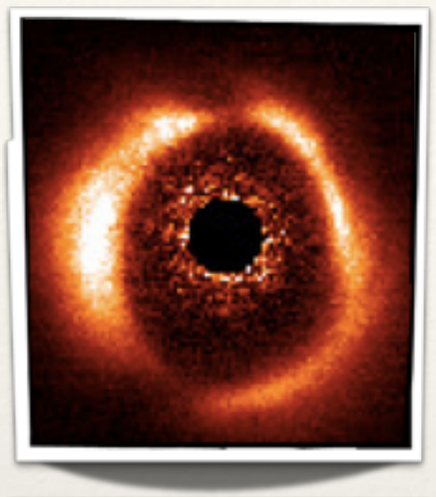
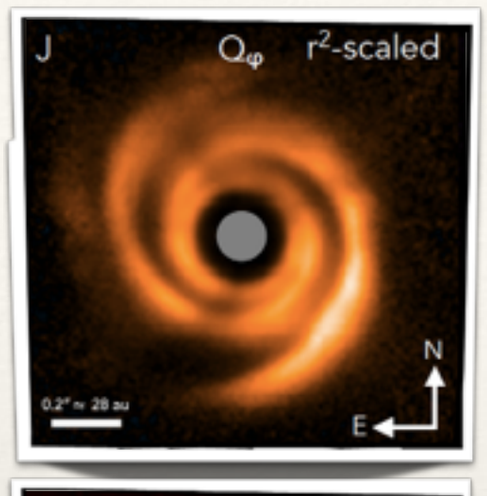
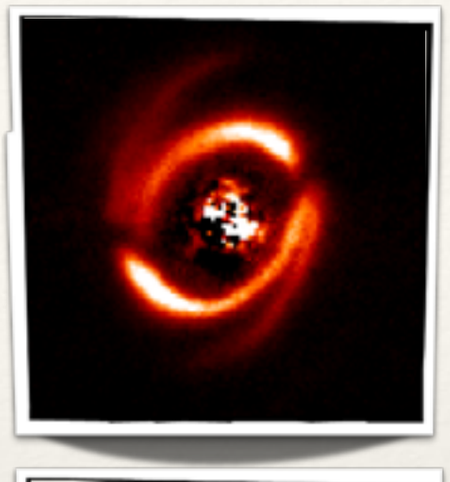
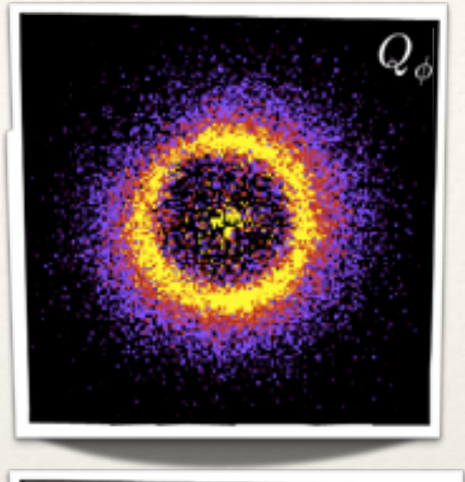
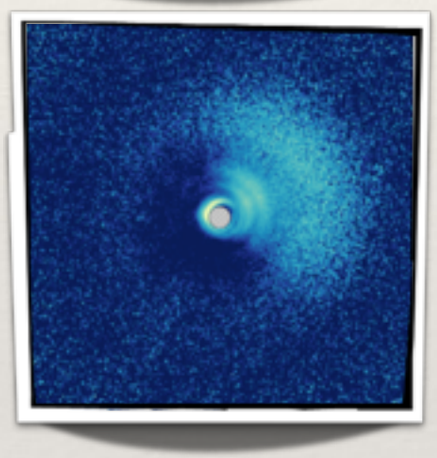
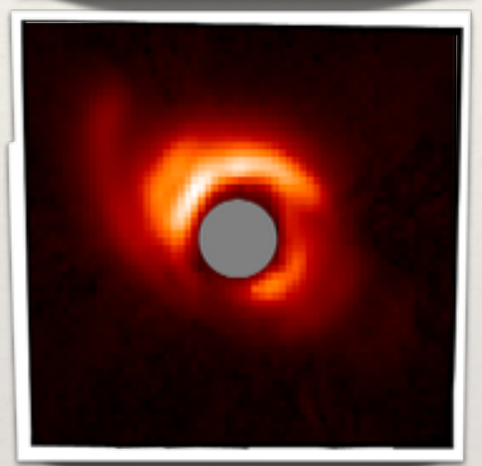
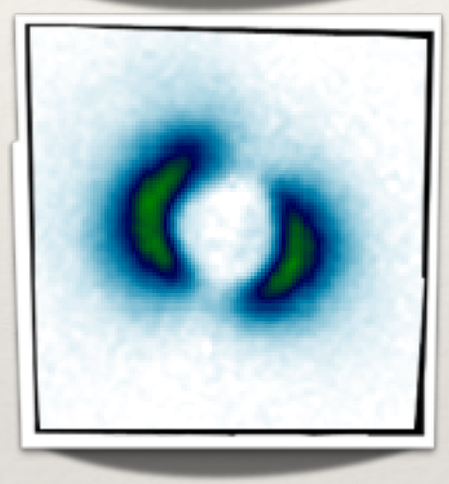
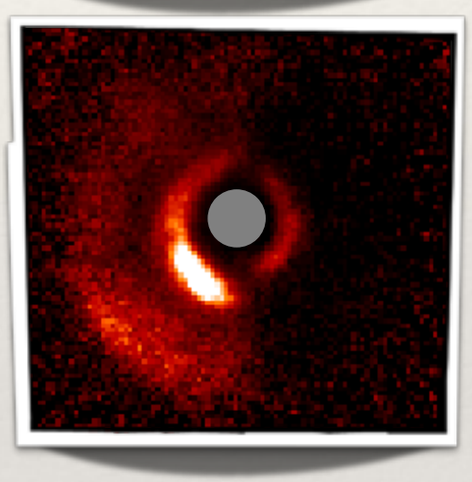



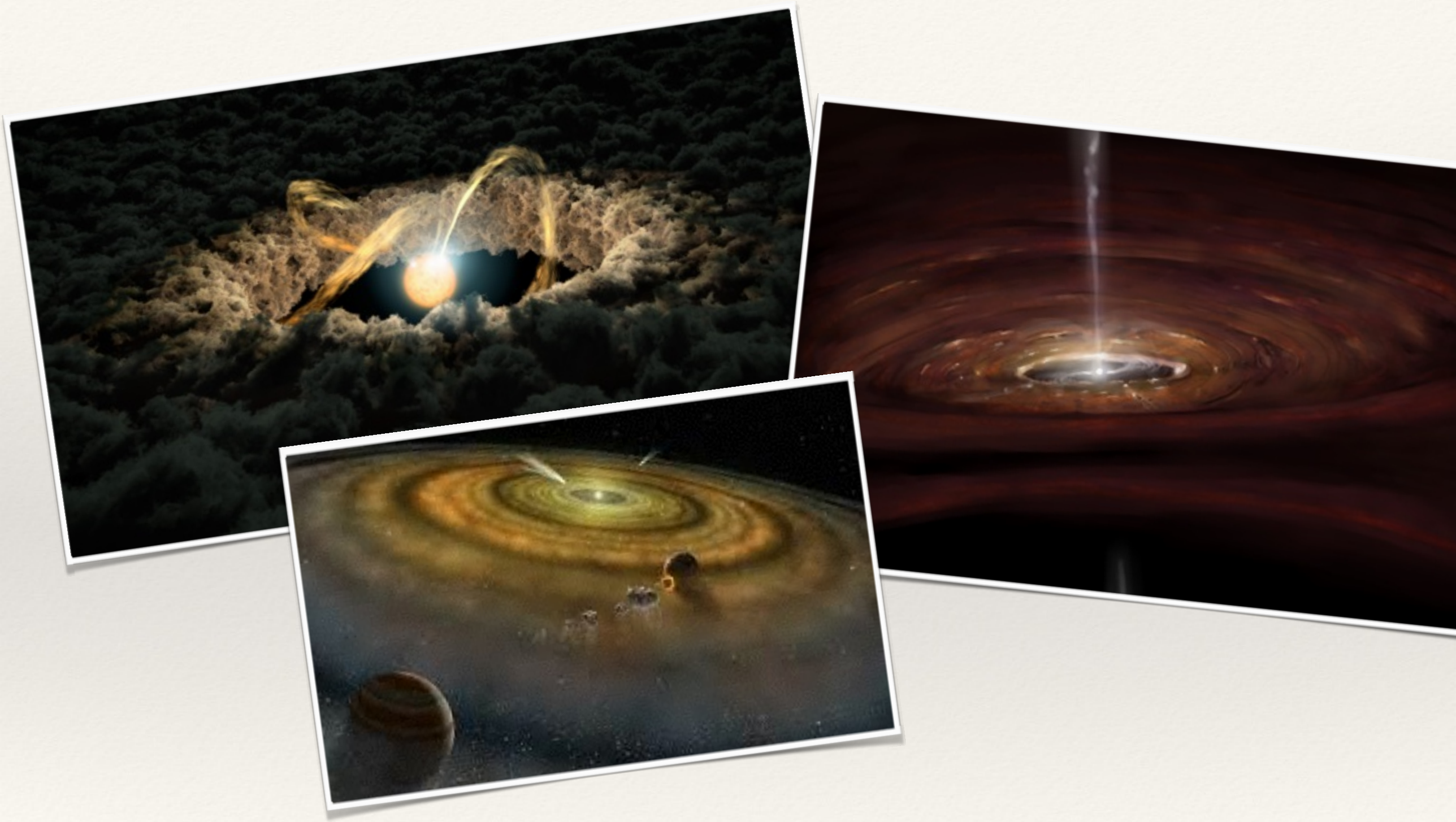





The UX Ori type stars and related topics - Wednesday, October 2, 2019

SHADOWS ON THE OUTER DISK AS MAPS OF THE INNER DISK

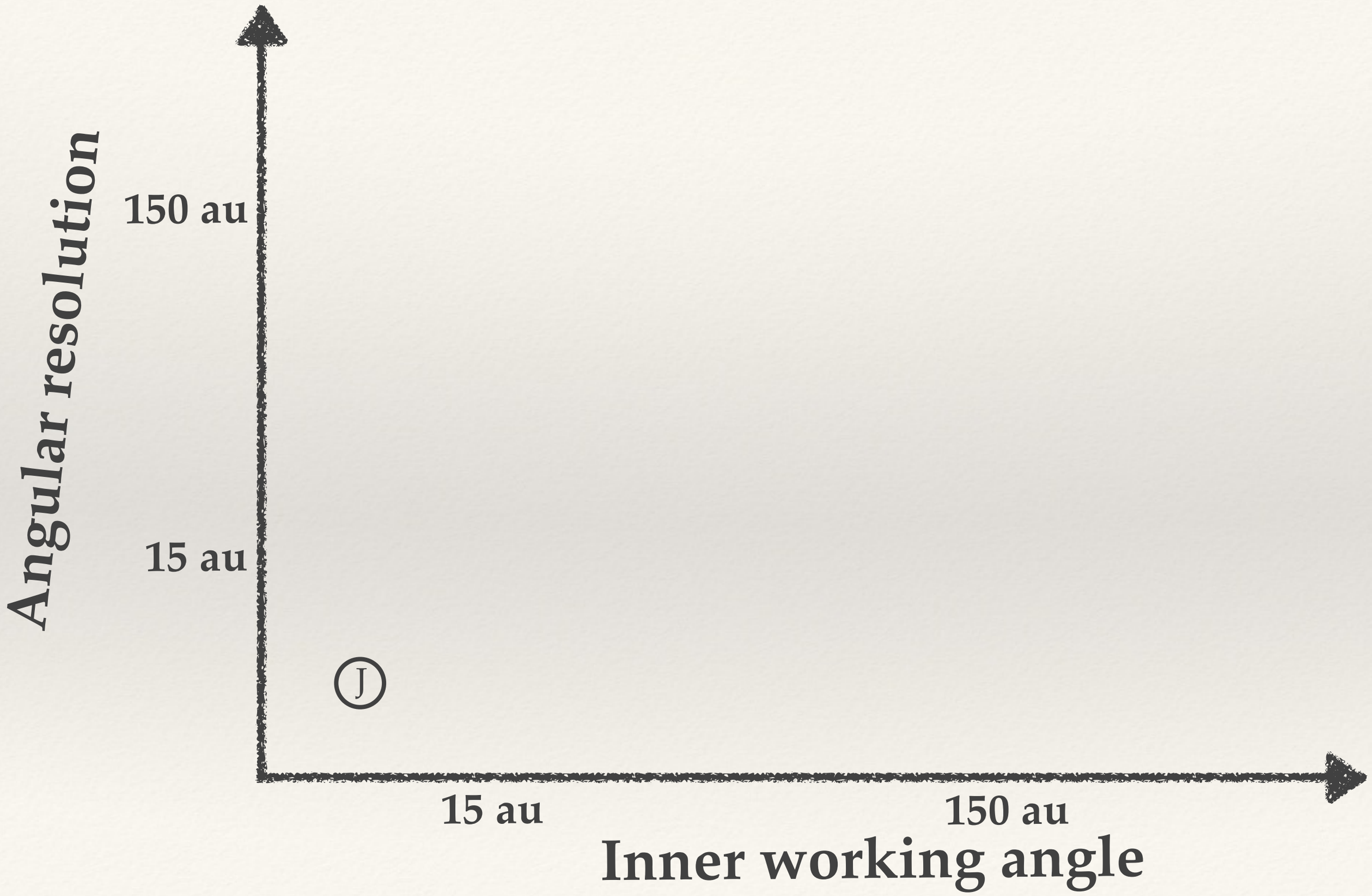
Antonio Garufi
OA Arcetri, INAF
with H. Avenhaus, F. Bacciotti, A. Banzatti, M. Benisty, C. Dominik, M. Kama, G. Meeus, L. Podio, P. Pinilla, S. Quanz, SPHERE/GTO

High-resolution disk imaging

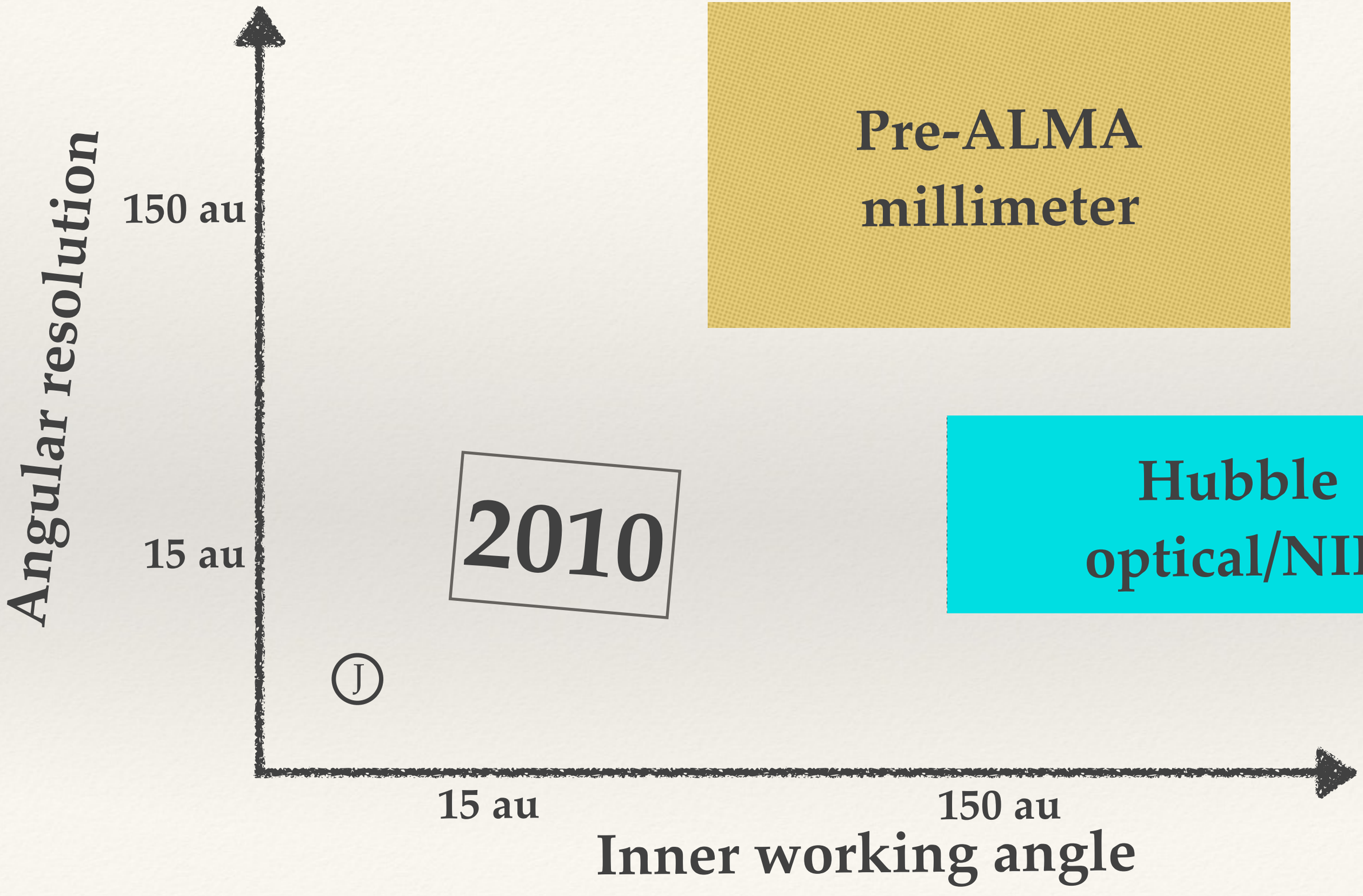


These are the best images of a protoplanetary disk…

High-resolution disk imaging



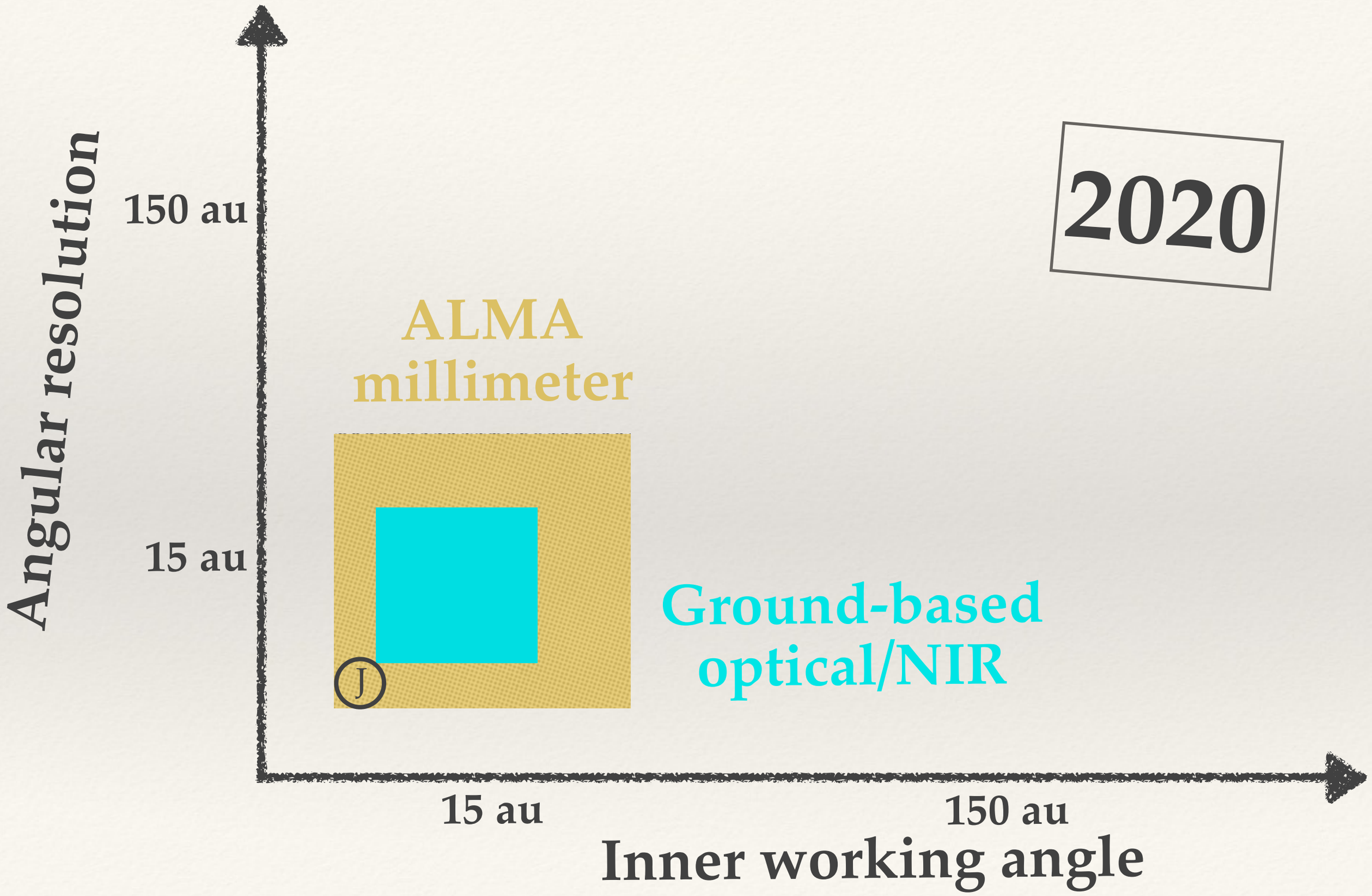
High-resolution disk imaging



Pre-ALMA millimeter

Hubble optical/NIR

High-resolution disk imaging



High-resolution disk imaging

The inner disk is **not** (yet) **mapped** by direct imaging.

Yet, we are developing some indirect methods to do it…

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…

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…

We developed **differential** techniques.

Angular-

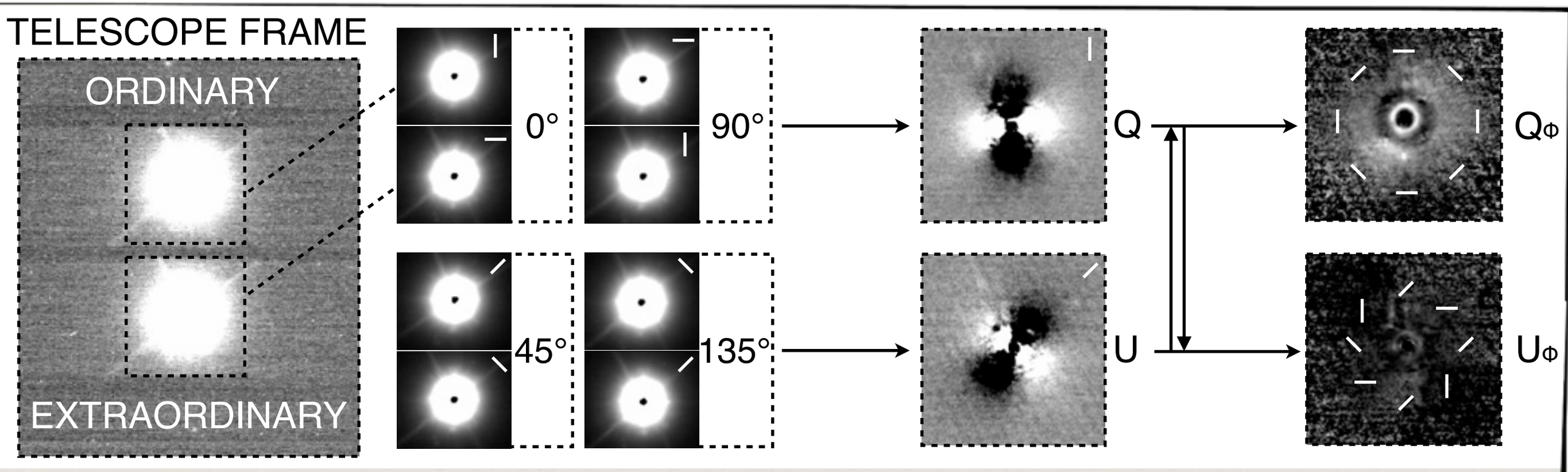
Polarimetric-

Reference star-

Spectral-

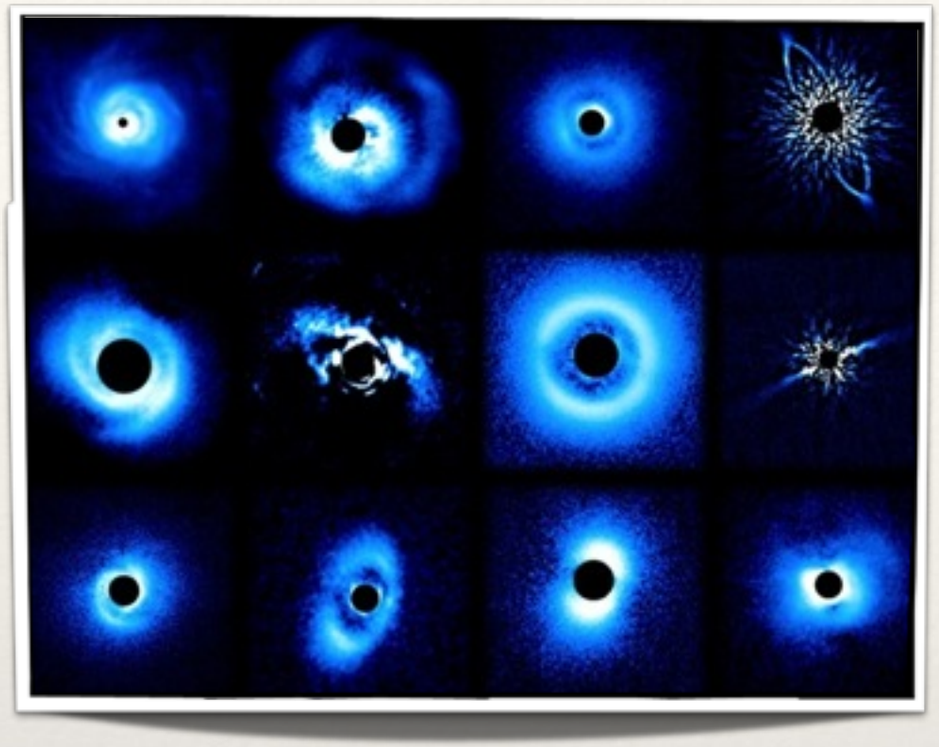
Polarimetric Differential Imaging

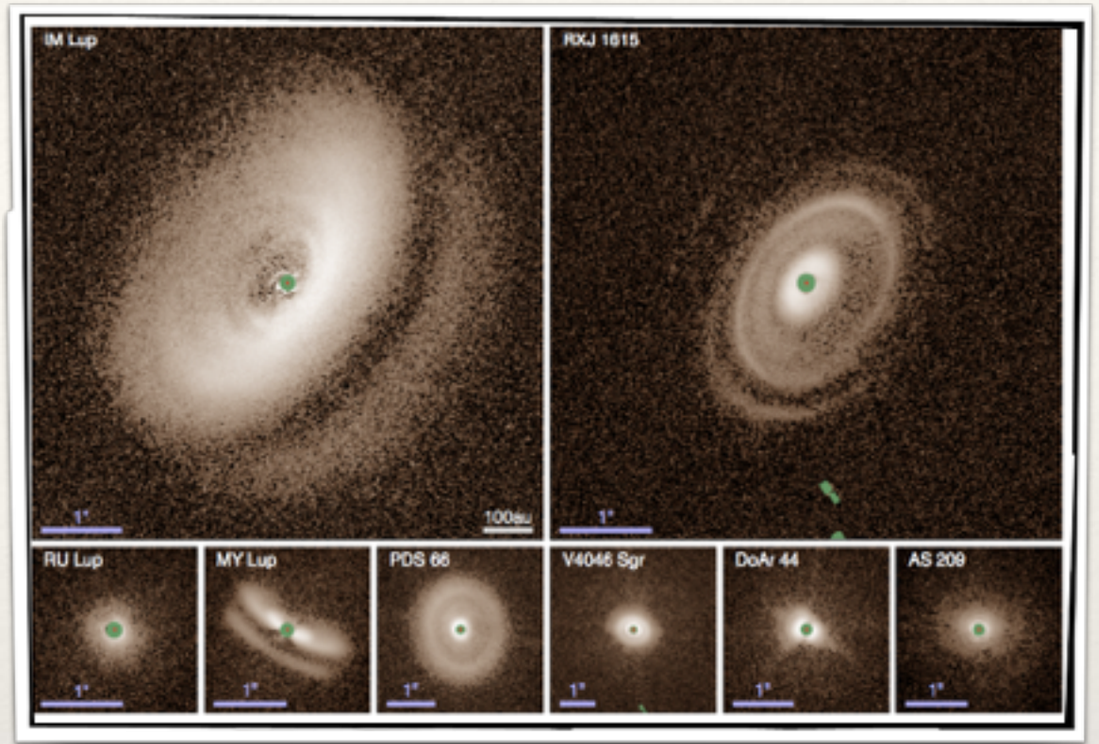
Stellar light is unpolarized. Scattered light is polarized.

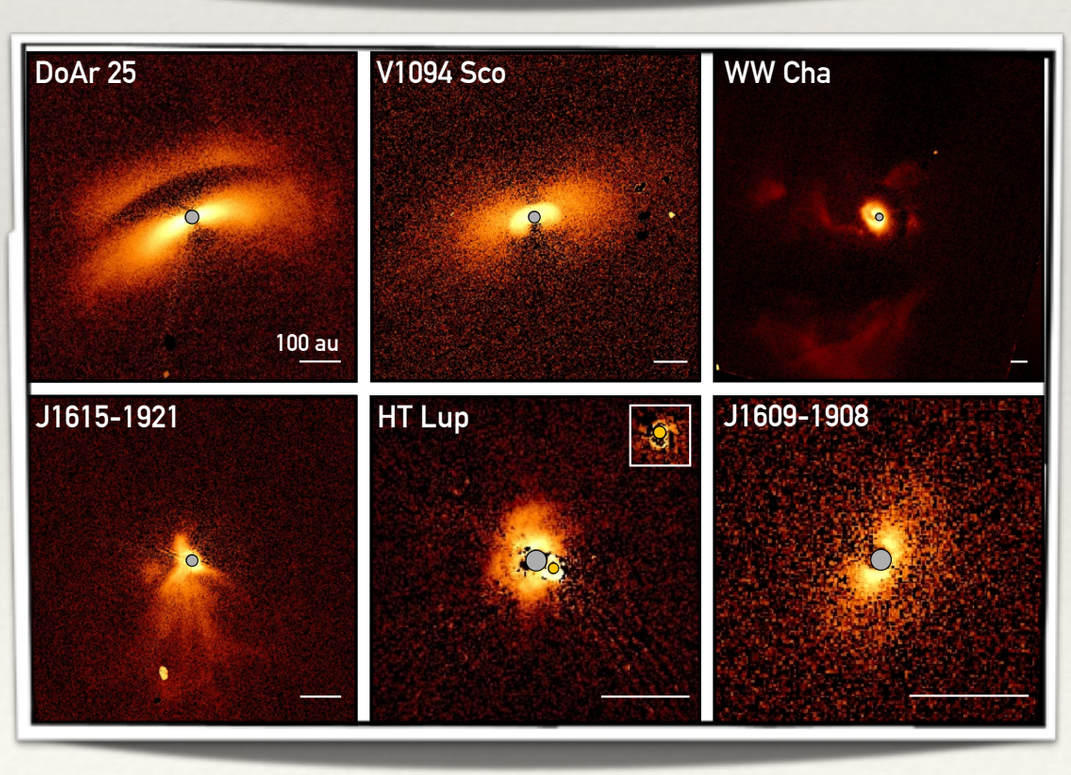


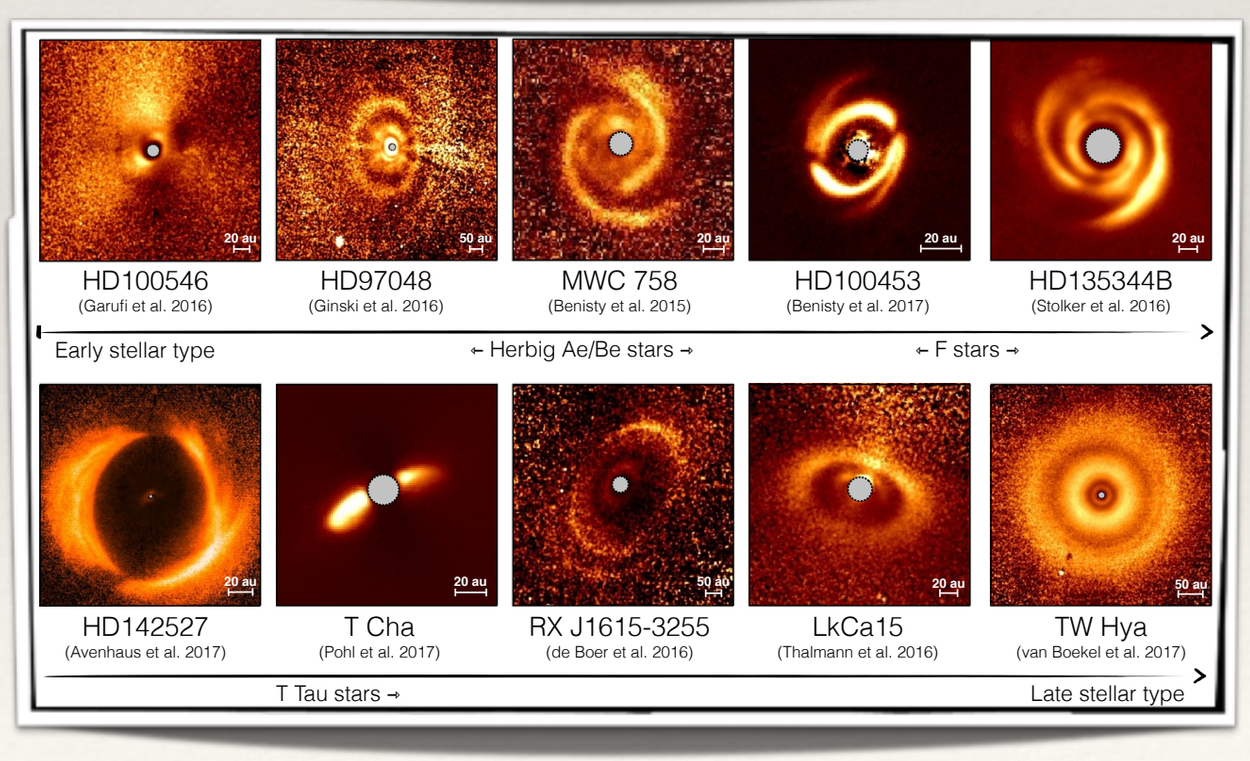
The distribution of disk scattered light depends on: disk geometry, dust properties, **illumination pattern**

The variety of disk sub-structures seen



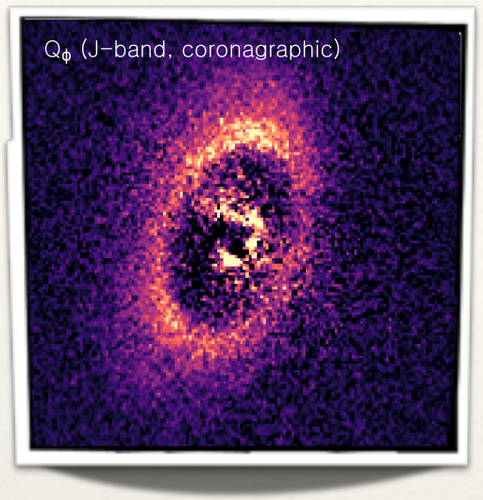


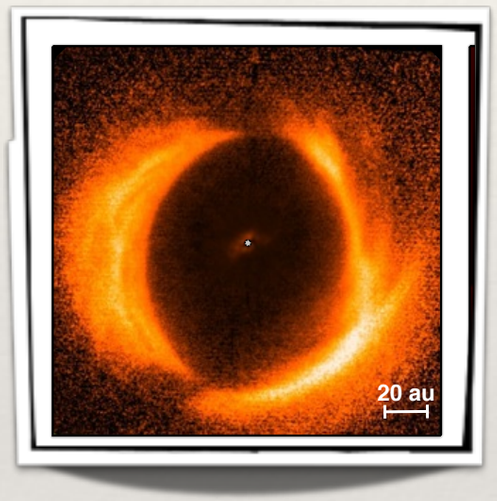


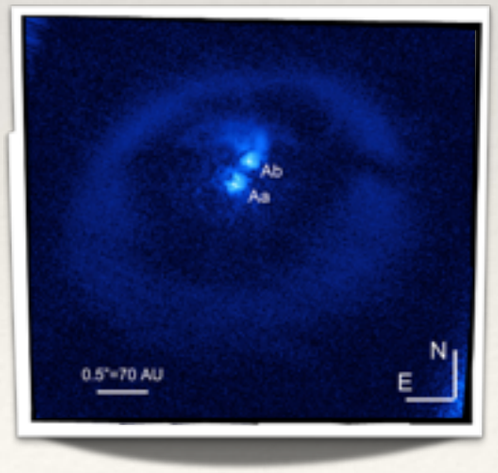


SEEDS from Subaru/HiCiao, Hashimoto et al., www.nao.ac.jp; DARTTS-S from VLT/SPHERE, Avenhaus et al. 2018, Garufi et al. 2020, DISK GTO from VLT/SPHERE, Garufi et al. 2017b +references therein

The variety of disk sub-structures seen





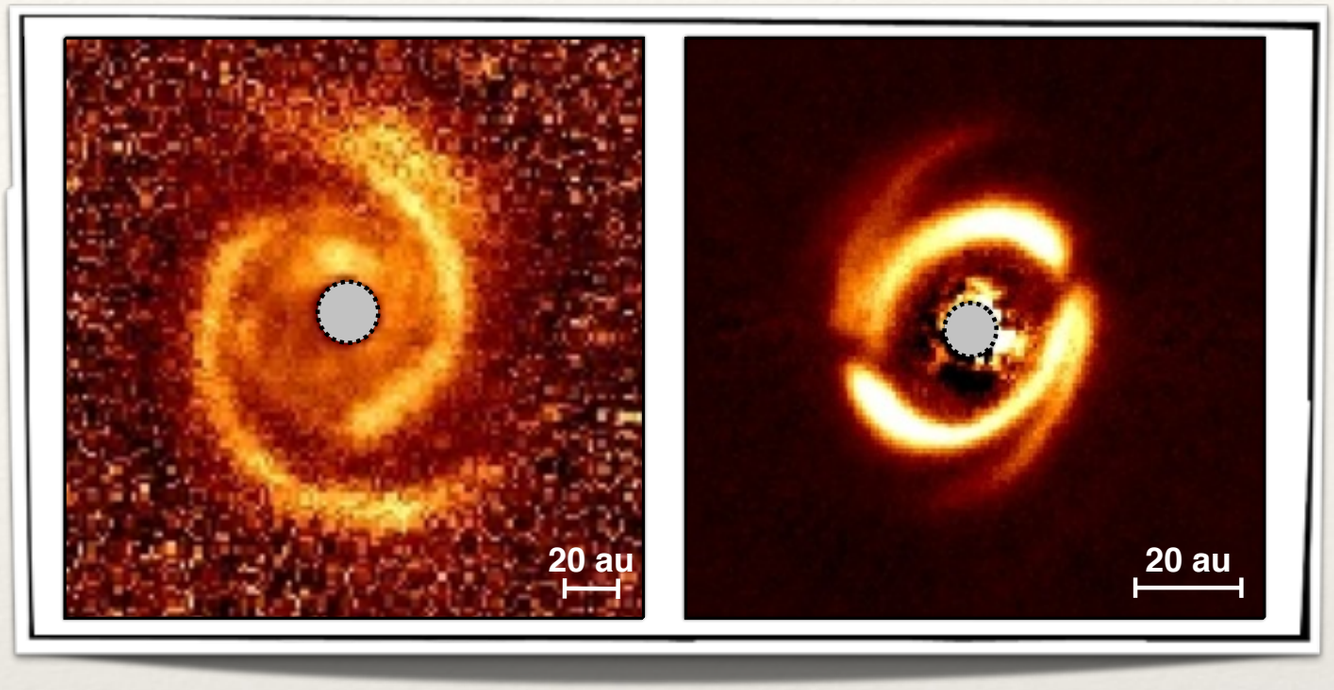


First obvious findings are **large inner cavities** (10s au).

Seen for small, large dust grains and gas but not always with the same size. Differential dust filtration has been invoked.

Keppler et al. 2018, Avenhaus et al. 2017, Yang et al. 2017

The variety of disk sub-structures seen

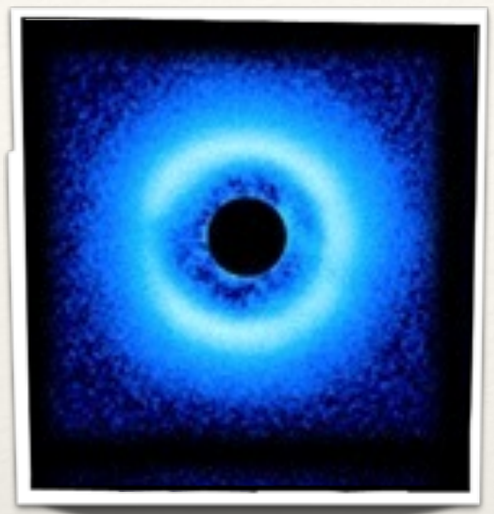


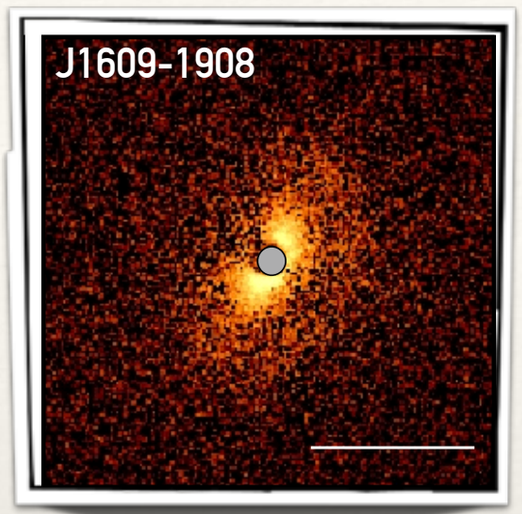
Spiral arms are relatively frequent (~10%) around Herbig stars.

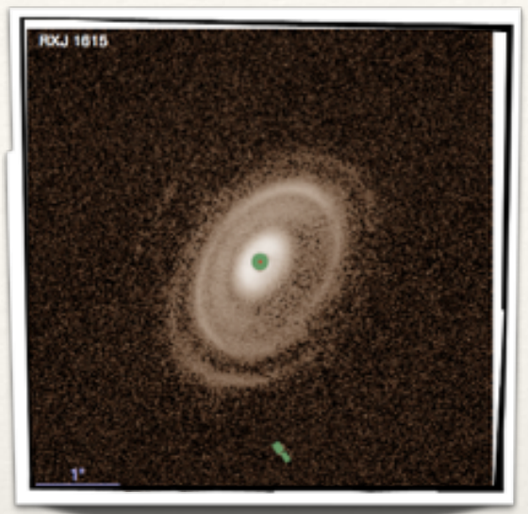
Their origin is highly debated.

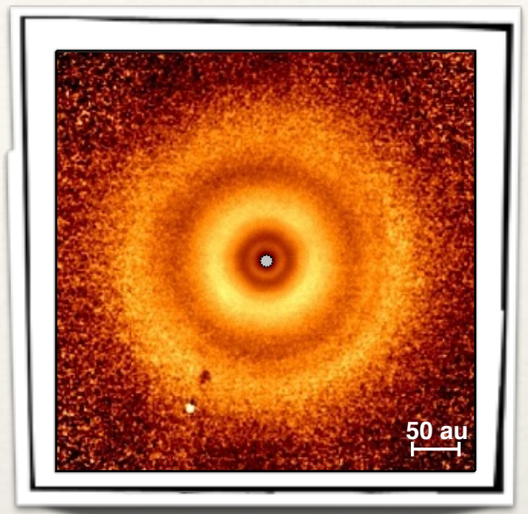
Hashimoto et al. 2011, Muto et al. 2012, Benisty et al. 2015, 2017

The variety of disk sub-structures seen







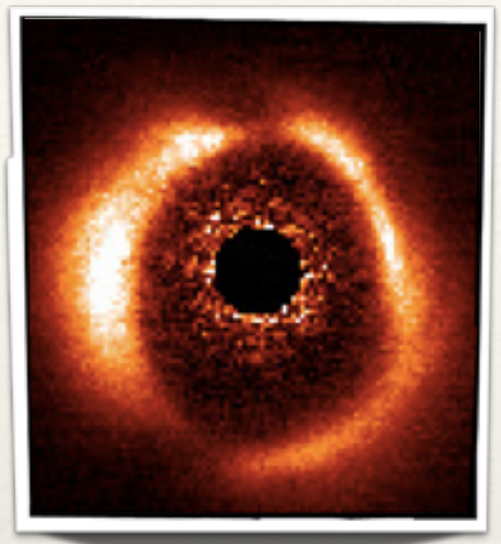


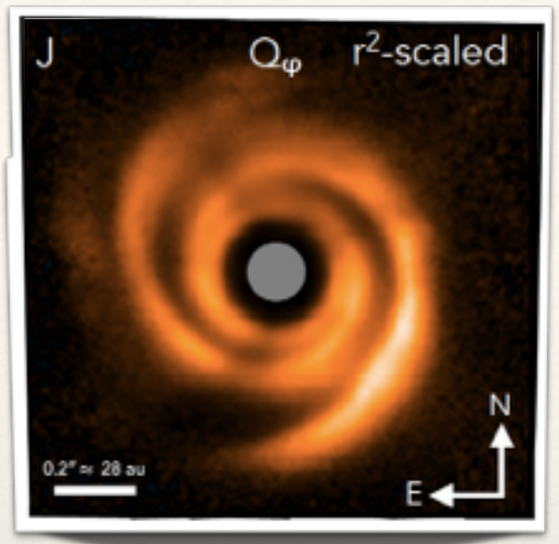
Rings and **annular gaps** are more frequent (~30%) and found around any type of stars.

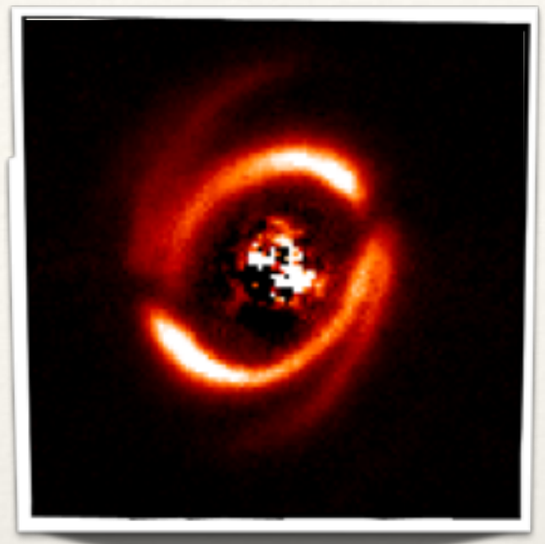
Disk sculpting by unseen planets is the favored explanation but it is uncertain whether this is consistent with planetary statistics.

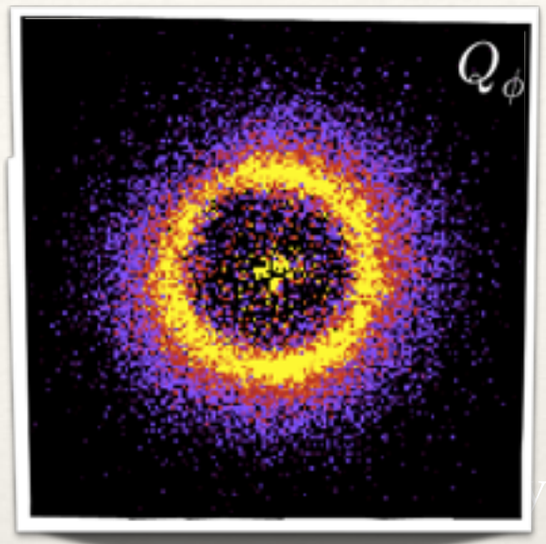
Mayama et al. 2012, Garufi et al. 2020, Avenhaus et al. 2018, van Boekel et al. 2017

The variety of disk sub-structures seen









y et al 2

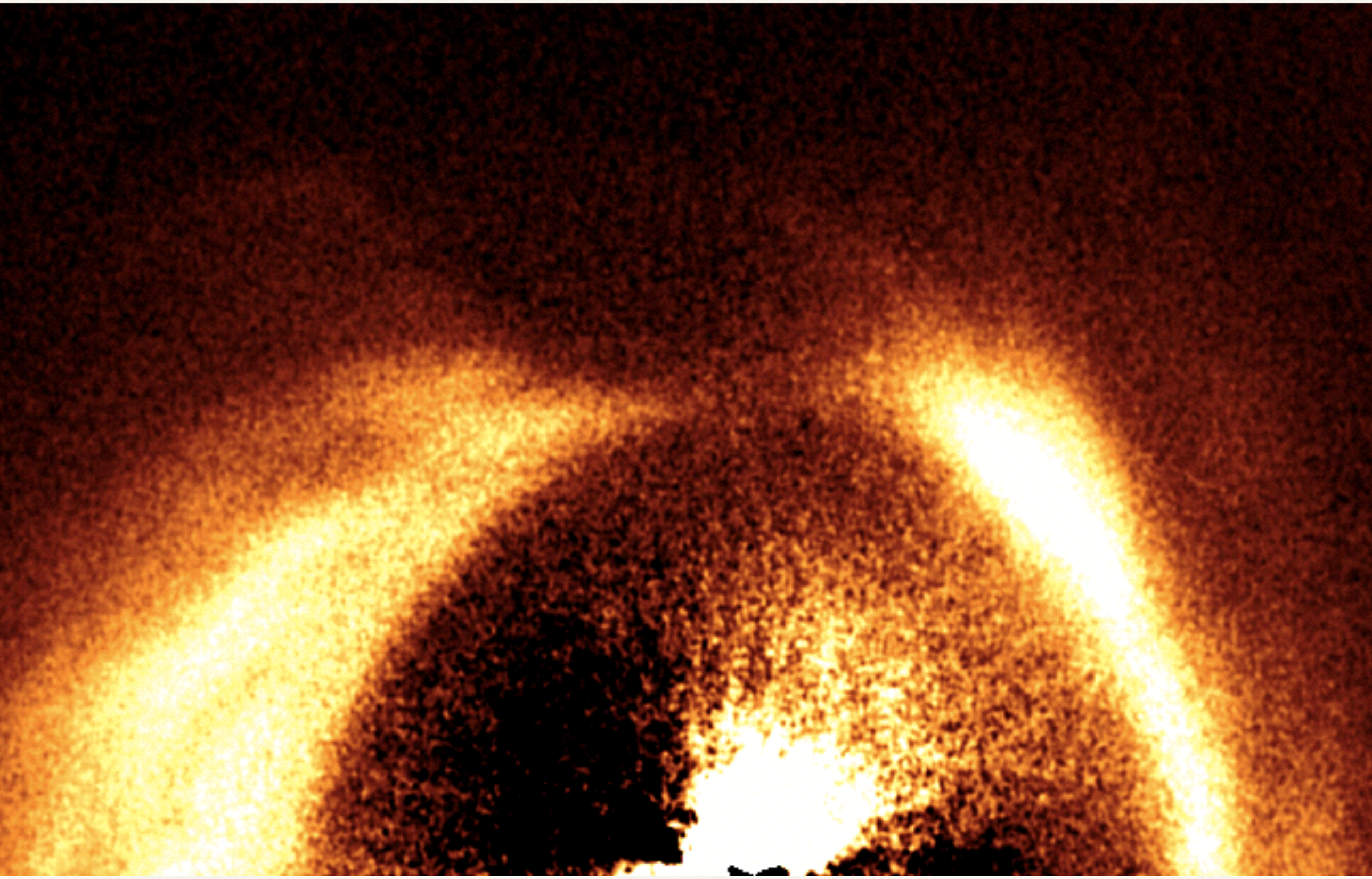
Shadows are seen as azimuthally extended dark lanes.

They are, in turn, very diverse.
They are narrow or broad,
pronounced or tenuous,
constant or variable…

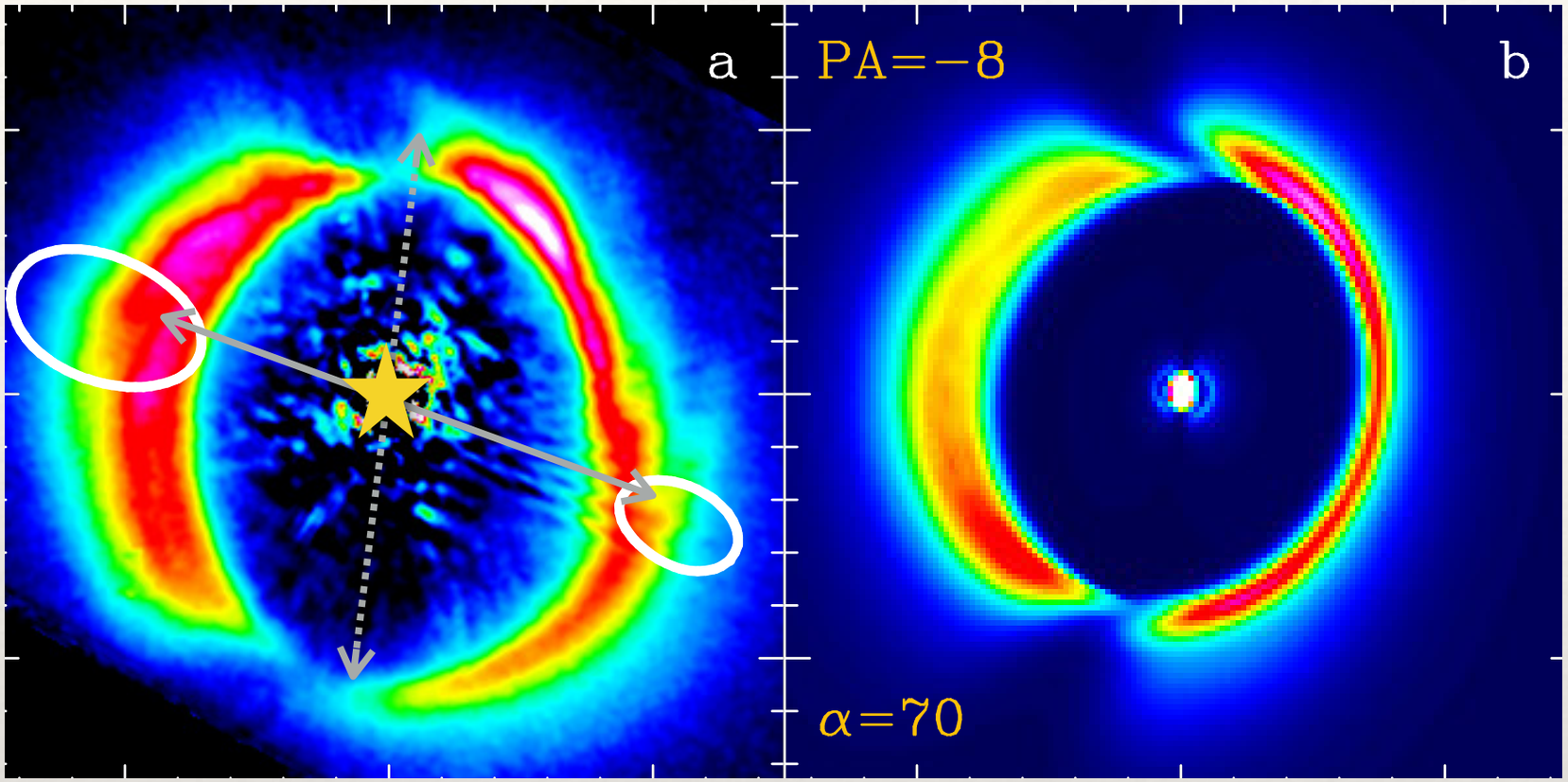
Benisty et al. 2017

Canovas et al. 2013, Stolker et al. 2016, Benisty et al. 2017, Pinilla et al. 2018

Disks with shadows

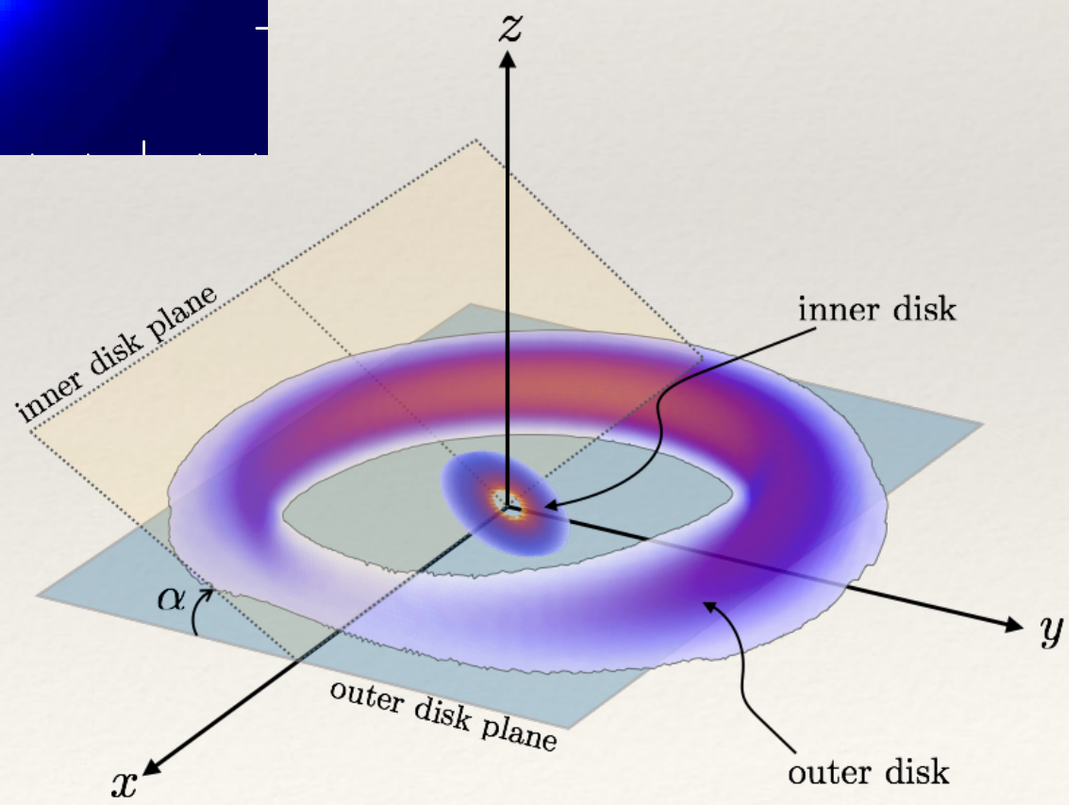


Disks with shadows

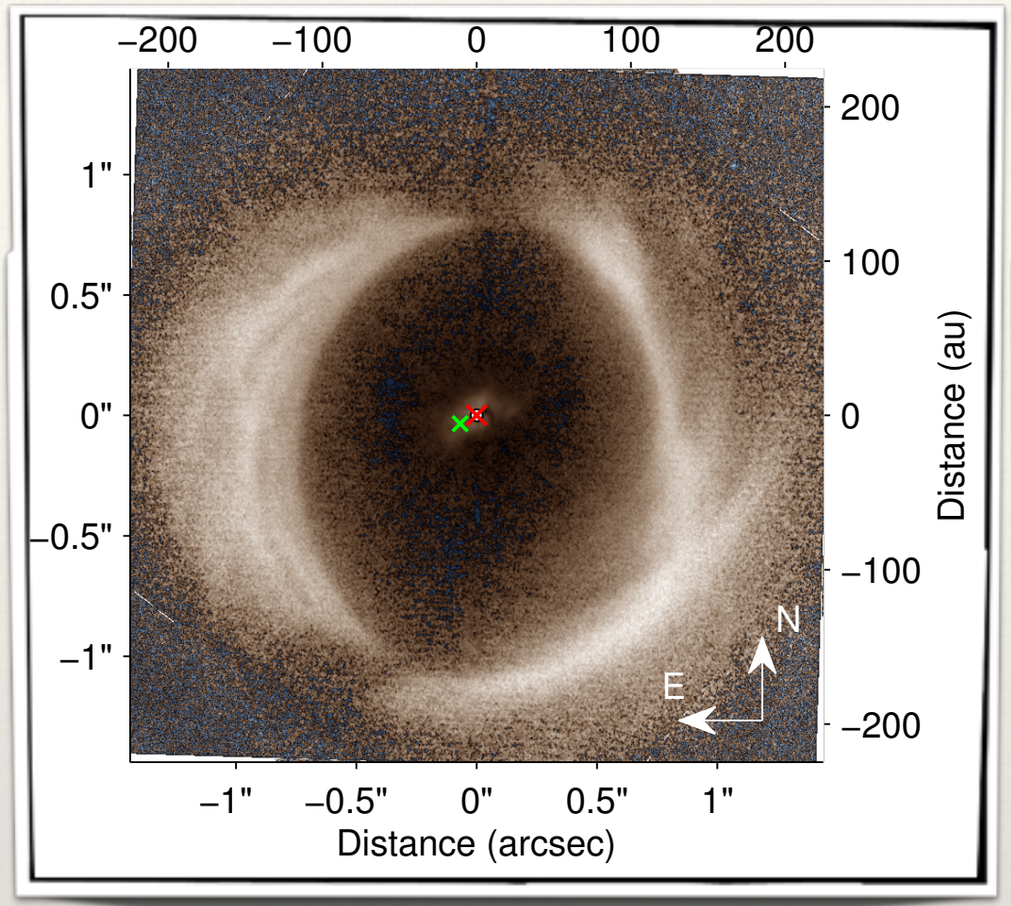


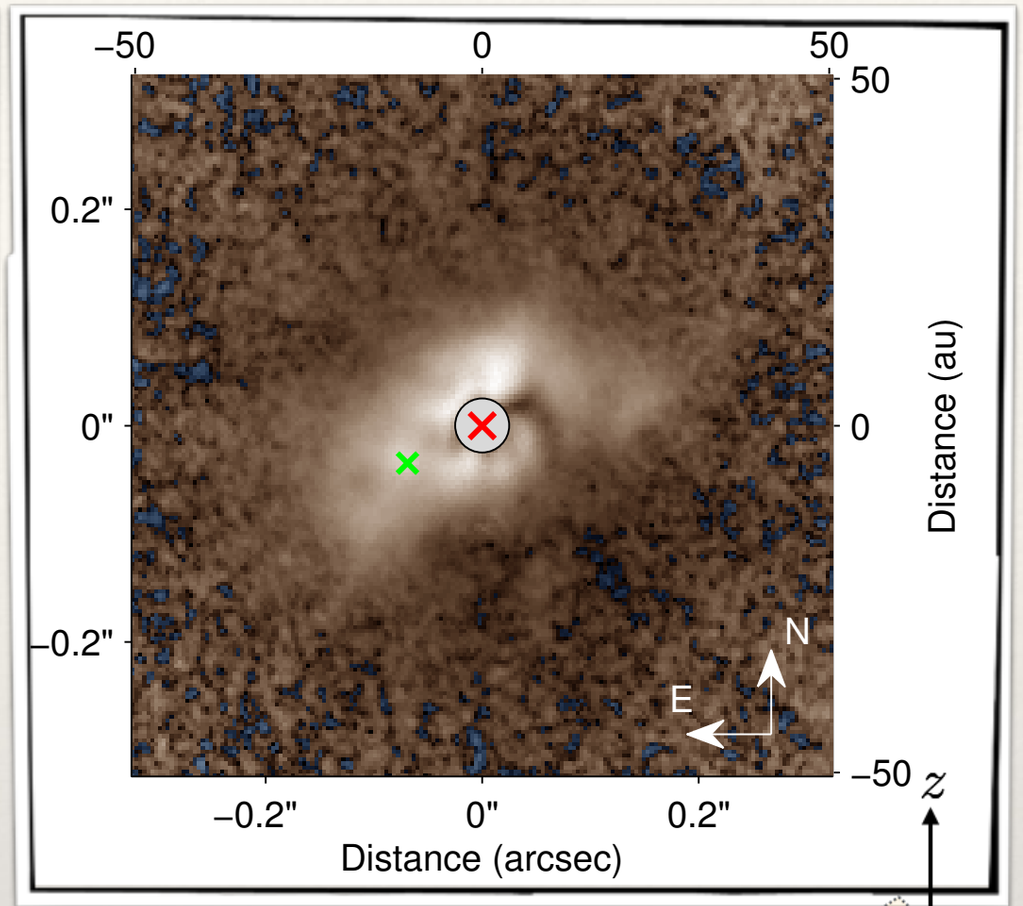
Marino, Perez, Casassus 2014

Radiative transfer predicts the **geometry** of the disk region casting shadows.



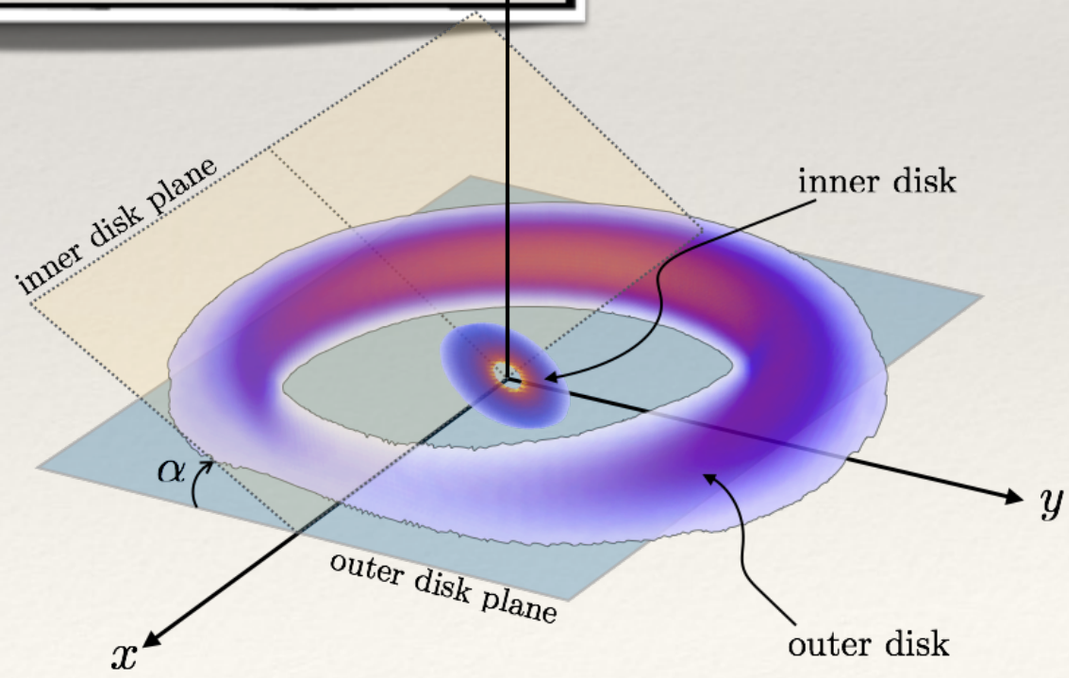
Disks with shadows



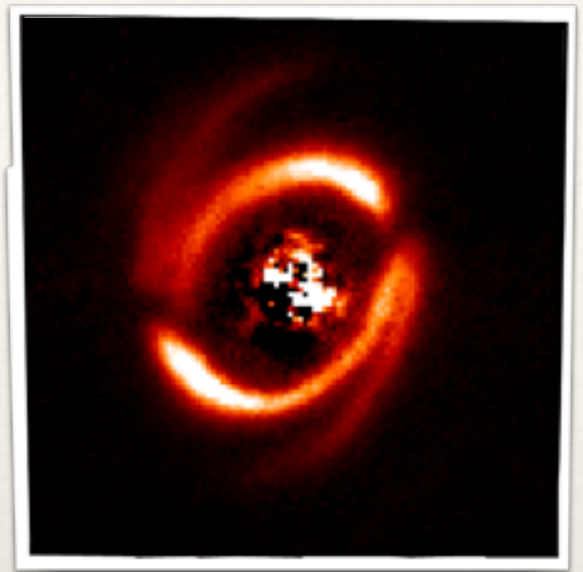


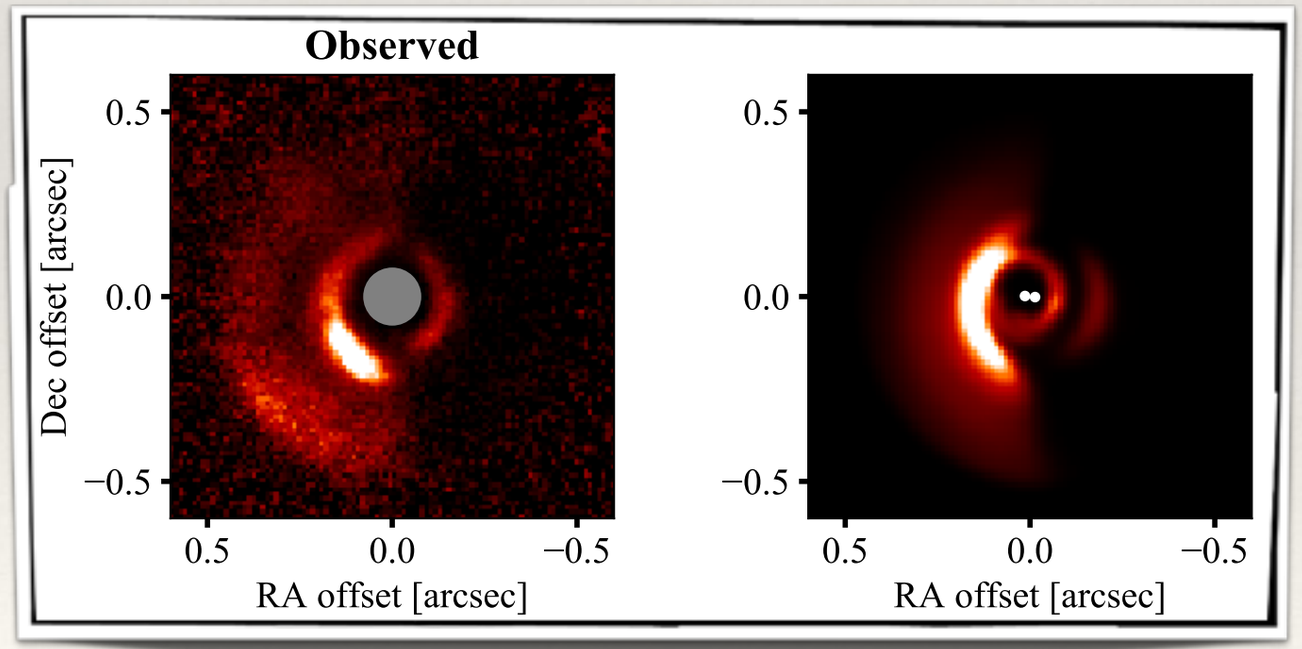
Avenhaus et al. 2017

These regions are normally beyond reach of direct **imaging**. But there are exceptions like this.



Disks with shadows

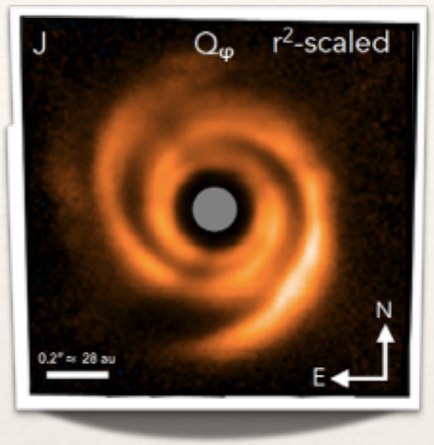


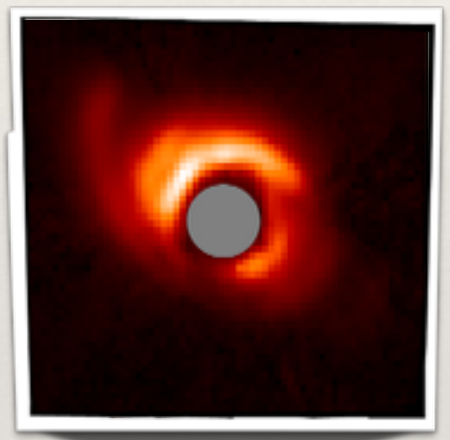


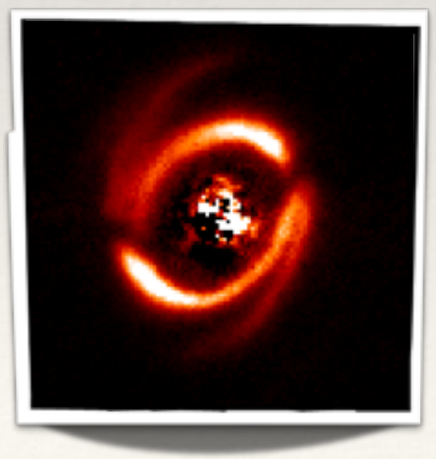
Benisty et al. 2017, 2018

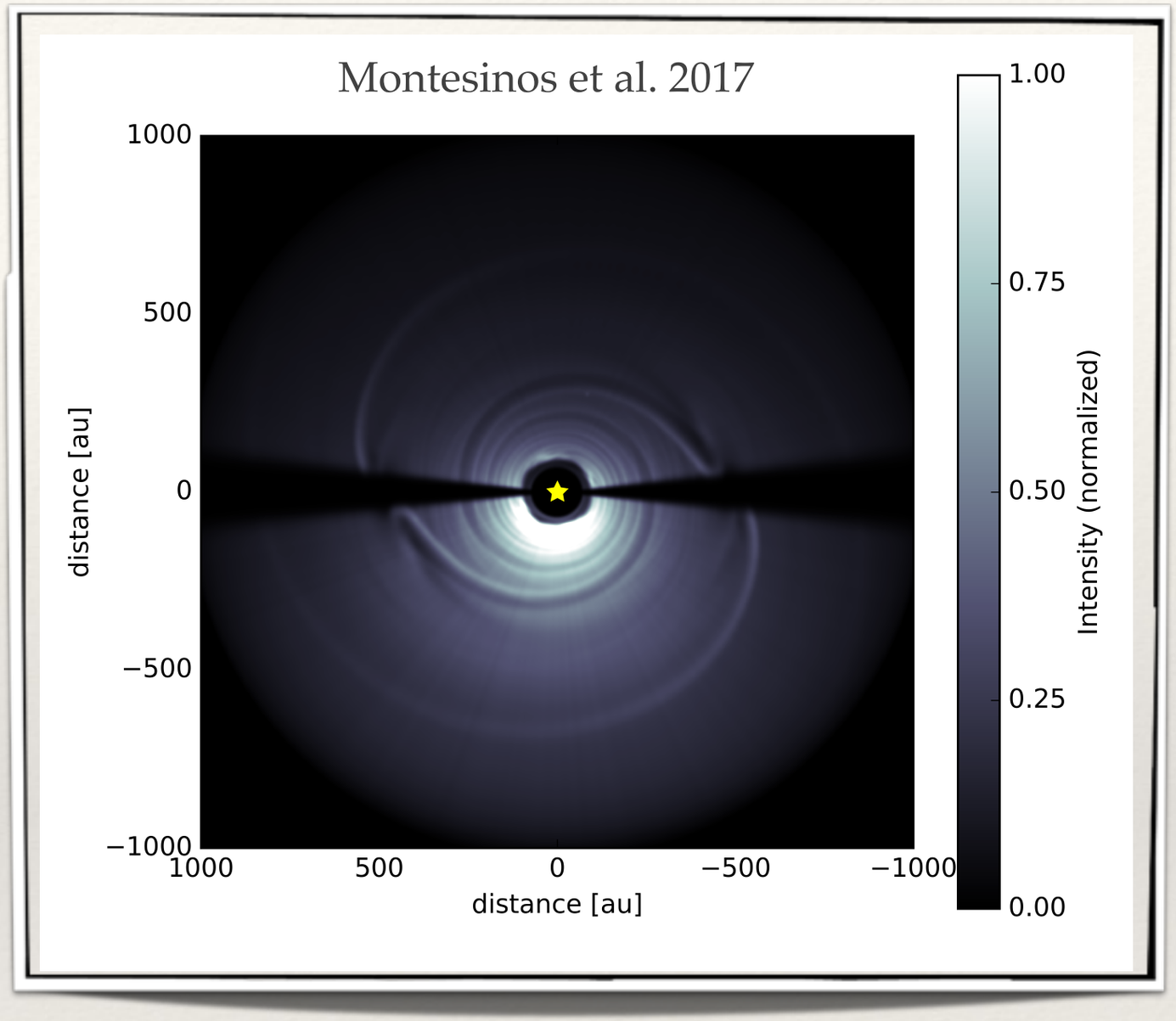
Narrow shadows are best produced with large misalignments (72° in HD100453) whereas **wider** shadows with smaller angle (30° for HD143006, see also Nealon et al. 2019).

Disks with shadows (and spirals)



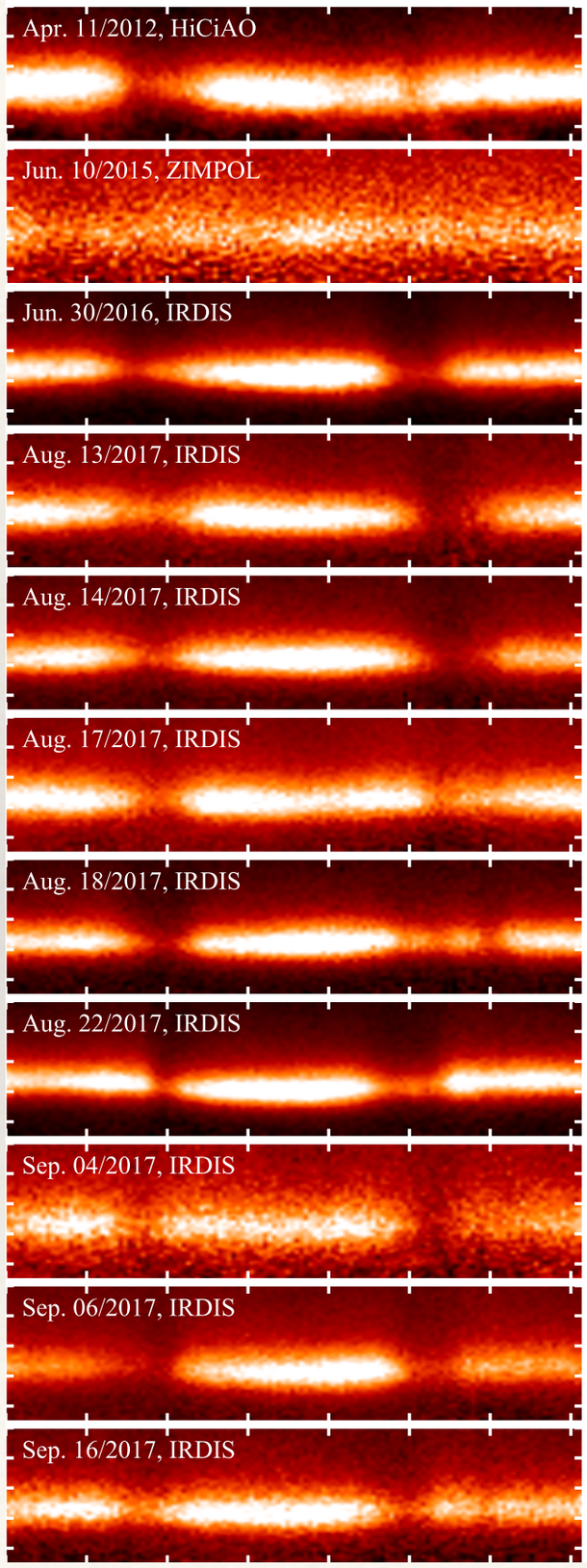


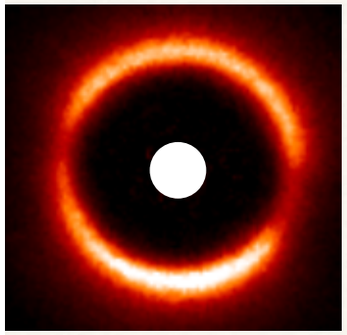


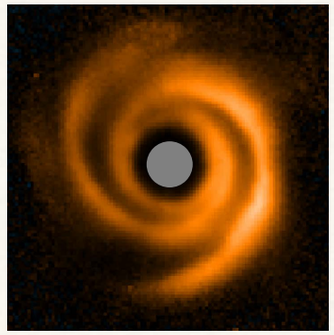


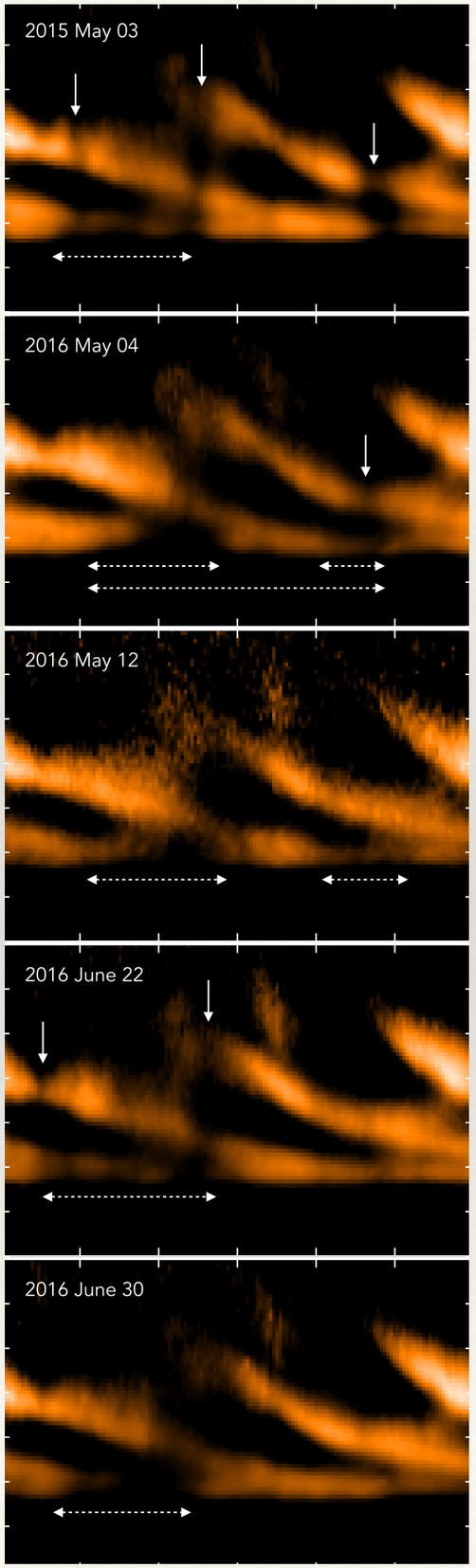
The **analogy** between the presence of shadow and spirals may be explained by the azimuthal pressure gradients on the disk.

Disks with shadows





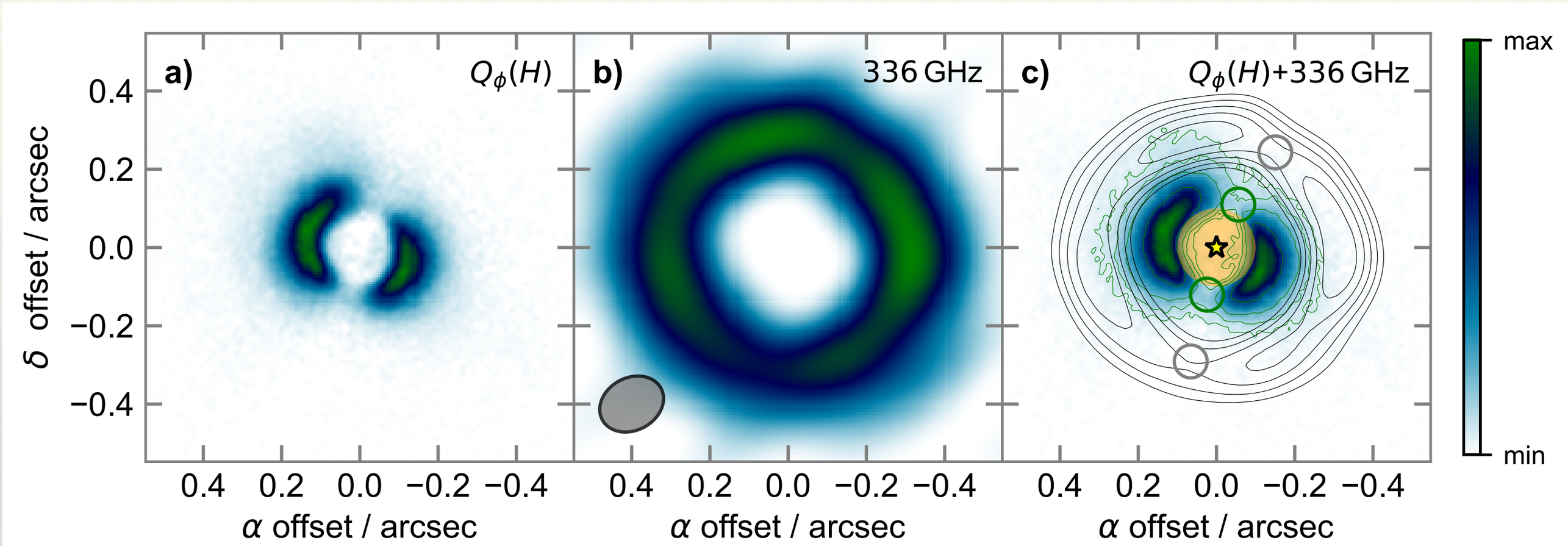




The shadow **variability** indicates that the inner regions are highly dynamic, possibly because of the interaction with companion(s).

Pinilla et al. 2018, Stolker et al. 2017

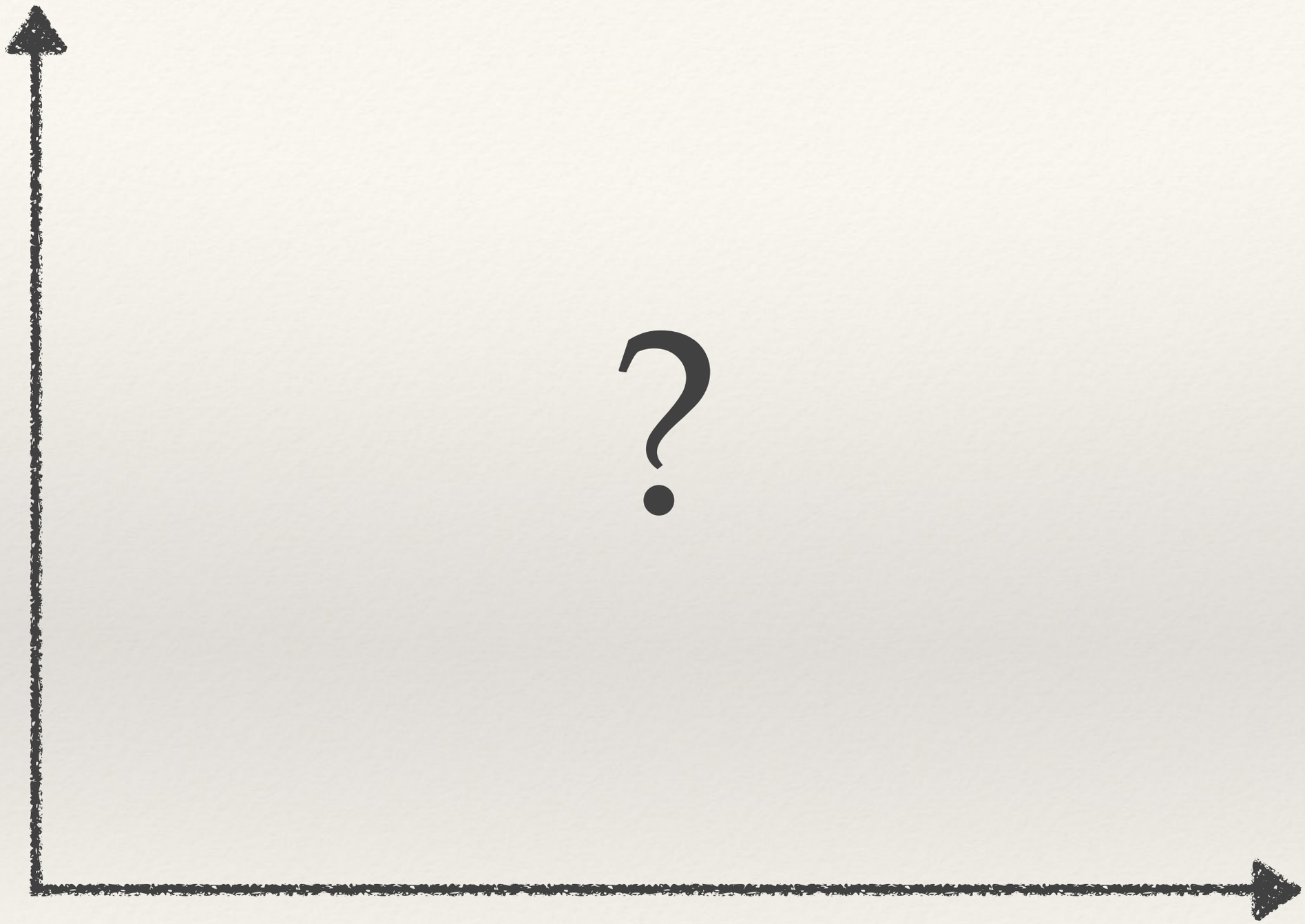
Disks with shadows



Shadows may have a **millimeter** (shallow) counterpart.

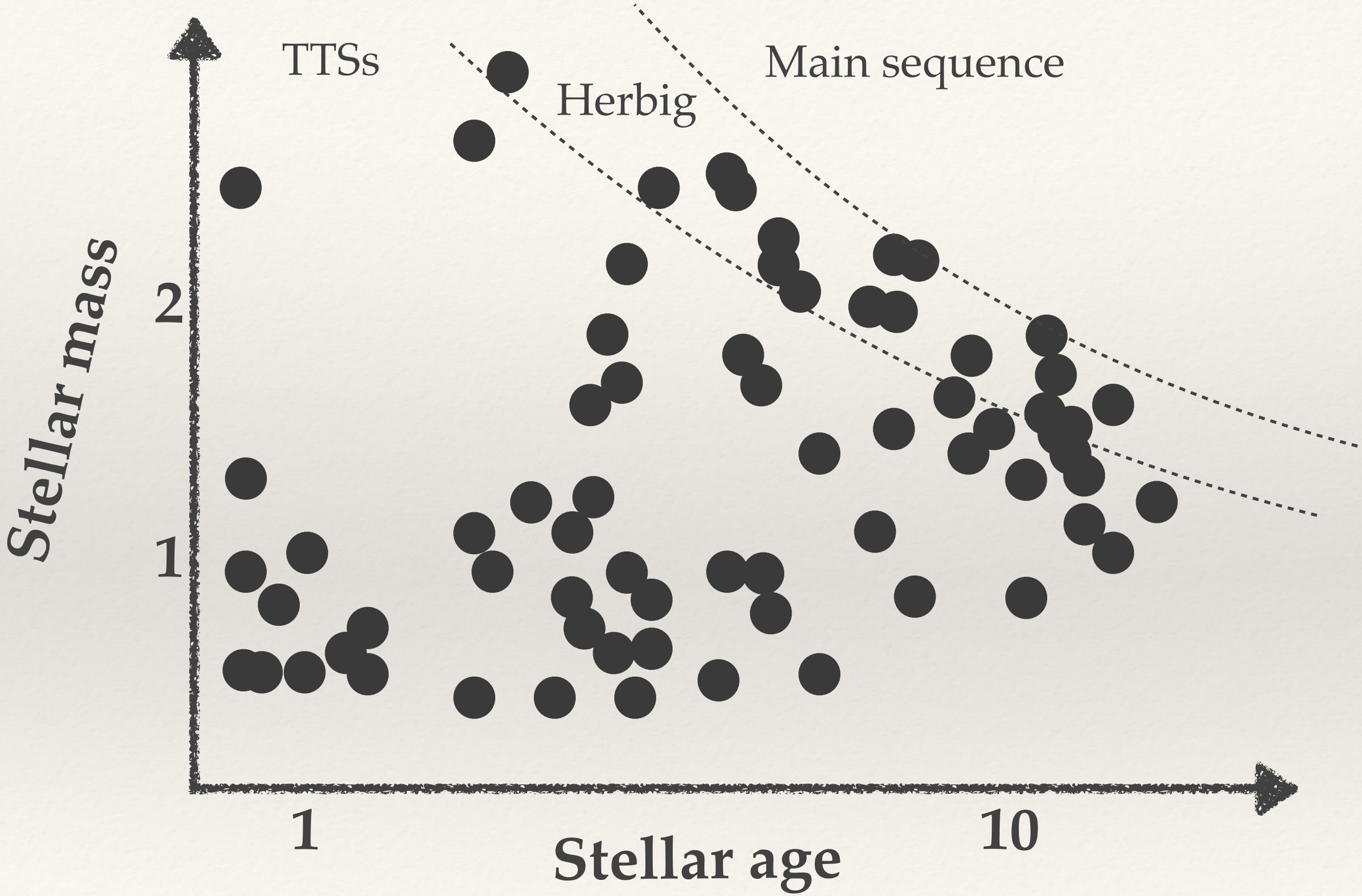
Casassus et al. 2018

Demography of shadows



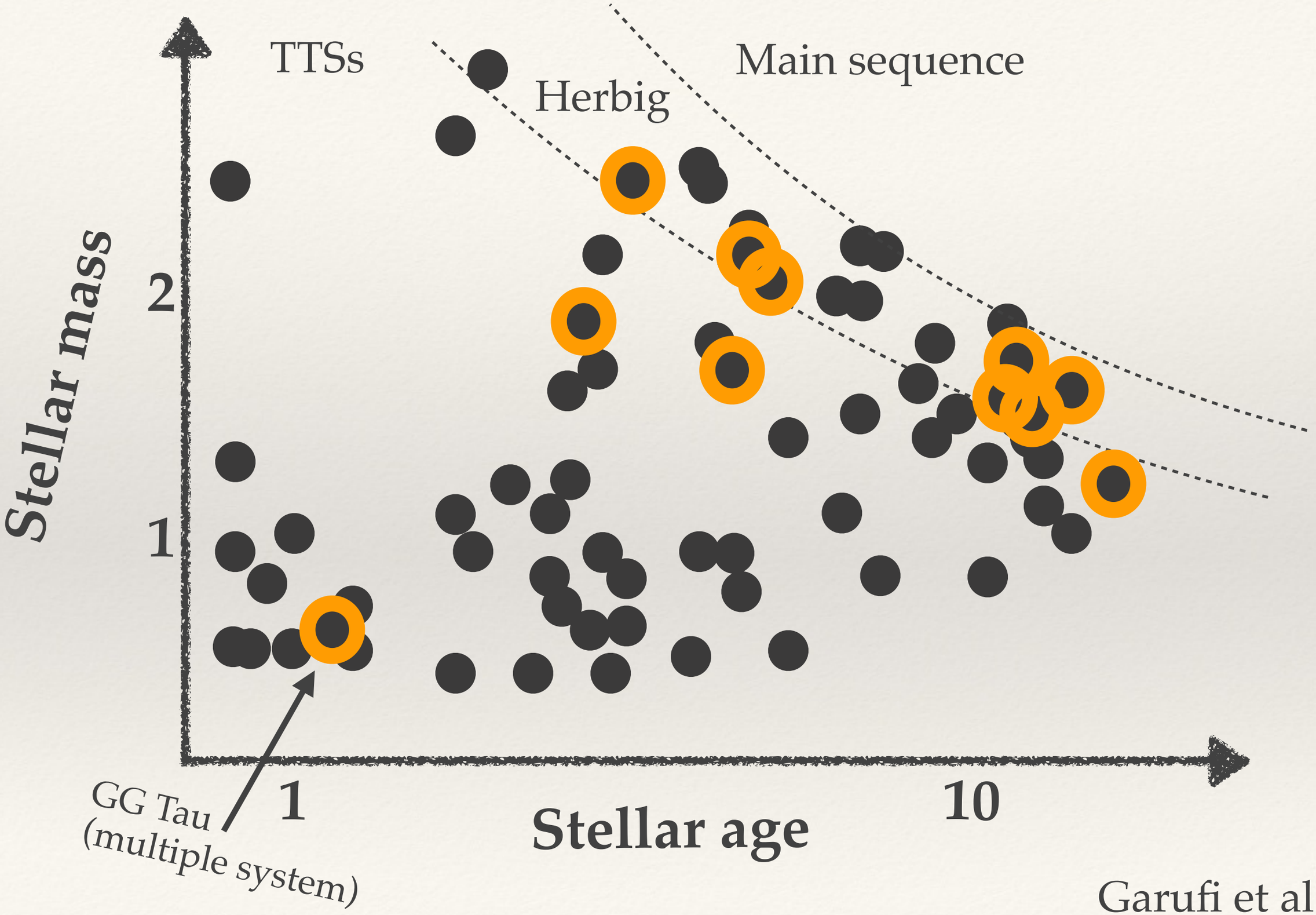
Being sufficiently common, we can study how the presence of shadows relate with stellar / disk properties

Demography of shadows



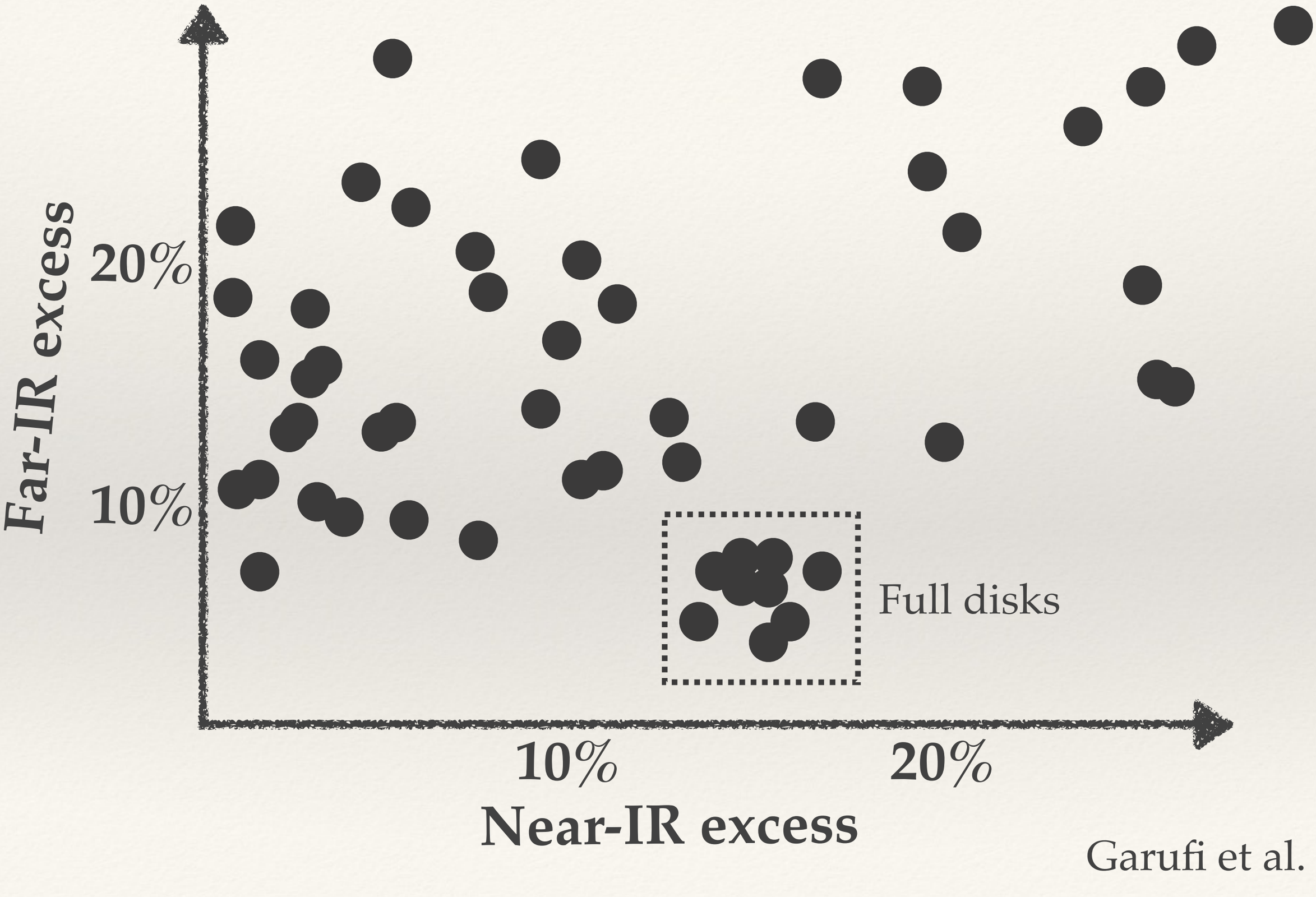
Garufi et al. 2018

Demography of shadows



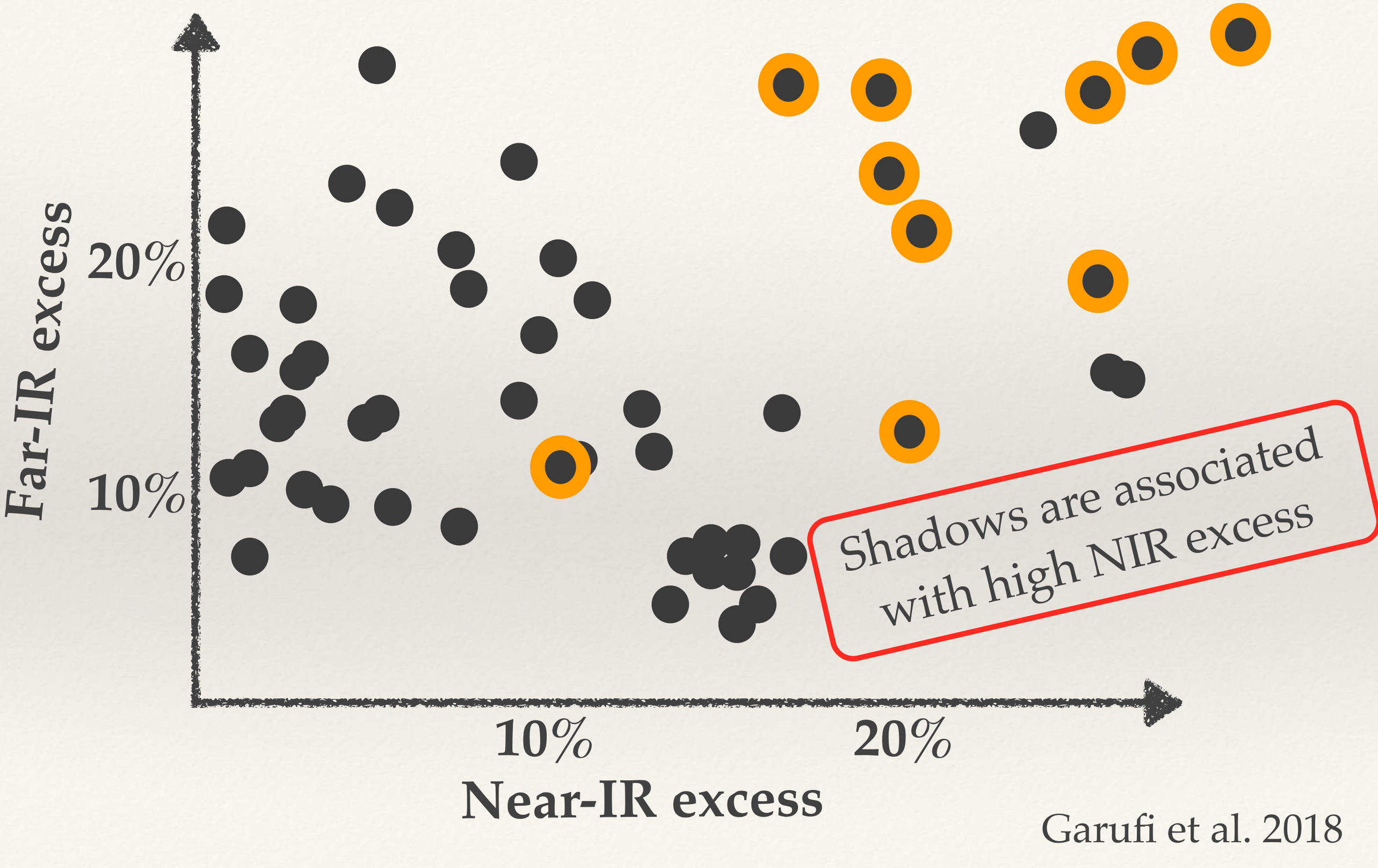
Garufi et al. 2018

Demography of shadows



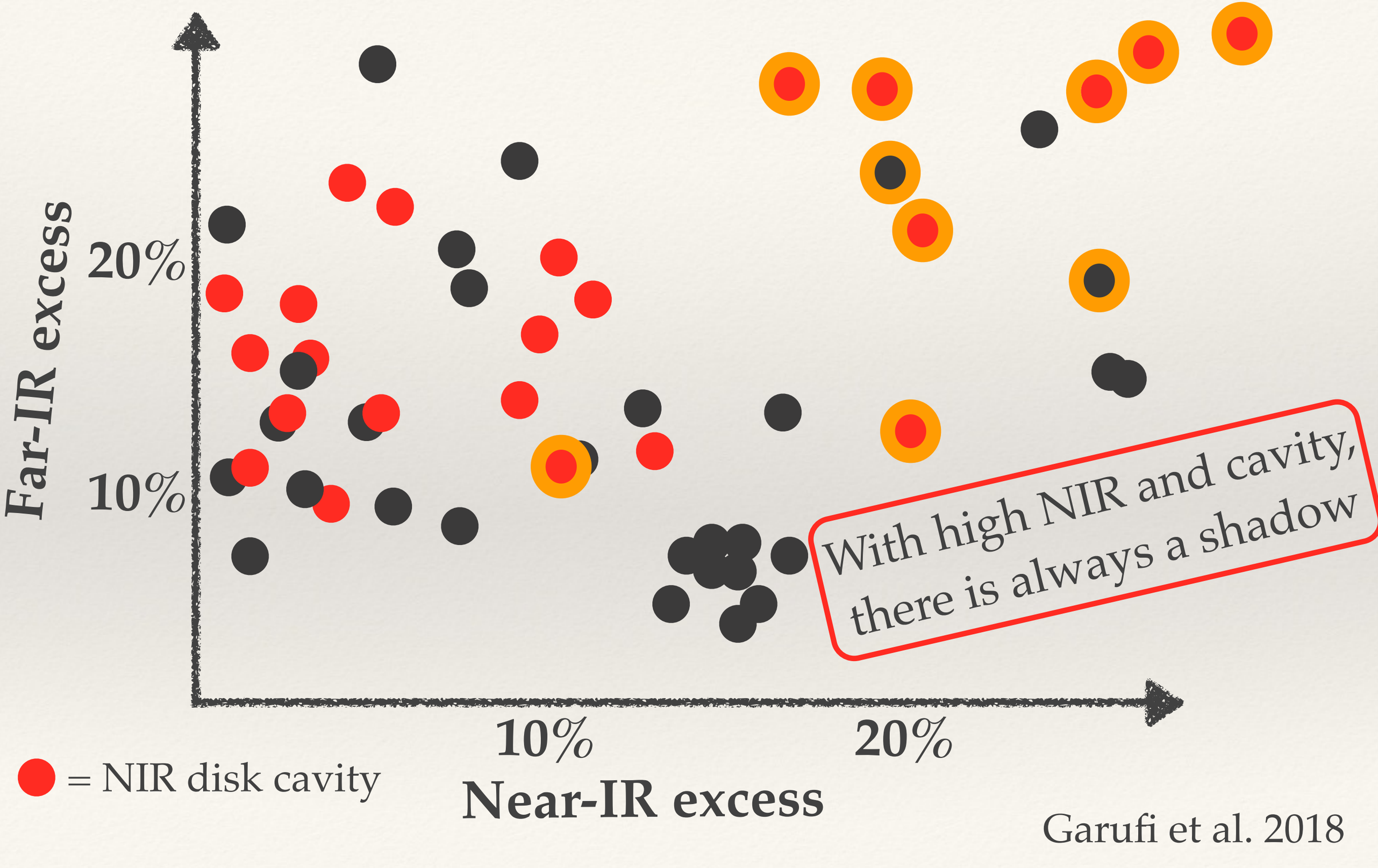
Garufi et al. 2018

Demography of shadows



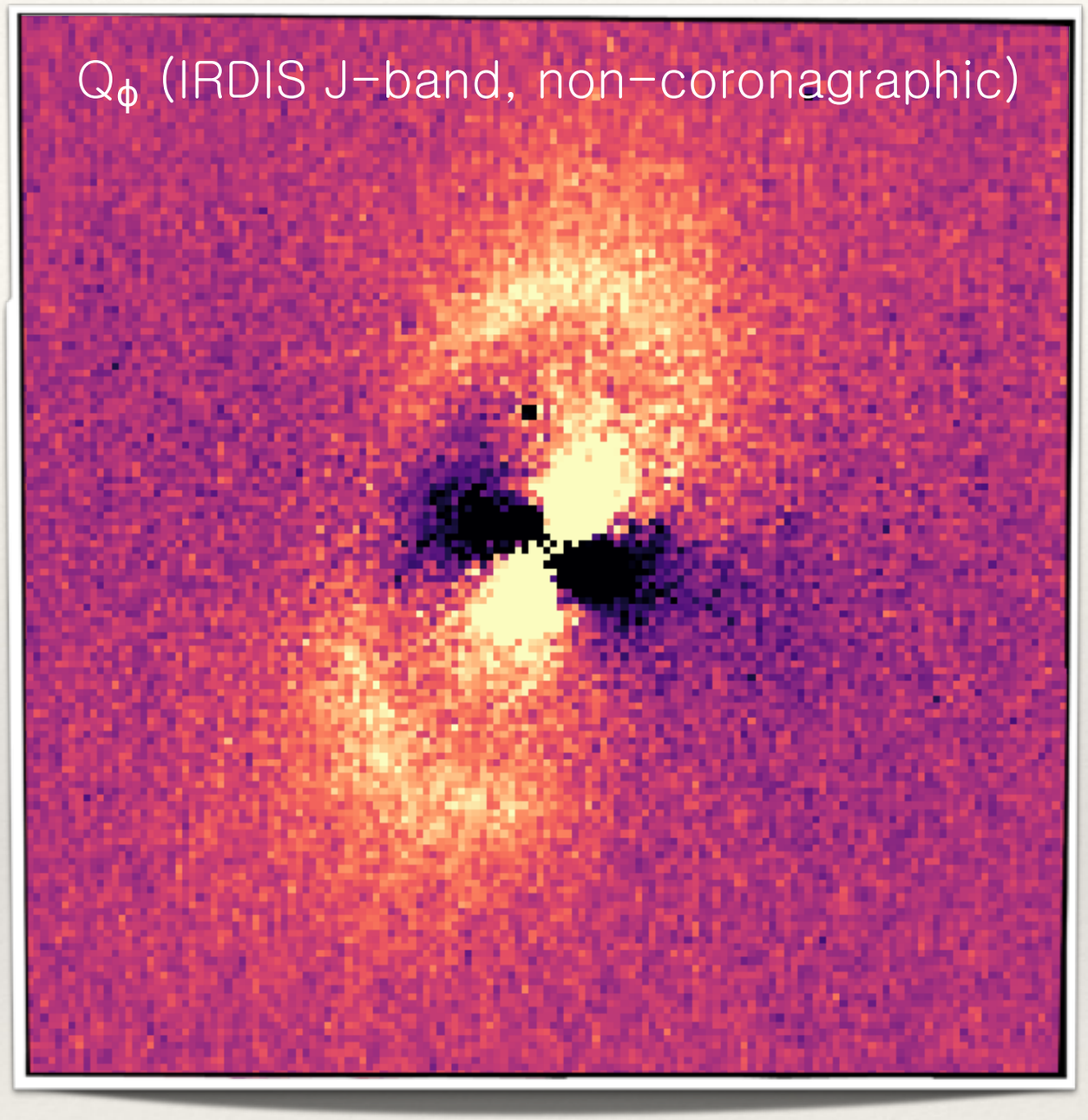
Garufi et al. 2018

Demography of shadows



Garufi et al. 2018

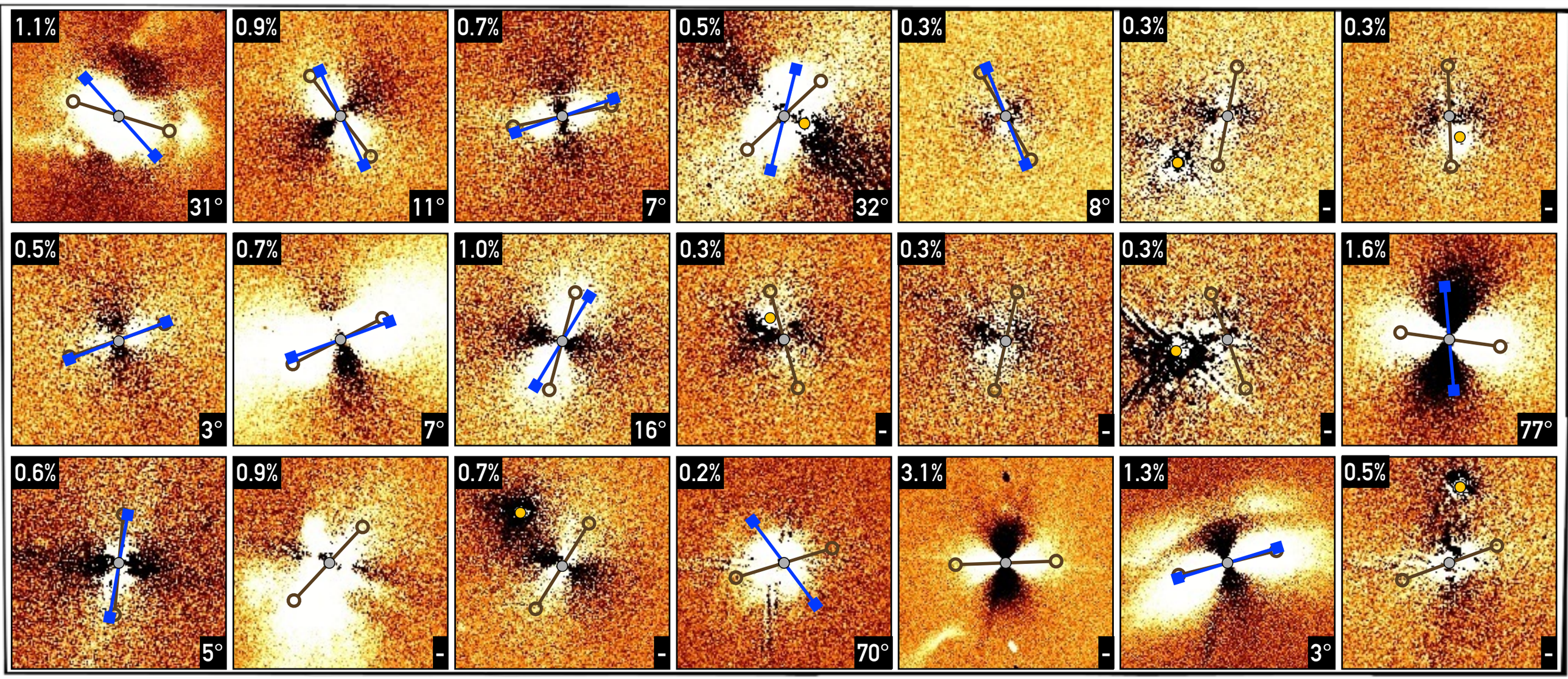
Other indirect proxies of the inner disk



We begin to characterize the **central unresolved** polarization from the inner disk.

Keppler et al. 2018

Other indirect proxies of the inner disk

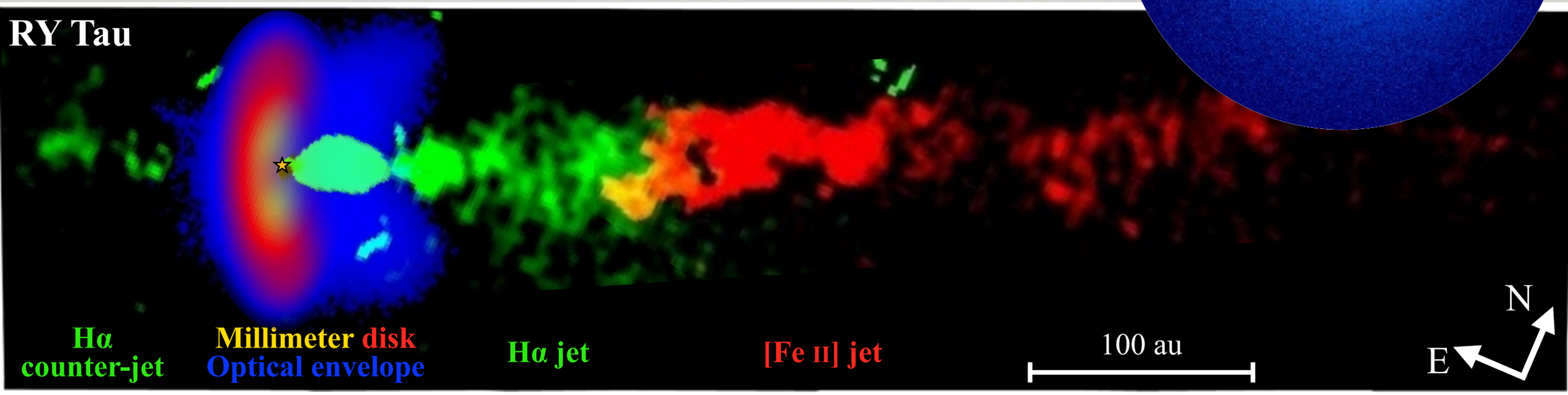


We begin to characterize the **central unresolved** polarization from the inner disk.

Garufi et al. 2020

The jet and envelope of RY Tau

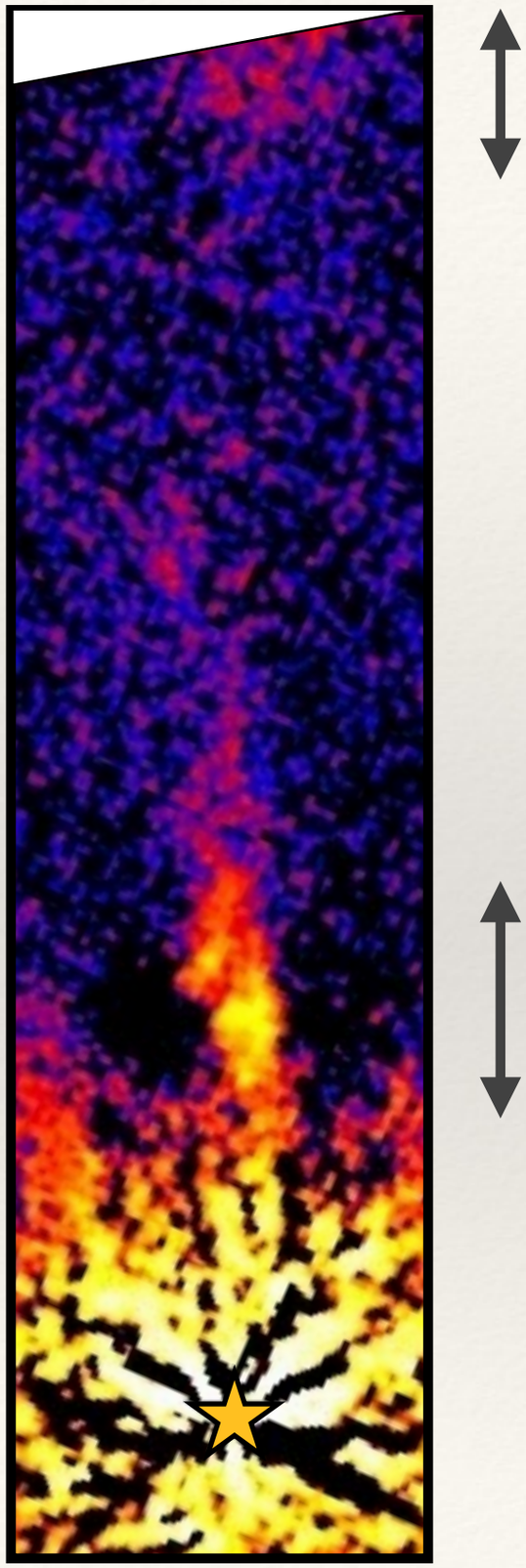
The disk in polarized light is unseen.
The envelope dominates.

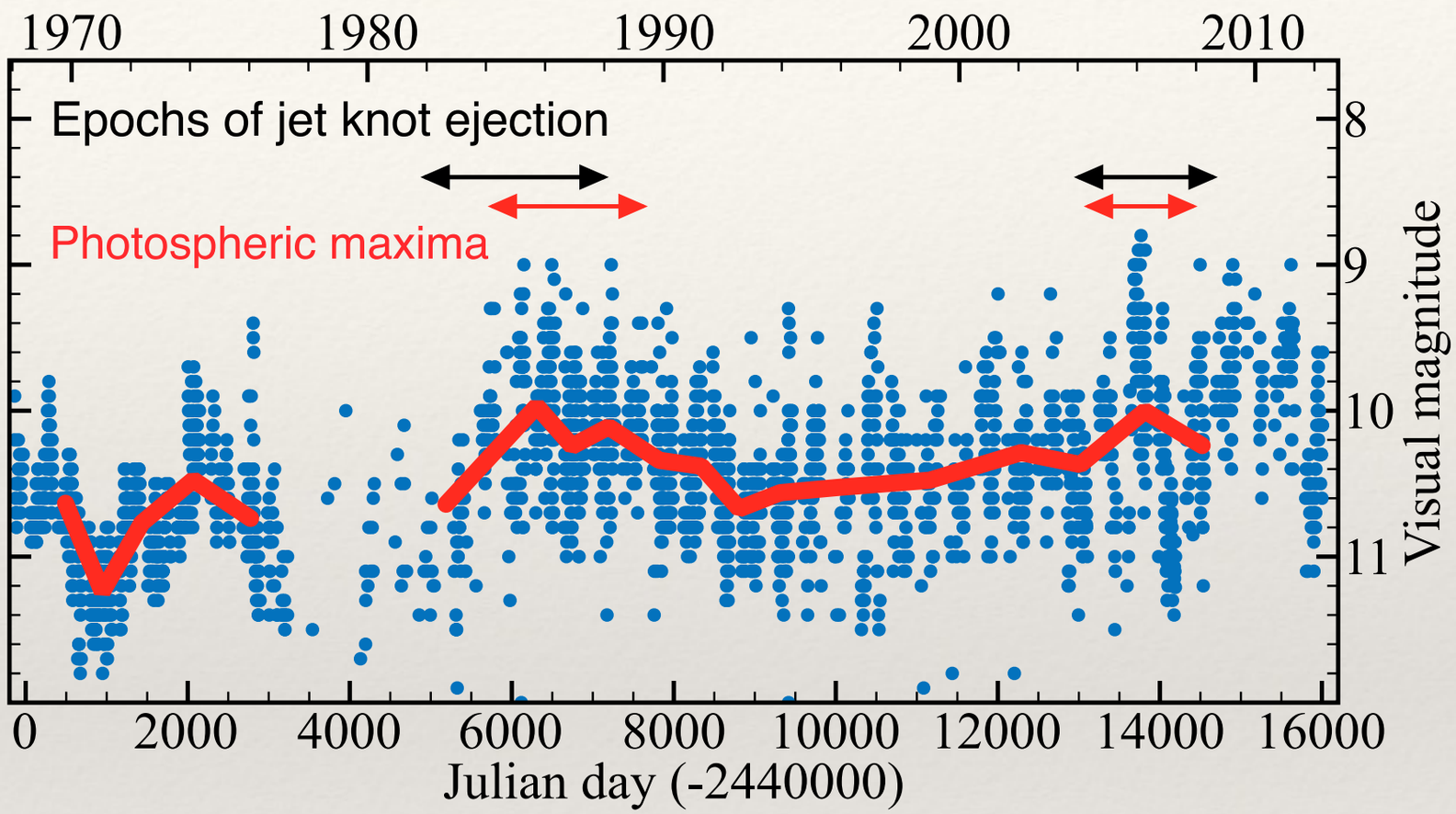


The jet is detected in optical and NIR lines.
It shows sub-structures and wiggling.

Garufi et al. 2019

The jet and envelope of RY Tau

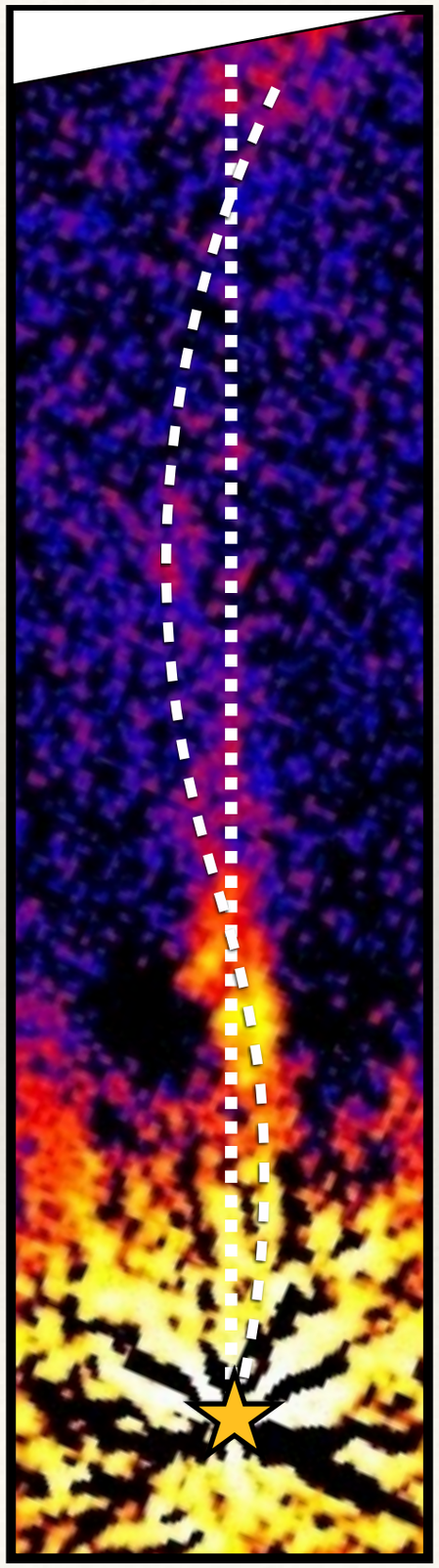


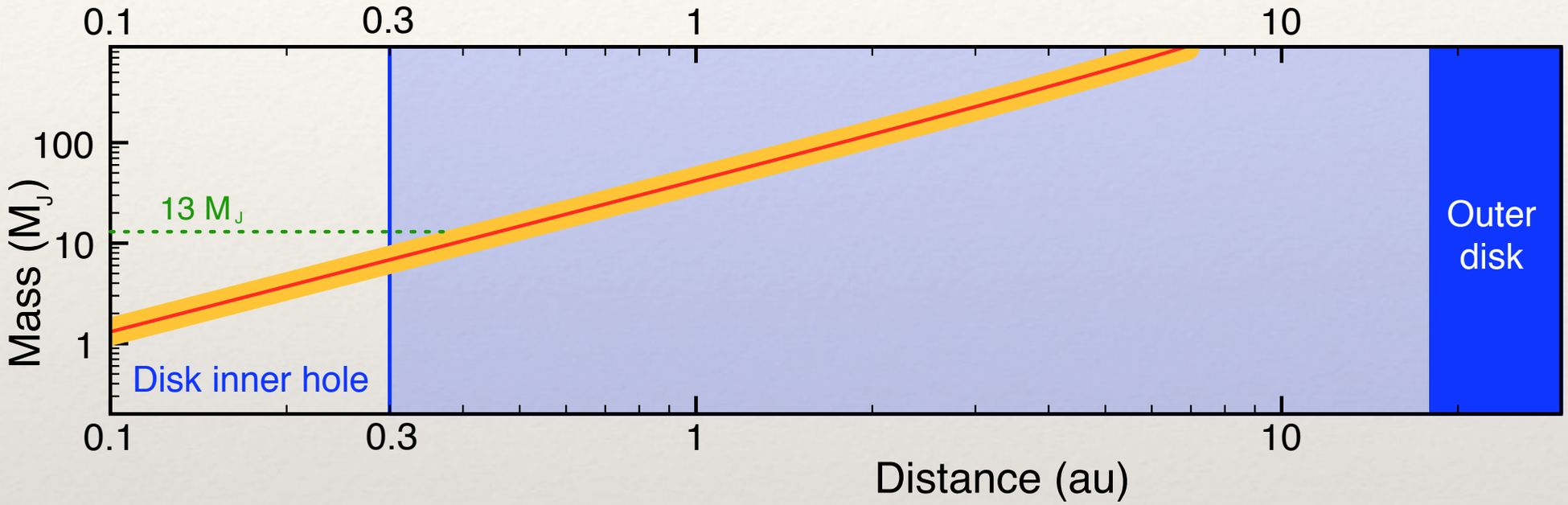


The jet bears record of the activity of the star and inner disk

Garufi et al. 2019

The jet and envelope of RY Tau





The jet wiggle may indicate the presence of a planetary companion that induces a disk warp.

Garufi et al. 2019

Conclusions

The NIR direct imaging cannot really characterize the **inner disk** yet.

But we are getting there…

Thank you.