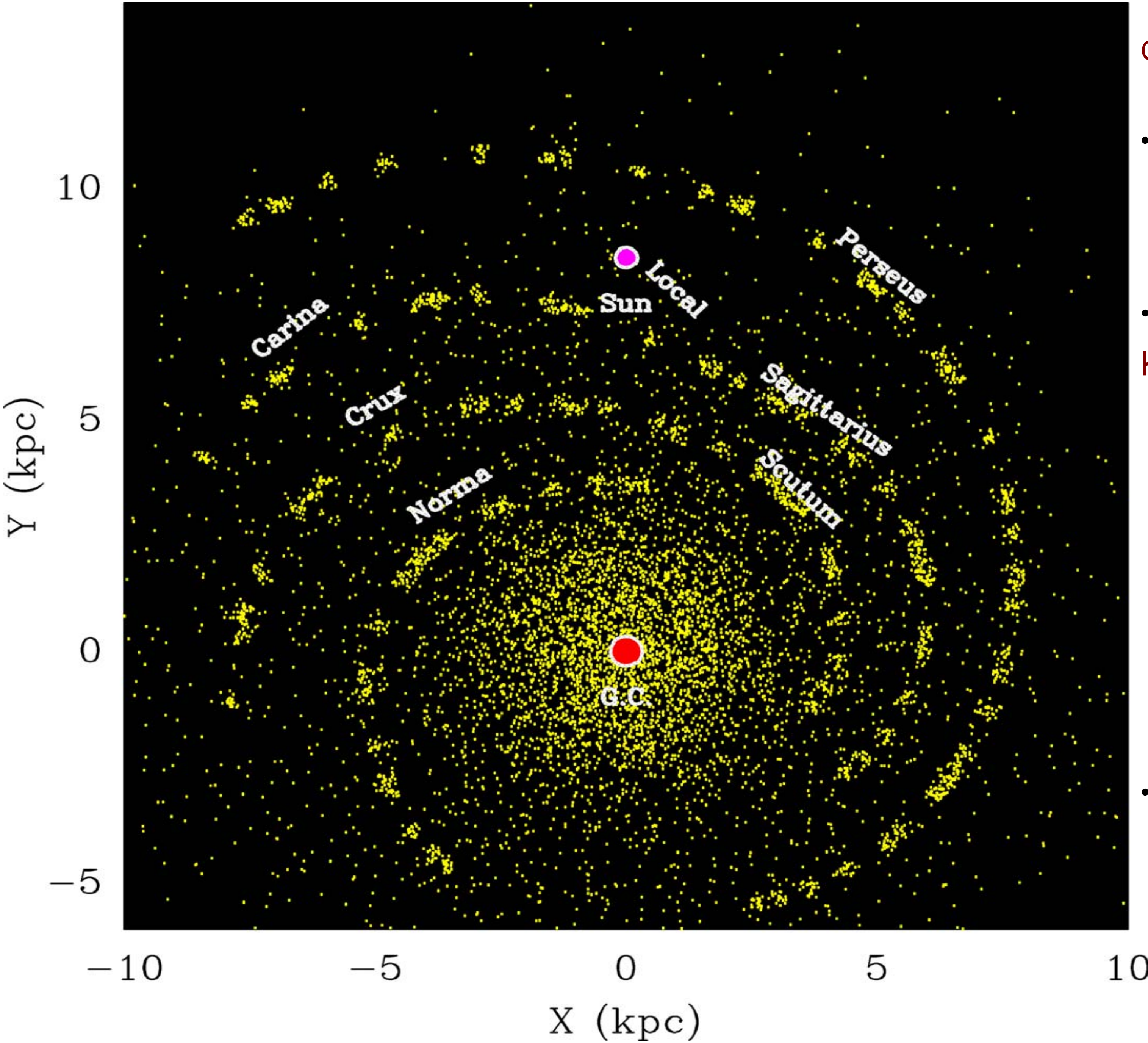
Tintoretto: The Origin of the Milky Way (about 1575)



Georgelin & Georgelin (1976)

- OB stars:

spectro-phot. D ≈ 20-30%

- HI and HII regions:

Kinematic D ← systematic errors

Taylor and Cordes (1993)

- Pulsars :

DM ← systematic errors

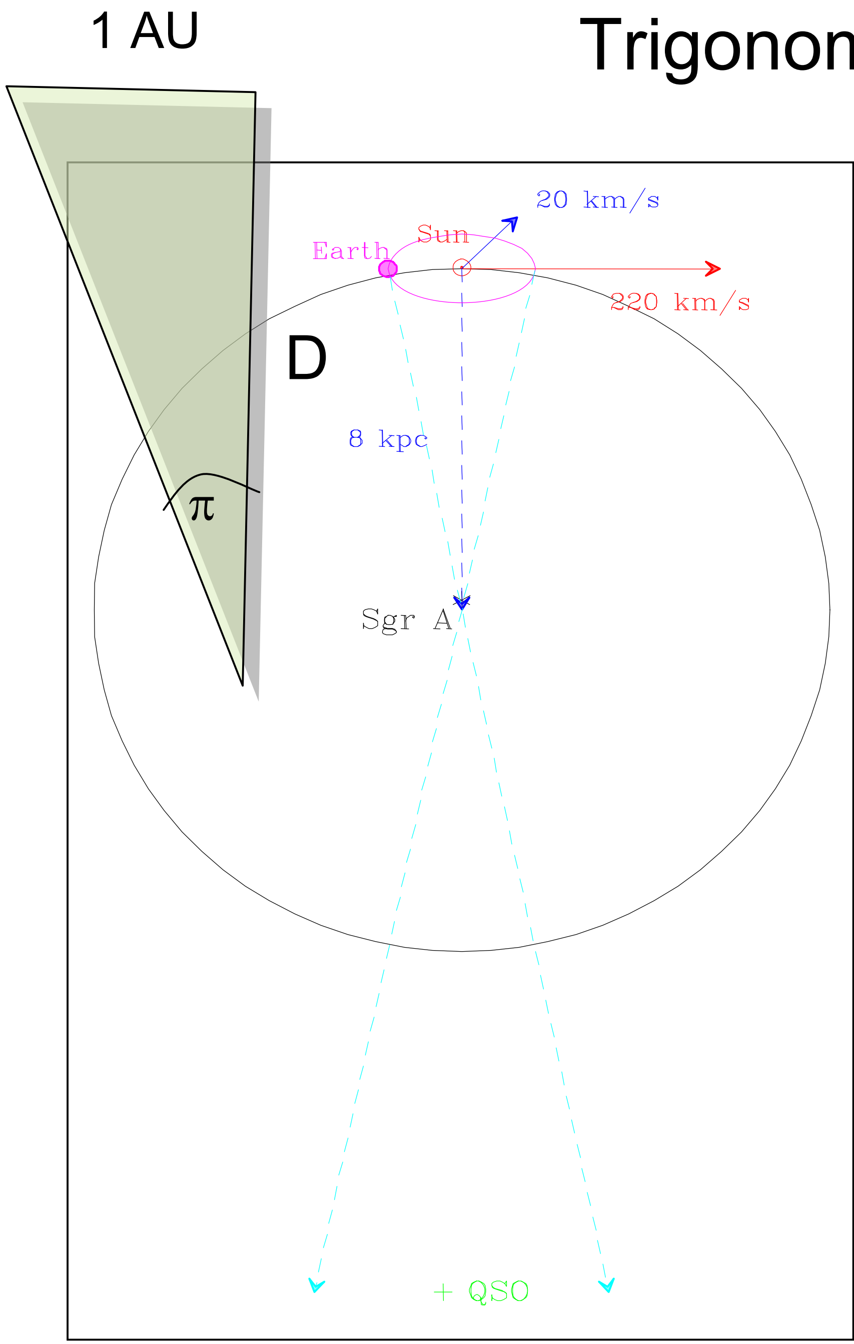
Strongest Interstellar Masers in the Milky Way

`

- OH 1.6 GHz
- CH_3OH (Methanol) 6.7 and 12 GHz
- H_2O 22 GHz

Single-dish and interferometric observations have demonstrated that they are associated with star-forming regions and therefore can be used to trace the densest gas component in spiral arms.

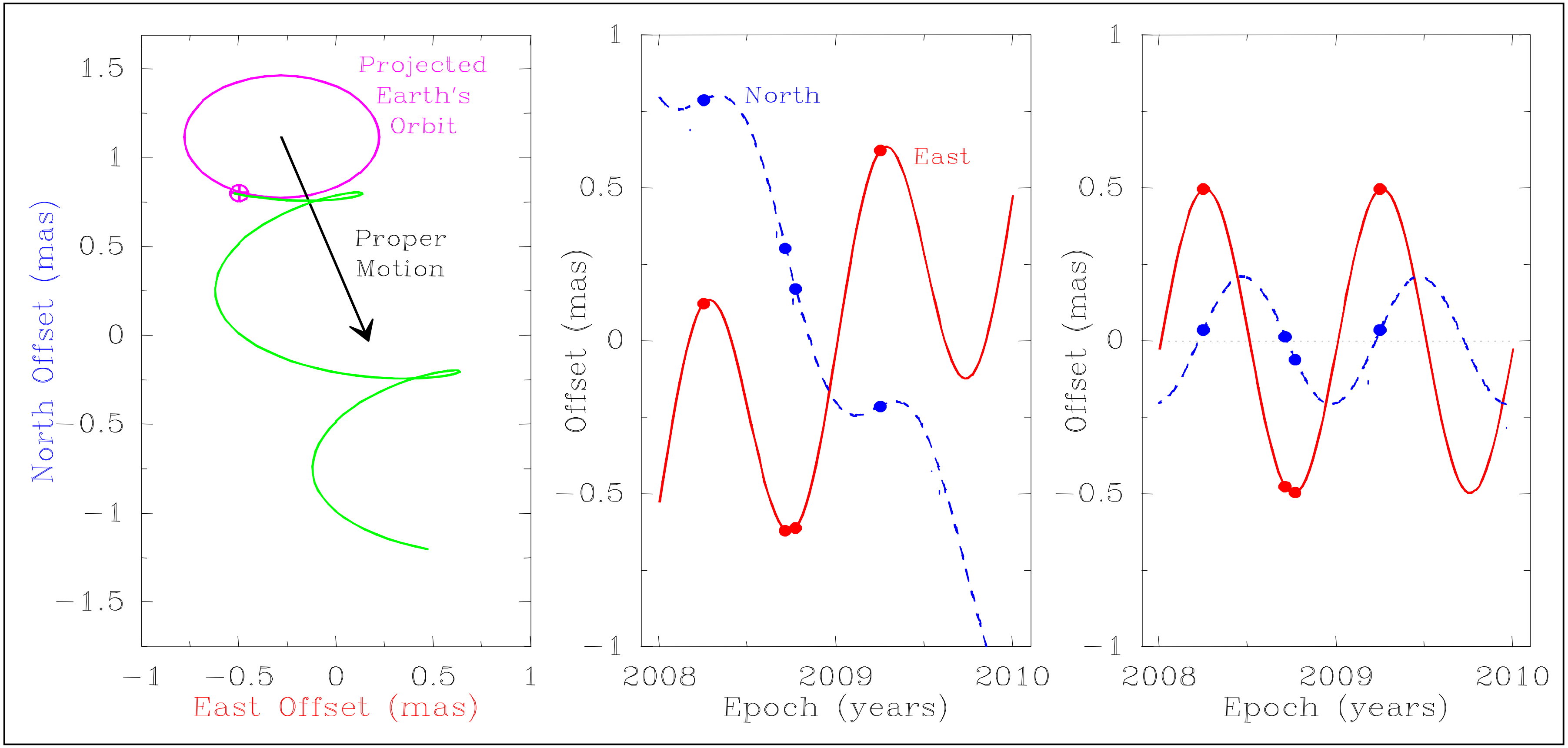
Trigonometric Parallax



- Triangulation using Earth's orbit as one leg of triangle

- 10 kpc → accuracy 10 μas

Parallax 1.01



Proper Motion = Sun Motion + Differential Galactic Rotation + Peculiar Motion

Four epochs close to the extrema of the parallax signature in R.A. is the best compromise to minimize correlation between parallax and proper motion.

HIPPARCOS

(Perryman et al 1997 A&A 323 49)

118,000 stellar parallaxes

σ_π ~ 0.8 mas

10% accuracy at 125 pc…

mapped solar neighborhood

Next great space missions:

GAIA & SIM: ~10 μas

NOW VLBI can ALREADY reach 10 μas

Atmospheric & Ionospheric Errors dominate phase-referenced VLBI observations

(Pradel, Charlot and Lestrade 2006,
Honma, Tamura and Reid 2008)

Frequency (maser)		Un-modeled Zenith Path Length	
		Wet Atmosphere	Ionosphere
43 GHz	(SiO)	5 cm	0.5 cm
22	(H_2O)	5	2
12	(CH_3OH)	5	6
6.7	(CH_3OH)	5	20
1.6	(OH)	5	300

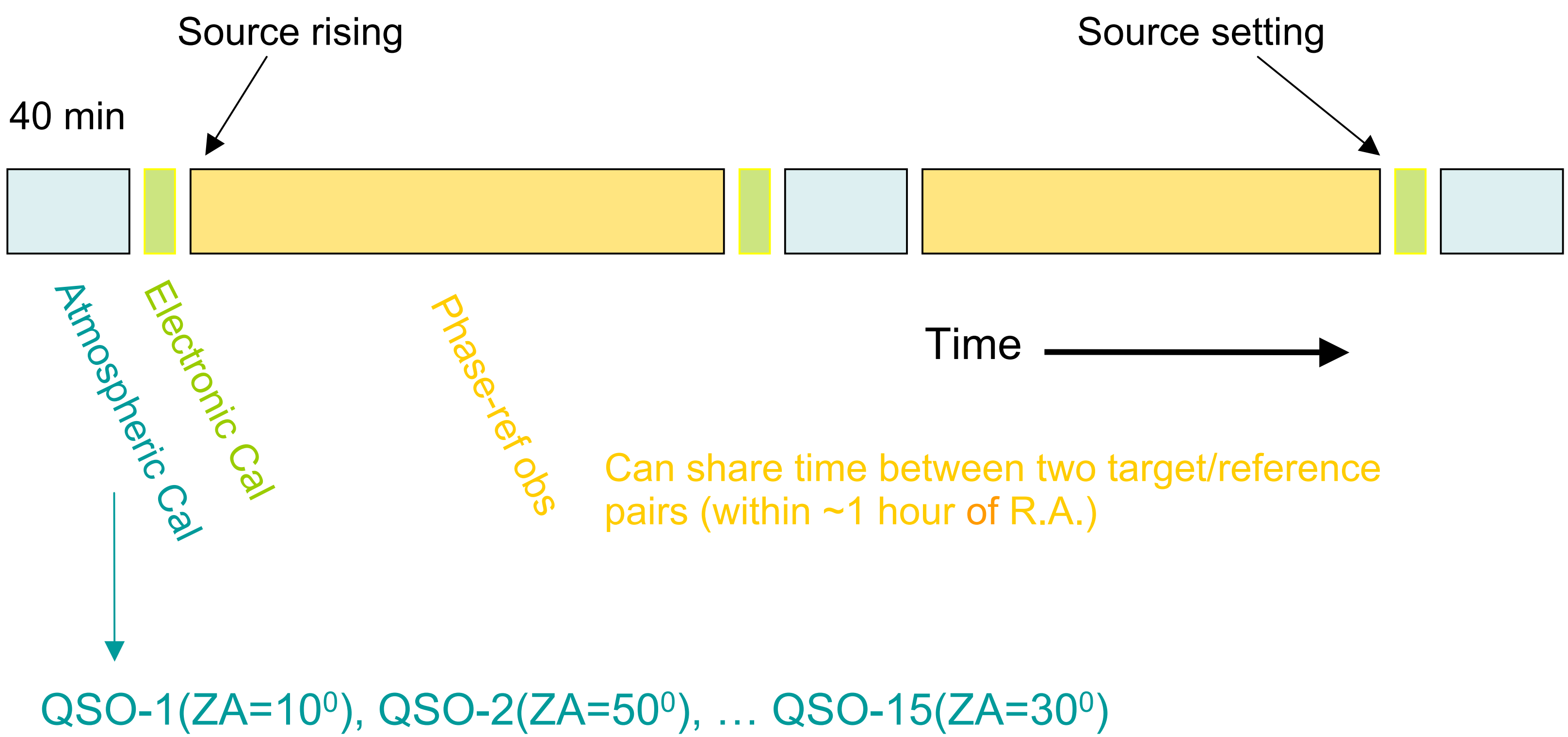
Simulations of VLBI data (@ ν > 10 GHz) shows that:

for target-reference separation of 1º,

astrometric accuracy is 50 μas at mid declination and

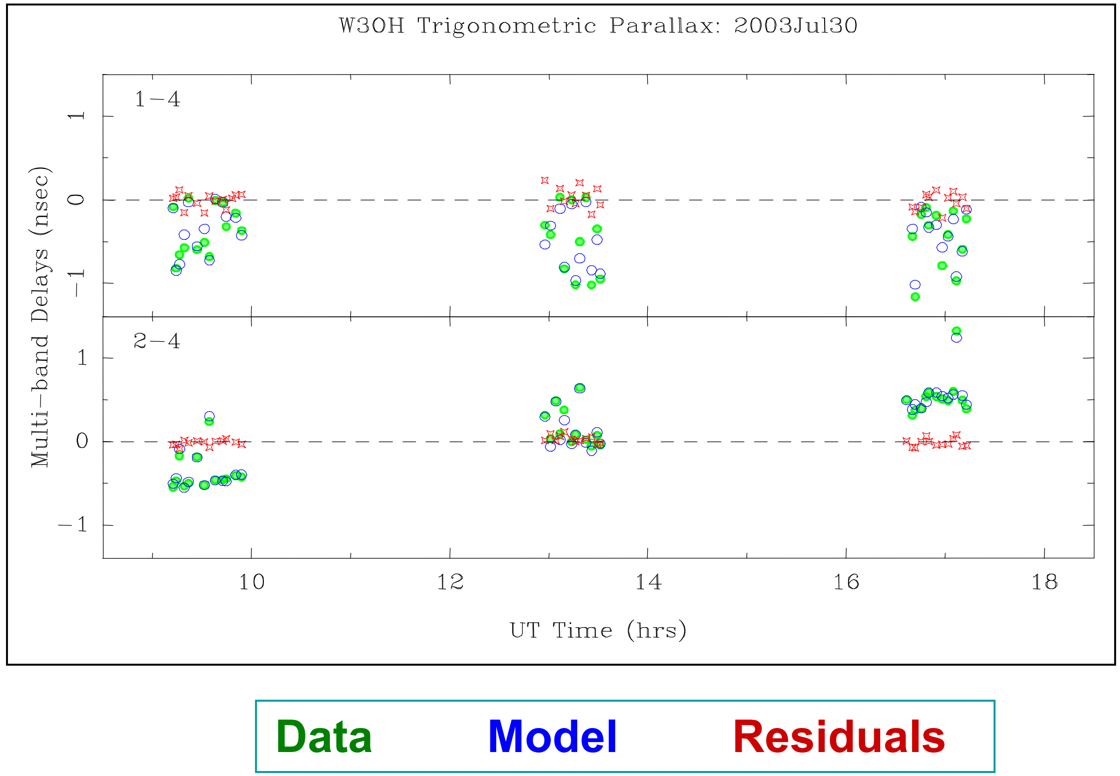
300 μas at low (-25º) and high (85º) declinations.

Typical Observing Sequence



Atmospheric Delay Calibration

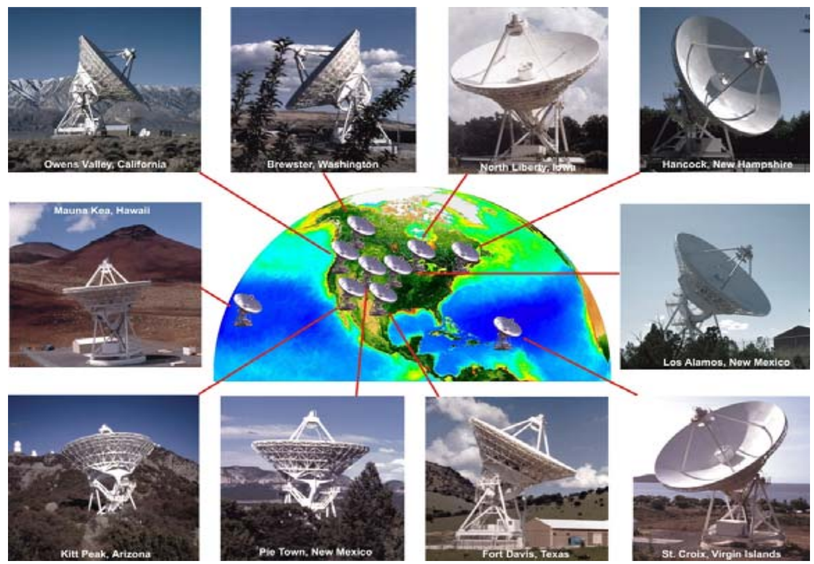
- Measure zenith delay (τ_0) above each antenna
- Spread observing bands to cover 500 MHz
  σ_τ ~ (1/BW) * (1/SNR)
- Observe QSOs over range of elevations
- Fit to atmospheric model:
  τ_0 ~ 0.5 cm accuracy



GPS measurements of tropospheric zenith delays are adopted by **VERA**

VLBA parallax of methanol and water masers

Mark J. Reid



Max-Planck-Institut
für Radioastronomie

Karl M. Menten

Andreas Brunthaler

Osservatorio di Arcetri

Luca Moscadelli

Nanjing University 南京大學

Xingwu Zheng

Ye Xu ， Bo Zhang

12 GHz Methanol VLBA : Parallax & Proper Motions

(Reid, Menten, Brunthaler, Zheng, Moscadelli, Xu)

8.4 GHz non-thermal →

12 GHz Methanol →

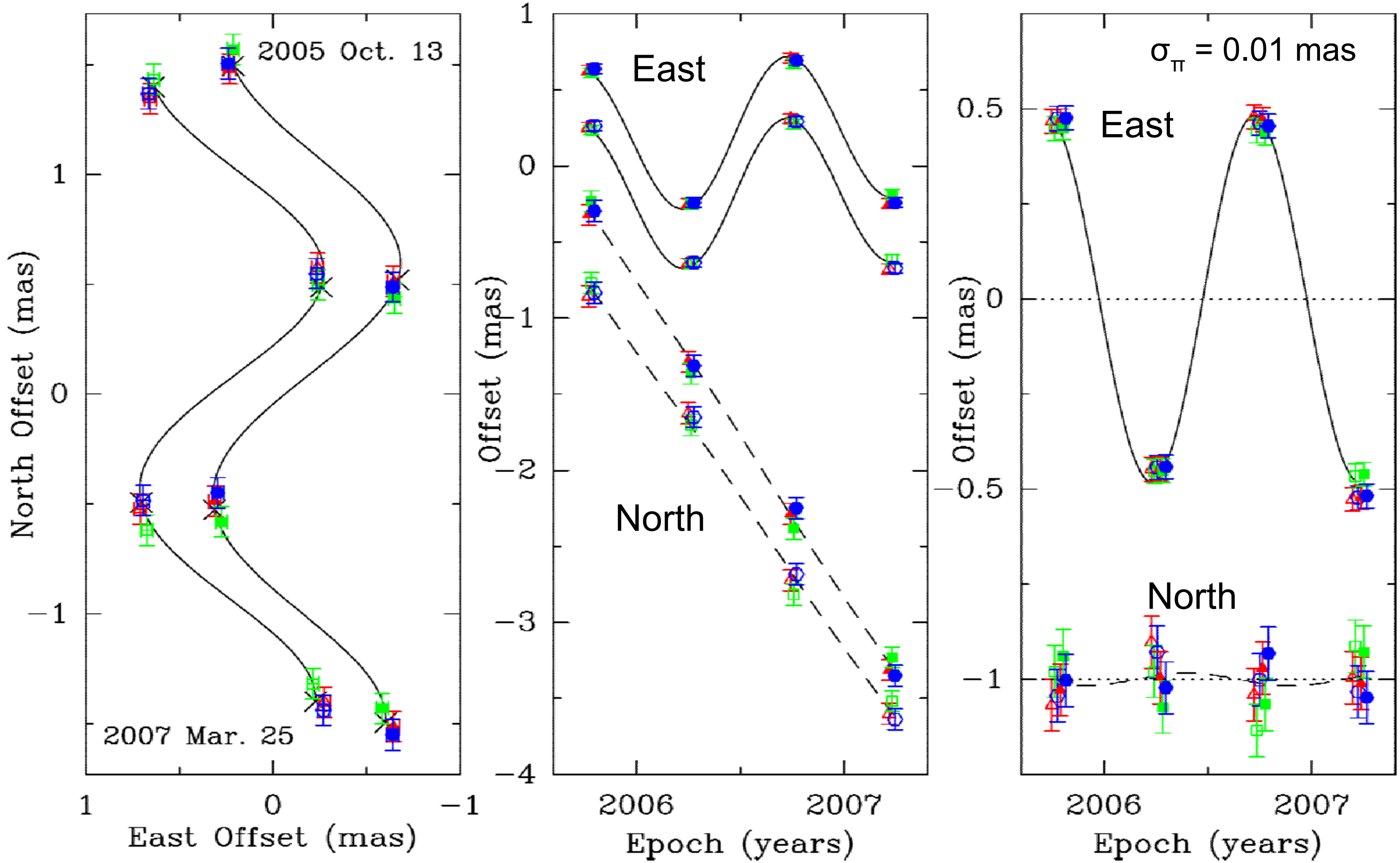
↓

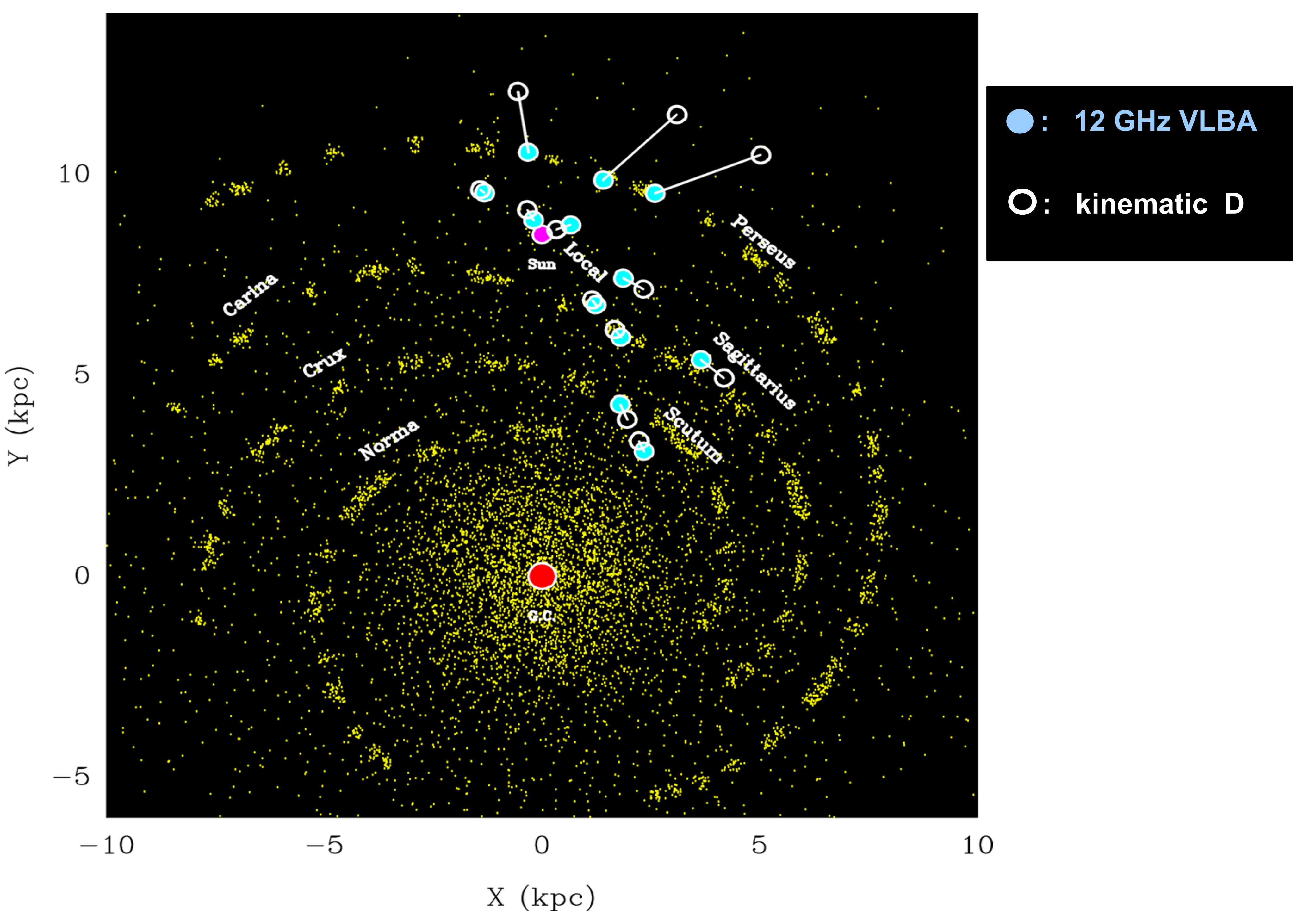
Source Name	Parallax	μ_x	μ_y
	(mas)	(mas y^{-1})	(mas y^{-1})
Orion	2.425 ± 0.035	3.3 ± 1.0	0.1 ± 1.0
Cep A	1.43 ± 0.08	1.66 ± 1.7	-3.77 ± 0.23
G232.6+1.0	0.596 ± 0.035	-2.17 ± 0.06	2.09 ± 0.46
W3OH	0.512 ± 0.01	-1.20 ± 0.2	-0.15 ± 0.2
S 252	0.482 ± 0.01	0.06 ± 0.03	-2.01 ± 0.06
G 35.20-0.7	0.468 ± 0.029	-0.21 ± 0.17	-3.65 ± 0.92
G 59.7+0.1	0.463 ± 0.02	-1.65 ± 0.03	-5.09 ± 0.10
NGC 7538	0.358 ± 0.019	-2.40 ± 0.2	-2.41 ± 0.2
G 35.20-1.7	0.319 ± 0.019	-0.75 ± 0.06	-3.65 ± 0.3
G 23.01-0.41	0.218 ± 0.017	-1.72 ± 0.2	-4.12 ± 0.2
W 51 IRS2	0.208 ± 0.071	-2.54 ± 0.15	-5.47 ± 0.18
G 23.44-0.18	0.170 ± 0.023	-1.93 ± 0.2	-4.10 ± 0.2

12 GHz Methanol VLBA Parallax Measurement for source **S 252**

(Reid et al. 2008)

Two maser spots (offset for clarity) relative to three background sources (red, green, blue)



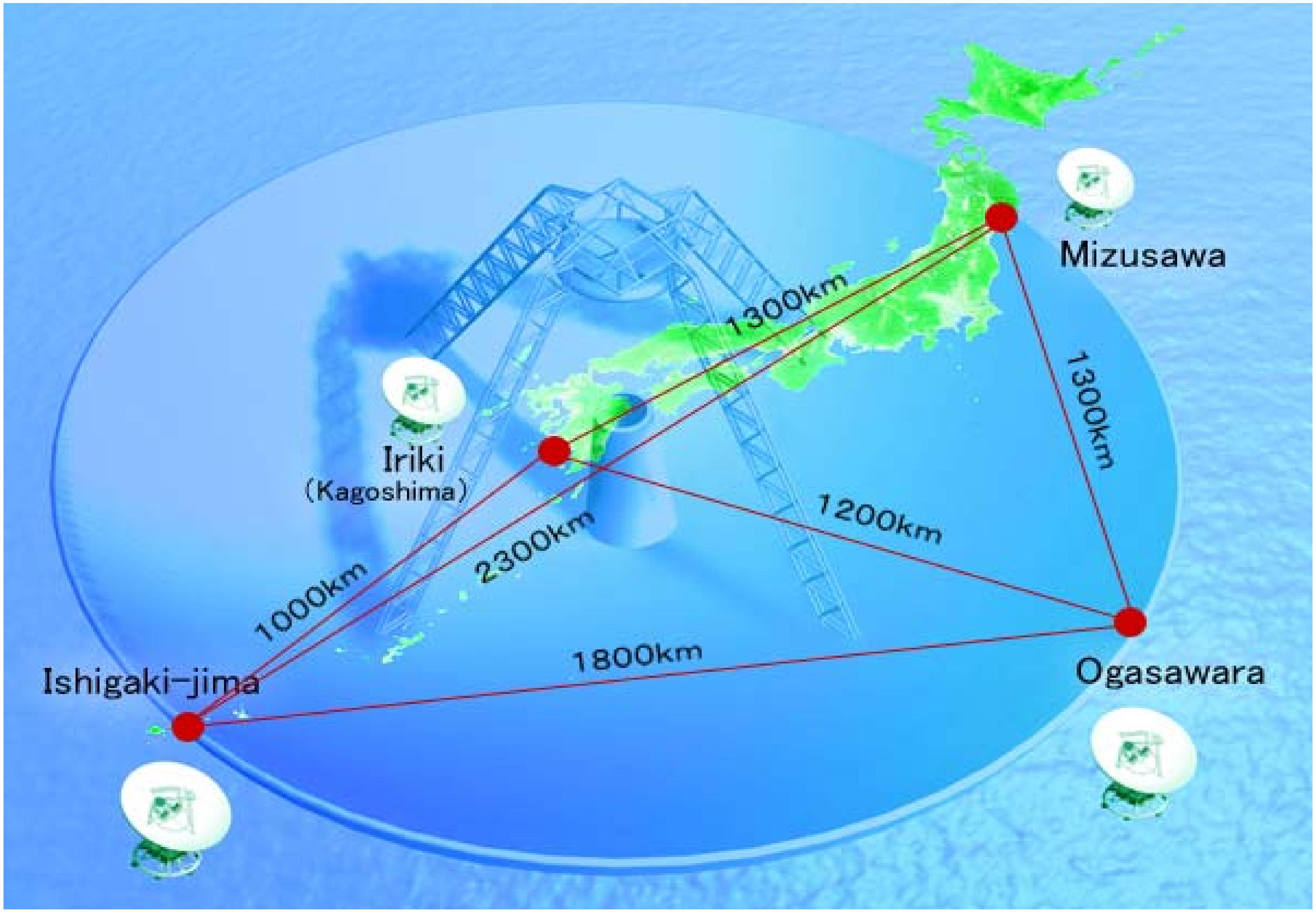


12 GHz VLBA
kinematic D
Perseus
Local
Sun
Carina
Crux
Norma
Sagittarius
Scutum
G.C.
Y (kpc)
X (kpc)

NAOJ National Astronomical Observatory of Japan

VERA

VLBI Exploration of Radio Astrometry

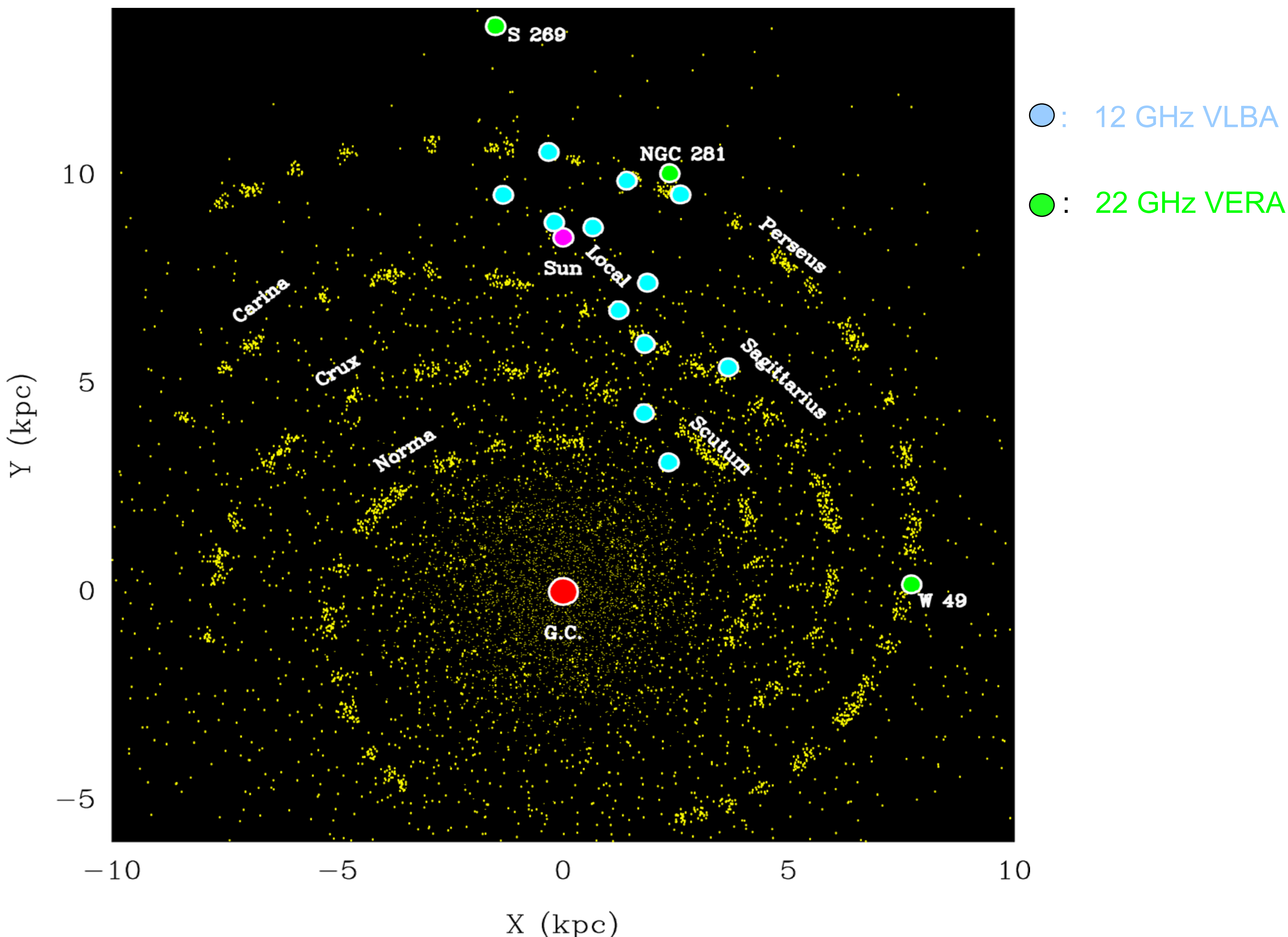


22 GHz Water VERA : Parallax & Proper Motions

(Honma, Choi, Hirota, Imai, Nakagawa, Sato, et al.)

22 GHz interstellar   22 GHz evolved star

Source Name	Parallax	μ_x	μ_y
	(mas)	(mas y^{-1})	(mas y^{-1})
ρ Oph	5.6 ± 1.0	-20.6 ± 0.7	-32.4 ± 2
NGC 1333	4.25 ± 0.32	17.9 ± 0.9	-7.9 ± 1.4
S Crt	2.33 ± 0.13	-1.56 ± 0.22	-5.16 ± 0.22
Orion-KL	2.29 ± 0.1	2.77 ± 0.09	-8.97 ± 0.21
VY CMa	0.88 ± 0.08	-2.09 ± 0.16	1.02 ± 0.61
NGC 281	0.355 ± 0.030	-2.63 ± 0.05	-1.86 ± 0.08
S 269	0.189 ± 0.010	-0.422 ± 0.010	-0.121 ± 0.042
W 49	0.088 ± 0.01	-3.38 ± 0.3	-5.62 ± 0.3

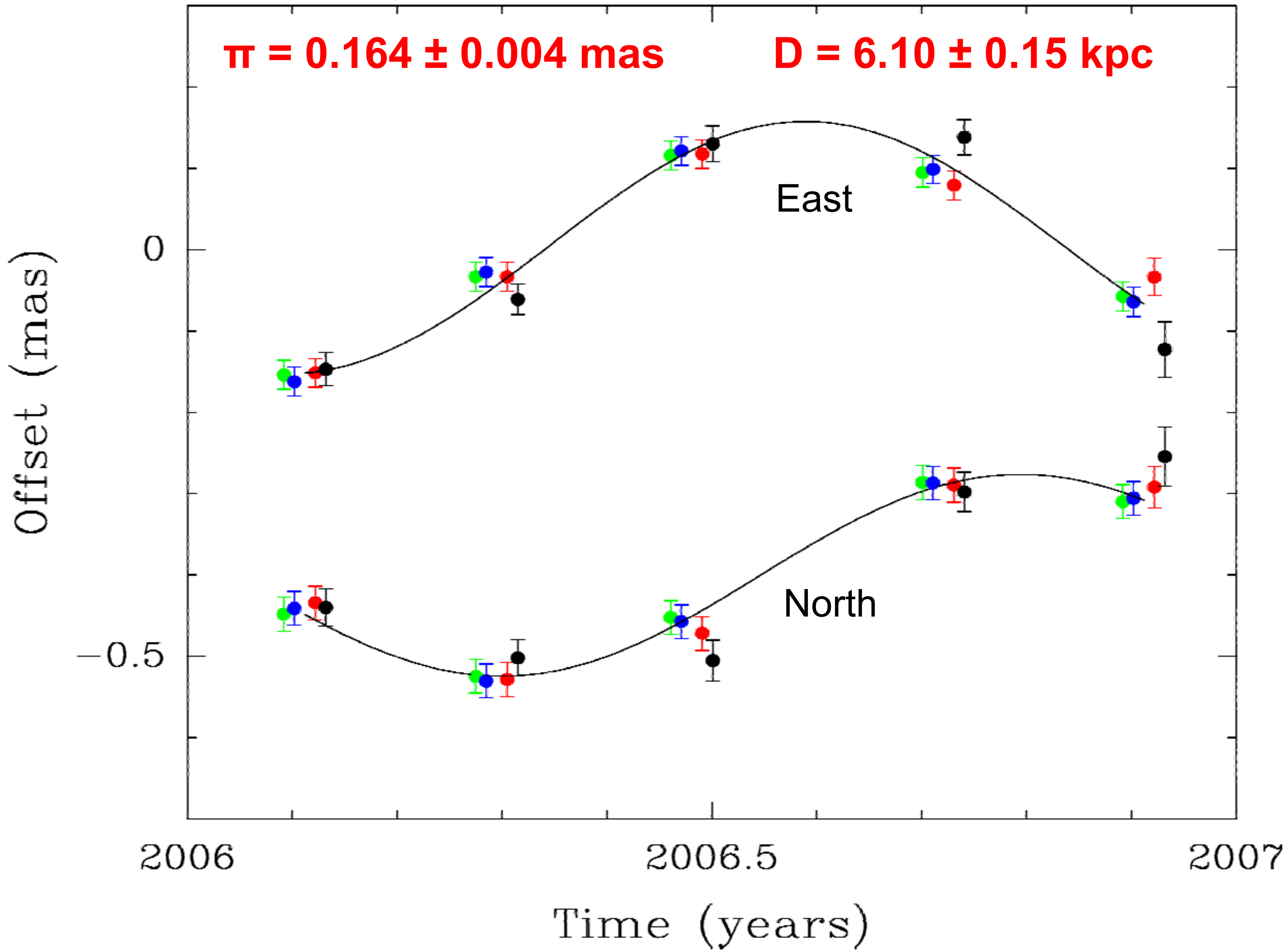


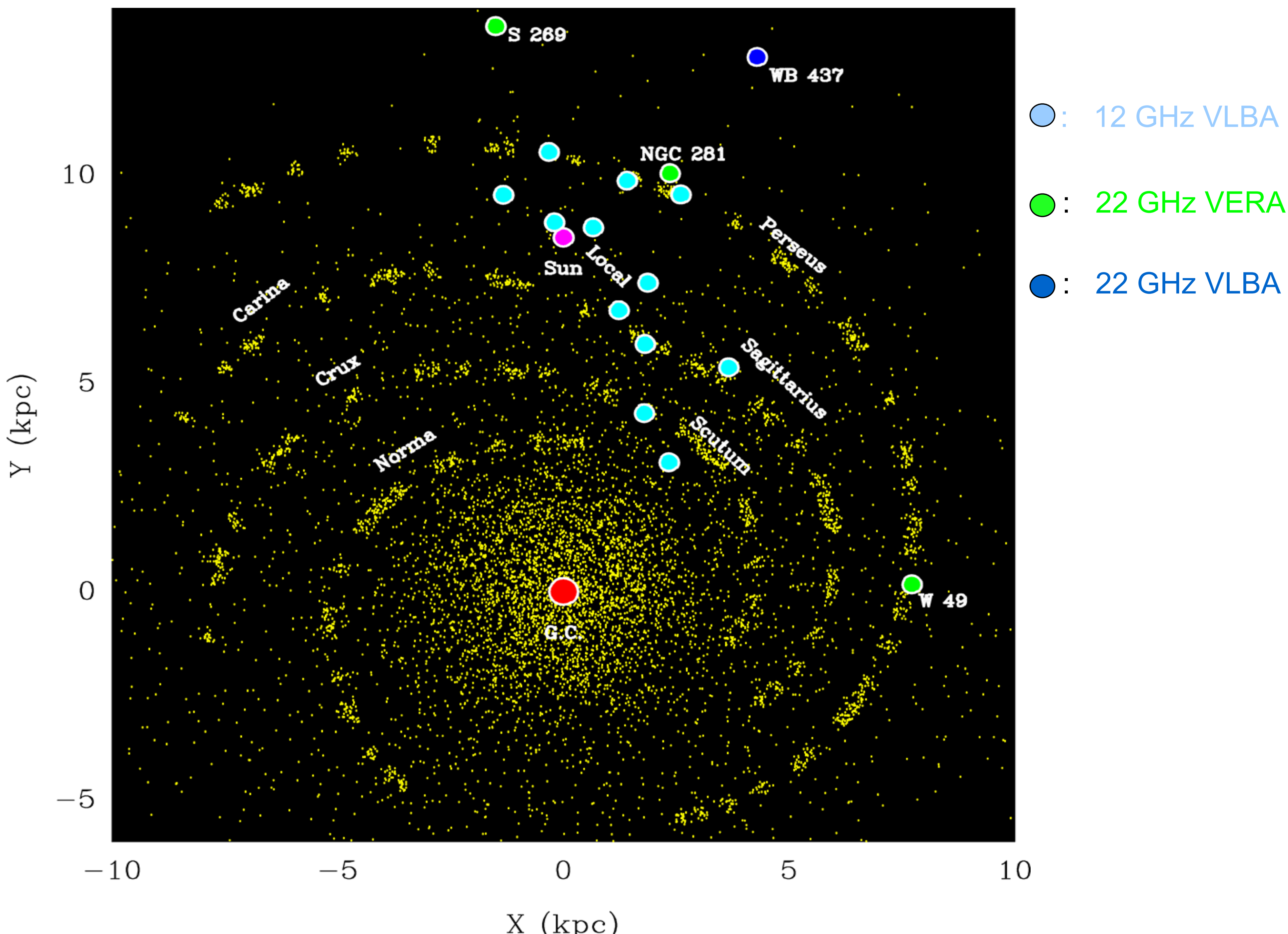
S 269
NGC 281
Perseus
Local
Sun
Carina
Crux
Sagittarius
Norma
Scutum
W 49
G.C.
: 12 GHz VLBA
: 22 GHz VERA
Y (kpc)
X (kpc)
10
5
0
−5
−10
−5
0
5
10

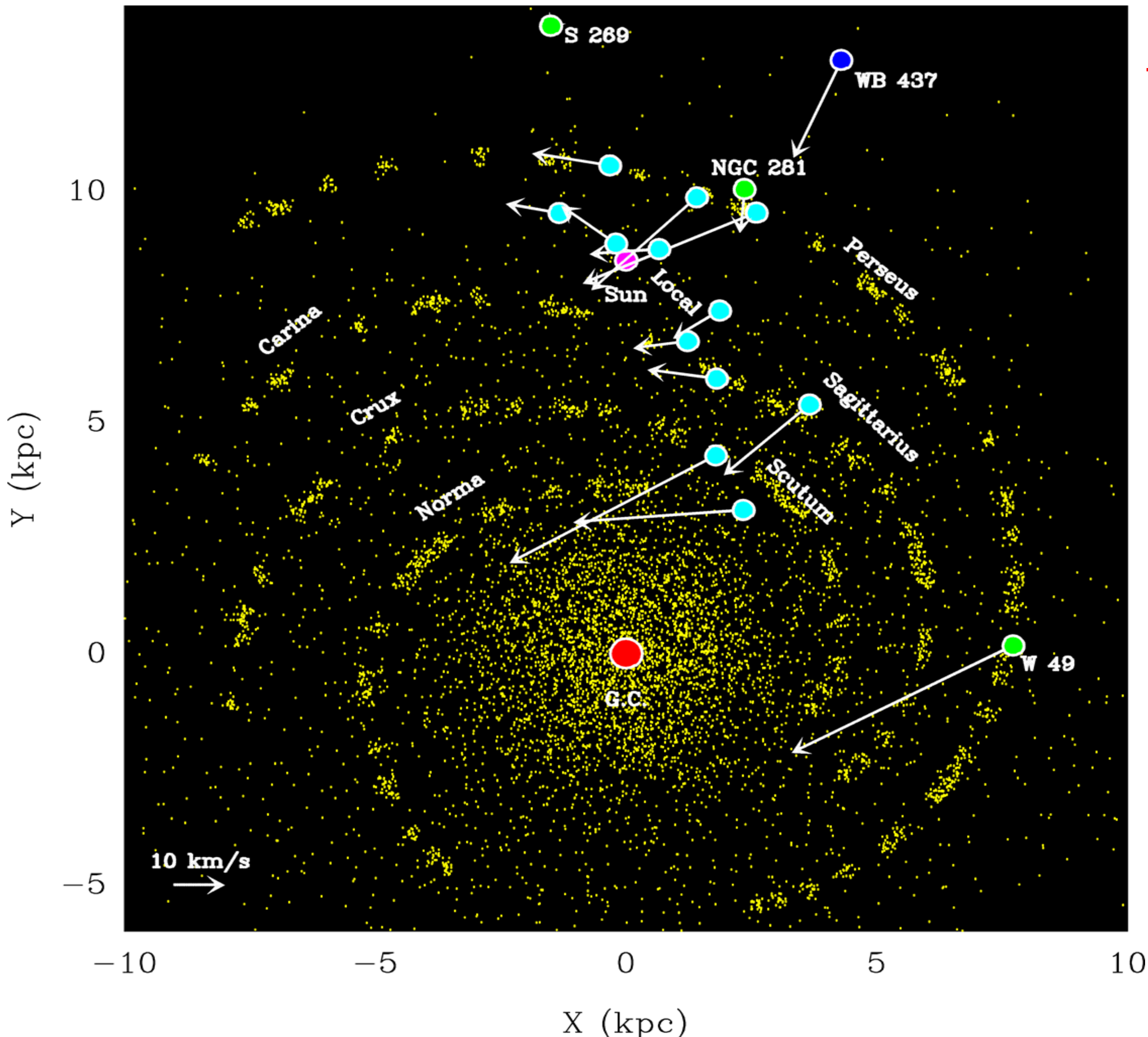
22 GHz Water VLBA Parallax Measurement for source **WB89-437**

Parallax signature: (Hachisuka, Brunthaler et al. 2008)

Four maser spots (shifted in time: green, blue, red, black) relative to one background source.




S 269
WB 437
NGC 281
Perseus
Sun
Local
Carina
Crux
Sagittarius
Norma
Scutum
W 49
G.C.
12 GHz VLBA
22 GHz VERA
22 GHz VLBA
X (kpc)
Y (kpc)
−10
−5
0
5
10



Peculiar motions

Flat MW Rotation:

R_0 = 8.5 kpc

(IAU)

Θ_0 = 220 km s^{-1}

HIPP. Solar Motion:

U_0 = 10.0 km s^{-1}

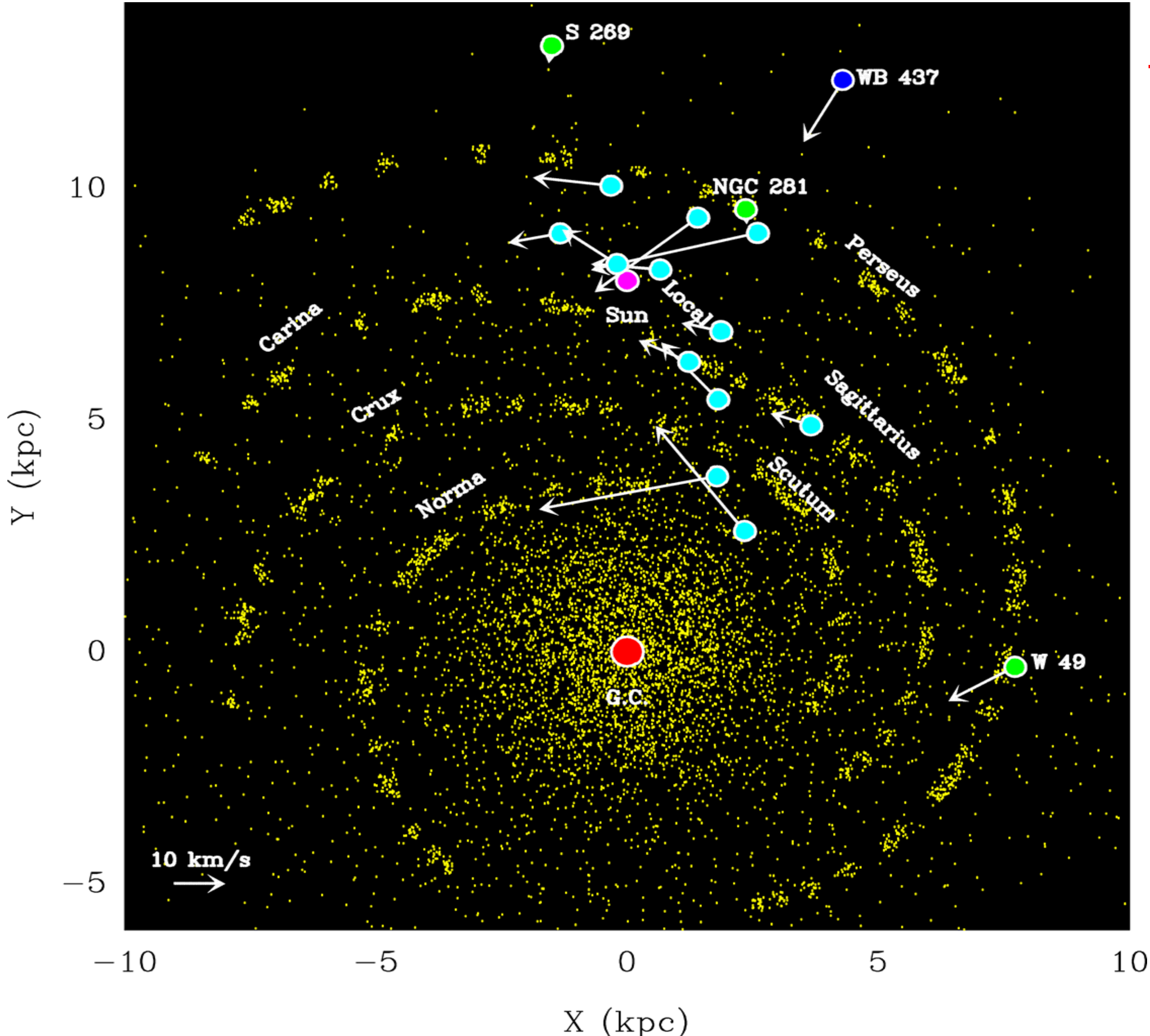
V_0 = 5.25 km s^{-1}

W_0 = 7.16 km s^{-1}

: 12 GHz VLBA

: 22 GHz VERA

: 22 GHz VLBA



Peculiar motions

Θ_0/R_0 = 29.5 km/s/kpc

(Reid & Brunthaler 2004)

Flat MW Rotation:

R_0 = 8.0 kpc *(Reid 1993)*

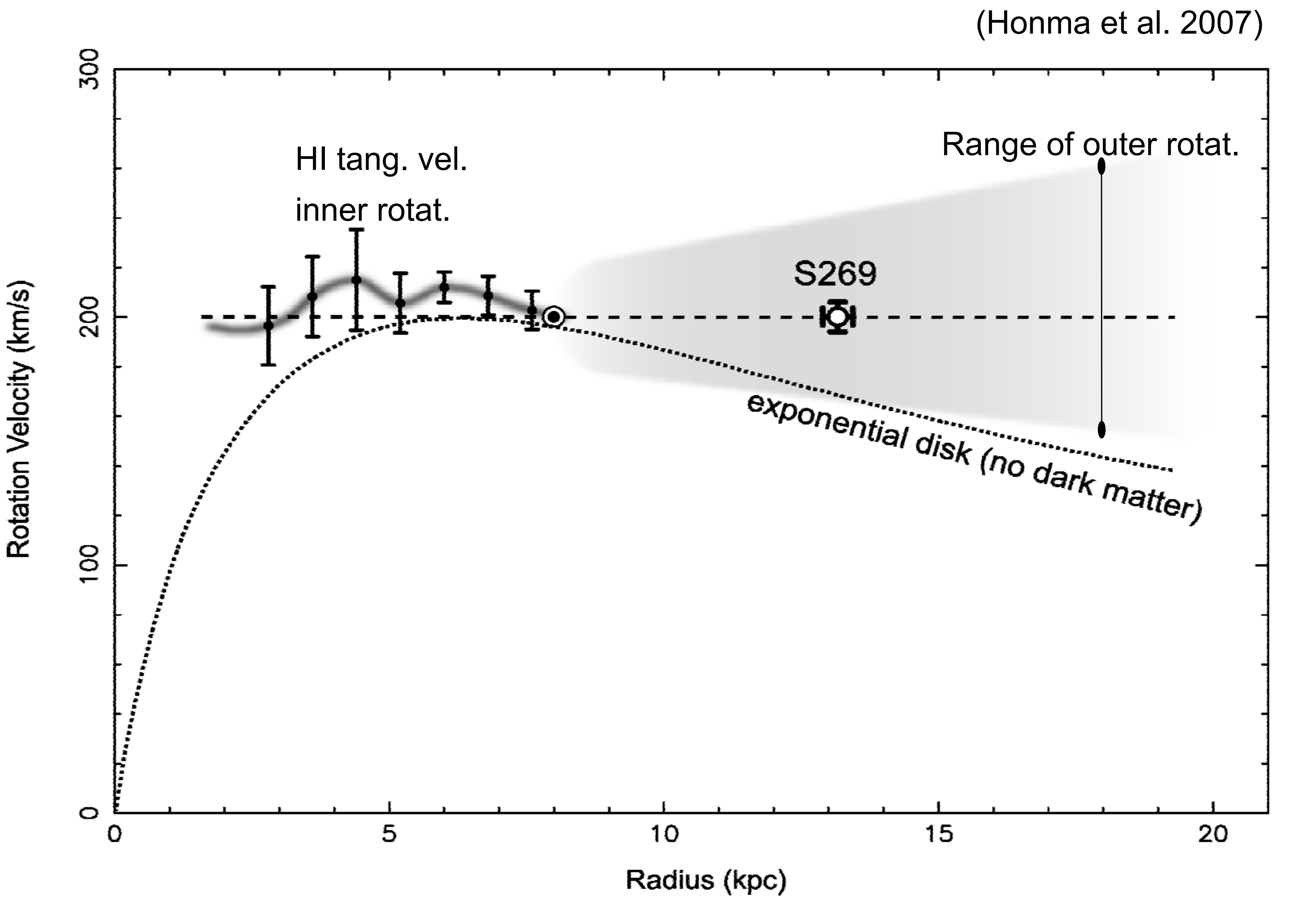
Θ_0 = 236 km s^{-1}

HIPP. Solar Motion:

U_0 = 10.0 km s^{-1}

V_0 = 5.25 km s^{-1}

W_0 = 7.16 km s^{-1}


(Honma et al. 2007)
Range of outer rotat.
HI tang. vel.
inner rotat.
S269
exponential disk (no dark matter)
Rotation Velocity (km/s)
0
100
200
300
Radius (kpc)
0
5
10
15
20

On-going VERA and VLBA Observations

VERA plans (Honma et al. 2008):

70-80 maser sources every year.

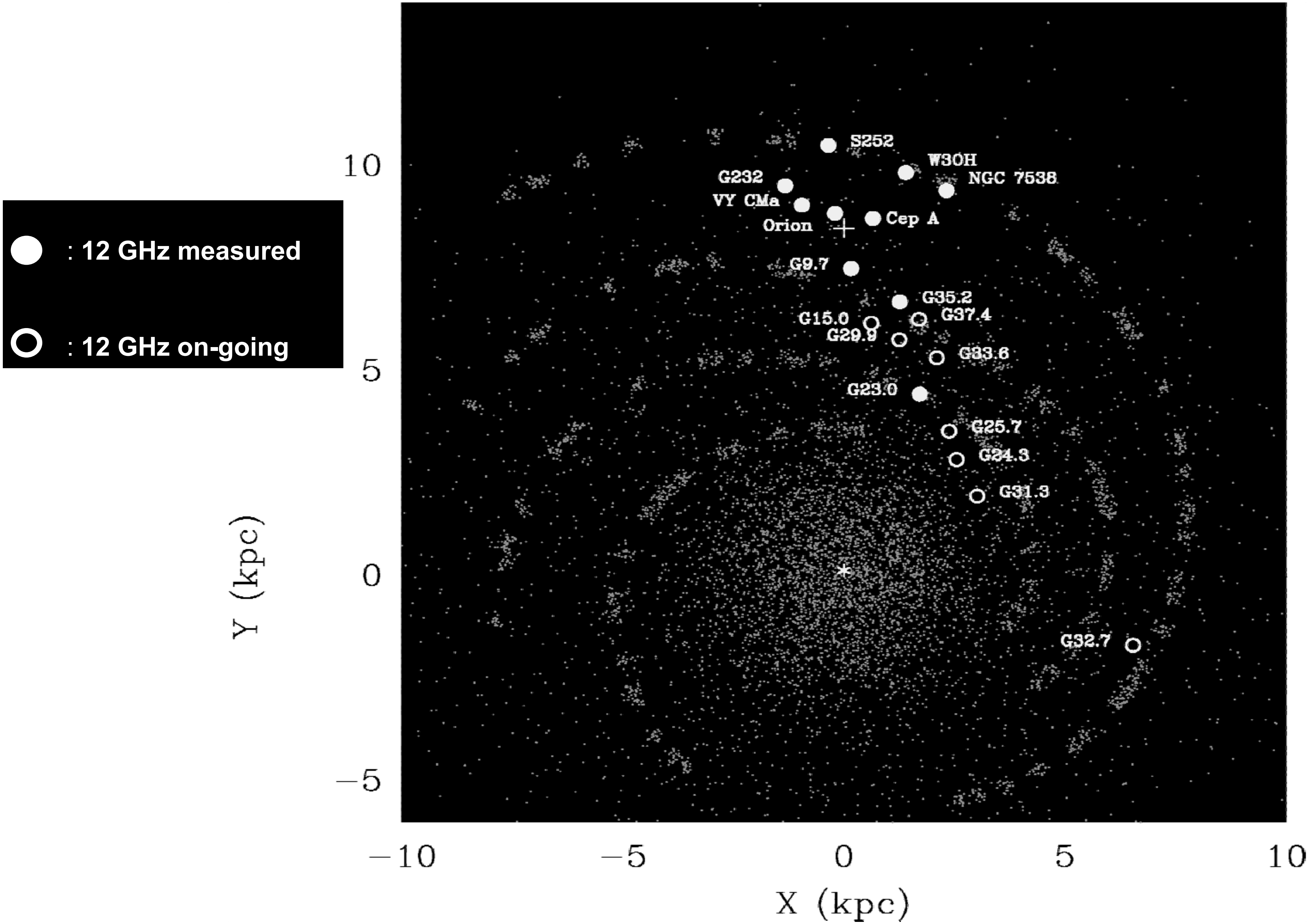
~1000 Galactic masers in 12-15 years.

our VLBA observations in 2008-2009:

8 CH_3OH 12 GHz masers.

8 H_2O 22 GHz masers.

Our on-going VLBA methanol 12 GHz observations

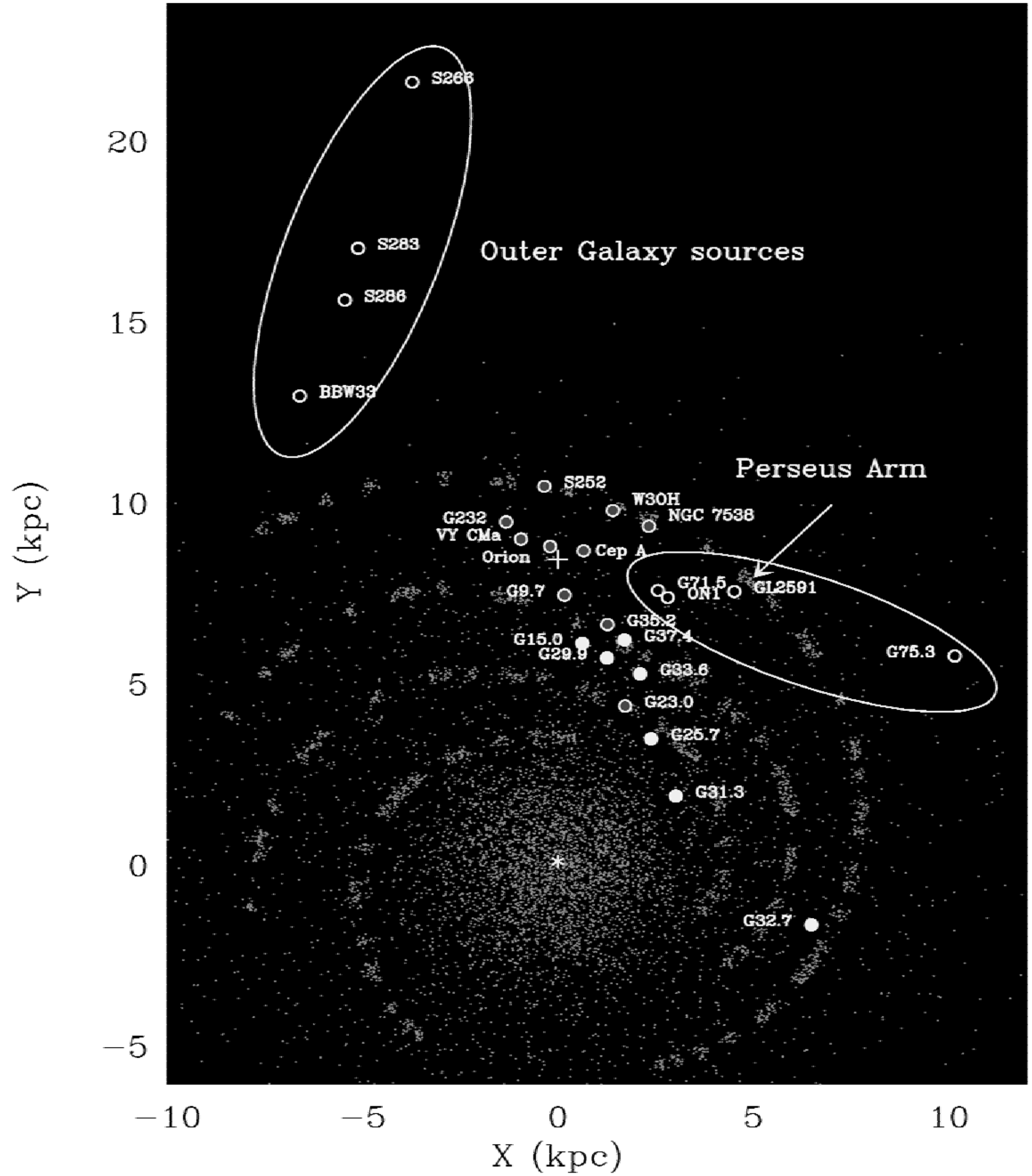


Our on-going VLBA water 22 GHz observations

: 12 GHz measured

: 12 GHz on-going

: 22 GHz on-going



AND **EVN** IS ALSO MEASURING MASER PARALLAX !

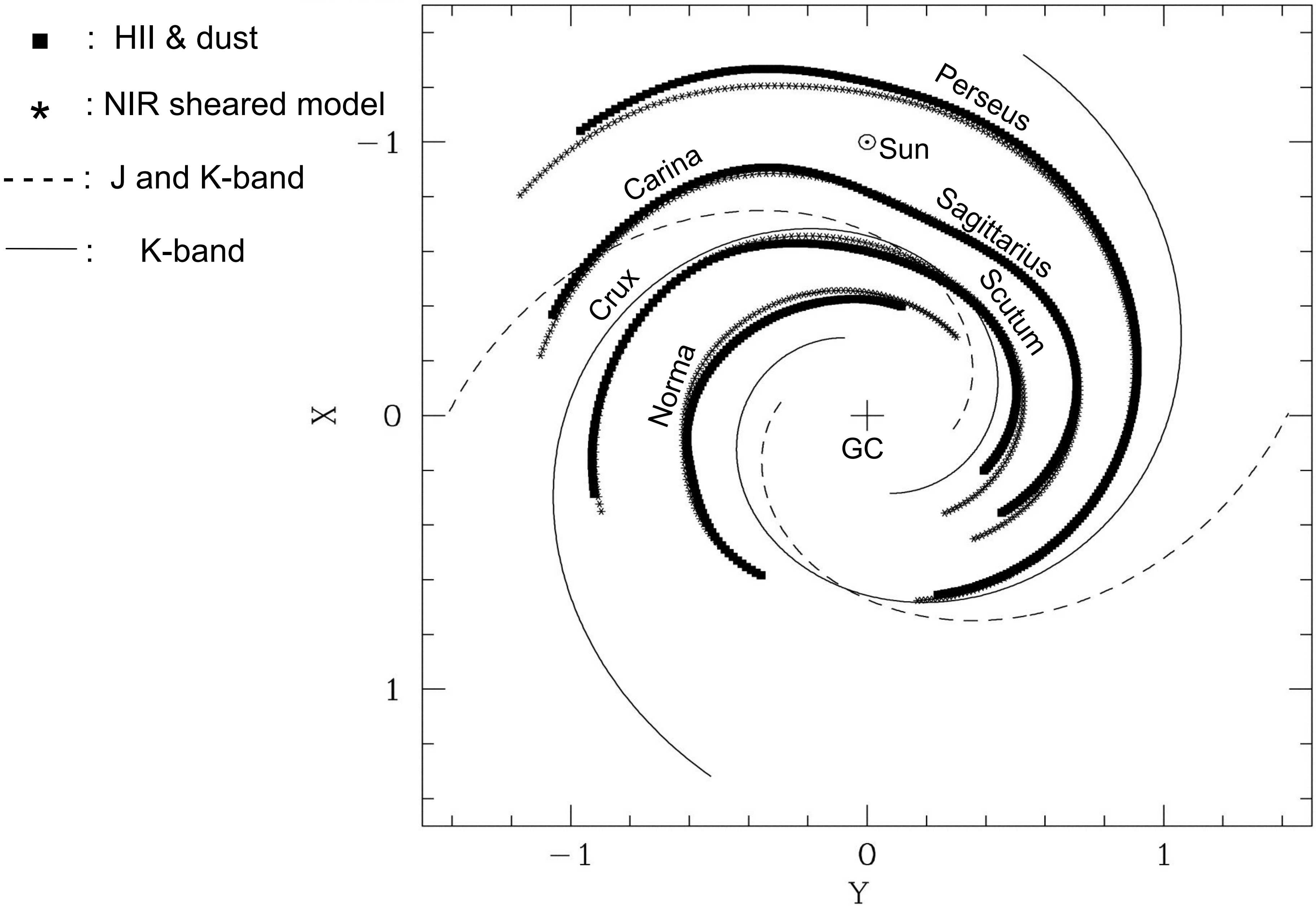
“DISTANCES TO GALACTIC METHANOL MASERS"

FRIDAY (26 SEPTEMBER) 12:10

TALK BY KAZI RYGL

COBE NIR (J & K) : TWO (only) dominant spiral arms

(Drimmel & Spergel 2001)

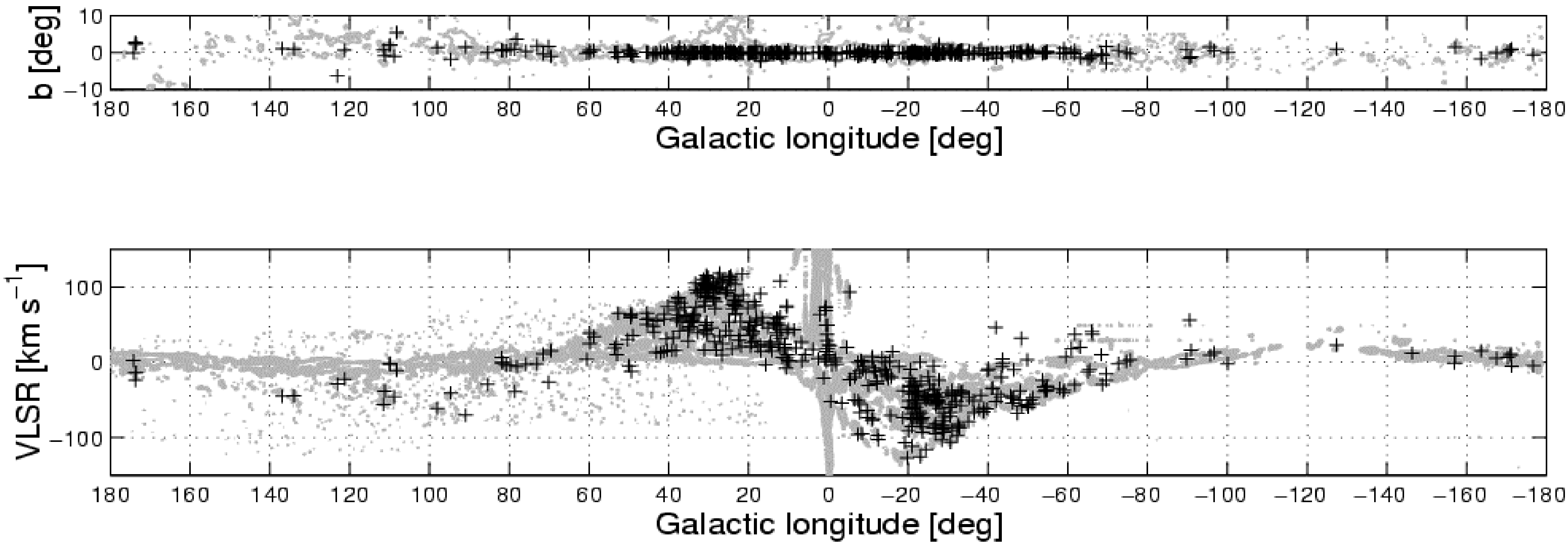


Association of CH_3OH 6.7 GHz masers with molecular clouds

Pestalozzi et al. (2007)

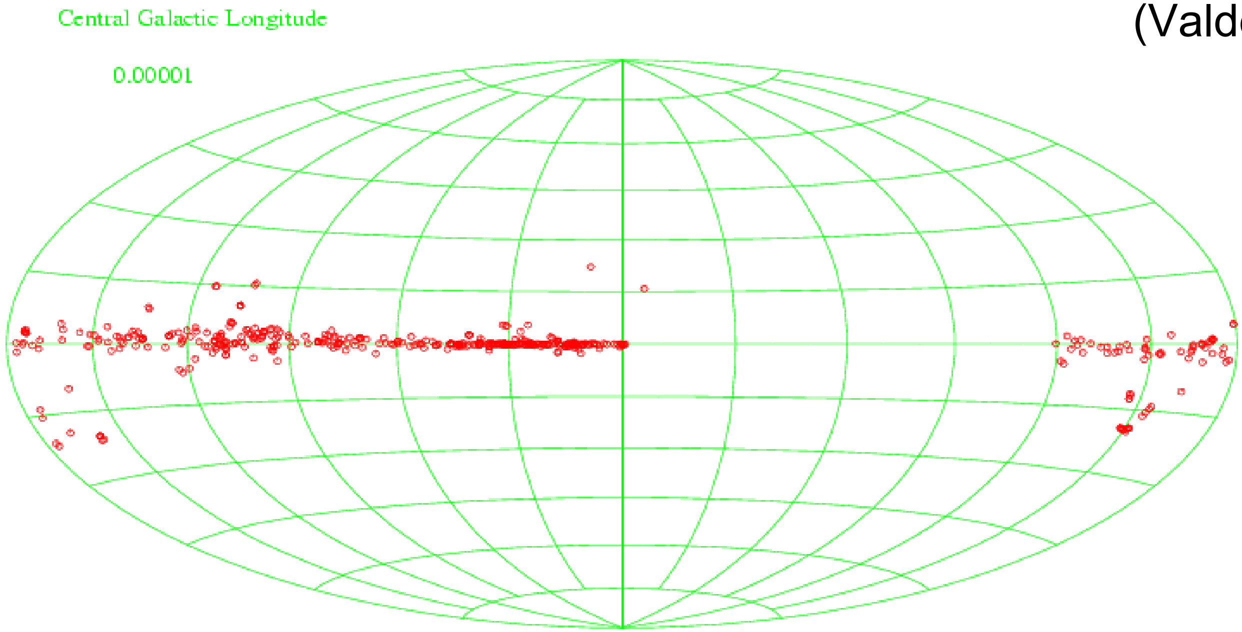
grey image: CO emission (Dame et al. 1987)

+ : 6.7 GHz methanol masers

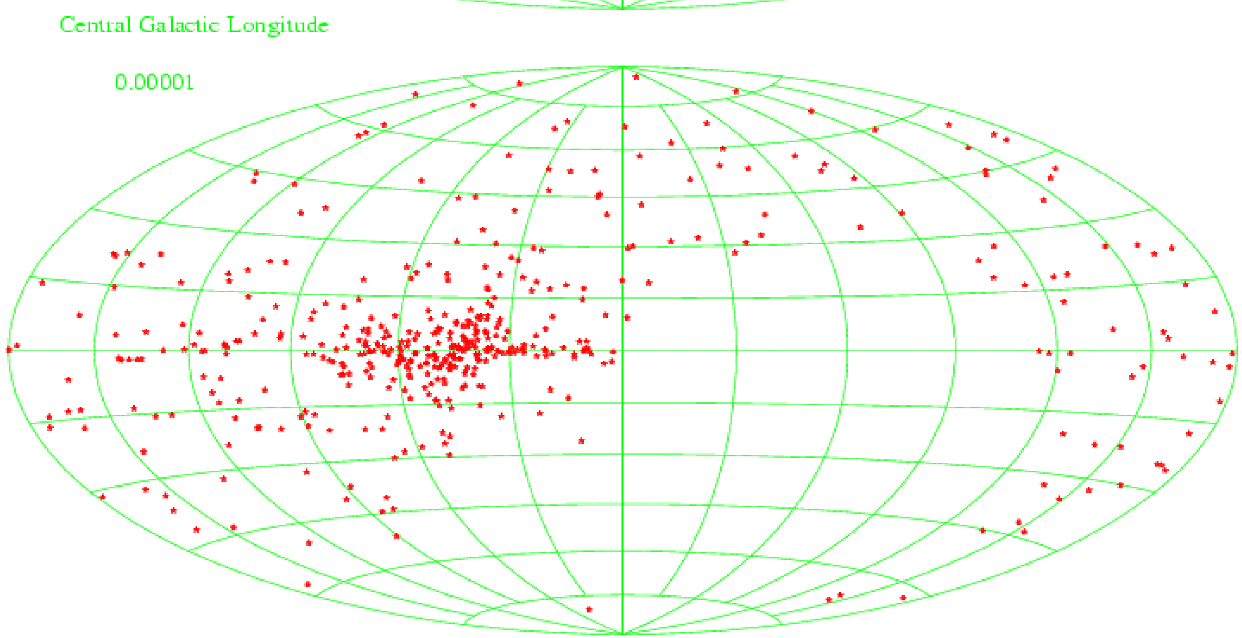


22 GHz water maser Arcetri Catalog distribution

(Valdettaro et al. 2001)



← Interstellar (SFR)



← Stellar

Excerpts from a 1609 Proposal:

From: Galileo Galilei & Johannes Kepler

To: Cosimo II de' Medici, Grand Duke of Tuscany

Re: Funds for a bigger telescope to measure stellar parallax

"If the Earth moves around the Sun, we should see stellar parallax!"

Grand Duke's advisors point out:

Referee 1) Che' idea pazzesca! (What a crazy idea !)

Referee 2) Even if the idea were correct, we don't know how far away the stars are; so there is no way to estimate the probability of success.

Referee 3) Null result doesn't prove or disprove anything.

Parallax: The Race to Measure the Cosmos[1]

- Centuries of failure…until 1838
- Friedrich Wilhelm Bessel

  using a Fraunhofer telescope

  61 Cygni: $\pi = 0.314''$

  ($\pi = 0.287''$)
- Followed closely by

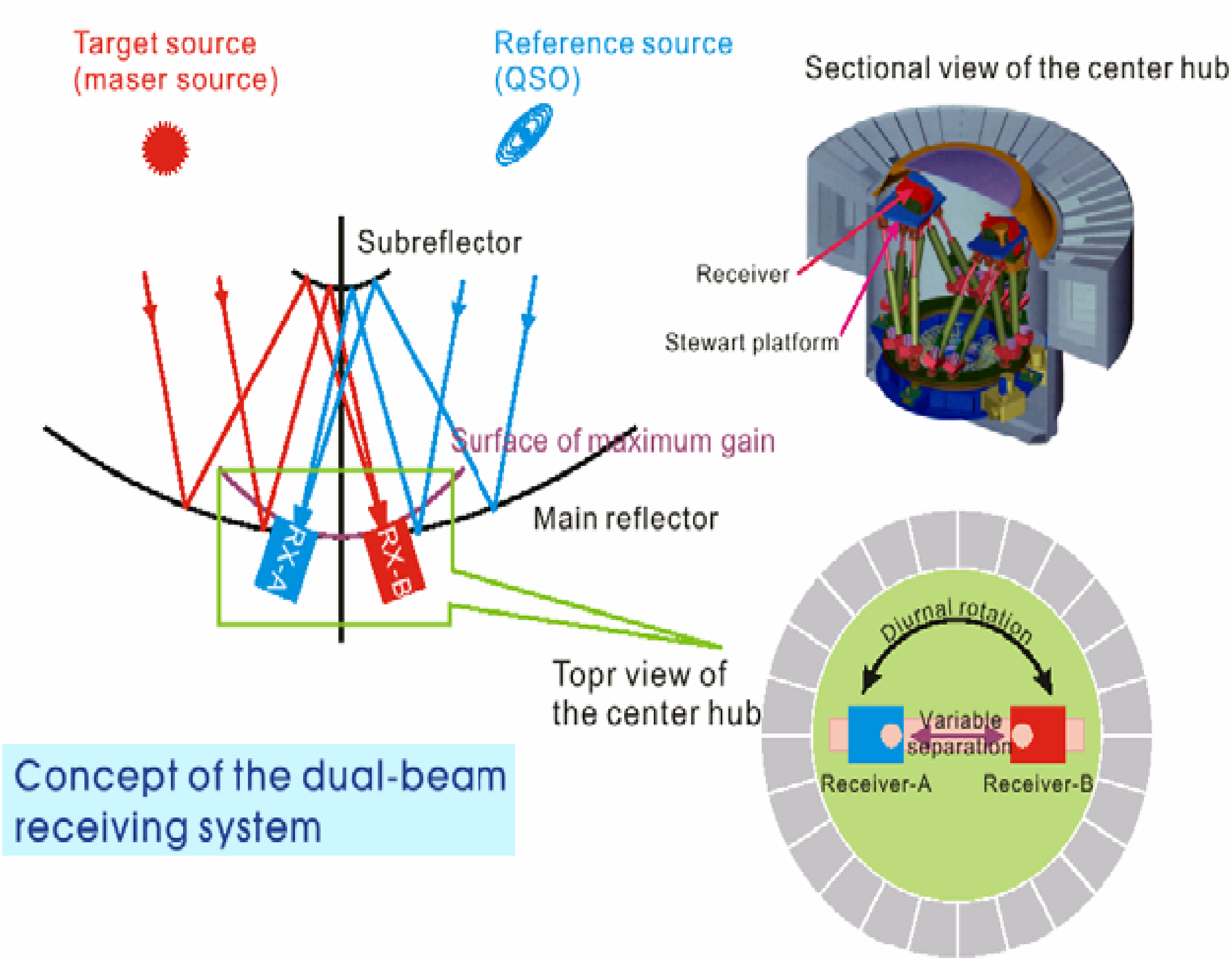
  Thomas Henderson (α Centuri)

  Wilhelm Struve (Vega)

Friedrich Wilhelm Bessel

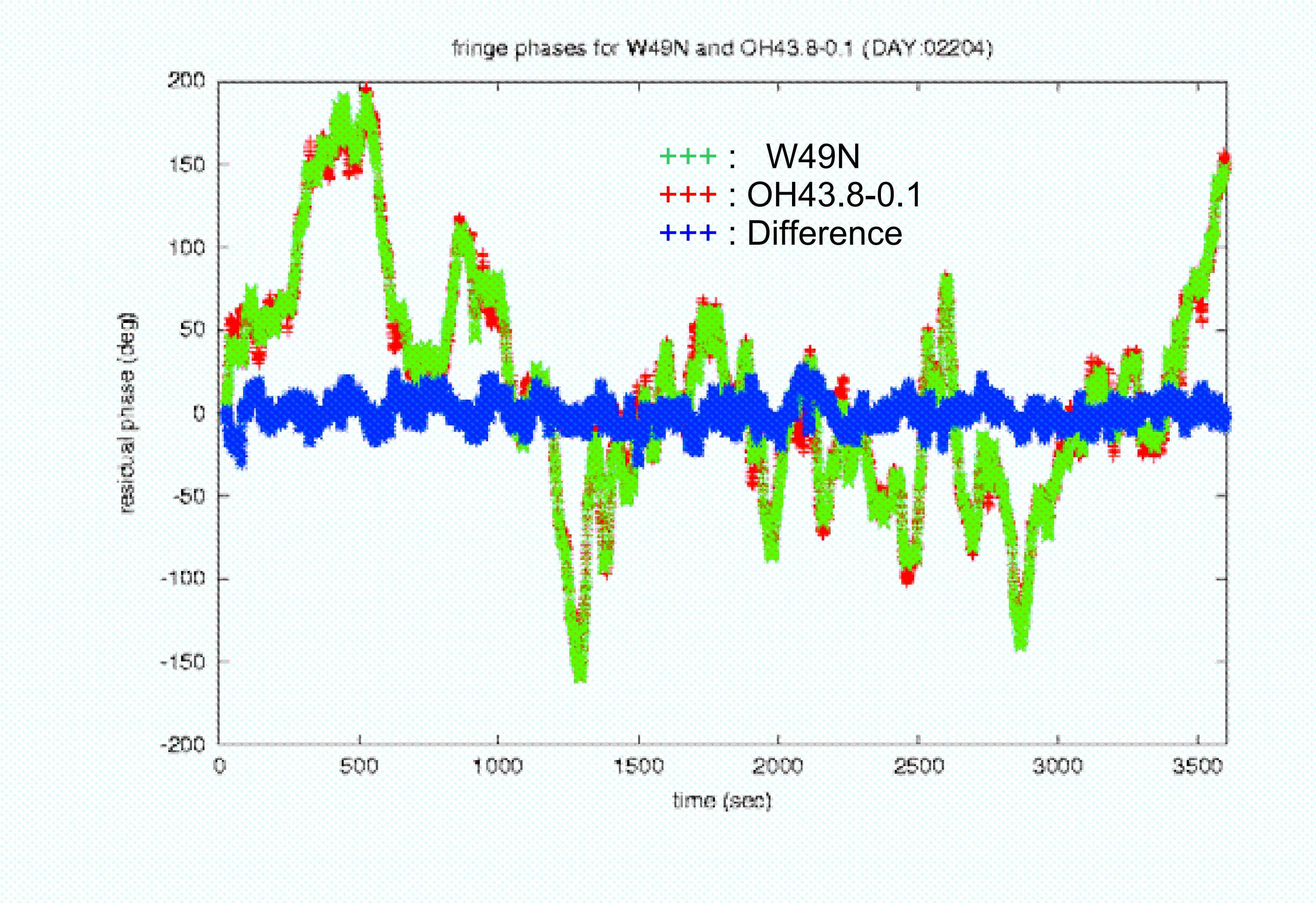
[1]Alan Hirshfeld 2001 (W.H. Freeman & Co., NY)

Kobayashi et al. 2008



VERA dual-beam phase fluctuations

Honma et al. 2003



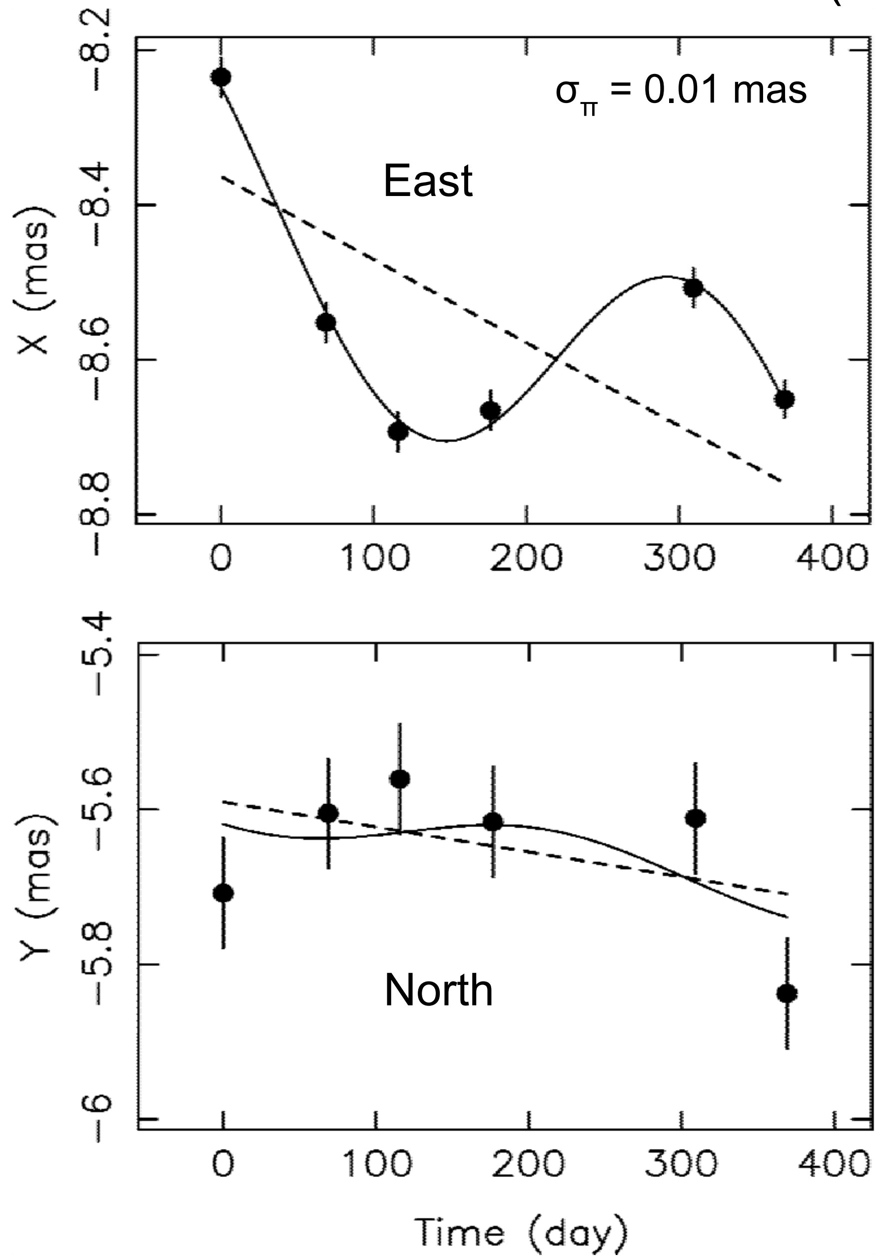
22 GHz Water VERA Parallax Measurement for source **S 269**

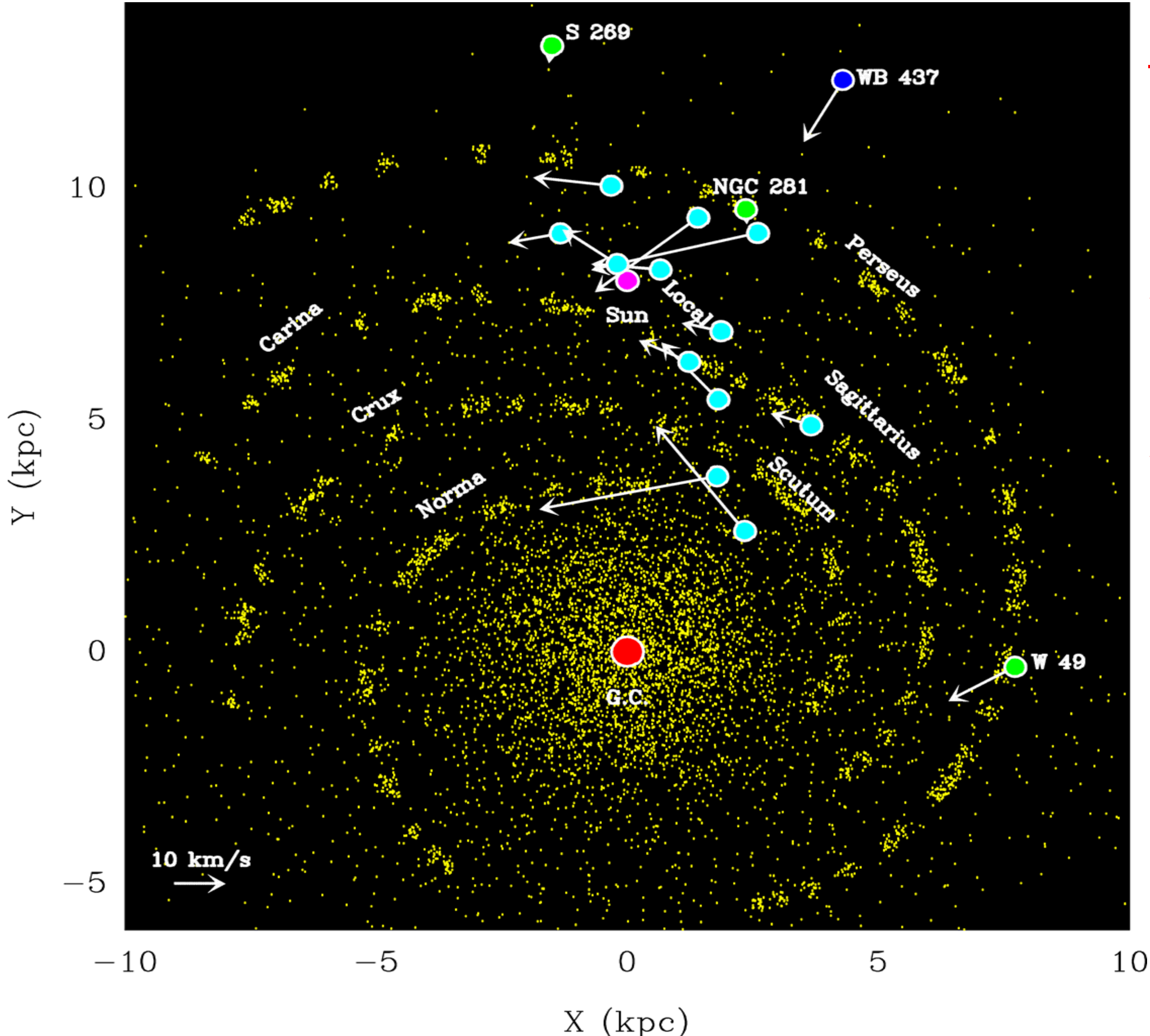
(Honma et al. 2007)

Parallax with proper motion:

single maser spot relative to

one background source.





Peculiar motions

Θ_0/R_0 = 29.5 km/s/kpc

(Reid & Brunthaler 2004)

Flat MW Rotation:

R_0 = 8.0 kpc (Reid 1993)

Θ_0 = 236 km s^{-1}

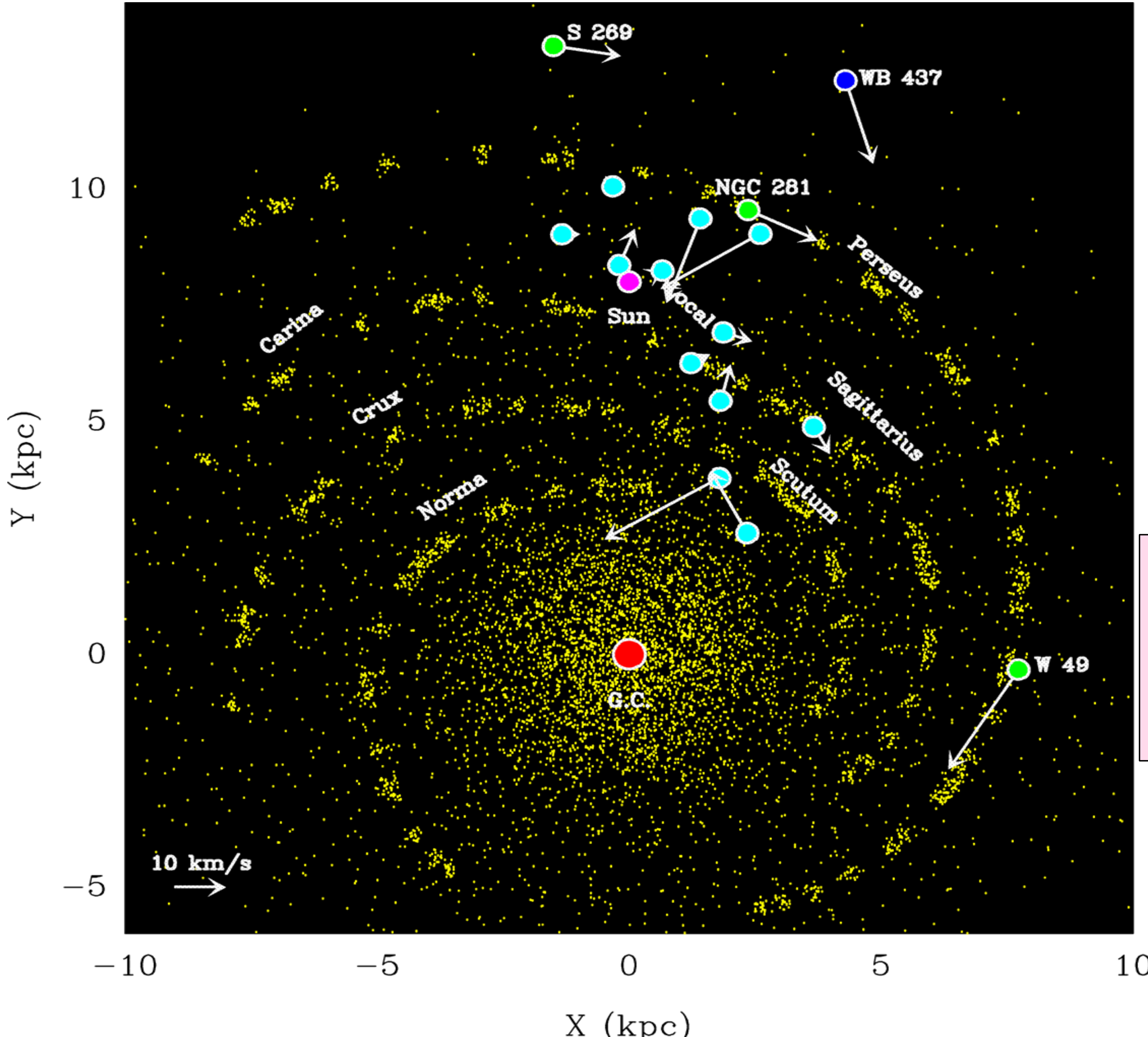
HIPP. Solar Motion:

U_0 = 10.0 km s^{-1}

V_0 = 5.25 km s^{-1}

W_0 = 7.16 km s^{-1}

- : 12 GHz VLBA
- : 22 GHz VERA
- : 22 GHz VLBA



Peculiar motions

Flat MW Rotation:

R_0 = 8.0 kpc

Θ_0 = 236 km s^{-1}

HIPP. Solar Motion:

U_0 = 10.0 km s^{-1}

V_0 = 5.25 km s^{-1}

W_0 = 7.16 km s^{-1}

Using fit solutions:

A_0 (GR) = 14 km s^{-1}

B_0 (GC) = 0 km s^{-1}

: 12 GHz VLBA

: 22 GHz VERA

: 22 GHz VLBA

Massive Star Birth

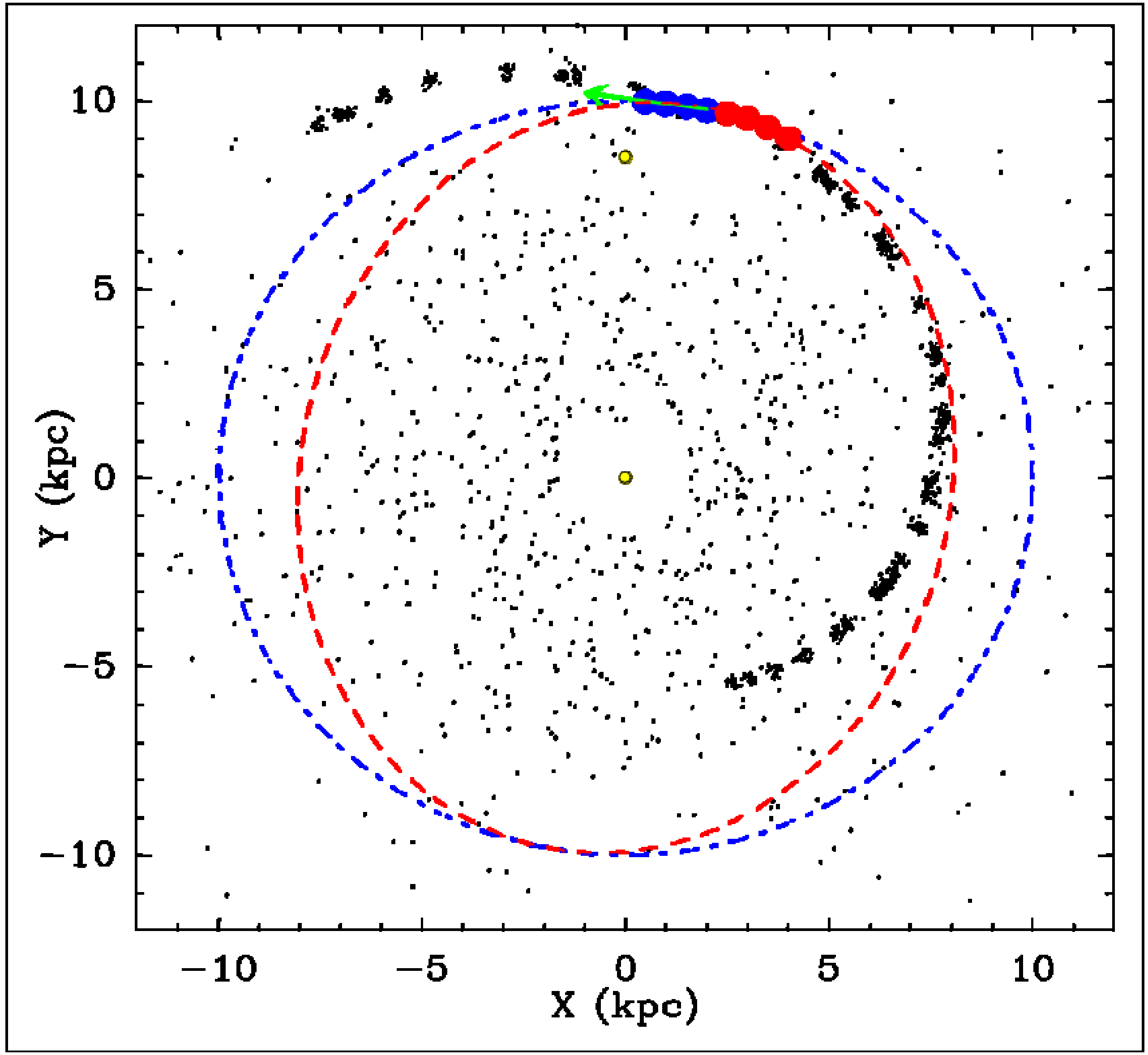
Possible Sequence:

1. Molecular cloud in circular orbit

2. Hit by Spiral shock

3. Goes into elliptical orbit (near apocenter)

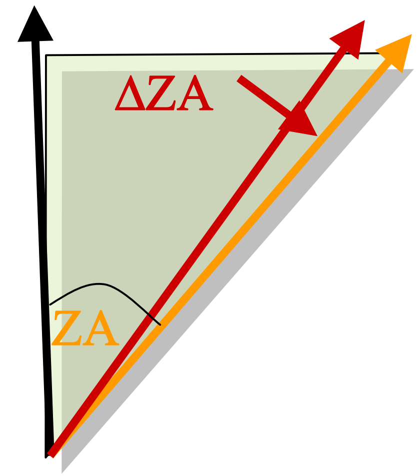
4. Compression triggers star formation.



Phase-referencing with **nodding** calibrators

Relative Atmospheric Delay Errors

$$\tau_A \approx \tau_0 \ \sec ZA$$



Difference between target and reference sources:

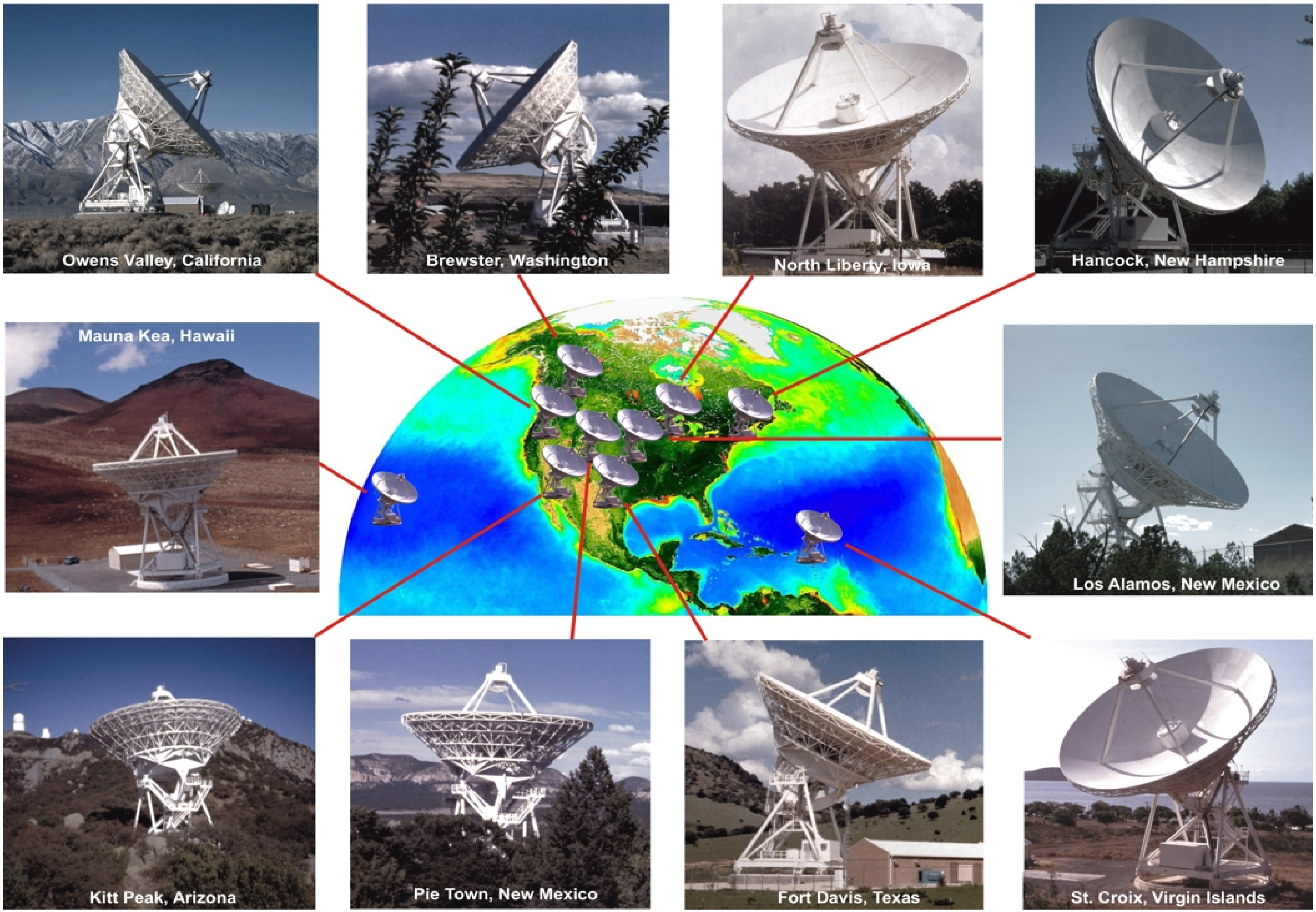
$$\Delta\tau_A = \left(\frac{\partial \tau_A}{\partial ZA}\right) \Delta ZA$$

$$\Delta\tau_A = \tau_0 \ \sec(ZA) \ \tan(ZA) \ \Delta ZA$$

Note: $\sec(ZA) \ \tan(ZA) \approx 3.5 \quad \text{for } ZA = 60°$

$\sec(ZA) \ \tan(ZA) \approx 8.0 \quad \text{for } ZA = 70°$

Very Long Baseline Array



VLBI **E**xploration of **R**adio **A**strometry