Dust in Protoplanetary disks

(hunting for the very first stages of planet formation)

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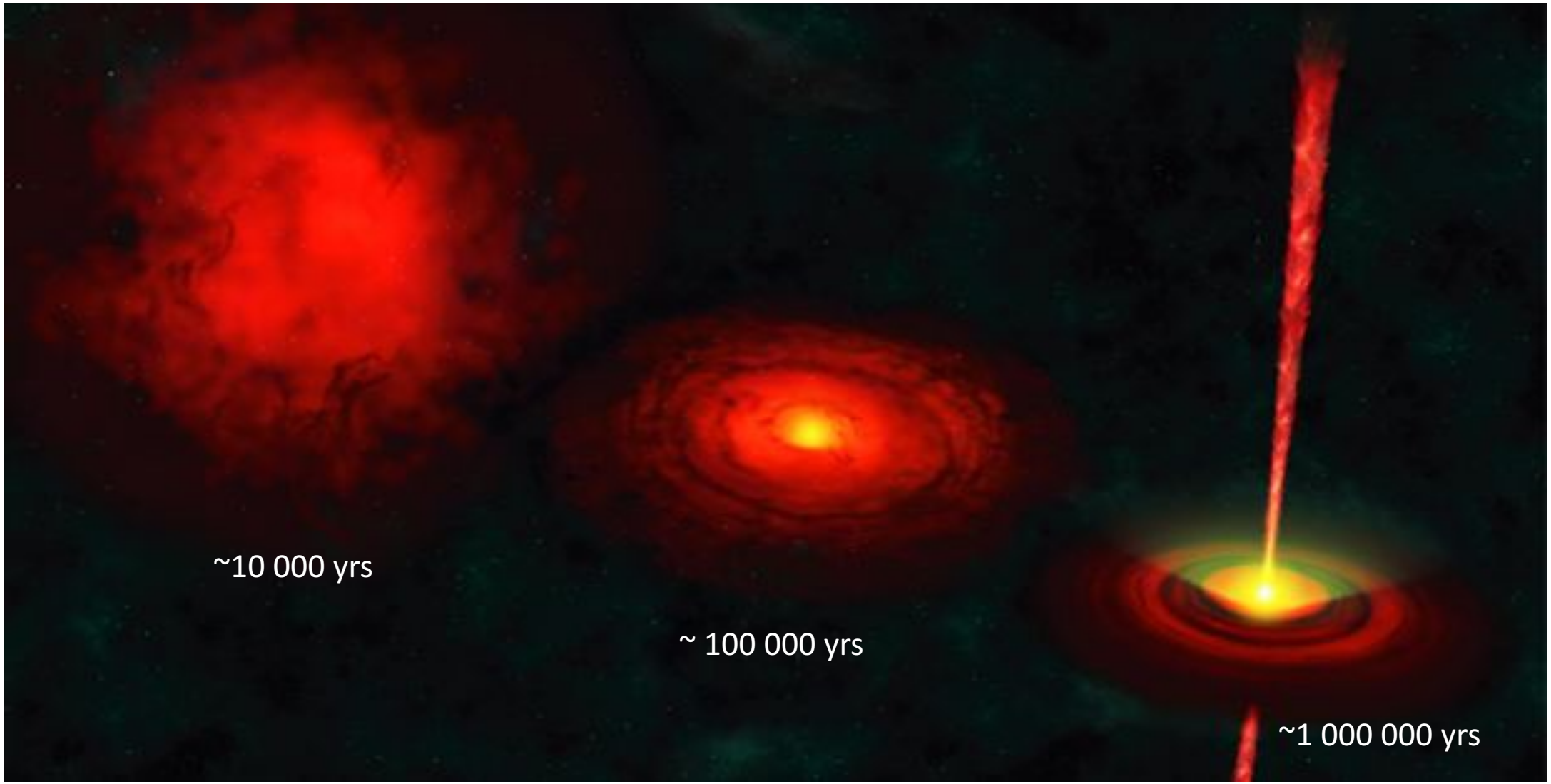
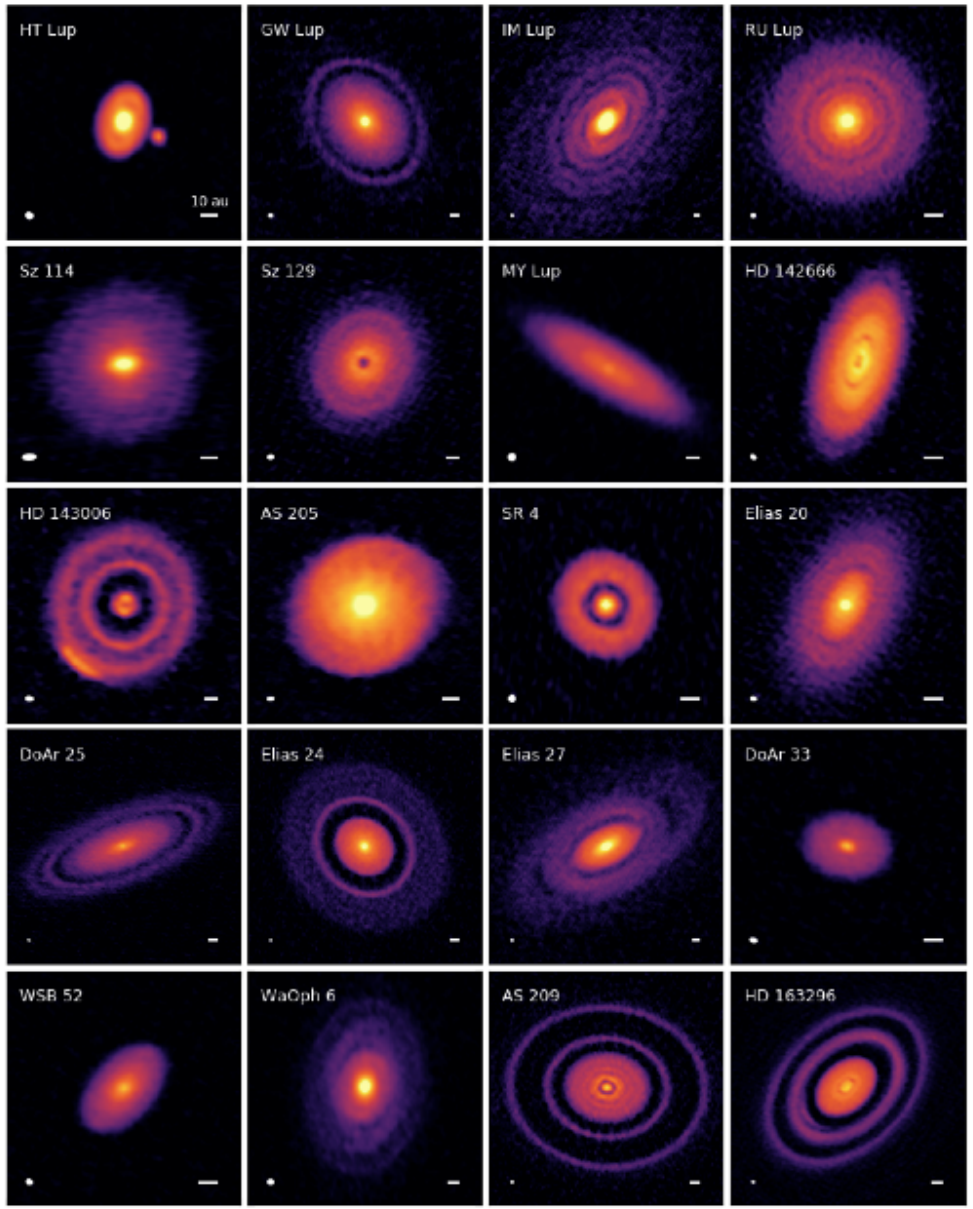
Star formation 101: collapse of a molecular core & angular momentum conservation

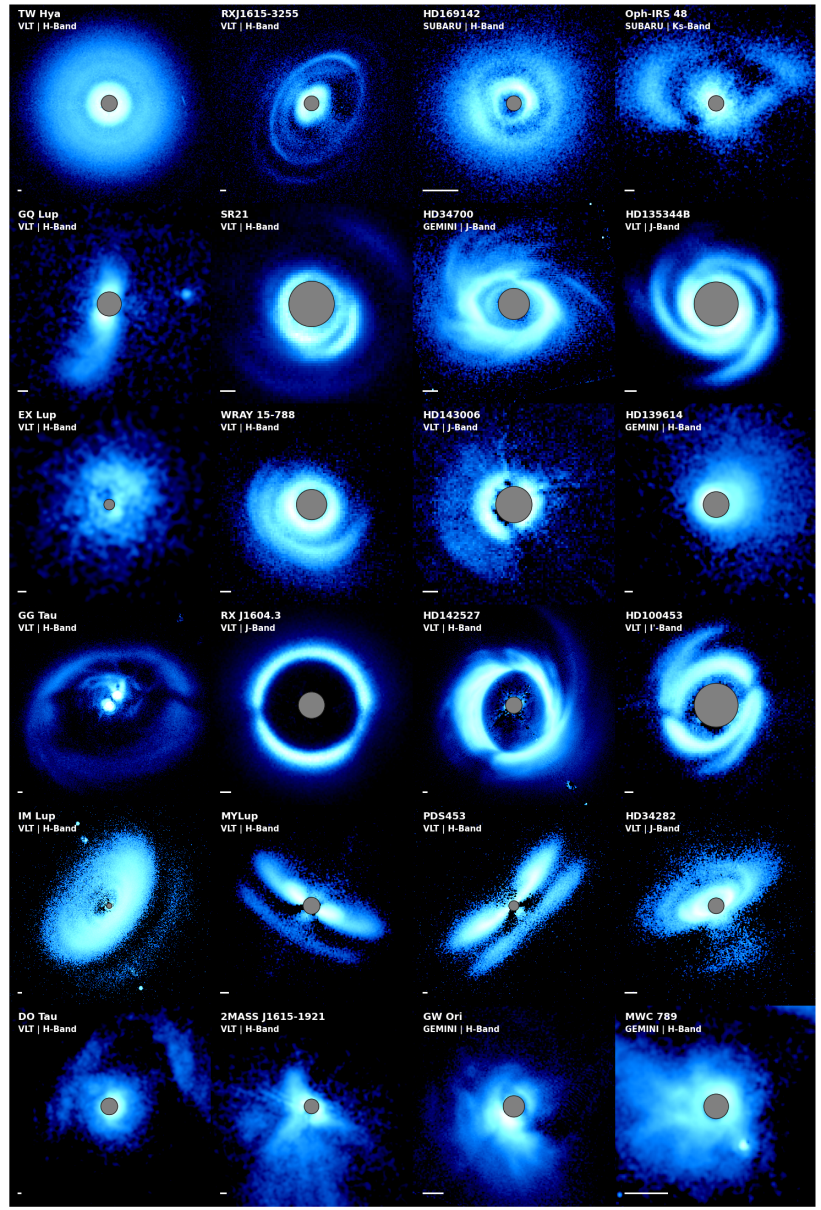


We now live in a 'data driven' era

Dust Thermal Emission – (sub)-millimeter



Scattered light - Near Infrared

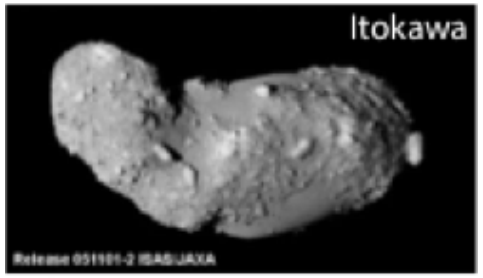


<- Andrews+2018
Benisty+2022 ->

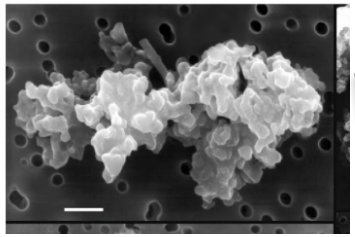
How do Pebbles grow into Planetesimals?

chondrules

asteroids



dust



10^{-6} m
micron-sized

μm mm cm m km 10000 km

10^{7}m, 10000 km

Growth by ~13 orders of magnitude in radius !!!

Recent Advances in Dust Evolution and Growth

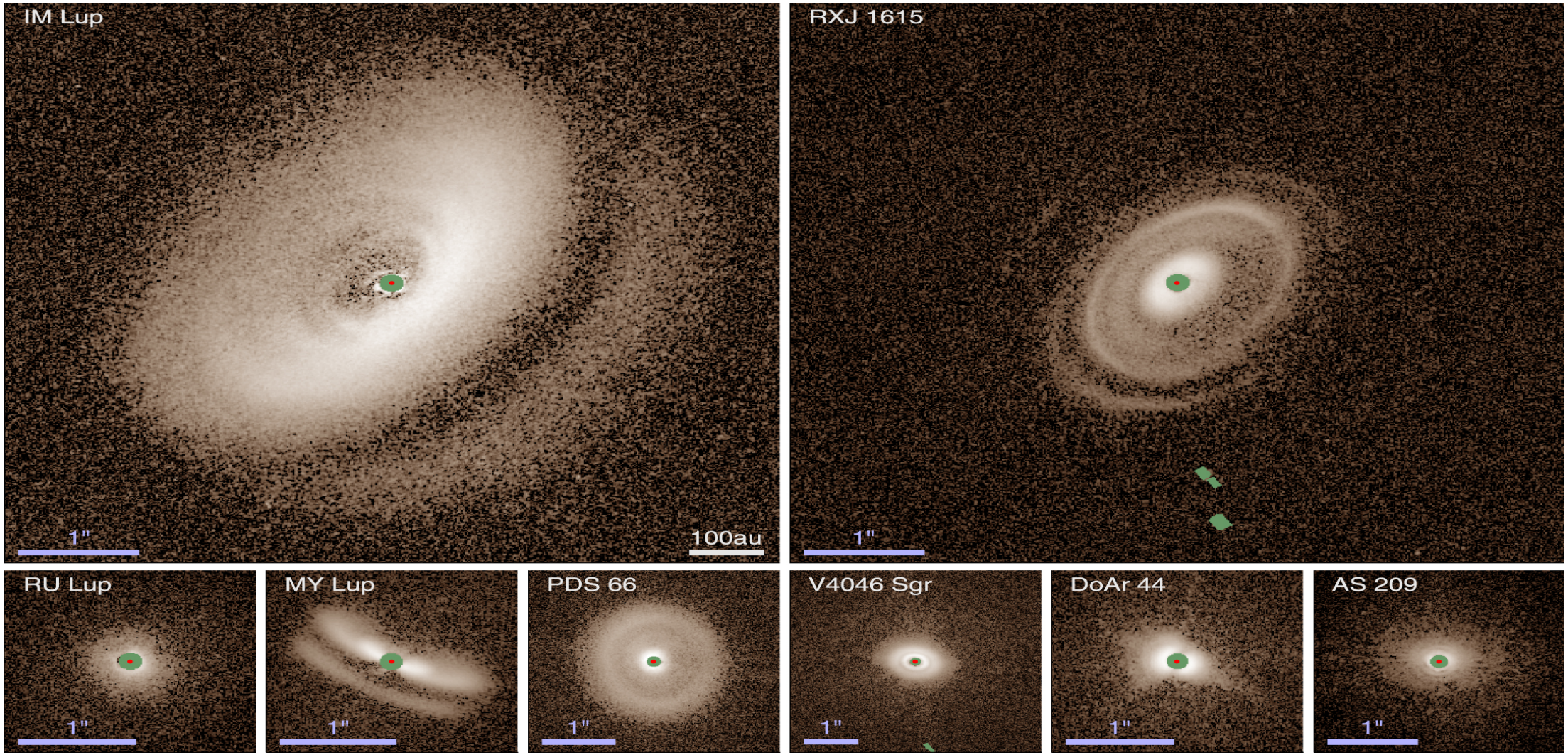
- Keep in mind that:
  - We aim to study micron- and mm- and cm-sized dust located ~500 light-years away!!!
  - Stars and disks evolve on timescales of ~Myr

- Need to use all the « tricks » available
  - Large samples of objects
  - Intensity maps
  - Linear Polarisation maps (and circular?)
  - Broad wavelength coverage
    - From Optical to Radio -> TO PROBE DIFFERENT REGIONS OF DISKS

- AND… model everything as coherently as possible
  - requires database(s) of dust properties

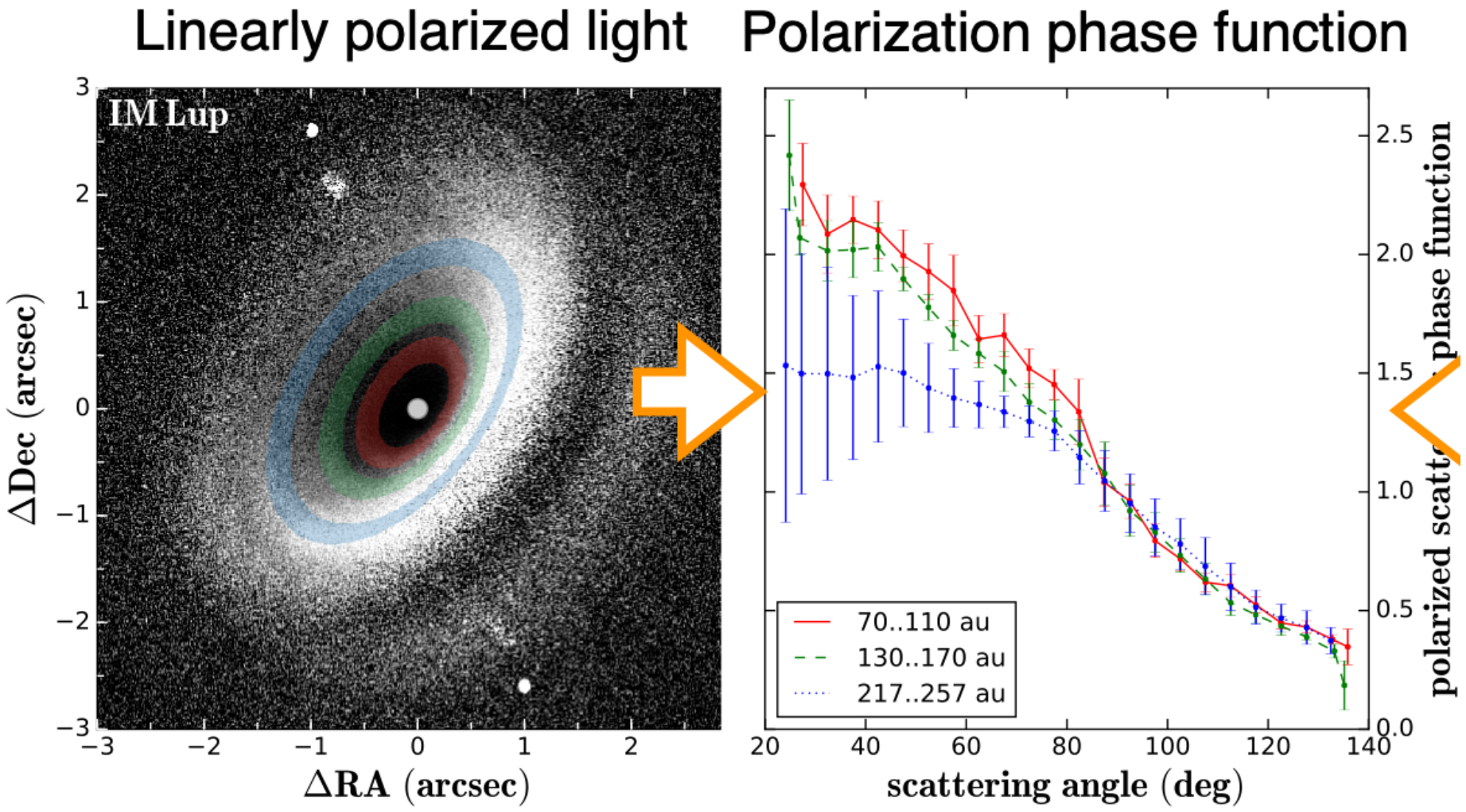
Recent advances I: High order AO systems

VLT / SPHERE H-band (1.6microns) **Polarised Intensity** Images



Avenhaus+ 2018, ApJ, 863.

Polarised Phase functions and Dust properties



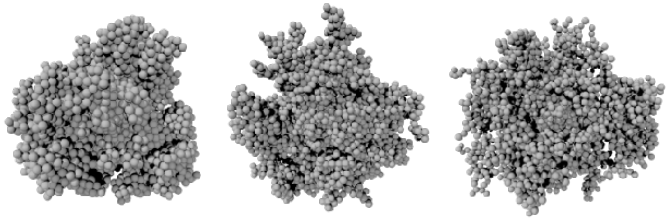
See Ryo Tazaki's talk image adated from Tazaki+ 2023

Ryo Tazaki's database -> well suited for NIR

AggScatVIR: Parameter coverage

7 wavelength grids: 0.554 μm, 0.735 μm, 1.04 μm, 1.25 μm, 1.63 μm, 2.18 μm, 3.78 μm

Compact aggregates (Df~3)



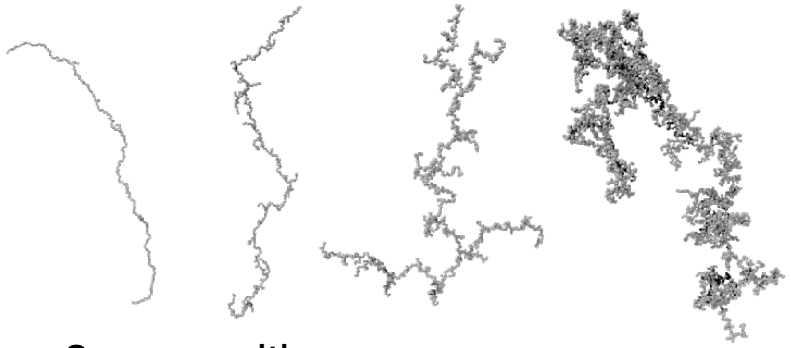
$\mathcal{P} \sim 60\,\%$ $\sim 70\,\%$ $\sim 87\,\%$

2 compositions,
3 monomer radii,
3 porosities,
7 aggregate radii (on average)
(4 realization for each)

2x3x3x7=126 SETS

Largest aggregate ~ 3 μm

Fluffy aggregates (Df<2)

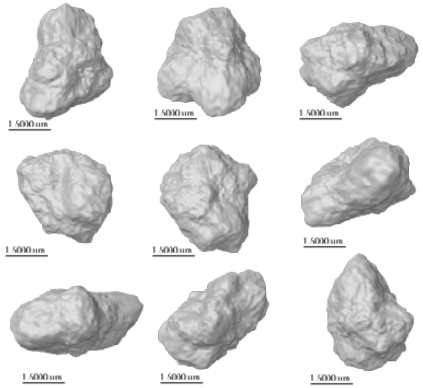


2 compositions,
5 monomer radii,
4 fractal dimensions,
5.35 aggregate radii (on average)
(4 realization for each)

2x5x4x5.35=214 SETS

Largest aggregate ~ 10 μm

Irregular grains



2 composition,
10 grain radii
(10 realization)

2x10=20 SETS

Largest grains ~ 1.6 μm

https://github.com/rtazaki1205/AggScatVIR

Microwave Analogy: a different, powerful approach

https://www.fresnel.fr/EMSCOP/

EMSCOP : A new scattering database

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Abstract : EMSCOP is a freely accessible database, developed and managed by Institut Fresnel (cf fresnel.fr/EMSCOP). It contains measurements and simulations of the scattering properties of various geometries of particles. For now, information on two types of particle is presented in this database : rough spheres and aggregates of 74 monomers. For each type, different samples with various pre-defined characteristics (fractal dimension varying from 1.5 to 2.8 for aggregates, and roughness percentage from 2 to 13 for rough spheres) were measured and simulated. The measurements were performed in the anechoic chamber of the CCRM (Centre Commun de Ressource en Micro-Onde) in Marseille, between frequencies of 3 to 18 GHz, i.e. that the size parameter of the particles varies from 1 to 20. The computations were performed with a homemade finite element code, for the same samples within the same frequency range, in order to cross validate the measurements. The data are given following the Jones or Mueller formalism.

INSTITUT FRESNEL MARSEILLE

IPAG Institut de Planétologie et d'Astrophysique de Grenoble

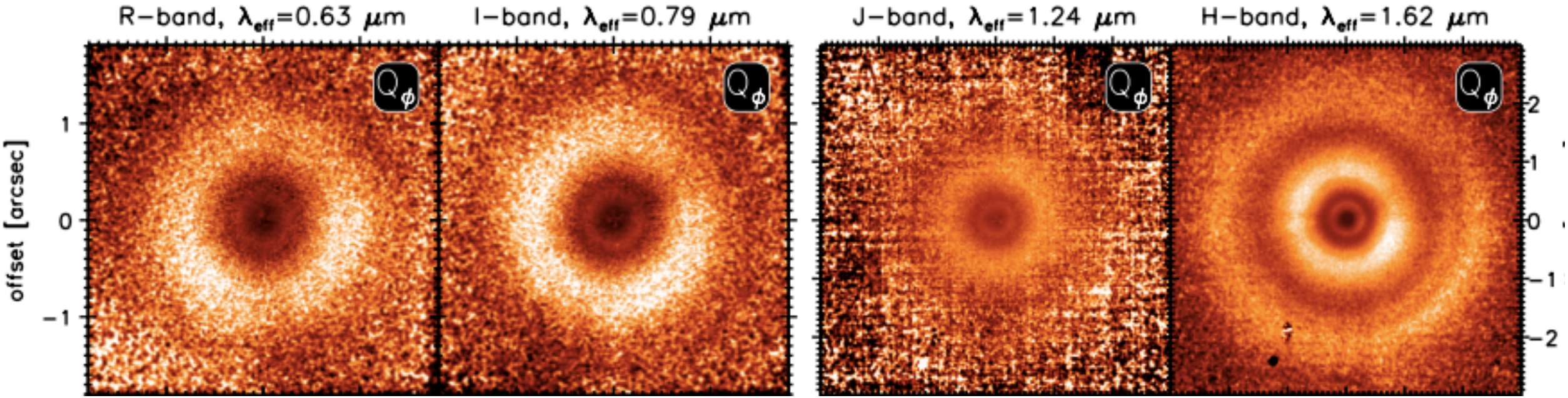
This database is from laboratory measurements and calculations

Wavelength coverage needed to go further

TW Hya

SPHERE / ZIMPOL

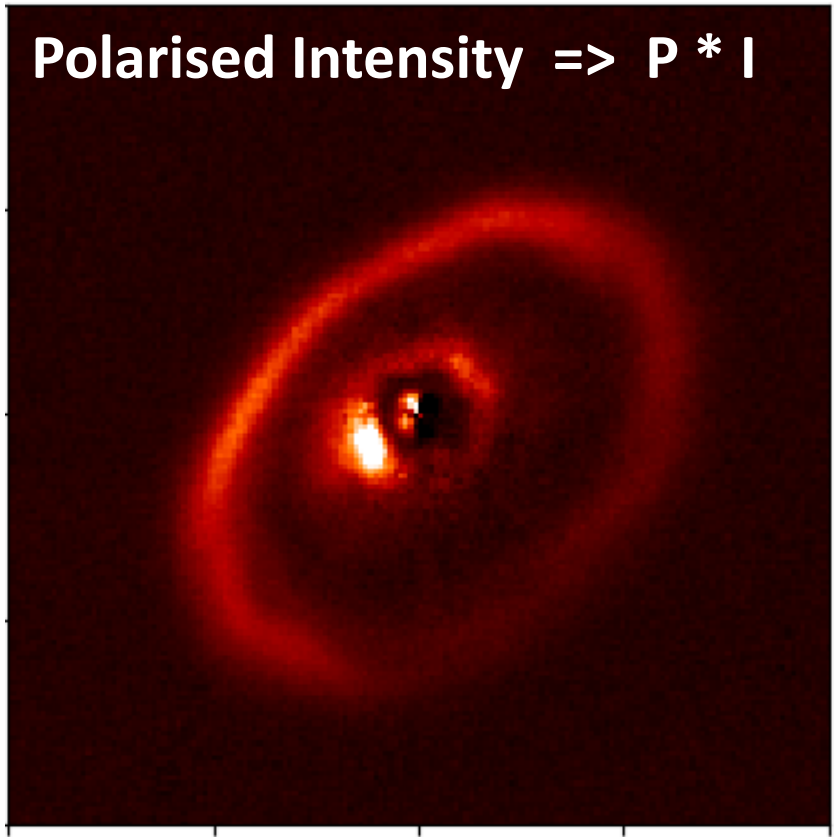
SPHERE / IRDIS

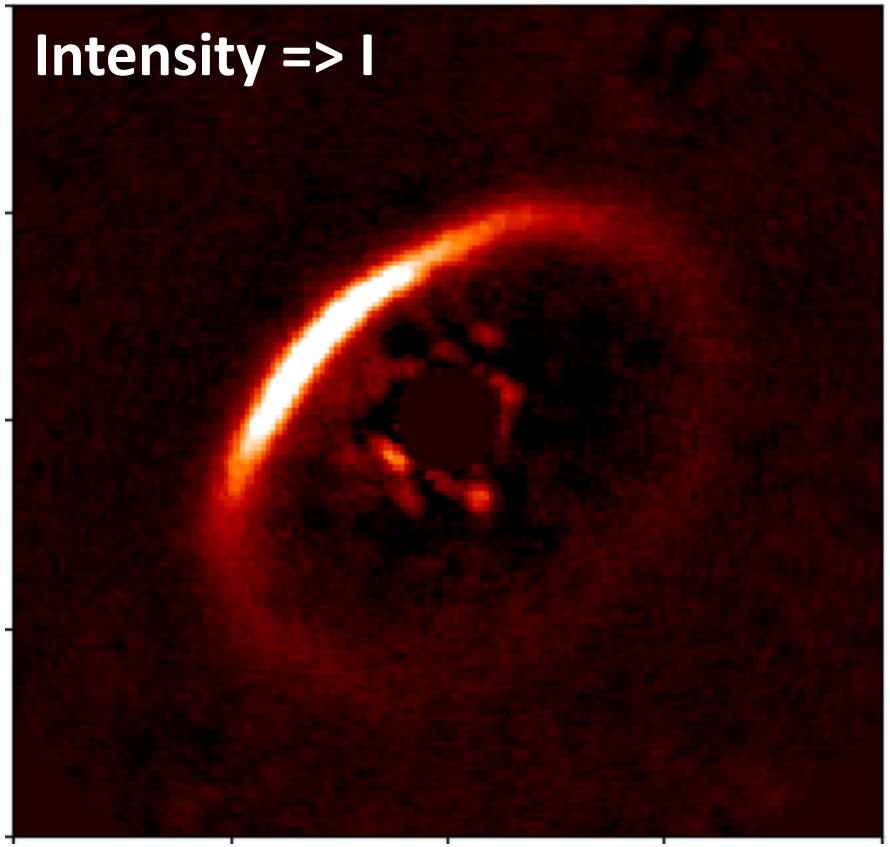


van Boekel+ 2017

Calibrated Intensity images needed

HD 163296





HD 163296, SPHERE H-Band image

Data processing with advanced pipeline is required !!!!

Stokes I (Intensity) images require advanced treatment

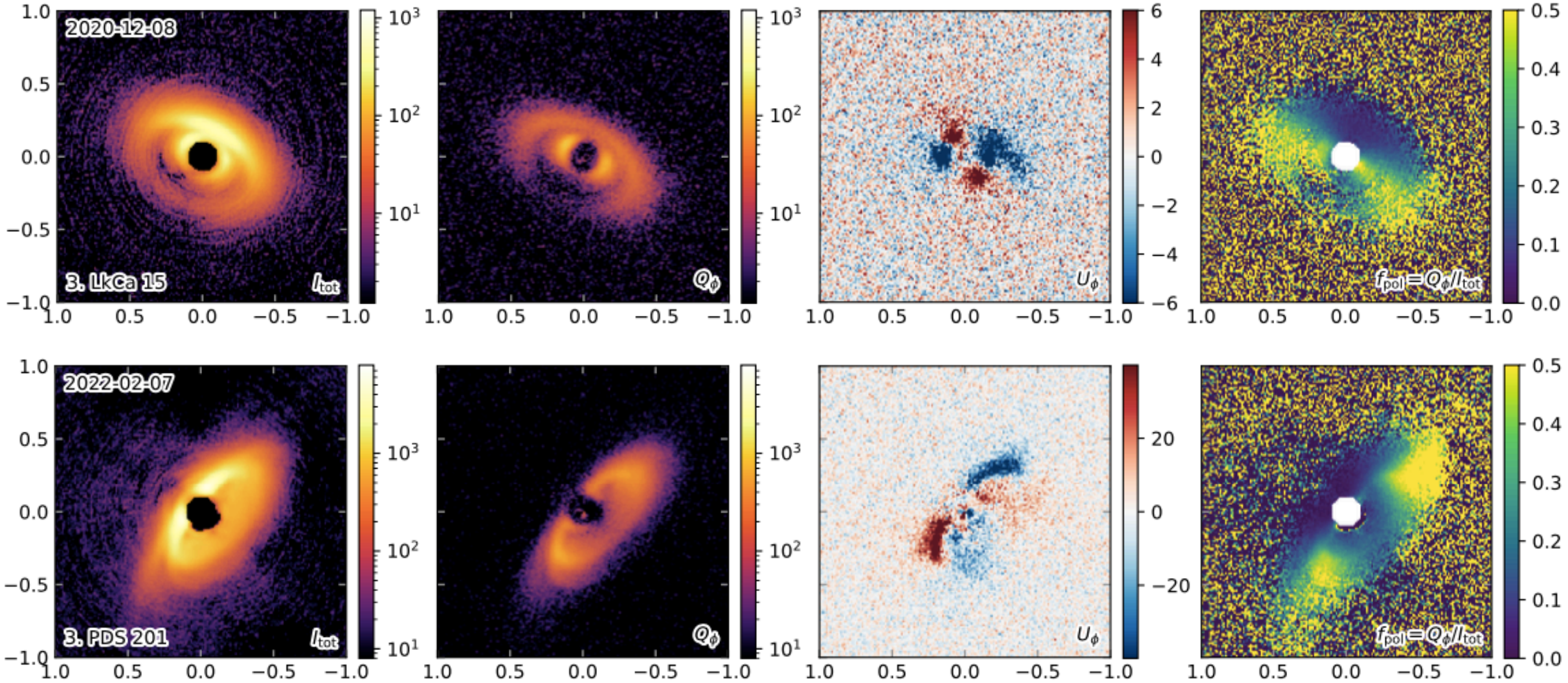


Image courtesy of Bin Ren, Nice Observatory. To be published in Ren+2023

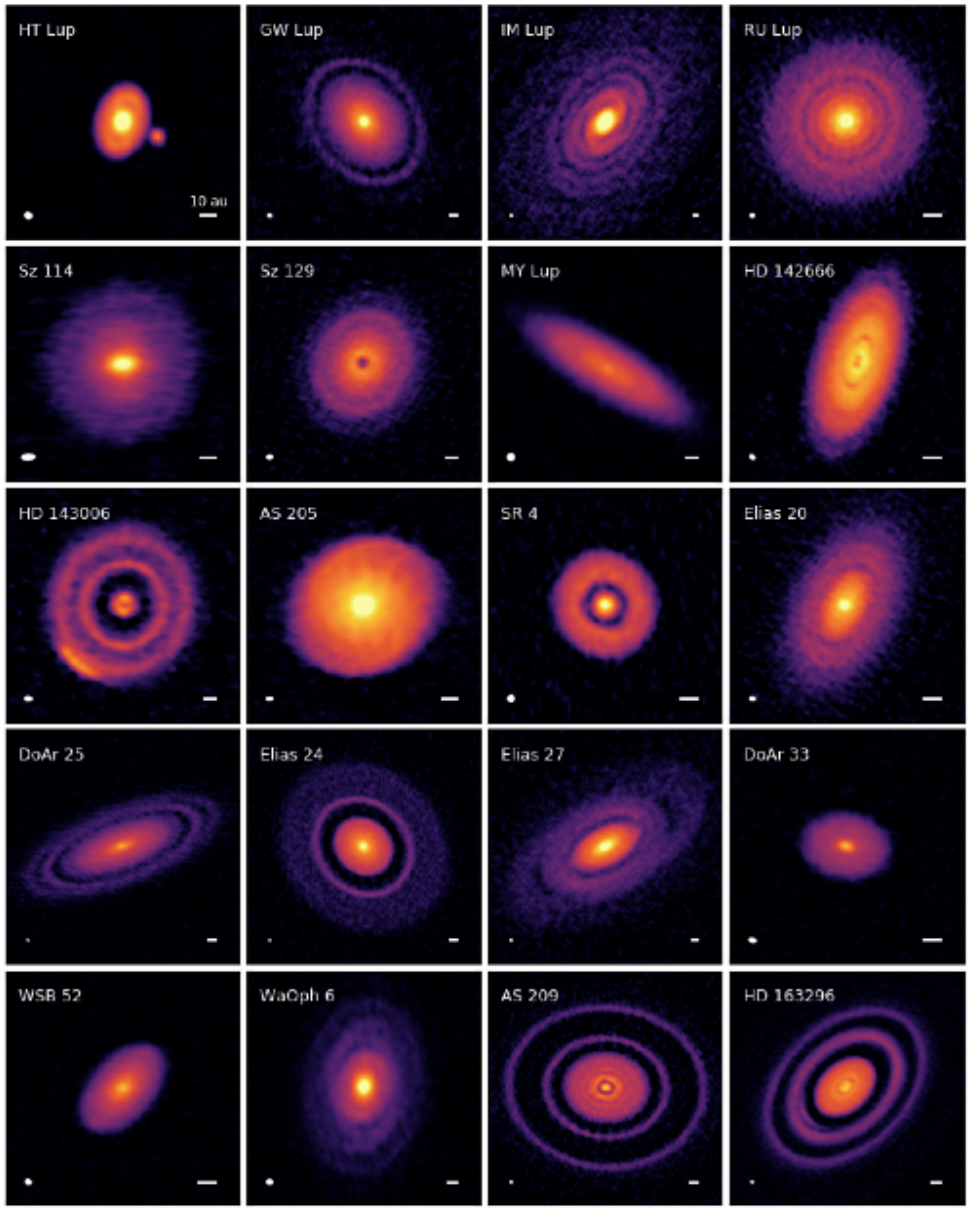
Remarks - I

- High contrast / high resolution images available
  - Mostly POLARISED INTENSITY
  - Mostly Near-Infrared

- On-going developments… number of images growing
  - Stokes I images
    - Necessary to obtain Intensity & Polarisation fraction vs. Color
  - Data in the optical (V, R, I bands)
  - Circular polarisation ???

- Databases of scattering properties are needed to feed models
  - Mie theory not sufficient anymore

Recent Advances II: Disks at longer wavelengths

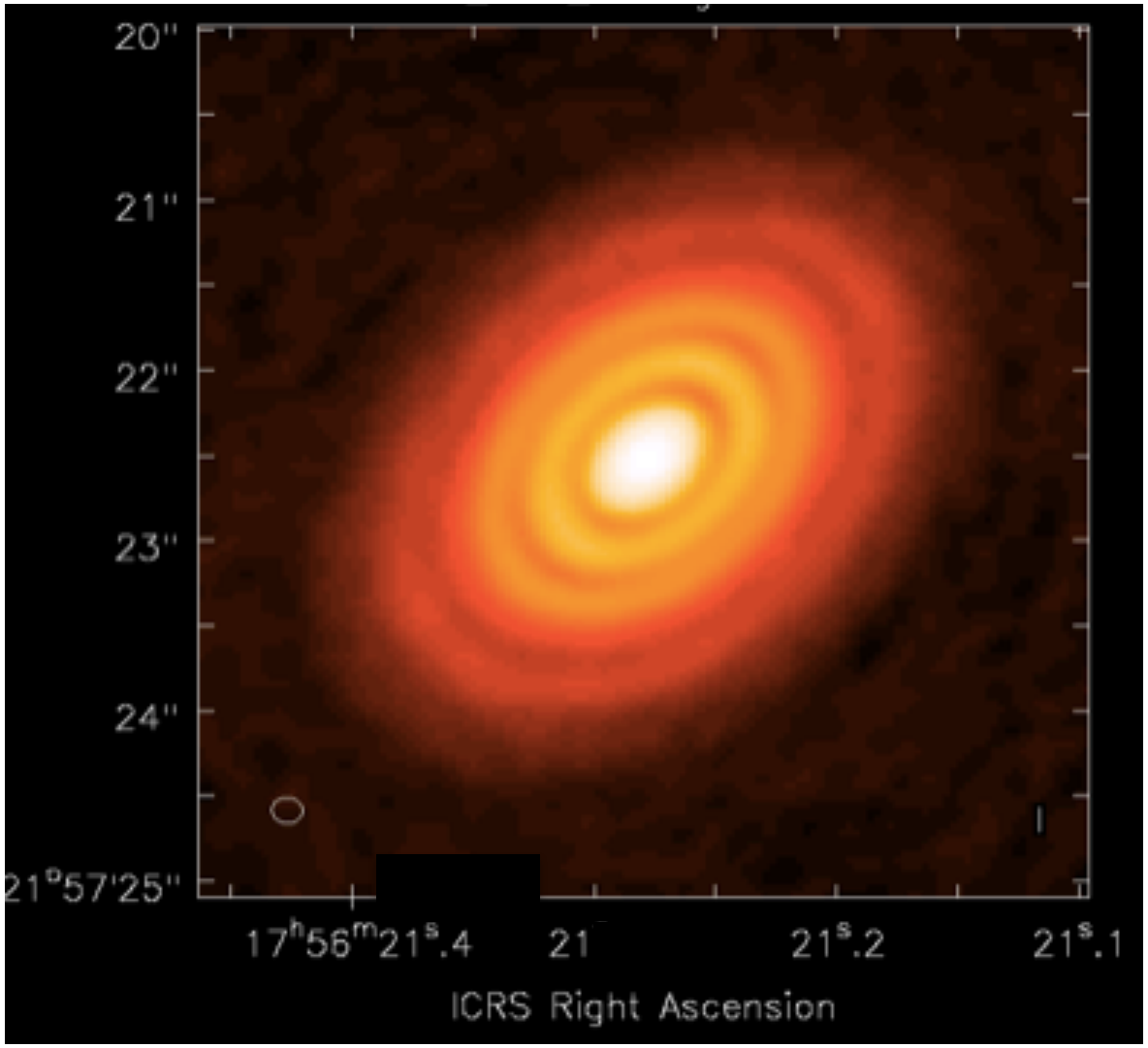


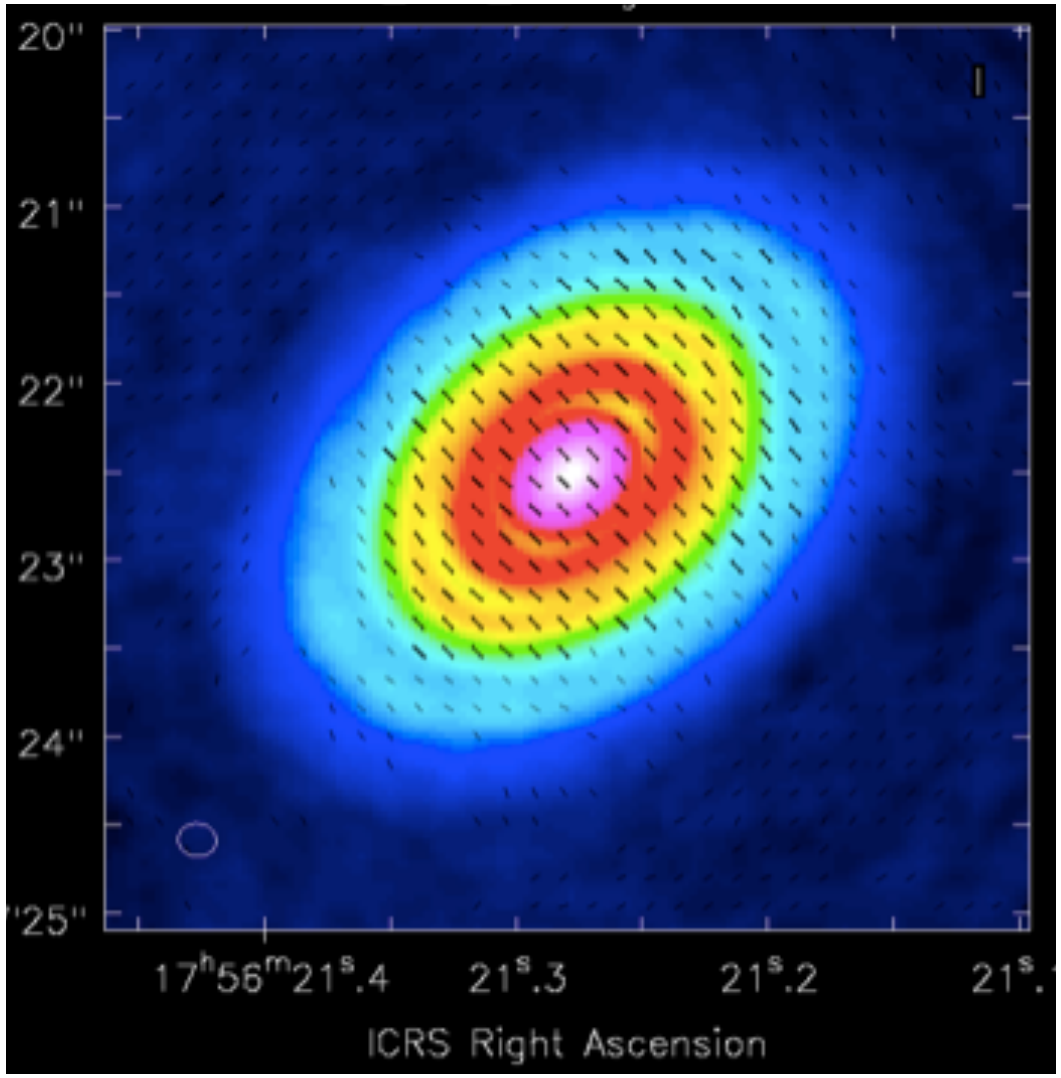
Dust Thermal Continuum Emission

Scattering?

Dust properties?

HD 163296 at 1.3mm w/ ALMA





Dent+ 2018

Polarimetry with ALMA

- Scattering or Aligned grains ???

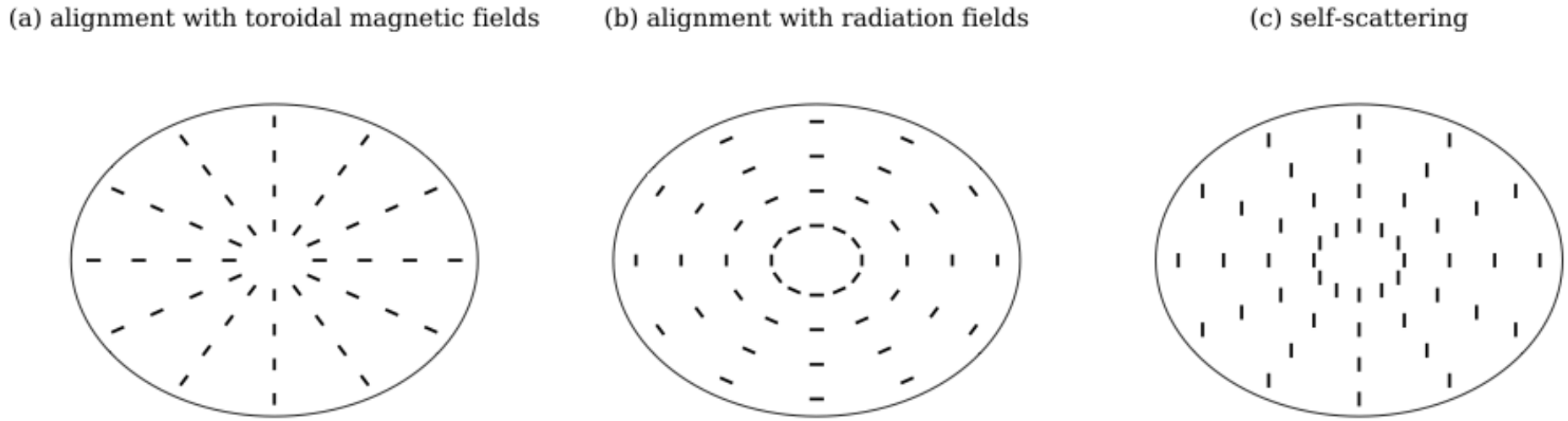
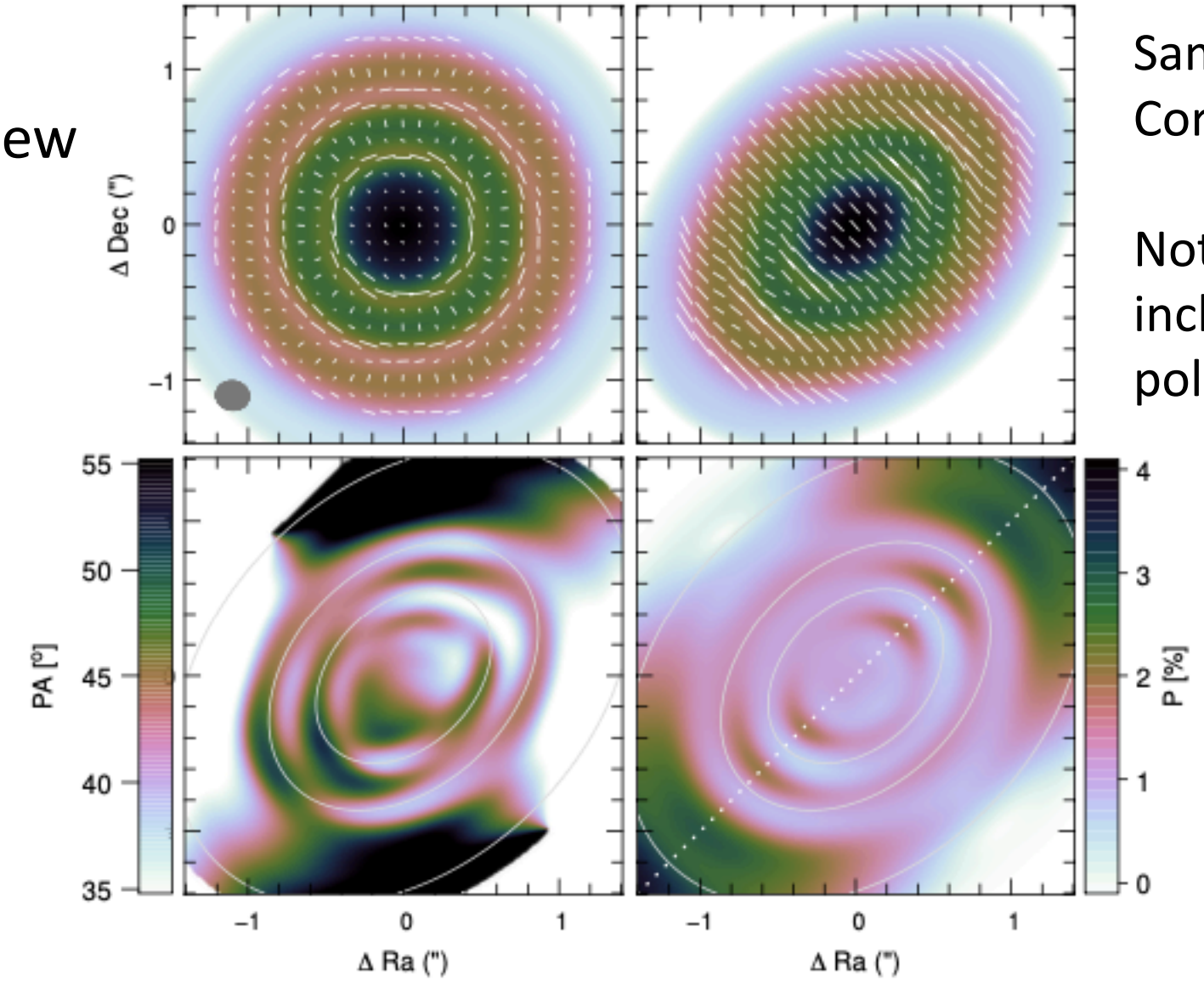


Image from Kataoka et al. 2017

Beware of inclination effects, especially for scattering -> will change the vector pattern
Exact dust distribution also important -> rings and gaps, for example
REQUIRES CAREFUL MODELING

HD163296 -> model of the ALMA linear polarisation

Pole-on view

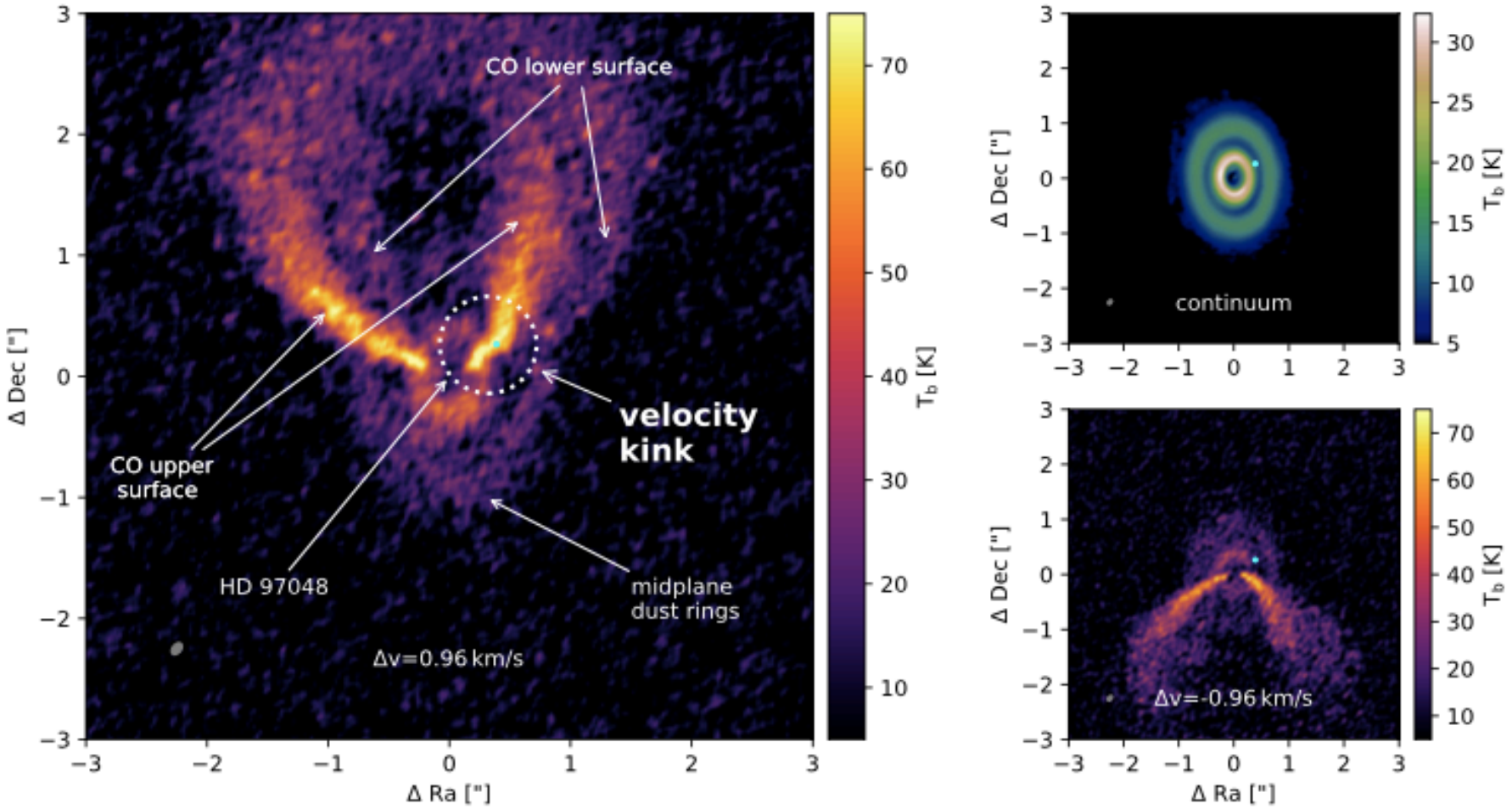


Same model
Correct inclination

Note the effect of inclination on the polarisation PA

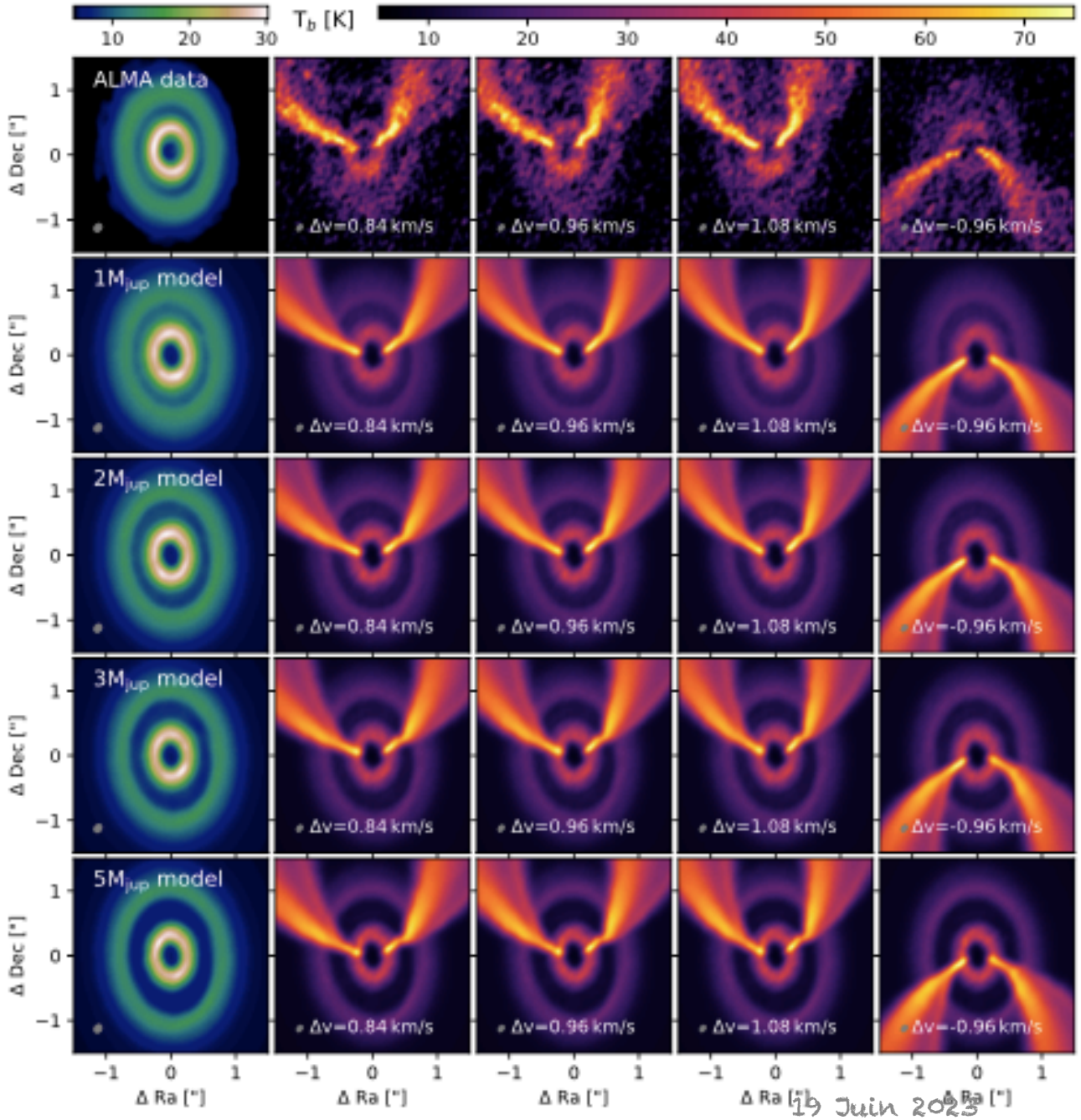
Dent+ 2019

Dust porosity in the midplane?



Pinte+2019

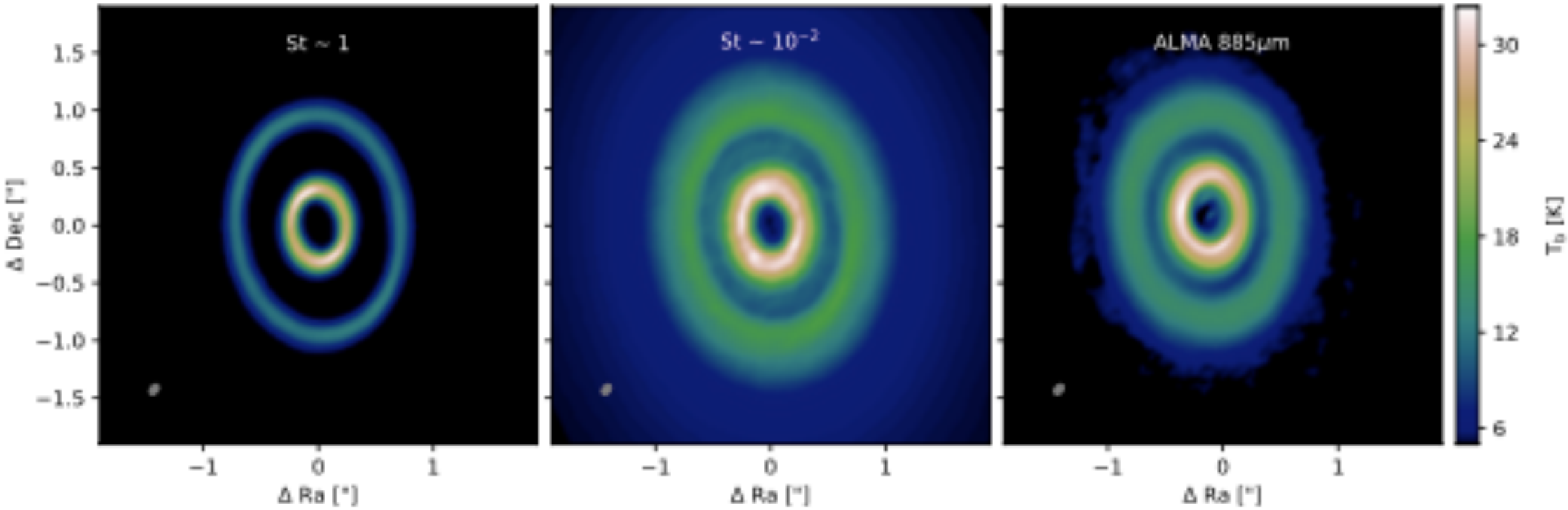
1. There is a planet, in a disk gap



2. We can estimate the planet mass

Pinte+2019

Porous dust needed, Is this a general statement?



3. 200 micron grains (best emitters) must have very low Stokes number !!!

Stokes number proportional to (dust bulk density * dust radius) / Gas surface density

REMARKS - II

- Images are now available in the mm-range with angular resolution comparable to Optical- NIR !!!
  - Traces a different dust population: midplane vs. surface

- Scattering is producing linear polarisation
  - Dust properties still unclear, requires modelling

- Evidence that dust in midplane is VERY porous ?

The need for DETAILED, 3D dust evolution models

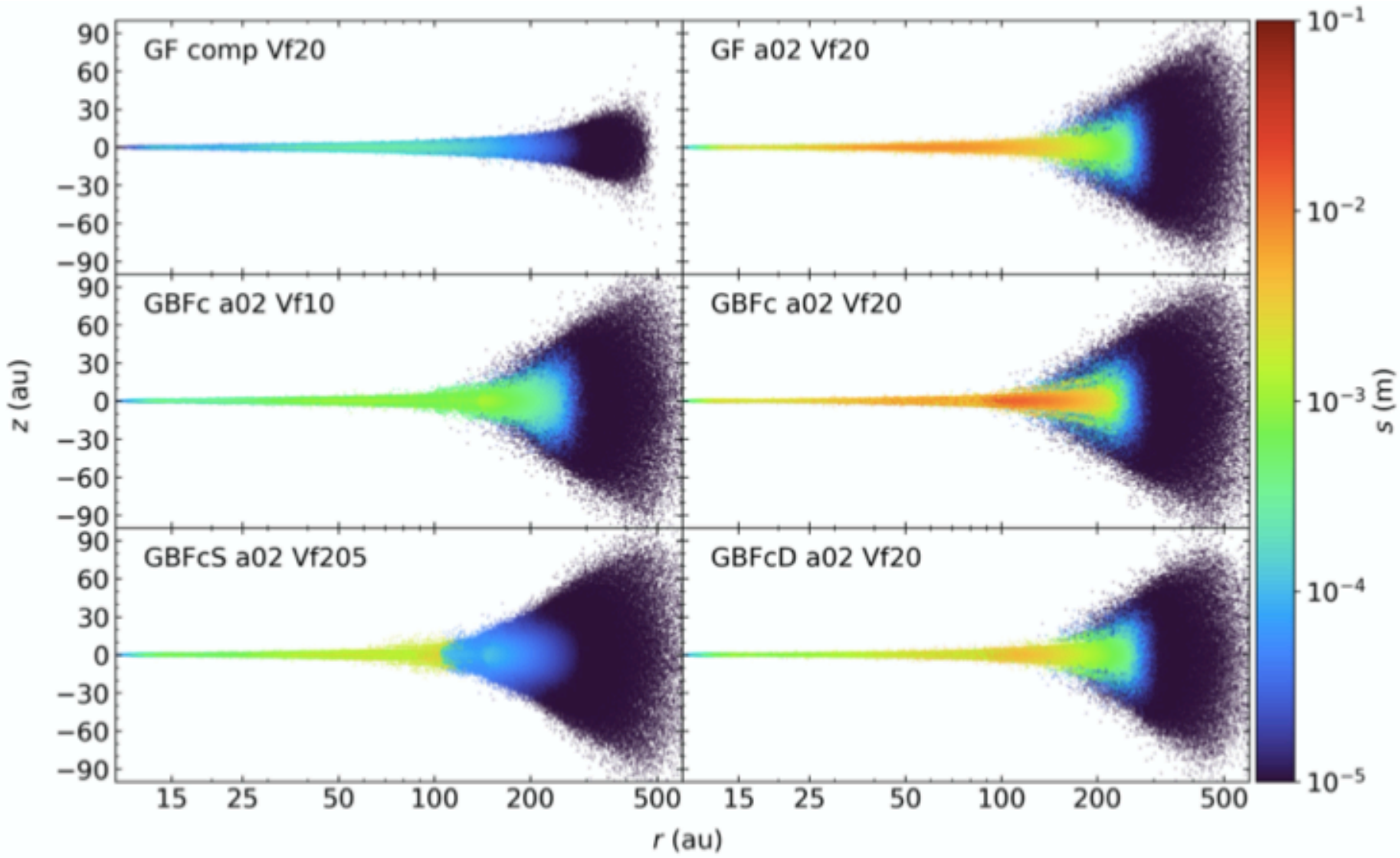
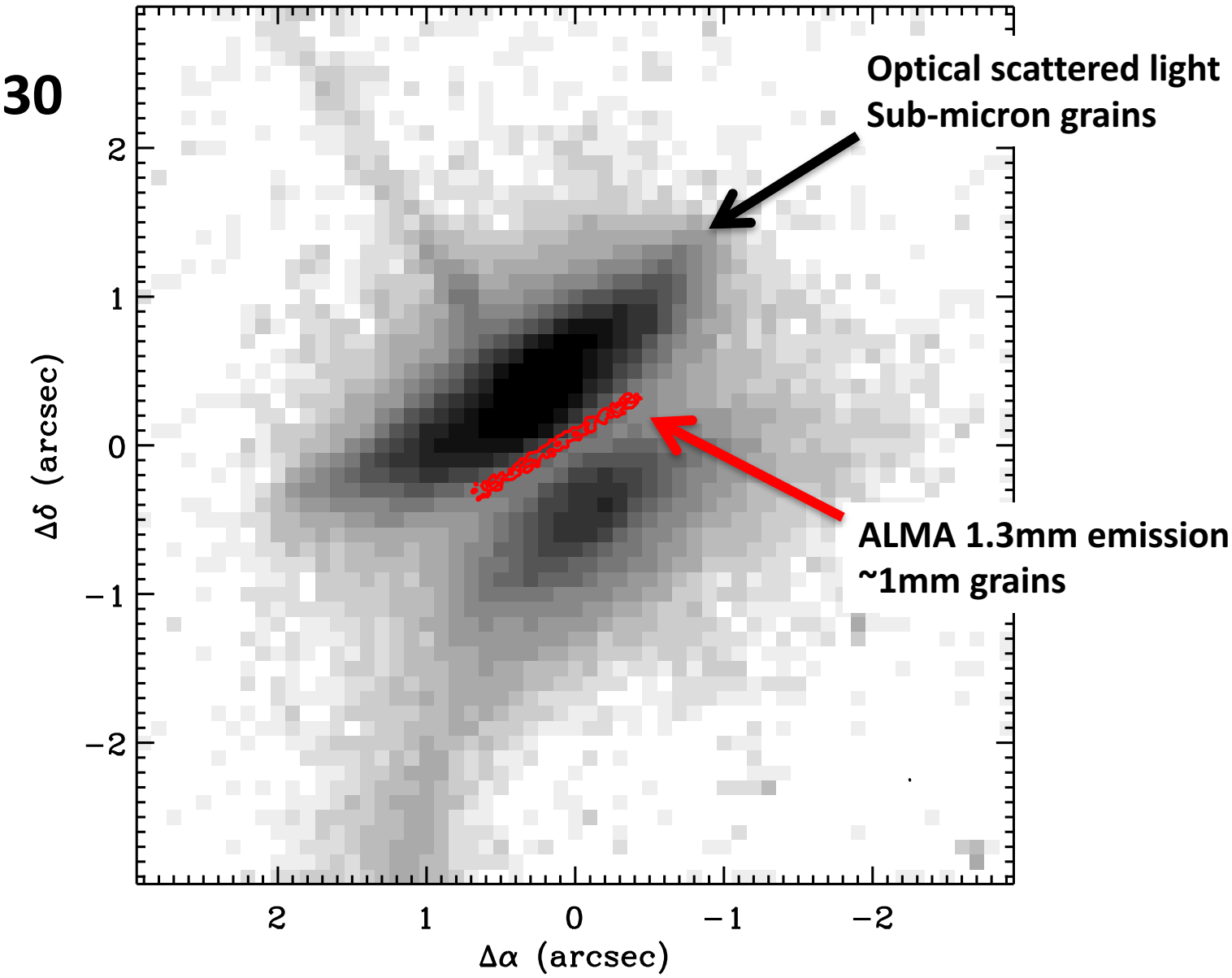


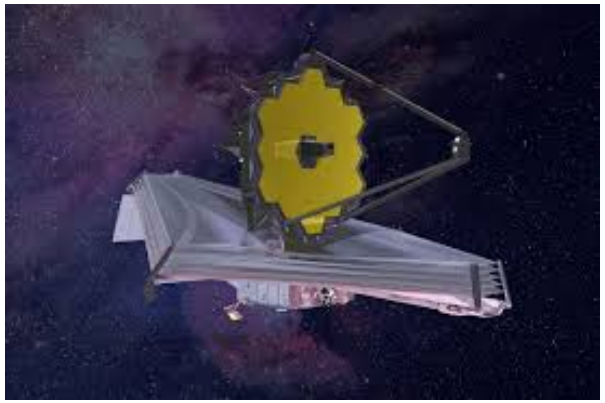
Image Credit Stephane MICHOULIER, Lyon

Surface vs midplane: but what in between?

HH 30



JWST to probe scattered light at intermediate altitudes / grain sizes



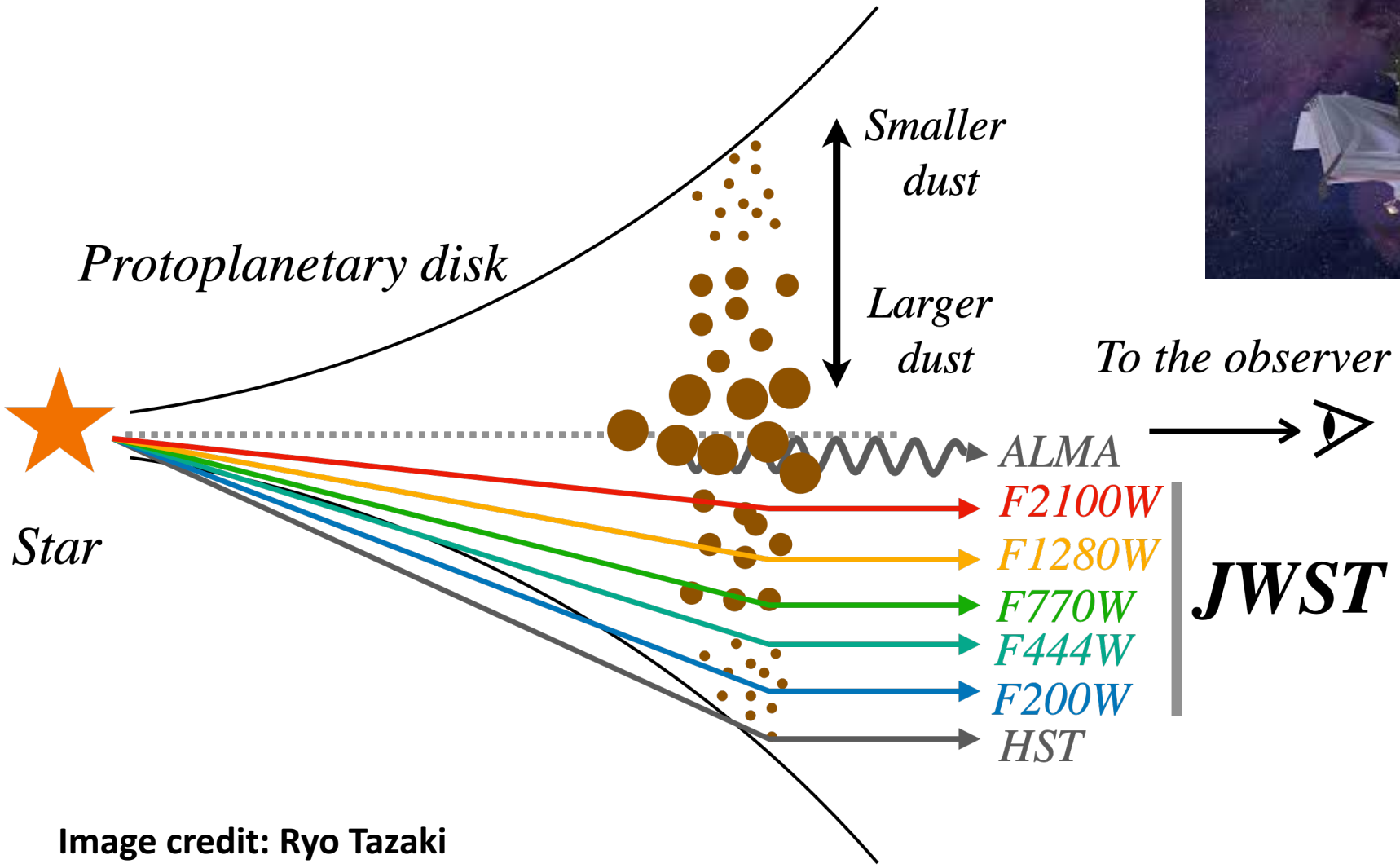
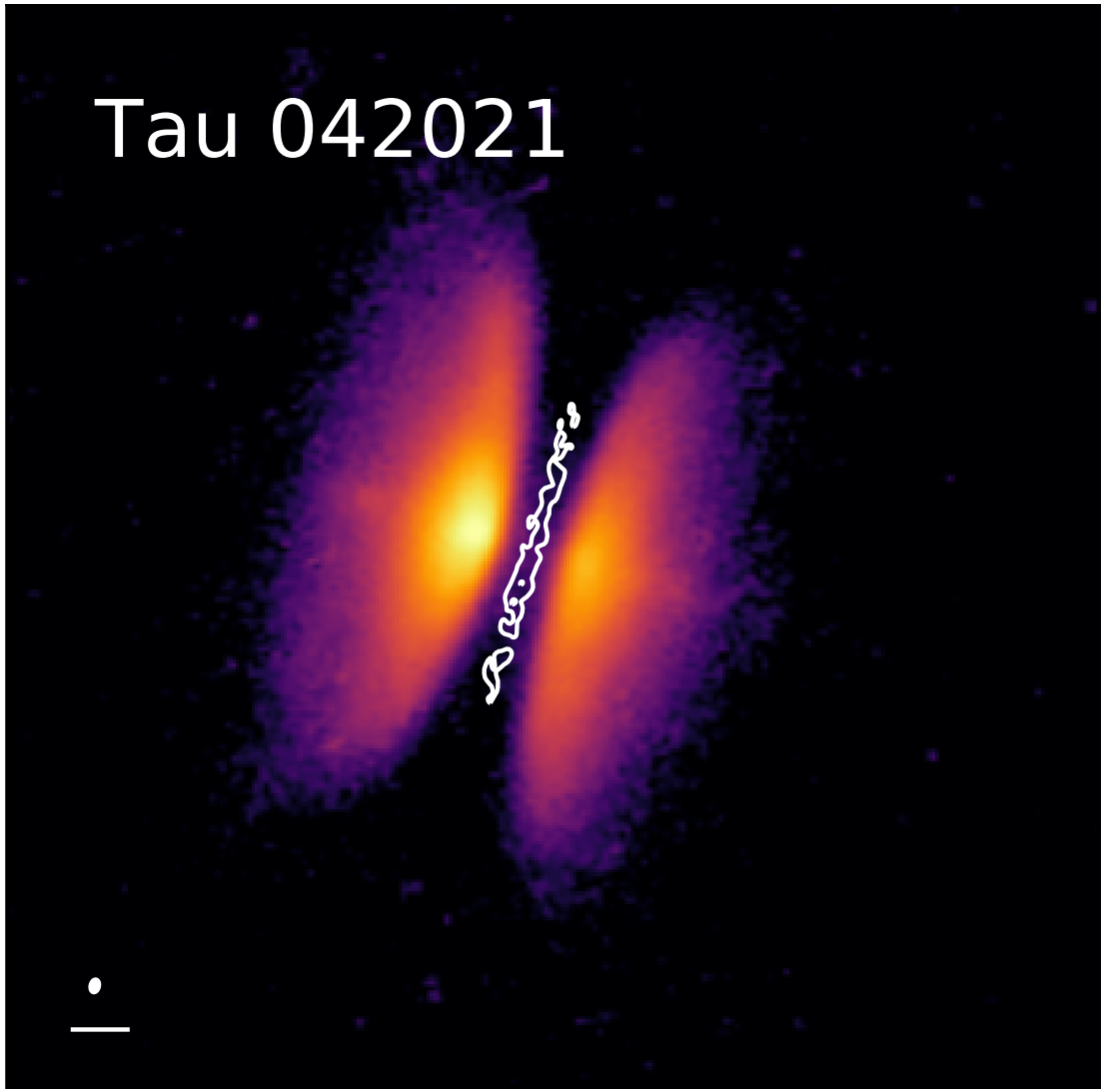


Image credit: Ryo Tazaki

Tau042021: HST vs. ALMA B7



Villenave+ 2020

- JWST images withdrawn

Duchene, Menard+ 2023, submitted 16/6/23

Current settling prescriptions don't work well…

- JWST images withdrawn

REMARK – III we have work ahead of us…

- Not that long ago our understanding of disk and dust evolution was limited by the quality (and amount) of data

- The situation is different now: we are in a “data driven” period where models are lagging behind
    - Turbulence ; vertical settling ; scattering properties …

- Interplay between observations, models AND lab results will be critical to fully understand dust evolution and early planet formation in disks

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