Techniques, Observations, and Diagnostics of Protoplanetary Disks: Outer Disk

Laura M. Pérez
Departamento de Astronomía, Universidad de Chile

2021 Sagan Exoplanet Summer Virtual Workshop
Circumstellar Disks and Young Planets

Universidad de Chile

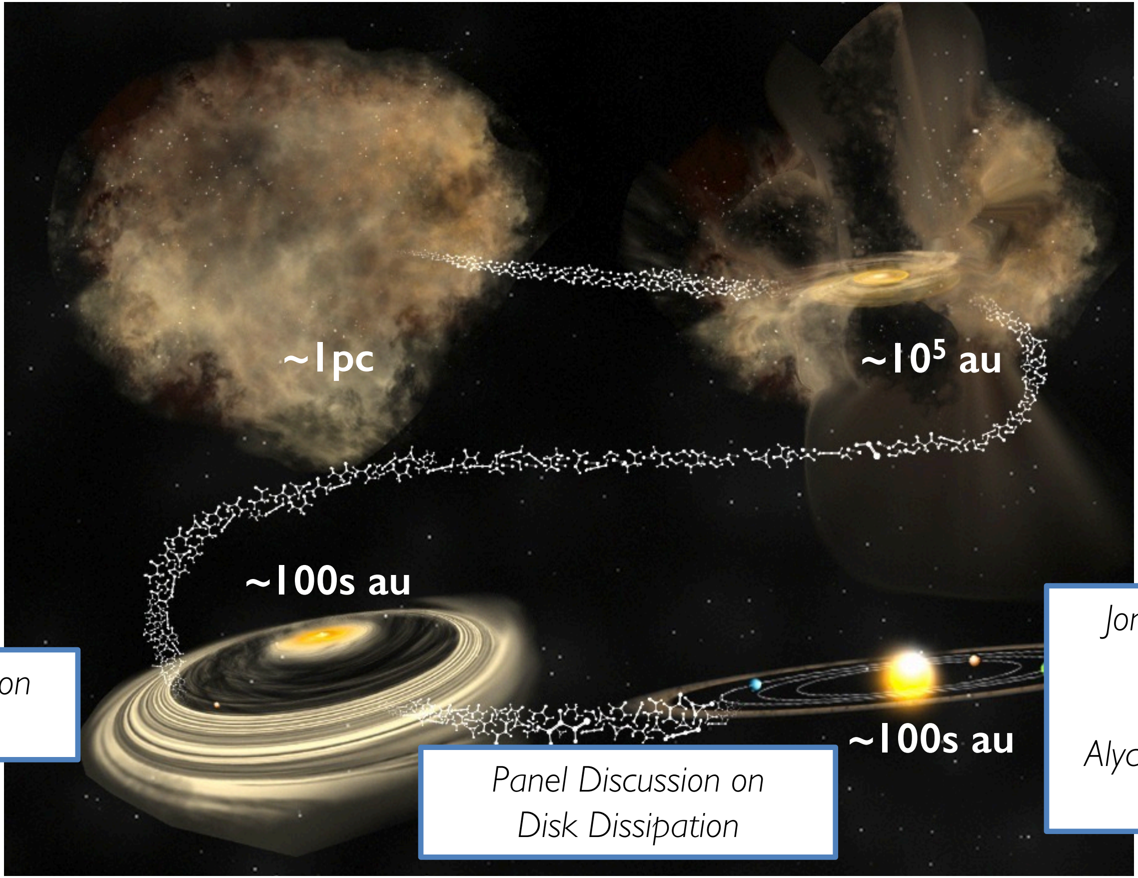
Centro de Astrofísica y Tecnologías Afines

Our current view of when are where planets form

*for low-mass stars, like our Sun

Pre-stellar Core

Class 0/I Phase



Protoplanetary Disk Phase

Tom Megeath's talk on "The First 3 Myr"

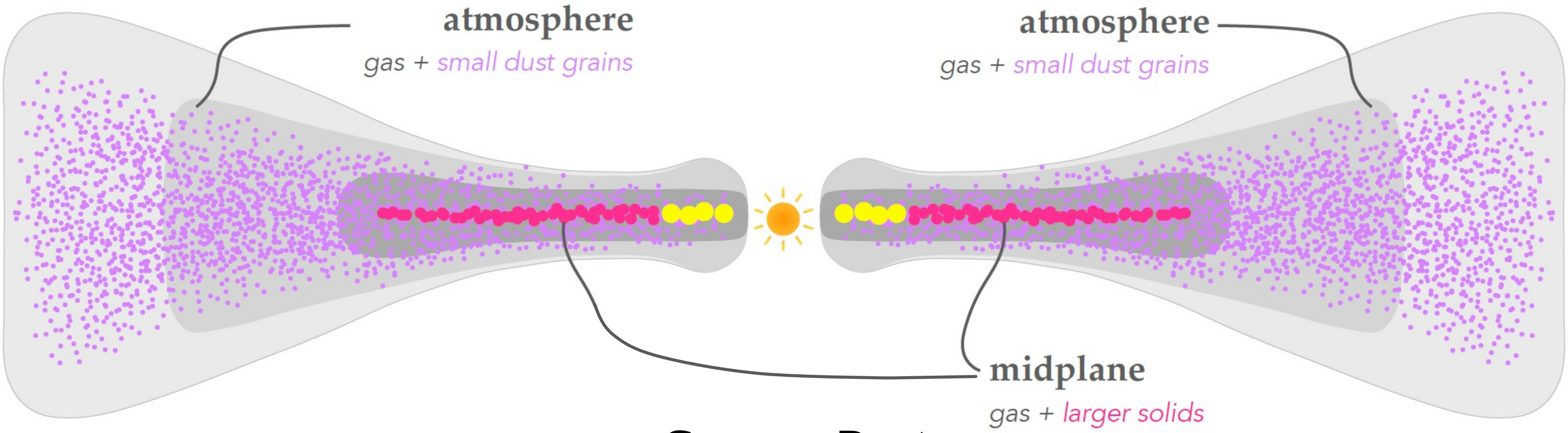
Panel Discussion on Disk Dissipation

Debris Disk Phase

Jonathan Gagné's talk on "The Next 100 Myr"
Mark Wyatt and Alycia Weinberger's talks on Debris Disks

A schematic view of a protoplanetary disk

A flared gaseous disk + a midplane with solids + components not co-located

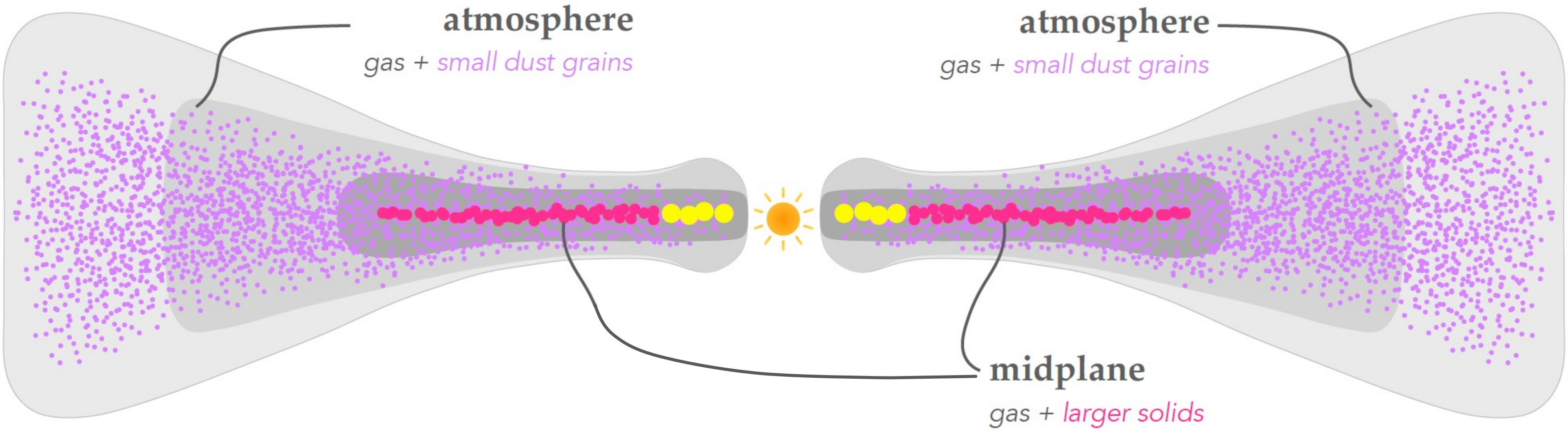


Gas	**Dust**
Dominates the total disk mass	Dominates the total disk opacity
Bulk of the material is H_2 with traces of other constituents	Solids range from sub-μm sized particles to large planetesimals
Radial/Vertical distribution is extended	Radial/Vertical distribution is compact

Figure adapted from Andrews 2020, ARAA

A schematic view of a protoplanetary disk

A flared gaseous disk + a midplane with solids + components not co-located



Disk diameter ~ 100 au
Distance to nearby star-forming regions ~150 pc
Typical angular size of a disk < 1"

Angular resolution

$$\theta \approx 1.22\,\frac{\lambda}{D} \approx 32\,mas\left(\frac{\lambda}{1\,\mu m}\right)\left(\frac{D}{8\,m}\right)^{-1}$$

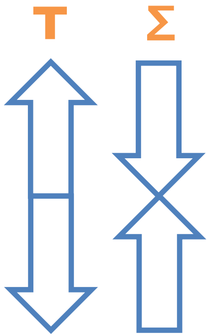
$$\approx 32\,mas\left(\frac{\lambda}{1\,mm}\right)\left(\frac{D}{8\,km}\right)^{-1}$$

Figure adapted from Andrews 2020, ARAA

Multi-wavelength observations trace different regions in a disk

Providing critical constraints on structure/distribution of material

Also, vertical temperature and density gradients



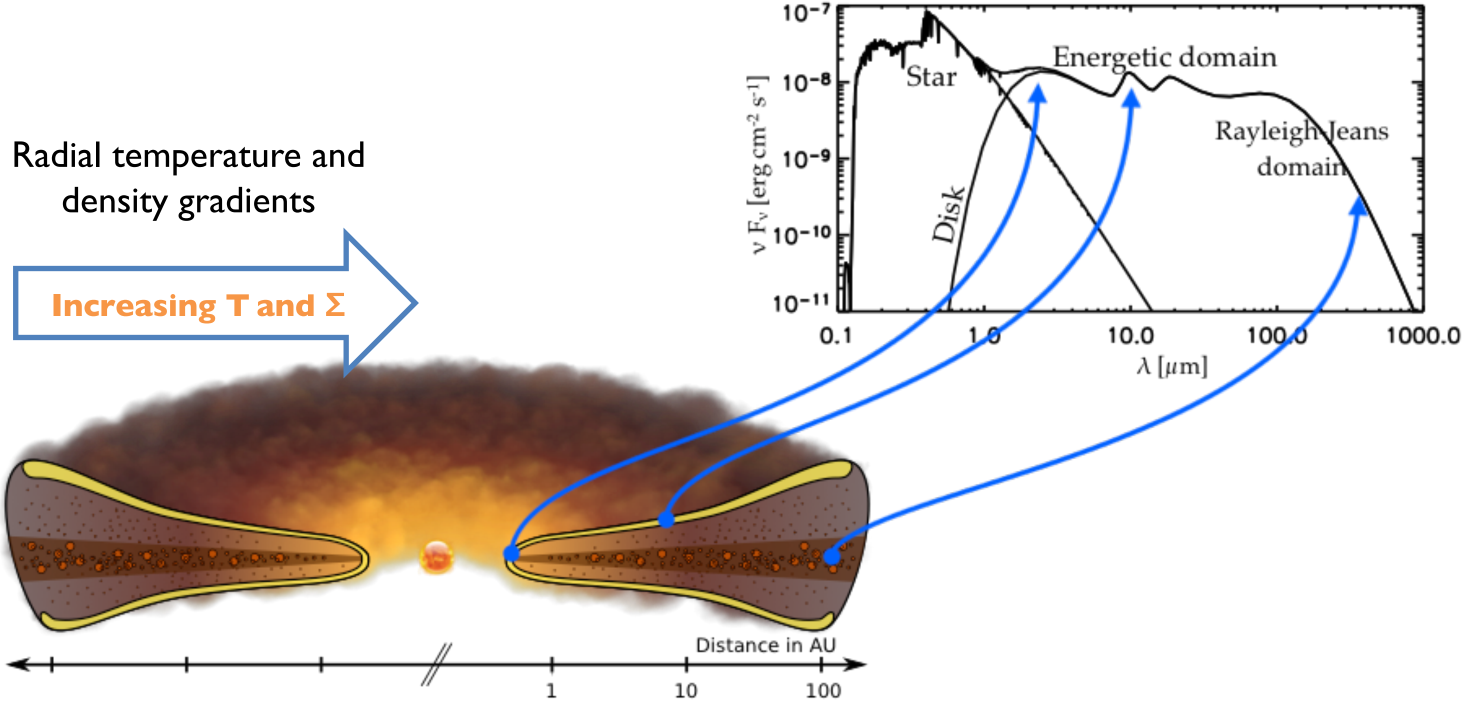
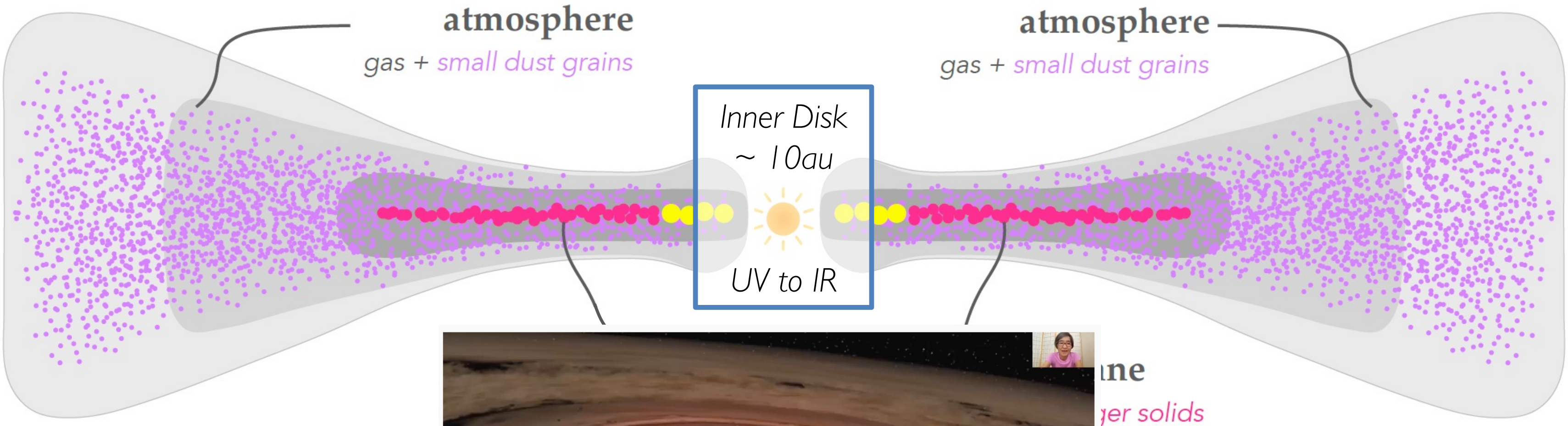


Figure c/o T. Birnstiel

How do we probe different disk regions?

The warmer innermost regions are better probed at shorter wavelengths



Joan Najita's talk

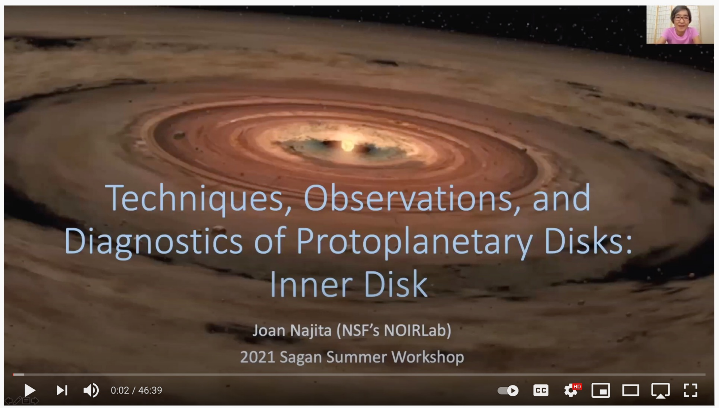


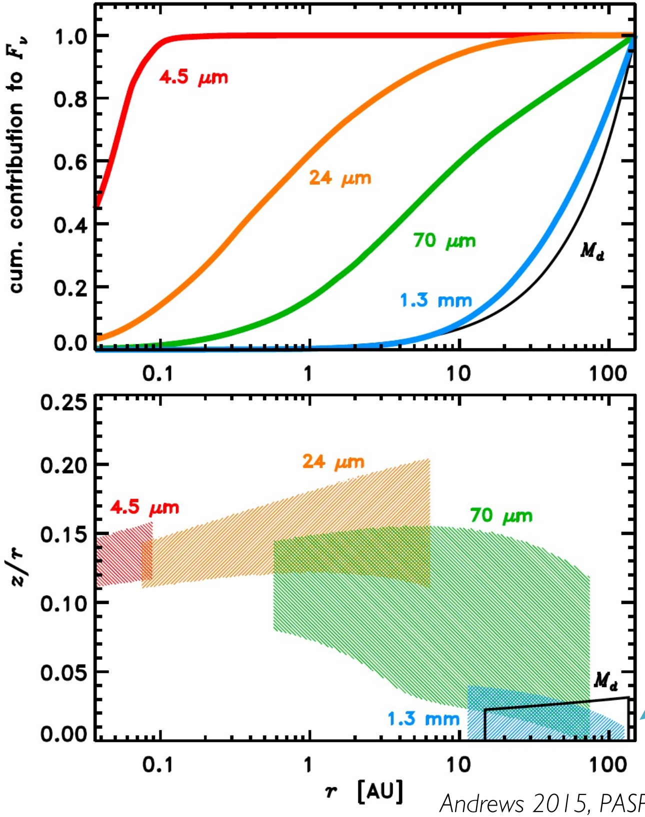
Figure adapted from Andrews 2020, ARAA

How do we probe different disk regions?

The colder outer disk and midplane can be probed at longer wavelengths

Cumulative contribution at each λ to the observed emission

From where in the disk is the observed flux being emitted from?



Andrews 2015, PASP

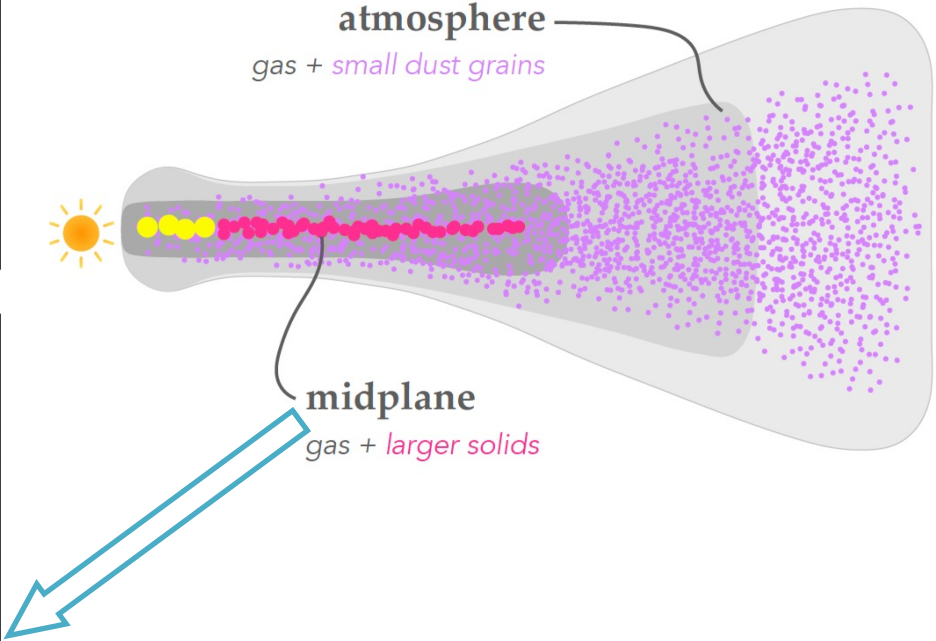


Figure adapted from Andrews 2020, ARAA

How do we probe different disk regions?

The disk surface and gaseus component can probed in scattered-light and emission lines, respectively

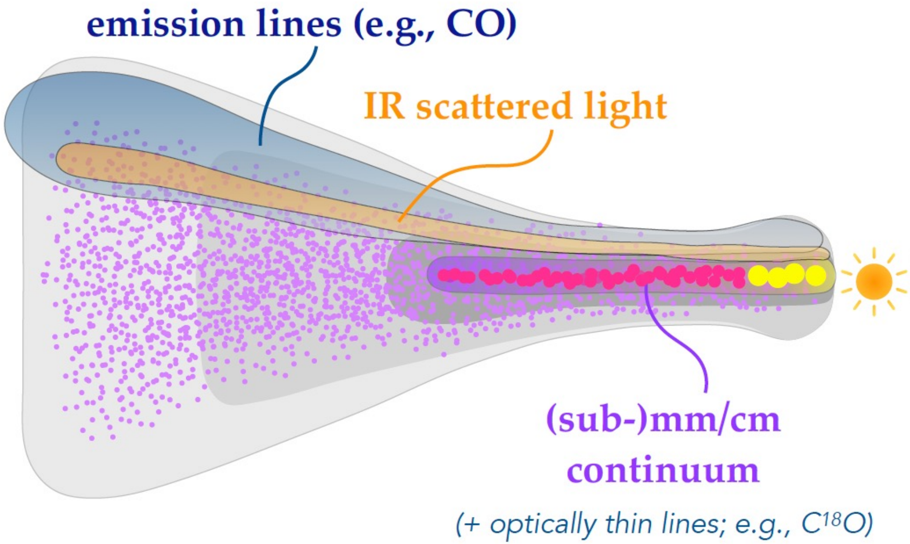
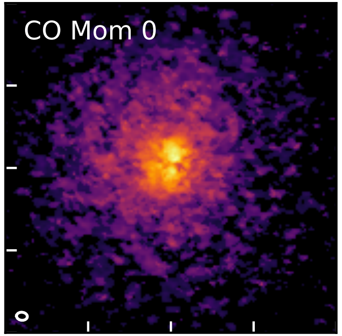


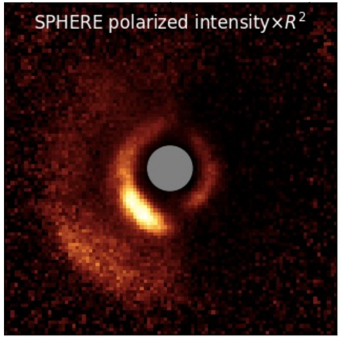
Figure adapted from
Andrews 2020, ARAA

The disk HD143006 in multiple tracers

Molecular Emission

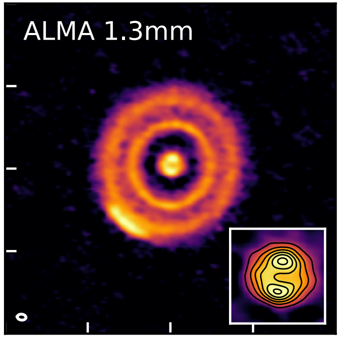


IR scattered-light



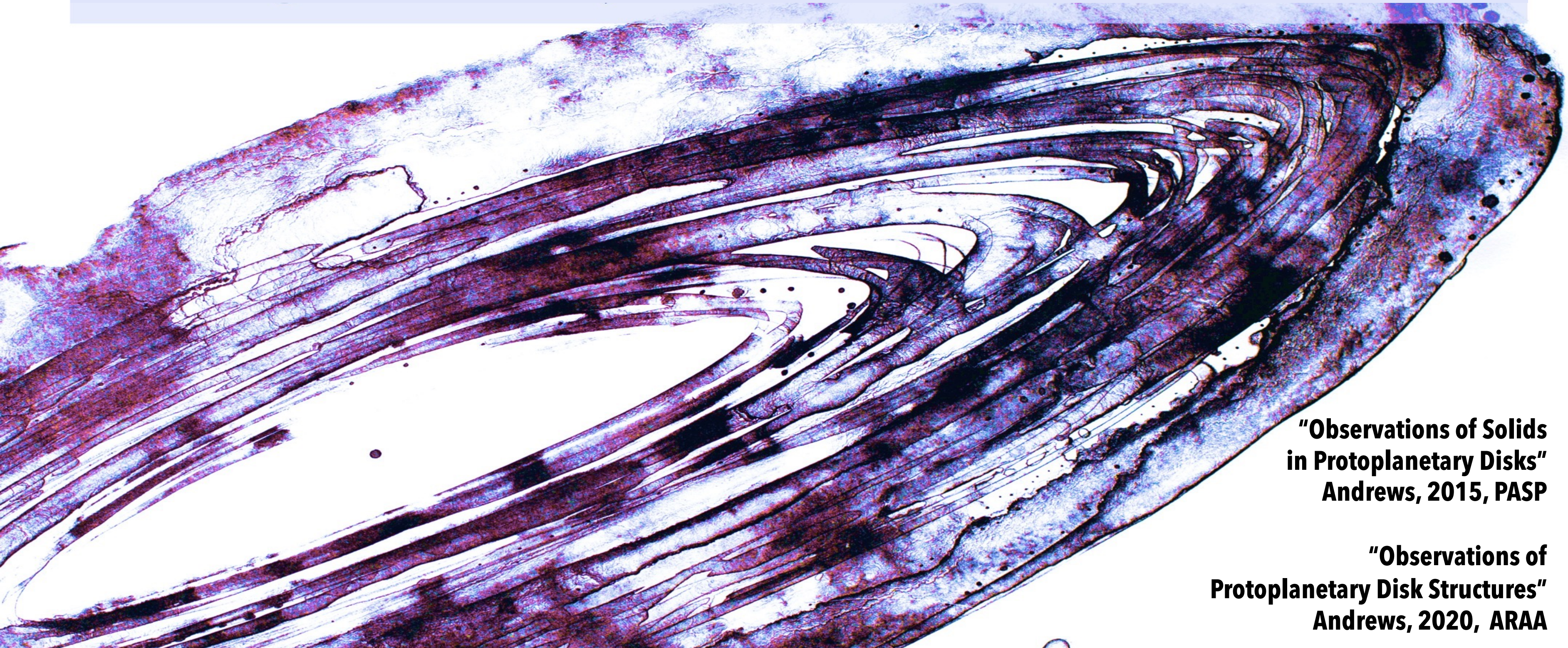
Benisty et al. 2018

Thermal Emission



Pérez et al. 2018

Part I. Thermal emission at long wavelengths



"Observations of Solids in Protoplanetary Disks"
Andrews, 2015, PASP

"Observations of Protoplanetary Disk Structures"
Andrews, 2020, ARAA

What do we learn about disks from long wavelength continuum observations?

Dust thermal continuum emission observed from near IR to cm wavelengths

Emergent intensity of dust thermal emission: $$I_\nu = B_\nu(T_{dust})(1 - e^{-\tau_\nu})$$

(excluding scattering)

Dust optical depth

Planck function at Dust Temperature

In the optically thick limit, $\tau_\nu \gg 1$: $$I_\nu \approx B_\nu(T_{dust})$$

(generally at short wavelengths)

In the optically thin limit, $\tau_\nu \ll 1$: $$I_\nu \approx \kappa_\nu \; \Sigma_{dust} \, B_\nu(T_{dust})$$

(generally at long wavelengths)

Absorption Opacity

Dust Surface Density

Thus, integrating I_ν over the disk: $$M_{dust} \approx \frac{d^2 F_\nu}{\kappa_\nu B_\nu(T_{dust})}$$

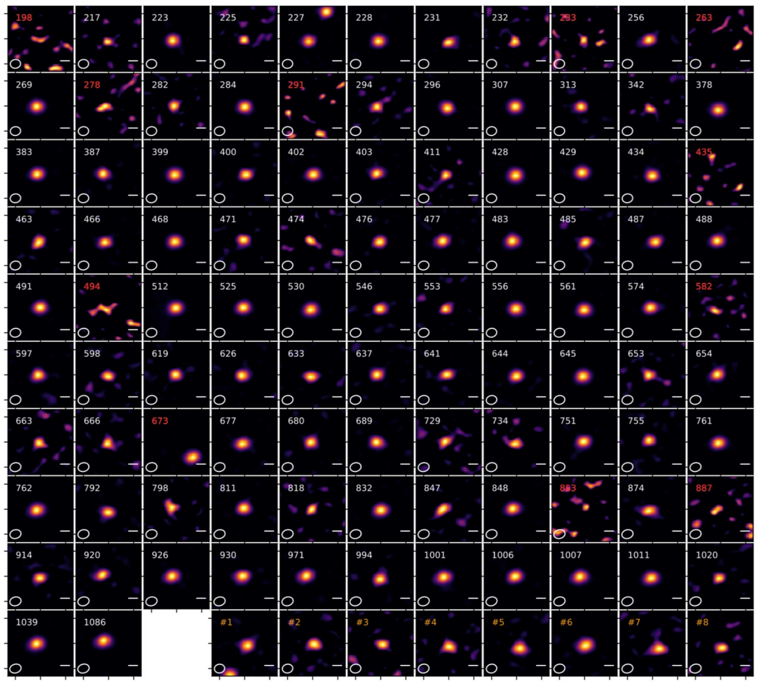
Solid Mass

Observed Flux density

Protoplanetary disk masses from thermal emission at long wavelengths

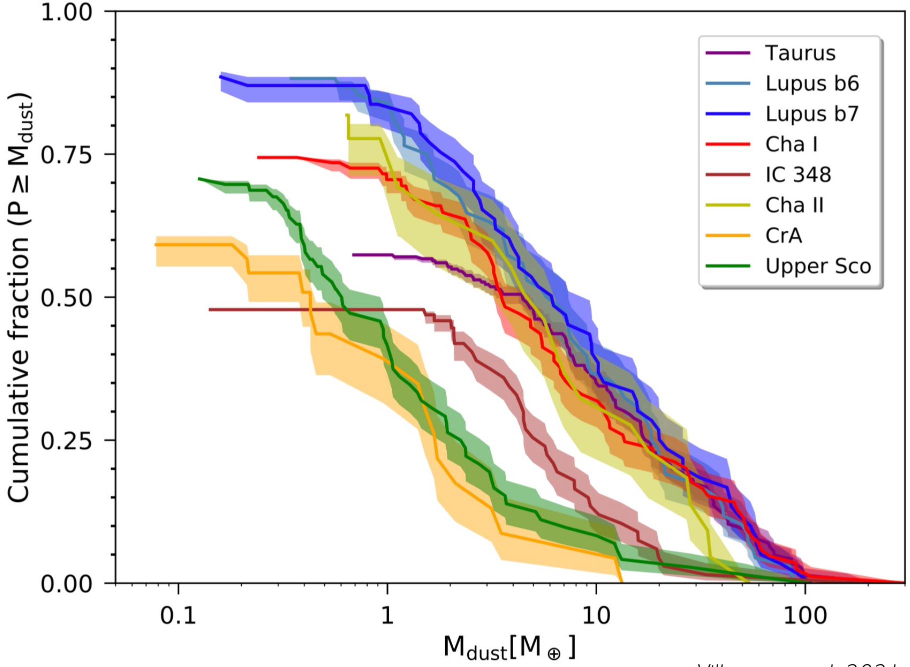
Based on the assumptions outlined before there have been multiple demographic surveys with ALMA

e.g., Lynds 1641



Grant et al. 2021

Solid disk mass evolution



Villenave et al. 2021

What do we learn about disks from long wavelength continuum observations?

Constraints of spectral index at long wavelengths: in the optically thin regime dust properties can be inferred

In the optically thin limit, $\tau_\nu \ll 1$:
(generally at long wavelengths)

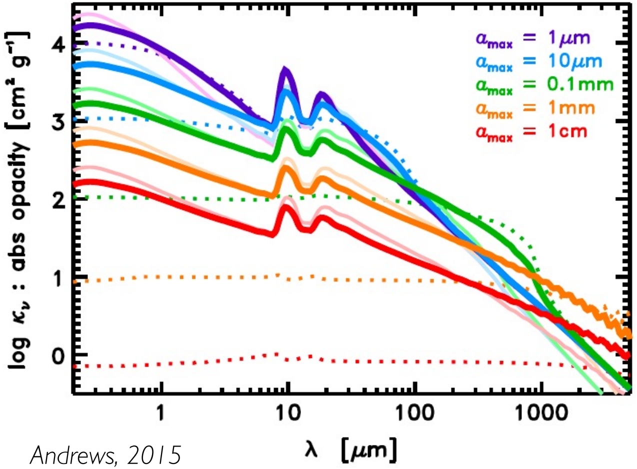
$$I_\nu \approx \kappa_\nu \; \Sigma_{dust} \, B_\nu(T_{dust})$$

In the Rayleigh-Jeans limit, $h\nu \ll kT$:
(generally at long wavelengths and/or high temperatures)

$$I_\nu \approx \kappa_\nu \; \Sigma_{dust} \, \nu^2$$

All dependence with frequency is here

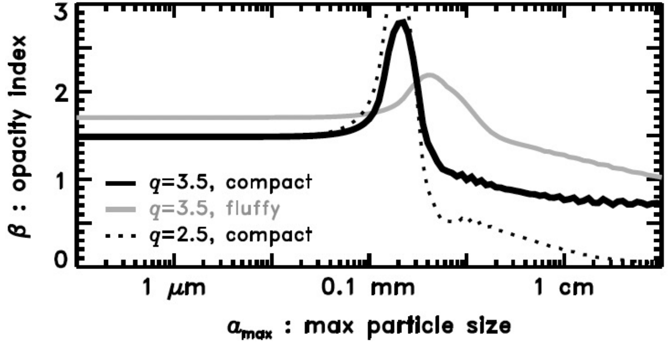
κ_ν for different particle-size distributions



Andrews, 2015

Goes as power-law at long wavelengths: $\kappa_\nu \propto \nu^\beta$

Opacity spectral index β
for different particle-size distributions



Lower β for large particle sizes

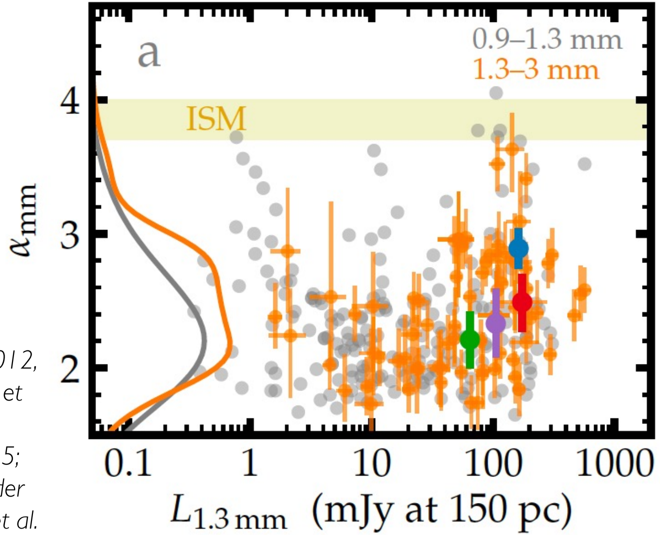
Dust properties from thermal emission at long wavelengths

Based on the assumptions outlined before there have been several grain growth and evolution studies

Spectral index of emission: $I_\nu \propto \nu^\alpha$

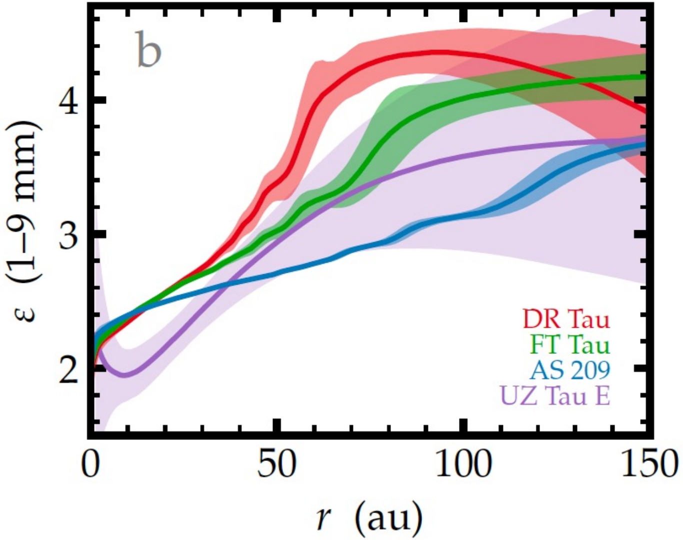
To quantify both contributions to the shape of the spectrum: from the opacity spectral index β and the Planck function $B_\nu(T)$.

Disk-integrated spectral indices from various surveys



Ricci et al. 2010a,b, 2012, 2013, 2014; Lommen et al. 2010; Harris et al. 2012; Cieza et al. 2015; Testi et al. 2016; van der Plas et al. 2017; Cox et al. 2017; Pinilla et al. 2017c; Ward-Duong et al. 2018
Figure from Andrews 2020

Resolved spectral indices in different disks



Tazzari et al. 2016; Tripathi et al. 2018

What do we learn about disks from long wavelength continuum observations?

There are several caveats to be considered in the assumptions before

Emission not necessarily optically thin:

(emergent intensity assuming $\tau_\nu \ll 1$)

$$I_\nu \approx \kappa_\nu \, \Sigma_{dust} \, B_\nu(T_{dust})$$

Scattering cannot be ignored:

(emergent intensity excluding scattering)

$$I_\nu = B_\nu(T_{dust})(1 - e^{-\tau_\nu})$$

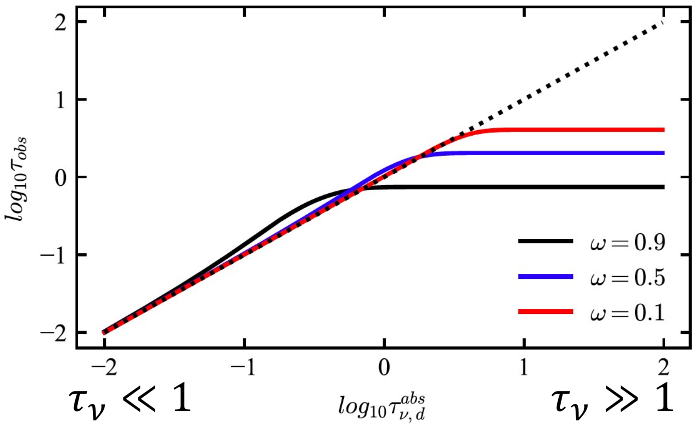
Emergent intensity of dust thermal emission when including scattering:

with ω_ν the albedo of the dust particles, dependent on particle properties (e.g., size)

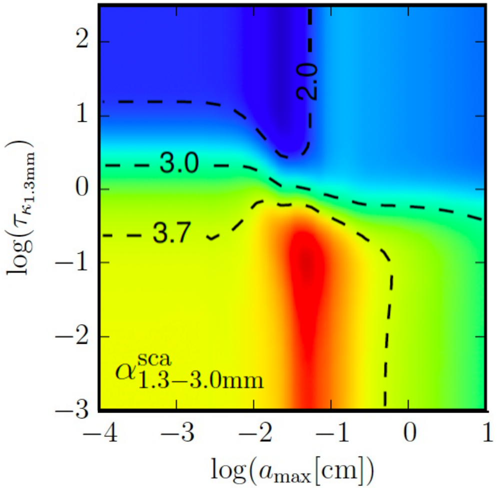
$$I_\nu = B_\nu(T_{dust})[1 - e^{-\tau_\nu} + \omega_\nu \mathcal{F}(\tau_\nu, \omega_\nu)]$$

Effect in inferred optical depth, (derived under standard assumptions)

Zhu et al., 2019



$\tau_\nu \ll 1$ $\tau_\nu \gg 1$



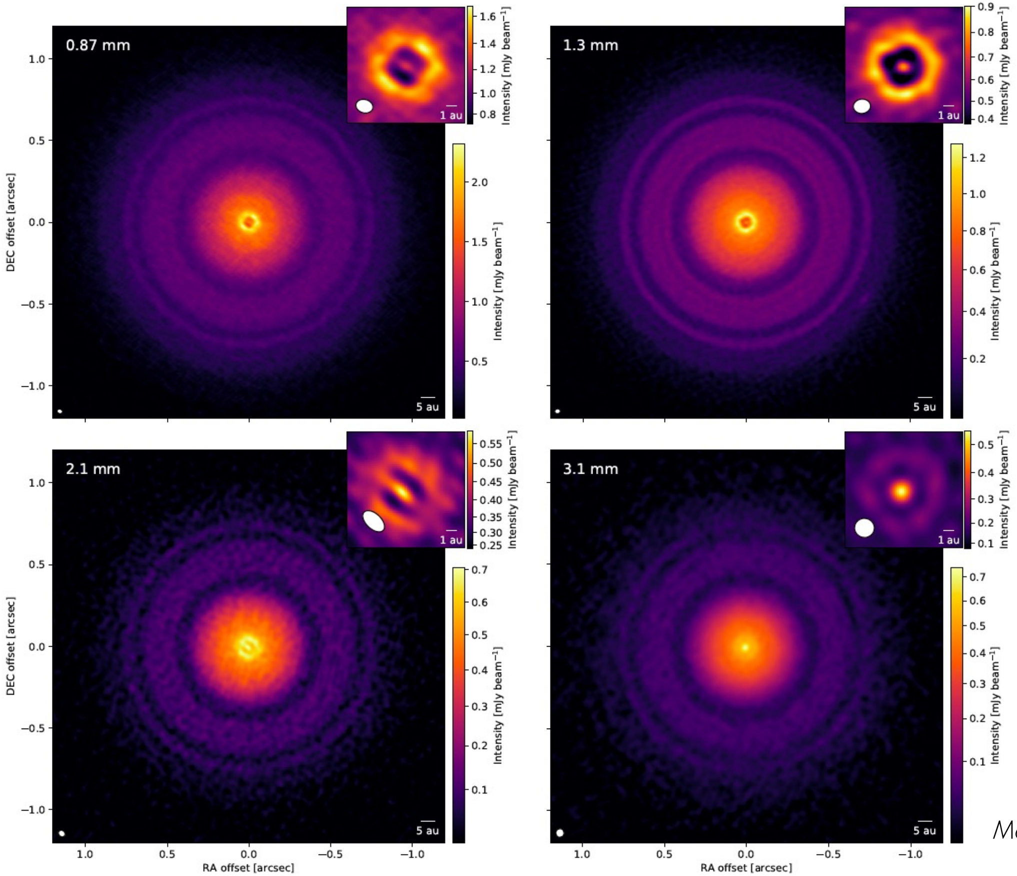
Effect in the spectral index

Sierra & Lizano, 2020

Dust properties from thermal emission at long wavelengths

Multi-wavelength resolved observations to constrain dust properties and solid mass in substructures

ALMA Observations at 50mas resolution (3au) of TW Hya disk



Macías et al. 2021

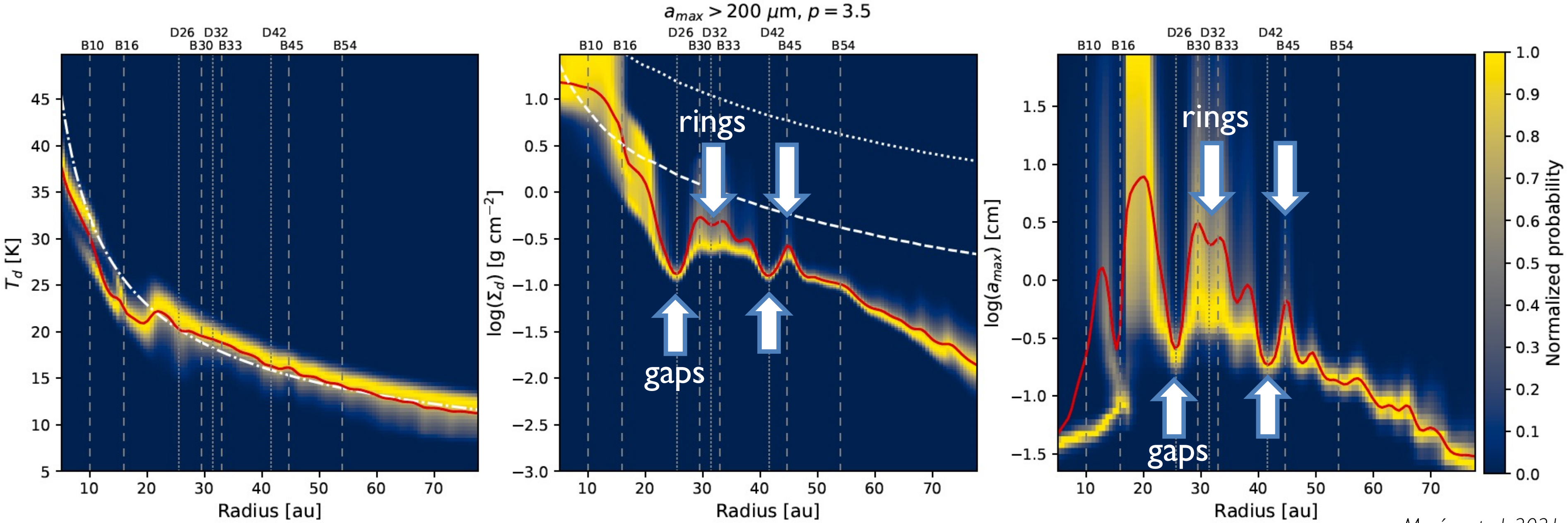
Dust properties from thermal emission at long wavelengths

Multi-wavelength resolved observations to constrain dust properties and solid mass in substructures

Emergent intensity is modeled including scattering:

I_ν is computed as a function of $\{T_{dust}, \Sigma_{dust}, a_{max}\}$, assuming certain dust composition and particle size distribution

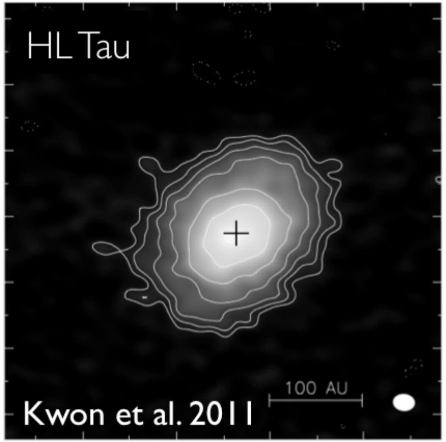
Til Birnstiel and Myriam Benisty's talk on "Dust Grain Evolution"

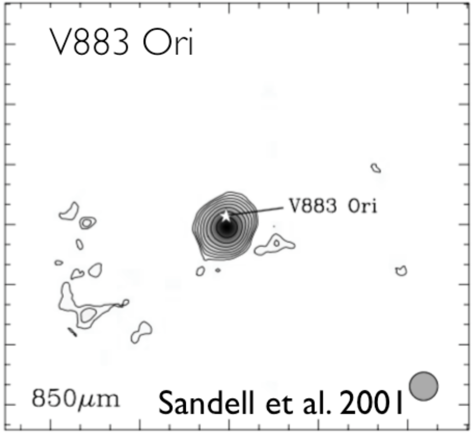


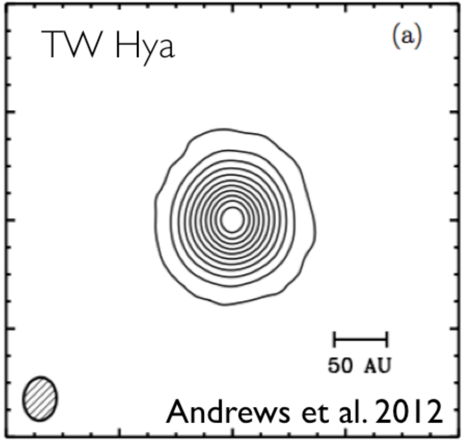
Macías et al. 2021

What do we learn about disks from long wavelength continuum observations?

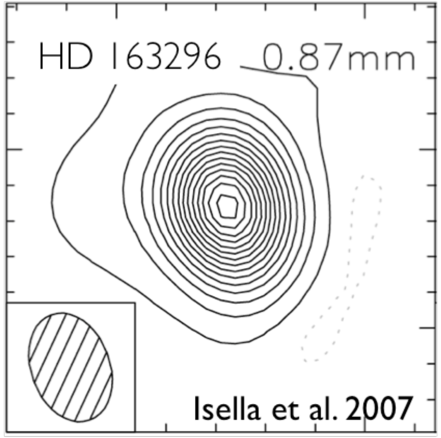
At long wavelenghts, sensitivity and resolution are critical to characterize substructures

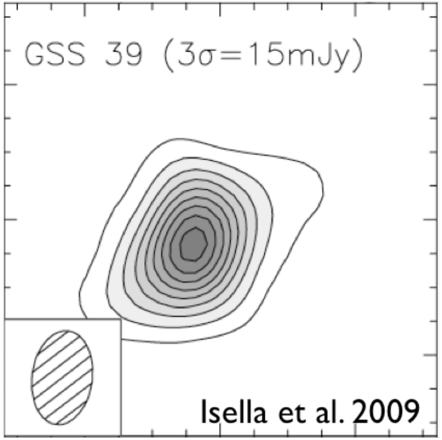


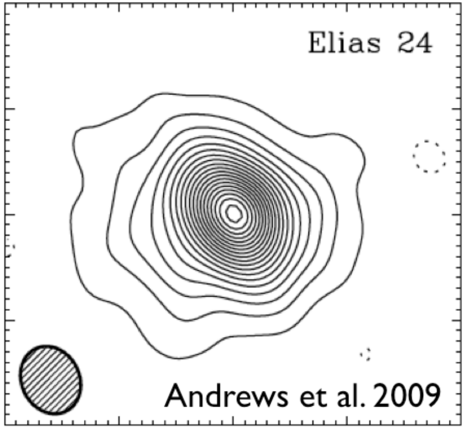




Disk observations from the pre-ALMA era showed little substructure

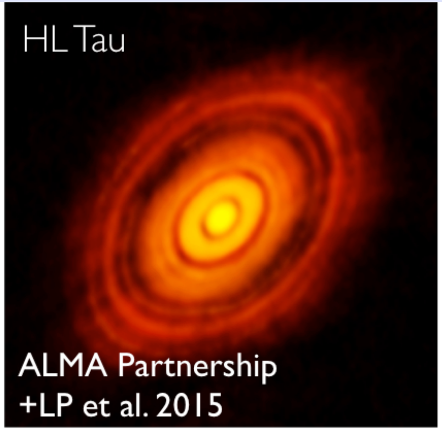


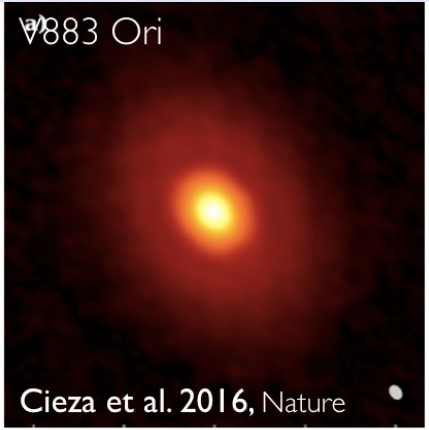


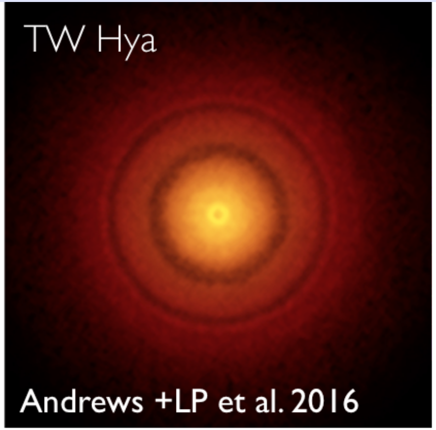


What do we learn about disks from long wavelength continuum observations?

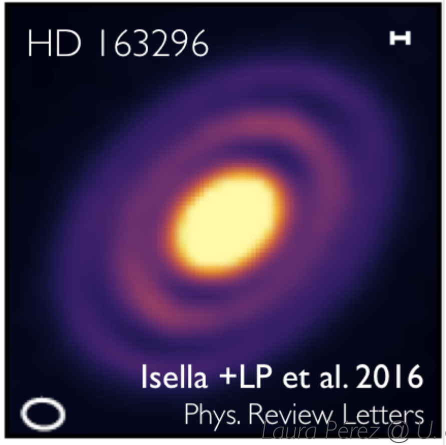
The era of ALMA: extraordinary sensitivity and resolution to characterize these disks

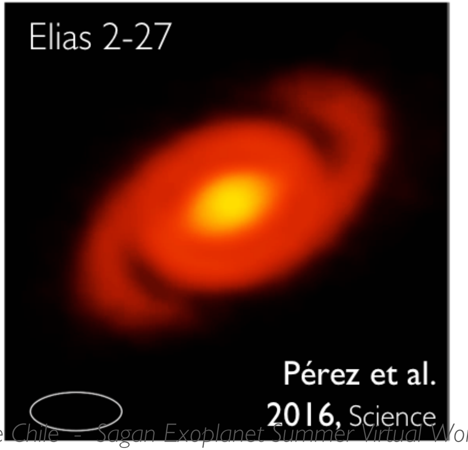


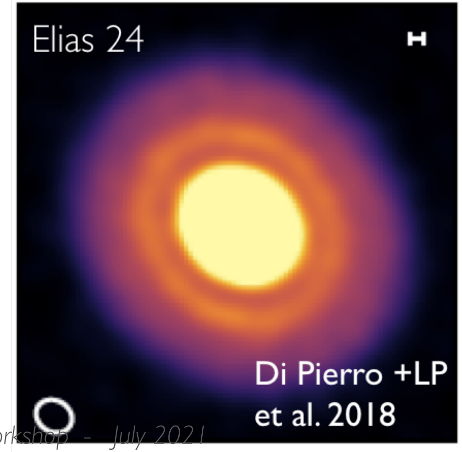




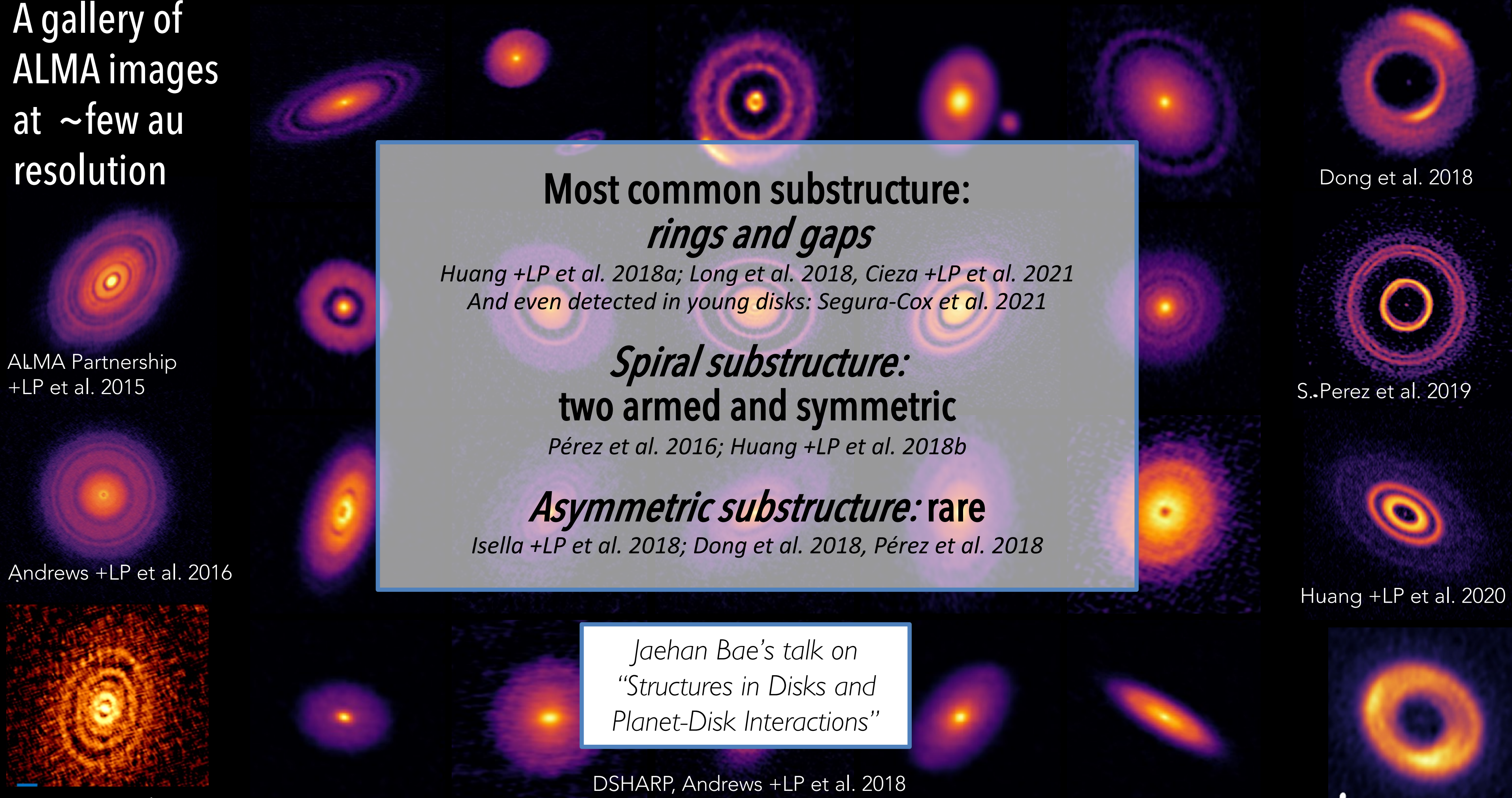
The same mm-wave gallery of disks, but as seen by ALMA now







A gallery of ALMA images at ~few au resolution



Most common substructure:
rings and gaps

Huang +LP et al. 2018a; Long et al. 2018, Cieza +LP et al. 2021
And even detected in young disks: Segura-Cox et al. 2021

Spiral substructure:
two armed and symmetric

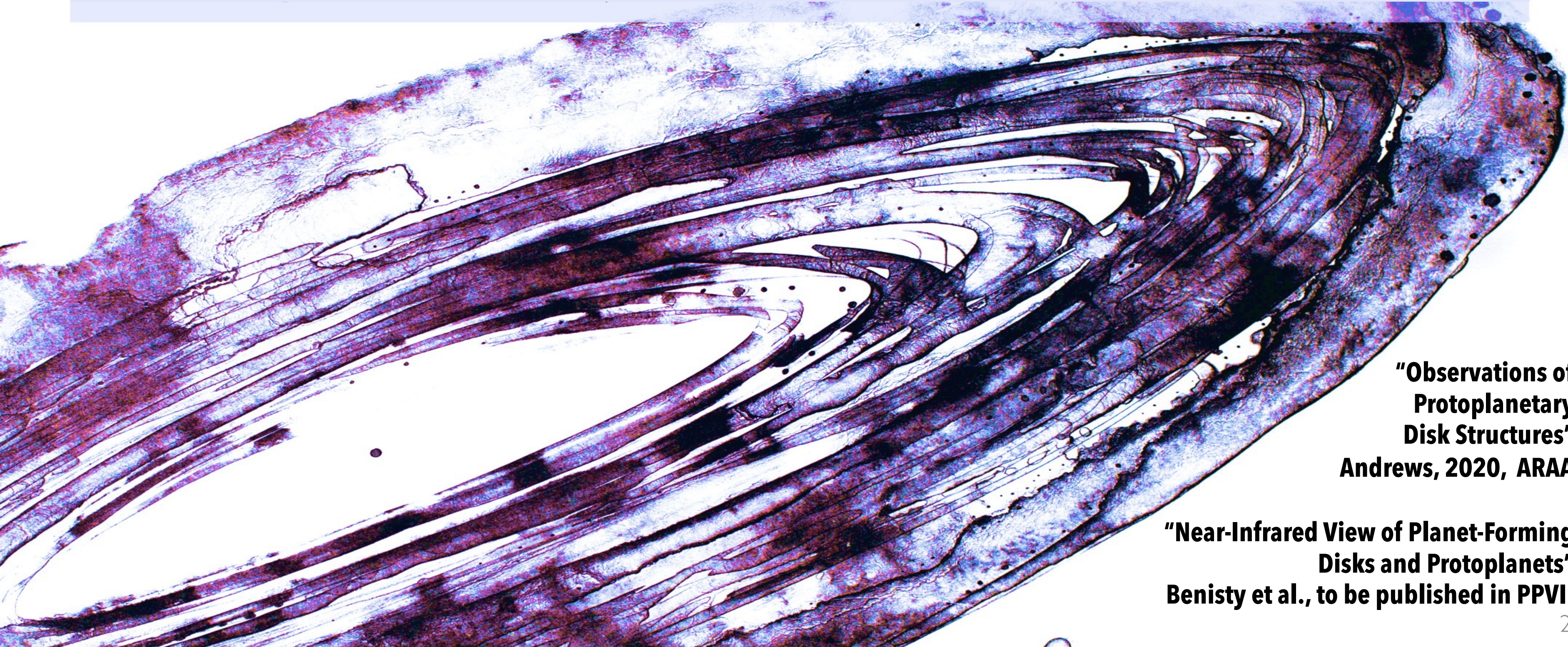
Pérez et al. 2016; Huang +LP et al. 2018b

Asymmetric substructure: **rare**

Isella +LP et al. 2018; Dong et al. 2018, Pérez et al. 2018

Jaehan Bae's talk on "Structures in Disks and Planet-Disk Interactions"

Part II. Scattered light at short wavelengths



"Observations of Protoplanetary Disk Structures"
Andrews, 2020, ARAA

"Near-Infrared View of Planet-Forming Disks and Protoplanets"
Benisty et al., to be published in PPVII

What do we learn about disks from short wavelength scattered-light?

Requires high-contrast imaging as stellar emission is orders of magnitude brighter

Grains in surface scatter incident radiation

At λ ~ optical, incident radiation is starlight
At λ ~ IR, incident radiation is starlight + disk emission

Stellar irradiation $\propto \frac{1}{r^2}$

Observations of the outer disk are sensitivity limited, as far away regions are poorly illuminated

A "natural" coronagraph

When light is scattered by dust grains it becomes polarized

Use the fact that scattered-light is polarized while starlight is not

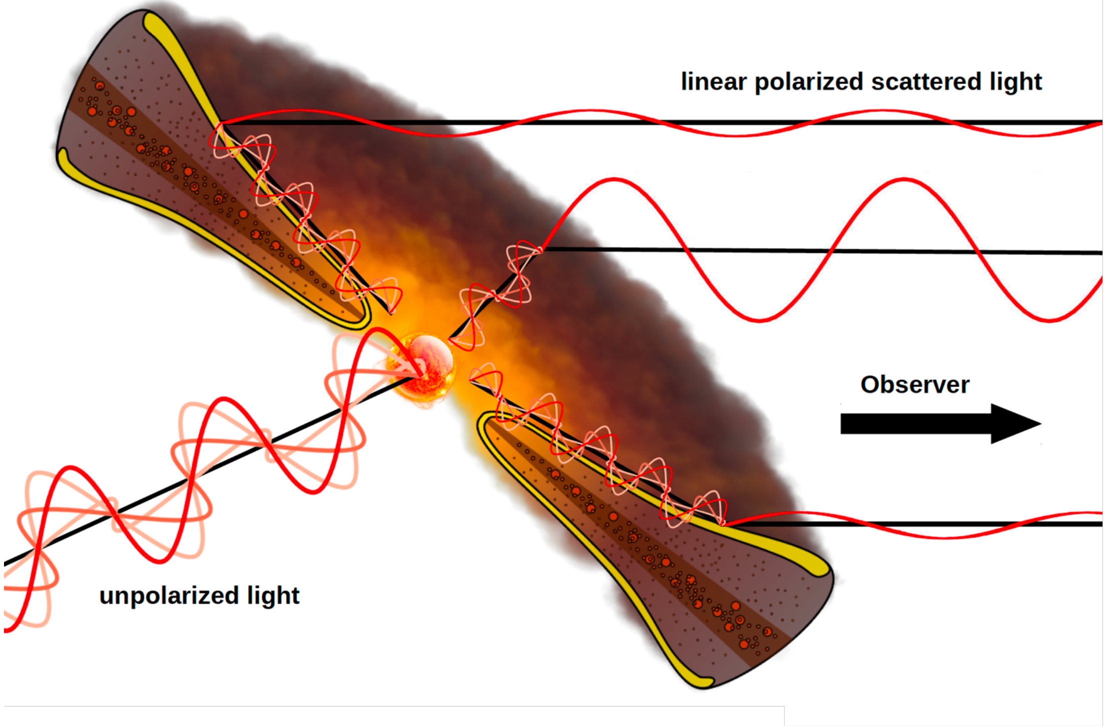


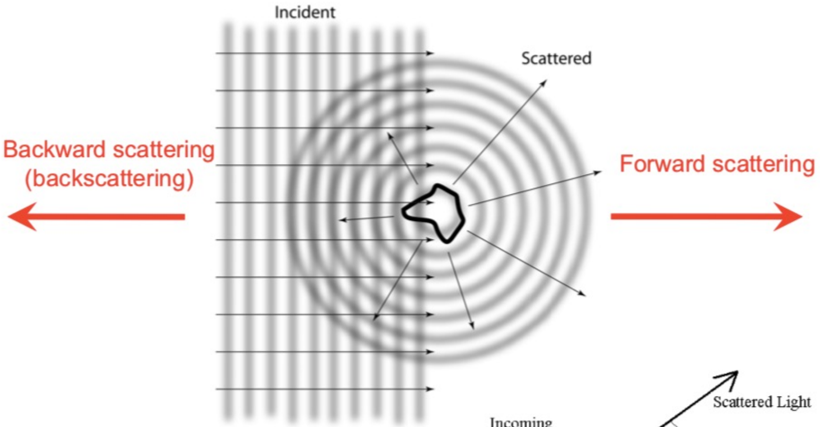
Figure c/o C. Ginski, T. Birnstiel

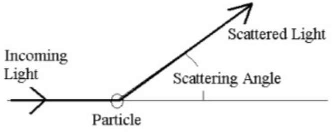
What do we learn about disks from short wavelength scattered-light?

Observed radiation in polarization and total intensity depends on several factors including projection effects

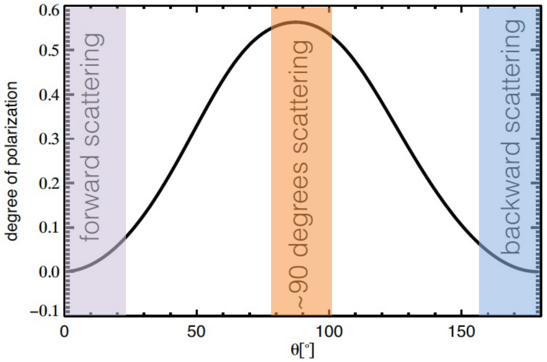
Grain properties are important

Depending on size, composition, porosity, etc., there will be variations in total intensity and polarized brightness with scattering angle.





Polarized brightness with scattering angle



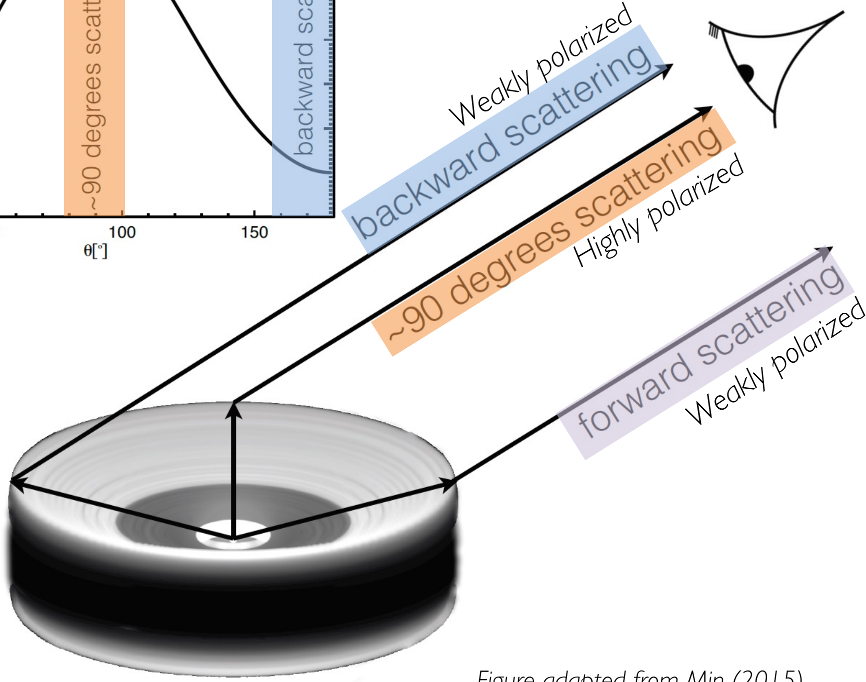


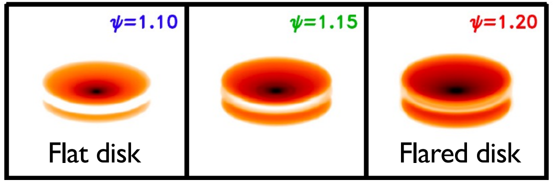
Figure adapted from Min (2015)

What do we learn about disks from short wavelength scattered-light?

Observed radiation in polarization and total intensity depends on several factors including projection effects

Vertical structure is important

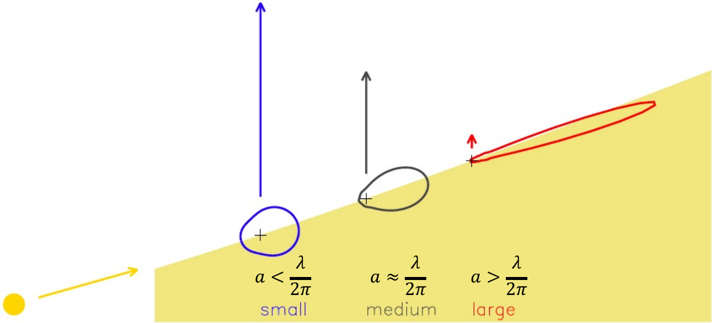
E.g., a disk with larger flaring absorbs more incident radiation



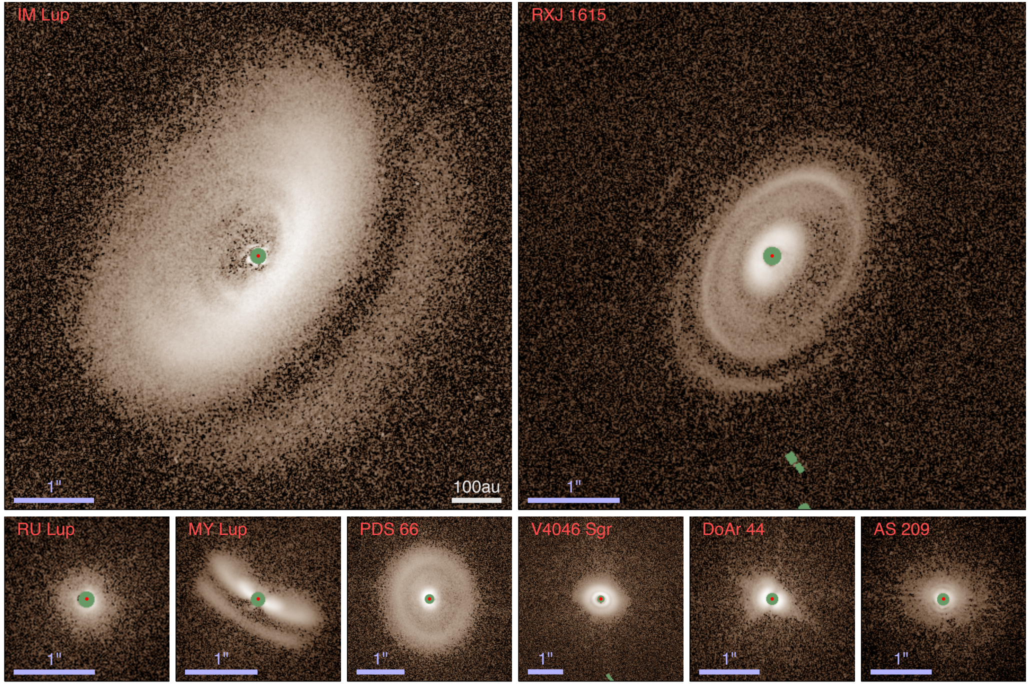
Andrews (2015)

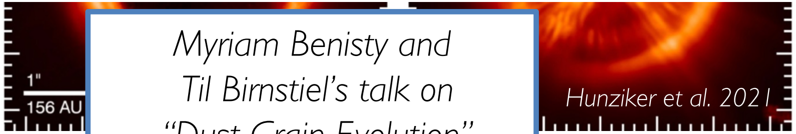
Projection effects are important

E.g., large particles become extremely forward scattering, so the viewing angle matters



Mulders et al. (2013)





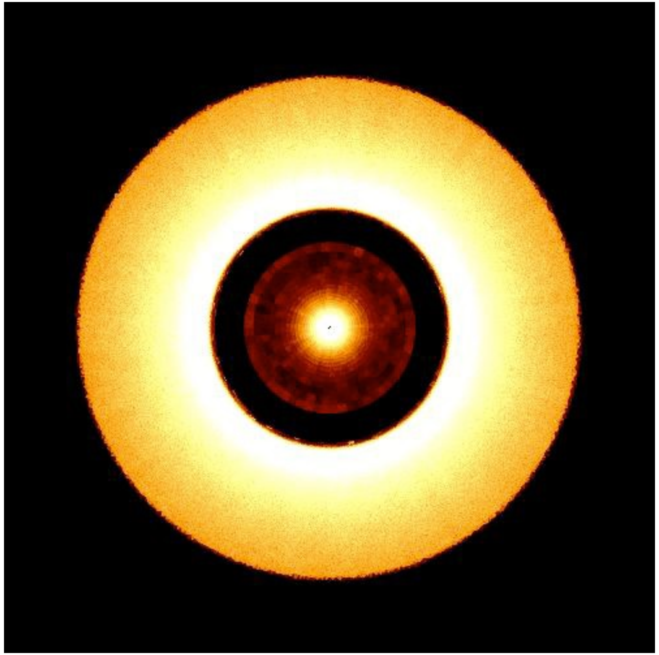
Hunziker et al. 2021

Myriam Benisty and Til Birnstiel's talk on "Dust Grain Evolution"

What do we learn about disks from short wavelength scattered-light emission?

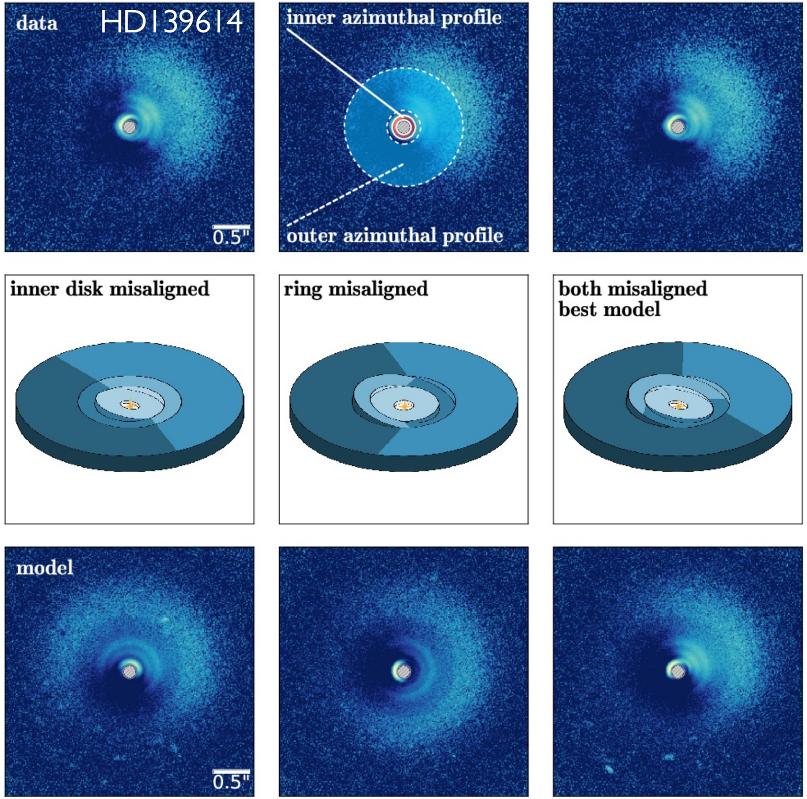
Observed emission in scattered light very sensitive to illumination: can probe vertical and radial disk structure

Simulation of inner/outer disk misalignment



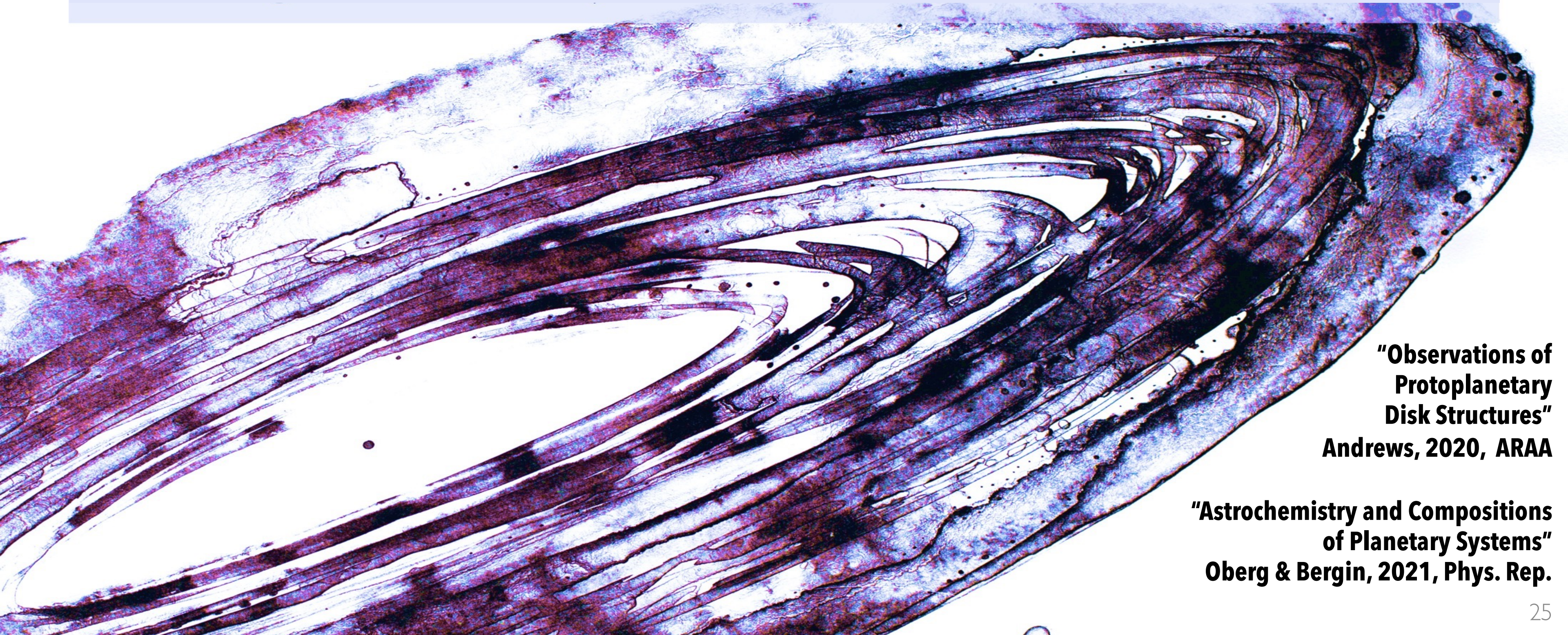
Michiel Min, U. Amsterdam

Observed shadows explained by multiple misaligned components



Muro-Arena et al. 2020

Part III. Molecular line emission at long wavelengths



"Observations of Protoplanetary Disk Structures"
Andrews, 2020, ARAA

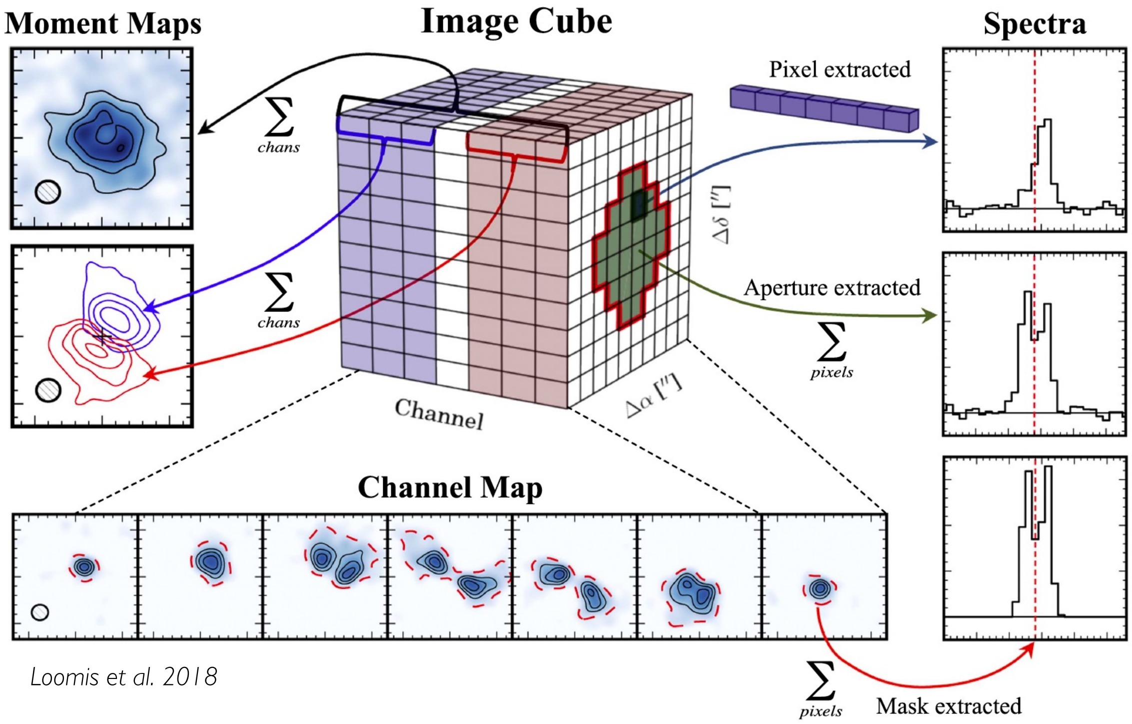
"Astrochemistry and Compositions of Planetary Systems"
Oberg & Bergin, 2021, Phys. Rep.

What do we learn about disks from long wavelength molecular line emission?

Observed intensity depends on gas temperature, abundance and distribution of the species, as well as the disk kinematics

An Image Cube

Maps the intensity distribution in distinct spectral frequency bins



Loomis et al. 2018

Line emission is sensitive to the disk kinematics

Spectral lines, well-resolved in frequency, probe the disk velocity field

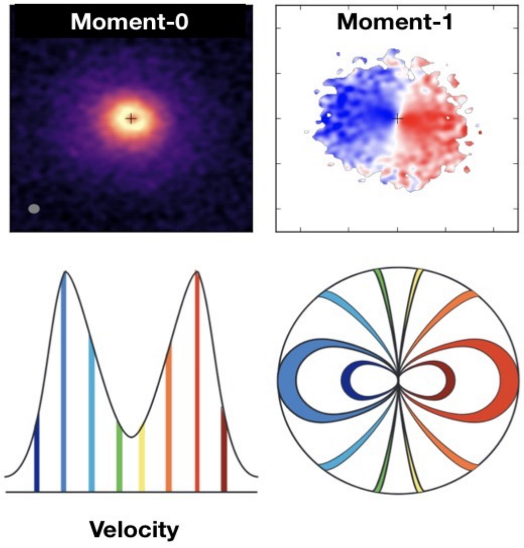


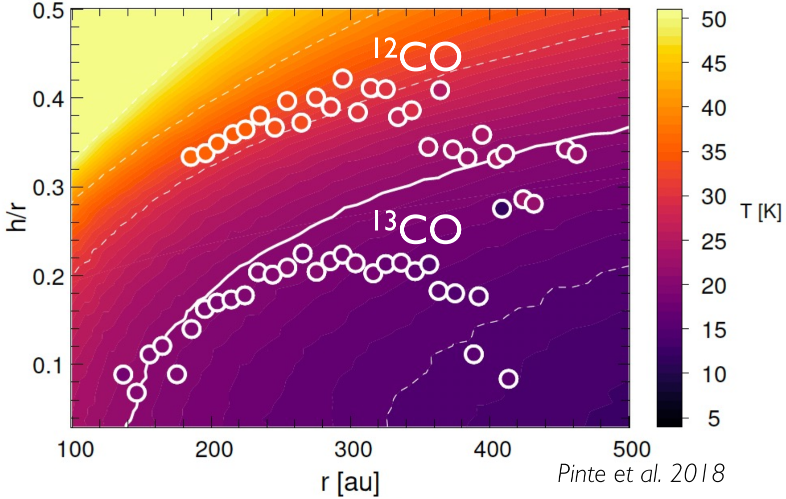
Figure adapted from Dionatos (2015), c/o V. Guzmán

What do we learn about disks from long wavelength molecular line emission?

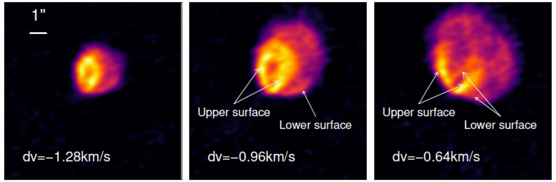
Spectral line emission allows us to probe several critical disk properties

Line emission is sensitive to temperature

The intensity of an optically thick line probes the temperature of the $\tau_\nu \approx 1$ *layer*

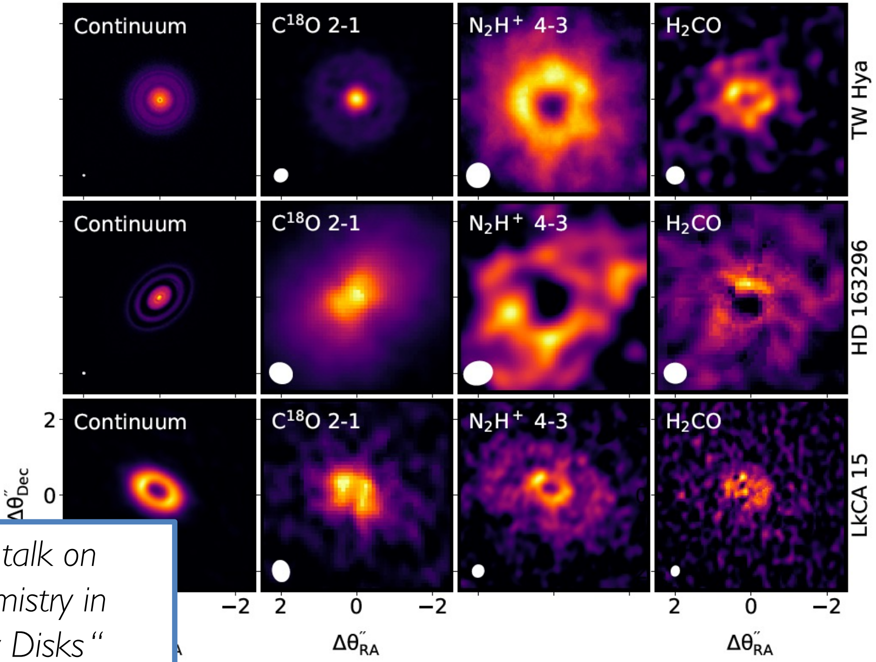


Pinte et al. 2018



Line emission is sensitive to density

The intensity of an optically thin line probes the temperature and density of the gas, as well as the abundance of the observed species



Oberg & Bergin, 2021

Karin Oberg's talk on "Gas and Chemistry in Protoplanetary Disks"

What do we learn about disks from long wavelength molecular line emission?

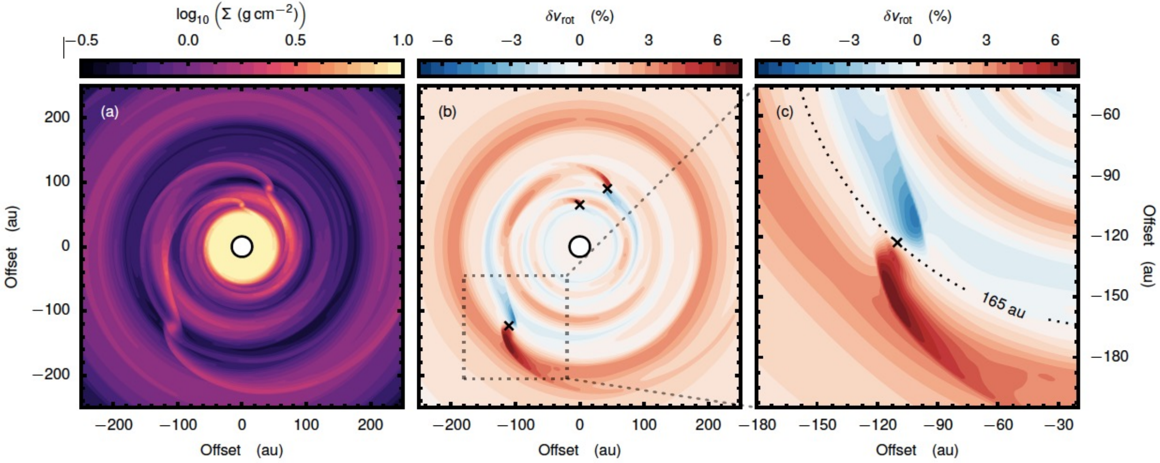
Spectral line emission allows us to probe the disk velocity field as well

Line emission is sensitive to the disk kinematics

Observations that are well-resolved in frequency, probe the disk velocity field

Embedded planets perturb the disk velocity field

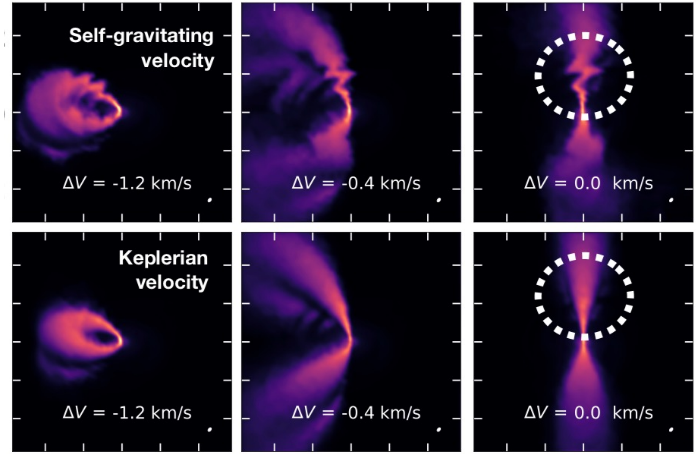
Gas Surface Density *Deviations from Keplerian velocities*



Teague et al. 2018

Perturbations due to GI

Deviations from Keplerian velocities over many channels



Hall et al. 2020

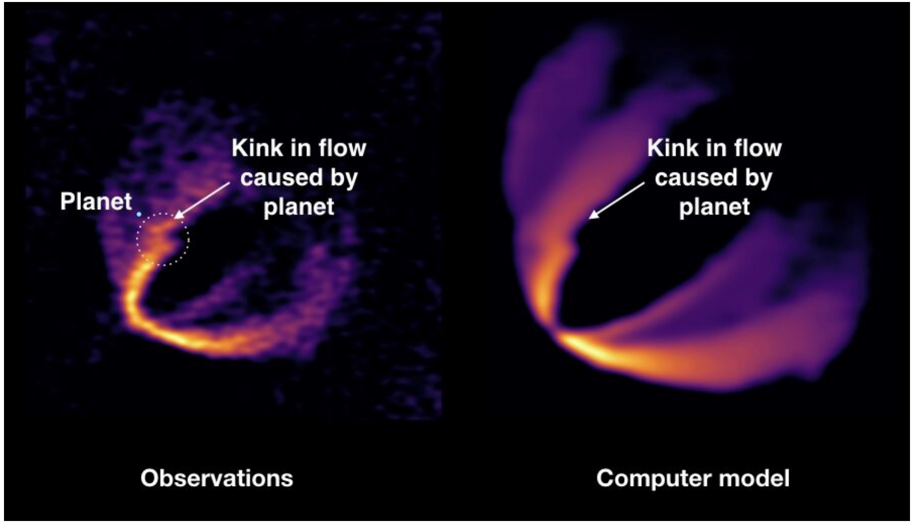
What do we learn about disks from long wavelength molecular line emission?

Spectral line emission allows us to probe the disk velocity field as well

Line emission is sensitive to the disk kinematics

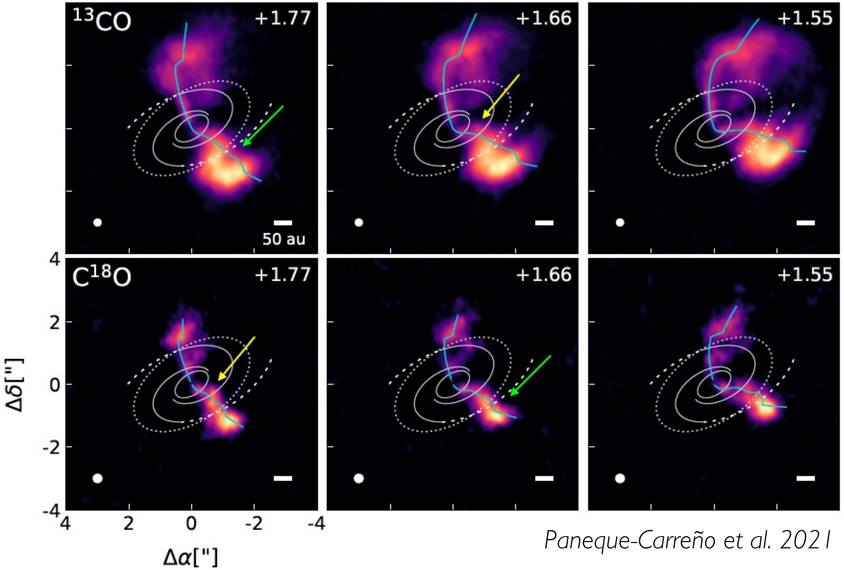
Observations that are well-resolved in frequency, probe the disk velocity field

Localized perturbation (embedded massive planet?)



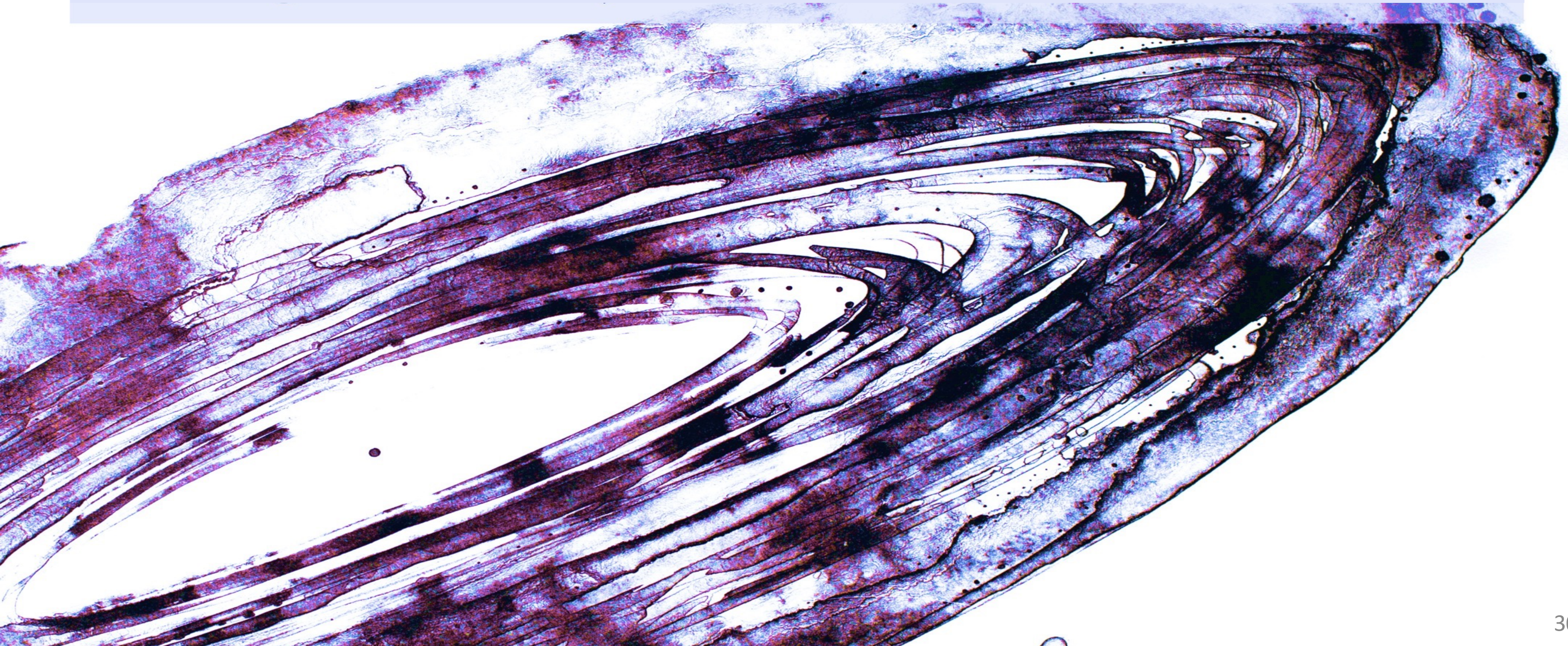
Pinte et al. 2018

Perturbations related to spirals (GI?)



Paneque-Carreño et al. 2021

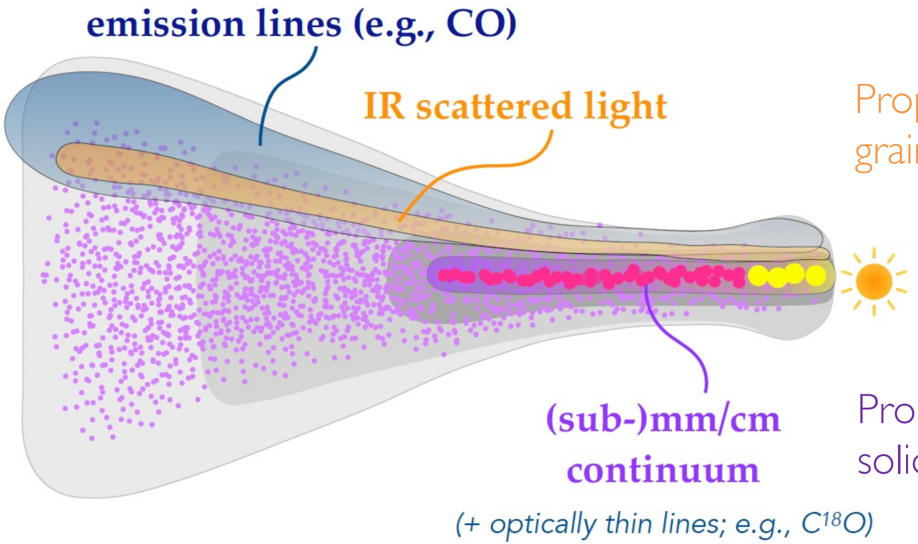
Concluding Remarks



Concluding Remarks

What can we learn from probing the different components in a protoplanetary disk using these different tracers?

Gas properties, disk structure and kinematics → Long wavelength molecular line emission



Properties of small grains and disk structure → Short wavelength scattered light

Properties of large solids and disk structure → Long wavelength thermal emission

Gas properties, disk structure and kinematics → Long wavelength molecular line emission

Figure adapted from Andrews 2020, ARAA

Research Group on Planet Formation at U. Chile

From protoplanetary disks studies to young planets searches

Prof. Laura Pérez

Dr. Anibal Sierra
Postdoc

Dr. Carolina Agurto-Gangas
Postdoc

Sebastian Jorquera
PhD student

Visitors

Adolfo Carvalho
Caltech

Dr. Myriam Benisty
UMI/CNRS/Grenoble

Dr. Gael Chauvin
UMI/CNRS/Grenoble

Former Members

Nicolás T. Kurtovic
MSc 2019

Teresa Paneque-Carreño
MSc 2020

Techniques, Observations, and Diagnostics of Protoplanetary Disks: Outer Disk

Laura M. Pérez
Departamento de Astronomía, Universidad de Chile

2021 Sagan Exoplanet Summer Virtual Workshop
Circumstellar Disks and Young Planets

Universidad de Chile
Centro de Astrofísica y Tecnologías Afines