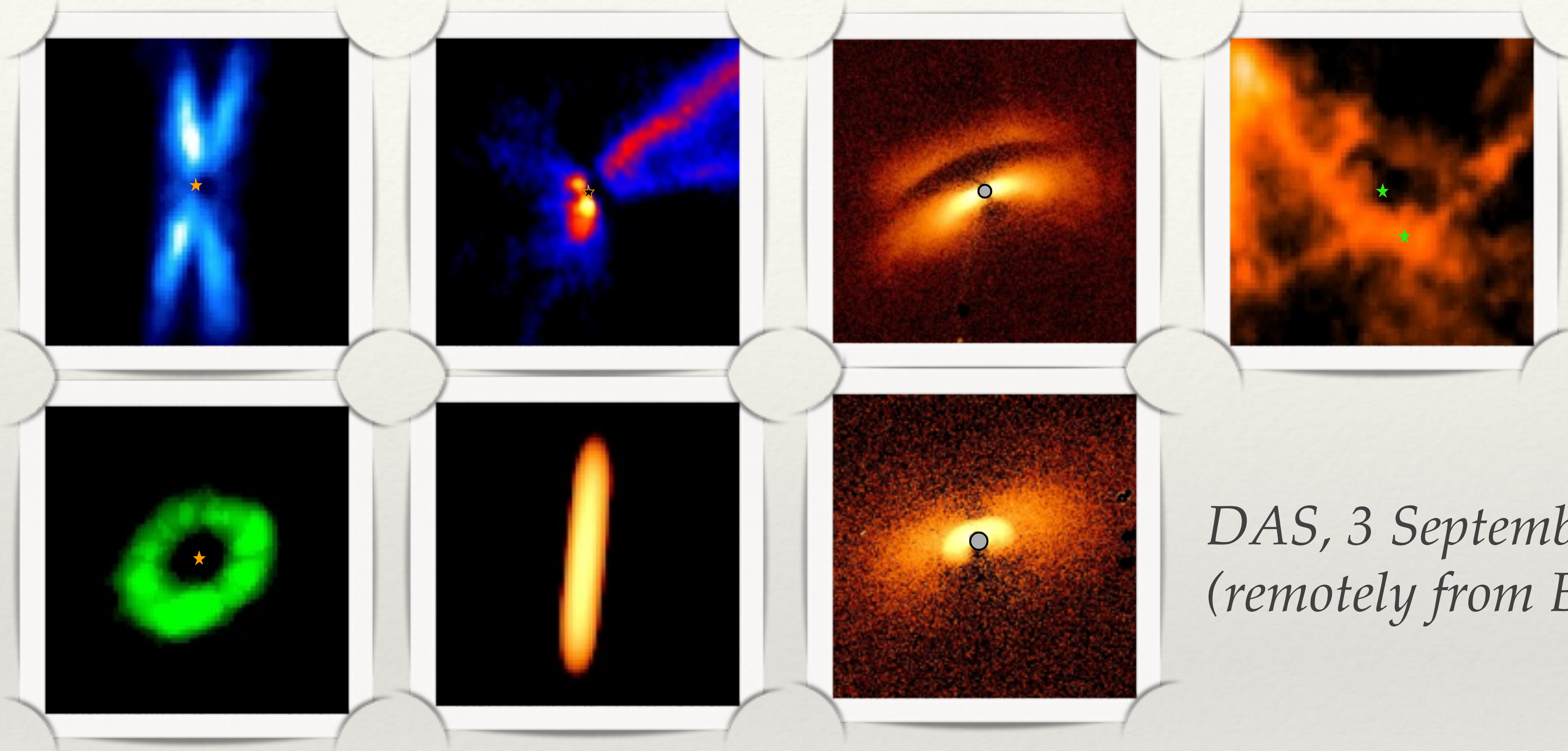


DAS, 3 September 2020 (remotely from Bologna, IT).

Imaging the planet formation. Sooner.

Antonio Garufi
OA Arcetri, INAF
and H. Avenhaus, **F. Bacciotti,** A. Banzatti, M. Benisty, **C. Codella,** C. Dominik, **D. Fedele**, C. Ginski, S. Perez, P. Pinilla, **L. Podio**, S. Quanz, SPHERE/GTO

Geographical background: Arcetri

Geographical background: Italy

Planet formation in a nutshell

The majority of stars host at least one **planet**.

.

A large variety of planetary systems exists.

.

Planets form in **protoplanetary disks**.

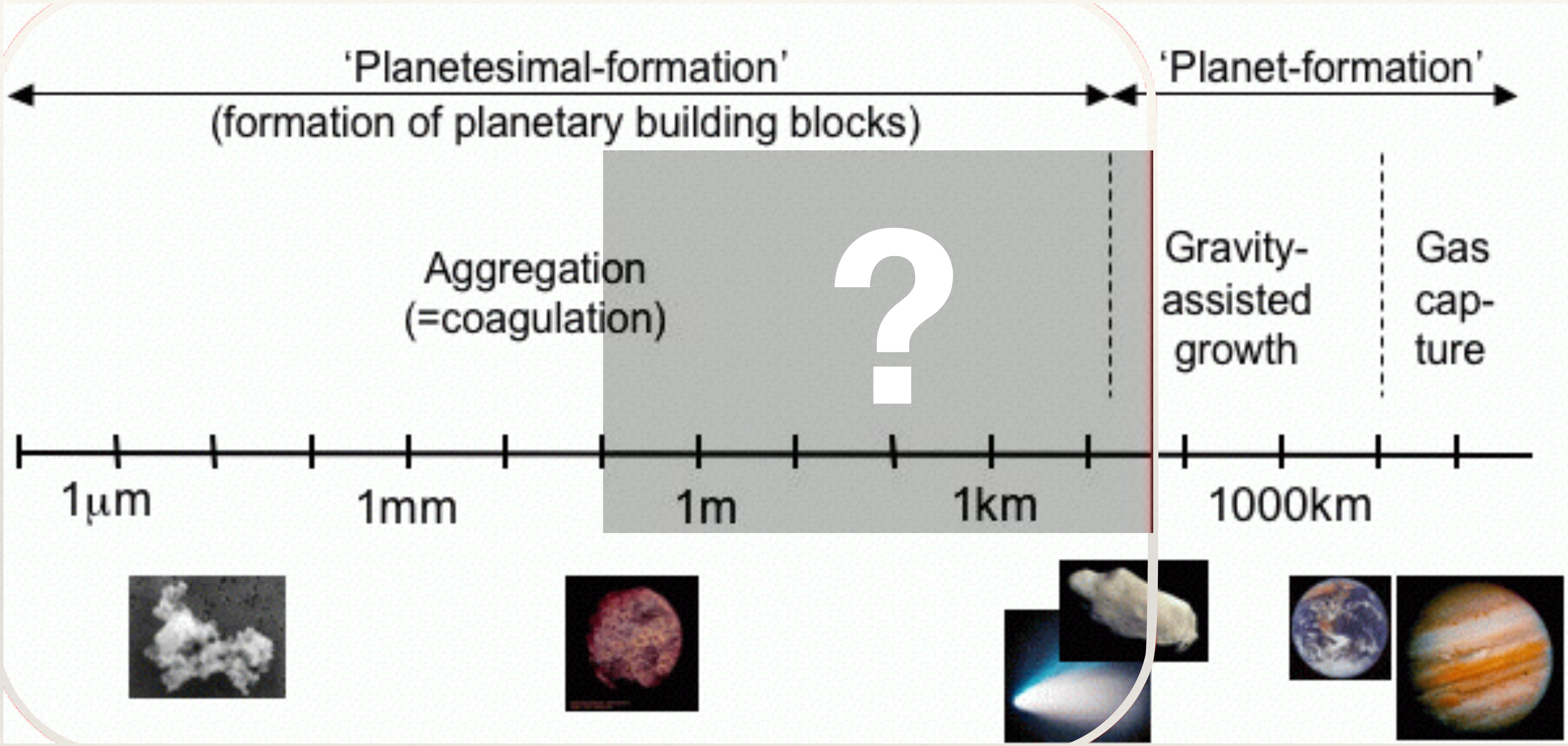
.

The formation of giant planets must be **rapid** (<10 Myr).

.

Planet formation is not “easy” for us. It is for Nature.

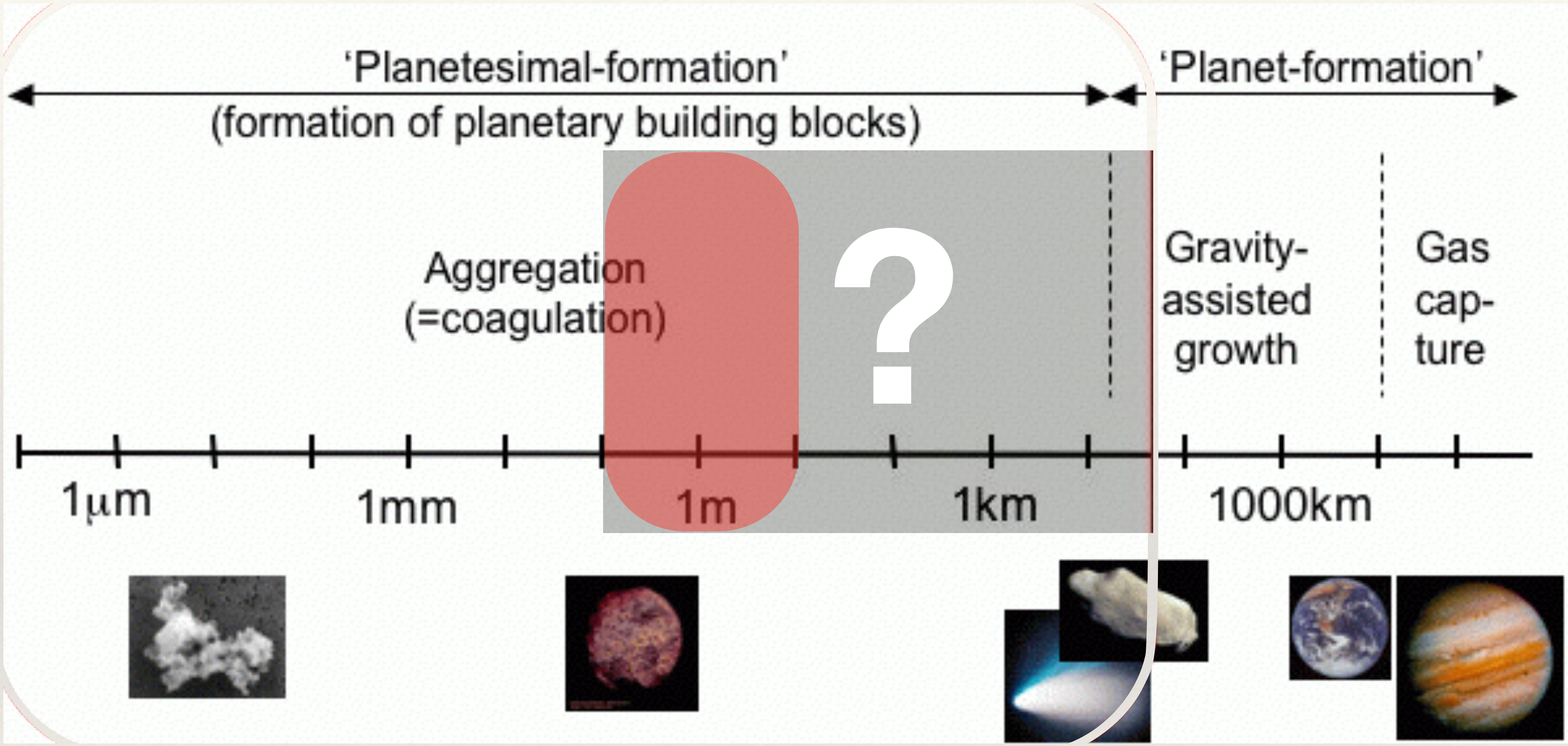
Planet formation in a nutshell



K. Dullemond

Out of 14 orders of magnitude involved,
6 are not observable.

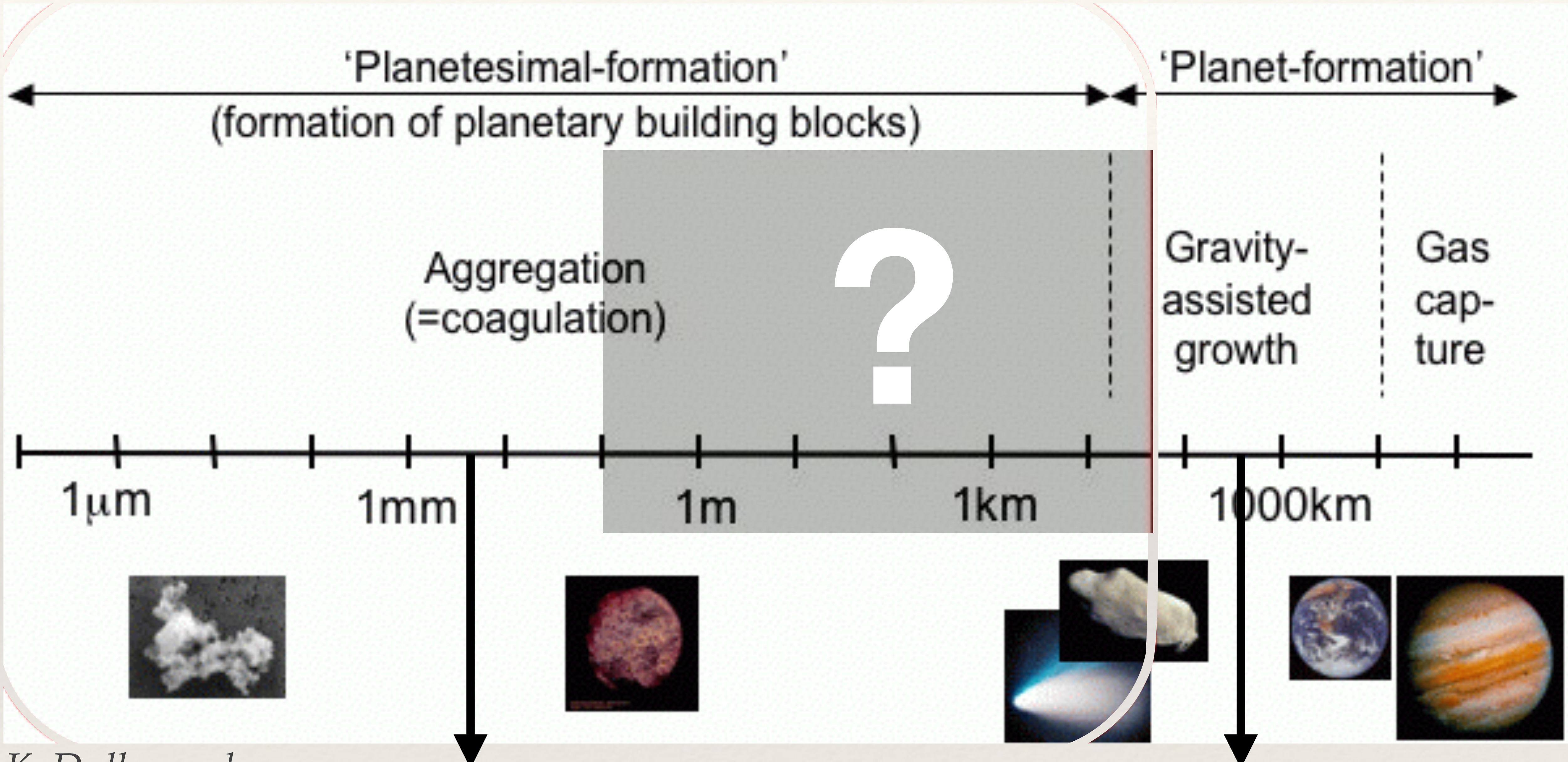
Planet formation in a nutshell



K. Dullemond

Out of 14 orders of magnitude involved,
6 are not observable, and 2 are the **meter barrier**.

Planet formation in a nutshell



K. Dullemond

The molecular gas in disks observed by ALMA…

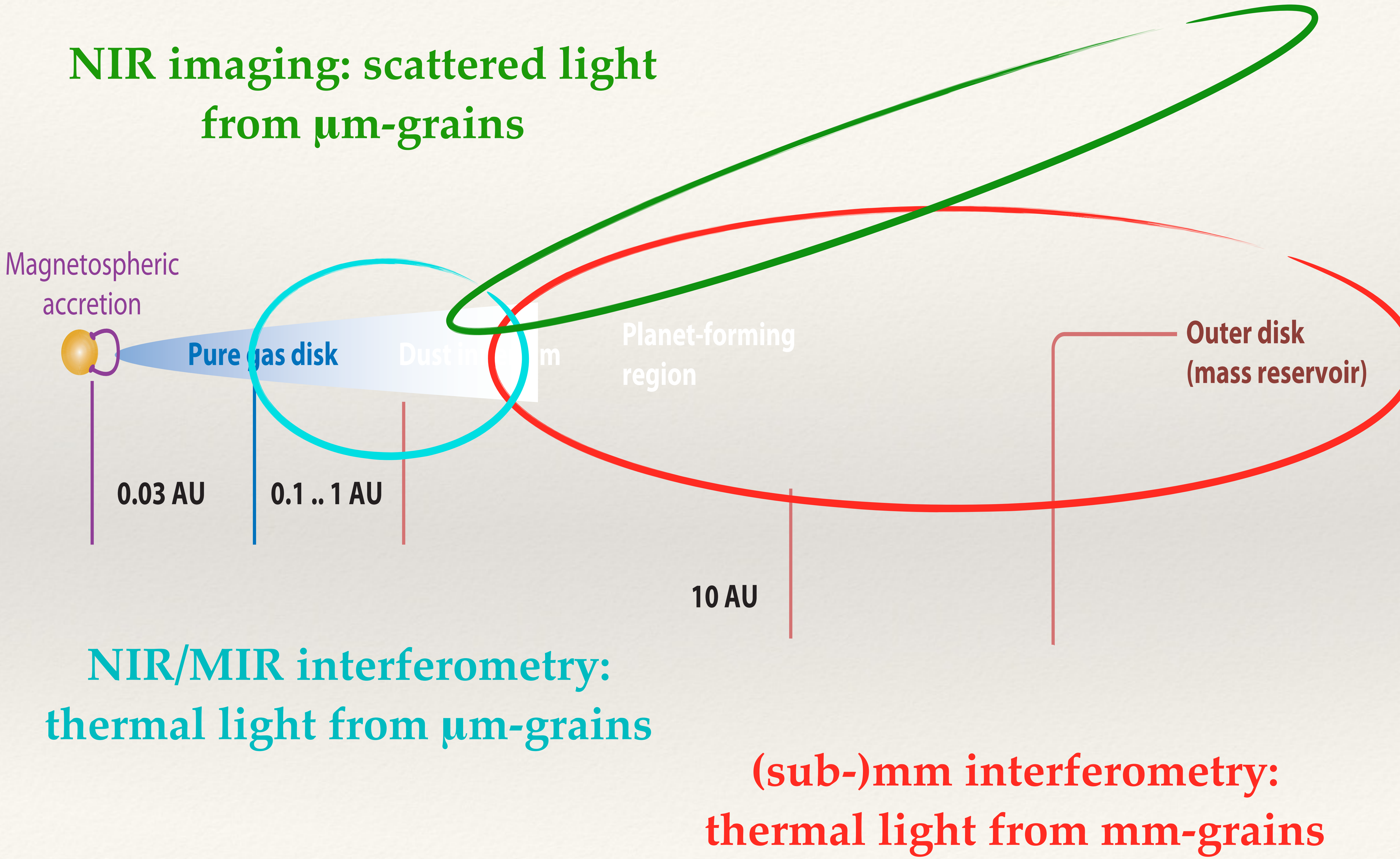
…is delivered to planetary atmospheres

Imaging protoplanetary disks

Dullemond & Monnier 2010

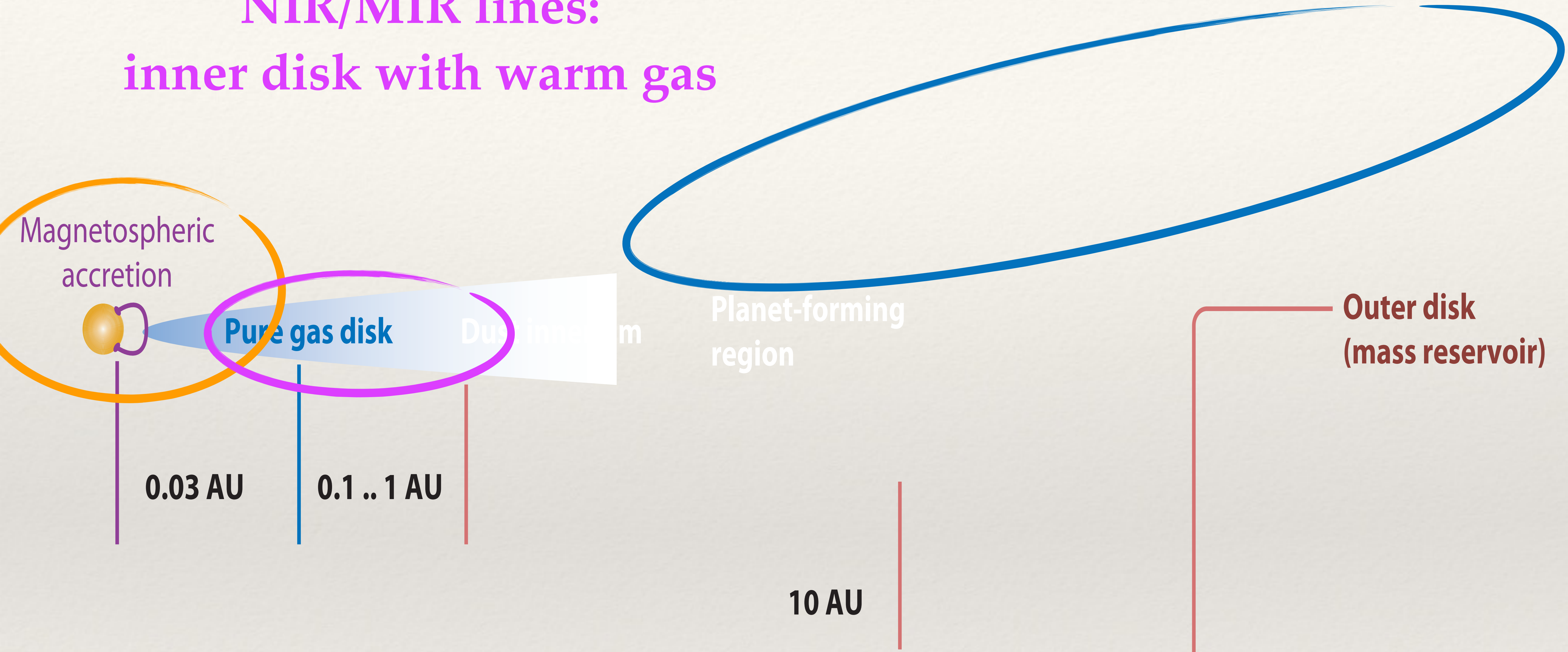
Imaging the planet-forming region of disks require **high resolution** and, in the visible, high **contrast**.

Imaging protoplanetary disks



Imaging protoplanetary disks

NIR/MIR lines:
inner disk with warm gas

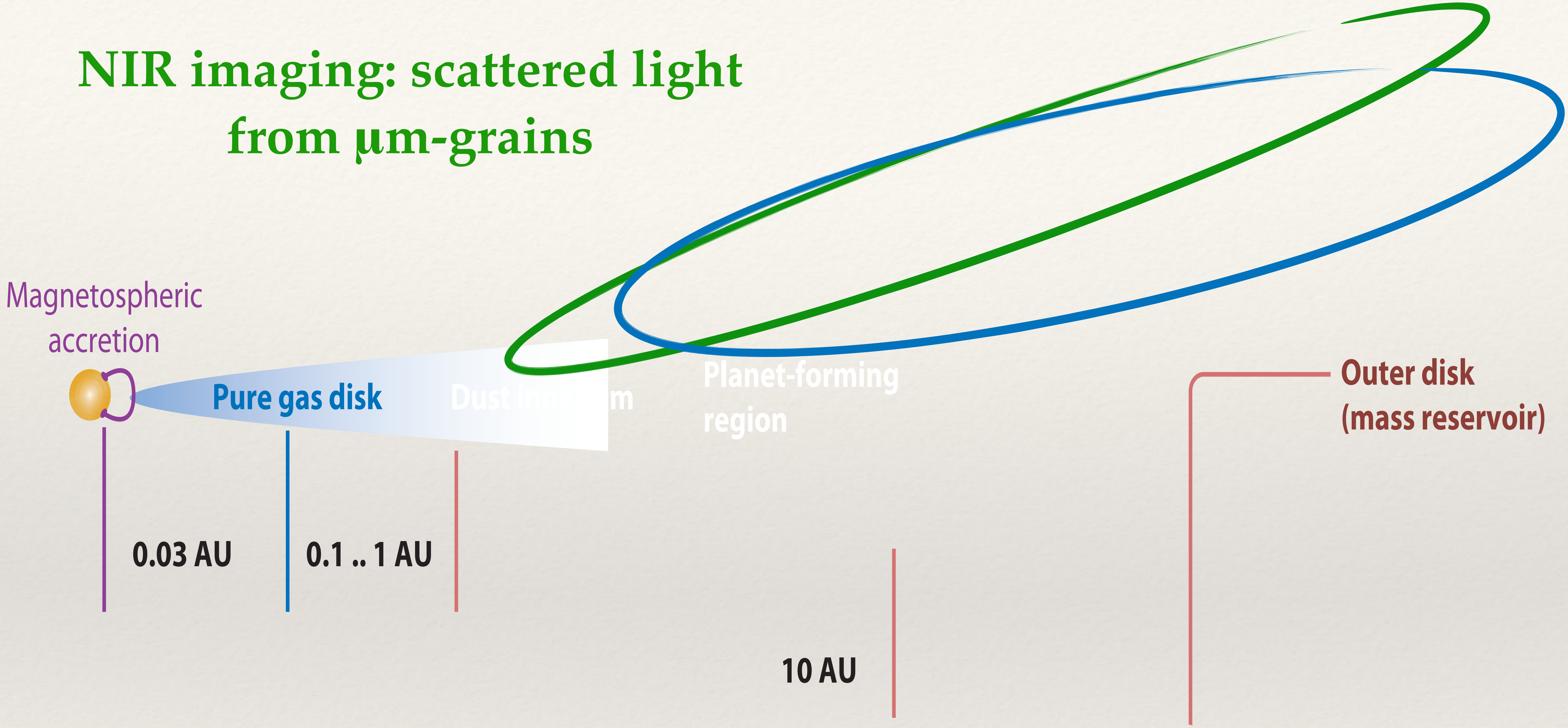


Optical/NIR lines:
stellar/accretion processes

(sub-)mm lines:
molecular layer of cold gas

Imaging protoplanetary disks

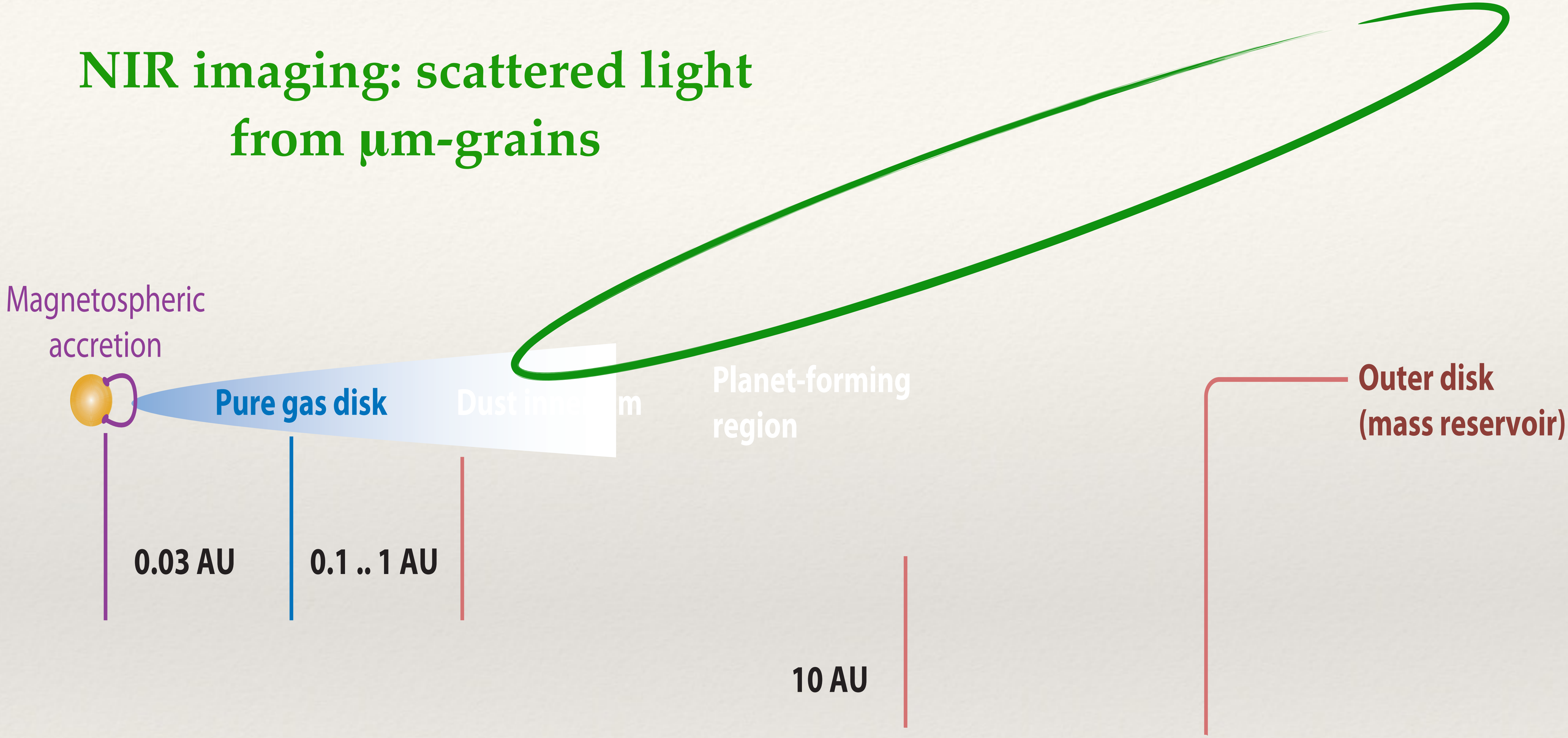
NIR imaging: scattered light from µm-grains



This talk is on these techniques.

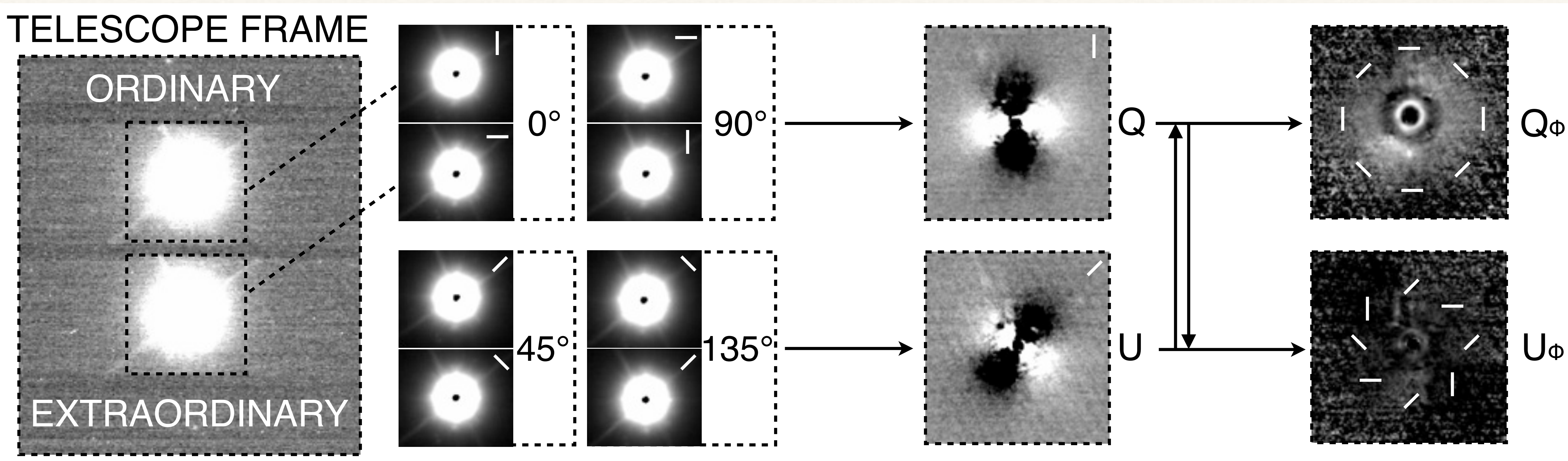
(sub-)mm lines: molecular layer of cold gas

Imaging protoplanetary disks



In the visible, the stellar flux dominates.
We need **differential** techniques to suppress it.

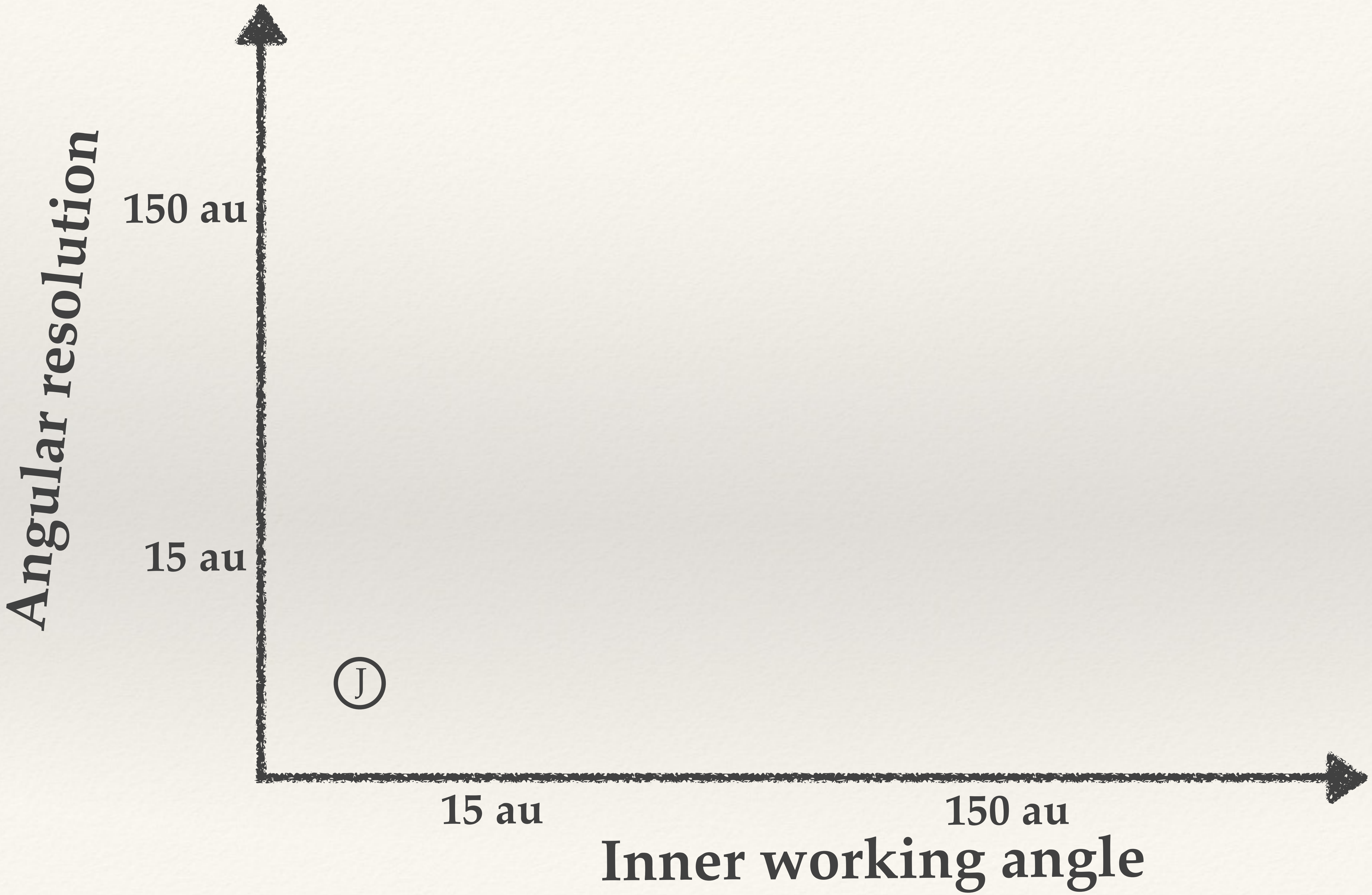
Dual Polarization Imaging



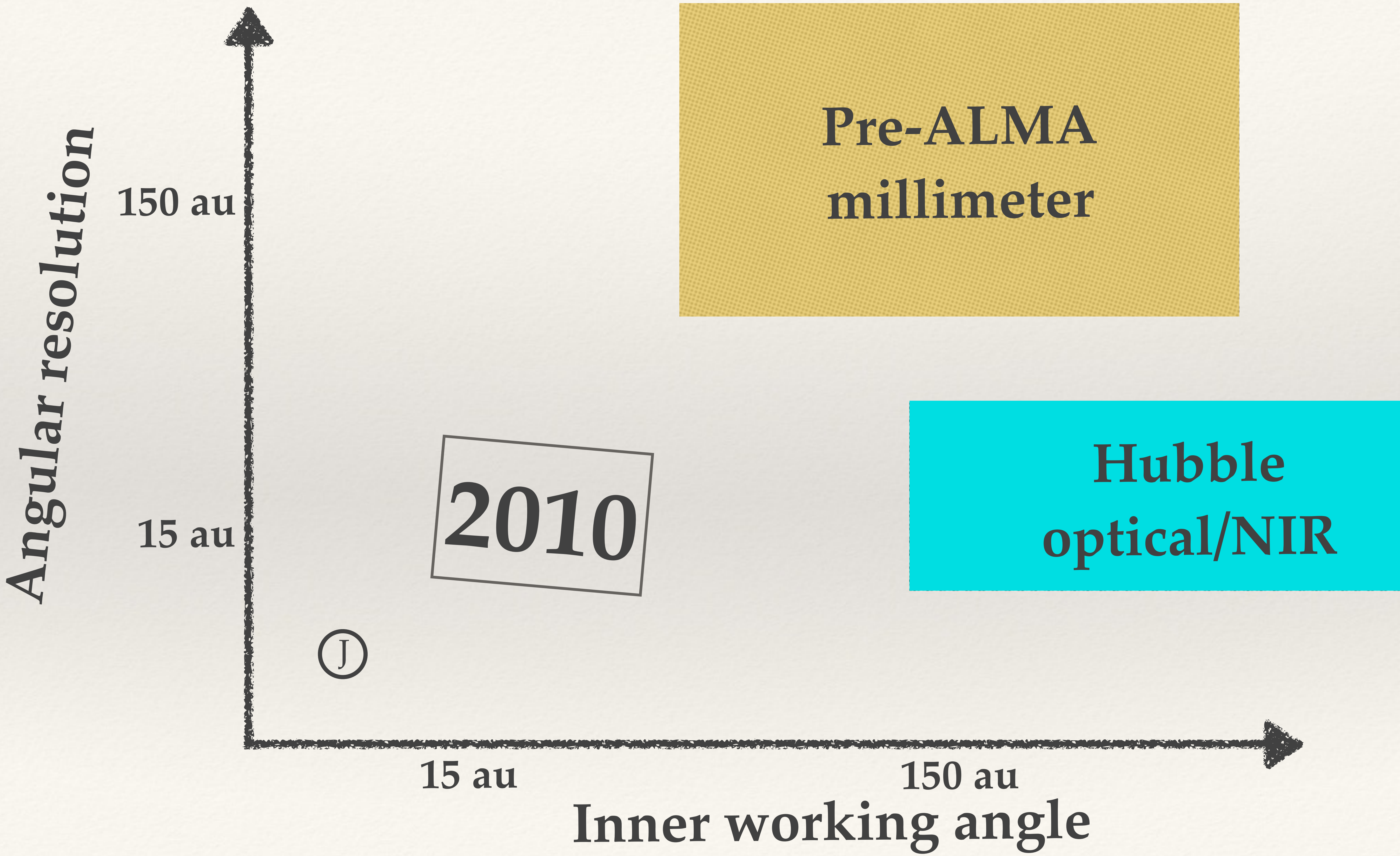
Stellar light is mainly unpolarized.
Scattered light from the disk is largely polarized.

Polarized light traces the small grains at the surface.

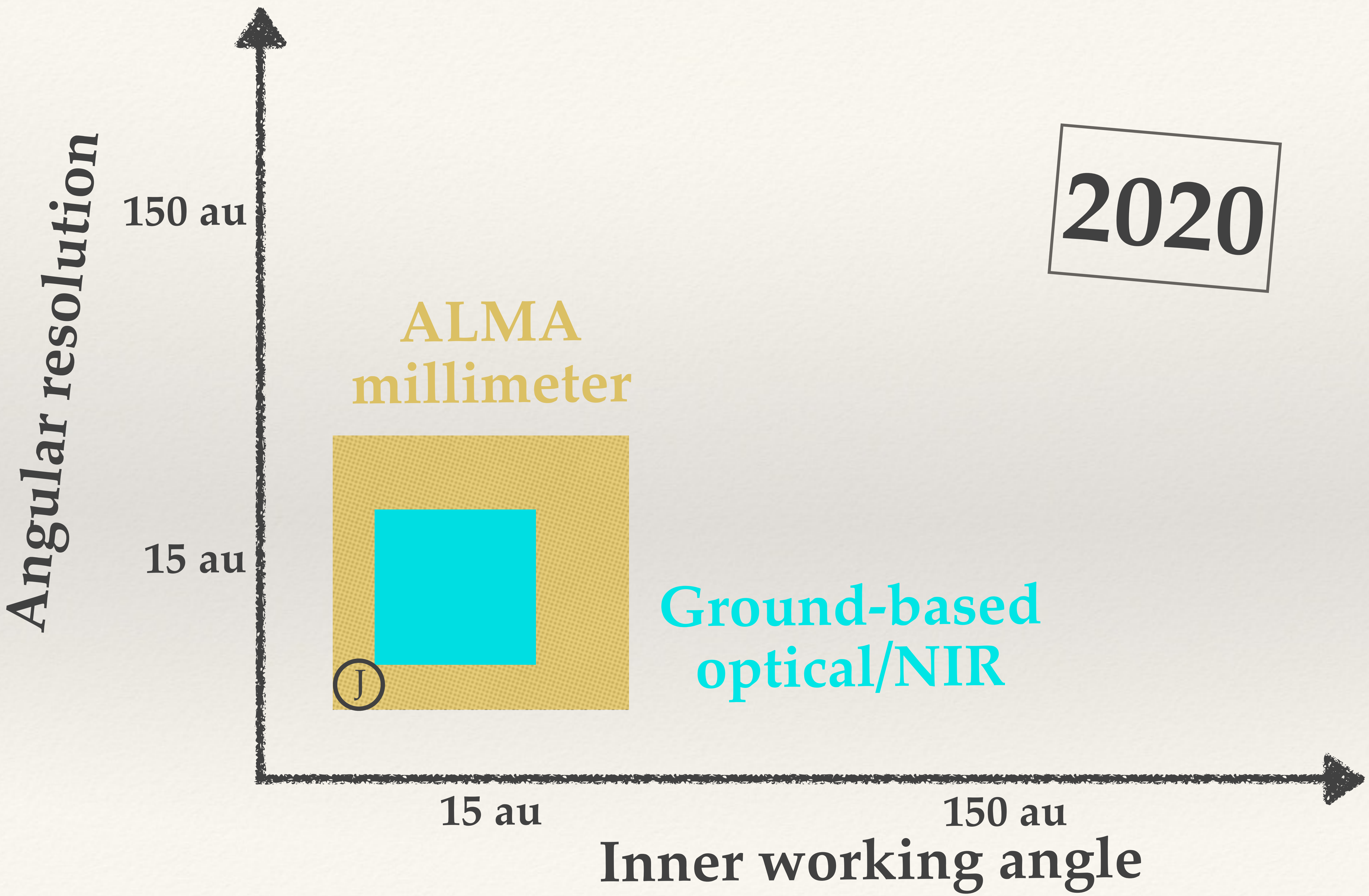
Imaging protoplanetary disks



Imaging protoplanetary disks



Imaging protoplanetary disks



Imaging protoplanetary disks

Over the last decade, about **200 disks** have been imaged with high resolution

(90 with ALMA, 150 with SPHERE/NACO/GPI/HiCiao)

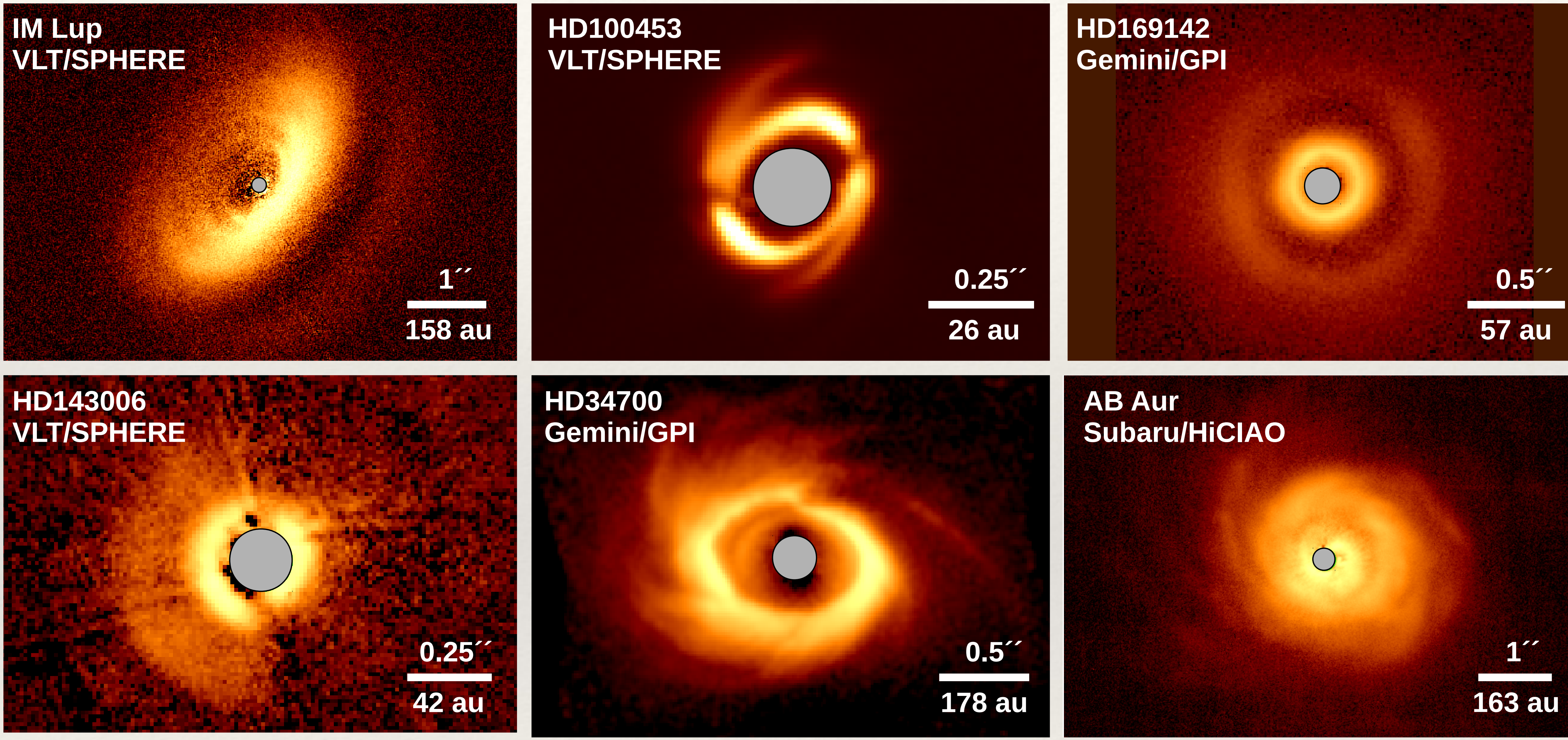
Imaging protoplanetary disks

Over the last decade, about **200 disks** have been imaged with high resolution

(90 with ALMA, 150 with SPHERE/NACO/GPI/HiCiao)

The most obvious result of this census is the ubiquity of disk **sub-structures.**

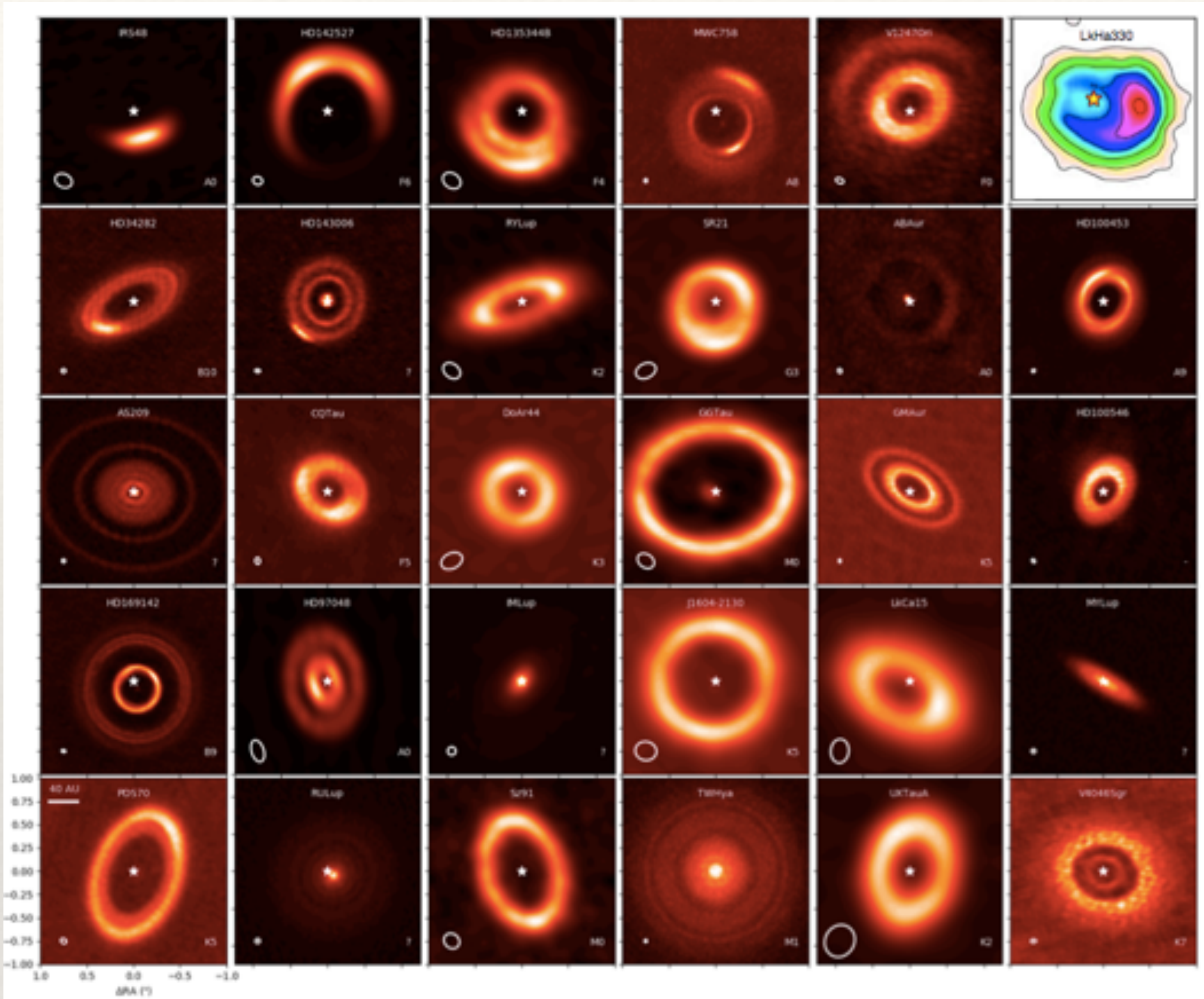
Imaging small dust grains



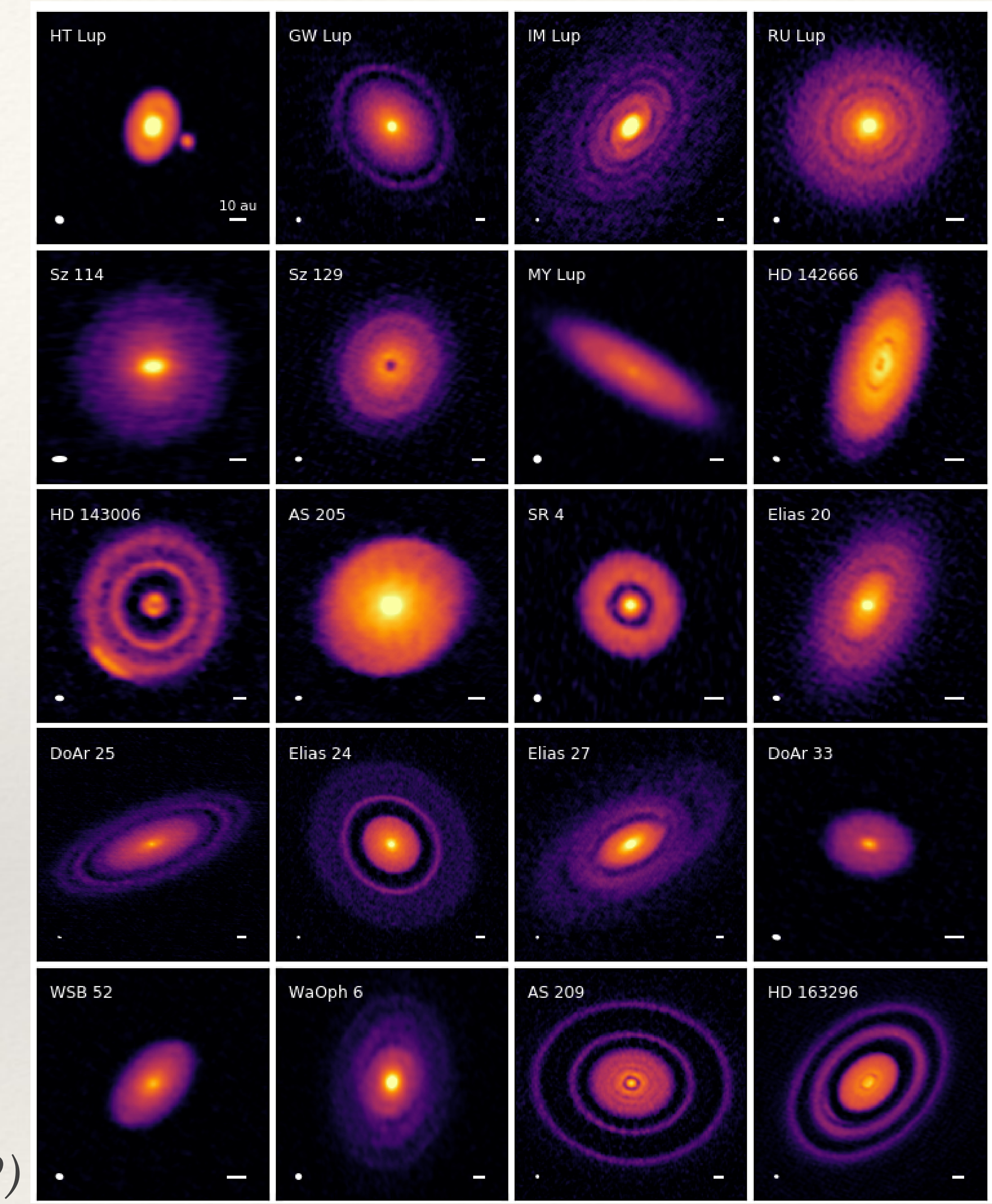
Benisty et al.

Rings, spirals, shadows, cavities in the NIR…

Imaging large dust grains



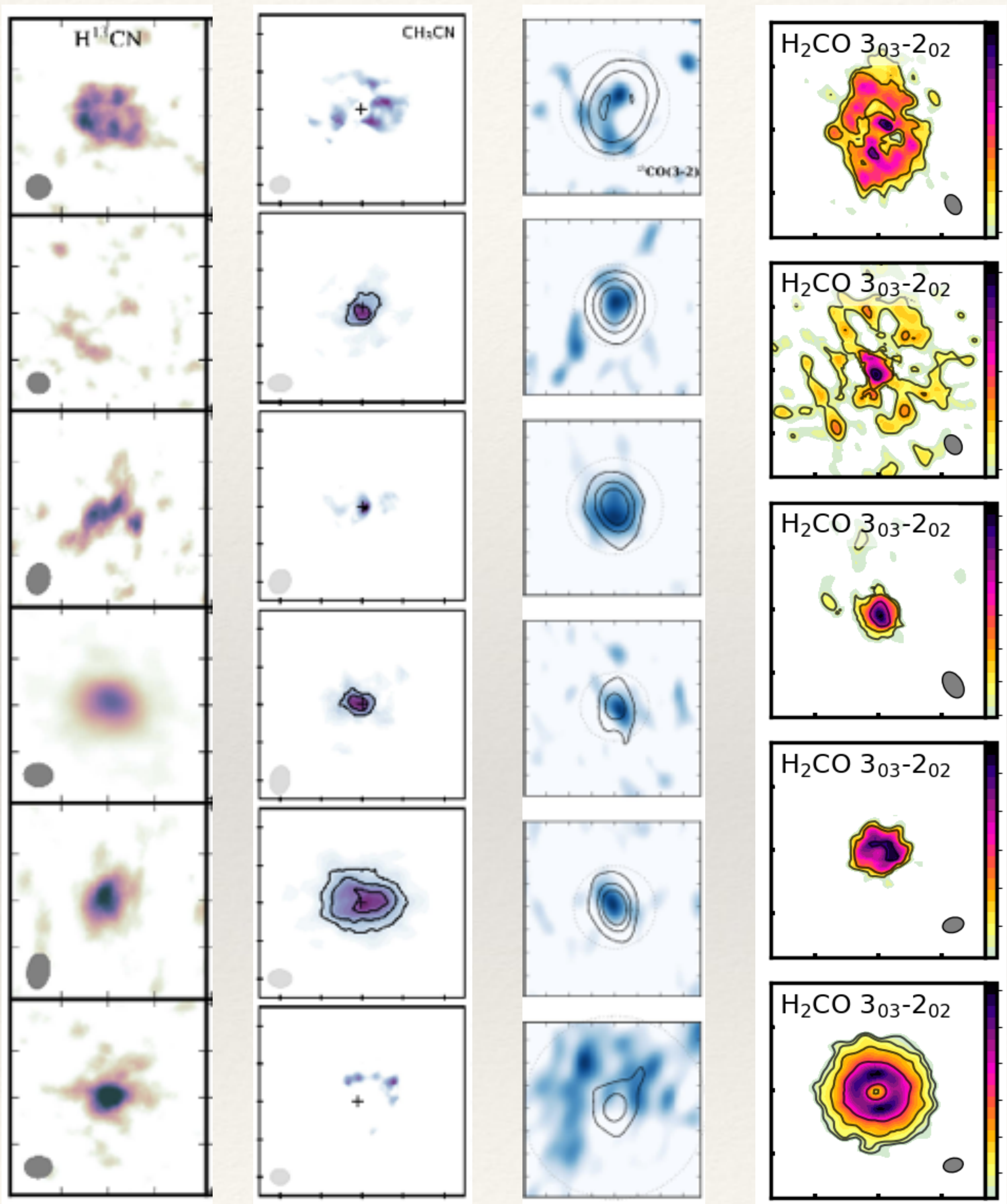
van der Marel from ALMA archive



Andrews et al. 2018 (DSHARP)

…and again rings, spirals, cavities
but also asymmetries in the millimeter.

Imaging gas



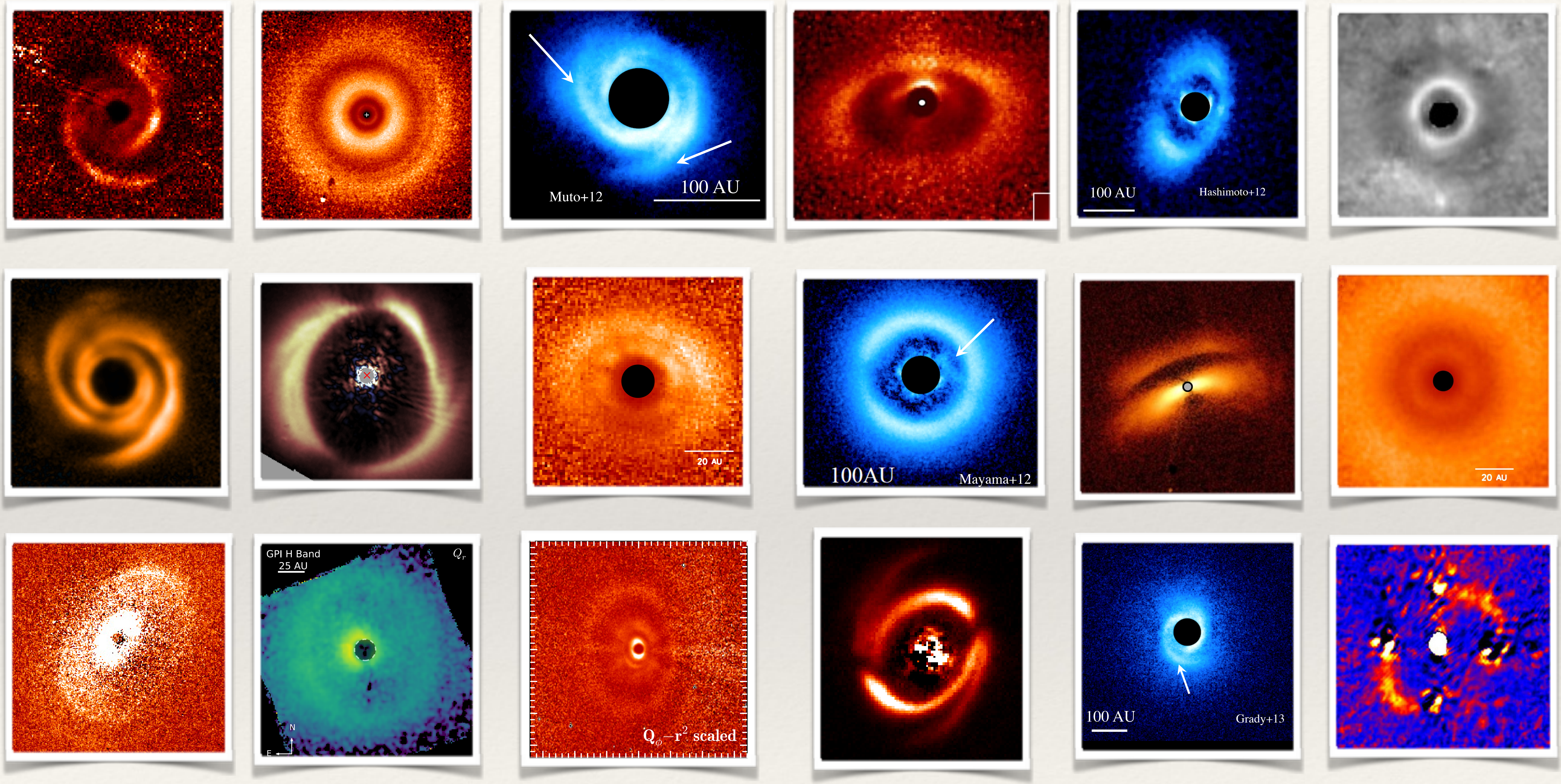
Gas is less characterized because of moderate angular resolutions and biases toward bright lines (^{12}CO).

Guzman et al. 2017, Bergner et al. 2017, Long et al. 2017, Pegues et al. 2020

Part I

Disks in NIR scattered light with SPHERE

Taxonomy of protoplanetary disks



As of 2018, nearly 100 disks were observed.

Evolution of protoplanetary disks from their taxonomy in scattered light: spirals, rings, cavities, and shadows

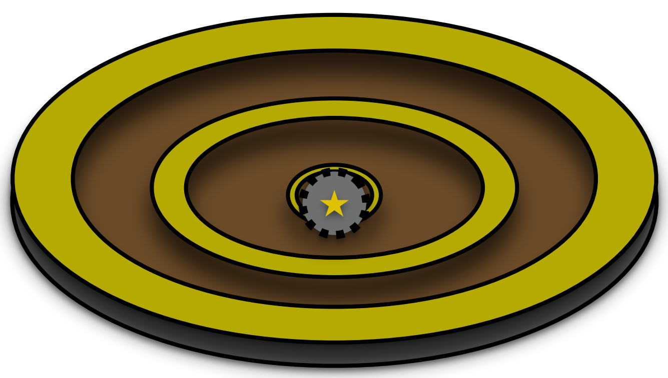
A. Garufi[1], M. Benisty[2,3], P. Pinilla[4], M. Tazzari[5], C. Dominik[6], C. Ginski[6], Th. Henning[7], Q. Kral[8], M. Langlois[12,13], F. Ménard[3], T. Stolker[9], J. Szulagyi[10], M. Villenave[11,3], and G. van der Plas[3]

The large sample allows to study how disk features relate with stellar and other disk properties.

Evolution of protoplanetary disks from their taxonomy in scattered light: spirals, rings, cavities, and shadows

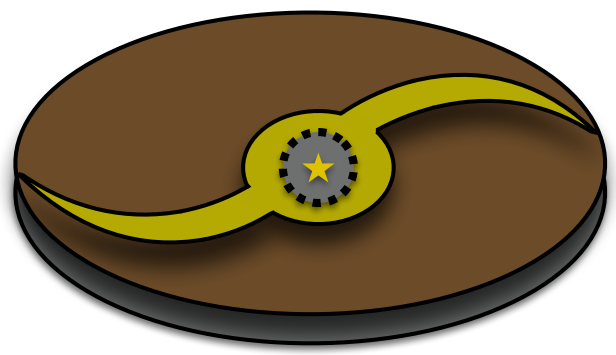
A. Garufi[1], M. Benisty[2,3], P. Pinilla[4], M. Tazzari[5], C. Dominik[6], C. Ginski[6], Th. Henning[7], Q. Kral[8], M. Langlois[12,13], F. Ménard[3], T. Stolker[9], J. Szulagyi[10], M. Villenave[11,3], and G. van der Plas[3]

Rings



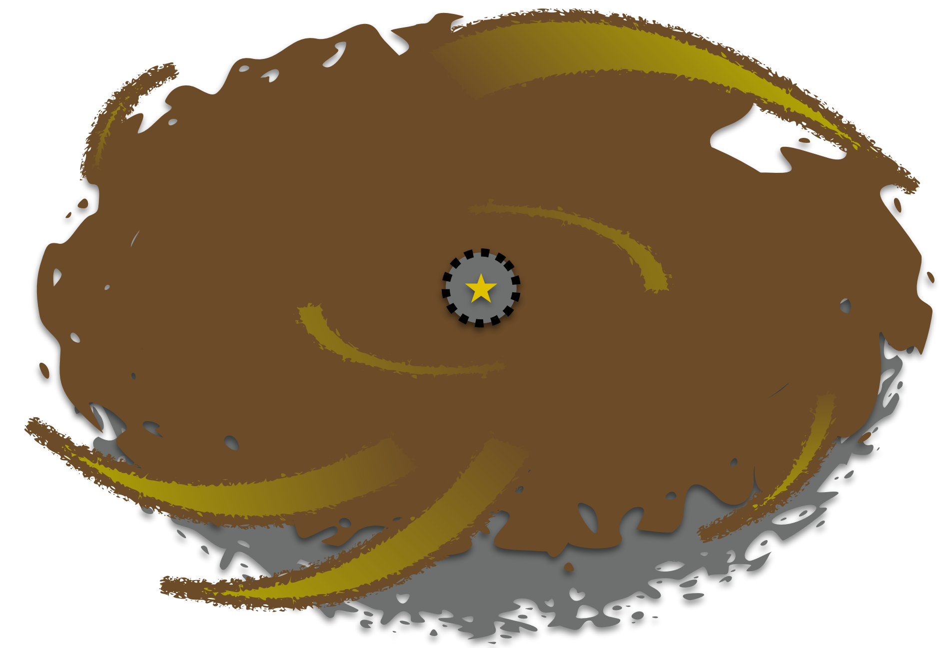
Multiple symmetric, bright annuli.
Prototypes: TW Hya, HD97048.

Spirals



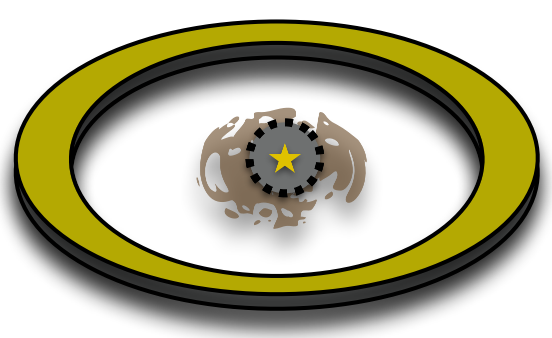
Symmetric, bright spirals on small scale.
Prototypes: HD135344B, MWC758.

Giant



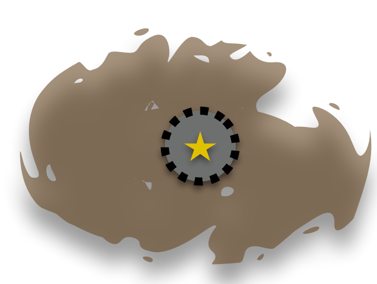
Wrapped, asymmetric arms on large scale.
Prototypes: HD100546, HD34282.

Rim



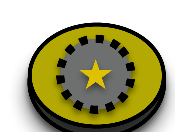
Mainly one ring around a cavity.
Prototypes: J1604, PDS70.

Faint



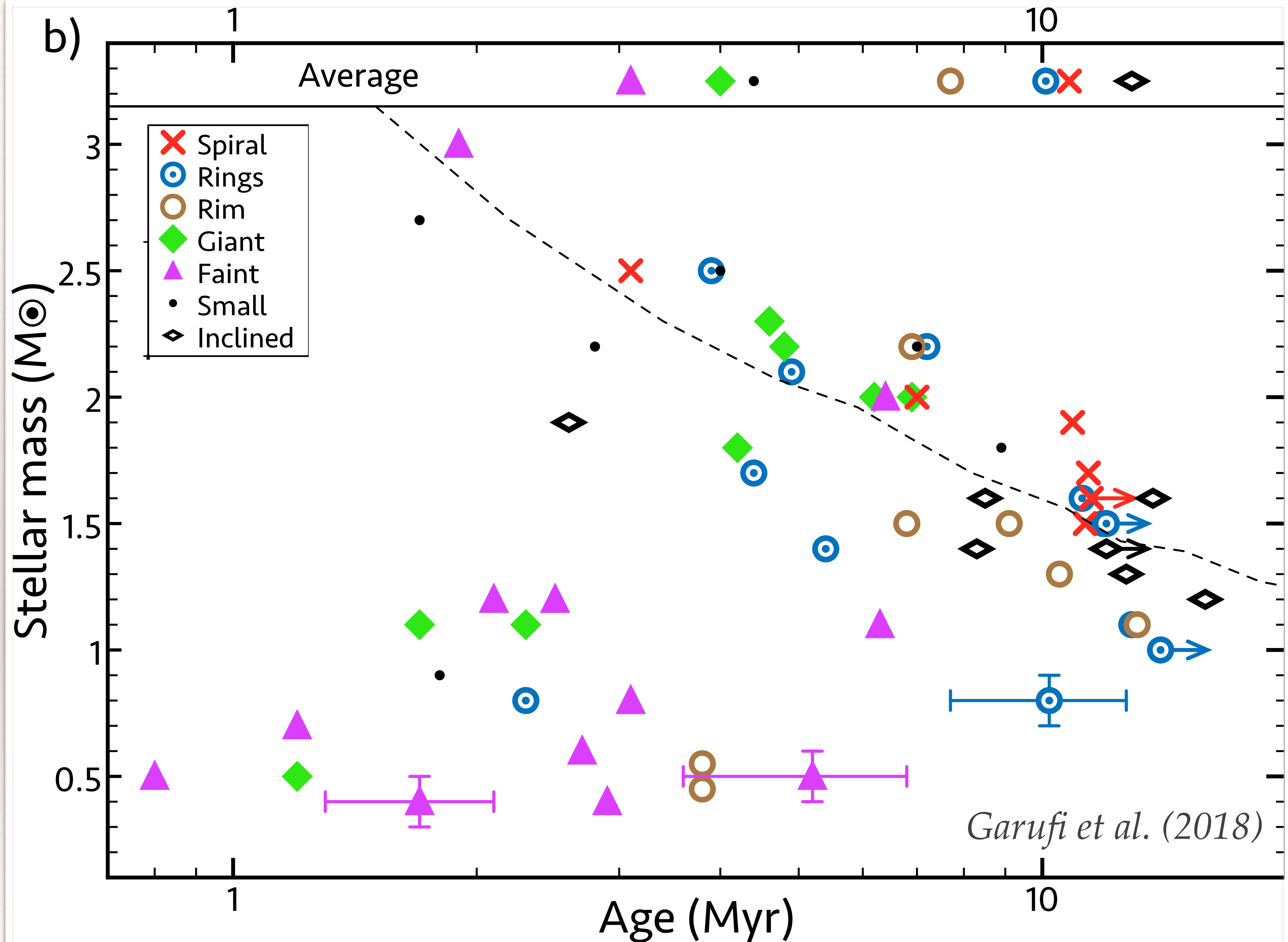
Low signal. No feature visible.
Prototypes: RU Lup, MWC480.

Small



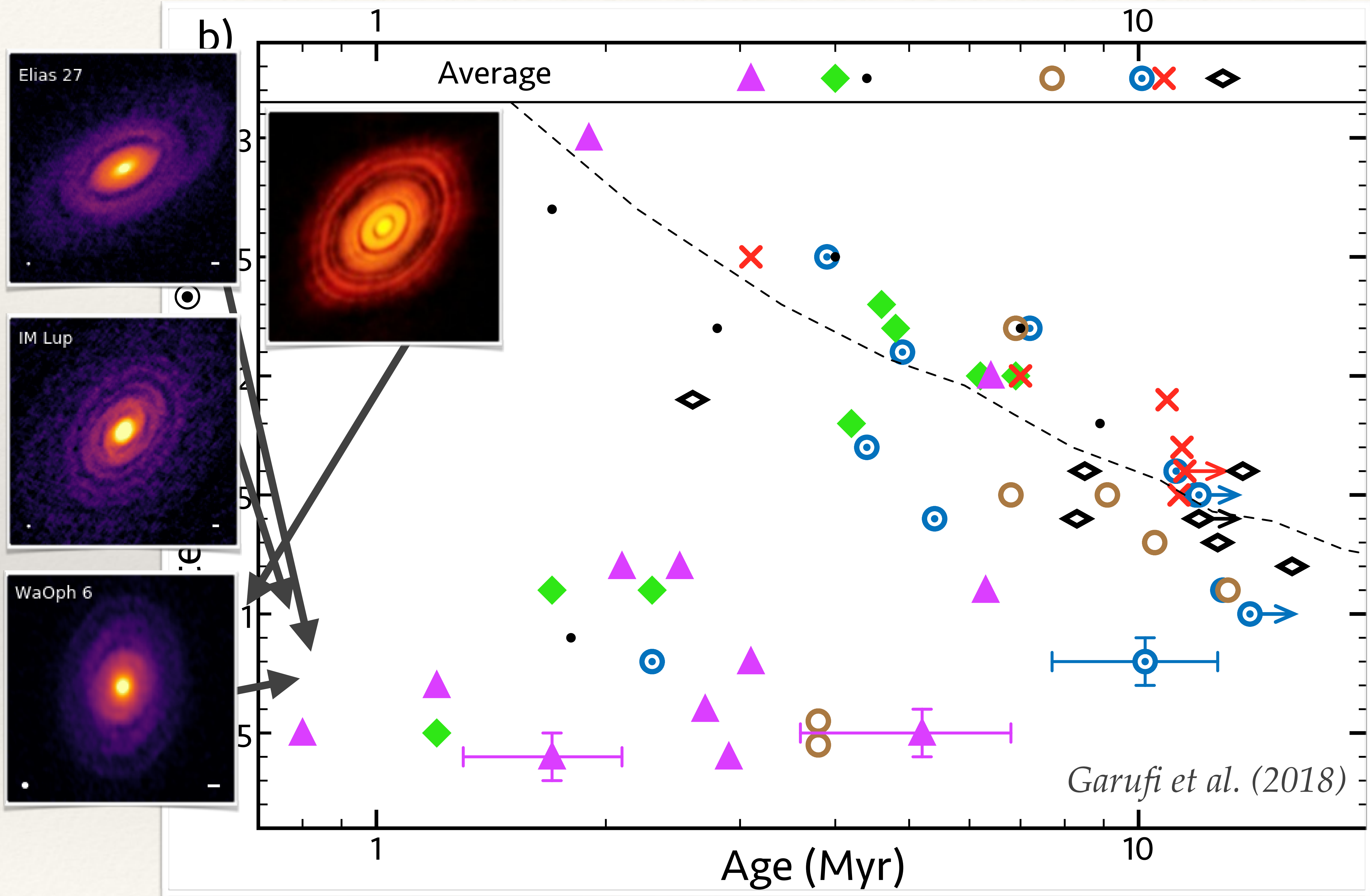
Signal on very small scale.
Prototypes: HD150193, CS Cha.

Taxonomy of protoplanetary disks



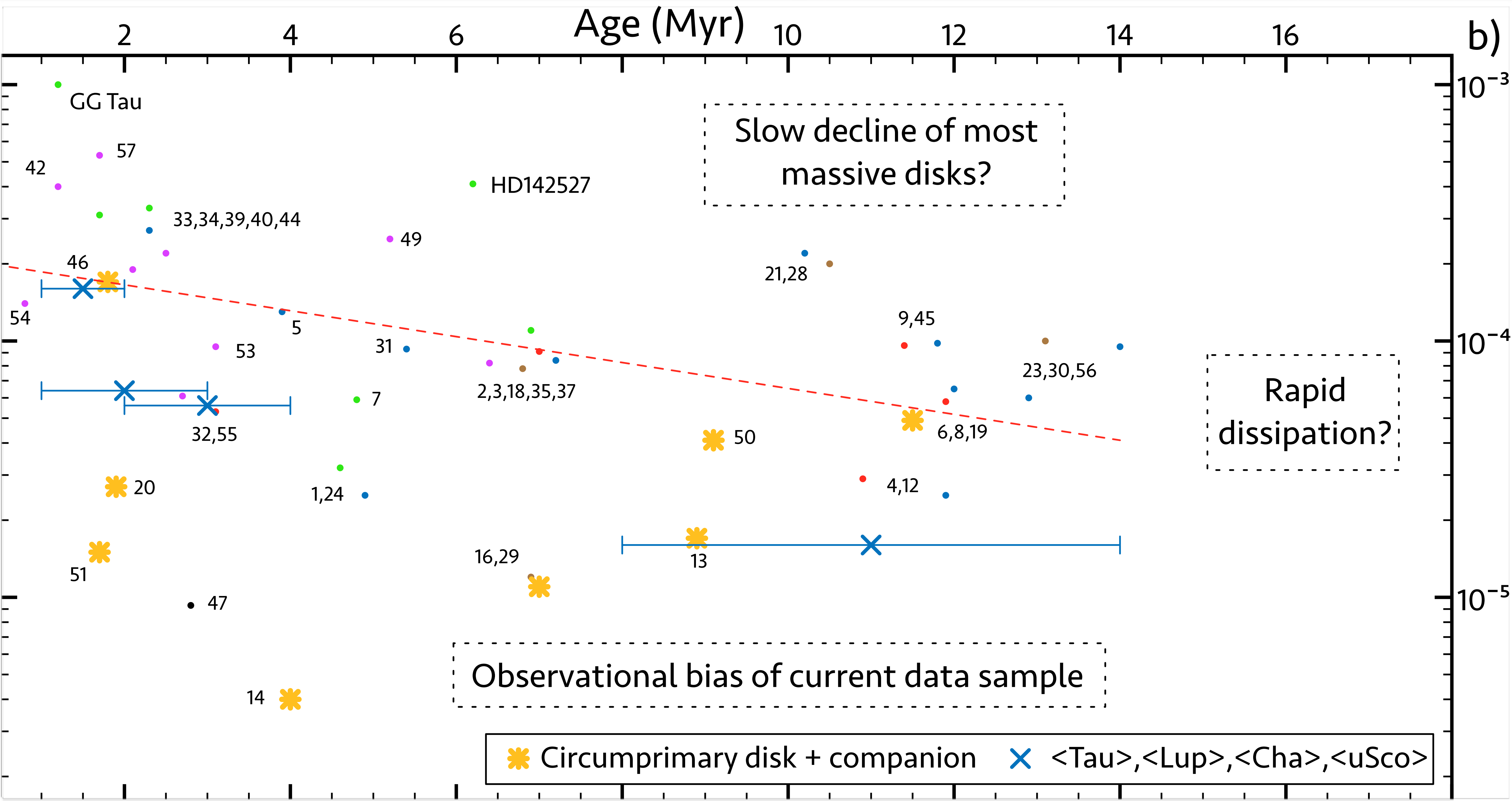
Young stars (< 2 Myr) are poorly represented.

Taxonomy of protoplanetary disks



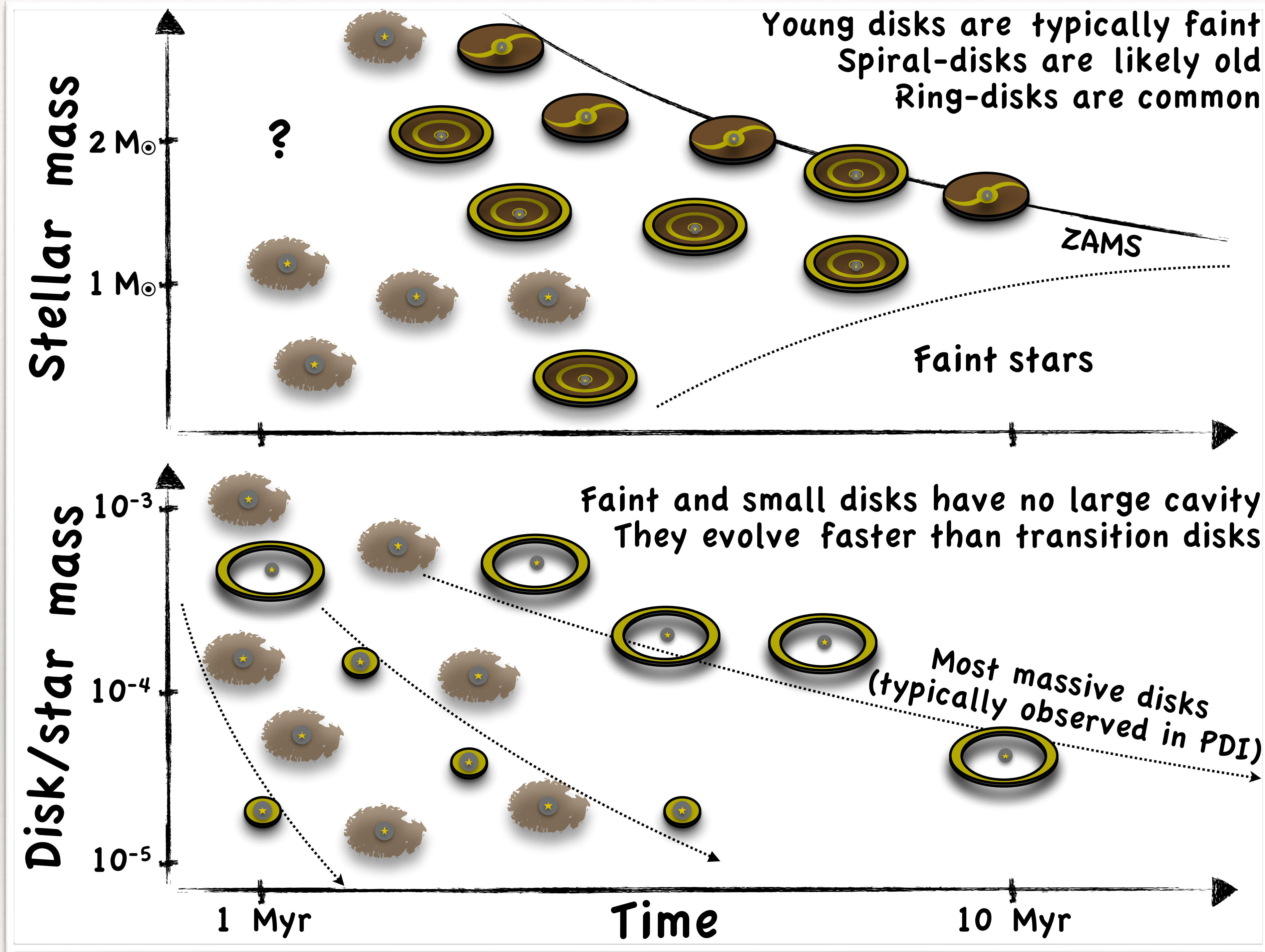
The few young ALMA sources show substructures

Taxonomy of protoplanetary disks



Mostly massive disks have been observed.

Taxonomy of protoplanetary disks



We must remember that we only know about **massive** (exceptional) **disks** around **old stars**.

Where shall we go from here?

When, where, and how often do planets form?

We need to alleviate the biases
by imaging younger, less special disks.

(SPHERE/DESTINYS by C. Ginski + ALMA Taurus survey by G. Herczeg).

Where shall we go from here?

When, where, and how often do planets form?

↓

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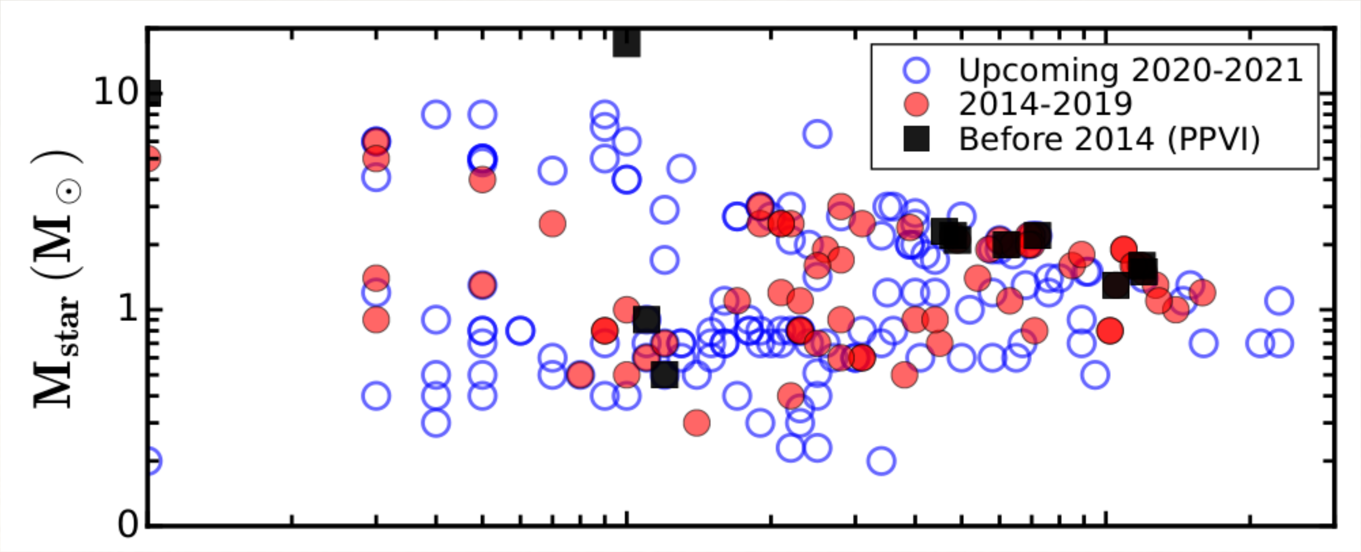
(SPHERE/**DESTINYS** by C. Ginski + ALMA Taurus survey by G. Herczeg).

DARTTS (ETH & Chile) + **ALMA-DOT** (Arcetri).

DESTINYS

SPHERE GTO is over but fun has just begun…

DESTINYS is a large program in open-time (P.I. Ginski) promising observations of >80 sources.



DARTTS

Disks Around TTSs with SPHERE

·

29 new targets studied
individually and demographically
(Avenhaus et al. 2018, Casassus et al. 2018, Garufi et al. 2020)

·

Both young (1-3 Myr) and old stars.

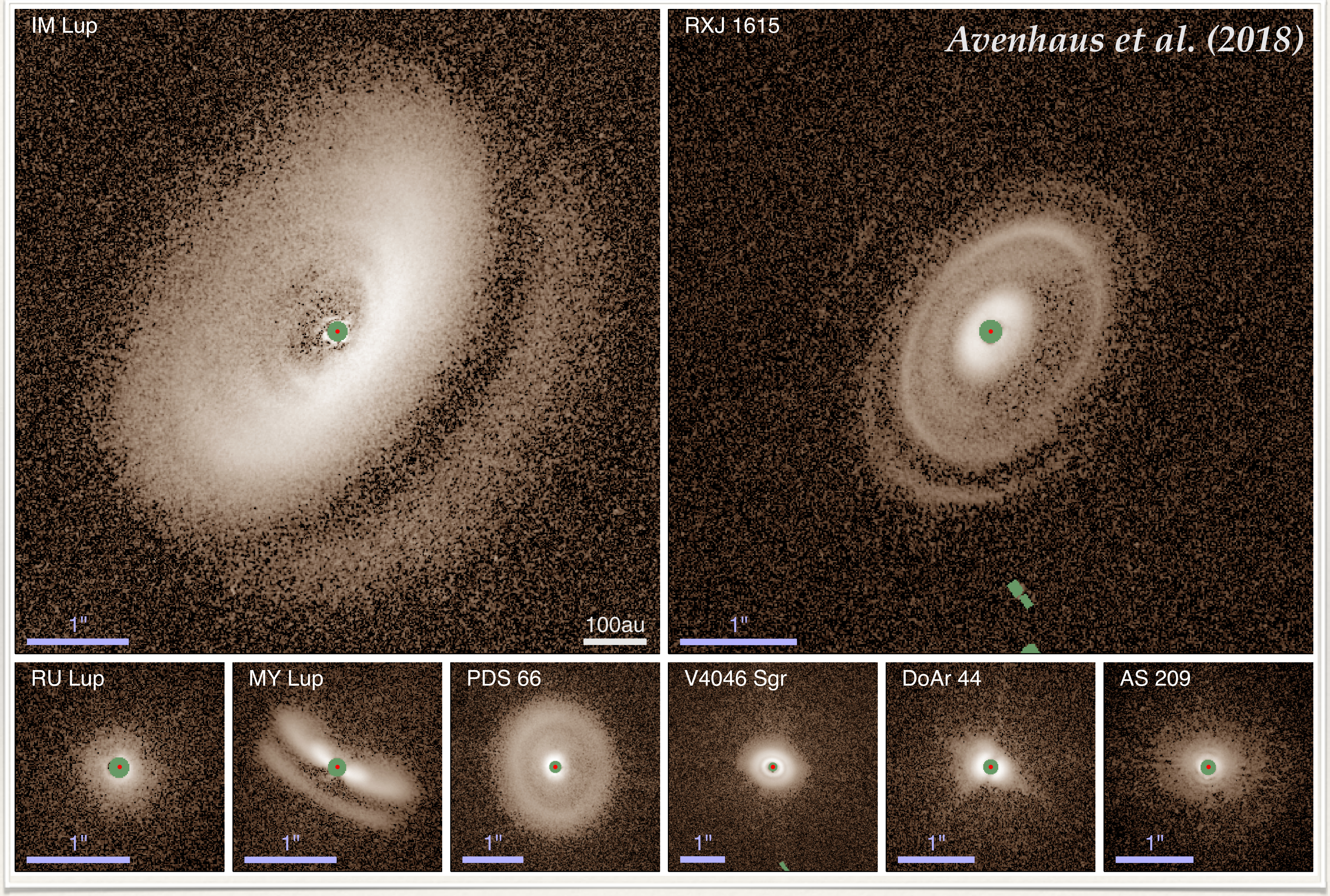
·

Only disks with available mm images.

·

Large variety of disk dust masses.

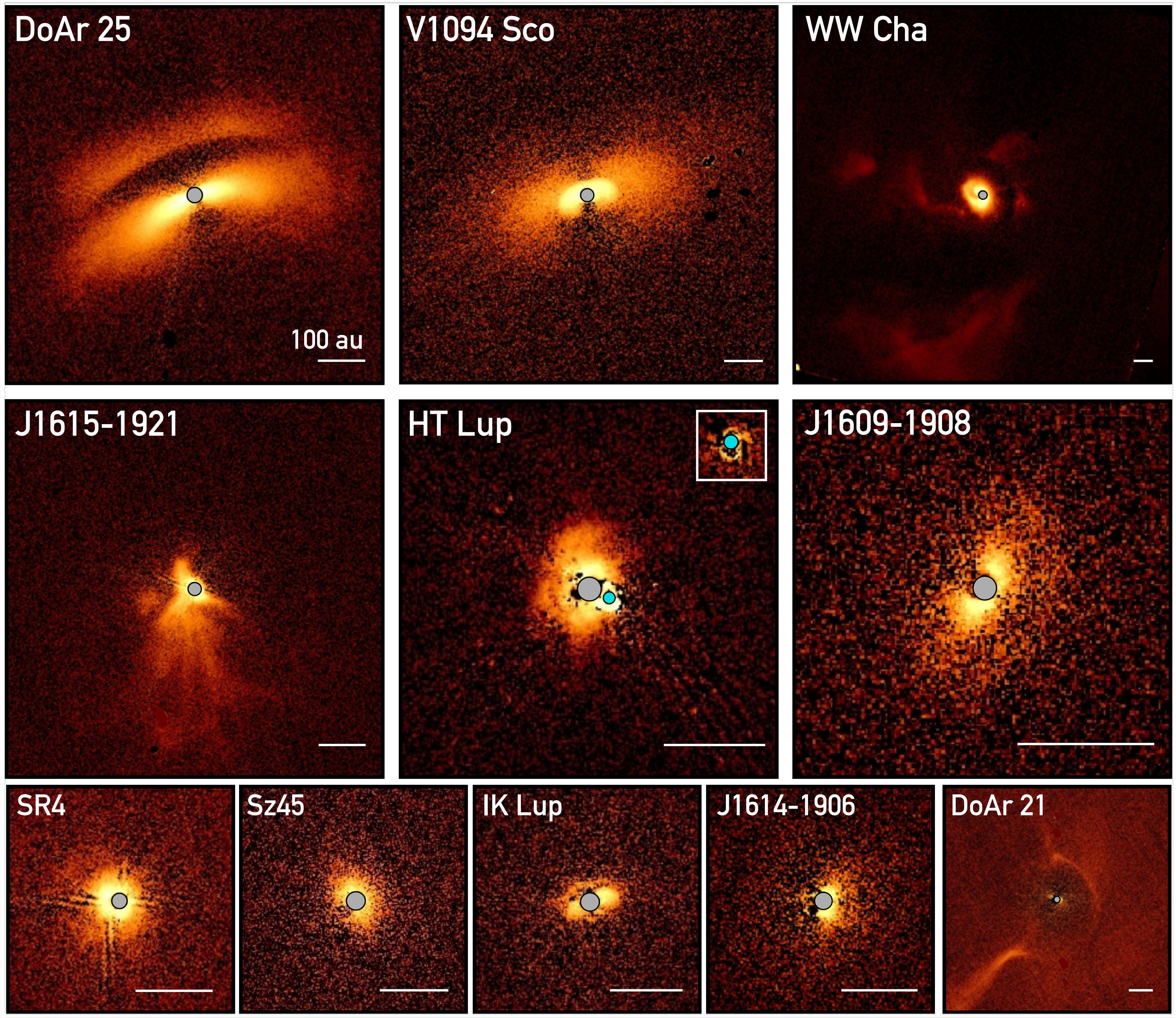
DARTTS I



Clear sub-structures (but no spiral) in most disks.

General agreement in the scale height (~16 au at r=100 au).

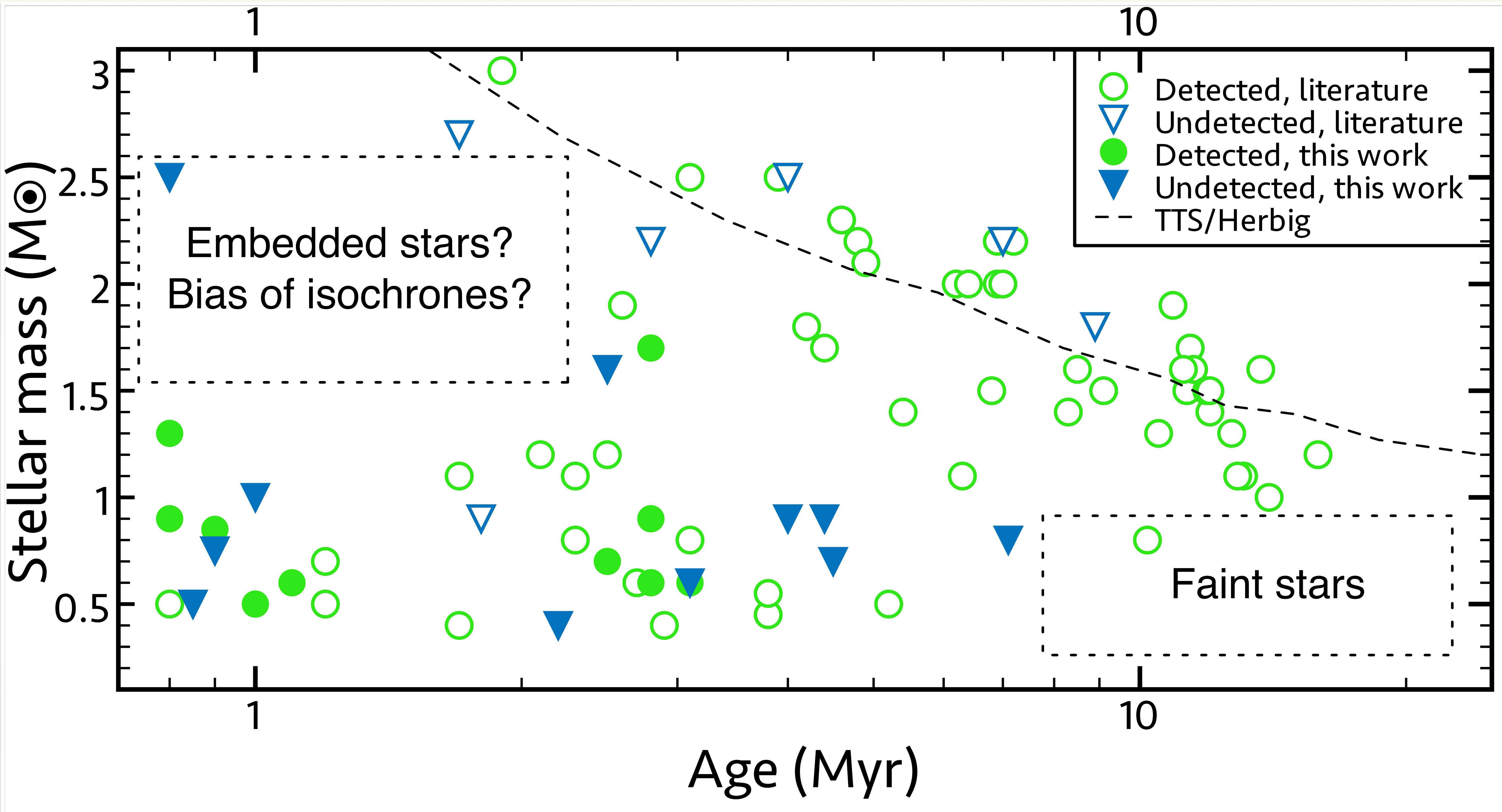
DARTTS II



Garufi et al. (2020)

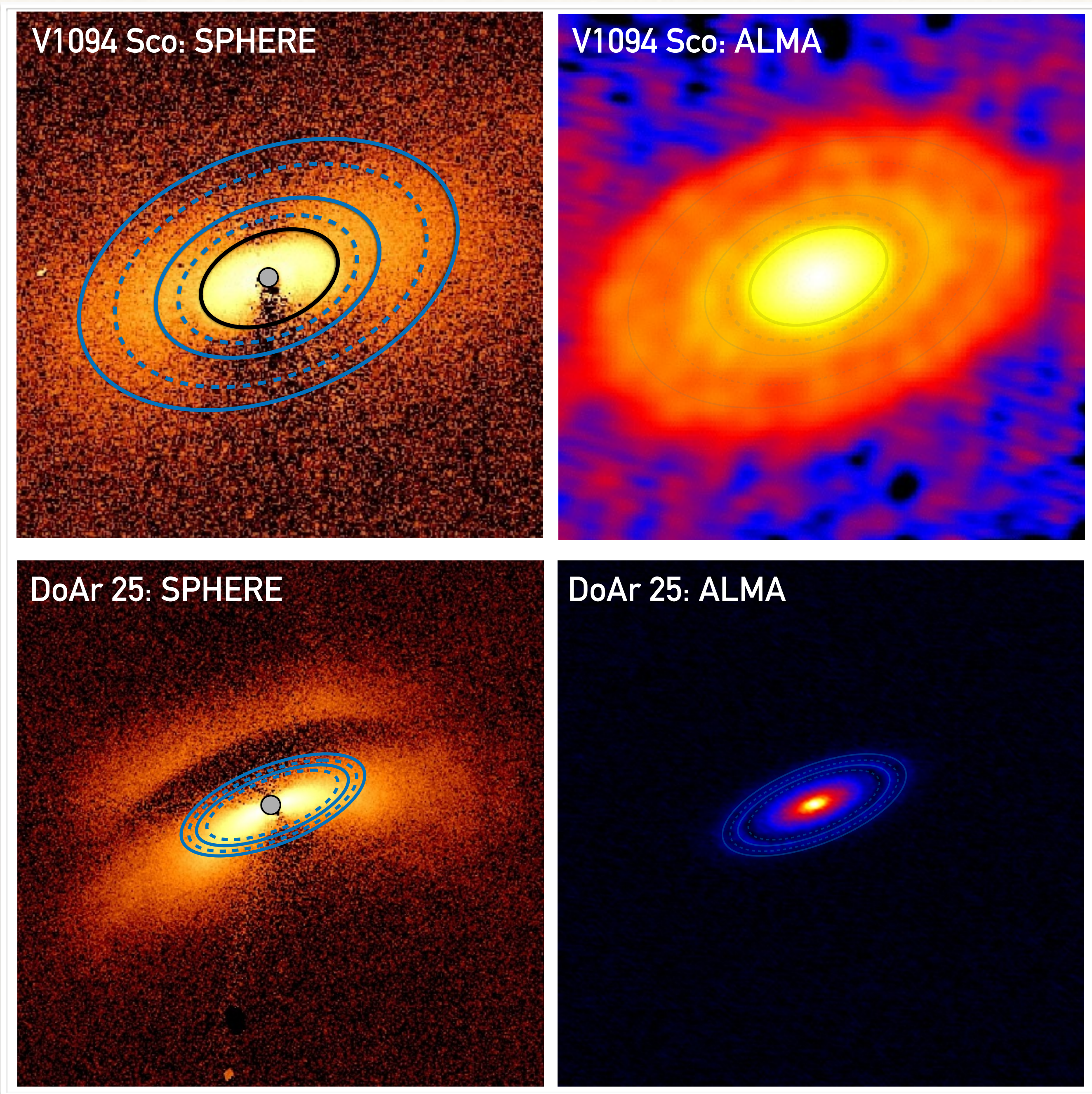
This is the largest release of polarimetric images of protoplanetary disks.

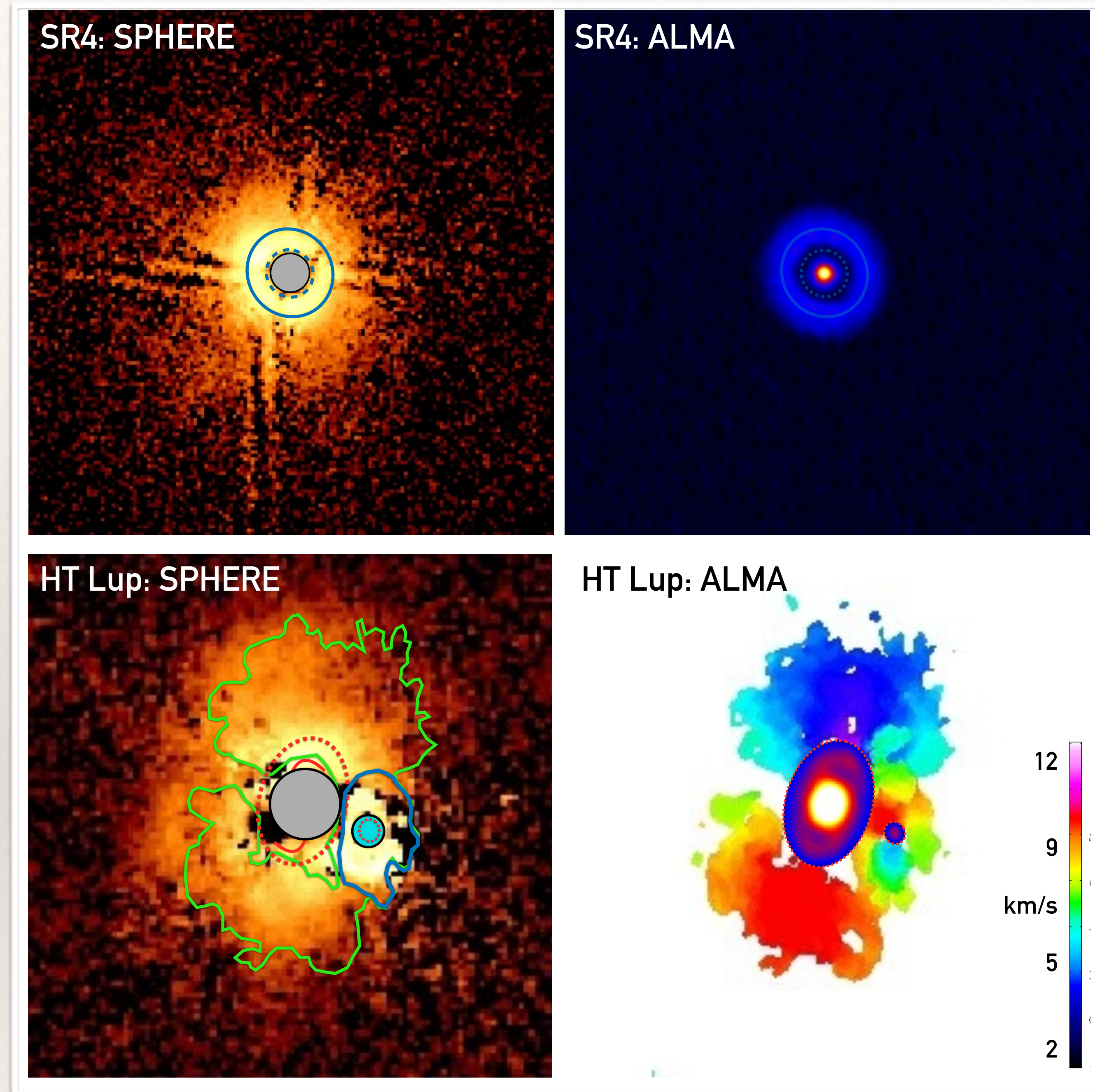
DARTTS II



The sample is on average younger than what is published so far.

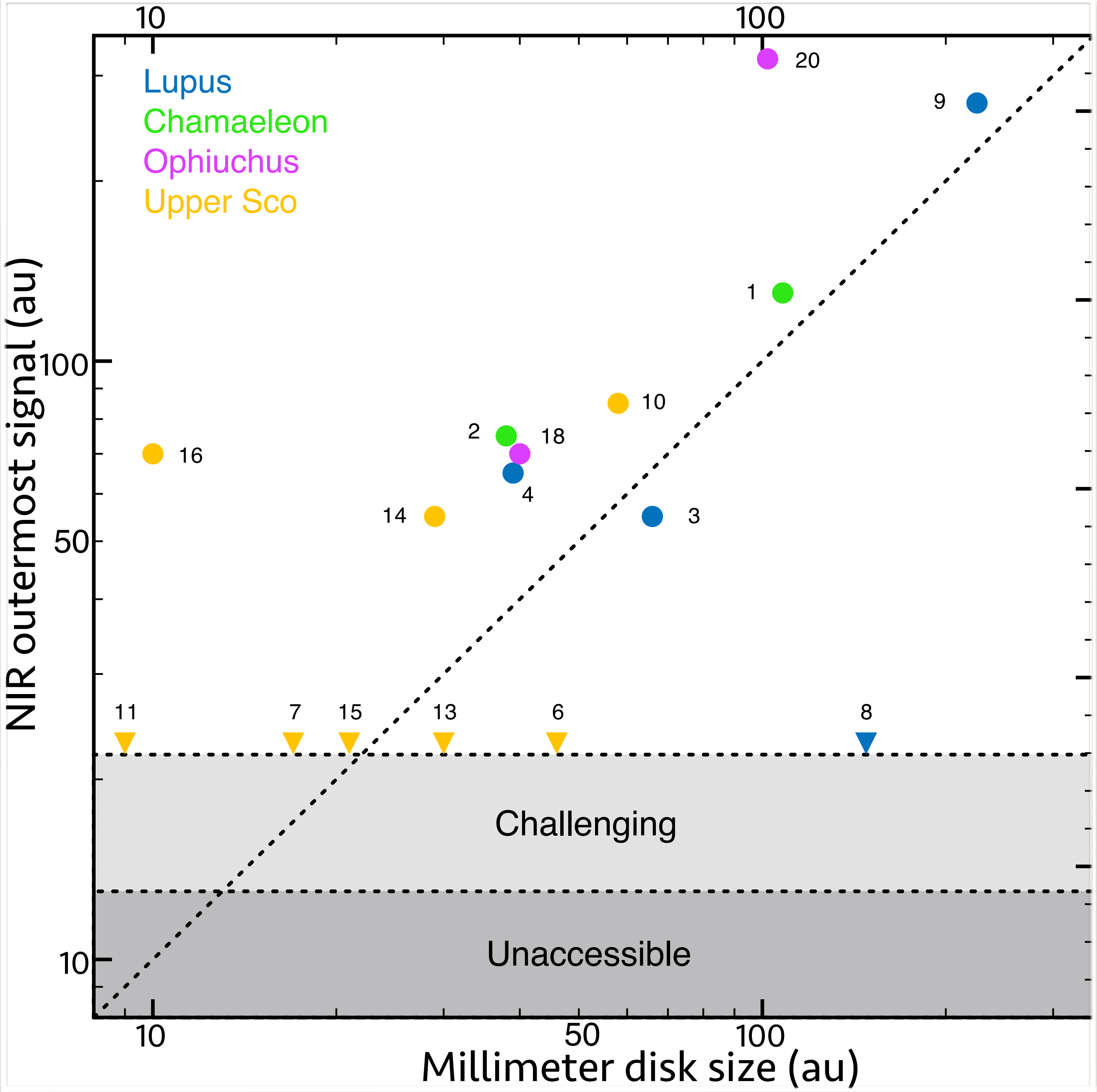
DARTTS II

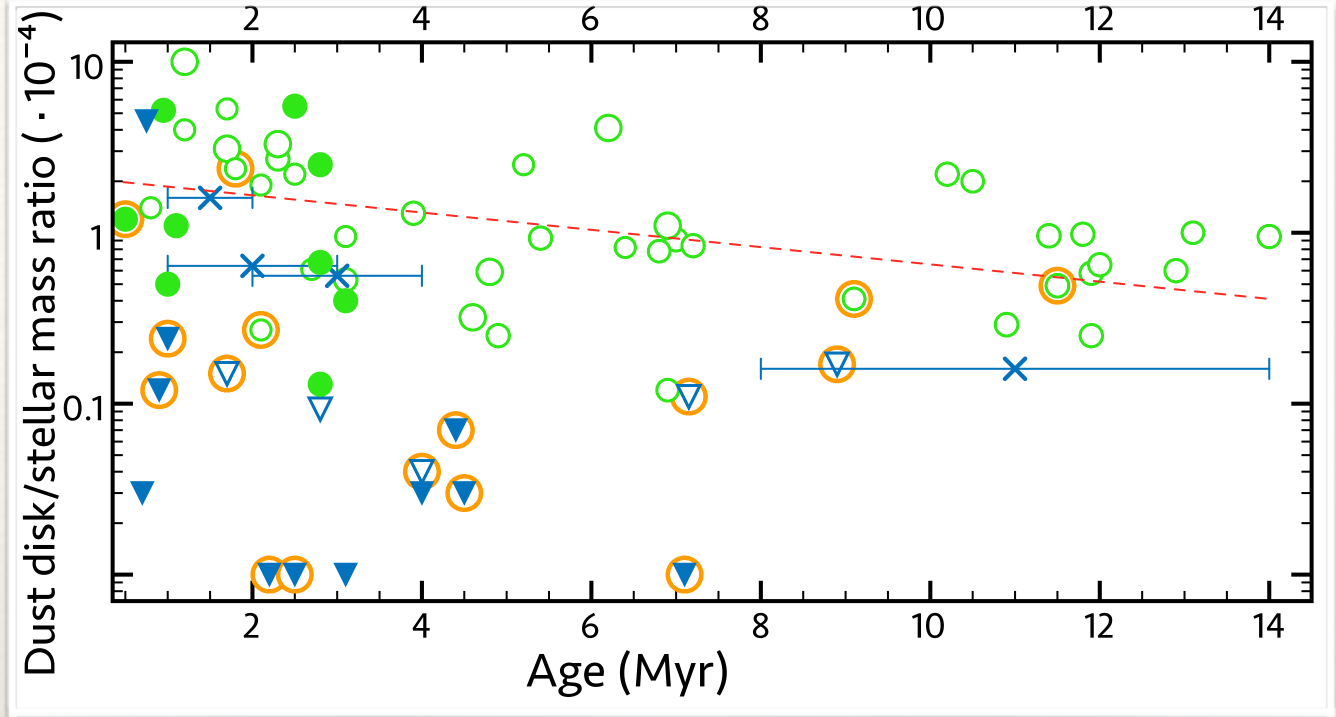


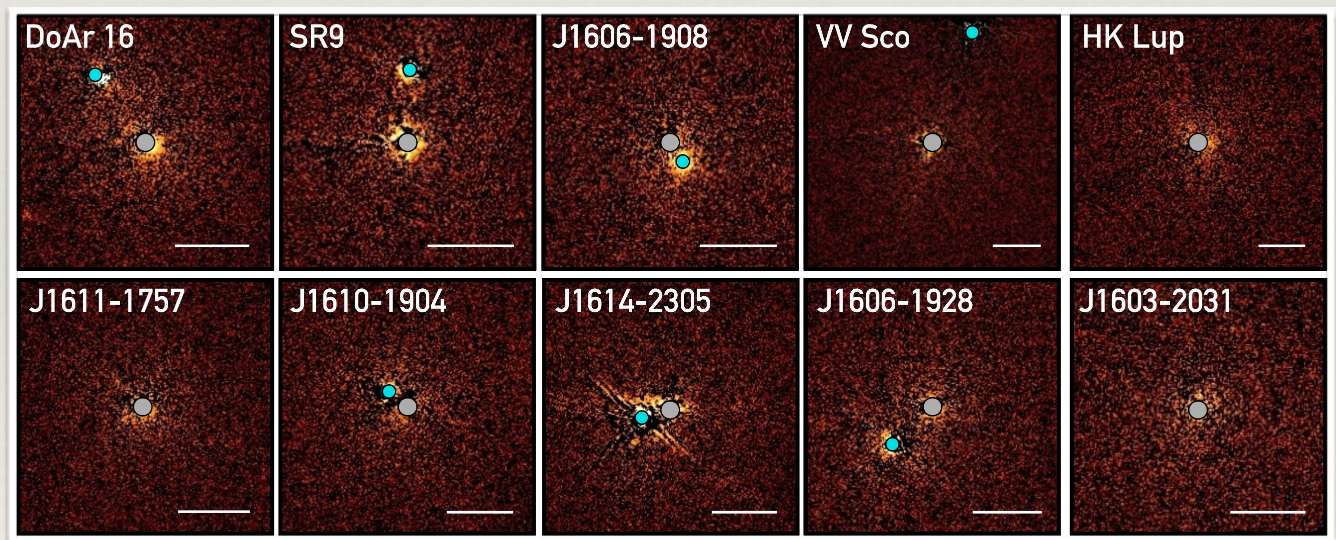


Sub-structures evident from ALMA but not from SPHERE.
Delayed effect by planets on smaller grains?

DARTTS II







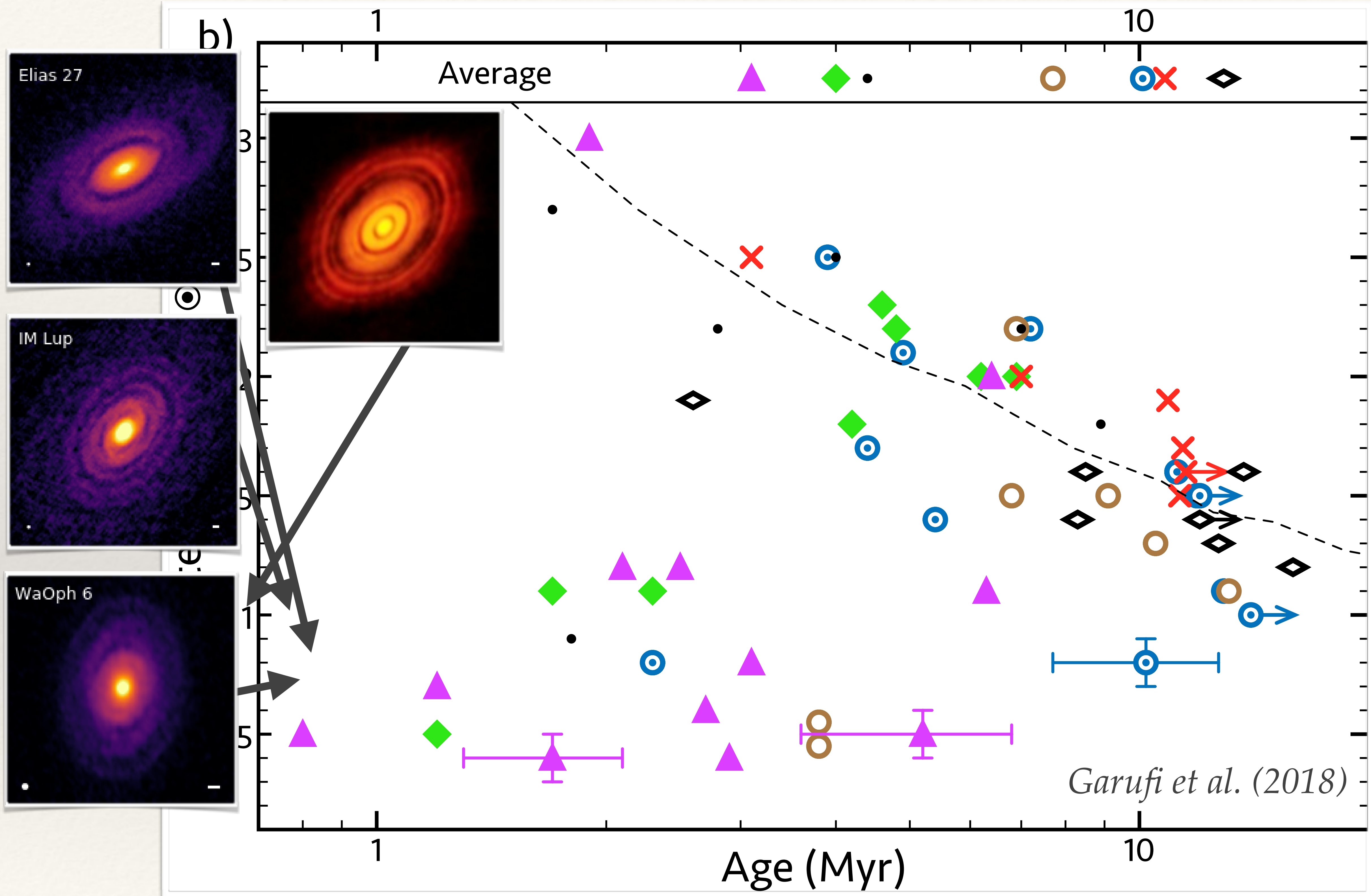
All non-detections but one are explained by the small disk size.

The recurrent presence of stellar companions confirms this view.

Part II

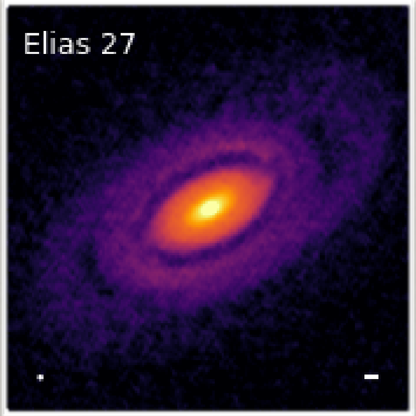
Disks from ALMA millimeter imaging of molecular lines

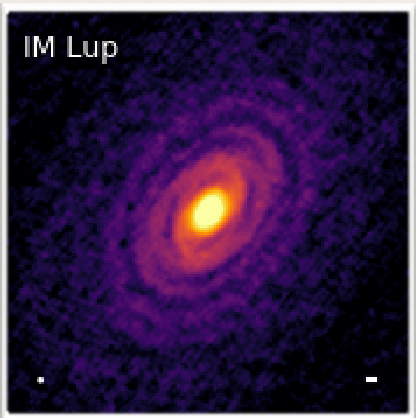
Gaseous disks with ALMA

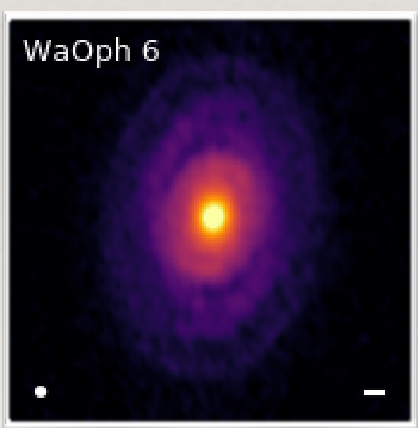


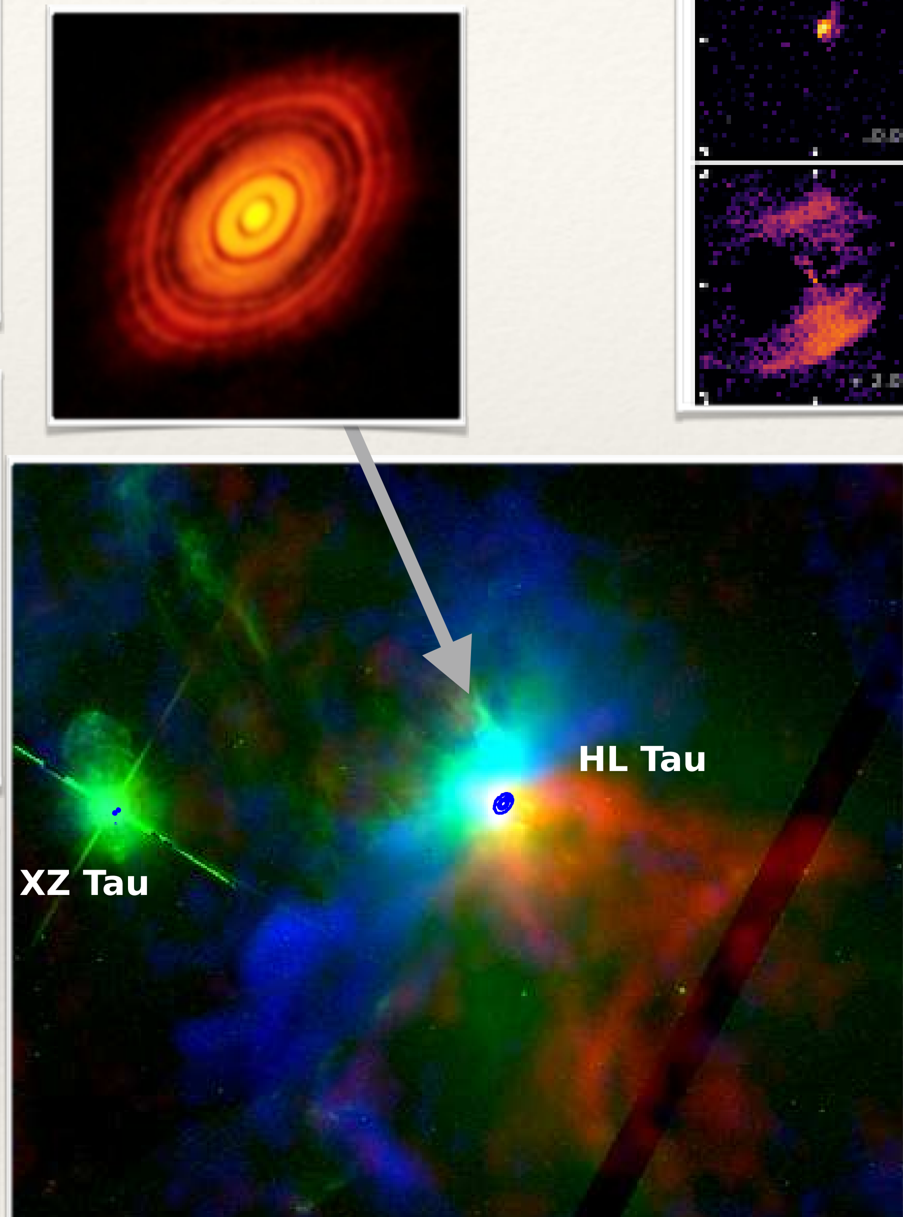
The few young ALMA sources show substructures

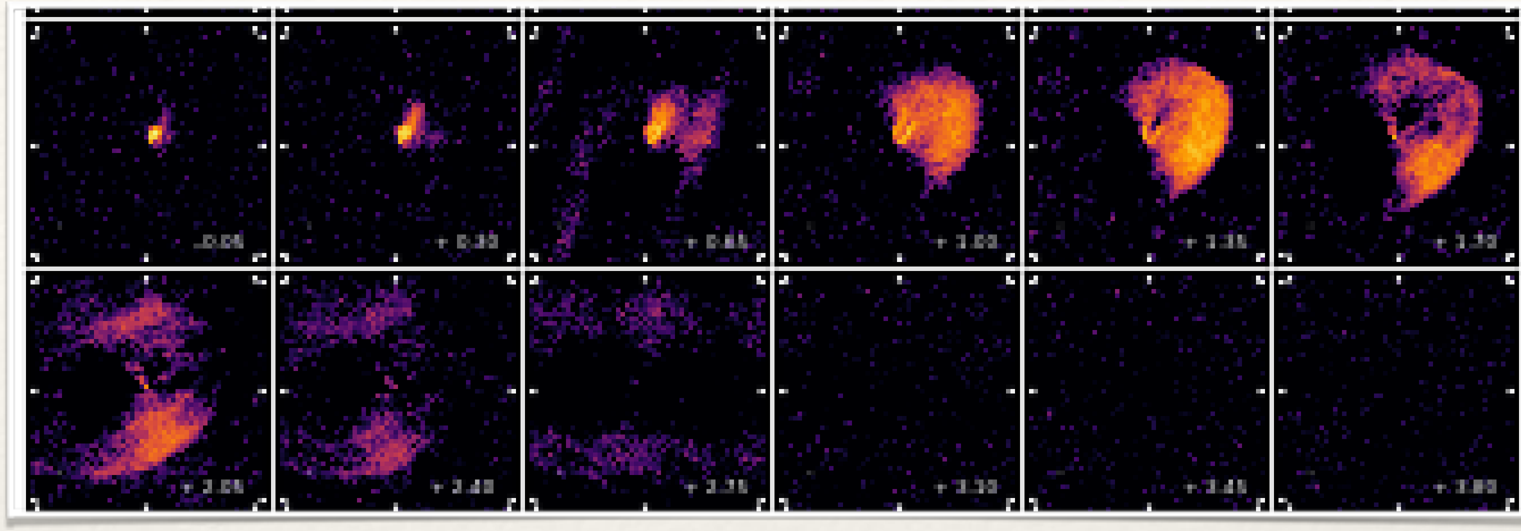
Gaseous disks with ALMA

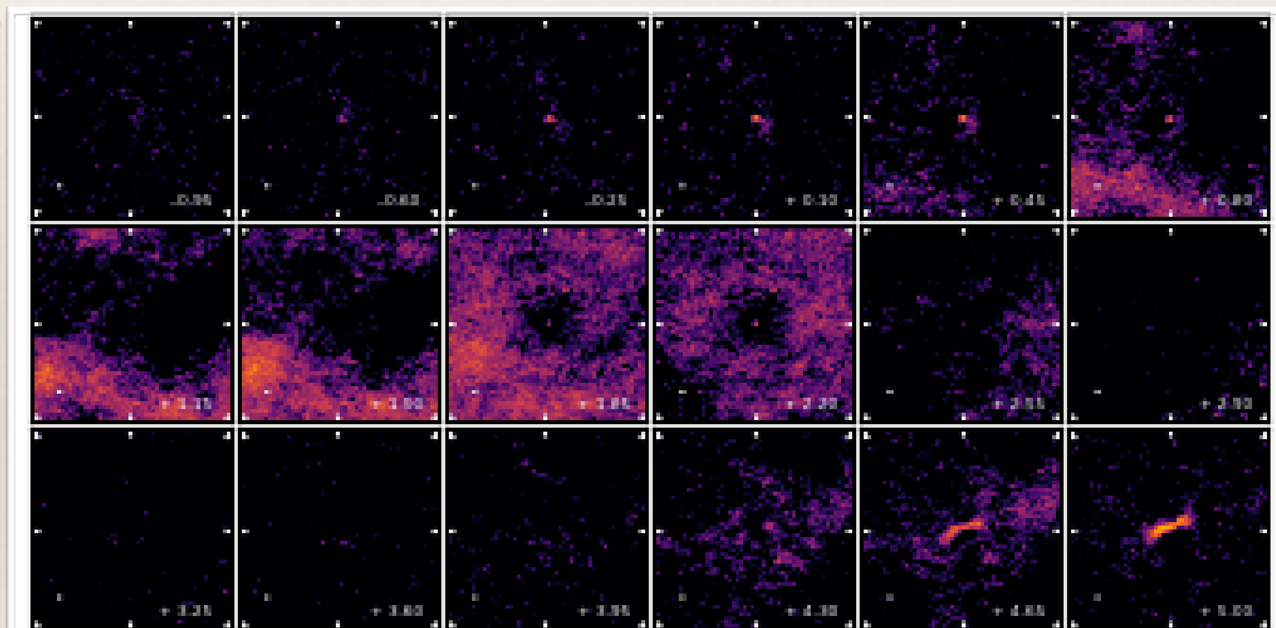












Andrews et al. 2018

ALMA et al. 2015

The ^{12}CO of these young disks is hardly accessible because of contaminating material (cloud, outflows…)

ALMA-DOT

ALMA chemical survey of
Disk-Outflow sources in Taurus

ALMA Cycle 4, 5, 6 in Band 5 and 6

PI: L. Podio

co-I: A. Garufi, C. Codella, F. Bacciotti, D. Fedele,
S. Mercimek, C. Favre, E. Bianchi, et al.

ALMA-DOT: motivations

1. Imaging the young gaseous disks with multiple molecules other than ^{12}CO

2. Imaging outflows and extended filamentary structures around the disk

3. Detect and characterize simple organic molecules (formaldehyde, methanol)

ALMA-DOT: papers

0. Podio, Bacciotti et al. 2019: DG Tau

I. Garufi, Podio et al. 2020: DG Tau B

II. Podio, Garufi et al. 2020: IRAS 04302

III. Podio, Garufi et al. subm.: DG Tau (n.2)

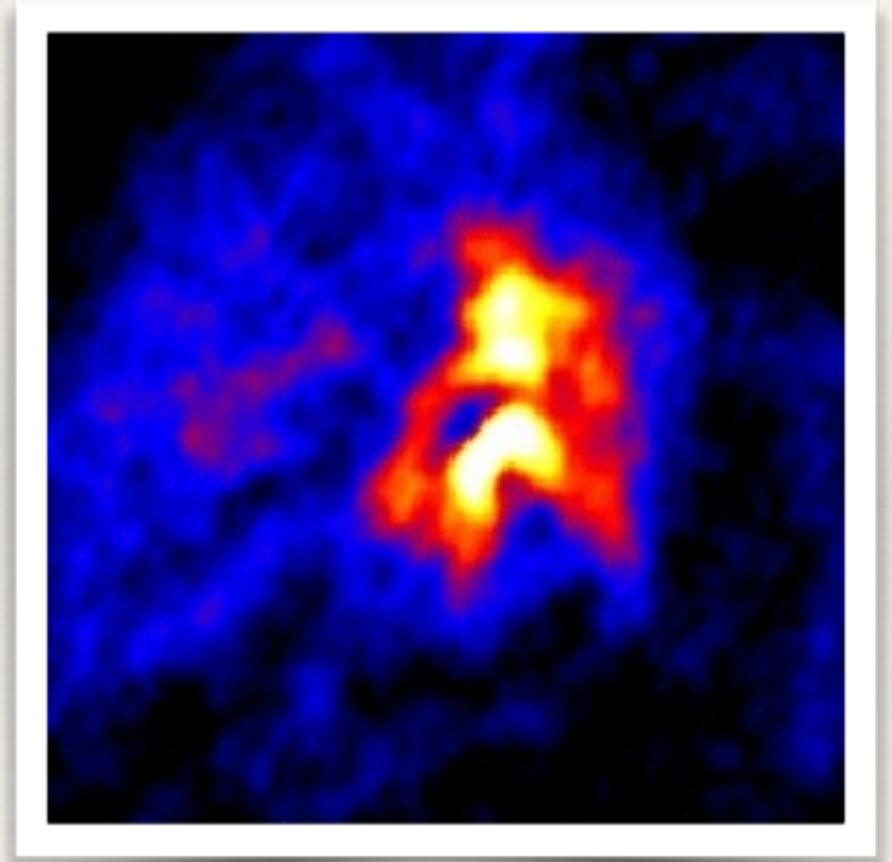
IV. Codella, Podio et al. subm.: H_2CS

V. Garufi, Podio et al. in prep.: overview

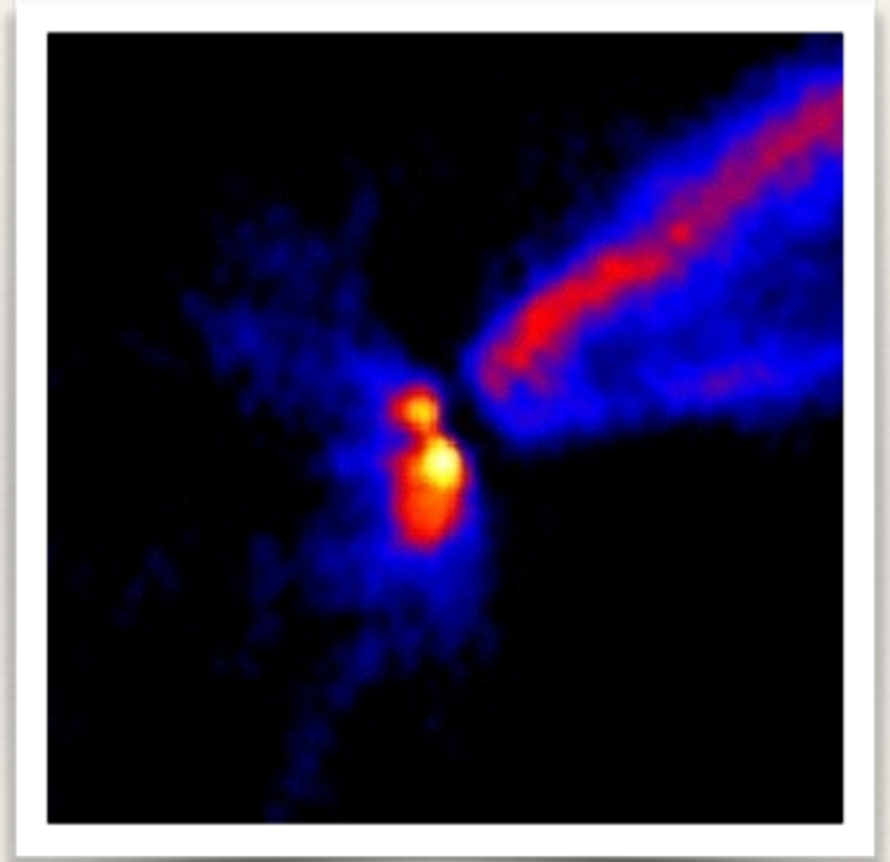
…

ALMA-DOT: molecules

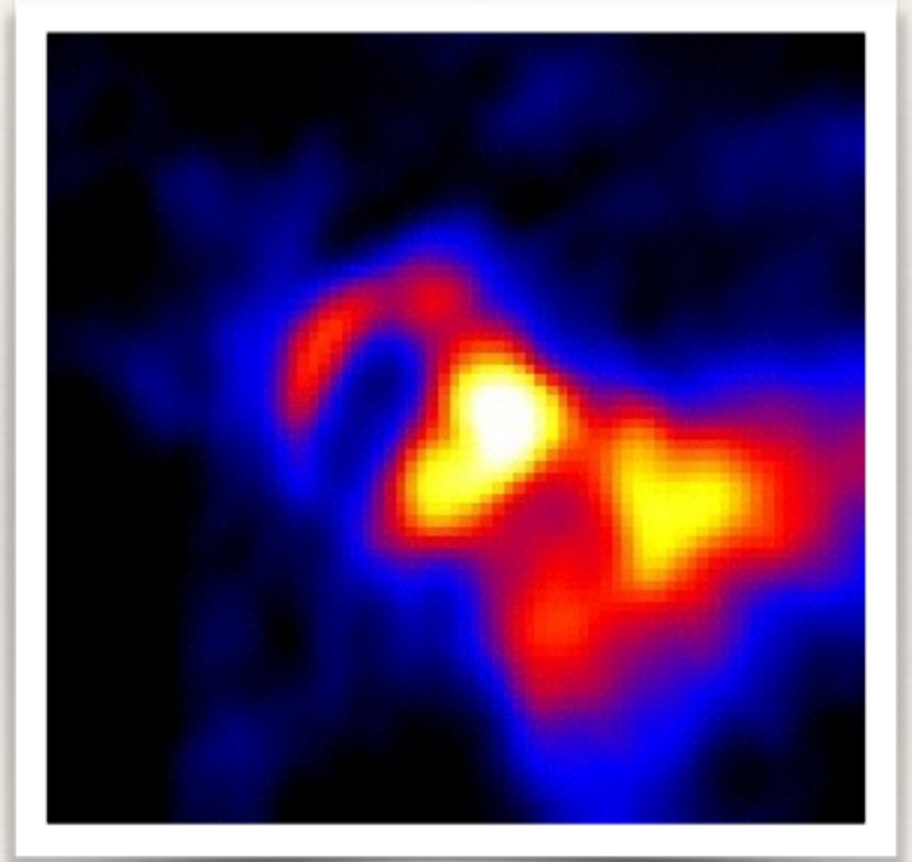
^{12}**CO** is the only molecule tracing the outflows.
The disk emission, as expected, is contaminated.



Haro 6-13



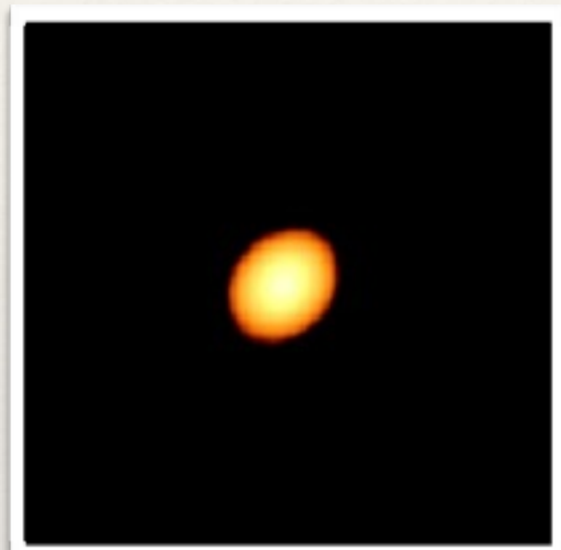
DG Tau B



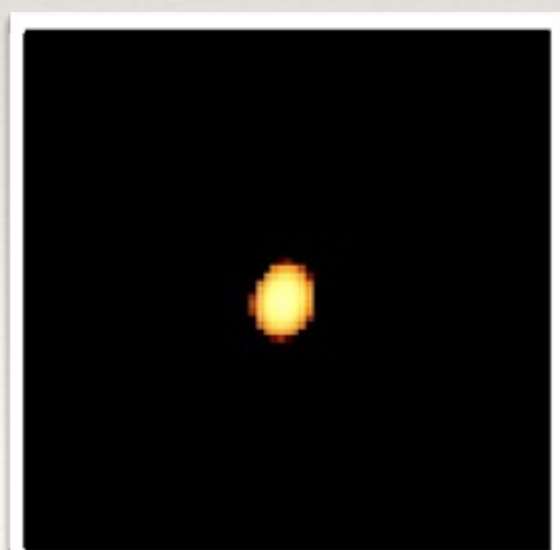
HL Tau

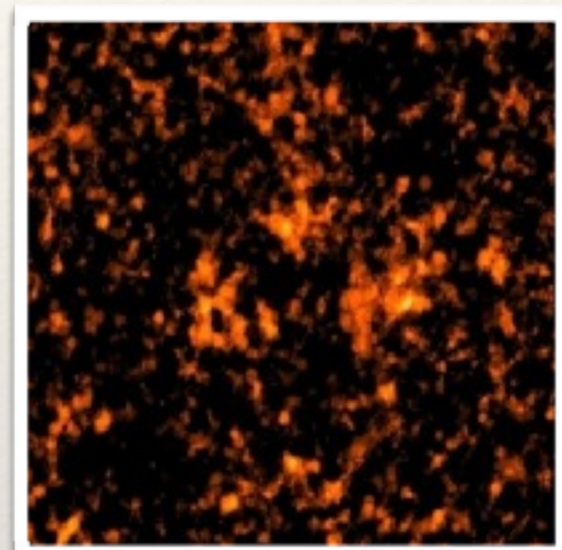
ALMA-DOT: molecules

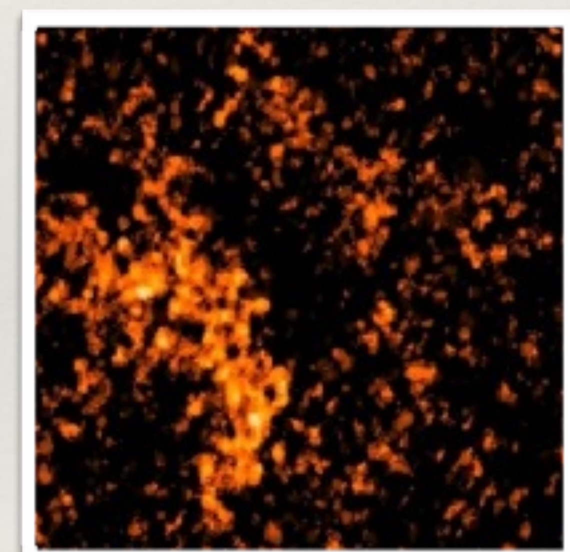
CN is spatially anti-correlated with the continuum.
It likely traces the UV field, and not the disk.

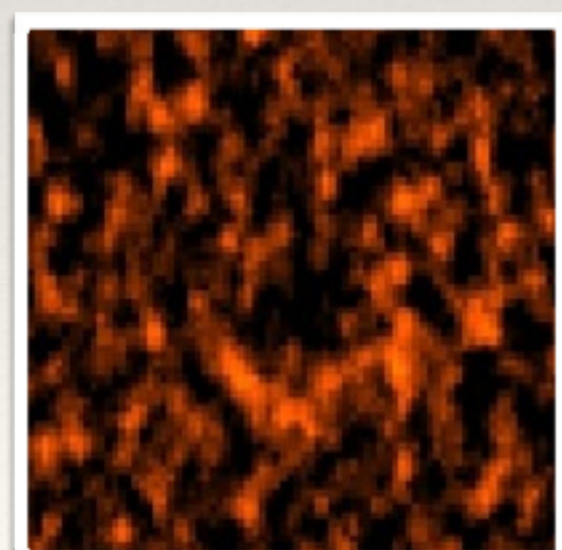

DG Tau


DG Tau B


Haro 6-13

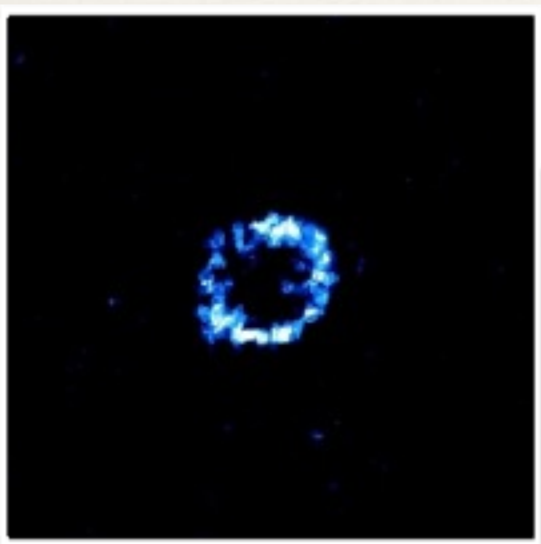

DG Tau


DG Tau B

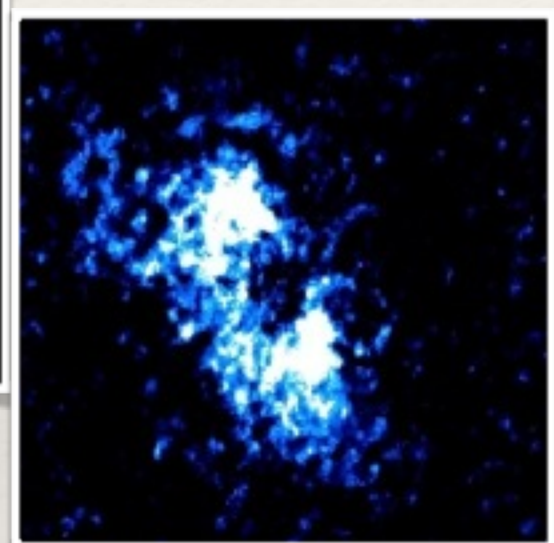

Haro 6-13

ALMA-DOT: molecules

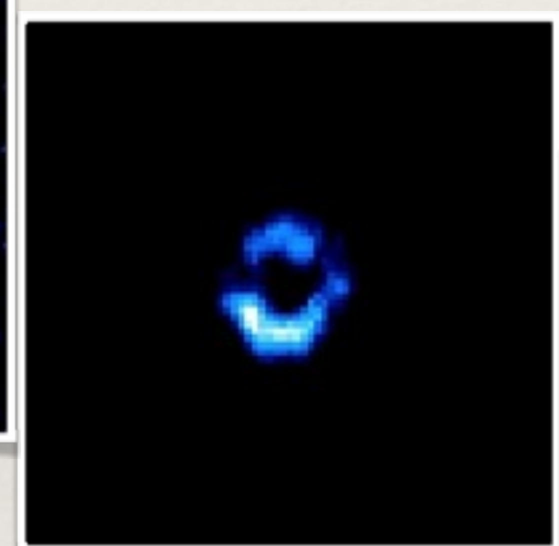
H_2CO is bright and is the best disk proxy.
Strong from the outer disk, dimmed in the <50 au.



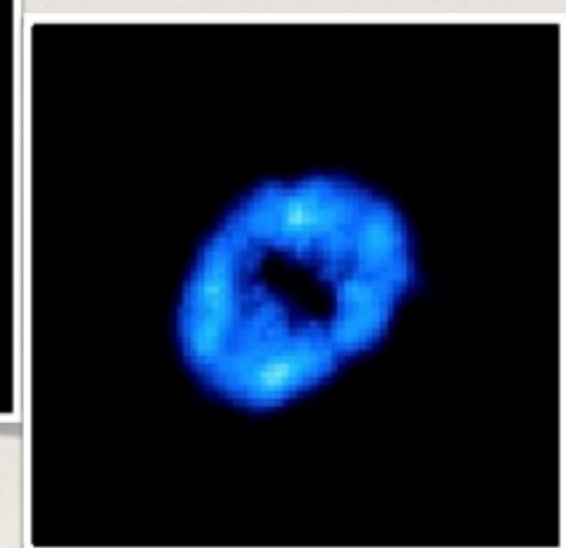
DG Tau



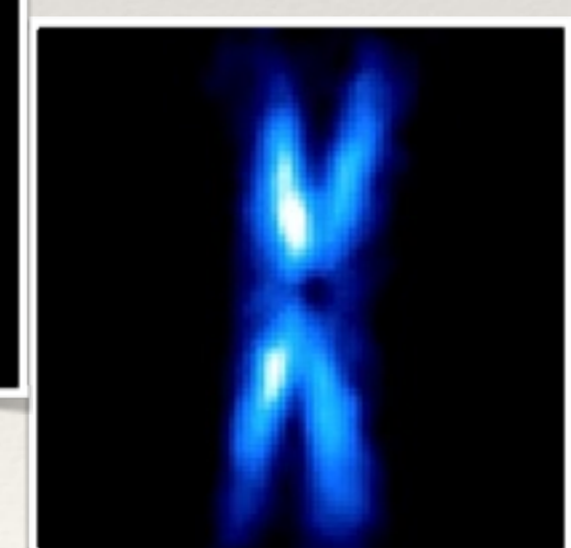
DG Tau B



Haro 6-13



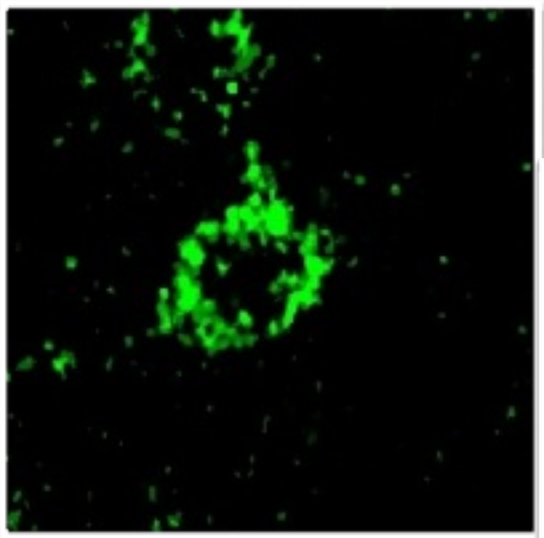
HL Tau



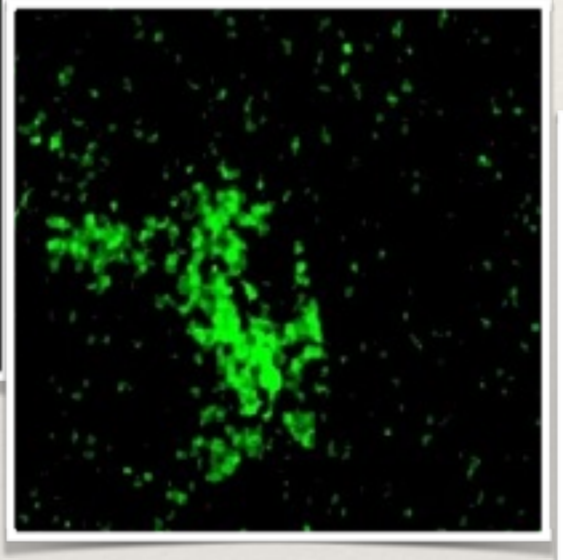
IRAS 04302

ALMA-DOT: molecules

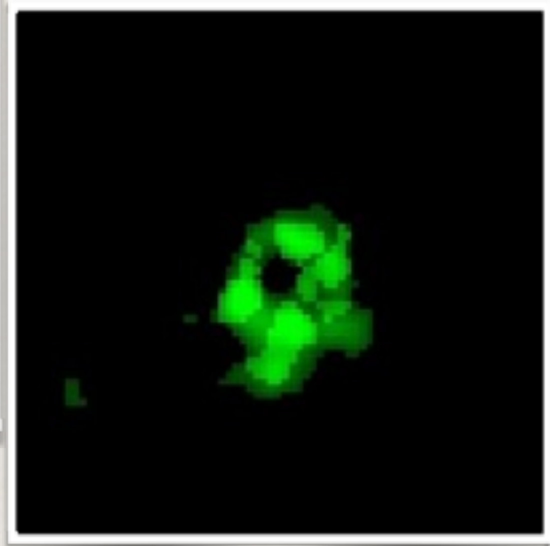
CS is impressively similar to H_2CO.



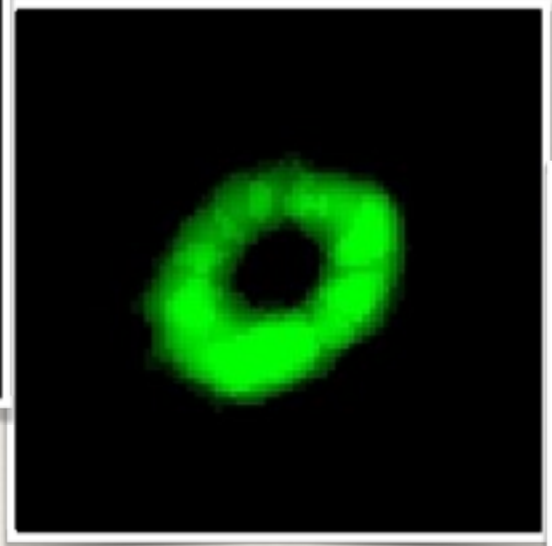
DG Tau



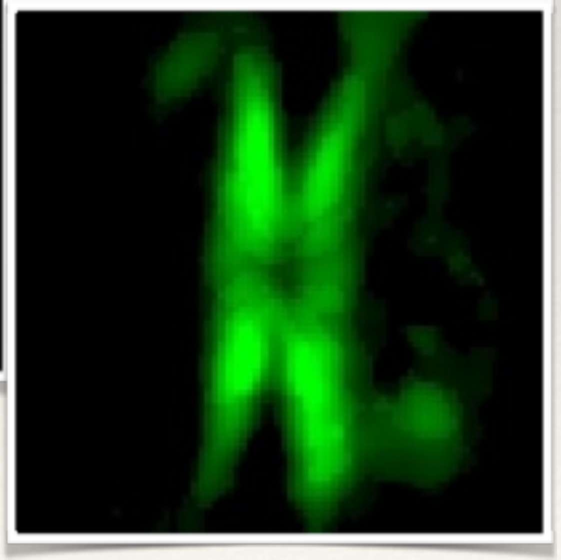
DG Tau B



Haro 6-13



HL Tau



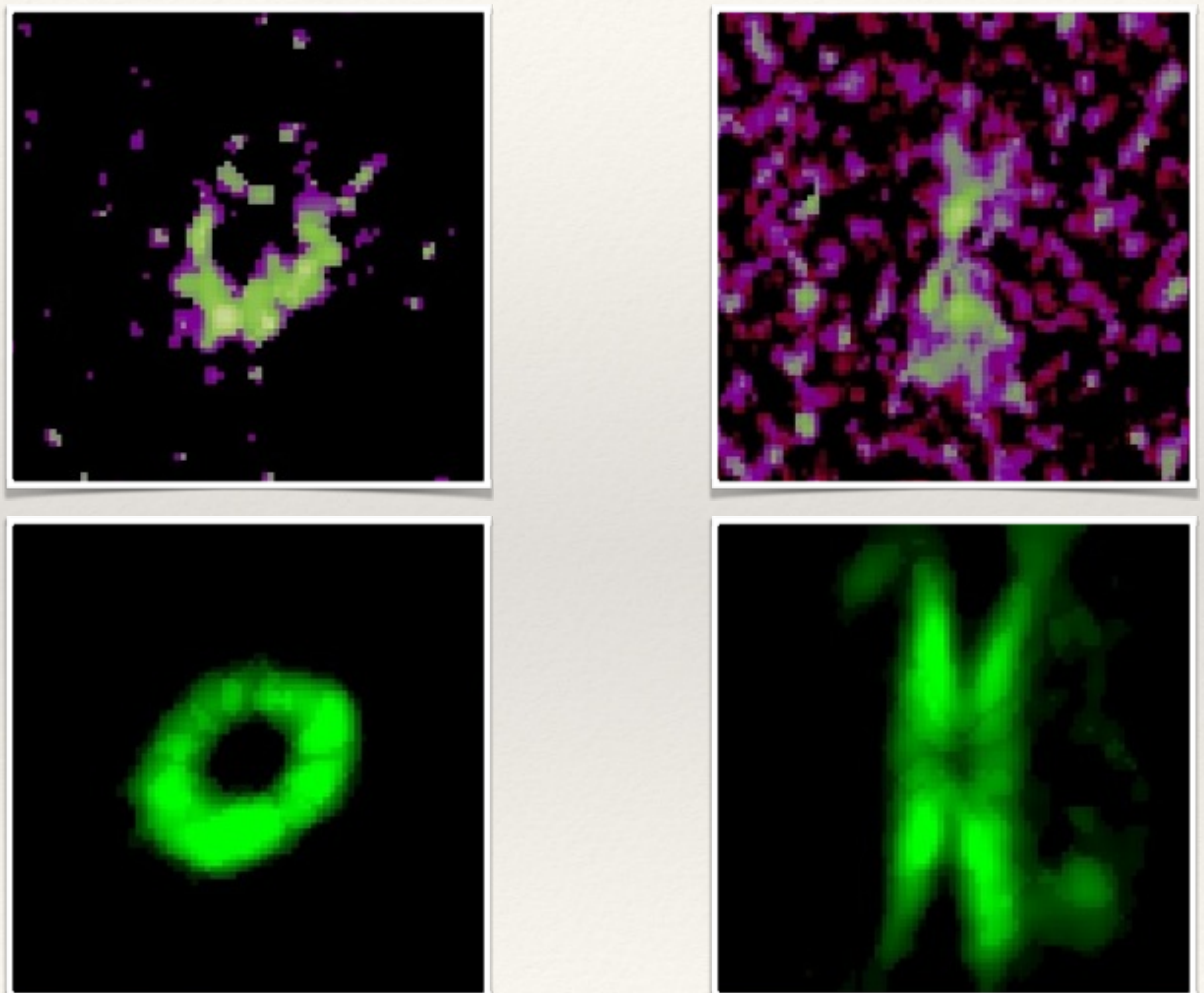
IRAS 04302

ALMA-DOT: molecules

H_2CS is detected in two disks (2_{nd} and 3_{rd} ever).

H_2CS

HL Tau

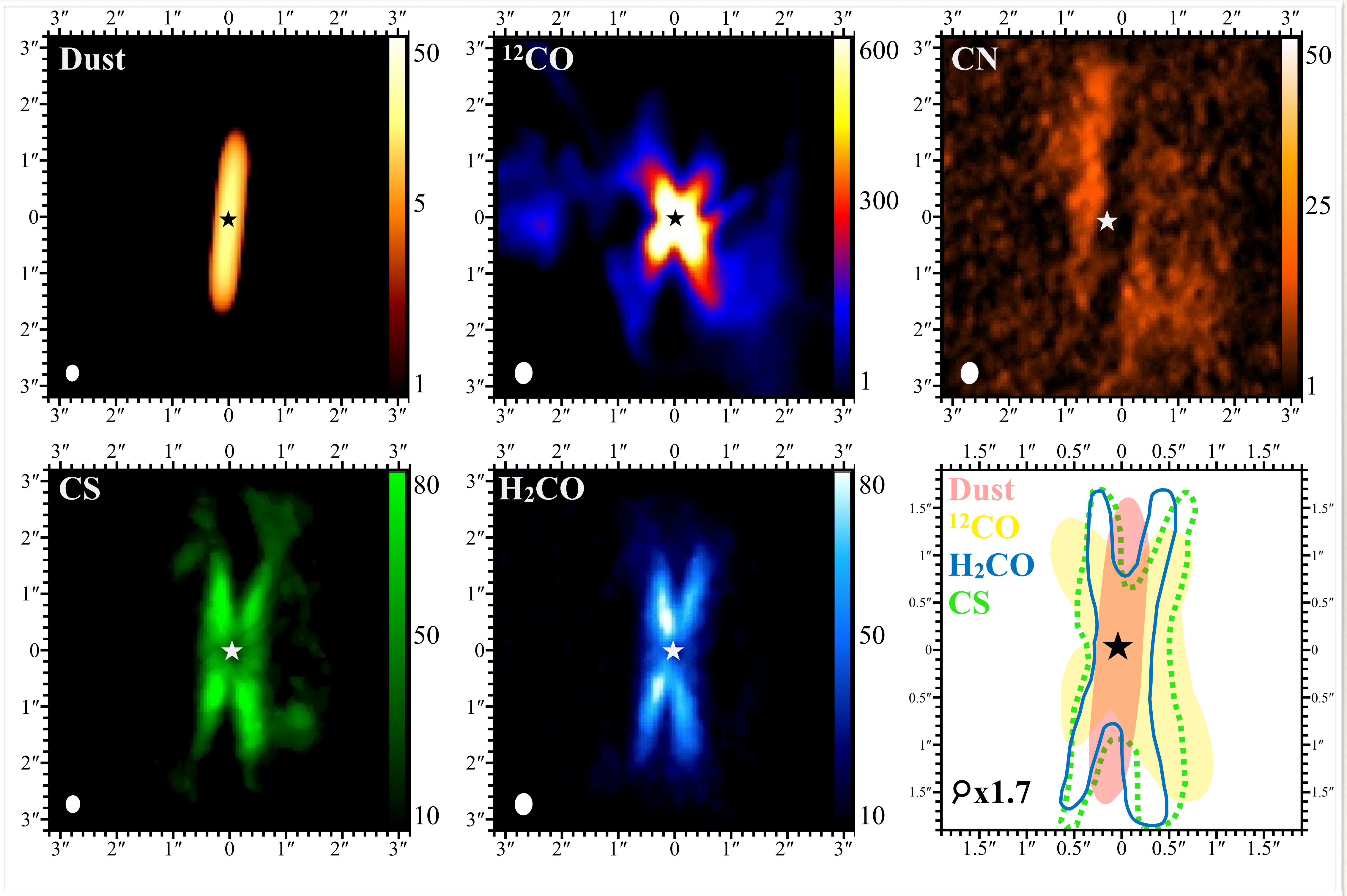


IRAS 04302

CS

ALMA-DOT: IRAS04302

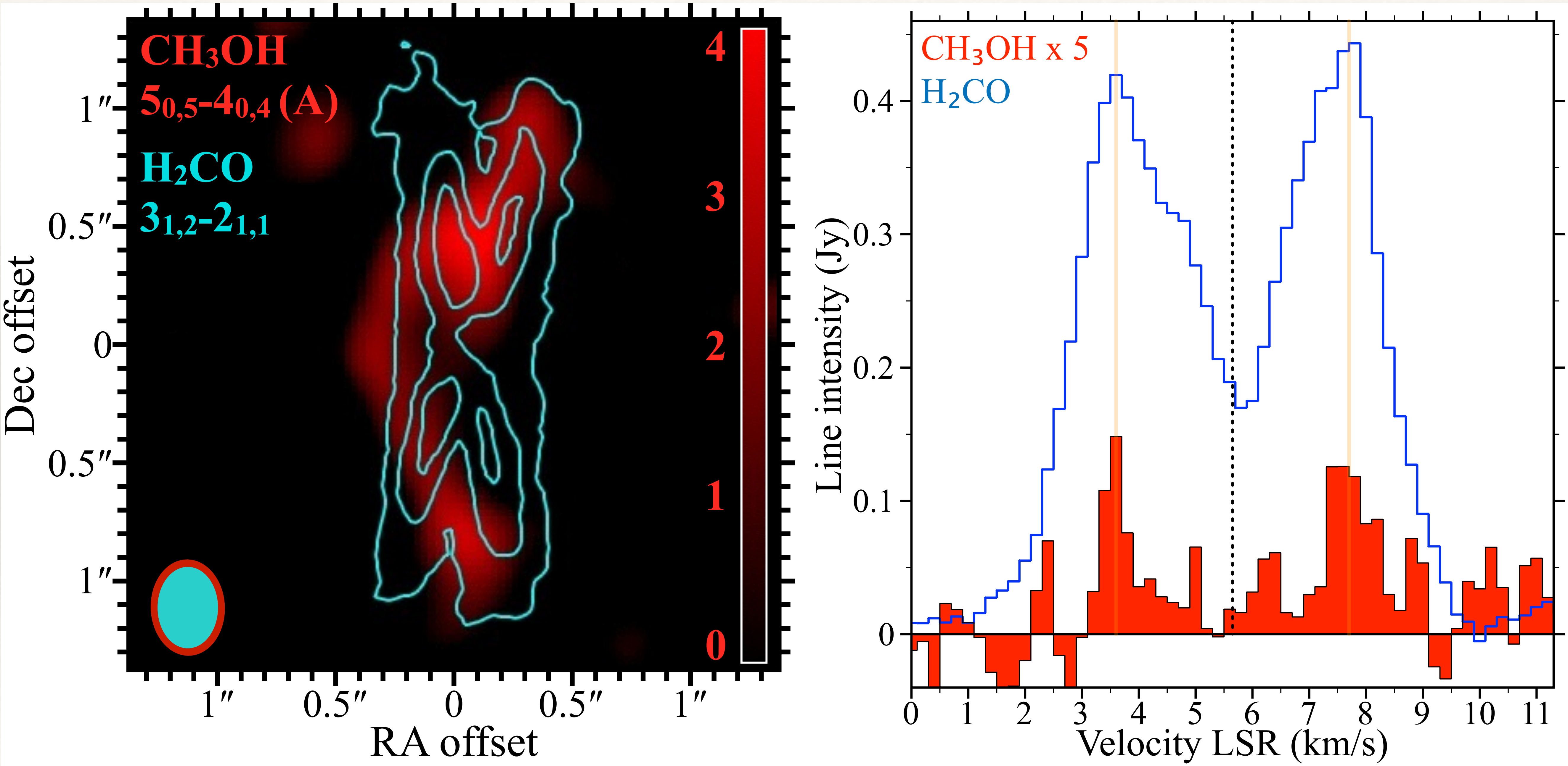
First multi-line characterization of the molecular layer.



Podio et al. 2020

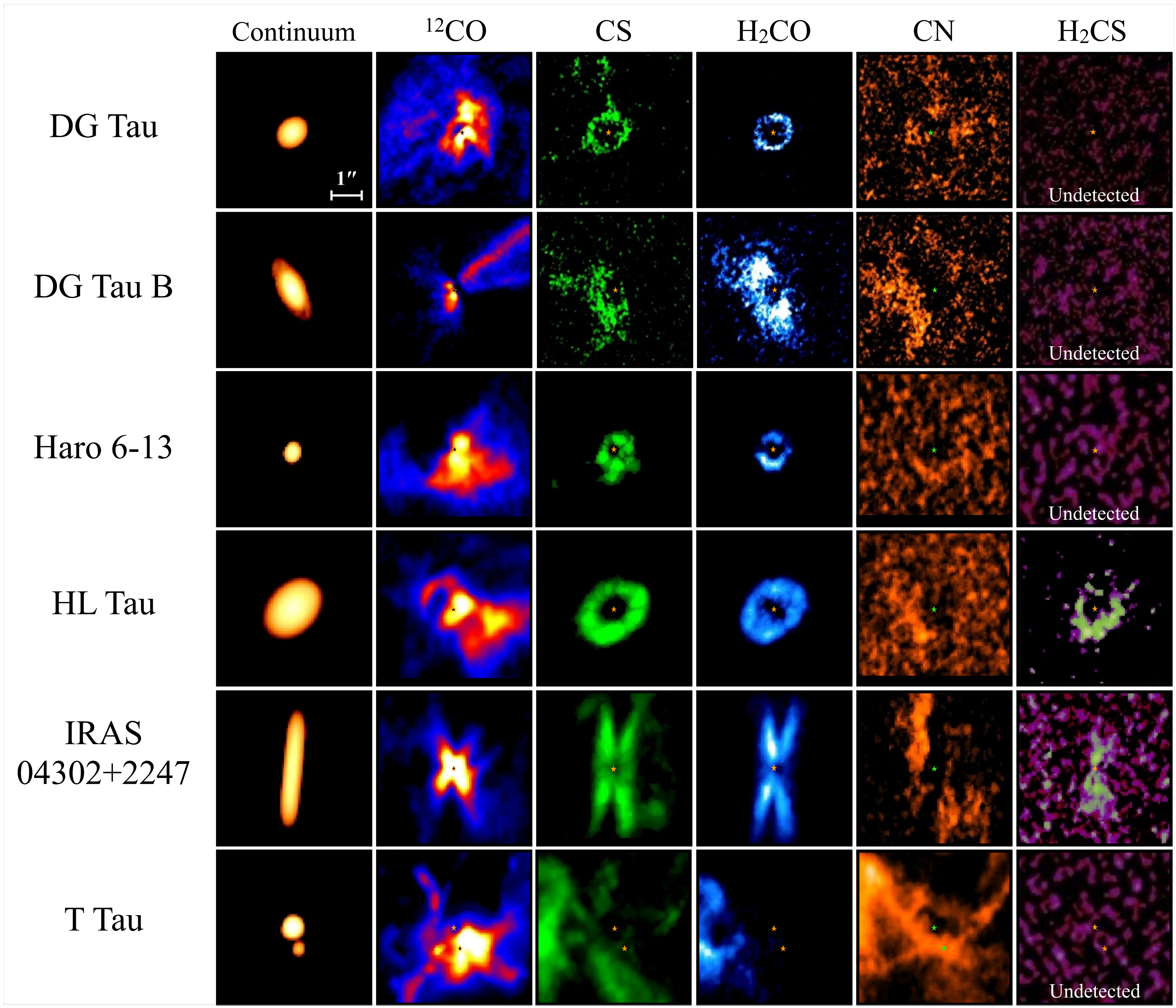
ALMA-DOT: IRAS04302

Second detection of methanol in a protoplanetary disk.

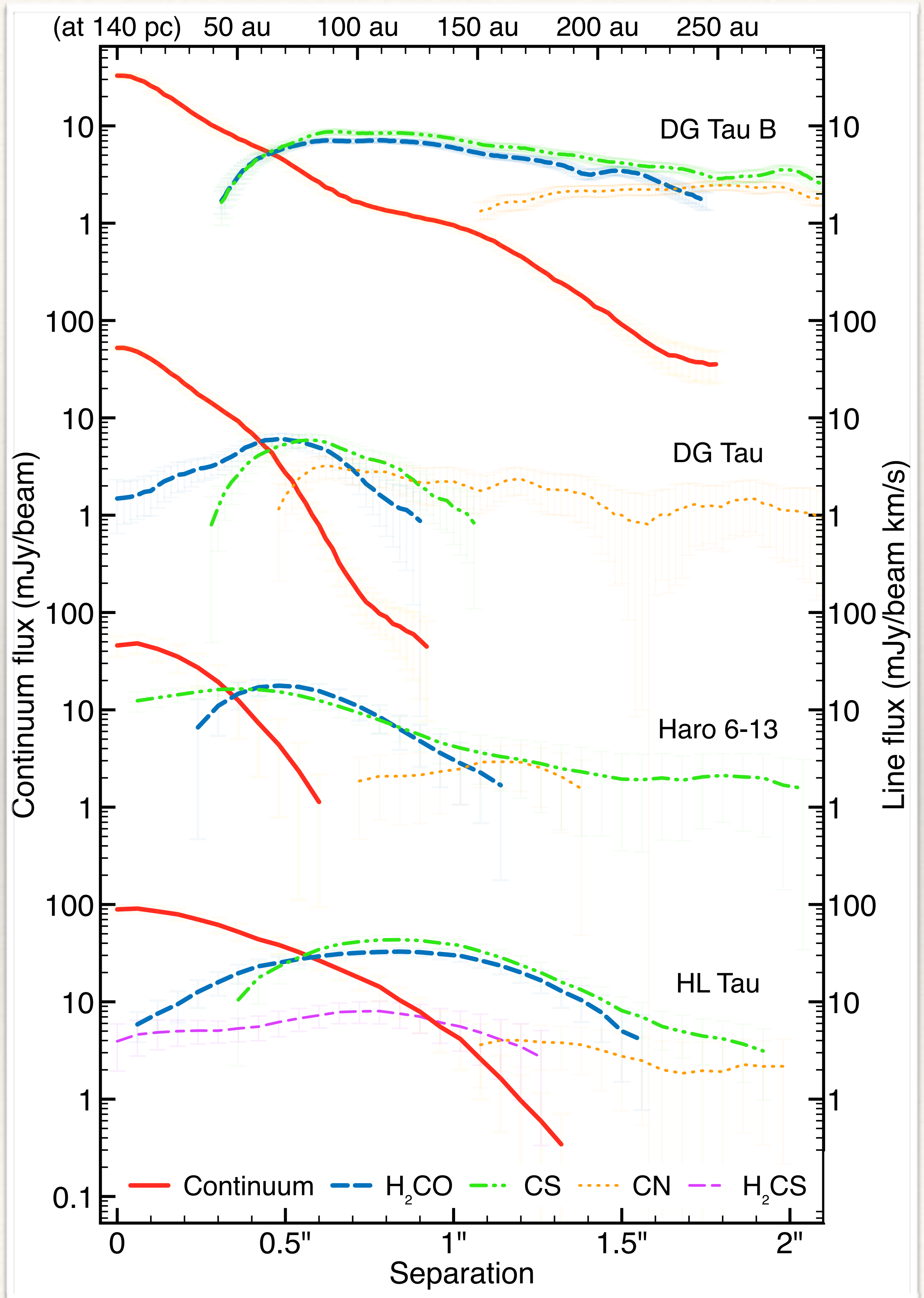


Podio et al. 2020

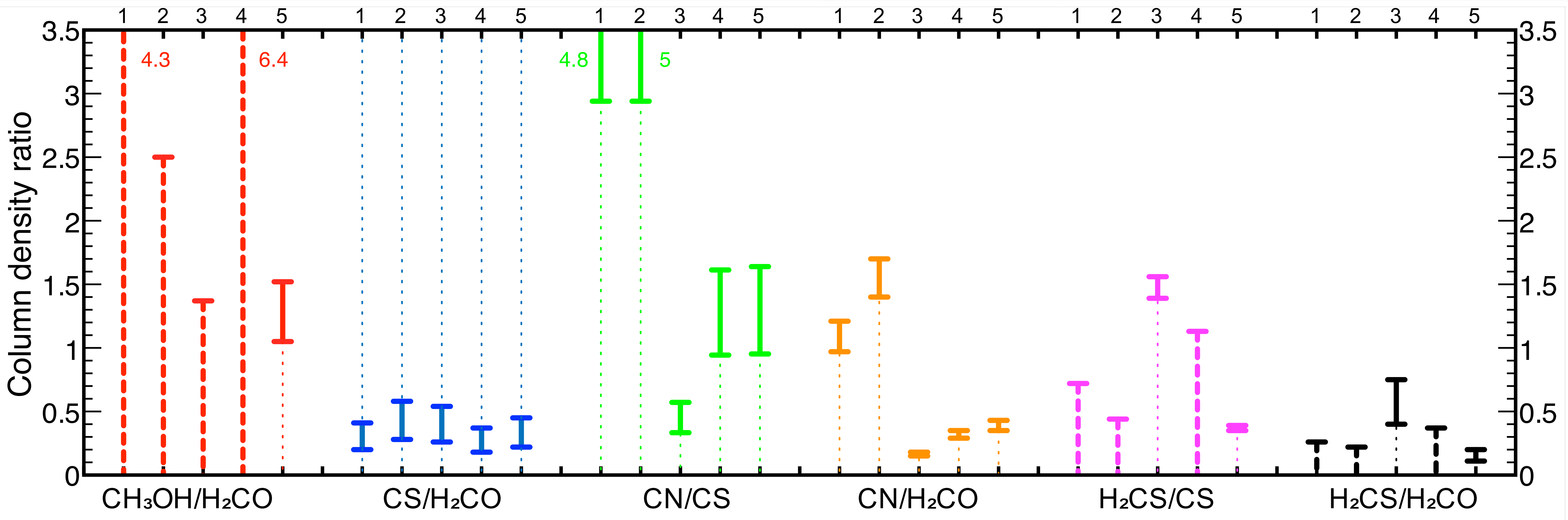
ALMA-DOT: overview



ALMA-DOT: distribution



ALMA-DOT: column densities



We have many limits or loose constraints but these ratios pave the way for future observations.

Closing

Ubiquity of disk sub-structures suggest **planets**.

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The current sample is biased toward **old** sources.

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Present and **future** efforts include alleviating biases.

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DARTTS and **DESTINYS** surveys observe
less massive disks around young sources.

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ALMA-DOT observes the chemistry of
young sources with unprecedented detail.

End

Thank you!