Microarcsecond astrometry with Gaia - The solar system, the Galaxy and beyond

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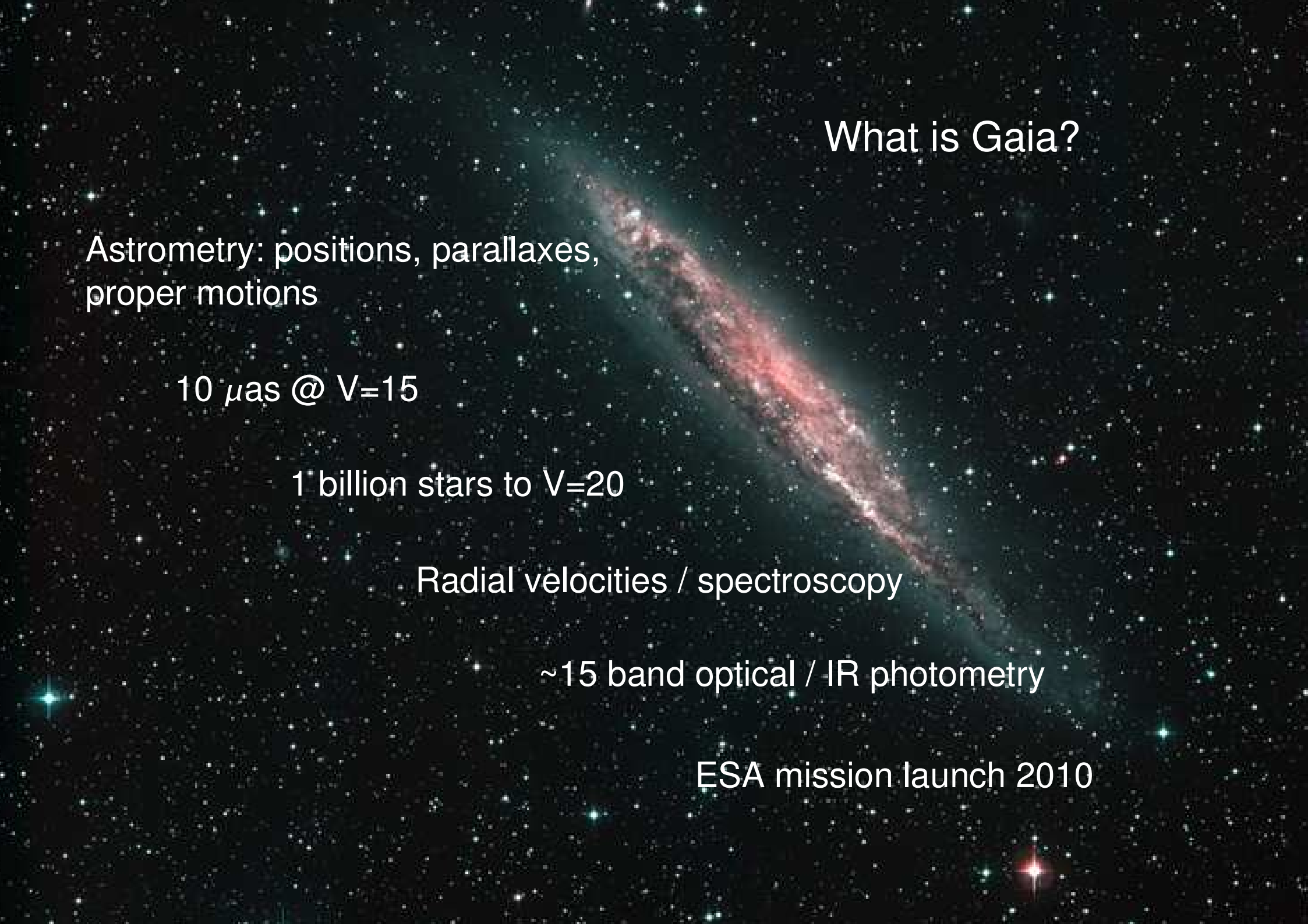
& Gaia Science Team

acknowledgements: Gaia Science Team, Michael Perryman, Gaia working groups, industrial partners


What is Gaia?
Astrometry: positions, parallaxes,
proper motions
10 μas @ V=15
1 billion stars to V=20
Radial velocities / spectroscopy
~15 band optical / IR photometry
ESA mission launch 2010

Gaia science objectives

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Preston, 7-11 June 2004

- Galactic structure and formation
- Dynamics *(dark matter, merger history)*
- Stellar astrophysics *(HRD, abundances, binaries)*
- Star formation *(OB assoc., clusters)*
- Exoplanets *(10^4 detections, 10^3 orbits, masses, transits*)
- Solar system *(10^5 minor planets, taxonomy, NEOs)*
- Extragalactic *(local group galaxies, SNe)*
- Cosmic distance scale *(geometric to 10 kpc, Cepheids, RR Lyr)*
- Reference frame *(quasars)*
- Fundamental physics *(light bending, γ to 5×10^{-7})*

Gaia vs. Hipparcos

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	Hipparcos	GAIA
Magnitude Limit	12.4	20
Completness	7.3-9.0	20
No. sources	120 000	26 million to V=15 250 million to V=18 1000 million to V=20
No. quasars	none	0.5-1 million
No. galaxies	none	1-10 million
Astrometric accuracy	~1000 uas	2-3 uas at V<10 5-15 uas at V=15 40-200 uas at V=20
Broad band photometry	2 (B,V – Tycho)	4
Medium band photometry	none	10 to 16
Spectroscopy	none	R=11 500 (848-874 nm)
Radial velocities	none	1-10 km/s to V=17-18
Target selection	input catalogue	onboard; mag. limited

Global astrometry

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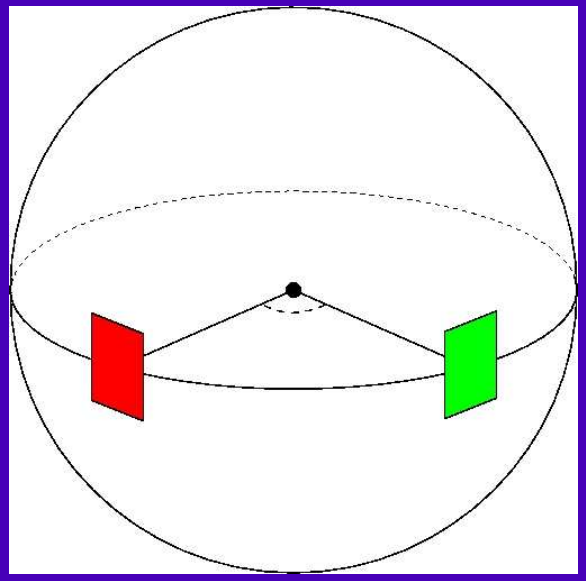
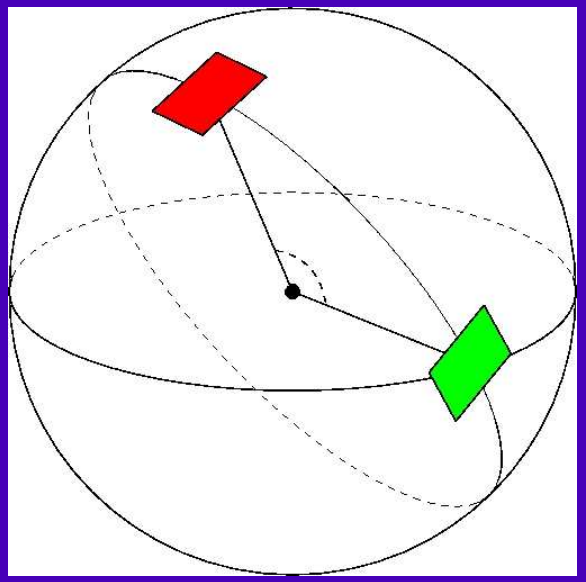
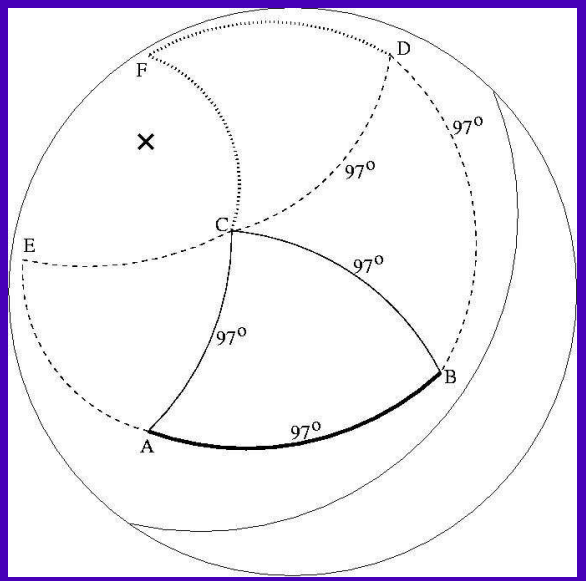




1. Observe simultaneously in two fields separated by a constant *basic angle*
2. Multiple observations at different orientations
3. Construct a network over celestial sphere
4. Measure positions of stars relative to each other
5. Simultaneously solve for astrometric parameters of stars plus satellite attitude (iteratively)



Scanning law

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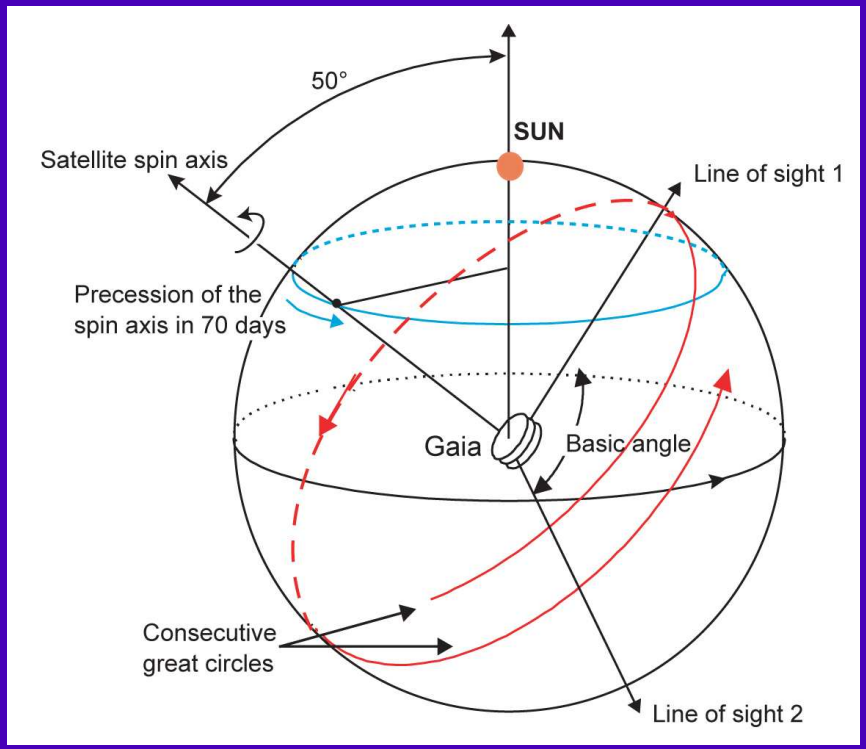
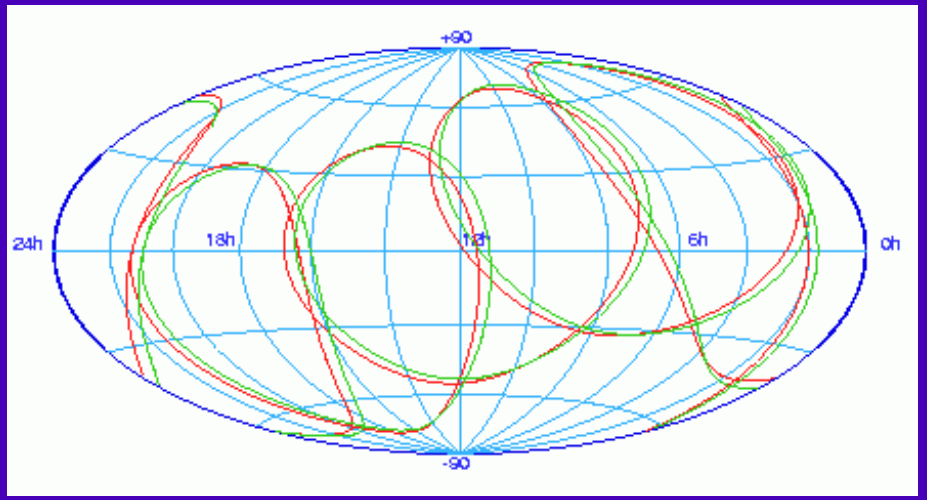
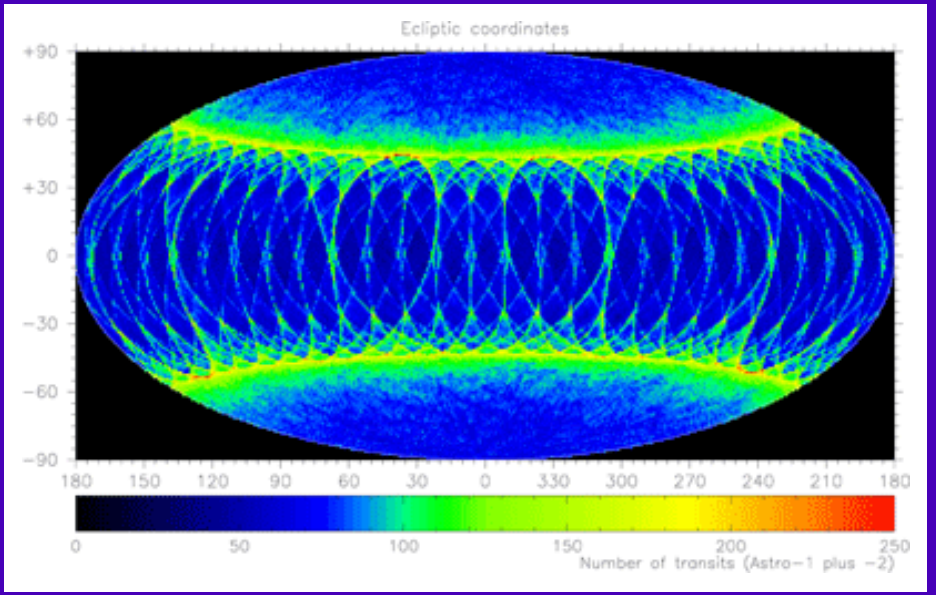
Continuous three-axis motion:
- axis rotation (period = 6 days)
- fixed sun angle precesion (70 days)
- orbit around sun (1 year)

Traces quasi great circles on sky
5 year mission







Satellite and orbit

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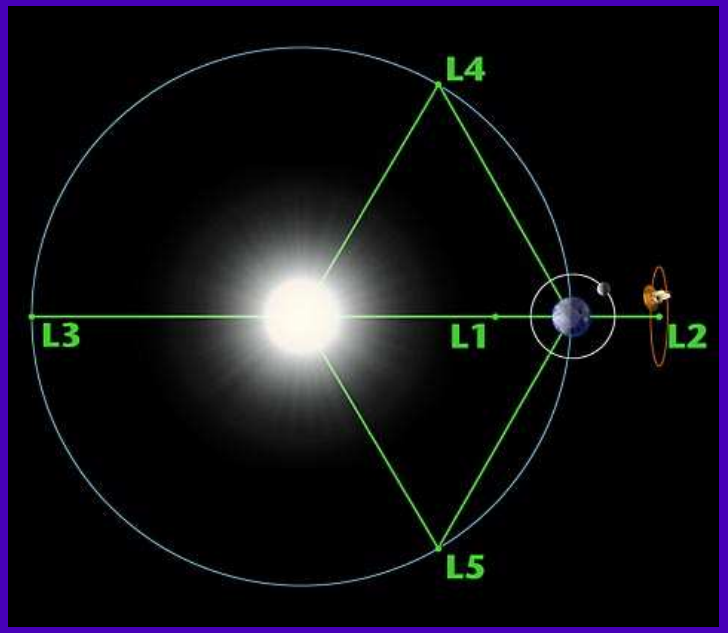
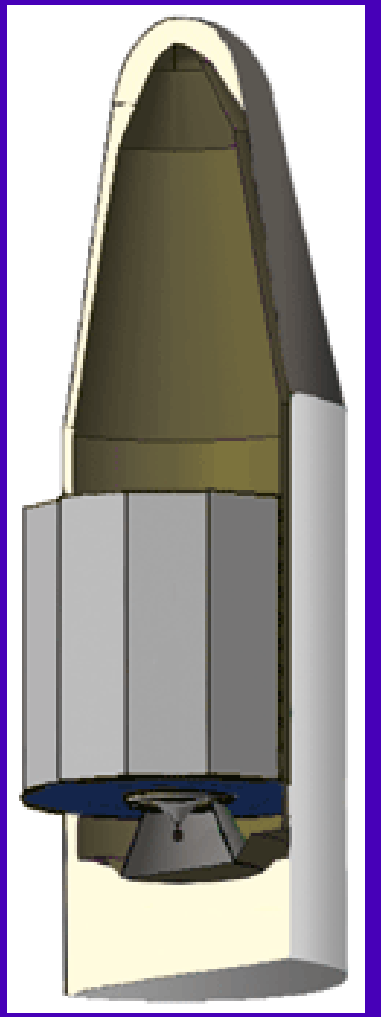


basic angle must be stable to 1 μas over 6 hours

⇒ 25 μK thermal stability
⇒ stable environment
⇒ no moving parts!
⇒ monitor basic angle variations

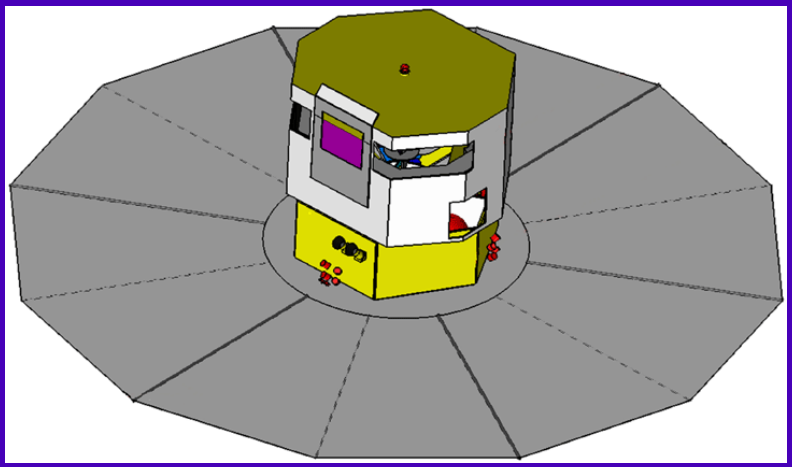
Lissajous' orbit about Earth-Sun L2 point (thermal stability, no drag etc.)



deployable sunshield
- 11m diameter
- passive cooling to 170K

PLM+SVM: 1400 kg; 3.1m high

phased antenna array
- 3 Mb/s for 8 hours per day
- single ground station



Payload overview

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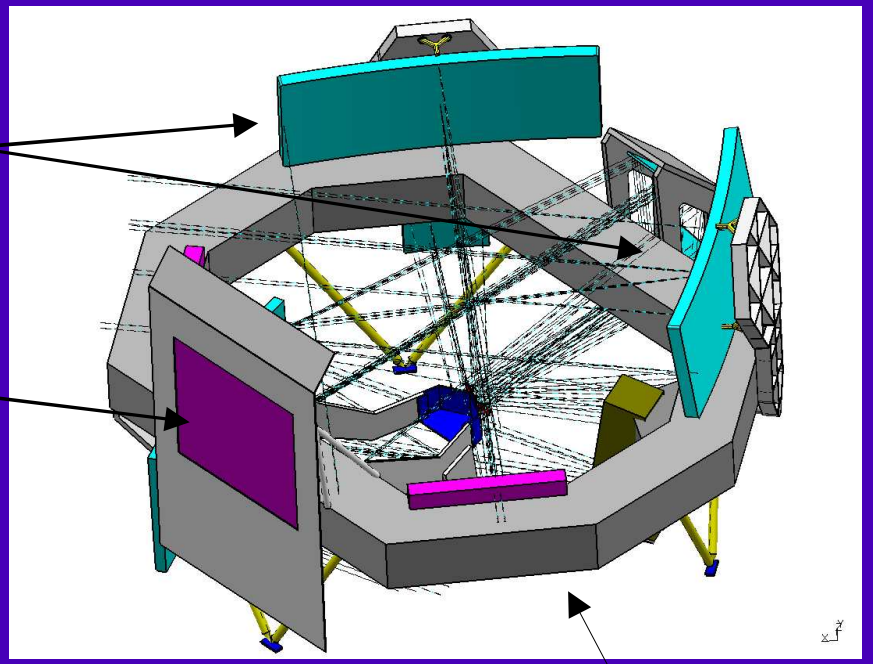
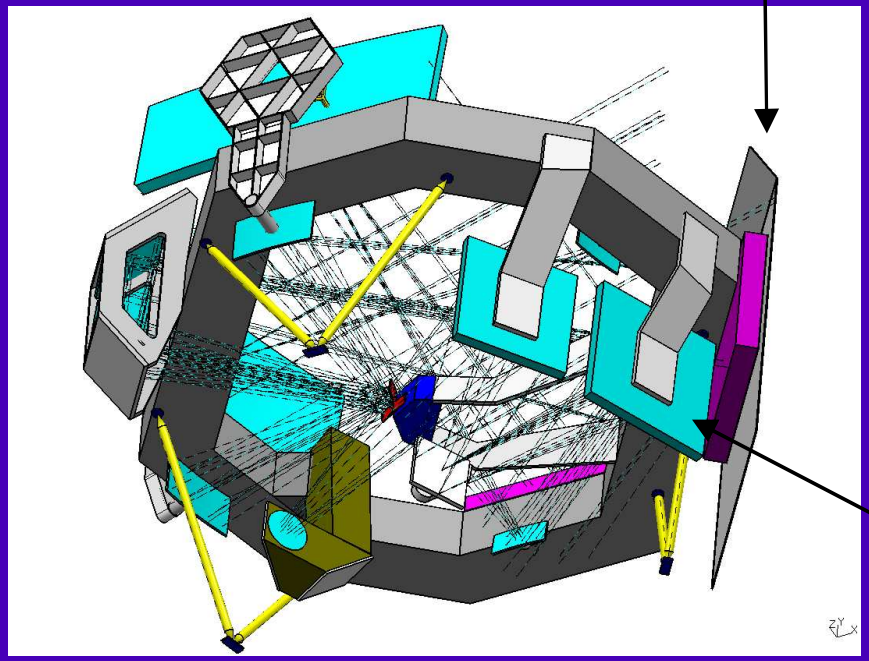
Astrometric instrument:
1.4m x 0.5m primary mirrors



Astrometric focal plane



SiC optical bench

Spectroscopic instrument:
0.56m x 0.45m primary mirror

Astrometric instrument optics

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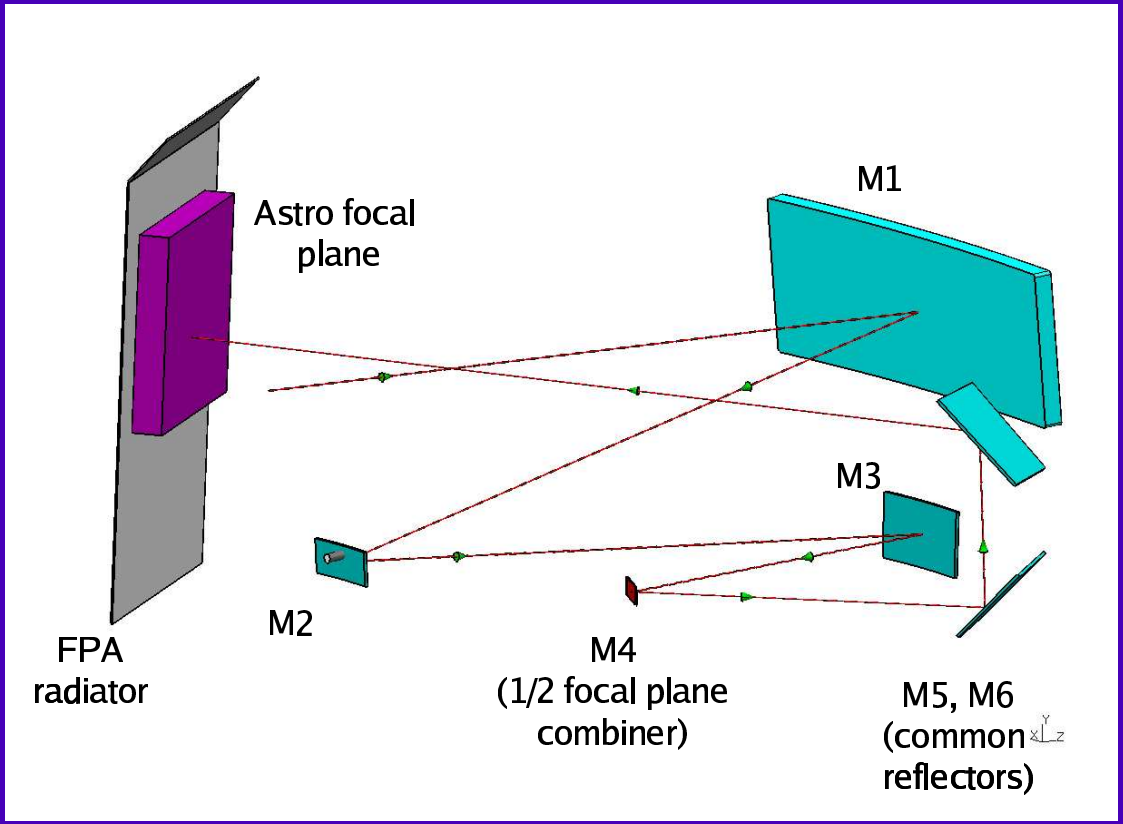

Astrometric focal plane

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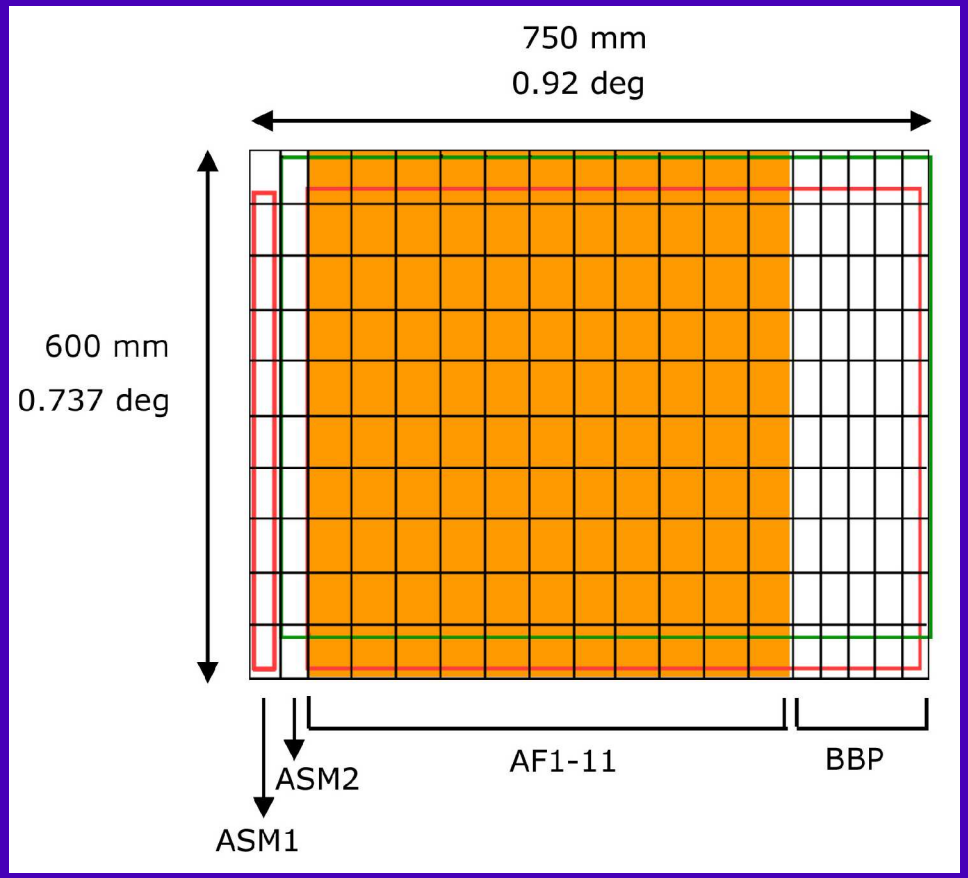

direction of motion across focal plane

Two FOVs superimposed on single CCD focal plane

180 CCDs (2000 x 5600 pixels)

CCDs clocked in TDI mode, 55s transit time

Mean of 2x41 passages over 5 years

Astrometry in `white' light (G band)

4 broad band photometry (BBP) for chromatic correction

real time on-board detection
=> star mappers (detect+confirm)
=> select CCD windows to transmit

Spectro focal plane

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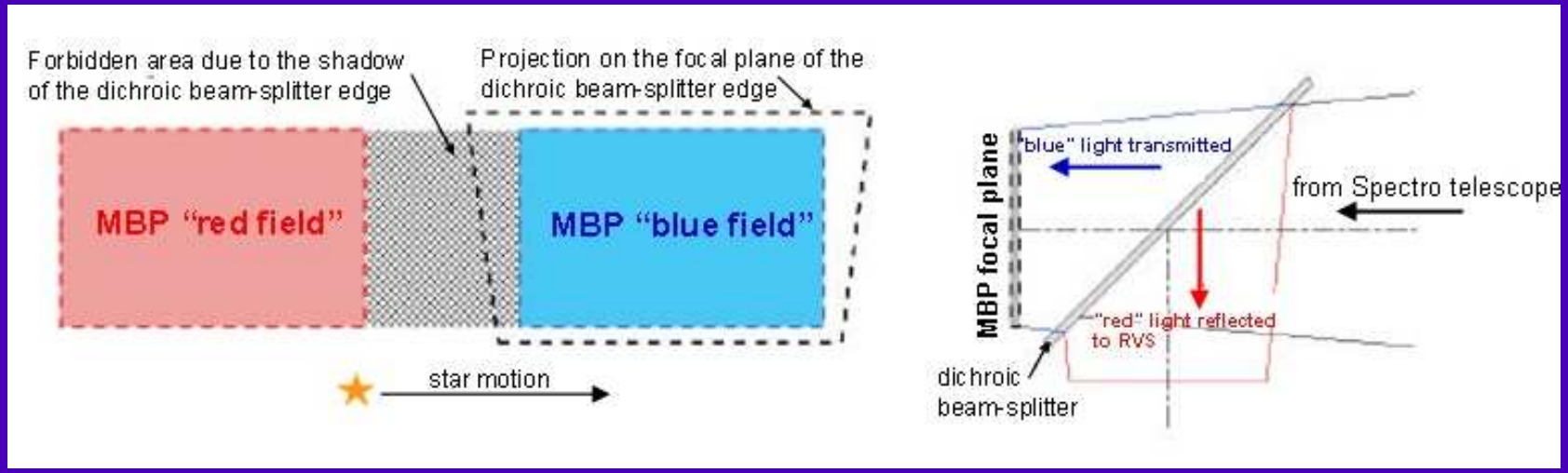
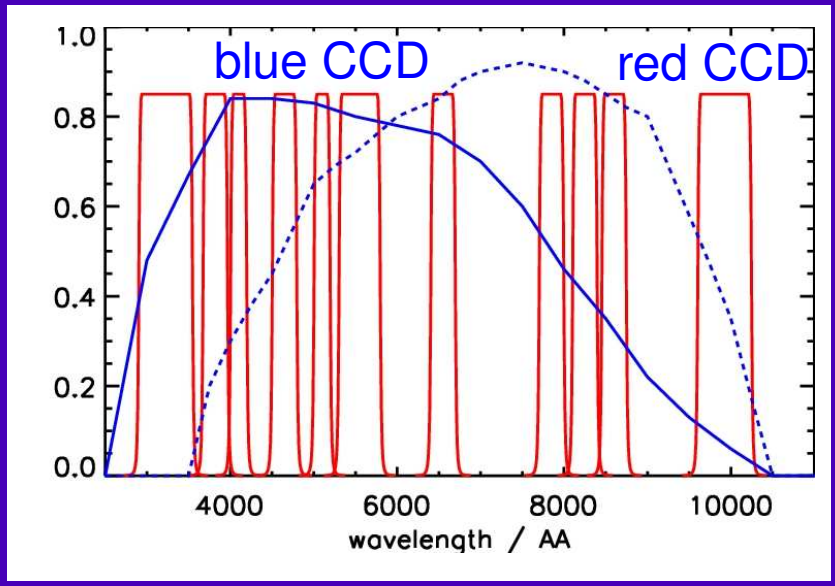


Spectro: RVS + Medium Band Photometer

MBP = Physical characterization of sources
- up to 16 filters
- discrete classification (star, galaxy etc.)
- Teff, [Fe/H], A_V, logg, [α/Fe]
- binaries
- identify new types of objects

Astro*physical* + Astro*metric* catalogue



Distance and velocity precision

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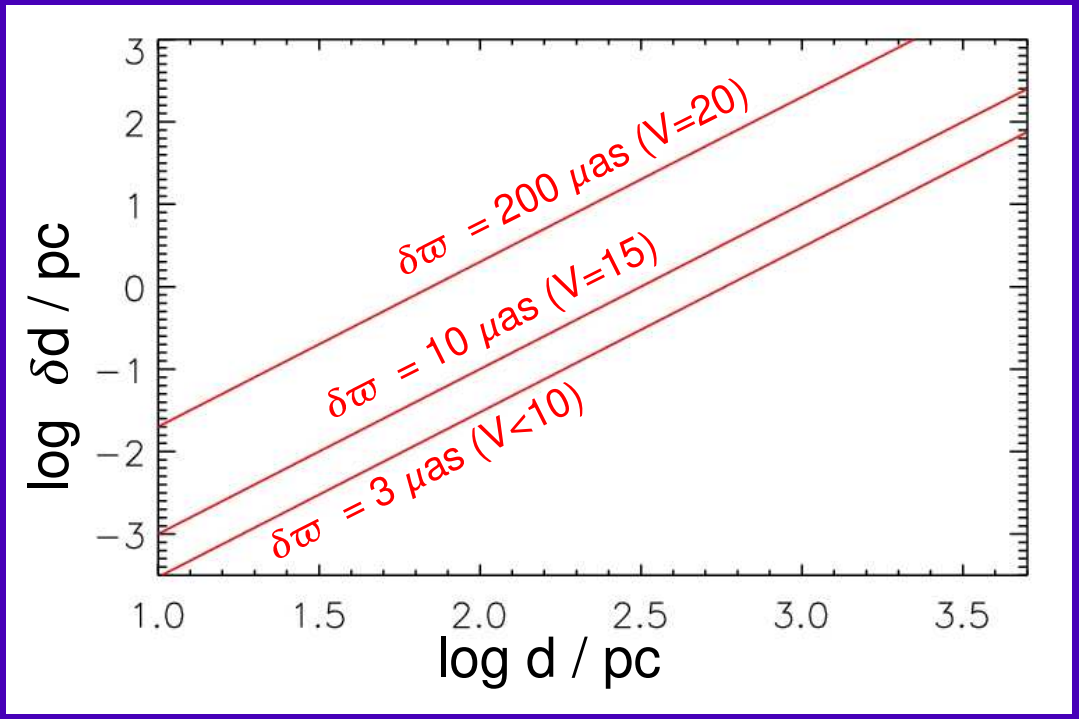

Scaling relations

astrometric error, $\delta\varpi \sim 1/\sqrt{f}$
distance error, $\delta d \sim d^2\, \delta\varpi$
trans. velocity error, $\delta v \sim d\, \delta\varpi$

[given star: $f \sim 1/d^2 \Rightarrow \delta\varpi \sim d$]

1 km/s = 200 μas/yr @ 1kpc

Distances

0.2% accuracy at 200 pc at V=15
1% accuracy at 1 kpc at V=15
20% accuracy at 1 kpc at V=20

<0.1% for 700 000 stars
<1% for 21 million stars
<10% for 220 million stars

Transverse velocities

0.1 km/s accuracy at 2 kpc at V=15
1 km/s accuracy at 20 kpc at V=15
1 km/s accuracy at 1kpc at V=20

<0.5 km/s for 44 million stars
<1 km/s for 85 million stars
<5 km/s for 300 million stars

Solar system

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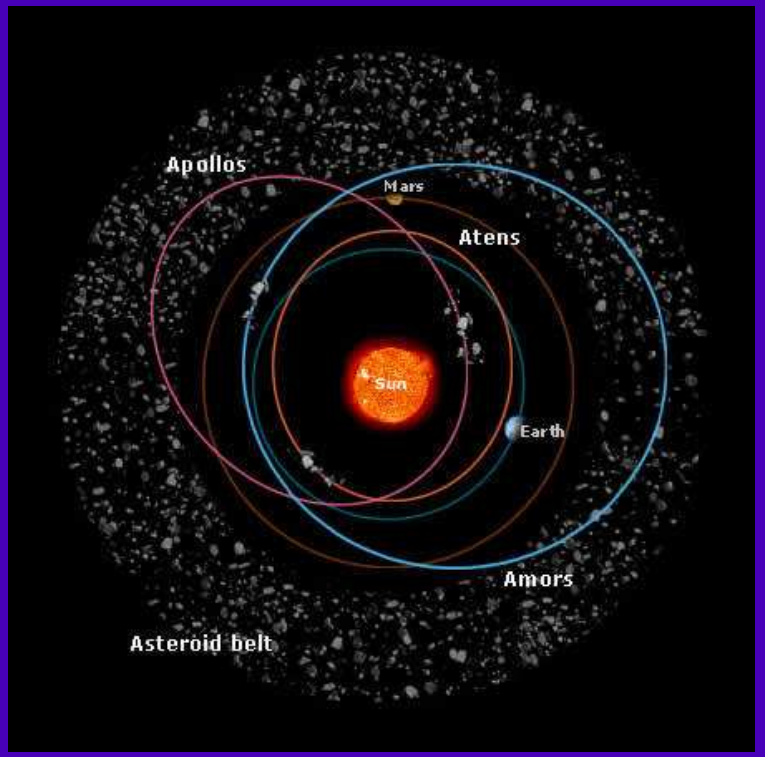

- Main belt asteroids
  - solar system formation
  - sizes, albedos, masses (~ 100, cf. 10 now)
- Near-Earth objects
  - high speed (0.1"/s ⇒ modified onboard detection)
  - expect 1600 Earth-crossing (vs. 100 now)
- Trojans (e.g. at Jupiter L4, L5)
  - formed in situ or captured? similar to asteroids?
- General Relativity
  - light bending (17 mas at Jupiter limb), γ to 5×10^{-7}, perihelion precession (J_2)
- Gaia capabilities
  - all sky complete survey to G=20, to within 35° of Sun ("daytime")
  - discovery of 10^5-10^6 new objects (cf. 65000 now)
  - very accurate orbital elements (~30 times better)
  - multi-band photometry (taxonomy, chemistry, space weathering)

Exosolar planets

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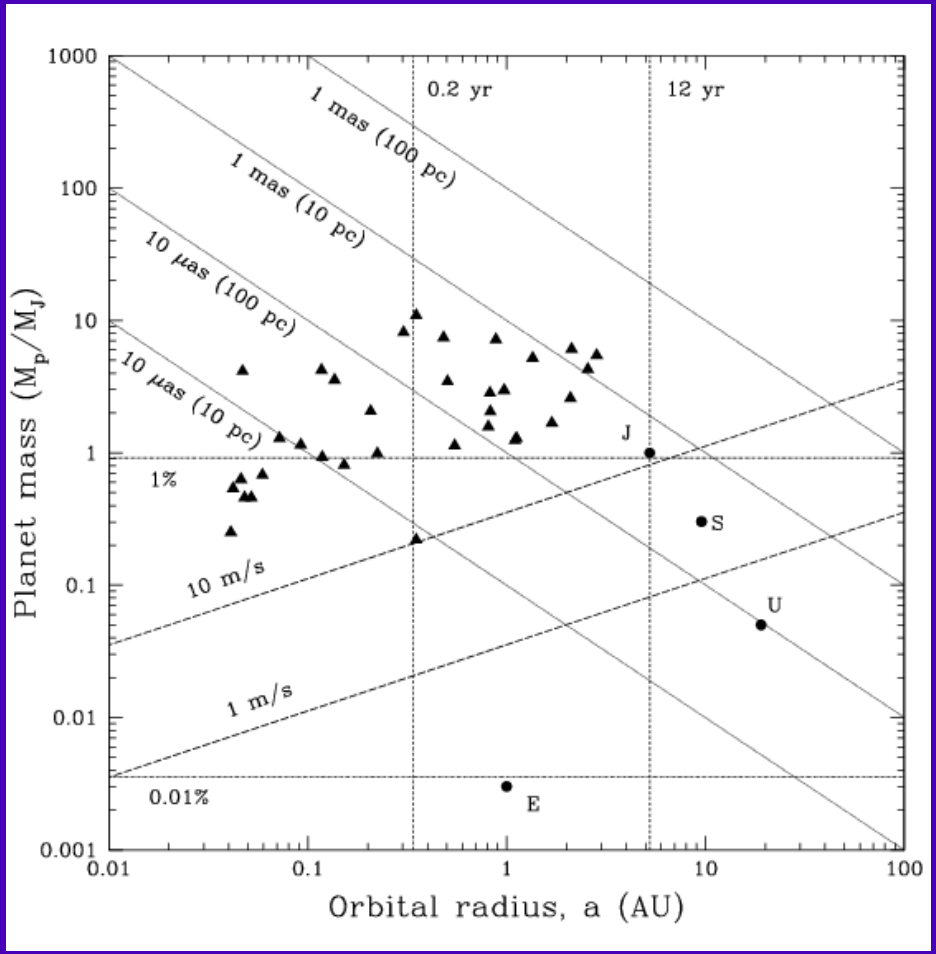
- astrometric companion search
  - $\alpha = (M_p/M_s)(a_p/d)$
  - 47 UMa: astrom. displacement 360 μas
  - no *sin i* ambiguity in mass
  - complements RV parameter space
- extensive survey
  - monitor 10^5 stars to 150-200 pc (V<13)
  - all stellar types to P ~ 10 years
  - ~ 5000 new planets expected
  - orbital solutions for 1000-2000 systems
  - masses to 10 M_E to 10pc
- transits
  - Jupiter across Sun @ SNR=10 ⇒ 1 millimag photometric precision
  - expect 6000 detections for 0-2 AU orbit around F-K stars
  - Venus around Sun ($1/115^2$) would require 0.01 millimag precision



Clusters and associations

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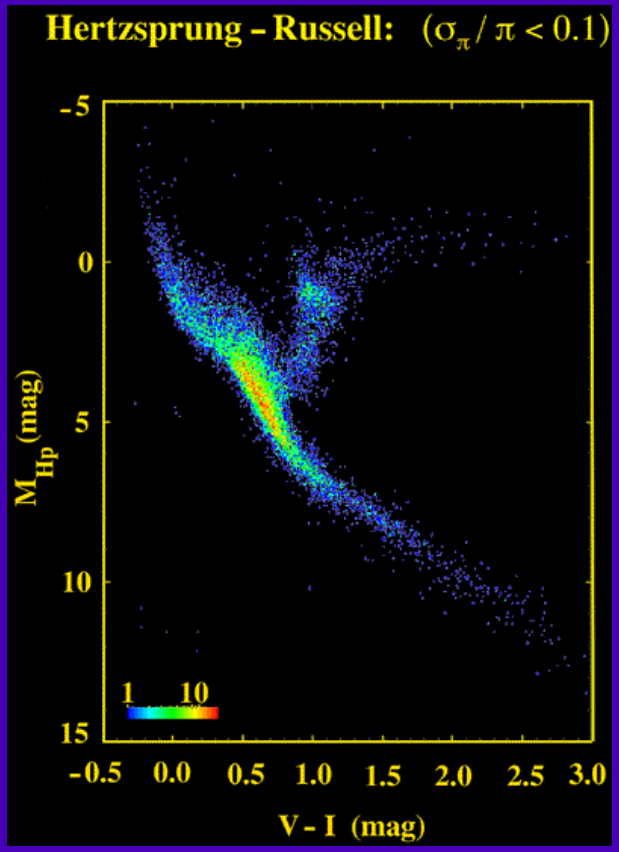
- ~70 clusters + SFRs within 500 pc (20 in 200pc)
  - *individual* distances to 0.5%, <2.5pc at V=15
  - transverse velocities to <1 km/s for
    - all stars down to M dwarfs out to 200pc
    - all giants and OB(A) stars out to 500 pc
  - search for new clusters (3D structure, 3D kinematics)
- Hertzprung-Russell Diagram
  - ages from MS turn off (more subgiants)
  - IMF (to BD limit in Hyades, to 1M_{sun} out to 3kpc)
- kinematics
  - mass segregation (dynamic vs. primordial)
  - ejection (BDs) evaporation, dispersion
- stellar structure
  - luminosity calibration (10% distances to: GV to 3kpc; AV + KIII to 10 kpc)
  - He abundances



Galactic structure

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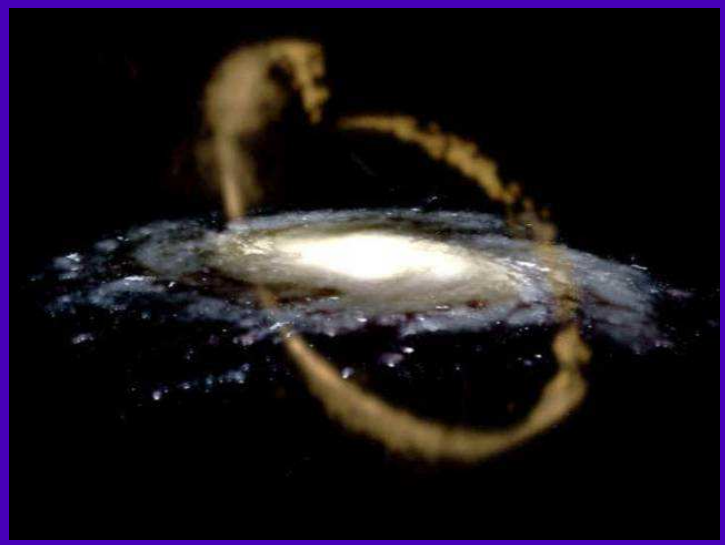
- galaxy formation
  - substructure in halo (merger history)
  - 0.5 km/s precision at V=15 at 10kpc
  - internal photom. parallaxes for outer halo (gG, gK, HB)
- evoluton of stellar populations
  - star formation history in 3D
  - age-metallicity relation (K, M dwarfs)
  - metallicity structure in disk components and halo
- Galactic disk
  - spiral arms (Cepeids, extinction map)
  - mass, dark matter, rotation curve



Extragalactic

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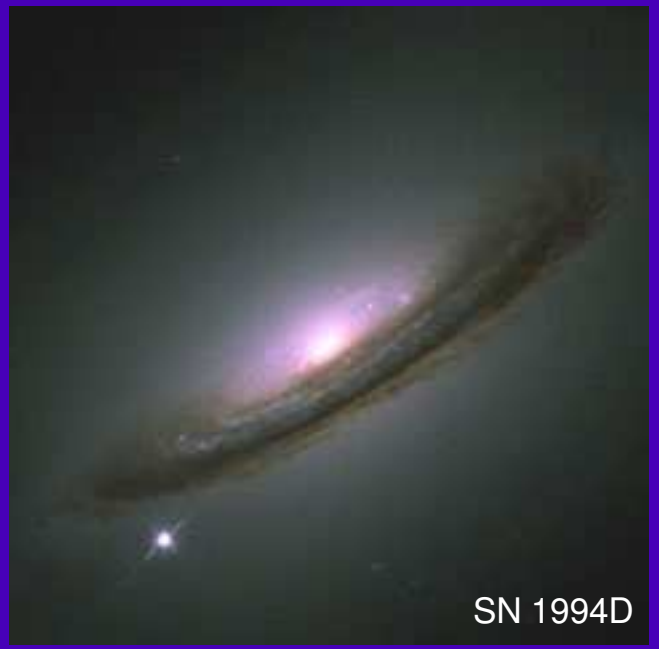
- local group
  - LMC ϖ=20μas; average geometric distance to ~1%
  - discrimination of foreground stars via proper motions
  - internal dynamics of dSph
- quasars
  - ~500 000; multicolour quasar survey + variability
  - quasi-inertial reference frame accurate to <1 μas/yr
  - galactocentric acceleration ~ 4 μas/yr
- supernovae
  - realtime onboard detection: ~ 50 per day
  - alerts system, ground-based follow-up
- cosmology
  - calibration of distance scale
  - 3D orbits in local group out to 1-2 Mpc (> 20 galaxies)
    ⇒ probe initial density fluctuations


LMC


SN 1994D

Cosmic distance ladder

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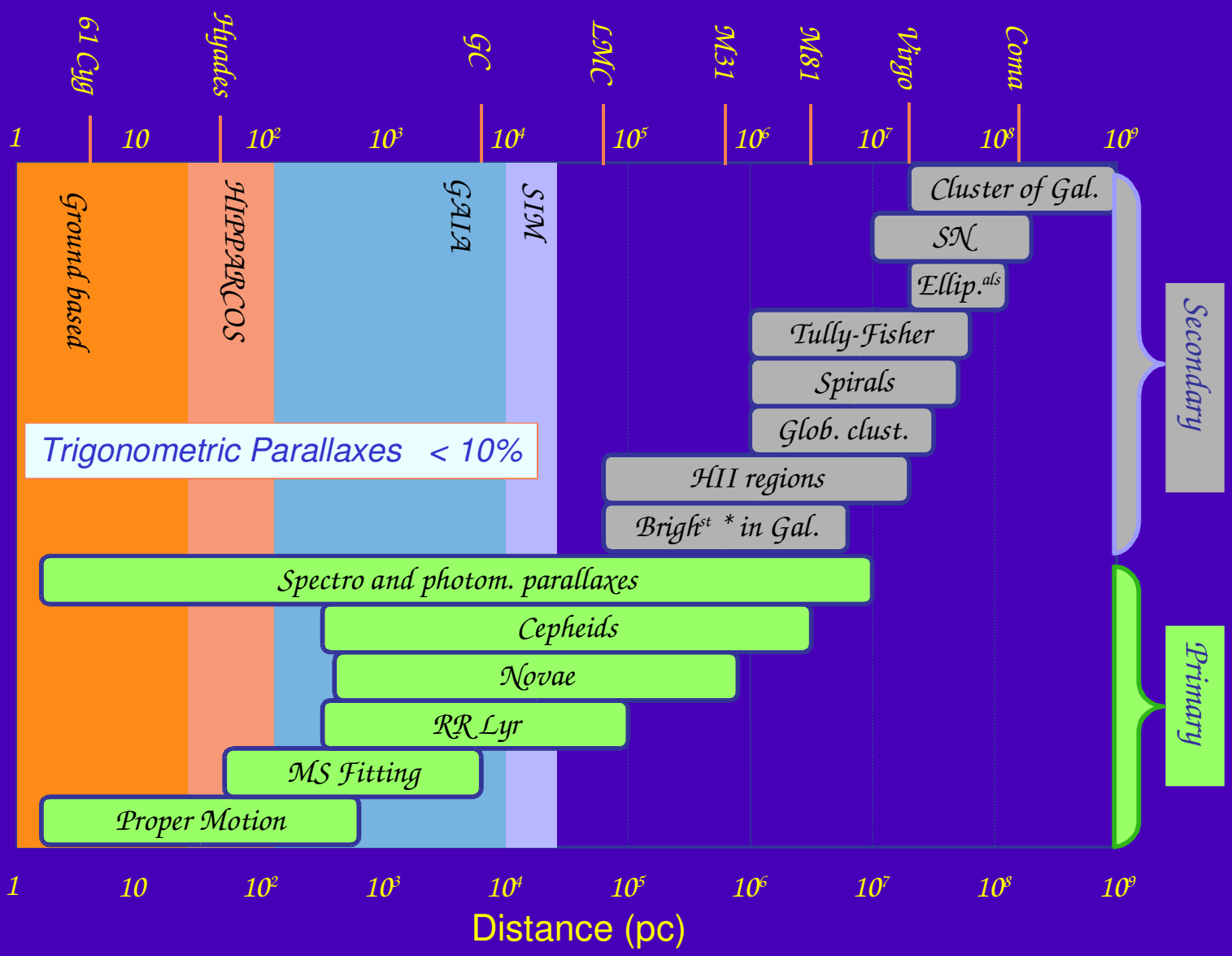

Schedule and data processing

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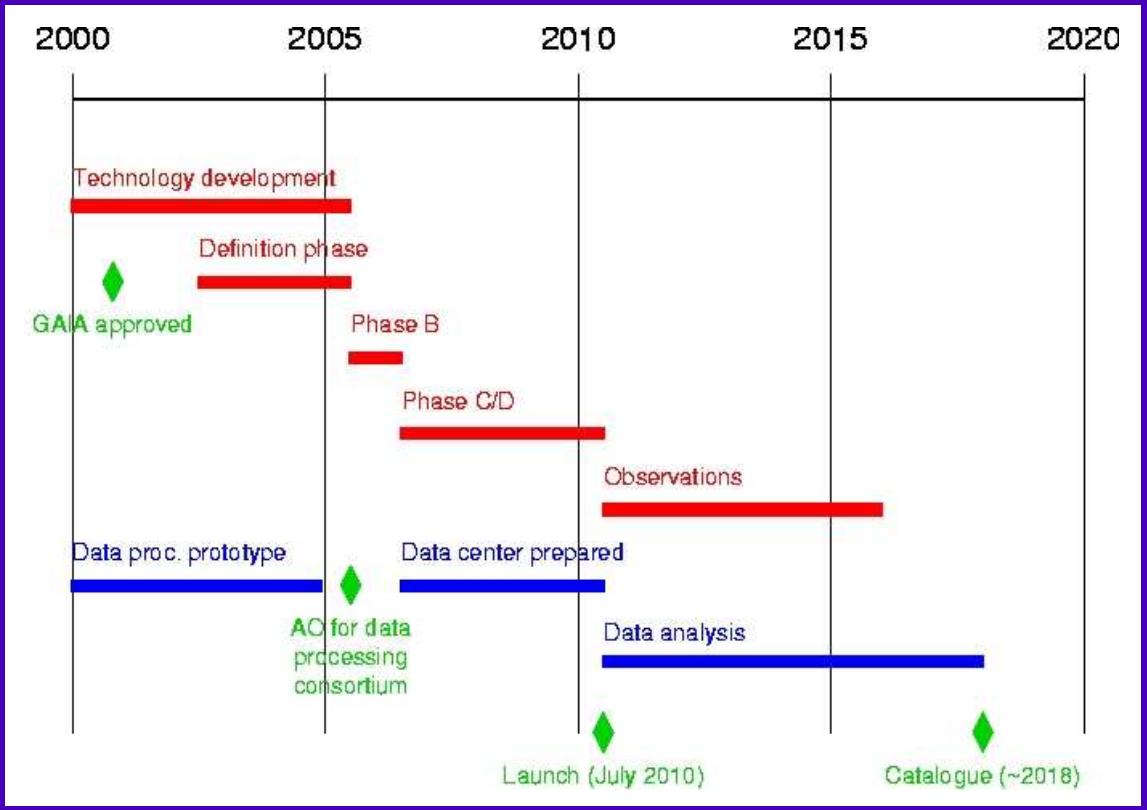
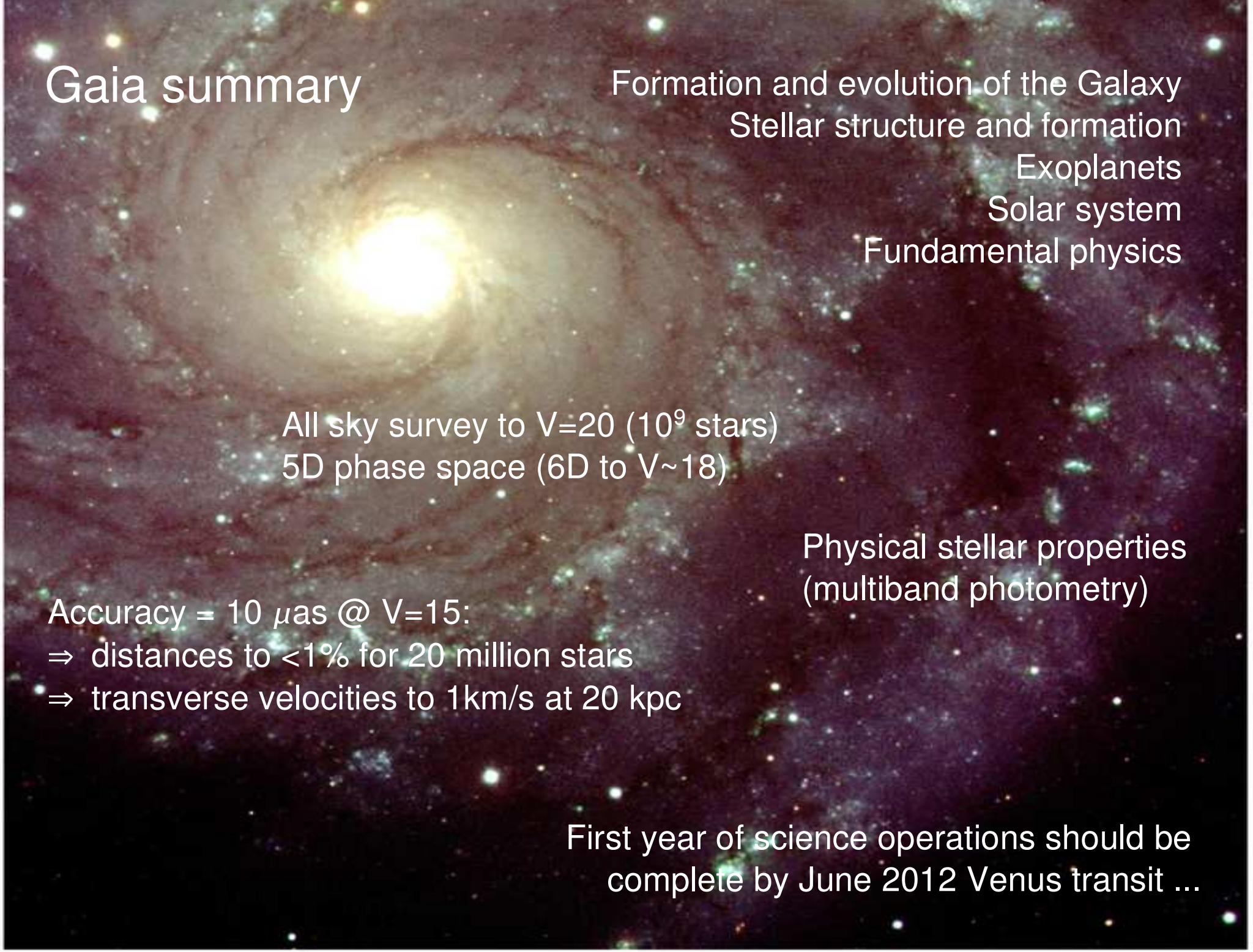


- Complex data stream
- Iterative adjustment of 100s millions of stars
- astrometric, photometric and spectroscopic data
- quick look processing (e.g. SNe)

- 10^{19} to 10^{21} FLOPS (cf. 10^{22} inst. SETI@home, 10^{17} inst. 1 PC for 1 year)
- 100 TB raw data, ~1 PB working space
- Cf. 1 TB text of books published in 1 year [~ 1 million], 20 TB SDSS raw
- 1s per star for *all* operations would require 30 years


Gaia summary
Formation and evolution of the Galaxy
Stellar structure and formation
Exoplanets
Solar system
Fundamental physics
All sky survey to V=20 (10^9 stars)
5D phase space (6D to V~18)
Physical stellar properties
(multiband photometry)
Accuracy = 10 μas @ V=15:
⇒ distances to <1% for 20 million stars
⇒ transverse velocities to 1km/s at 20 kpc
First year of science operations should be
complete by June 2012 Venus transit ...