Calculating optical properties of irregular grains (and perhaps regoliths…)

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Tadashi Mukai led the way…

- Mukai, S, & **Mukai, T.** 1990, "Analysis of photopolarimetric data of comets at small phase angles by rough surface scattering", Icarus, 86, 257
- Mukai, S., & **Mukai, T.** 1991, "Scattering Properties of Cometary Dust Based on Polarimetric Data", ASSL, 173, 249
- Kozasa, H., Blum, J., & **Mukai, T.** 1992, "Optical Properties of Dust Aggregates I. Wavelength Dependence", A&A 263, 423
- Kozasa, T., Blum, J., Okamoto, H, & **Mukai, T.** 1993, "Optical Properties of Dust Aggregates II. Angular Dependence of Scattered Light", A&A 276, 278
- Kimura, H., Okamura, H., & **Mukai, T.** 2002, "Radiation Pressure and the Poynting-Robertson Effect for Fluffy Dust Grains", Icarus 157, 349
- **Mukai, T.**, Nakamura, A. M., & Sakai, T. 2006, "Asteroidal surface studies by laboratory light scattering and LIDAR on HAYABUSA", Adv. Sp. Res., 37, 138
- Levasseur-Regourd, A. C., **Mukai, T.**, Lasue, J., & Okada, Y. 2007, "Physical Properties of Cometary and Interplanetary Dust", Plan. Sp. Sci. 55, 1010

And many more papers…

Plan

- **What is the geometry of interstellar or interplanetary grains?**
- **Ballistic Agglomerates as candidates for irregular aggregates.**
  - *Two new classes: BAM1 and BAM2*
  - *How to measure size and porosity for a random aggregate?*
- **How to calculate scattering and absorption for irregular geometries?**
- **The discrete dipole approximation**
- **Some scattering properties of ballistic aggregates**
- **Moderate-porosity candidates for dust in a debris disk**
- **Moderate-porosity candidates for cometary dust.**
- **Future: applying DDA to dust layers.**

Grain Geometry?

- Modeling usually assumes spherical grains (because calculations are easy).
- Polarization of starlight and polarization of infrared emission: real grains are NOT spherical.
- What is ***actual*** grain geometry?

Dust Grain Geometry

- Interplanetary Dust Particles (IDPs)

228 John Bradley

Bradley, J. P. 2003, Treatise on Geochemistry, vol.1, 689-711

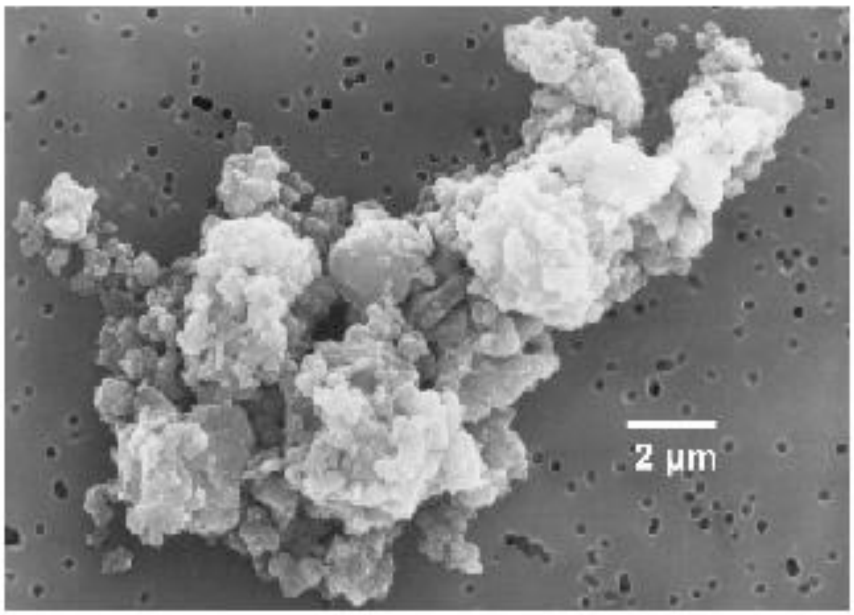


Fig. 1. Secondary electron image of chondritic porous (CP) interplanetary dust particle (IDP) U220B43.

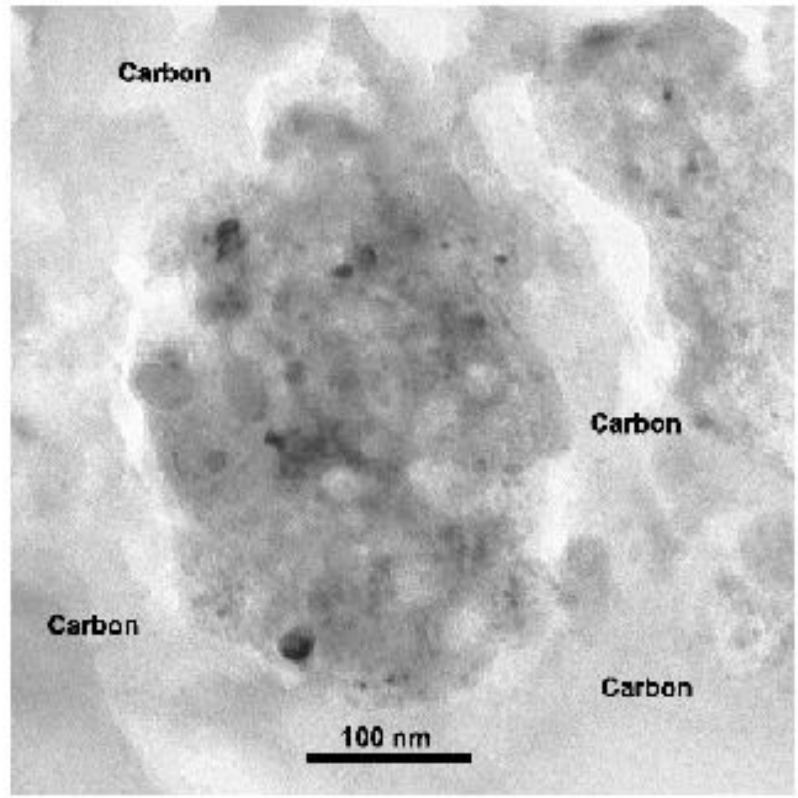
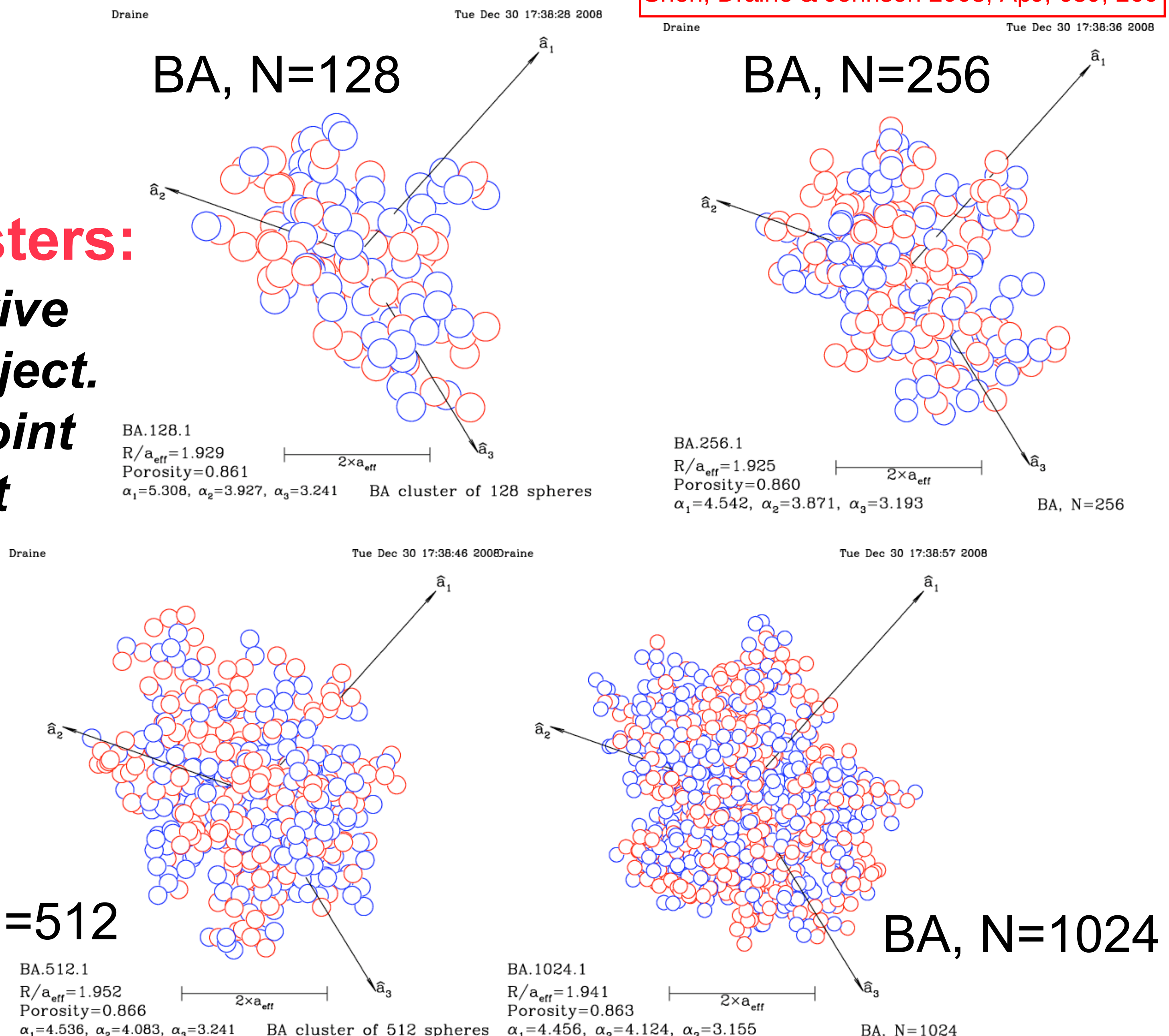


Fig. 8. Brightfield transmission electron micrograph of a GEMS embedded a amorphous carbon material in IDP L2011R11. The remnants of a deeply eroded relict grain with "swiss cheese" microstructure can be seen towards the center of the grain.

BA clusters ≡ BPCA clusters:

monomers arrive on random traject. and stick at point of first contact

Shen, Draine & Johnson 2008, ApJ, 689, 260



Two New Classes of Random Aggregates: BAM1 and BAM2

BA growth process $\rightarrow$

- very low filling factor (≈ 0.14)
- high "porosity" (≈ 0.86)
- very fragile

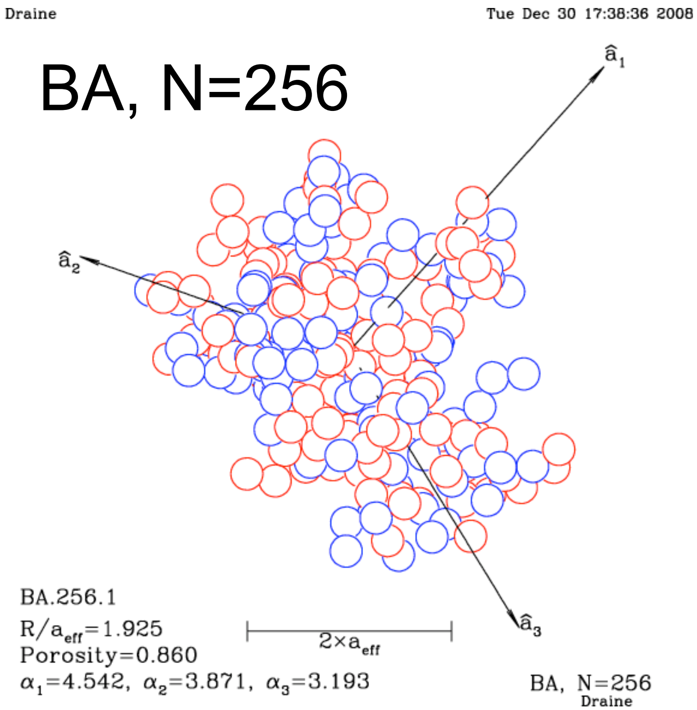
Real IDPs appear to be more robust than **BA** aggregates.

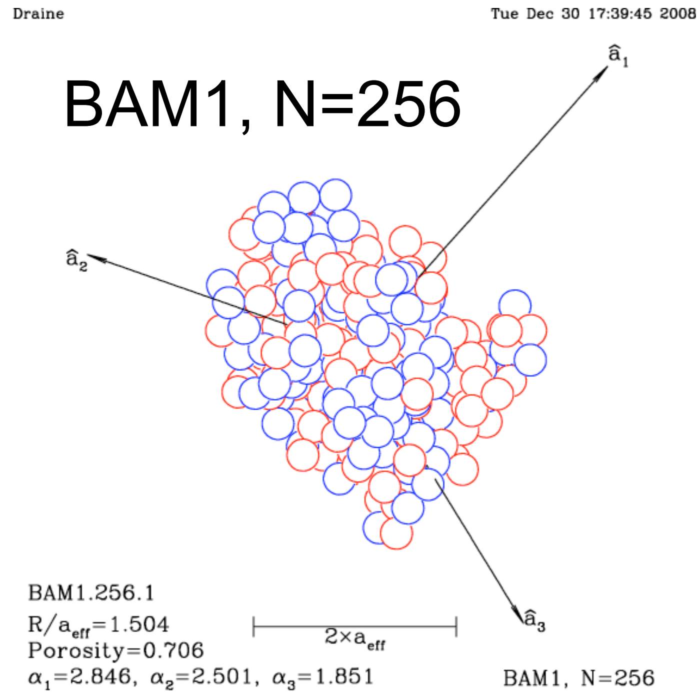
Would like to have aggregates that are random but somewhat more dense than **BA** clusters. Consider two new classes of random agglomerates: **BAM1** and **BAM2**.

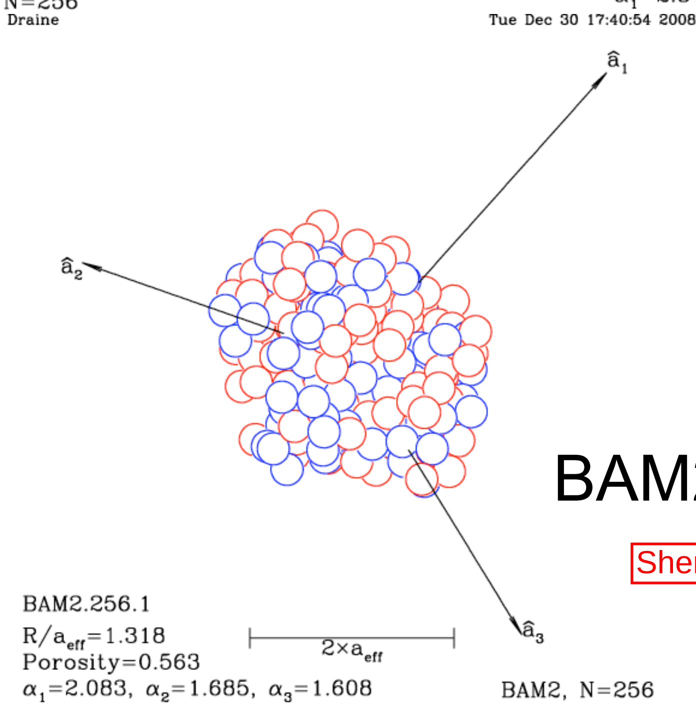
Monomers arrive on random trajectories, just as for **BA**.

- **BAM1**: At first contact, roll to make contact with a second monomer, then stop.
  BAM1 more dense than **BA**.
- **BAM2**: At first contact, roll to make contact with second monomer, then roll again to make contact with third monomer, then stop.
  BAM2 more dense than **BAM1**.

Algorithms are not difficult to implement for spherical monomers.



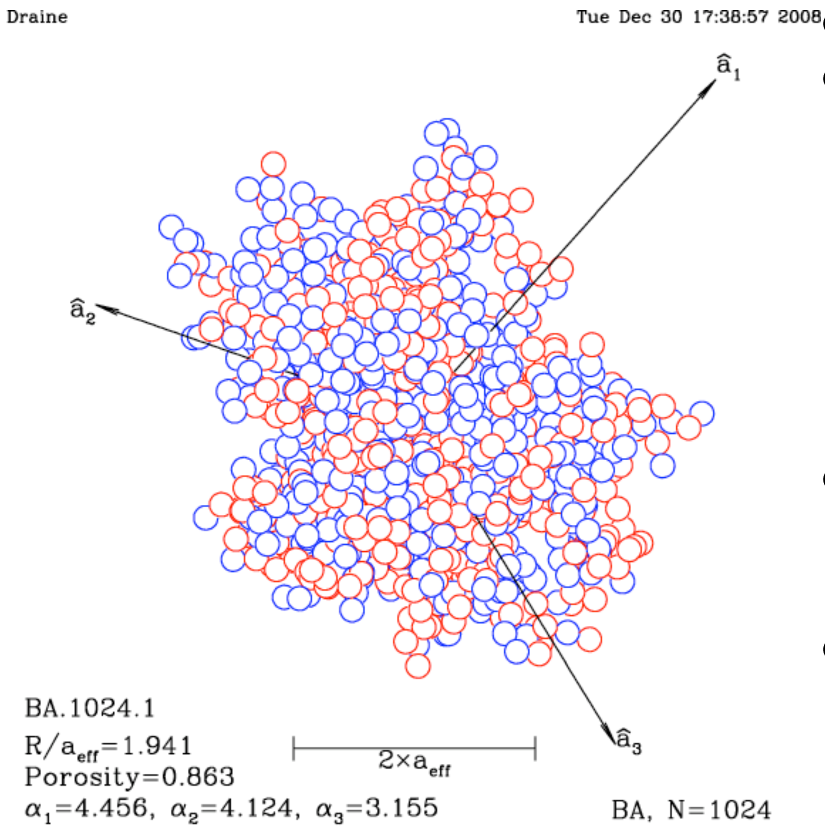




BAM2, N=256

Shen, Draine & Johnson 2008, ApJ, 689, 260

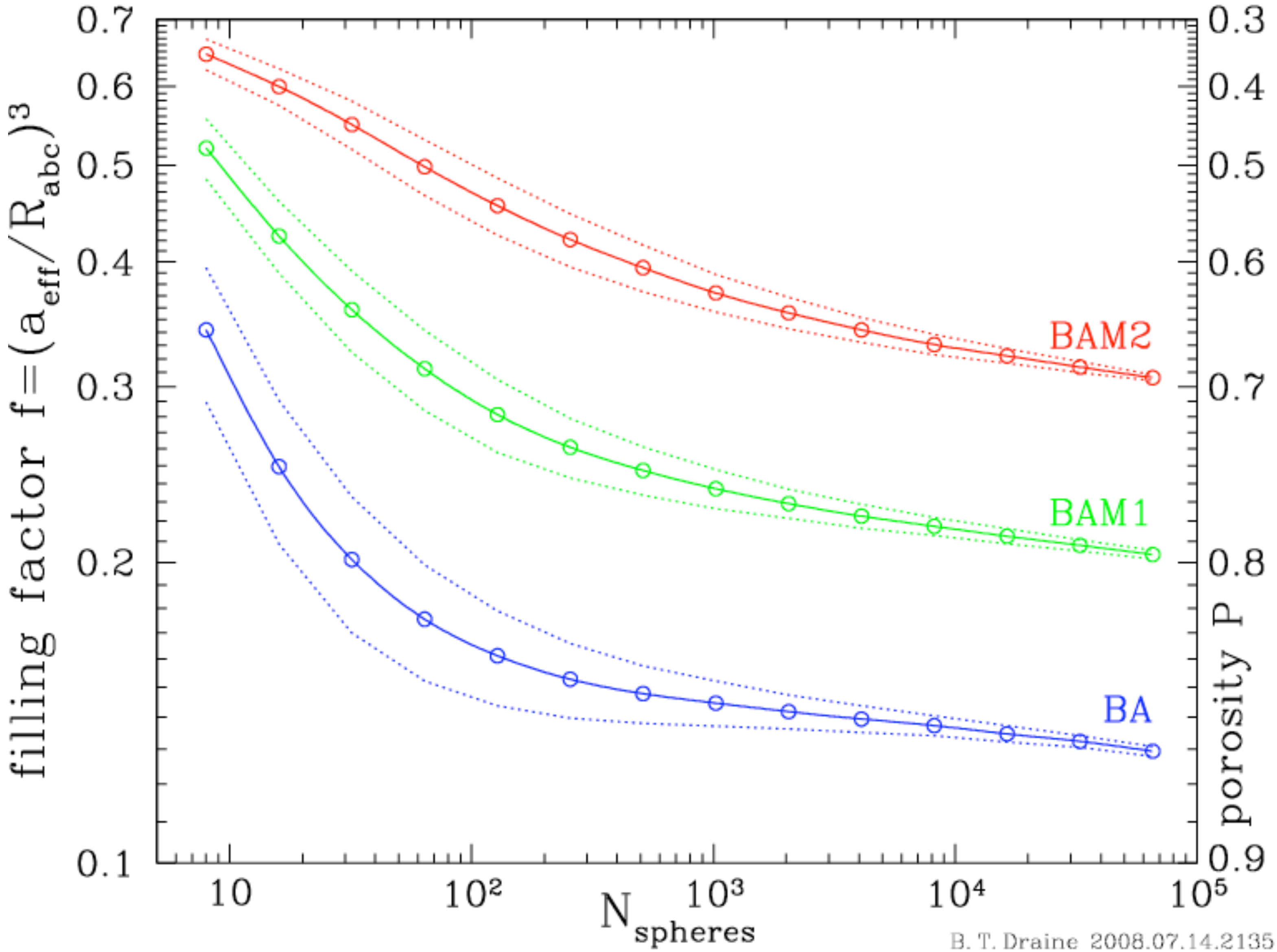
How to measure "porosity"?



Shen, Draine & Johnson 2008, ApJ, 689, 260

- For extended material, $\mathcal{P}$ = fraction of total volume that is unoccupied.
- For cluster, how to define "total volume"?
- Consider ellipsoid with semi-axes a, b, c and density $(1 - \mathcal{P})\rho$, with $a, b, c, \mathcal{P}$ such that total mass M and moment of inertia tensor I_{ij} are same as for cluster.
  This serves to define a, b, c and $\mathcal{P}$.
  This is porosity definition of Shen, Draine & Johnson (2008)
- 3×3 moment of inertia tensor I_{ij} easy to calculate and to find eigenvalues.
  $\mathcal{P}$ is easily calculated from eigenvalues.
- Equivalent porous ellipsoid has semiaxes a, b, c
  - b/a, c/b, c/a characterize asymmetry
  - Define characteristic size $R_{abc} \equiv (abc)^{1/3}$
    Size parameter $x = 2\pi R_{abc}/\lambda$

Porosity vs. N for BA, BAM1, BAM2



Shen, Draine & Johnson 2008, ApJ, 689, 260

Asymmetry of BA, BAM1, BAM2 clusters

Equivalent ellipsoid with semi-axes a,b,c

Asymmetry ***decreases*** as BA⇒BAM1⇒BAM2

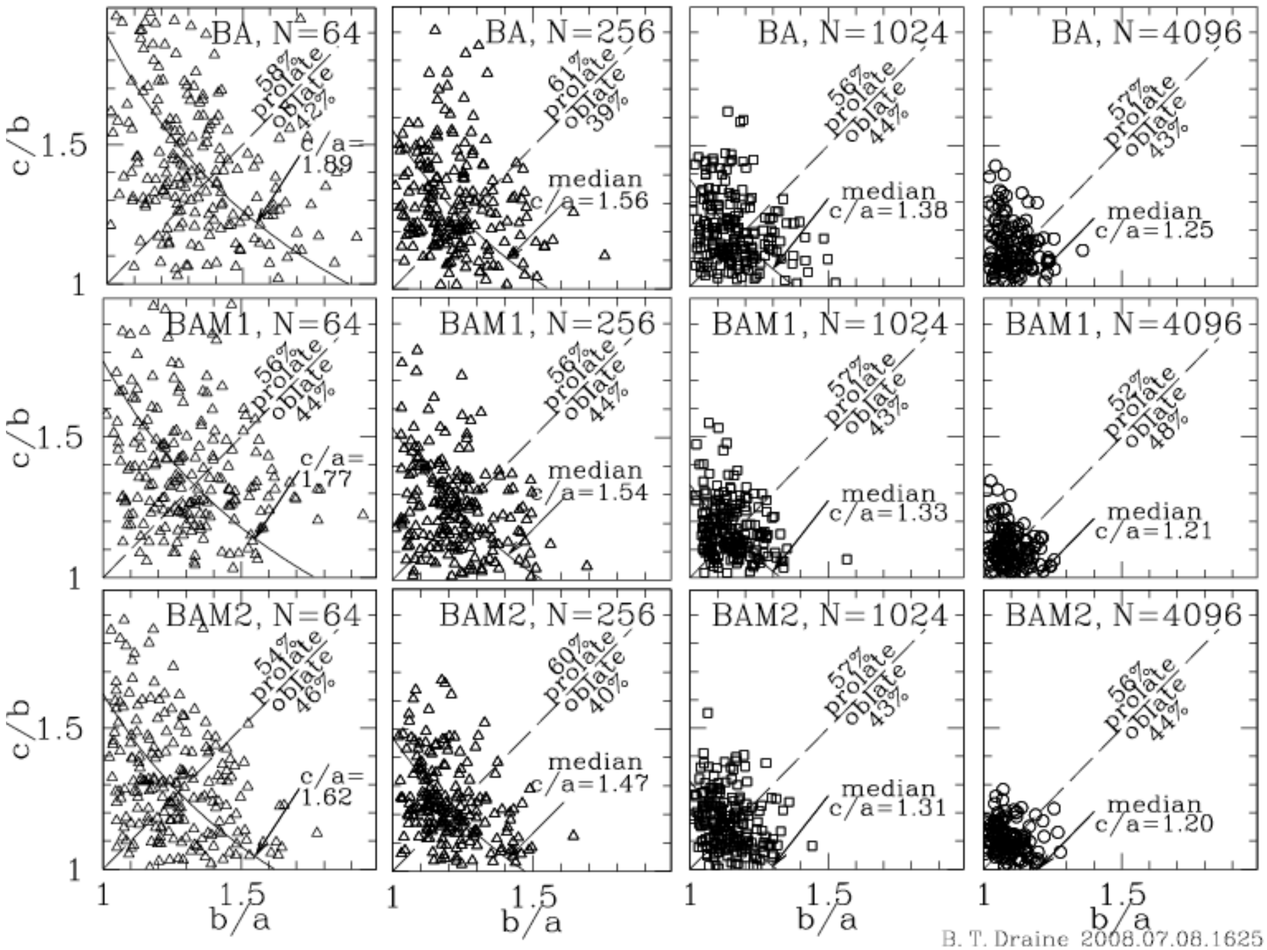
Asymmetry ***decreases*** as N increases

N=256: median c/a=

1.56 for BA

1.54 for BAM1

1.47 for BAM2



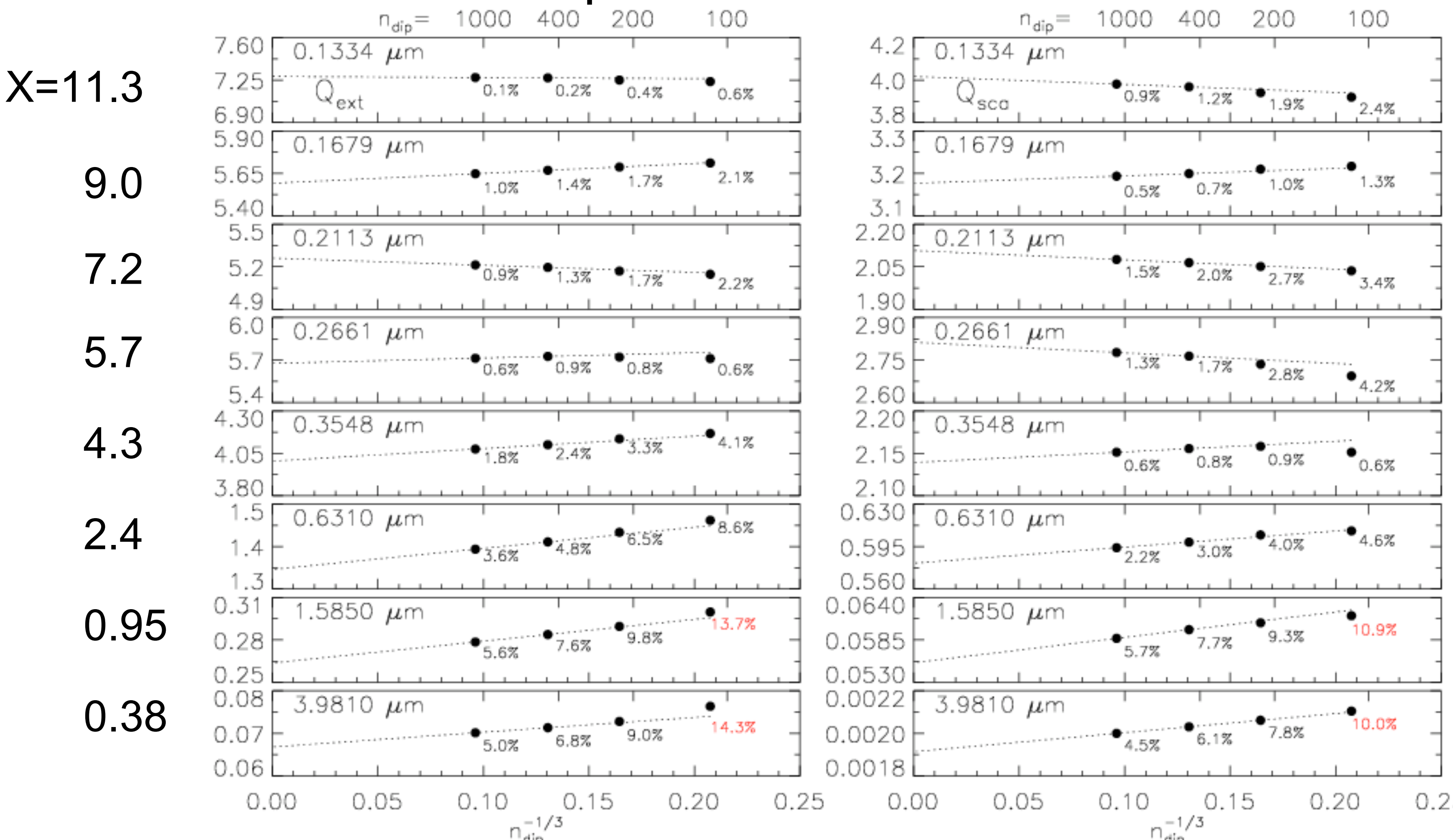
Shen, Draine & Johnson 2008, ApJ, 689, 260

How to calculate absorption and scattering properties of irregular clusters?

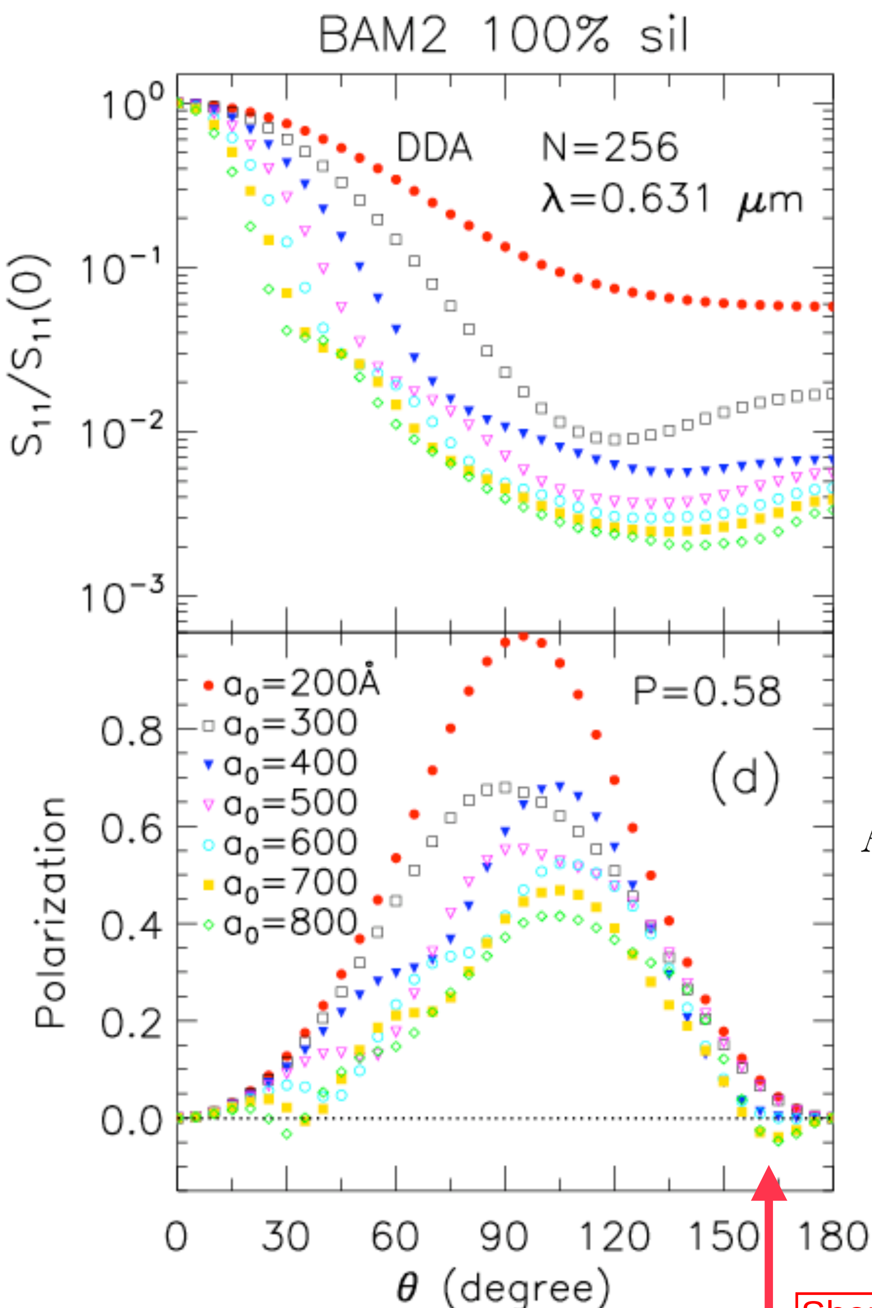
1. **Effective Medium Theory + Mie Theory**
   - **Fast**
   - **Moderate accuracy for total cross sections**
   - **Not accurate for scattering and polarization**
2. **"Exact": Generalized Multisphere Mie for clusters of spheres (Mackowski 1991; Xu 1997)**
   - **For each sphere, use $L \times (L+1)$ multipoles $Y_{\ell m}$.**
   - **Computationally demanding**
     (must solve $3N \times L \times (L+1)$ coupled equations).
   - **Does not apply to anisotropic materials (e.g., graphite).**
3. **Discrete Dipole Approximation (DDA):**
   - **Represent target by array of dipoles with interdipole spacing d**
   - **If $d \ll \lambda$ and $d \ll$ structural scales in target, then DDA is accurate (error→0 as $d/\lambda \to 0$ and $d/R \to 0$)**
   - **Can treat any geometry**
   - **Can treat general anisotropic materials.**
   - **Computationally demanding (feasible up to $2\pi R/\lambda \sim 15$)**
   - **Public domain Fortran 90 code (DDSCAT 7.0).**

DDA Accuracy for
N=256 BA cluster, 50% graphite+50% silicate
a_{eff}=0.127μm, P=0.853 ⇒ R=0.241μm

n_{dip} = # dipoles in *one* sphere



Shen, Draine & Johnson 2008, ApJ, 689, 260



Effect of varying cluster size R

$N = 256$ BAM2 $(P = 0.58)$:

$$
\begin{array}{lcl}
a_0 & & \\
200\,\text{Å} & \leftrightarrow & R = 0.17\,\mu\text{m} \\
 & & 2\pi R/\lambda = 1.68 \\
800\,\text{Å} & \leftrightarrow & R = 0.68\,\mu\text{m} \\
 & & 2\pi R/\lambda = 6.75
\end{array}
$$

As R/λ increases:

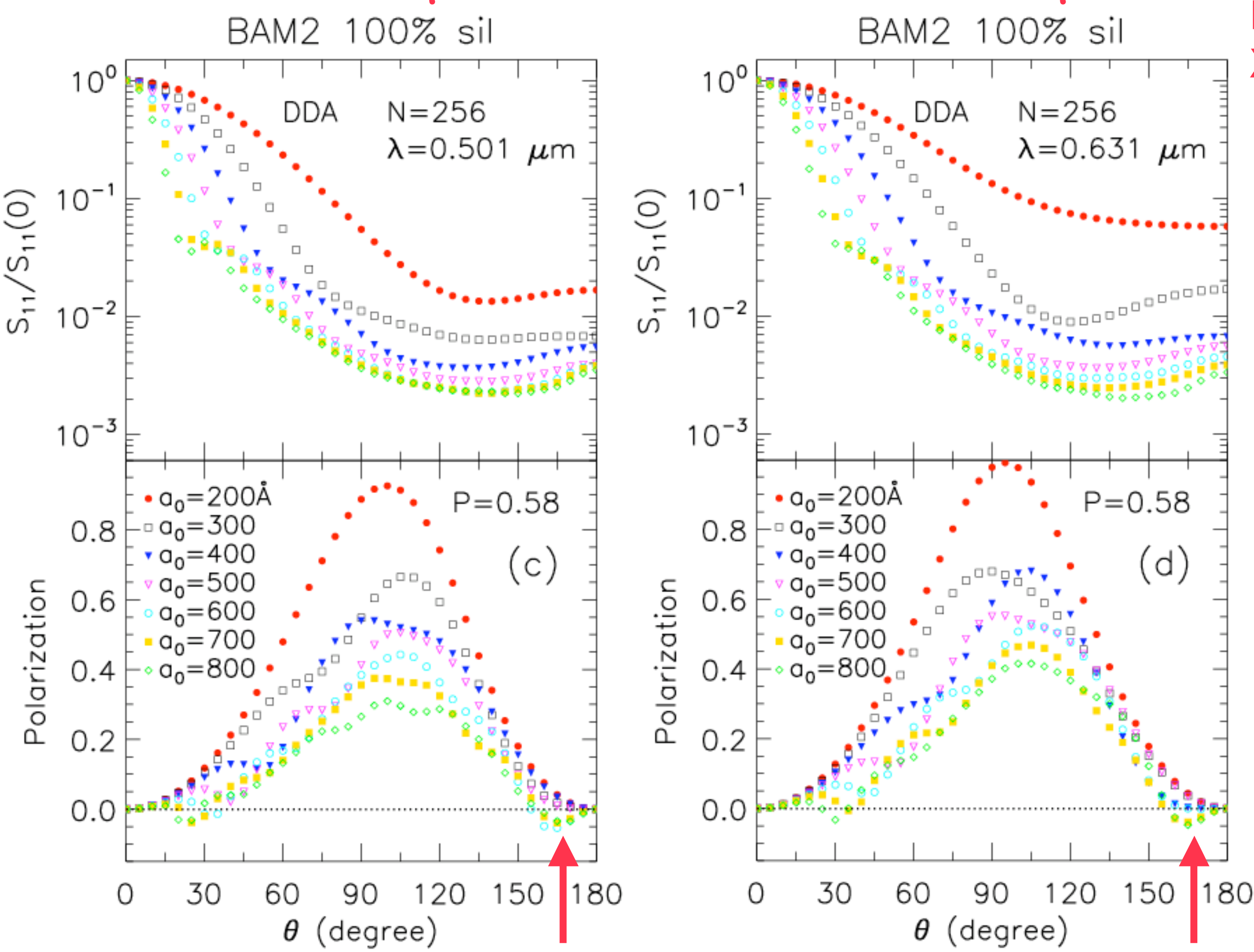
- Increasing forward/backward asymmetry
- decreasing polarization
- **appearance of negative polarization at $\theta \approx 160° - 180°$ for $2\pi R/\lambda \gtrsim 5$ $(\alpha \approx 20° - 0°)$**

Shen, Draine & Johnson 2009 (to be accepted in ApJ)

Dependence of polarization on wavelength

λ=0.501μm **λ=0.631μm**

a_0=0.02→0.08μm
R=0.17→ 0.68μm
X= 2.1 → 8.5
(for λ=0.50μm)



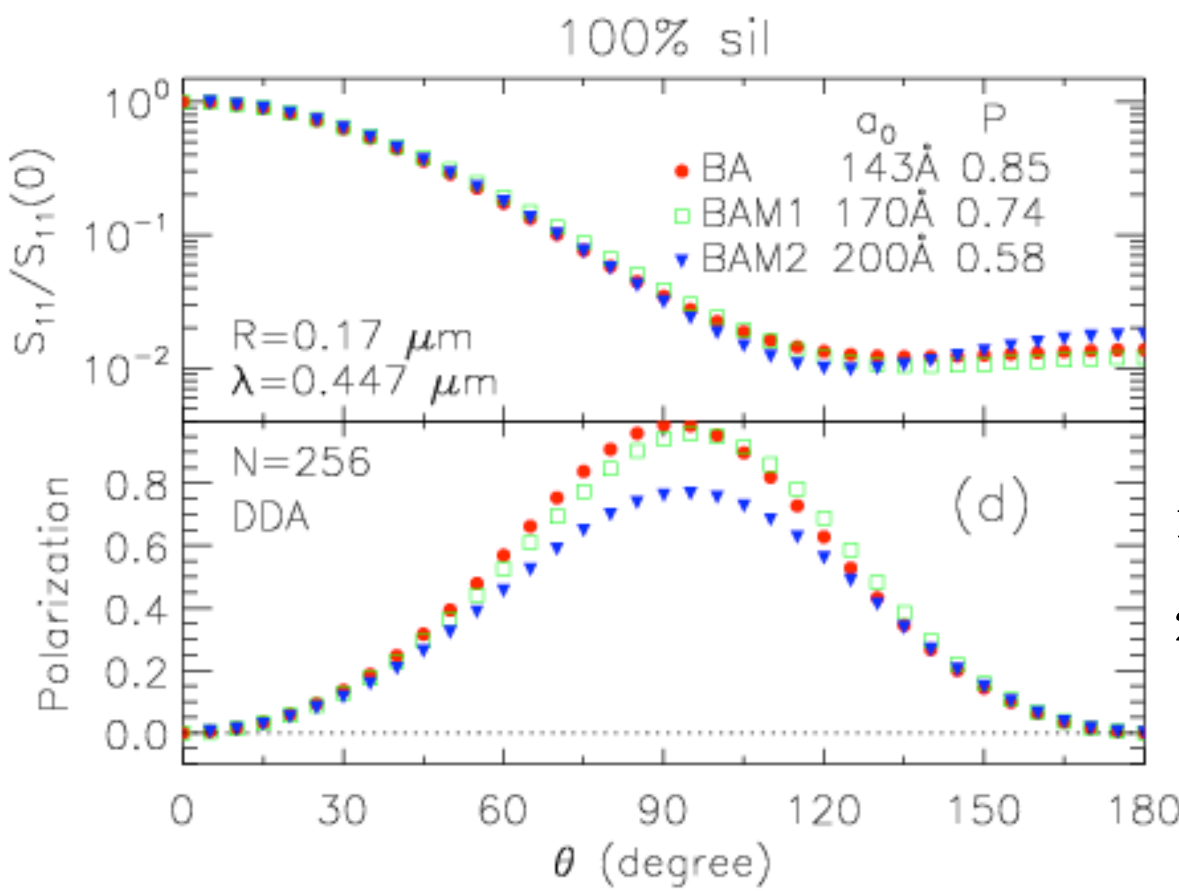
P(0.63μm) >P(0.50μm)

pol<0

Shen, Draine & Johnson 2009 (to be accepted in ApJ)

CPS School, Kobe
2009.01.09

Effect of Varying Porosity P

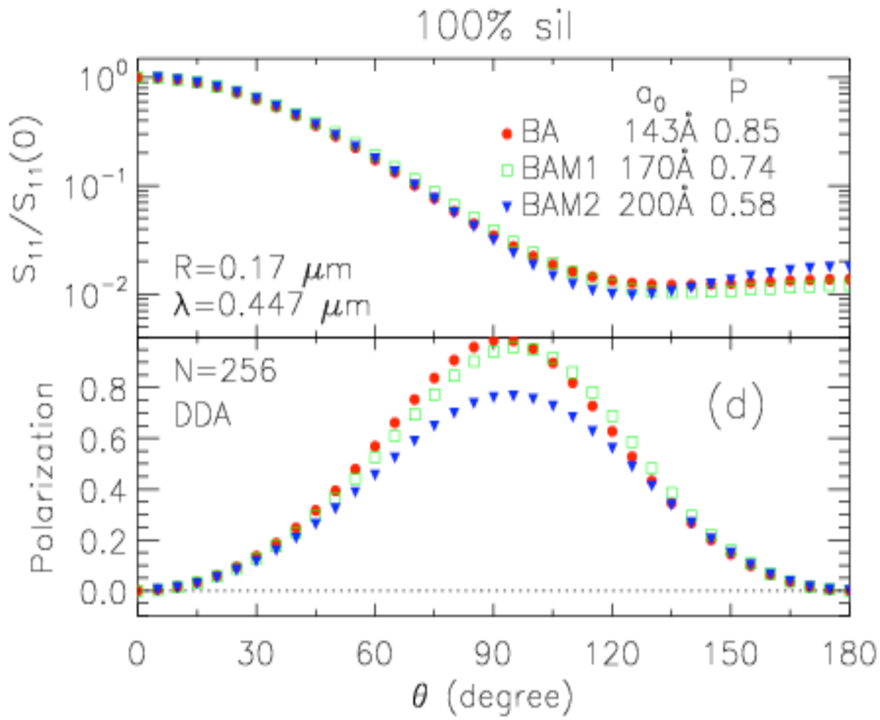


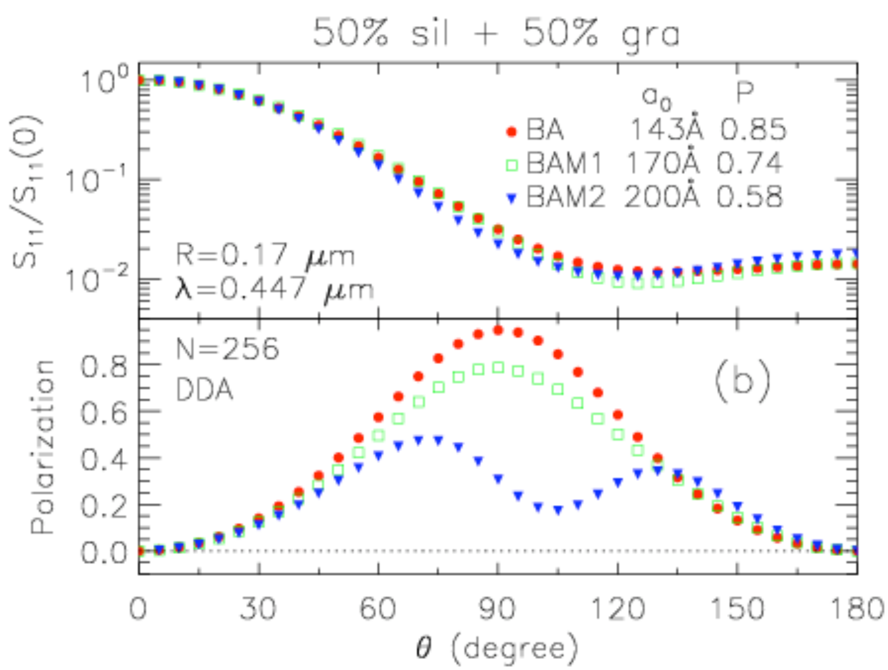
Shen, Draine & Johnson 2009 (to be accepted in ApJ)

Compare clusters with

- **same composition (silicate)**
- **same size $\mathbf{R = 0.17\,\mu m}$ $\mathbf{(2\pi R/\lambda \approx 2.4)}$**
- **varying porosity $\mathbf{P = 0.58 - 0.85}$.**

1. **P has minimal effect on shape of phase function.**
2. **Lower P → lower polarization.**





Shen, Draine & Johnson 2009 (to be accepted in ApJ)

Effect of Varying Composition

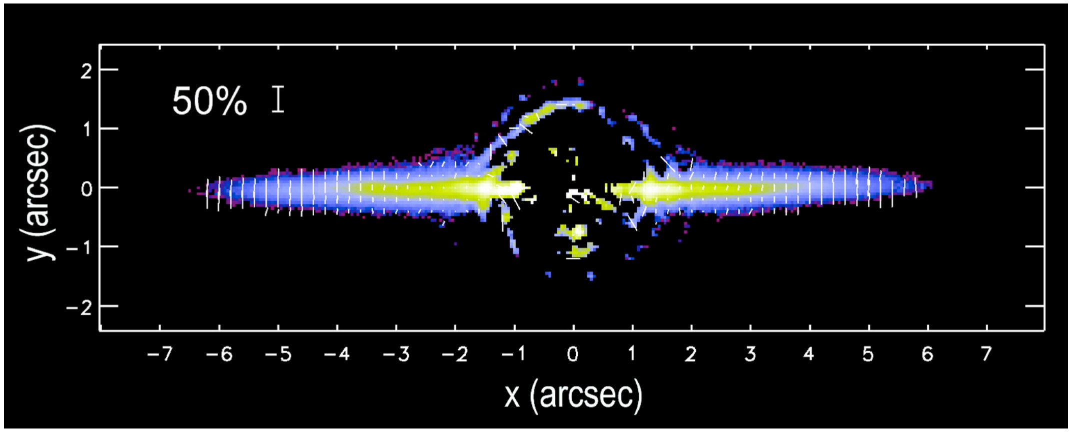
N = 256 BA, BAM1, BAM2 clusters

$R = 0.17\,\mu\mathrm{m}$, $2\pi R/\lambda \approx 2.4$

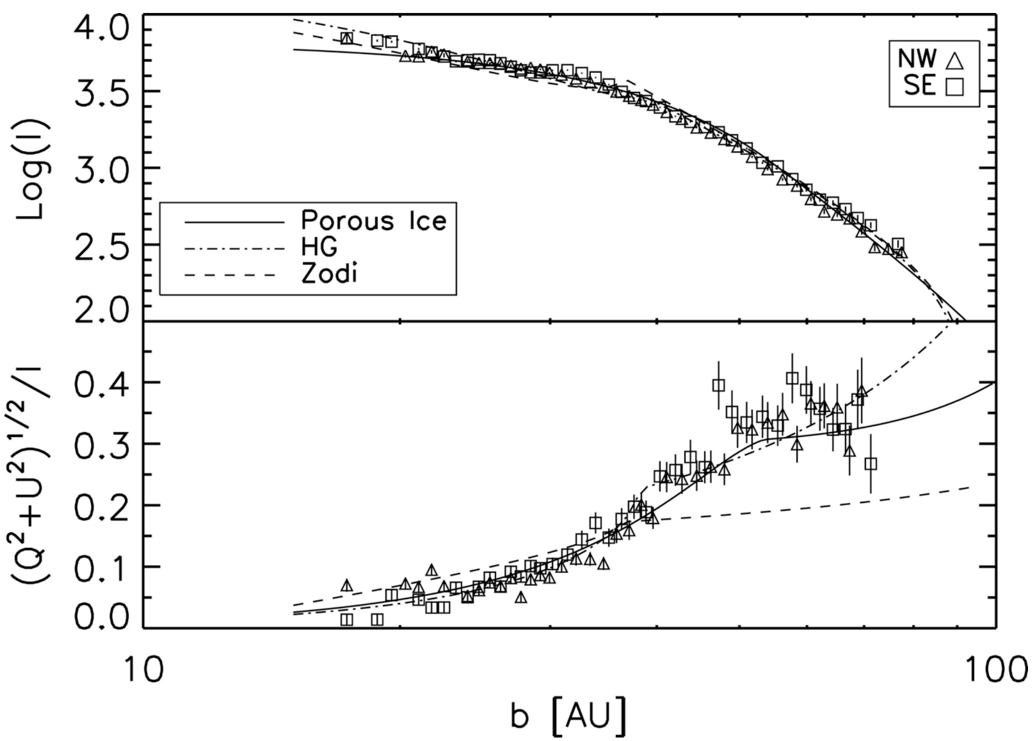
1. **100% silicate**
2. **50% silicate+50% graphite (random)**
   → increased absorption

- **composition has relatively small effect on shape of phase function**
- **composition has larger effect on polarization:**
  increased absorption
  → reduced polarization

Graham, Kalas & Mathews 2007,ApJ,654,595



Debris Disk Around AU Mic (M1 dwarf, d=9.9pc)



Graham et al (2007) used HST ACS to obtain polarization map at λ=0.61μm

Model to reproduce I(b) and pol(b)

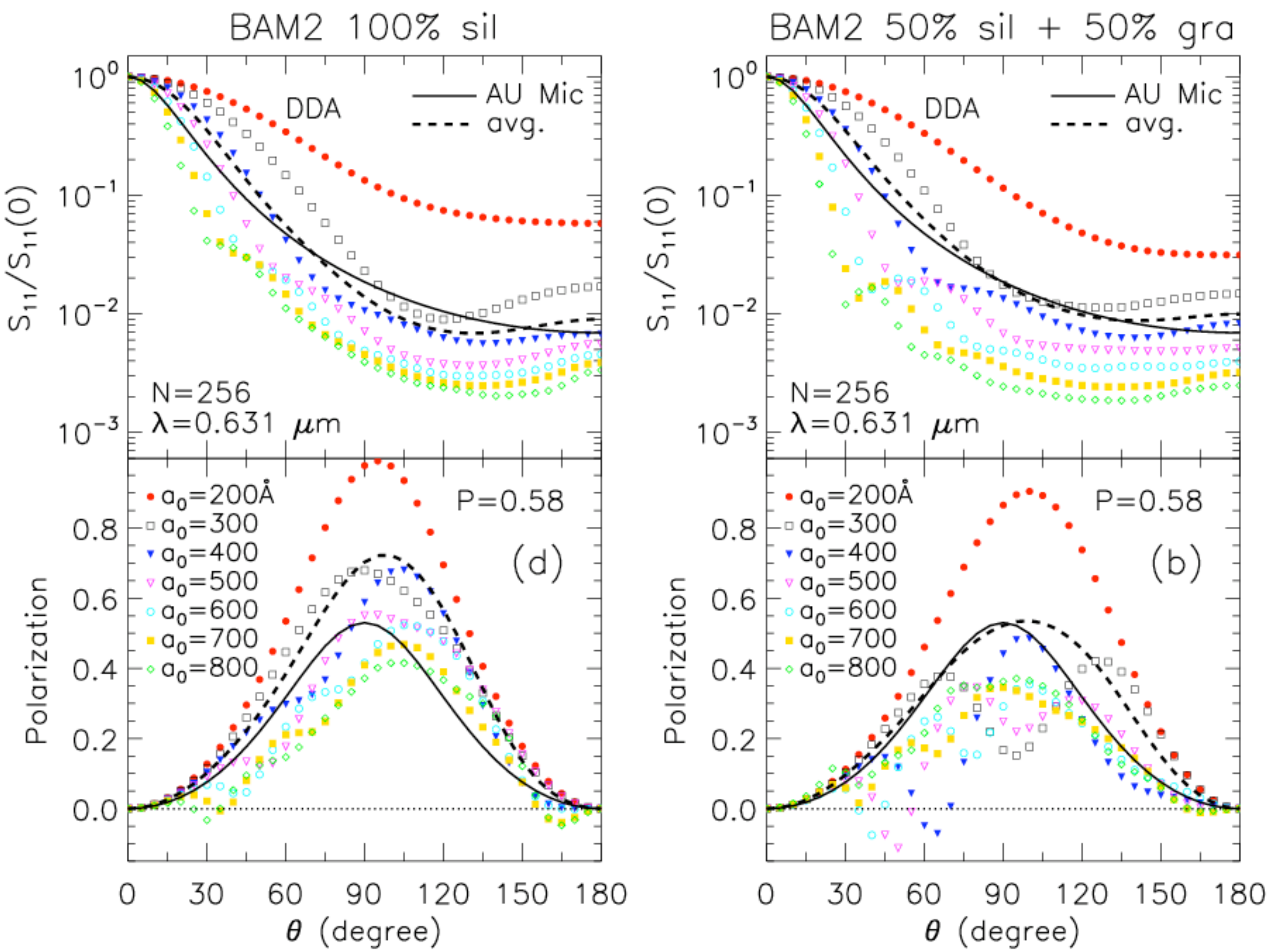
Based on EMT-Mie theory, Graham et al. claim water-ice model with porosity P=0.91±0.09 fits data.

Are lower porosity clusters also able to reproduce observations?

Graham, Kalas & Mathews 2007,ApJ,654,595

BAM2 N=256 clusters, P=0.58

a_0=0.02→0.08μm
R=0.17→ 0.68μm
X= 1.7 → 6.8



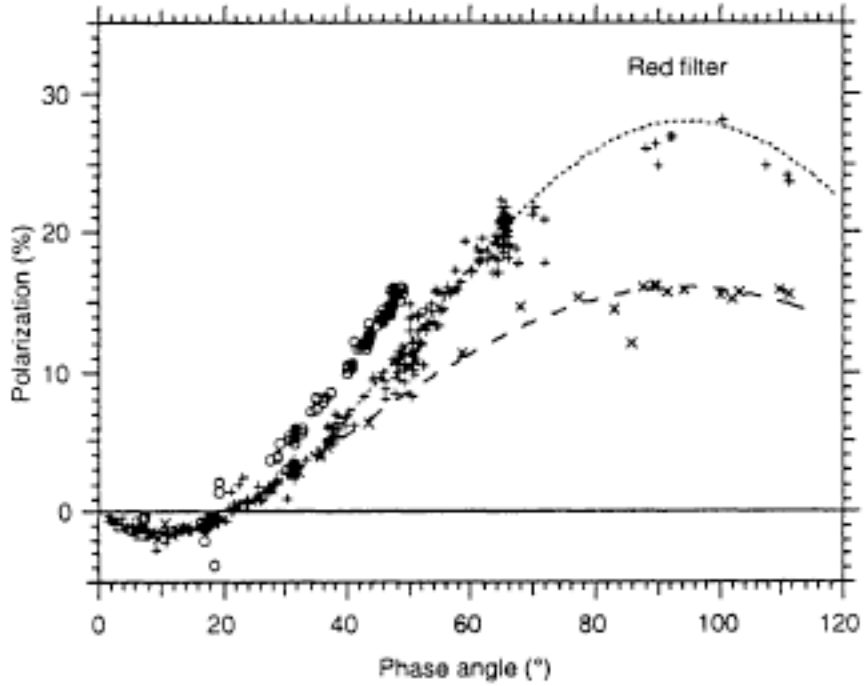
Shen, Draine & Johnson 2009 (to be accepted in ApJ)

solid line: “HG” param. inferred by Graham et al

dashed: average for dn/dR ∝ $R^{-3.5}$ for 0.13<R<0.55μm

good fit obtained for 50%sil+50%graph. with P=0.58 (<< 0.91)

Cometary dust



Levasseur-Regourd & Hadamcik 2001,ESASP.495,587L

BAM2 clusters with P≈0.63
and R ≈1.25μm appear to reproduce
High-polarization comets.
Mix of 100% sil + 50/50 sil/gra clusters
would reproduce neg. pol. branch.
Might need even larger R…

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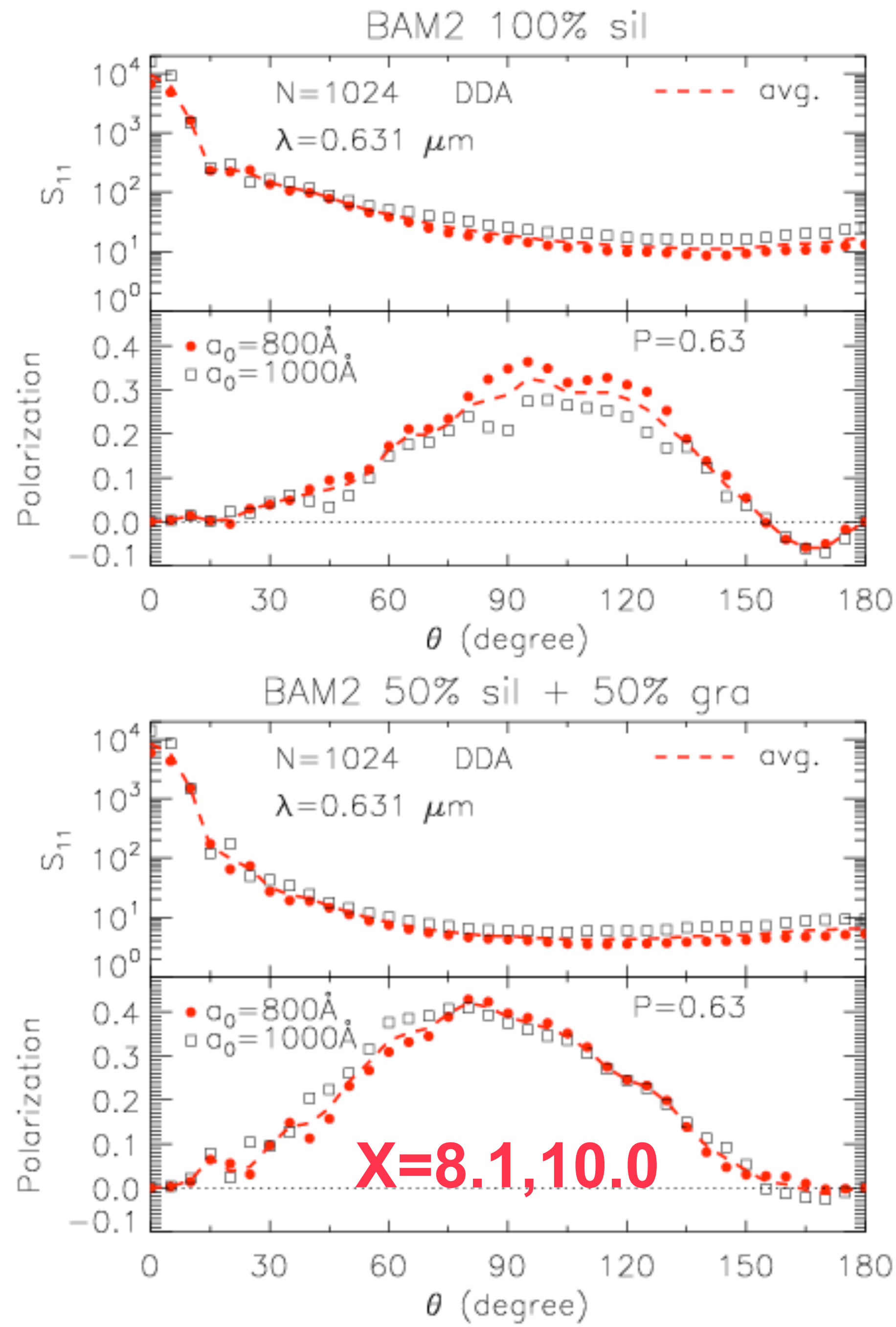
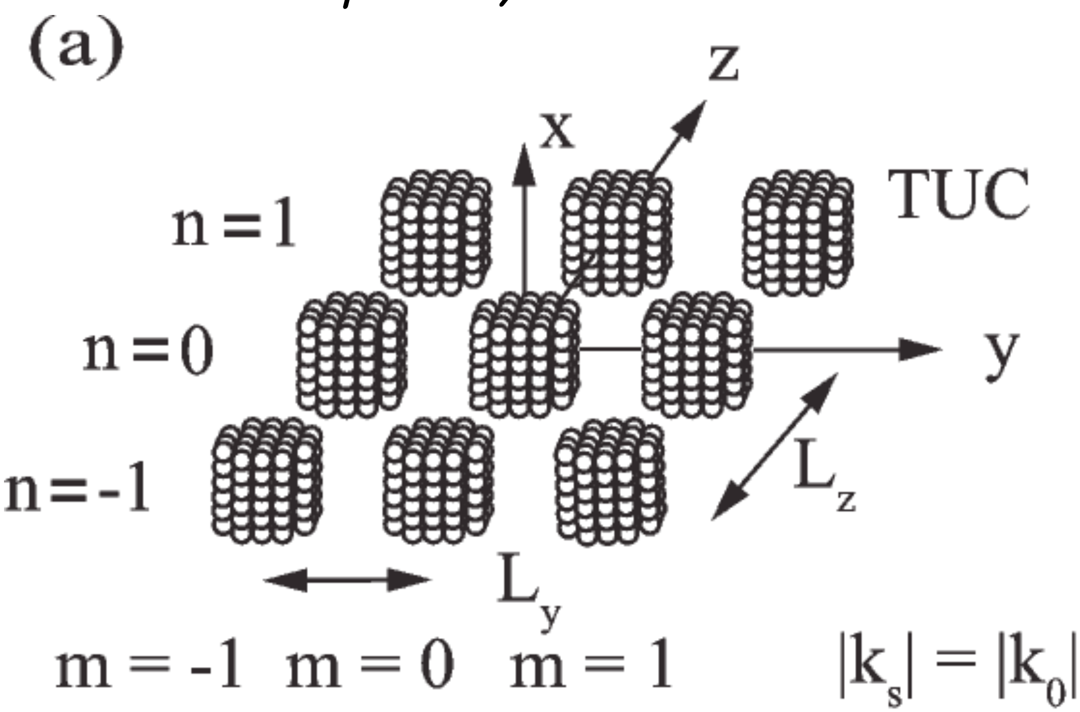
2009.01.09



Shen, Draine & Johnson 2009 (to be accepted in ApJ)

Can DDA be used to model dust layer = nano-regolith?

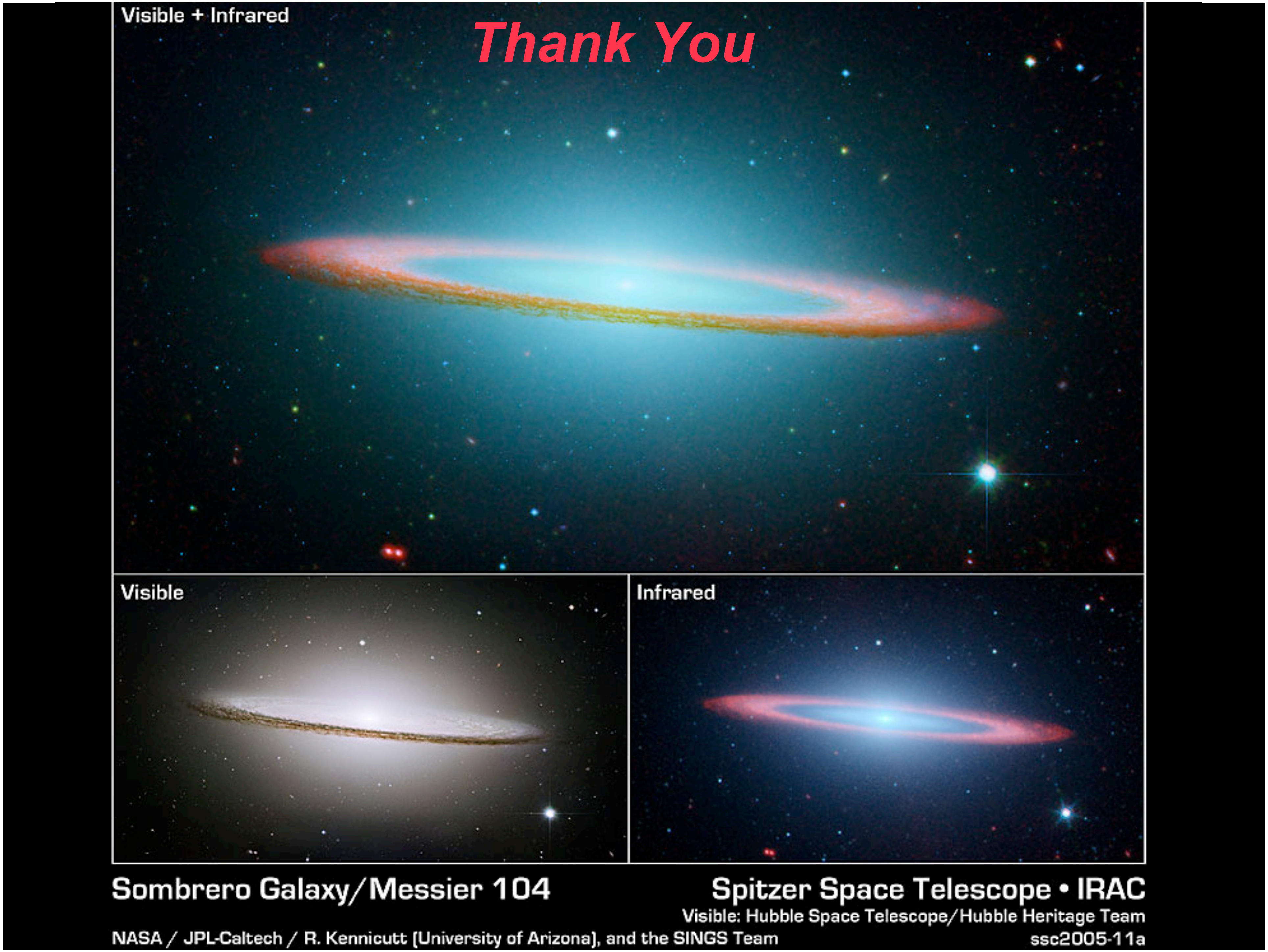
DDA can be used for periodic array of "Target Unit Cells" (TUCs) (Draine & Flatau 2008, JOSA A25, 2693).
TUC could be an irregular aggregate.
Near-field interactions/multiple scattering are taken into account.
DDSCAT 7.0 includes this capability.



Draine & Flatau 2008, JOSA, A25, 2693

Summary

- New definition of porosity P (and size R) for finite structures.
- 2 new classes of random ballistic agglomerates, BAM1 and BAM2. Library of cluster realizations is available on-line.
- BA, BAM1, BAM2 allow variation of P.
- Porosity: at fixed R, λ, and composition
  - porosity has only small effect on shape of phase function
  - reduced porosity $\rightarrow$ reduced polarization at $\theta \approx 90°$
- Size: at fixed P and composition
  - increased $R/\lambda \rightarrow$ increased forward/backward asymmetry
  - increased $R/\lambda \rightarrow$ reduced peak polarization
- **AU Mic debris disk:** BAM2 aggregates with $P \approx 0.6$ and size dist. extending up to $R \approx 0.55\,\mu$m gives good fit.
- **Cometary dust:** BAM2 aggregates with $P \approx 0.6$ and $R \approx 1.25\,\mu$m are consistent with "high polarization" comets.
- **Moderate porosity aggregates should be considered as candidates for dust in debris disk and comets.**
- **DDA can be applied to dust layers.**


Visible + Infrared
Thank You
Visible
Infrared
Sombrero Galaxy/Messier 104
Spitzer Space Telescope • IRAC
Visible: Hubble Space Telescope/Hubble Heritage Team
NASA / JPL-Caltech / R. Kennicutt (University of Arizona), and the SINGS Team
ssc2005-11a

References

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- Levasseur-Regourd & Hadamcik, ESASP 495, 587L (2001)
- Draine & Flatau, JOSA A25, 2693 (2008)
- Spitzer M101
  URL:http://gallery.spitzer.caltech.edu/Imagegallery/image.php?image_name=ssc2005-11a