VLBI Astrometry

for probing astrophysics, celestial reference frames and general relativity

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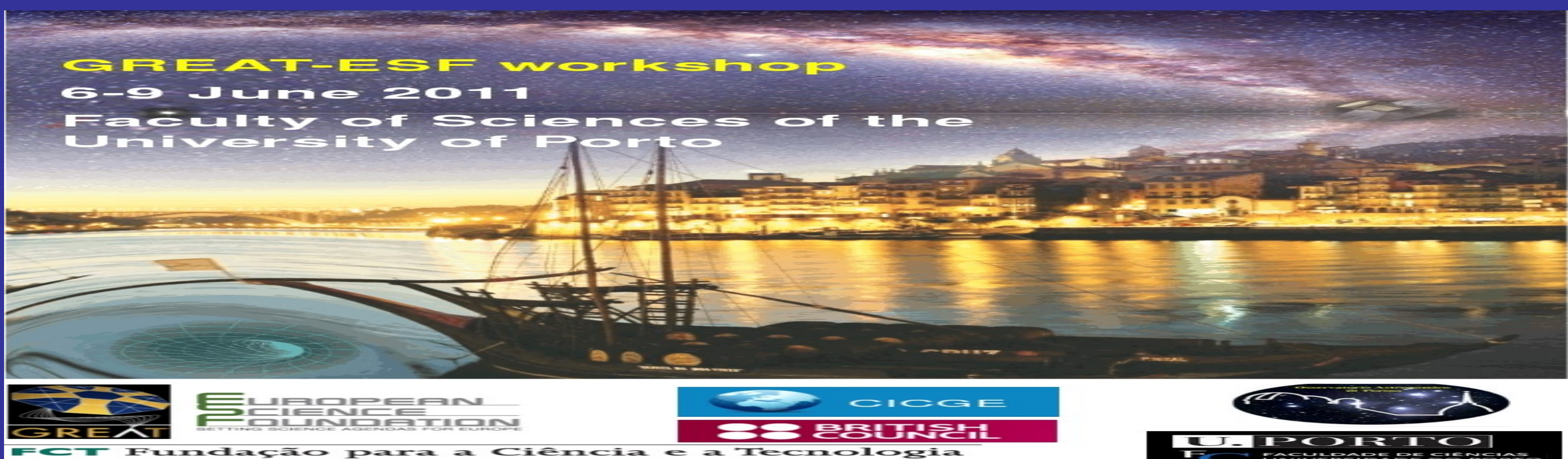
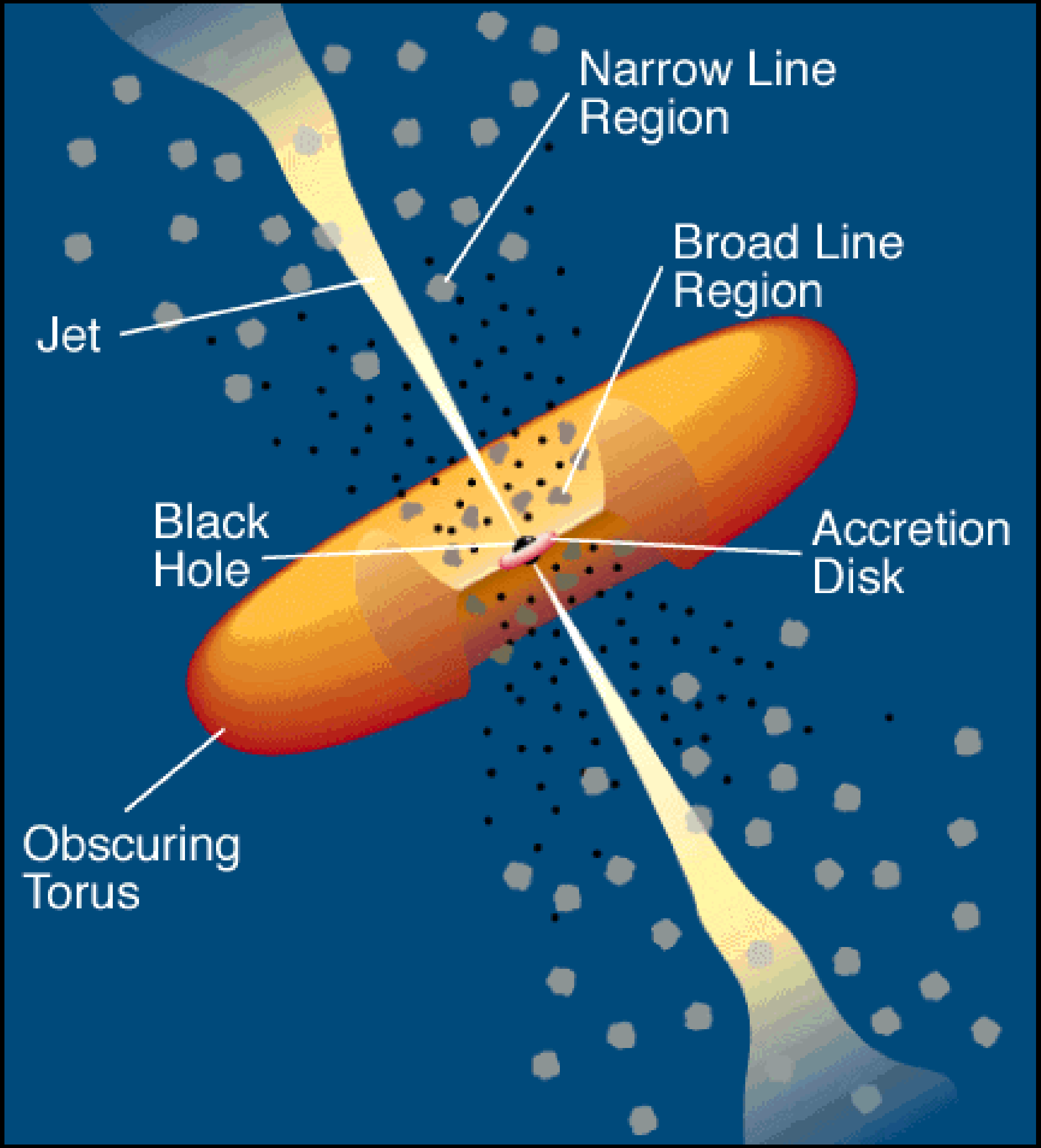
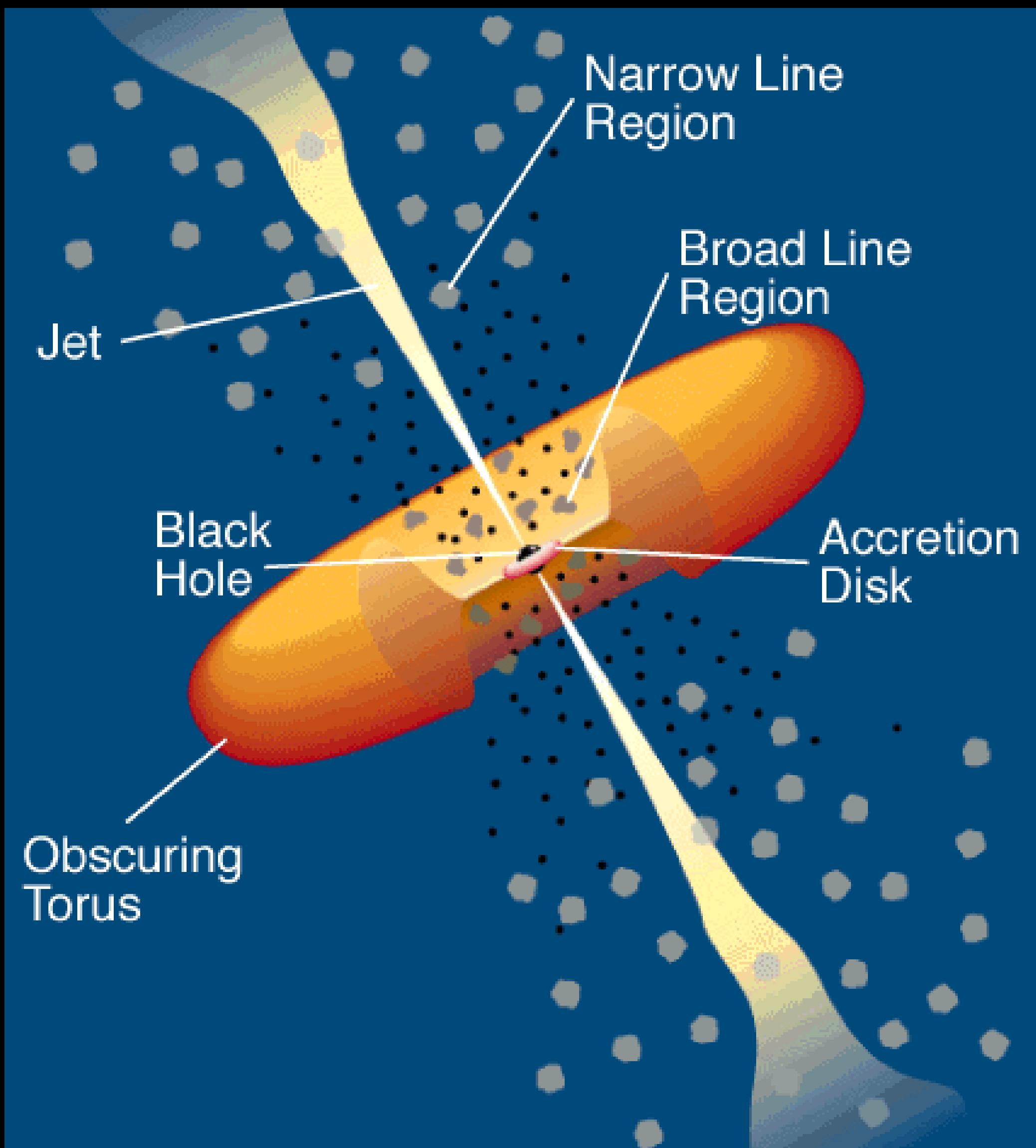


Outline

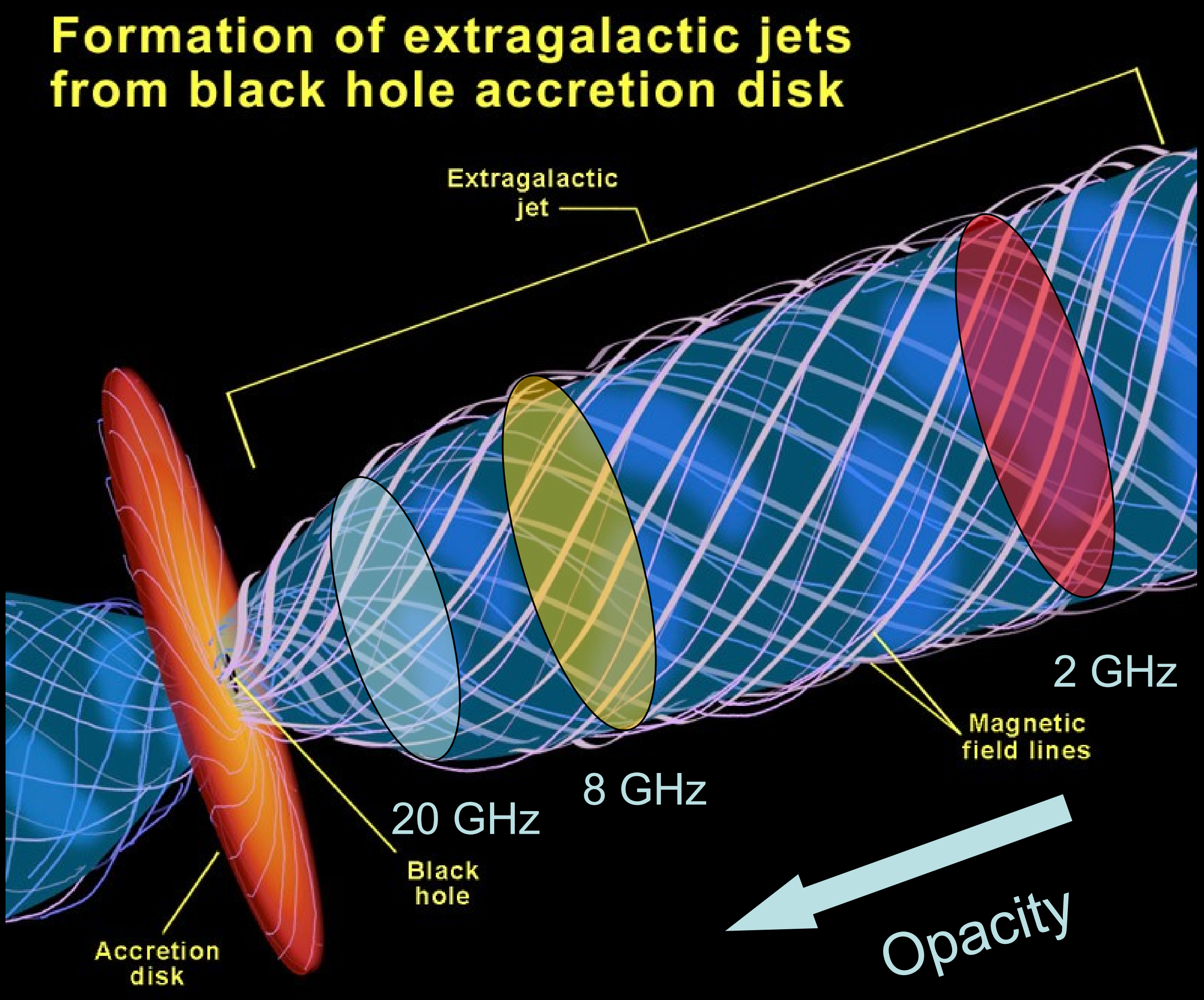
- Astrophysics of the core region: how close to the gravitational center of the quasar?
- Celestial reference frames: how stable?
- Tests of general relativity: how sensitive?
- Conclusions

Where is the core, the gravitational center of the quasar?




Narrow Line Region
Broad Line Region
Jet
Black Hole
Accretion Disk
Obscuring Torus

Opacity effect on locating the core



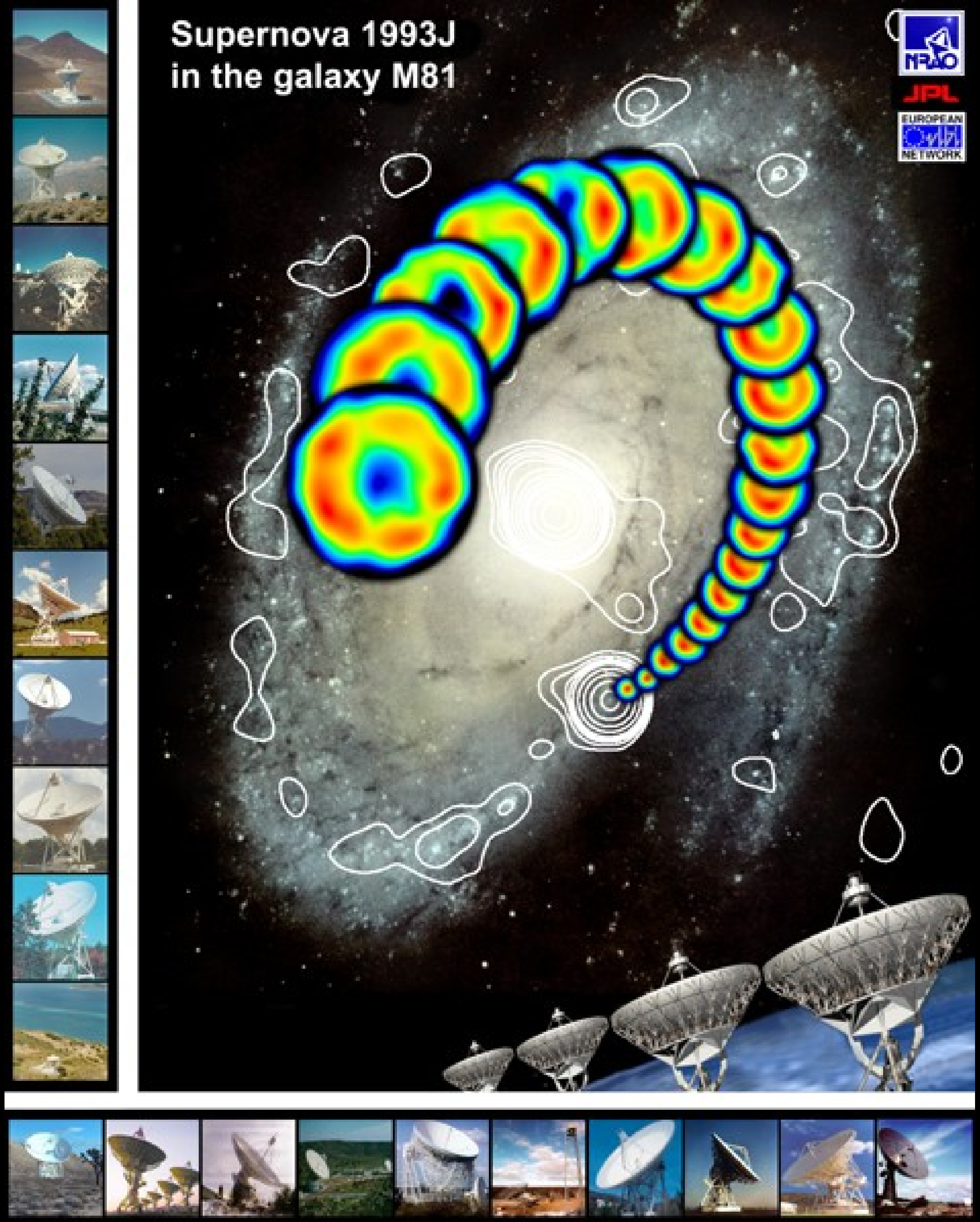
Opacity effect: Marcaide & Shapiro (1983)

Opacity study – relative to outside source: Bietenholz et al. (2004)

Opacity study - relative to optically thin jet component: Sokolovsky et al. (2011)

Where is the core?

The core-jet nuclear region of M81 as an example of opacity effects in a compact AGN



Evolution of SN1993J

Position of Explosion Center known within 45µas (160AU).

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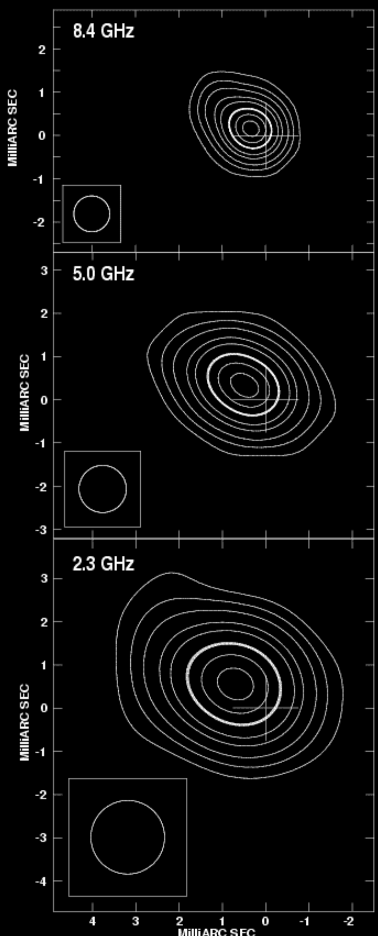
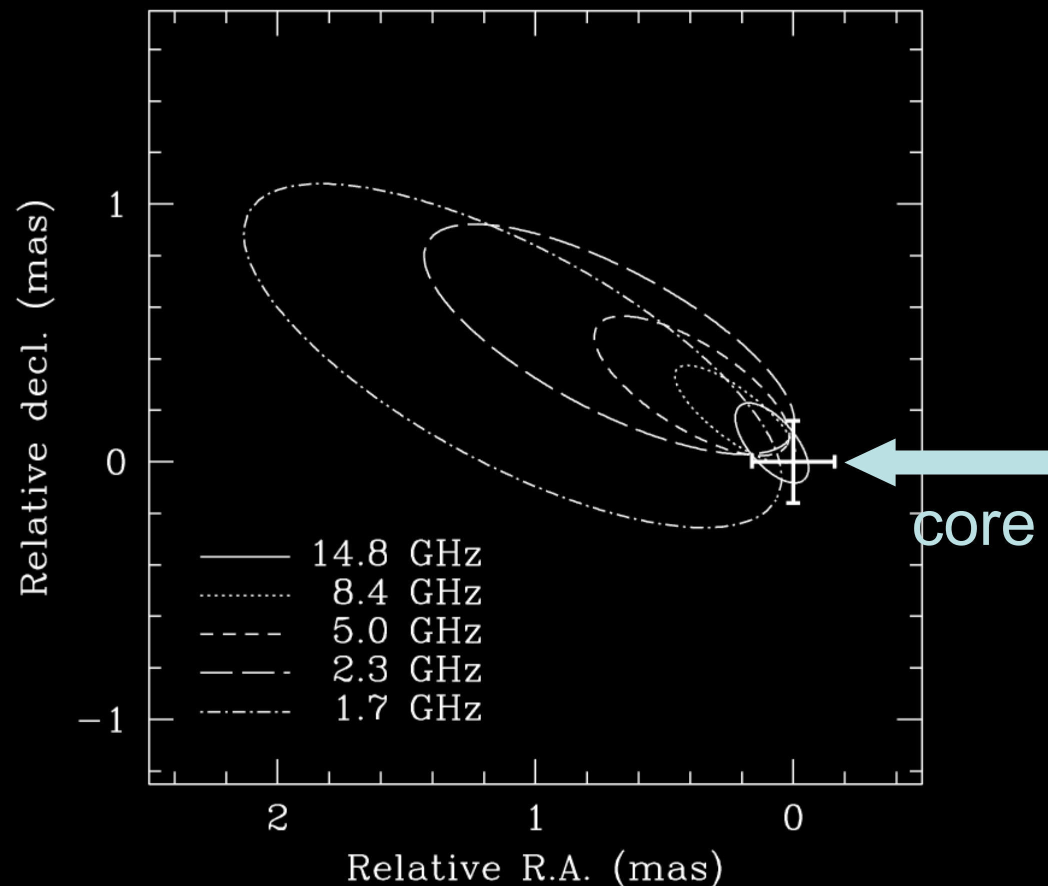
Center of SN stable within 9 µas / yr

8.4 GHz, from *t* = 50d to *t* = 2787d

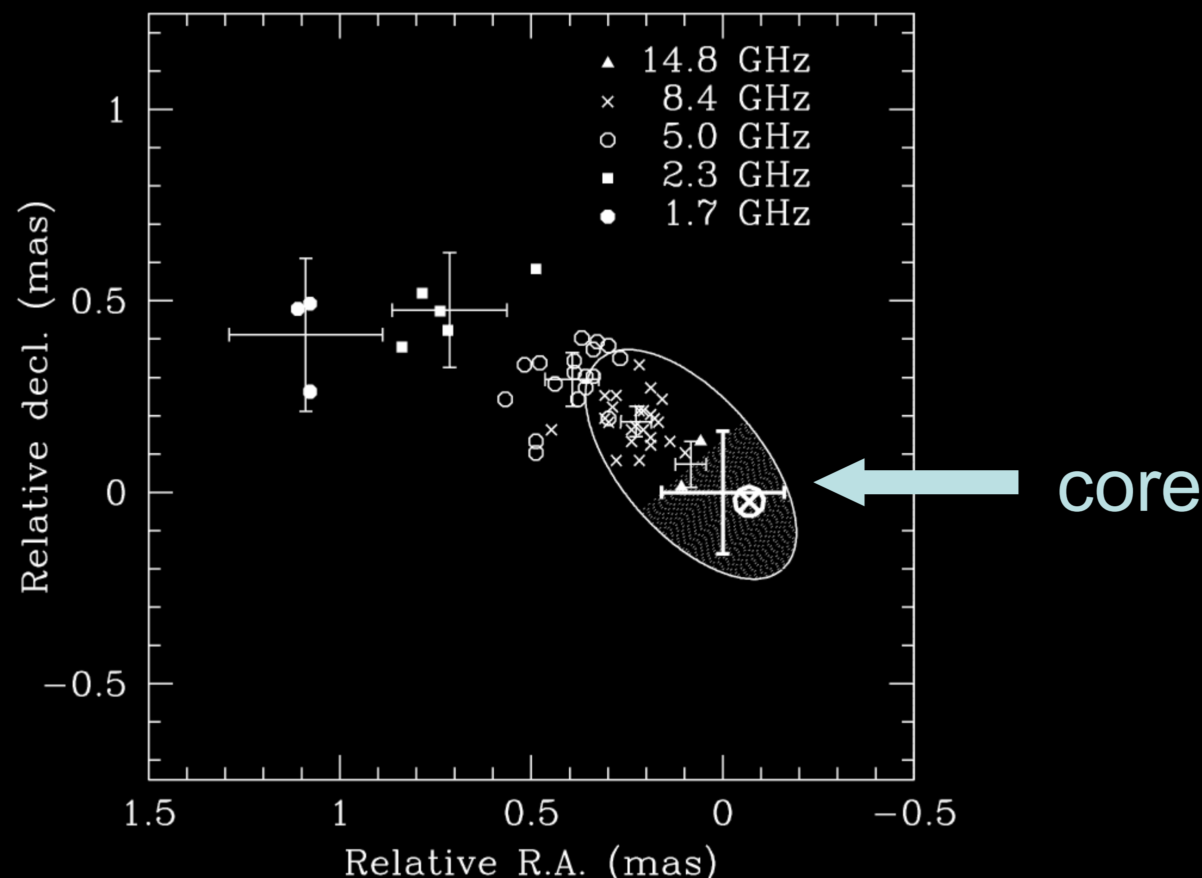
Free download: www.yorku.ca/bartel

The compact radio source M81* at several frequencies w.r.t. the explosion center of SN 1993J



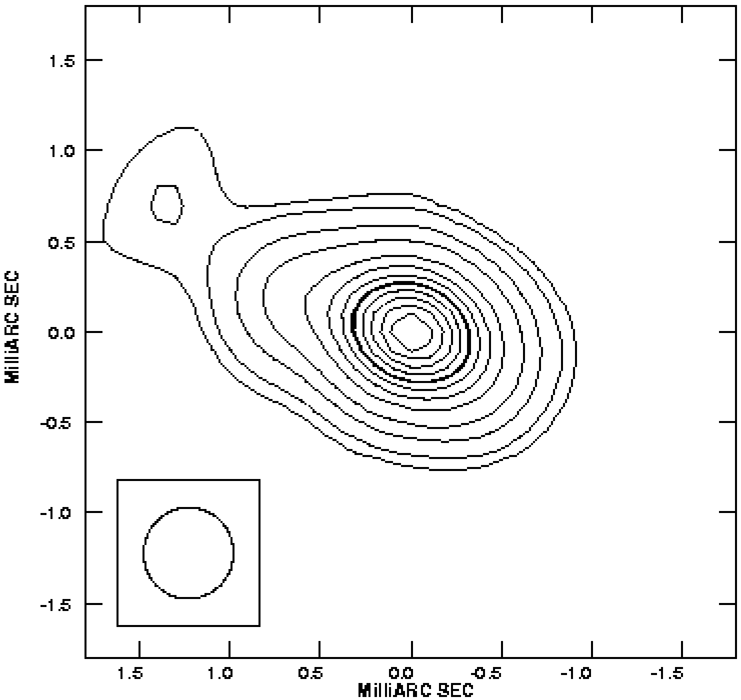


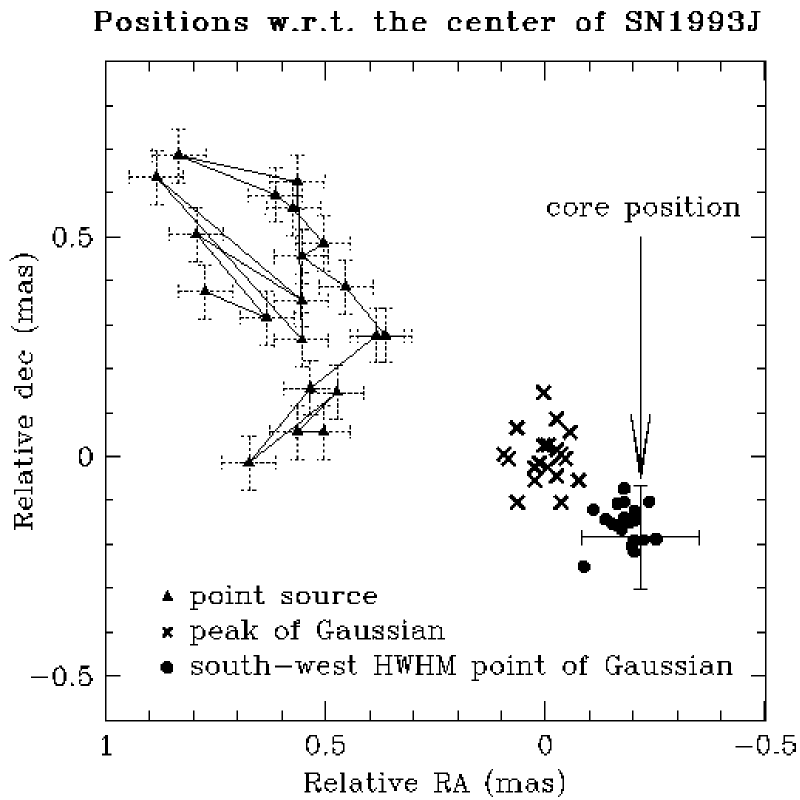
Distribution of M81* emission positions at several frequencies w.r.t. the explosion center of SN 1993J



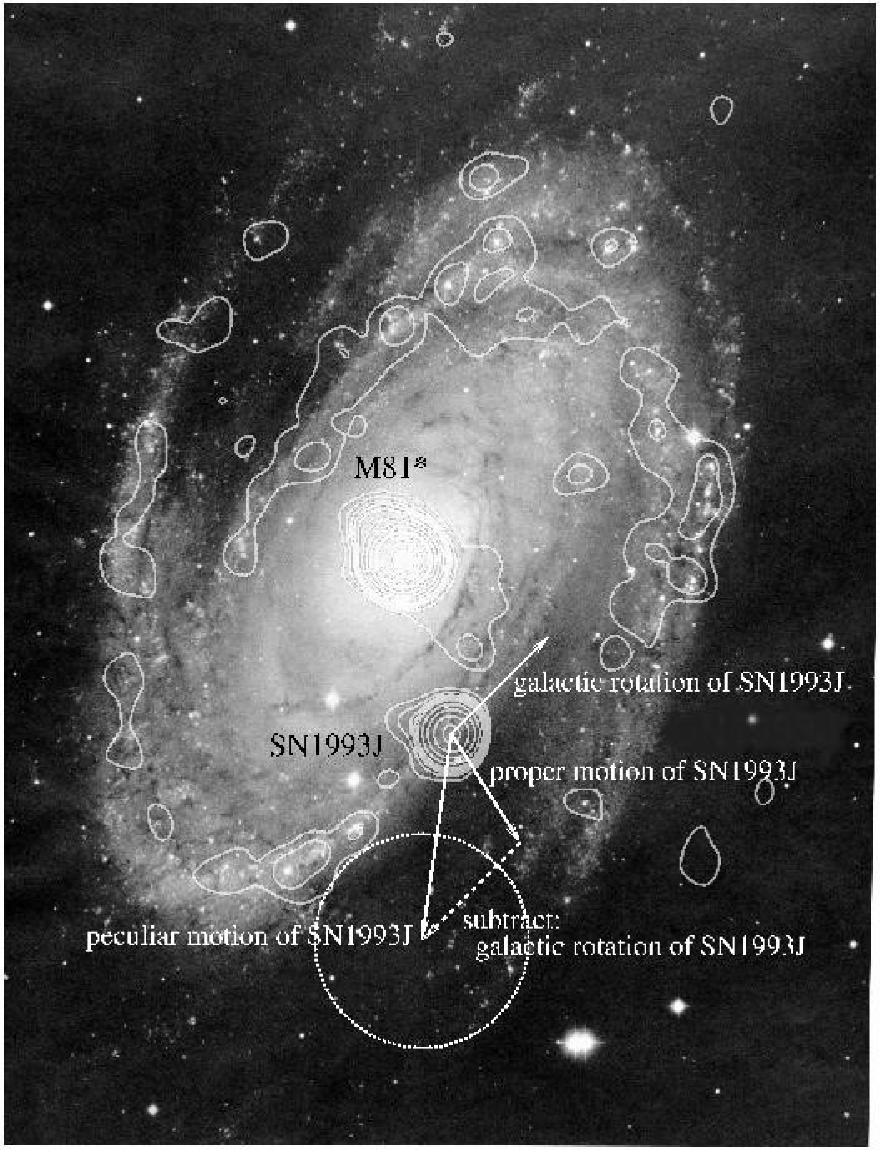
The core as the least jittery part of M81*

Core-jet in the center of M81

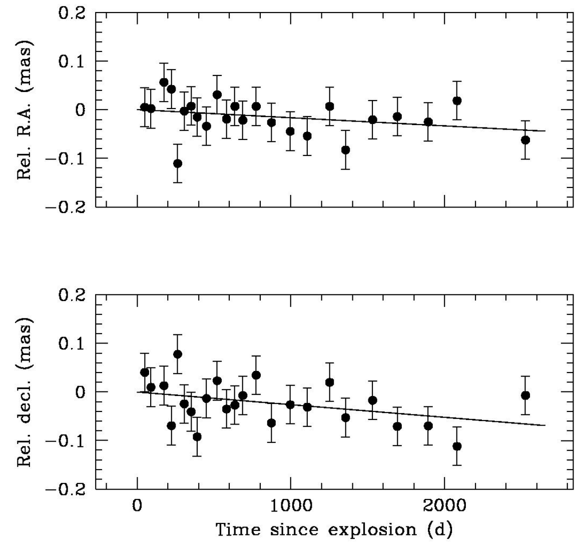




Rms scatter of core position: 60 μas = 160 AU.



Proper motion of geometric center of SN1993J
w.r.t. core of M81



Explosion center:
± 45 μas or ± 160 AU

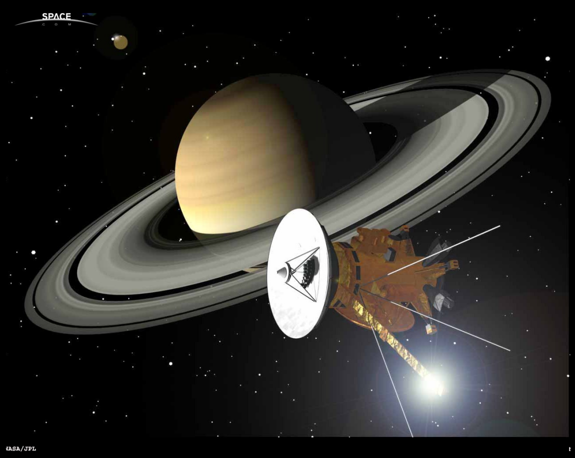
Proper motion:
± 9 μas/yr or ± 160 km/s

Peculiar proper motion:
320 ±160 km/s to south

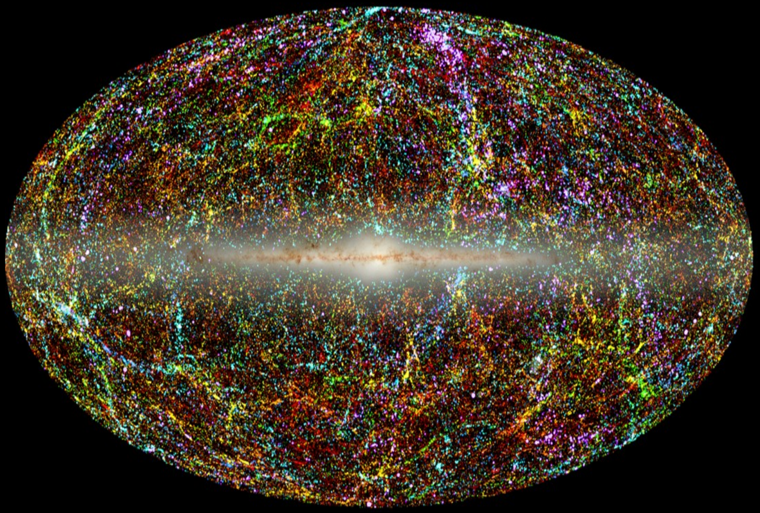
See, Reid et al. 2009 for methanol maser astrometry in Galaxy

Celestial reference frames – how stable?

Solar system dynamic reference frames:
Saturn in ICRF 0.3 mas accuracy Jones et al. (2011)
Also: pulsar timing and astrometry: Earth <1mas accuracy



Extragalactic reference frames:
Bartel et al. (1986) 3C 345
RA: <0.02 mas/yr, dec:<0.05 mas/yr



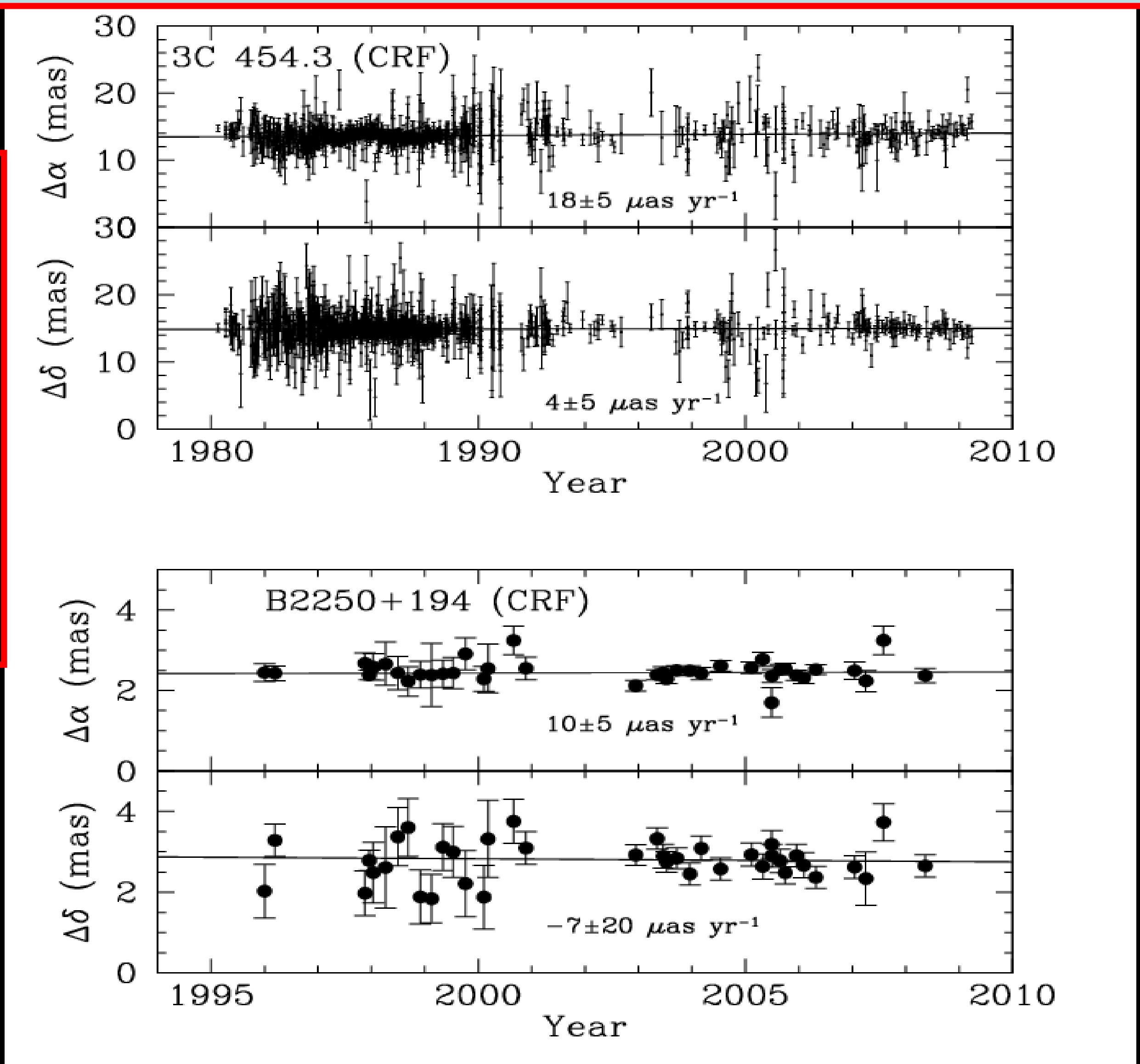
Rioja, Porcas (2000): 1038+528
<0.01 mas/yr

Fomalont et al. (2011): 4 sources
RA: <0.02 mas/yr, dec: <0.03 mas/yr

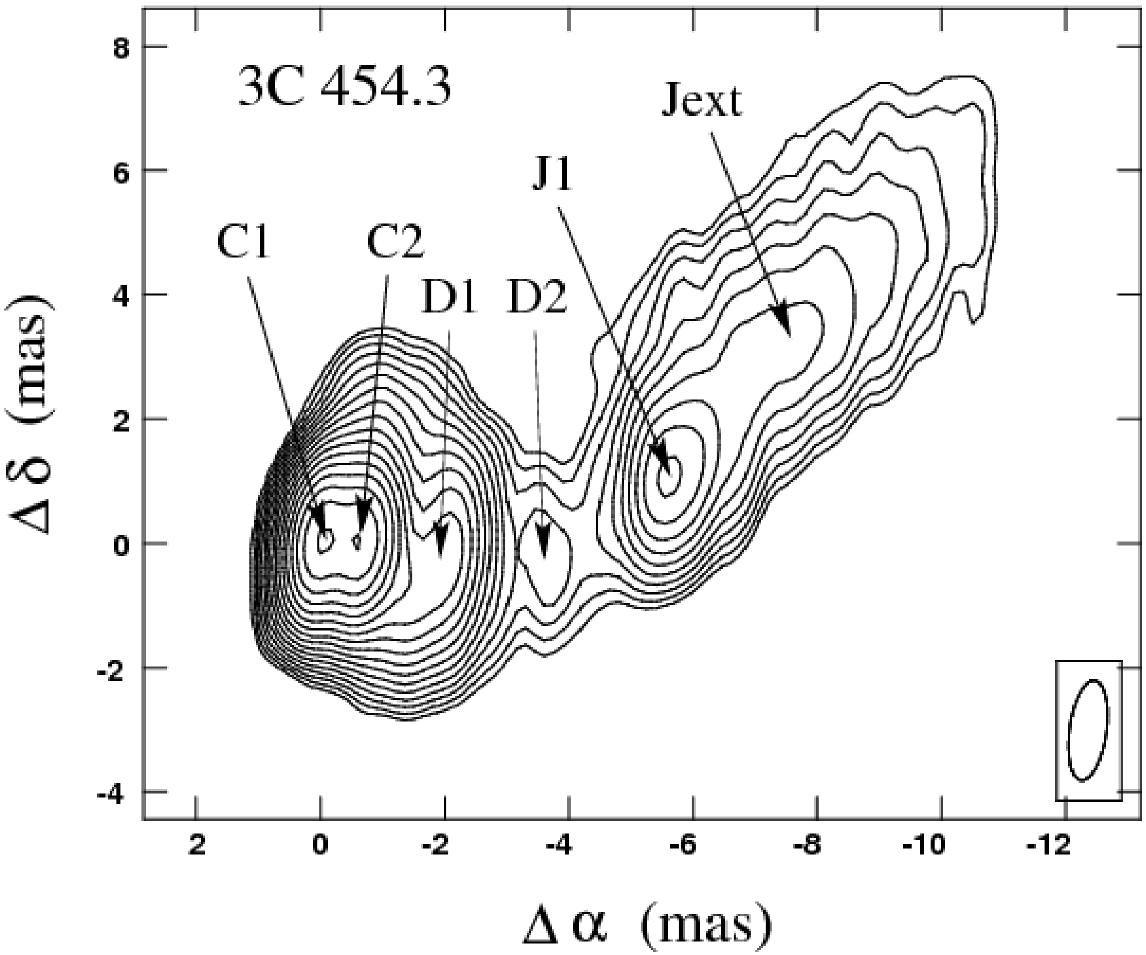
Proper motion of 2 extragalagtic sources w.r.t. a CRF of ~ 4000 sources (updated ICRF)

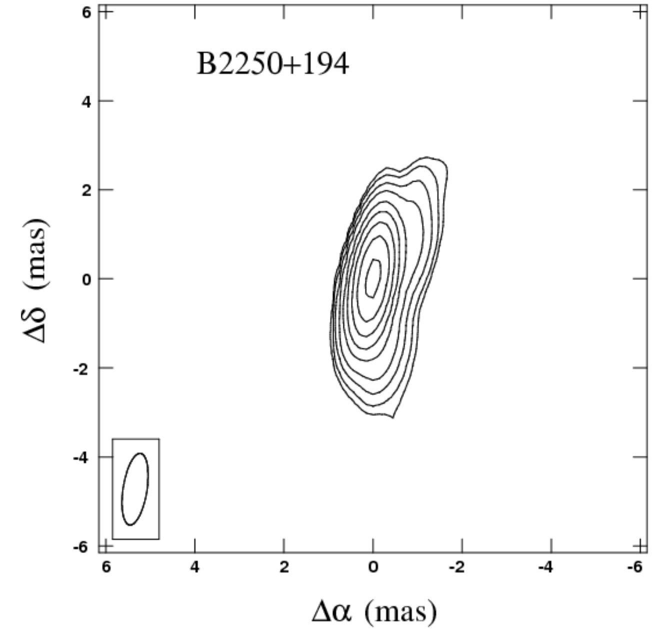
Proper motion:
<30 μas/yr (1σ)
<1c

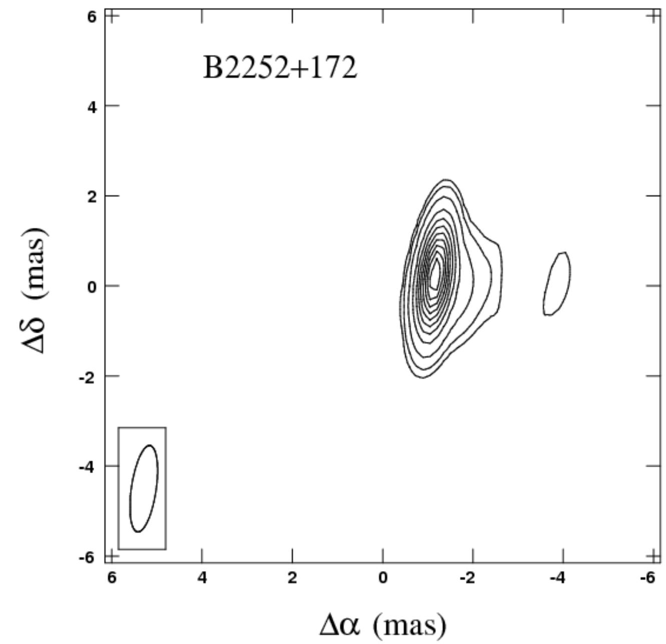
However,
no fiducial reference point



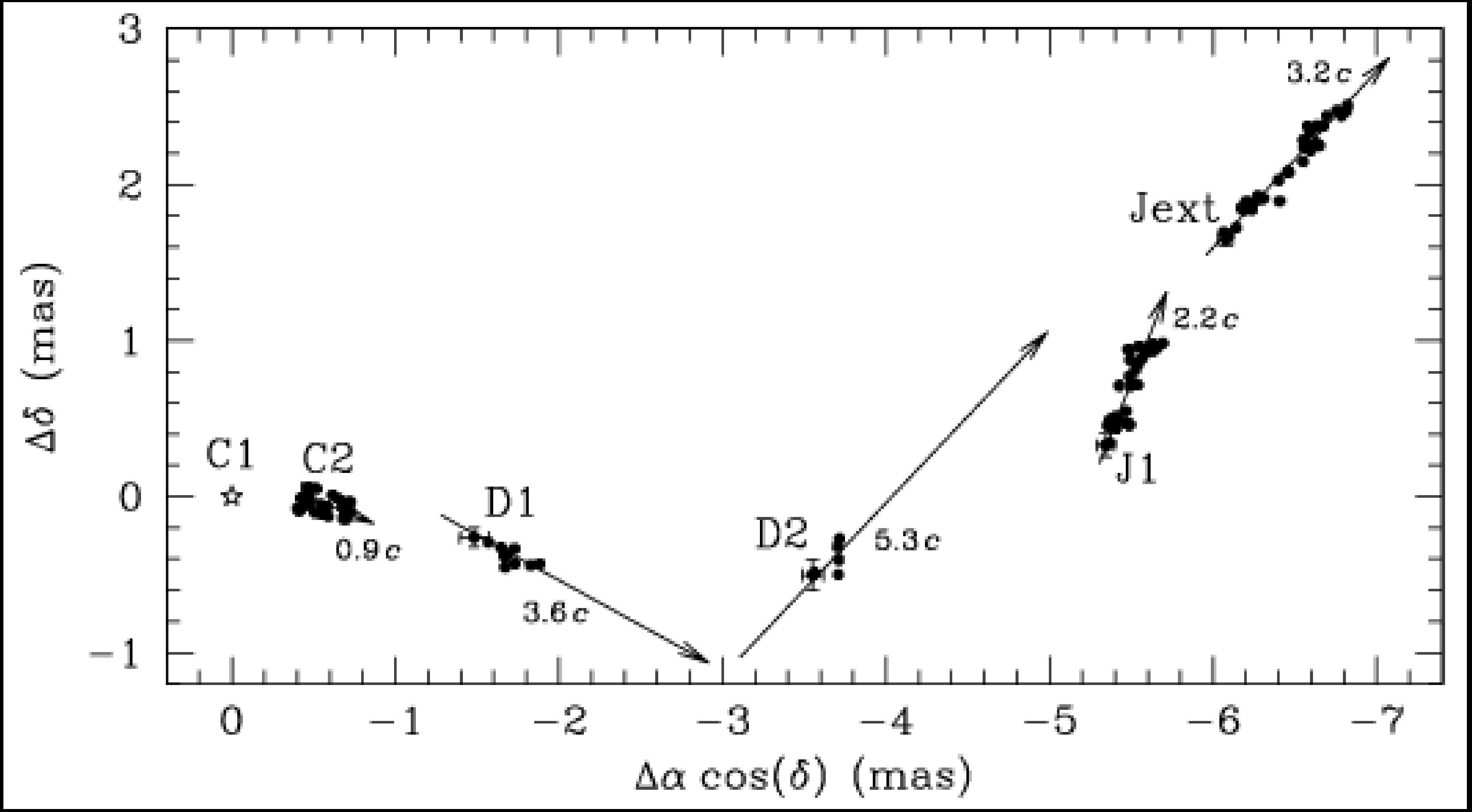
Three extragalactic sources nearby on the sky for relative astrometry



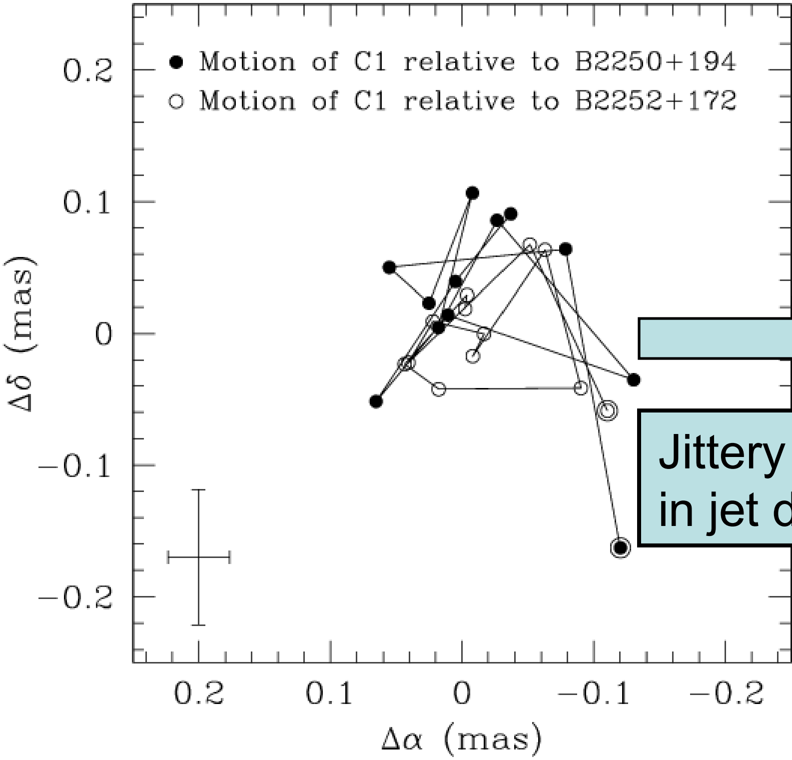




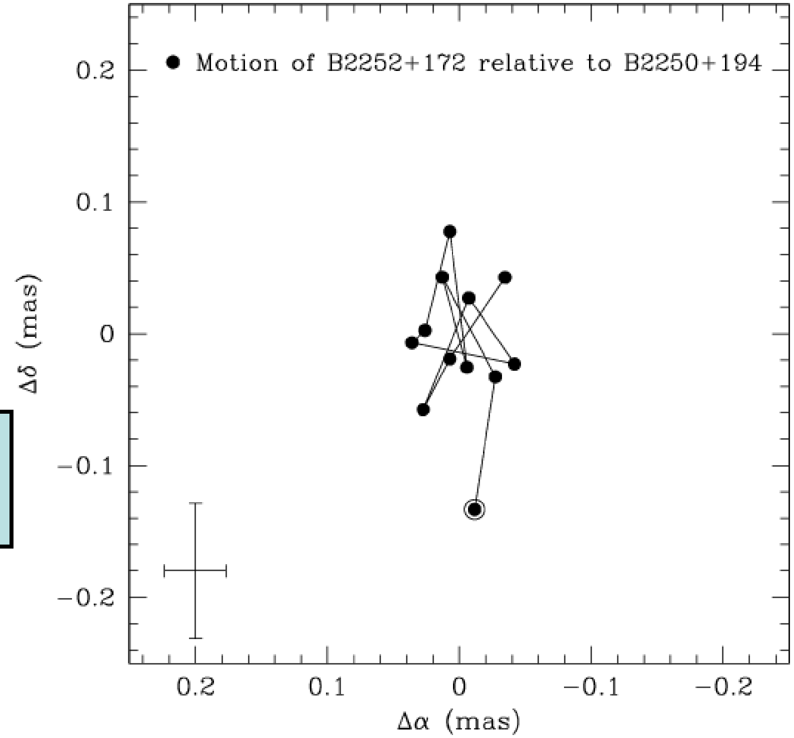
Motion of 3C 454.3's jet components w.r.t. the "core," C1



Motion of “core” components



Jittery motion in jet direction

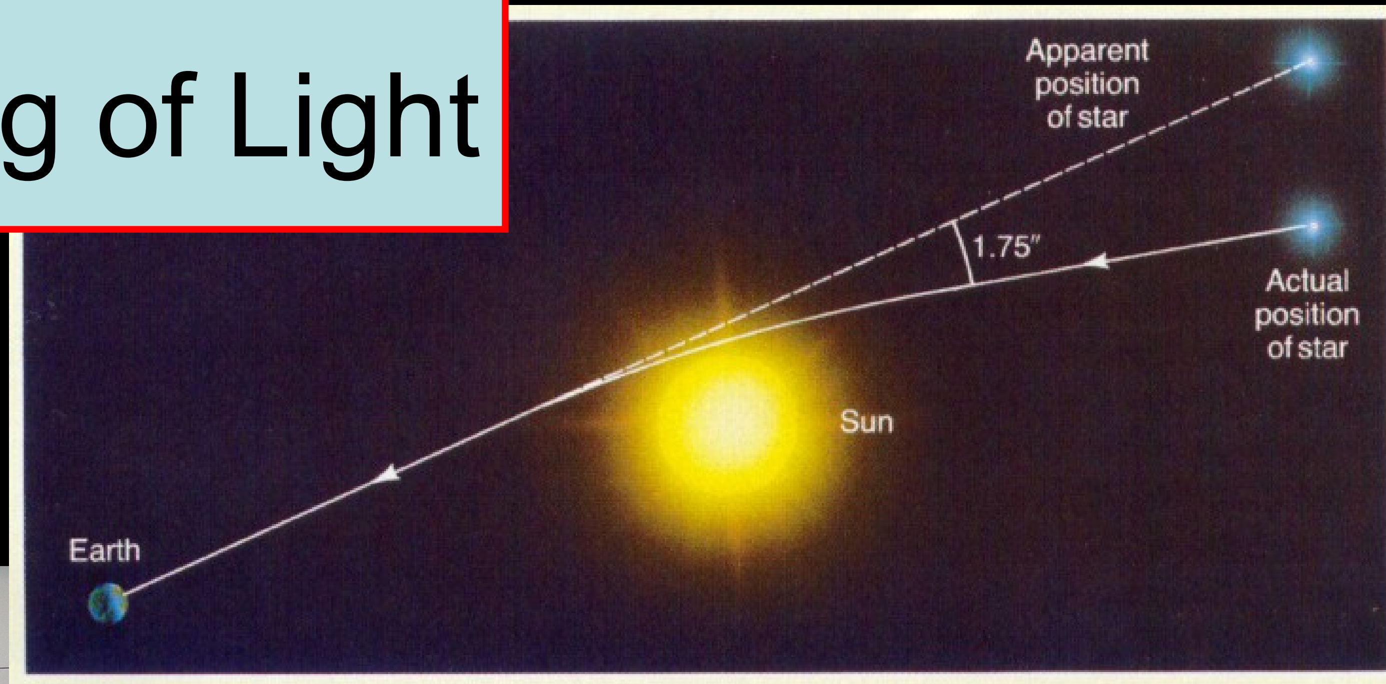


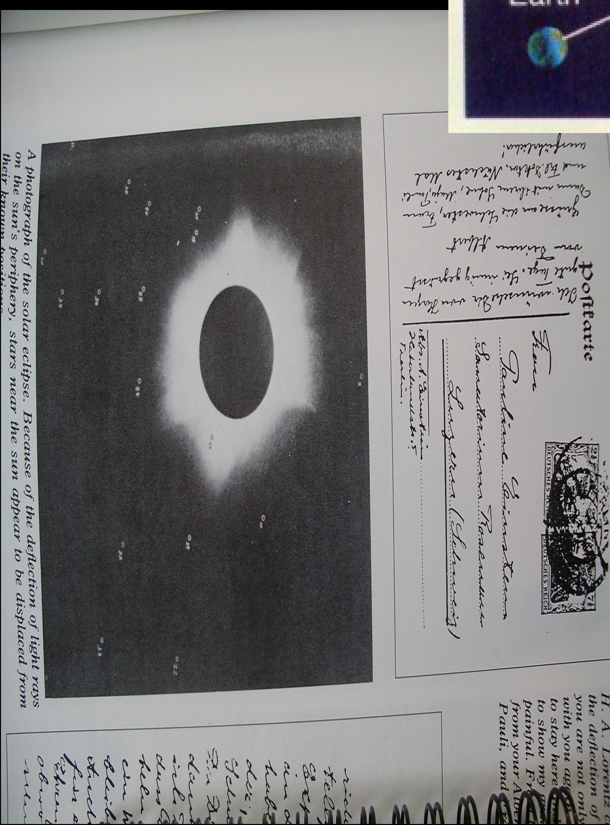
C1 (ICRF, 1σ)
RA: <39 μas/yr <1.0c;
dec:<30 μas/yr <0.8c

(1σ)
RA: <11 μas/yr <0.3c;
dec:<25 μas/yr <0.7c

Tests of general relativity – how sensitive?

Bending of Light

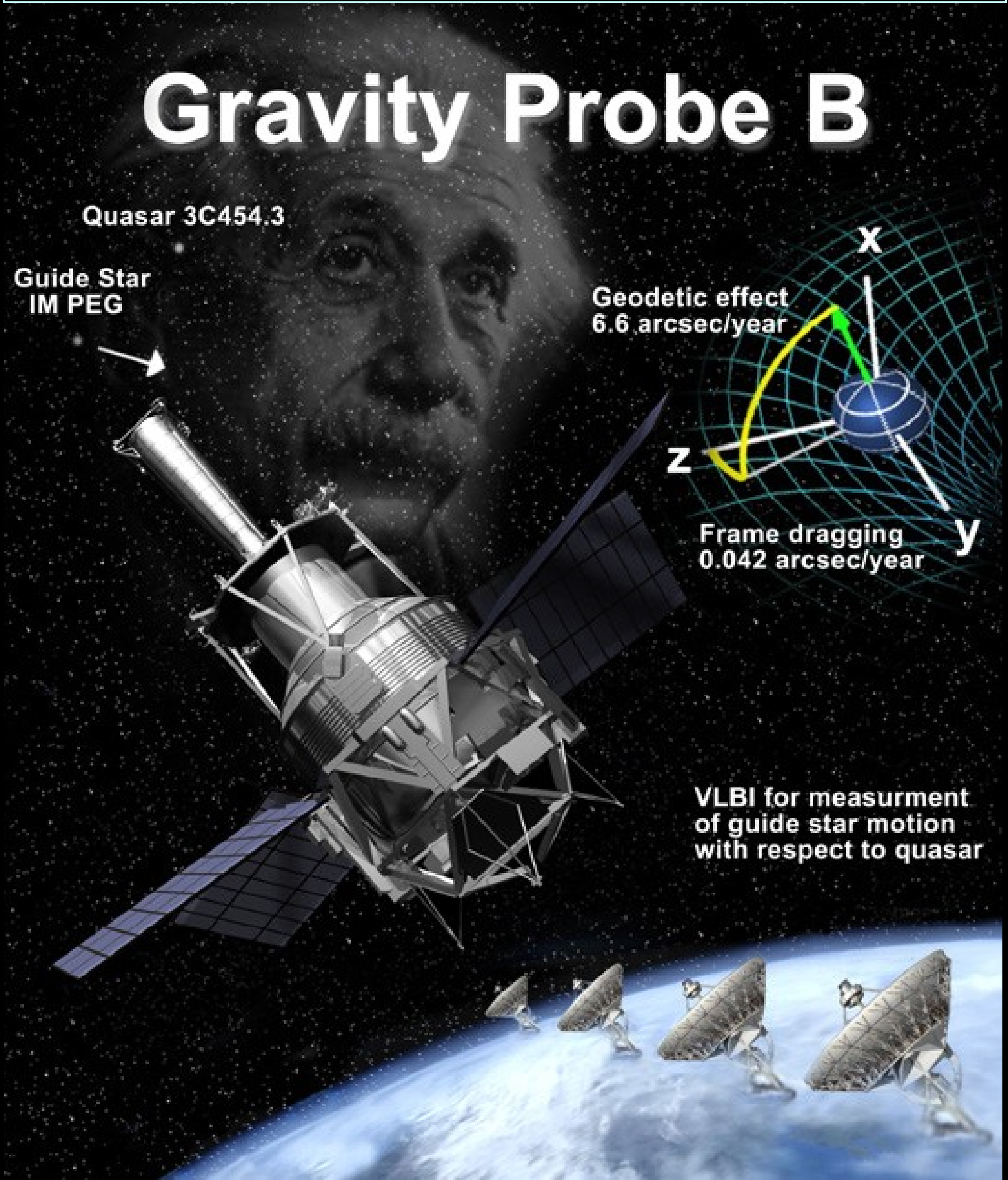




Agreement:

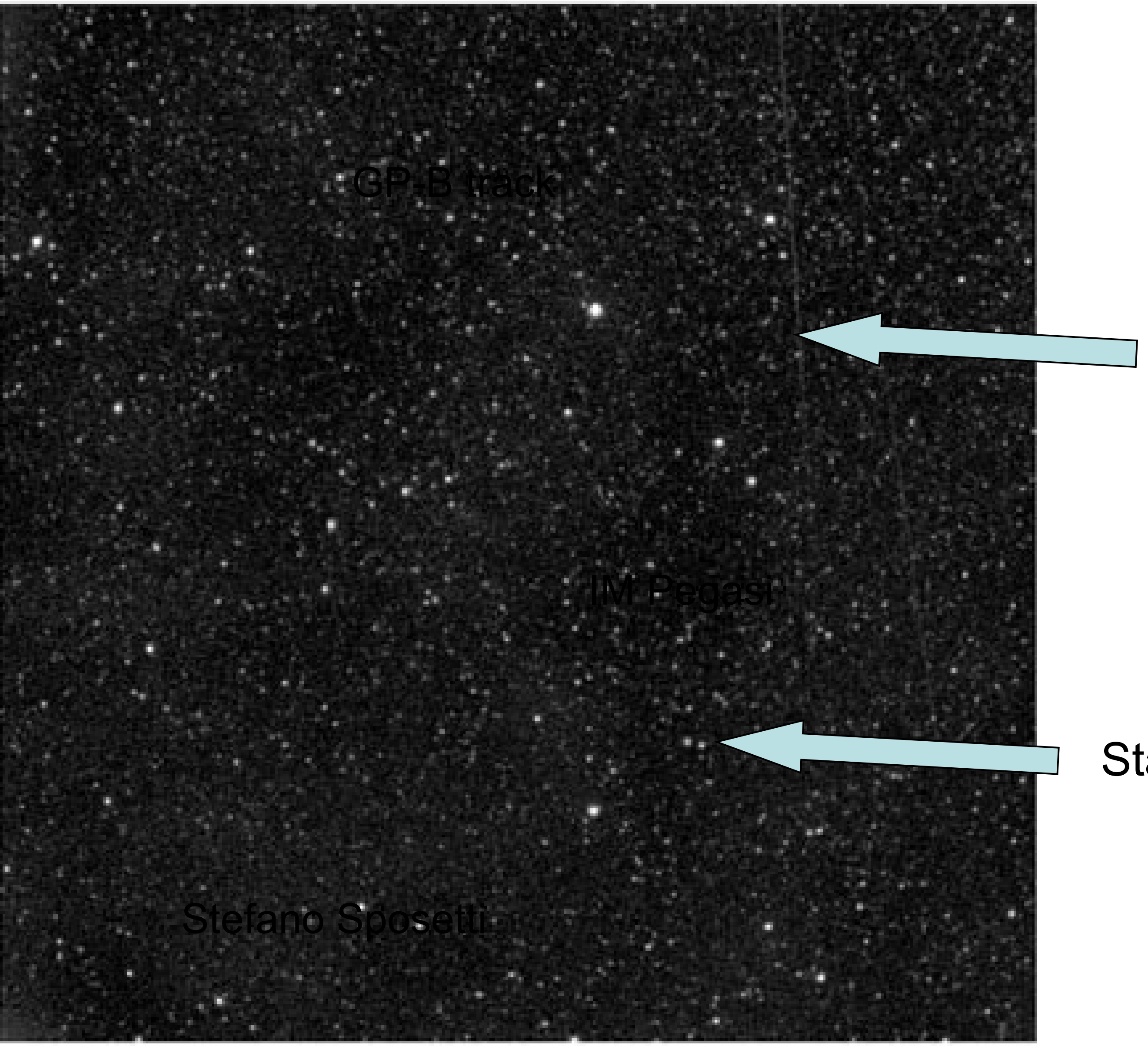
- ~10% best value, from Eddington expedition (published 1920)
- 0.02±0.08% ,VLBI, Lebach et al. (1995)
- 0.006±0.026%, VLBI, Fomalont and Kopeikin (2009)

VLBI Astrometry for the NASA/Stanford Gyroscope Relativity Mission



Shapiro, I., Bartel, N., Bietenholz, M., Lebach, D.E., Lederman, J., Lestrade, J.-F.,Luca, Petrov, L., Ransom, R., Ratner, M. (2011)

Essentials of Gravity Probe B



Testing Einstein’s Universe

Excerpts from a 26 min movie

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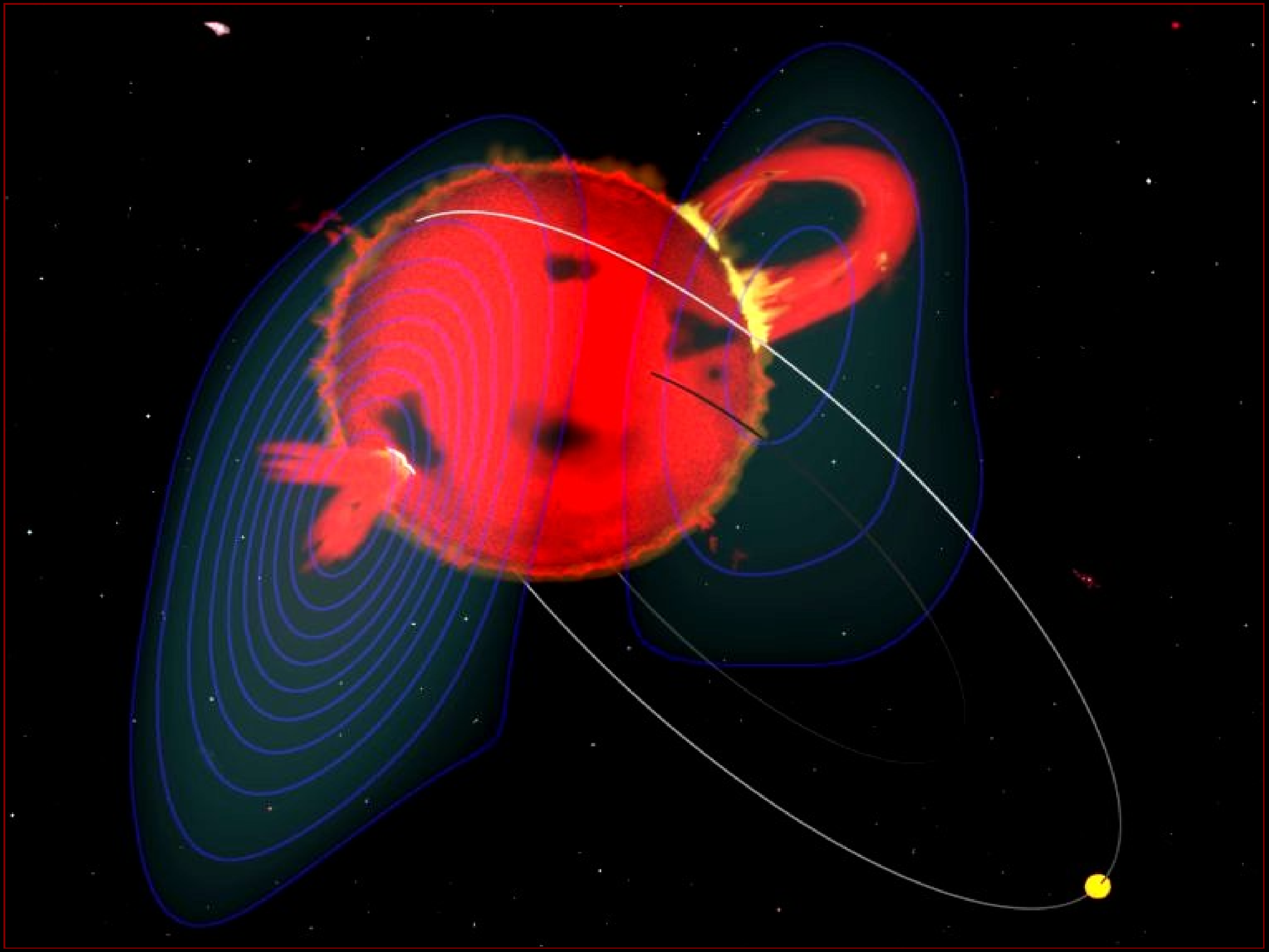
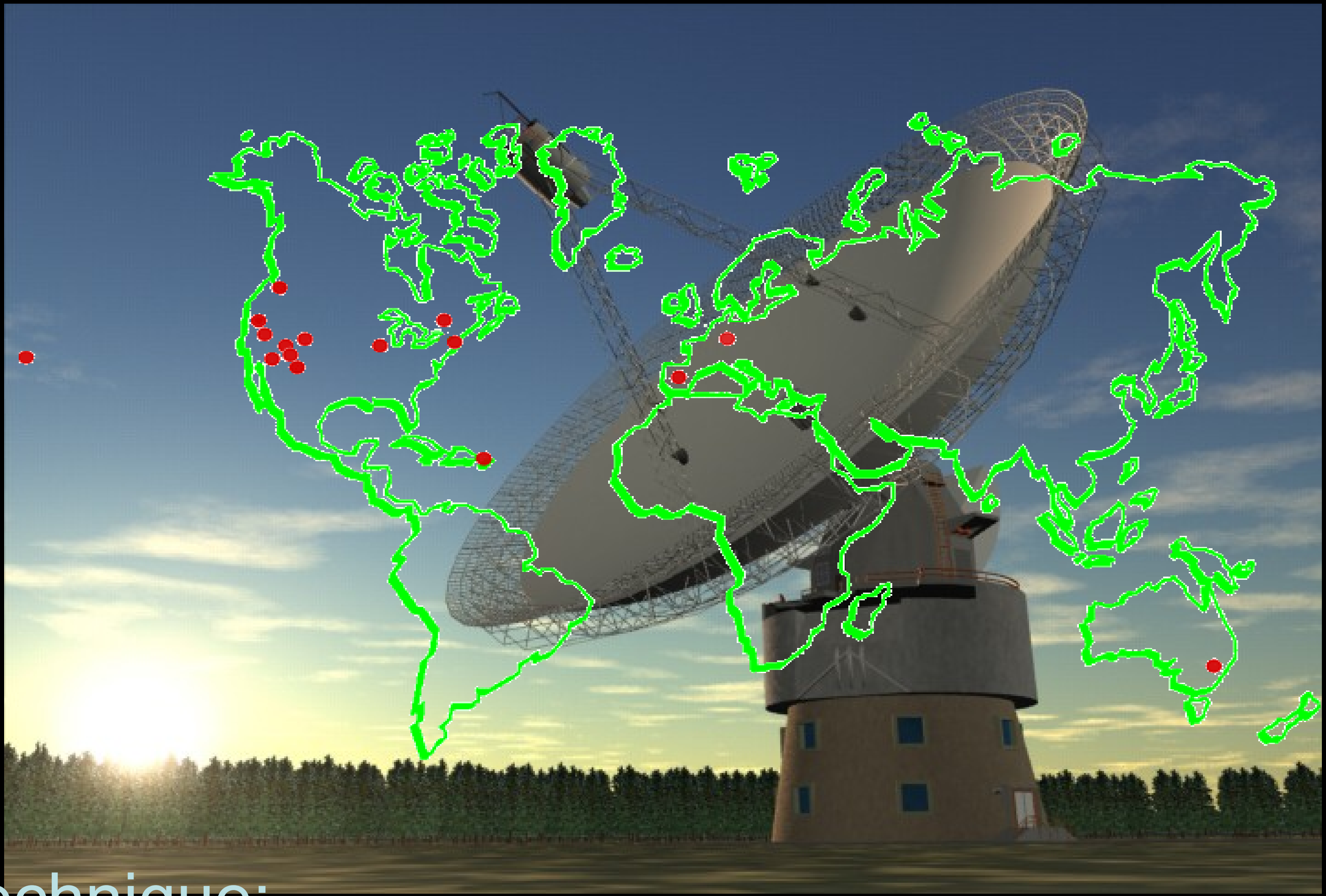
www.astronomyfilms.com

c/o Norbert Bartel

IM Pegasi, the guide star for Gravity Probe B

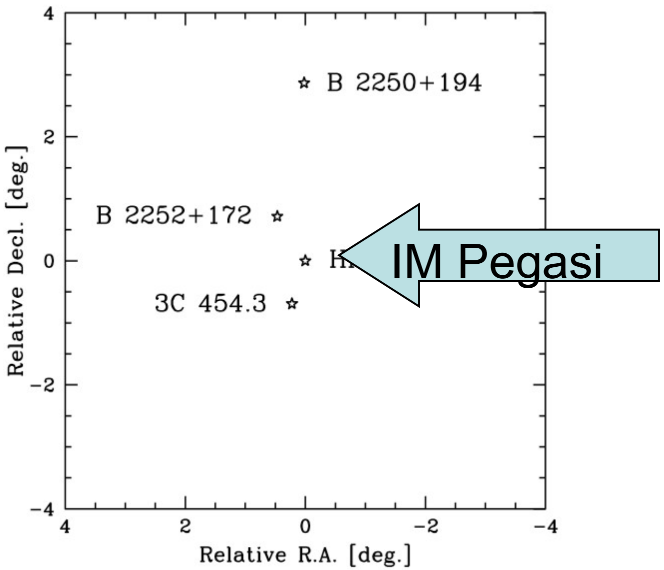


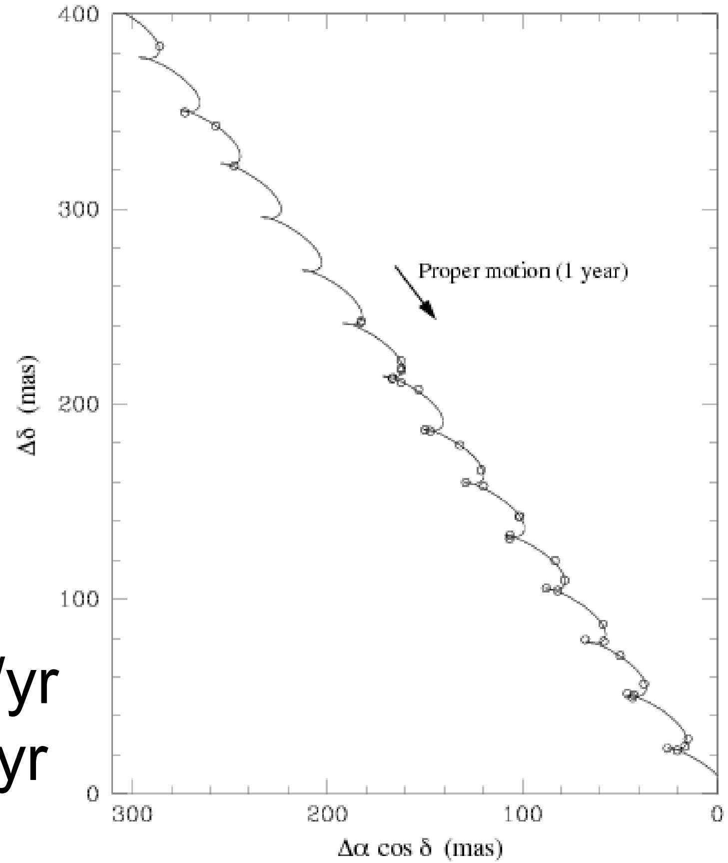
VLBI array



Technique:
Phase-referenced VLBI mapping and use of a Kalman filter to estimate atmospheric fluctuations.

Proper motion and annual parallax of IM Pegasi relative to the ICRF





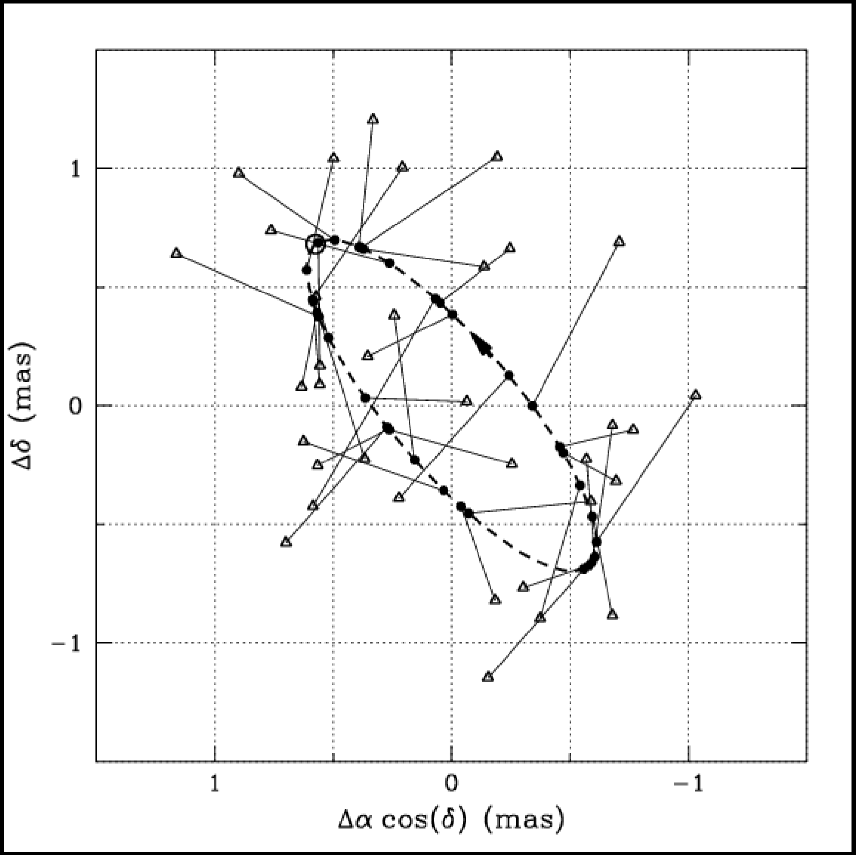
Proper motion:

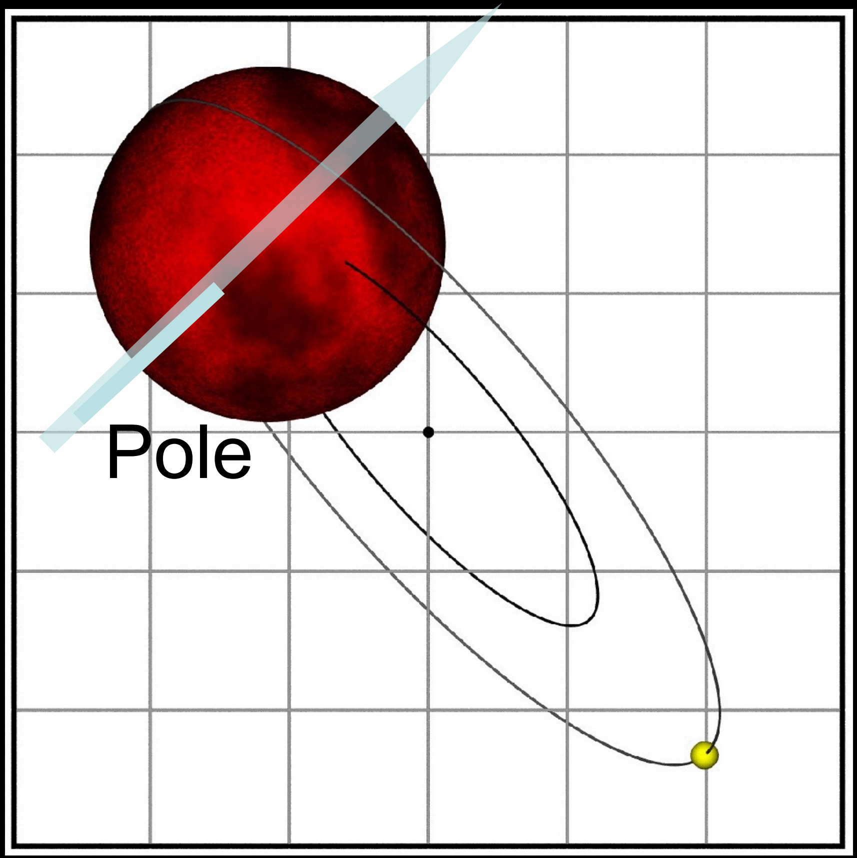
RA: -20.833±0.090 mas/yr

Dec: -27.267±0.095 mas/yr

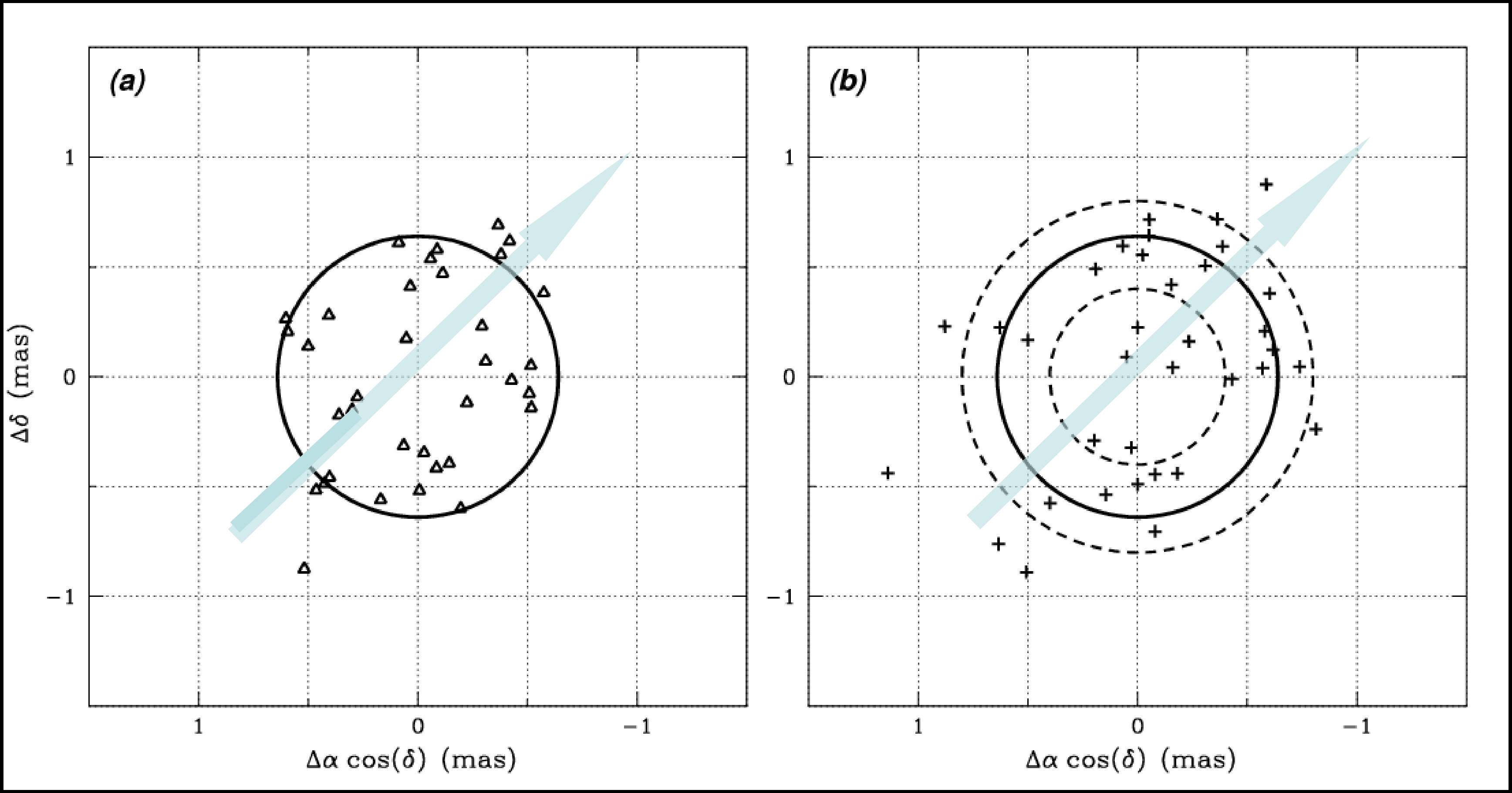
Parallax: 10.370±0.074 mas

Binary orbit





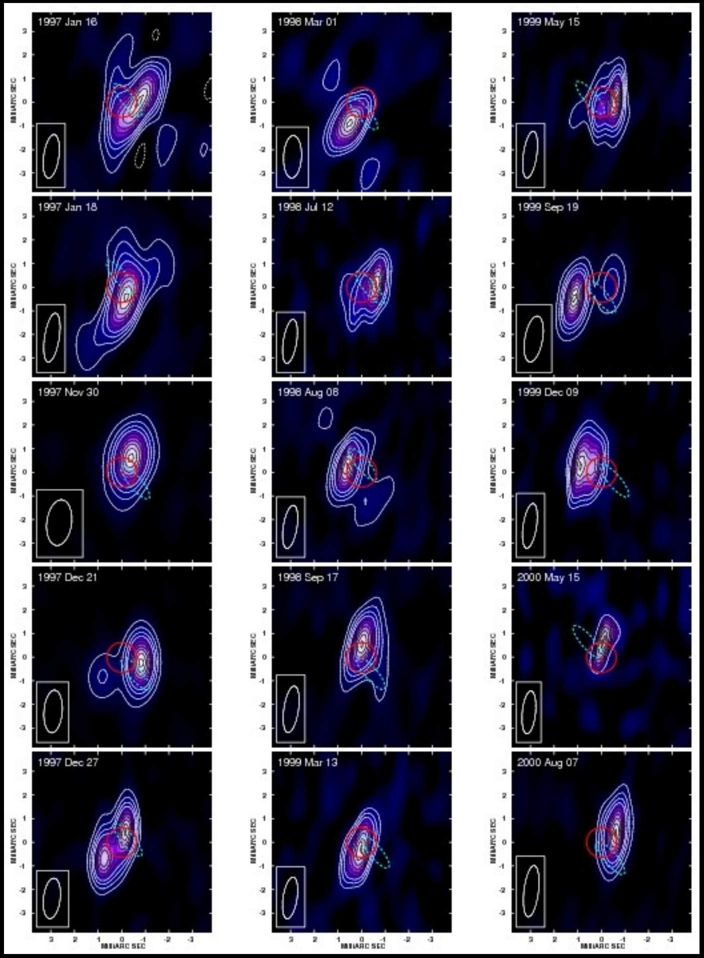
Scatter of radio emission locations across disk of primary

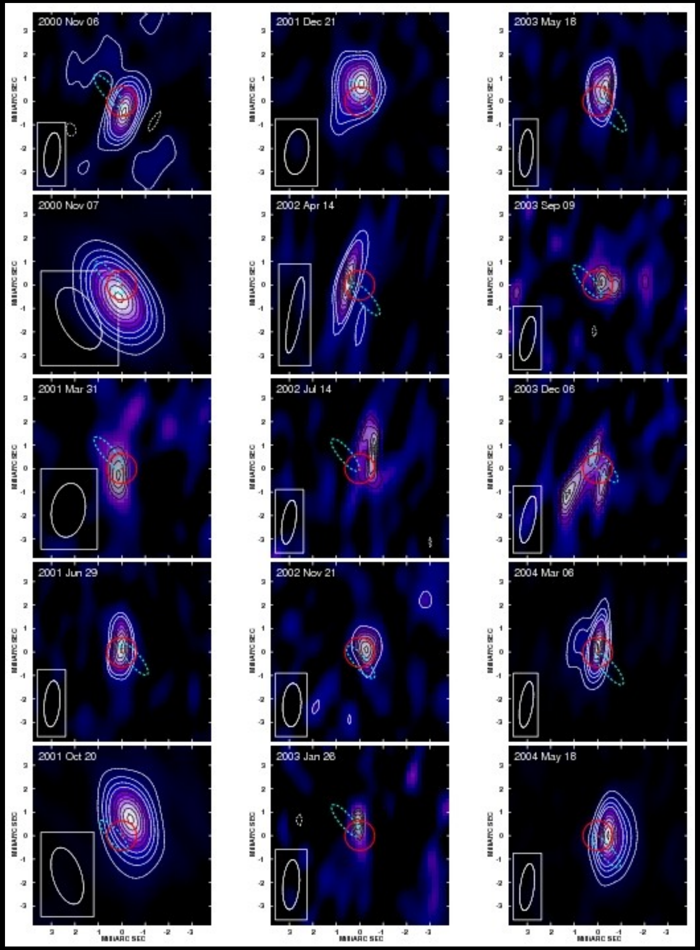


Location of Gaussian

Location of emission peak

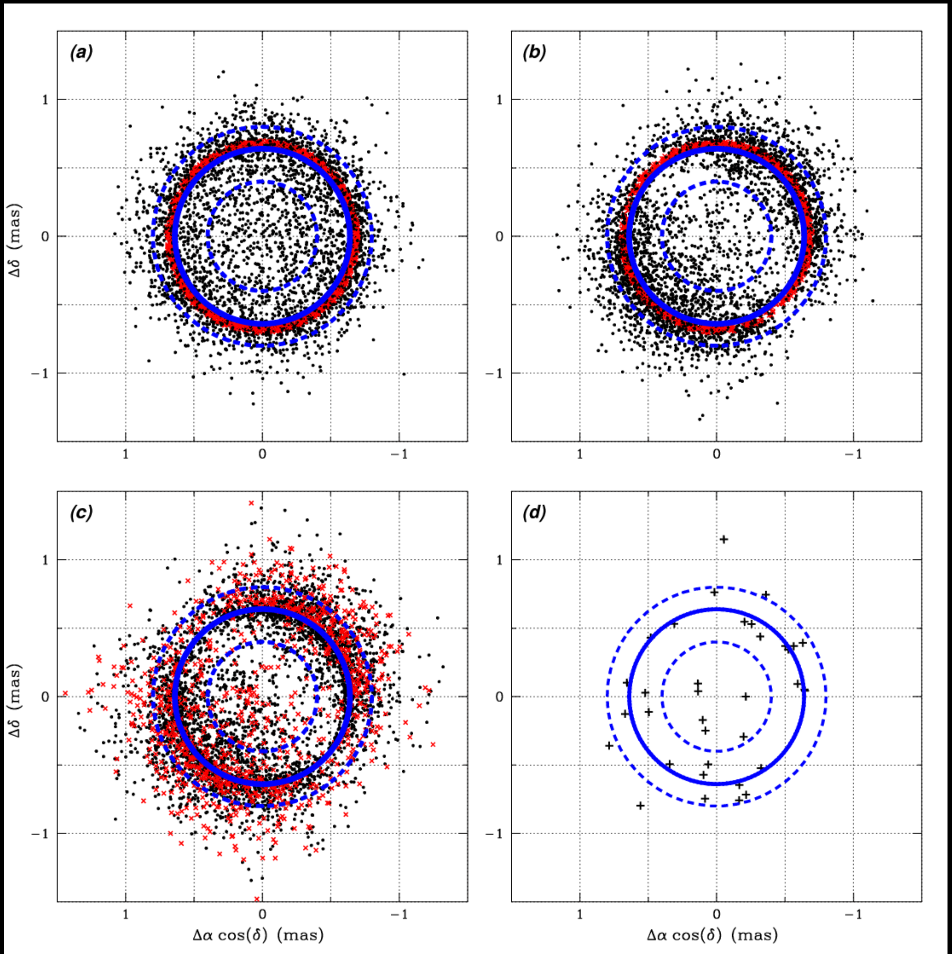
Radio emission structure of IM Pegasi





Movie of a star

Simulation of scatter of radio emission locations across disk of primary



Results:

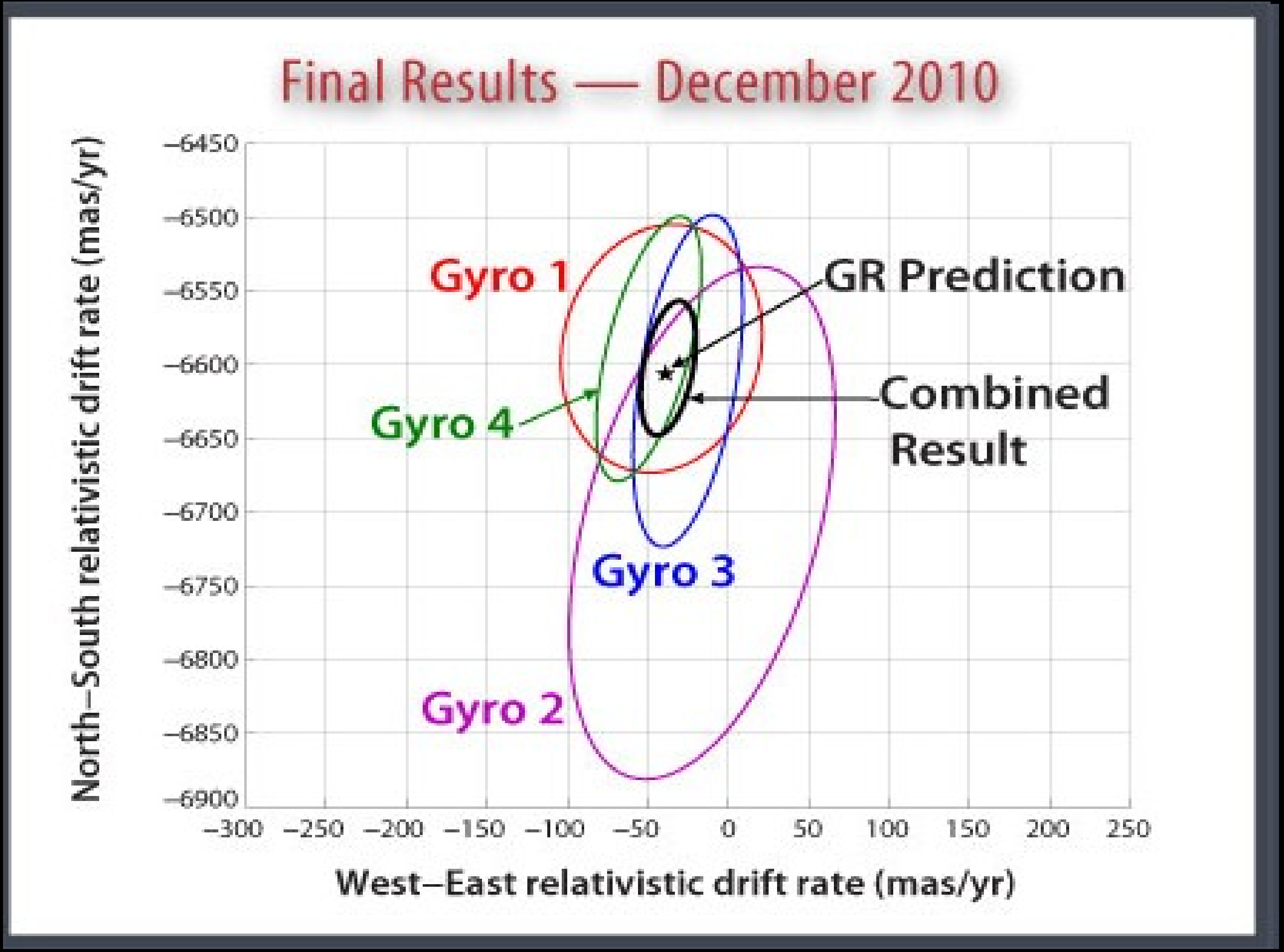
Emission close to surface, 2/3 within 25% of radius

Emission preferentially along spin axis

Emission 8±3 times more frequently at poles than at equator

Emission related to optical dark zones

Results for the precession of the gyroscopes



Everitt et al. 2011

Gravity Probe B
Final Experimental Results

Gyroscope N—S Geodetic
W---E Frame-Dragging

Weighted-Average Results for All Four Gyroscopes:

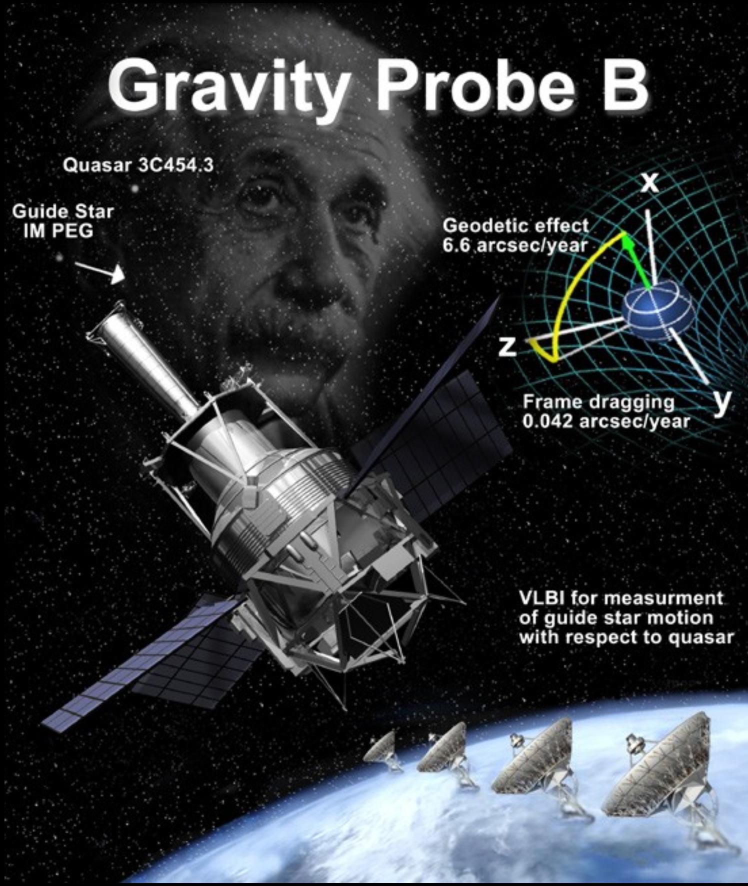
Geodetic: -6,601.8±18.3 mas/yr

Frame dragging: -37.2±7.2 mas/yr

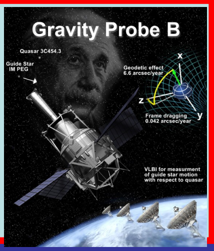
Agreement With General Relativity:

Geodetic: -0.07± 0.28 %

Frame dragging: 5 ± 18 %



Conclusions



- The core and likely gravitational center of a quasar can be best probed at sufficiently high frequencies
- (20 GHz) where opacity effects (due to synchrotron self absorption) are minimized.
- Some quasar cores have been shown to be stationary at the 30 μas/yr (1 c) level.
- IM Pegasi is the best studied radio star and shows properties related to the star's optical characteristics.
- Gravity Probe B detected frame dragging at the 5σ significance level.