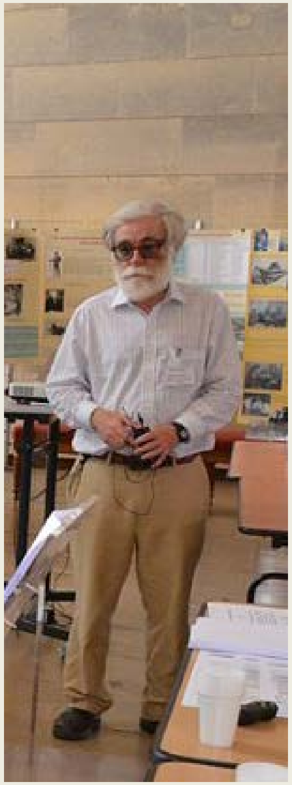
Remembering Hector de Vega
a really nice person



Gaia & the Distance Scale

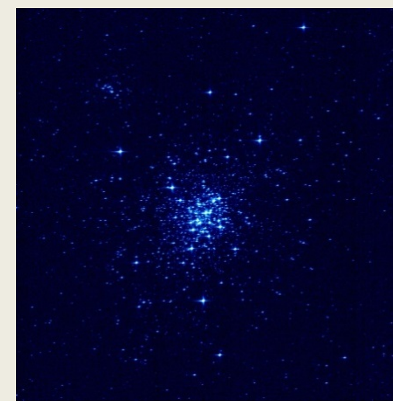
Stereoscopic Census of our Galaxy

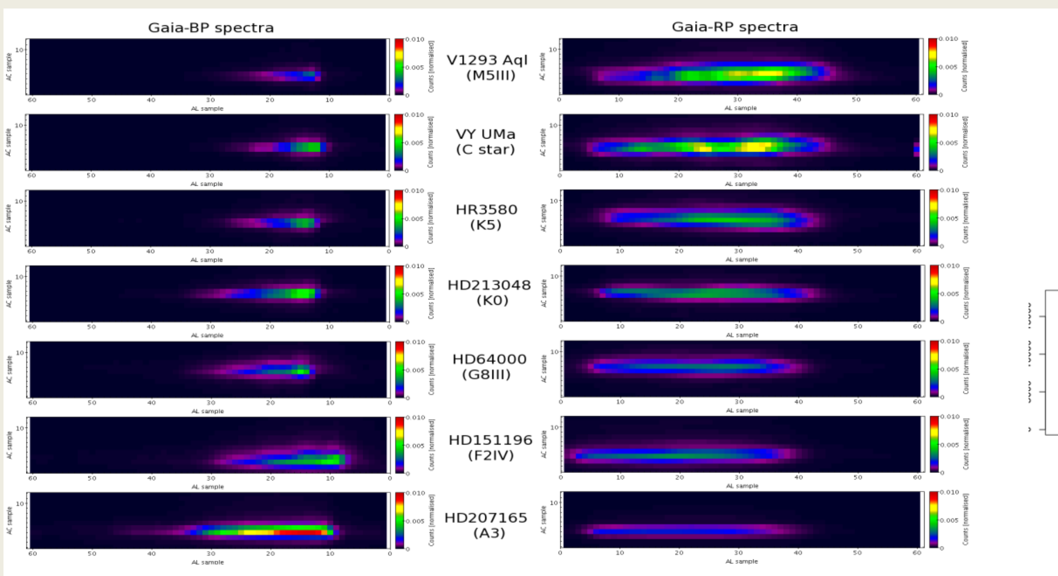
http://gaia.ac.uk

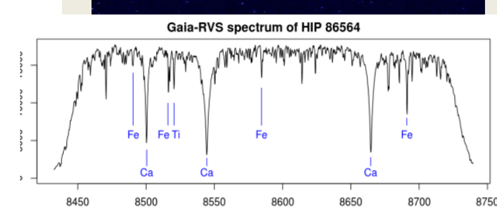
one billion pixels for one billion stars

one percent of the visible Milky Way

Gerry Gilmore UK Gaia PI

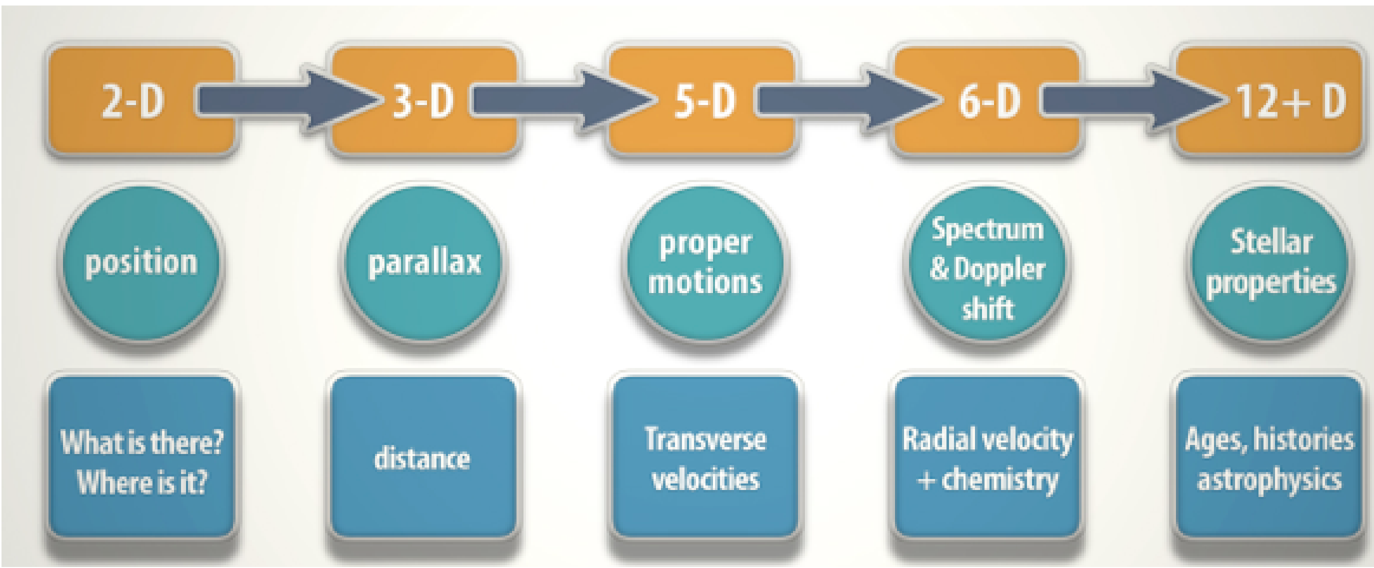






How does one study the Milky Way?

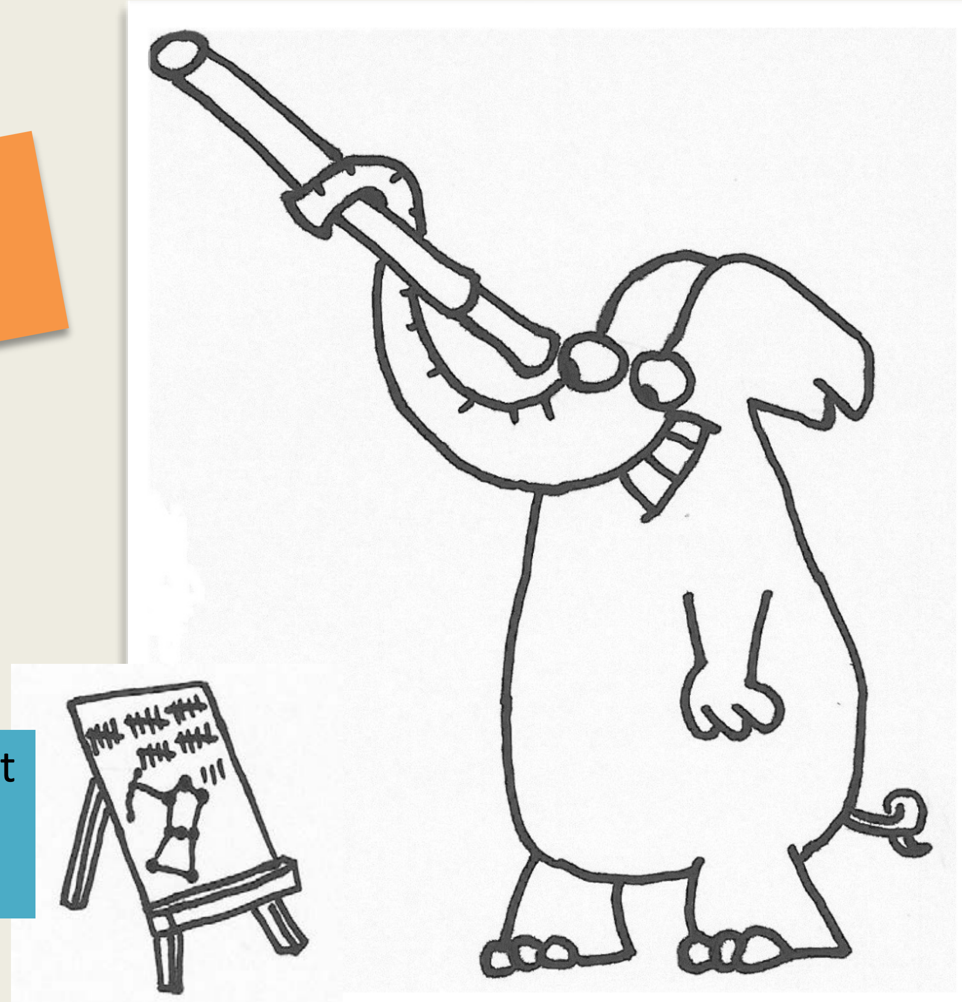
scientific discovery involves knowing an object exists, how it moves, its composition



Stellar orbits, star formation history, origin of the elements, Galaxy assembly, dark matter, cosmological initial conditions, fundamental physics, solar system(s), …

There is an elephant in the astrophysics room:
all distances depend on too few, inaccurate, stellar parallaxes

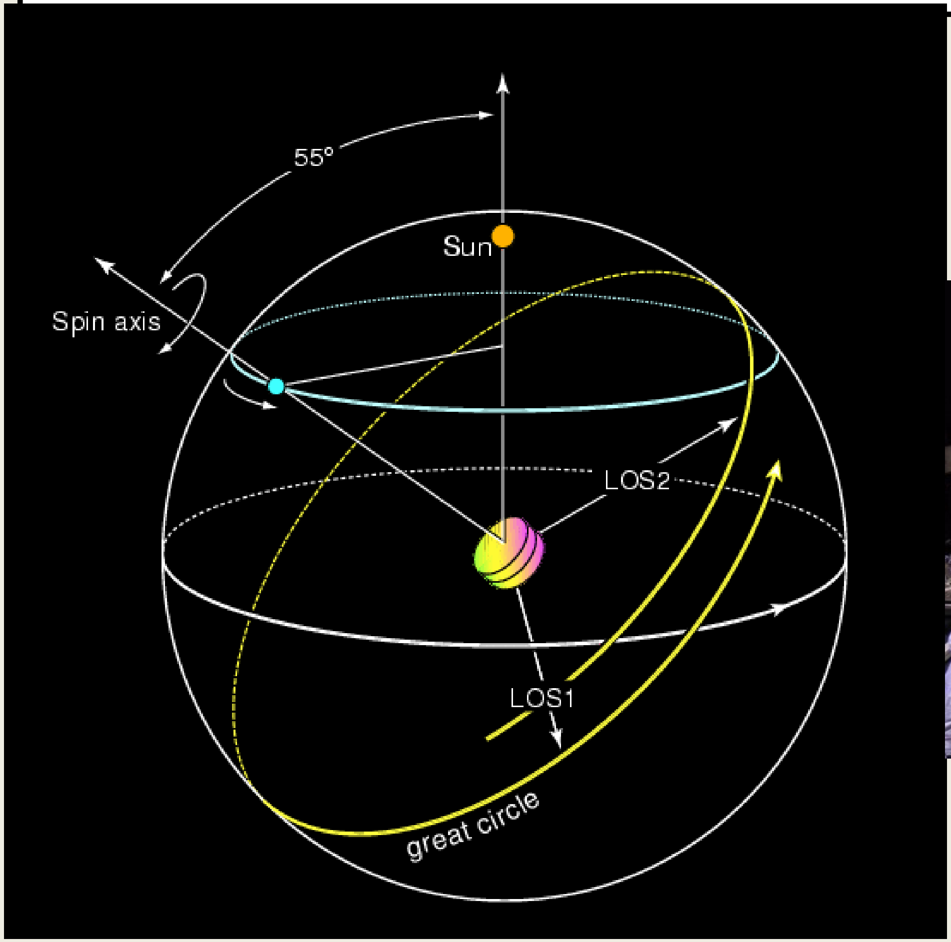
The distance scale
is the weak link
in modern astrophysics



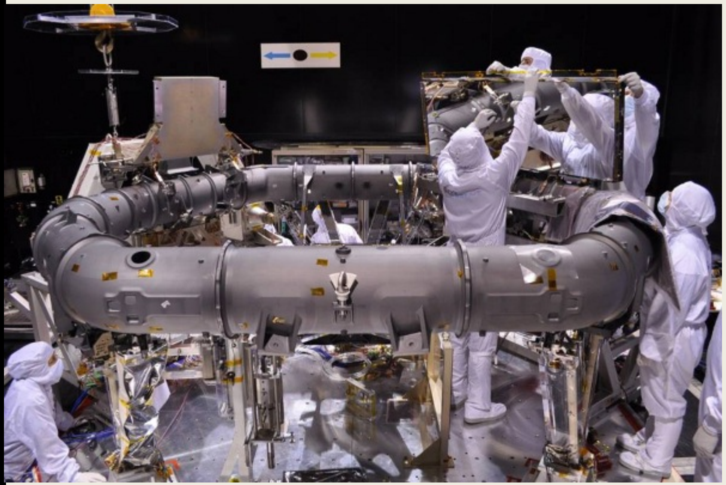
I gave my friend an elephant
He said: “thanks”
I said: “don’t mention it”

Thanks to Ian for the elephant

How does Gaia work?: Sky Scanning Principle



Observe sky with two telescopes



Precision: 50pico-rad, human hair at 1000km, 2cm on the moon...

Non-variable tracers will be accurately calibrated

Luminosity calibrations with Hipparcos and Gaia

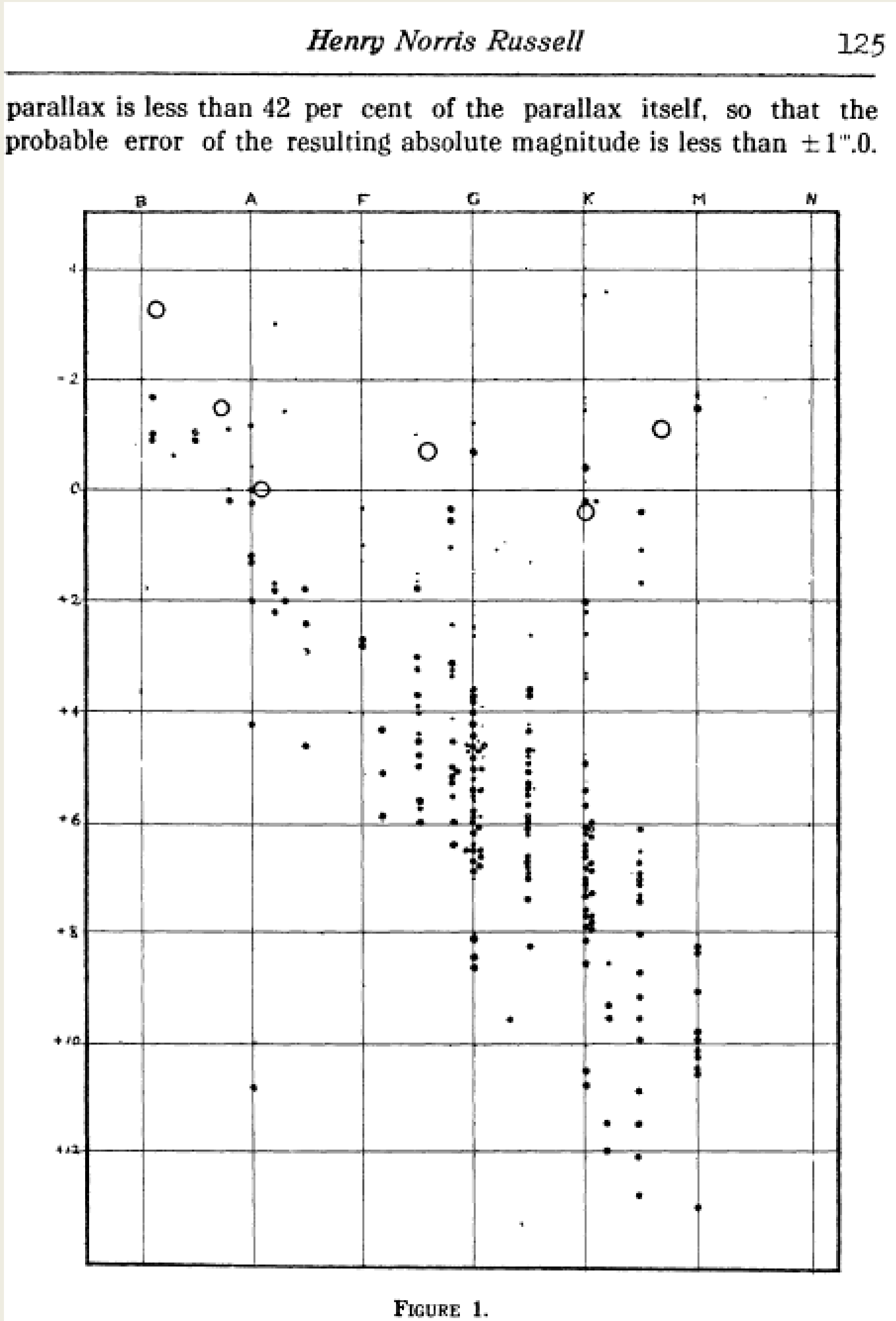
	Hipparcos	Hipparcos 2	Gaia
$\sigma_\pi/\pi < 0.1$ %	-	3	100 000 ★
$\sigma_\pi/\pi < 1$ %	442 ★	719 ★	~ 11 x 10^6 ★ up to 5-10 kpc (Mv<-5) up to 1-2 kpc (Mv<5)
$\sigma_\pi/\pi < 10$ %	22 396 ★	30 579 ★	~ 150 x 10^6 ★ up to 30-50 kpc (Mv<-5) up to 2-5 kpc (Mv<5)
Error on Mv	0.3 mag at 100 pc		0.1 mag at 10 kpc
Stellar pop.	mainly disk		all populations, even the rarest
HR diagram < 10 %	-4 to 13, -0.2 to 1.7		all mag and colours

Gaia and dark matter

- Precision high-statistical weight studies of dark matter distribution in local Milky Way

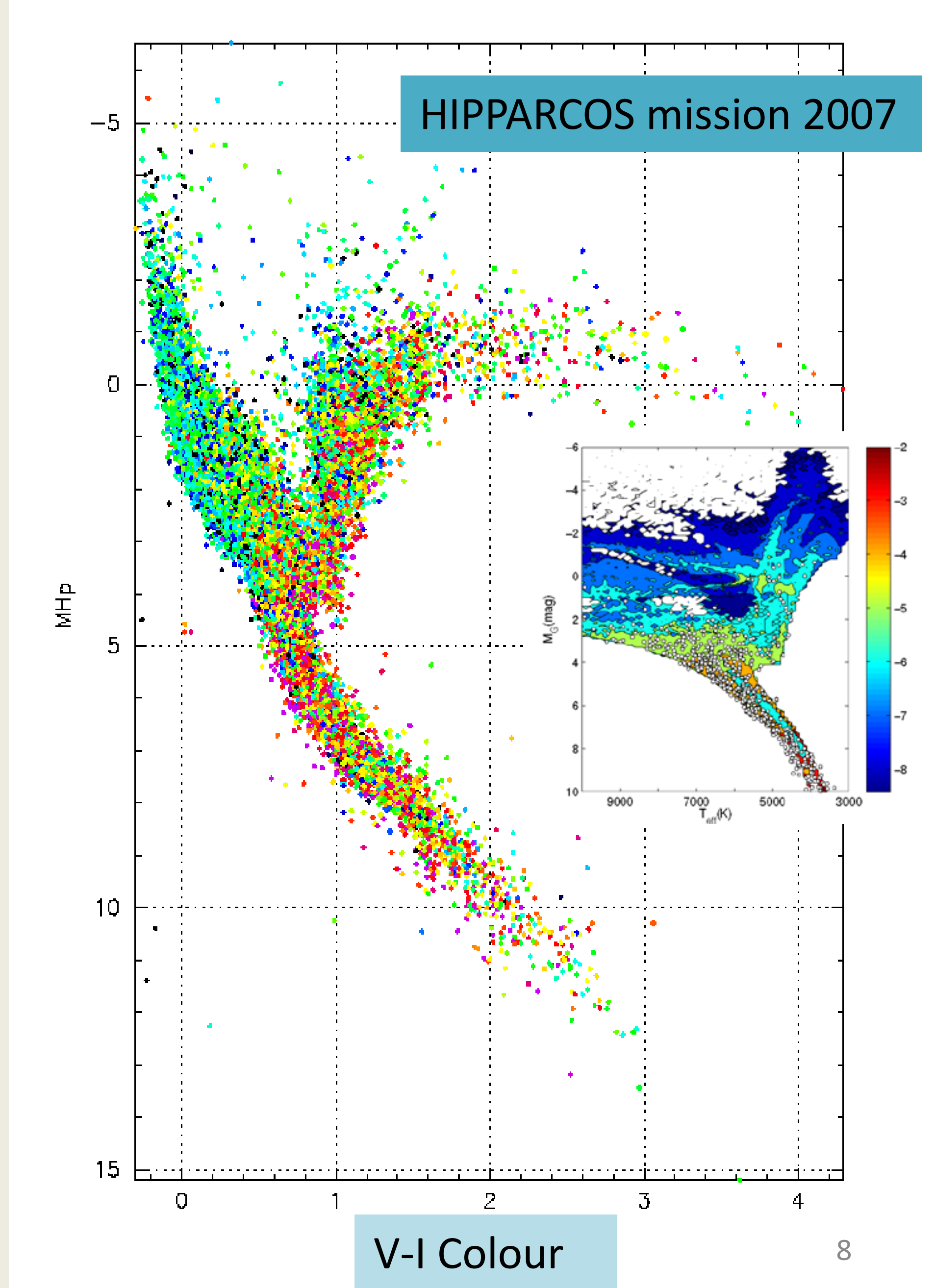
- Possible: detection of dark sub-structures – this requires examples in high stellar-density environs
- Not possible – 3-d mapping of cores in distant dSph

Why is astrometry interesting?



parallax is less than 42 per cent of the parallax itself, so that the probable error of the resulting absolute magnitude is less than ±1".0.

FIGURE 1.



Stellar distances: the Cambridge connection

ASTRONO[MICAL JOURNAL]
FOUNDED BY B. A. GOULD.
Nos. 618-619.
VOL. XXVI. ALBANY, N.Y., 1910 OCTOBER 2

DETERMINATIONS OF STELLAR PA[RALLAX]

[FROM PHOTOGRAPHS TAKEN AT THE CAMBRIDGE OBSERVATORY (ENGLAND) BY AR[illegible]
[illegible] RUSSELL.

The present communication contains the final results of the first series of observations for stellar parallax made at the *Cambridge Observatory*. The plans for the work* were prepared by Mr. A. R. HINKS, Chief Assistant at the Observatory, and [illegible] d a Research Assistant of the *Carnegie Institution* for the purpose of this investigation. Mr. HINKS and the writer are also jointly responsible for the photographic observations in nearly equal shares. The former contributes 43%. For the measurement and reduction of the plates, which was begun at Cambridge and completed at Princeton, and for the results and conclusions here detailed, the writer is alone responsible.

The determinations of photometric magnitude and spectrum were made at the *Harvard College Observatory*, the latter by Mrs. FLEMING, and the former by Prof. E. C. PICKERING, to whom the writer's most hearty thanks are due for this extremely important addition to the value of the work.

I. METHODS OF OBSERVATION AND REDUCTION.

A detailed account of the methods employed in the present work, with the reasons for their adoption, is given in the paper by Mr. HINKS and the writer, already referred

The photographs were taken with the SHEEPSHANKS Equatorial of the Cambridge Observatory† — a *coudé* telescope of the polar siderostat type, of 12 inches effective aperture and 19.3 feet focal length. The stability of this instrument, and the performance of its driving clock and

were made to guide by hand.

The plates, coated on plate-glass, cover a field a little less than 1½° square. Four exposures were usually made on each, separated by ½ mm. in declination. With the standard exposure of five minutes, stars are shown to the eleventh (photographic) magnitude.

Separate plates w
at once — because
whose success depe
the same plate at th
be spoiled by the fail
conditions of the wo
ment should be be
All plates wer
meridian, to avo
systematic errors,
tude, which may a
from instrumental ca
In order to obtain
along with the muc
were photographed
a small patch of ge
diminished the pho
ing through it by a
glass plate, placed
This worked very
until the gelatine p
of the glass. The
fourth magnitude w
a number of the
ons at two epoch
otions. Data co
ill be given later
It should be an
ee from this dang
ates.

* HINKS and RUSSELL, *M.N.*, LXV., pp. 775–787.
† Described by SIR ROBERT BALL, *M N.*, LIX., pp. 152–155.

* The alternative m
circumstances to syste
See KOSTINSKY. *Pub*
part 2, pp. 69, 138.
p. 101.
† Called hour-angl
No. 1, p. 68.
‡ This device is du

§8. *The Sheepshanks Telescope*. Professor Adams died in January 1892, leaving to the Observatory a portable equatoreal by Cooke and a valuable collection of books. He was succeeded as Lowndean Professor and Director of the Observatory by Sir Robert Ball. In a memorandum to the Syndicate in March 1893, the new Director pressed for the erection of a refracting telescope suitable for stellar photography, with a view to work on stellar parallax.

... that it should be carried on the same mounting as the ... telescope which could be used as a guiding telescope. It was hoped to prov... the greater part of the cost from the special Sheepshanks Fund and to appeal to the public for subscriptions to meet the balance. The appeal was not successful and it was decided to look to the Sheepshanks Fund for the whole sum. Professor Stokes, Mr Newall and the Director were appointed a committee to prepare plans and on their recommendati... a 12 ... apochromatic by Cooke was ordered in 1895. On the suggesti... Dr Common and ... it was agreed in March 18... modified form of equatoreal *coudé* mounting designed by Sir Howard Grubb of Dublin.

(a) SHEEPSHANKS TELESCOPE

1994 workshop at IoA/RGO/ESA on
Future Possibilities for Astrometry in space

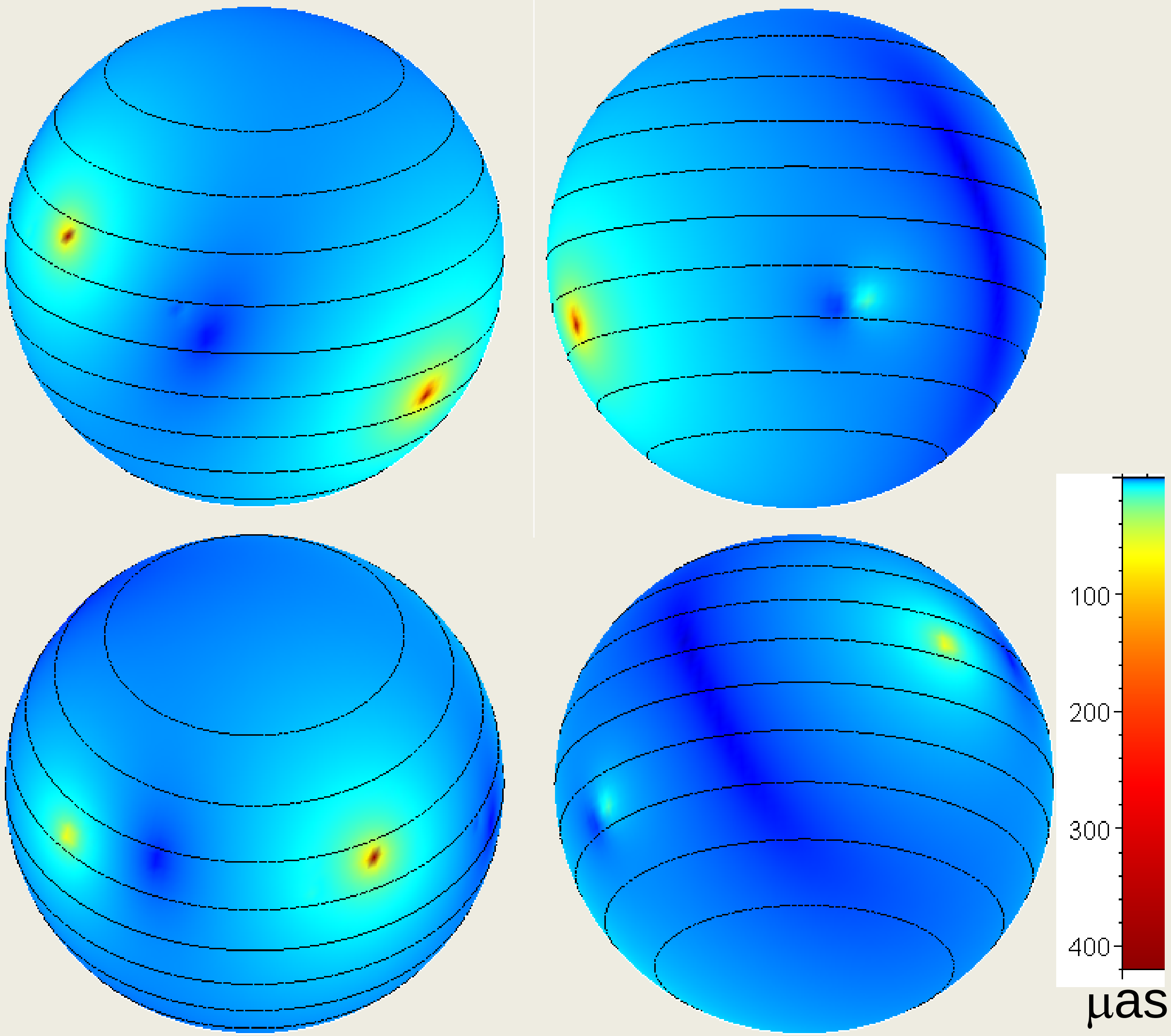
Gaia will repeat the Eddington 1919 light-bending test 100 years later, with 100,000 times higher precision

Gaia will measure light bending by Jupiter to test GR

- From positional displacements:
  - γ to 5×10^{-7} (cf. 10^{-5} presently) $\Rightarrow$ scalar-tensor theories
  - effect of Sun: 4 mas at 90°; Jovian limb: 17 mas; Earth: ~40 μas
- From perihelion precession of minor planets:
  - β to 3×10^{-4} - 3×10^{-5} ($\times$10-100 better than lunar laser ranging)
  - Solar J_2 to 10^{-7} - 10^{-8} (cf. lunar libration and planetary motion)
- From white dwarf cooling curves:
  - dG/dT to 10^{-12} - 10^{-13} per year (cf. PSR 1913+16 and solar structure)
- Gravitational wave energy: $10^{-12} < f < 10^{-9}$ Hz
- Microlensing: photometric (~1000) and astrometric (few) events
- Cosmological shear and rotation (cf. VLBI)

Monopole gravitational light deflection

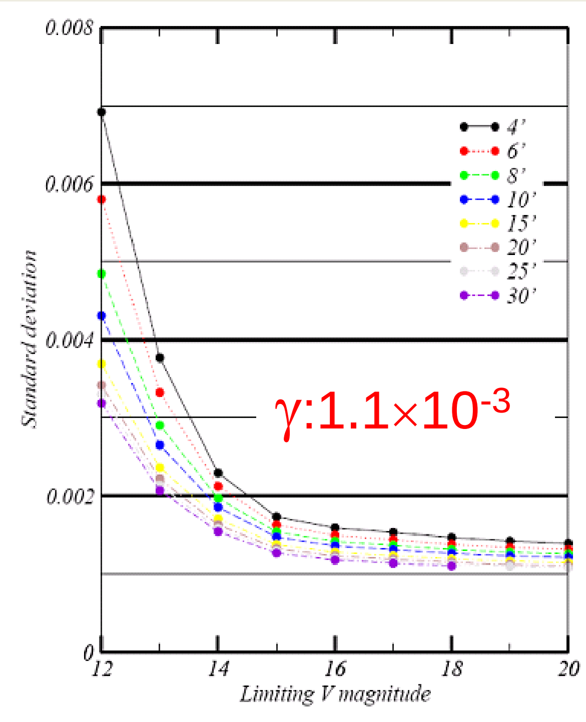
- Monopole light deflection: distribution over the sky on 25.01.2006 at 16:45 equatorial coordinates



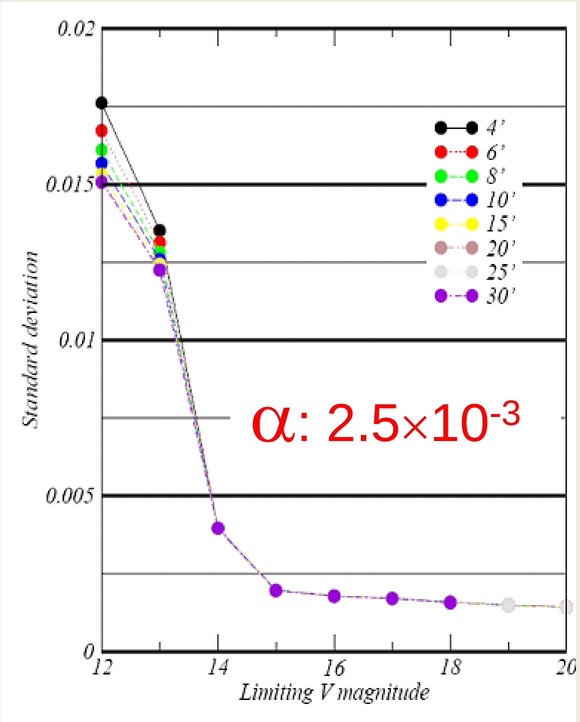
body	(μas)	>1μas
Sun	1.75″	180 °
Mercury	83	9 ′
Venus	493	4.5 °
Earth	574	125 °
Moon	26	5 °
Mars	116	25 ′
Jupiter	16270	90 °
Saturn	5780	17 °
Uranus	2080	71 ′
Neptune	2533	51 ′

Light deflection from the planets

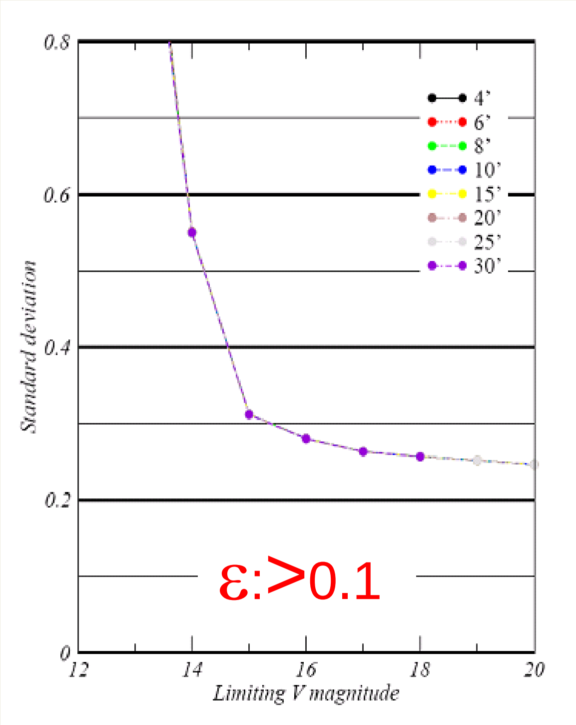
Jupiter: monopole



gradient-gravitomagnetic



quadrupole



Anglada-Escudé, Klioner, Torra, 2006
Crosta, Mignard, 2006

For other planets the results are worse: 0.1-0.007 for the monopole

Problem: rings, dust, gas, etc. in the vicinity of the giant planets

Relativistic effects with asteroids

Schwarzschild effects due to the Sun: perihelion precession
Preliminary results with limited number of sources and
with perihelion only:

$$\sigma_\beta < 10^{-3}$$

$$\sigma_{J_2} < 10^{-7}$$

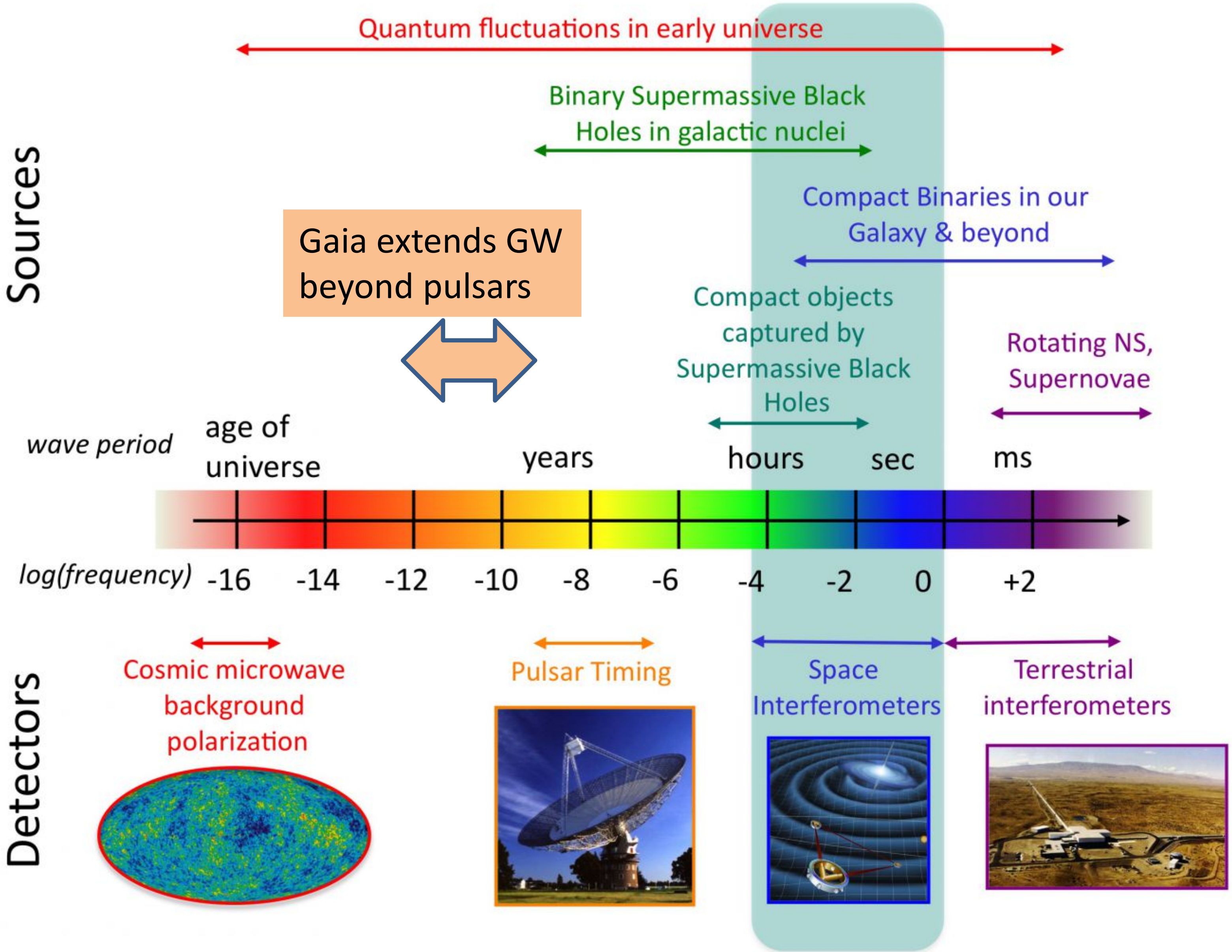
$$\sigma_{\dot{G}/G} < 5\times 10^{-13}\ \mathrm{yr}^{-1}$$

Non-Schwarzschild (3-body) effects: related to the tests of the Strong Equivalence Principle

test non-standard combinations of the PPN β and γ

e.g. $\eta = 4\gamma - \beta - 3$

The Gravitational Wave Spectrum



Pattern matching in positions/proper motions

II. Constraint on very low frequency gravitational waves:

- constraint of stochastic GW flux with $\nu < 3 \times 10^{-9}$ Hz
  (similar study done for VLBI: Gwinn et al., ApJ, 1997)

- attempts to fit a pattern of apparent motions induced by an individual GW with $\nu < 1.3 \times 10^{-7}$ Hz
  (matched filtering can be used, synergy with LISA & ground based)

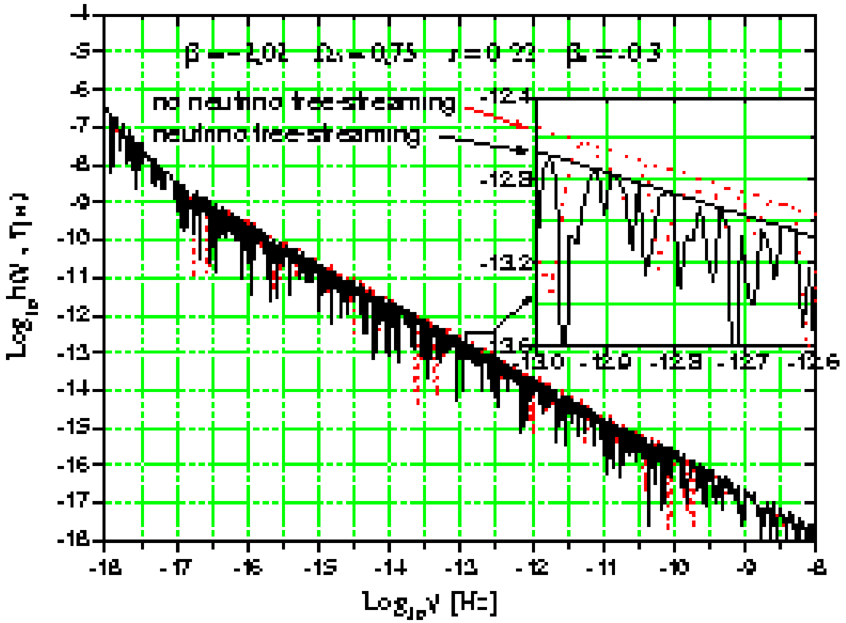
The harmonic coefficients for n>1 give the GW-flux constraints

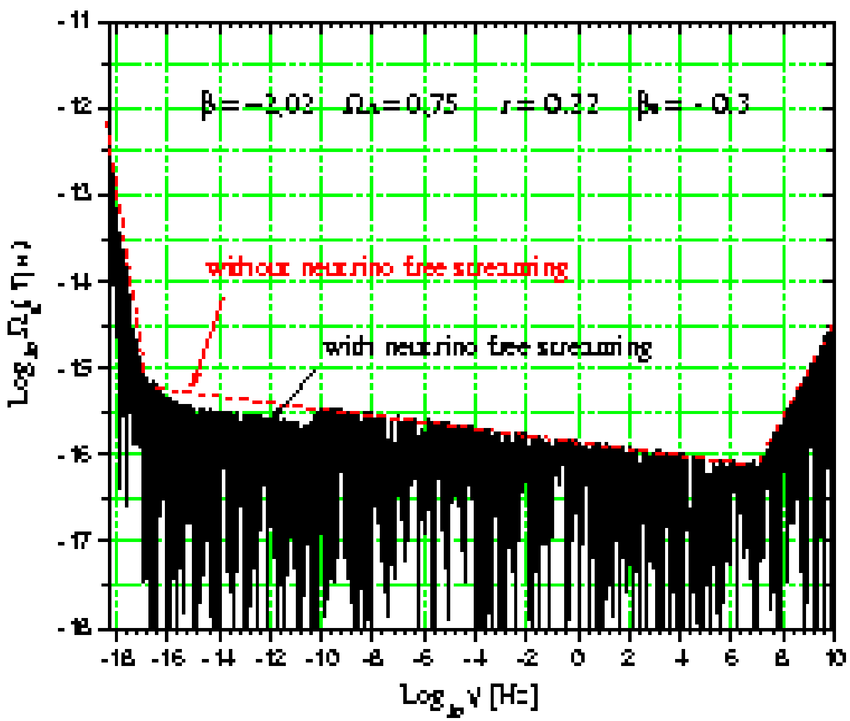
From Gaia for $\nu < 3 \times 10^{-9}$ Hz (95% confidence; preliminary analysis):

$$h^2 \Omega_{GW} < 0.001 \div 0.005$$

- Will Gaia contribute to cosmology and fundamental physics?

  - Gaia MAY detect?/constrain very low frequency gravitational waves, from coherence/stability of reference frame. a la VLBI
  - Gravitational wave energy: $10^{-12} < f < 10^{-9}$ Hz
  - This range – well below pulsars – is a sensitive test of inflation models, and later neutrino effects eg PRD 75 104009 2007
  - Need a many light-year detector – use star fields!





Galaxies, Quasars, and the Reference Frame

- Parallax distances, orbits, and internal dynamics of nearby galaxies
- Galaxy survey, including large-scale structure
- ~1,000,000 quasars: kinematic and photometric detection
- ~10,000 supernovae [few/day ➔ real-time alerts]
- Ω_M, Ω_Λ from multiple quasar images (4000 to 20 mag)
- Galactocentric acceleration: 0.2 nm/s^2 $\Rightarrow$ Δ(aberration) = 4 μas/yr
- Globally accurate reference frame to ~0.4 μas/yr

- Will Gaia contribute to cosmology and fundamental physics?

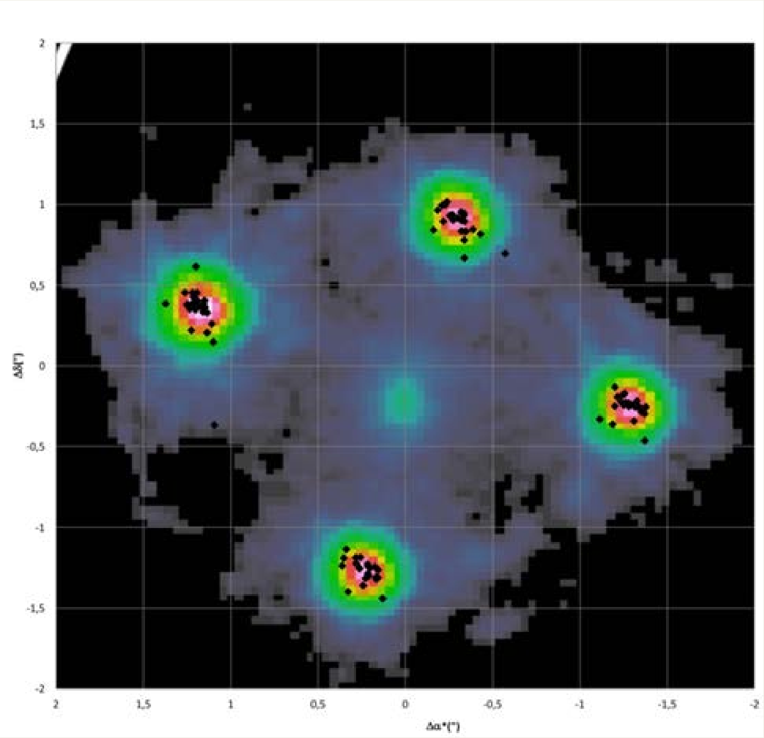
Gaia will discover 500,000 quasars, all with high-resolution imaging to quantify strong-lensing structure (11 qso lenses known in DR3…),

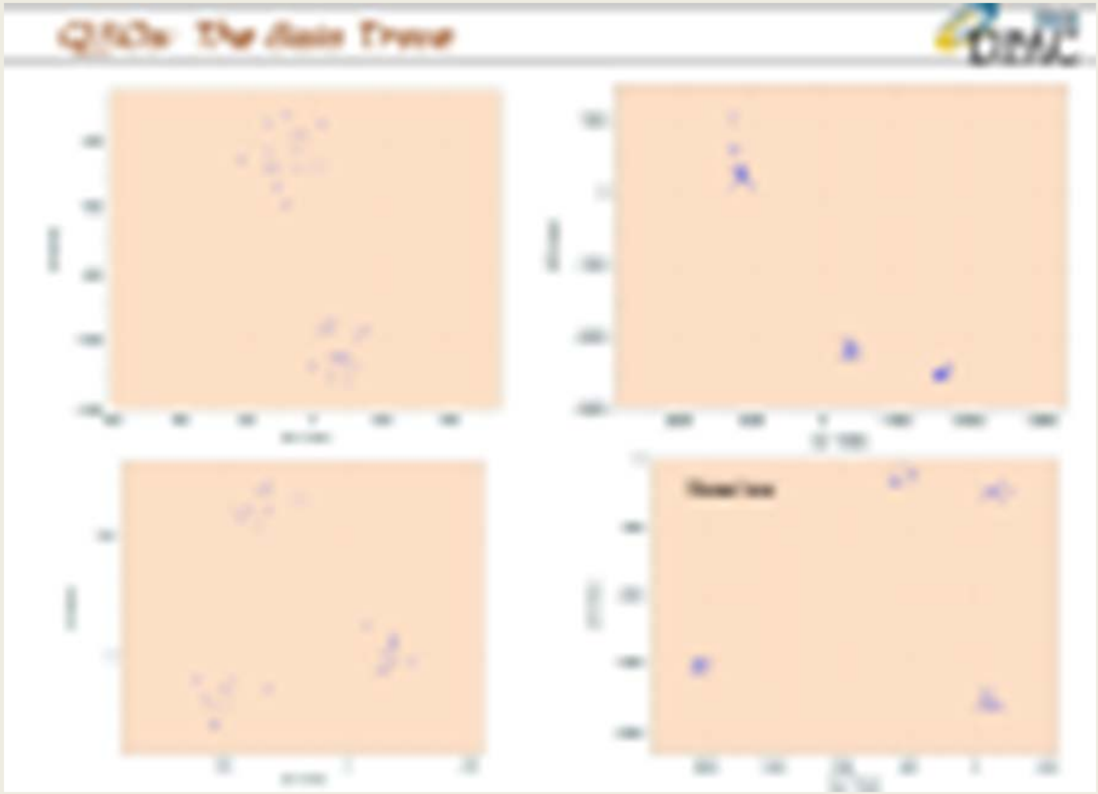
[discovery: spectrophotometry, emission lines, astrometry]

2000 new strong-lensed QSO expected, under standard CDM

Ω_M, Ω_Λ from multiple quasar images

The separation DF is also a measure of the small-scale perturbation spectrum





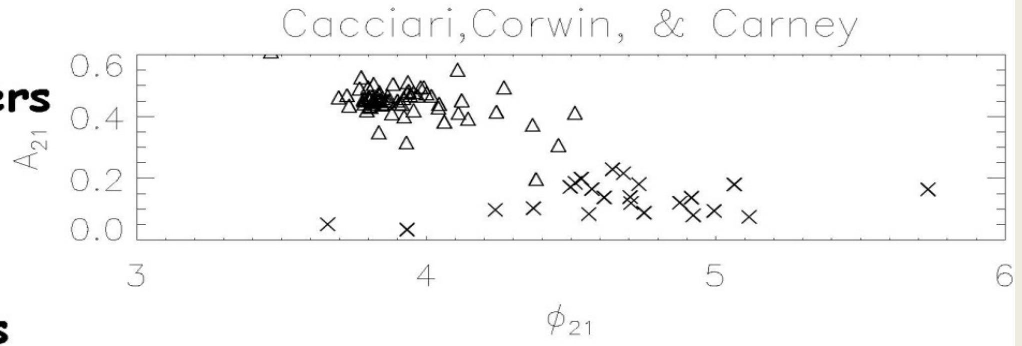
Pulsating variables from Hipparcos to Gaia

	Hipparcos	Gaia
Cepheids	273 (2 new) ~ 100 with $\sigma_\pi < 1$ mas P : 2 to 36 days	Census of galactic Cepheids with G ≤ 20 ~ 9000 Cepheids (*) All periods, colours and metallicity Up to 5-8 kpc with $\sigma_\pi/\pi < 1\%$ All galactic with $\sigma_\pi/\pi < 10\%$
Pop II Cepheids	~ 30	~ 2000
in LMC	none	1000-2000 Cepheids with $\sigma_\pi/\pi \sim$ 80-100 % Mean distance expected to 7-8 % (**)
RR Lyrae	186 (9 new) only RR Lyr with good π	All galactic RR Lyrae: 70000 (***) All metallicity Up to 1.5 kpc with $\sigma_\pi/\pi < 1\%$, $\sigma_\pi/\pi < 10\%$ In globular clusters: mean $\sigma_\pi/\pi < 1\%$

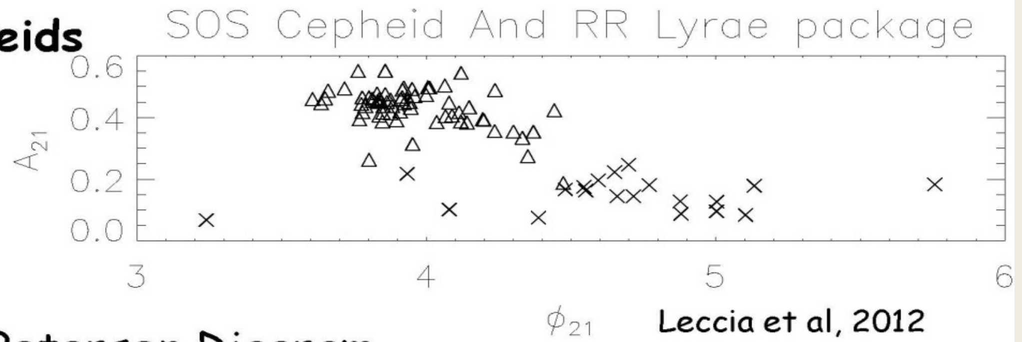
Windmark et al. 2011 (*) (**) Clementini 2010 (***) Eyer & Cuypers 2000

Example 1:Cepheid/RR Lyrae (Clementini,Bologna)

1. **Determine the Fourier parameters**



2. **Identify Blazhko RR Lyrae stars and double mode RR Lyrae/Cepheids**



Leccia et al, 2012

3. **Identify pulsation mode**

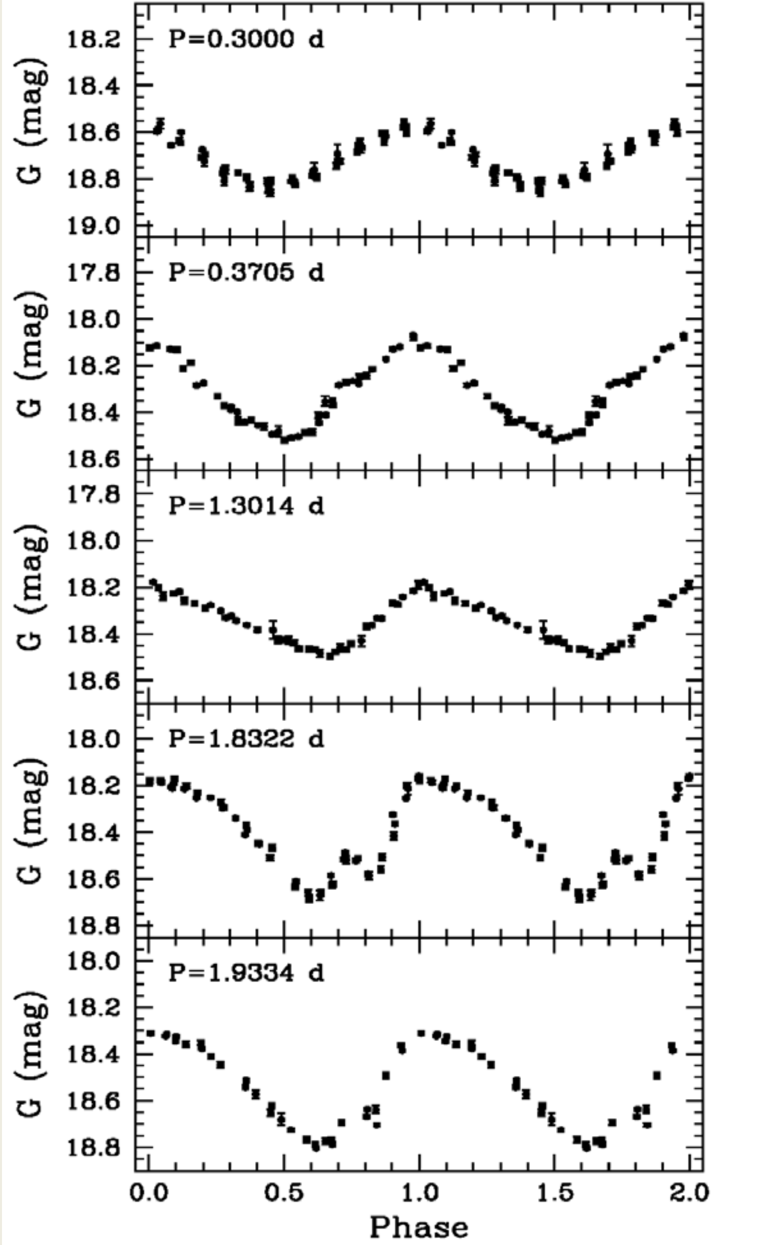
4. **Determine stellar parameters**

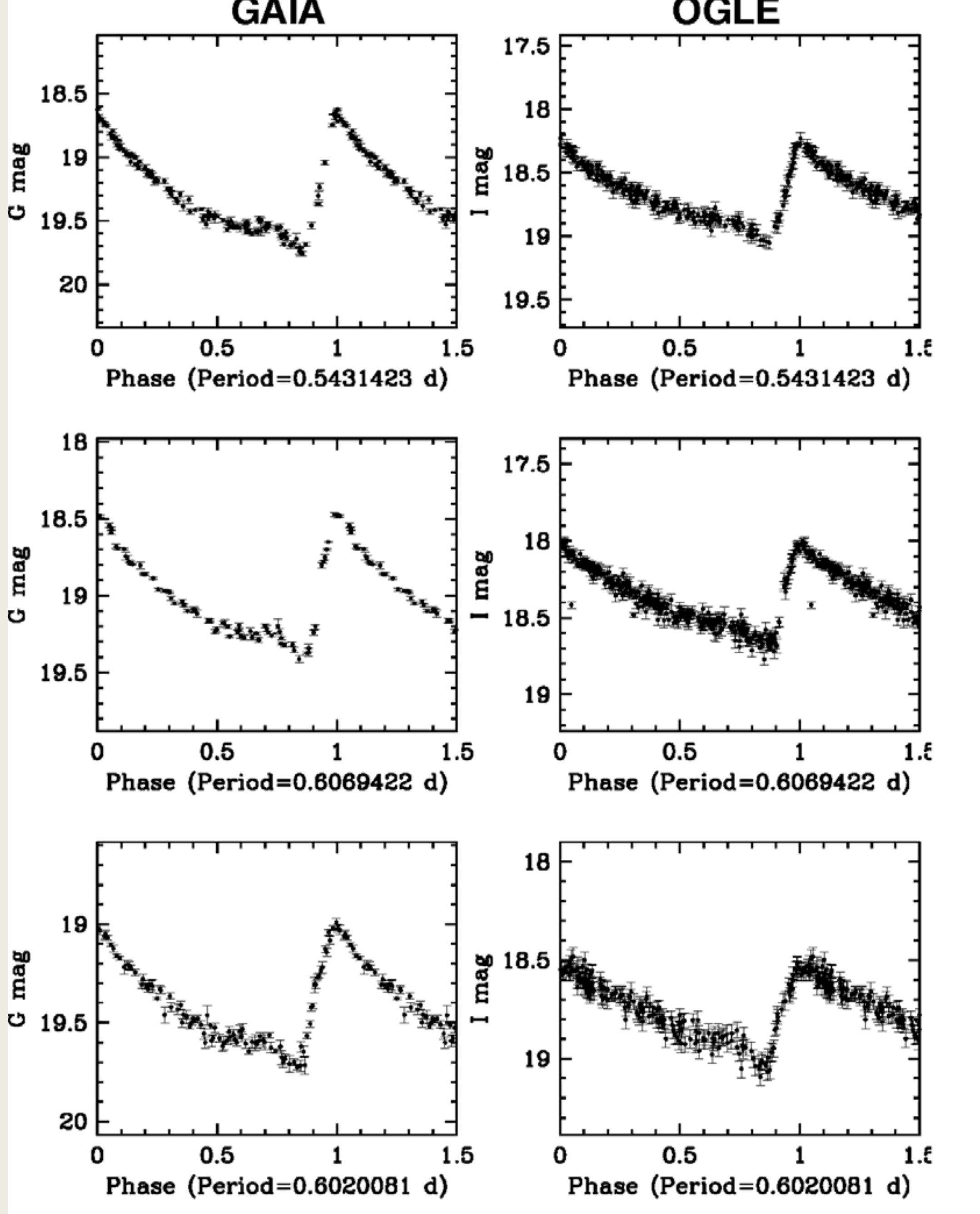
Petersen Diagram

Baade-Wesselink analysis

5. **Identify binarity**

6. **Determine period changes**





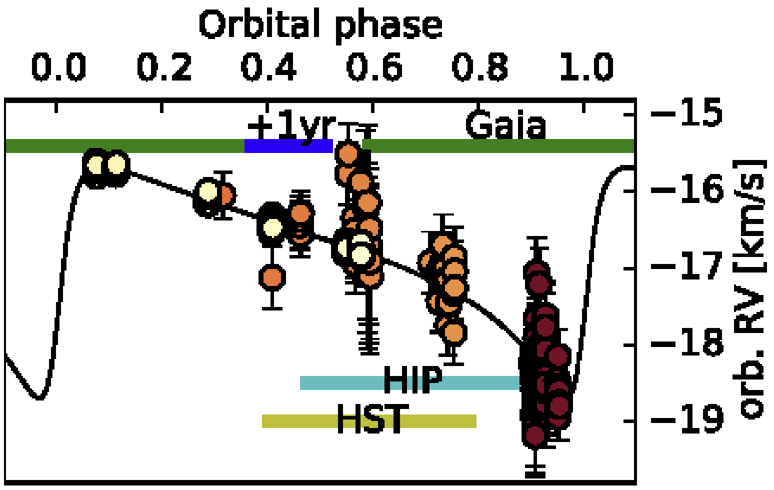
Classical overtone Cepheid
3 candidate anomalous Cepheids
Type 2 Cepheid

CEPHEIDS

There are ~12 Cepheids with $G < 6$ → distances relevant for cosmic distance scale (e.g. Benedict et al. 2007)

Example: δ Cep (HIP 110991) $G = 3.9$

Discovered to be spectroscopic binary with precision radial velocities (P = 2200 d, ecc = 0.67, a_rel = 5.8 AU, $M_1 \sim 5\ M_{Sun}$ $M_2 \sim 0.2\ M_{Sun}$)



Anderson, Sahlmann, Holl, et al. 2015, ApJ, 804

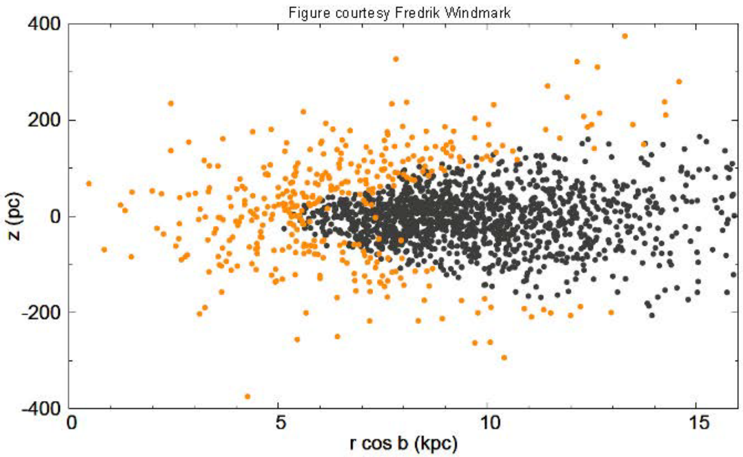
Minimum astrometric orbit size: $a_1 \sin i = 0.84$ mas

Gaia will observe δ Cep about 90 times over 5 years

→ Gaia will detect the the astrometric orbit detection with high signal-to-noise

→ accurate parallax determination

Galactic Cepheids



Cepheids in the inner Galaxy, with -5° < l < 5°

- Observable by Gaia
- Too faint for Gaia

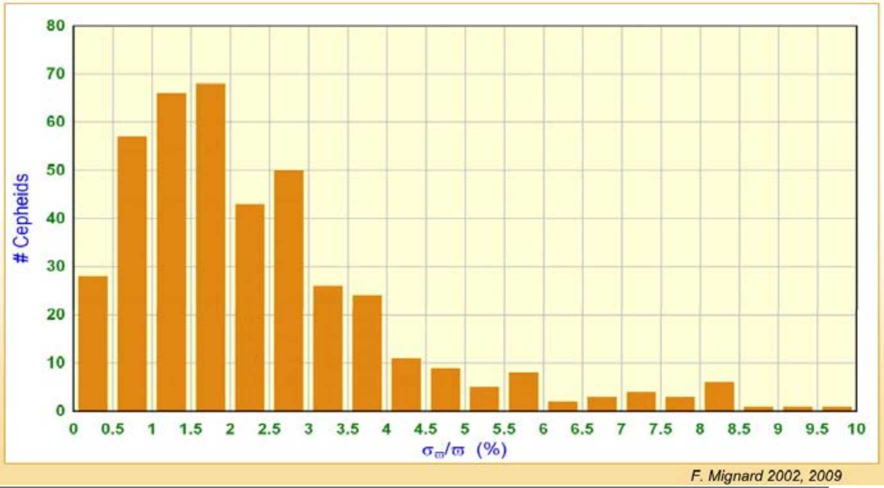
- Gaia will observe ~9,000 Galactic Cepheids (2011arXiv1104.2348W)
- Hundreds are visible near and behind the Galactic centre
- Beyond 5 kpc, all Cepheids are observed outside the plane

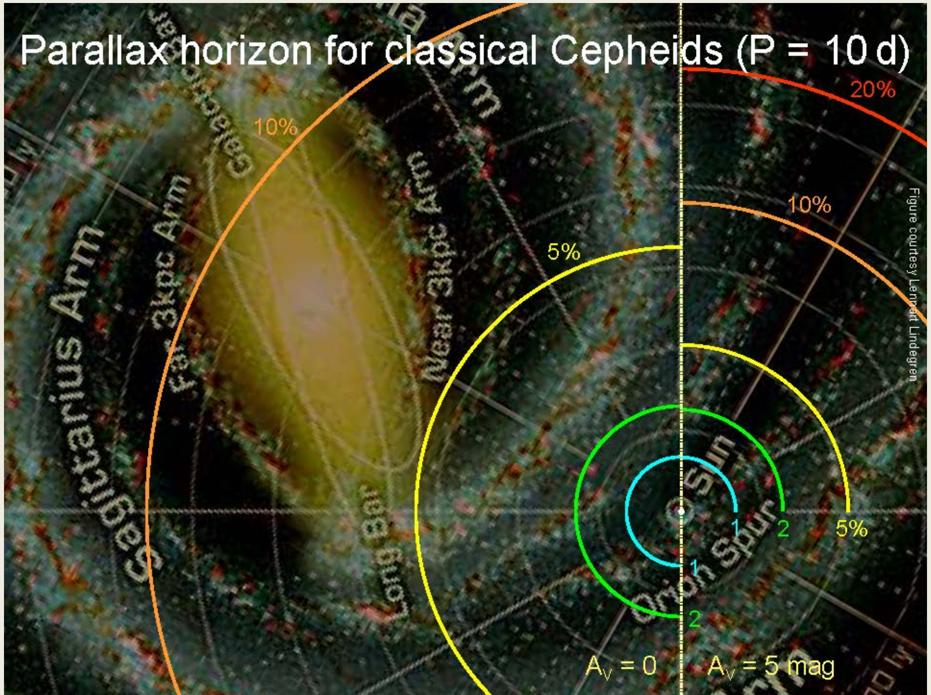
15 d < 0.5 kpc, 65 d< 1 kpc, 165 d < 2 kpc

- bright enough (V < 14)

In the plot : 400 galactic cepheids from David Dunlap DB

- distance and magnitude → Gaia predicted accuracy for parallax





Galactic		273	Hipparcos 1997
	Known	509	Fernie et al. 1995
		455	Berdnikov et al 2000
		872	ASAS catalogue, as in 2011 Pojmanski
	Estimated for Gaia	**2,000-8,000**	**Eyer & Cuypers (2000)**
		9,000	**Windmark (2011)**

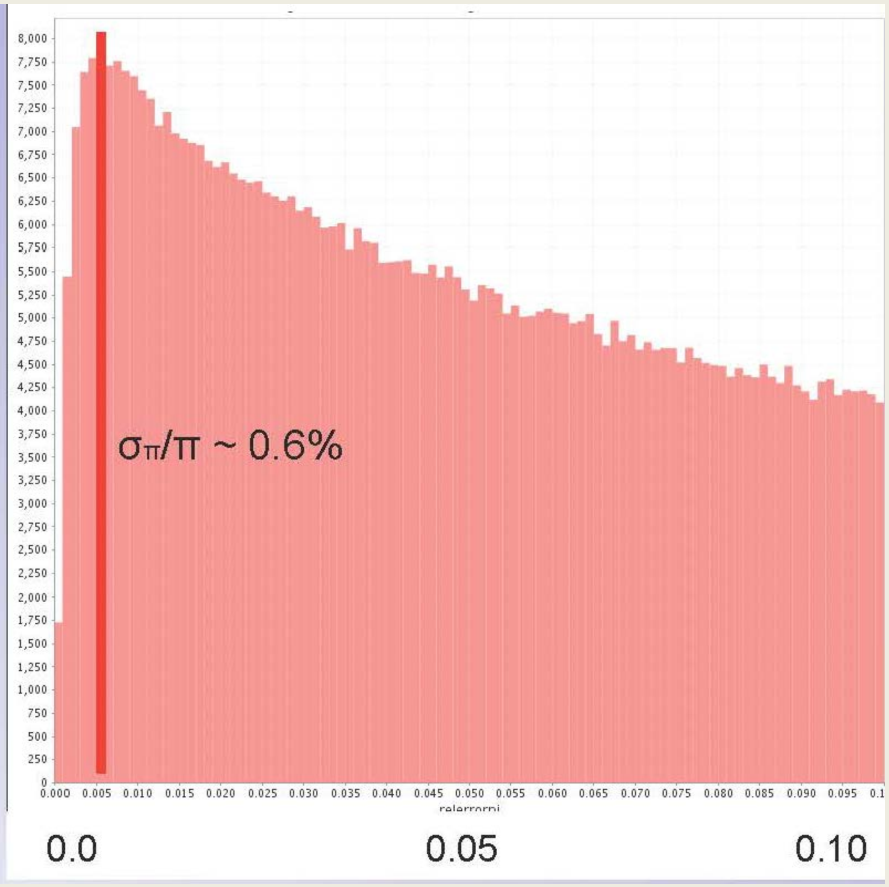
optimist: Gaia will multiply by 10 the Galactic Cepheid number

LMC	Known	3,361	OGLE-III, Soszynski et al 2008-2010
SMC		4,630	

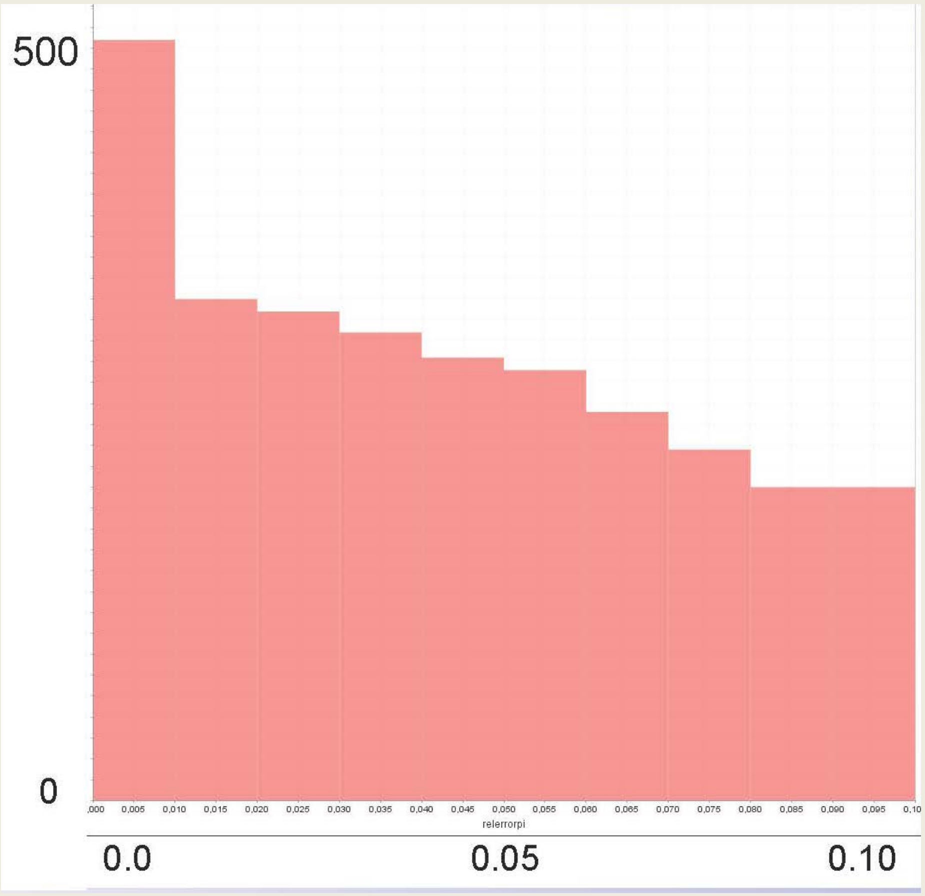
Astrometry distance accuracy DF simulated

P-L relation will be known to an accuracy < 0.01mag.
Gaia's Cepheid calibration will be limited by extinction uncertainties
- and the astrophysical variance we haven't noticed yet

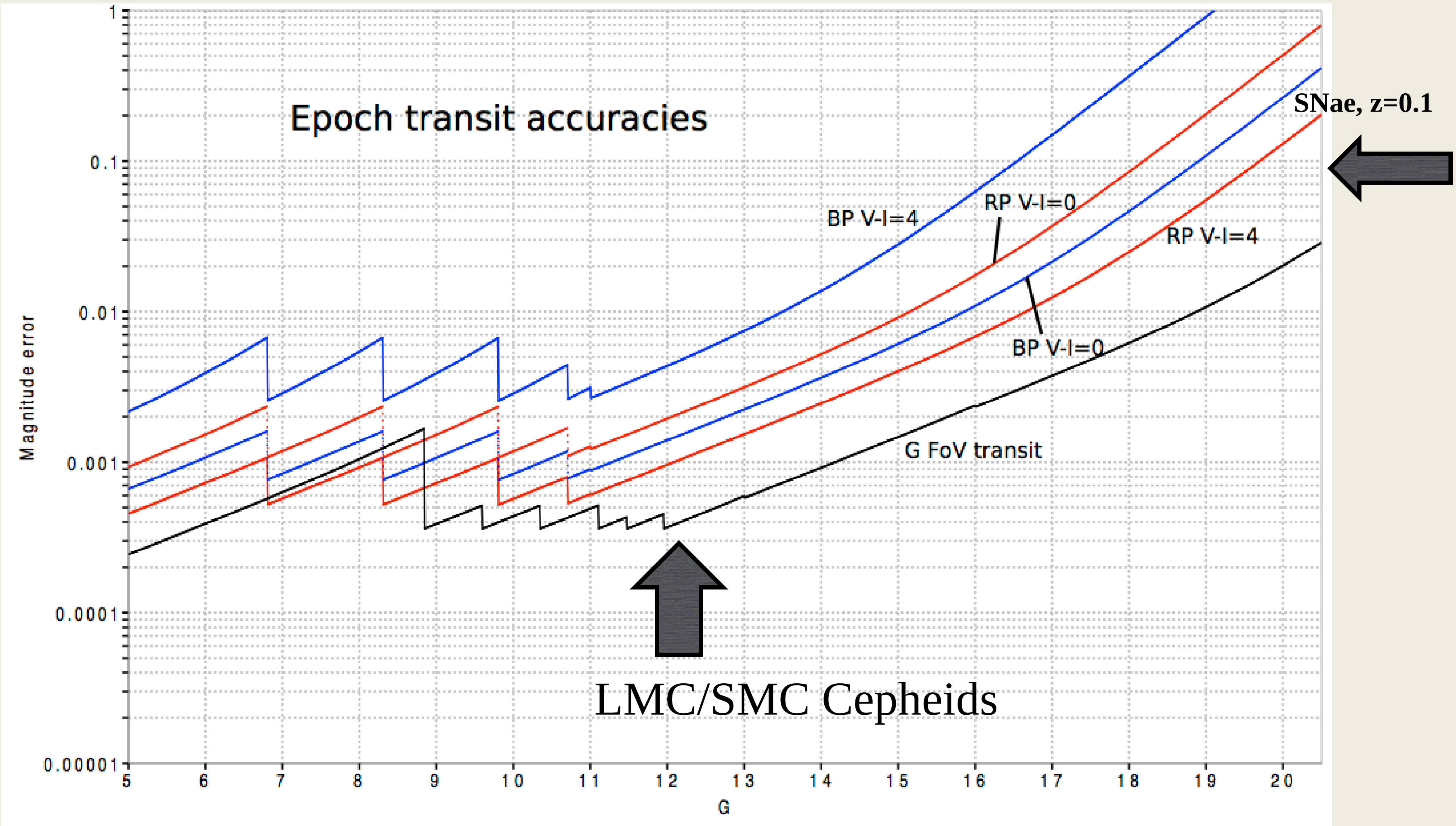
All stars

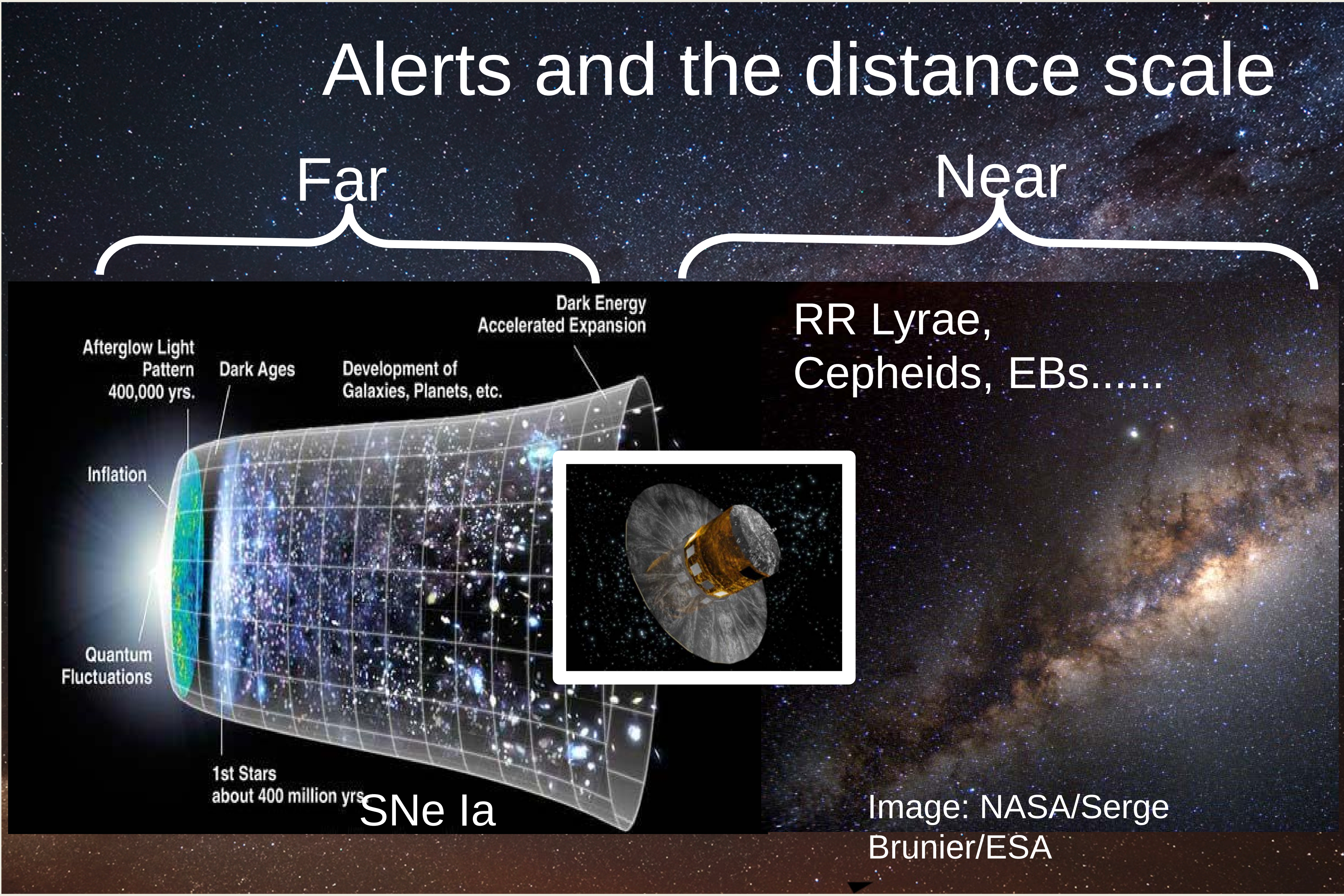


Cepheids



Precision Photometry





Serge Brunier

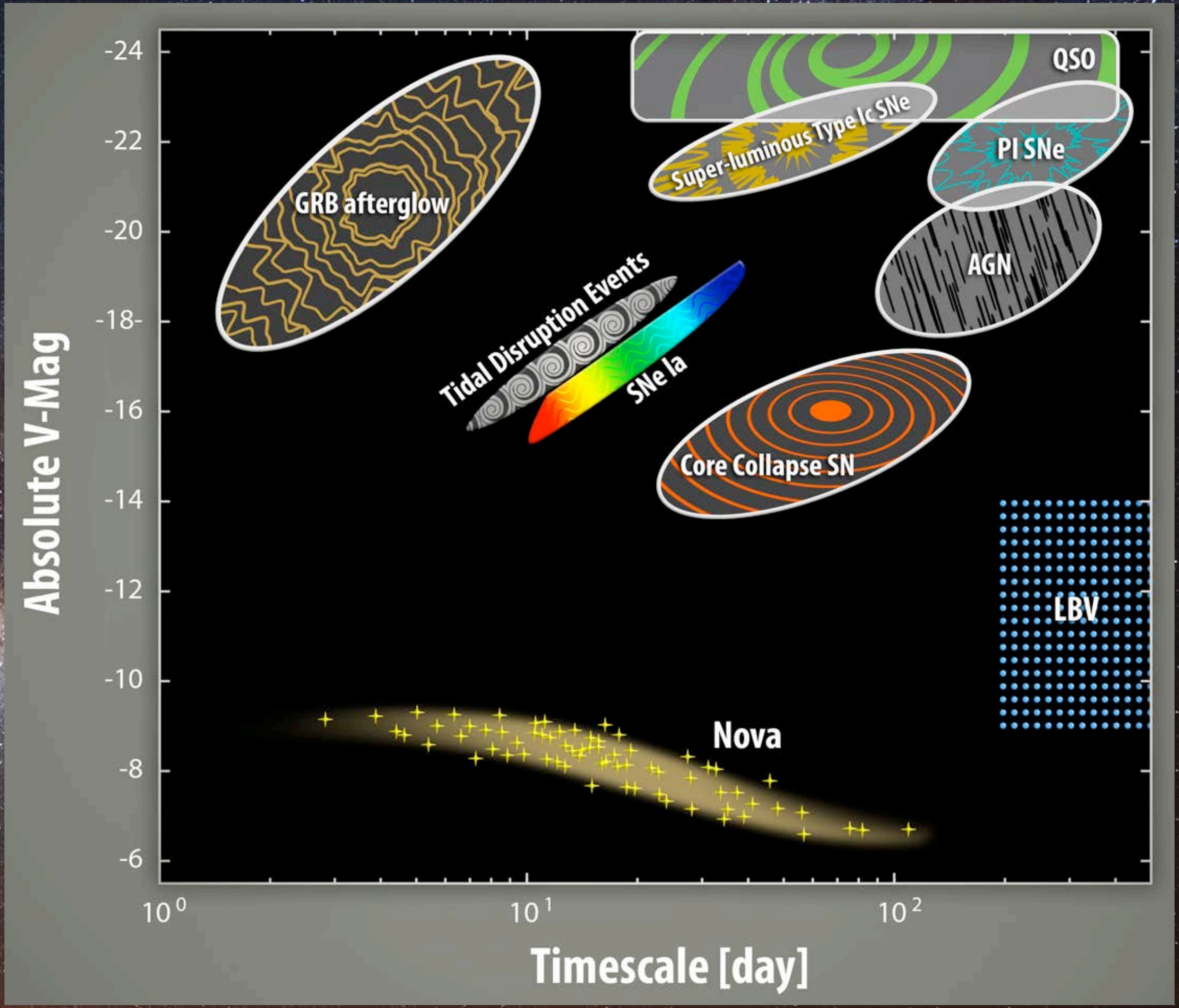
What alerts?

We want to find:

Extragalactic (SNe, AGN flares, TDEs, GRB afterglows...)

Galactic (CVs, M-star flares, Fuor's, W UMa's, microlensing, LMXBs...)

The unknown...



Publishing Alerts

There are opportunities for you to be involved with Gaia data now

Science Alerts Follow-up through Gaia-FUN-TO
http://gsaweb.ast.cam.ac.uk/followup

+ valuable outreach potential

Gaia in the UK

Search

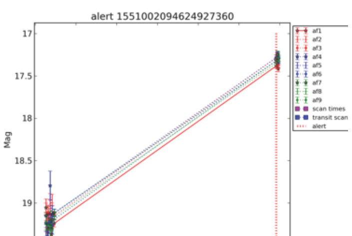
…edia Blog Contact

…C …estamp	RA	Dec	AlertMag	HistMag	HistStdDev	Class	Comment
14-09- …:32:01	208.40506	34.82615	18.73	19.68	0.05	unknown	blue star, now faded, ROSAT source within error, CV?
14-11- …:47:20	211.56593	36.38459	18.96	Not known	Not known	unknown	blue in BP/RP; 5 arcsec from SDSS galaxy z=0.105
14-10- …:01:38	10.16959	-28.95650	18.41	19.63	0.06	unknown	Galaxy (2dFGRS TGS287Z263), small offset?
14-10- …:30:00	240.01542	33.18725	15.24	20.20	0.02	CV	Known Dwarf Nova: VW CrB (Blue SDSS star r=19.9, very blue in BP/RP)
14-10- …:35:31	37.28835	-32.96673	17.61	18.39	0.04	unknown	
14-10- …:06:23	182.44766	29.73023	18.40	18.97	0.03	unknown	very blue SDSS star at r=19.2
14-10- …:49:49	202.47026	31.90307	18.23	19.18	0.08	unknown	SDSS star at r=20
14-10- …:00:00	185.09378	28.41434	18.43	Not known	Not known	SN II	offset from SDSS galaxy;last non-det 2014-07-31;blue BPRP spectrum
14-10- …:34:25	57.51597	17.06699	19.22	19.95	0.10	unknown	
14-10- …:24:57	59.71412	14.18758	18.26	19.04	0.08	unknown	
14-10- …:38:02	59.52069	14.54791	17.70	18.34	0.06	unknown	

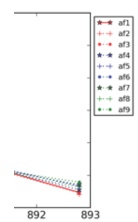
…AM CVn: *Gaia14aae* 3

…tions of Gaia14aae used in this work.

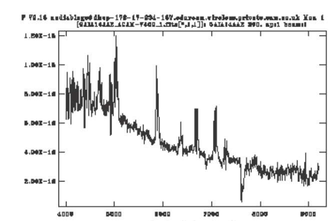
	…date (UT)	Filter	Exposures (s)
	…4 08 11	*G*	45
	…2 - 2015	*V*	129×180
Loiano 1.5m Cassini	2014 10 24	*g*	3×300, 91×30
Telescope + BFOSC	2014 10 25	*g*	135×30
Bialkow 0.6m, Poland	2014 10 18	*BV*	30×120
	2014 10 19	*BV*	37×120
CIECEM 0.35m, Spain	2014 10 21 to 2014 11 18	clear	40×180, 8×150 111×120, 399×90
pt5m, La Palma	2014 10 25	*V*	61×60
	2014 10 22	*V*	36×60, 21×120
0.6m ASV, Serbia	2014 10 21	*BVRI*	6×300
Belogradchik AO 0.6m, Bulgaria	2014 10 21	*BVR*	2× 300
Asiago 1.82m Copernico	2014 12 11	*r*	169×20
	2014 12 12	*g*	169×20
4.2m WHT+ACAM	2014 12 18	*V*	491×5
Mercator	2015 01 15	*g r+i*	232×30
Catalina (*historic*)	2005 - 2014	clear	107×30
Pan-STARRS1 (*historic*)	2010 - 2014	*grizy*	66×30



…e 3rd known eclipsing …didate Ia progenitor)



…in Gaia, also seen in ASAS



WHT follow up sees strong Helium lines - AM CVn classification

Supernova discovery statistics for 2015

These are supernova stastics for the year 2015. If there are other statistics you are interested in, please let me know.
Page re-generated at: 2015/06/22.522 UT

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787 objects were discovered by PS1 (prof)
153 objects were discovered by CRTS (prof)
113 objects were discovered by Gaia Photometric Science Alerts programme (prof)
 86 objects were discovered by All Sky Automated Survey for SuperNovae (ASAS-SN) (prof)
 81 objects were discovered by OGLE-IV wide field survey (prof)
 64 objects were discovered by DECam (prof)
 56 objects were discovered by PTF (prof)
 50 objects were discovered by Subaru/Hyper Suprime-Cam (prof)
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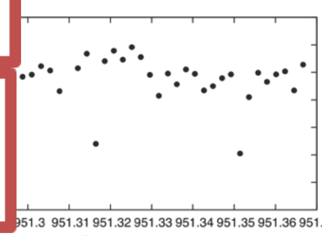
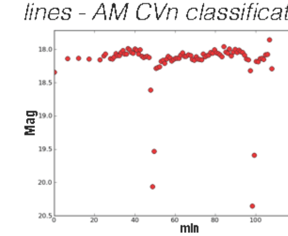


Amateurs follow up and see eclipses!



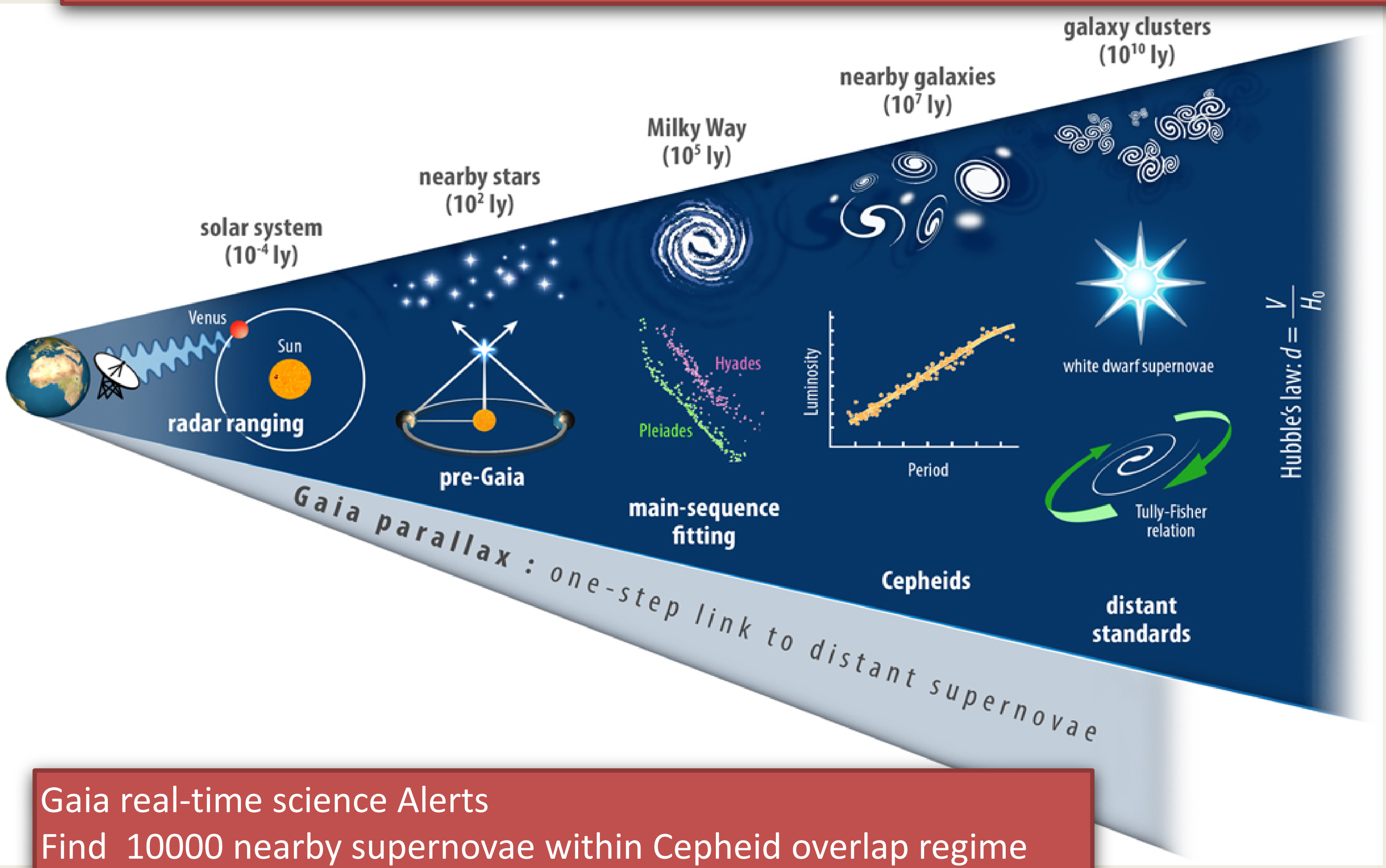
Loiano Telescope follow-up confirms Period is ~50 mins

SN Ia

Precision Cosmology with Gaia

All distance indicators will have precision calibrations

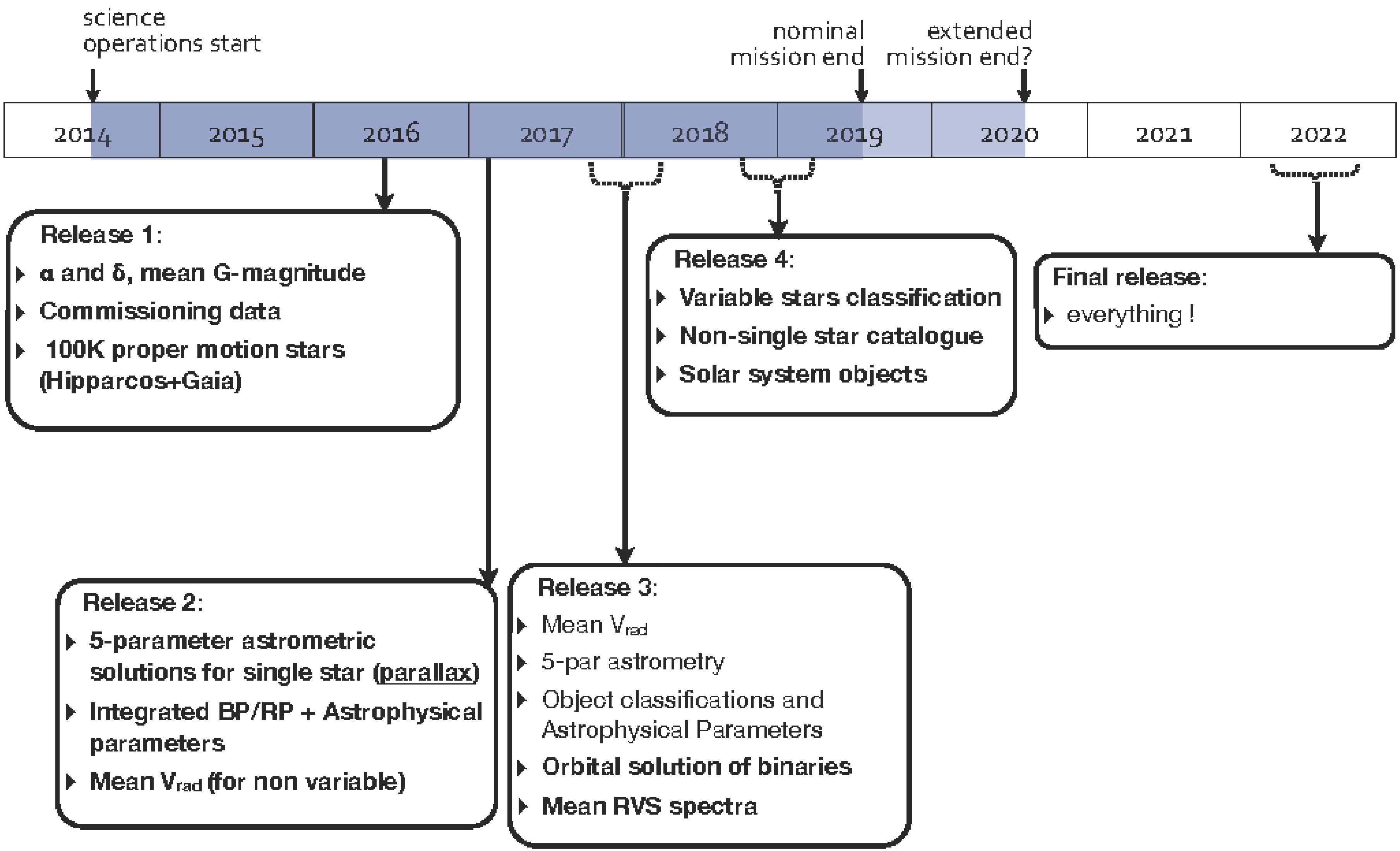
Precision calibration from parallaxes of 9000 local Cepheids



Gaia real-time science Alerts

Find 10000 nearby supernovae within Cepheid overlap regime

Release scenario



a few Gaia numbers

- One billion stars = 1% of the Milky Way's stars
- One billion pixel camera
- Total project cost 960Meuro
- Project lifetime: 1993 – 2023
- Accuracy – 10microarcsec = 10^{-10} rad: = thickness of a human hair at 1000km
- Einstein light bending at the Sun's edge is 1750000microarcsec
- Must know Gaia's location within 150m: it is about 1.5Mkm away
- Gaia will travel about 16Mkm over 5 years
- Satellite global timing network extended to picosecs for Gaia
- In one picosec light travels 0.3mm
- Satellite communications link is 300W, total power use 1276W
- 100Tb raw data collected at May 17, 25 billion transits
- 2 telescopes, 35m focal length, rectangular mirrors
- 3.5M hours of work to study, design & build = 300people x 7 years
- 400 scientists working on data processing
- Over 30,000 mission documents in archive
- Launch burned 225 tonnes of kerosene+oxygen in 5 minutes
- In orbit micro-propulsion system ejects 1 microgram of nitrogen per thrust
- Gaia measures 40 million stars per day on average
- 10^13 individual position measurements; 10^10 unknowns, 100's of iterations

PLUS: 1million galaxies; 500,000 QSOs; 10,000 Supernovae – in real-time; 250,000 asteroids; 15,000 extra-solar planets; 200,000 white dwarfs; 50,000 brown dwarfs, the new, ...