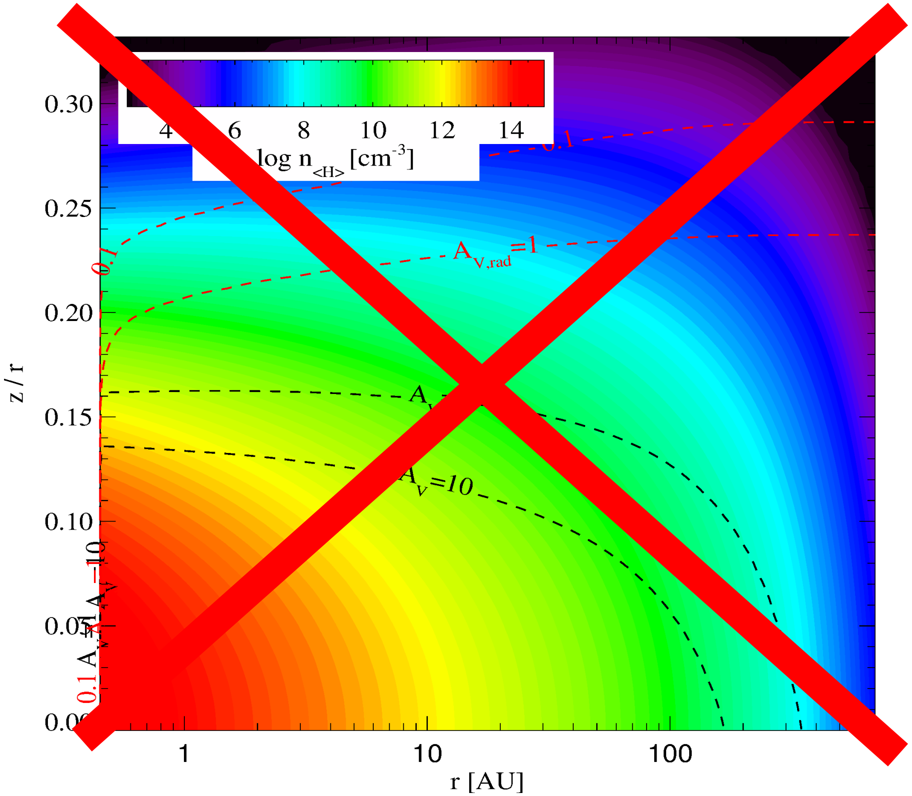
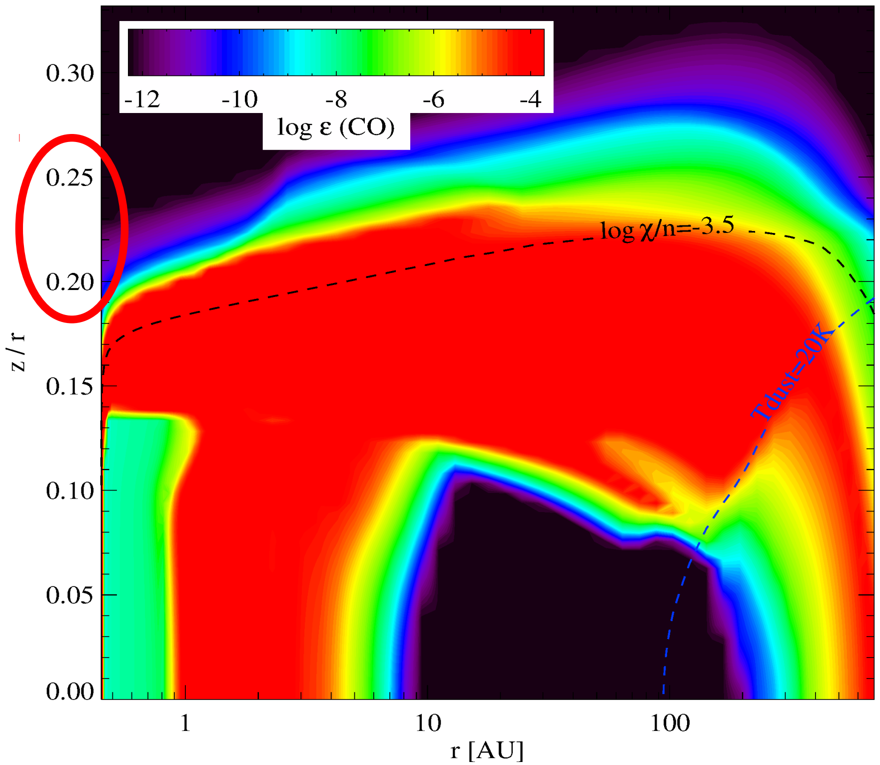
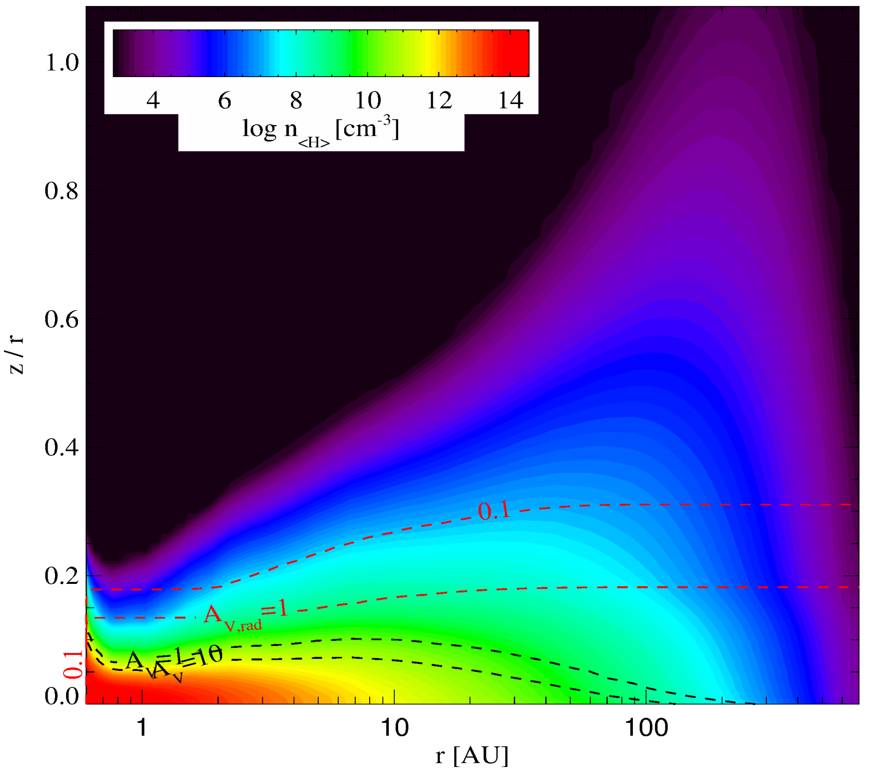
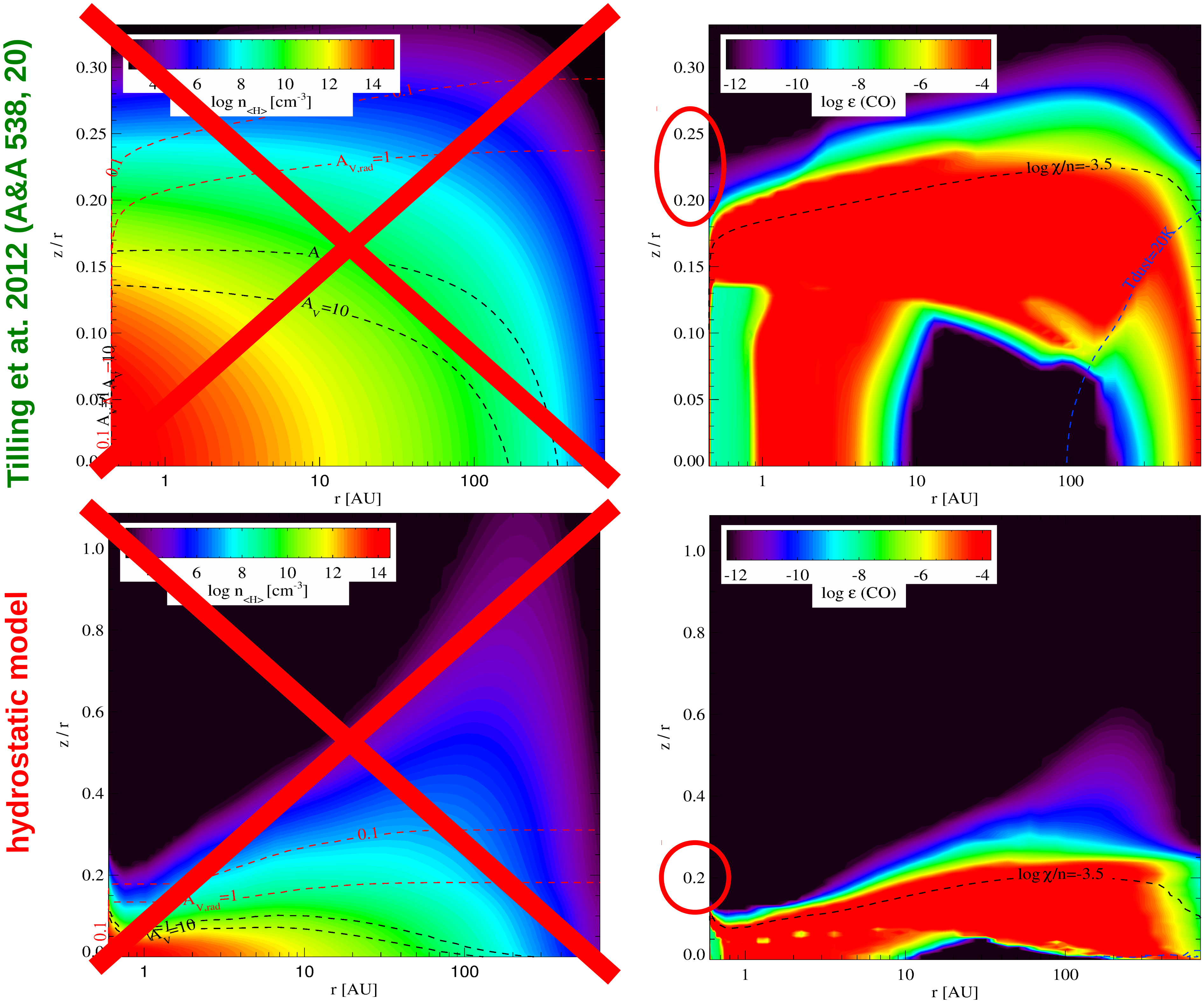


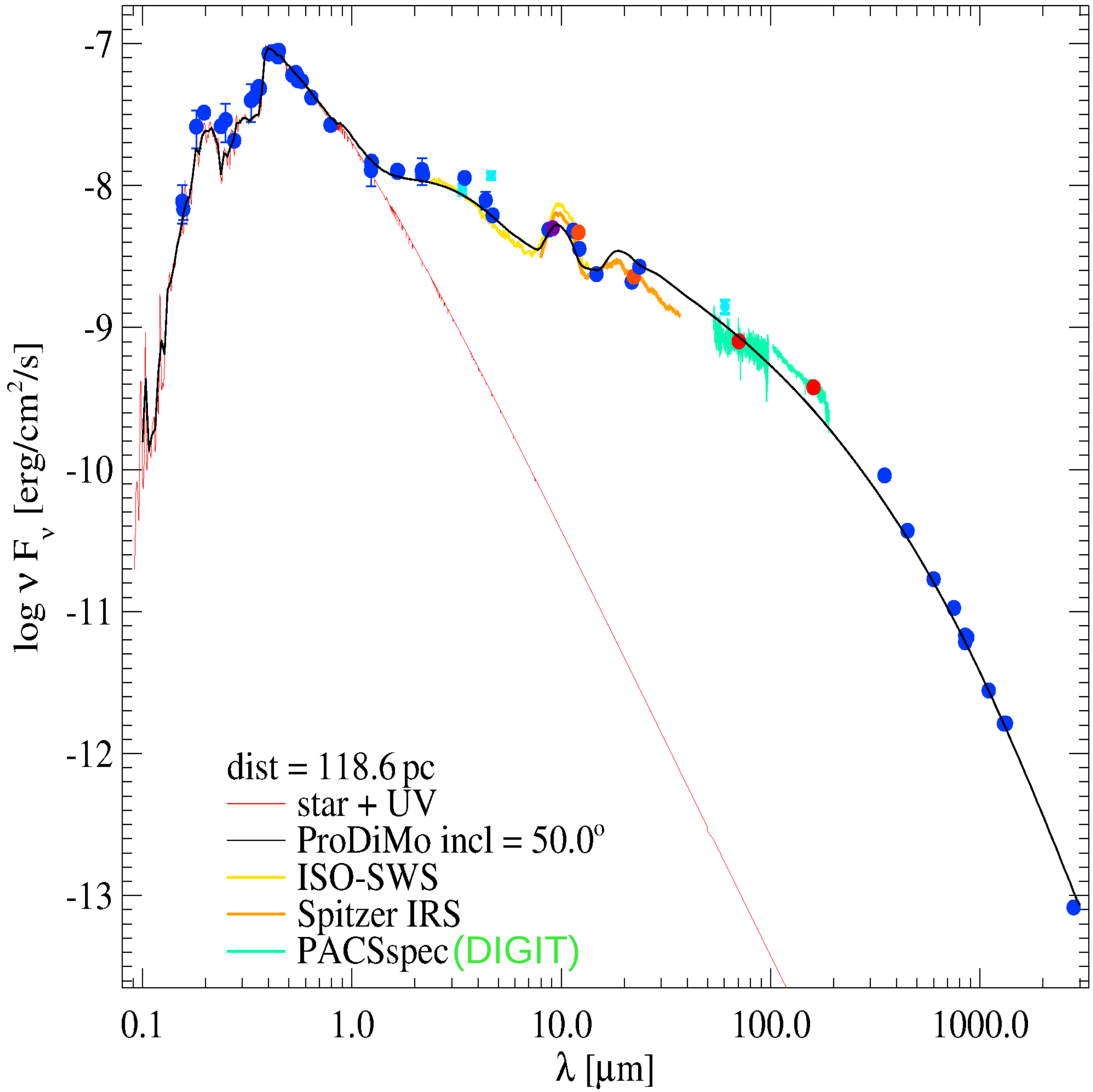

hydrostatic model





Tilling et at. 2012 (A&A 538, 20)
hydrostatic model
log n<H> [cm-3]
log ε (CO)
z / r
r [AU]
A_V,rad=1
A_V=10
log χ/n=-3.5
Tdust=20K

# Fit of continuum observations




**tapered edge surface density**

$$\Sigma(r) \propto r^{-\epsilon_1} \exp\left(-(r/R_{\rm tap})^{2-\epsilon_2}\right)$$

Tilling et al. (2012) $R_{\rm tap}$ = 125 AU → ***119 AU***

$\varepsilon_1$ = 0.9, $\varepsilon_2$ = 0.9 → ***1.03, 0.58***

**disk flaring**

$$H(r) = H_0 \,(r/r_0)^\beta$$

Tilling et al. (2012) $\beta$ = 1.07 → ***1.19***

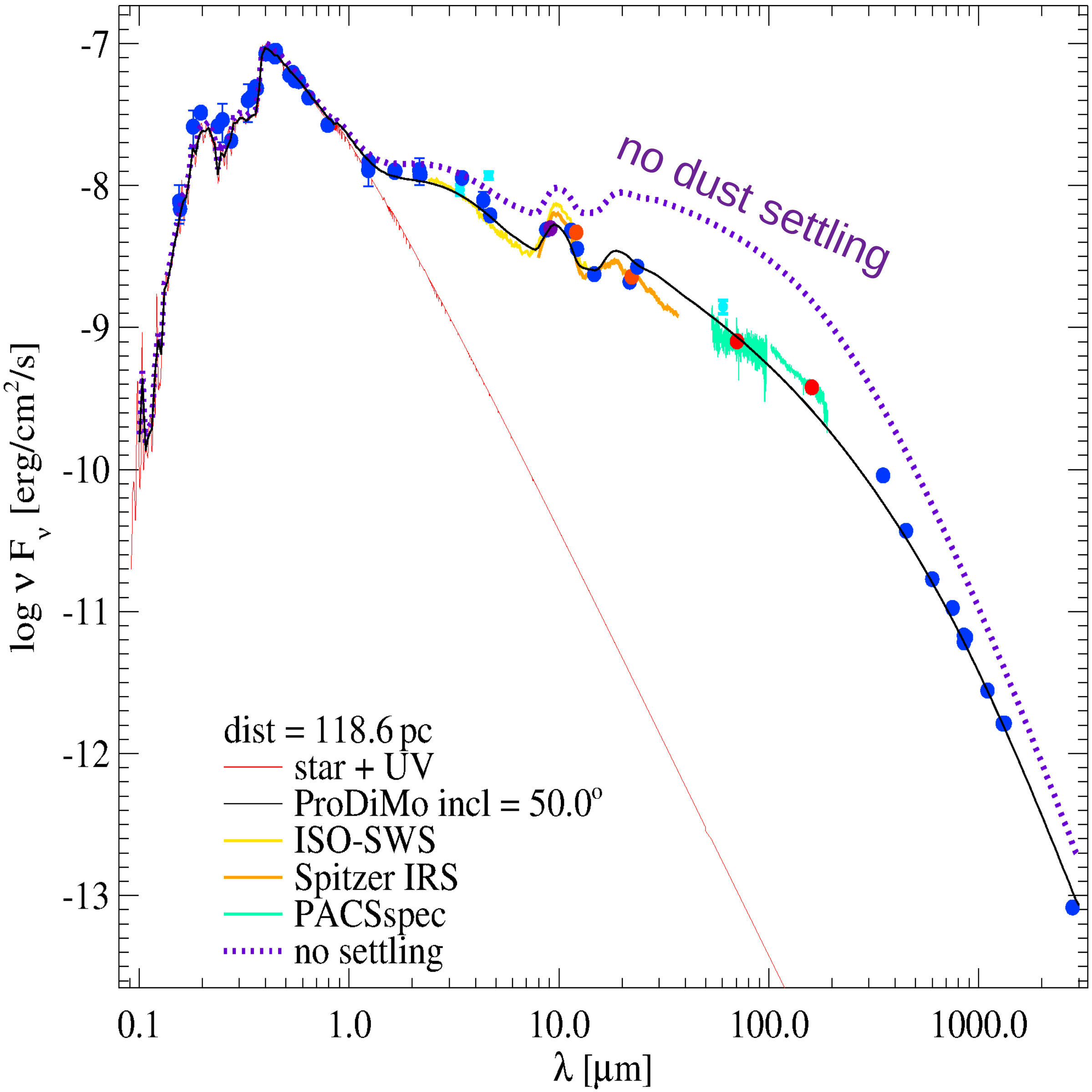
**dust settling**

$$\left(\frac{H(r,a)}{H(r)}\right)^2 = \sqrt{3}\,\frac{\Omega \rho_{\rm mat} a}{\rho c_s\, \alpha_{\rm vis}}$$

Tilling et al. (2012) $\alpha_{\rm vis}$ = oo → ***8.1(-6)***

**UV gas opacities (!)**

# Fit of continuum observations

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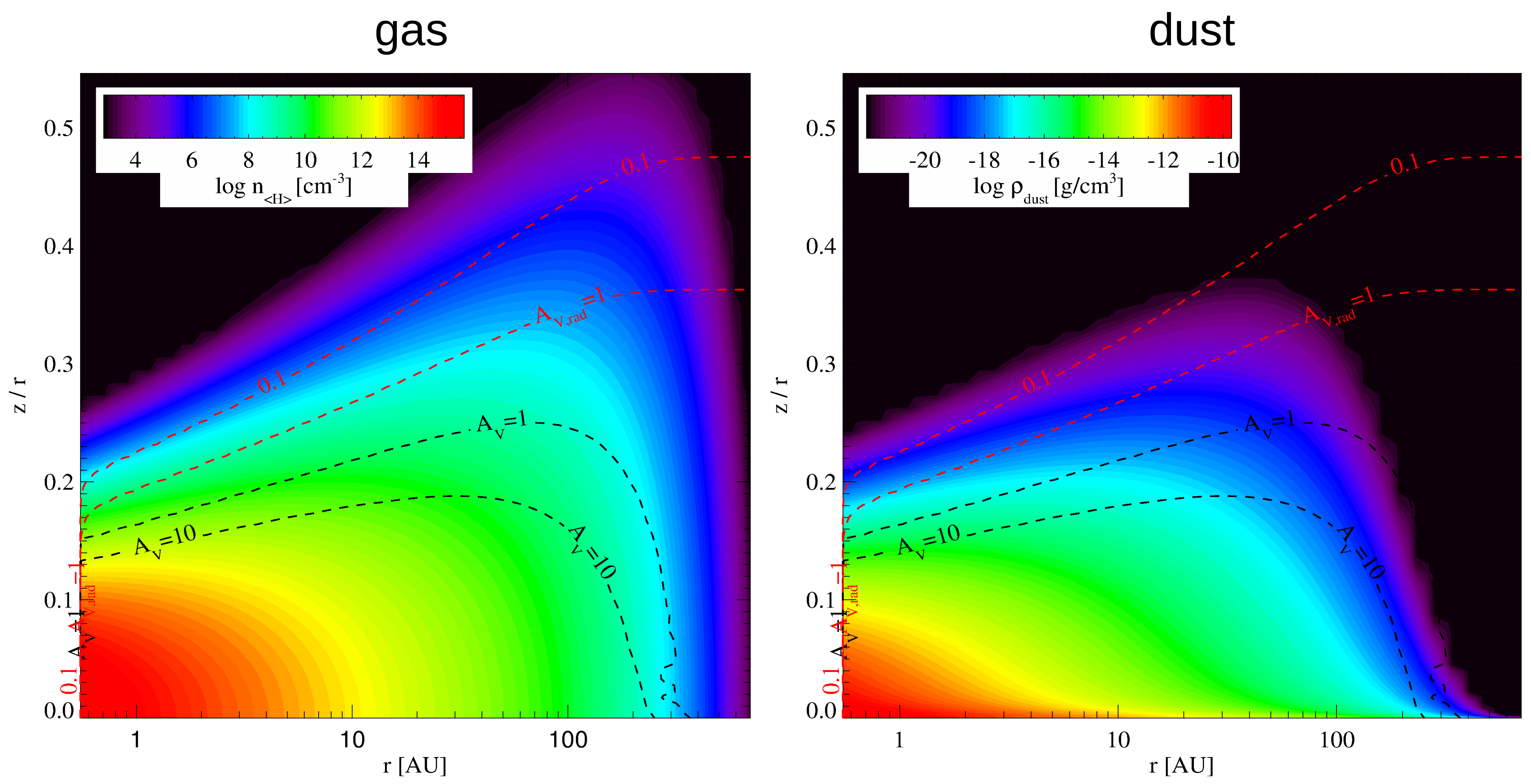
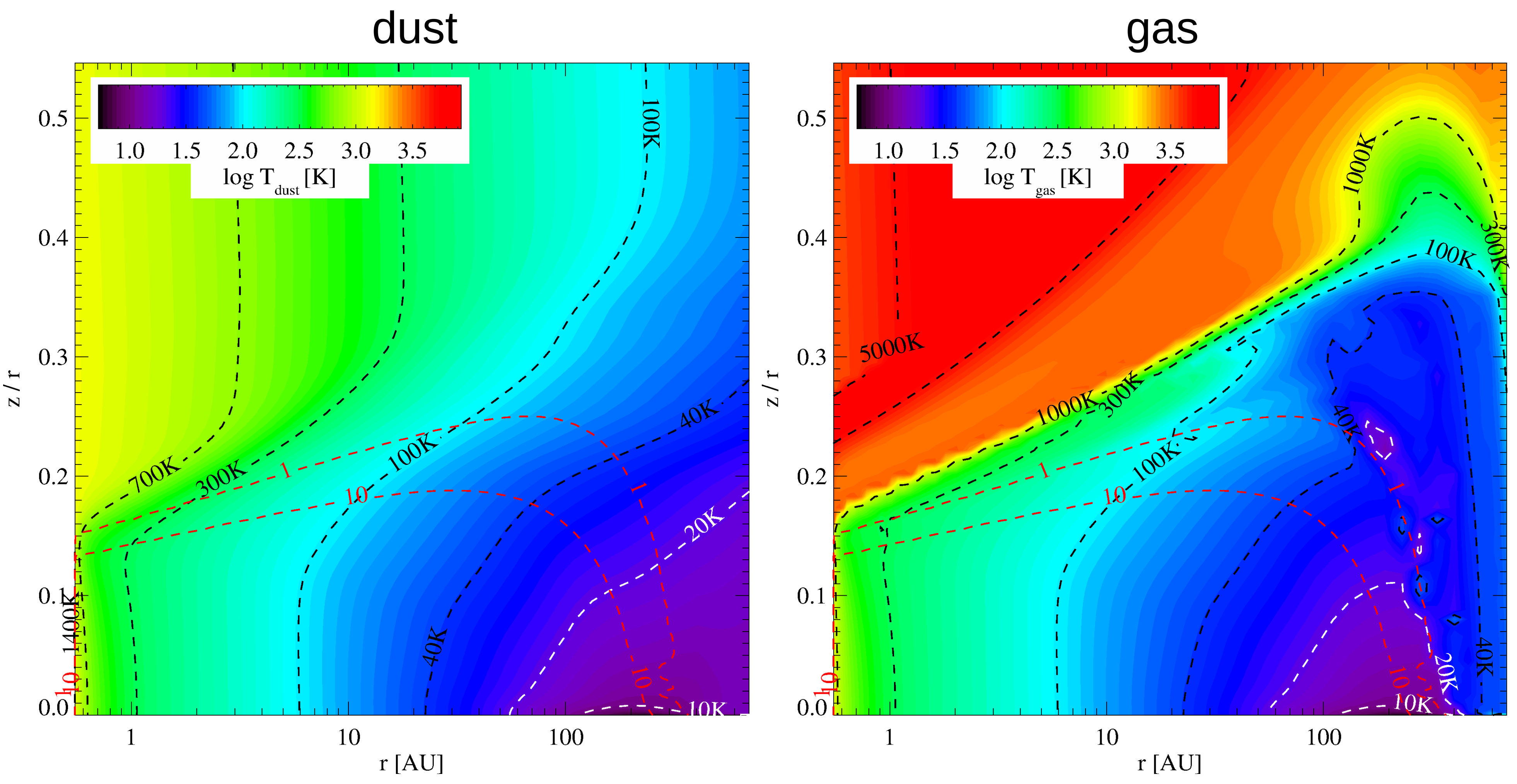
**UV gas opacities (!)**

# Density Structure

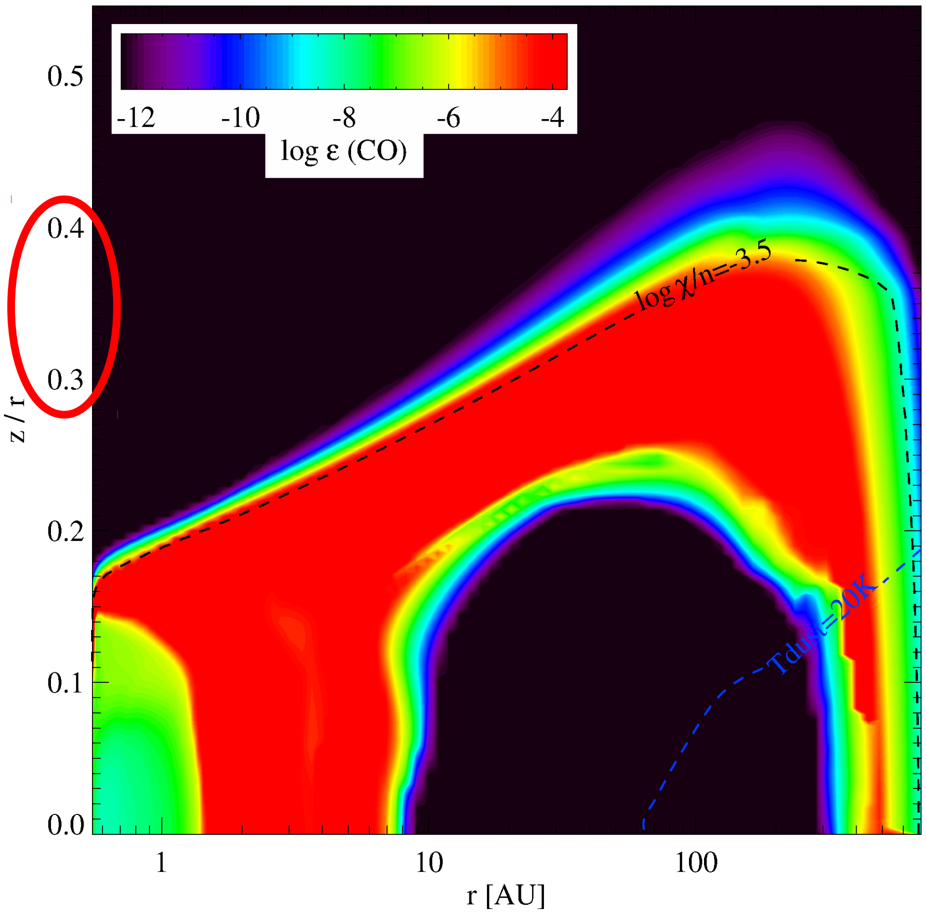


# Temperature Structure

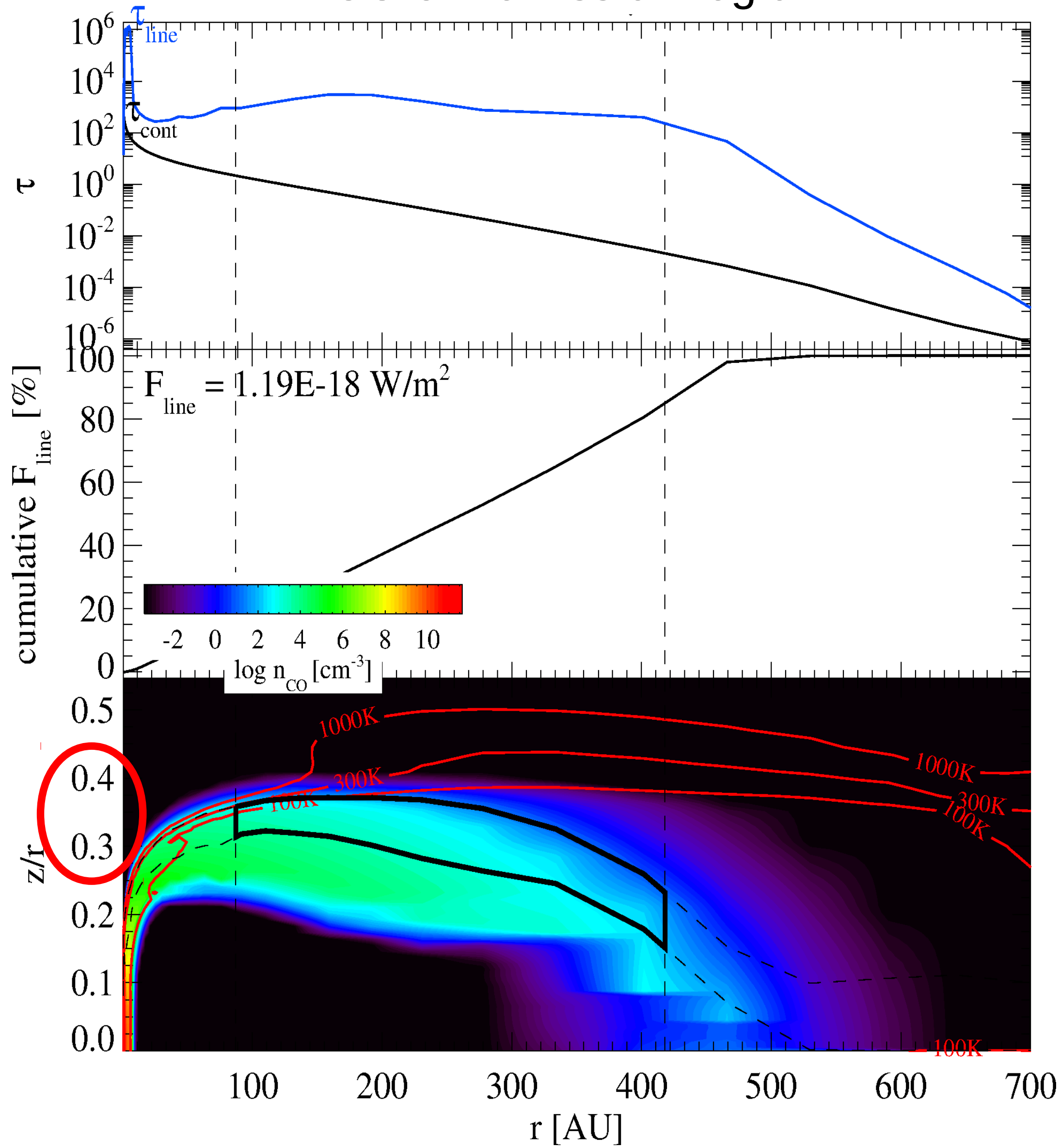


# CO line emission

## CO concentration

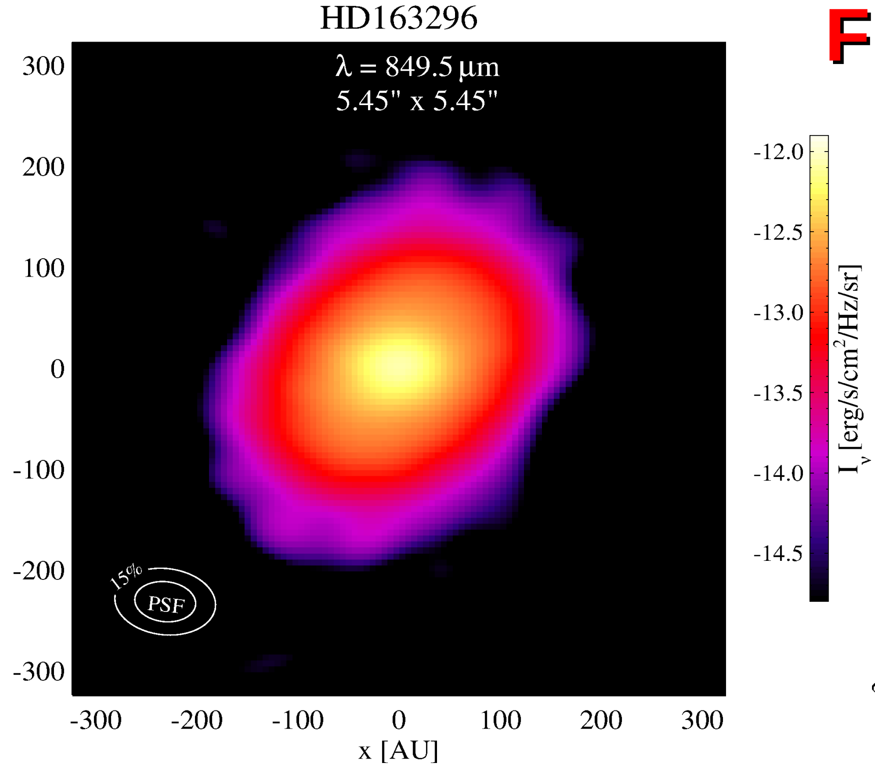



## CO 3-2 emission region

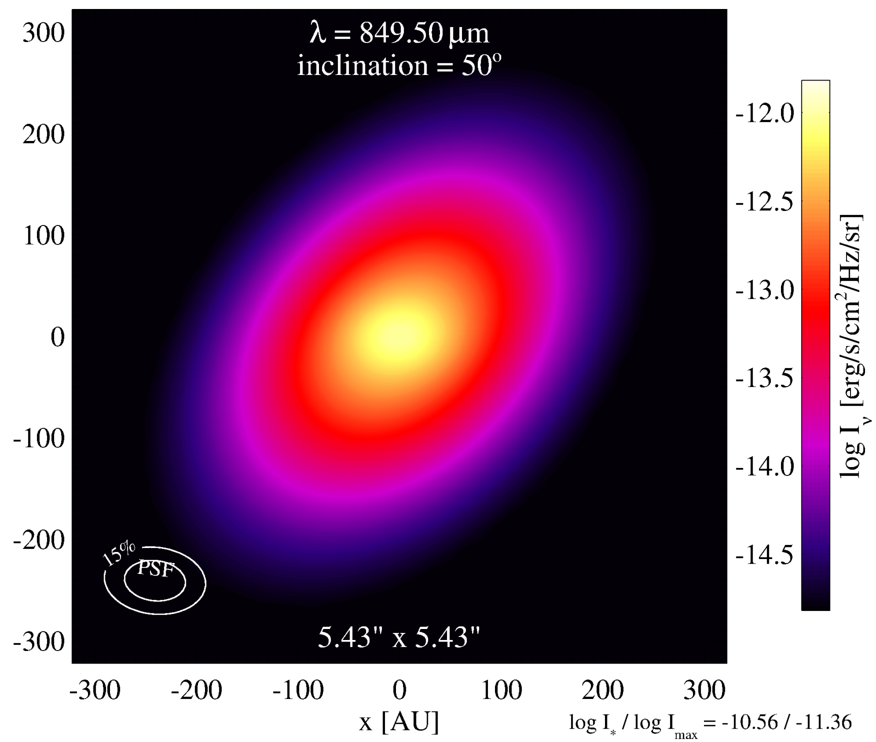


# Fit of continuum observations

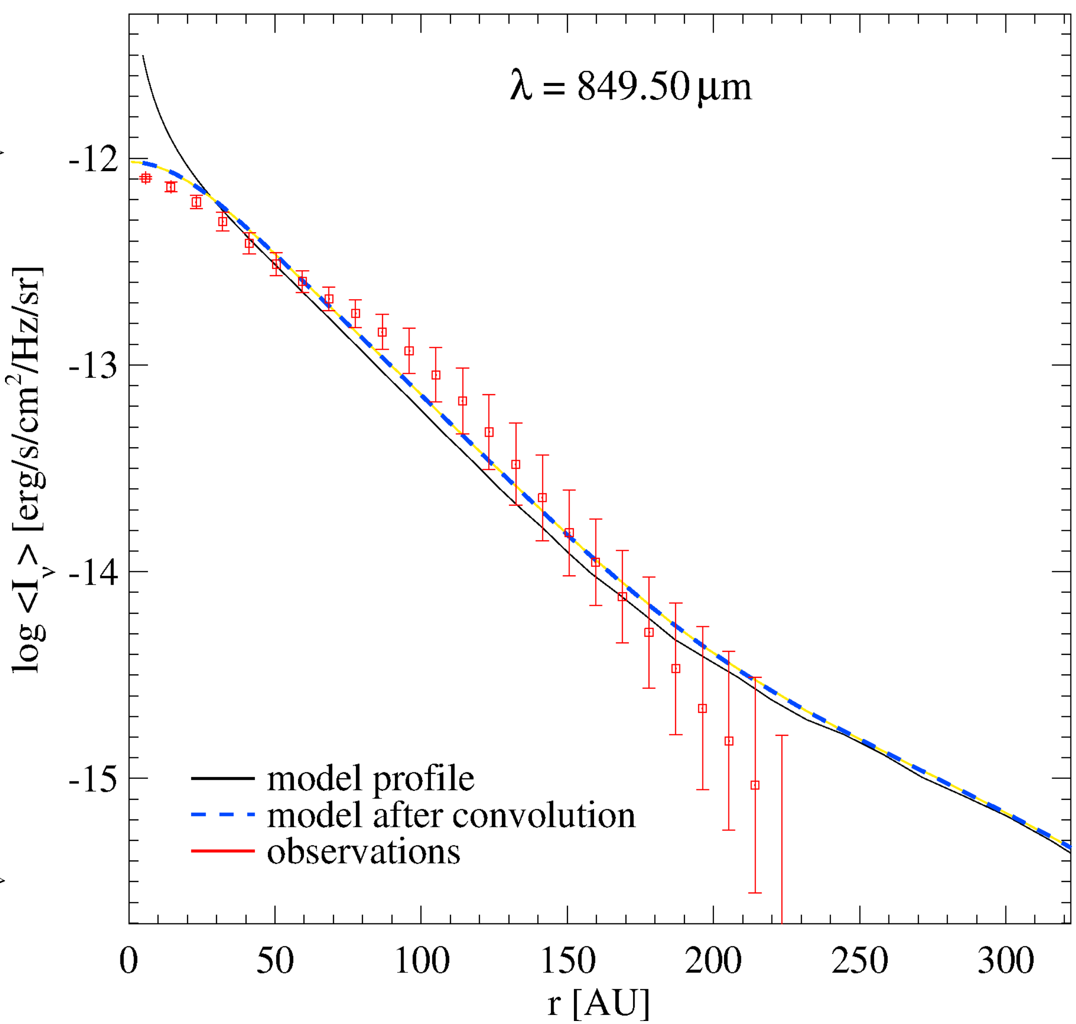
observation




model

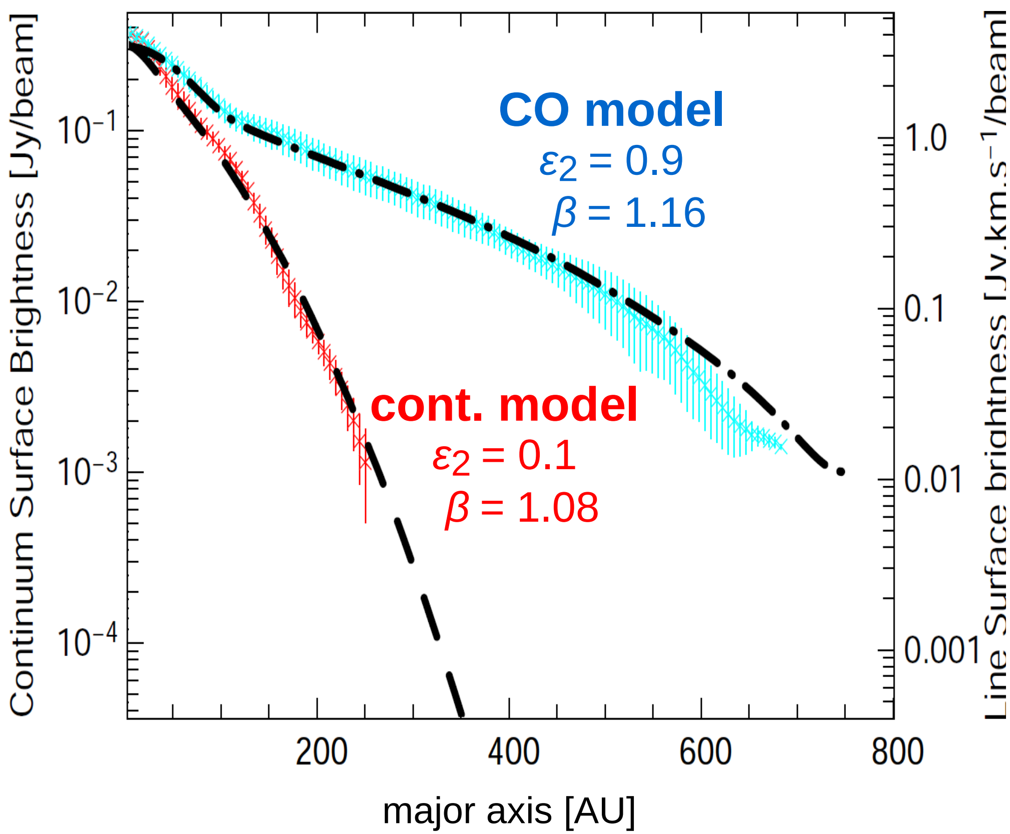


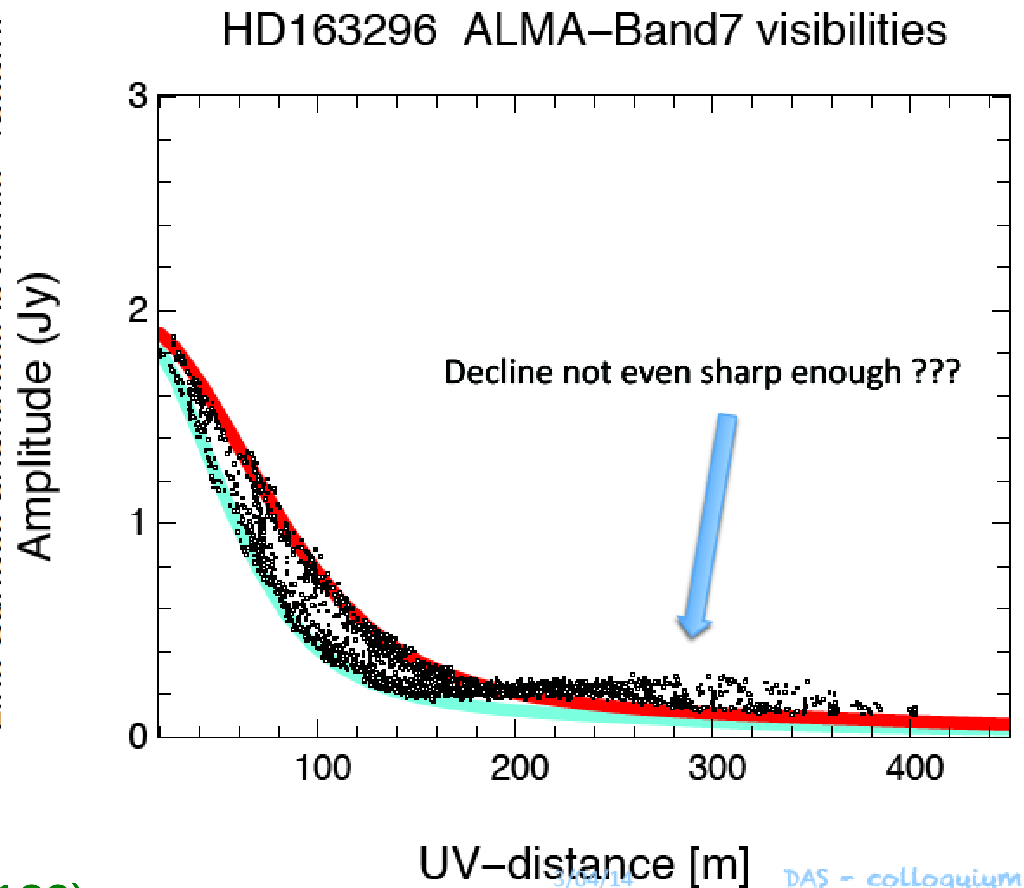

simple image data analysis (circular means)



# Fit of continuum observations

F. Menard: more careful analysis in visibility plane (elliptical de-projection)



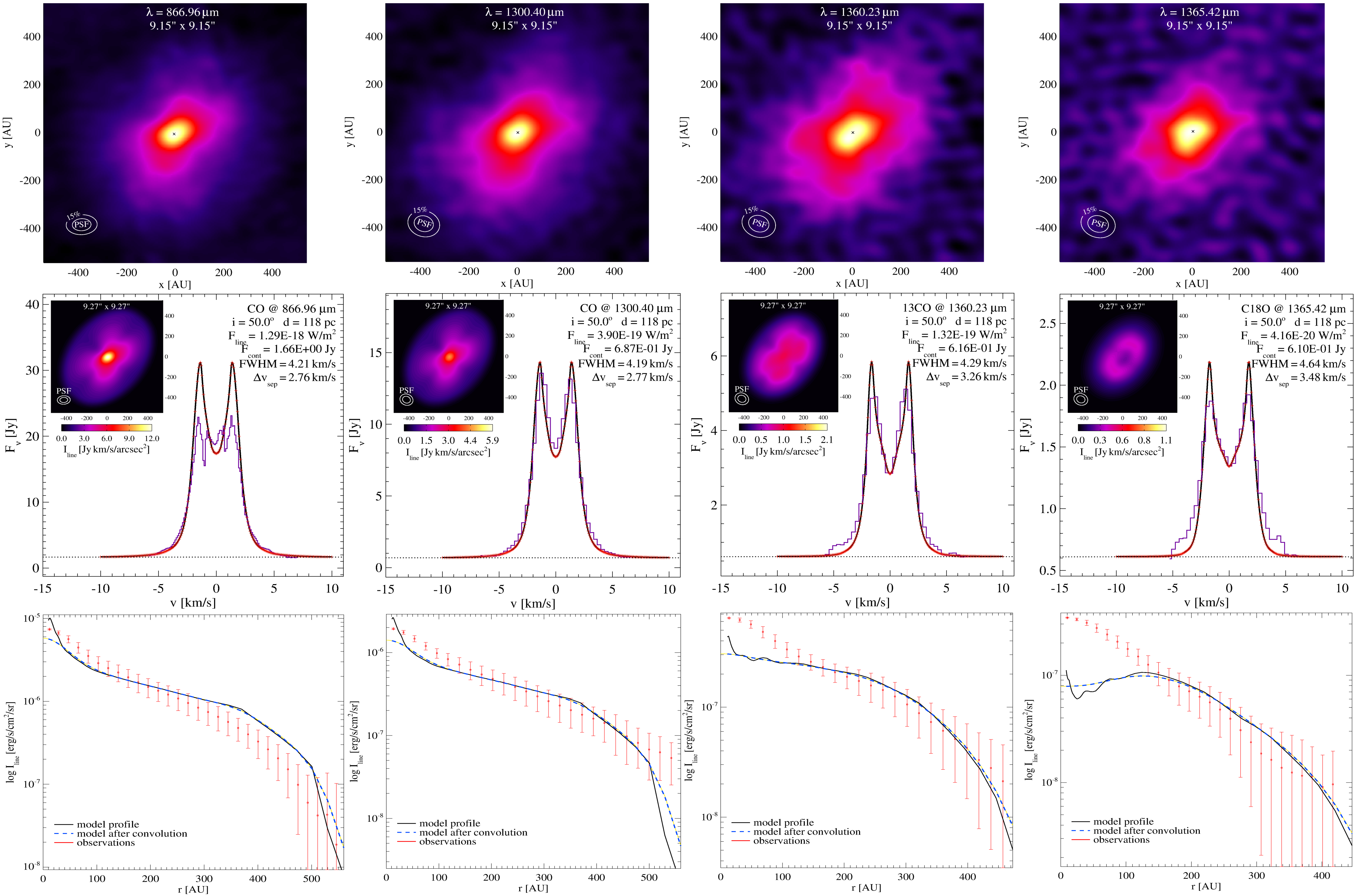

de Gregorio-Monsalvo et al. 2013 (A&A 557, 133)



- continnum: very sharp drop of surface brightness ~125 AU
- line: extended to at least 600 AU
- first evidence of radial drift?

# Fit of ALMA CO line data

CO 3-2 | $^{12}CO$ 2-1 | $^{13}CO$ 2-1 | $C^{18}O$ 2-1



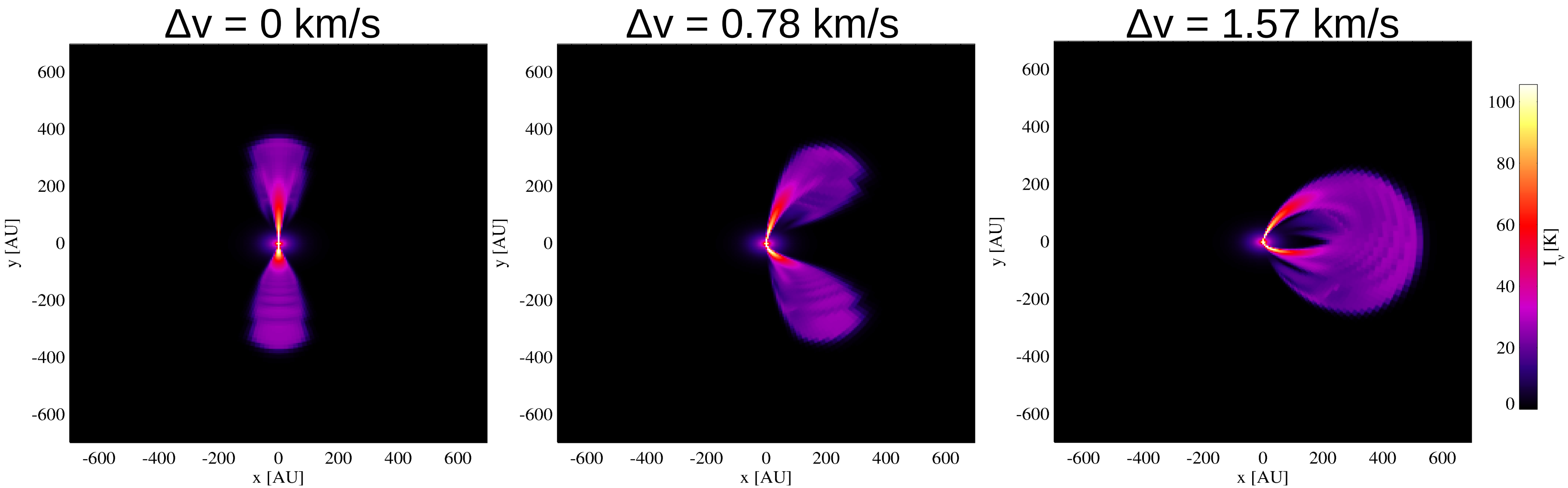
# Fit of other line data

| | observed | Tilling+2012 | new model 1053 |
|---|---|---|---|
| CO 90.16 $\mu$m | <7.4 | 1.1 | 5.2 |
| CO 144.78 $\mu$m | 6.7 | 1.82 | 2.5 |
| CO 200.27 $\mu$m | 11 | 4.7 | 12 |
| CO 216.93 $\mu$m | 10 | 5.3 | 11 |
| CO 236.61 $\mu$m | 12 | 5.9 | 12 |
| CO 260.24 $\mu$m | 12 | 6.3 | 13 |
| CO 289.12 $\mu$m | 9.0 | 6.4 | 13 |
| CO 325.23 $\mu$m | 16 | 6.3 | 12 |
| CO 371.65 $\mu$m | 10 | 6.1 | 10 |
| CO 433.56 $\mu$m | 8.0 | 5.5 | 7.6 |
| CO 866.96 $\mu$m | 1.11 | 1.04 | 1.29 |
| CO 1300.4 $\mu$m | 0.404 | 0.346 | 0.389 |
| $^{13}$CO 1360.2 $\mu$m | 0.138 | 0.117 | 0.132 |
| C$^{18}$O 1365.4 $\mu$m | 0.045 | 0.042 | 0.055 |
| $^{13}$CO 2720.4 $\mu$m | 0.0124 | 0.00101 | 0.00103 |
| [OI] 63.18 $\mu$m | 171 | 115 | 1380 |
| [OI] 145.52 $\mu$m | < 6 | 3.6 | 38 |
| [CI] 370.42 $\mu$m | 5.0 | 1.8 | 2.8 |
| o-$H_2O$ 29.84 $\mu$m | 44 | 15 | 12 |
| p-$H_2O$ 63.32 $\mu$m | 16 | 2.4 | 11 |
| o-$H_2O$ 63.45 $\mu$m | 11 | 2.1 | 6.1 |
| o-$H_2O$ 71.95 $\mu$m | 14 | 1.8 | 12 |
| p-$H_2O$ 78.74 $\mu$m | 11 | 1.6 | 19 |
| OH 79.12 $\mu$m | 12 | 1.3 | 2.5 |
| OH 79.18 $\mu$m | <9 | 1.3 | 2.6 |

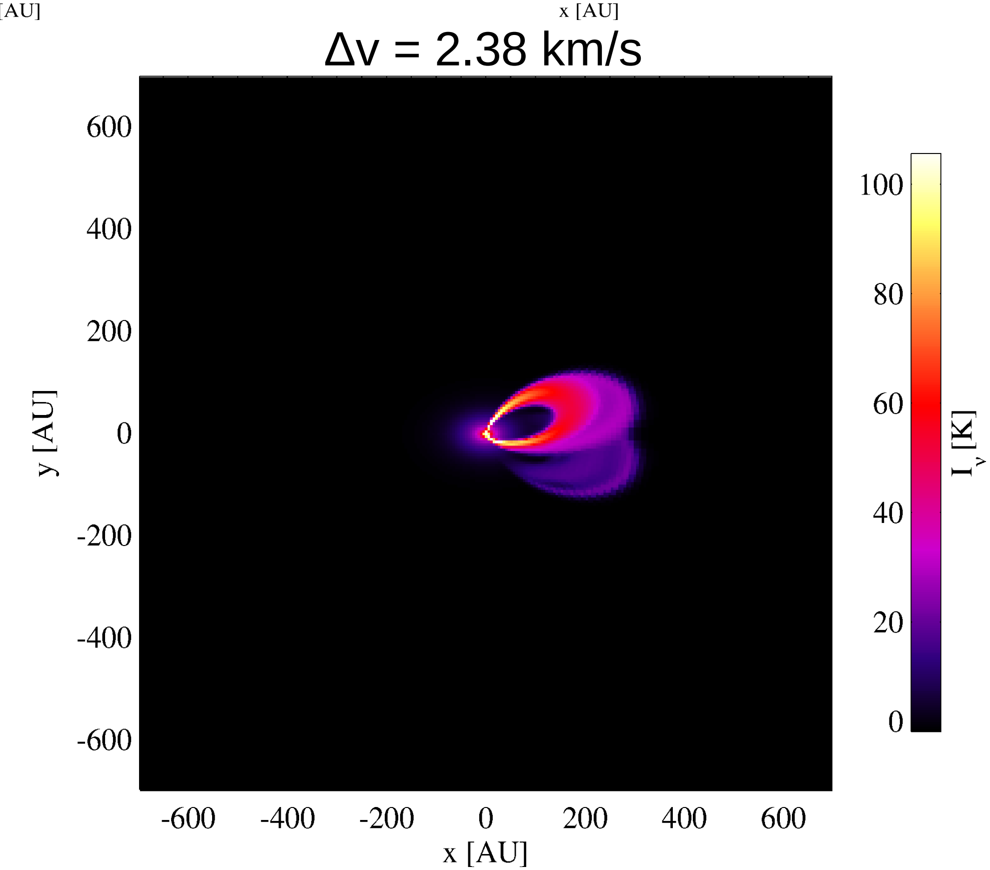
deeper GASPS data: Meeus et al. (2014, in prep.)

CO SPIRE data: van der Wiel et al. (2014, in prep)

# Fit of CO 3-2 channel maps







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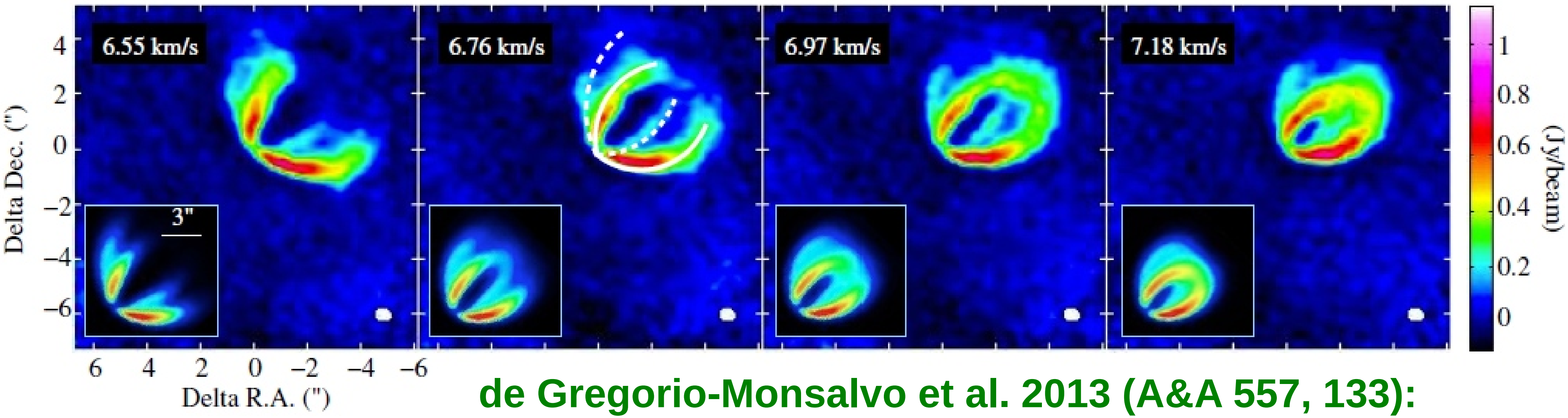
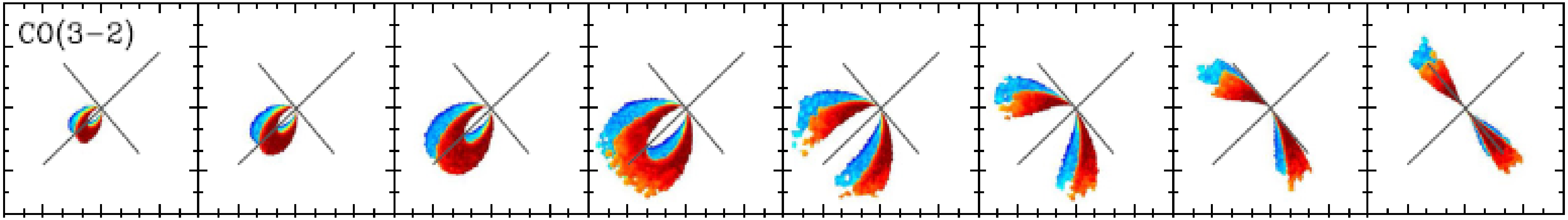



**de Gregorio-Monsalvo et al. 2013 (A&A 557, 133):**

based on detailed MCFOST dust radiative transfer,

Tgas = Tdust, constant CO concentration (no CO in midplane)

CO emits from z/r ~ 0.35




**Rosenfeld et al. 2013 (ApJ 774, 16):**

special purpose double-cone model,

parametric T(r,z), constant CO concentration (no CO in midplane)

CO emits from z/r = 0.27

# Summary

- recently published HD163296 models can either fit the continuum observations ***or*** the ALMA CO channel maps, ***but not both***
  - ***SED*** requires a ***flat outer dust distribution***
  - ***ALMA CO channel maps*** require ***strongly flared outer gas distribution***, CO emits at $z/r \approx 0.4$

  → ***this is direct evidence for (very strong!) dust settling***
- ***continuum images: very sharp outer edge***

  → ***possibly first evidence for radial drift***
- ***what is better?***
  - ***"compromise" model***, providing decent fits to most line and continuum observations, ***or***
  - ***special purpose models***, that can fit certain observations very well, but are inconsistent with other observations

  → ***you decide***