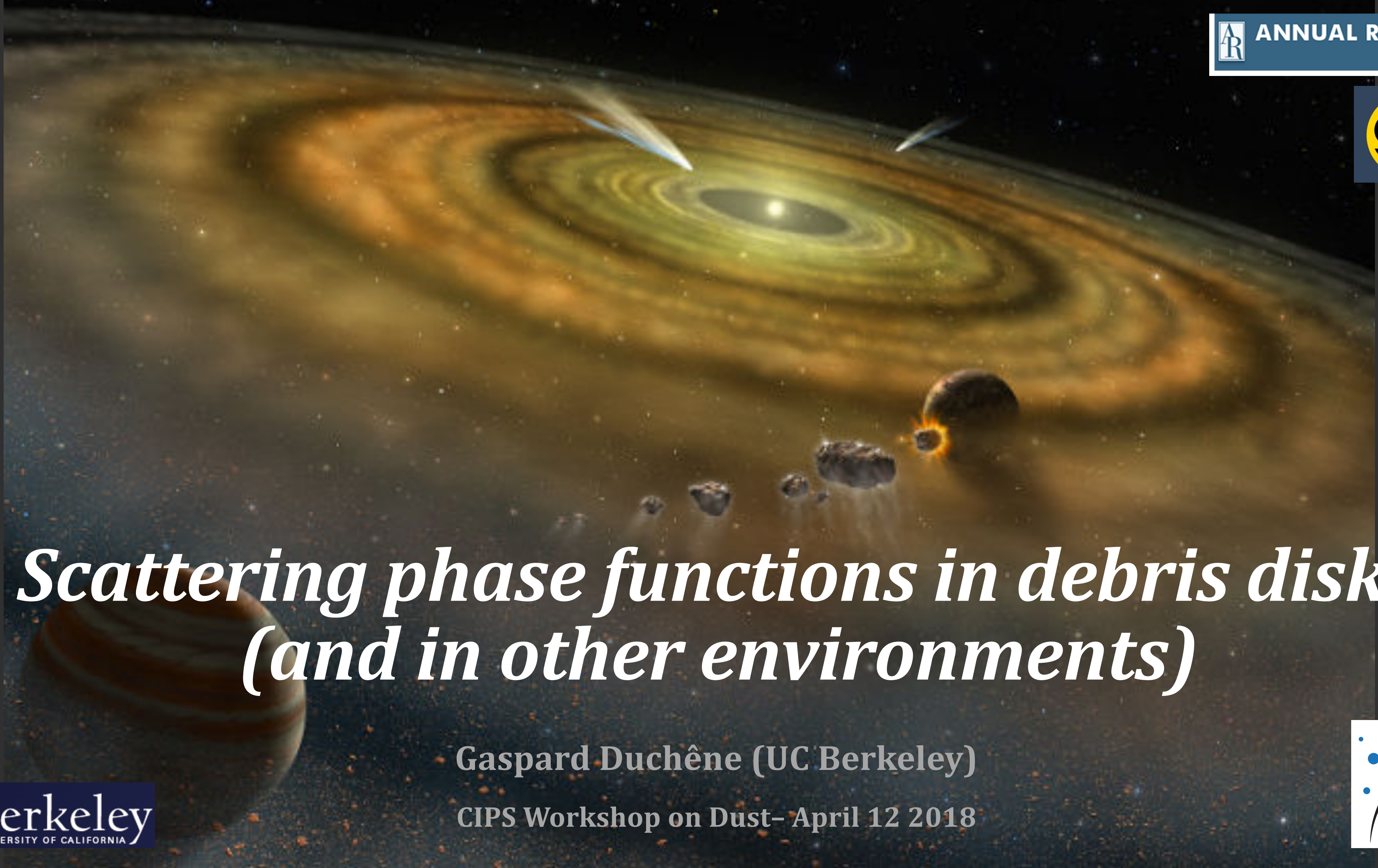


© L. Cook, NASA

ANNUAL REVIEWS

gpi

Scattering phase functions in debris disks (and in other environments)

Gaspard Duchêne (UC Berkeley)

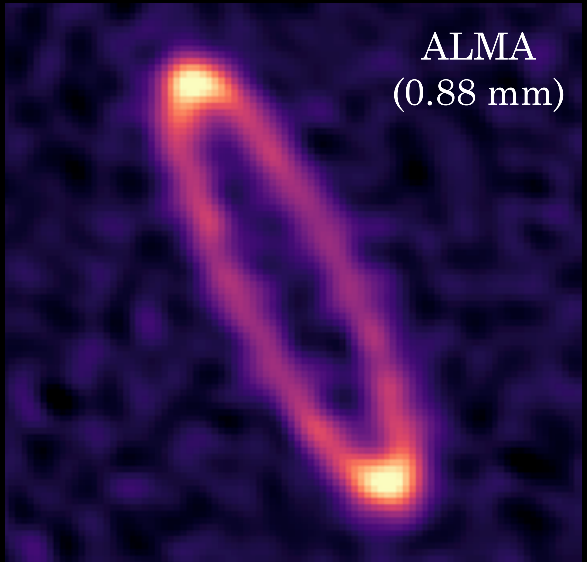
CIPS Workshop on Dust– April 12 2018

Berkeley
UNIVERSITY OF CALIFORNIA

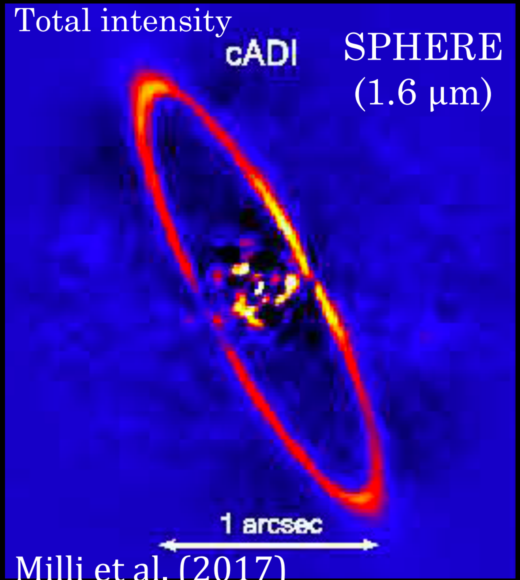
IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

Probing dust properties through imaging

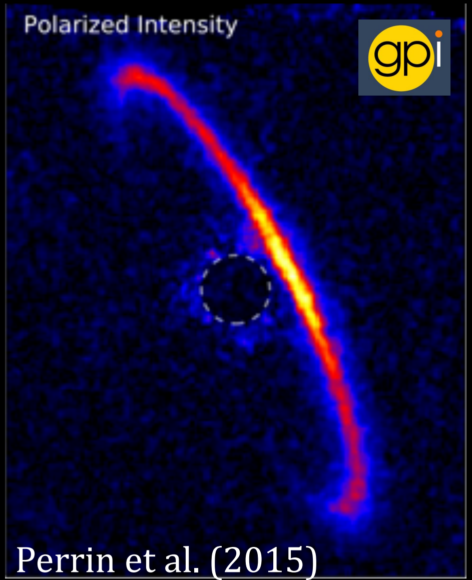
- Light interacting with a (population of) dust grains can be
  - Absorbed and re-emitted (isotropically)
  - Scattered (unevenly) in all directions (also inducing linear polarization)
- Both phenomena depend on the incoming photon's wavelength and on the grain(s) properties, such as grain size, shape, composition



Kennedy et al. (2018)



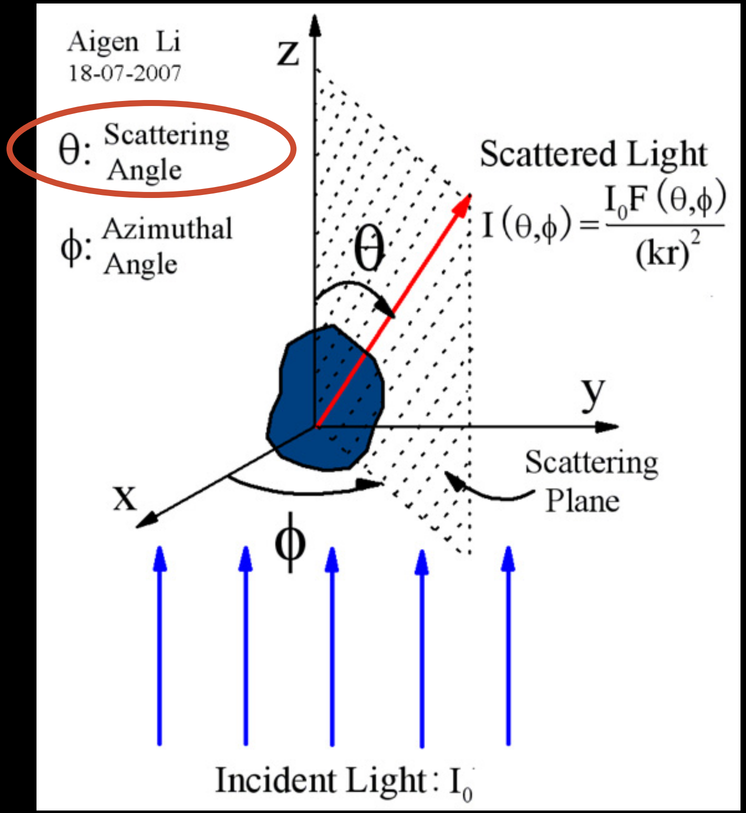
Milli et al. (2017)



Perrin et al. (2015)

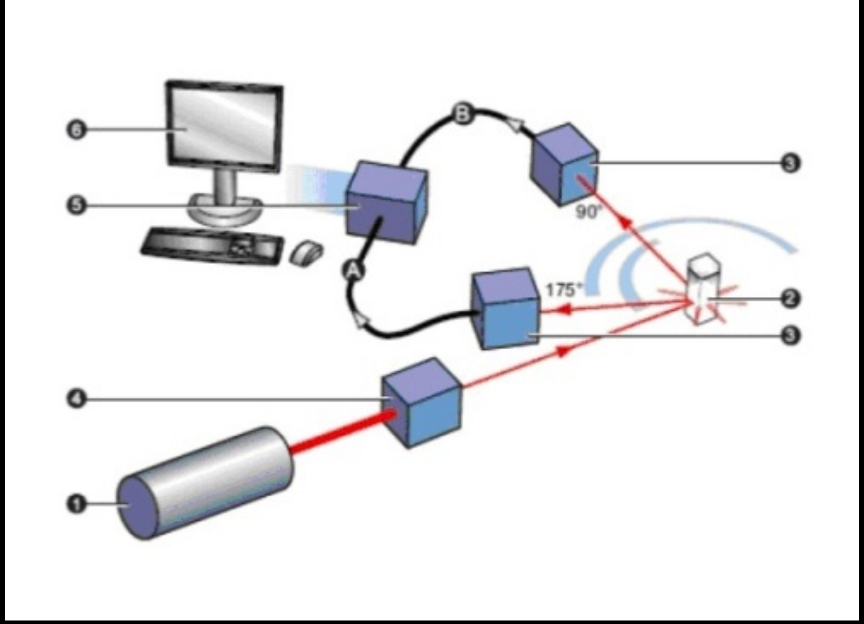
Scattering phase function

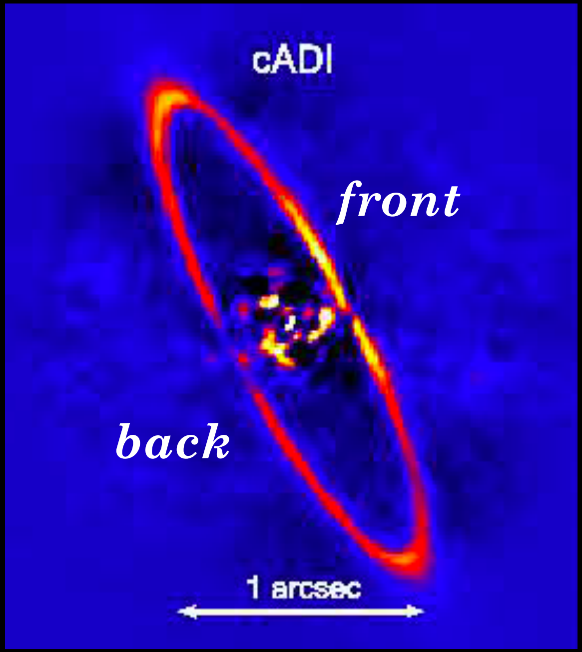
- Focus in this talk is on a single observable quantity: the scattering phase function
  - Measured in total intensity (Stokes I) for an illuminated dust population
  - Throwing away polarization information…
- Two dependent variables
  - Scattering angle
    - Forward scattering (θ < 90º)
    - Backward scattering (θ > 90º)
  - Azimuthal angle
    - Depends on asymmetry of dust grain
    - Irrelevant for an ensemble by symmetry?



Scattering phase function

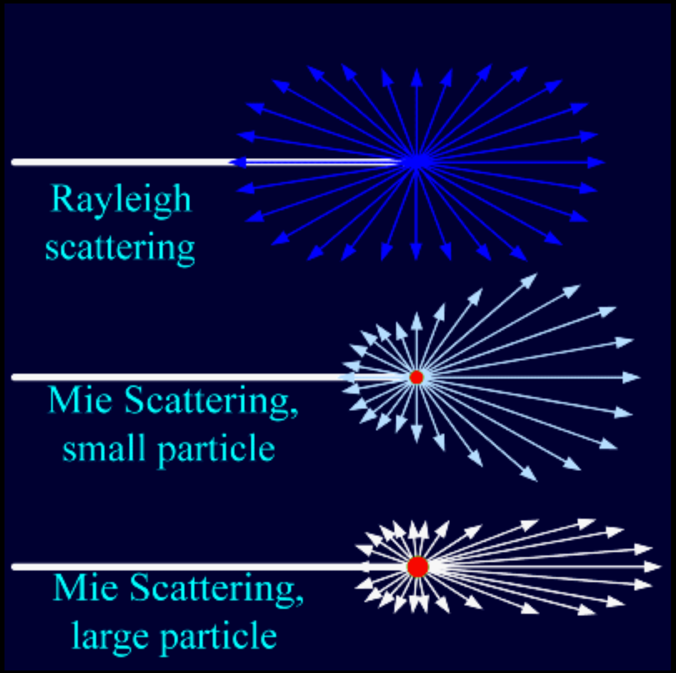
- The phase function describes how scattering off a dust grain is distributed in space
  - Need observations over a range of scattering angles θ
- This is one of the easiest things to measure for debris disks





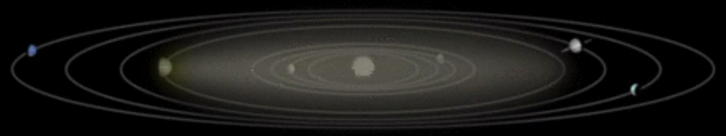
Scattering phase function

- The phase function describes how scattering off a dust grain is distributed in space
  - Need observations over a range of scattering angles θ
- This is one of the easiest things to measure for debris disks
- Some expected behaviors
  - Rayleigh scattering (very small grains)
  - Mie scattering (solid homogeneous spheres)



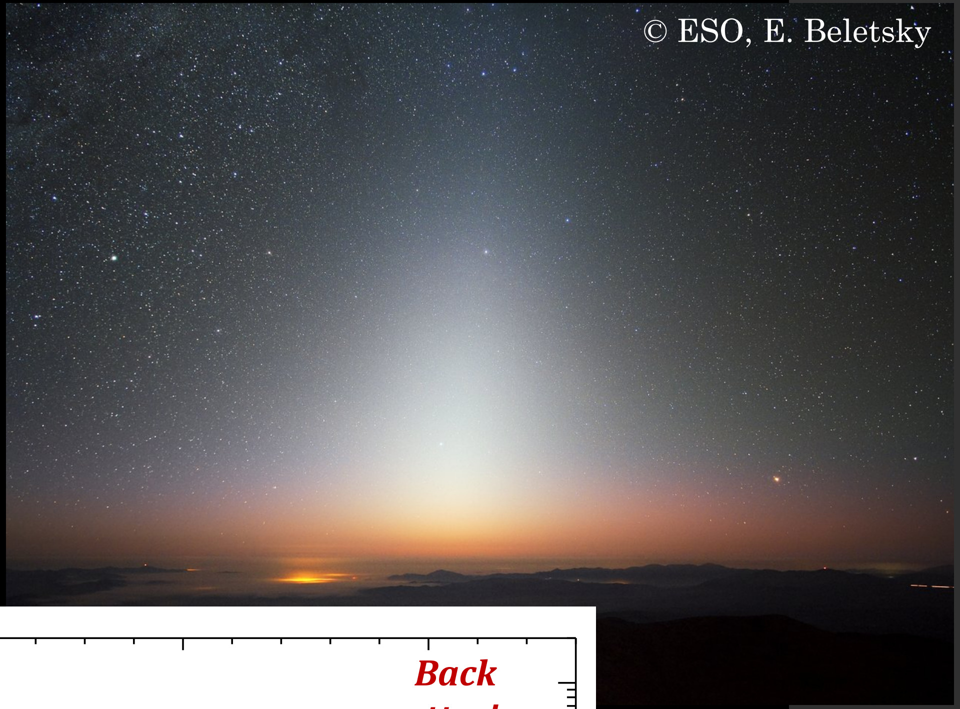
Zodiacal dust

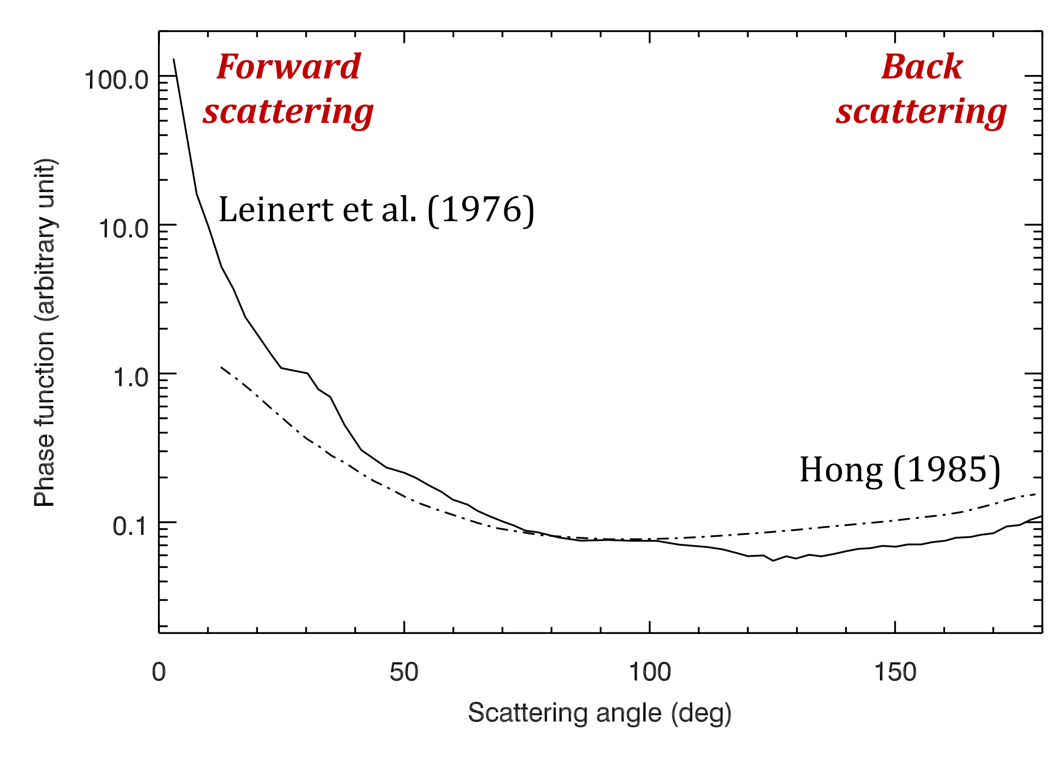
- While seeing the dust around Earth’s orbit is easy, inferring the scattering phase function relies on understanding its density structure
  - Ambiguous, since we’re in the middle of it…
  - Substructures (cometary streams)
- Significant modeling effort has been performed in the context of CMB studies (annoying foreground…)
  - No recent update to the zodiacal phase function unfortunately



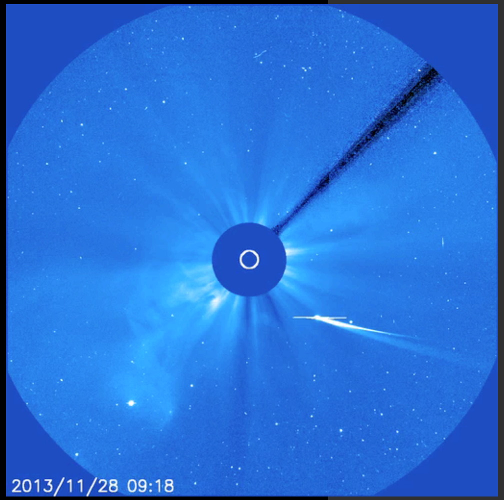
Zodiacal dust

- The zodiacal dust phase function is best characterized by
  - A strong forward scattering peak
  - A mild back scattering peak
  - A flat behavior around $\theta \approx 90°$



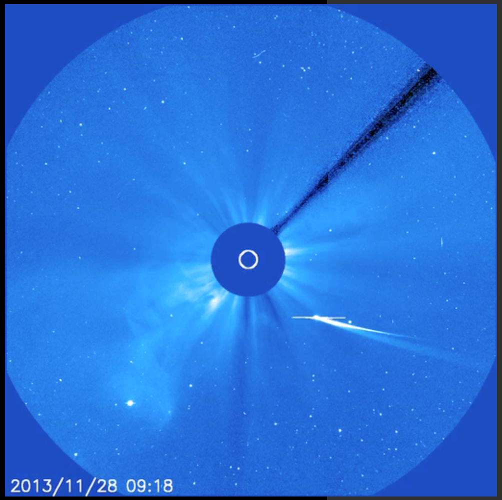


Cometary dust

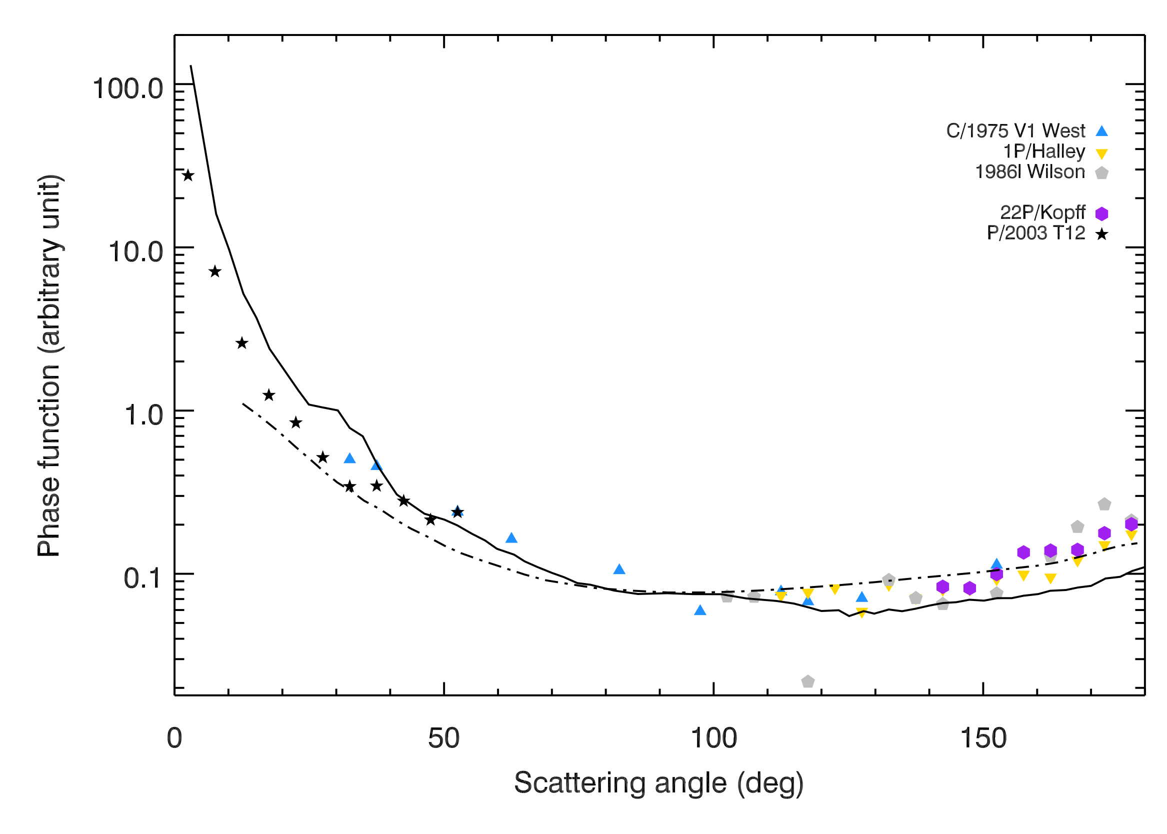


- The rapid orbit of comets allows to probe broad ranges of scattering angles
  - Under some assumptions…
- Most observations are made from Earth
  - Limited range of scattering angles probed (spends most time close to 180°)
  - Observations close to 0° are impossible
  - Activity is weak around apoastron
  - Comets are variable over days, weeks, months, …
  - Individual dust grains move under radiation forces
  - More on *Rosetta* later…

Cometary dust



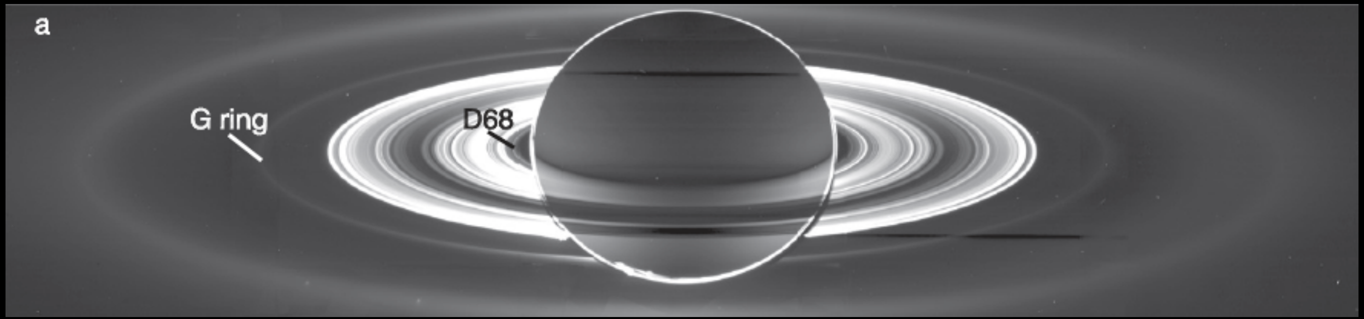
- The resulting phase function is a good match to the zodiacal dust phase function
  - Not a big surprise if comets feed the zodiacal light



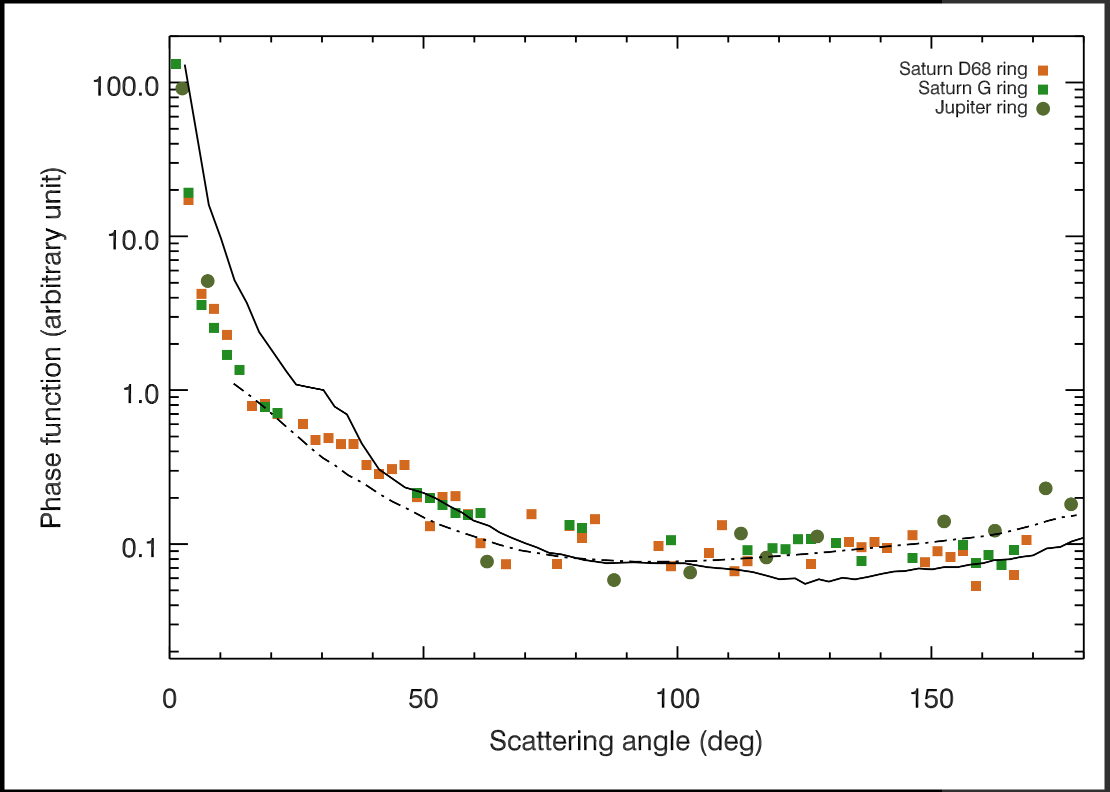
Saturn's and Jupiter rings

© NASA/JPL

- Great in situ data from *Cassini*, *Voyager* and *Galileo*
  - For Saturn, focus on the fainter G and inner D rings (optically thin)
- All three phase functions match the zodiacal one!
  - Also "volcanic ash" and "Sahara sand"…
- That's the first real surprise!
  - These dust populations are not comet-like

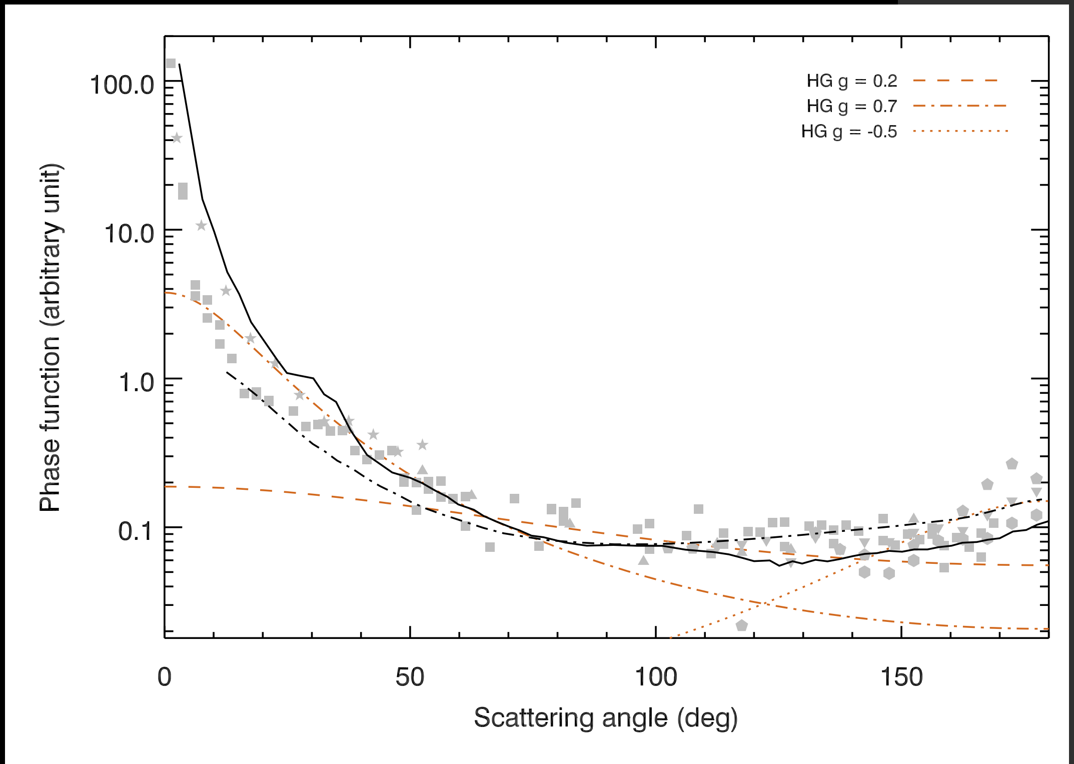


Hedman & Stark (2015)



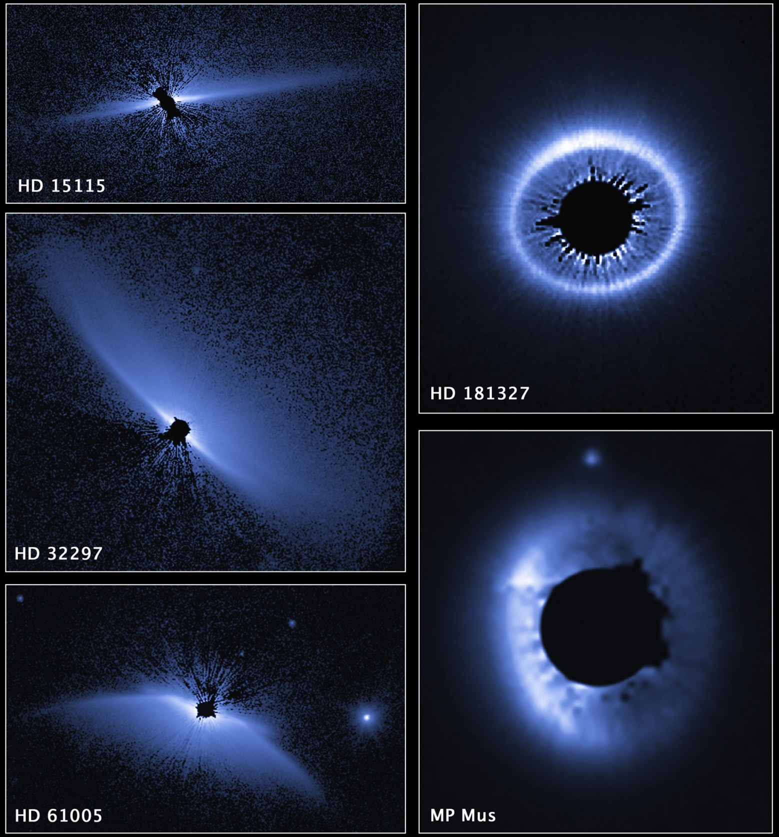
Solar System summary

- Most Solar System dust populations match a nearly unique phase function, irrespective of their detailed composition/environment
- This “generic” Solar System phase function does not match an Henyey-Greenstein phase function
  - A “3-parameter” HG function is often adopted
  - Practical, but not informative…

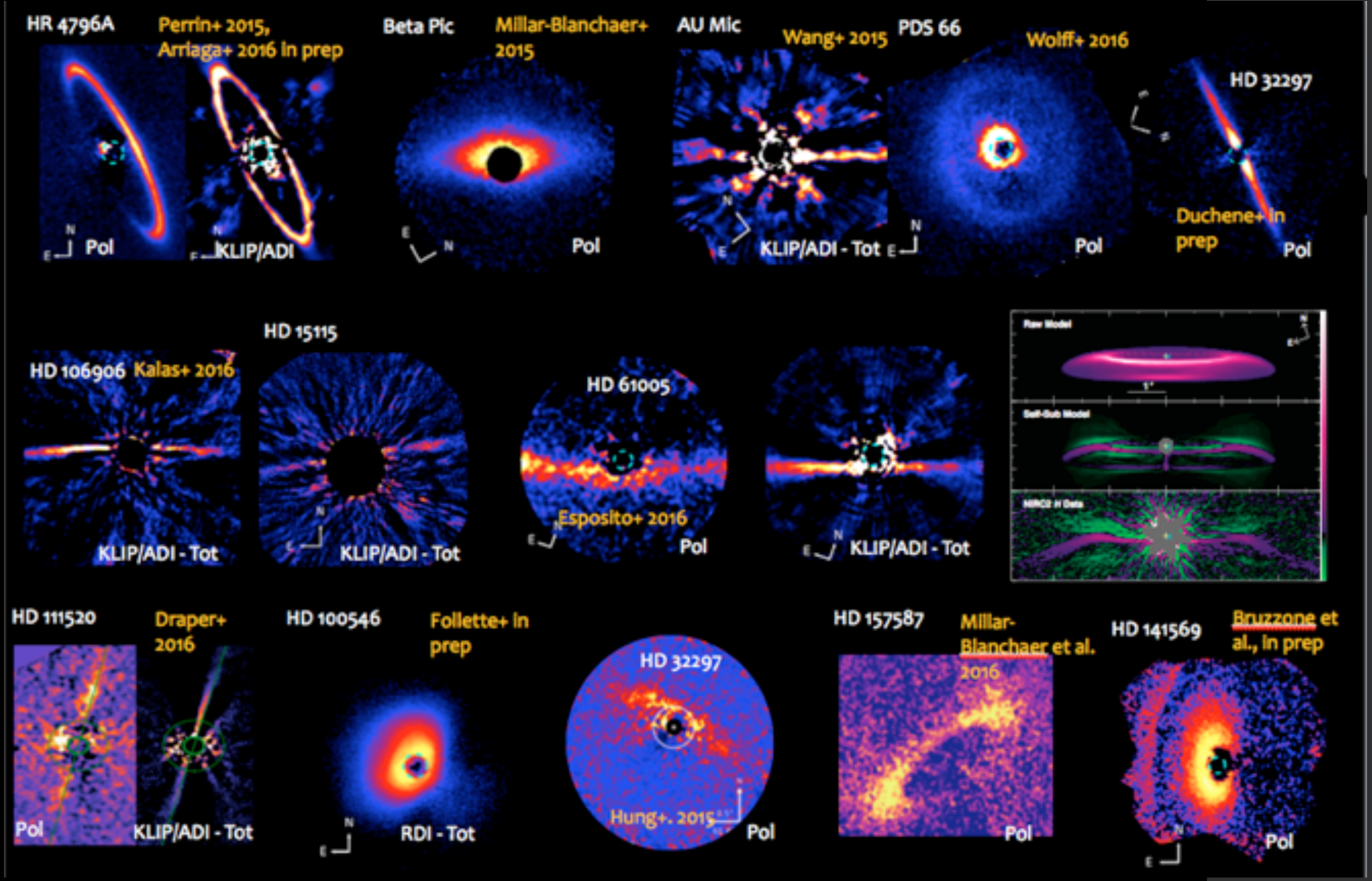


Phase function in debris disks

- Several dozen debris disks have been imaged to date, allowing us to characterize their scattering phase function

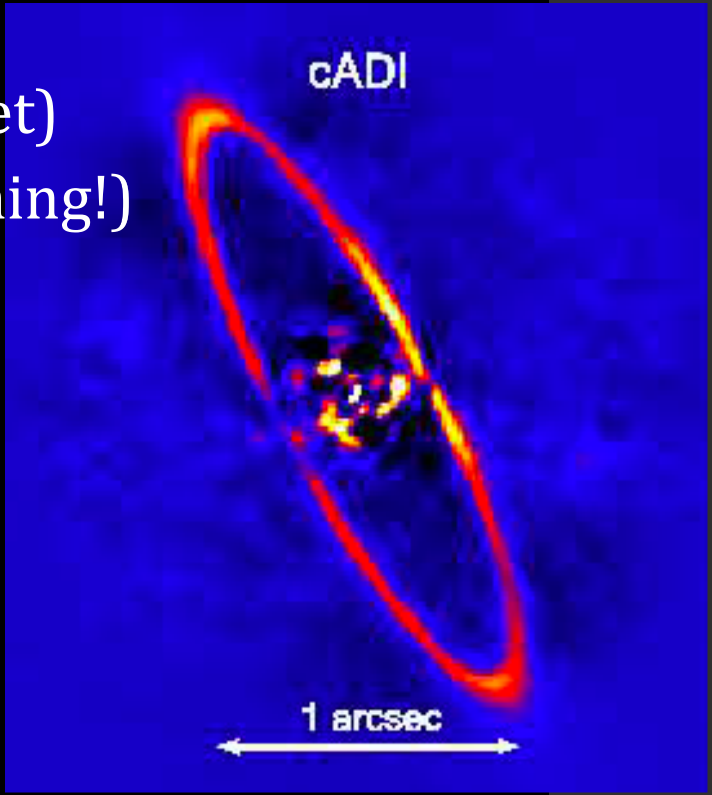


Schneider et al. (2014)

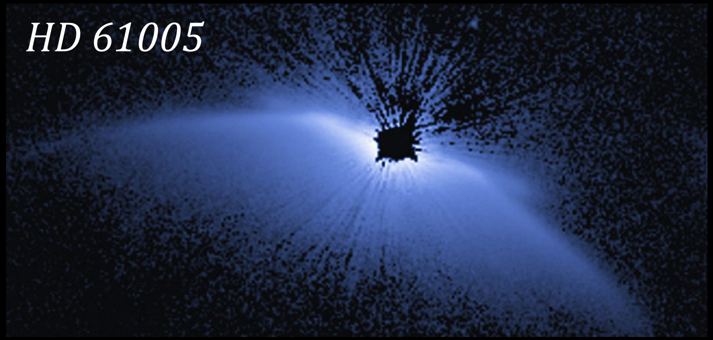


Phase function in debris disks

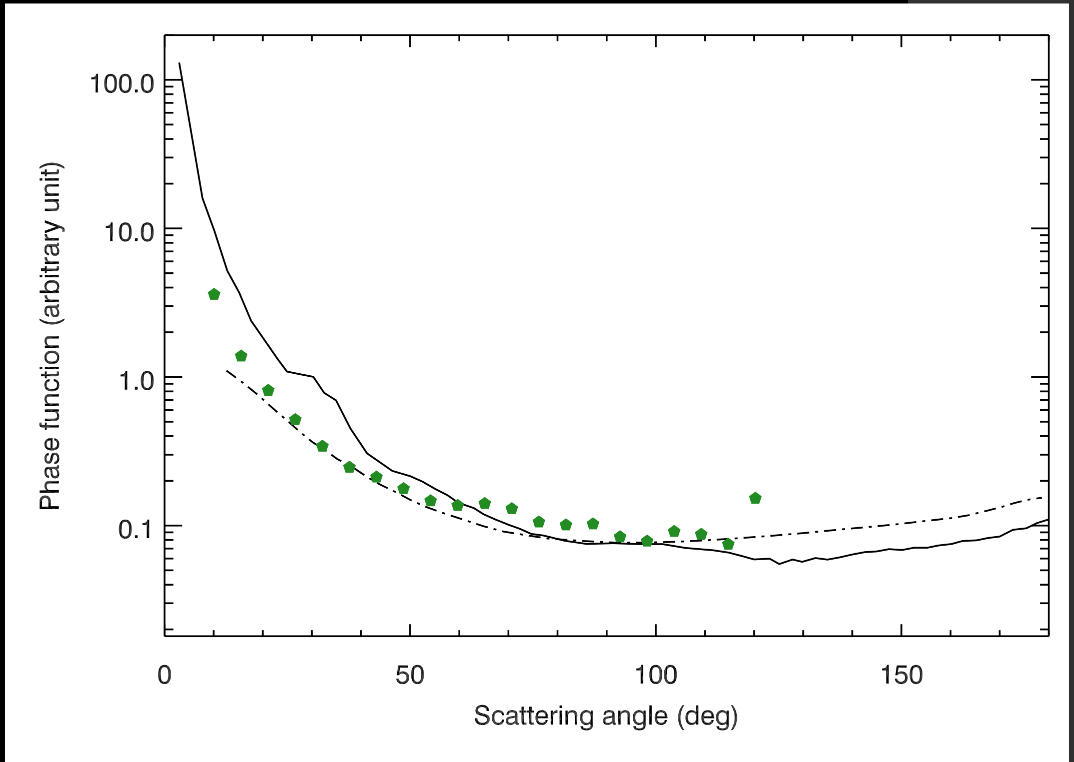
- Basic methodology:
  - Determine geometry of the belt
  - Determine scattering angle at all locations along the belt
  - Measure surface brightness at all locations along the belt
  - Correct for differences in stellar illumination (if belt is offset)
  - Correct for optical depth (thin in general, but limb brightening!)
  - Plot intensity vs scattering angle



Phase function in debris disks



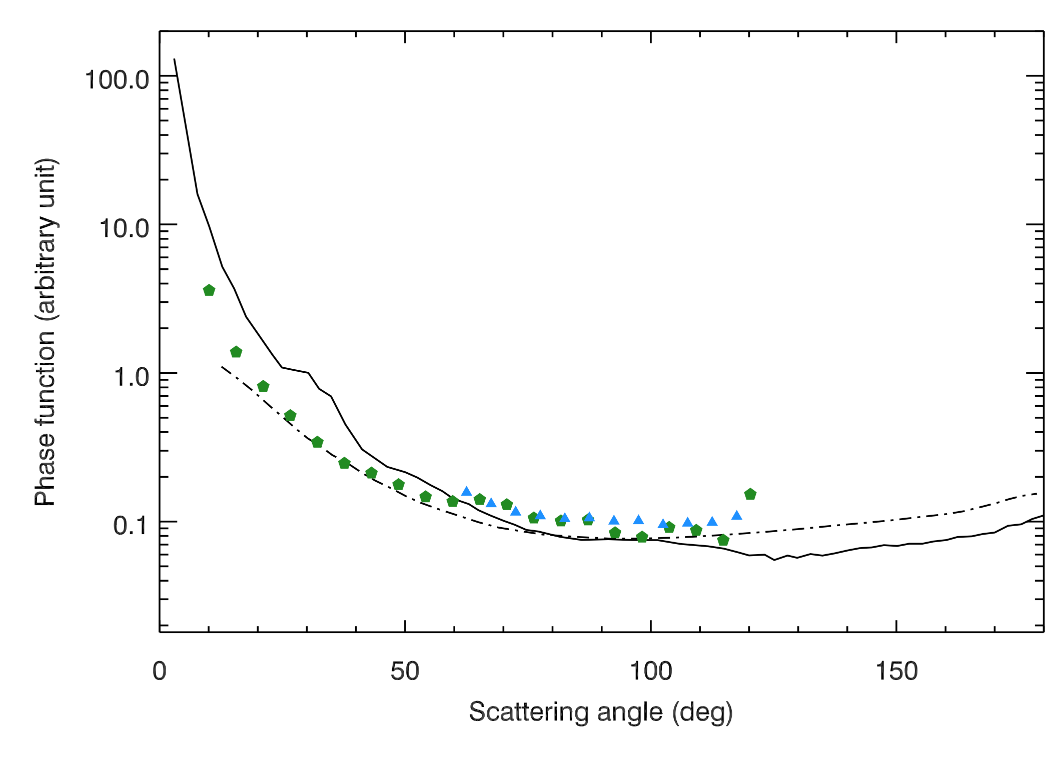
Olofsson et al. (2016)



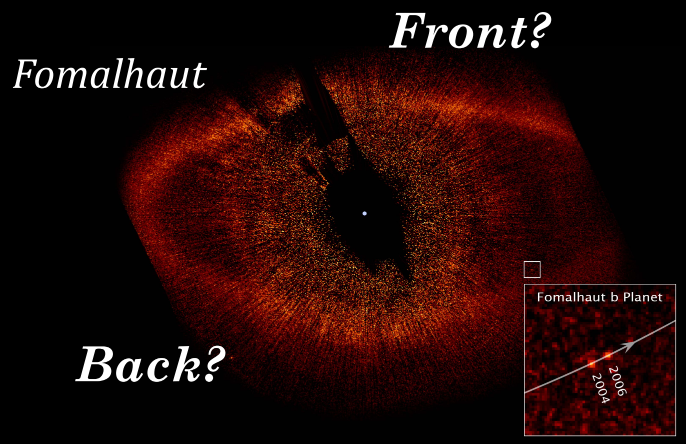
Phase function in debris disks

HD 181327

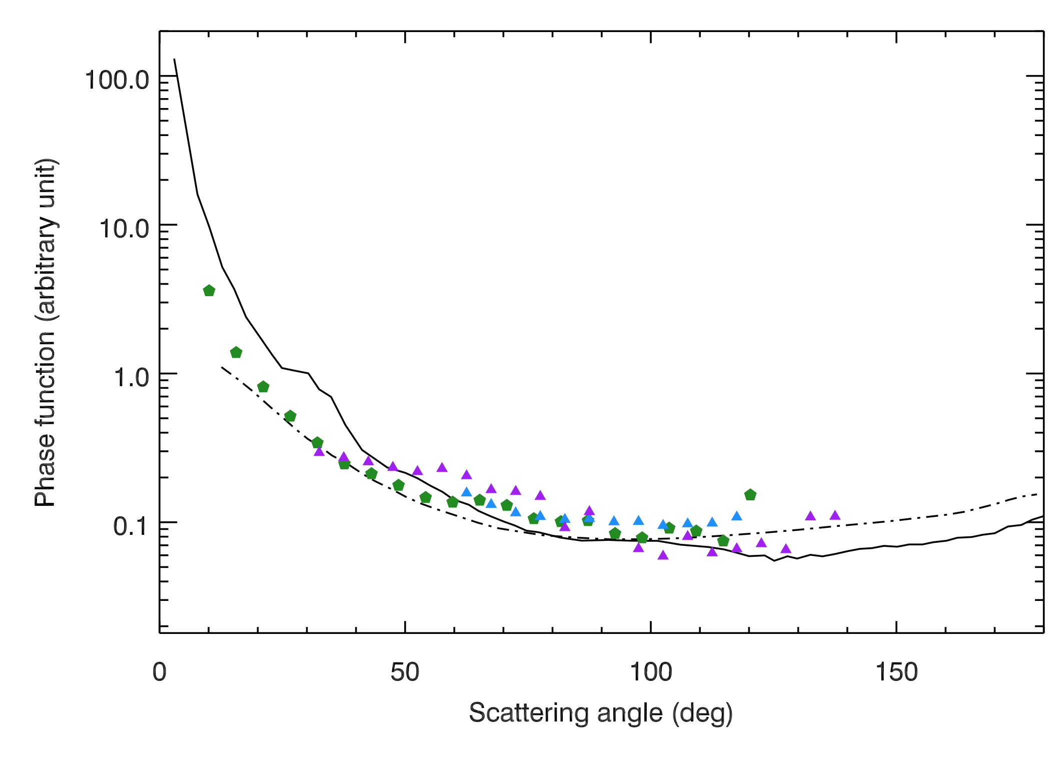
Stark et al. (2014)



Phase function in debris disks

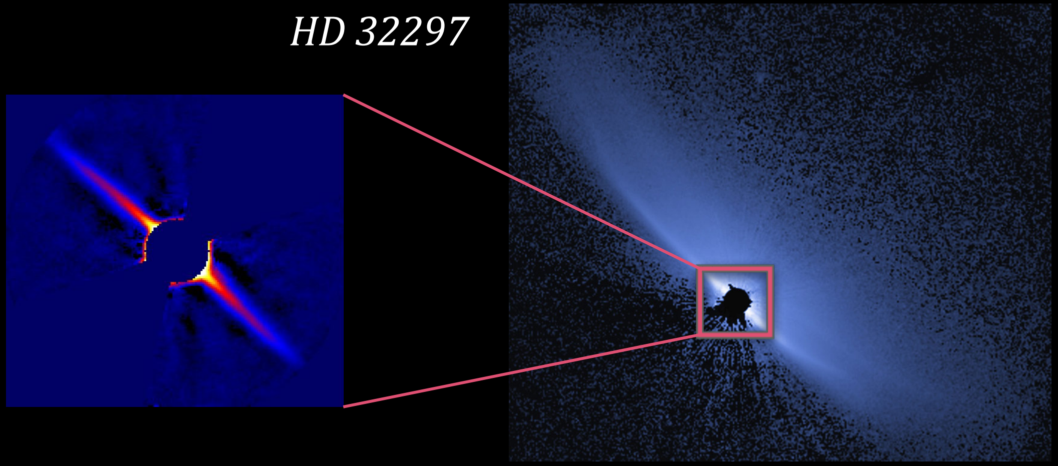


Kalas et al. (2008)

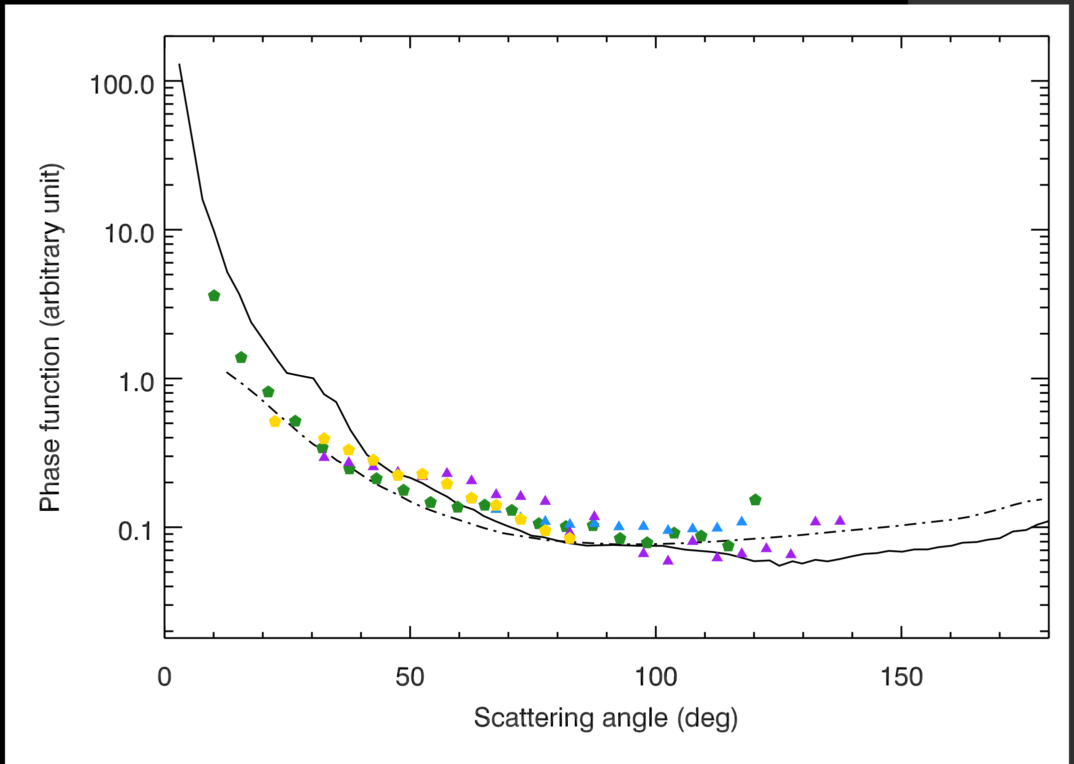


Phase function in debris disks

HD 32297

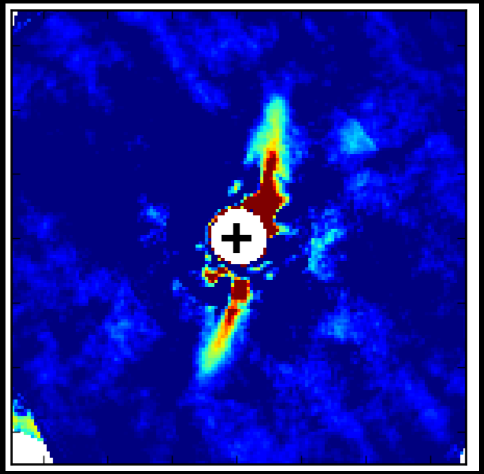


Duchêne et al. (in prep.)

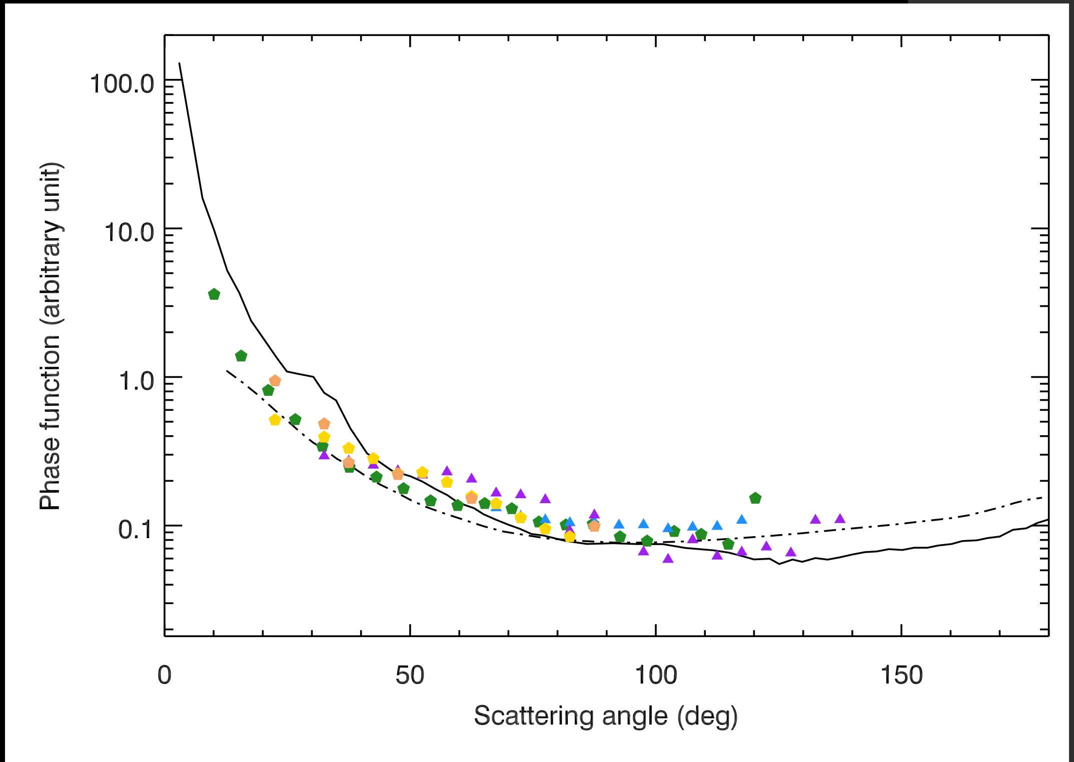


Phase function in debris disks

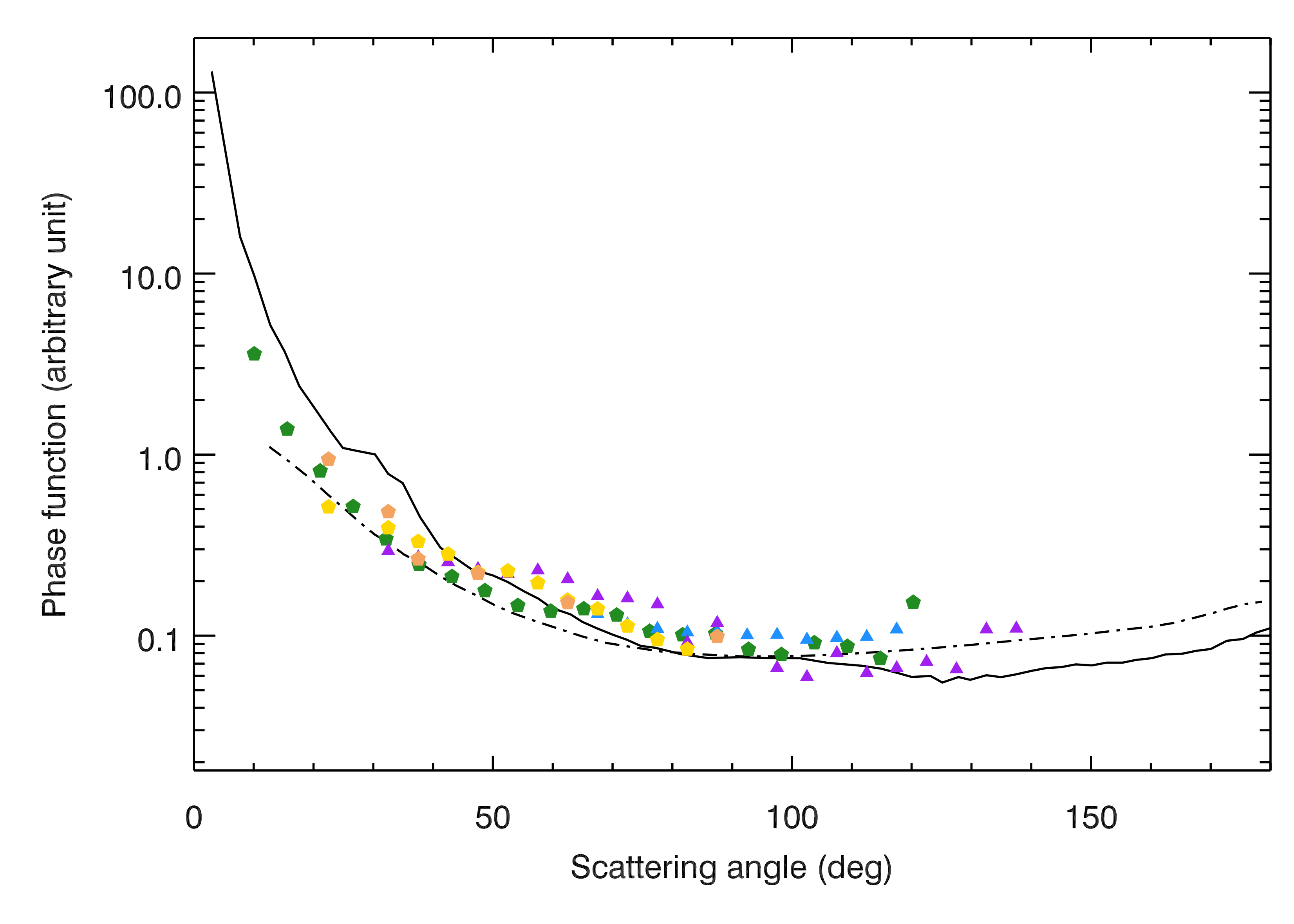
HD 35841



Esposito et al. (submitted)



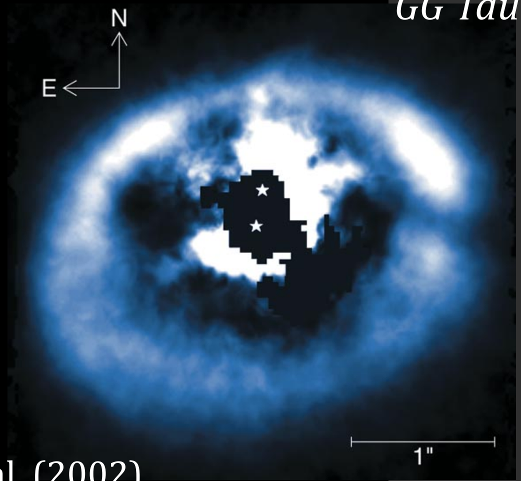
Phase function in debris disks



What about protoplanetary disks?

- Gas-rich disks surrounding ≈ 1 Myr-old Pre-Main Sequence disks are expected to have a much more pristine dust population (no blowout)
- High optical depths in these disks make scattered light analysis hard to interpret due to multiple scattering
- It has been done in the GG Tau circumbinary ring

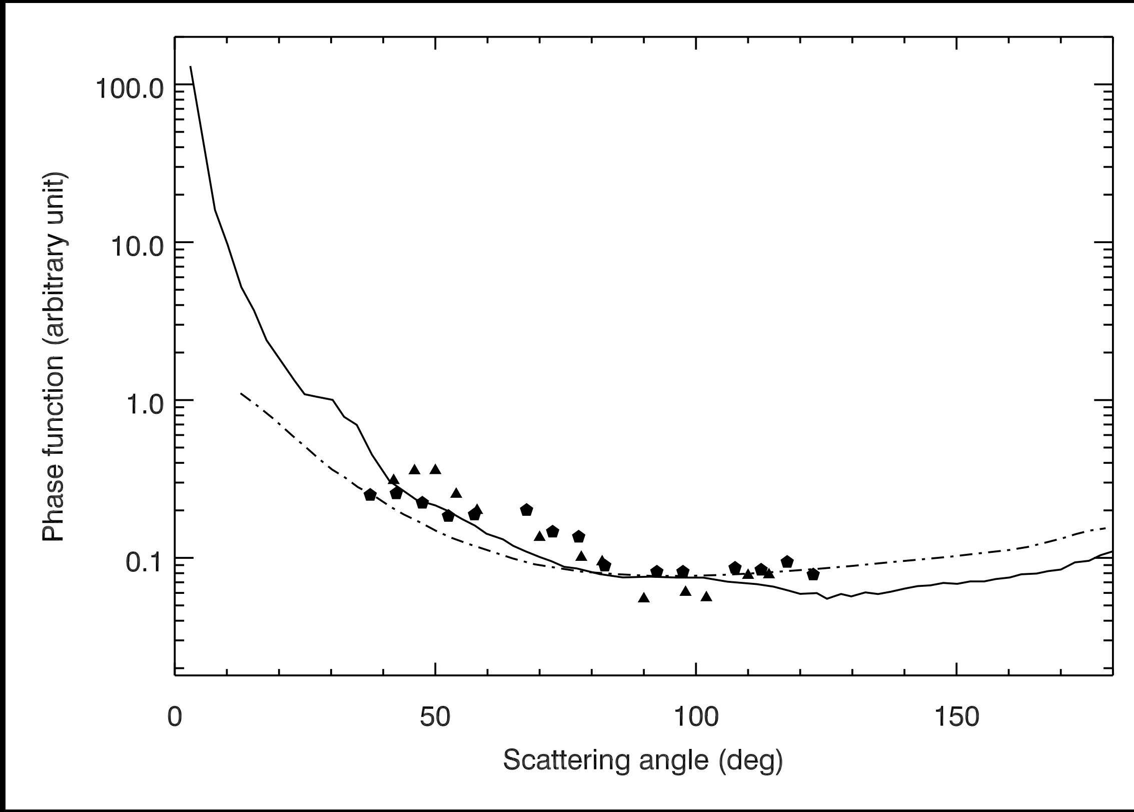
GG Tau



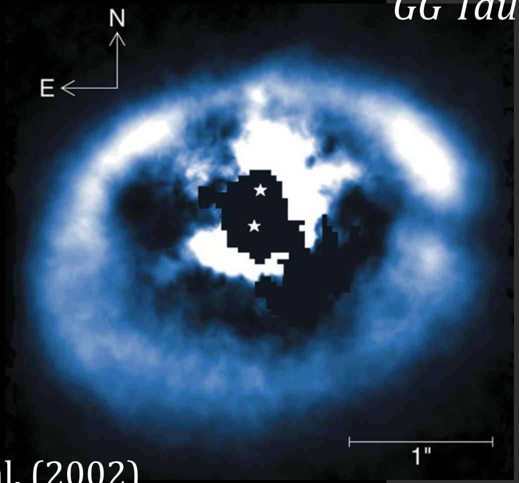
Itoh et al. (2002)

What about protoplanetary disks?

- And again, we find the same phase function as the "generic" Solar System one…
  - No significant wavelength dependence from 0.8 to 4 μm

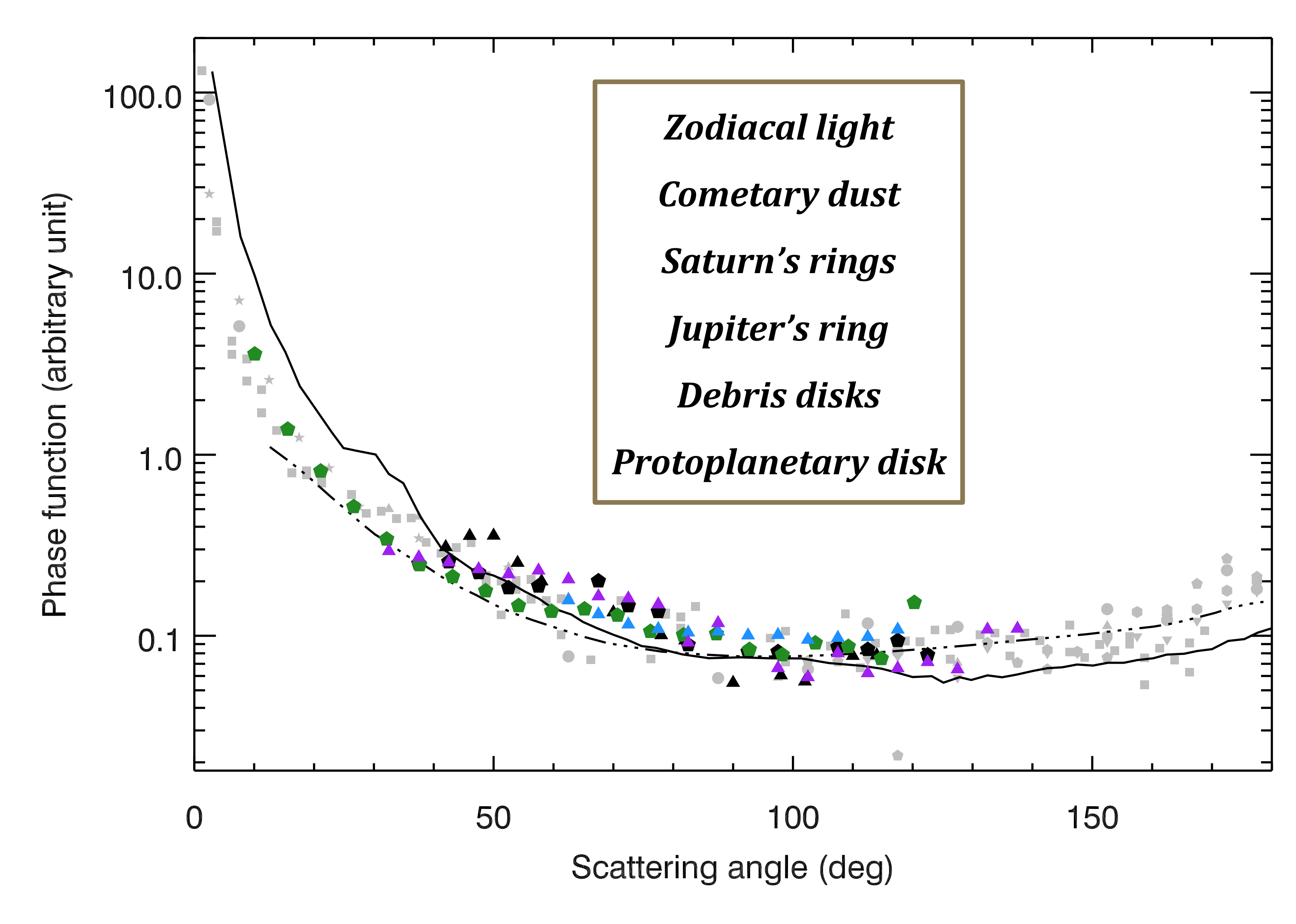


GG Tau



Itoh et al. (2002)

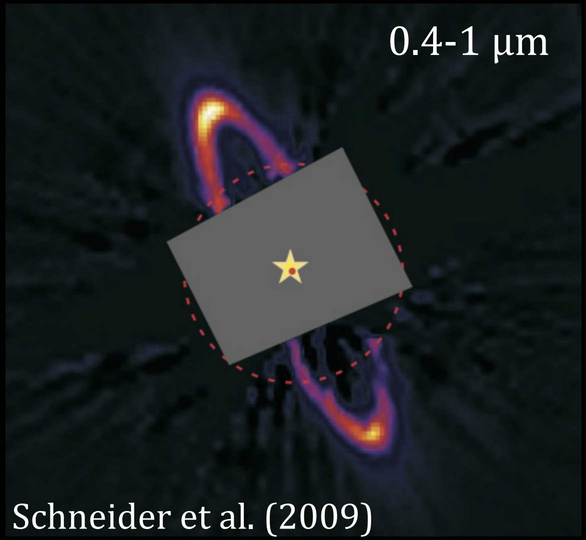
A single phase function for all dust populations!



What does it all mean?

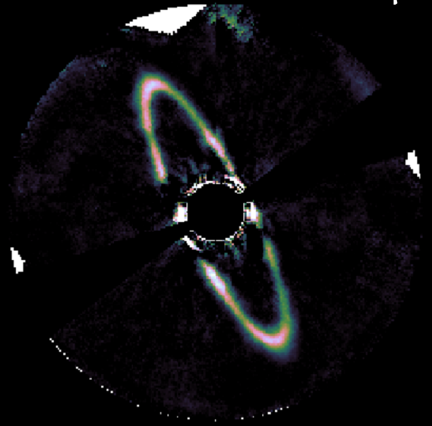
- The original motivation was to use the observed phase function (and other measurable quantities) to infer the dust population
  - The inversion problem is difficult, with no unique solution
  - Multi-wavelength observations are necessary, but may not be sufficient
  - Adding polarization brings in an additional set of constraints

HR 4796A

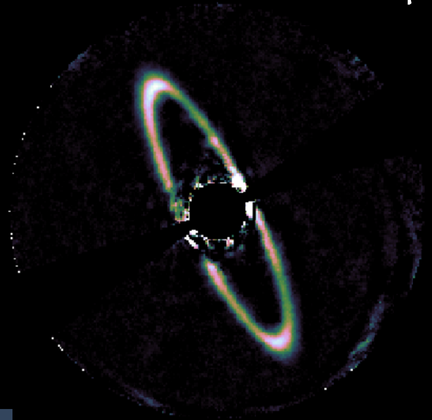


Schneider et al. (2009)

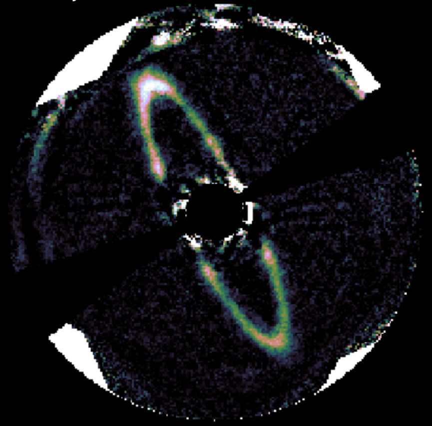
1.65 μm



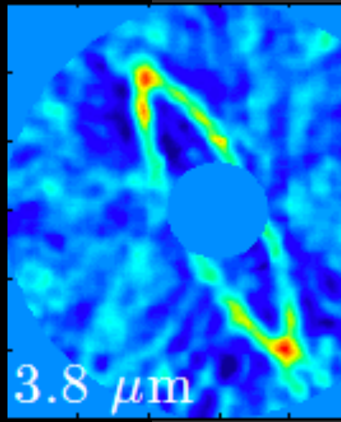
2.05 μm



2.25 μm



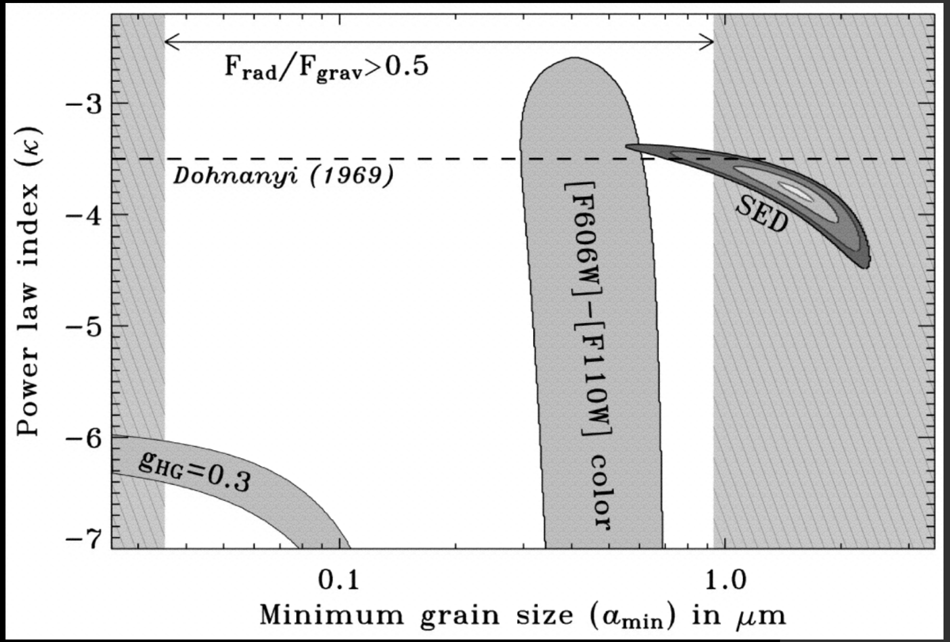
Rodigas et al. (2015)



What does it all mean?

- The original motivation was to use the observed phase function (and other measurable quantities) to infer the dust population
  - The inversion problem is difficult, with no unique solution
  - Multi-wavelength observations are necessary, but may not be sufficient
  - Adding polarization brings in an additional set of constraints
- There is no single good global fit (yet!)
  - This hints at more complex dust properties
  - Complex grain size distributions
  - Non-spherical grains
  - Spatially differentiated dust

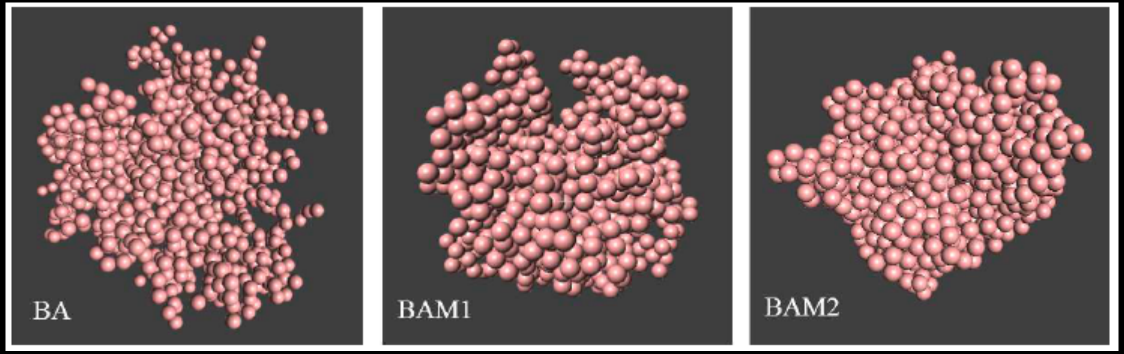
HD 181327



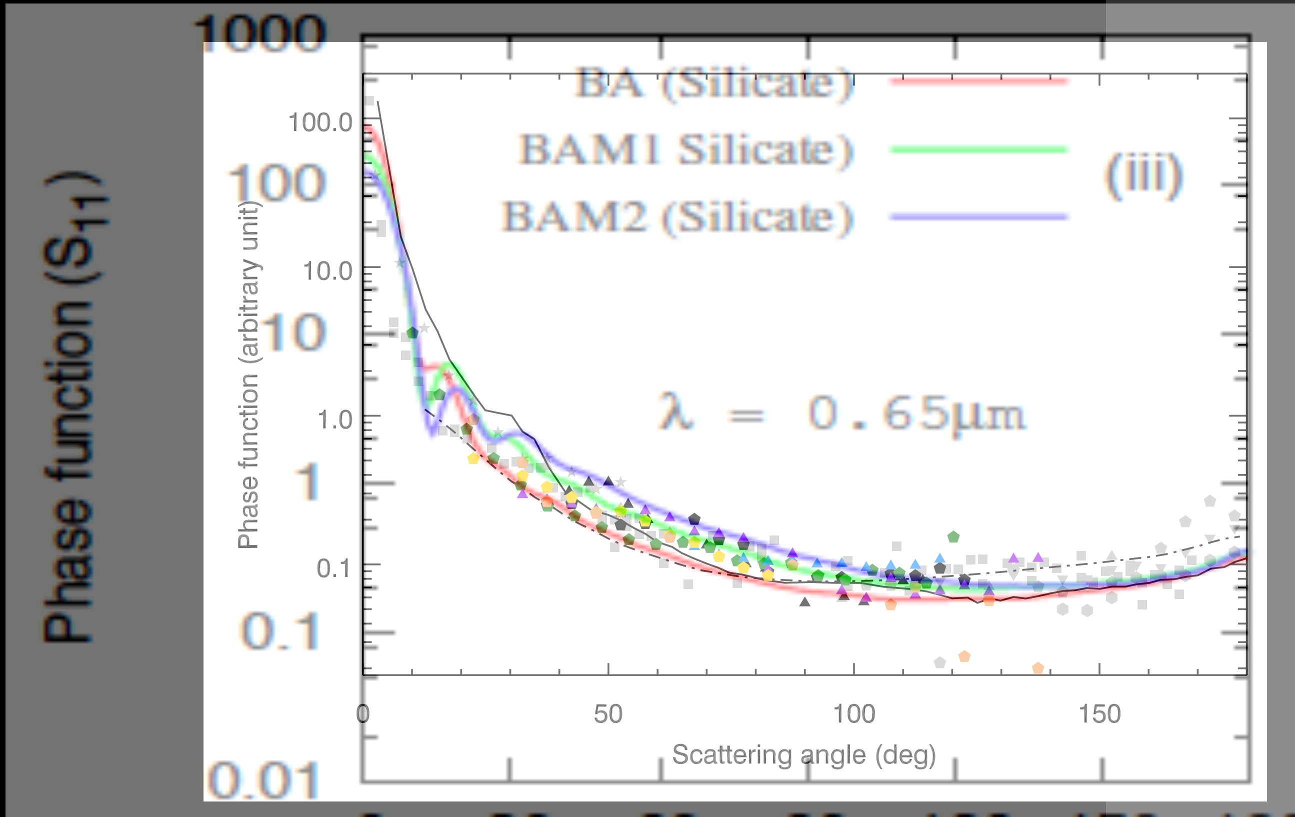
Schneider et al. (2006)

Fluffy aggregates?

- This is a recurring theme in this workshop…
  - Very good match to the "generic" phase function
- Could it apply to all environments?
- Why the similarity, though?
  - Composition does not matter?
  - Grain size does not matter?

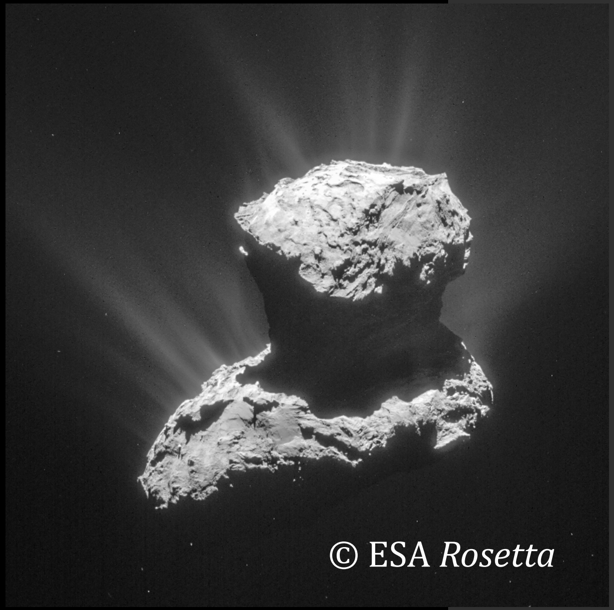


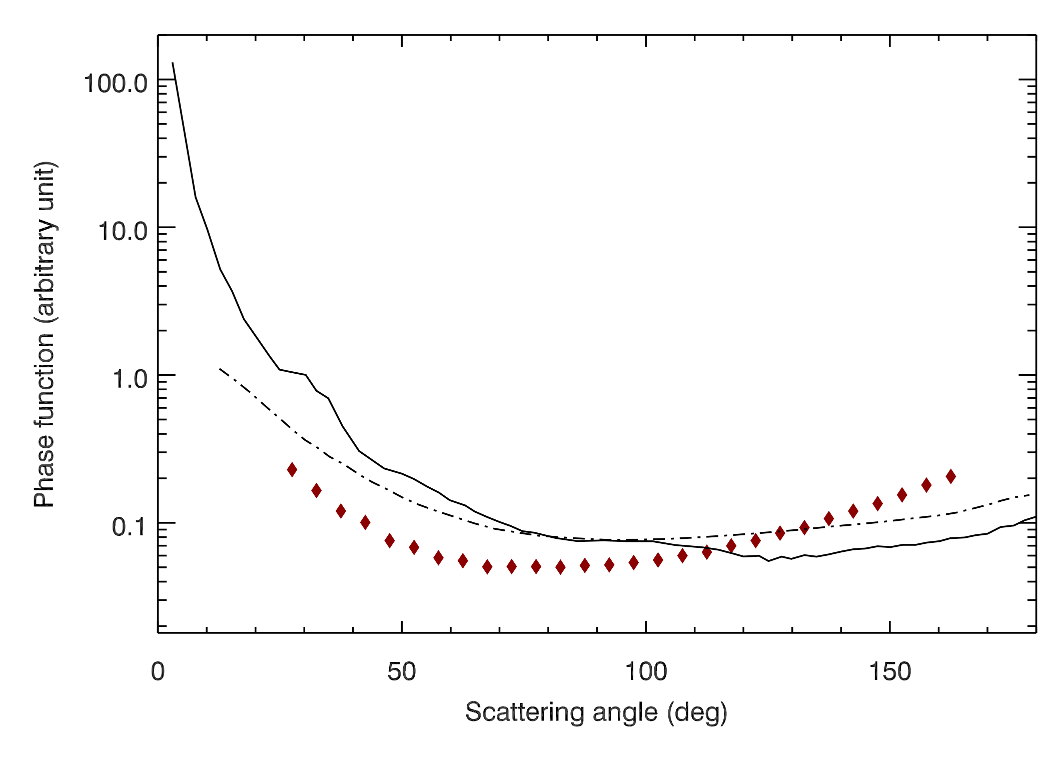
Roy et al. (2017)



For every rule an exception…

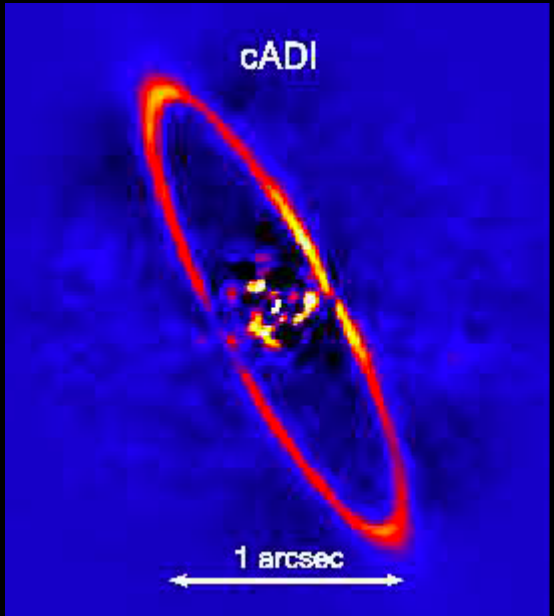
- The dust in comet 67P/C-G (*Rosetta* mission) has a markedly different phase function
  - Minimum of the phase function at smaller scattering angle
  - Stronger back scattering peak than other comets
- Is this a "special" comet?
  - 67P belongs to the Jupiter-family
- Is this a "special" time?
  - Around perihelion
- Is this a "special" dust?
  - Large-ish particles, close to the comet



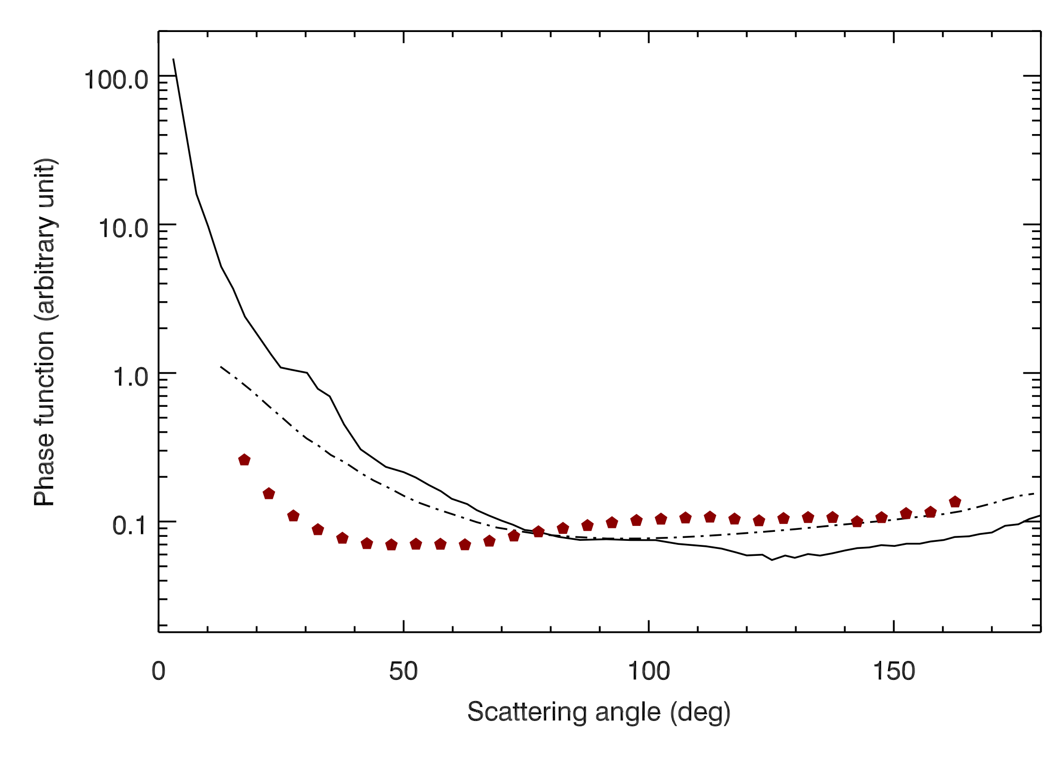


For every rule an exception…

- The HR 4796 ring also deviates from the “generic” phase function
  - Particularly large grains compared to other disks?
  - Optical depth effects affecting interpretation?
  - Intrinsic disk asymmetry?
- Similar to comet 67P’s phase function
  - Coincidence?



Milli et al. (2017)



Summary and perspective

- Scattering off dust grains follows a surprisingly (disappointingly?) close to universal phase function
- There is something to learn!