DANIEL MENTIPLAY, DANIEL PRICE, CHRISTOPHE PINTE

DUSTY PROTOPLANETARY DISCS WITH PHANTOM + MCFOST

Credit: S. Andrews (Harvard-Smithsonian CfA); B. Saxton (NRAO/AUI/NSF); ALMA (ESO/NAOJ/NRAO)

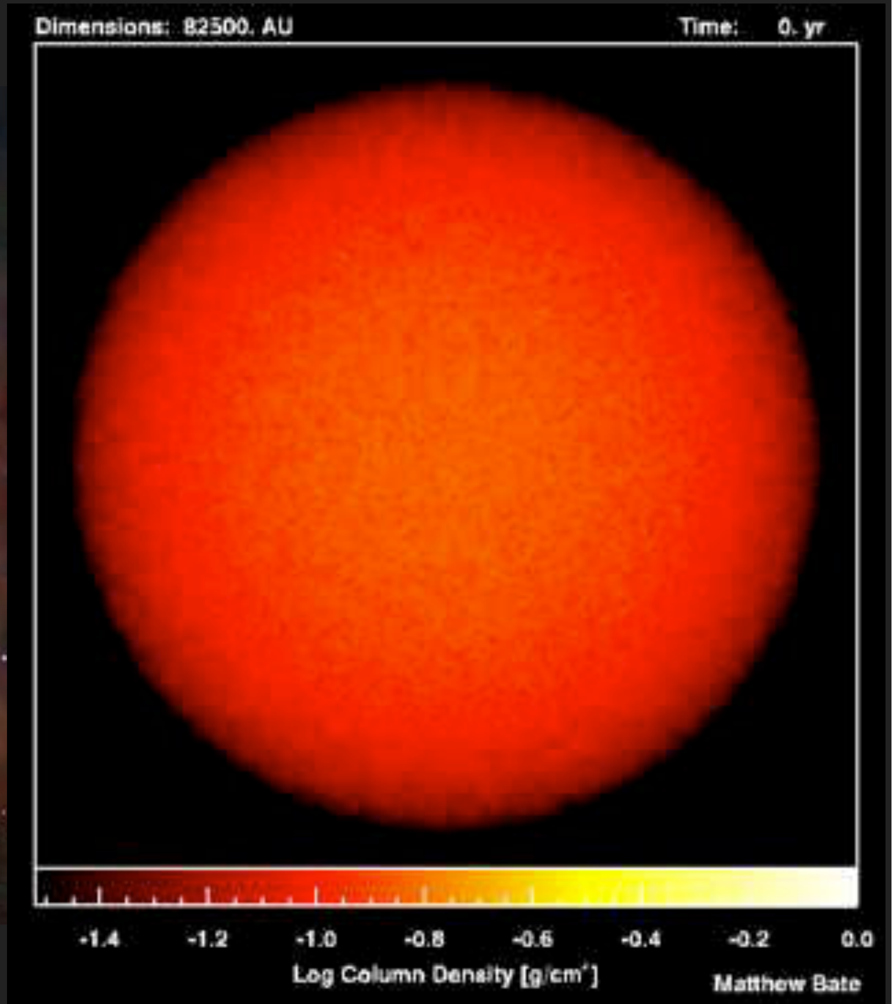
OVERVIEW

- *Dusty protoplanetary discs*: where planets are born
- Tools
    - 3d global *dust* + *gas hydro* simulations in PHANTOM
    - *Radiative transfer* and synthetic images in MCFOST
- The nearest gas-rich protoplanetary disc: *TW Hydrae*
- *Radiation* + *hydro* = radiative equilibrium hydrodynamics

THE ENVIRONMENT FOR PLANET FORMATION

Discs around young stars in Orion Nebula

Credit: NASA, ESA and L. Ricci (ESO).

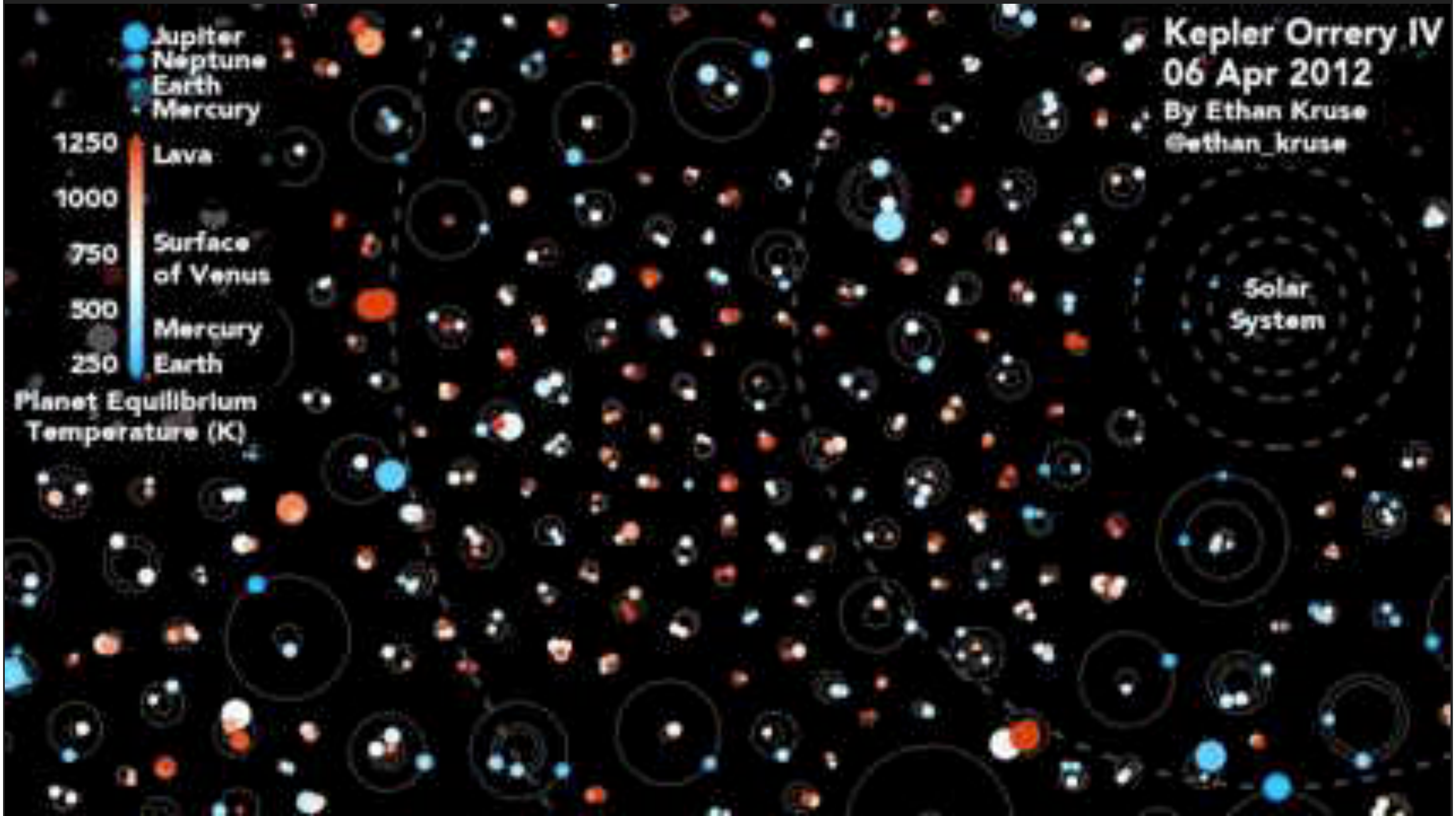


Star cluster formation simulation

Credit: Matthew Bate

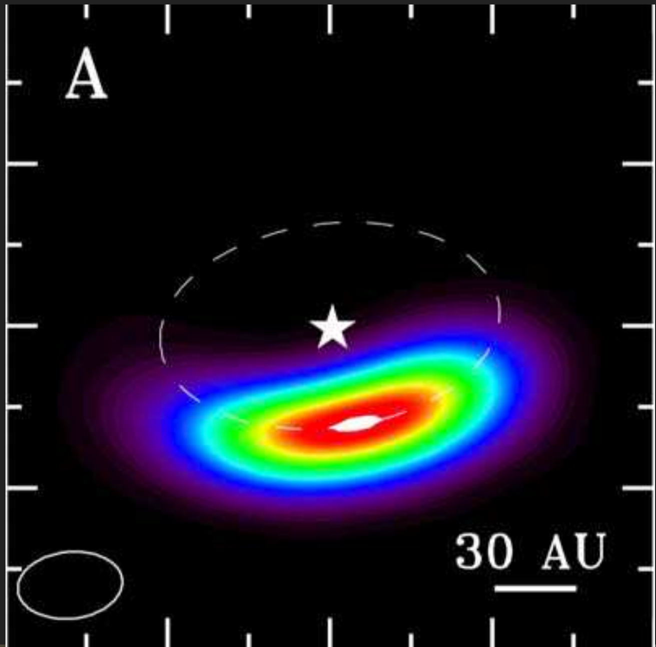
KEPLER ORRERY IV

Planetary systems discovered by Kepler

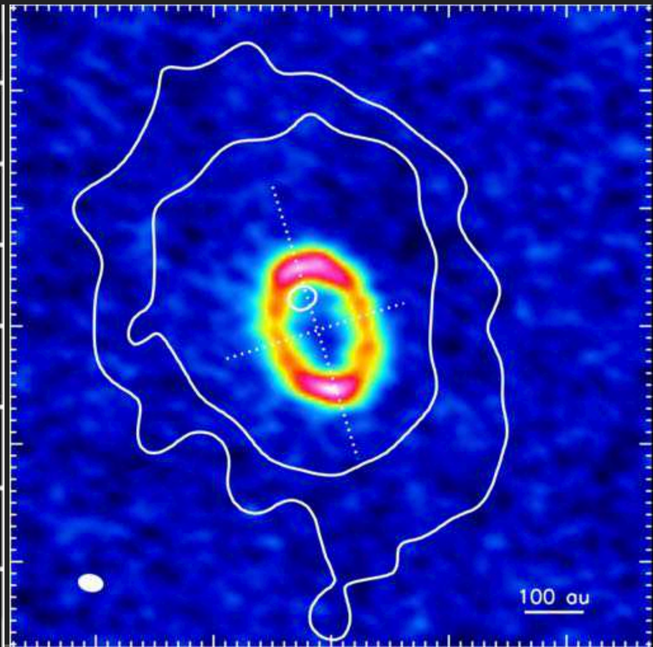


OBSERVATIONS OF PROTOPLANETARY DISCS IN THE ALMA ERA

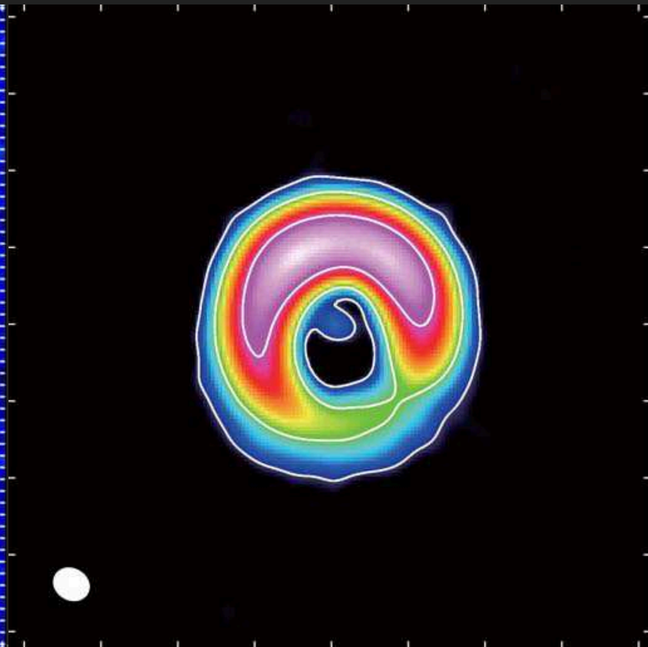
Oph IRS 48



Sz 91



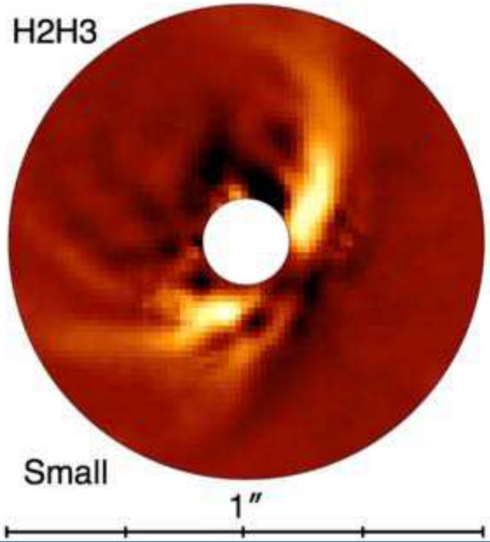
HD 142527



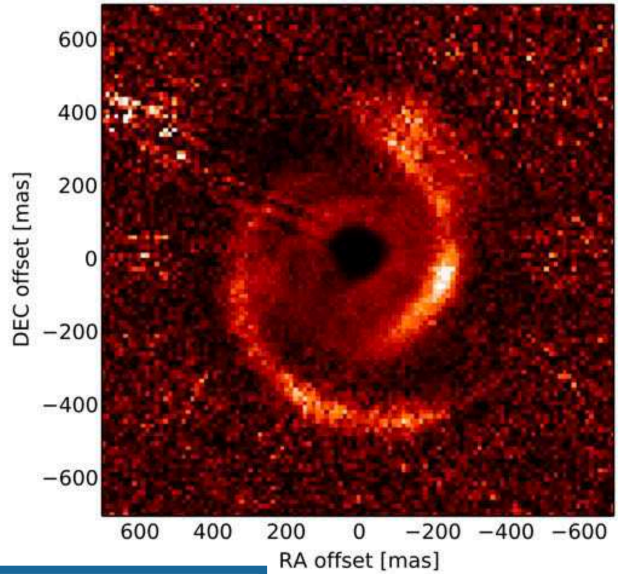
Credit: van der Marel+2013, Canovas+2016, Muto+2015, www.almaobservatory.org

SCATTERED LIGHT

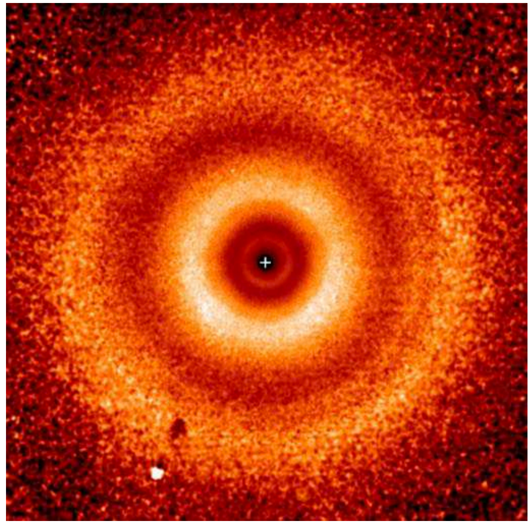
HD 100453

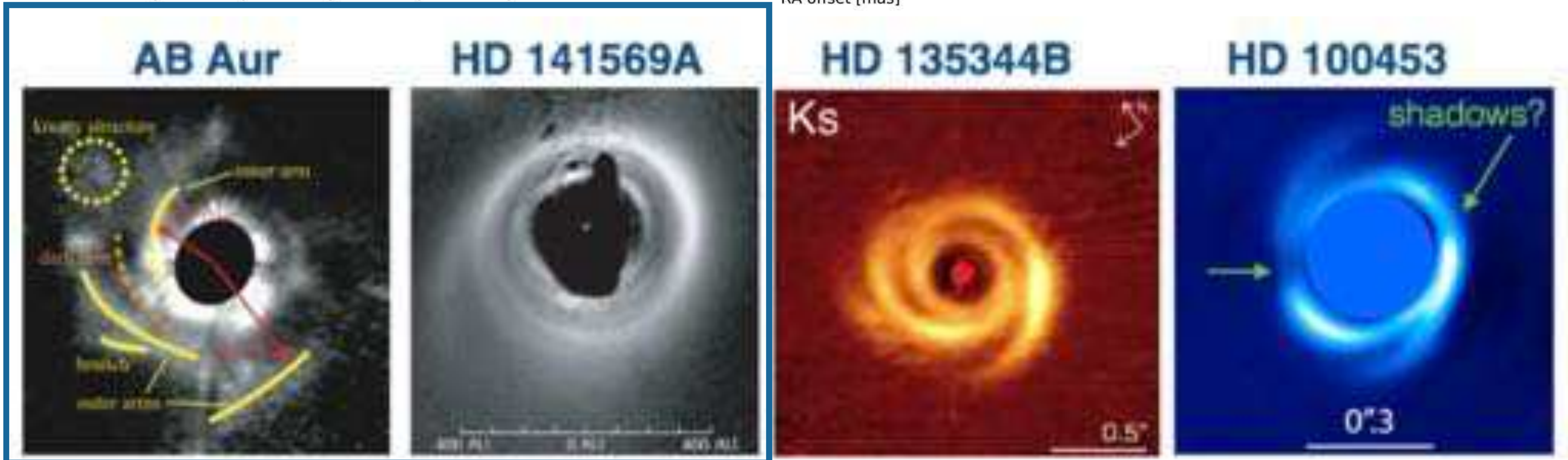


MWC 758



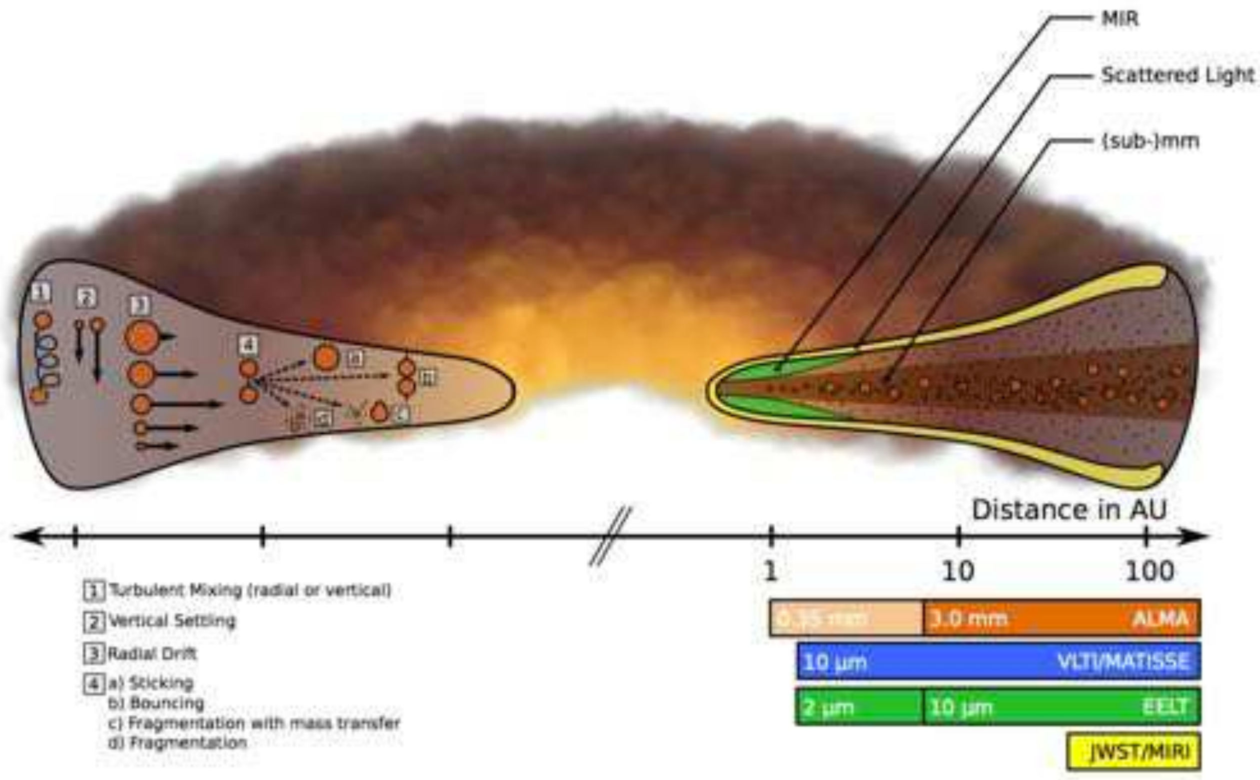
TW Hya





Credit: Benisty+2015, Garufi+2016, van Boekel+2017, Casassus2016

DUST DYNAMICS IN PROTOPLANETARY DISCS



Dimensionless stopping time

St ≪ 1 (μm grains):

- Dust stuck to gas

St ≫ 1 (cm+ grains):

- Dust de-coupled from gas

St ~ 1 (mm/sub-mm grains):

- Dust responds strongly via drag force

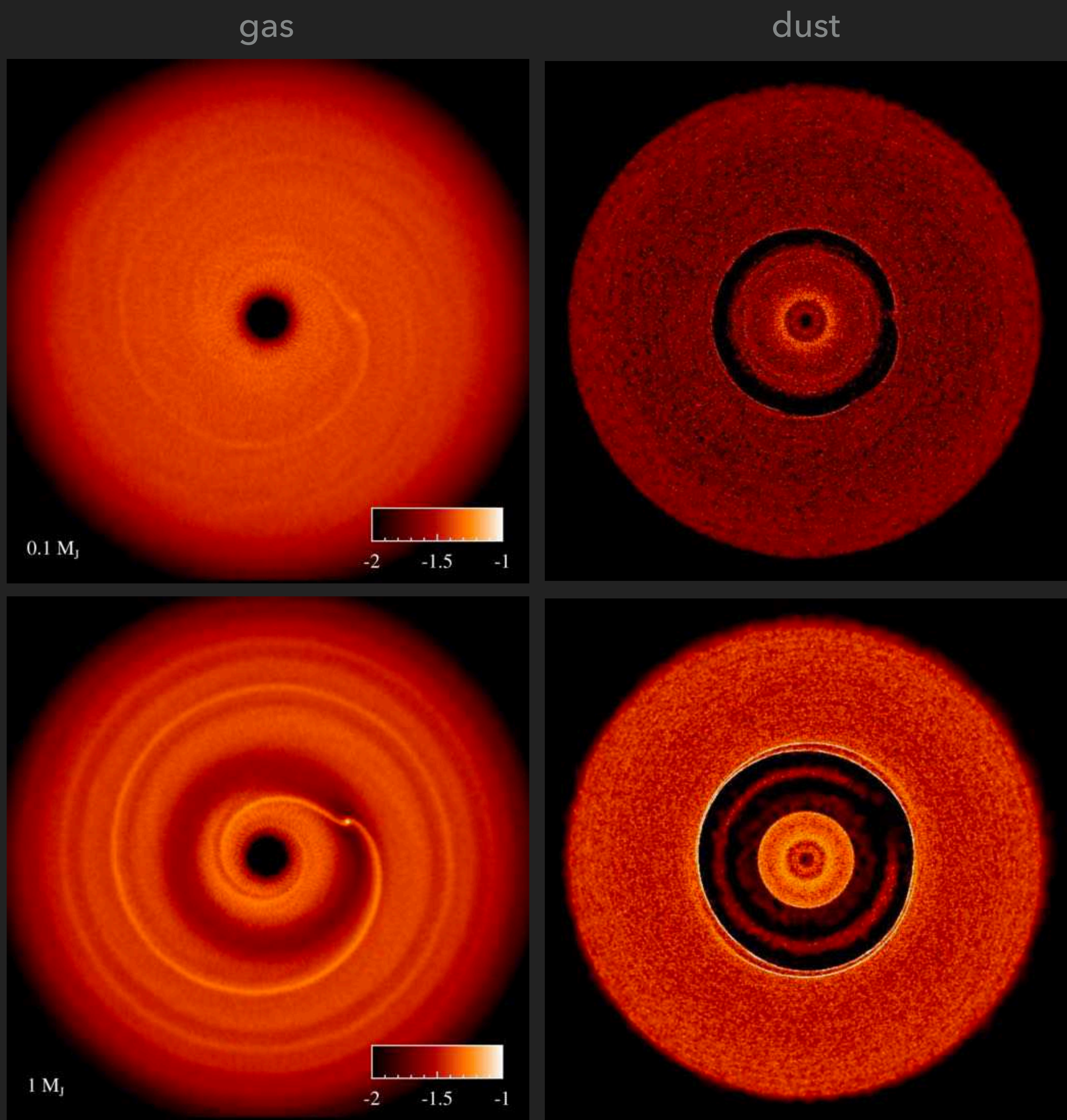
gas in sub-Keplerian orbit + dust in Keplerian orbit = dust drag

Credit: Testi+2014

PLANET-DISC INTERACTION: GAP OPENING

Drag *resisted* regime: gap opened by tidal torque alone

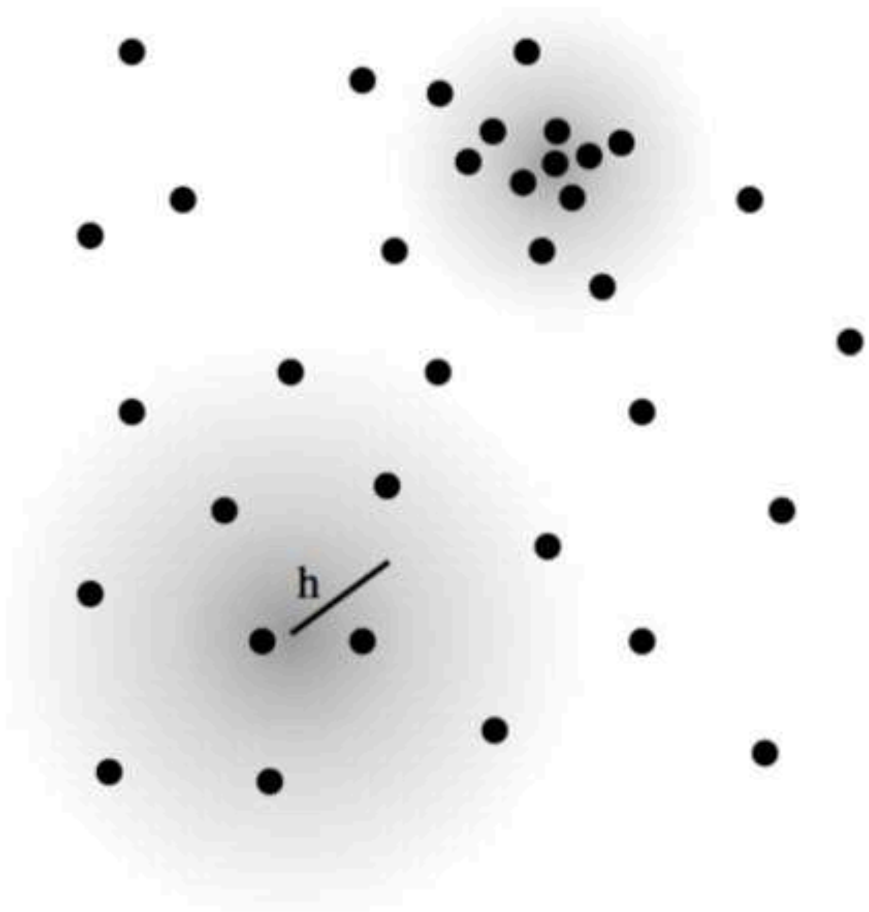
Drag *assisted* regime: gap opened by tidal torque + drag



Credit: Dipierro+2016

SPH WITH PHANTOM

- Smoothed Particle Hydrodynamics–fluid is discretised into particles
- Density is a weighted sum over neighbours
- Equations of motion from Lagrangian: good conservation
- Resolution follows the mass
- Global discs in 3d including dust, planets, binaries, etc.



Credit: Price2012

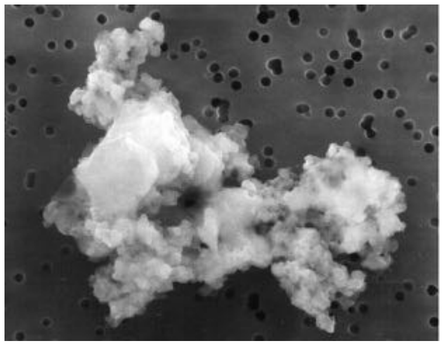
DUST IN PHANTOM

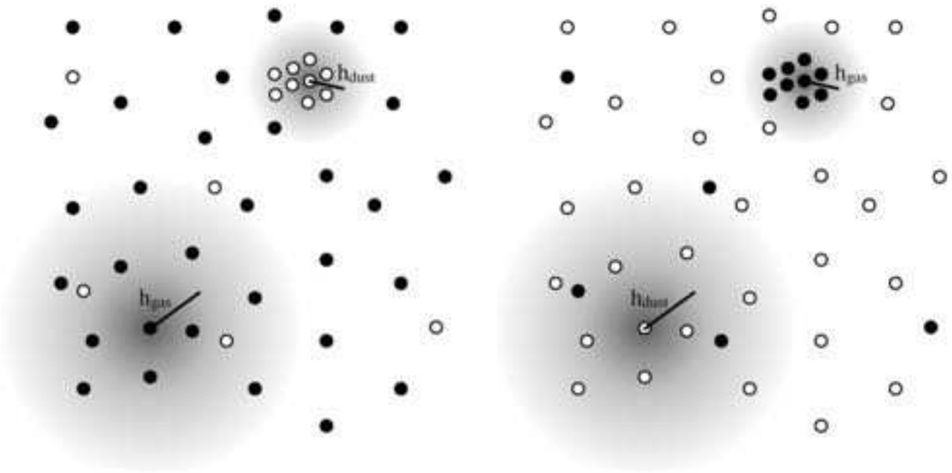
We treat dust as a pressure-less fluid

Two methods

2-fluid: separate set of particles for dust grains; see figure

1-fluid: one set of particles, evolve dust-fraction on gas particles





Note:

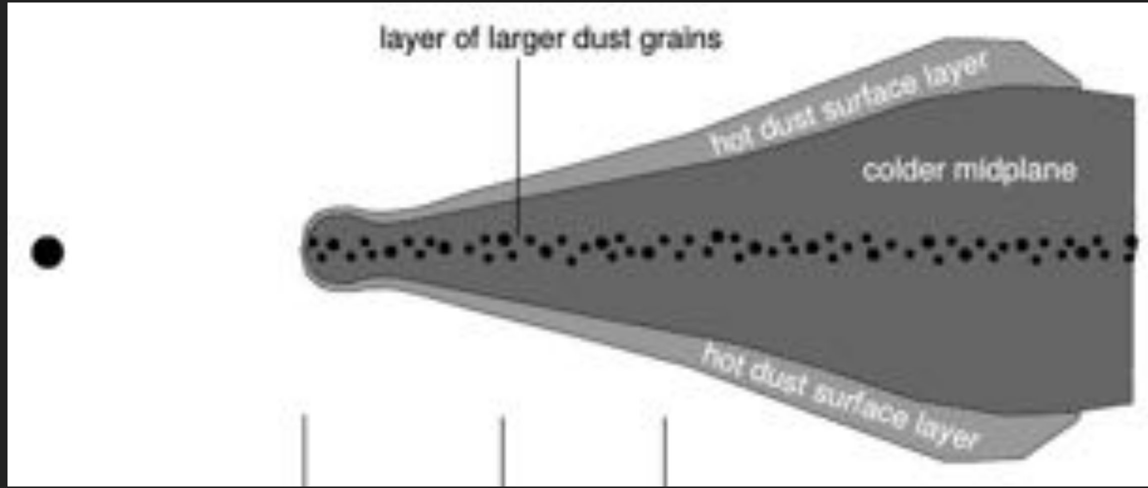
Only one grain size per calculation

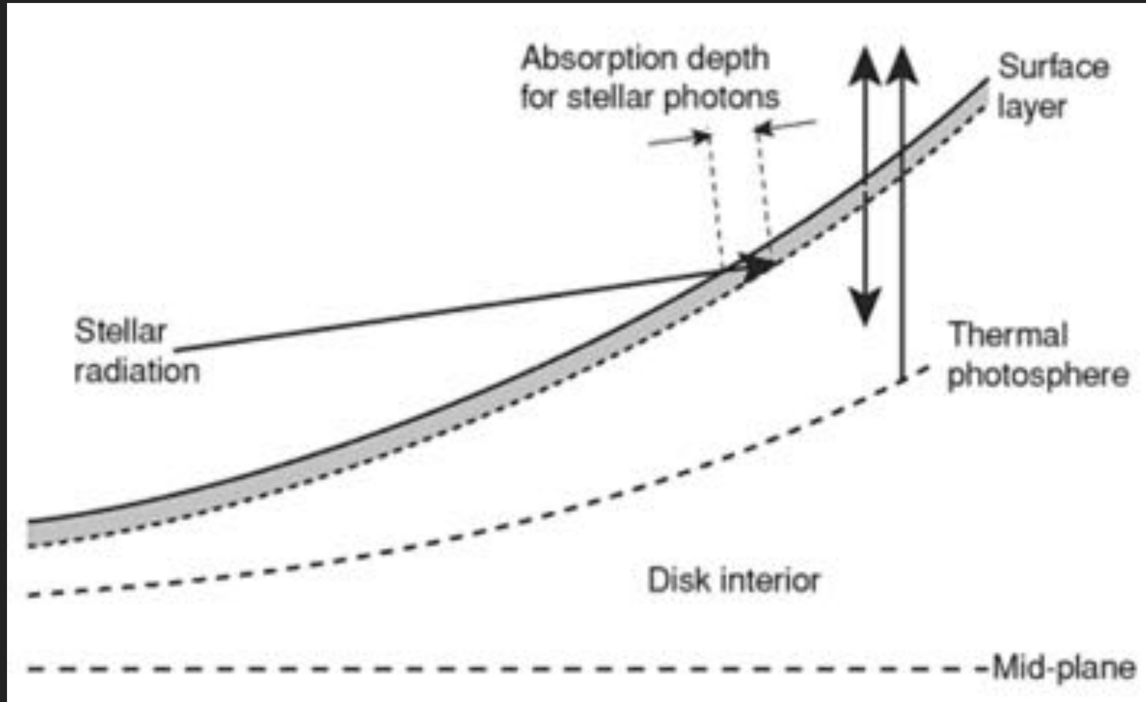
Dust (and gas) can interact gravitationally with stars and embedded planets

Credit: Laibe+Price2012, NASA/JPL

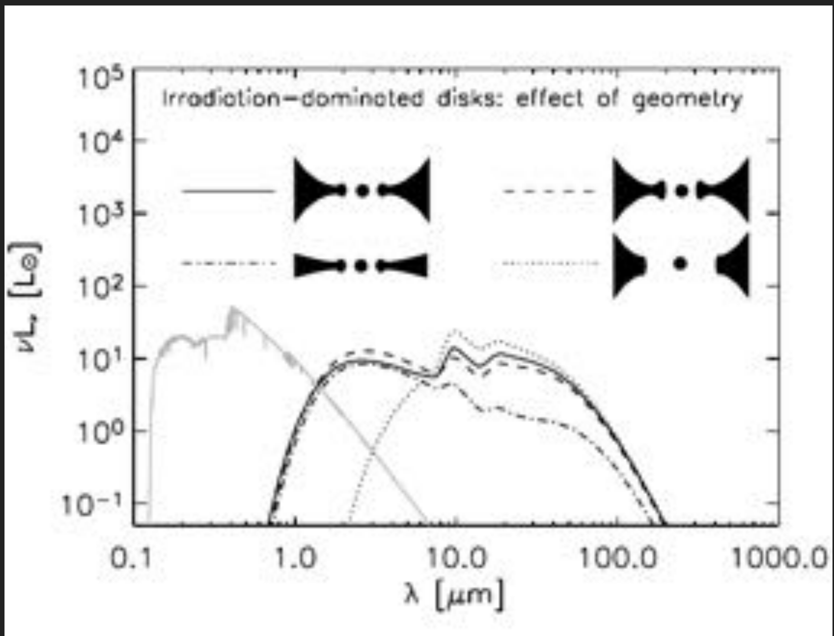
STELLAR IRRADIATION

- Dust sets opacity
- Radiation sets the disc temperature
- Compare with observation





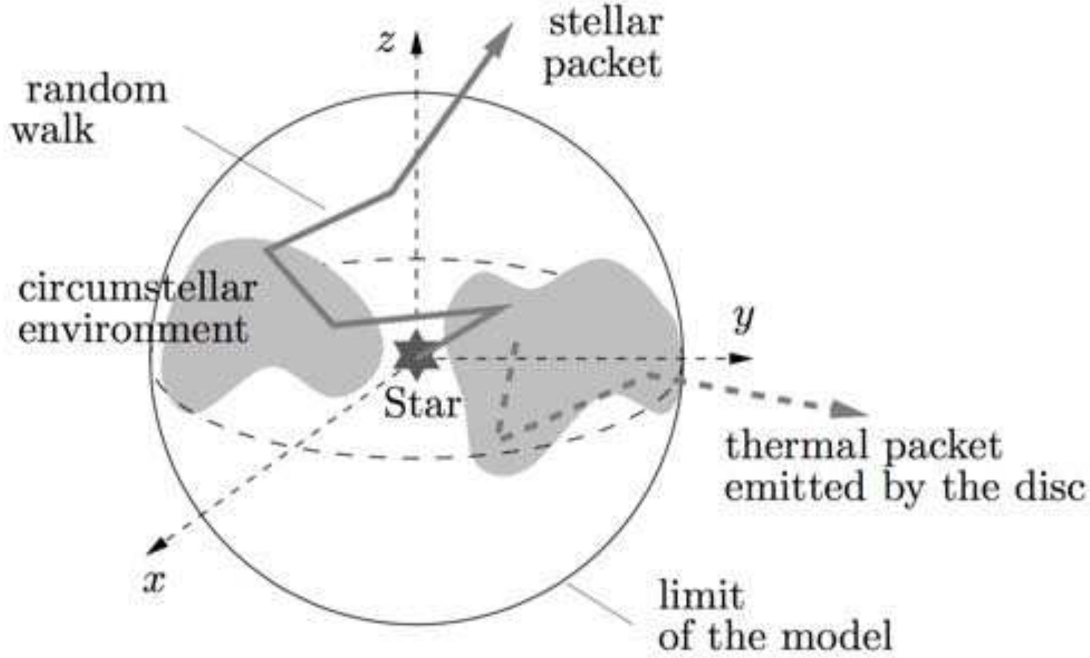
Dust in hot upper layers of disc reprocesses starlight

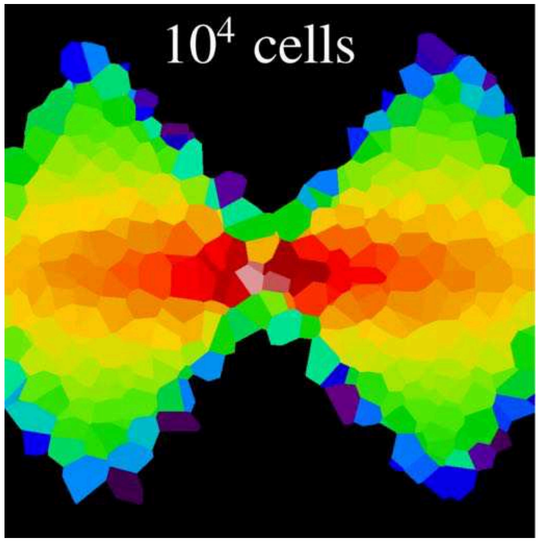


Credit: Dullemond+2007, Armitage2010

MONTE CARLO RADIATIVE TRANSFER WITH MCFOST

- Absorption, emission, scattering, polarisation
- Frequency-dependent
- Determine disc temperature



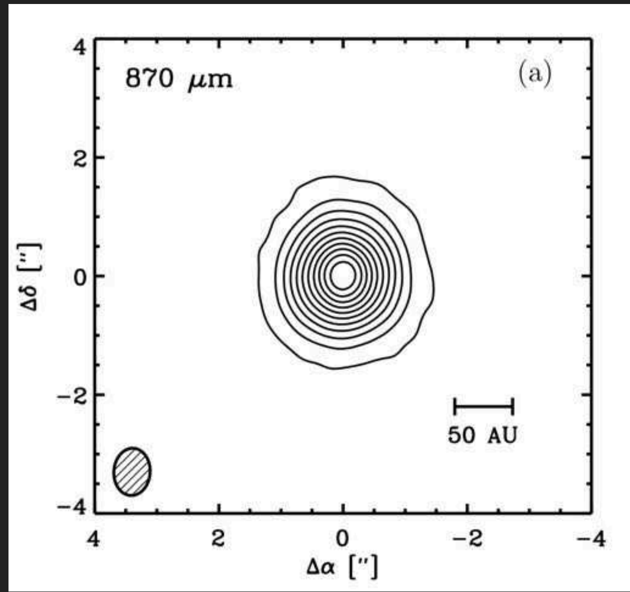


- Voronoi-mesh for SPH data
- Post-process PHANTOM simulations– produce synthetic observations

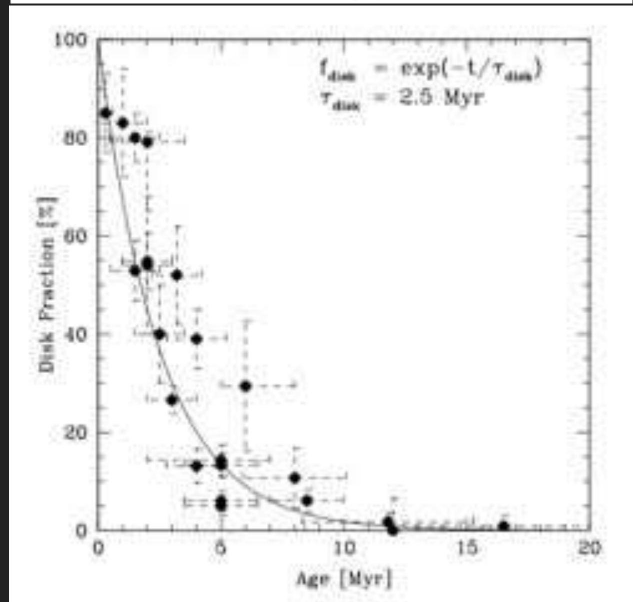
Credit: Pinte2015, Camps2013

THE NEAREST GAS-RICH PROTOPLANETARY DISC

- Distance: 59.5 pc (Gaia) ⇨ very close, cf. Taurus at 140 pc
- Age: ≈10 Myr ⇨ older than expected
- Disc mass (gas): ~10^{-4} – 10^{-1} $M_{\odot}$ ⇨ debate in literature
- Face-on: inclination ~7° ⇨ can see dust features (if there)

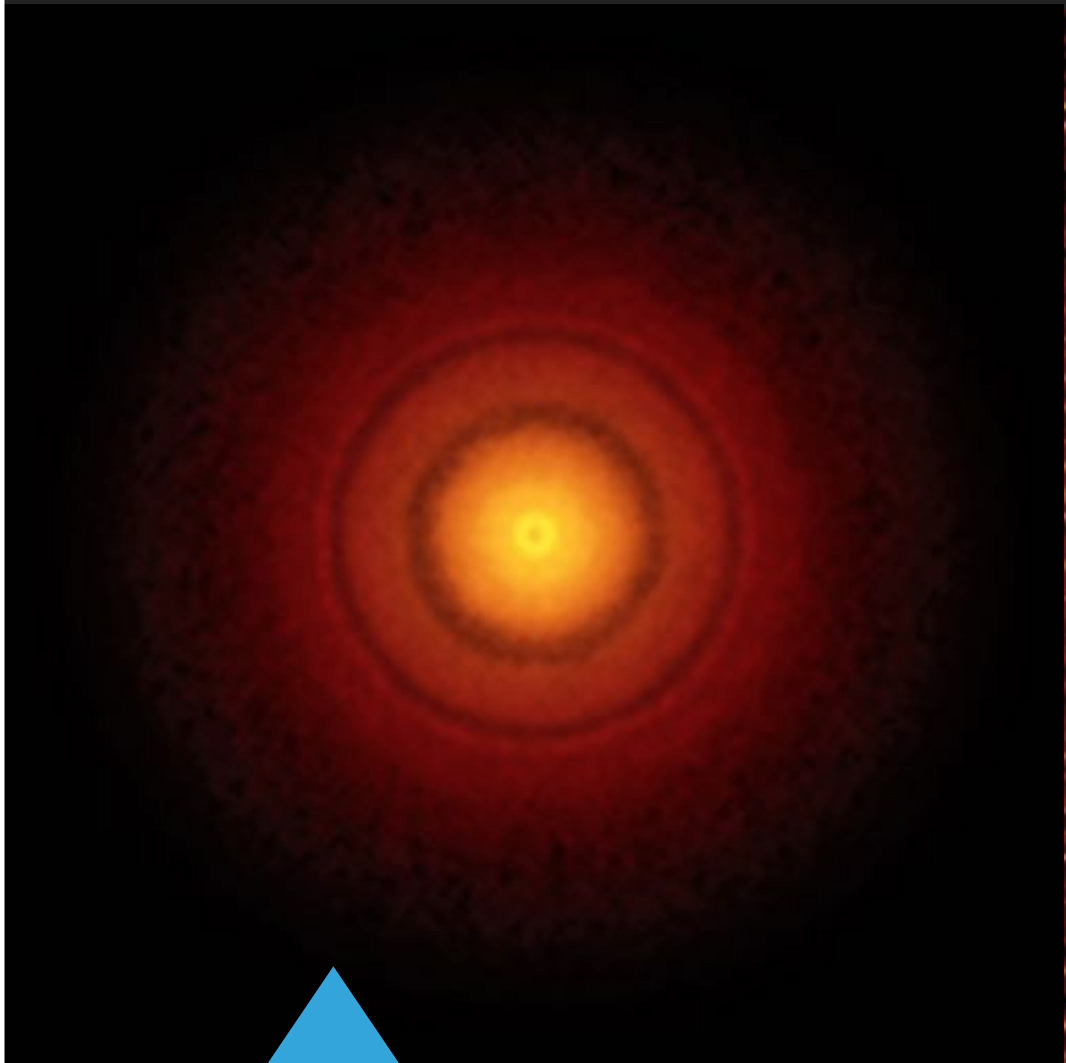


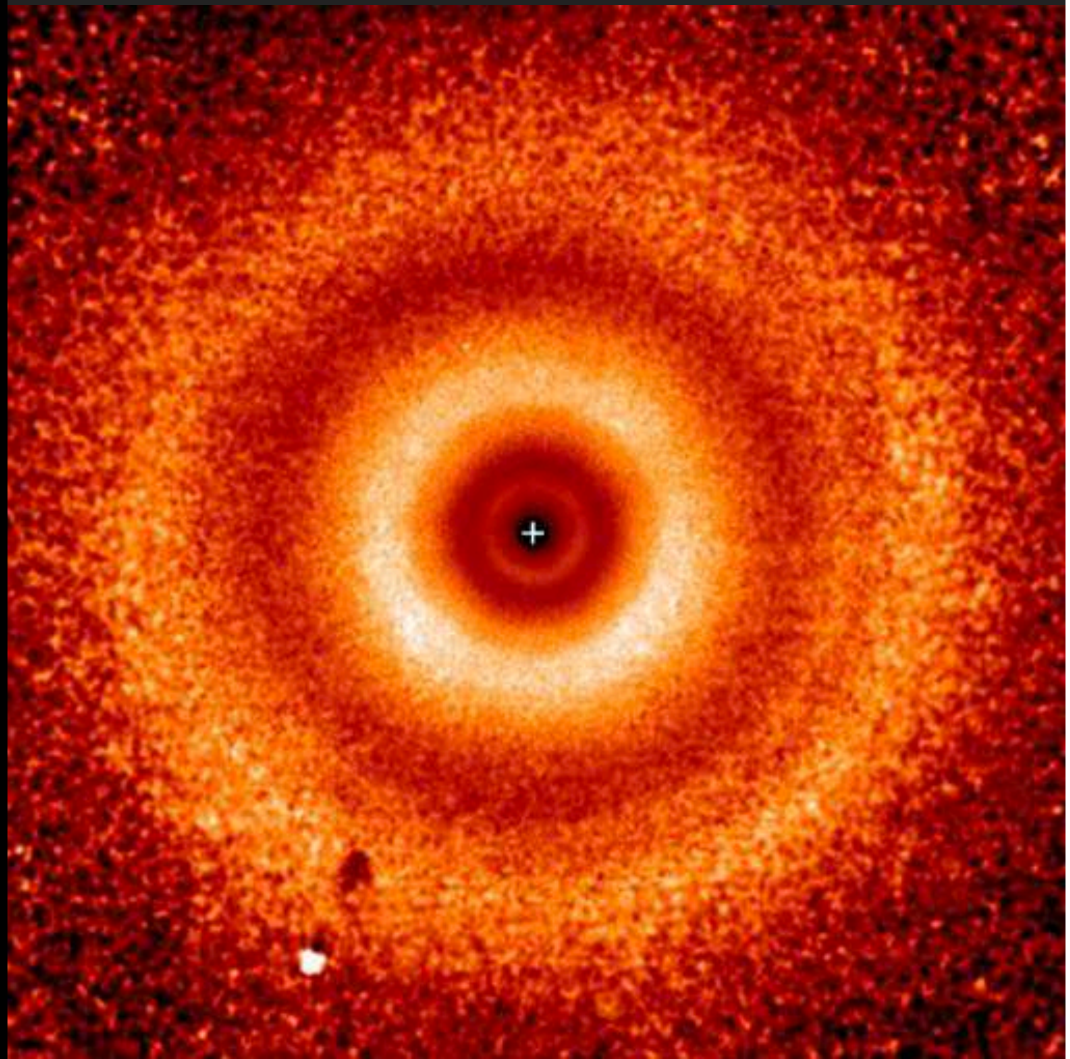
a blob



Credit: Andrews+2012, Mamajek2009

ALMA AND SPHERE OBSERVATIONS



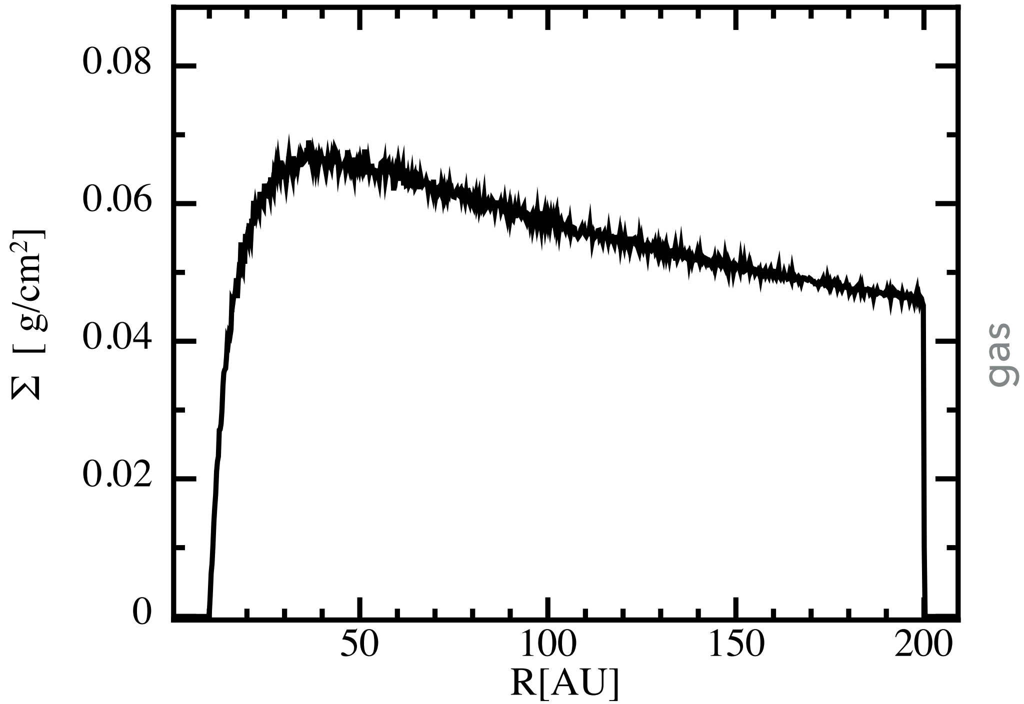


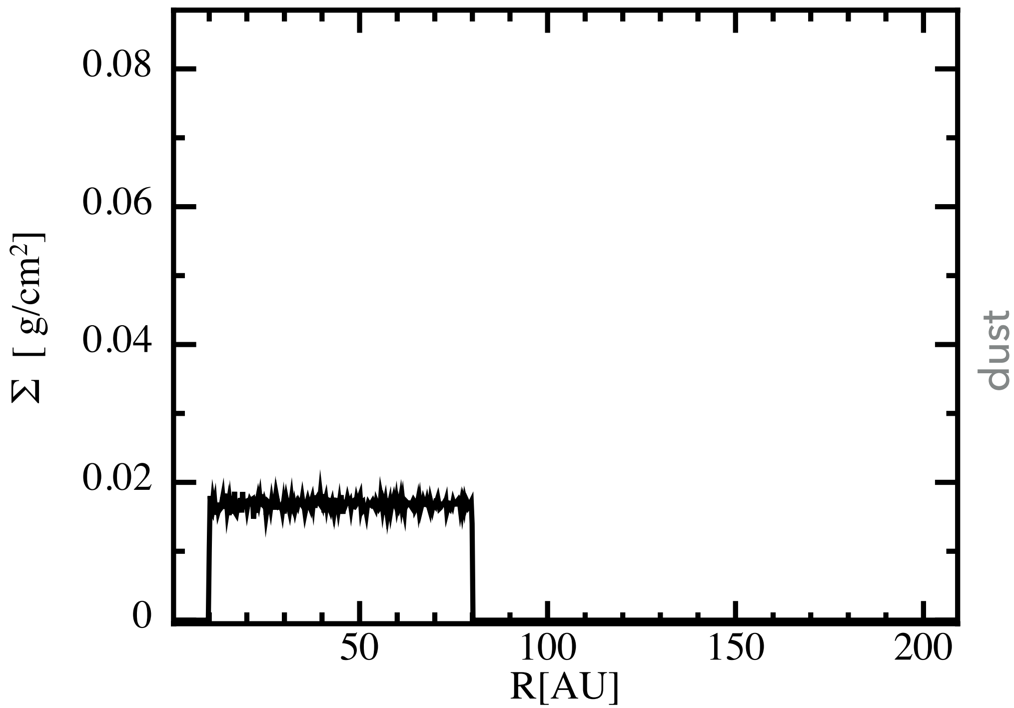
not a blob

Credit: S. Andrews, ALMA (ESO/NAOJ/RNAO); van Boekel+2017

DISC MODEL

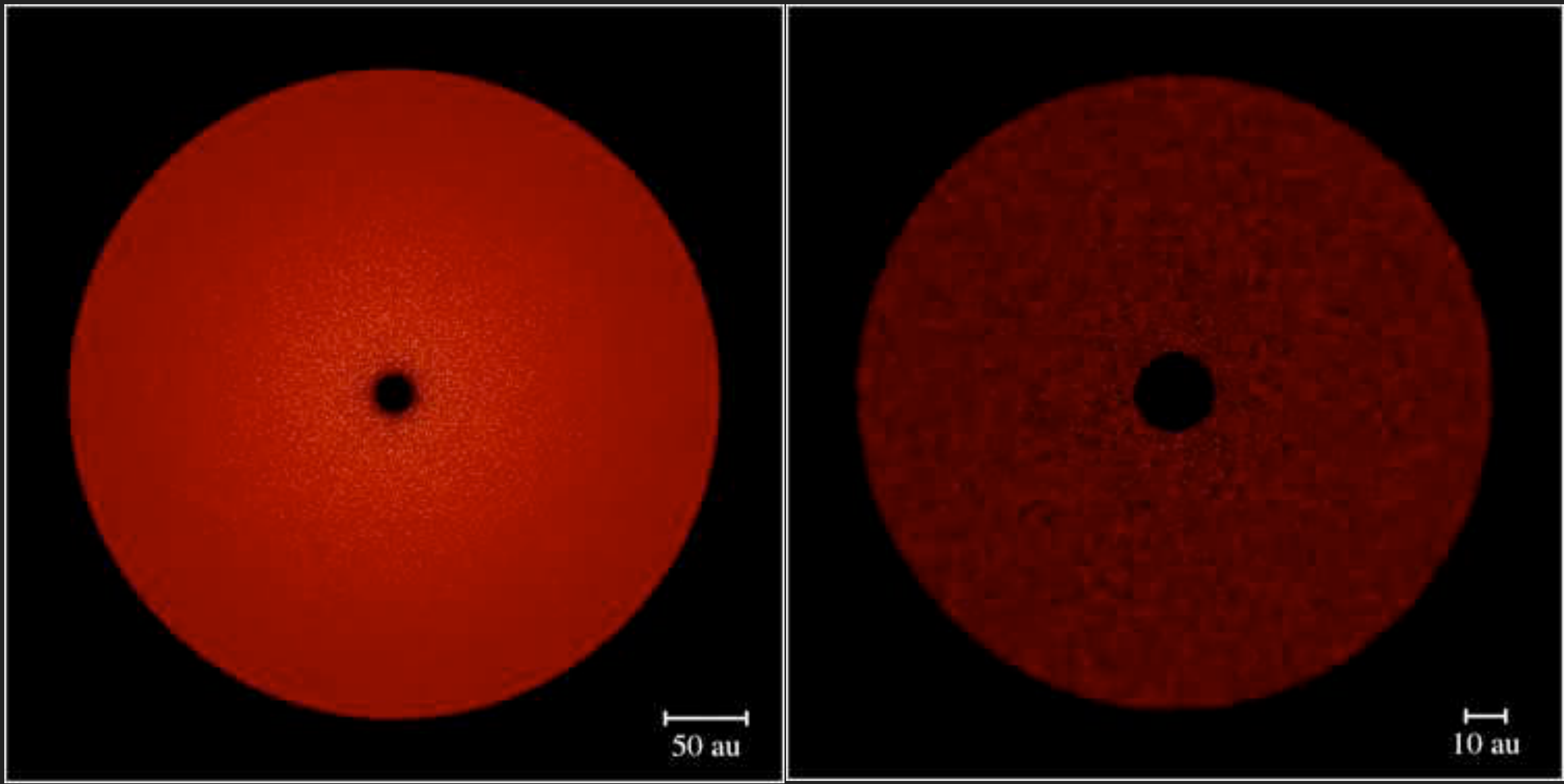
- Gas disc: $7.5\times10^{-4}\,M_\odot$ to 200 au with surface density $\Sigma \sim R^{-0.5}$
- Dust: 100 µm with St ≈ 1, disc to 80 au
- H/R (at R=10au) = 0.034
- Resolution: 10^7 gas + 2.5×10^5 dust
- Planets:
  - 8 Earth-mass at 24 and 41 au
  - Saturn-mass at 94 au





PHANTOM DUST+GAS HYDRO SIMULATION

Gas Dust

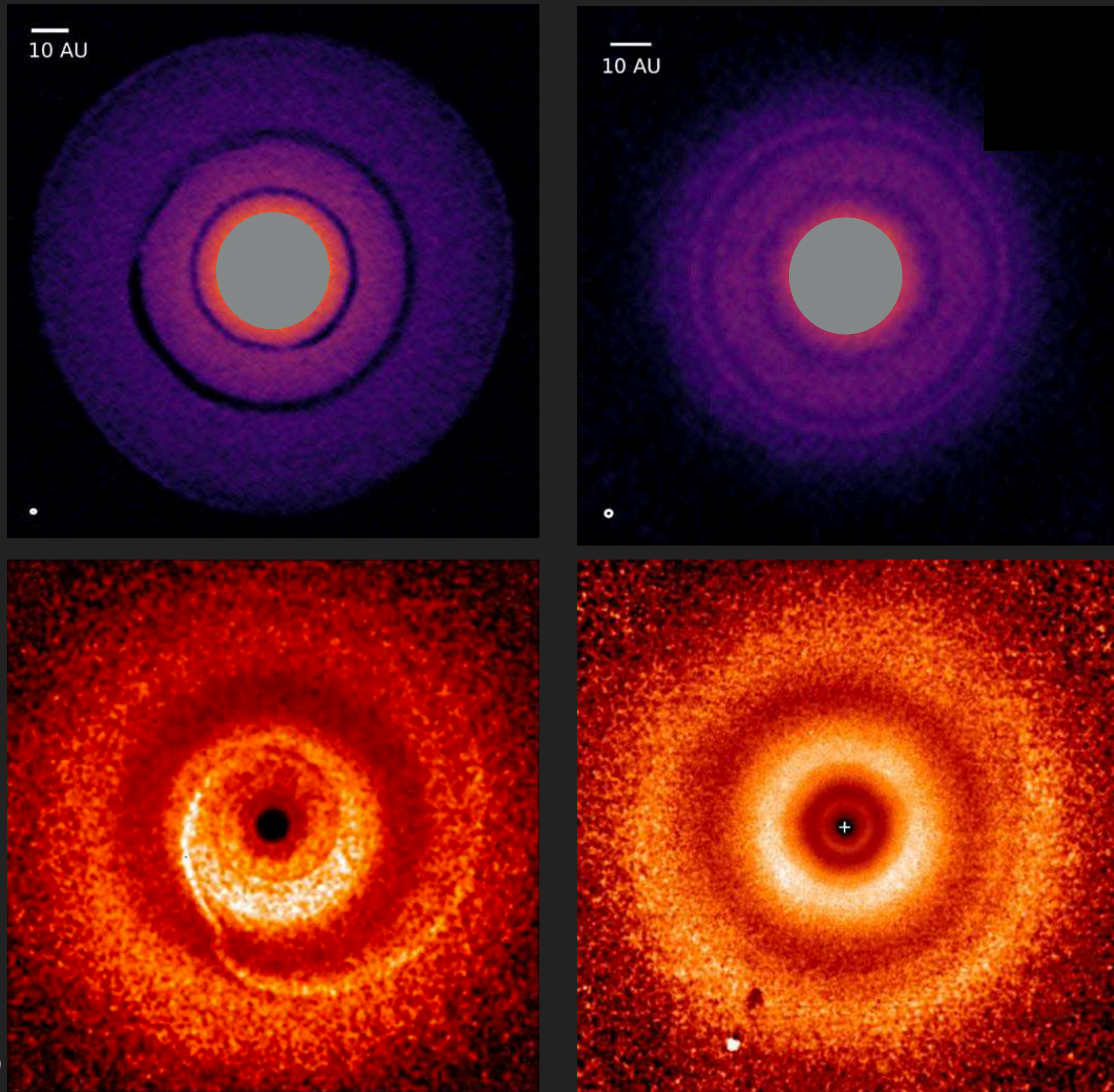


Rendered column density movie over 65 orbits at 41 au (location of middle planet)

SYNTHETIC OBSERVATIONS IN MCFOST

- 870 µm continuum emission: MCFOST + CASA ALMA simulator
- 1.6 µm polarised scattered light: MCFOST + artificial noise

simulation observation



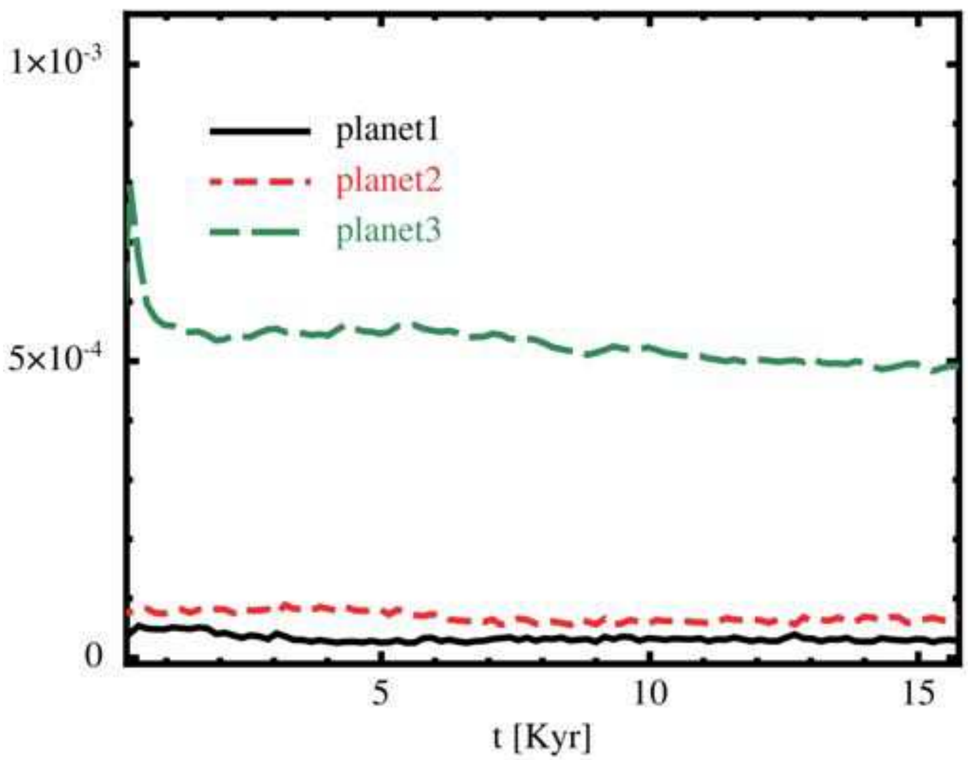
Credit: van Boekel+2017, Andrews+2016

PLANETARY ACCRETION

Super-Earths

10%: from 8 to ≈9 $M_\oplus$

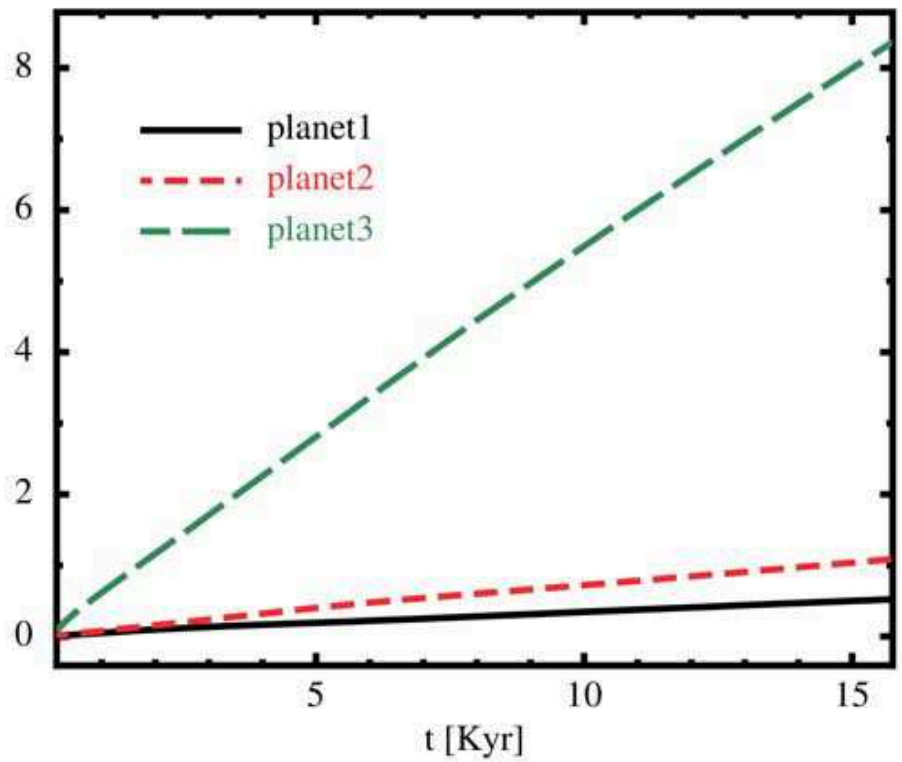
$\dot{M}$ [$M_\oplus$/yr]



Saturn

10%: from 0.3 to 0.32 M_J

M_{acc} [$M_\oplus$/yr]

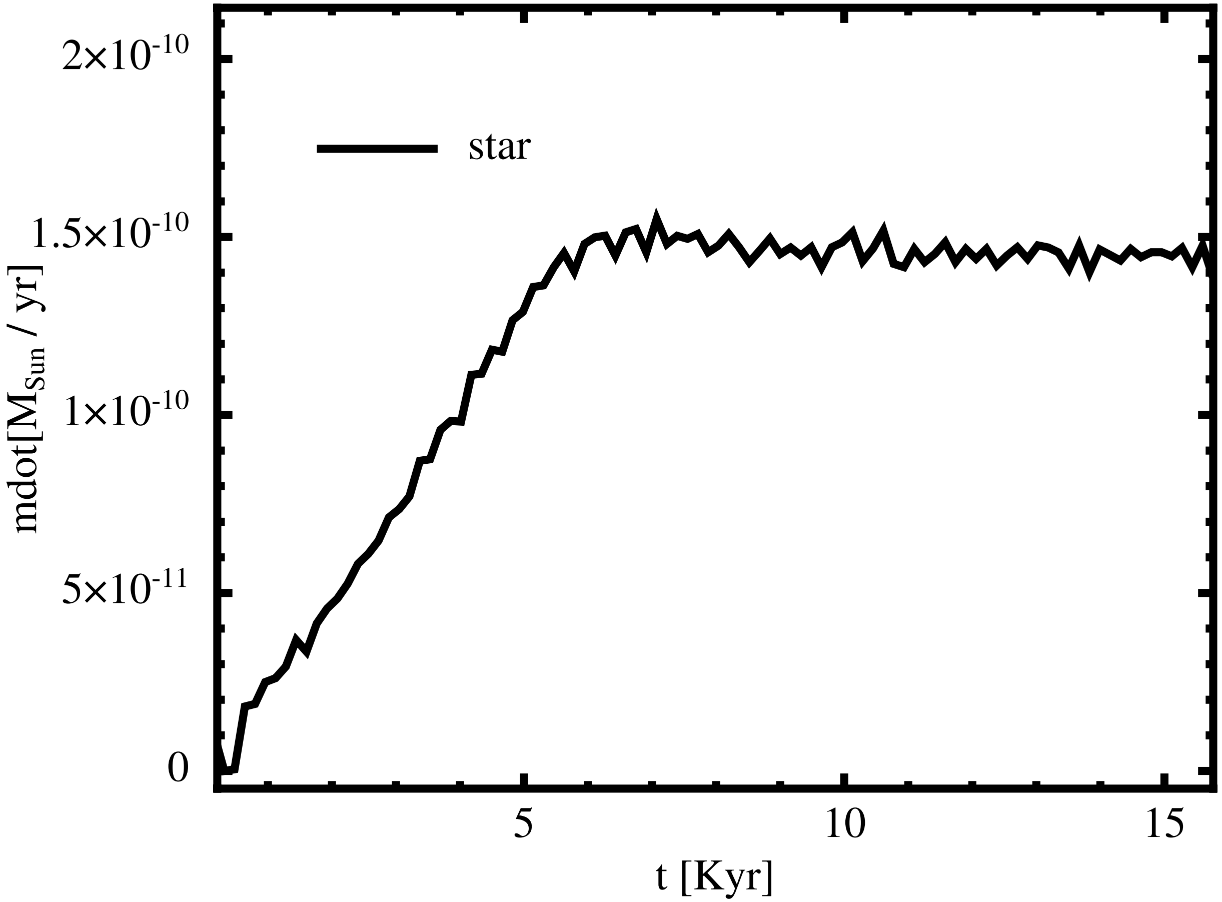


STELLAR ACCRETION RATE

- Measured accretion rate ≈ $1.5\times10^{-9}\ M_\odot$/yr
- Could increase viscosity BUT

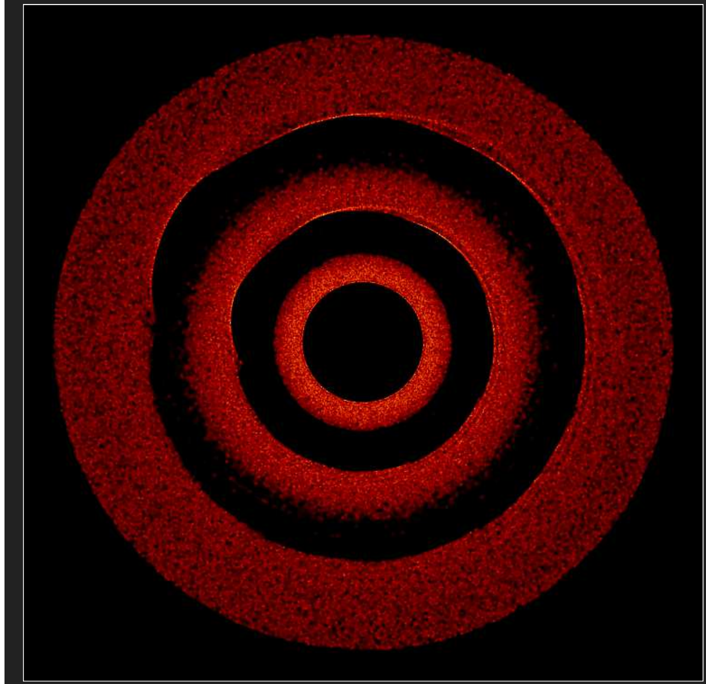
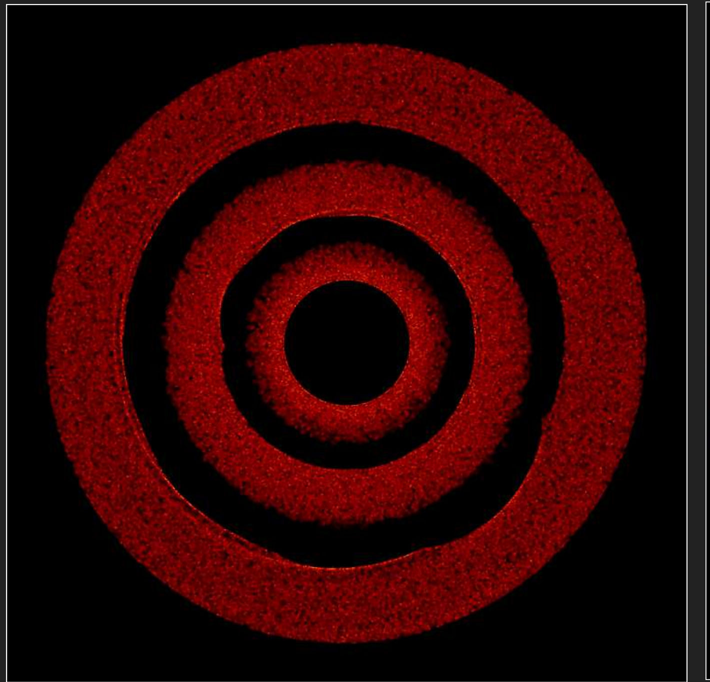
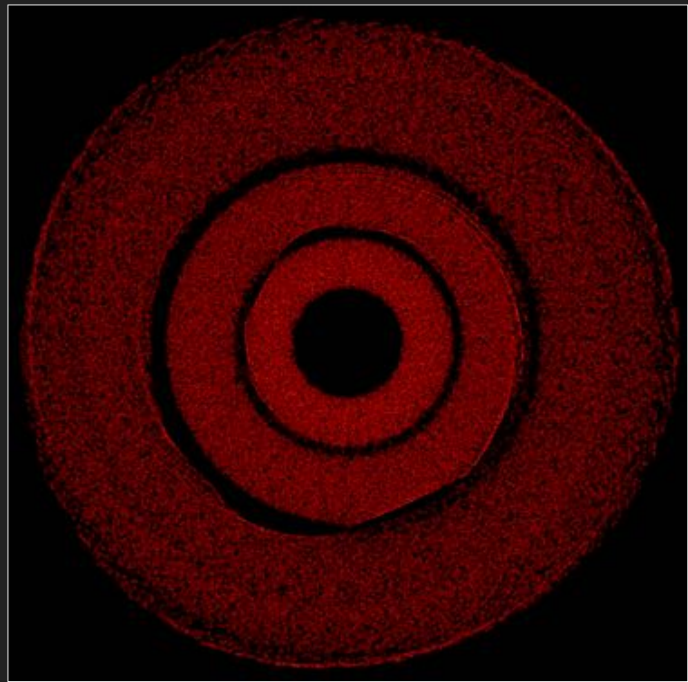
  planets accrete too much

  ⇒ gaps too wide



PLANET MASSES

Grain size & approx. Stokes number

1 mm: St ~ 5	1 mm: St ~ 5	100 μm: St ~ 0.5
		
$M_{24au} = 16\ M_{\oplus}$	$M_{24au} = 8\ M_{\oplus}$	$M_{24au} = 8\ M_{\oplus}$
$M_{41au} = 12\ M_{\oplus}$	$M_{41au} = 8\ M_{\oplus}$	$M_{41au} = 8\ M_{\oplus}$

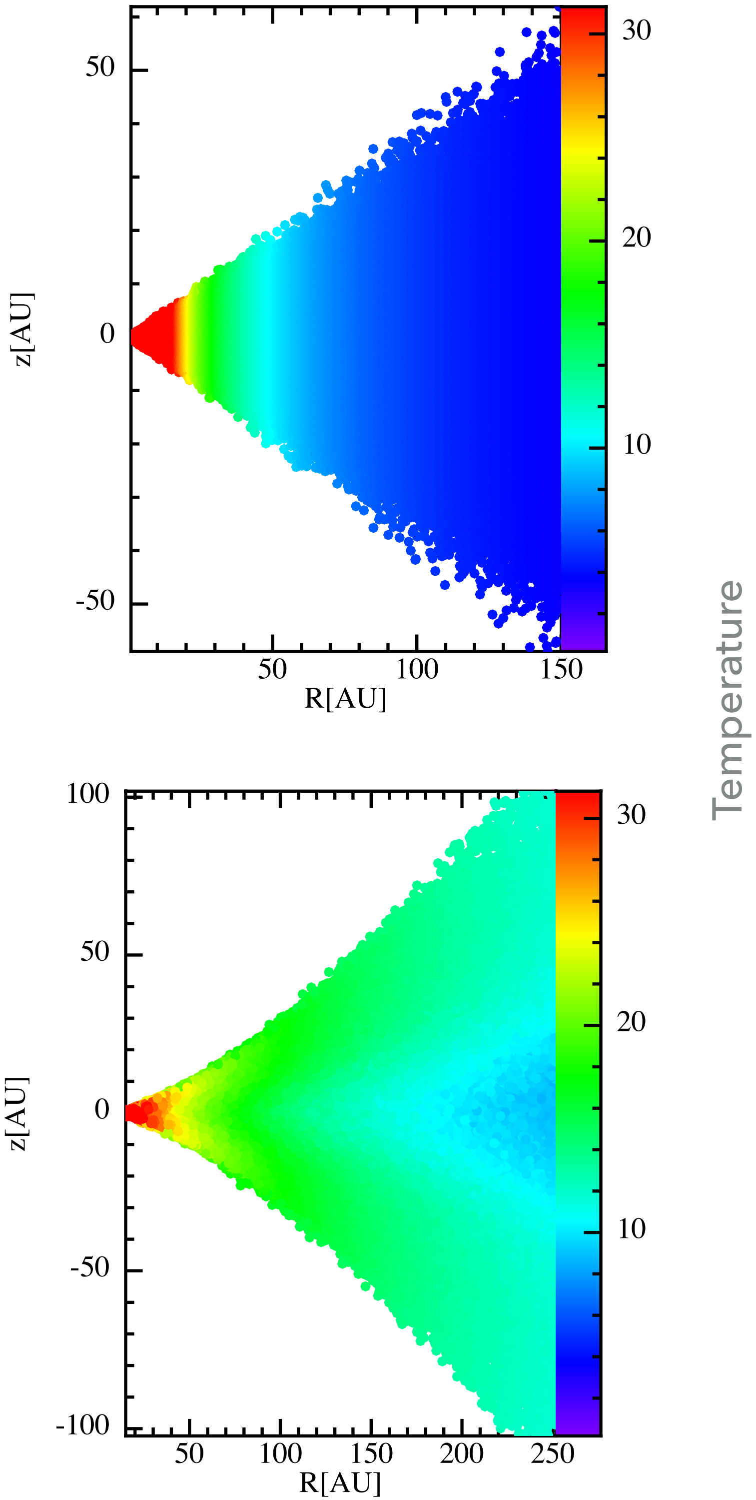
Initial planet masses

RESULTS

- We explain the narrow gaps in ALMA dust emission with super-Earths (8–10 $M_{\oplus}$) at 24 and 41 au.
- We explain the dip in scattered light with a Saturn-mass planet at 94 au with mass low enough to hide strong spiral arm within instrument sensitivity.
- *We can infer presence of otherwise **undetectable planets** 'caught in the act' of formation, including super-Earths: the most common planets.*

PHANTOM + MCFOST

- Current hydro simulations use vertically isothermal approx.
  - Discs are not vertically isothermal
- Method:
  - Pass SPH particles from PHANTOM to MCFOST
  - Use MCFOST to determine disc temperature
  - Pass temperature back



WHAT WE CAN DO

- PHANTOM (hydrodynamics) → MCFOST (radiative transfer) to compare with observations
- TW Hydrae: a pair of super-Earths and Saturn
- PHANTOM (hydrodynamics) + MCFOST (radiative transfer)

WHAT WE WANT TO DO

- PHANTOM multigrain: all grain sizes together
- PHANTOM + MCFOST: radiative equilibrium hydrodynamics
- Dust around cavities: dynamics + radiation


Thanks for listening...
any questions?