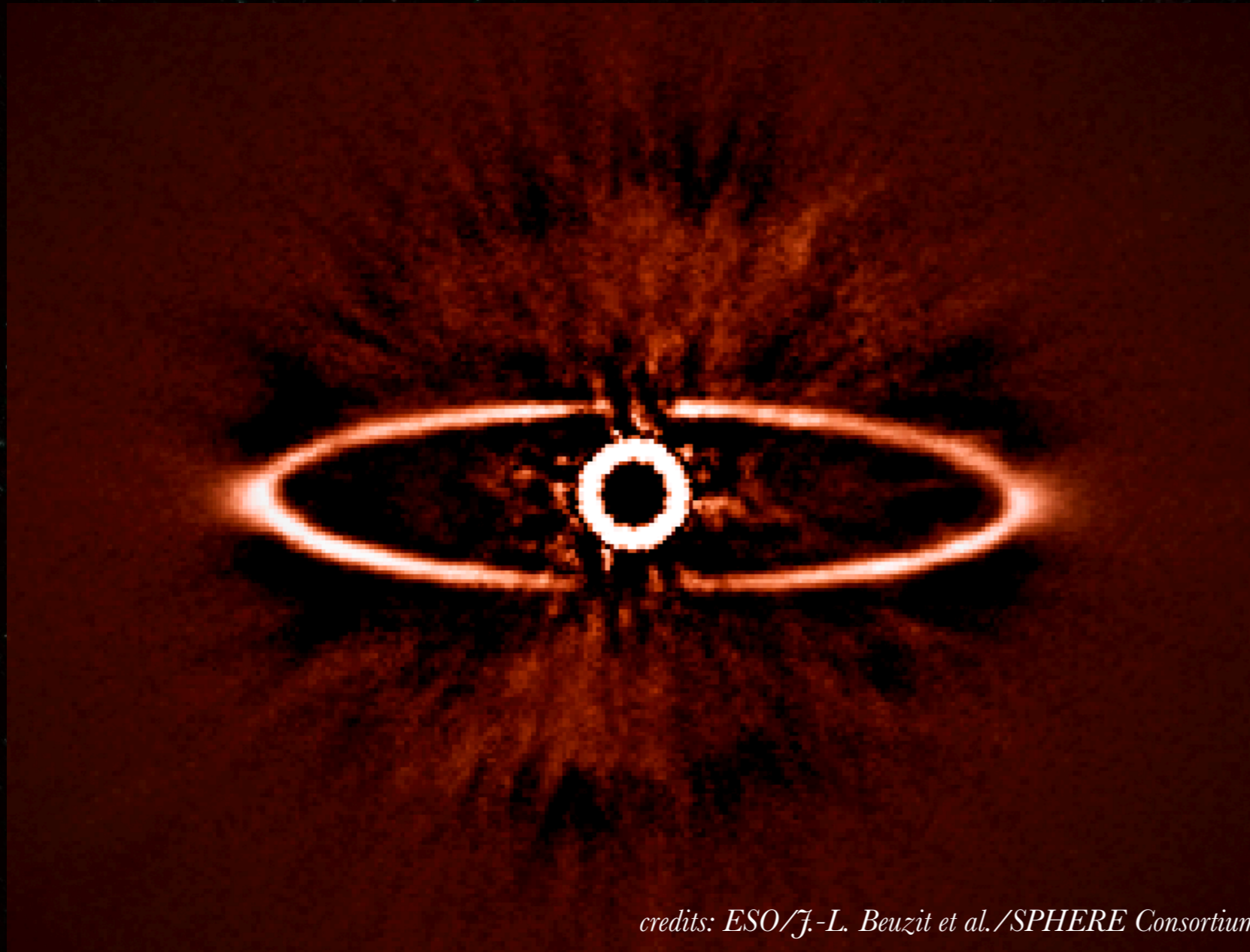


The dust in Sauron's eye:

Observational and experimental results on the HR4696 debris disk



**Myriam Bonduelle,
Julien Milli, Olivier Poch
&
the ÉPOPÉE team**

credits: ESO/J.-L. Beuzit et al./SPHERE Consortium

Debris disks : -dust & gas

-reservoirs of planetesimals (km-sized)

↘ collisions ↘

dust / ice particles
 μm and mm sized

scattered light observations
 $\lambda_{\text{obs}} \sim \text{vis/NIR}$

↓
thermal emission

$\lambda_{\text{obs}} \sim \text{sub-mm/mm}$

Debris disk around HR 4796 A :

- $d_{\text{star}} = 70.8 \text{ pc}$ (Gaia DR3)

- $\sim 10 \text{ Myr}$



Artist's impression — Credits : NASA/JPL Caltech

scattered light
observations

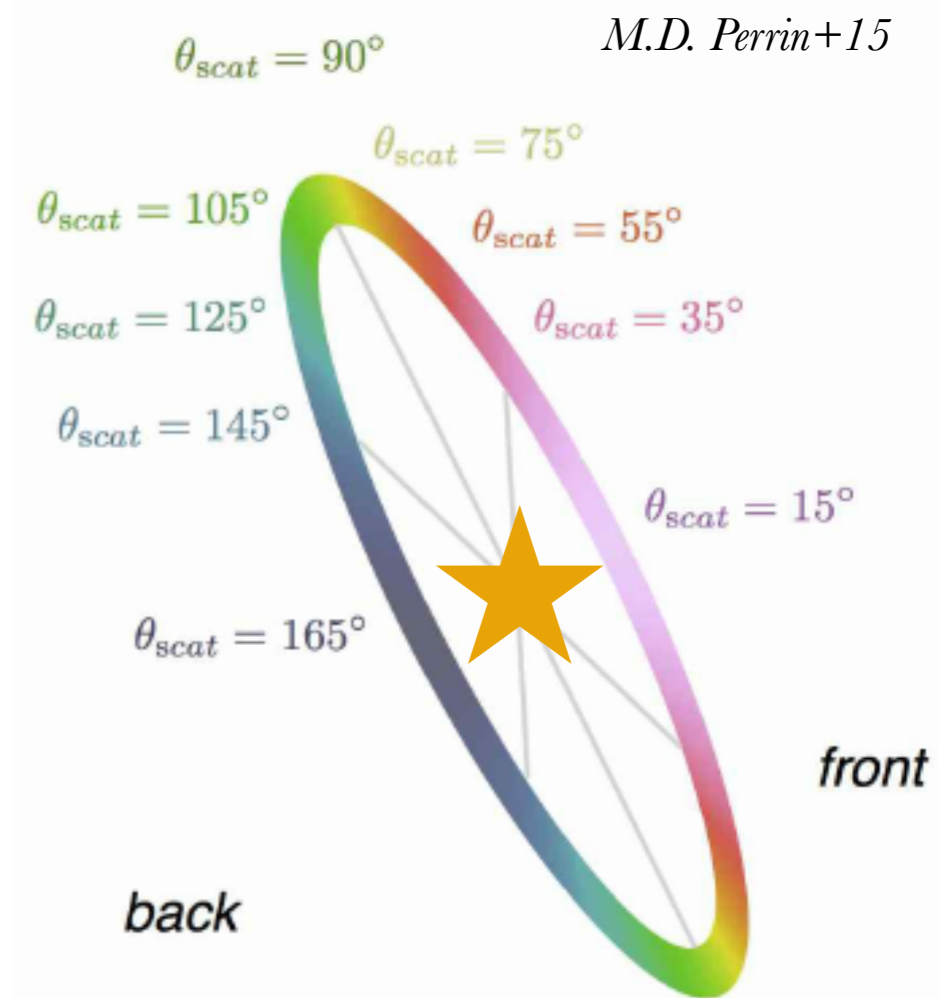
$\lambda_{obs} \sim vis/NIR$

- ➔ light from the star scattered by the dust particles
- ➔ total intensity I & polarised intensity Q_{ϕ}
- ➔ dominated by particles of a size $\approx \lambda_{obs}$

Access to:

-spectral reflectance

$$I = f(\lambda) @ a \text{ given } \theta_{scat}$$



Depending on the geometry of the disk, not all scattering angles are accessible

scattered light
observations

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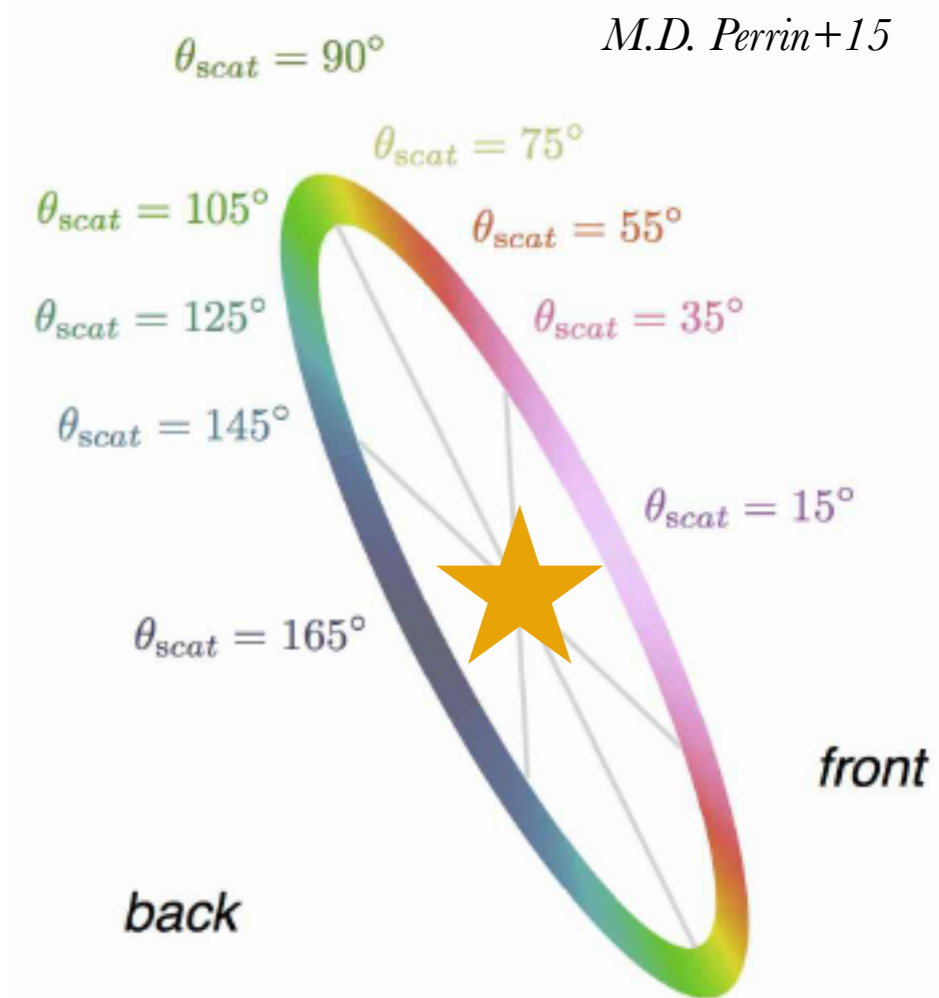
Access to:

-spectral reflectance

$$I = f(\lambda) \text{ @ a given } \theta_{scat}$$

-scattering phase function (SPF)

$$I = f(\theta_{scat}) \text{ @ a given } \lambda$$



Depending on the geometry of the disk, not all scattering angles are accessible

scattered light
observations

$\lambda_{obs} \sim vis/NIR$

- ➔ light from the star scattered by the dust particles
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Access to:

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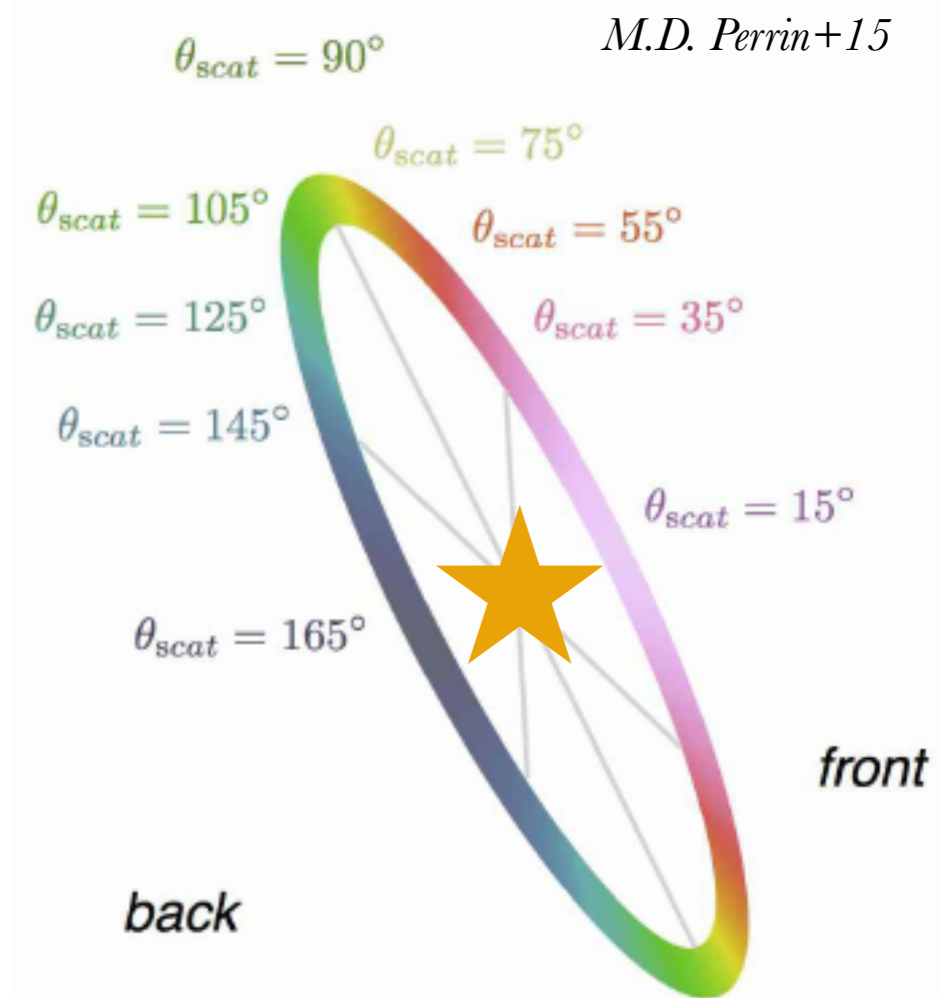
$$I = f(\lambda) \text{ @ a given } \theta_{scat}$$

-scattering phase function (SPF)

$$I = f(\theta_{scat}) \text{ @ a given } \lambda$$

-degree of linear polarisation (DoLP)

$$Q_{\phi}/I = f(\theta_{scat}) \text{ @ a given } \lambda$$



Depending on the geometry of the disk, not all scattering angles are accessible

scattered light
observations

$\lambda_{obs} \sim vis/NIR$

- ➔ light from the star scattered by the dust particles
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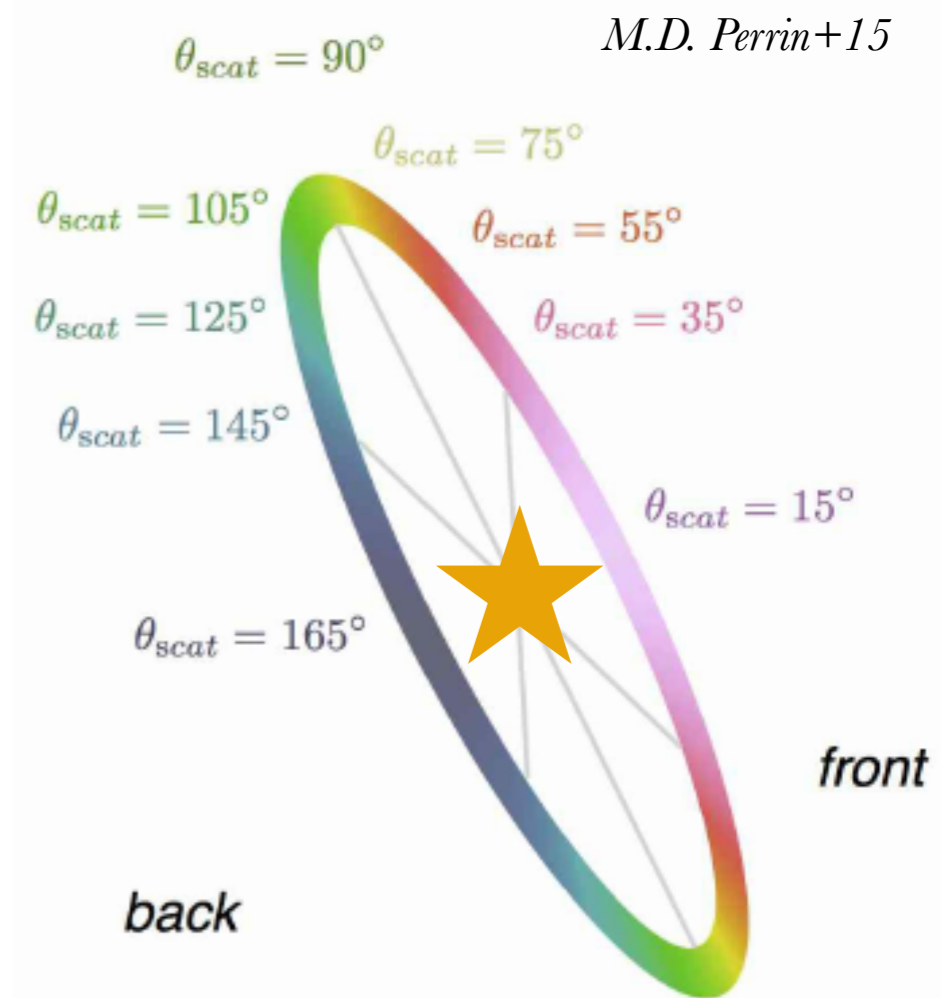
Access to:

-spectra, SPF, DoLP



depend on the properties of the
observed dust particles:
-shape, size, composition...

*degeneracies remain : necessity for a pluri-
disciplinary approach (laboratory measurements,
multi- λ observations...)*

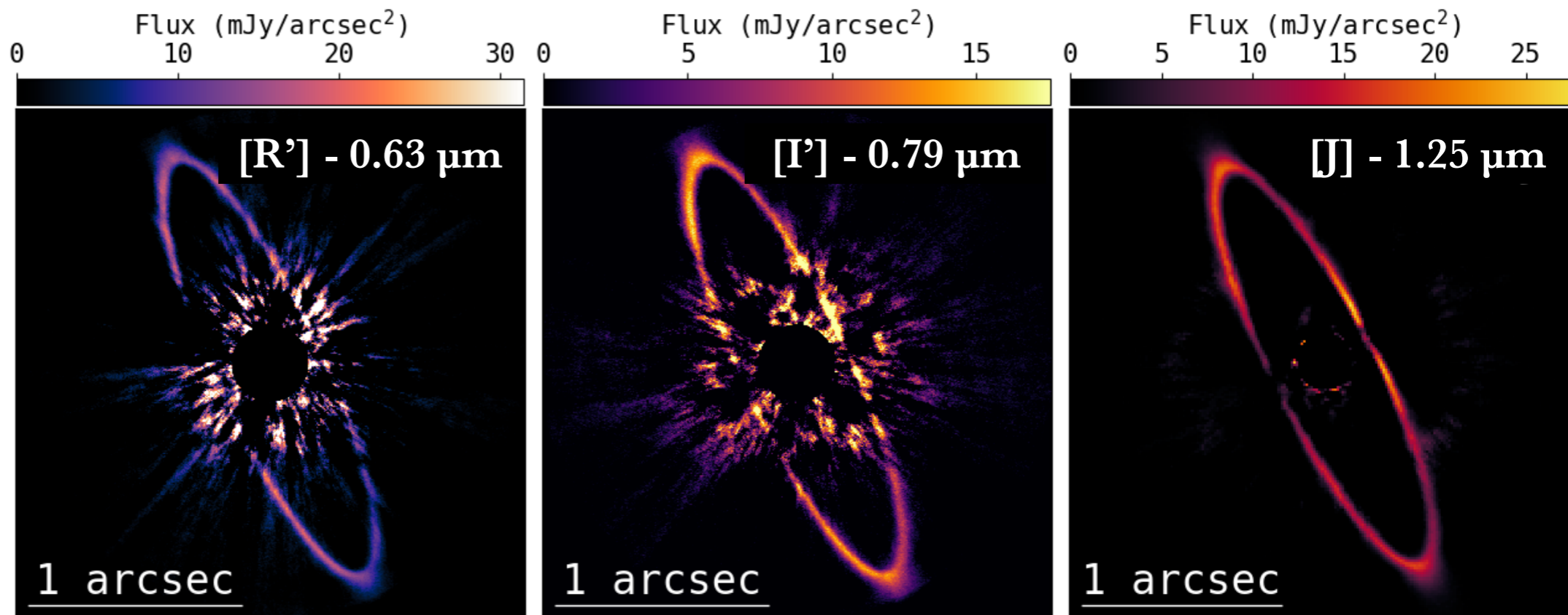


*Depending on the geometry of the disk, not all
scattering angles are accessible*

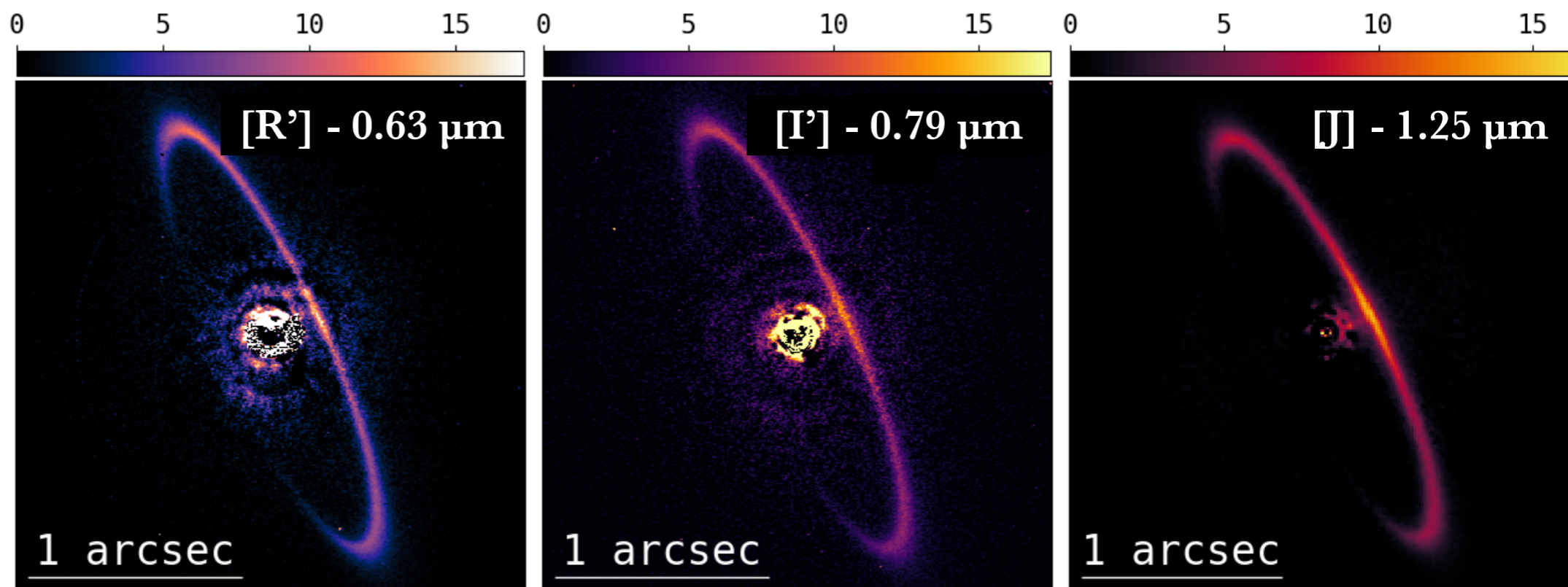
I.3: Observing HR 4796:

Dataset

Total Intensity
PCA



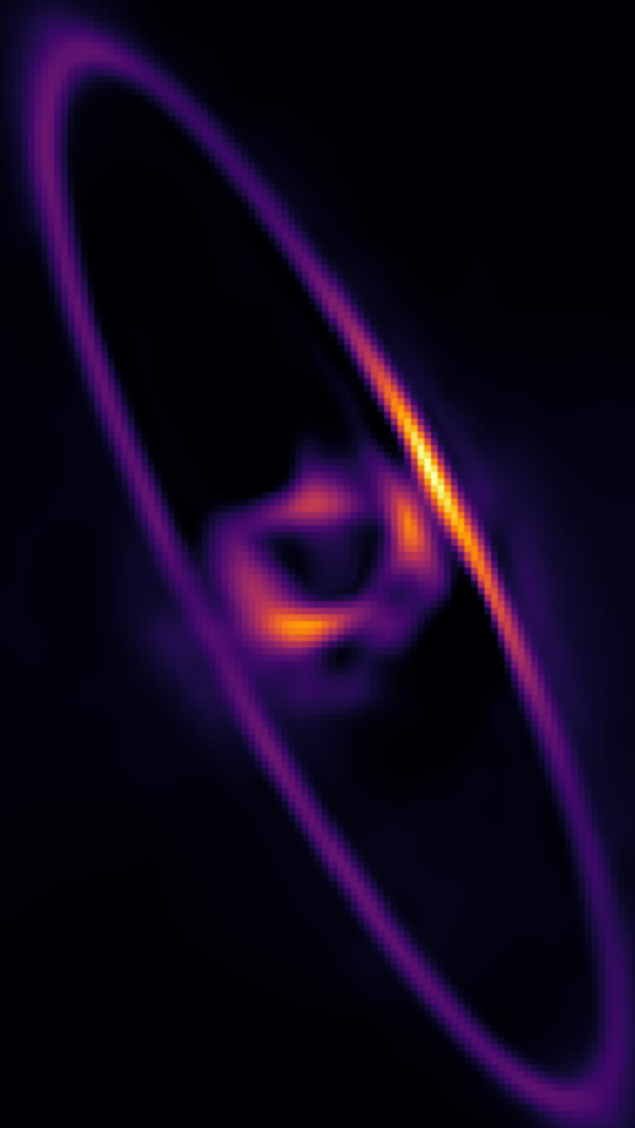
Polarised light
 $Q\phi$



What are the characteristic of HR 4796 ?

→ forward-models

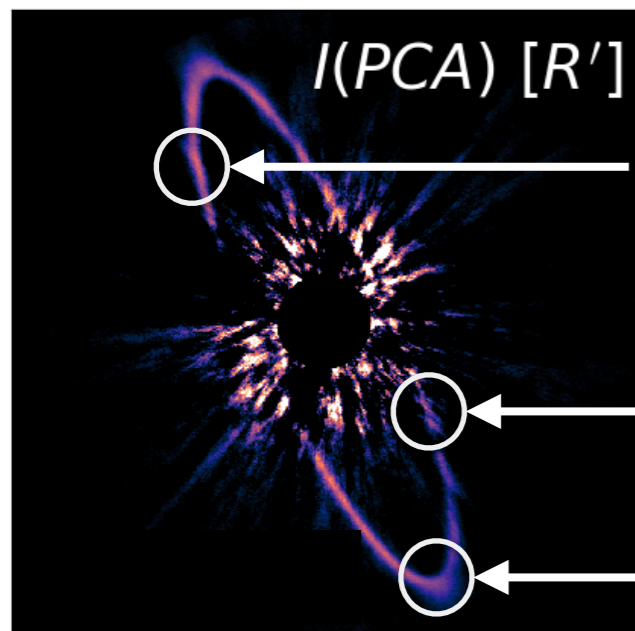
*morphological description
&
phase functions (SPF + DoLP)*



Joint forward modelling : ADI + PDI

- Model:
- 7 [6] “morphological” free parameters (*Augereau+99, Milli+17*)
 - Parameters describing the phase functions (SPF & DoLP)

▶ **SPF** : $I = f(\theta)$ @ a given λ

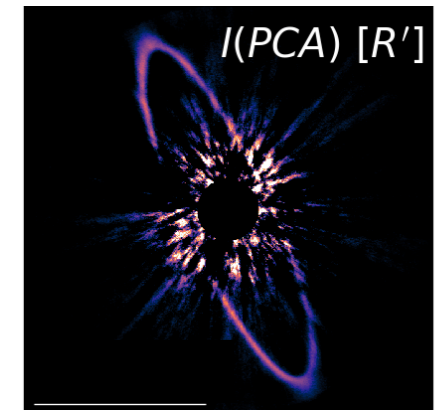
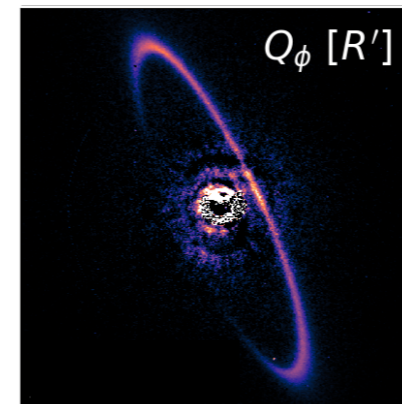


$\theta = 125^\circ$

$\theta = 55^\circ$

$\theta = 90^\circ$

▶ **DoLP**: $\frac{Q_\phi}{I} = f(\theta)$ @ a given λ



▶ **double Henyey-Greenstein** (*cf Milli+17*)

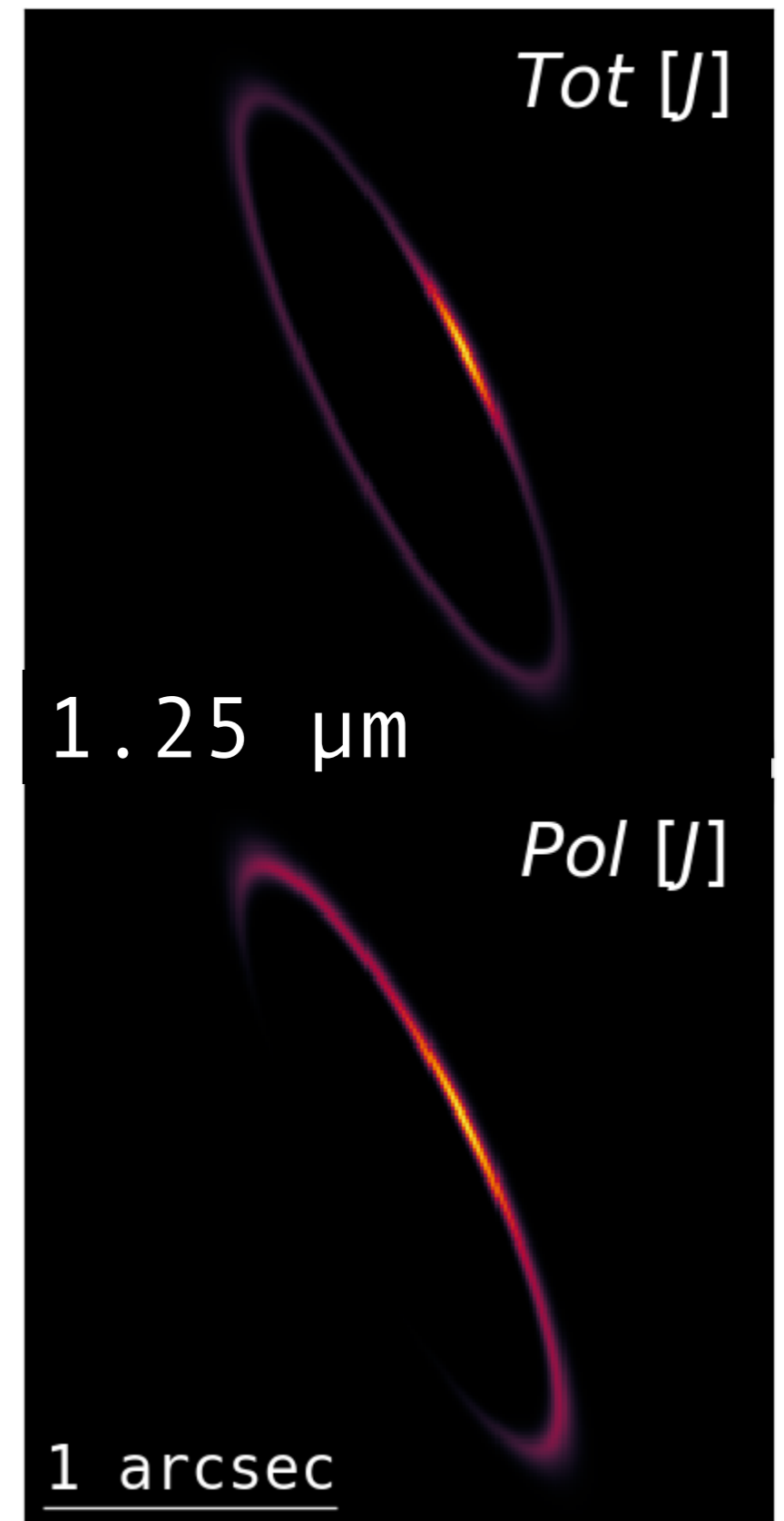
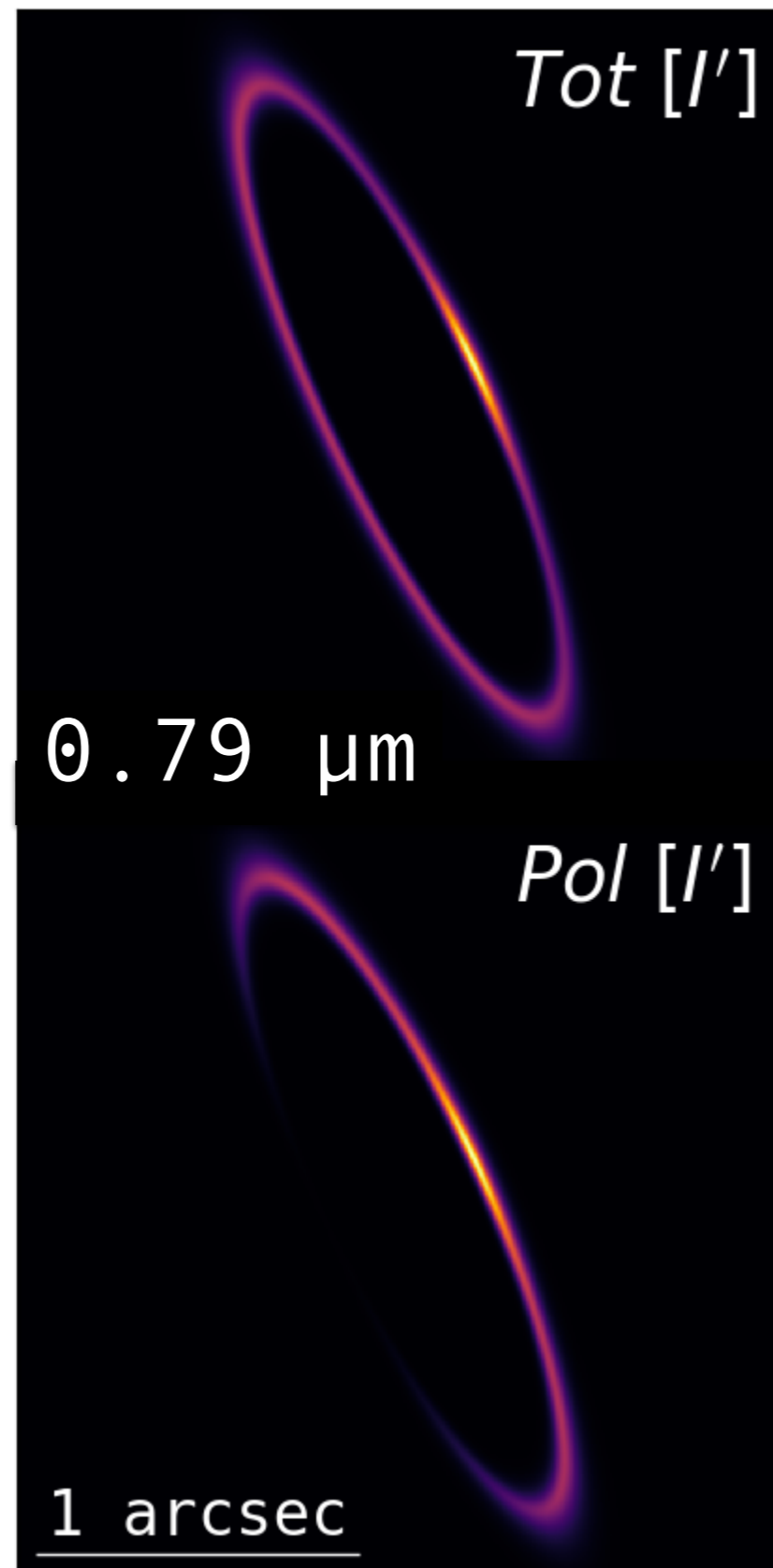
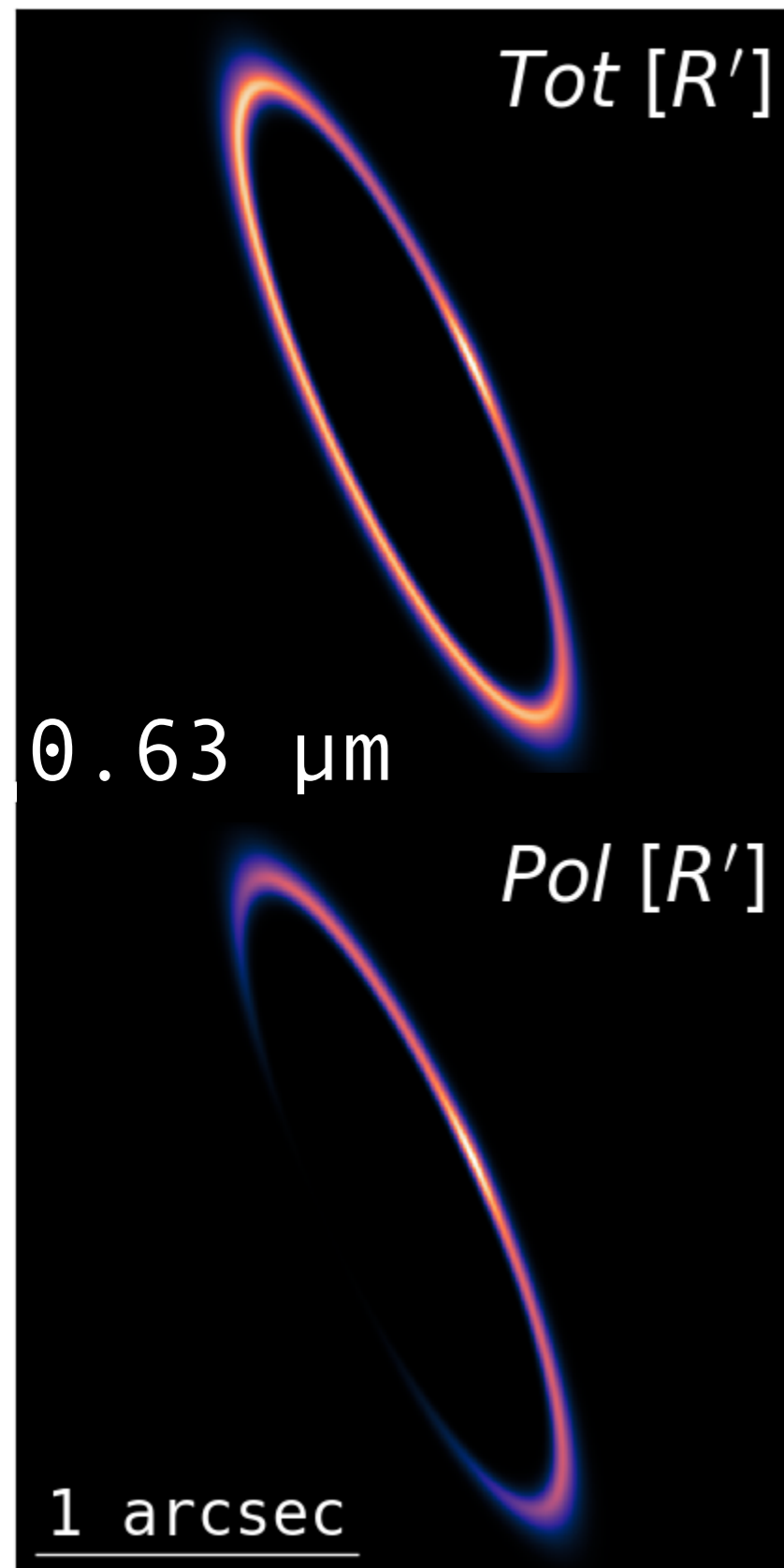
4 parameters

▶ **beta function** (*cf Ren+23*)

3 parameters

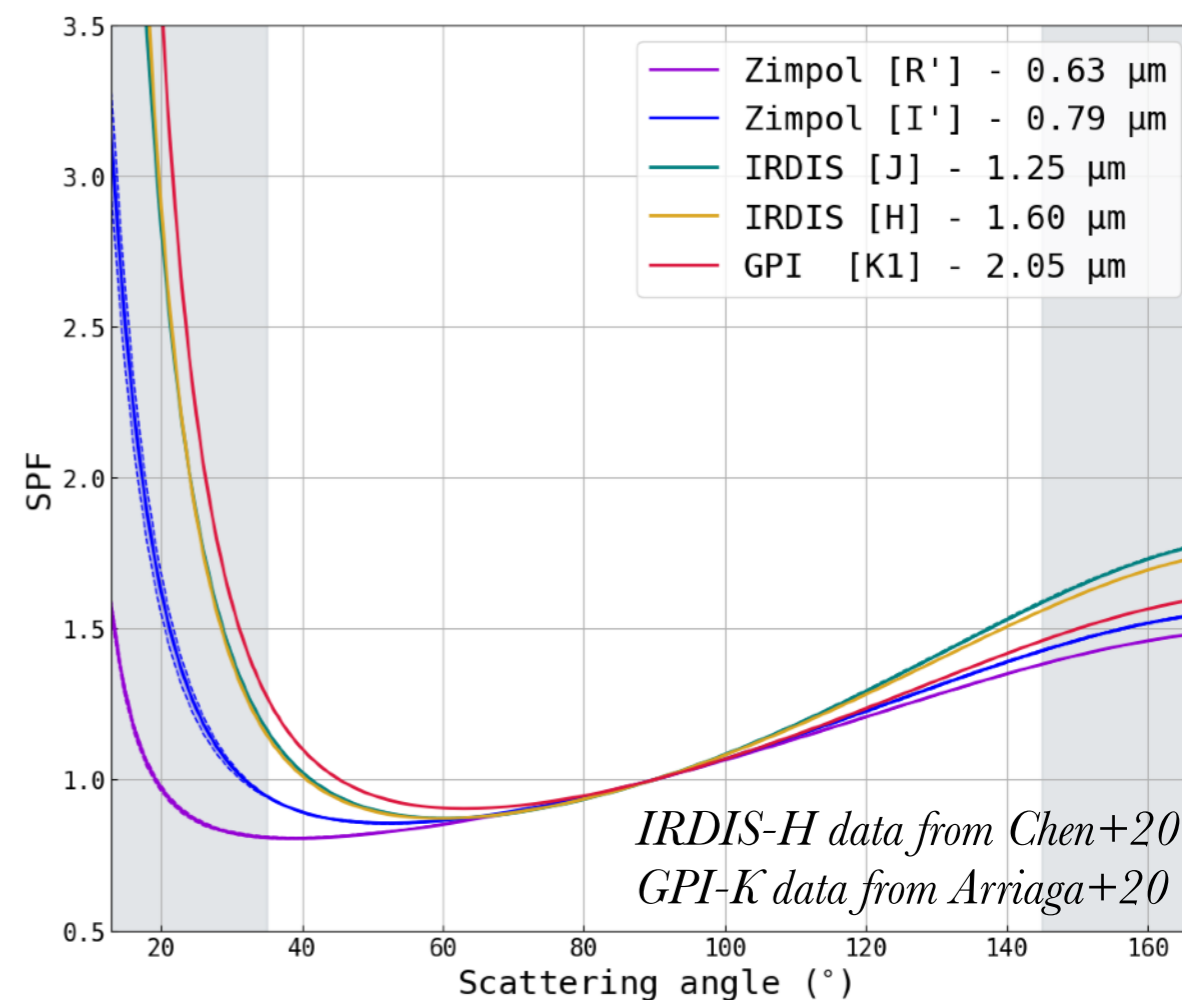
▶ Total = 14 free parameters (7 morph., 4 SPFs, 3 DoLP)

II.2: Modelling HR 4796:
MCMC results



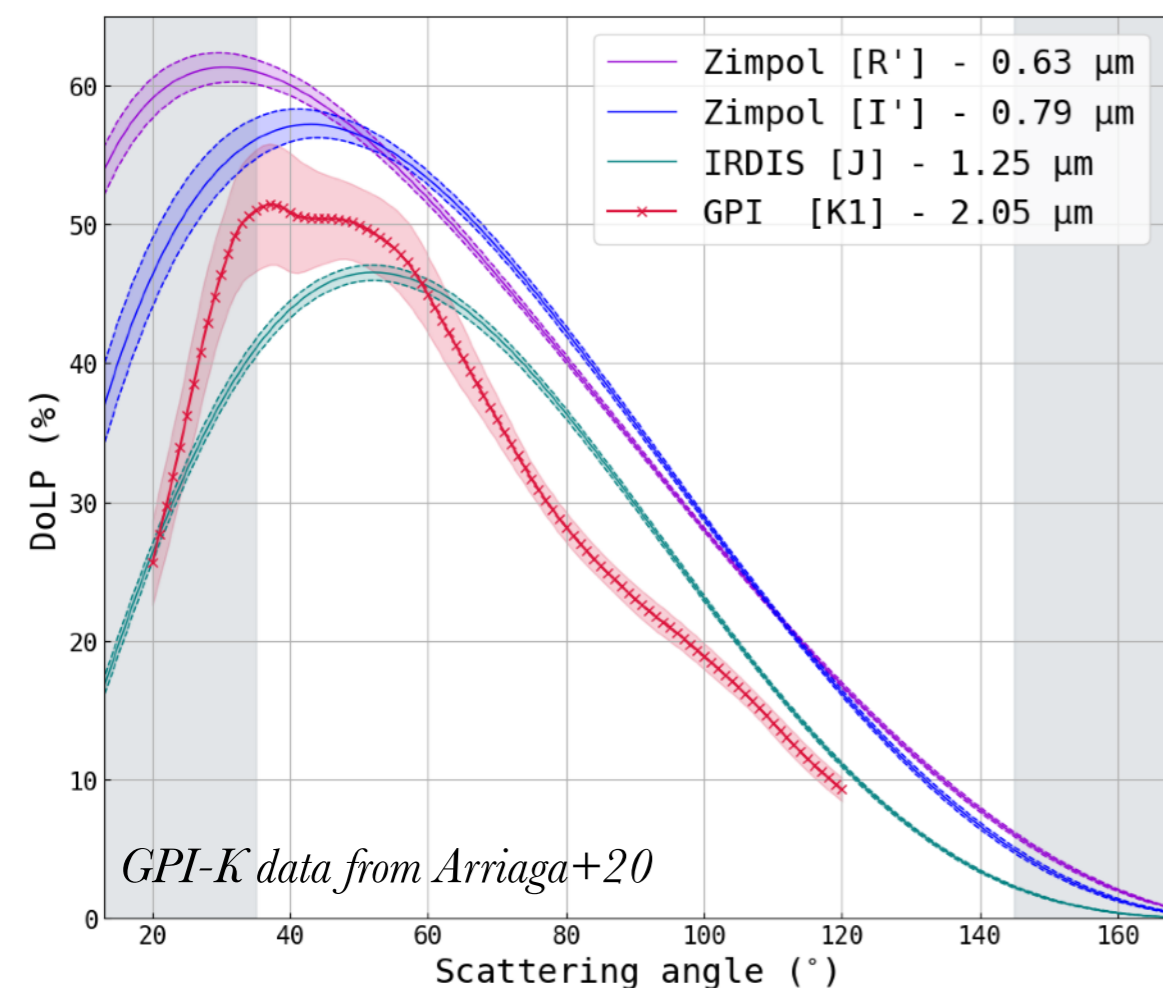
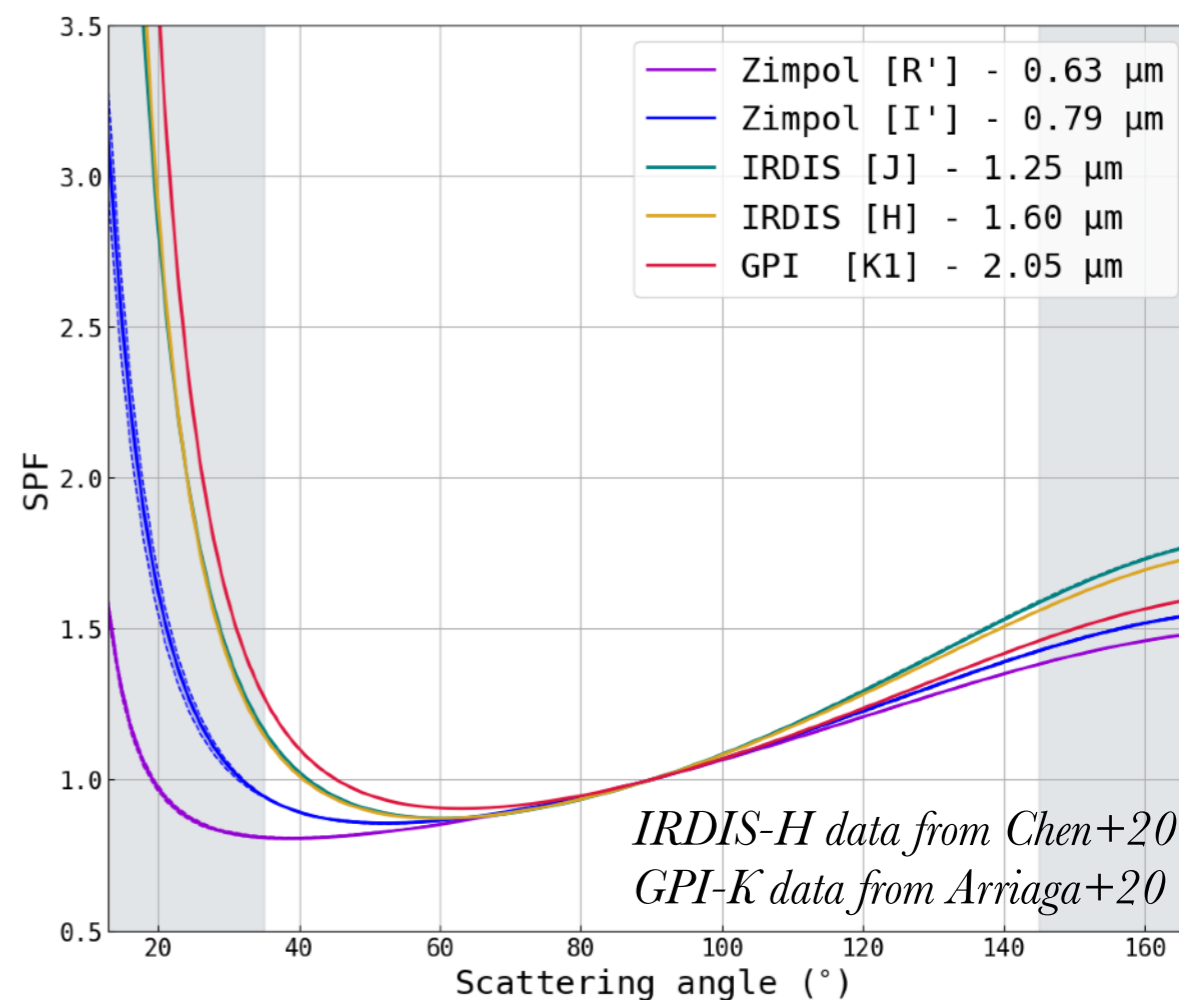
SPF — double Henyey-Greenstein:

- ▶ **strongly backward scattering** (*surface roughness ?*)
- ▶ **compatible with DHS model in Chen+20** (*amorphous silicates & carbon + iron; size particles $\geq 25 \mu\text{m}$*)



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DoLP — beta function:

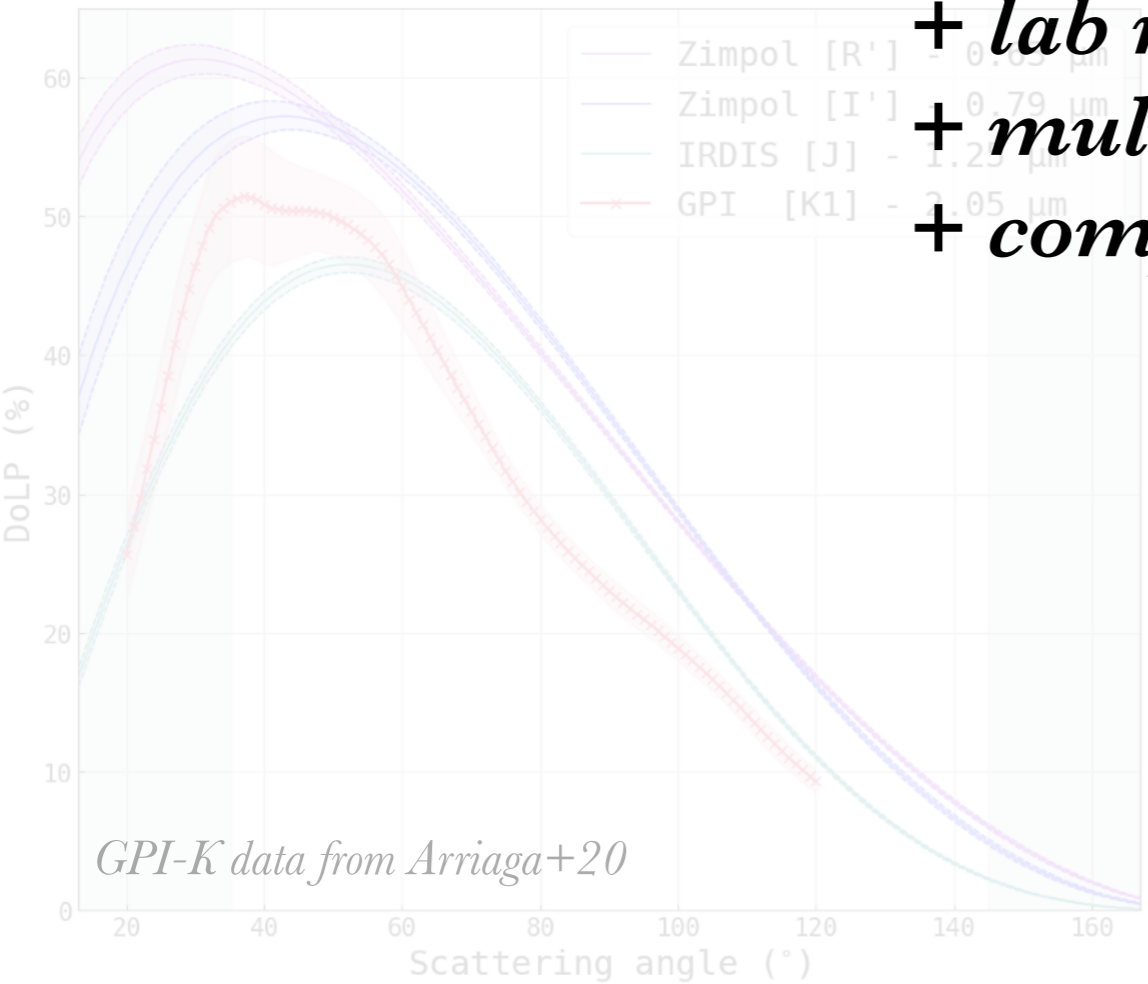
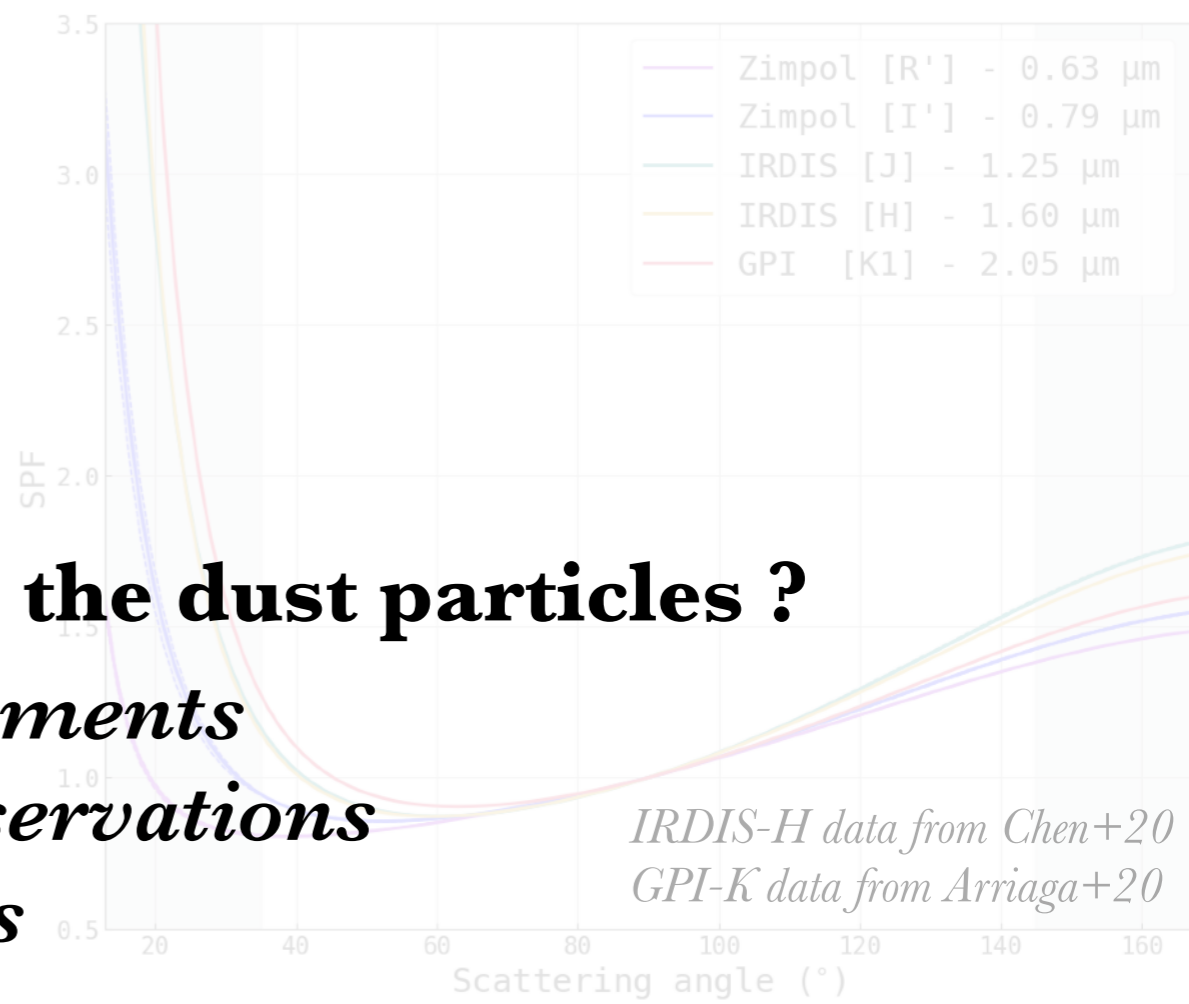
- ▶ peaks at 'small' $\theta_M : < 50^\circ$
- ▶ peaks at high $P_M : > 50 \%$
- ▶ **no clear λ dependancy**

SPF — double Henyey-Greenstein:

- ▶ strongly backward scattering (*surface roughness ?*)
- ▶ compatible with DHS model in **Chen+20** (*amorphous silicates & carbon + iron; size particles $\geq 25 \mu\text{m}$*)

What are the properties of the dust particles ?

- + lab measurements
- + multiple observations
- + comparisons



DoLP — beta function:

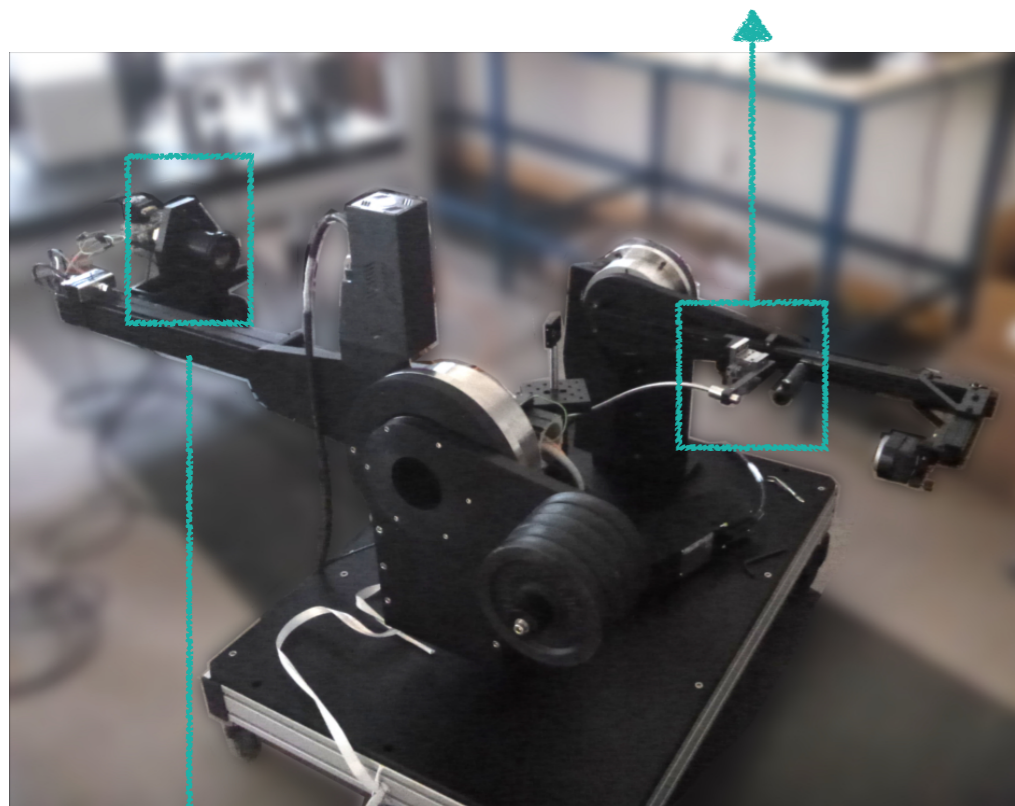
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SHADOWS

Spectrophotometer with Changing Angles for the Detection Of Weak Signals

- reflectance spectrometry
- $\lambda = [0.3 - 5.0] \mu\text{m}$
- wide range of illumination and observation angles

Rotating polariser => ensure that the incident light is not polarised



Measuring polariser

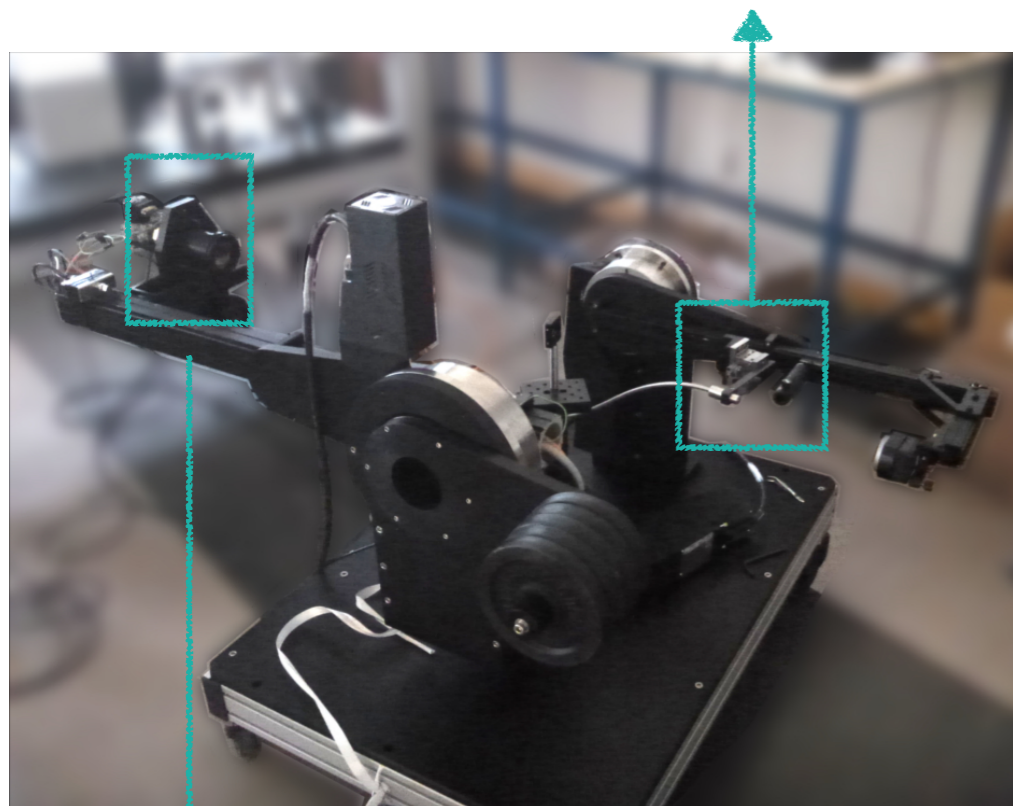
Potin+18

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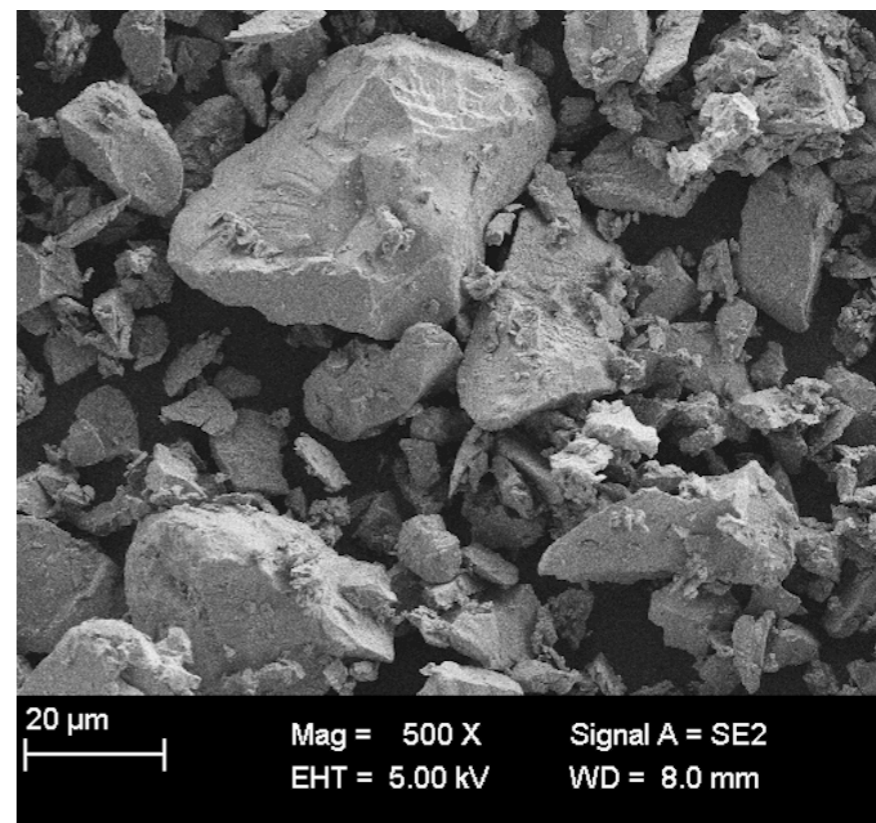


Measuring polariser

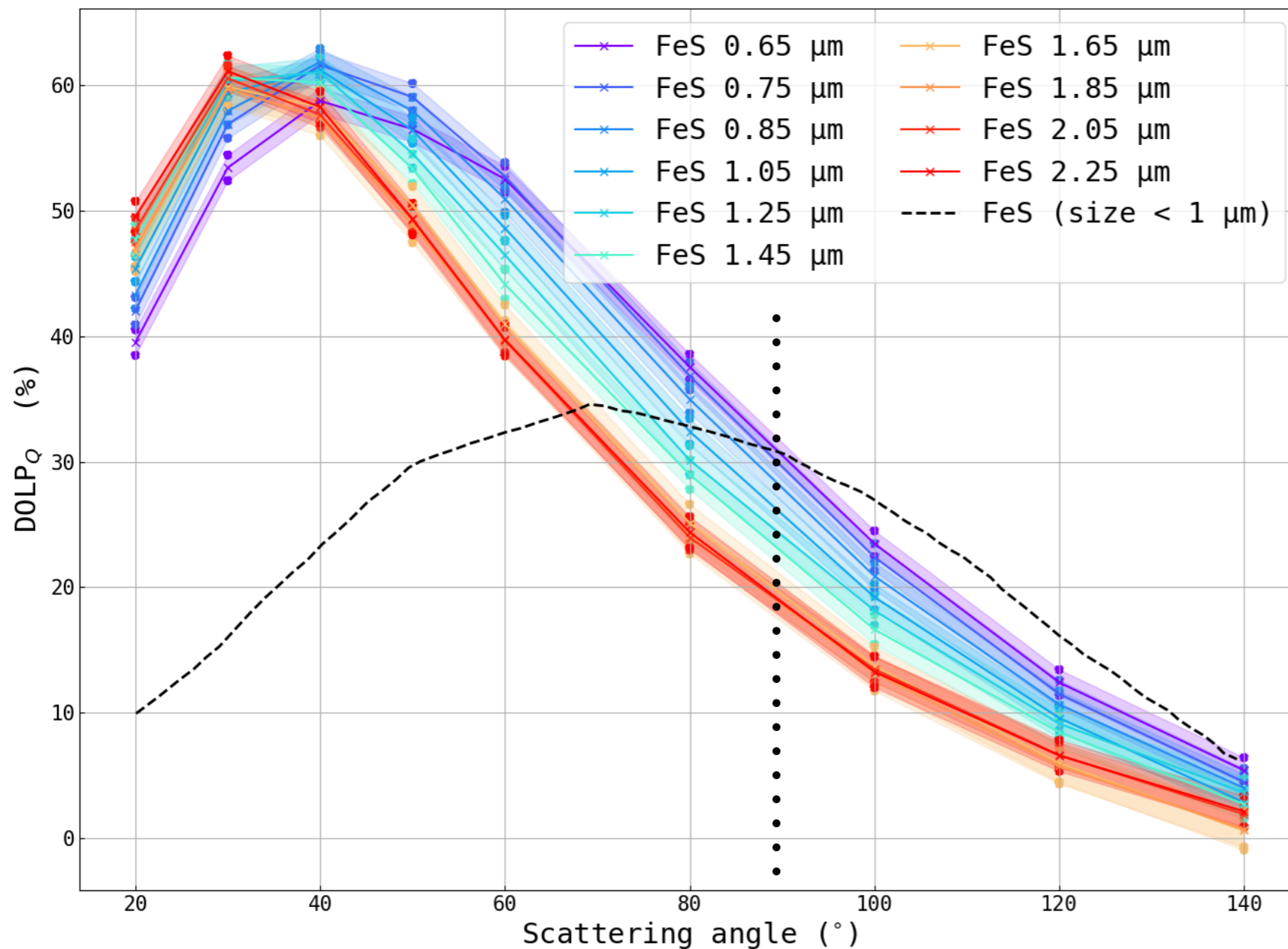
Potin+18

Sample : iron sulphide (FeS)

- 55 vol\% troilite and 45 vol\% pyrrhotite
- $3 \mu\text{m} < \text{particle size} < 100 \mu\text{m}$



Big opaque minerals : measurements on FeS

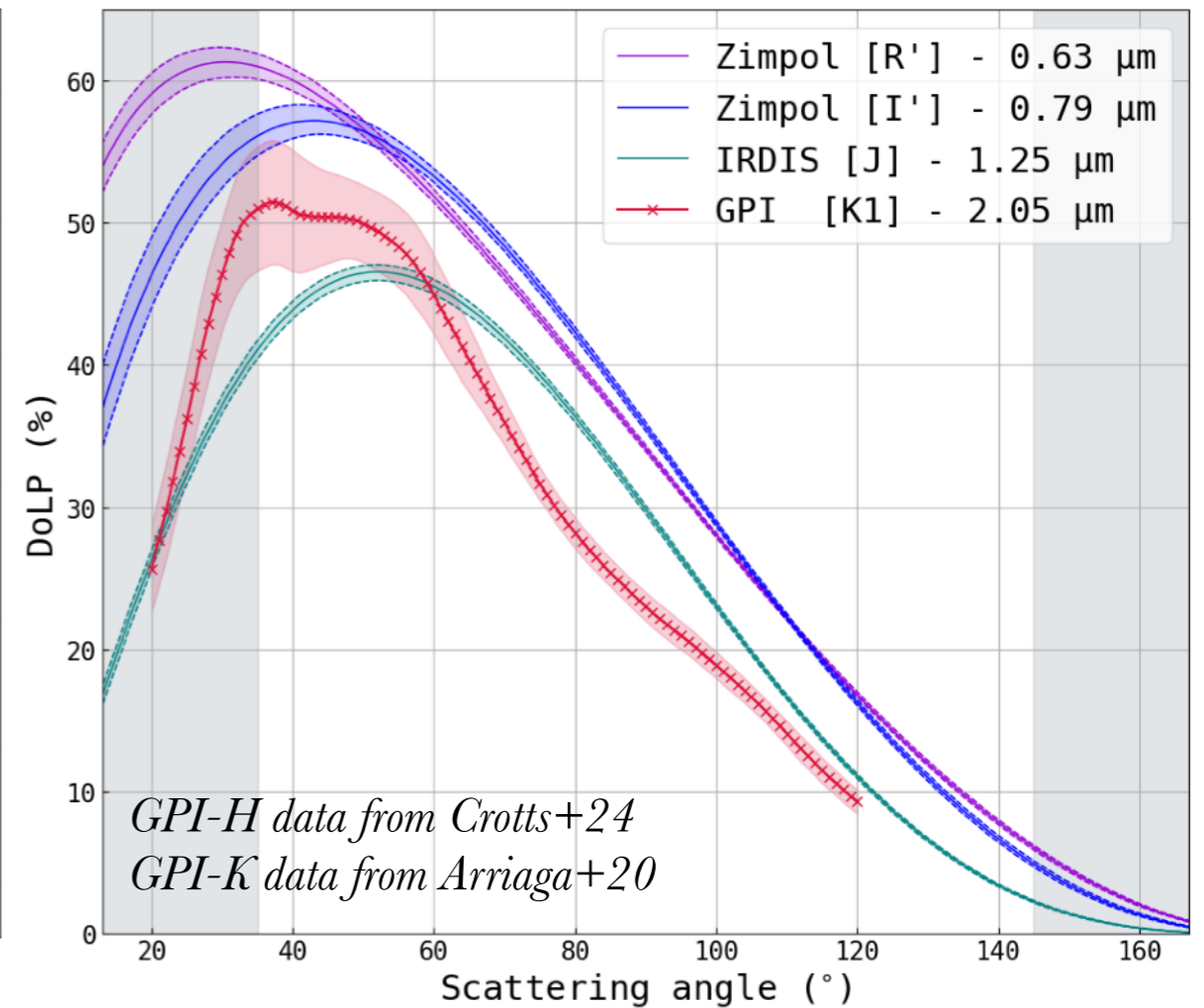
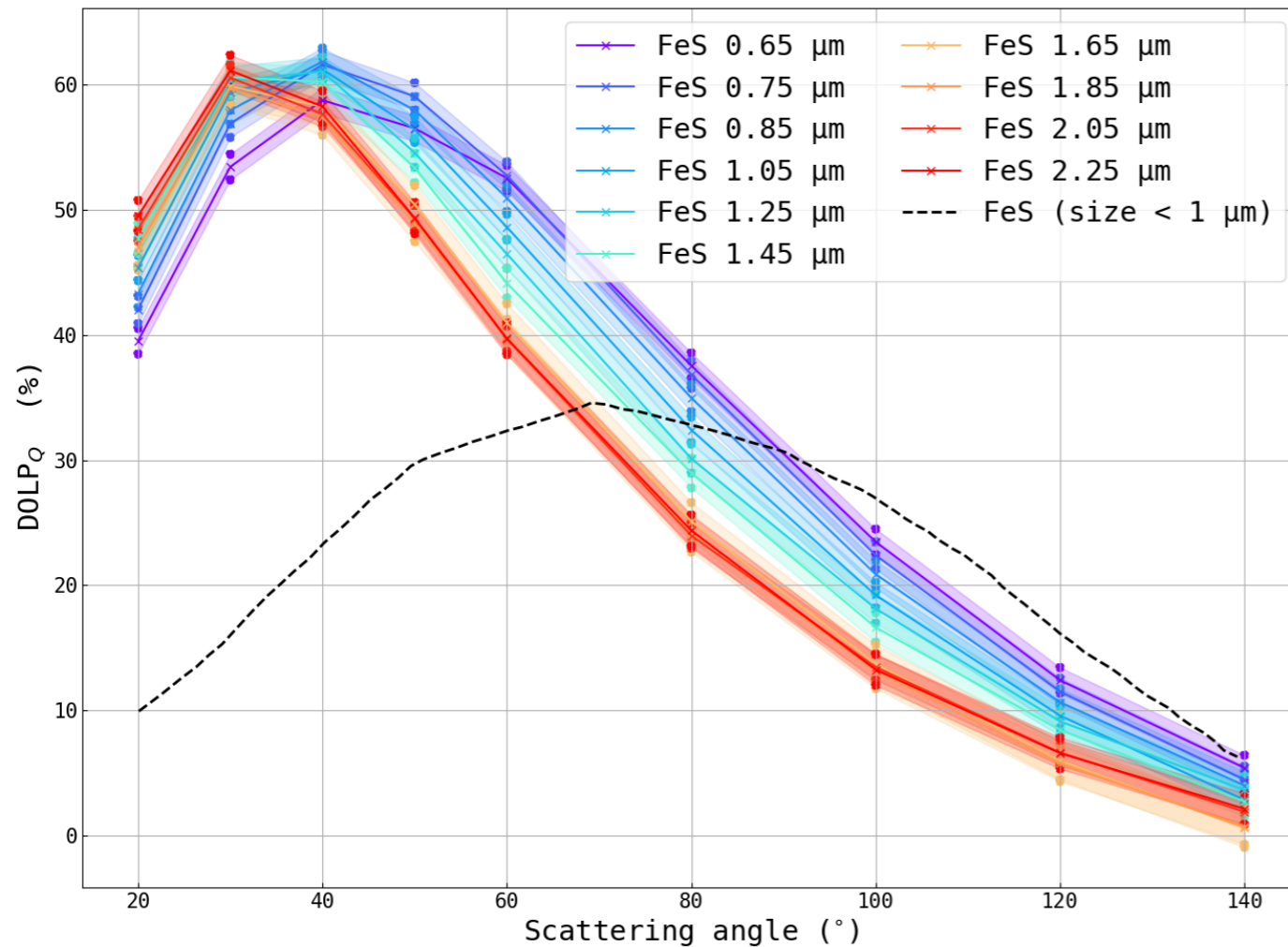


Main sample :
 $3 \leq s \leq 100 \mu\text{m}$

=> comparison to the
*PROGRA² experiment for lifted
particles*

➔ at 90°: smallest λ have the highest P_M (expected for big particles)

Big opaque minerals : measurements on FeS

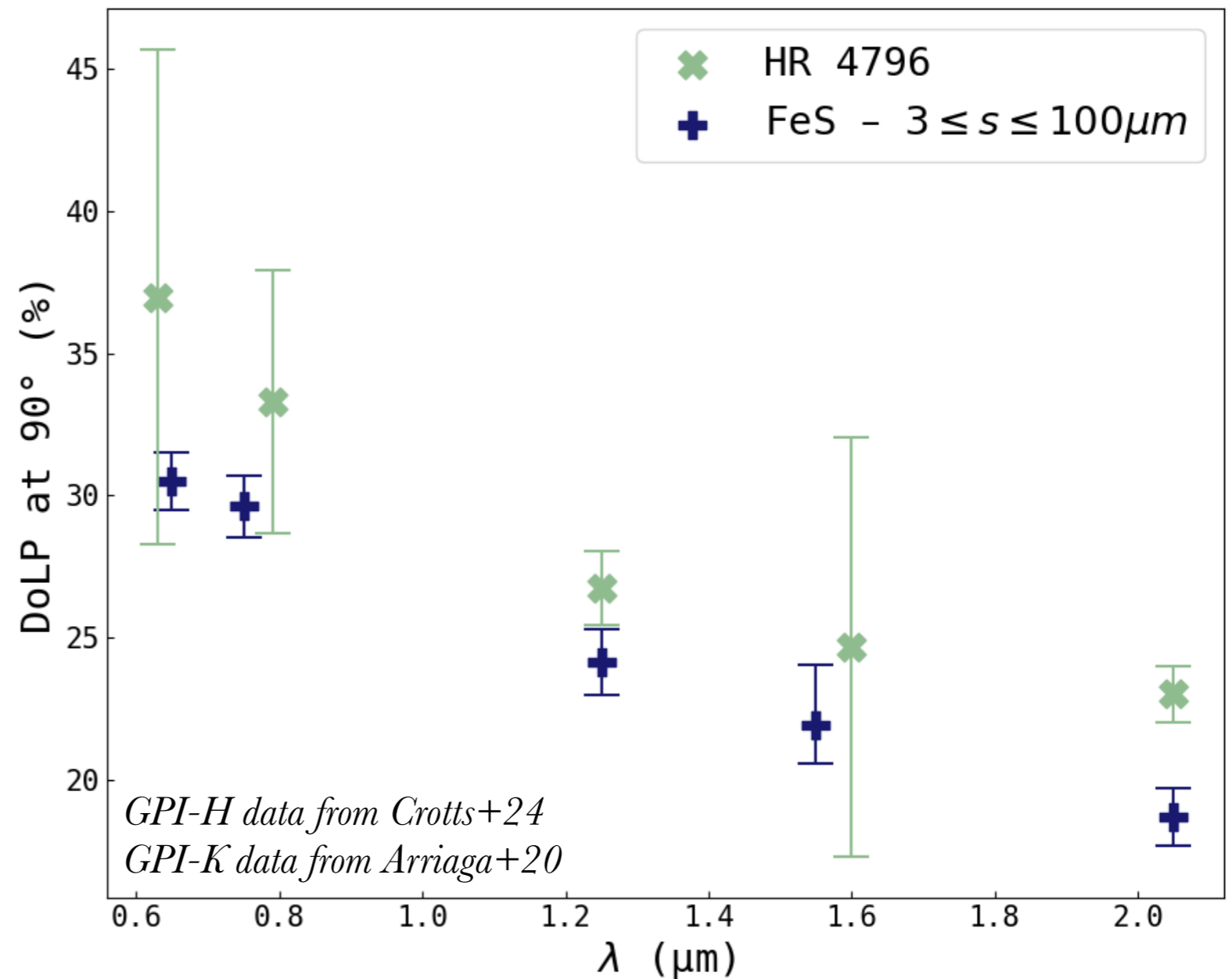
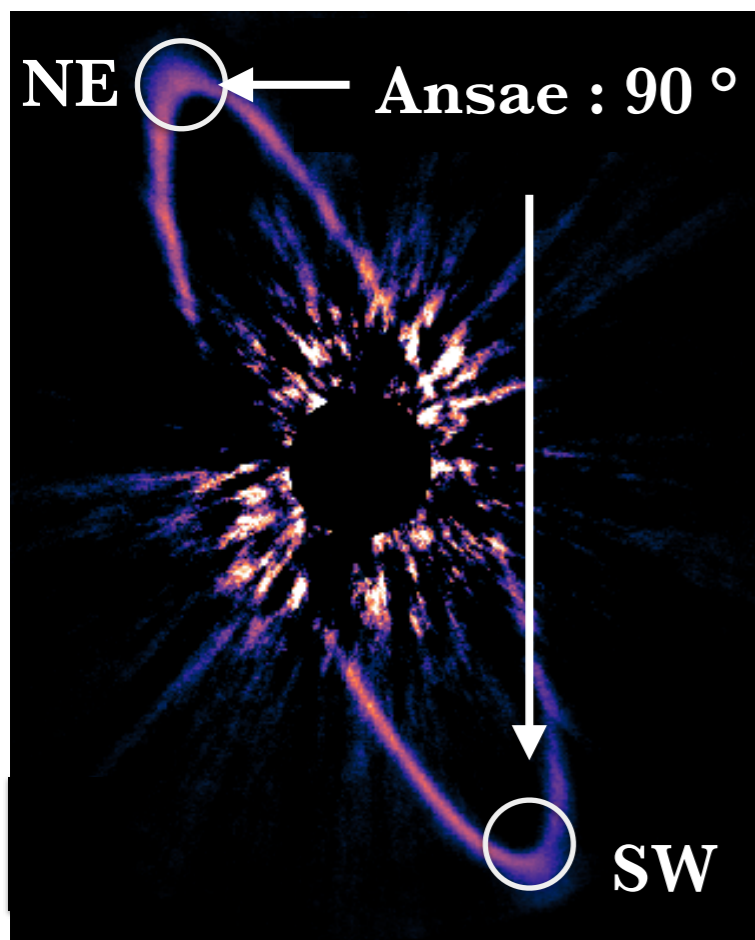


- ▶ $3 \leq \text{size} \leq 100 \mu\text{m}$ opaque minerals : good candidate to explain HR 4796's DoLP (both for P_M and θ_M)

IV.3: Dust properties of HR 4796: DoLP Comparison

DoLP @ $\theta_M = 90^\circ$

Aperture photometry directly
on the data :

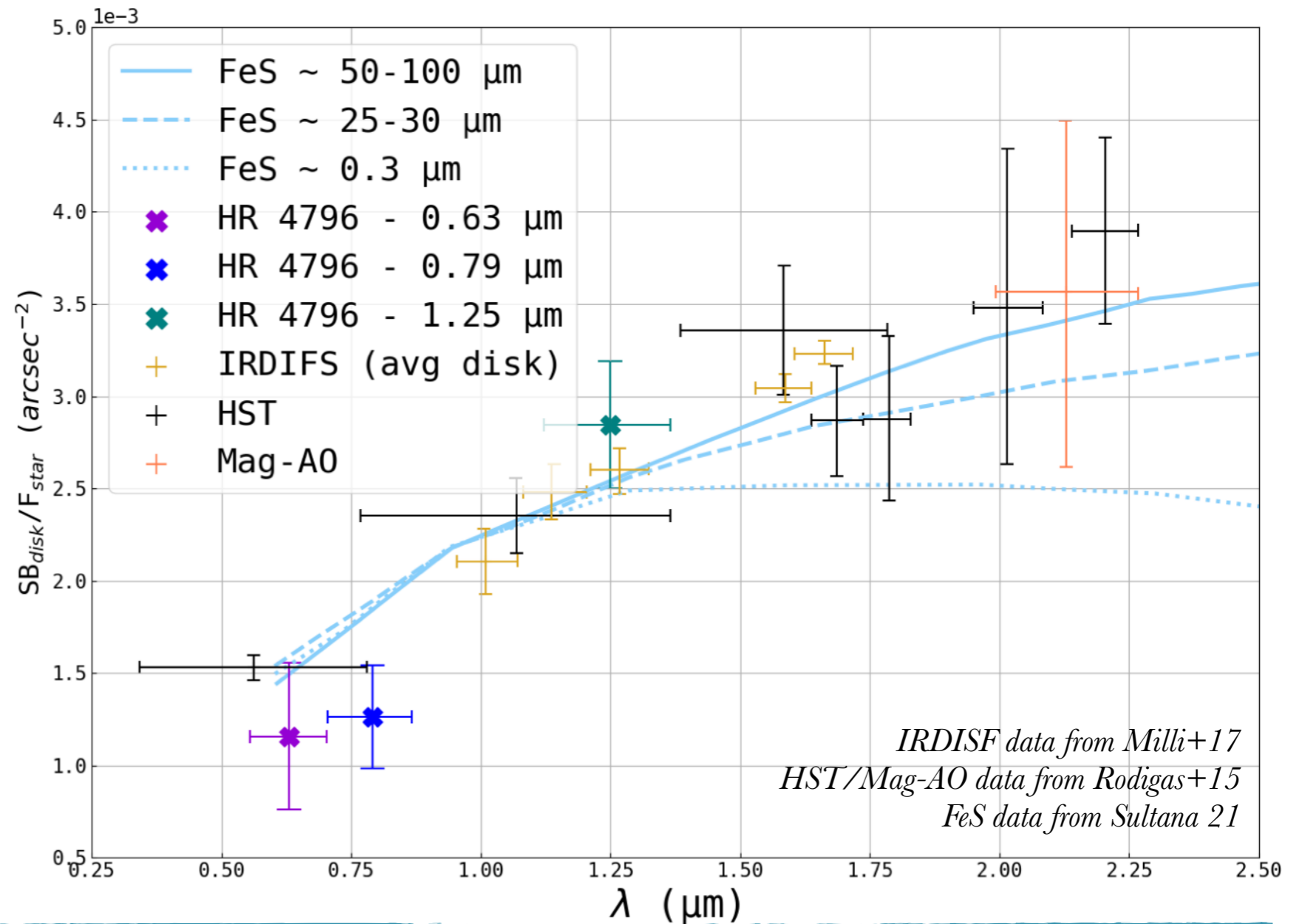
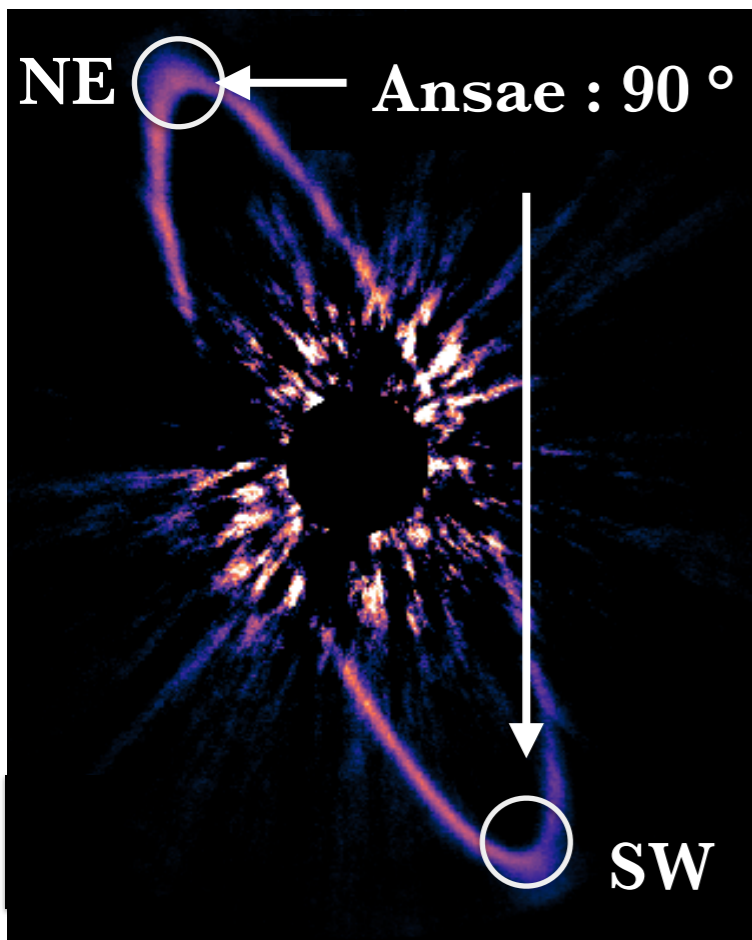


- ▶ the higher the λ , the lower the DoLP
- ▶ negative slope for both the observations and the measurements

IV.4: Dust properties of HR 4796: Spectral slope comparison

Spectral reflectance @ $\theta_M = 90^\circ$

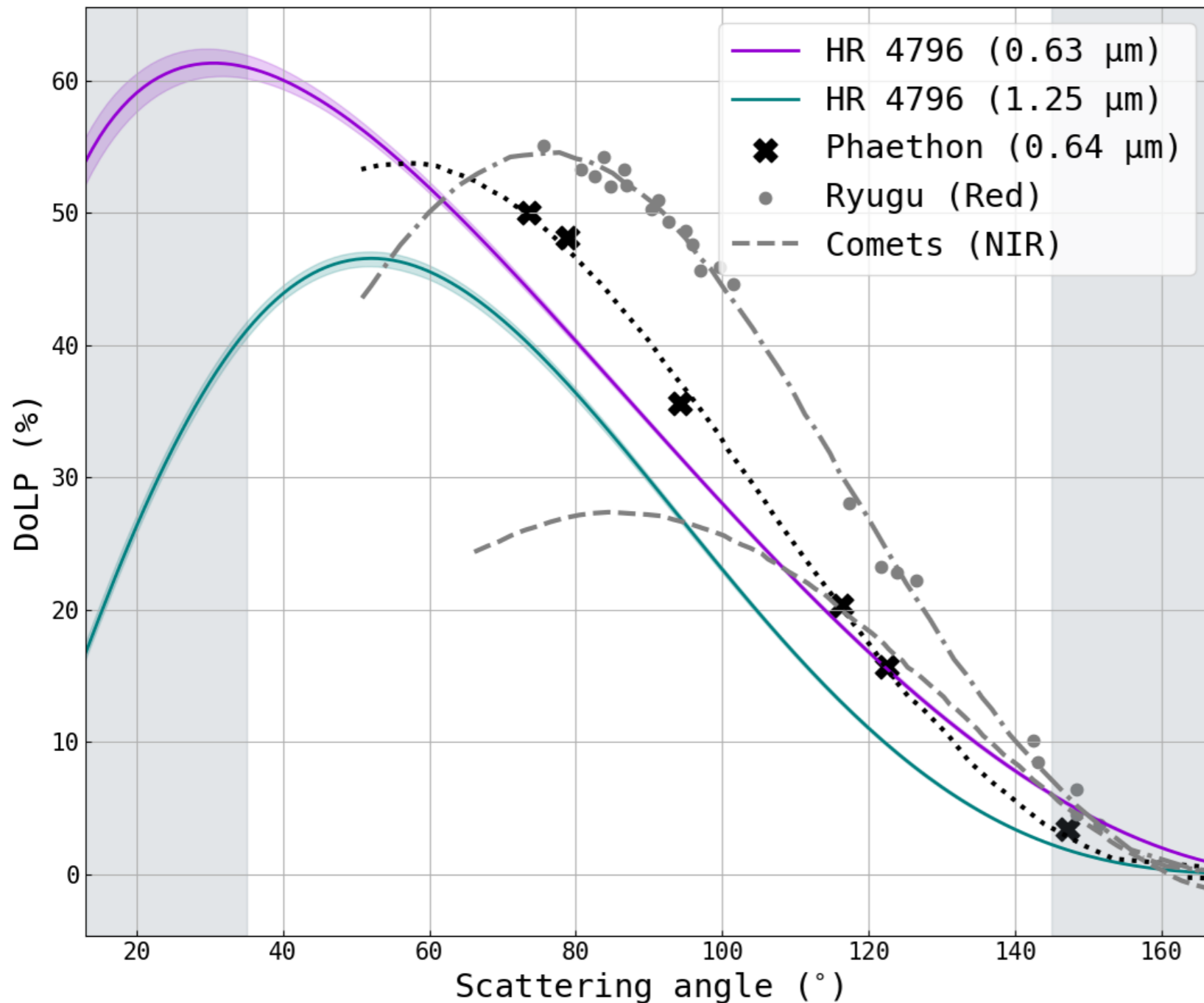
Aperture photometry directly
on the data :



- ▶ red slope
- ▶ agreement with previous observations of HR 4796
- ▶ agreement with big FeS particles

IV.5: Dust properties of HR 4796: Comparison with Solar System objects

- ▶ Comets in the NIR : P_M too low and θ_M too big
- ▶ Low albedo asteroids; highly processed bodies : higher DoLP



Slope of DoLP = $f(\lambda)$

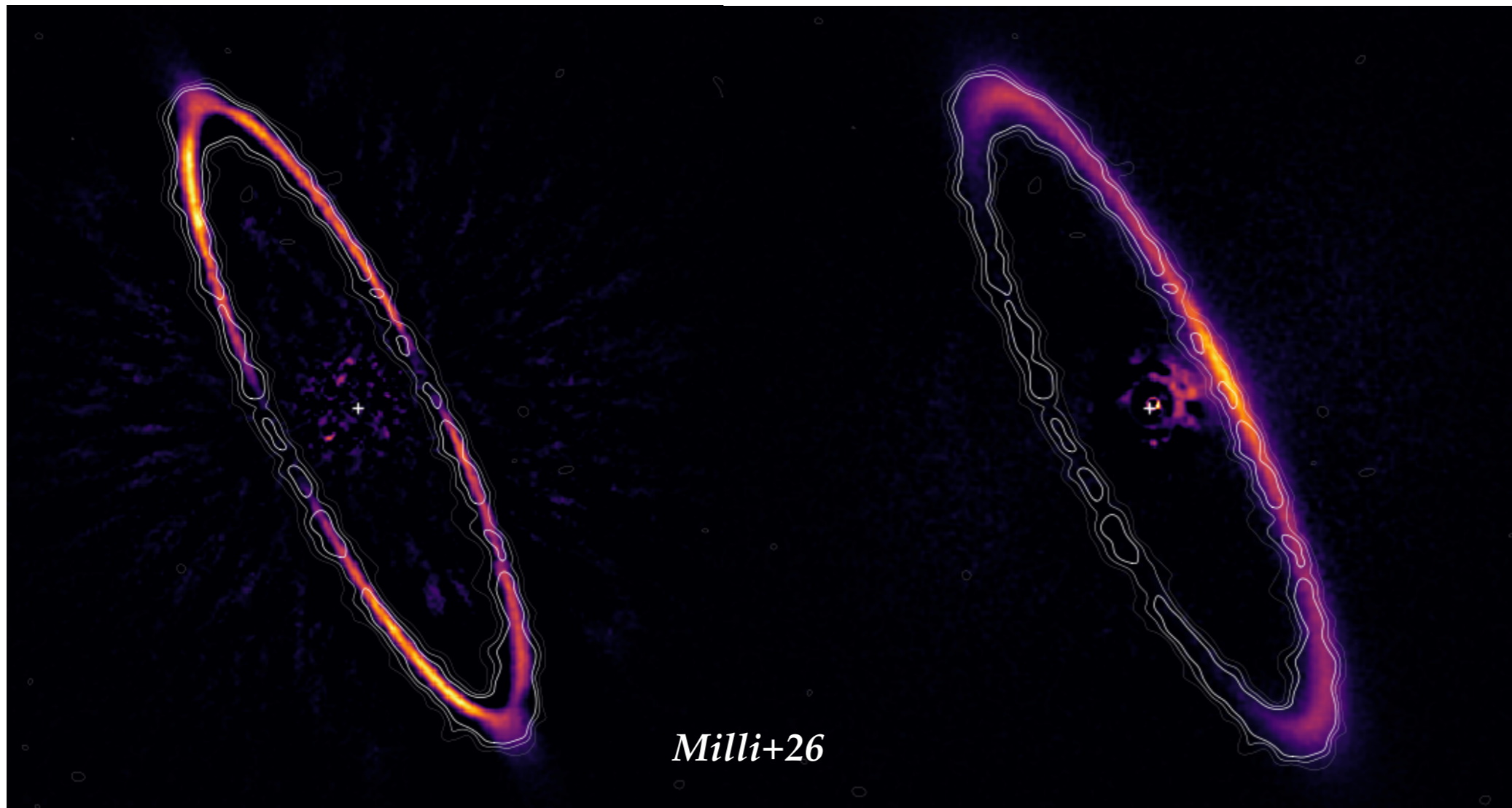
- ▶ asteroids : negative
(compact) *Mukai+97*
- ▶ comets : positive
(porous) *Kolokolova+24*

Comets data from Kiselev+15
Phaethon data from Ito+18
Ryugu data from Kuroda+21; Hadamcik+23

V: HR 4796's quirks:
ALMA & SPHERE

ALMA (thermal emission, white contours)
SPHERE (scattered light)

*The ALMA survey to Resolve
exoKuiper belt Substructures*



- ➔ **μm and mm grains are colocated: dynamically cold disk (*Lisse+17*) ?**
- ➔ **bigger halo of small (sub)- μm grains also seen with HST/STIS (*Schneider+18*)**

Conclusion

- ➔ In the visible and near infrared, big (50-100 μm) opaque minerals seem to be the main scatterers
- ➔ HR 4796's characteristics are close to those of highly processed objects of the Solar System (low albedo asteroids). Space weathered particles ?

HR 4796: young, but dynamically cold disk made of processed, devolatilised material ?

=> cf Bonduelle+26 (submitted)