Astrometry

William F. van Altena ARAA (1983)

7. Conclusion

The field of astrometry is in the midst of a major revolution in terms of the accuracy obtained or expected in the near future for positions, proper motions, and parallaxes.

…

The Space Telescope should yield parallaxes better than 0.5 mas, and HIPPARCOS will produce around 100,000 parallaxes of the brighter stars good to around 2 mas.

…

Finally, radio astrometry offers the potential for obtaining precise positions, motions, and parallaxes for radio sources on an absolute system.

Radio Astrometry from the Milky Way to Distant Galaxies

Mark J. Reid
Harvard-Smithsonian CfA

- Galactic Center Astrometry
- SFR Parallaxes & Proper Motions
- Extra-Galactic Proper Motions
- H_o from H_2O Masers

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):

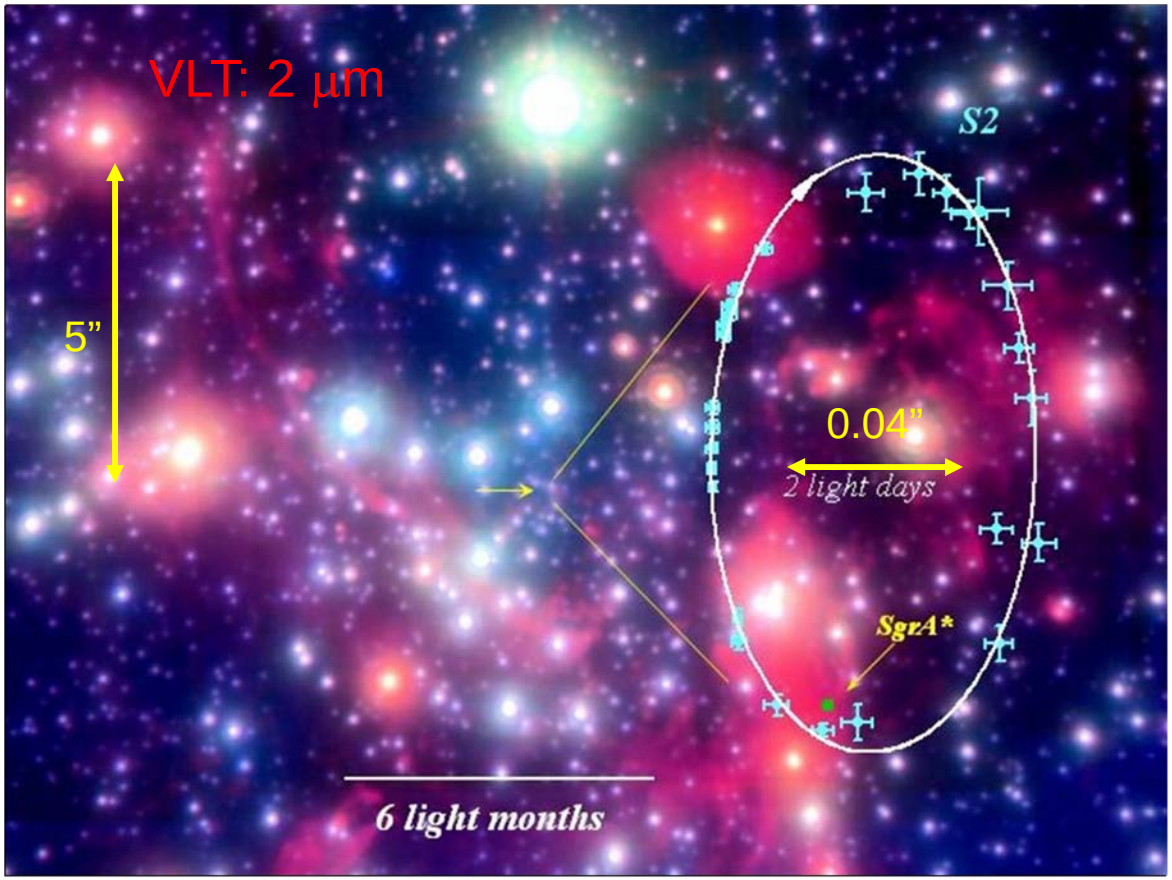
$\Delta\Theta$ ~ 1 deg (0.02 rad)

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

Galactic Center Stellar Orbits

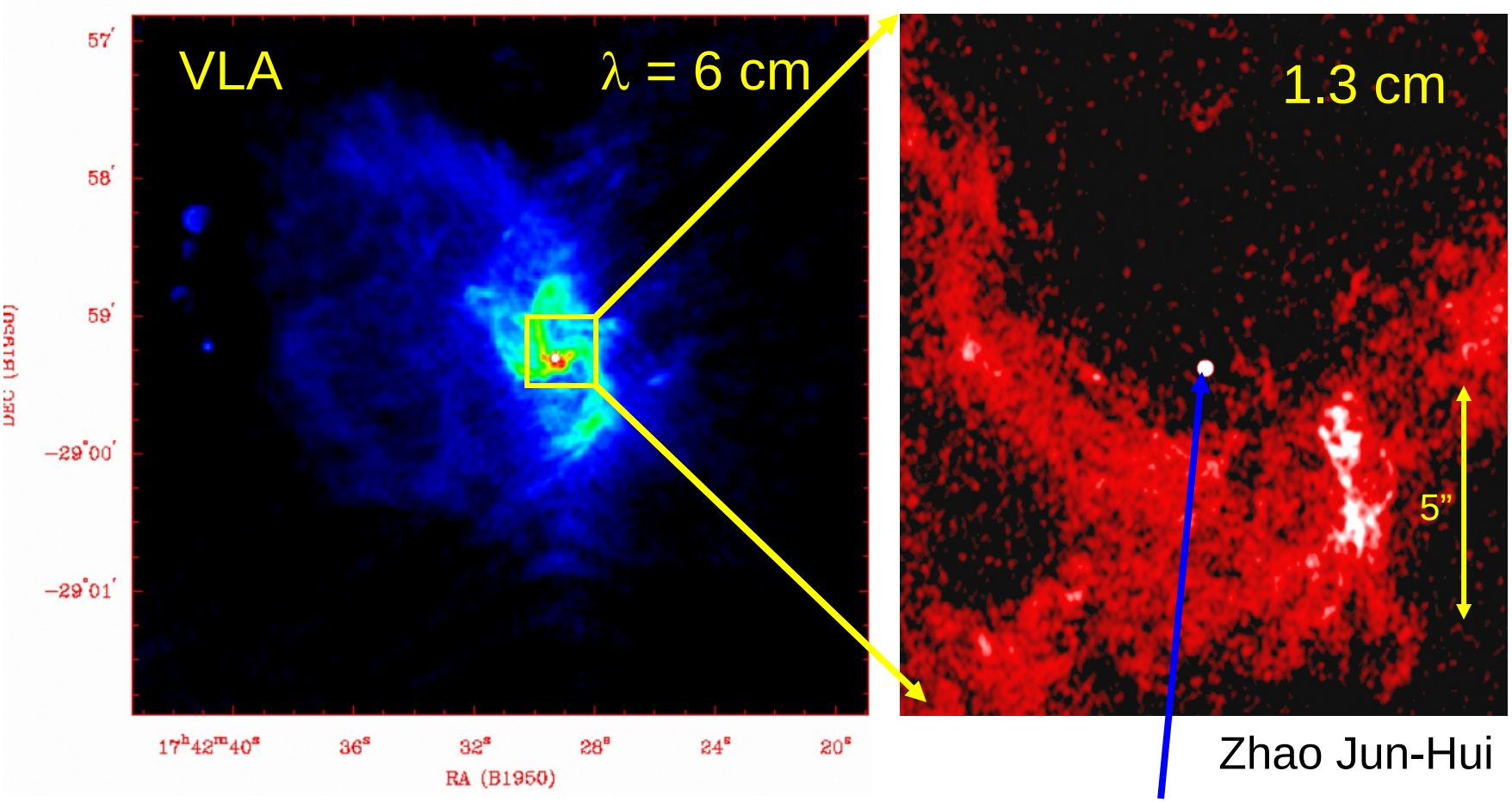
- $M = 4 \times 10^6 M_{sun}$
- $R < 50$ AU
- Den. $> 10^{17} M_{sun}/pc^3$

Ghez et al / Genzel et al

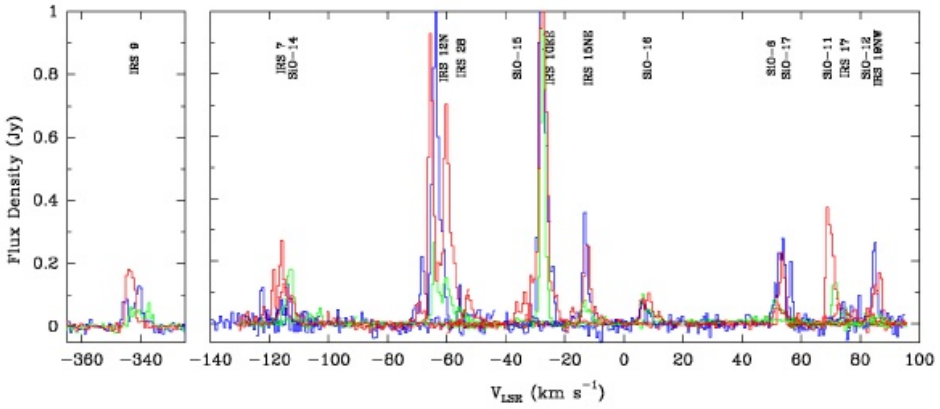


What can radio observations tell us?...

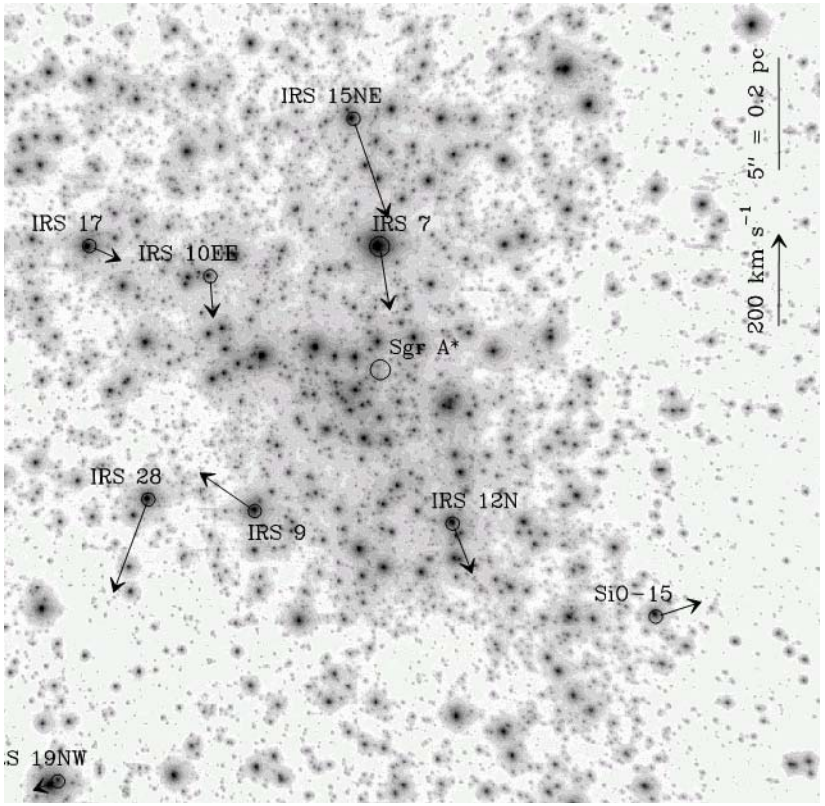
Where is the Galactic Center?



Where is the Galactic Center?



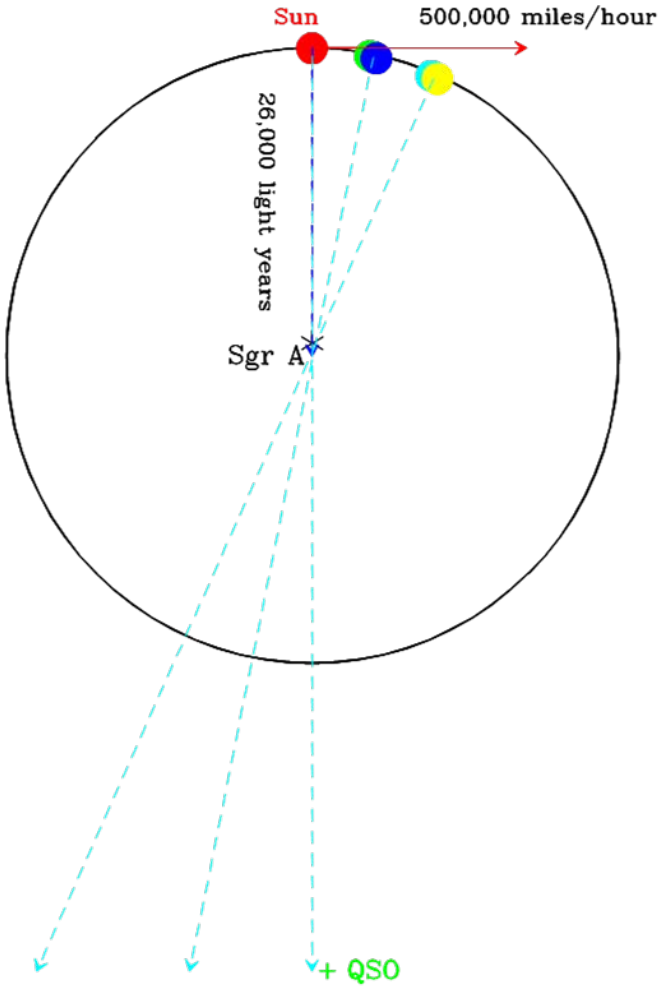
Combined IR + Radio astrometry shows Sgr A* at focal position of stellar orbits (+/-10 mas)

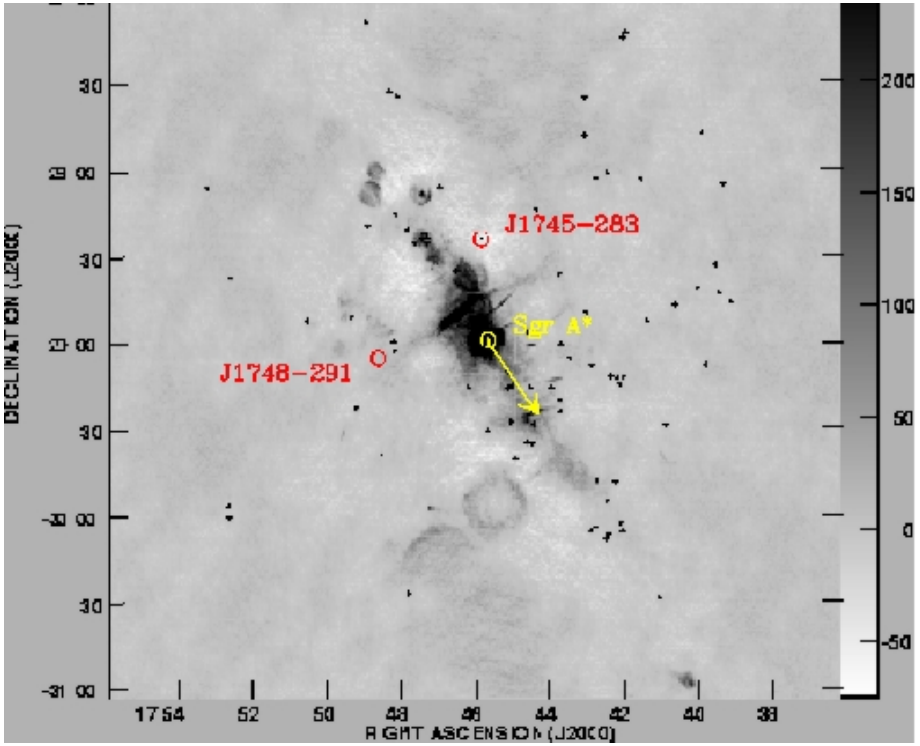


All stars there move fast.

How fast does Sgr A* move?

Sgr A* 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

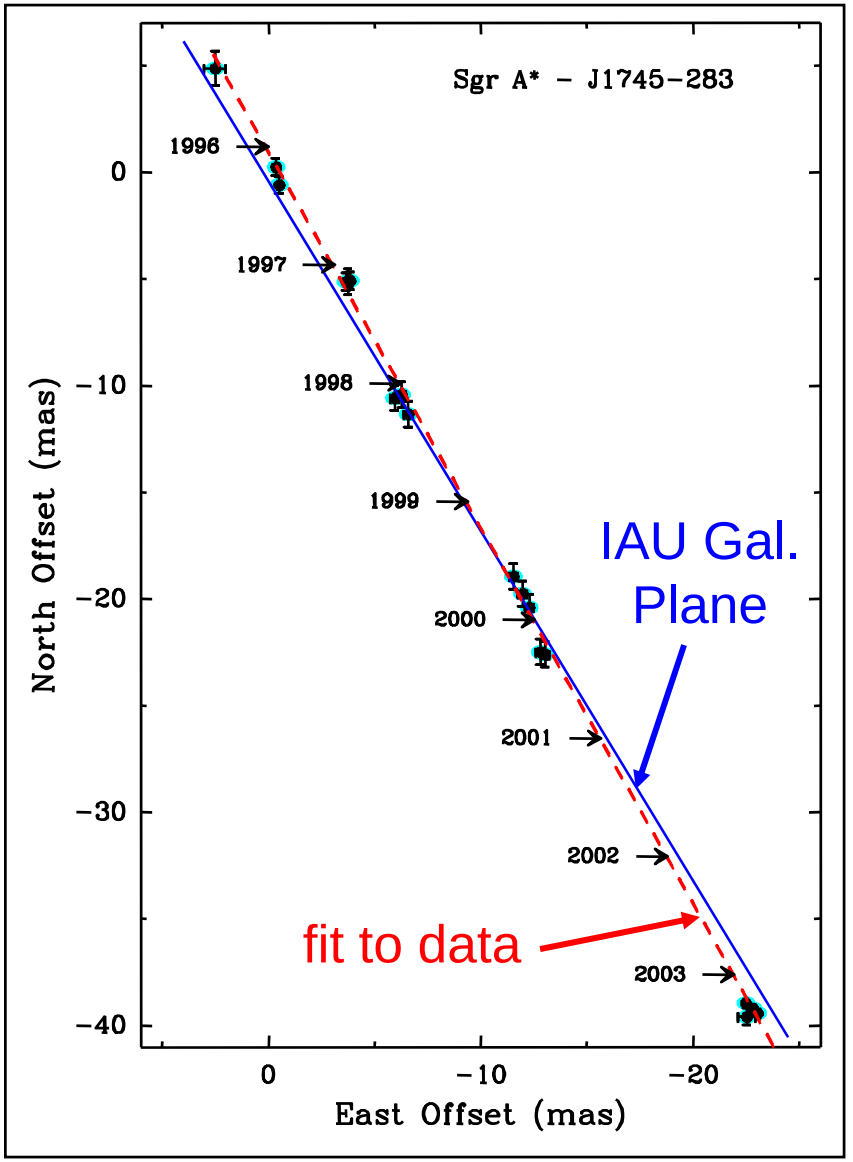
- Could re-define Galactic Plane

  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)

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}

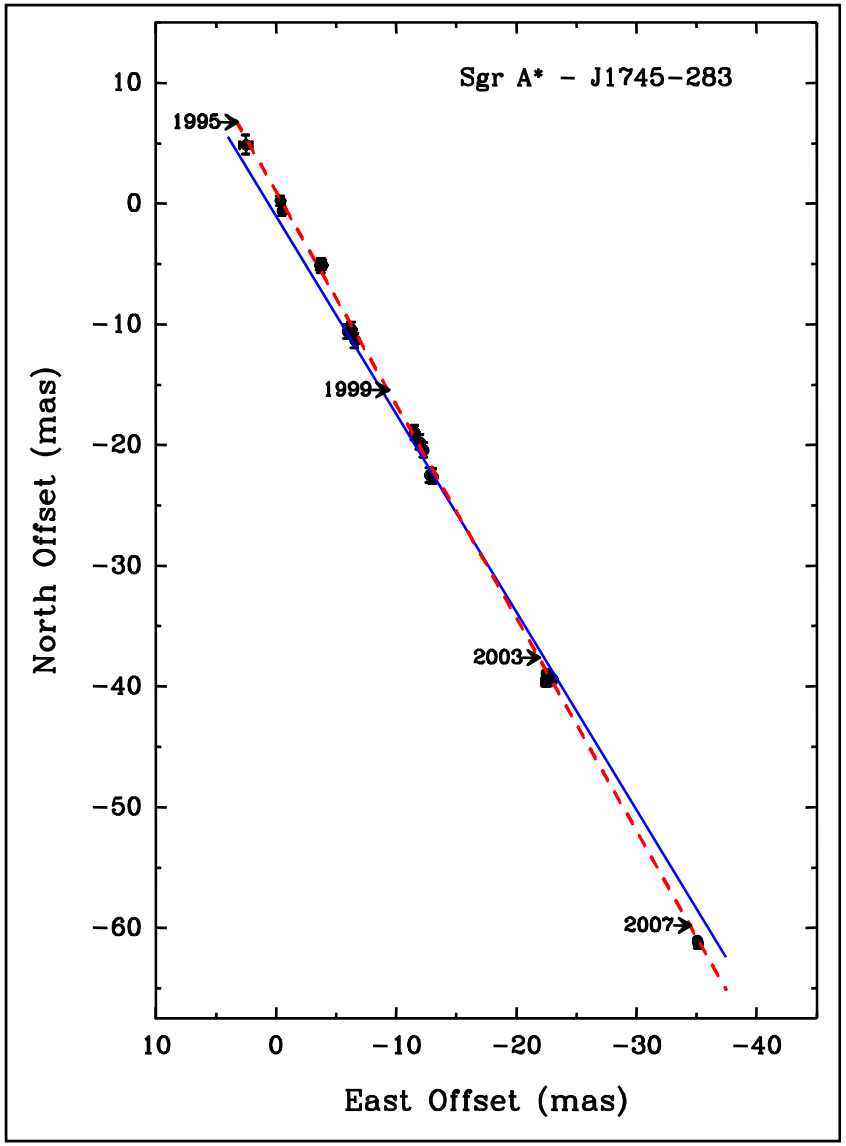
Observed size:

$R < 0.5$ 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?

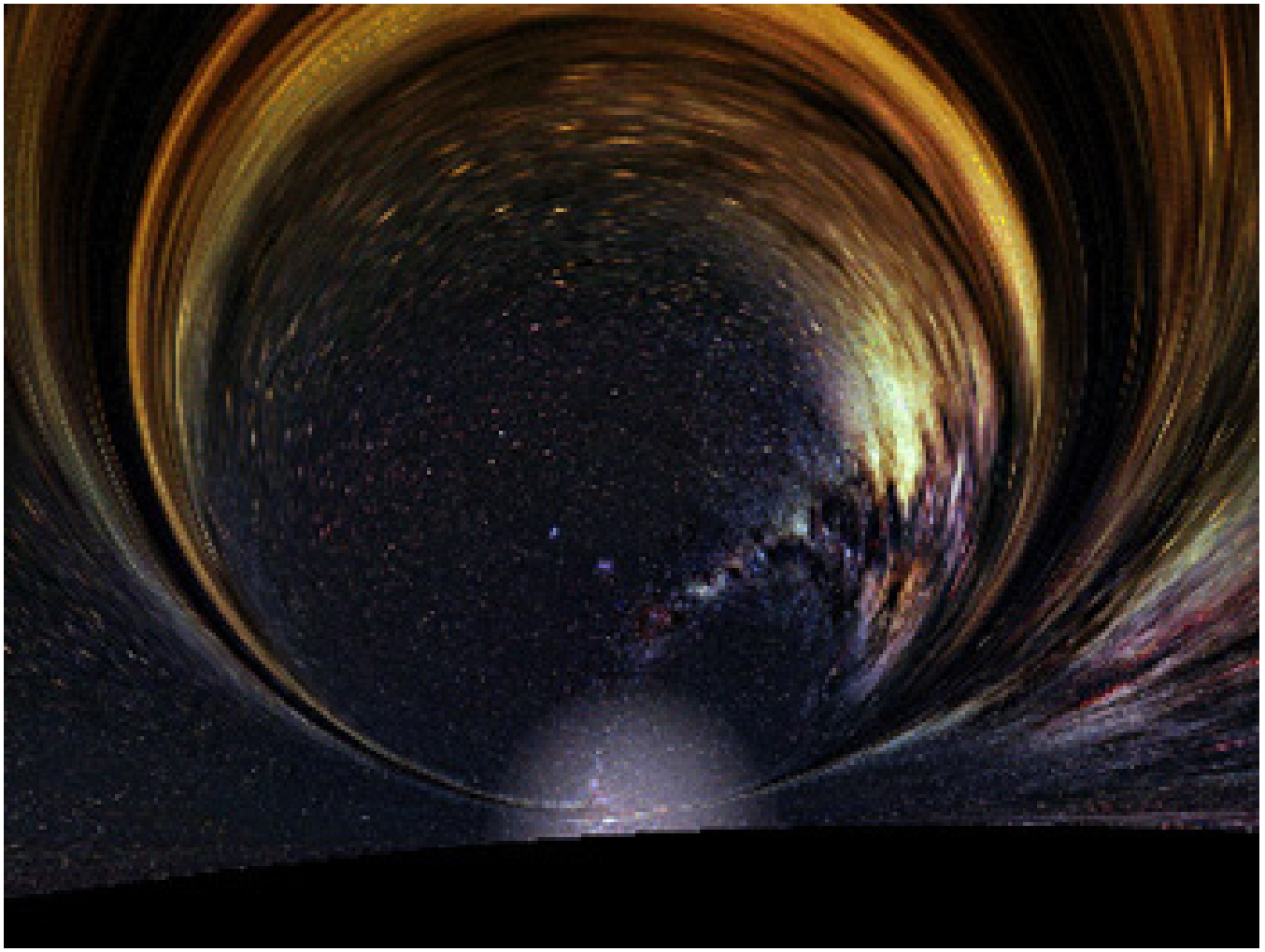
Object	Density (M_{sun}/pc^3)	Method	Mass within Radius (M_{sun})	
M 87	10^6	HST	$3x10^9$	7 pc
NGC 4258	10^{10}	VLBA : H_2O	$4x10^7$	0.1 pc
Sgr A*	10^{17}	IR Star orbits	$4x10^6$	50 AU
Sgr A*	$>10^{22}$	VLBA p.m.	$>4x10^5$	0.5 AU
SMBH	10^{24}	$3R_{Sch}$	$4x10^6$	3*0.08 AU

$3R_{Sch}$ = 30 μas @ 8 kpc

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

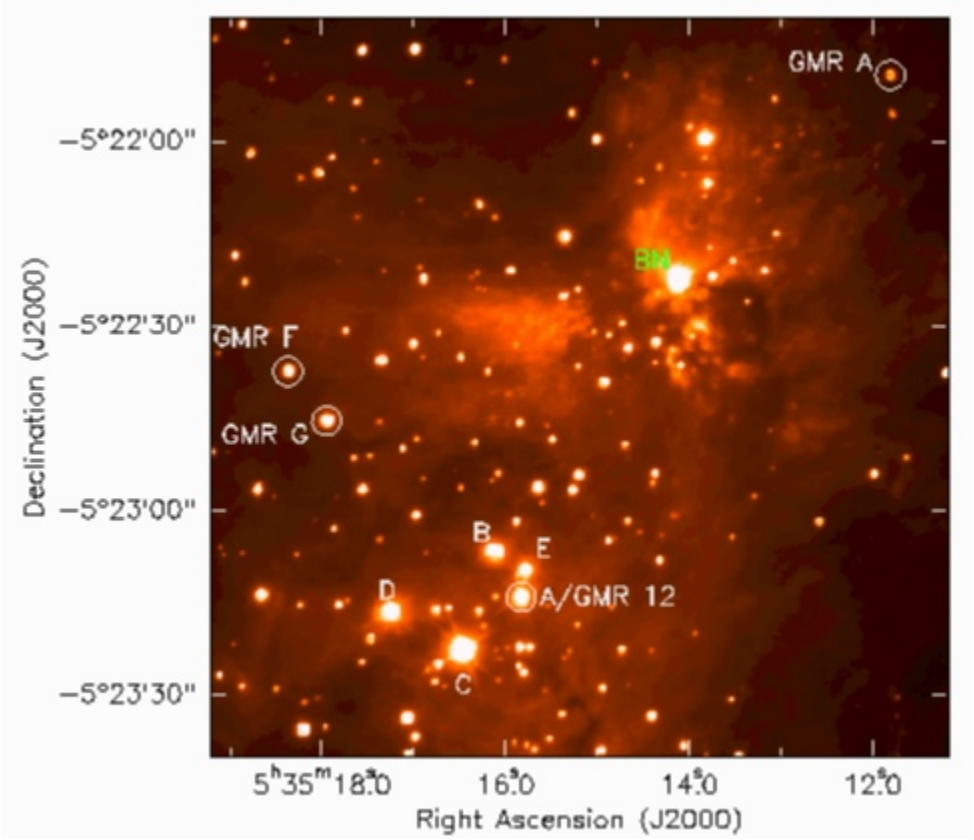
Fringes: Hawaii→Arizona @ 1.3mm (60 μas) ! (Doeleman et al 2008 Nature 455 78)

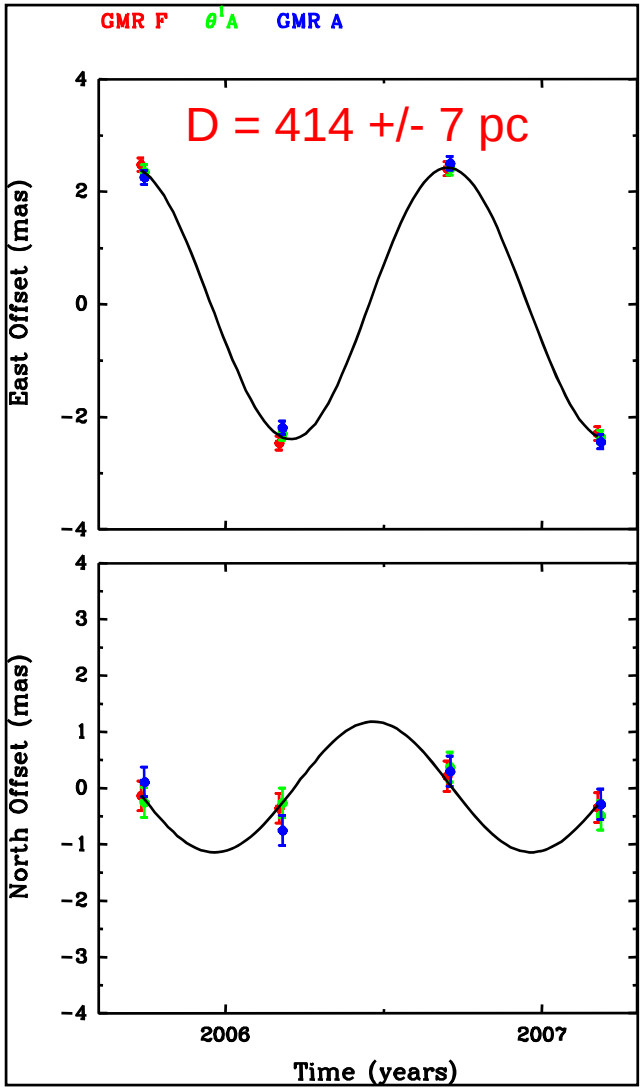
Milky Way Viewed From Inside Sgr A*



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

Orion Nebular Cluster Parallax





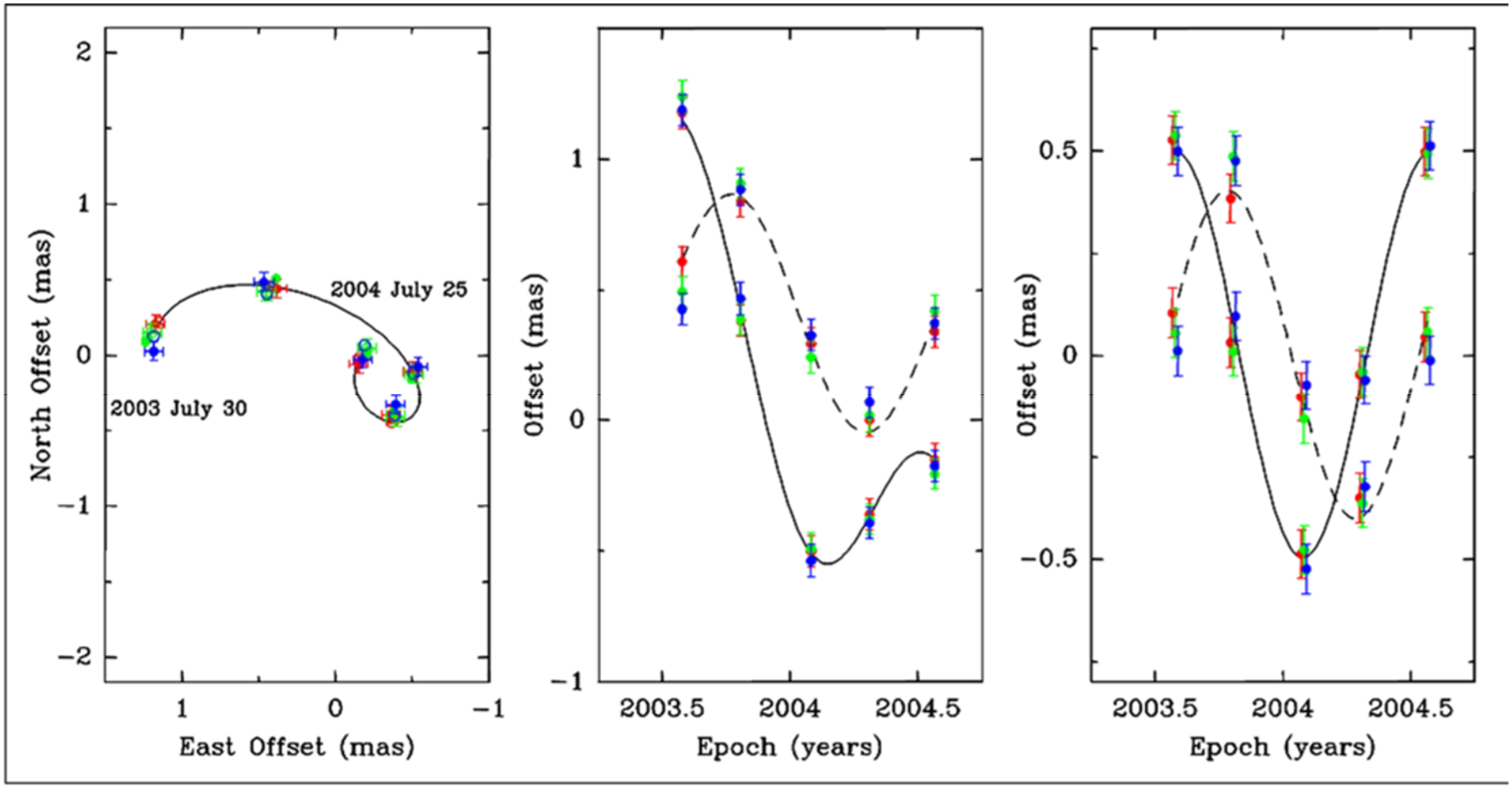
389 +/- 22 pc Sandstrom et al (2007)

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

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

Menten, Reid, Forbrich & Brunthaler (2007)

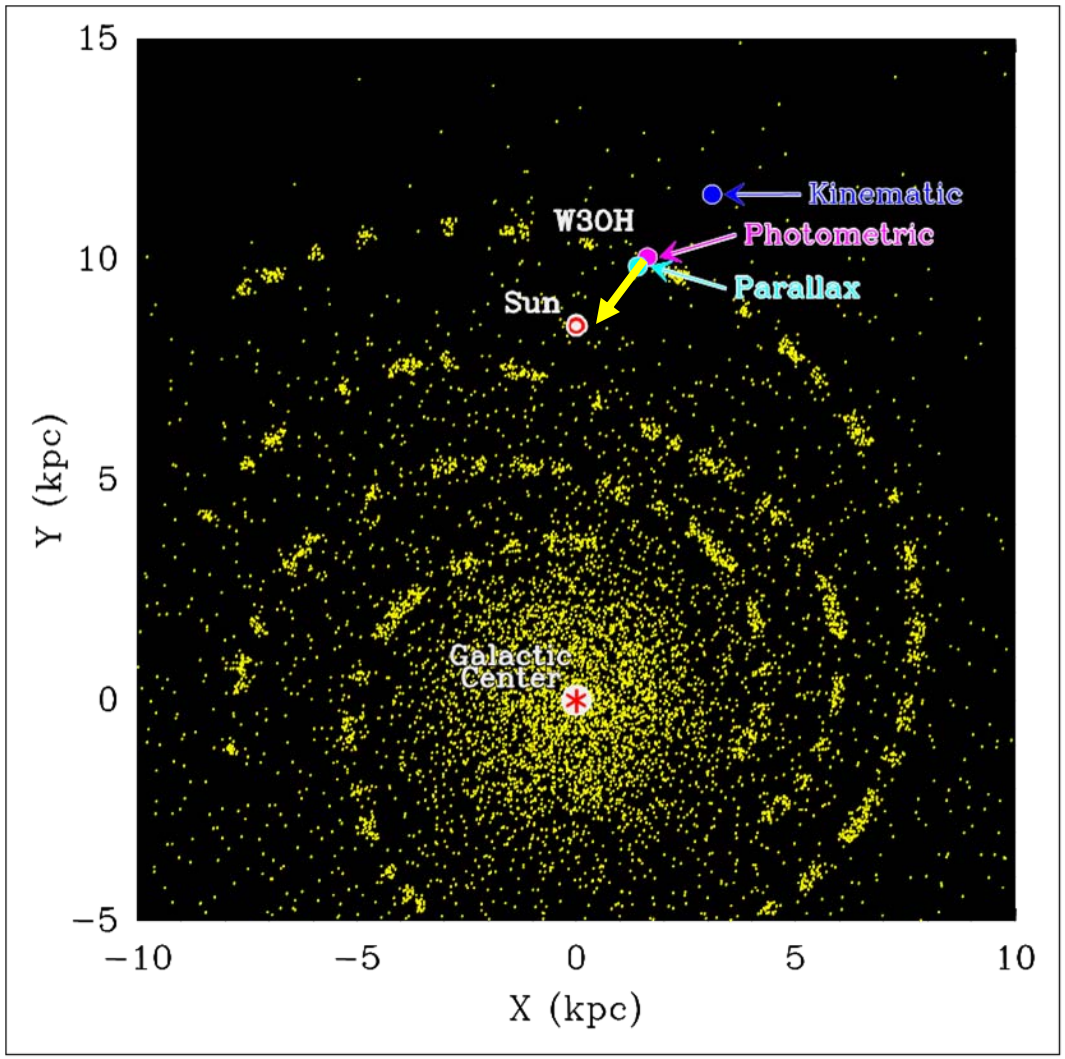
W3OH Parallax



Xu, Reid, Zheng & Menten (2006)

$\pi = 0.512 \pm 0.010$ mas

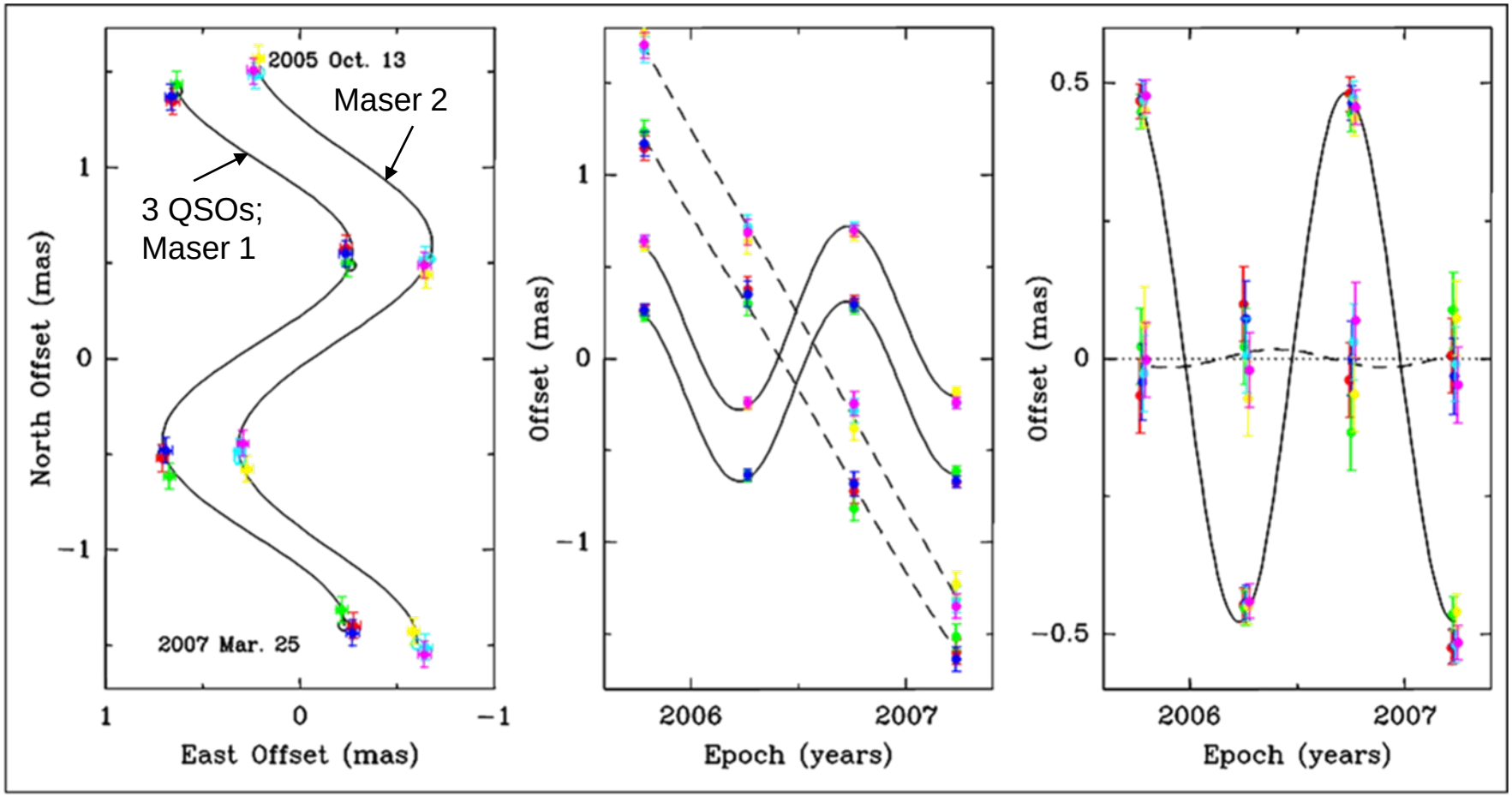
W3OH Parallax



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

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

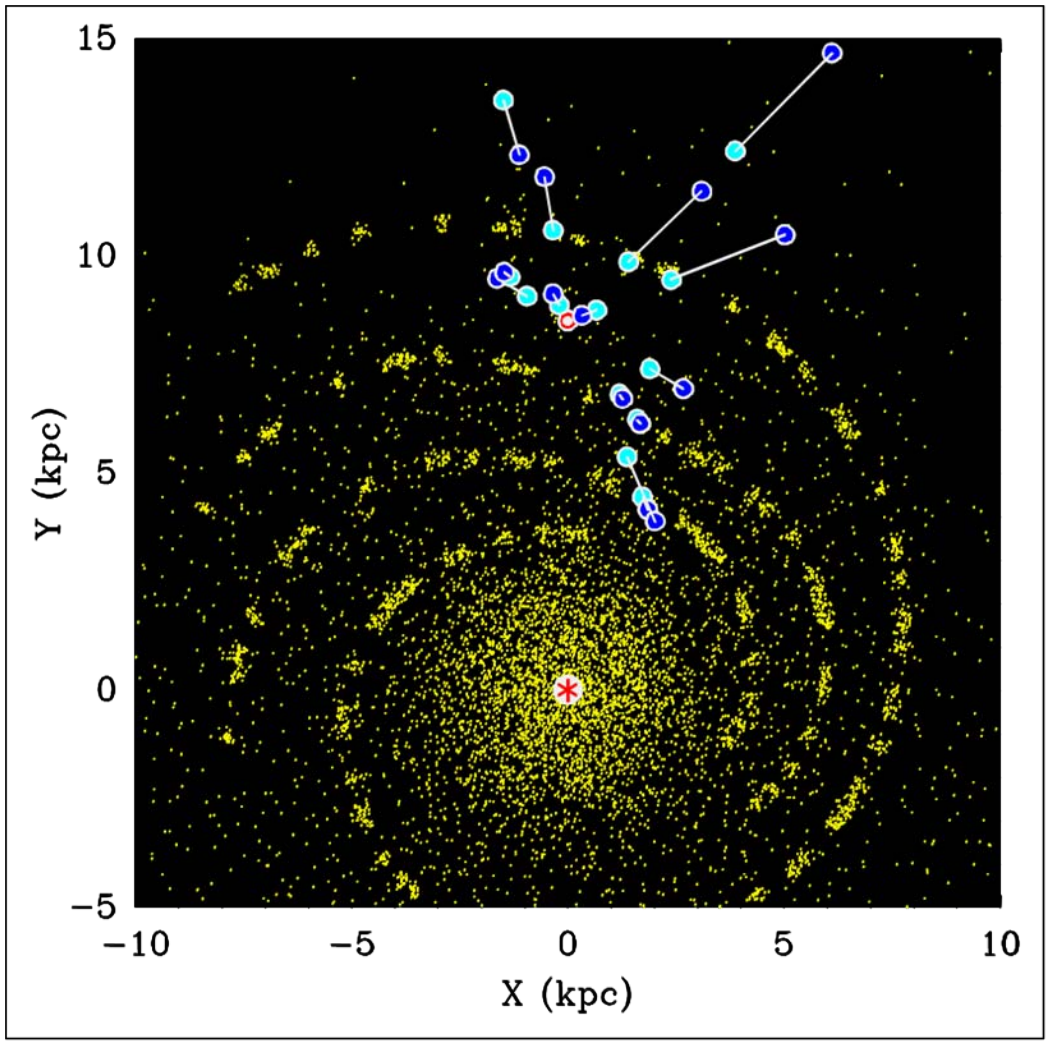
S 252 Parallax



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

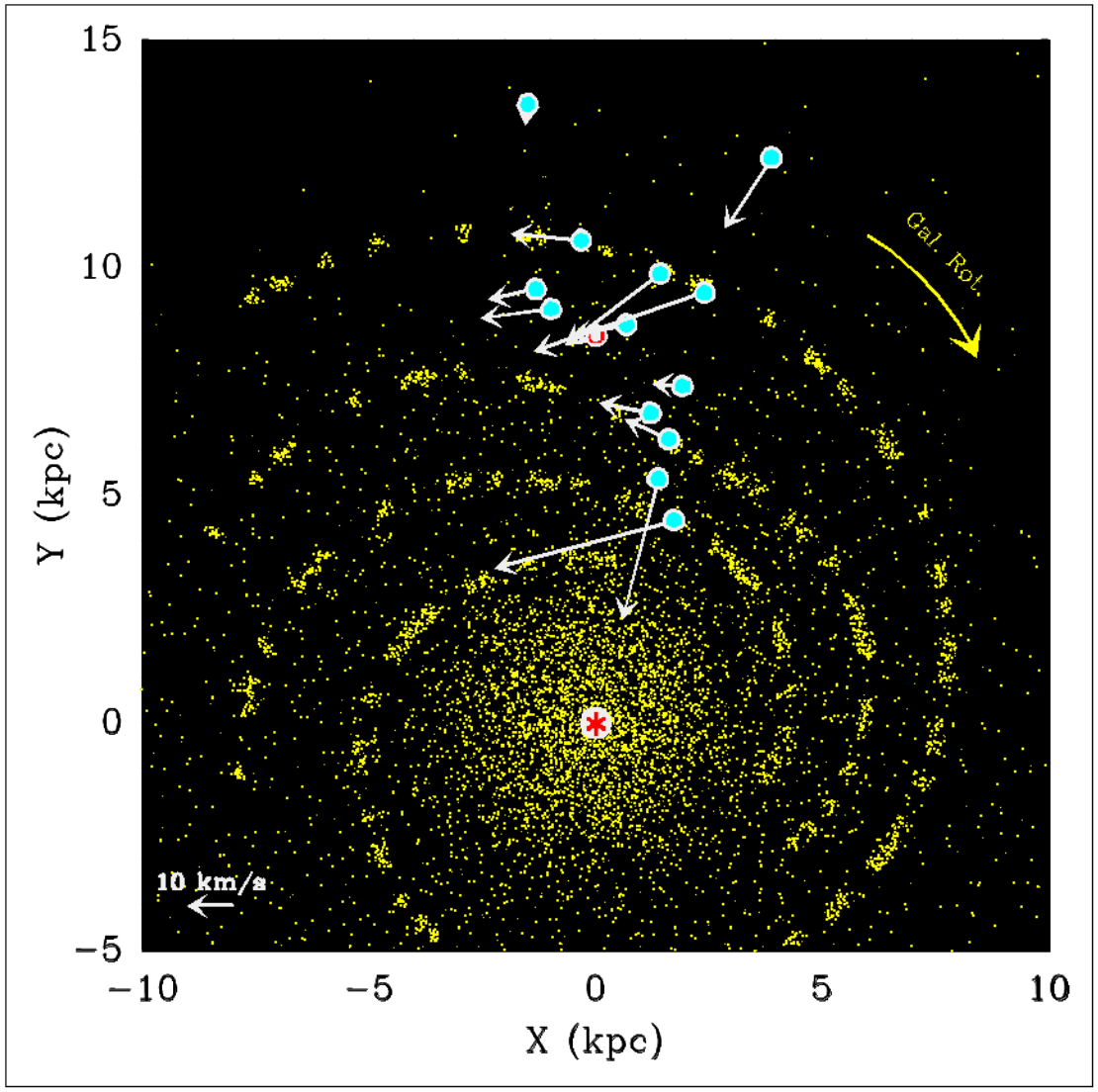
$= 236 / 8.0$

$= 251 / 8.5$

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

Honma et al; Hachisuka et al

Peculiar Motions of Star Forming Regions



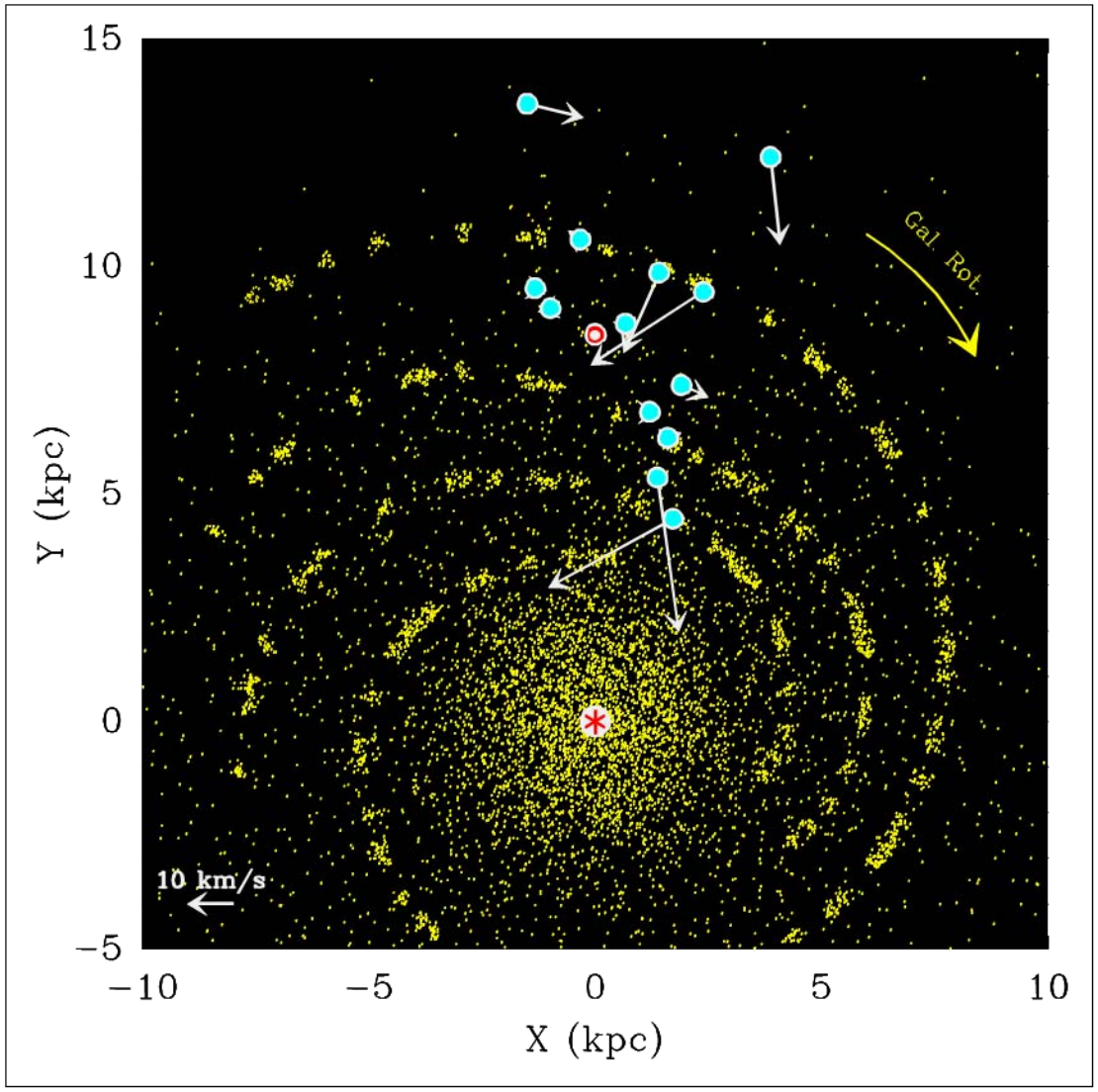
- In rotating frame:
  R_o = 8.5 kpc
  Θ_o = 220 km/s

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

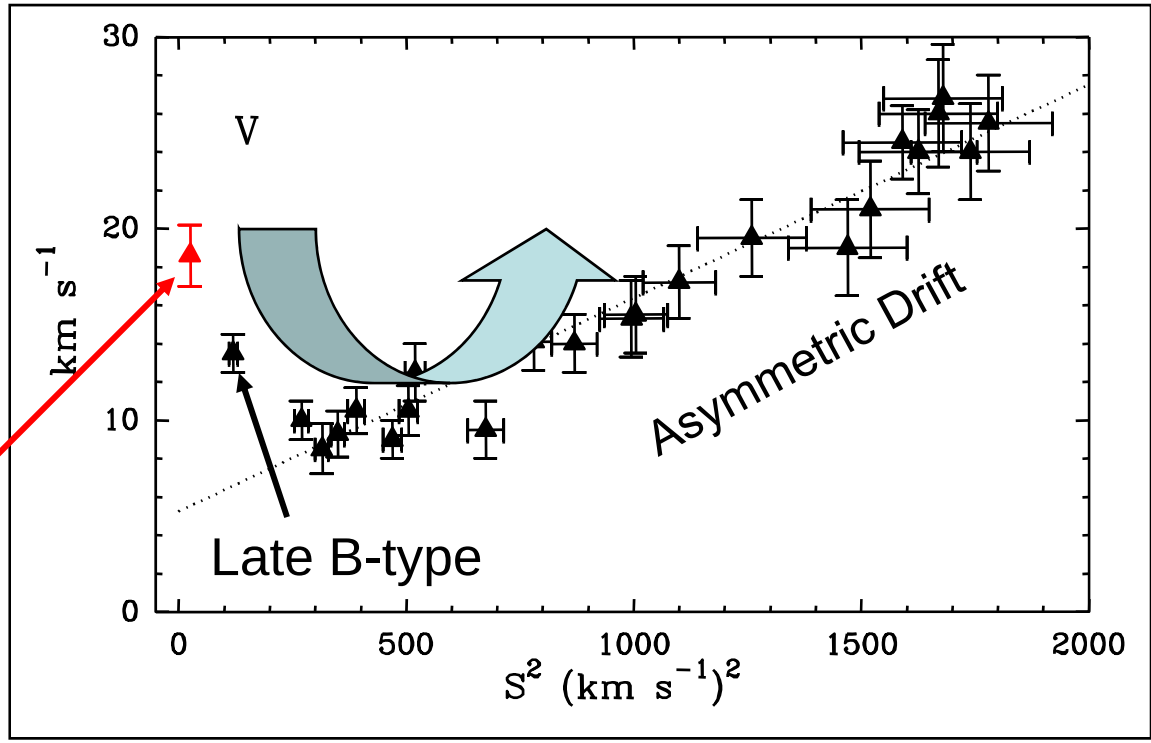
Residual motions considerably smaller

Solar Motion

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

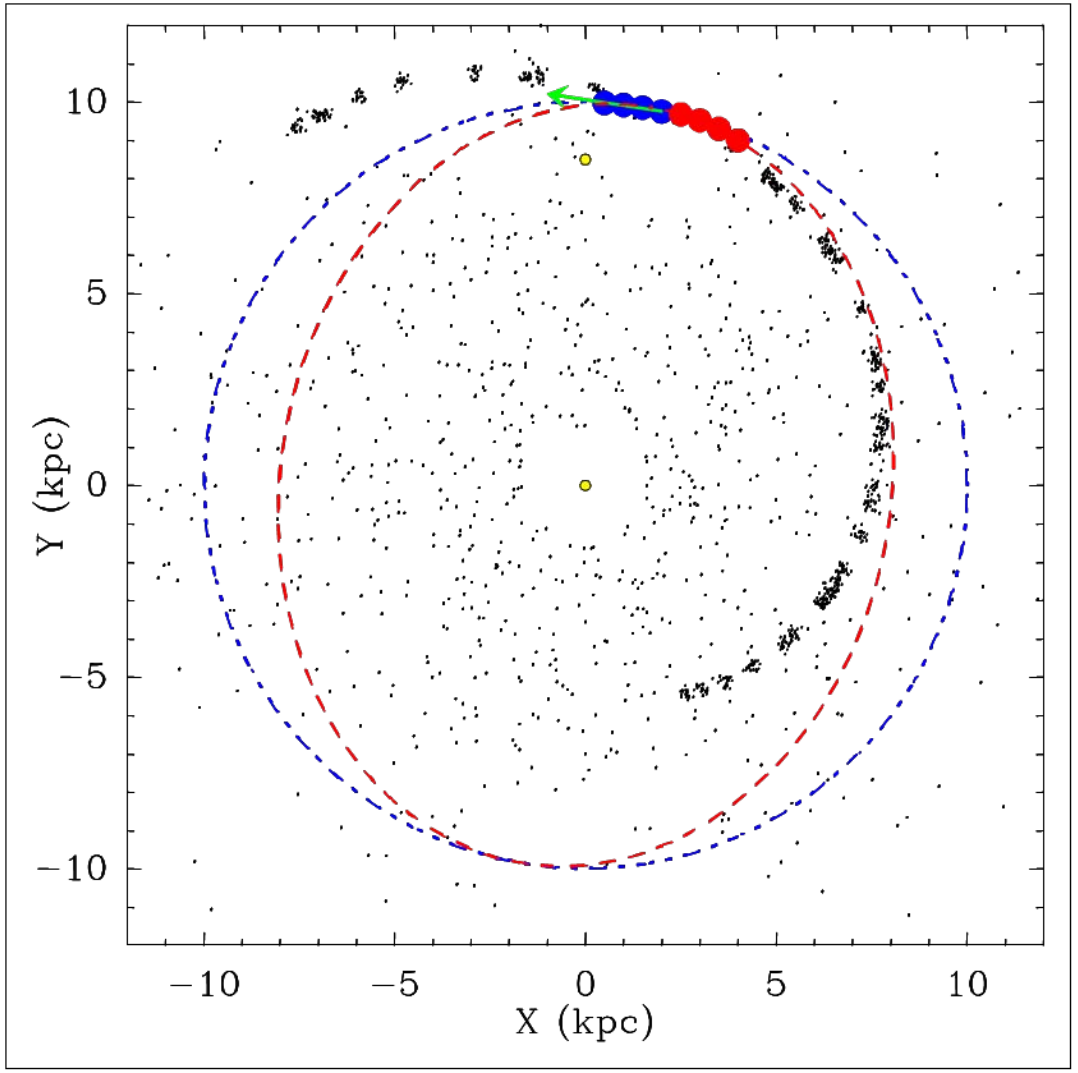
Massive stars born rotating ~13 km/s slower than Galaxy spins;

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



Extreme Supergiants

Extreme red supergiants with L → 10^6 L_{sun}

"Fabulous 4": NML Cyg, S Per, VY CMa, VX Sgr

H_2O and SiO masers in circumstellar envelopes

VY CMa

0.4 < D < 1.8 kpc

Association with NGC 2362 → D = 1.5 kpc (M-S fitting)

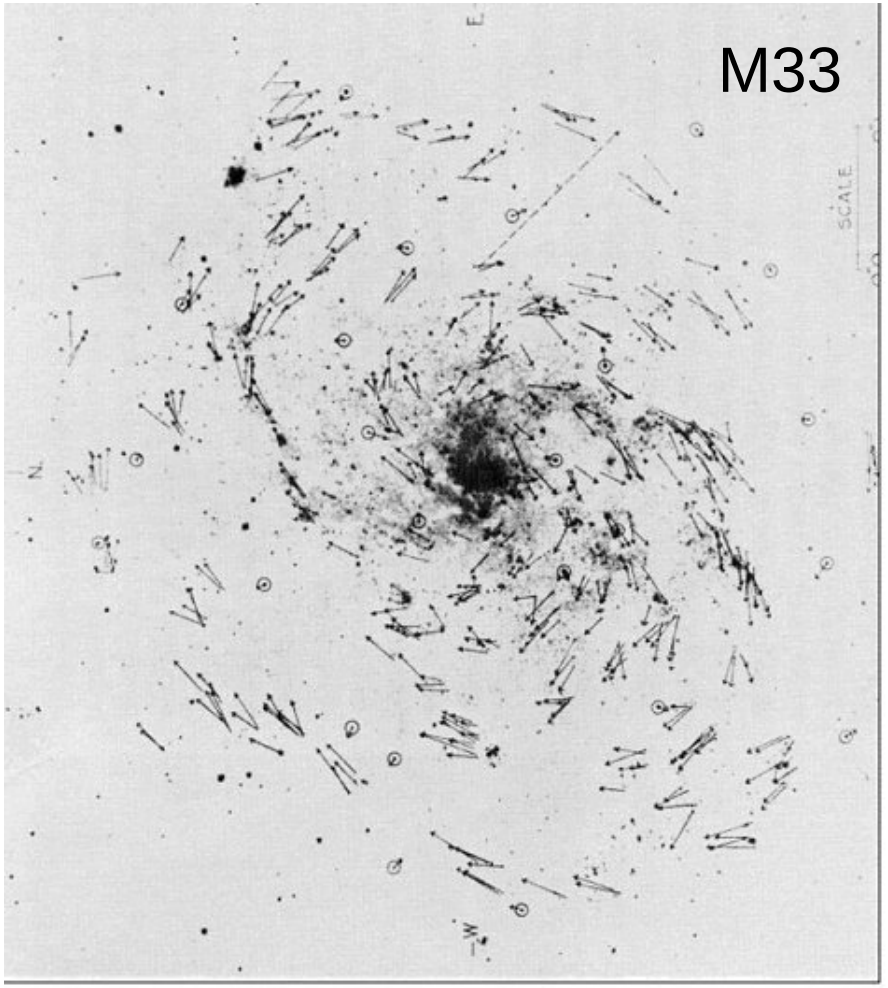
Parallax measured to be 1.1 kpc...

L = 3 x 10^5 L_{sun} (quite reasonable)

NGC 2362 cluster closer than thought?

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

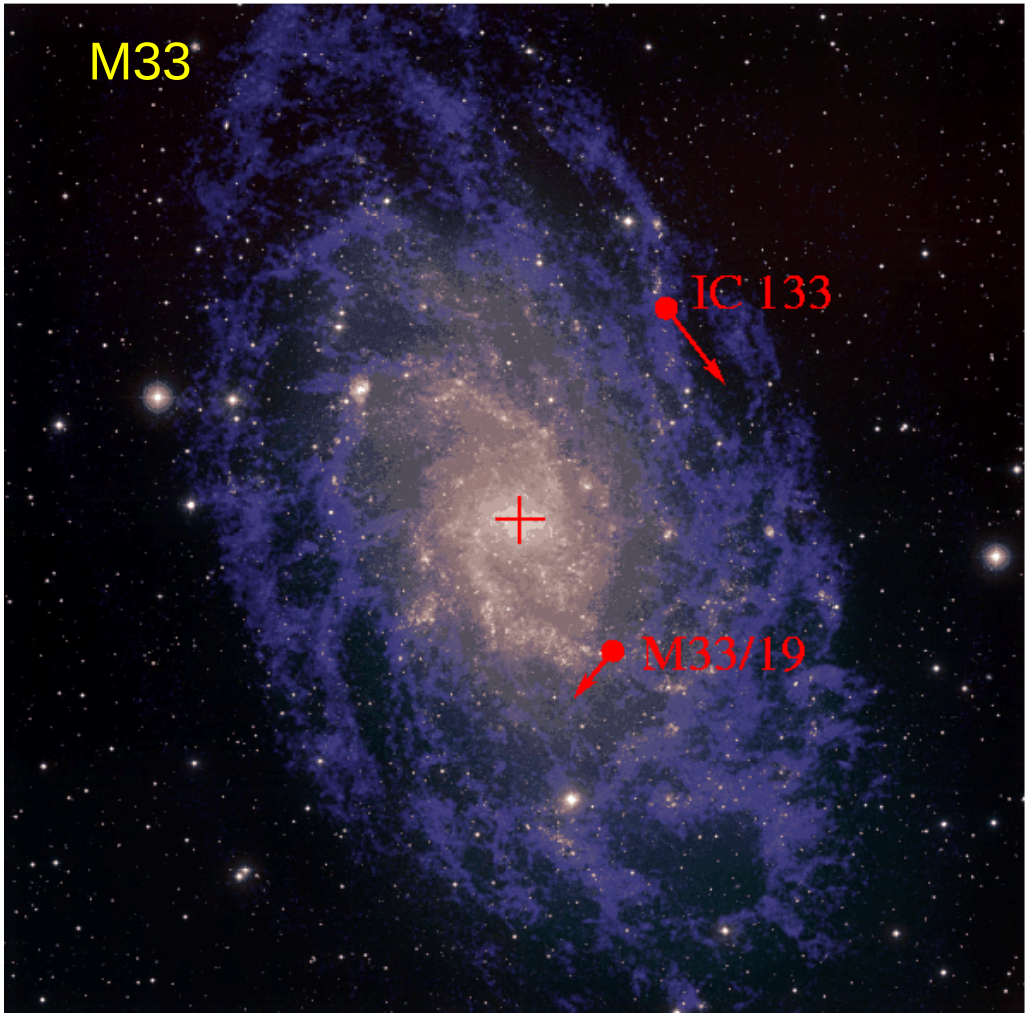


Extragalactic Proper Motions

- 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 & IC10
  1) see spin (van Maanen)
  2) see galaxy's motion



Andreas Brunthaler's PhD Thesis

Extragalactic Proper Motions

- M33/IC133 – M33/19 masers

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

HI: $\Delta v_x = 106 \pm 20$, $\Delta v_y = 35 \pm 20$ km/s

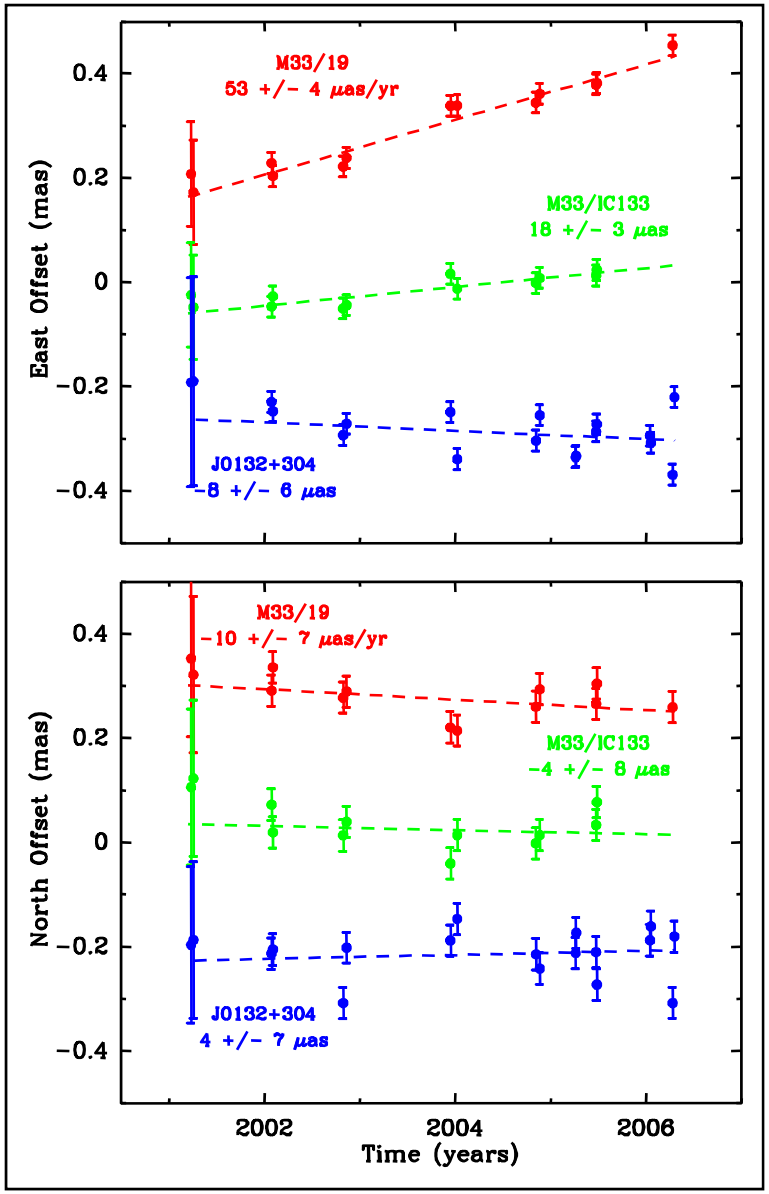
$D = 750 \pm 50 \pm 140$ kpc

σ_μ σ_V

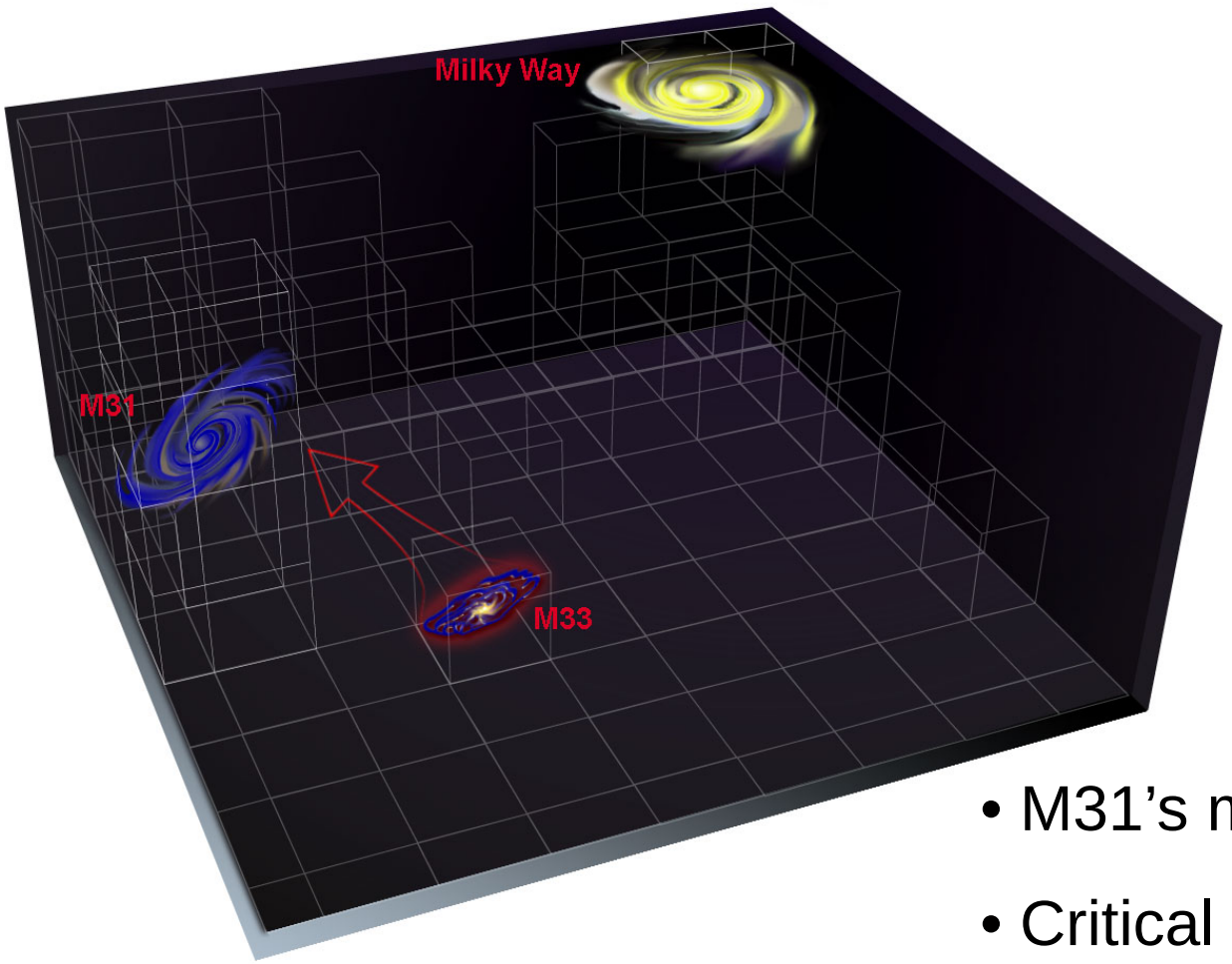
- Improvements in Rotation Model & 3rd maser source:

$\sigma_D < 10\%$ possible

Brunthaler, Reid & Falcke



Extragalactic Proper Motions



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

Tidal Heating of M33

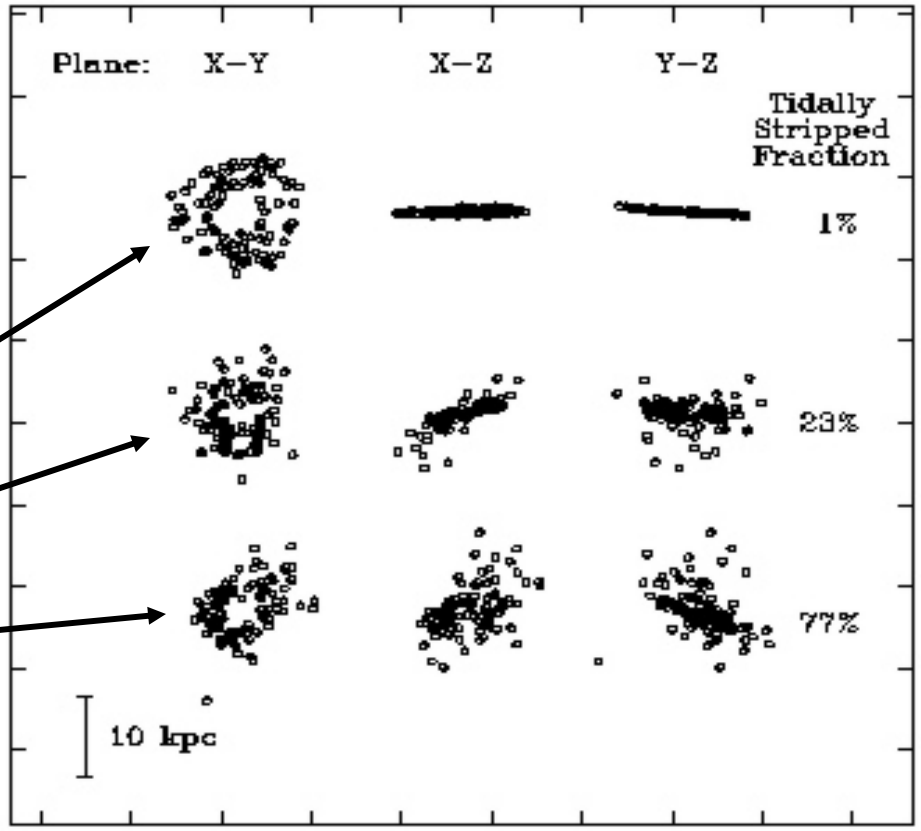
- Try M31 proper motions; then calculate orbits

- Tidal heating of M33 for trial proper motions of M31:

  μ_{M31} = (100,-100) km/s

  (-50, -50) km/s

  (0, 0) km/s

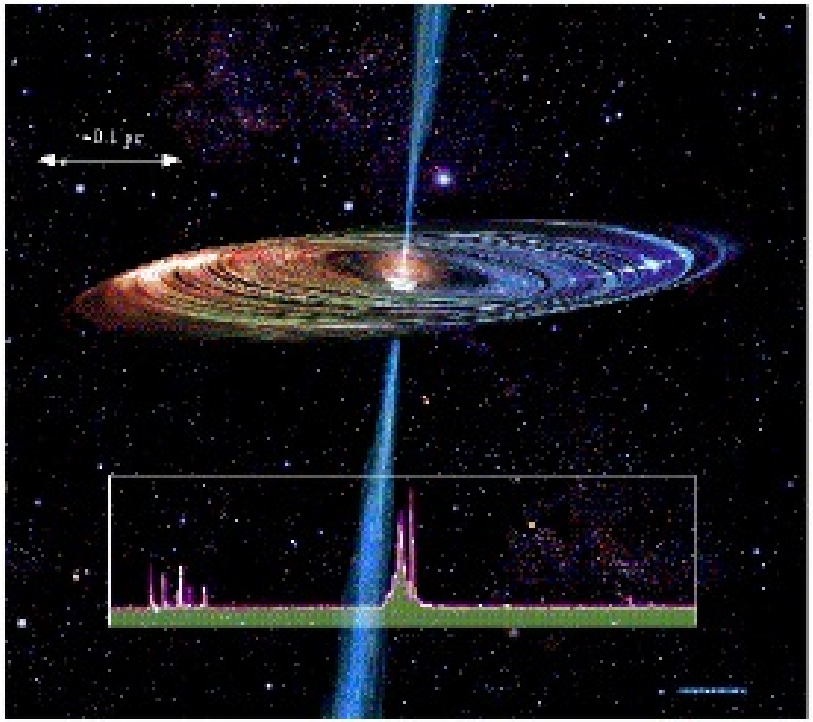


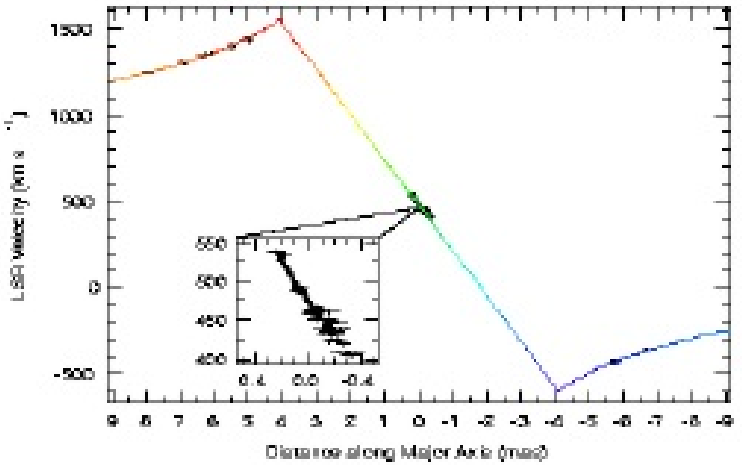
μ_{M31} ~ 0 km/s → M33 destroyed

μ_{M31} ~100 km/s → M33 OK

Loeb, Reid, Brunthaler & Falcke (2005)

NGC 4258

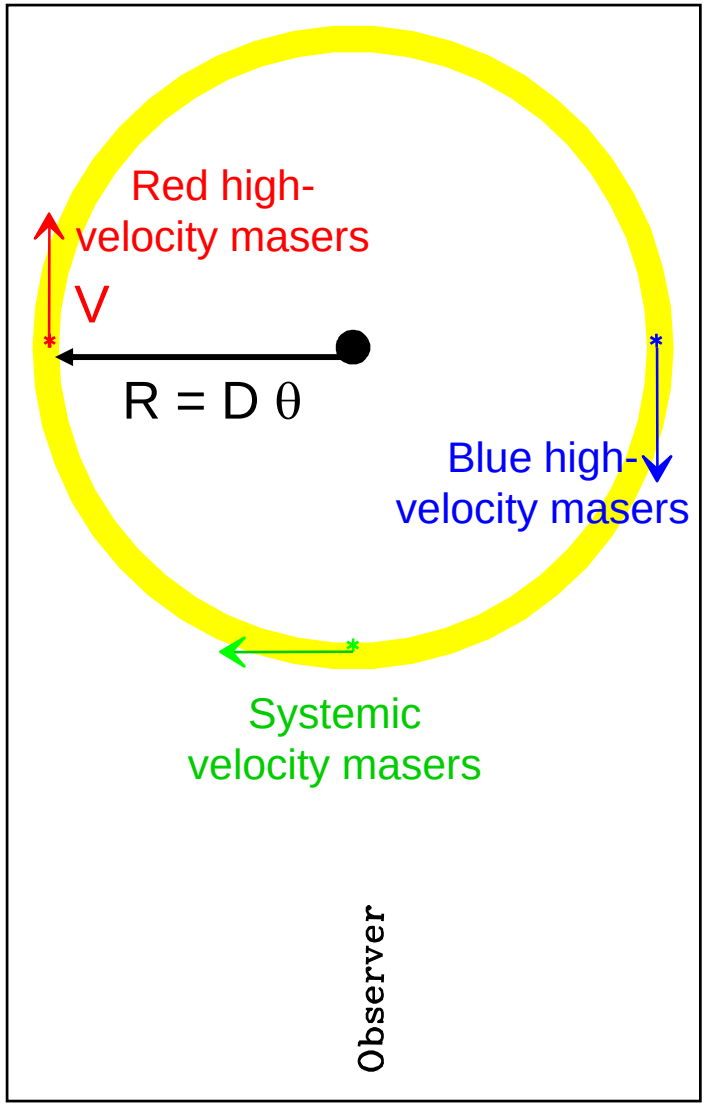




- Seyfert galaxy
- H_2O masers in an edge-on, sub-parsec disk
- Rotation speed ~1000 km/s
- $M \sim 3 \times 10^7 M_{sun}$
- Geometric model ➔ D = 7.2 +/- 0.5 Mpc
- Used by Hubble Key Project to re-calibrate Cepheid PL relation

Herrnstein, Moran, Greenhill et al (1999)

AGN Maser Distance Measurements



$A = V^2 / R$

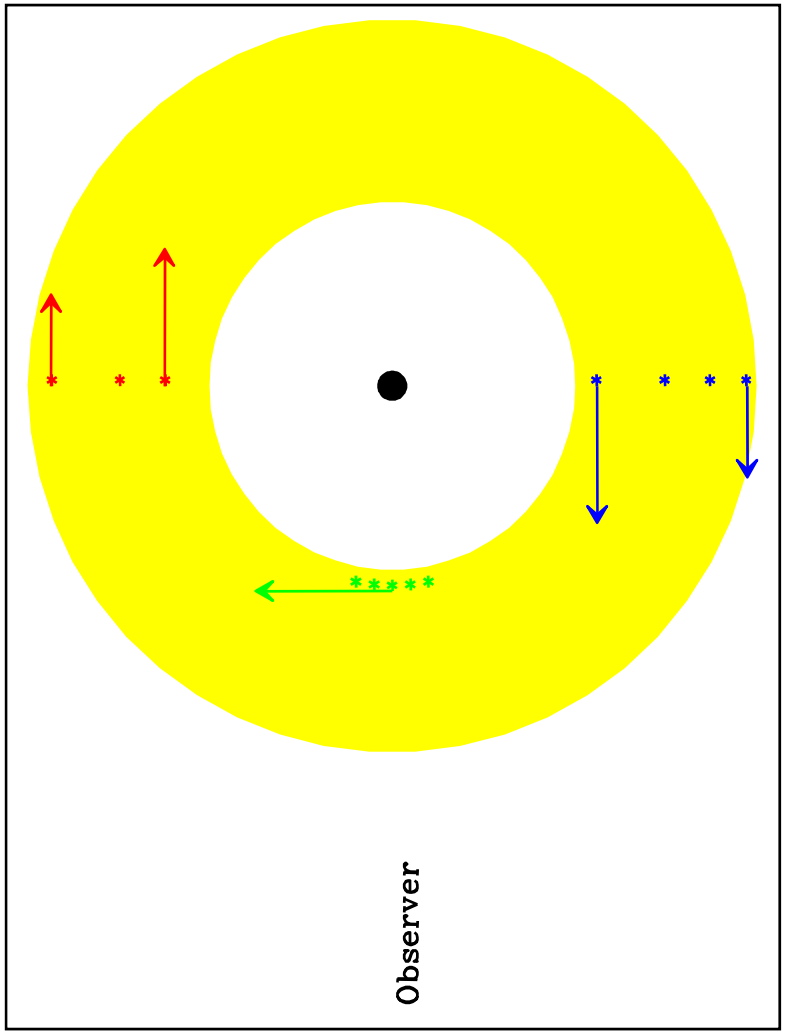
$R = D\,\theta$

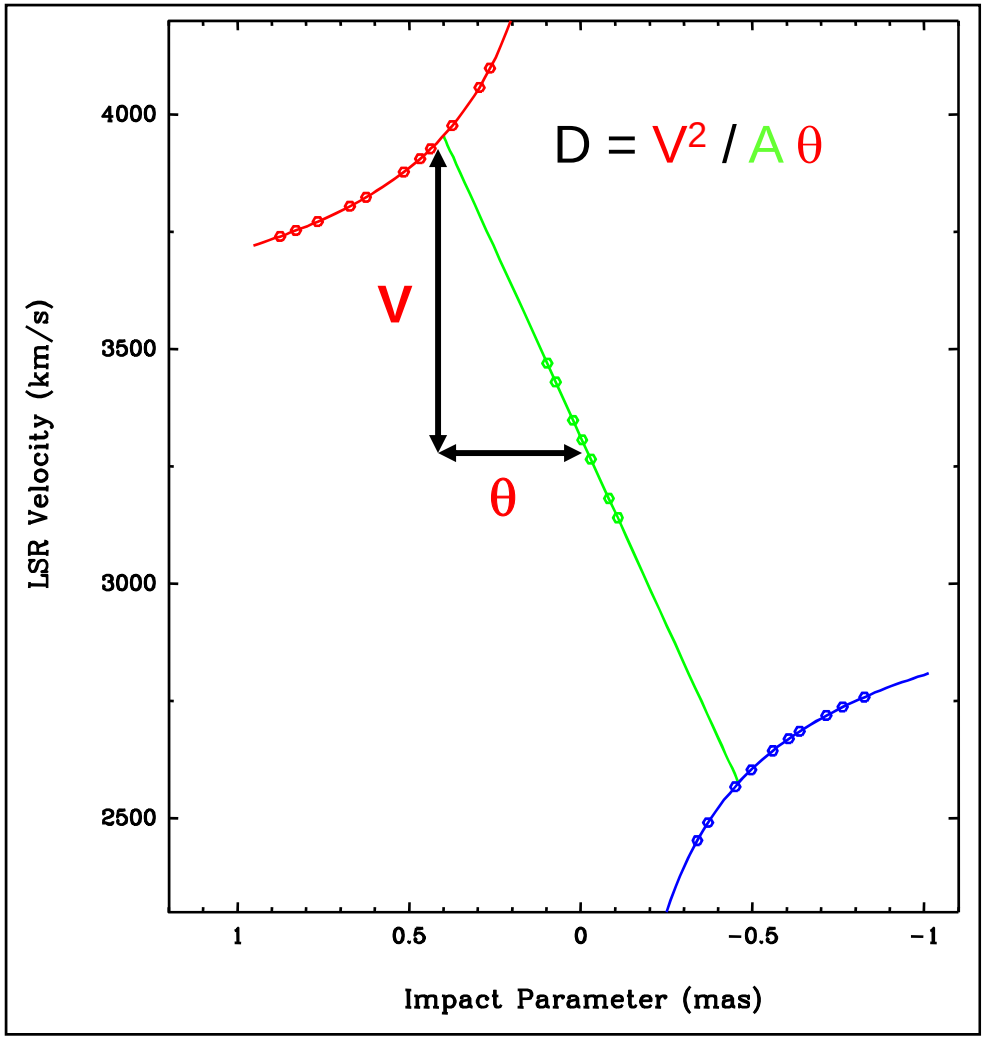
$\therefore \quad D = V^2 / A\,\theta$

High Velocity
Maser Map

Drift of systemic masers
over time

Maser Distance Measurements (2)



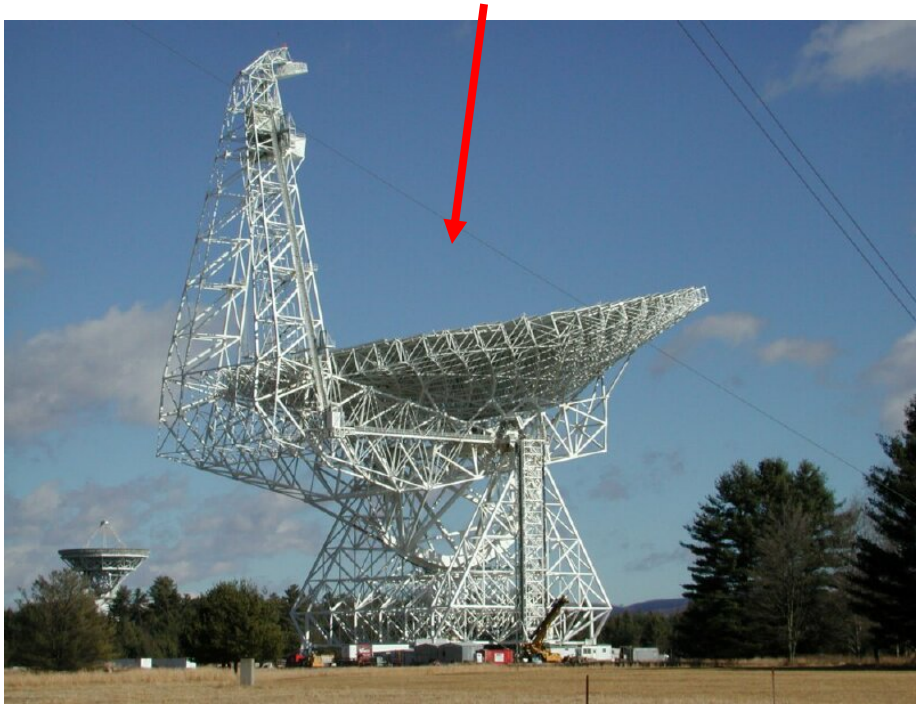


Maser Cosmology Project

Braatz, Condon, Greenhill, Henkel, Lo & Reid

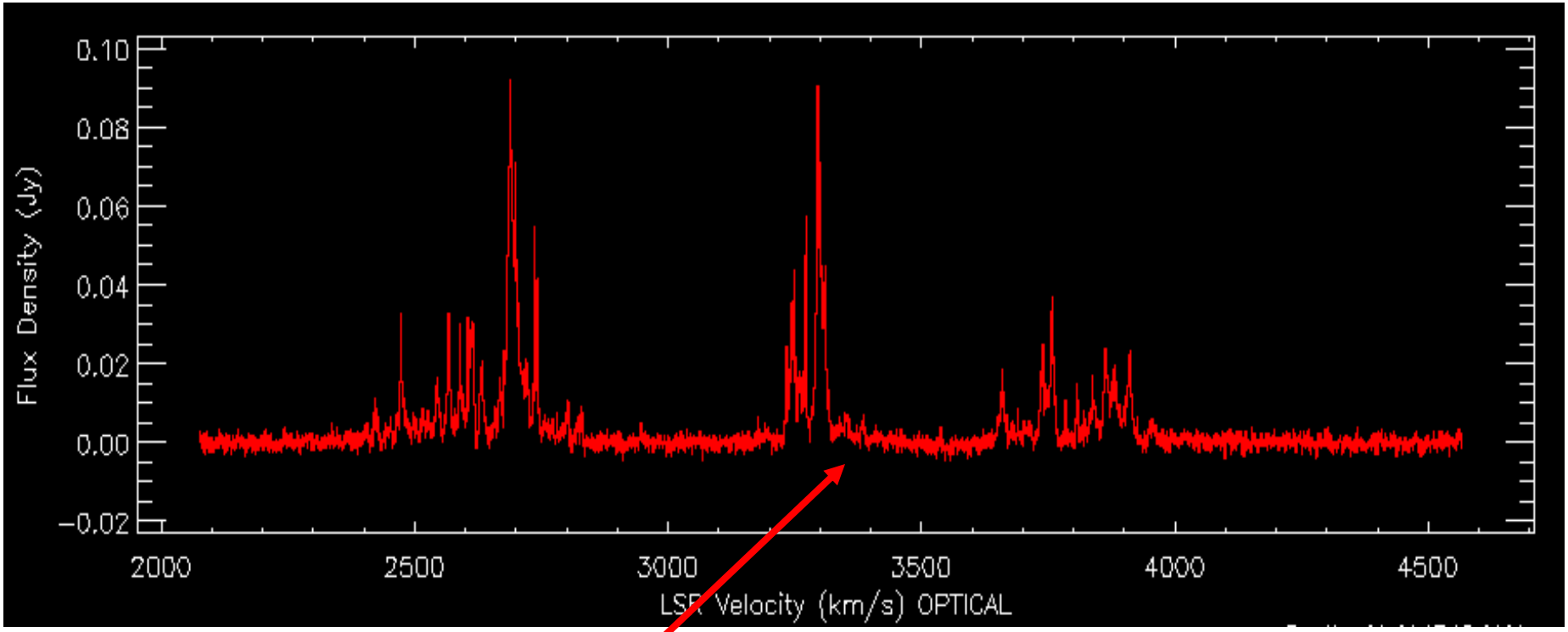
- Goal: H_o accurate to 3%; constain Dark Energy Eq. of State
- How: Geometric Distances to H_2O masers in Hubble Flow

GBT finds masers



VLBA maps them

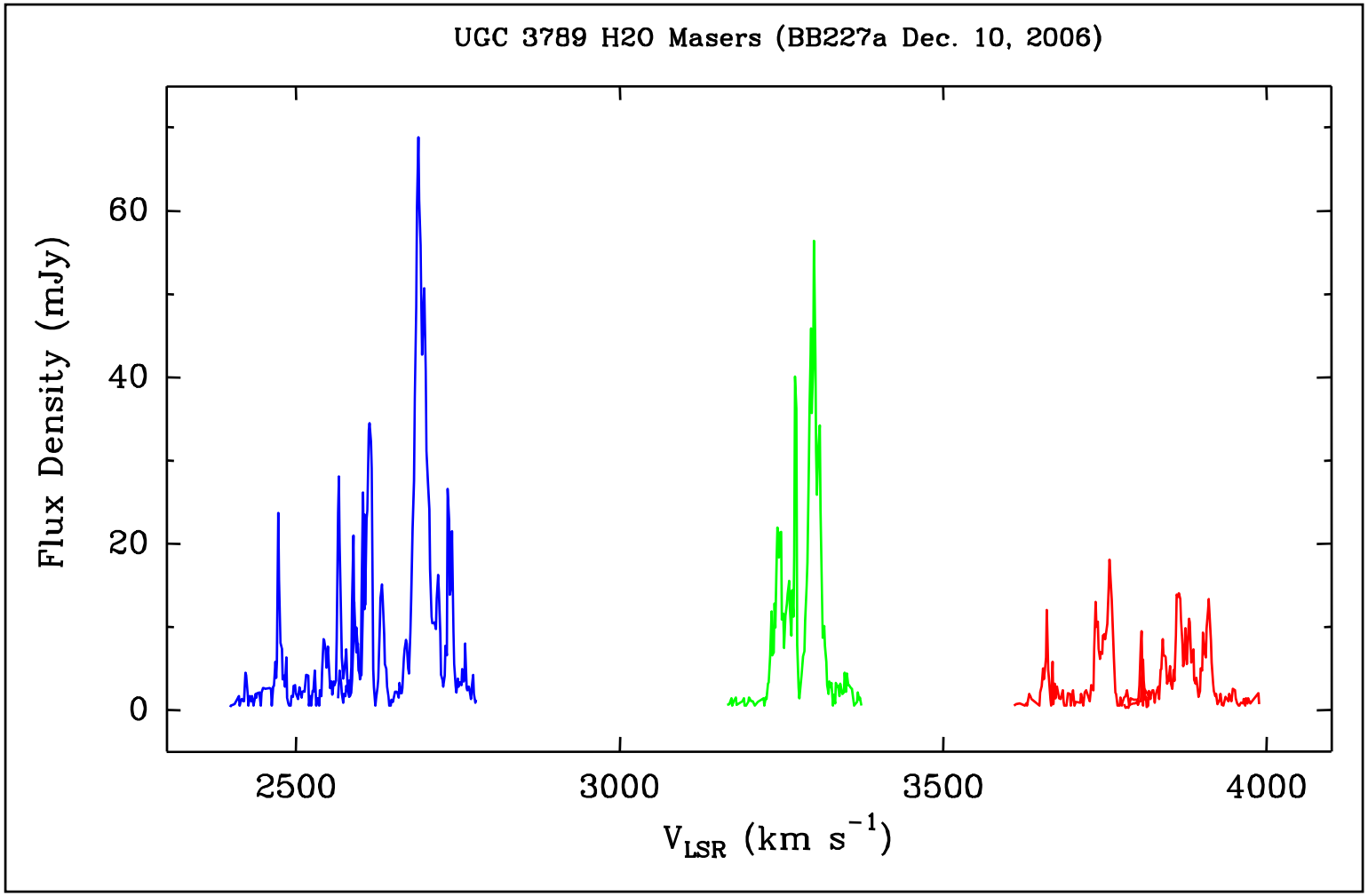
UGC 3789



J. Braatz: GBT

V_{CMB} = 3385 km/s ➔ D ~ 50 Mpc

UGC 3789: VLBA + GBT



Interferometer spectrum: rms noise ~1 mJy

UGC 3789 map

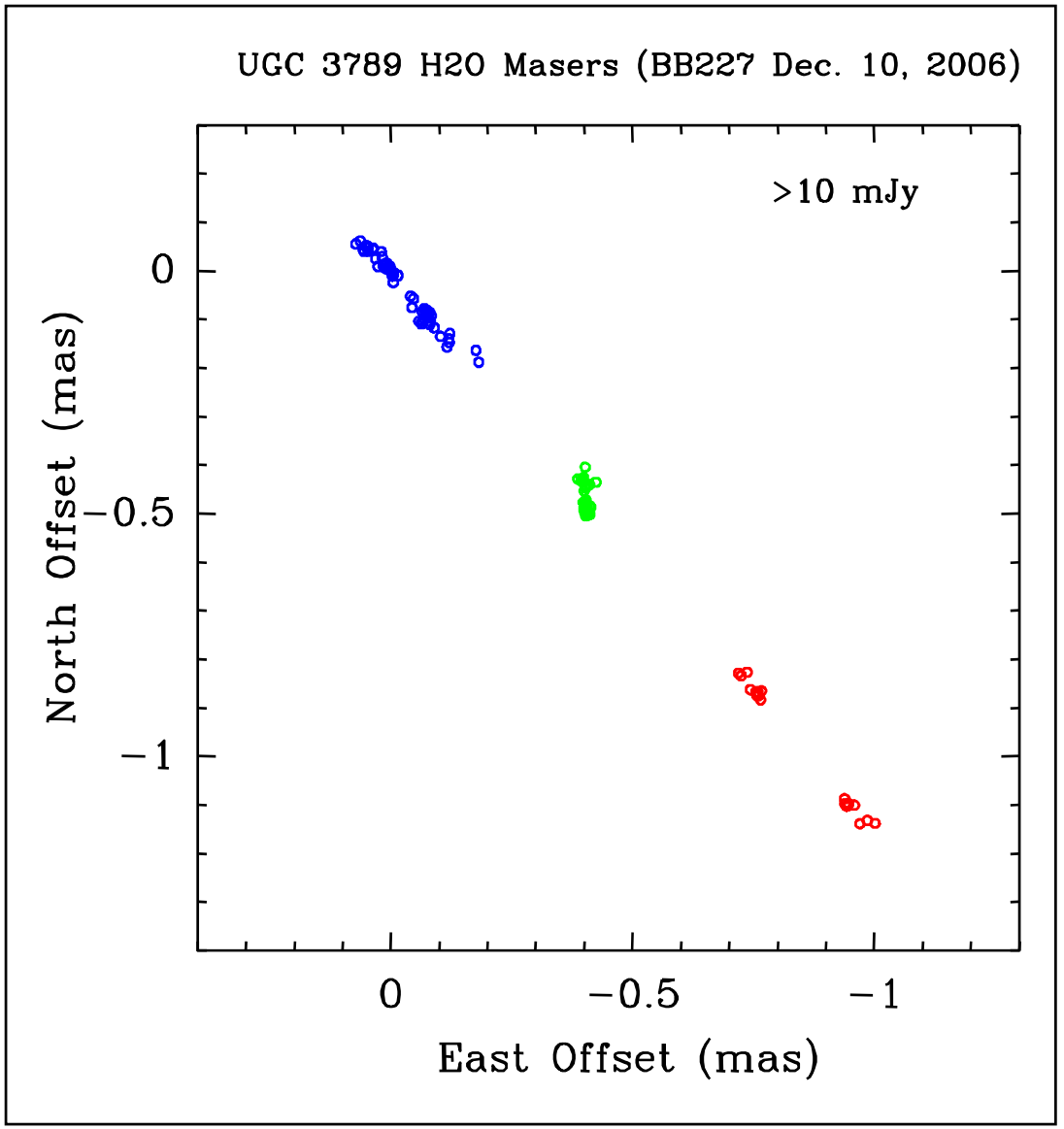
- Similar to NGC 4258

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

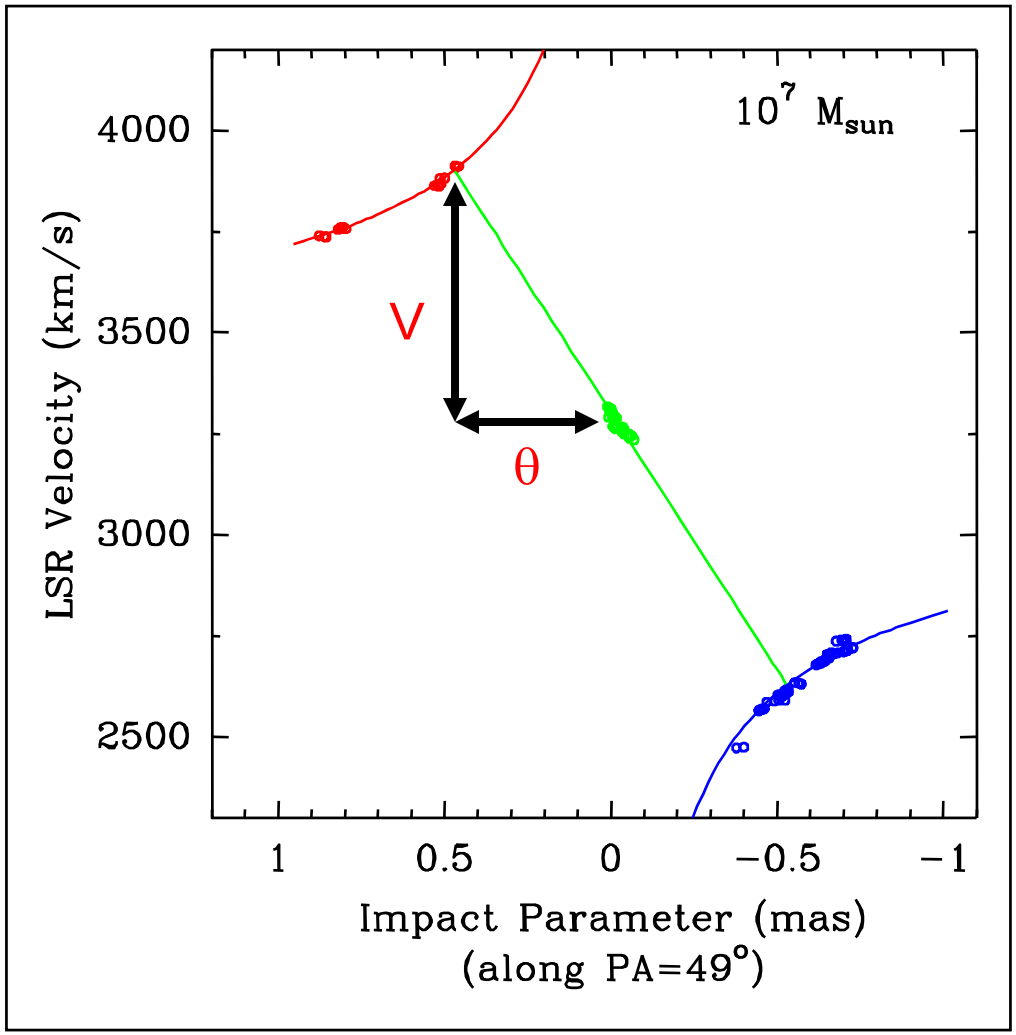
- Keplerian high vel. masers

  ~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 ~ 625 km/s

  θ ~ 0.52 mas

  A ~ 3.4 km/s/yr

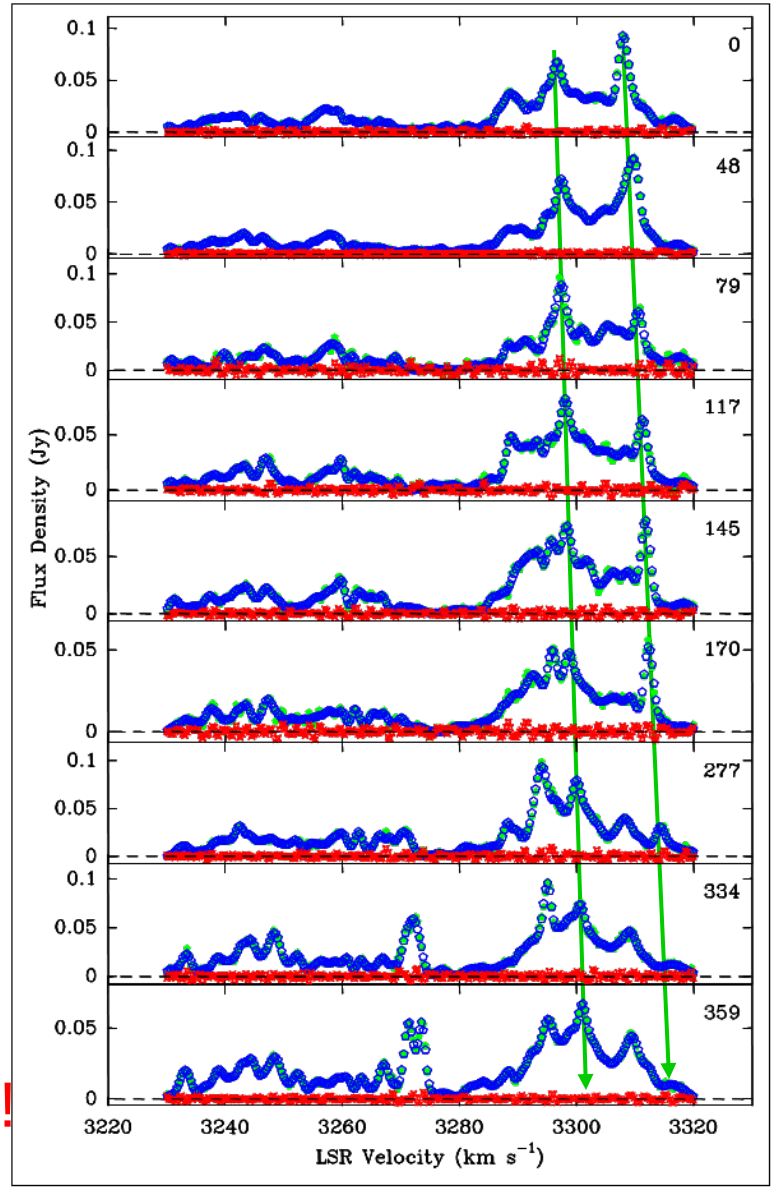
  } D = 47 Mpc +/- 5

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

  = 72 +/- 7 +/- 4

  from σ_D σ_{Vcmb}~200 km/s

- Comparable to Hubble Key Project!



The Next 5 Years

- R_o & Θ_o from parallax & p.m. data with 3% accuracy
- Map of Milky Way spiral structure
- Proper motions of ~4 Local Group Galaxies
- H_o with 3% accuracy from 5 to 10 AGN H_2O masers