*The determination of asteroid physical properties from Gaia observations. General strategy and a few problems.*

Alberto Cellino – SF2A, Besançon, 29 June 2009

# *A collective effort of many people active in the CU4 of the GAIA DPAC*

***(D. Hestroffer, P. Tanga, J.M. Petit, J. Berthier, W. Thuillot, F. Mignard, M. Delbò,...)***

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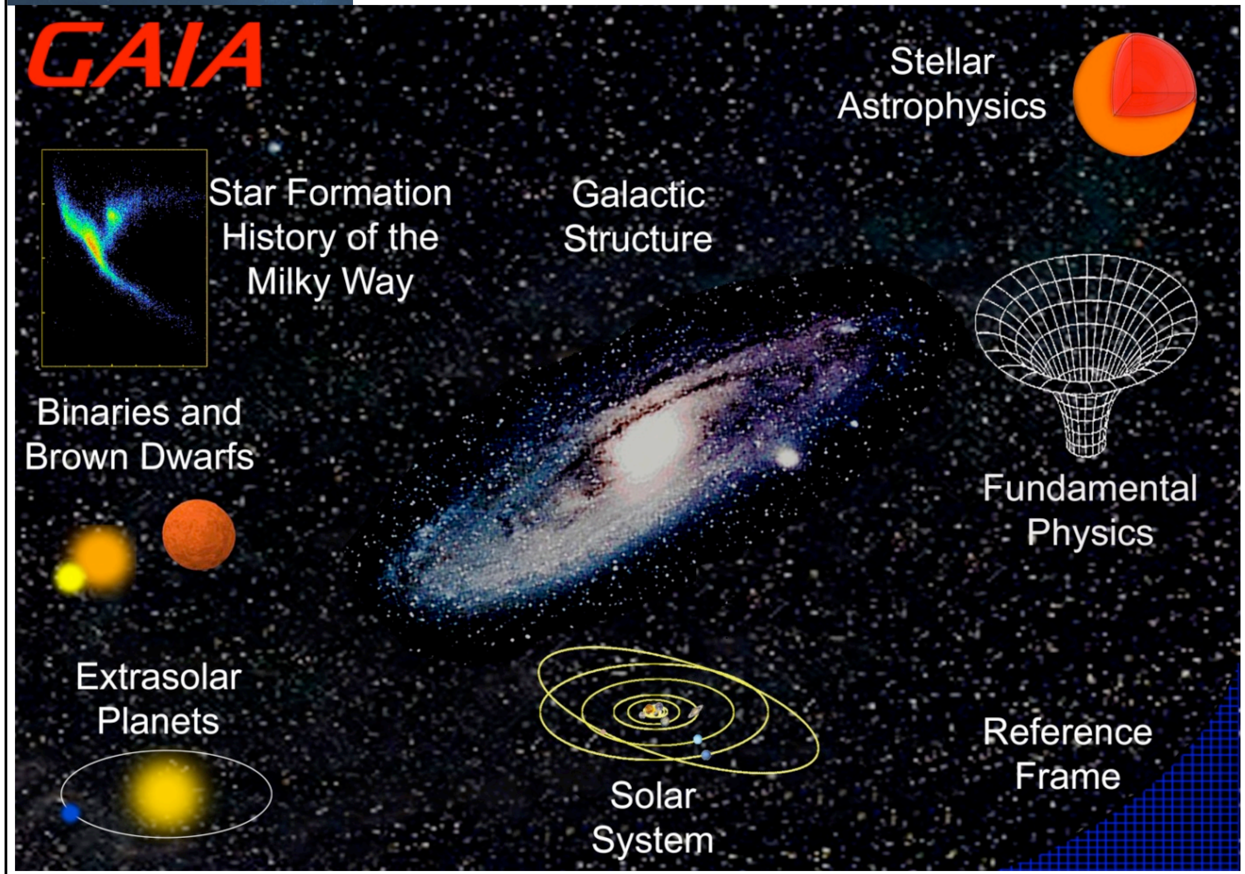
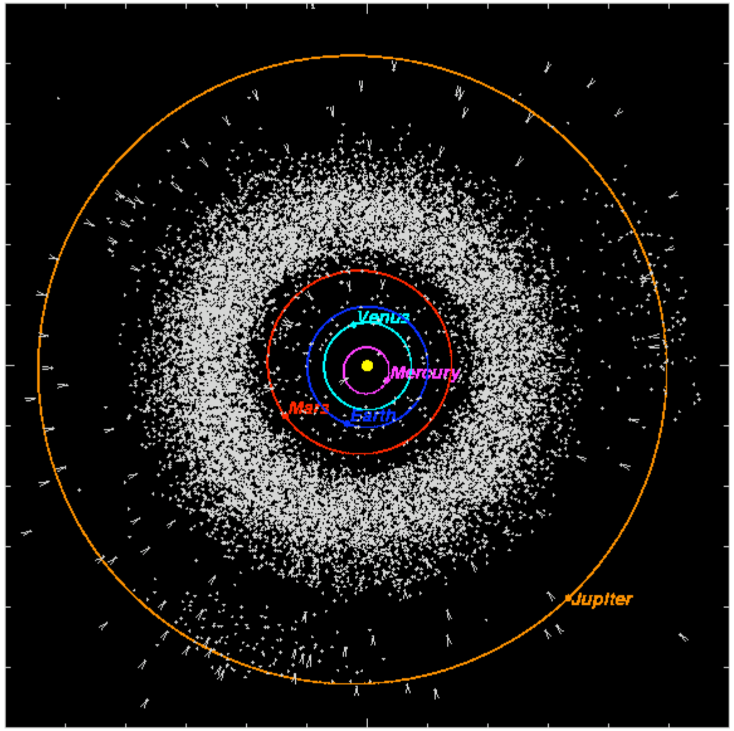



**The impact of GAIA on Asteroid Science will be extremely important !**





# Some important problems in current asteroid science:

- The determination of asteroid masses and densities
- The direct measurement of asteroid sizes and shapes
- The determination of spin properties for a large sample
- A possible size-dependence of asteroid albedos
- The distribution of taxonomic classes within the Main Belt

GAIA will play a decisive role in the solution of the above problems.



- Astrometry for:
  - ~$10^5$ Main Belt + Near Earth Asteroids
  - Comets and some TNOs
  - Natural asteroid / planet satellites

- Direct size measurement:
  - ~$10^3$ largest objects (> 20 mas) seen as extended

- Photometry → spin properties, overall shapes
- Spectroscopic properties → asteroid taxonomy
- 65 observation (on average) per object (Main Belt)



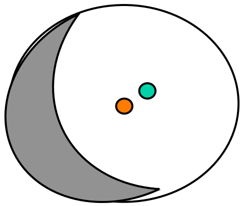
# Gaia unprecedented astrometric accuracy

- Astrometry

| ground-based | Gaia single measurement |
| --- | --- |
| *0.05 - 1 arcsec* | *0.1 – 1 mas* |

***Orbit improvement (> 100)***

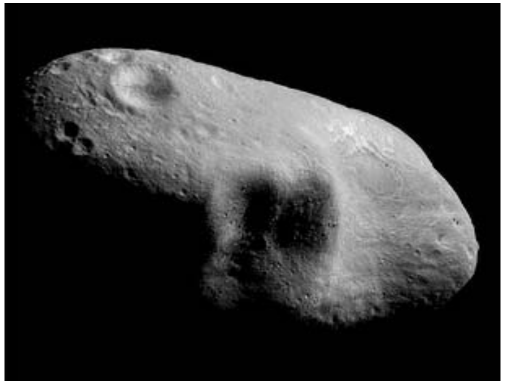
- Larger sensitivity to « small » effects:
  - **Mutual perturbations** (<100 mas)
    - **Masses** of ~100 objects
  - **Angular size effects** (<0.1 x diameter)
    - Photocenter-barycenter difference



  - **Non-gravitational accelerations**
    - Thermal emission (Yarkovsky, ~0.1 mas)
    - Comet jets
  - **Relativity effects**

# Asteroid masses are sorely needed:

- To understand internal structure and evolution :

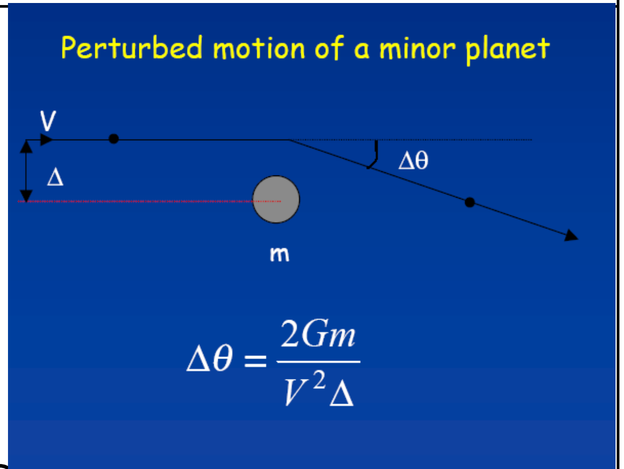


- The great unknowns : density, porosity…
- Gravitational aggregates or solid bodies?
- The origin of shapes
- The collisional history
- Impact risks and mitigation strategy

- To improve Solar System ephemerides :
    - Current accuracy : ~1 km/ 10 yr Earth, Mars
      ~100 km / 10 yr for several NEOs



# Masses : current estimates




Conservative approach :

*single encounter* accuracy on the mass : ~$10^{-12}$ $M_\odot$

But :

- *many close approaches* to the same perturber

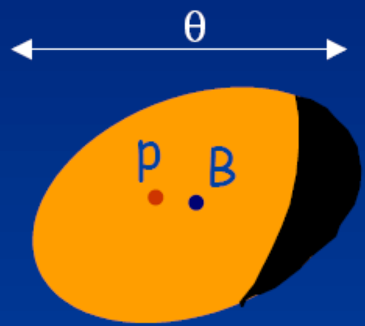
A final accuracy of ~$10^{-14}$ $M_\odot$ can probably be reached

In the case of 1 Ceres : 0.01% instead of 10% !!



## A problem

- Difference between photocenter and barycenter
- Depends on the phase, surface optical properties, shape
- Difficult to model for complex shapes




| D (km) | θ mas | BP mas |
|---|---|---|
| 10 | 6 | 0.2- 1 |
| 50 | 30 | 1 - 5 |

- Ongoing investigations :
  - general model with various scattering law
  - comparison with spherical shapes
  - systematic effect vs. random noise

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# Yarkovsky effect measurement

$$\Delta M = -\frac{3}{4}\frac{n}{a}\, da/dt\, \Delta t^2$$

Yarkovsky drift effect on mean anomaly

$$\epsilon_i = \sqrt{(\Delta\delta_i)^2 + \cos^2\delta_i\,(\Delta\alpha_i)^2}$$

Corresponding position offset

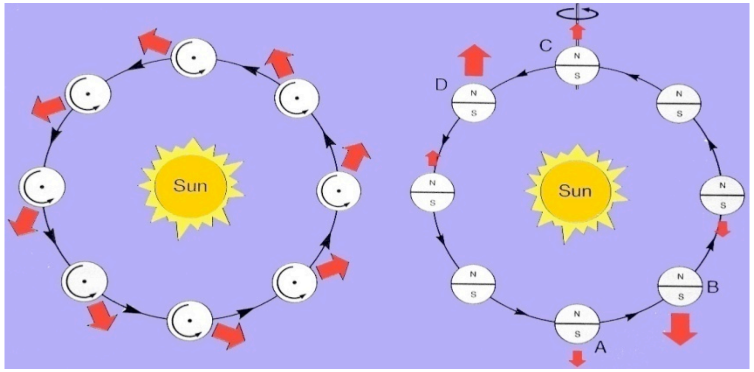
$$\sigma_i = e^{0.44(V_i-20)+1.35}$$

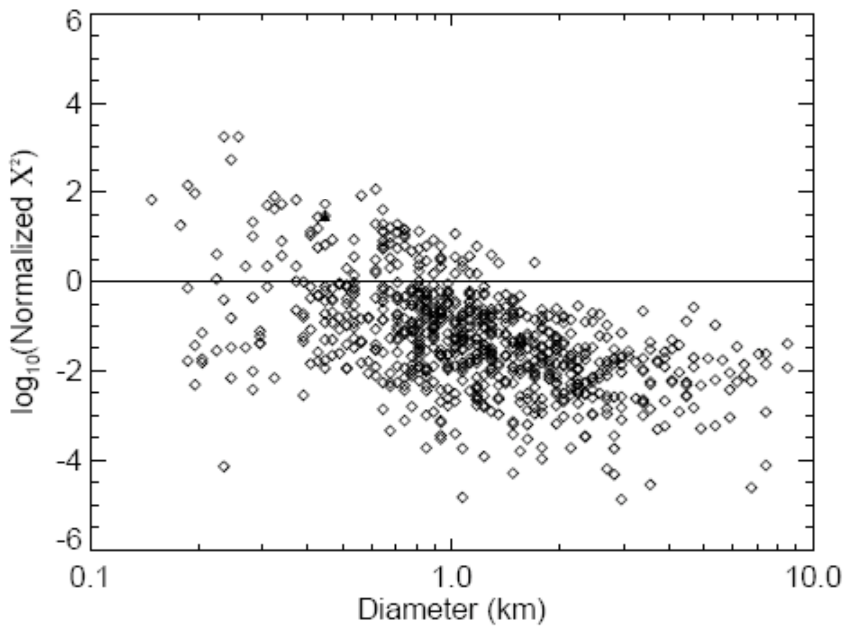
Gaia astrometric uncertainty (approx.)

$$\chi^2 = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{\epsilon_i}{\sigma_i}\right)^2$$

91 NEAs observed at least 10 times with V < 20 and $\chi^2 > 1$.

35 NEAs have been found to have $\chi^2 > 9$




Delbò, Tanga, Mignard, 2006

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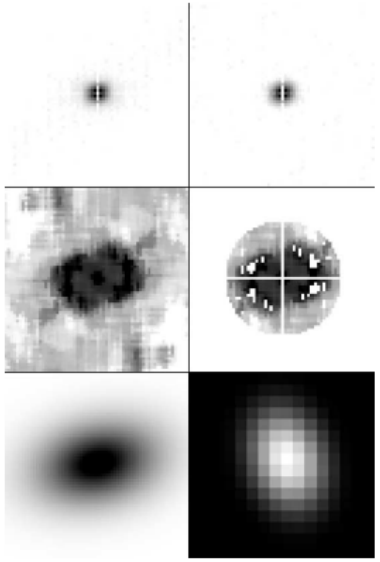
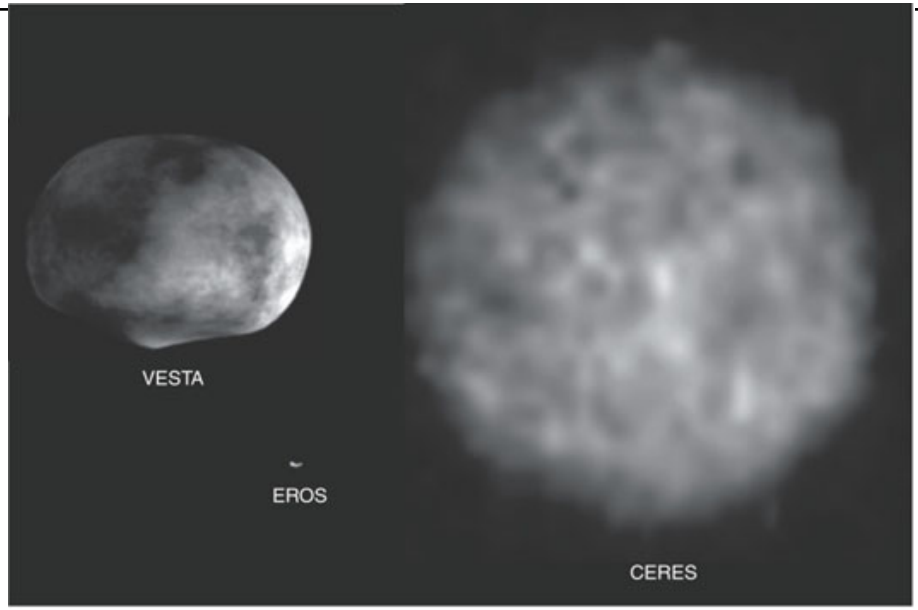


Speckle Interferometry

HST




**The size distribution of Main Belt asteroids is a major constraint for models of the collisional evolution of the asteroid belt. Moreover, sizes and shapes are needed to derive average densities when masses are known. However, asteroid size data are generally *not* known from direct size measurements!**



# What do we mean by “signal”?

**The signal is a vector of a few numbers**, corresponding to the collected photoelectrons in each column of pixels in the window. The signal is nothing else than the along-scan photoelectron distribution.

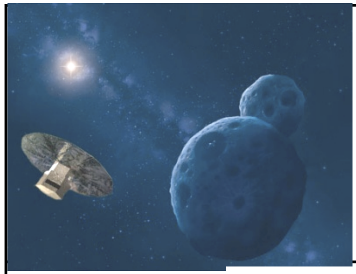
**From the signal we can derive:**

**Photocenter**

The photocenter is the mean (in pixels) of the photoelectron distribution.

**Width**

The width of the signal is the standard deviation (in pixels) of the photoelectron distribution.



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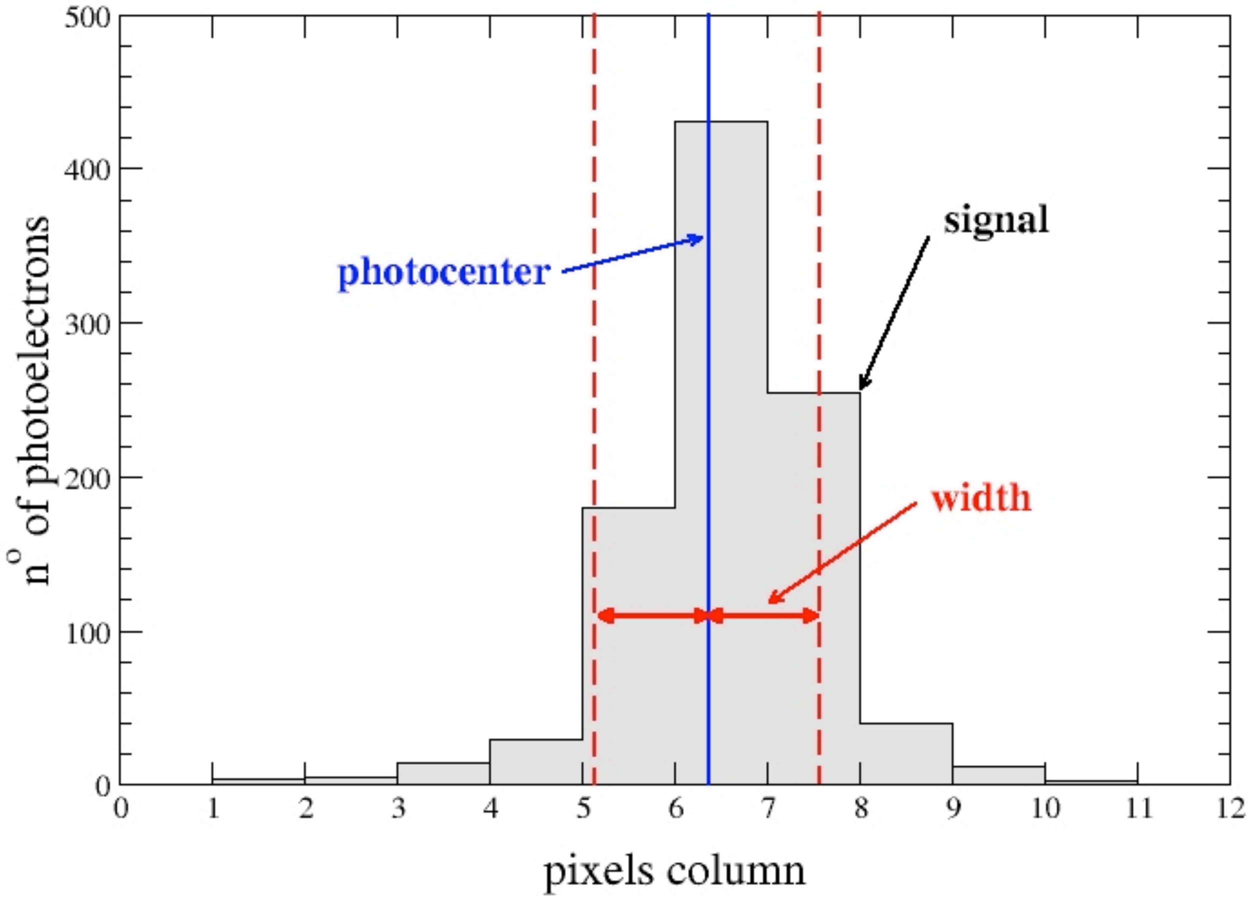
# Width - angular size function. How to measure asteroids



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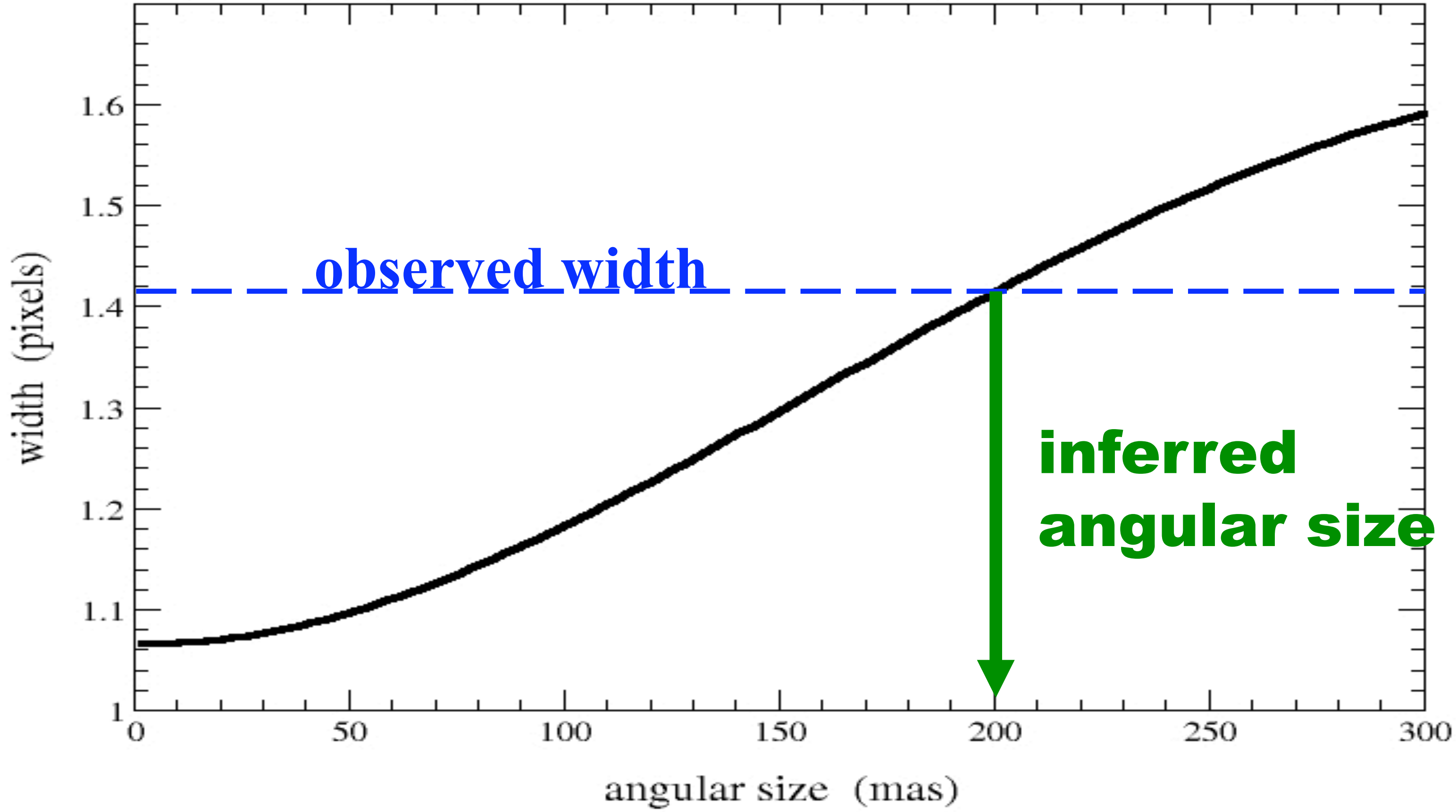
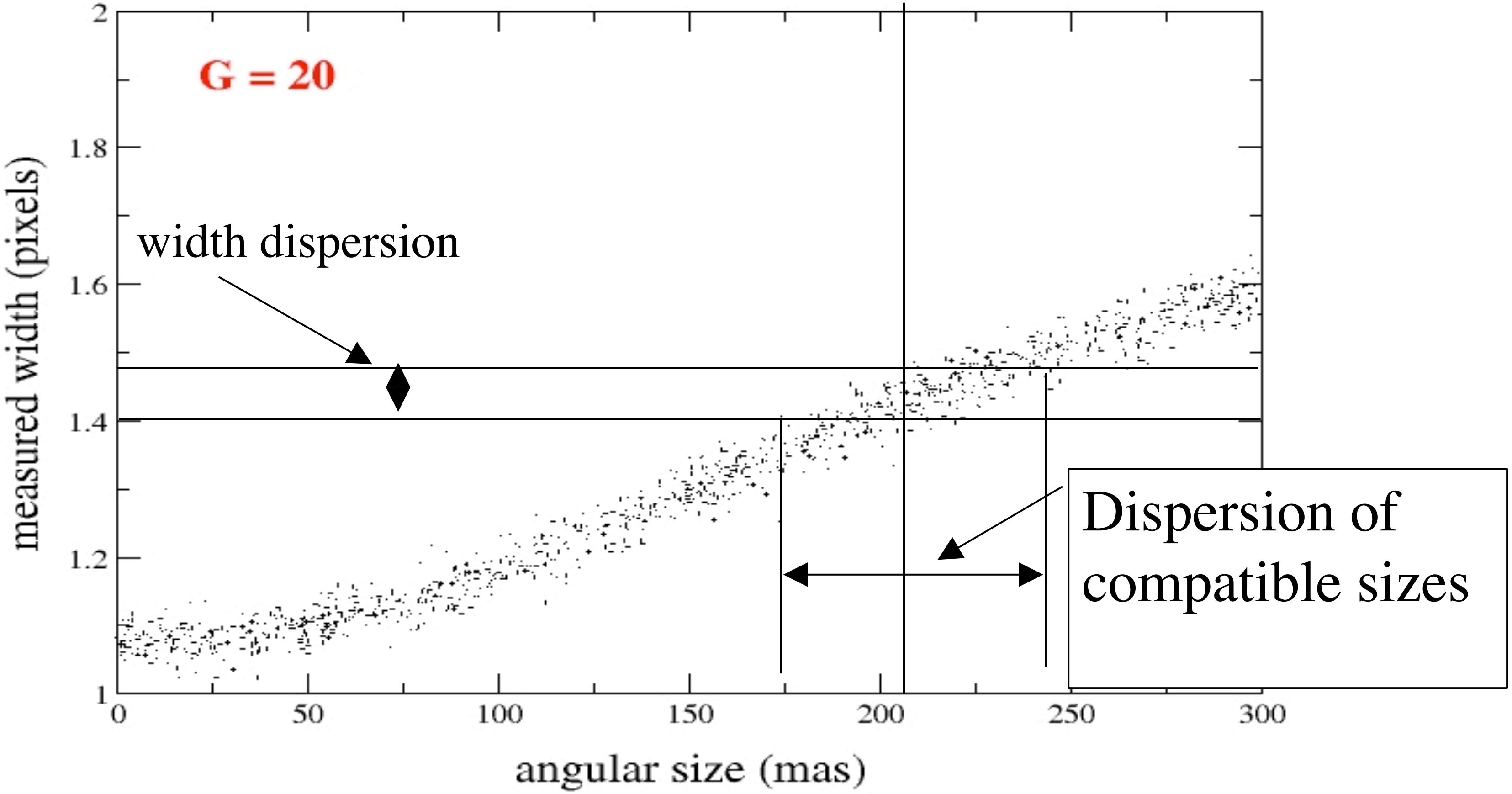
# The basic idea





## but the signal is subject to stochastic effects (photon statistics, etc.)



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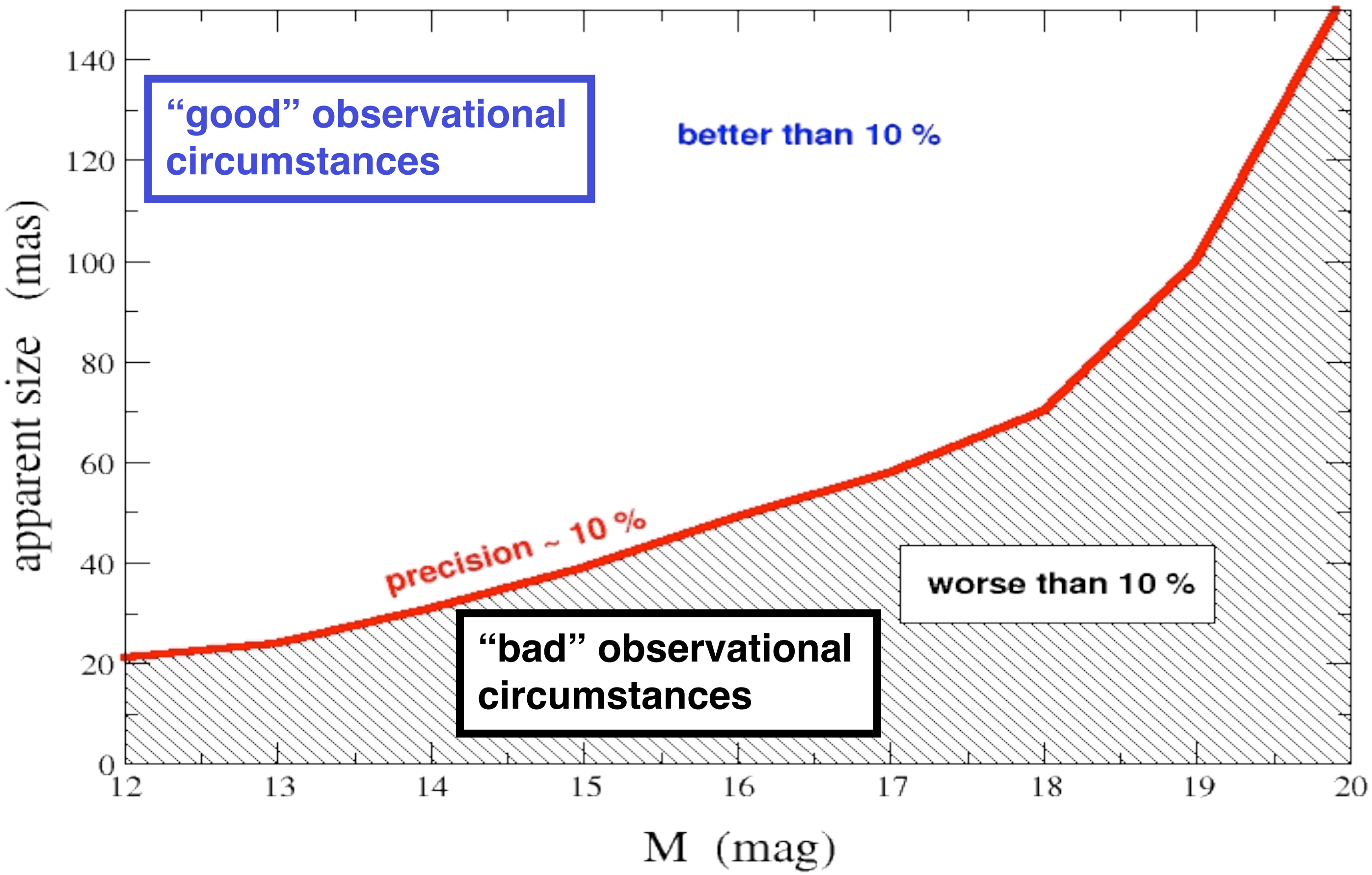
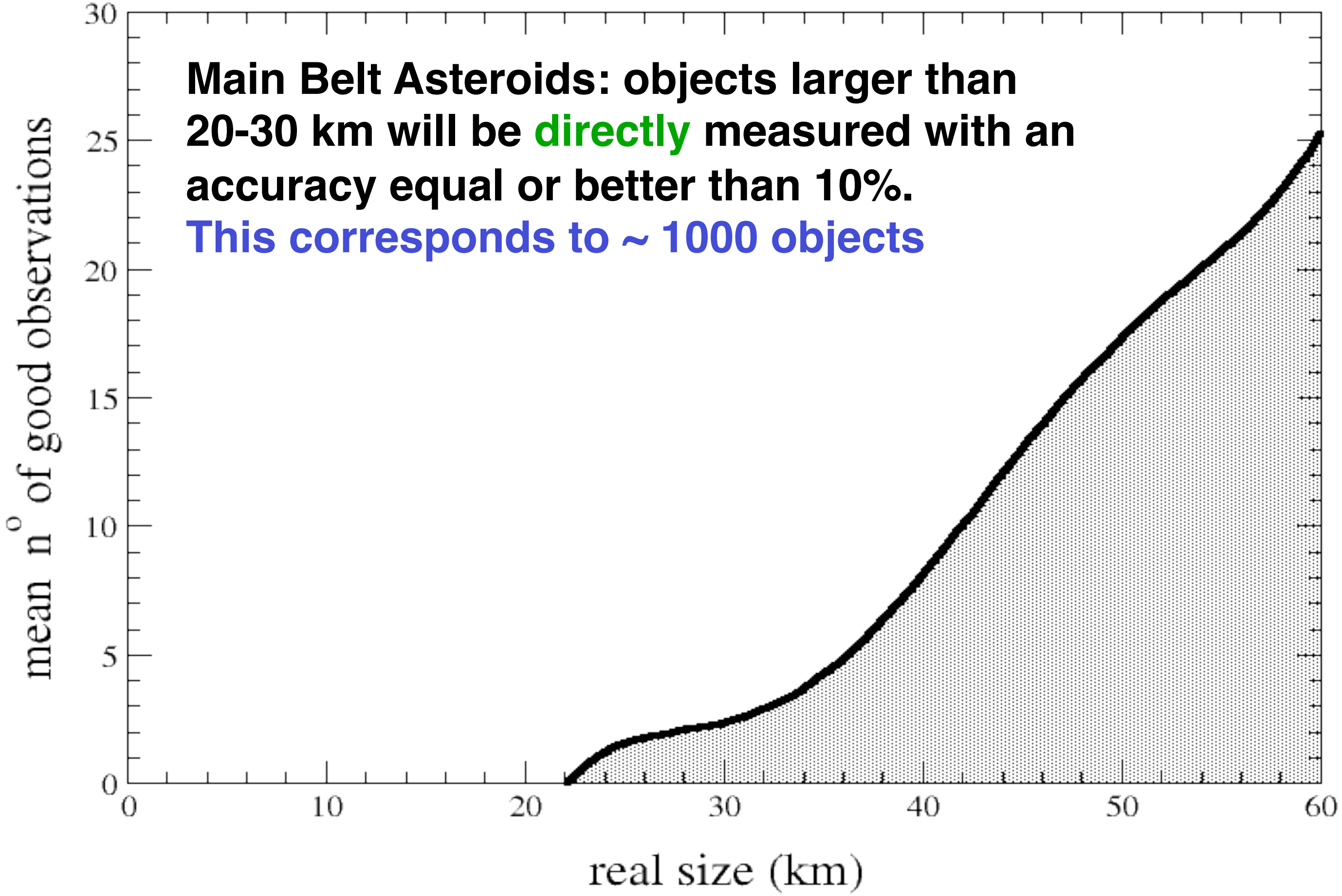
## Angular size measurement accuracy for single transits





# Number of "good" observations vs. diameter




**Main Belt Asteroids: objects larger than 20-30 km will be directly measured with an accuracy equal or better than 10%.**

**This corresponds to ~ 1000 objects**

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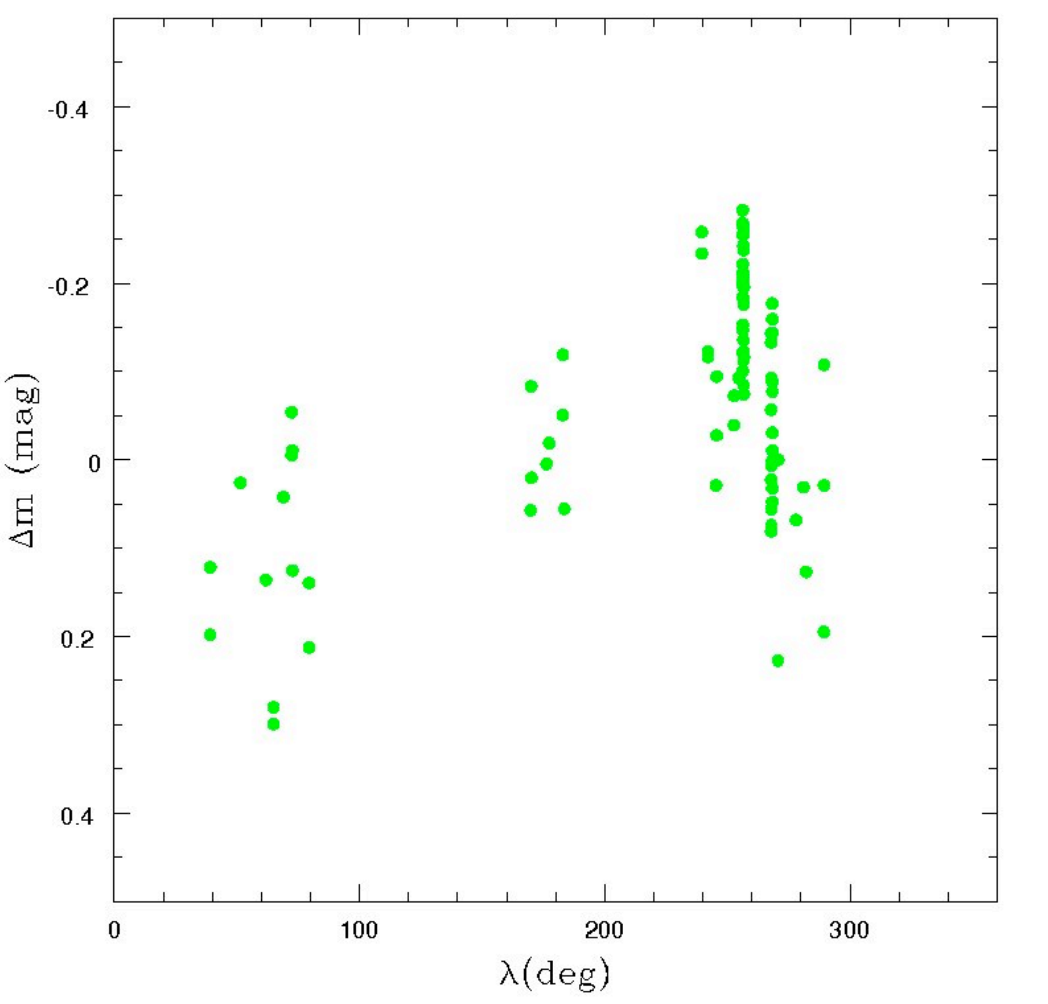



# GAIA disk-integrated photometry

Sparse photometric measurements (no light-curves)

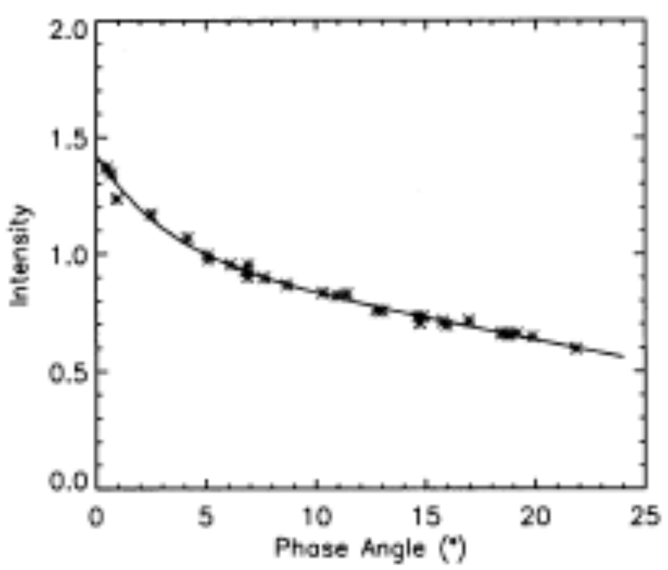
Expected accuracy for asteroid brighter than V=18.5: 0.01 mag

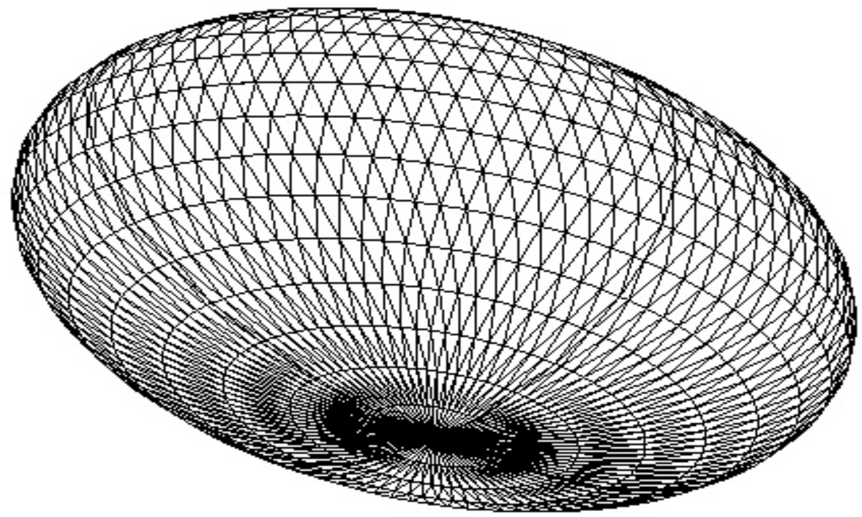
Good coverage of aspect angle variation over five years **(65 observations per object, on the average).**

Simulations of Gaia observations of (15) Eunomia



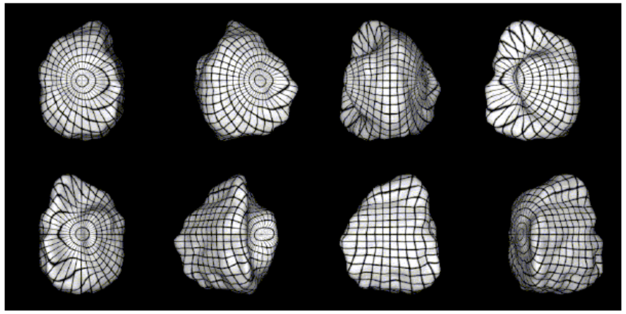
**The inversion problem: The objects are assumed to be triaxial ellipsoids. A "genetic" algorithm is used to solve for the unknown spin period, spin axis direction, two axial ratios, rotational phase at t=0, and a phase-magnitude linear coefficient.**

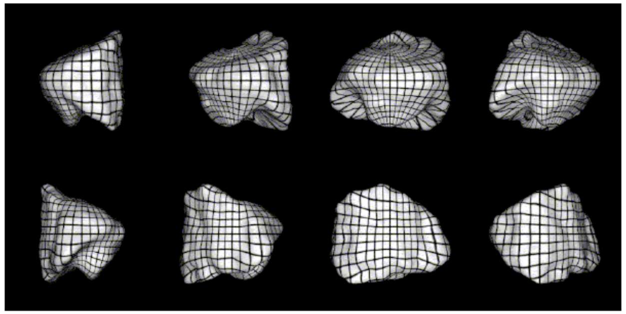




# The effectiveness of the inversion method tested by means of extensive numerical simulations:





- Triaxial ellipsoid shapes
- Complex shapes: digital shapes of (15) Eunomia, (6489) Golevka, (433) Eros
- Geometric and Hapke light scattering
- Photometric errors
- Different simulated orbits, spin periods and poles
- Application of the code to previous HIPPARCOS photometric data

**The results are generally encouraging**

**More than 10,000 asteroids should be potentially invertible**



**A systematic analysis of the old HIPPARCOS photometric data of asteroids has been carried out.**

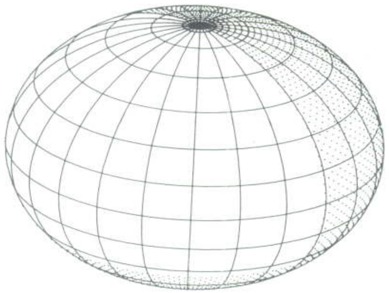
**The data set includes measurements for 48 asteroids, for which the rotational periods are known from full lightcurves, as well pole solutions in most cases.**

***Only 23 objects*** **have numbers of photometric measurements and nominal photometric accuracies that put them (in some cases, marginally) in the domain of possible photometric inversion** ***for ideal triaxial ellipsoids*****. Some of them are known to exhibit complex lightcurves suggesting irregular shapes and/or albedo features.**

**The right period has been derived for 13 (+4) objects.**



# The cases of 4 Vesta and 1 Ceres are interesting.



Vesta is a spheroid with a hemispheric-scale albedo spot, dominates the photometric lightcurve.

*The inversion algorithm finds a solution consistent with the spin axis direction determined from ground-based observations, but a spin period which is exactly twice the correct one.*

***This is fully understandable, since the algorithm tries to fit a photometric variation with two maxima and minima.***

The same happens for 1 Ceres, which has a shape very close to a sphere, and a very modest photometric variation. The results of the inversion suggest that the lightcurve should be dominated by albedo markings, and this is in agreement with some recent HST observations.

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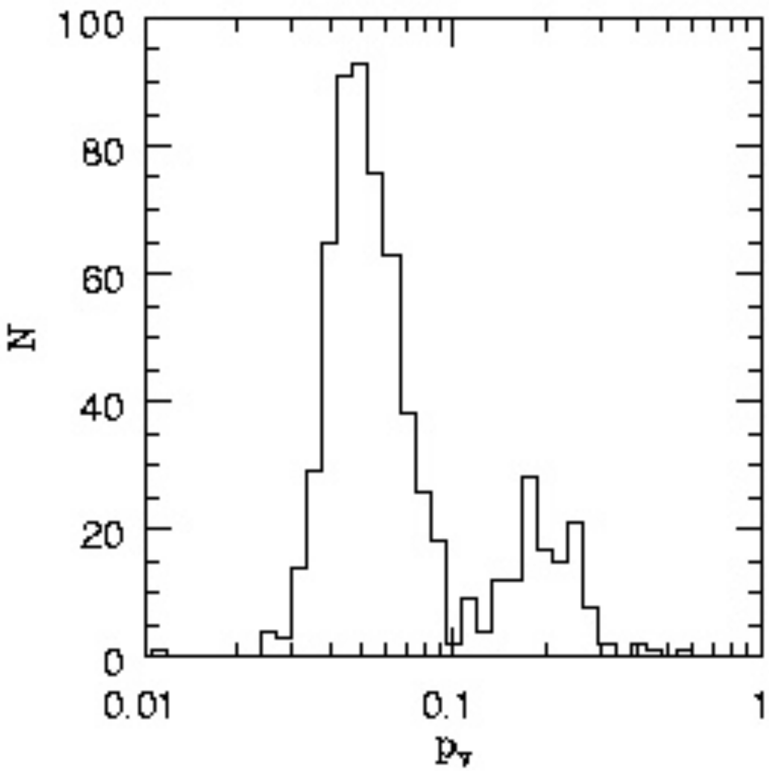
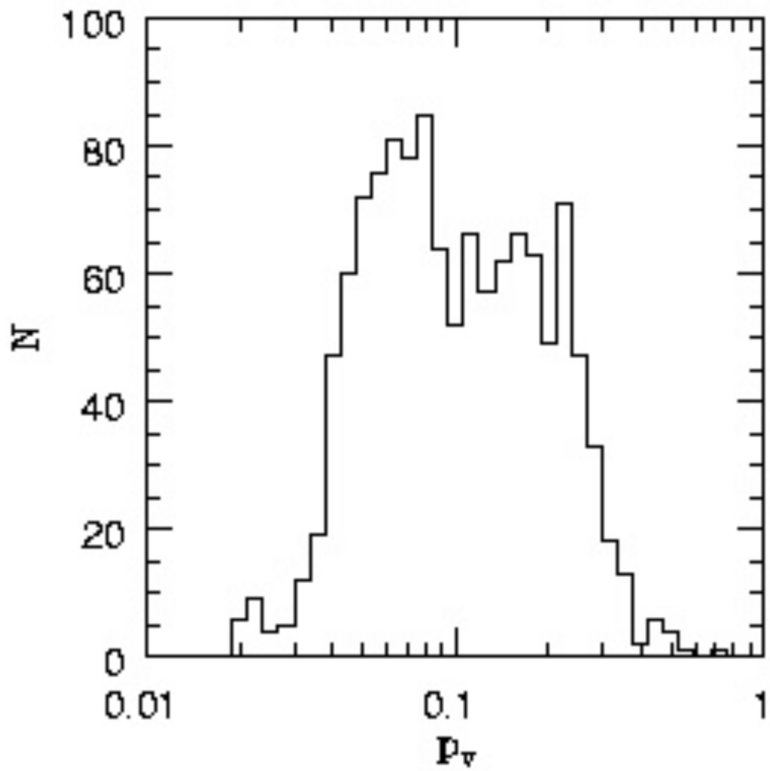
## IRAS albedo distributions: to be checked!




**D > 50 km**




**D < 50 km**



$$\log(D) = K - 0.2H - 0.5\log(p_V)$$

**Gaia will not observe at zero phase angle, then some extrapolation to zero phase of the actual magnitudes measured at different phase angles has to be done.**

**A linear phase – mag relation will be assumed, without taking into account any "opposition effect". The slope of the linear phase – mag relation is also determined by photometric inversion, under the assumption that the slope is constant and does not depend on the aspect, obliquity and rotation angles.**

**Work is in progress to develop a better magnitude system, allowing us to make more reliable extrapolations to zero phase angle, to obtain better estimates of the absolute magnitude.**

# Spectroscopic observations and taxonomy classification

| Spectral characteristics | | |
|---|---|---|
| | Blue Photometer | Red Photometer |
| **spectral range** | 330-680 nm | 650-1000 nm |
| **spectral dispersion** | 4-34 nm/pixel | 7-15 nm/pixel |

The construction of an extensive Gaia-based asteroid taxonomy will be a natural by-product of the detections of about 300,000 asteroids down to magnitude 20.

This taxonomy will have two major advantages:

1. it will be homogeneous, since it will be derived by a single instrument;

2. it will include for many objects the Blue spectral region (not included in the most taxonomic classifications based on spectroscopic surveys carried out in recent years.

The Blue part of the reflectance spectrum is known to be very important, in particular as a diagnostic tool to distinguish among different sub-classes of primitive, low albedo objects, including the very interesting F-class asteroids.

# Expected results from GAIA physical characterization of asteroids: the Gaia revolution

| Physical parameter | nº of bodies | accuracy |
|---|---:|---:|
| Sizes | ~1,000 | <10 % |
| Spins and Shapes | ~10,000 | |
| New Taxonomy Classification | ~100,000 | |
| Masses | ~100 | ~1 % |
| Densities | ~100 | <10 % |