The complex interplay between gas and dust in protoplanetary disks

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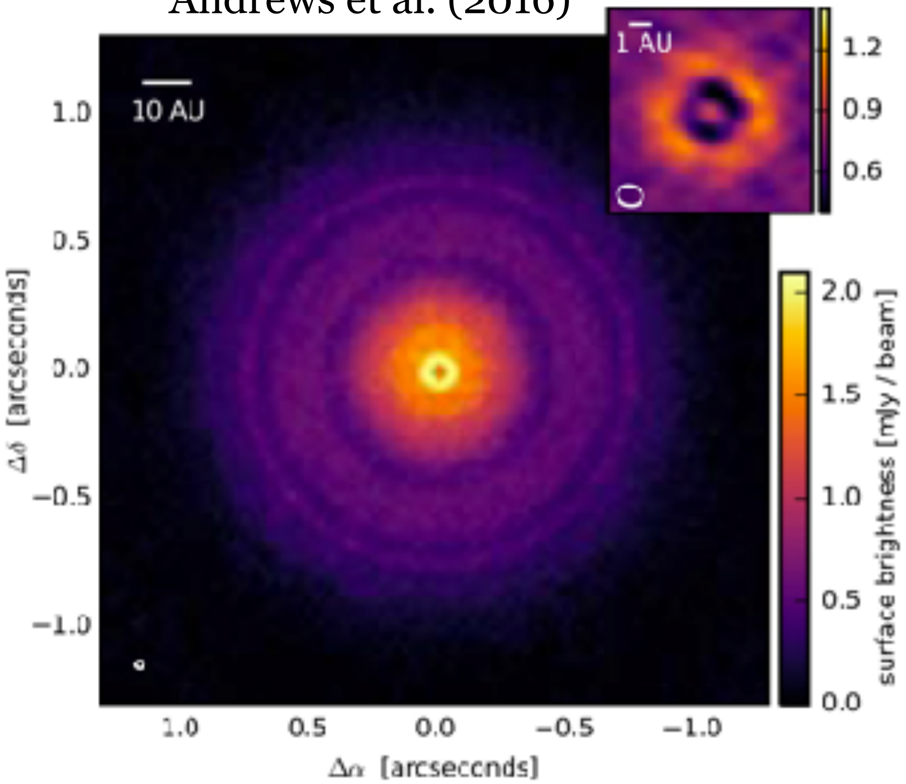
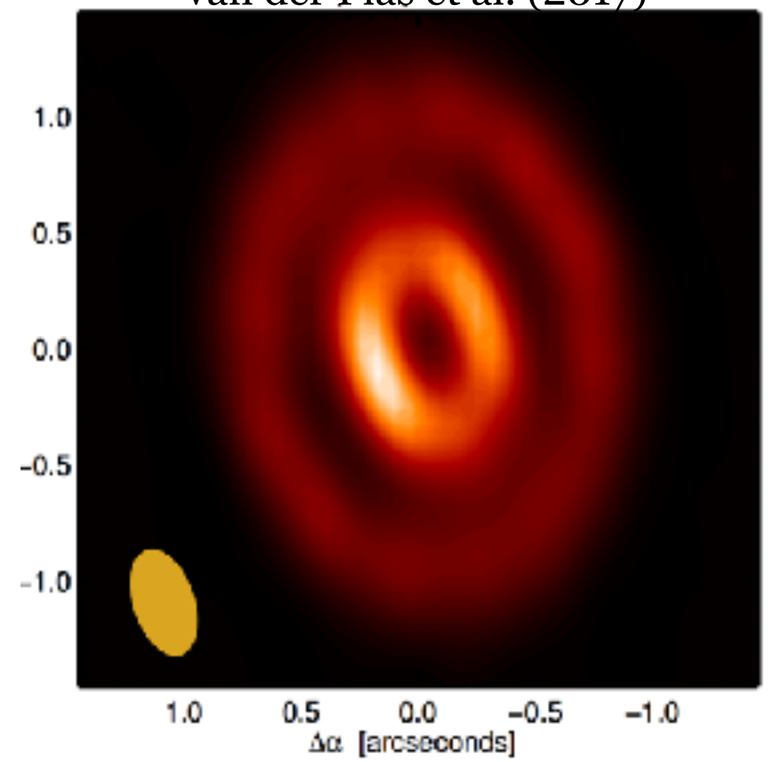
Protoplanetary disks, Roma, 28/6/2018

Substructures in thermal continuum

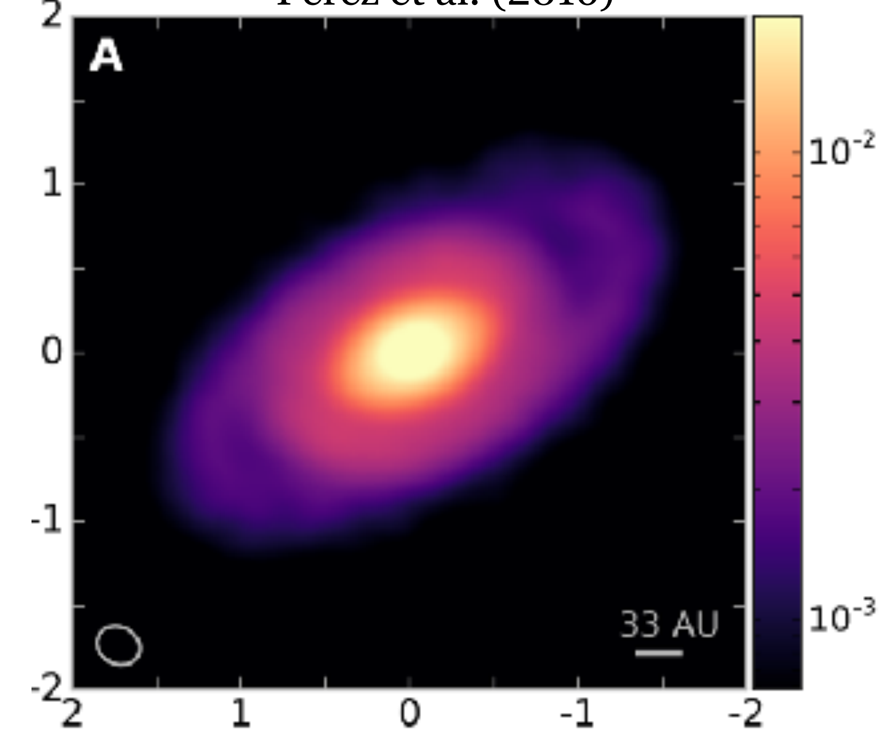
Andrews et al. (2016)

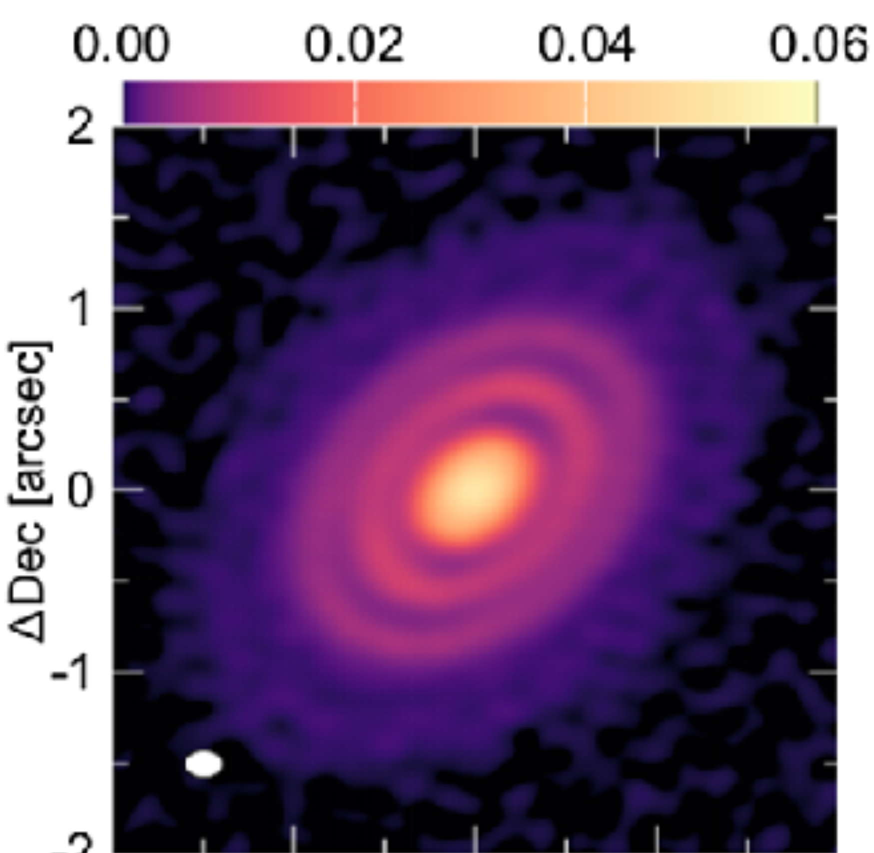


van der Plas et al. (2017)

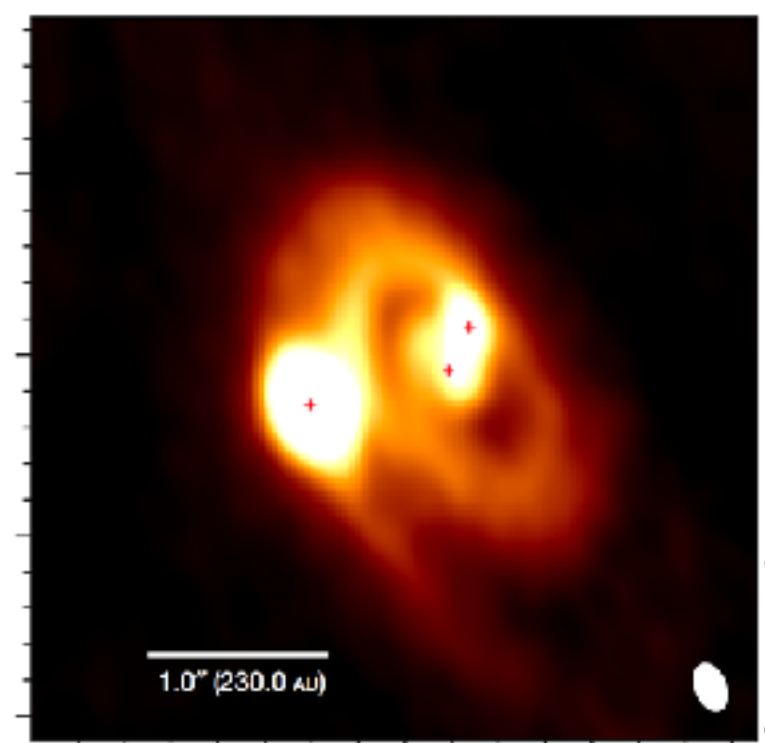


Perez et al. (2016)

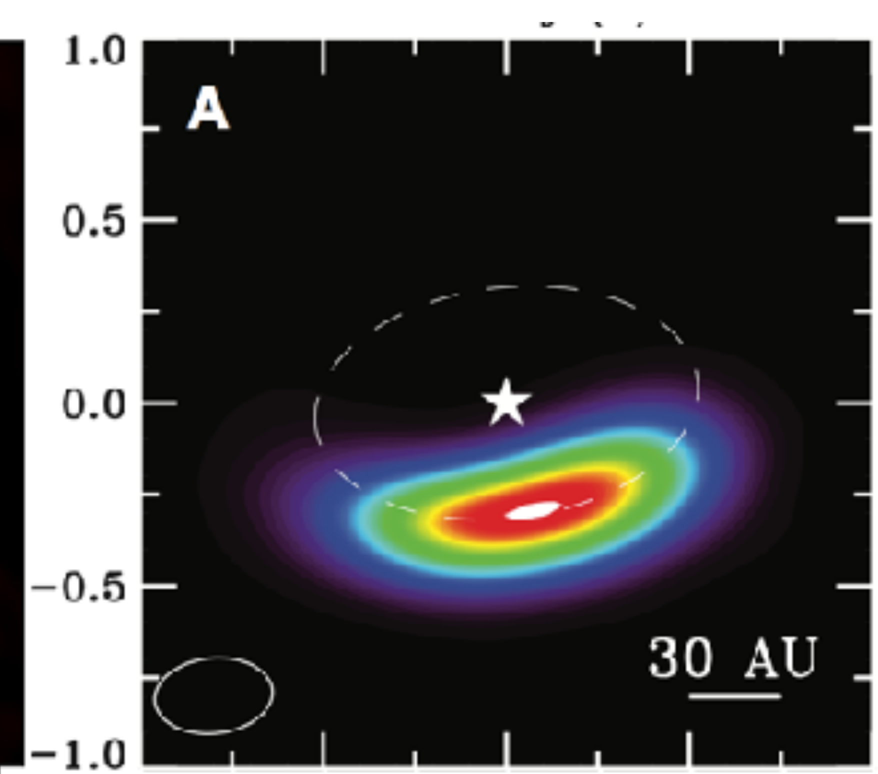




Isella et al. (2016)



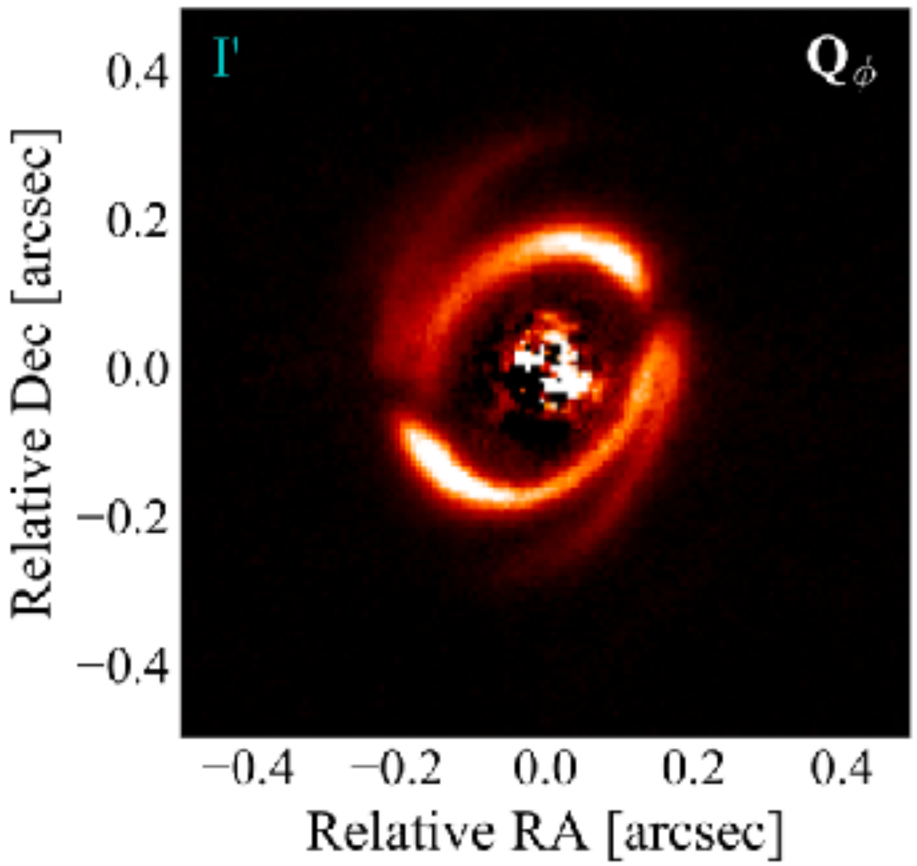
Tobin et al. (2016)



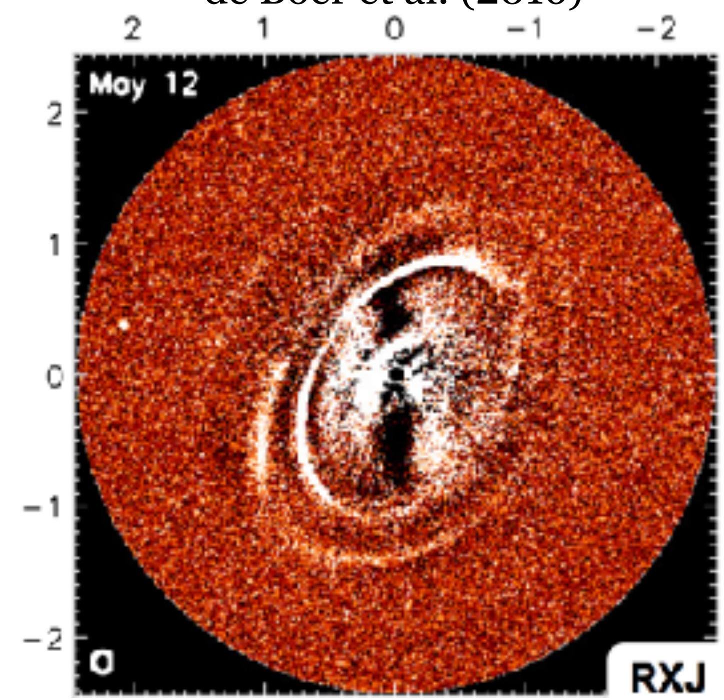
van der Marel et al. (2013)

Complementary information from scattered light in OIR

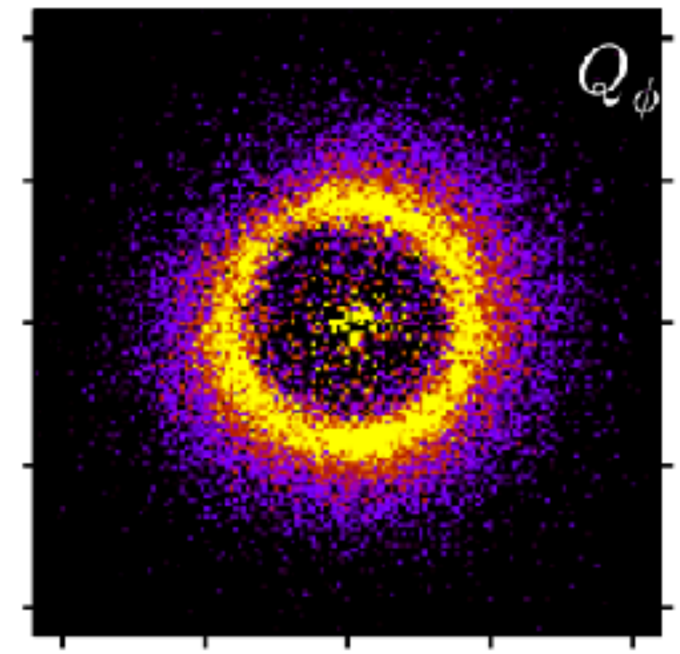
Benisty et al. (2017)

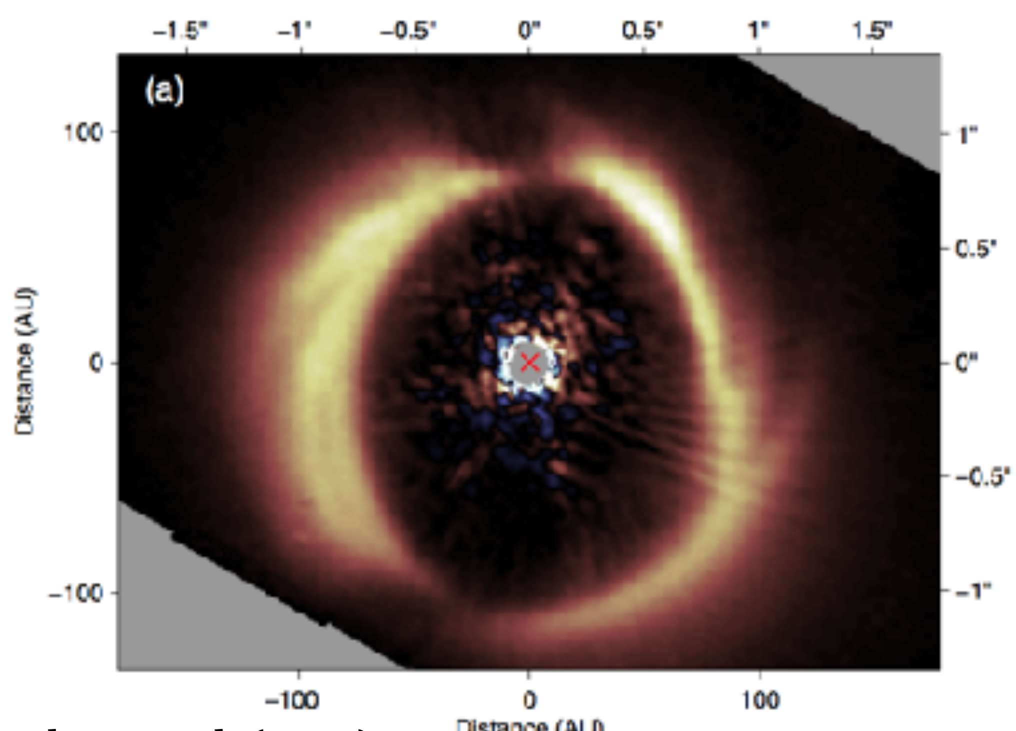


de Boer et al. (2016)



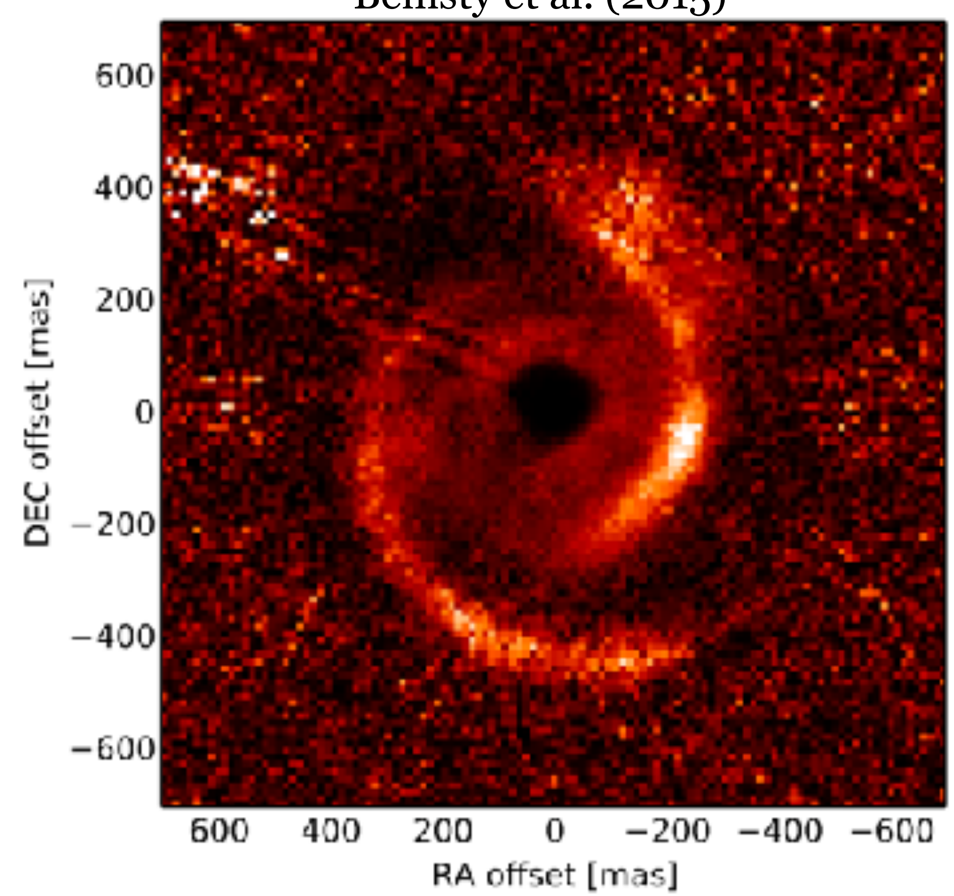
Pinilla et al. (2015)



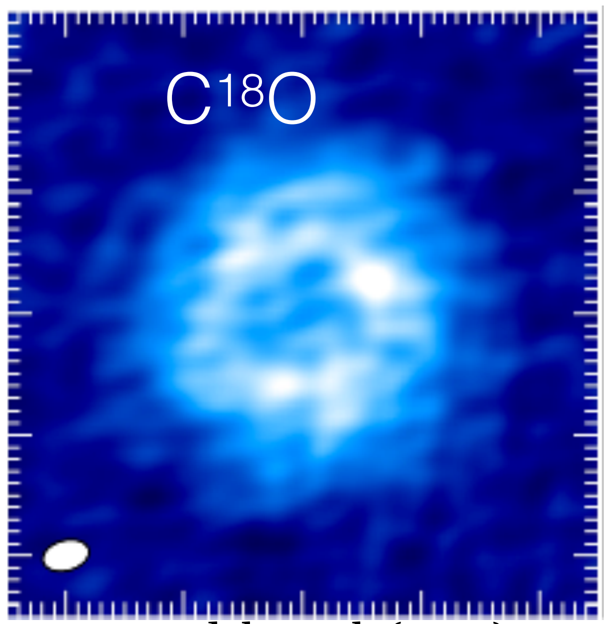


Avenhaus et al. (2014)

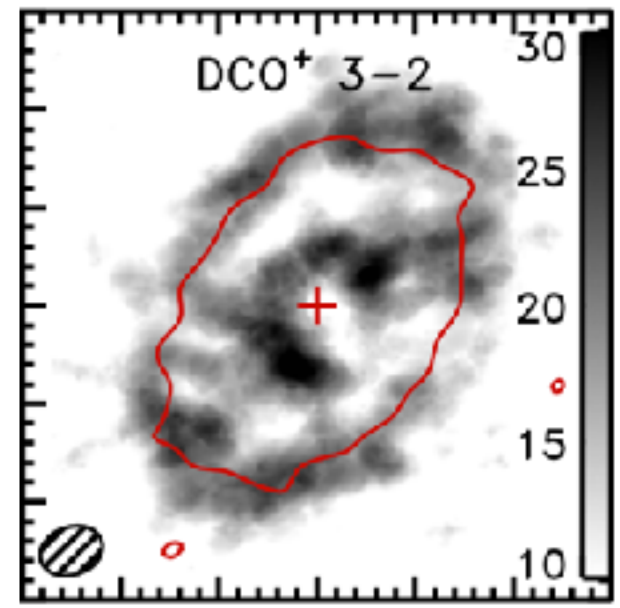
Benisty et al. (2015)



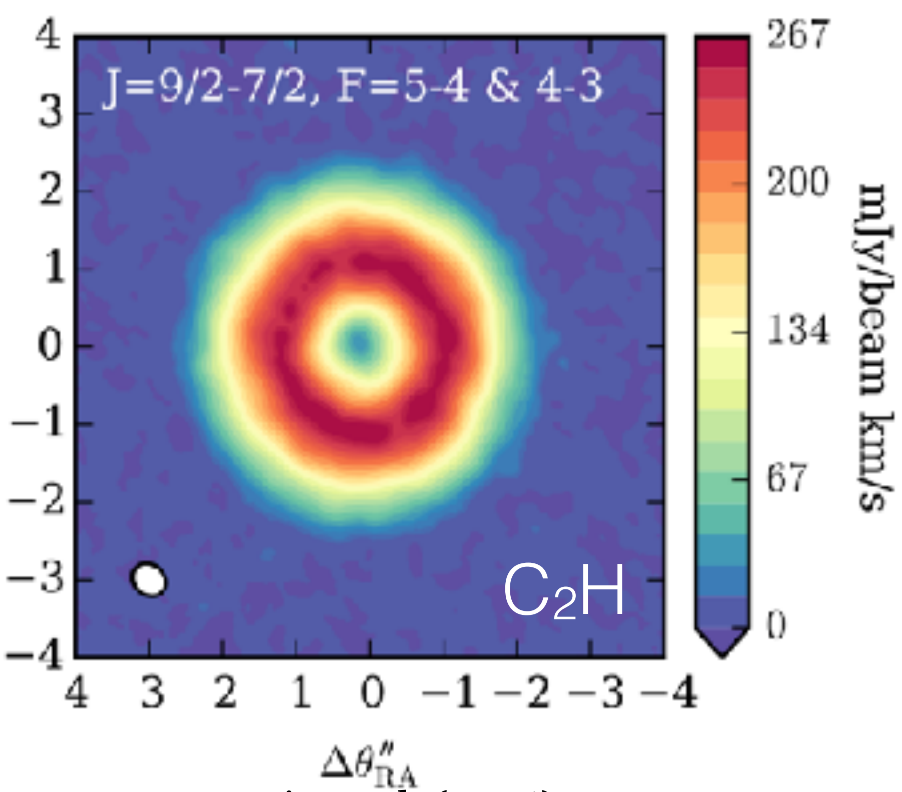
Substructure in molecular lines: tracing physics and chemistry



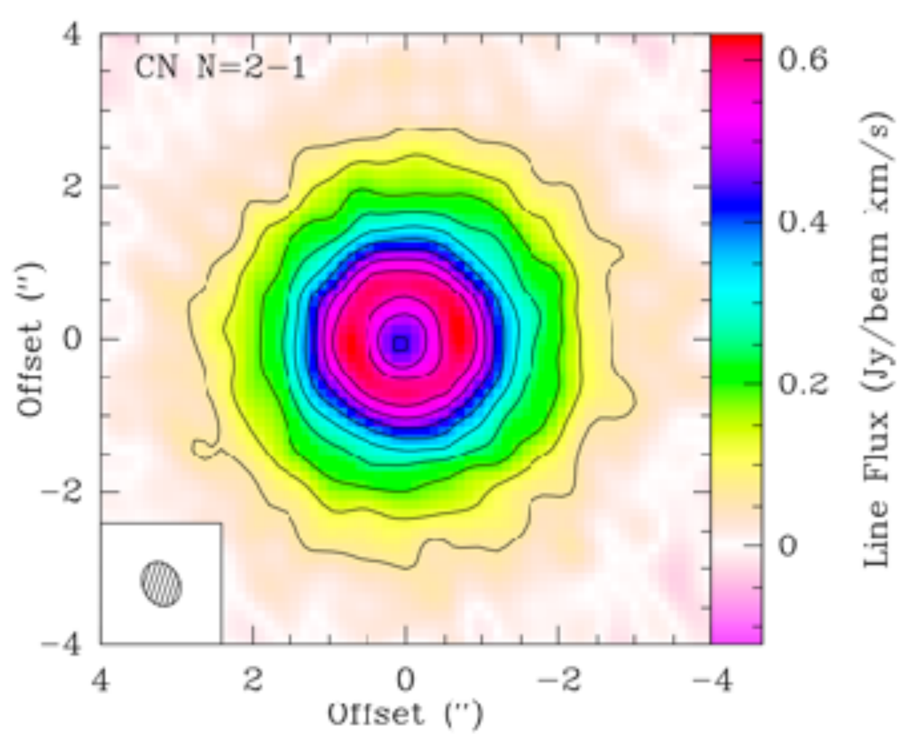
Fedele et al. (2017)



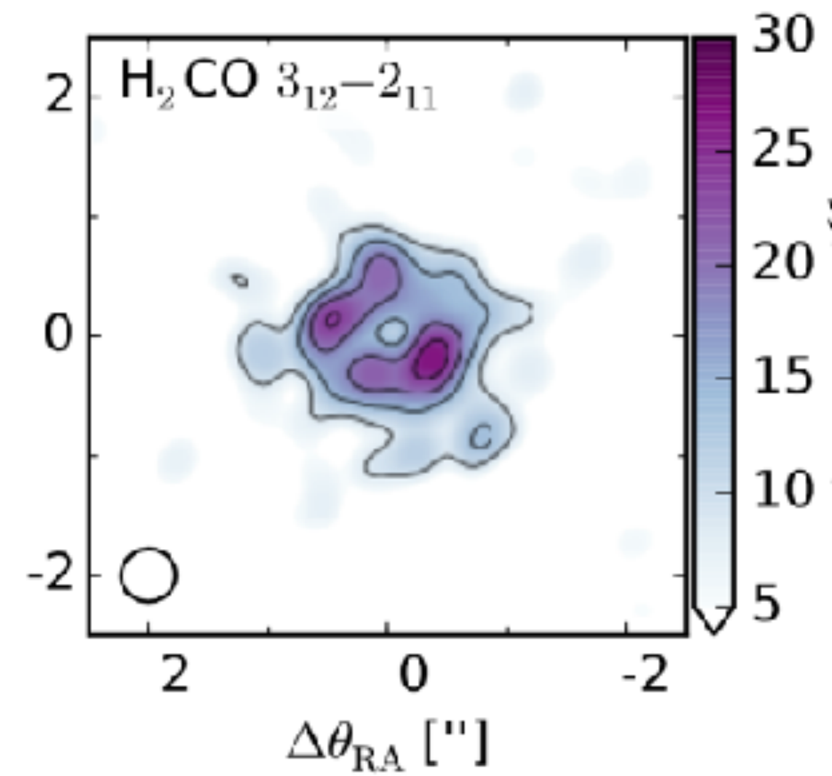
Oberg et al. (2015)



Bergin et al. (2016)



Teague et al. (2016), Cazzoletti et al. (2018)



Oberg et al. (2017)

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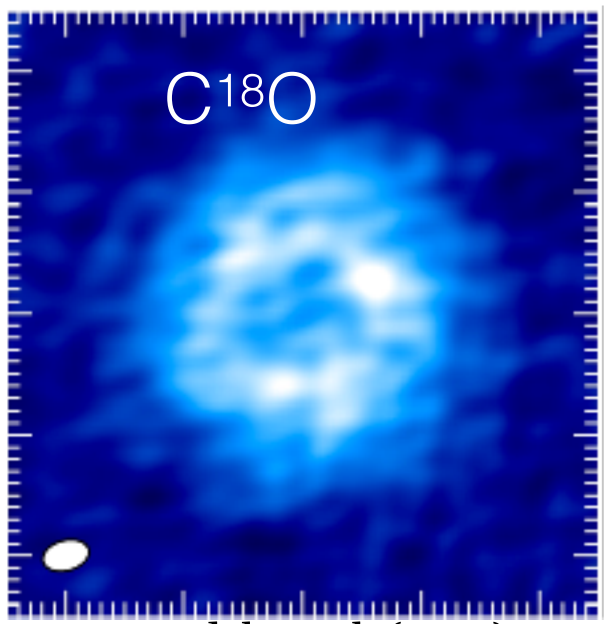
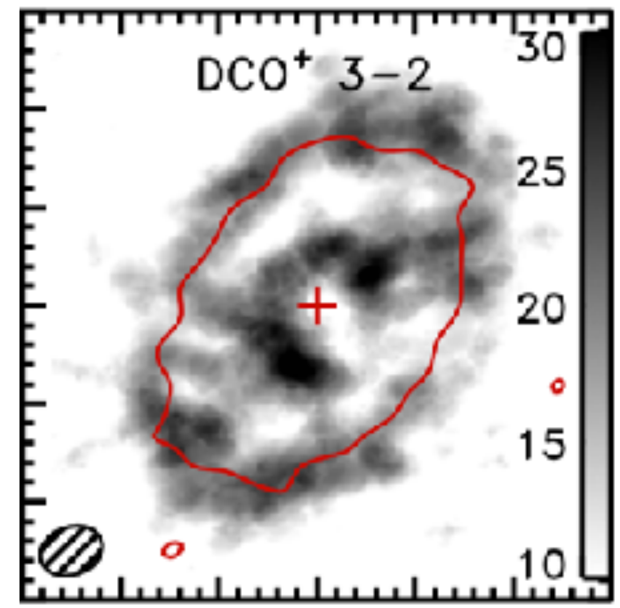


Σ_{gas}

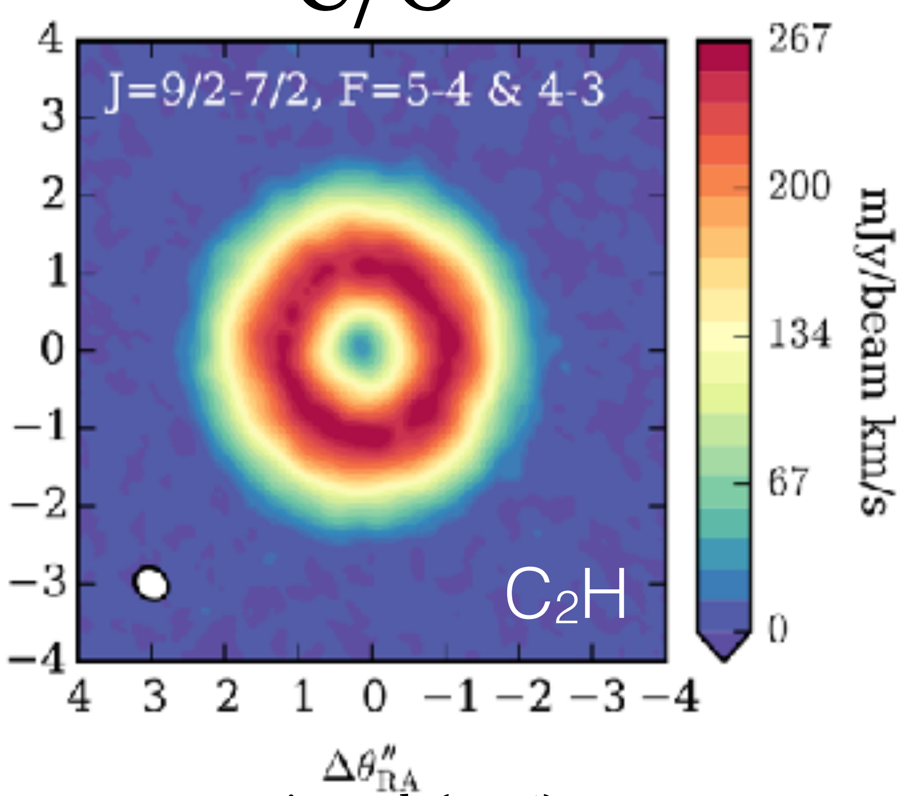
Fedele et al. (2017)



CO snowline & non-thermal desorption

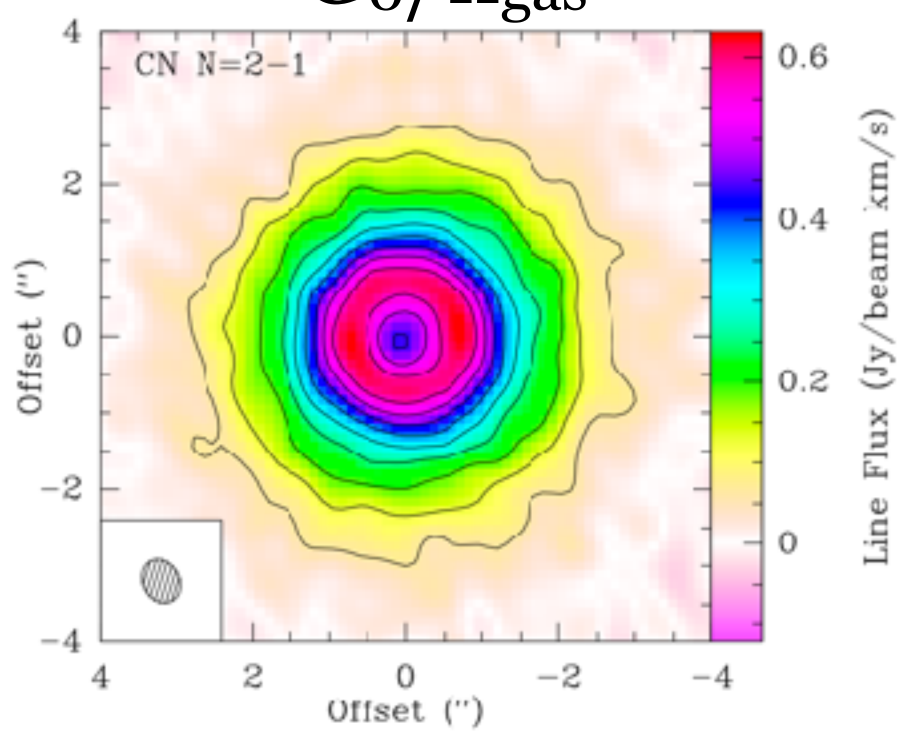
Oberg et al. (2015)

C/O



Bergin et al. (2016)

G_O/n_{gas}



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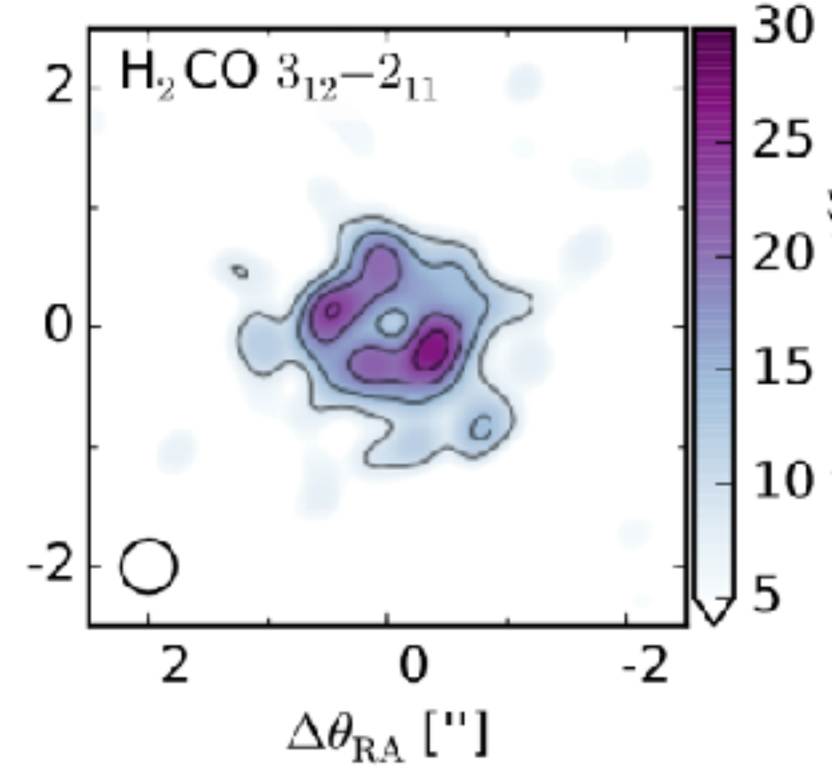
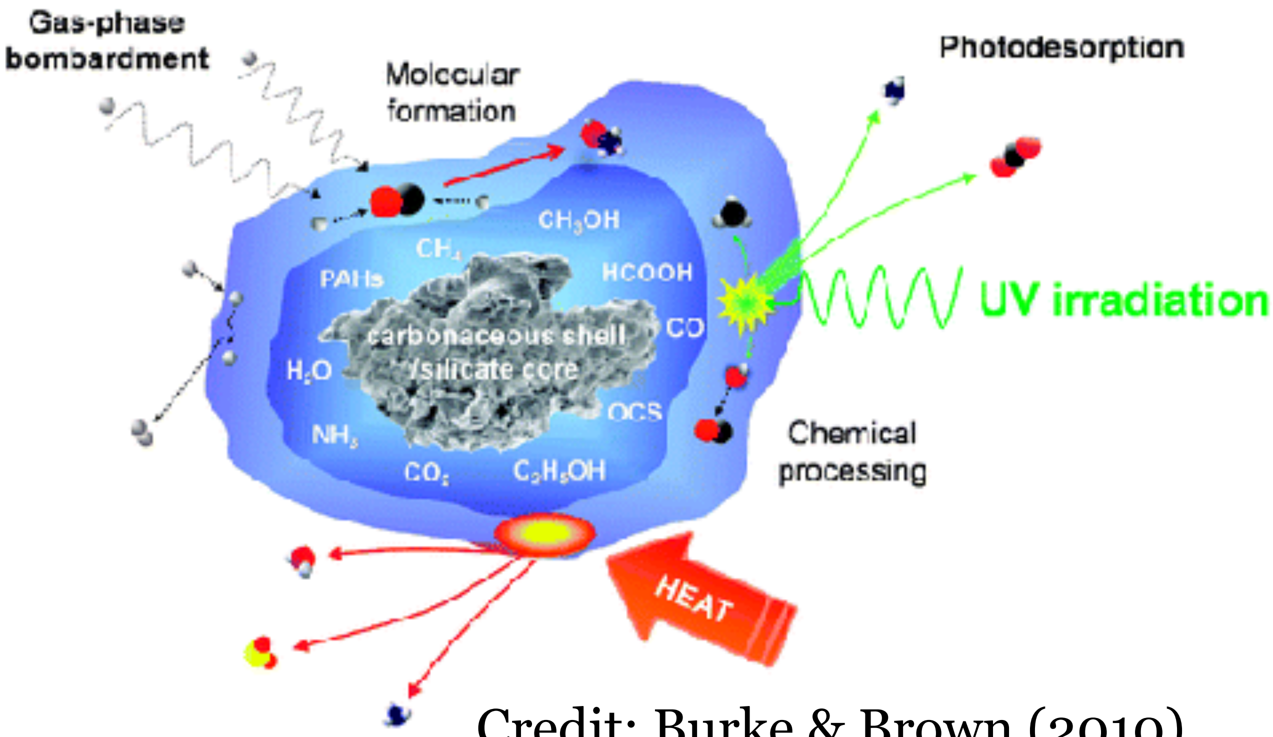


Oberg et al. (2017)

How does the dust affect the gas properties?

Thermo-chemistry depends significantly on dust surface area:

- Opacities
  dust temperature and photo-processes
- Gas grain collisions
  gas temperature
- H_2 formation
- Hydrogenation
- Freeze-out and desorption



Credit: Burke & Brown (2010)

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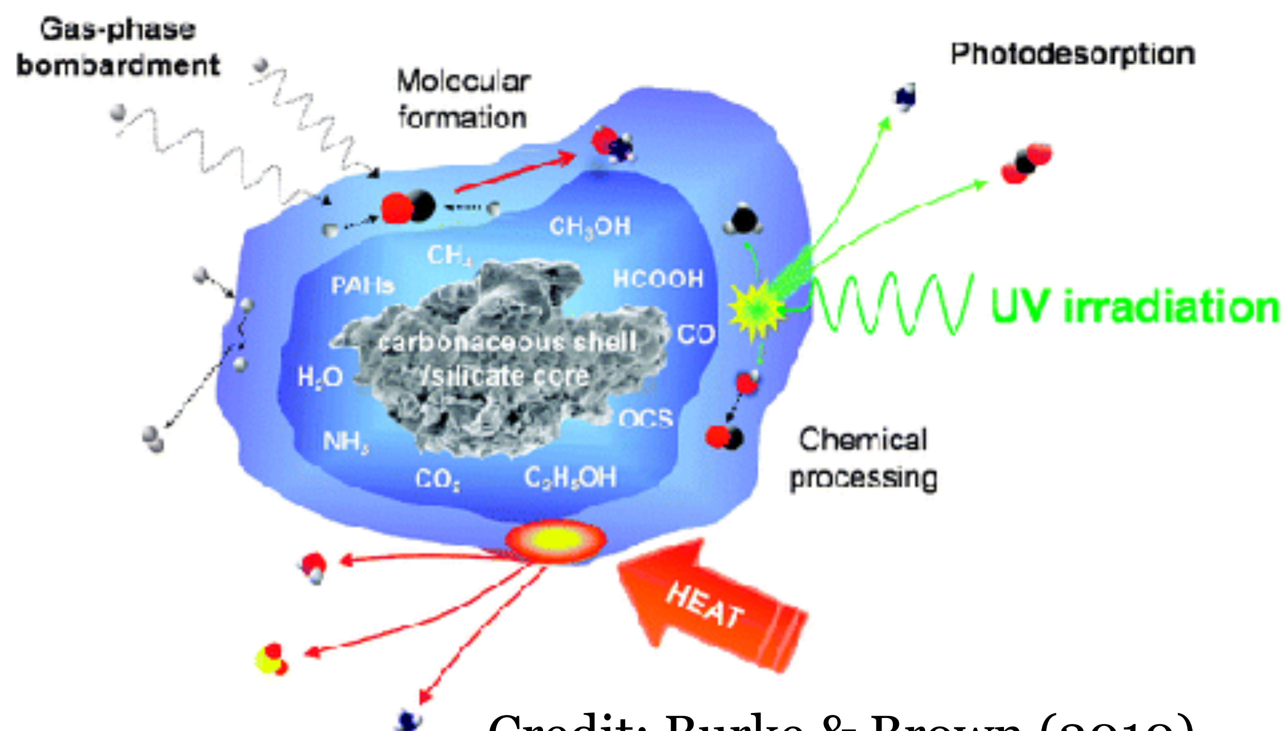

Credit: Burke & Brown (2010)

Are gaps and rings signposts of planets?

- Zonal flows

  Johansen et al. (2009), Uribe et al. (2011), Dittrich et al. (2013), Simon & Armitage (2014)
- Radial gradient of disk viscosity

  Regaly et al. (2012), Flock et al. (2015, 2017), Pinilla et al. (2016)
- Self-induced dust traps

  Gonzalez et al. (2017)
- Secular gravitational instability

  Youdin (2011), Takahashi & Inutsuka (2014)
- Particle growth by condensation near ice lines

  Saito & Sirono (2011), Ros & Johansen (2013), Stammler et al. (2017)
- Sintering of dust particles

  Okuzumi et al. (2016)
- Planet-disk interaction

  Rice et al. (2006), Zhu et al. (2011), Gonzales et al. (2012), Pinilla et al. (2012), Dipierro et al. (2016), Rosotti et al. (2016), Dong & Fung (2016), Bae et al. (2017), Isella & Turner (2016) and many others
- Photoelectric instability

  Kuchner et al. (2018)
- Baroclinic instability & dust settling

  Loren-Aguilar & Bate (2015)

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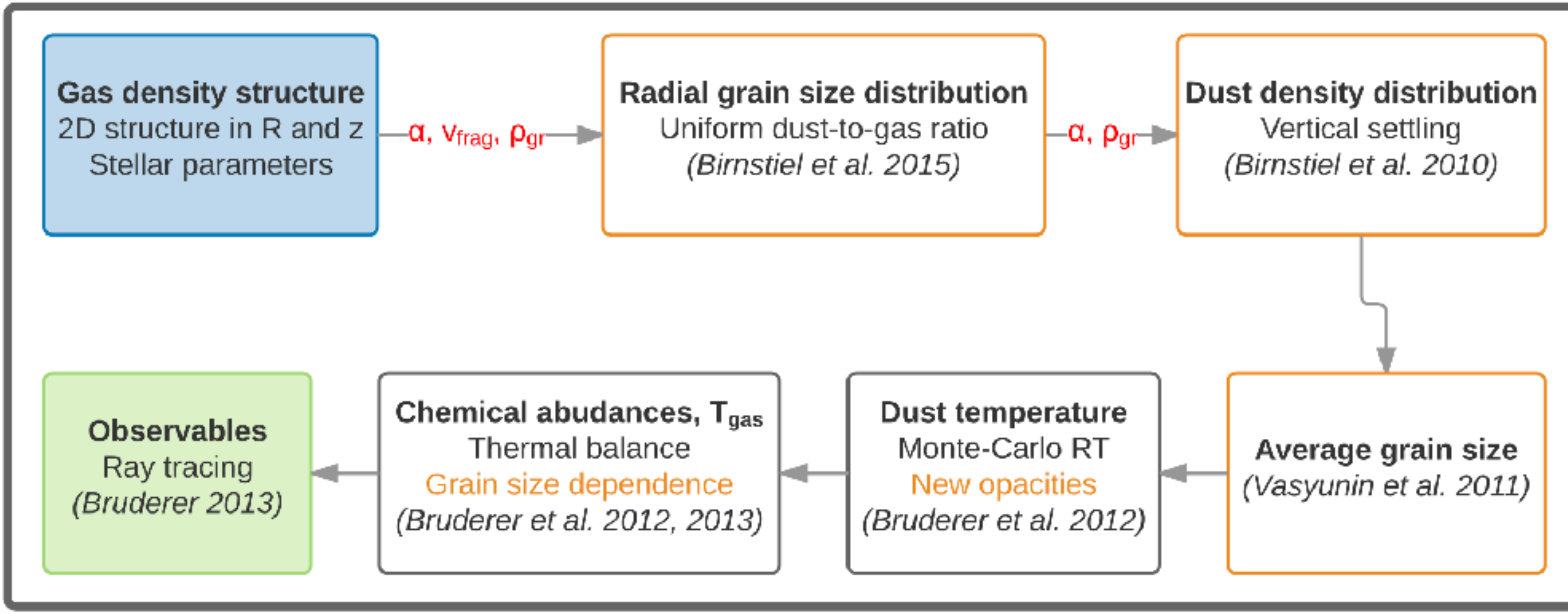
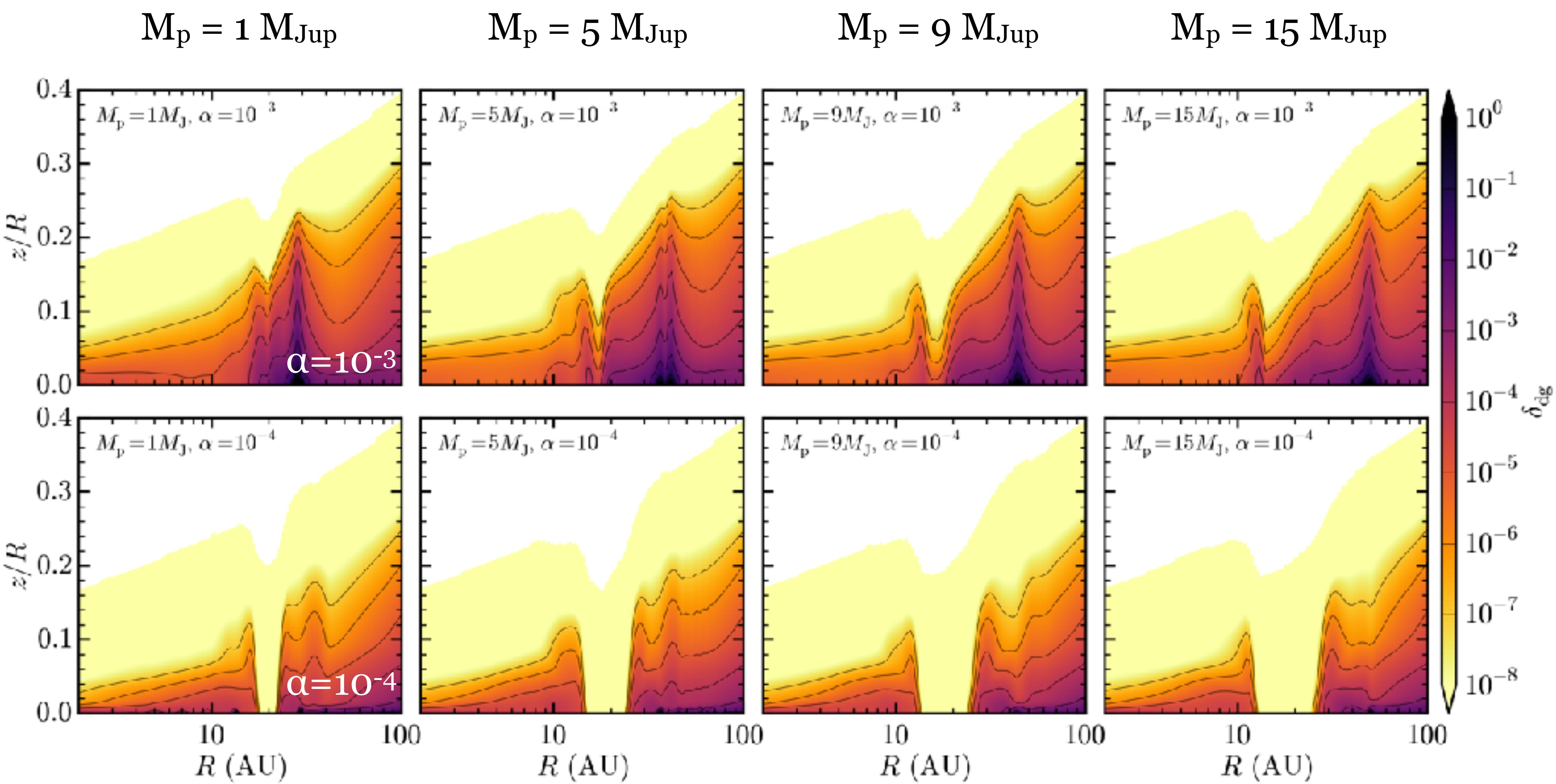
: thermo-chemical code



Bruderer et al. (2012, 2013), Facchini et al. (2017)

- **α** is turbulent parameter, regulating angular momentum transport, dust particles relative velocities, and settling
- fragmentation velocity $v_f = 10$ m s^{-1}

Hydro models of disks hosting massive planets



Gas gap is almost dust free

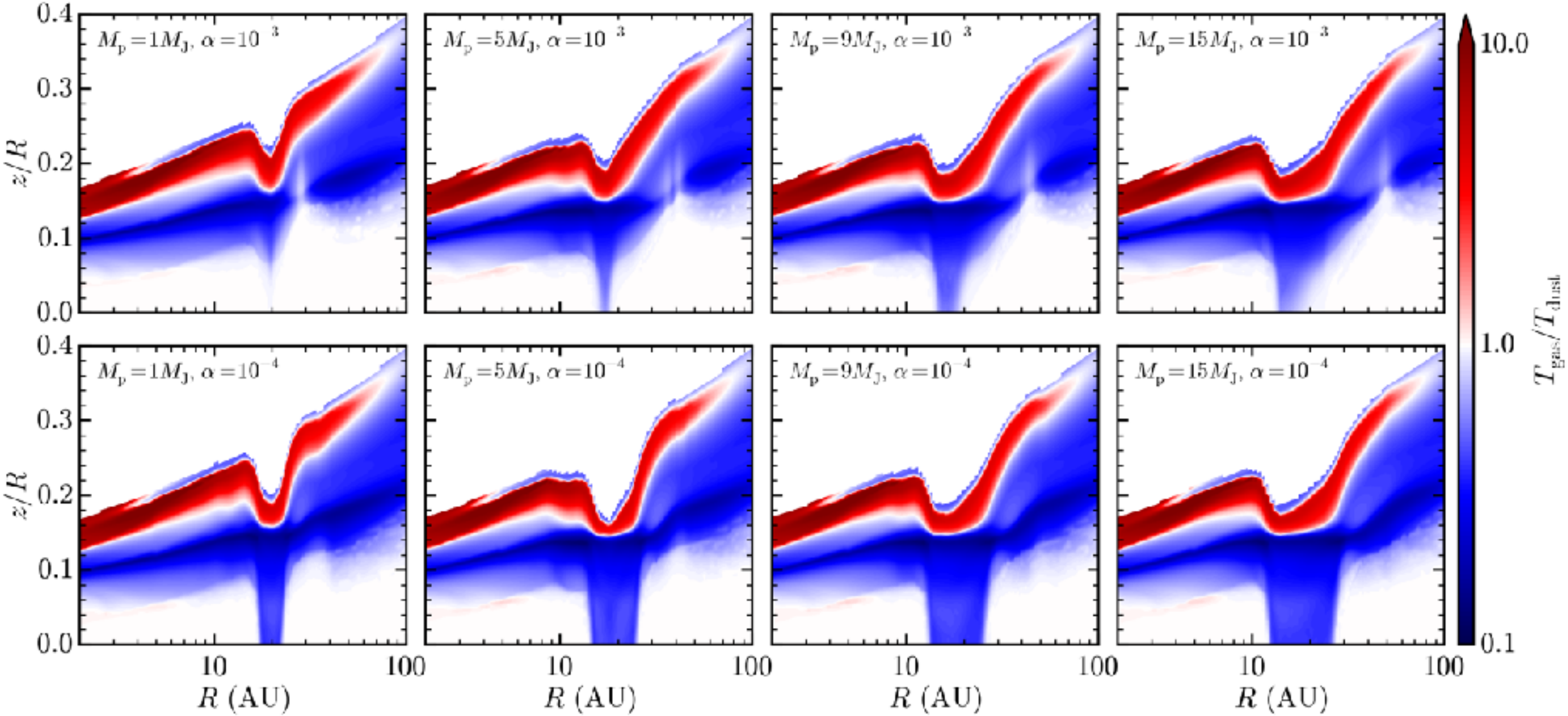
Facchini et al. (2018b)

Hydro models from de Juan Ovelar et al. (2016)

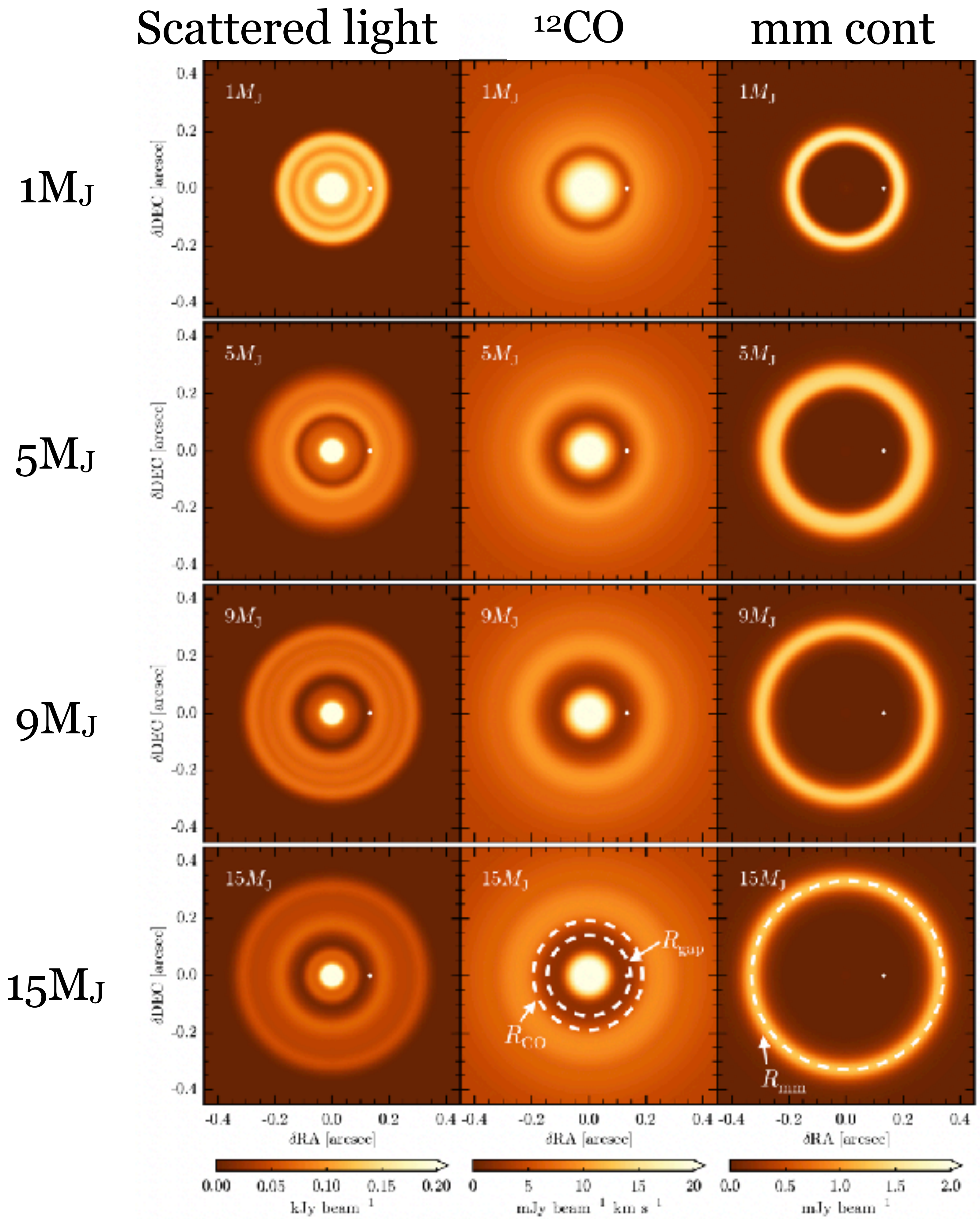
FARGO2D (gas only) + dust evolution on azimuthally averaged profile

Thermal structure

$M_p = 1\ M_{Jup}$ $M_p = 5\ M_{Jup}$ $M_p = 9\ M_{Jup}$ $M_p = 15\ M_{Jup}$

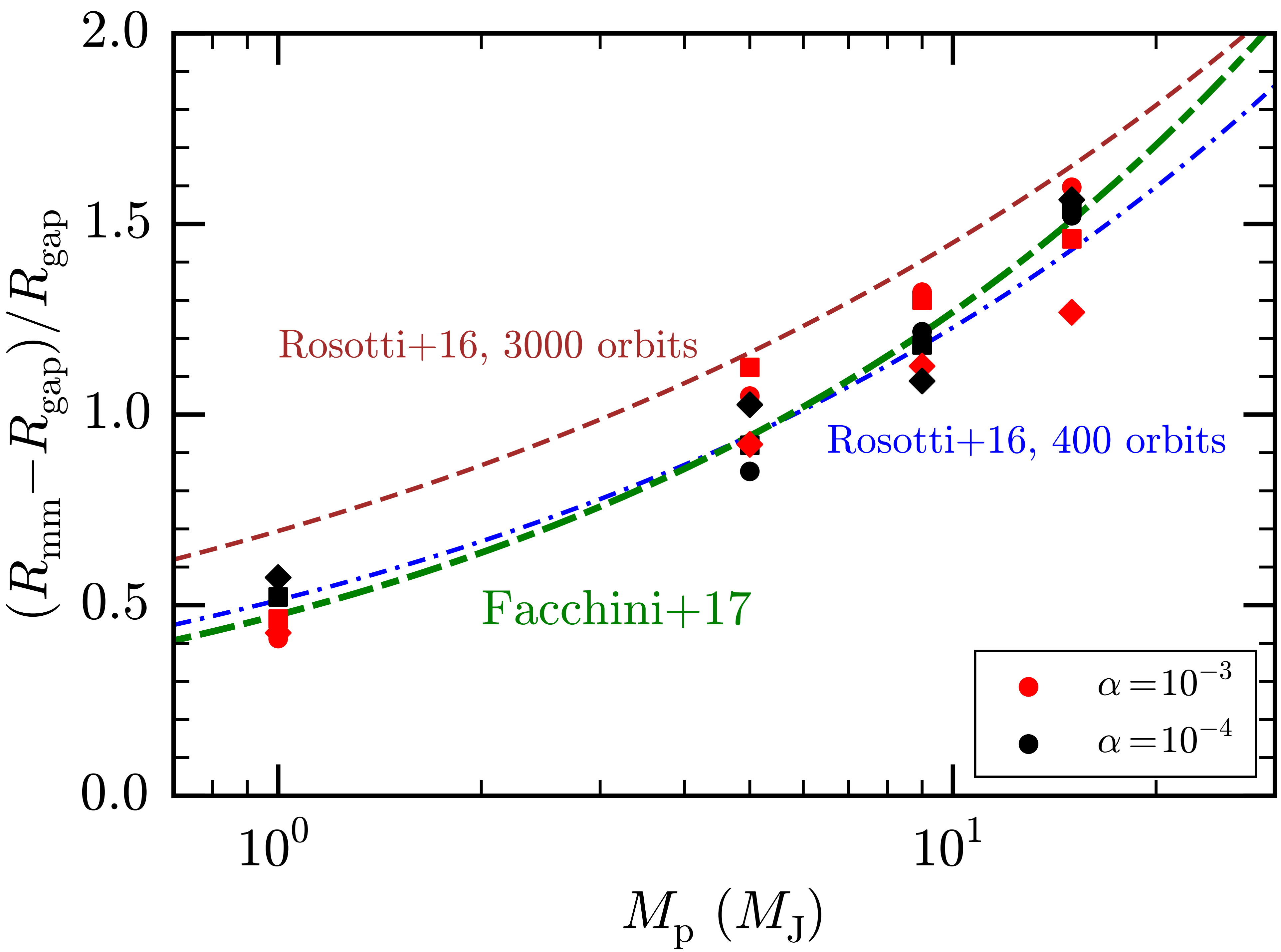


Within dust gap the gas is cold



1) R_{mm} increases with planet mass
2) Gap width increases with planet mass
3) Scattered light and gas show similar structures (Teague et al. 2017)

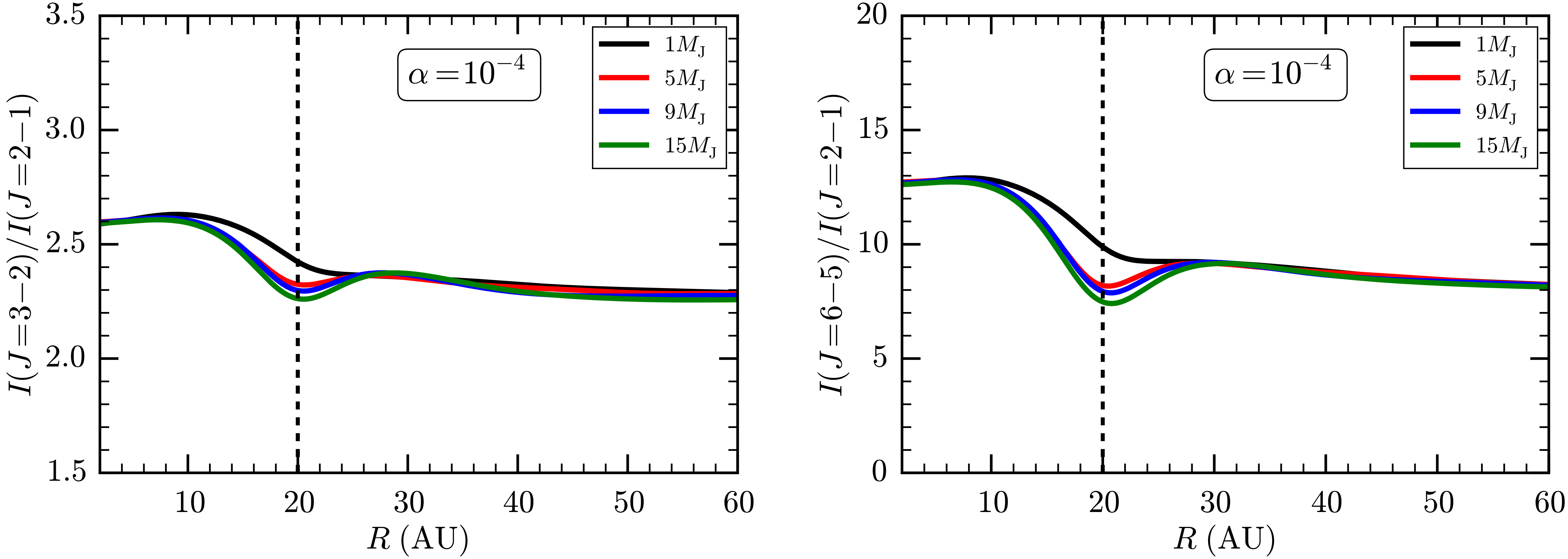
$$(R_{\rm mm} - R_{\rm gap})/R_{\rm gap}$$



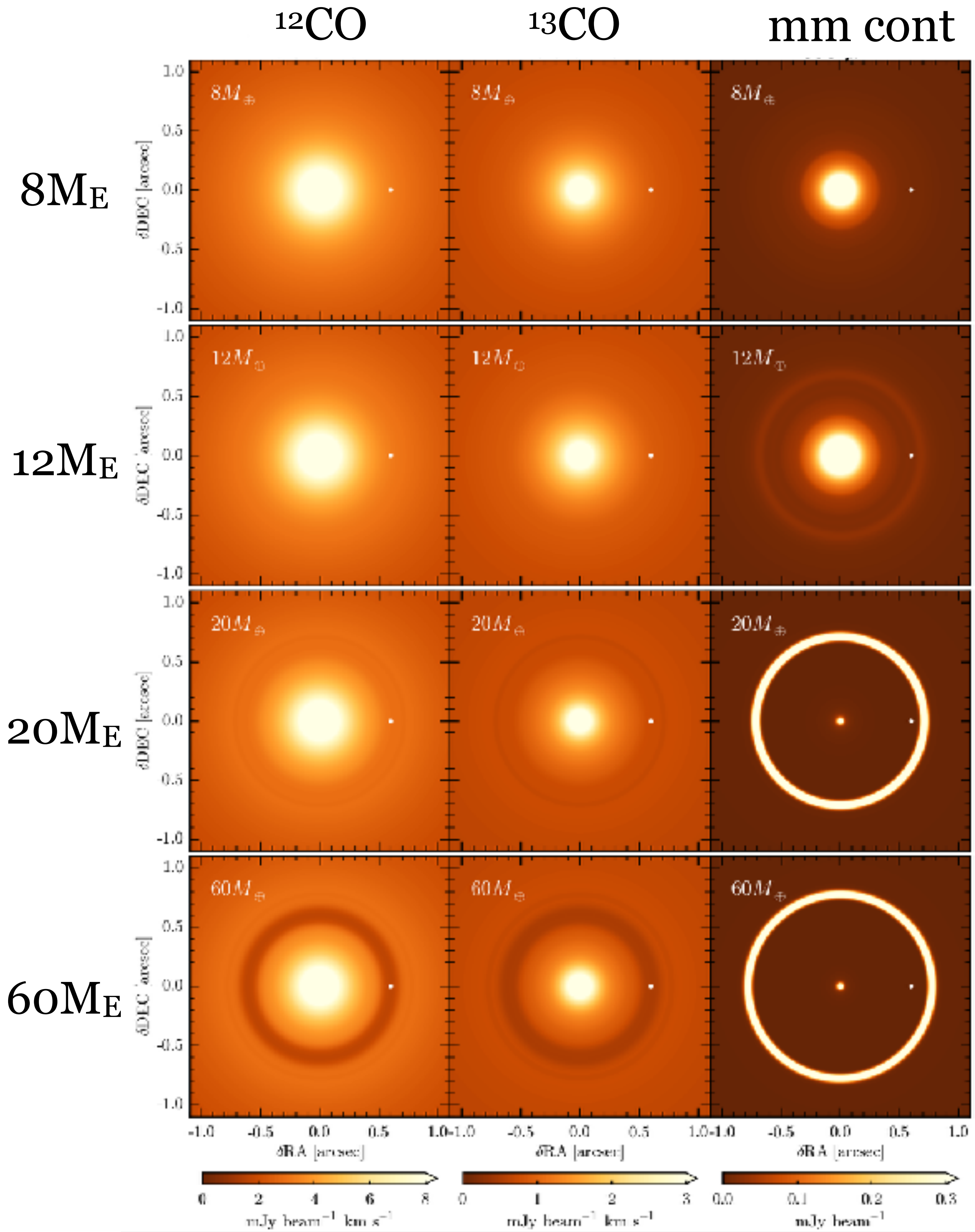
Location of submm radius and location of the gap **traced in gas** vs planet mass:

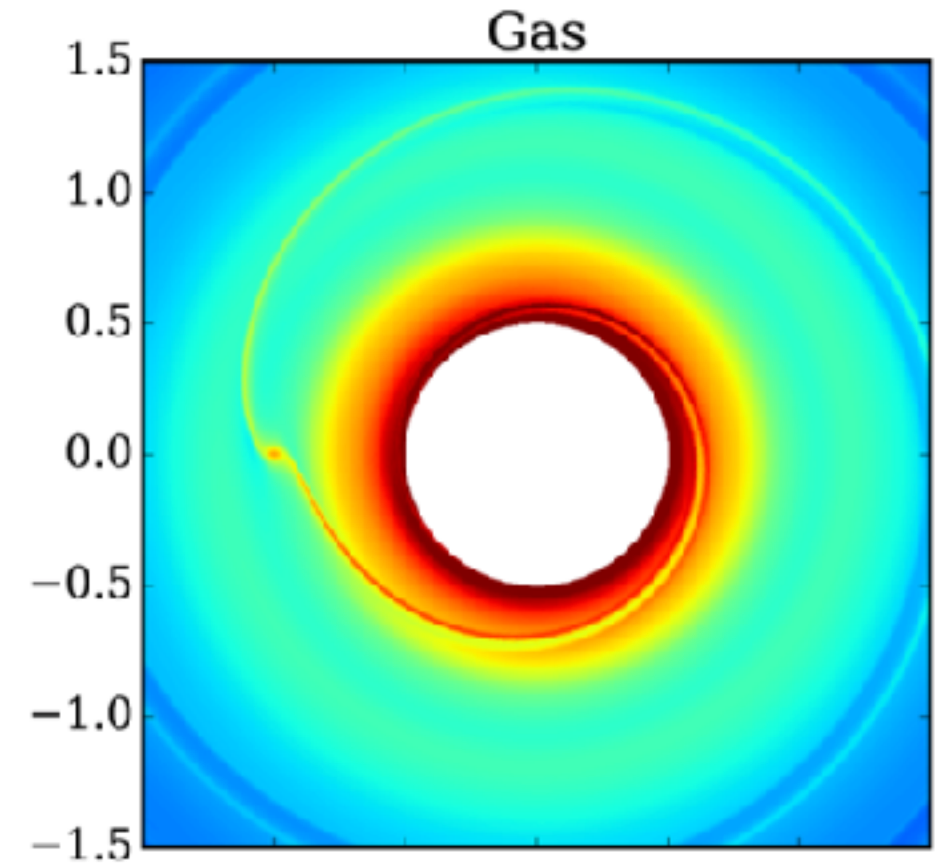
- Clear trend
- No strong dependence on turbulence
- No strong dependence on H/R

Surface density or temperature gaps?



- Line ratios show that there is a temperature gap
- CO 6-5 is crucial to have enough energy leverage
- Gas temperature needs to be treated properly to retrieve surface density gaps from gaps in CO emission





Hydro models from Rosotti+16

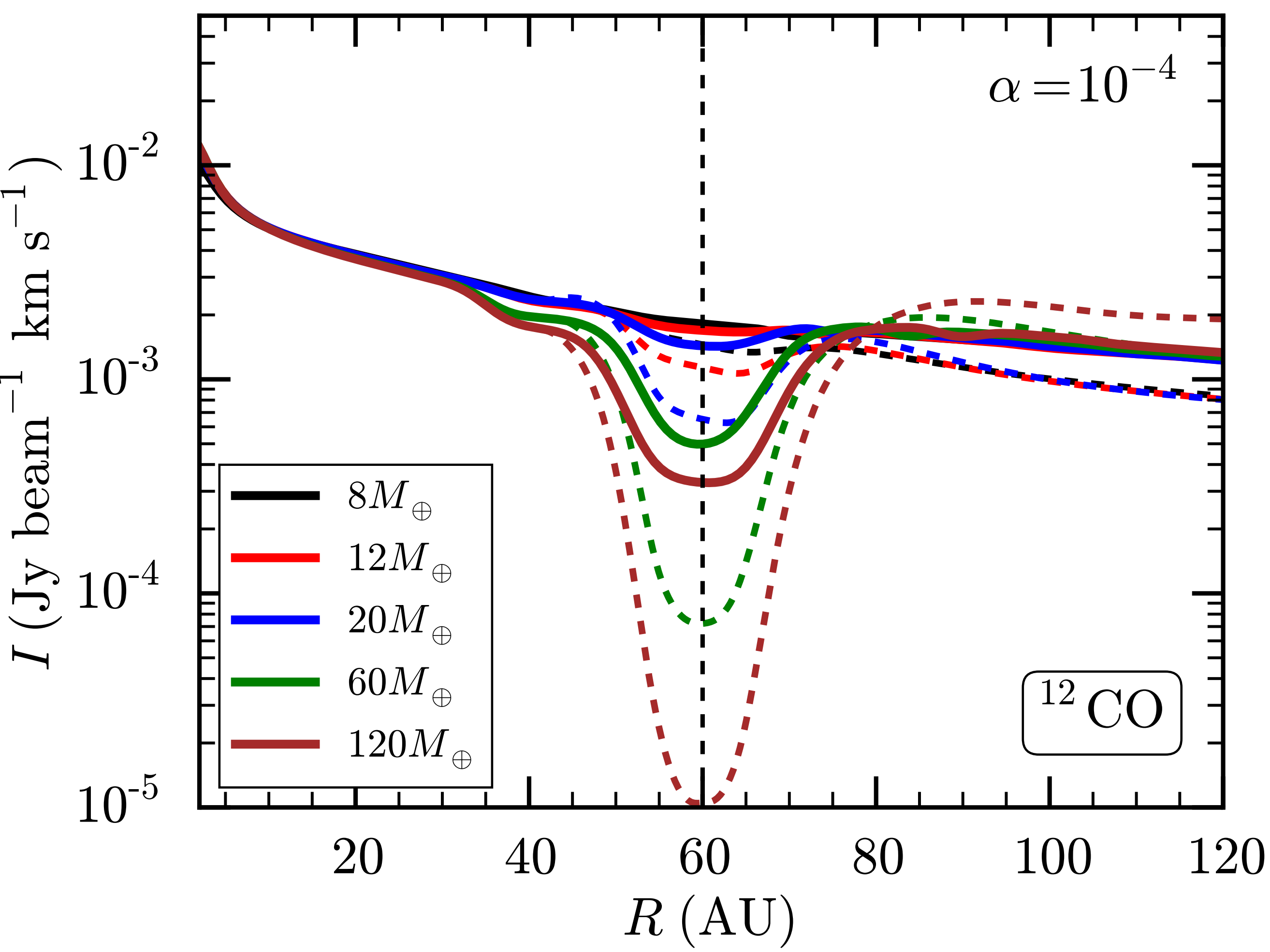
FARGO2D gas+dust

Parameter space study:
$\alpha = 10^{-2}, 10^{-3}, 10^{-4}$
M_p = 8,12,20,60,120 M_E
H/R = 0.025,0.05,0.1

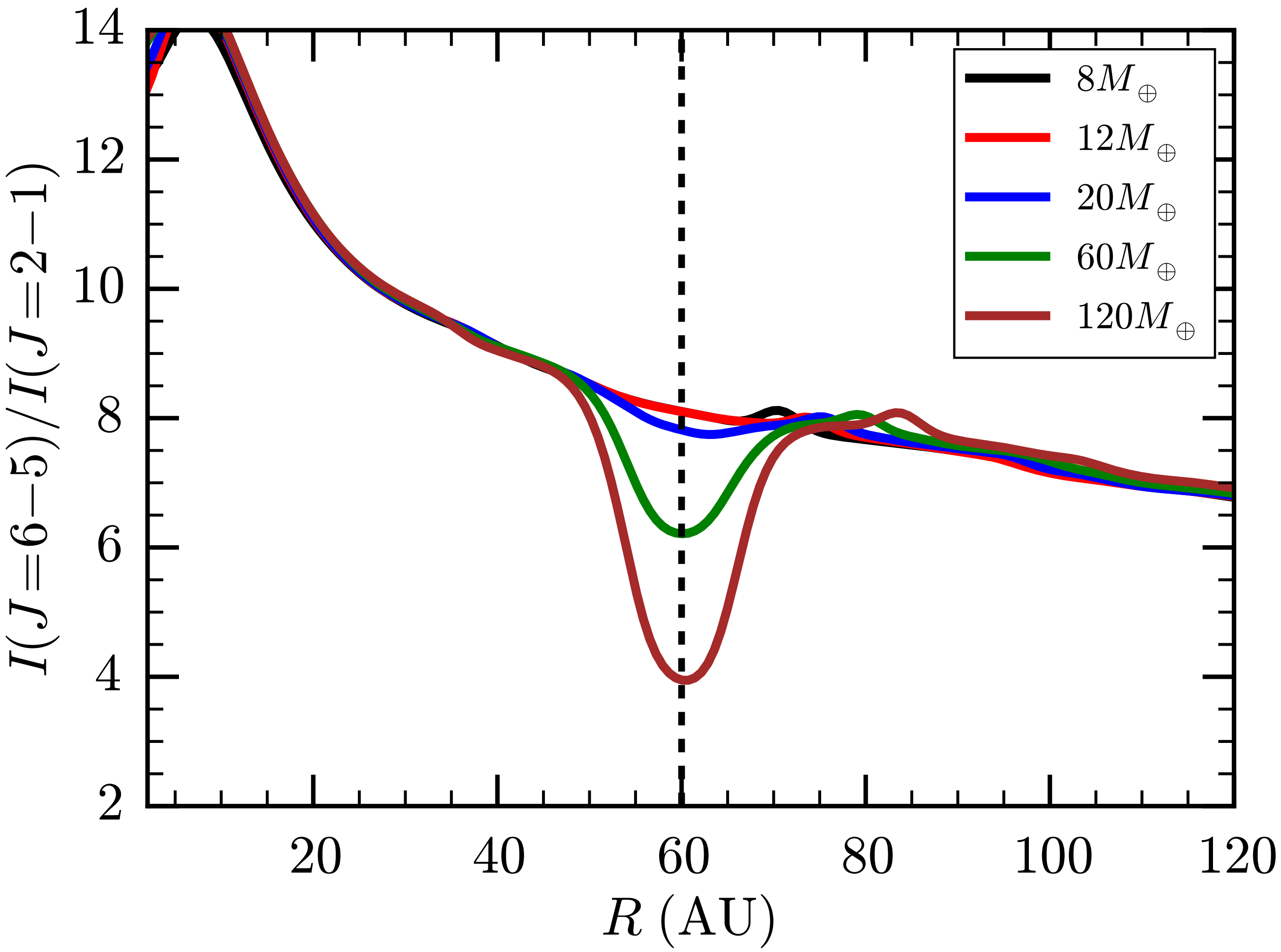
Facchini et al. (in prep.)

BOTH surface density AND temperature gaps

Radial intensity profiles



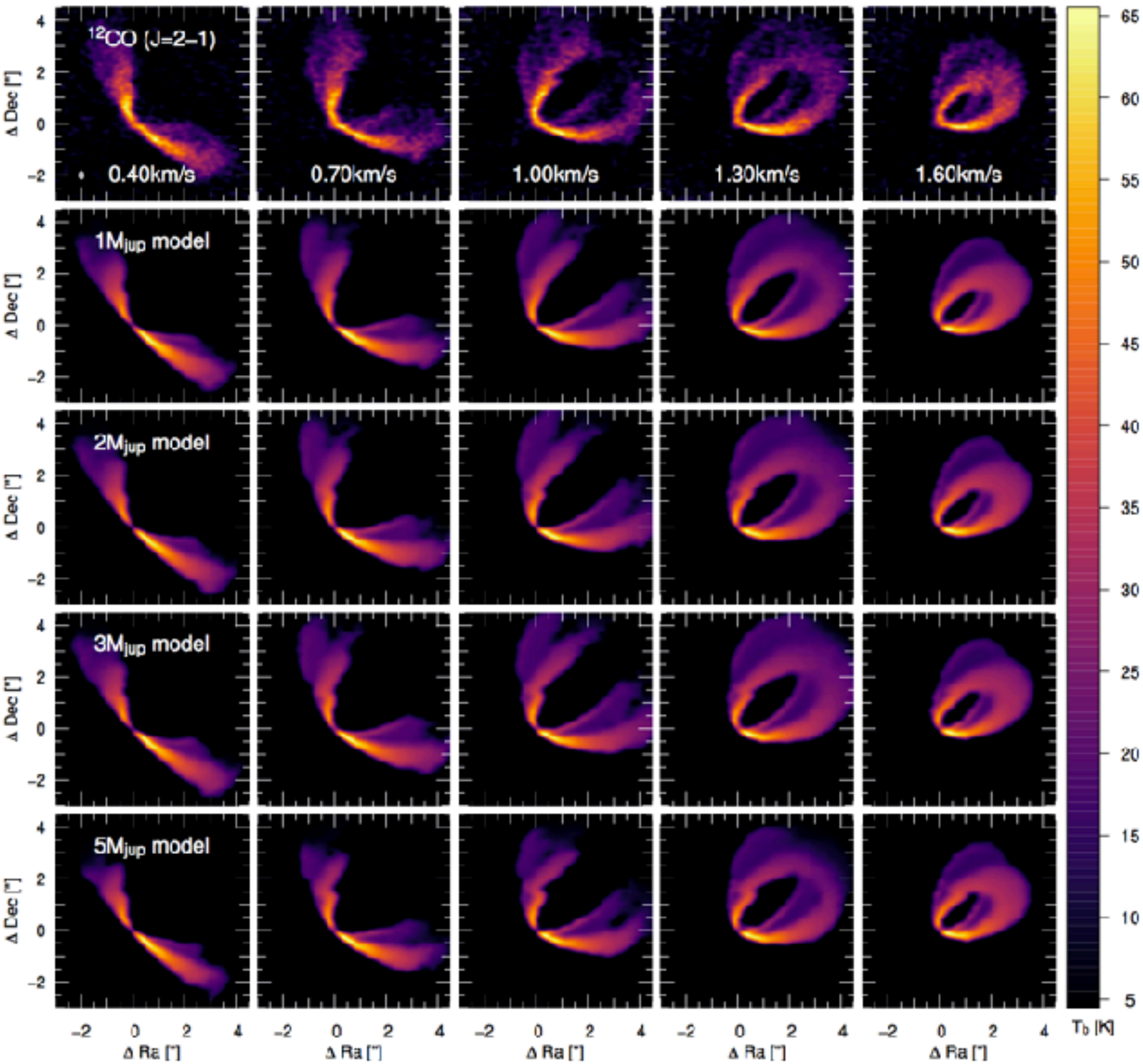
Line ratio profiles

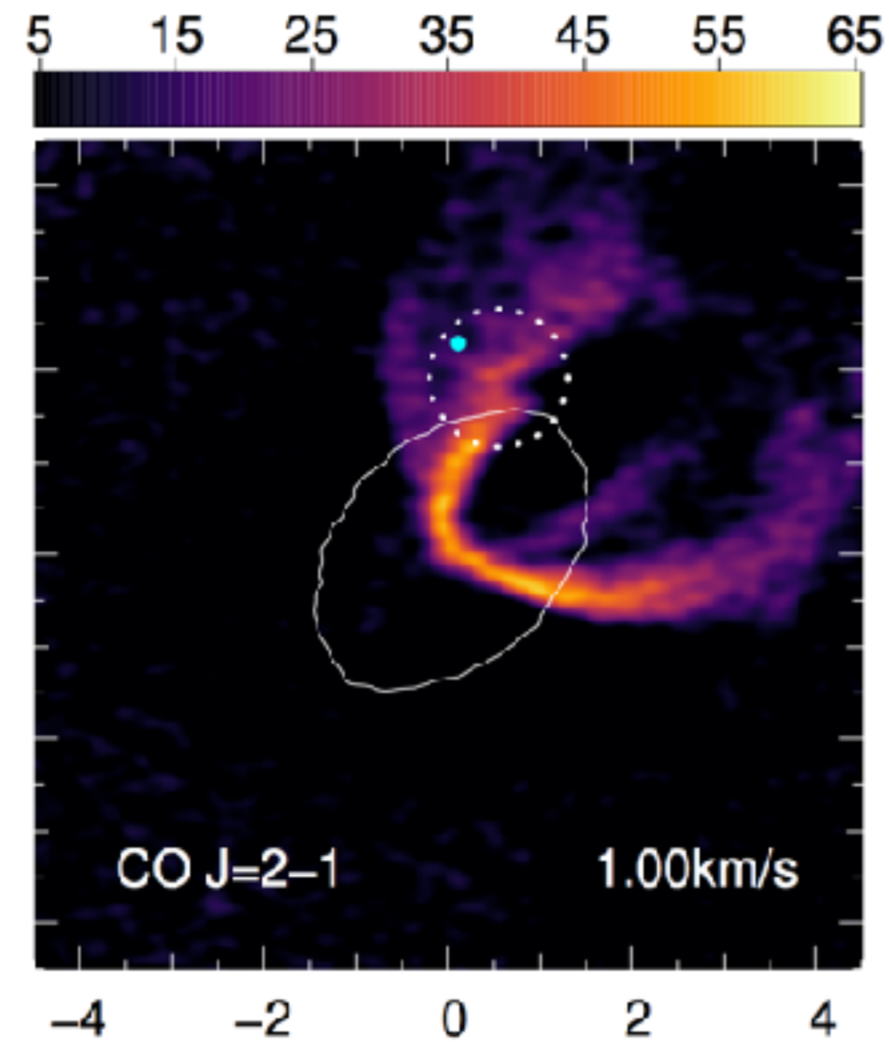


Facchini et al. (in prep.)

Need to be careful when interpreting gaps from optically thick molecules

An alternative approach: planets via kinematical tracers





Pinte et al. (2018)

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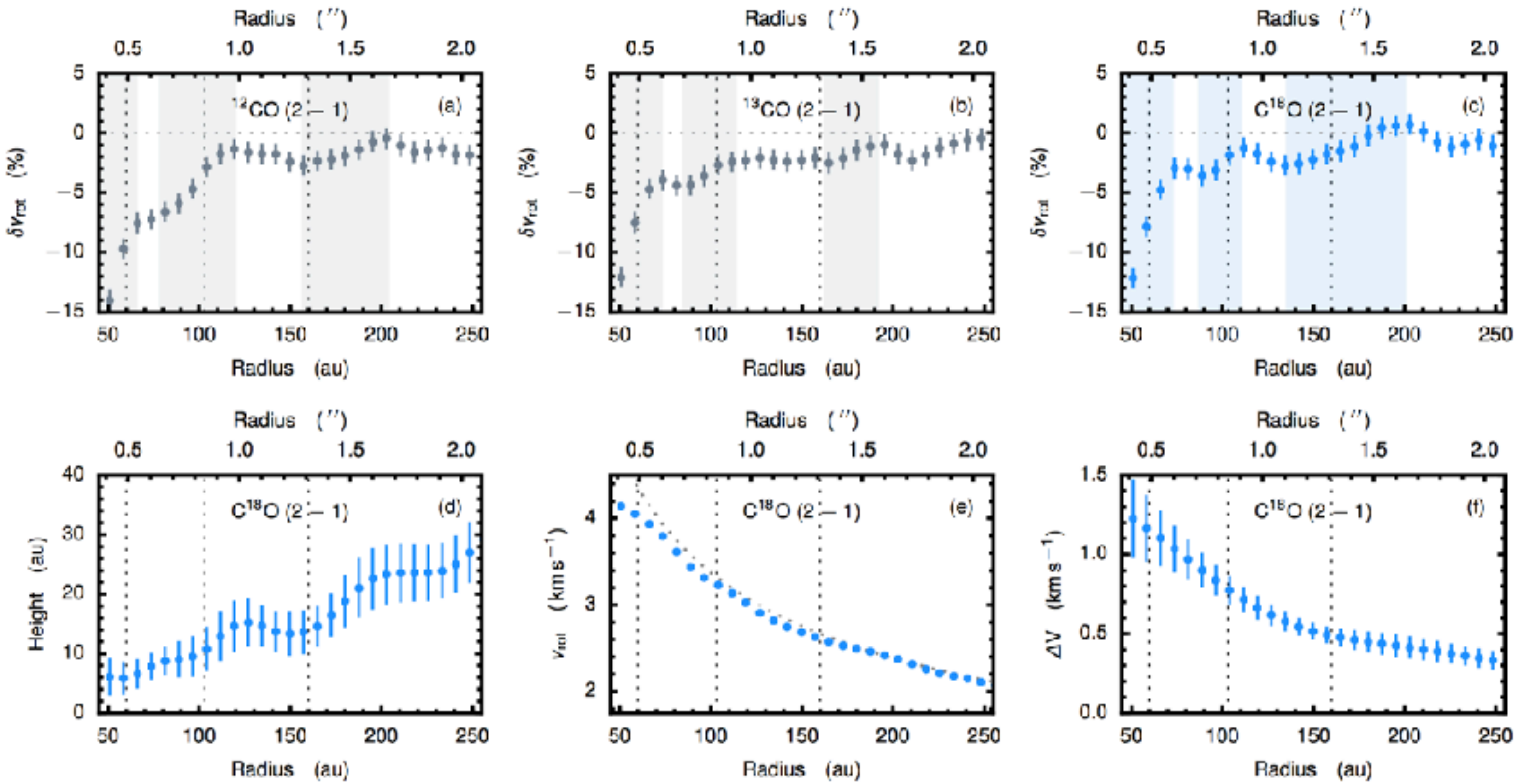
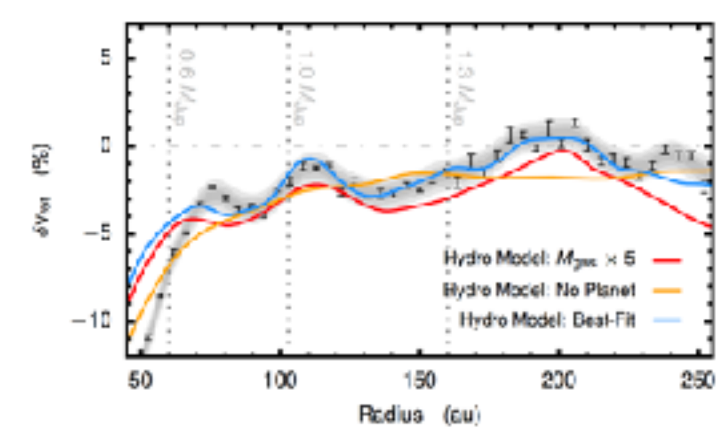


$$\frac{v_{\rm rot}^2}{r} = \frac{GM_\star r}{(r^2 + z^2)^{3/2}} + \frac{1}{\rho_{\rm gas}} \frac{\partial P}{\partial r}$$



Teague et al. (2018)

TAKE AWAY

- The interaction between gas and dust in disks occurs dynamically, thermally and chemically

- Gaps observed in **gas** are key to understand the origin of the structures observed in dust continuum

- **Multi-wavelength** observations of continuum structures needed to constrain the gas-dust dynamical interaction

- Planet opened gaps can also be **thermal gaps**

- **Planet masses** can be inferred comparing **gas and submm continuum spatial** structures