Detecting planet gaps in disks with ALMA

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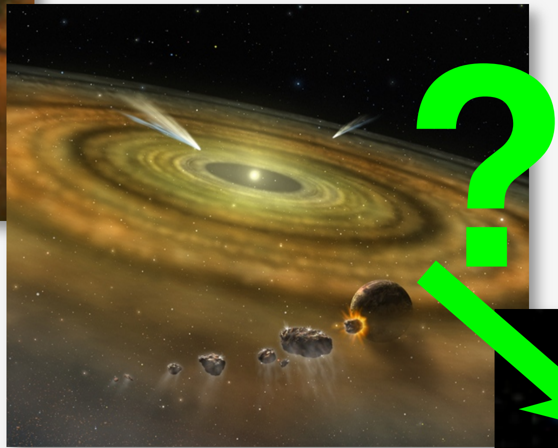

From clouds
to envelopes,
to disks,
to planets

***Big questions** in planet formation:*
(signposts of planets)

- *Detect grain growth?*
- *Detect grain dynamics?*
- *Detect planet/disk interactions?*
- *Timescale for gas dispersal (and planet formation)?*

Dust & gas dynamics are very different

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gas-dust interaction:

- gas pressure supported and sub-keplerian; dust Keplerian
- ΔV b/w gas & dust grains ⇒ gas drag results in **vertical settling**
- inward pressure gradient ⇒ **radial migration** of dust grains

dust distribution:

- small grains (1-10 μm): dust coupled to gas
- medium grains (100 μm-10 cm): strong influence of gas drag
- large grains (1-10 m): dust insensitive to gas

(for standard CTTS disk conditions)

Dust + gas simulations: settling & migration

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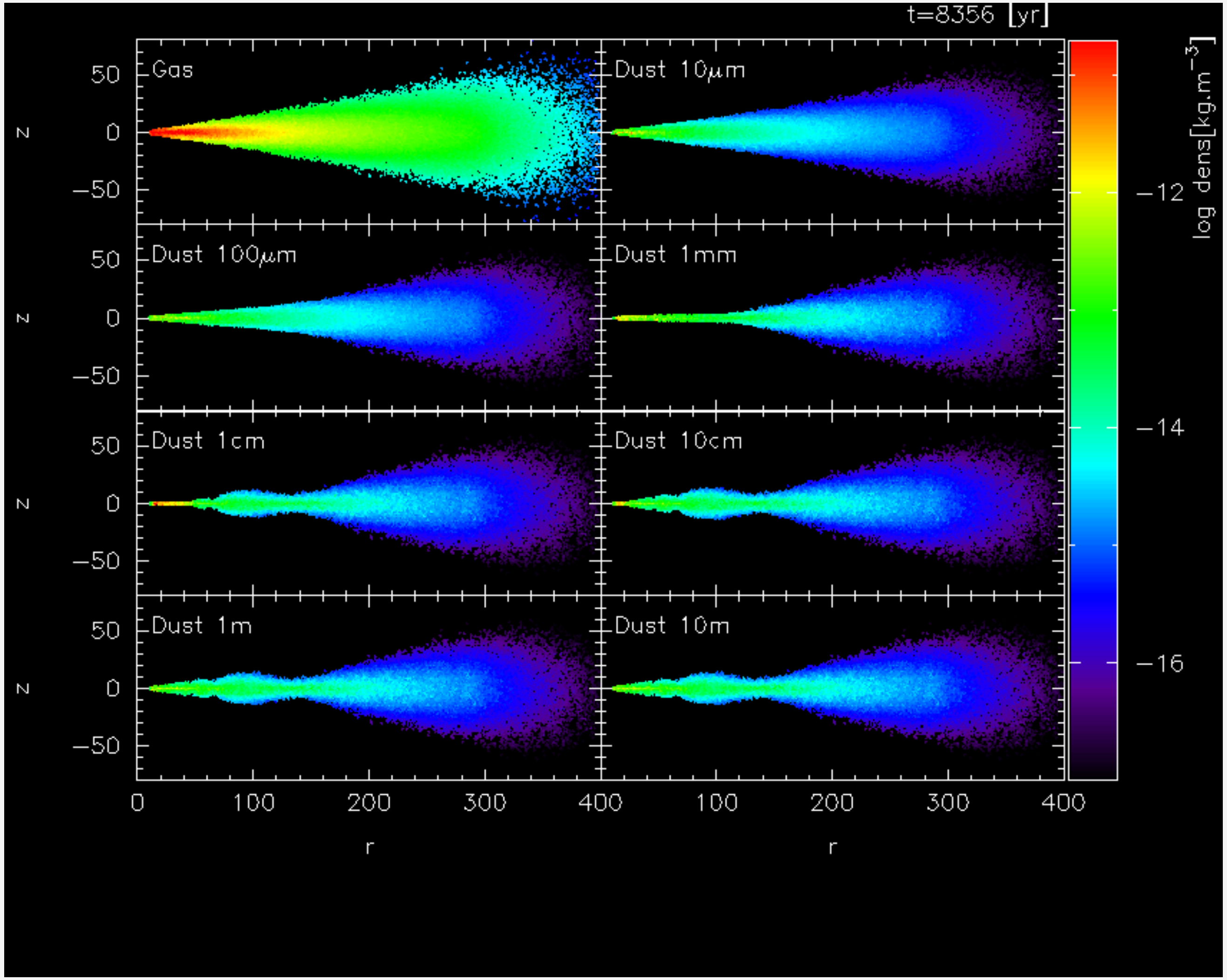


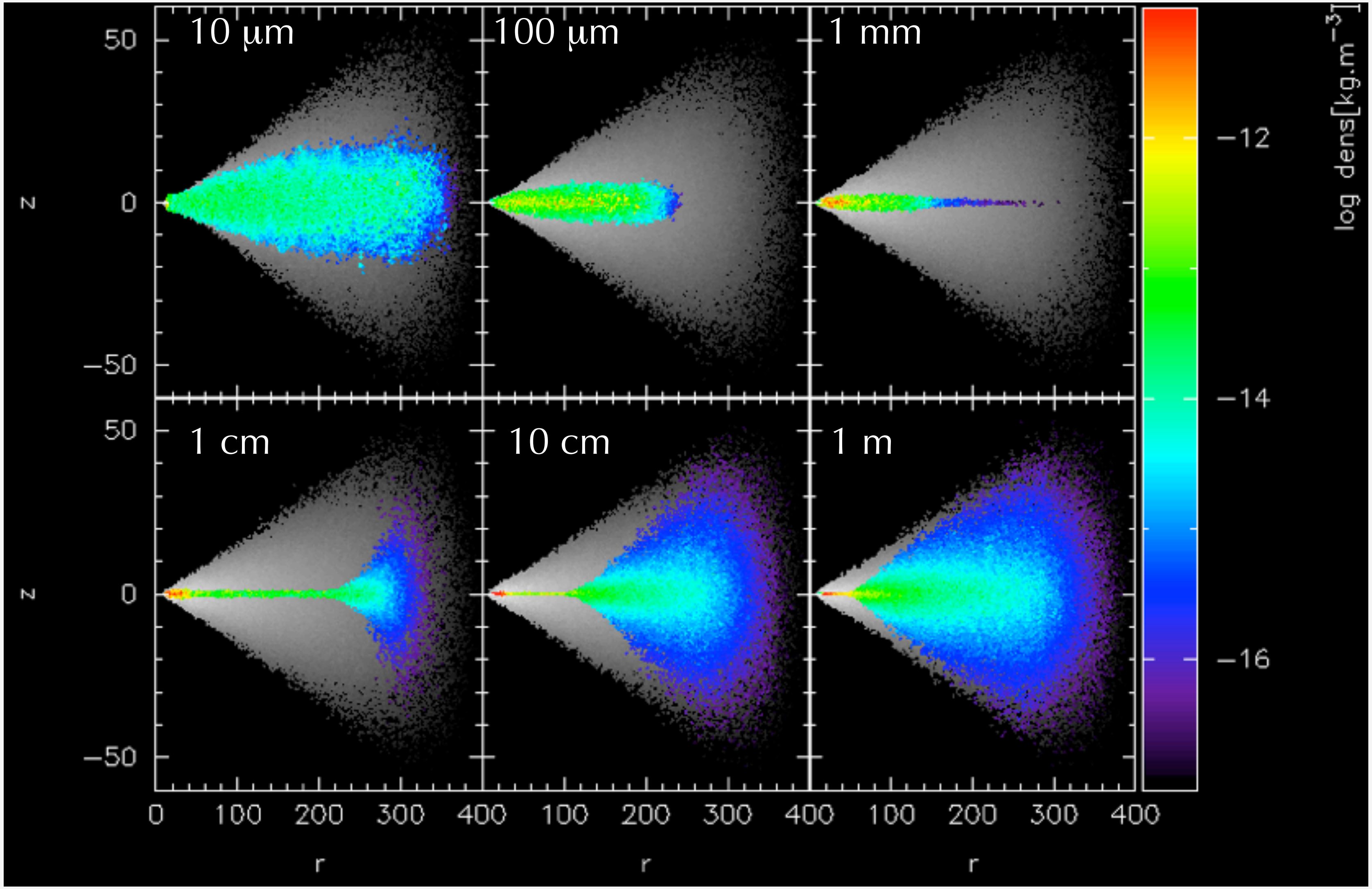
Gas
100 μm
1 cm
1 m
10 μm
1 mm
10 cm
10 m

CTTS disk: $M_\star$ = 1 $M_\odot$, M_d = 0.01 $M_\odot$, R_d = 400 AU
Dust 1% disk mass
Fixed grain size: 1 μm - 10 m

3D gas+dust SPH simulations

Barriere-Fouchet et al. (2005); Maddison et al. (2003)

Dust + gas simulations: settling & migration



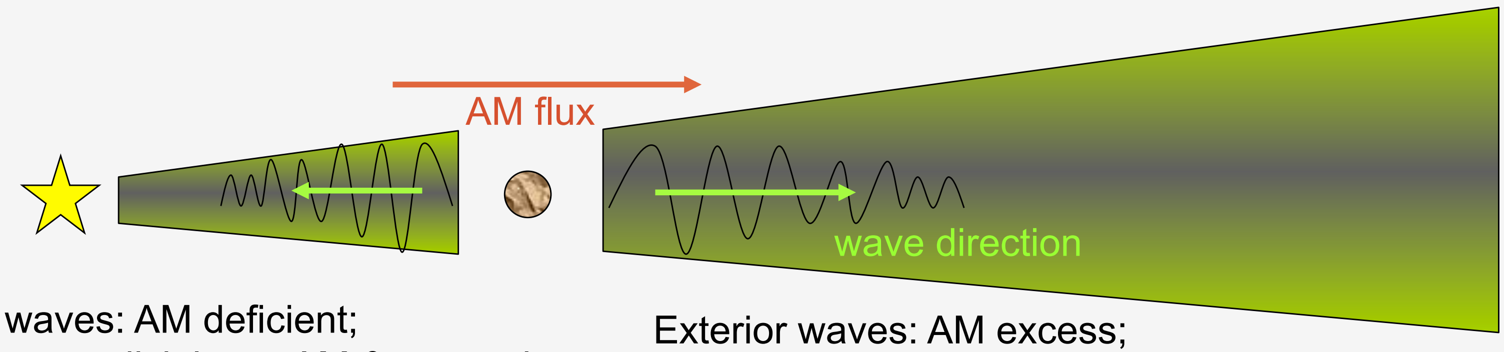
CTTS disk: $M_\star$ = 1 $M_\odot$, M_d = 0.01 $M_\odot$, R_d = 400 AU
Dust 1% disk mass
Fixed grain size: 1 μm - 10 m

3D gas+dust SPH simulations

Barriere-Fouchet et al. (2005); Maddison et al. (2003)

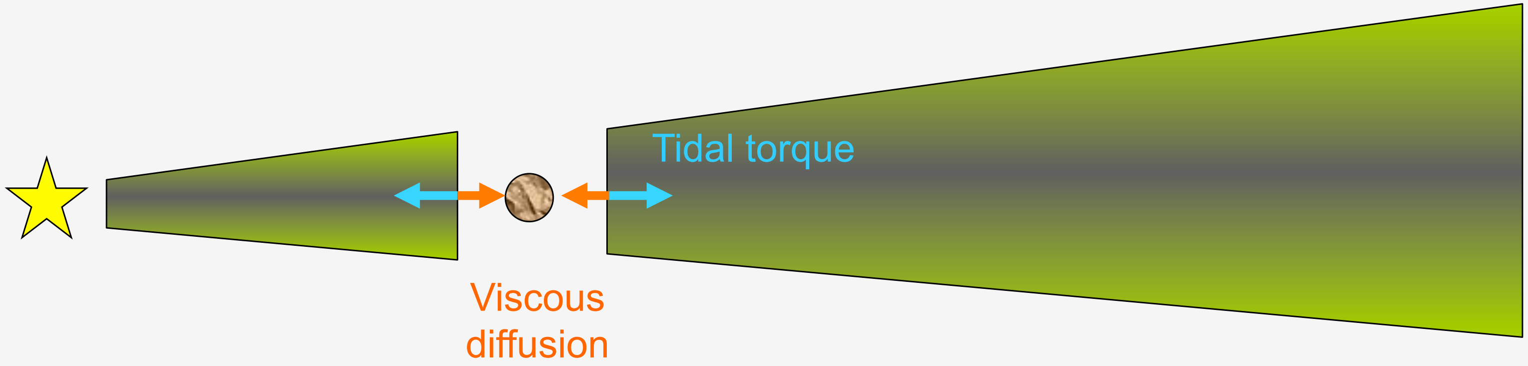
Adding a planet

- Planet gravitationally perturbs disk
- Launches spiral density wave
- Resulting tidal torques transfer angular momentum ➔ gap results
- Equilibrium between tidal and viscous torques

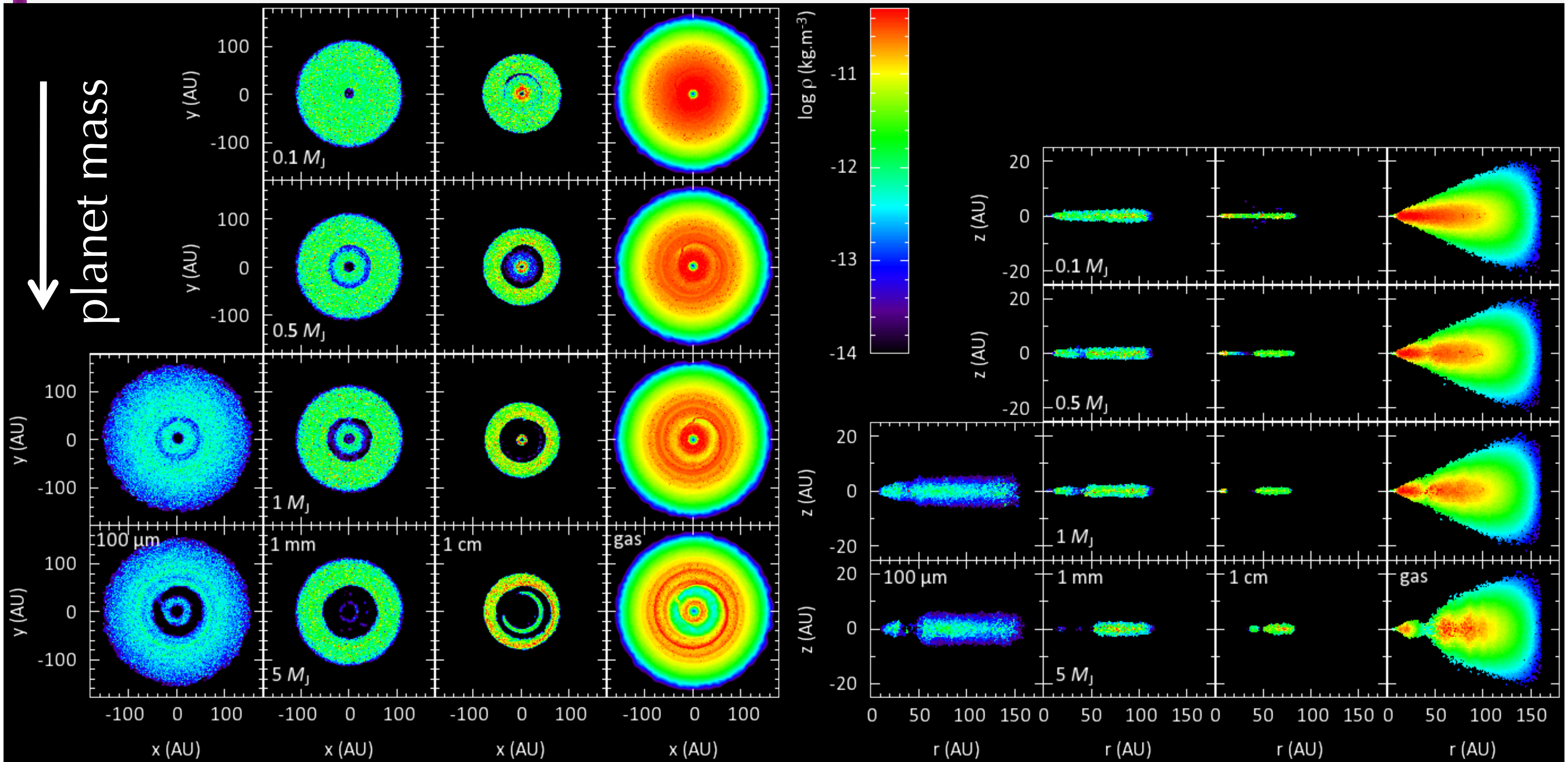


Interior waves: AM deficient;
wave damps, disk loses AM & moves in

Exterior waves: AM excess;
wave damps, disk gains AM & moves out



Planetary gaps in gas + dust disks



grain size

Planet @ 40AU
M_{disk}=0.02 M_{sun}
M_{dust}=0.01 M_{gas}

Fouchet et al. (2010)

Planetary gaps in gas + dust disks

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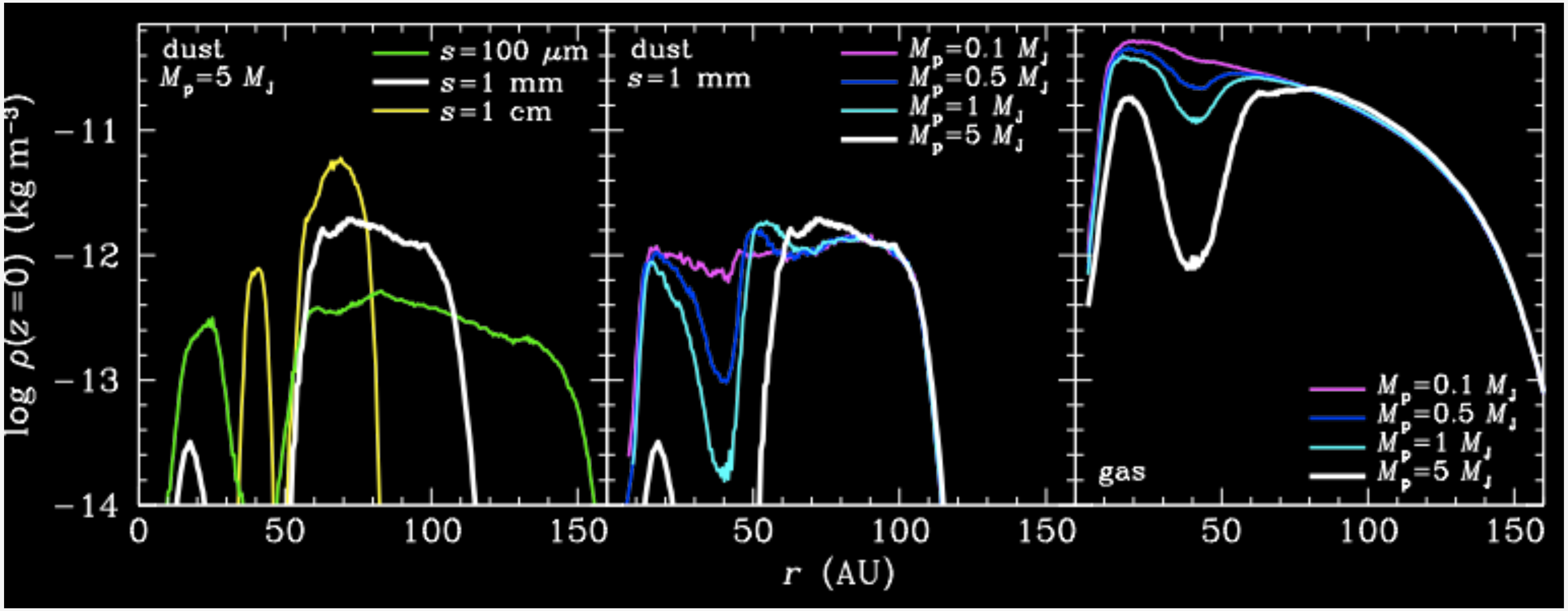


dust: vary s　　dust: vary M_p　　gas: vary M_p

Planet gap wider and deeper in the dust than in the gas

- dust concentrates at outer gap edge
- radial migration dependant on grain size
- dust trapping at corotation

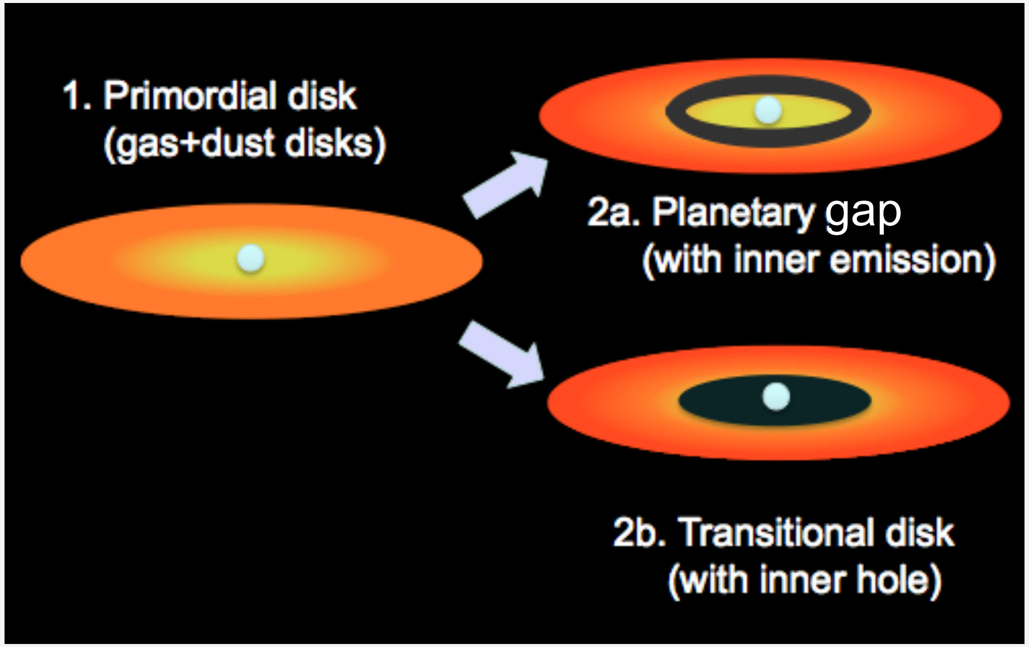
➔ will these gaps be observable with ALMA??

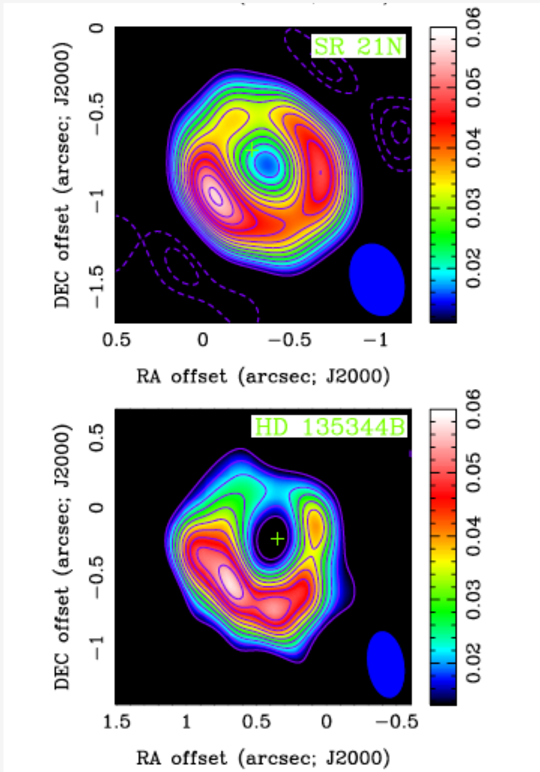
Fouchet et al. (2010)

Aims of this work:

- *To explore conditions under which ALMA will detect planet gaps*

- *To determine if ALMA can distinguish between planet gaps and transition disks with inner holes*





340 GHz dust continuum images (Brown et al. 2009)

Previous work: ALMA at its optimum

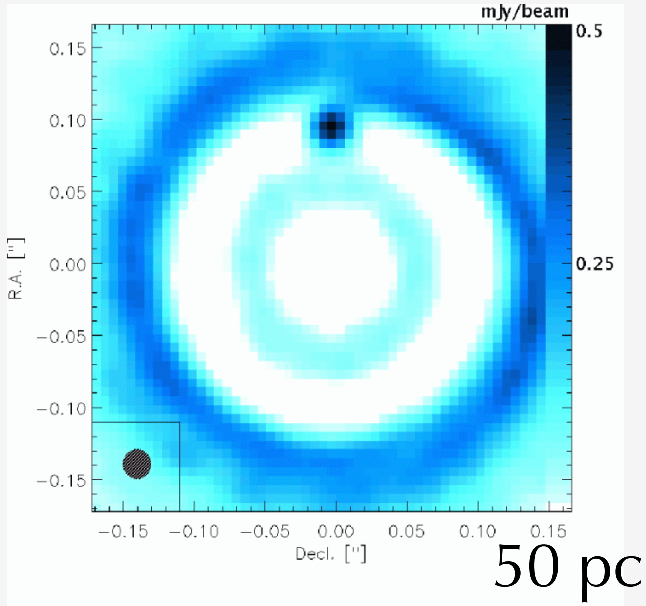
- Assume dust & gas fully mixed

- Source distance: 50 pc &100 pc

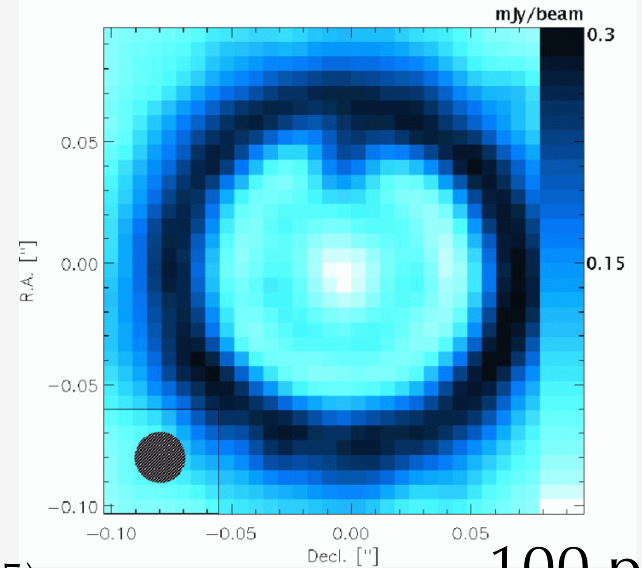
- "Maximum" ALMA:
  900 GHz / 330 µm,
  extended config (0.02″),
  8h integration

- Conservative constant phase noise

⇒ Need for more realistic simulations



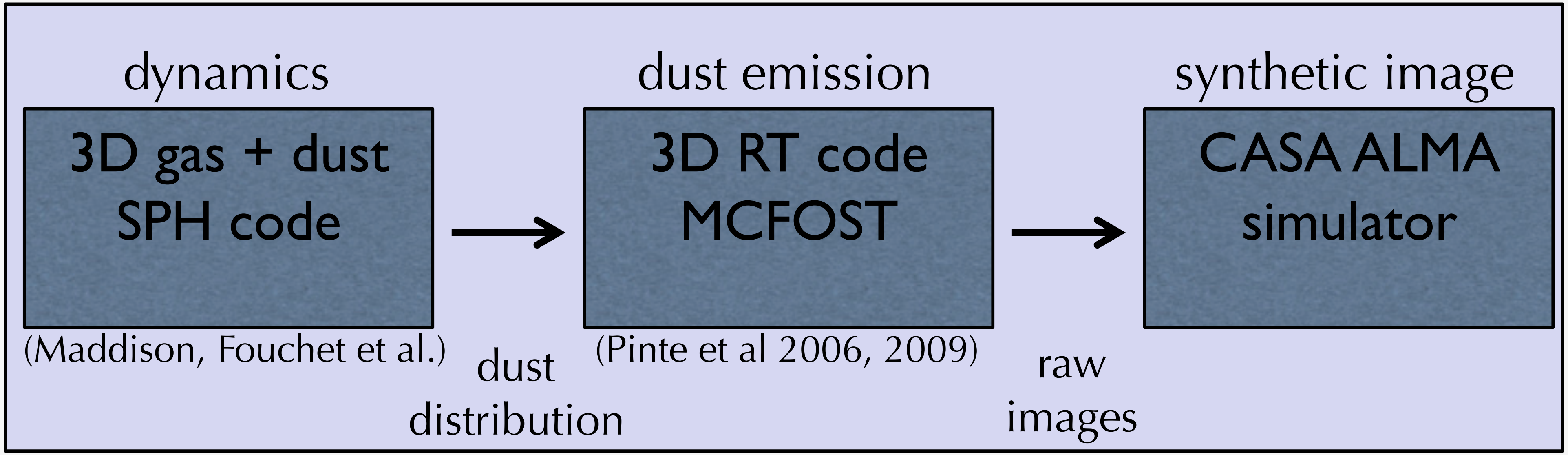
50 pc



100 pc

M_p = 1 M_j @ 5 AU
M_d = 0.01 M_{sun}
M_* = 0.5 M_{sun}
at 330 µm
(Wolf & D'Angelo 2005)

Synthetic ALMA image pipeline:



Details:

- 3D density mapped to MCFOST grid using SPH kernel
- interpolate as a function of grain size: $dn(a) \propto a^{-3.5}\,da$ [0.035μm, 1cm]
- assume grains < 100 μm coupled to gas
- Monte Carlo + ray-tracing produces thermal emission maps
- CASA simulator: synthetic visibilities with thermal noise + phase noise (2D precipitable water vapor screen)
- In CASA vary T_{int}, wavelengths, configurations, star forming regions (d,δ)

Raw synthetic images (from MCFOST)

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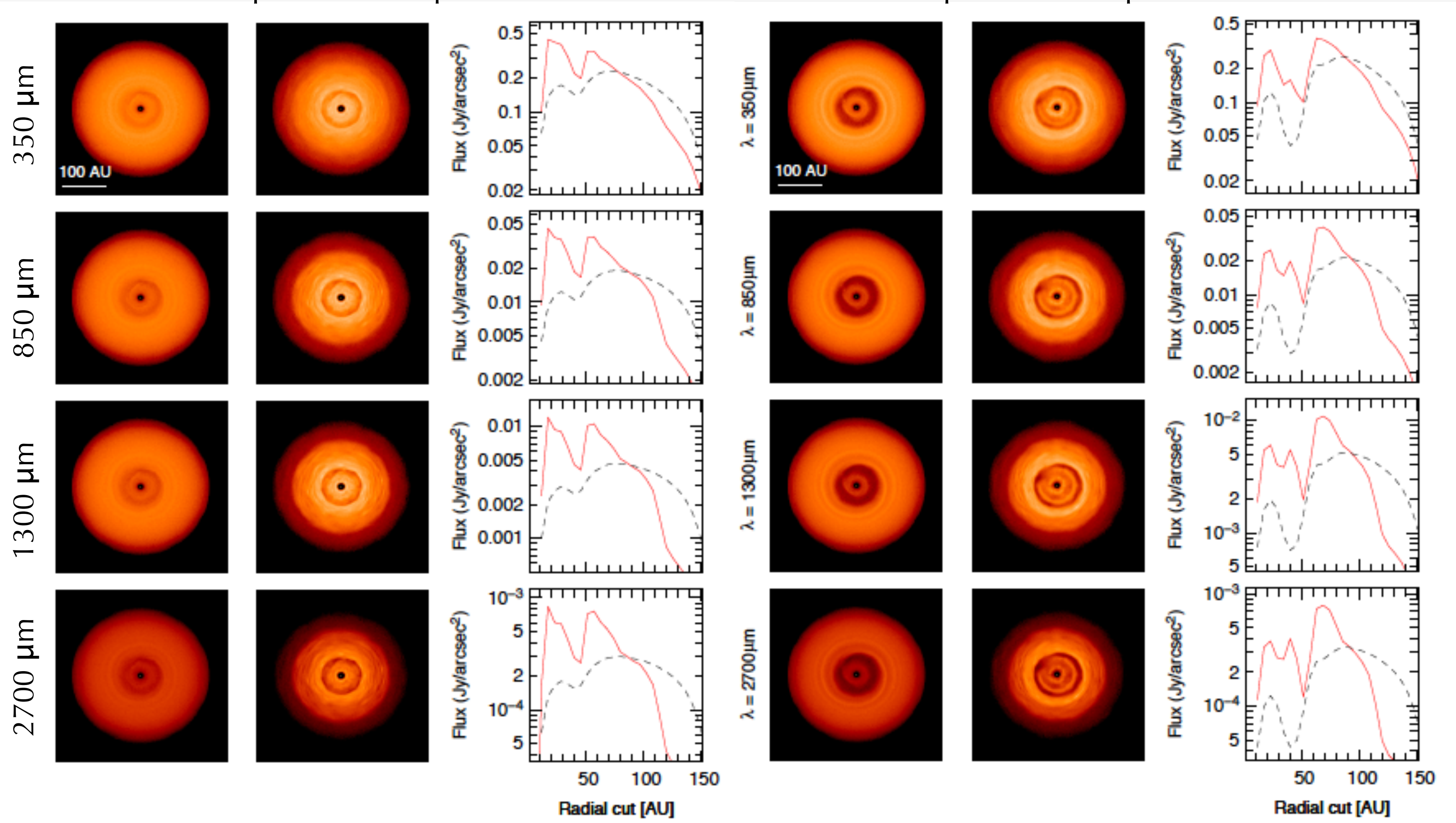
$M_p = 1\ M_{Jup}$ $M_p = 5\ M_{Jup}$

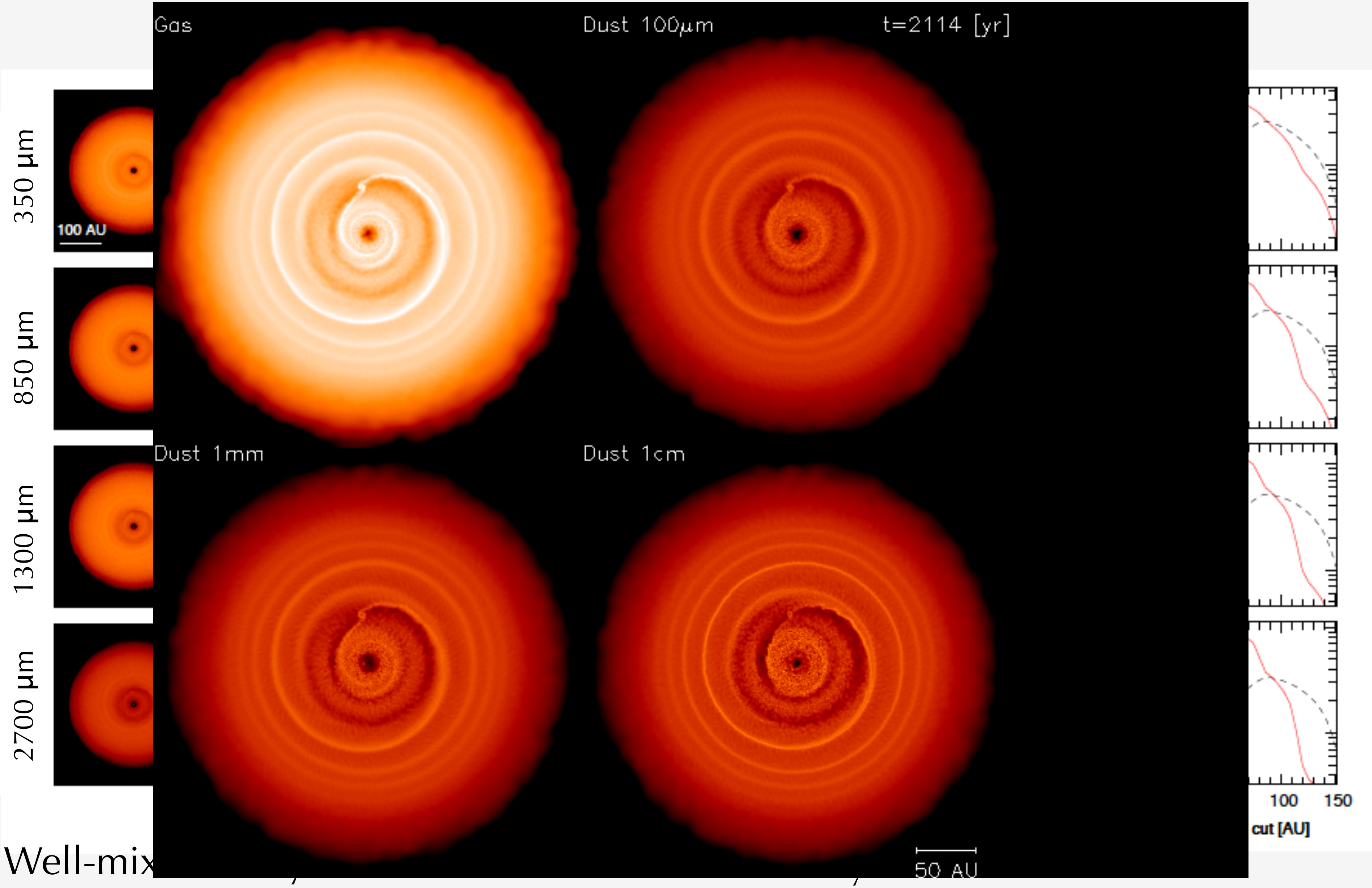


Well-mixed Dynamic Radial cut

—— Dynamic
- - - - - - Well-mixed

Figs 2 & 3

Raw synthetic images (from MCFOST)



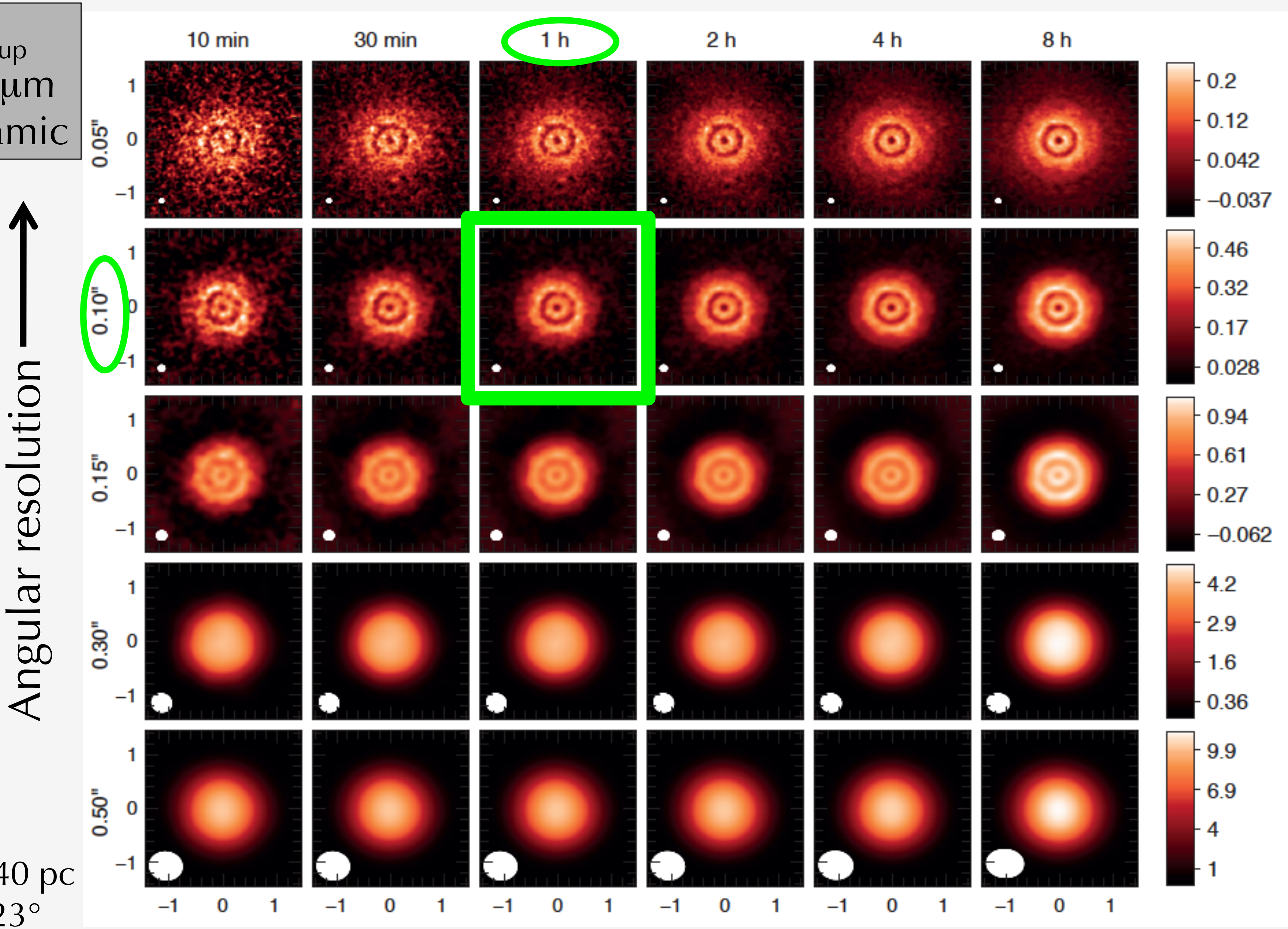
Well-mix

------- Well-mixed

Figs 2 & 3

Synthetic ALMA images (no phase noise)

1 M_{jup}
850 µm
dynamic



d =140 pc
δ = -23°

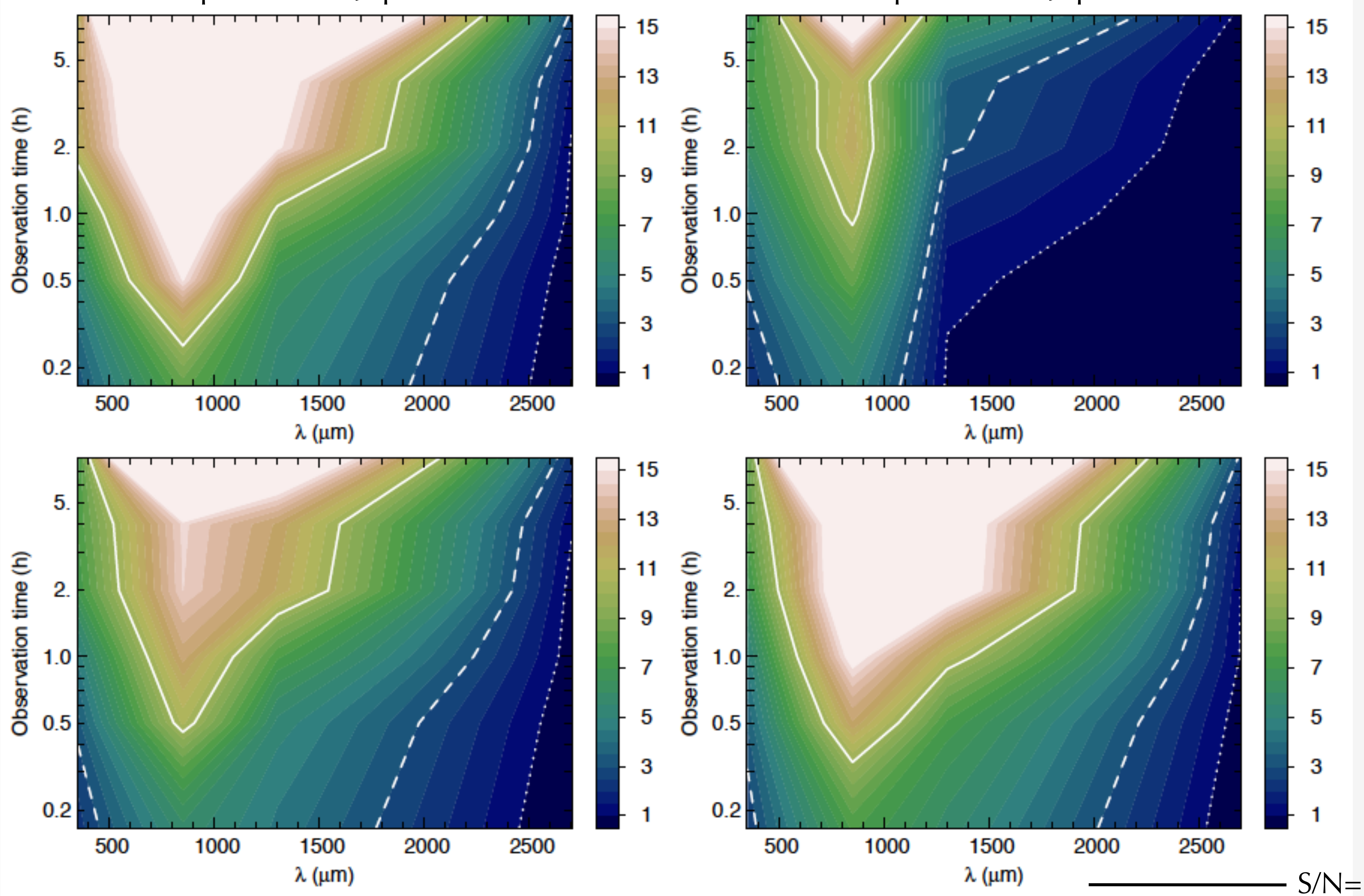
Fig 4

Signal/Noise maps (T_{int} vs λ)

$M_p = 1\ M_{Jup}$ | $M_p = 5\ M_{Jup}$

Inner disk

Outer disk



S/N=10
S/N=3
S/N=1

Inner = 0.07″ – 0.21″ & Outer = 0.35″ – 0.70″

Fig 5

Optimal parameters (T_{int} = 1hr, θ = 0.10″)

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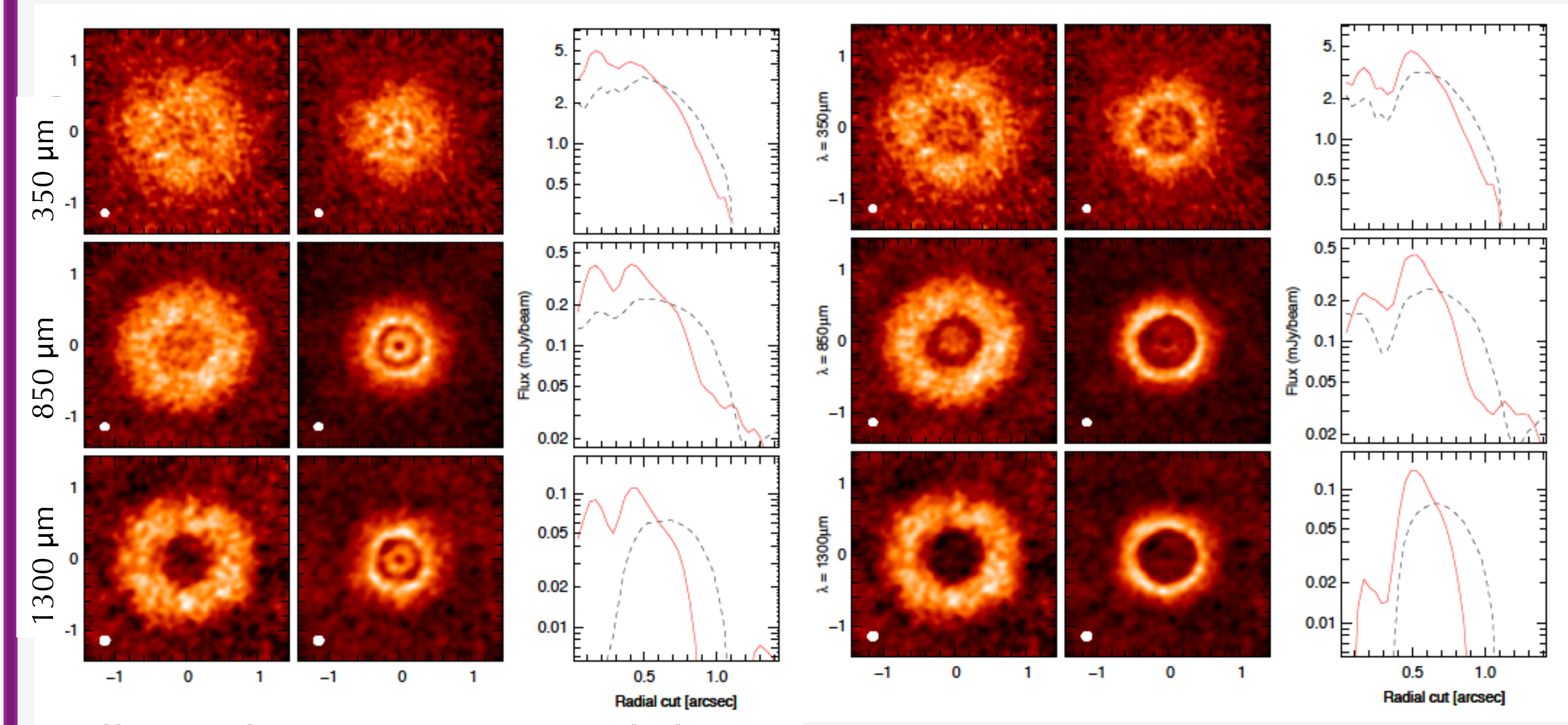
No phase noise

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



Well-mixed Dynamic Radial cut

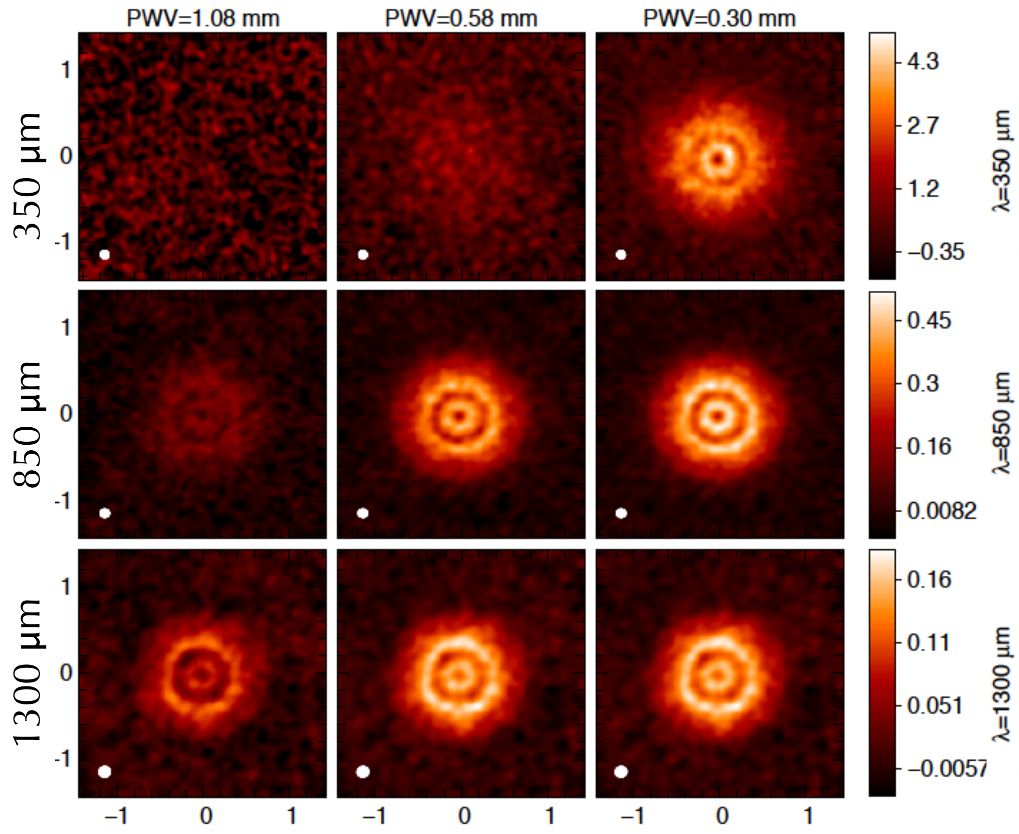
Dynamic
Well-mixed

Figs 6&7

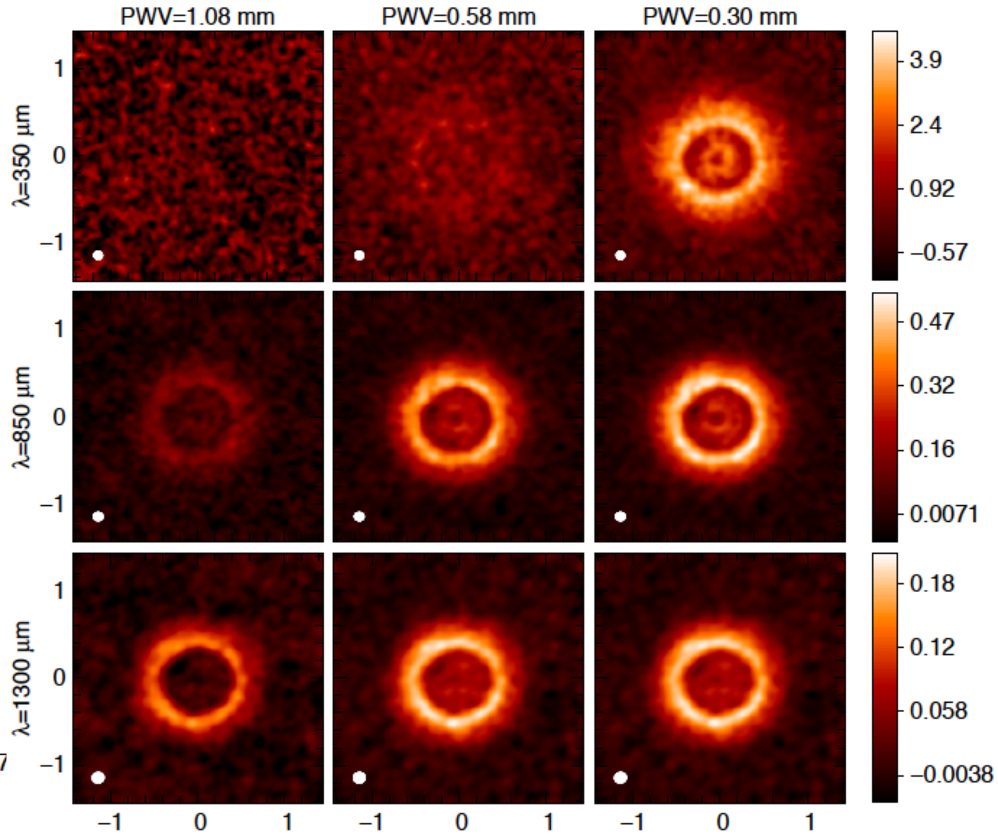
Optimal parameters with phase noise

T_{int} = 1hr, θ = 0.10″
Dynamic

$M_p = 1\ M_{Jup}$



$M_p = 5\ M_{Jup}$



Less water vapour

Percentile:
50% 25% 10%

Need good conditions to see inner disk in 5 M_{Jup} case…

Figs 8&9

Pushing ALMA to the limits

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Highest resolution:

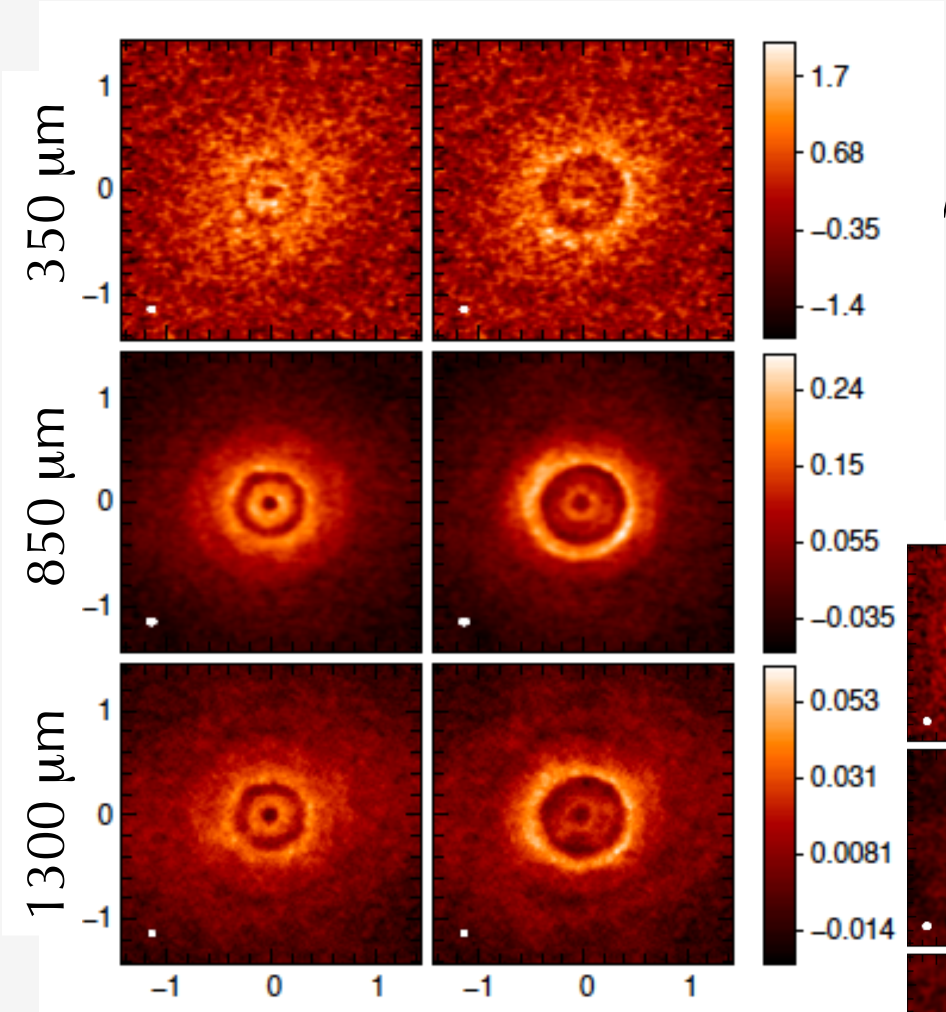
- 850 μm best to recover smallest details

- 350 μm appears more difficult than estimated by Wolf & D'Angelo (2005)

$M_p = 1\ M_{jup}$ $M_p = 5\ M_{jup}$

$T_{int} = 8hr$
$\theta = 0.05''$

Dynamic
No phase noise



$T_{int} = 1hr$
$\theta = 0.10''$

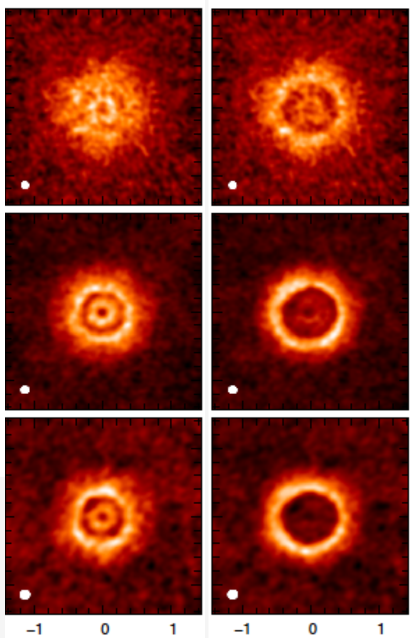


Fig 13

Pushing ALMA to the limits (+ phase noise)

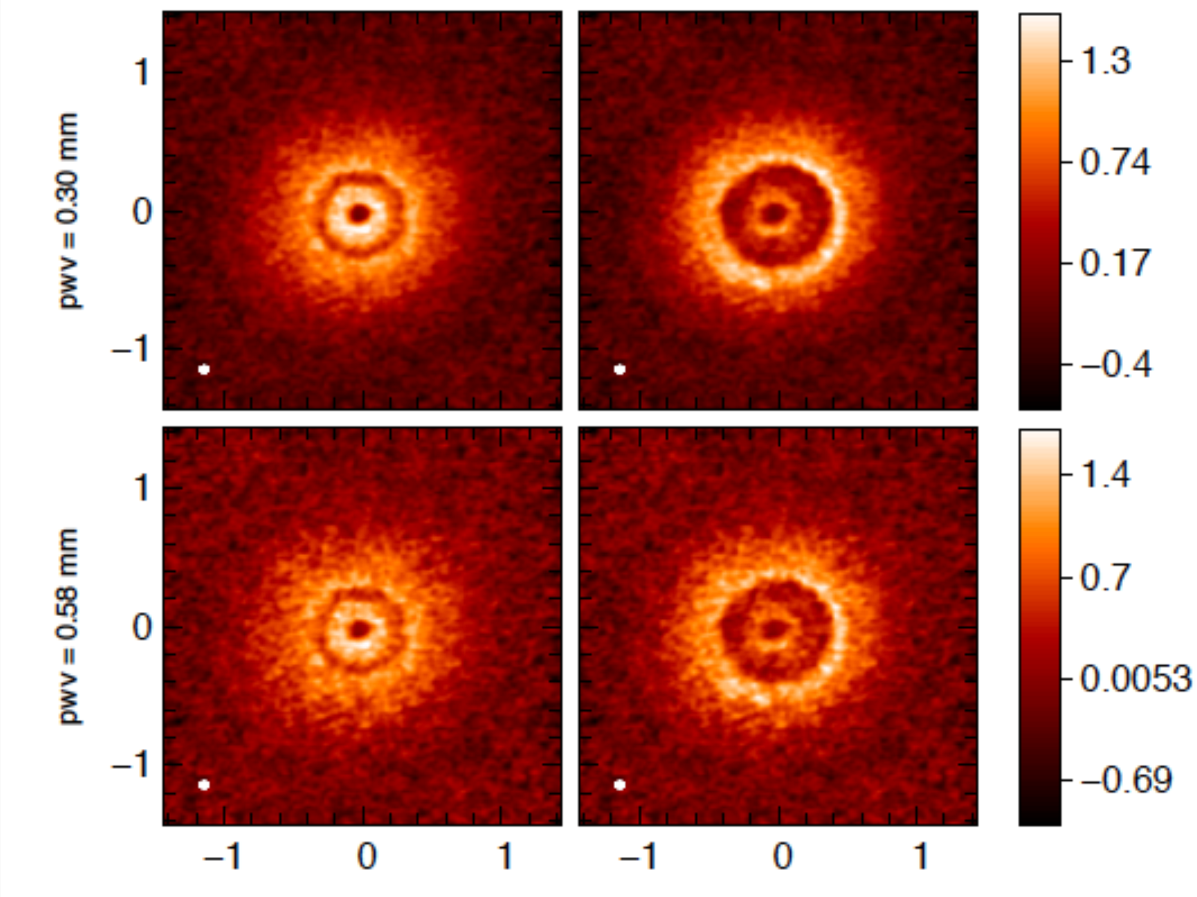
SWIN BUR NE CENTRE FOR ASTROPHYSICS AND SUPERCOMPUTING

T_{int} = 8hr
θ = 0.05″

λ = 350 μm $M_p = 1\ M_{jup}$ $M_p = 5\ M_{jup}$

Dynamic with phase noise

Less water vapour



Need good conditions to confirm gap (cf. cavity)

Fig 14

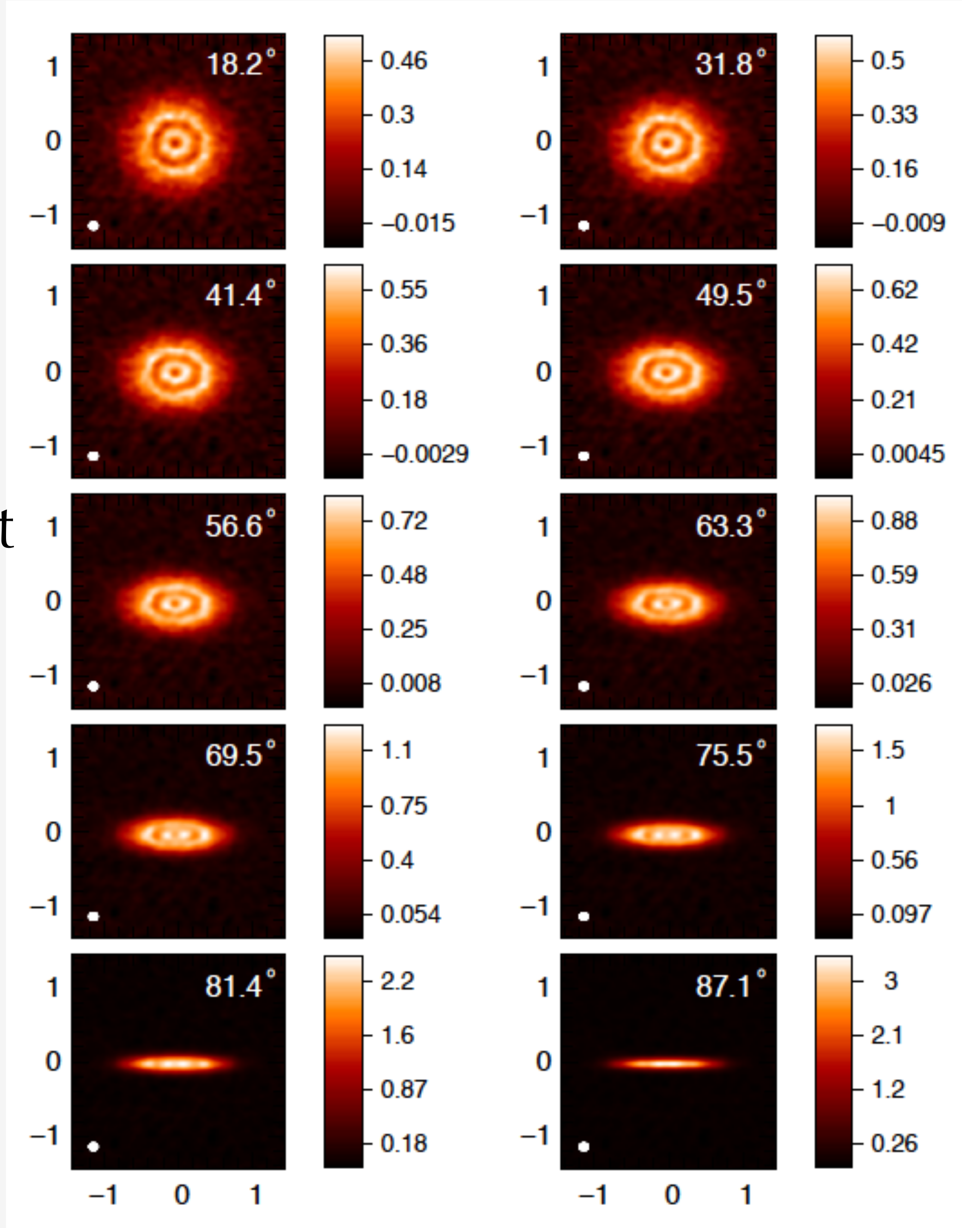
Source inclination

1 M_{jup}
850 µm
dynamic

T_{int} = 1hr, θ = 0.10″
No phase noise

Very little inc effect due to dust settling (causes thermal continuum)

No flared outer region to mask the gap for high inc (at 850µm)



cos(i) = 0.05, 0.15, …,0.95

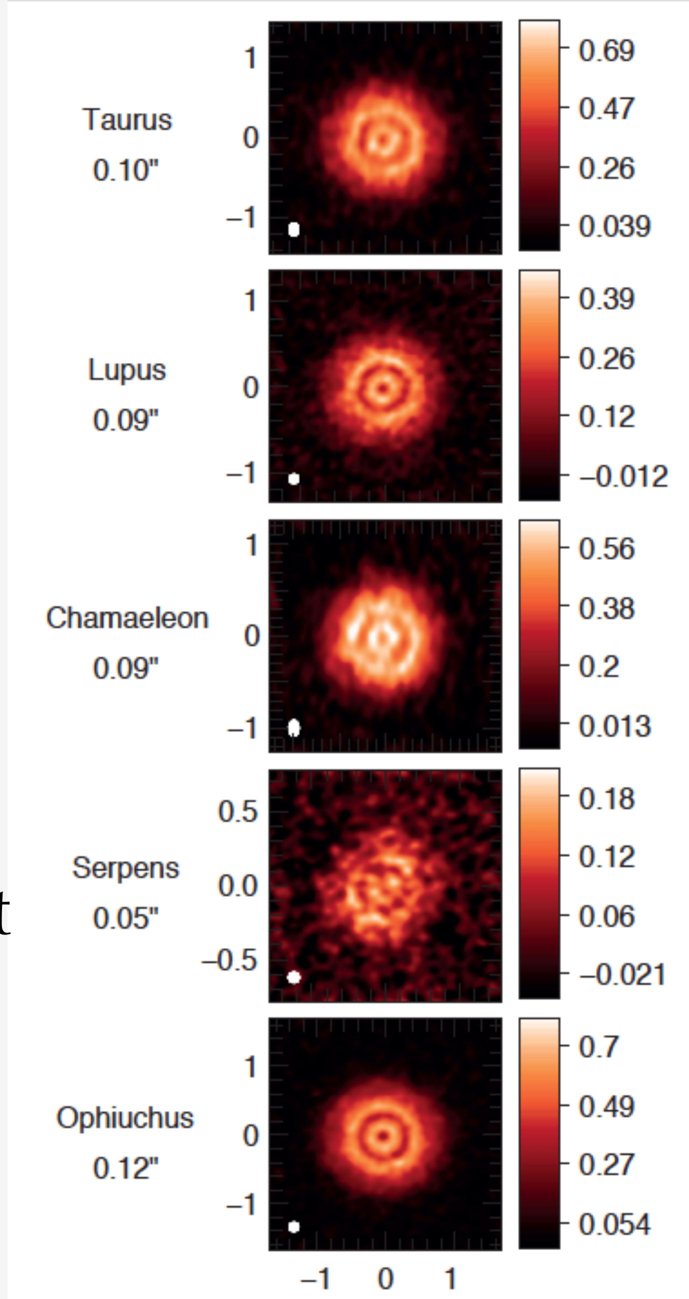
Fig 11

Star forming region (distance & declination)

1 M_{jup}
850 µm
dynamic

little δ effect even for low elevations [Cham 36°] – great *uv* coverage

➔ good prospects for detecting planet gaps in nearby SFR



T_{int} = 1hr
No phase noise

Taurus
d=140 pc, δ=-23°

Lupus
d=150 pc, δ=-34°

Chamaeleon
d=160 pc, δ=-77°

Serpens
d=260 pc, δ=+01°

Ophiuchus
d=120 pc, δ=-24°

Fig 12

Summary

- Gas and dust dynamics very different, not well-mixed & thus 2-phases dust + gas hydro sims required for realistic maps

- Developed a pipeline to study disks as seen by ALMA :
  3D 2-phase SPH → radiative transfer → ALMA simulator

- Sharper features seen in self-consistent dynamic case

- Gap detection in ~1h, optimum wavelength 850 μm & 1.3 mm depending on phase noise (image deterioration → WVR!)

- 1 M_{Jup} gap generally well resolved (good prospects for nearby SFR); faint inner region of 5 M_{jup} requires good conditions & higher freq (carefully when cf. gap and cavity)

- Characterisation of dust content: ideally want multi-λ

More details: see Gonzalez et al. (2012, A&A)