Review talk

Debris discs in the JWST-ALMA era

Tracing planetary system evolution through circumstellar dust

8th Sep 2025, University of Hertfordshire

Minjae G. Kim
Research Fellow and ESA project lead
Mullard Space Science Laboratory, University College London, UK

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Minjae G. Kim
Deputy director
Korea AeroSpace Administration (KASA), Republic of Korea

1. Debris discs overview

2. Outstanding questions

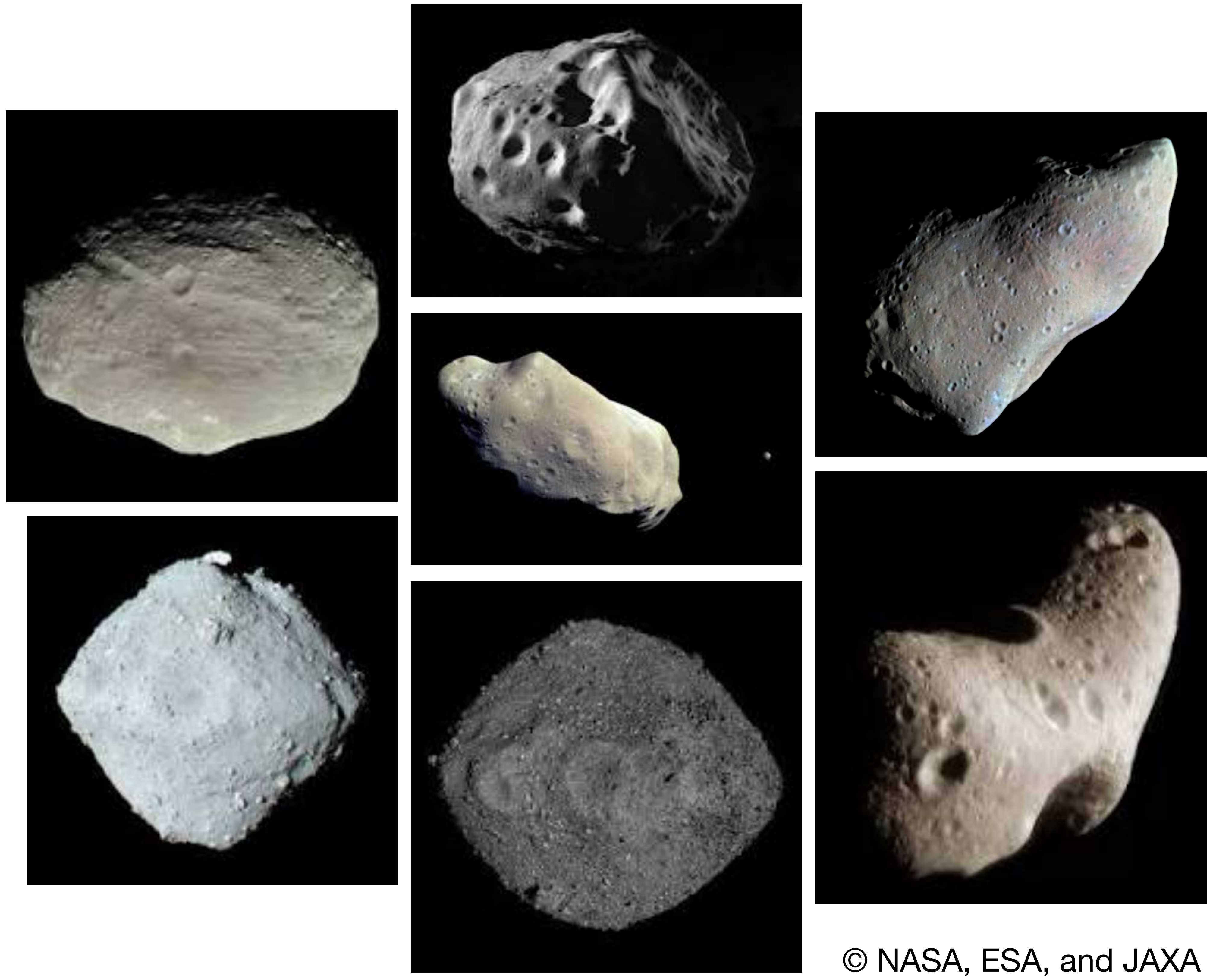
3. Recent discoveries

Debris discs overview

What are debris discs?

Definition

- Collections of small bodies: asteroids,



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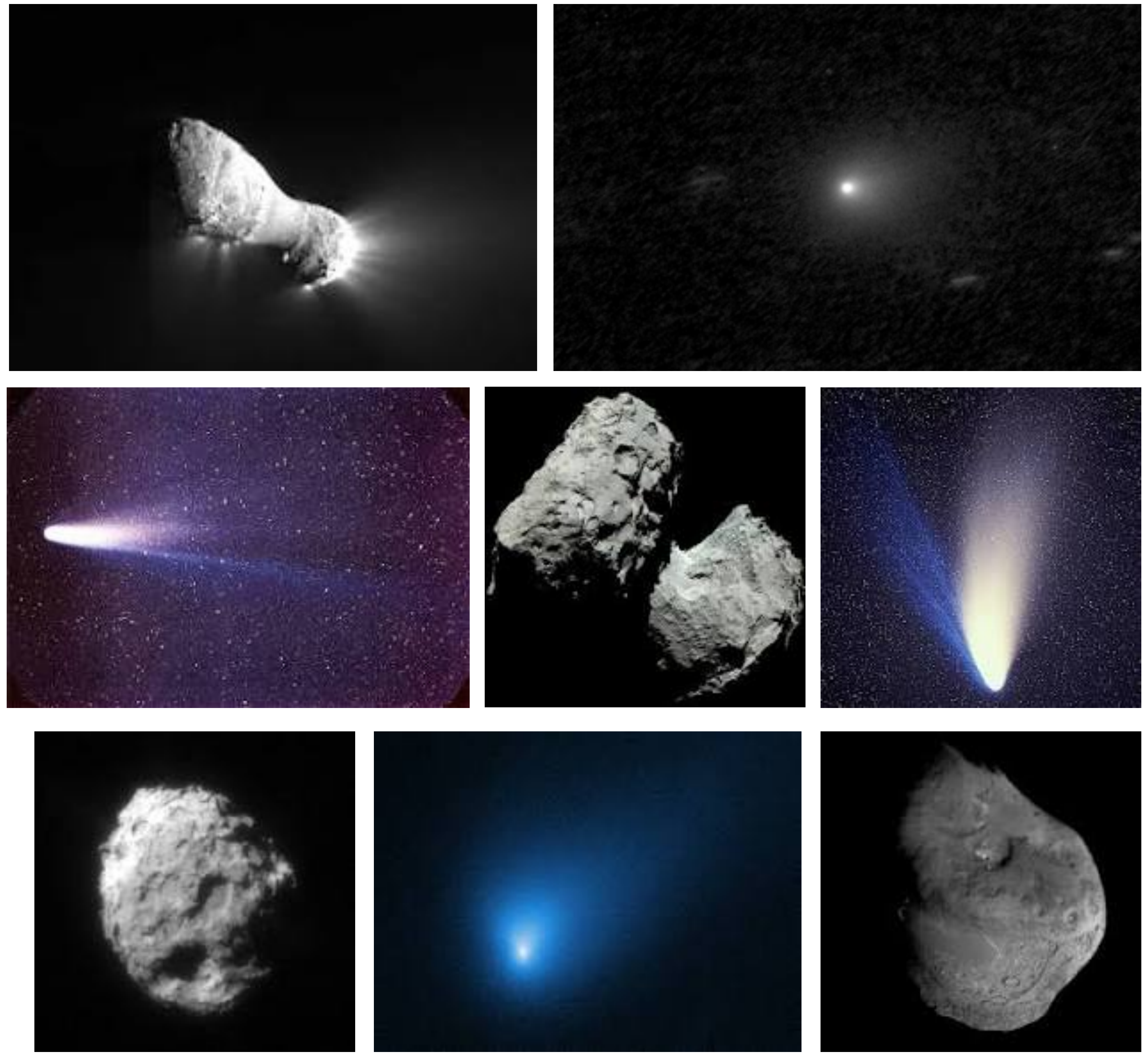
What are debris discs?

Definition

- Collections of small bodies: asteroids, comets



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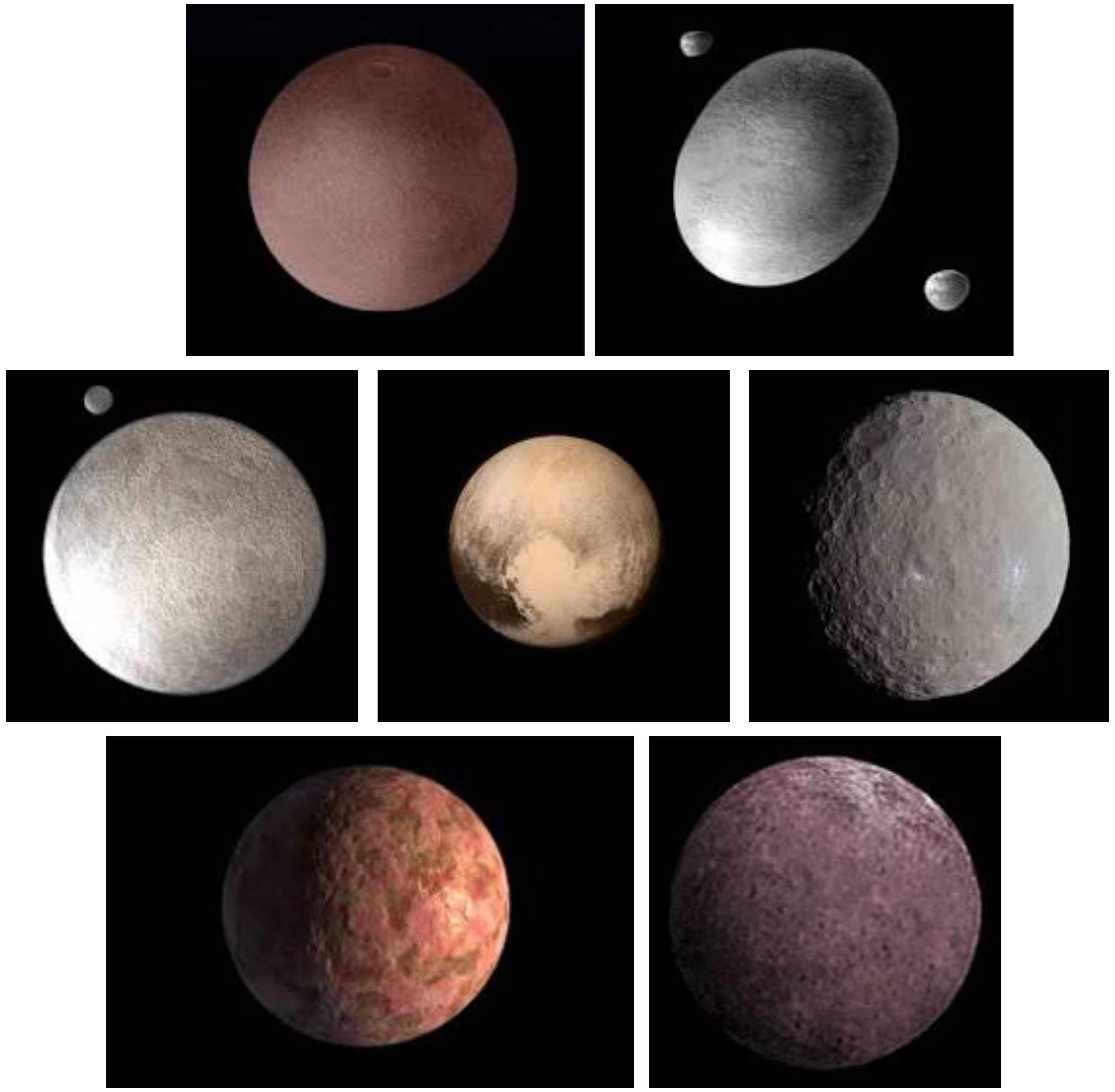
Definition

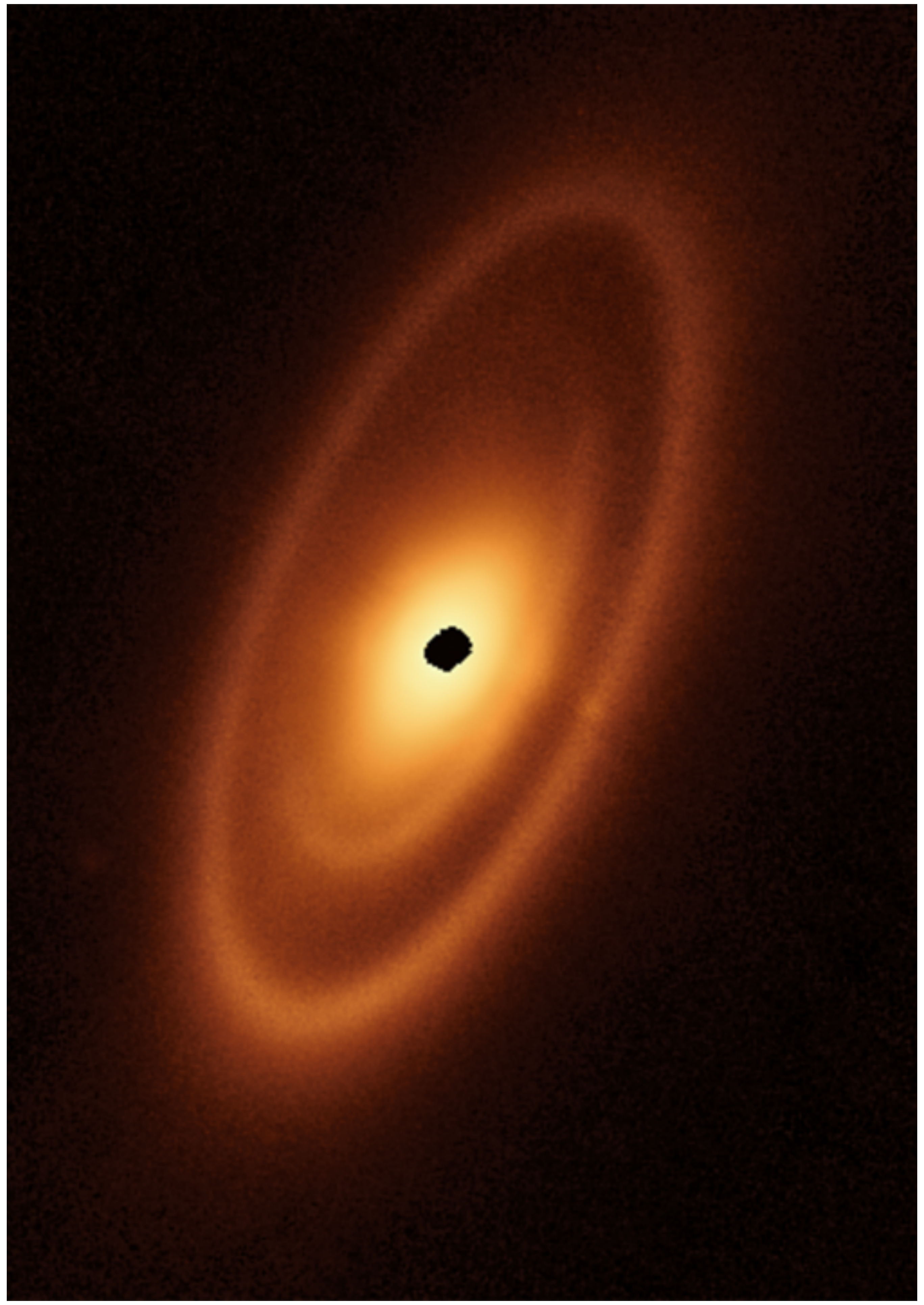
- Collections of small bodies: asteroids, comets, dwarf planets



What are debris discs?

Definition

- Collections of small bodies: asteroids, comets, dwarf planets, and dust around main-sequence stars



Gáspár et al. 2023

What are debris discs?

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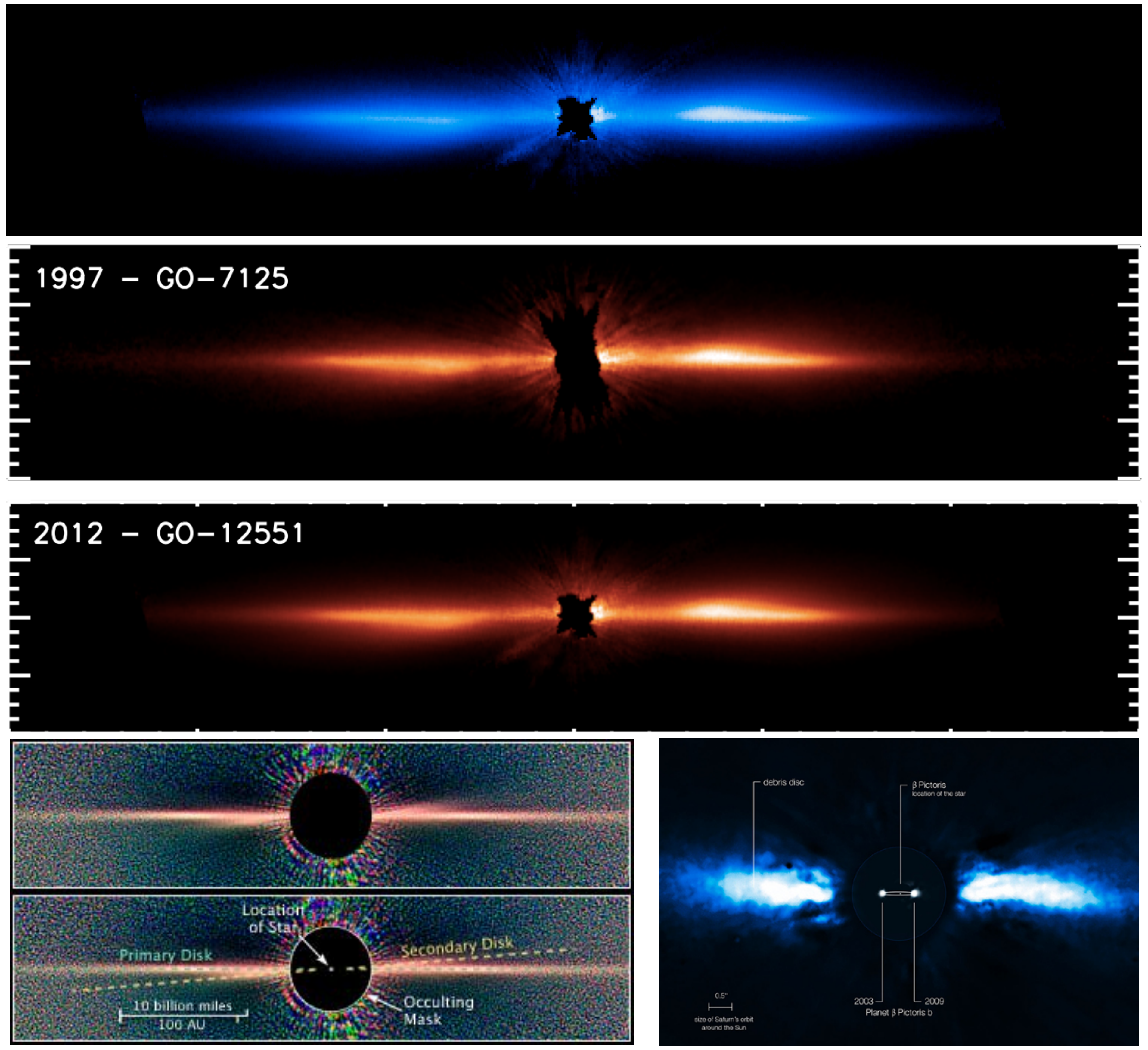
- After gas dispersal, so optically thin across all wavelengths



Golimowski et al. 2006, Lagrange et al. 2010, Apai et al. 2015, NASA, and G. Schneider

What are debris discs?

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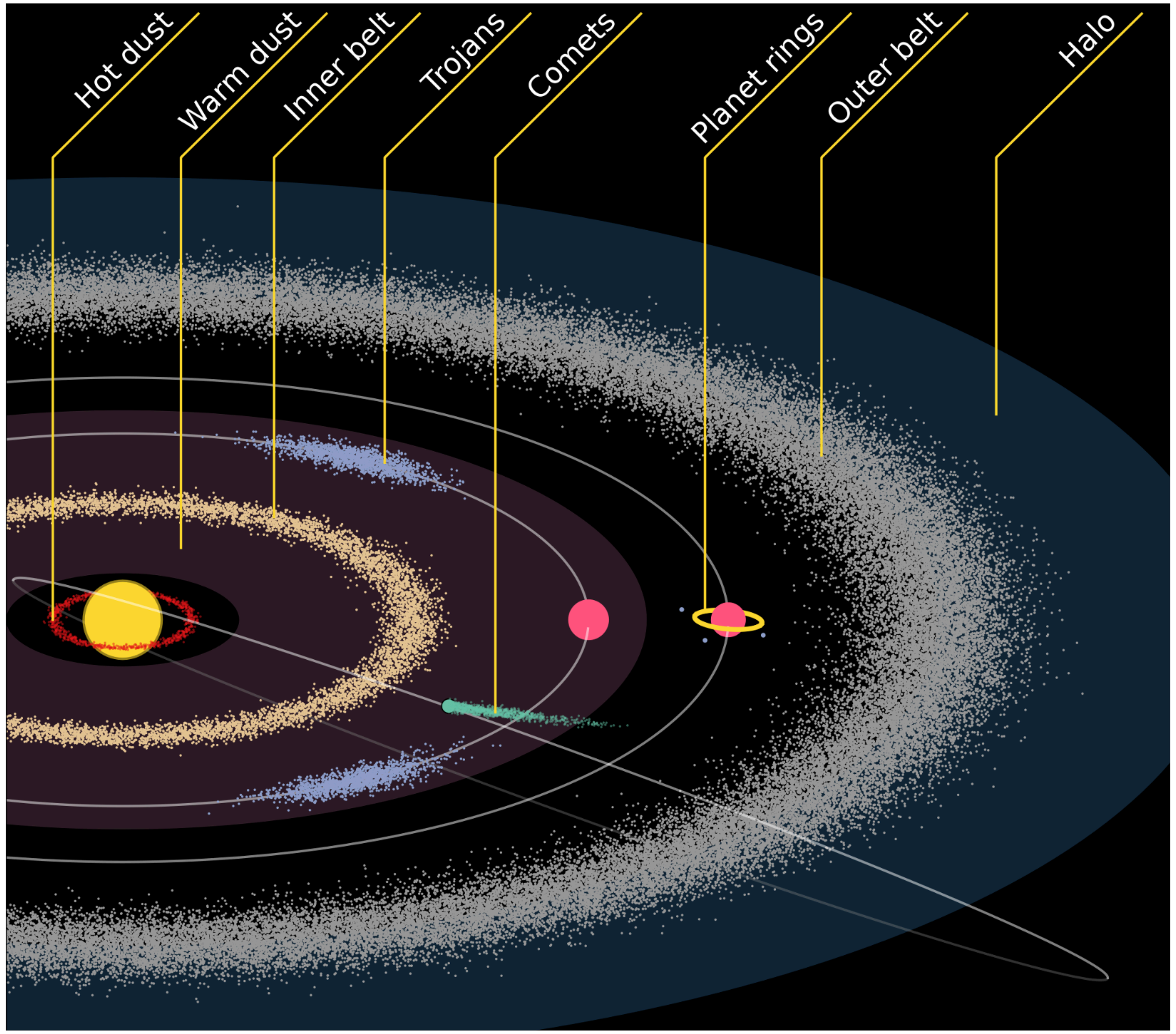
- Solar System Analogues: Asteroid Belt, Kuiper Belt, Zodiacal dust, and maybe Oort Cloud (?)



Pearce et al. 2024

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- After gas dispe… all wavelengths
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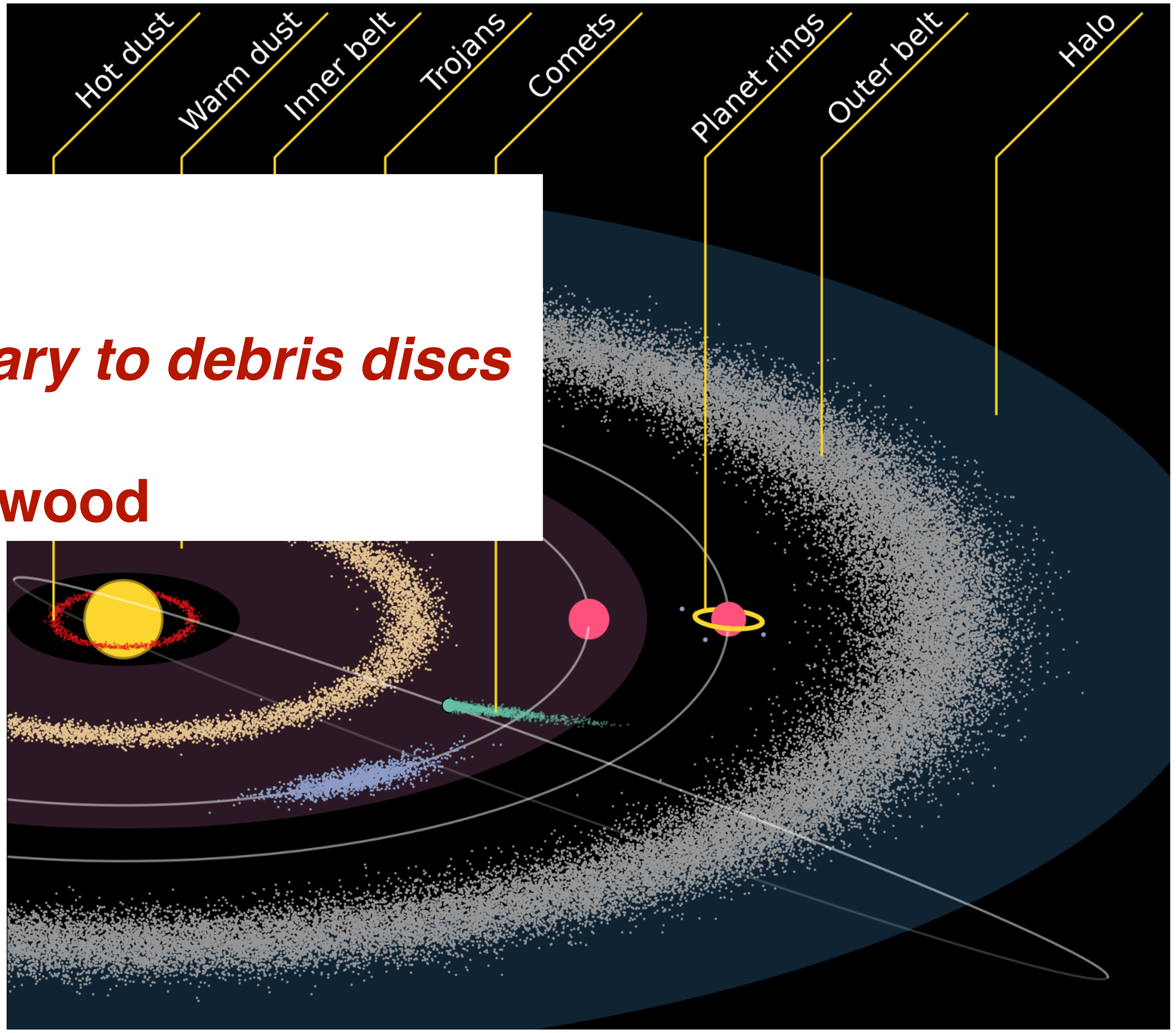
9th Sep 09:15

The transition from protoplanetary to debris discs

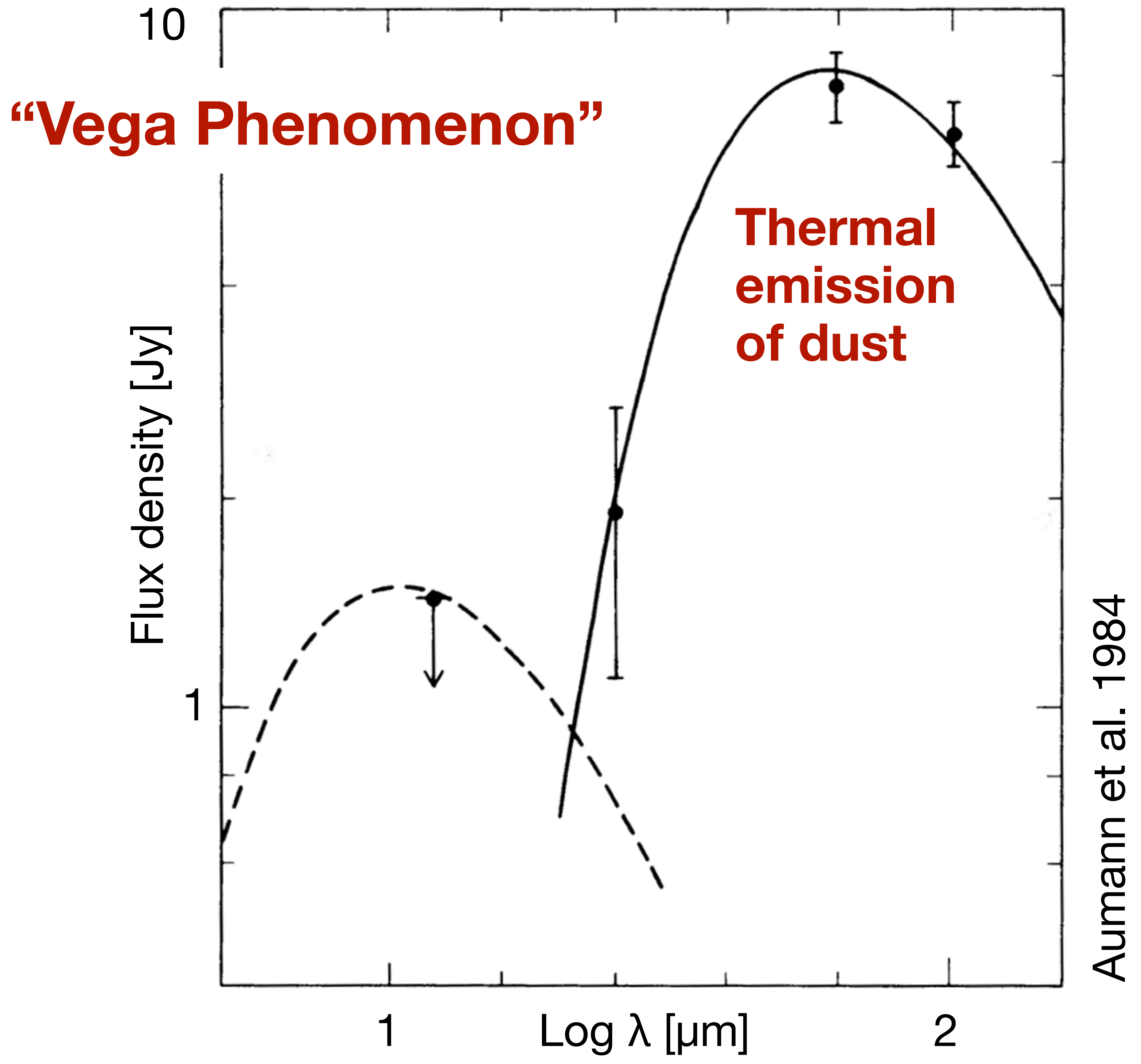
by Benjamin Homewood



Pearce et al. 2024

How do we detect debris discs?

Spectral Energy Distributions (SEDs)



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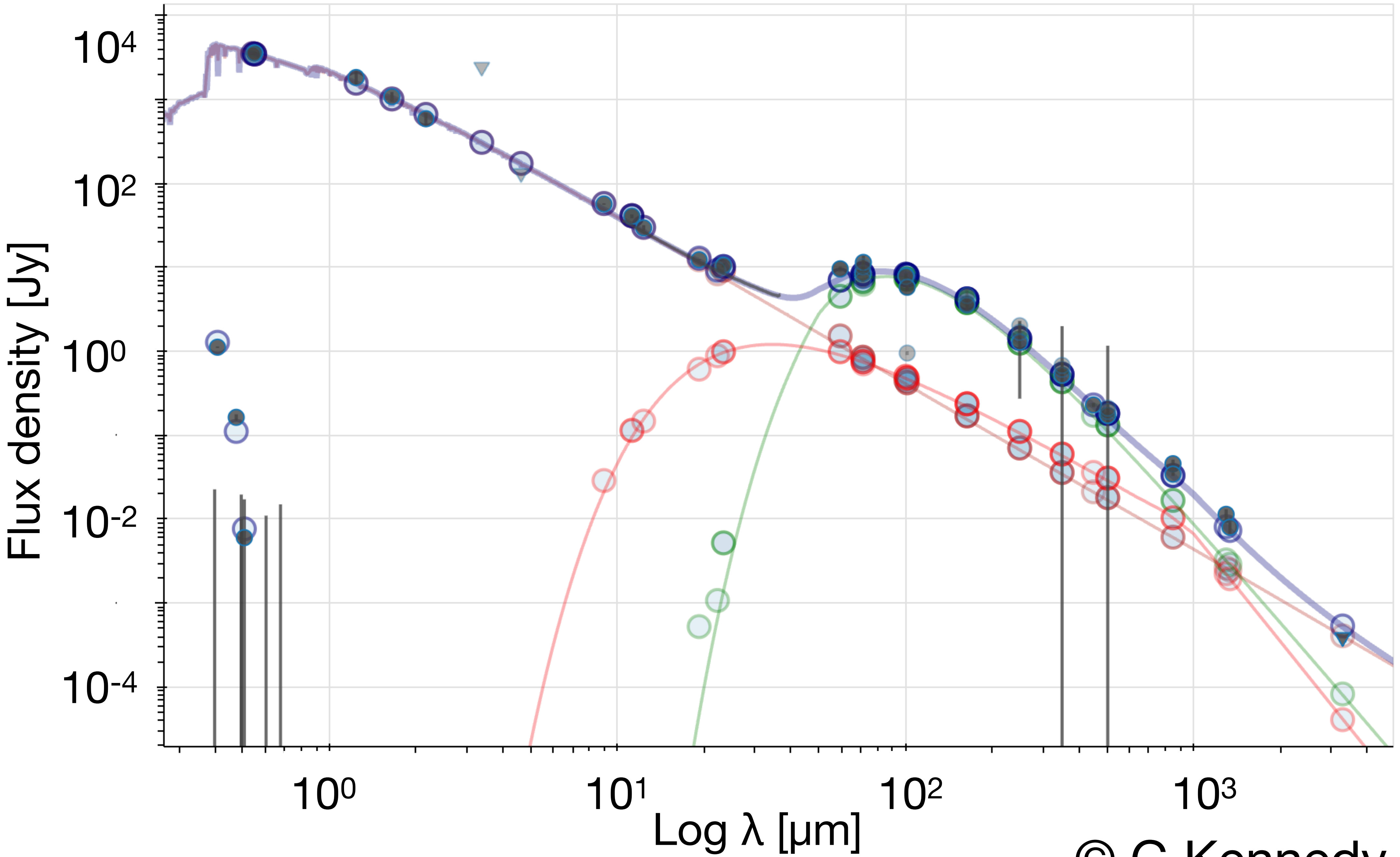

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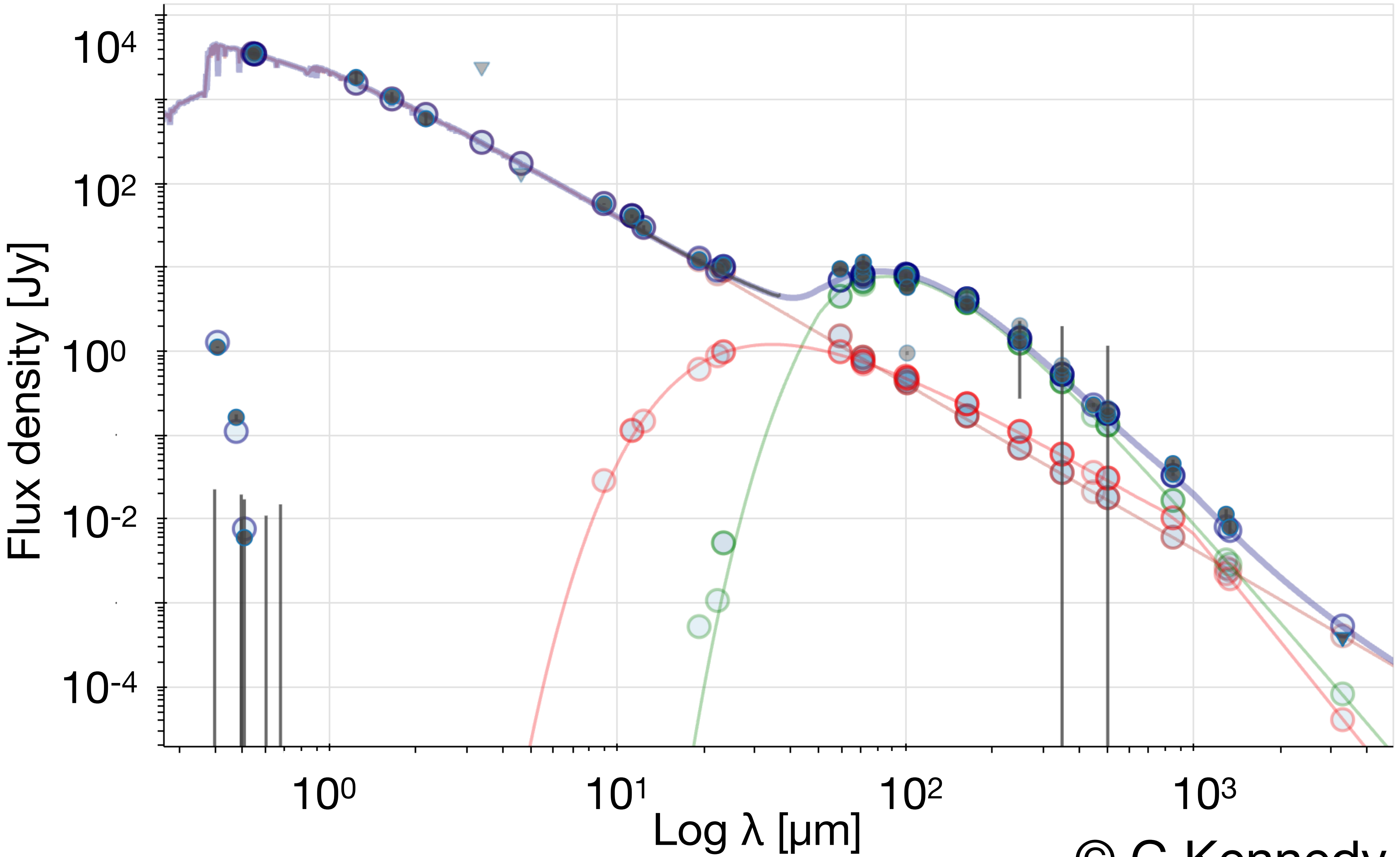

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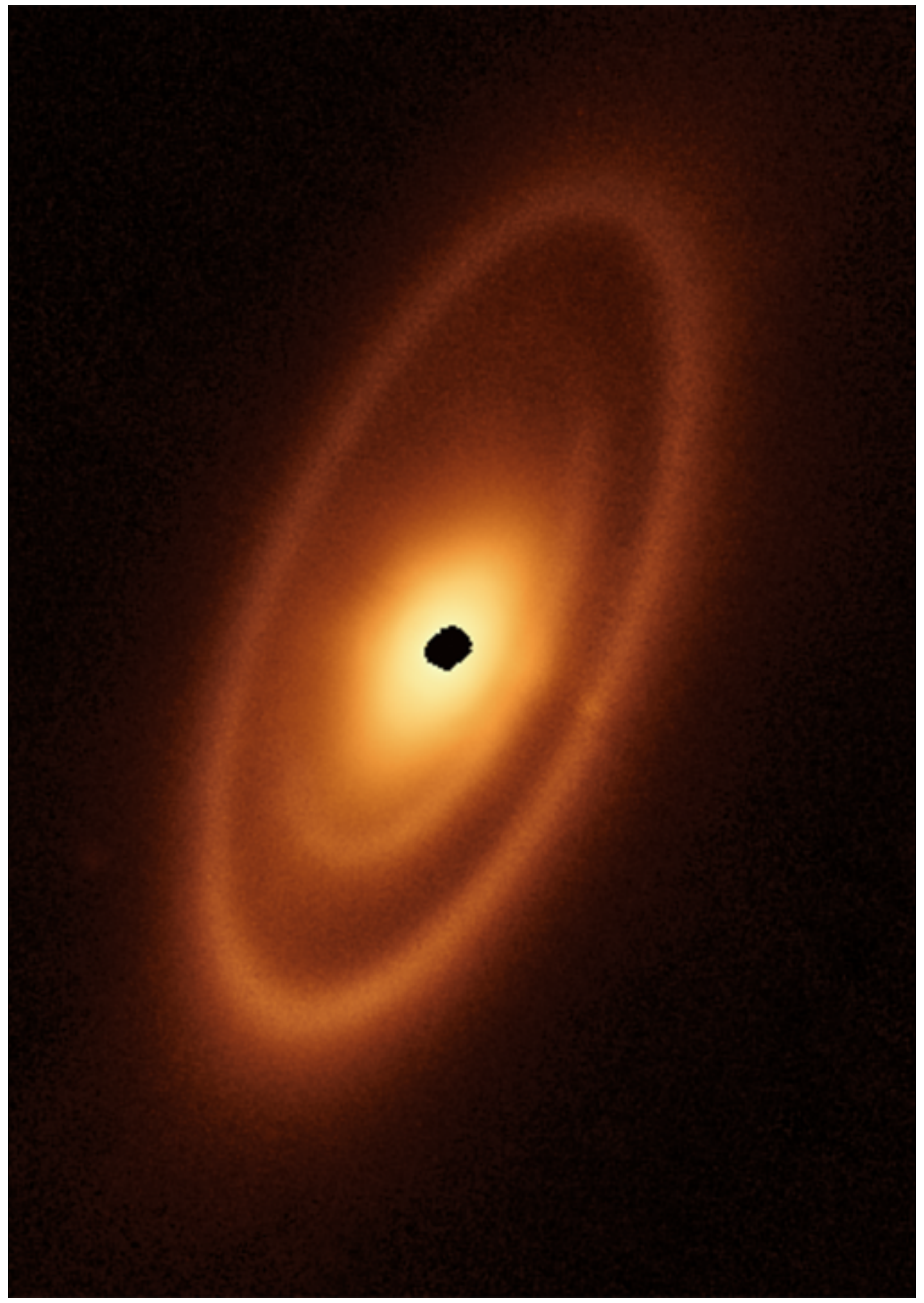
Resolved Images



Gáspár et al. 2023

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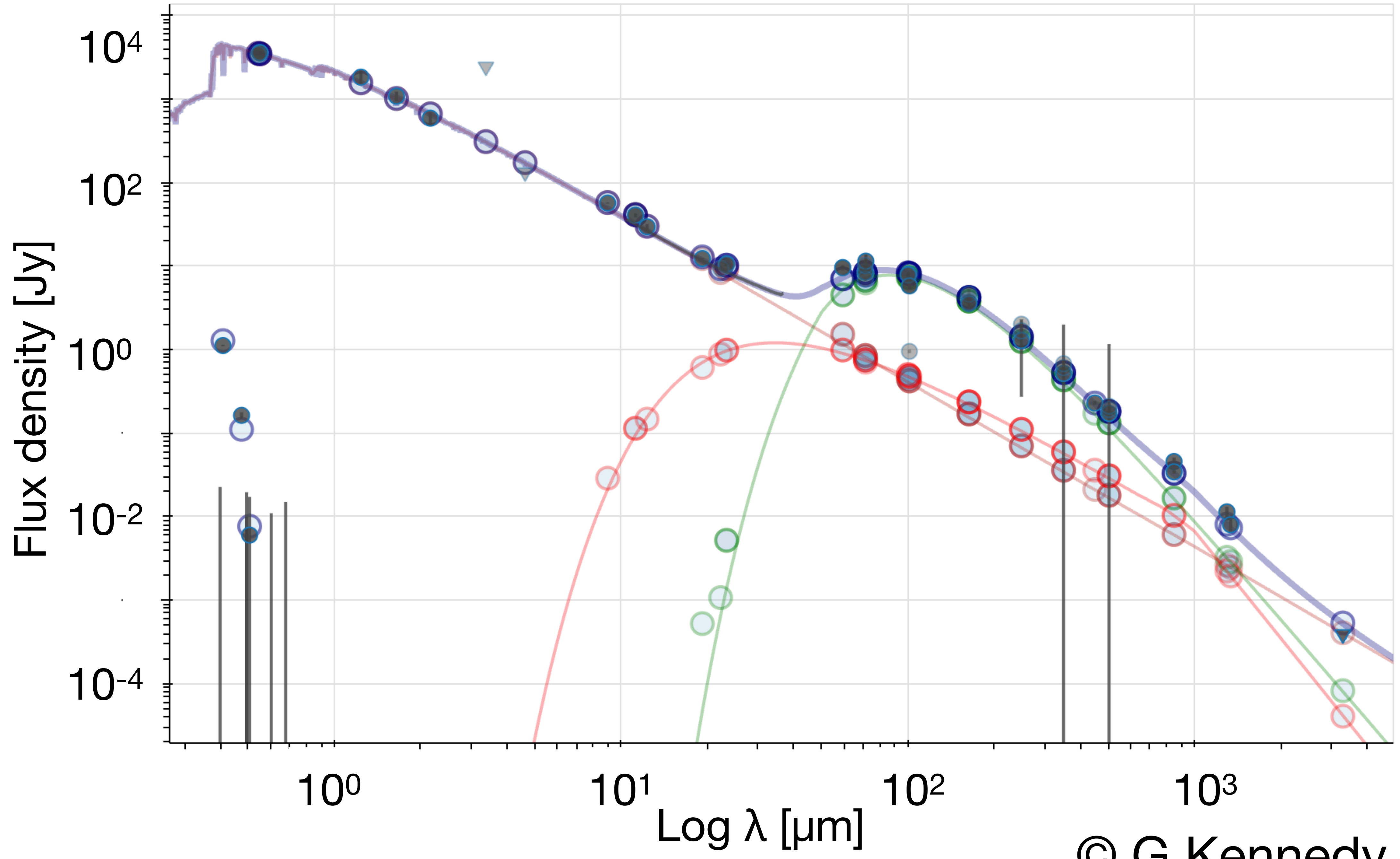

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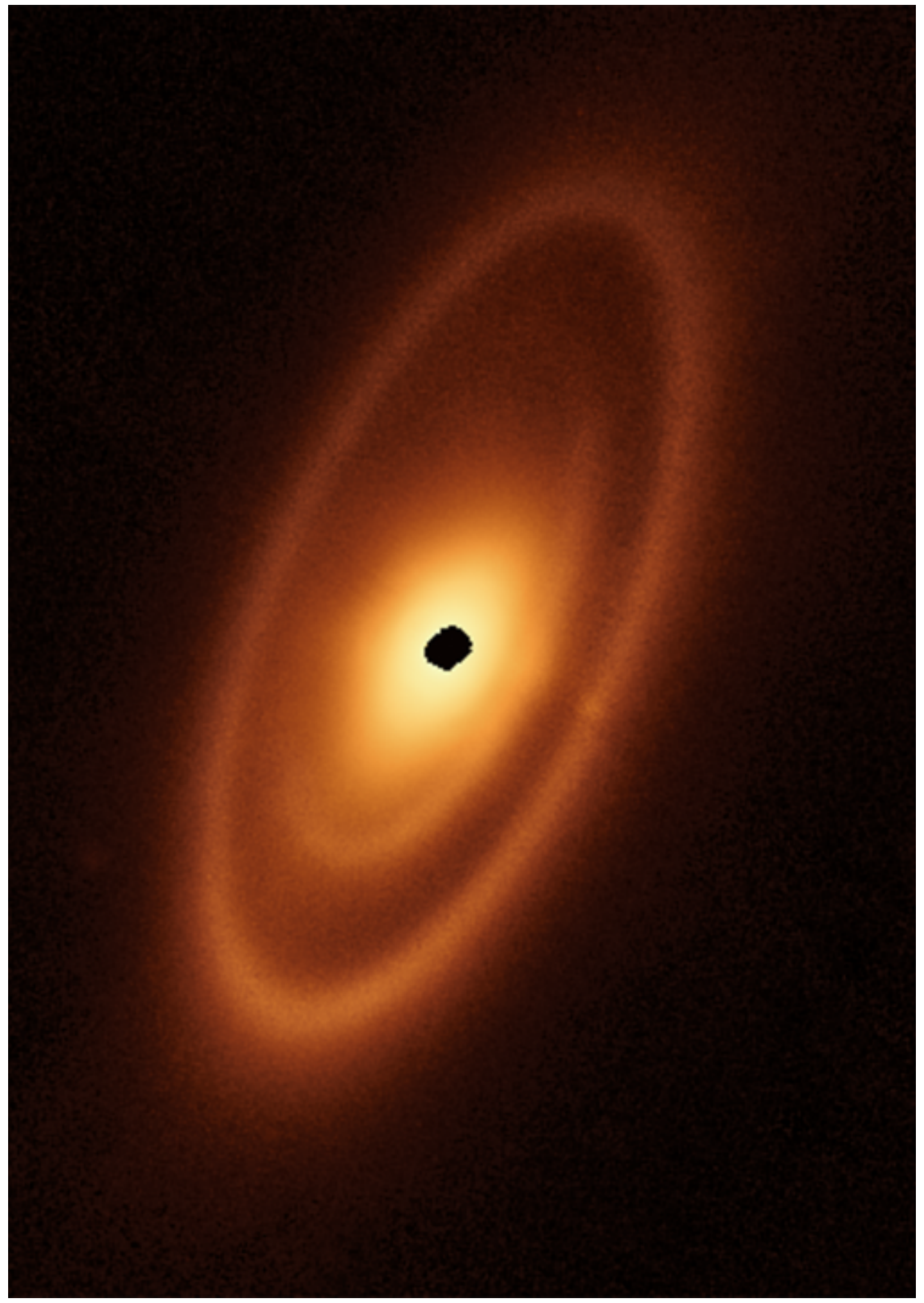
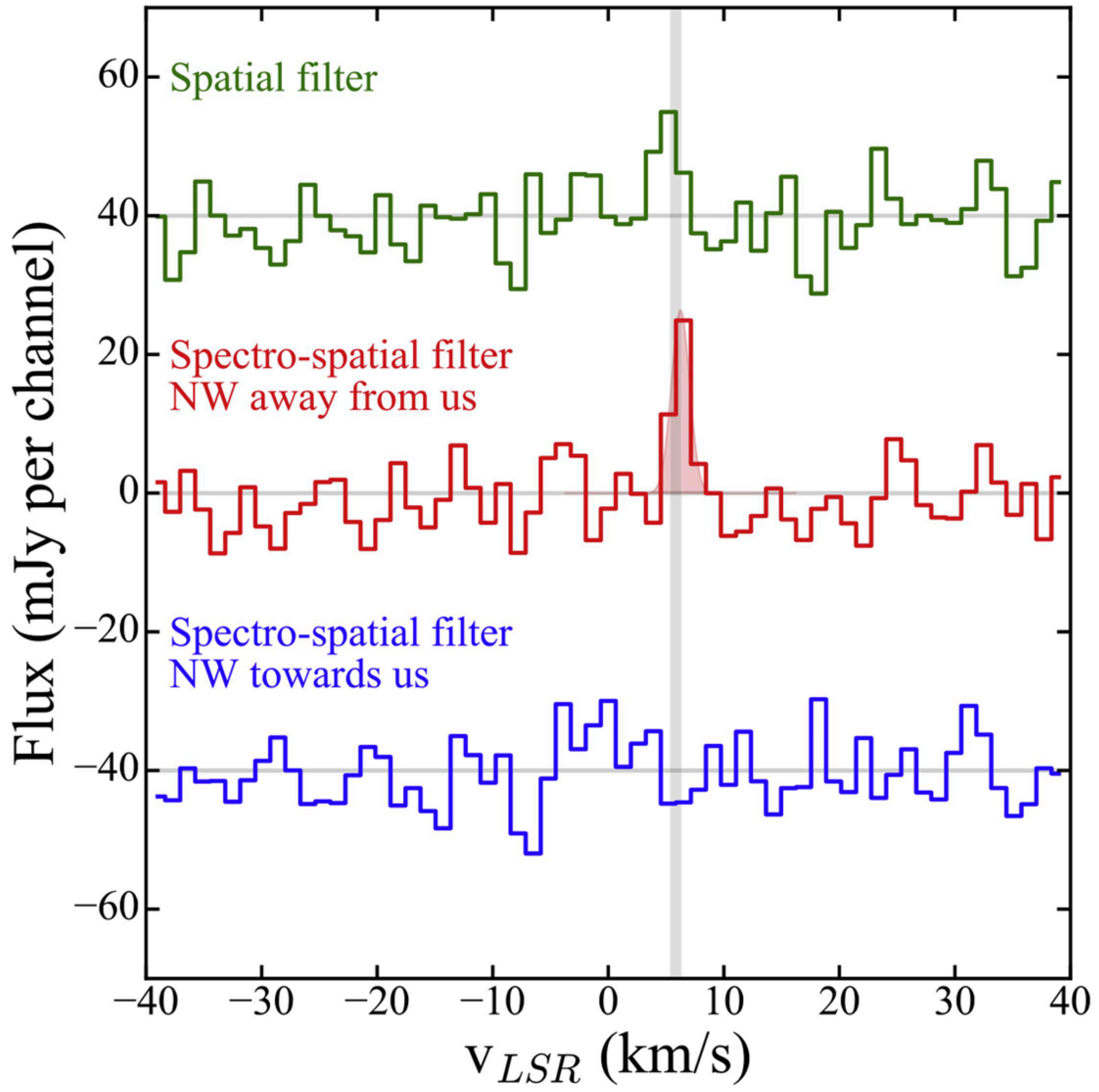


Gáspár et al. 2023

Gas emission lines



Matrà et al. 2017

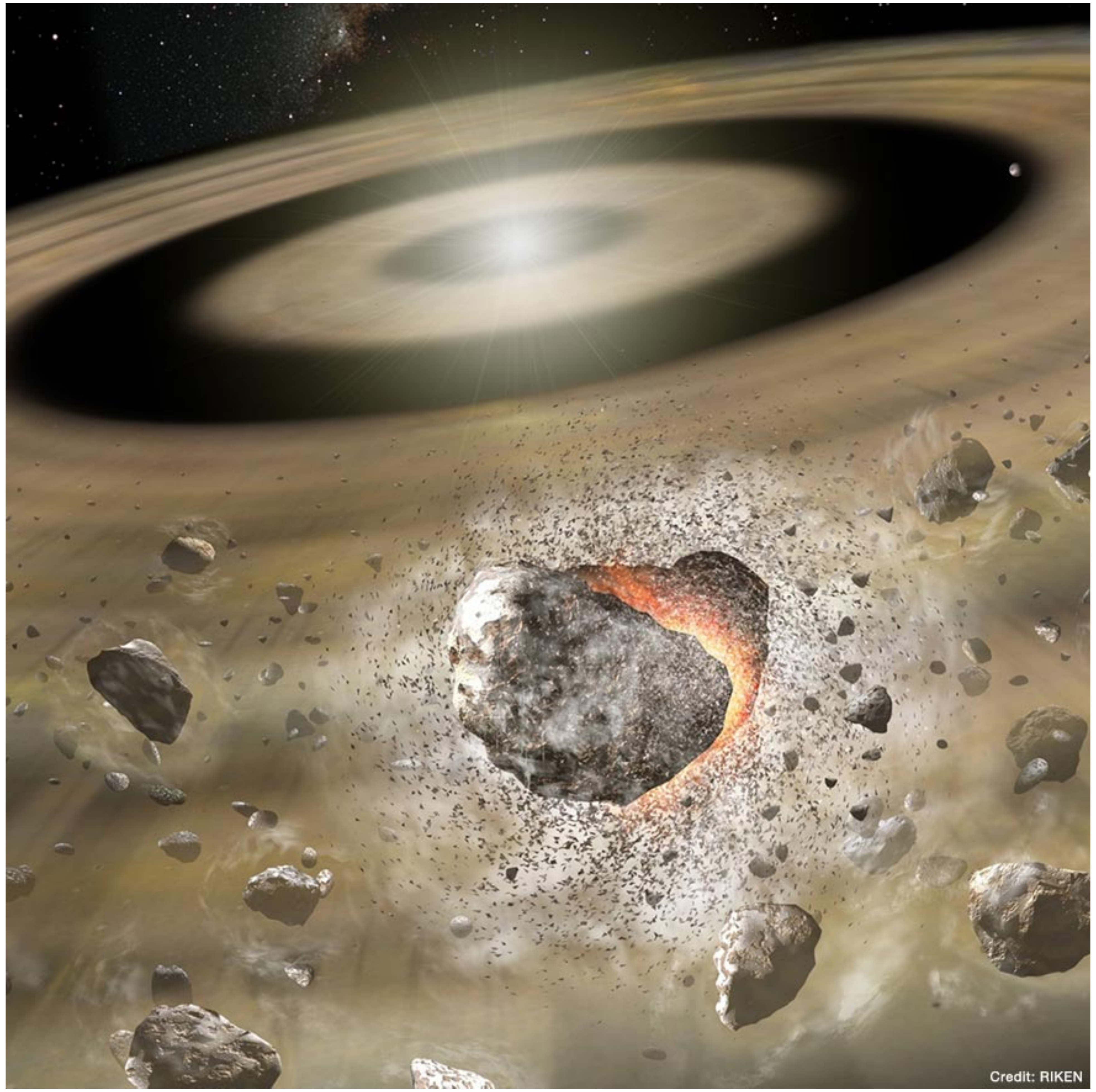
Key concept: Collisional Cascade

<u>Basic process</u>

- Planetesimals → Collisions → Fragments → Dust

<u>Key properties</u>

- Size distribution: $n(s) \propto s^{-3.5}$
- Small bodies vastly outnumber large ones
- Mass dominated by largest bodies



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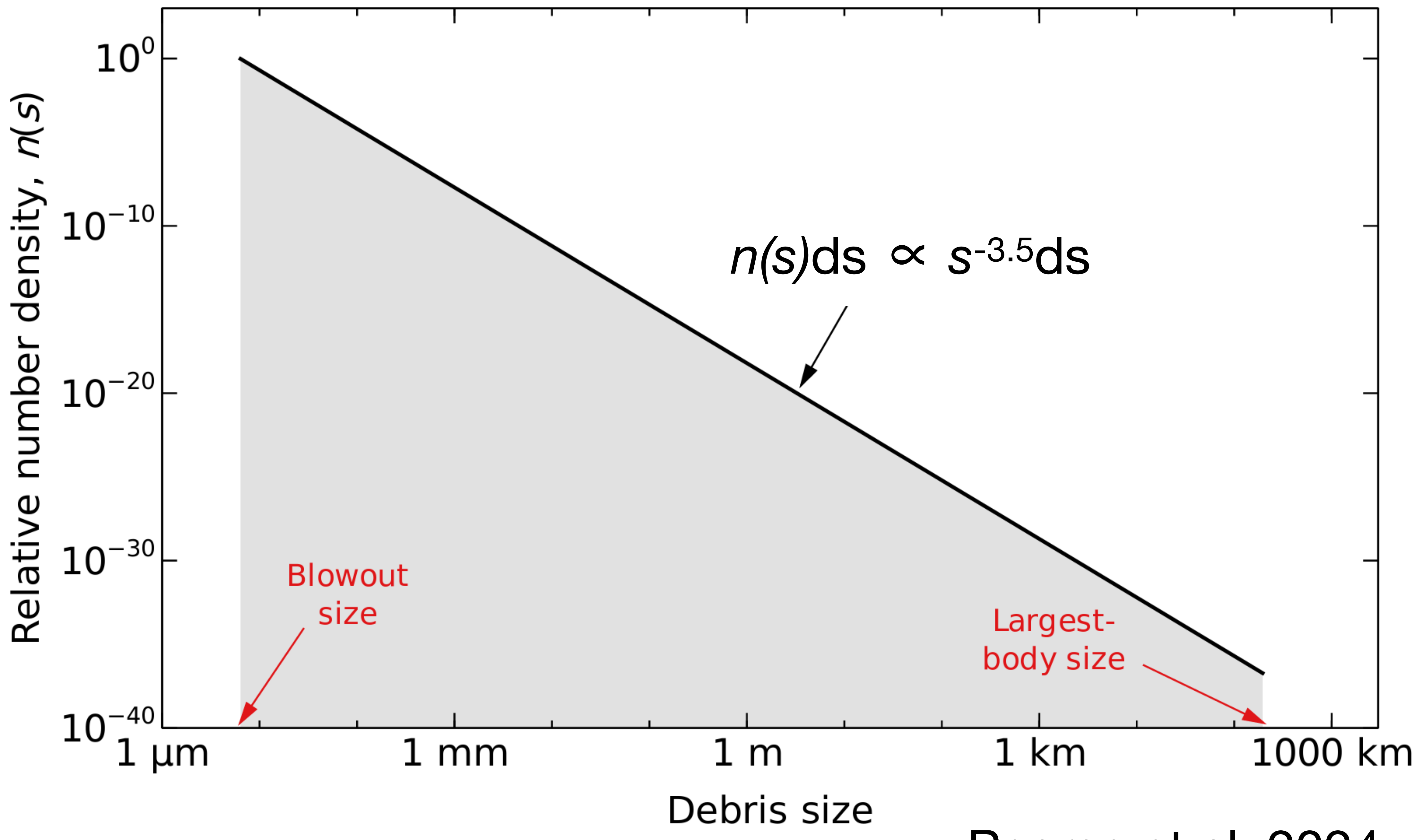

Pearce et al. 2024

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Basic process

- Planetesimals –
  → Dust

Key properties

- Size distribution
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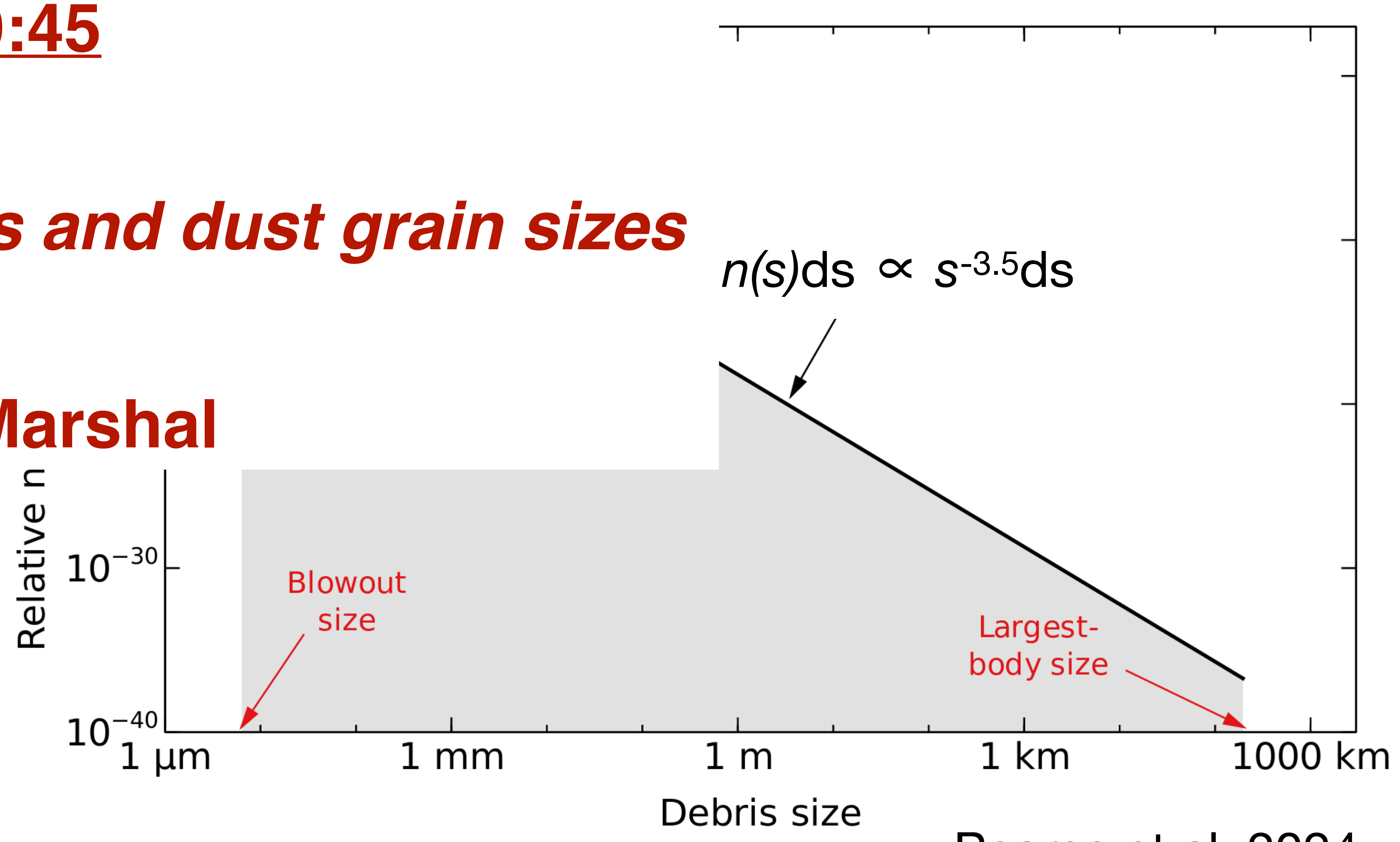
9th Sep 09:45

Planetesimals in debris discs and dust grain sizes

by Jonathan Marshal



Pearce et al. 2024

Forces shaping dust grain dynamics

Gravity dominating large grains & planetesimals

Forces shaping dust grain dynamics

Radiation Pressure pushing small grains outward, creating "blowout size"

Forces shaping dust grain dynamics

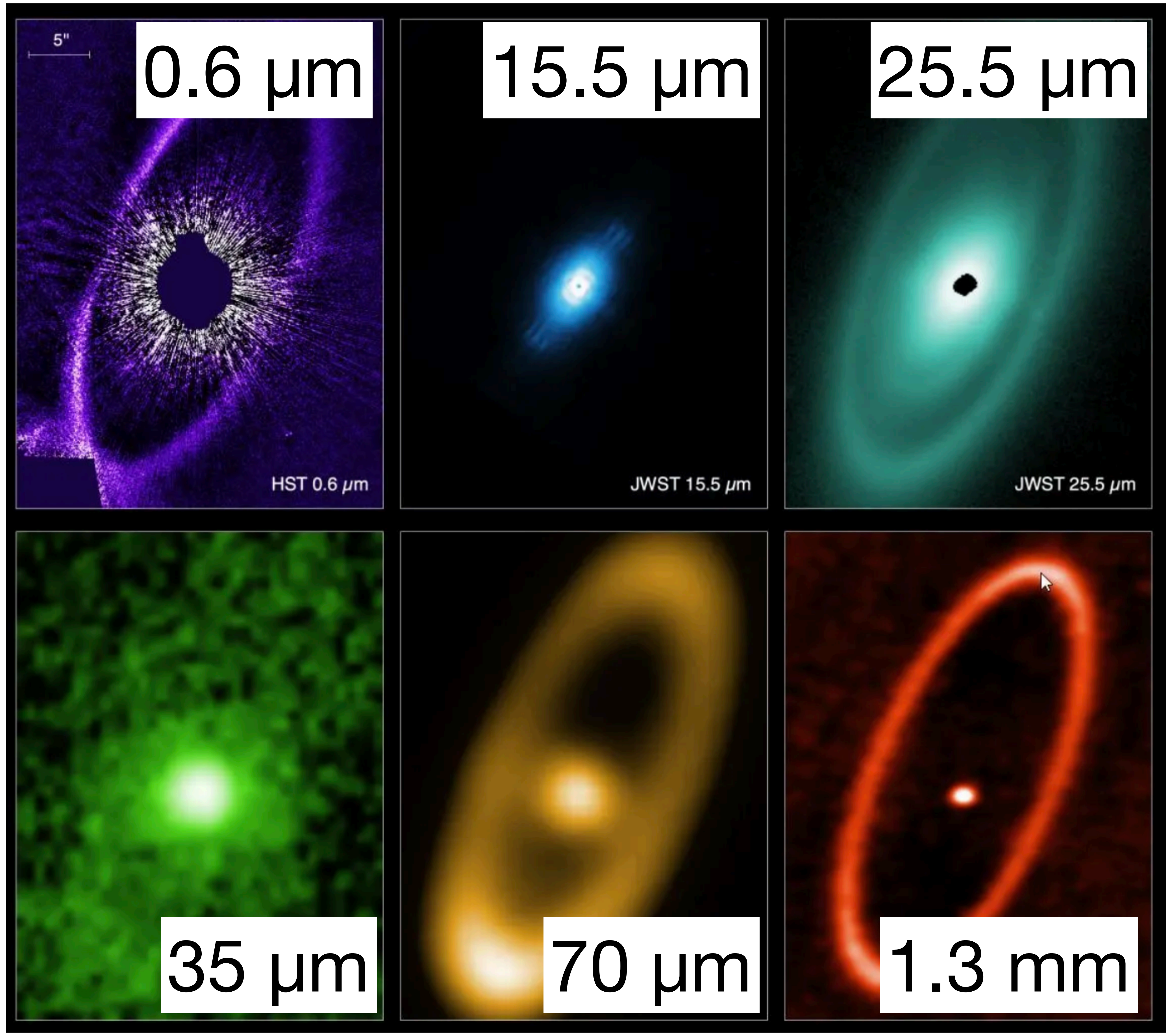
Poynting-Robertson (P-R) Drag
causing dust to spiral slowly inward and circularising eccentric orbits

Forces shaping dust grain dynamics

Stellar Winds and Stellar Winds Drag

Key concepts: Multi-wavelength observations

Gáspár et al. 2025



Scattered light (~0.1 - ~15 μm)

- Reflects starlight from small grains, showing extended halos
- Requires coronagraphs (star ~$10^6 \times$ brighter)

Key concepts: Multi-wavelength observations

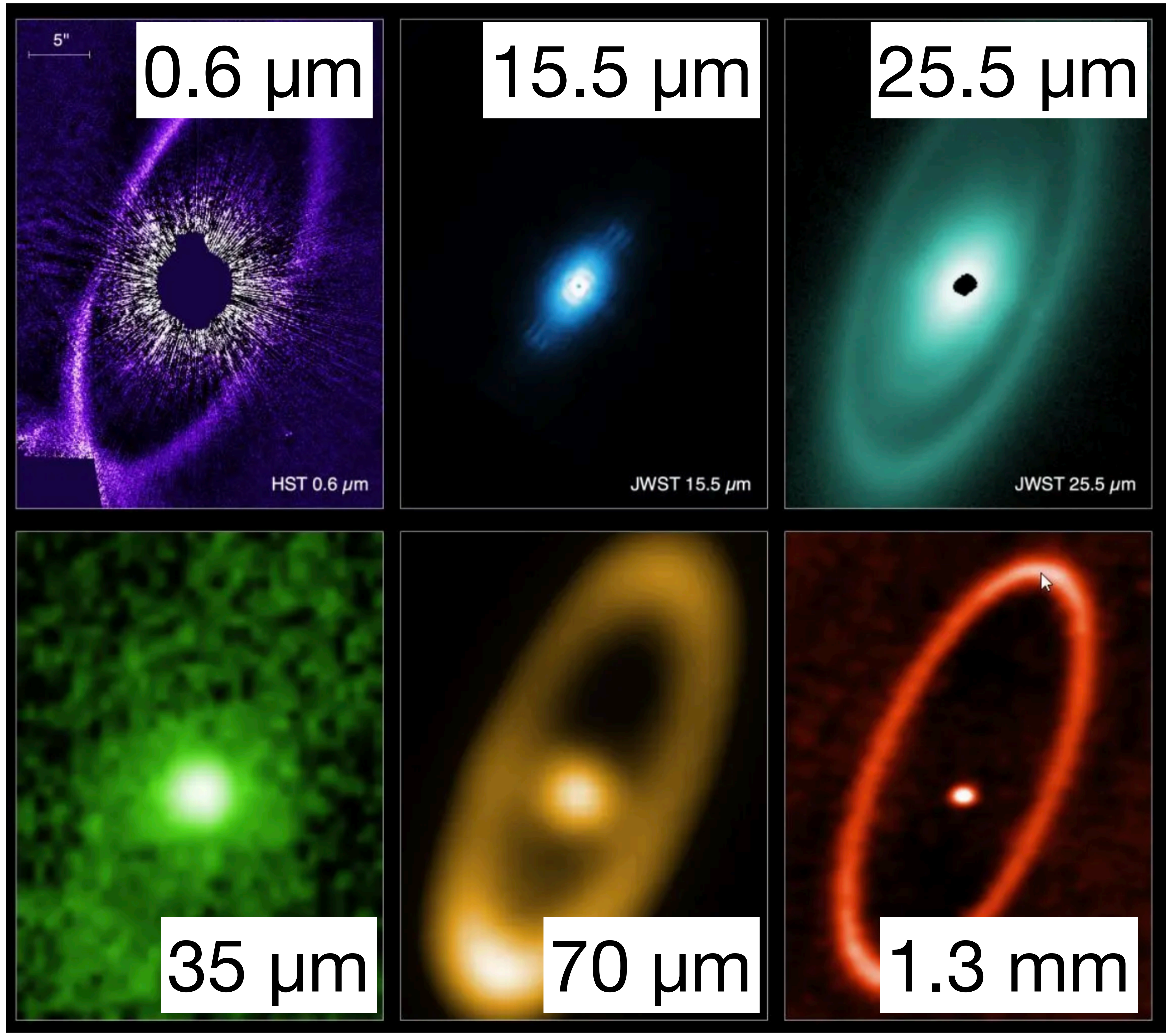
Scattered light (~0.1 - ~15 μm)

- Reflects starlight from small grains, showing extended halos
- Requires coronagraphs (star ~10^6 × brighter)

Thermal emission (~15 μm - ~1 cm)

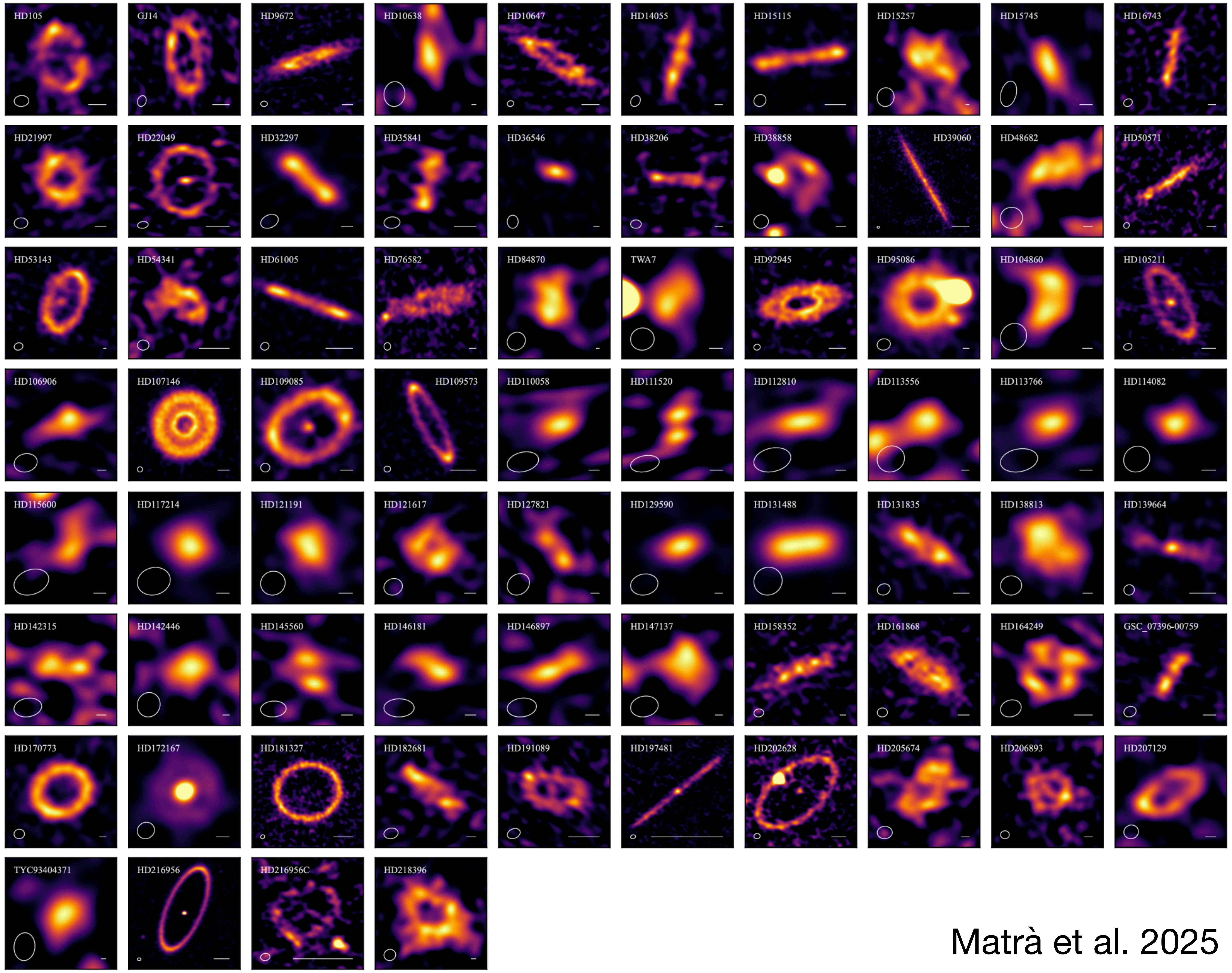
- Heat radiated by dust
- Probes larger grains, more compact distributions

Gáspár et al. 2025



UCL

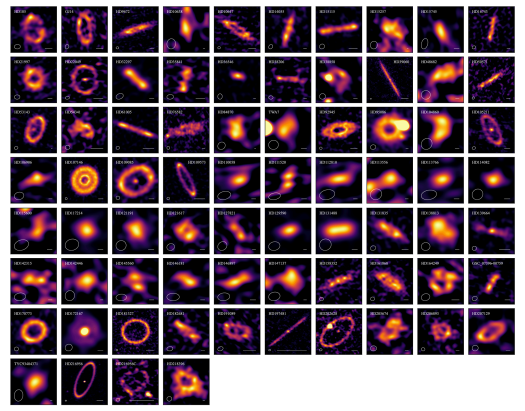
Resolved Images: REASONS survey



REsolved **A**LMA and **S**MA **O**bservation of **N**earby **S**tars

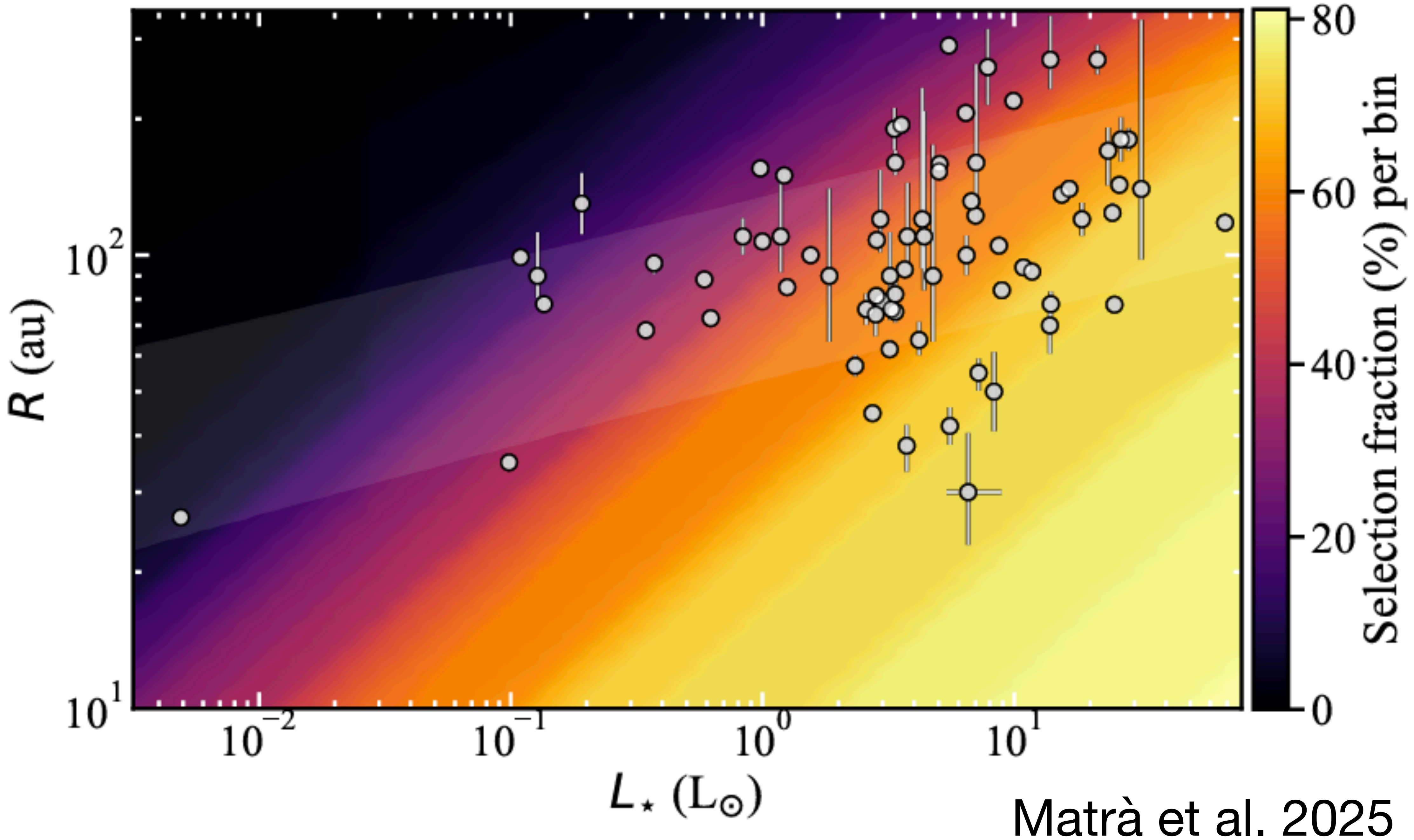
Matrà et al. 2025

Resolved Images: REASONS survey



Key concept: Radial distribution

- Resolving all imagable discs (74 Exo Kuiper belts) in (sub-) mm
- Belt width/location correlates with L_* (Matrà et al. 2019; Sepulveda et al 2019)
- Possibly indicating the formation of planetesimal belts could be related to snow-line or at least massive planet's orbit?



Matrà et al. 2025

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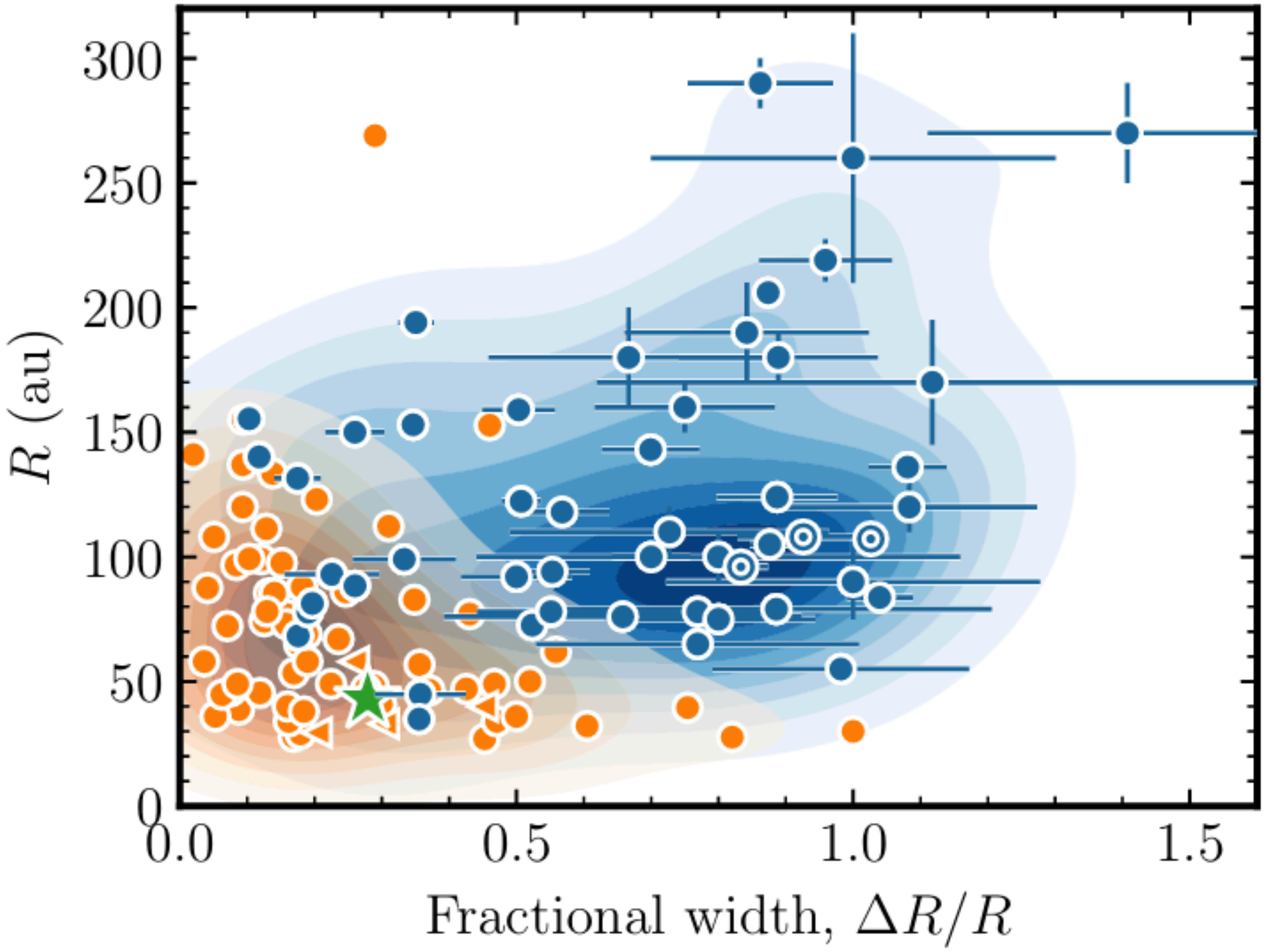
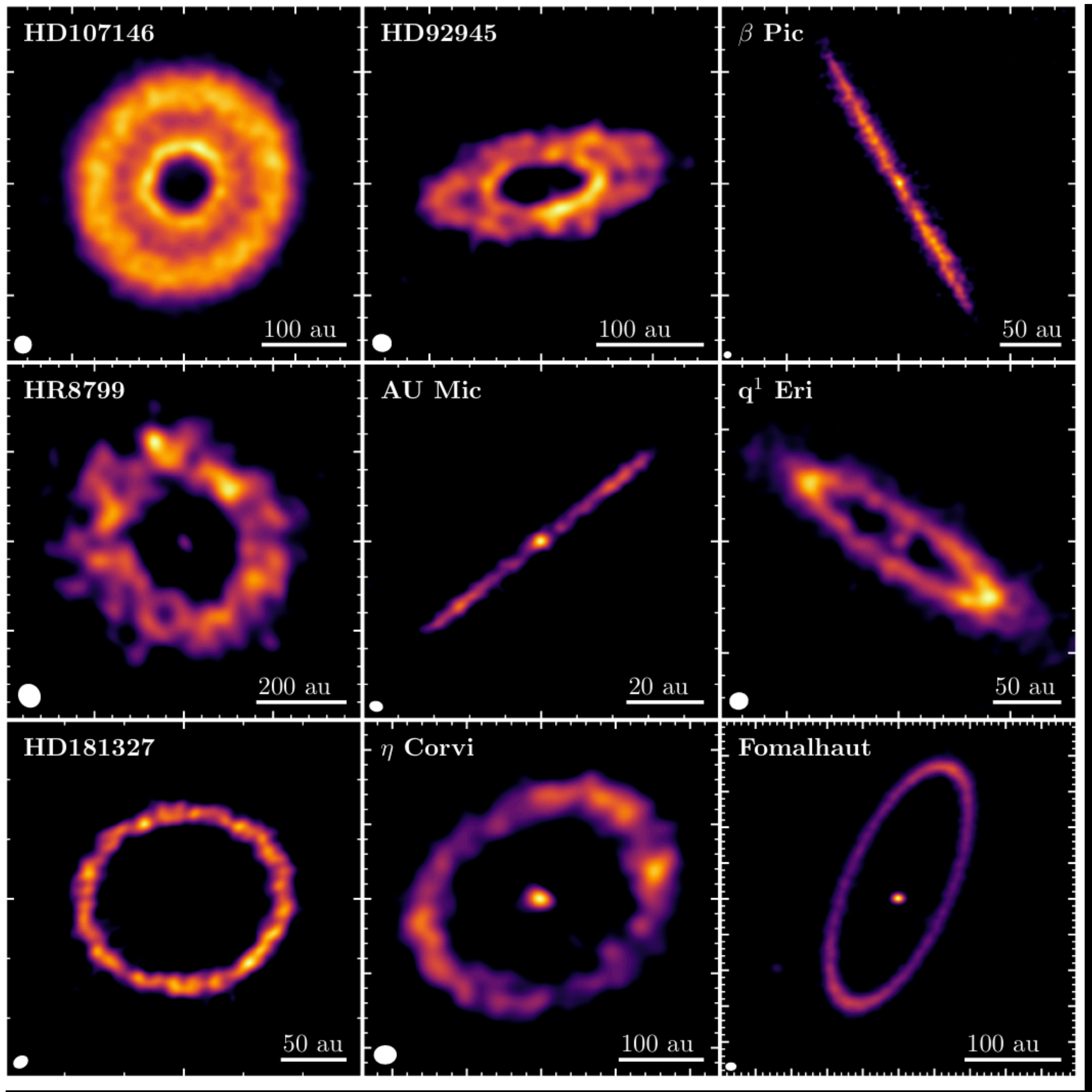
Matrà et al. 2025



UCL

Resolved Images: ARKS programme

Marino et al. 2022
Marino et al. 2018a, 2019
Matra et al. 2019a
Faramaz et al. 2021
Daley et al. 2019
Lovell et al. 2021b
Pawellek et al. 2021
Marino et al. 2017a
MacGregor et al. 2017
Marino et al. submitted



ALMA survey to Resolve exoKuiper belt Substructures

Marino et al. submitted

Resolved Images: ARKS programme

Marino et al. 2022
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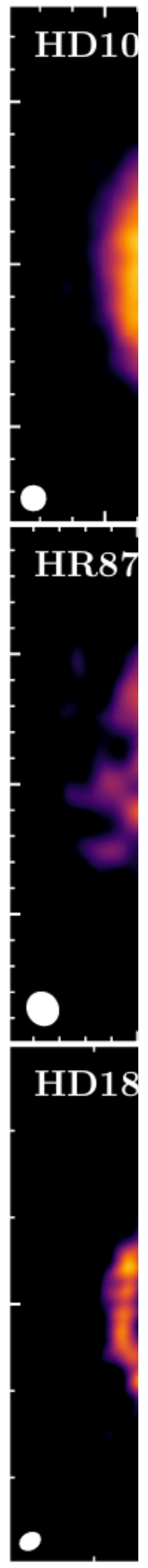


8th Sep 15:30

(Sub)mm Analysis of HD 32297’s Edge-on Debris Disc

by Patricia Luppe

8th Sep 16:00

Asymmetric debris discs: how do eccentric rings glow?

by Joshua Lovell

ALMA survey to Resolve exoKuiper belt Substructures

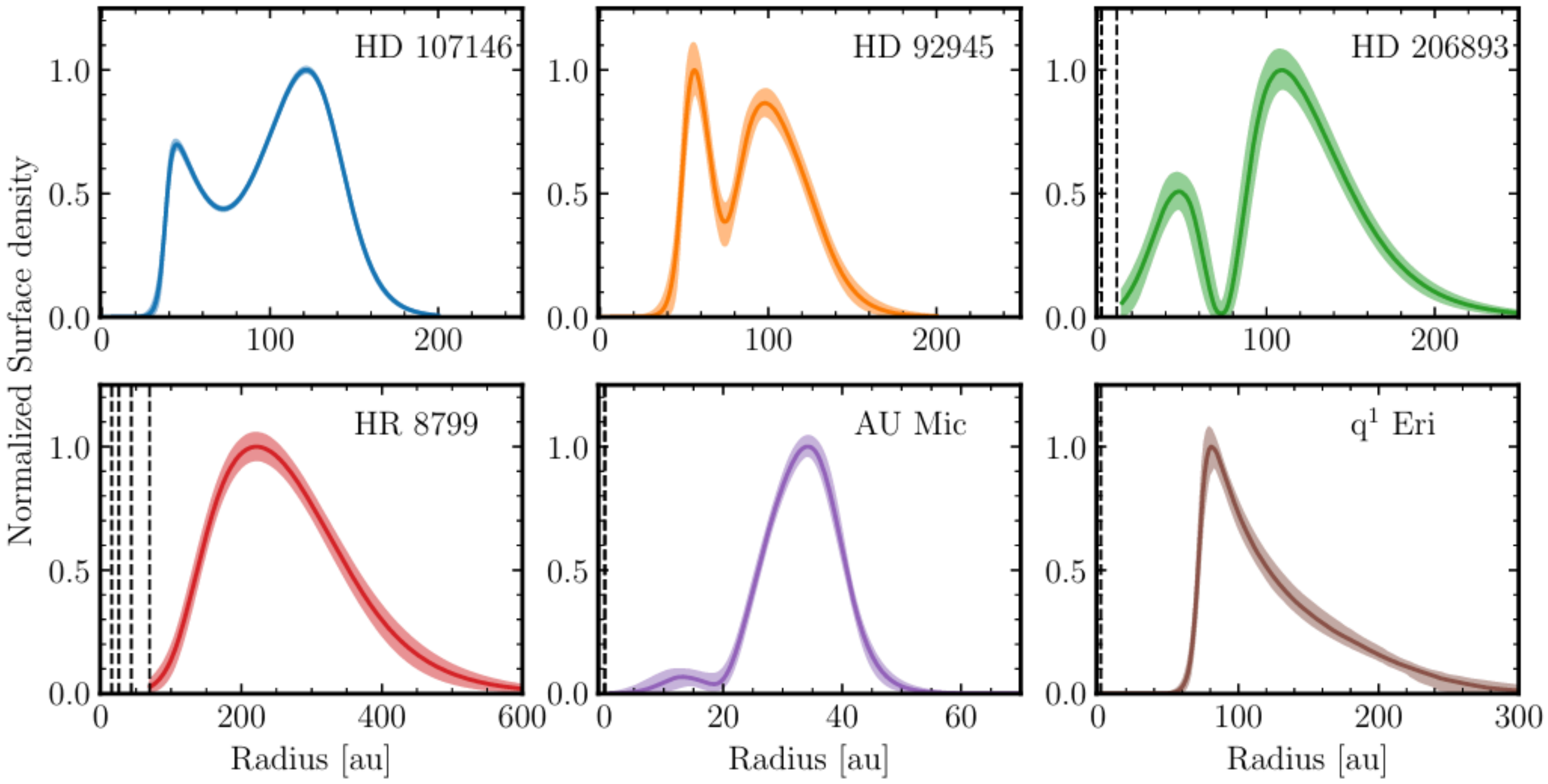
Marino et al. submitted

Resolved Images: ARKS programme

- High resolution 18 Exo Kuiper belts + 6 belts from literatures including 10 more face-on and 8 edge-on debris discs

  Much more complicated than a simple "ring"

- From face-on disc's radial profiles showing broad discs, gaps, halos, shallow outer edges, sharply confined…



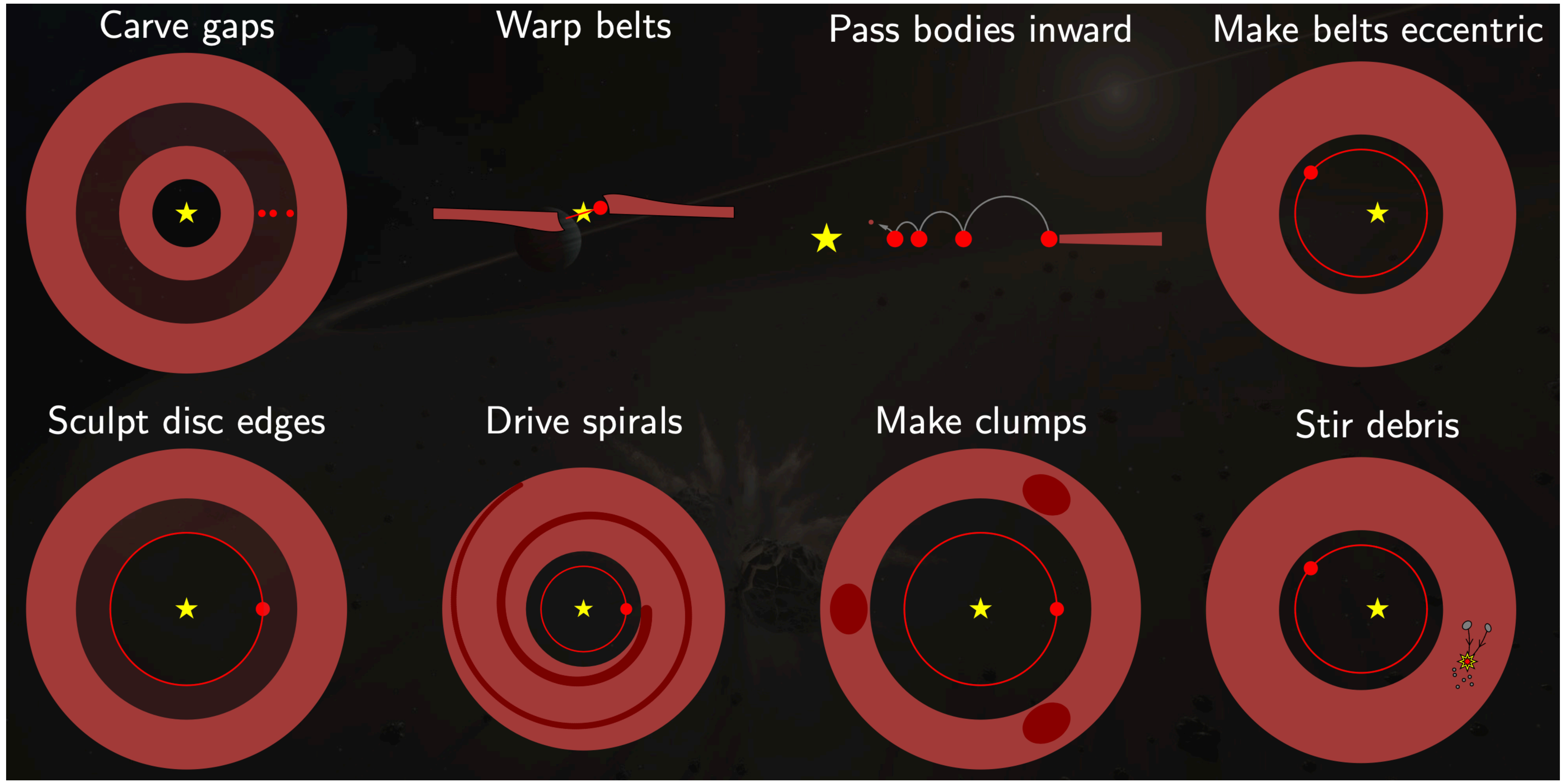
Marino et al. 2022

Planetary interactions in debris discs

3 main mechanisms

- **Scattering**
- **Secular perturbation**
- **Mean-Motion Resonances**

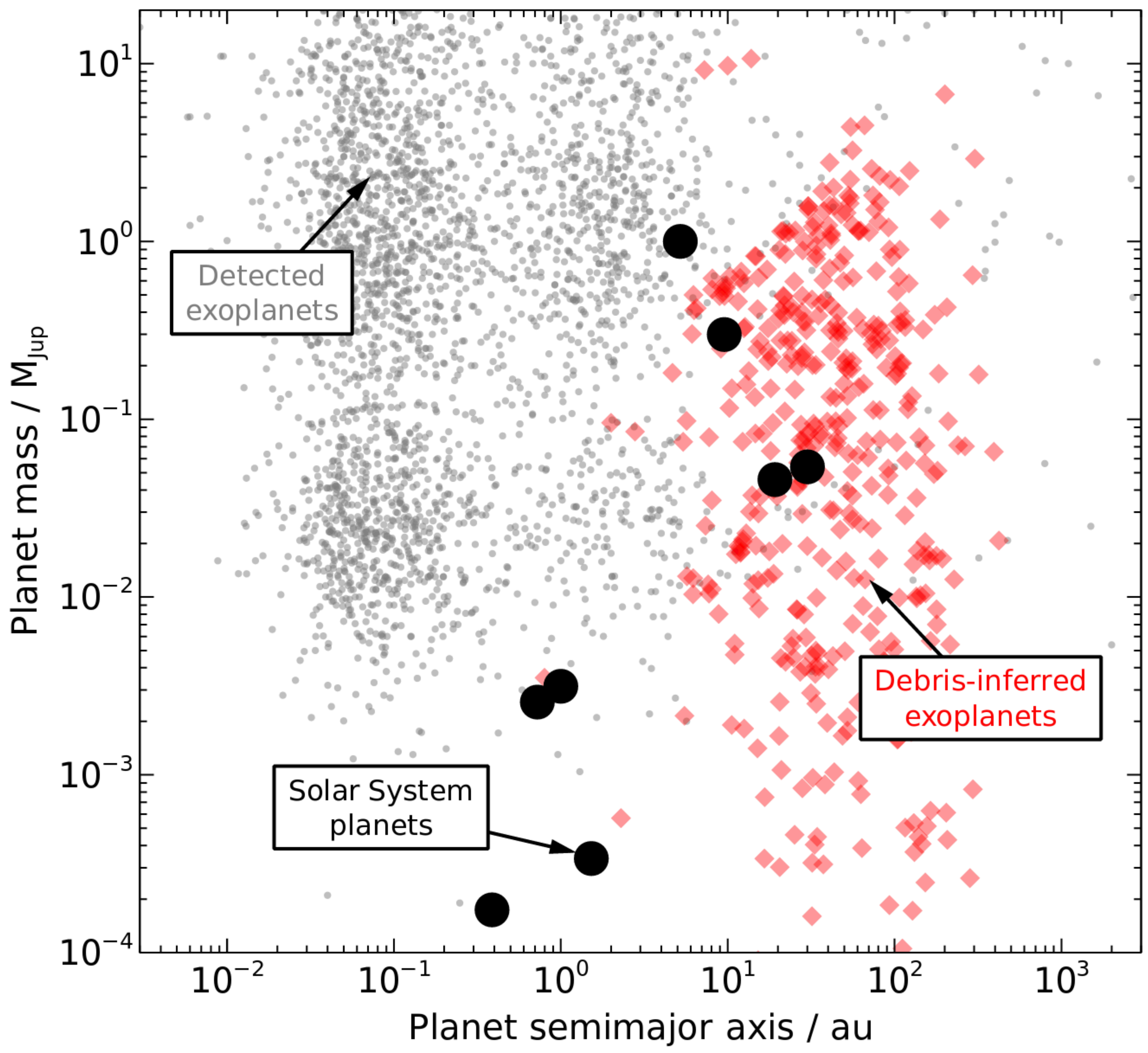
Possibly creating gaps, sharp edges in discs, warped, eccentric discs, clumps, stabilises(like P-N 3:2 resonance)/destabilises orbits



Evidence for unseen planets

Planet estimates

- Detection challenge: outer system planets



Pearce et al. 2022a, 2024

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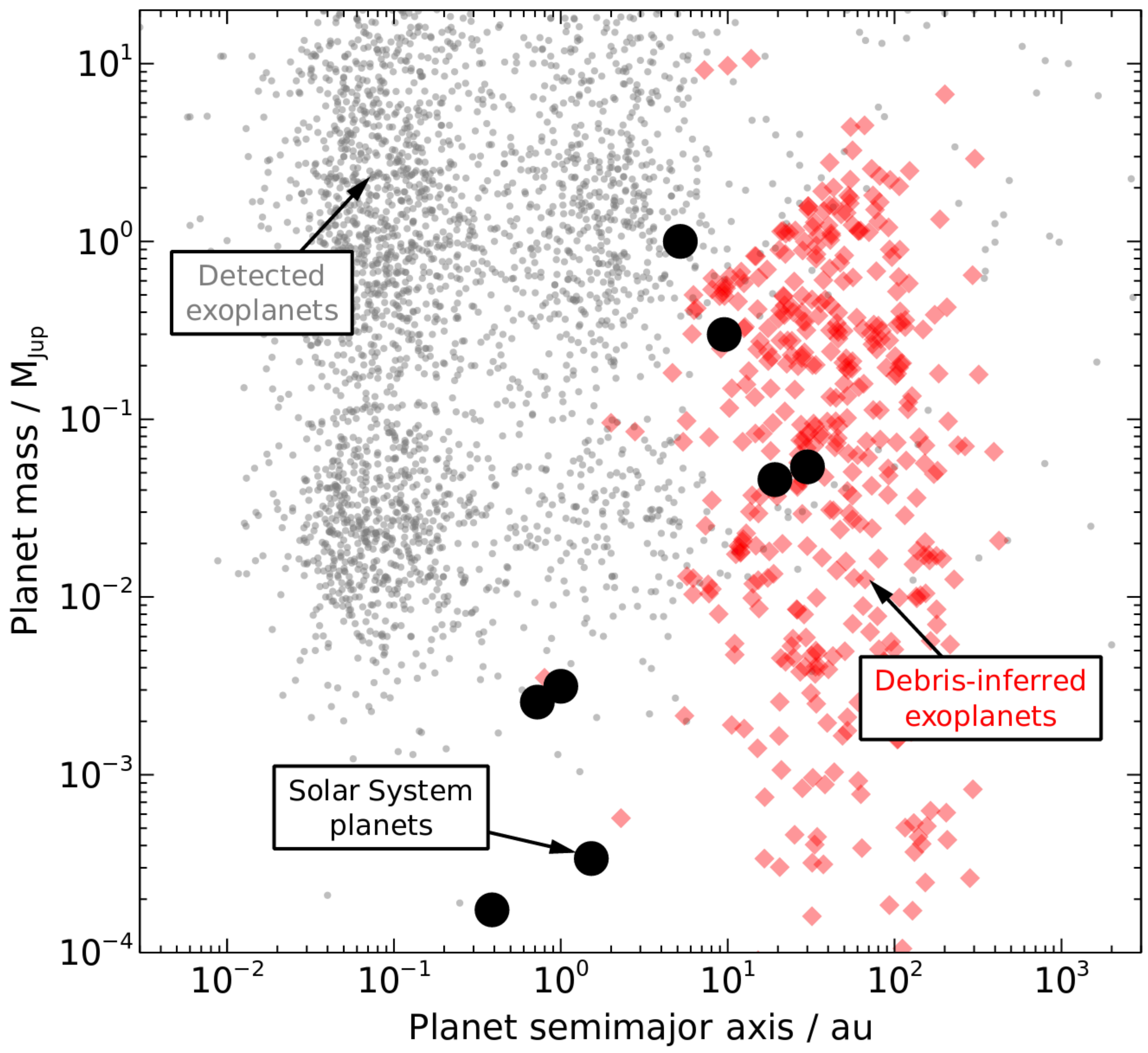
- Predicted masses with JWST: 0.1-10 M_{Jupiter}

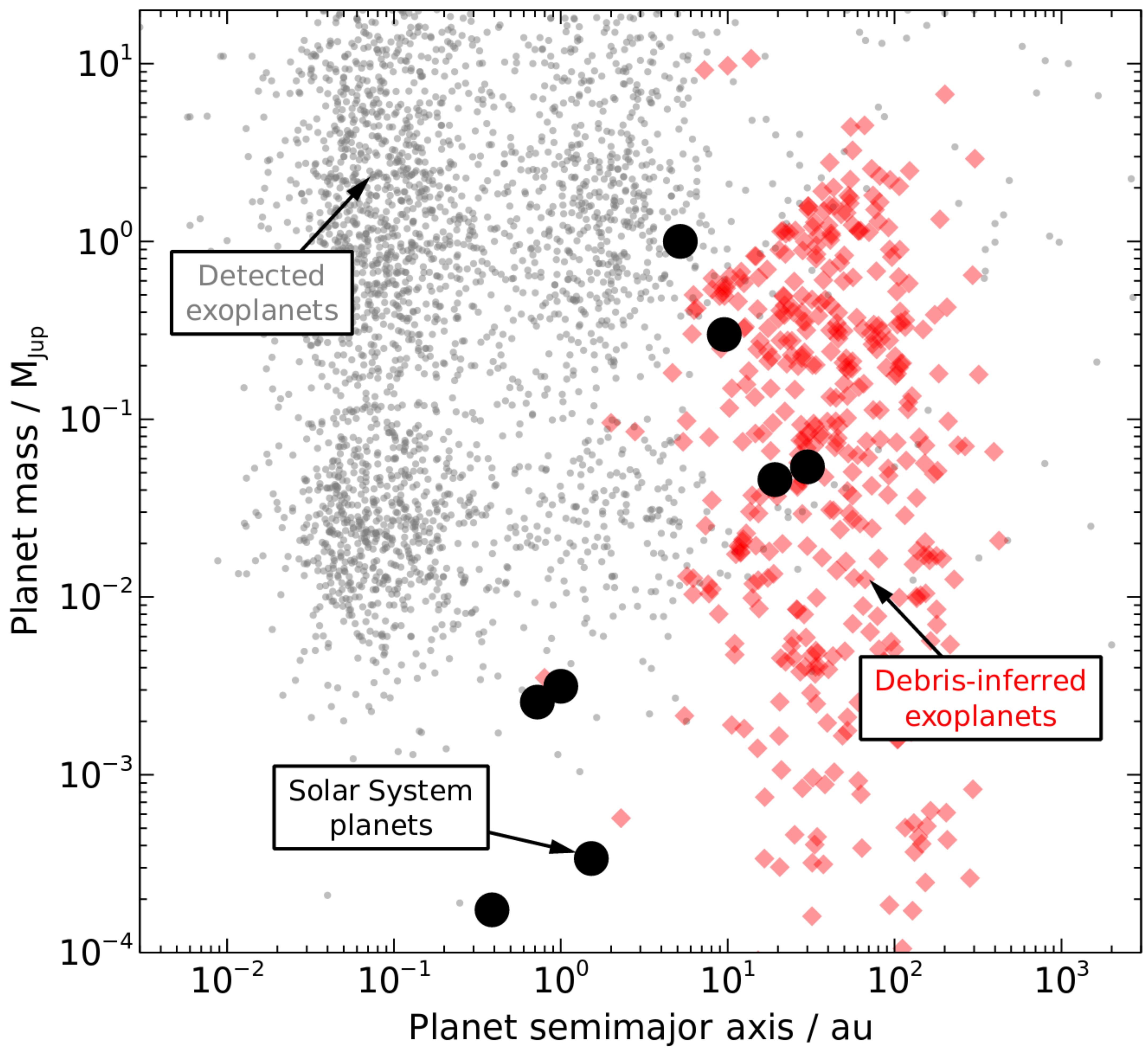


Pearce et al. 2022a, 2024

Evidence for unseen planets

Planet estimates

- Detection challenge: outer system planets
- Predicted masses with JWST: 0.1-10 M_{Jupiter}
- Locations: 10-100 AU



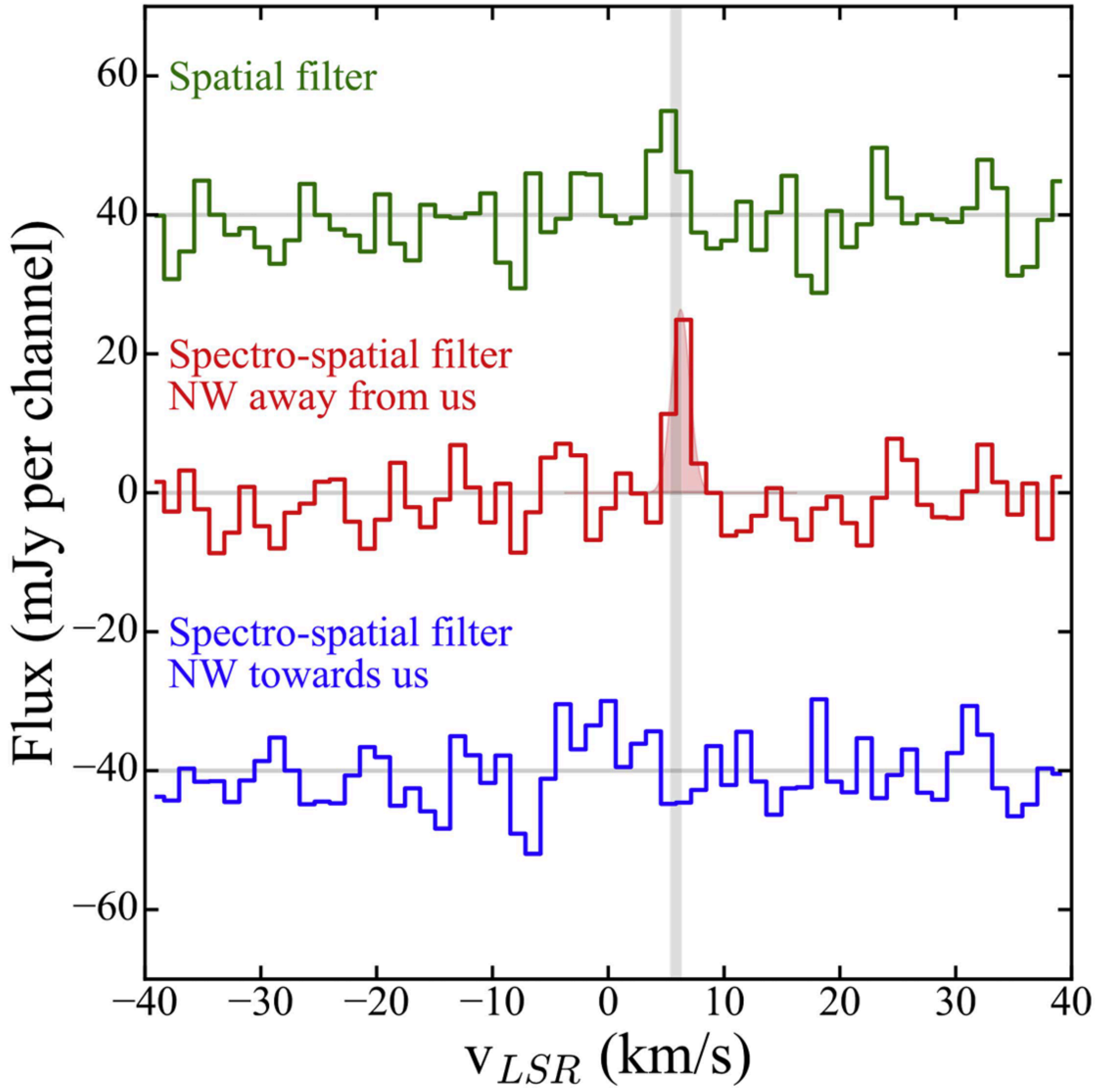
Pearce et al. 2022a, 2024

Outstanding questions

Gas in debris discs

CO detections

- ~50 systems with CO emission
- Predominantly young systems (<100 Myr) and A-type stars



Matrà et al. 2017

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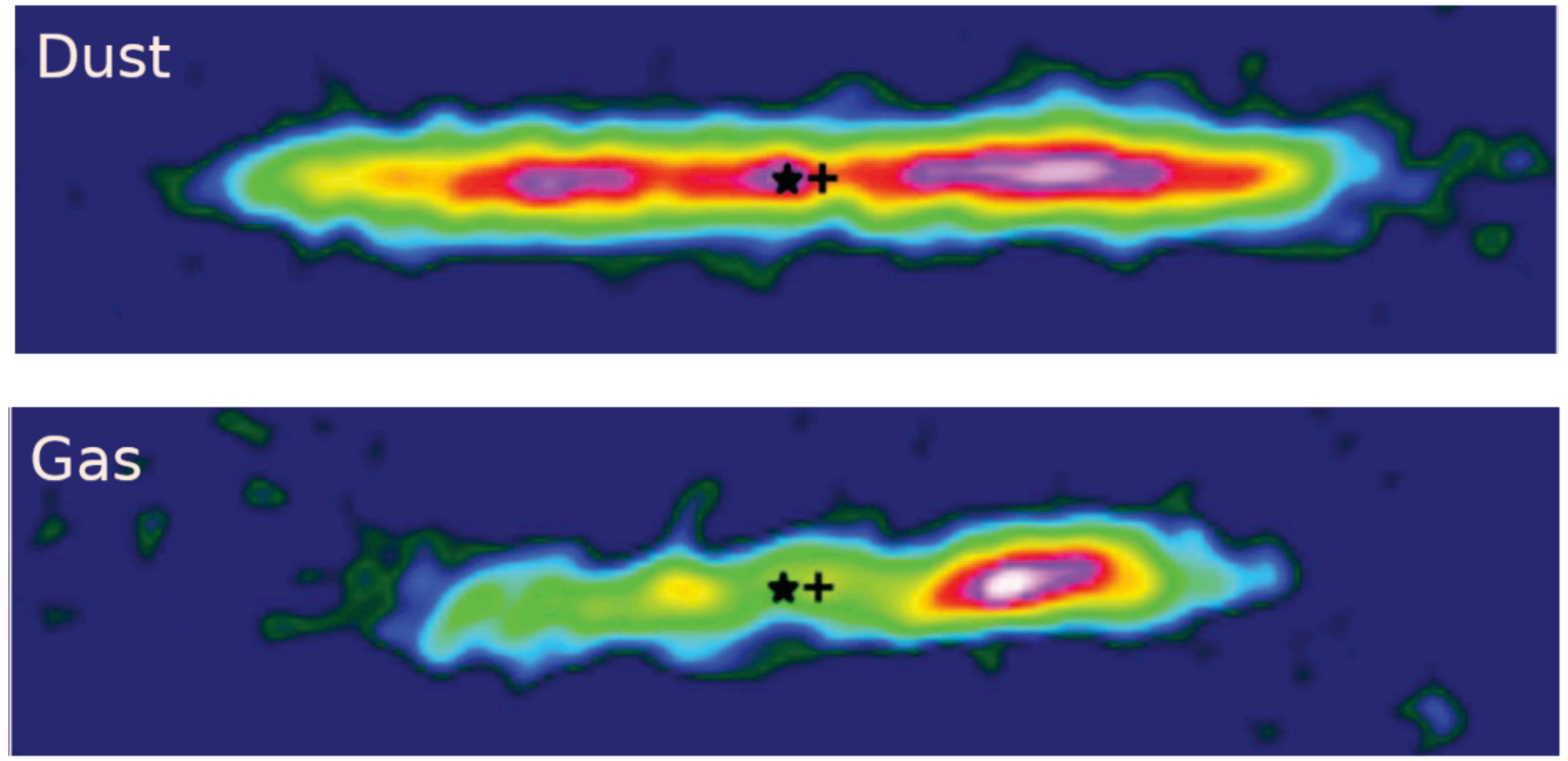
Two types of gas populations

- **Gas co-located with dust belts** (tens to hundreds of AU): β Pictoris system shows CO gas overlapping with millimetre dust

Dust and gas in the β Pictoris system by ALMA



Dent et al. 2014

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Two types of gas populations

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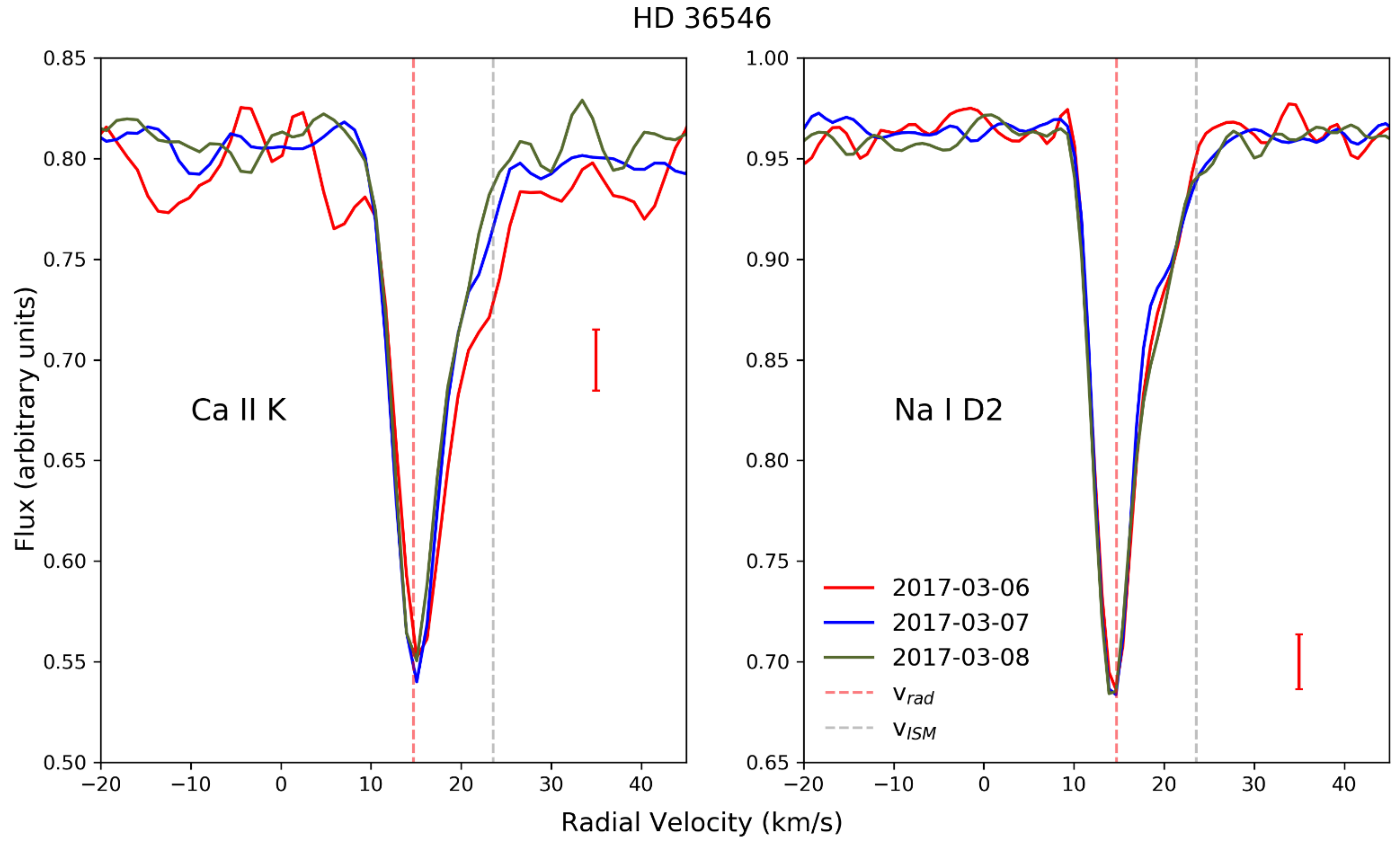
- **Gas from star-grazing exocomets**: absorption signatures as comets pass close to stars - detection rate: ~14%



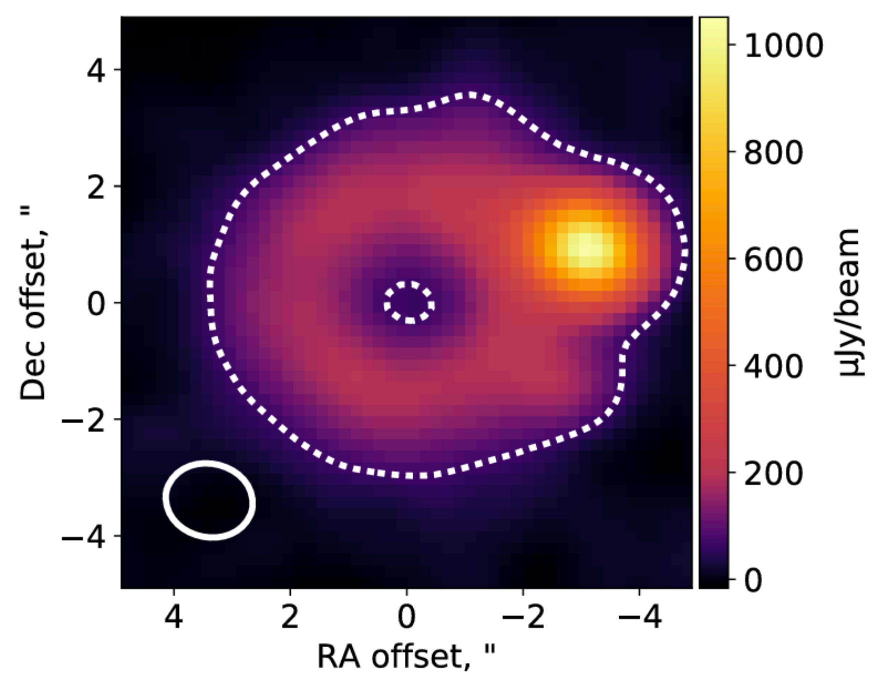
Rebollido et al. 2020

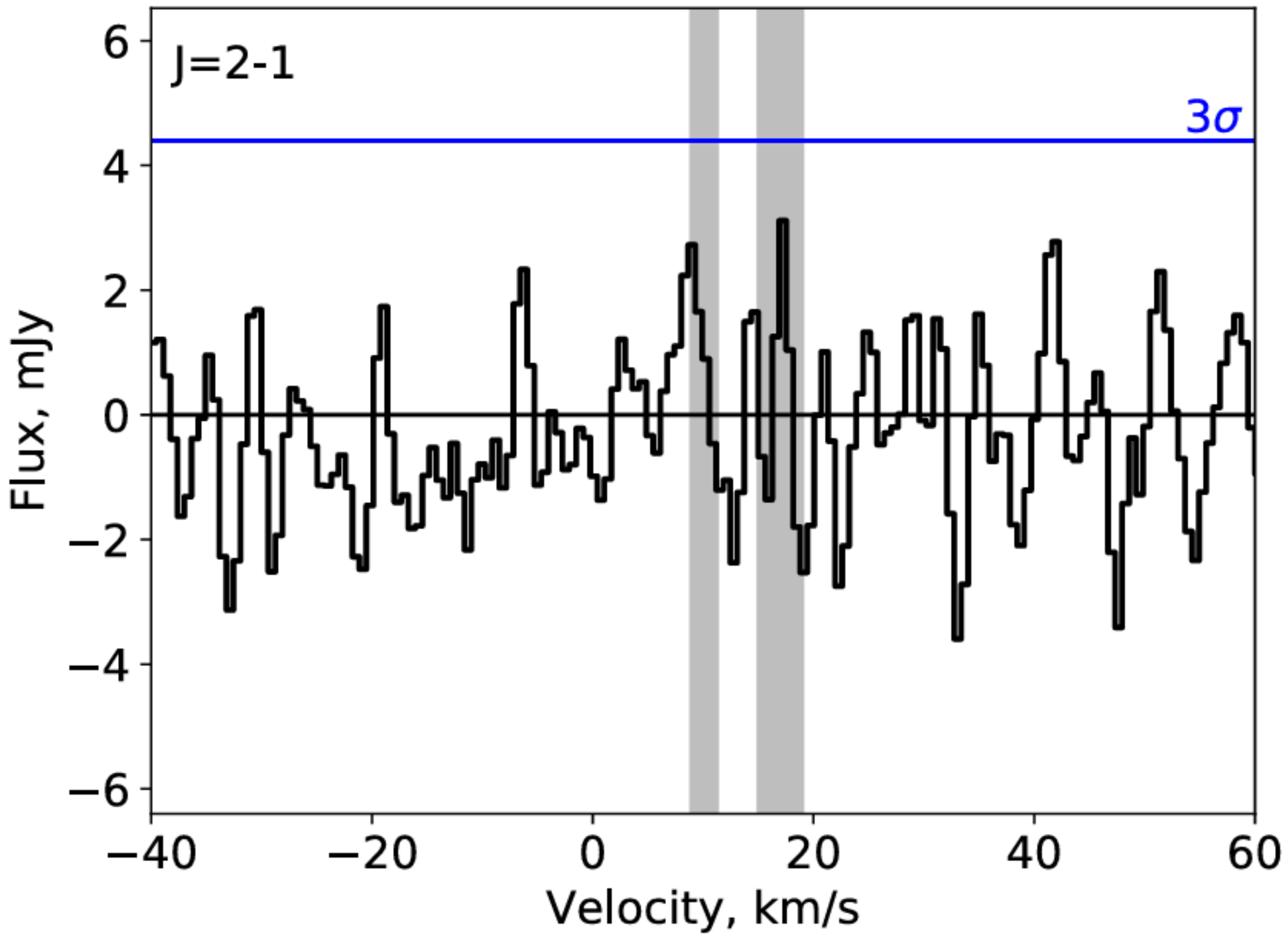
Gas in debris discs

Uncertain gas origins

- **Primordial** (leftover from protoplanetary disc, e.g., H_2 and Noble Gases)?
- **Secondary** (released by collisions, e.g., CO and/or ongoing evaporation of small bodies, e.g., atomic species)?

Booth et al. 2019



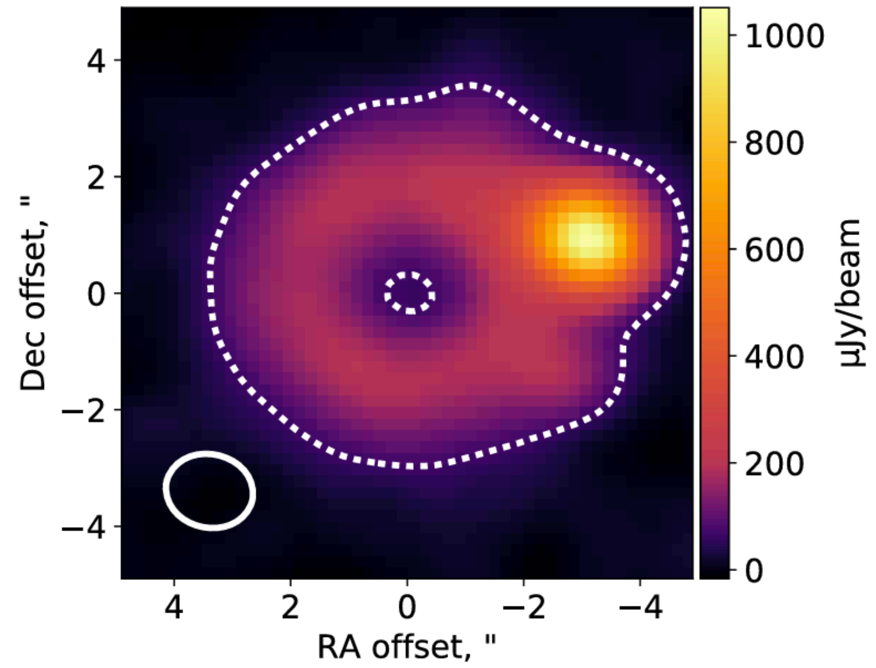


Gas in debris discs

<u>9th Sep 14:30</u>

<u>Uncertain</u>

Gas Heating & Cooling in Debris Discs: Insights from β Pic 9



- **Primordia**
  disc, e.g.,

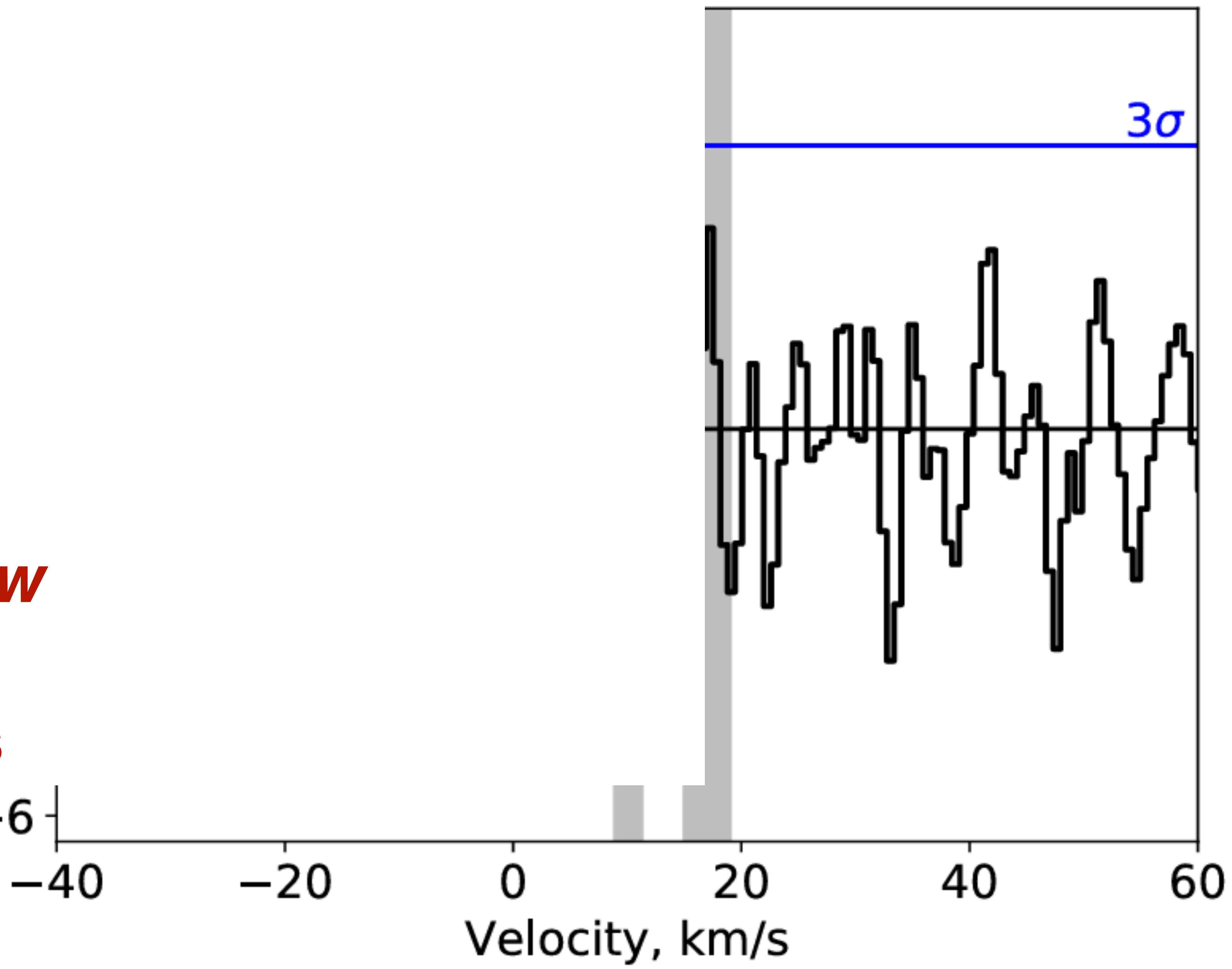
by Sana Ahmed

- **Secondar**
  CO and/o
  bodies, e.

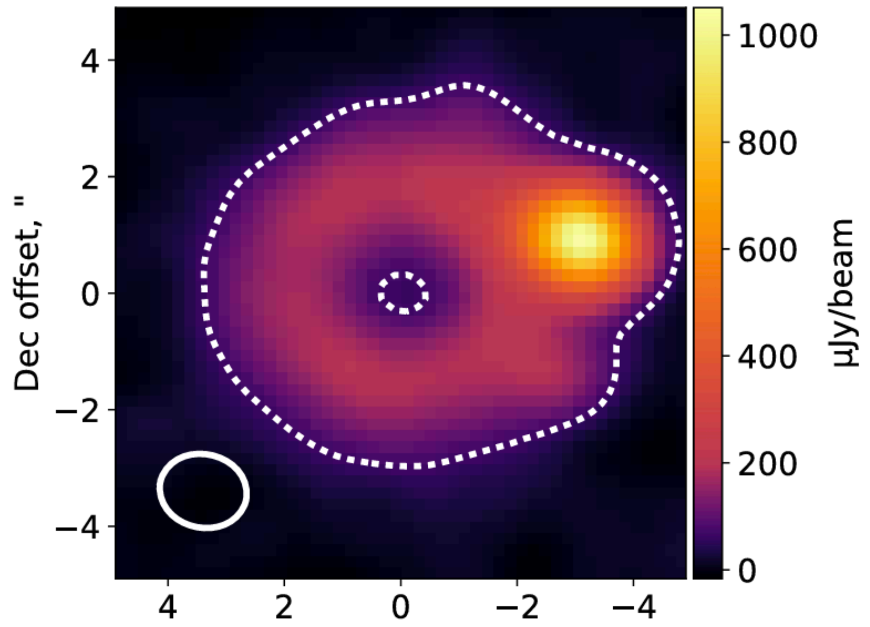
<u>10th Sep 14:45</u>

Exocomets Overview

by Daniela Iglesias



Gas in debris discs



Booth et al. 2019

Uncertain gas origins

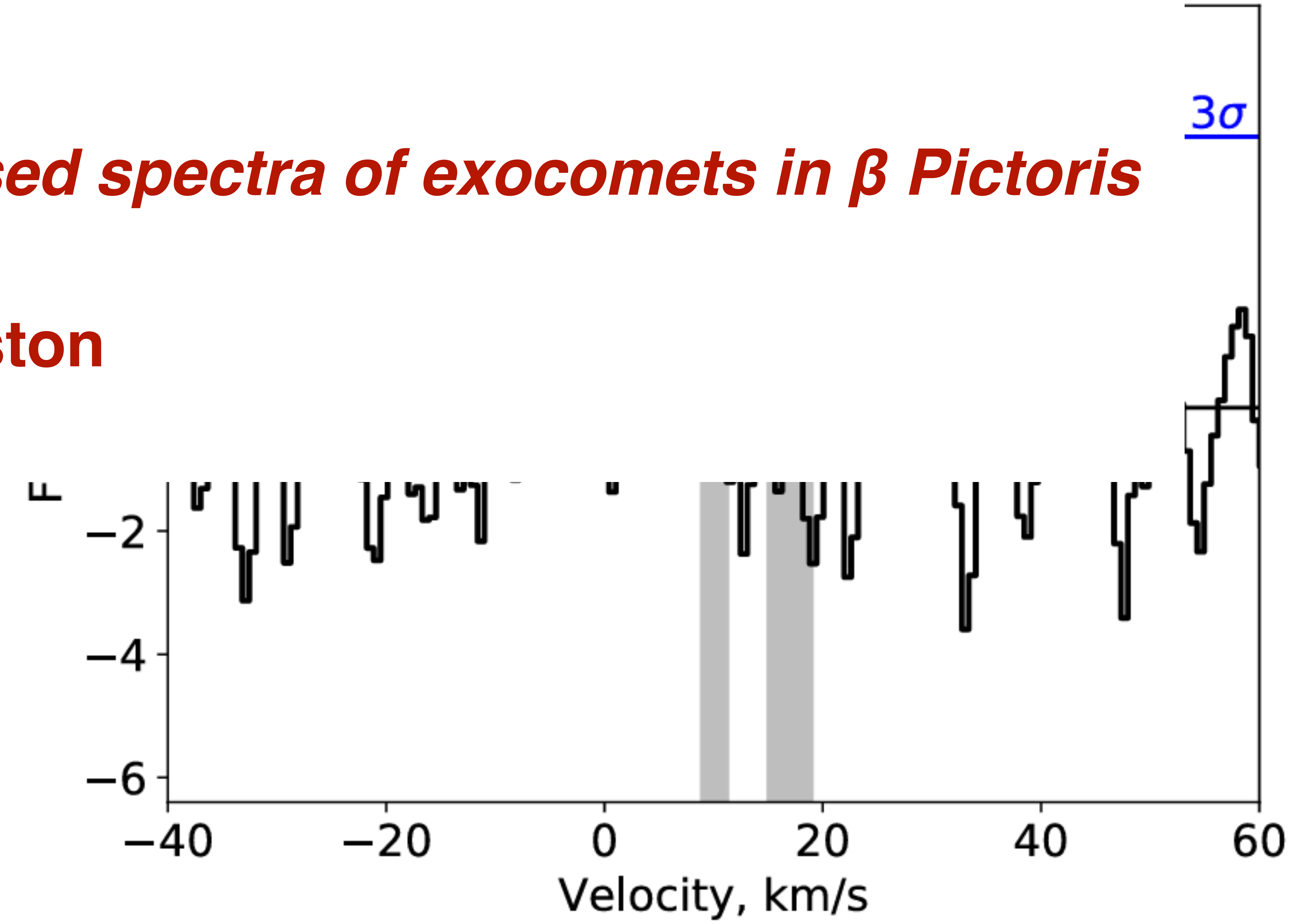
Poster

-

Simultaneous TESS photometry and ground-based spectra of exocomets in β Pictoris

-

By Michael Elston



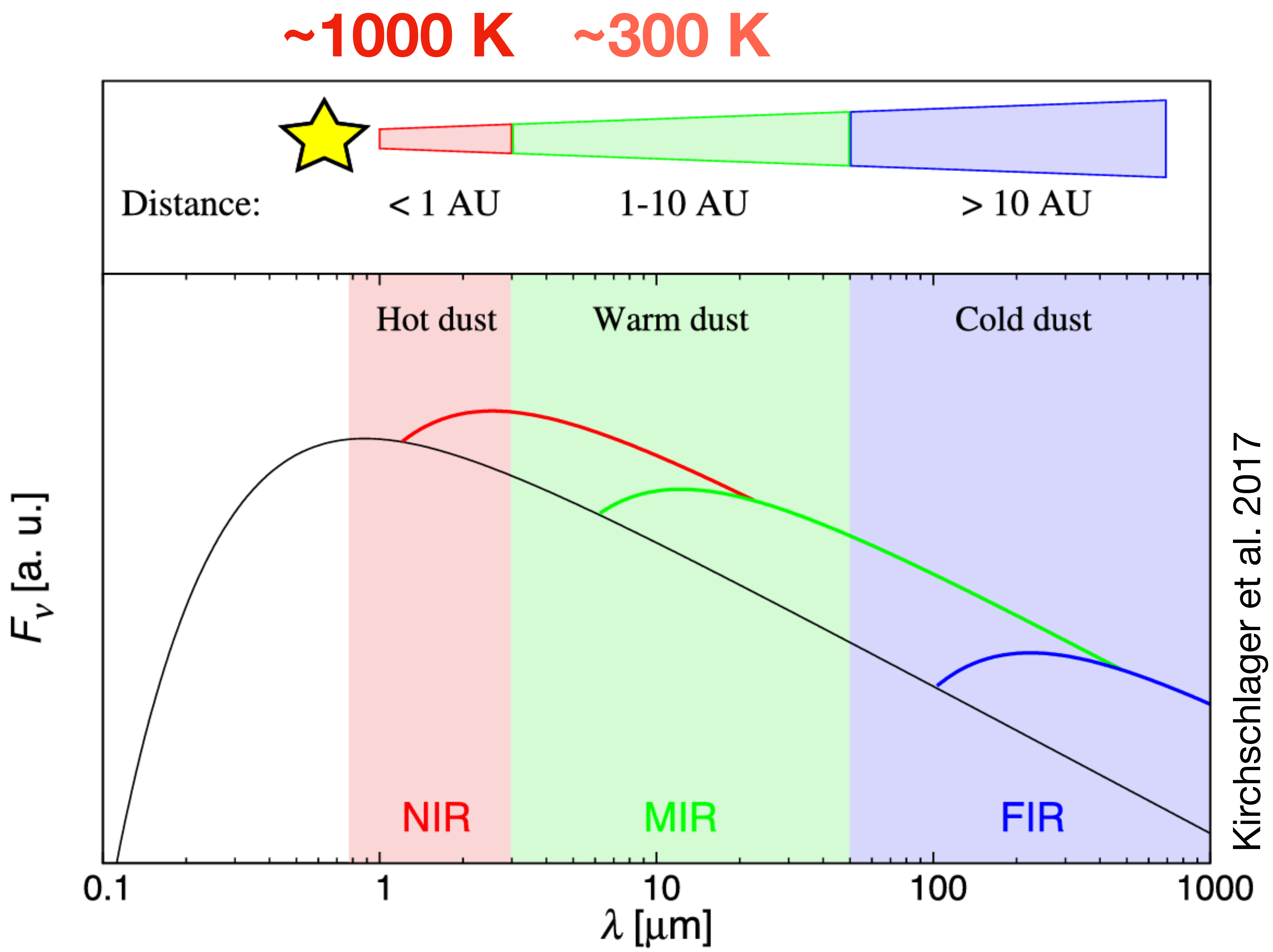
Hot dust mystery

Main Problem: How they survive?

- Hot dust detected around 20-30% of MS stars
- Too close for stable planetesimal belts

Proposed solutions

- P-R drag migration from outer regions
- Cometary delivery and sublimation
- Giant impact events
- Magnetic trapping mechanisms
- Gas drag



Kirchschlager et al. 2017

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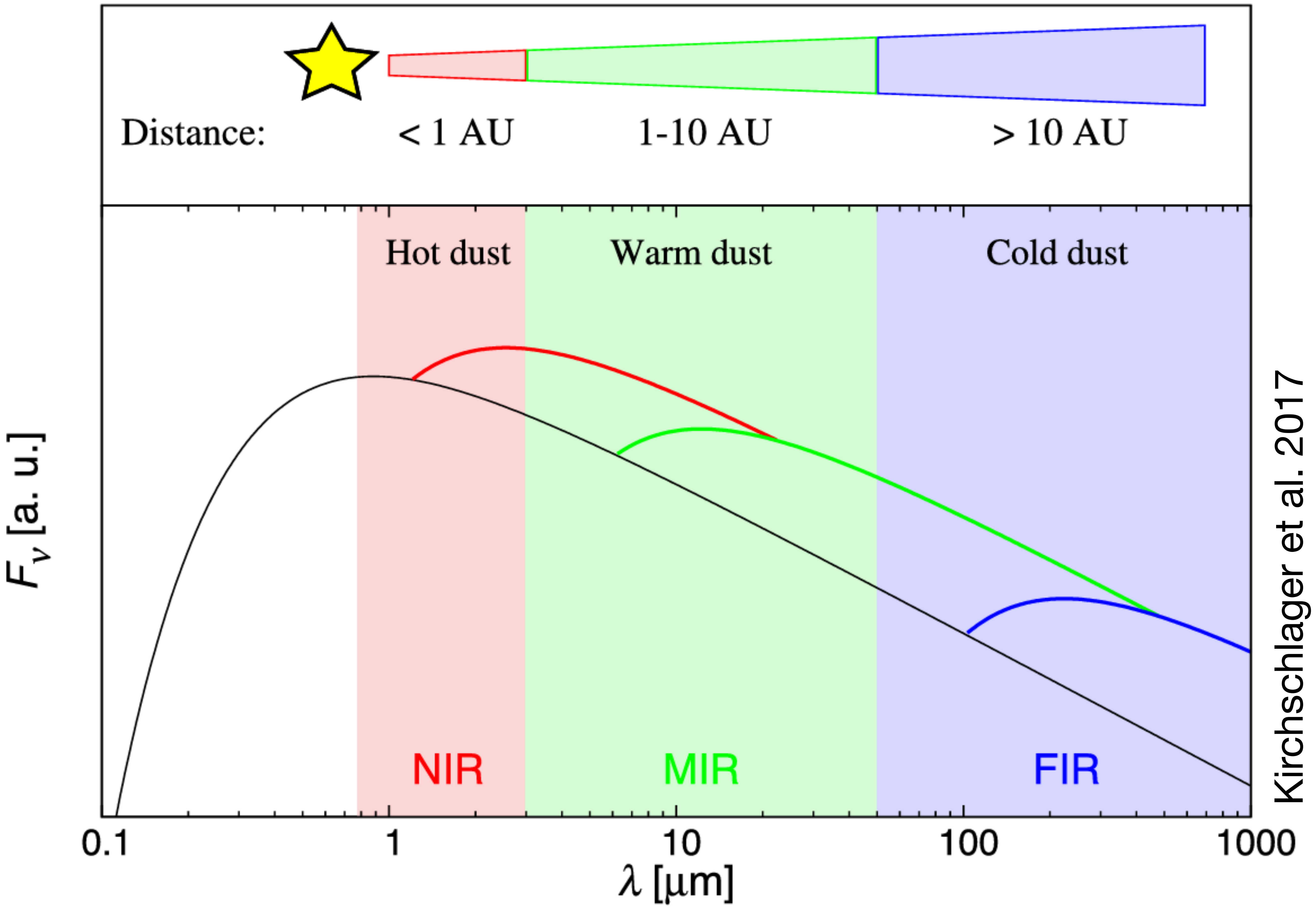
~1000 K ~300 K



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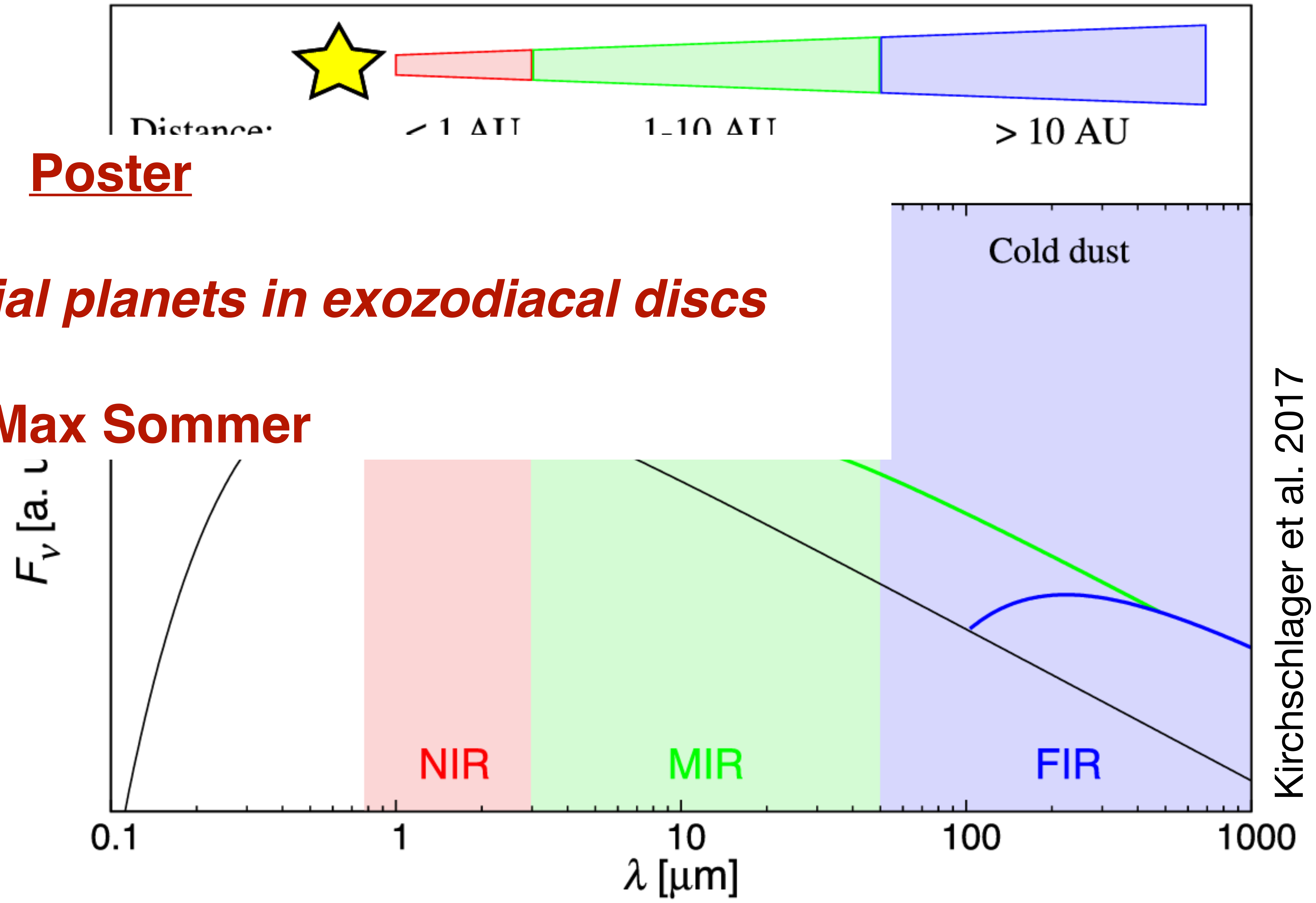


Poster

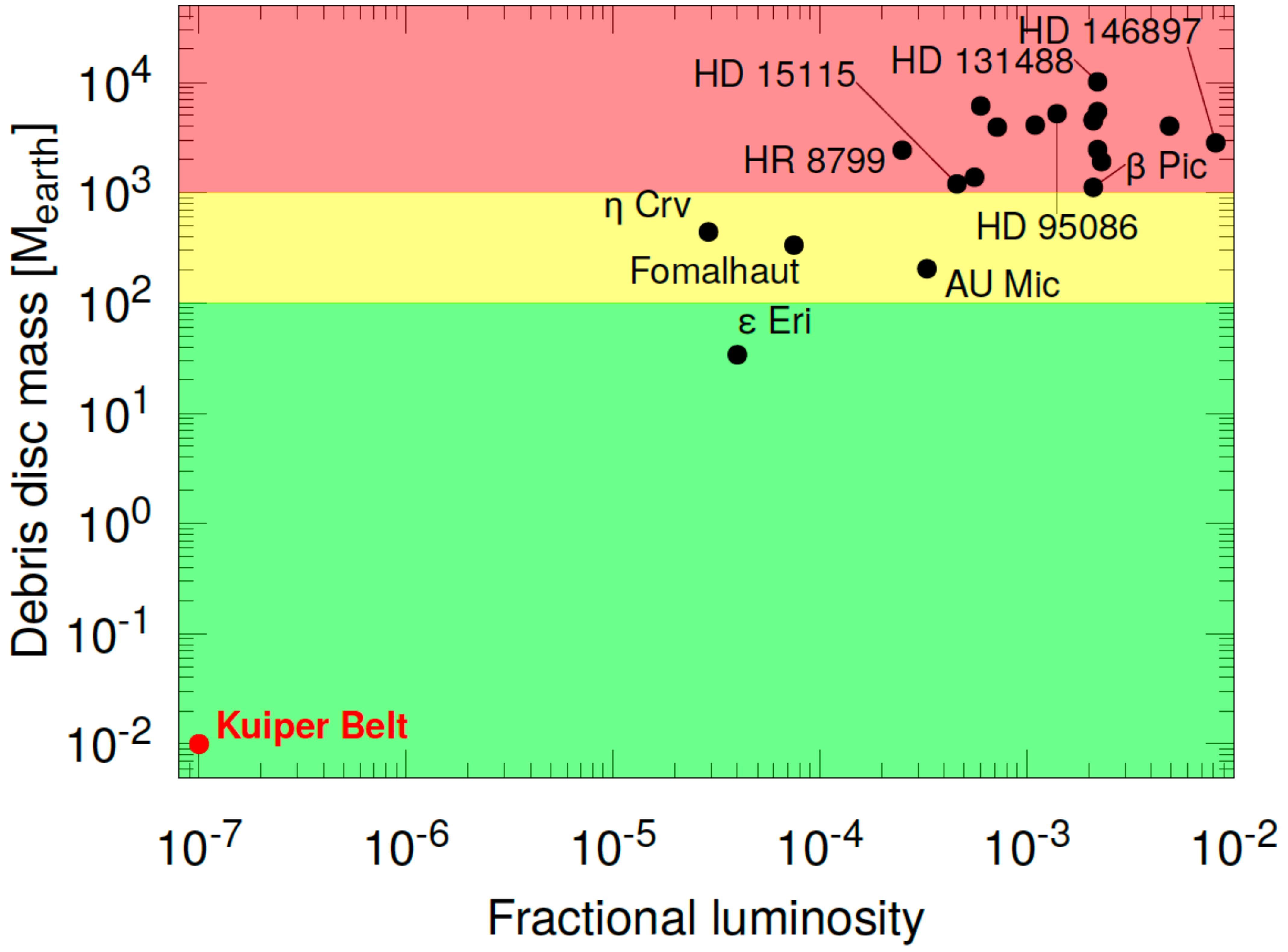
Signatures of terrestrial planets in exozodiacal discs

by Max Sommer

“Debris disc mass problem”

Problem

- Inferred $M_{\rm disc}$: ~10^3-10^4 $M_\oplus$ vs.
  Maximum possible $M_{\rm disc}$: ~10^2-10^3 $M_\oplus$



Krivov and Wyatt 2020

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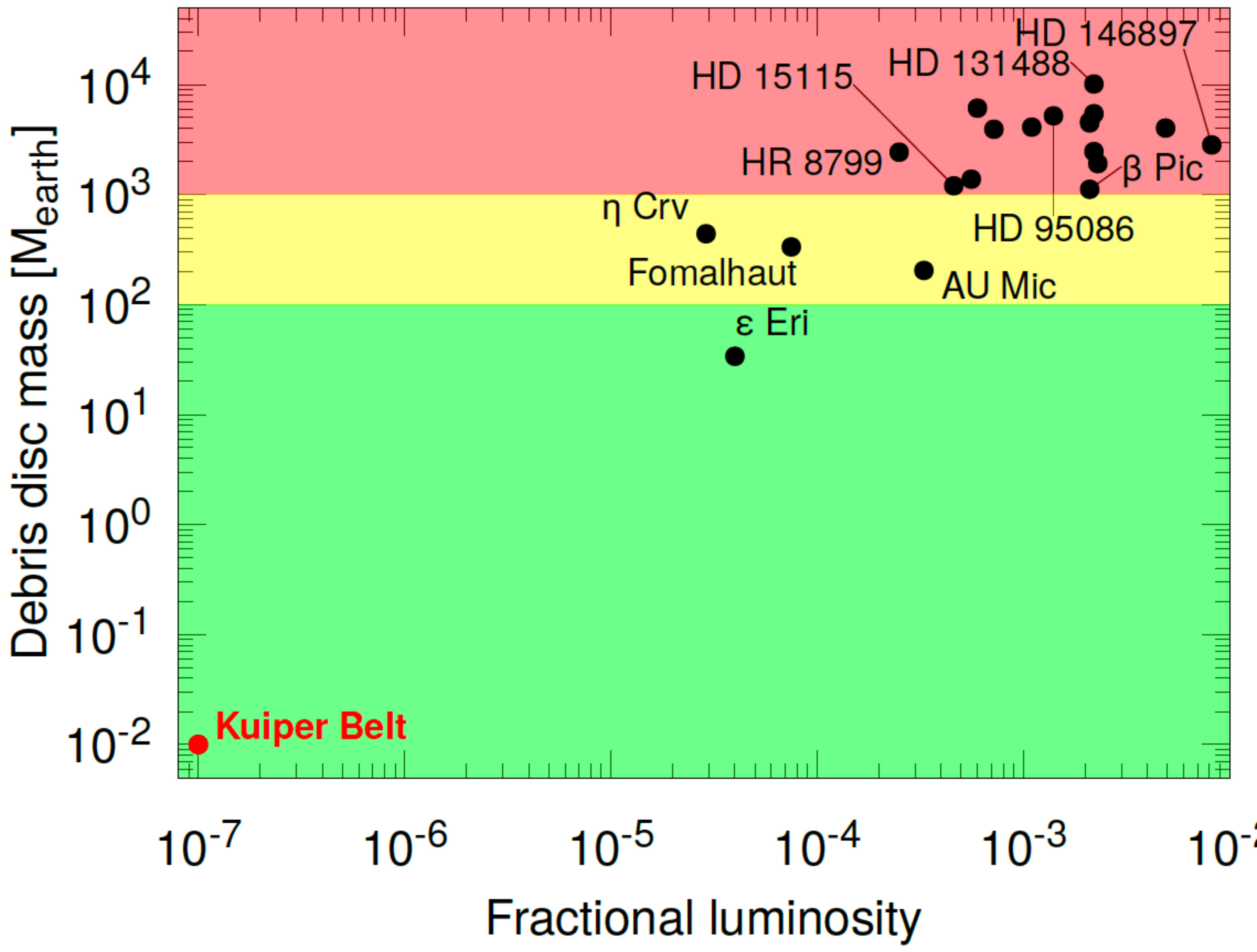
Solution

- Dust opacity uncertainty
- Steeper size distribution
- Recent giant impacts
- Young "collisional age"
- Planetesimals (should) born small?



Krivov and Wyatt 2020

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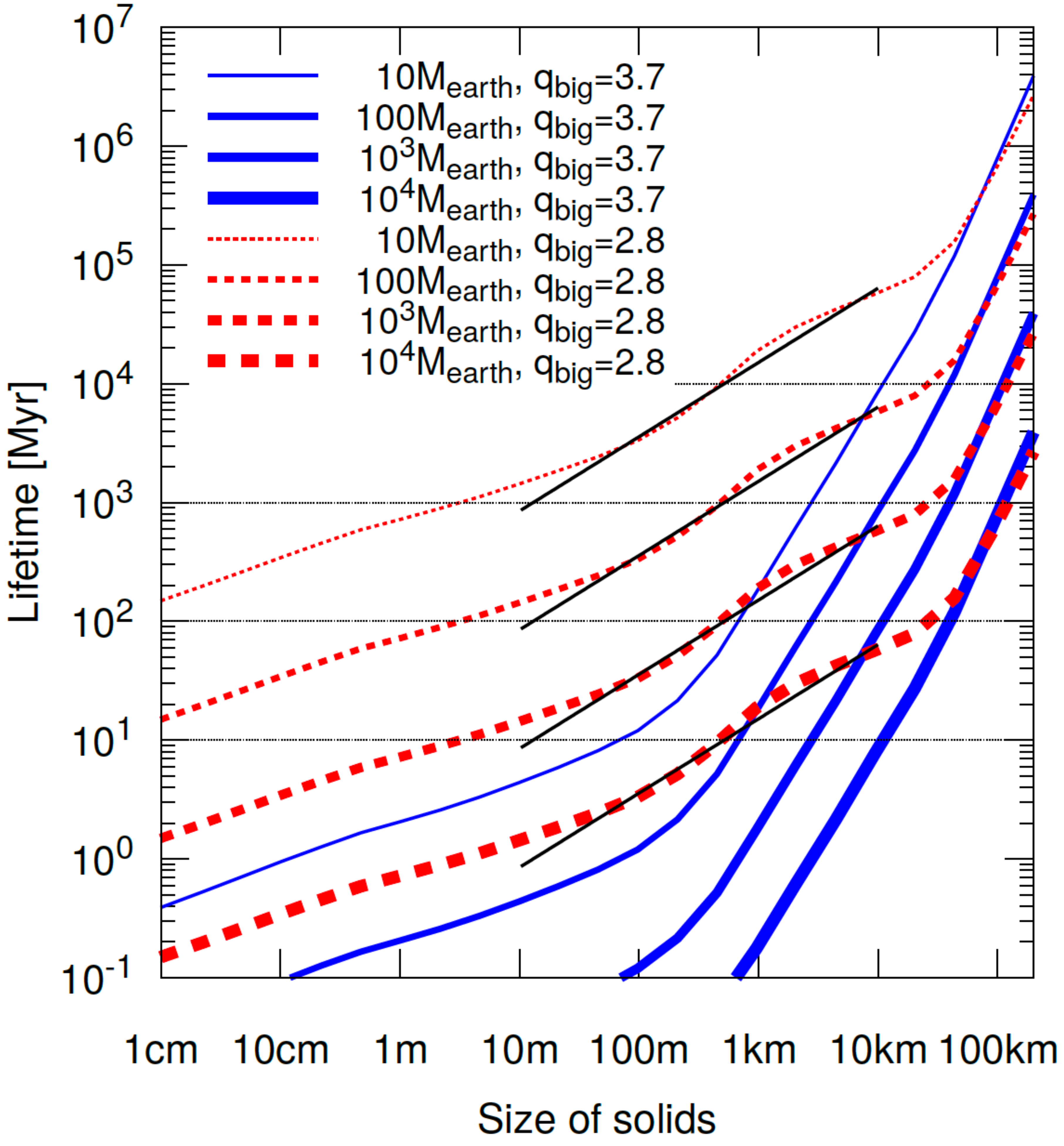

Krivov and Wyatt 2020

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Problem

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- ~~Dust opacity~~
- ~~Steeper size~~
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- ~~Young "colli~~
- **Planetesim**

8th Sep 14:30

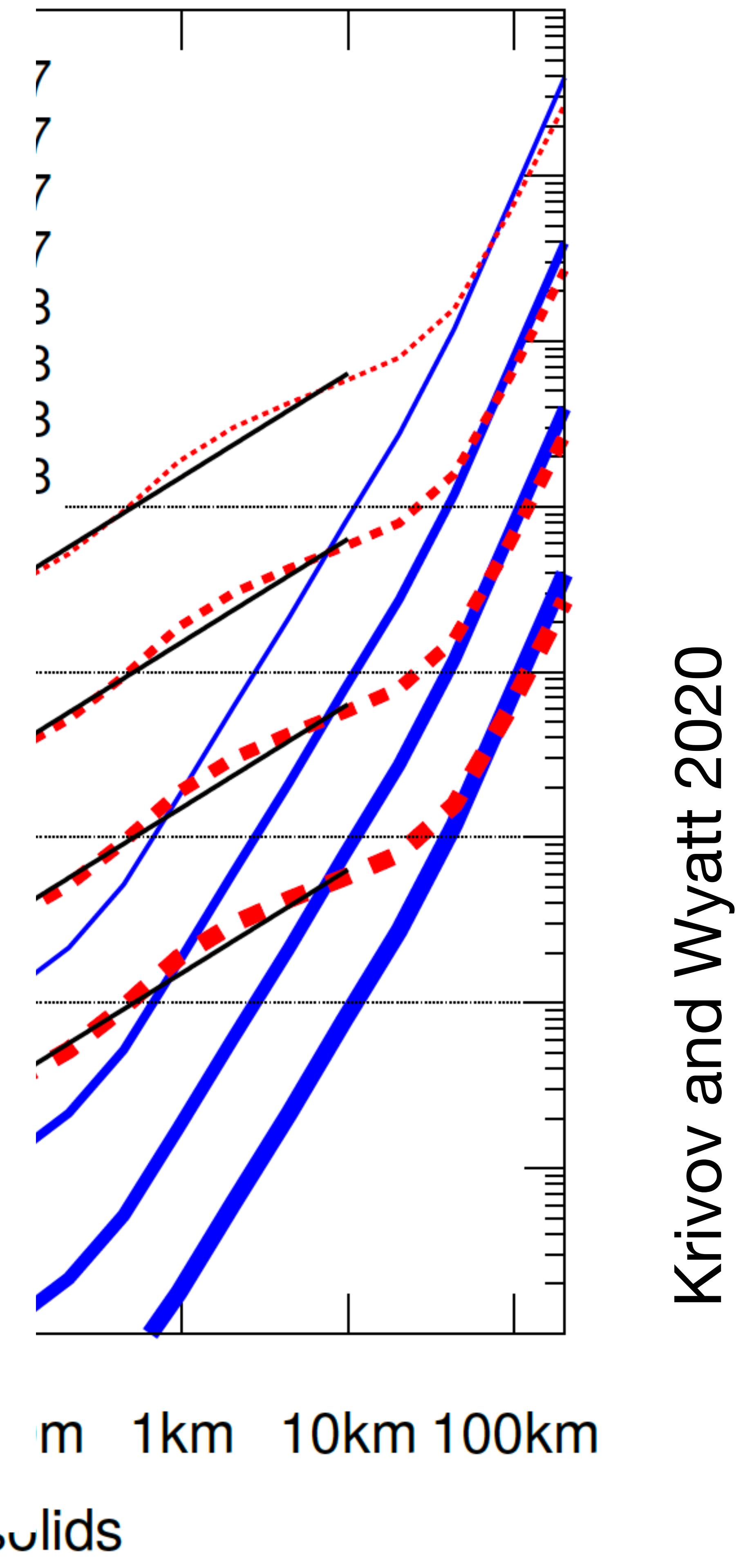
Debris-disc masses: first constraints from narrow discs

by Tim Pearce

Poster

Unusual Planetary Systems with Massive Debris Discs

by Zoe Parker

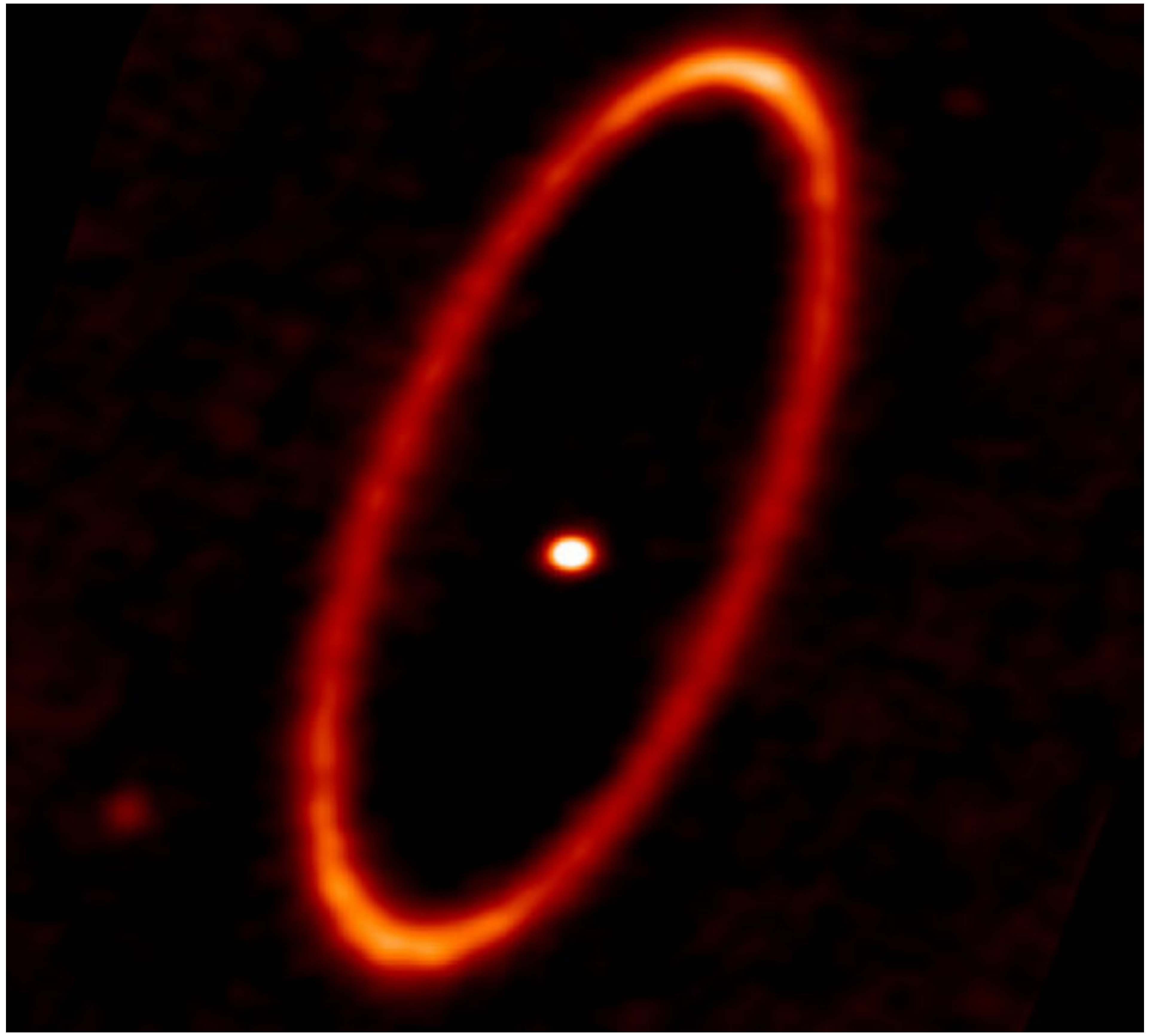


Recent discoveries

JWST revolutionary discoveries (1)

Fomalhaut: Pre-JWST view

- Single outer ring at ~140 AU

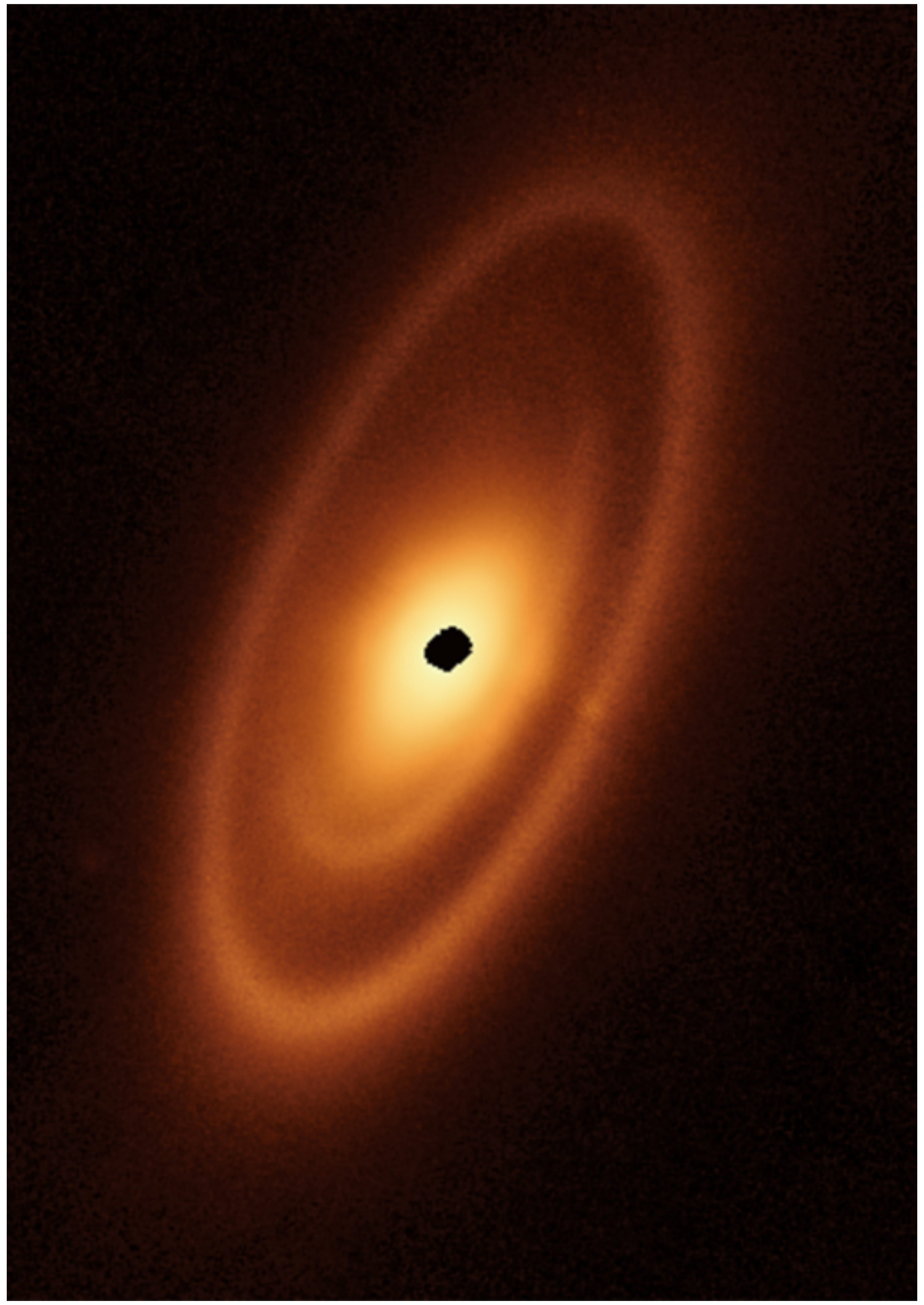


MacGregor et al. 2017

JWST revolutionary discoveries (1)

Fomalhaut: Pre-JWST view vs. JWST Revelation

- Single outer ring at ~140 AU vs. three nested belts spanning 10-300 AU with
  - Inner belt at ~23 AU (previously undetected)
  - Intermediate belt at ~50 AU with inclination offset
- Importance of PR drag! (Sommers et al. 2025)



Gáspár et al. 2023

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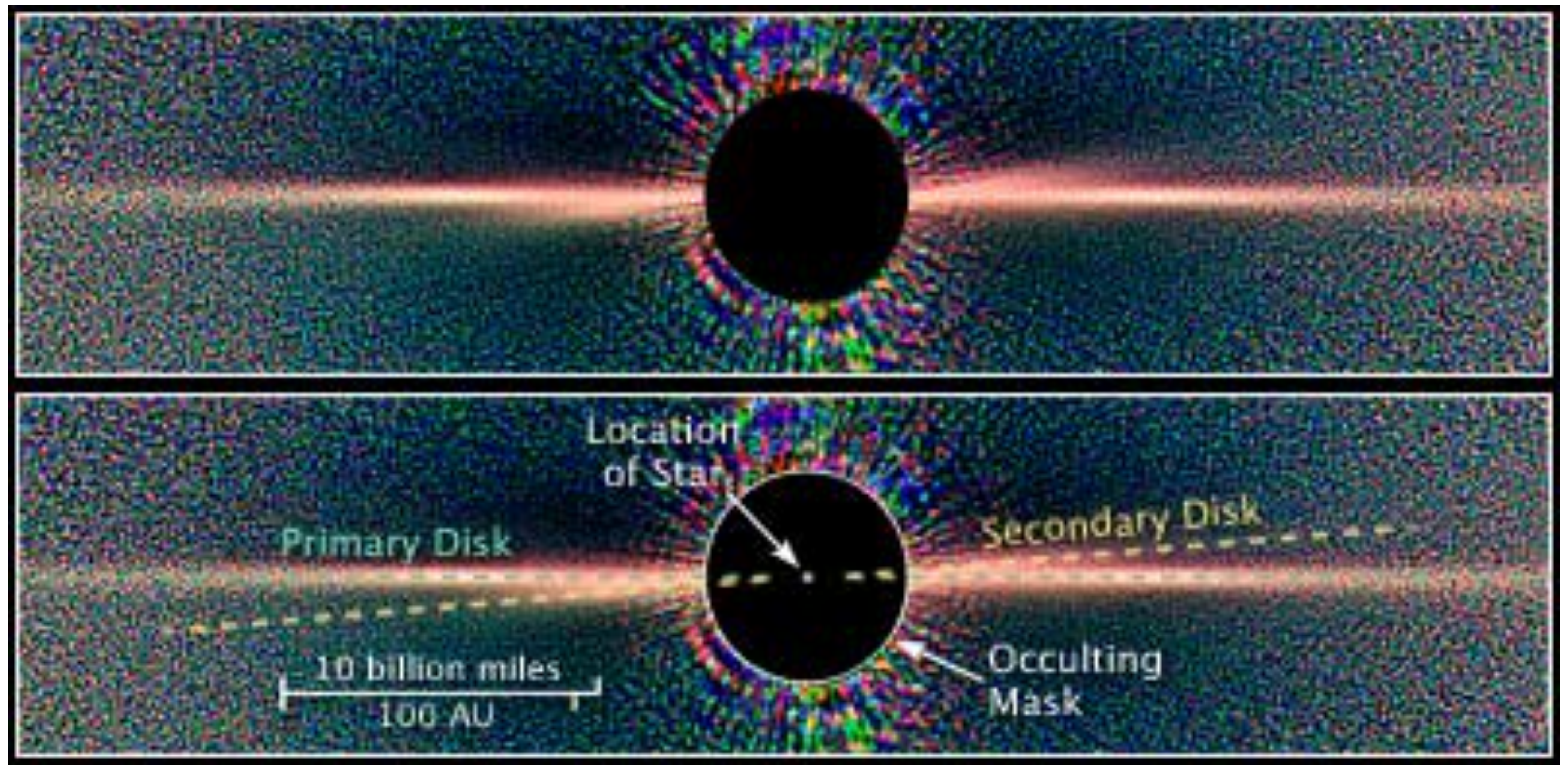
<u>β Pictoris: Pre-JWST view</u>

- Two misaligned disc: Secondary disc - bluer than the main disc



Golimowski et al. 2006

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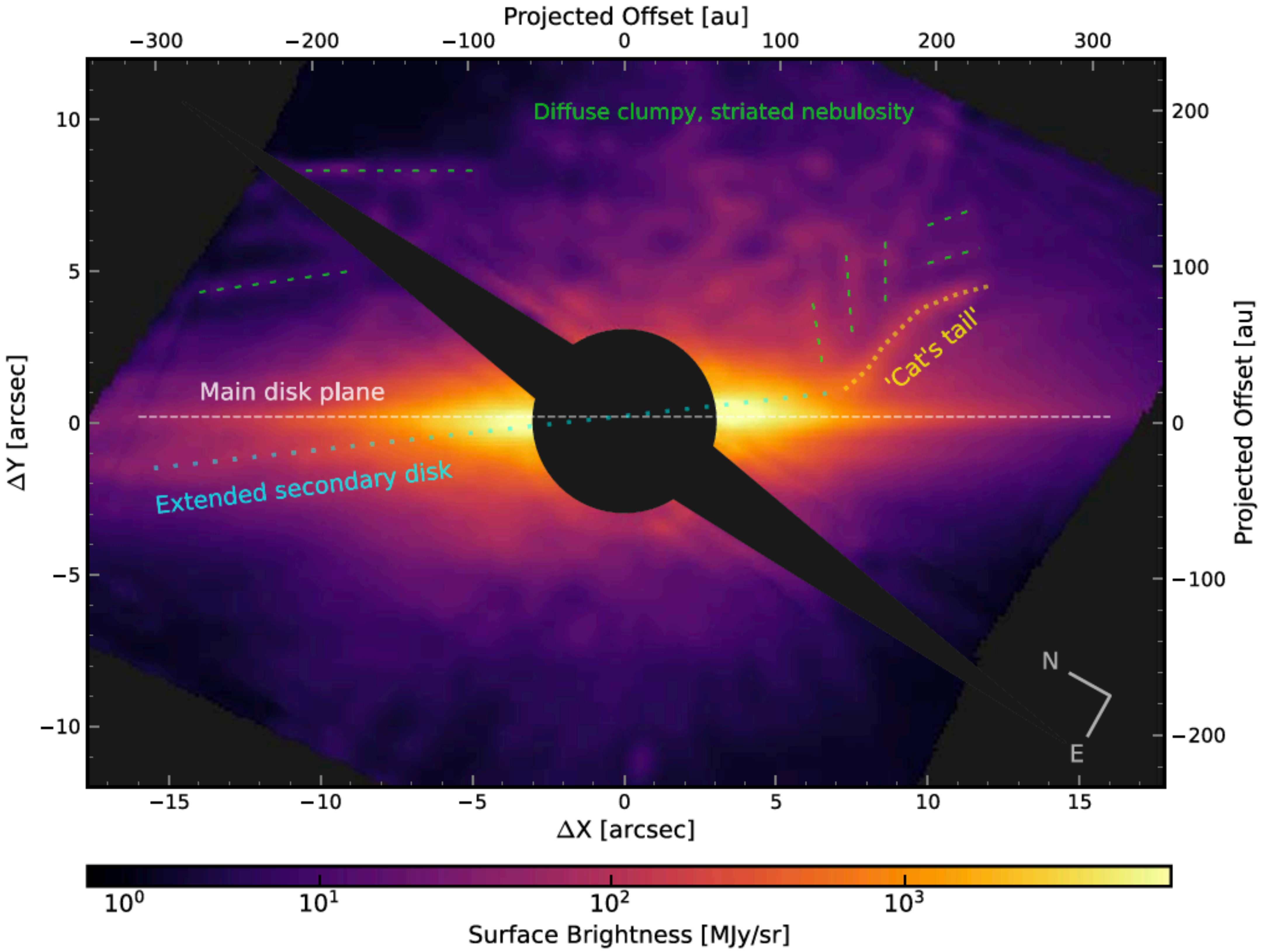
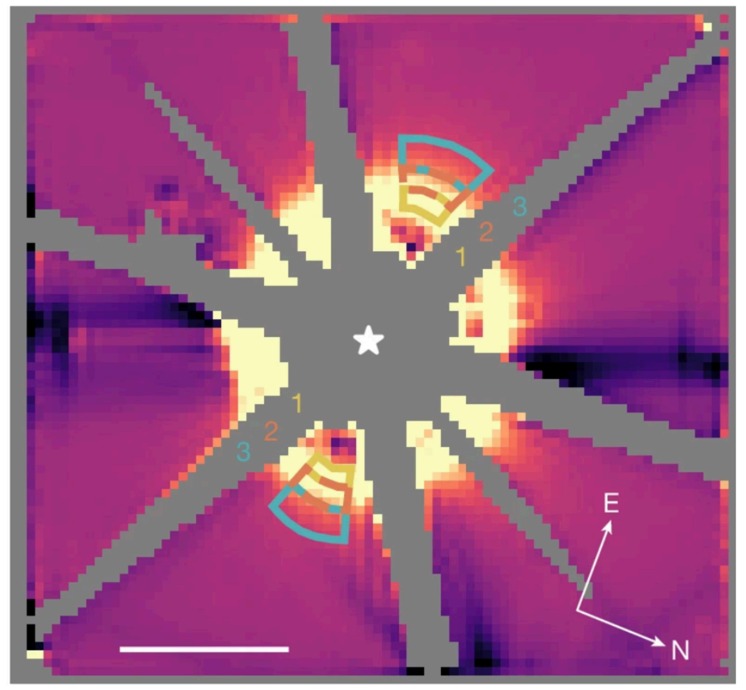
- Two misaligned disc: Secondary disc - bluer than the main disc
- 125-265 AU “Cat's Tail” - strong evidence for ongoing dynamical processes



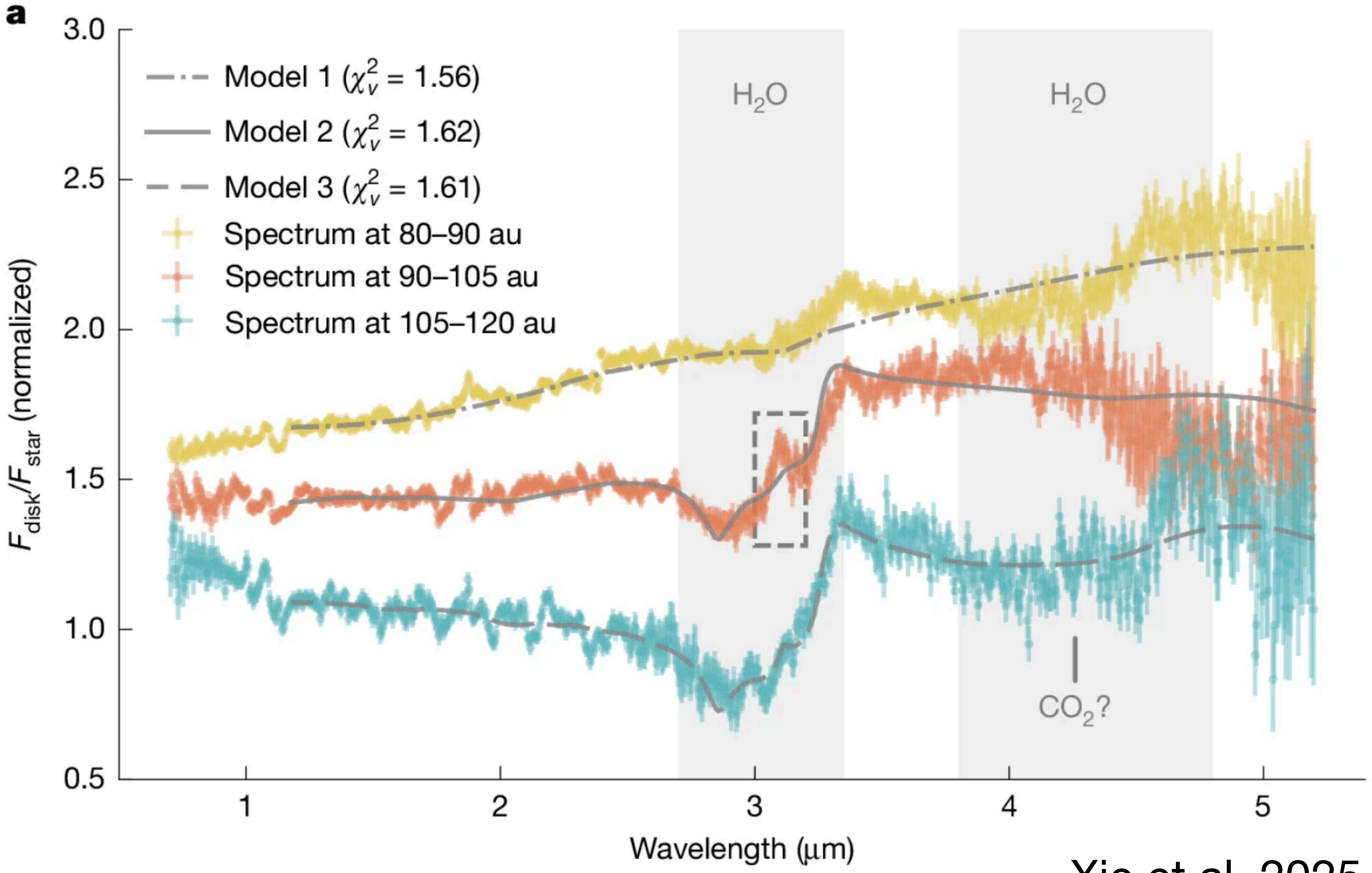
Rebollido et al. 2024

JWST revolutionary discoveries (2)



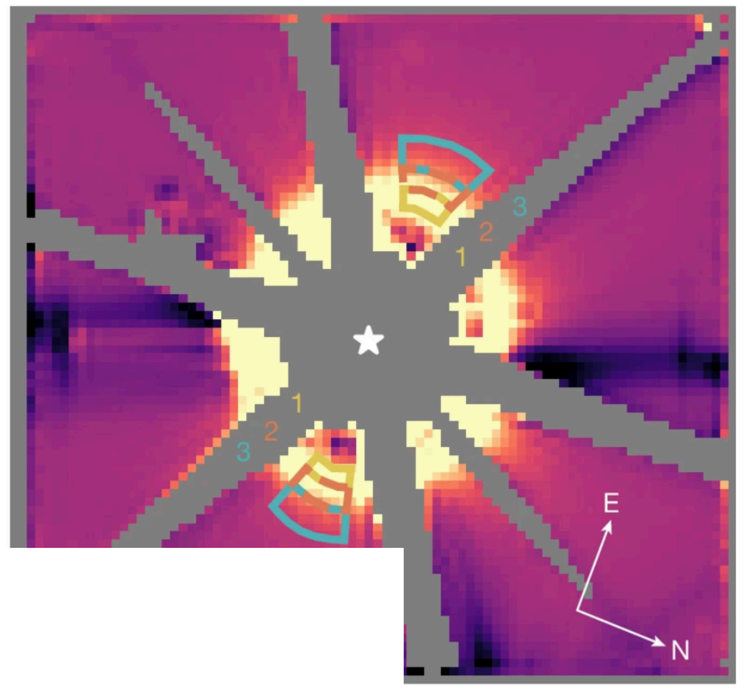
Water ice detection

- HD 181327: First (crystalline) water ice confirmed
- Mass fractions: 0.1% to 21% across disc



Xie et al. 2025

JWST revolutionary discoveries (2)



Water ice detection

- H
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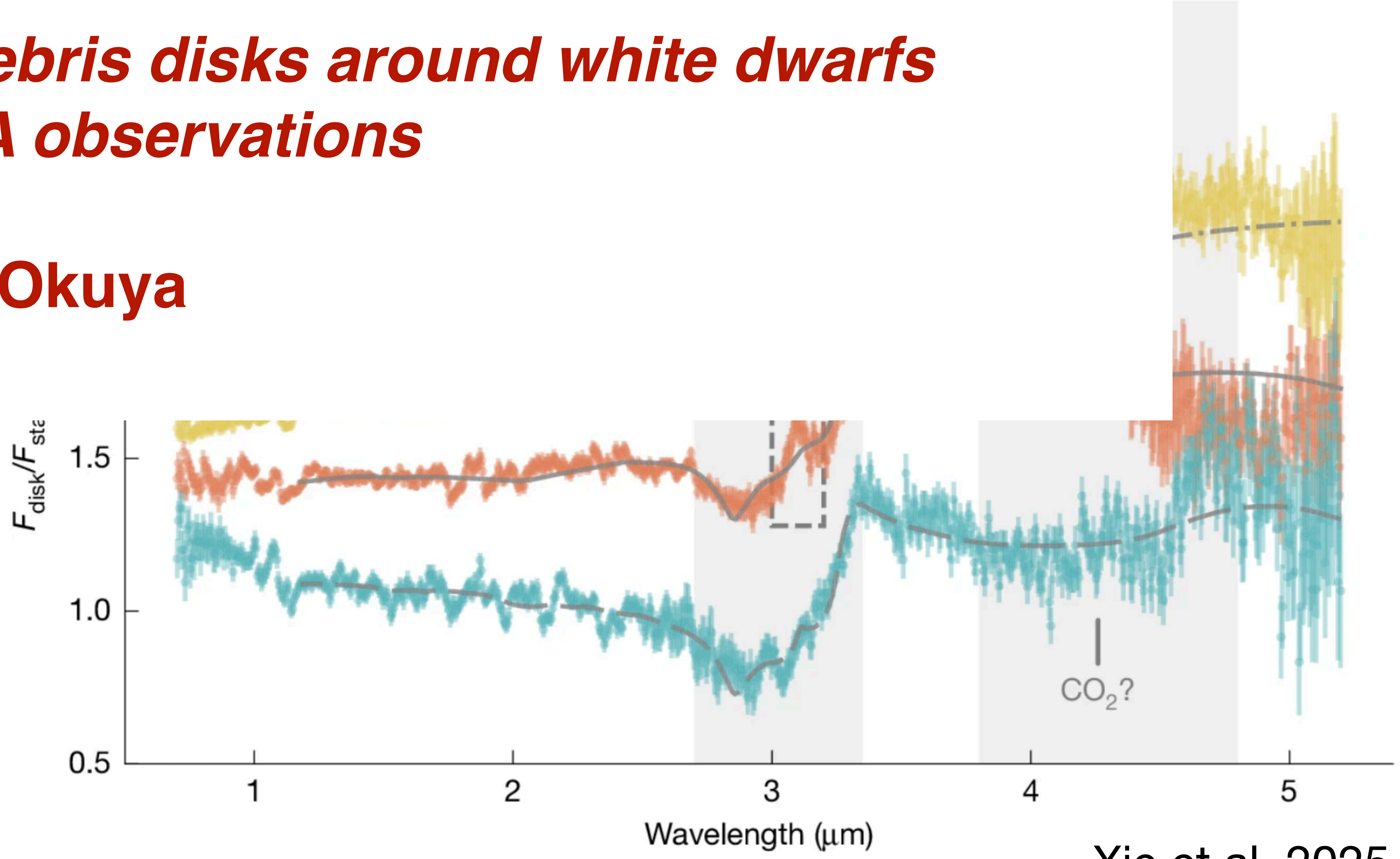
- M

Poster

Detecting water ice and vapor in debris disks around white dwarfs with future PRIMA observations

by Ayaka Okuya



Xie et al. 2025

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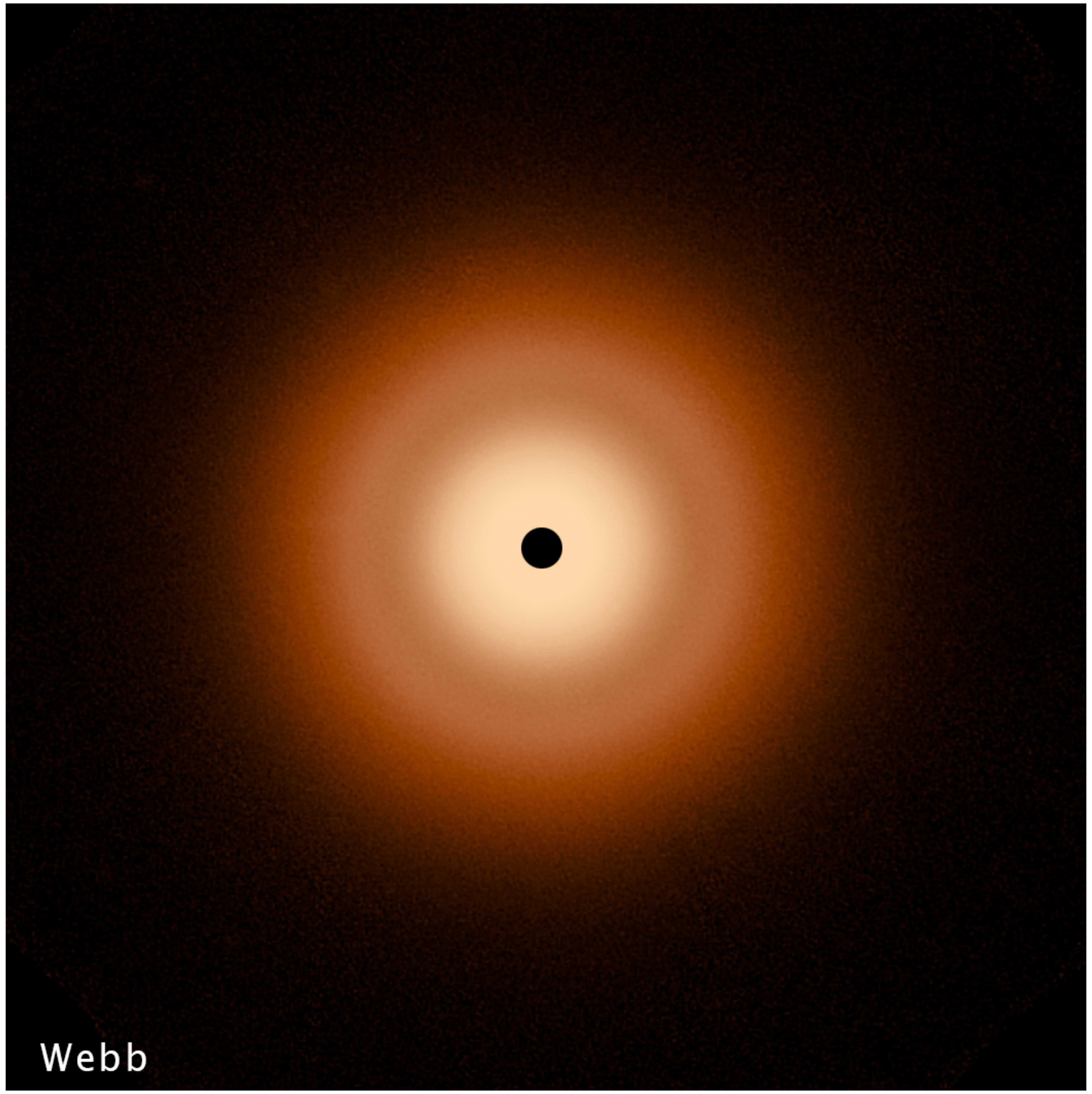
Circular Vega

- Remarkably smooth disc spanning 80-170 AU
- Exceptional circularity (eccentricity ≲0.002)
- No evidence for embedded planets > M_{Neptune}

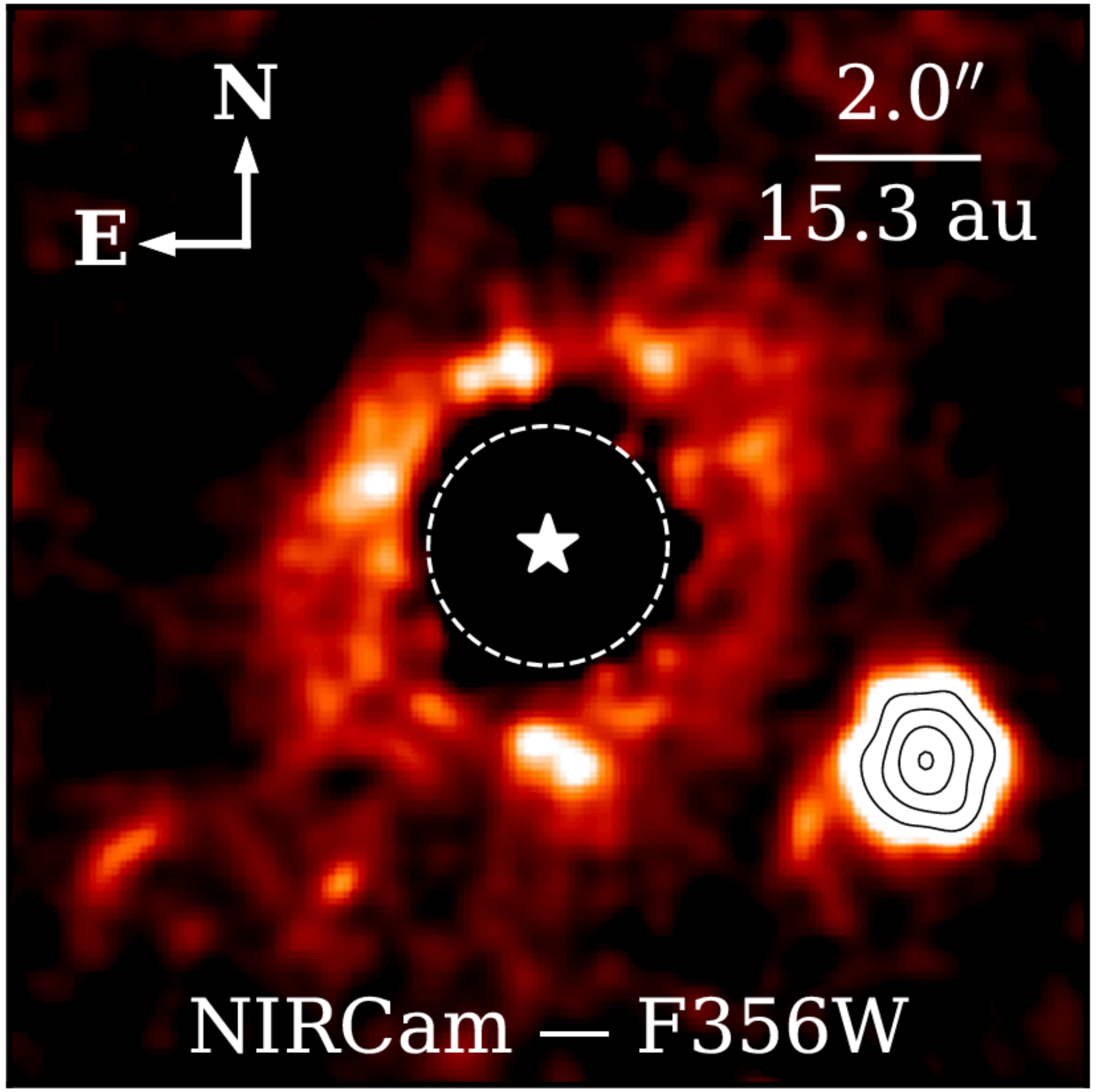


Su et al. 2024

JWST revolutionary discoveries (3)

Fomalhaut C

- Latest spectral type (M4)/oldest star (440 Myr) in scattered-light
- Unusually red disc colour → requiring steep size distributions
- Companion detection limits rule out M_{Saturn} beyond ~10 AU and M_{Jupiter} beyond ~5 AU



Lawson et al. 2024

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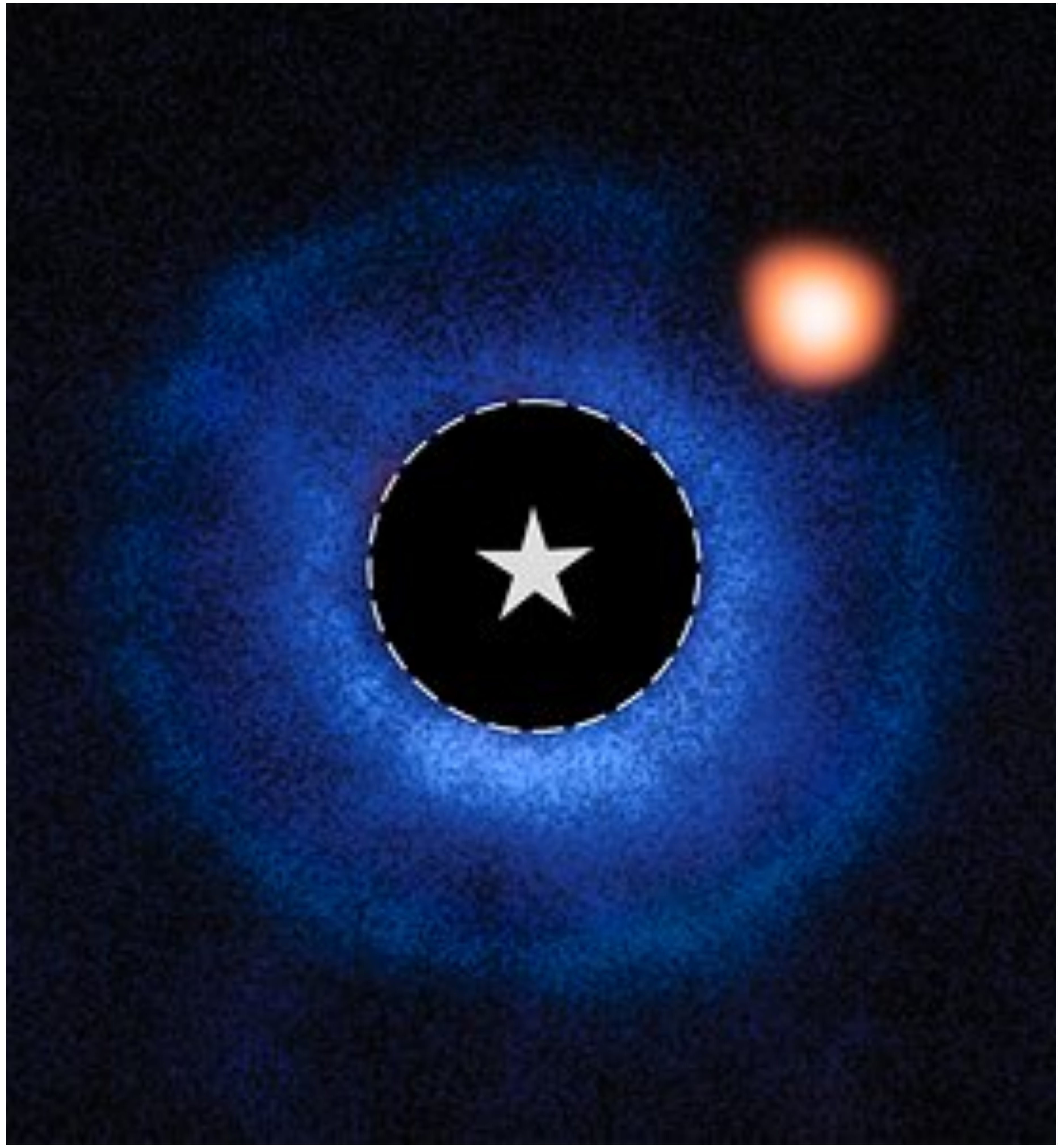
TWA 7b in TWA 7 system

- Estimated planet mass of ~0.3 M_{Jupiter} at ~52 AU
- Planet responsible for sculpting debris disc radial structures!

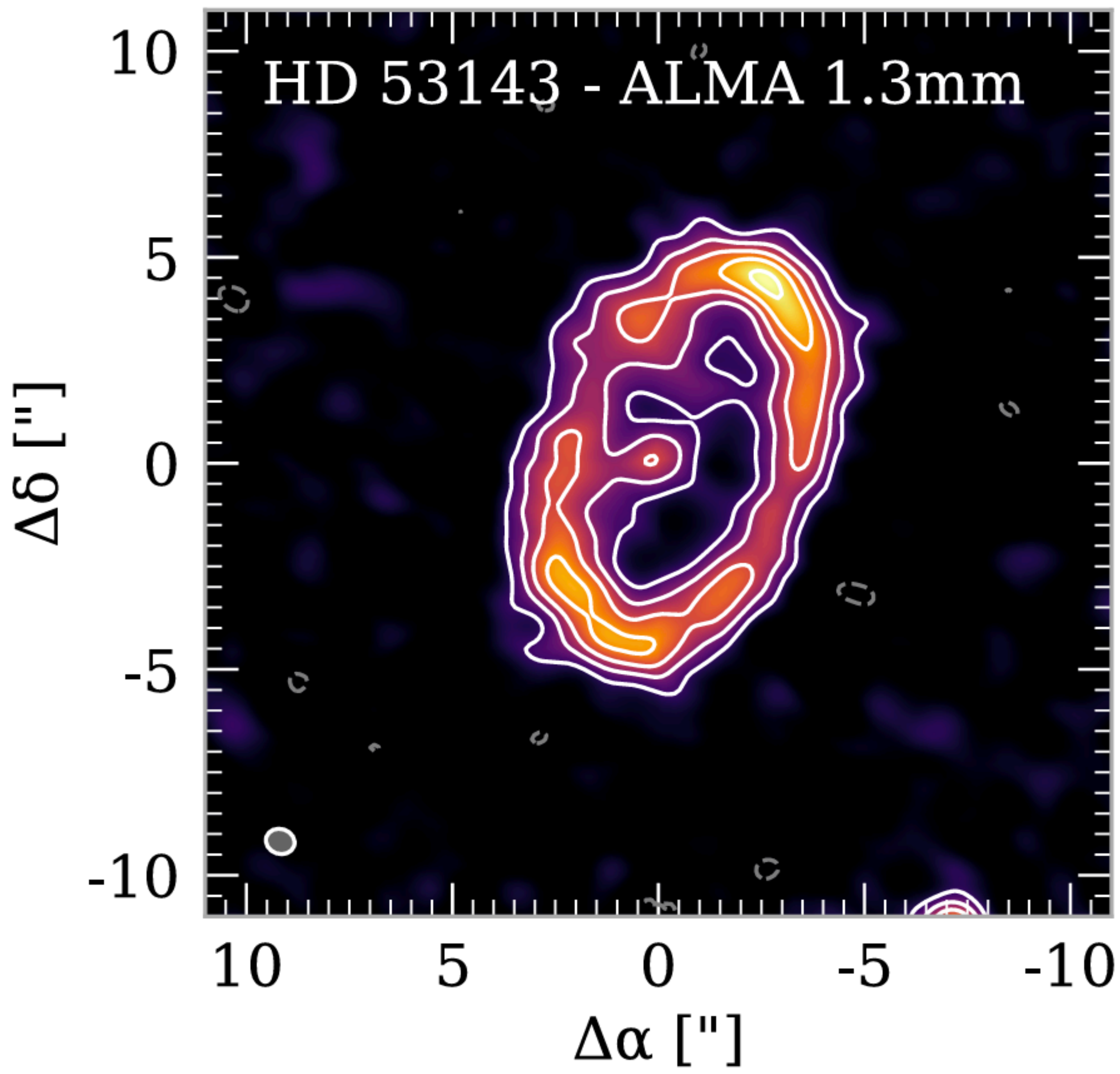


Lagrange et al. 2025

ALMA's record-breaking discoveries

Most eccentric disc: HD 53143

- Forced eccentricity: 0.21 ± 0.02
- "Apocenter glow" detection
- Evidence for past planetary scattering



MacGregor et al. 2024

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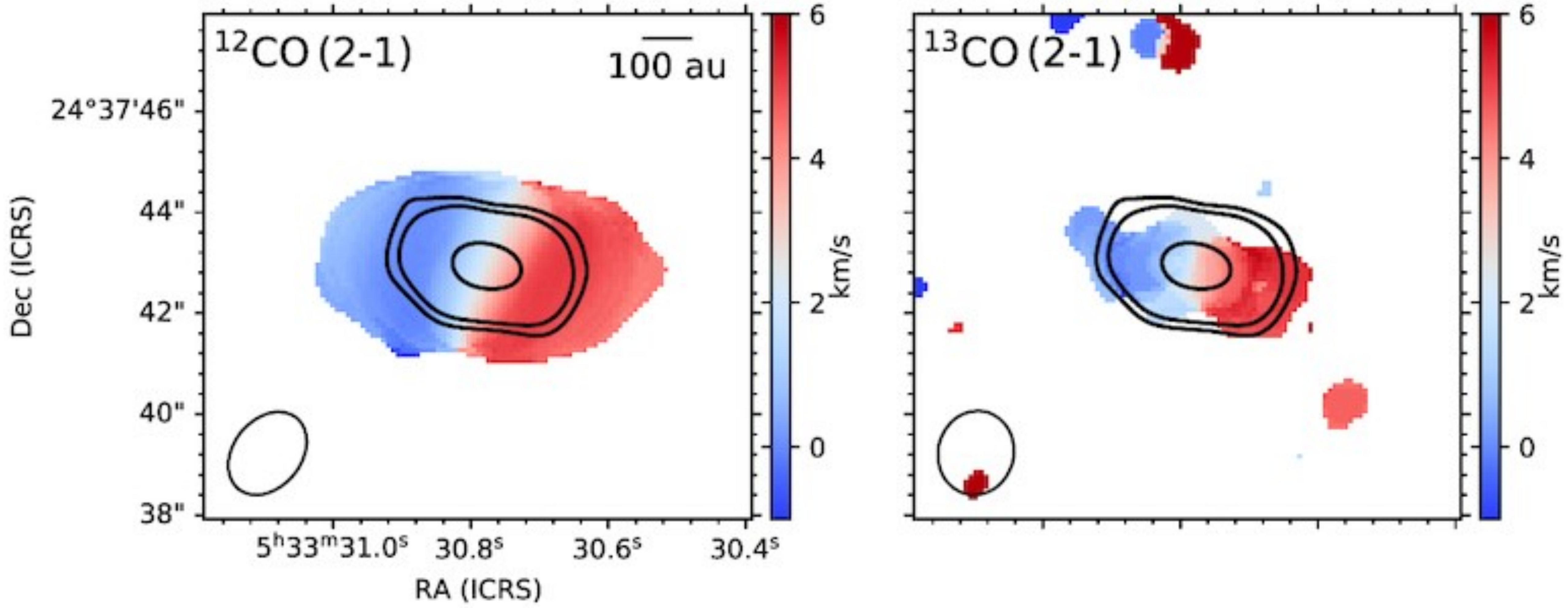
Gas Chemistry

- HD 36546: Both ^{12}CO and ^{13}CO detected
- β Pictoris: First CI (carbon) emission
- Underlying geometric or dynamical structure maintaining the asymmetry?



Rebollido et al. 2022

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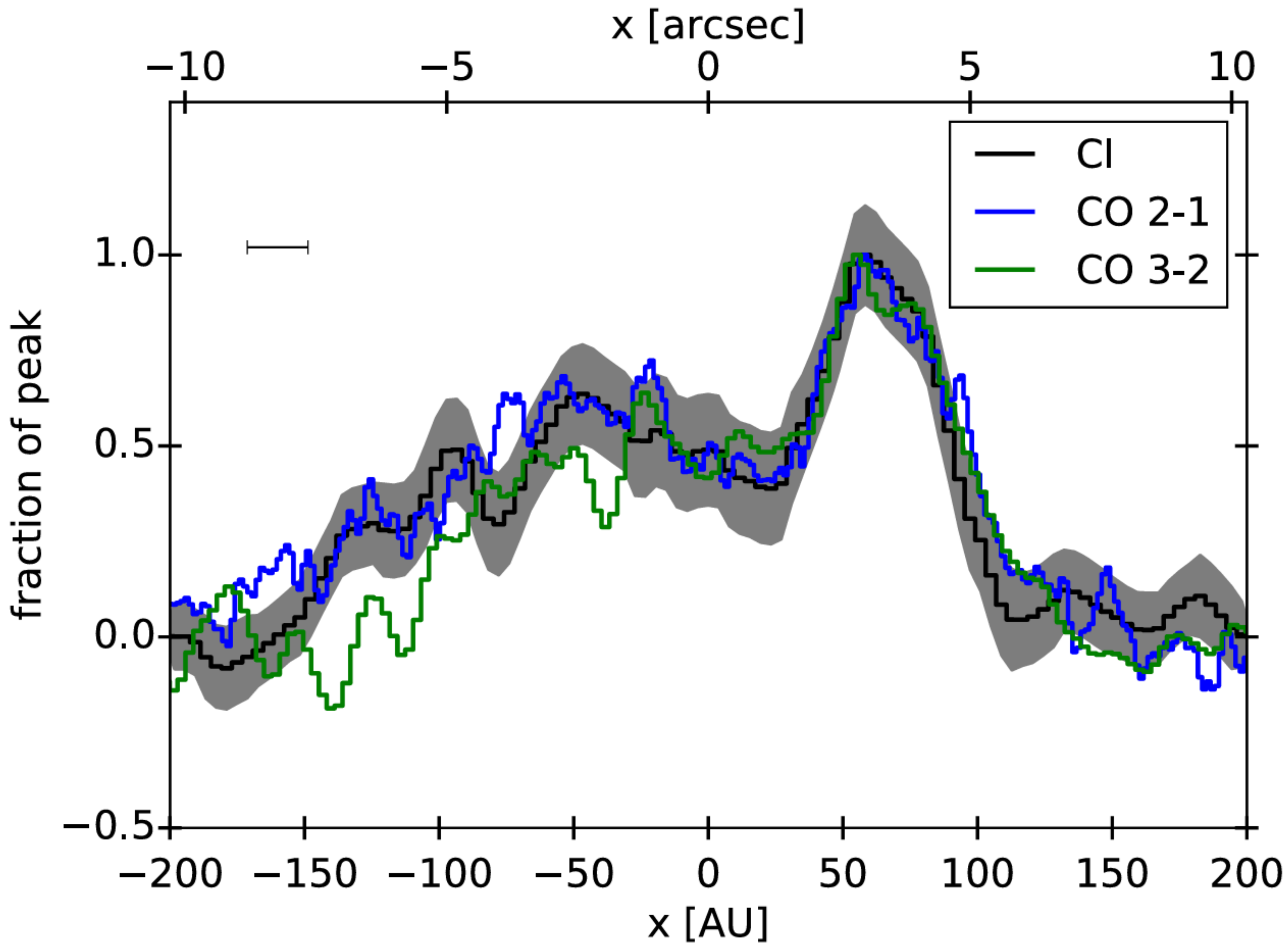


Cataldi et al. 2018

“It was total solar eclipses that really set the pathway for me”

To the memory of ***Dr. Glenn H Schneider*** (1955-2025), whose pioneering work in HST coronagraphy and debris disk imaging inspired many in our field.

Take home msgs

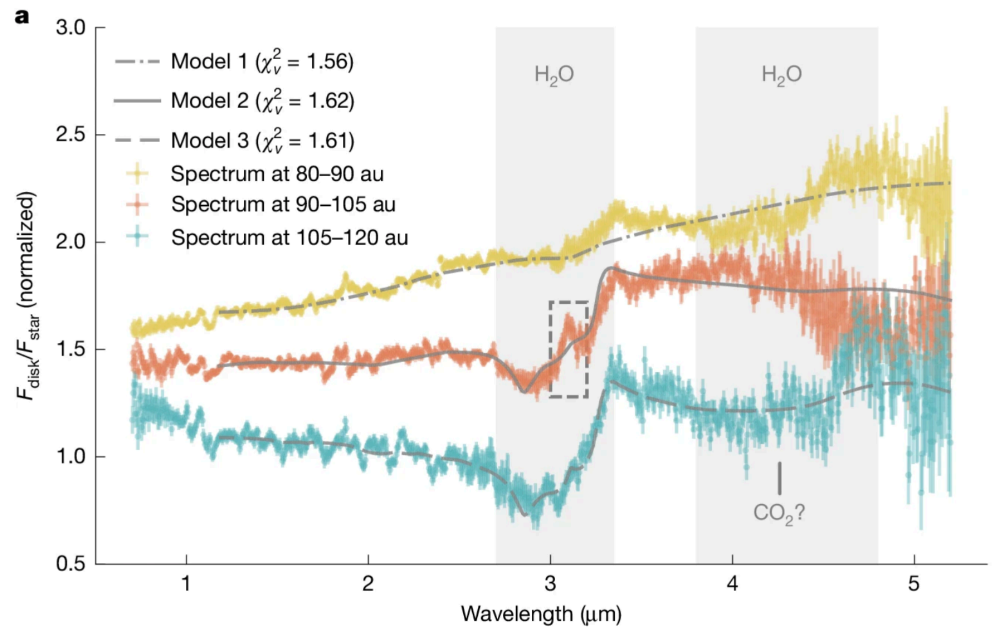
Thank you so much for your attention!

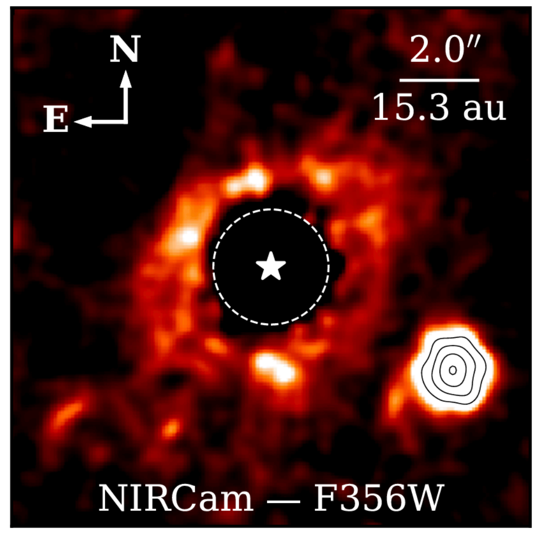
Fundamental mysteries in debris discs

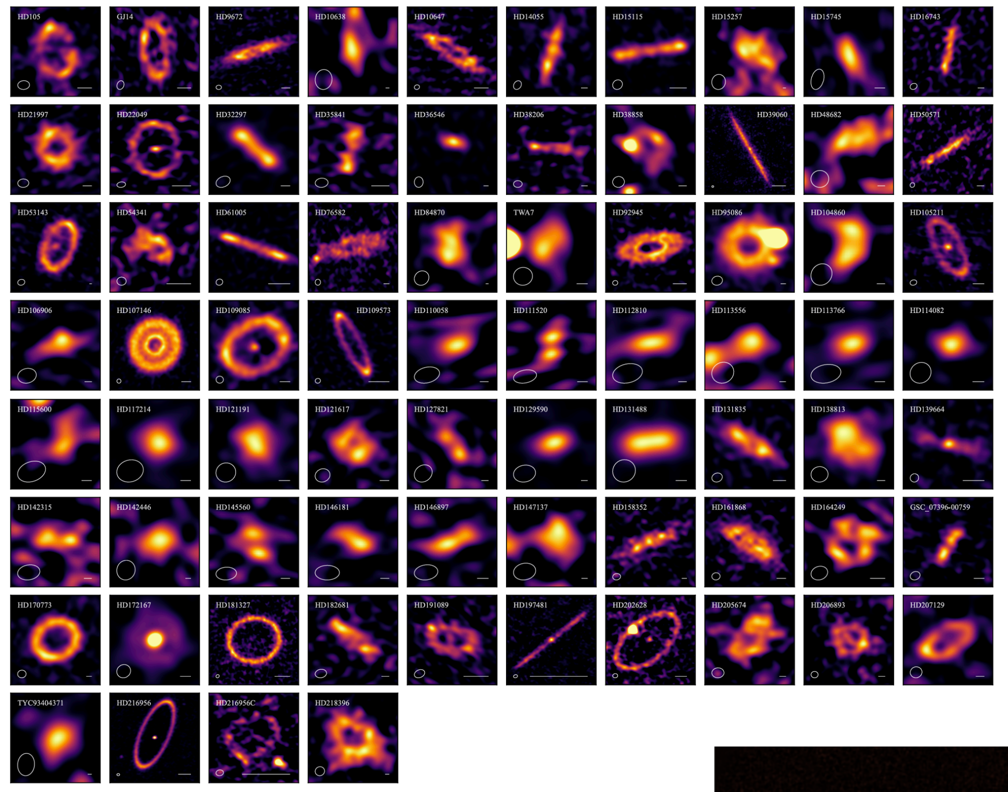
- Disc masses: Cannot detect large planetesimals
- Gas origins: Primordial vs secondary?
- Hot dust survival: No complete model
- Stirring mechanisms: How do orbits get excited?

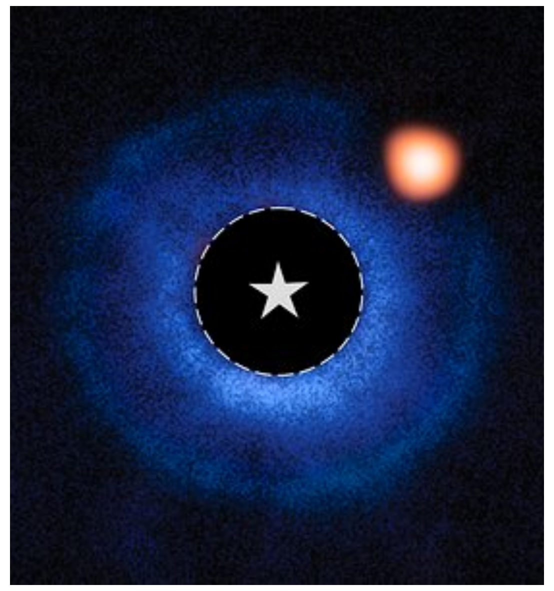
Future targets

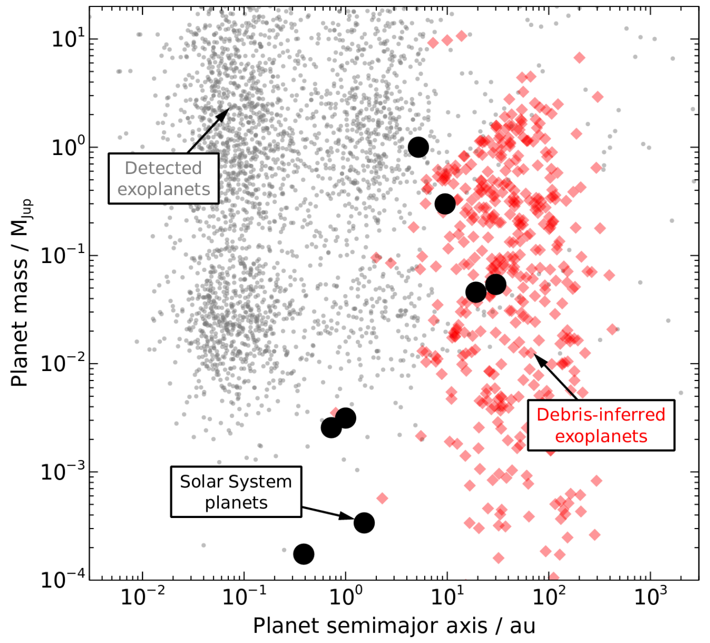
- Morphological diversity origins - planet-disc connection validation
- Chemical complexity understanding











Extra slides

Origins and evolution

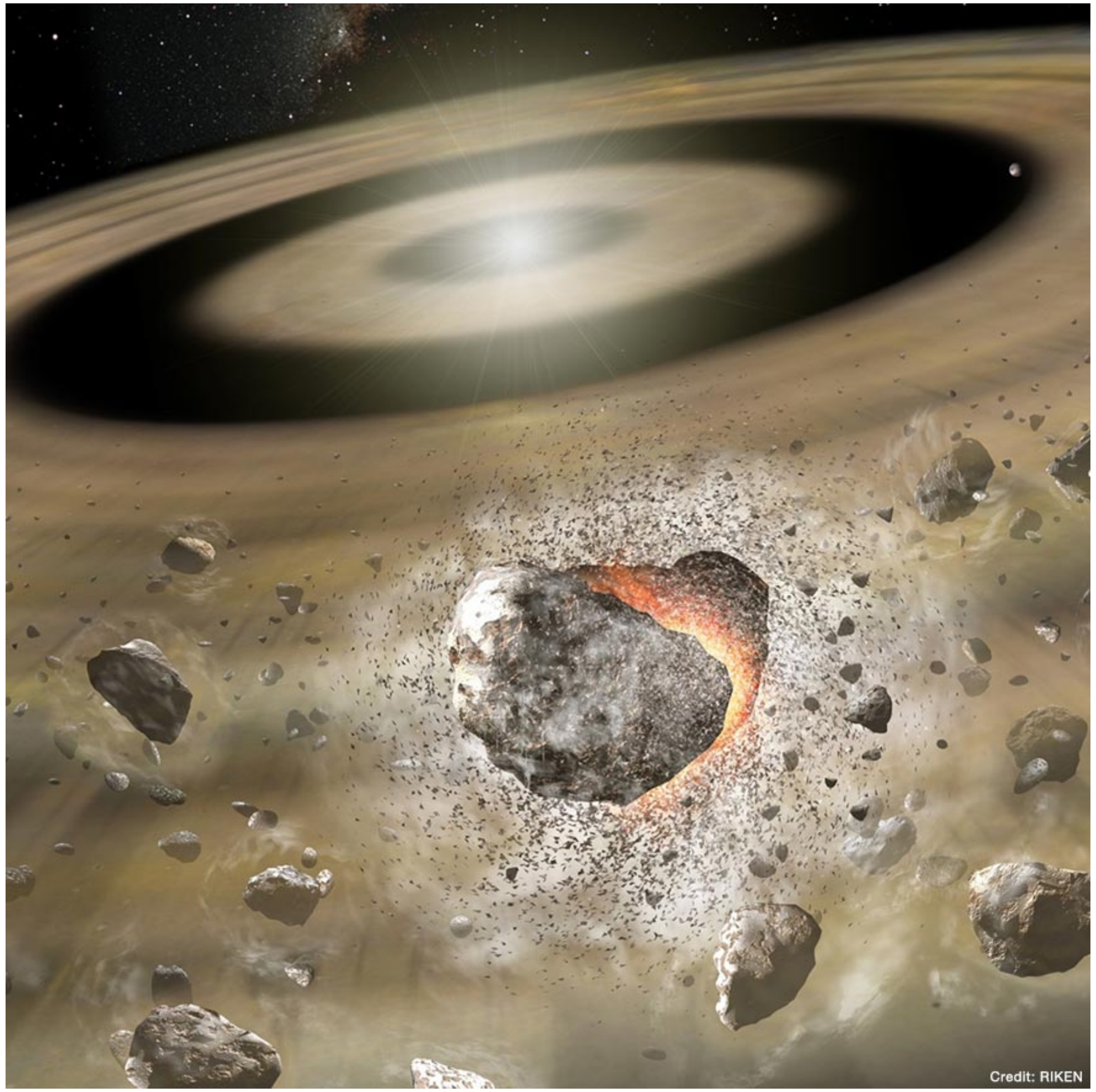
Debris Disc Lifecycle:

Starting from descendants of gas-rich protoplanetary discs

Gas dispersal leaves population of planetesimals

Stirring process exciting orbits to enable destructive collisions

Collisional cascade: self-sustaining fragmentation chain leading to size distribution $n(s) \sim s^{-3.5}$



How do collisions begin?

Planetesimals need excited (eccentric/inclined) orbits

1. **Self-Stirring**: Large planetesimals within belt

Problem: Requires implausibly high masses for most systems

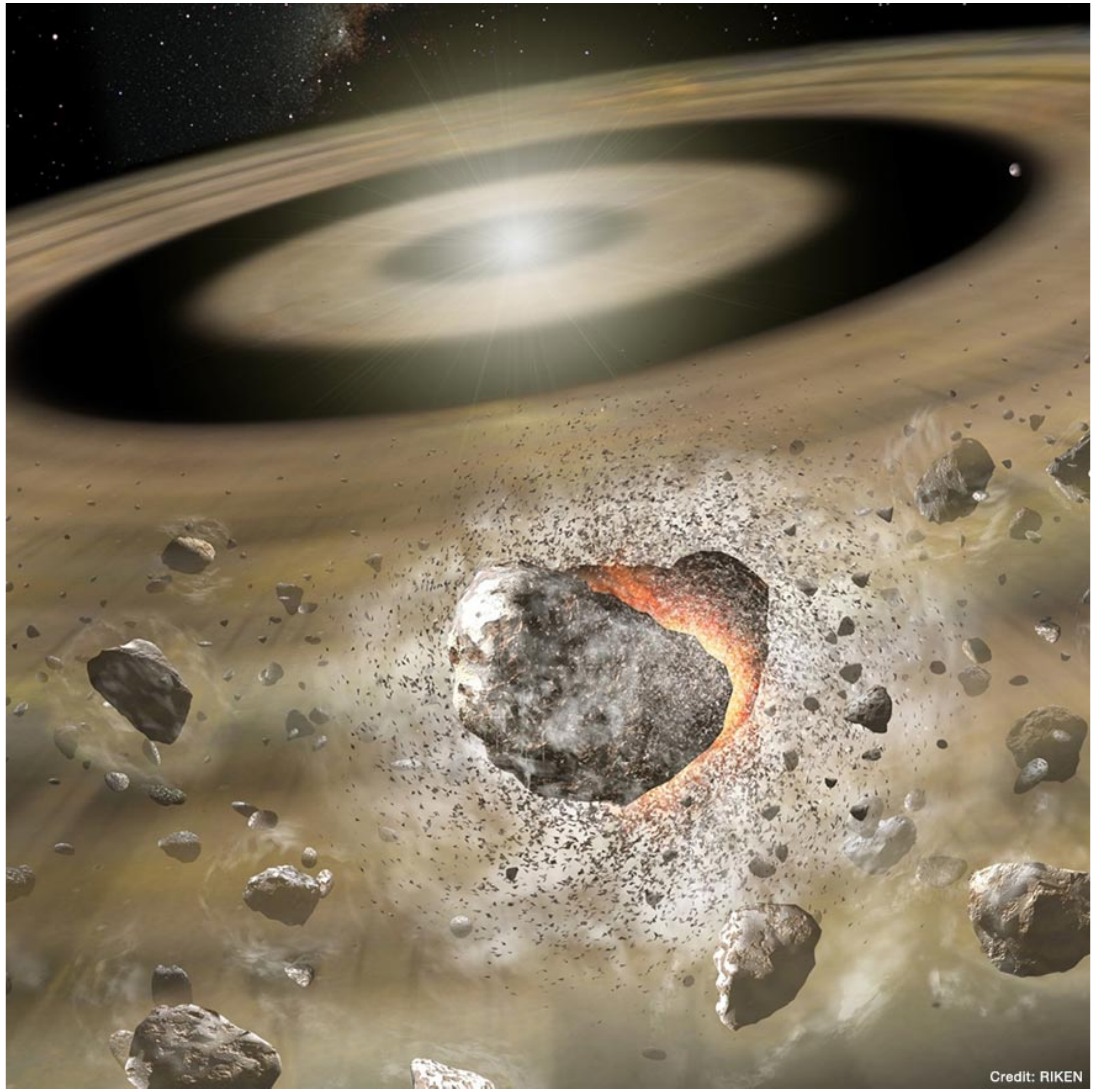
2. **Planetary Stirring**: Embedded or nearby planets (most favored)

Problem: May be inhibited by disc self-gravity

3. **Stellar Flybys**: Passing stars excite orbits

Problem: Too rare to explain observed disc fraction

Current Status: No single mechanism fully explains debris disc activity—likely multiple processes operate

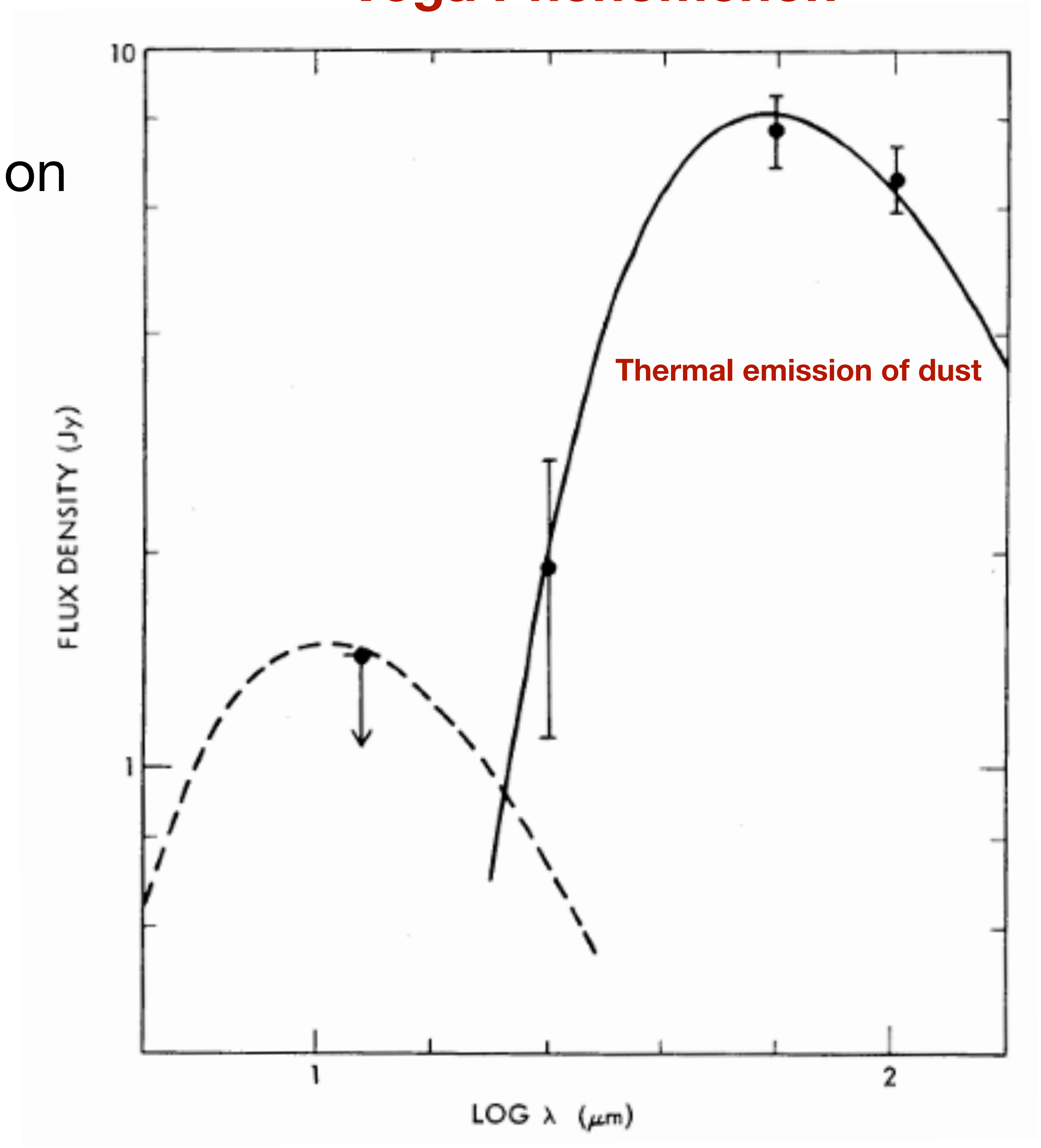


Spectral Energy Distributions

The discovery method

- Infrared excess (known as “Vega Phenomenon”) = extra emission from dust

“Vega Phenomenon”



Aumann et al. 1984

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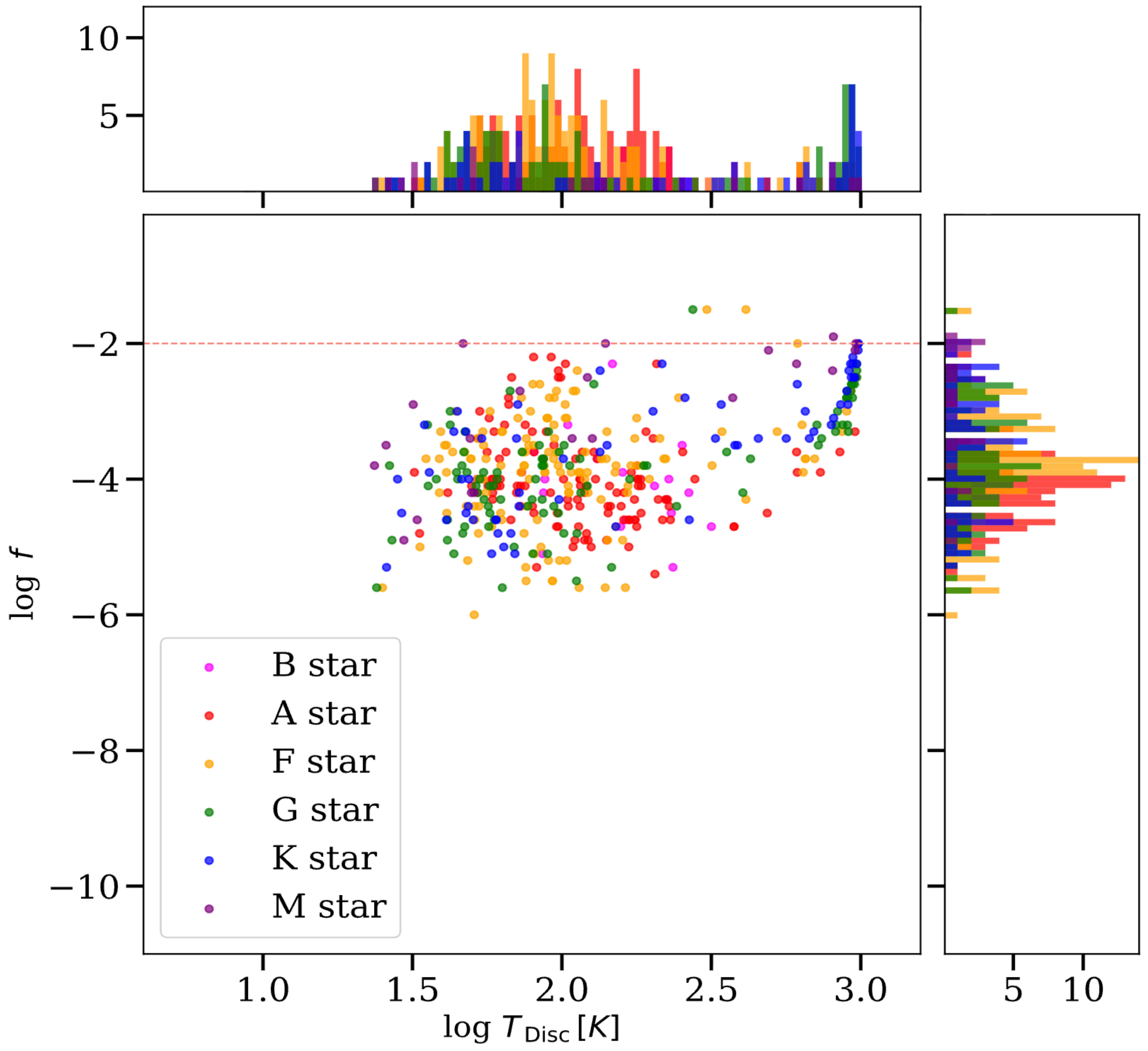
- Fractional infrared luminosities ~ $\frac{L_{\rm dust}}{L_{\rm star}}$ ~ $10^{-6...-2}$



Kim & Kennedy in prep.

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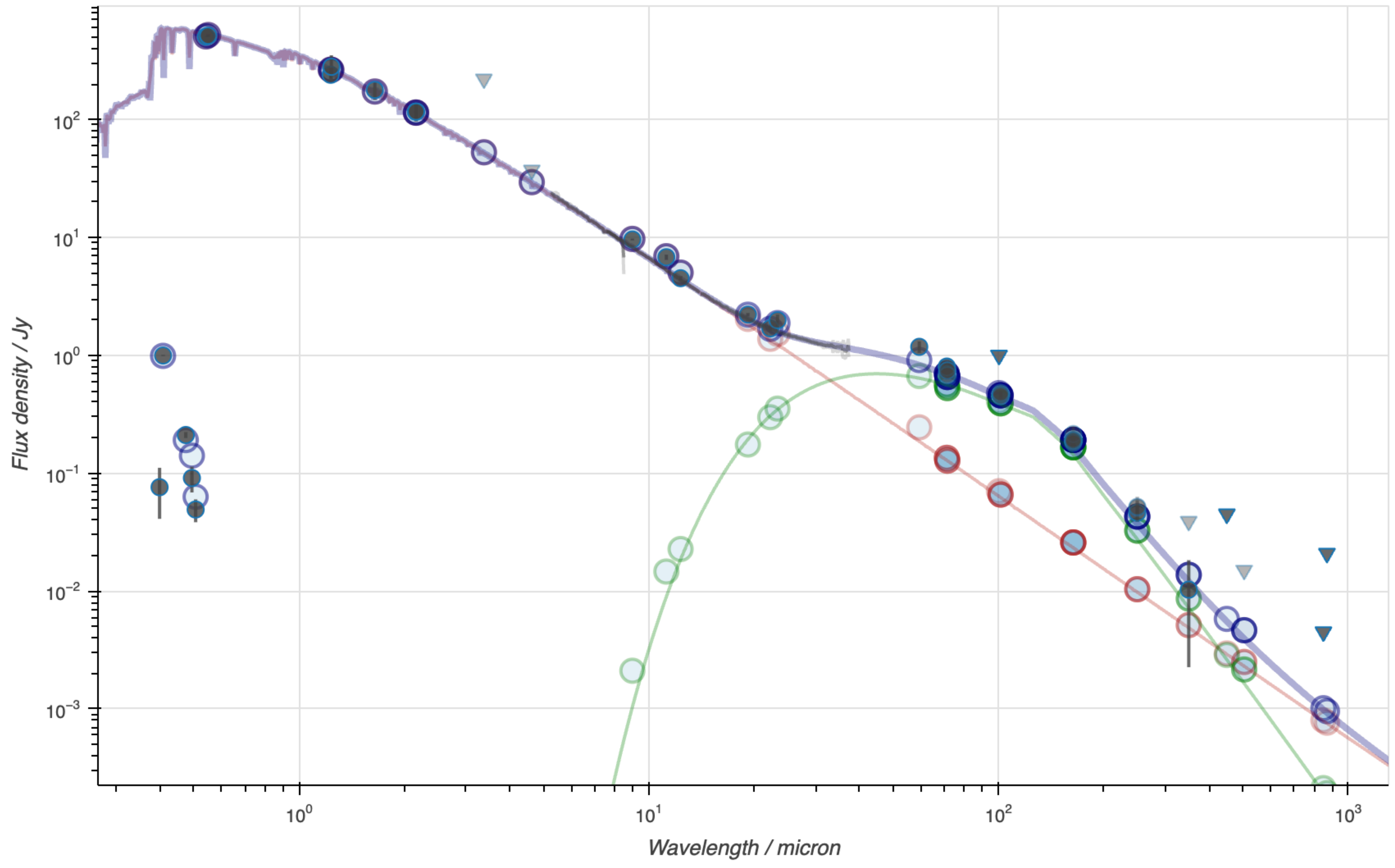
What we learn

- Dust quantity: Total excess flux
- Dust location: Temperature → distance

$$R_{\text{BB}} = 1\ \text{AU} \times \left[\frac{T_{\text{BB}}}{278\,K}\right]^{-2} \times \left[\frac{L_*}{L_\odot}\right]^{0.5}$$

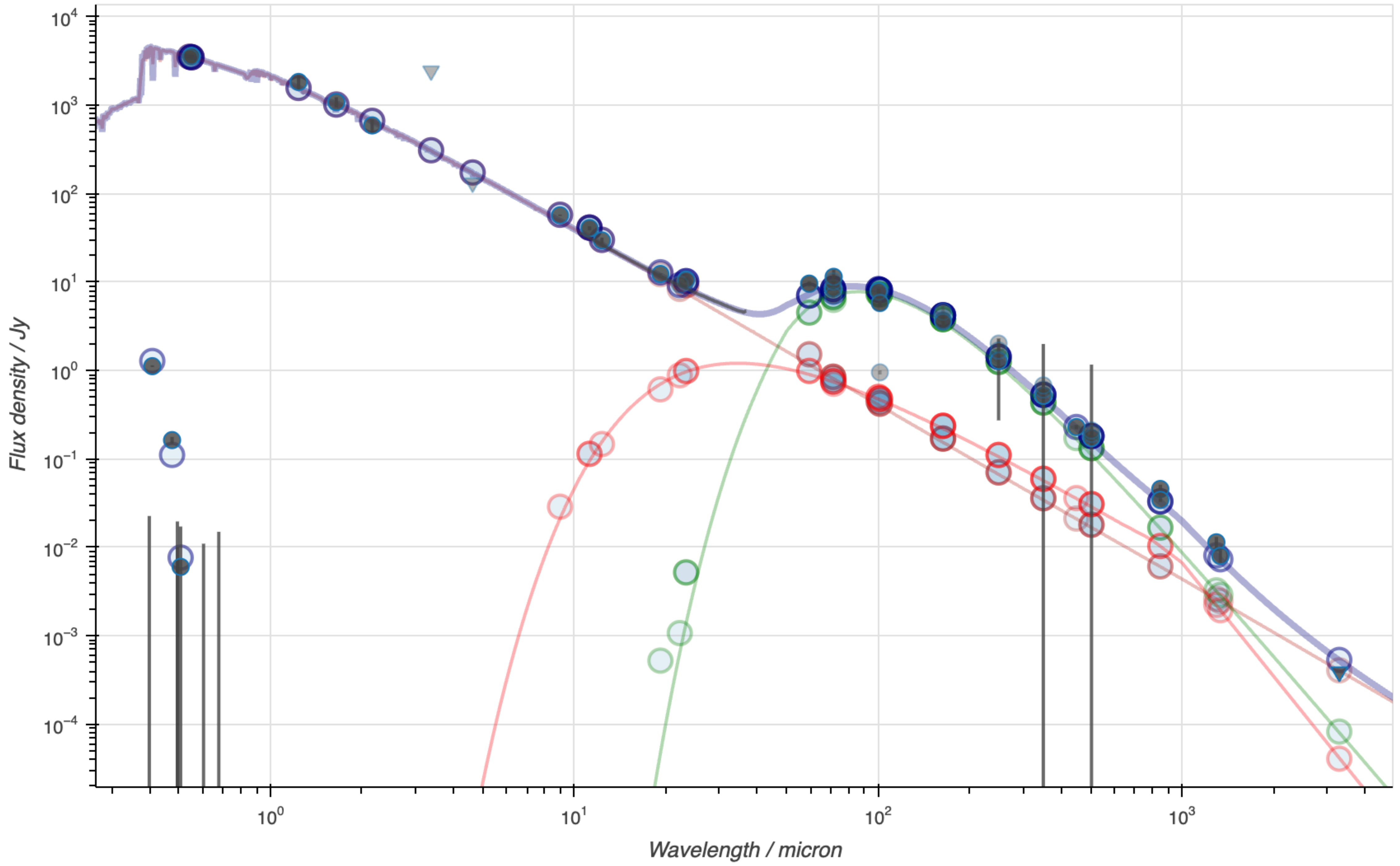
© G.Kennedy



Spectral Energy Distributions

Multi-component example (warm + cold dust components)

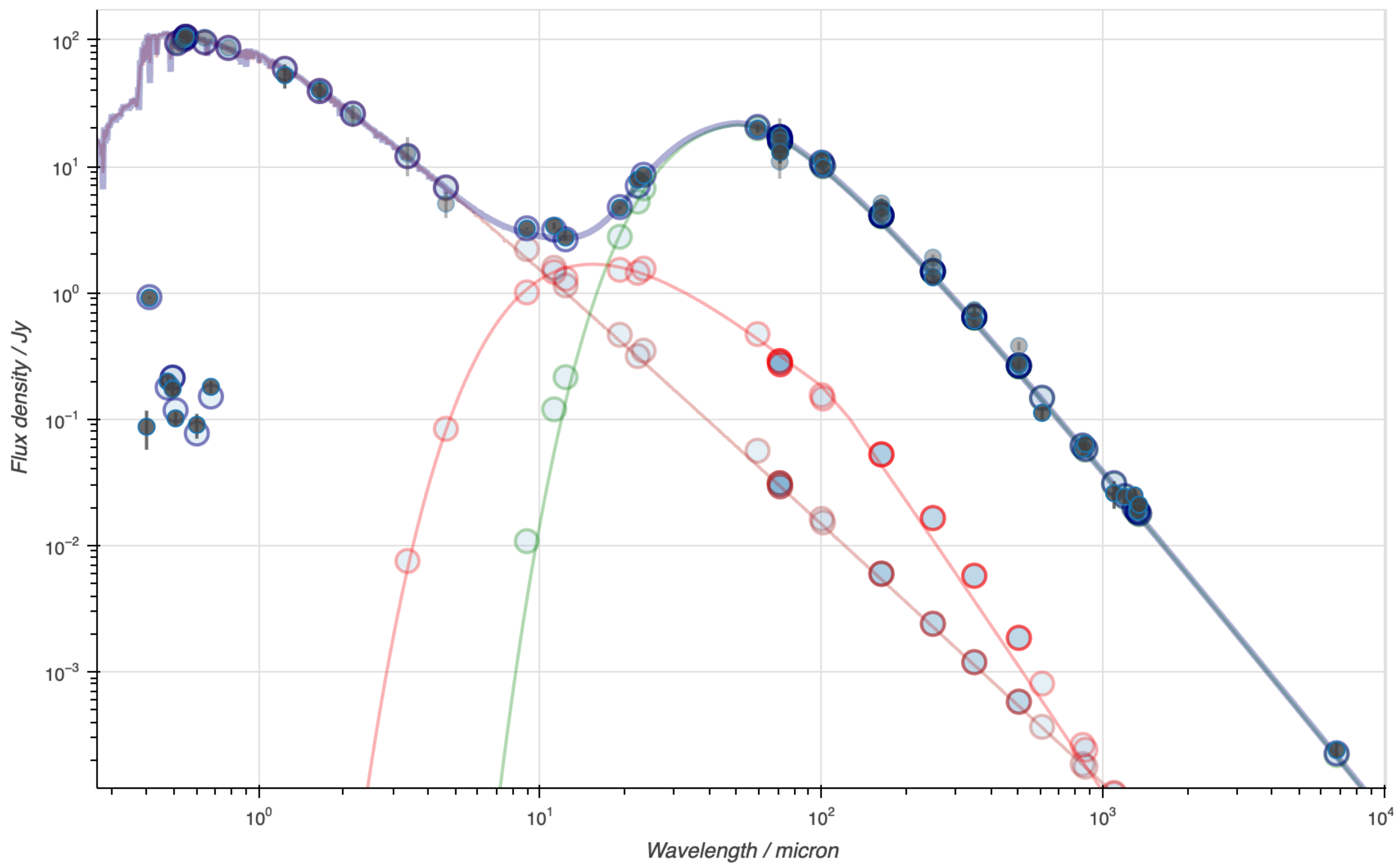
- Vega



Spectral Energy Distributions

<u>Multi-component example (warm + cold dust components)</u>

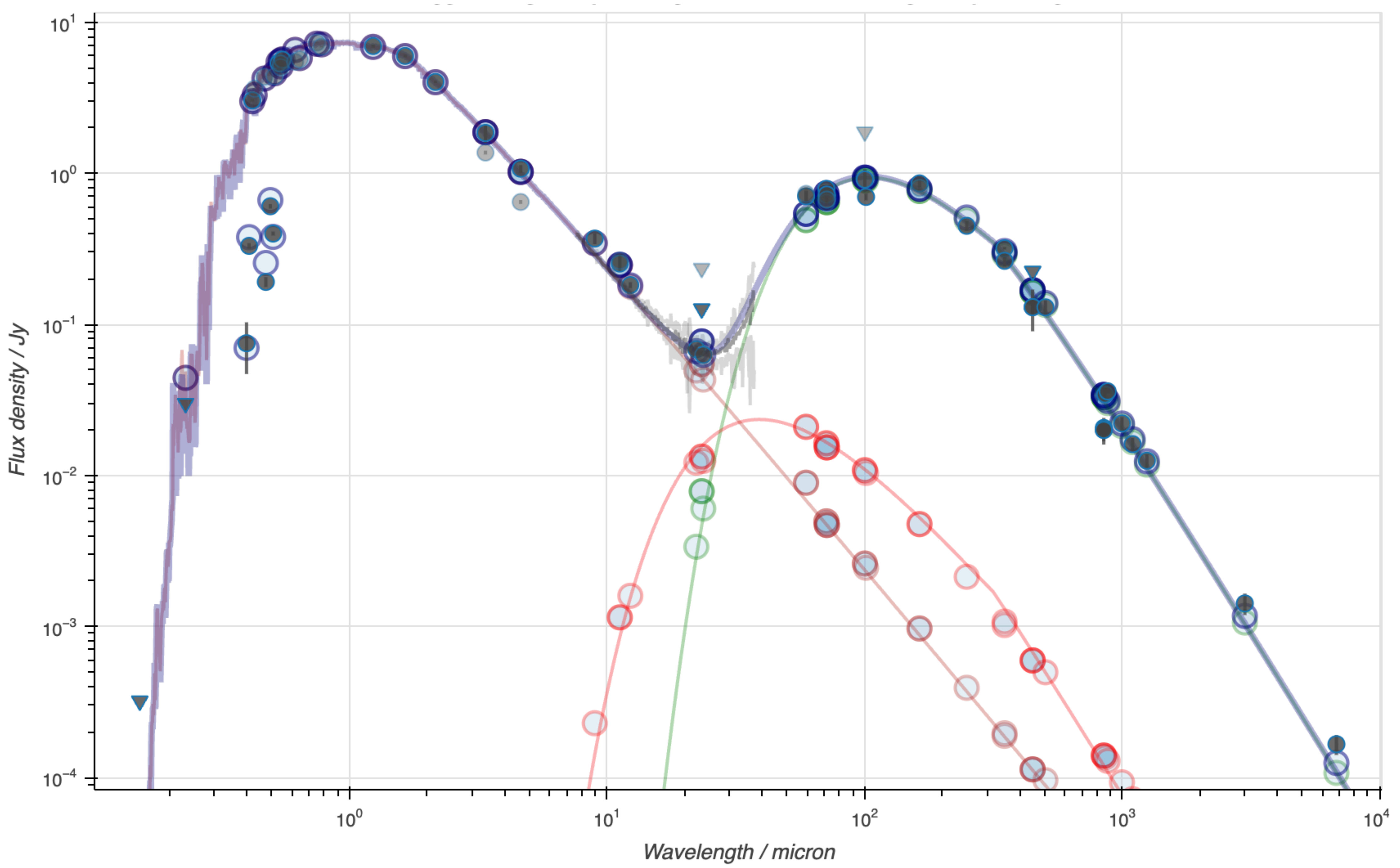
- Vega, β Pic



Spectral Energy Distributions

<u>Multi-component example (warm + cold dust components)</u>

- Vega, β Pic, and HD 107146



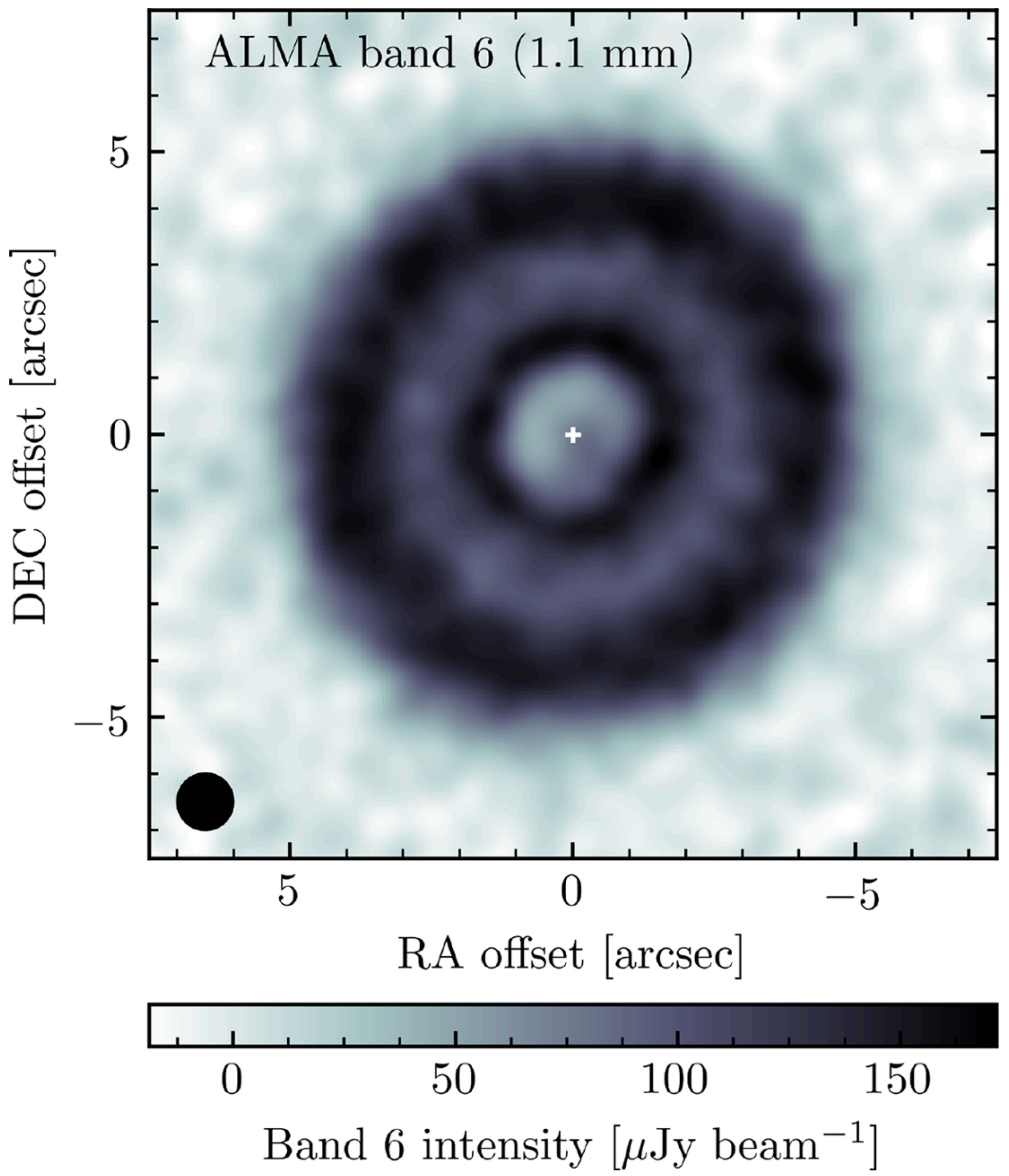
Resolved Images

Current Status

- ~200 debris discs now resolved
- Diverse morphologies revealed

Common Features

- Symmetric rings: HD 107146



Marino et al. 2018

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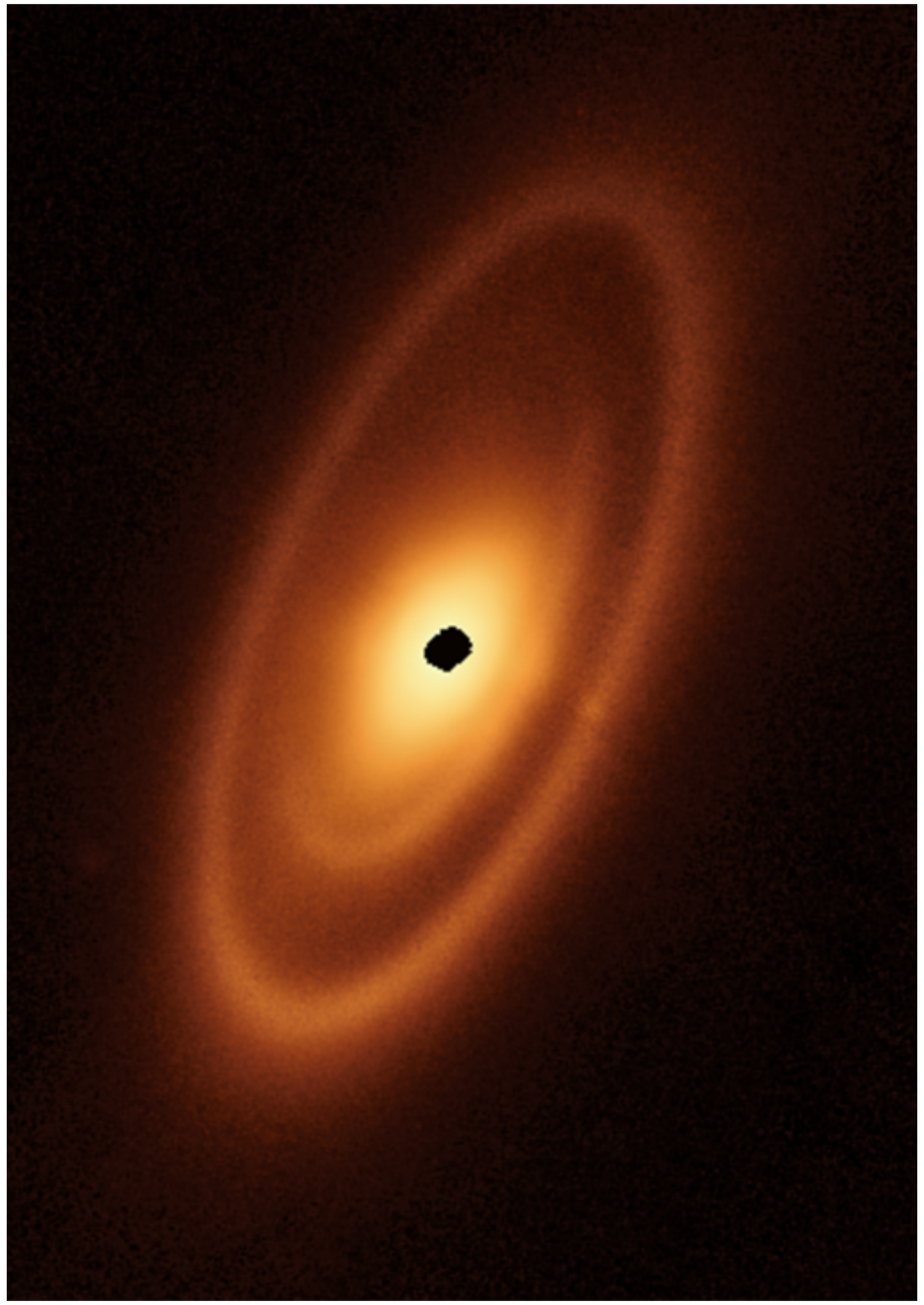

Gáspár et al. 2023

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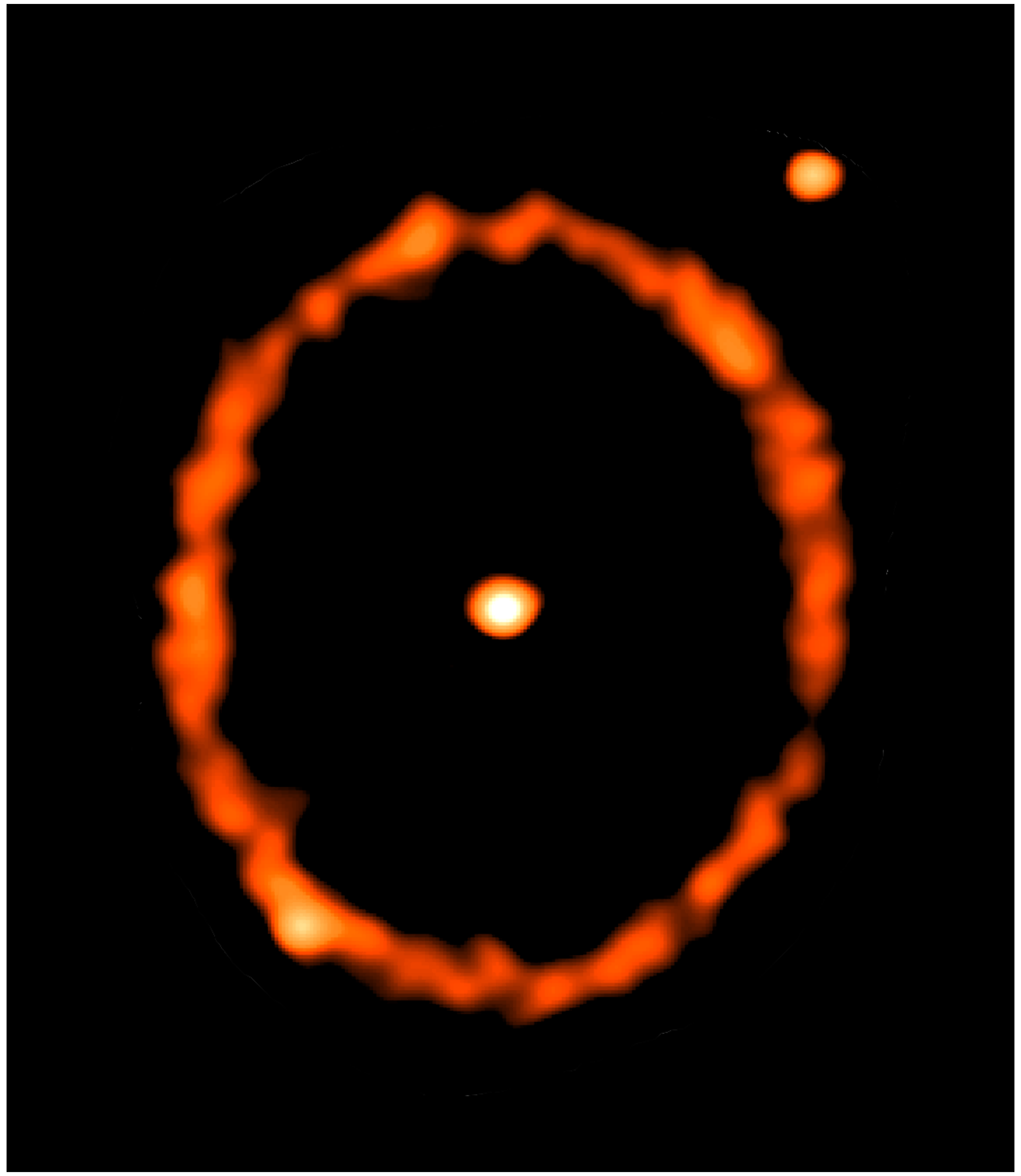

Booth et al. 2023

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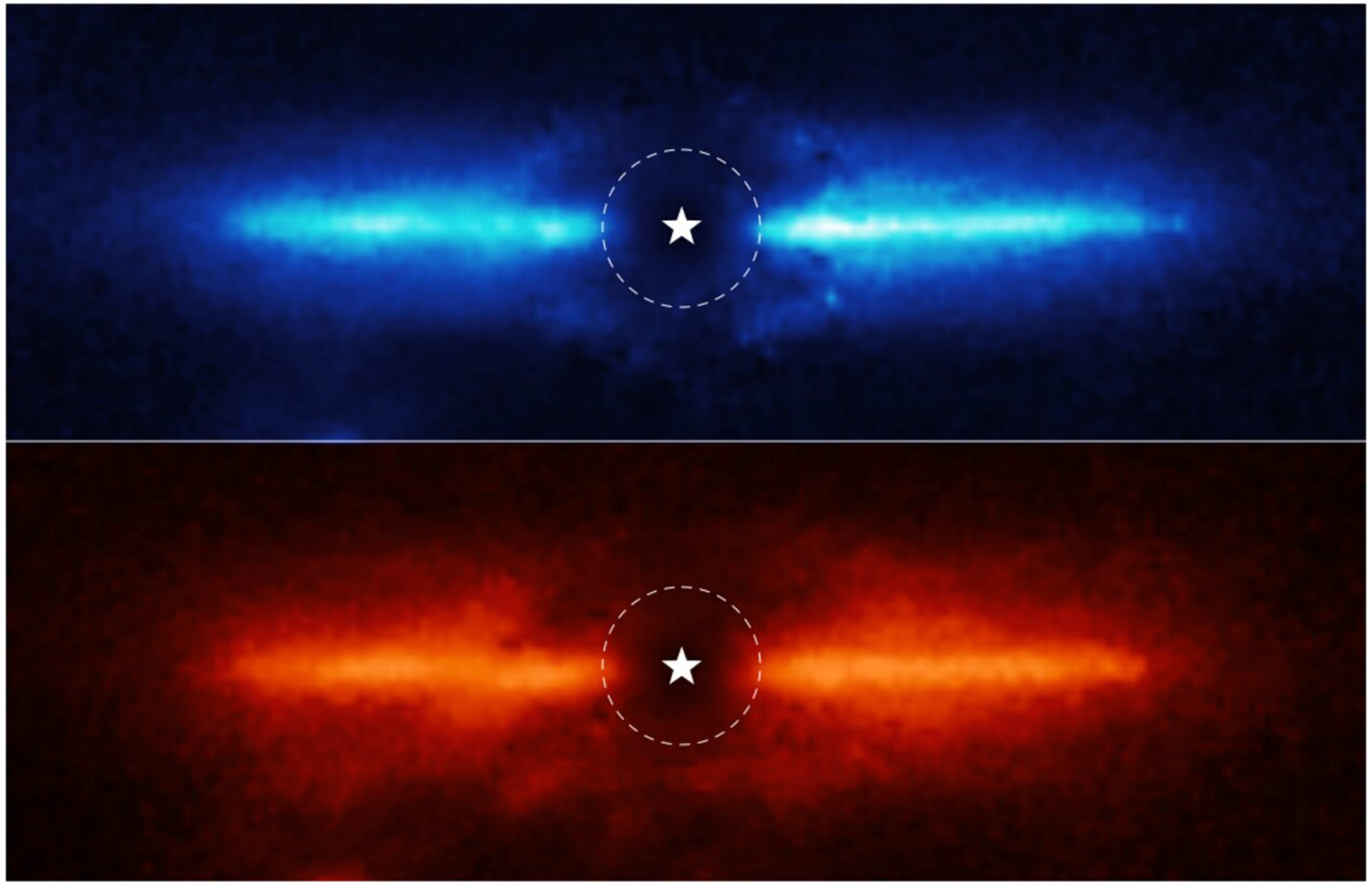
- Asymmetric features: AU Mic



NASA, ESA, CSA, and K. Lawson, A. Pagan

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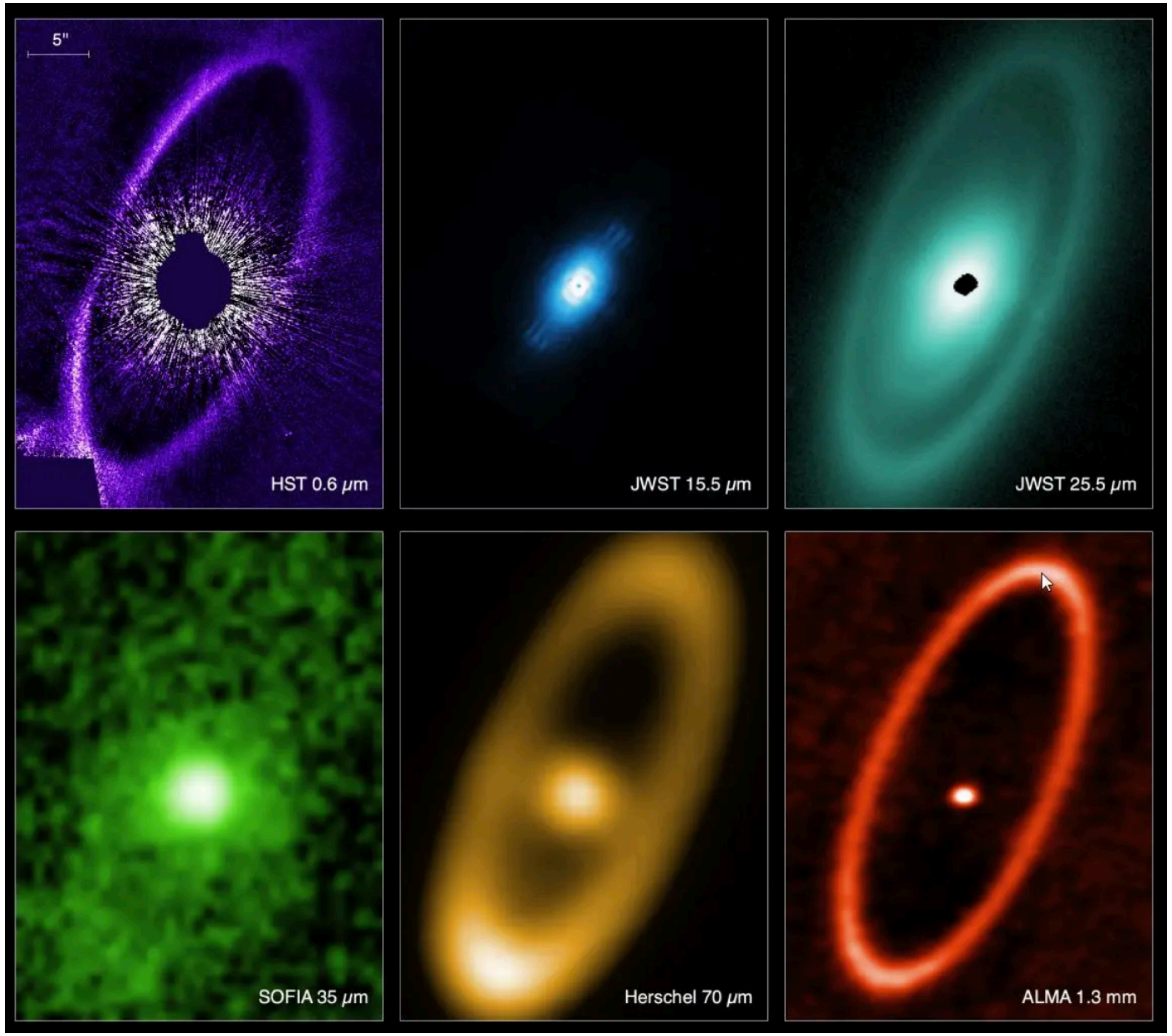
Key Finding

- Compact at long wavelengths (large grains)
- Extended at short wavelengths (small grains)



Gáspár et al. 2023