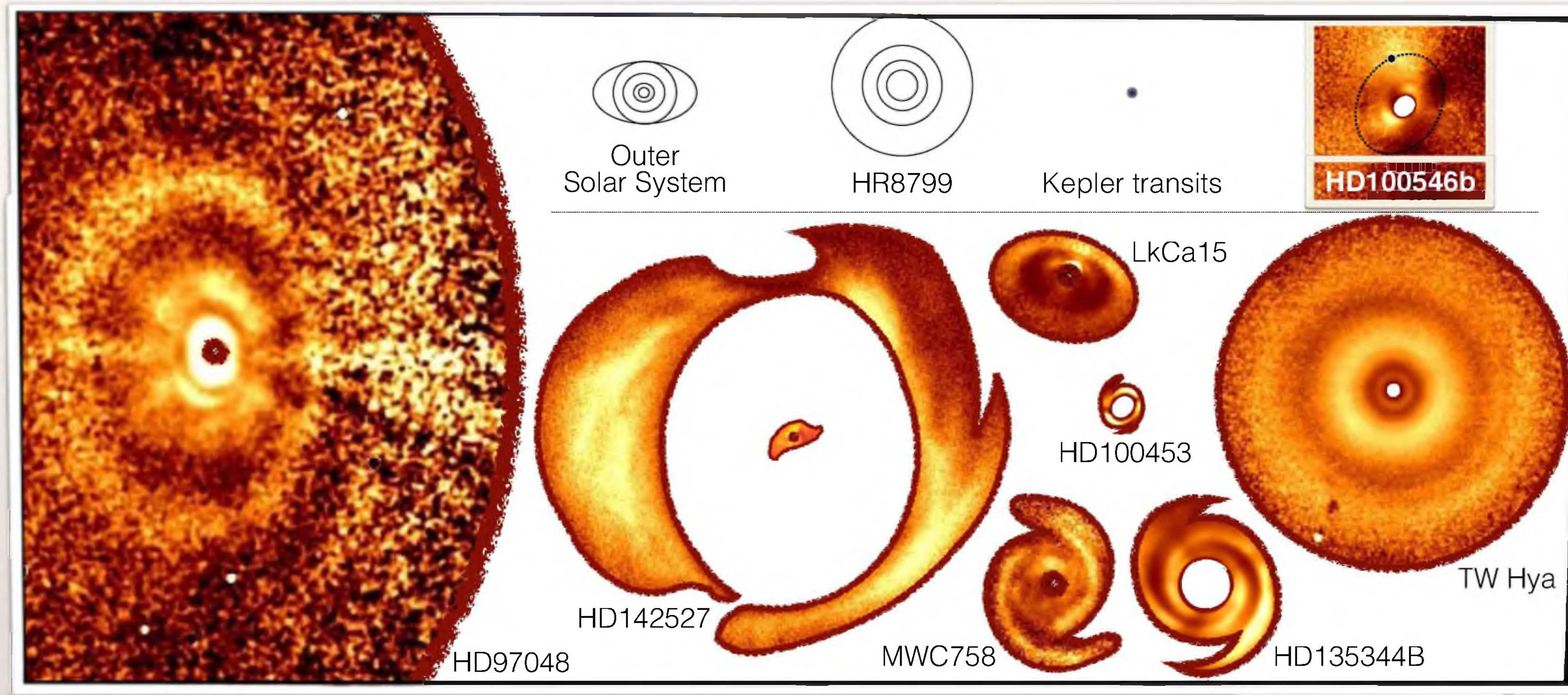
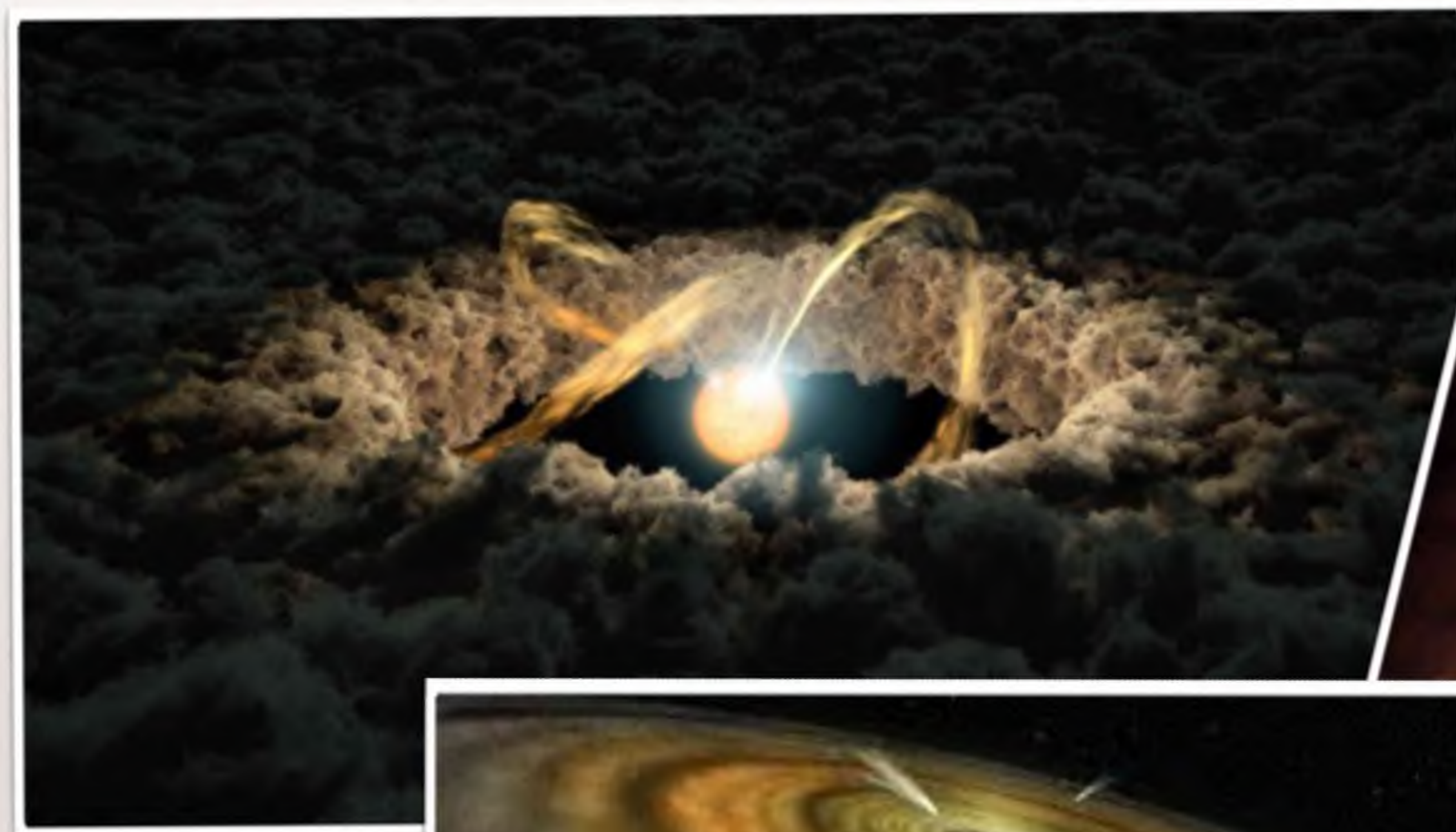


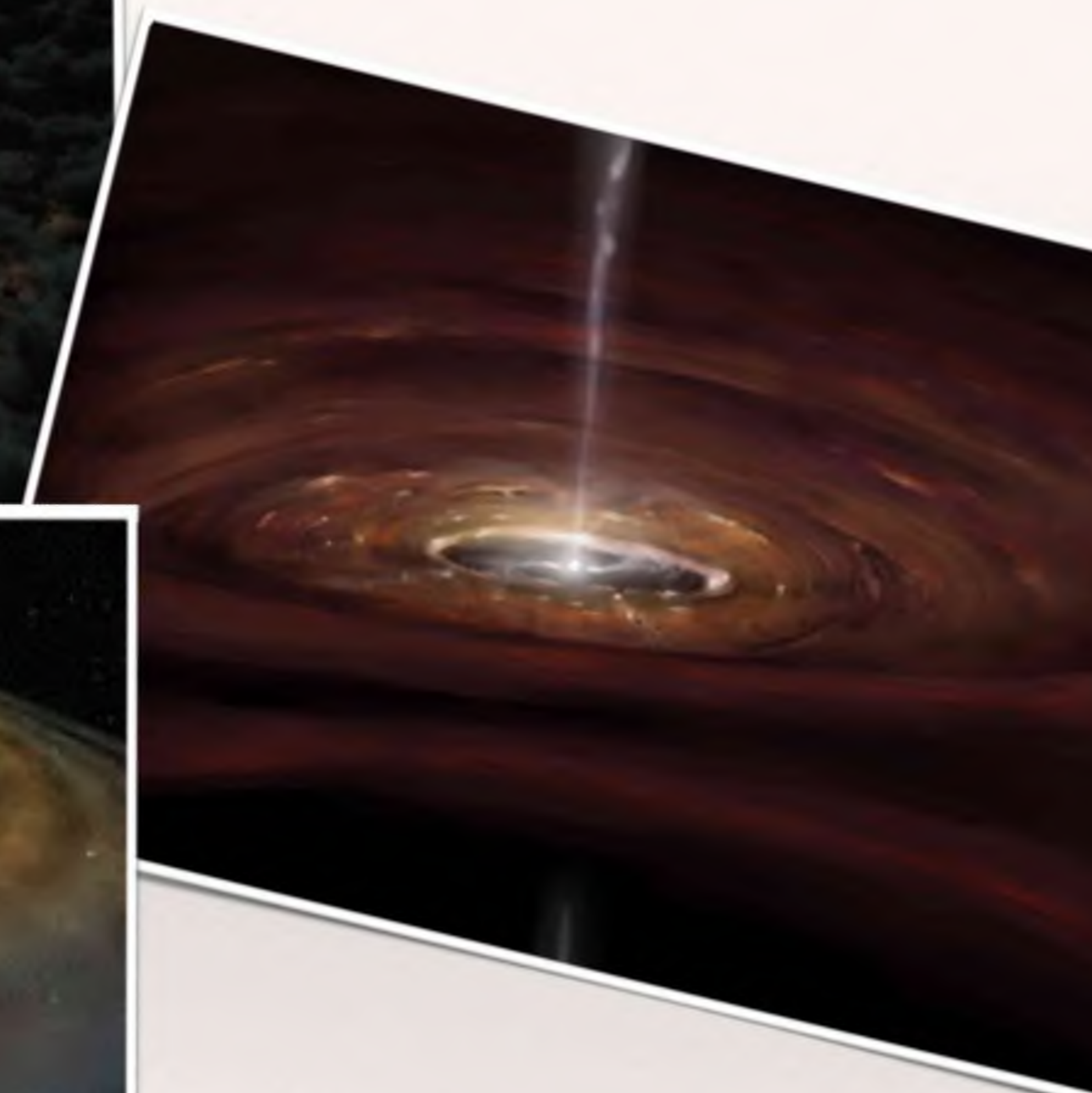
Gaia's view of PMS evolution, 21 June 2019, Leeds (UK)

Our first 100 protoplanetary discs
(with high-resolution imaging)

Antonio Garufi
OA Arcetri, INAF
with H. Avenhaus, F. Bacciotti, A. Banzatti, M. Benisty, C. Dominik, M. Kama, G. Meeus, L. Podio, P. Pinilla, S. Quanz, SPHERE/GTO

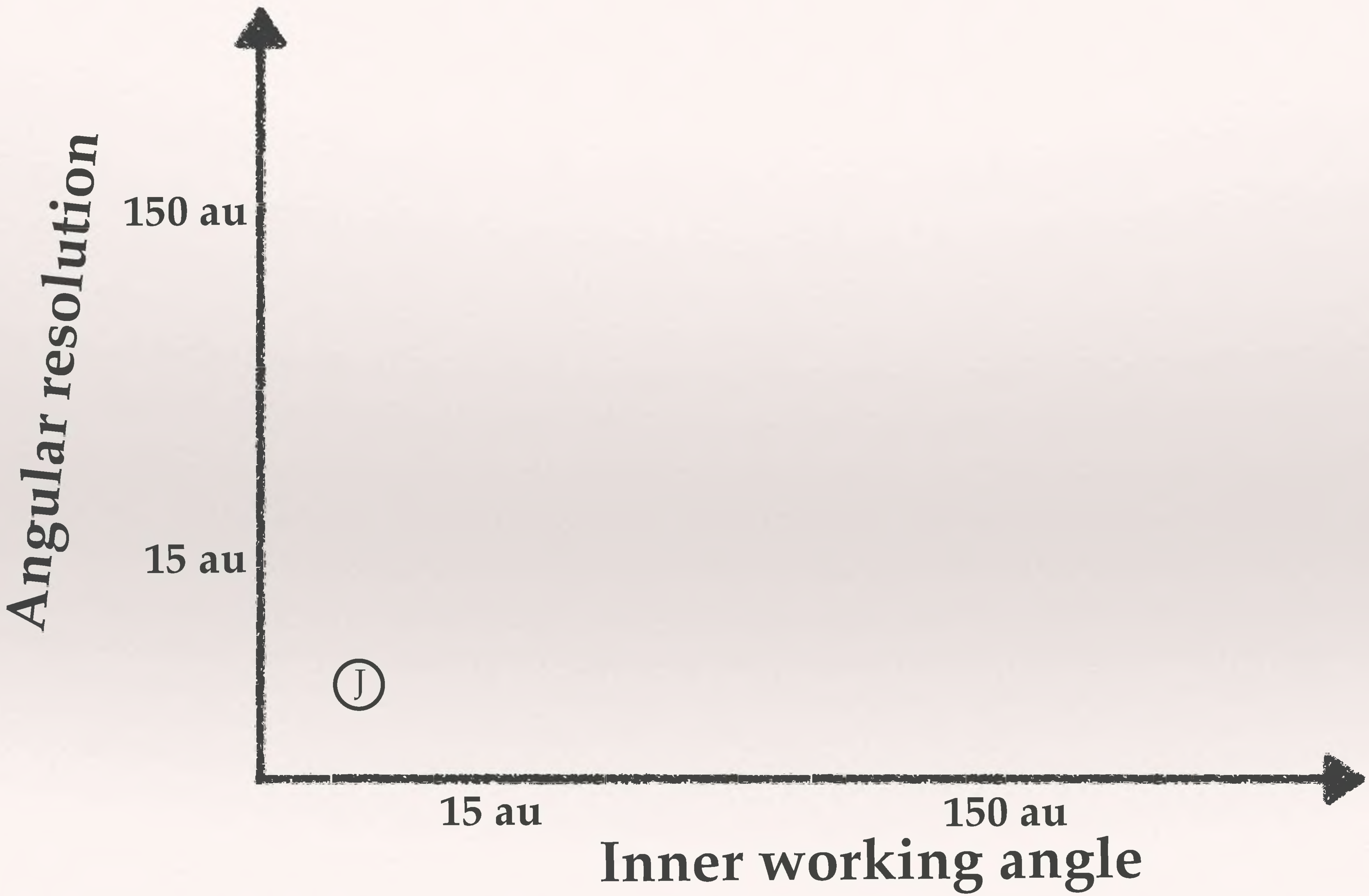
High-resolution disk imaging





These are the best

High-resolution disk imaging



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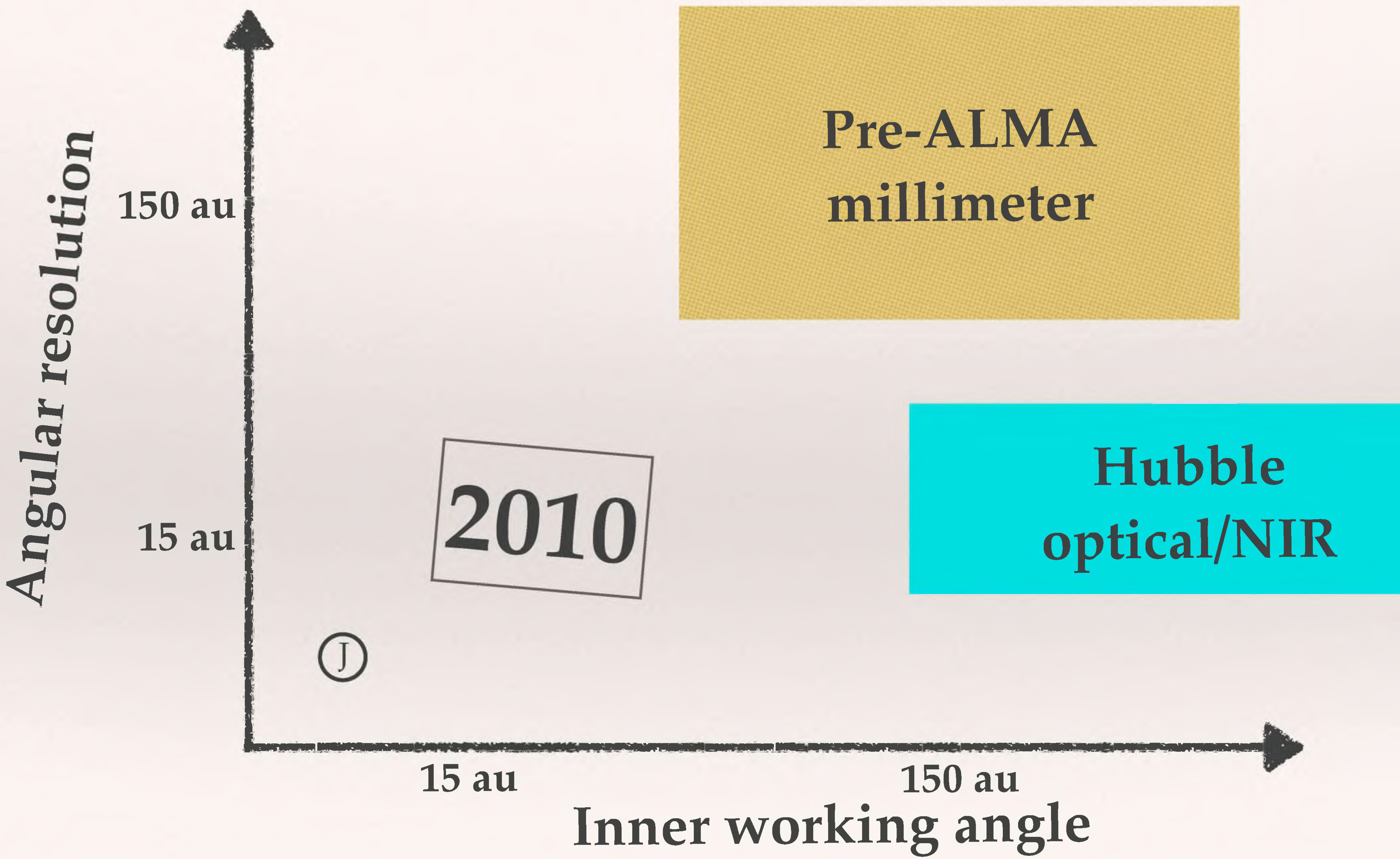

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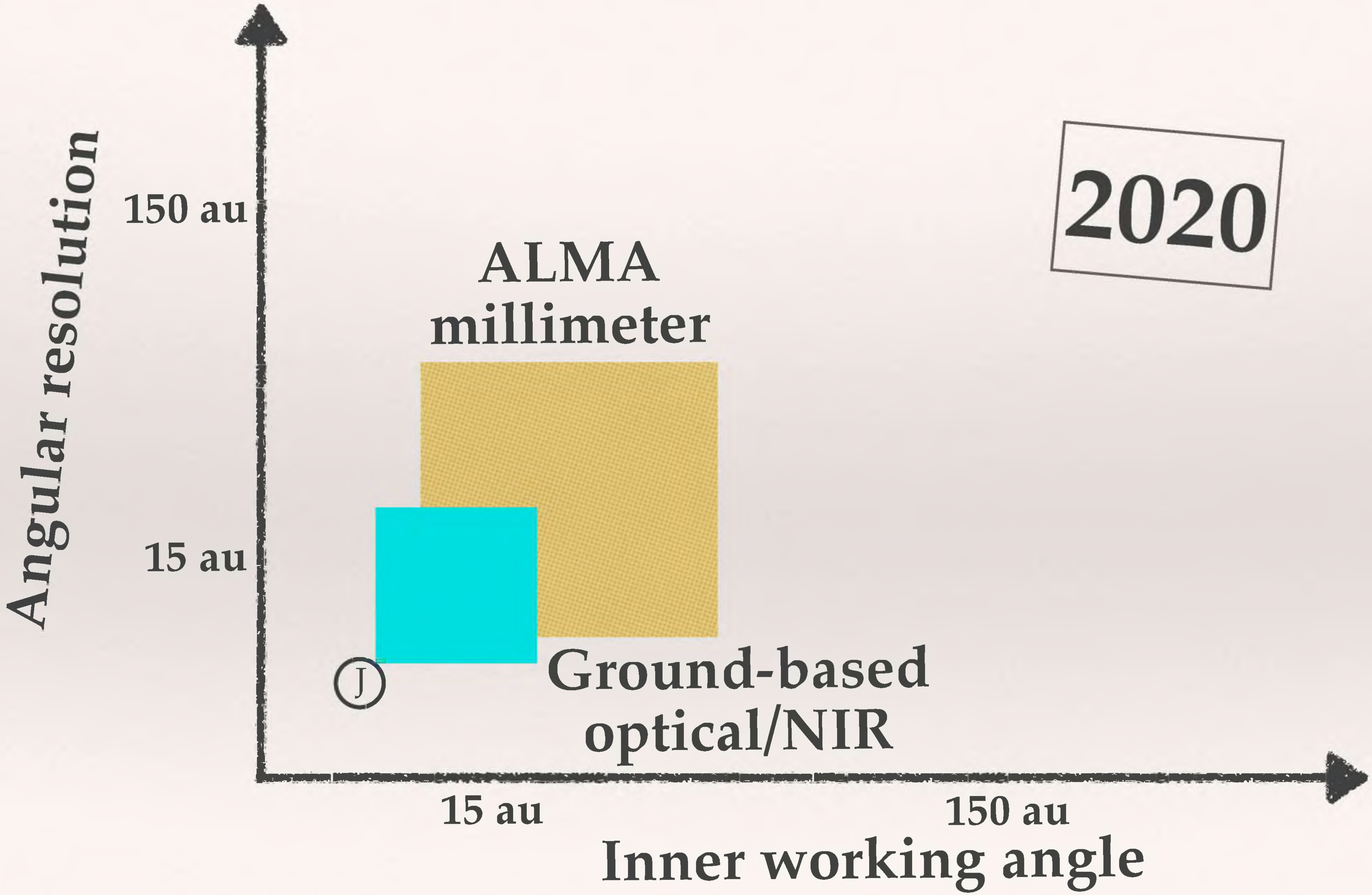

High-contrast NIR imaging

Most objects are bright at these wavelengths.

It is not a matter of sensitivity but of **contrast**:
star/disk, envelope/ disk, star/ planet, disk/ planet…

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↓

We developed **differential** techniques.

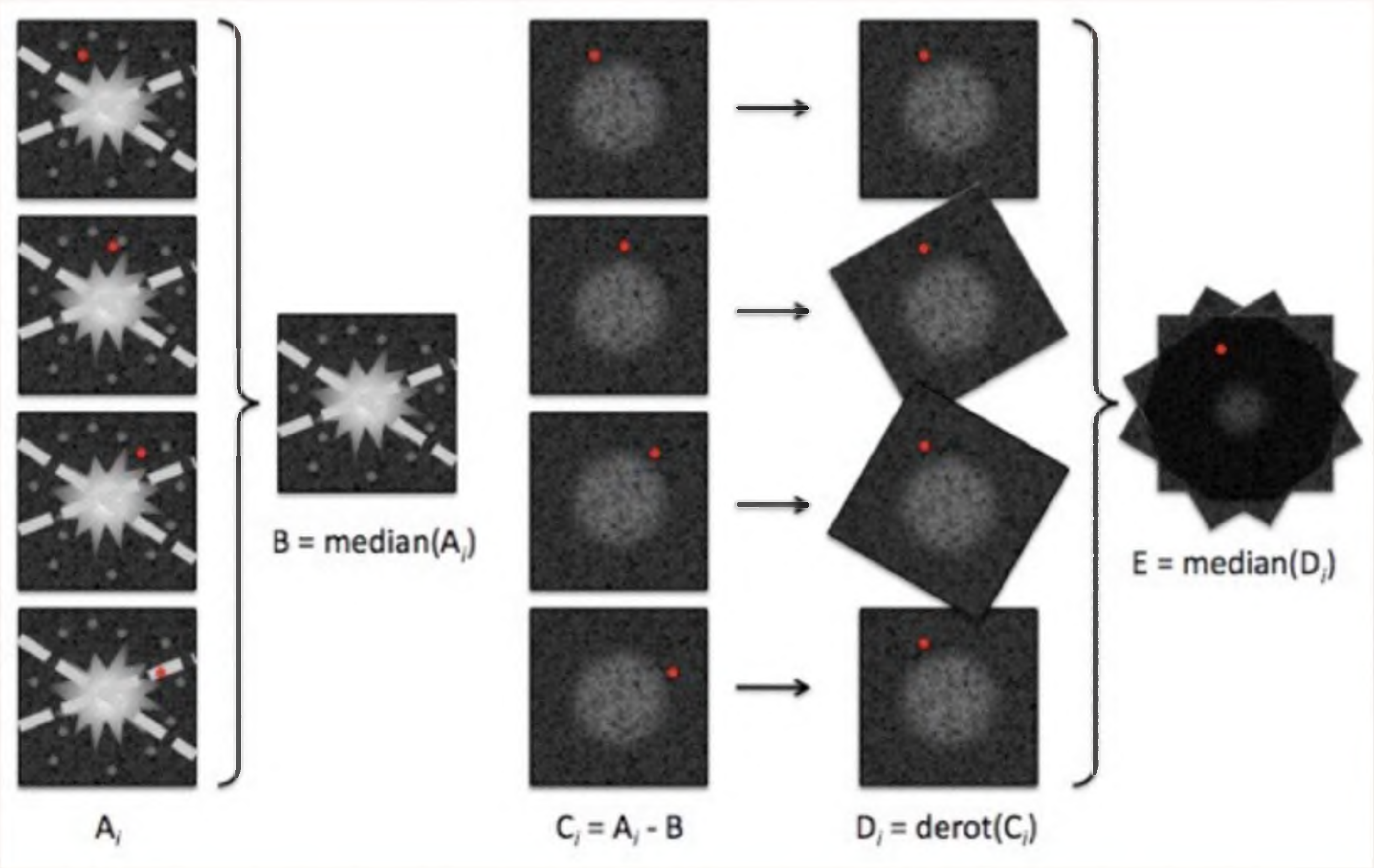
Angular-

Polarimetric-

Reference star-

Spectral-

High-contrast NIR imaging

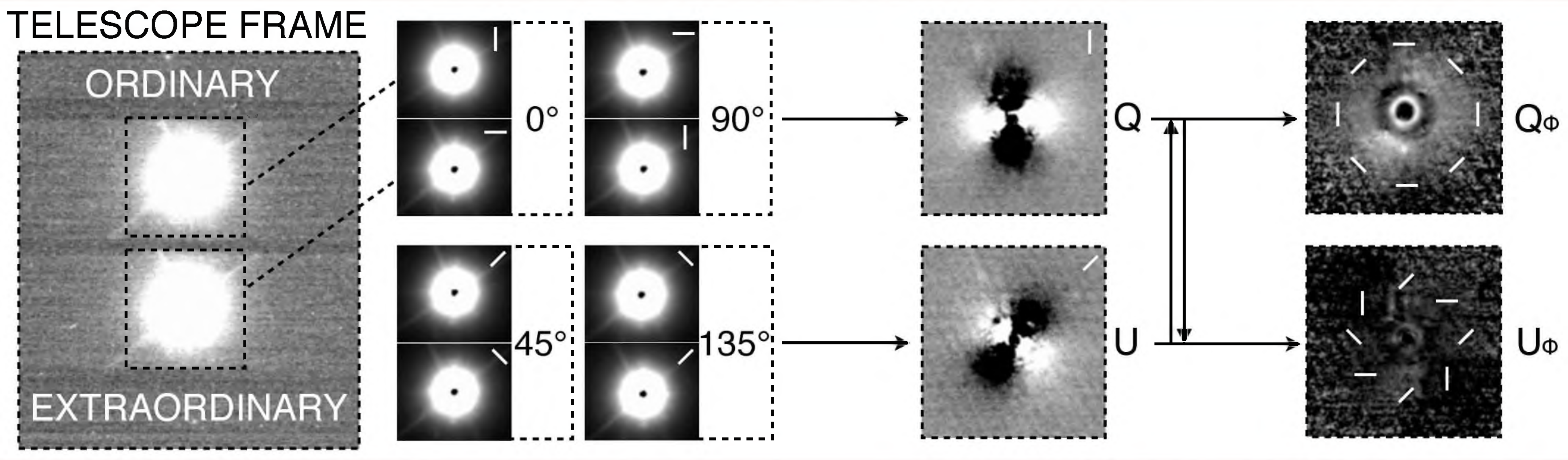


Angular differential imaging:

planets, jets, debris disks…

High-contrast NIR imaging

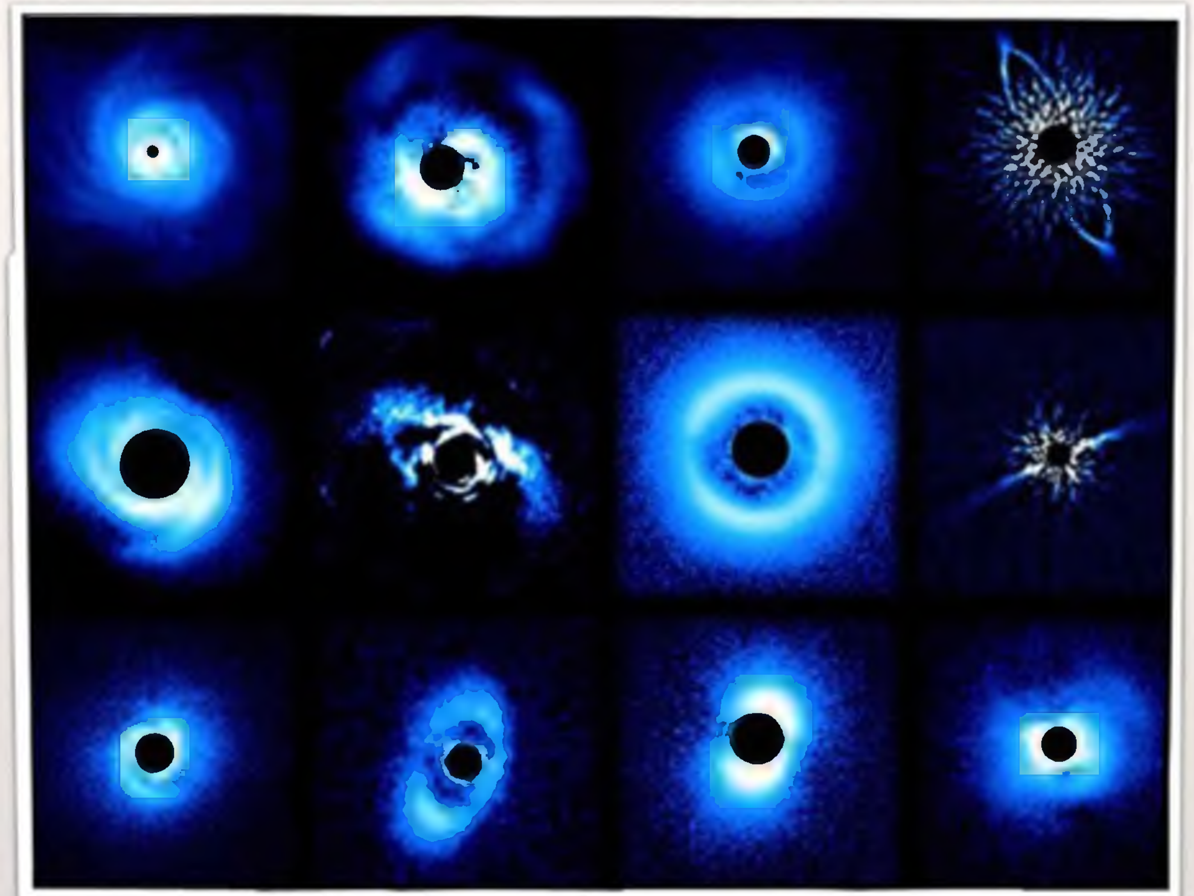
Stellar light is unpolarized. Scattered light is polarized.

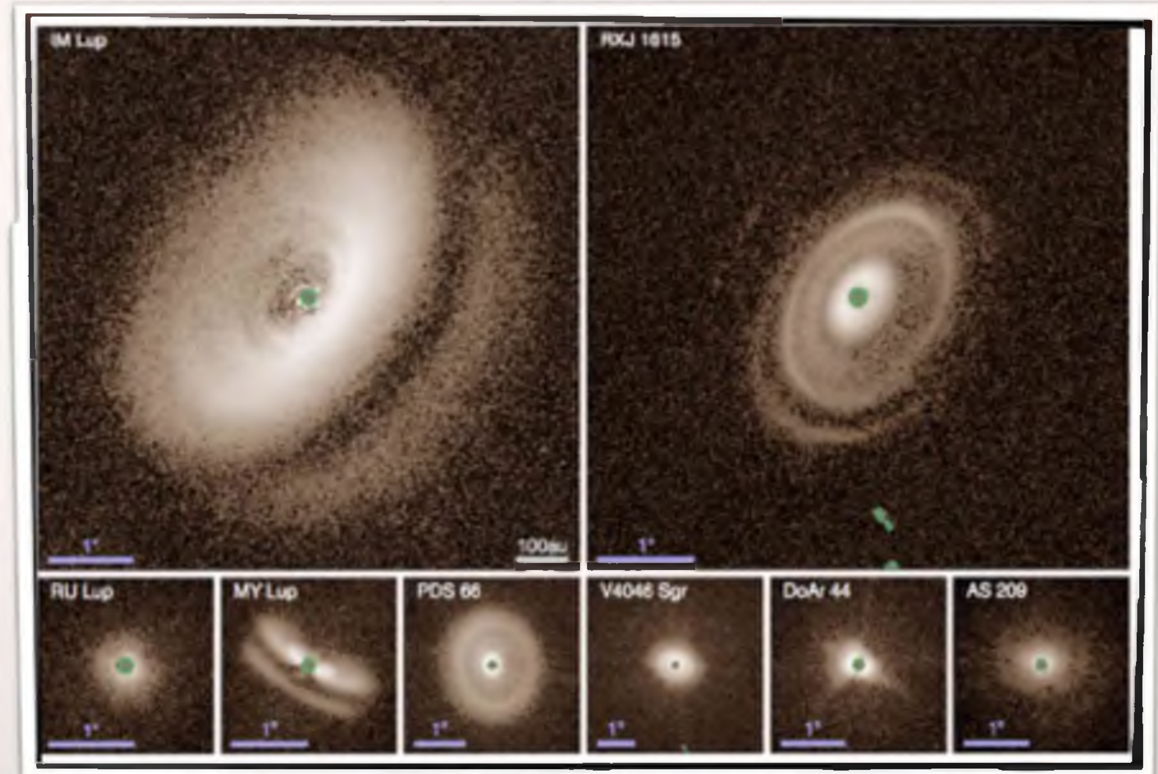


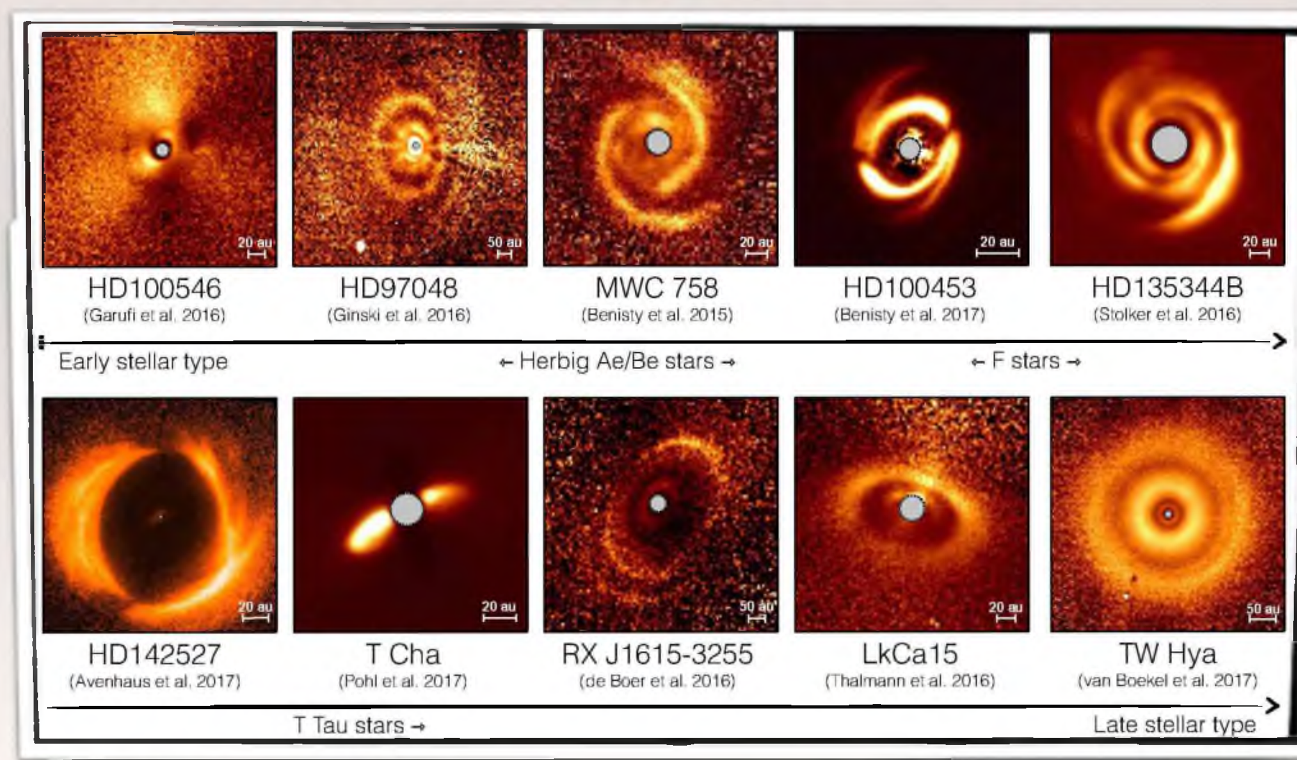
Polarimetric differential imaging:

Scattered light from circumstellar disks

The first 100 protoplanetary disks imaged







During the last decade, more than 100 ‘protoplanetary’ disks (1-10 Myr) have been imaged with high resolution (ALMA and NIR scattered-light).

SEEDS from Subaru/HiCiao, Hashimoto et al., www.nao.ac.jp; DISK GTO from VLT/SPHERE, Garufi et al. 2017b +references therein; DARTTS-S from VLT/SPHERE, Avenhaus et al. 2018

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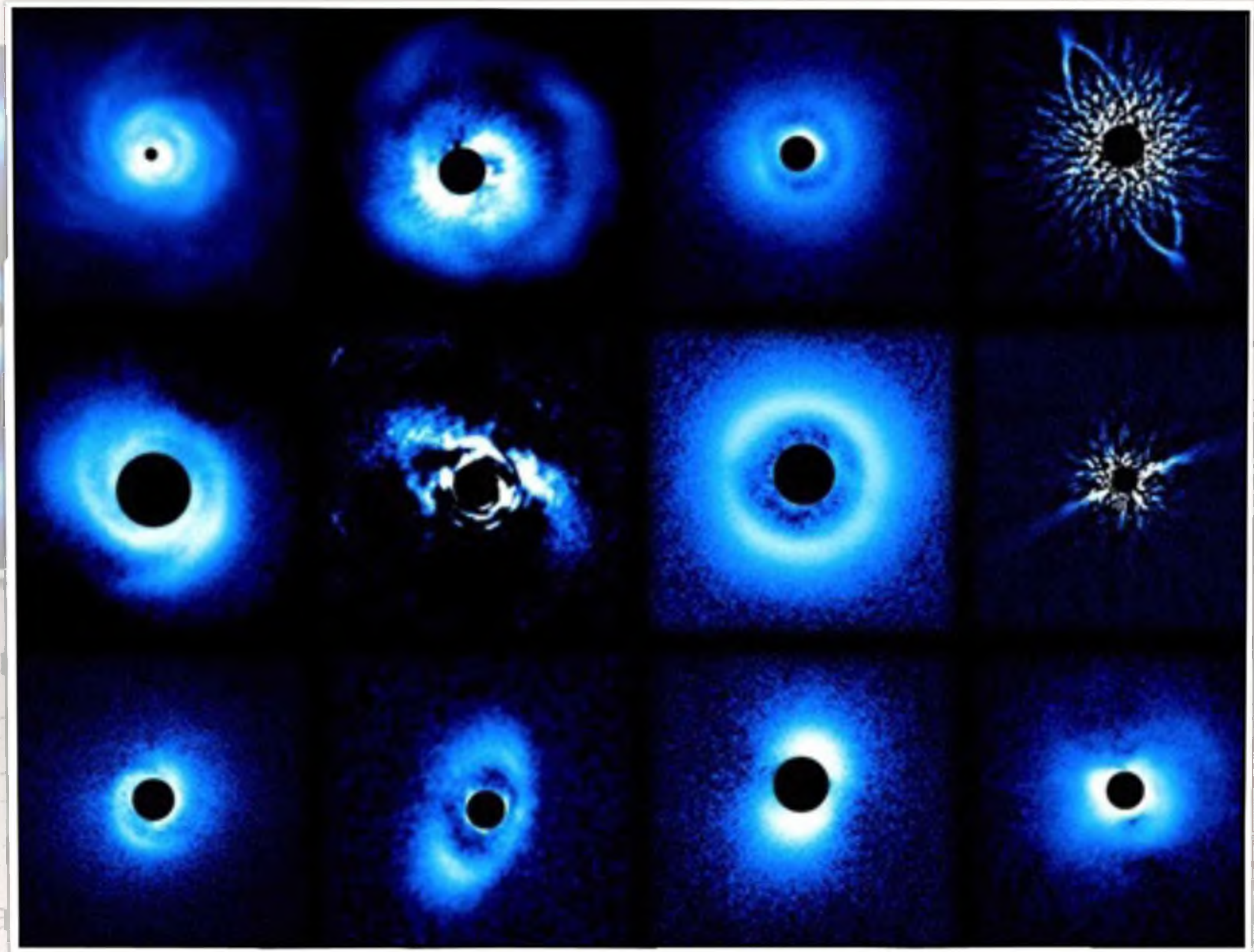

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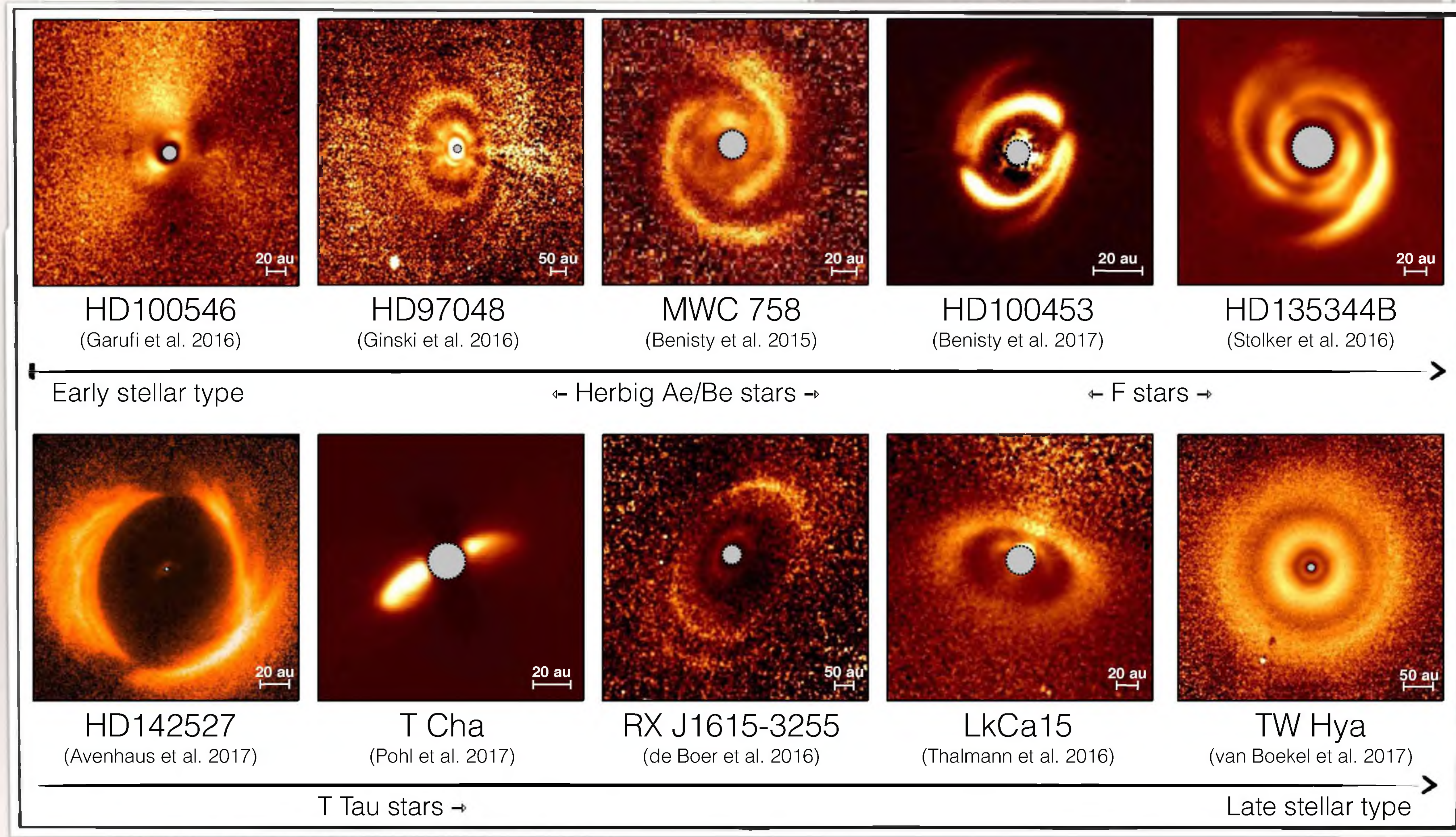

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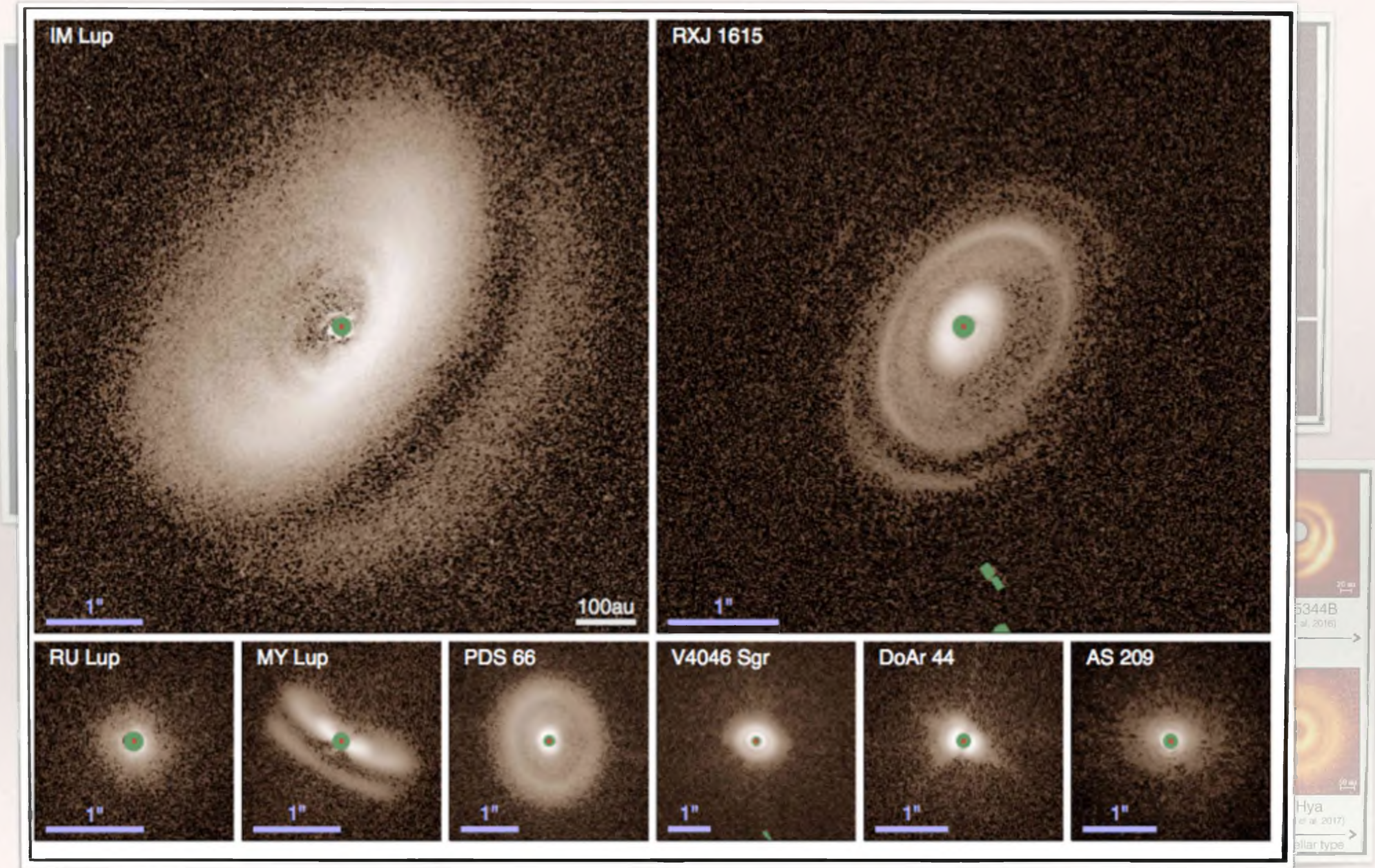

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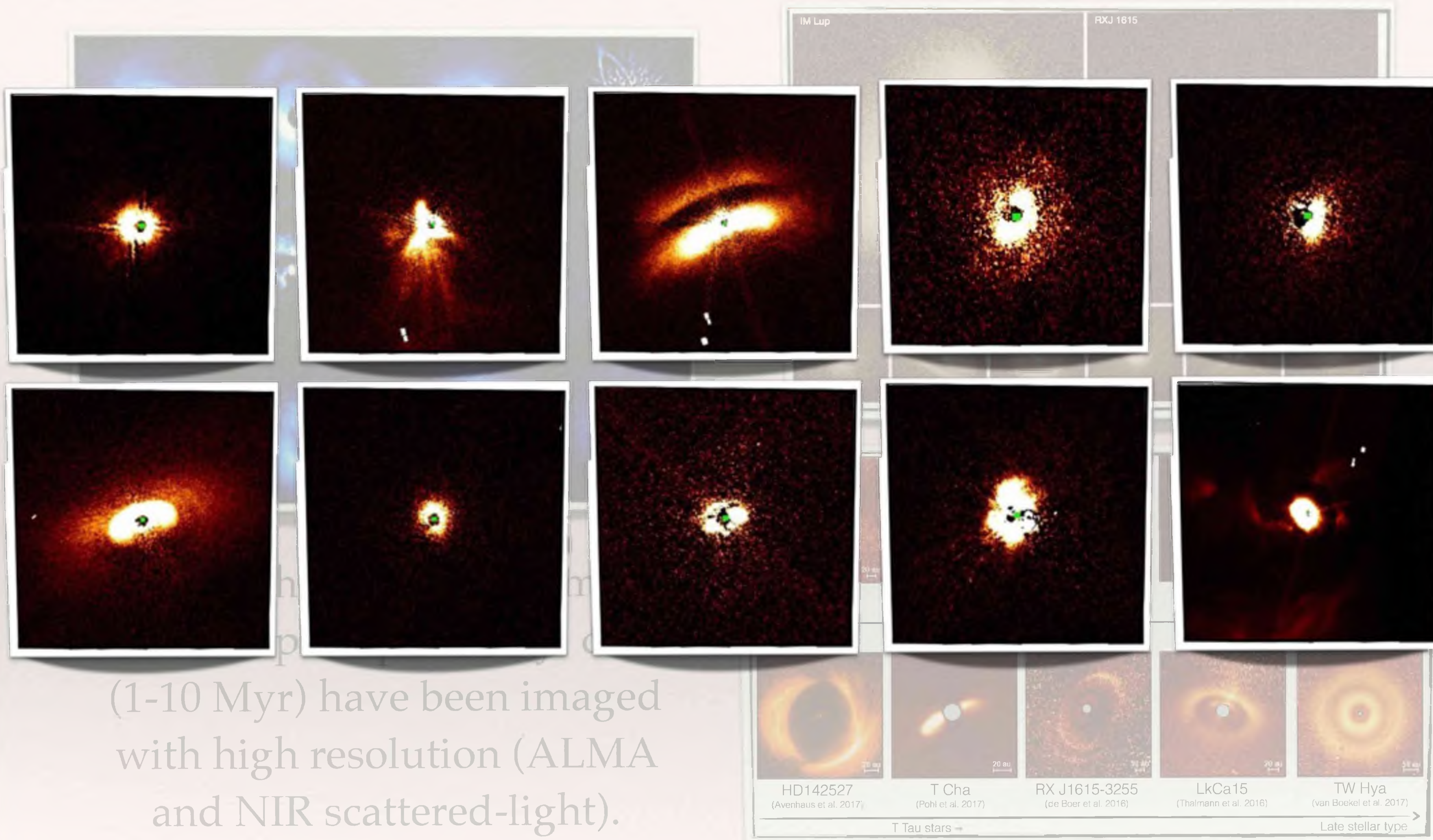

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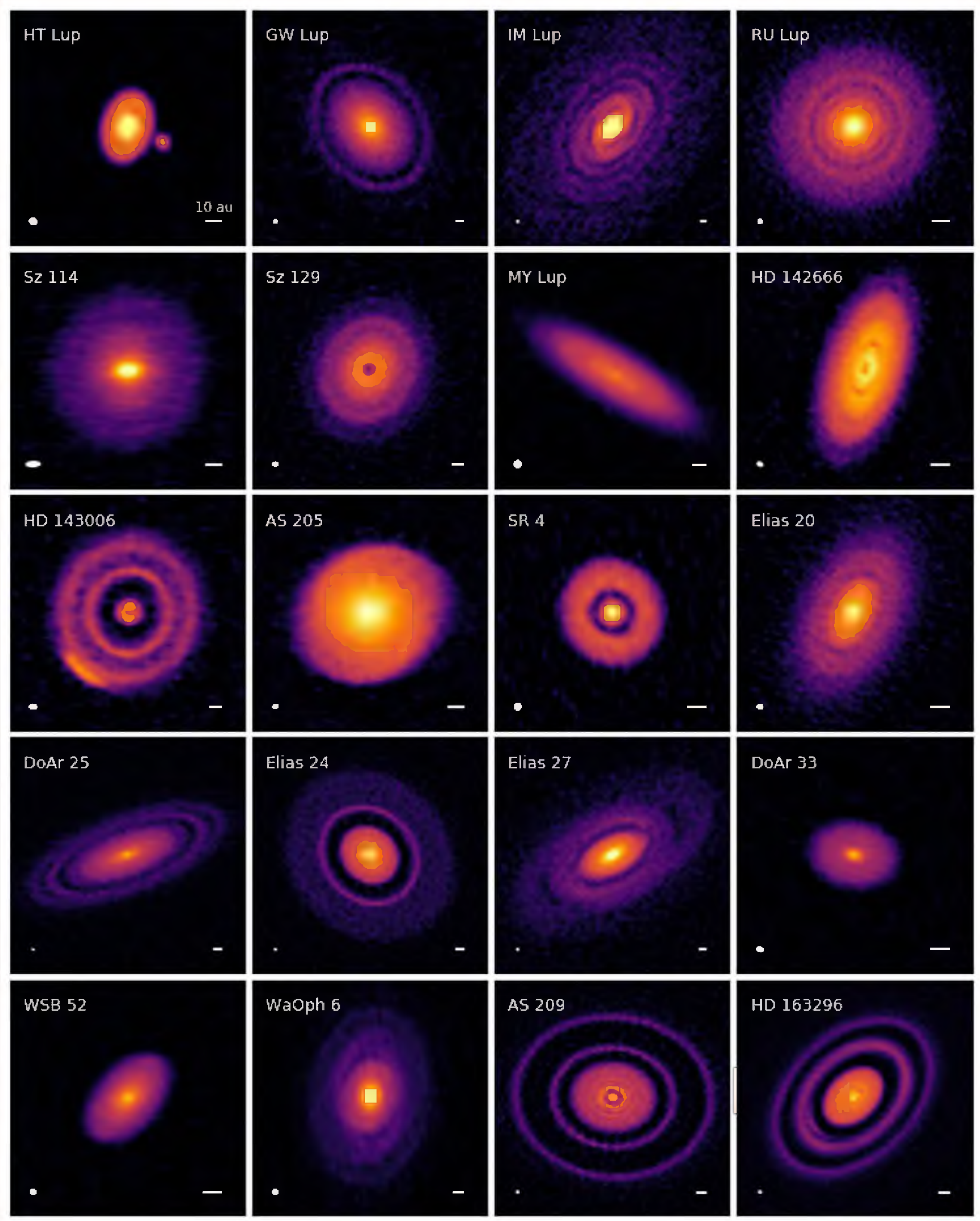
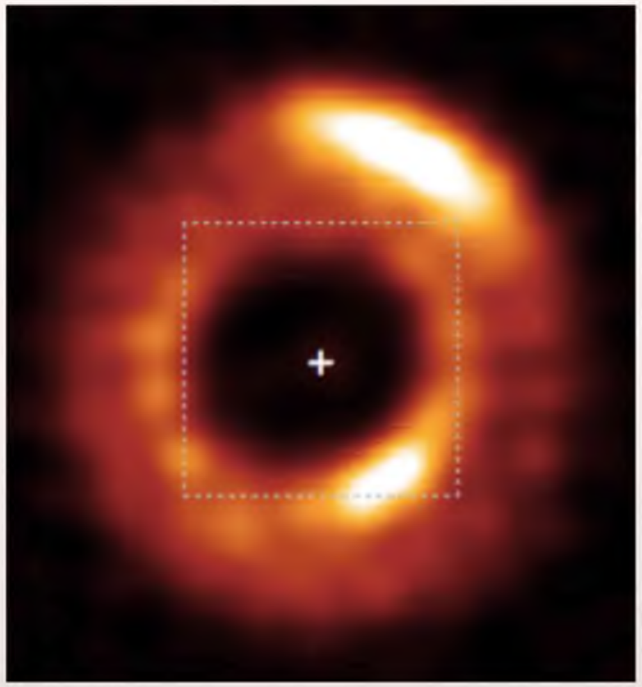
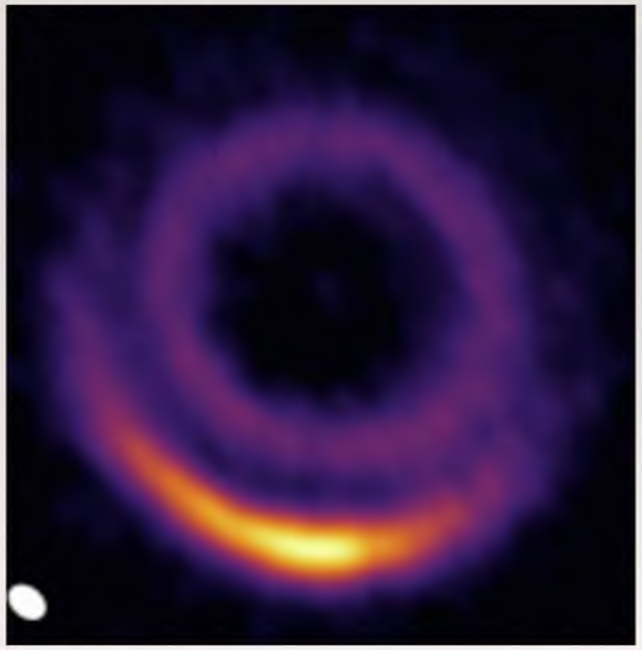
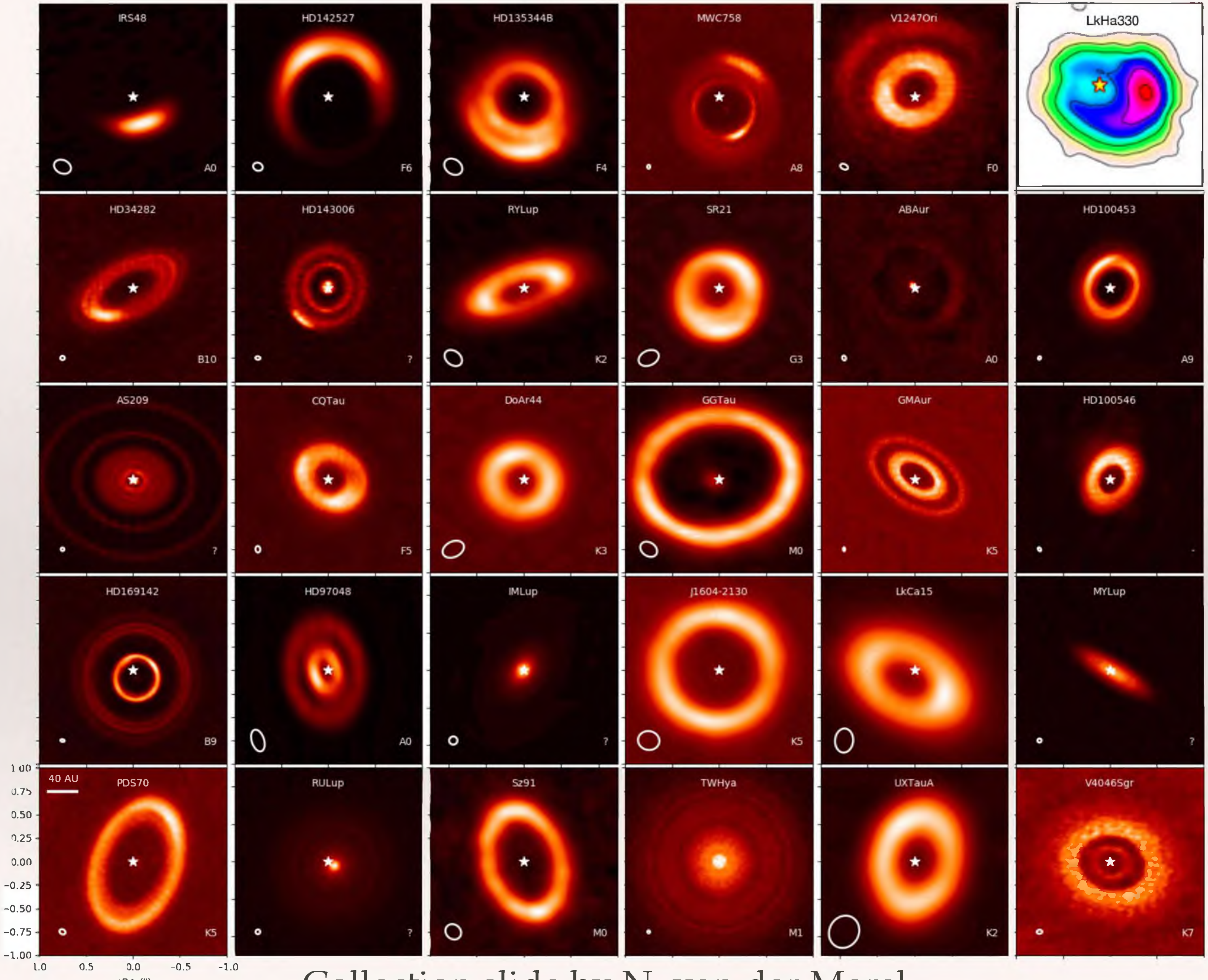






DSHARP with ALMA (**Andrews** et al. 2018 and related papers), **Boehler** et al. 2018, **Cazzoletti** et al. 2018

The first 100 protoplanetary disks imaged



Collection slide by N. van der Marel

Taxonomy of 100 protoplanetary disks

Method:

So far, mostly studies on individual objects (or lower-resolution surveys).

First taxonomical/statistical work now…

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First taxonomical/statistical work now…

General finding:

Most (all?) disks show sub-structures.

Their most likely origin is the interaction with (unseen) planets.

Caveat:

We hardly (almost never) detect planets in these disks.

Disk cavity

Fact #1:

Very high occurrence: resolved in ~⅔ of the PDI sample.

(To be compared to the 10% from photometric surveys.)

Disk cavity

Facts #1 and #2:

Very high occurrence: resolved in ~⅔ of the PDI sample.

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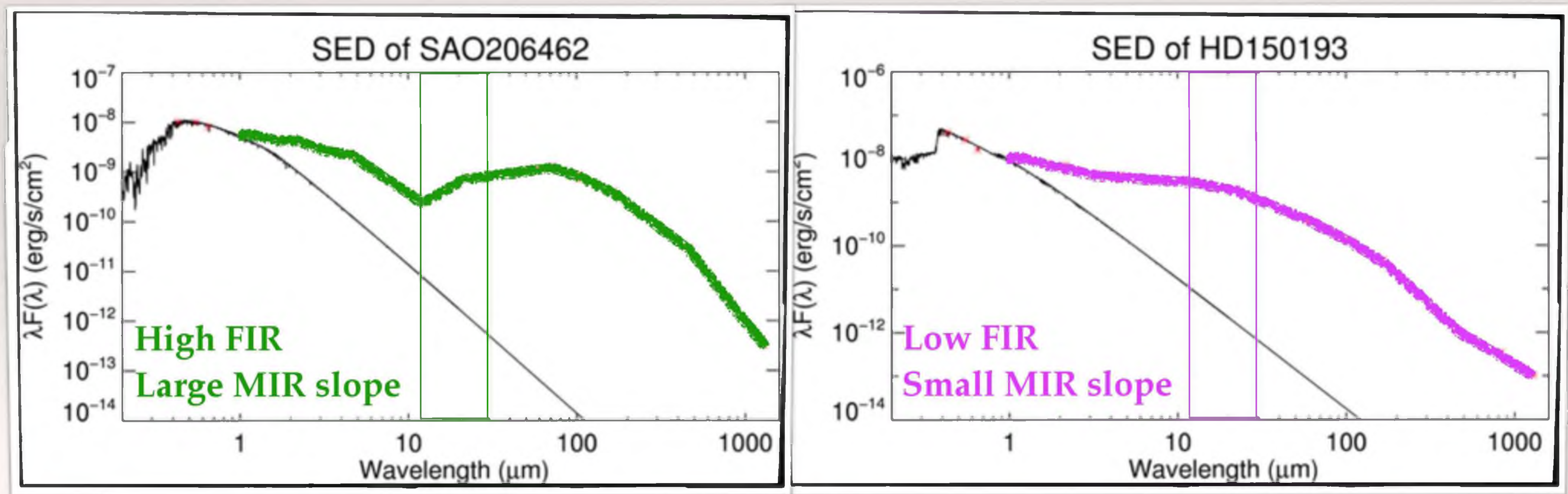
Cavities explain the Meeus observational dichotomy

Group I vs **Group II**



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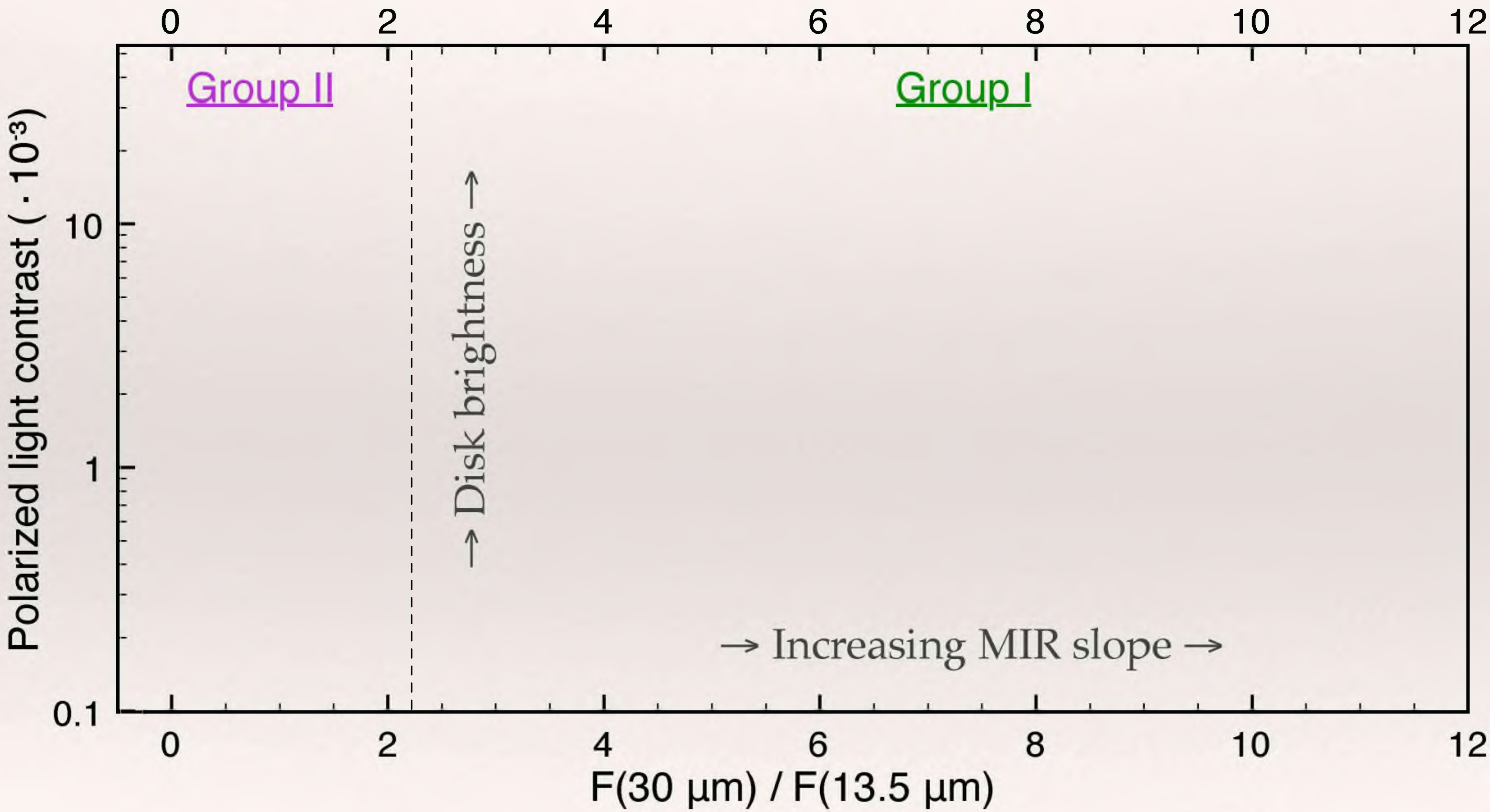

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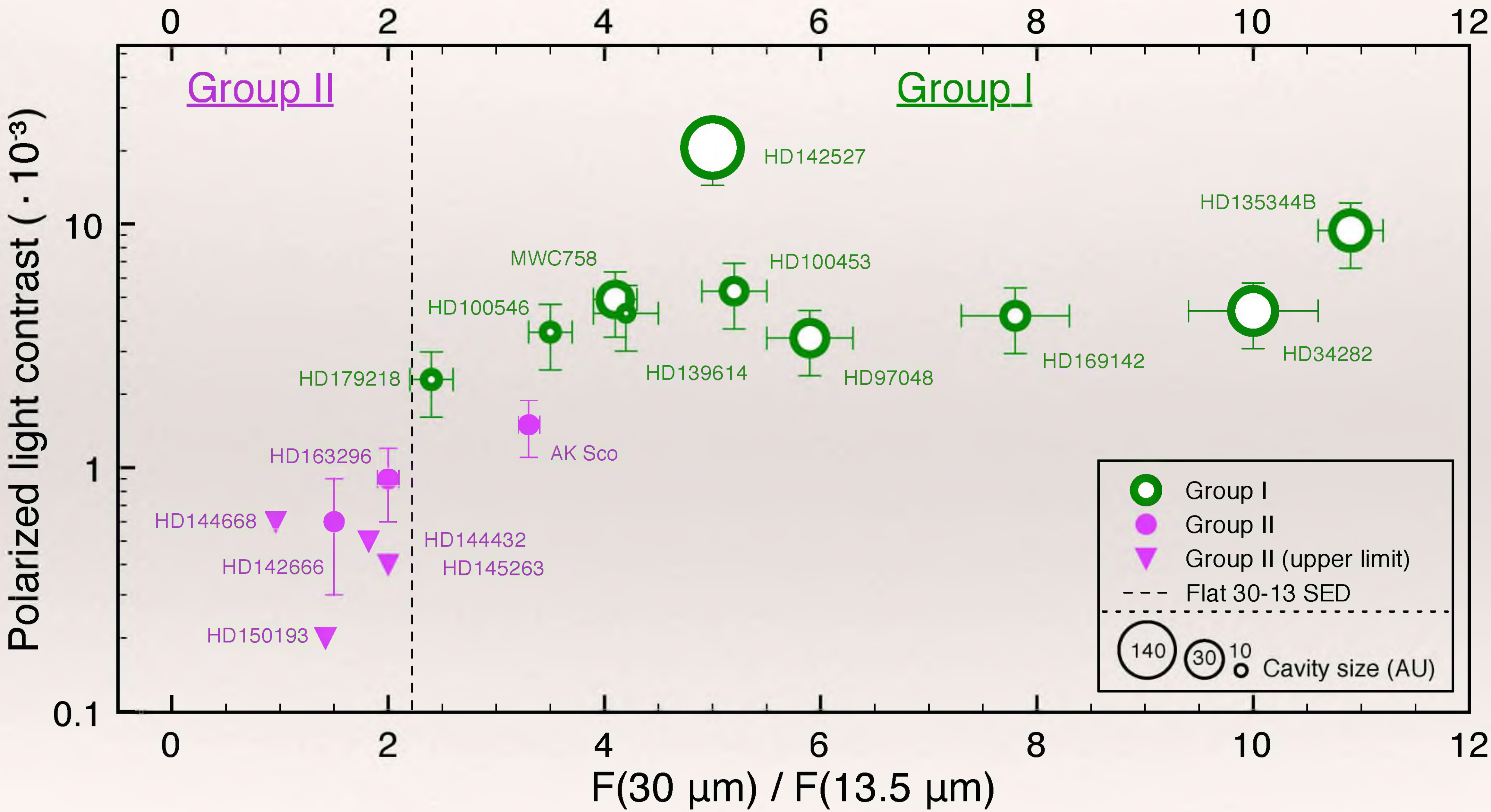


Garufi et al. 2017a. See also Currie 2010, Maaskant et al. 2013, Menu et al. 2015.

Disk cavity

Fact #3:

Very high occurrence: resolved in ~⅔ of the sample.

(To be compared to the 10% from photometric surveys.)

$\Uparrow$

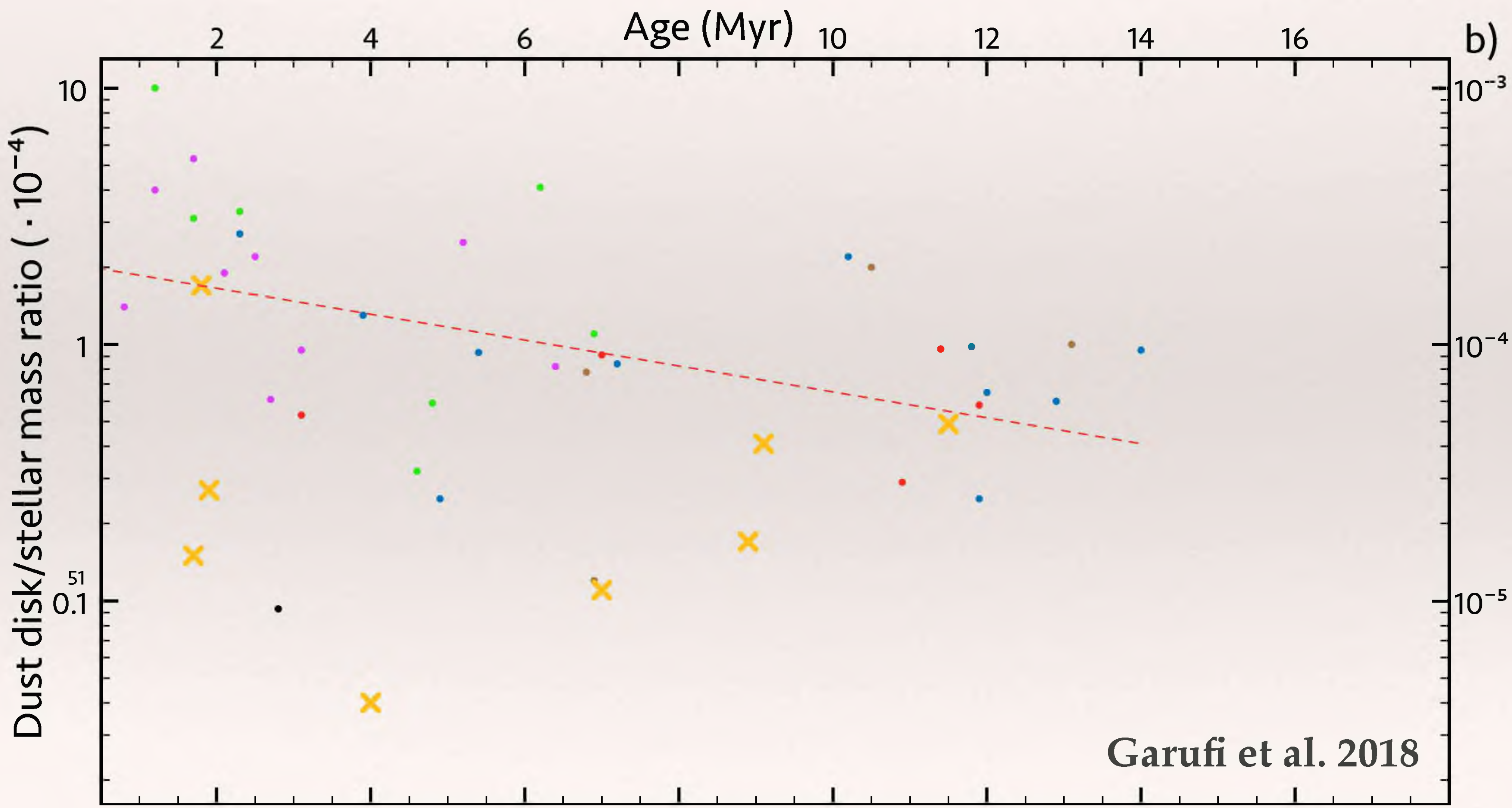
Disks with a cavity are brighter in scattered light.

We have an observational bias.

Disk masses

Fact #3:

We have more observational biases.
Primarily, massive disks around old stars have been observed.



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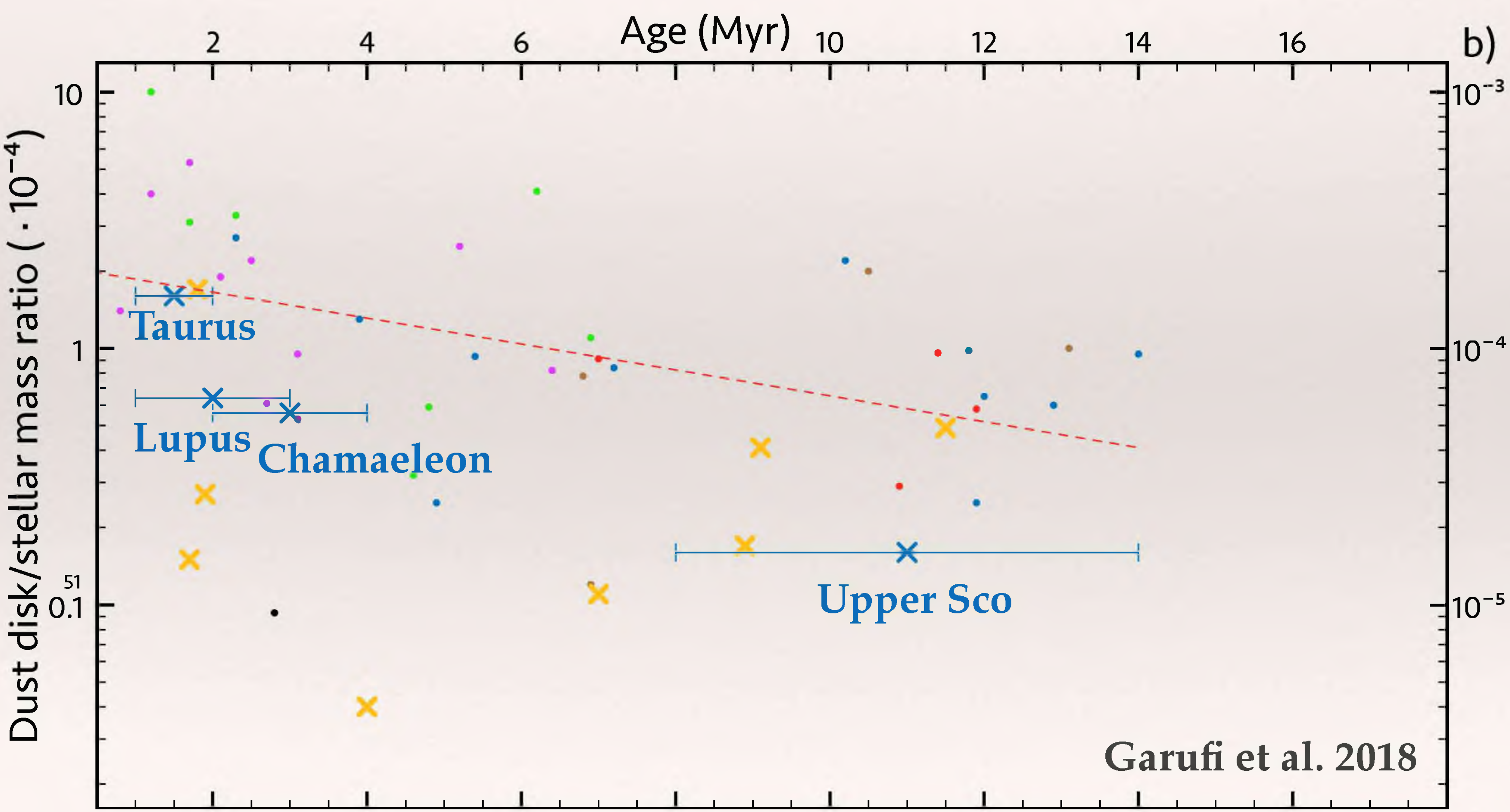

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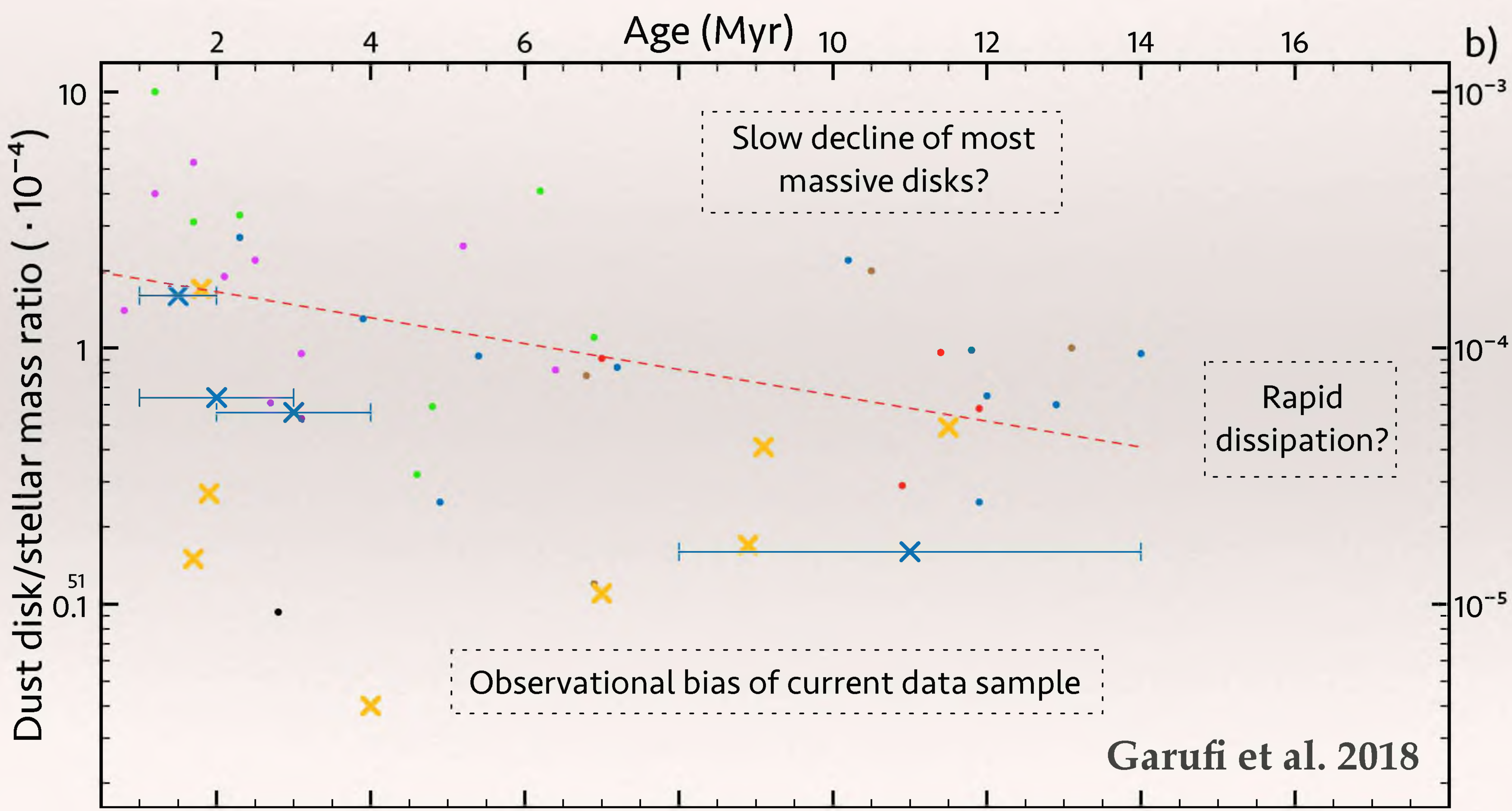
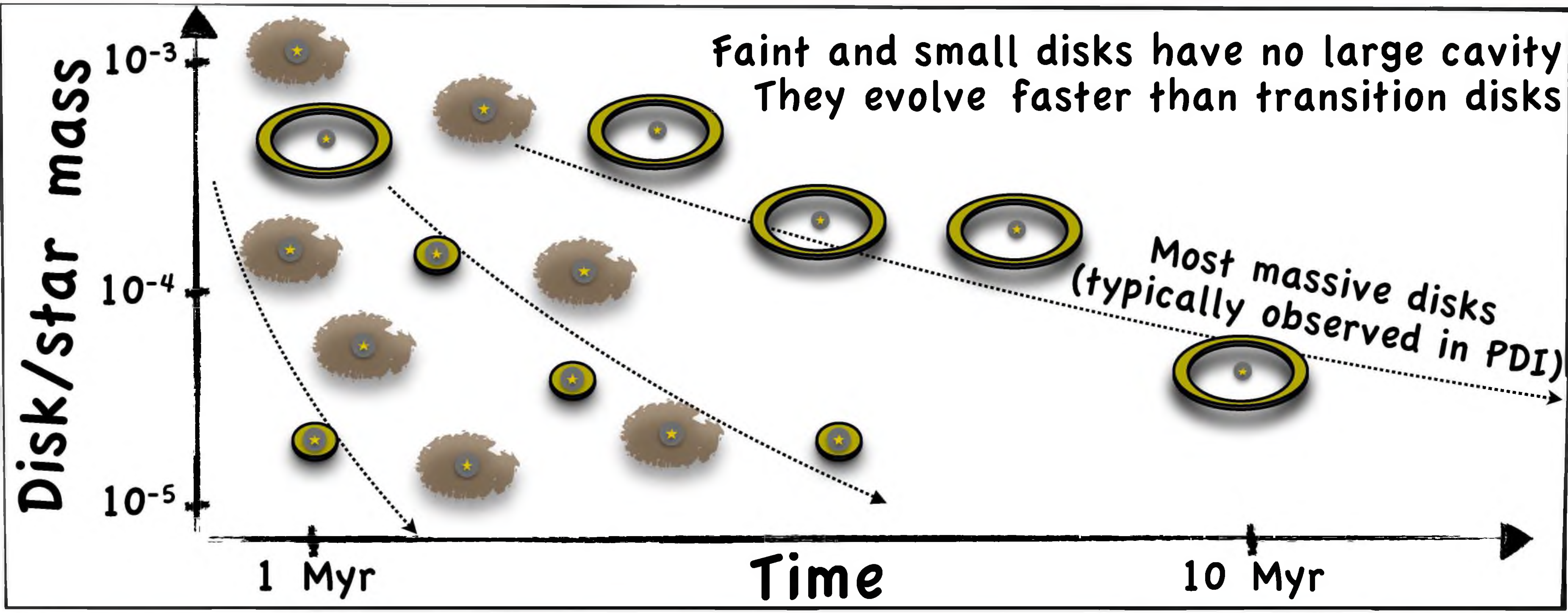


Disk masses

Conclusion #1:

We have mostly observed long-living, massive disks with a cavity (see also Owen 2015, Pinilla et al. 2018).



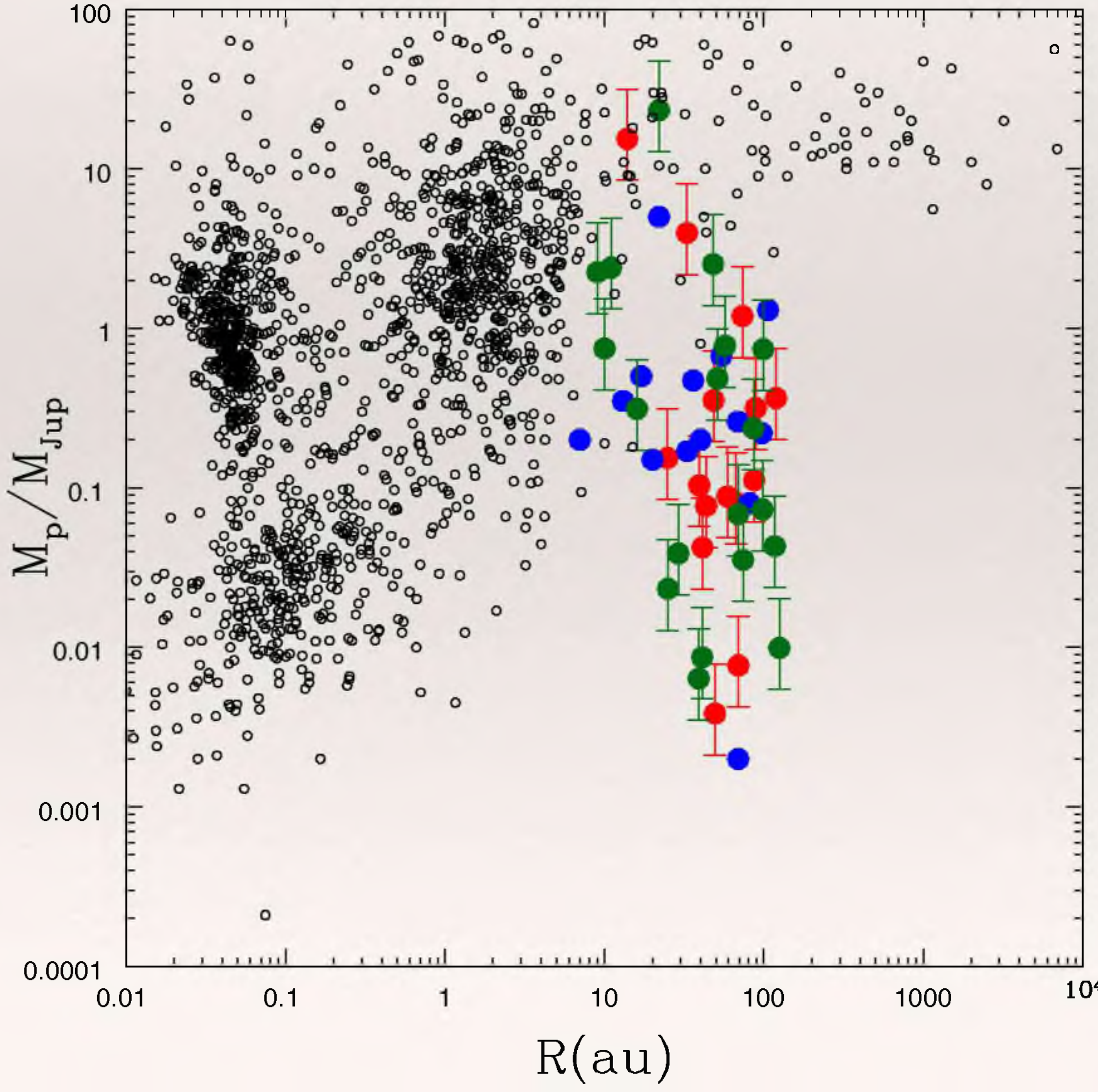
Garufi et al. 2018

Disk (and planet) masses

Framework:

Disks at this stage (1-10 Myr) may not be massive enough to form giant planets (Manara et al. 2018).

Planets responsible for the observed sub-structures may have escaped our searching campaigns.

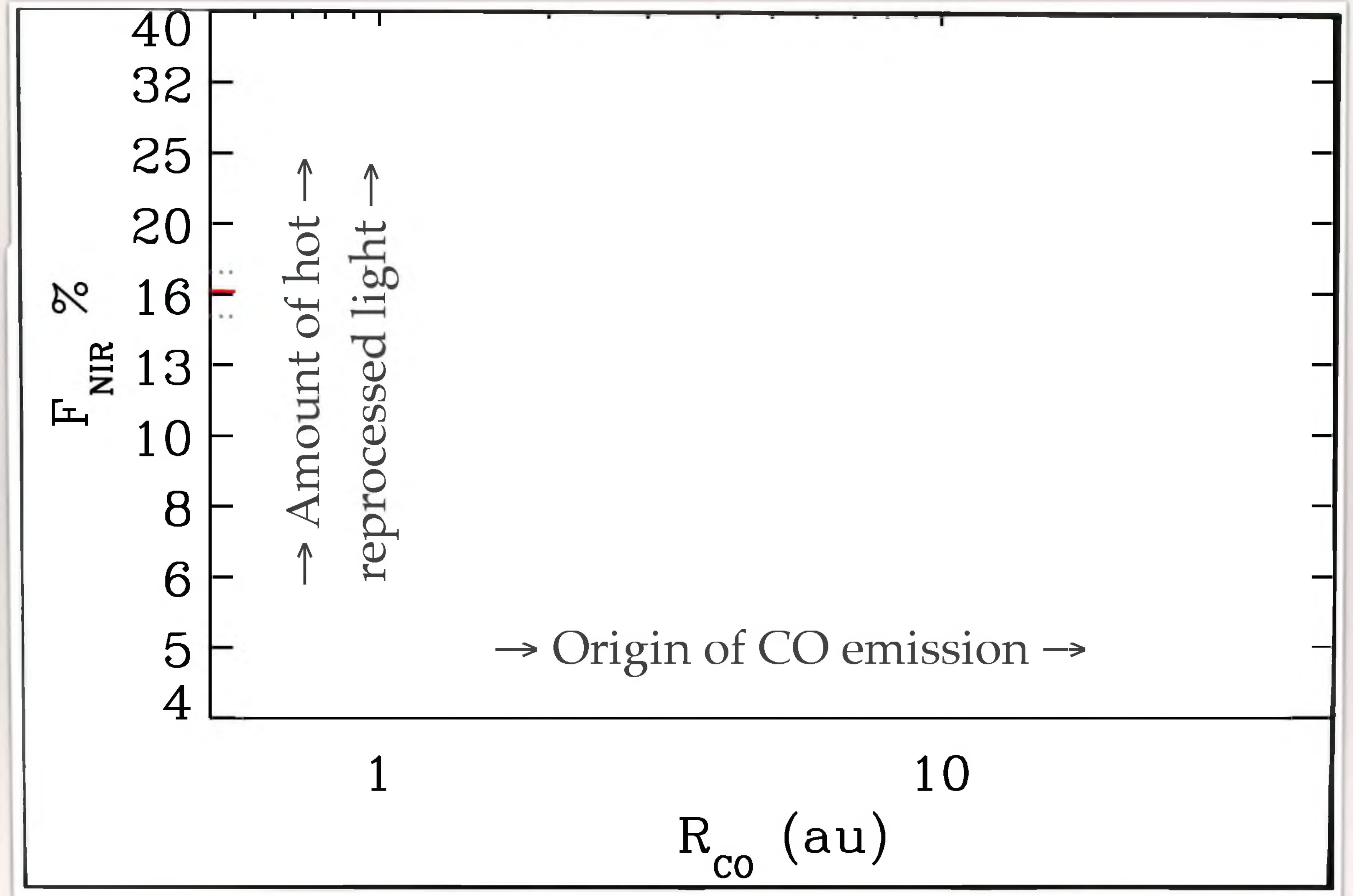


Lodato et al. 2019

Within the disk cavity

Fact #4:

Another observational dichotomy is among the transition disks (Group I).



Banzatti et al. 2018

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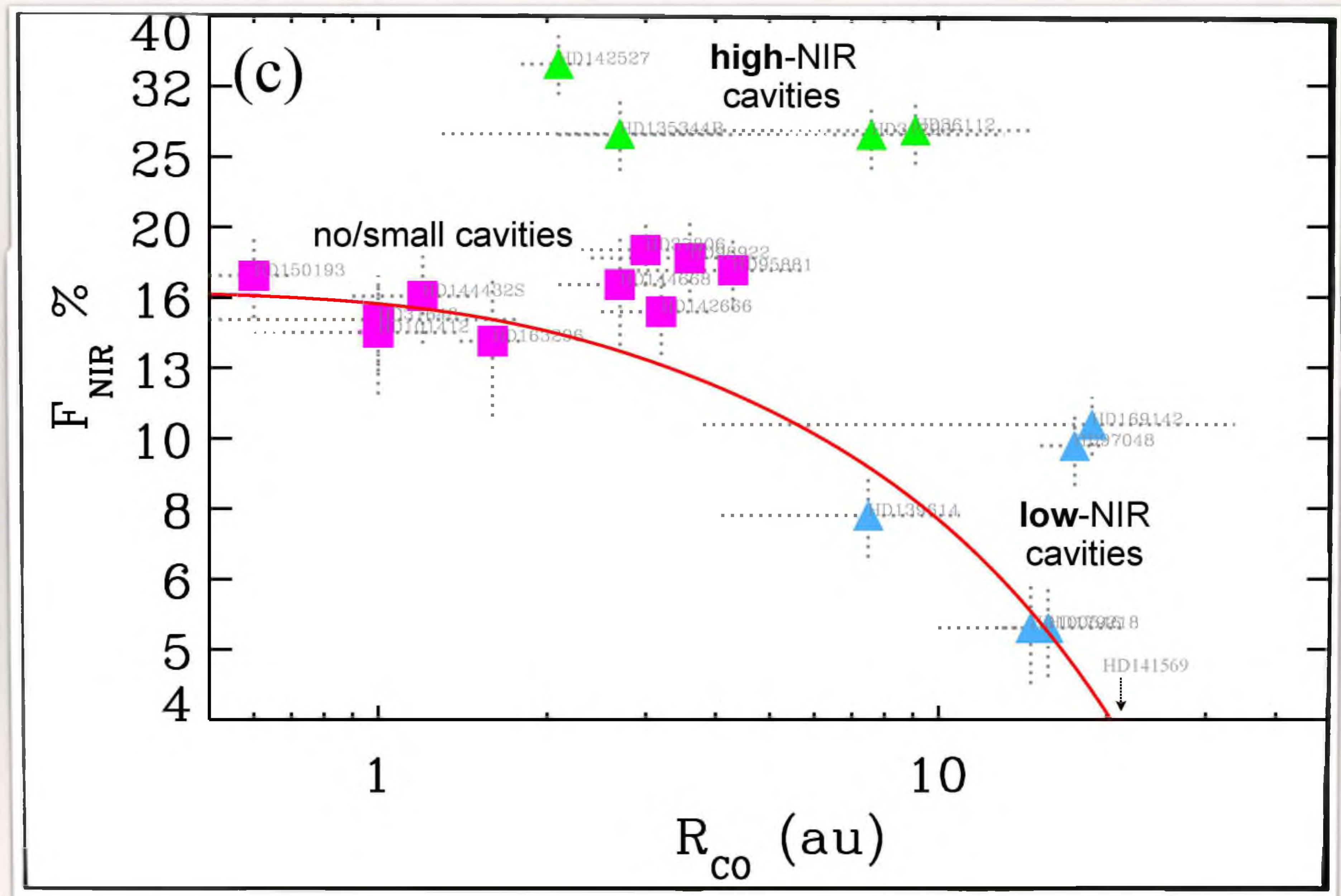

Banzatti et al. 2018

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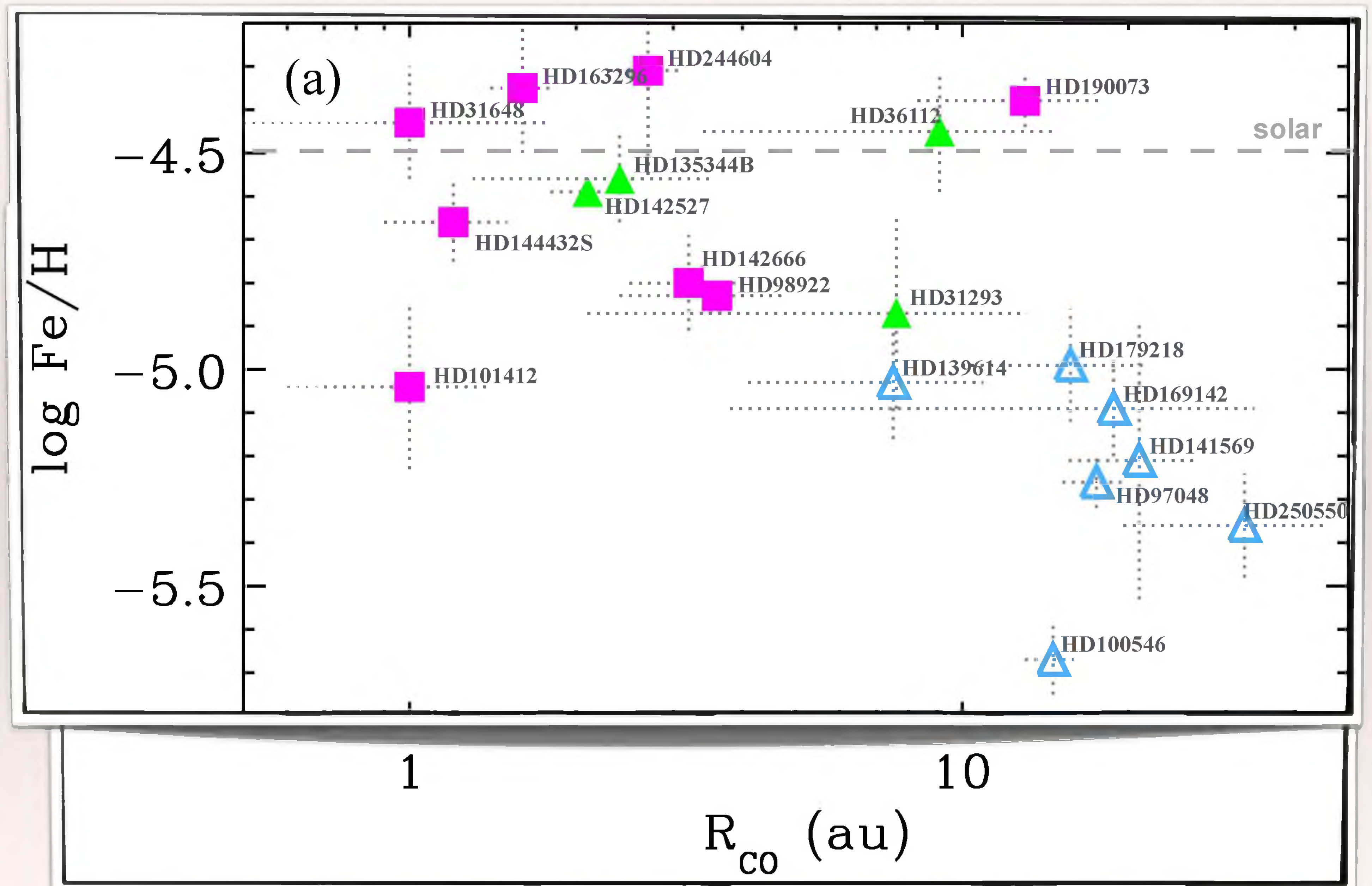


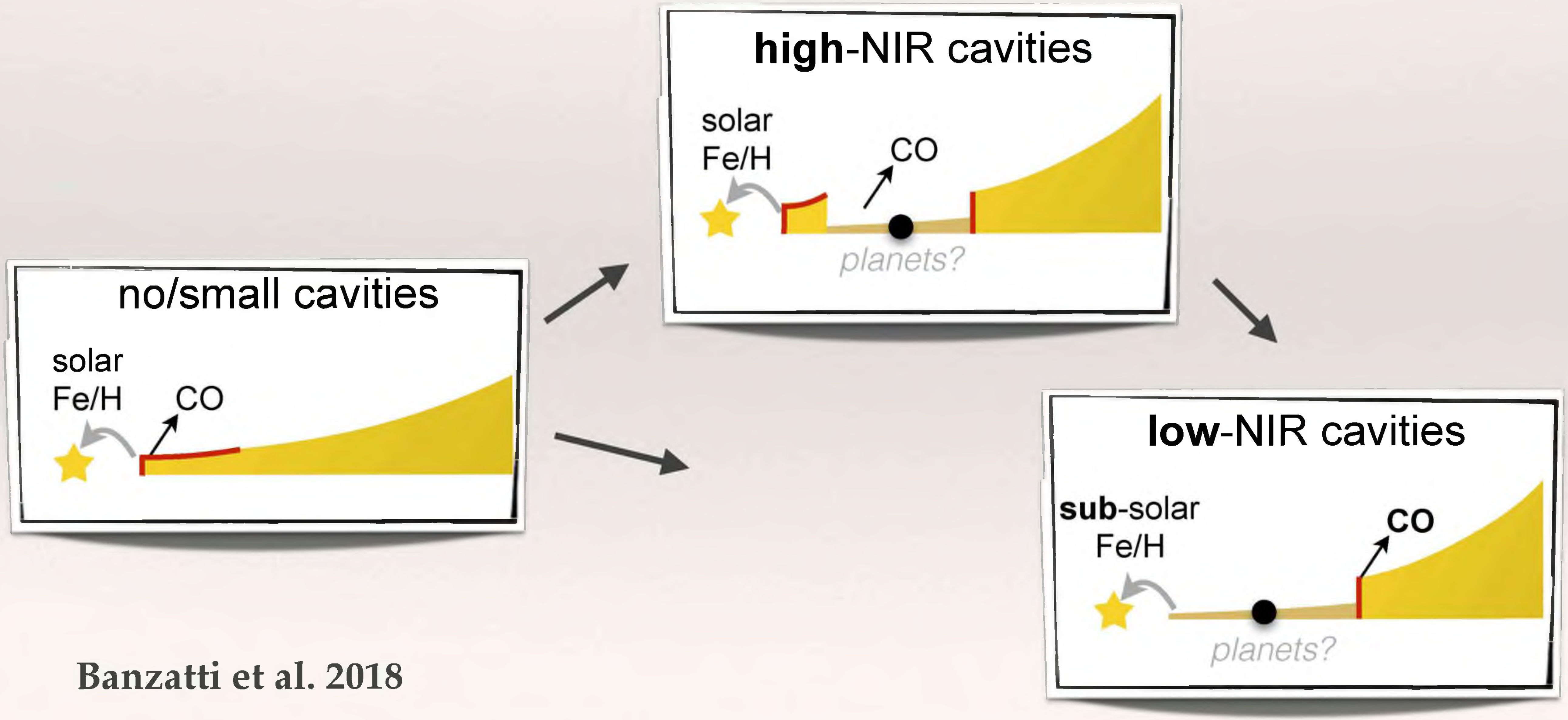
Banzatti et al. 2018 (see also Kama et al. 2015)

Within the disk cavity

Conclusion #2:

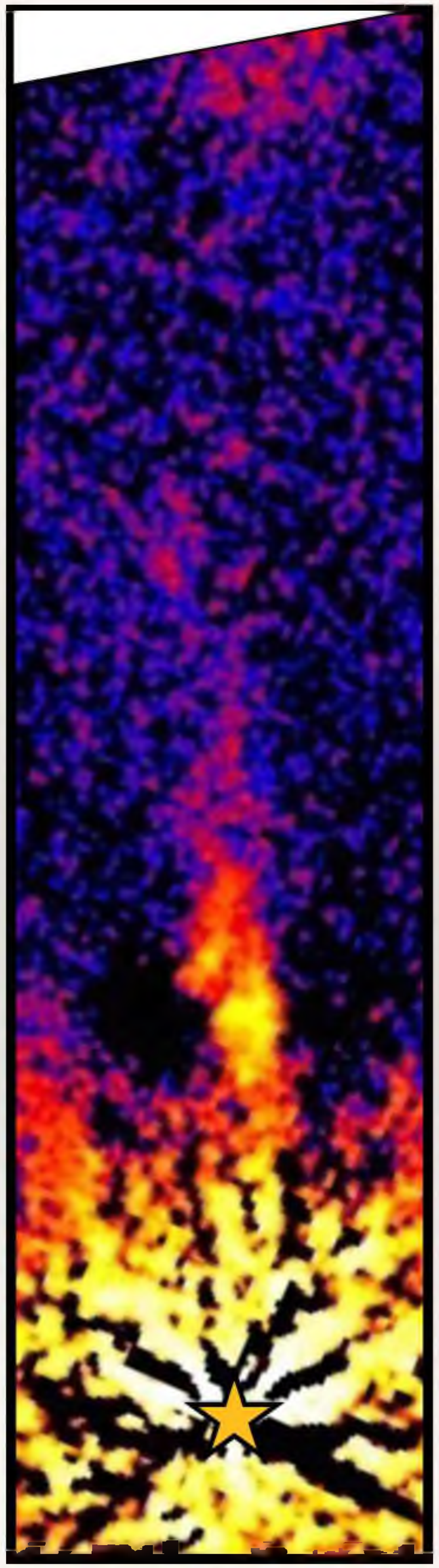
There are two families of disk cavities.

Transition disks have depleted/increased NIR and low/solar abundance of refractory elements, with CO emission from large/small radii.



Banzatti et al. 2018

Within the disk cavity



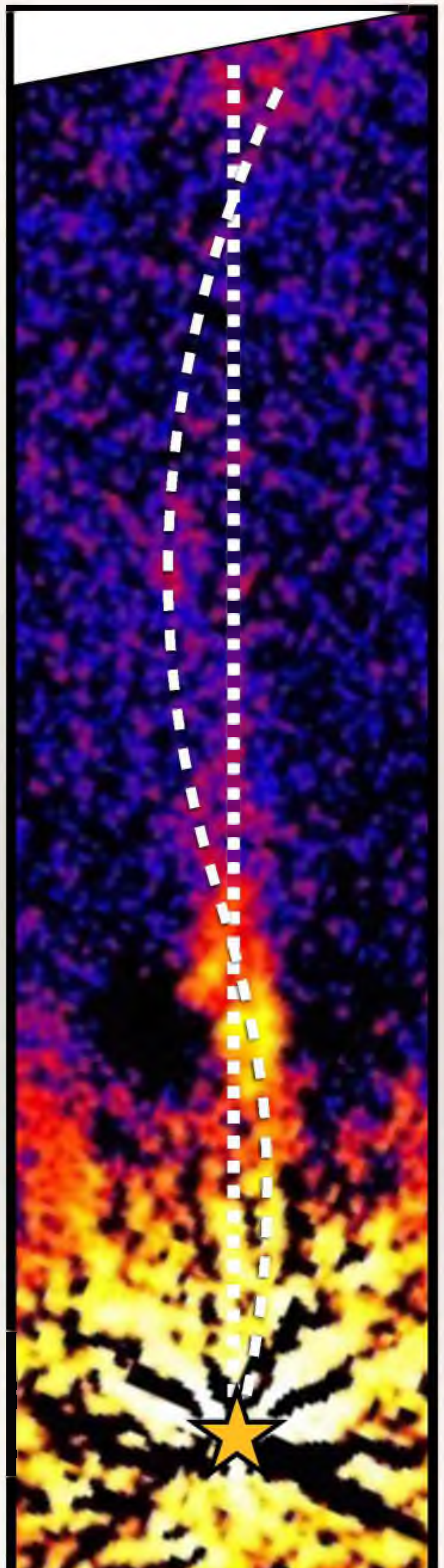
Fact #5:

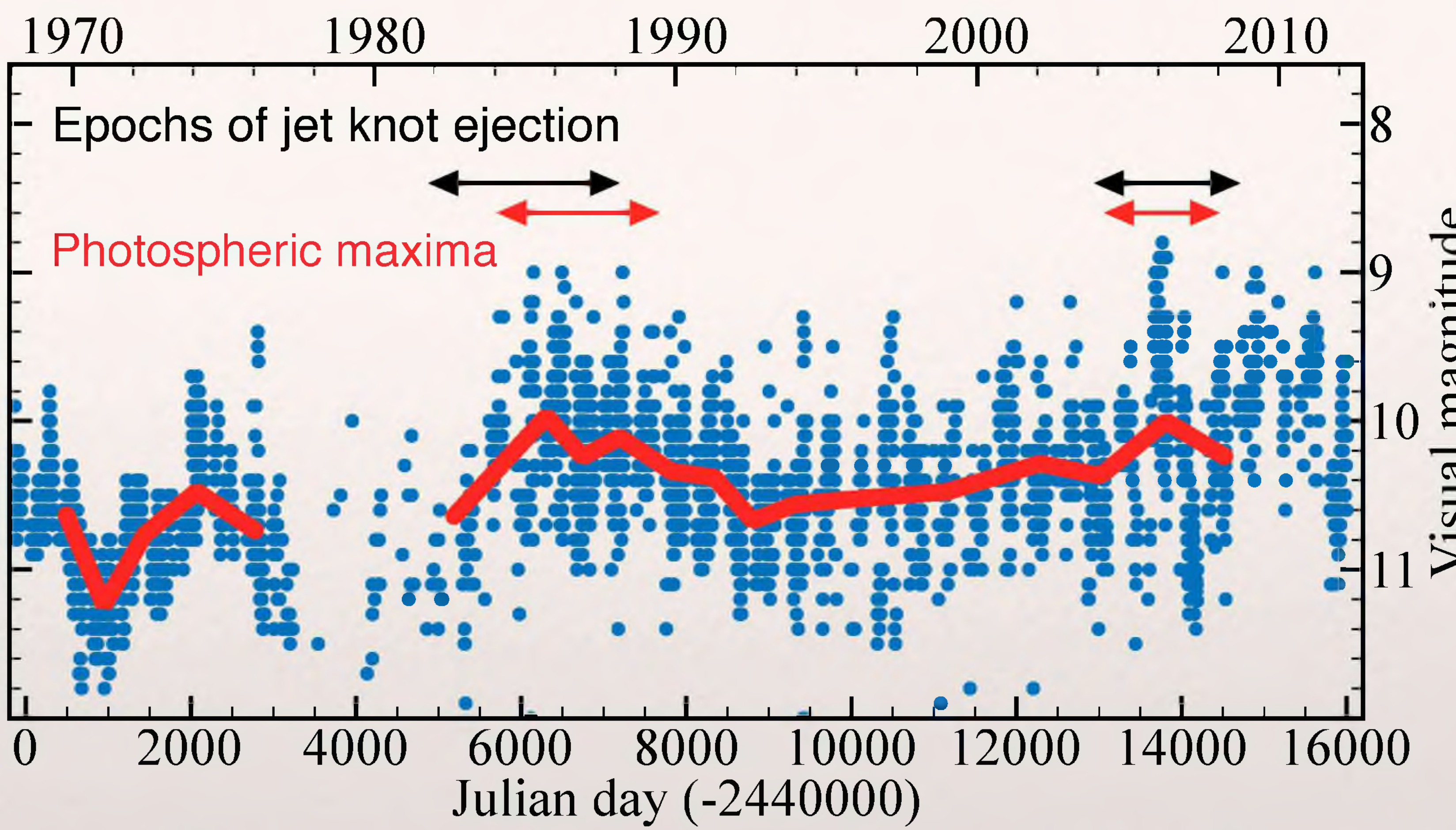
The morphology of optical jets bears record of the stellar physics and geometry of the inner disk.

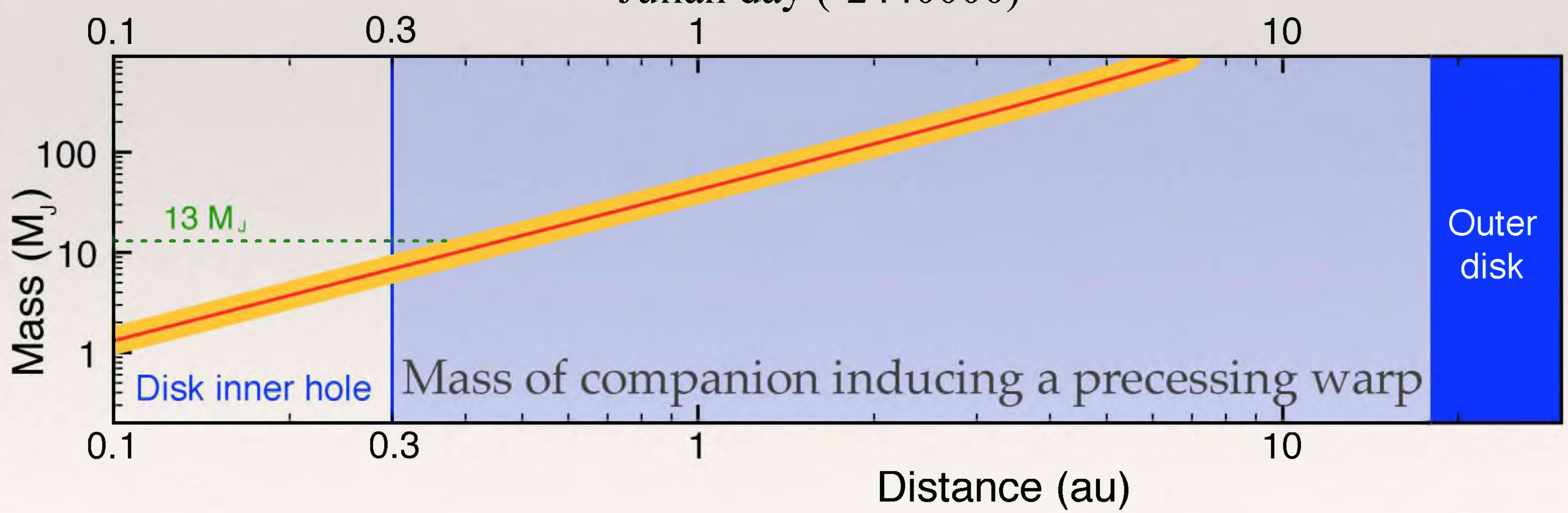
Jet knots → Increased accretion/ejection events.
Jet wiggling → Disk warp, misalignment?

Garufi et al. 2019

Within the disk cavity





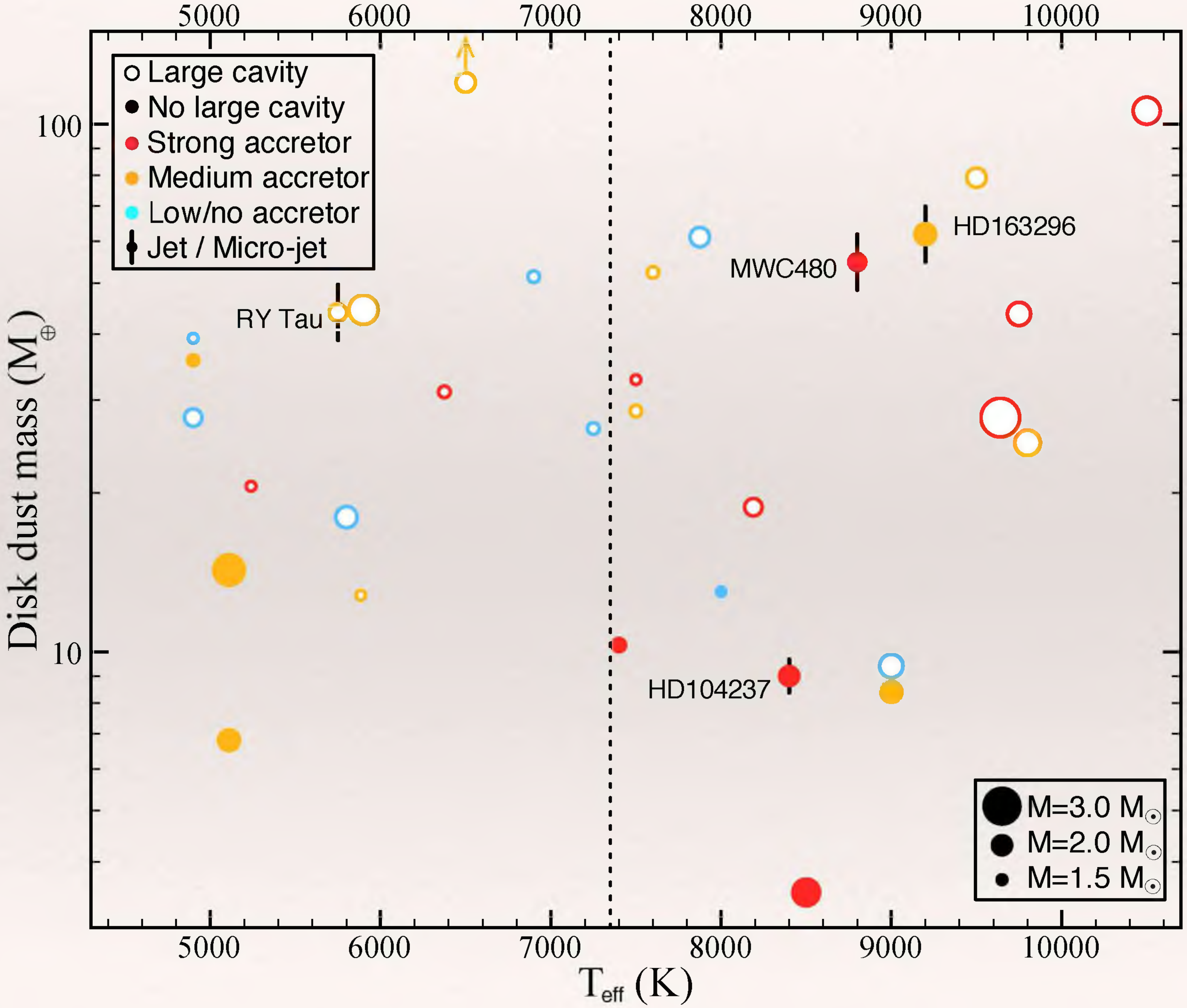


Garufi et al. 2019 (following Zhu 2019)

Within the disk cavity

Conclusion #3:

The brightness and morphology of jets depend on the inner disk properties.



Garufi et al. 2019

Spirals & Shadows

Fact #6:

Spirals are detected in ~10% of Herbig stars. Never detected in TTSs.

Spirals & Shadows

Fact #6 and #7:

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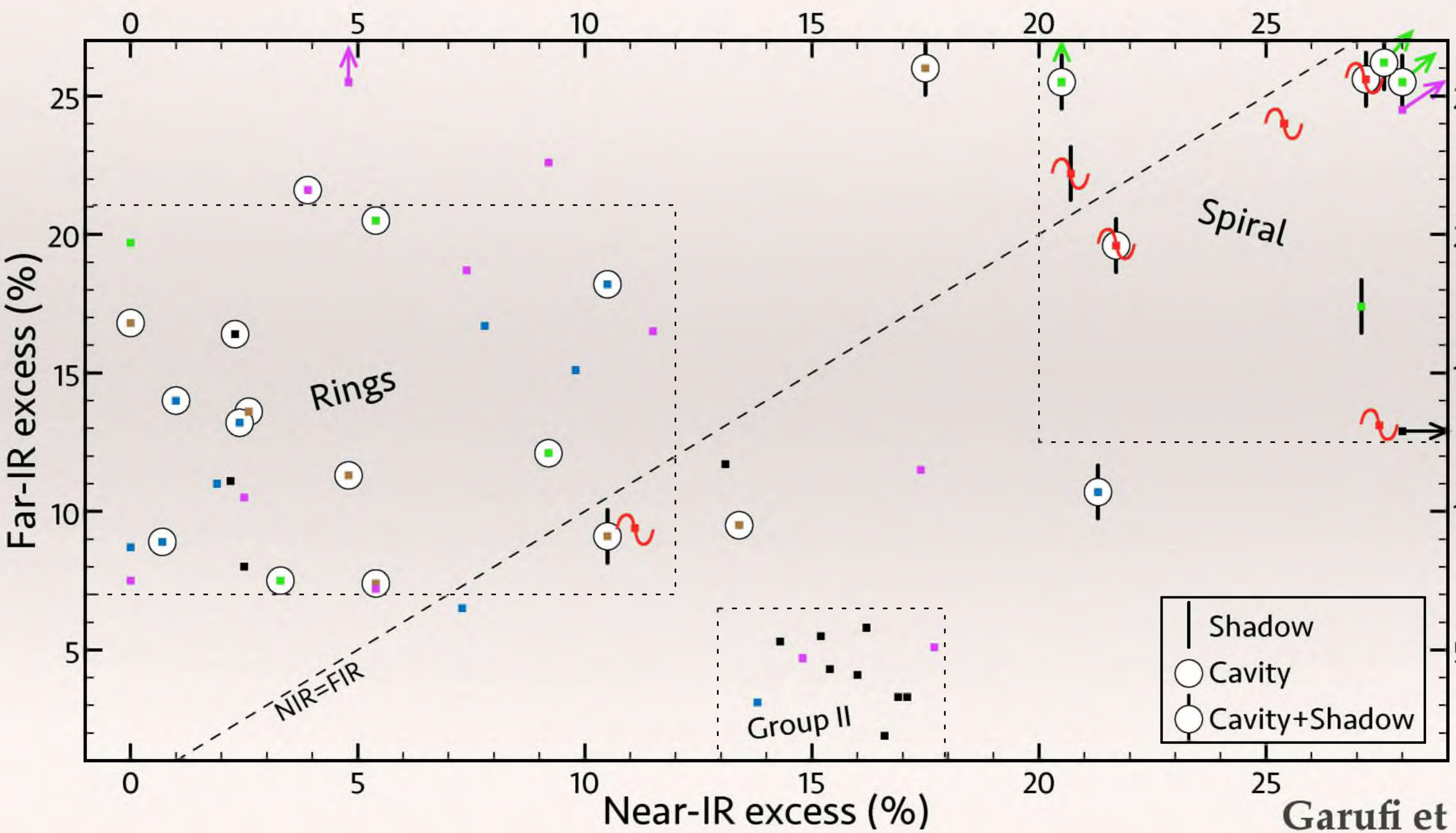
Both spirals and shadows are associated with a high NIR.



Garufi et al. 2018

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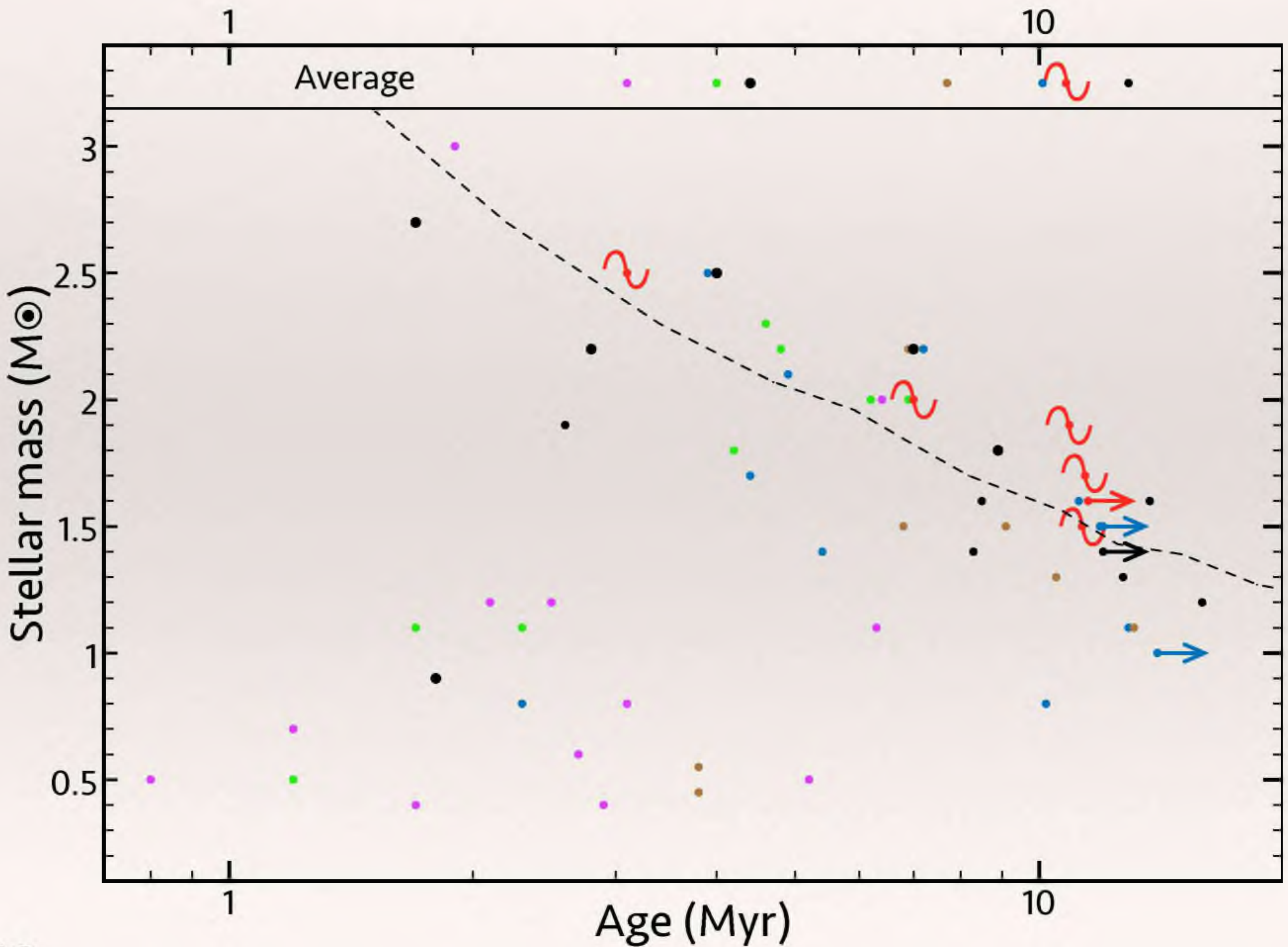

Garufi et al. 2018

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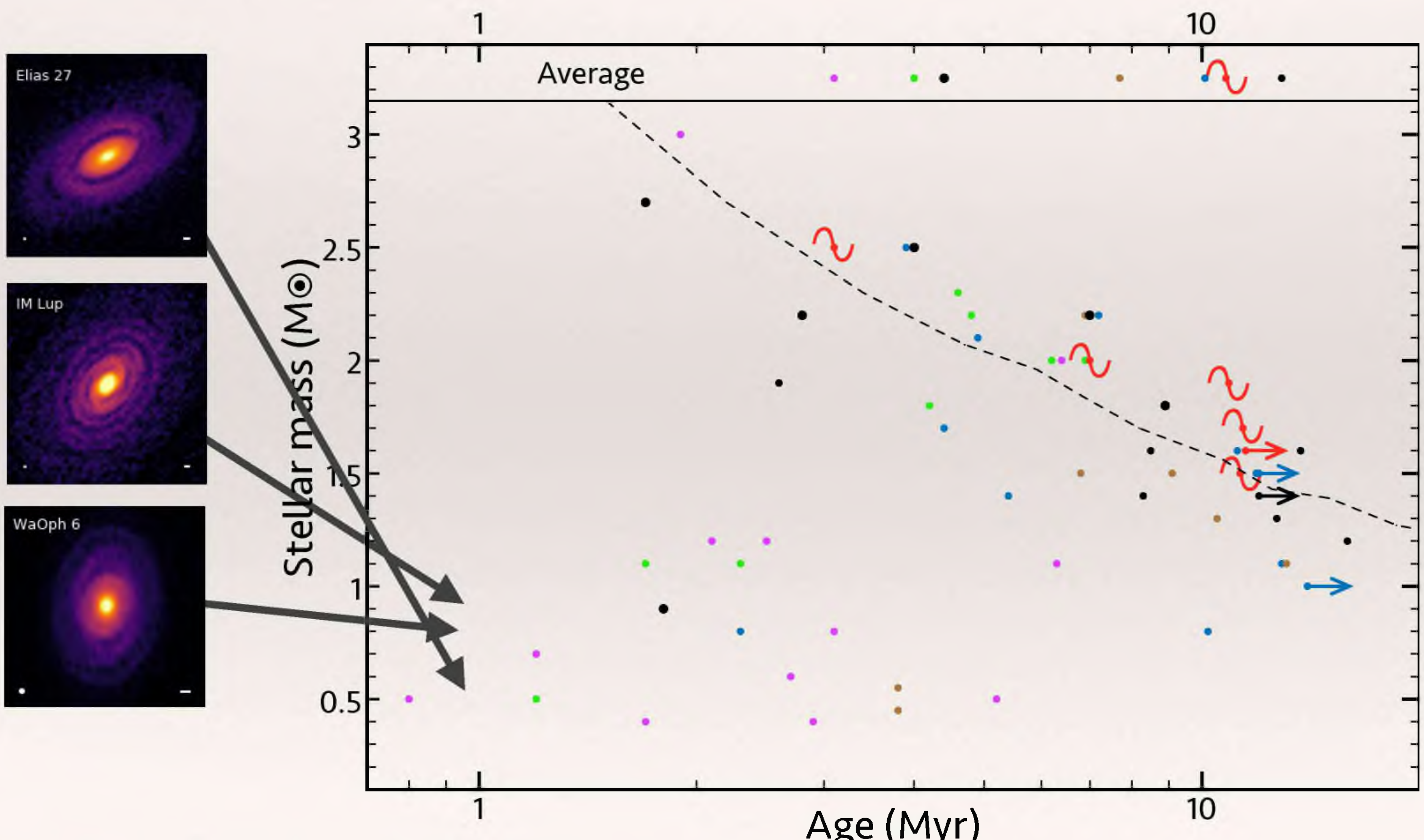

Garufi et al. 2018 (vs DSHARP)

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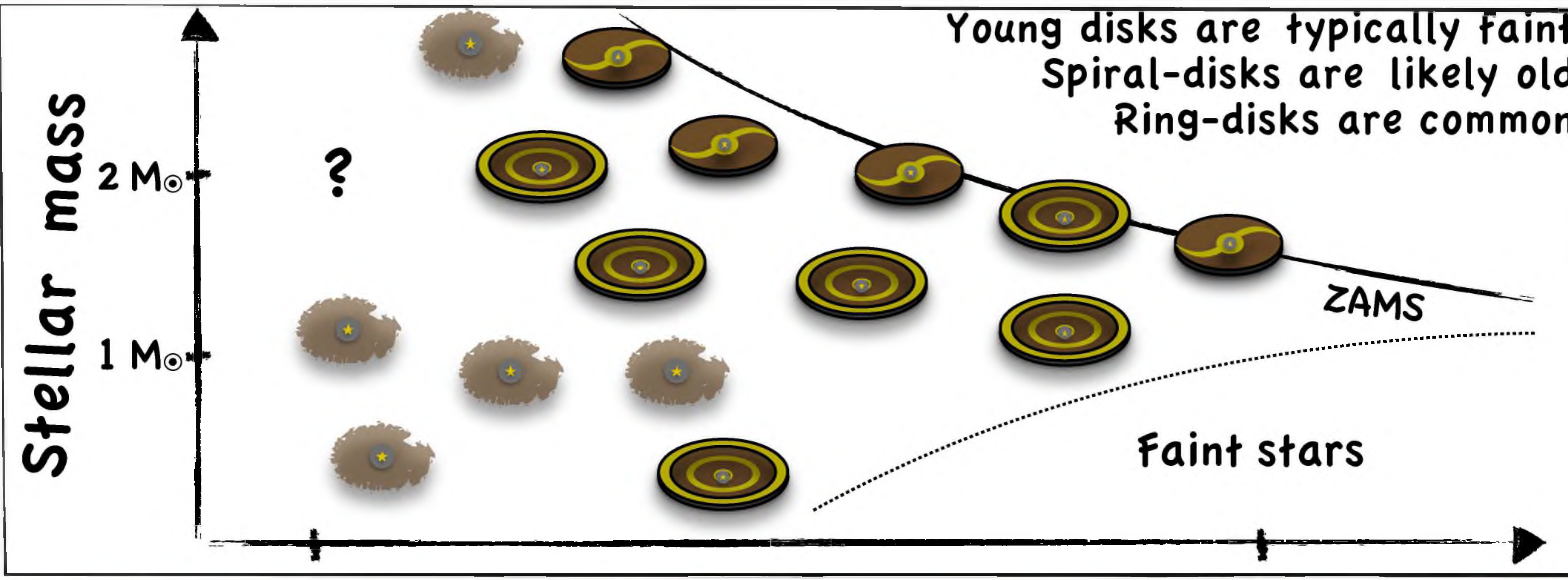
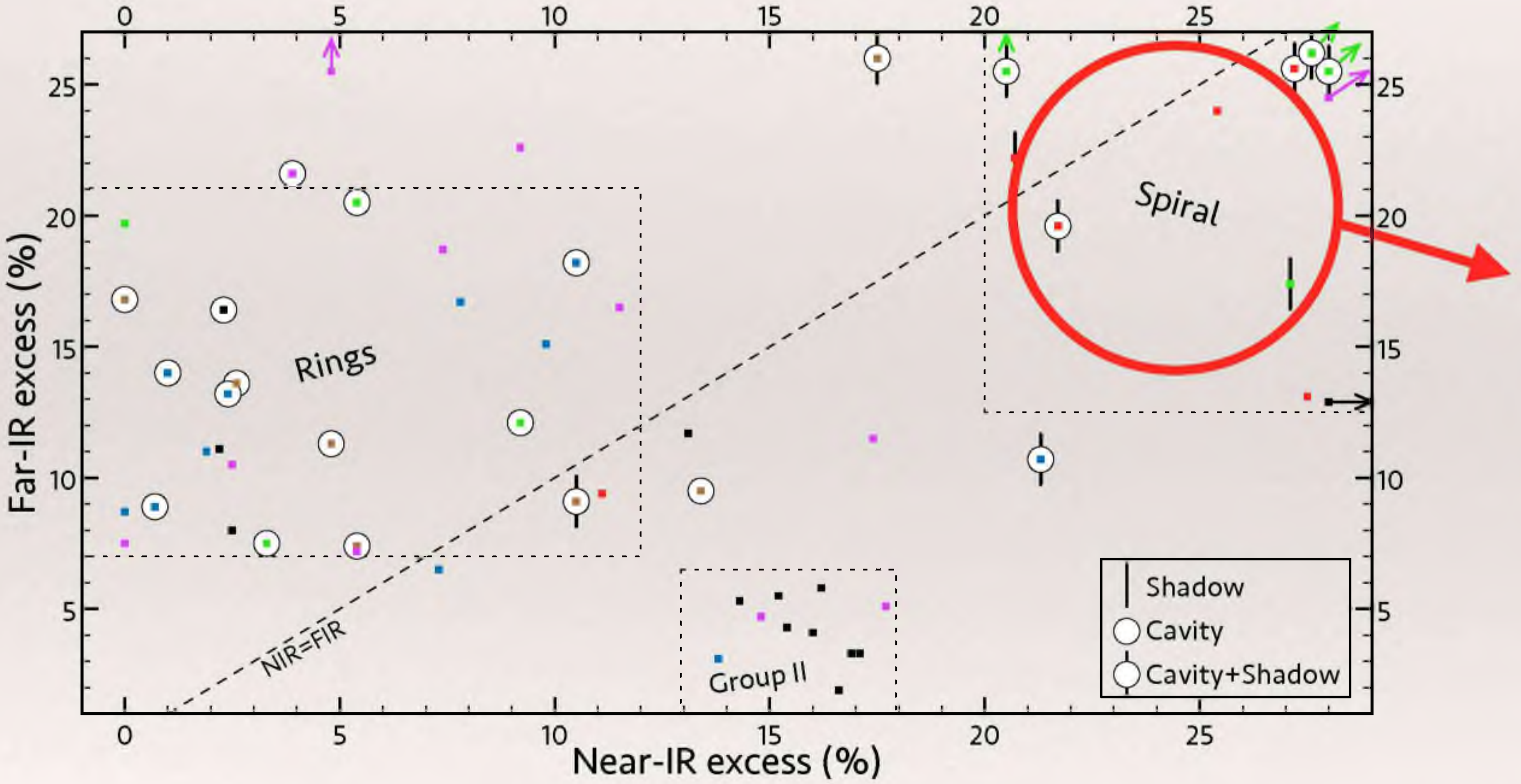


Garufi et al. 2018

Spirals & Shadows

Conclusion #4:

The link between high NIR, shadows, and spirals could be a misaligned companion that stirs up the inner disk, induce a warp, and excite spirals.



Garufi et al. 2018

Zhu 2019

Spirals & Shadows

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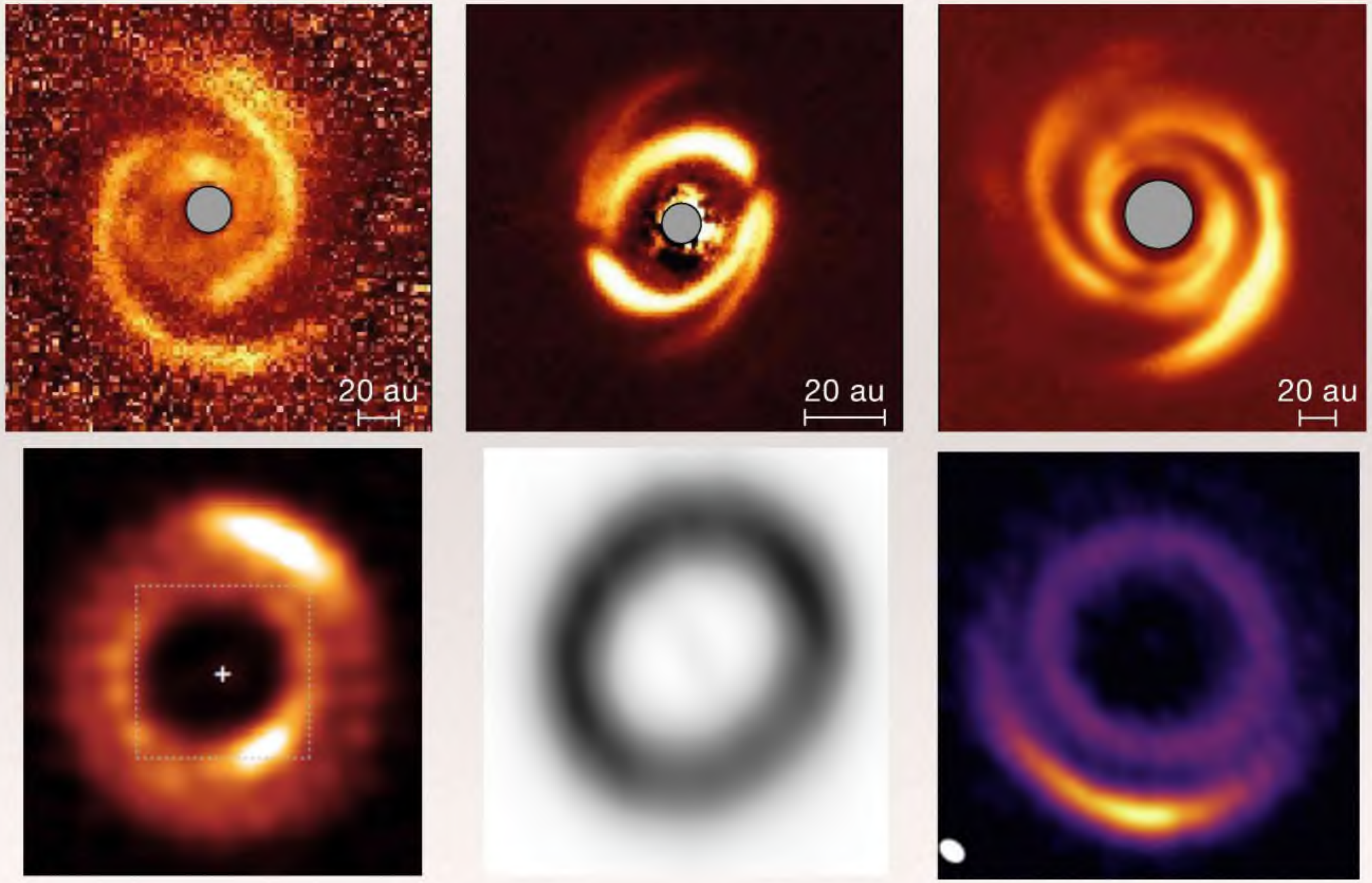
But what about the relative azimuthal asymmetries in the mm?



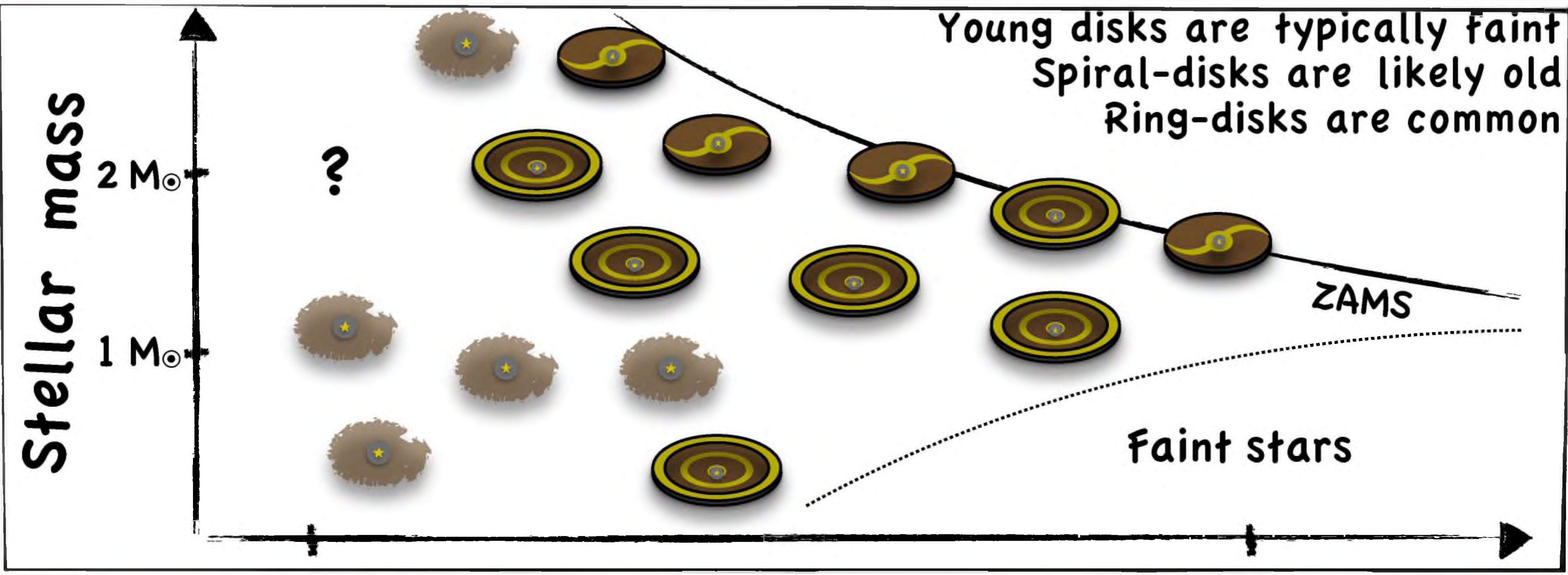
Benisty et al. 2015, 2017, Stolker et al. 2017, Boehler et al. 2018, van der Plas et al. 2019, Cazzoletti et al. 2018

Imaging stars at younger (st)ages

Fact #7:

Young disks (Class I) are nearly absent from this analysis.

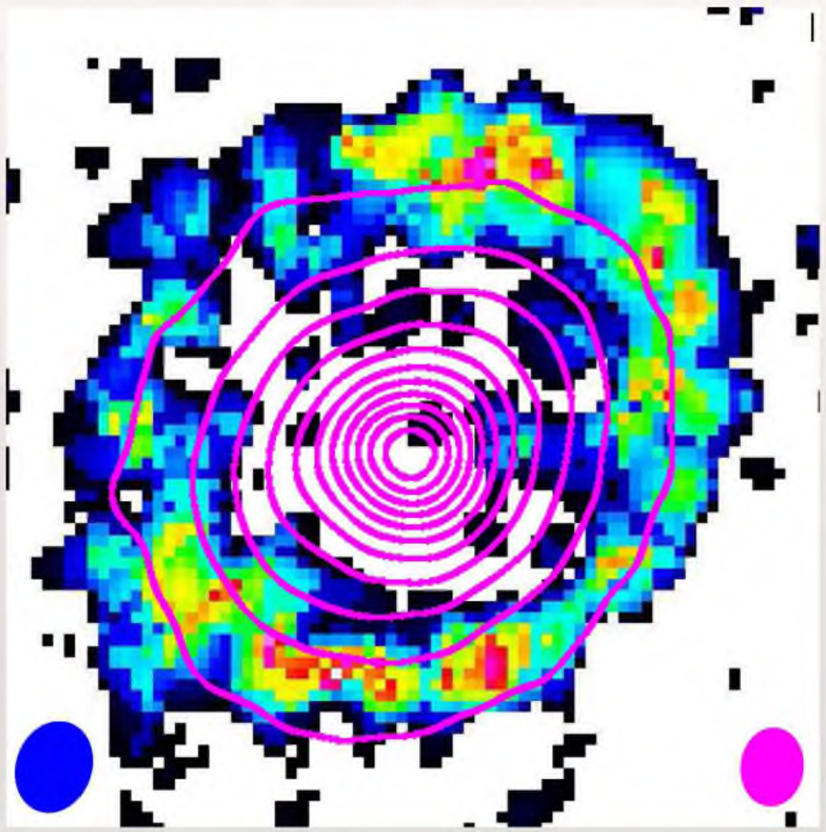
They are hardly accessible in the NIR, and mostly ignored by ALMA.



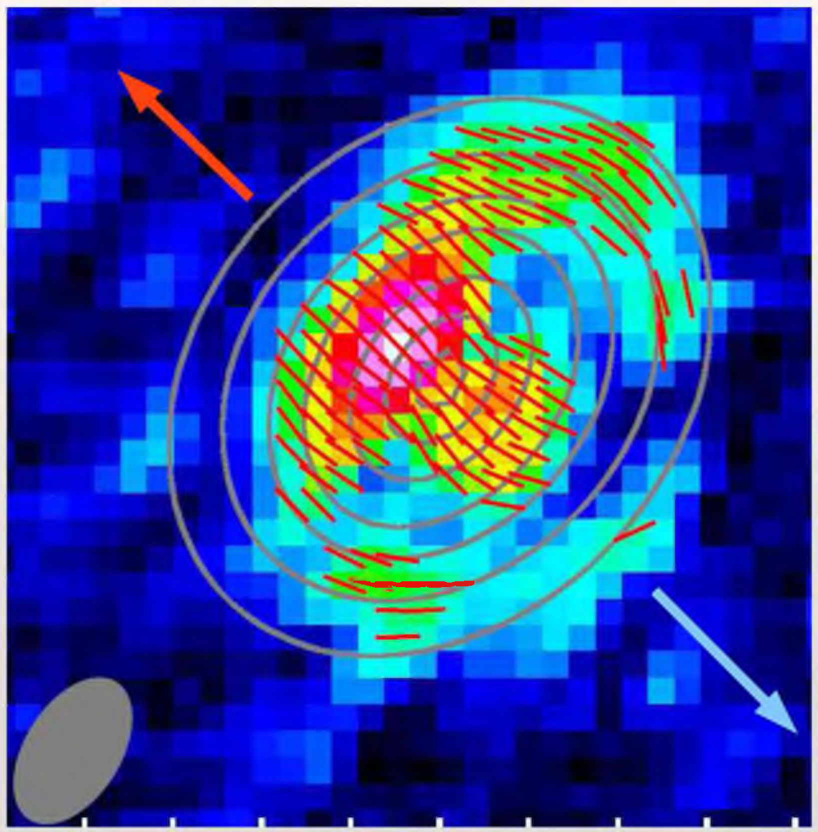
Garufi et al. 2018

Imaging stars at younger (st)ages

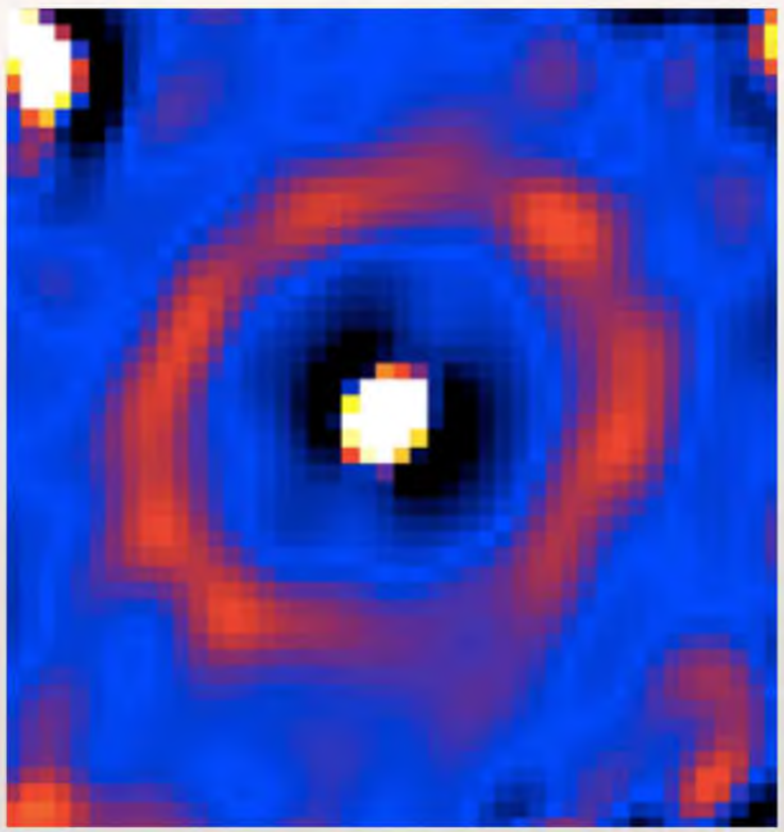
With ALMA, we have access to younger, embedded sources.



Gas
(H_2CO)
Podio et al. 2019



Continuum
(polarization)
Bacciotti et al. 2018

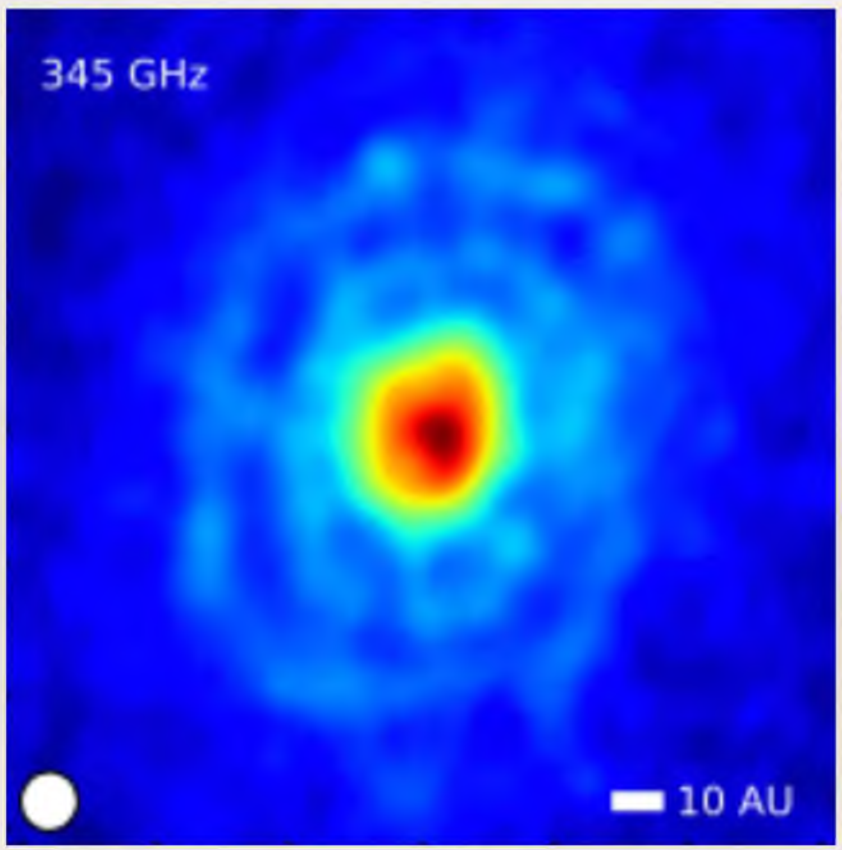


Continuum
(unsharp masking)
Podio et al. in prep.

Imaging stars at younger (st)ages

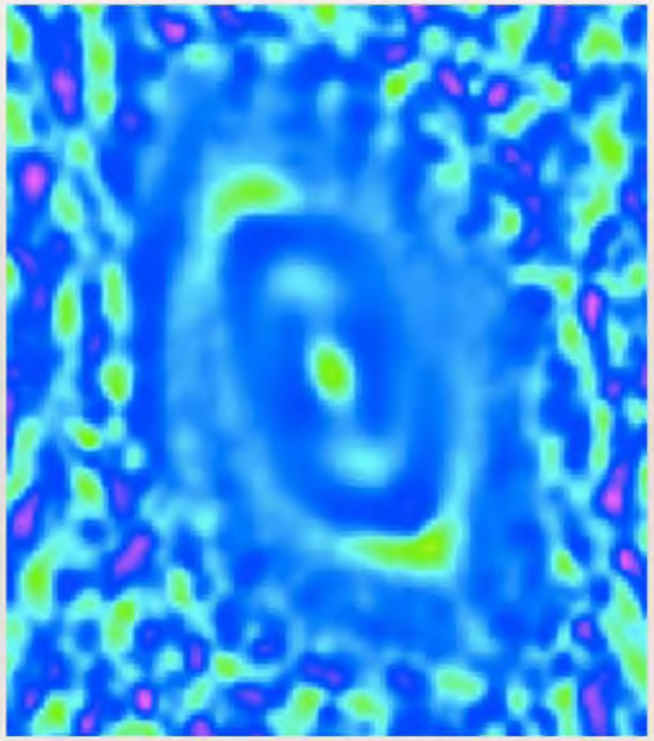
Sub-structures in both the dust and the gas seem to be present very early in the disk evolution.

Are planets formed soon after the star formation?

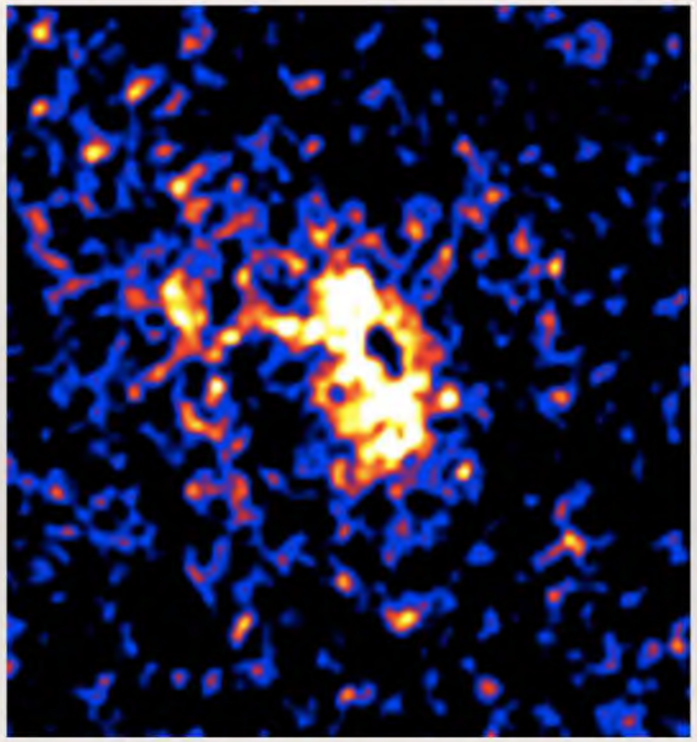


Continuum

Sheehan et al. 2018



Continuum



H_2CO

Garufi et al. in prep.

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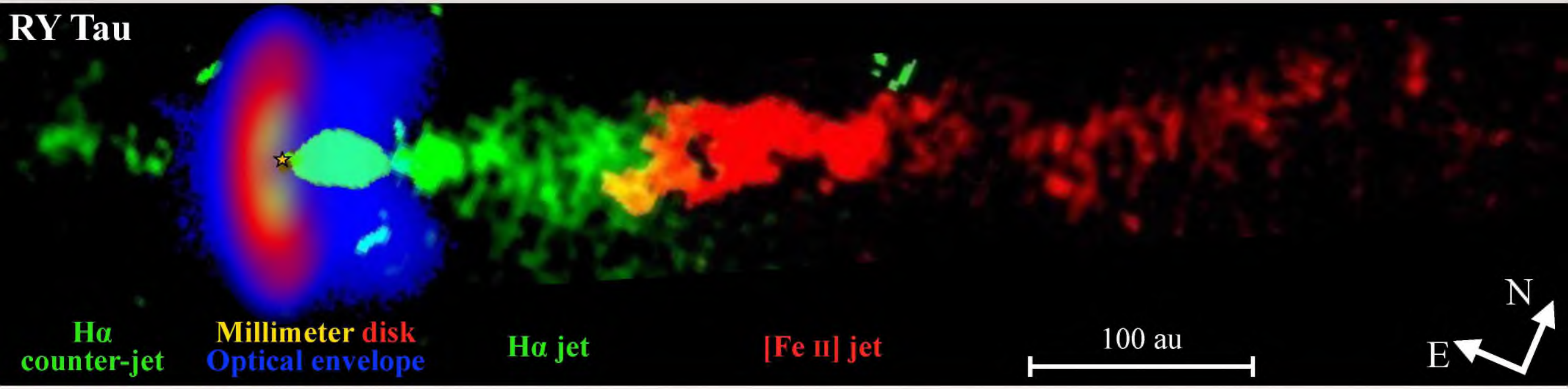
#2: There are two families of disk cavities, **high-NIR** and **low-NIR**. The gas/dust interplay from the two is clearly different.

#3: The inner disk morphology leaves an imprint on the optical **jet**. Wiggling is a possible evidence of the presence of a disk **warp**.

#4: Spirals and **shadows** could be associated with misaligned **companions** responsible for a puffed-up and warped inner disk portion.



The system of RY Tau, Garufi et al. 2019 (+ Long et al. 2018b)