Space Astrometry: 2/3
a synopsis of the
Hipparcos scientific results

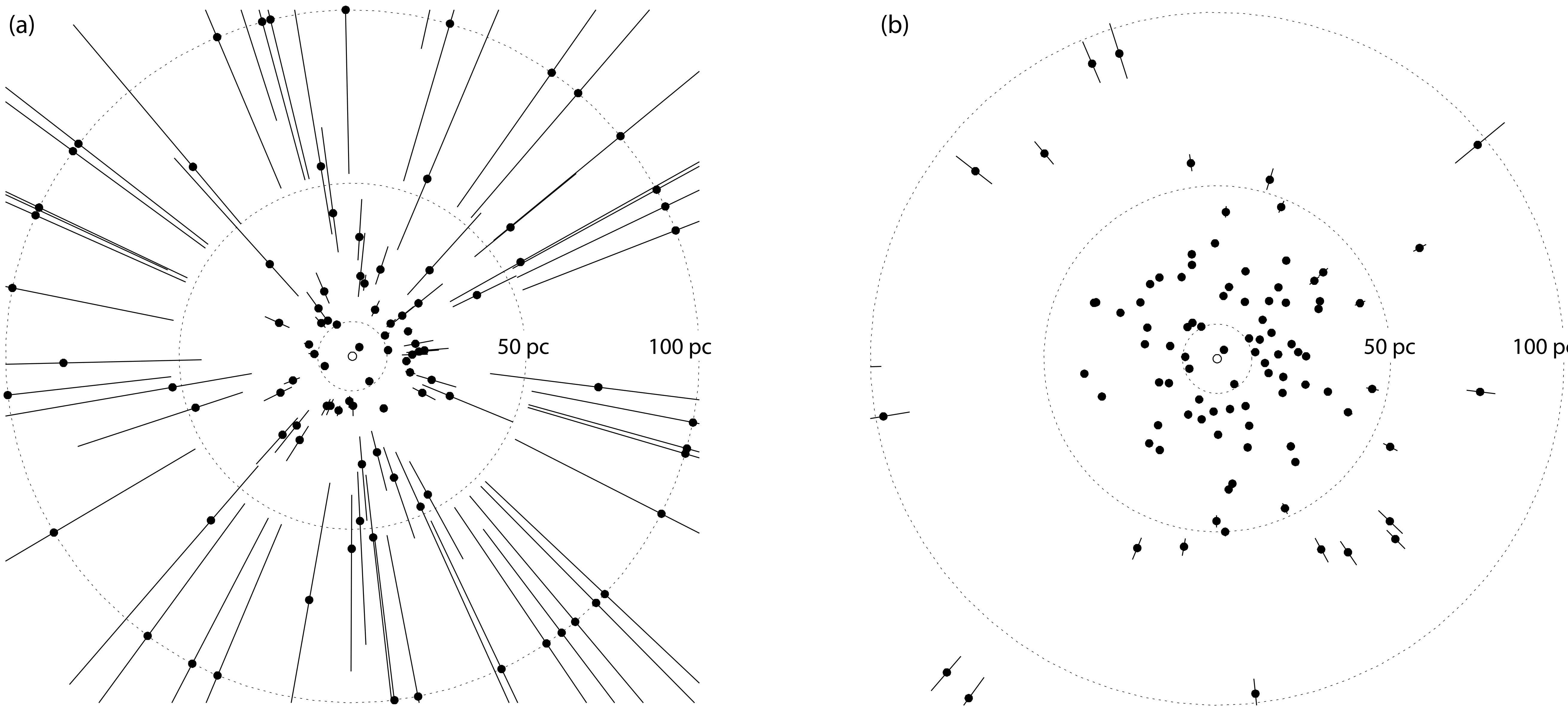
Michael Perryman

Lecture program

1. Space Astrometry 1/3: History, rationale, and Hipparcos
2. **Space Astrometry 2/3:** Hipparcos scientific results
3. Space Astrometry 3/3: Gaia
4. Exoplanets: prospects for Gaia
5. Some aspects of optical photon detection

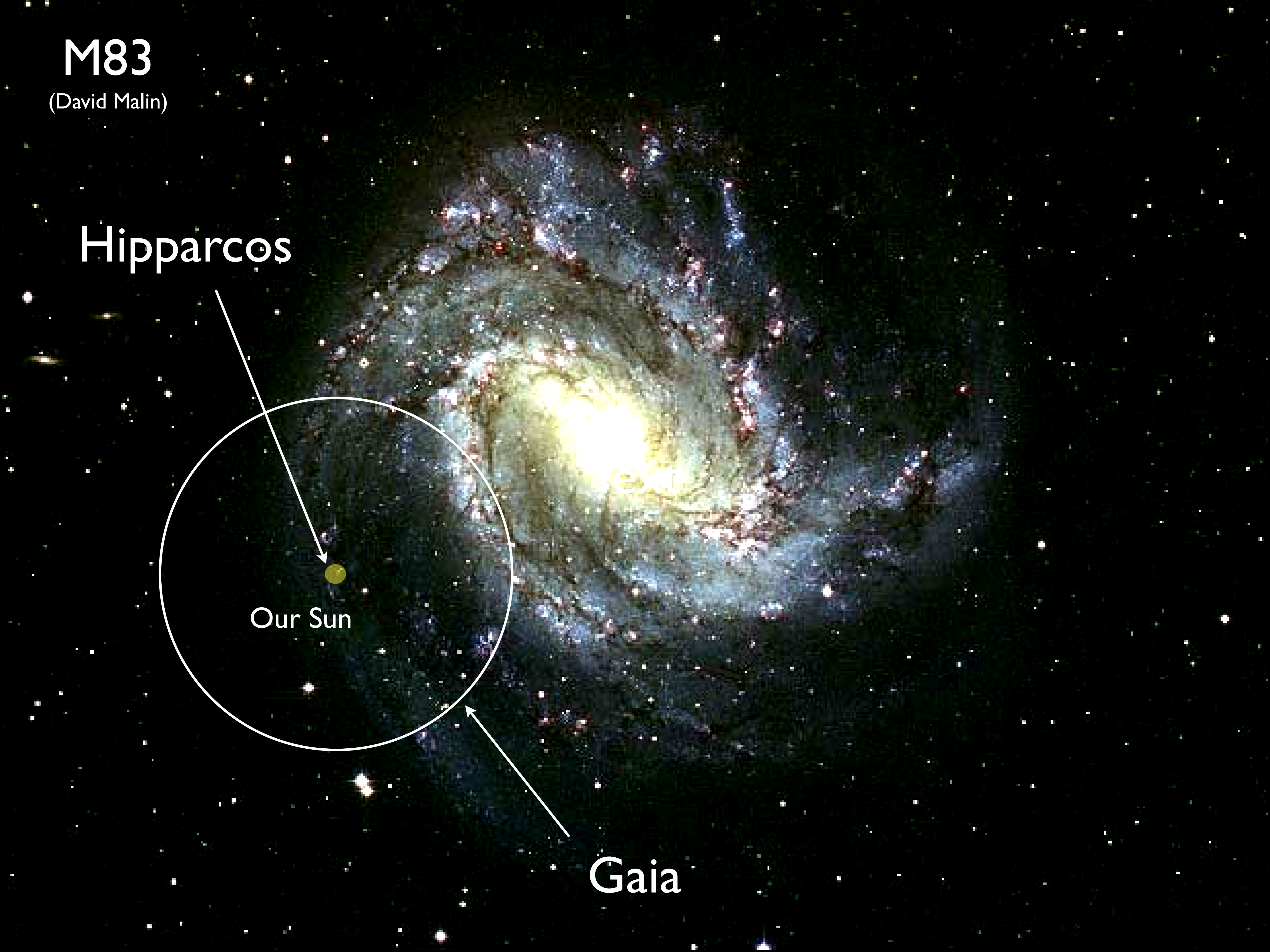
Hipparcos distances to exoplanet host stars

100 brightest radial velocity host stars (end 2010)
(versus RA, independent of dec)



ground-based: van Altena et al (1995)
(unknown assigned π = 10±9 mas)

Hipparcos parallaxes
(Perryman et al 1997)

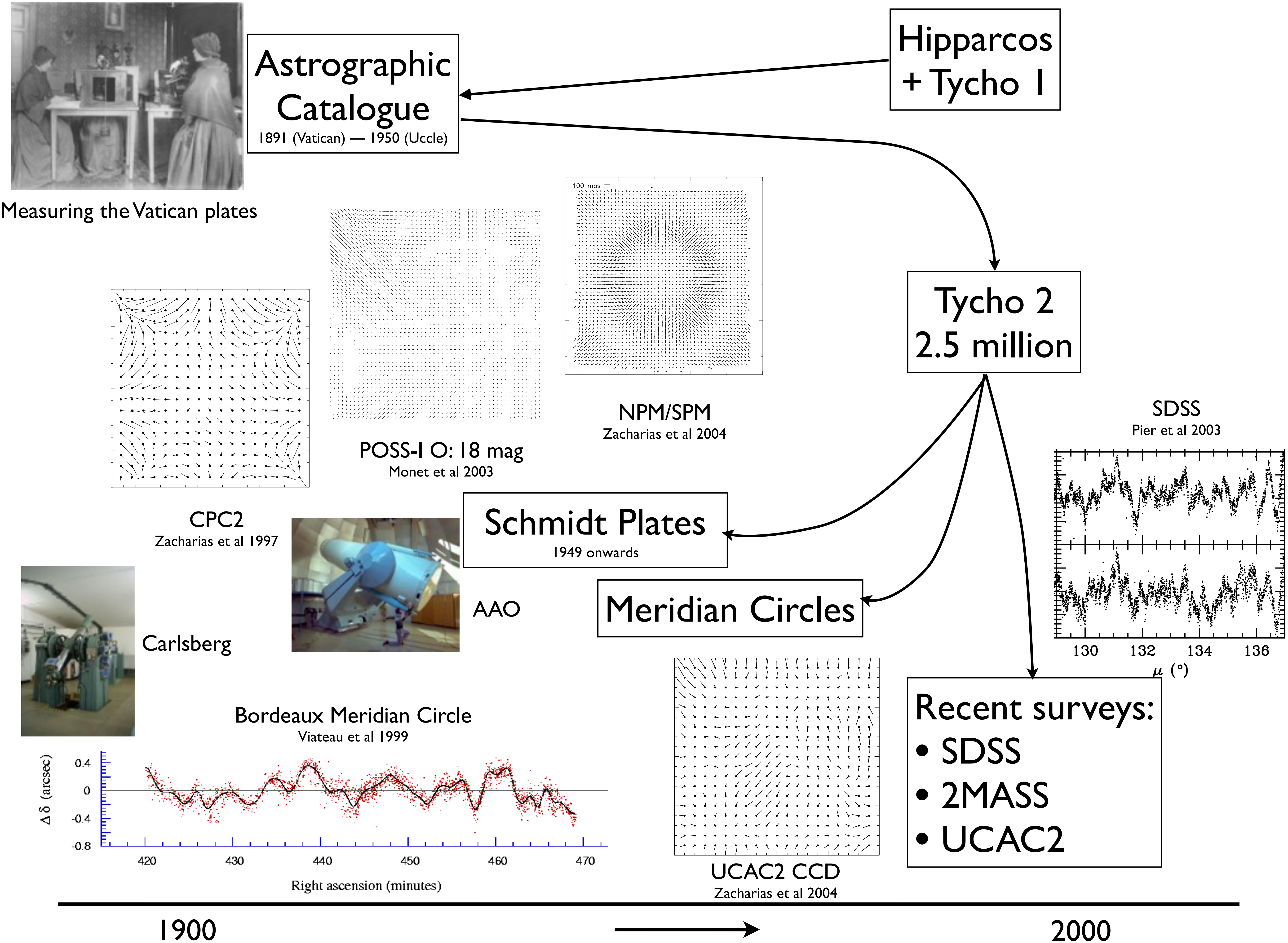

M83
(David Malin)
Hipparcos
Our Sun
Gaia

Outline of Talk

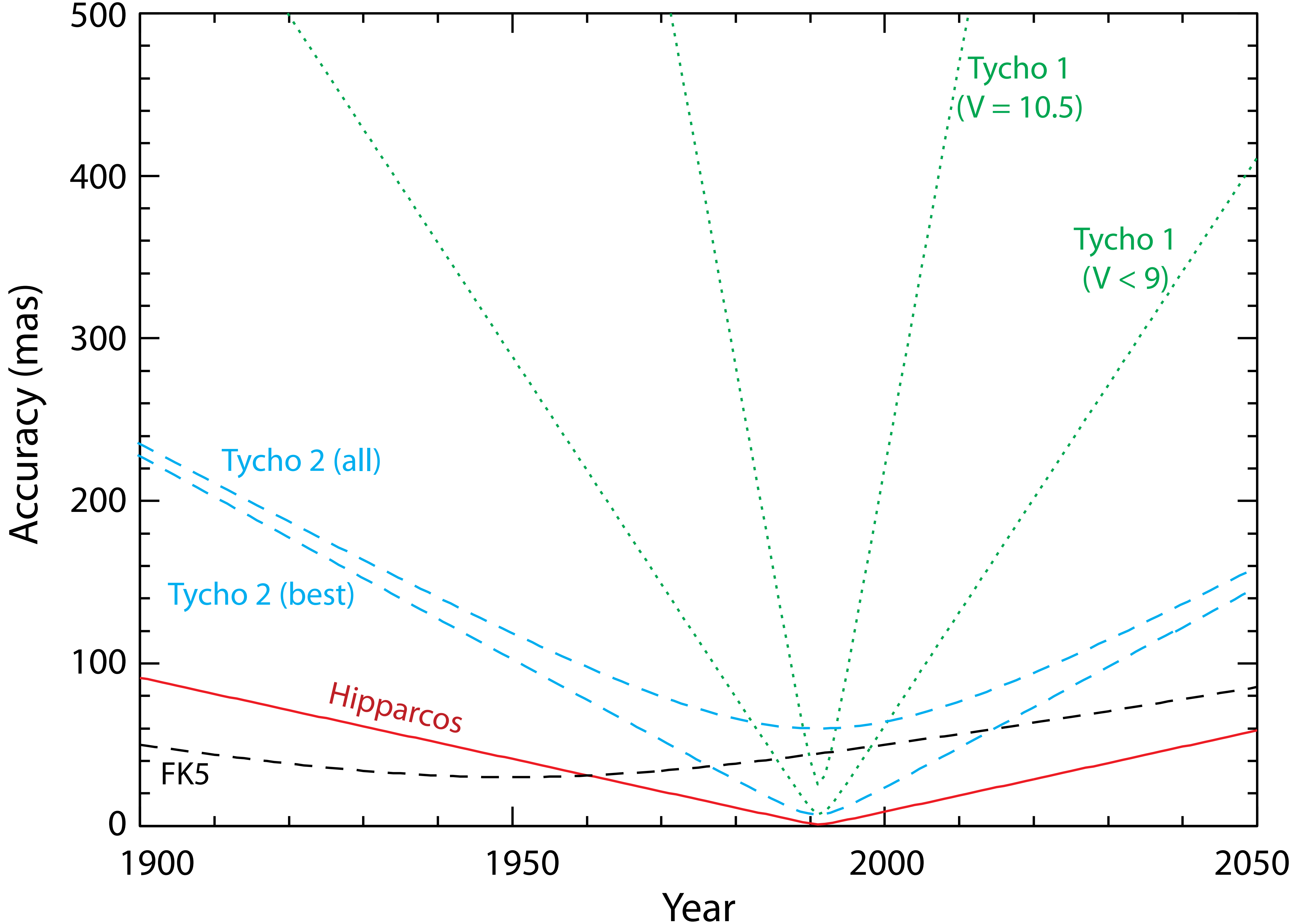
1. **Reference Frame**
2. Galaxy Structure and Dynamics
3. Stellar Structure and Evolution
4. Solar System and Exoplanets

Use as the Reference Frame

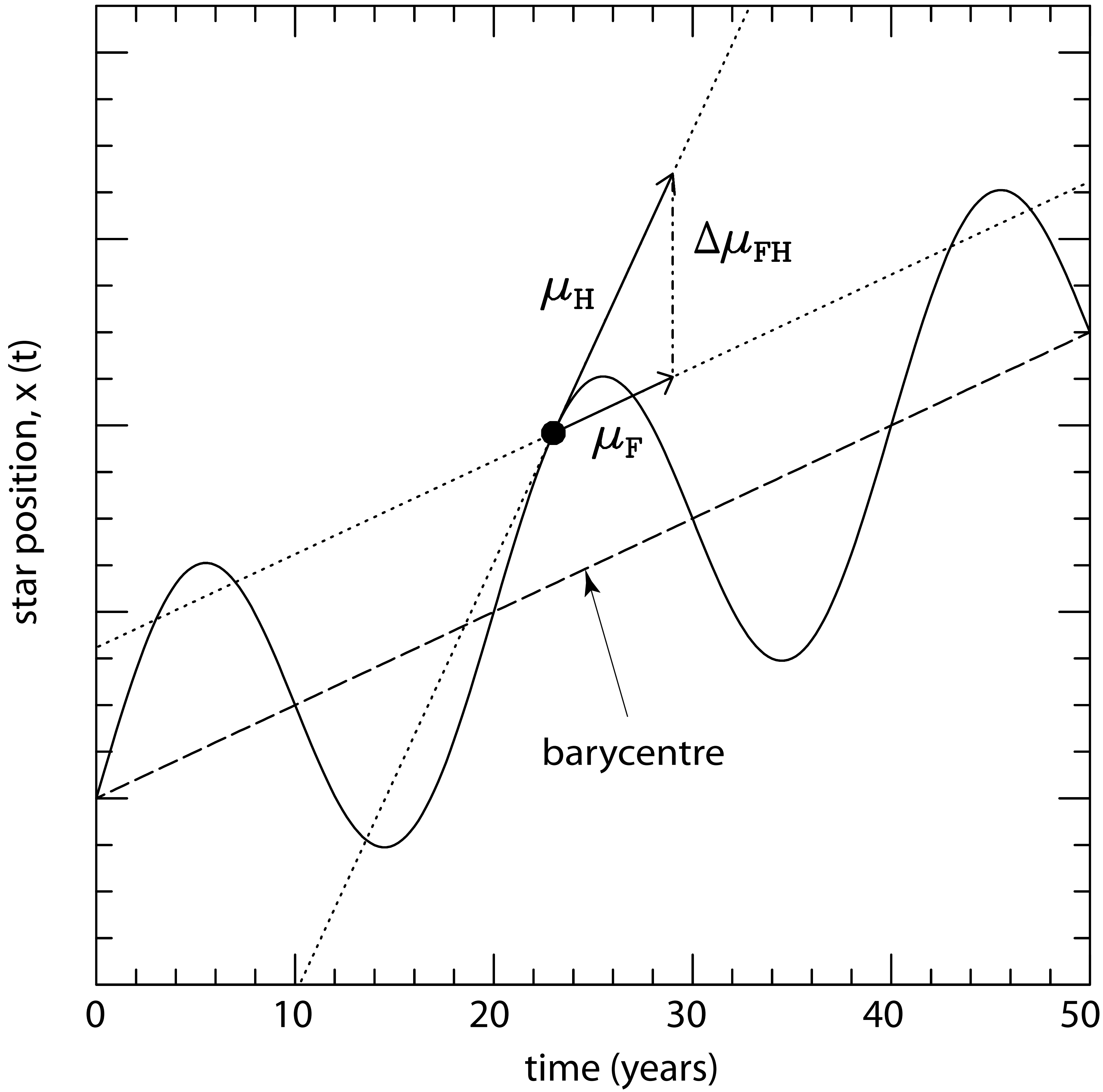
- distinction between reference <u>system</u> and reference <u>frame</u>
- the IAU adopted ICRS (materialised by radio sources) as the celestial reference <u>system</u> to supersede the equator/equinox J2000 materialised by the catalogue FK5 (and before that, B1950/FK4)
- Hipparcos provides the reference <u>frame</u> for optical astronomy
- all major catalogues and ground surveys are now referred to it
- all telescopes (ground/space) ‘point’ using Hipparcos/Tycho stars
- still confusion between: J2000 used as an epoch (valid), and J2000 used as shorthand for the reference system (superseded)


Astrographic Catalogue
1891 (Vatican) — 1950 (Uccle)
Measuring the Vatican plates
Hipparcos + Tycho 1
Tycho 2
2.5 million
100 mas
NPM/SPM
Zacharias et al 2004
POSS-I O: 18 mag
Monet et al 2003
CPC2
Zacharias et al 1997
SDSS
Pier et al 2003
130
132
134
136
μ (°)
Schmidt Plates
1949 onwards
AAO
Carlsberg
Meridian Circles
Bordeaux Meridian Circle
Viateau et al 1999
0.4
0
-0.4
-0.8
Δδ (arcsec)
420
430
440
450
460
470
Right ascension (minutes)
UCAC2 CCD
Zacharias et al 2004
Recent surveys:
• SDSS
• 2MASS
• UCAC2
1900
2000

Degradation of the reference frame with time



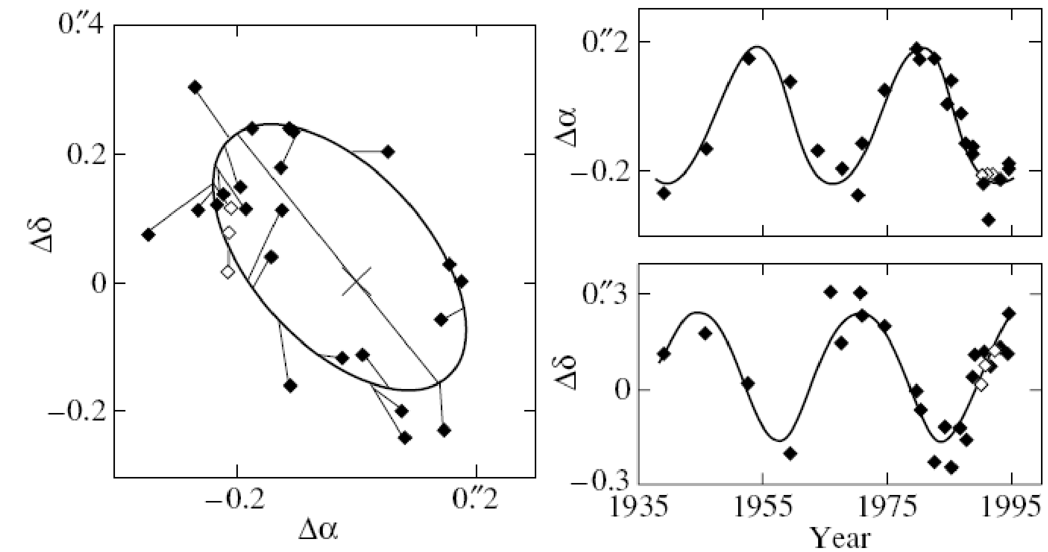
Binary Systems



$\Delta\mu$ binaries
(Wielen 2001)

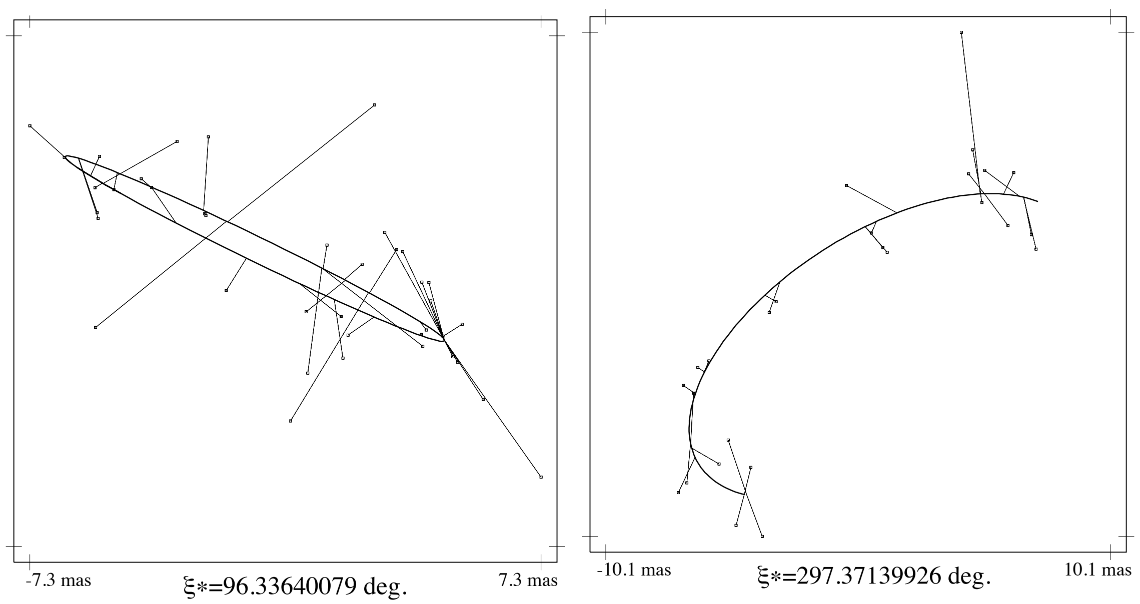
Binary Systems

24 publications treating
>16000 systems

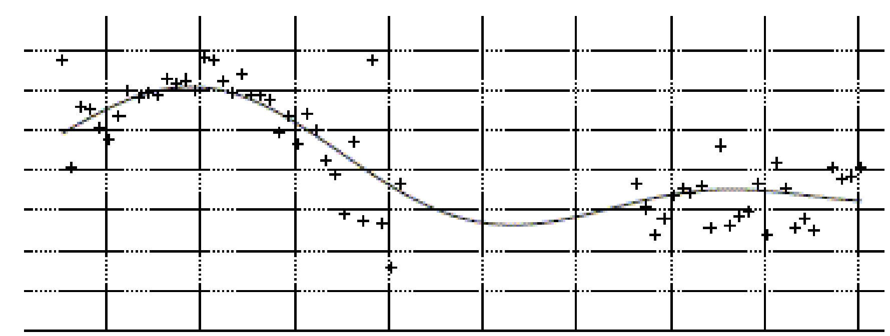


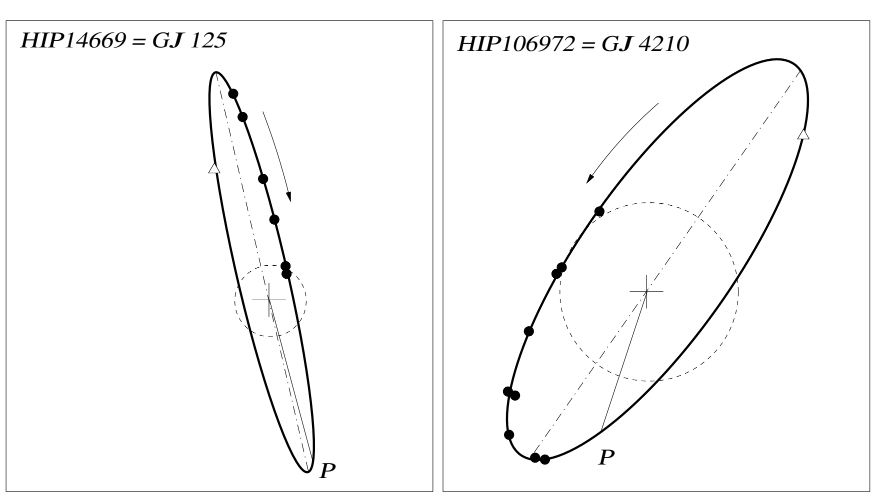
...from early-epoch catalogues
(e.g. Gontcharov & Kiyeva 2002)

...from intermediate astrometric data
(e.g. Pourbaix & Jorissen 2000)



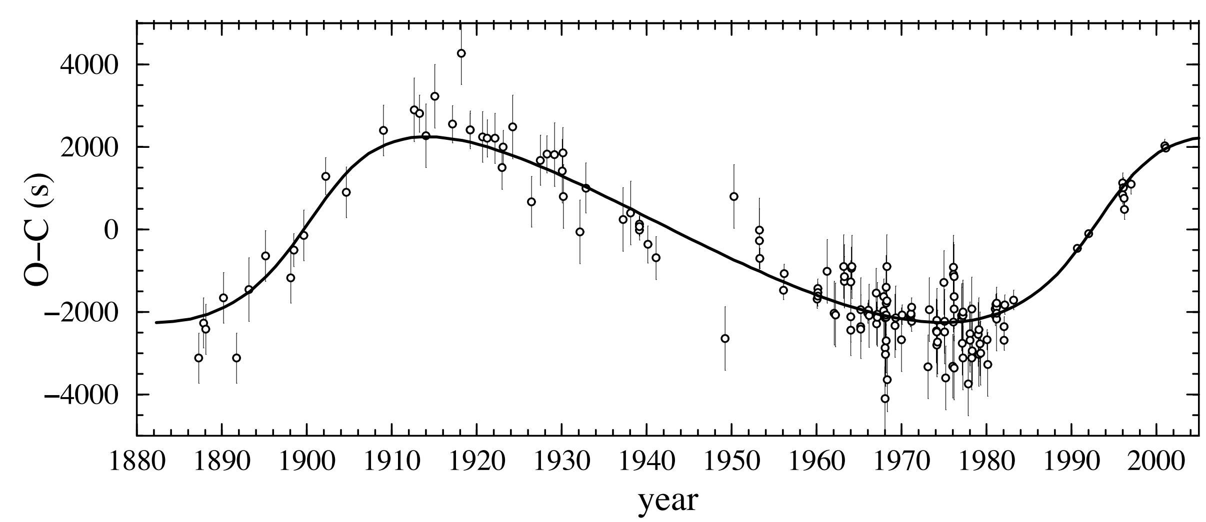
...from Earth orientation observations
(Vondrák & Stefka 2007)





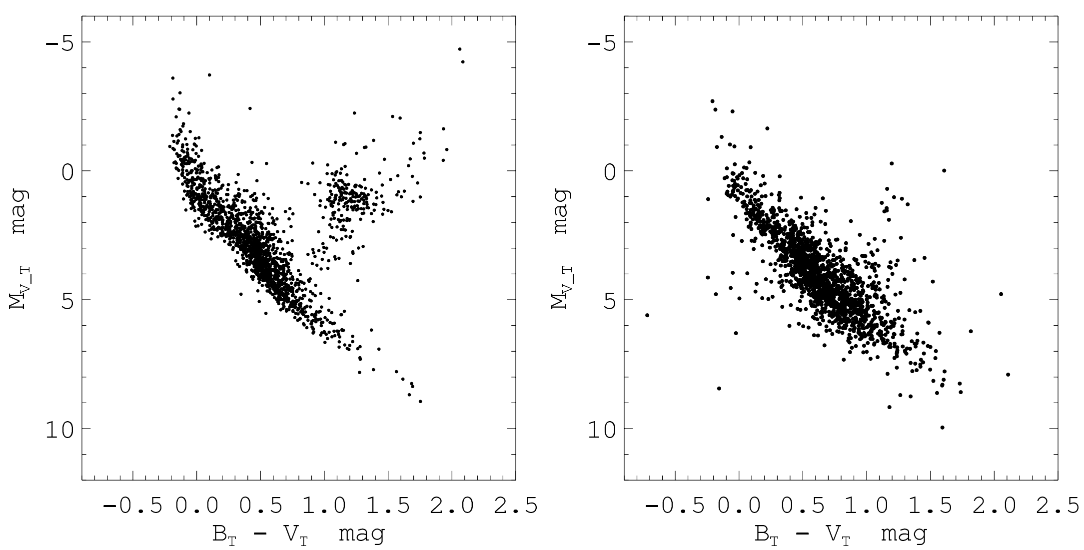
...from speckle data
(e.g. Balega et al 2005)

... using eclipsing binary timings
(Ribas, Arenou & Guinan 2002)

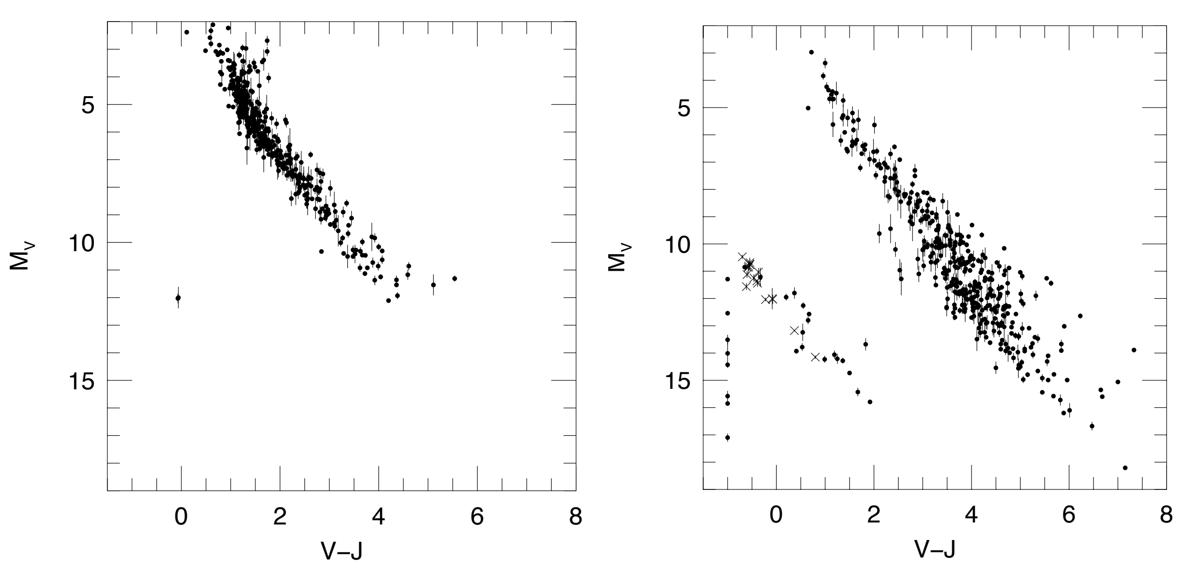


Binary Systems (cont.)

Some special HR diagrams...

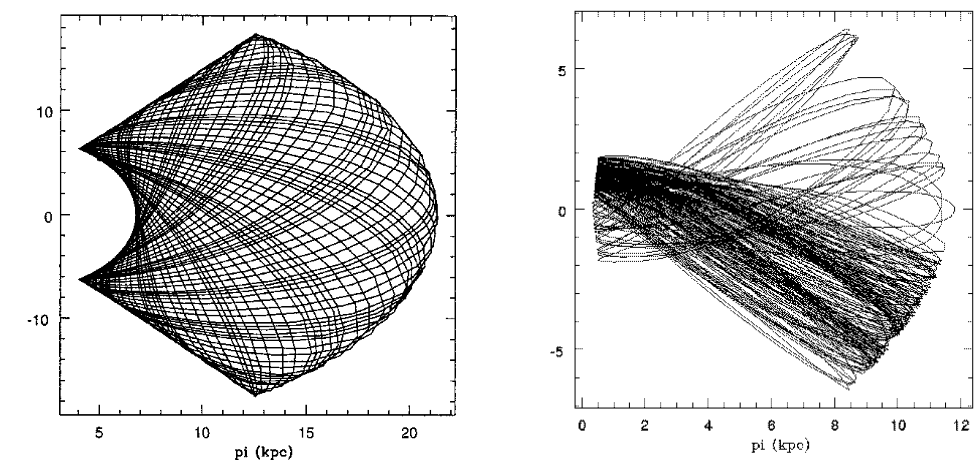


1697 primaries (left) + secondaries (right)
from the Tycho Double Star Catalogue
(Fabricius & Makarov 2000)

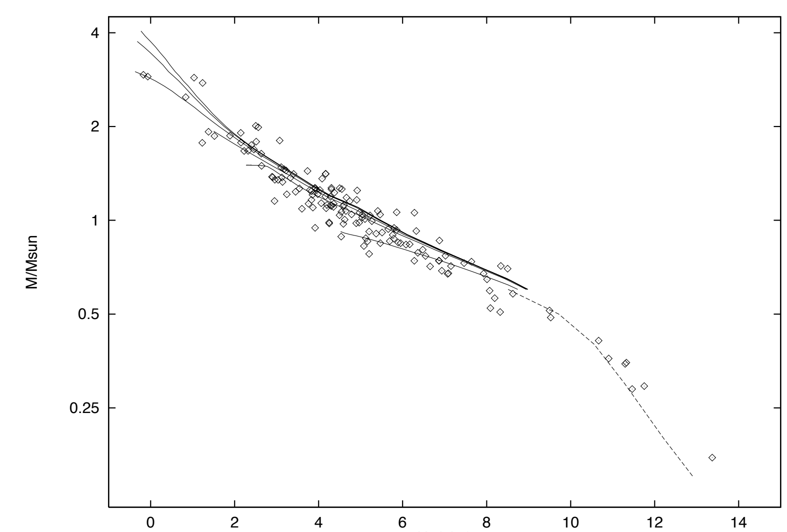


424 common proper motion primaries (l) + secondaries (r)
(Gould & Chanamé 2004)

Some special binaries...

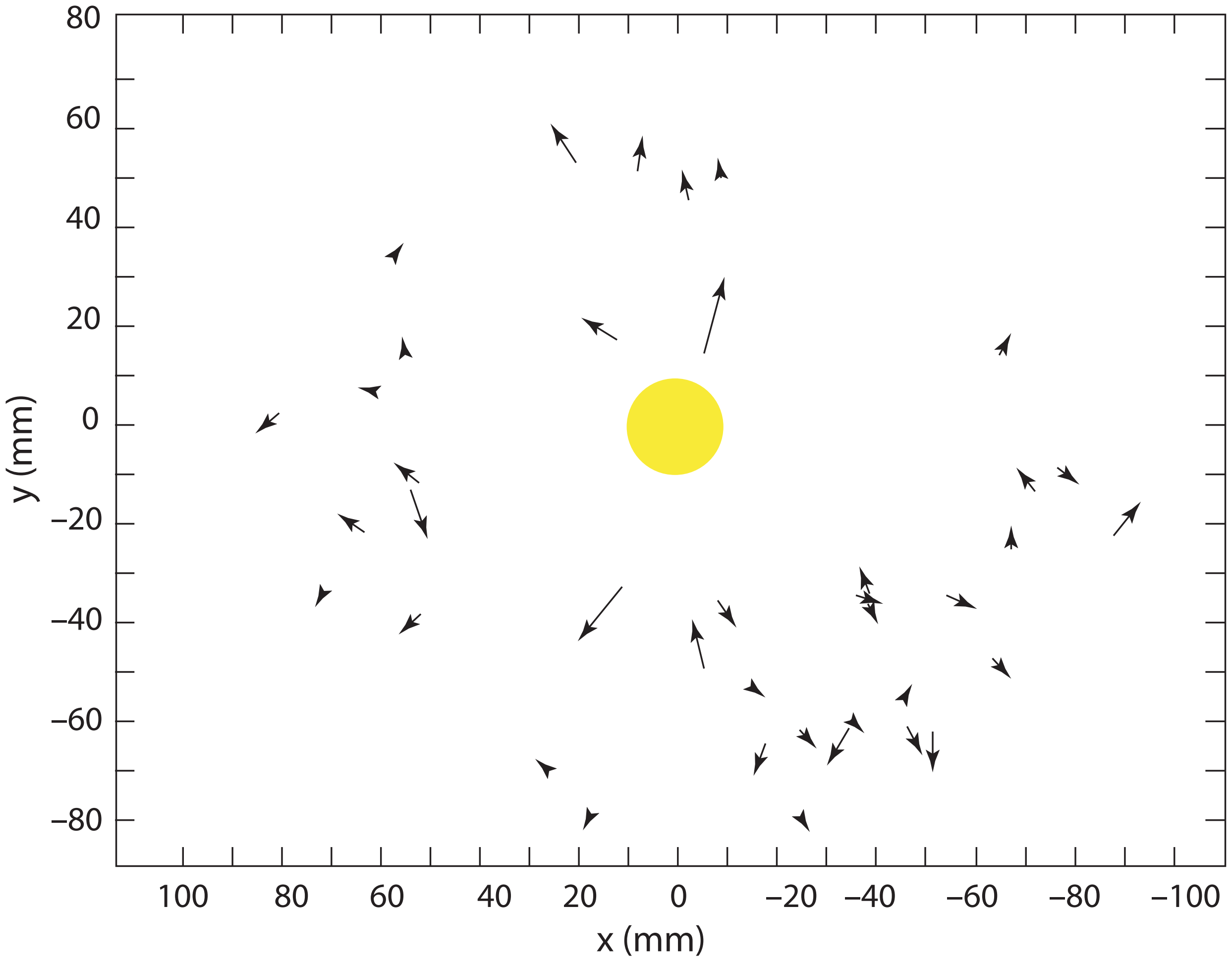


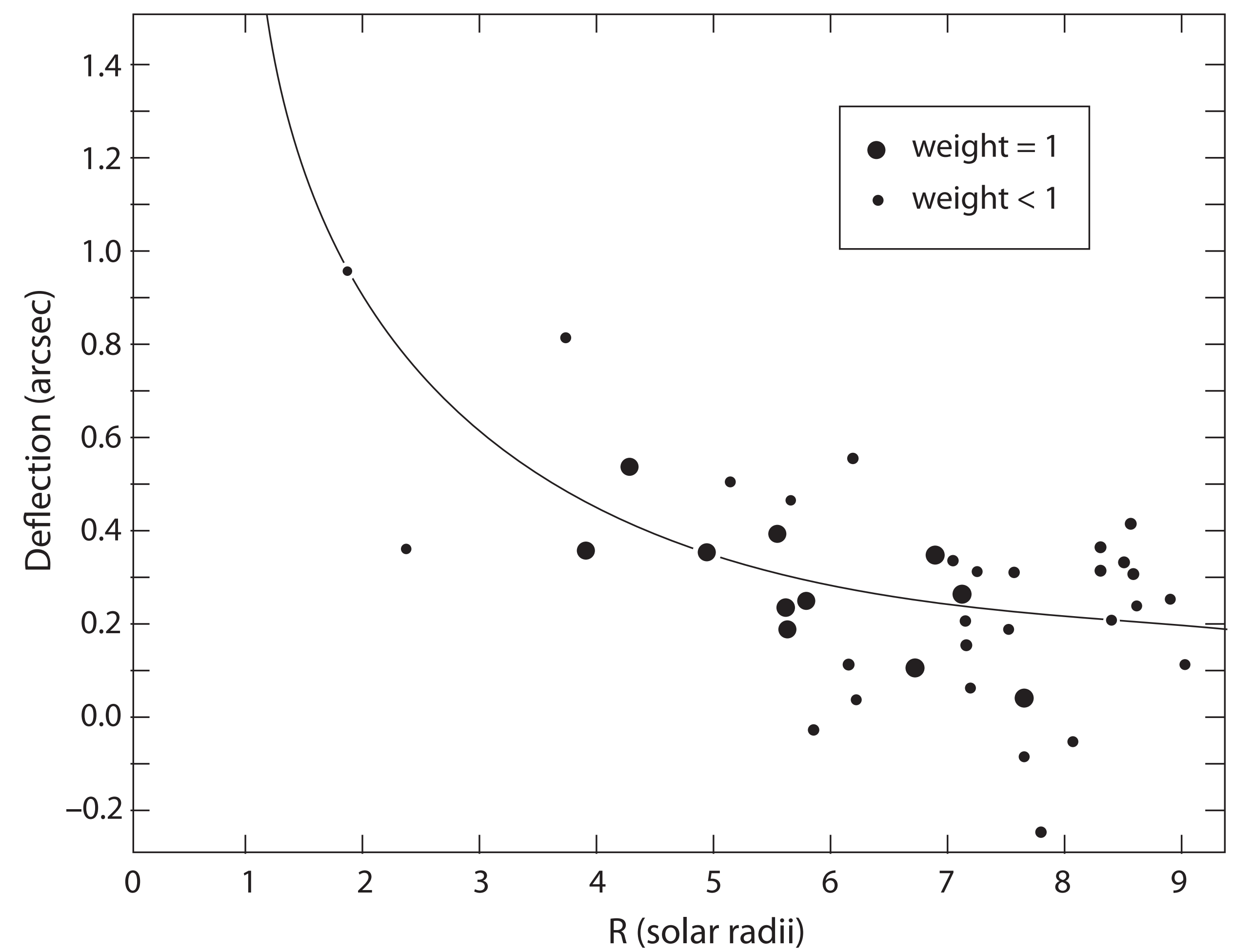
Wide halo binaries (a> 25 AU):
small binding energies and hence good tracers of
mass concentrations versus Galactic orbit
(Allen & Poveda 2000)



Masses: 146 individual main sequence stars with σ_M<15%
(Söderhjelm 1999)

Relativistic Light Deflection (1/2)

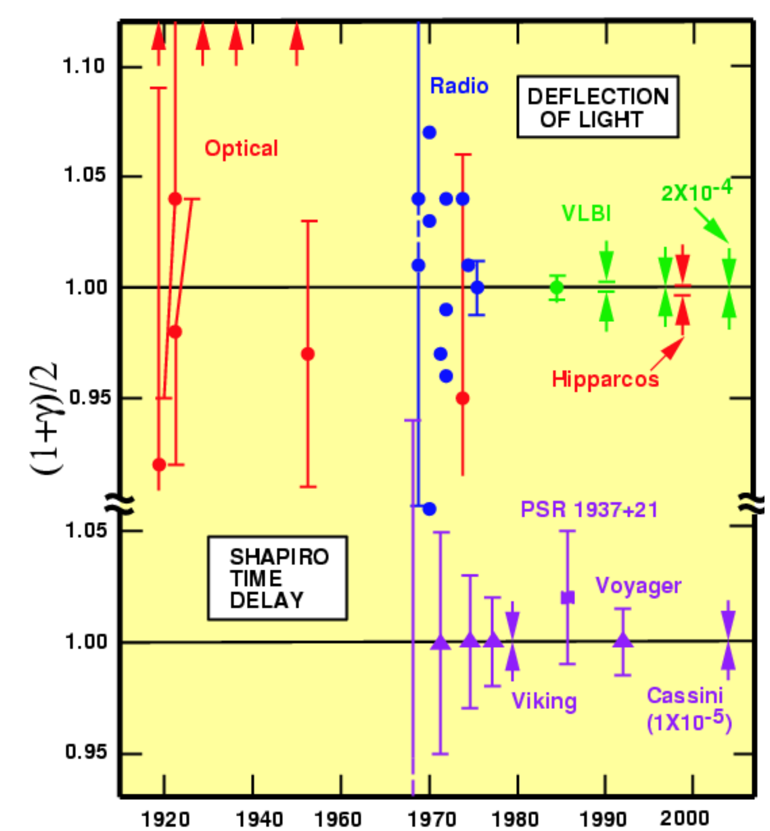




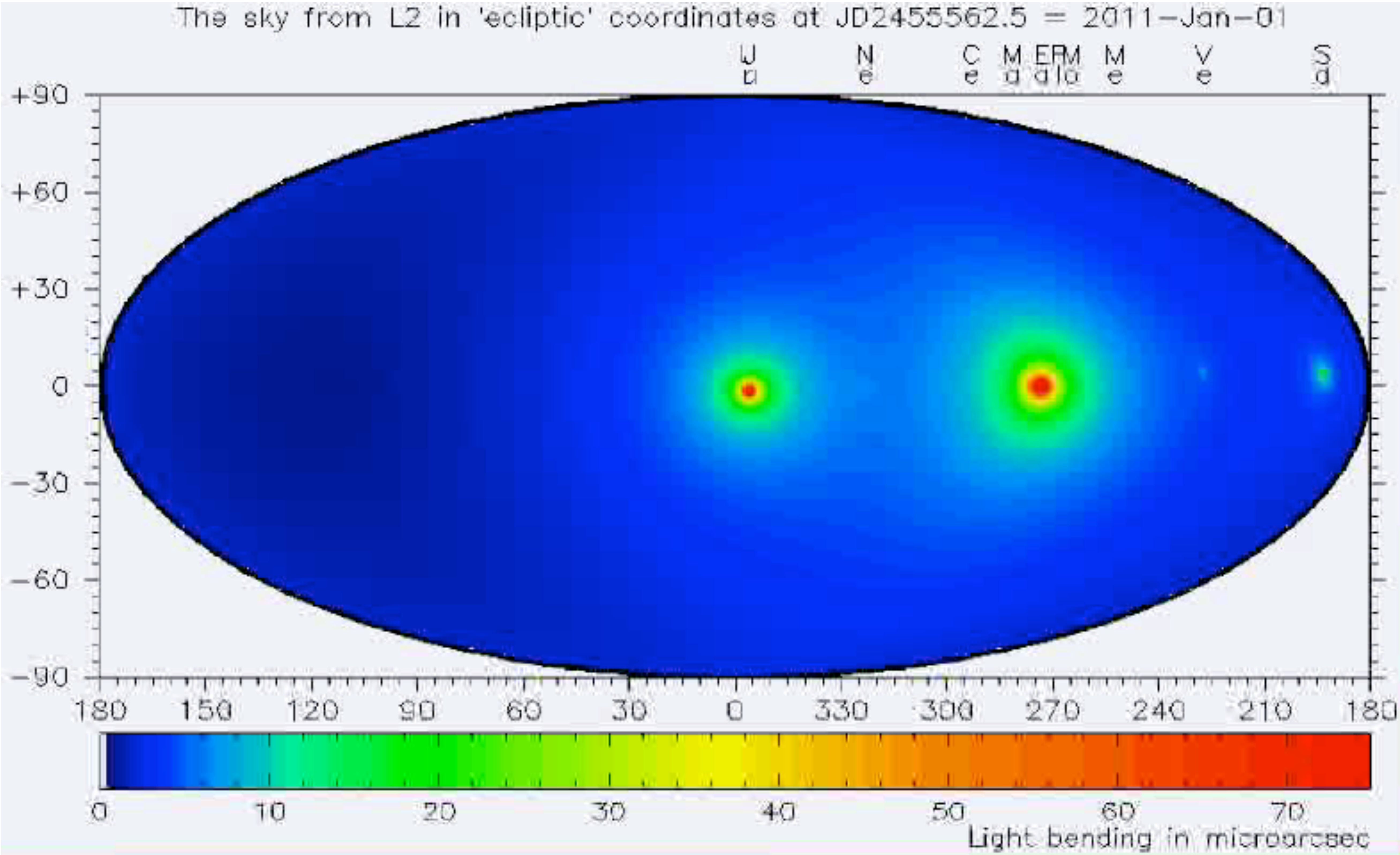
State-of-the-art (ground):
Texas 1973 solar eclipse
(Jones 1976)

From Hipparcos residuals:
$(1+\gamma)/2 = 0.9985 \pm 0.0015$
(Froeschlé et al 1997)

Constraints
on γ
(Will 2006)



Relativistic Light Deflection (2/2)



Light deflection seen by Gaia (Jos de Bruijne)

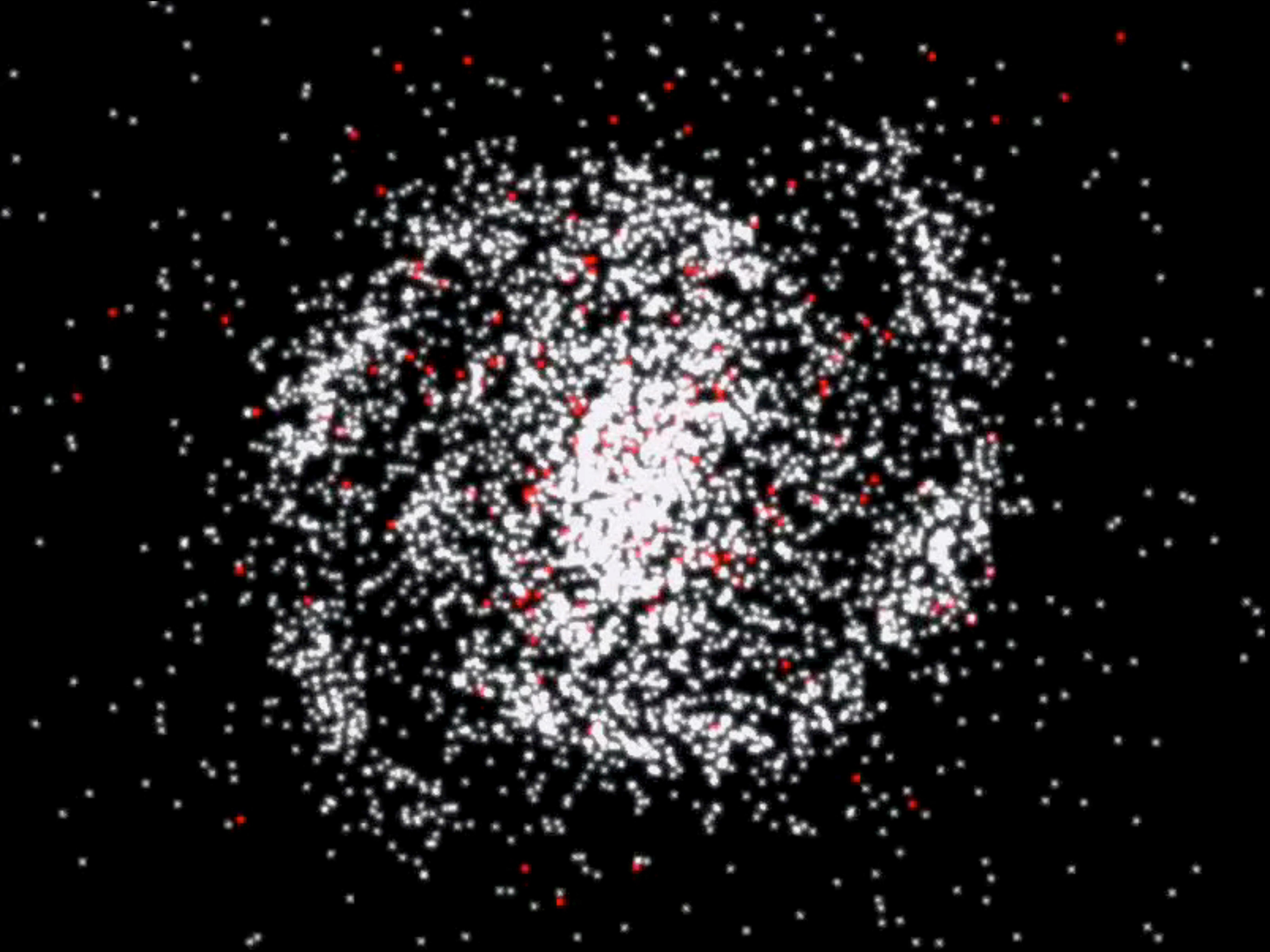
Outline of Talk

1. Reference Frame
2. **Galaxy Structure and Dynamics**
3. Stellar Structure and Evolution
4. Solar System and Exoplanets

Problem 1: Galactic Structure and Rotation

Aims include determining:

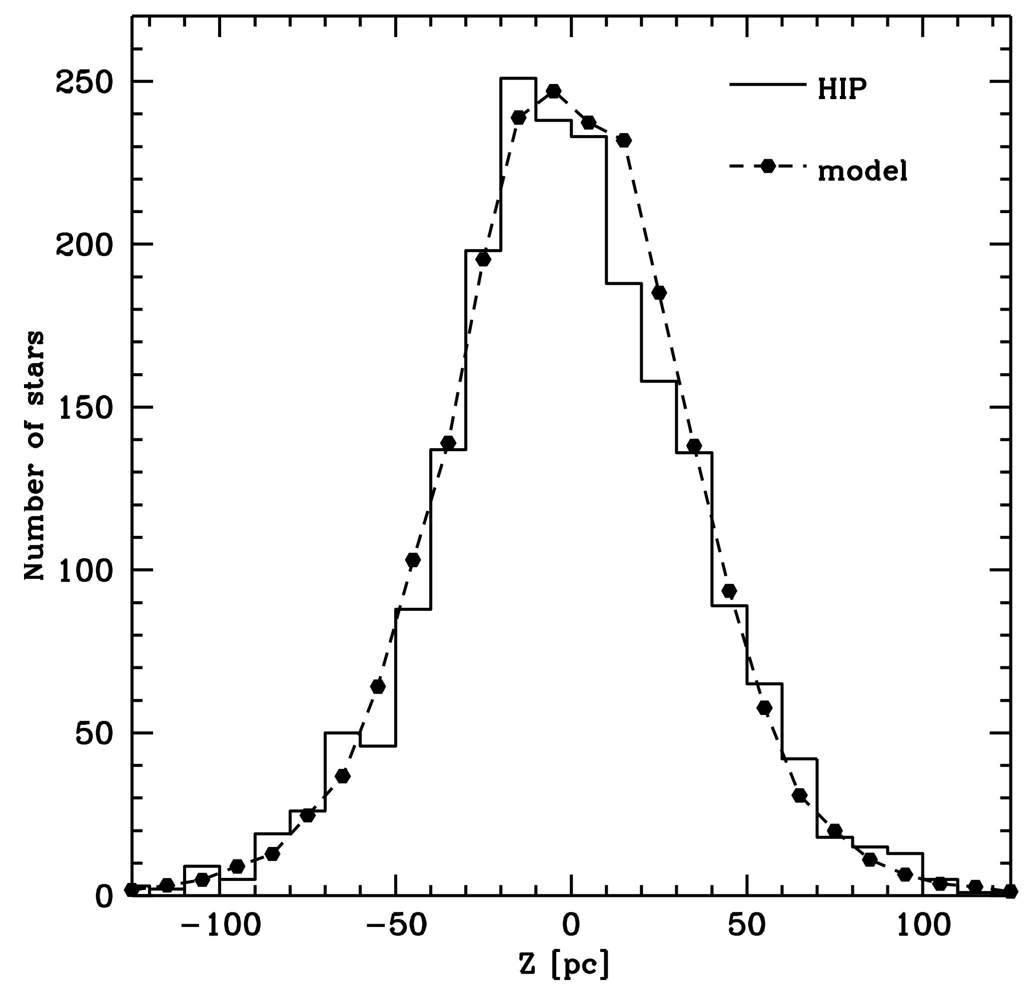
- distance of Sun from Galactic centre, R_0
- local standard of rest (for circular orbits)
- solar motion *uvw* (with respect to LSR)
- rotation curve (as a function of R)
- Oort constants, assuming circular motion
    - angular rotation rate = $A-B$
    - local derivative = $A+B$



Sun’s distance from Galactic plane

Distance from Galactic plane, Z_0
(important for phase of Sun’s orbit)

- pre-Hipparcos: 10−42 pc
- Pham 1997 (F stars): 9±4 pc
- Holmberg et al 1997 (F stars/red giants): 8±4 pc
- Chen 2001 (SDSS): 27±4 pc
- Maíz Apellániz 2001 (O-B5 stars): 24±2 pc
- Branham 2003 (90,000 stars): 35±1 pc



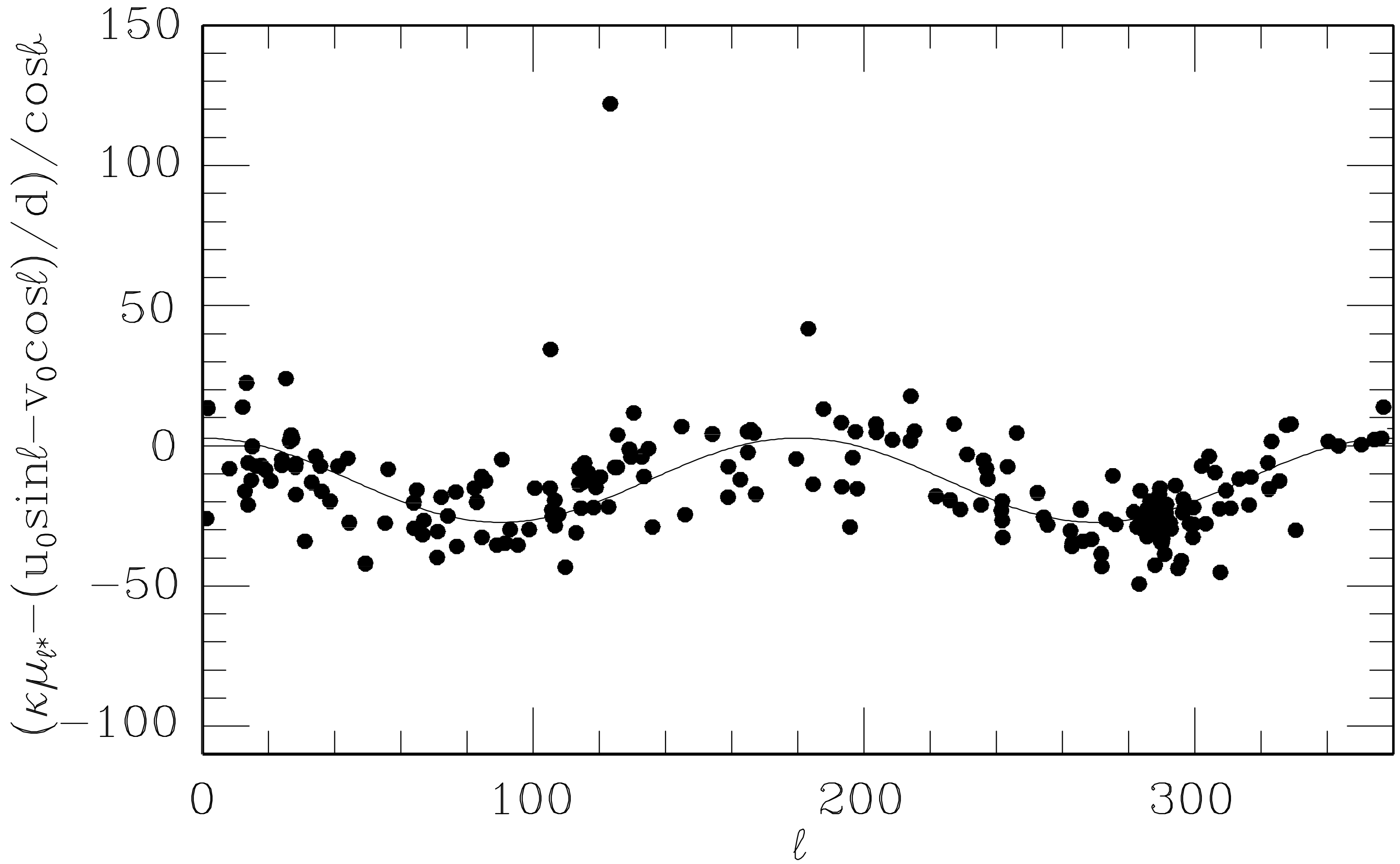
Holmberg et al 1997

Results on Solar Motion

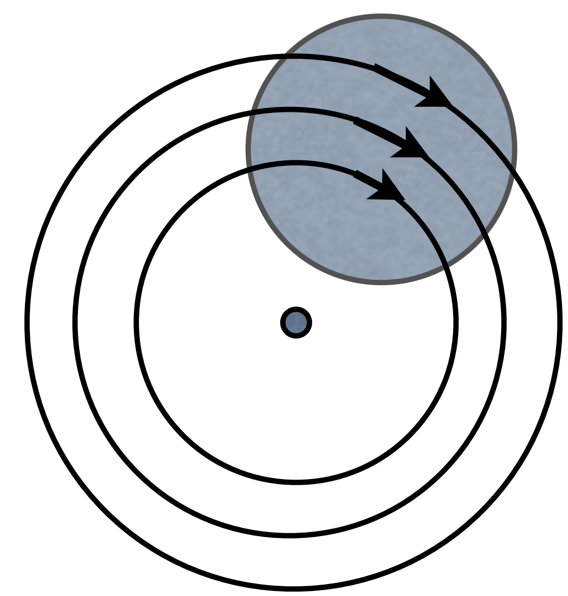
Reference	Class	Solar motion wrt LSR ($\mathrm{km\,s^{-1}}$) $u_\odot$	$v_\odot$	$w_\odot$	Total $V_\odot$
Pre-Hipparcos					
Mihalas & Binney (1981)	Compilation	9	12	7	16.5
Evans & Irwin (1995)	APM-based	7.3 ± 1.5	13.9 ± 2.3	8.8 ± 2.2	18.0
Hipparcos – Oort–Lindblad:					
Feast & Whitelock (1997)	Cepheids	9.3	11.2	7.61 ± 0.64	16.4
Miyamoto & Zhu (1998)	Cepheids	10.62 ± 1.20	16.06 ± 1.14	8.60 ± 1.02	21.1
Hipparcos – Ogorodnikov–Milne:					
Miyamoto & Zhu (1998)	O–B5 stars	11.59 ± 0.49	13.39 ± 0.48	7.12 ± 0.44	19.1
"	Cepheids	10.46 ± 1.19	15.95 ± 1.14	8.96 ± 1.03	21.1
Mignard (2000)[1]	A0–A5 dwarfs	9.92 ± 0.25	10.71 ± 0.26	6.96 ± 0.21	16.2
"	A5–F0 dwarfs	11.58 ± 0.32	10.37 ± 0.33	7.19 ± 0.31	17.1
"	F0–F5 dwarfs	11.46 ± 0.37	11.16 ± 0.37	7.02 ± 0.41	17.5
"	K0–K5 giants	7.99 ± 0.35	14.97 ± 0.36	7.39 ± 0.40	18.5
"	K5–M0 giants	8.72 ± 0.49	19.71 ± 0.51	7.28 ± 0.55	22.7
"	M0–M5 giants	7.37 ± 0.61	20.29 ± 0.63	6.85 ± 0.66	22.6
Branham (2000)	all Hipparcos	10.30 ± 0.06	19.13 ± 0.05	7.09 ± 0.04	22.8
Branham (2002)	OB stars	14.49 ± 0.12	19.68 ± 0.09	2.81 ± 0.07	24.6
Branham (2006) and priv. comm.	OB stars	7.76 ± 0.83	10.15 ± 0.89	5.29 ± 0.71	13.8
Hipparcos – vectorial harmonics:					
Vityazev & Shuksto (2004)	113 646 stars	–	–	–	23.3
Makarov & Murphy (2007)	non-binary	9.9 ± 0.2	15.6 ± 0.2	6.9 ± 0.2	19.7
Hipparcos – spiral-density wave:					
Mishurov & Zenina (1999b)[2]	Cepheids	7.8 ± 1.3	13.6 ± 1.4	–	–
Lépine et al. (2001)[2]	Cepheids	8.8 ± 1.0	11.9 ± 1.1	–	–
Hipparcos – other:					
Dehnen & Binney (1998a)	Dwarfs	10.0 ± 0.36	5.25 ± 0.62	7.17 ± 0.38	13.4
Brosche et al. (2001)	K0–K5 giants	9.0 ± 0.5	21.0 ± 0.5	7.7 ± 0.4	24.1
Fehrenbach et al. (2001)[3]	$\bar{d}$ = 46 pc	9.79	13.20	3.25	16.7
"	$\bar{d}$ = 195 pc	8.24	11.58	5.97	15.4
"	$\bar{d}$ = 378 pc	2.93	10.36	4.79	11.8
Hogg et al. (2005)[4]	Dwarfs	10.1 ± 0.5	4.0 ± 0.8	6.7 ± 0.2	12.8

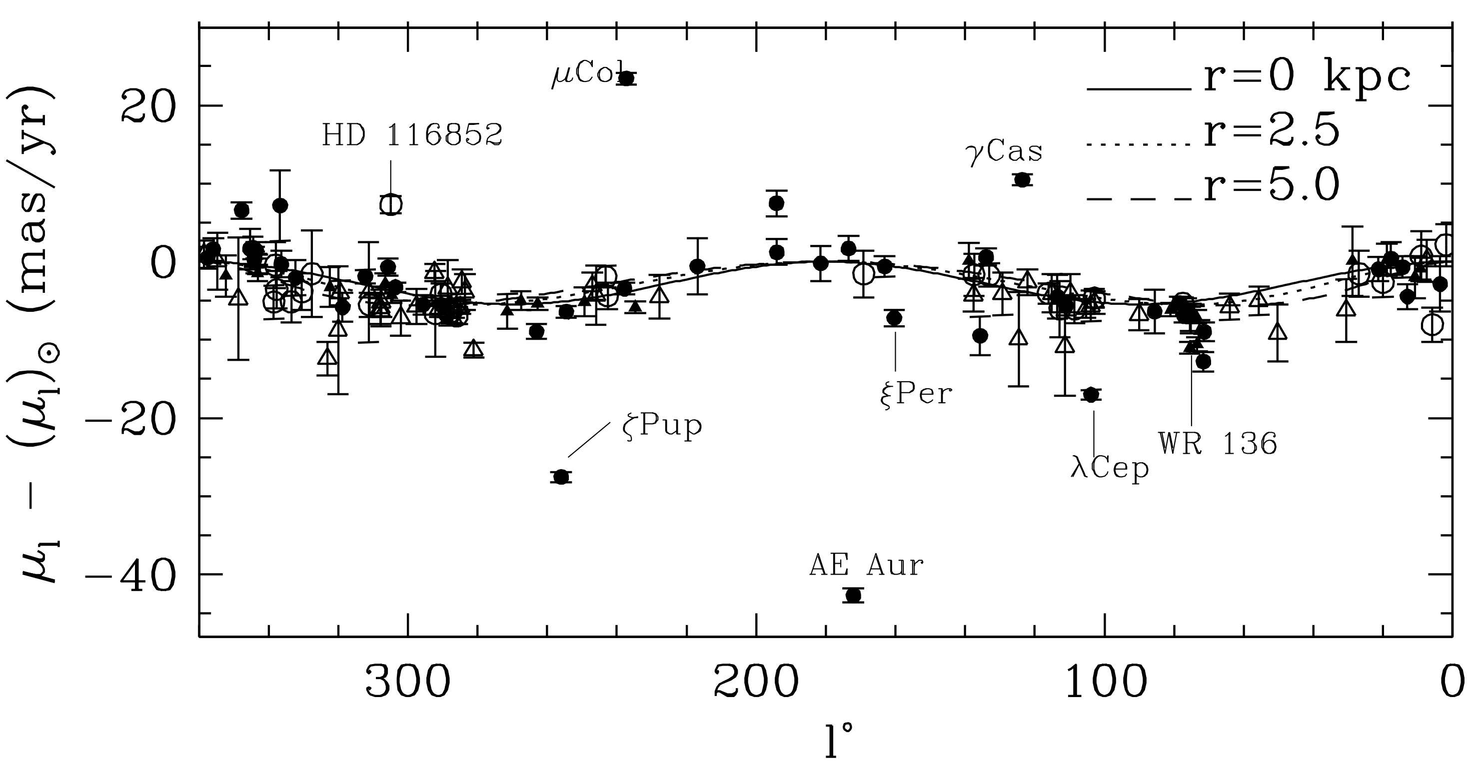
cf Schonrich et al (2010) considering Galactic metallicity gradient: *UVW* = 11.10, 12.24, 7.25

Galactic Rotation (1)



Cepheids:
Feast & Whitelock (1997)

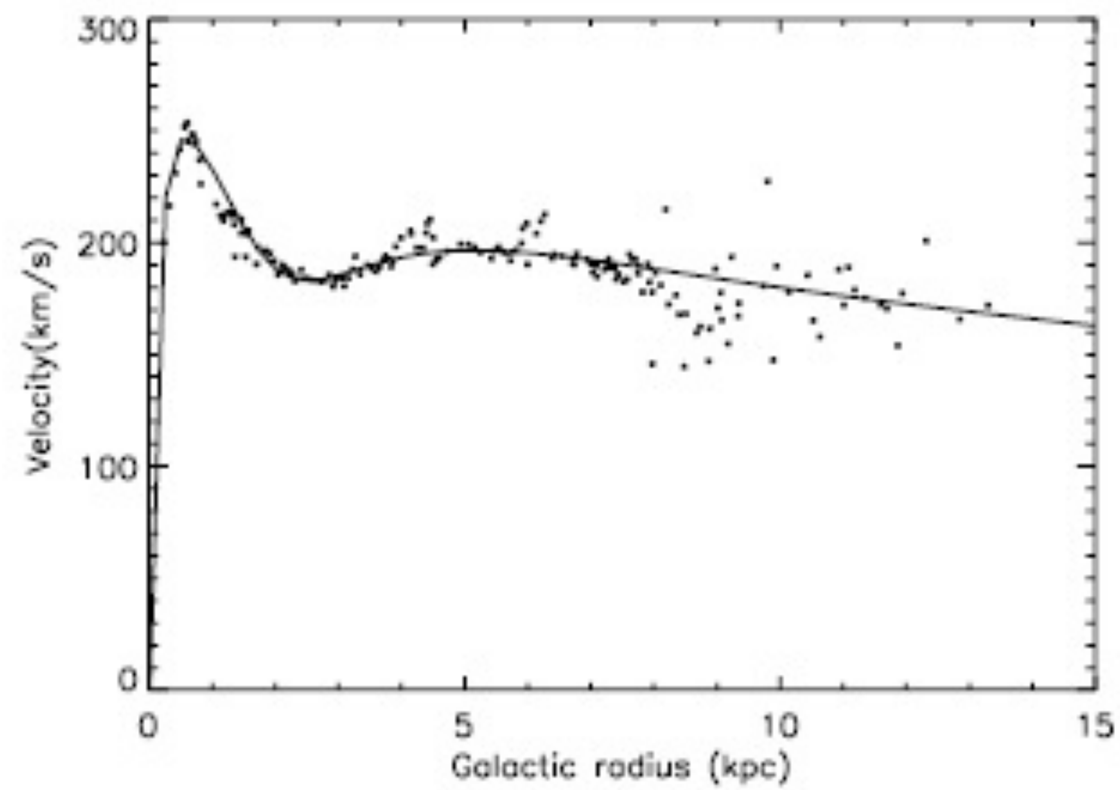




O and Wolf-Rayet stars:
Moffat et al (1998)

Galactic Rotation (2)

- galaxy disk does not rotate as solid body
- large-scale rotation from e.g. CO data
- provides evidence for dark matter
- nearby stars give detailed motion
- complications due to young stars, spiral arms, etc



Successive approximations:

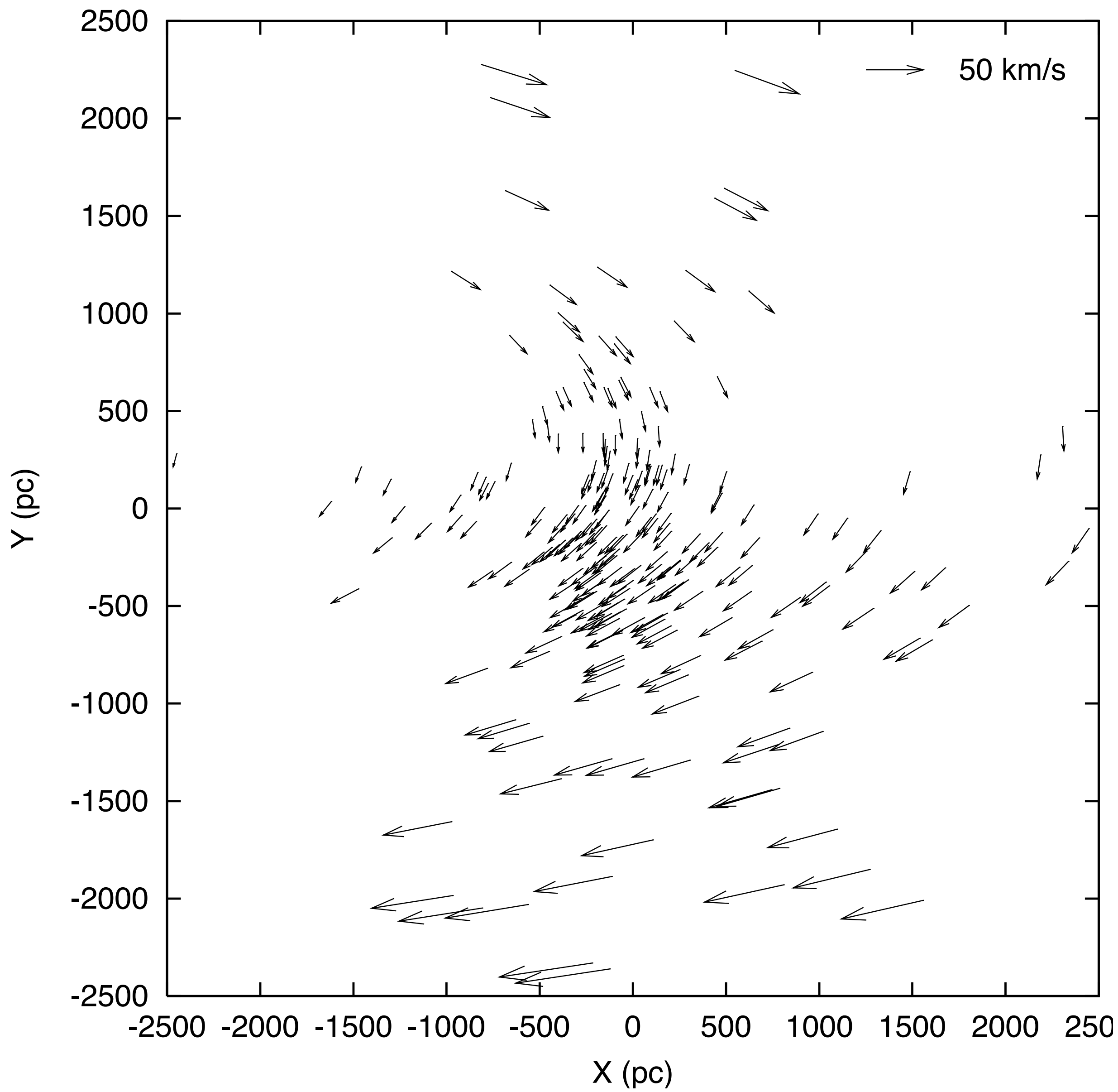
(1) Oort−Lindblad approximation (assumes circular motion), with Oort constants A, B:
Feast & Whitelock (1997); Liu & Ma (1999); Olling & Dehnen (2003)

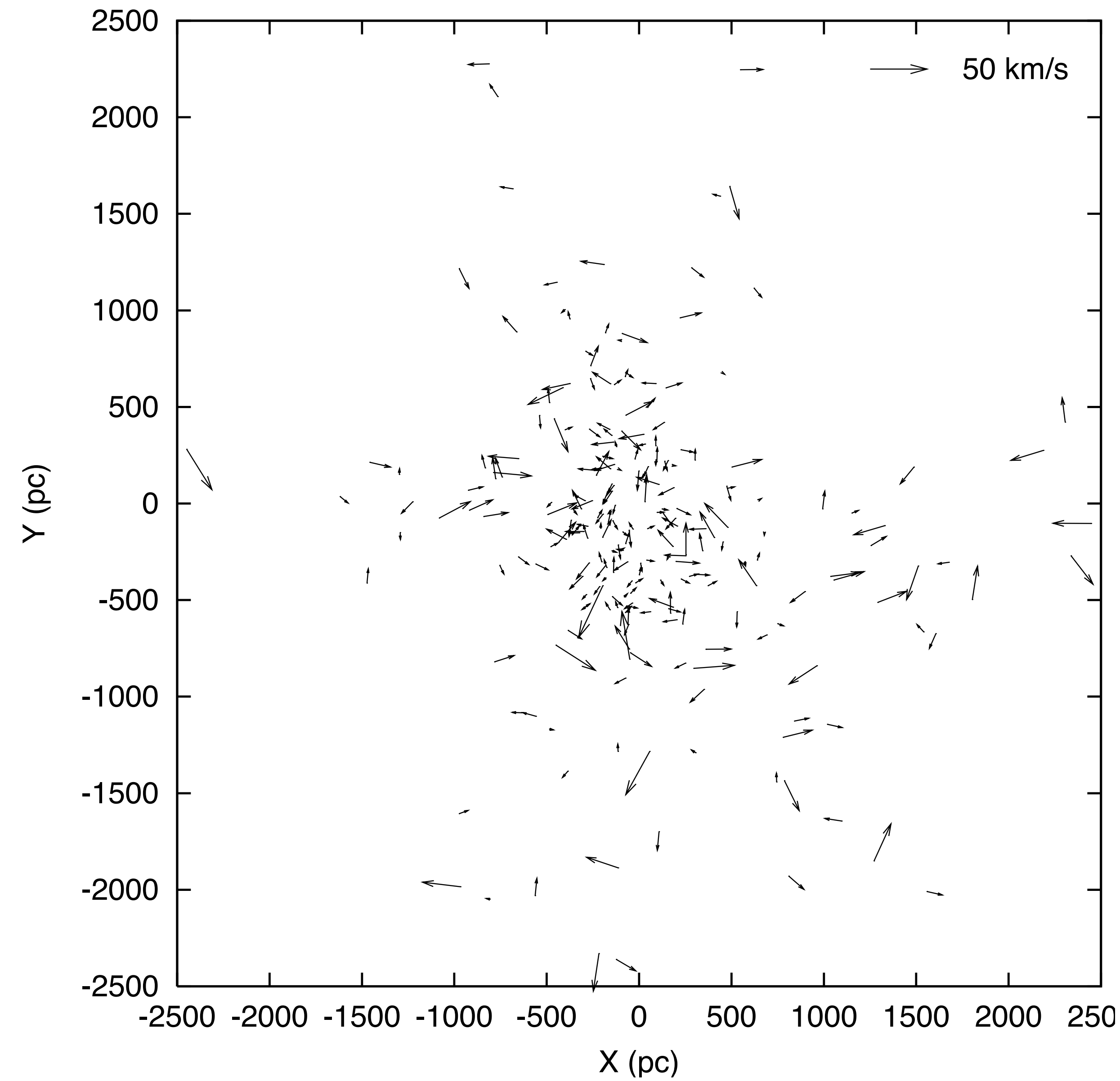
(2) Ogorodnikov−Milne formulation based on a 3x3 velocity tensor:
Miyamoto & Zhu (1998); Mignard (2000); Uemura et al (2000); Branham (2000-06)

(3) vector harmonic development:
Mignard & Morando (1990); Vityazev & Shuksto (2004); Makarov & Murphy (2007)

Galactic Rotation (3)

Velocity field and residuals for 243 O−B5 stars
using Ogorodnikov-Milne model:
Uemura et al (2000)

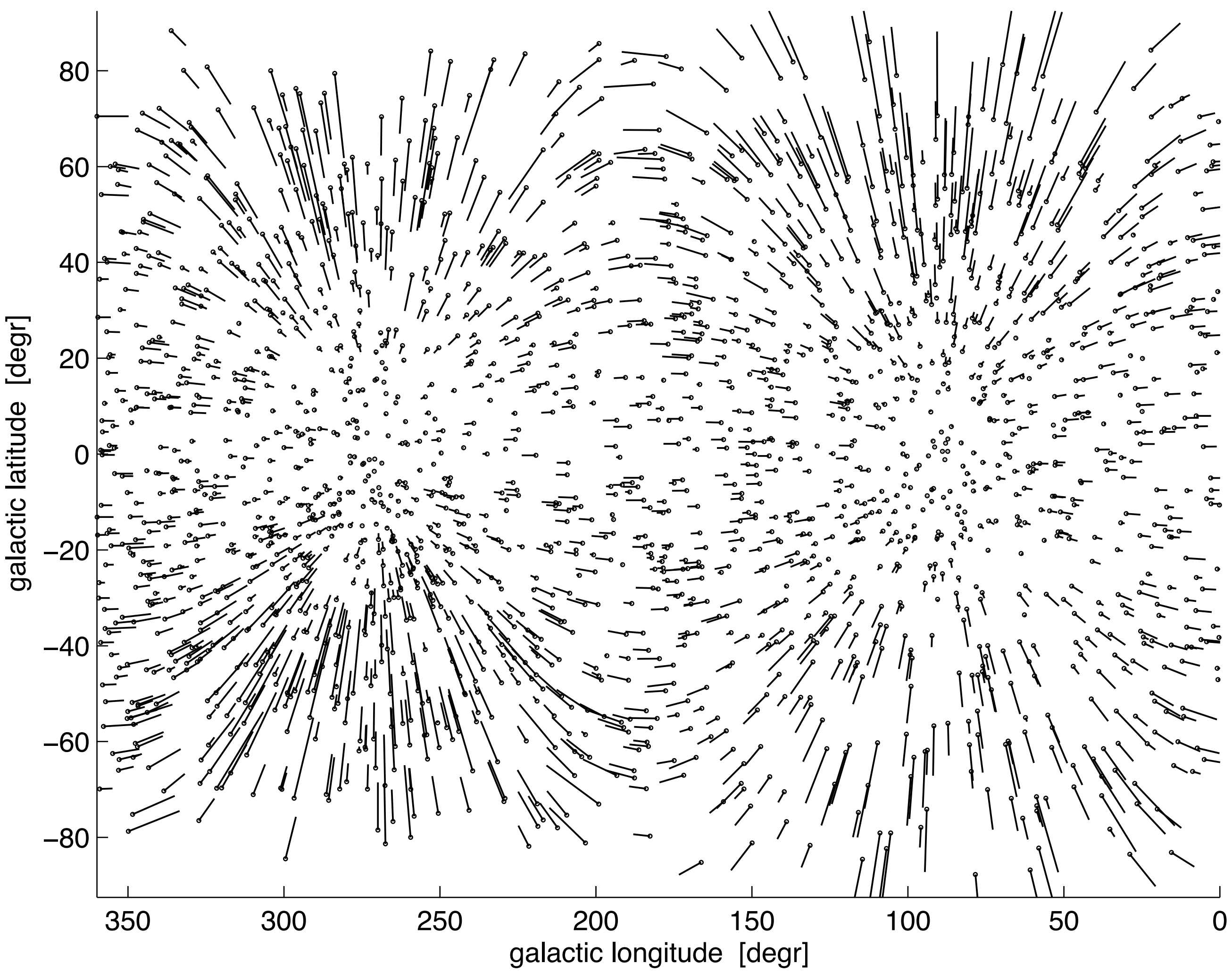




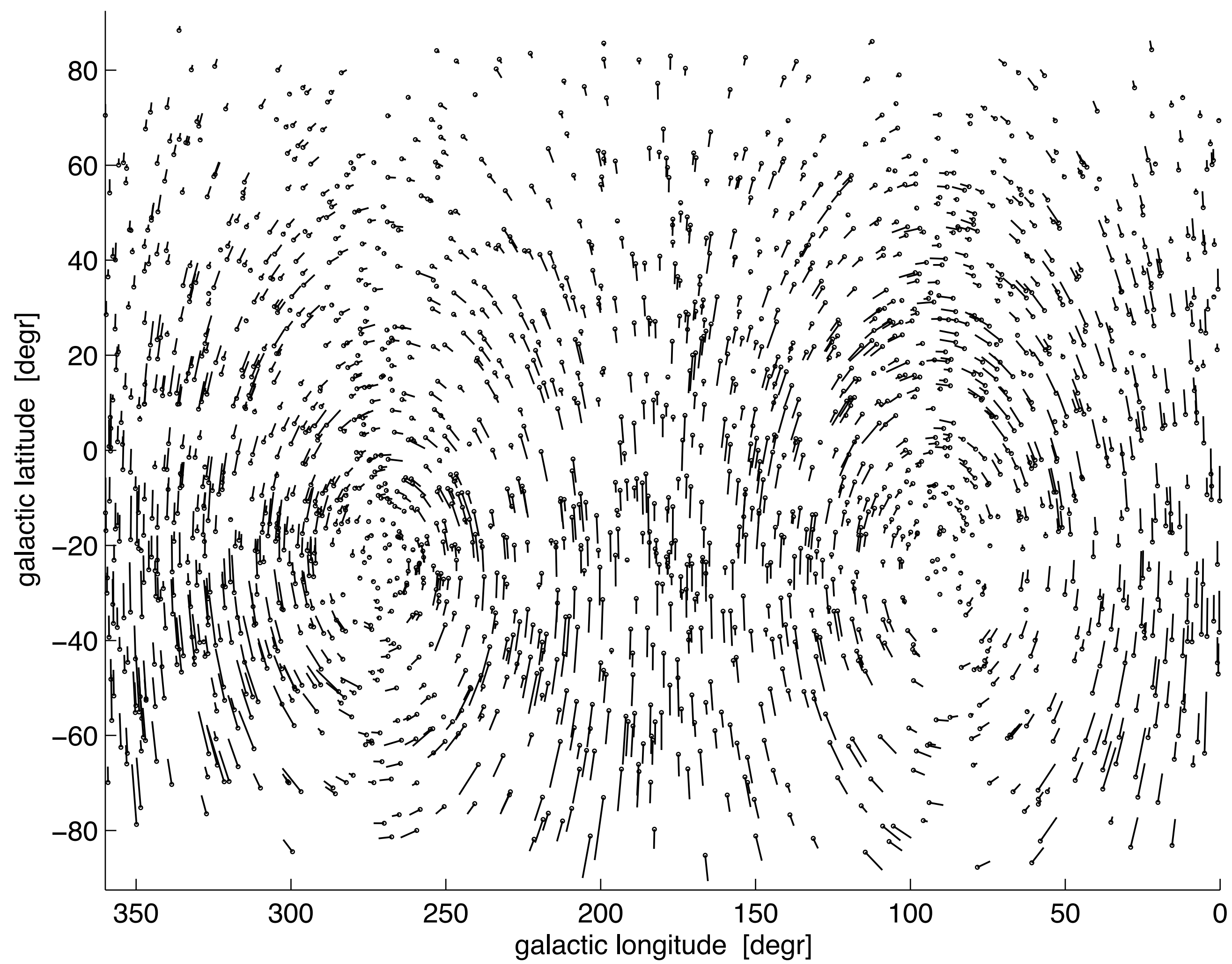
Galactic Rotation (4)

Decomposition by vectorial harmonics:
Makarov & Murphy (2007)

Vertical gradient of rotational velocity



Unexpected `magnetic' vector harmonics



Higher degree terms not present in classical linear model:

- linear gradient of rotational velocity with distance from the plane
- uncertain dependency on population (thin or thick disk)
- upward vertical motion of stars towards GC (opposite to stationary warp model)

Results on Galactic Rotation

Reference	A	$-B$	$A-B=$ Θ_0/R_0	$-(A+B)=$ $(d\Theta/dR)_{R_0}$	R_0 (kpc)	Θ_0 (km s^{-1})
Pre-Hipparcos:						
Oort (1927a)[1]	19	24	43	+5		
IAU (1964) standard[2]	15	10	25	−5	10	250
Kerr & Lynden-Bell (1986)[3]	14.4 ± 1.2	12.0 ± 2.8	26.4 ± 1.6	-2.5 ± 3.1	8.5 ± 1.1	220 ± 20
Hanson (1987)[4]	11.3 ± 1.1	13.9 ± 0.9	25.2 ± 1.9	$+2.6\pm1.4$		
Olling & Merrifield (1998)[5]	11.3 ± 1.1	13.9 ± 0.9	25.2 ± 1.9	$+2.6\pm1.4$	7.1 ± 0.4	184 ± 8
Hipparcos – Oort–Lindblad:						
Feast & Whitelock (1997) Cepheids	14.8 ± 0.8	12.4 ± 0.6	27.2 ± 1.0	-2.4 ± 1.0	8.5 ± 0.5	231 ± 15
Olling & Dehnen (2003) dwarfs[6]	9.6 ± 0.5	11.6 ± 0.5	21.1 ± 0.5	$+2.0\pm0.5$		
Olling & Dehnen (2003) giants[7]	15.9 ± 1.2	16.9 ± 1.2	32.8 ± 1.2	$+1.0\pm1.2$		
Liu & Ma (1999) O–B[14]	17.6 ± 0.2	14.6 ± 0.2	32.2 ± 0.3	-3.0 ± 0.3		
Hipparcos – Ogorodnikov–Milne:						
Miyamoto & Zhu (1998) Cepheids	16.5 ± 1.1	12.1 ± 0.9	28.6 ± 1.4	-4.4 ± 1.4		
Miyamoto & Zhu (1998) O–B5	16.1 ± 1.1	15.5 ± 0.9	31.6 ± 1.4	-0.6 ± 1.4		
Mignard (2000) dwarfs[8]	10.9 ± 0.8	13.3 ± 0.6	24.2 ± 1.1	$+2.4\pm1.1$		
Mignard (2000) giants[9]	13.0 ± 1.0	11.4 ± 1.0	24.4 ± 1.4	-1.6 ± 1.4		
Branham (2000) all[10]	10.8 ± 0.5	11.0 ± 0.5	21.8 ± 0.7	$+0.2\pm0.7$		
Branham (2002) O–B	14.9 ± 0.8	15.4 ± 0.7	30.3 ± 1.1	$+0.5\pm1.1$		
Branham (2006) O–B	16.1 ± 0.7	10.7 ± 0.6	26.8 ± 1.0	-5.3 ± 1.0		
Hipparcos – vectorial harmonics:						
Vityazev & Shuksto (2004) 113 646 stars	13.5 ± 2.0	12.6 ± 1.6	26.1 ± 2.6	-0.9 ± 2.6		
Makarov & Murphy (2007) non-binary	13.8 ± 1.4	13.4 ± 1.2	27.1 ± 1.8	-0.4 ± 1.8		
Hipparcos – spiral-density waves:						
Lépine et al. (2001) Cepheids	17.5 ± 0.8	8.8 ± 1.5	26.3 ± 1.7	-8.7 ± 1.7		

cf Brunthaler et al (2011) using VLBI−BeSSeL + Sgr A*: $R_0 = 8.3\pm0.23$, $\theta_0 = 239\pm7$ (for specific UVW)

Summary

Distance to Galactic centre (using Galactic centre stars):

R_0 = 8.2 kpc

Sun's distance from the Galactic plane:

Z_0= 20 (+/-10?) pc

Solar motion with respect to LSR (Dehnen & Binney 1988):

$u_0 = +10.00$, $v_0 = +5.25$, $w_0 = +7.17$ km/s

Galactic rotation (Feast & Whitelock 1997):

$A=+14.82$, $B=-12.37$ km/s/kpc

$\Omega_0 = (\Theta/R)_{R_0} = A-B = +27.19$ km/s/kpc

$(d\Theta/dR)_{R_0} = -(A+B) = -2.45$ km/s/kpc (slightly decreasing)

Circular velocity at $R_0 = R_0\, \Omega_0$ = 223 km/s

Galactic rotation period = 226 Myr

The uncertainties affect, e.g.:

- dynamical effects of the local mass density based on vertical motions of stars in the disk
- constraints on dark matter distribution
- disk and local star formation models
- Galactic escape velocity
- models of spiral arms
- phase of Sun's vertical oscillatory motion
- Sun's passage through the spiral arms

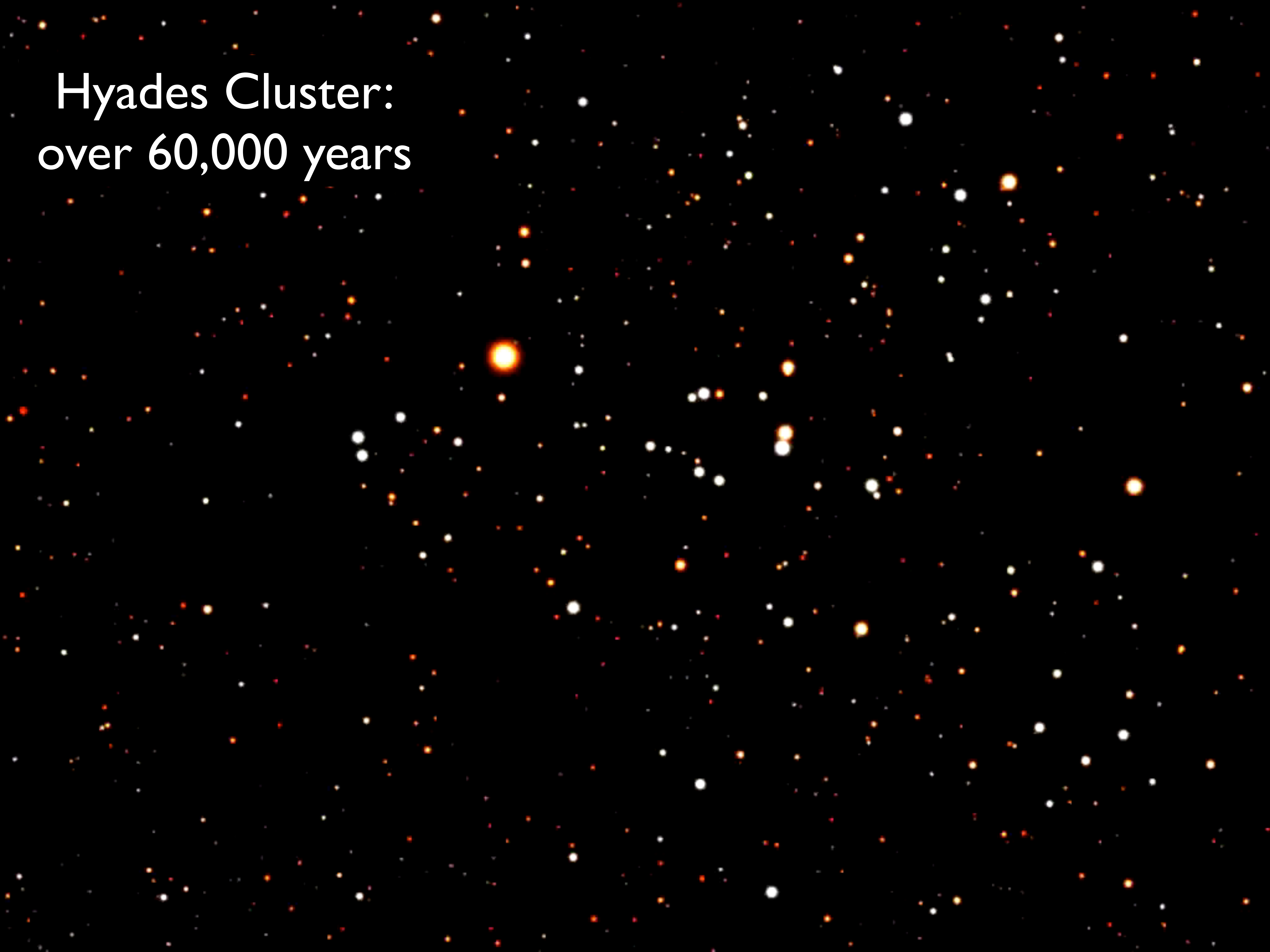
Problem 2.
The Hyades and Pleiades

Detailed Sub-Structure: Clusters, Associations, Moving Groups, Streams...

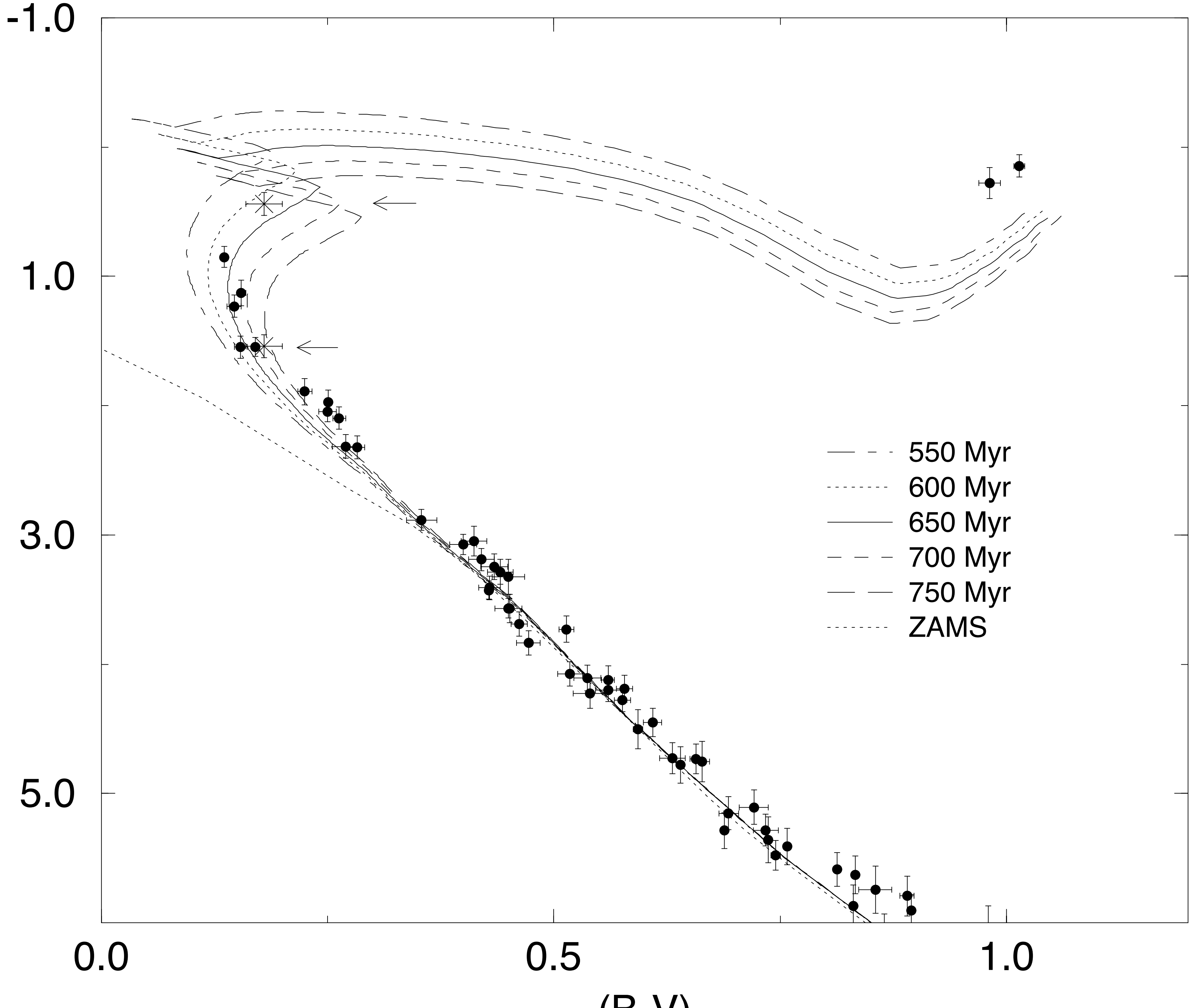
Detection methods (delicate with Hipparcos):

- Convergent-point analyses: Hyades (Perryman et al 1998)
- Spaghetti method: parallax + positions/proper motions (Hoogerwerf & Aguilar 1999)
- Global convergence mapping (Makarov & Urban 2000)
- Orbital back-tracking (Hoogerwerf et al 2001, Ortega et al 2002, ...)
- Epicycle correction (Makarov et al 2004)
- Wavelet transforms (Chereul et al 1997, 1998, 1999)
- Vector-point diagrams (Platais et al 1998, Kharchenko et al 2005)

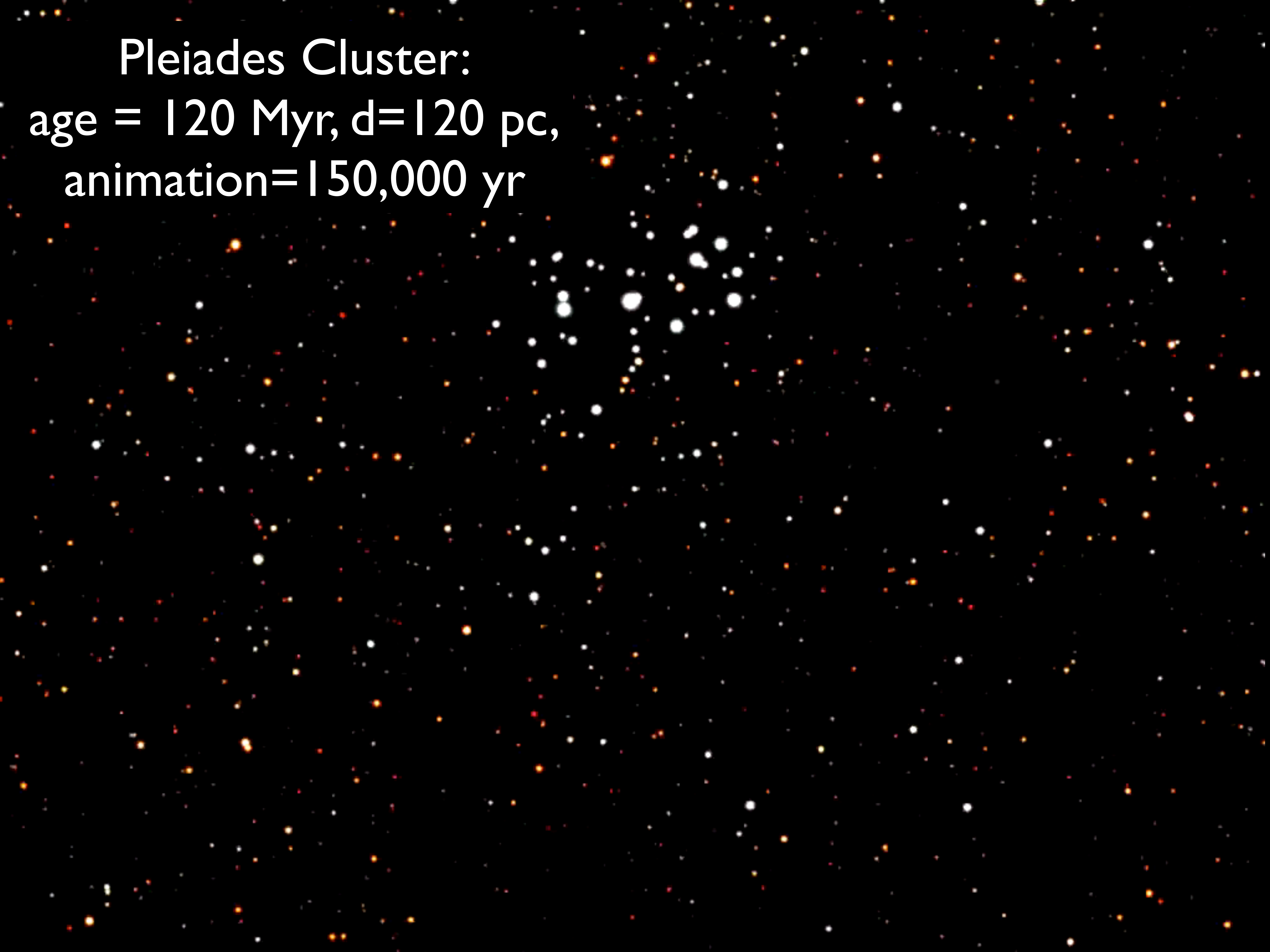
Identification of cluster members will be facilitated by Gaia's parallaxes, proper motions, radial velocities, and multi-colour photometry


Hyades Cluster:
over 60,000 years

Hyades main sequence fitting



The Pleiades star cluster


Pleiades Cluster:
age = 120 Myr, d=120 pc,
animation=150,000 yr

Hyades and Pleiades

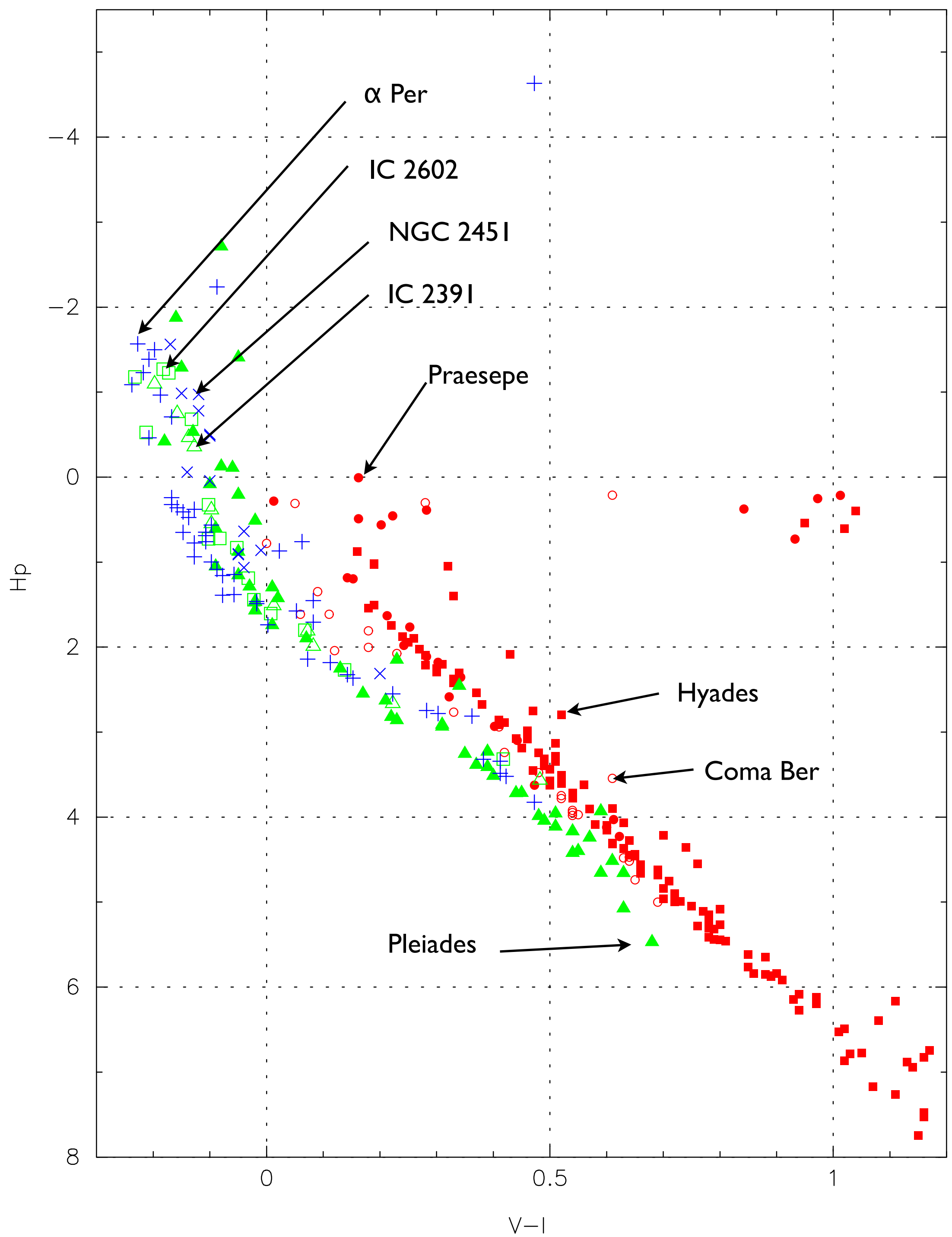
Hyades:

- distance (~70 members) = 46.3±0.3 pc
- chemical composition: Y = 0.26, Z = 0.024; age = 625±50 Myr (Perryman et al 1998)
- internal velocity dispersion $\sigma_v = 0.3$ km/s (de Bruijne et al 2001, Narayanan & Gould 1999)
- N-body simulations: initial mass $\sim 1200\ M_\odot$ (Madsen 2002)

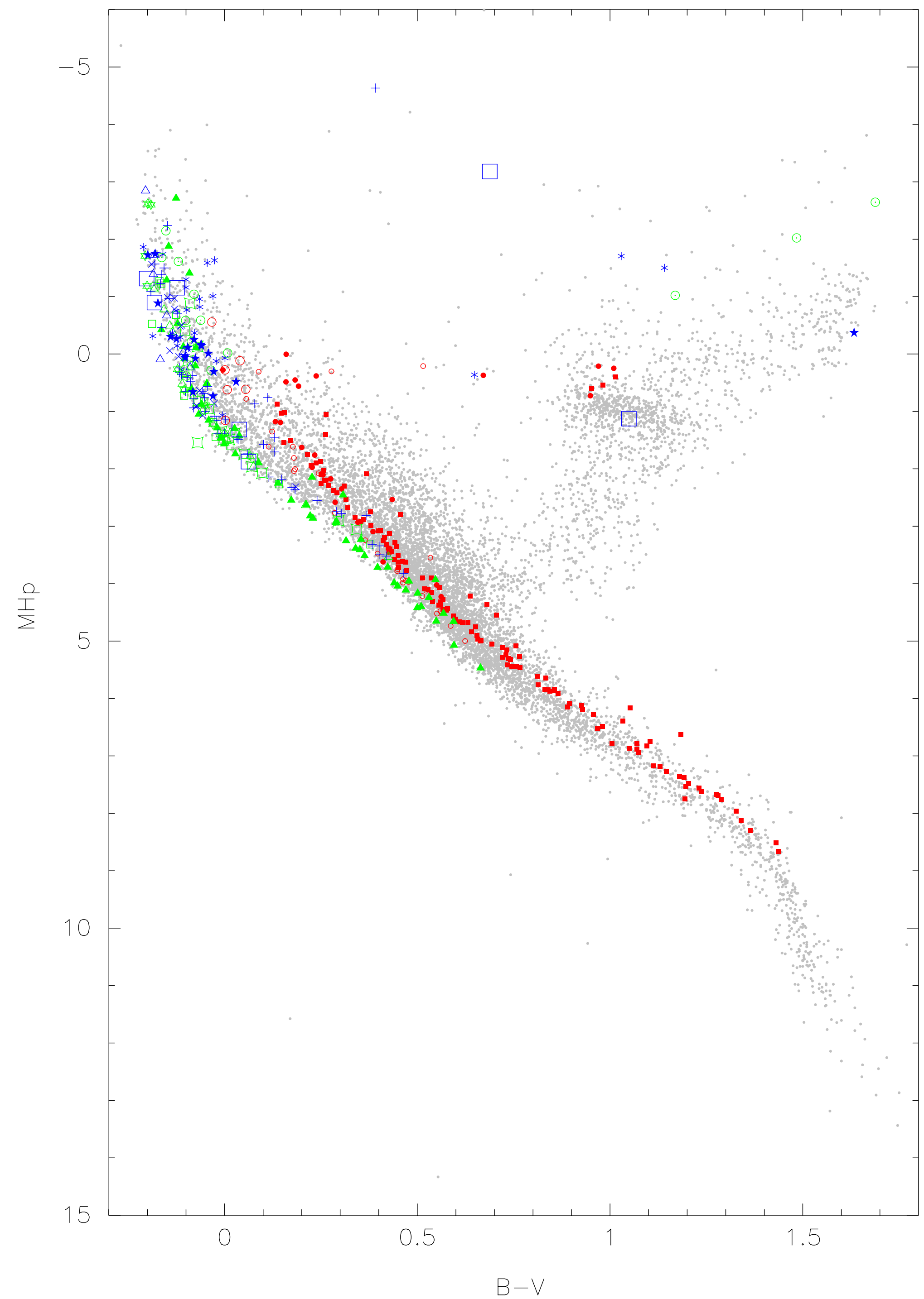
Pleiades:

- distance (main sequence) = 133.8 −135.5±3 pc (Percival et al 2005, An et al 2007)
- distance (Hipparcos) = 118.3±3.5 (van Leeuwen 1999) to 122.2±2.0 (van Leeuwen 2007)

Not just a problem for Hyades and Pleiades...



Eight nearest clusters; both figures from the comprehensive re-reduction of the data
(van Leeuwen 2007)



9344 single stars with parallaxes < 5%, with 20 open clusters:
oldest in red (Hyades, Praesepe); Pleiades etc in green; youngest in blue

The cluster distance problem

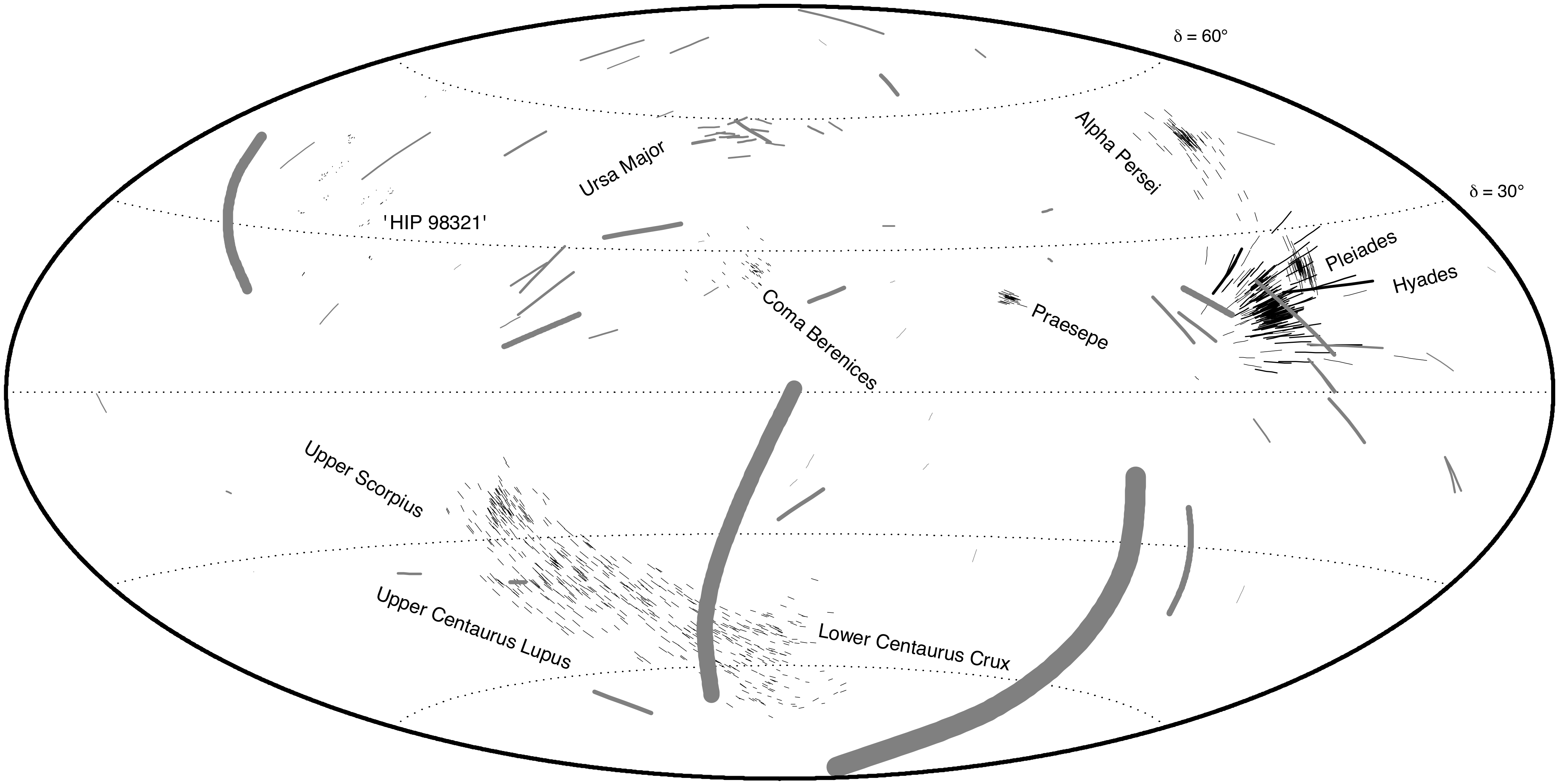
- Complications:
  - small-scale correlations (documented in Hipparcos Catalogue)
  - main-sequence fitting and Hipparcos parallaxes sample distinct parts of the main sequence
  - metallicity determination; temperature scale; He (Efremov 1997, Belikov 1998)
  - binaries HD 23642 (Munari 2004, Southworth 2005), HD 23850 (Pan 2004, Zwahlen 2004)
  - other distance estimates: HST FGS3 (Soderblom 2005); asteroseismology (Fox et al 2006)
  - cluster non-sphericity (Raboud & Mermilliod 1998, Stello & Nissen 2001)
  - extended star formation over time (Herbig 1962, Belikov 1998, Raboud & Mermilliod 1998)
  - X-ray diagnostics (Makarov & Robichon 2001)
  - grey extinction (Jones 1972)

- Preparing for a more detailed Hyades/Pleiades investigation with Gaia:
  - acquire multiple-epoch radial velocities for full space motions, binary studies, membership
  - acquire multicolour photometry and spectroscopy for metallicity and reddening
  - develop dynamical models including N-body simulations

Others...

- nearby stars (following Gliese & Jahreiss)
- local mass density
- properties of open clusters
- structure and dynamics of spiral arms
  (cf Xu et al 2013, VLBA−BeSSeL survey using H_2O masers)
- halo stars within 100 pc
- distance to the LMC

Clusters and Associations on the Sky

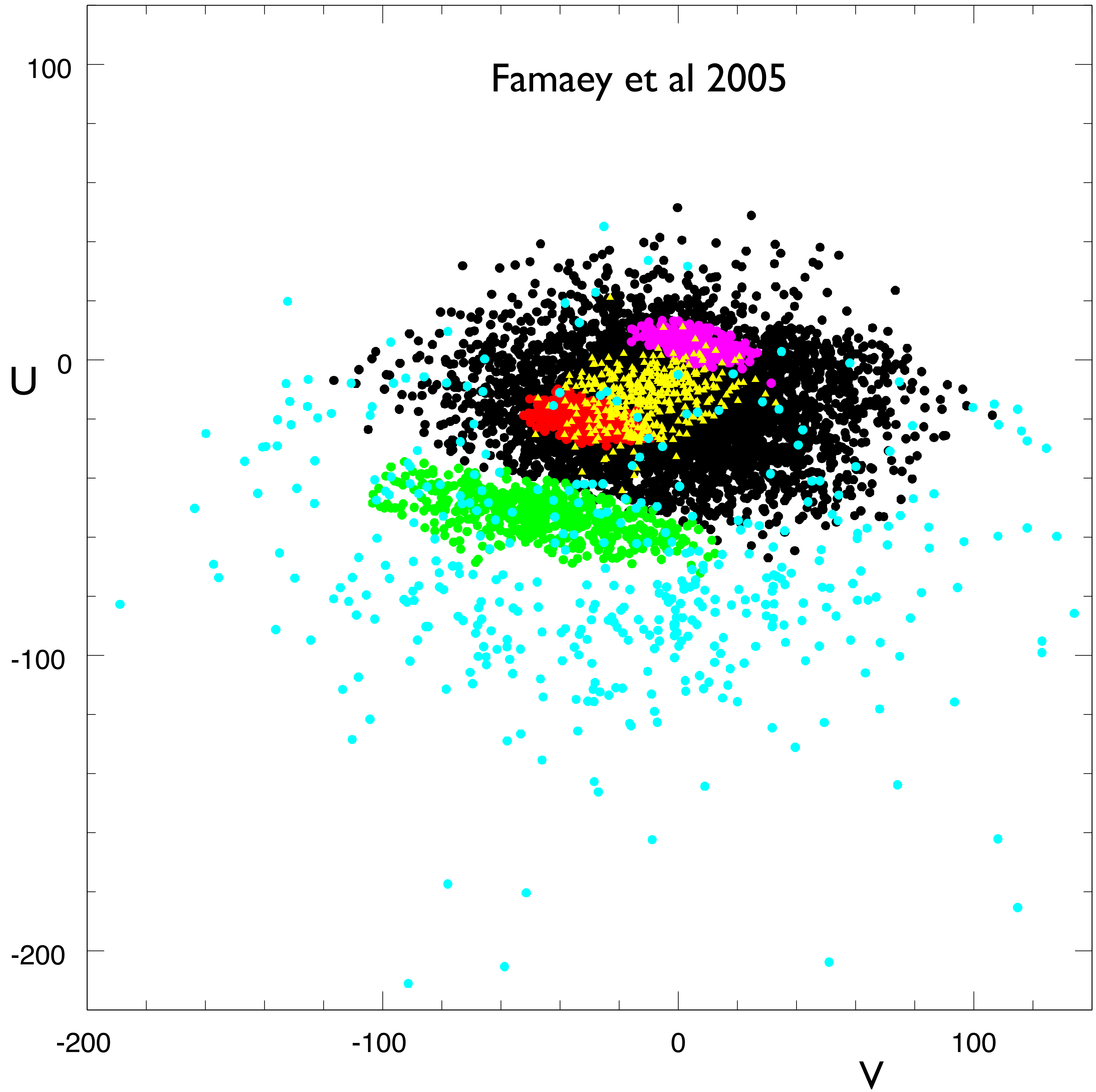


Convergent motions over 200,000 years
(Madsen et al 2002)

Detects:

- clusters (Hyades, Pleiades, Coma,...)
- moving groups (Ursa Major,...)
- associations (Scorpius, Centaurus,...)

Moving Groups in the Galactic U-V Plane



Moving Groups in the Galactic U-V Plane

These (old) ‘moving groups’ cover various phenomena:

- evaporating open clusters: Hyades group
- spiral-arm shocks: Pleiades group (Asiain et al 1999, Famaey et al 2005, Gieles et al 2007)
- resonance due to rotating bar: Hercules stream (Dehnen 1998)
- other moving groups:
    - Castor: 0.2 Gyr (Barrado y Navascues 1998, Montes et al 2001)
    - Ursa Major: 0.3 Gyr (Eggen 1998, Chupina et al 2001, King et al 2003)
    - HR 1614: 2-6 Gyr (Eggen 1998, Feltzing & Holmberg 2000)


HIP 16404
Stars nearby are travellers from far away
(view of Galactic disk over 300 Myr)
HIP 49616
HIP 117254
our Sun

Mass in the Galactic plane (over ~60 Myr)

Distribution of Matter

Characterised by:

- mass per unit volume (Oort limit)
- total surface density projected on the plane (scale height)
- density + velocity distribution → potential (K-z relation)

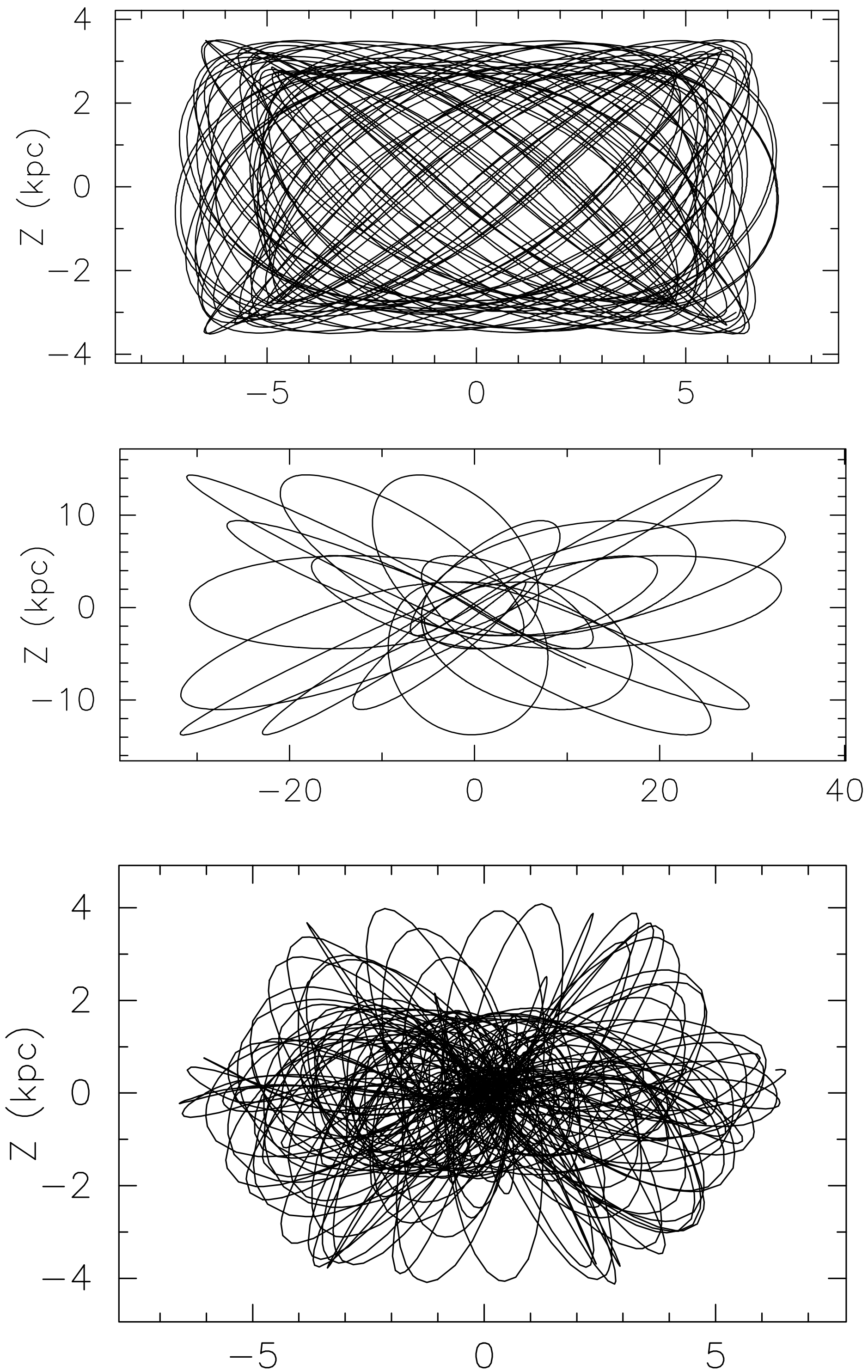
Important for:

- physical/chemical evolution of star formation
- disk stability and properties of dark matter
- Galactic escape velocity (~500 km/s; also runaway + hypervelocity stars)

Results:

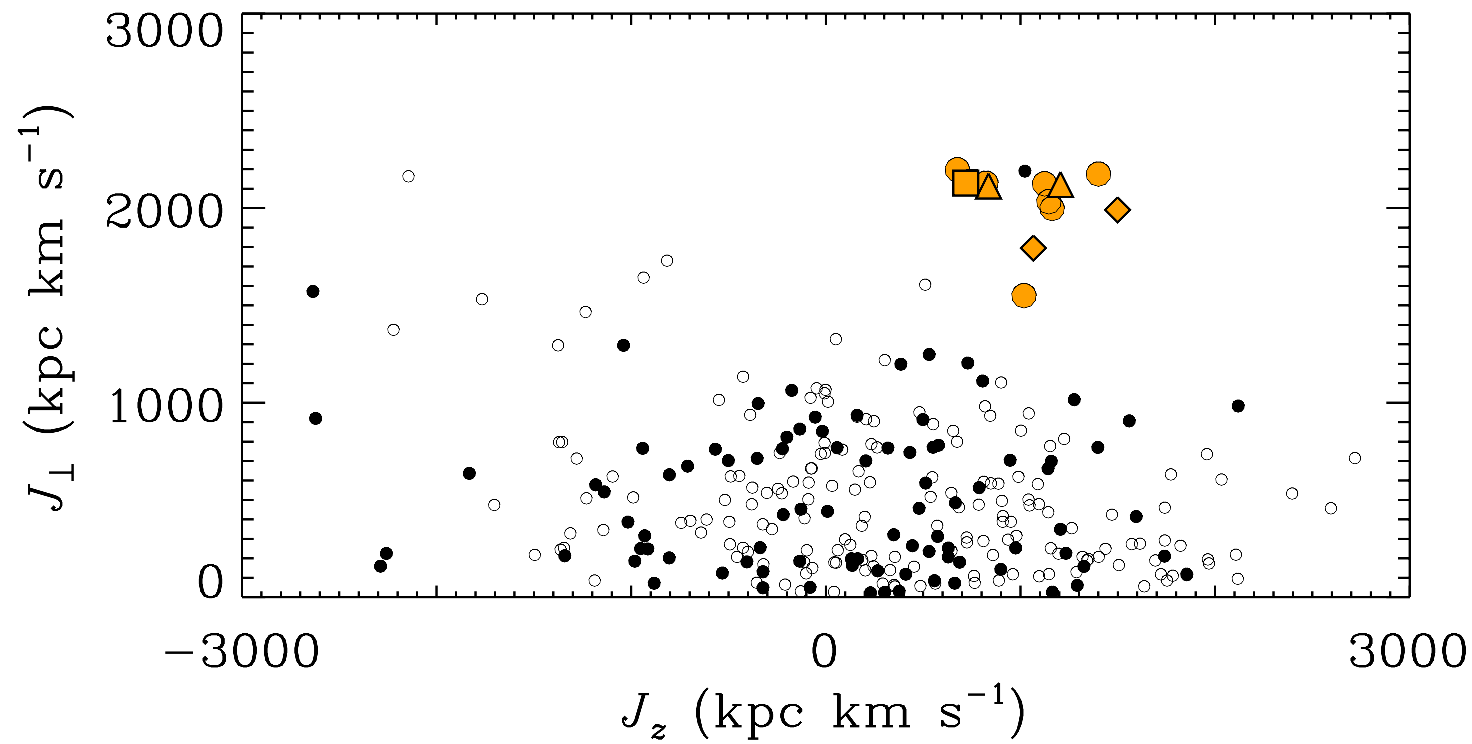
- no dark matter distributed as the disk (Crézé et al 1998)
- Oort limit (Holmberg & Flynn 2004): $\rho_0 = 0.102\ M_\odot\ \mathrm{pc}^{-3}$
- vertical oscillation period: $P_\perp = (\pi/G\rho_0)^{0.5} = 82$ Myr

Large-Scale Dynamical Structure (2/2)



Galaxy orbits for globular clusters for 10^{10} yr: disk, thick disk, and halo orbits

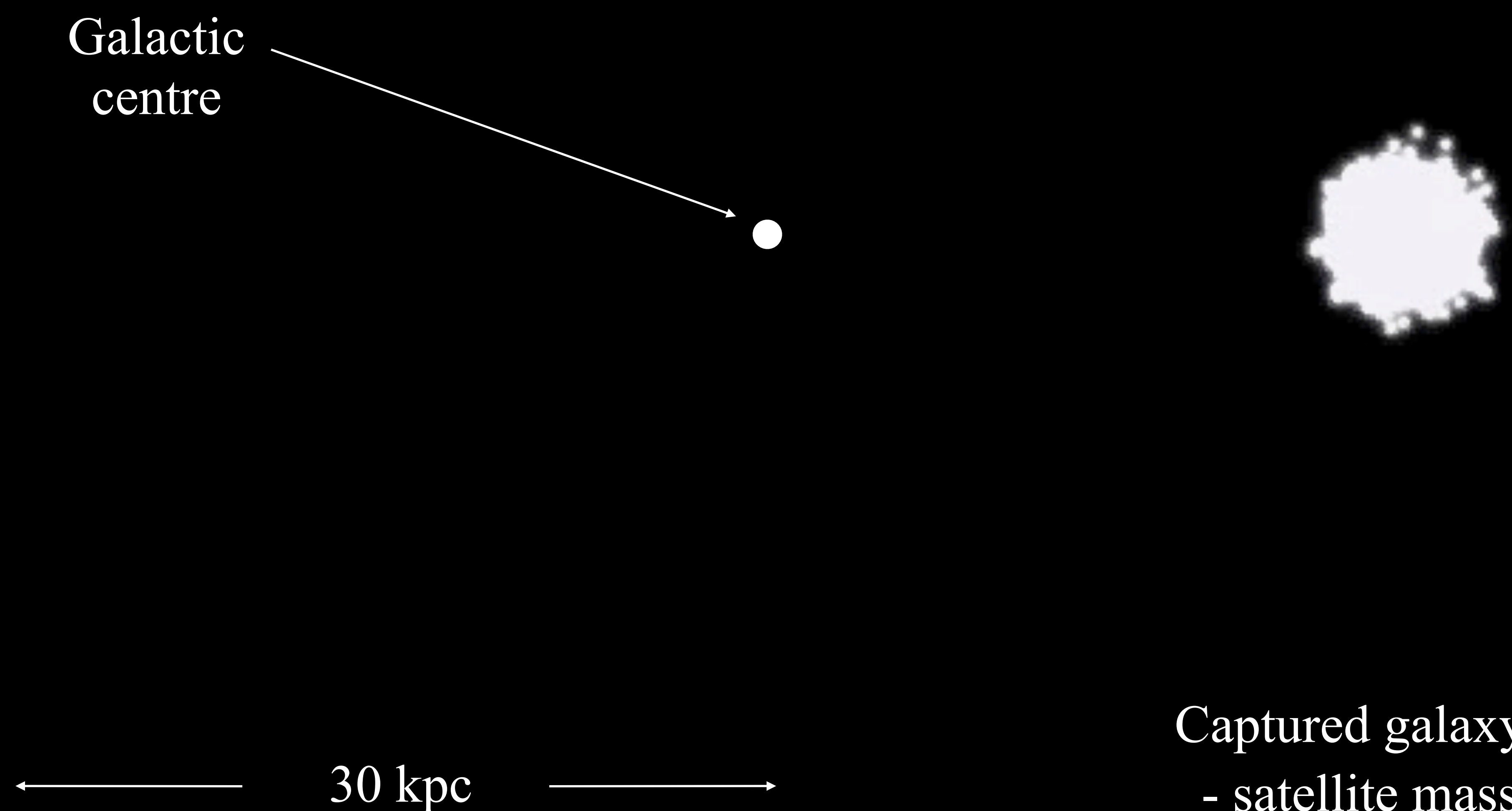
(Dinescu et al 1999)



Galaxy formation (infall) directly observed in angular momentum space

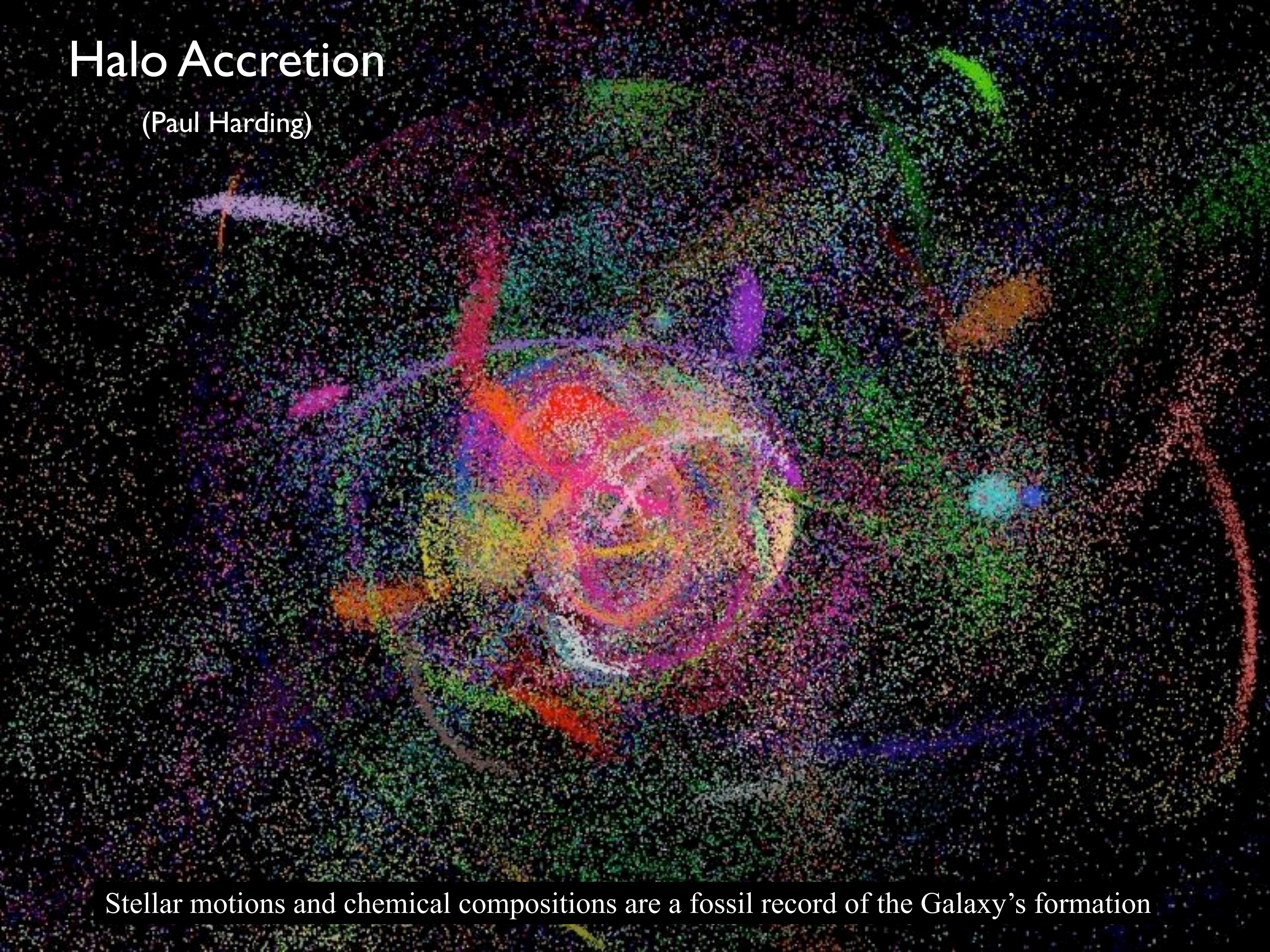
(Helmi et al 1999; Chiba & Beers 2000)

Our Galaxy has been built from mergers...



Captured galaxy:

- satellite mass: 4×10^8 M_o
- pericentre: 7 kpc
- simulation over 3 Gyr


Halo Accretion
(Paul Harding)
Stellar motions and chemical compositions are a fossil record of the Galaxy’s formation

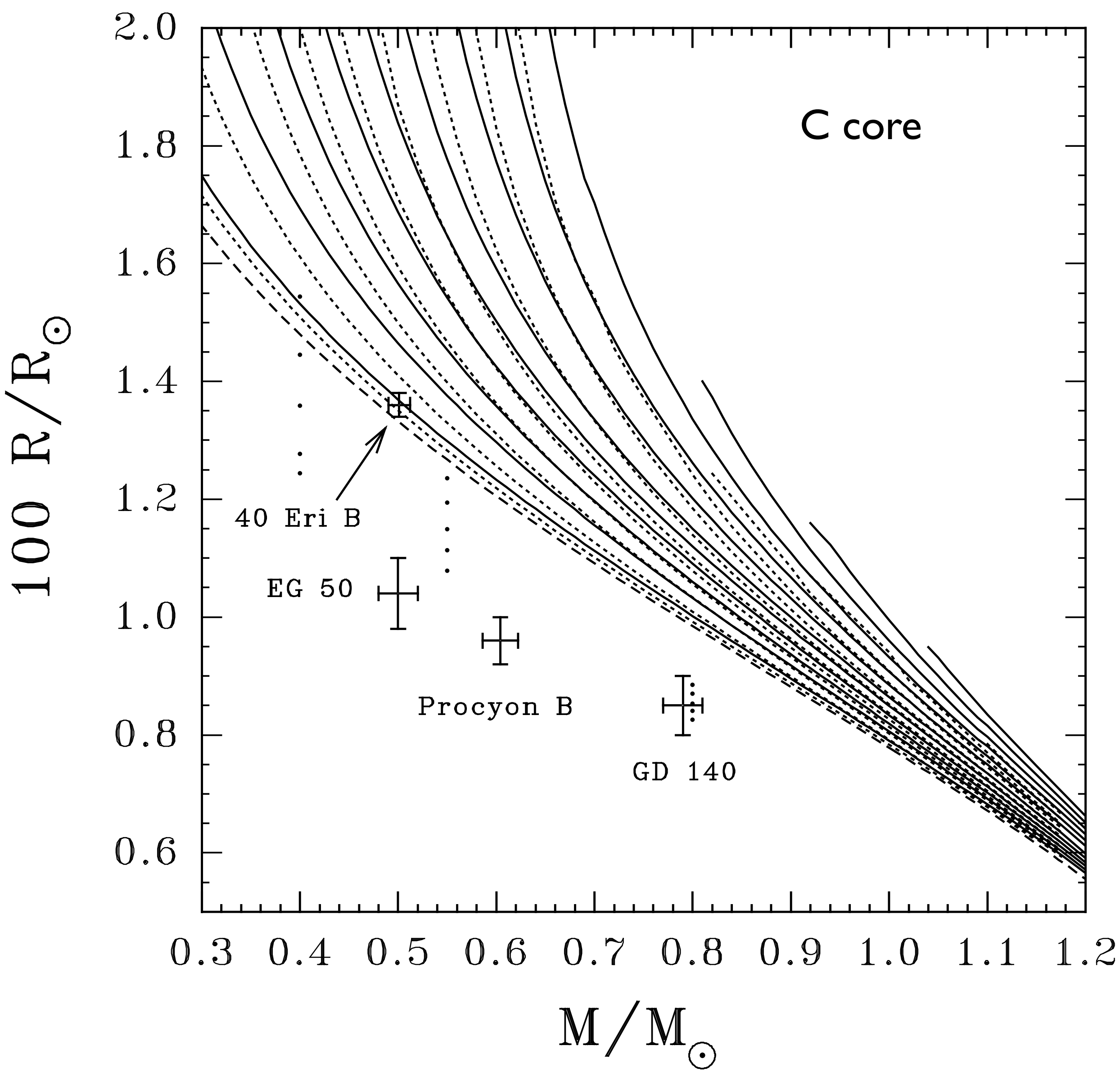
Outline of Talk

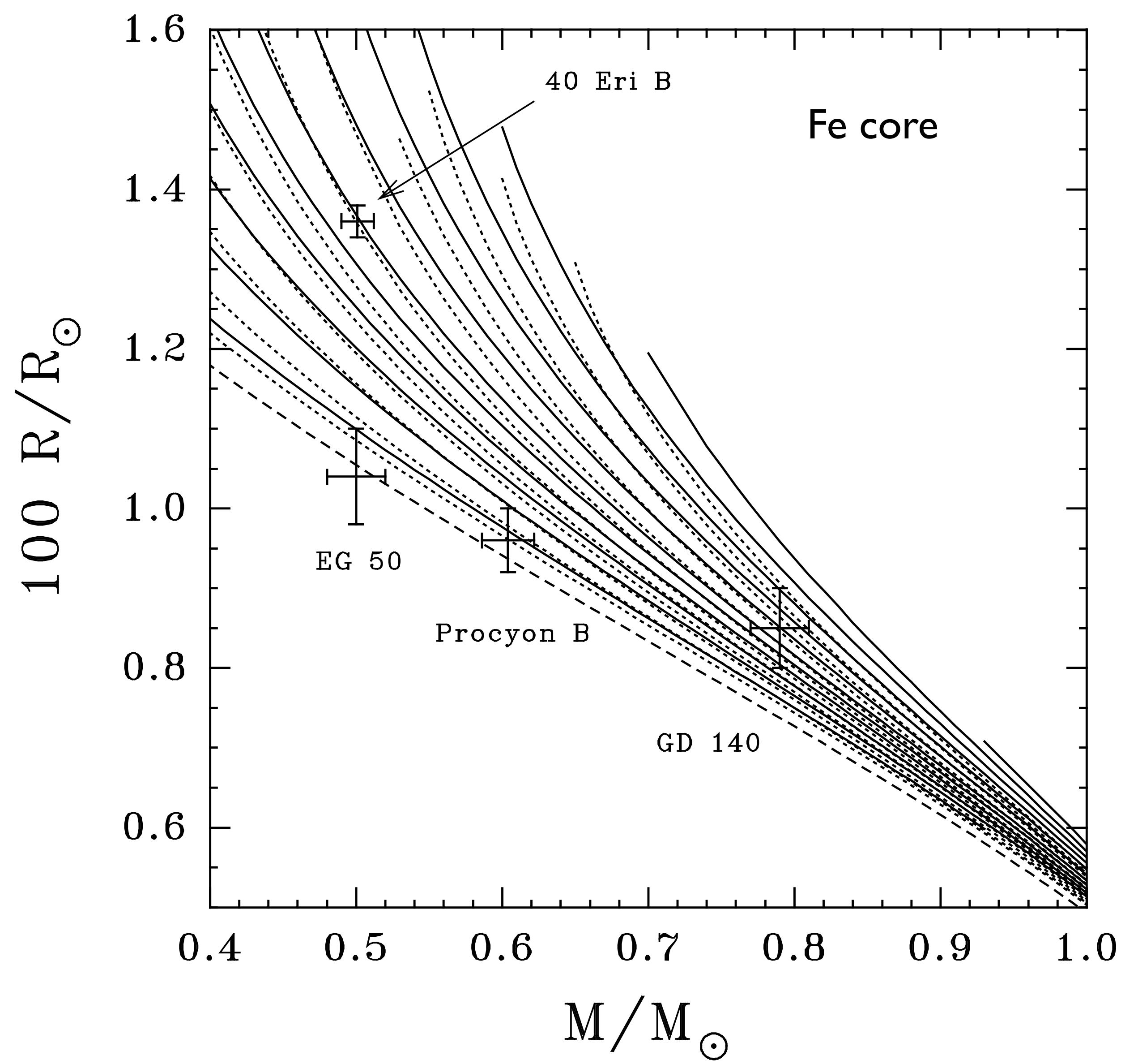
1. Reference Frame
2. Galaxy Structure and Dynamics
3. **Stellar Structure and Evolution**
4. Solar System and Exoplanets

Many Detailed Studies of....

- Absolute magnitude versus spectral type (bolometric corrections: Bessell 2007)
- Zero-age main sequence
- Physics of giants, subgiants, horizontal branch, asymptotic giant branch
- Mass loss
- Physics of binary systems (mass and radius)
- Abundances: [Fe/H], He, α-elements, lithium
- Chemical enrichment of the Galaxy
- Stellar rotation
- Magnetic field
- Stellar pulsation

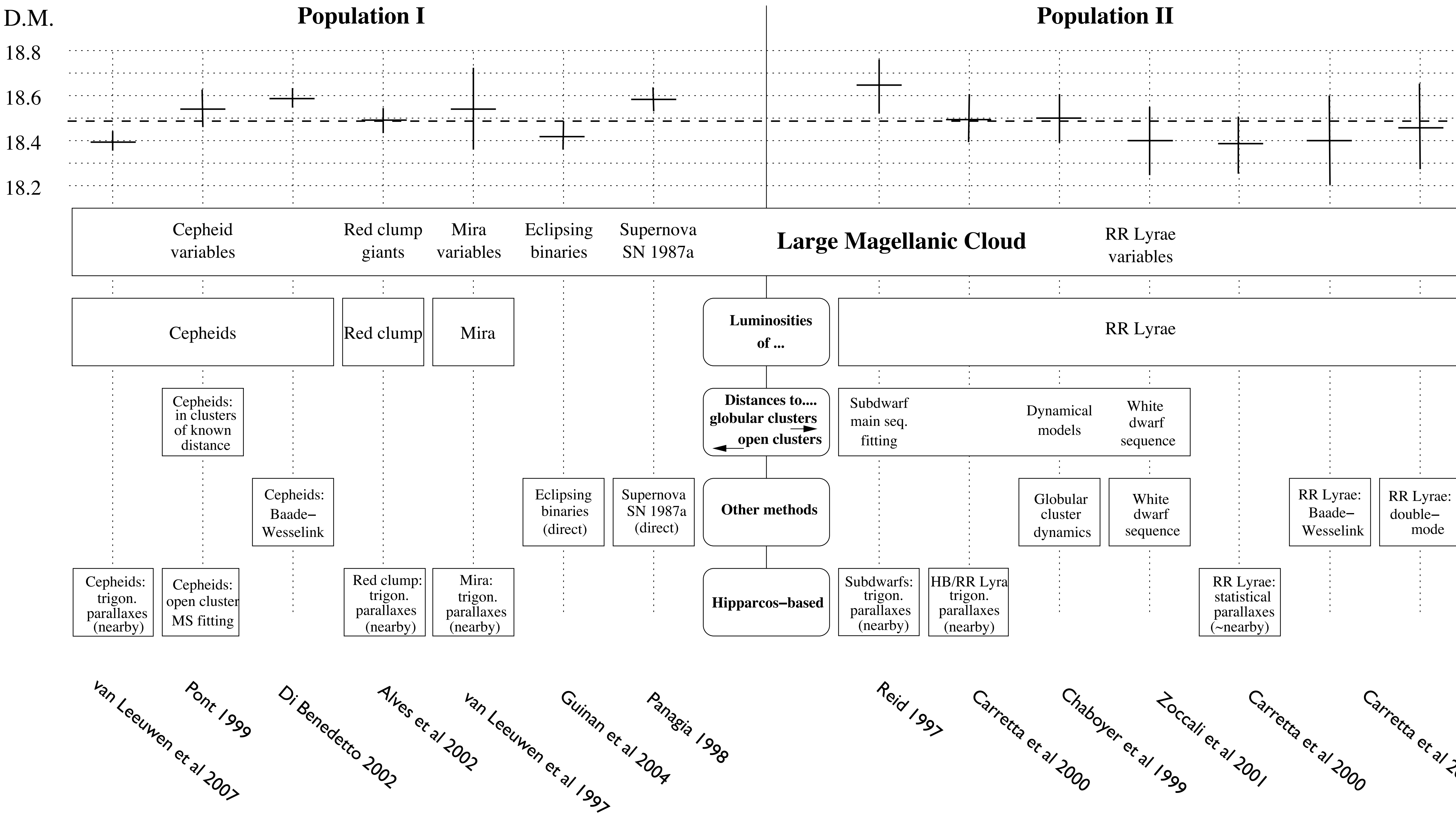
White Dwarfs





Mass-radius relation for white dwarfs for T_{eff} = 5000−145,000 K;
Hipparcos data from Provencal et al (1998, 2002)
He, O or Si cores have similar density (mean molecular weight per electron ~2)
Fe cores difficult to reproduce from stellar models (Iben & Renzini 1983)
Strange matter cores have been proposed by Panei et al (2000); Mathews (2006)

Distance to the Large Magellanic Cloud



Straight mean of direct/indirect Population I/II methods gives: $(m-M)_0=18.49$

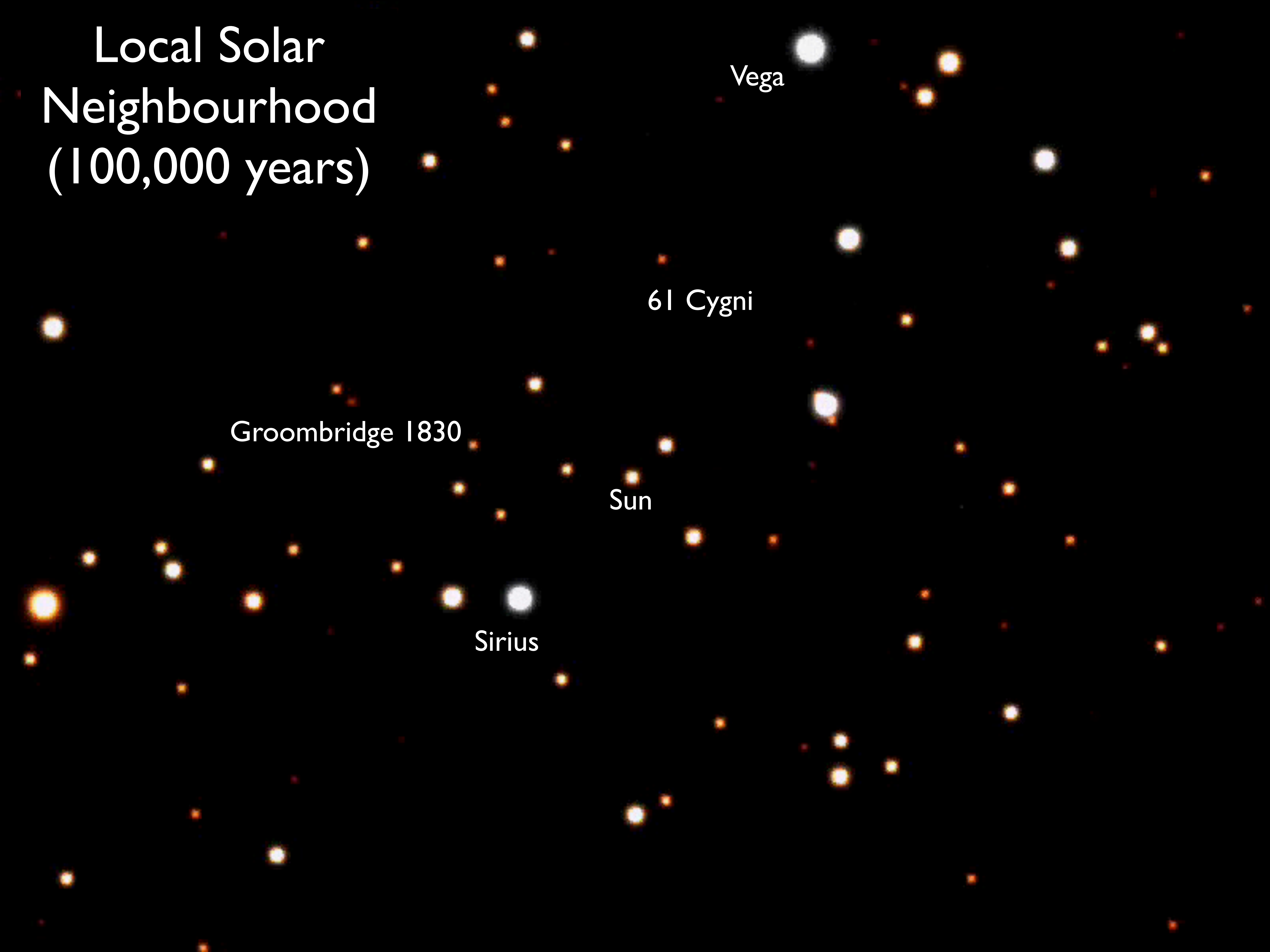
....consistent with $H_0=72\pm8$ with $(m-M)_0=18.50$
(Freedman et al 2001)

Compared with other recent values:
- 73±3 from WMAP (Spergel et al 2007)
- 75±7 from gravitational lens B1608+656 (Koopmans et al 2003)
- 76±4 from Sunyaev-Zel'dovich effect (Bonamente et al 2006)
- 73±4 from Type Ia supernovae (Reiss et al 2005)

Outline of Talk

1. Reference Frame
2. Galaxy Structure and Dynamics
3. Stellar Structure and Evolution
4. **Solar System and Exoplanets**

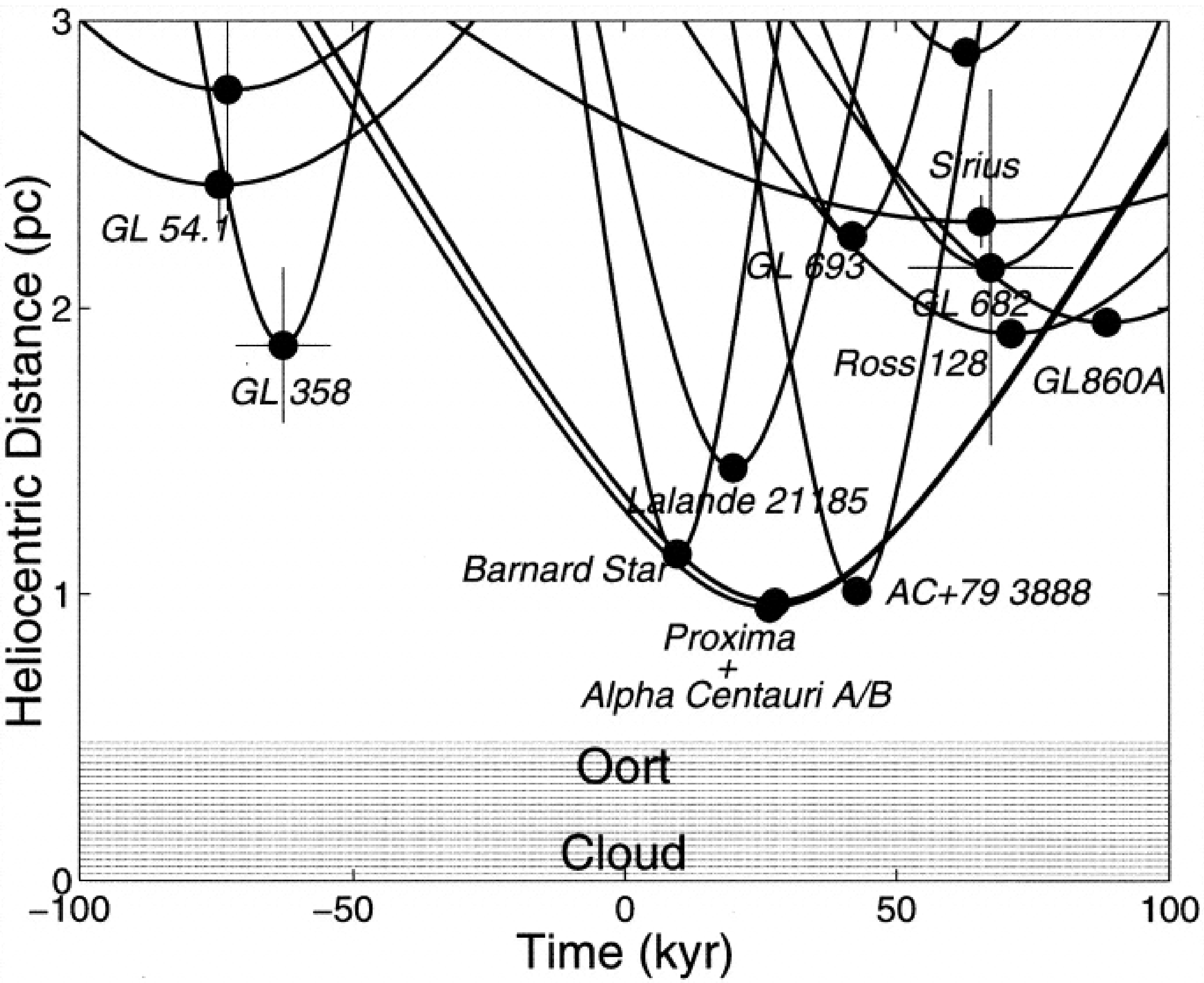
Local Solar Neighbourhood (100,000 years)



Gliese 710

(d=19 pc, V=14 km/s, t=1.4 Myr)

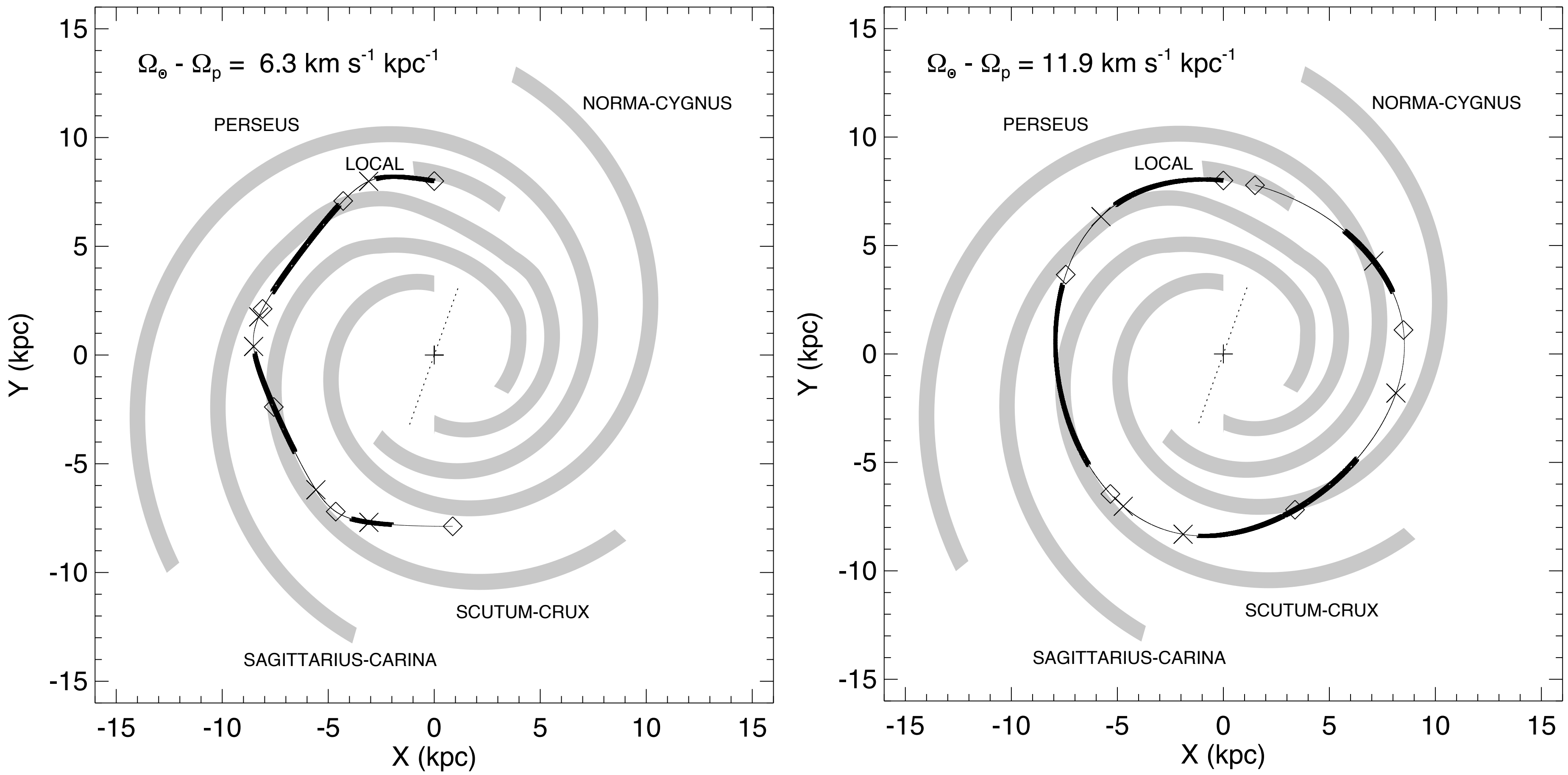
Stellar Encounters with our Solar System



Nearby star passages may trigger cometary impacts from Oort Cloud
(here over ±100,000 years):
Garcia Sanchez et al 1999, 2001; Frogel & Gould 1998; Serafin & Grothues 2002

Earth's Environment and Climate

(1) Sun's passage through the spiral arms matches ice-house epochs for a spiral arm pattern speed of Ω_p~14−17 km s^{-1} kpc^{-1}
(Gies & Helsel 2005; see also Shaviv 2003; Svensmark 2006)



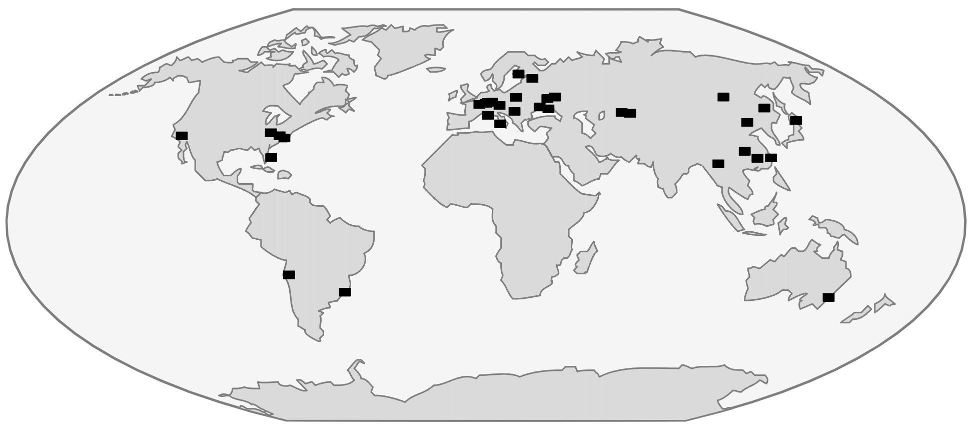
(2) Maunder Minimum (1645−1715):

- coldest excursion of little ice-age, and correlated with disappearance of sun spots
- probe of solar activity, solar dynamo, sun spot cycle, and climate
- monitoring Sun-like stars within 60 pc probes activity versus age (Wright 2004, 2006)

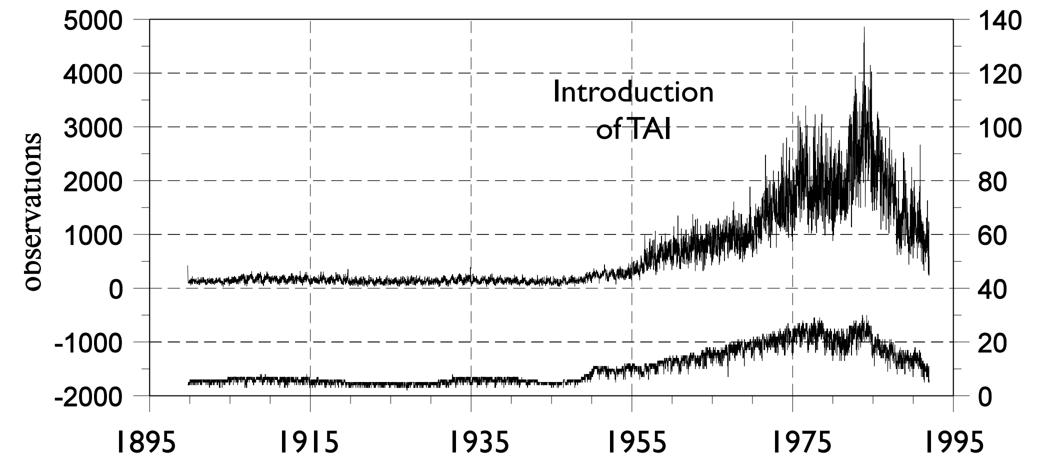
(3) Various other studies of Sun's orbit, spiral arm + Galactic plane passages (vertical oscillation period ~ 82 Myr), cratering records, geological crustal features, and relation between cosmic ray production and glaciation

Earth's Polar Motion
(since ~1895)

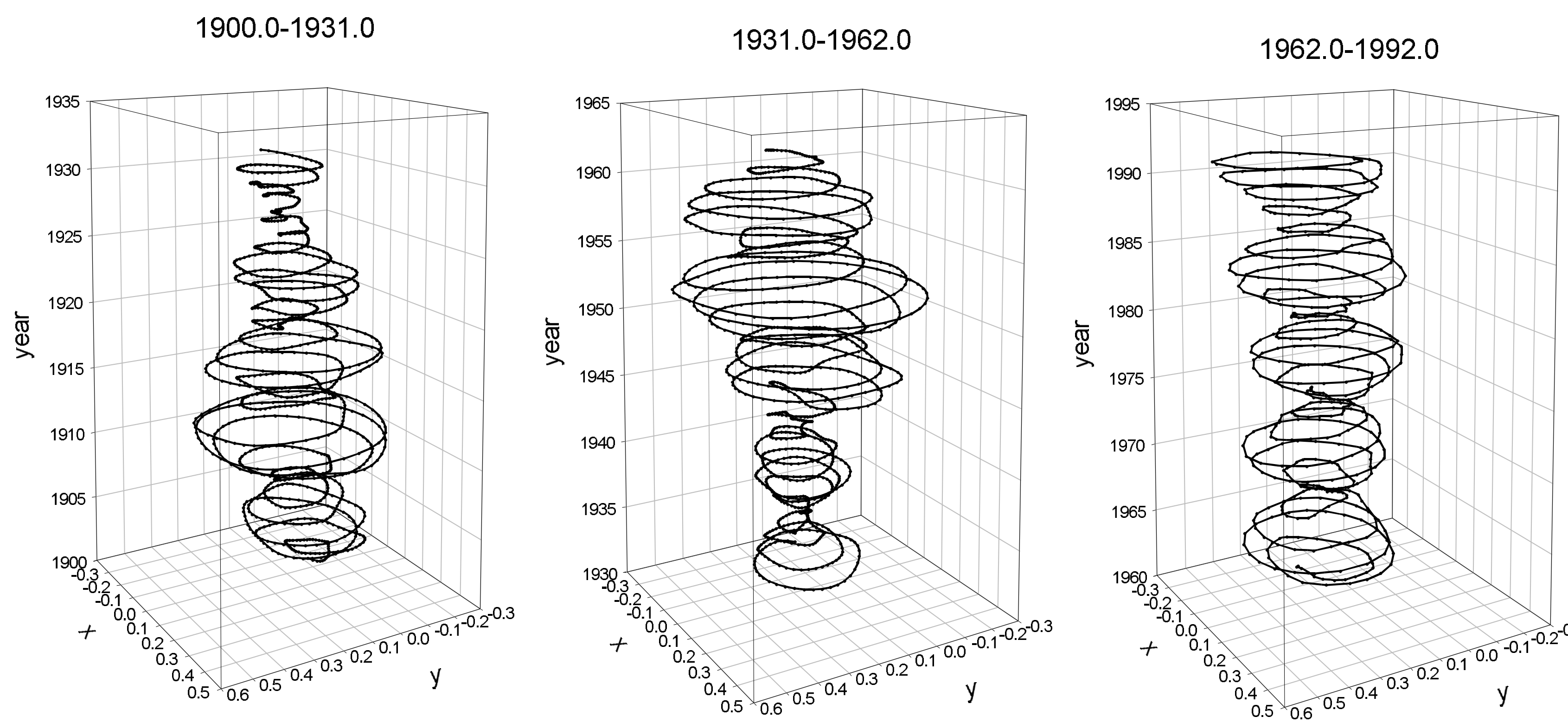
- small irregular movements of the Earth's geographic poles relative to crust
- originates from misalignment between rotation and symmetry axes
- dominant term: seasonal redistribution of mass ~0.3 arcsec (Chandler 1891)
- originally measured by visual and photographic zenith tubes, now VLBI and GPS
- ILS (1900), IPMS (1962), IERS (1988), BIH (1955), IAU MERIT (1978)
- all historical measurements reanalysed within Hipparcos reference frame



Participating observatories (Vondrák & Ron 2000)



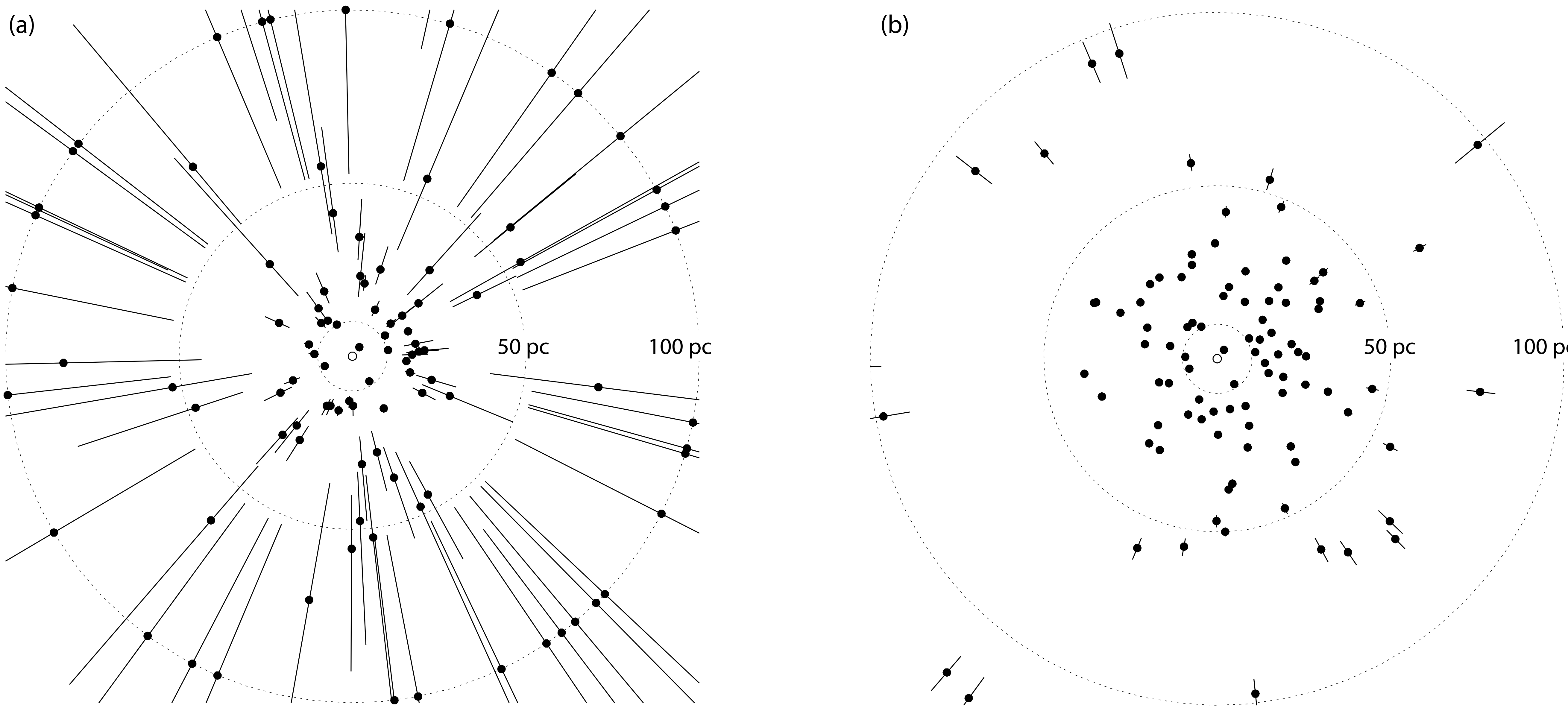
Number of instruments (Vondrák et al 1997)



Polar motion versus time
(Vondrák & Ron 2000)
... illustrating 6-year beating between the Chandler period (435 d) and annual term

Hipparcos distances to exoplanet host stars

100 brightest radial velocity host stars (end 2010)
(versus RA, independent of dec)

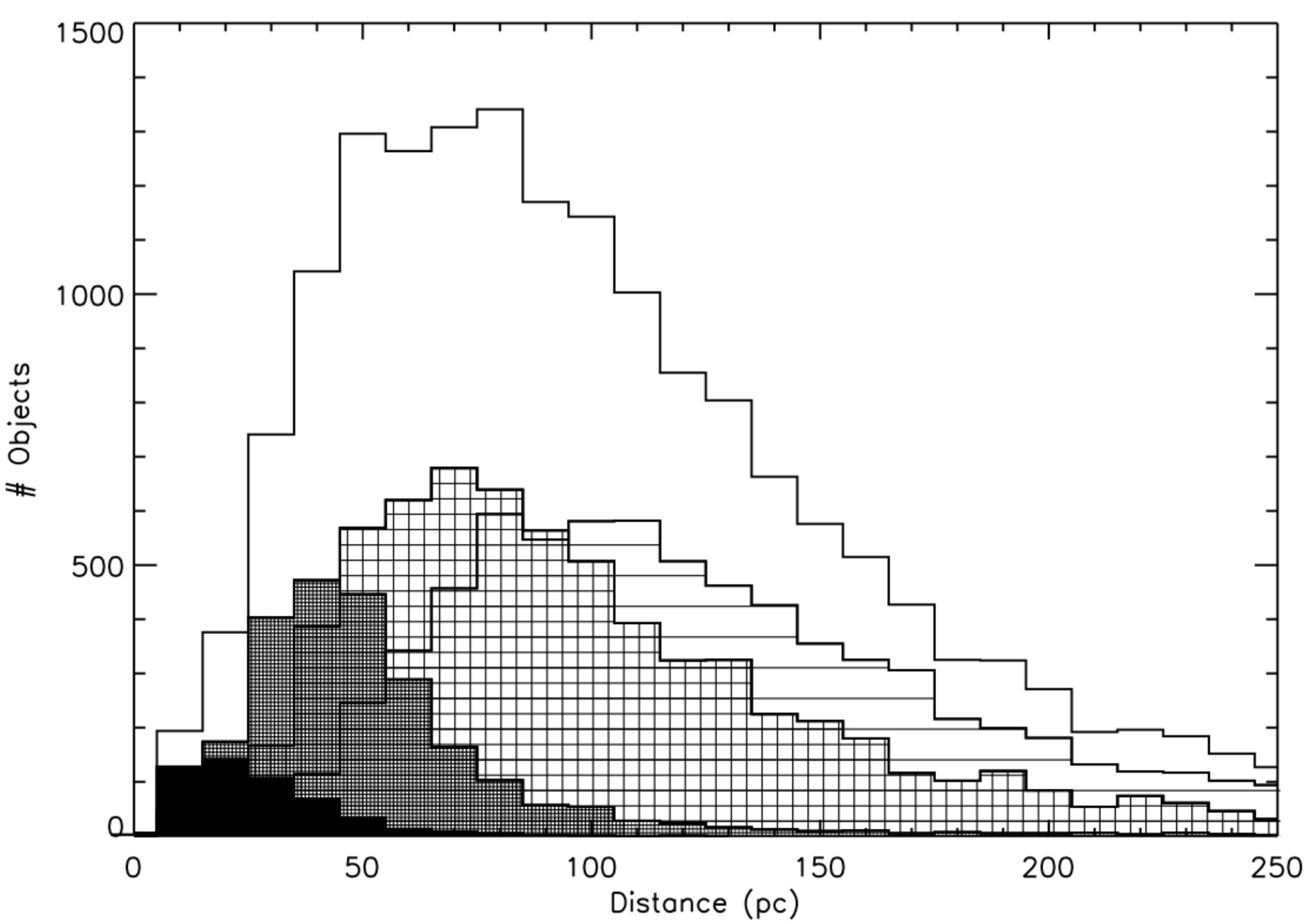


ground-based: van Altena et al (1995)
(unknown assigned π = 10±9 mas)

Hipparcos parallaxes
(Perryman et al 1997)

Search Optimisation for SETI (1/3)

Search Optimisation for SETI (2/3)



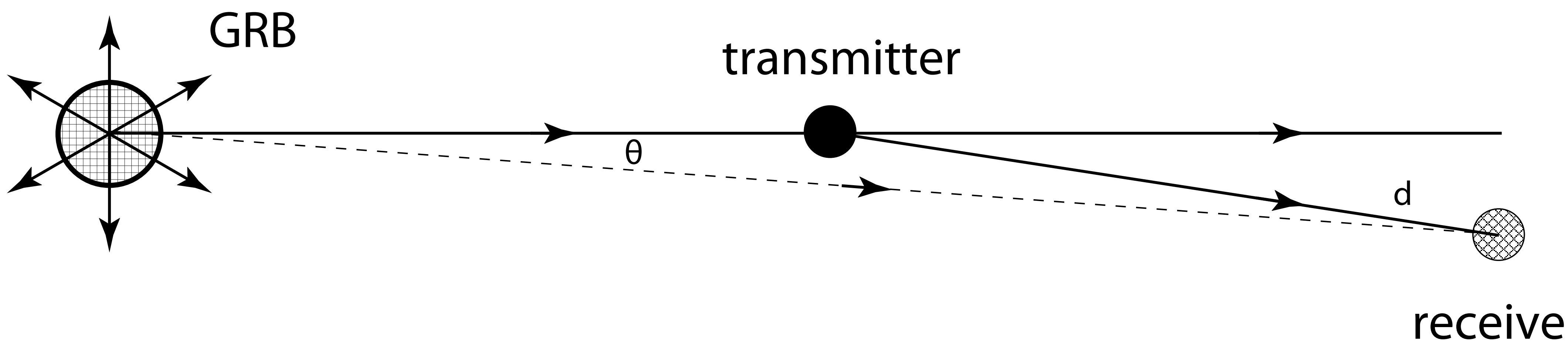
Potentially habitable stars vs spectral type - M/K/G/F/all (Turnbull & Tarter 2003)

Search for solar twins:
non-binary stars identical to the Sun in terms of:
age, mass, luminosity, chemical composition, temperature, surface gravity, magnetic field, rotational velocity, chromospheric activity

One of the 'best' candidates is HR 6060 at 14pc, already identified by Cayrel (1996), and confirmed with the Hipparcos data by Porto de Mello (1997)

Search Optimisation for SETI (3/3)

Q: How can 2 civilisations, both unaware of the existence of the other, optimise where and when to send a signal, and where and when to look?



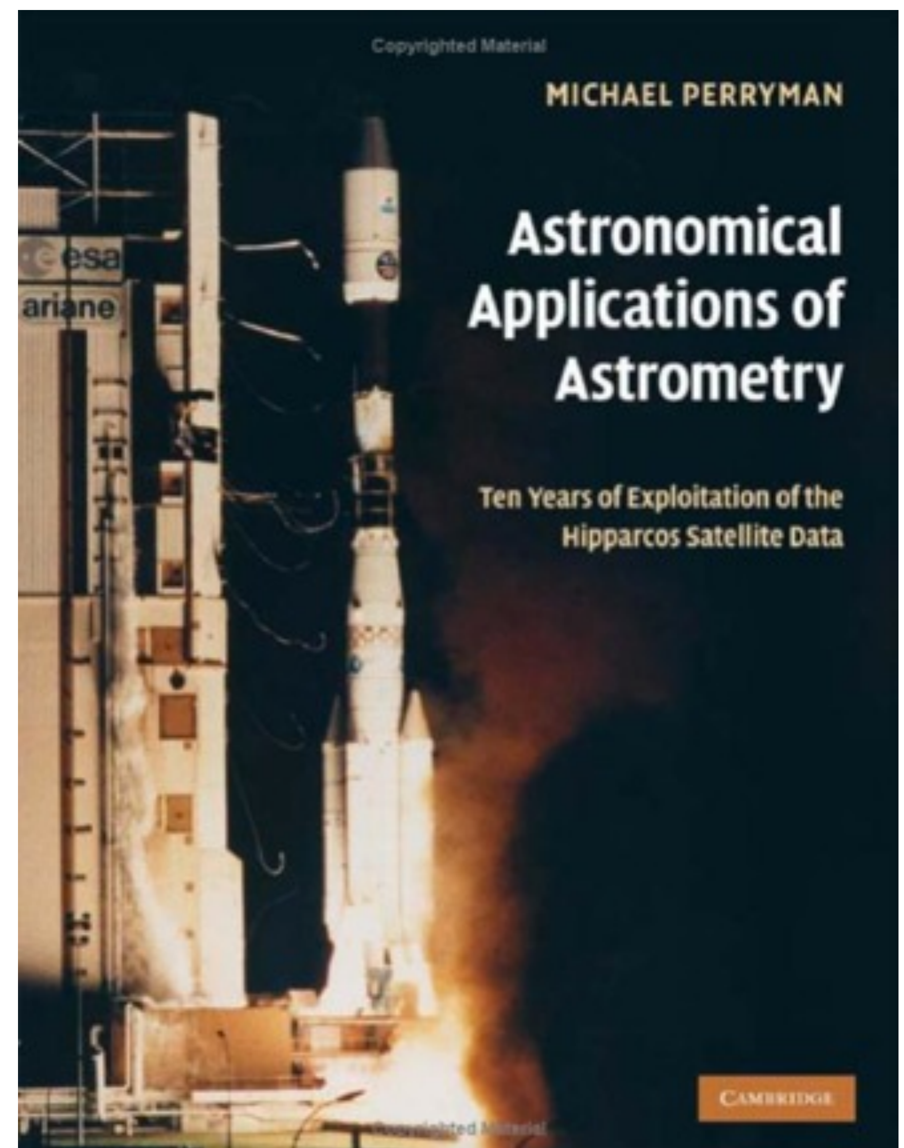
A: Use a gamma-ray burst as a timing/location beacon (Corbet 1999):

- transmitter sends 'downstream' when GRB pulse received
- receiver looks 'upstream' when GRB pulse received
- wait time depends on geometry: for d = 20 pc and θ=1°, t = 3.63 days
- if θ is known to 1 mas, σ_t = 1.8 hr (Hipparcos)
- if θ is known to 1 μas, σ_t = 1 min (Gaia/SIM)

In Conclusion...

- Hipparcos Catalogue of 120,000 stars: published 1997 (updated: van Leeuwen 2007)
- Tycho Catalogue (1 million stars, 1997) and its update/ replacement Tycho 2 (2.5 million stars, 2000)

- 2000 or more papers since 1997, impacting a wide range of astrophysics
- my review of results published by Cambridge University Press in 2009



Some limitations of Hipparcos

- a modest telescope aperture (30cm)
- modulating grid leading to ~30% light loss
- a low-efficiency photocathode detector (~10%)
- sequential (non-multiplexed) star observations

These shortcomings are addressed by Gaia, which uses the same principles as Hipparcos to improve accuracies by x50

End