Astrometry: What does RMS have to offer?

New Worlds, New Horizons:

Astrometry: a Frontier Discovery Area

“In this decade...

• GAIA will map out the structure of the Milky Way in exquisite detail, enabling us to complete our understanding of our galactic neighborhood.

Direct geometric measurements of distances

• to the galactic center,
• to major regions of star formation in the Milky Way,
• to nearby galaxies, and,
• most importantly, to galaxies at cosmological distances are possible using precision radio astronomy."

The Very Long Baseline Array (VLBA)

Comparable future space missions like GAIA and 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)

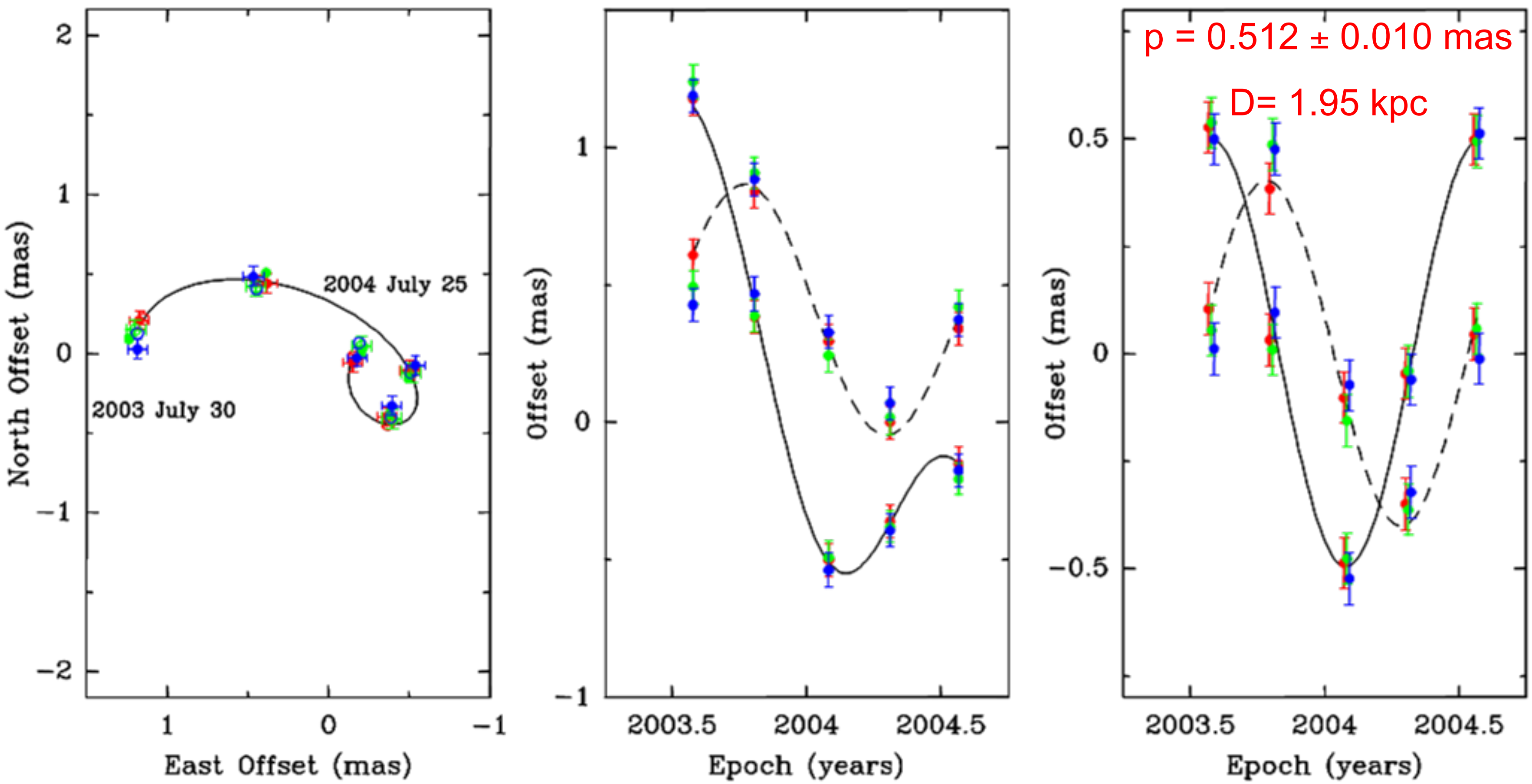
shift position by ~ 2θ_f ~ 500 μas

Relative positions (to QSOs):

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

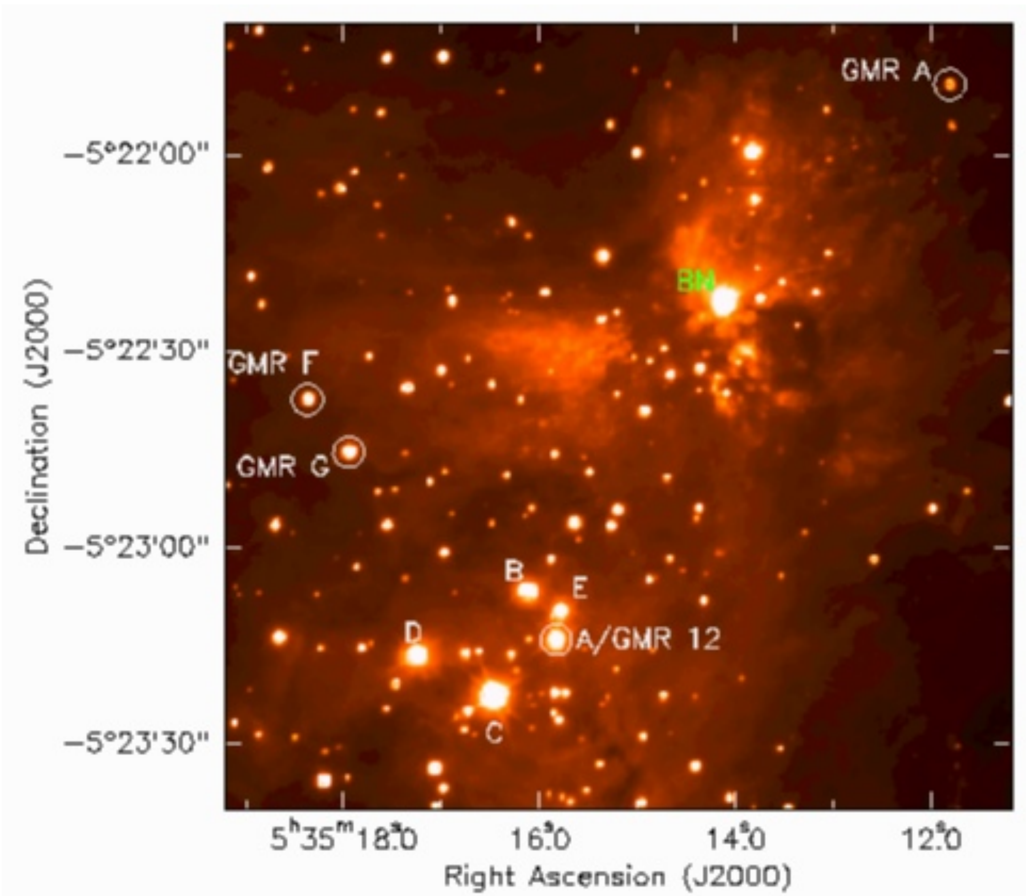
cancel systematics: $\Delta\Theta * 2\theta_f$ ~ 10 μas

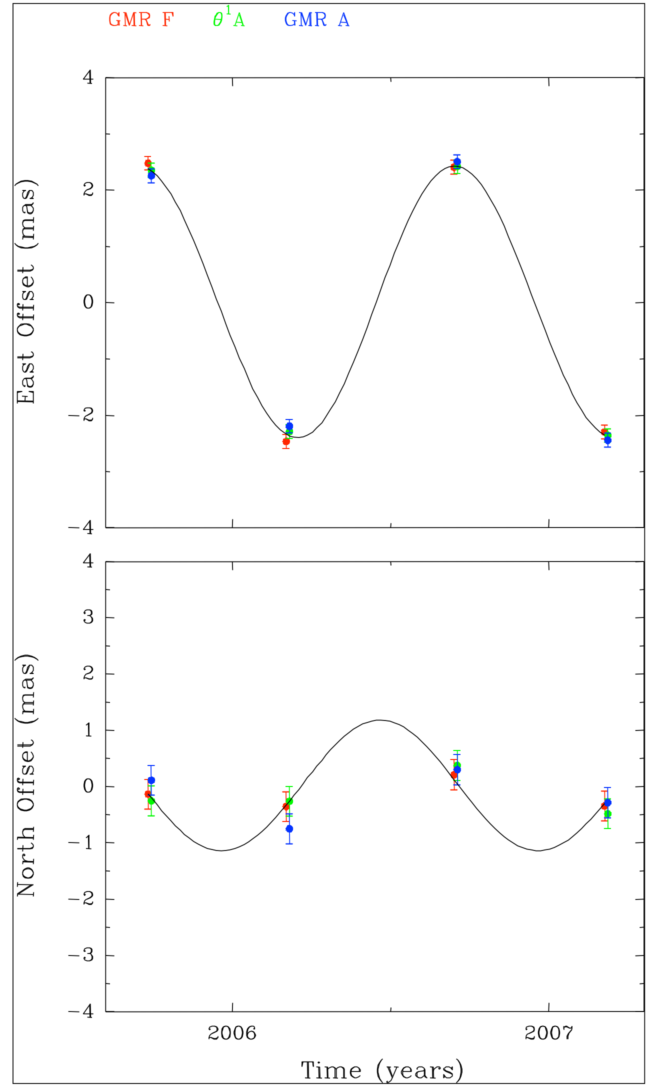
Star Forming Region Parallax: W3(OH) CH_3OH masers



Xu, Reid, Zheng & Menten (2006)

Orion Nebular Cluster: Stellar Parallaxes



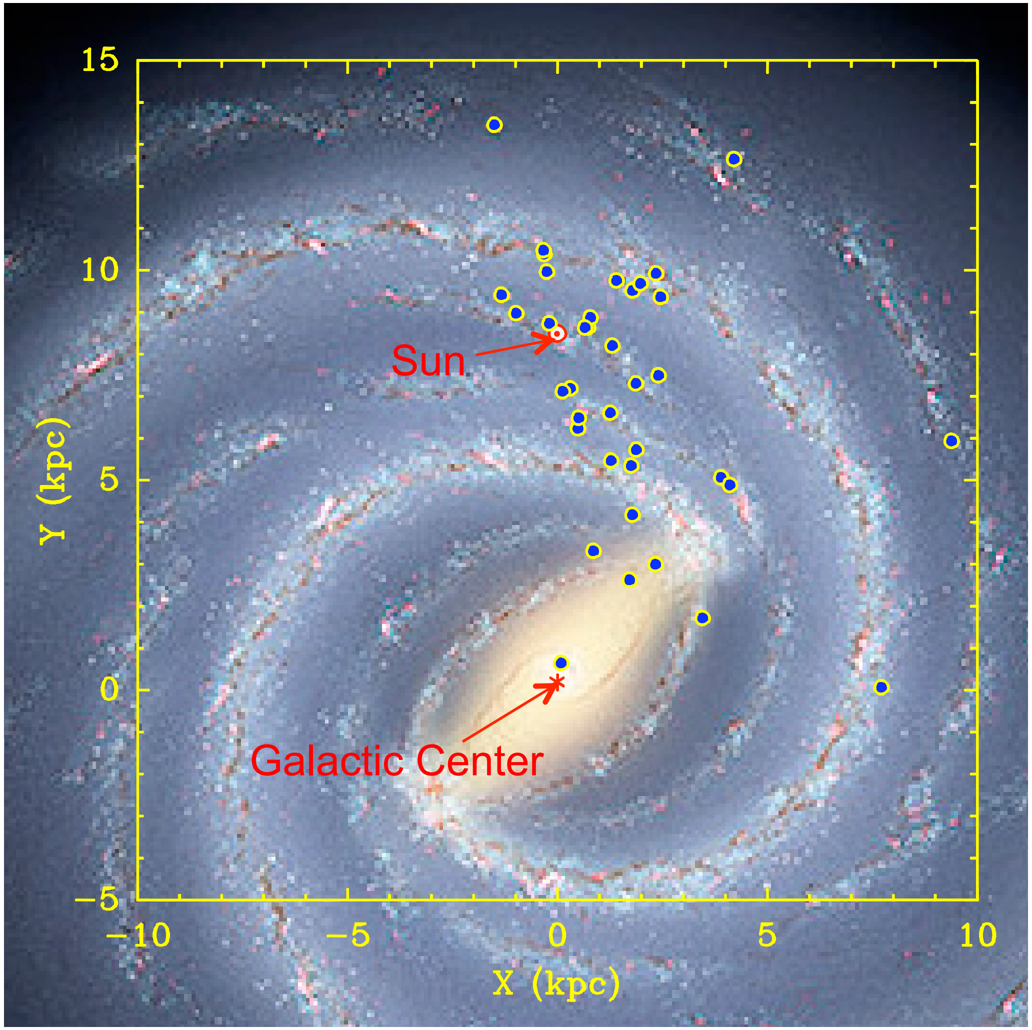


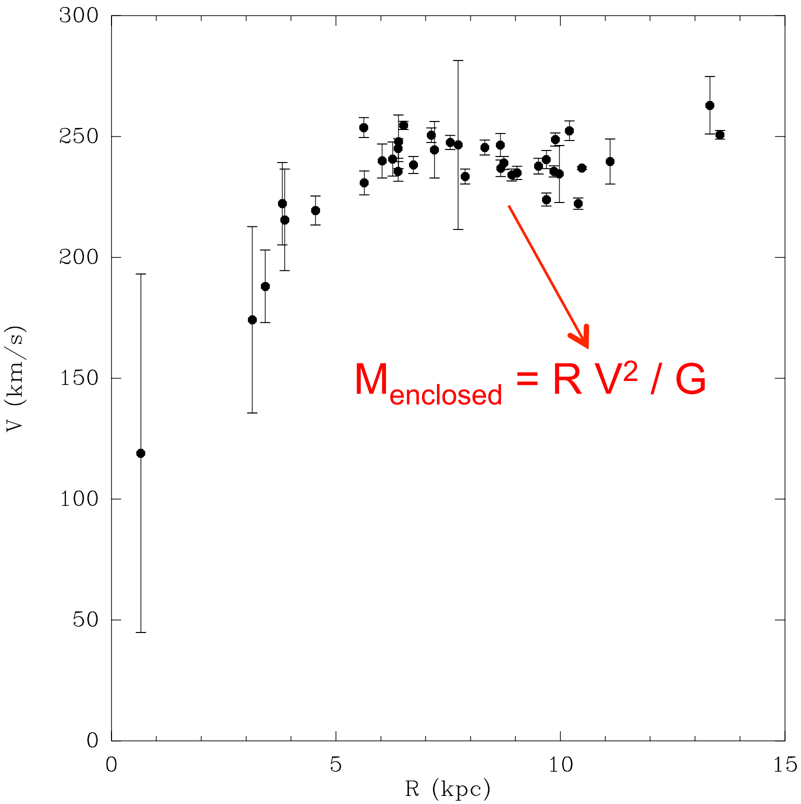
D = 414 ± 7 pc (VLBA)

= 419 ± 6 pc (VERA)

Menten, Reid, Forbrich & Brunthaler (2007)

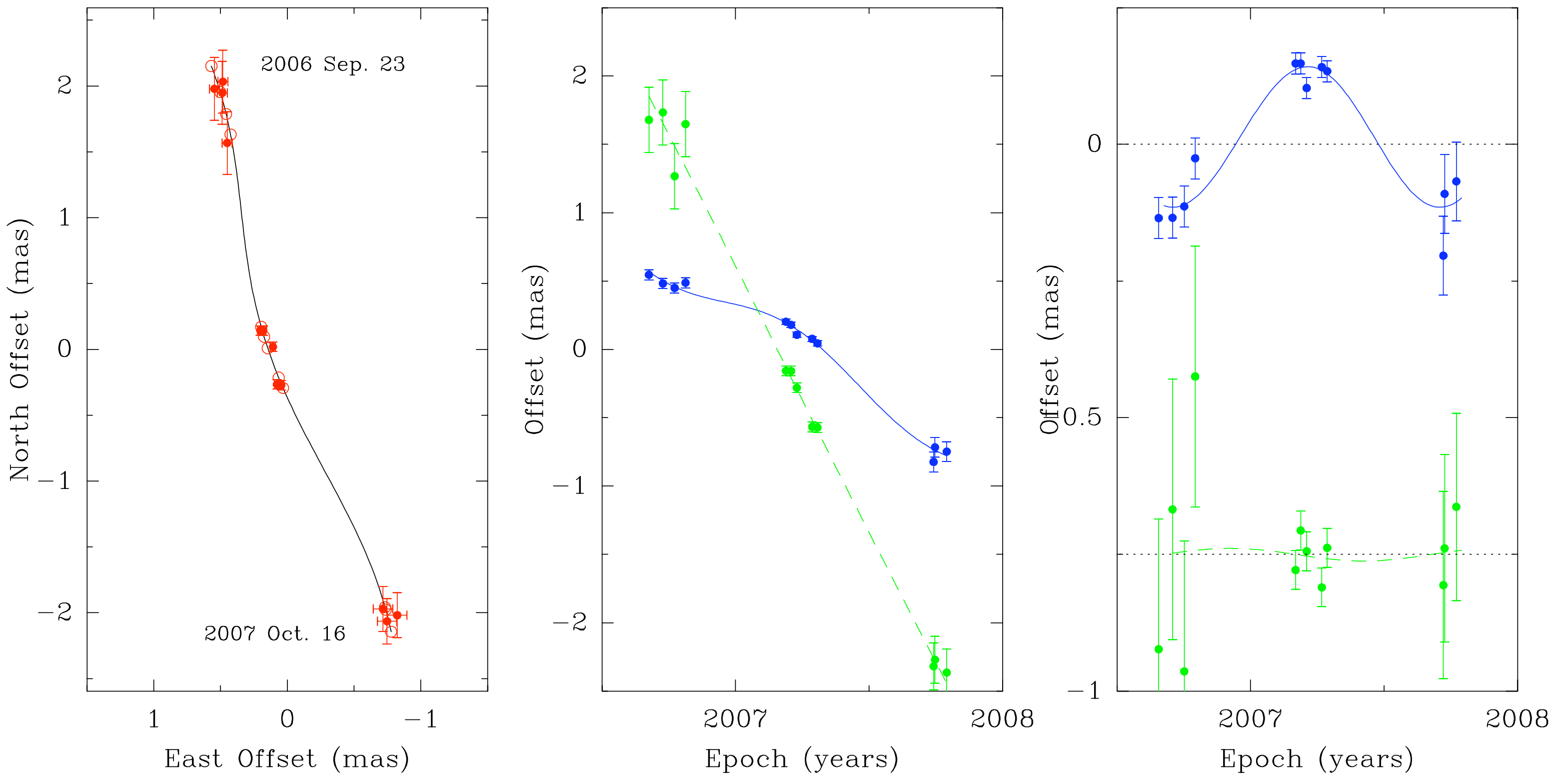
Latest Results: (VLBA and VERA parallaxes)





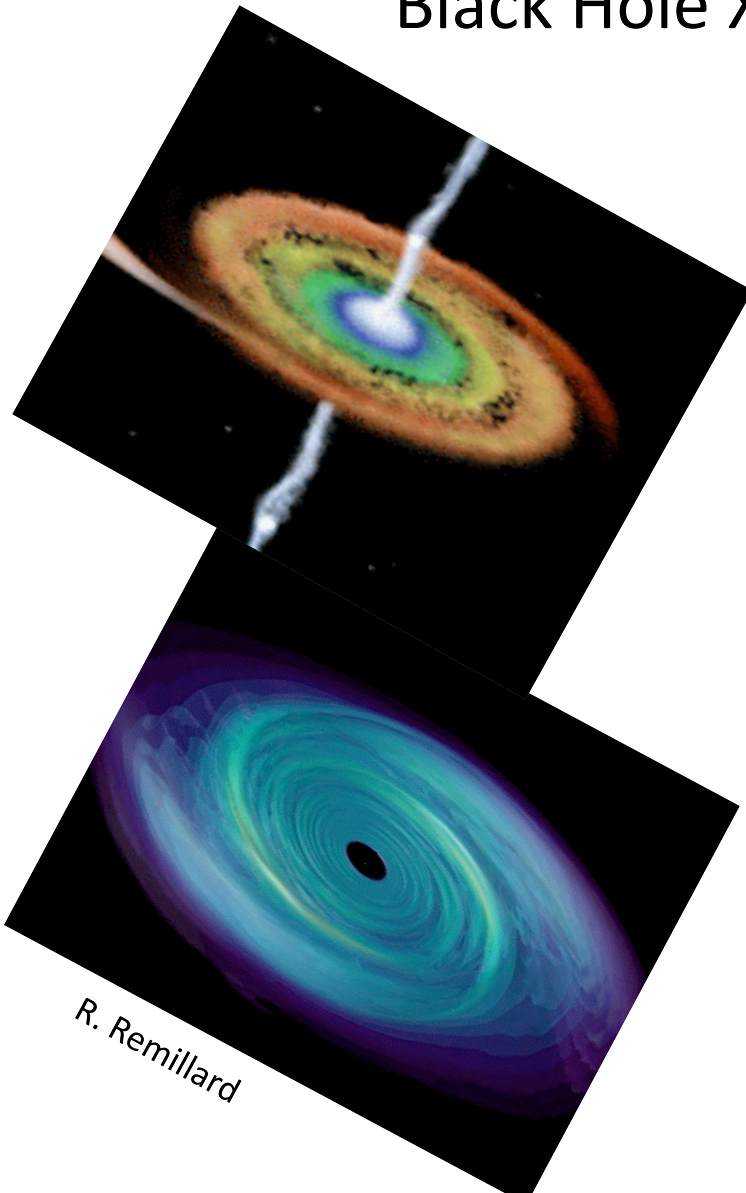
R_0 = 8.4 kpc; Θ_0 = 247 km/s

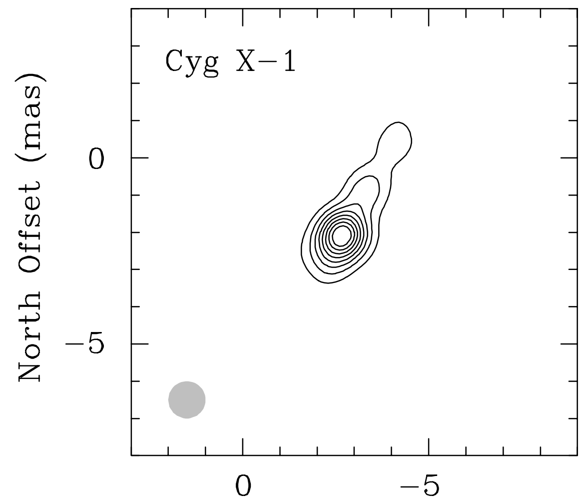
Parallax for Sgr B2(Middle) H_2O masers

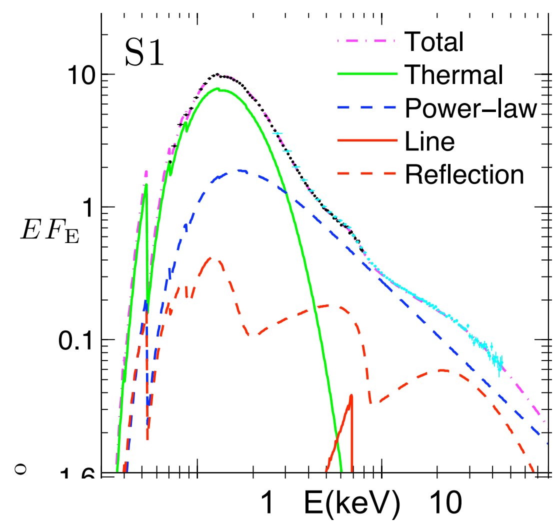


p = 129 ± 12 μas (D=7.8 ± 0.8 kpc)

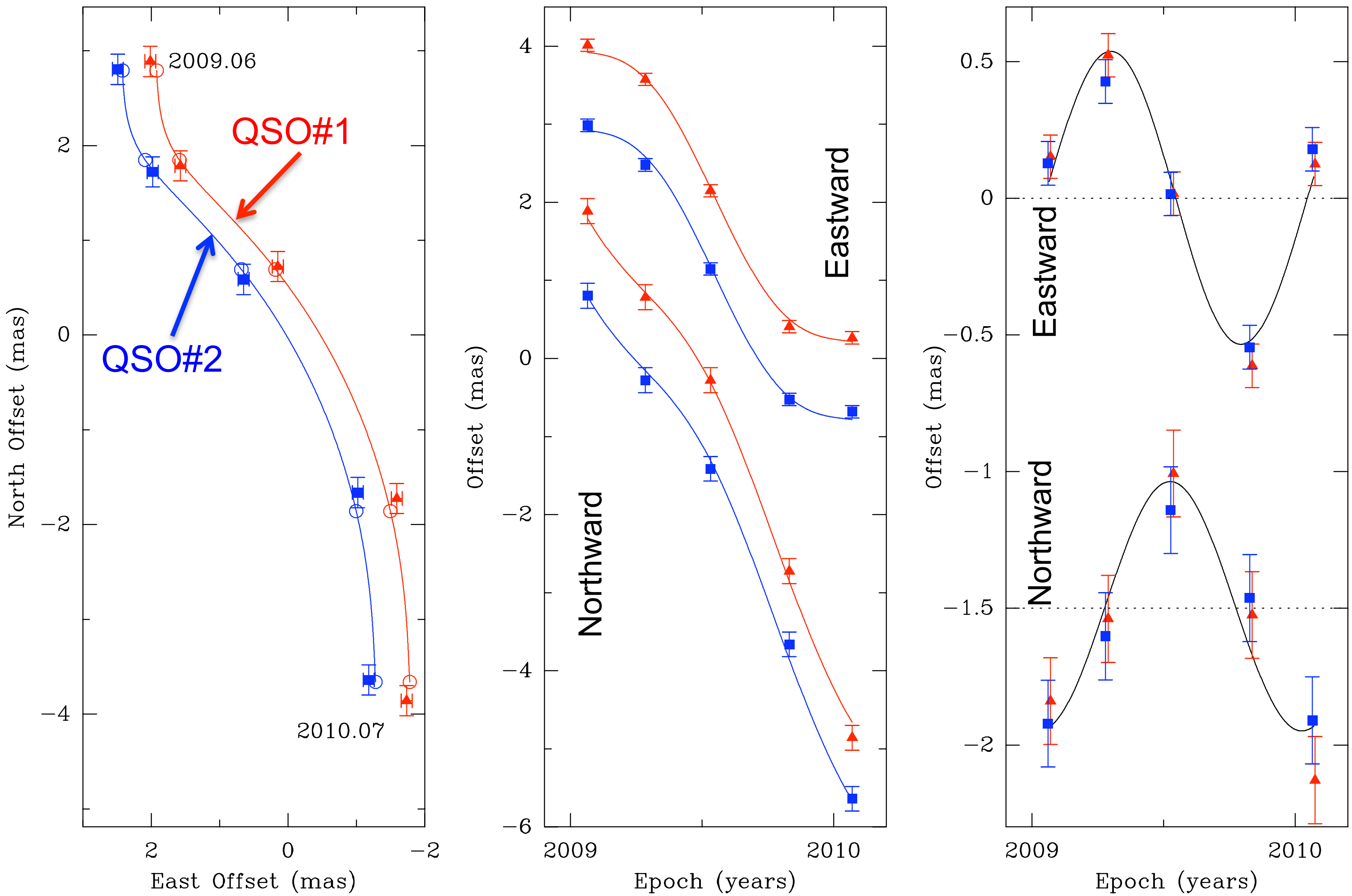
Black Hole X-ray binaries







Cyg X-1 Trigonometric Parallax: 0.539 ± 0.033 mas



Reid et al 2011

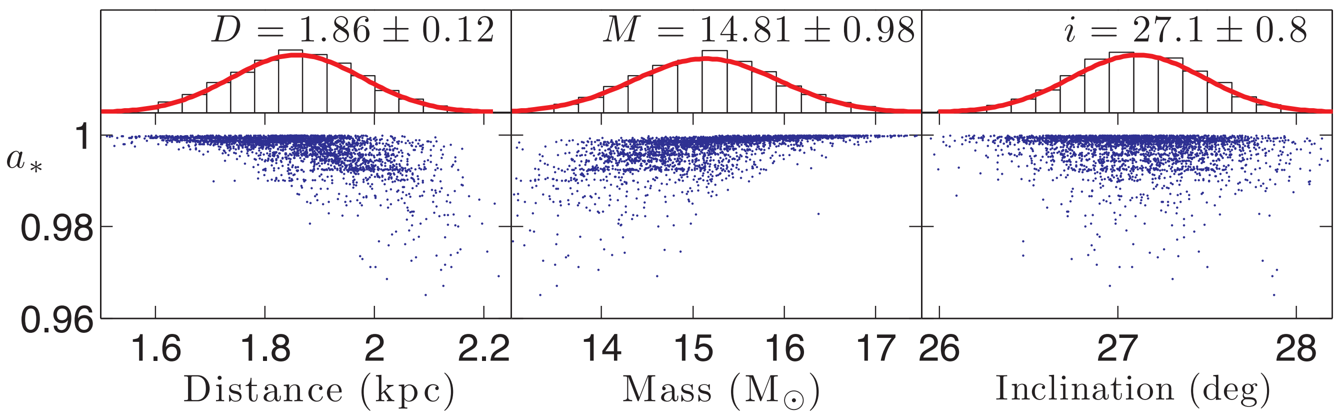
Once distance is known accurately…

Model Fitting Binary Optical Data (Orosz et al 2011)

SED,
Light curves
Velocity curves

$M_{O\text{-}star} = 19 \pm 2 \ M_{sun}$
$M_{BH} = 15 \pm 1 \ M_{sun}$
Orbit Inclination = $27^o \pm 1^o$

Modeling X-ray data Black Hole Spin (Gou et al 2011)



a_*

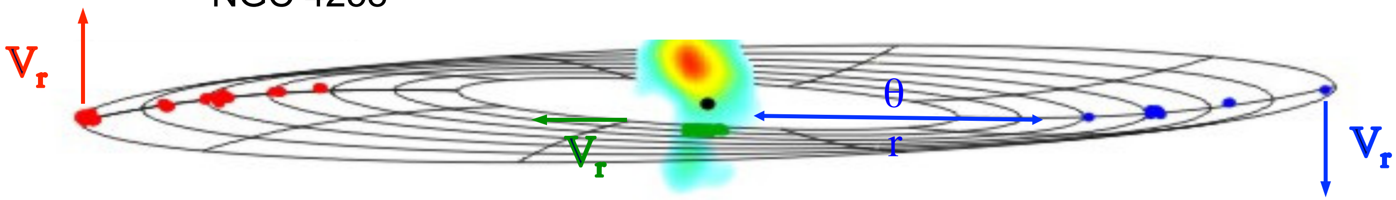
← Priors

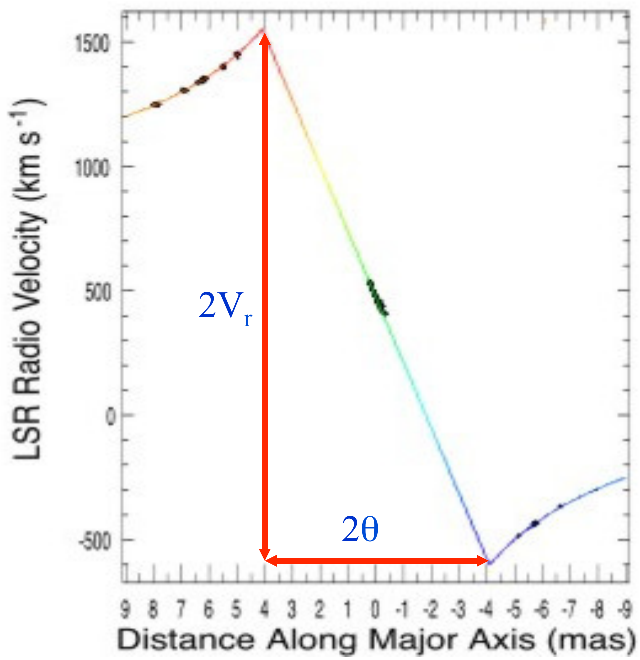
← Posterior PDF

$a_* > 0.97$

SMBH Accretion Disks

NGC 4258





Herrnstein et al. 1999

Conceptually:

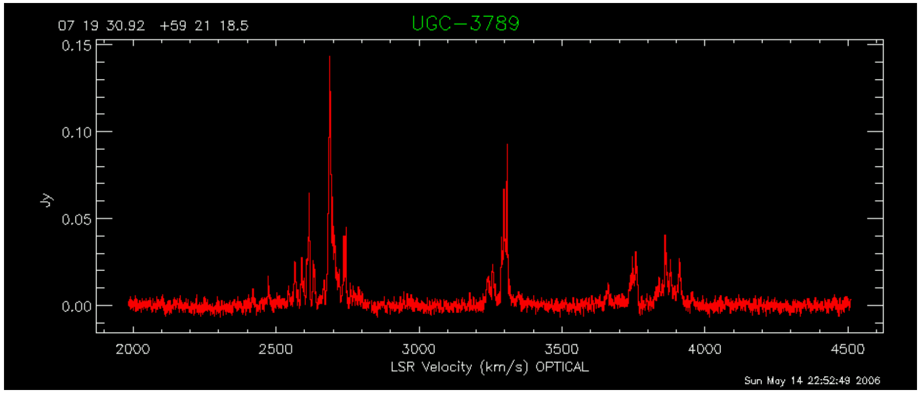
$$D = r/\theta$$

$$a = V_r^2/r$$

$$D = V_r^2/(a\ \theta)$$

D = 7.2 ± 0.3 Mpc

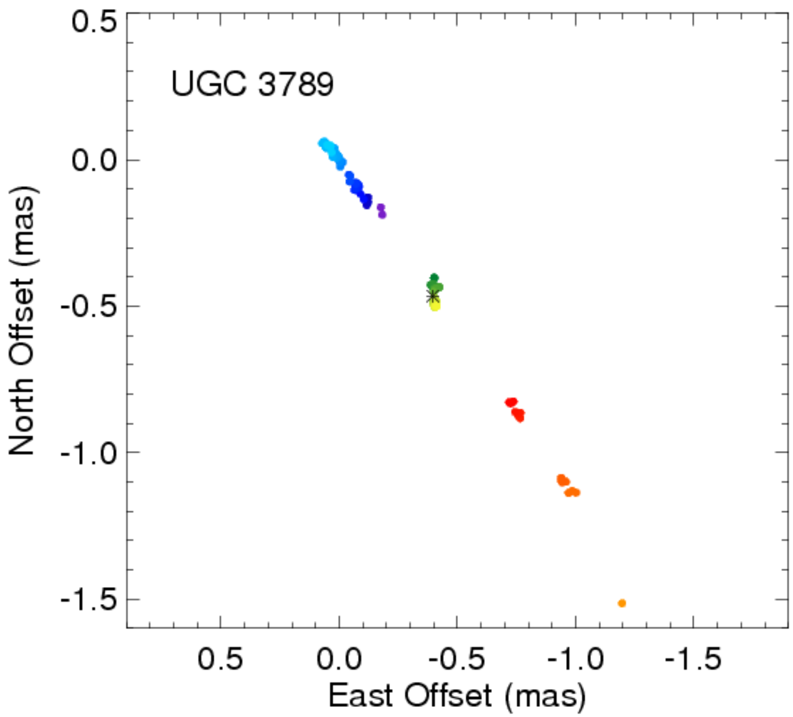
UGC 3789

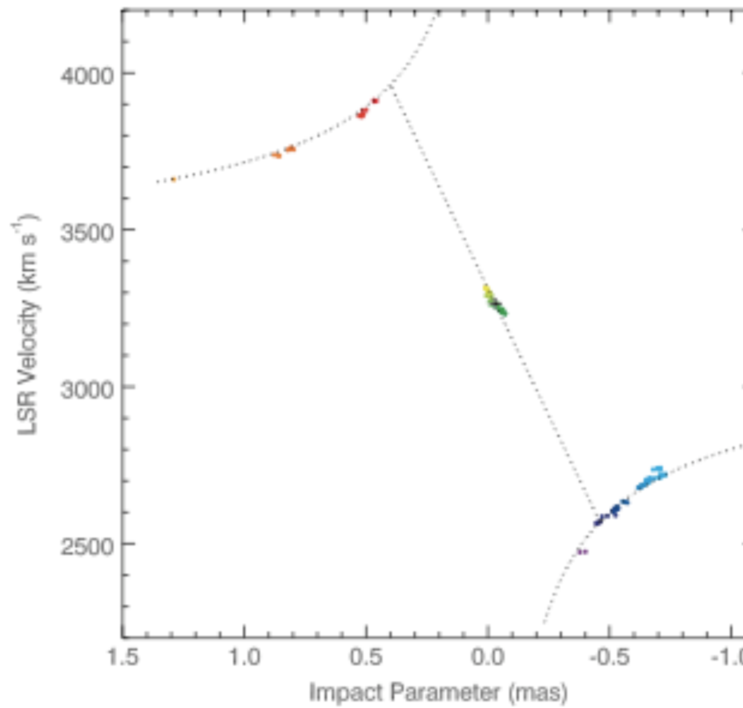


D_a = 49.9 ± 7.0 Mpc

H_0 = 69 ± 11 km s^{-1} Mpc^{-1}

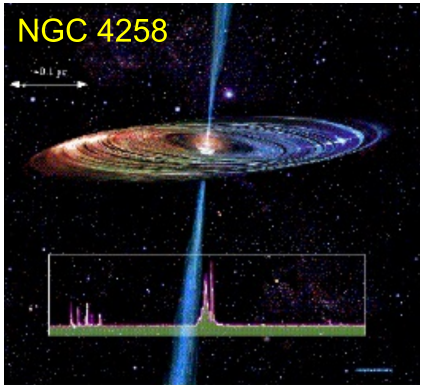
Braatz et al. 2010

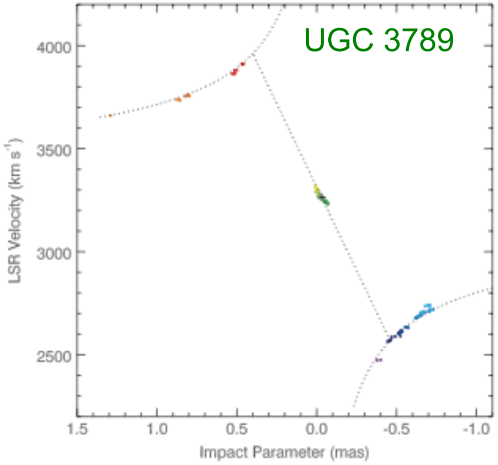




Super-Massive Black Hole Accretion Disks

1. Do SMBHs control early galaxy evolution (eg via AGN feedback)?
2. How do AGN accretion disks work?

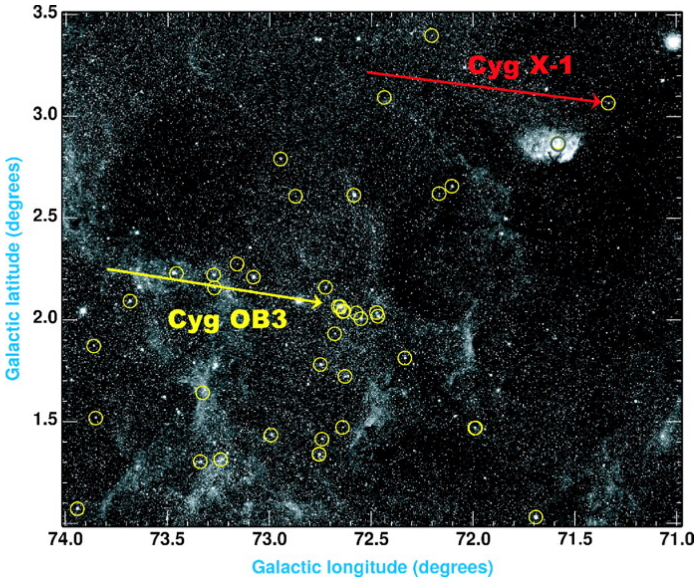




- "Gold Standard" black hole mass measurements; test and calibrate the M_{BH}-σ relation (σ_M ~ few%); Seyfert galaxy with M_{BH}~ 10^7 M_{sun} fall below M-σ relation
- Sub-pc resolution imaging of AGN accretion disks via H_2O masers (~150 now known) with 3D velocities; get physical parameters of accretion disks (possibly to high-*z*):
  - measurement of (or limits on) disk mass
  - T ~ 10^3 K and n ~ 10^9 cm^{-3} (to allow masing)
  - B-fields possible from Zeeman effect
  - Study warps and spiral structure?

Stellar Black Holes & Neutron Stars

1. How do black holes form and evolve?
2. Did Einstein have the last word on gravity?
3. What is the equation of state of neutron stars?

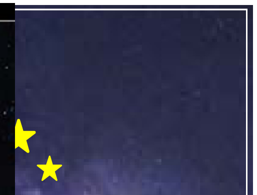


- VLBI parallaxes (+optical/x-ray data) → accurate binary parameters and BH spins
- Directly tracing binary orbits
- Some BH's may form without a "bang"

- Distances (parallaxes) to NS's in binaries are key to determining their masses, which then place strong constraints on the equation of state of ultra-dense matter.
- Proper motions indicate birth places and ages.
- With pulsar parallaxes & DMs can model Milky Way n_e

The Milky Way

1. What Is the kinematic and spiral structure of the Milky Way?
2. What are the masses of its (disk, bar/bulge, halo) components?

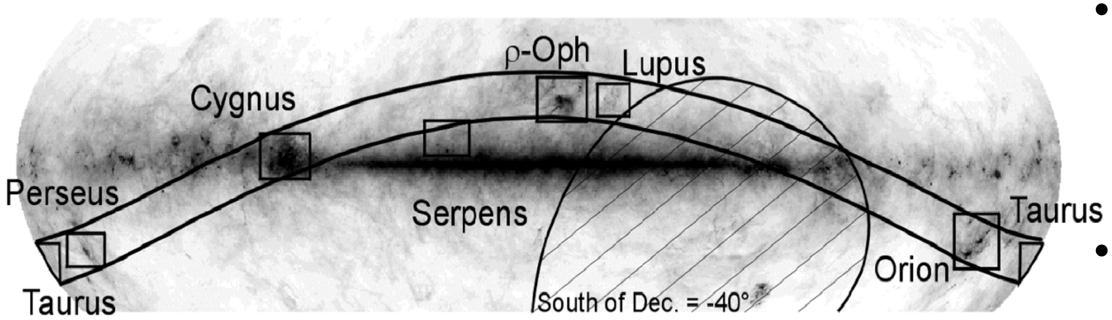


BeSSeL: VLBA
Japan: VERA

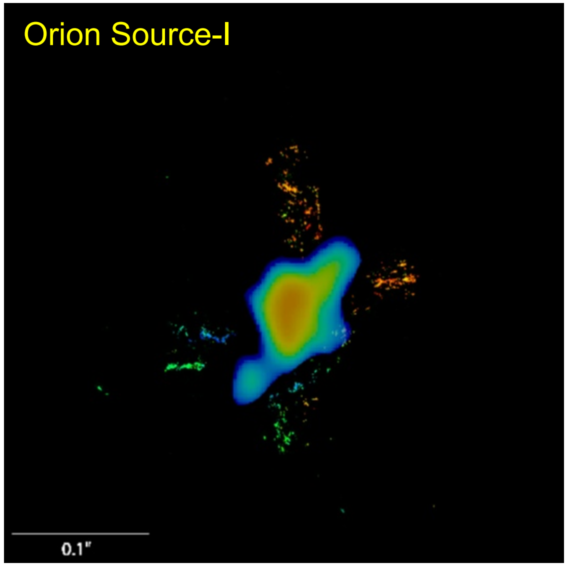
- Map spiral structure of Milky Way
- Characterize the dynamics of the
- Measure fundamental parameter
- Trace component mass distributions (with Gaia)

Star Formation

1. How do low mass and massive stars form?
2. How do accretion disks work and drive outflows?



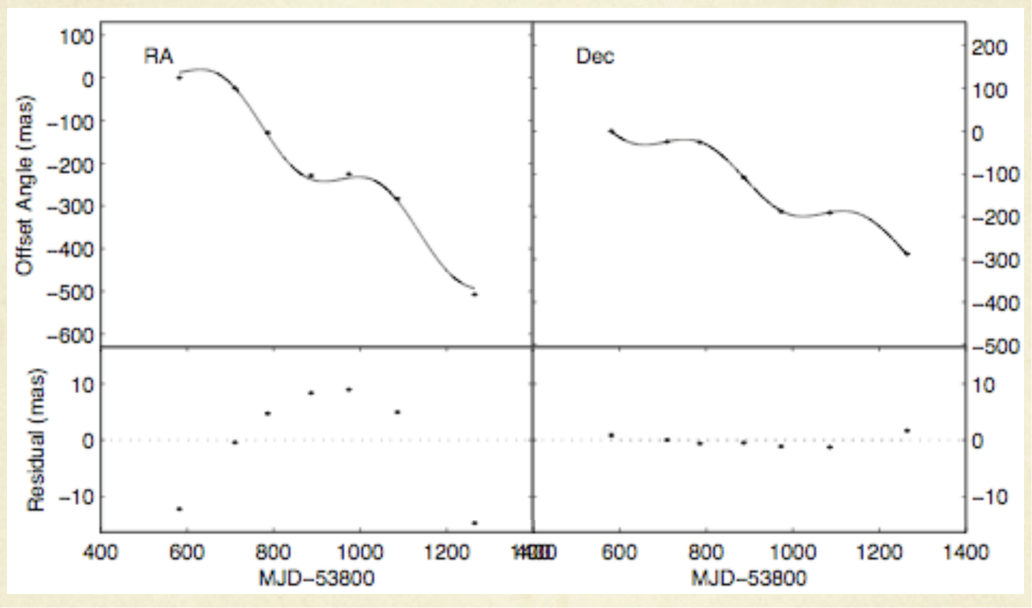
- Parallaxes (±1%) of 200 low-mass YSOs…accurate sizes of disks, luminosities, masses and ages. (L. Loinard)
- Resolve Pleiades distance controversy (C. Melis)



- Direct imaging/measurement of disk outflows with sub-AU resolution and 3D velocity information (L. Greenhill)

Exosolar Planets

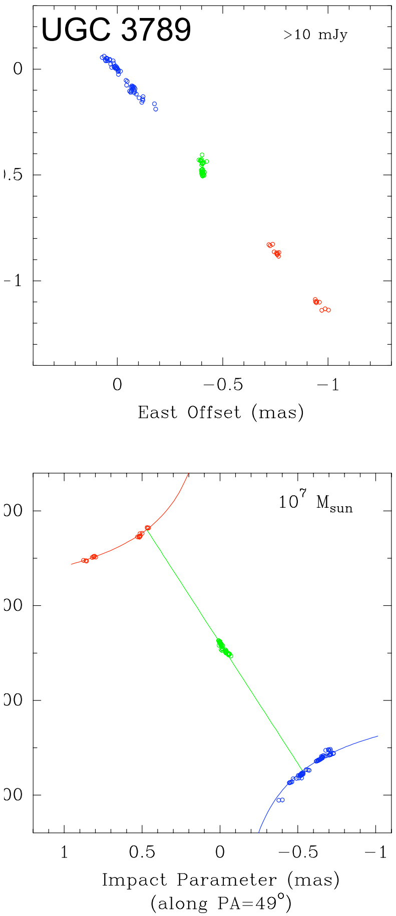
1. Are planetary systems around low mass stars different from solar mass stars?
2. What is fraction of long-period planets around low mass stars?



- RIPL (G. Bower): low-mass star planet search by reflex motion
- Can rule out planet >10 M_J @ 1 AU in only 10 days!
- Hints of planets in data
- Sensitivity limited…need more BW/area

Cosmological Parameters

1. Can the extragalactic distance scale be improved?
2. What is the value of Ho (and hence *w*)?



- "Rotational parallaxes" (eg, M 33, Andromeda) allow better calibration of Cepheid P-L-metallicity relation

- *Direct* measurement of H_0 from H_2O masers : ~150 known

  Megamaser Cosmology Project goal: 10 galaxies each with σ_{Ho} ~ 10% → 3% final uncertainty

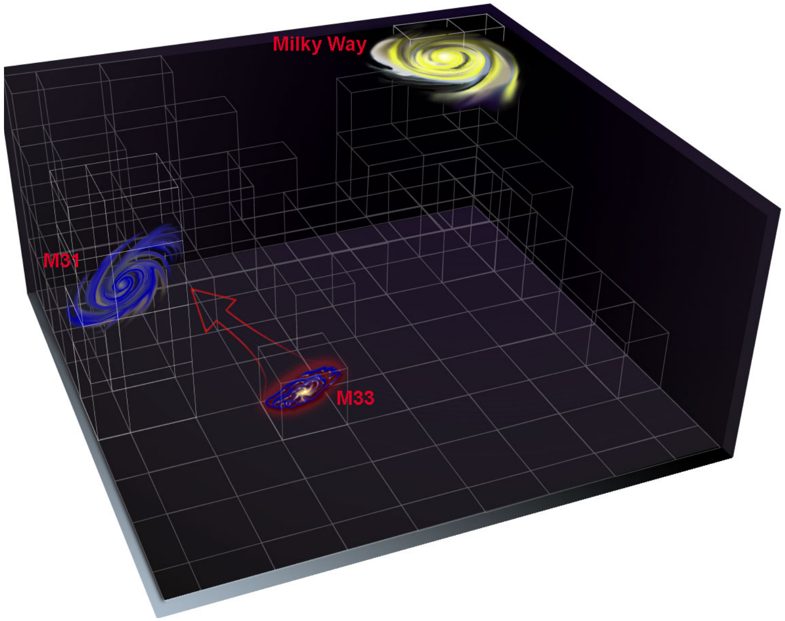
  Ho = 72 ± 5 km/s/Mpc for NGC 4258 (by re-cal'ing Cepheids)

  Ho = 69 ± 11 km/s/Mpc for UGC 3789 (directly)

  Ho = 70's km/s/Mpc for NGC 6264 (directly)

Galaxy Interactions and Mergers

1. How Is matter distributed in the Local Group of galaxies?
2. What is the history and fate of the Milky Way and the Local Group?
3. What happens to SMBHs in merging galaxies?



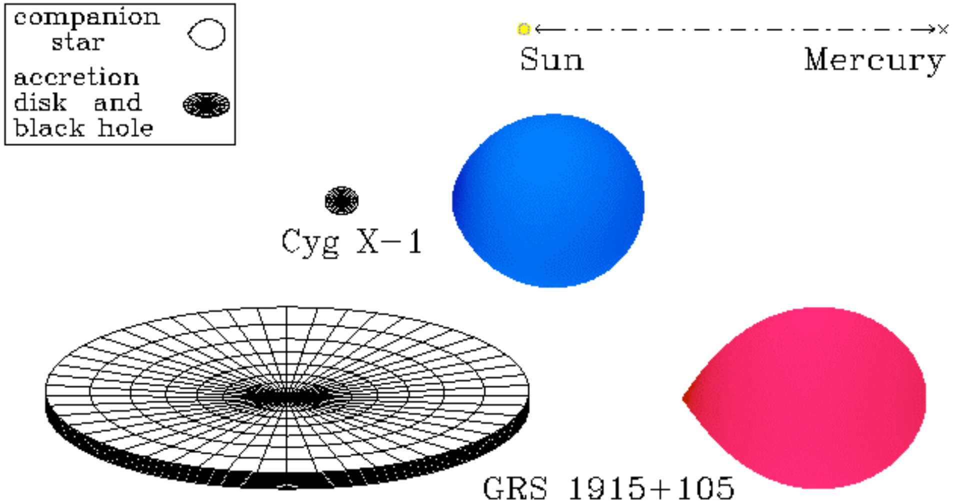
- Proper motion measurement of Andromeda is key to the dynamical fate of the Local Group
- Measurement of the masses of the dark matter halos of Andromeda and Milky Way
- Measure proper motions of binary SMBHs

Future Plans

- Astrometry needs:
  - Long interferometric baselines (~8000 km)
  - High sensitivity (via BW and/or collecting area)
  - Low/stable H_2O-vapor sites and rapid slew/settling antennas

- Next decade's plans:
  - Continue VLBA BW upgrade → 4 GHz/dual polarization (32 Gb/s sampling)
  - Increase collecting area of VLBA/EVLA (ie "North American Array" on roadmap to SKA-high)
  - Astrometric VLBI array in southern hemisphere (on roadmap to SKA-mid)

Cyg X-1: a High Mass X-ray Binary



J. Orosz

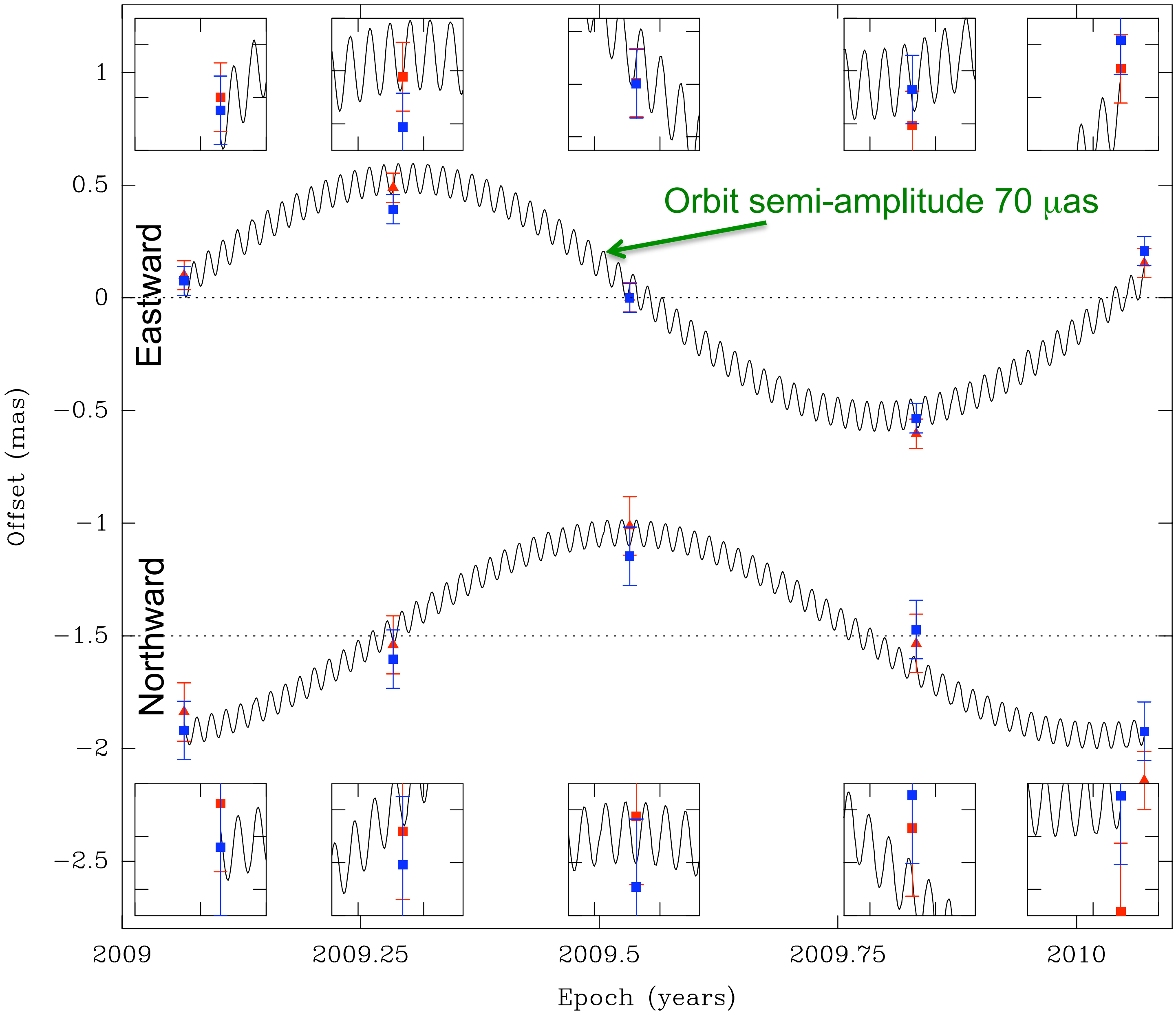
Many questions:

- O- or B-type stellar companion?
- Does it fill its Roche lobe?
- BH and companion masses?
- Orbit/disk inclination?

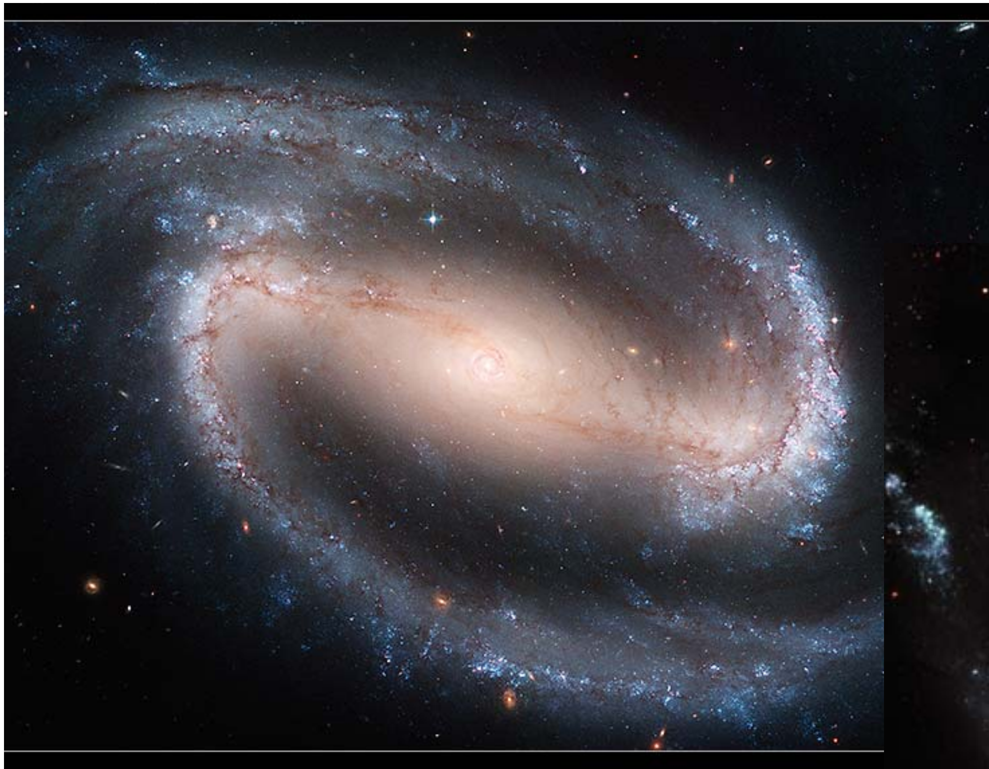
Distance (kpc)	Inclination (deg)	Black Hole Mass Estimates Minimum (M_{sun})	Best (M_{sun})
1.2	58	3.1	4.0
1.4	46	4.0	6.3
1.6	39	5.0	9.4
1.8	34	6.1	13.4
2.0	30	7.2	18.4
2.2	28	8.5	24.4
2.4	25	9.9	31.7

from Caballero-Nieves et al (2009)

BH Orbit about Binary Center of Mass



What does the Milky Way look like?



Hipparcos measurement range