Connecting Hydrodynamic Simulations of Planet Formation with Observations

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https://szulagyi-group.ethz.ch/

European Research Council
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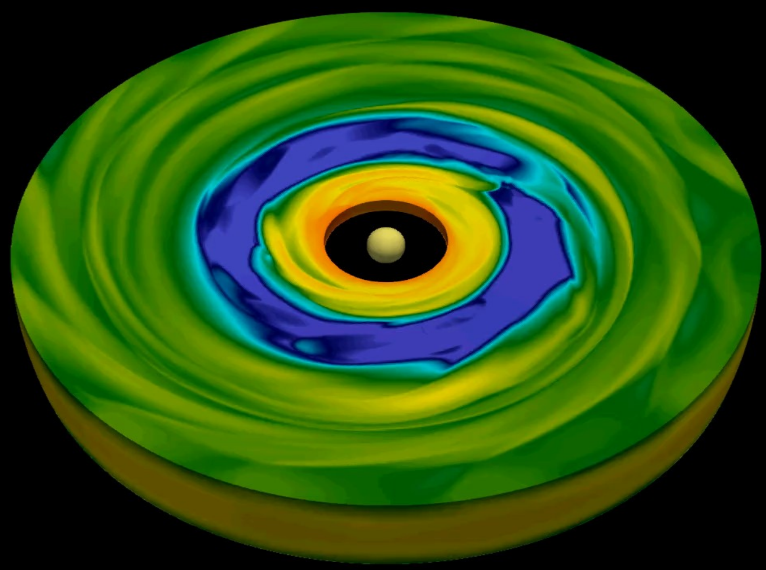
INTRODUCTION

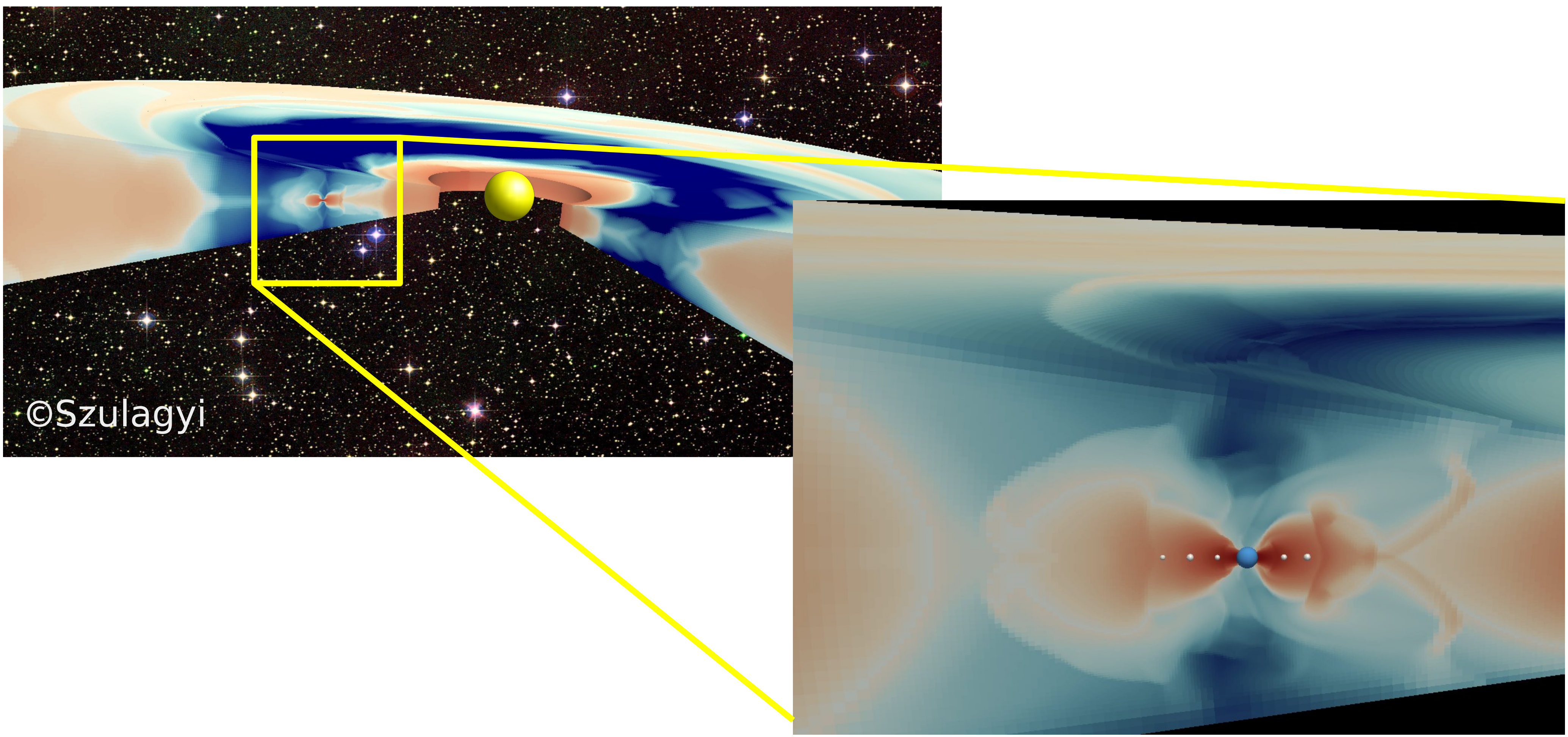
Density model



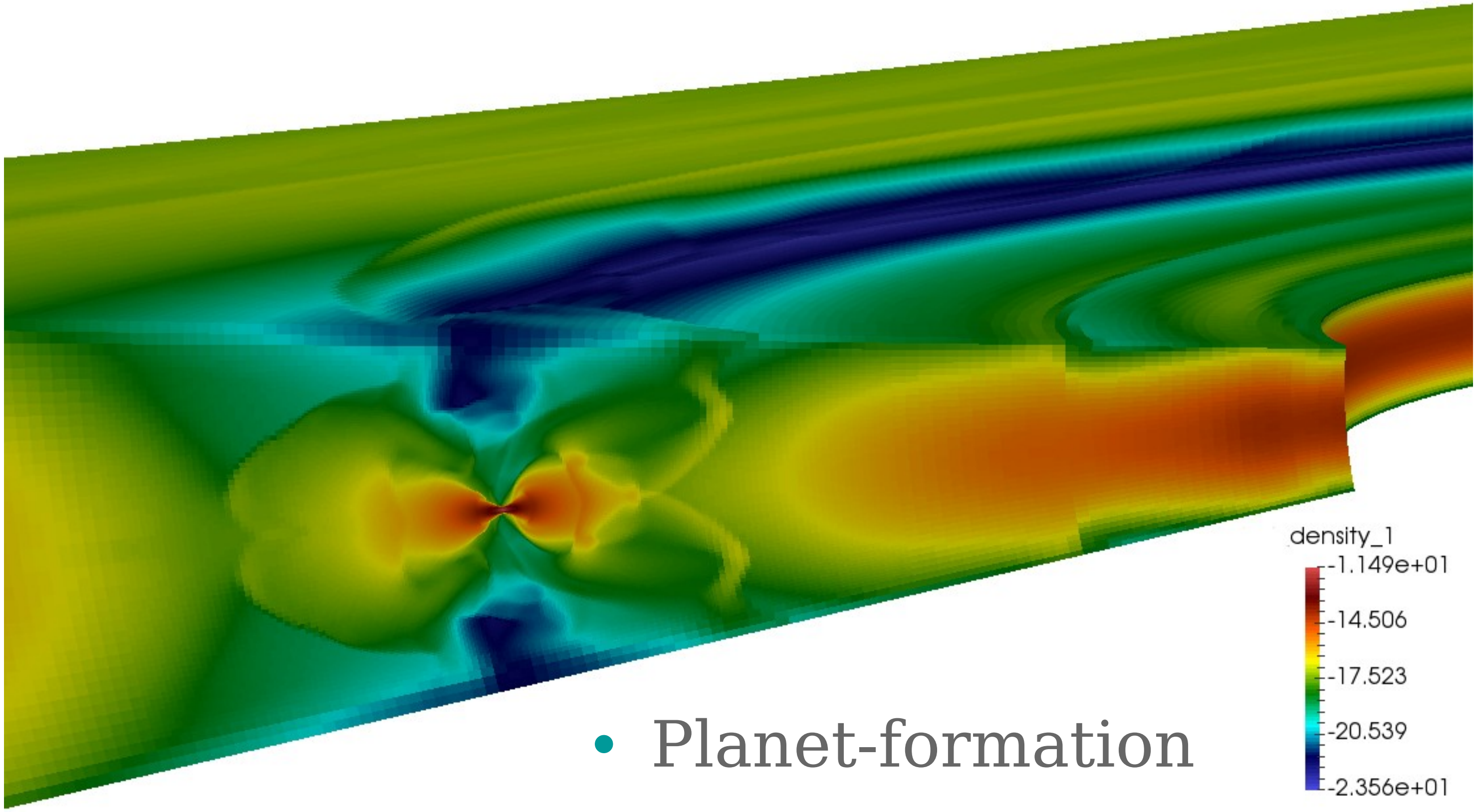
This simulation & video: Judit Szulagy
Code: JUPITER (Szulagyi et al. 2016)

Definition

- Circumplanetary disk: gaseous disk around a planet, formed within the planet formation process (not Brown Dwarf Disks!). Disk within a disk. Fed by the circumstellar disk.
- Circumplanetary debris disk: e.g. end result of planet-planet collision; but it could be evolved gaseous CPD

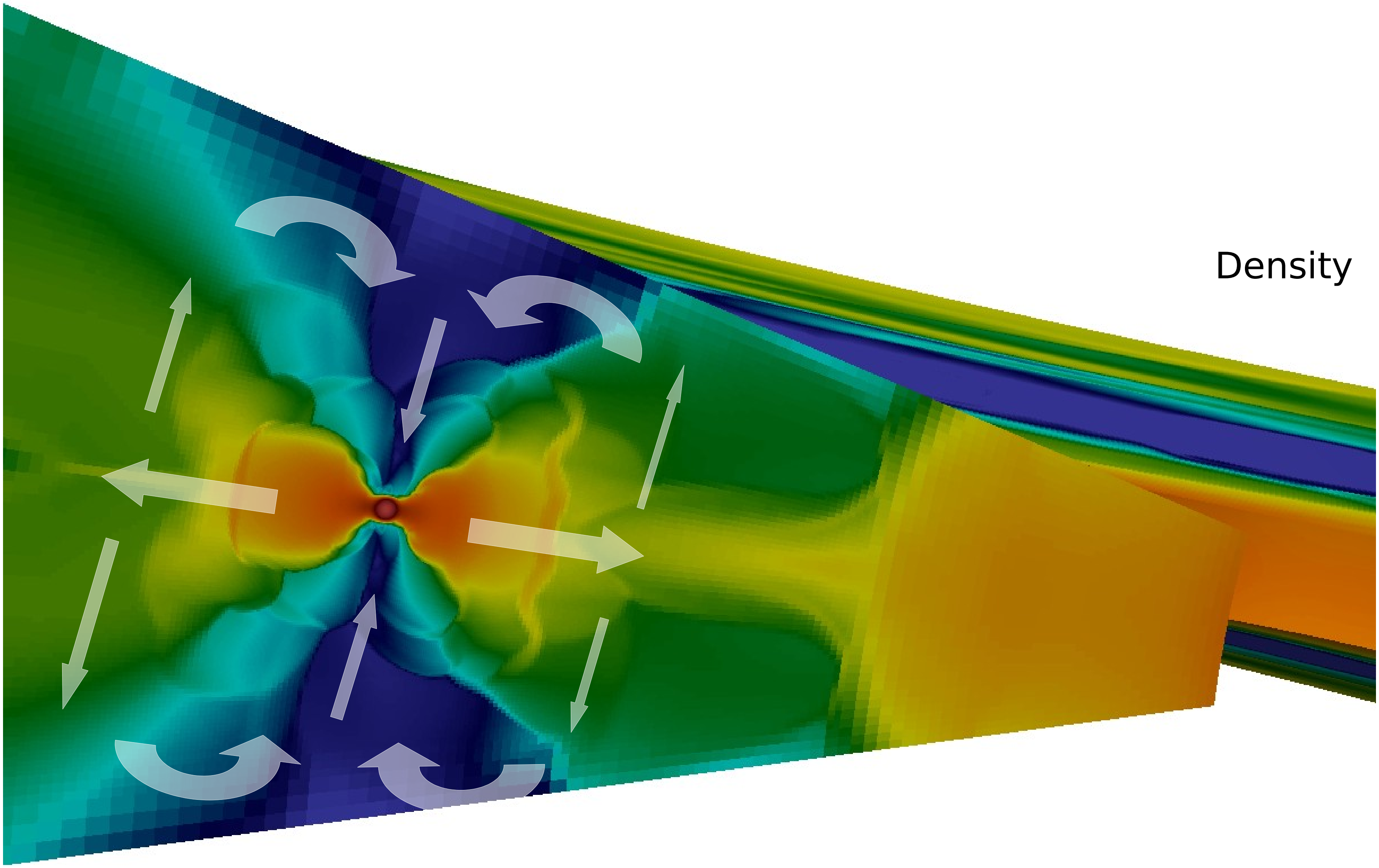


Importance of circumplanetary disks



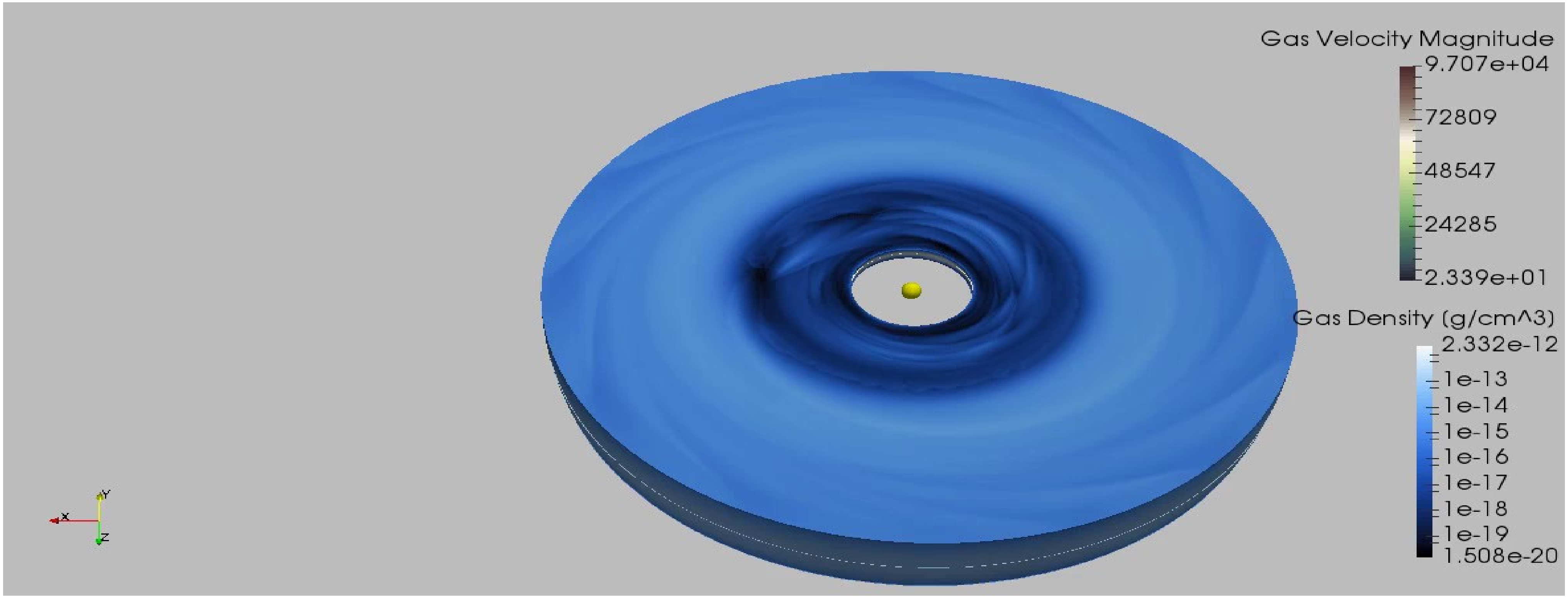
- Planet-formation
- Satellite-formation
- Composition of planets + moons
- Observation of forming planets

Meridional circulation



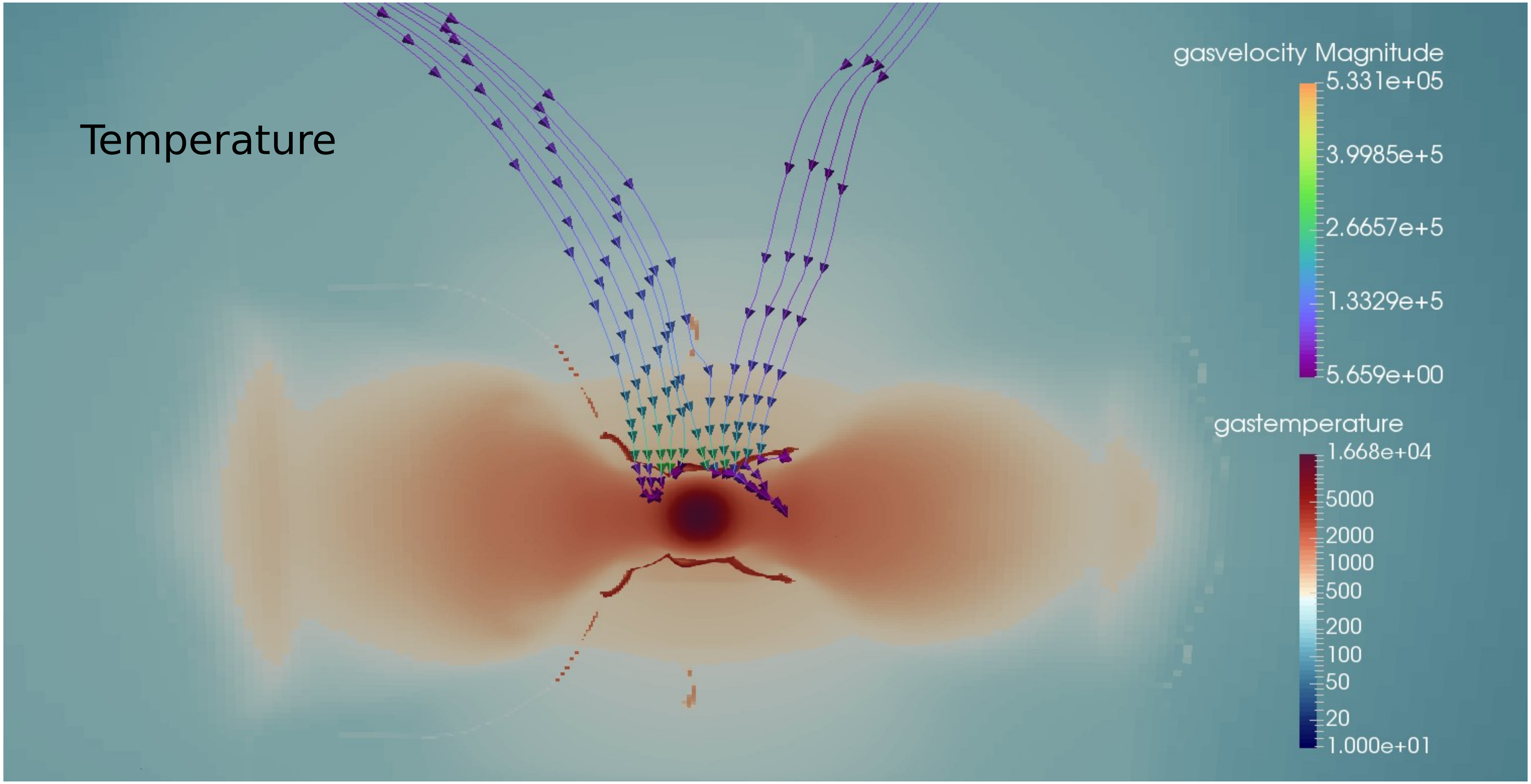
Density

Szulagyi et al. 2014, Fung & Chiang 2016,
Observed by Teague et al. 2019 (Nature)



Judit Szulagyi

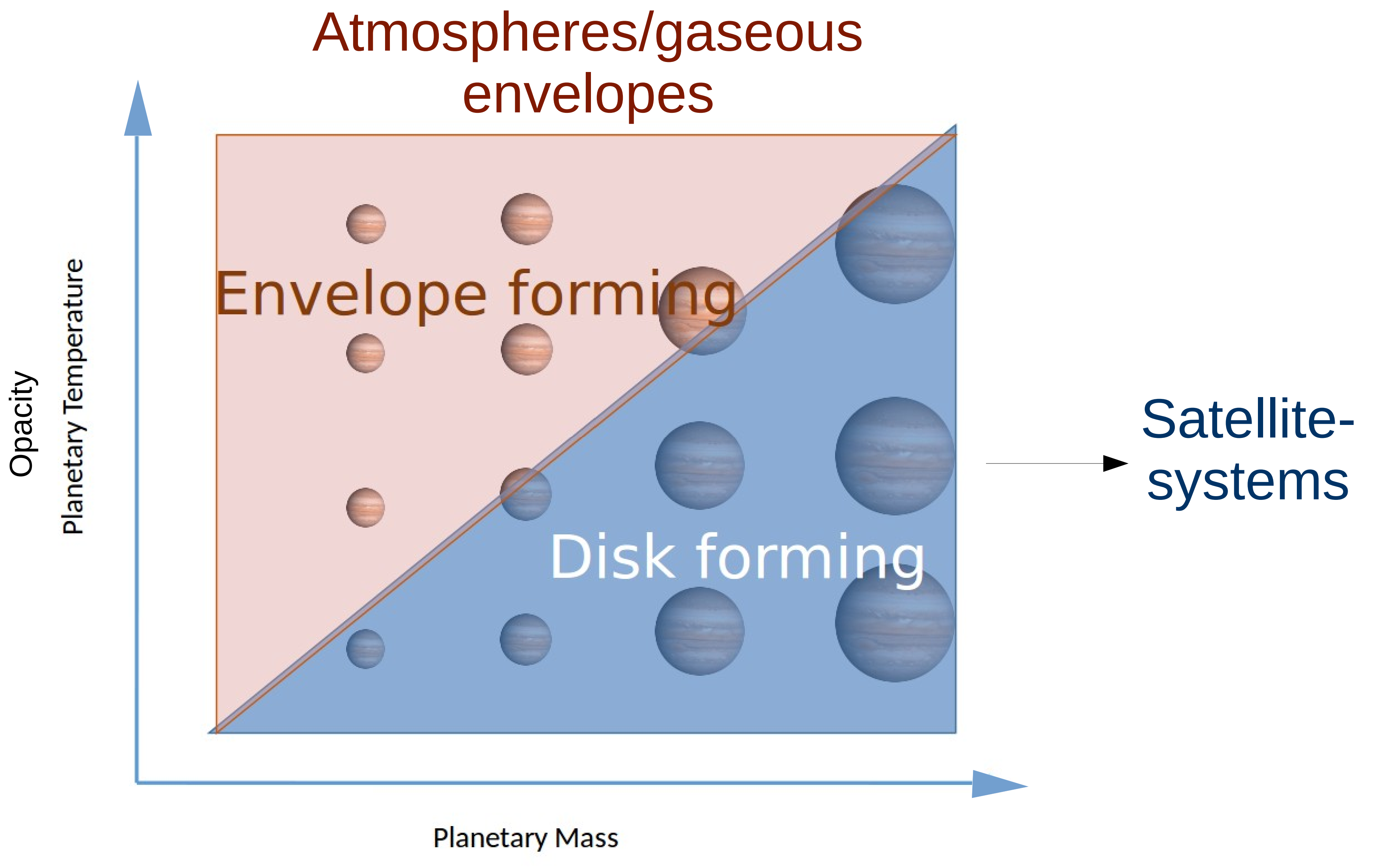
Temperature, Shock-front



- Temperature is high in forming planet vicinity
- Accretion shock is on the CPD, not on the planet!!!

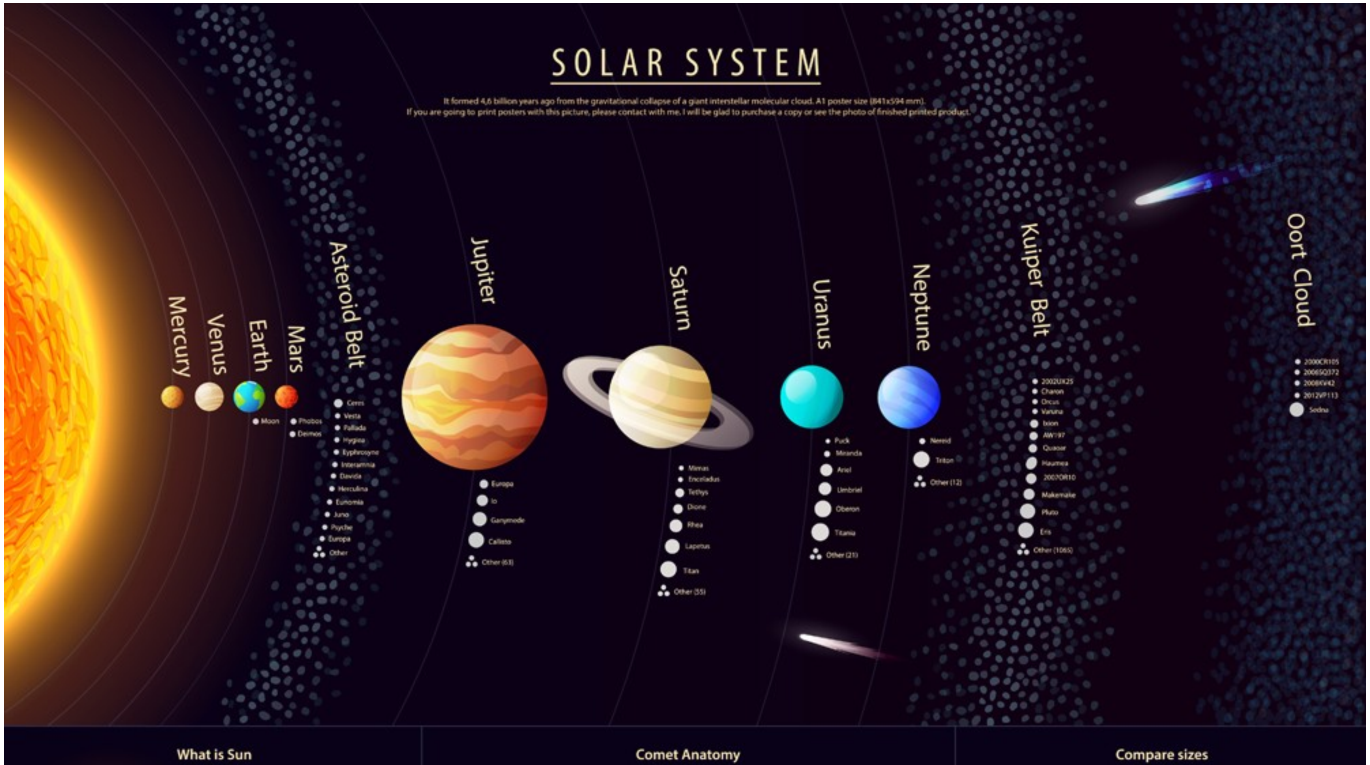
Szulagyi et al. 2016, Szulagyi & Mordasini 2017, Szulagyi & Ercolano 2020

Circumplanetary Envelope / Disk



The ways a planet can have (a) moon(s)

1) Capture a moon (e.g. Phobos & Deimos of Mars, Triton of Neptune)
2) Planet-planet collision: the Moon of Earth
3) Formation in a circumplanetary disk



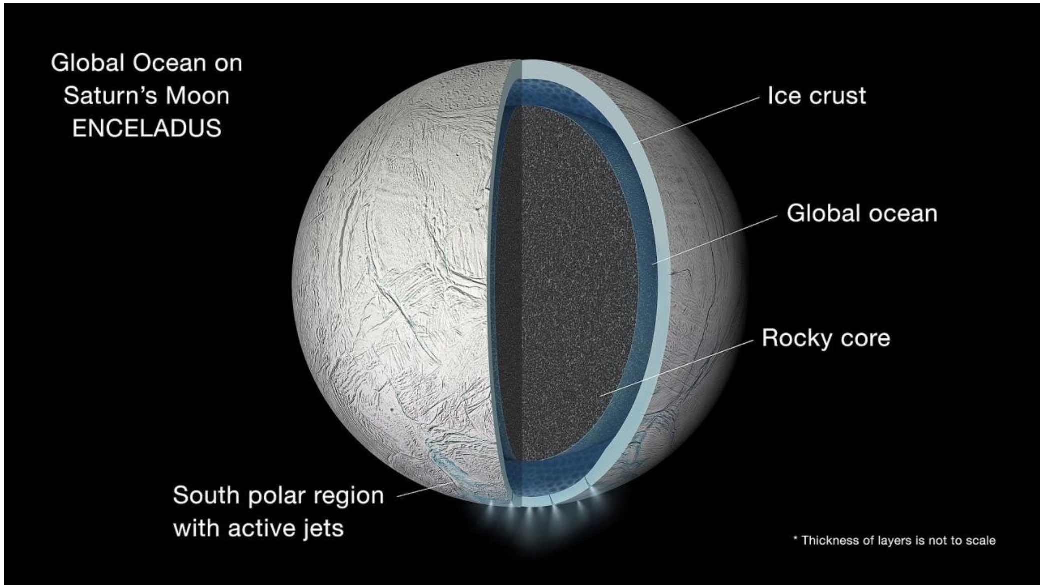
EXOMOONS

Second moon discovery outside the Solar System

- Kepler 1708b-i, a moon 5,500 light-years from Earth
  - Kipping et al. 2022, Nature Astronomy
  - 4 Jupiter-mass planet at 1.6 AU + 2.6 Earth-radii moon

Why should we care about moons?

- Most habitable places in the Solar System after Earth: Europa, Enceladus
  - Often have under-surface water-oceans
  - Almost all of them 50% of water ice – due to their formation process → likely the case for moons around exoplanets as well
- More numerous than planets

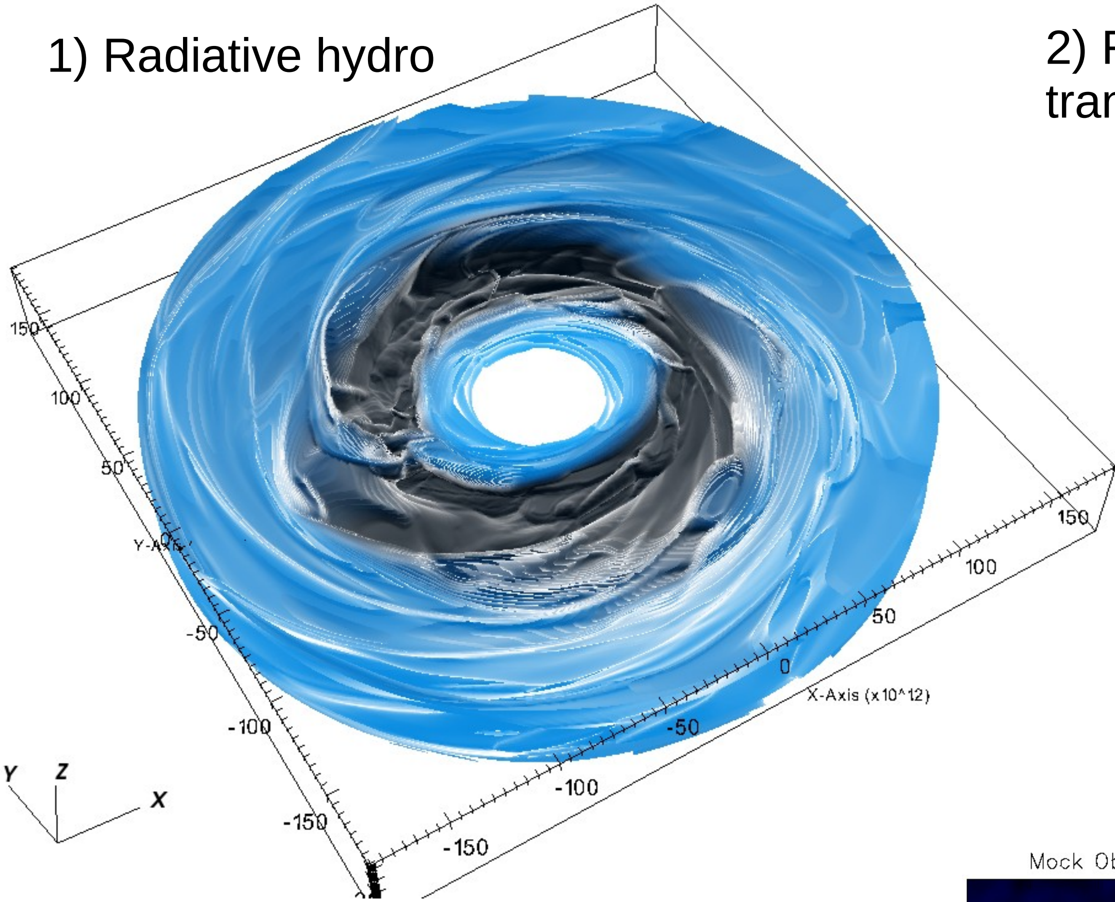


I. DETECTING FORMING PLANETS WITH ALMA

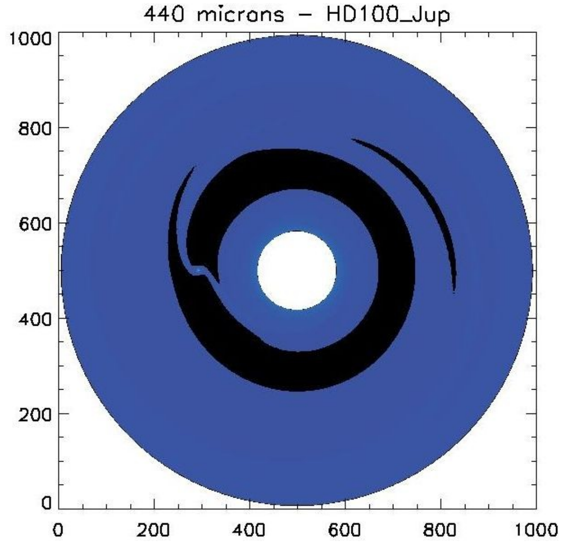
Sub-mm / Radio

Szulagyi et al. 2018a

1) Radiative hydro



2) RADMC3D (wavelength dependent radiative transfer to make intensity images)



3) Beam convolution/interferometry (with CASA)

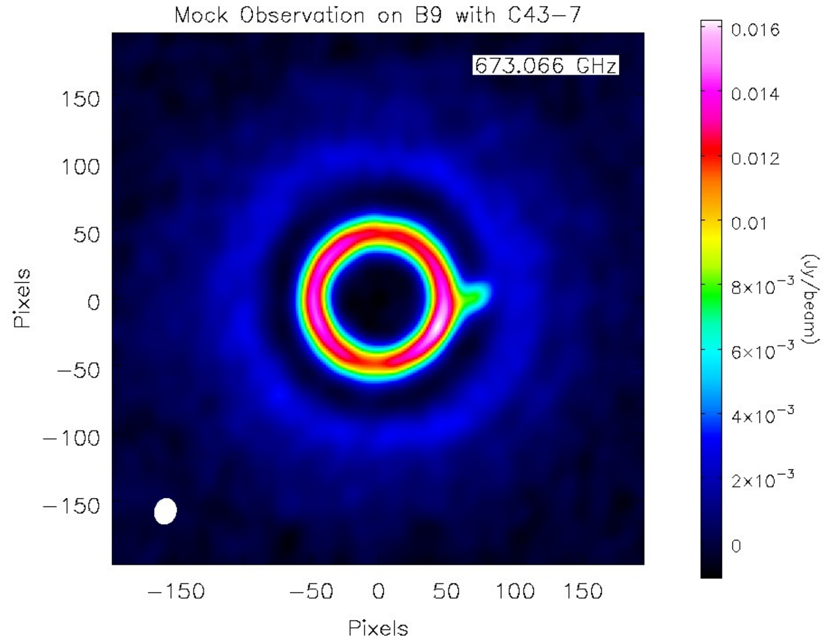
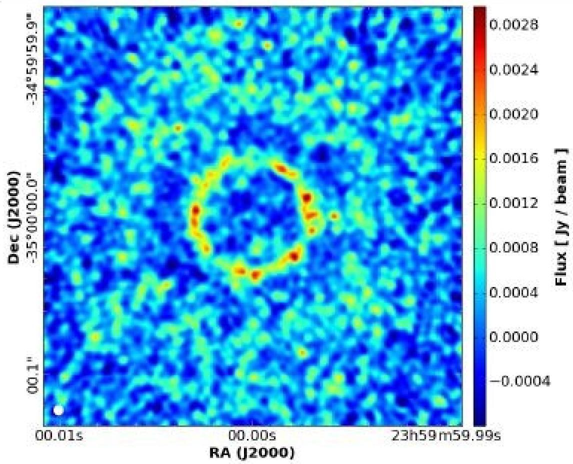
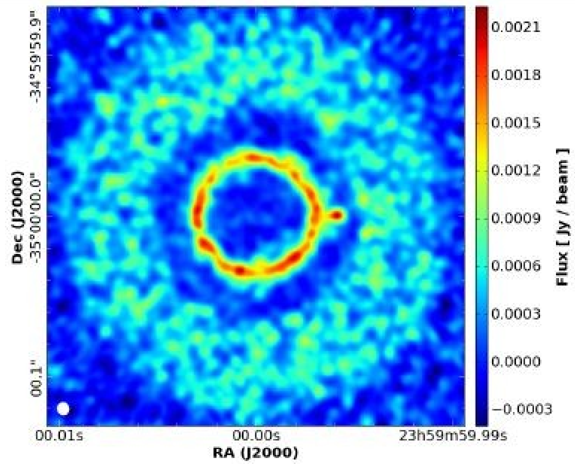


Table 1. Mock Observations on the different ALMA Bands of the 3 Jupiter-mass hydro-simulation

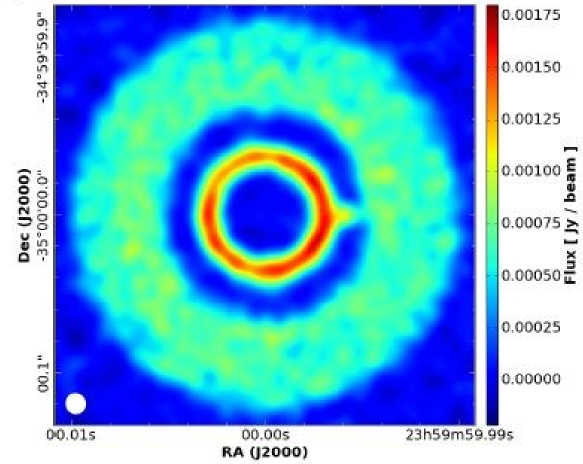
Band 10
(350 microns, 856.5 GHz)
RMS=$4.5e-4$ Jy



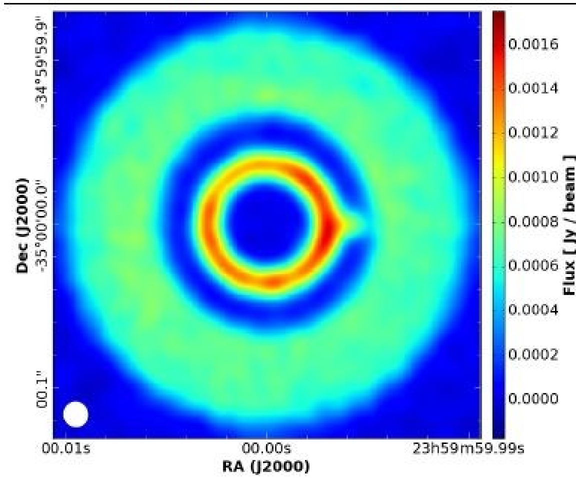
Band 9
(440 microns, 681 GHz)
RMS=$1.8e-4$ Jy



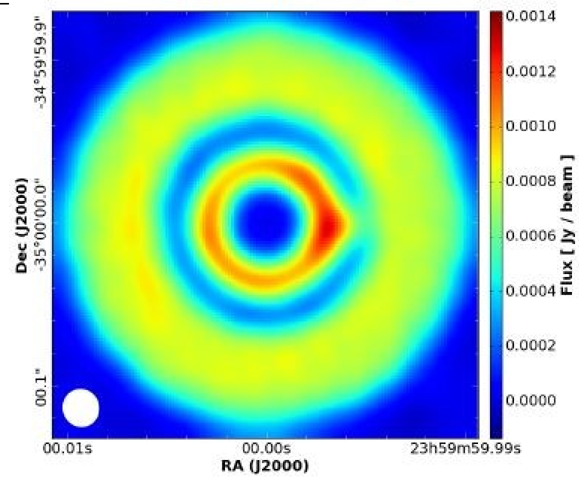
Band 8
(740 microns, 405 GHz)
RMS= $5.3e-05$ Jy



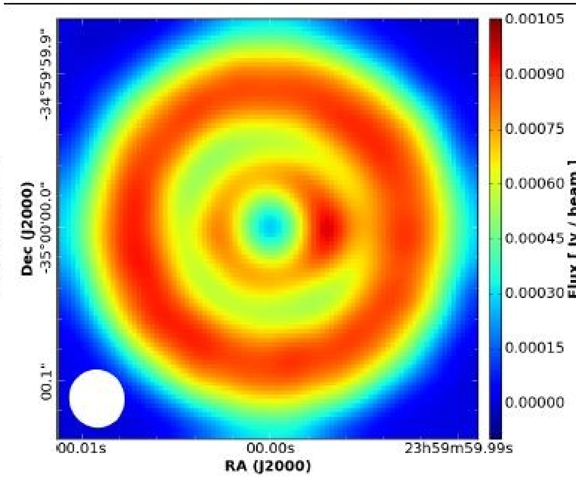
Band 7
(870 microns, 344.5 GHz)
RMS= $2.0e-05$ Jy



Band 6
(1300 microns, 230 GHz)
RMS= $1.3e-05$ Jy

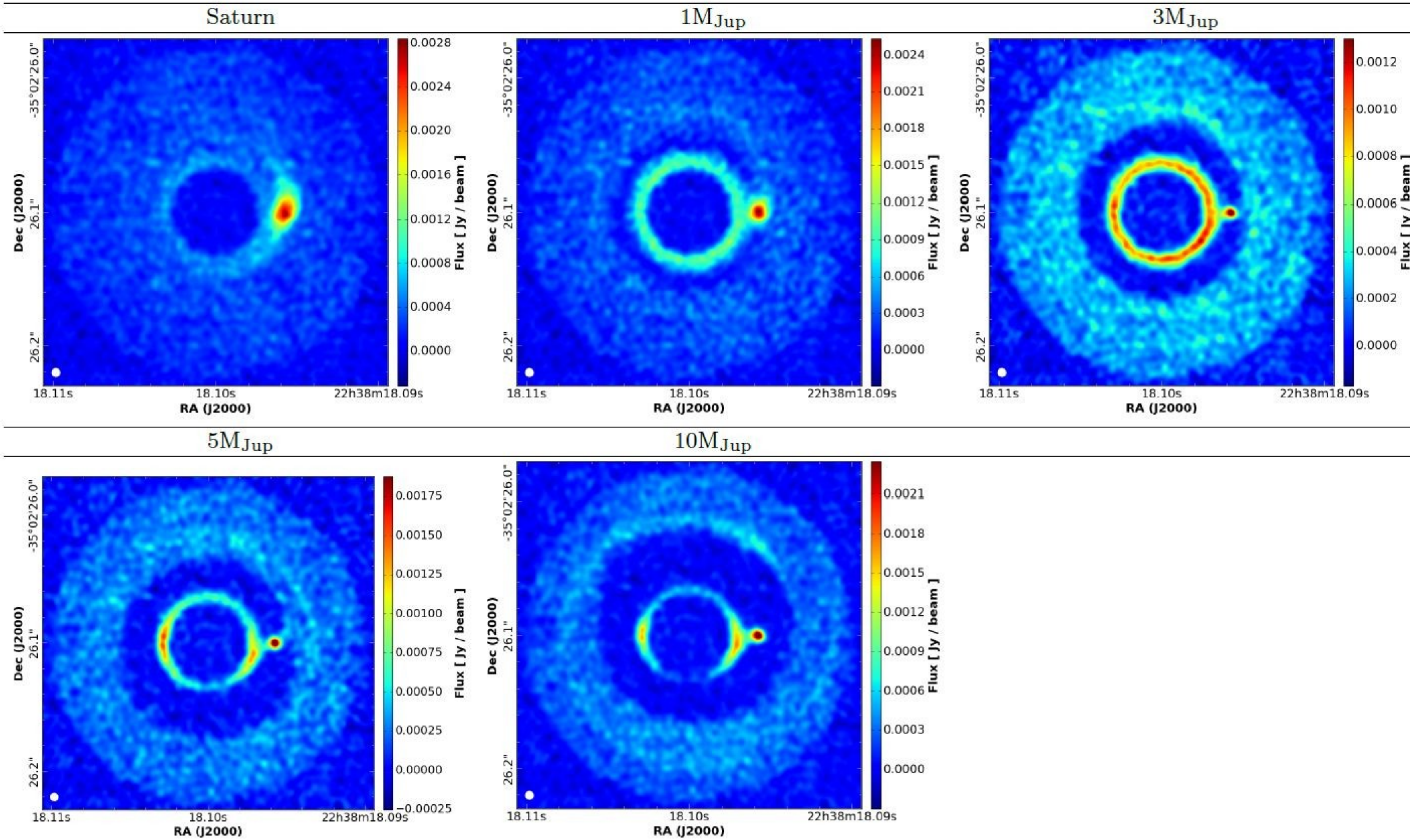


Band 4
(2100 microns, 142.8 GHz)
RMS= $1.1e-05$ Jy



Szulagyi et al. 2018a

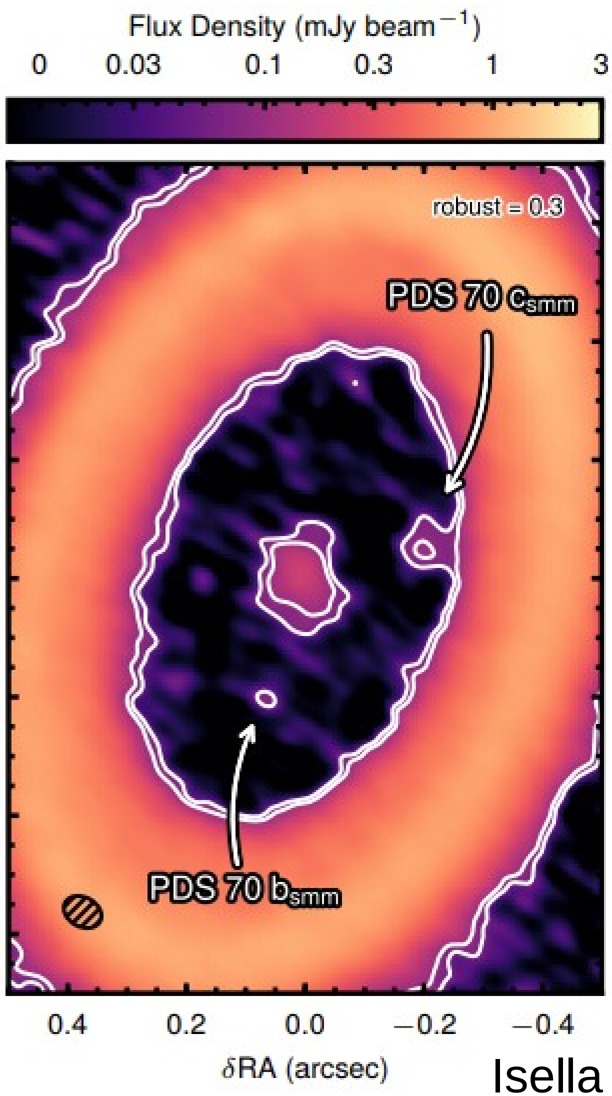
Table 4. Mock continuum observations for various planet masses in ALMA Band 9 (440 microns) simulations

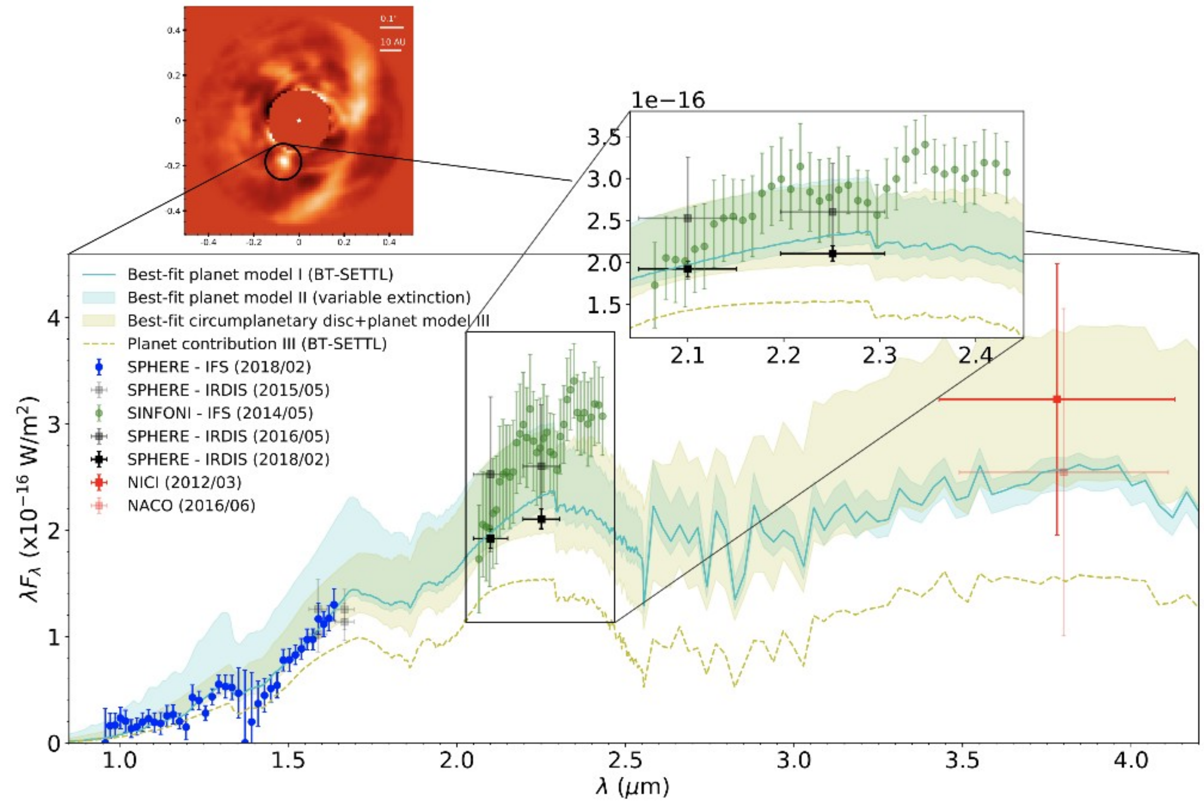


Szulagyi et al. 2018a

First possible detections

June, 2019





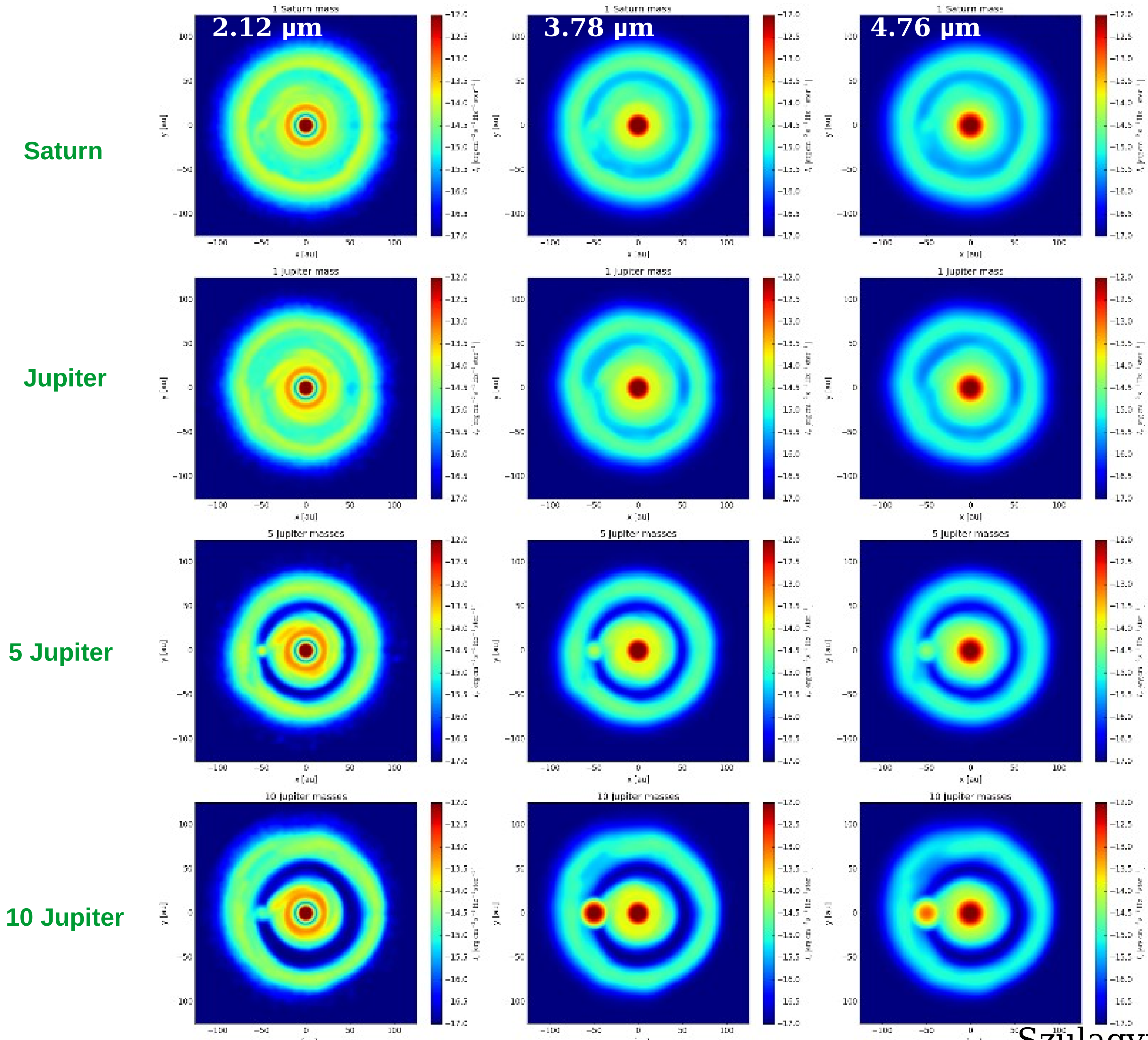
Predictions: Szulagyi et al. 2019a → Christiaens et al. 2019

Isella et al. 2019 ← Predictions: Szulagyi et al. 2018a

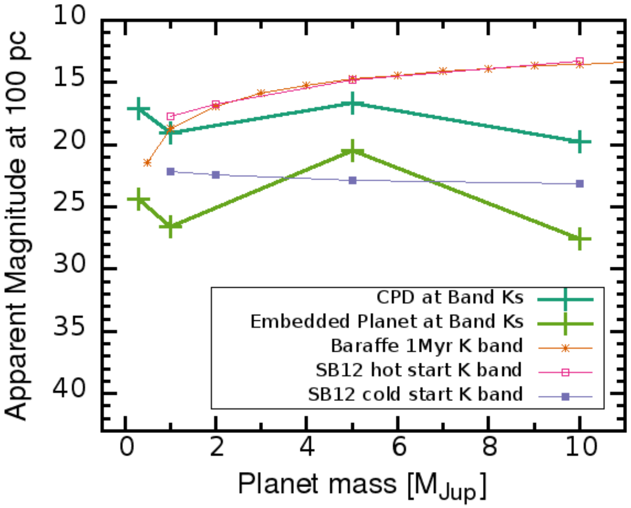
II. NEAR-IR/MID-IR

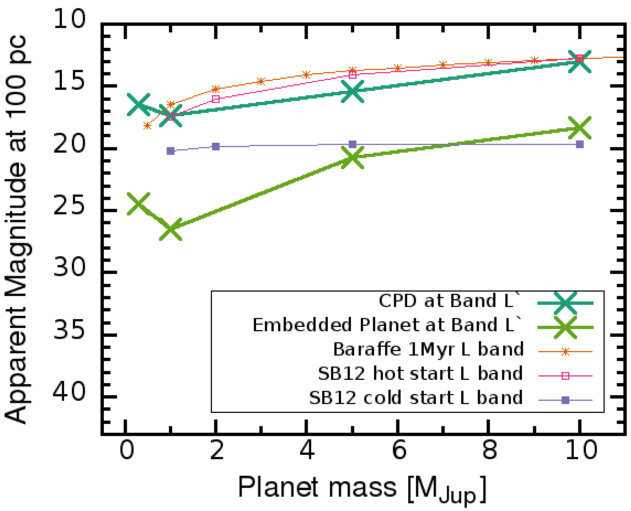
NaCo / ERIS (VLT)

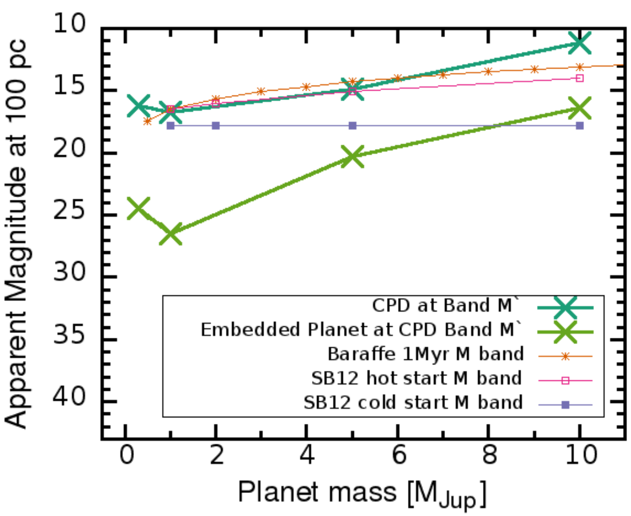
Szulagyi et al. 2019



Szulagyi et al. 2019



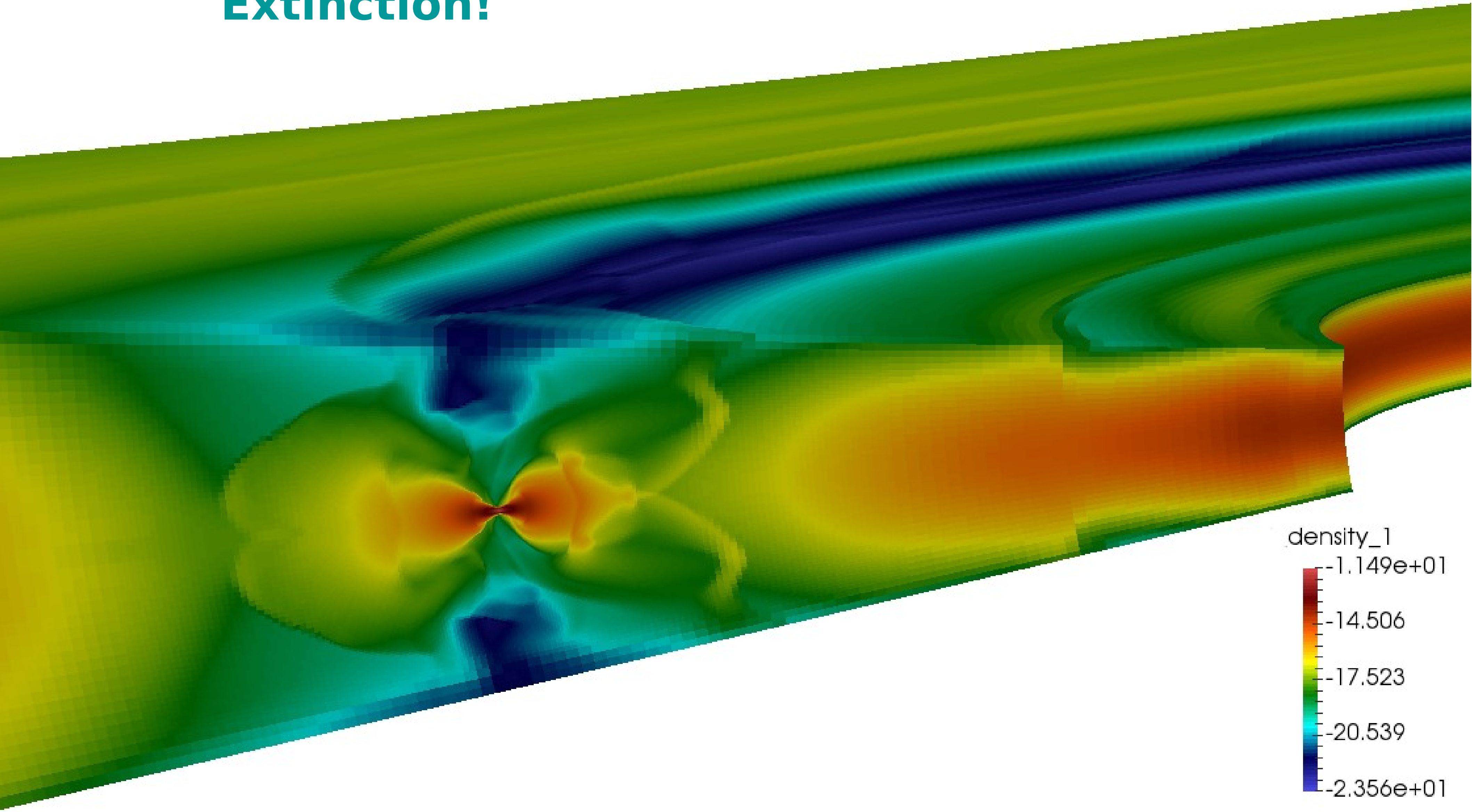




- Comparing with planet evolution models (hot-start, cold-start)
- The brightness of the planet is much lower than even the cold-start models <= extinction
- Brightness does not scale with the planet mass…
- CPD+planet is always significantly brighter than the planet
- Take home message: the observed brightness cannot be used to estimate the planet mass (in the formation phase)

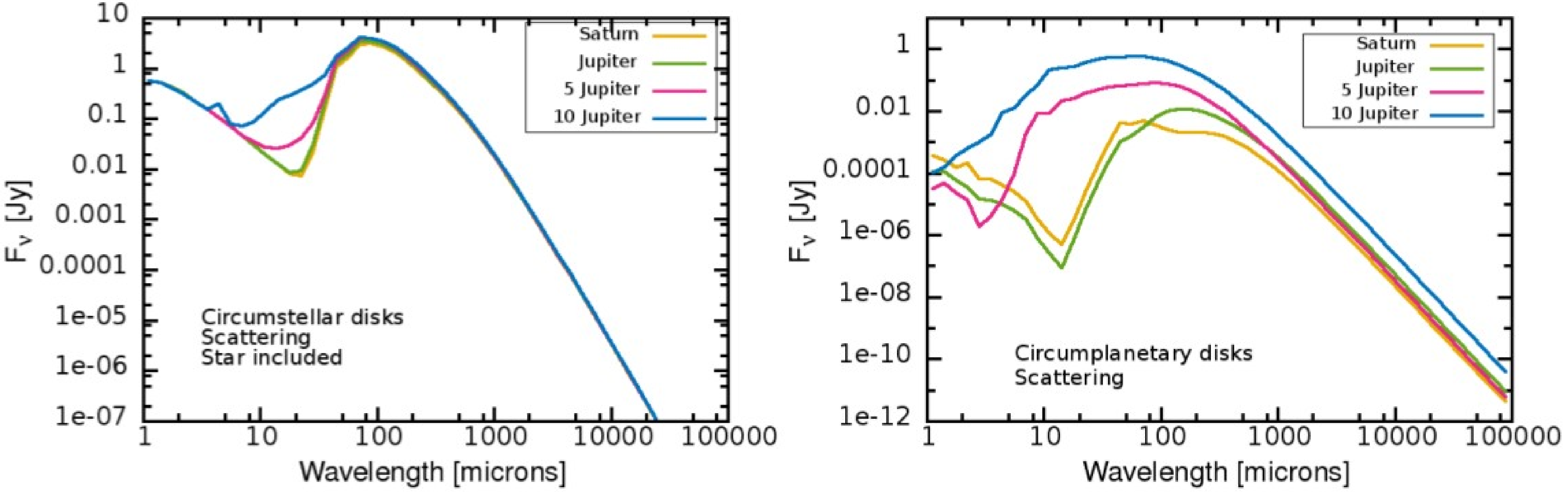
Szulagyi et al. 2019

Extinction!



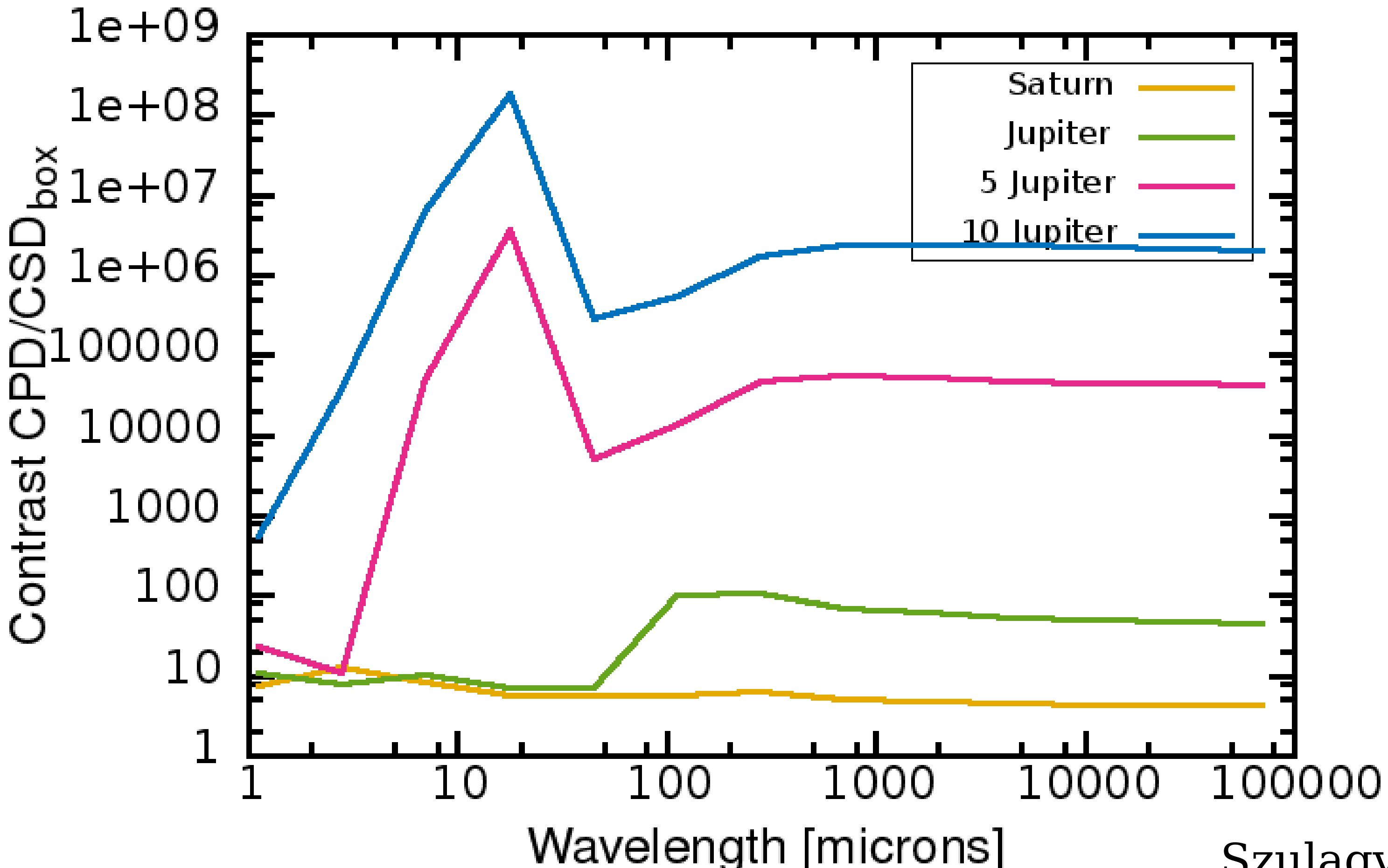
Szulagyi et al. 2019

SEDs

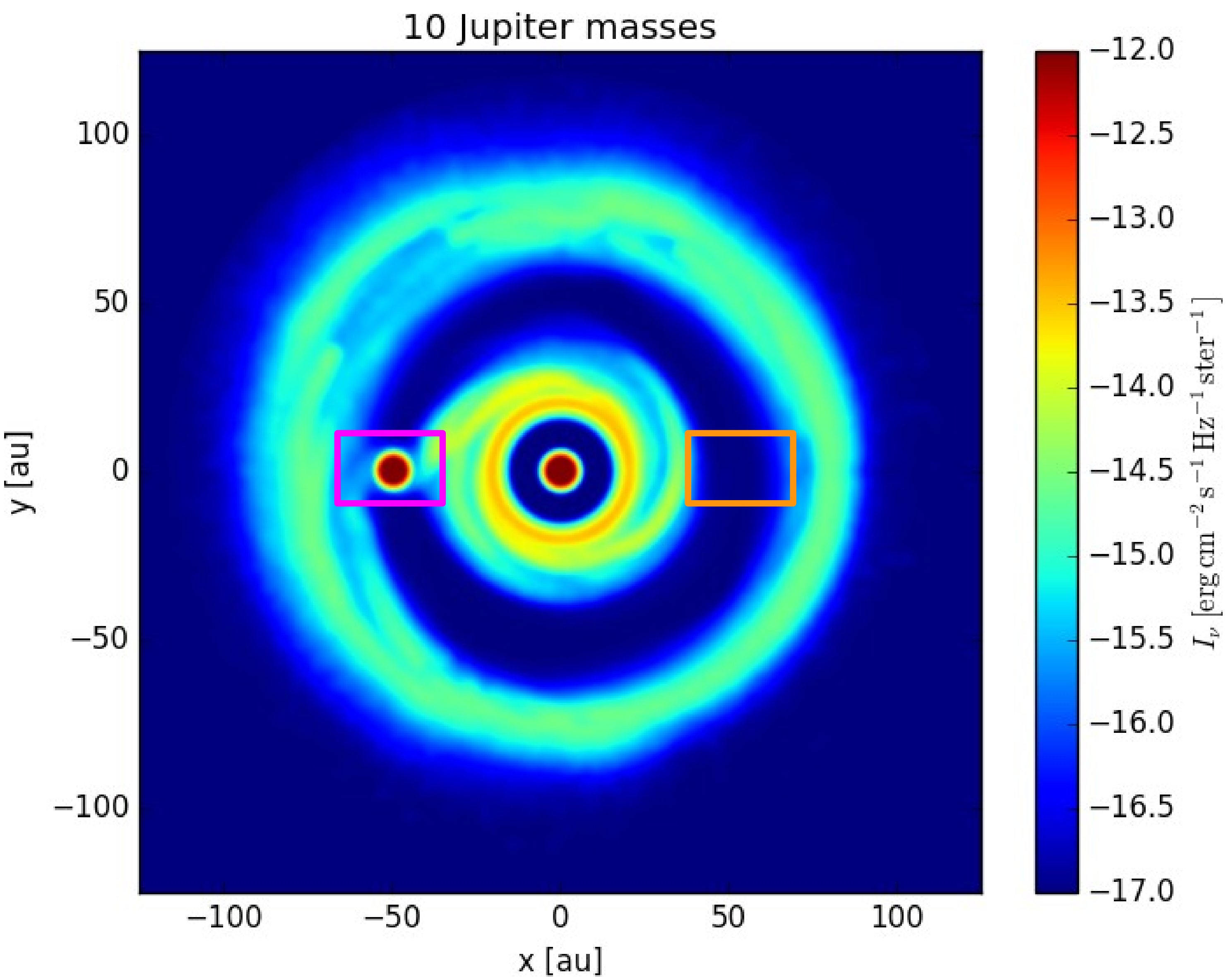


Szulagyi et al. 2019

Which wavelength is the best to detect the forming planet?

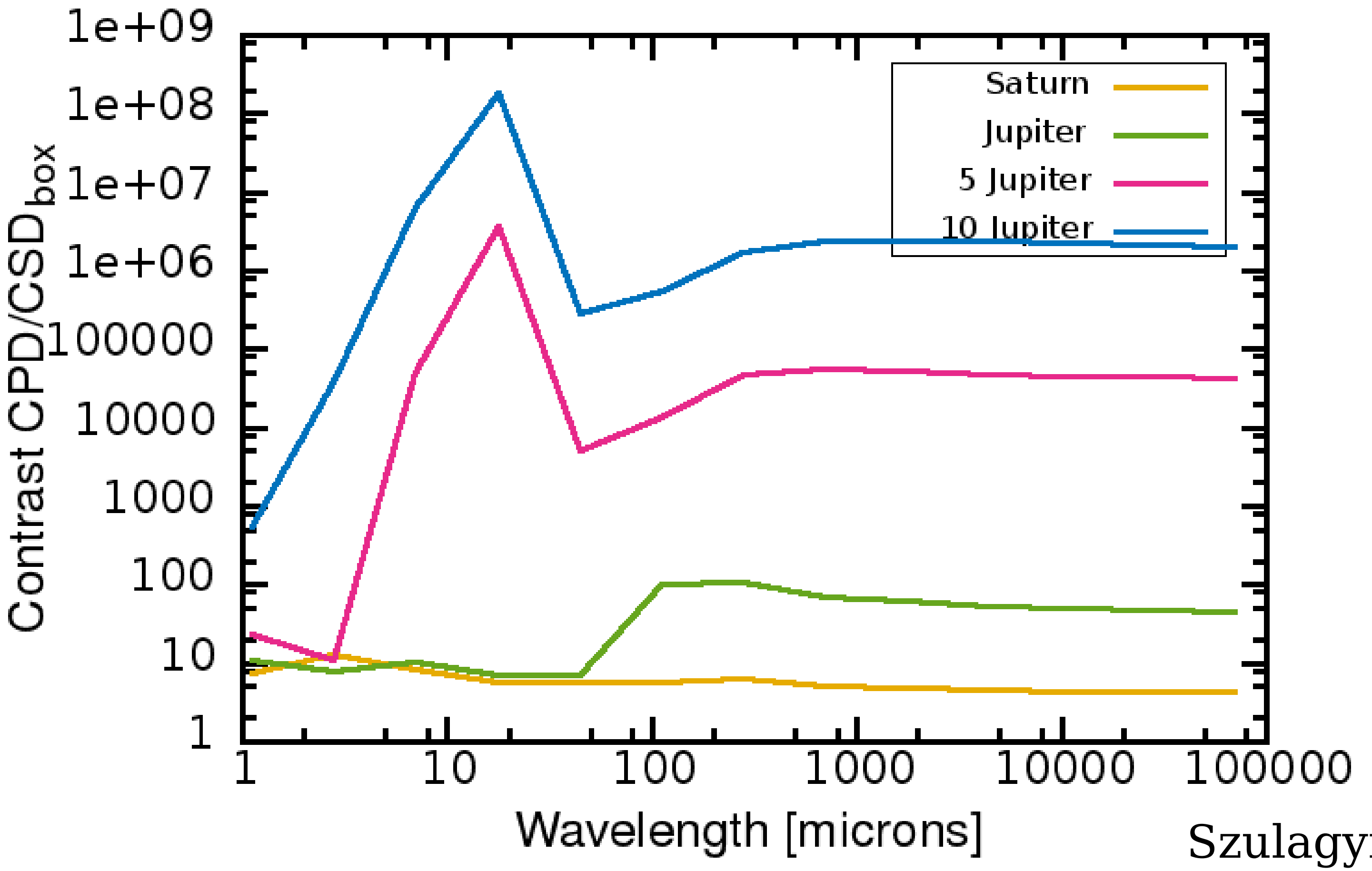


Szulagyi et al. 2019

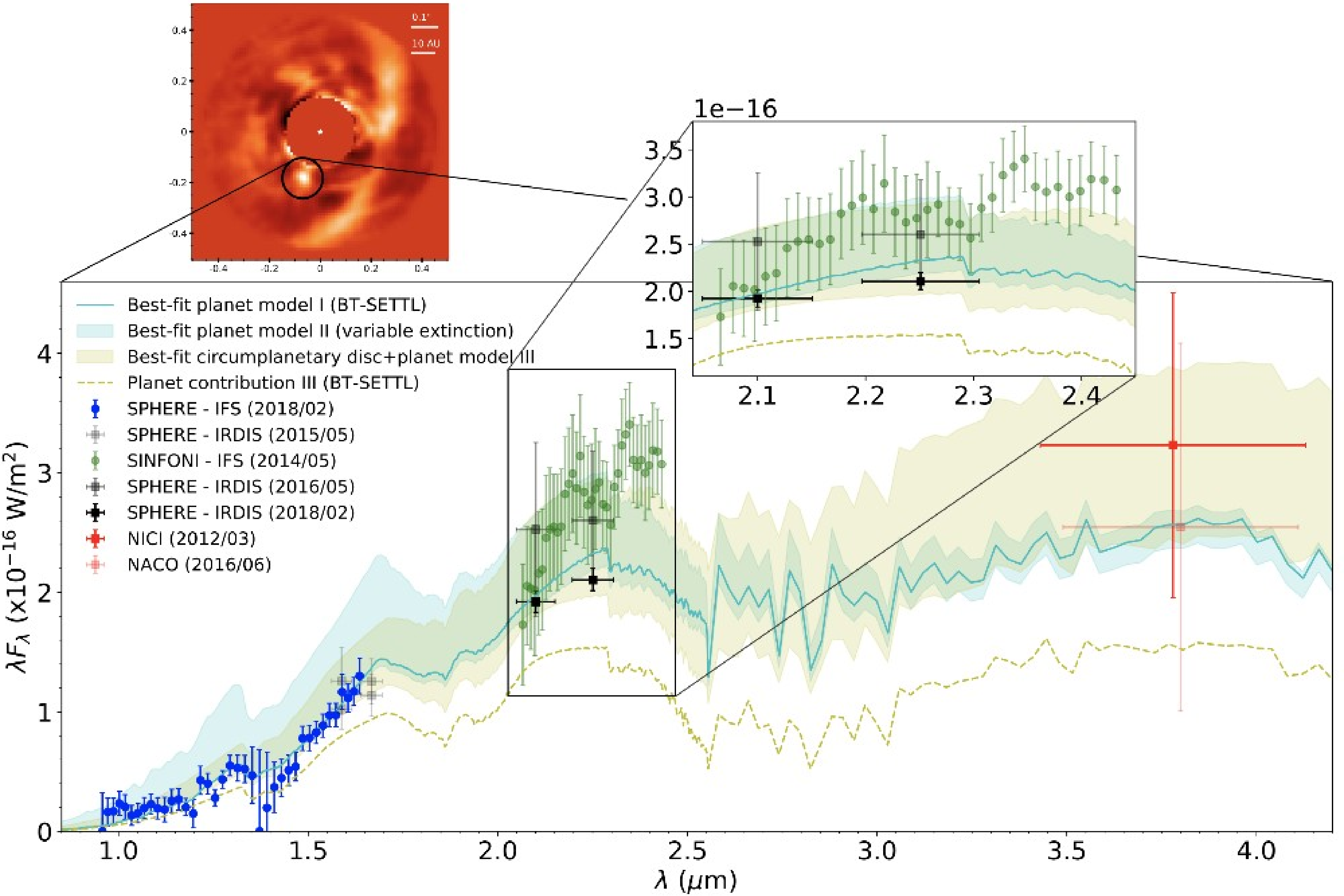


Contrast: [magenta box] / [orange box]

Which wavelength is the best to detect the forming planet?



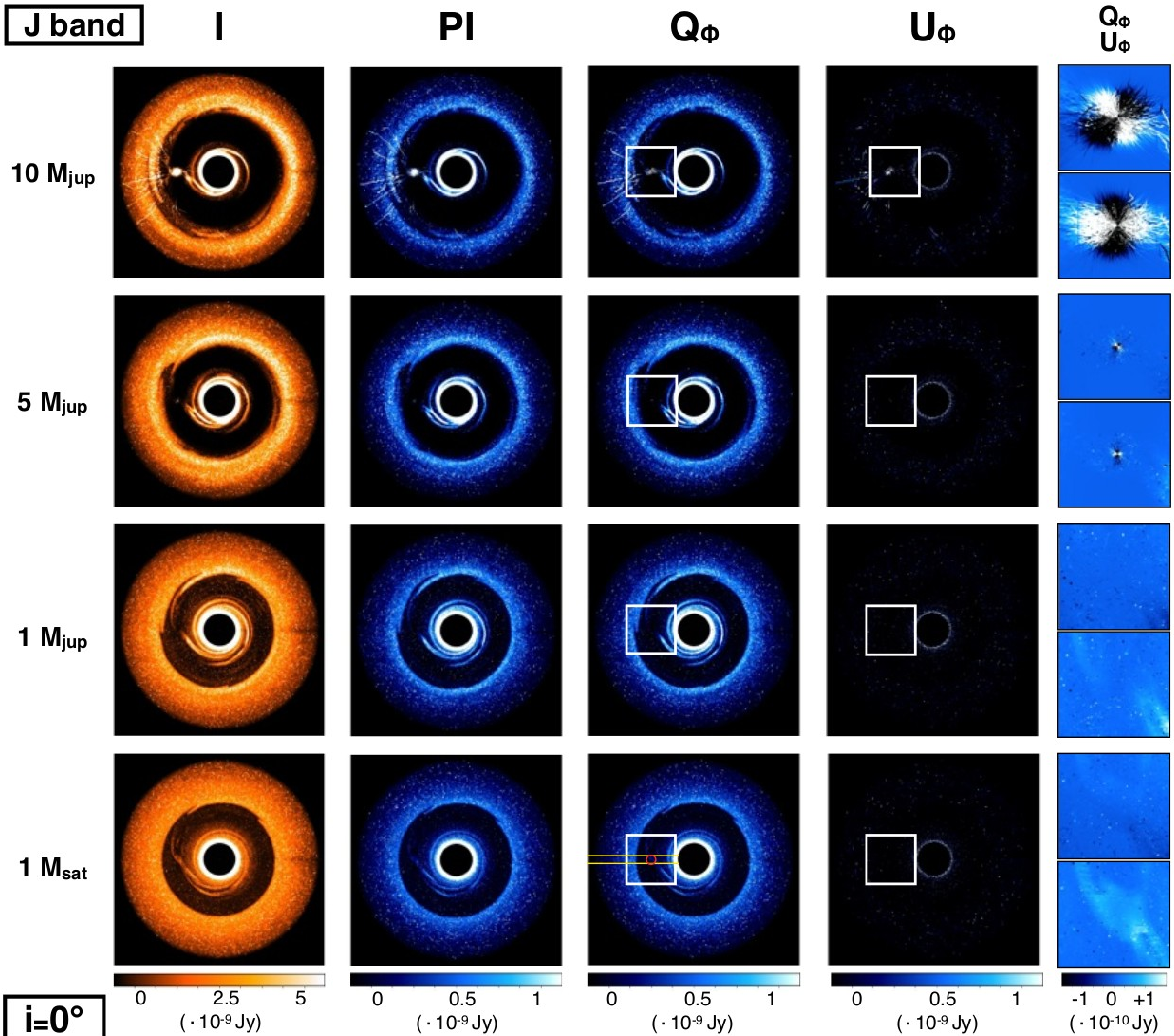
Szulagyi et al. 2019



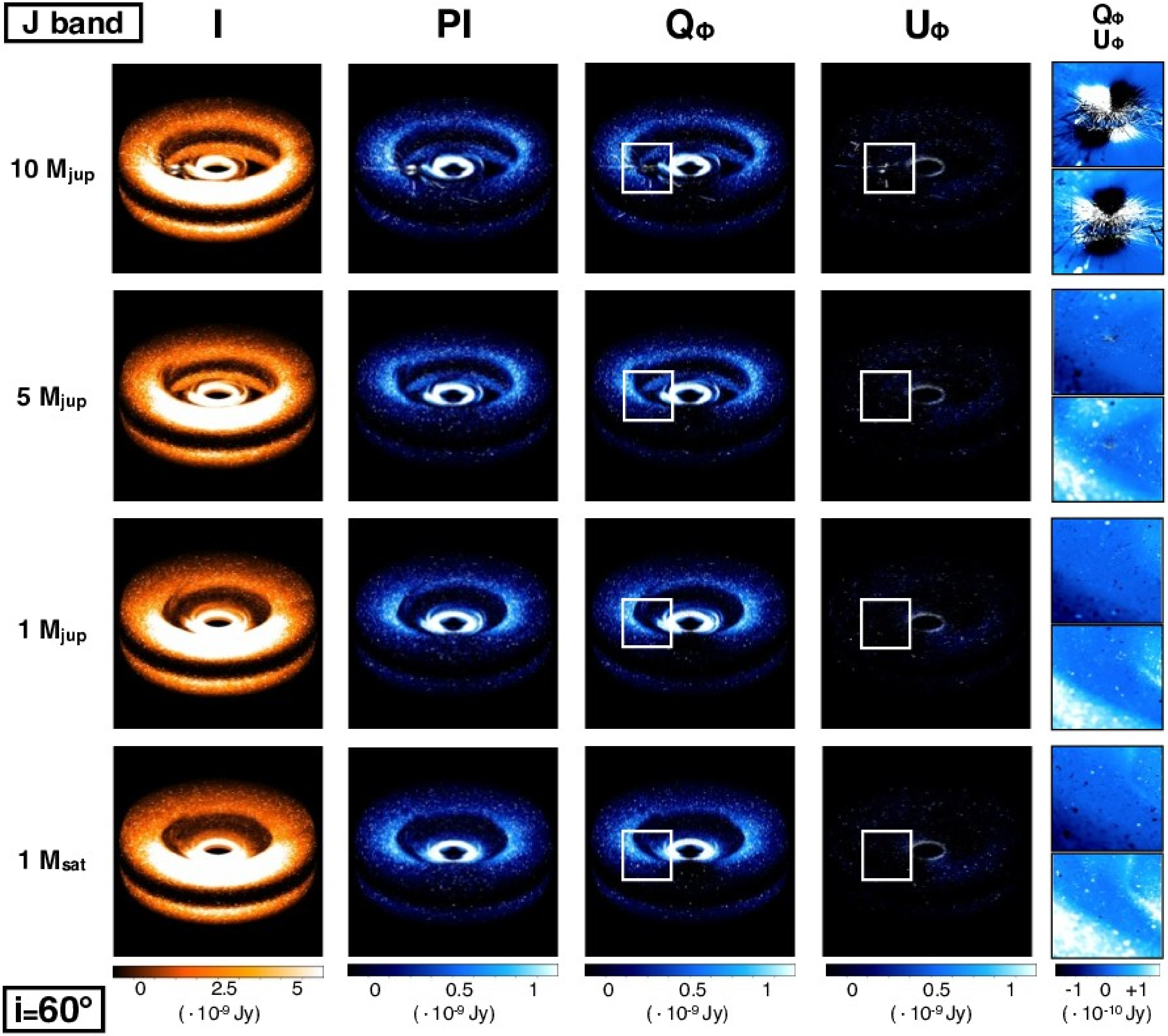
Christiaens et al. 2019

III. SCATTERED LIGHT + POLARIZATION

SPHERE / GPI



J band
I
PI
QΦ
UΦ
QΦ
UΦ
10 Mjup
5 Mjup
1 Mjup
1 Msat
0
2.5
5
(· 10-9 Jy)
0
0.5
1
(· 10-9 Jy)
0
0.5
1
(· 10-9 Jy)
0
0.5
1
(· 10-9 Jy)
-1
0
+1
(· 10-10 Jy)
i=0°


J band
I
PI
QΦ
UΦ
QΦ
UΦ
10 Mjup
5 Mjup
1 Mjup
1 Msat
i=60°
0
2.5
5
(· 10-9 Jy)
0
0.5
1
(· 10-9 Jy)
0
0.5
1
(· 10-9 Jy)
0
0.5
1
(· 10-9 Jy)
-1
0
+1
(· 10-10 Jy)

IV. HYDROGEN RECOMBINATION LINES

H-alpha, Pa-beta, Br-gamma

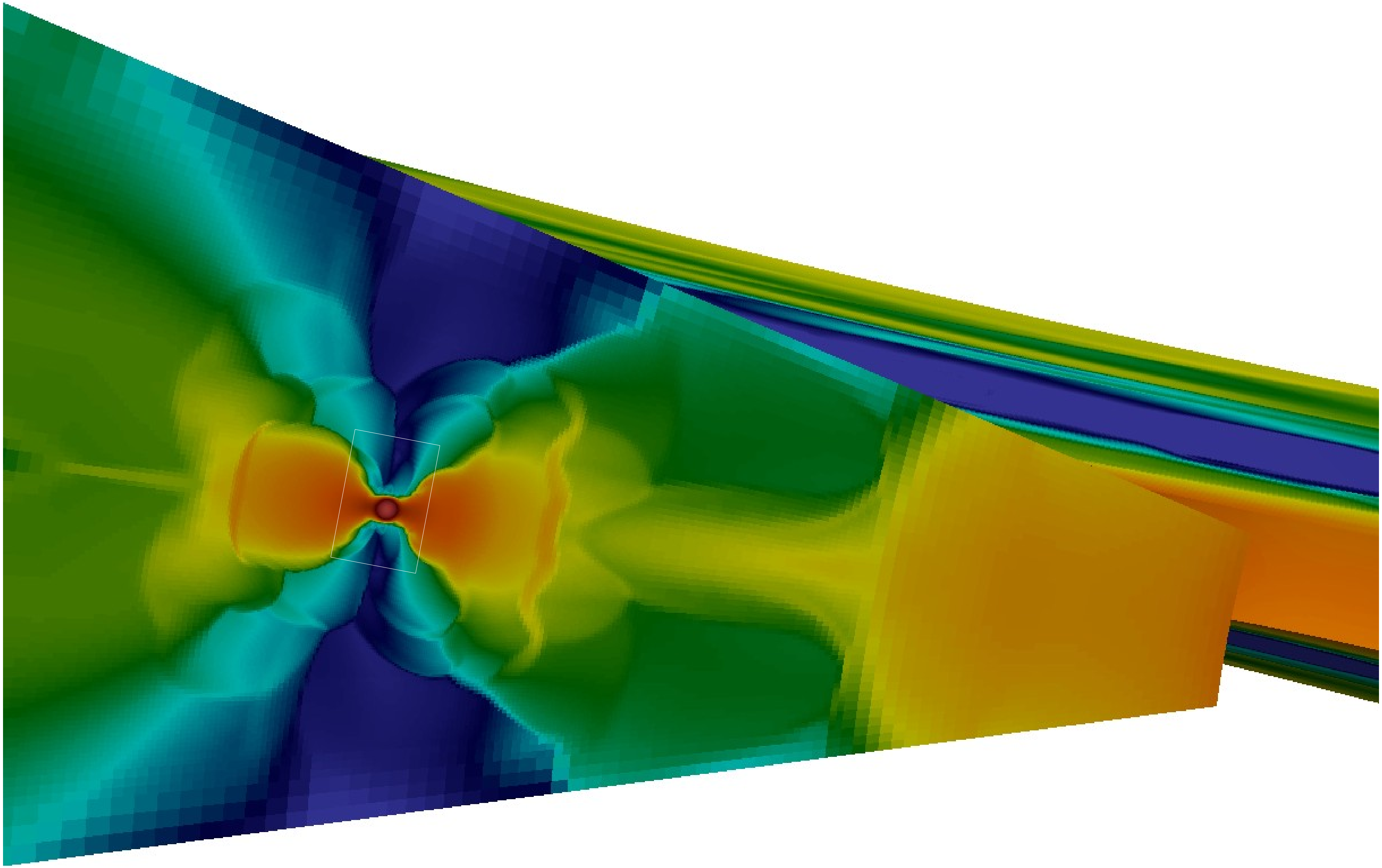
Szulagyi & Ercolano 2020

H-alpha, Pa-beta, Br-gamma fluxes

- Why these? – accretion tracer lines (luminosity ∝ accretion rate)
- In the past, only determined for stars (T Tauri formula was used for planets)
- Hydrogen ionization – temperature > 10’000 K
- Easily absorbed – extinction
- Variability?

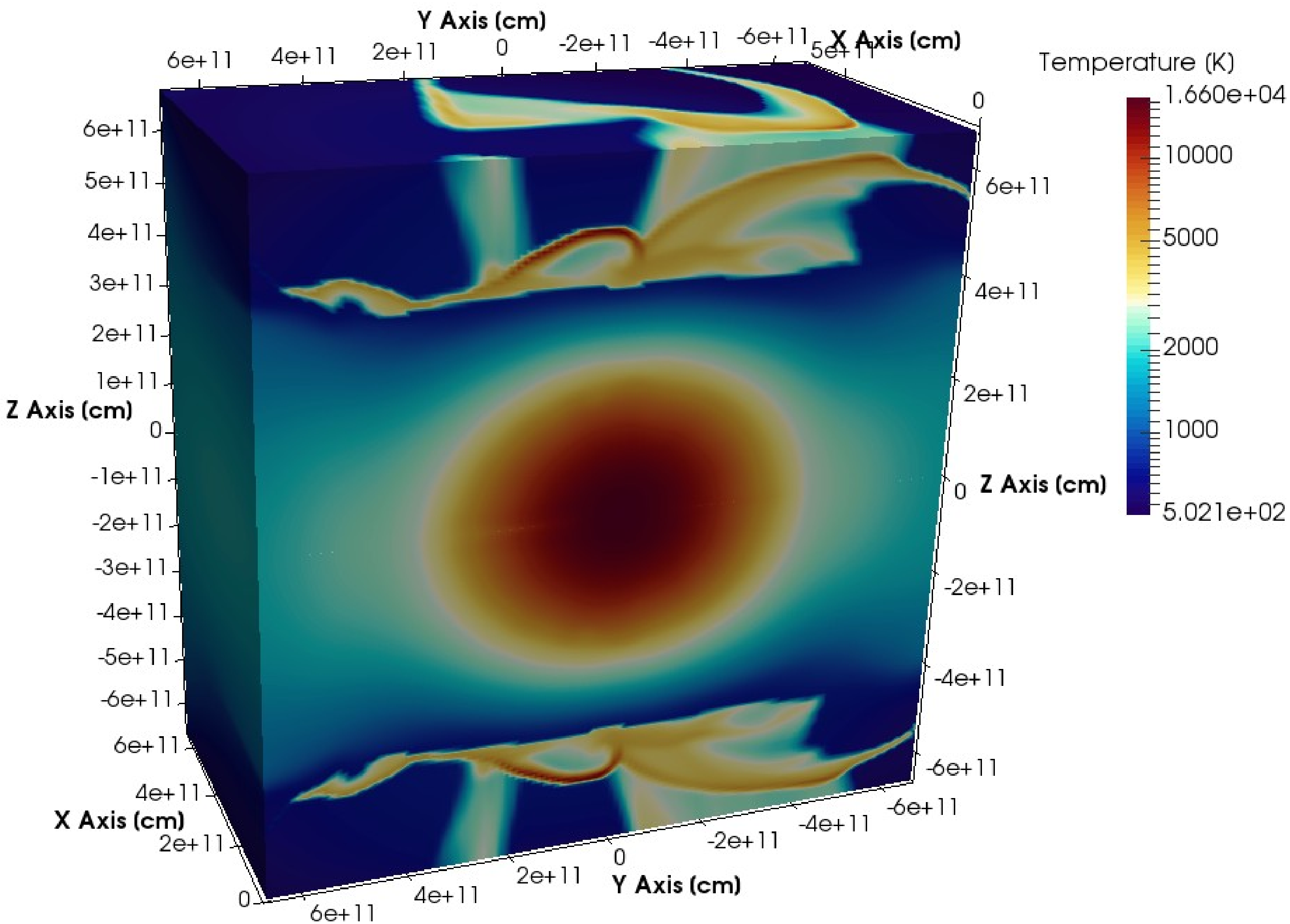
Observations :

- **LkCa15b** (Sallum et al. 2015)
- **PDS70b** (Wagner et al. 2018, Haffert et al. 2019)



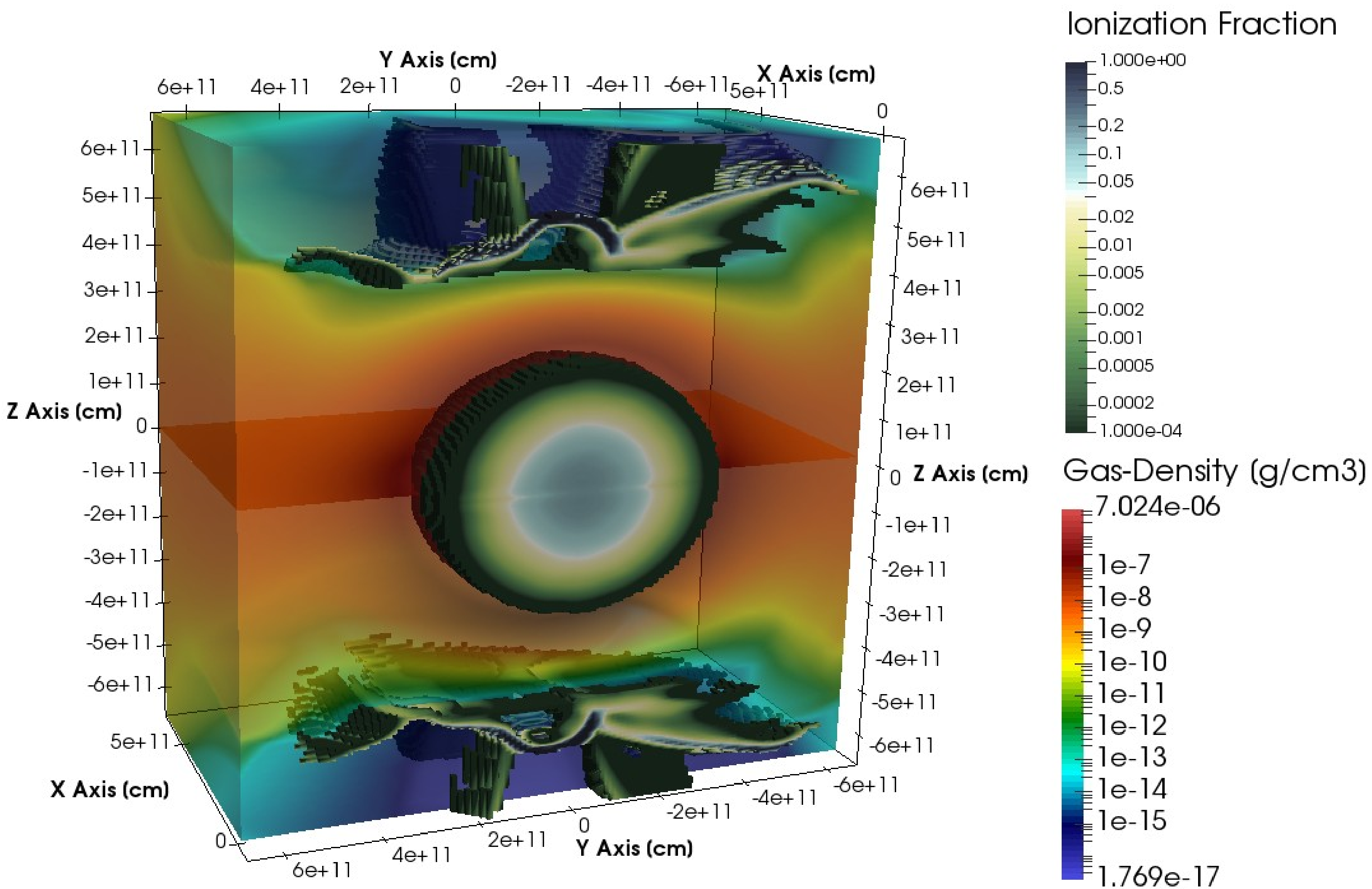
Accretion Shock

Temperature map – zoom to planet



Szulagyi & Ercolano 2020

Accretion Shock – Ionization



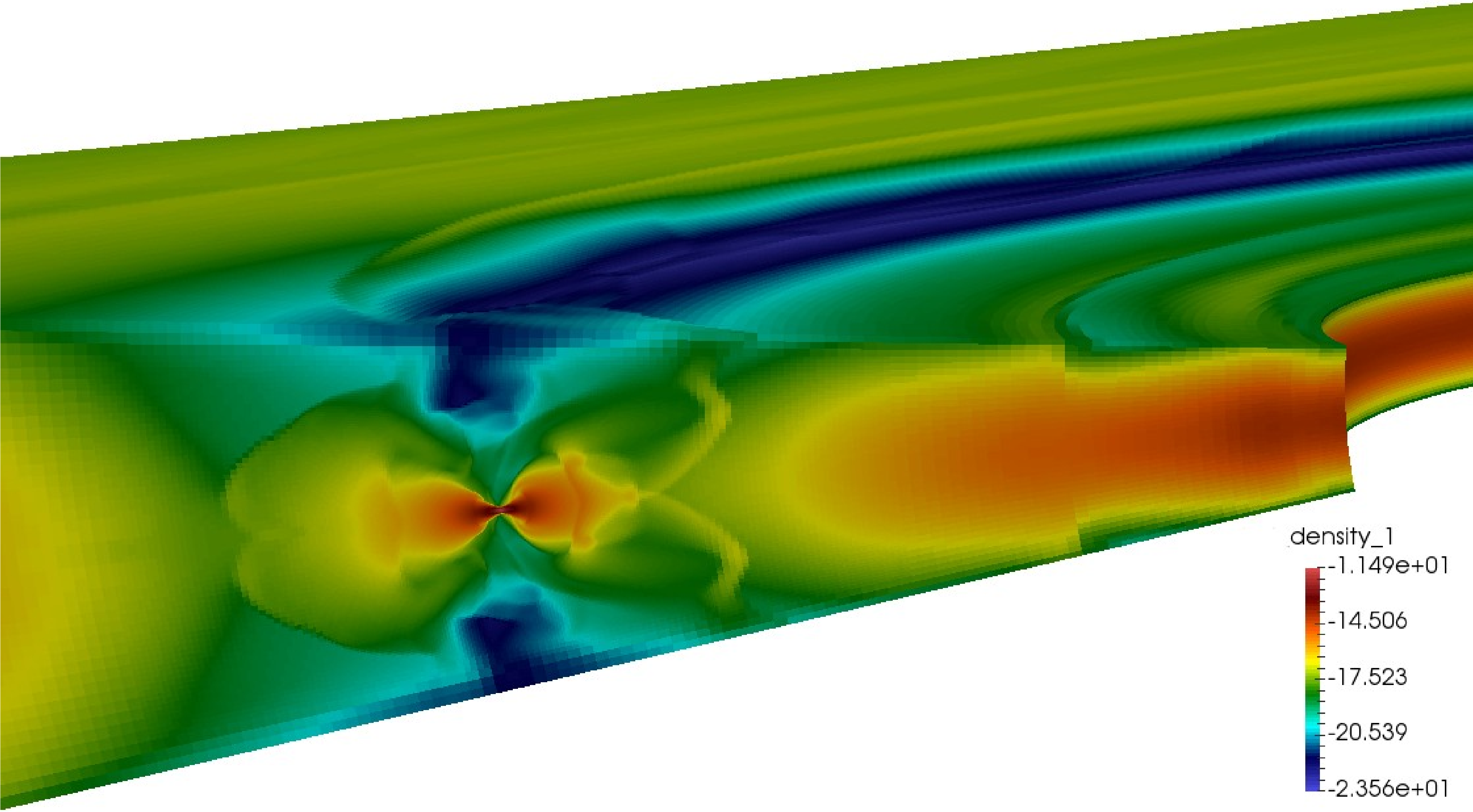
Szulagyi & Ercolano 2020

H-alpha, Pa-beta, Br-gamma fluxes

- Self-consistently calculated the line fluxes from ionization rates with a photoionization code
- Self-consistently calculated extinction – huge problem for detection
- Only lines from planets ≥10 Jupiter-mass can be detected with current instrumentation & realistic opacities
- This explains the very low detection rate of H-alpha from forming planets from observations
- All detectable flux comes from the CPD, not from the planet → these measure CPD accretion rate, not planet accretion rate
- Variability: up to 58%
  - due to various extinction (column density), variable accretion rate

Szulagyi & Ercolano 2020

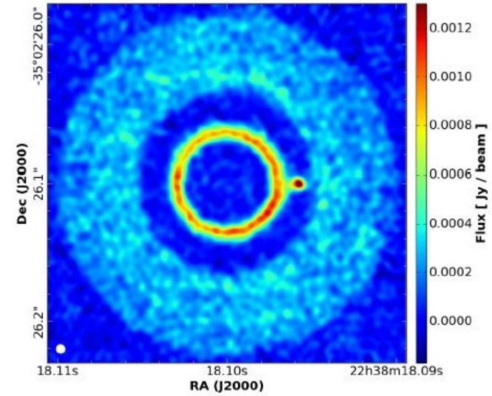
Extinction is a problem

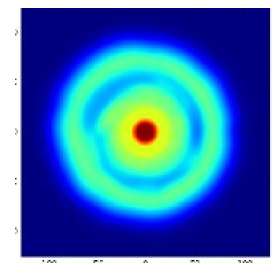


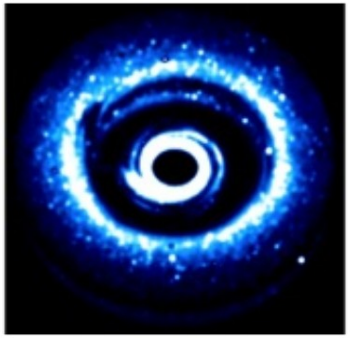
3 M_{Jup} planet

Summary of Observational Predictions

Wavelength/method/instrument







✔ – Sub-mm/radio
  - Szulagyi et al. 2018a

✘ – Near/mid IR
  - Szulagyi et al. 2019

✘ – Polarized Scattered Light
  - Szulagyi & Garufi 2021

✘ – Hydrogen Recombination Lines (H-alpha etc.)
  - Szulagyi & Ercolano 2020

✔: even Saturn-mass (potentially below that)

✘: only 10 Jupiter-mass planets or larger

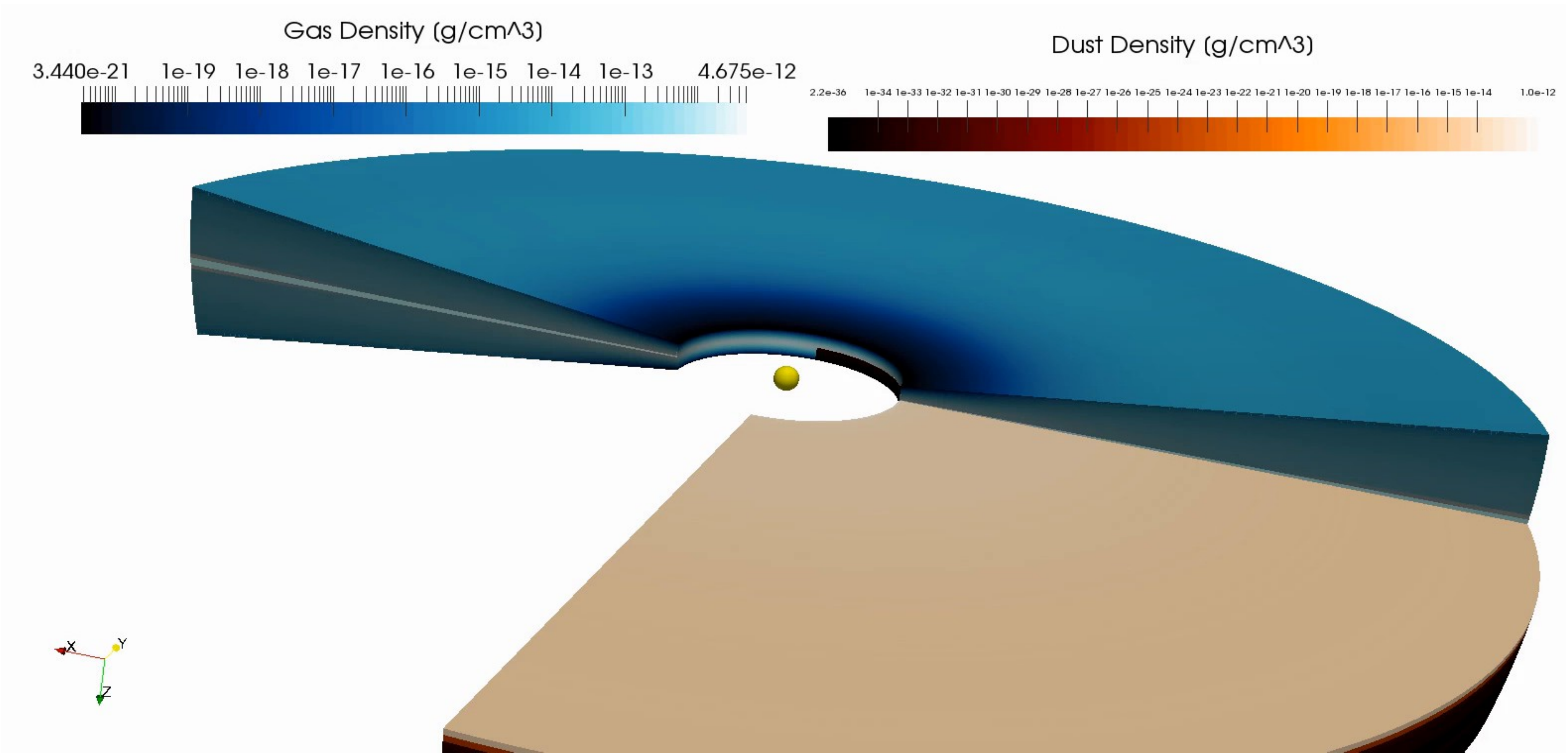
Take Home Message

- With most traditional methods, only heavy forming planets (≥10 Mjup) can be observed, but ALMA could do smaller mass planets too (≤Saturn)
- Observed brightness cannot be used to infer planetary masses on any wavelength – we detect the CPD, not the planet
  - Results depend on density (and temperature) of the CPDs
  - extinction is a big problem

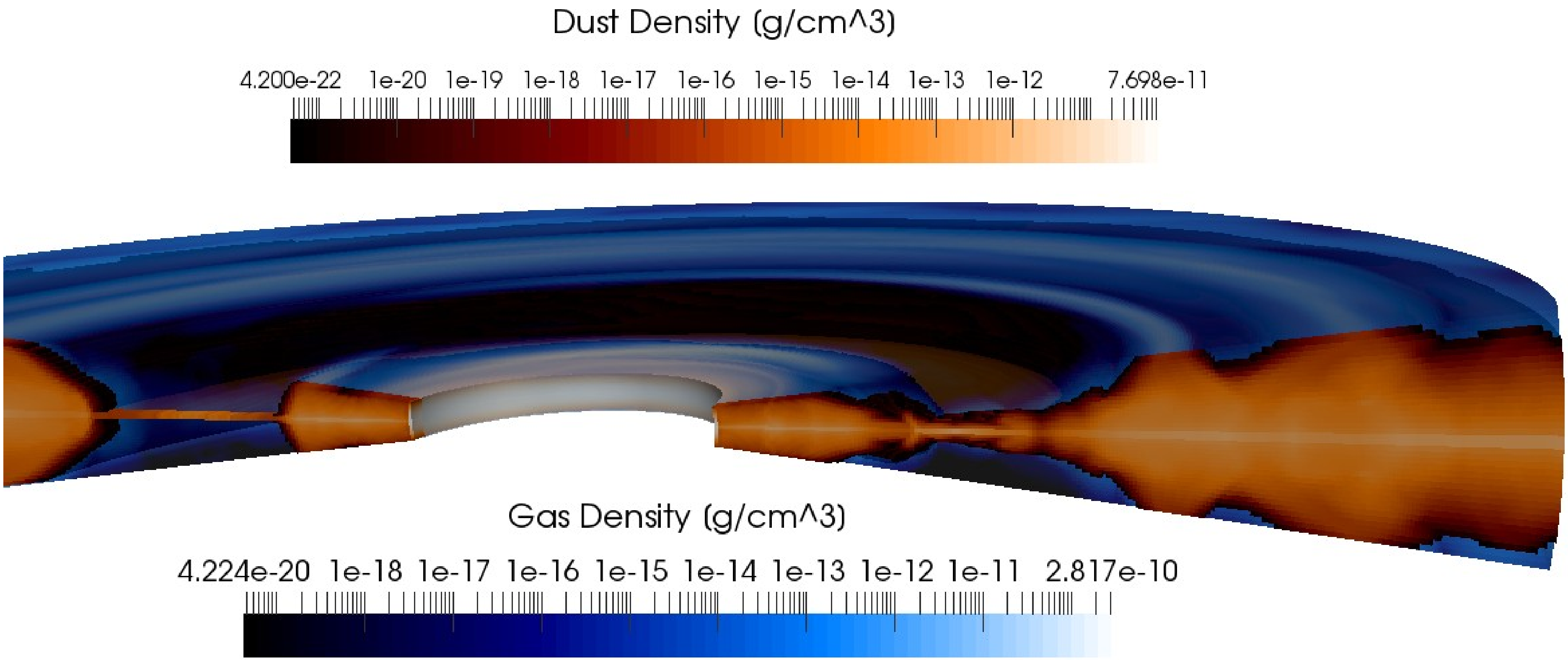
Fabian Binkert
PhD student

3D DUST+GAS SIMULATIONS

Binkert, Szulagyi et al. 2021 - arXiv:2103.10177
Szulagyi, Binkert et al. 2021 - arXiv:2103.12128

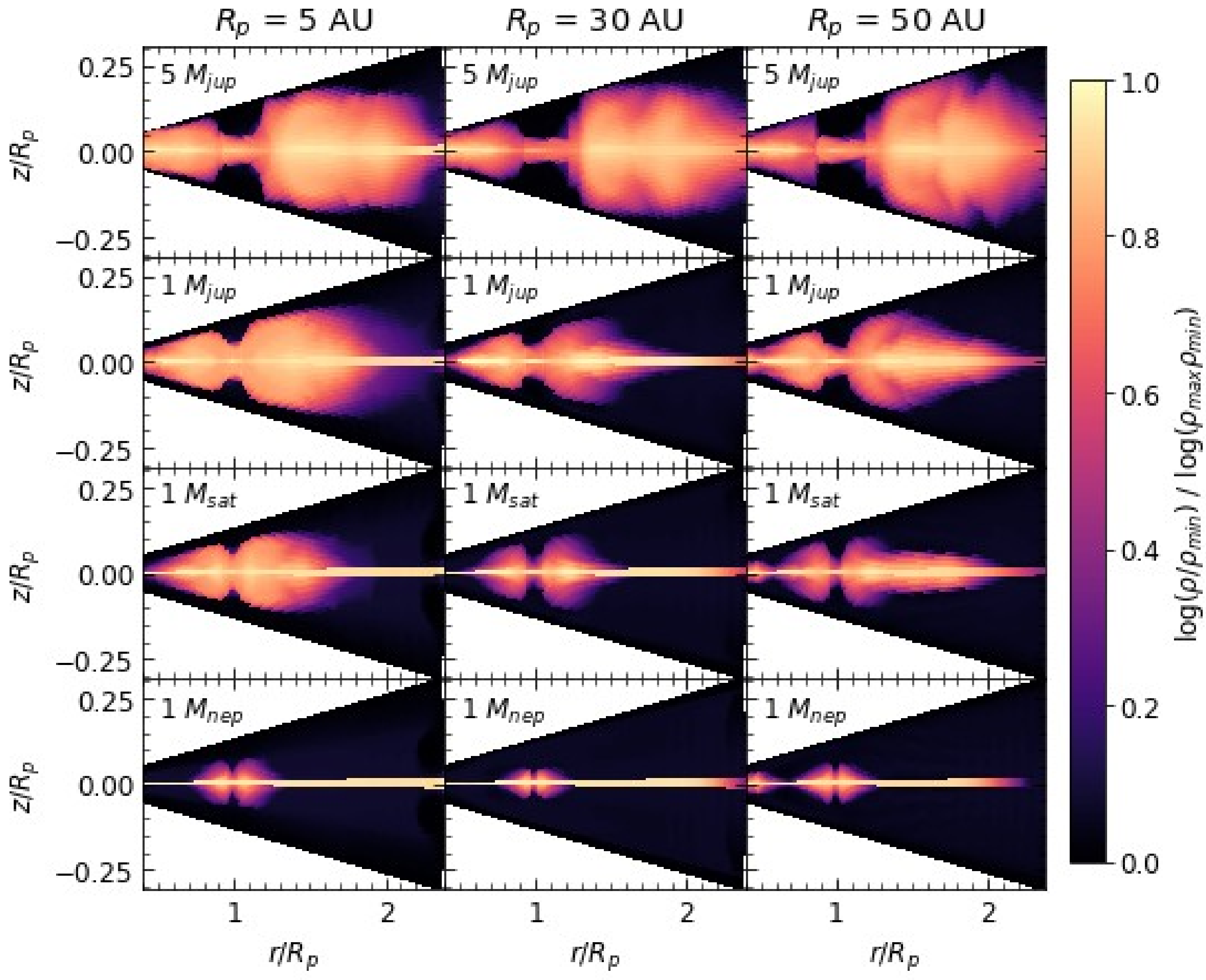

Gas Density (g/cm^3)
3.440e-21 1e-19 1e-18 1e-17 1e-16 1e-15 1e-14 1e-13 4.675e-12
Dust Density (g/cm^3)
2.2e-36 1e-34 1e-33 1e-32 1e-31 1e-30 1e-29 1e-28 1e-27 1e-26 1e-25 1e-24 1e-23 1e-22 1e-21 1e-20 1e-19 1e-18 1e-17 1e-16 1e-15 1e-14 1.0e-12
X
Y
Z

Szulagyi



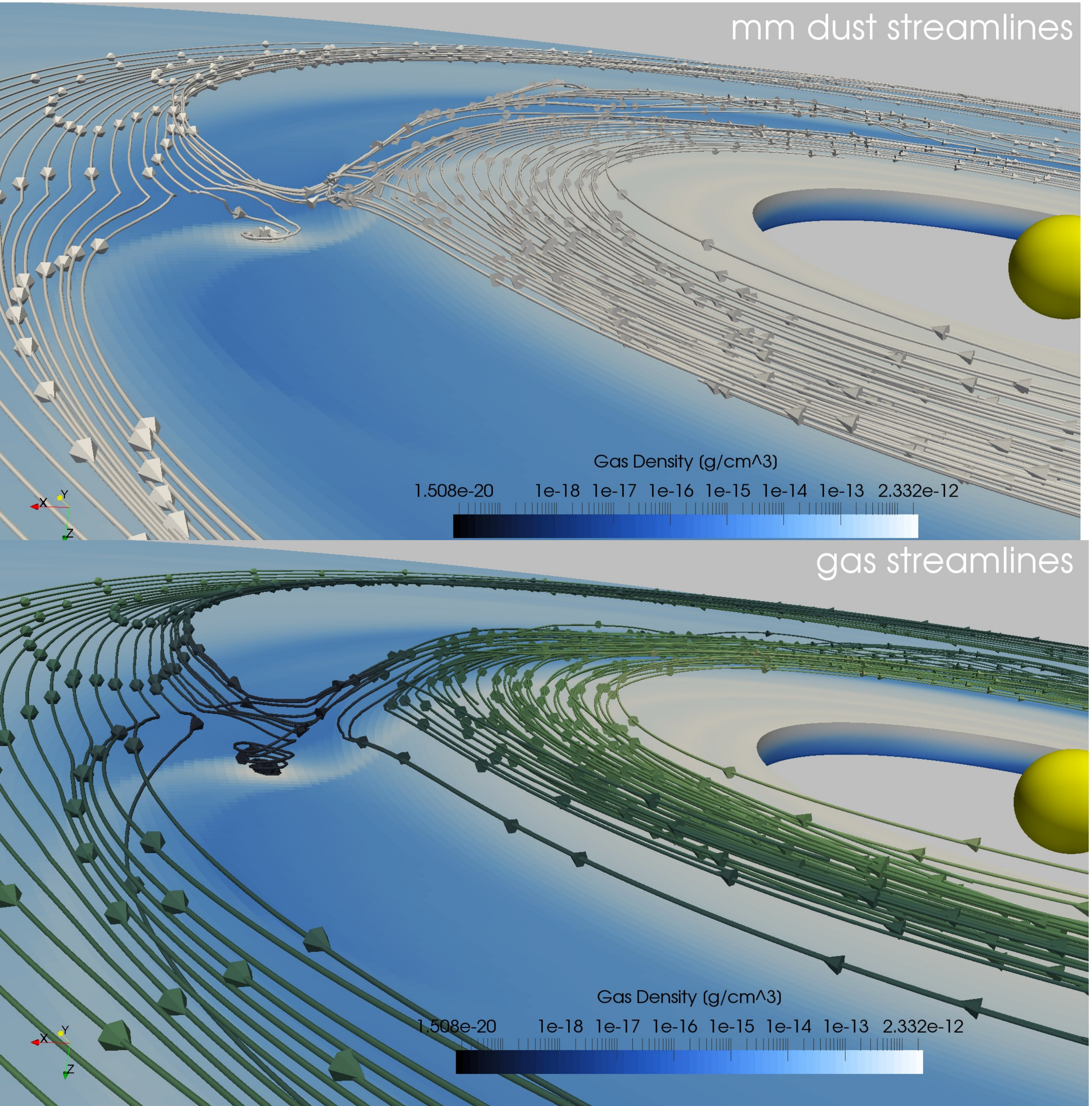
Szulagyi, Binkert et al. 2021

Binkert, Szulagyi et al. 2021

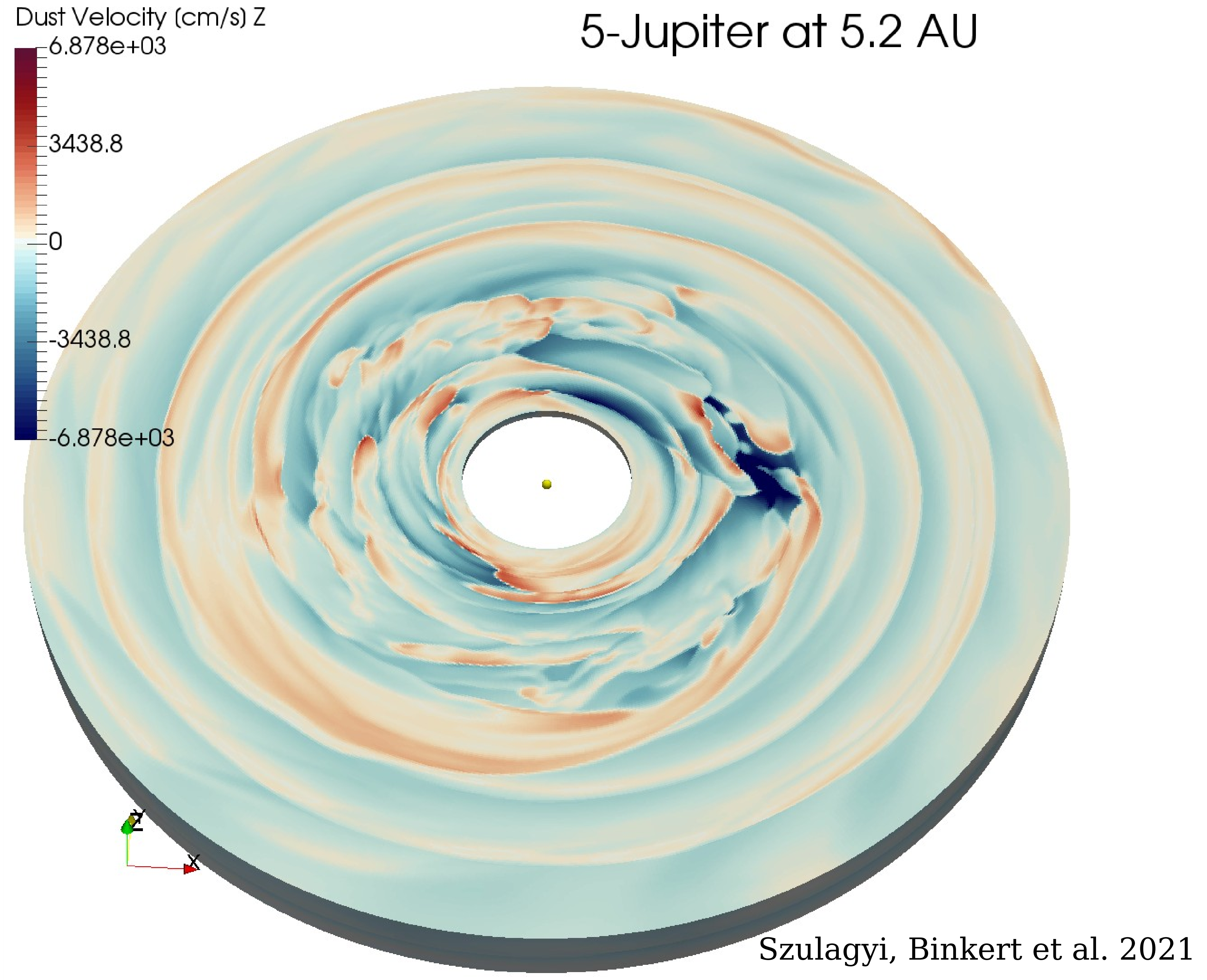


Vertical slices of dust density

Meridional circulation of Dust – Delivery to the CPD

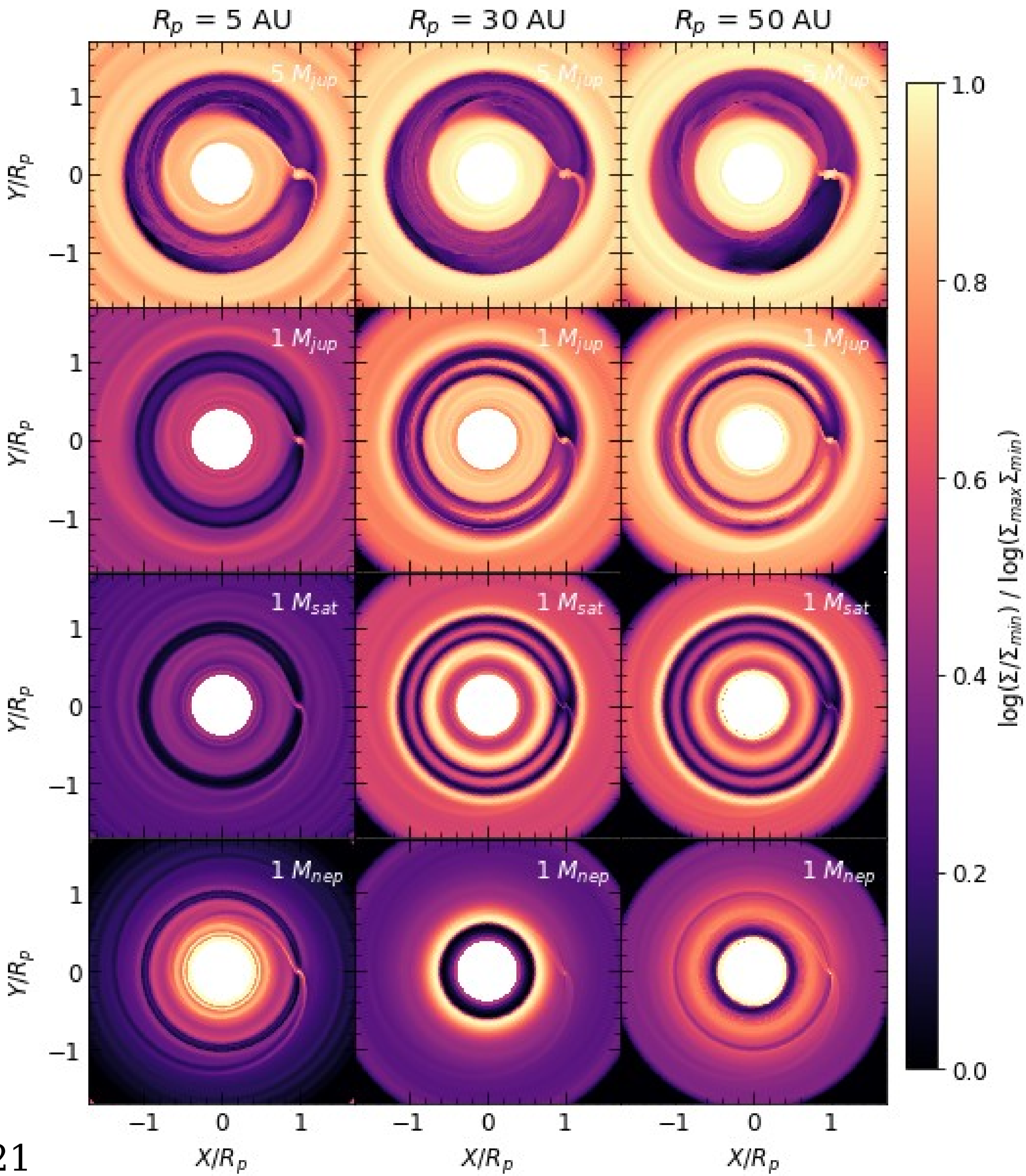


Szulagyi, Binkert et al. 2021


Dust Velocity (cm/s) Z
6.878e+03
3438.8
0
-3438.8
-6.878e+03
5-Jupiter at 5.2 AU
Z
X
Szulagyi, Binkert et al. 2021

Midplane - dust density

→ one planet can open multiple dust gaps, while opening one gas gap

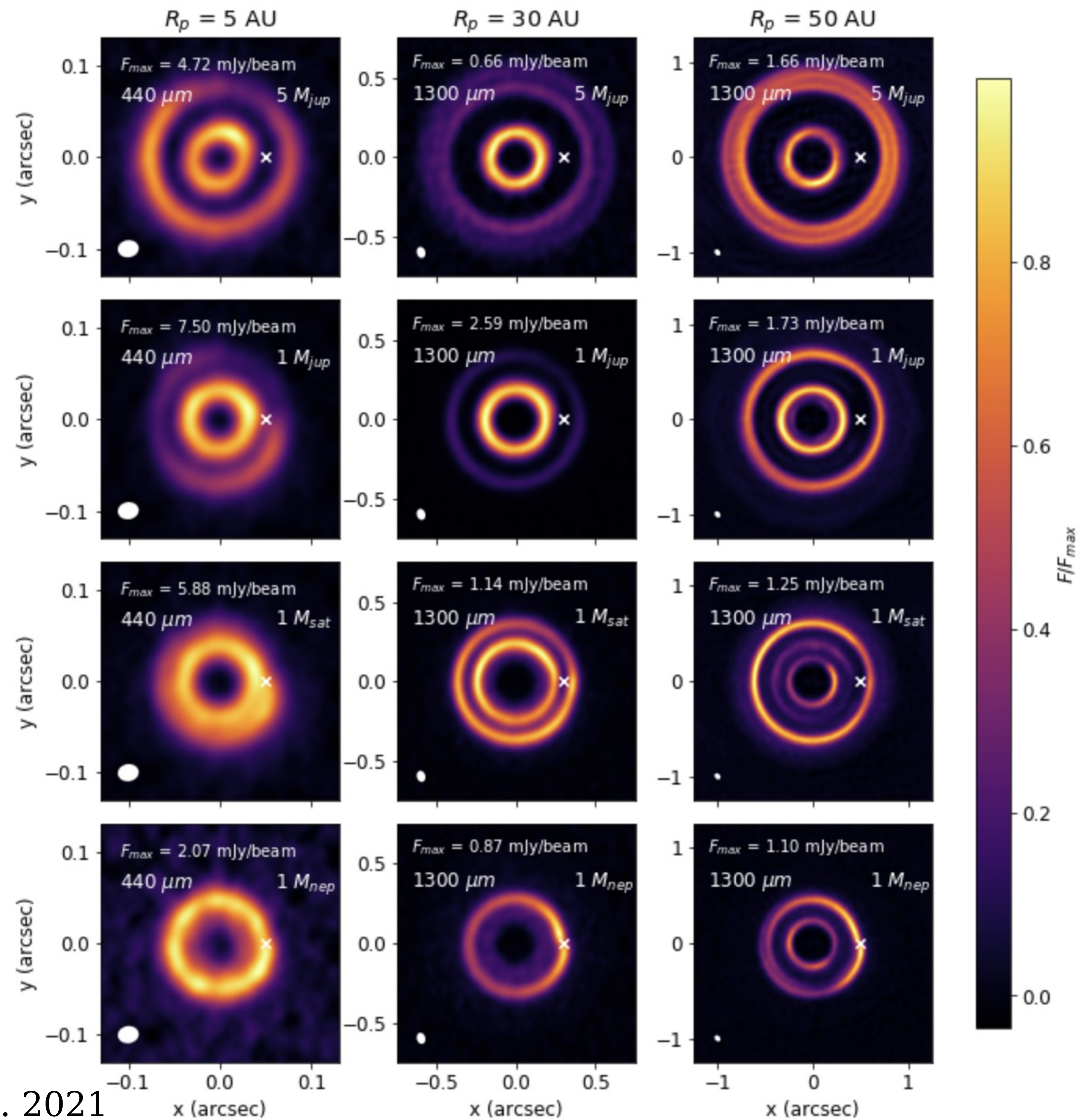


Binkert, Szulagyi et al. 2021

ALMA mocks

- multiple gaps for Saturn mass planets or larger

- Neptune or smaller planets: spiral wakes = asymmetrical ring

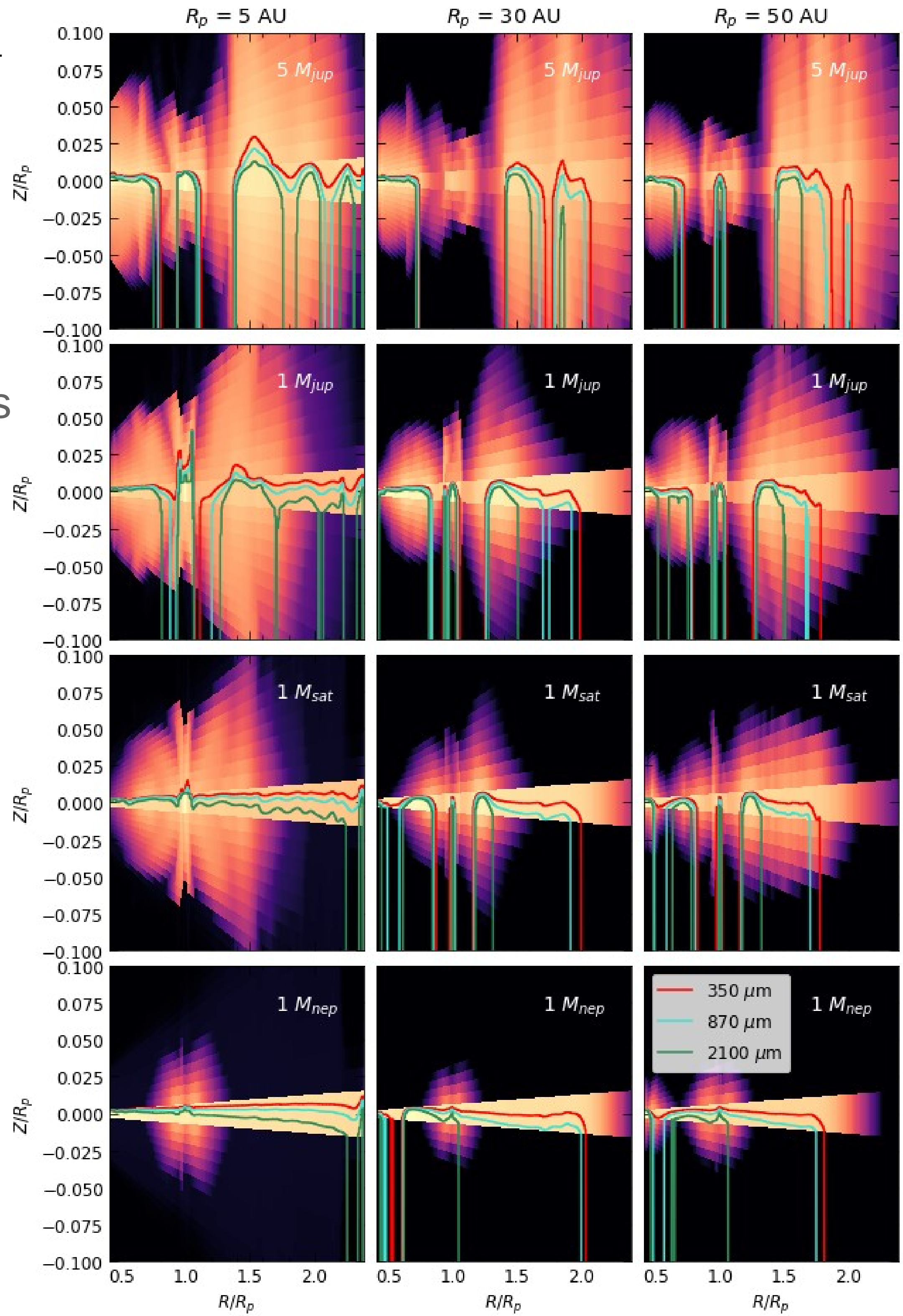


Binkert, Szulagyi et al. 2021

Binkert, Szulagyi et al. 2021

Optically thick below the contour lines → hidden dust mass

Comparison between the disk mass from hydro vs. disk mass from ALMA mocks



Disk masses from ALMA observations are underestimated by a factor of 2-10x

Take Home Message

- If planets present in the disk → stir up the dust
  - Due to meridional circulation by the spiral wakes of the planet
- Disk masses from ALMA observations are greatly underestimated (2-10x) due to this dust stirring
- Meridional circulation bridges over the gap, and sufficiently deliver even larger solids to the CPD → moon formation
  - Pebble isolation mass is not a problem