DSHARP:
Disk Substructures at High Angular Resolution Project

Alice Young, Michail Moussine

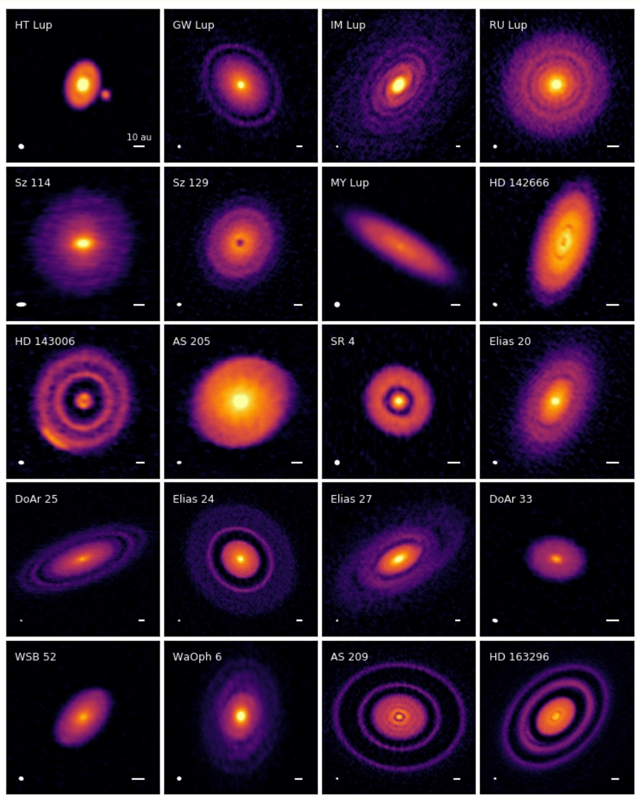
Contents

- Introduction and Motivation
- Technical process
  - Array Observatory, Survey Design, Sample
- Observations
- Results and Comparison
- Outlook and Conclusion

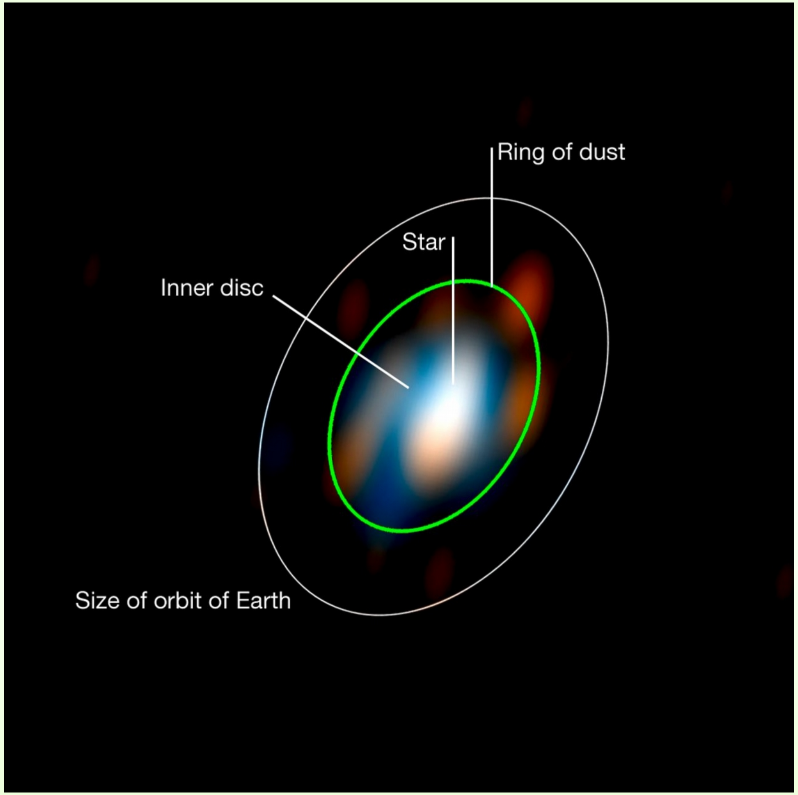
Introduction to DSHARP

Comparison to other surveys

2018



2010



Disk around young star HD 163296 (IR)

Source: DSHARP I., DOI:10.3847/2041-8213/aaf741

ESO/S. Renard, VLT 2010

DSHARP – Project goals

- Find and characterise *substructures* (small-scale material concentrations) in the spatial distributions of solid particles for a sample of 20 nearby protoplanetary disks

DSHARP – Project goals

- Find and characterise *substructures* (small-scale material concentrations) in the spatial distributions of solid particles for a sample of 20 nearby protoplanetary disks
- Deep, high resolution (35 mas, or 5 AU) survey of the 240 GHz (1.25 mm) continuum emission

DSHARP – Project goals

- Find and characterise *substructures* (small-scale material concentrations) in the spatial distributions of solid particles for a sample of 20 nearby protoplanetary disks
- Deep, high resolution (35 mas, or 5 AU) survey of the 240 GHz (1.25 mm) continuum emission
- Research and understanding of protoplanetary disks and planet formation in general

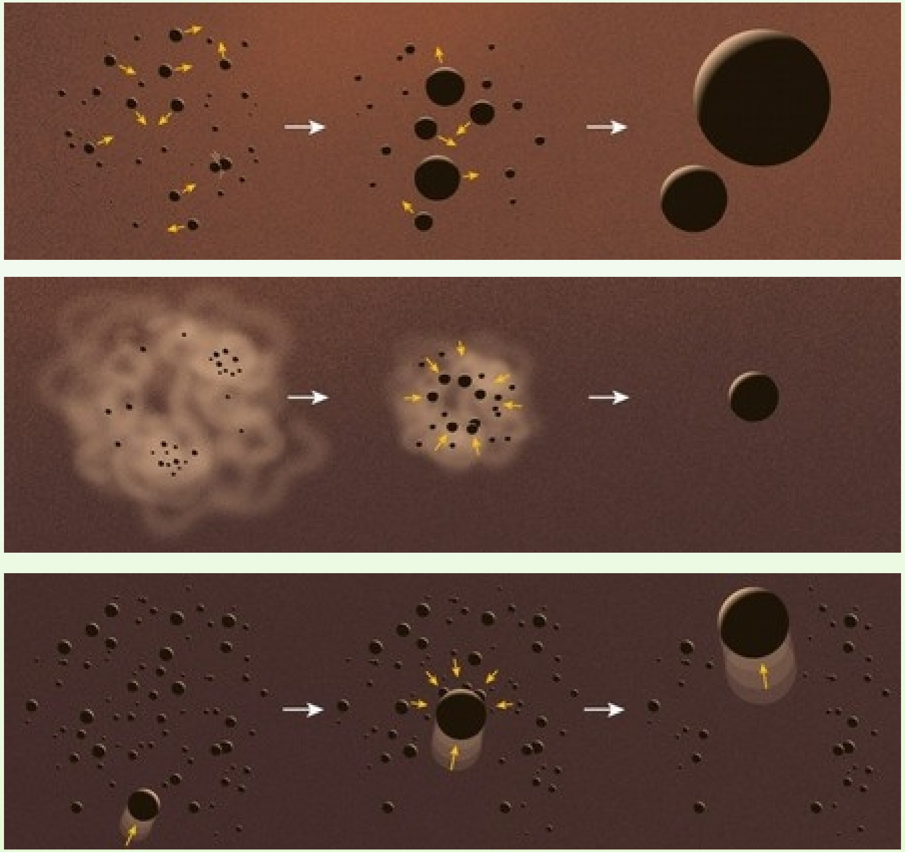
Motivation:
Why was this survey done?

Motivation

- Different theories on planet formation

Motivation

- Different theories on planet formation



Early to contemporary theories

- Core Accretion
- Streaming instability
- Pebble Accretion

Source: Nature, Rebecca Boyle, 2018

Motivation

- Different theories on planet formation
- Discrepancies between observations and expectations (e.g. large planetesimals in very young protoplanetary disks)
- Disks exhibit substructures previously not considered
- Planet formation can be examined closer than ever before

Substructures in Protoplanetary Discs – Expectations

- Substructures may be in the form of:
  - rings/gaps
  - vortices
  - spirals
- Look for signatures of particle traps and their substructures:
  - azimuthal asymmetries
  - additional rings
  - warped geometries
  - spiral arms (and planetesimals even)

Substructures in Protoplanetary Discs – Consequences

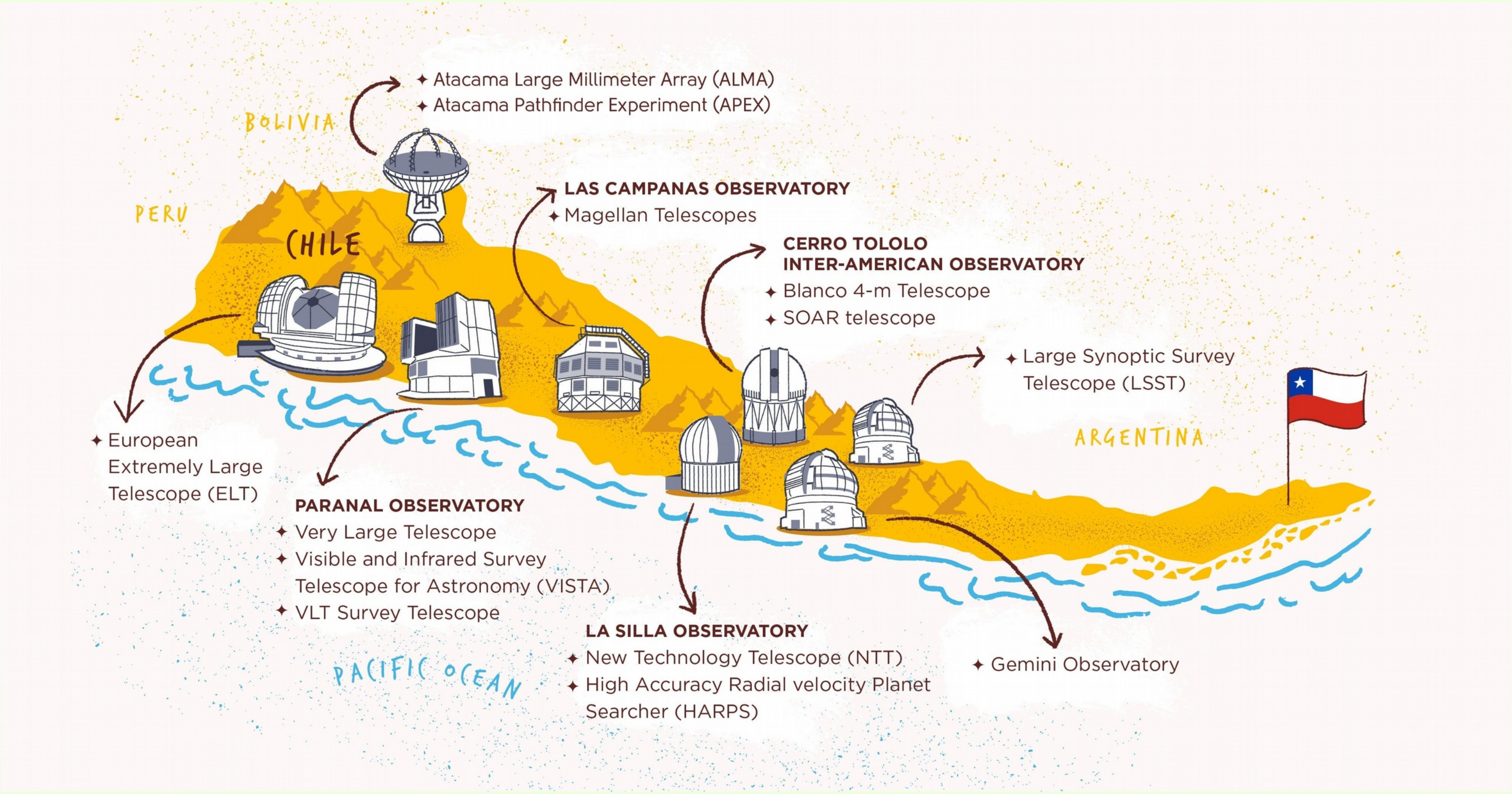
- Clearing discrepancies between spatial distributions of continuum and spectral line emissions
- There are already suggestions, that substructures are quite common and thus significant factors in many disk evolution and planetary formation processes

ALMA:
Atacama Large Millimeter/submillimeter Array

Atacama Large Millimeter/submillimeter Array (ALMA)

Source: Google Maps

Atacama Large Millimeter/submillimeter Array (ALMA)



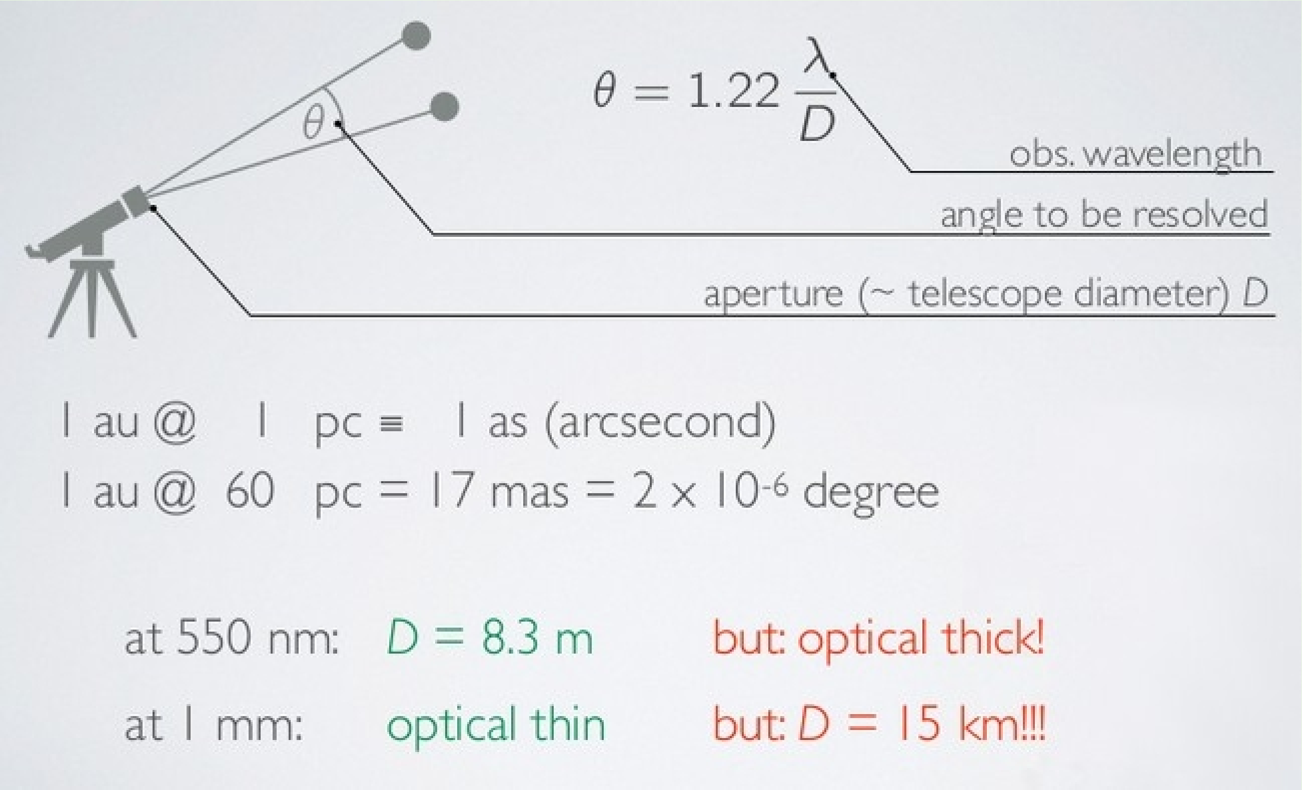
Source: Symmetrymagazine.org, Sandbox Studio, Chicago with Pedro Rivas

Atacama Large Millimeter/submillimeter Array (ALMA)

- International Project of ESO, AUI/NRAO and NAOJ
- Astronomical Interferometer

Atacama Large Millimeter/submillimeter Array (ALMA)

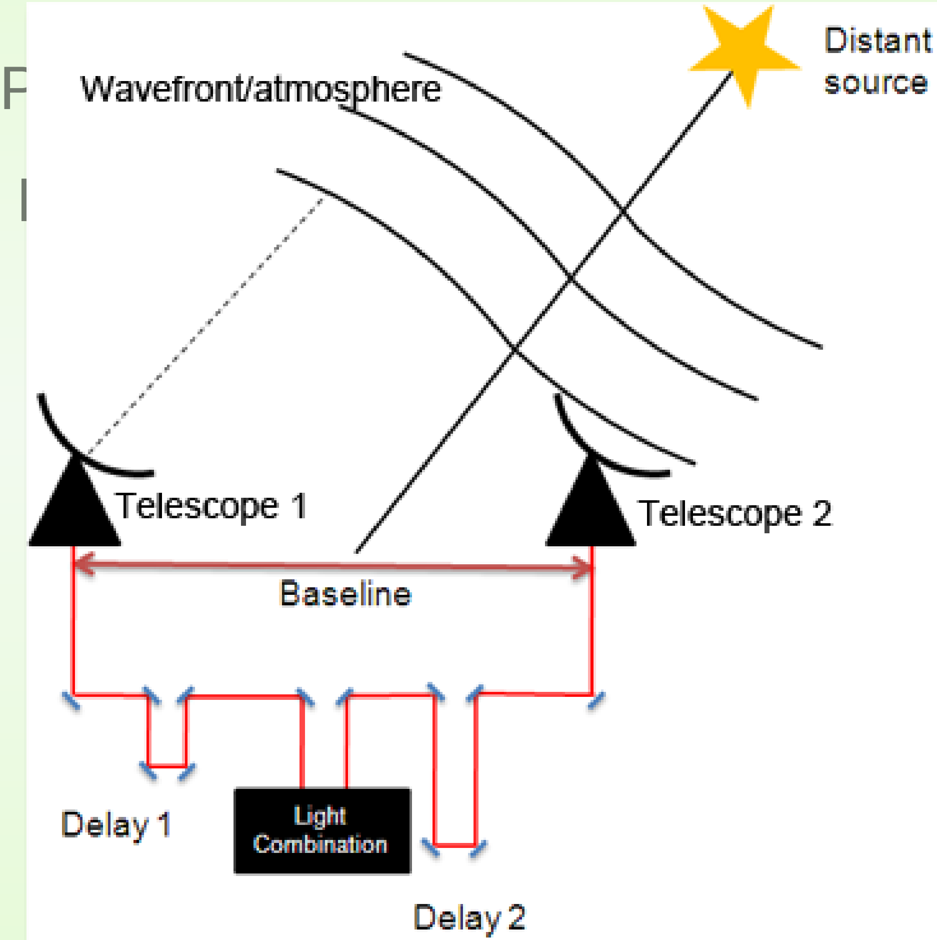
- Interna
- Astron



Source: LMU, Birnstiel, Formation and Evolution of Planets and Protoplanetary Disks lecture

Atacama Large Millimeter/submillimeter Array (ALMA)

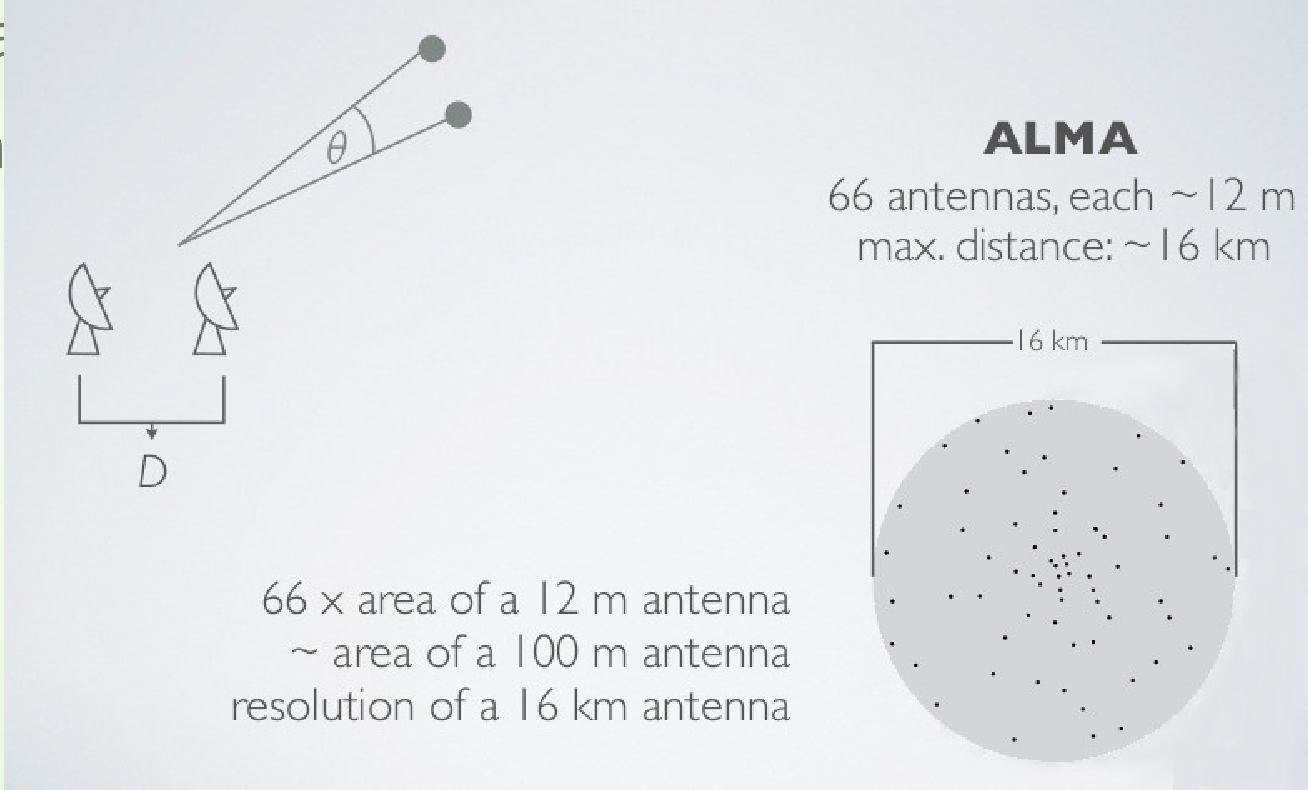
- International P… …AOJ
- Astronomical I…



Source: Magdalena Ridge Observatory

Atacama Large Millimeter/submillimeter Array (ALMA)

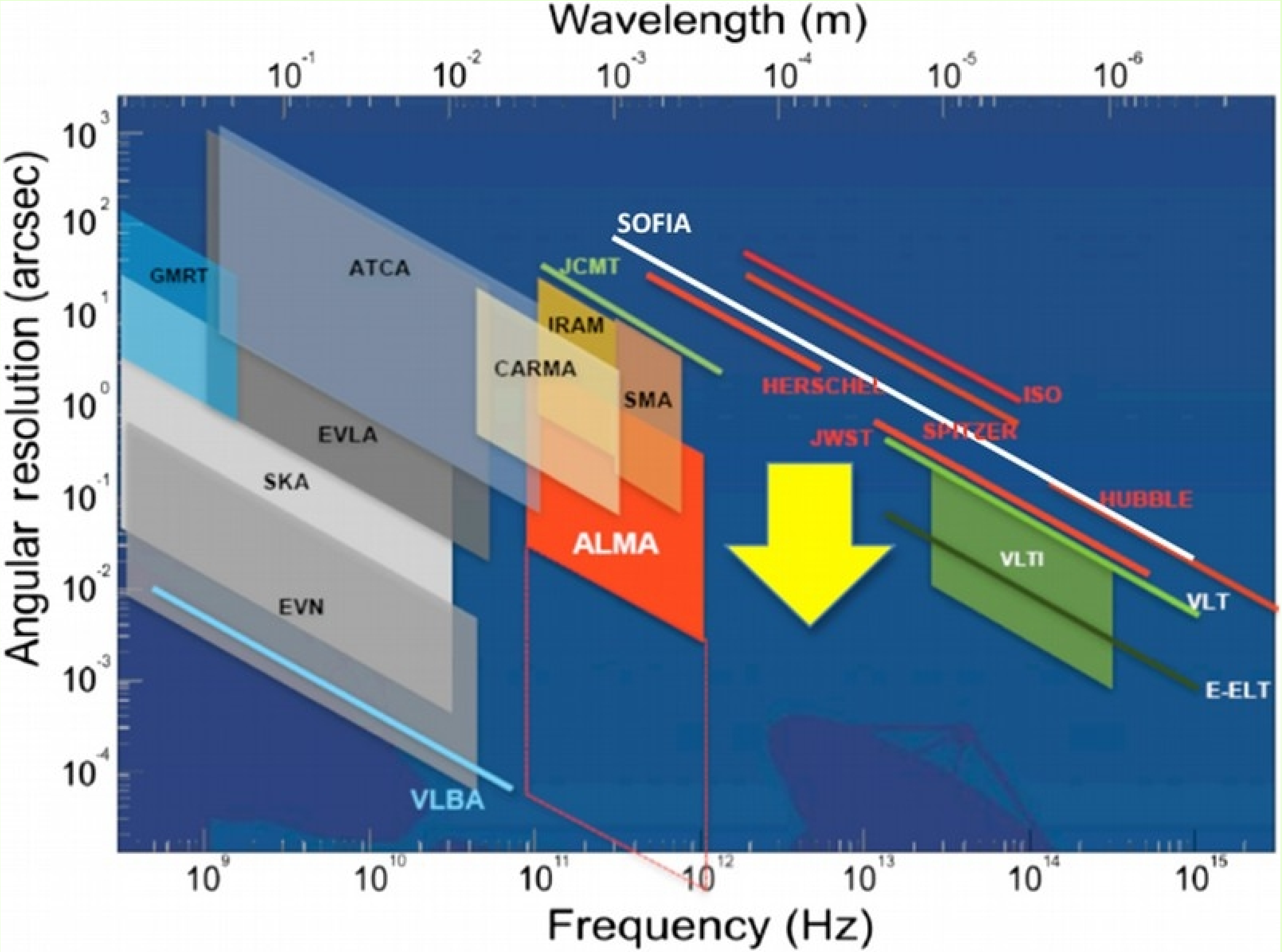
- Interna
- Astron



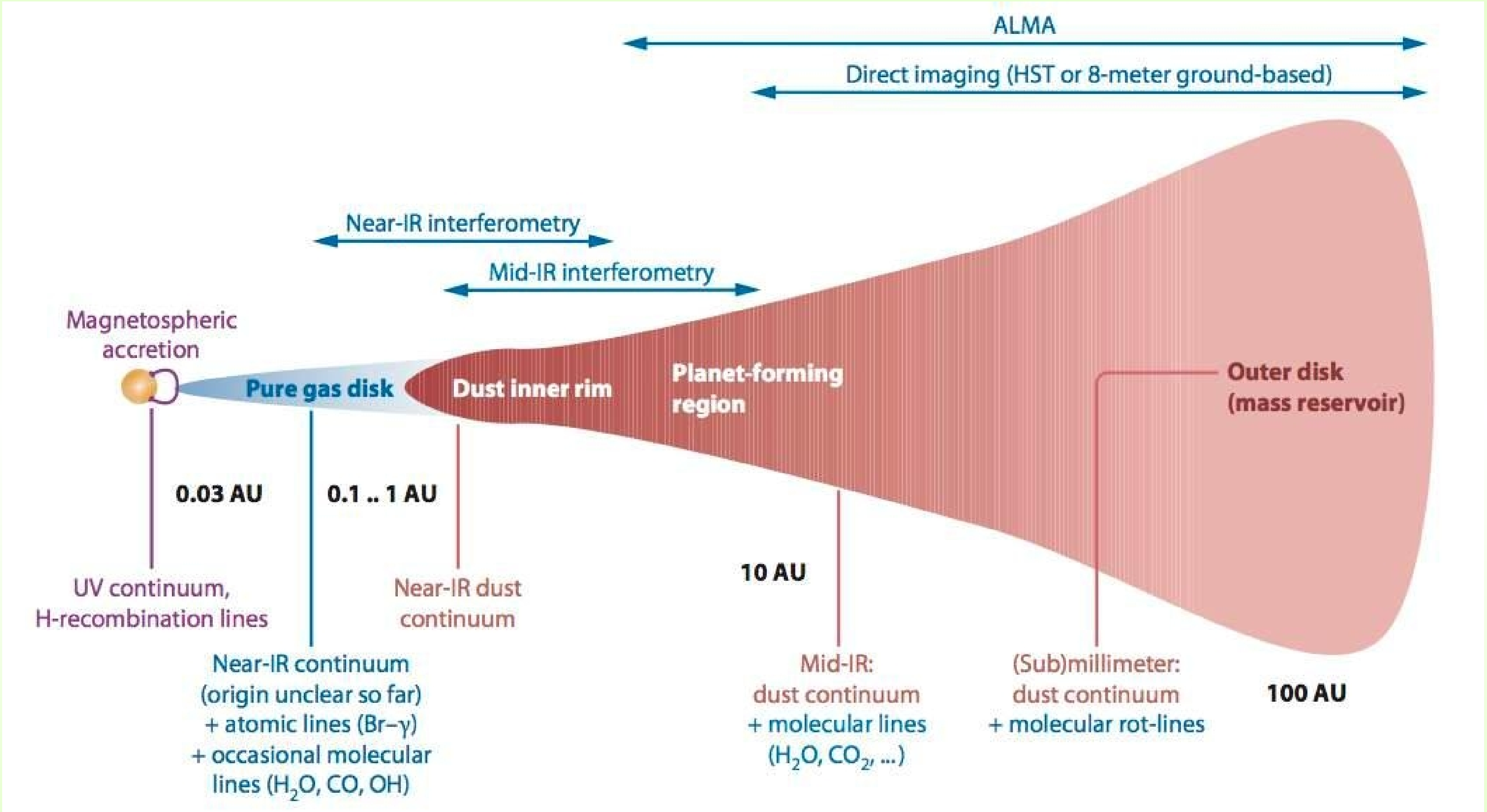
Source: LMU, Birnstiel, Formation and Evolution of Planets and Protoplanetary Disks lecture

Atacama Large Millimeter/submillimeter Array (ALMA)

- International Project of ESO, AUI/NRAO and NAOJ
- Astronomical Interferometer
- 66 Antennae, each 12 m in diameter
- Operating at wavelengths of 0.32 to 3.6 mm
- Maximum distance between antennas can vary from 150 metres to 16 kilometres
- Operating in Far-Infrared to Millimeter regime, atmospheric absorption of that light imposes an issue
  - → Located at high elevation (~5 km) and low humidity in the Atacama desert



Source: Farah et al., 10.1117/1.JATIS.5.2.020901 (2019)



Source: Roser Juanola-Parramon, © Springer International Publishing Switzerland 2016

Survey Selection

Survey selection:
Going from over 200 to 20 targets

Main criteria:

- Access to wide range of spatial scales down to a FWHM resolution of ~5 AU
  - essential for identifying disk substructures in ALMA continuum images
  - comparable to the (disk-averaged) pressure scale height, h_P, which at 5 AU has features resolved in the outer disk, and detectable down to a radius $r \approx 10$ au (for sufficient contrast)
- Ability to detect a ∼10% contrast out to Solar System size-scales ($r \approx 40$ au).

Survey selection:
Going from over 200 to 20 targets

- More constrains given by:
  - Stellar Class object selection – Class II
  - ALMA technical restrictions

Narrowing down targets: Choosing Class II YSO

- Why Class II?

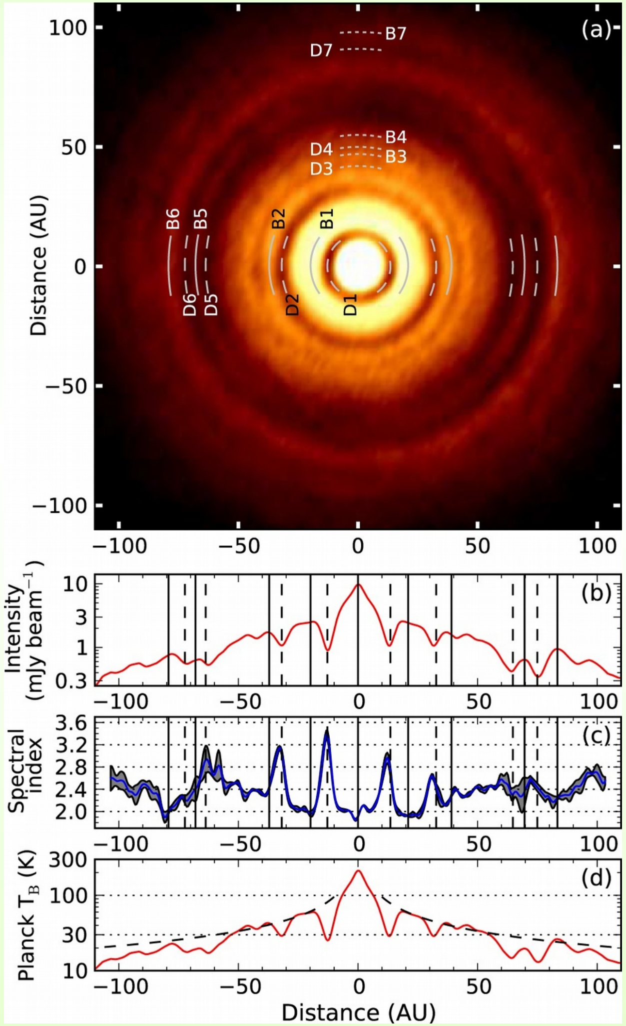
→ SED in MIR/FIR

– Excess IR emission from disc

→ Avoid confusion with envelope emission

- Excluding “transition” disks because they exhibit substructures already

Spectral Energy Distribution (SED) in Planet formation

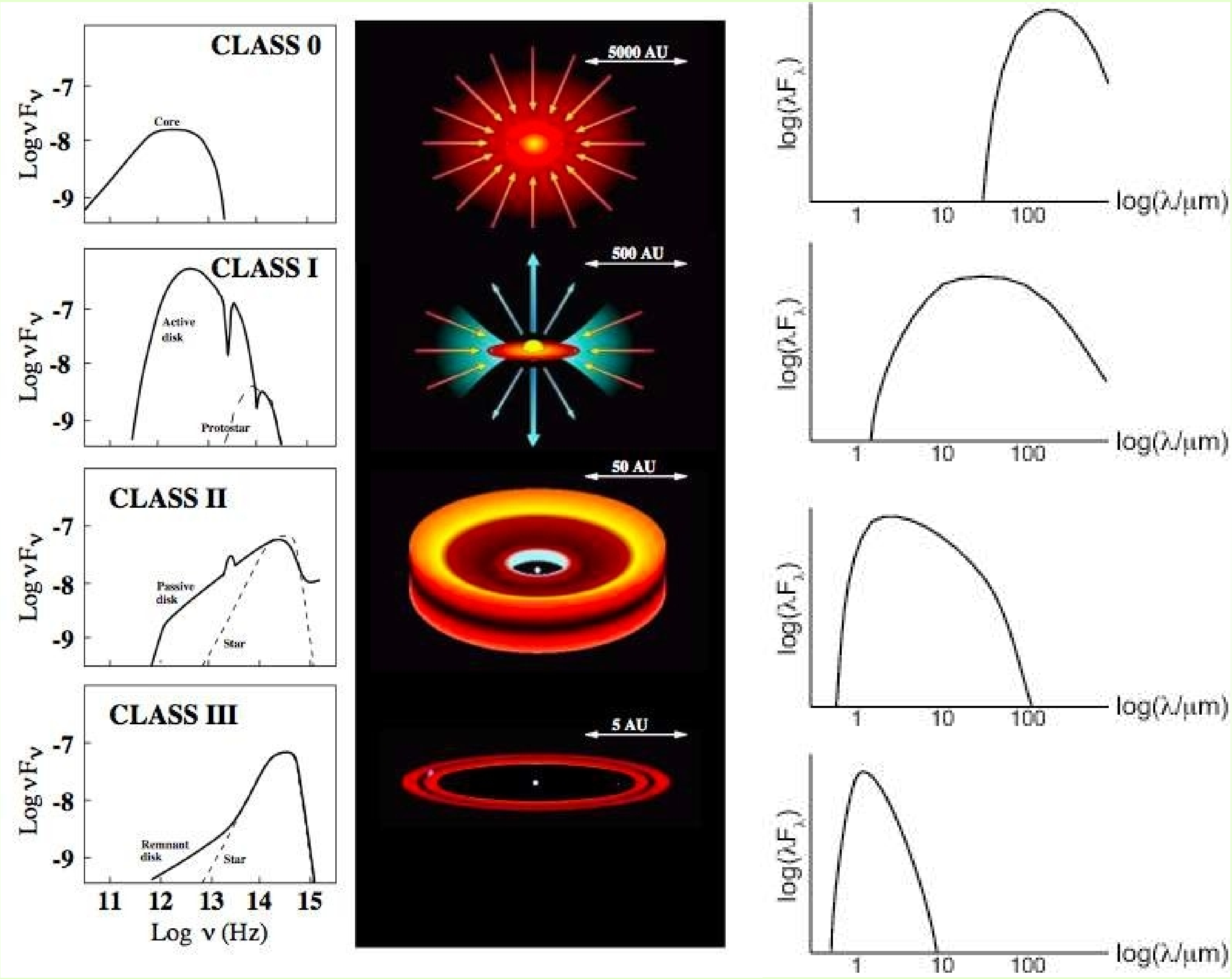


Source: ALMA *Partnership* et al. 2015 ApJL 808 L3

Classification of stellar objects and YSO:

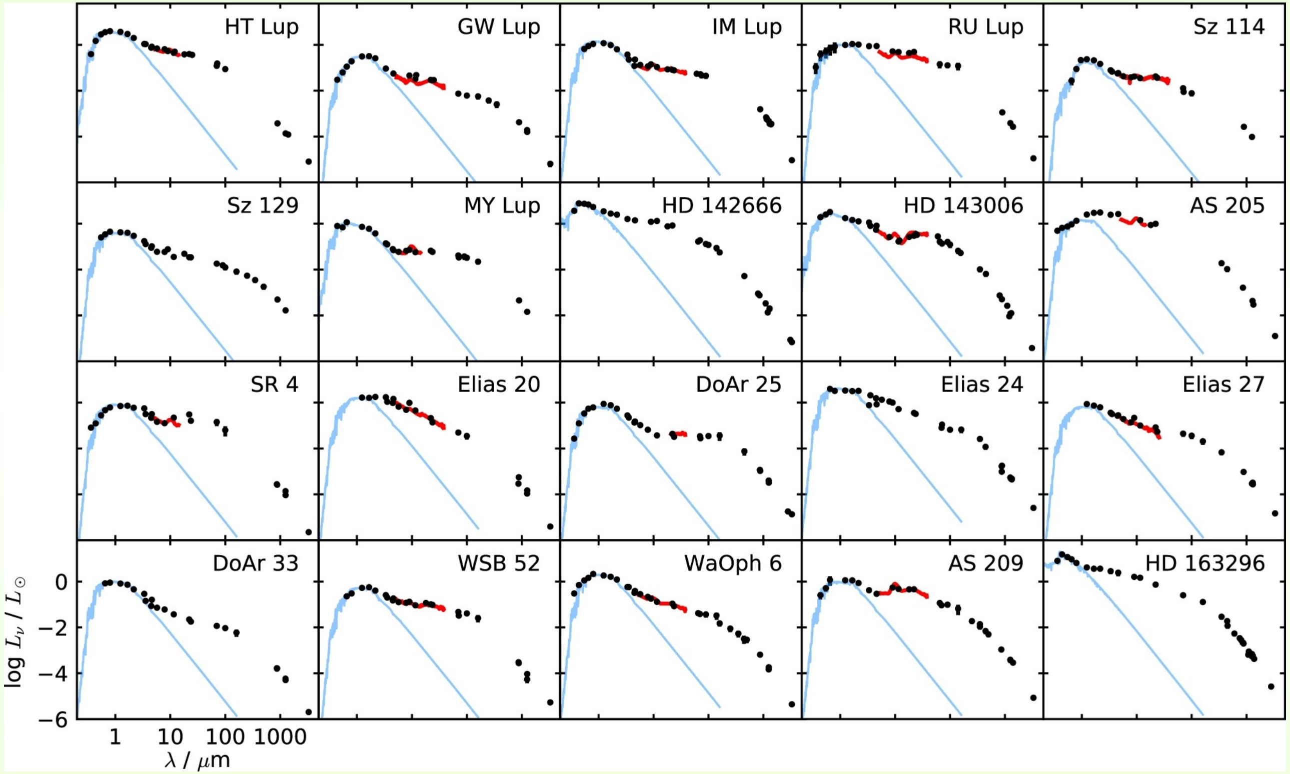
Excess emission characterising type and quality of observed matter

Evolutionary stages differentiable



Source: Andrea Isella, Caltech Astronomy (lecture notes)

Spectral Energy Distribution (SED)



Source: DSHARP I., DOI:10.3847/2041-8213/aaf741

Survey selection:
Going from over 200 to 20 targets

- More constrains given by:
  - Stellar Class object selection – Class II
  - ALMA technical restrictions

→ Optimal window of 240 GHz, and mean age of 1 Myr

- Contrast criterion, taking fiducial numbers for orientation:
  - For a target at 140 pc, with a synthesized beam FWHM of 35 mas, measure a 10% deviation from an otherwise smooth brightness profile out at r = 40 au (∼3 mas).
  - Taking a cut on the 3 mas peak brightness

Survey selection:
Going from over 200 to 20 targets

- Final constraint set by ALMA time allowance (30 h) and overhead cost

→ 10 targets per configuration (mostly 2 regions, at 50 and 35 mas resolution respectively)

What did this work accomplish?
What can we see?

See Observations and Results

References

- DSHARP I.: DOI:10.3847/2041-8213/aaf741
- www.almaobservatory.org/en/press-release/alma-campaign-provides-unprecedented-views-of-the-birth-of-planets/
- Some of the other referenced DSHARP papers:

  DOI:10.3847/2041-8213/aaf7a0

  DOI:10.3847/2041-8213/aaf742

  DOI:10.3847/2041-8213/aaf747
- www.tat.physik.uni-tuebingen.de/~kley/research/planetform.html
- www.til-birnstiel.de/
- public.nrao.edu/news/2018-alma-survey-disks/
- www.eso.org/public/teles-instr/alma/
- DOI:10.1051/0004-6361/201118136
- Wikimedia Commons
- DOI:10.1088/0004-637X/808/1/102
- DOI:10.1088/0004-637X/813/1/41
- www.cv.nrao.edu/course/astr534/
- astro.unl.edu/naap/


End of part 1.
...for now.
Source: ann13016a, ESO/C. Malin

Extras

Extras

- ALMA Cycle 4 Project
- Bias Reduction – and Implementation
- Astronomical Interferometry
- Comparison to other surveys:
  Old and New
- Scale Height, FWHM

Atacama Large Millimeter/submillimeter Array (ALMA)

Source: ann16054a, 2016-17, ALMA (ESO/NAOJ/NRAO)

Bias – if it can't harm you, it'll help you

- Bias favours targets with brighter continuum emissions
- Preferential selection of larger disks

  → Beneficial for achieving DSHARP goals!

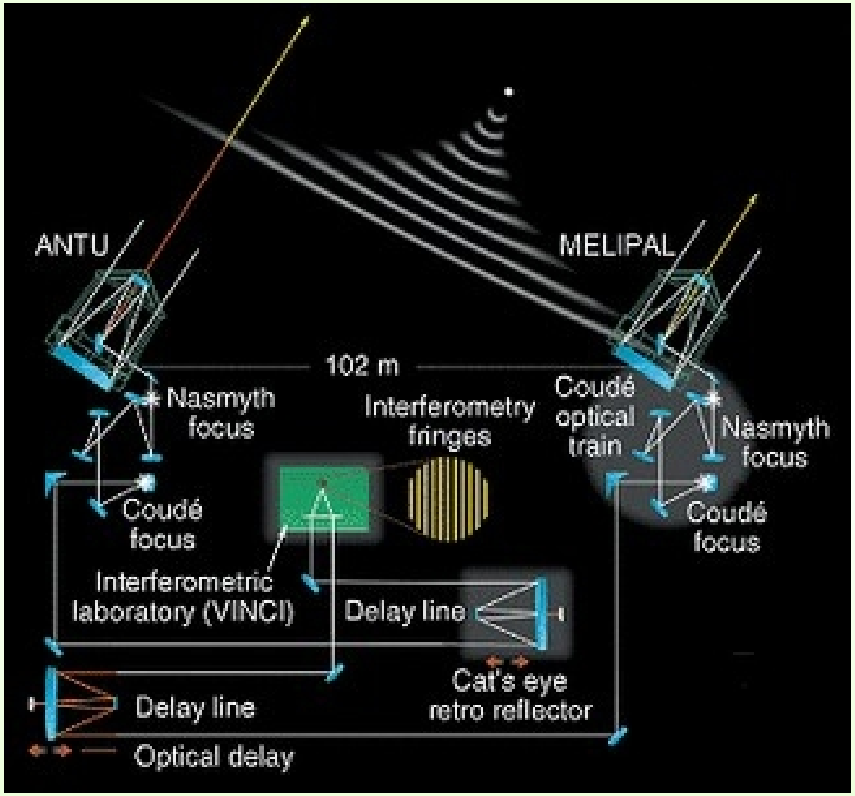
- Predictions for substructure sizes comparable to gas pressure scale height (h_P), which increases ~linearly with disk radius r

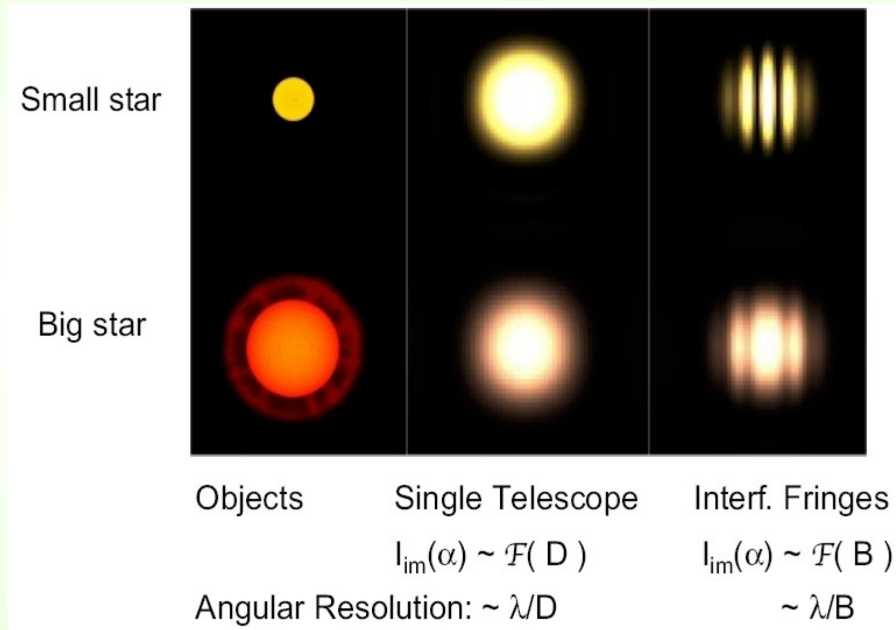
  “For a fixed resolution it should be easier to identify and characterise the larger substructures expected at larger disk radii.”

- Typical host star mass of $M_* \sim 0.3 M_\odot$, continuum emission faint ($F_\nu \approx$10-15 mJy) and compact ($R_{eff} \approx$10-20 AU) – DSHARP averages are $M_* \approx 0.8 M_\odot$, $R_{eff} \approx$50 AU.

Source: DSHARP I., DOI:10.3847/2041-8213/aaf741

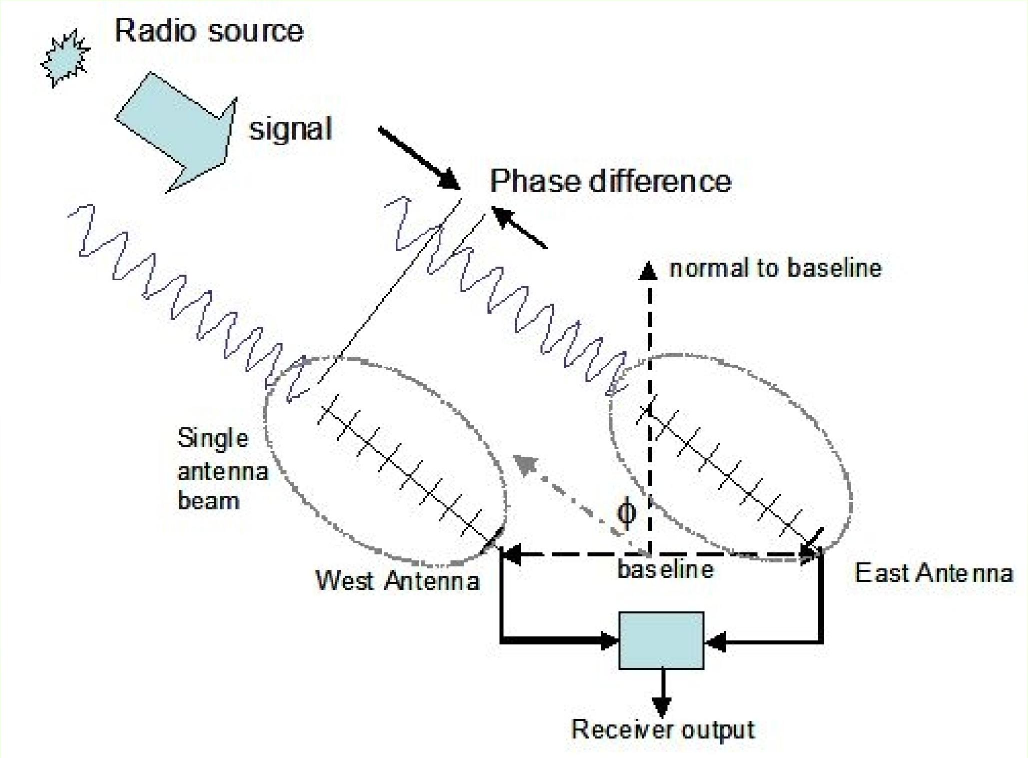
Astronomical Interferometry

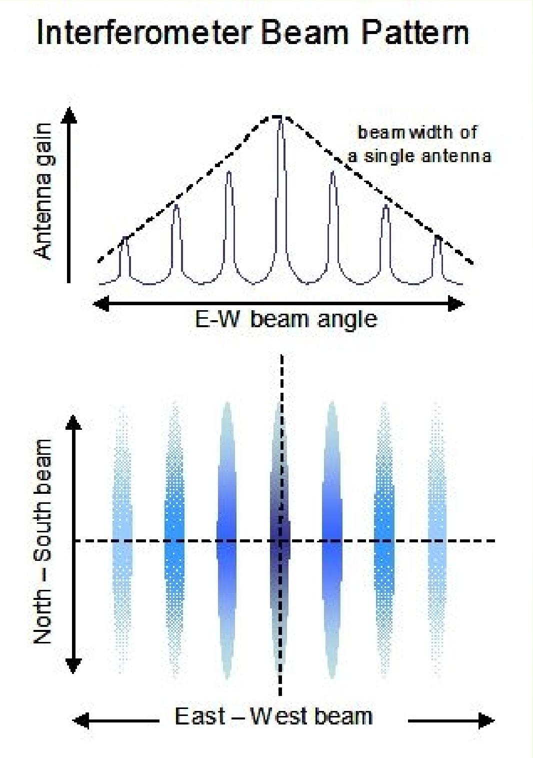




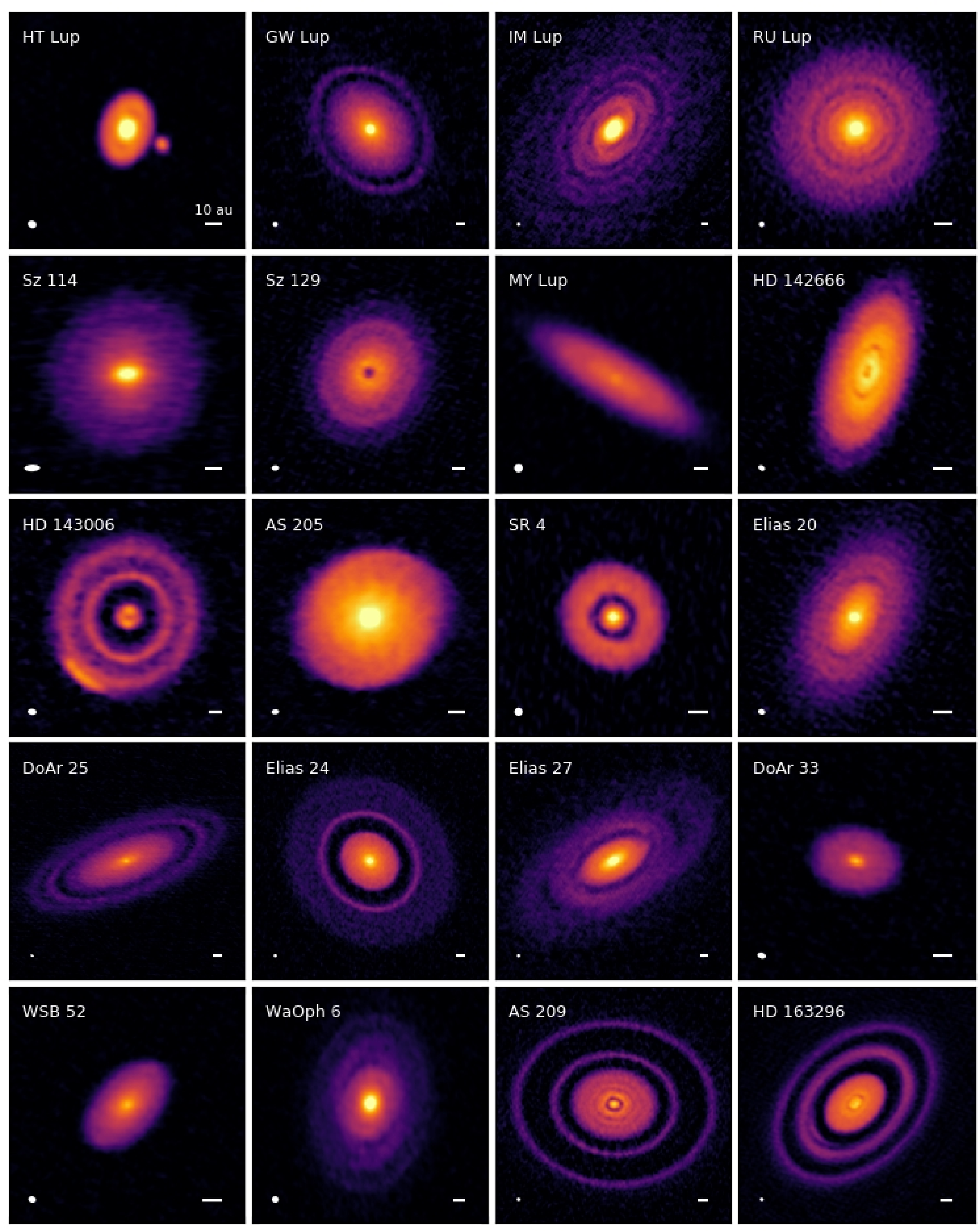
Source: AIU, Uni Jena

Astronomical Interferometry





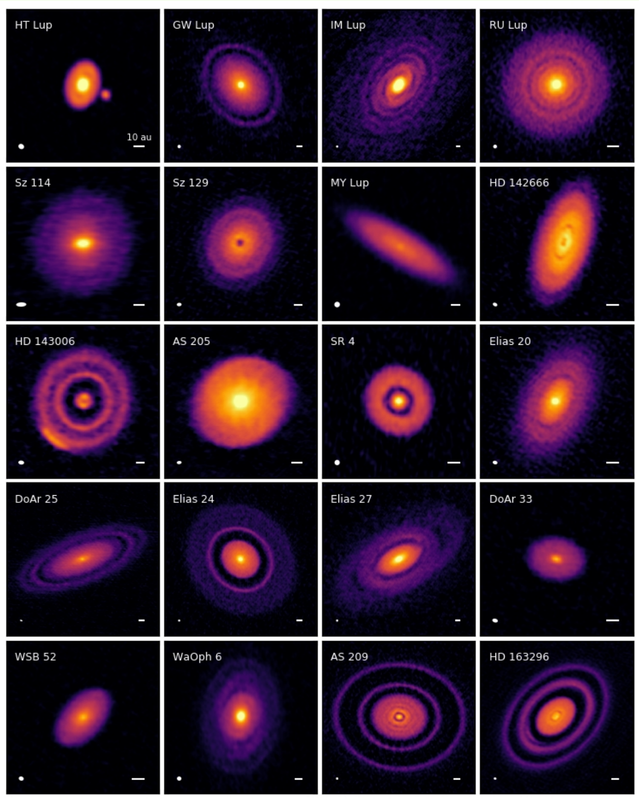
Source: sites.google.com/site/radioastronomydm/



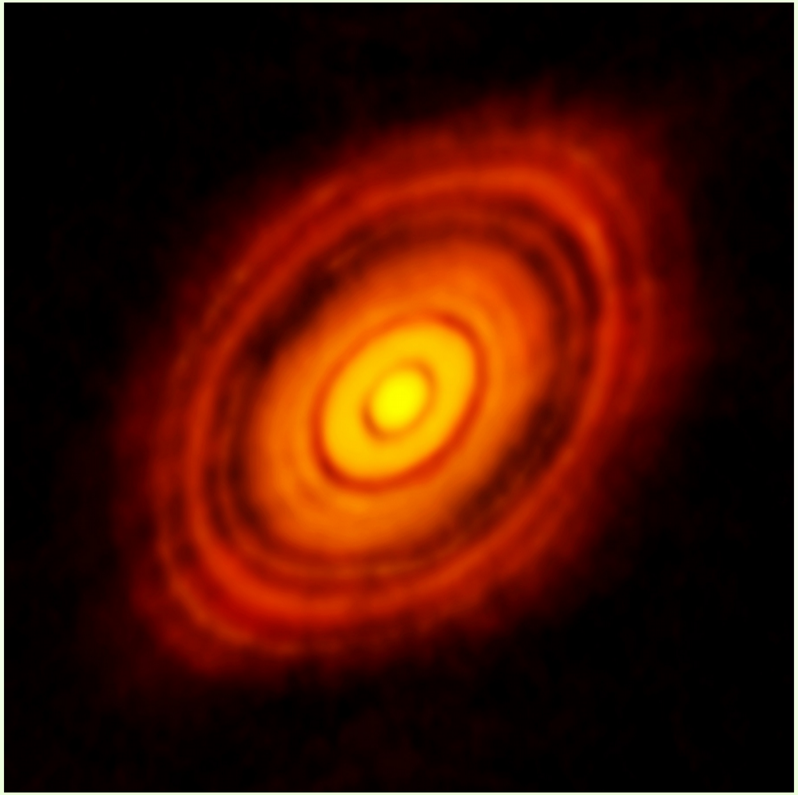
Source:
DSHARP I.,
DOI:10.3847/2041-8213/aaf741

Comparison to other surveys

2018



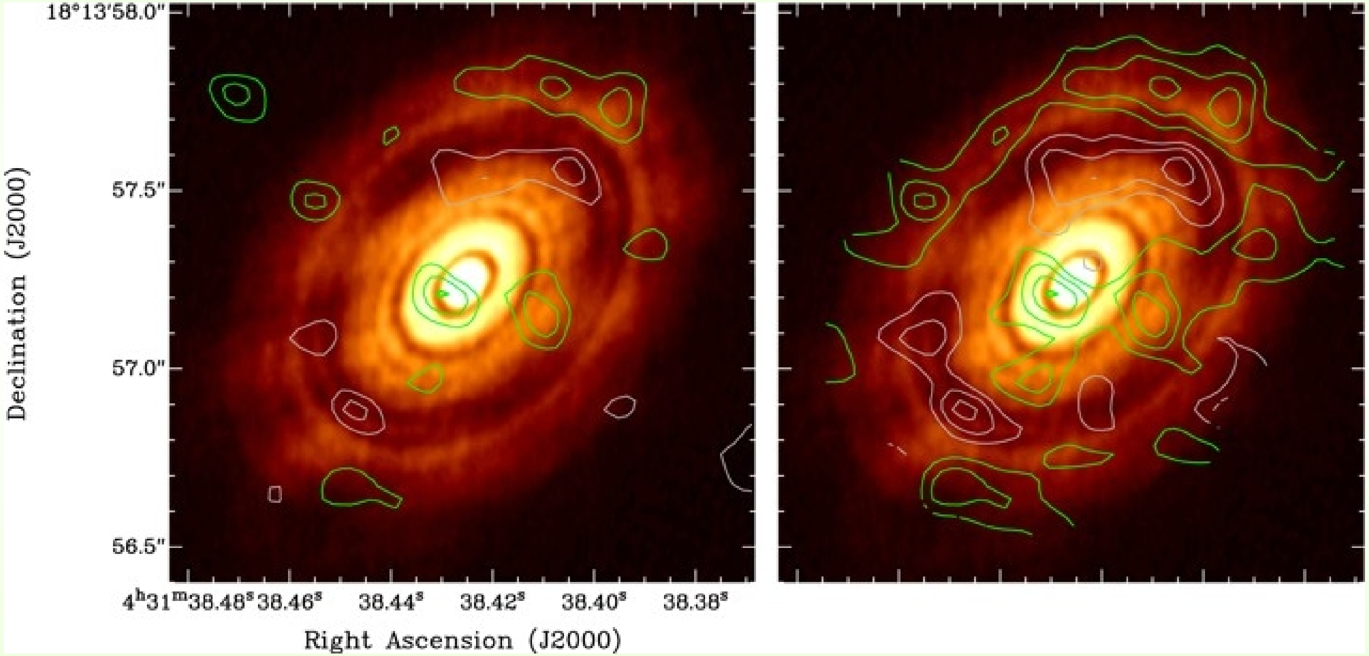
HL Tauri 2014



Source: DSHARP I., DOI:10.3847/2041-8213/aaf741

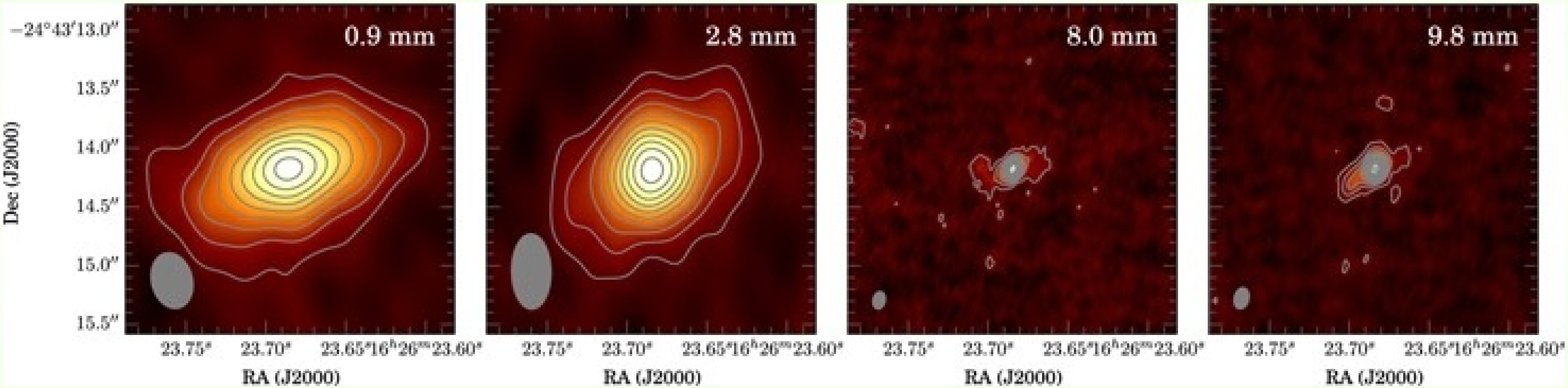
Source: eso1436a, 2014, ALMA (ESO/NAOJ/NRAO)

ALMA SV data of HL Tau



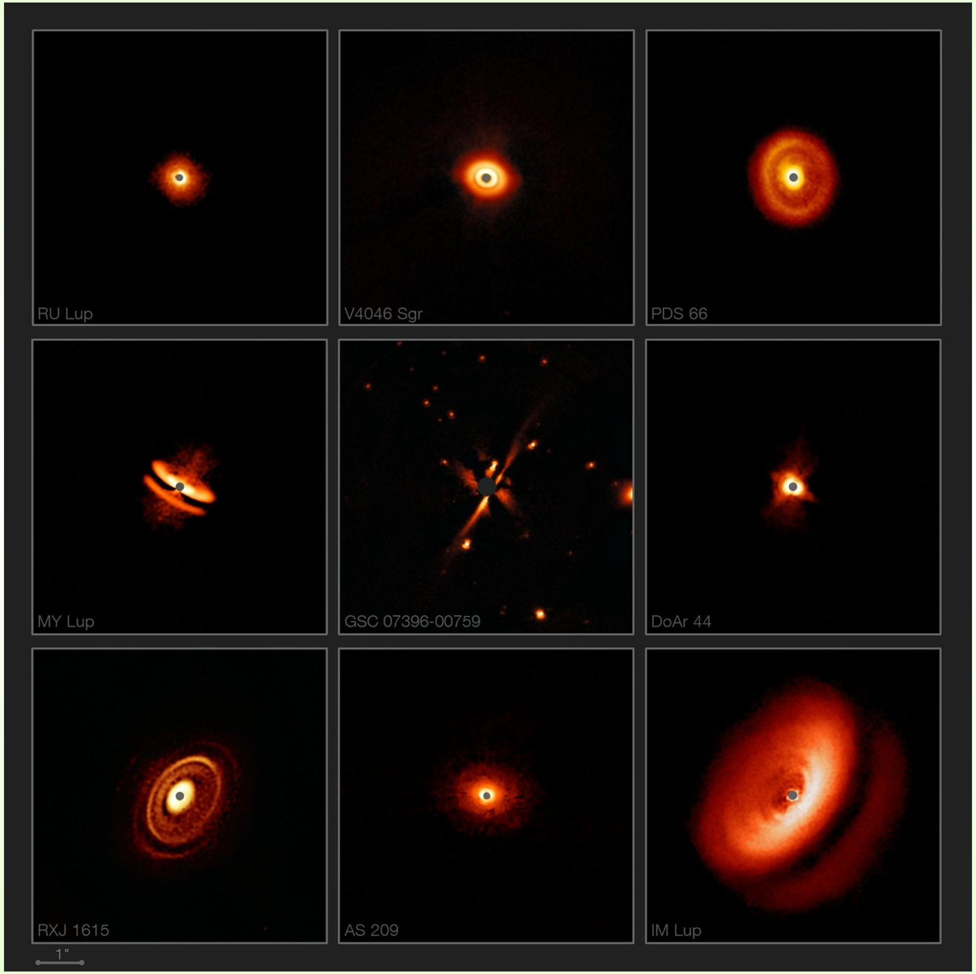
Source: Kwon et al., 2015, DOI:10.1088/0004-637X/808/1/102

Aperture synthesis images of continuum emission toward the young star DoAr 25



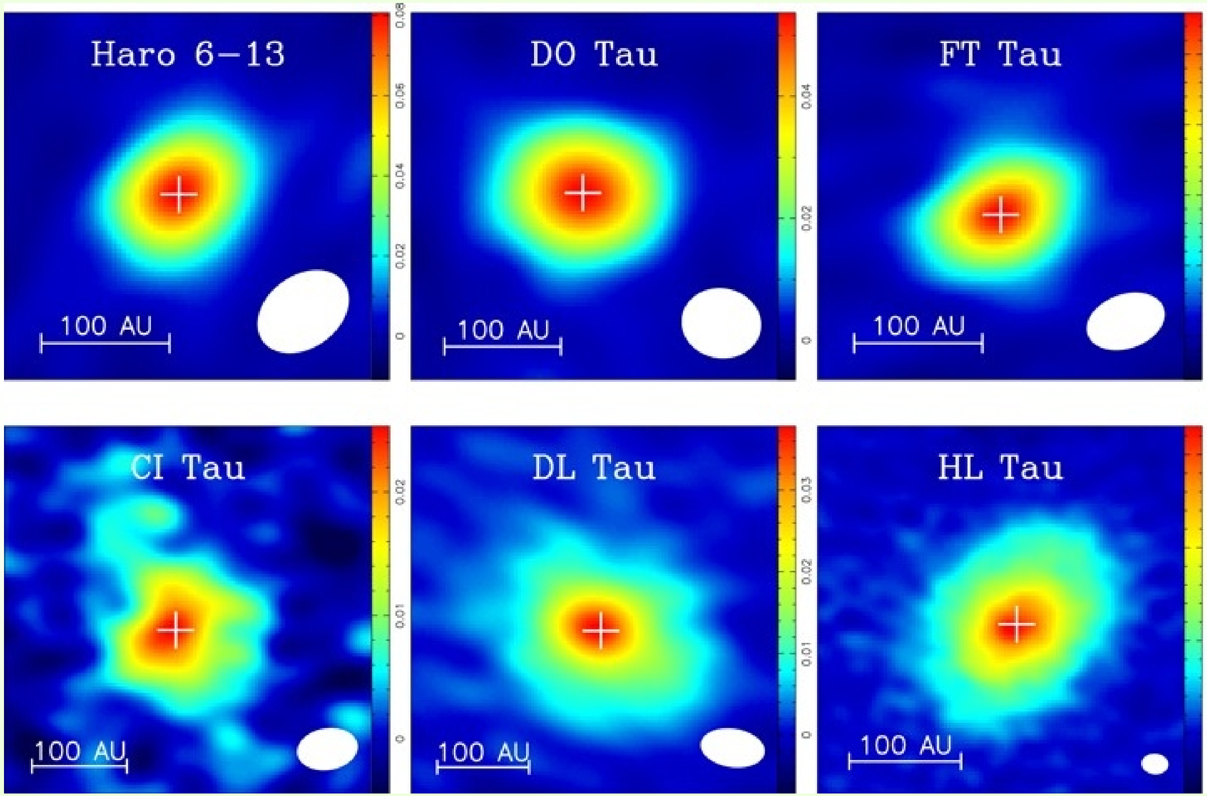
Source: Pérez et al., 2015, DOI:10.1088/0004-637X/813/1/41

Sphere instrument at VLT, YSOs with discs



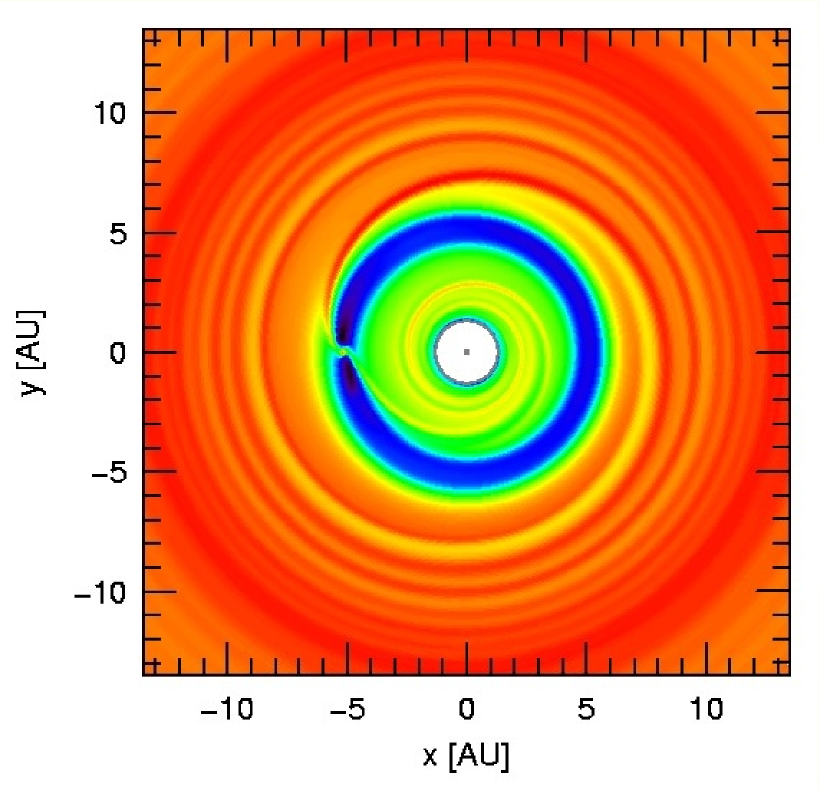
Source: ESO/H. Avenhaus et al./E. Sissa et al./DARTT-S and SHINE collaborations, 2018

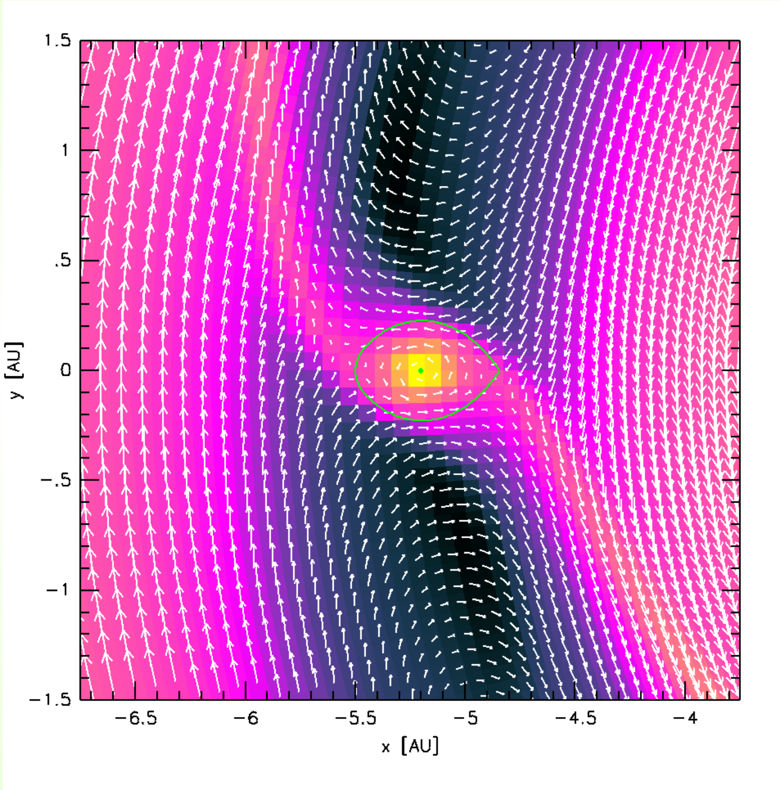
Protoplanetary disk images in λ = 1.3 mm continuum.



Source: Kwon et al., 2015, DOI:10.1088/0004-637X/808/1/102

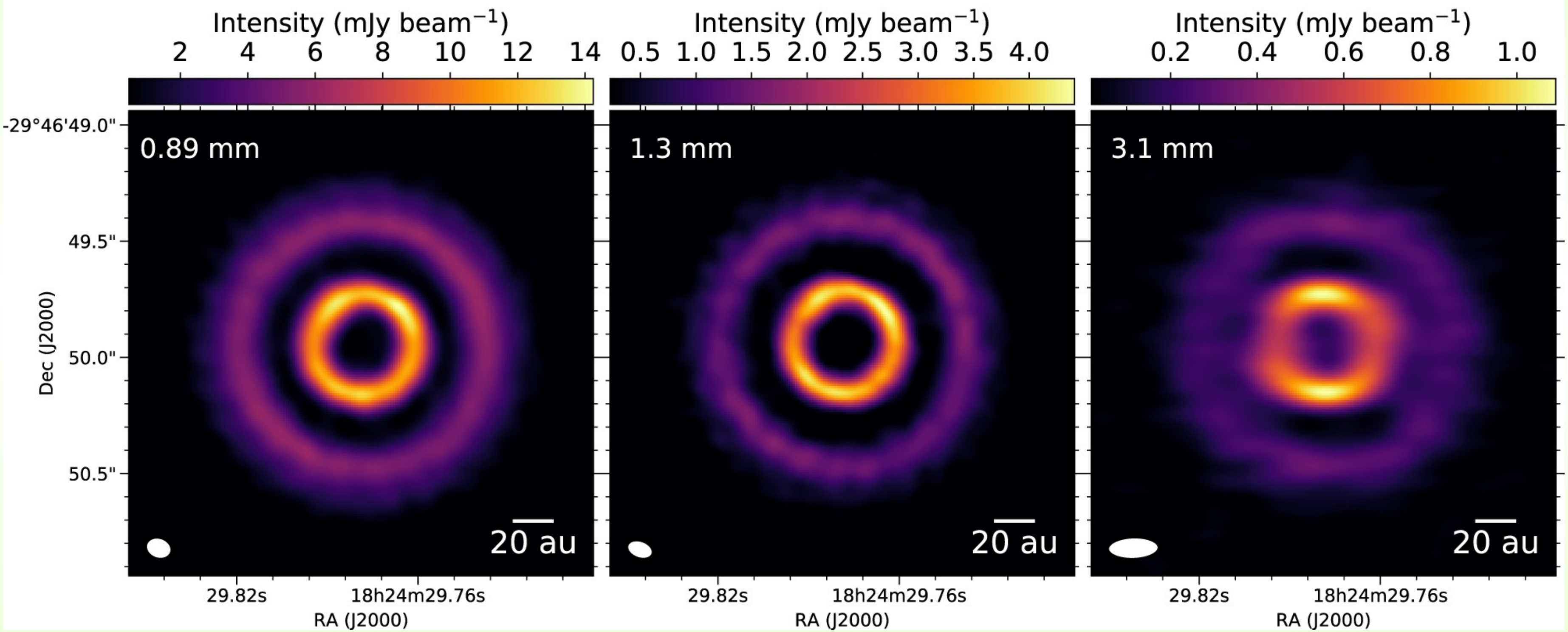
Planet Formation: Accretion Simulations





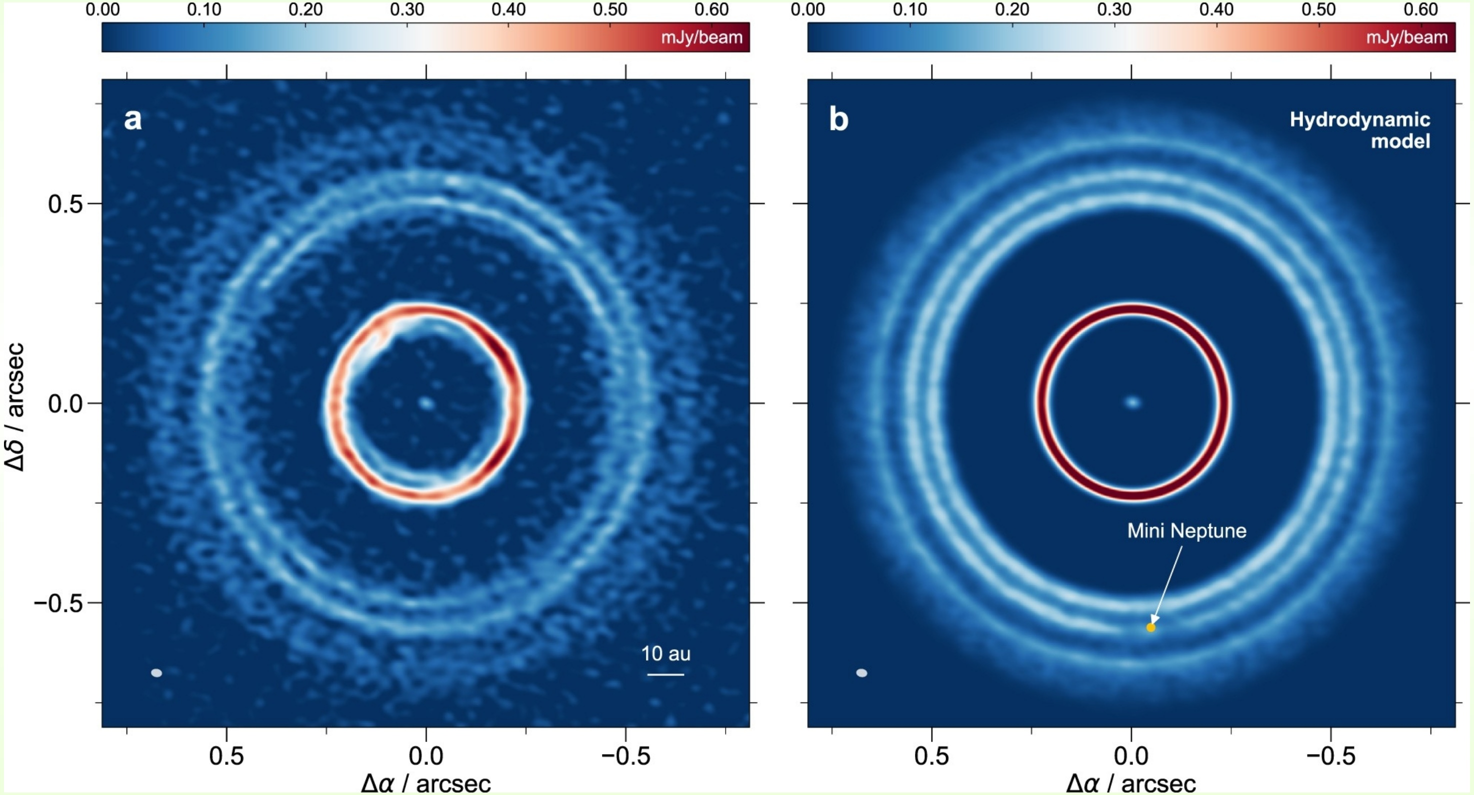
Source: “Mass Flow and Accretion through Gaps in Accretion Discs”, W. Kley, Uni Tübingen (1999)

Newer Surveys: Continuum emission of the multi-ring disk of HD 169142



Source: DOI:10.3847/1538-4357/ab31a2

Newer Surveys: ALMA observation of HD169142



Comparison between observation (l.) and simulated model (r.)

Source: Sebastián Pérez et al 2019 AJ 158 15

Scale Height H

$$dP = -\rho g\, dz = -\left(\frac{\mu m_H P}{kT}\right) g dz \qquad PV = NkT = \frac{M}{\mu m_H} kT$$

$$\int_{P_0}^{P} \frac{dP}{P} = \int_0^z -\left(\frac{\mu m_H g}{kT}\right) dz \qquad P = \frac{\rho}{\mu m_H} kT$$

$$\ln P \Big|_{P_0}^{P} = -\frac{\mu m_H g}{kT} z \Big|_0^z$$

$$\ln P - \ln P_0 = -\frac{\mu m_H g}{kT} z$$

$$\ln \frac{P}{P_0} = -\frac{\mu m_H g}{kT} z$$

$$P = P_0 e^{-\frac{\mu m_H g}{kT} z} = P_0 e^{-\frac{z}{H}}$$

Elevation	Density
0	ρ_0
H	$(1/e)\rho_0 = 0.368\rho_0$
2H	$(1/e2)\rho_0 = 0.135\rho_0$
3H	$(1/e3)\rho_0 = 0.050\rho_0$
4H	$(1/e4)\rho_0 = 0.018\rho_0$

Source: UNL Astronomy

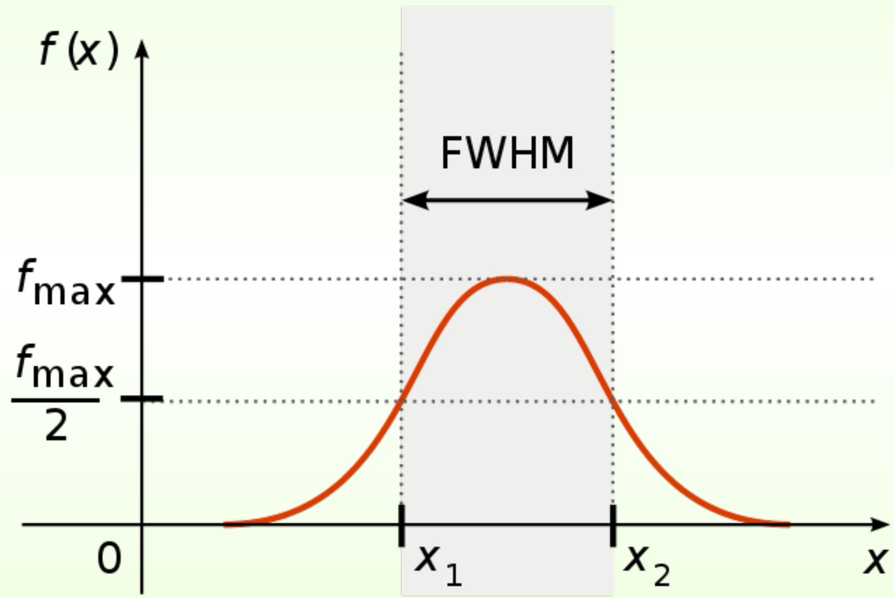
Full width at half maximum (FWHM)

Normal distribution

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(x-x_0)^2}{2\sigma^2}\right]$$

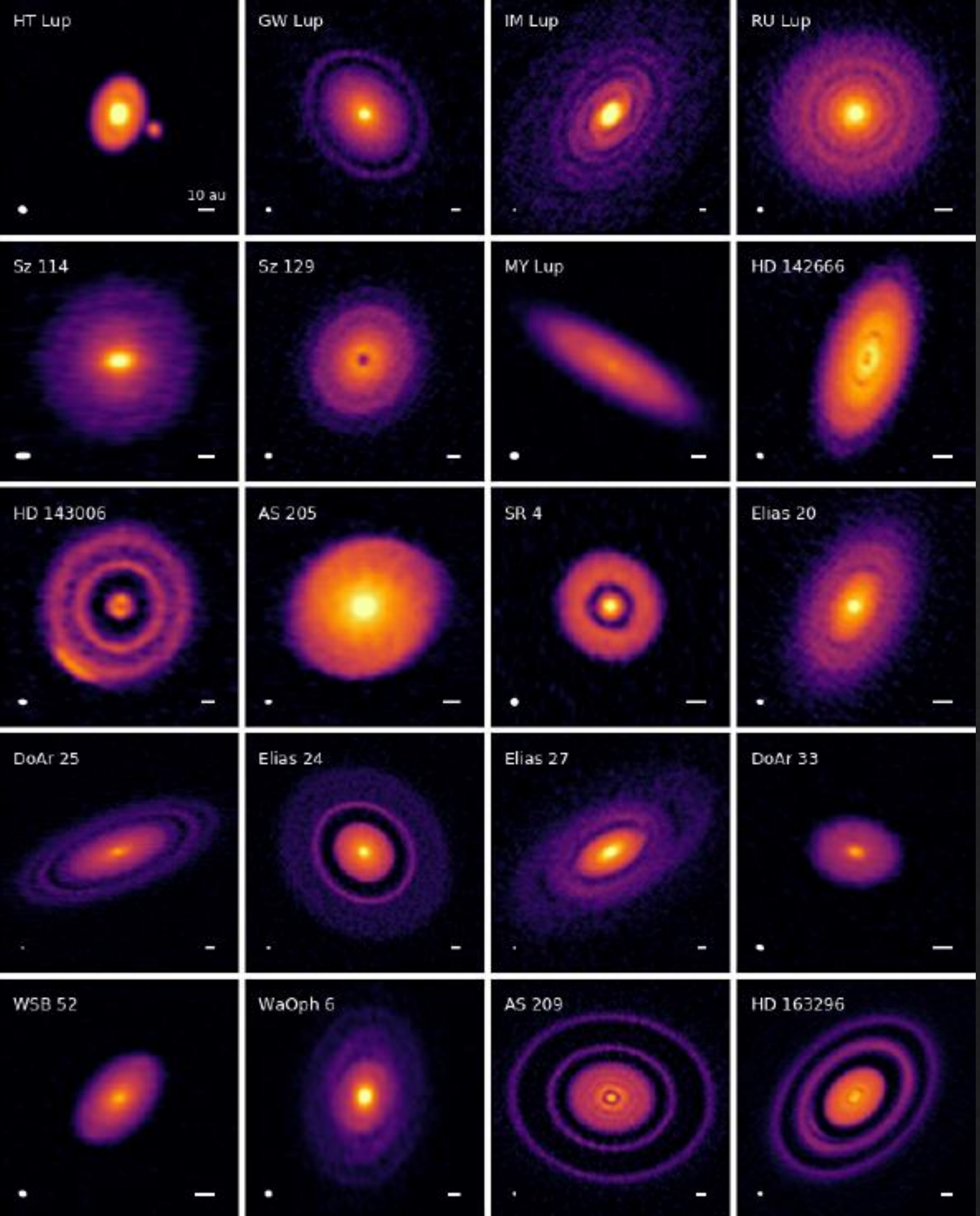
σ standard deviation
x_0 expected value

$$\mathrm{FWHM} = 2\sqrt{2\ln 2}\,\sigma \approx 2.355\,\sigma.$$



Source: Wikimedia Commons

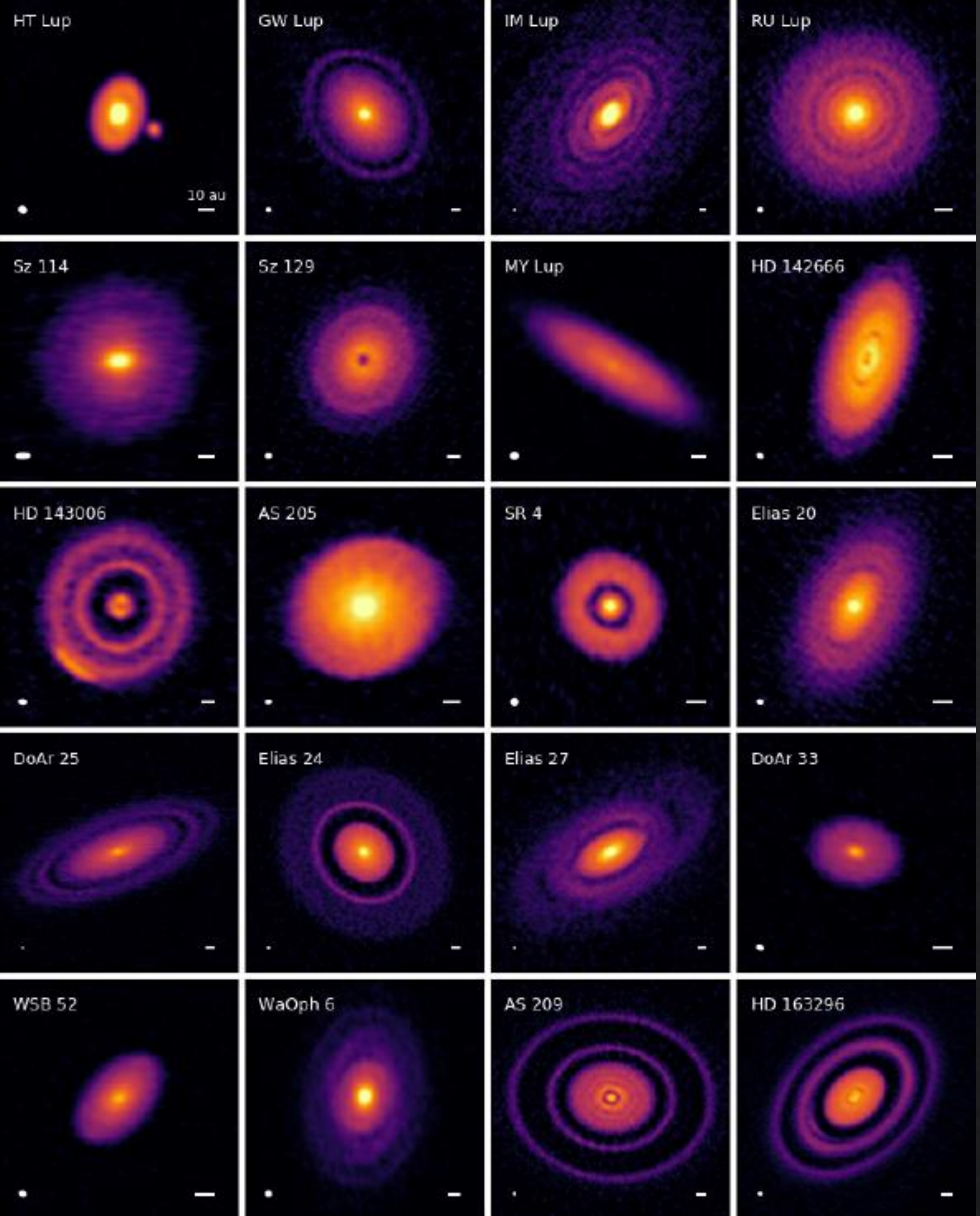

DSHARP: Disk Substructures at
High Angular Resolution Project
Part Two



The Resulting Observations

- Unprecedented resolution to probe regions closer to host star than ever before
- Principal DSHARP conclusions:
  - Most common substructure are concentric bright rings and dark gaps
  - Spiral morphologies found in sub-set of disks
  - Azimuthal asymmetries are rare in this sample

Image from Andrews et al. (2018)



The Resulting Observations

- Unprecedented resolution to probe regions closer to host star than ever before
- Principal DSHARP conclusions:
  - **Most common substructure are concentric bright rings and dark gaps**
  - Spiral morphologies found in sub-set of disks
  - Azimuthal asymmetries are rare in this sample

Image from Andrews et al. (2018)

Causes of Ring Substructures

- Numerous simulations to replicate disk structures
- **<u>Case Study:</u> AS 209**
- Unusual features:
  - Number of rings
  - Narrowness of rings
  - Wide gaps in outer disk
- Possible processes to form rings:
  - Snowline-induced gaps
  - Pressure variations due to magnetohydrodynamical (MHD) turbulent disks
  - Planet-disk interaction

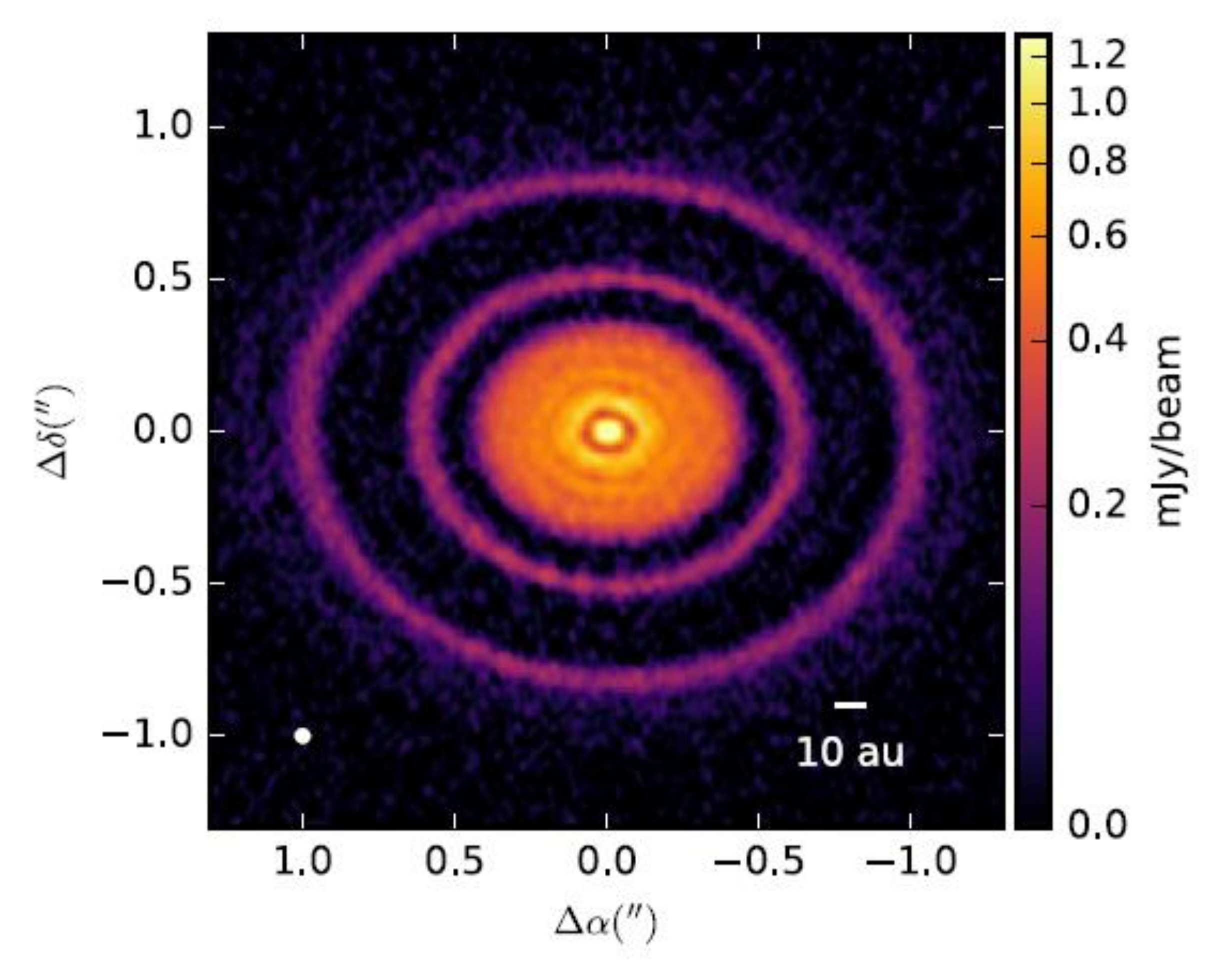


Image from Guzmàn et al. (2018)

Causes of Ring Substructures

- Numerous simulations to replicate disk structures
- **<u>Case Study:</u> AS 209**
- Unusual features:
  - Number of rings
  - Narrowness of rings
  - Wide gaps in outer disk
- Possible processes to form rings:
  - **Snowline-induced gaps**
  - Pressure variations due to magnetohydrodynamical (MHD) turbulent disks
  - Planet-disk interaction

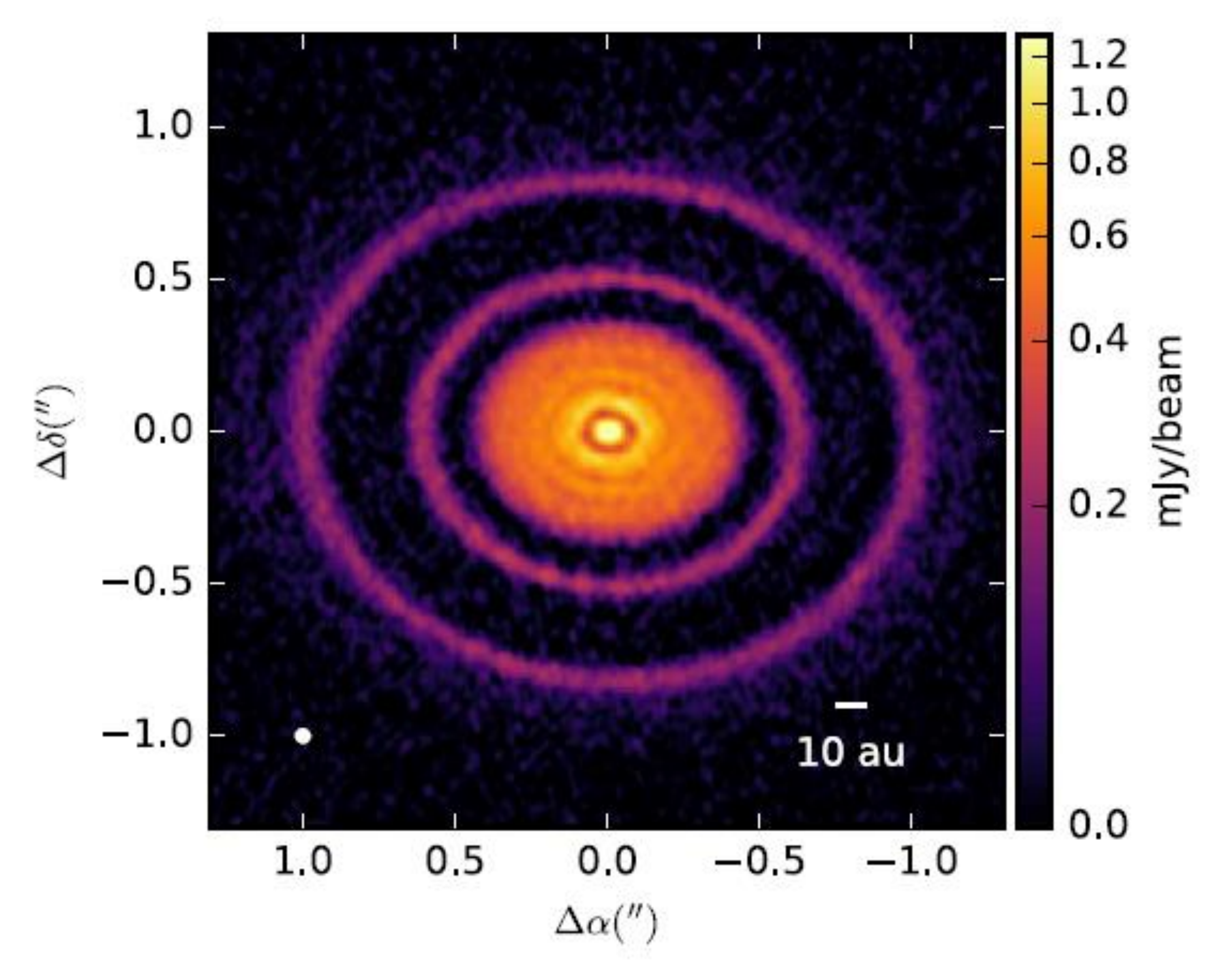


Image from Guzmàn et al. (2018)

Snowline Induced Gaps

- Rings due to changes in dust properties at location of snowlines for main ices:
  - H_2O, NH_3, CO and N_2
- Material is concentrated at condensation fronts
  - μm and mm size dust grains grow to cm size which are invisible at mm-wavelengths
- Support for this theory:
  - Two outer gaps in disk near 60 and 100 AU have temperatures of 20 and 15 K
    - Close to condensation temperatures of ^{12}CO and N_2
- Problems with this Theory:
  - Observed gaps are too wide to be due to snowlines alone
  - Only H_2O line is efficient enough to produce these features
    - Located at 2 AU → not resolved by DSHARP

Causes of Ring Substructures

- Numerous simulations to replicate disk structures
- **<u>Case Study:</u> AS 209**
- Unusual features:
  - Number of rings
  - Narrowness of rings
  - Wide gaps in outer disk
- Possible processes to form rings:
  - Snowline-induced gaps
  - **Pressure variations due to magnetohydrodynamical (MHD) turbulent disks**
  - Planet-disk interaction

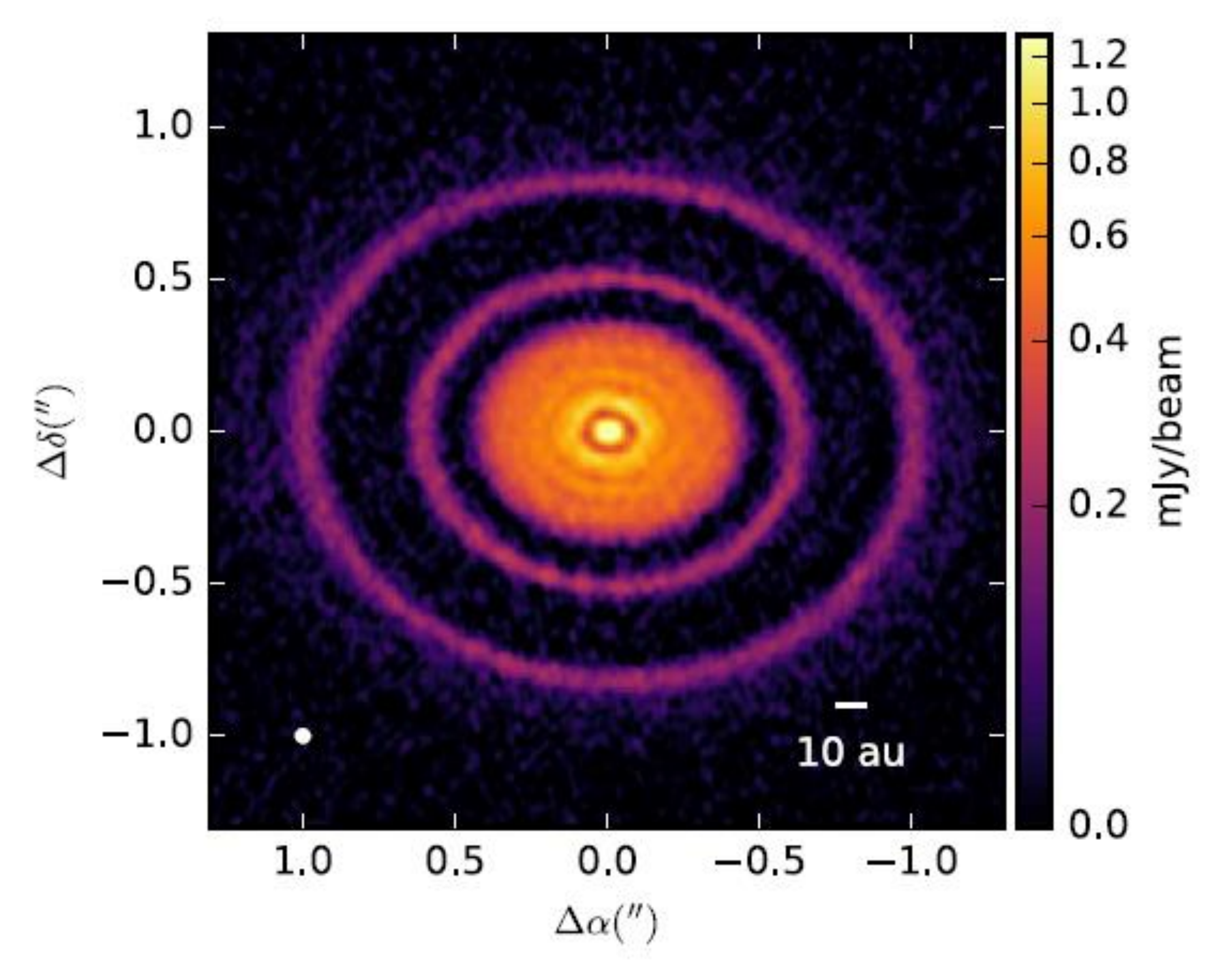
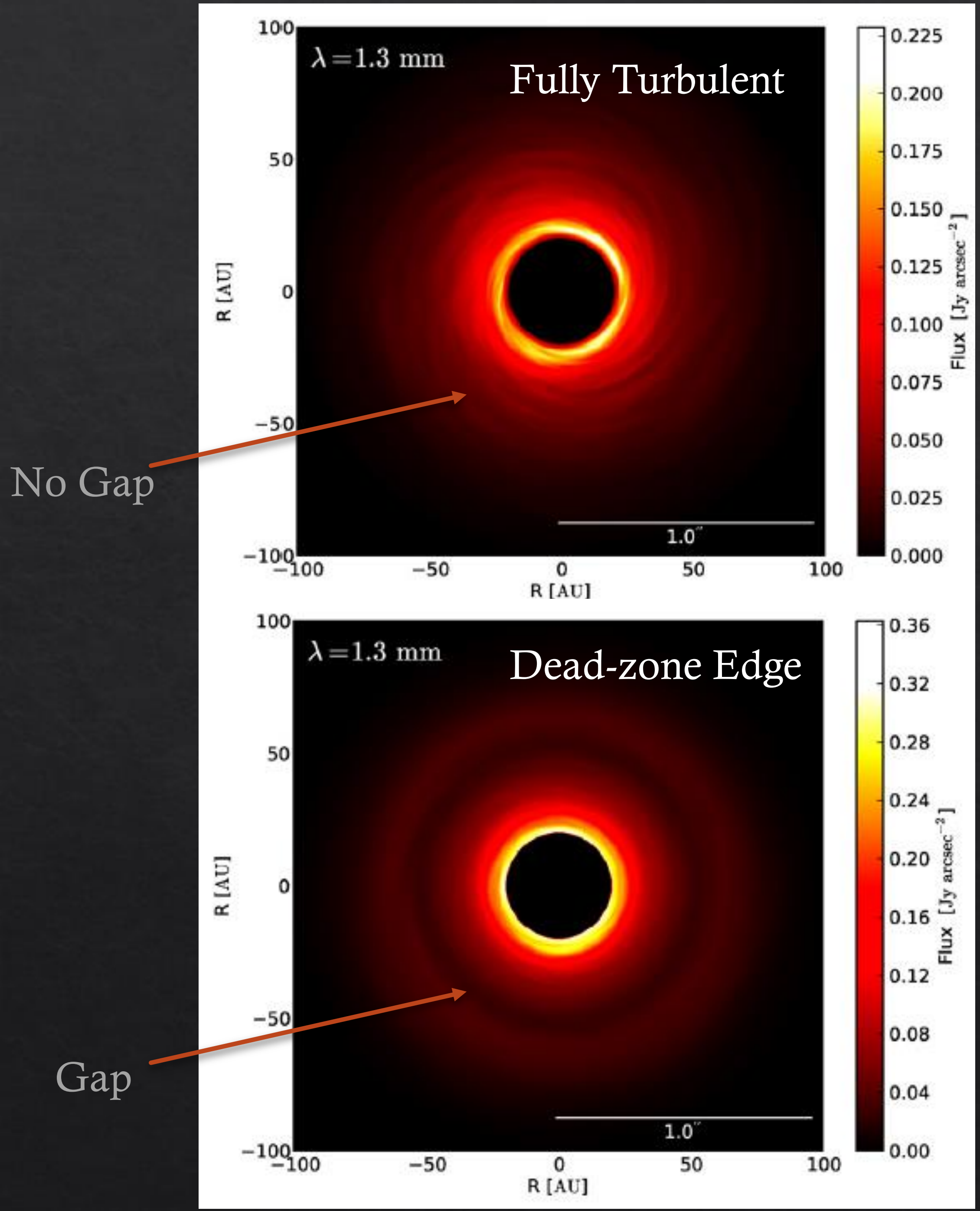


Image from Guzmàn et al. (2018)



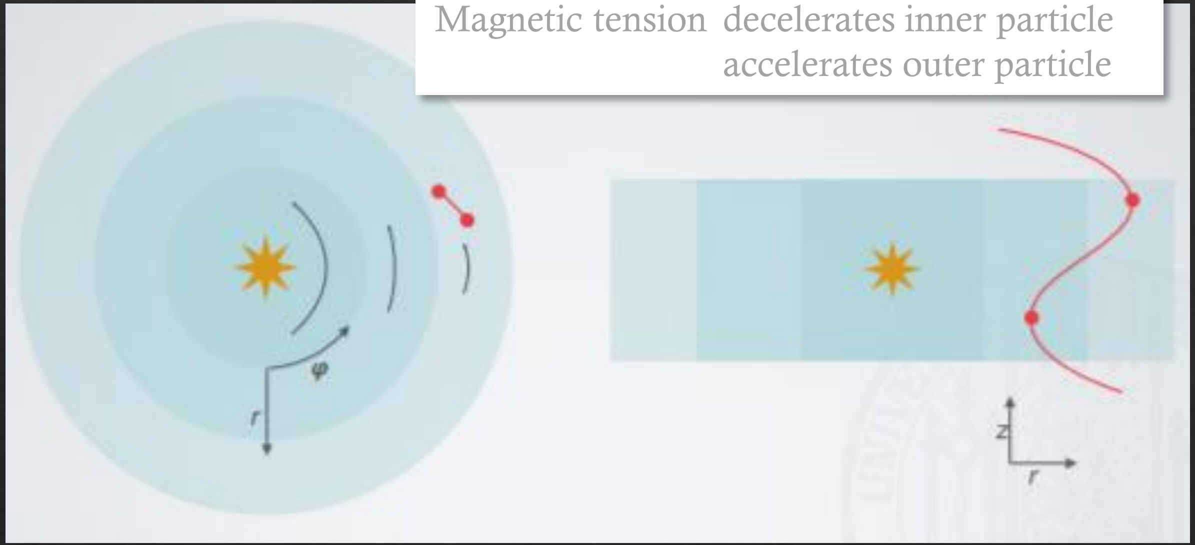
Rings due to MHD

- Possible processes:
  - Zonal flows due to magnetorotational instabilities
    - Usually only produce variations of a few tens of percent
  - Dead-zone boundaries in midplane of disk
    - Doesn't fit well with widely separated multi ring structure in outer disk
  - Spontaneous magnetic flux
    - Not understood well enough to test

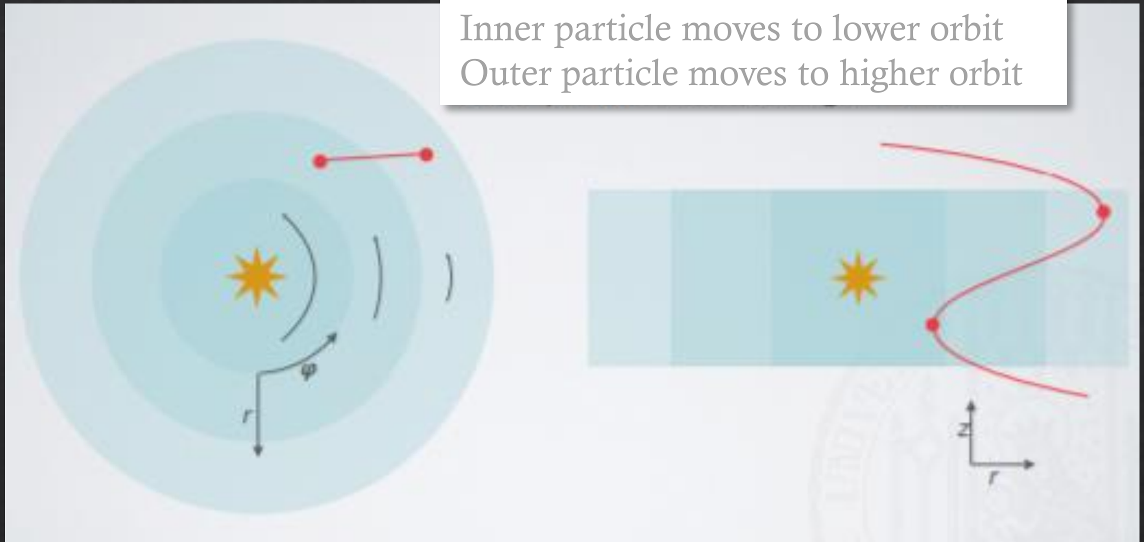
Image from Flock et al. (2015)

Magnetorotational instabilities (MRI)

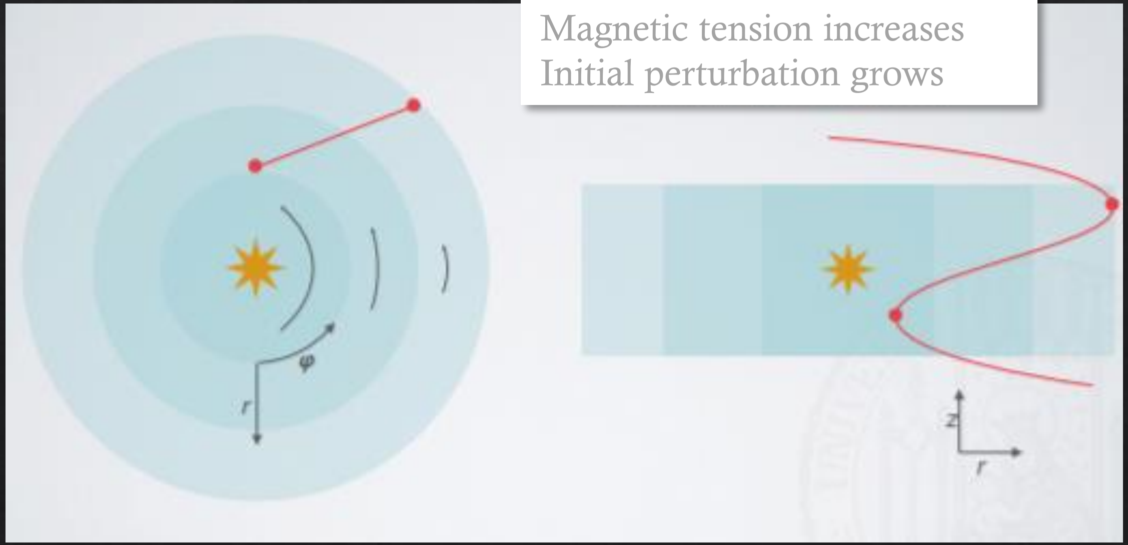
Magnetic tension decelerates inner particle
accelerates outer particle



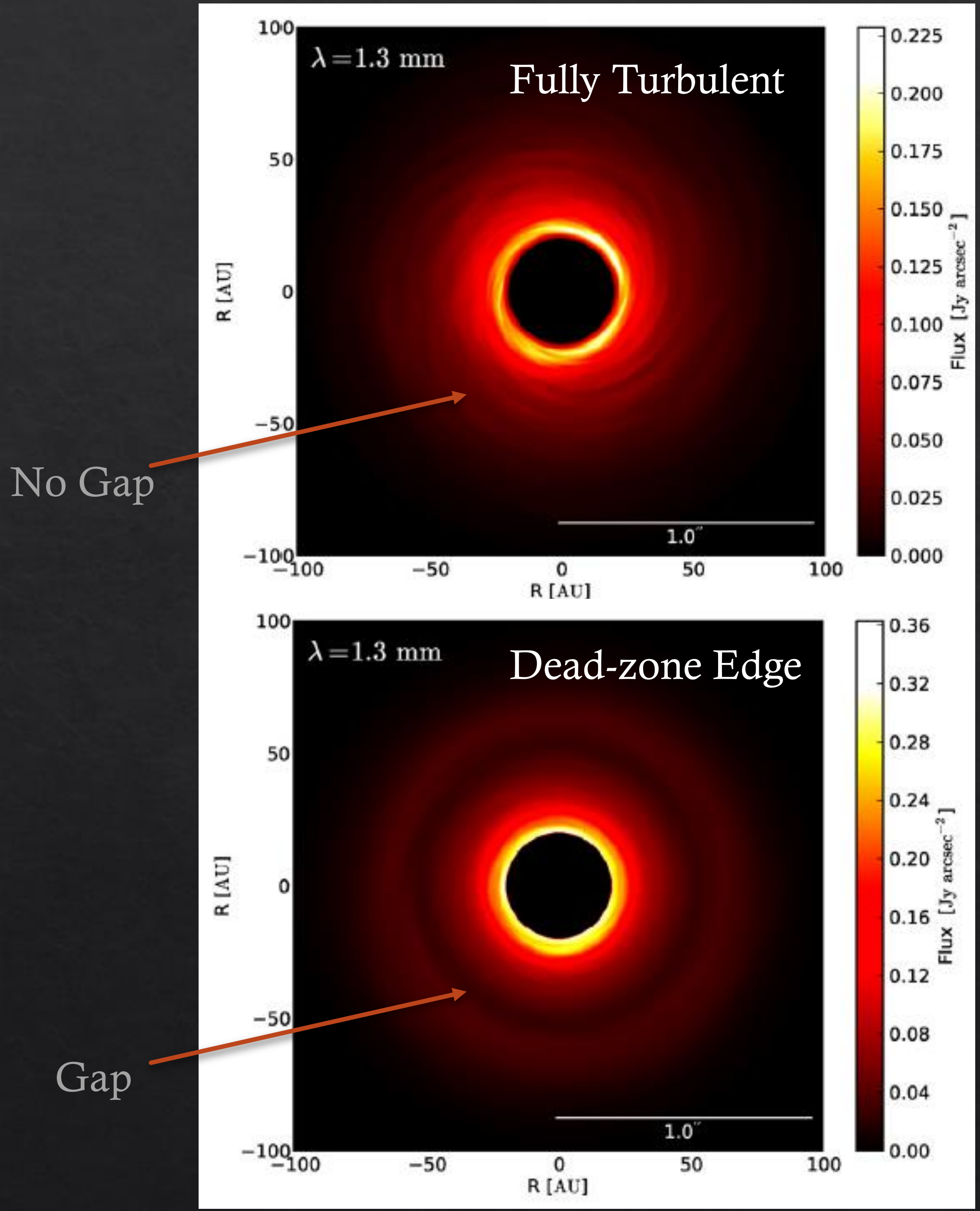
Inner particle moves to lower orbit
Outer particle moves to higher orbit



Magnetic tension increases
Initial perturbation grows



Images from Birnstiel (2019)



Rings due to MHD

- Possible processes:
  - Zonal flows due to magnetorotational instabilities
    - Usually only produce variations of a few tens of percent
  - Dead-zone boundaries in midplane of disk
    - Doesn't fit well with widely separated multi ring structure in outer disk
  - Spontaneous magnetic flux
    - Not understood well enough to test

Image from Flock et al. (2015)

Deadzones

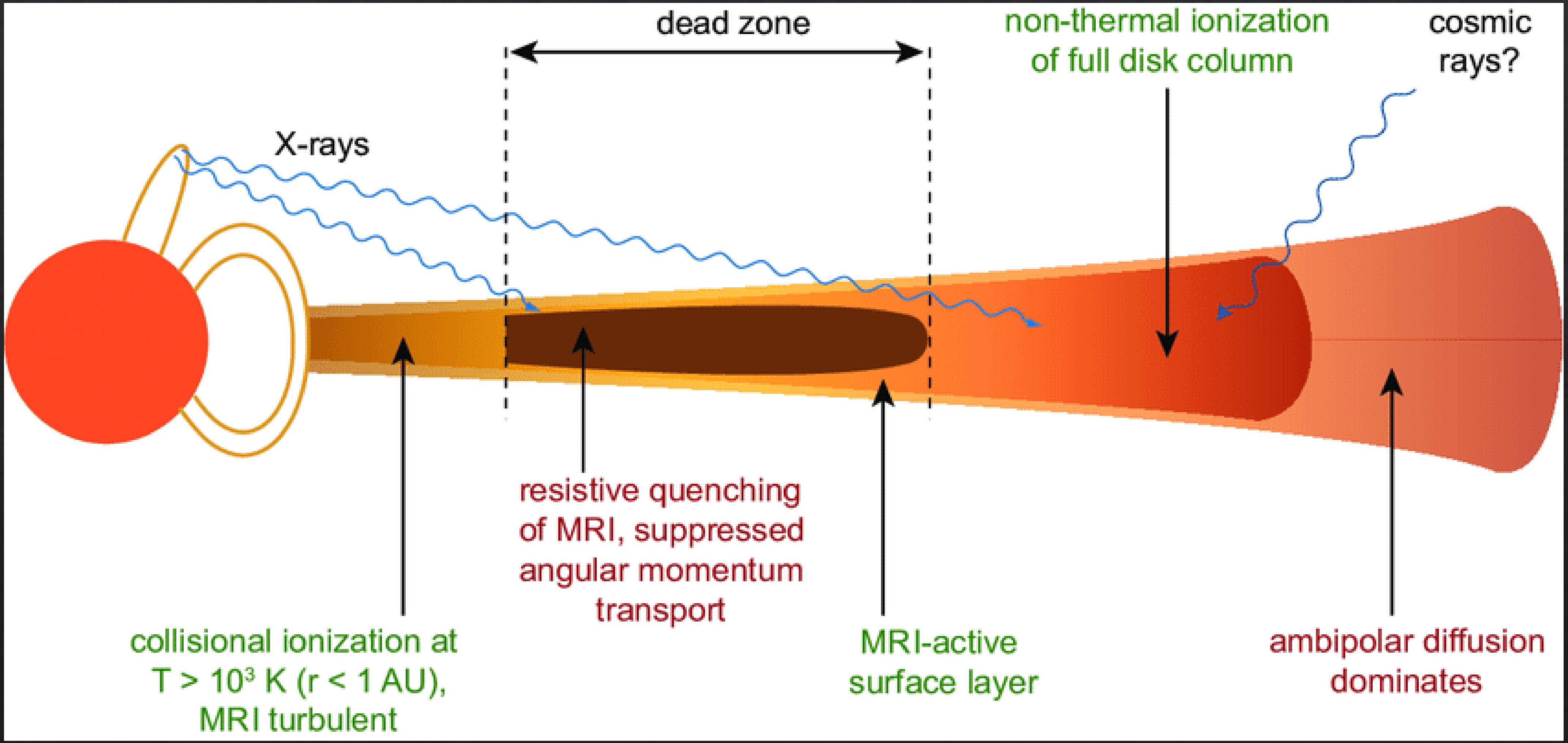
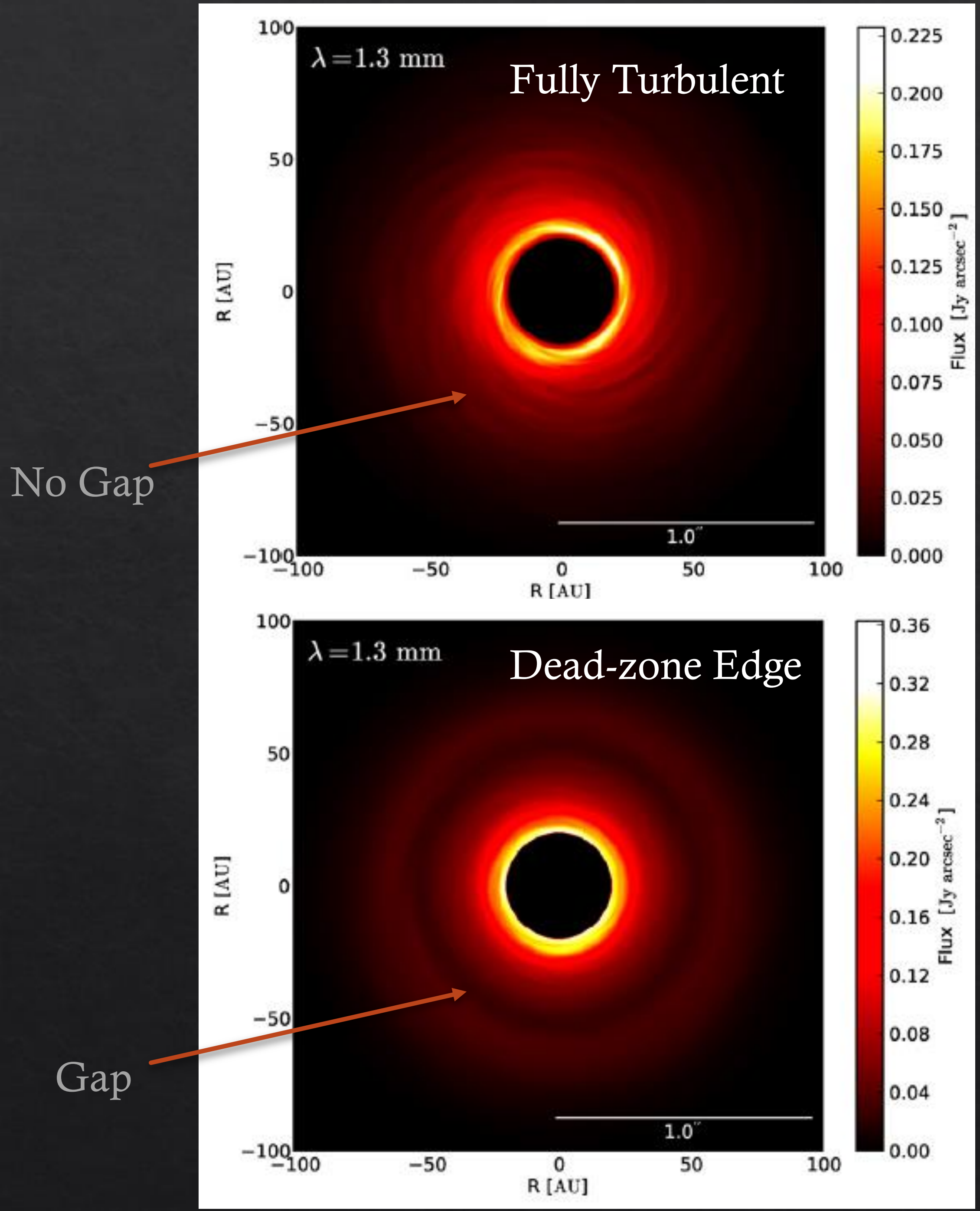


Image from Armitage (2011)

Rings due to MHD



- Possible processes:
  - Zonal flows due to magnetorotational instabilities
    - Usually only produce variations of a few tens of percent
  - Dead-zone boundaries in midplane of disk
    - Doesn't fit well with widely separated multi ring structure in outer disk
  - Spontaneous magnetic flux
    - Not understood well enough to test

Image from Flock et al. (2015)

Causes of Ring Substructures

- Numerous simulations to replicate disk structures
- **<u>Case Study:</u> AS 209**
- Unusual features:
  - Number of rings
  - Narrowness of rings
  - Wide gaps in outer disk
- Possible processes to form rings:
  - Snowline-induced gaps
  - Pressure variations due to magnetohydrodynamical (MHD) turbulent disks
  - **Planet-disk interaction**

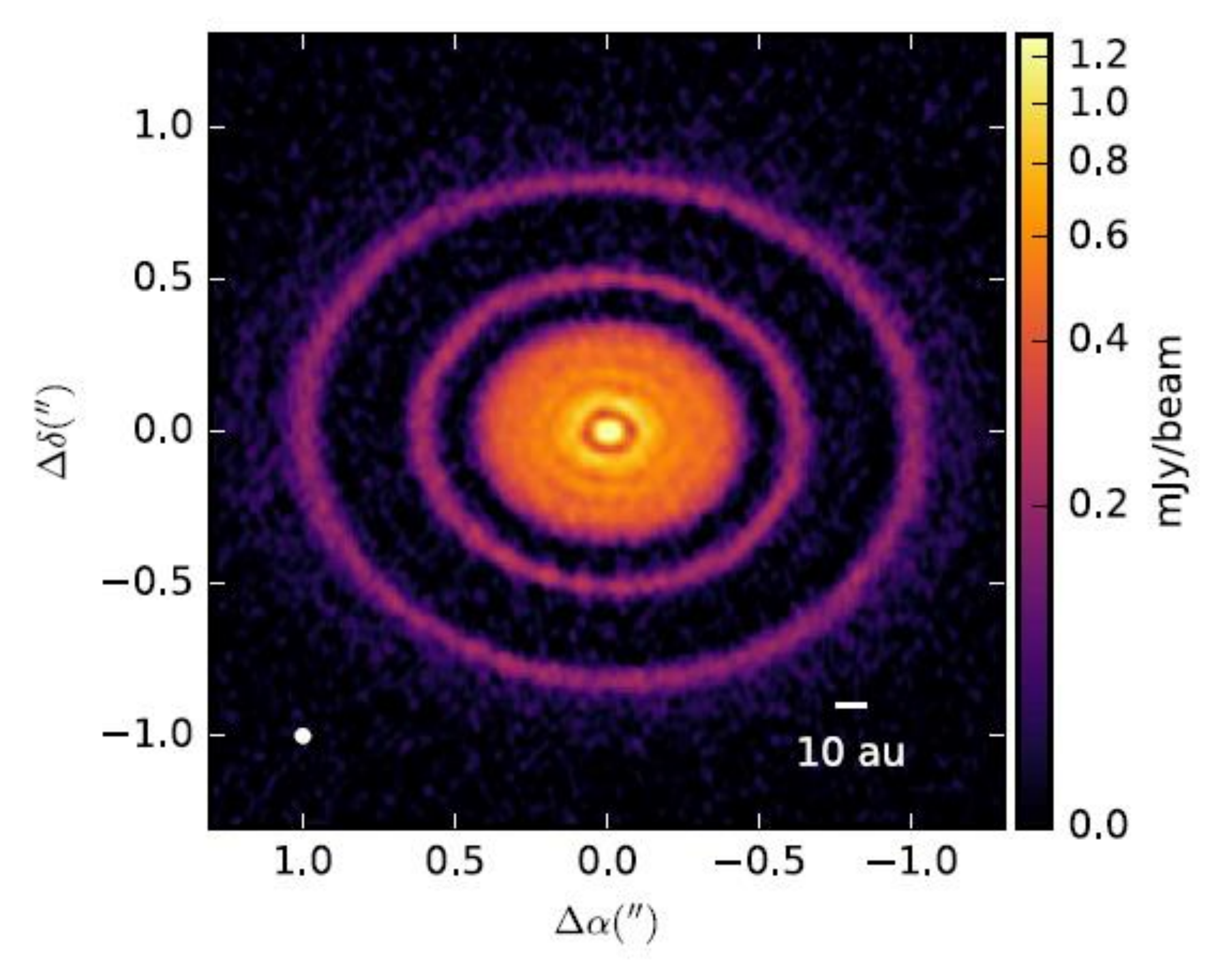
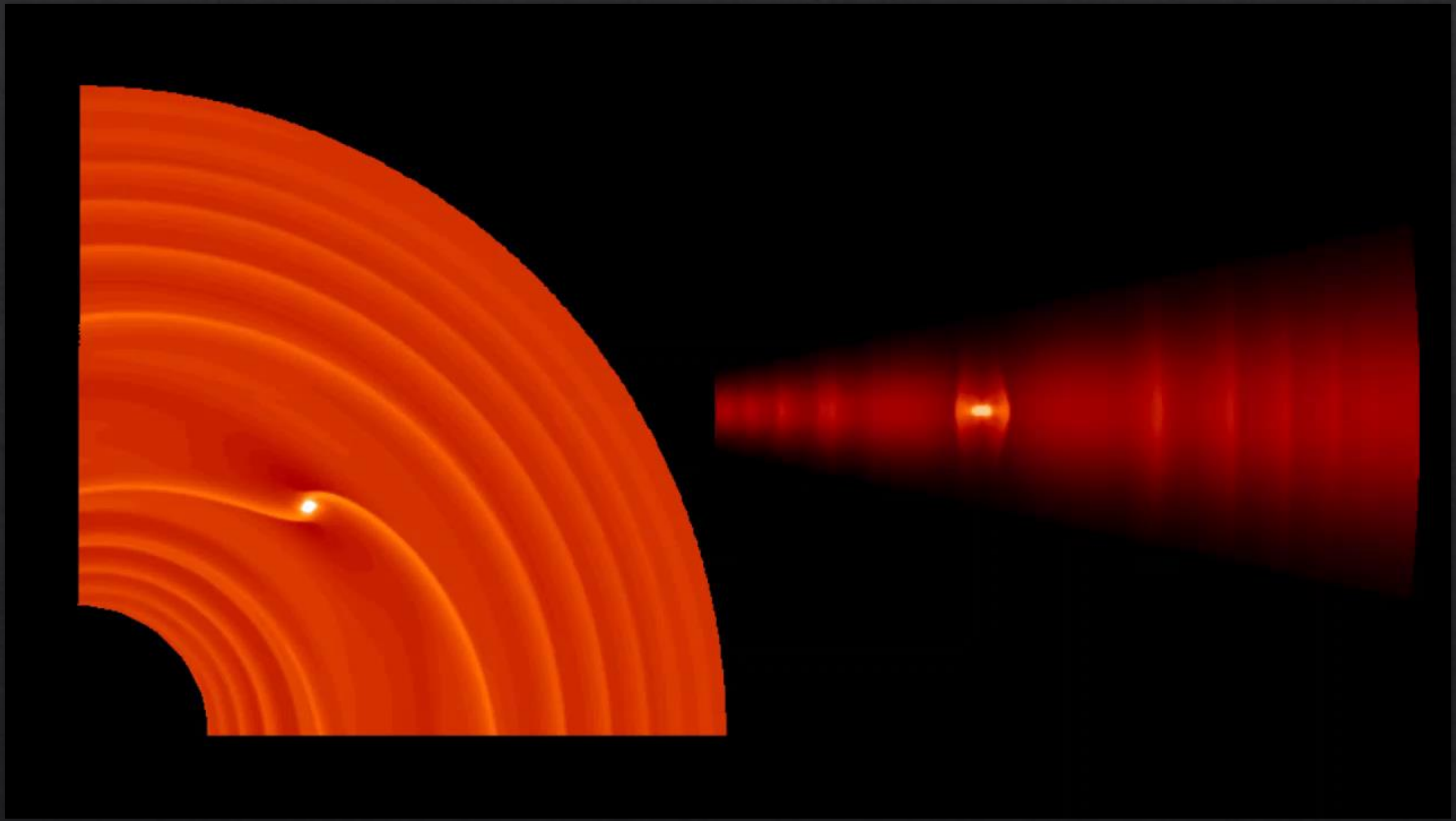


Image from Guzmàn et al. (2018)

Rings due to Planet Interaction

- Depth of gap depends on several factors; mass of planet, time the planet has had to carve gap, disk aspect ratio (h/r), disk viscosity
- Planets create gaps in process called “gap opening”
- Many different configurations could produce AS 209 features
  - **Fedele et al. (2018):** 0.2 M_{Jup} planet at 95 AU creates gap at 100 AU
    - Also predicts feature within the gap
  - **Dong et al. (2018):** ~0.1 M_{Jup} planet at 80 AU creates gaps at 40, 60 and 100 AU
  - **Zhang et al. (2018):** 0.087 M_{Jup} planet at 99 AU creates various rings in inner 60 AU and outer disk

Gap Opening

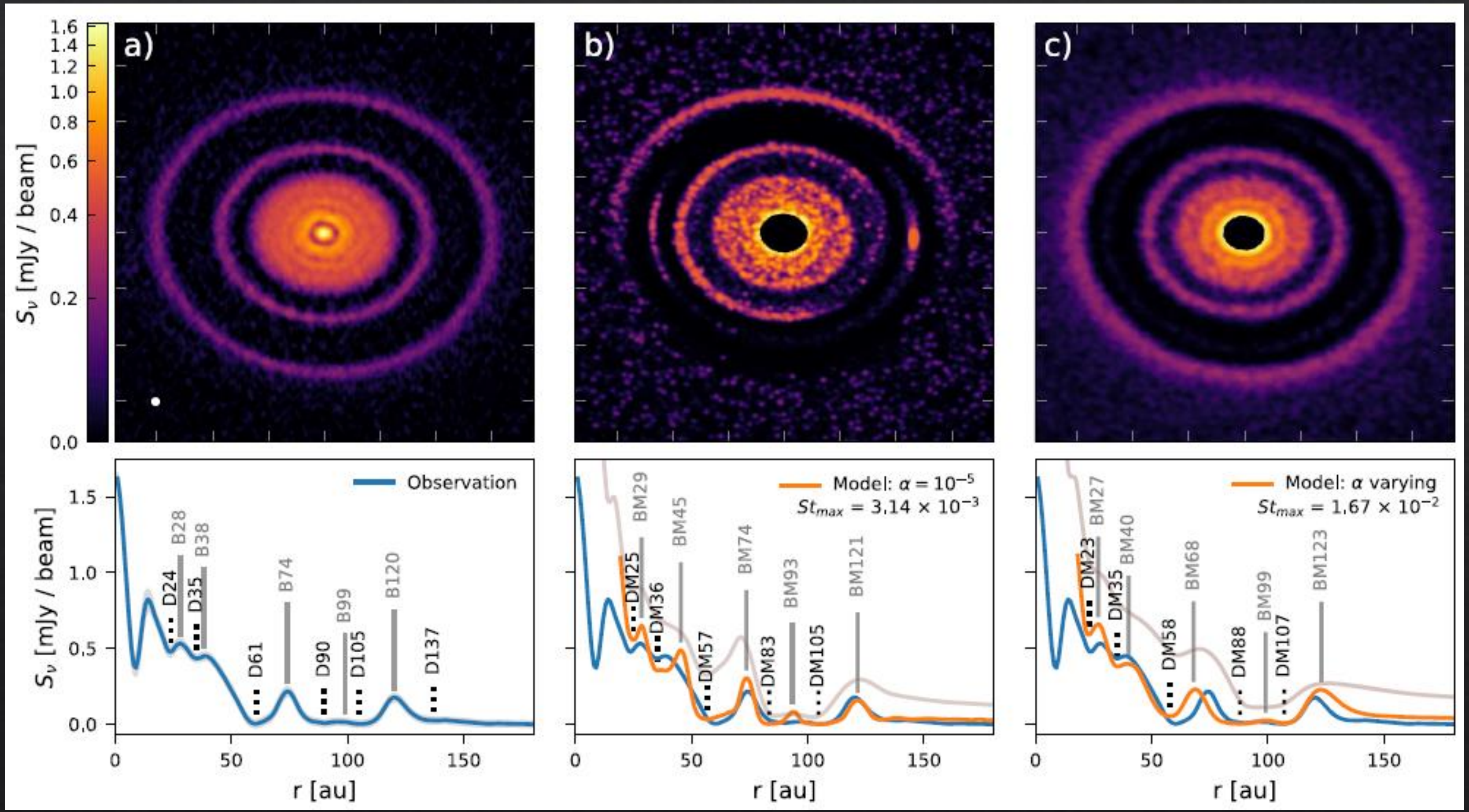


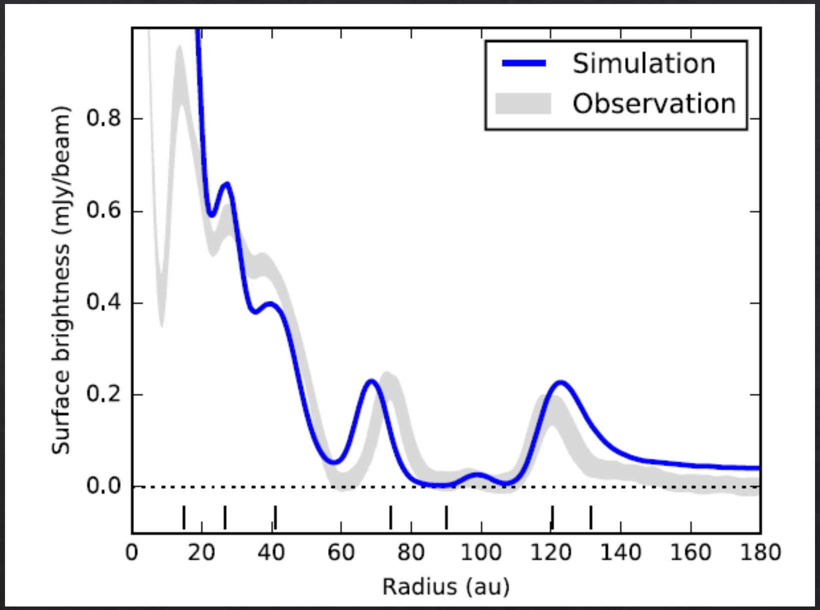
Video from Kley et al. (2012)

Rings due to Planet Interaction

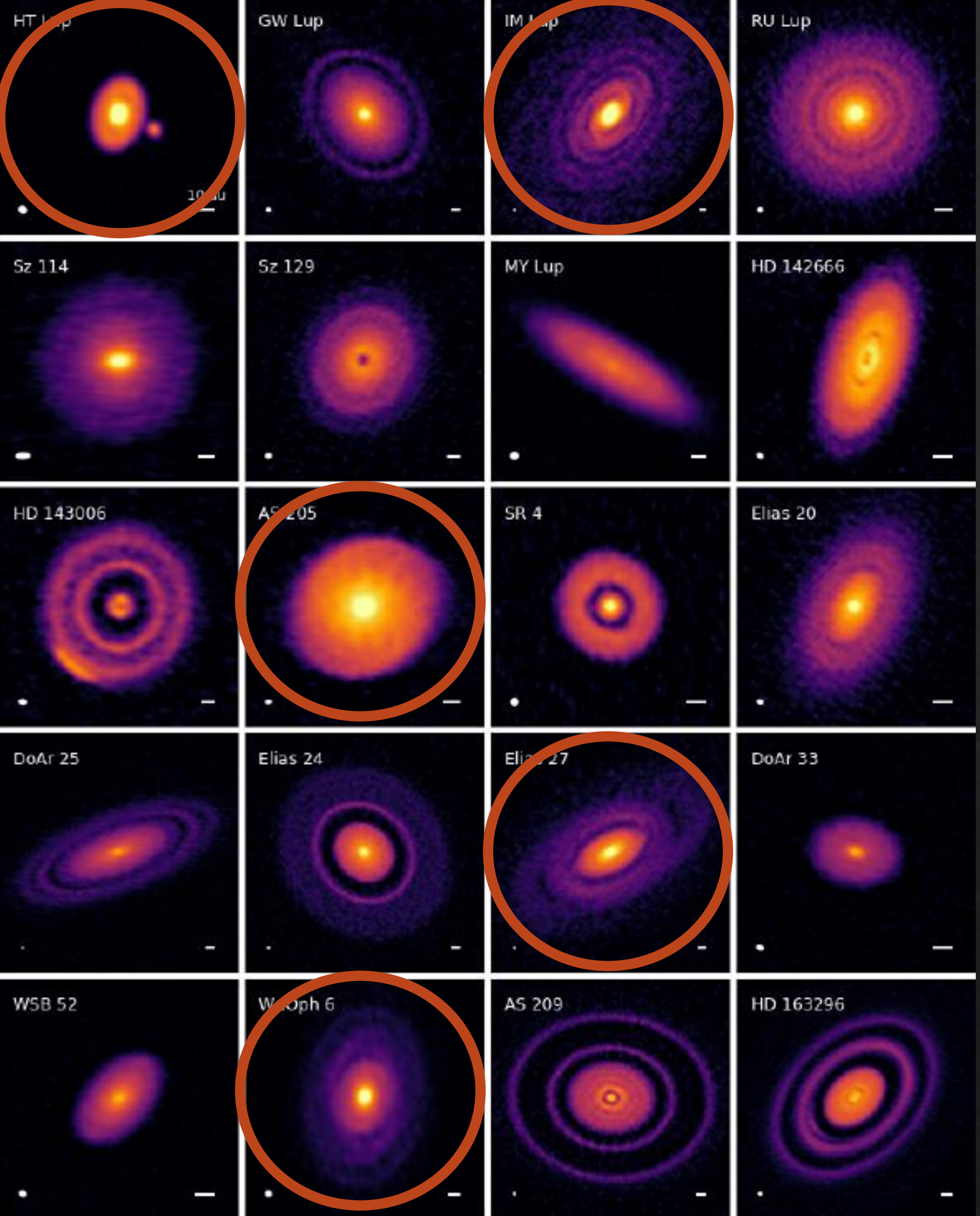
- Depth of gap depends on several factors; mass of planet, time the planet has had to carve gap, disk aspect ratio (h/r), disk viscosity
- Planets create rings in process called “gap opening”
- Many different configurations could produce AS 209 features
  - **Fedele et al. (2018):** 0.2 M_{Jup} planet at 95 AU creates gap at 100 AU
    - Also predicts feature within the gap
  - **Dong et al. (2018):** ~0.1 M_{Jup} planet at 80 AU creates gaps at 40, 60 and 100 AU
  - **Zhang et al. (2018):** 0.087 M_{Jup} planet at 99 AU creates various rings in inner 60 AU and outer disk

Zhang et al. (2018) Simulation





Images from Guzmàn et al. (2018) *(above)* and Zhang et al. (2018) *(left)*



The Resulting Observations

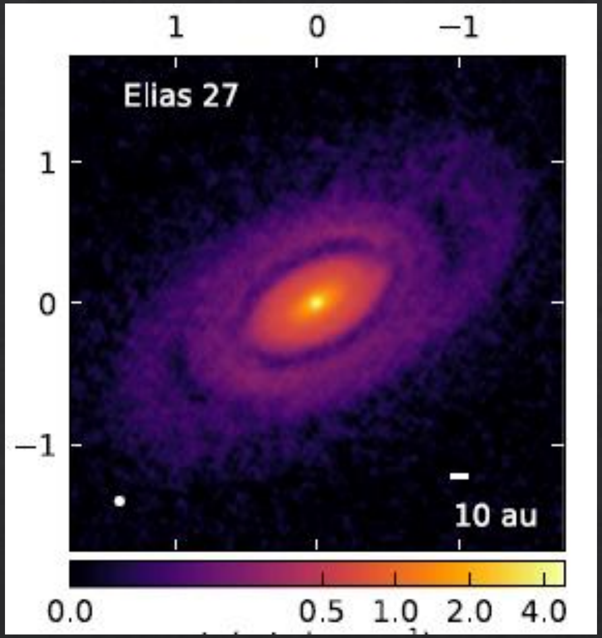
- Unprecedented resolution to probe regions closer to host star than ever before
- Principal DSHARP conclusions:
  - Most common substructure are concentric bright rings and dark gaps
  - **Spiral morphologies found in sub-set of disks**
  - Azimuthal asymmetries are rare in this sample

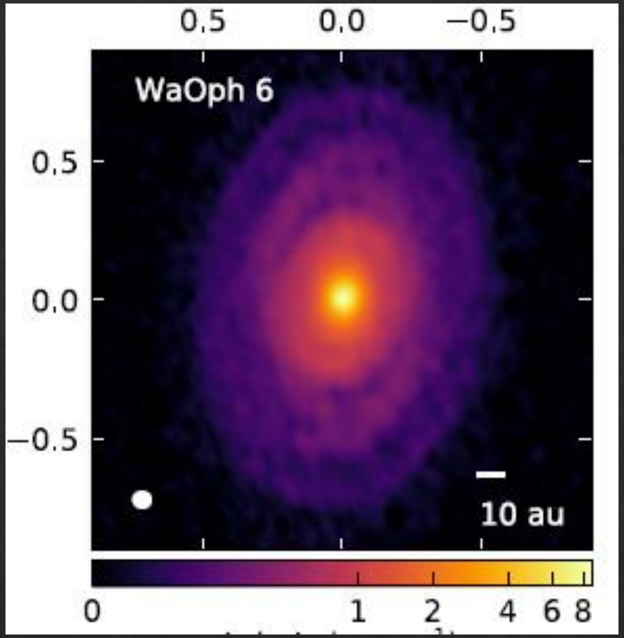
Image from Andrews et al. (2018)

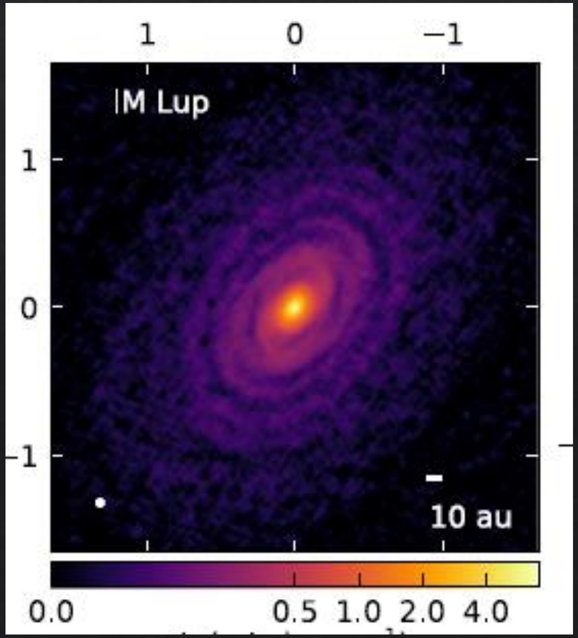
Spiral Morphologies

- Observed spirals in five disks:
  - Elias 27
  - IM Lup
  - WaOph 6
  - HT Lup A
  - AS 205 N

  } Due to multi-disk systems (HT Lup A, AS 205 N)
- Three disks studied have two-fold rotational symmetry
- Possible origins for spiral structure:
  - Planetary companions → trigger spiral density waves
  - Gravitational instability → more likely in younger sources
  - Shadowing from misaligned disk
  - Stellar encounters







Images from Huang et al. (2018)

Conclusion

- ALMA and the DSHARP survey offered astronomers a chance to see protoplanetary disks with unprecedented resolution
- Observations of protoplanetary disks are important tests for formation and evolution theory
  - Used to test simulations
  - Impose "time limits" for simulations (especially for planet formation)
- Increasing resolution in the future will help probe inner AU of protoplanetary disks
- Many steps in disk evolution are still unclear (ie. role of magnetic fields, dust growing processes, timescales for planet formation)

Bibliography

- Andrews, Sean M., et al. "The Disk Substructures at High Angular Resolution Project (DSHARP). I. Motivation, Sample, Calibration, and Overview." *The Astrophysical Journal*, vol. 869, no. 2, 26 Dec. 2018, doi:10.3847/2041-8213/aaf741.
- Armitage, Philip J. "Dynamics of Protoplanetary Disks." *Annual Review of Astronomy and Astrophysics*, vol. 49, no. 1, 22 Sept. 2011, pp. 195–236., doi:10.1146/annurev-astro-081710-102521.
- Birnstiel, Til. "Magnetorotational Instability." Formation and Evolution of Protoplanetary Disks. USM Masters Lecture Series, 2019, Munich, USM.
- Flock, M., et al. "Gaps, Rings, and Non-Axisymmetric Structures in Protoplanetary Disks." *Astronomy & Astrophysics*, vol. 574, 28 July 2015, doi:10.1051/0004-6361/201424693.
- Guzmán, Viviana V., et al. "The Disk Substructures at High Angular Resolution Program (DSHARP). VIII. The Rich Ringed Substructures in the AS 209 Disk." *The Astrophysical Journal*, vol. 869, no. 2, 20 Dec. 2018, doi:10.3847/2041-8213/aaedae.
- Huang, Jane, et al. "The Disk Substructures at High Angular Resolution Project (DSHARP). III. Spiral Structures in the Millimeter Continuum of the Elias 27, IM Lup, and WaOph 6 Disks." *The Astrophysical Journal*, vol. 869, no. 2, 20 Dec. 2018, doi:10.3847/2041-8213/aaf7a0.
- Kley, W., and R.p. Nelson. "Planet-Disk Interaction and Orbital Evolution." *Annual Review of Astronomy and Astrophysics*, vol. 50, no. 1, 22 Sept. 2012, pp. 211–249., doi:10.1146/annurev-astro-081811-125523.
- Zhang, Ke, et al. "Evidence Of Fast Pebble Growth Near Condensation Fronts In The Hl Tau Protoplanetary Disk." *The Astrophysical Journal*, vol. 806, no. 1, 10 June 2015, doi:10.1088/2041-8205/806/1/l7.
- Zhang, Shangjia, et al. "The Disk Substructures at High Angular Resolution Project (DSHARP). VII. The Planet–Disk Interactions Interpretation." *The Astrophysical Journal*, vol. 869, no. 2, 20 Dec. 2018, doi:10.3847/2041-8213/aaf744.