The Structure of the Milky Way and Dynamics of the Local Group from Micro-arcsecond Astrometry with the VLBA

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- Black Hole(s) in the Galactic Center
- Spiral Structure and Star Formation
- Local Group Dynamics

Micro-arcsec Astrometry with the VLBA

Comparable to GAIA & SIM

Fringe spacing:

$\theta_f \sim \lambda/D$ ~ 1 cm / 8000 km = 250 μas

Centroid Precision:

0.5 θ_f / SNR ~ 10 μas

Systematics:

path length errors ~ 2 cm (~2 λ)

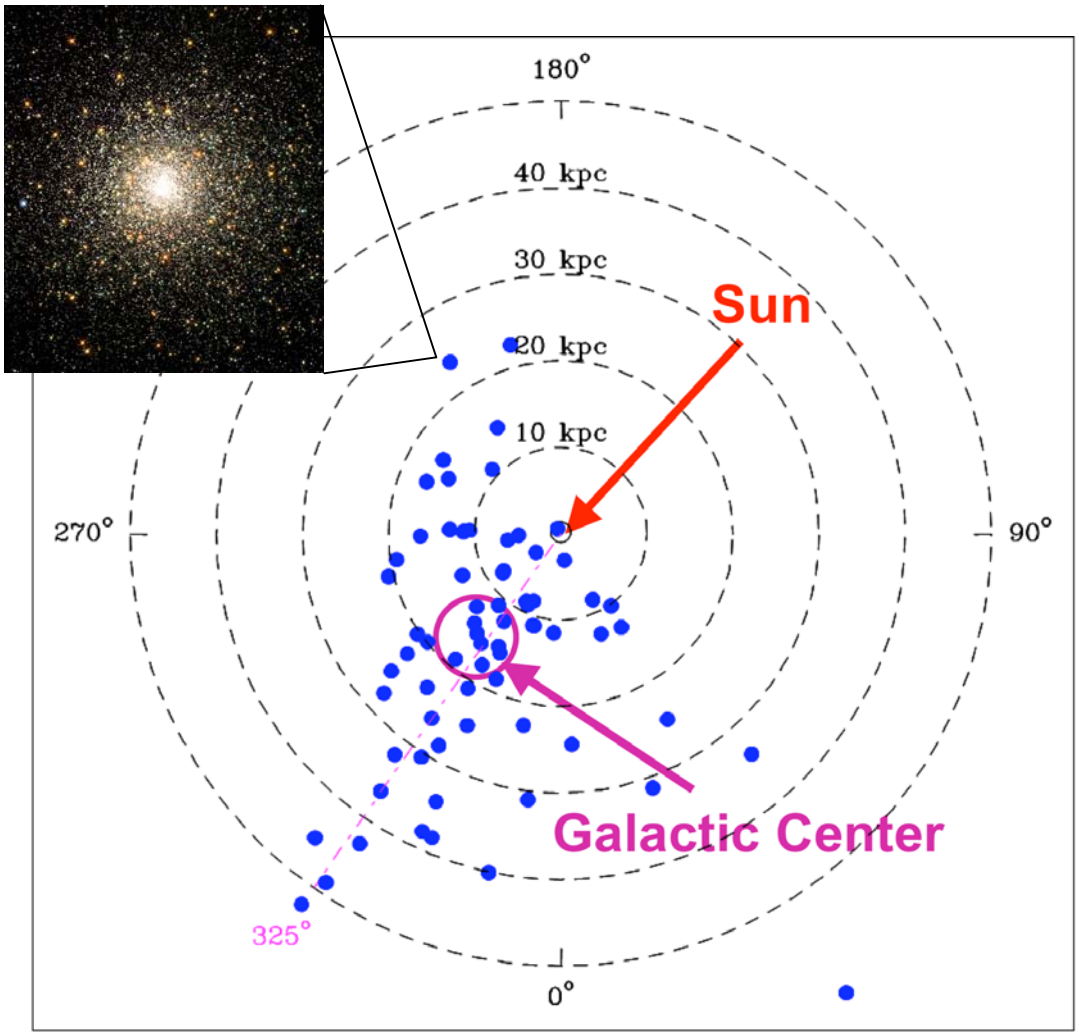
shift position by ~ $2\theta_f$ ~ 500 μas

Relative positions (to QSOs):

$\Delta\Theta$ ~ 1 deg (0.02 rad)

cancel systematics: $\Delta\Theta * 2\theta_f$ ~ 10 μas

Where are we in the Milky Way?



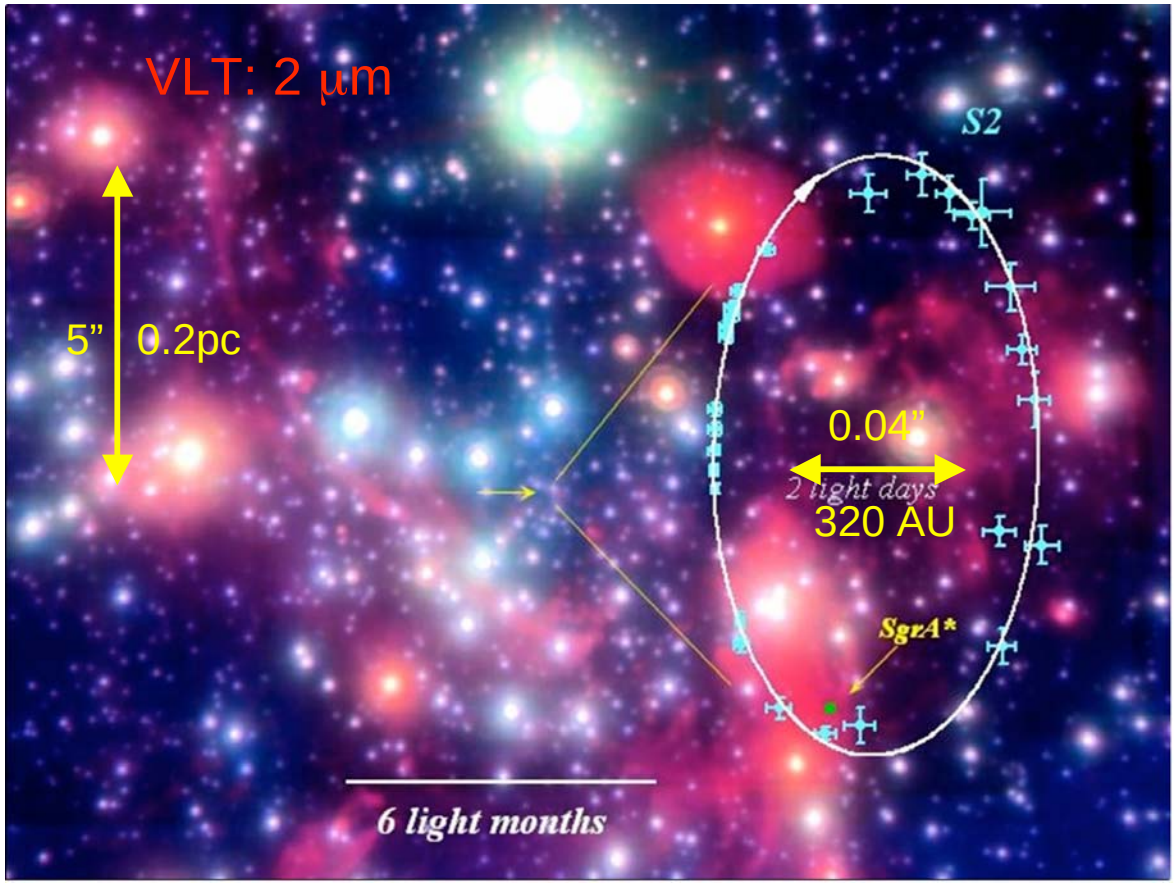
Harlow Shapley
(ca. 1920)

Globular Clusters projected on Galactic Plane based on Cepheid distances

Galactic Center Stellar Orbits

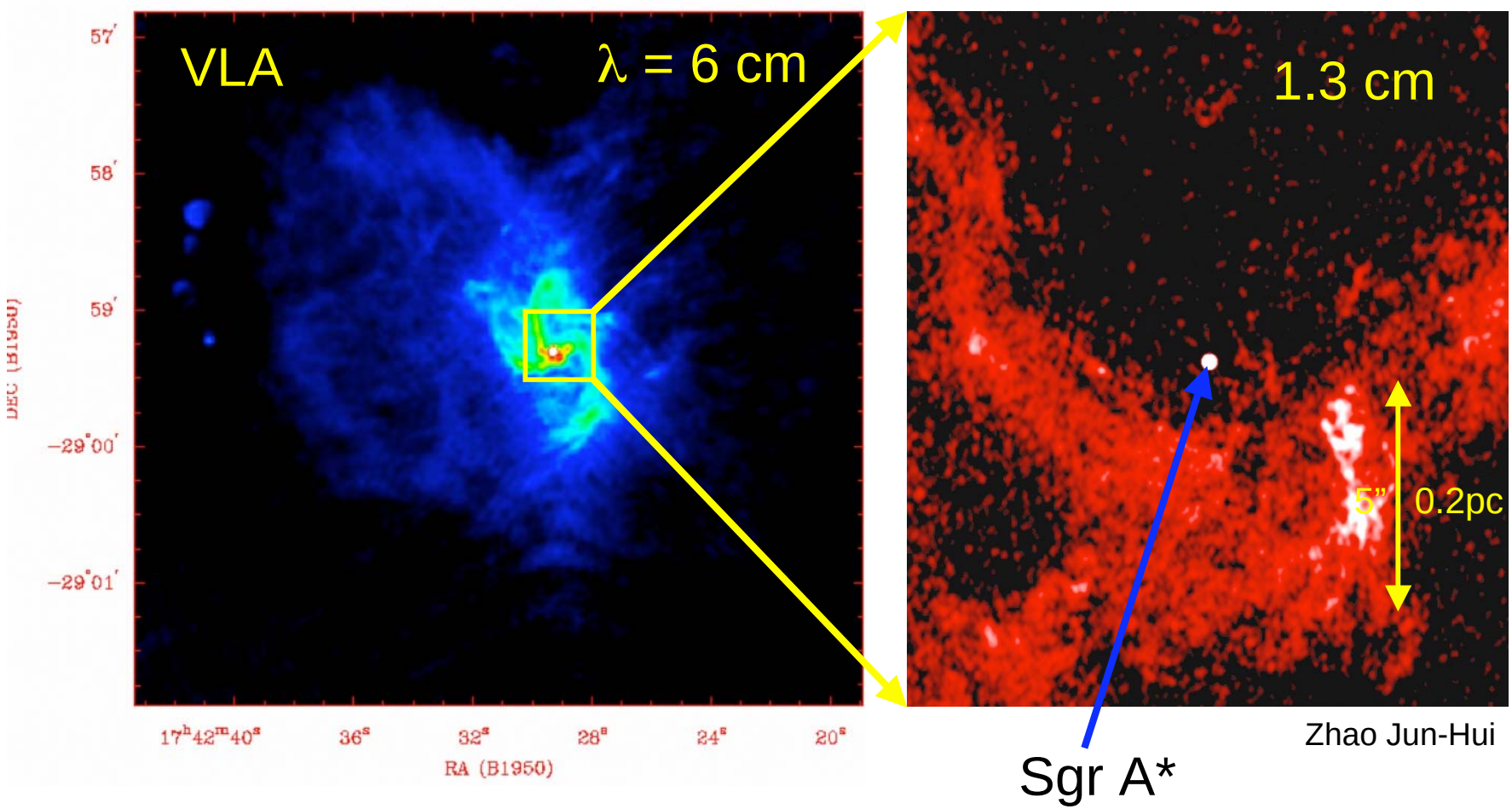
- $M = 4 \times 10^6\ M_{sun}$
- $R < 50$ AU
- Den. $> 10^{17}\ M_{sun}/pc^3$

Ghez et al / Genzel et al

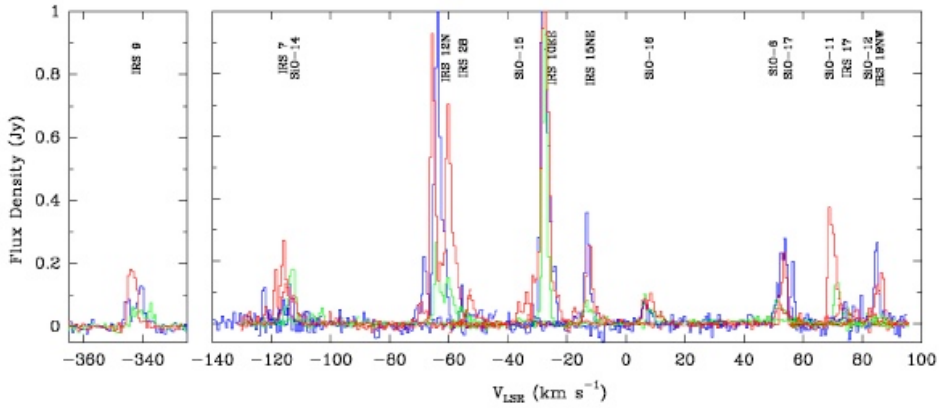


What can radio observations tell us?...

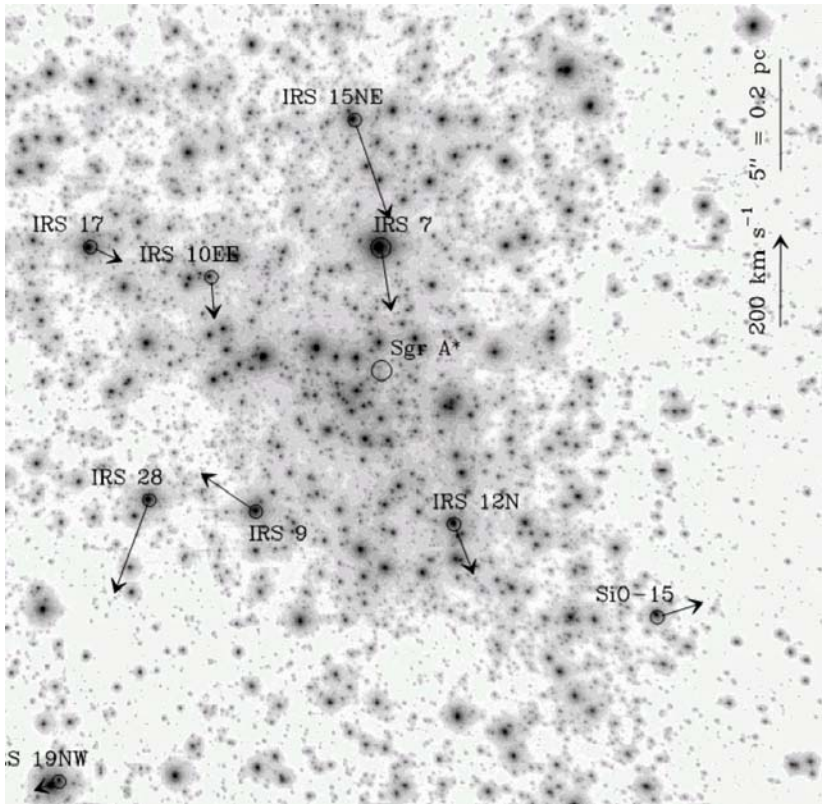
Where is the Galactic Center?



Where is the Galactic Center?

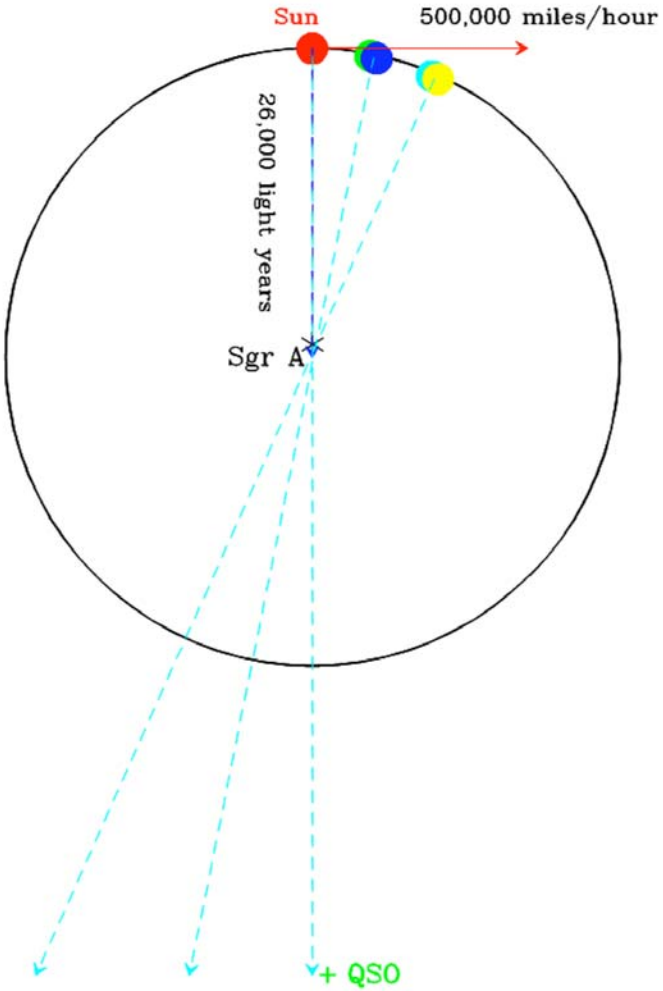


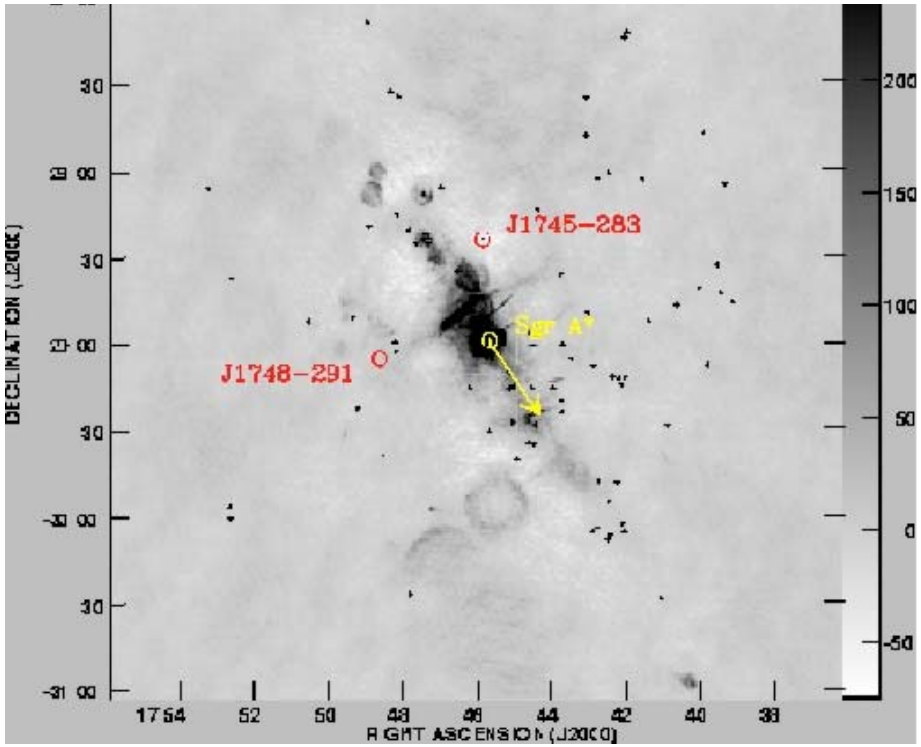
Combined IR + Radio astrometry shows Sgr A* at focal position of stellar orbits (+/-3 mas)



All stars there move very fast, but how fast does Sgr A* move?

Sgr A*'s Proper Motion





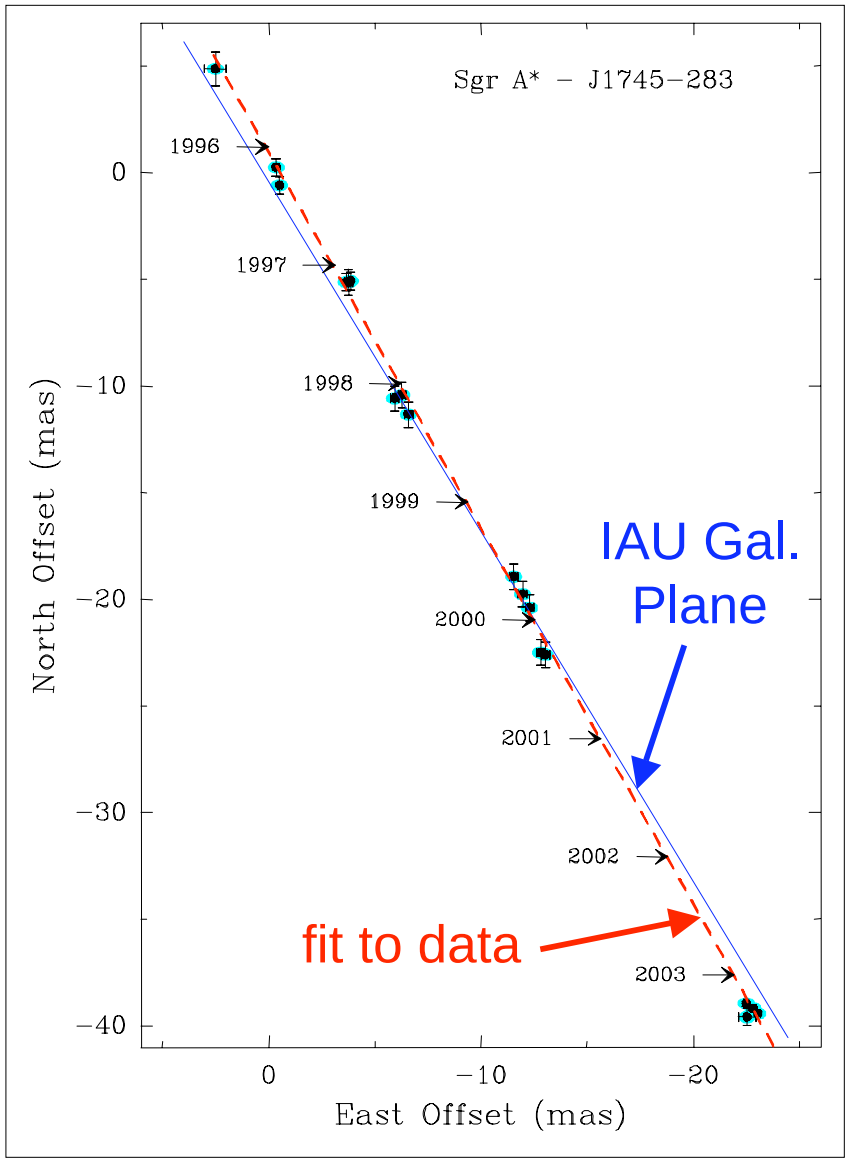
Proper Motion of Sgr A*

- Parallel to Galactic Plane:
  6.379 (+/- 0.024) mas/yr ➔
  Θ_o/R_o = 29.5 km/s / kpc

- Perpendicular to Gal. Plane:
  7.2 km/s motion of Sun

- Could re-define Galactic Plane
  Now: HI & Sun in plane
  New: LSR orbit & Sgr A* in plane

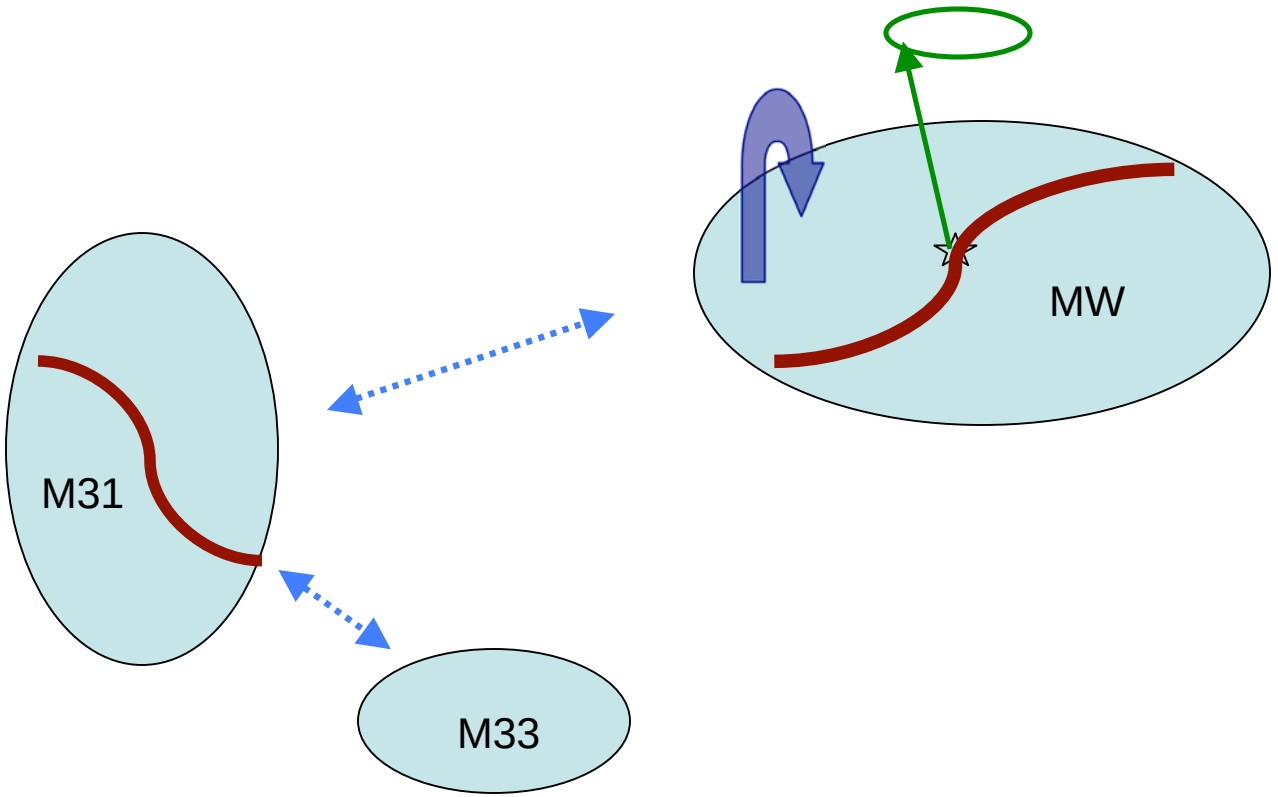
- Sgr A*'s motion ⊥ to Gal. Plane
  -0.4 +/- 0.9 km/s !



Reid & Brunthaler (2004)

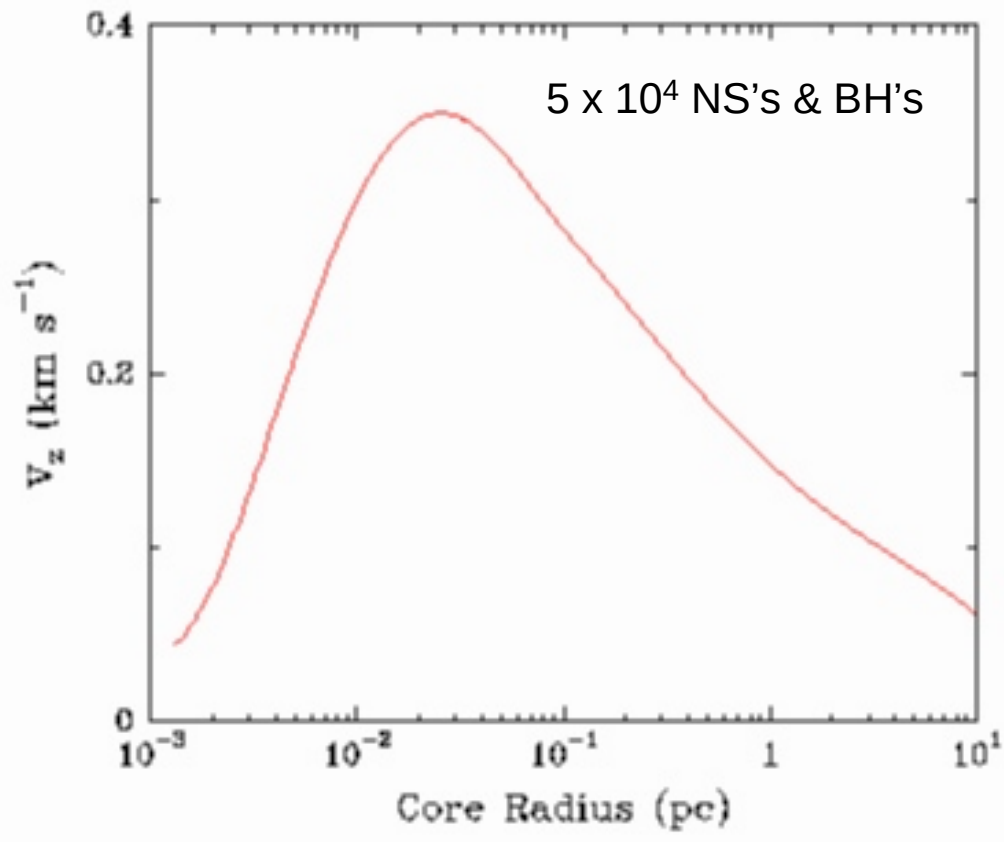
Milky Way “Tumbling”

- Local Group torques -> spin axis precession
- Expected “tumbling” speed ~ R_o H_o ~ 0.6 km/s



Cluster of Dark Stellar Remnants?

- Massive remnants sink to GC
- Stellar orbit sol'ns allow ~10% of enclosed mass in remnants
- Contributes to Sgr A*s motion



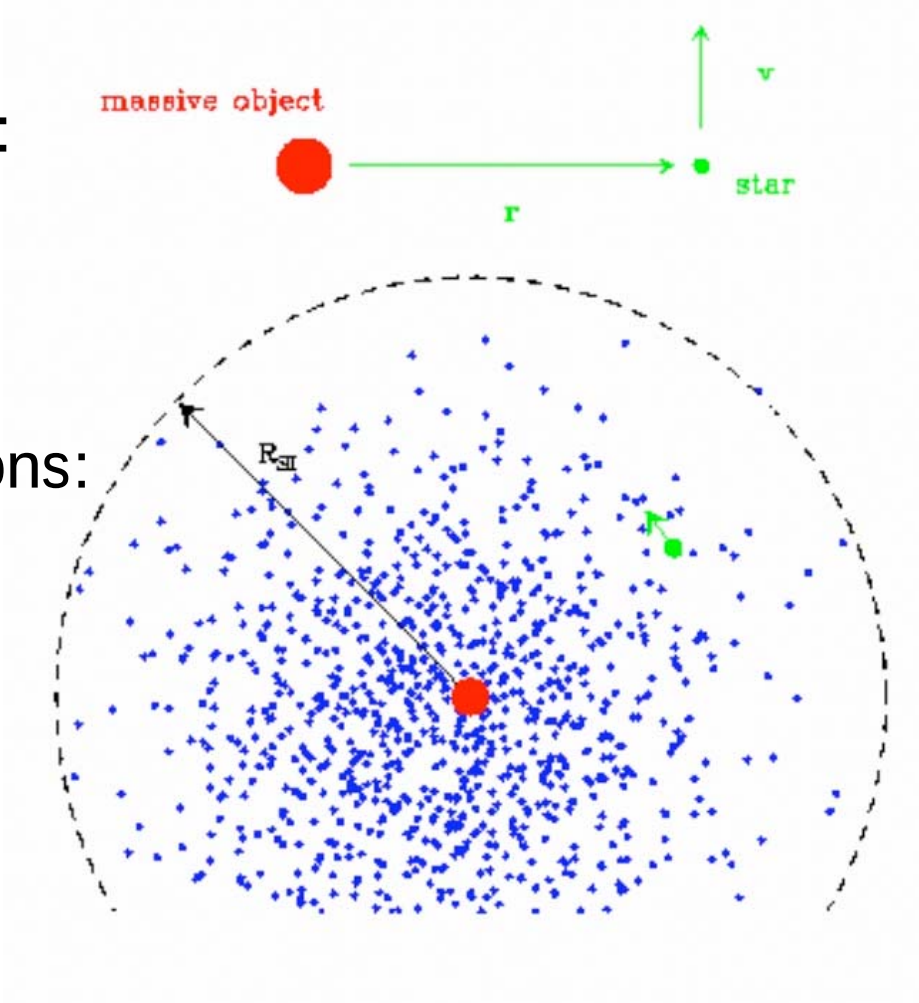
Stars orbiting Sgr A*

- Star orbiting a massive object:

$$MV = mv$$

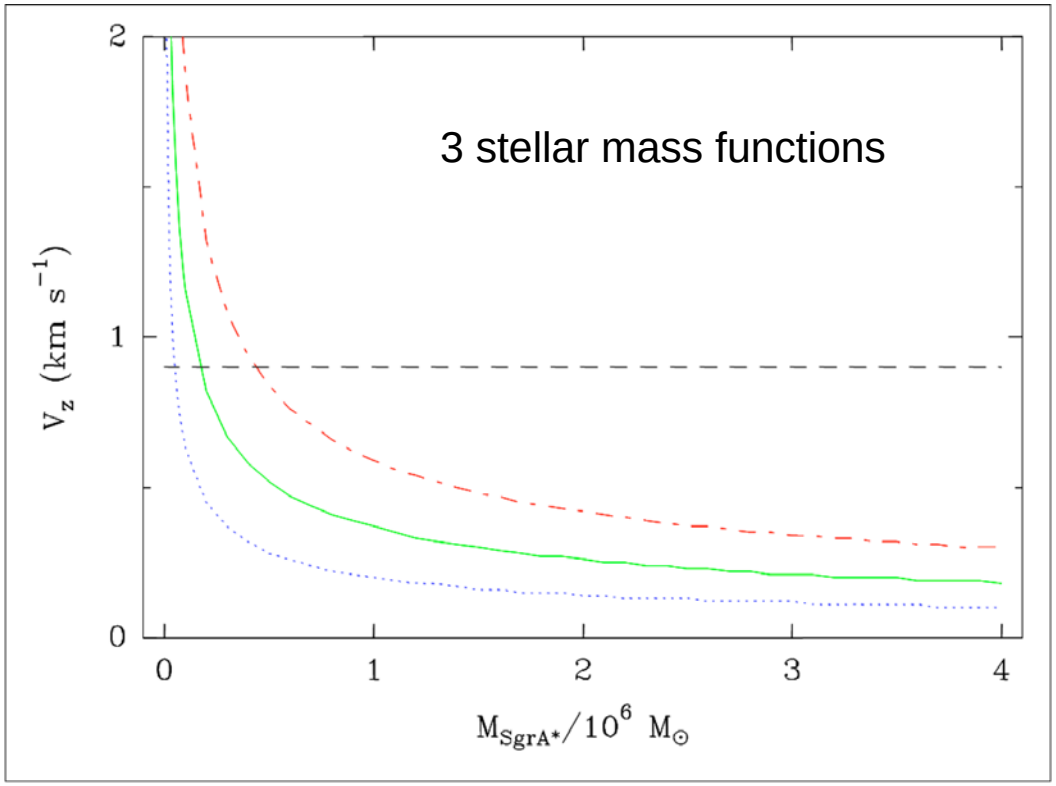
- Many stars...random fluctuations:

$$MV^2 \sim mv^2$$



SMBH “Brownian motion”

- ~10^6 stars orbiting Sgr A*
- Calculate orbit segments
- Stellar c.o.m. changes
- Sgr A* moves to keep total system c.o.m. constant



Maximum likelihood: $M_{SgrA*} > 0.4 \times 10^6 M_{sun}$

Latest Results: Sgr A* Proper Motion

IR Stellar Orbits:

$M_{IR} \sim 4 \times 10^6 M_{sun}$

$R < 50$ AU

Radio Observations:

Sgr A* motionless ➔

$M > 10\%$ of M_{IR}

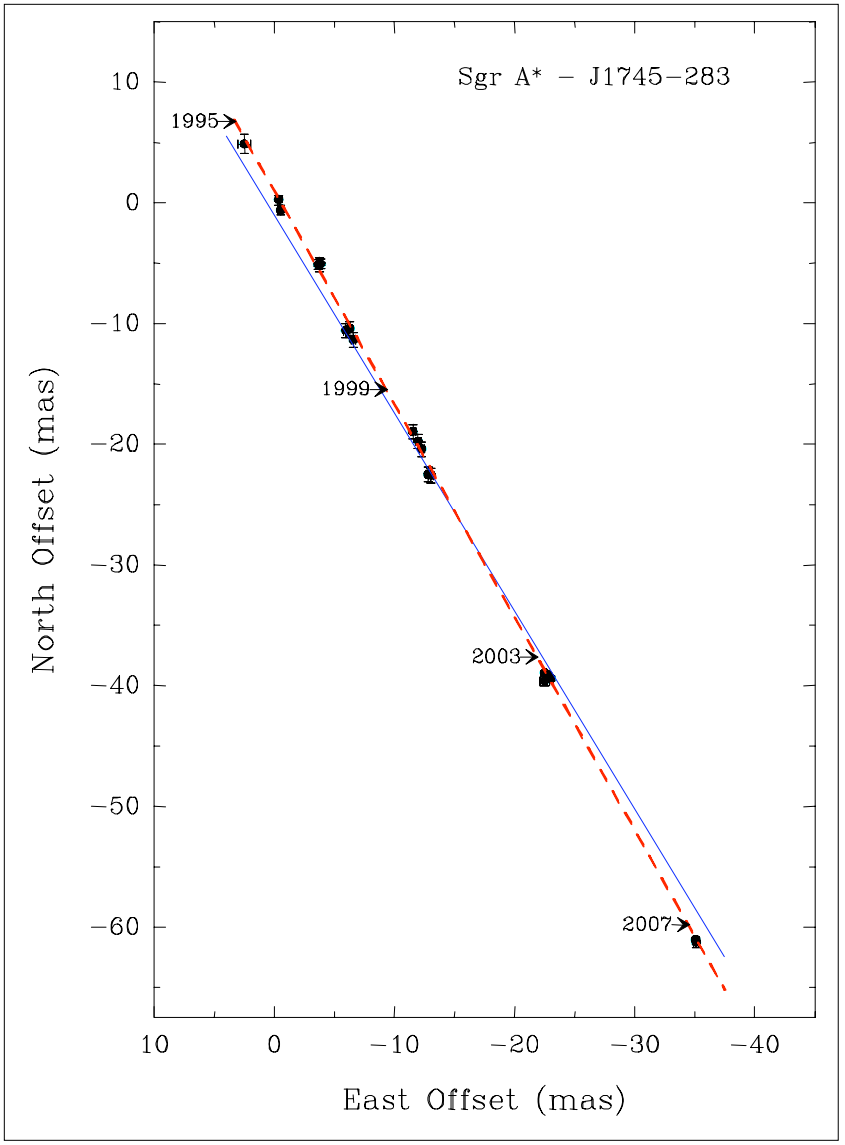
Observed size:

$R < 0.5$ AU

IR + Radio data combined:

- Dark mass = luminous source
- Density > $10^{22} M_{sun}/pc^3$

Overwhelming evidence for a Super-Massive Black Hole



Must Sgr A* be a SMBH?

Object	Density (M_{sun}/pc^3)	Method	Mass within Radius (M_{sun})	
M 87	10^6	HST	$3x10^9$	7 pc
NGC 4258	10^{10}	VLBA : H_2O	$4x10^7$	0.1 pc
Sgr A*	$>10^{17}$	IR Star orbits	$4x10^6$	50 AU
Sgr A*	$>10^{22}$	VLBA p.m.	$>4x10^5$	0.5 AU
SMBH	10^{24}	$3R_{Sch}$	$4x10^6$	3*0.08 AU

$3R_{Sch}$ = 30 μas @ 8 kpc

VLBI (JCMT/SMA-ALMA-LMT-SMT-CARMA) @ 0.8 mm ➔20 μas

Fringes: Hawaii→Arizona @ 1.3mm (60 μas) !

(Doeleman et al 2008 Nature 455 78)

Intermediate mass BHs in GC?

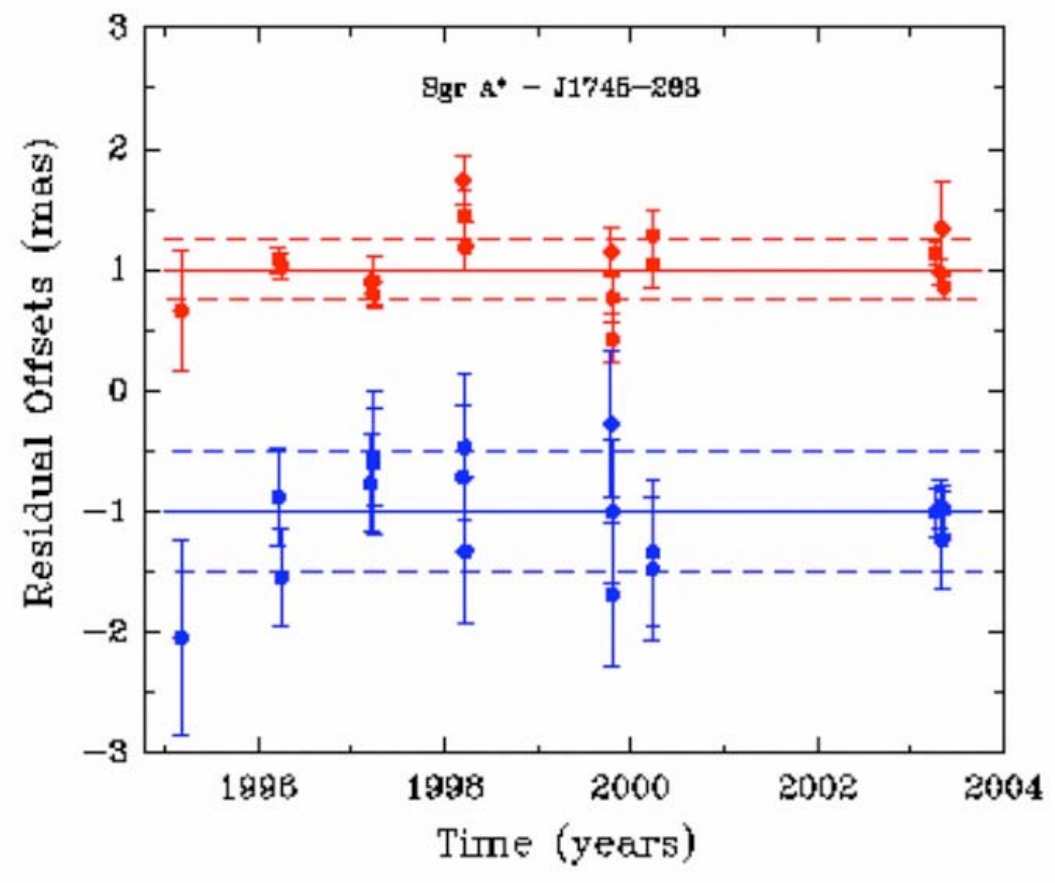
- "Paradox of stellar youth"
- Dense cluster (IMBH) sinking by dynamical friction (Hansen & Milosavljevic; Yu & Tremaine 2003)
- Would move Sgr A*

  long period orbit … V_z

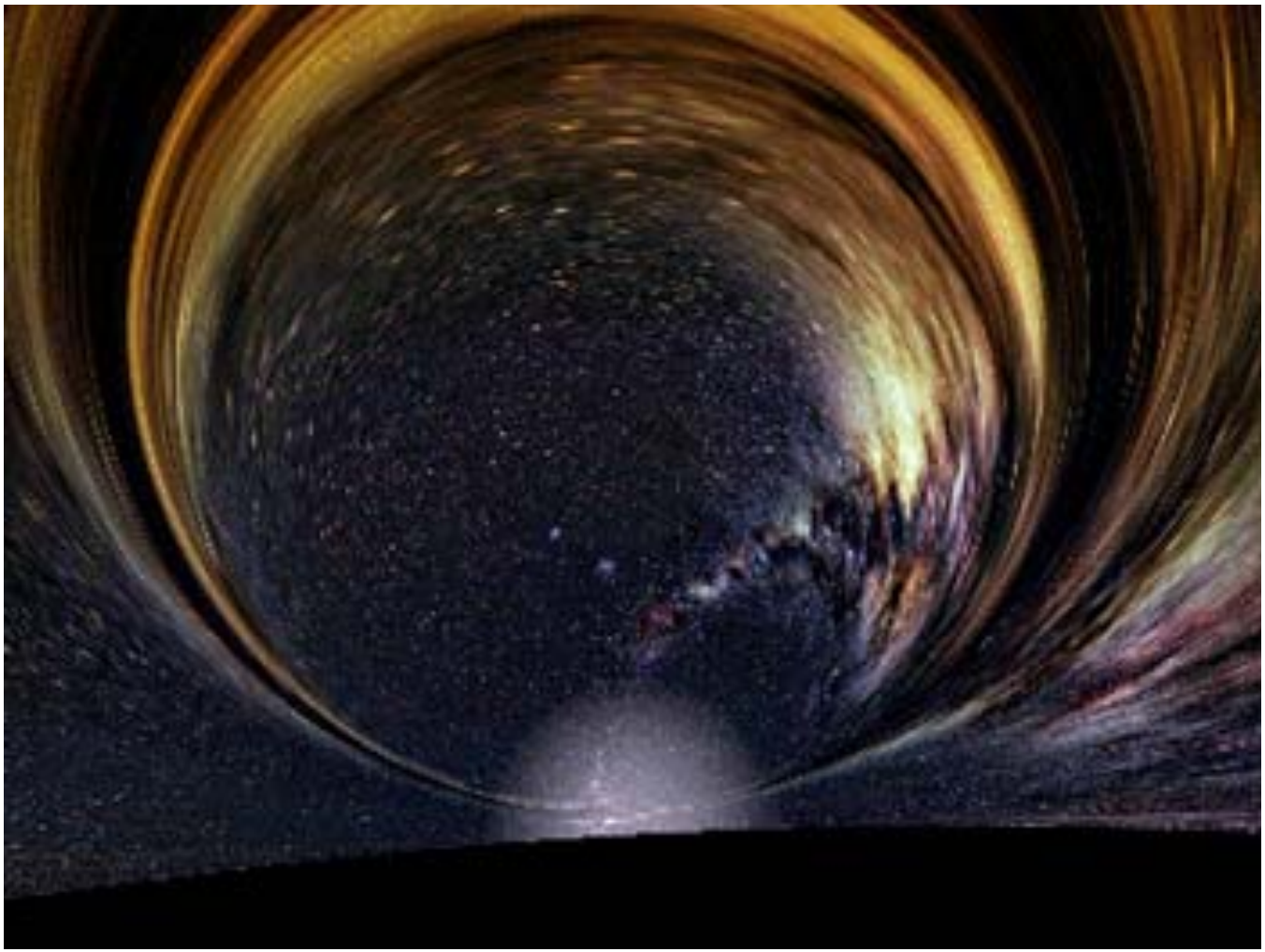
  short period orbit… "noise"
- Exclude IMBH > 10^4 M_{sun}

  $10^3 < r < 10^5$ AU

  (eg, IRS 13 cluster)

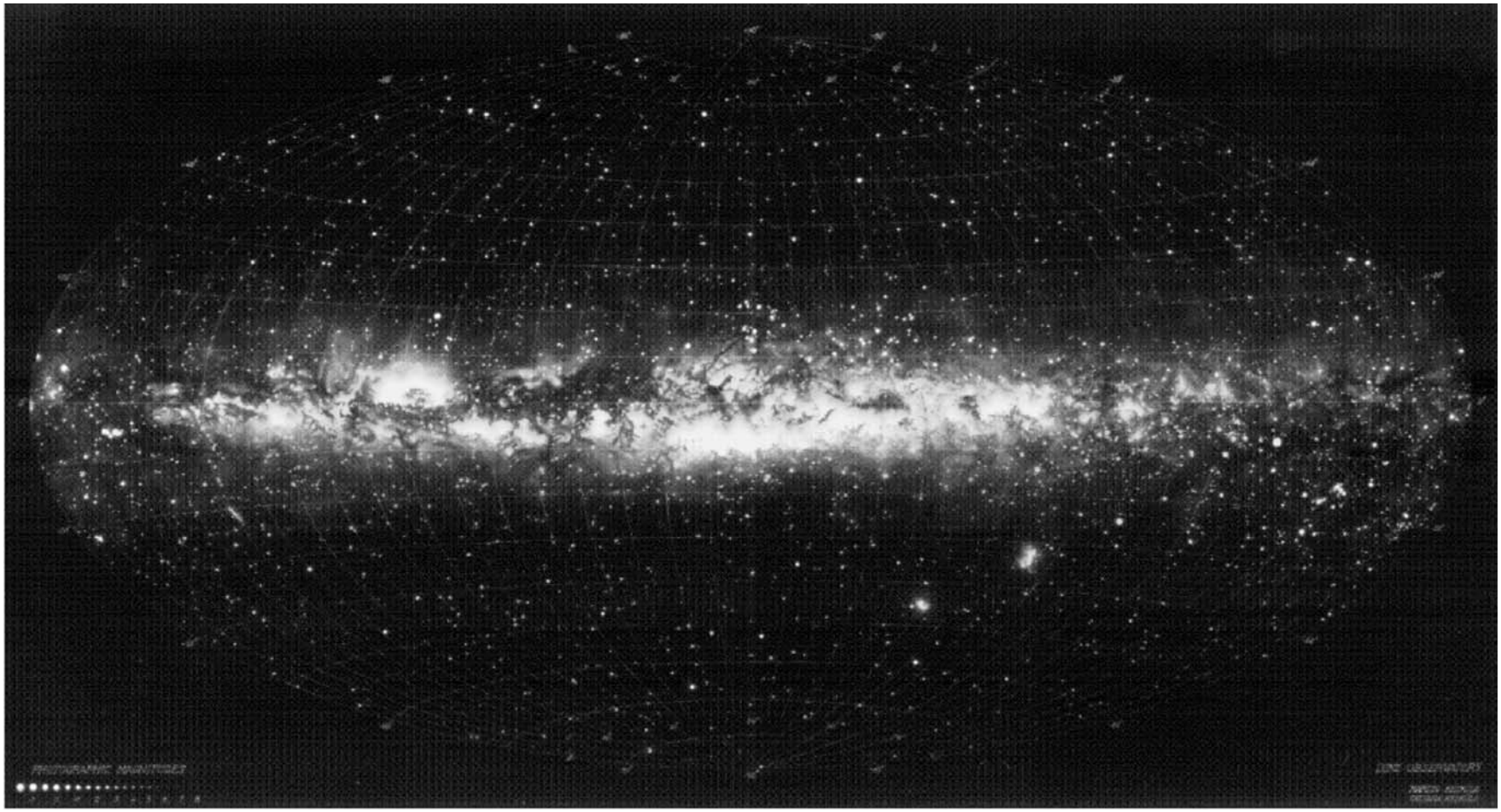


Milky Way Viewed From Inside Sgr A*



Thomas Lucas Productions, Inc. (www.tlproductions.com)

Our Milky Way Galaxy



But what does the Milky Way look like?

Need to measure distances to young stars which trace spiral arms…

Parallax: The Race to Measure the Cosmos[1]

- Starting ~1600, stellar parallax was "Holy Grail"

  1) Prove heliocentric cosmology

  2) Determine size of "universe"

- "Who's who" of astronomers tried, eg,

  Tycho Brahe, Galileo, Hooke,
  Bradley, Herschel …

- Fraunhofer built world's best telescope for Bessel who measured

  61 Cygni: π = 0.314"

  (π = 0.287")

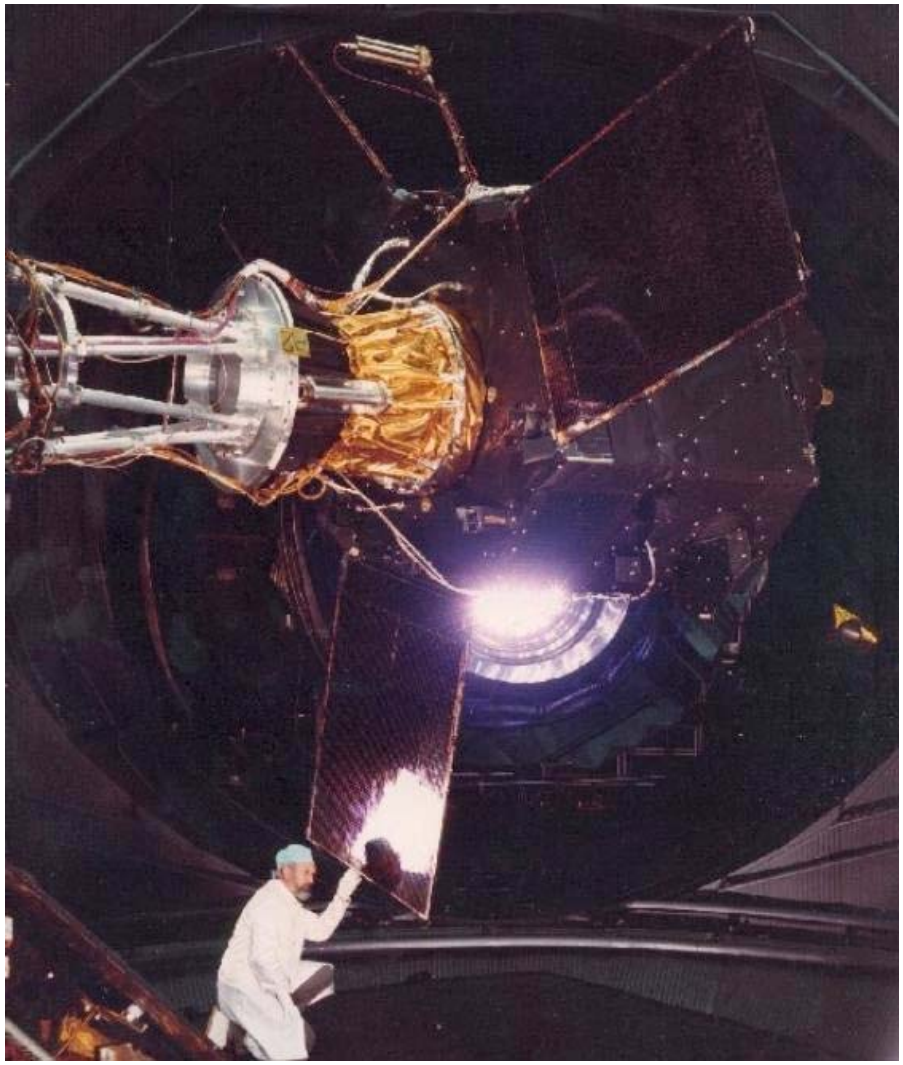
Joseph Fraunhofer (ca. 1820)

Friedrich Wilhelm Bessel (1838)

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

HIPPARCOS

(HIgh Precision PARallax COllecting Satellite)



(Perryman et al 1997 A&A 323 49)

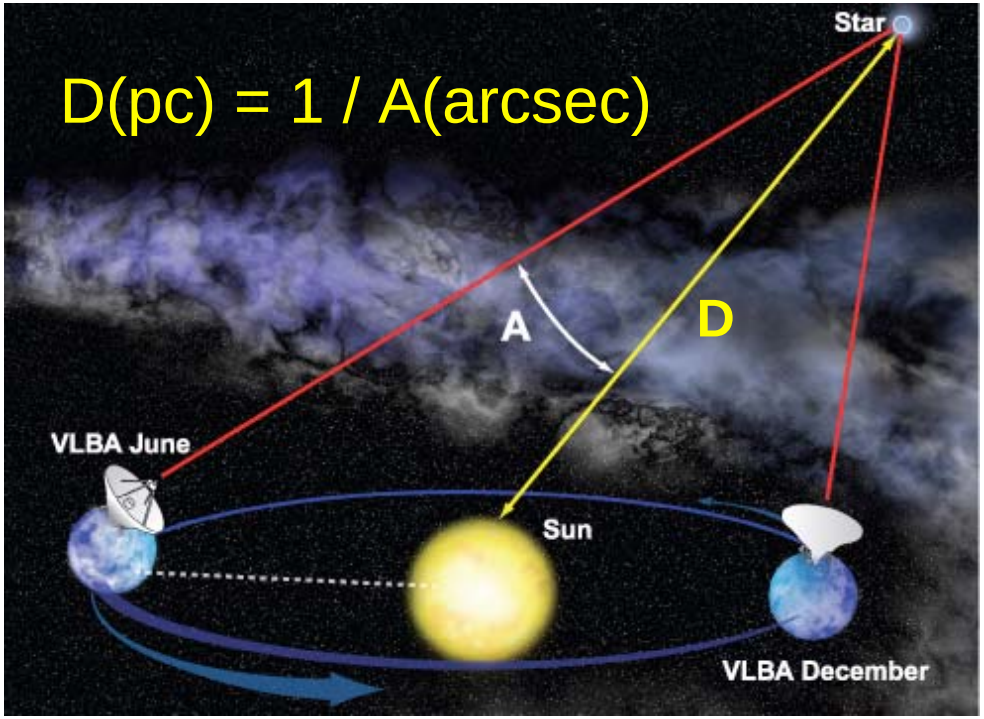
118,000 stellar parallaxes

σ_π ~ 0.001 arcsec

10% accuracy at 0.1 kpc…

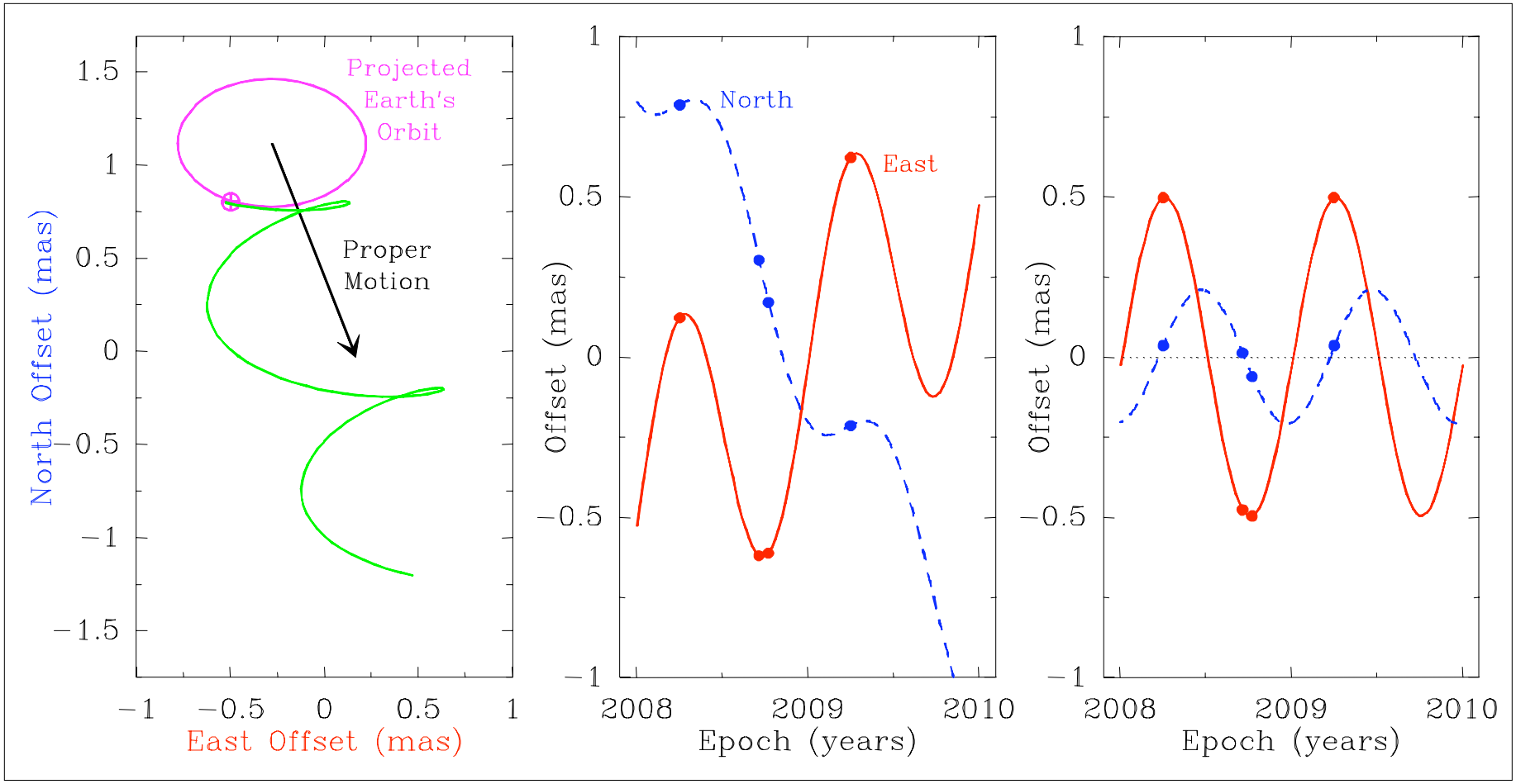
Mapped solar neighborhood, but can't give structure of Milky Way

Stellar (Annual) Parallax

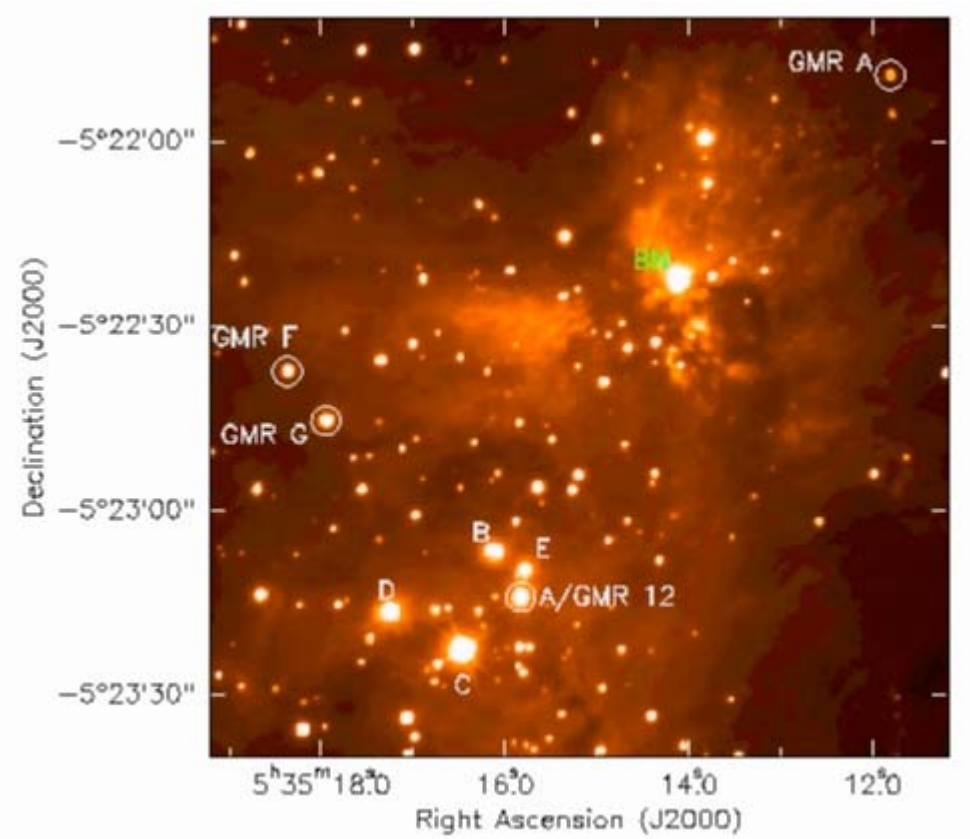


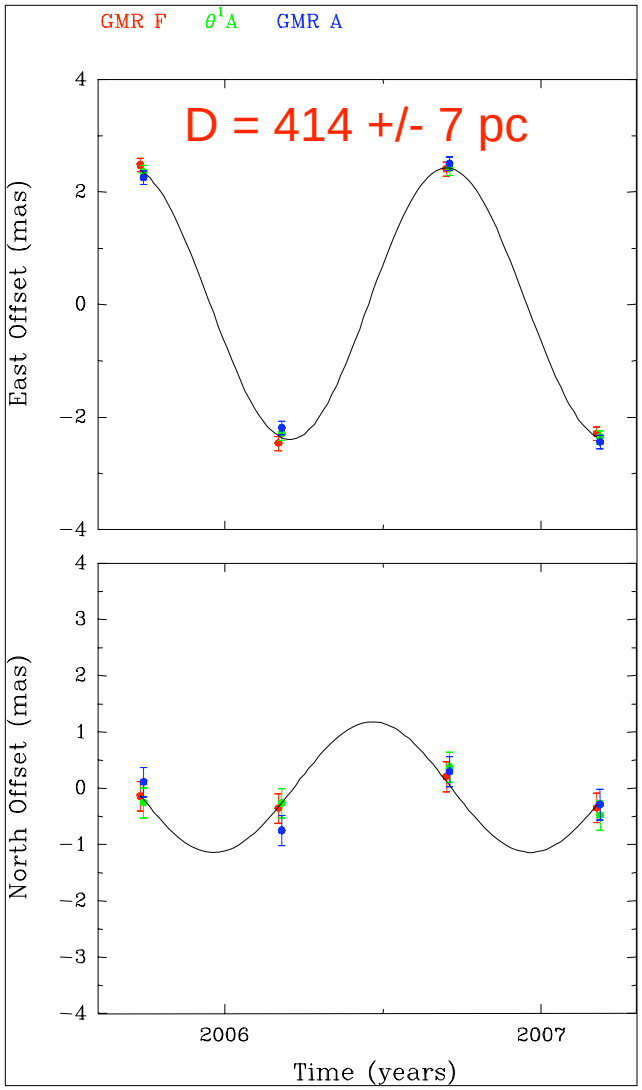
- Use masers associated with young massive stars
- Measure position shifts vs. background quasars
- Obtain distance and 3-dimensional motions

Parallax 1.01



Orion Nebular Cluster Parallax





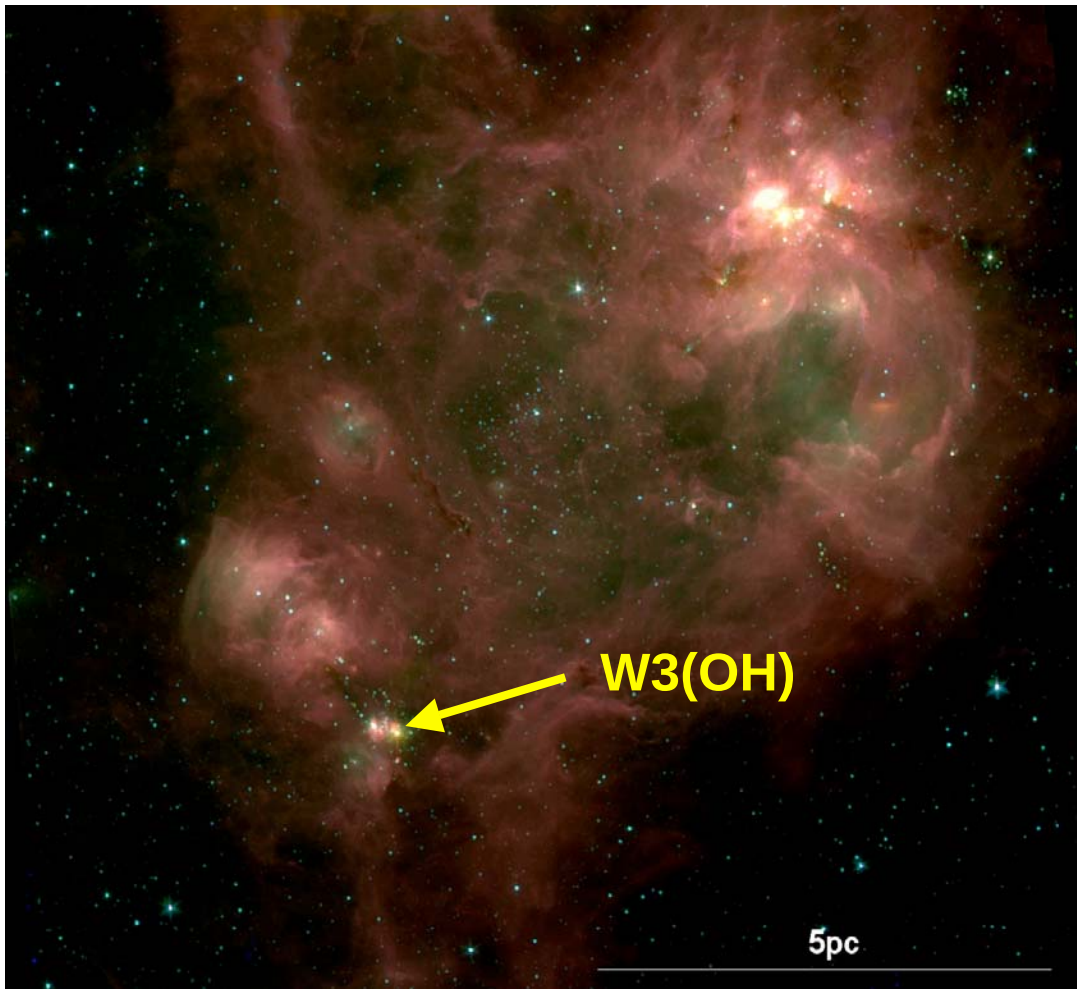
389 +/- 22 pc Sandstrom et al (2007)

437 +/- 19 pc Hirota et al (2007)

414 +/- 7 pc Menten et al (2007)

Menten, Reid, Forbrich & Brunthaler (2007)

Milky Way Parallaxes



T. Megeath (Spitzer Space Telescope)

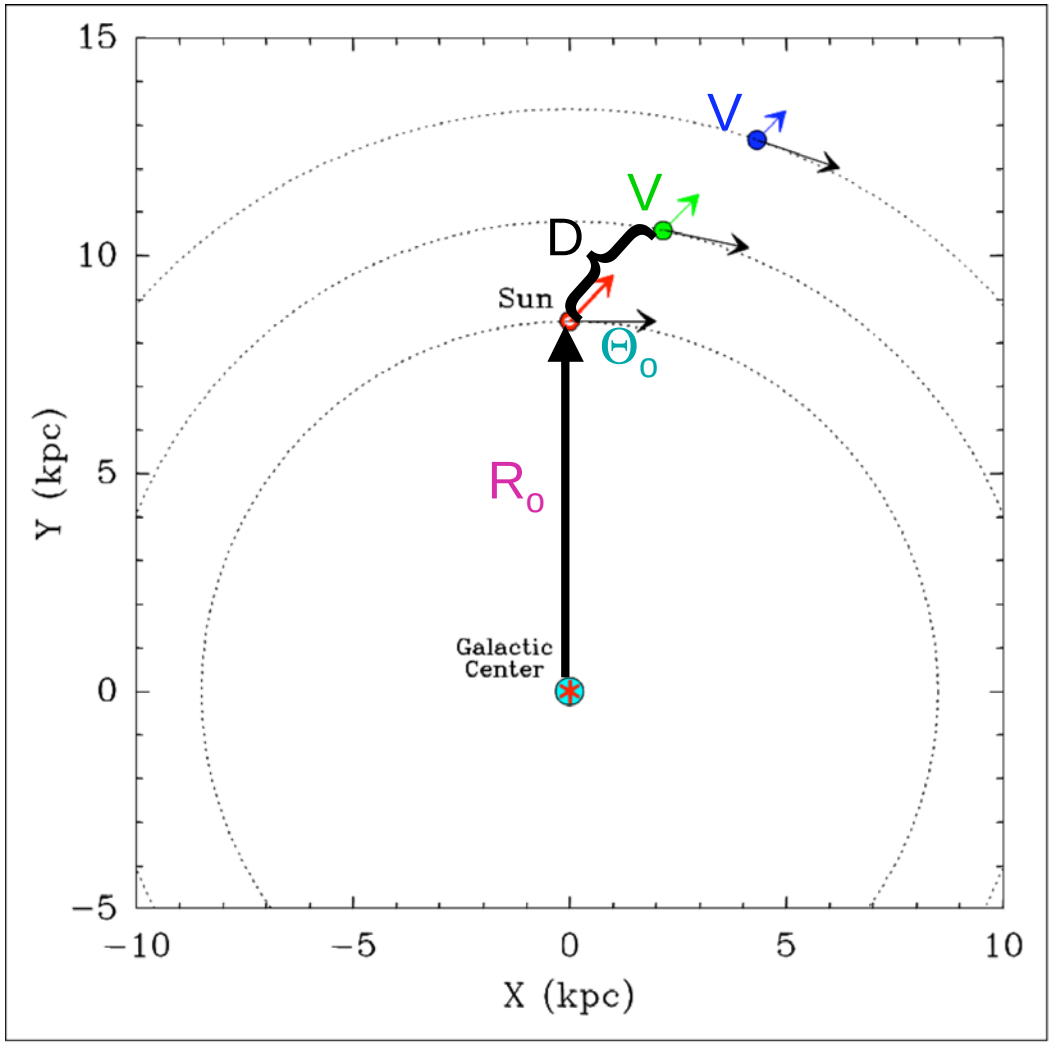
Distance estimates:

Kinematic = 4.3 kpc

Photometric = 2.2 kpc

(R. Humphreys 1970's)

Kinematic Distances



Doppler shift:

$V_{Dop} = V - V_{sun}$

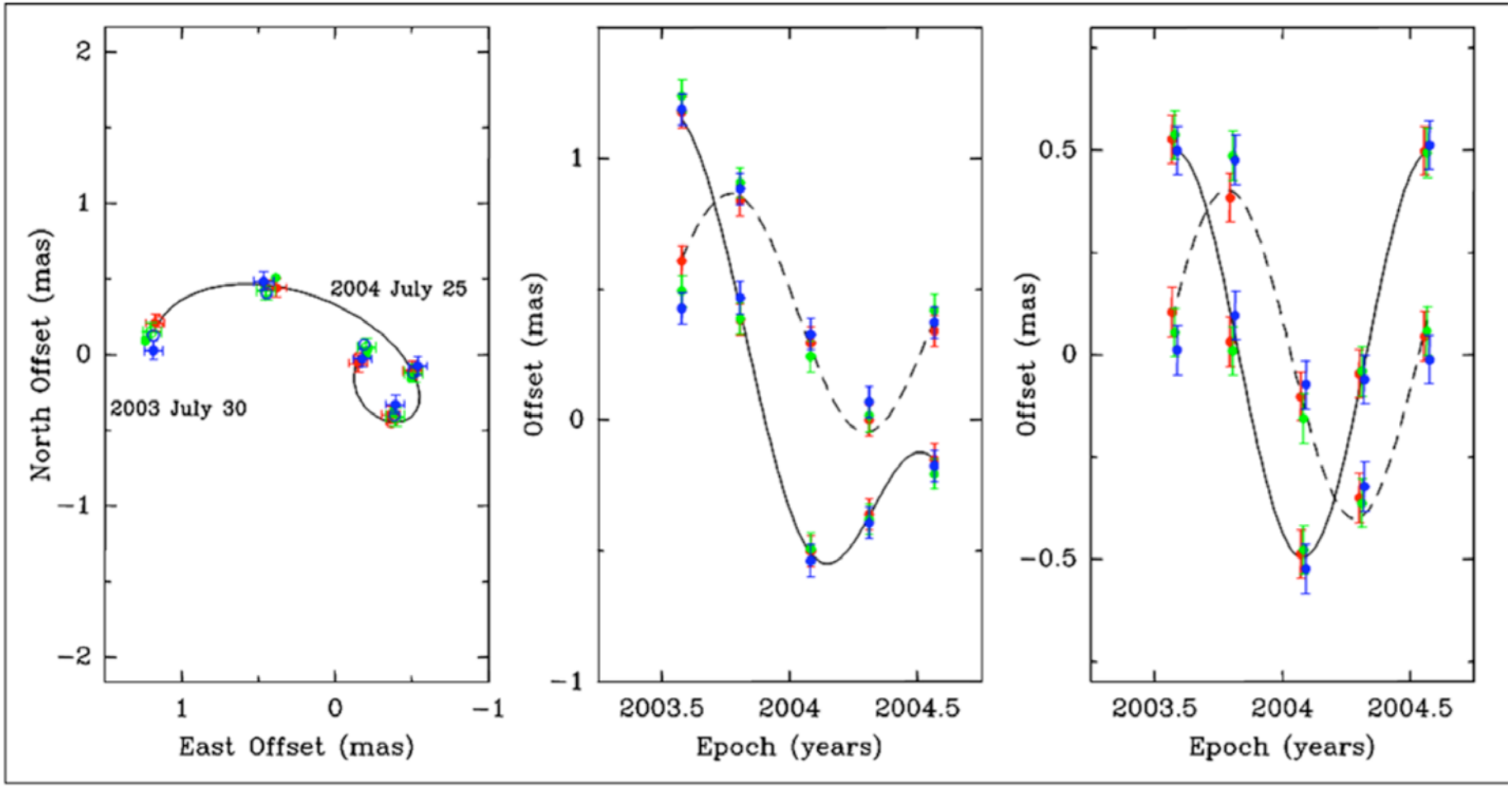
Model (Gal. Rotation):

$V_{mod}(R_o, \Theta_o, l, D)$

Adjust D to match

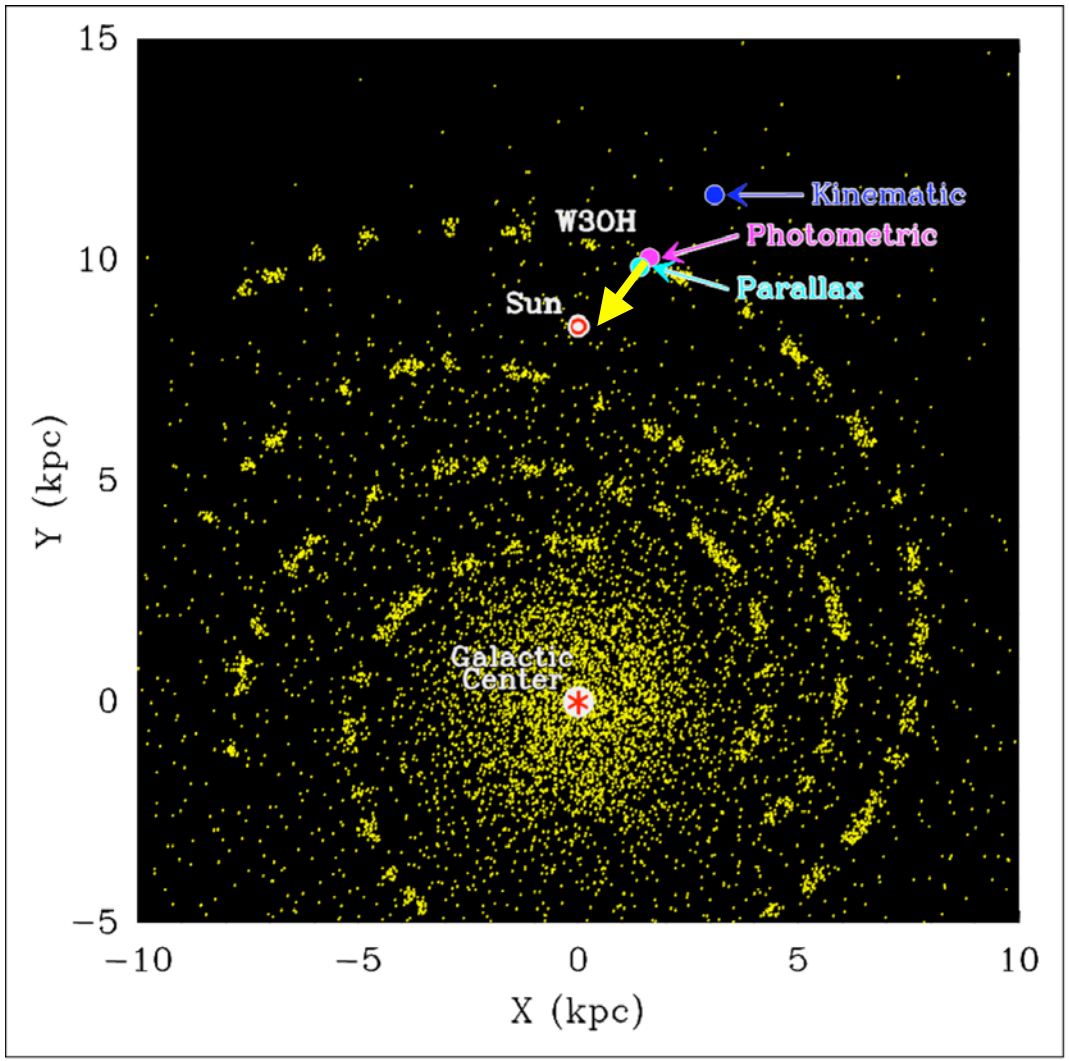
V_{mod} to V_{Dop}

W3OH Parallax



Xu, Reid, Zheng & Menten (2006) $\pi = 0.512 \pm 0.010$ mas

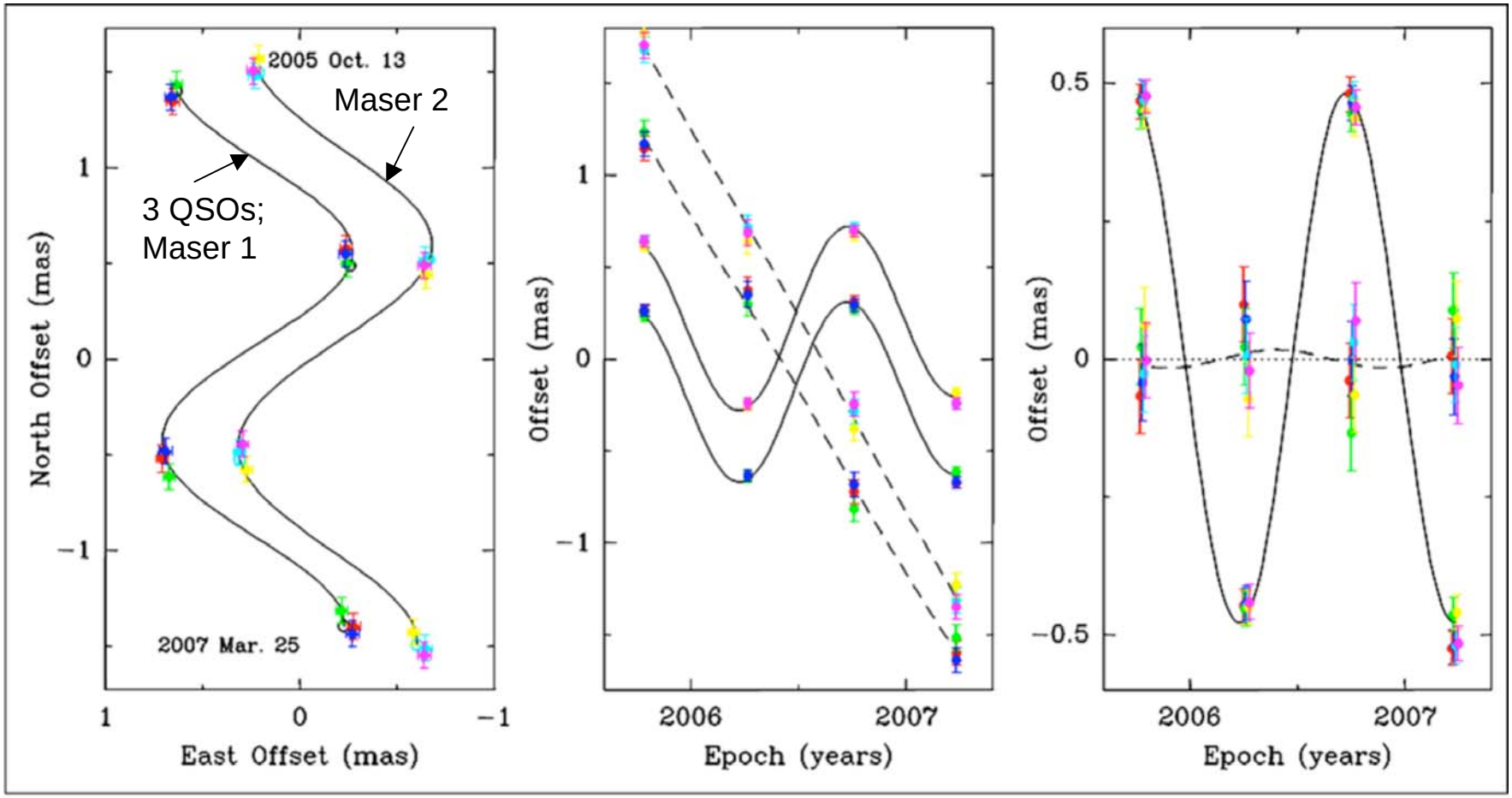
W3OH Parallax



Schematic Model of Milky Way:
Taylor-Cordes / Georgelin & Georgelin

- $D_{photo} \sim D_{parallax}$
- D_k way off
- In Perseus Arm, not in Outer Arm
- Large peculiar V

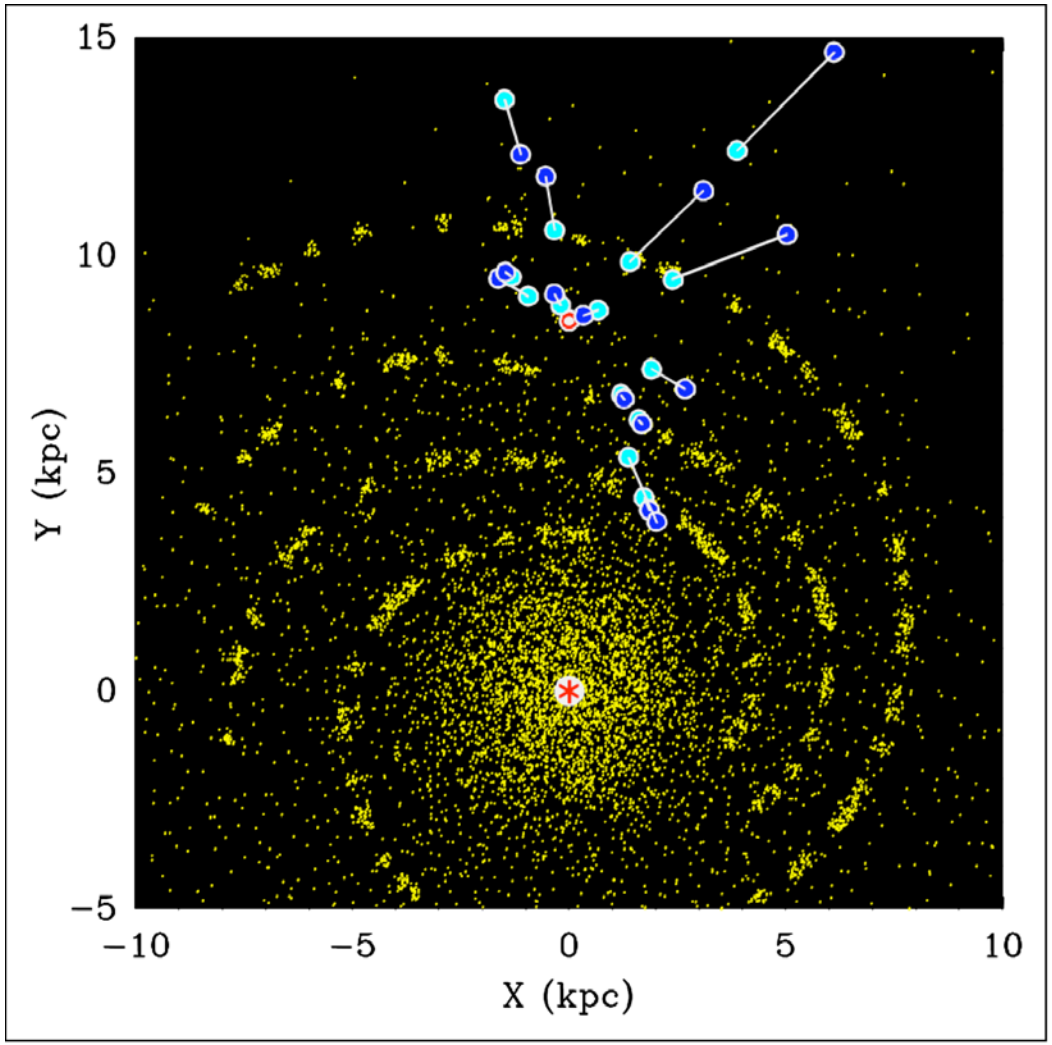
S 252 Parallax



Reid et al (2008)

π = 0.480 +/- 0.010 mas

Methanol Maser Parallaxes



Kinematic distances (D_k):

Problem: $D_k > D_\pi$

Partial fix:

$R_o < 8.5$ kpc and/or

$\Theta_o > 220$ km/s

Sgr A* p.m. requires

$\Theta_o/R_o = 29.5$ km/s/kpc

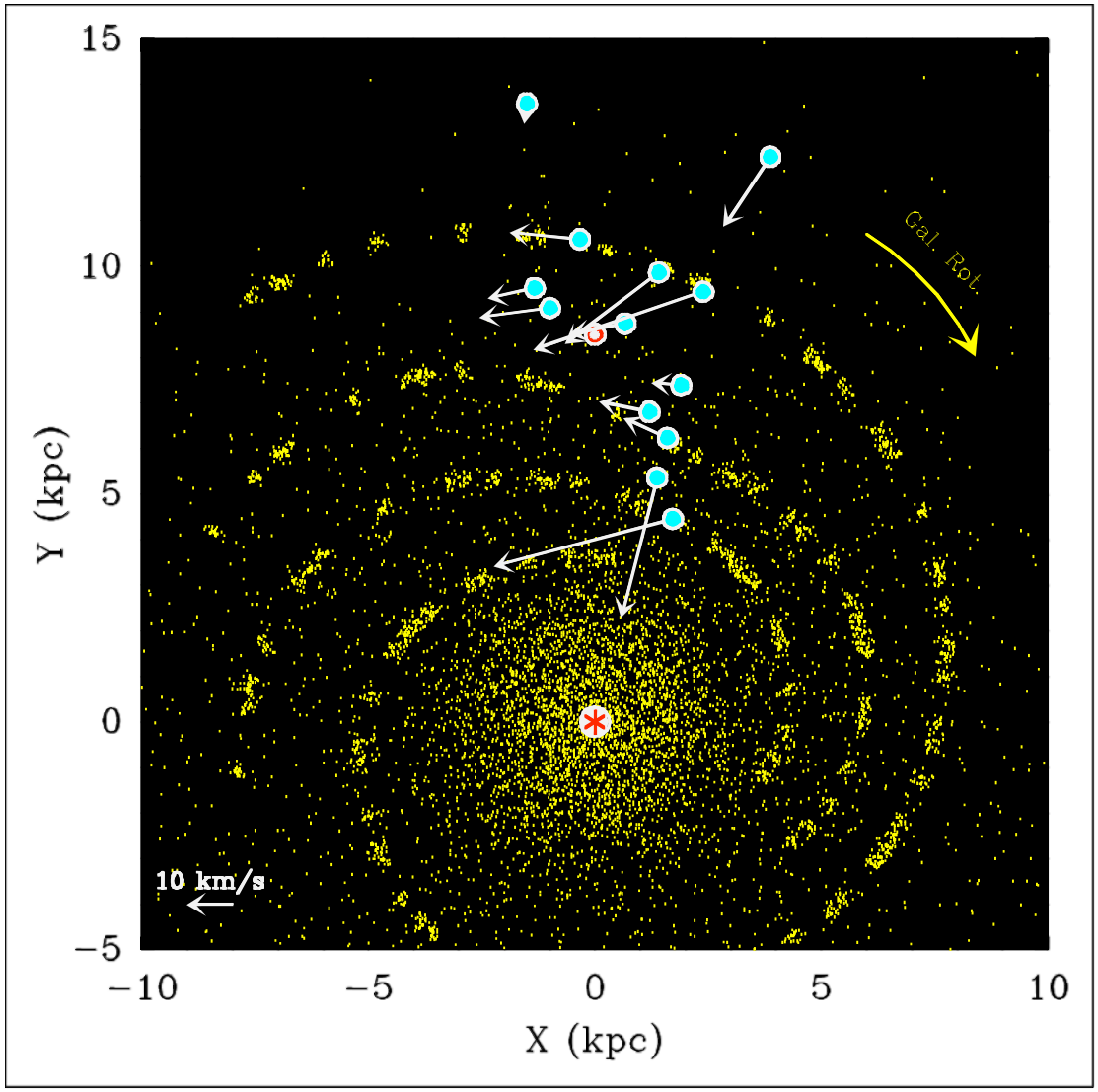
$= 236 / 8.0$

$= 251 / 8.5$

Brunthaler, Menten, Moscadelli, Reid, Xu, & Zheng

Honma et al; Hachisuka et al

Peculiar Motions of Star Forming Regions



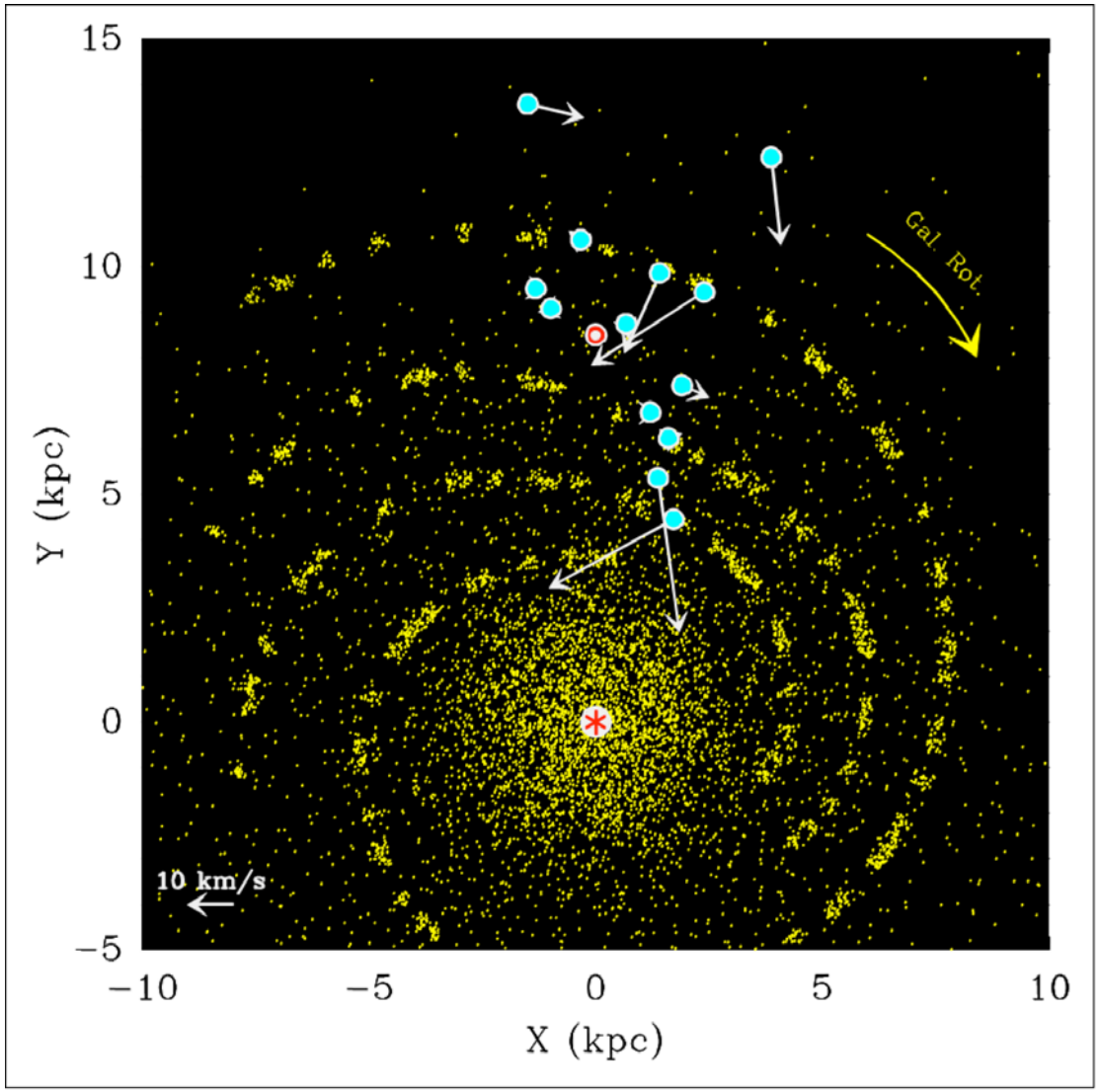
- In rotating frame:
  R_o = 8.5 kpc
  Θ_o = 220 km/s

Clear systematic motions

- Update Galaxy model:
  R_o = 8.5 kpc
  Θ_o = 251 km/s

Systematic motions smaller, but significant

Peculiar Motions of Star Forming Regions



Galactic model:

R_o = 8.5 kpc

Θ_o = 251 km/s

& Solar Motion:

U = 8 km/s

V = 18 km/s

W = 10 km/s

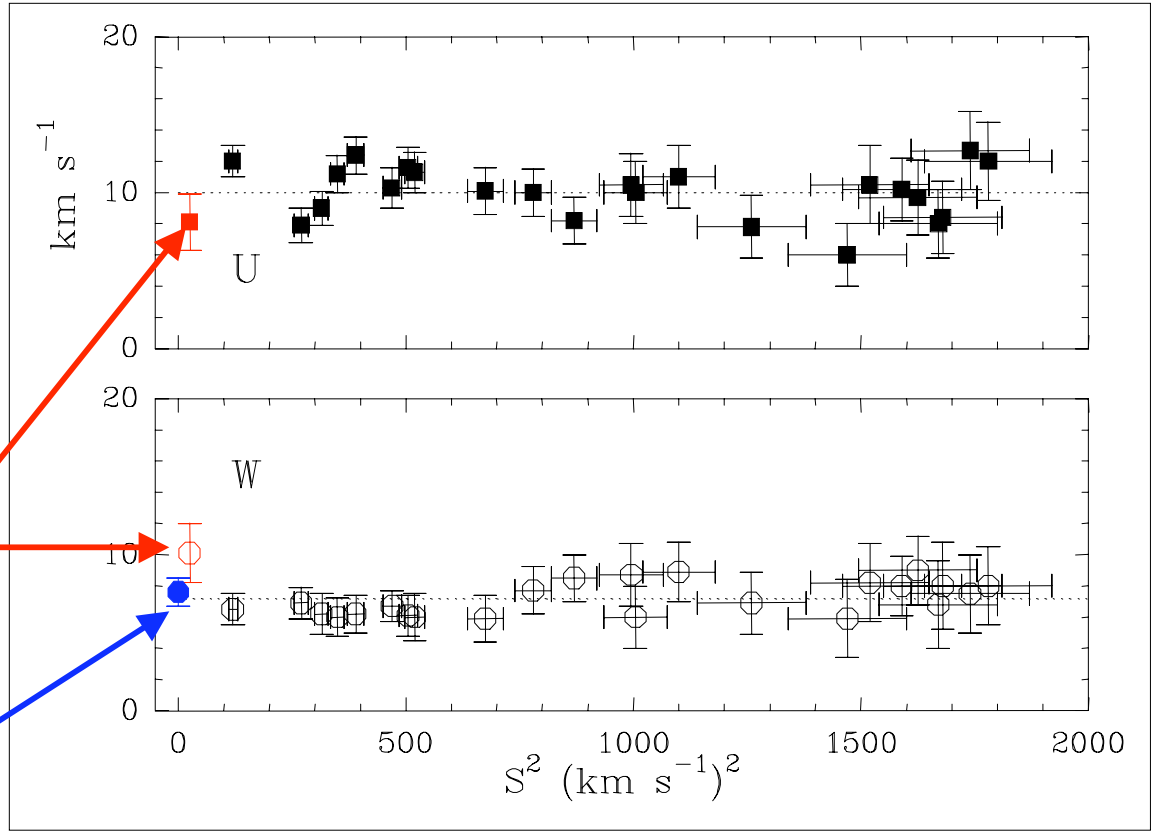
Residual motions considerably smaller

Solar Motion

- Hipparcos & VLBA

  U: → Gal. Center

  W: →North Gal. Pole



Maser parallax/P.M.

Sgr A* proper motion

Dehnen & Binney (1998) Hipparcos data (black)

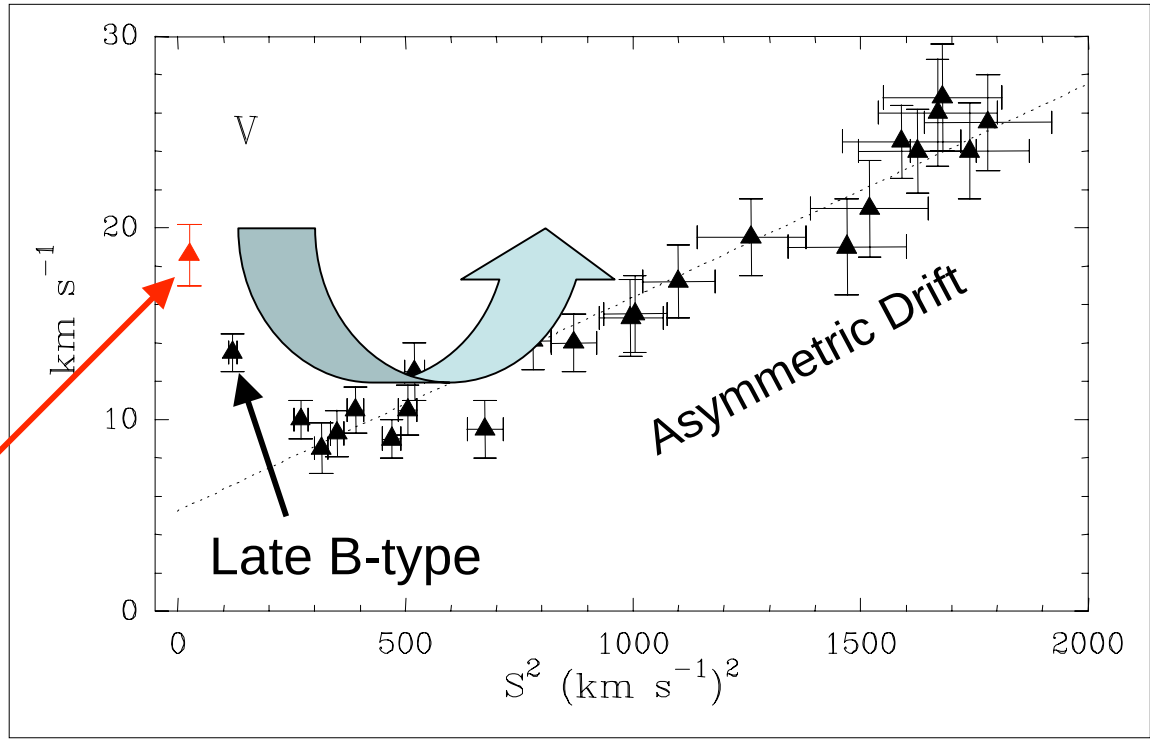
Excellent agreement between Hipparcos and VLBA

Solar Motion

V → Gal. Rot.

"Asymmetric Drift:"
V appears larger when measured against older stars with higher dispersion

Maser π & p.m.



Dehnen & Binney (1998) Hipparcos data in black

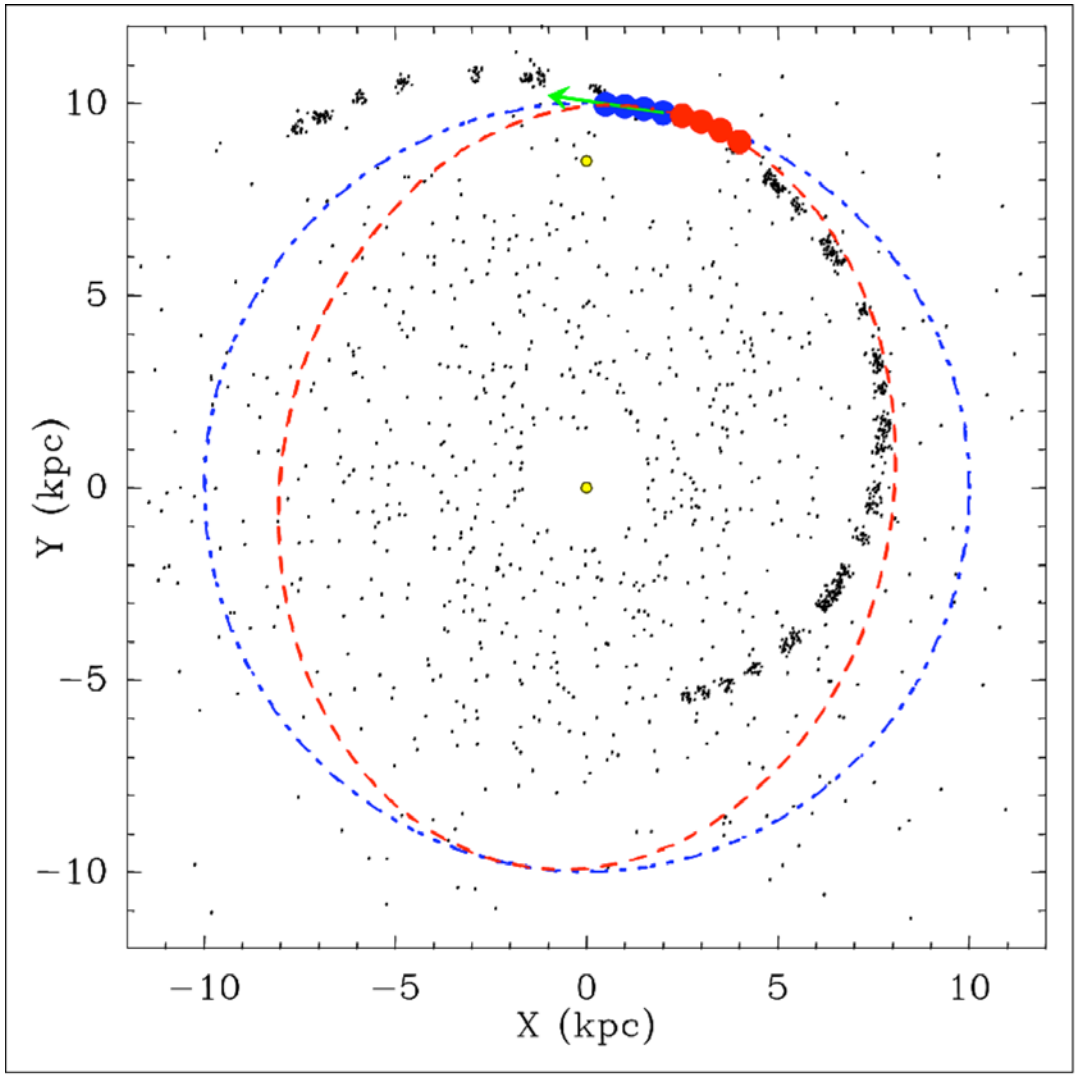
Massive stars born rotating ~13 km/s slower than Galaxy spins;

as they age, first speed up and then slow down again.

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

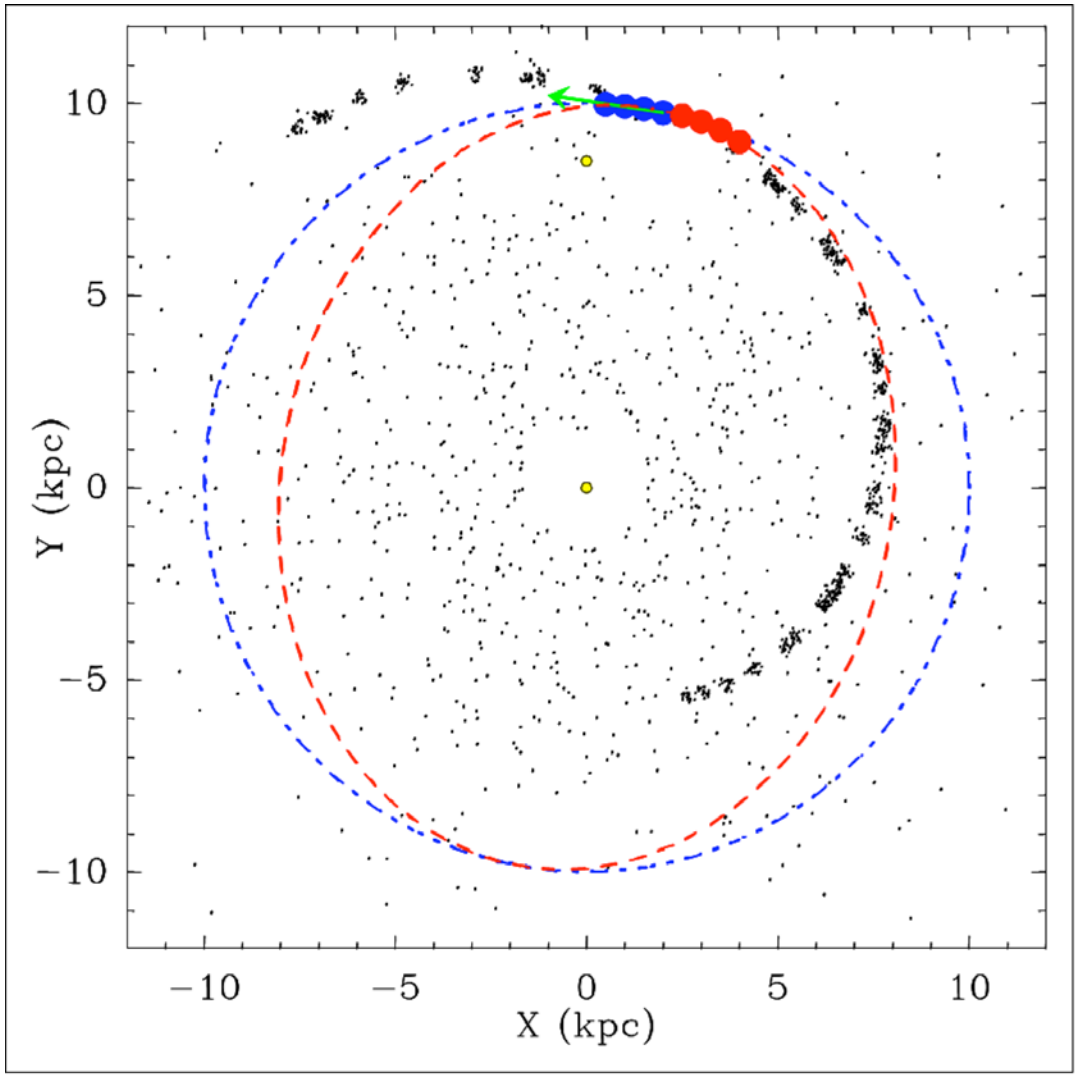


Spiral Density Wave Theory

Gravity works oppositely!

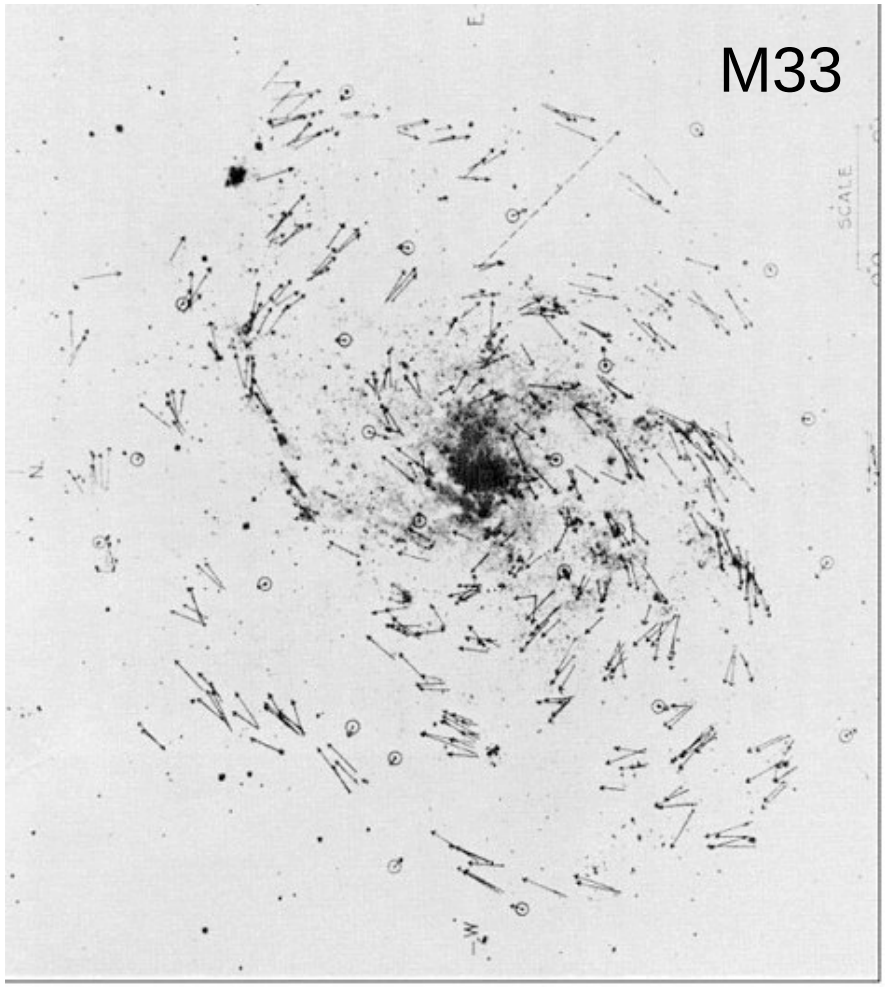
Star encountering arm would gain angular momentum and move outward

So how can old stars participate in spirals?



Local Group Proper Motions

- 1920s van Maanen claimed to see M33 spin!
- mas/yr motions ➔ Spiral nebulae nearby (Galactic)
- Hubble argued more distant (extra-galactic)
- van Maanen's error not found

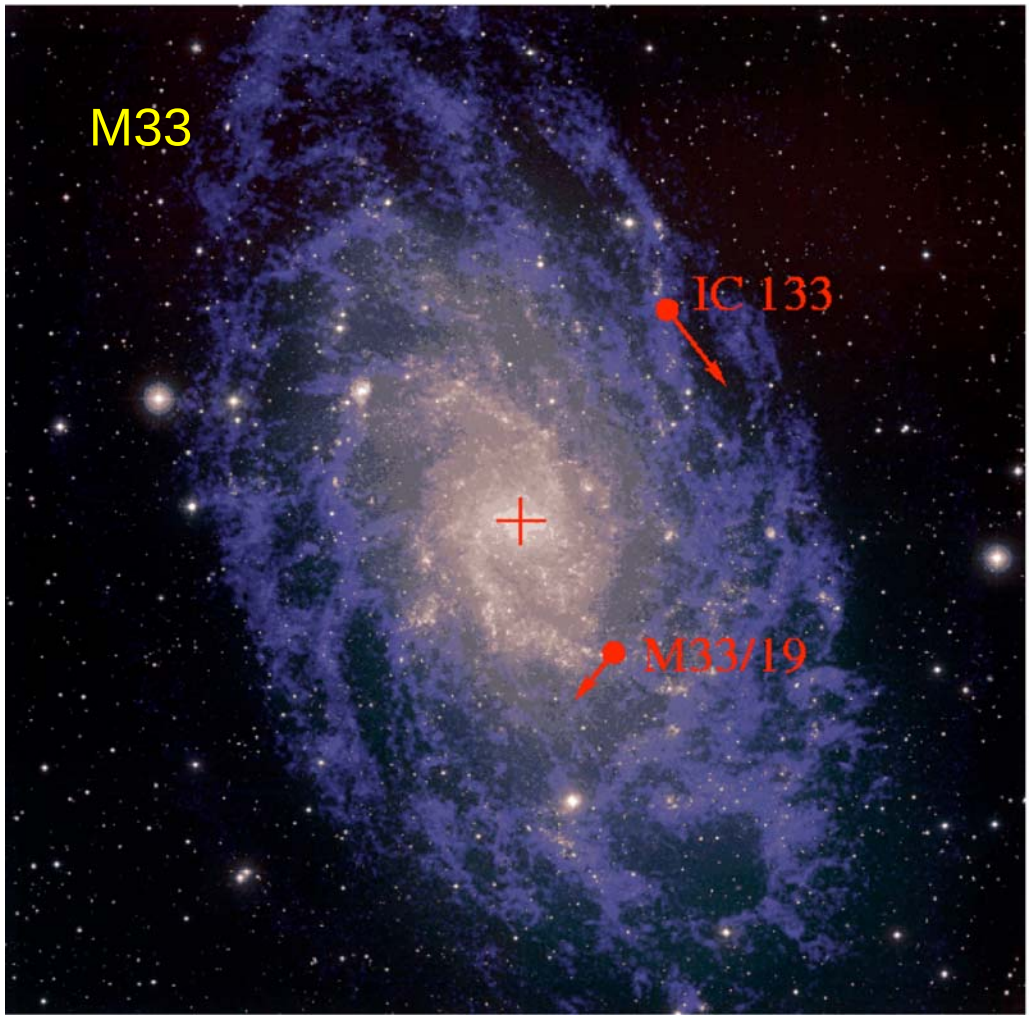


Extragalactic Proper Motions

- Parallax accuracy:
  σ_D ~ 10% at 10 kpc
  can't do galaxies yet

- Proper motion:
  same techniques, but
  $\sigma_\mu \sim T^{-3/2}$

- M33
  1) see spin (van Maanen)
  2) see galaxy's motion



Andreas Brunthaler's PhD Thesis

Extragalactic Proper Motions

- M33/IC133 – M33/19 masers

VLBA: $\Delta\mu_x$ = 30 +/- 2, $\Delta\mu_y$ = 10 +/- 5 μas/yr

HI: Δv_x = 106 +/-20, Δv_y = 35 +/- 20 km/s

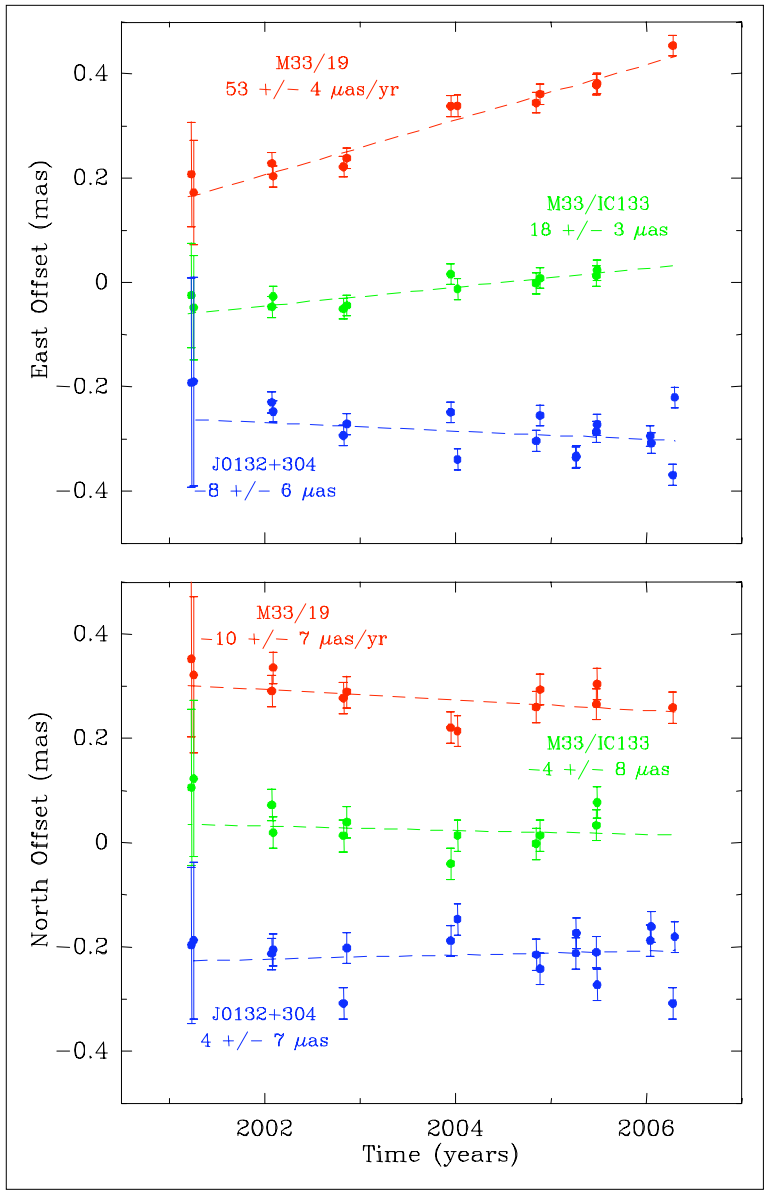
D = 750 +/- 50 +/- 140 kpc

σ_μ σ_v

- Improvements in Rotation Model & 3rd maser source:

σ_D < 10% possible

Brunthaler, Reid & Falcke



M33's Motion

M33/19 apparent motion:

East , North

36 (3), -12 (6) μas/yr

122 , -43 km/s

@ 730 kpc

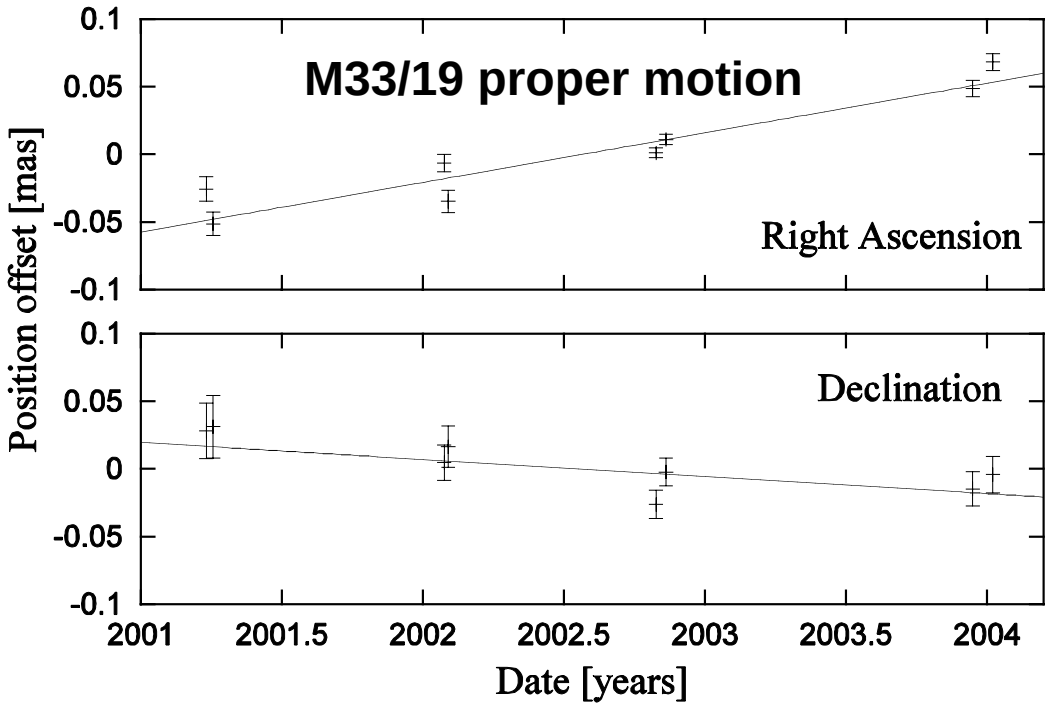
Correct to galaxy center

Remove Sun's motion around center of Milky Way

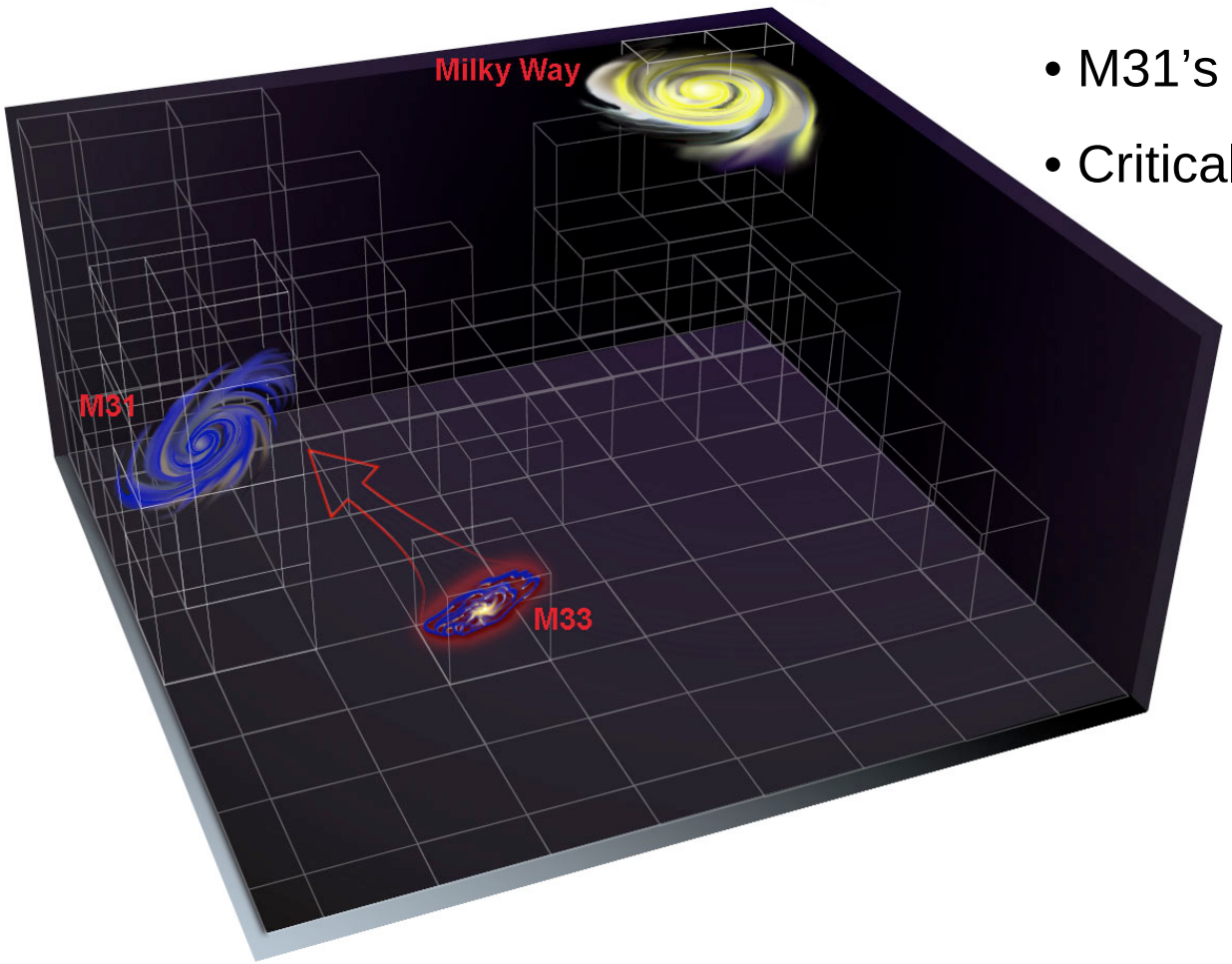
Combine results both sources

M33's motion:

-101, +156 km/s @ 730 kpc



Extragalactic Proper Motions



- M31's motion unknown
- Critical for L.G. dynamics

Local Group Orbits

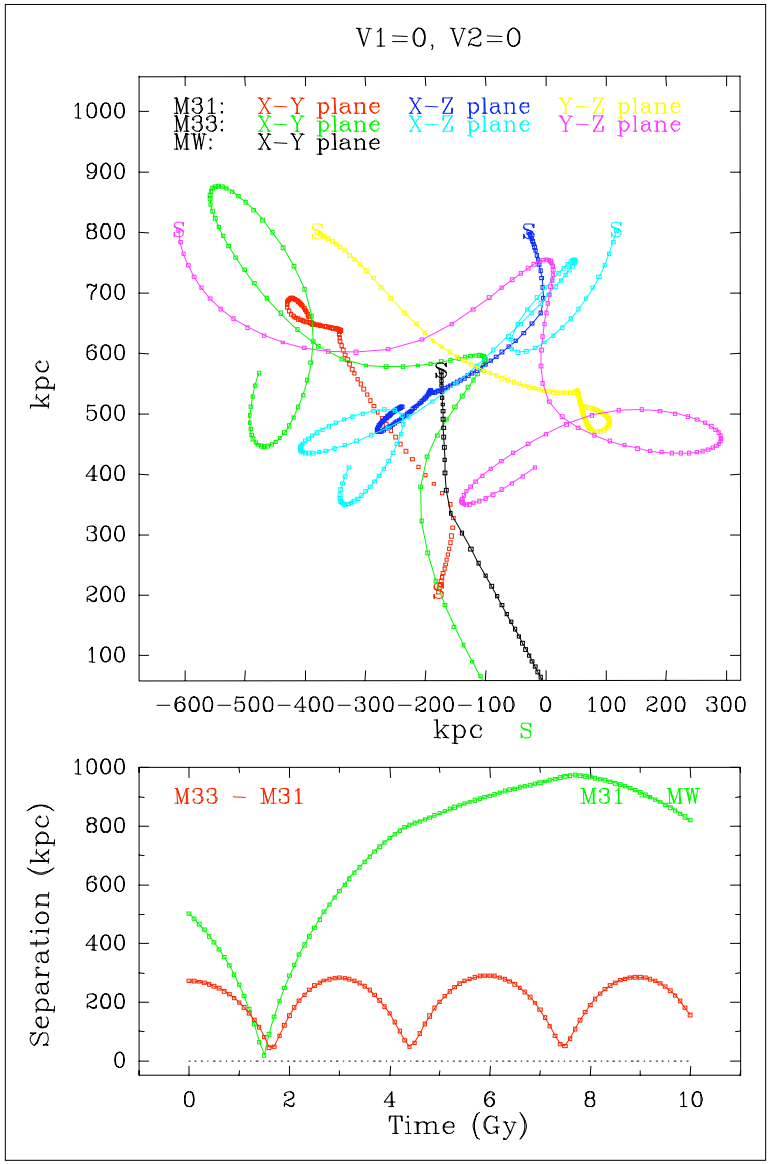
Assumptions:

- M31 proper motion (eg, zero)
- M31 DM halo = 3.4 x 10^{12} M_{sun}
- MW DM halo = 2.3 x 10^{12} M_{sun}

Calculate orbital histories:

- M33 encounters M31 repeatedly
- MW hits M31 ~8 Gy ago

Loeb, Reid, Brunthaler & Falcke (2005)



Tidal Heating of M33

- Try non-zero M31 proper motions; then calculate orbits

- Tidal heating of M33:

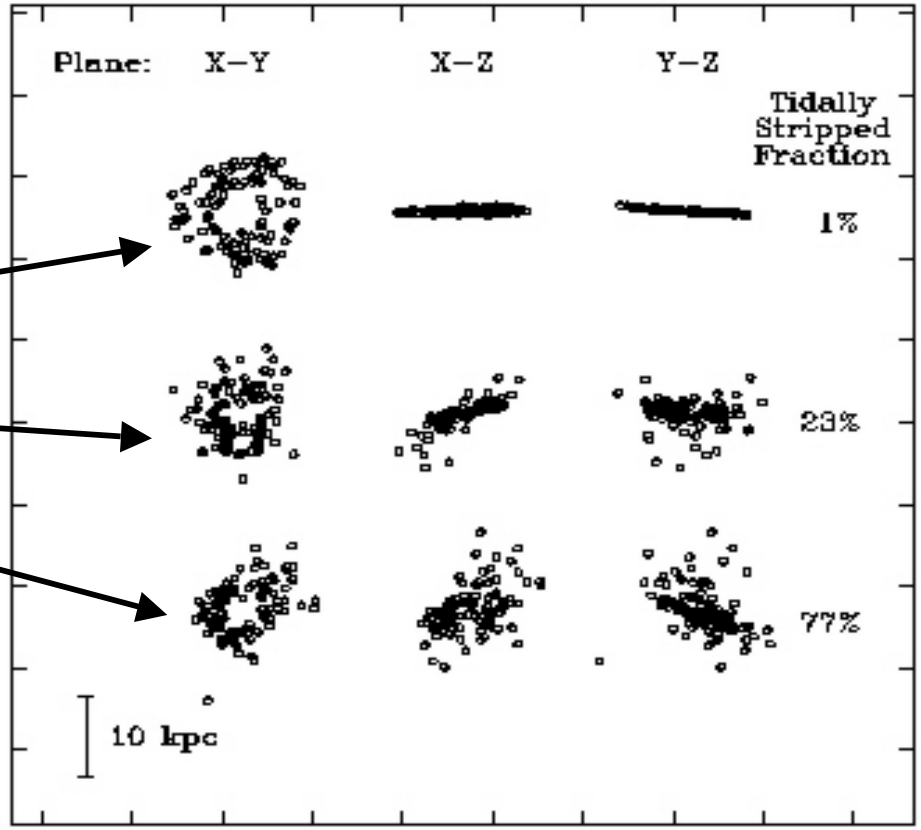
  μ_{M31} = (100,-100) km/s

  (-50, -50) km/s

  (0, 0) km/s

μ_{M31} ~ 0 km/s → M33 destroyed

μ_{M31} ~100 km/s → M33 OK



Loeb, Reid, Brunthaler & Falcke (2005)

But sensitive to dark matter mass…

Dark Mass in Local Group Galaxies

Uncertainty of D.M. halo masses

Using 75% of previous values, ie,

M31 DM halo = 2.6 x 10^{12} M_{sun}

MW DM halo = 1.7 x 10^{12} M_{sun}

M31 & M.W. never close, but

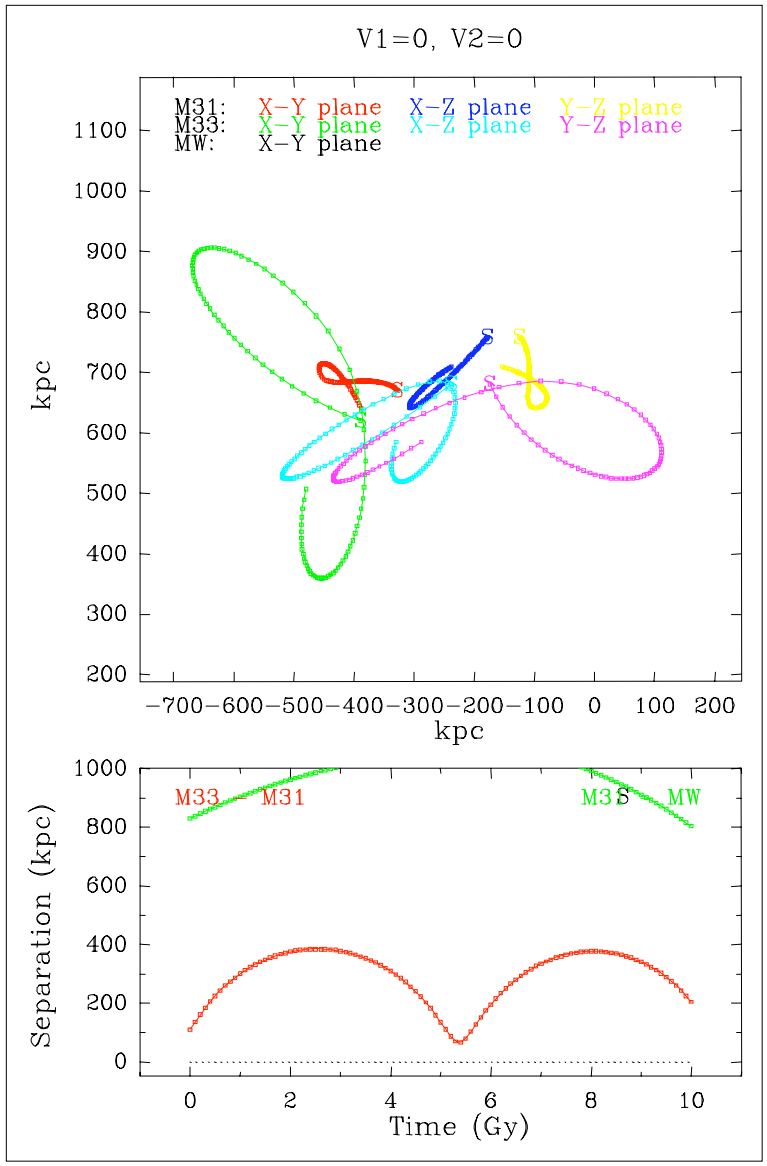
M33 still encounters M31

(NB: for MW Sgr A*'s motion gives

Θ_o/R_o=29.5 km/s

if R_o=8.5 kpc, then

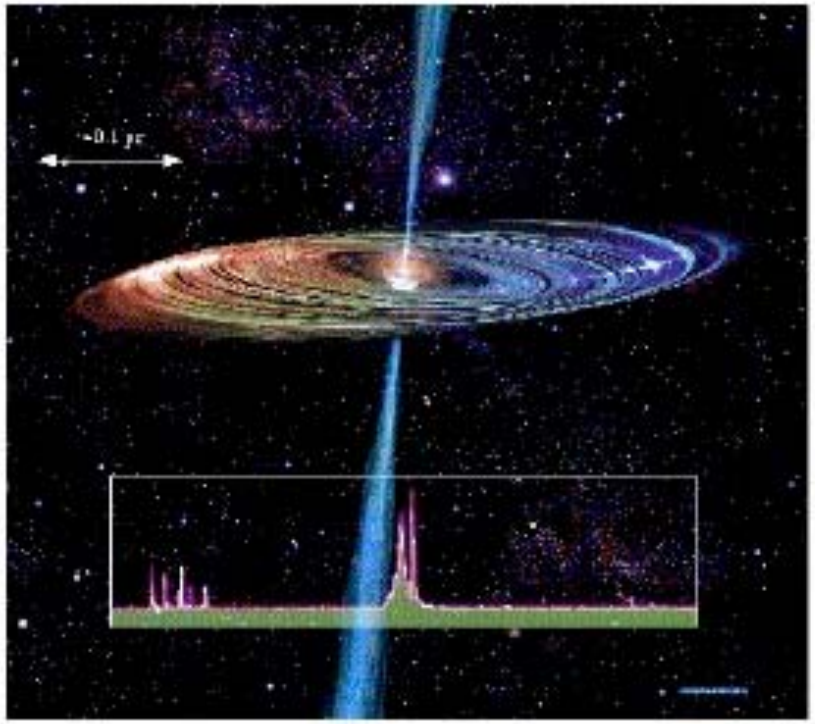
Θ_o=251 km/s like M31!)

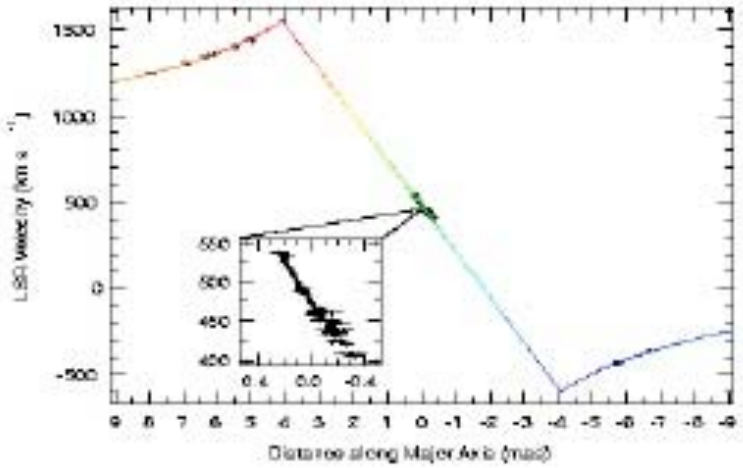


The Next 5 Years

- R_o & Θ_o from parallax & p.m. data with 3% accuracy
- Map of Milky Way spiral structure (northern portion) and critical tests of spiral density wave theory
- Proper motions of ~4 Local Group Galaxies, possibly including M31 (Andromeda)

NGC 4258

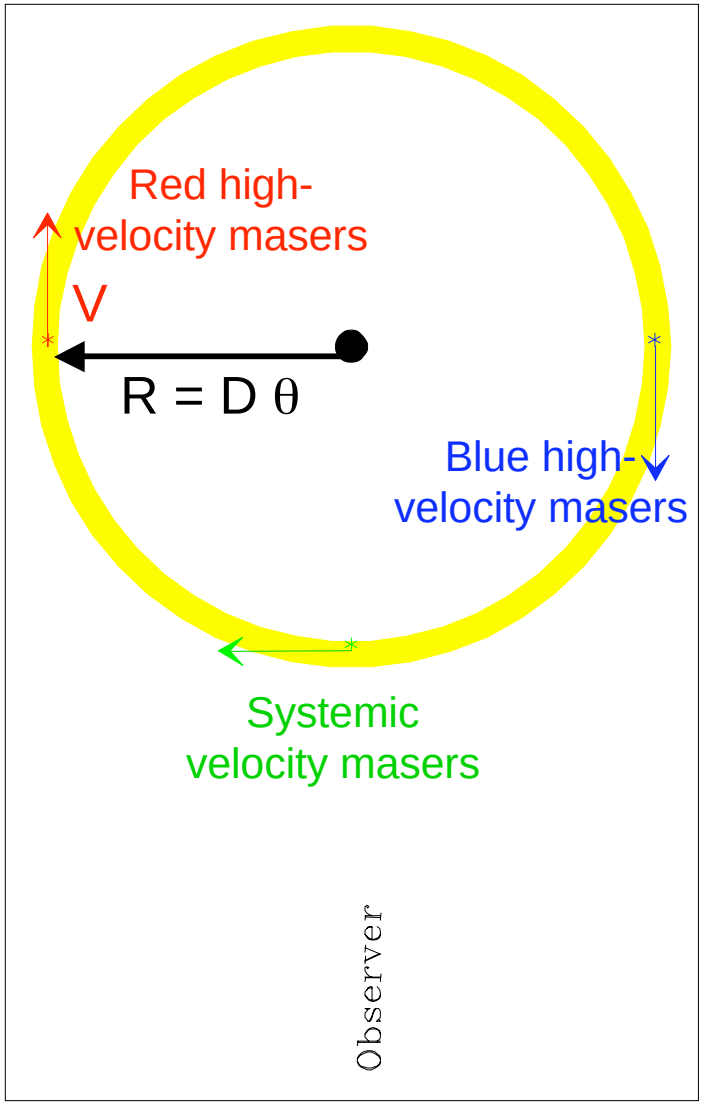




- Seyfert galaxy
- H_2O masers in an edge-on, sub-parsec disk
- Rotation speed ~1000 km/s
- $M \sim 3 \times 10^7 M_{sun}$
- Geometric model ➔
  D = 7.2 +/- 0.5 Mpc
- Used by Hubble Key Project to re-calibrate Cepheid PL relation

Herrnstein, Moran, Greenhill et al (1999)

AGN Maser Distance Measurements



$A = V^2 / R$

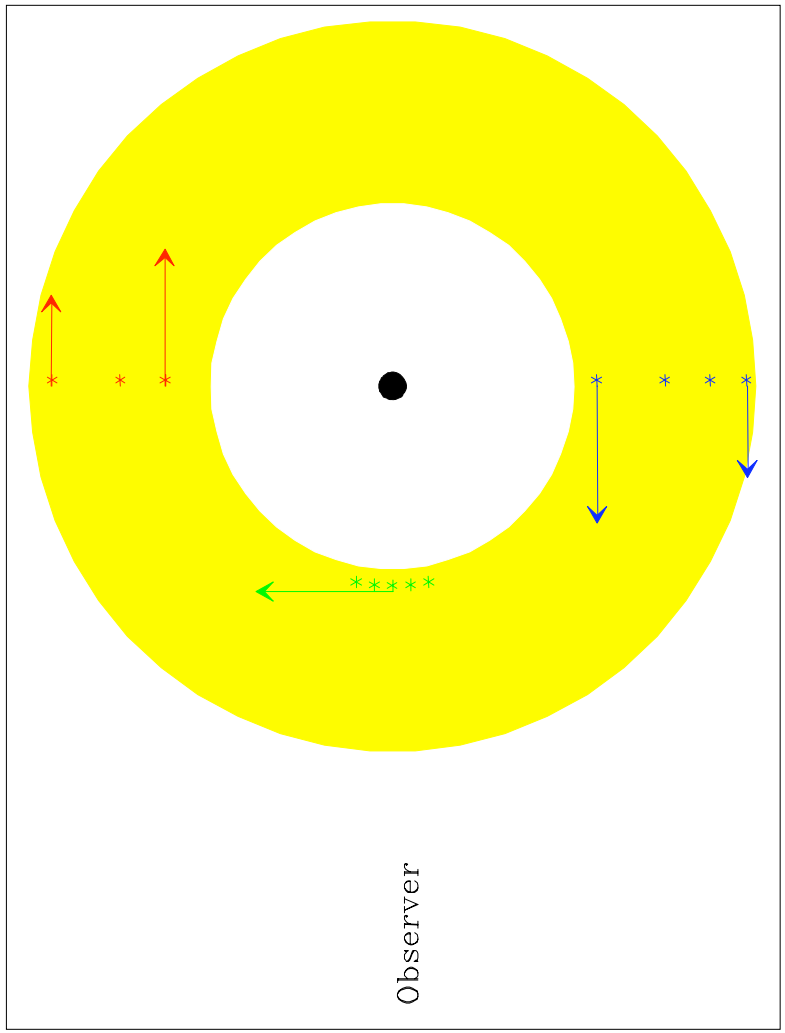
$R = D\,\theta$

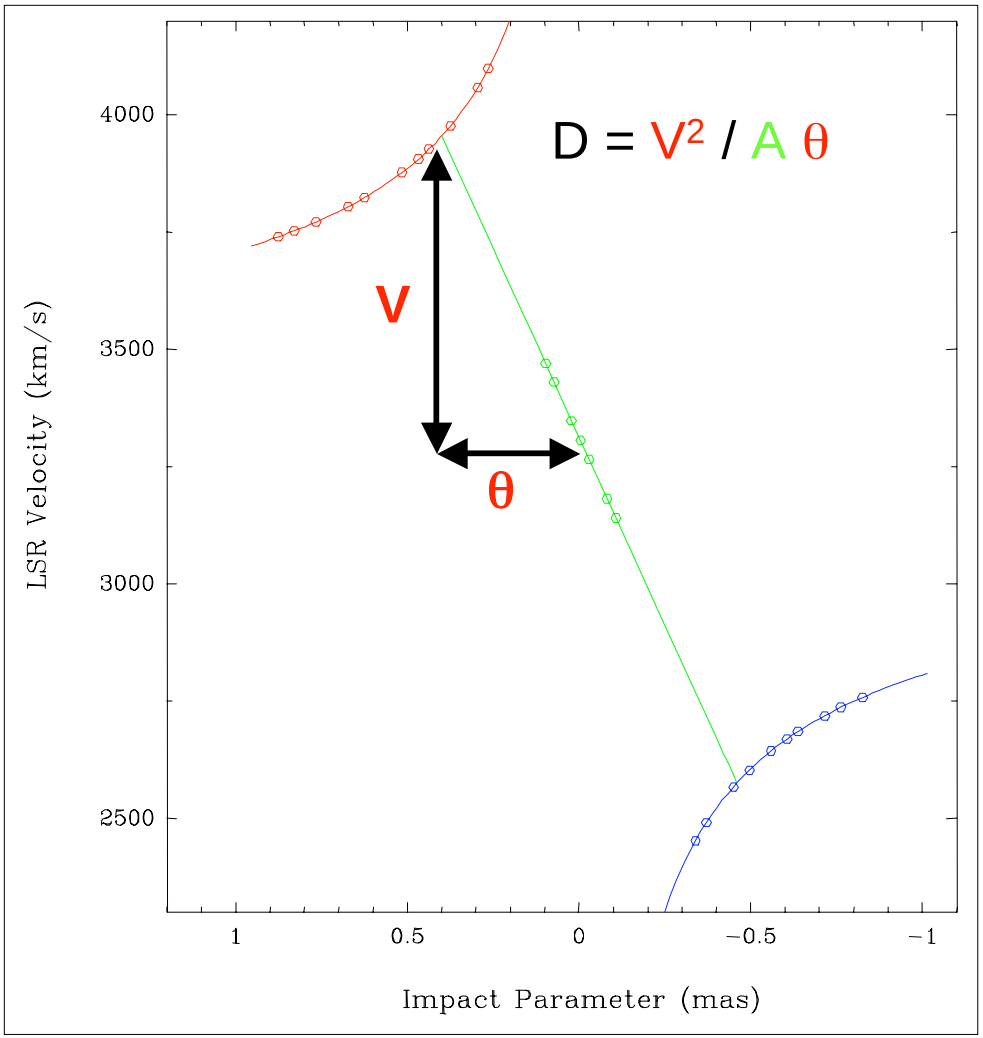
$\therefore \quad D = V^2 / A\,\theta$

High Velocity
Maser Map

Drift of systemic masers
over time

Maser Distance Measurements (2)



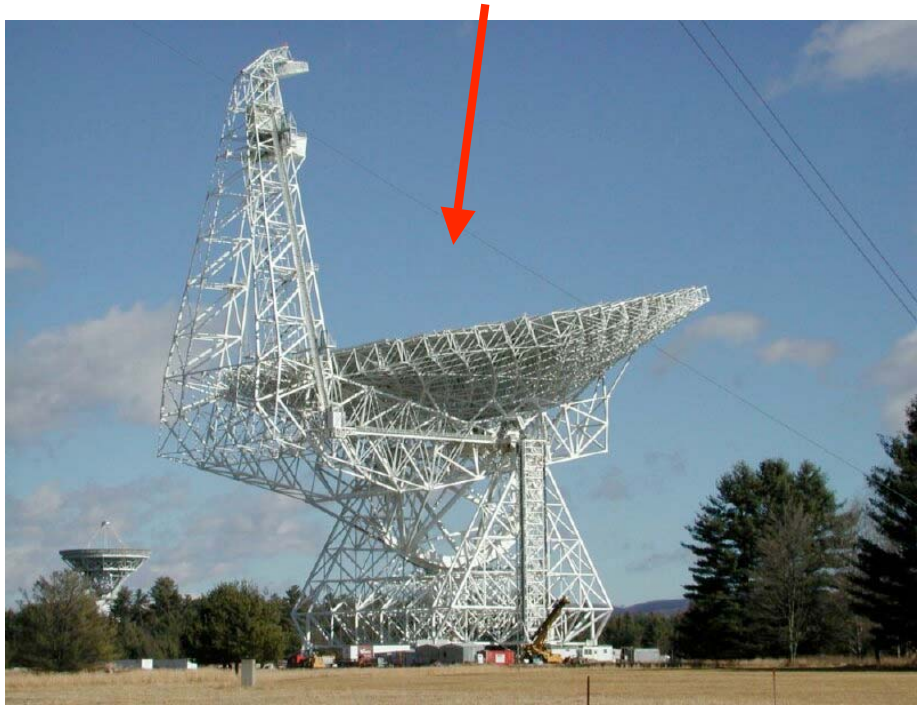


Maser Cosmology Project

Braatz, Condon, Greenhill, Henkel, Lo & Reid

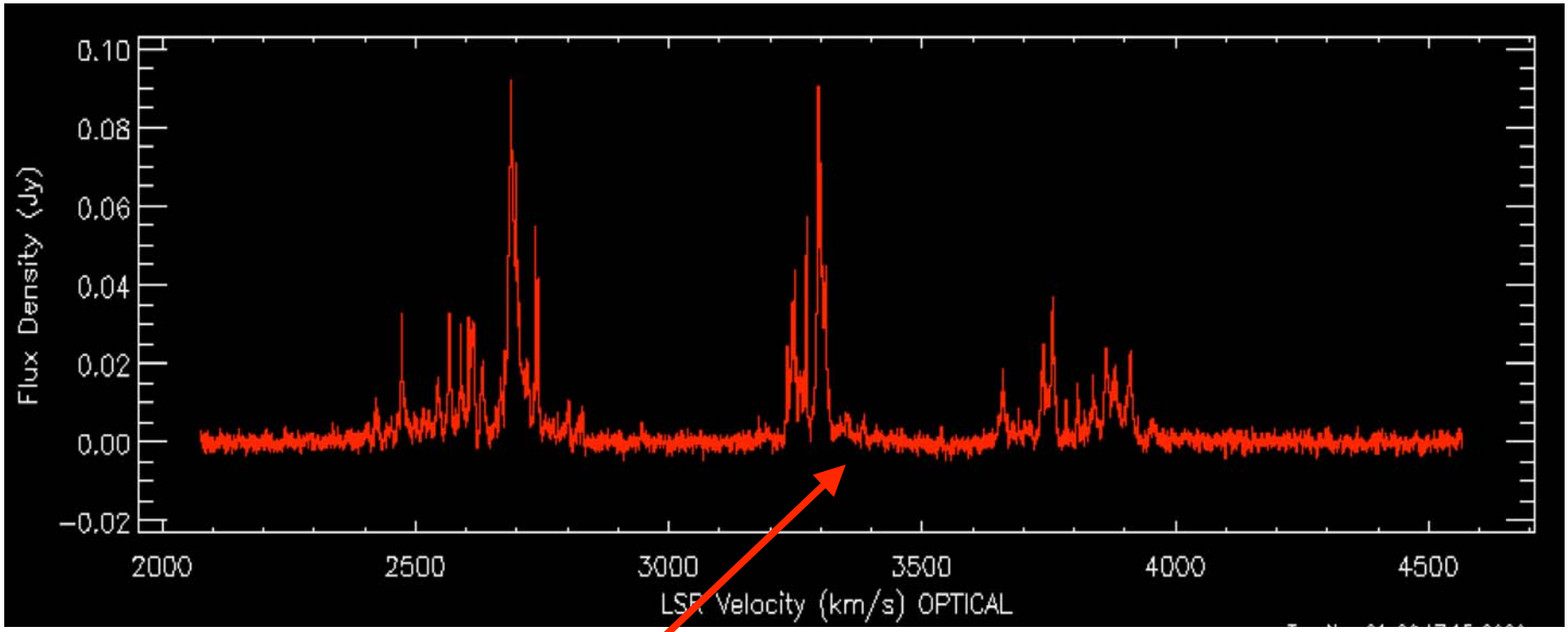
- Goal: H_o accurate to 3%; constain Dark Energy Eq. of State
- How: Geometric Distances to H_2O masers in Hubble Flow

GBT finds masers



VLBA maps them

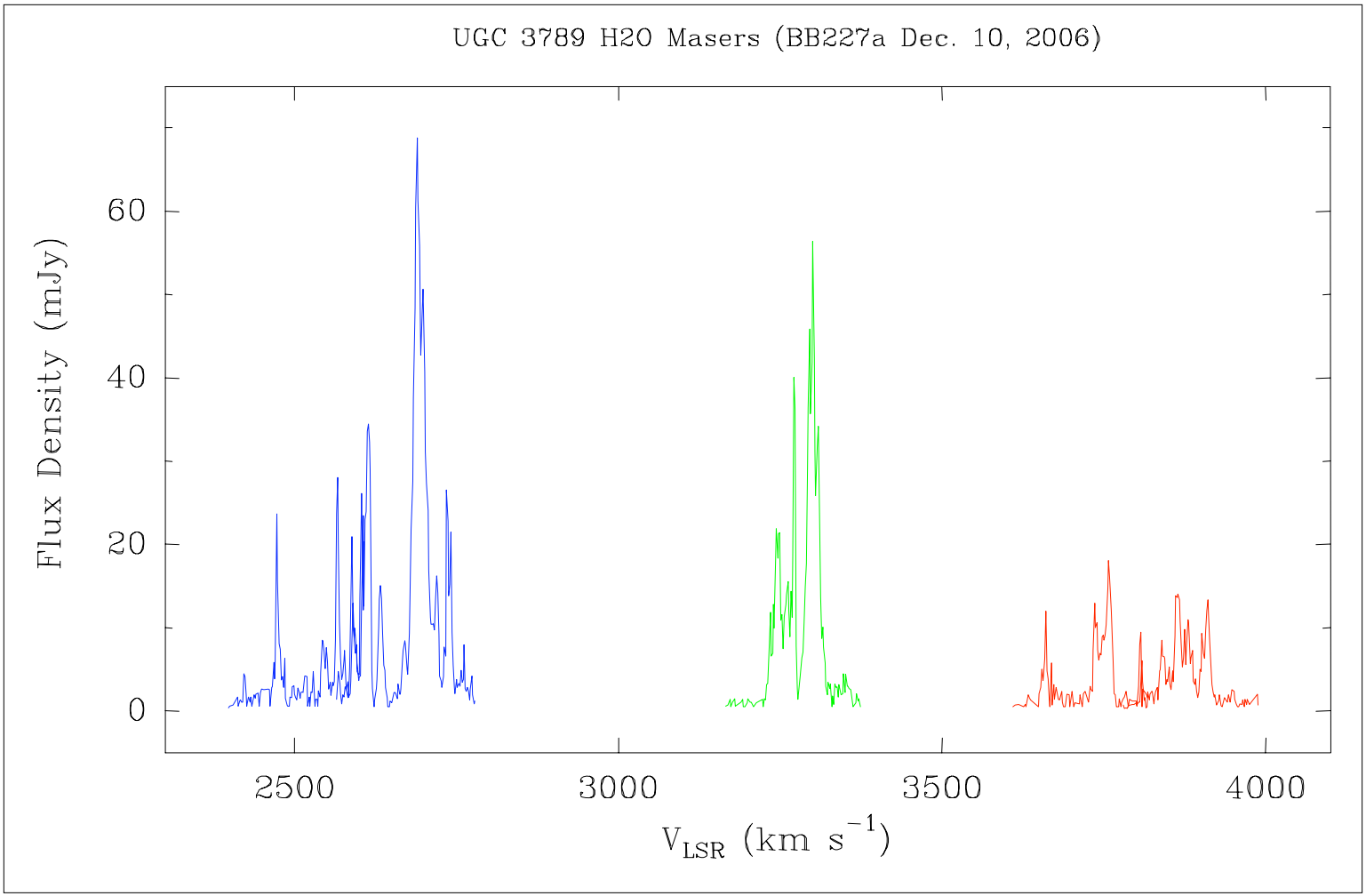
UGC 3789



J. Braatz: GBT

V_{CMB} = 3385 km/s ➔ D ~ 50 Mpc

UGC 3789: VLBA + GBT



Interferometer spectrum: rms noise ~1 mJy

UGC 3789 map

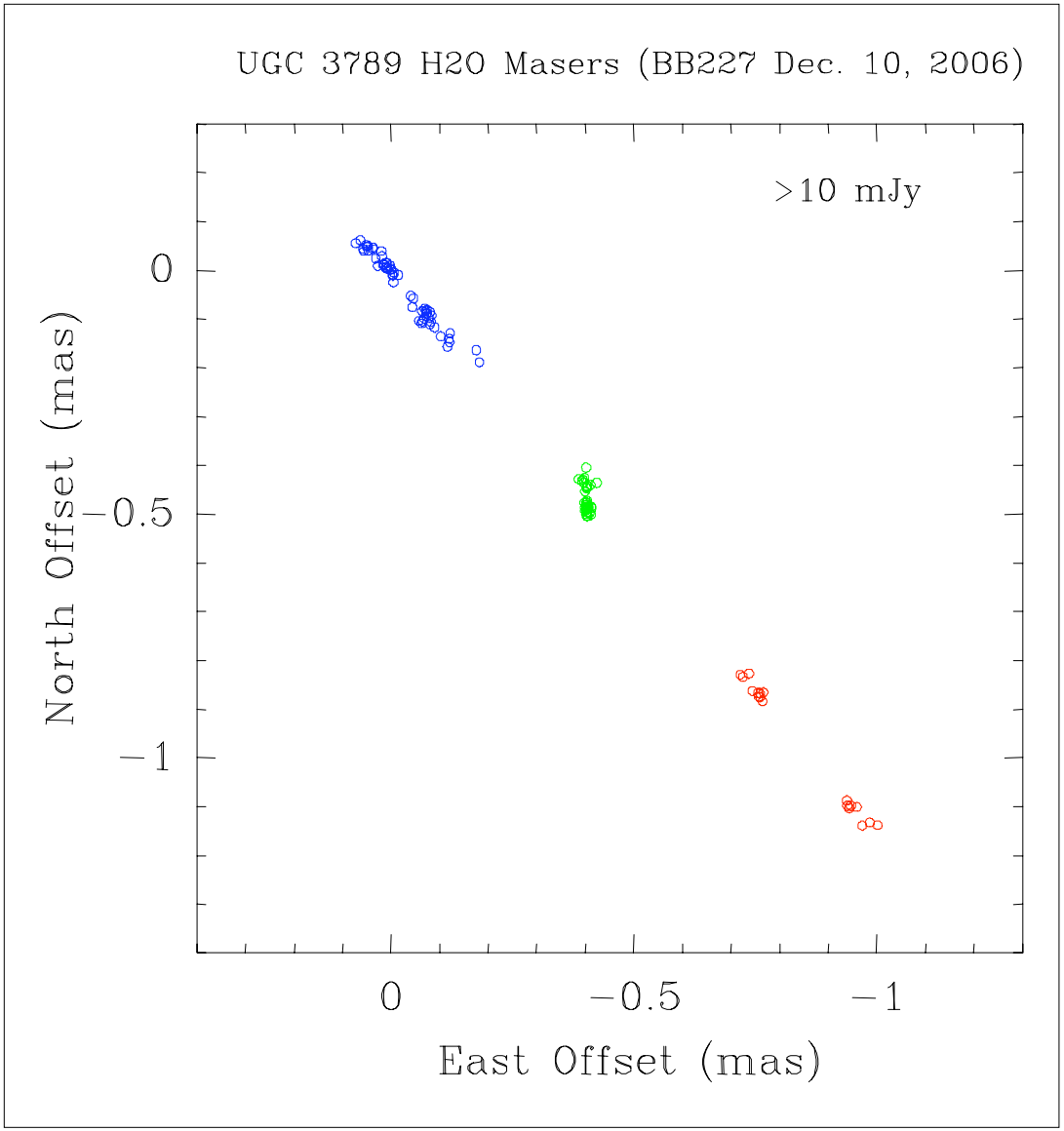
- Similar to NGC 4258

Edge-on disk

Systemic vel. masers between red and blue high vel. masers

~7 times smaller angle

~7 times more distant



UGC 3789 Position-Velocity Diagram

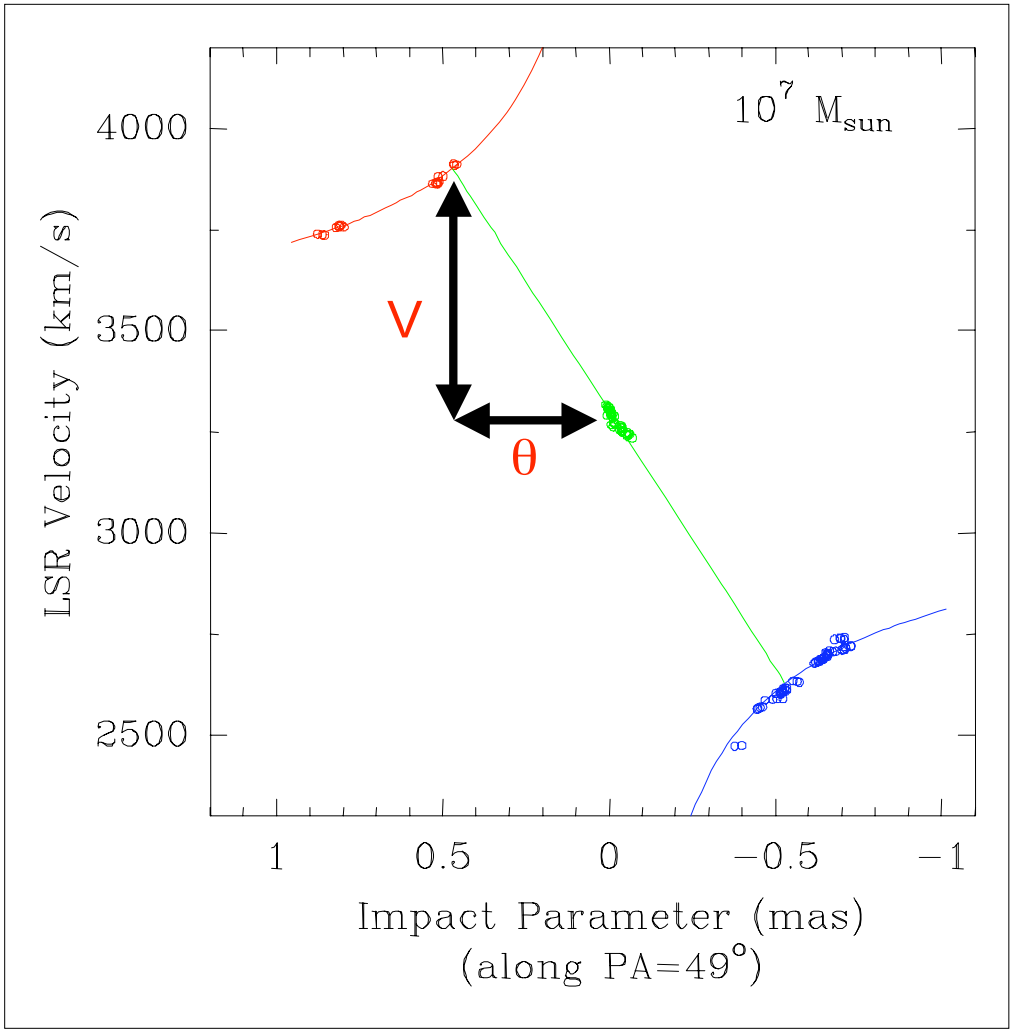
- Keplerian high vel. masers

  ~10^7 M_{sun} SMBH

- Systemic maser P-V ~ linear

  (slight "bend" ➔ changing R)

- V = 625 km/s, θ = 0.52 mas



UGC 3789

- Accelerations ~ 3.4 km/s/year
- $D = V^2 / A\,\theta$ …Preliminary Analysis

$V \sim 625$ km/s

$\theta \sim 0.52$ mas

$A \sim 3.4$ km/s/yr

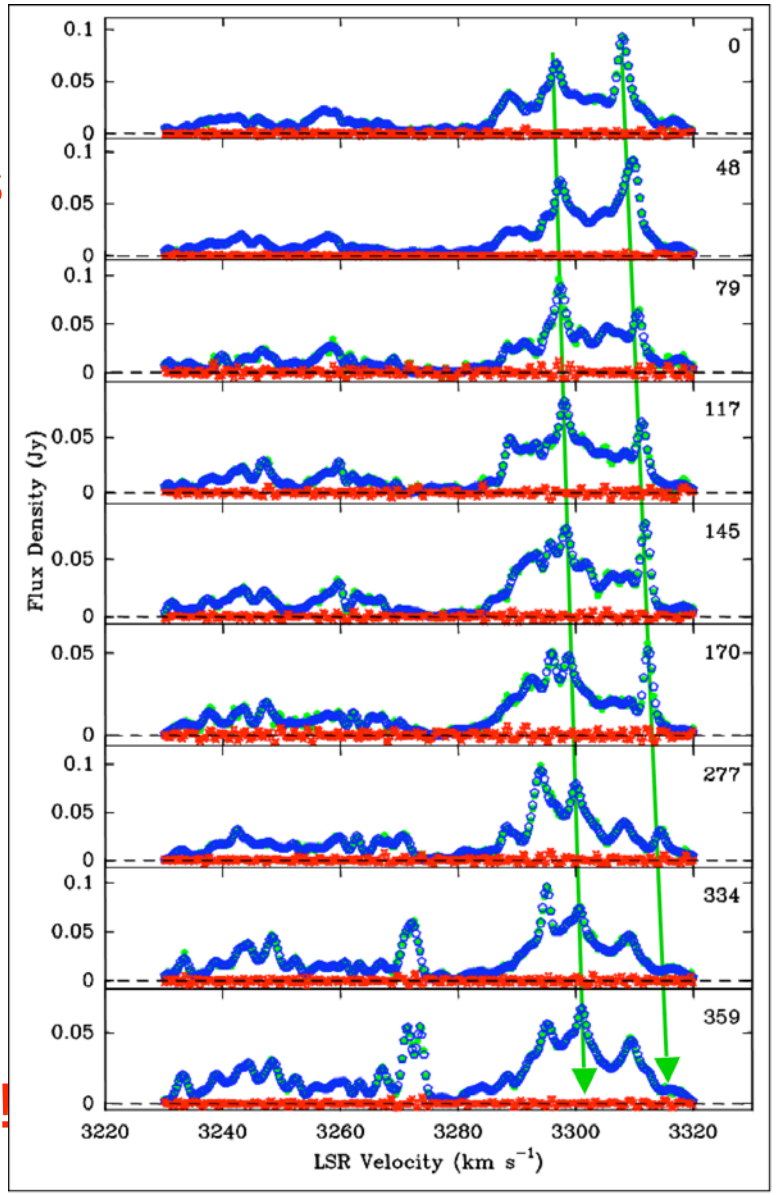
} D = 47 Mpc +/- 5

- $H_o = V_{cmb}/D = 3385$ km/s / 47 Mpc

  = 72 +/- 7 +/- 4

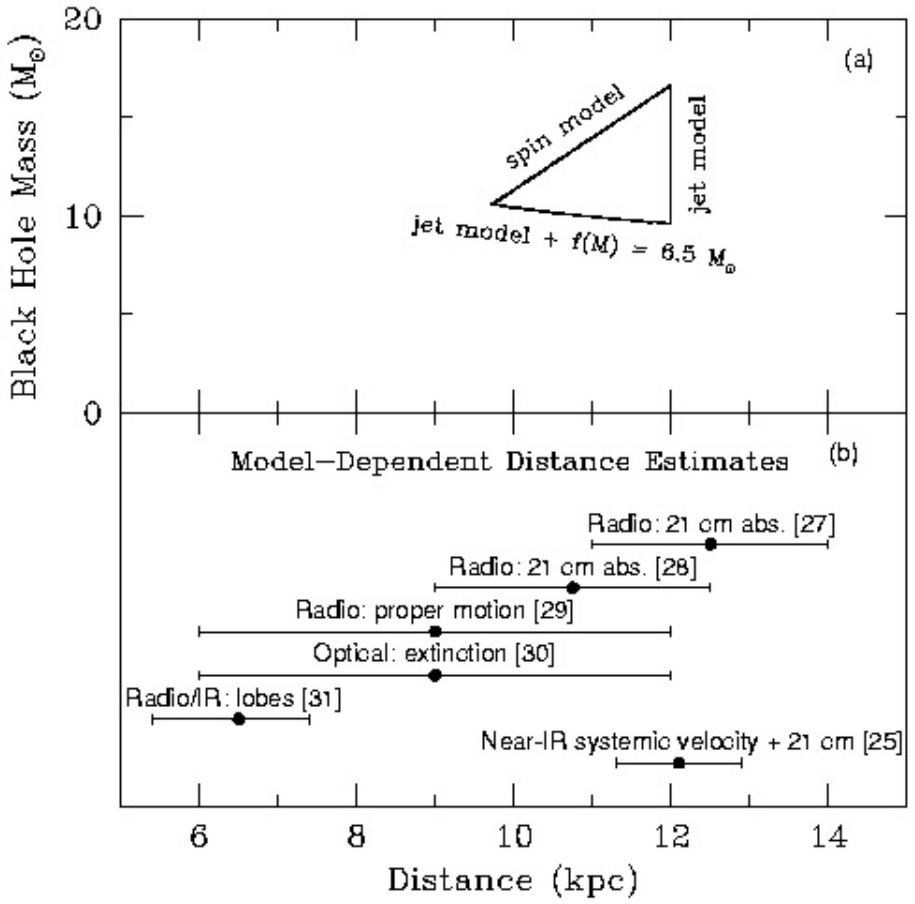
  from σ_D σ_{Vcmb}~200 km/s

- Comparable to Hubble Key Project!



Projects in Progress:

- Hyper-luminous stars
  (VY CMa, NML Cyg)
- R_o from Sgr B2 H_2O parallax
- BH spin: GRS1915+105 distance



McClintock, Reid, et al