Launch: 08:57:30 20/11/2013

Gaia

Stereoscopic Census of our Galaxy

http://www.rssd.esa.int/Gaia

one billion pixels for one billion stars

Gerry Gilmore

UK Gaia PI

Cambridge University

- ESA Cornerstone mission. First proposal 1990.
- Study phase 1990's
- Mission approved 2000. ESA-only.
- Data to be globally public. No GTO science.

Main Performances and Capabilities

Accuracies:

- 20 μas at V = 15 0.2 mas at V = 20
- radial velocities to <10 km/s complete to V ~ 16.5
- sky survey at ~0.2 arcsec spatial resolution to V = 20 (mmag)
- multi-colour multi-epoch spectrophotometry to V = 20 (20 samples)
- dense quasar link to inertial reference frame

Capabilities:

- 10 μas ≡ 10% at 10 kpc [~1cm on the Moon]
- 100 μas/yr at 20 kpc ≡ 10 km/s

⇒ GAIA will quantify 6-D phase space for over 300 million stars,
and 5-D phase-space for over 10^9 stars

- Two orders of magnitude improvement over current best precision
- 13 magnitudes improvement in sample completeness
- First large-area high-spatial resolution survey
- Unbiased sample of 1% of Galactic stars
- Fundamental physics, GR, cosmology, NEOs, planets, transients,...

my view of Gaia

ESA's premier astrophysics mission of the decade

Low dispersion spectroscopy provides radial velocity, and some chemical elemental information

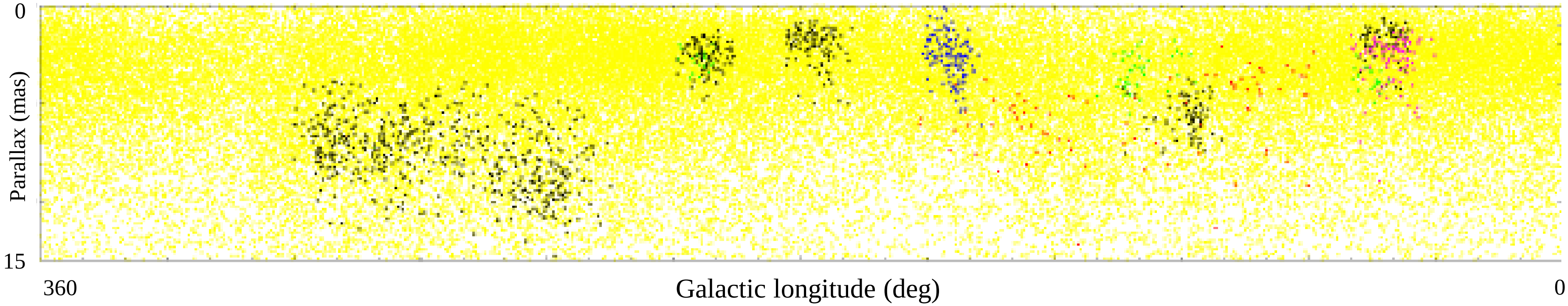
High dispersion spectroscopy provides detailed multi-element chemical abundances ➔ intrinsic properties

2-D	3-D	5-D	6-D	12+ D
position	parallax	proper motions	spectrum	Astrophysical parameters
Ultra-precision, over years	distance	Transverse velocities	Radial velocity + chemistry	Ages, histories, astrophysics

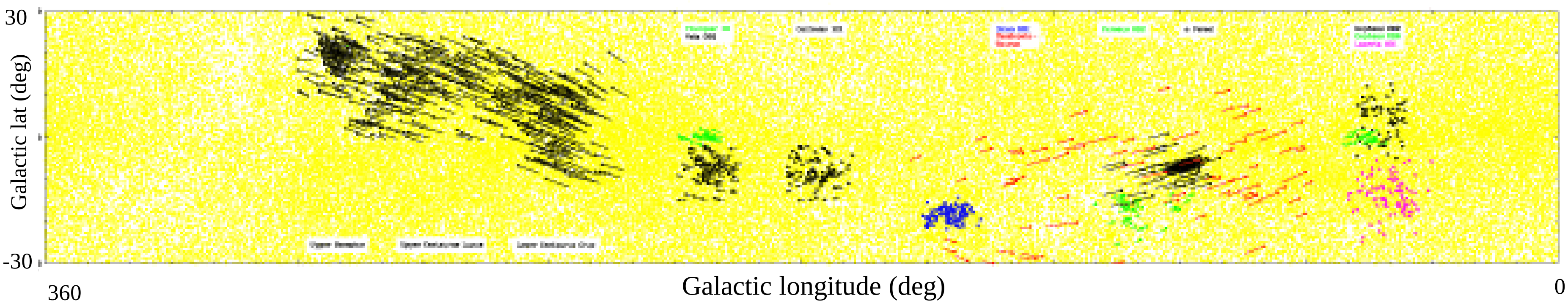
Stellar orbits, star formation history, origin of the elements, Galaxy assembly,....
Dark Matter, Cosmological initial conditions, fundamental physics, solar system(s)

Structure of Star Forming Regions

Parallaxes of OB association members (Hipparcos)



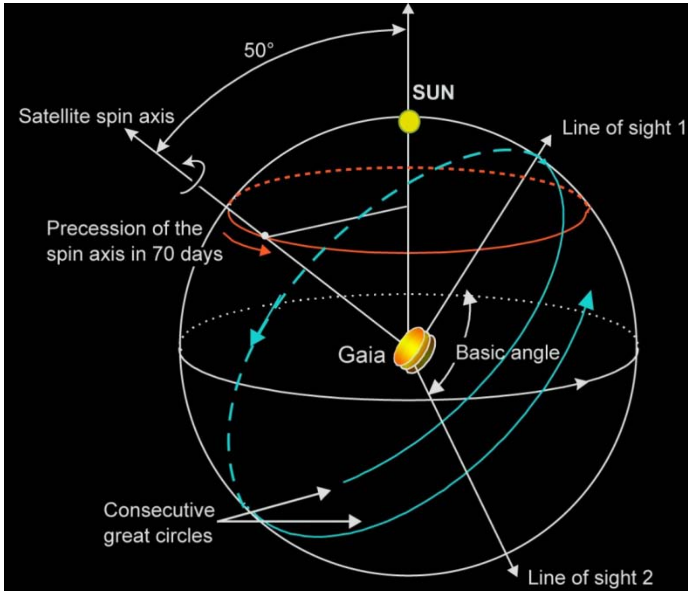
Positions and proper motions of selected members

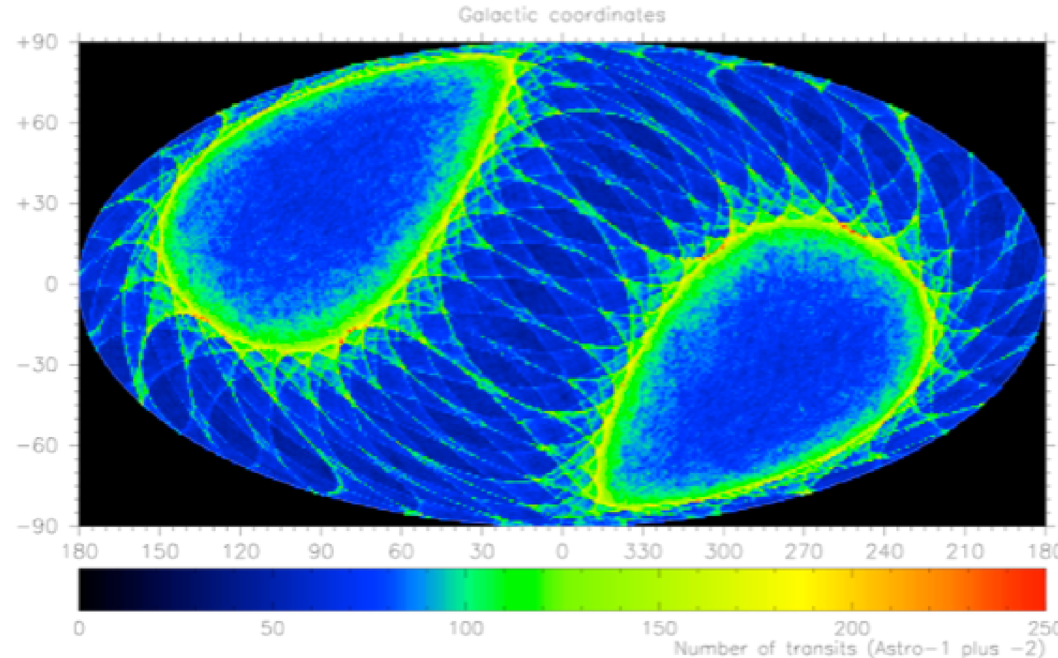


GAIA will allow:

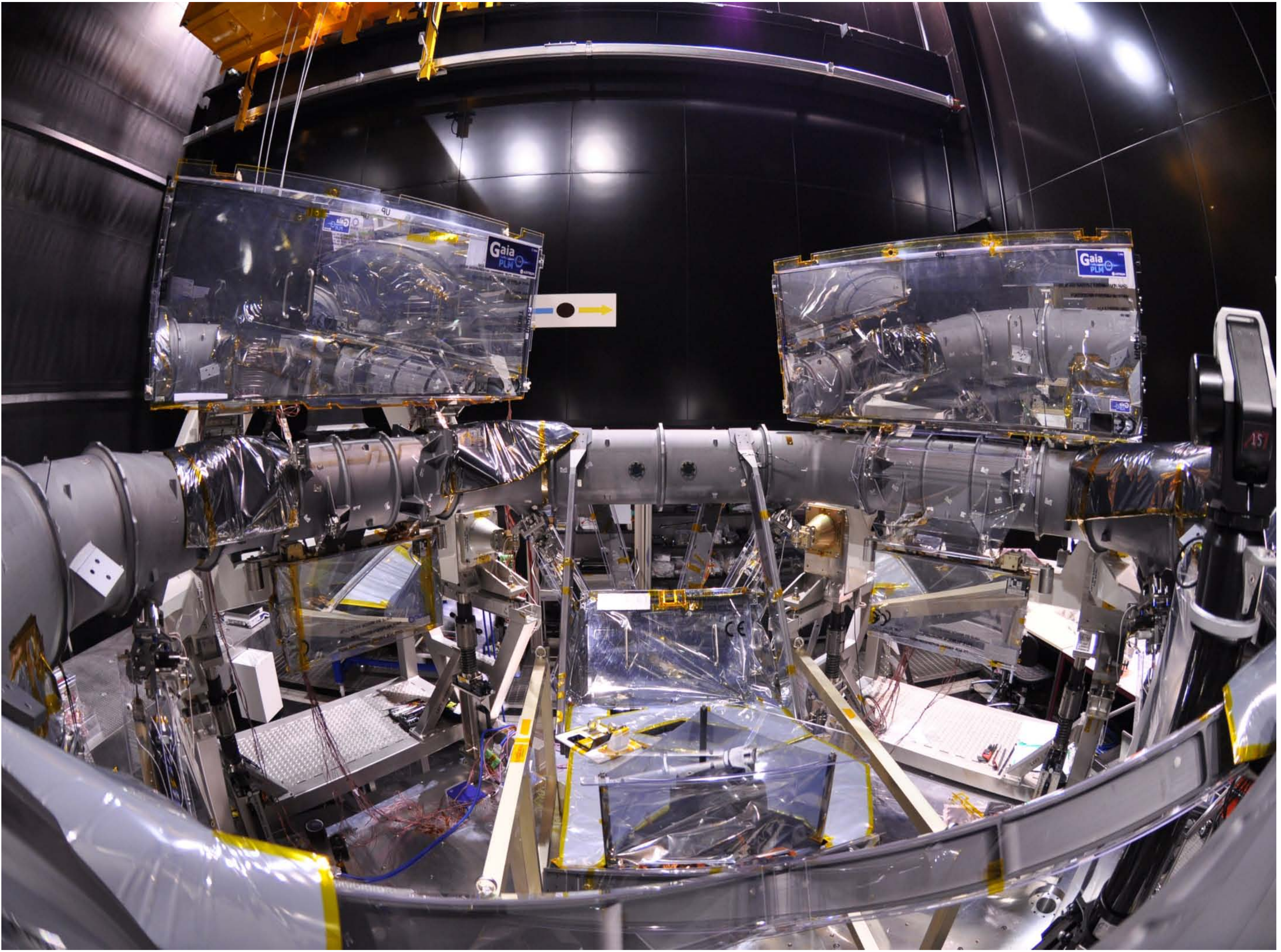
- detection of stellar groups across the Galaxy
- tracing back of orbits to time and location of formation

Sky Scanning Principle

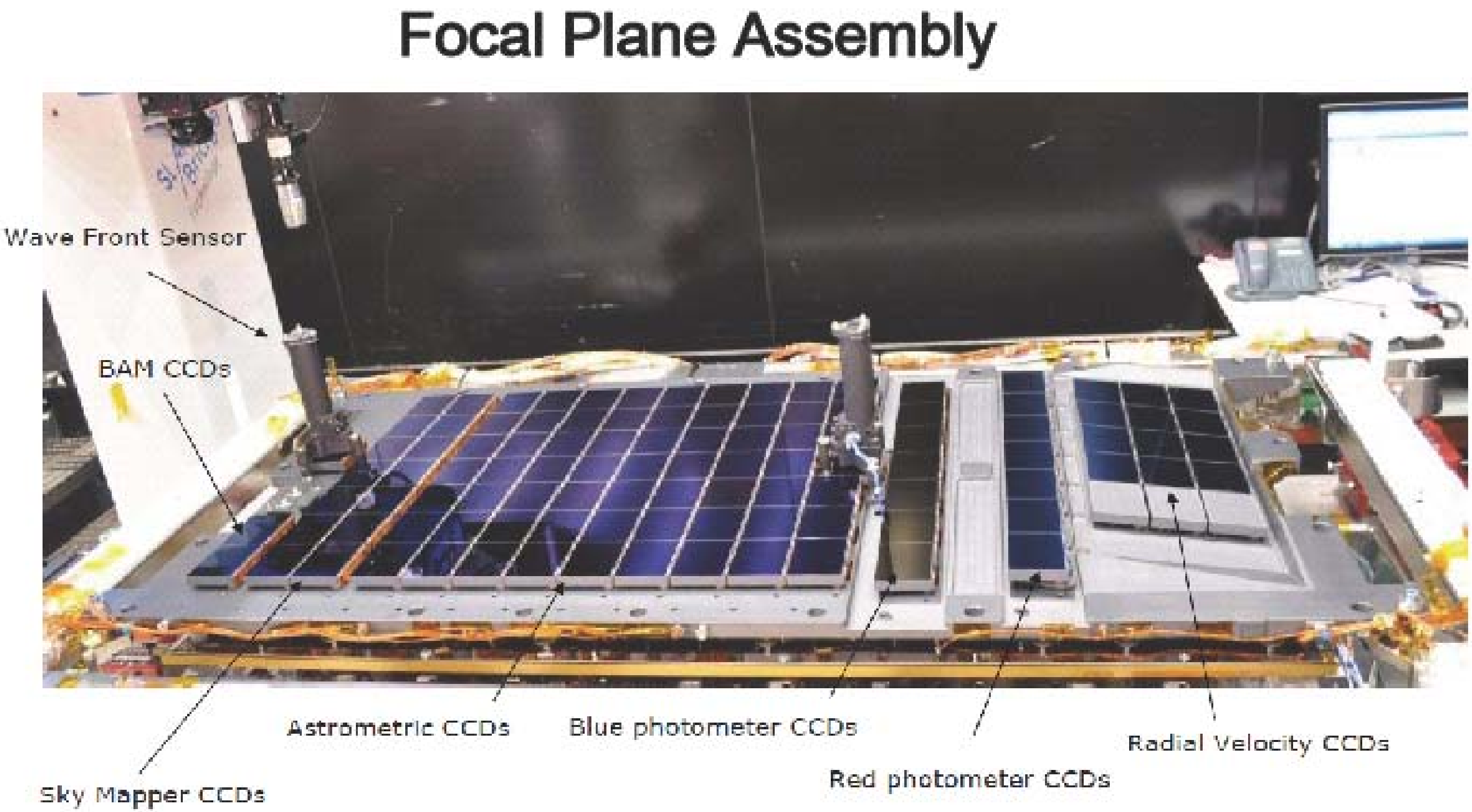




- Two telescopes - time between subsequent FOVs: 106.5m
- Time between successive scans: 6 h
- Field revisited every ~70 days
- Each object measured ~80 times (200 at the nodes)
- [Single CCD = 4.4secs – 9 repeats; +spectrophotom; +RV]

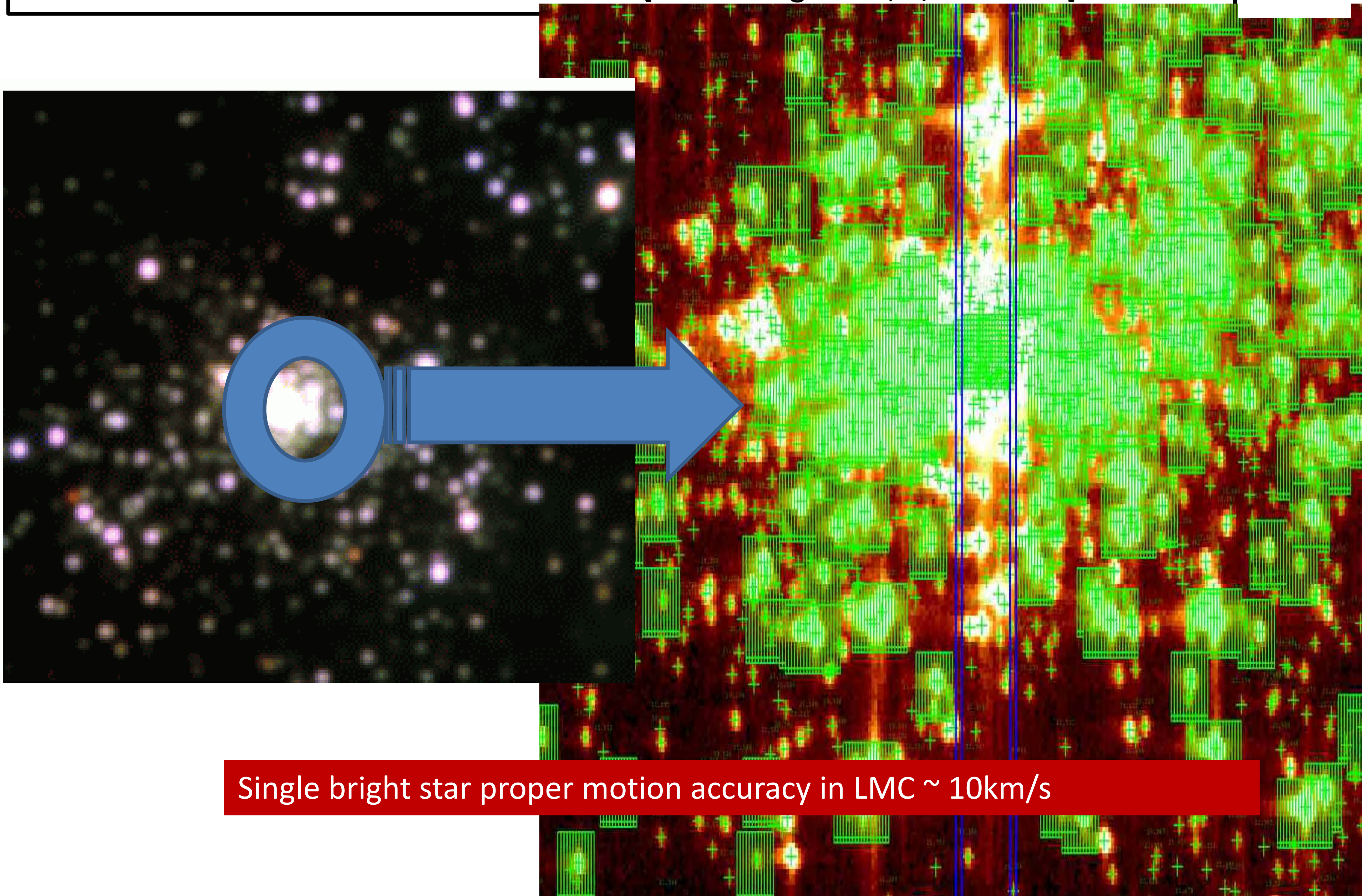

Gaia
PLM
Gaia
PLM

How Gaia works



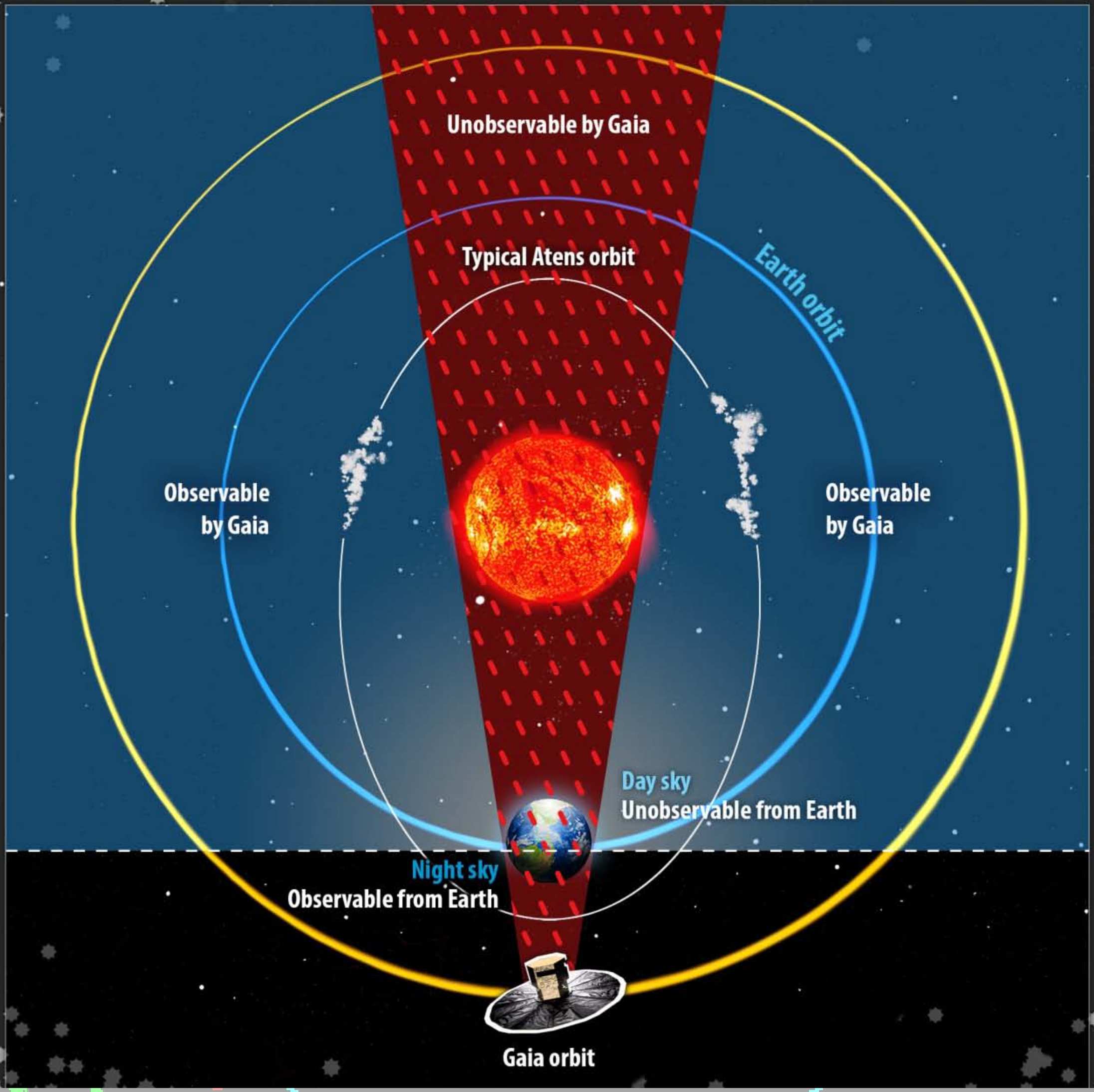
Data flow: 50Gb/day for 5-6 years; total processed data and archives ➔ 1PByte
Computational challenge : 1.5 x 10^{21} FLOP – and highly sophisticated algorithms

The heart of Gaia is the largest focal plane ever built. 106 large (e2v) CCDs, 1m x 0.4m
What will they see? This is R136 , a star cluster at 50Kpc, as seen by one Gaia CCD
Green box = Gaia will measure that source. [4secs integration, 1/106 CCDs]



Single bright star proper motion accuracy in LMC ~ 10km/s

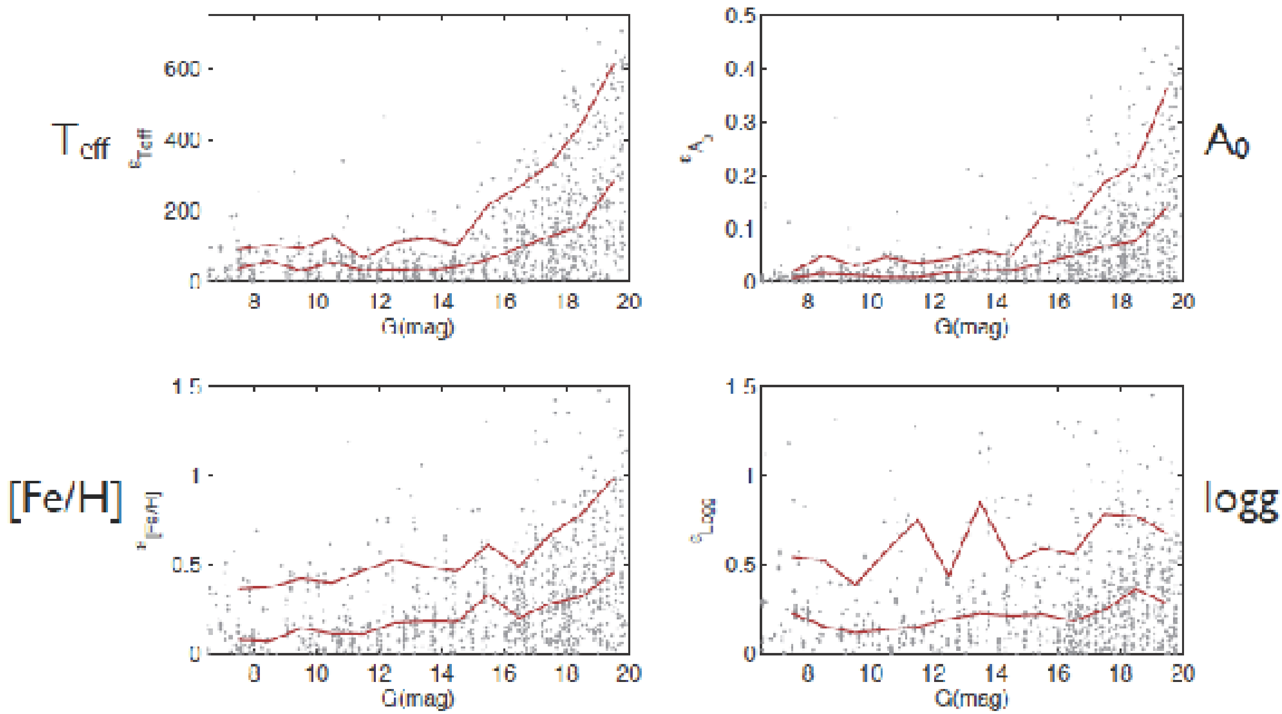
GAIA is the ideal Nemesis survey
a different type of dark matter.....



Gaia will produce astrometry, photometry, spectra, spectrophotometry, RVs, periods for variables, orbits for NEOs, abundances, astrophysical parameters, Av,.....

2. Science performances

Stellar parameters



50% and 90% bounds shown

Courtesy of C. Bailer-Jones

More in http://www.mpia.de/Gaia

These stellar data will allow reliable identification of clean tracer samples
➔ Multiple DF analyses for consistency/systematics analyses

Galaxies, Quasars, and the Reference Frame

- Parallax distances, orbits, and internal dynamics of nearby galaxies
- Galaxy survey, including large-scale structure
- ~500,000 quasars: kinematic and photometric detection
- ~10,000 supernovae [few/day ➔ real-time alerts]
- Ω_M, Ω_Λ from multiple quasar images (3500 to 21 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?

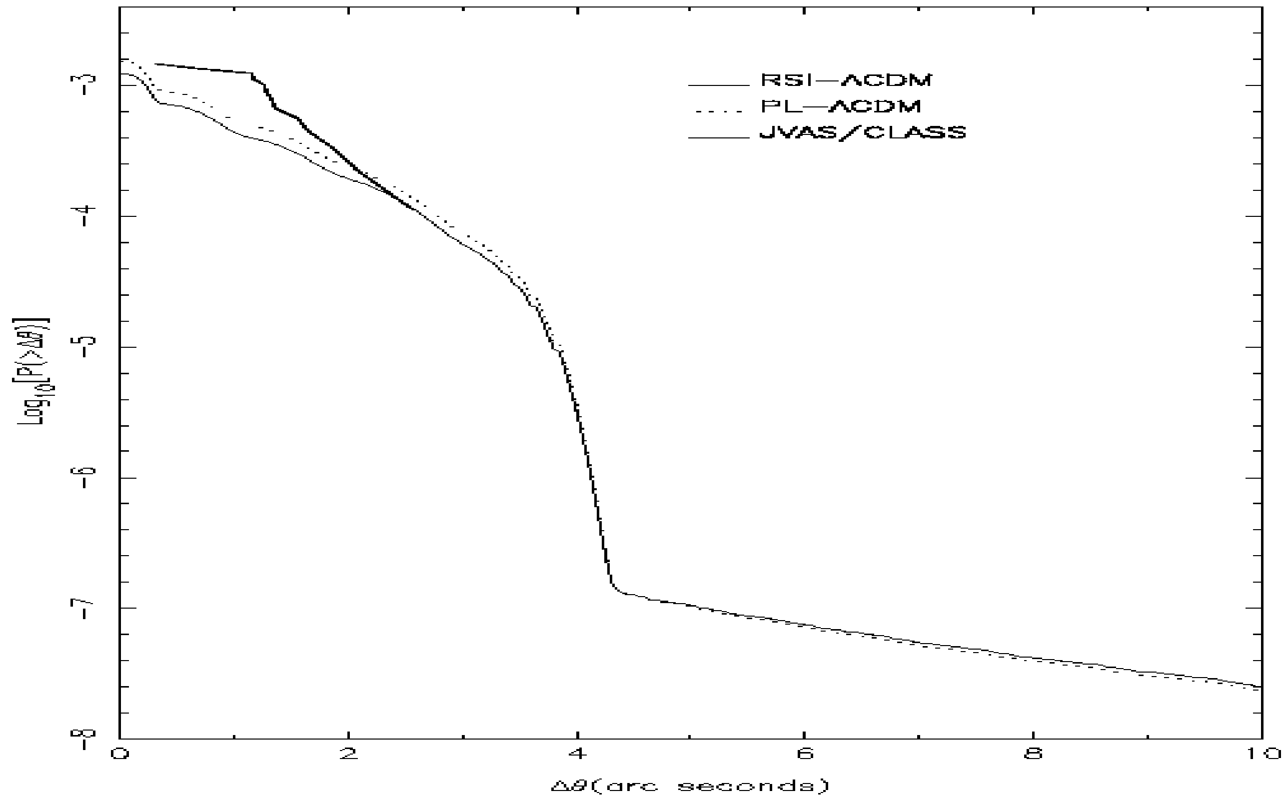
Gaia will discover 500,000 quasars, all with high-resolution imaging to quantify strong-lensing structure (11 qso lenses known in DR3…),

[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

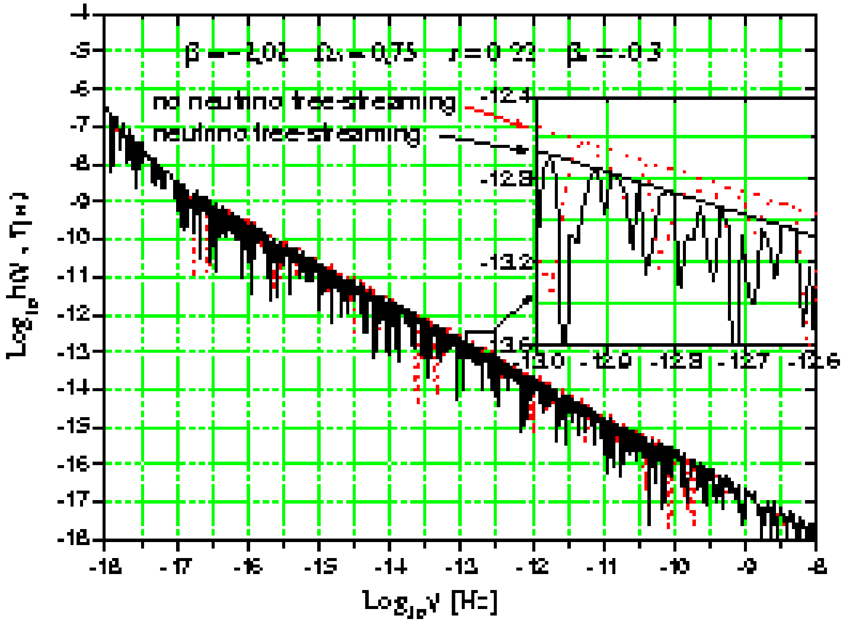


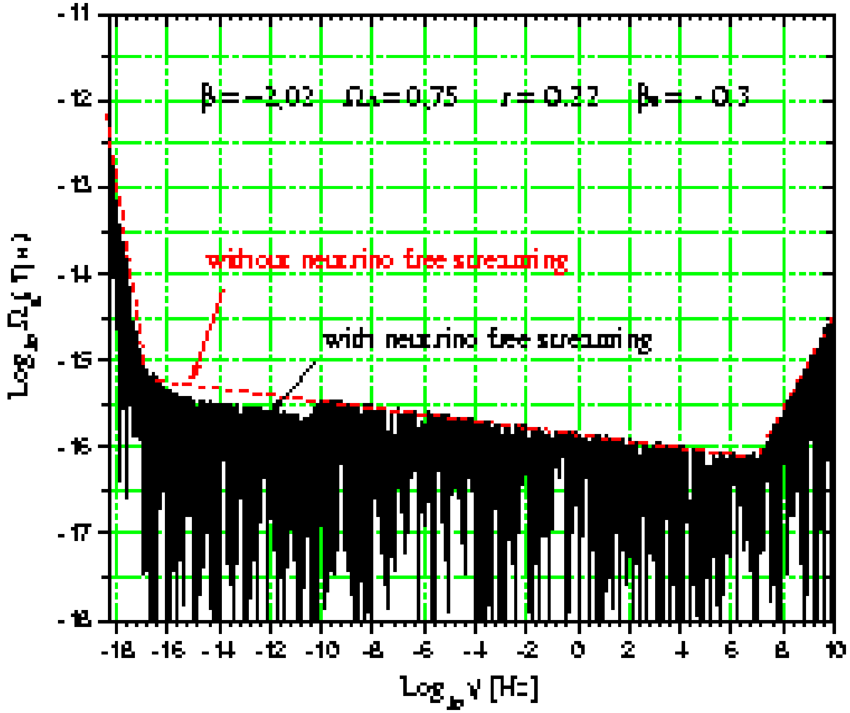
- Will Gaia contribute to cosmology and fundamental physics?

•Gaia MAY detect?/constrain very low frequency gravitational waves, from coherence/stability of reference frame. a la VLBI

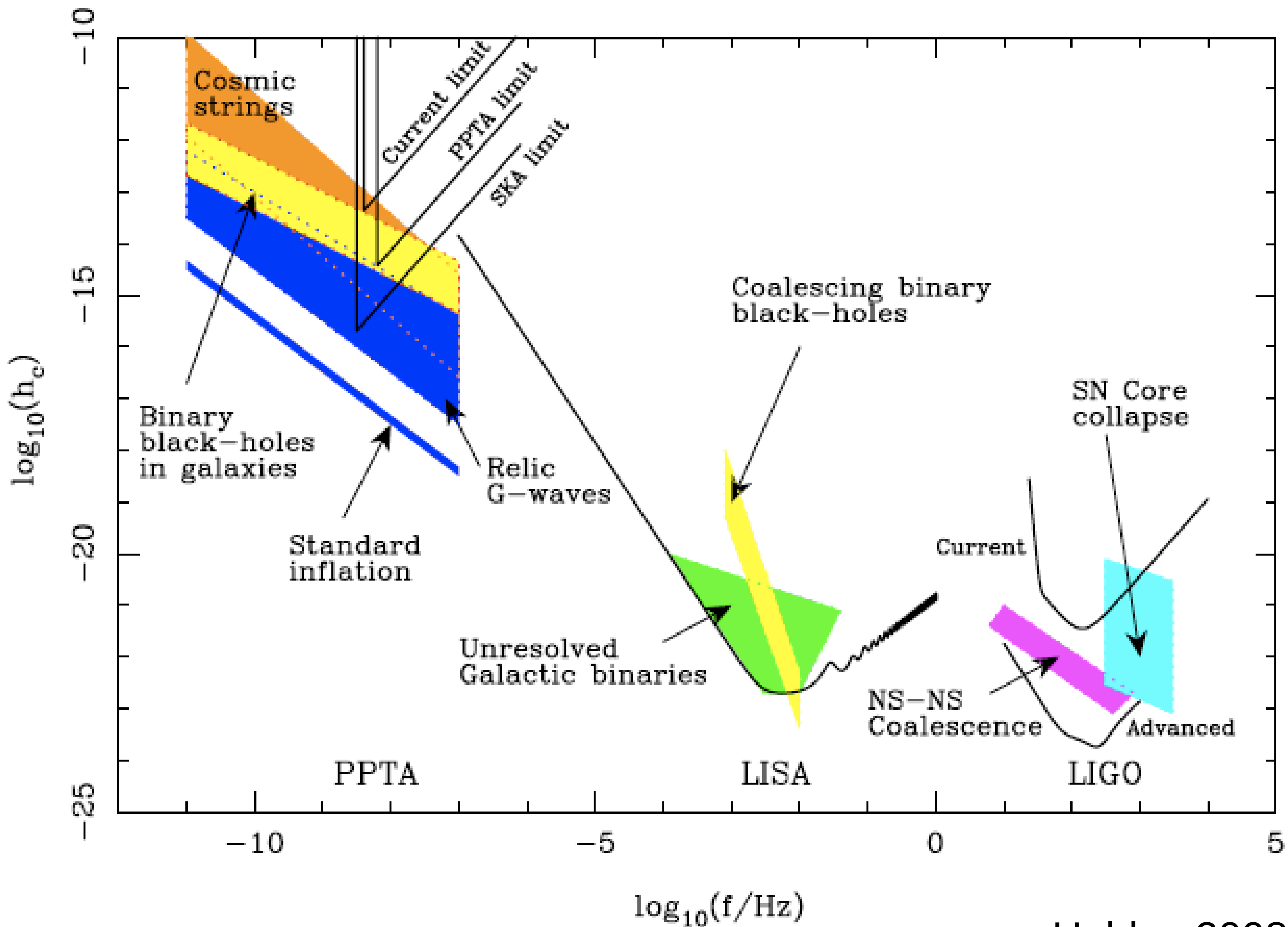
•Gravitational wave energy: $10^{-12} < f < 10^{-9}$ Hz

•This range – well below LISA – is a sensitive test of inflation models, and later neutrino effects eg PRD 75 104009 2007





Gravitational Wave Spectrum

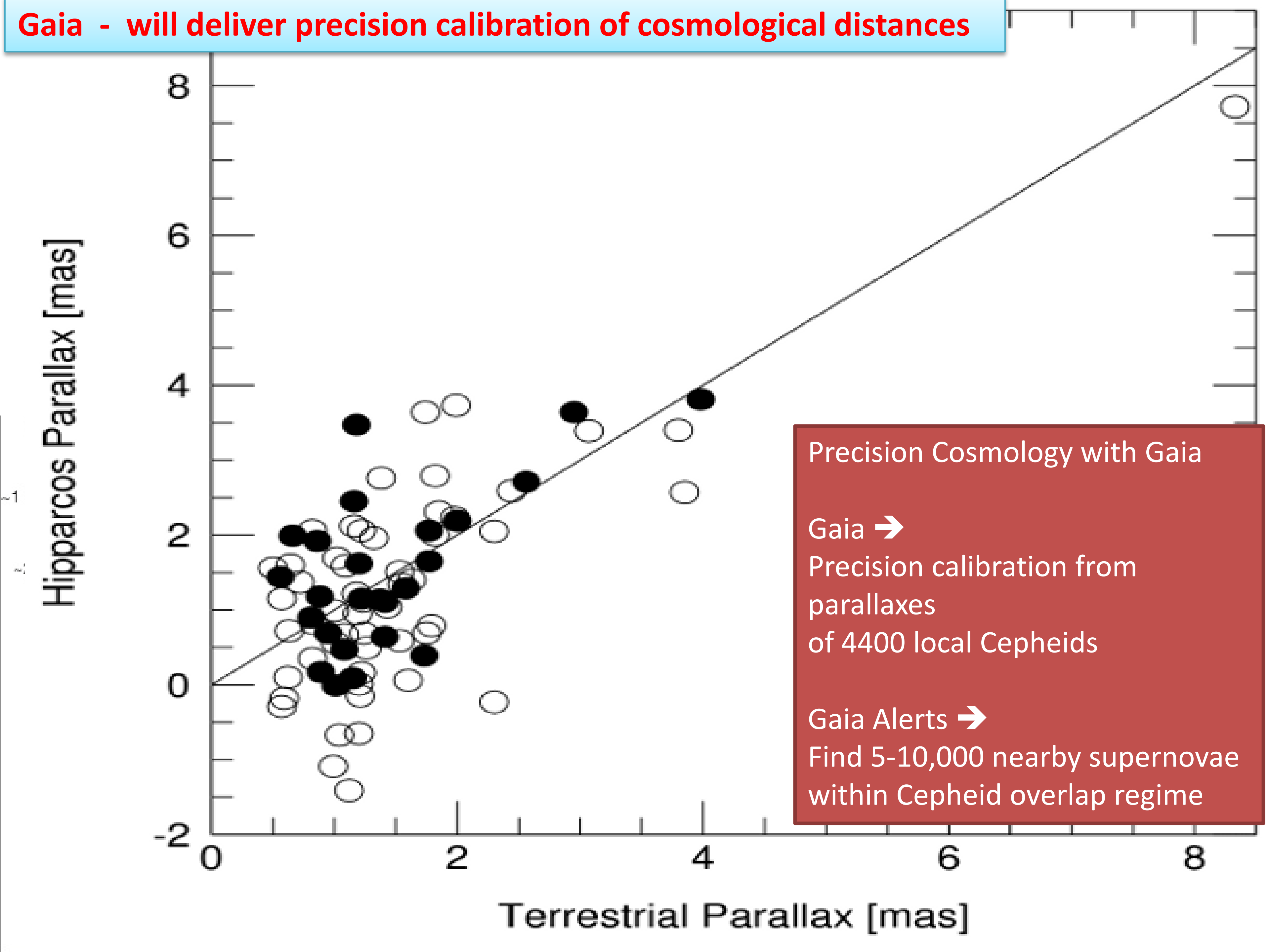


Hobbs, 2008

Summary: General Relativity/Metric

- 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)

Gaia - will deliver precision calibration of cosmological distances

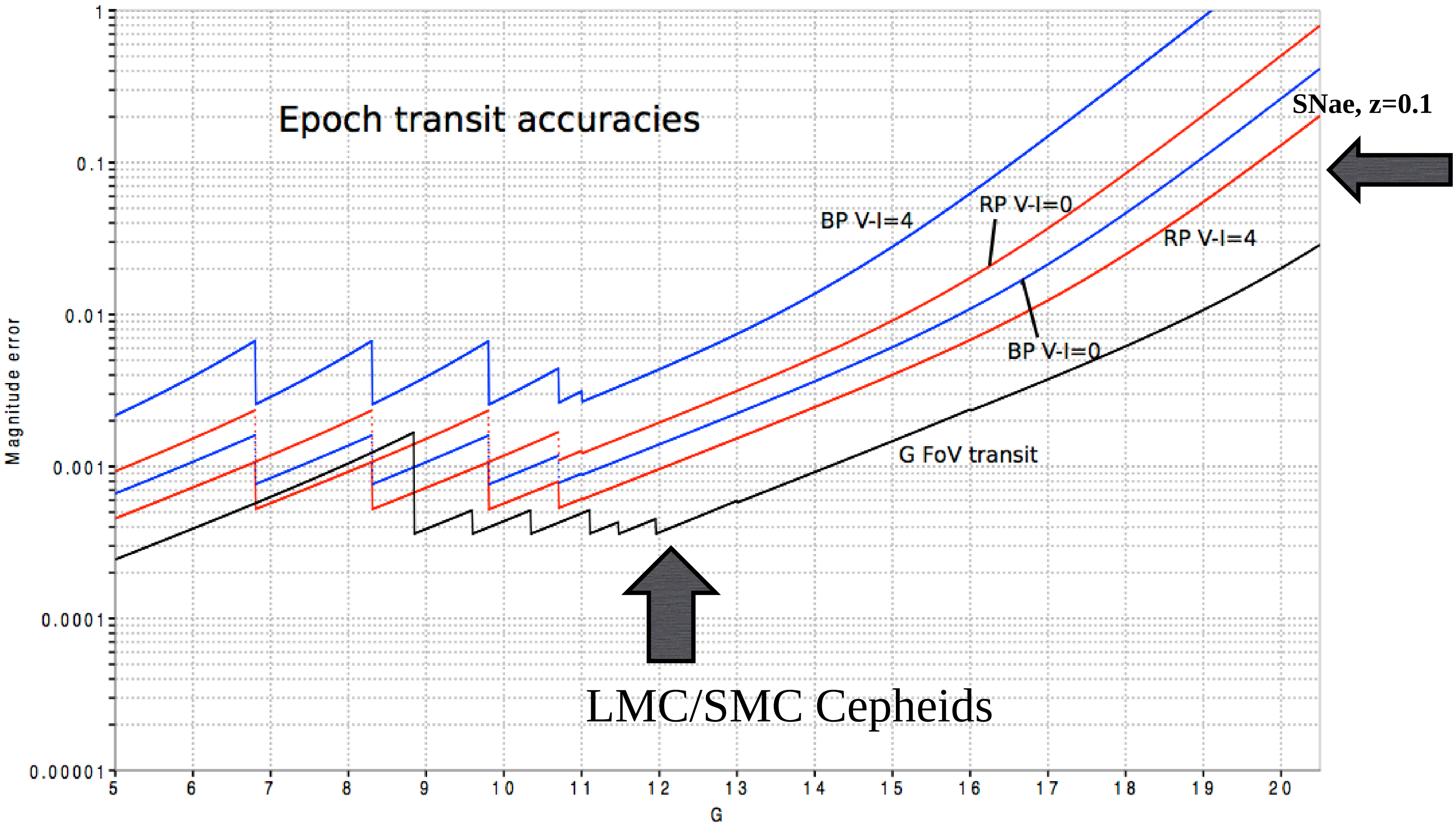


Precision Cosmology with Gaia

Gaia →
Precision calibration from parallaxes
of 4400 local Cepheids

Gaia Alerts →
Find 5-10,000 nearby supernovae within Cepheid overlap regime

Photometry


Epoch transit accuracies
SNae, z=0.1
BP V-I=4
RP V-I=0
RP V-I=4
BP V-I=0
G FoV transit
LMC/SMC Cepheids
Magnitude error
G
1
0.1
0.01
0.001
0.0001
0.00001
5
6
7
8
9
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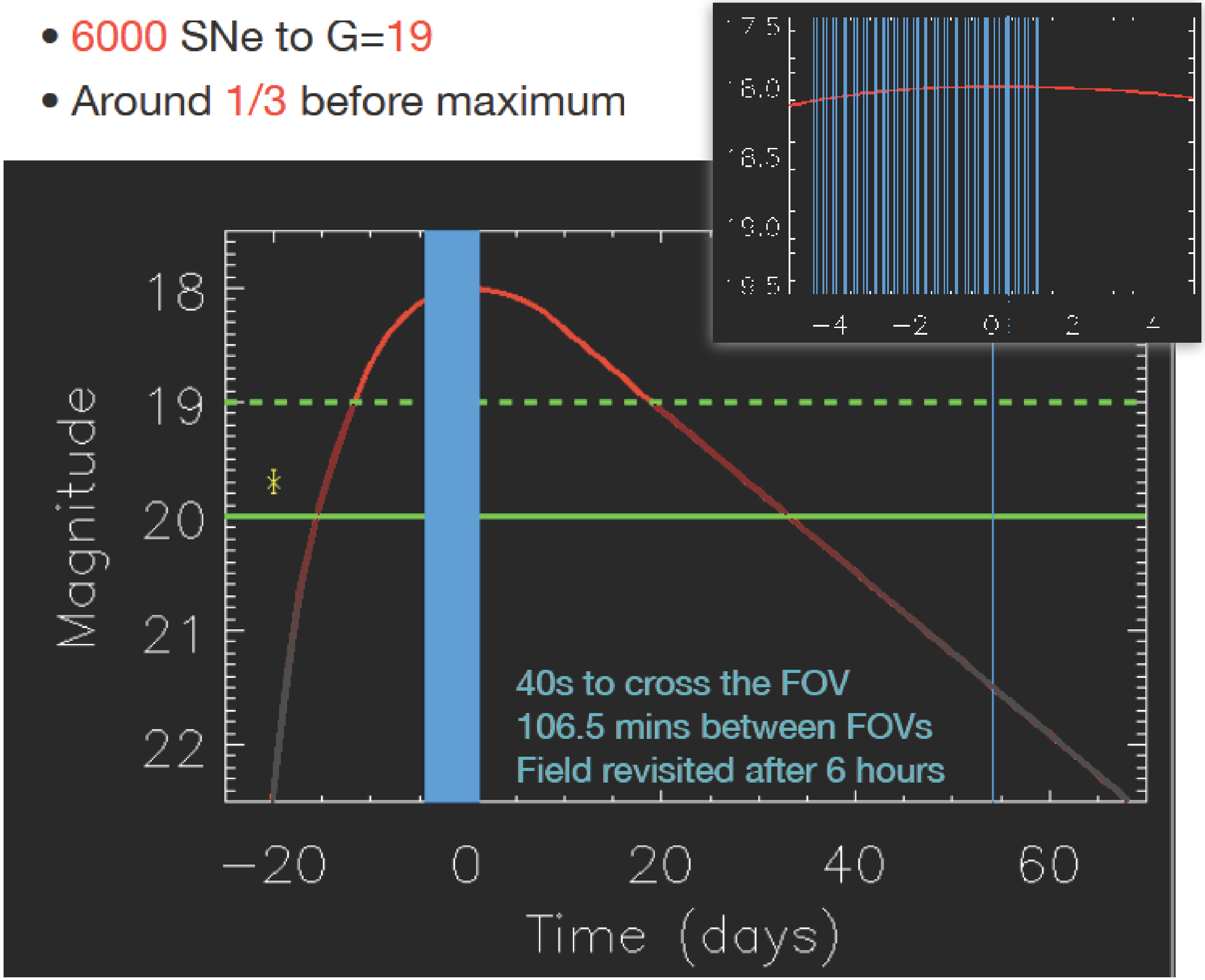
20

Supernovae

- 6000 SNe to G=19
- Around 1/3 before maximum



- Successiv
transits will measure consistency slope.

- Host galax
contribution determines whether sou
new to Gaia.

Science Alerts: published through VOEvent with no restrictions

aims:

- detect unexpected and rapid changes in the flux, spectrum or position
- or appearance of new objects
- trigger ground-based follow-up ➔ tested with PTF
- provide targets to the community to be studied at peculiar states

methods:

- run in near-real-time: between couple of hours and 24h after observation
- use photometric, spectroscopic and astrometric Gaia data
- cross-match against existing information
- Gaia spatial resolution makes for a real challenge – crowded fields
- **Motivation**
- Collaboration interests in special cases, esp rare objects
- Excellent outreach potential via public robotic telescopes

All data are released to whole community – no GTO, no restrictions

DR3 will probe kinematics out to ~few kpc: radial velocities are limiting
Map inner galaxy through low-dust windows, local disk, some halo

gaia

Data release scenario (II)

First release: launch + 22 Months Sep-2013 →Jul-2015	• Positions (α,δ) and G-mag for single-like stars (90% of the sky) • the Hundred Thousand Proper Motions (HTPM) catalogue based on the Hipparcos stars 20x improvement, need RVs
Second release: launch + 28 Months Jan-2016	• Updates of above + • **Mean radial velocities for stars** with non-variable radial velocity (90% of the sky)
Third release: launch + 40 Months Jan-2017	• **Positions (α,δ), proper motions, and parallaxes** and G-mag for single stars (90% of the sky) • Orbital solution for period between 2 months and 75% of the observation duration • Integrated photometry RP/BP • Spectrophotometry from RP/BP for sources for which astrophysical parameters are simultaneously released • **Source classification based on BP/RP and astrometry** for stars with sufficiently high quality data • Mean RVS spectra for sources where single epoch spectra are usable and APs are simultaneously released

Post DR3 – RV's will get fainter, eventually reach ~10kpc

gaia

Data release scenario (III)

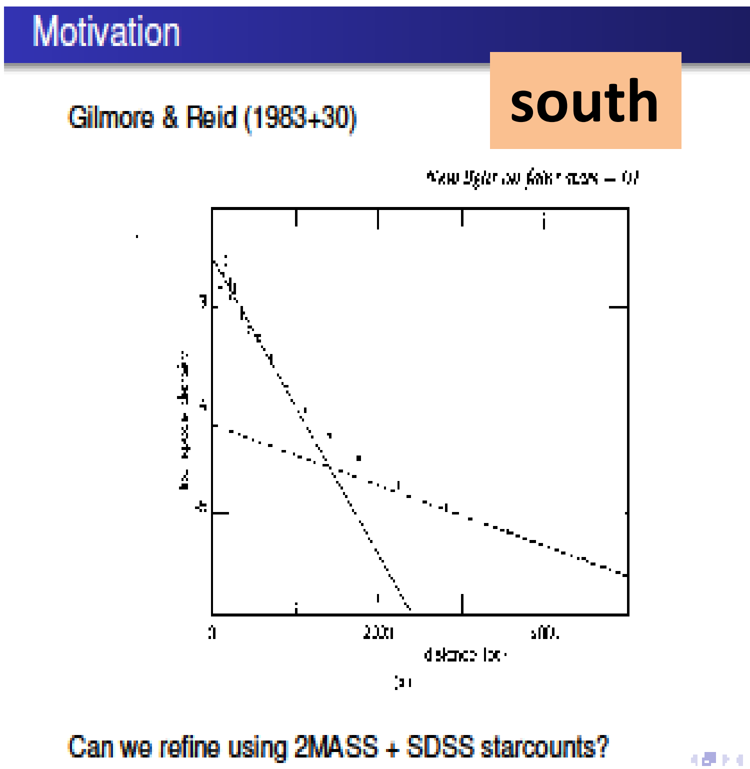
Fourth release: launch + 65 Months Feb-2019	Updates of all above + • Source classification plus **multiple stellar astrophysical parameters** derived from BP/RP, RVS and astrometry for the majority of stars • **Variable star classifications and parameters** as available, and the epoch photometry • **Solar system results** with preliminary orbital solutions and individual epoch observations • Non-single star catalogue
Final release: End Mission + 3 years (36 months) **Sep-2021/2022**	Full astrometric, photometric, radial velocity catalogue • All available variables and non-single stars solutions • Source classifications (probabilities) plus multiple astrophysical parameters derived from BP/RP, RVS and astrometry for stars, unresolved binaries, galaxies and quasars. Precision improved with respect to 4th release. Some parameters may not be available for fainter stars. • Non Single Stars solutions and exo-planet list • All epoch and transit data for all sources • All Ground Based Observations made for data processing purposes (or links to it)

All data are released to whole community – no GTO, no restrictions

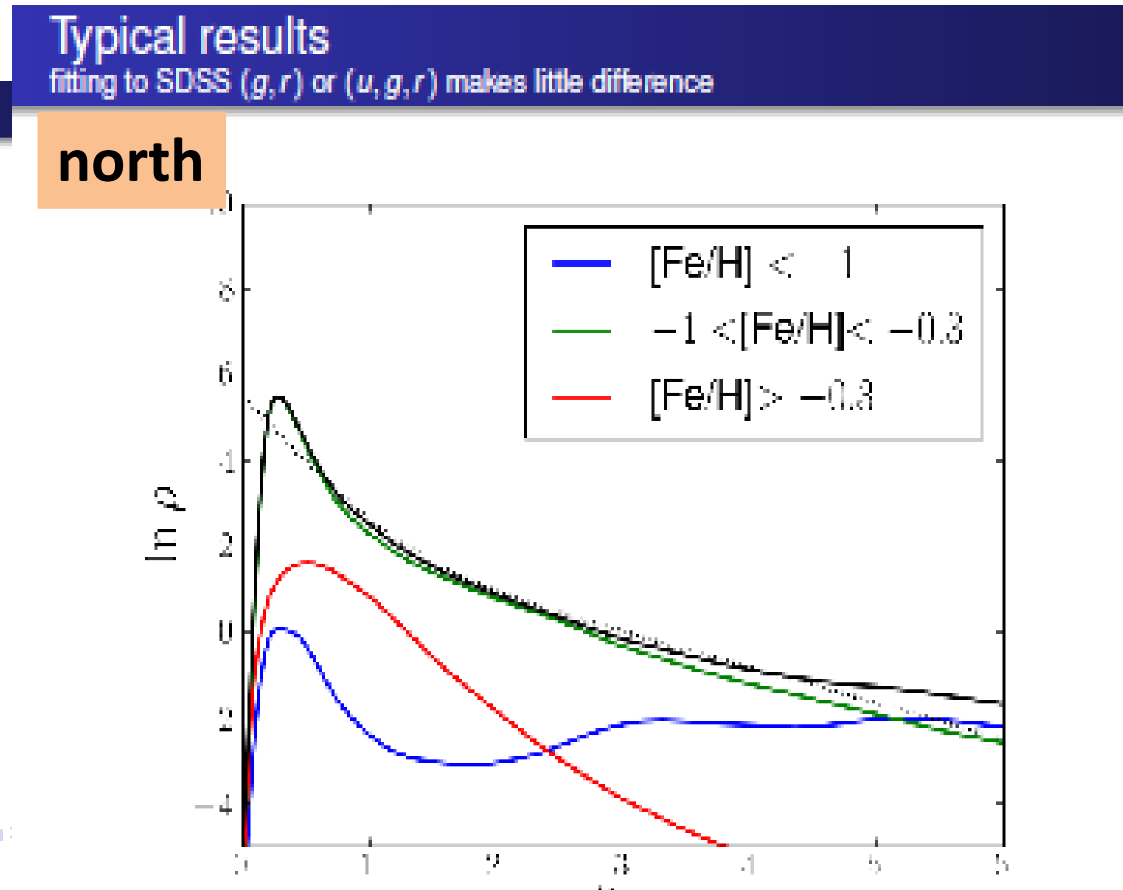
Local dark matter density:

a remarkably stable result?: Kuijken & Gilmore 1989/91

- **Galactic structure rho(z):** Gilmore & Reid 1983
- **Gaia will provide direct distances, and precise 3-D kinematics**



south



north

John Magorrian – density profile from digital survey data matches G&R photographic….

Local dark matter:

most recent analysis: RAVE 500,000 star survey

Force perpendicular to the Galactic plane

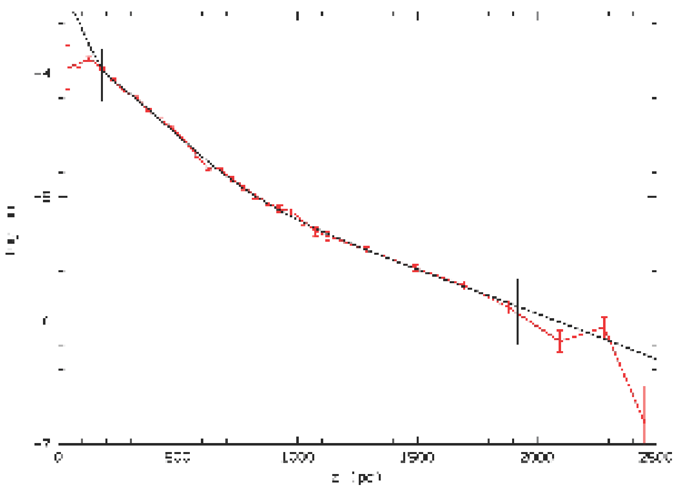
$$\Phi(z) \propto \Sigma_0(\sqrt{z^2 + D^2} - D) + \rho_{eff} z^2$$

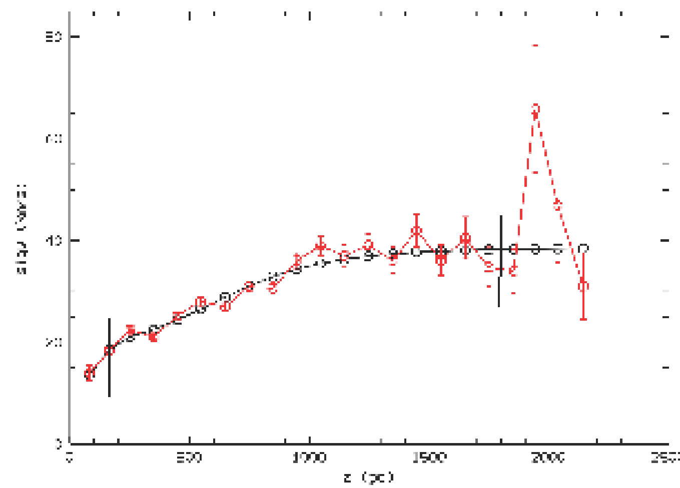
fit from z = 200 to 1100 pc-> to 1800pc

Σ_{1kpc}=67M_0/pc^2	[61-73]	[65-71]
D=445pc	[320-600]	[390-510]
ρ_{eff}=0	[0-0.009]	[0-0.006]

or if ρ_{eff}=0.008 fixed

Σ_{1kpc}=71±4M_0/pc^2
D=410±120pc

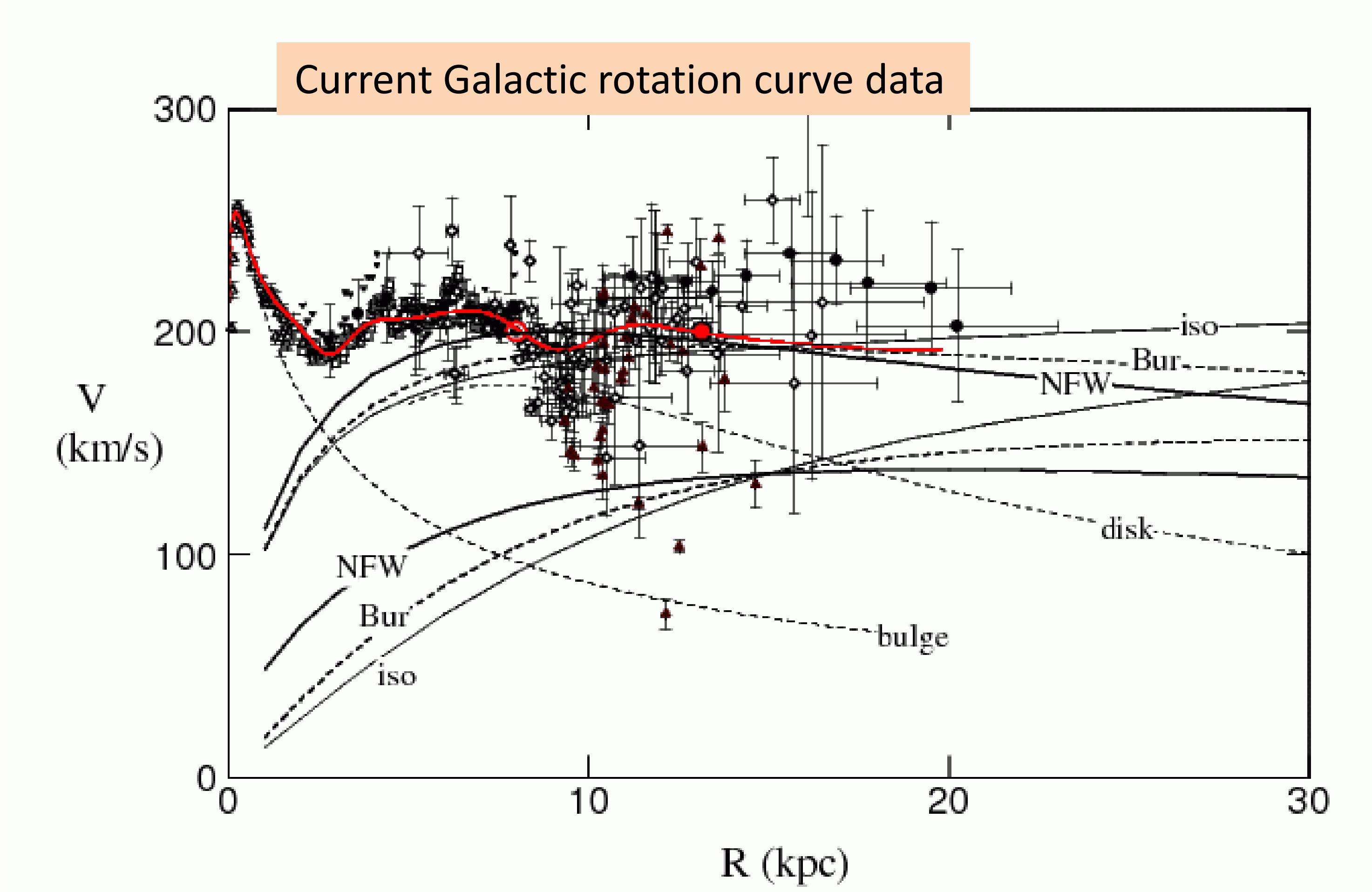




Olivier Bienayme – kinematic profile from digital survey data matches K&G….

Gaia will very substantially improve data on intermediate scales

is this poor data or a more complex situation?



Sofue in vol5 of Planets, Stars and Stellar systems, ed Gilmore 2013

Work to learn how to model Gaia dynamics is now actively underway – more needed!!

Local disk dynamics

Mass estimators in the *Gaia* era

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ABSTRACT
Forthcoming astrometric missions such as the *Gaia* satellite will bring to the fore the problem of estimating the enclosed mass from a set of positions, radial velocities and proper motions of tracer stars. Here, we show how to construct the tracer mass estimator when the proper-motion data are available in addition to the usual line-of-sight velocity data. Notably, the mass estimators do not require any assumption on the anisotropy, as it is naturally incorporated through the different components of proper motions. In addition, the separate treatment of the proper motions and the line-of-sight velocities is desirable because they are observationally independent and thus the propagation of the combined uncertainties is rather straightforward. The extension to projected data is also sketched, together with a possible application of measuring the masses of Galactic globular clusters.

cluster is assumed to lie at a distance of 5 kpc and the sample size is 10 or 100 tracers with projected positions and proper motions. As the histograms are quite tight, we have replaced FRE with the fraction of good estimates (FGE), where 'good' means that the mass estimate is within 10 per cent of the true mass. We see that 10 tracers are too small for reliable results, but 100 tracers are ample. The right-hand panel shows the estimated masses as a function of

$$GB_\alpha \langle r^{\alpha-1} M\rangle = \frac{(1+\alpha)\langle \mu_R^2 \varphi^\alpha\rangle + \langle \mu_\phi^2 \varphi^\alpha\rangle}{\langle \mu_R^2\varphi^\alpha\rangle + (1+\alpha)\langle\mu_\phi^2\varphi^\alpha\rangle}\langle v_\ell^2 R^\alpha\rangle \qquad (29)$$

with $\langle v_\ell^2 R^\alpha\rangle = s^\alpha \langle v_\ell^2 \varphi^\alpha\rangle$. This again is in fact equivalent to equations (24) and (25) of Paper I with β replaced by equation (28) and the boundary term dropped. If one preferred the explicitly solved

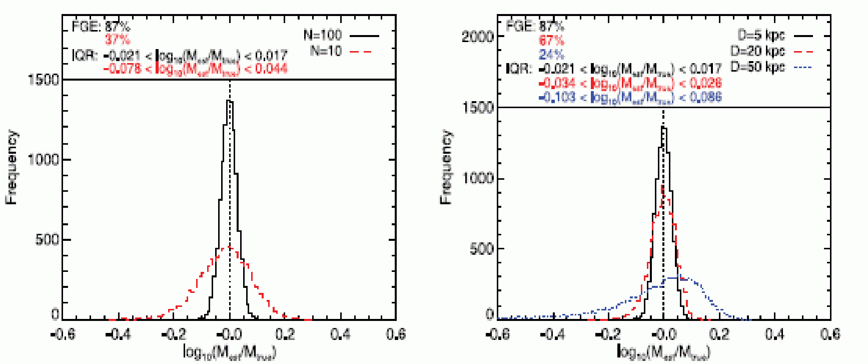


Figure 2. Left: estimates of enclosed mass of a globular cluster using 10 (dashed) and 100 (solid) tracers from 10^5 Monte Carlo realizations. Proper-motion errors of 100 μas yr^{-1} and a distance of 5 kpc are assumed. Right: estimates of enclosed mass as a function of globular cluster distance, namely 5 (solid), 20 (dashed) or 50 (dotted) kpc, assuming that 100 stars can be measured per globular cluster. The model has parameters $\alpha = 0$ and $\gamma = 3$.

Hattori et al, Gaia-ESO Survey

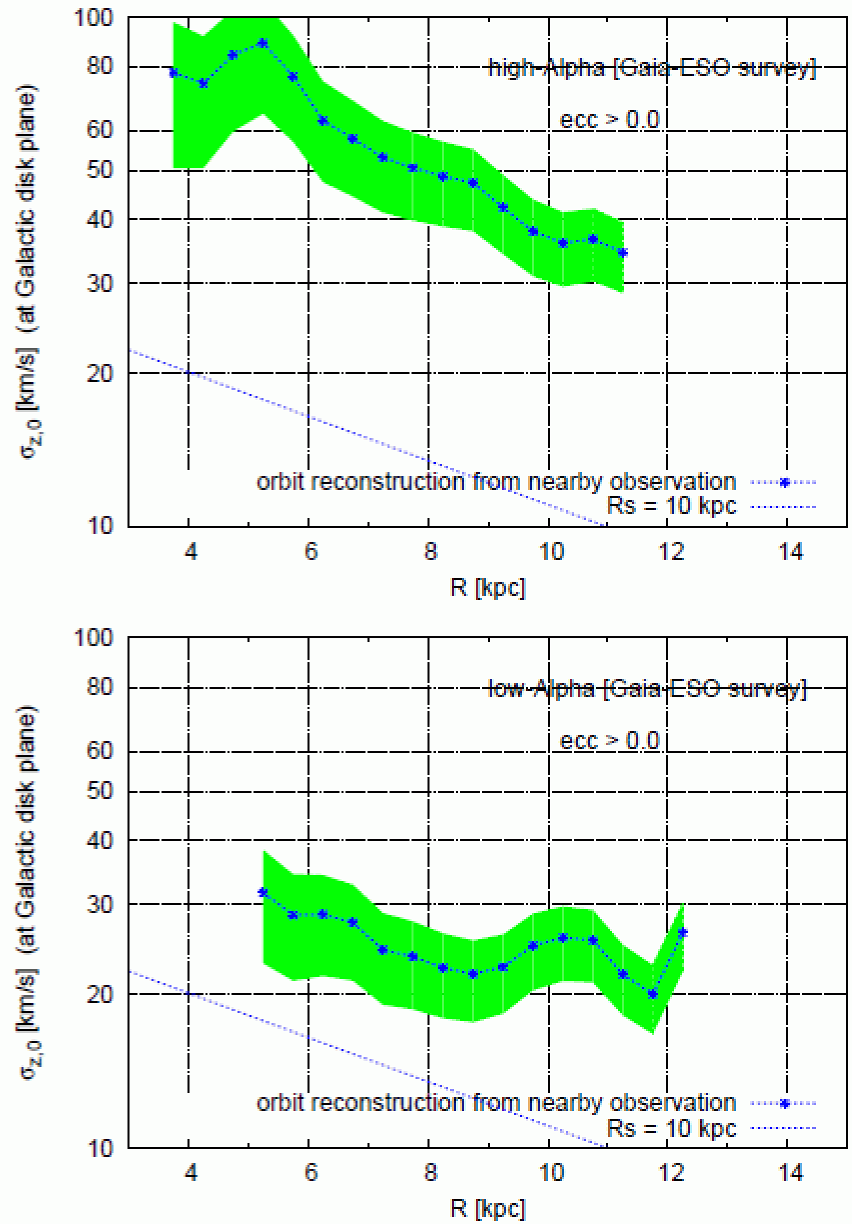


Figure 2: [Main result] Reconstructed radial profile of $\sigma_{z,0}$ (the velocity dispersion in z-direction at the Galactic plane). As a reference, I also show $\sigma_{z,0}(R) \propto \exp[-R/10\ \mathrm{kpc}]$.

New Astronomy Reviews 2013

Local disk dynamics

Dynamics for Galactic Archaeology

James Binney

Rudolf Peierls Centre for Theoretical Physics, Keble Road, Oxford O

Abstract

Our Galaxy is a complex machine in which several processes taneously: metal-poor gas is accreted, is chemically enriched and then drifts inwards, surrendering its angular momentu stars are formed on nearly circular orbits in the equatorial diffuse through orbit space to eccentric and inclined orbits; lar bar surrenders angular momentum to the surrounding dis while acquiring angular momentum from inspiralling gas; of the disc are constantly disturbed by satellite objects, bot dark, as they sweep through pericentre. We review the conc quired to bring these complex happenings into focus. Our fir be the construction of equilibrium models of the Galaxy, for u our hopes of determining the Galaxy's mean gravitational fi quired for every subsequent step. Ideally our equilibrium m formulated so that the secular evolution of the system can b perturbation theory. Such theory can be used to understan fuse through orbit space from either the thin gas disc in wh disc stars formed, or the debris of an accreted object, the pre many halo stars. Coupling this understanding to the still ver dictions of the theory of stellar evolution and nucleosynthesis extract a complete model of the chemodynamic evolution of generic Galaxy. We discuss the relation of such a model to c ulations of galaxy formation, which provide general guidanc relied on for quantitative detail.

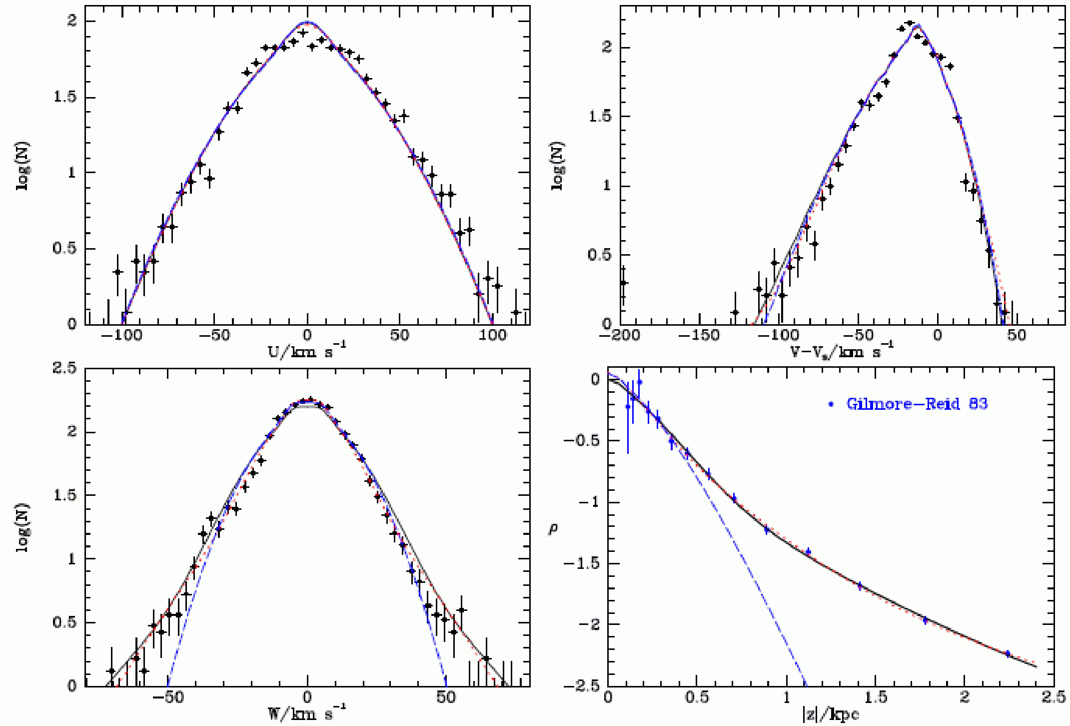


Figure 2. Fitting models in Potential I. The blue dashed curves show the result of choosing the parameters of the thin-disc DF to optimise the fits of this model with no thick disc to the GCS velocity distributions of local stars shown in the first three panels. The full curves show the results obtained when a thick disc is included and the Gilmore-Reid points for the density shown in the bottom-right panel are included in the data to be fitted, without adjusting the previously-determined thin-disc DF. The red dotted curves show the fits obtained when the parameters of both discs are simultaneously adjusted to optimise the fits to the GCS histograms and the Gilmore-Reid points. The parameters of the DFs responsible for the blue dashed, full and red-dashed curves are respectively listed in columns (a) to (c) of Table 2, respectively.

Distribution Function modelling RAVE 500000 star data

Jason Sanders - Action-Angle Approach

Maximize correlation between Θ and Ω structure of stream

Halo dynamics: streams as probes.
BUT Gaia will not deliver the radial velocities

Results: Pal 5

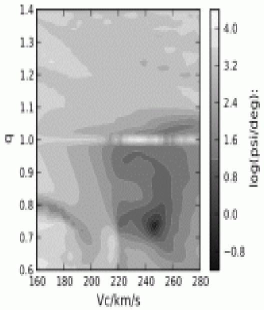
A few example analysis approaches from a recent workshop at Surrey: 1) streams => potential

Jason Sanders

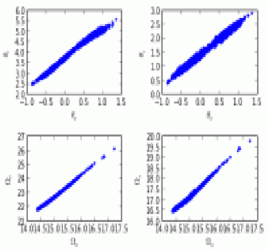
Using the axisymmetric logarithmic potential defined by two parameters V_c and q:

$$\Phi(R,z) = \frac{V_c^2}{2}\log\left(R^2 + \frac{z^2}{q^2}\right).$$

Here is a plot of the minimum misalignment between the frequency and angle structure of the stream as a function of these two potential parameters.

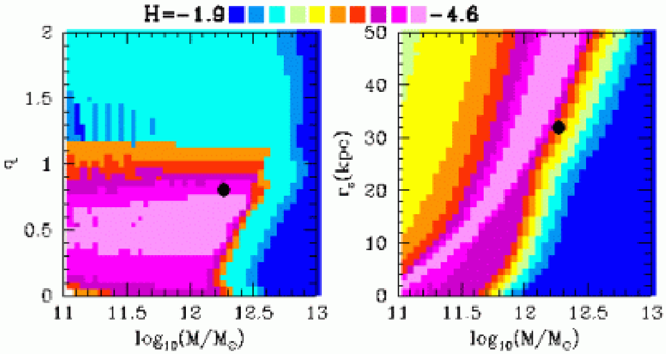


and here is the angle and frequency structure of the stream in the best-fitting potential defined as $V_c = 244km/s$ and $q = 0.74$



Jorge Peñarrubia

Disc & bulge fixed. Fitting 3 parameters of NFW halo. 1000 random particles



Solutions: Pal 5

- $M_{Halo} = 1.81194 \times 10^{12}\, M_\odot$
- $R_{Halo} = 32260\, pc$
- $q_z = 0.8140$
- $M_{Pal5}(t = today) = 23780\, M_\odot$
- $d_{Sun} = 23190\, pc$
- $V_C(R_{Sun}) = 249.01\, km/s$
- $V_C(R_{Pal5}) = 247.84\, km/s$
- $V_C(R_{Halo}) = 251.99\, km/s$
- $a(R_{Sun}, 0, 0) = 7.44\, pc/Myr^2$
- $a(R_{Pal5}) = a(7816pc, 240pc, 16640pc) = 3.34\, pc/Myr^2$
- $a(R_{Halo}, 0, 0) = 1.97\, pc/Myr^2$

Halo dynamics: streams as probes.
BUT Gaia will not deliver the radial velocities

- Publication Policy

Andreas Küpper/Ana Bonaca - Streakline Method

From present-day position & velocity of the progenitor of interest, integrate the orbit of a cluster particle of a given mass in a test potential backwards for several Gyr. Then integrate forward to present time. While doing so, generate test stream particles. Compare the present-day distribution of stream test particles to the observations. Define likelihood, calculate likelihood, put in MCMC, stirr, ready.

Andreas Küpper/Ana Bonaca - Streakline Method

Constraining the stream with a axisymmetric logarithmic potential we obtain:

1. with N=66 stars

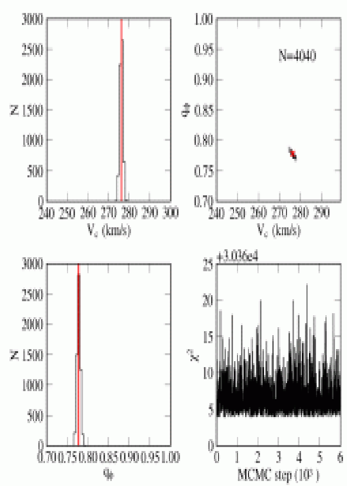
$V_c = 272^{+4}_{-5}$ km/s

$q_z = 0.79^{+0.03}_{-0.02}$

2. with N=4040 stars

$V_c = 276.1^{+0.7}_{-0.8}$ km/s

$q_z = 0.777 \pm 0.004$



Adrian Price-Whelan - Orbit Rewinder

Need:

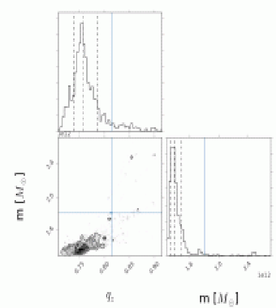
- Present-day 6D position of progenitor
- 6D data for a sample of stars stripped from the progenitor

Integrate orbits of progenitor and stars *back* in time; the stars recombine into the progenitor in the correct potential, but their orbits diverge in an incorrect potential. See this paper or these movies for more detail (correct, incorrect).

q_z MCMC step (10^3)

Adrian Price-Whelan - Orbit Rewinder

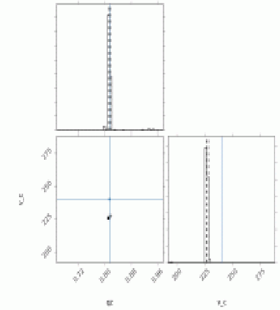
- By randomly sampling **100 stars** from the Pal5 stream.



- $q_z = 0.76 \pm 0.01$
- $M = 1.39^{+0.1}_{-0.05} \times 10^{12}\ M_\odot$

Palomar 5 with simple potential:

- Whoa, ok this is a bit surprising. I've run again with just a 2 parameter logarithmic halo, similar to what Ana and Jason used. Here the results are much better, but it may just be that biases are working out to make it look better than it is...posting the relevant posterior anyways.



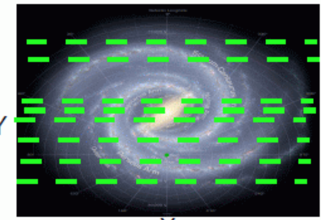
Disk potentials…

Bar & spiral pattern speeds

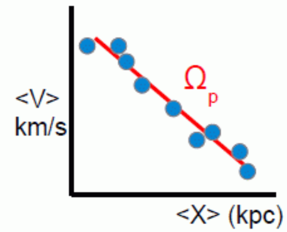
Why pattern speeds are important? cf Monari, Santi-Fabrega & Penniger' talks on monday

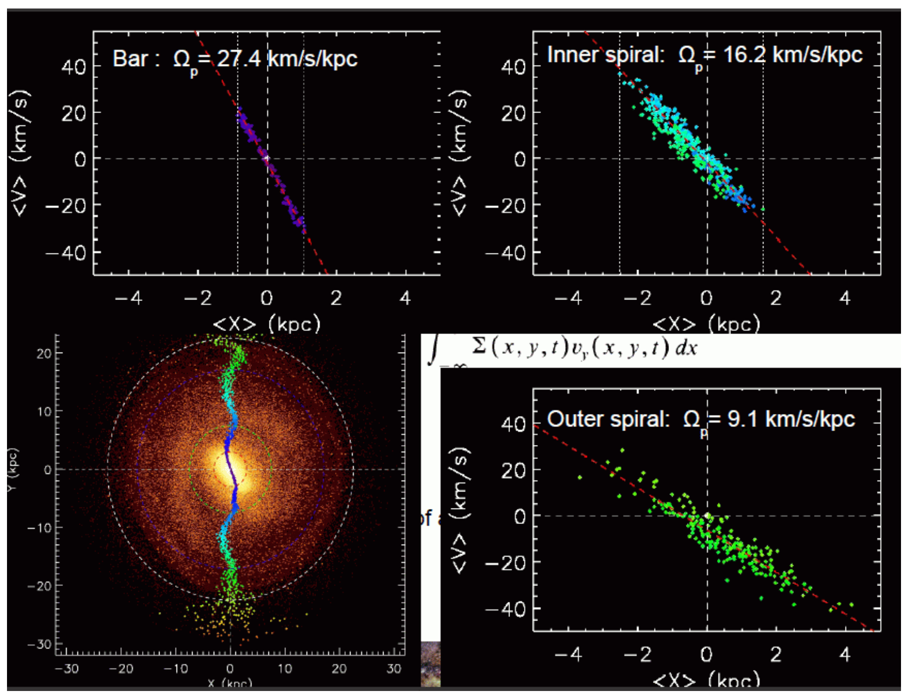
Tremaine-Weinberg method (Tremaine & Weinberg 1984)

$$\Omega_p \sin i \int_{-\infty}^{\infty} \Sigma(X,Y)\,X\,dX = \int_{-\infty}^{\infty} \Sigma(X,Y)\,V_{\|}(X,Y)\,dX.$$



- Independent from dynamical modeling
- A few tens of bar pattern speeds determined (e.g. Gerssen+99, Debattista & Williams 04, Hernandez+05, Fahti+07, Chemin & Hernandez 09)
- Fast bars in early type and/or massive discs
- Slow bars (Ω_p < 20 km/s/kpc) in late type





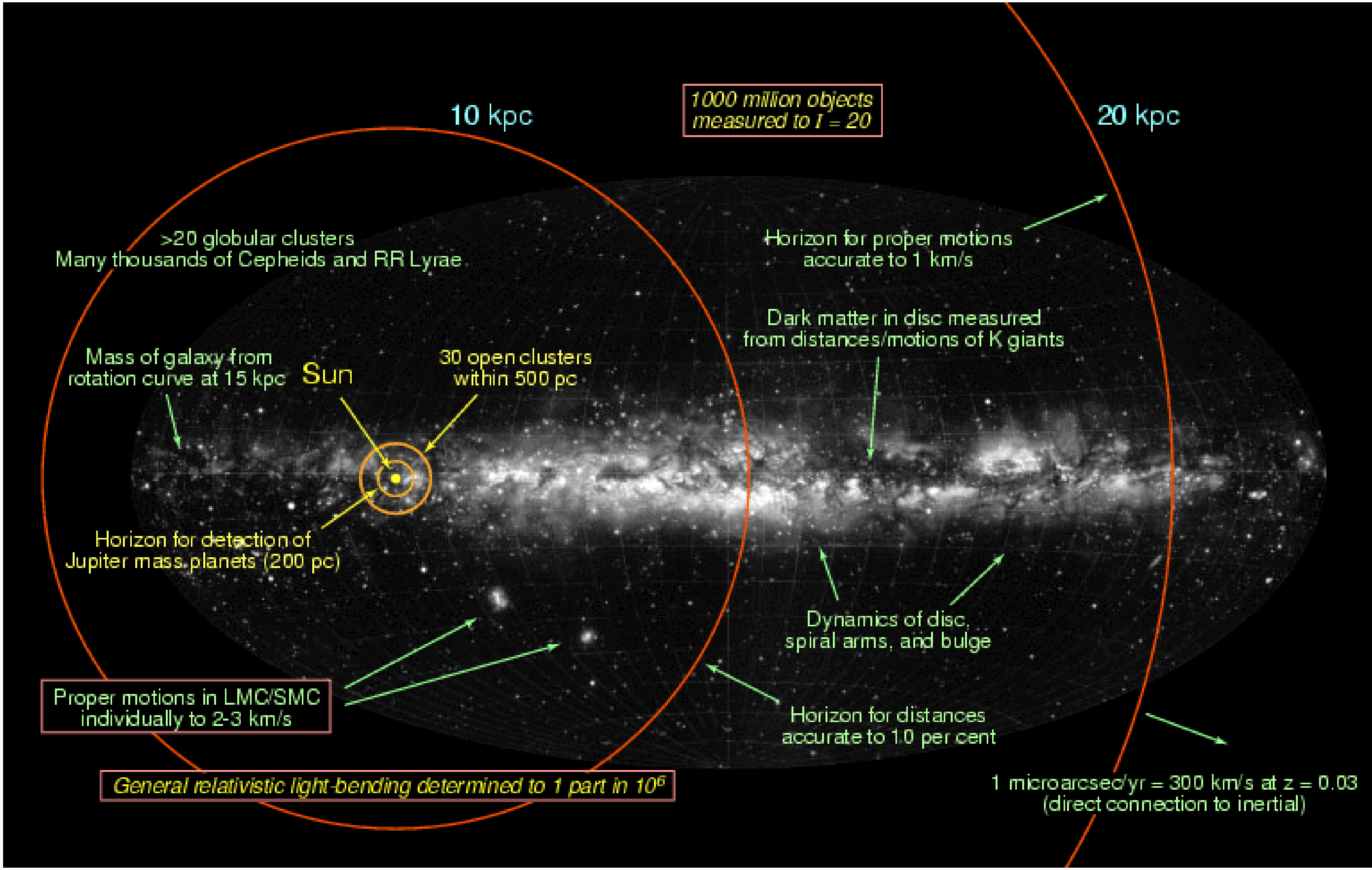
The Gaia legacy for DM

- Quantifying the Galactic potential within ~5kpc will be limited only by our ability to analyse kinematics
- At larger distances Gaia's calibration of secondary calibrators (eg RRLyrae) will quantify the potential, given RV data and suitable analyses.....
- Mapping the central kpc will be challenging
- Finding pure DM halos will be challenging

- Gaia will NOT: resolve orbits in faint dSph

- We'll know a lot about the potential in 2017.....

Gaia: mapping Dark Matter, forming the Galaxy



10 μas = 10% distances at 10 kpc

10 μas/yr = 1 km/sec at 20 kpc

Outreach with Science Alerts

- Science Alerts can be exciting not only for professionals
- a platform will be built to provide alerts to the general public
- not only alerts, but also tools for observing, data reduction, studying
- cool projects, *e.g.* “Adopt a Supernovae”
- amateurs, schools, universities...