Remote Sensing of Comets Using Polarimetry

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Content

1. Introduction: Some facts on polarization in comets
2. Modeling of light scattering by cometary dust particles
3. Cometary dust as seen from its negative polarization
4. Cometary dust as seen from its positive polarization
5. Estimation of the geometric albedo with the Umov effect
6. Summary

1. Some facts on polarization in comets

Why Polarization?

A convenient way to describe interaction of light with some target is to use formalism of Stokes vectors and Mueller matrices. Stokes vector is a four-dimension vector that is defined as follows:

$$\mathbf{S} = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

Stokes vectors are defined in reference to the scattering plane, which is determined by locations of source of light (the Sun), target (Comet), and detector of light (Telescope)

Using Stokes vectors one can easily express unpolarized light S=[I,0,0,0]^T

Why Polarization?

If the light is characterized with Stokes vectors, then, interaction of light with a target can be expressed with a 4x4 Mueller matrix:

$$\mathbf{M} = \frac{1}{(kR)^2}\begin{pmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{pmatrix}$$

However, if target particles are randomly oriented, Mueller matrix is reduced as follows:

$$\mathbf{M} = \frac{1}{(kR)^2}\begin{pmatrix} M_{11} & M_{12} & 0 & 0 \\ M_{12} & M_{22} & 0 & 0 \\ 0 & 0 & M_{33} & M_{34} \\ 0 & 0 & -M_{34} & M_{44} \end{pmatrix}$$

Why Polarization?

Interaction of the sun-light with cometary dust particles yields:

$$\mathbf{S}^{Obs} = \mathbf{M}^{Comet} \times \mathbf{S}^{Sun} = \frac{1}{(kR)^2}\begin{pmatrix} M_{11} & M_{12} & 0 & 0 \\ M_{12} & M_{22} & 0 & 0 \\ 0 & 0 & M_{33} & M_{34} \\ 0 & 0 & -M_{34} & M_{44} \end{pmatrix} \times \begin{pmatrix} I \\ 0 \\ 0 \\ 0 \end{pmatrix} = \frac{I}{(kR)^2}\begin{pmatrix} M_{11} \\ M_{12} \\ 0 \\ 0 \end{pmatrix}$$

Only *I* and *Q* elements in Stokes vector of the scattered light are non-zero.

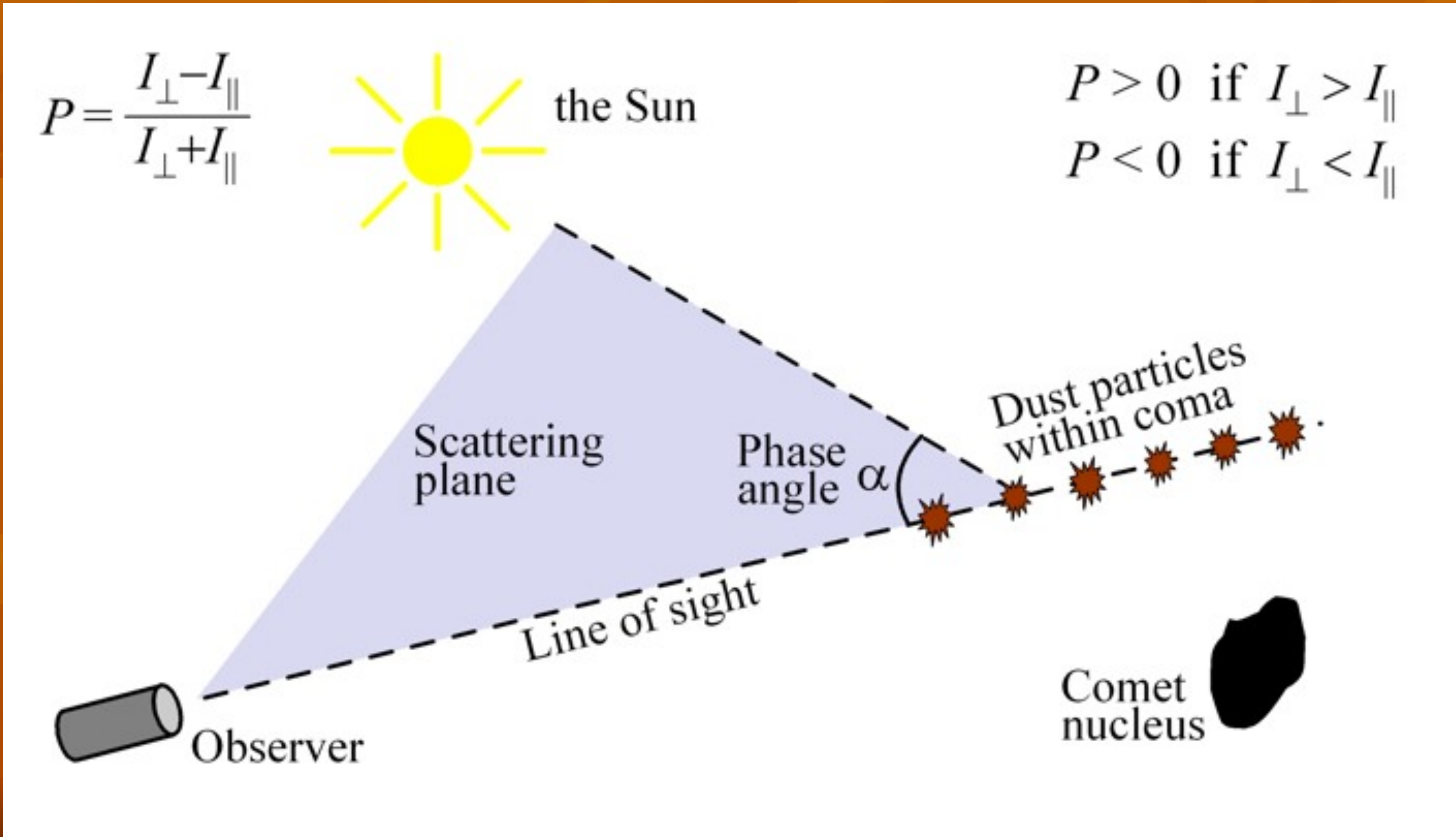
Element Q exceeds U and V for at least two orders of magnitude.

Here, we focus on the degree of linear polarization *P*:

$$P = -\frac{Q}{I} \times 100\% = -\frac{M_{12}}{M_{11}} \times 100\% = \frac{I_{\perp} - I_{\parallel}}{I_{\perp} + I_{\parallel}} \times 100\%$$

P in comets

P in comets varies with phase angle α



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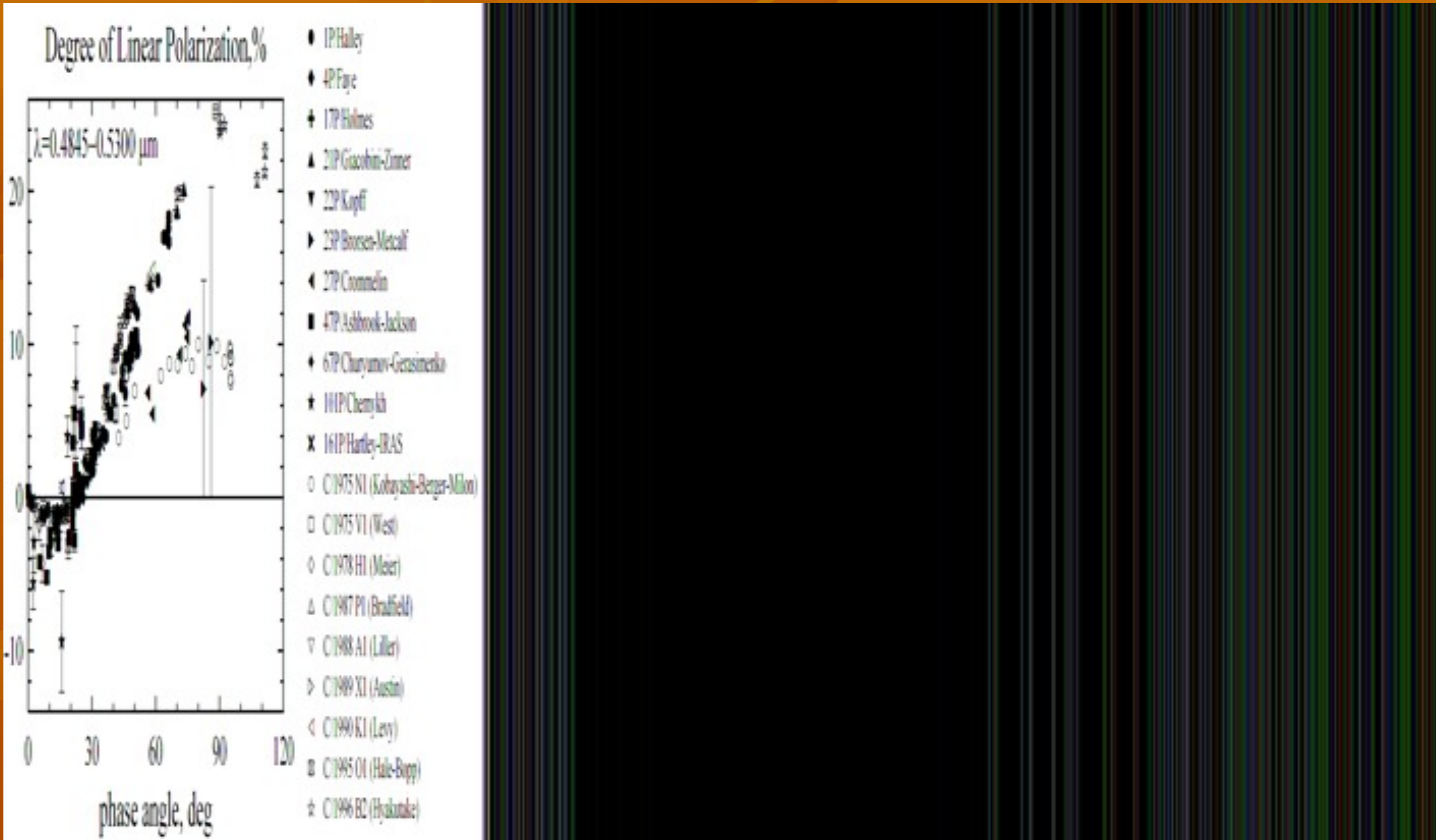
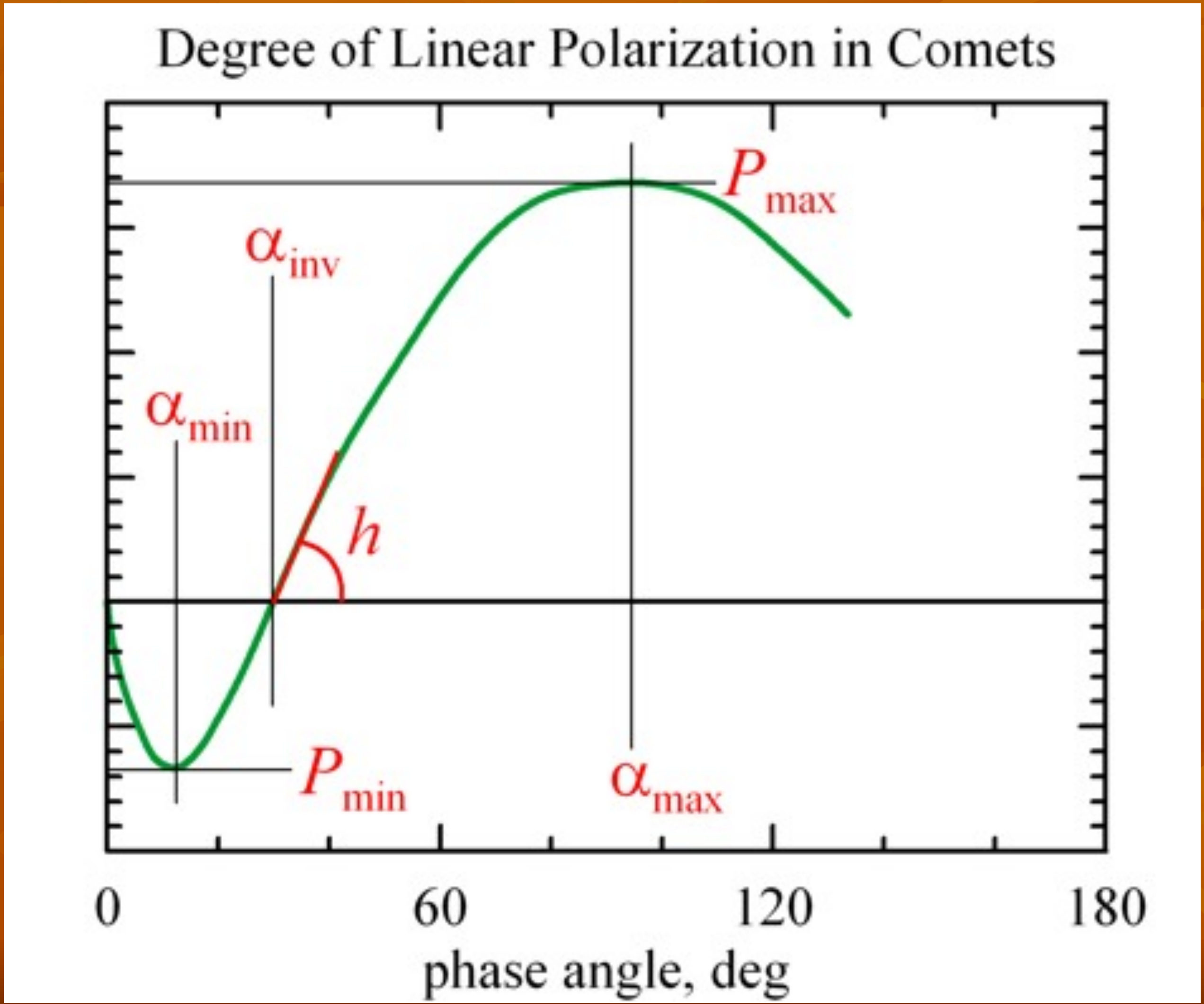
Aperture-averaged *P* in comets



Aperture-averaged *P* in comets

Typical angular profile of *P* measured in whole comets:



Principal characteristics

- $P_{min} \approx -1.7\%$
- $\alpha_{min} \approx 10–11°$
- $P_{max} \approx 10–30\%$
- $\alpha_{max} \approx 90–100°$

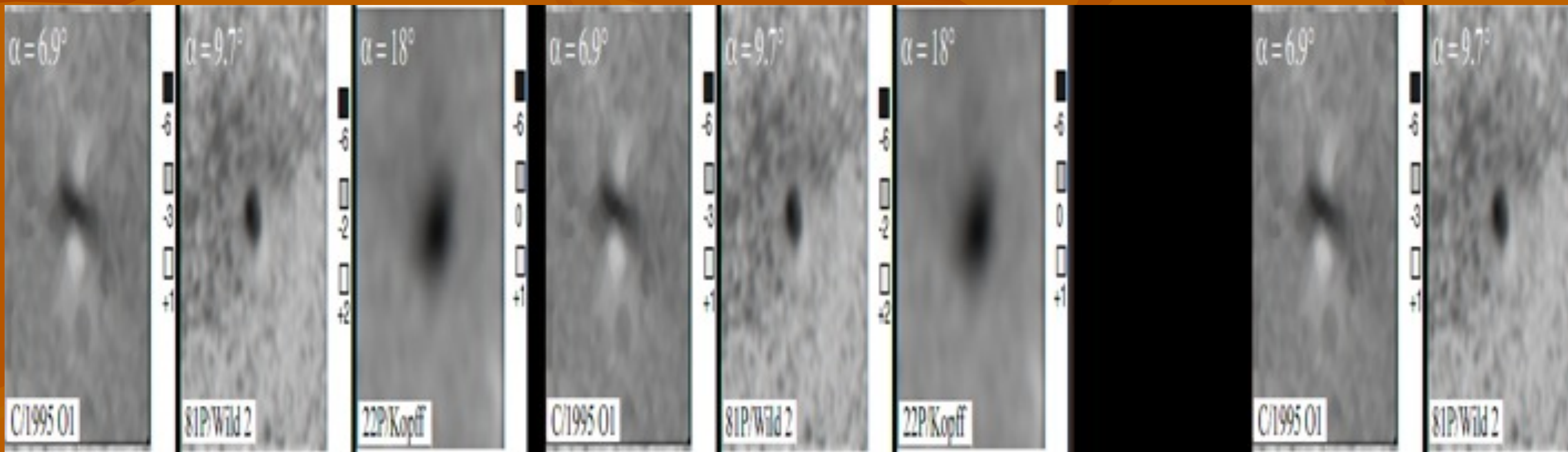
Cumulative characteristics

- h and α_{inv}

Spatially resolved polarimetry of comets

However, *P* is a time-varying characteristic; it depends on wavelength λ and varies throughout entire coma.

R=4.2 AU *R*=1.8 AU *R*=1.6 AU

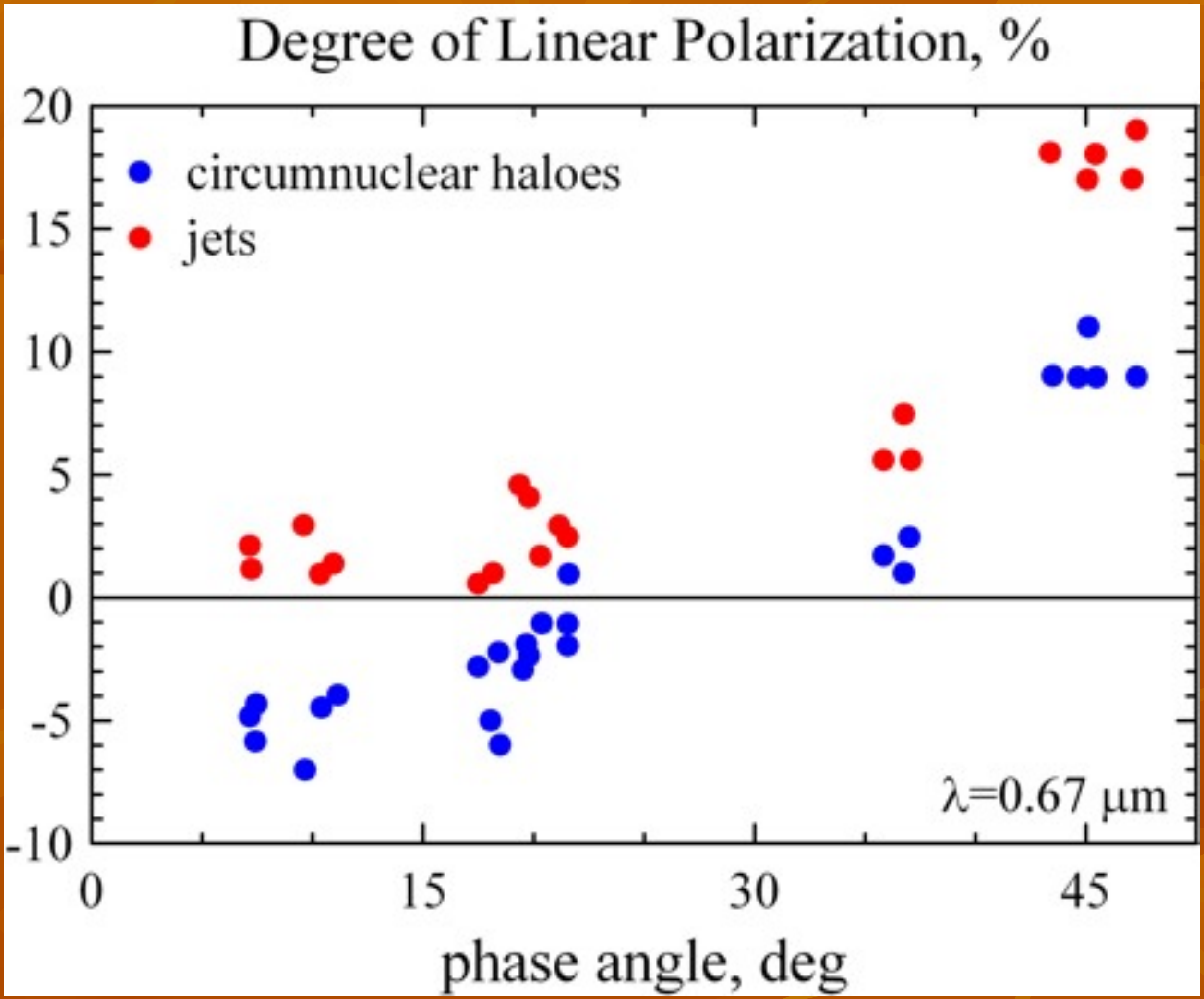


38000 km 9000 km 4400 km

Hadamcik & Levasseur-Regourd, 2003

Spatially resolved polarimetry of comets

Two noticeable features in a coma:



Circumnuclear Halo

P_{min}=–6%

α_{min}=15°

P_{max}<10% (?)

α_{max}< 90° (?)

Jets

P_{min}=0%

α_{min}=0°

P_{max}>30%

α_{max}>90° (?)

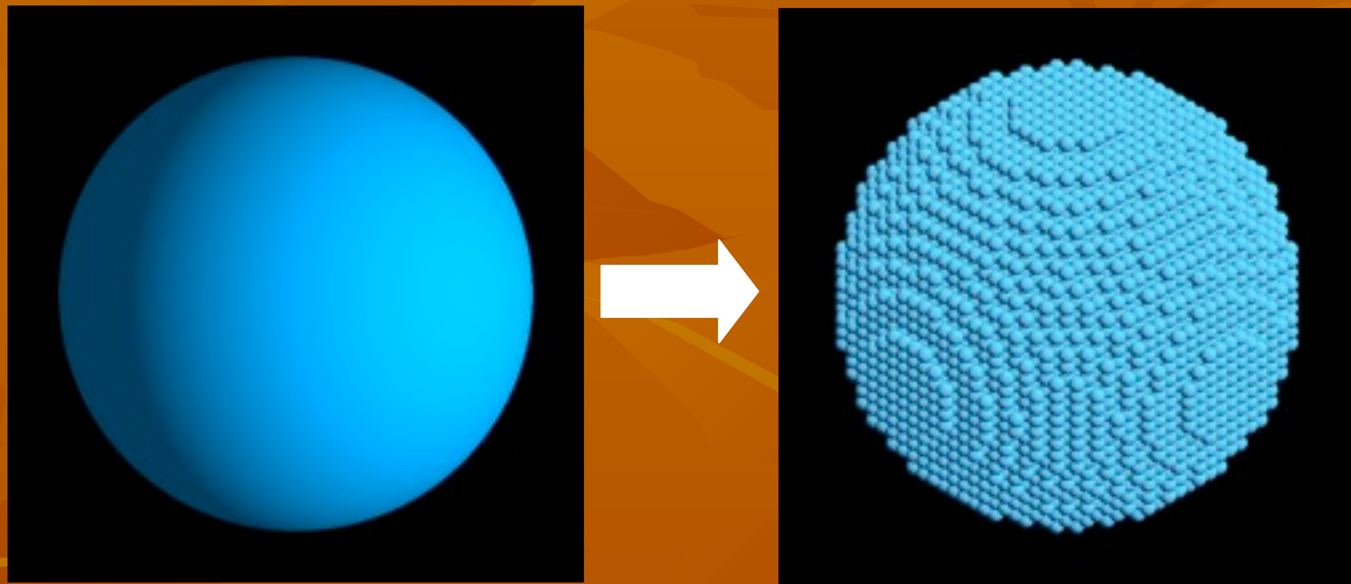
Hadamcik & Levasseur-Regourd, 2003

2. Modeling of light scattering by cometary dust particles

Simulation of light scattering

We compute light scattering by micron-sized particles using the discrete dipole approximation (DDA)

Concept:



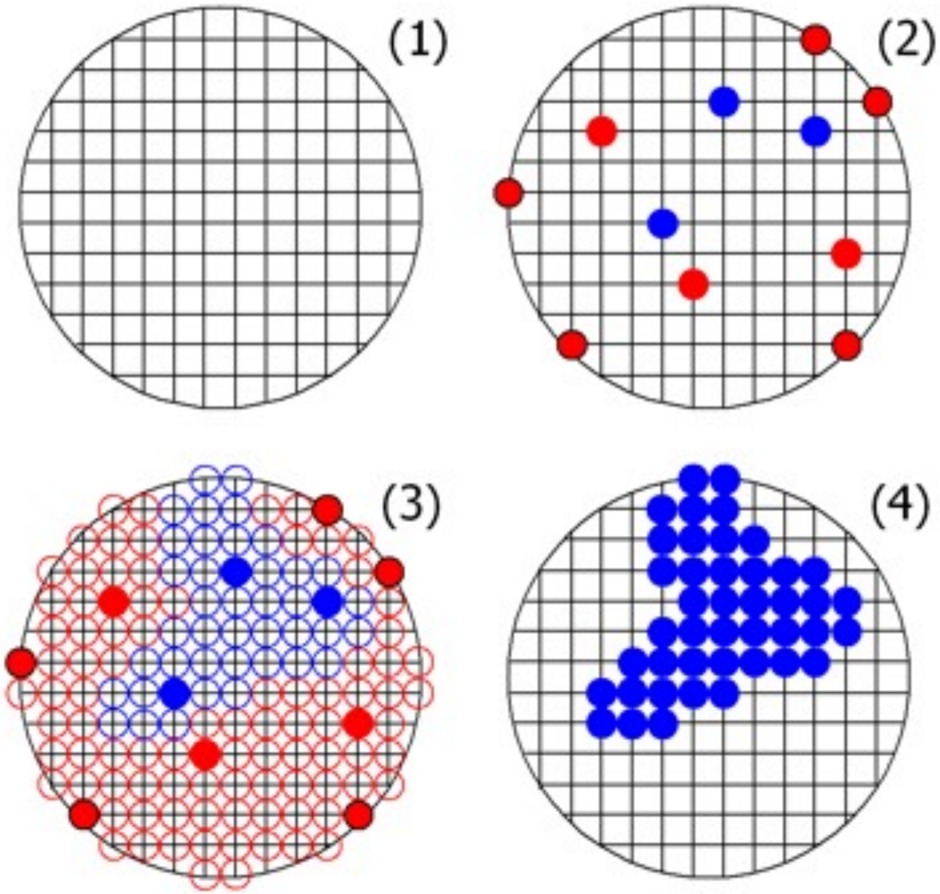
Advantages:

(1) arbitrary shape and internal structure
(2) simplicity in preparation of sample particles

Penalty:

long computations

Modeling cometary dust particles



Initial matrix is divided for surface layer and internal volume.

Parameters for surface layer:
(1) depth;
(2) number of seeds for empty space.

Parameters for internal volume:
(1) number of seeds for a material;
(2) number of seeds for empty space.

Legend
- seeds for empty space
- seeds for empty space
- seeds for material

Simulation of light scattering

sparse agglomerate
ρ = 0.169

agglomerated debris
ρ = 0.236

pocked spheres
ρ = 0.336

seeds (s.l.) – 100
depth (s.l.) – 0.5%
seeds (empty) – 50
seeds (matter) – 21

seeds (s.l.) – 100
depth (s.l.) – 0.5%
seeds (empty) – 20
seeds (matter) – 21

seeds (s.l.) – 100
depth (s.l.) – 12.5%
seeds (empty) – 0
seeds (matter) – 50

Simulation of light scattering

Other parameters of light scattering by small particles

(1) *size parameter* $x = 2\pi r/\lambda$ (r – radius of circumscribing sphere and λ – wavelength).

In most cases, x varies from 1 throughout 24-40

(2) *complex refractive index m* (it relates chemical and mineral composition of the given material with its ability to scatter and absorb light)

Agglomerated debris particles are considered at 27(!) various m:

1.1+0i, 1.2+0i, 1.313+0i, 1.313+0.02i, 1.313+0.05i, 1.313+0.1i, 1.4+0i, 1.4+0.02i, 1.4+0.05i, 1.4+0.1i, 1.5+0i, 1.5+0.02i, 1.5+0.05i, 1.5+0.1i, 1.6+0.0005i, 1.6+0.01i, 1.6+0.02i, 1.6+0.05i, 1.6+0.1i, 1.6+0.15i, 1.7+0i, 1.7+0.02i, 1.7+0.05i, 1.7+0.1i, 1.758+0.0844i, 1.855+0.45i, 2.43+0.59i

Simulation of light scattering

Averaging:

(1) over 500+ random shapes.

In addition, light-scattering properties of each particle are averaged over 100 azimuthal orientations (i.e., particle is rotated around direction of the incident light propagation). Standard deviation of the degree of linear polarization *P* does not exceed 1% throughout all phase angles.

(2) over particle sizes with power-law size distribution

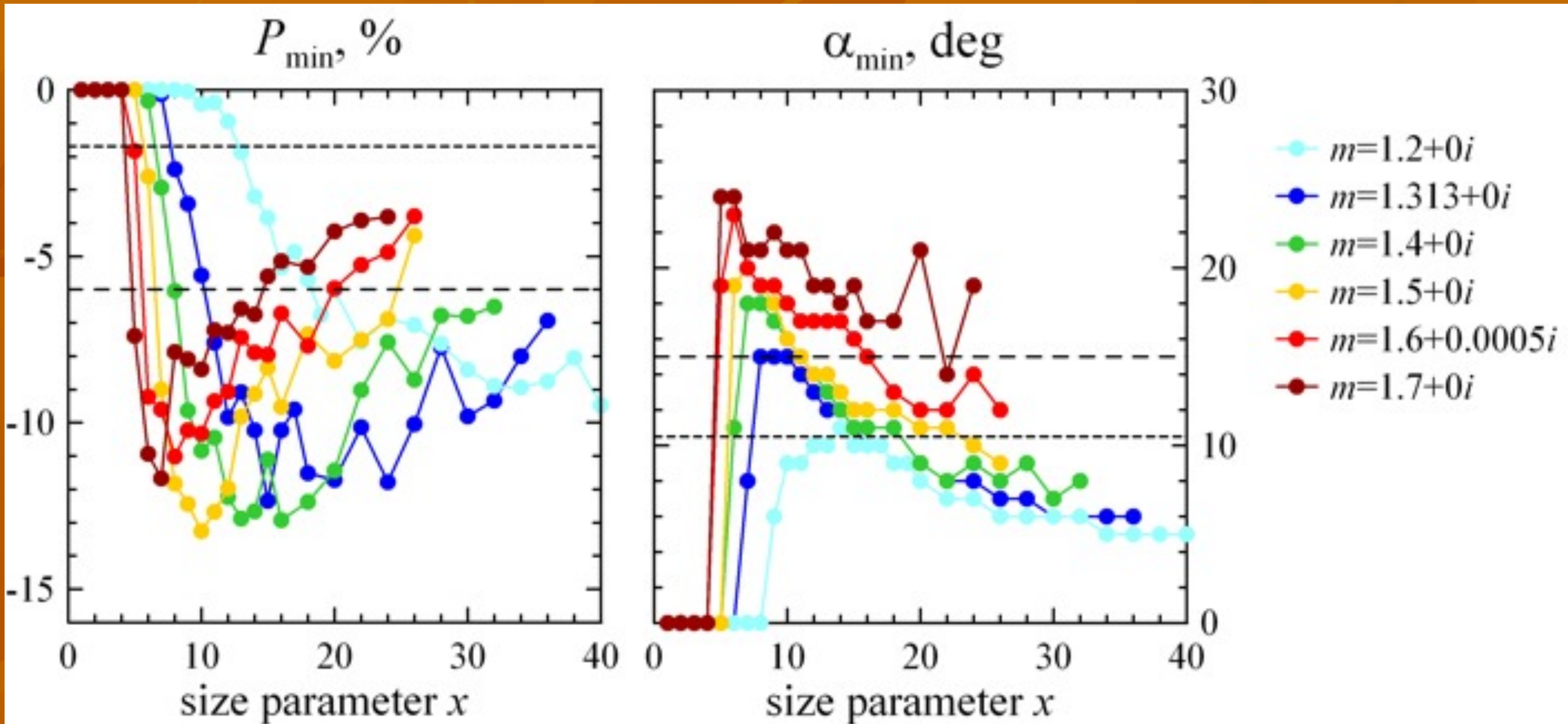
$$r^{-a}.$$

The power index a is varied from 1.5 to 3.5.

Such size distribution is well consistent with *in situ* study of comet 1P/Halley (e.g., Mazets et al., 1986)

3. Cometary dust as seen from its negative polarization

Negative polarization for various Re(m)

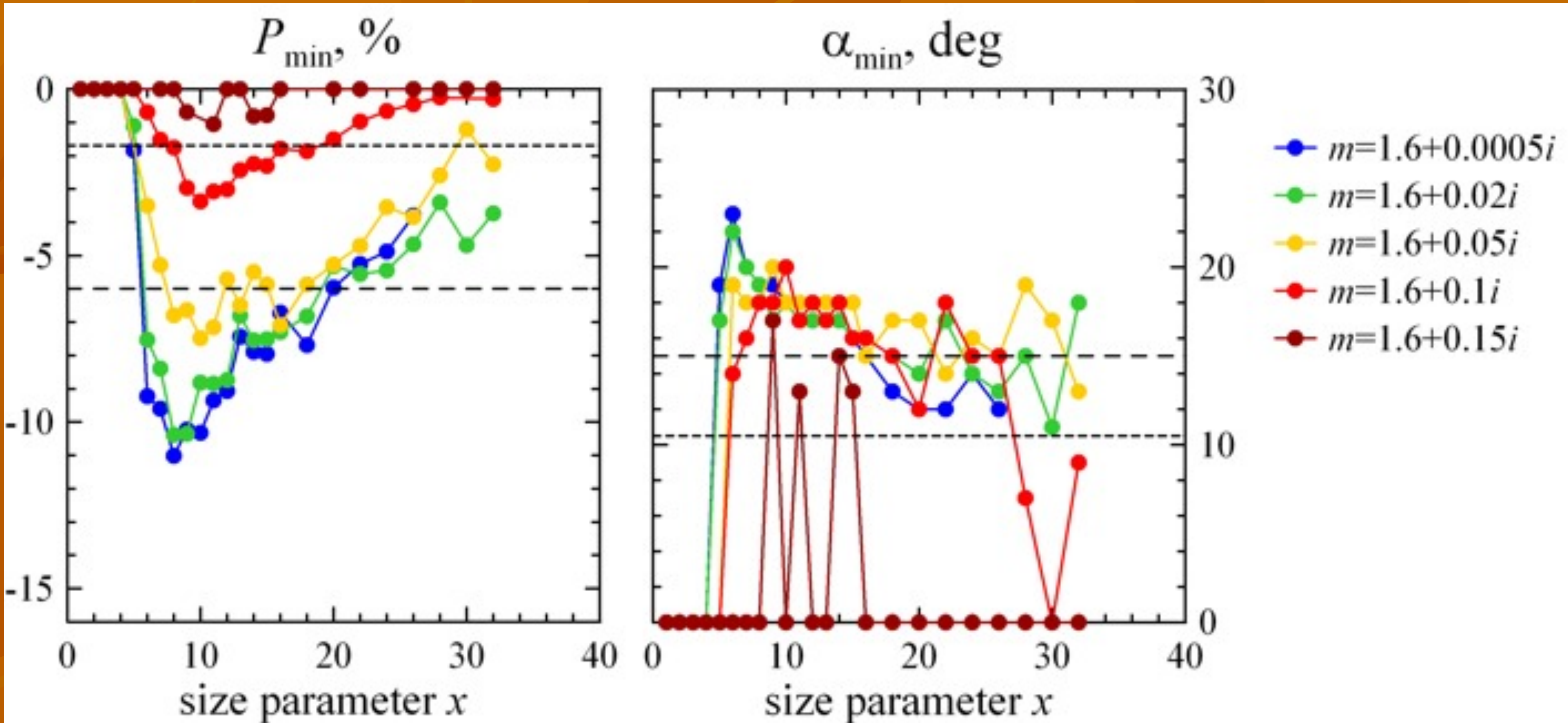


Increase of Re(m):

(1) does not affect amplitude in function P_{min} vs. x

(2) shifts maximum in function P_{min} vs. x toward smaller x

Negative polarization for various Im(m)

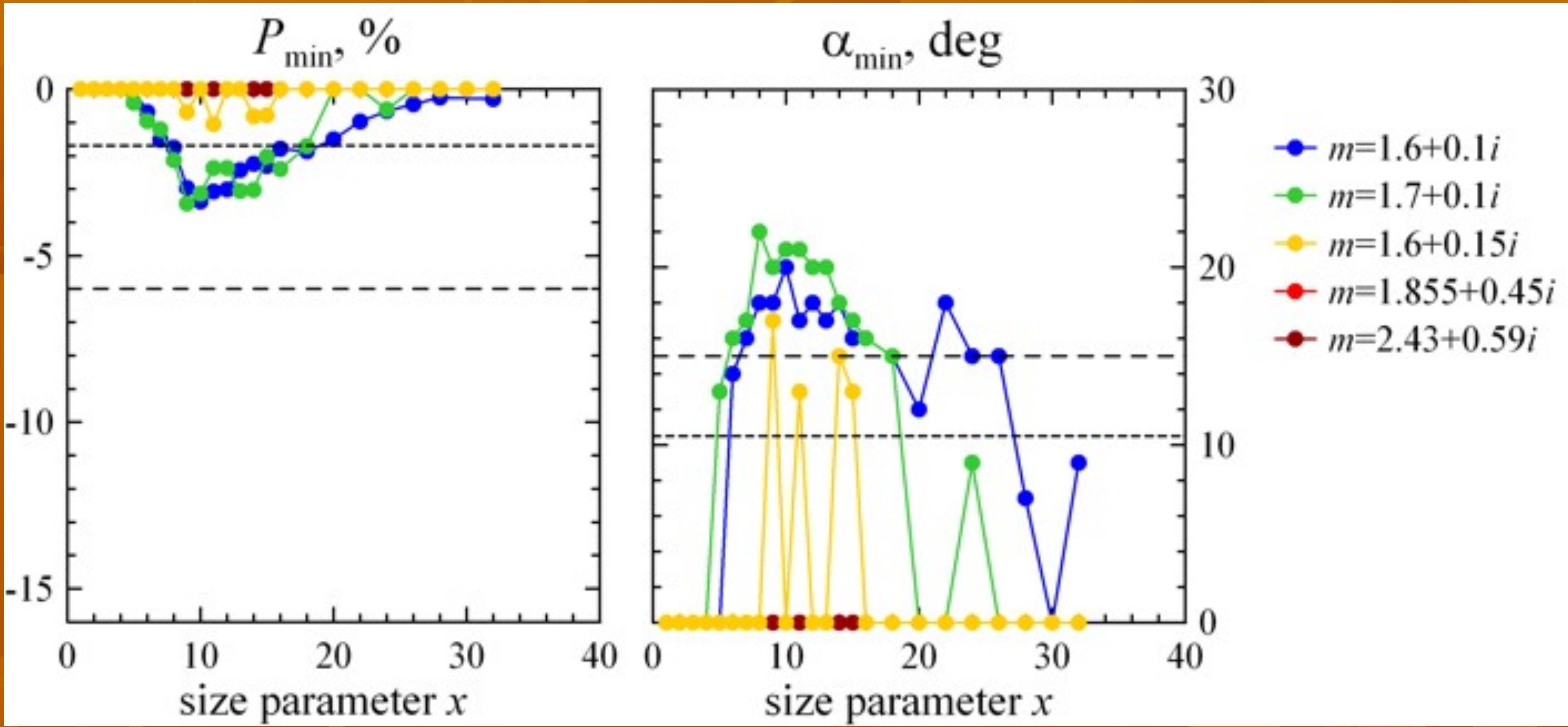


Increase of Im(m):

(1) decreases substantially P_{min}

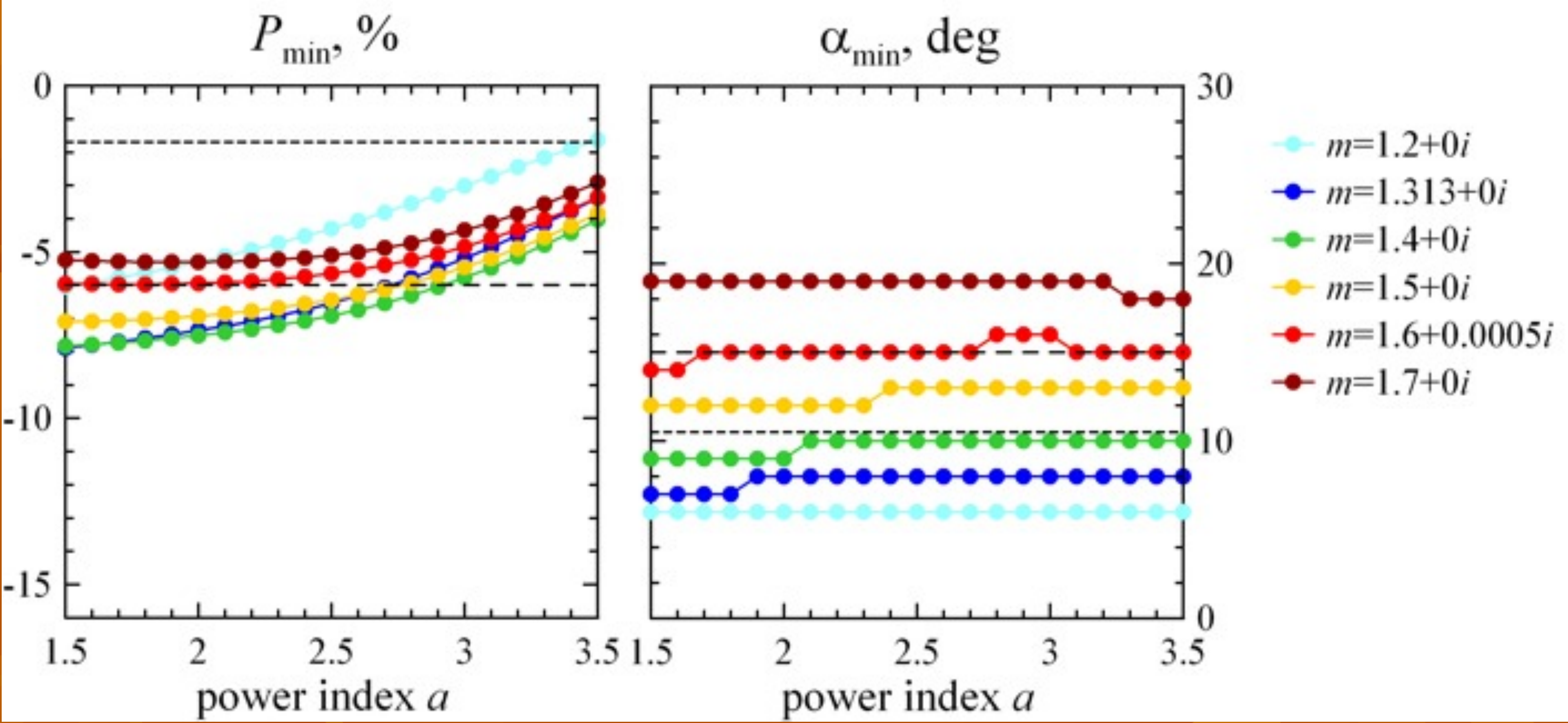
(2) does not affect location of maximum in function P_{min} vs. x

Negative polarization for various Im(*m*)



Highly absorbing (Im(*m*)≥0.15) carbon-rich materials cannot reproduce the negative polarization measured from a whole cometary coma because P_{min}≈0 throughout all *x*.

Negative polarization for various Re(m)

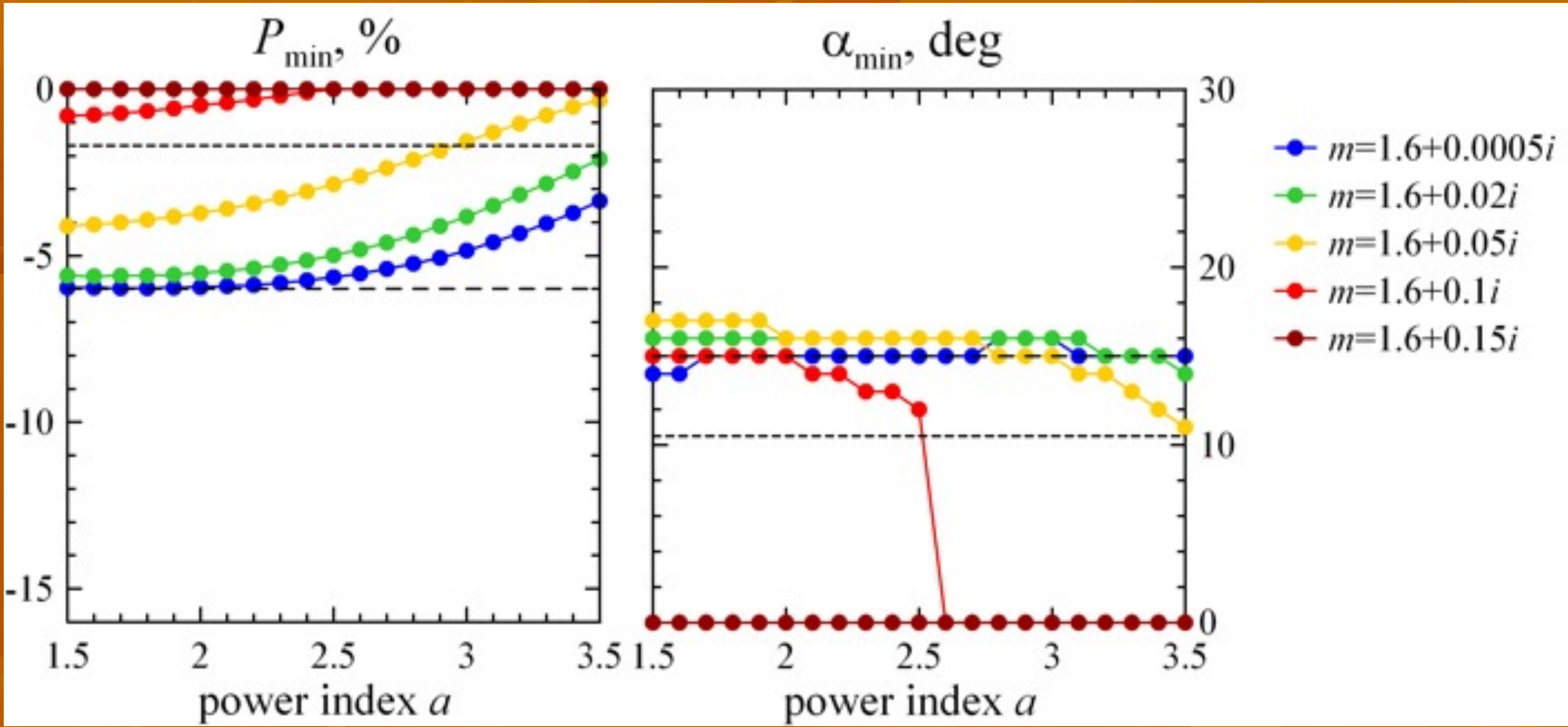


Size-averaging:

(1) substantially dampens P_{min} as compared to that for fixed size

(2) makes α_{min} an extremely stable

Negative polarization for various Im(m)

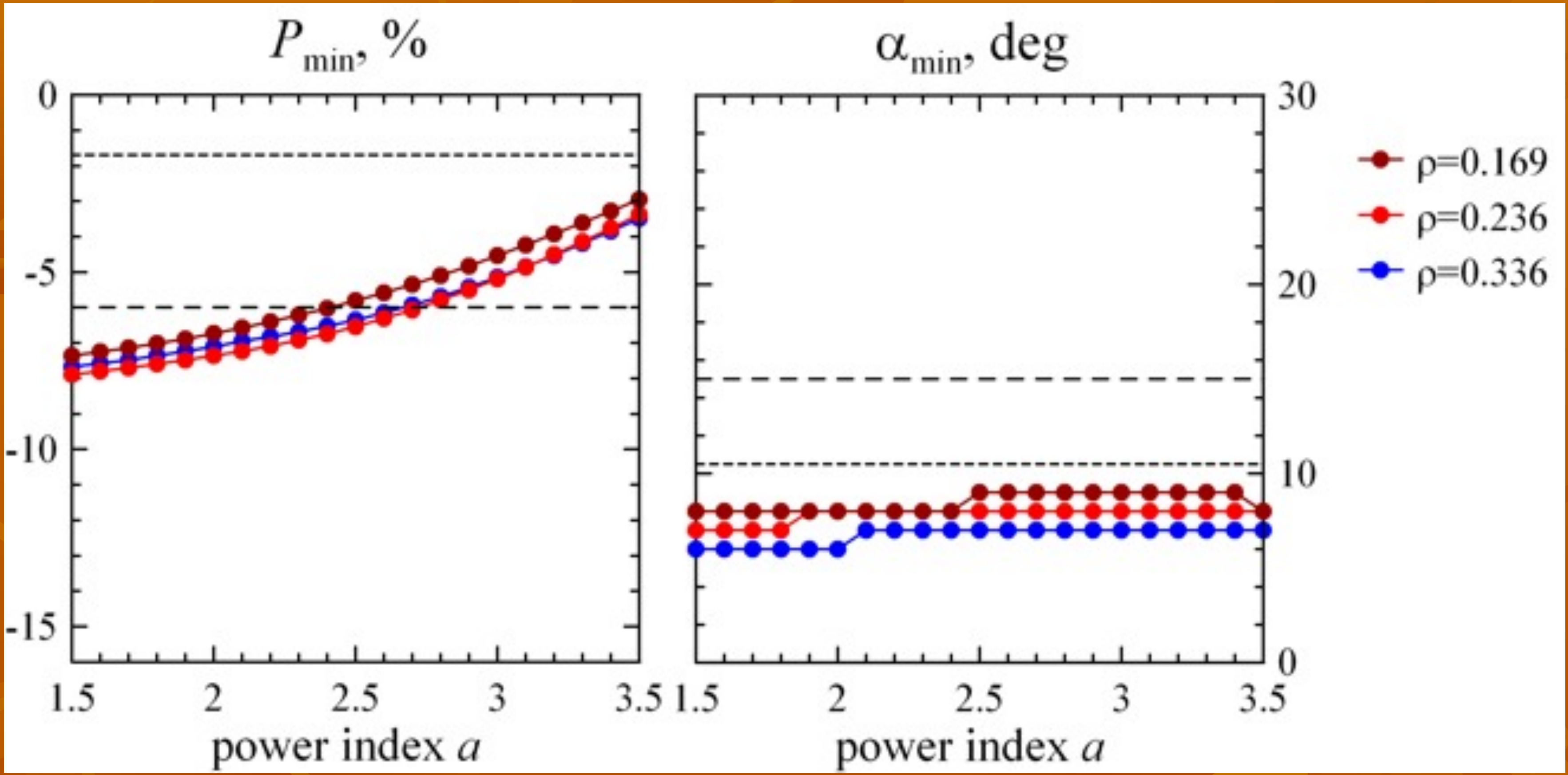


Size-averaging constrains absorption of cometary materials:

(1) in cometary haloes Im(m)≤0.02

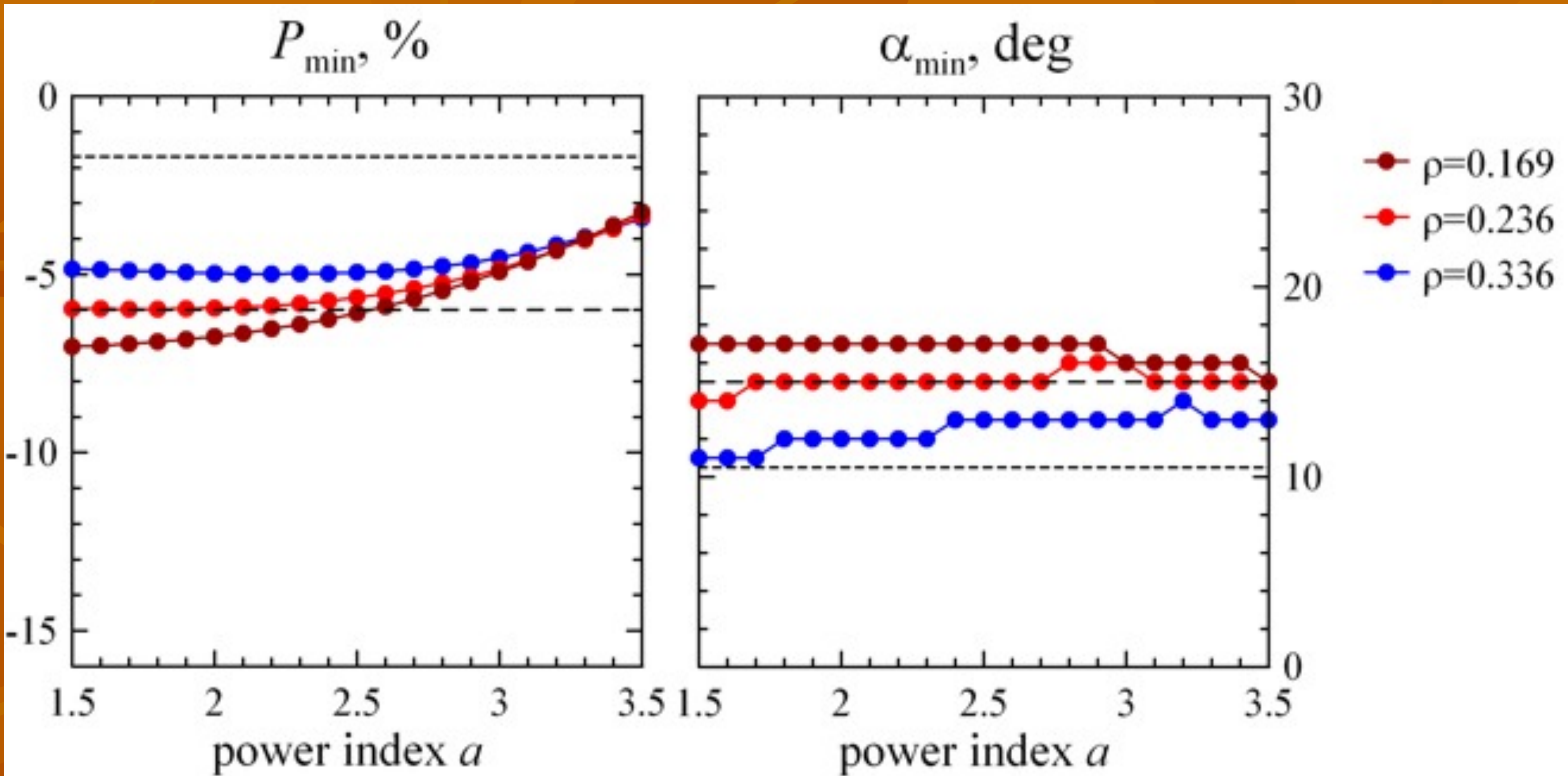
(2) in whole coma Im(m)≤0.07–0.08

Negative polarization vs. morphology at *m*=1.313+0*i*



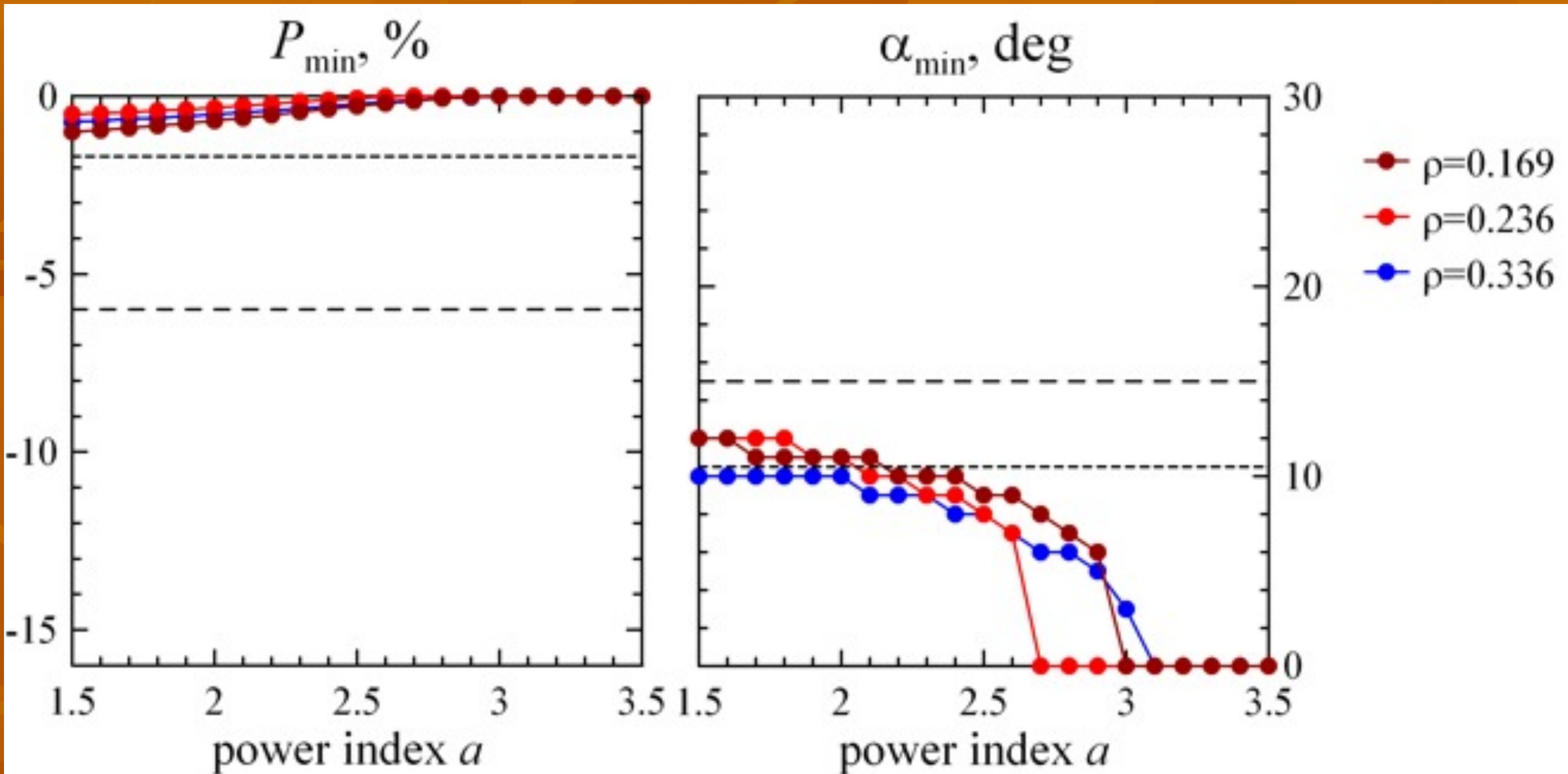
Particle morphology does not affect the negative polarization significantly.

Negative polarization vs. morphology at *m*=1.6+0.0005*i*



Particle morphology does affect P_{min} at a<2.5. It is comparable with accuracy in polarimetry of comets (i.e., ±1%). The impact of the morphology on P_{min} is much less than that of absorption.

Negative polarization vs. morphology at m=1.5+0.1i



Particle morphology does not affect the negative polarization significantly.

Summary on the negative polarization

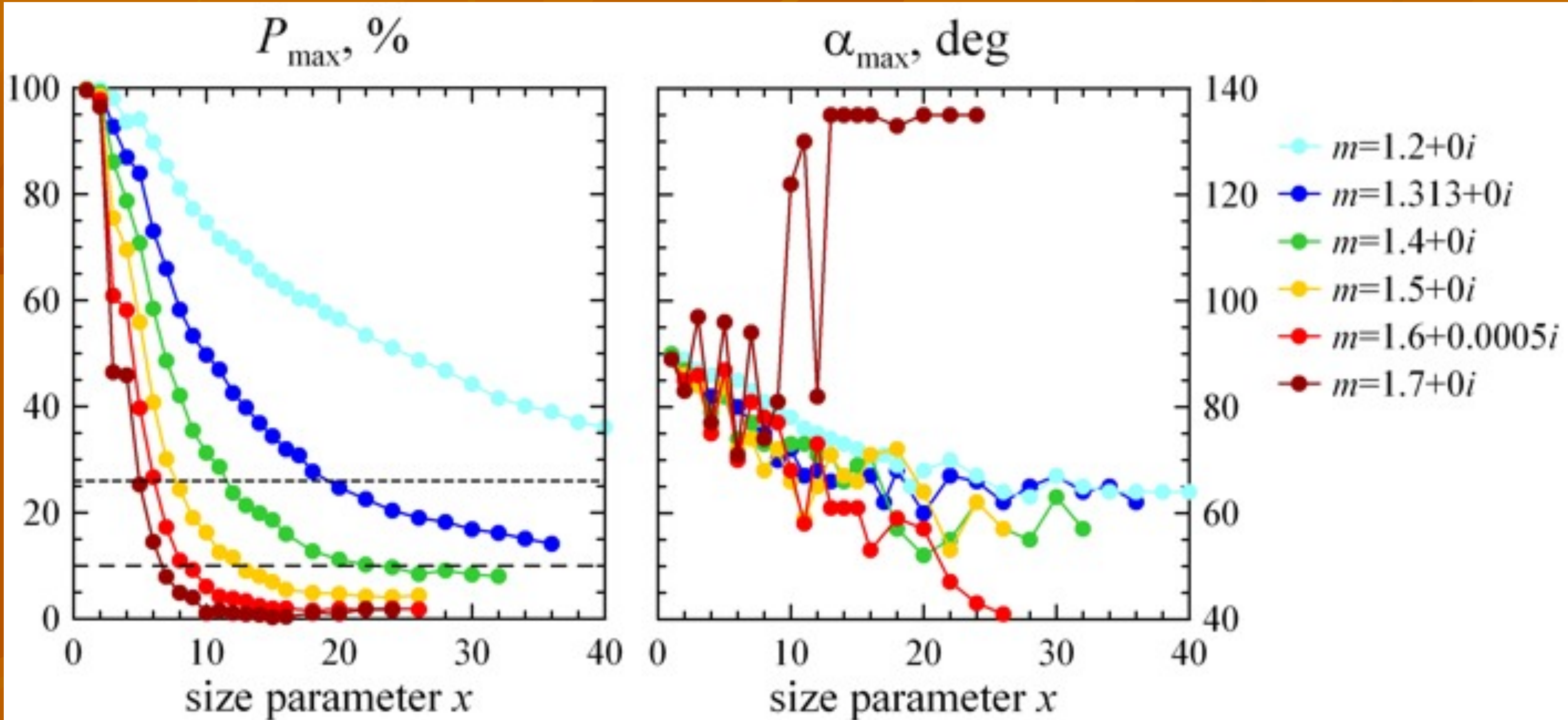
1. The negative polarization produced by single-scattering irregularly shaped particles is unambiguously dependent on Im(*m*). It can be used to determine local excess for Mg-rich silicates and carbonaceous materials in a cometary coma.

2. The index a in power-law size distribution may also affect considerably the negative polarization. However, its solely variation cannot explain dramatic difference in negative polarization of *whole coma*, *circumnucleus halo*, and *jets*.

3. True morphology of irregular agglomerates produces only minor impact on the negative polarization. It is typically less than the accuracy in polarimetric observations of comes.

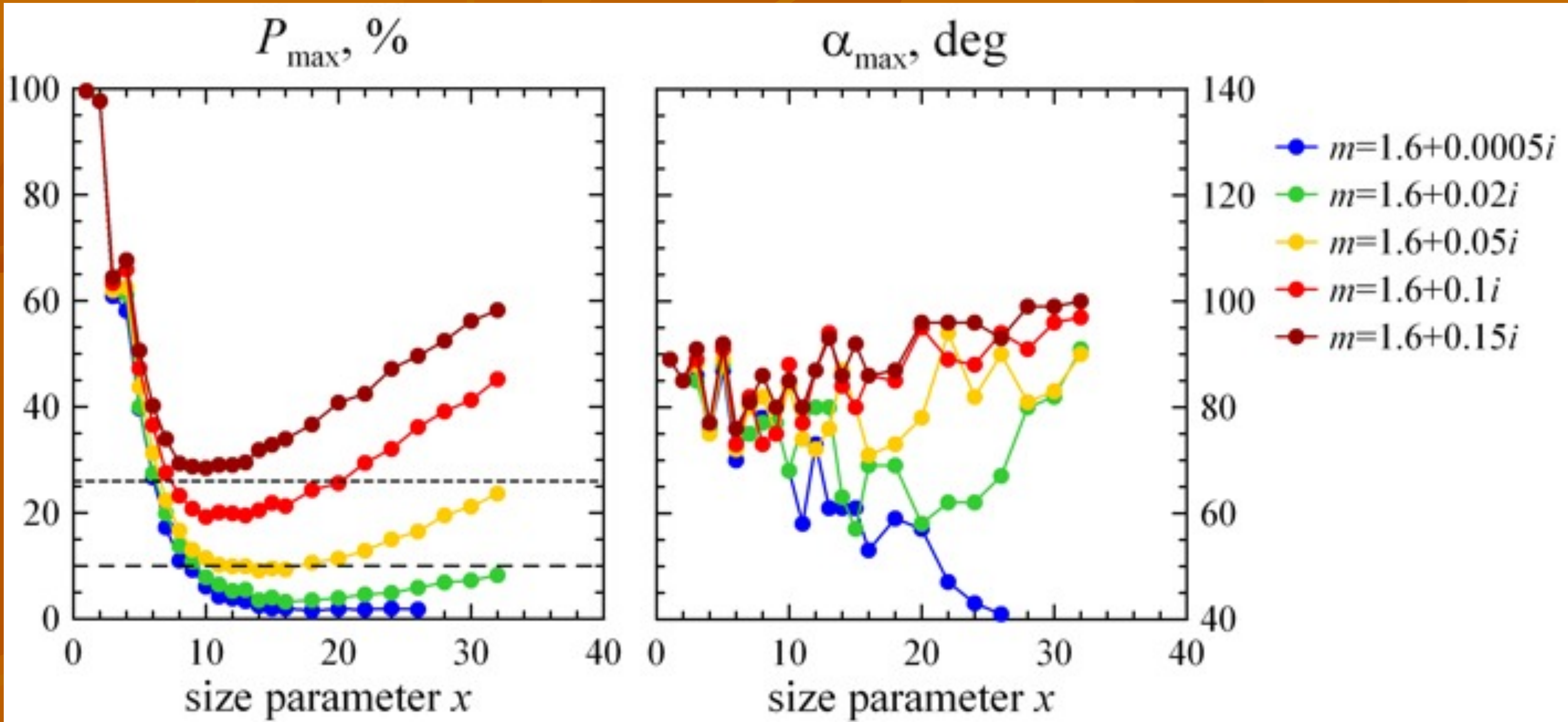
4. Cometary dust as seen from its positive polarization

Positive polarization for various Re(*m*)



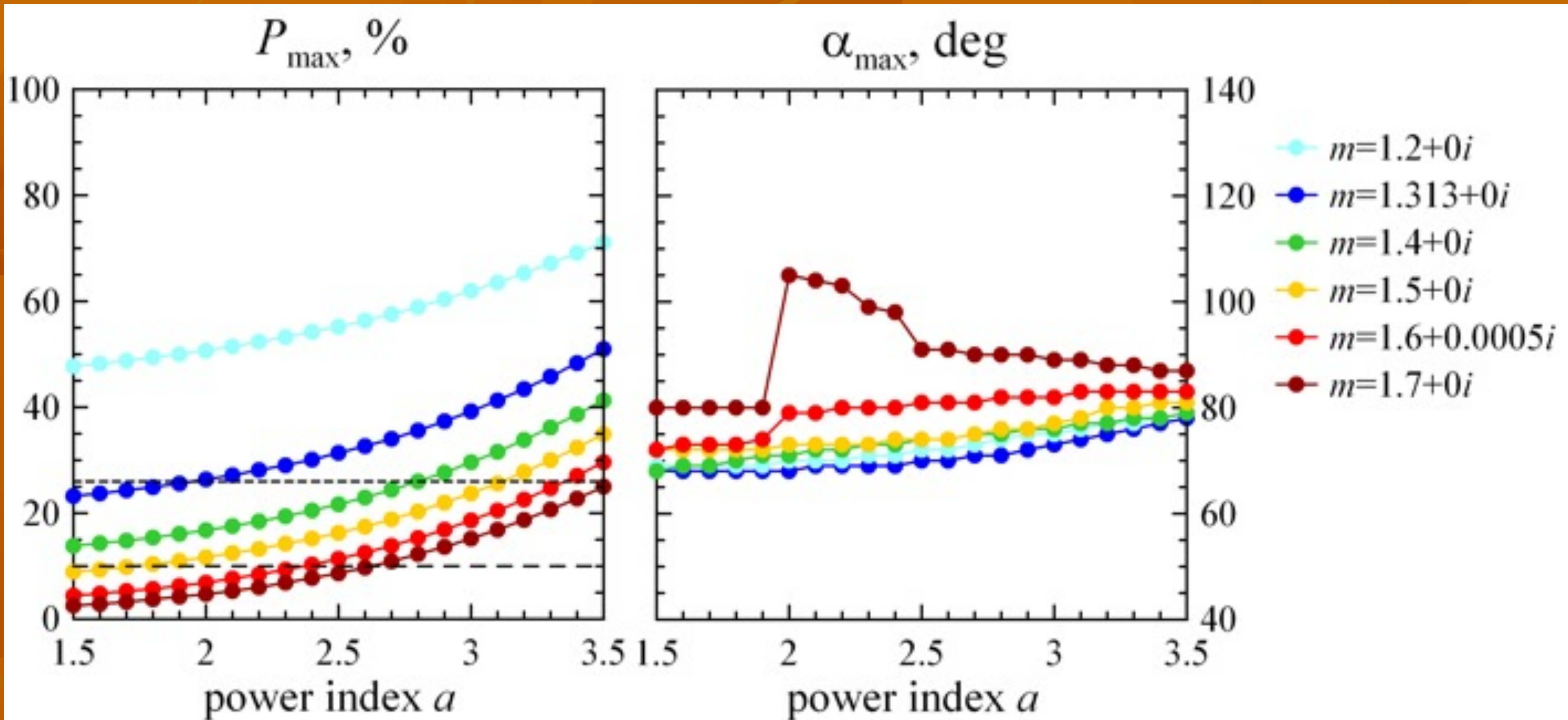
Increase of Re(*m*) dramatically decreases the amplitude of positive polarization P_{max}.

Positive polarization for various Im(m)



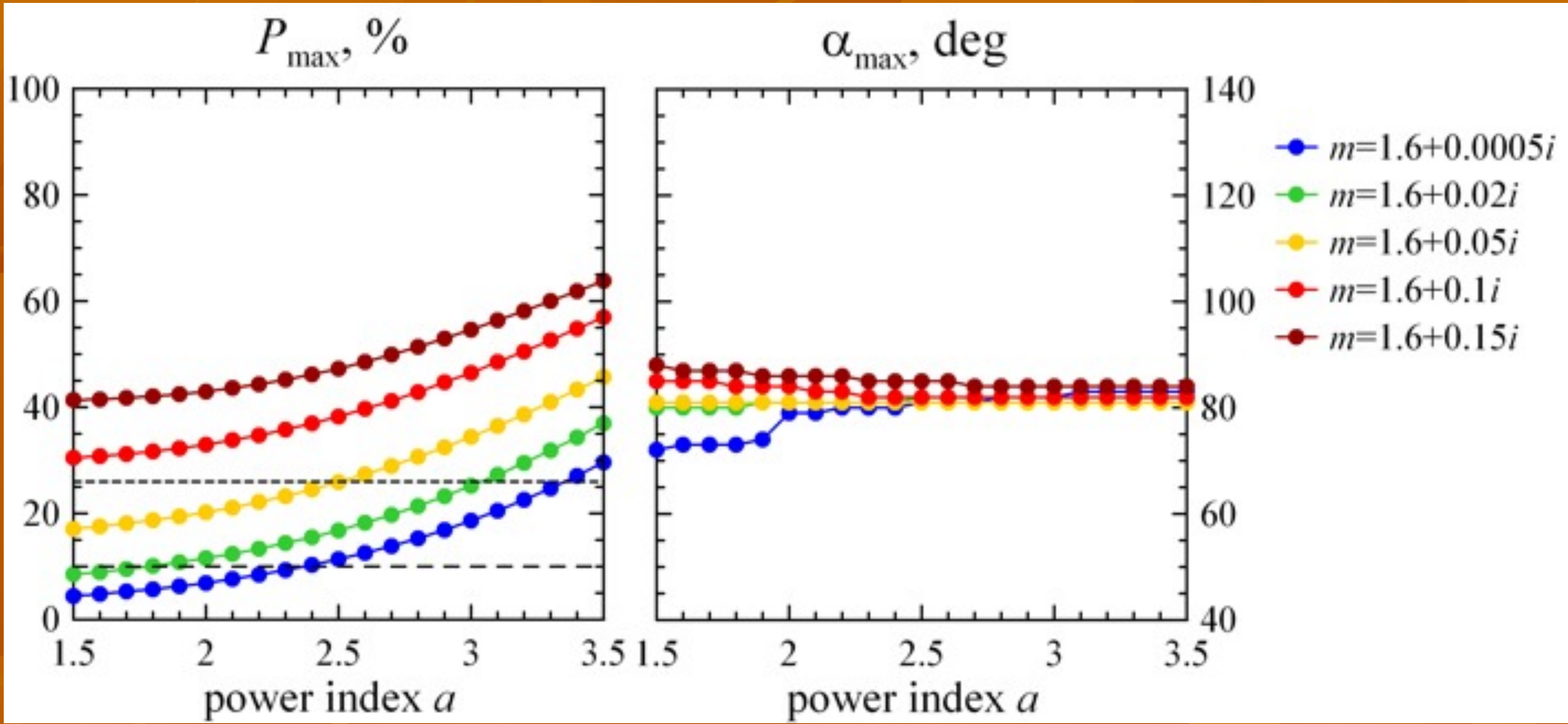
Increase of absorption substantially increases P_{max}. It also makes a non-monotonic behavior in function P_{max} vs. x; whereas, lowest value of P_{max} is achieved at x=10–16.

Positive polarization for various Re(m)



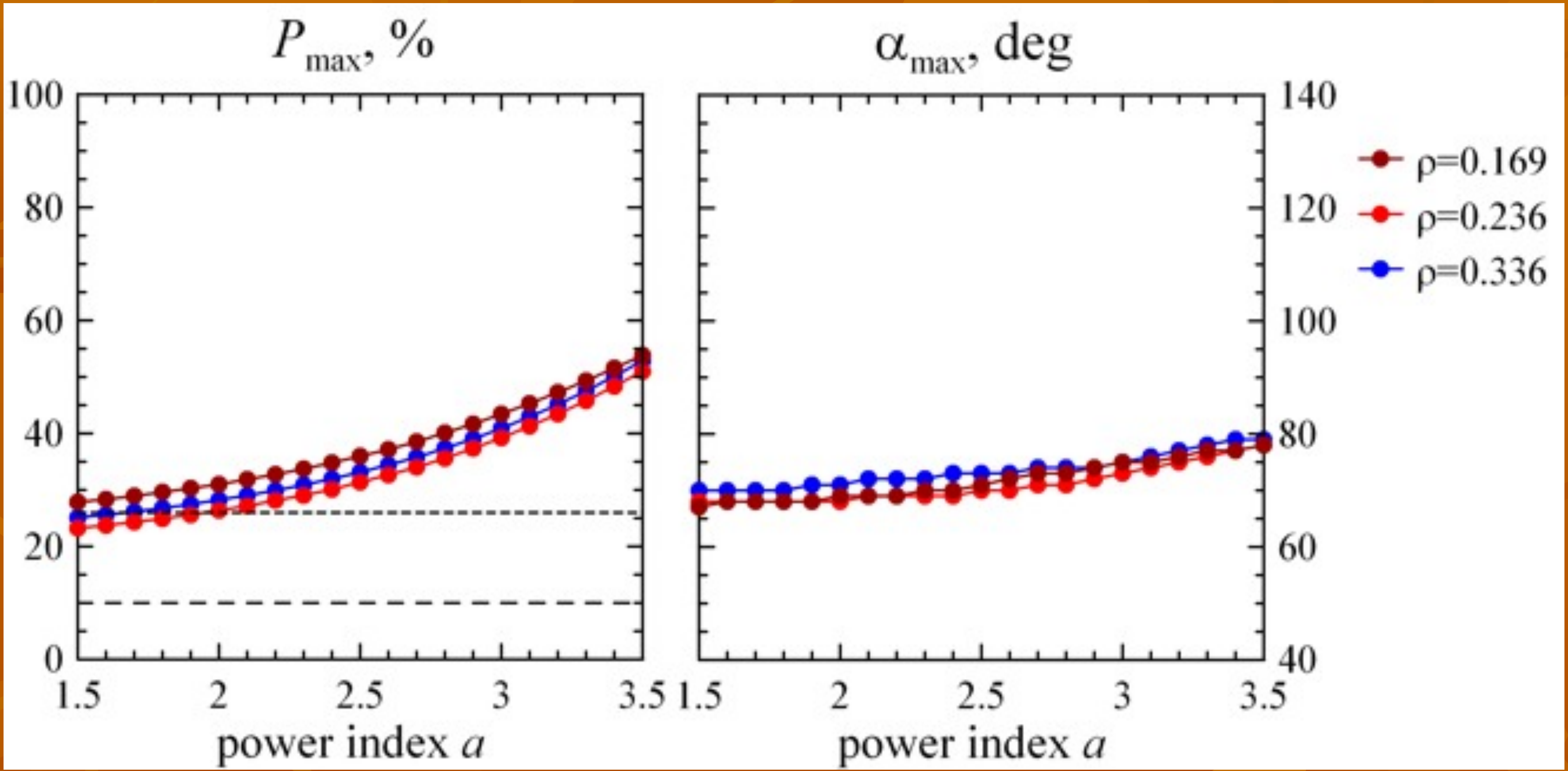
Size-averaging constrains the refractive index of cometary materials. Whole-coma P_{max} cannot be reproduced with optically soft materials at Re(m)<1.3.

Positive polarization for various Im(m)



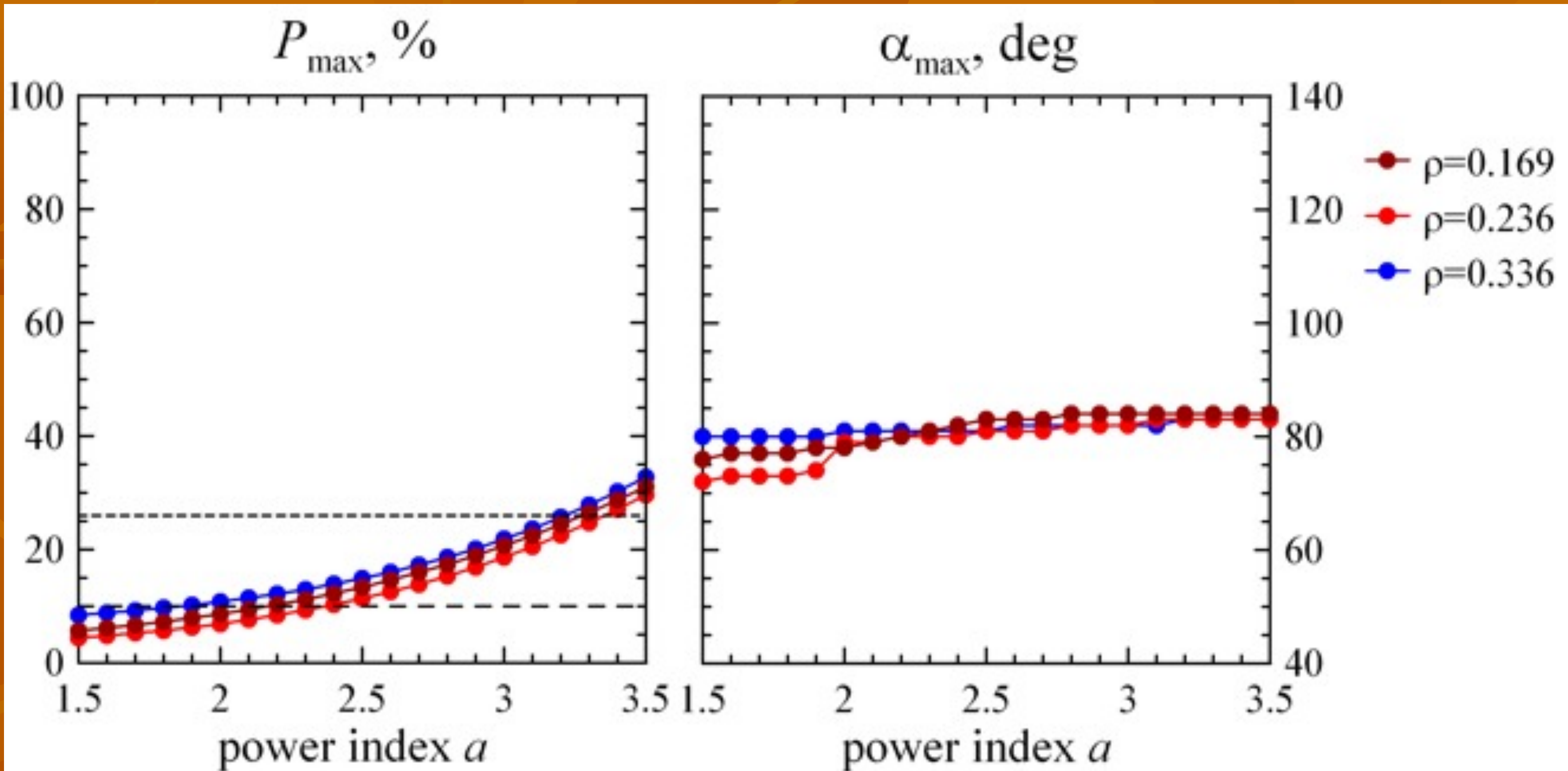
Size-averaging constrains the material absorption in comets. Whole-coma P_{max} cannot be obtained at Im(m)≥0.1. Mixture of particles with high and low Im(m) could fit the observations.

Positive polarization vs. morphology at m=1.313+0i



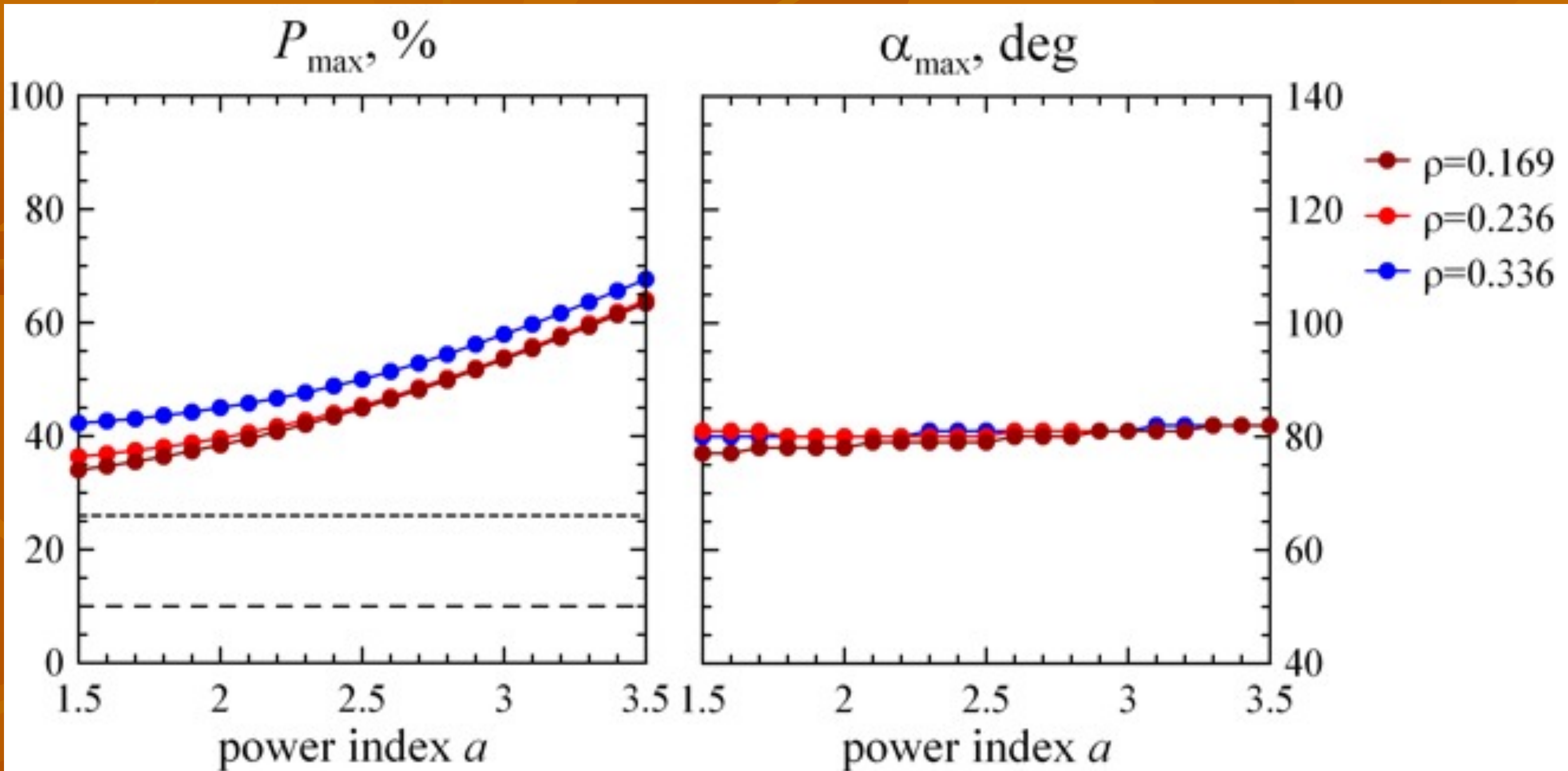
Particle morphology does not affect the positive polarization significantly. Nevertheless, potentially, such difference in P_{max} could be detected.

Positive polarization vs. morphology at m=1.6+0.0005i



Particle morphology does not affect the positive polarization significantly. Nevertheless, potentially, such difference in P_{max} could be detected.

Positive polarization vs. morphology at m=1.5+0.1i



Particle morphology does not affect the positive polarization significantly. Nevertheless, potentially, such difference in P_{max} could be detected.

Summary on the positive polarization

1. The positive polarization produced by single-scattering irregularly shaped particles is unambiguously dependent on Im(*m*). It can be used to determine local excess for Mg-rich silicates and carbonaceous materials in a cometary coma.
2. P_{max} observed in comets cannot be reproduced with optically soft Re(*m*)<1.3 and highly absorbing Im(*m*)≥0.1 materials. Thus, abundance of carbonaceous materials (with high Im(*m*)) in comets should imply simultaneous presence of weakly absorbing cometary materials.
3. True morphology of irregular agglomerates produces only secondary effect on the positive polarization.

5. Estimation of the geometric albedo with the Umov effect

What is the Umov effect?

N. Umov (1846-1915)

The brighter is a powder,
the lower is its linear polarization

Umov, Phys. Zeits. 6, 674-676 (1905)

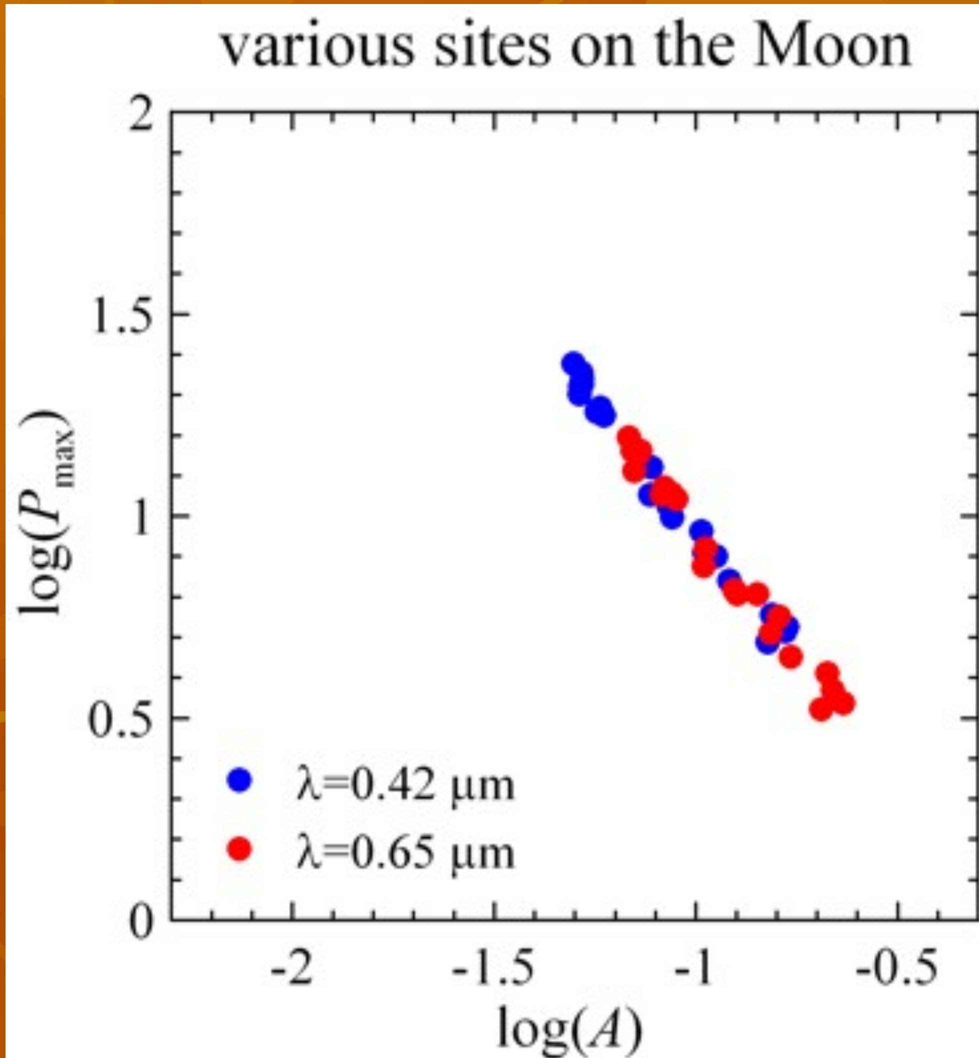
Origin of the effect

depolarization that is caused by multiple scattering in regolith

In 1960-1970, the qualitative law has been quantified as follows:

log(P_{max}) linearly depends on log(A).

the Umov effect for the Moon



Shkuratov & Opanasenko, Icarus 99, 468-484 (1992)

the Umov effect for single-scattering particles?

Why such extension could make sense:

(1) The Umov effect holds for quite dark surfaces

(2) In dark surfaces, single-scattering contributes substantially into the whole light scattering

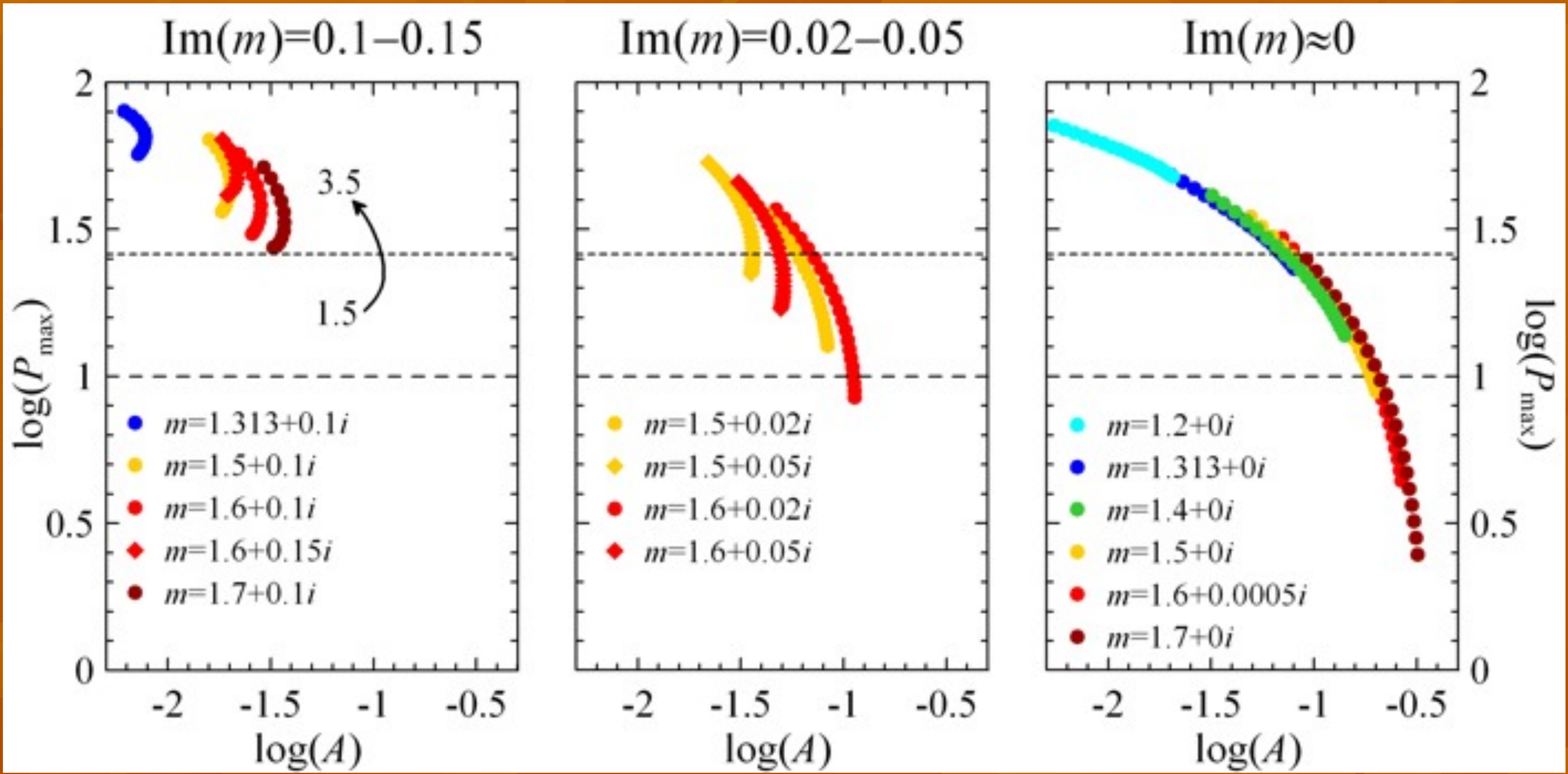
Geometric albedo for the case of single particles:

$$A=(M_{11}(0)\pi)/(k^2G)$$

Here, $M_{11}(0)$ is the total intensity Mueller matrix element at backscattering, k – the wave number, and G – the geometric cross-section of the particle.

A in comets from the Umov effect

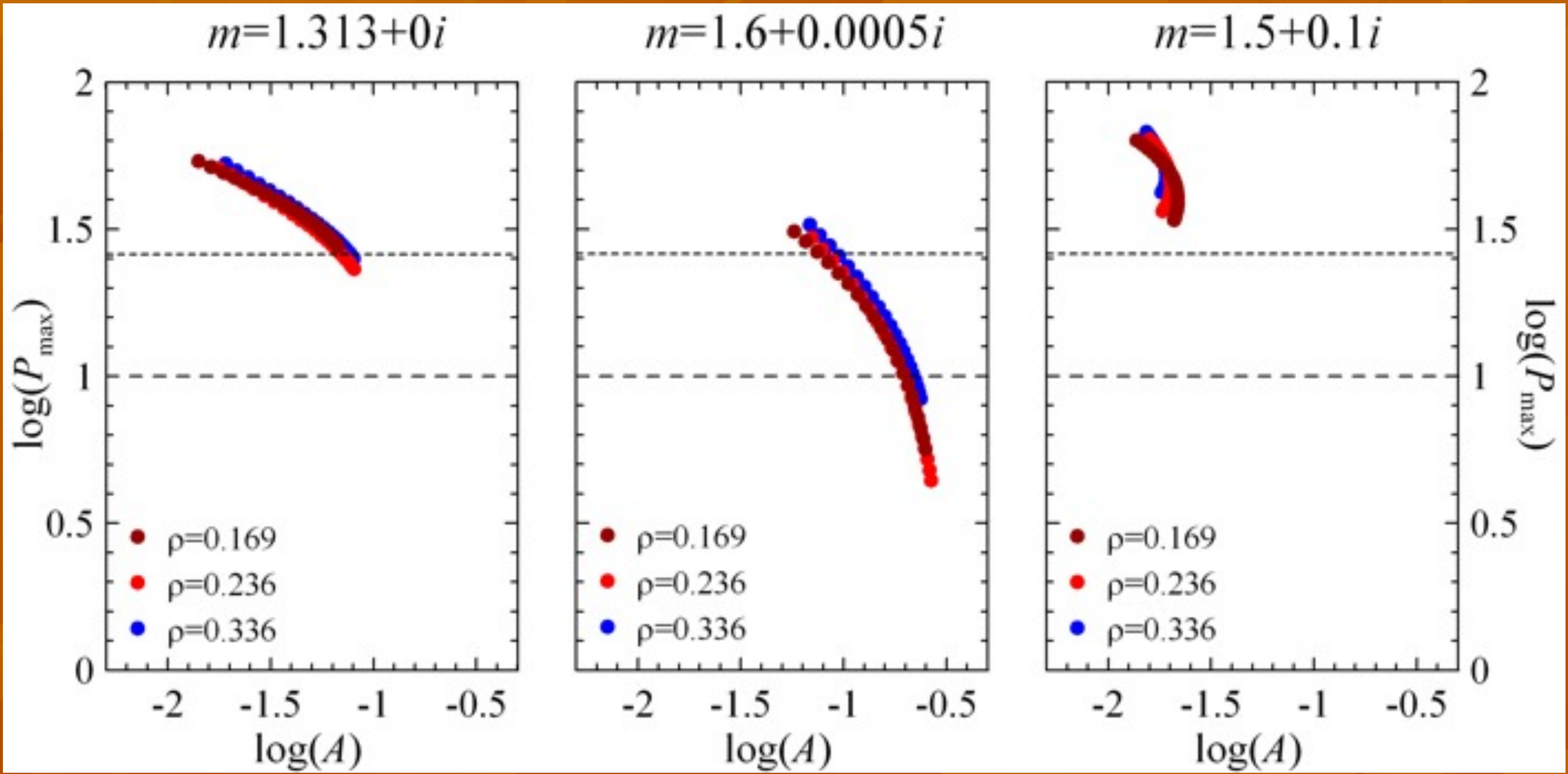
Agglomerated debris particles ρ=0.236



Haloes	P_{max}≈10%:	*A*=0.11–0.21
Whole comets	P_{max}≈26%:	*A*=0.04–0.08

A in comets from the Umov effect

Agglomerates with different morphology



Variation of agglomerate morphology produces rather small impact on the diagrams log(*A*) vs. log(P_{max})

Conclusion

1. Degree of linear polarization is an important source of information on dust in comets. Both, the negative and the positive polarization branches reveal dramatic dependence on the material absorption. Thus, they could be used for detection of time- and spatial variations in chemical composition.

2. Maximum of the positive polarization P_{max} correlates with the geometric albedo *A* of target particles through the Umov effect. When applied to whole coma, it provides *A*=0.04–0.08 that is well consistent with other methods.
   However, the Umov effect predicts also a substantial variation of *A* throughout coma. For instance, in the innermost part of coma, i.e., circumnucleus halo, it could be a few times higher as compared to whole coma *A*=0.11–0.21.