La Scala delle Distanze

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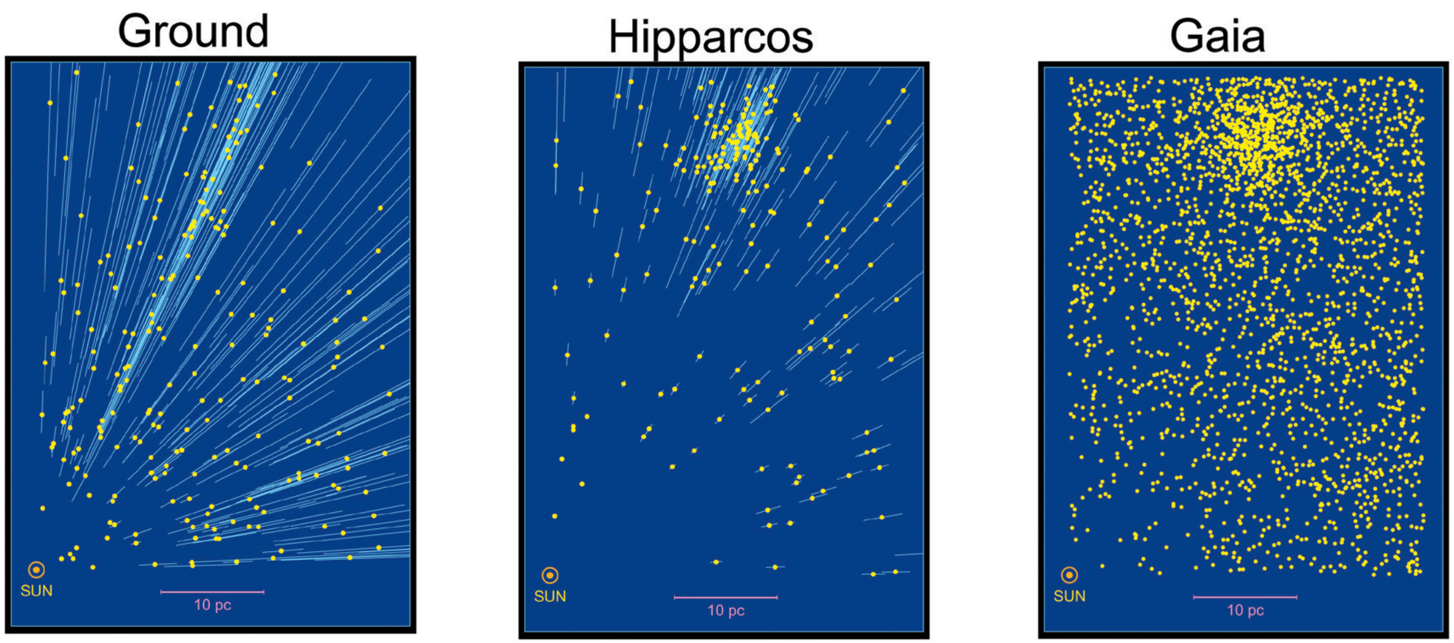


"L'Italia in Gaia", INAF – Roma, Sala Cimino, 14 Febbraio 2013

The Hubble Law

" In standard big bang cosmology the universe expands uniformly; and locally, according to the Hubble law,

$$v = Ho \times d$$

where *v* is the recession velocity of a galaxy at a distance *d*, and *Ho* is the Hubble constant, the expansion rate at the current epoch."

Freedman et al. 2001, Ap.J. 533, 47

"The uncertainty on the distance is the major contribution to the error budget on *Ho*"

The GREAT ITN

WP6: Grand Challenges – Distance Scale & Transient Sky

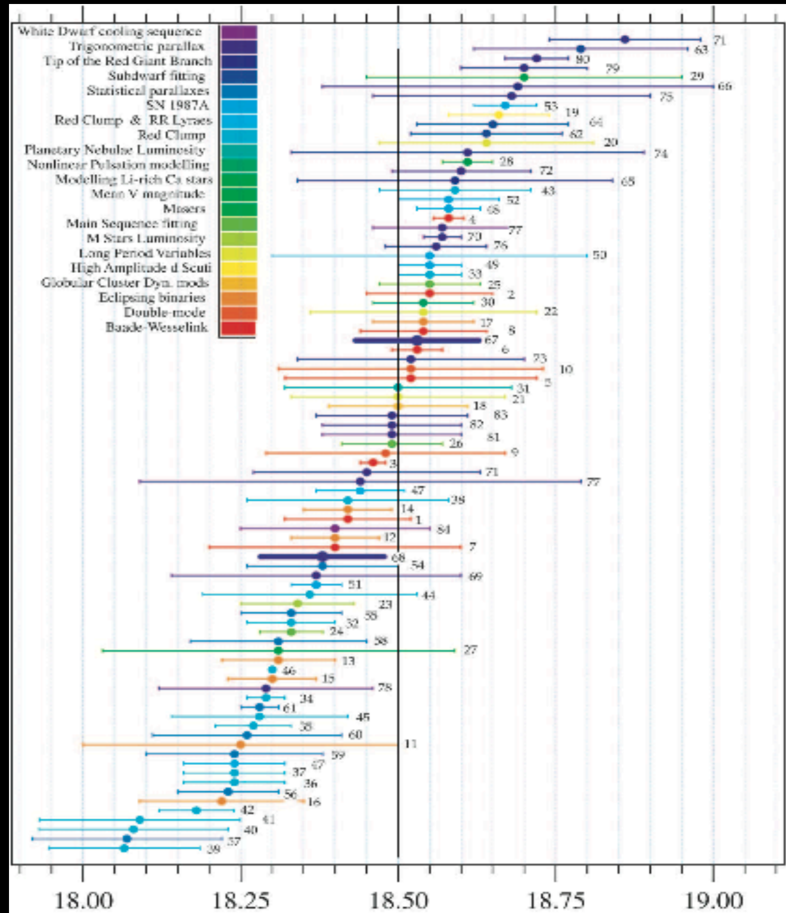
Gaia's primary mission is obtaining distances to objects in the local Universe. At the same time, due to its frequent repeated observations of the sky, where each object will be observed on average nearly one hundred times, Gaia will also have a significant impact revealing the transient sky.

Task 6A: The Distance scale

The Gaia satellite will have a dramatic impact on the definition of the cosmic distance scale (DS), providing the direct measure via parallaxes of the local primary distance indicators and, in turn, a direct re-calibration of the secondary distance indicators. This will significantly improve our knowledge of the Hubble constant. At the same time Gaia will offer a unique opportunity to assess the systematics affecting the various indicators contributing to the cosmic DS as well as to establish new standard candles.

Distance to the Large Magellanic Cloud (LMC)

The LMC is the First Step of the cosmological distance ladder

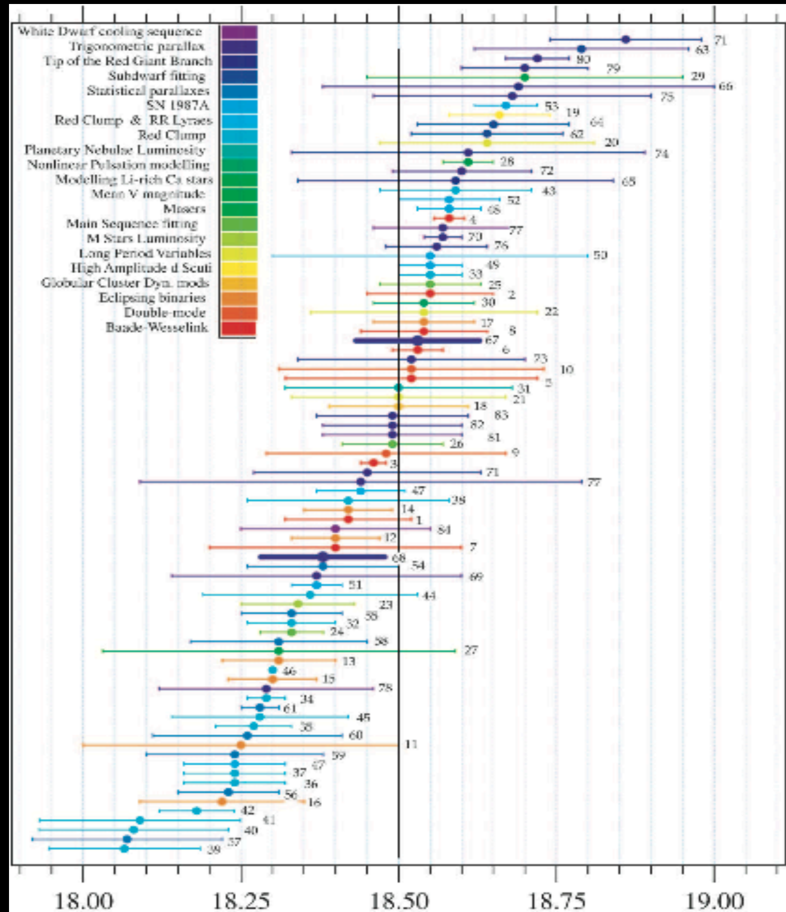


The distance modulus of the Large Magellanic Cloud as derived from different techniques (Benedict et al. 2002)

Distance to the Large Magellanic Cloud (LMC)

The LMC is the first step of the cosmological distance ladder

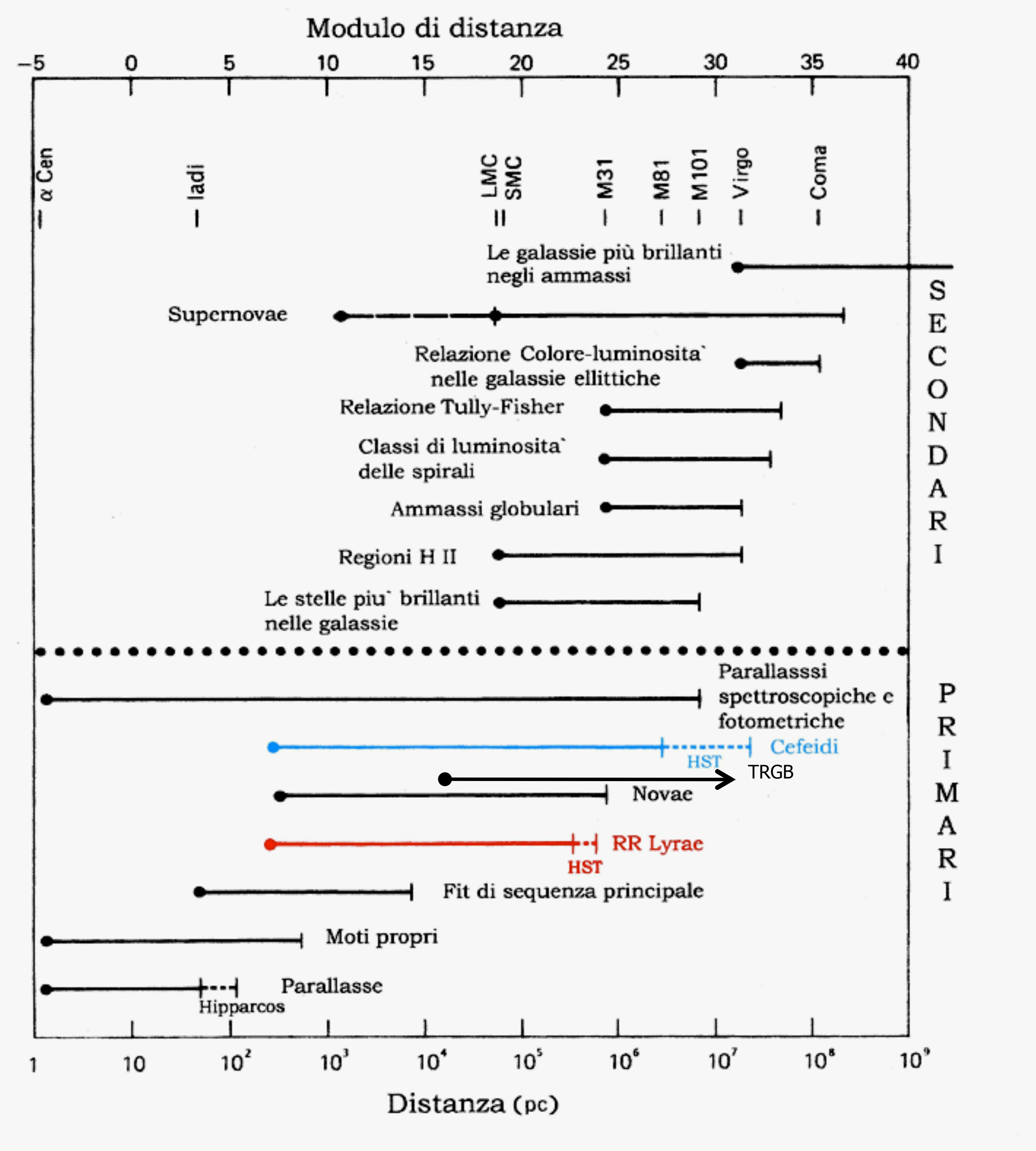
Scala Rotta – Paolo Quaresima – Olio su tela



The distance modulus of the Large Magellanic Cloud as derived from different techniques (Benedict et al. 2002)

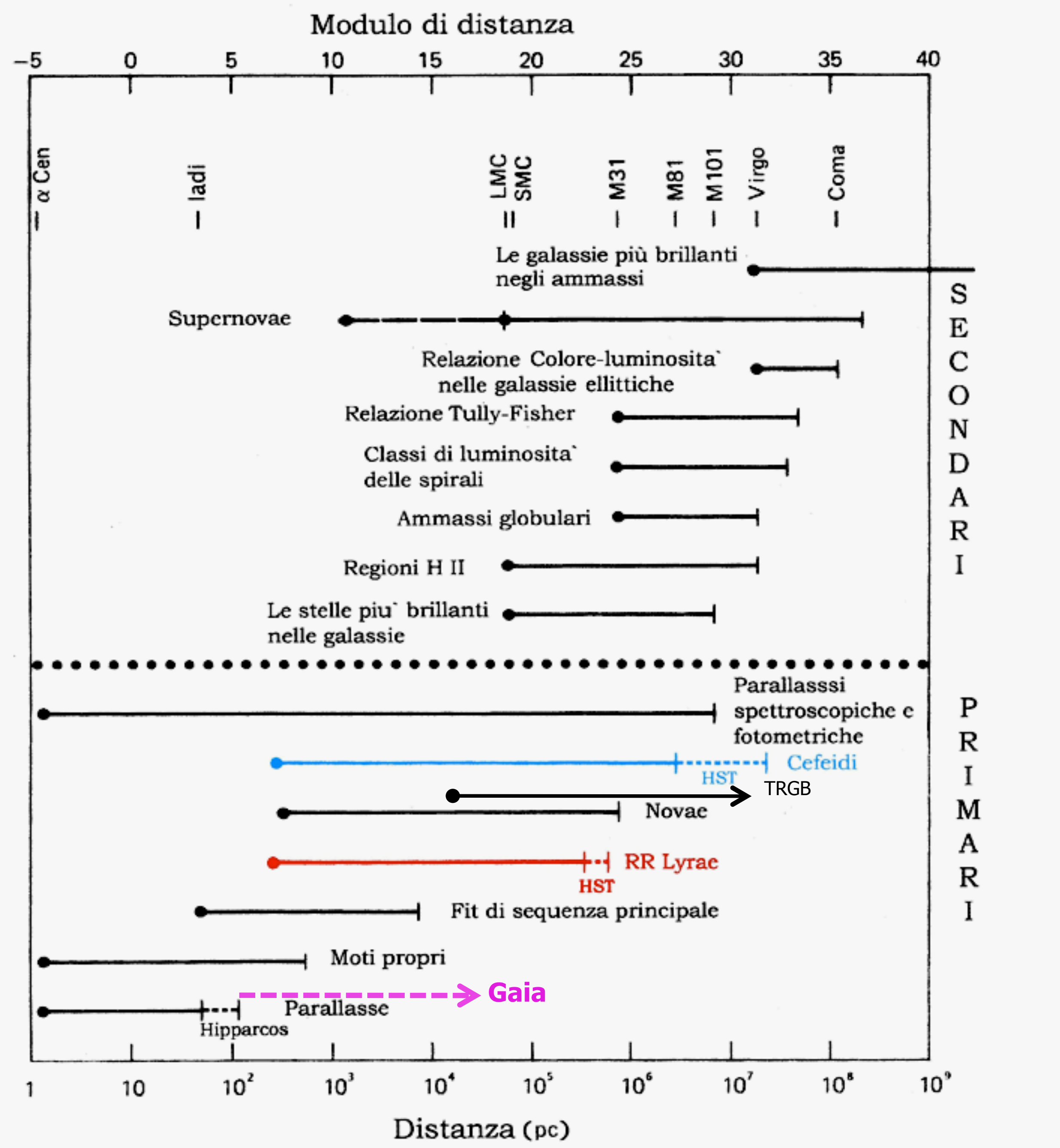
Distance Ladder

"Given the range spanned by the astronomical distances, the astronomical distance ladder is made by overlapping techniques and distance indicators, starting from the most closeby **that we can calibrate directly.** These are the so-called **standard candles**"



Distance Ladder

Gaia will provide **trigonometric parallaxes**, hence geometric distances to unprecedented accuracy **of most powerful "primary" distance indicators**, thus allowing a reassessment of the entire cosmic distance ladder.



Requirements for a standard candle

Aaronson & Mould (1986) requirements:

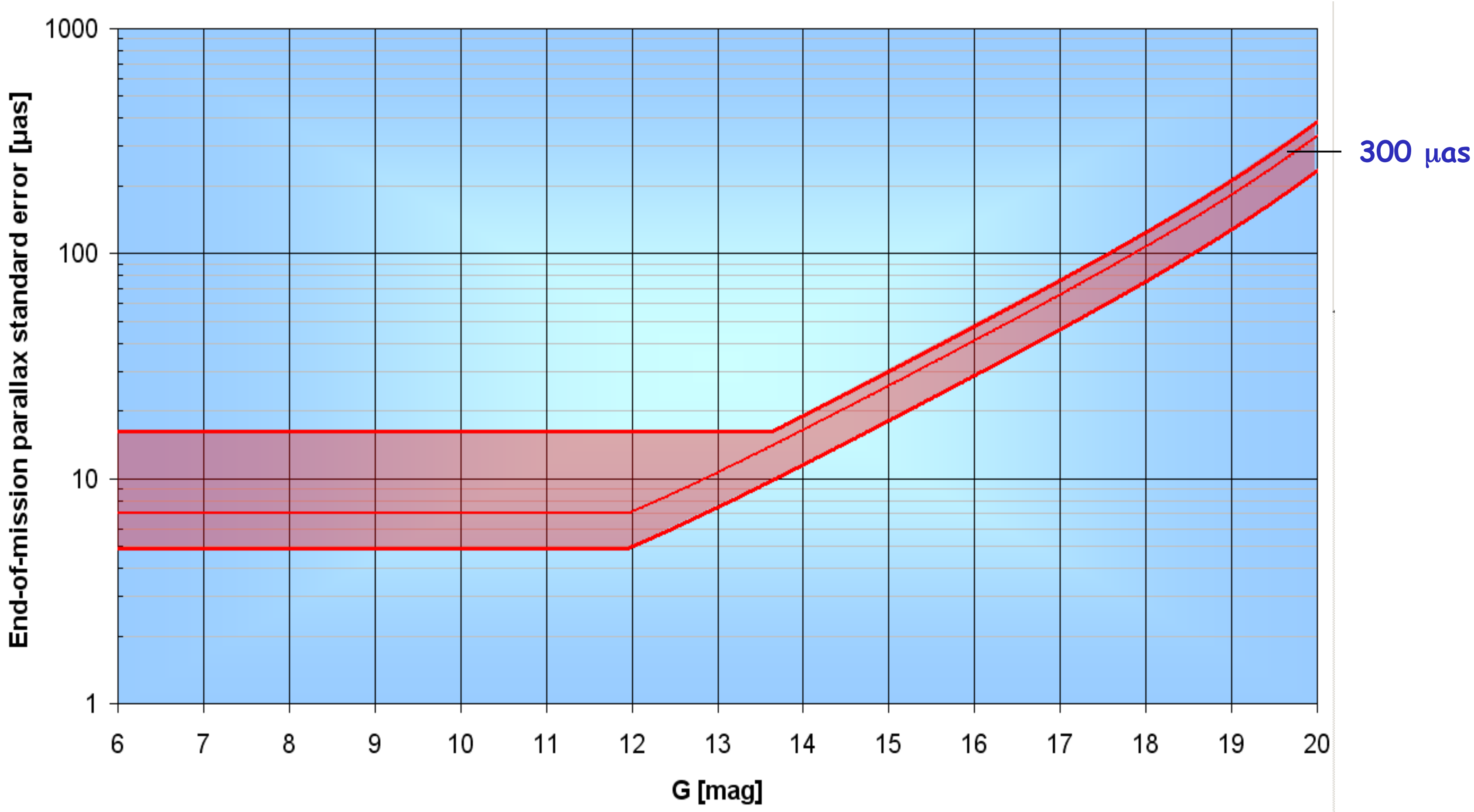
- ❑ numerous and easily recognizable objects
- ❑ objective measurables (e.g. stellar magnitudes)
- ❑ luminosity based on well known physics
- ❑ high intrinsic luminosity
- ❑ small luminosity range
- ❑ minimal corrections

Standard candles that Gaia will impact significantly

- ❑ metal poor subdwarfs
- ❑ RR Lyrae stars
- ❑ Long Period Variables (LPVs)
- ❑ Cepheids
- ❑ Type Ia SNe (alerts: ~6000 new SNe, ~ 85% type Ia)

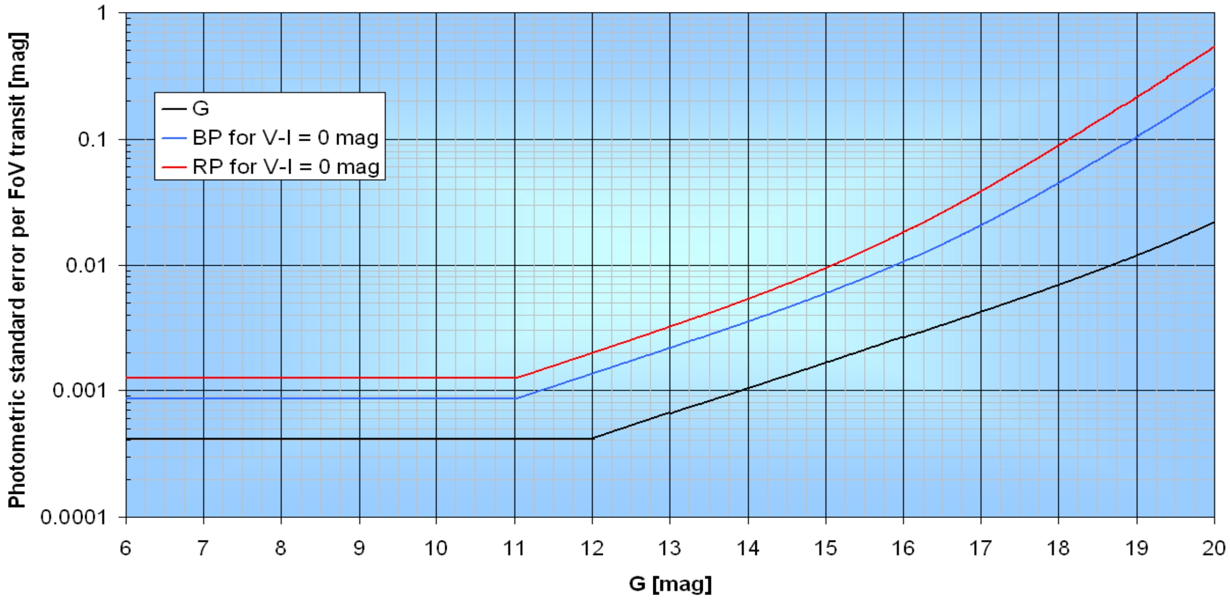
Gaia performance: astrometry

Sky average end-of-mission performance (mean of 70 parallax measures)
Error on pm is about 0.54 error on parallax



Gaia performance: integrated photometry

Sky average single transit



G: 330-1050 nm

BP: 330-680 nm
(3-27 nm/px)

RP: 640-1050 nm
(7-15 nm/px)

Internal eom B1V-G2V-M6V at	σG	σBP (mmag)	σRP
V ≤ 16	≤1	4-5-9	5-5-4
V = 19	2	13-18-120	34-18-8
V = 20	3	29-43-301	83-43-17

External accuracy depends on:

- ➔ number & spectral type of SPSS (CalSpec, Gaia grid)
- ➔ accuracy of SPSS SEDs
- ➔ specific spectral range for BP/RP spectra

Expected absolute accuracy: ~ 1% to a few %

Local standard candles

Metal-poor field subdwarfs M_V= +5.0 to +7.5 mag

Presently, ~ 30 subdwarfs available (Hipparcos) within 100 pc

Gaia: within 1 kpc distance to σ_π/π < 2–6 %
a factor 10 (1000) in distance (volume) ➔ several thousands expected

Pulsating variables with Gaia

	Hipparcos	Gaia
Classical Galactic Cepheids	273 observed (2 new) P: 2 to 36 days ~ 100 with $\sigma_\pi < 1$ mas	Census of galactic Cepheids with $G \leqslant 20$: ~ 9000 Cepheids All periods, colours and metallicities Up to 1-2 kpc with $\sigma_\pi/\pi < 1\,\%$ All galactic Cepheids with $\sigma_\pi/\pi < 10\,\%$ Cluster membership
Population II Cepheids	~ 30	~ 2000
LMC Cepheids	None	1000-2000 Cepheids with $\sigma_\pi/\pi \sim 50 - 100\,\%$ Mean distance of groups of Cepheids expected to 10 % Mean distance of LMC expected to 0.5 % Depth of LMC expected to 1 %
RR Lyrae	186 observed (9 new) Only RR Lyr with accurate π 126 with $\sigma_\pi/\pi \sim 30\,\%$	All galactic RR Lyrae: $\sim 70\,000$ **+15000-40000 in the Bulge** All metallicities Up to 1 kpc with $\sigma_\pi/\pi < 1\,\%$ In globular clusters: mean $\sigma_\pi/\pi < 1\,\%$
All pulsating variables		Extensive surveys of all types of variables Astrometry, photometry and spectroscopy Extensive sampling versus period, colour, metallicity Determination of the zero-points and slopes the P-L(-C) relations Determination of the intrinsic dispersion of the P-L(-C) relations Cluster membership

adapted from Turon & Luri review at the Distance Scale ESF Conference, Naples, May 2011

Cepheids and RR Lyrae stars

- Easily recognizable thanks to the light variations
- Periods and amplitudes unaffected by distance and reddening, and related to Mass, Luminosity, Teff (Y,Z) $\Rightarrow$ constraints on intrinsic stellar parameters
- Trace populations with different age and chemical composition:
  - t <100 Myr - Classical Cepheids
  - t~1-5 Gyr -Anomalous Cepheids
  - t >10 Gyr (RR Lyrae, Type II Cepheids)
- Most important standard candle in the Local Group (RR Lyrae stars, M_V-[Fe/H], PL_KZ) and beyond, up to 20 Mpc (Cepheids, PL, PLC, Weseneiht) $\Rightarrow$ calibration of secondary indicators $\Rightarrow$ measure of H_0

Cepheids and RR Lyrae stars : open issues

Cepheids:
PL,PLC, Wesenheit relations (optical/NIR)

- Coeficients of the relations
- Dependence of the Cepheid's properties and PL on the chemical composition
- Linearity of the PL relation
- Binarity/reddening/pulsation mode
- Discrepancy pulsational/ evolutionary mass

⇒ error on H_0 > 4-5 % ???

RR Lyrae stars:
M_V=a[Fe/H]+b
M_K=αlogP+β[Fe/H]+γ

- Slope, zero point, linearity of the M_V-[Fe/H] relation
- Dependence on off-ZAHB evolution, detailed chemical composition (Y, α-elements)
- Zero point and coefficients of the M_K(logP,Z) relation

⇒ error on distances > 10%

for both types of variables moving to the infrared is an advantage

MW field RR Lyrae stars

RR Lyrae Mv= 0.5-0.6 mag

Presently, 126 RR Lyraes with < V > = 10 to 12.5 (750 - 2500 pc)
$\sigma_\pi/\pi \geq 30$ % (Hipparcos) (Fernley et al. 1998)

GEOS database photometry:
- <V> = <p> – 0.15
- <V> = <B> – 0.30 ➔ V mid IS
- <V> = <H> – 0.08

Mv = 0.52 for all (~ [Fe/H]=-1.5 dex)

$\langle V \rangle = (V_{max} + V_{min})/2$

Zero reddening

➔ Individual end-of-mission σ_π/π estimates

~ 5 % (~ 340 RRL)	to	≤ 1%	≤ 1.5 kpc
~ 15 % (~ 1000 RRL)	to	≤ 5%	≤ 4 kpc
~ 26 % (~ 1750 RRL)	to	≤ 10%	≤ 5.7 kpc
~ 43 % (~ 2900 RRL)	to	≤ 20%	≤ 8 kpc
~ 60 % (~ 4000 RRL)	to	≤ 30%	≤ 10 kpc

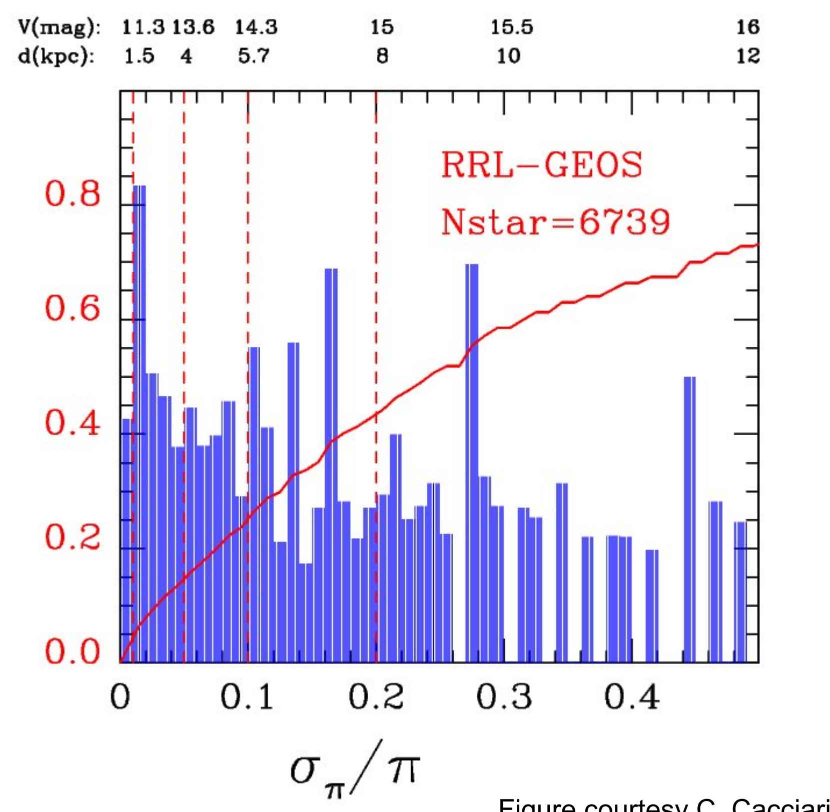
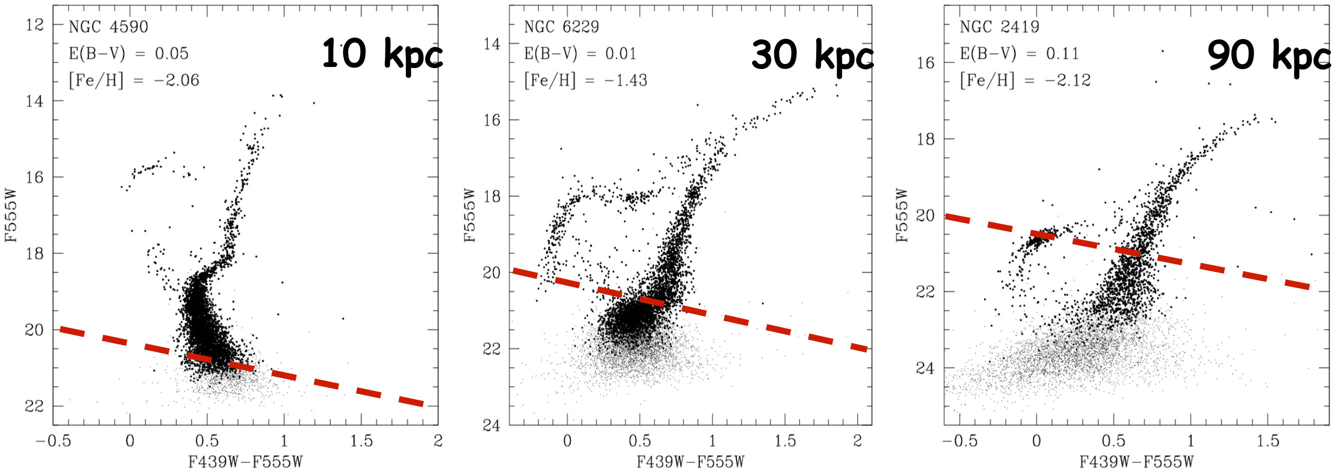


Figure courtesy C. Cacciari

Expected from Gaia
~ 15-40 10³ bulge
~ 70 10³ halo
(Turon & Luri, 2011)

Globular cluster RR Lyrae stars



Piotto et al. (2002)

V(HB), reddening & distance from Harris' Catalogue 2011 update

V(RGB) = V(HB) – 0.5 mag

Cluster σ_π/π from end-of-mission **mean of 1000 RGB** star measures

Reference distance from lowest reddening cluster

~ 49 % (~ 77 GCs) to ≤ 1% ≤ 16 kpc
~ 75 % (~118 GCs) to ≤ 3% ≤ 25 kpc
~ 84 % (~132 GCs) to ≤ 5% ≤ 33 kpc

MW Globular Cluster online Catalogue
Harris (1996) 2011 update

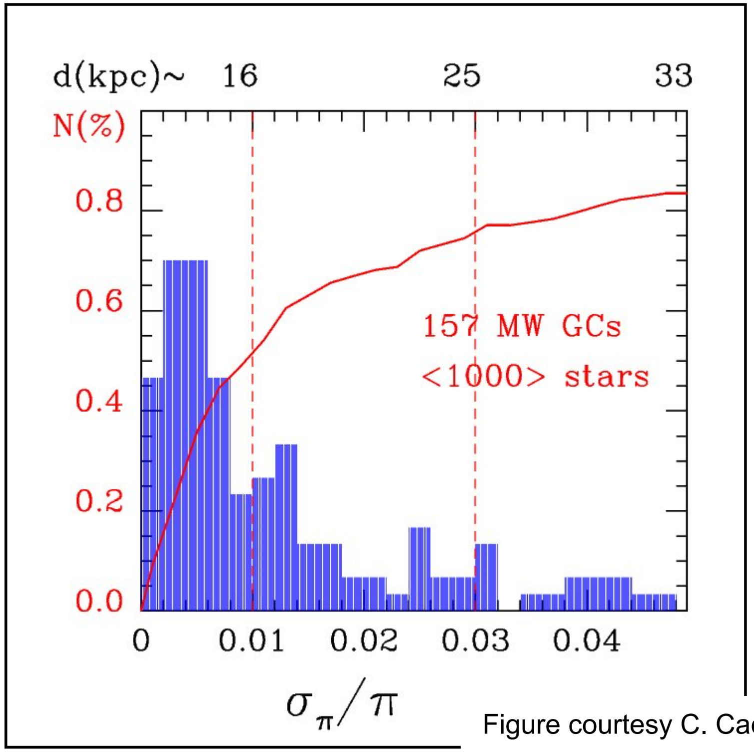
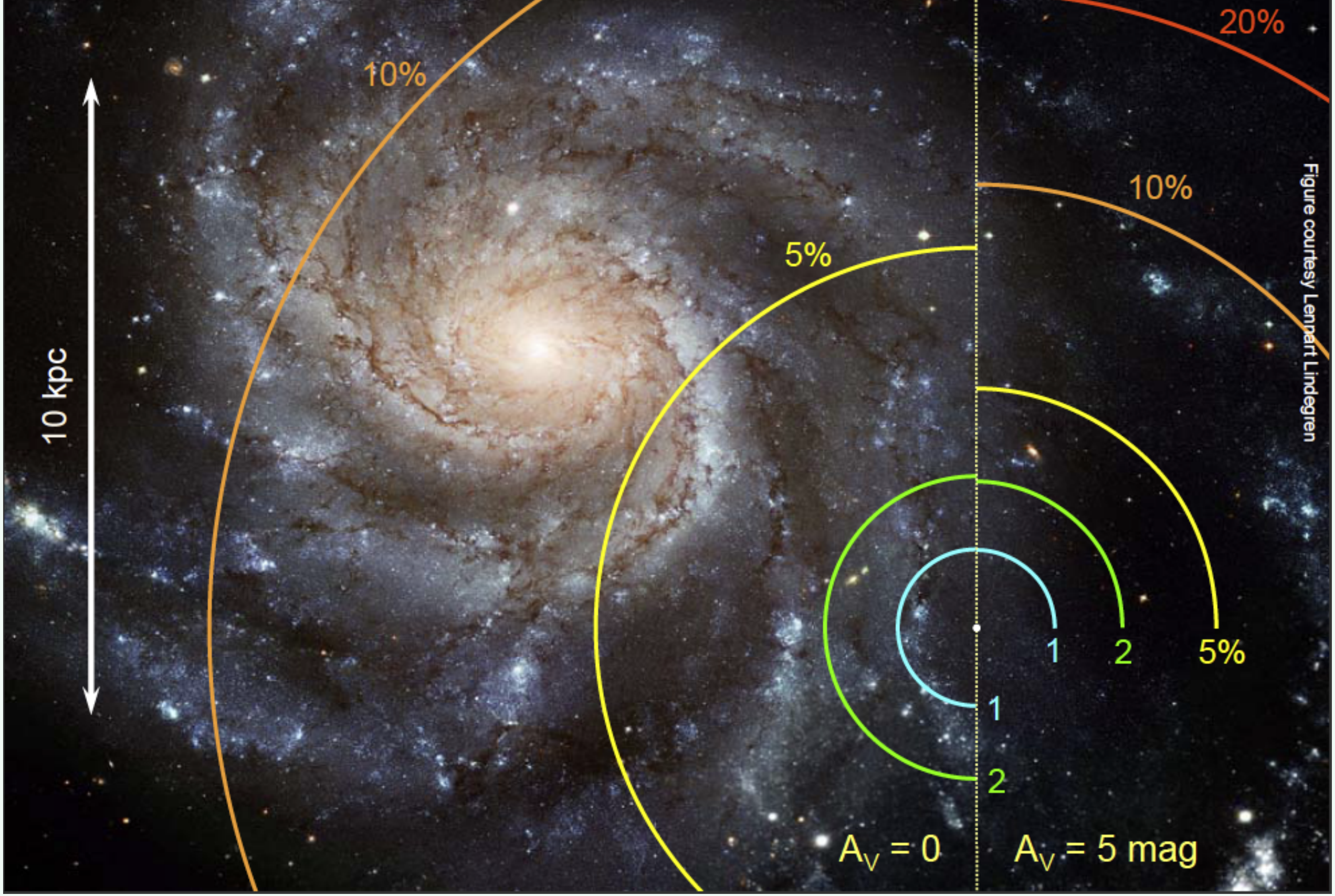


Figure courtesy C. Cacciari

Parallax horizon for classical Cepheids (P = 10 d)



MW Cepheids

Only ~ 800 Galactic Cepheids are known – most are located in the Solar neighbourhood, up to ~ 9000 are expected to be discovered by Gaia

400 Galactic Cepheids from David Dunlap DB
distance and magnitude ➔ Gaia predicted accuracy for parallax
15 @ d < 0.5 kpc
65 @ d < 1 kpc
165 @ d < 2 kpc

Presently, ~ 250 Cepheids with parallax & photometry
(10 with HST parallax)
only ~ 100 with $\sigma_\pi \lesssim 1$ mas
(Hipparcos)

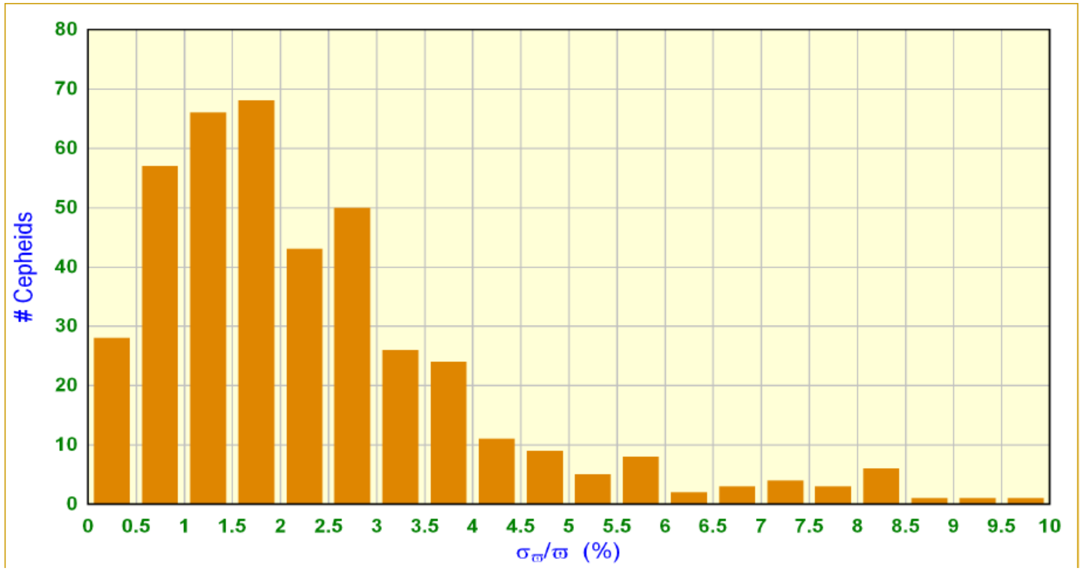


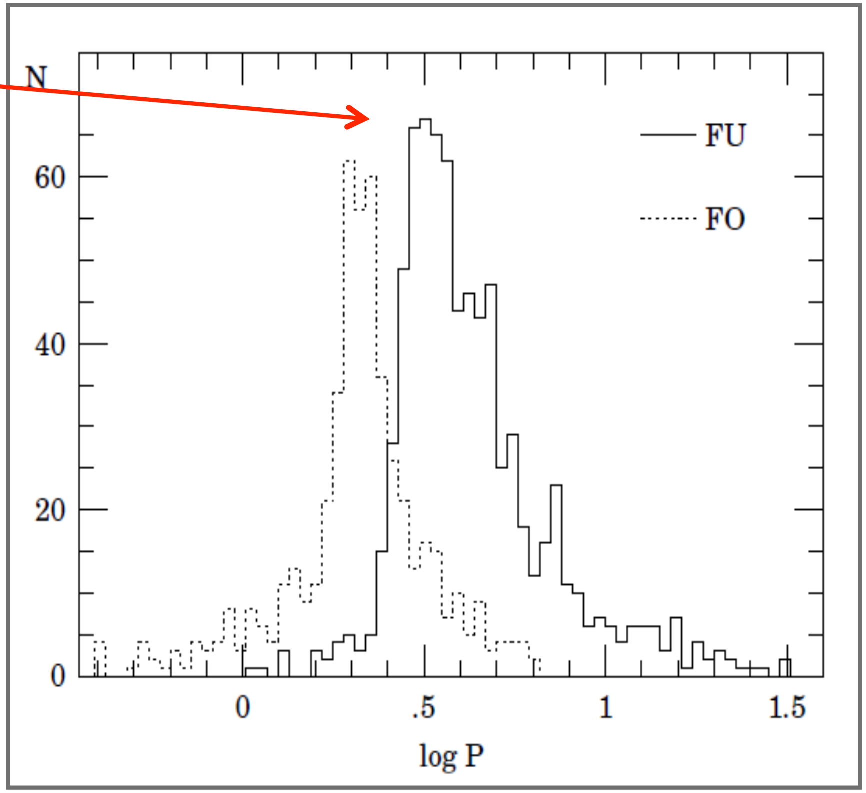
Figure courtesy A. Brown

Most (~ 3/4) Galactic Cepheids will have Gaia individual parallaxes to < 3%

MC Cepheids

~ 3300/2100 Cepheids are known (and observable by Gaia) in the LMC/SMC

600 Cepheids in the LMC (OGLE, Udalski et al. 1999)



The bulk of the distribution for fundamental LMC pulsators lies at Period = 3 – 5 days

Mv ~ -3 ➔ V ~ 15.8 – 16

➔ individual distances to ~ 150%

➔ mean of 400 to ~ 7-8 %

Cepheids with P ≥ 10 d

Mv ≤ ~ - 4.2 ➔ V ~ 14.5

individual distances to ~ 80%

Ultra-long period (> 100 d) Cepheids

Mv ≤ ~ - 7 ➔ V ~ 12

4 in LMC, 3 in SMC (Bird et al. 2009)

➔ **individual distances to ~ 45% (LMC) - 55% (SMC)**

➔ direct (trigonometric) calibration of the cosmological distance scale

Sinergy among Gaia and past or future surveys of pulsating stars

Visual	Infrared	Spectroscopy	Astrometry
EROS MACHO SUPERMACHO OGLE II-III-IV MOA	ISO DENIS SIRIUS 2MASS SAGE SPITZER	Gratton et al. 2004 Borissova et al. 2004,2006 Romaniello et al. 2008	
STREGA@VST STEP@VST GAIA LSST	VVV VMC CRRP	GAIA RVS GES? WEAVE? MOONS?	GAIA

The Fundamental Cosmic Distance Scale: State of the Art and the Gaia Perspective

Naples, May 3-6, 2011

http://www.oacn.inaf.it/ESFdistance

see also: **GREAT WGA8 Distance scale**, at:
http://camd08.ast.cam.ac.uk/Greatwiki/WGA8DistanceScales

Thank you !