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GAIA and asteroid sizes estimation: the impact of the scattering law

Regolith on Solar System Bodies
Meudon
December 1-3, 2010

GAIA

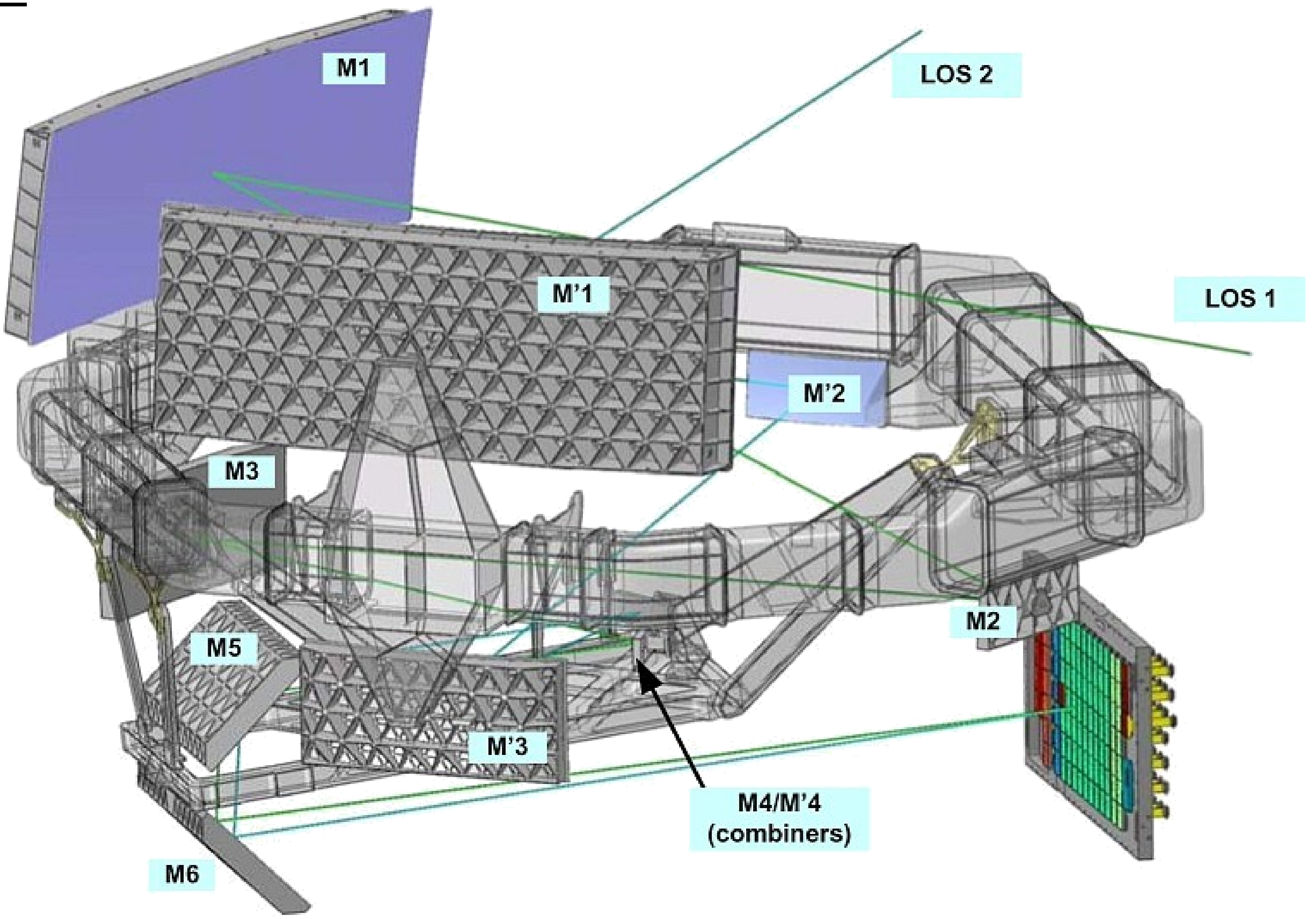
astrometry space mission
ESA Horizon 2000+ long-term program

Operation period: ~2013-2017

Objectives:

1. Galaxy origin and formation;
2. Physics of stars and their evolution;
3. Galactic dynamics and distance scale;
4. **Physics of the Solar System**;
5. Large-scale detection of all classes of astrophysical objects including brown dwarfs, white dwarfs, and planetary systems;
6. Fundamental physics

Payload



Mirror size: 1.45 m x 0.50 m

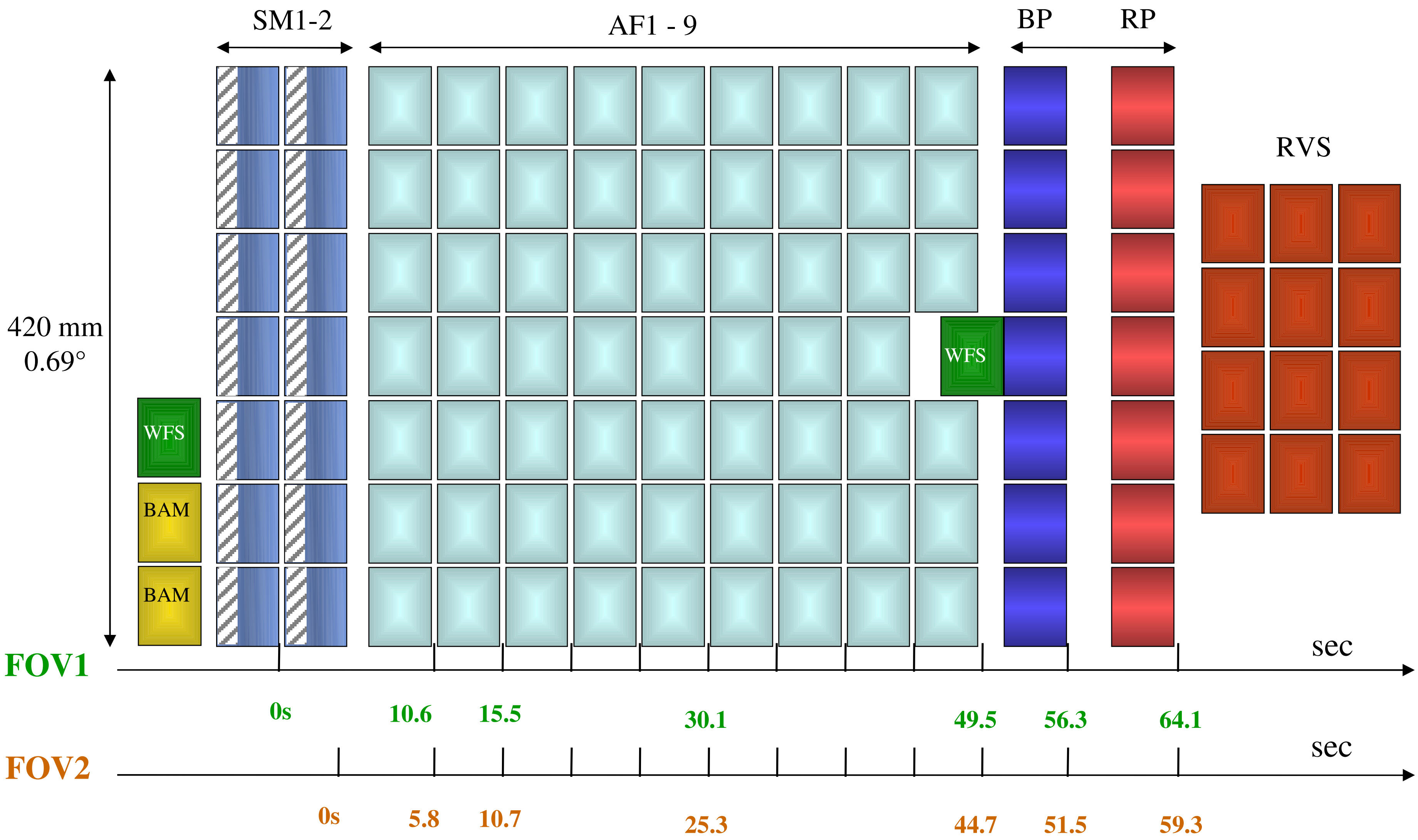
Focal length: 35 m

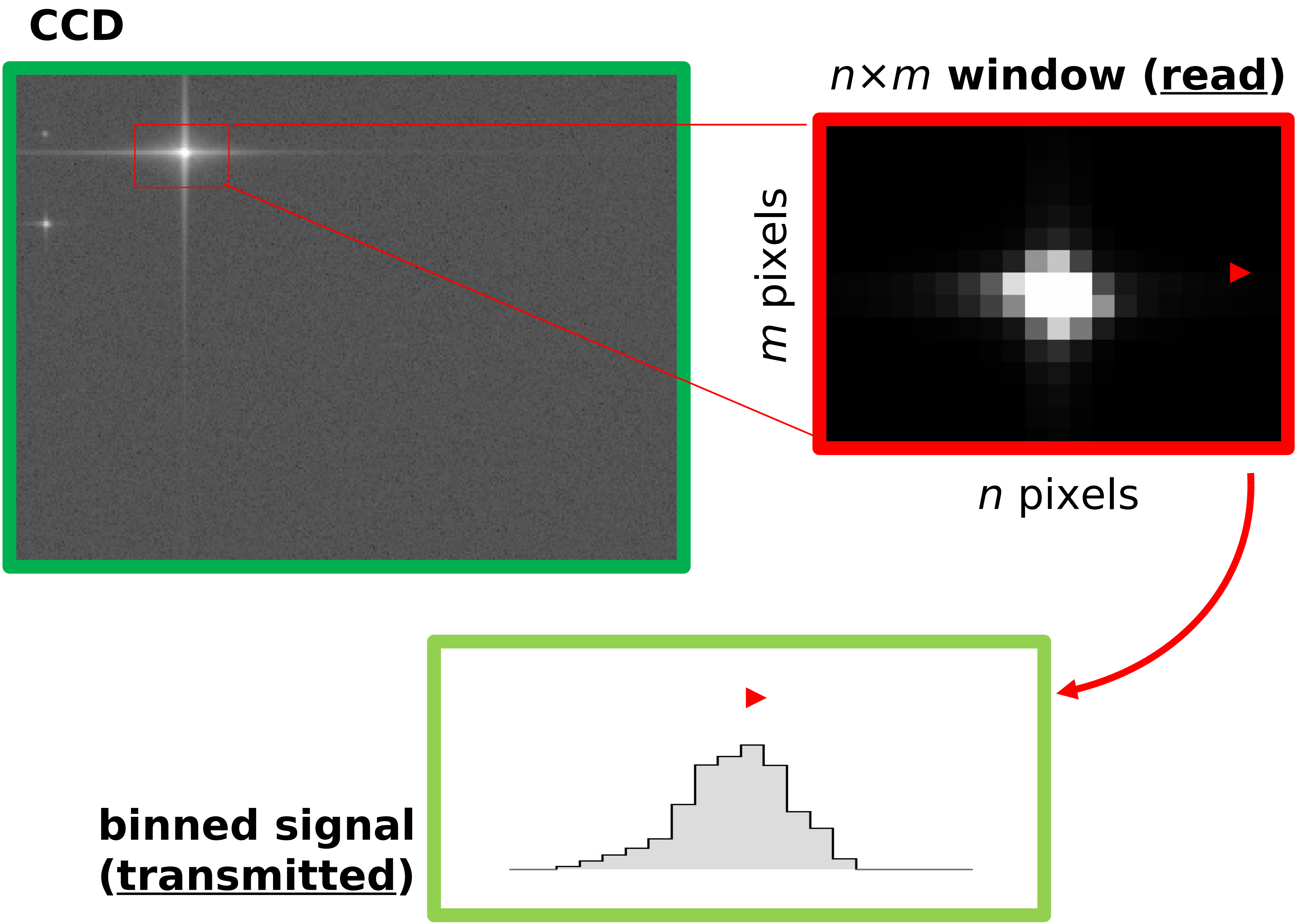
Source: Astrium

Focal plane

1 pixel 60 x 180 mas

106 CCDs (4.5 x 2 kpix) = 1 Gpixel




CCD
n×m window (read)
m pixels
n pixels
binned signal
(transmitted)

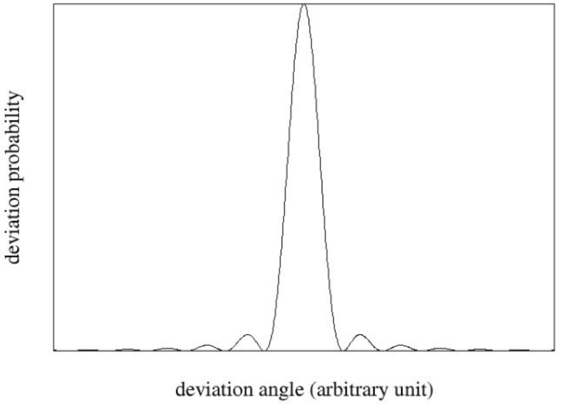
PSF and signal computation

The CCD signal (***S***) is the convolution between optical image (***L***) (source photometric distribution) and effective PSF (ψ_{eff}):

$$S = L * \psi_{eff}$$

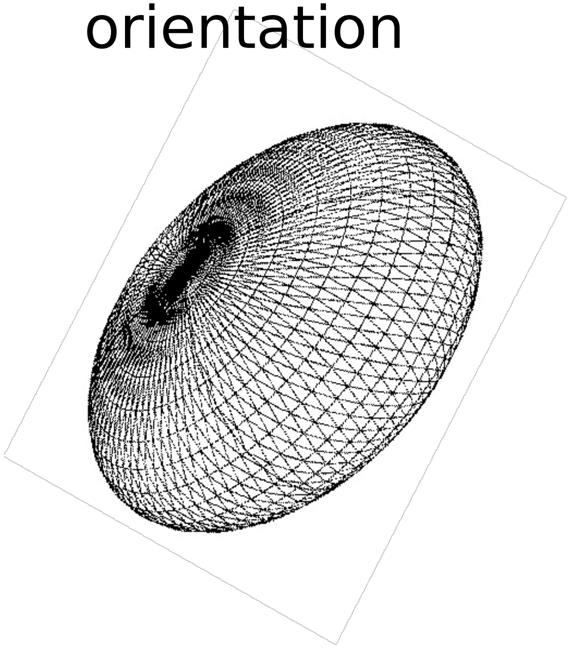
Effective PSF (ψ_{eff}) is the convolution between optical PSF (ψ_{opt}), pixel area and TDI smearing:

$$\psi_{eff} = \psi_{opt} * \Pi_{\Delta x} * \Pi_{\Delta y} * \Pi_{\Delta t}$$



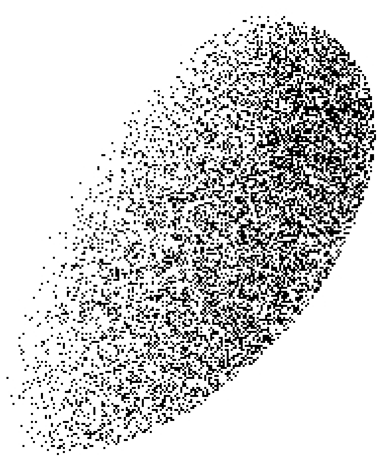
Optical image formation

shape, size and
orientation



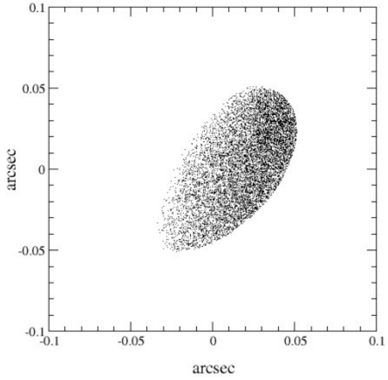
illumination
conditions

Scattering Law (*Reflection Coefficient*, or *Bidirectional Reflectance Distribution Function)*

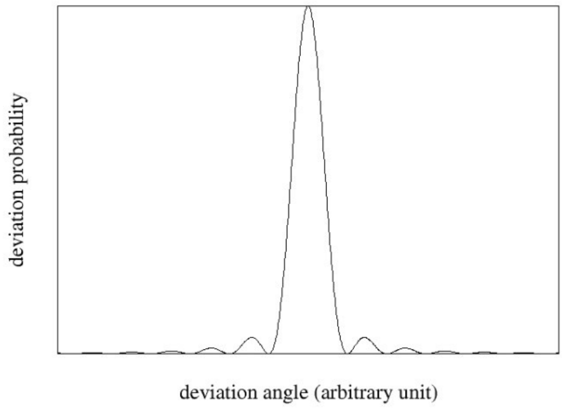


apparent source
photometric
distribution (***L***)

image (g) **PSF (f)** **signal (g*f)**



*



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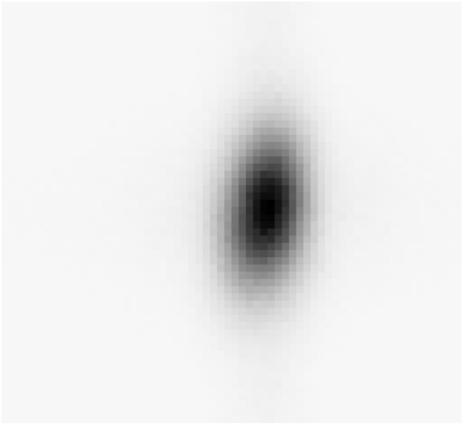


?

$$(f * g)(t) = \int f(\tau) g(t - \tau)\, d\tau$$

<u>CCD signal analysis in GAIA</u>

The signal analysis is based on a comparison of the observed signal with a “simulated” signal (best fit).

The simulation of the signal requires an input model of the source.

The input model is defined by (input parameters):

- object shape;
- object orientation;
- illumination conditions;
- surface reflectance properties (**<u>scattering law</u>**);

The model parameters to be determined (free parameters) are:

- astrometric position
- magnitude;
- **angular size**;
- proper angular motion;

Error sources and GAIA sensitivity

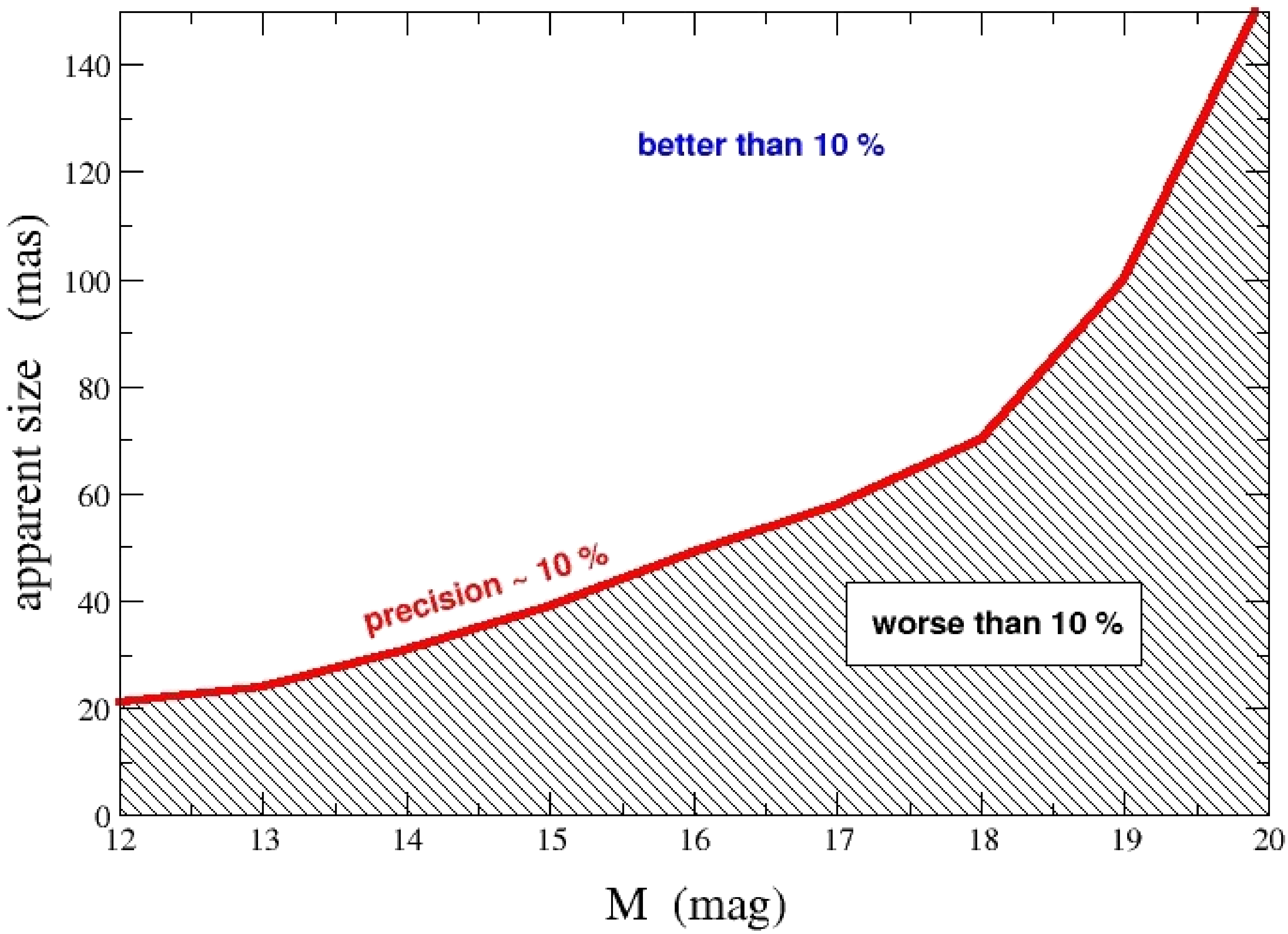
The observed signal is affected by a number of sources of error:

- photo-count statistics;
- read-out noise;
- background;
- charge transfer inefficiency;
- CCDs radiation damage;
- etc...

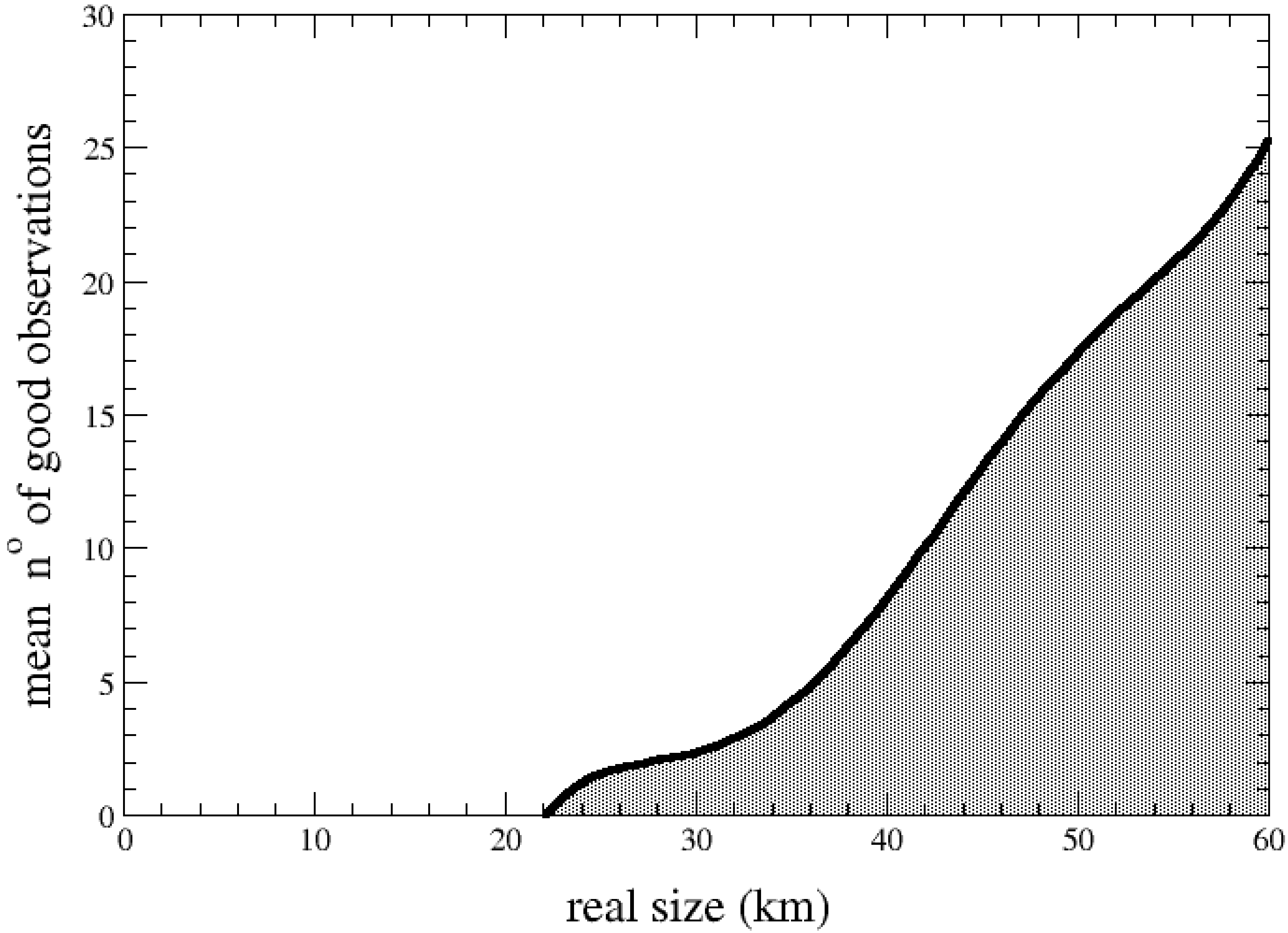
Assuming all input model parameters perfectly known, which is the precision of GAIA in measuring the apparent angular size of the source (**sensitivity in size estimation**)?

The sensitivity depends basically on angular extension of the source (impacting for the photons distribution on CCD) and its magnitude (impacting for photon statistics).

GAIA sensitivity: angular size



GAIA sensitivity: Main Belt asteroid sizes



But, what about model parameters?

In GAIA data reduction pipeline disk-integrated photometry is employed in order to determine shapes and rotational properties.

Disk-integrated photometry makes use of the integral of the signal (sum of photons) and not of the analysis of the photon-electrons in each pixels.

An input model is assumed: object is a tri-axial ellipsoid spinning around its minor axis.

Six parameters are necessary to describe the geometry of this system (two axial ratios, two spin coordinates, period and initial rotation), so **in principle** six magnitude measurements are enough to extract some information about it.

Error sources: model parameters

Model parameters from GAIA disk-integrated photometry introduce their own uncertainties:

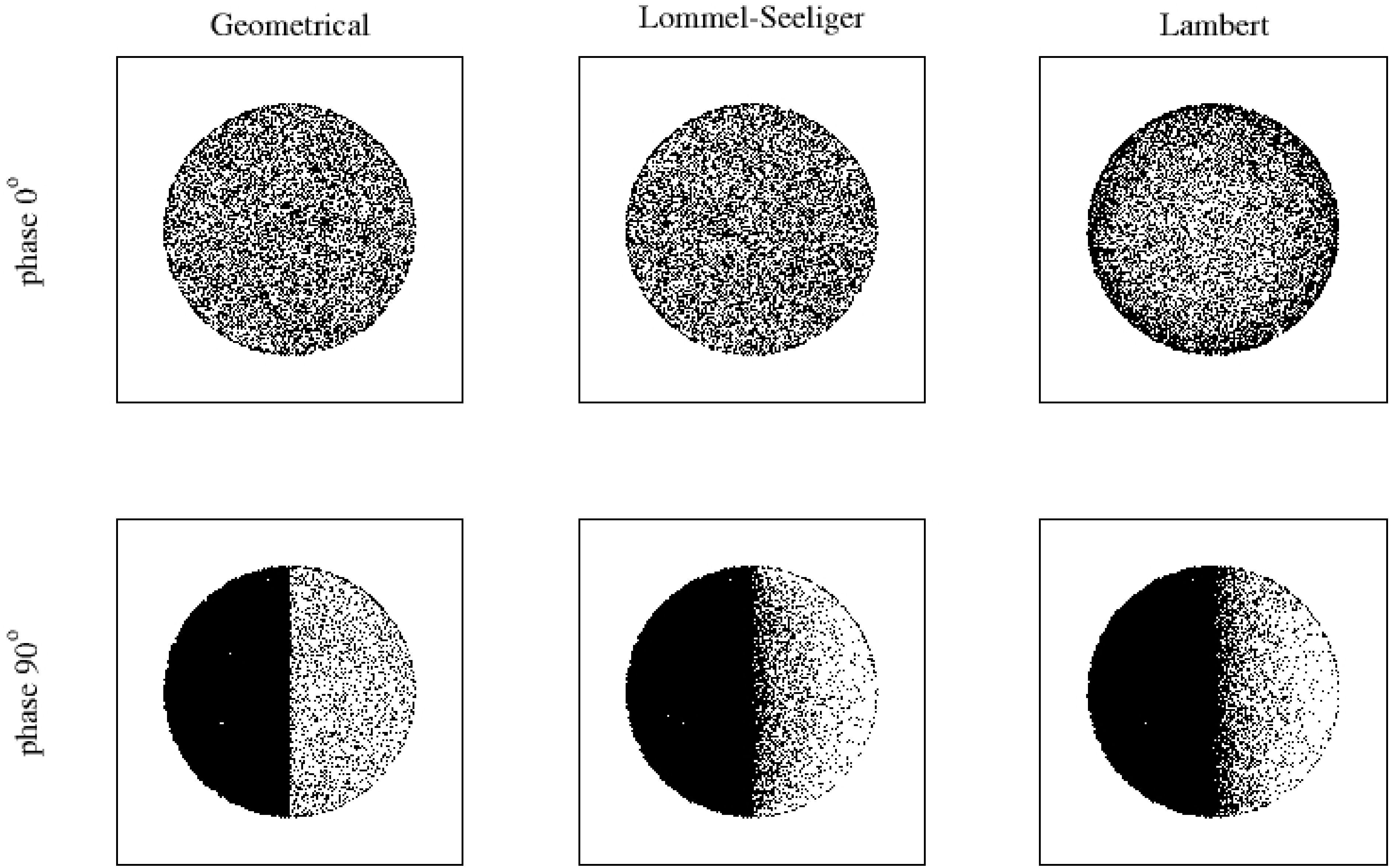
- shape: tri-axial ellipsoid is suitable for asteroids (at least for statistical investigations)?

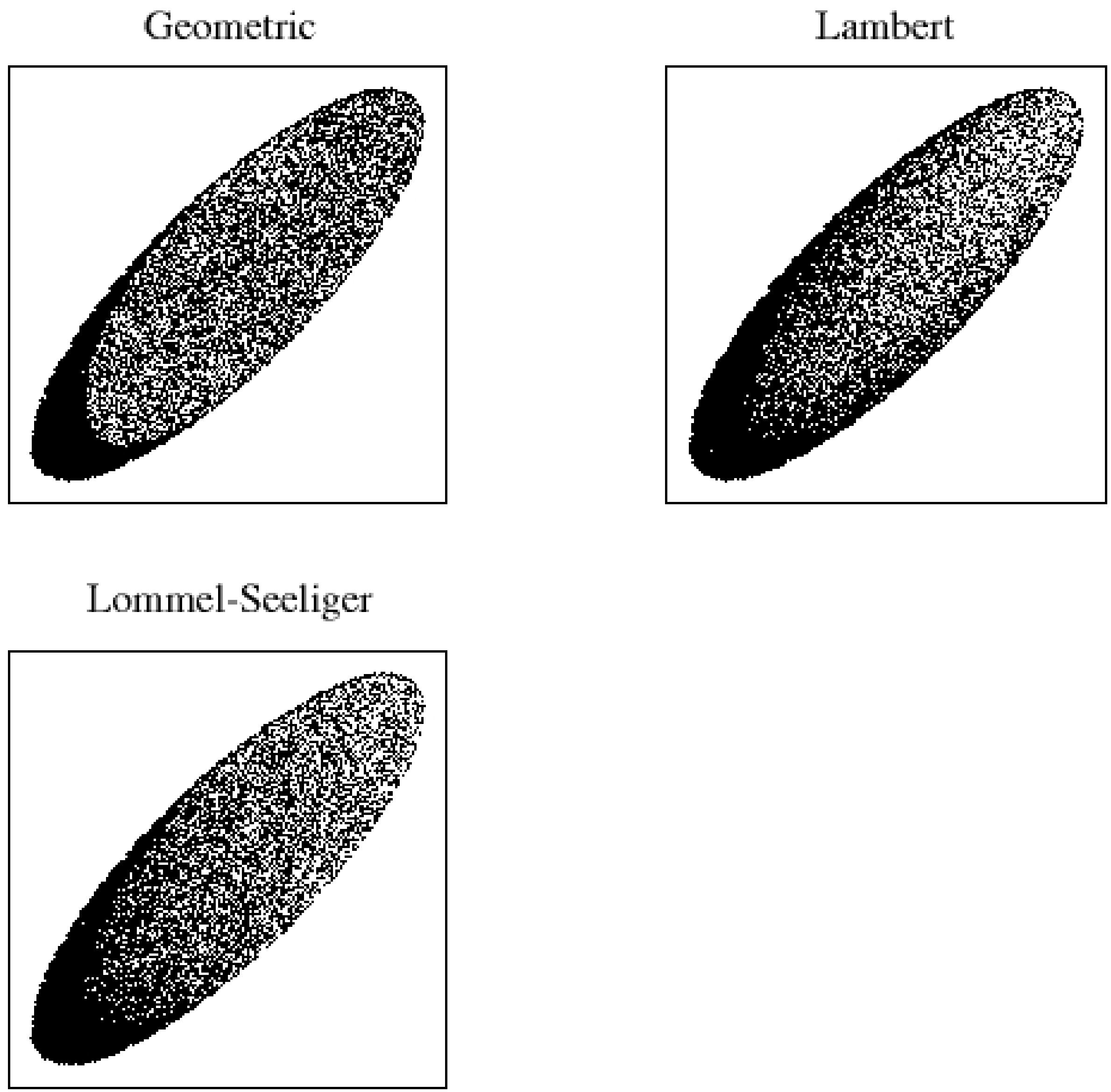
- which is the uncertainty of the spin orientations from disk-integrated photometry?

- error in the determination of the rotation period seems much smaller than the other sources of error;

Respect to uncertainty from model shape and spin axis orientation producing probably random errors, uncertainty in scattering law introduces clearly **systematic errors**.

Numerical simulations have shown that the choice of the scattering law accounts for a difference up to 10% in the reconstructed angular size.


Geometrical
Lommel-Seeliger
Lambert
phase 0°
phase 90°


Geometric
Lambert
Lommel-Seeliger

A little more generalization

Empirical scattering laws can be defined on the basis of, for instance, a linear superposition of two or more scattering laws.

The measured size is then function of the coefficients of the superposition.

More in general if the assumed scattering law depends on one ore more (unknown) parameters, the reconstructed size depends in its turn on the same parameters.

So the most correct way to communicate the result of the signal analysis is not to specify the reconstructed size for a particular scattering law, but rather it should be to give the function size/parameters based on a general scattering law of reference.

A simple example

Given the Lambert and Lommel-Seeliger reflection coefficients:

$$R_L = \textit{const.} \qquad\qquad R_{LS} \propto 1/(\cos\varepsilon + \cos\iota)$$

a “more general mixed” reflection coefficient can defined as (*):

$$R \propto (1-\mathbf{w})R_{LS} + \mathbf{w}R_L \qquad\qquad 0 \le \mathbf{w} \le 1$$

Reconstructed size S(**w**) depends on the **w** parameter. On a first order approximation (small dS for small d**w**):

$$S(\mathbf{w}) \approx S(0) + \mathbf{w}\,(dS/d\mathbf{w}) \approx (1-\mathbf{w})S_{LS} + \mathbf{w}S_L$$

where S_{LS} is the size obtained assuming a pure Lommel-Seeliger scattering law (**w** = **0**), and S_L is the size obtained in the pure Lambertian case (**w** = **1**).

(*) (K. Muinonen private suggestion)

Conclusions and questions

In the GAIA final catalogue should not included only one value of the “measured” size for each of the resolved asteroid.

The final GAIA results should be enriched with parameters like S_{LS} and S_L, or other sets of parameters related to a explicitly specified scattering law of reference.

In this way the “consumer” of the data will have the possibility to use them according to his estimation of the parameters of the scattering law, calibrated on the basis of further and independent observations.

A standard empirical scattering law is needed to parameterize the size determination based on GAIA observations.

But what kind of function is suitable to represent the general reference scattering law for Solar System bodies like asteroids?

Thank you