An Observational Overview of Substructures in Protoplanetary Disks



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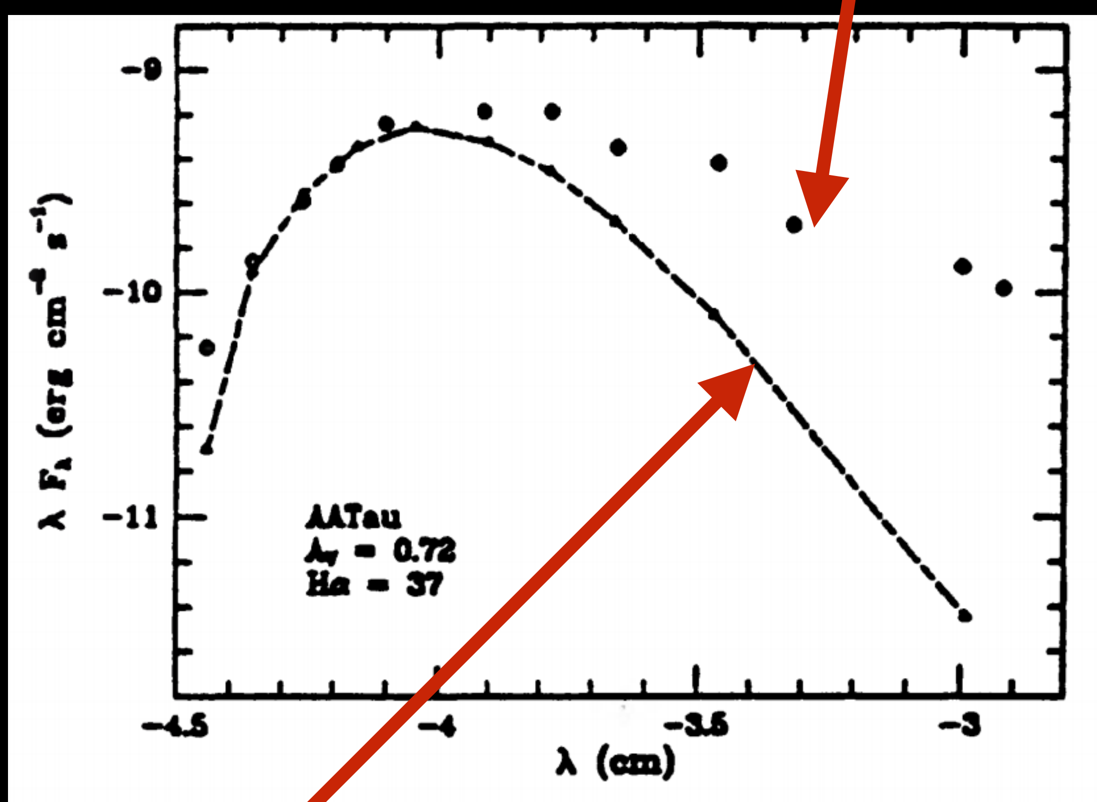
MIAPP

Image credits: Metropolitan Museum of Art

SEDs provided the earliest observational evidence of substructures

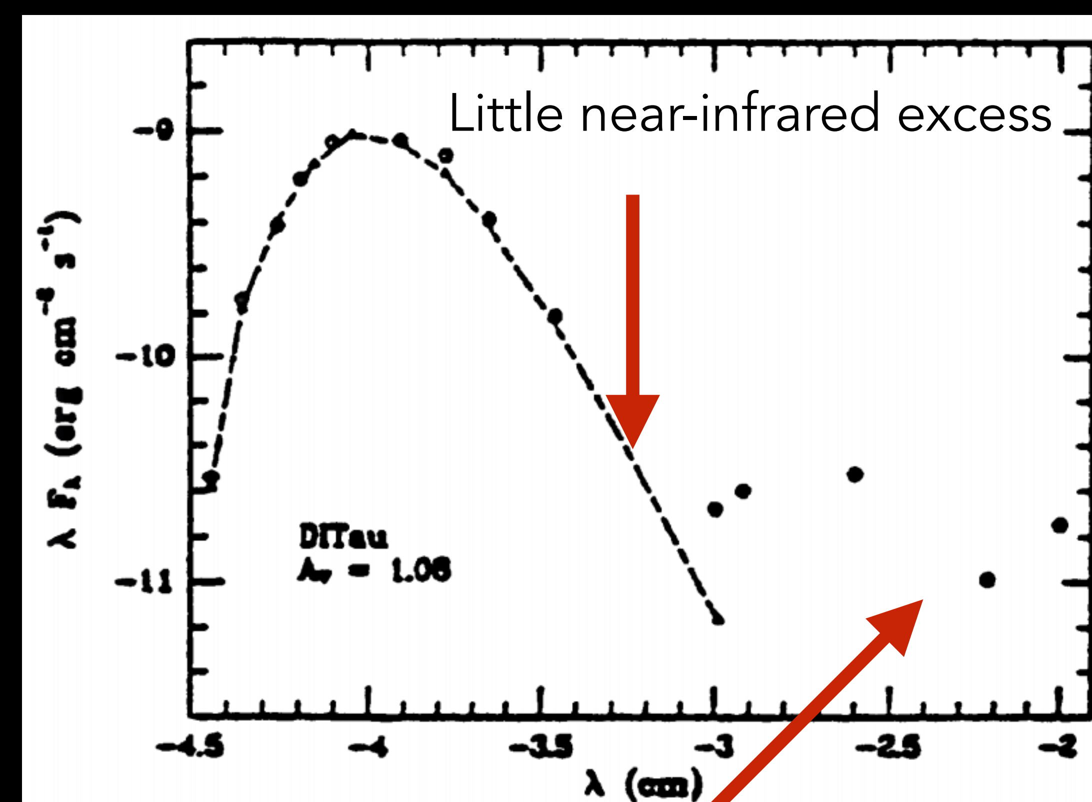
Typical SED of young star

Infrared excess



Template star SED

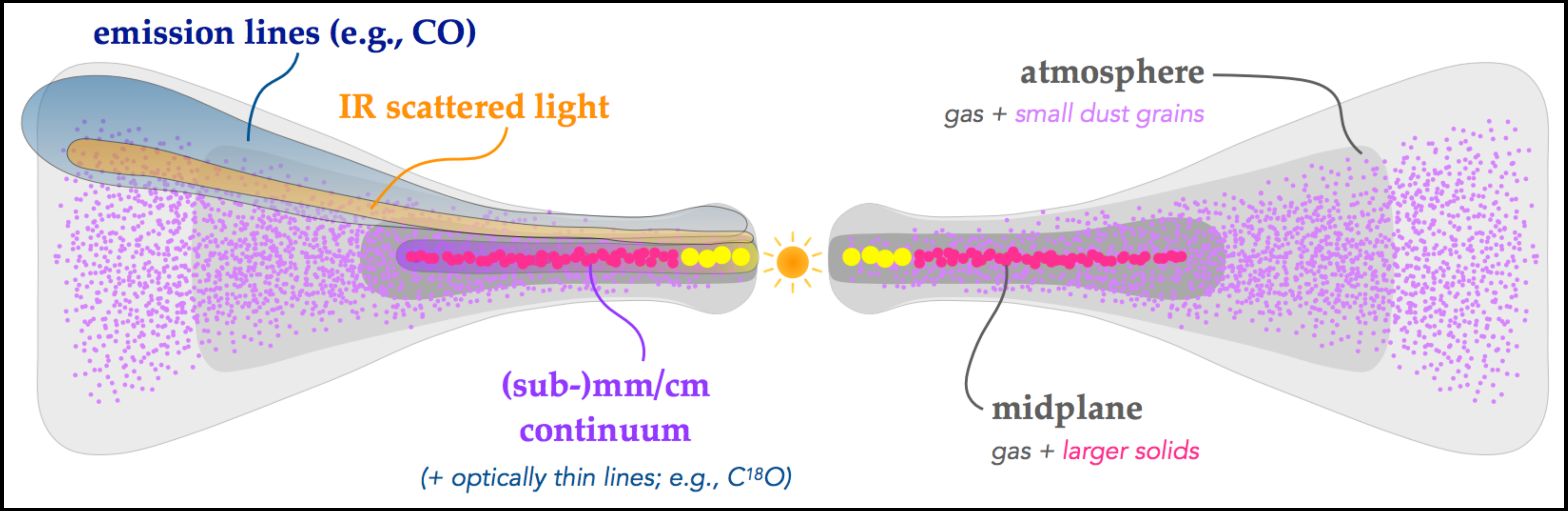
SED of "transition" disks



Mid-infrared and far-infrared excess remain

Strom et al. 1989

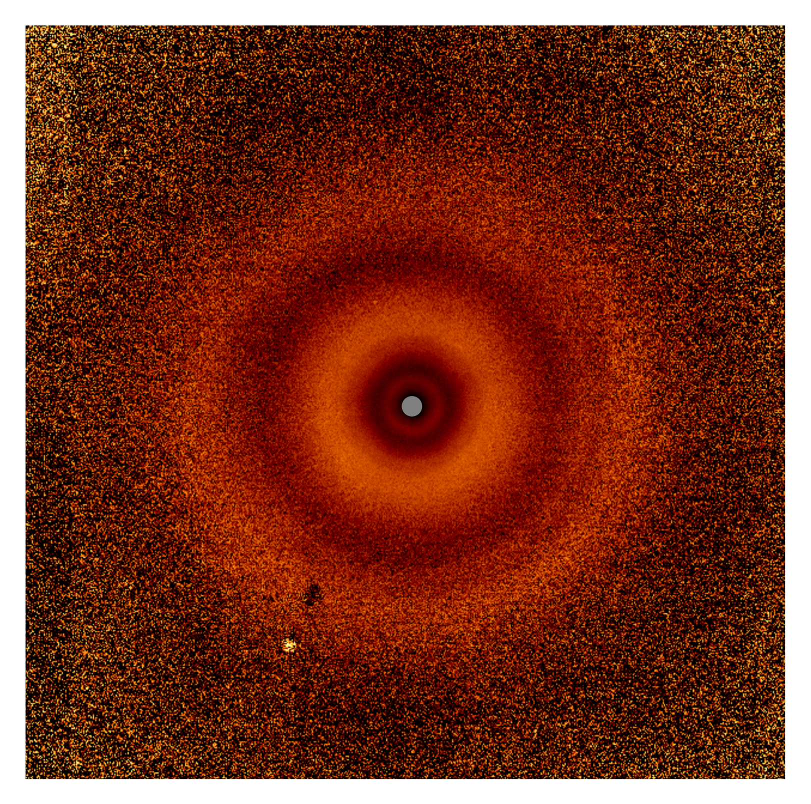
Spatially resolving disk substructure at different wavelengths



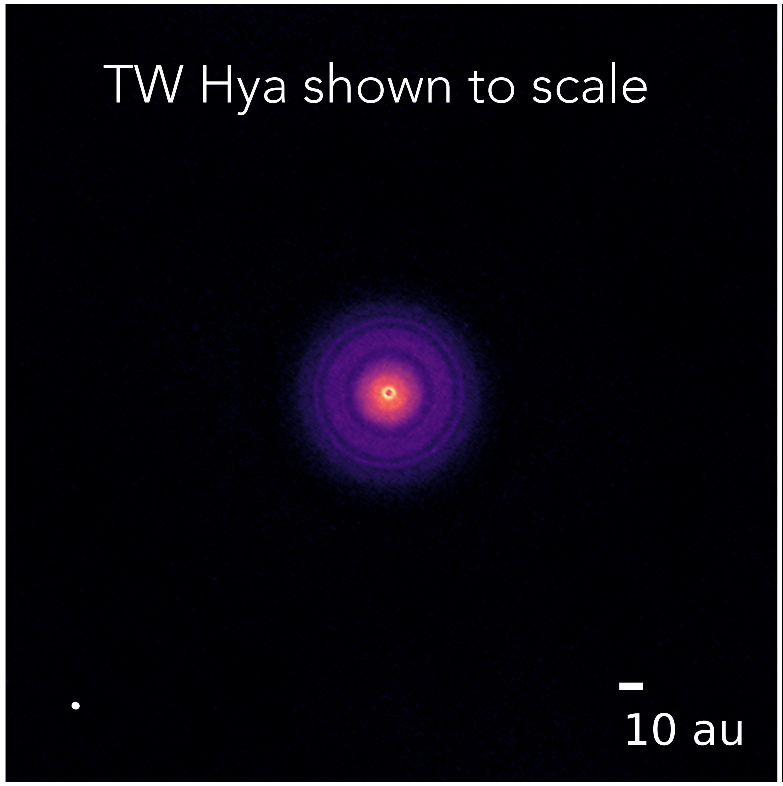
Vertical cross-section of a protoplanetary disk (Andrews 2020)

Three views of a protoplanetary disk

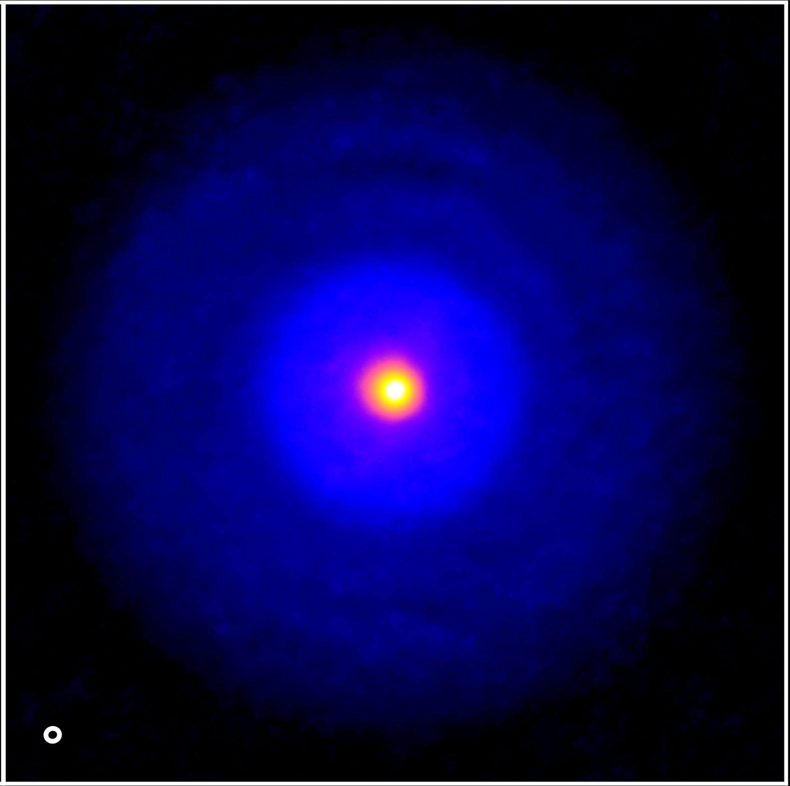
Scattered light (SPHERE)
van Boekel et al. 2016

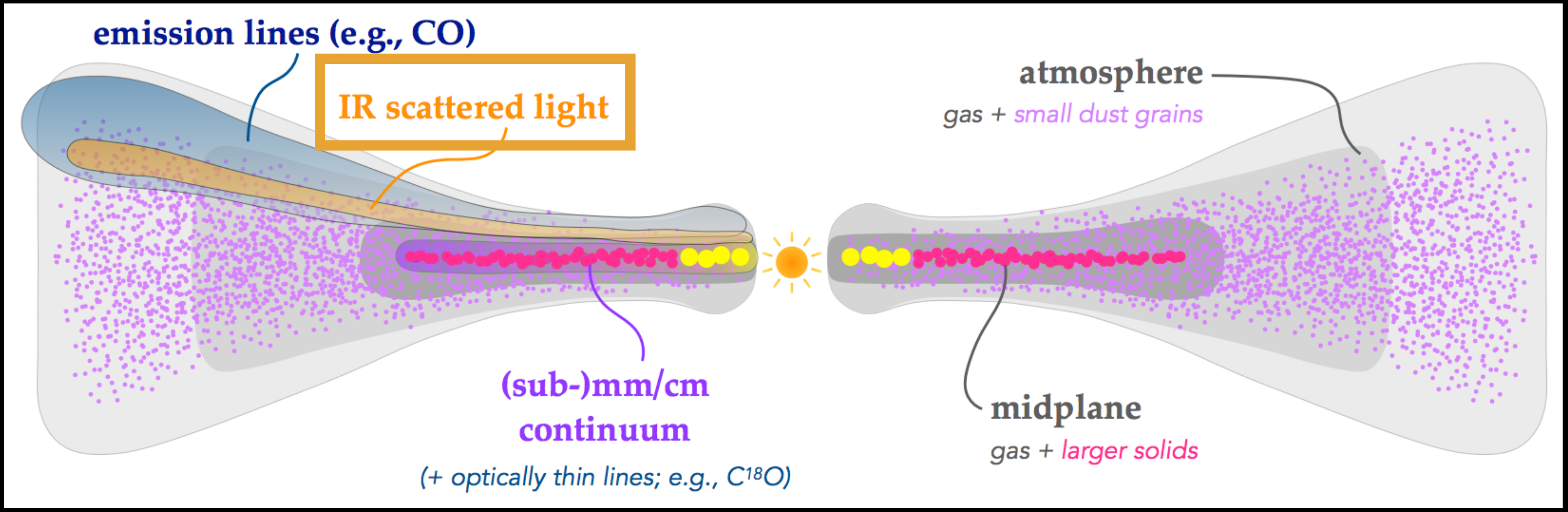


Millimeter continuum (ALMA)
Andrews et al. 2016



CO emission as a gas proxy (ALMA)
Huang et al. 2018a





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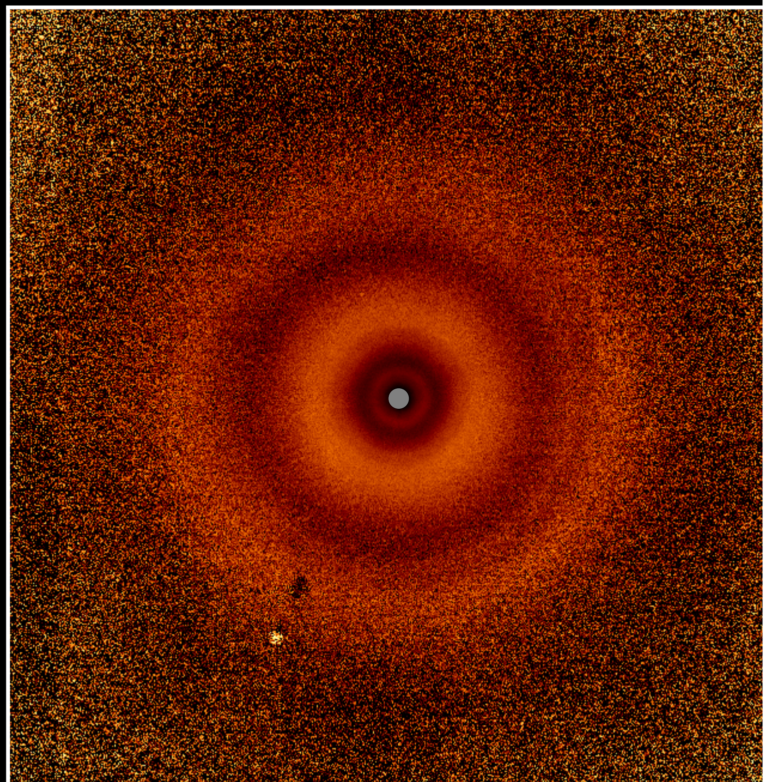
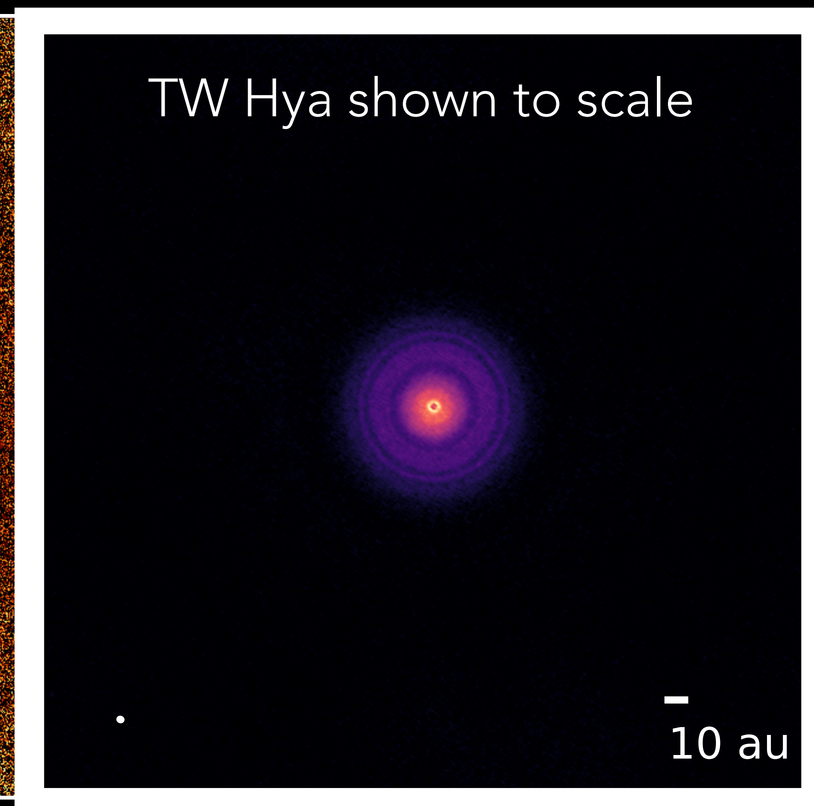
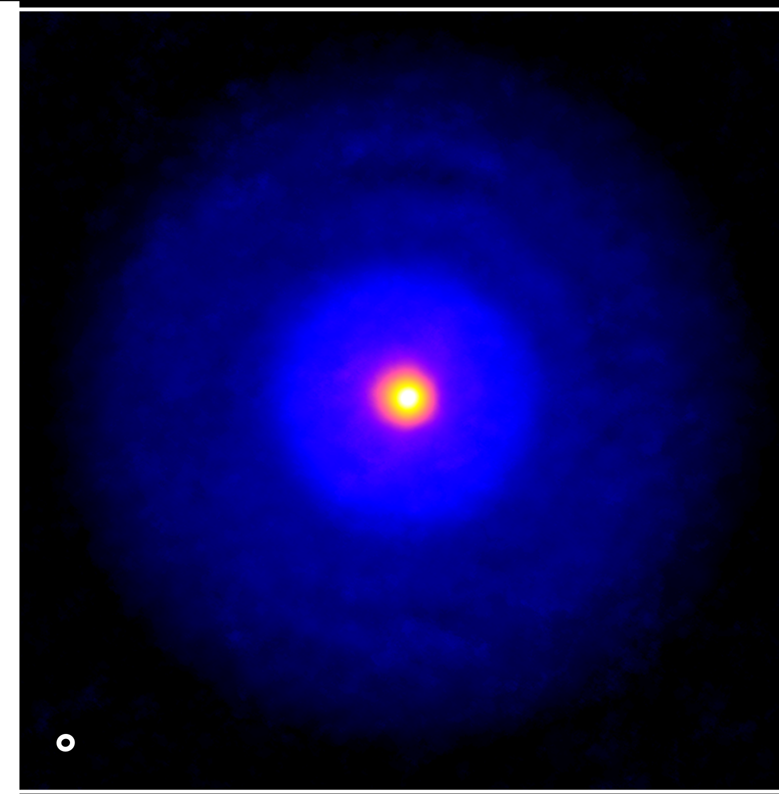
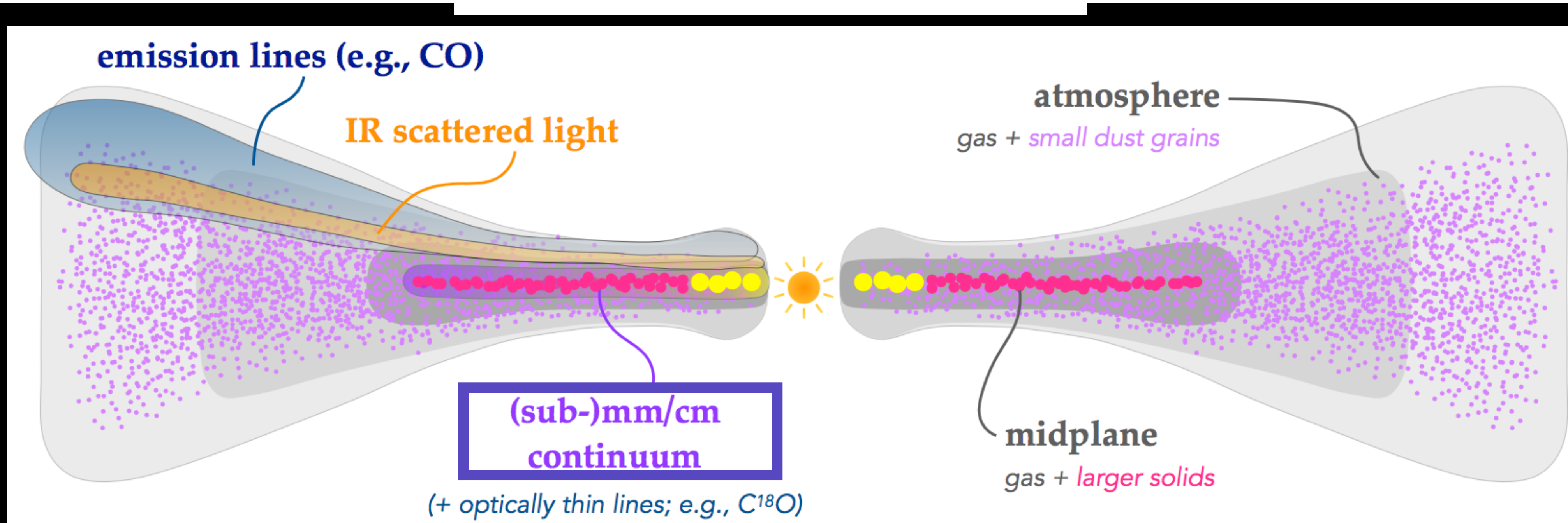




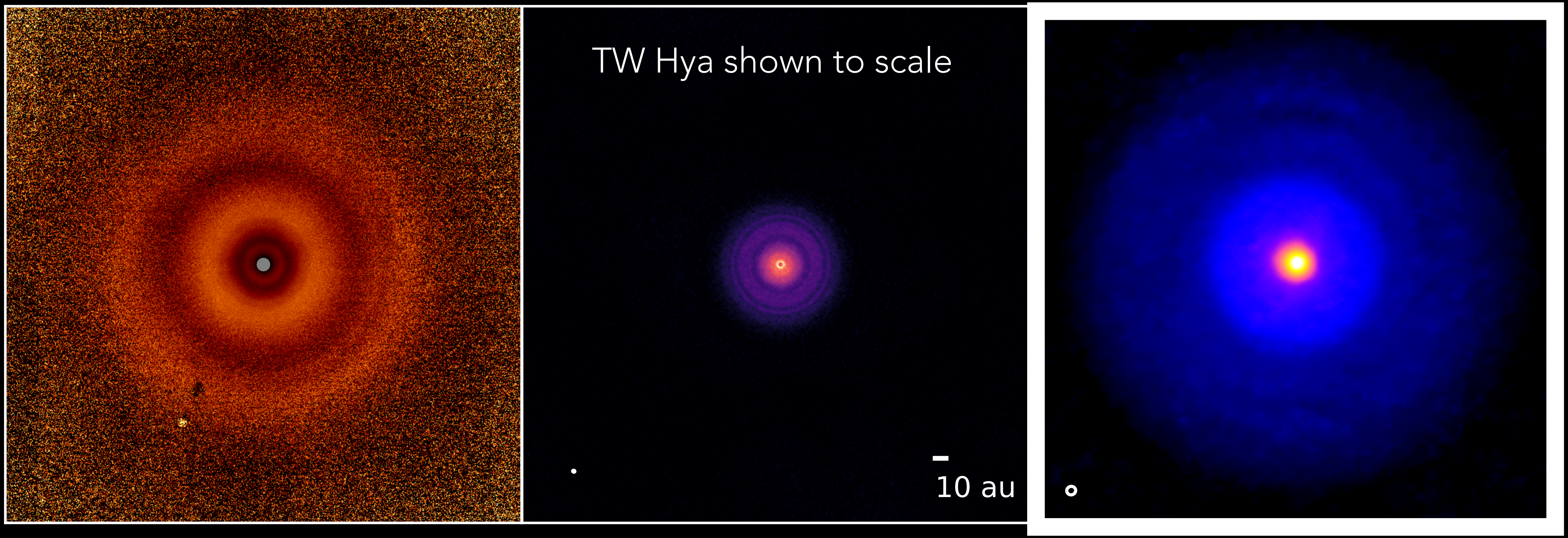


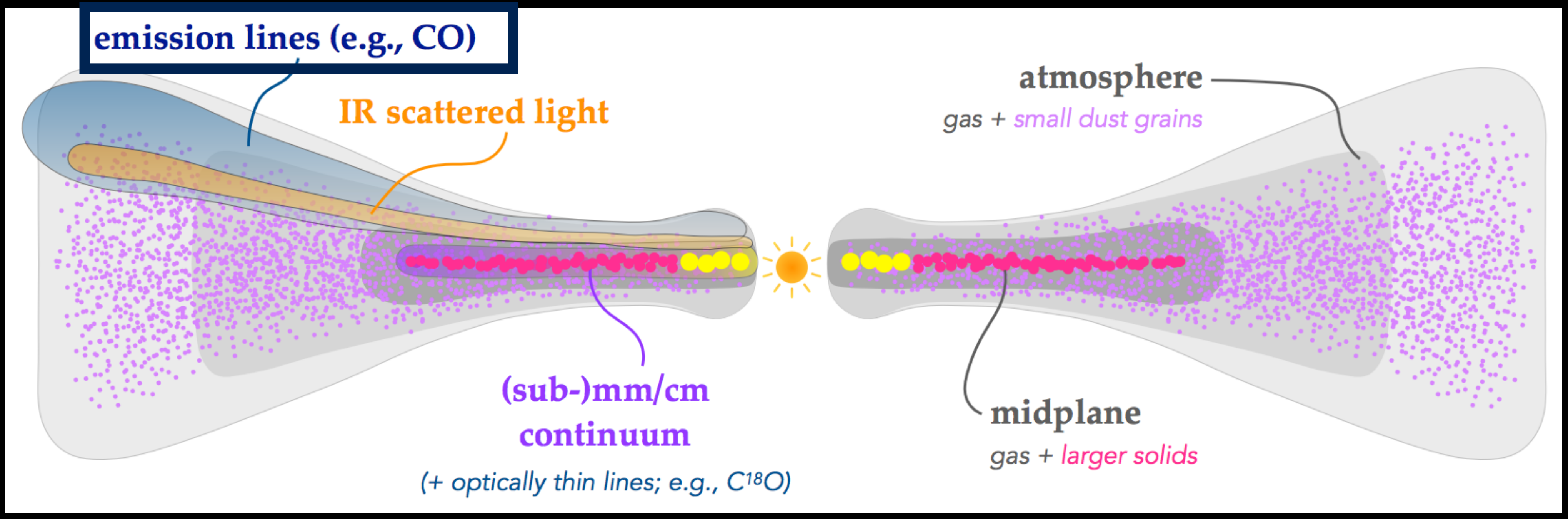


Vertical cross-section of a protoplanetary disk
Andrews 2020

Three views of a protoplanetary disk

Scattered light (SPHERE)	Millimeter continuum (ALMA)	**CO emission as a gas proxy (ALMA)**
van Boekel et al. 2016	Andrews et al. 2016	**Huang et al. 2018a**



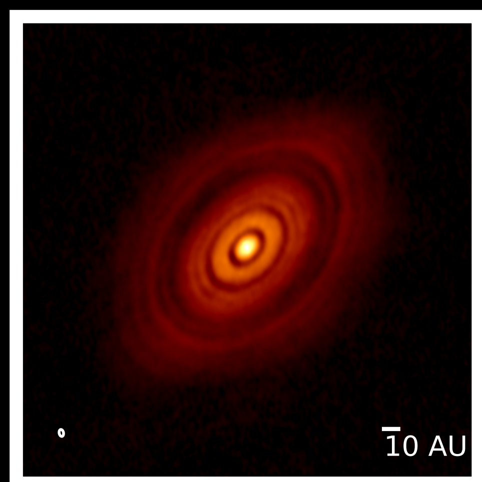


Vertical cross-section of a protoplanetary disk
Andrews 2020

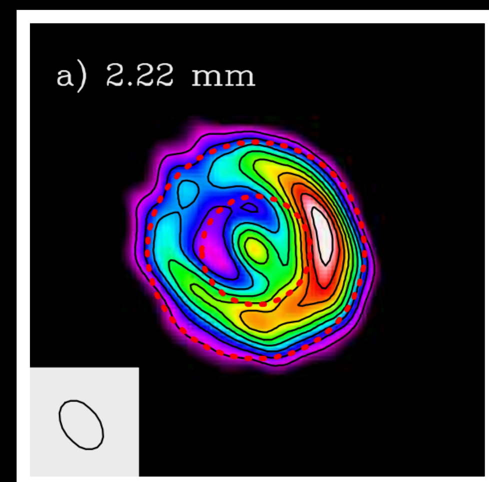
Facilities currently used to characterize disk structures at millimeter wavelengths

ALMA | NOEMA | SMA | VLA

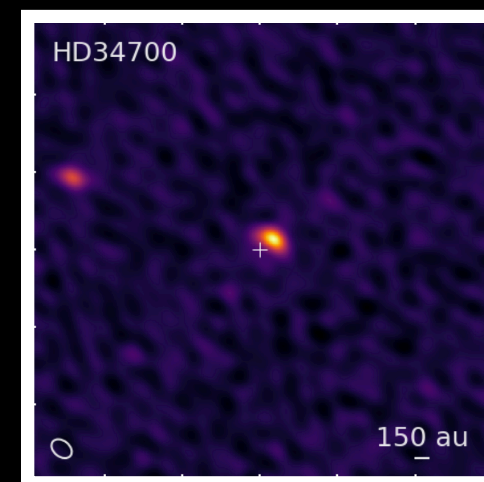
Continuum



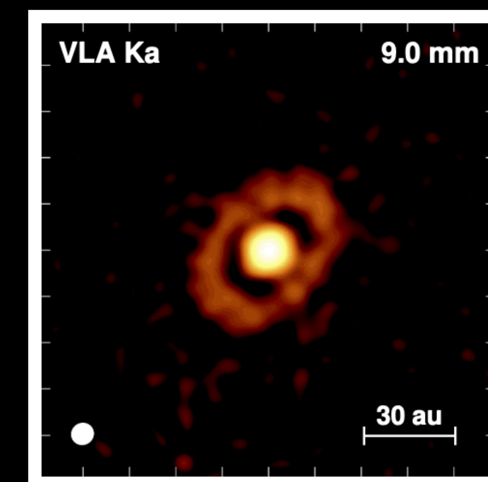
HL Tau
ALMA Partnership 2015



AB Aur
Fuente et al. 2017

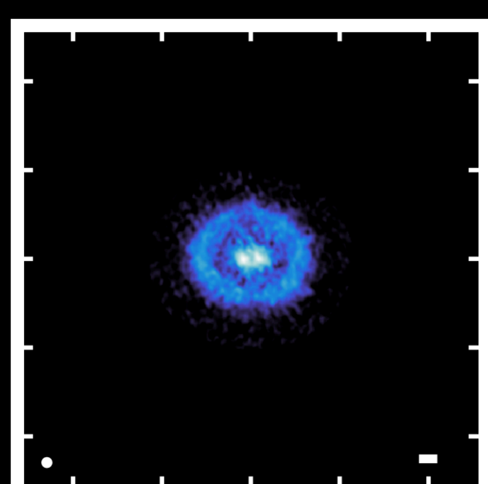


HD 34700
Benac et al. 2020

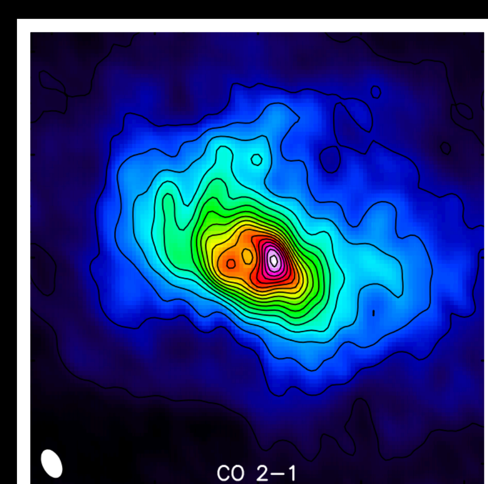


HL Tau
Carrasco-Gonzalez et al. 2019

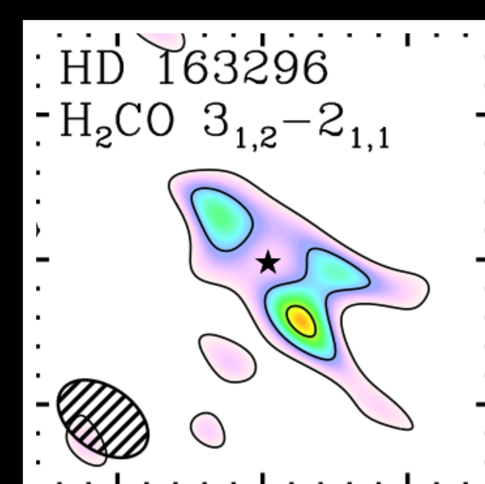
Molecular Emission



AS 209
Zhang et al. 2021



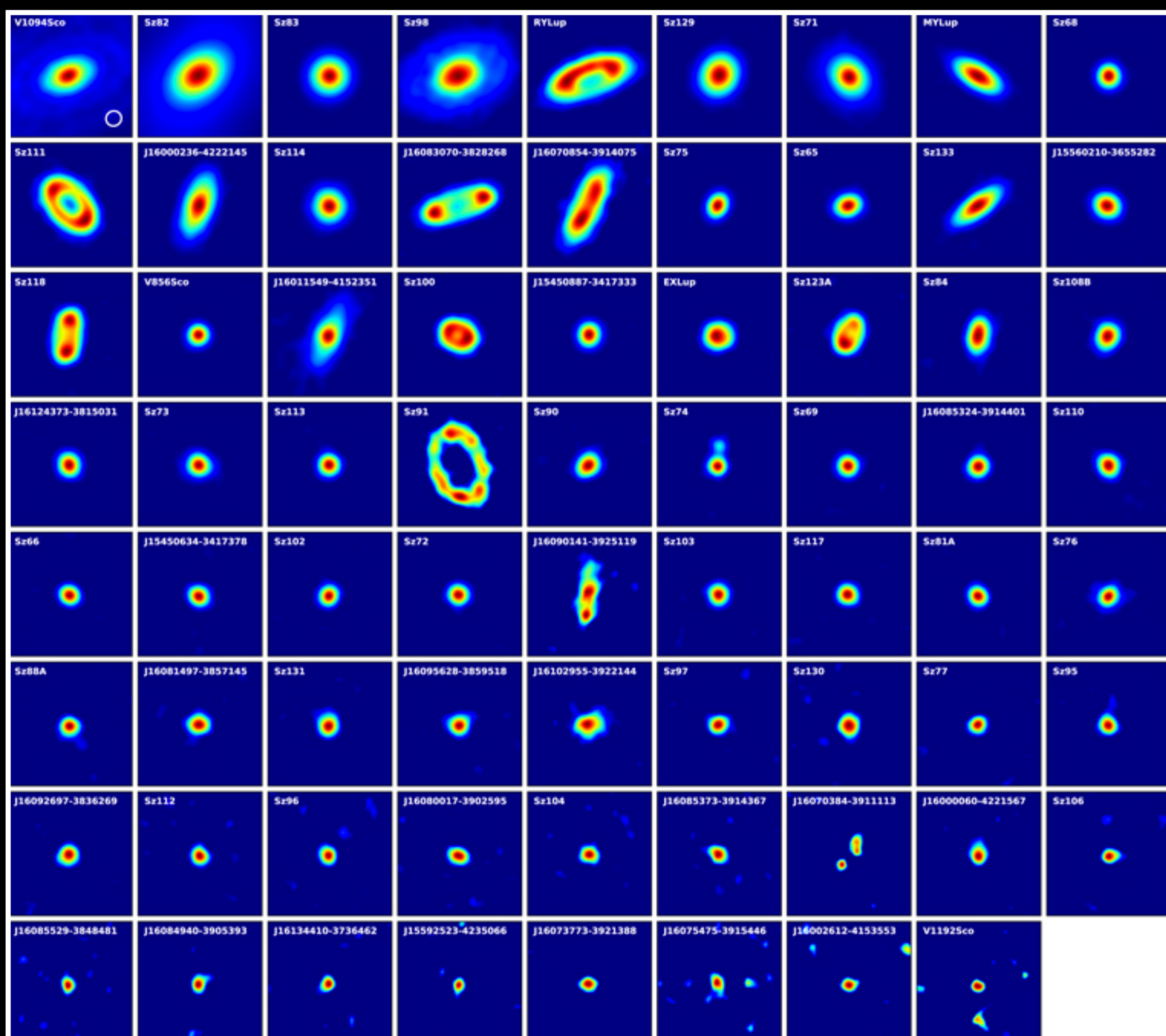
AB Aur
Rivière-Marichalar et al. 2020



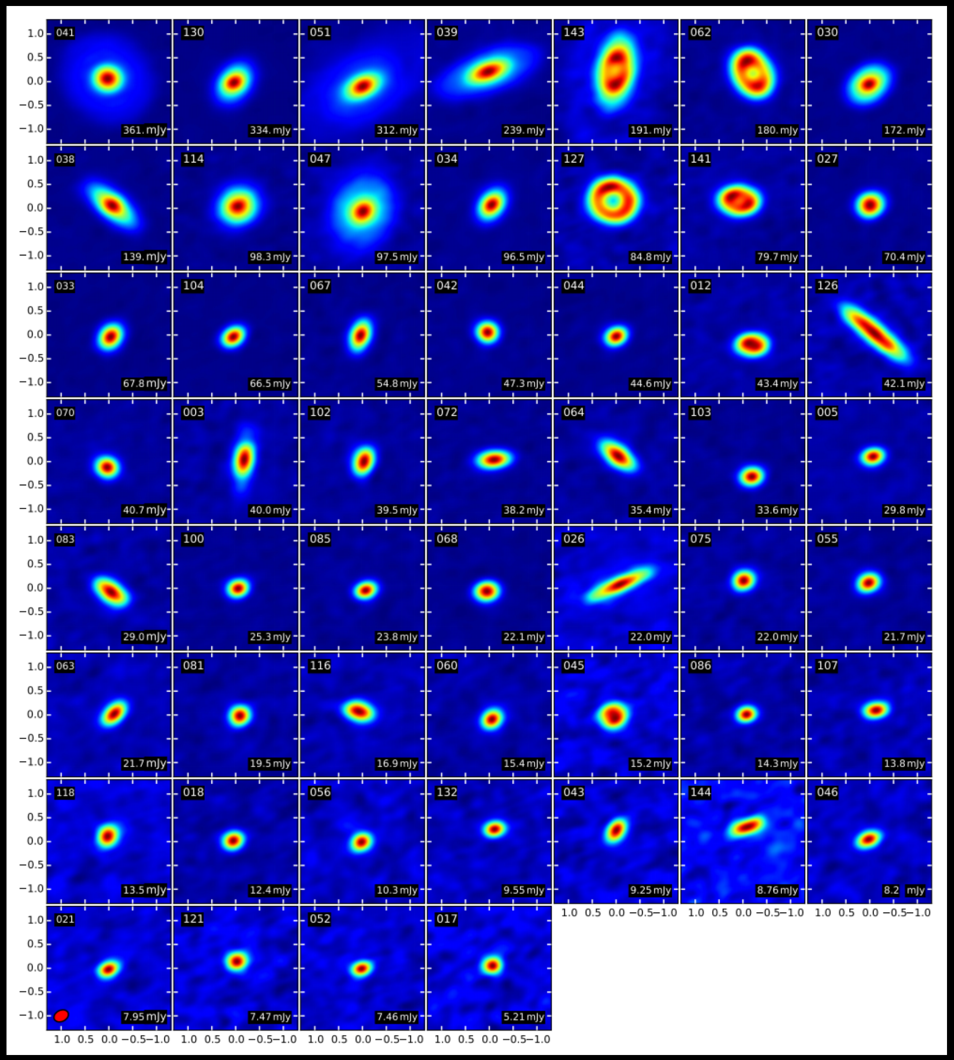
HD 163296
Qi et al. 2013

Large disk cavities were the first type of disk substructure to be systematically characterized

Ansdell et al 2016: ~10% of detected Class II disks in Lupus have visible cavities at a spatial resolution of ~40 au



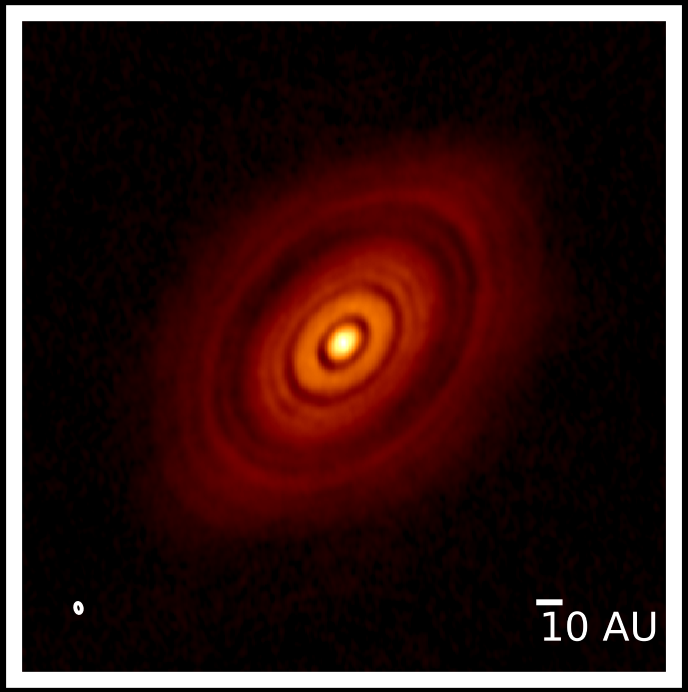
Cieza et al. 2019: ~5% of detected Class II disks in Oph have visible cavities at a spatial resolution of ~28 au



Caveat: Disks in the bottom third or so of the millimeter brightness distribution have not been well-characterized!

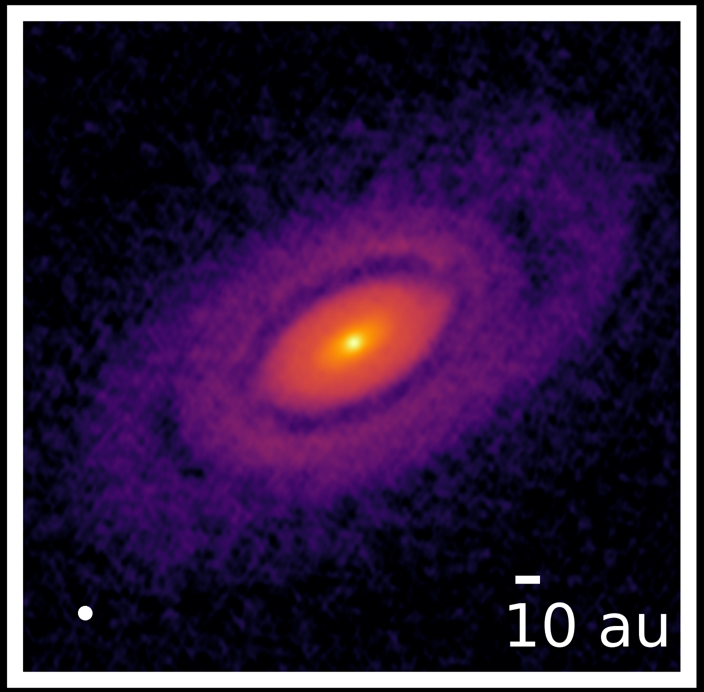
Types of substructures detected in millimeter continuum emission

Annular gaps and rings



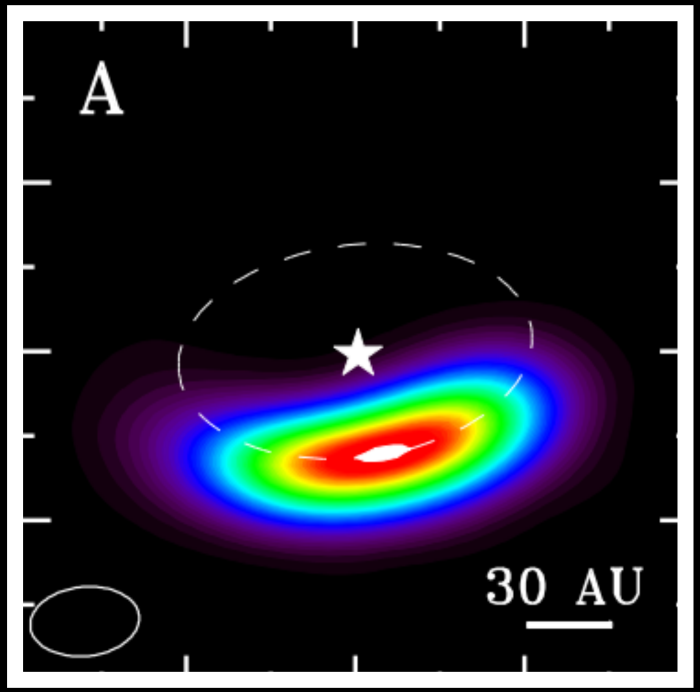
HL Tau
ALMA Partnership 2015

Spiral arms



Elias 27
Huang et al. 2018c

Arcs



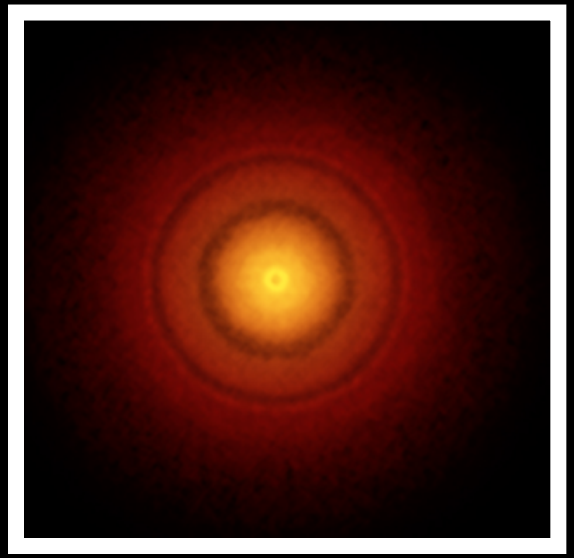
Oph IRS 48
van der Marel et al. 2013

The current landscape of high(er) resolution millimeter continuum observations

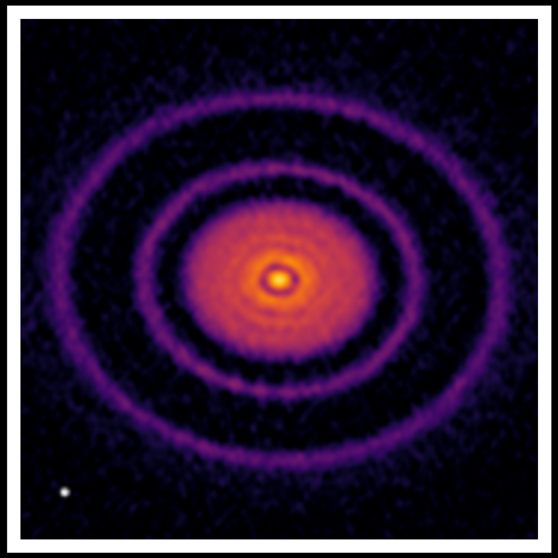
- As of October 2021, ALMA continuum images of ~60 protoplanetary disks at <10 au resolution have been published
  - ~85% exhibit clear gap/ring, spiral, and/or asymmetric structure
  - Most of the disks without clear substructure are either edge-on and/or part of multiple systems
- Roughly another 110 disks have published ALMA images at 10-20 au resolution
  - Roughly 1/3 of these exhibit clear gap/ring and/or asymmetric structure
  - Most of the disks without clear substructure are in multiple systems, hosted by M-type stars, and/or spatially unresolved

See, e.g., Huang et al. 2018b, Long et al. 2018, Andrews 2020, Ansdell et al. 2020, Cieza et al. 2021, Francis and van der Marel 2020, Kurtovic et al. 2021, Villenave et al. 2021, van der Marel & Mulders 2021, Otter et al. 2021 and references therein

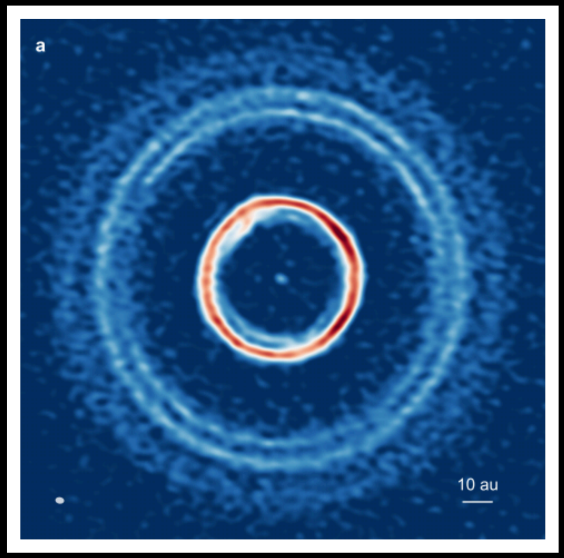
Gaps/rings in mm continuum emission



TW Hya
Andrews et al. 2016



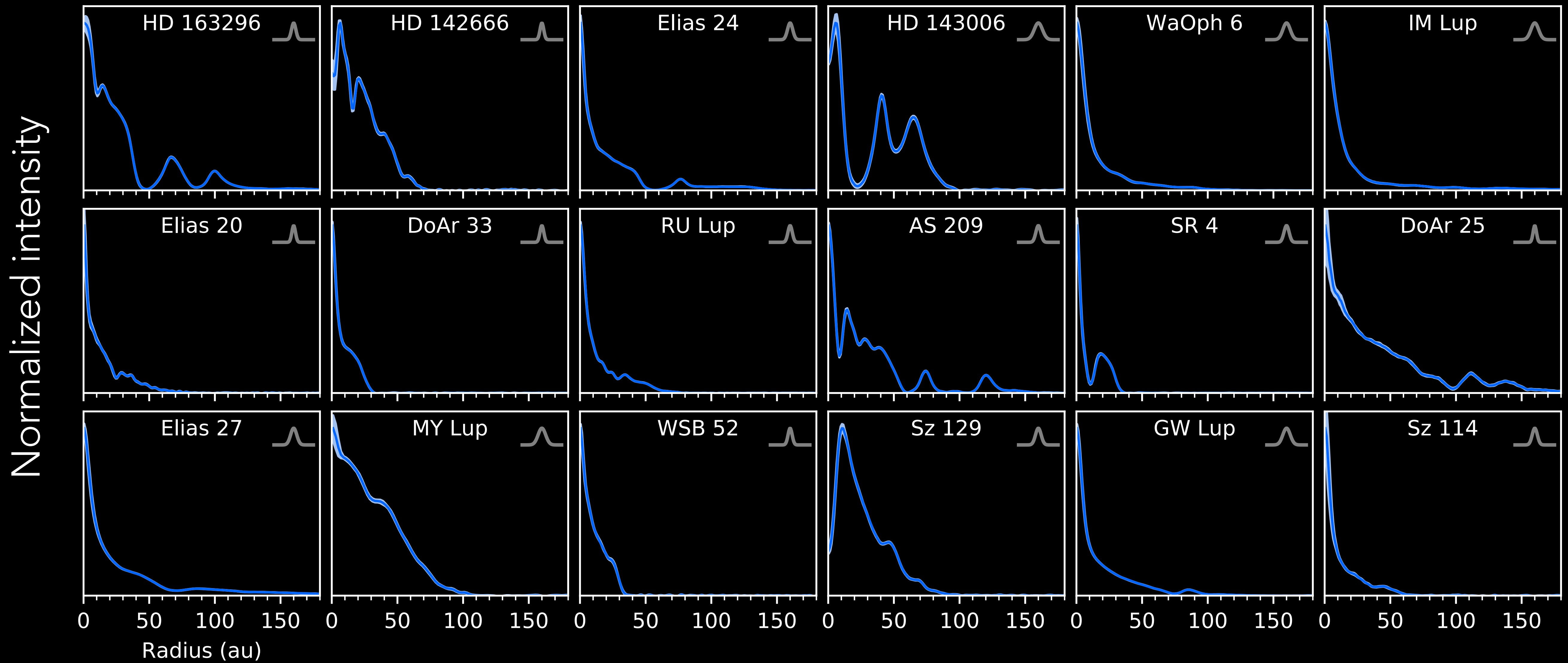
AS 209
Guzmán et al. 2018



HD 169142
Pérez et al. 2019

- Of the disks known to have mm continuum substructure, nearly all have gaps and rings
- Disks with gaps and rings have hosts with spectral types ranging from M5 to A0
- Gaps and rings have been detected in both young (<1 Myr) and older ($\gtrsim$10 Myr) disks
- Gaps and rings have been detected as close in as a few au (resolution limit set by ALMA) and as far out as several hundred au

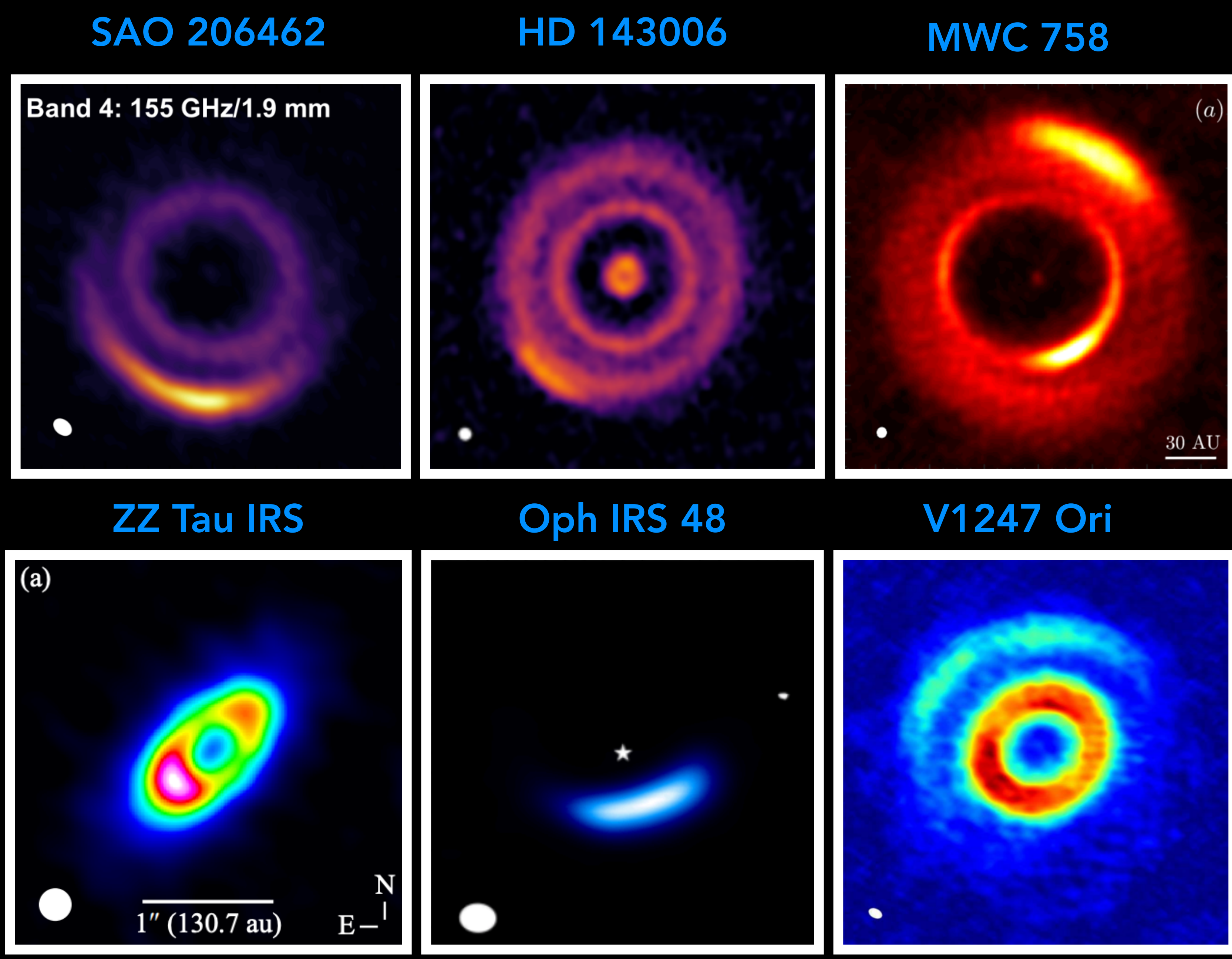
Annular gap widths and depths



Huang et al. 2018b

- Gap widths range from a few au to a few tens of au
- Some gaps vary in intensity by only a few percent from adjacent rings, while others appear to be nearly depleted

Large-scale asymmetries in millimeter continuum emission



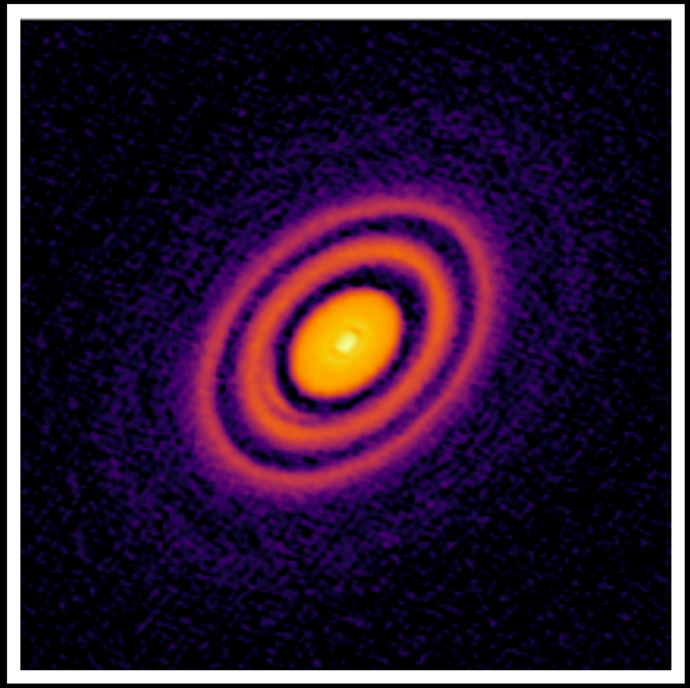
- Reported in about half of Herbig disks imaged at high resolution, but only in a handful of T Tauri disks so far
- Often appear in conjunction with large central cavities

See, e.g., van der Marel et al. 2013, Garufi et al. 2018, Cazzoletti et al. 2018, Dong et al. 2018, Kraus et al. 2018, Pérez et al. 2018, van der Marel et al. 2020, Hashimoto et al. 2021

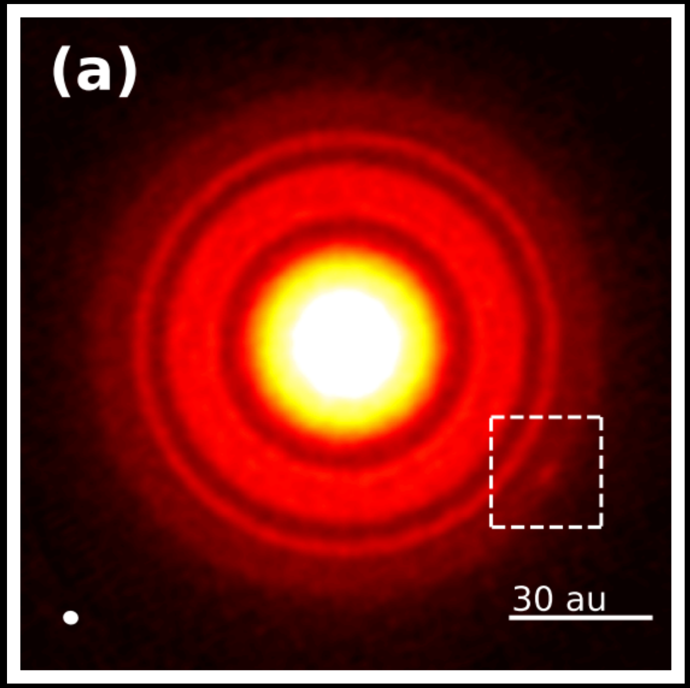
Small-scale asymmetries in millimeter continuum emission

- High-resolution, high-sensitivity observations have also revealed subtle asymmetries in disks previously thought to be axisymmetric
- Unclear whether these asymmetries share common origins with the large-scale asymmetries visible in other disks

HD 163296
Isella et al. 2018

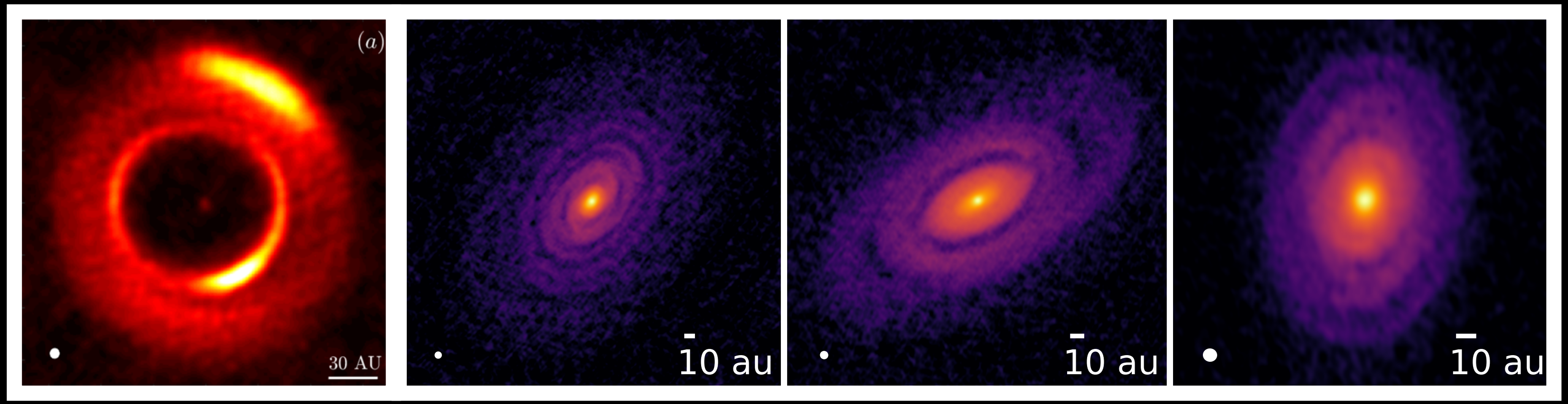


TW Hya
Tsukagoshi et al. 2019

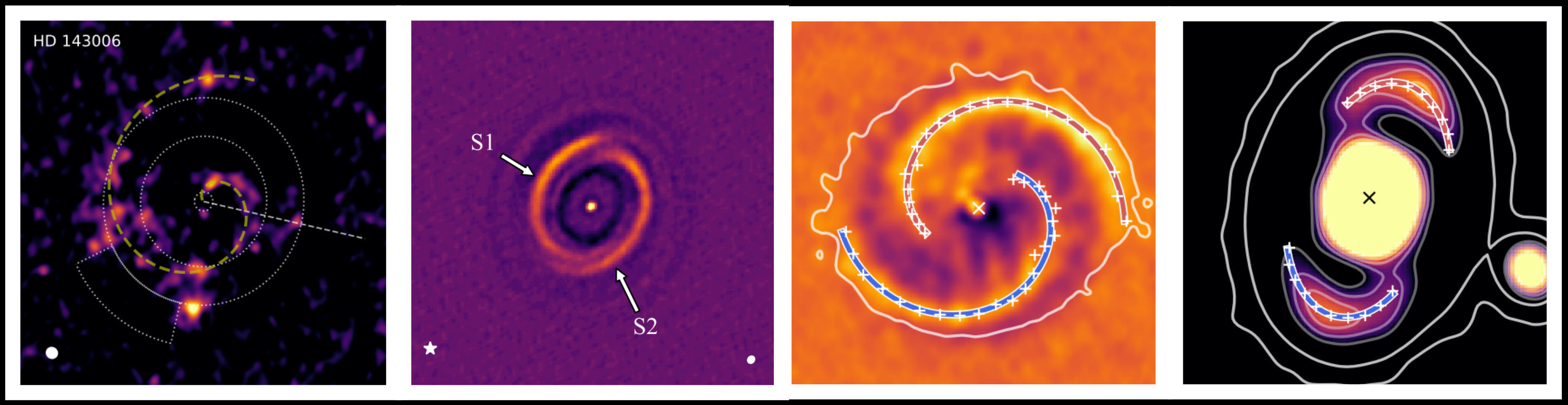


Millimeter continuum spirals

MWC 758 | IM Lup | Elias 27 | WaOph 6



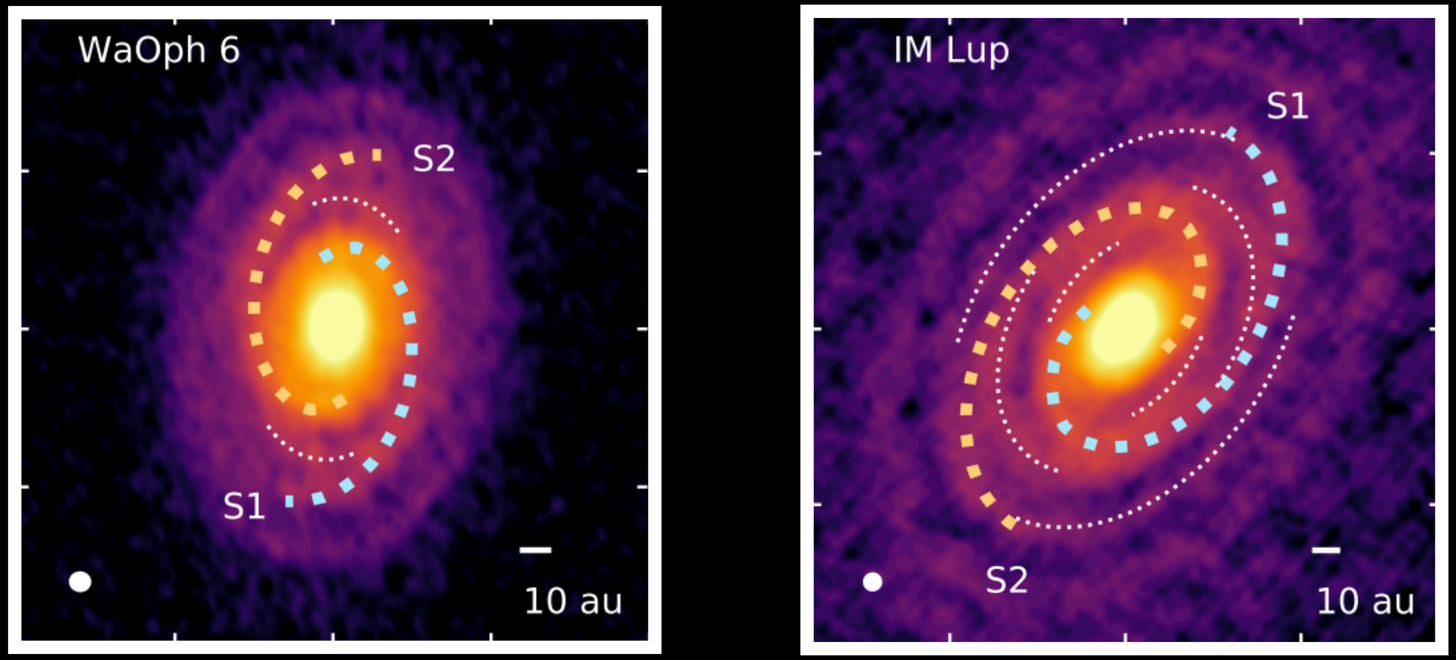
HD 143006 | HD 100453 | AS 205 N | HT Lup A



- Appear to be much rarer than gaps/rings and somewhat rarer than large-scale asymmetries
- Mostly 2-armed patterns
- Detected around both T Tauri and Herbig Ae stars
- Detected in both binary and single-star systems
- Often detected in conjunction with other types of substructures (gaps/rings and/or large-scale asymmetries)

See, e.g., Pérez et al. 2016, Dong et al. 2018, Huang et al. 2018c, Kurtovic et al. 2018, Rosotti et al. 2020, Andrews et al. 2021

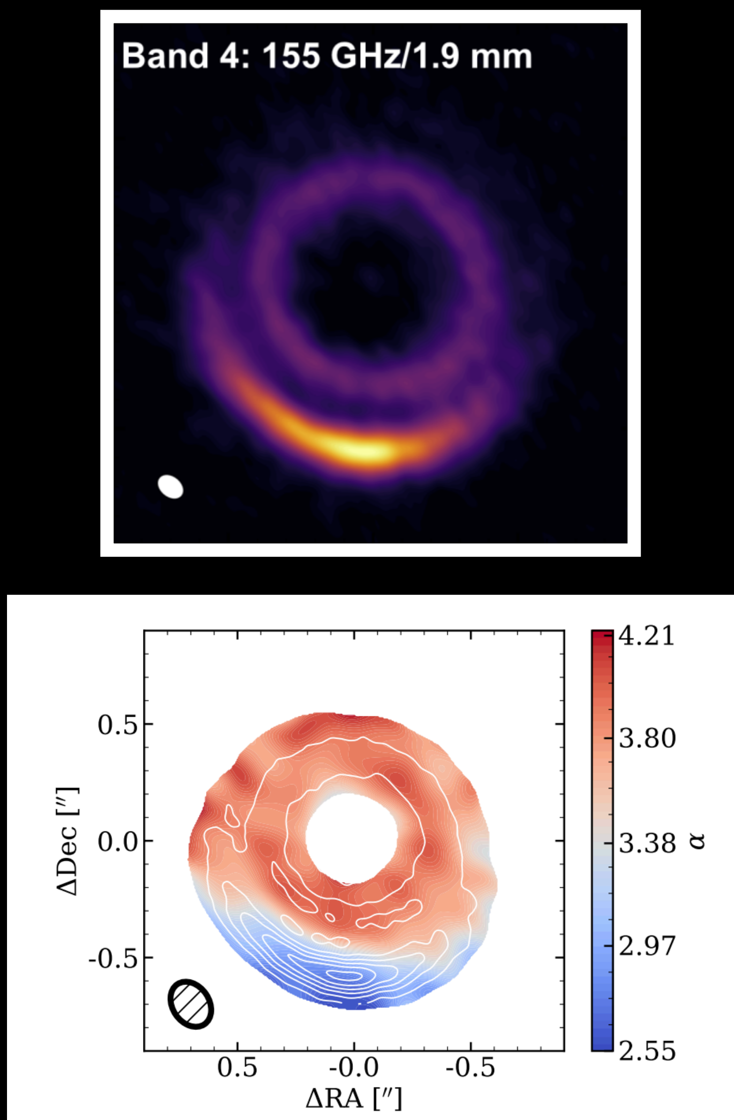
Complex detail in spiral structures



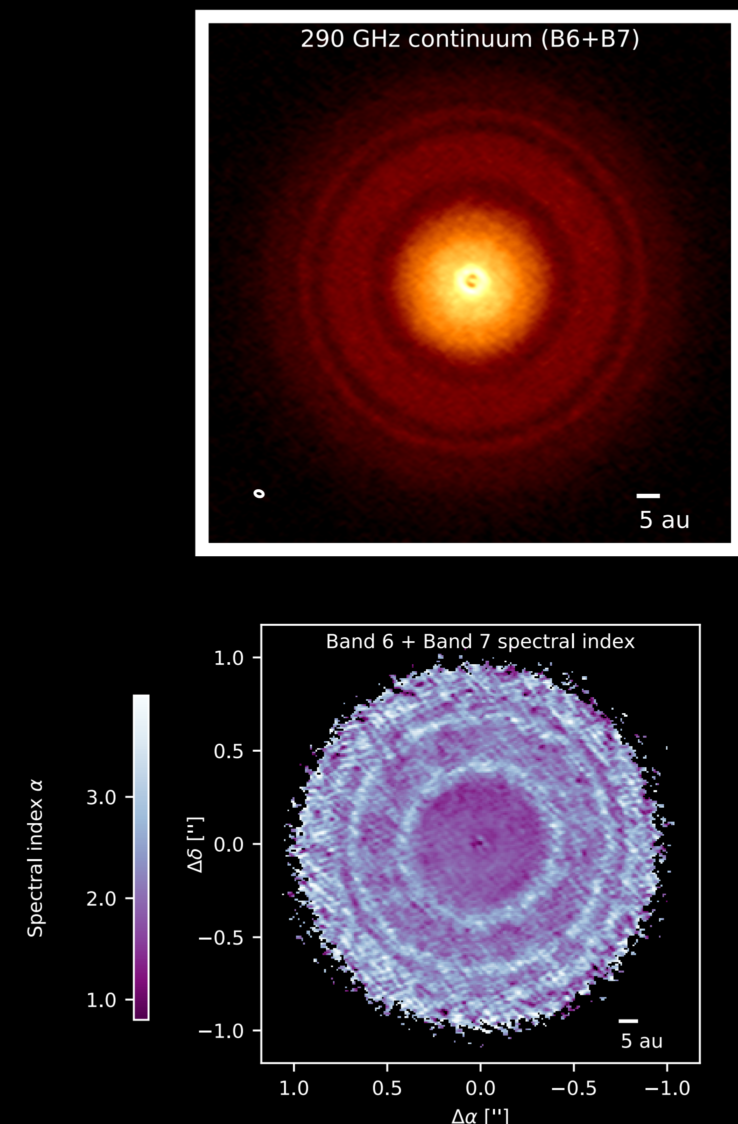
Huang et al. 2018c

- Some disks show smaller-scale substructures that appear to intersect with the dominant spiral pattern
- Unclear whether these substructures are examples of spiral “feathering” or additional ring structures

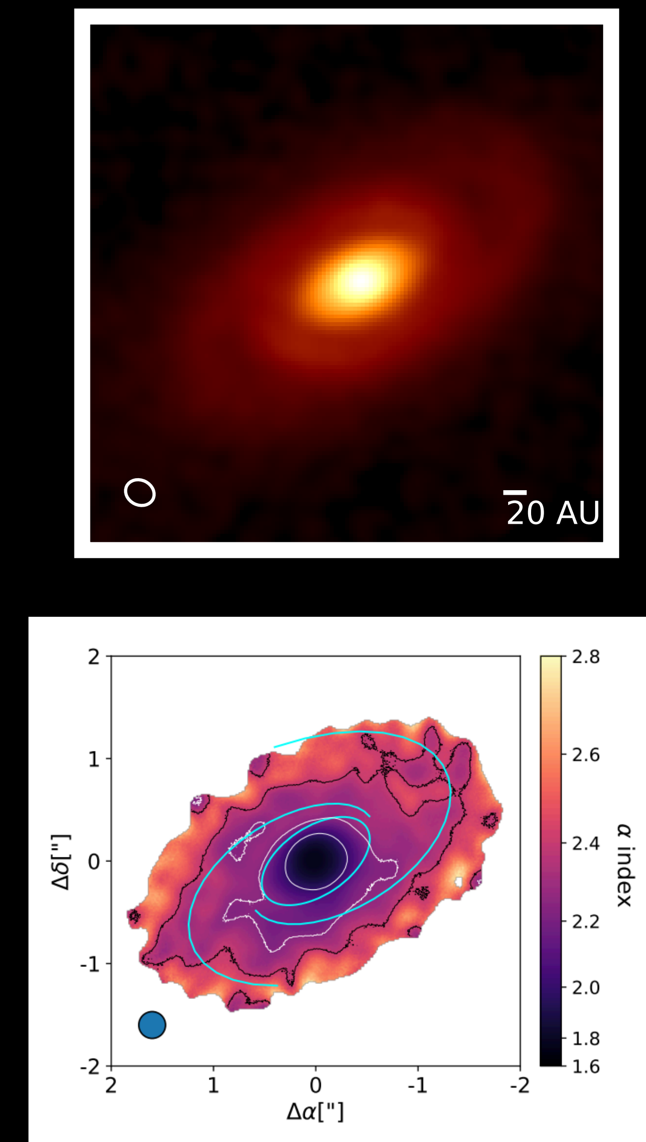
Spectral indices of disk substructures



SAO 206462
Cazzoletti et al. 2018



TW Hya
Huang et al. 2018a

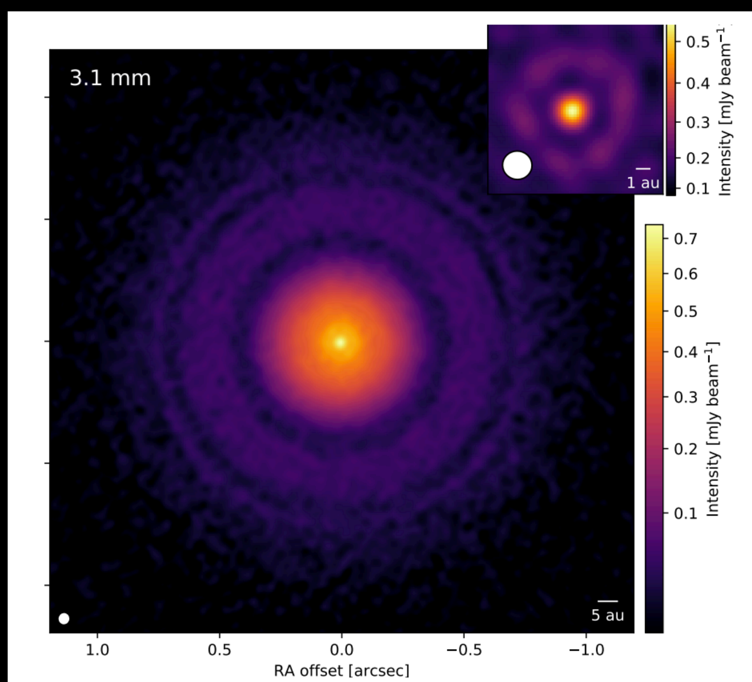


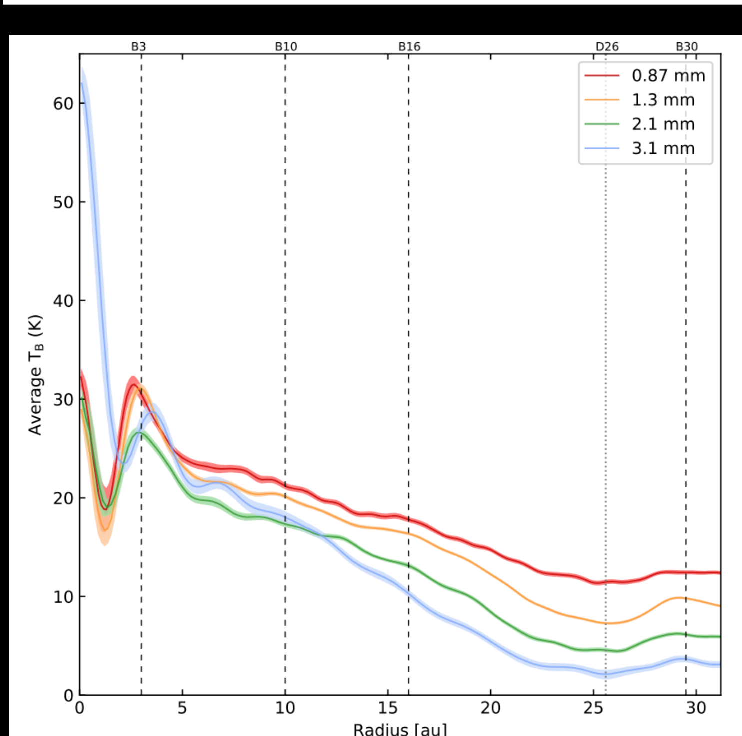
Elias 27
Paneque-Carreño et al. 2021

- Spectral index measurements are used to probe grain size variations
- Spectral indices can vary strongly across substructures, suggestive of dust trapping
- Optical depth presents a challenge to spectral index interpretation

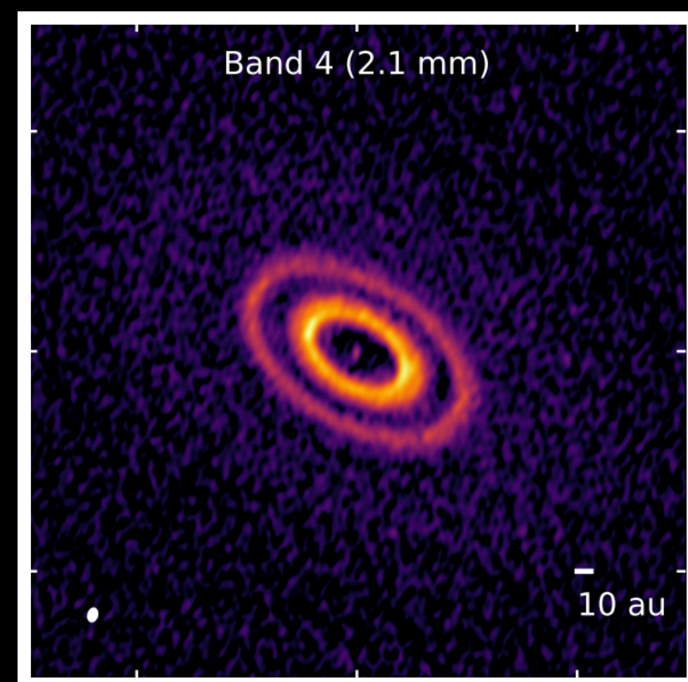
Free-free emission sometimes contributes to millimeter emission in the inner disk

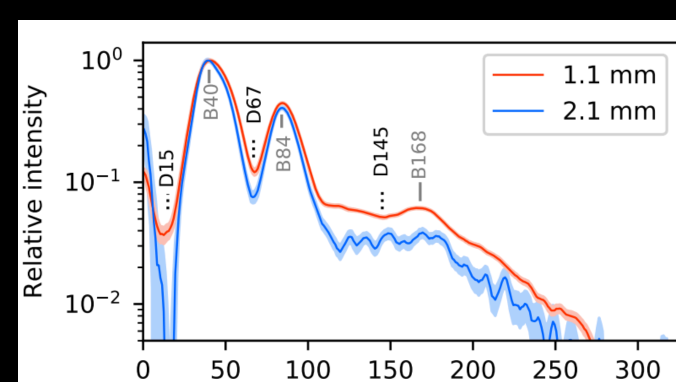
TW Hya
Macías et al. 2021





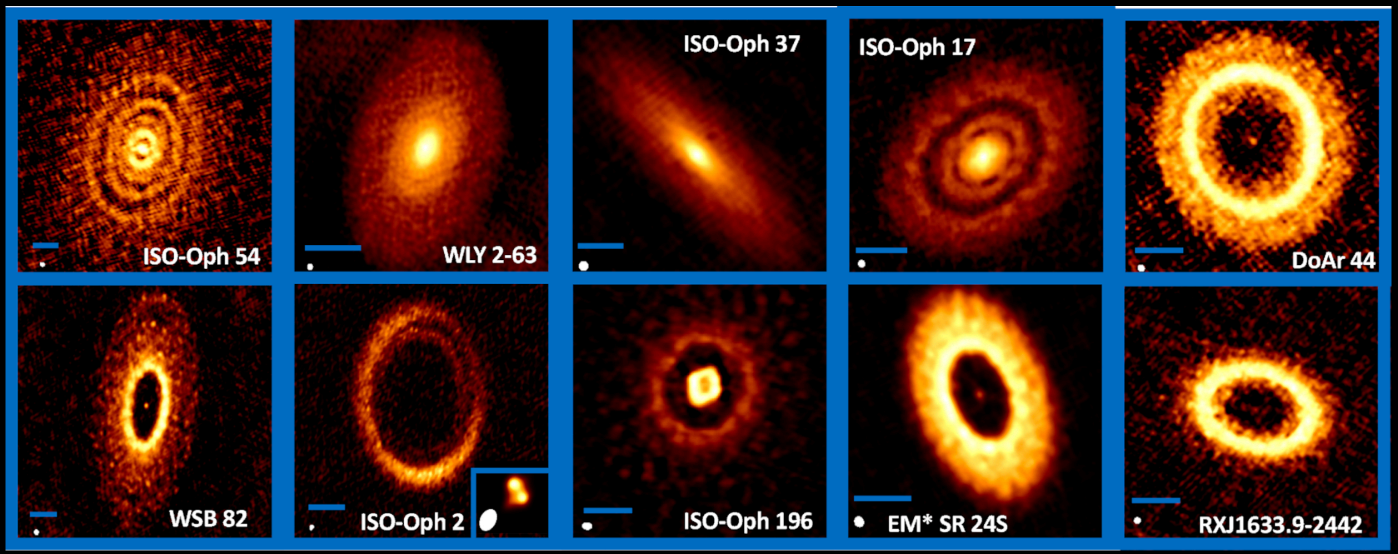
GM Aur
Huang et al. 2020a



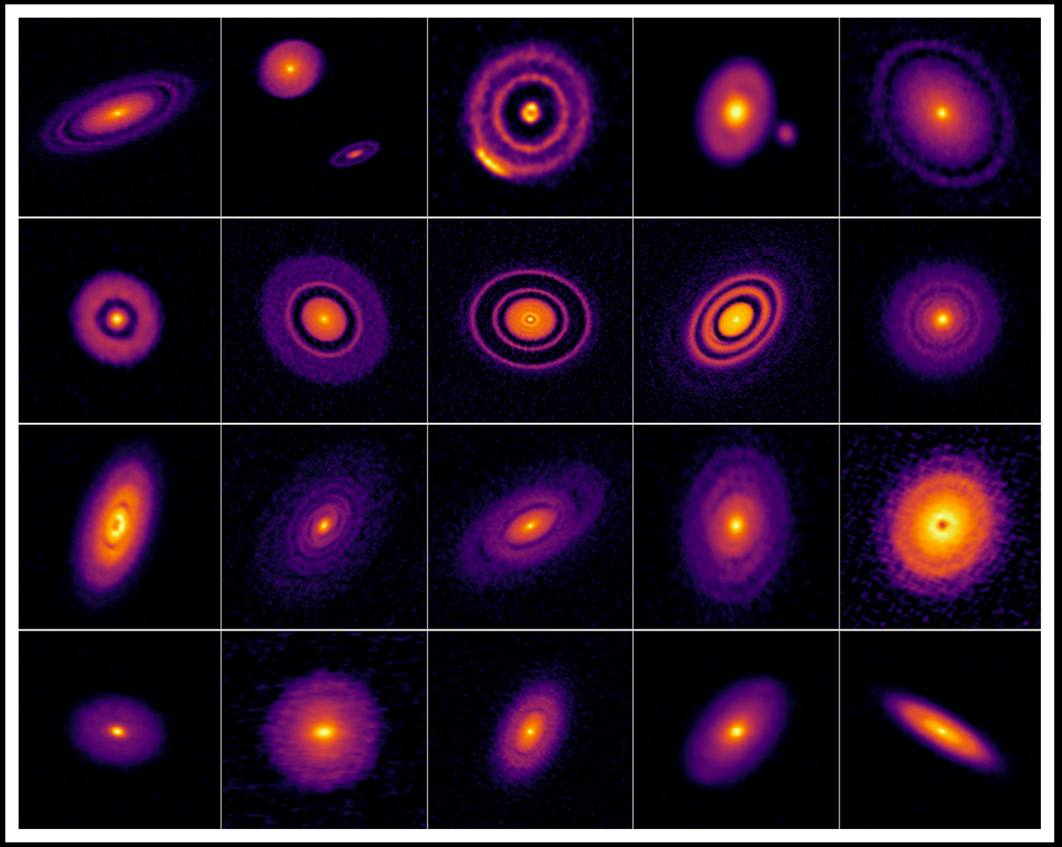


Low spectral indices (<2) of some "inner disks" suggests that free-free emission is a significant contributor, even at higher ALMA frequencies (Bands 6 and 7)

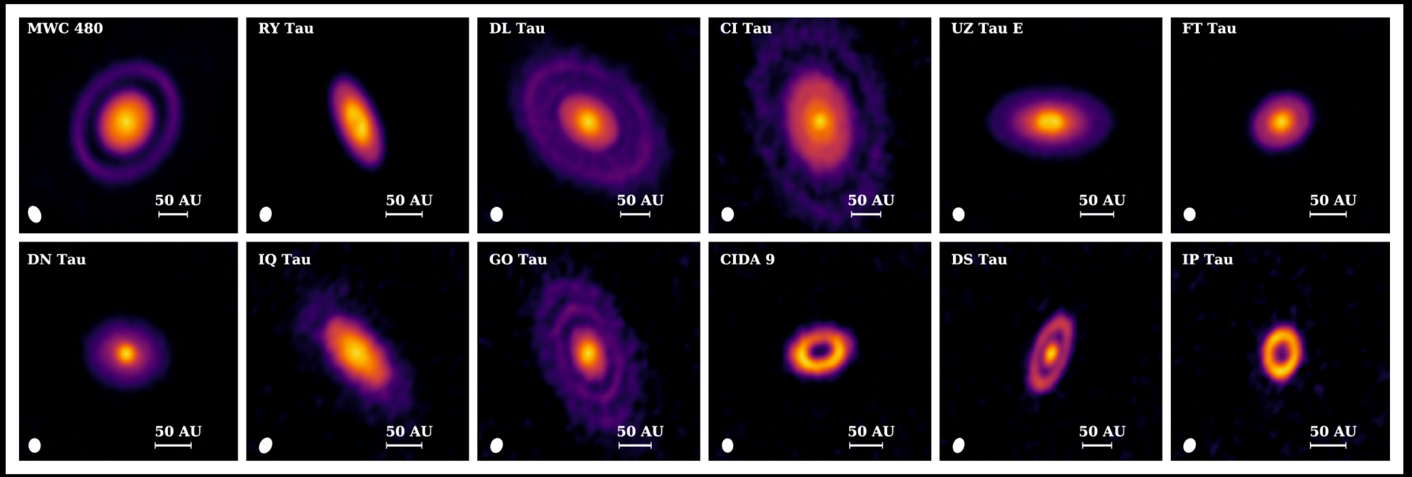
Limitations in our understanding of millimeter continuum substructures: Selection Bias



ODISEA (Cieza et al. 2021): Selected targets in Ophiuchus that had bright millimeter continuum emission



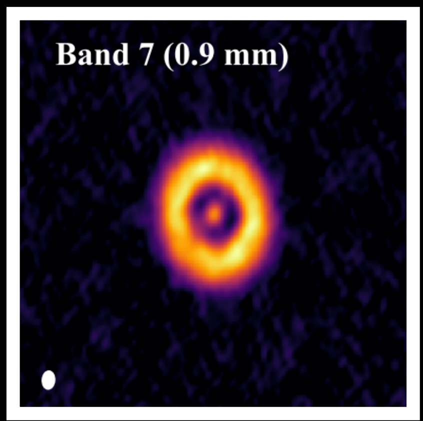
DSHARP (Andrews et al. 2018): Selected targets with bright peak millimeter continuum fluxes



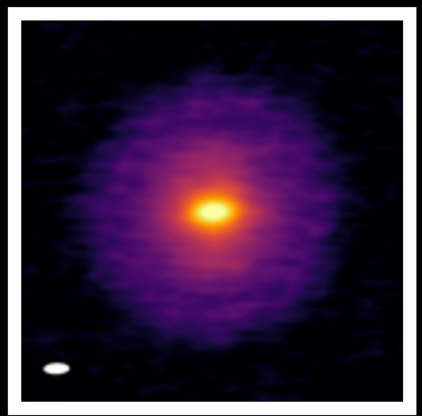
Long et al. 2018, 2019: Selected targets with spectral types earlier than M3

Substructures in disks around late spectral type stars

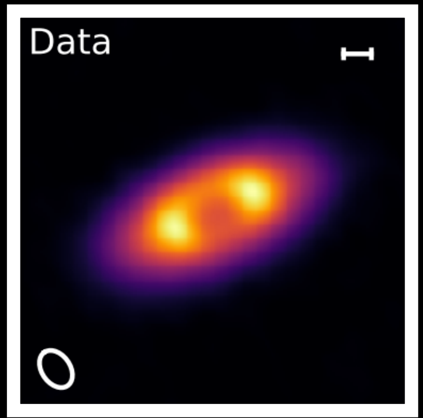
CIDA 1



Sz 114

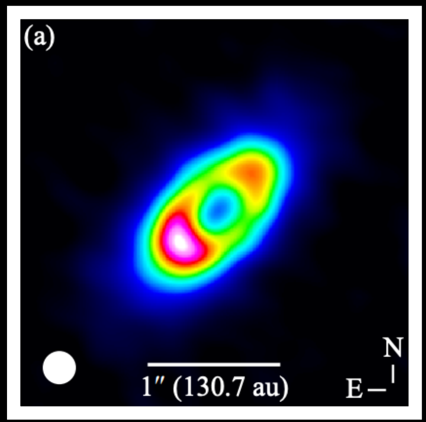


MHO 6

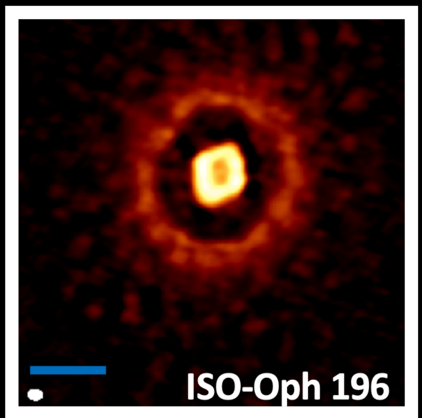


See, e.g., Andrews et al. 2018, Long et al. 2018, Pinilla et al. 2021, Kurtovic et al. 2021, Hashimoto et al. 2021, Cieza et al. 2021

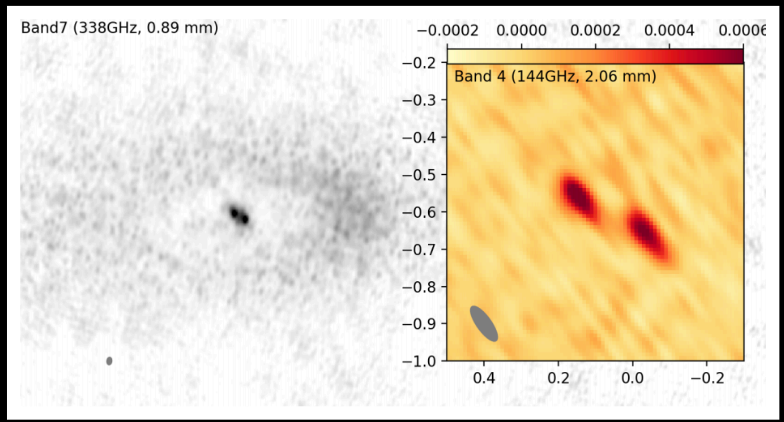
ZZ Tau IRS



ISO-Oph 196



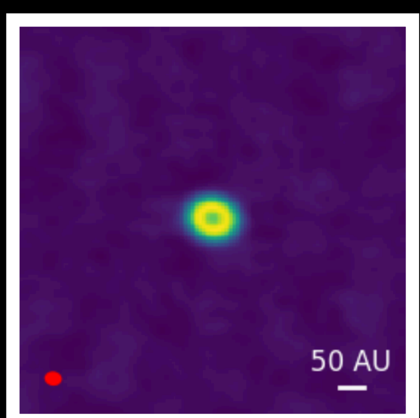
IRAS 04158+2805



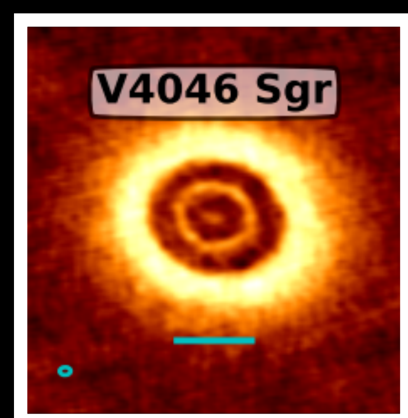
- Although a large fraction of PMS stars have M4-M5 spectral types (typically with masses up to a few tenths of a solar mass), relatively few have been observed at high resolution.
- Gaps/rings and asymmetries have been detected in disks around late spectral type stars, although observations are biased toward disks with high millimeter fluxes
- No mm continuum spiral arms have been reported for spectral types later than M0

Limitations in our understanding of millimeter continuum substructures: Heterogeneous sensitivity and resolution

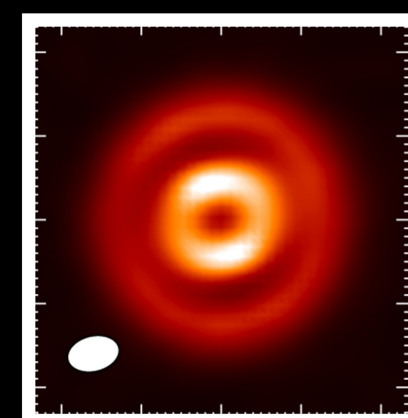
Resolving substructures within substructures



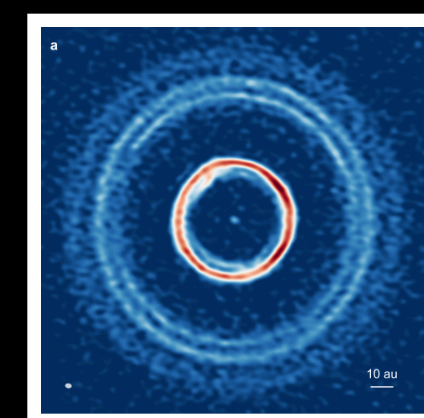
Kastner et al. 2018



Francis & van der Marel 2020

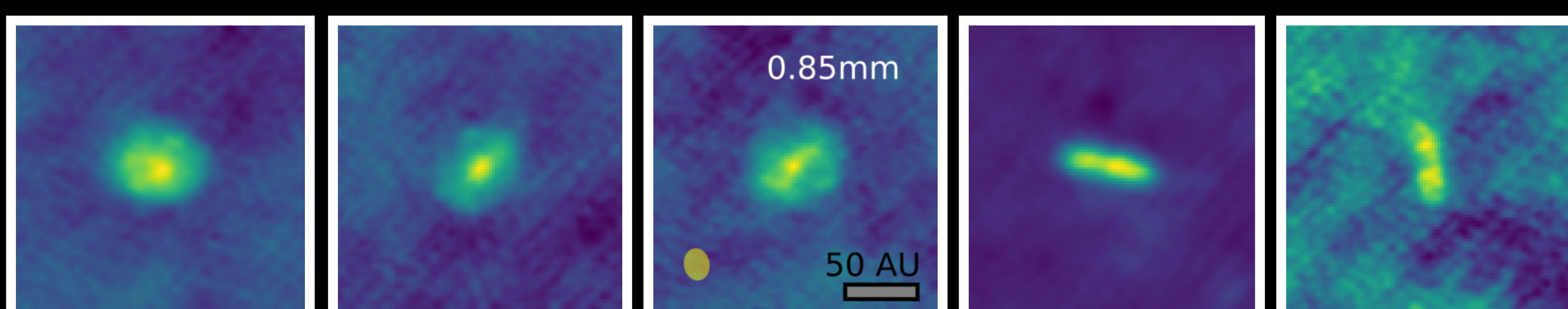


Fedele et al. 2017



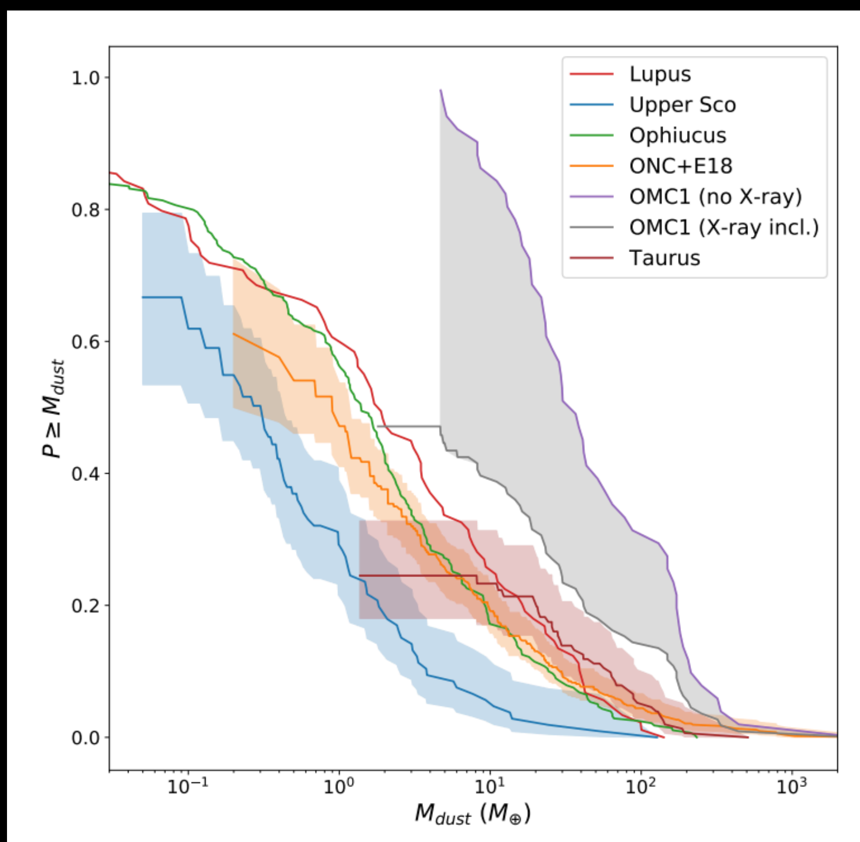
Pérez et al. 2019

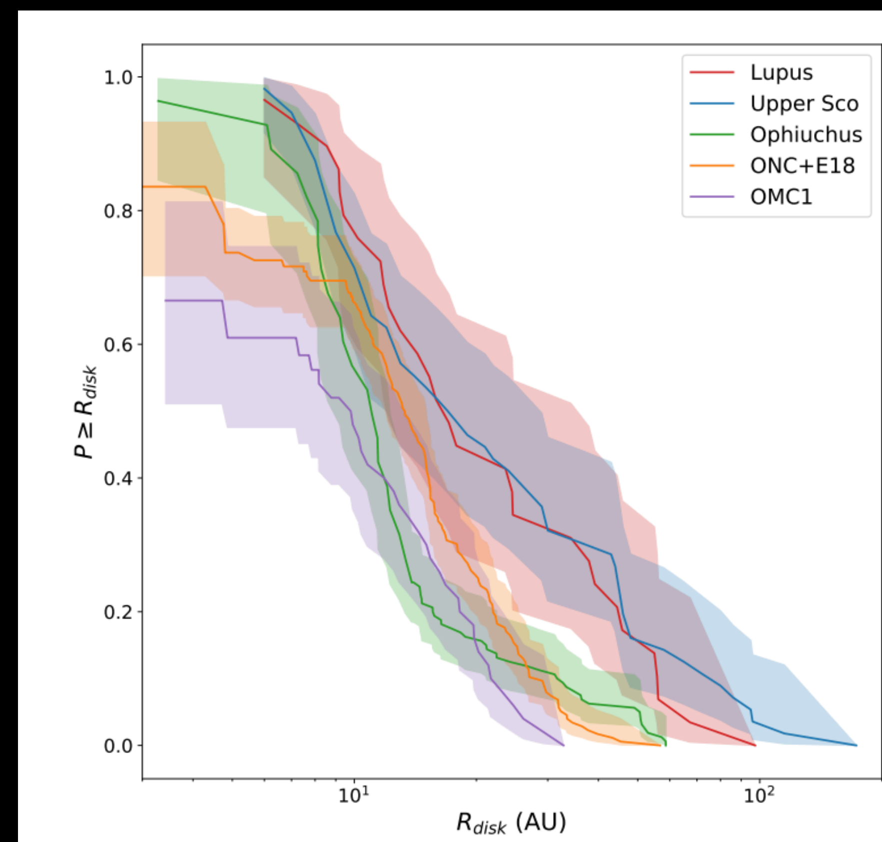
Which of these disks have substructures?



Otter et al. 2021

Limitations in our understanding of millimeter continuum substructures: Variations between star-forming regions

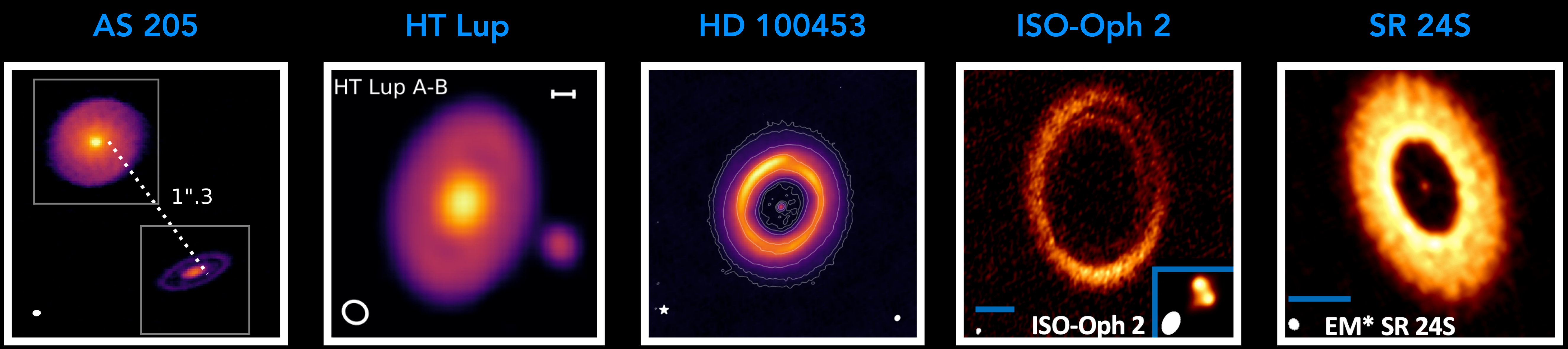




Otter et al. 2021

Disk bulk properties vary between star-forming regions, but detailed information about disk structures in high-UV environments such as Orion is inherently harder to obtain due to the much larger distances compared to popular star-forming regions such as Taurus and Ophiuchus

Limitations in our understanding of millimeter continuum substructures: Role of multiplicity



Do substructures in systems with companions systematically differ from single systems?

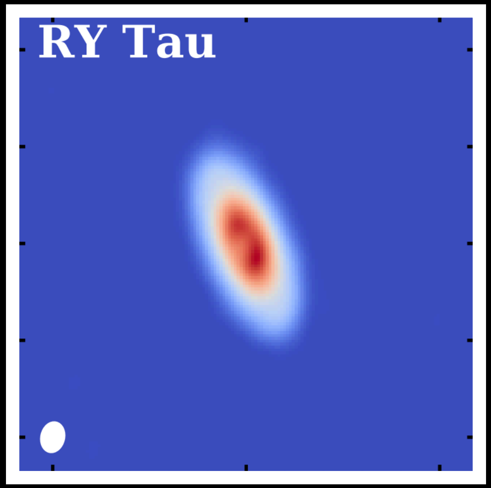
Which substructures can be attributed to the influence of companions?

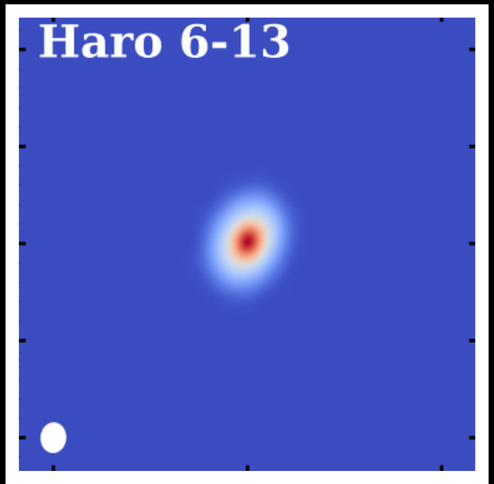
Which systems actually have companions?

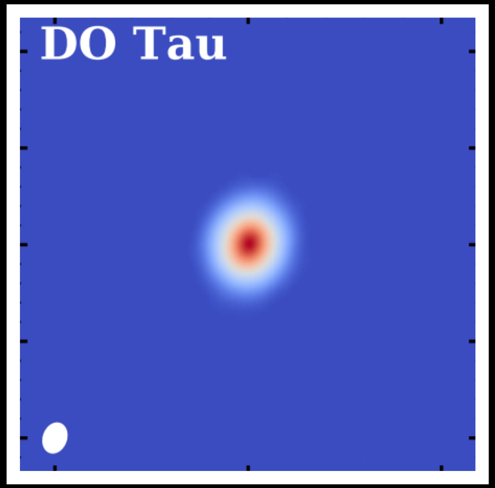
See, e.g., Long et al. 2019, Kurtovic et al. 2018, Rosotti et al. 2020, González-Ruilova et al. 2020, Cieza et al. 2021, Francis and van der Marel 2020, Muro-Arena et al. 2021

Limitations in our understanding of millimeter continuum substructures: Ambiguity in Evolutionary Classification

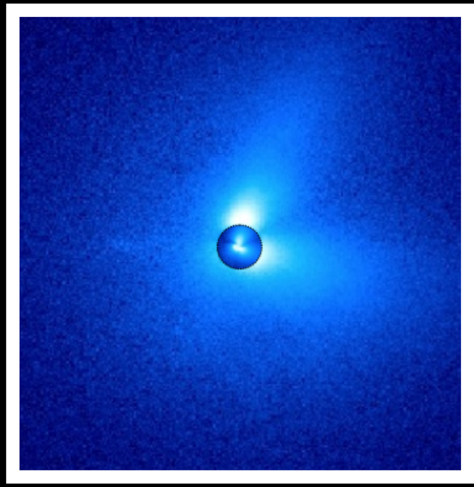
Millimeter continuum images: Long et al. 2019



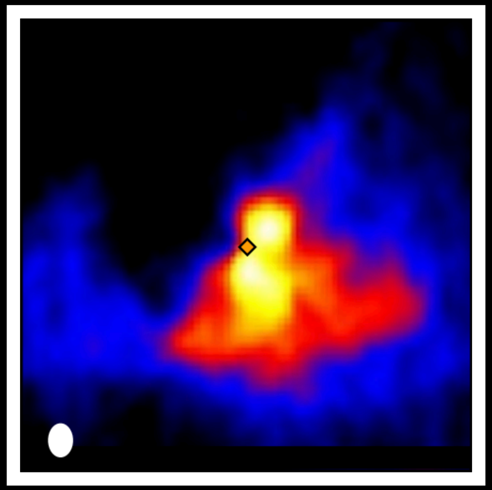




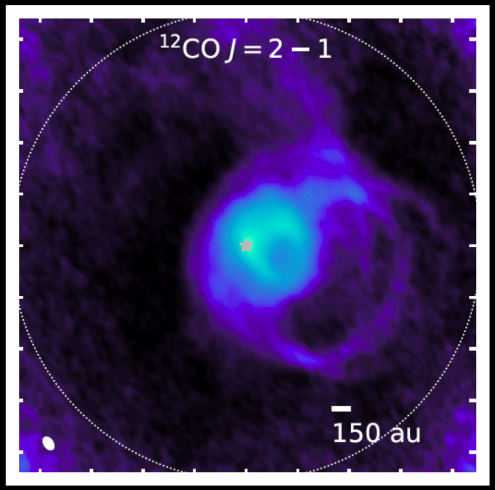
Polarized intensity
Garufi et al. 2019



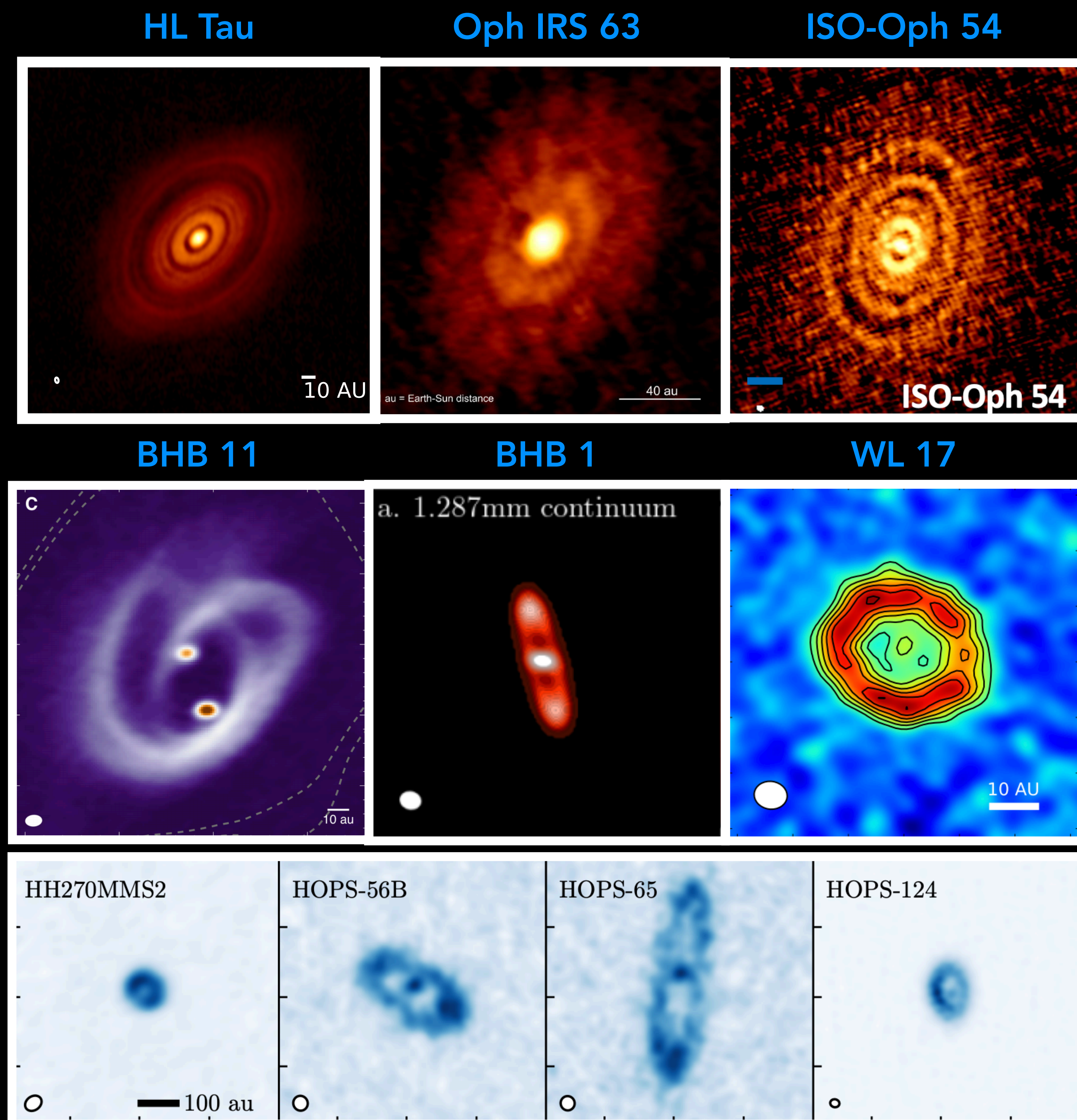
CO
Garufi et al. 2021



CO
Huang et al. in prep



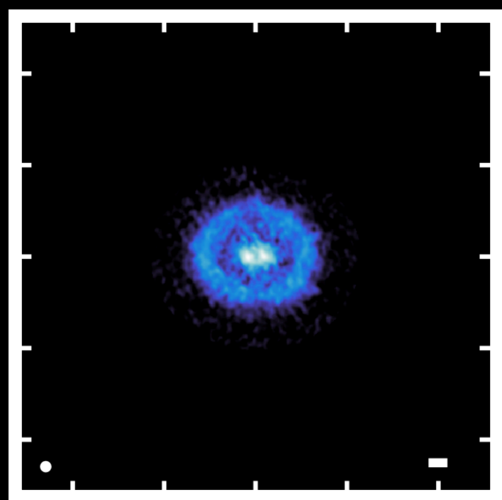
Continuum substructures in (partially) embedded disks



See, e.g., ALMA Partnership 2015, Tobin et al. 2016, Cieza et al. 2016, Sheehan & Eisner 2017, Alves et al. 2019, Lee et al. 2020, Sheehan et al. 2020, Alves et al. 2020, de Valon et al. 2020, Segura-Cox et al. 2021, Cieza et al. 2021

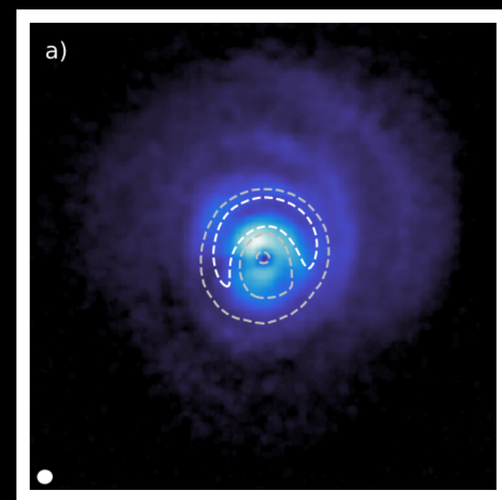
Types of substructures detected in molecular emission

Annular gaps and rings



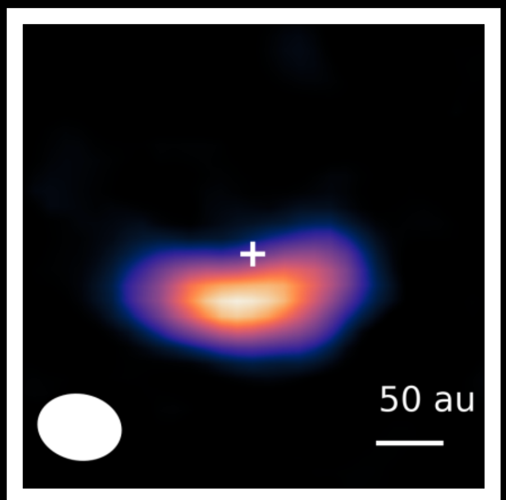
AS 209
Zhang et al. 2021

Spiral arms



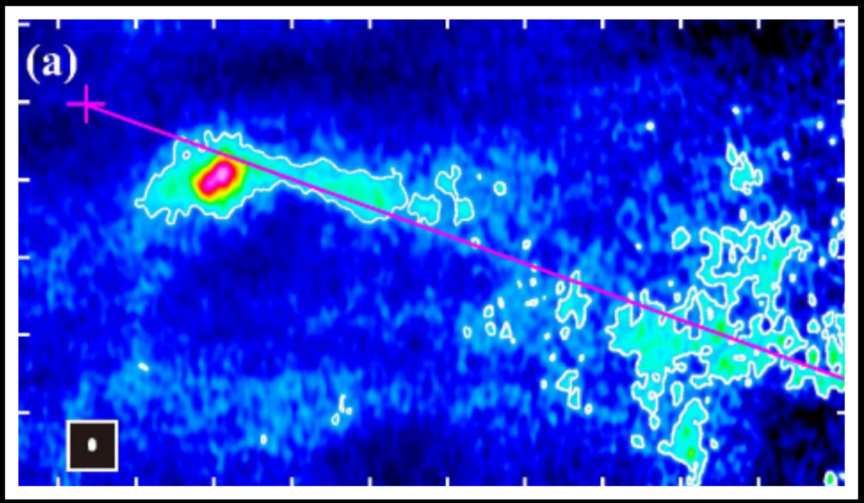
HD 142527
Garg et al. 2021

Arcs



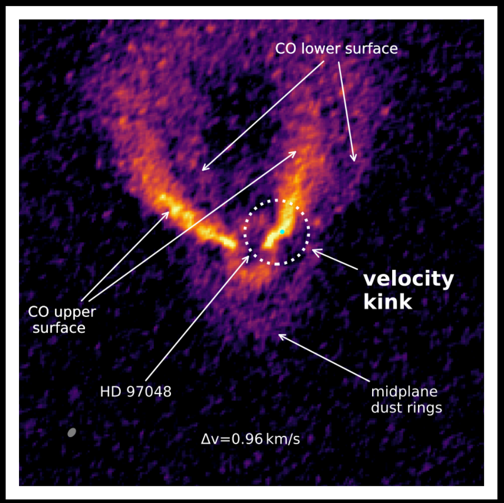
Oph IRS 48
Booth et al. 2021

Tails/streamers



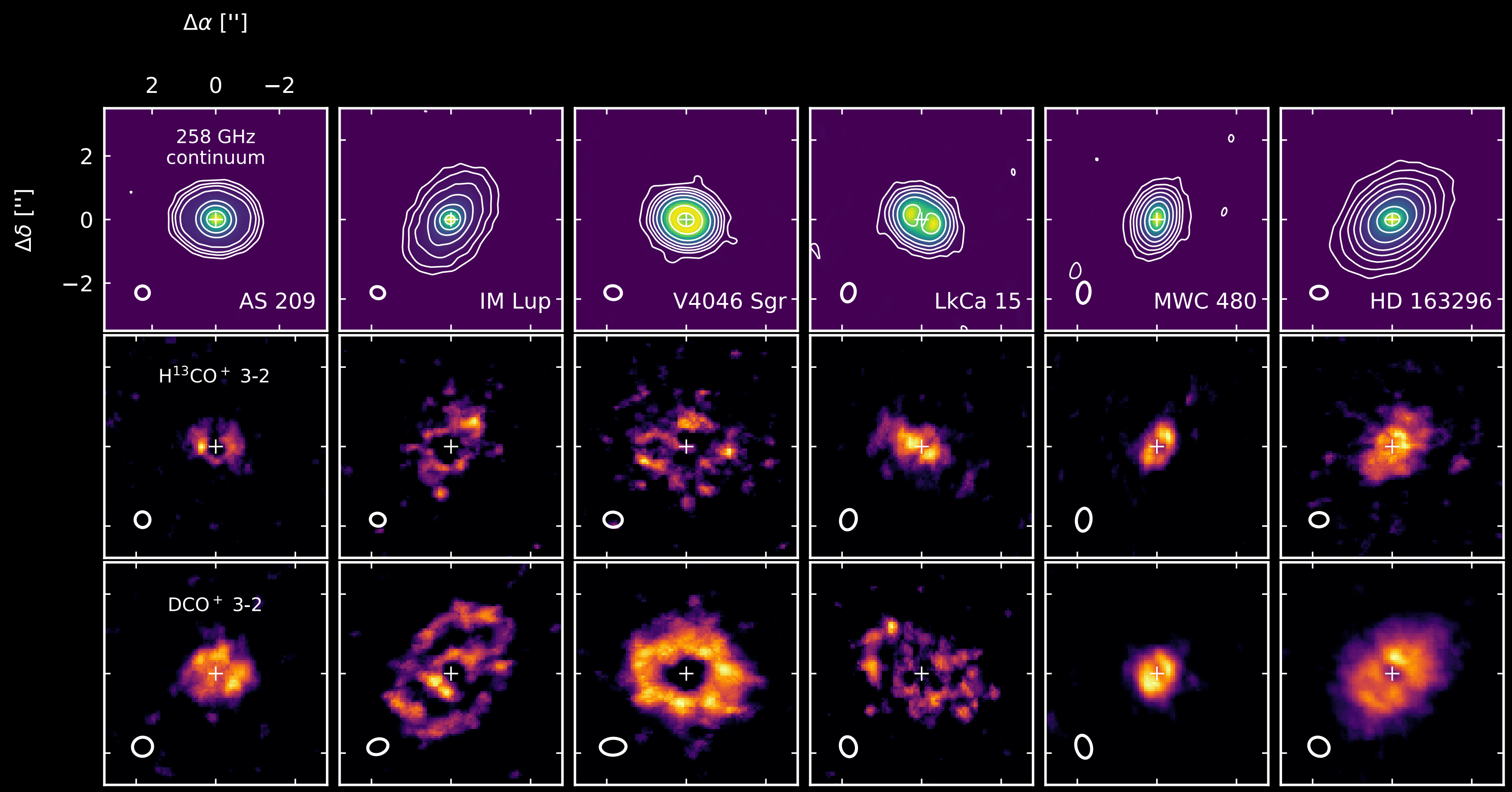
SU Aur
Akiyama et al. 2019

Kinematic substructure

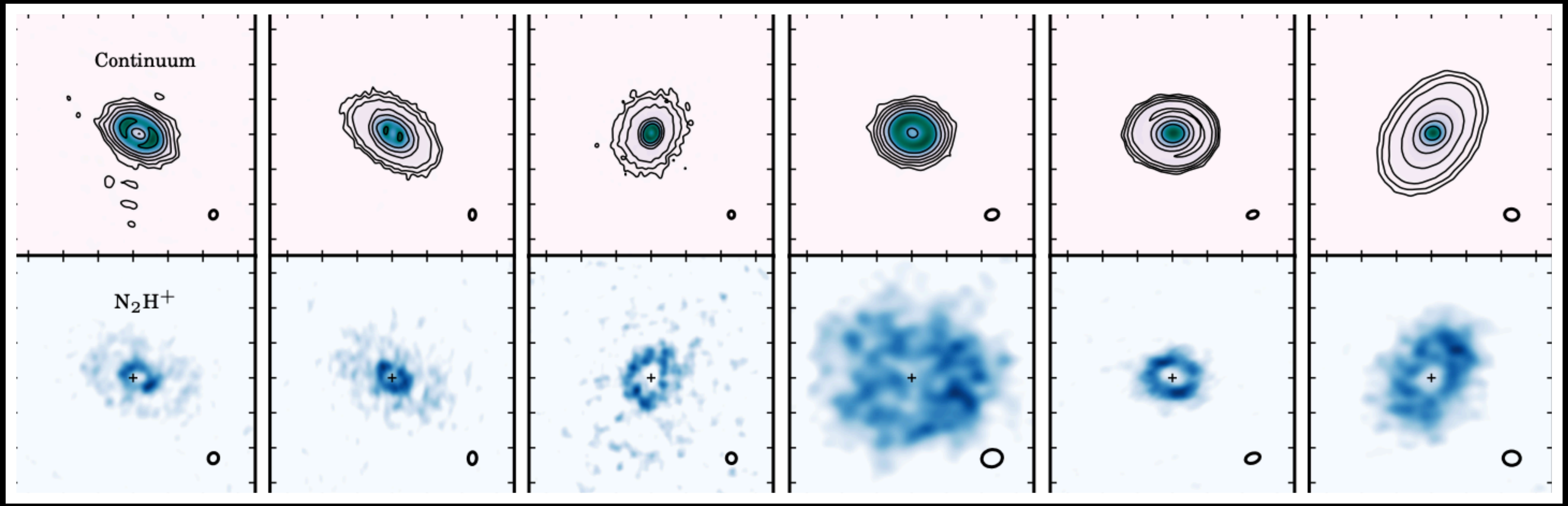


HD 97048
Pinte et al. 2019

Molecular substructures appear to be common even at moderate resolution (due to chemistry)

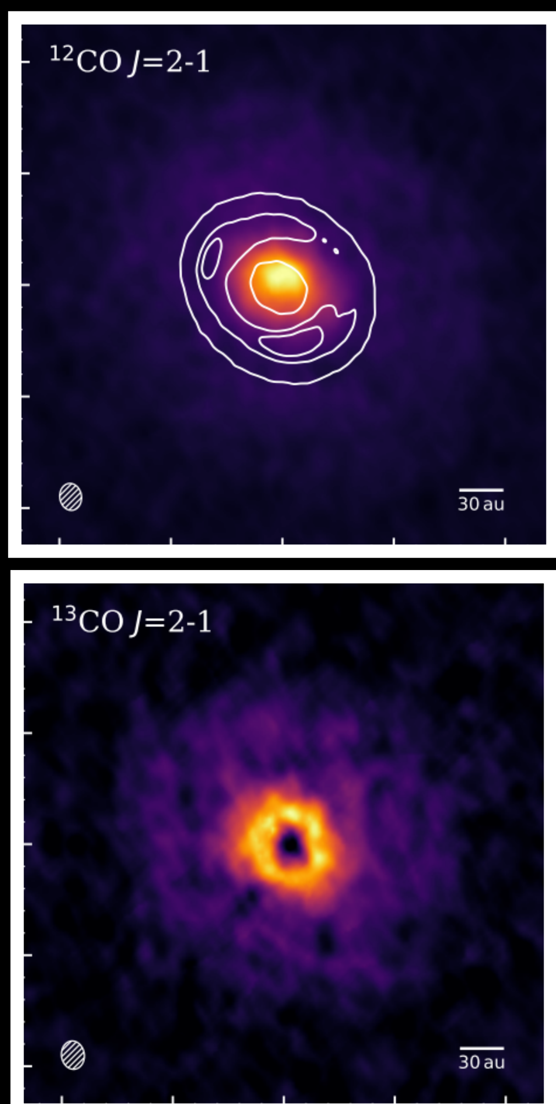


Huang et al. 2017

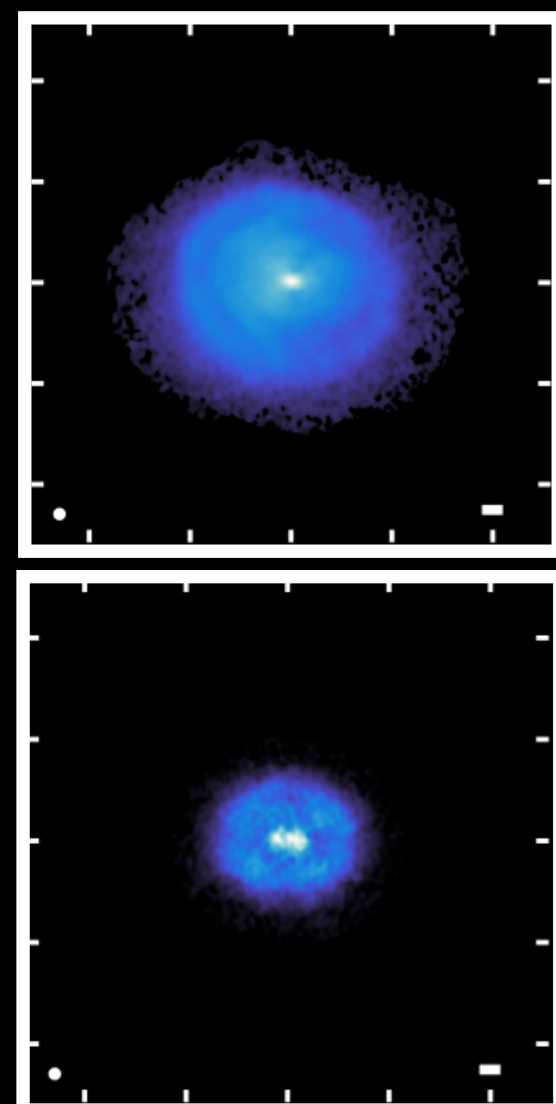


Qi et al. 2019

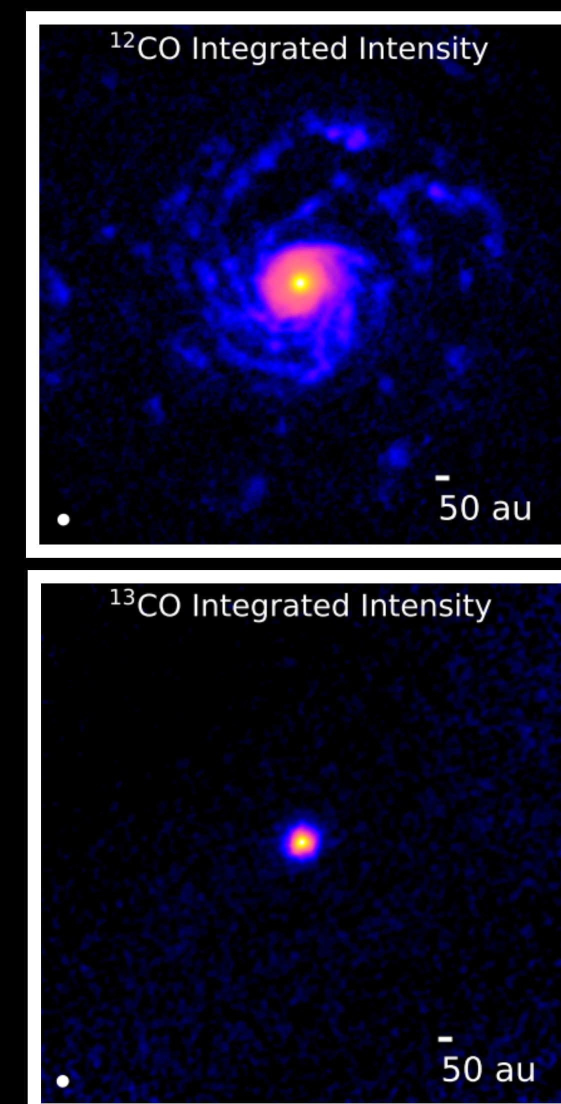
Optical depth has a strong effect on which structures show up in which molecular tracers



CQ Tau
Wölfer et al. 2021

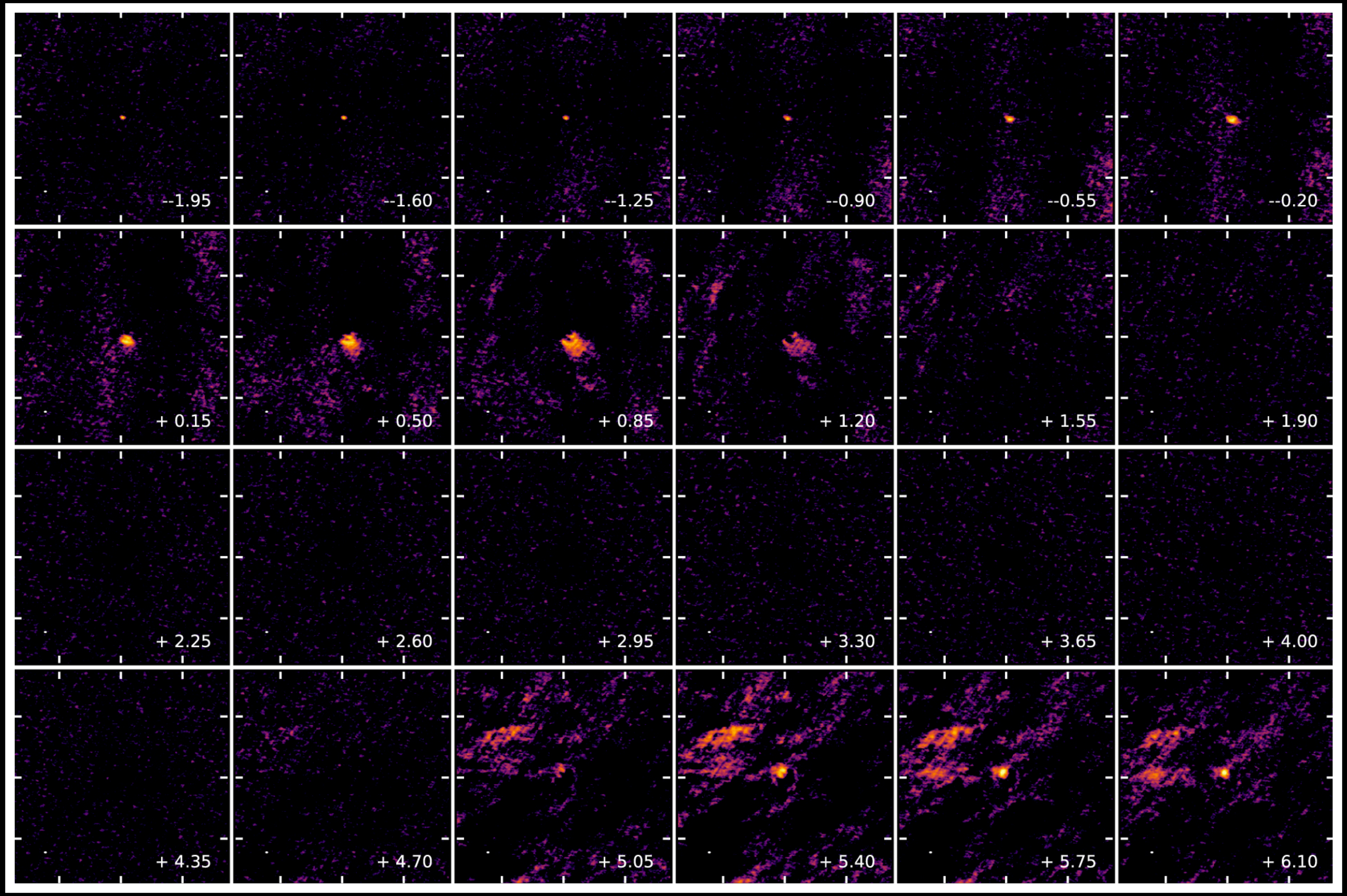


AS 209
Zhang et al. 2021



RU Lup
Huang et al. 2020b

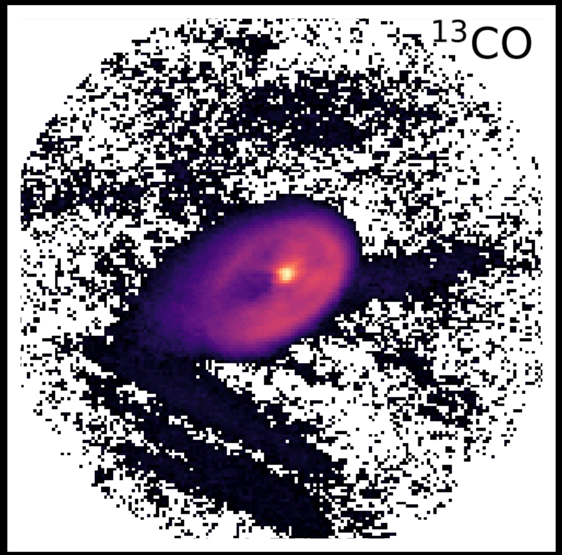
Contamination by external material can also make it challenging to characterize disk structures in molecular emission



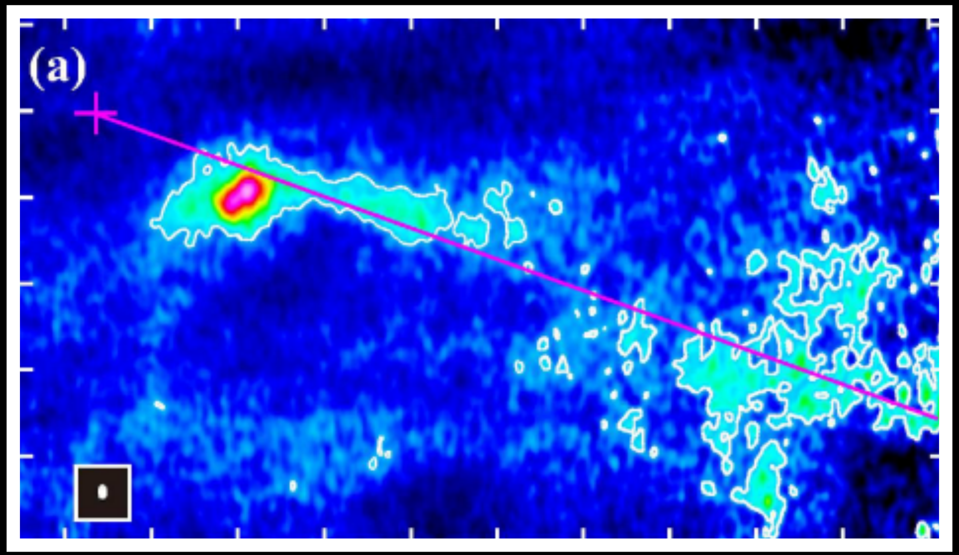
Elias 24

Andrews et al. 2018b

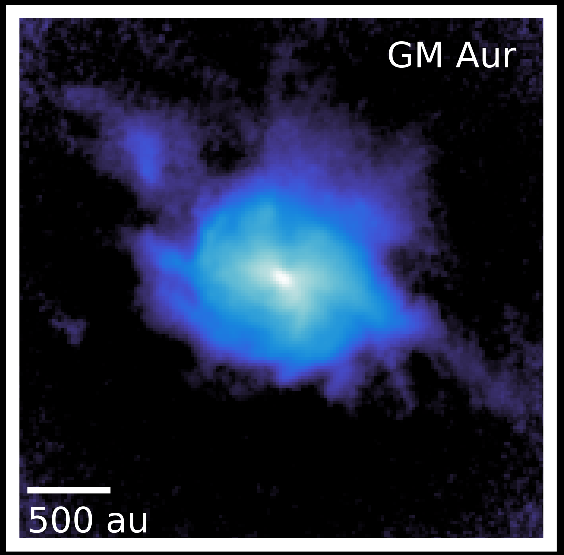
…but sometimes the ``contamination" is what's interesting



Elias 27
Paneque-Carreño et al. 2021



SU Aur
Akiyama et al. 2019

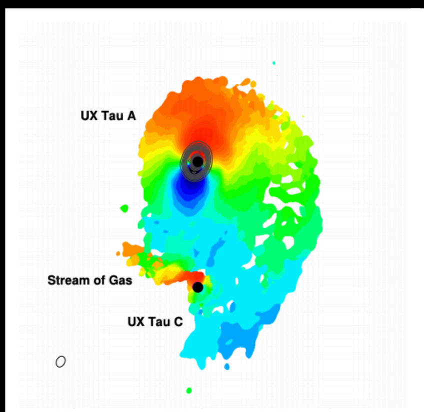


GM Aur
Huang et al. 2021

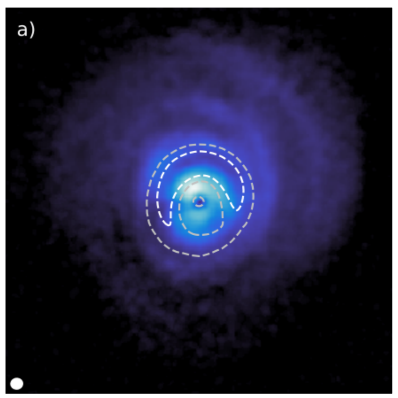
Molecular spirals

Binary systems

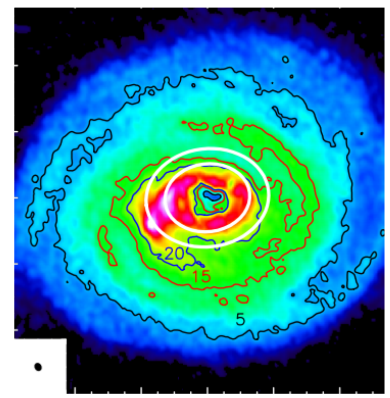
UX Tau



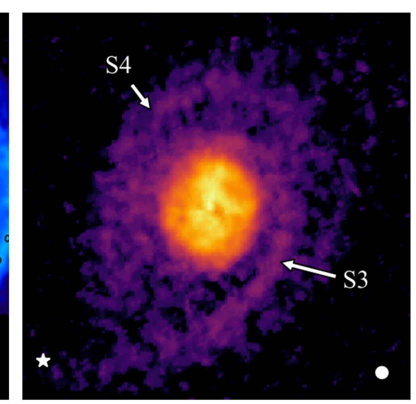
HD 142527



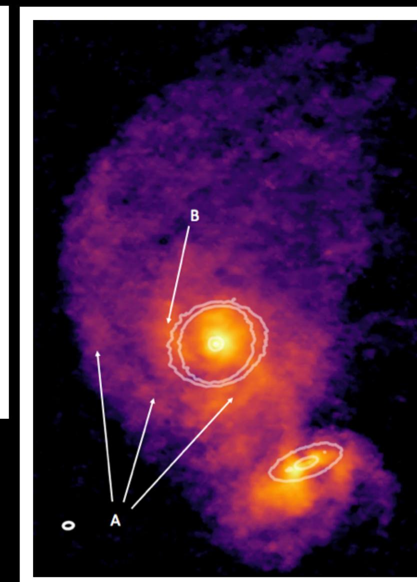
GG Tau



HD 100453



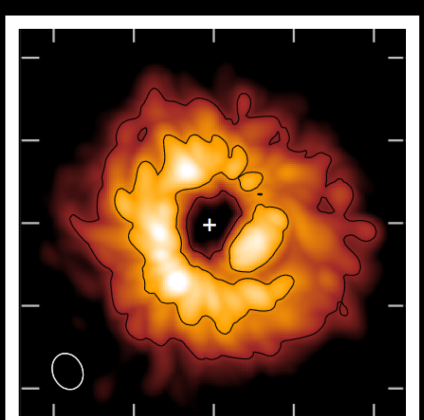
AS 205



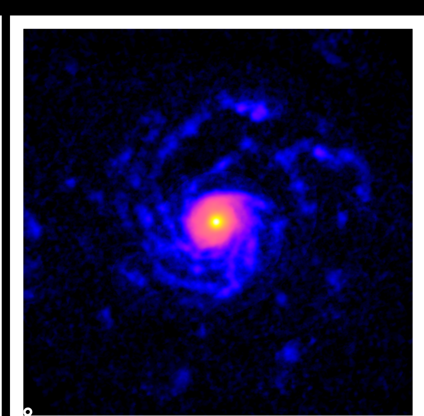
See, e.g., Tang et al. 2017, Boehler et al. 2017, Kurtovic et al. 2018, Yen et al. 2019, Teague et al. 2019, Zapata et al. 2020, Rosotti et al. 2020, Phuong et al. 2020, Huang et al. 2020b, Rivière-Marichalar et al. 2020, Garg et al. 2021, Wolfer et al. 2021, Huang et al. in press

Single star systems

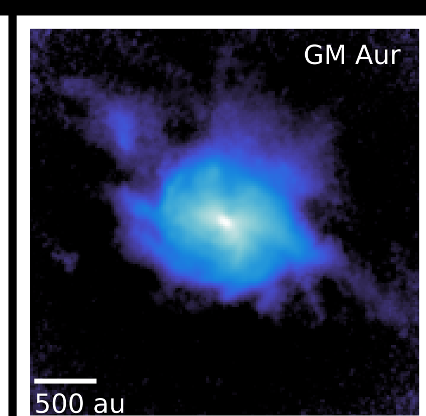
MWC 758



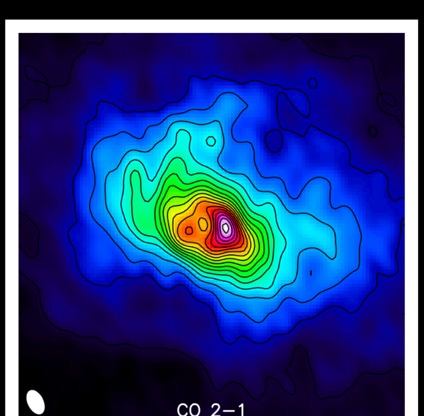
RU Lup



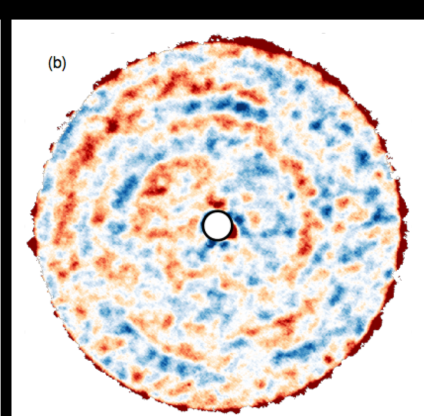
GM Aur



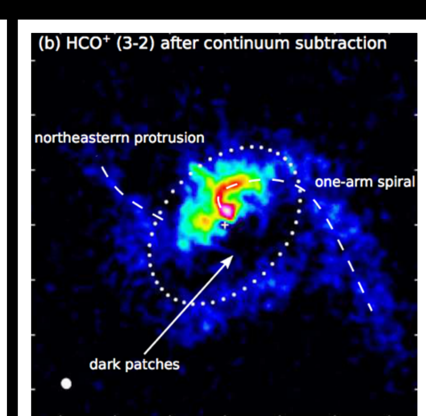
AB Aur



TW Hya



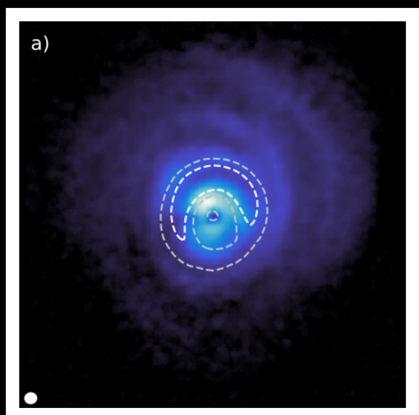
HL Tau



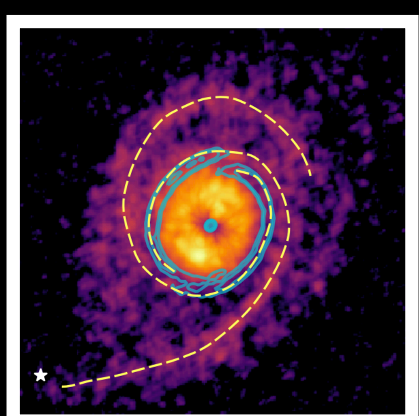
- Predominantly detected in CO (isotopologue) emission
- Oftentimes irregular in appearance
- Number of detected arms can range from one to five
- Detected around both T Tauri and Herbig Ae stars

Molecular spirals vs. millimeter continuum

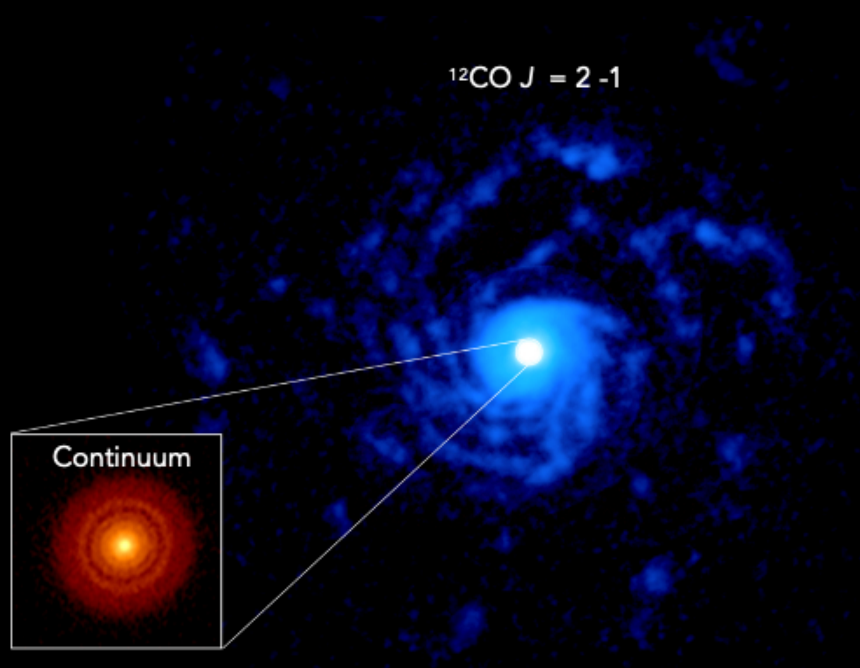
HD 142527
Garg et al. 2021



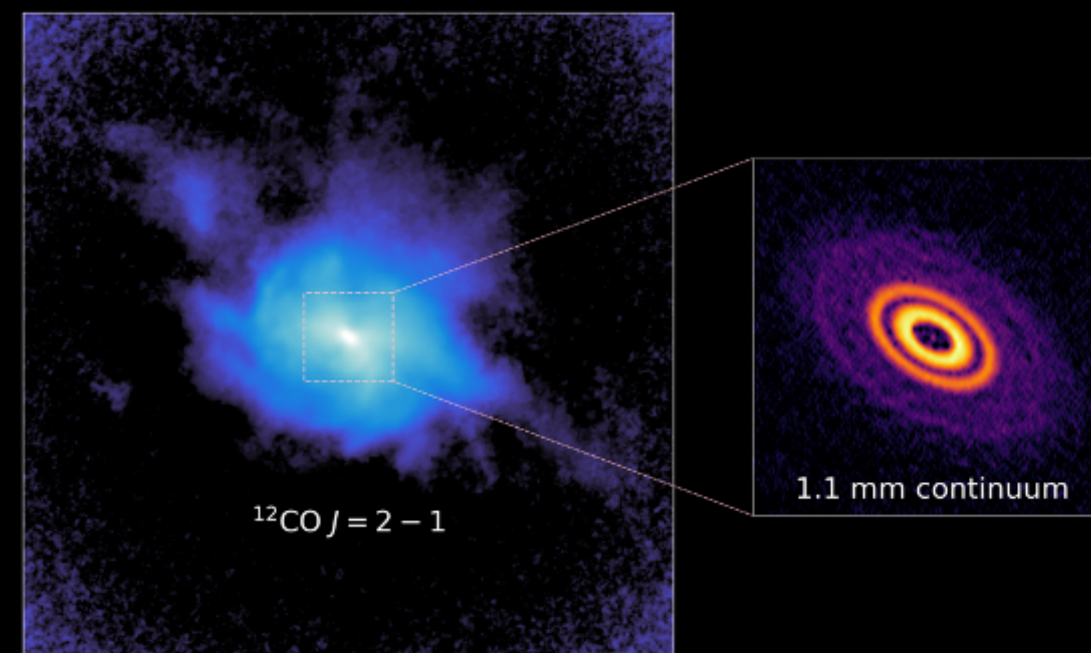
HD 100453
Rosotti et al. 2020



RU Lup
Huang et al. 2020b



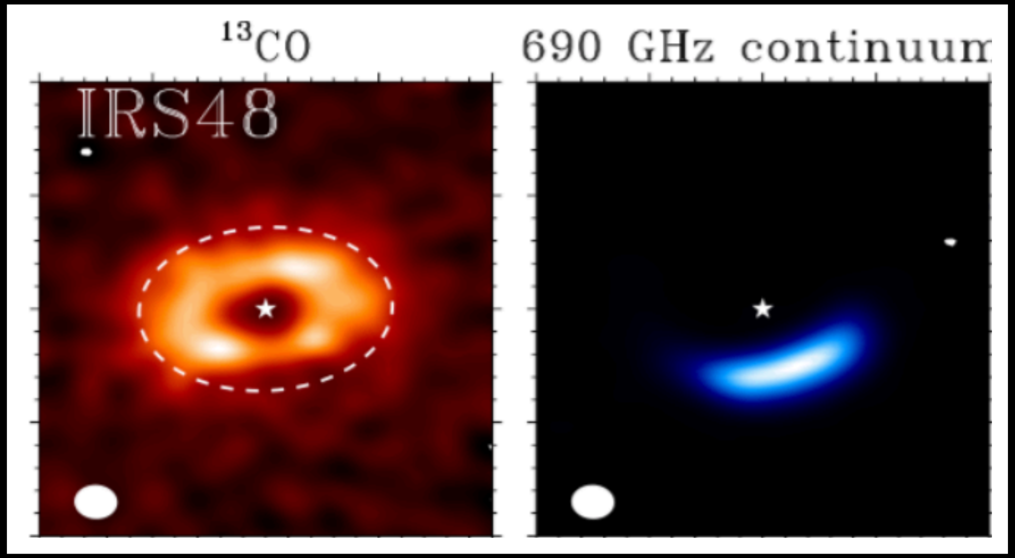
GM Aur
Huang et al. in press
(from the MAPS ALMA Large Program)



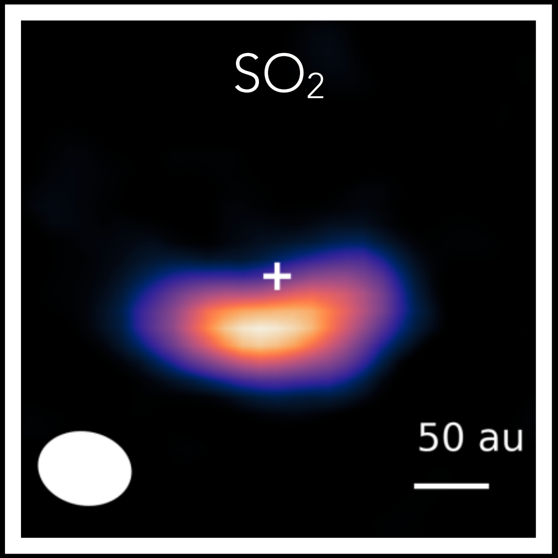
- Millimeter continuum counterparts for molecular spirals have so far only been detected in wide binary systems
- Molecular spirals often extend far beyond the millimeter continuum

Molecular asymmetries don't appear to reflect gas surface density variations

Ice sublimation at a dust trap?



van der Marel et al. 2016

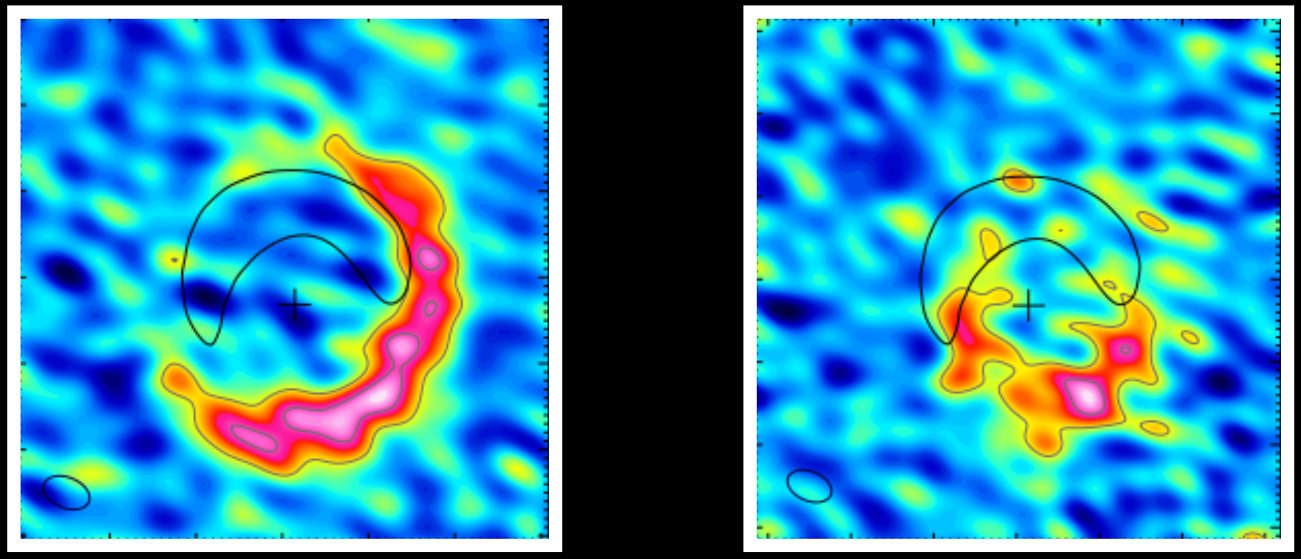


Booth et al. 2021

Asymmetries resulting from high dust opacity?

CS

HCN



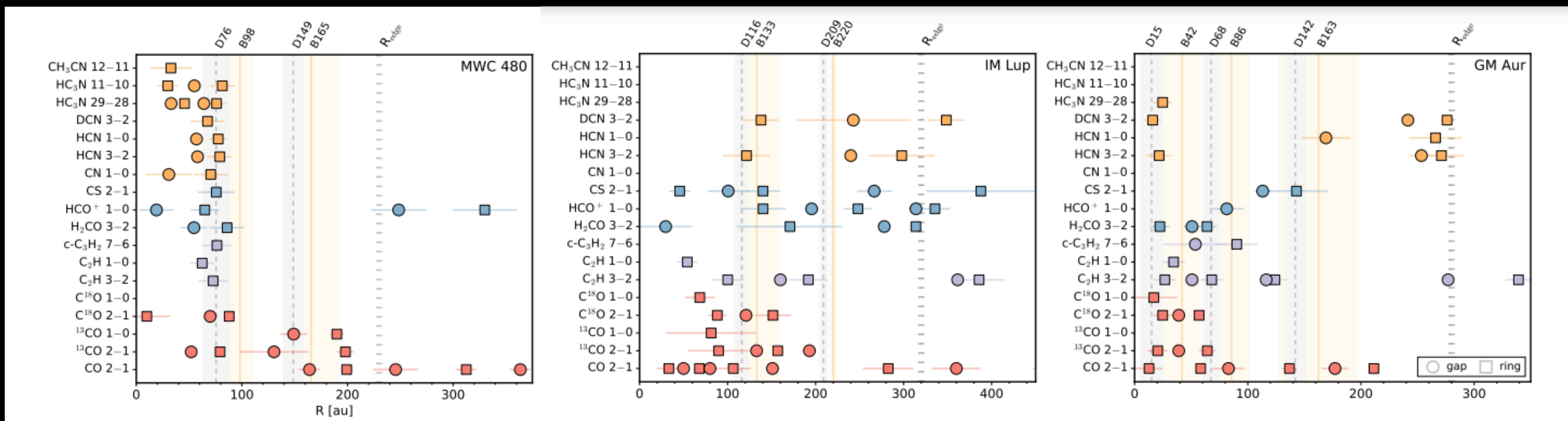
HD 142527
van der Plas et al. 2014

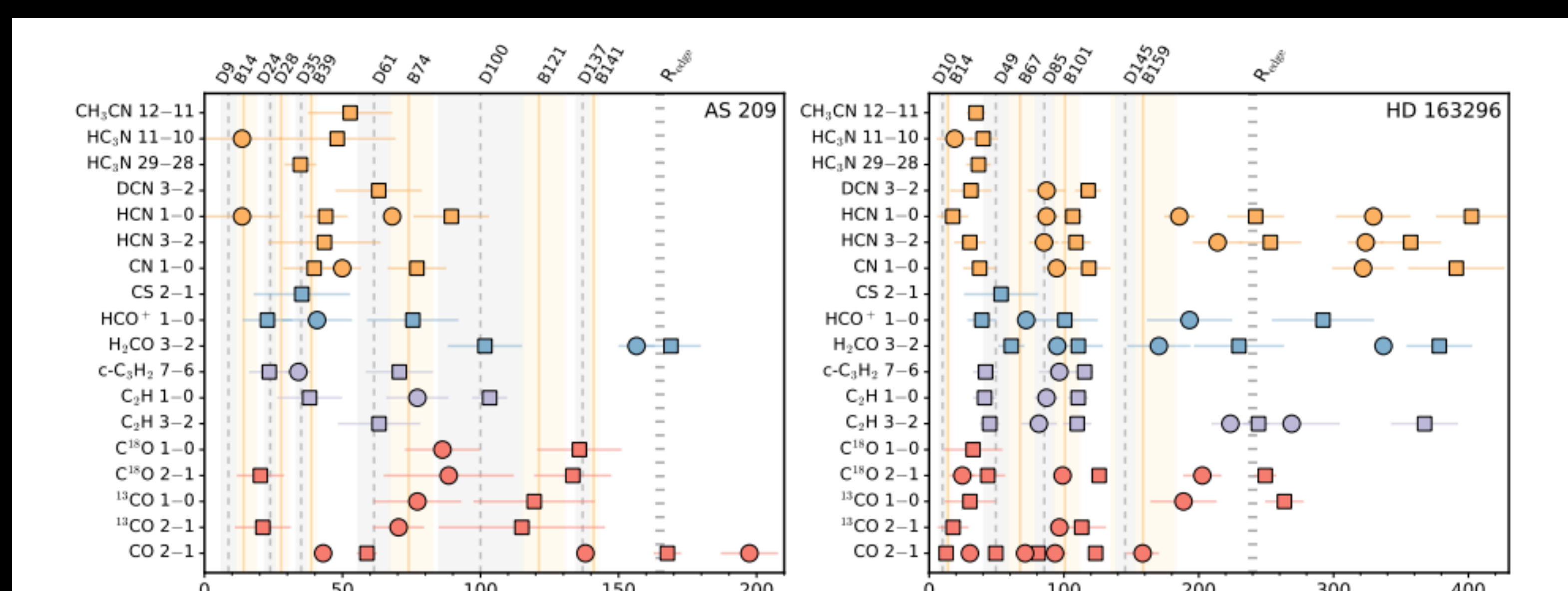
The current landscape of high(er) resolution molecular line observations

- As of October 2021, molecular line observations of ~40 disks have been published at a spatial resolution <20 au
  - Of these, nearly all have been imaged in ^{12}CO 2-1 or 3-2
  - ^{13}CO 2-1 or 3-2 observations have been published for ~15 of these
  - A handful have been published in other molecular tracers ($C^{18}O$, HCO+, CS, HCN, C2H, primarily from MAPS Large Program)
- Most high resolution molecular line observations have been secondary targets in programs primarily aimed at resolving continuum substructures, so integration times, spectral resolution, and *uv* coverage are often suboptimal for molecular emission
- The Cycle 8 exoALMA Large Program will image 15 disks in ^{12}CO, ^{13}CO, and CS at a spatial resolution of ~15 au

See, e.g., DSHARP papers, MAPS papers, Kraus et al. 2017, Huang et al. 2018a, Kudo et al. 2018, Tsukagoshi et al. 2018, Facchini et al. 2019, Pinte et al. 2019, Rosotti et al. 2019, Keppler et al. 2019, Pérez et al. 2020, González-Ruilova et a. 2020, Kurtovic et al. 2021, Yu et al. 2021, Wölfer et al. 2021, Rosotti et al. 2021

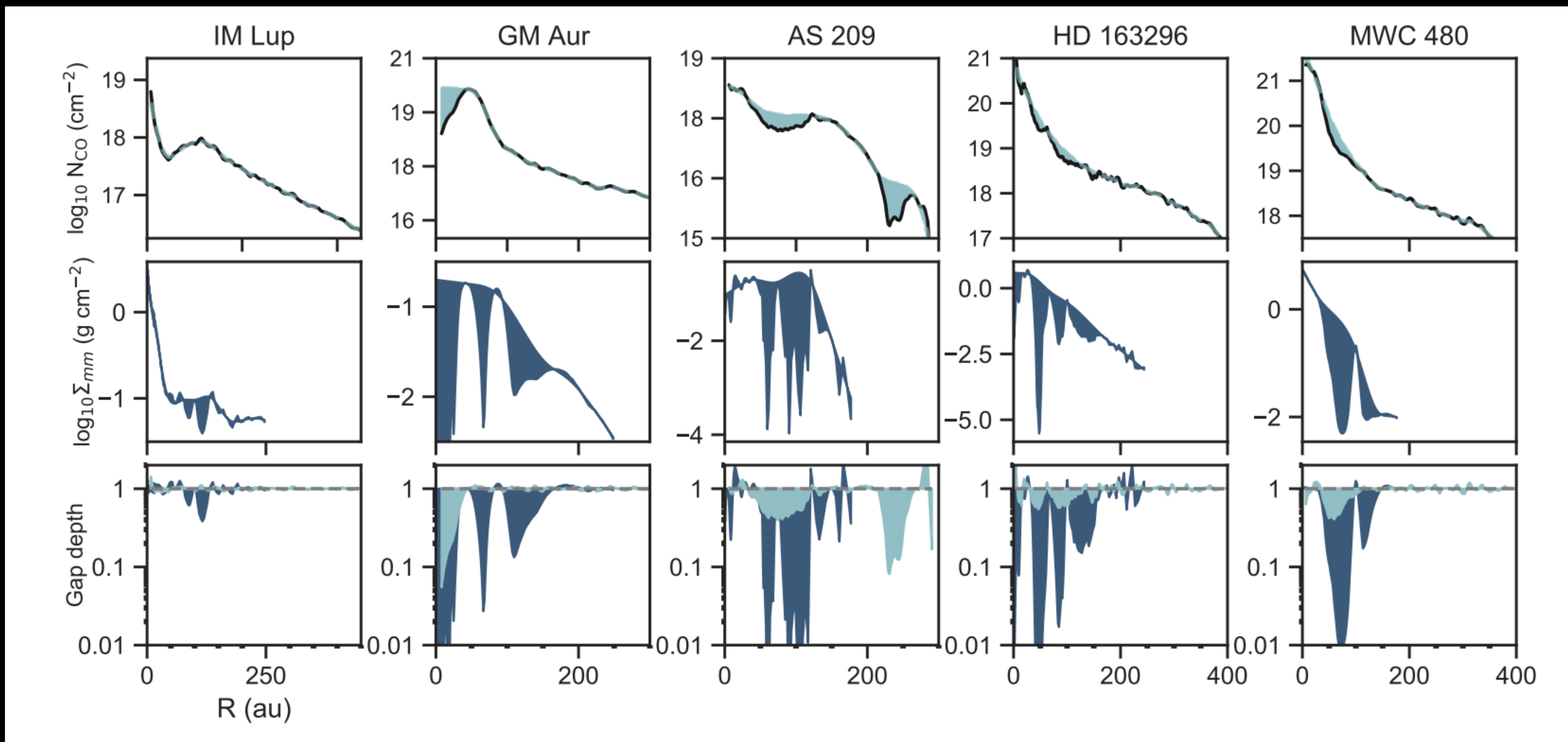
Molecular gaps and rings are found at a wide range of locations





Law et al. 2021a

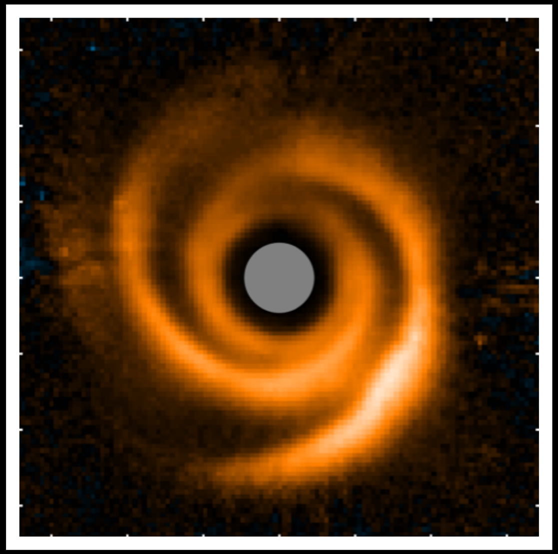
Gap properties in CO emission don't appear to have a predictable relationship with dust continuum gaps



Zhang et al. 2021

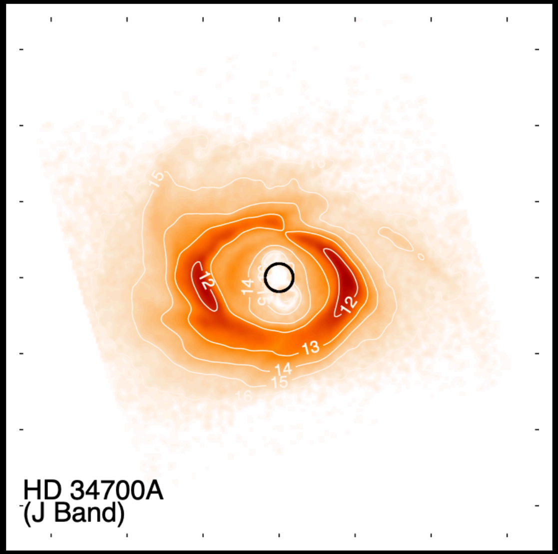
Facilities currently used to characterize disk structures in scattered light

VLT/SPHERE



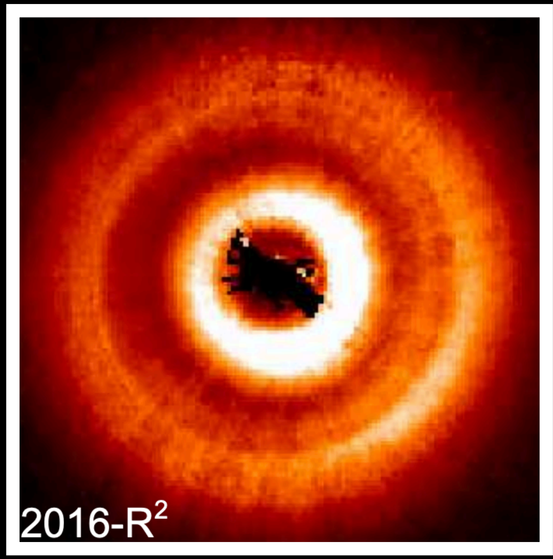
HD 135344B
Stolker et al. 2017

GPI



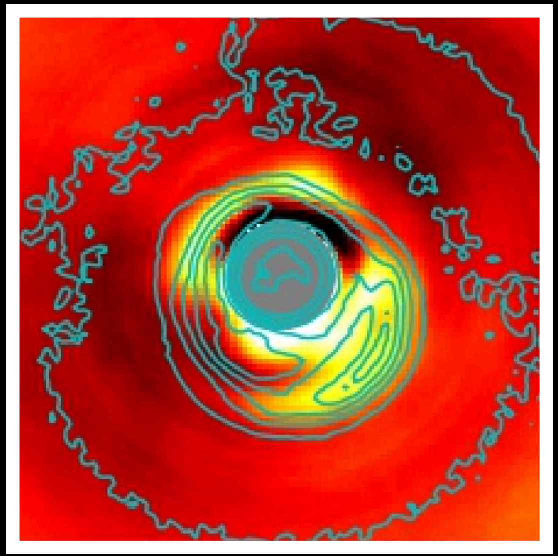
HD 34700
Monnier et al. 2019

HST/STIS



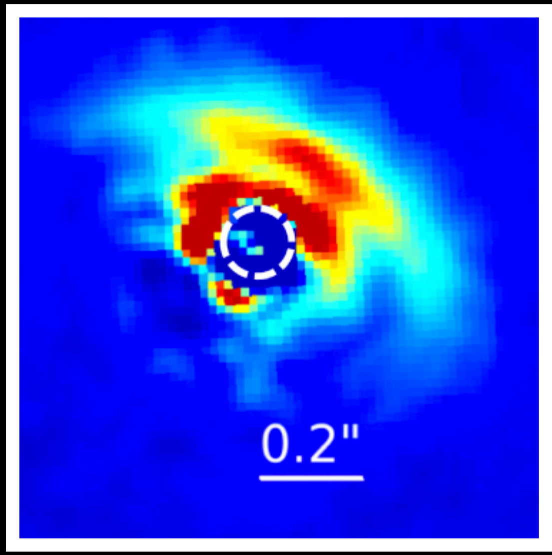
TW Hya
Debes et al. 2017

Keck/NIRC2-PWFS



SR 21
Uyama et al. 2020

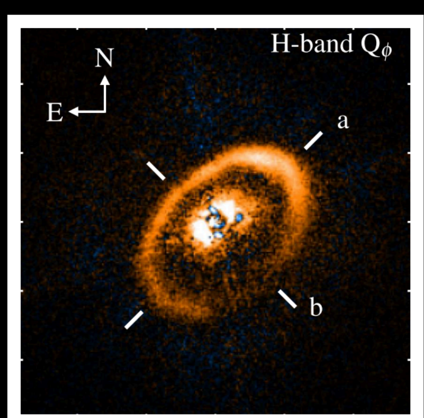
Subaru/SCExAO



LkCa 15
Currie et al. 2019

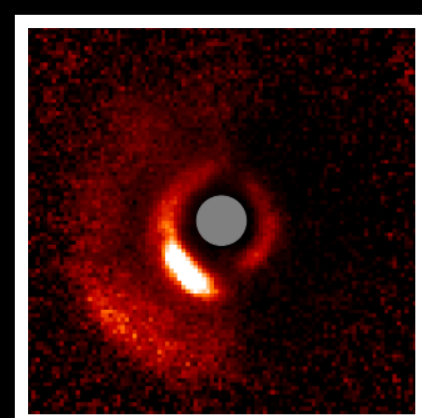
Types of substructures detected in scattered light

Gaps and Rings



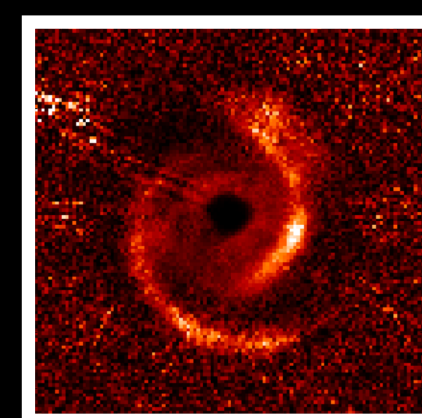
HD 163296
Muro-Arena et al. 2020

Shadows



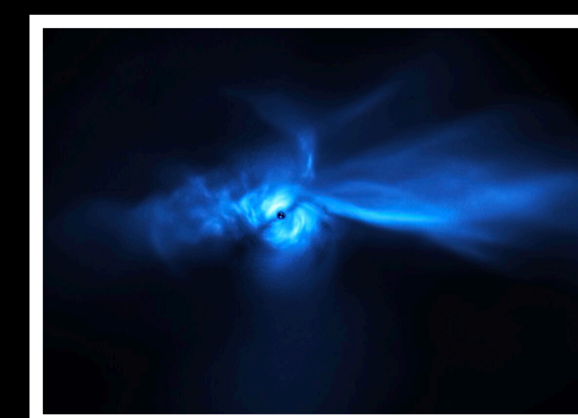
HD 143006
Benisty et al. 2018

Spiral Arms



MWC 758
Benisty et al. 2015

Tails/Streamers



SU Aur
Ginski et al. 2021

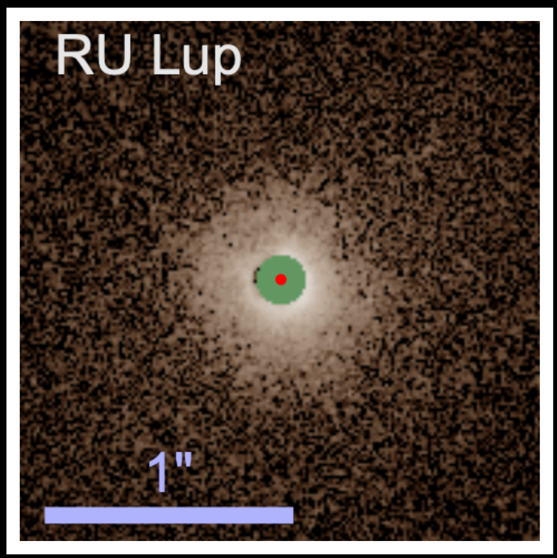
Demographics of Substructures in Scattered Light

- ~130 polarimetric images of disks have been published (Subaru, GPI, VLT), ~80 of which resulted in resolved disk detections
- Among the resolved disks, about half exhibit clear substructures. Those without substructures tend to be compact, faint, and/or highly inclined
- Major ongoing surveys: Gemini-LIGHTS (44 Herbig and T Tauri stars with GPI), DESTINYS (85 Herbig and T Tauri stars with VLT/SPHERE)

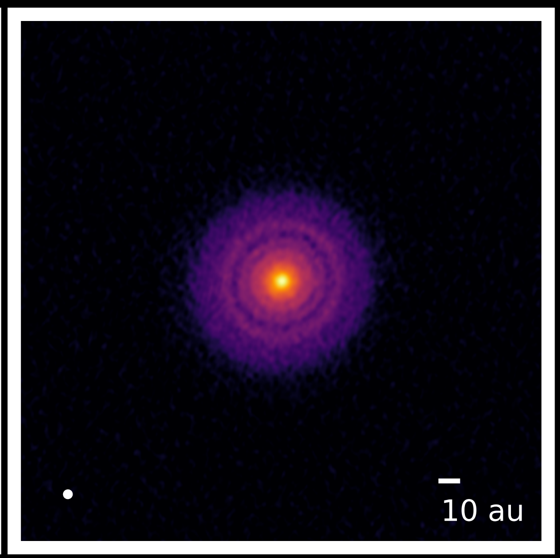
See Benisty et al. PPVII chapter (under review), Garufi et al. 2018

Faint/compact disks in scattered light are not necessarily faint/compact disks in mm continuum!

Scattered light | **mm continuum**

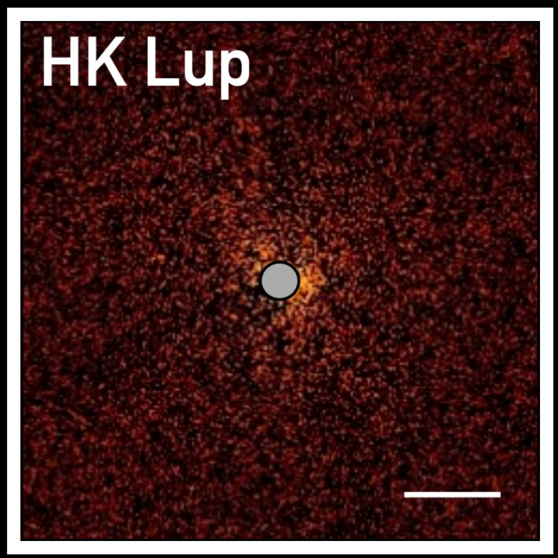


Avenhaus et al. 2018

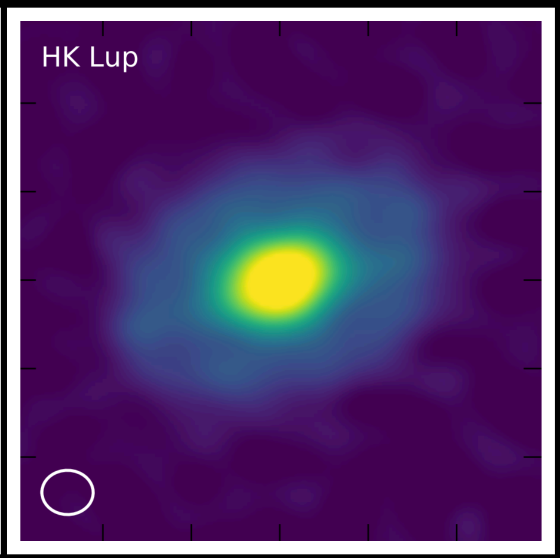


Andrews et al. 2018b

Scattered light | **mm continuum**

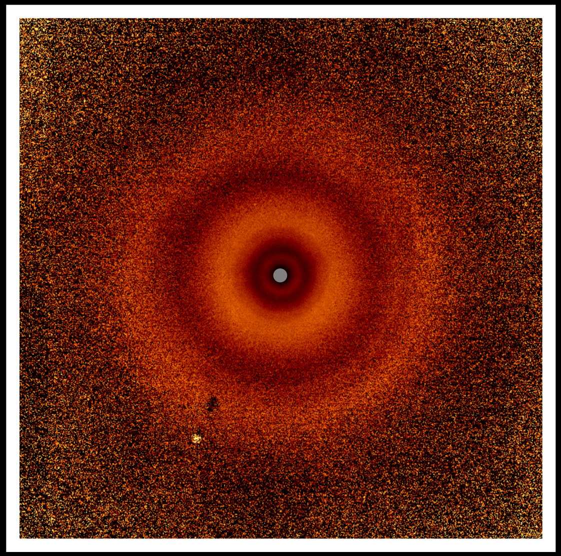


Garufi et al. 2020

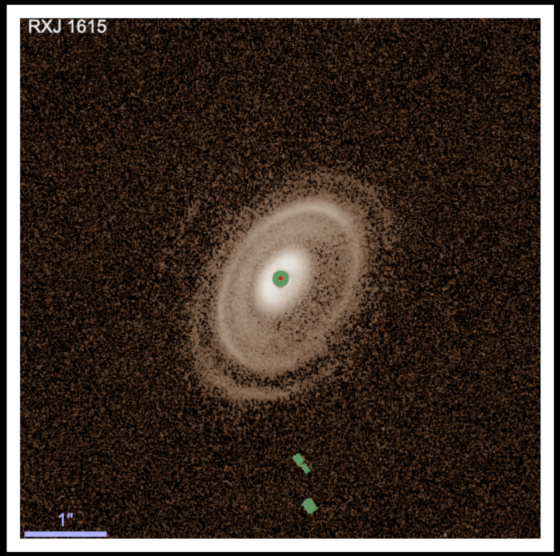


Andrews et al. 2018a

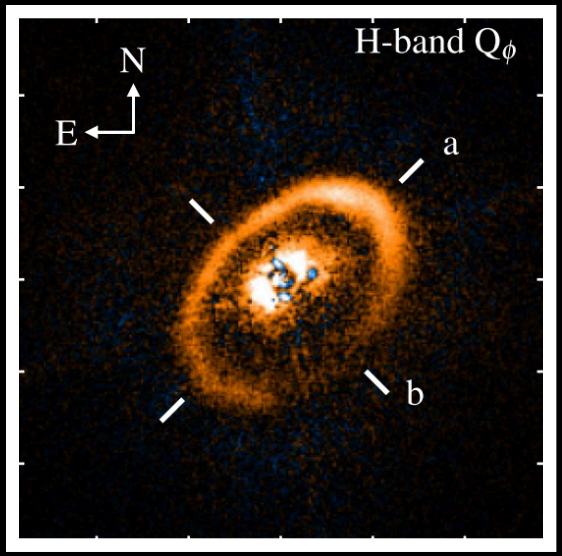
Rings and gaps in scattered light



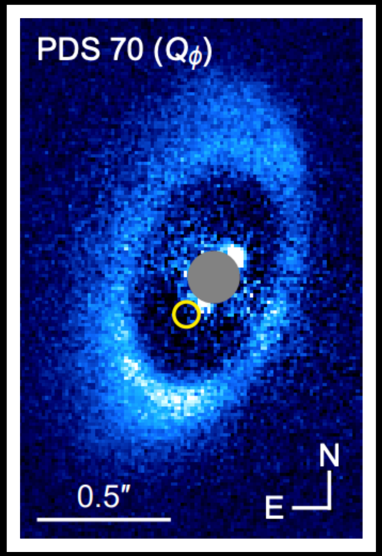
TW Hya
van Boekel et al. 2017



RXJ 1615
Avenhaus et al. 2018



HD 163296
Muro-Arena et al. 2018

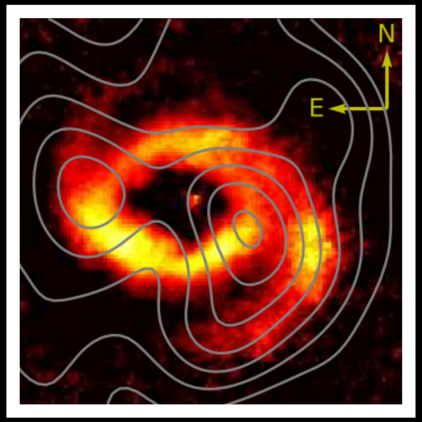


PDS 70
van Holstein et al. 2021

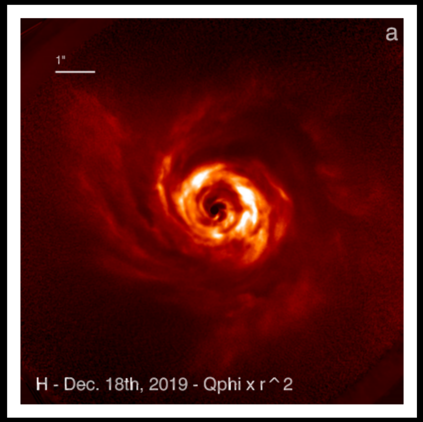
- Identified in ~1/4 of disks detected in scattered light so far (appear to be somewhat less commonly detected compared to millimeter continuum emission)
- Found in disks across a range of spectral types
- Often associated with disks that have low near-IR excess

See Benisty et al. PPVII chapter (under review), Garufi et al. 2018

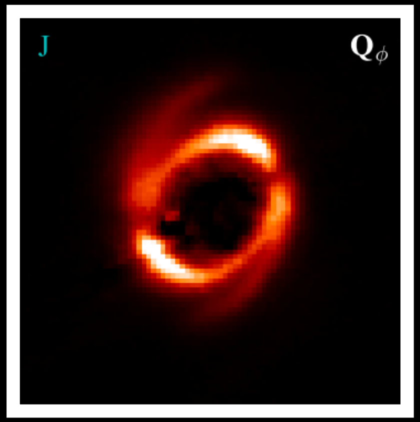
Spiral structures in scattered light



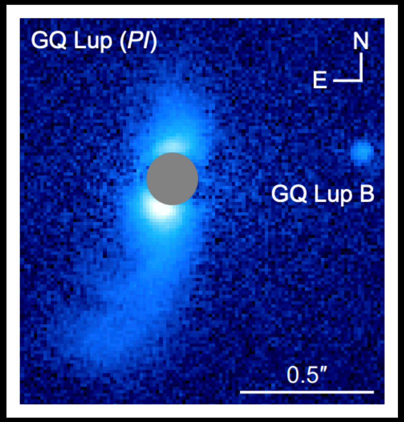
LkHα 330
Uyama et al. 2018



AB Aur
Boccaletti et al. 2020



HD 100453
Benisty et al. 2017

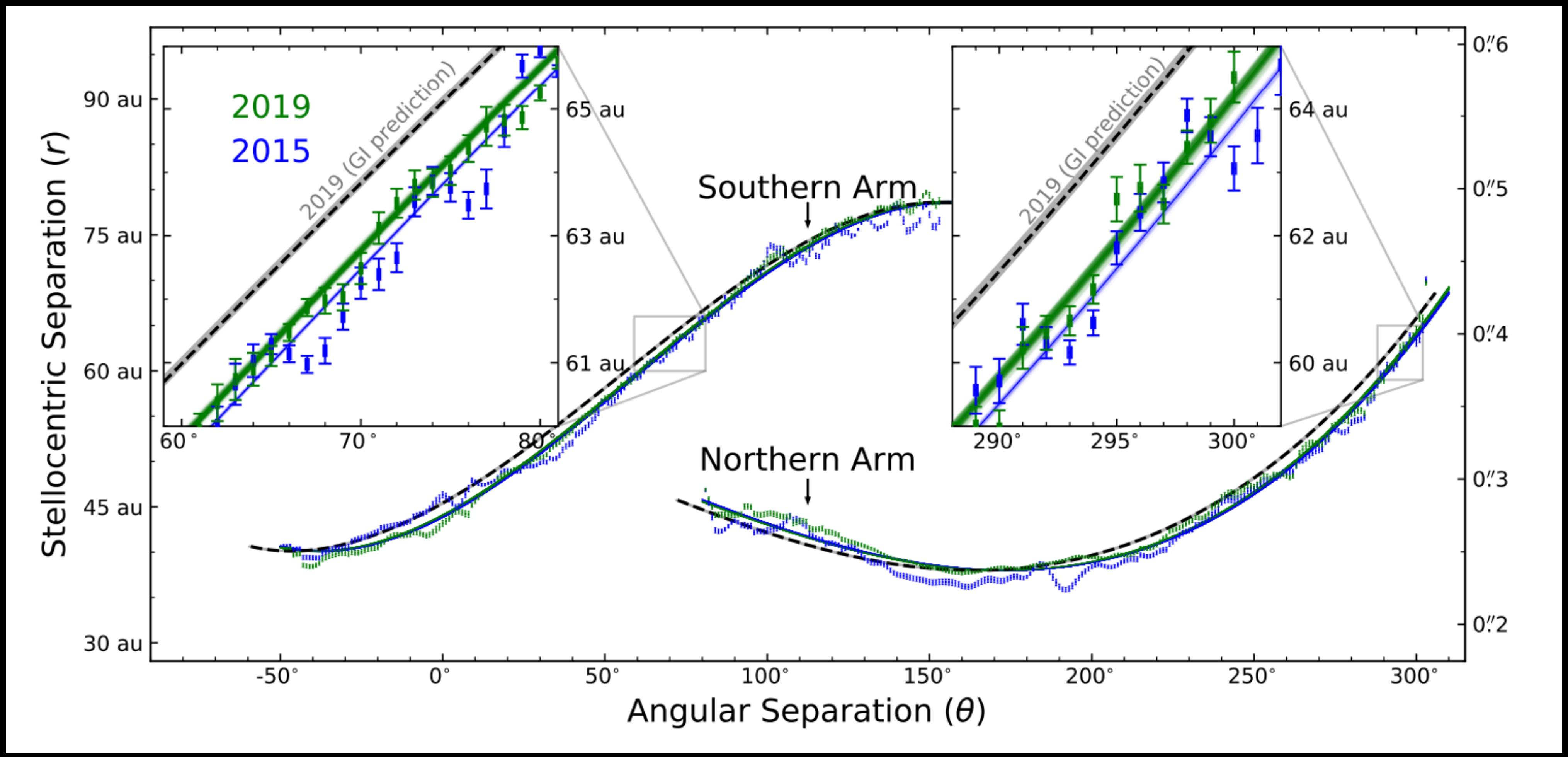


GQ Lup
van Holstein et al. 2021

- Initially detected only around Herbig stars hosting transition disks, but now examples around T Tauri stars are being identified
- Identified in ~1/5 of disks detected in scattered light so far (spiral arms have been detected more often in scattered light than in millimeter continuum)
- Can have one to many arms
- Sometimes associated with (sub)stellar companions
- Often associated with high near-IR excess

See Benisty et al. PPVII chapter (under review), Garufi et al. 2018

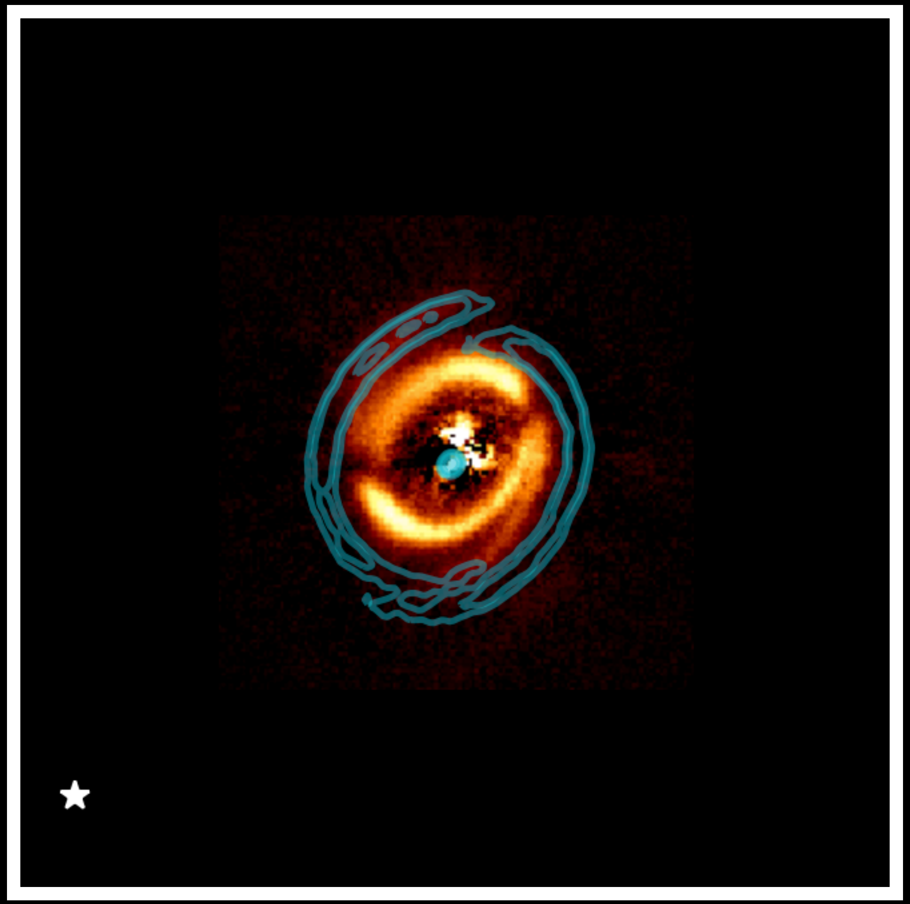
Tracking spiral pattern speeds



The pattern speed of the spiral arms in MWC 758 appear to be inconsistent with expectations for gravitational instability

Ren et al. 2020

Spiral pitch angles: mm continuum vs. scattered light

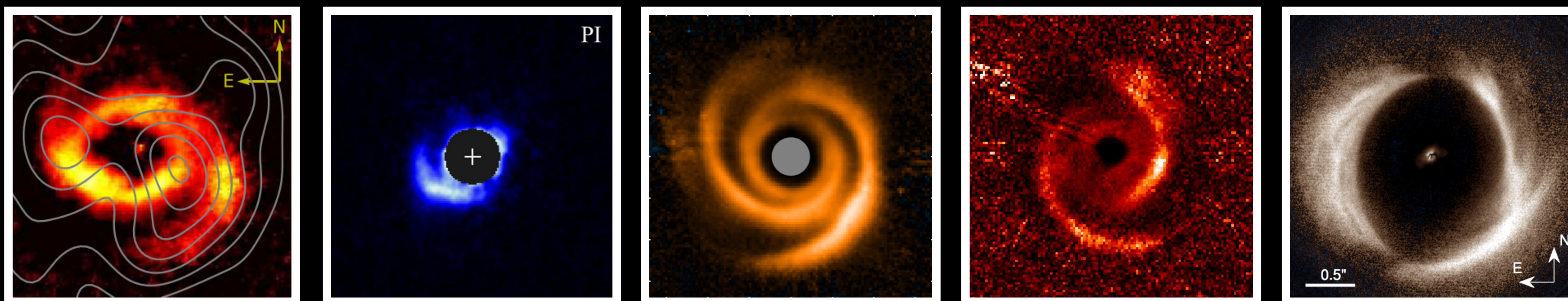


Rosotti et al. 2019

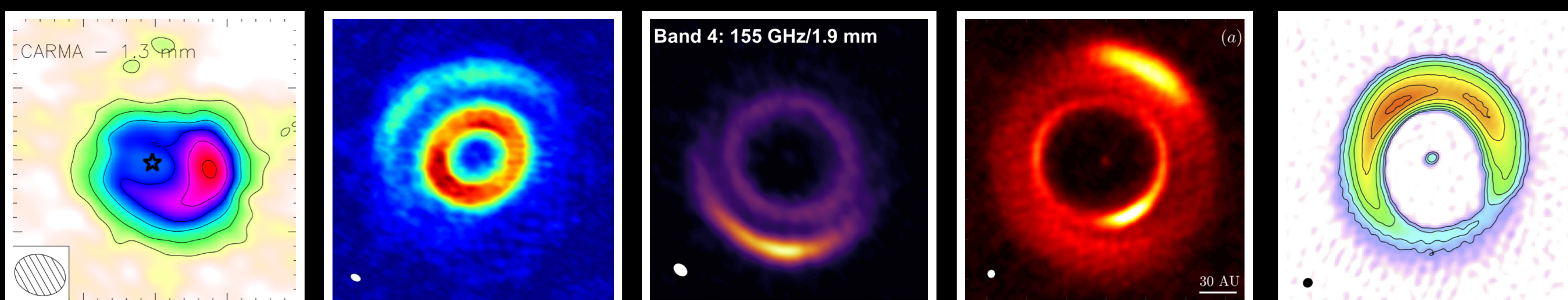
The spiral pitch angles in HD 100453 are larger in scattered light than in mm continuum, presumably due to the vertical temperature gradient

A link between scattered light spiral arms and mm continuum asymmetries?

Scattered Light



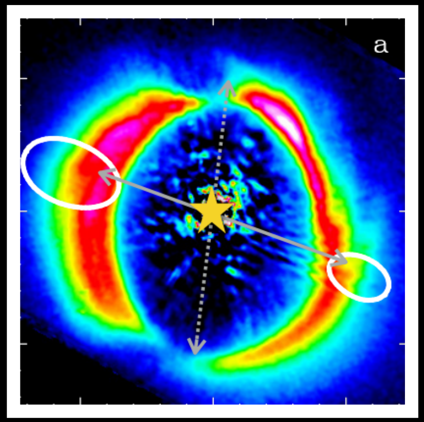
Millimeter continuum

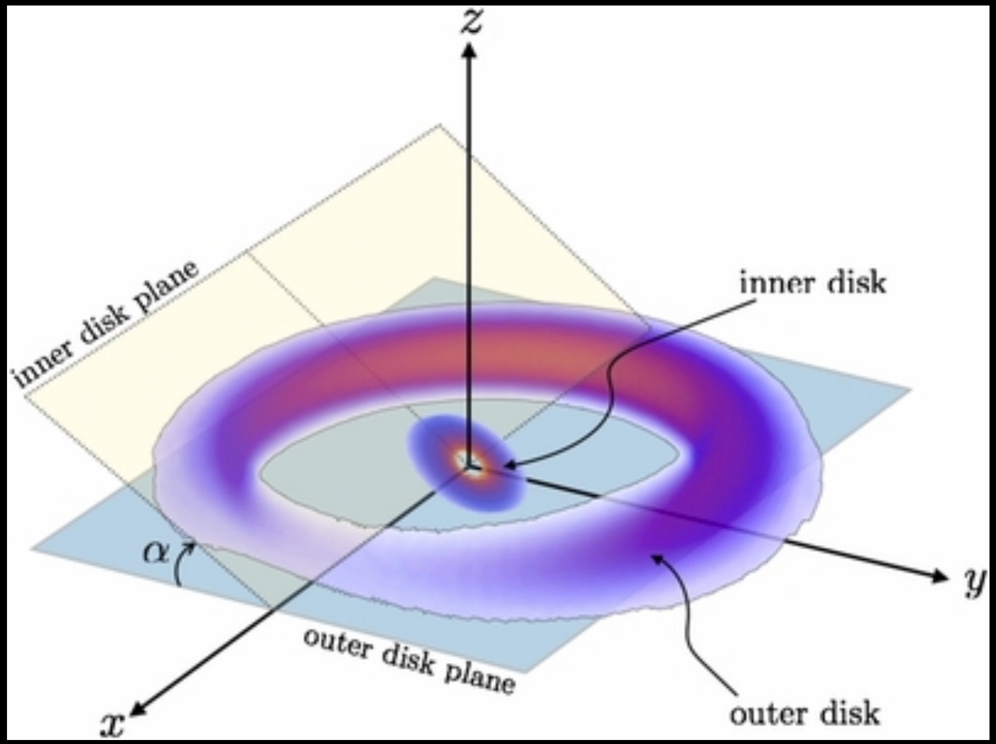


LkHα 330	V1247 Ori	SAO 206462	MWC 758	HD 142527
Uyama et al. 2018	Ohta et al. 2016	Stolker et al. 2016	Benisty et al. 2015	Avenhaus et al. 2017
Isella et al. 2013	Kraus et al. 2017	Cazzoletti et al. 2018	Dong et al. 2018	Ohashi et al. 2018

Shadows in scattered light

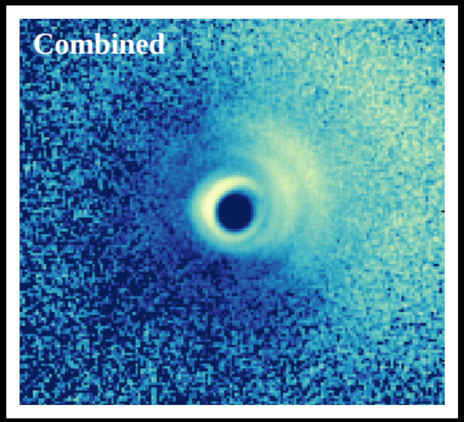
Narrow shadows

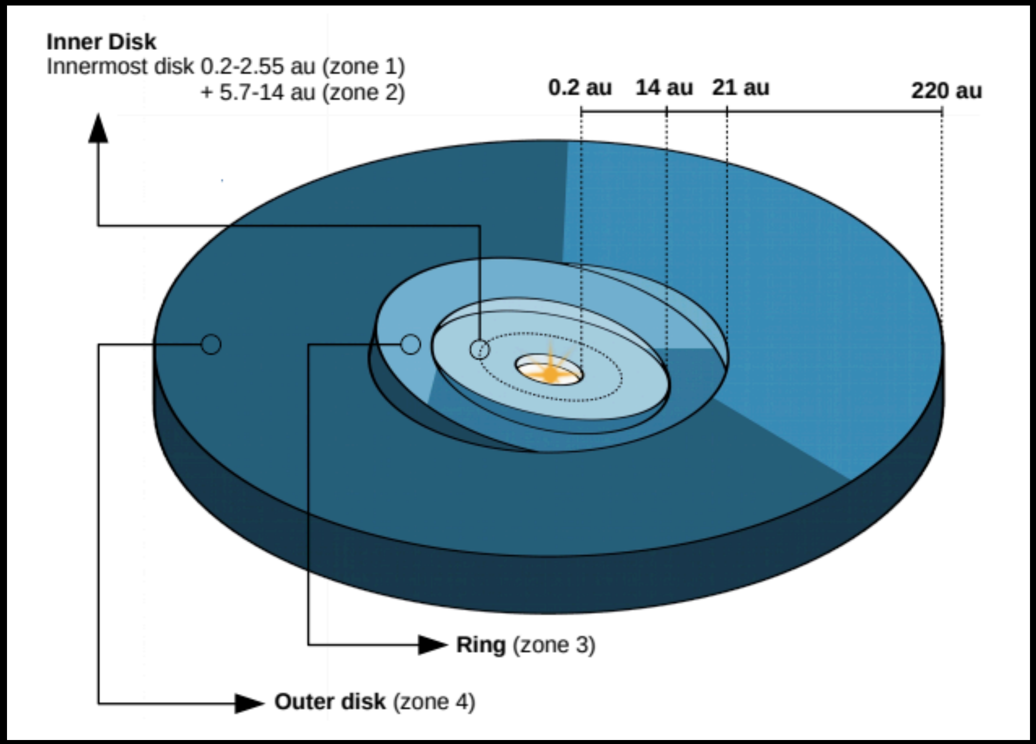




HD 142527
Marino et al. 2015

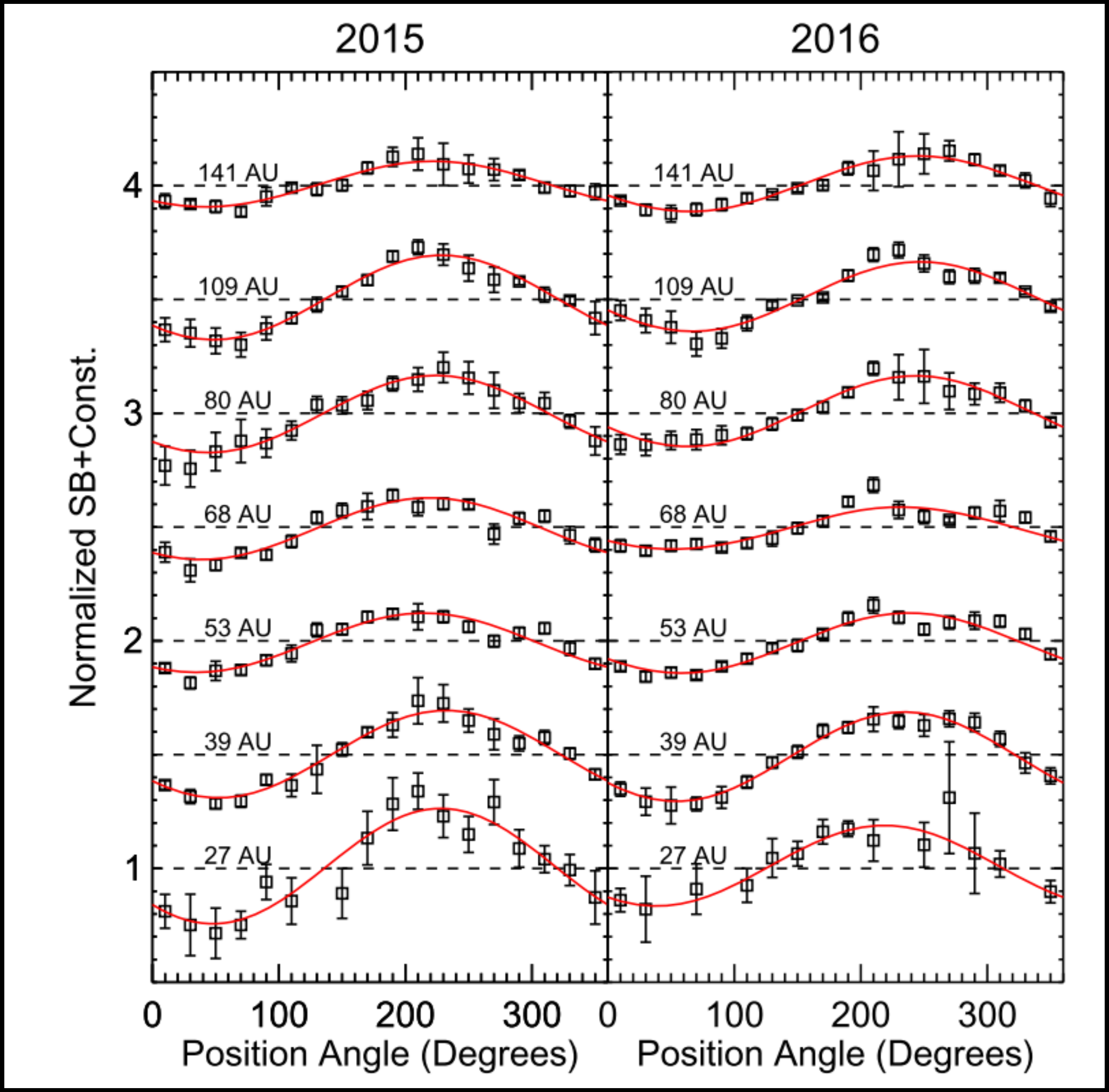
Broad shadows



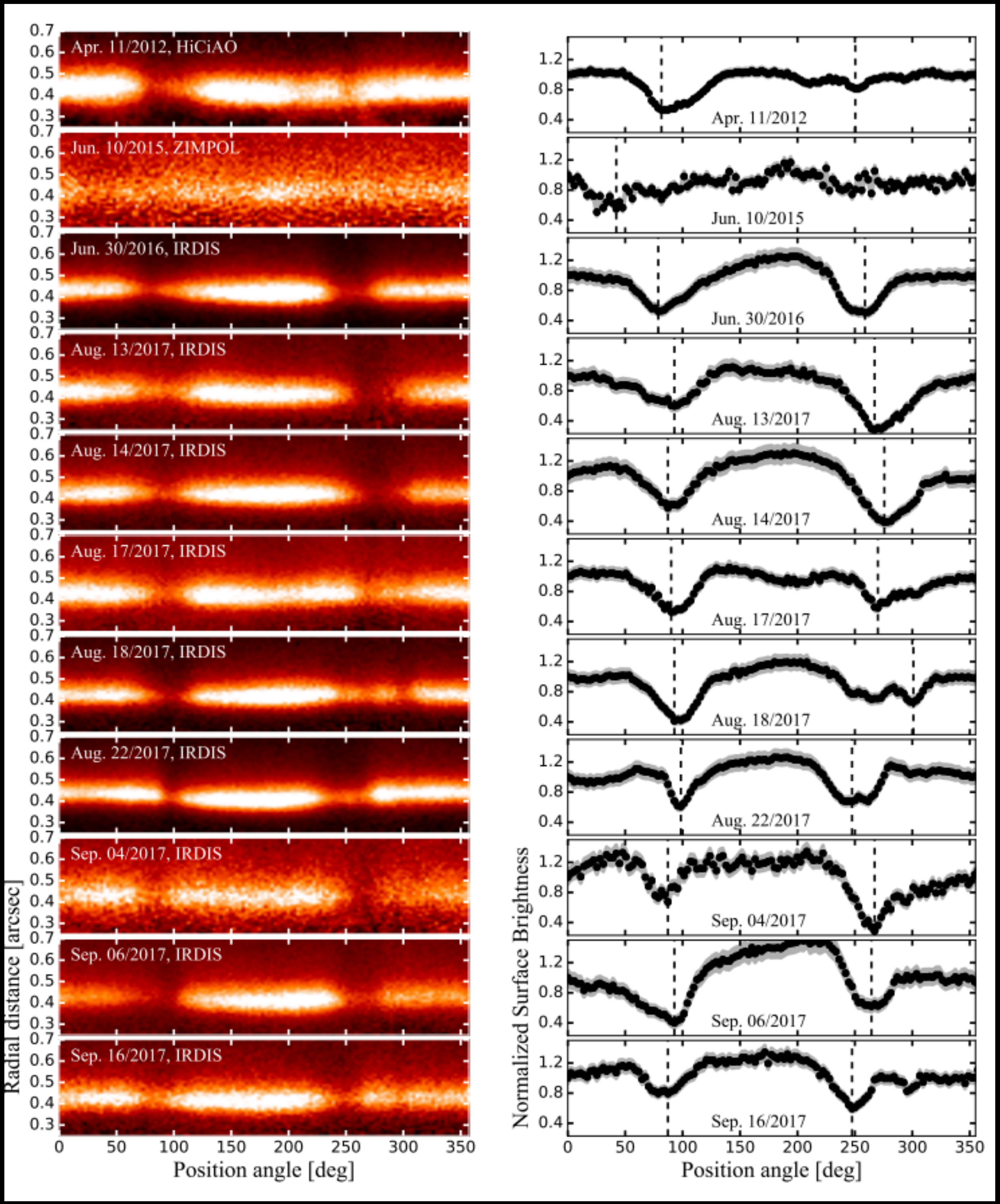


HD 139614
Muro-Arena et al. 2020

Time variability in disk shadows



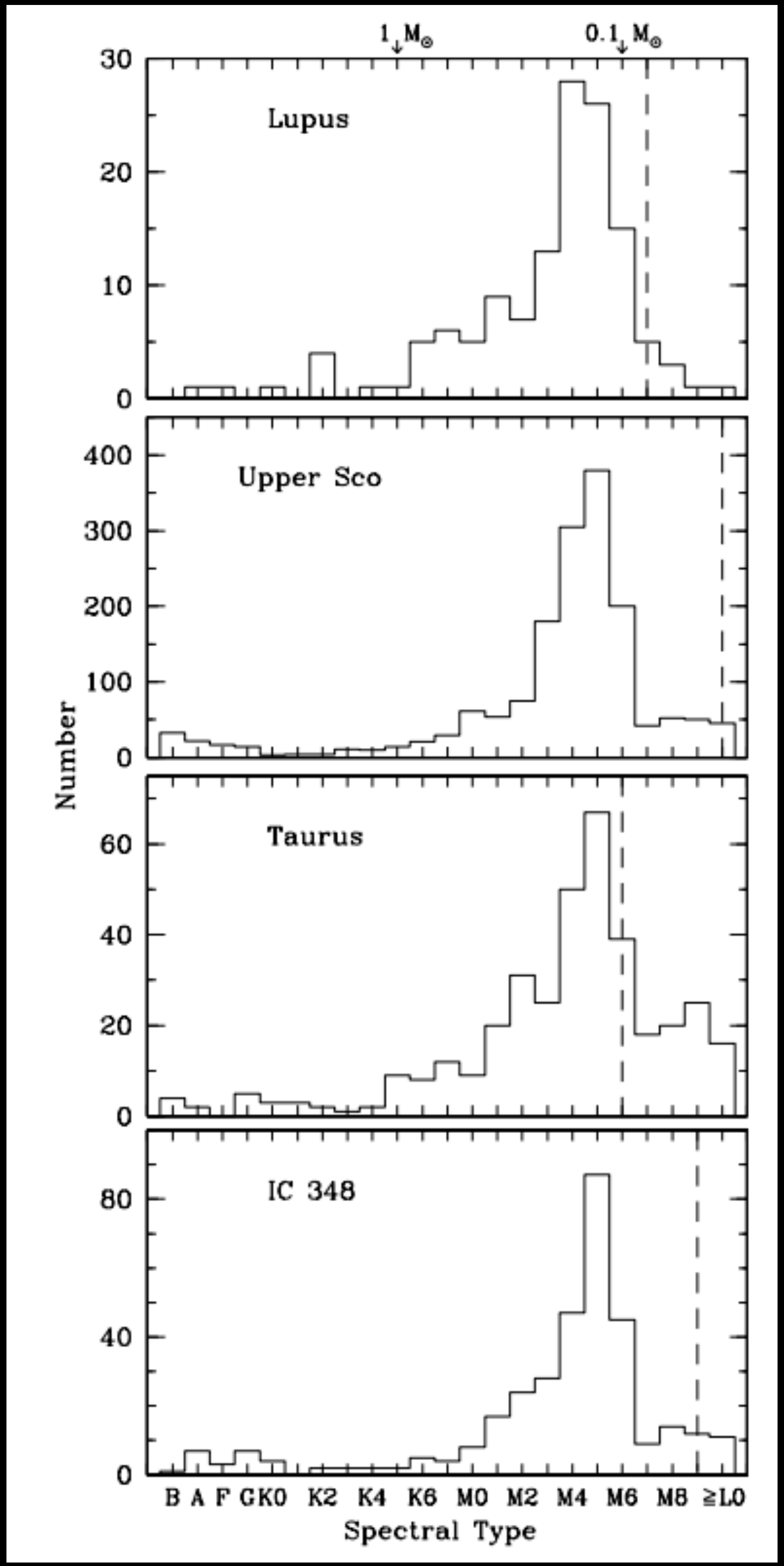
TW Hya
Debes et al. 2017



RX J1604.3-2130
Pinilla et al. 2018

Limitations in our understanding of scattered light substructures: Faintness of low-mass stars

AO guiding systems require bright stars, which leaves most disks around M-type stars inaccessible from the ground

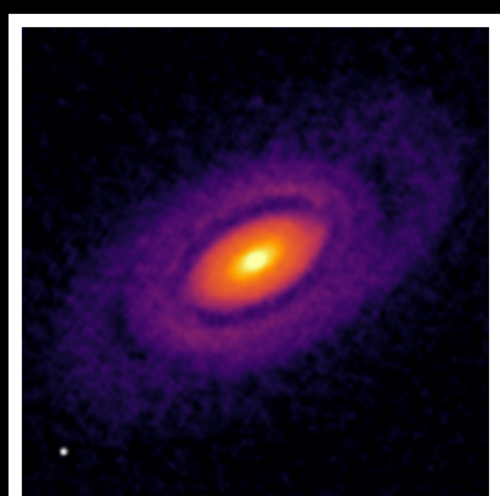


Luhman 2018

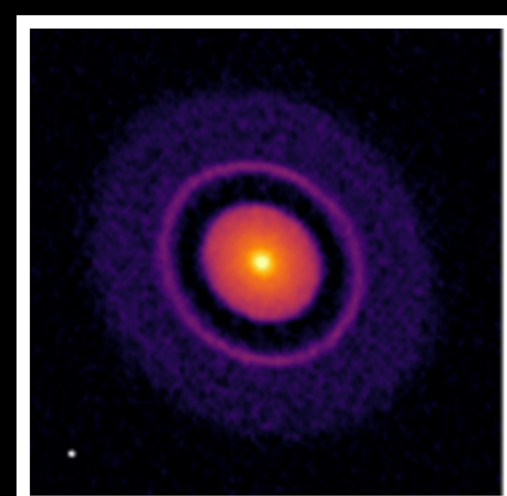
Limitations in our understanding of scattered light substructures: Extinction

Sources that are readily mapped in millimeter continuum (especially in Ophiuchus) can be difficult/impossible to image from the ground in scattered light due to high foreground extinction

Elias 27
A_v=15



Elias 24
A_v=9



Elias 20
A_v=14

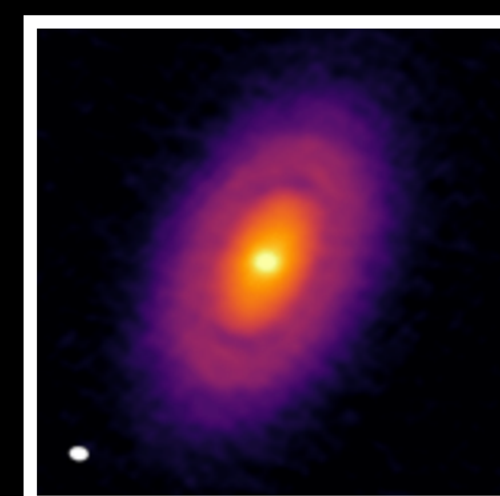
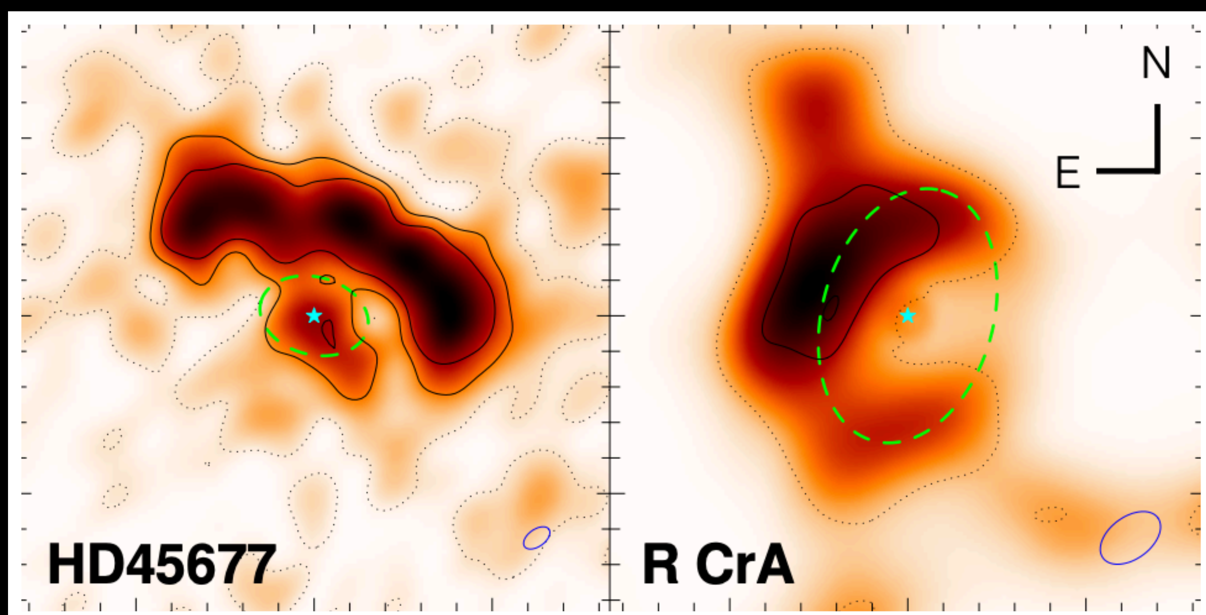


Image credits: Andrews et al. 2018
Extinction values: Cieza et al. 2021

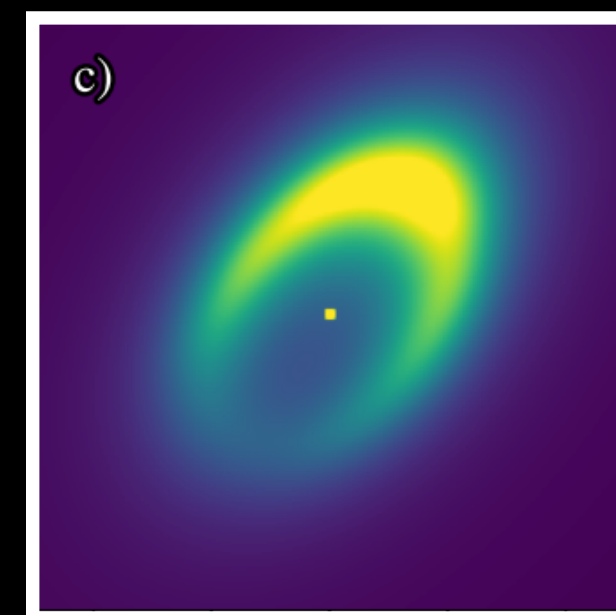
Mapping inner disk substructures with IR interferometry

Reconstructed H-band disk images from VLTI/PIONIER



Kluska et al. 2020

Best-fit model to VLTI/MATISSE mid-IR observations of HD 163296



Varga et al. 2021

- Can achieve milliarcsecond-scale angular resolution
- Generally sensitive to emission from the inner few au of the disks
- Observations of Herbig Ae stars are more favorable because they are more luminous and their dust sublimation radii are larger compared to T Tauri stars

Key observables for disk substructures

- Occurrence rate
- Appearance at different wavelengths
- Location in disk (radial and vertical)
- Width and contrast of substructures
- Number of substructures within a given disk
- Pitch angle (for spiral arms)
- Trends with stellar mass, age, disk mass, disk size, SEDs, multiplicity
- Kinematic behavior
- Time variation

Where to find reduced datasets

- DSHARP: https://bulk.cv.nrao.edu/almadata/lp/DSHARP/
- MAPS Large Program data: http://alma-maps.info/data.html
- High-resolution TW Hya continuum data: https://lweb.cfa.harvard.edu/~sandrews/#data
- High-resolution MWC 758 continuum data: ApJ online supplemental data for Dong et al. 2018
- TW Hya and RU Lup CO data, high-resolution GM Aur continuum data: https://sites.lsa.umich.edu/jnhuang/data/
- Data from Kurtovic et al. 2021 (Disks around very low mass stars): https://github.com/nicokurtovic/VLMS_ALMA_2018.1.00310.S

Summary and Outlook

- Many disks are highly structured in millimeter continuum emission, molecular emission, and/or scattered light
- The occurrence rate of substructures and trends with stellar and disk properties appears to vary between different kinds of tracers.
- Substructures in one tracer do not necessarily have counterparts in other tracers (is this because they trace different parts of the disk or they have different origins?)
- Existing observations of substructures are biased toward more massive disks and disks around stars that are solar-mass or higher