Hipparcos: some scientific results

(with a focus on fundamental physics)

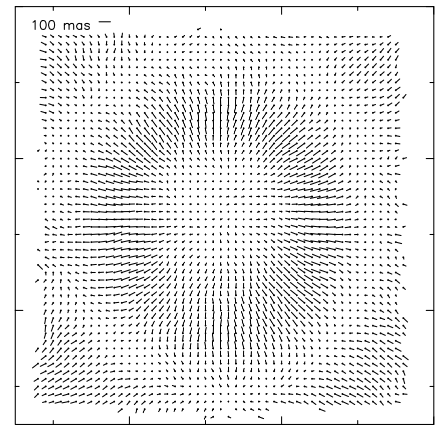
Michael Perryman

(Erlangen, 8-10 October 2014)

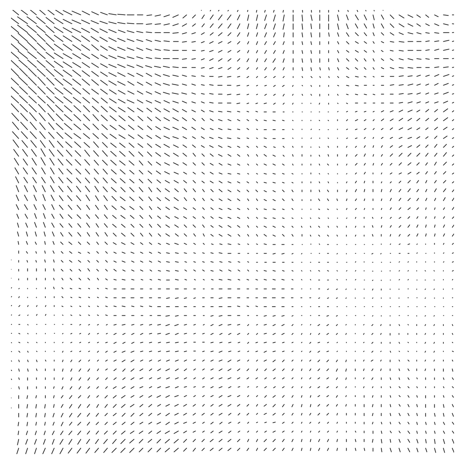
Measuring the Vatican plates

Astrographic Catalogue
1891 (Vatican) — 1950 (Uccle)

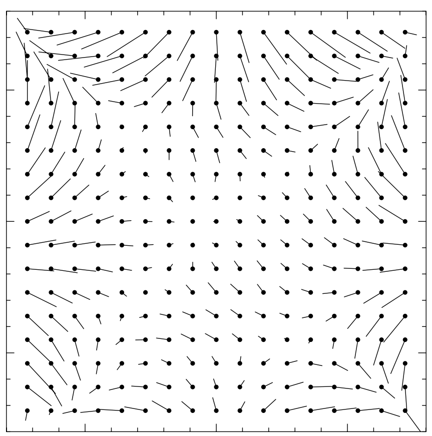
Hipparcos + Tycho 1



NPM/SPM
Zacharias et al 2004

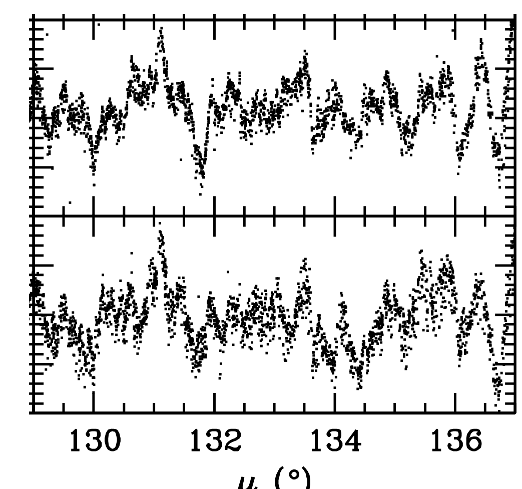


POSS-I O: 18 mag
Monet et al 2003



CPC2
Zacharias et al 1997

Tycho 2
2.5 million



SDSS
Pier et al 2003

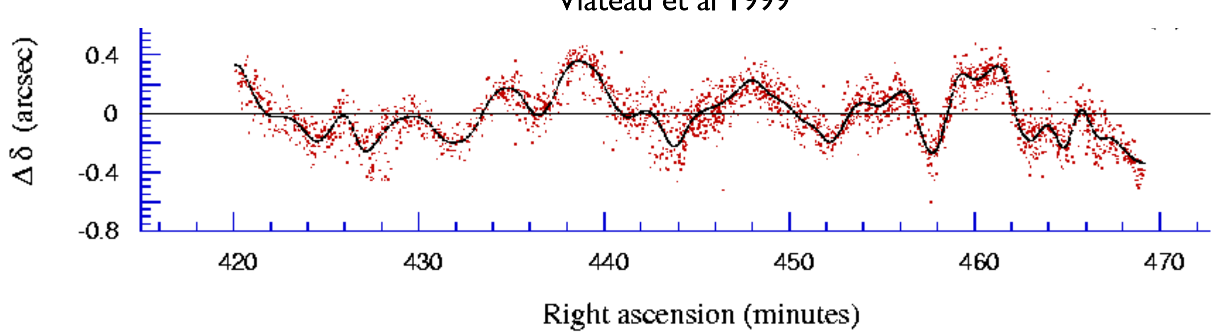
Schmidt Plates
1949 onwards

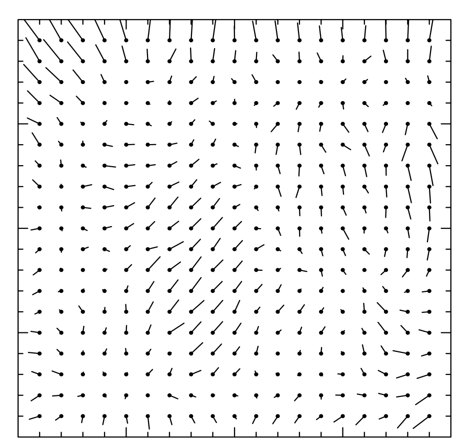
AAO

Meridian Circles

Carlsberg

Bordeaux Meridian Circle
Viateau et al 1999



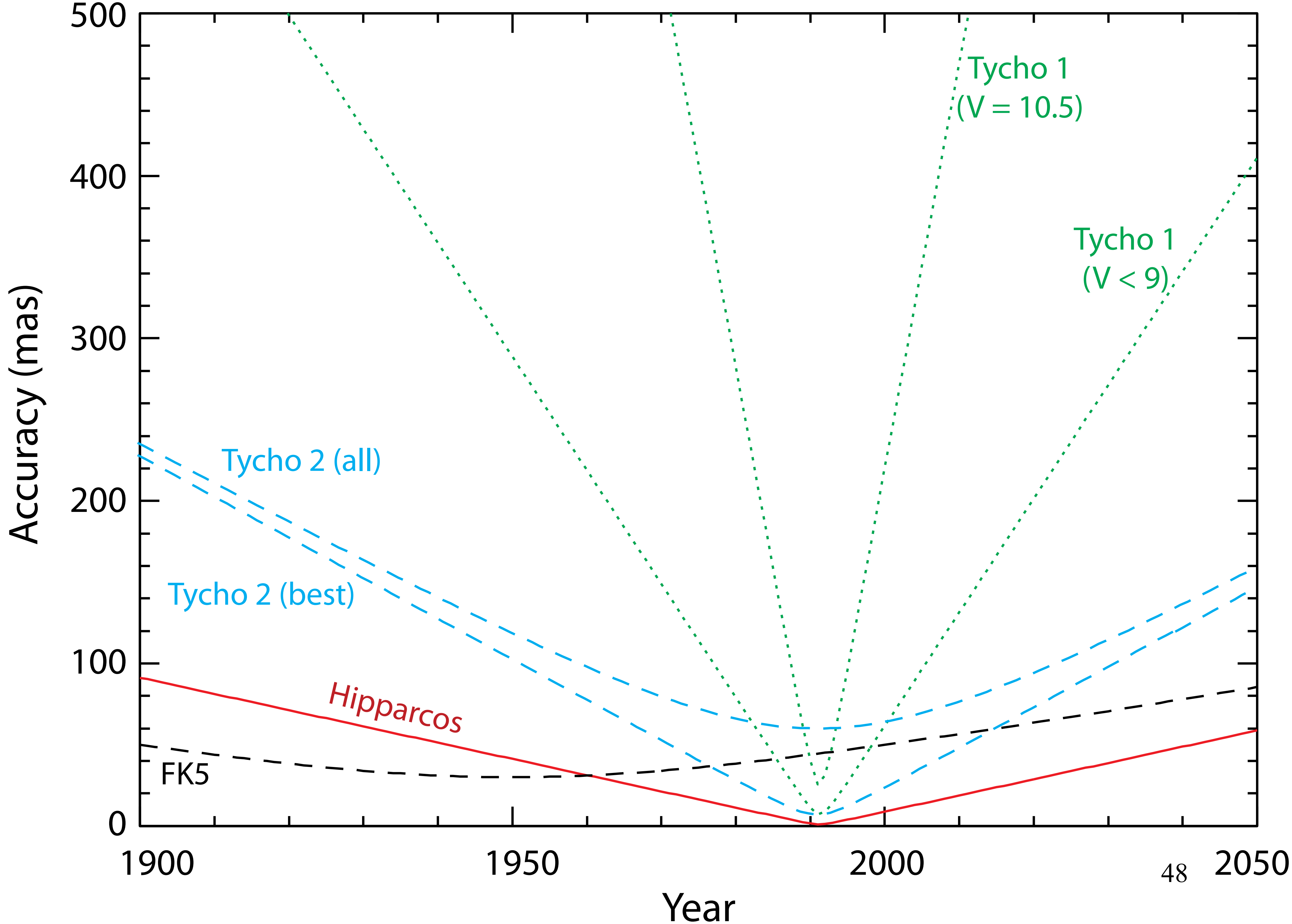


UCAC2 CCD
Zacharias et al 2004

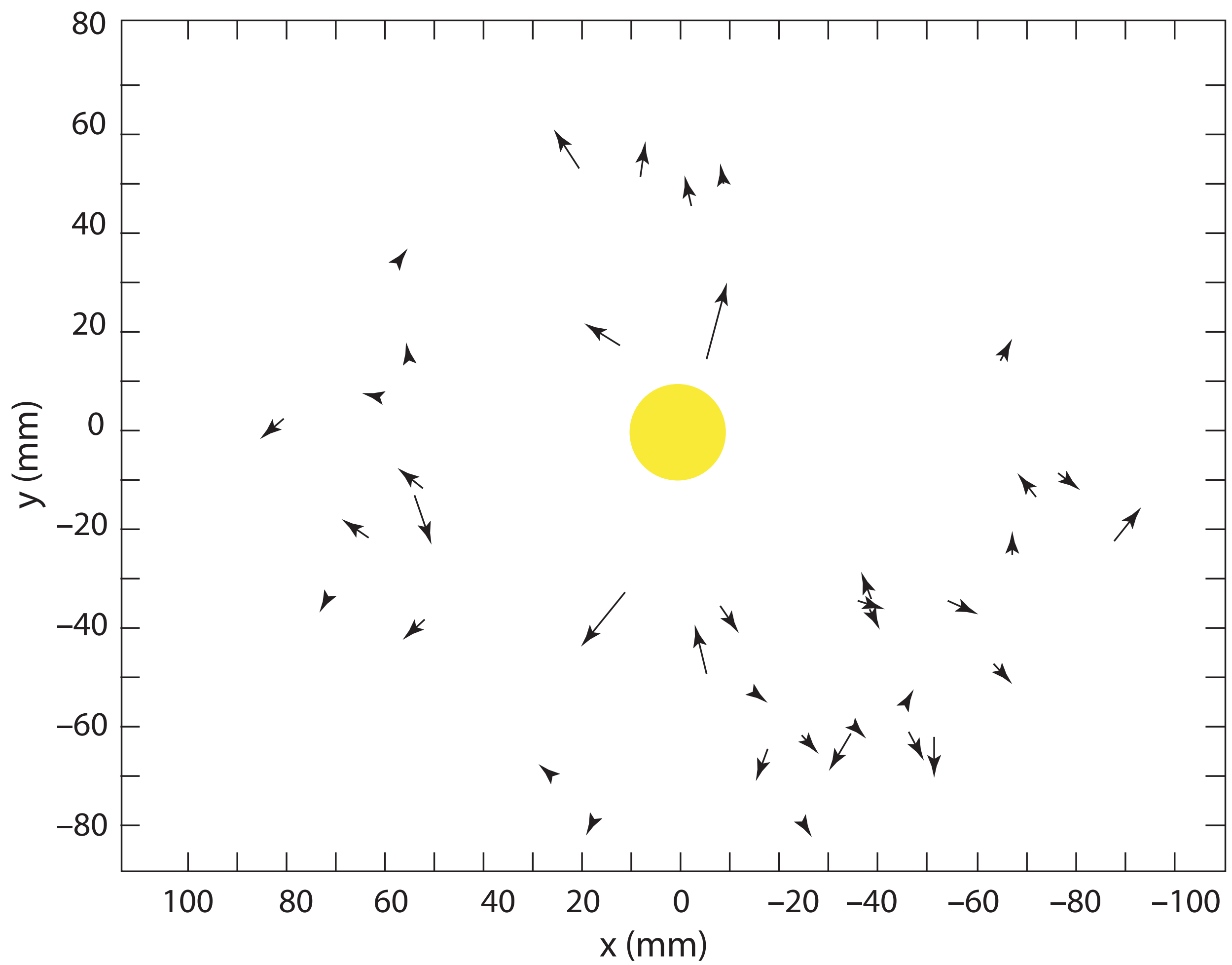
Recent surveys:
- SDSS
- 2MASS
- UCAC2

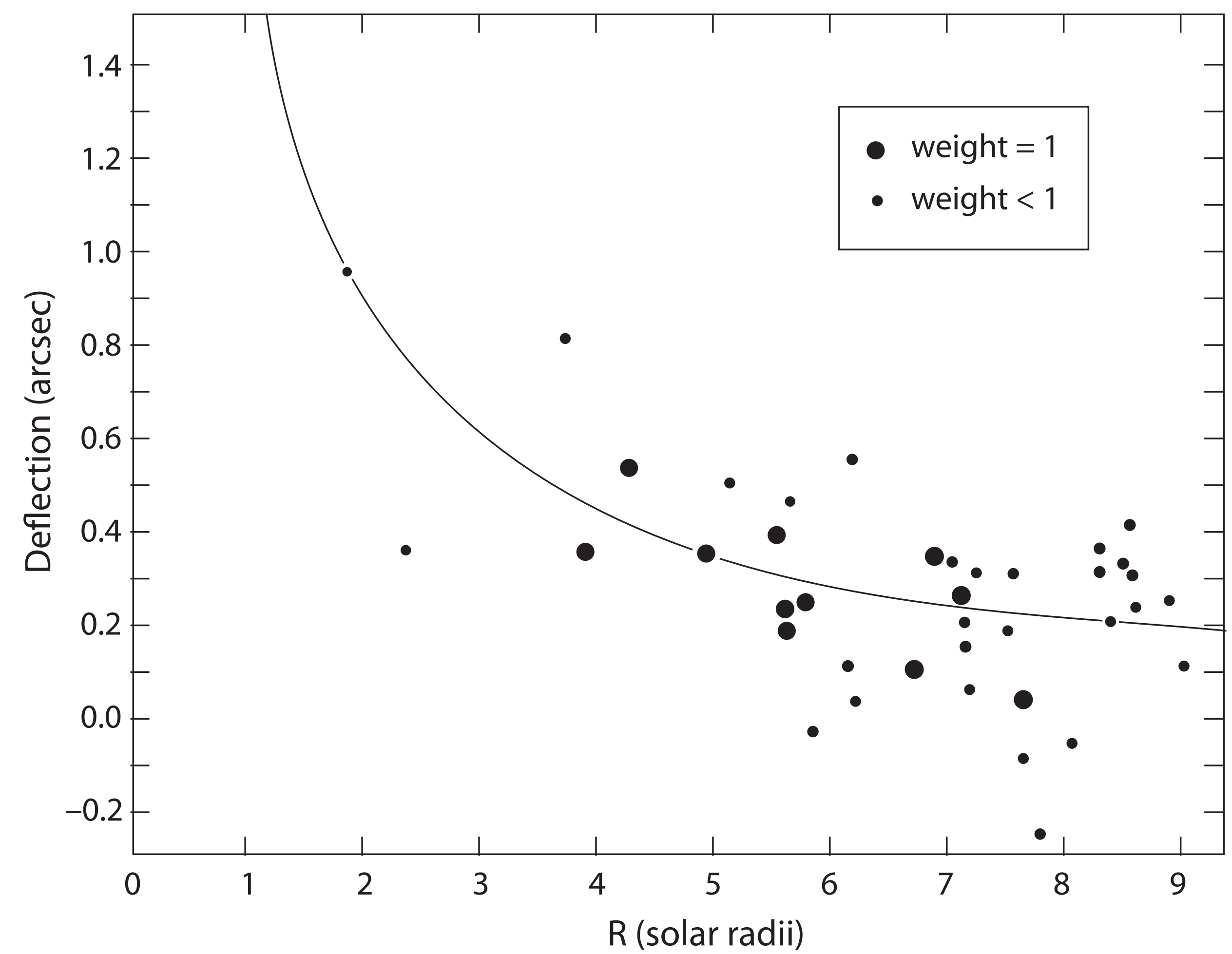
1900 → 2000

Degradation of the reference frame with time



Relativistic Light Deflection (1/2)



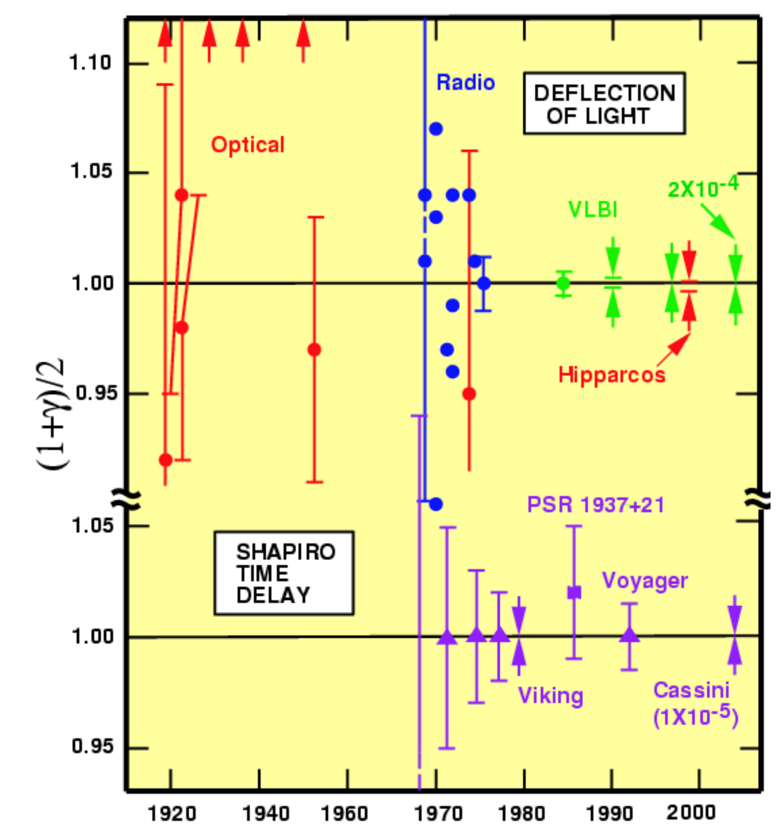


State-of-the-art (ground):
Texas 1973 solar eclipse
(Jones 1976)

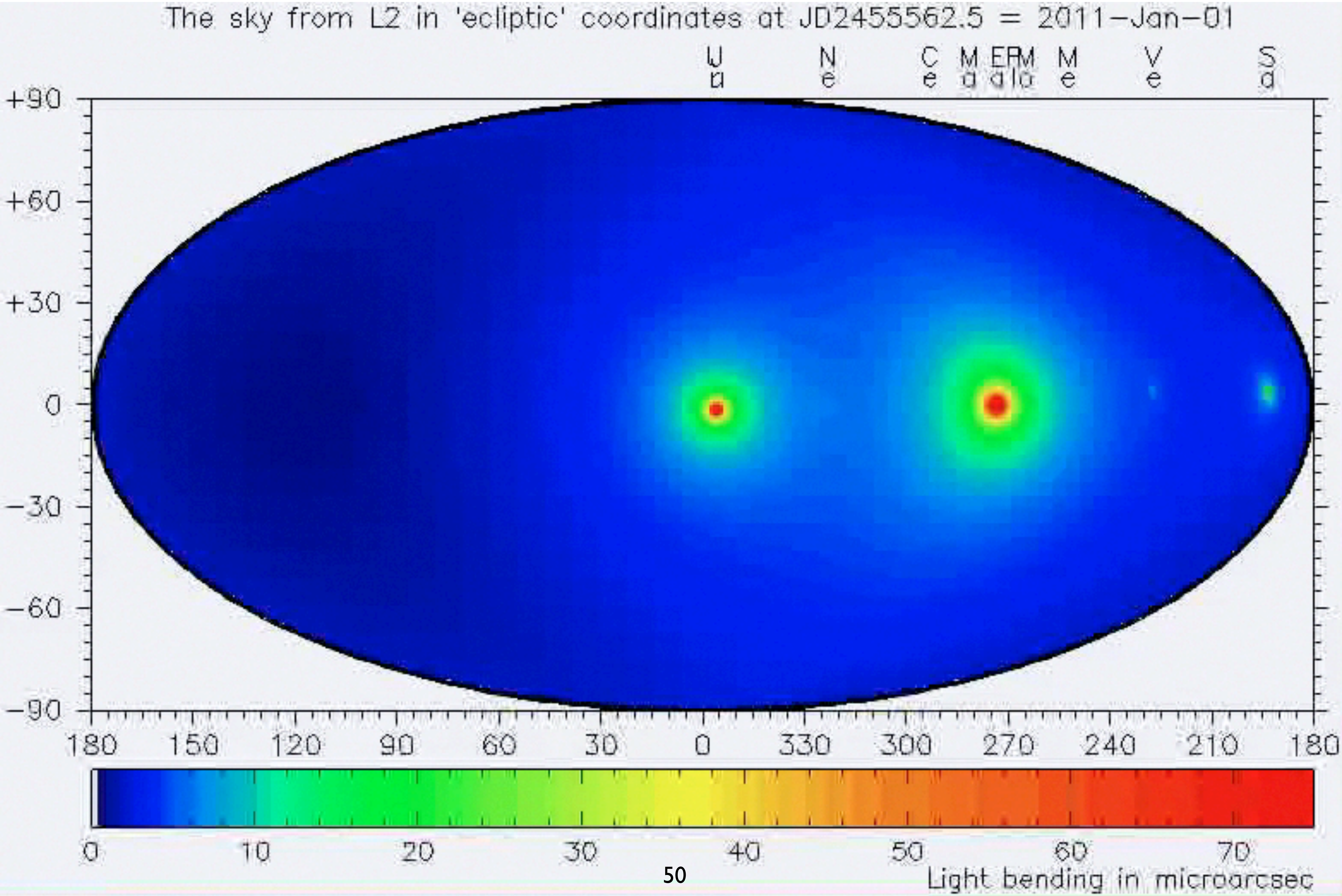
From Hipparcos residuals:
$(1+\gamma)/2 = 0.9985 \pm 0.0015$
(Froeschlé et al 1997)

Expected from Gaia:
γ to 1 part in 10^7

Constraints on γ
(Will 2006)



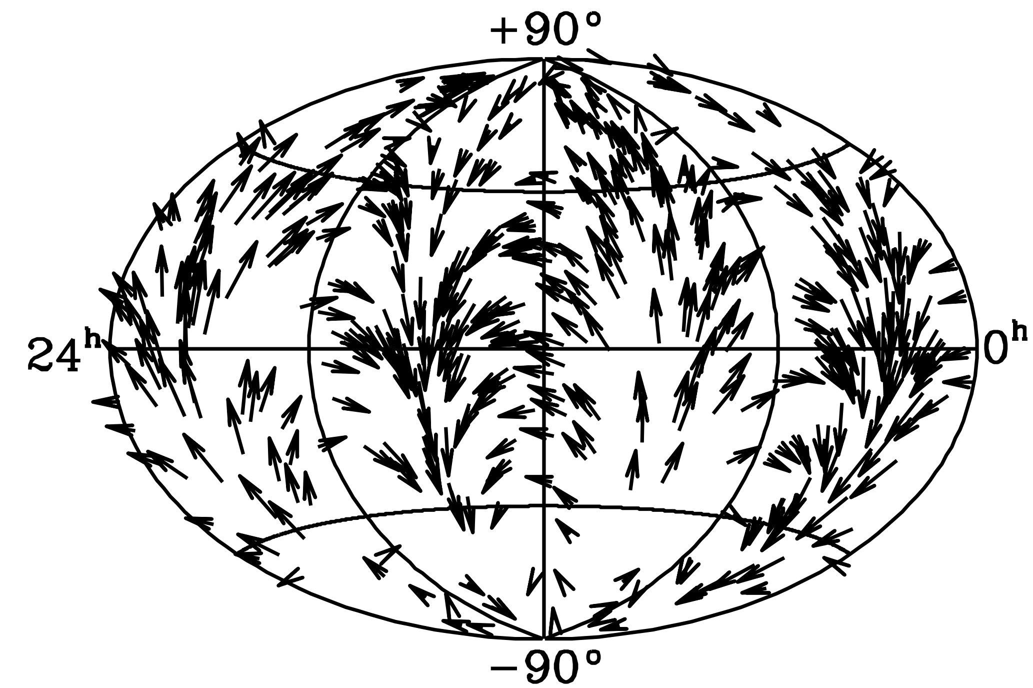
Relativistic Light Deflection (2/2)



Gravitational Wave Detection

Principle: gravitational waves with a period longer than the time span of observations produce a simple pattern of apparent proper motions over the sky, composed primarily of second-order transverse vector spherical harmonics

Proper motions expected for a single gravitational wave



Gwinn et al (1997) ApJ 485, 87 applied to VLBI radio positions:

$\Omega_{GW} < 0.11\ h^{-2}$ for $\nu < 2\times10^{-9}$ Hz (h=H/100km s^{-1}/Mpc)

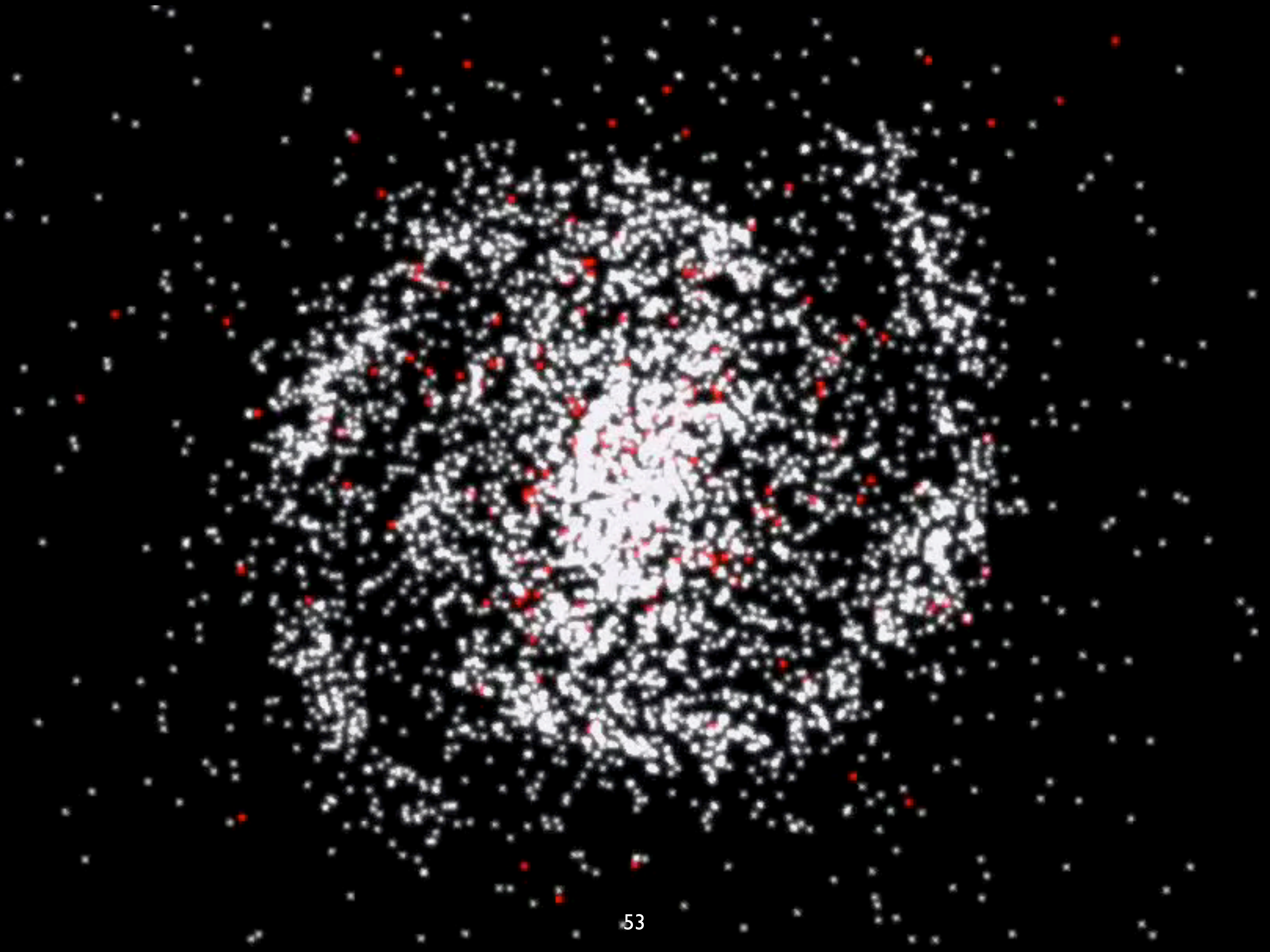
Mignard & Klioner (2012) A&A 547, A59 applied to Gaia:

$\Omega_{GW} < 0.00008\ h^{-2}$ for $\nu < 6.4\times10^{-9}$ Hz

Galactic Structure and Rotation

Aims include determining:

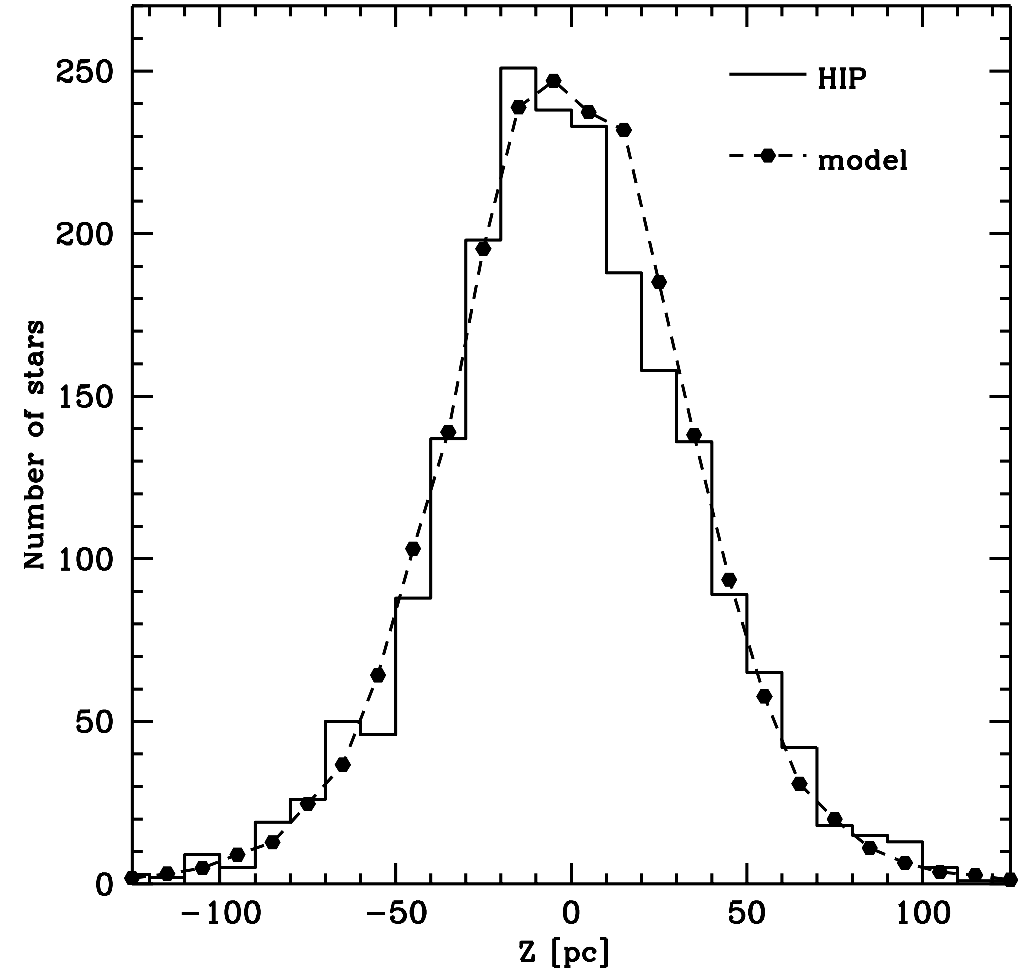
- distance of Sun from Galactic centre, R_0
- local standard of rest (for circular orbits)
- solar motion *uvw* (with respect to LSR)
- rotation curve (as a function of R)
- Oort constants, assuming circular motion
    - angular rotation rate = $A-B$
    - local derivative = $A+B$



Sun's distance from Galactic plane

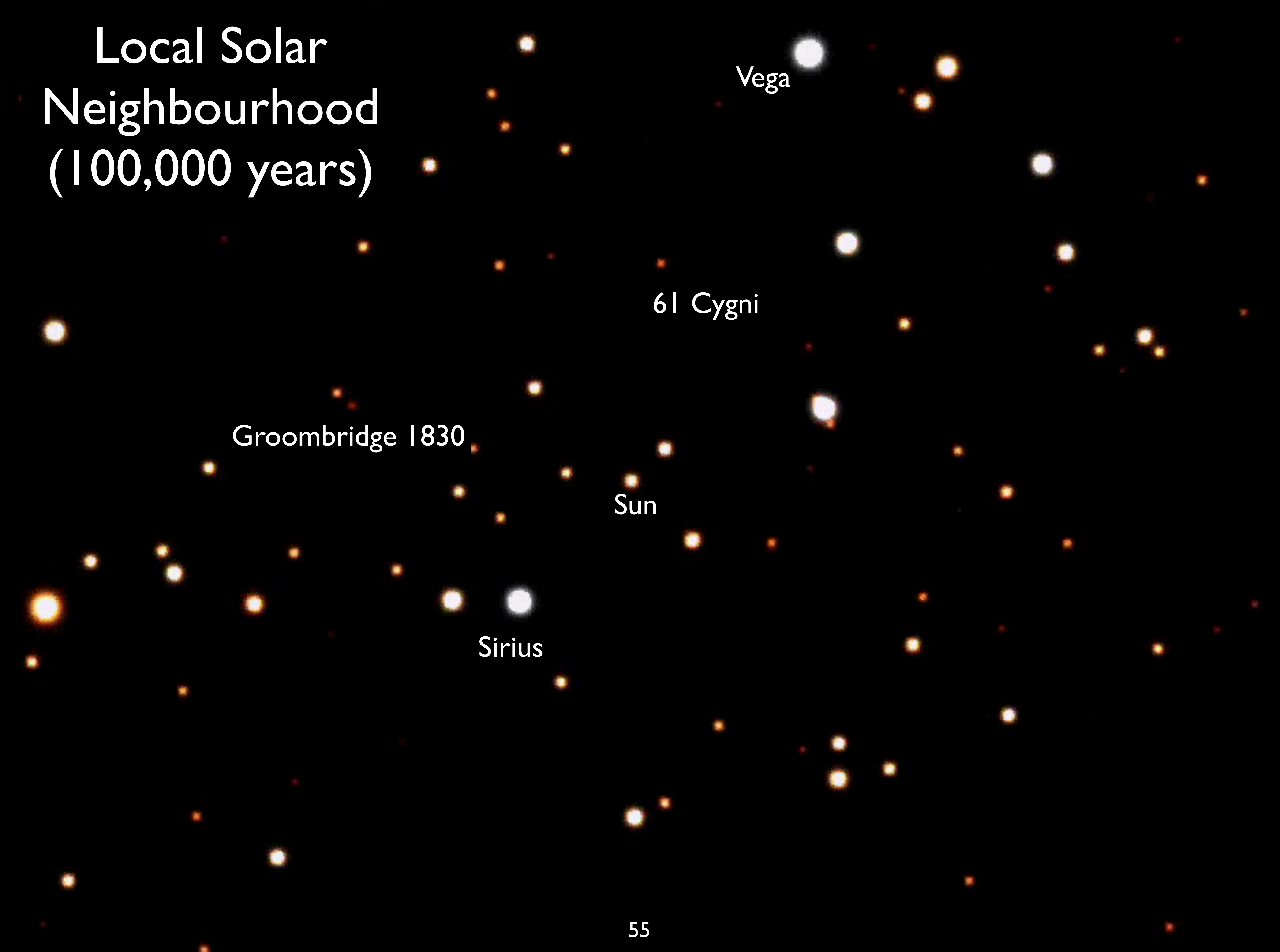
Distance from Galactic plane, Z_0
(important for phase of Sun's orbit)

• 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

Local Solar Neighbourhood (100,000 years)

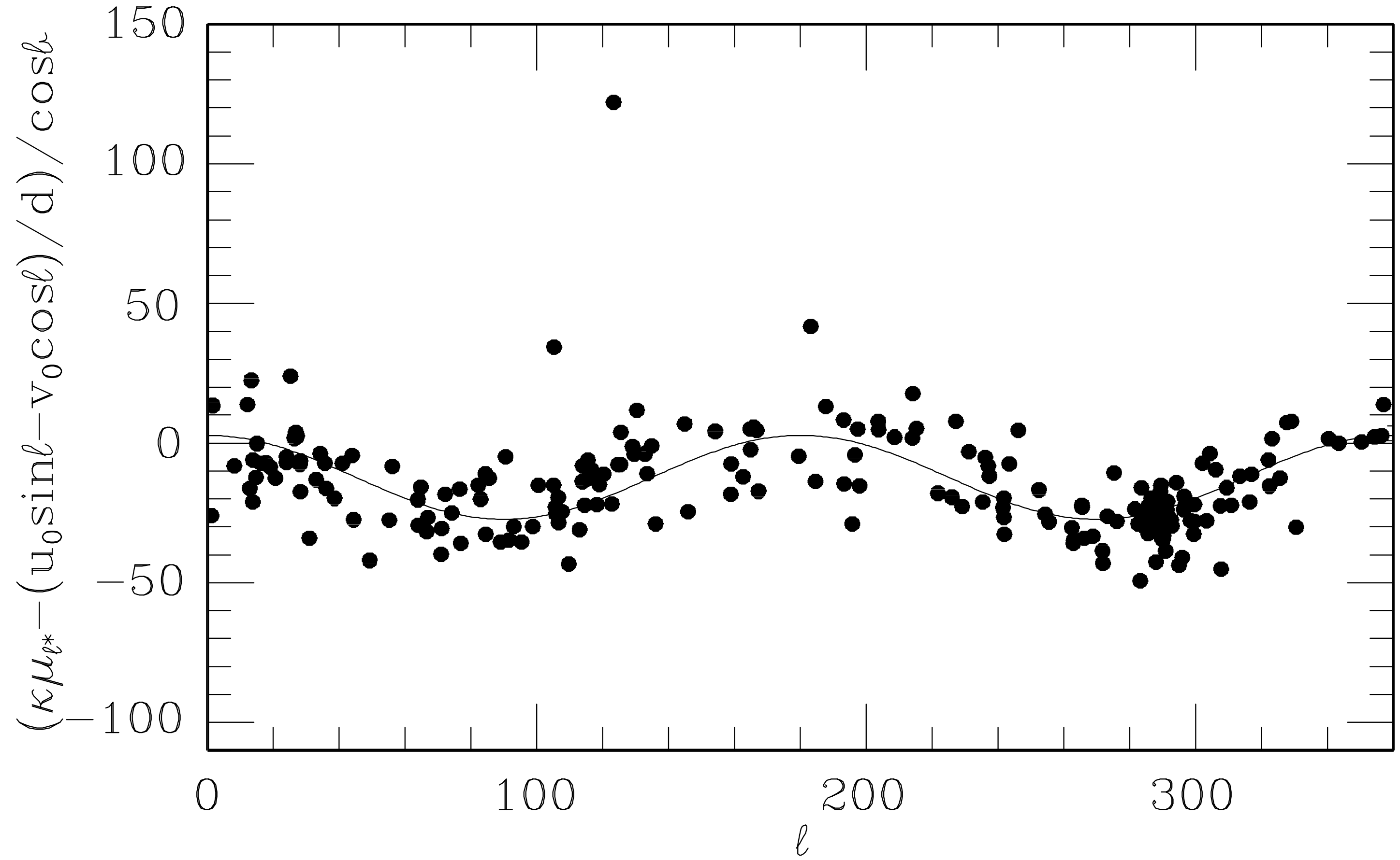


Results on Solar Motion

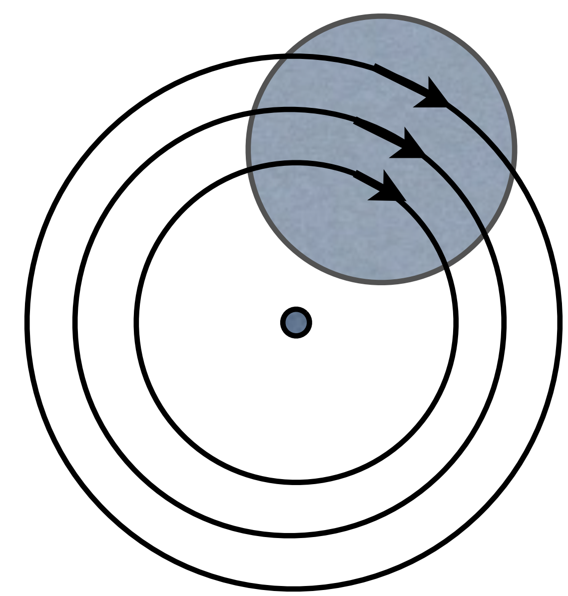
Reference	Class	Solar motion wrt LSR (km s^{-1}) $u_\odot$	$v_\odot$	$w_\odot$	Total $V_\odot$
Pre-Hipparcos					
Mihalas & Binney (1981)	Compilation	9	12	7	16.5
Evans & Irwin (1995)	APM-based	7.3 ± 1.5	13.9 ± 2.3	8.8 ± 2.2	18.0
Hipparcos – Oort–Lindblad:					
Feast & Whitelock (1997)	Cepheids	9.3	11.2	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 & Shukhto (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

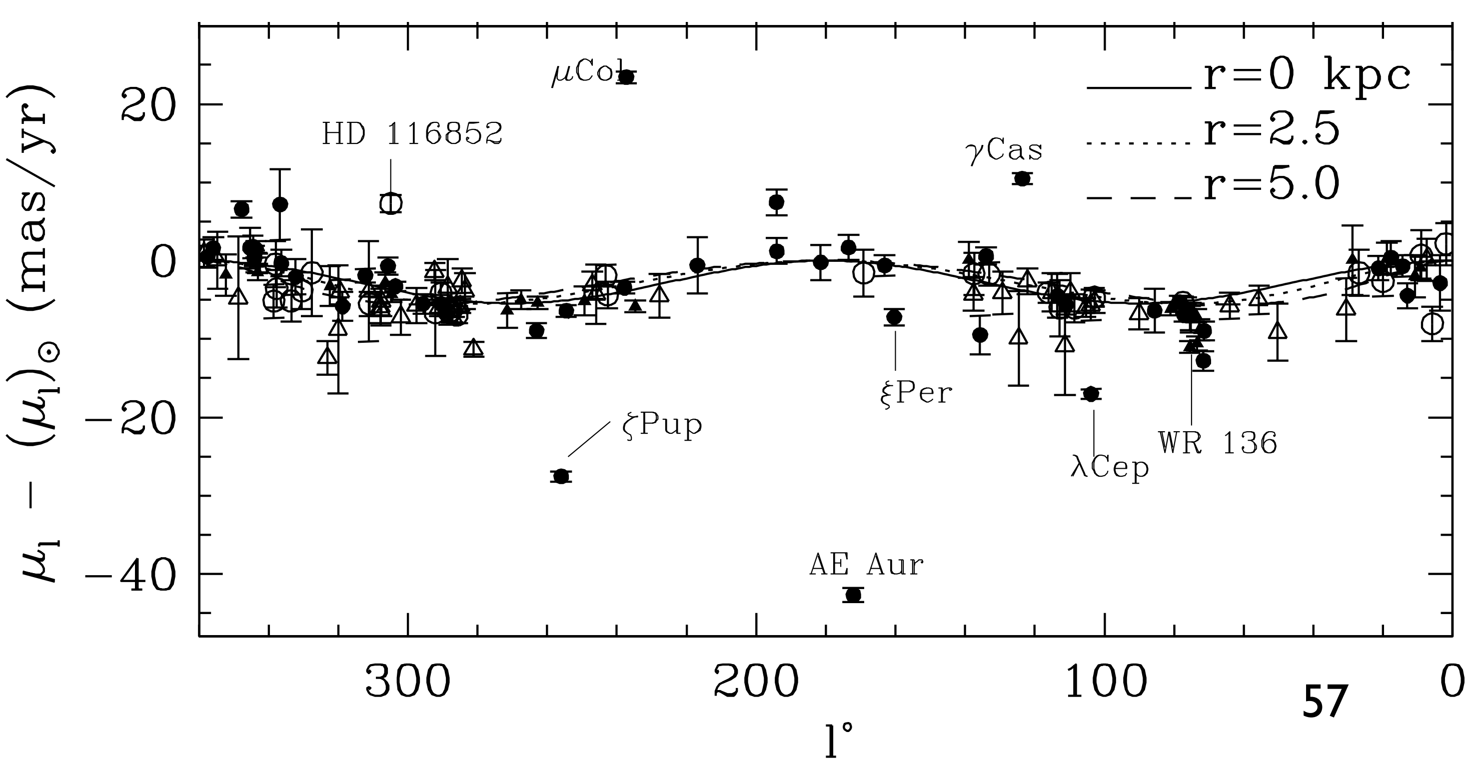
cf Schonrich et al (2010) considering Galactic metallicity gradient: *UVW* = 11.10, 12.24, 7.25

Galactic Rotation (I)



Cepheids:
Feast & Whitelock (1997)





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

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 primordial tilting of the Galaxy

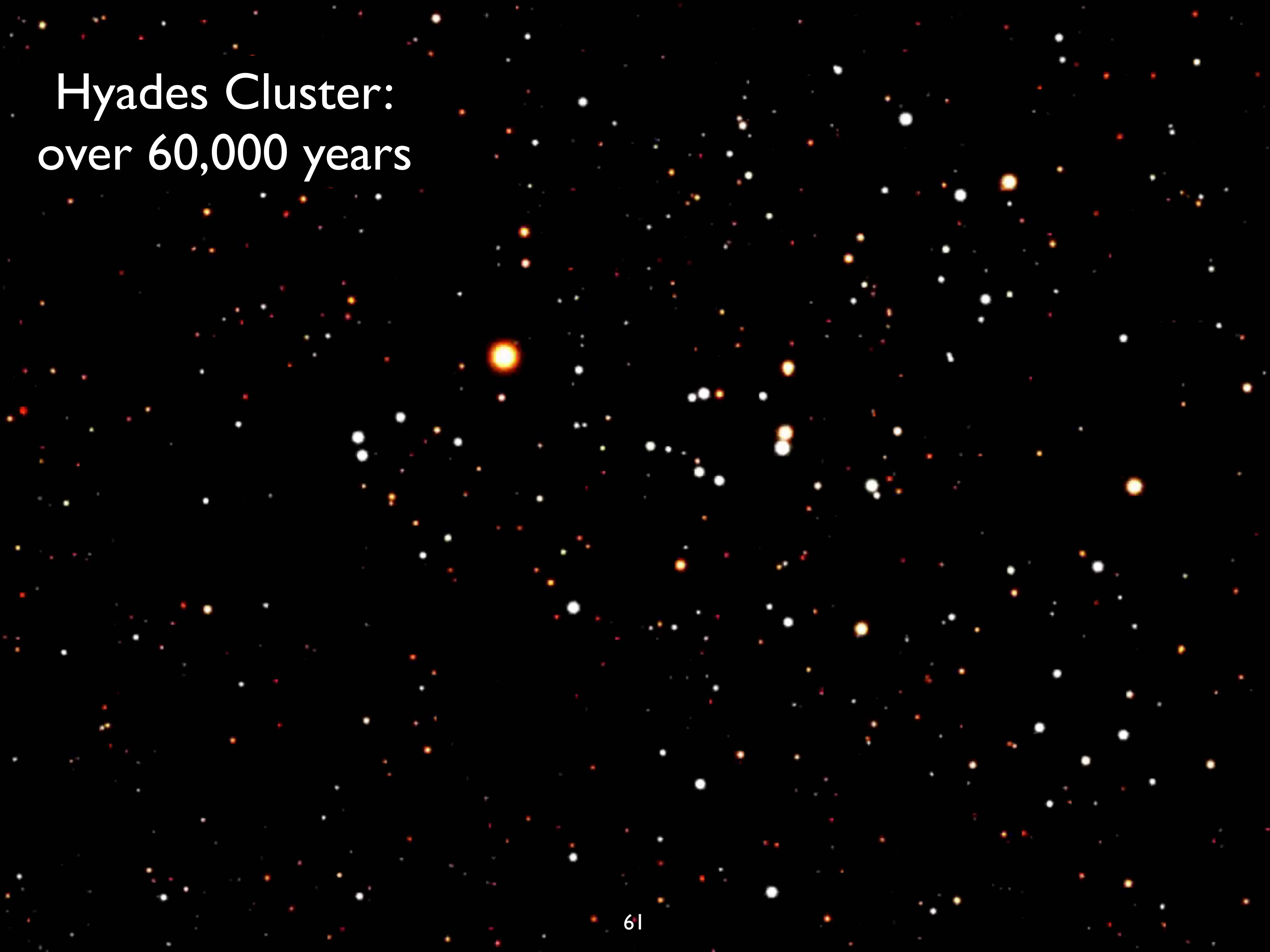
(Perryman, Spergel & Lindegren (2014), ApJ 789, 166)

Hierarchical structure formation models predict that the dark matter halo is triaxial, and tumbles with a characteristic rate of ~ 2 rad/Hubble time, or about 30 microarcsec/year

This (and other effects) results in the rotation of the angular momentum vector of the Galaxy stellar disk population with respect to the quasar reference frame

Gaia should establish the spin vector of the transformation from any rigid catalogue frame to the quasi-inertial quasar system to better than 1 microarcsec/year

Gaia should reveal any signature of the disk orientation varying with time, and test theories of cosmology and gravity


Hyades Cluster:
over 60,000 years

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 σ_v = 0.3 km/s (de Bruijne et al 2001, Narayanan & Gould 1999)
- N-body simulations: initial mass ~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)

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)

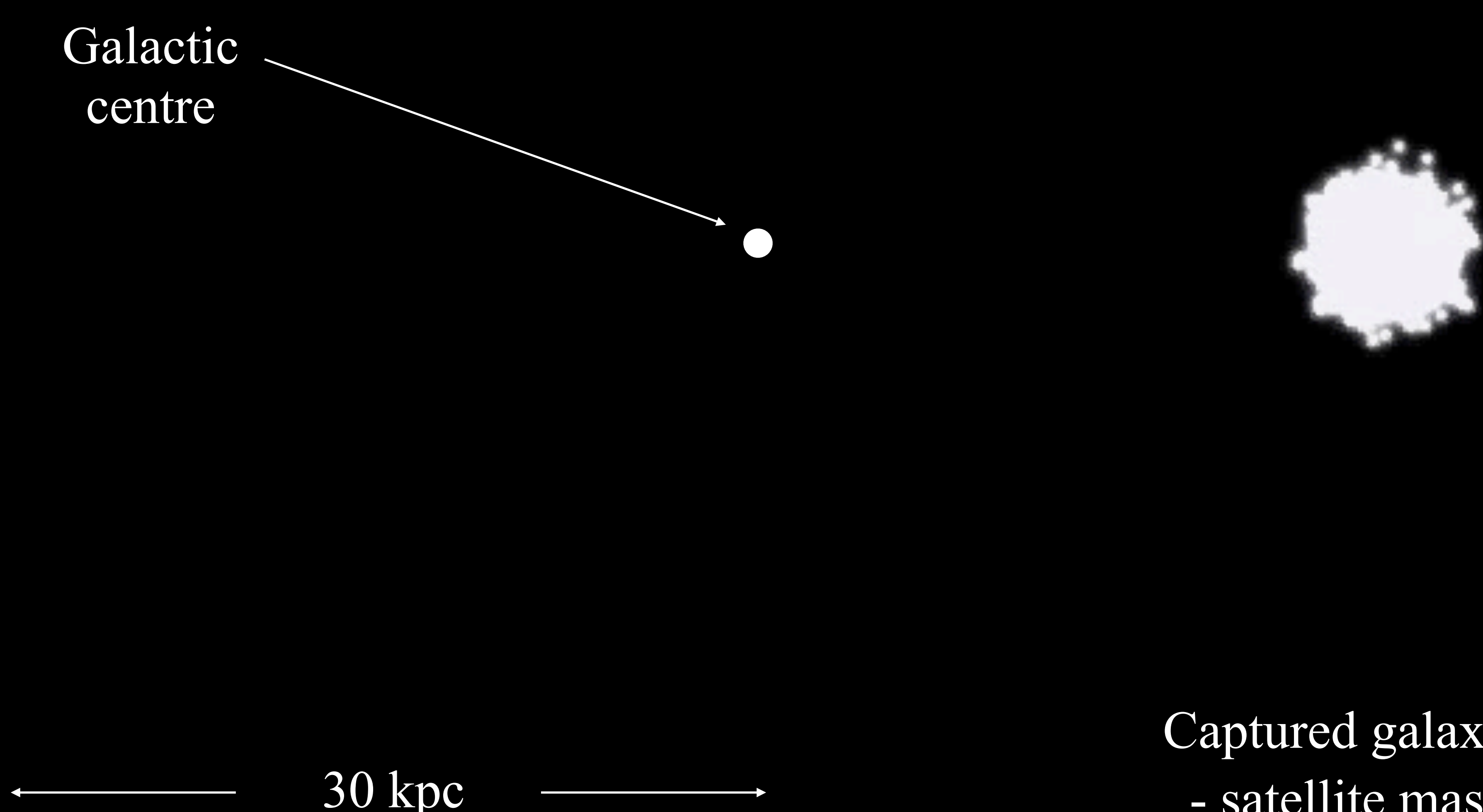
Important for:

- 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): $\rho_0 = 0.102\ M_\odot\ pc^{-3}$
- vertical oscillation period: $P_\perp = (\pi/G\rho_0)^{0.5} = 82$ Myr

Our Galaxy has been built from mergers...

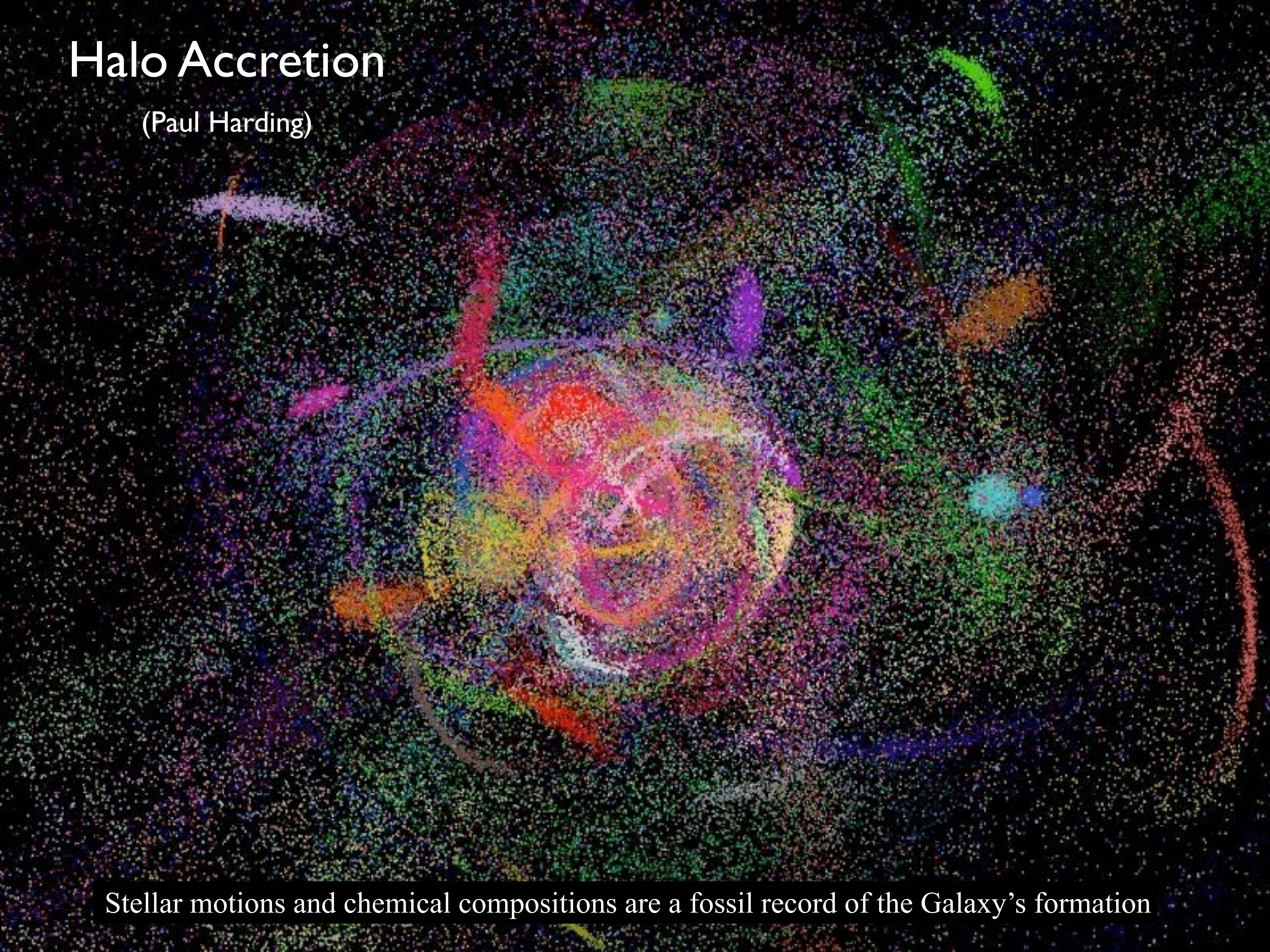


Captured galaxy:

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

Halo Accretion

(Paul Harding)



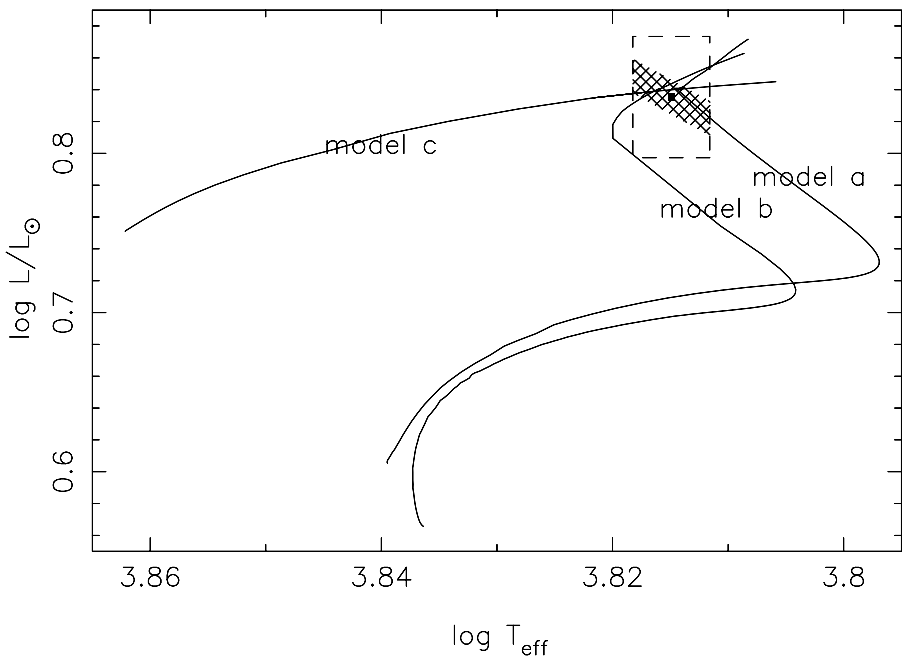
Stellar motions and chemical compositions are a fossil record of the Galaxy’s formation

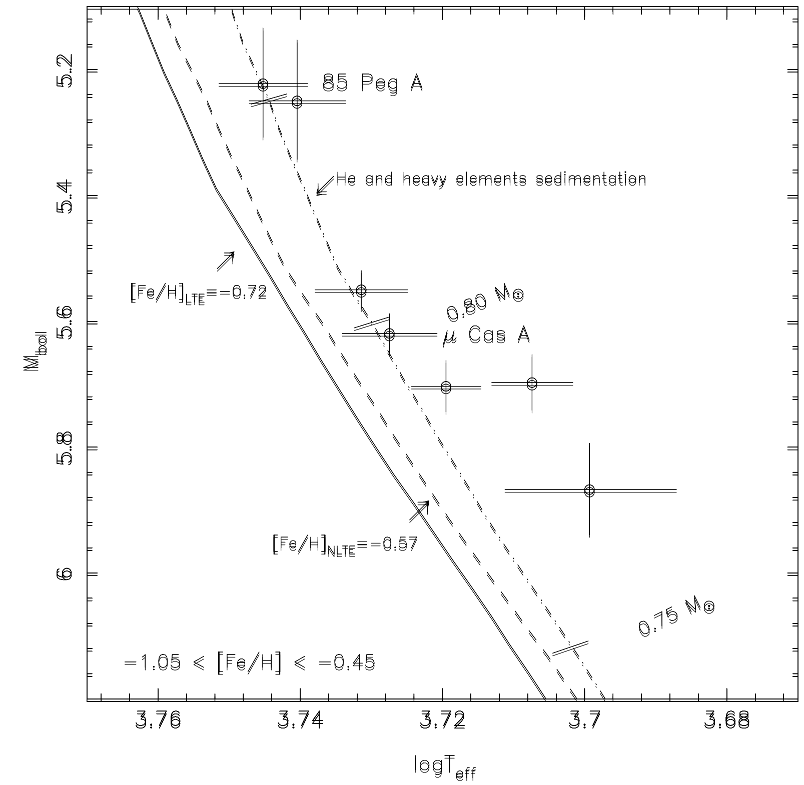
Examples of Stellar Modeling...

Procyon A: (a) preferred model; (b) without diffusion; (c) without overshooting:

- R=2.048±0.025 $R_\odot$; age = 2314±10 Myr
- WD progenitor age = 614 Myr; M=2.5$M_\odot$

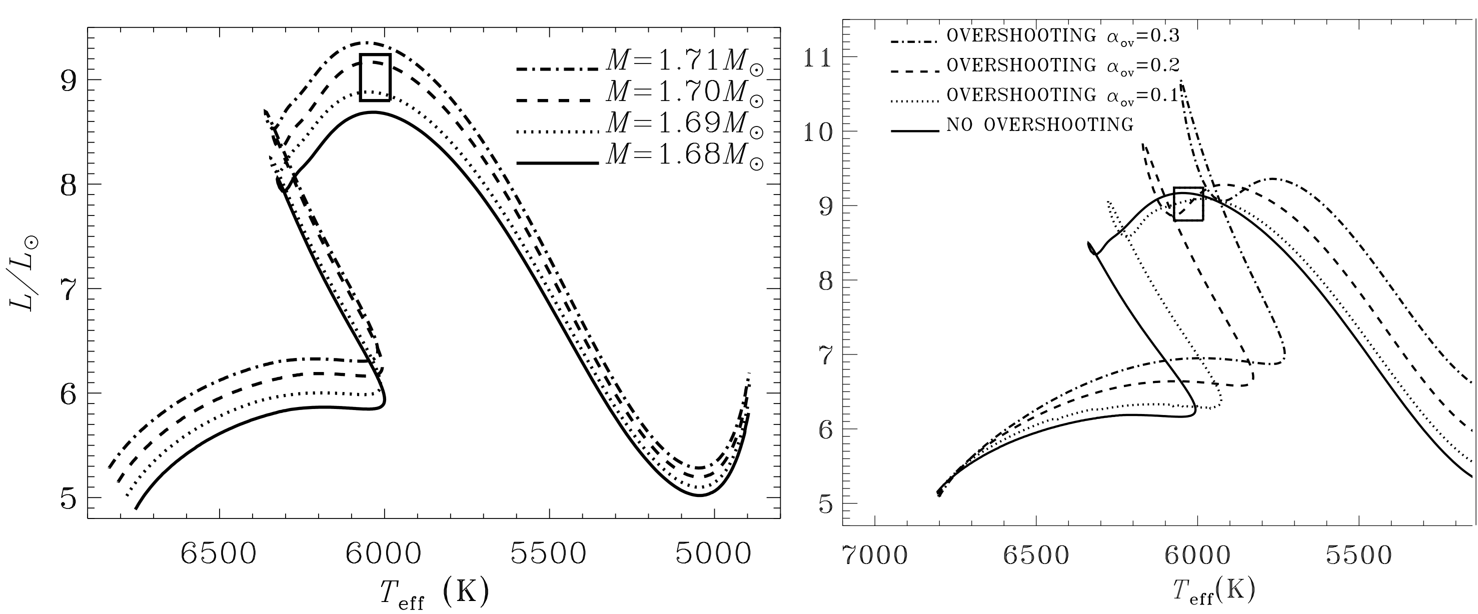
(Kervella et al 2004)





Nearby, unevolved, moderately metal-poor stars, with 10 Gyr isochrones showing effects of He and metal sedimentation

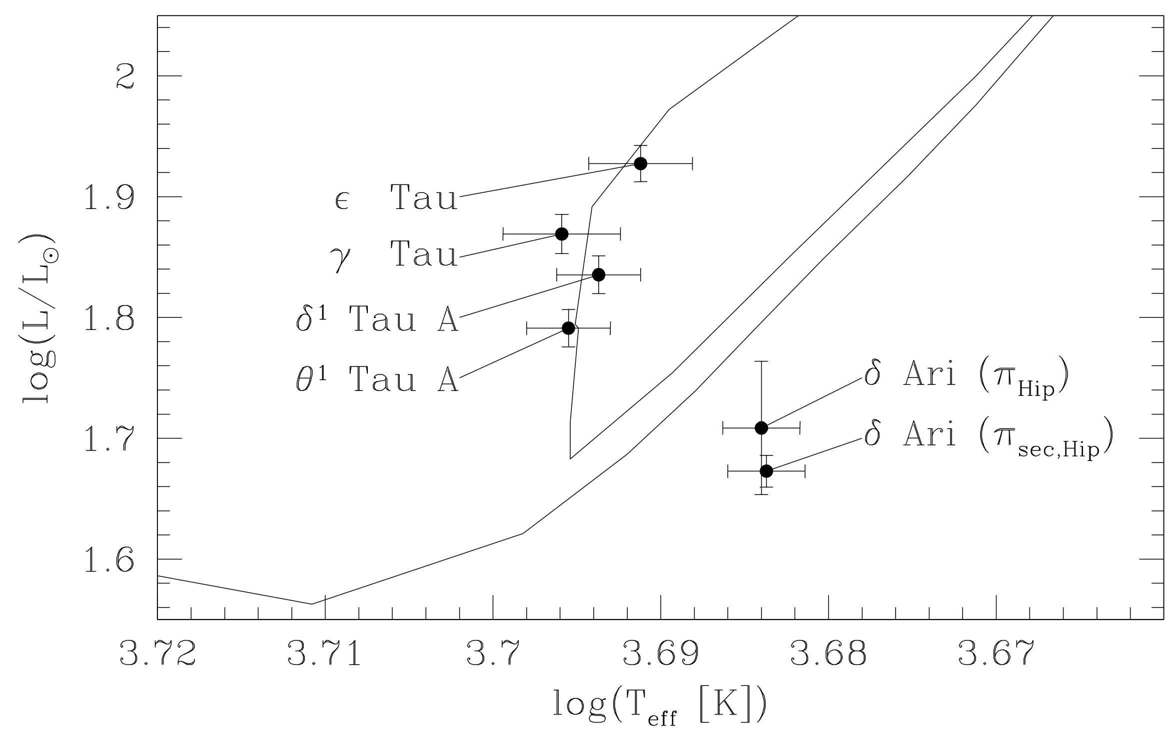
(Lebreton 2000)



Asteroseismology of η Boo, Z=0.04.

Left: M=1.70±0.005 $M_\odot$ Right: with overshooting

(Di Mauro et al 2003)

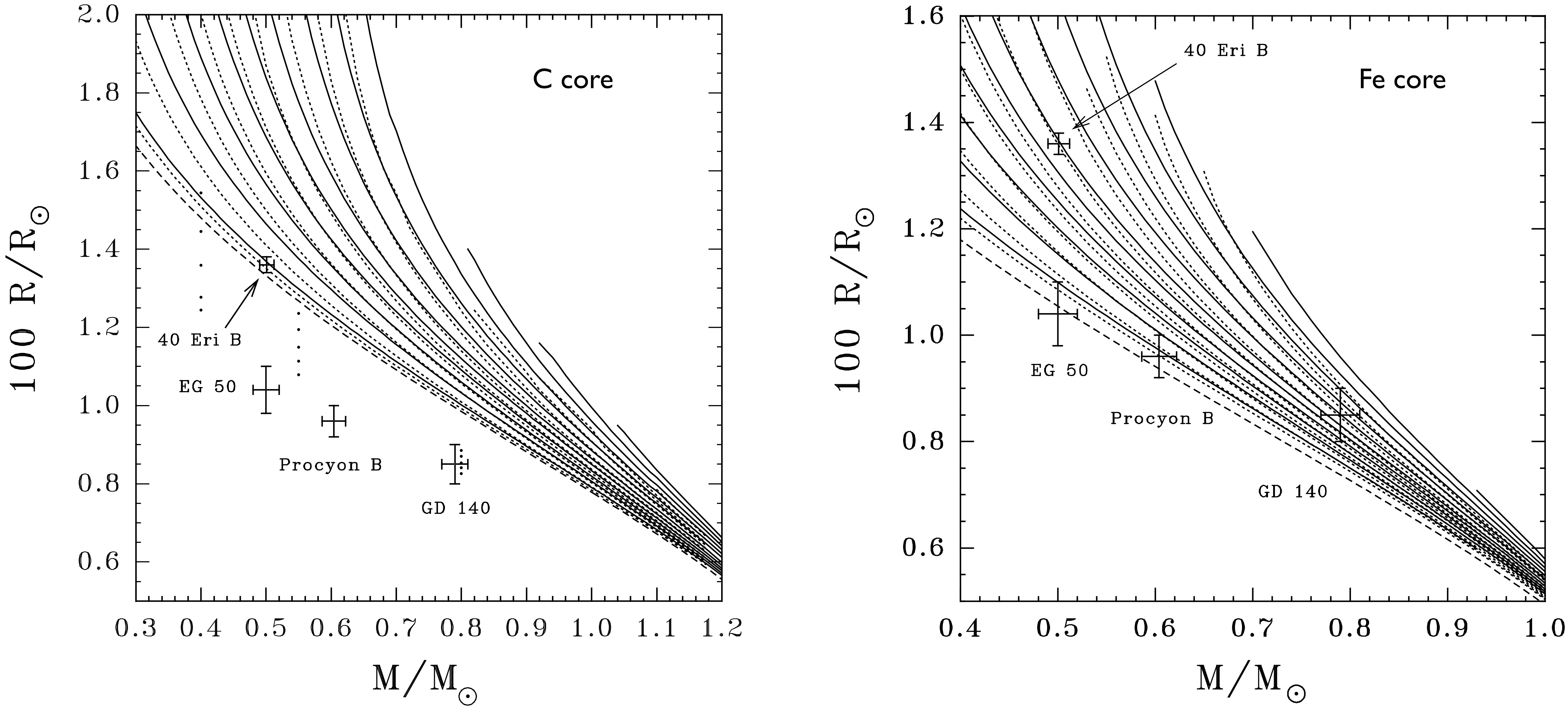


Hyades red giant clump region:

Y=0.273, Z=0.019, 631 Myr

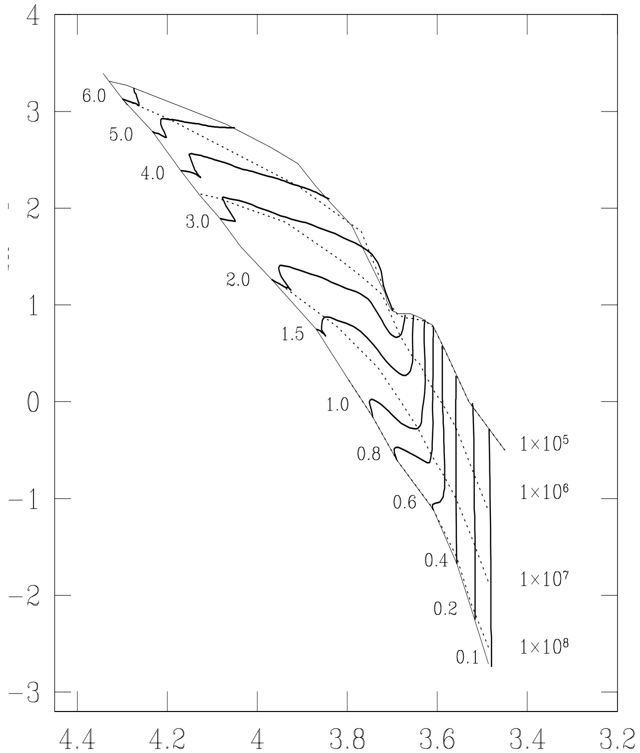
(Girardi et al 2000; de Bruijne et al 2001)

White Dwarfs

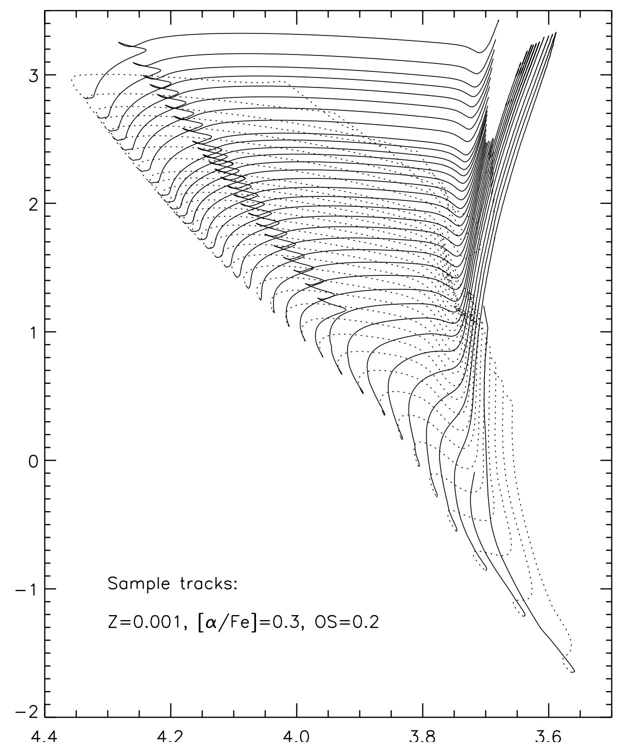


Mass-radius relation for white dwarfs for T_{eff} = 5000−145,000 K;
Hipparcos data from Provencal et al (1998, 2002)
He, O or Si cores have similar density (mean molecular weight per electron ~2)
Fe cores difficult to reproduce from stellar models (Iben & Renzini 1983)
Strange matter cores have been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

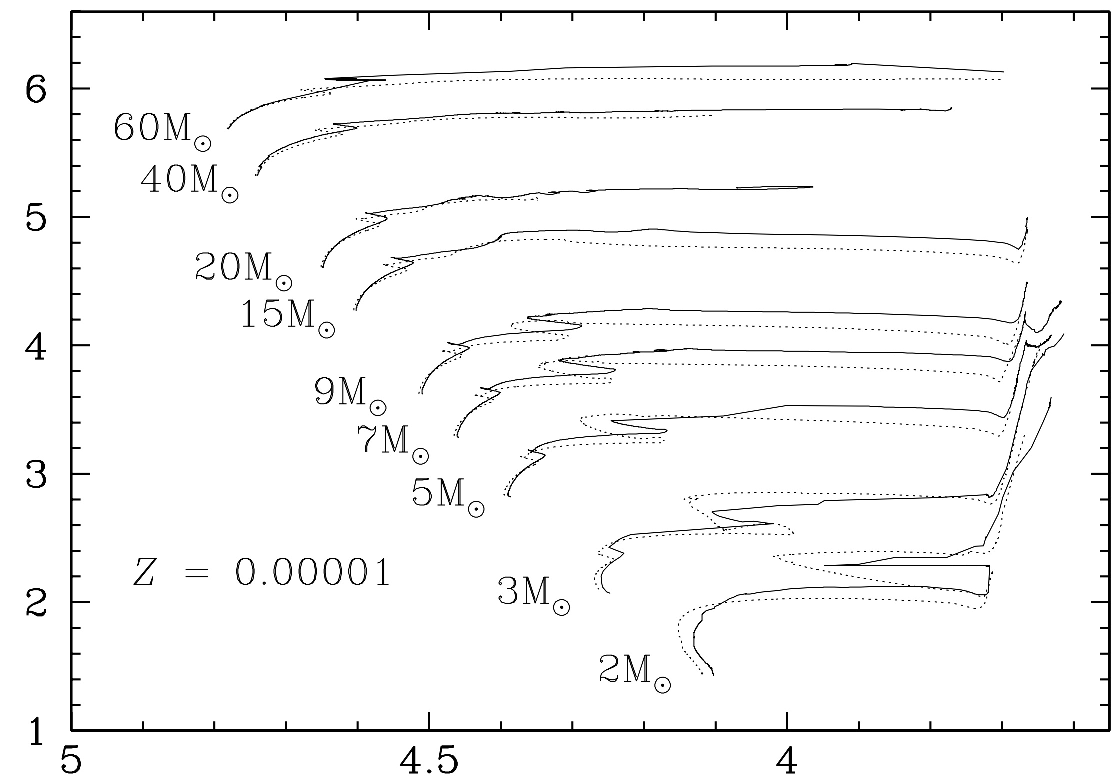
Some Evolutionary Models...



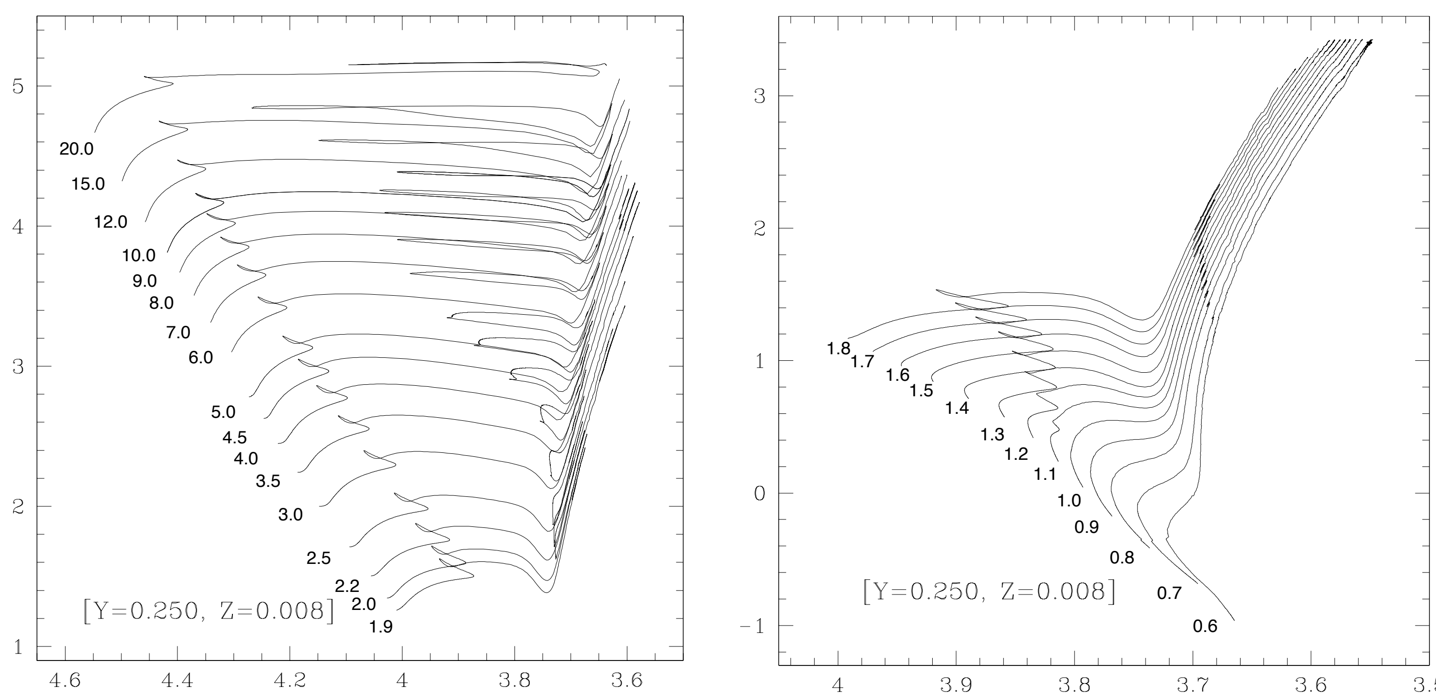
Pre-main sequence
(Palla & Stahler 1999)



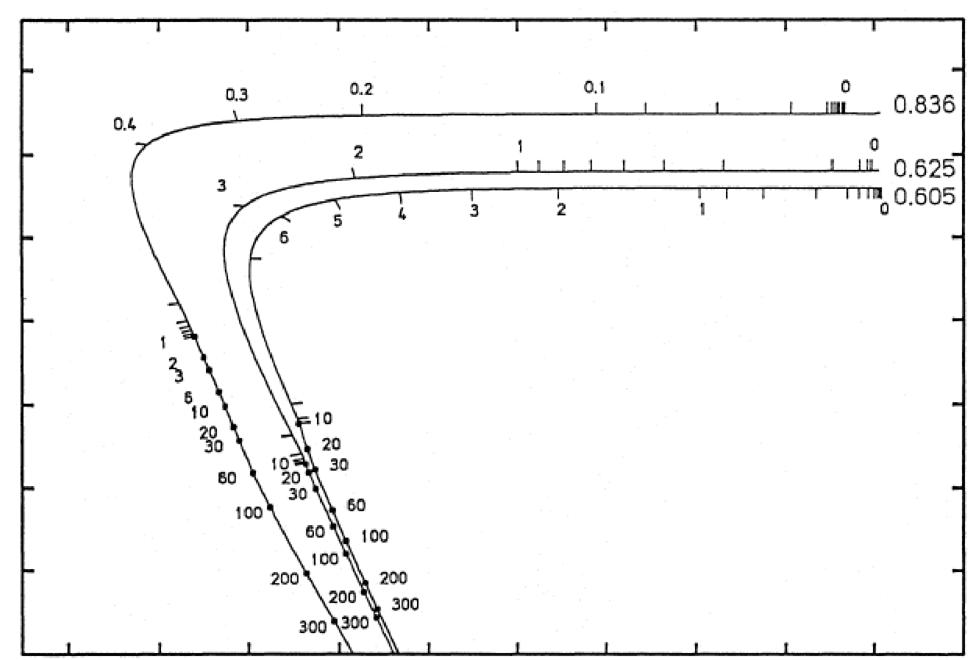
Yonsei-Yale
(Yi et al. 2003)



Rotating models
(Meynet & Maeder 2002)

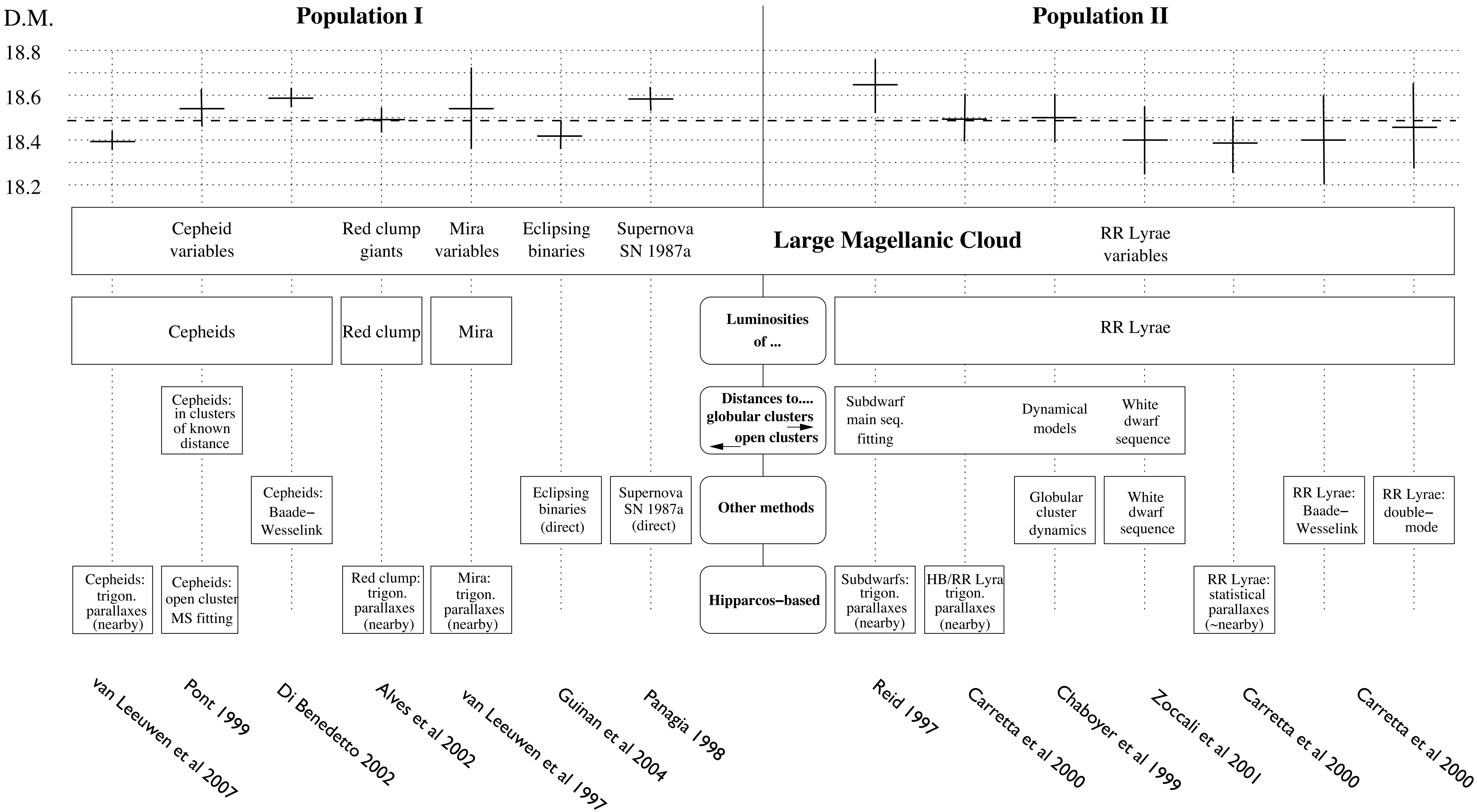


α-element enhanced
(Salasnich et al. 2000)



Post asymptotic giant branch
(Bloecker 1995)

Distance to the Large Magellanic Cloud

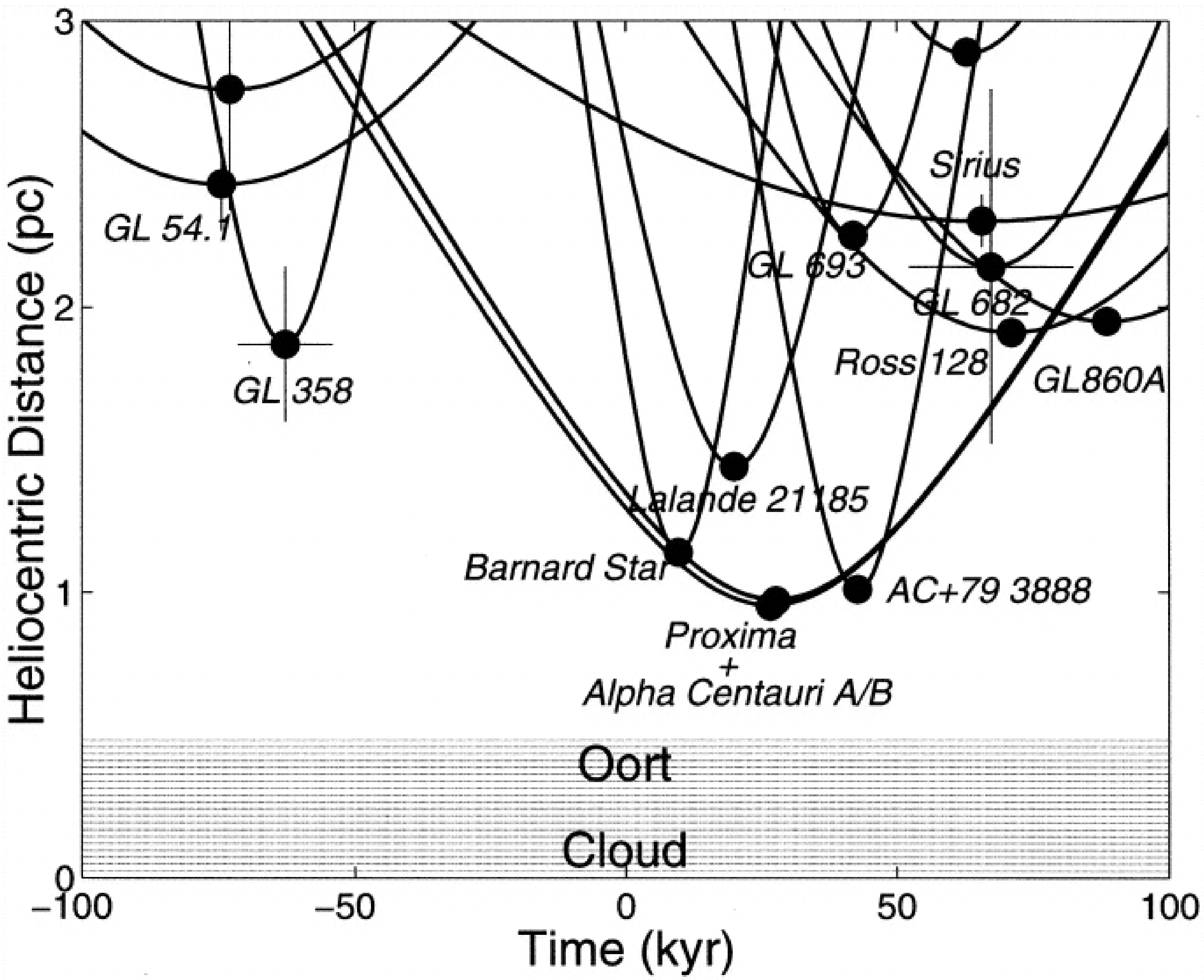


Straight mean of direct/indirect Population I/II methods gives: $(m-M)_0=18.49$

....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)

Stellar Encounters with our Solar System

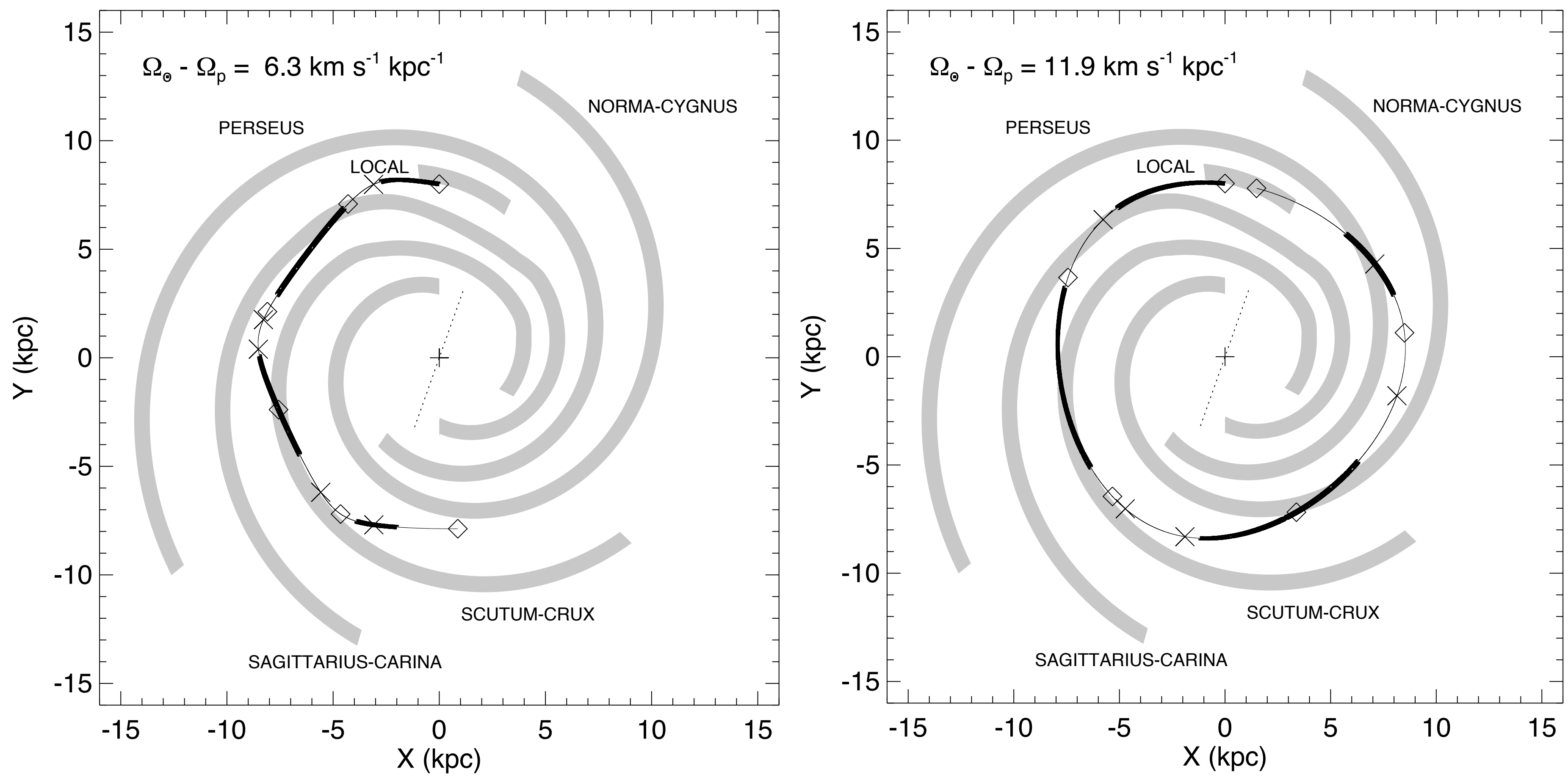


Nearby star passages may trigger cometary impacts from Oort Cloud (here over ±100,000 years):

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 $\Omega_p \sim 14-17$ km s^{-1} kpc^{-1}
(Gies & Helsel 2005; see also Shaviv 2003; Svensmark 2006)



(2) Maunder Minimum (1645−1715):

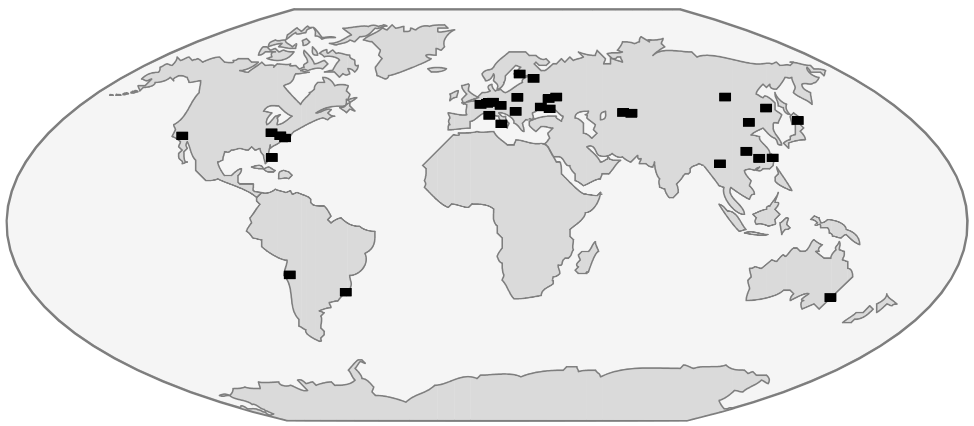
- coldest excursion of little ice-age, and correlated with disappearance of sun spots
- probe of solar activity, solar dynamo, sun spot cycle, and climate
- monitoring Sun-like stars within 60 pc probes activity versus age (Wright 2004, 2006)

(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

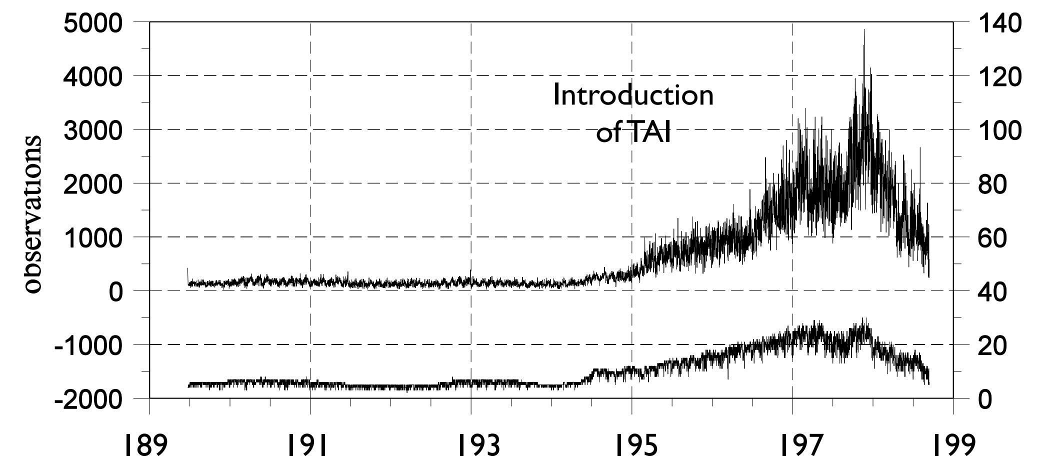
Earth's Polar Motion

(since ~1895)

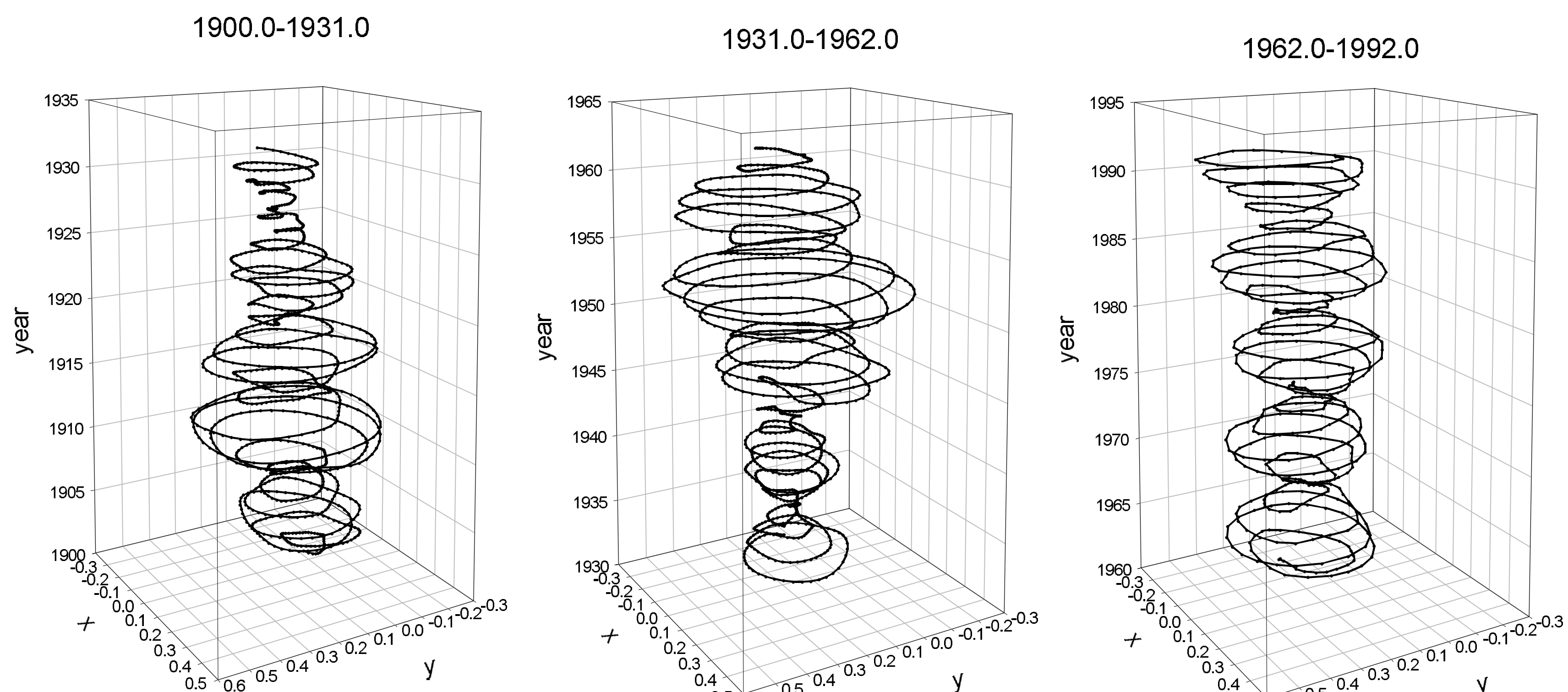
- small irregular movements of the Earth's geographic poles relative to crust
- originates from misalignment between rotation and symmetry axes
- dominant term: seasonal redistribution of mass ~0.3 arcsec (Chandler 1891)
- originally measured by visual and photographic zenith tubes, now VLBI and GPS
- 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)



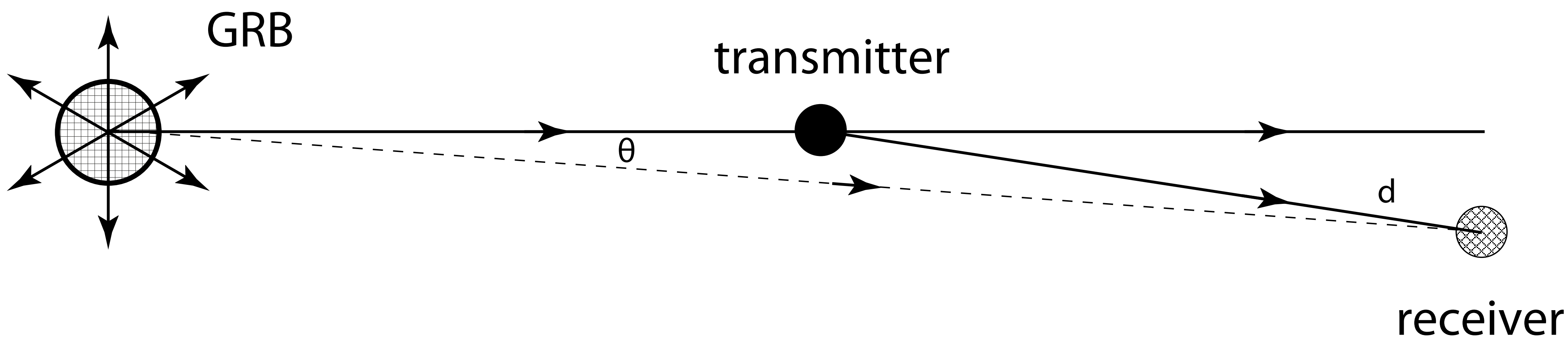
Polar motion versus time

(Vondrák & Ron 2000)

... illustrating 6-year beating between the Chandler period (435 d) and annual term

Search Optimisation for SETI

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)

End