Past and Future General Relativity Experiments: Equivalence Principle, Time Delay, and Black Holes

Irwin Shapiro

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Translation of Title

(a.k.a Outline)

- **Tests of the (Weak) Equivalence Principle**
  - Short Description of Long History
  - Low Repetition Einstein Elevator Experiment (Balloon)
  - High Repetition Einstein Elevator Experiment (Laboratory)
- **Measurements of Time Delay**
  - Brief History
  - Present Status
  - Glorious Future
- **Imaging of Black Holes**
  - Evidence for Existence of Black Holes
  - Imaging Possibilities:
    - Optically Thin Sources
    - Optically Thick Sources
  - Practical Considerations
- **Conclusion**

Tests of the (Weak) Equivalence Principle

- **History**
  - Johannes Grammaticus
  - Newton to Eötvös
  - Eötvös to Dicke, Braginski, and Adelberger
  - Lunar Laser Ranging

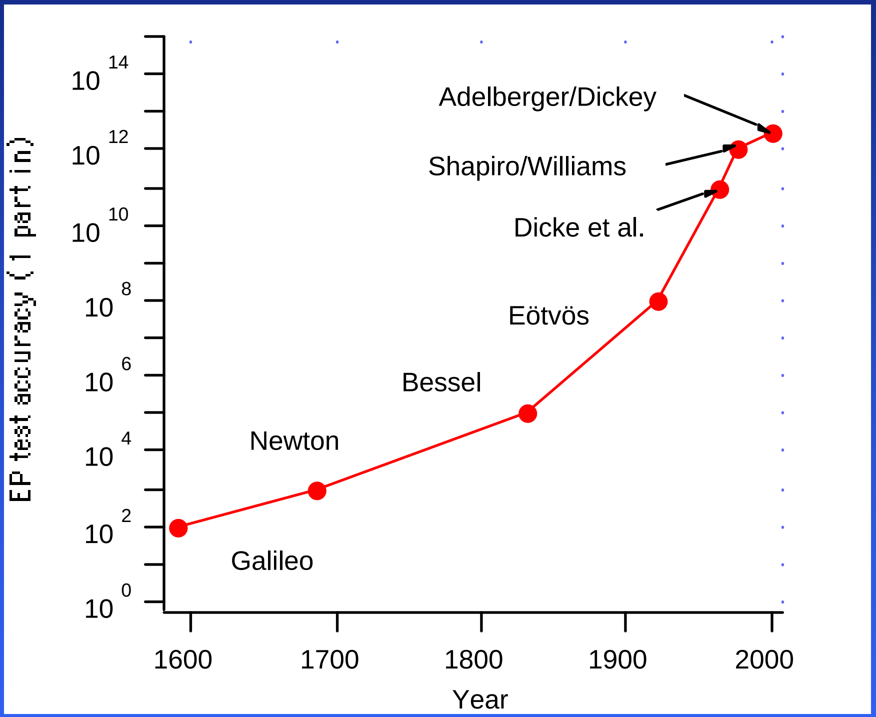
• Einstein Elevator Experiment via Balloon Launch

(E. Lorenzini, V. Iafolla, J. Ashenberg, …, S. Glashow, and I. Shapiro)

- Basic Idea
- Schematics of Equipment
- Key Design Features:
  - Detector
    - (Packaging Proof Masses, Torque Sensitivity, and Frequency Discrimination)
  - Release Mechanism
    - (Rapid Damping of Transients)
- Error Analysis and Accuracy Goal
- Status:
  - Detailed Component Design
  - Funding Issues

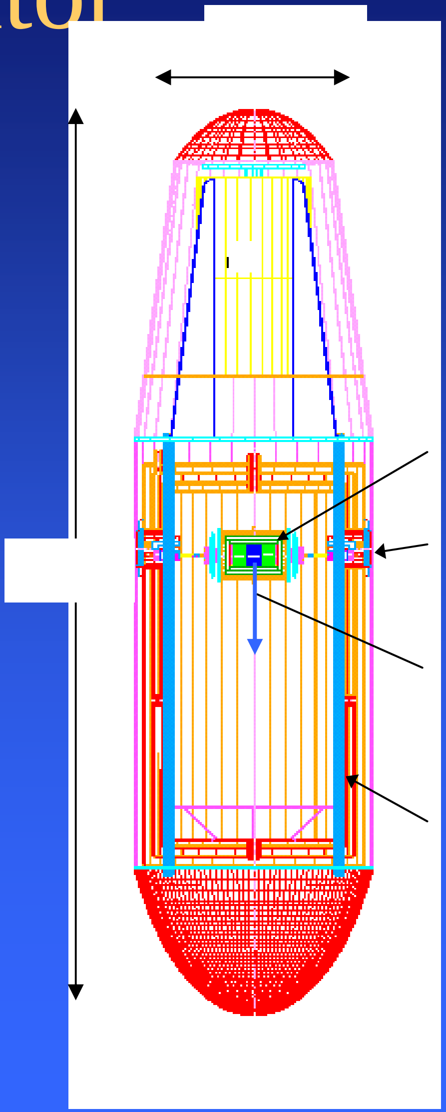
Historical progress in testing the EP

Authors	Accuracy	Method
Eötvös, 1922	10^{-8}	Torsion balance
Dicke et al., 1964	10^{-11}	Torsion balance
Braginski, 1972	10^{-12}	Torsion balance
Shapiro/ Williams, 1976	3×10^{-12}	Lunar Laser Ranging
Dickey et al., 1996	5×10^{-13}	Lunar Laser Ranging
Adelberger et al., 1999	5×10^{-13}	Torsion balance

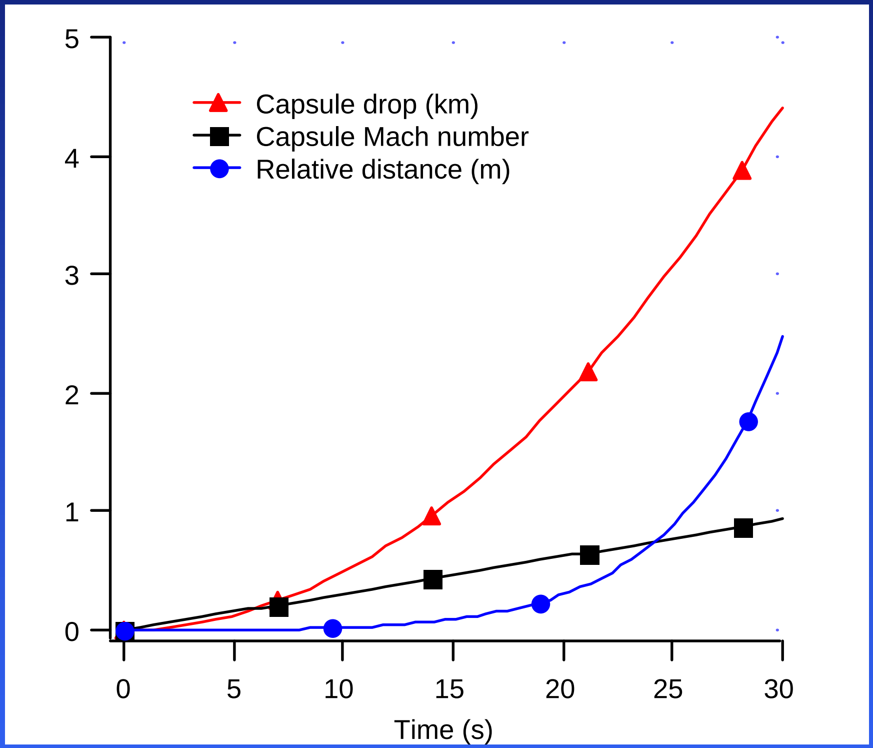


Planned Test of EP in an Einstein Elevator

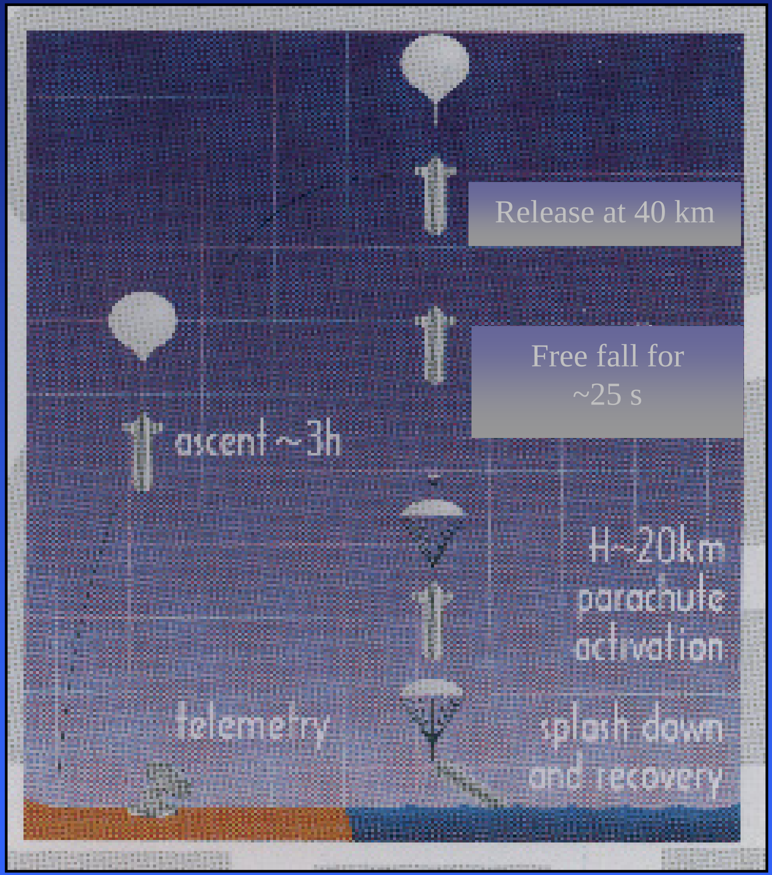
- Use differential accelerometer with two proof masses of different materials
- Capsule released first from balloon at an altitude of 40 km
- Detector released from top of capsule to free fall for ~25 s inside the evacuated capsule
- Detector rotates (at 0.5 Hz) during free fall to modulate violation signal
- Vacuum isolates detector from external noise sources
- Estimated accuracy in testing the EP is 5 parts in 10^{15} at 95% confidence level
- Experiment is repeatable at intervals of a few weeks



Flight sequence



Expected free-fall characteristics of experiment for a capsule mass of 1700 kg



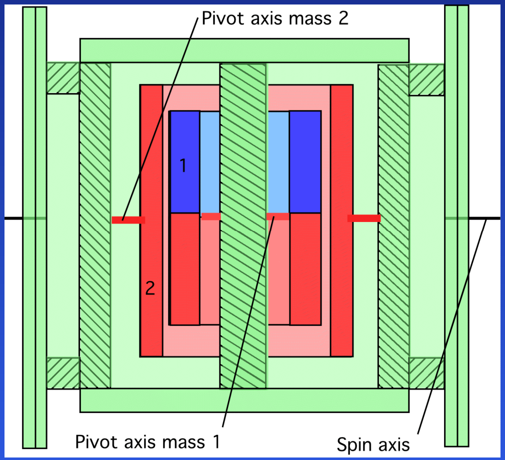
Rotational detector configuration

- **Purely-rotational detector configuration**

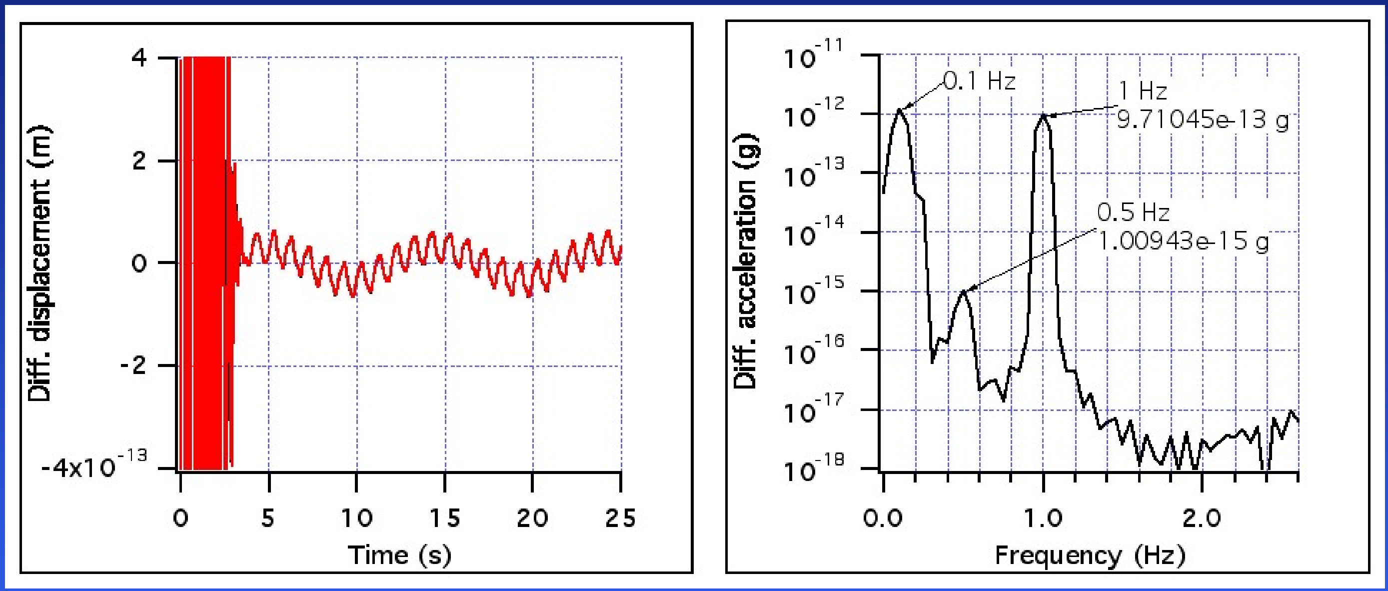
  - *S*pin axis *coincident with* pivot axes of proof masses

  - Gravity gradient torque about pivot axis modulated *at twice signal frequency*

  - EP violation torque modulated *at the spin frequency*



Simulation results



Simulation results for realistic error at release and construction imperfections

Advantages of purely-rotational detectors

- Comparatively low sensitivity to motion of instrument package
- Low sensitivity to effects of gravity gradient forces and torques and hence relaxed requirements on orientation of detector with respect to local gravity vector and axial symmetry of proof masses
- EP violation torque (with an arm length of a few cm) is strong when compared to (inertial and gravitational) differential torques consistent with realistic errors and imperfections

Estimated Error Budget

Noise Source	Max. differential acceleration	Frequency content
Brownian noise	1×10^{-14} g/$\sqrt{\text{Hz}}$	white
Amplifier noise	4×10^{-15} g/$\sqrt{\text{Hz}}$	white
Capsule's vibrations	10^{-17} g/$\sqrt{\text{Hz}}$	white
Drag in capsule	6×10^{-17} g	$1/t_{fall}$
Capsule-equipment ferromagnetism	5×10^{-16} g	f_S
Radiometer effect	2×10^{-16} g	f_S
Earth's gravity gradient torques (for realistic construction and orientation errors of detector)	10^{-16} g 10^{-12} g	f_S $2f_S$
Higher-order gravitational coupling to capsule mass	10^{-16} g	f_S, $2f_S$, $3f_S$,...
Others	$< 10^{-17}$ g	various
Error sum (rms) for a 20-s integration time	2.4×10^{-15} g	at f_S

t_{fall} = free-fall time, f_S = signal frequency

Estimated accuracy in 20-s integration time is 5 parts in 10^{15} at 95% confidence level.

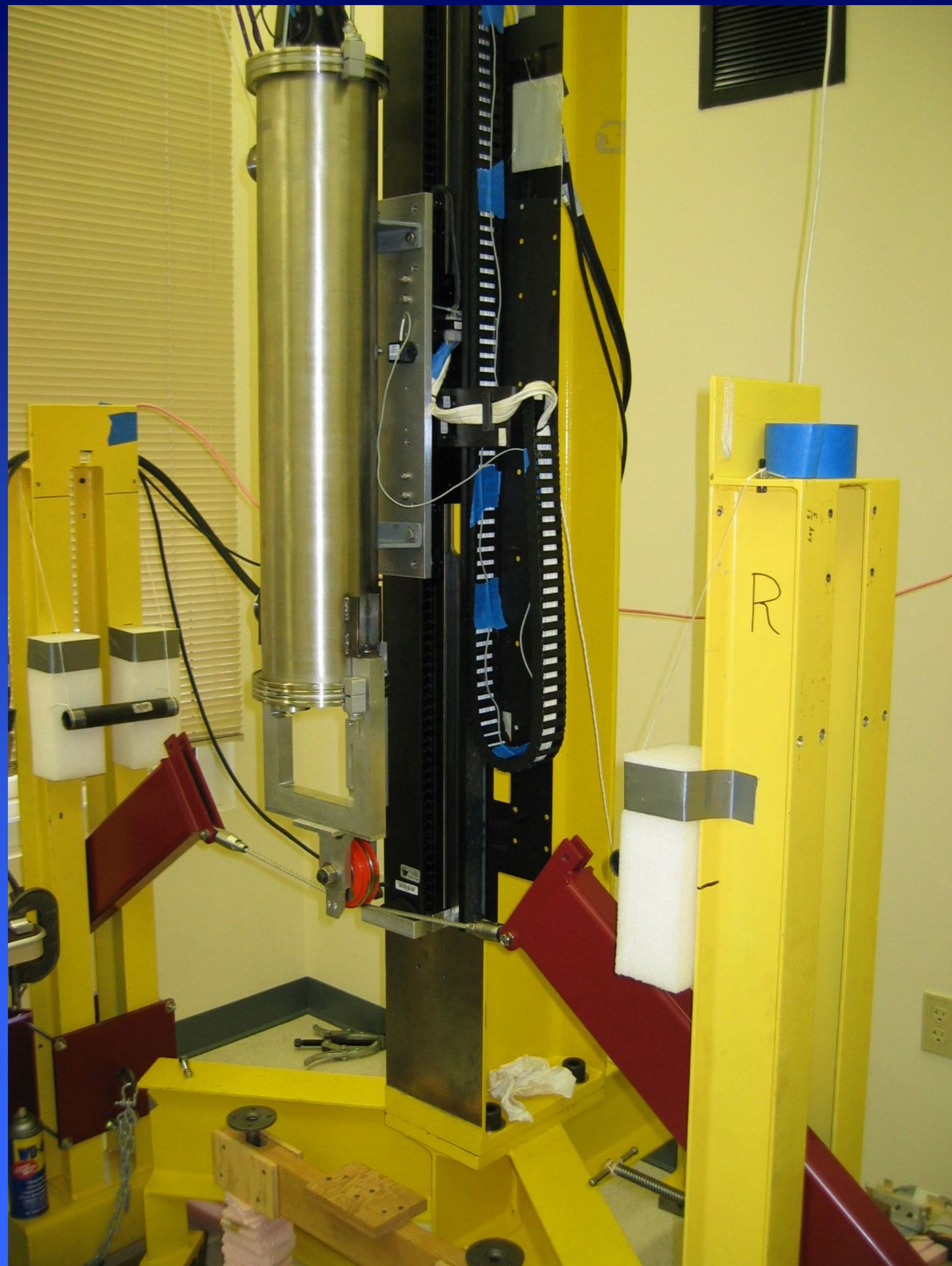
Conclusions

- Selection of appropriate configuration for detector and inertia characteristics of package makes experiment in vertical free fall rather insensitive to dynamics of the instrument package and gravity gradients
- As a result, test accuracy is not limited by effects related to dynamics, proof mass centering, and orientation of the detector with respect to gravity vector but rather by the intrinsic noise of the differential accelerometer
- Vertical free fall from a balloon could make possible EP tests about two orders of magnitude more accurate than presently achieved with torsion balances

• Einstein Elevator Experiment via Repetitive Bouncing

(R. Reasenberg and J. Phillips)

- Basic Idea
- Schematics of Equipment
- Key Design Features:
  - Test Mass Assembly
  - Picometer Laser Gauge
  - Bounce Mechanism
- Error Analysis and Accuracy Goal
- Status:
  - Generation I (of III) Mostly Built
  - Funding Issues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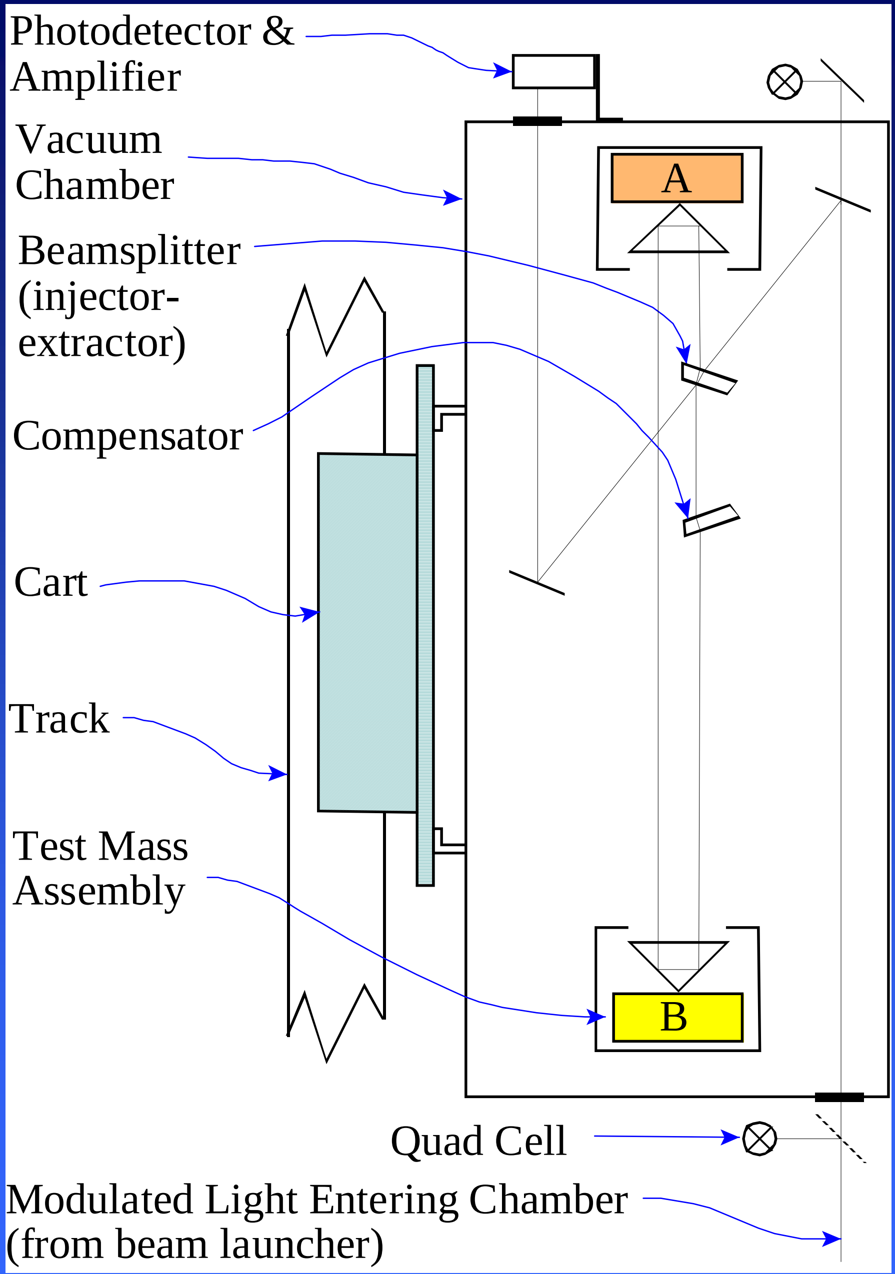
POEM Chamber Optics, Gen-I

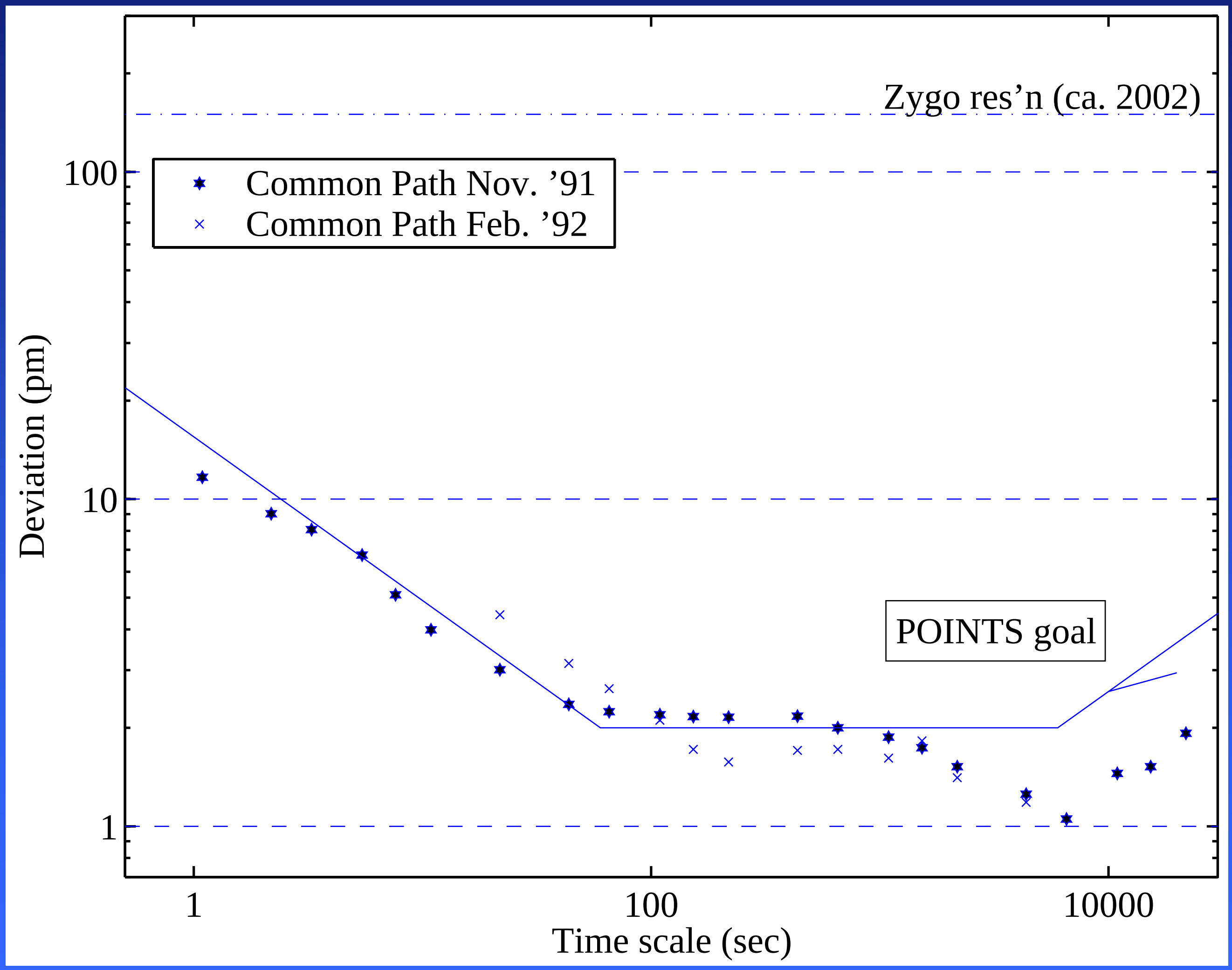
Key Technologies:

Motion system;

Laser gauge.



Classic TFG Performance



Measurements of Time Delay

- **Brief History**
  - Basic Idea (and Its Rate of Change)
  - Radar Realization:
    - Radar Equation
    - Signal-to-Noise Barrier
    - Solar Corona Issue
  - Spacecraft Ranging Transponders:
    - Viking Experiment (Landers and Orbiters)
  - Spacecraft Doppler Transponders:
    - Cassini Experiment
      - (High Radio Frequencies and Low Non Gravitational Forces)
- **Present Status**
  - Accuracy of Cassini Experiment (B. Bertotti et al., 2003)
- **Glorious Future**
  - Radio to Light (Earth to Space)
  - Proposed Experiment: LATOR (S. Turyshev et al.)
  - Funding and Time Scale

Radar Basics

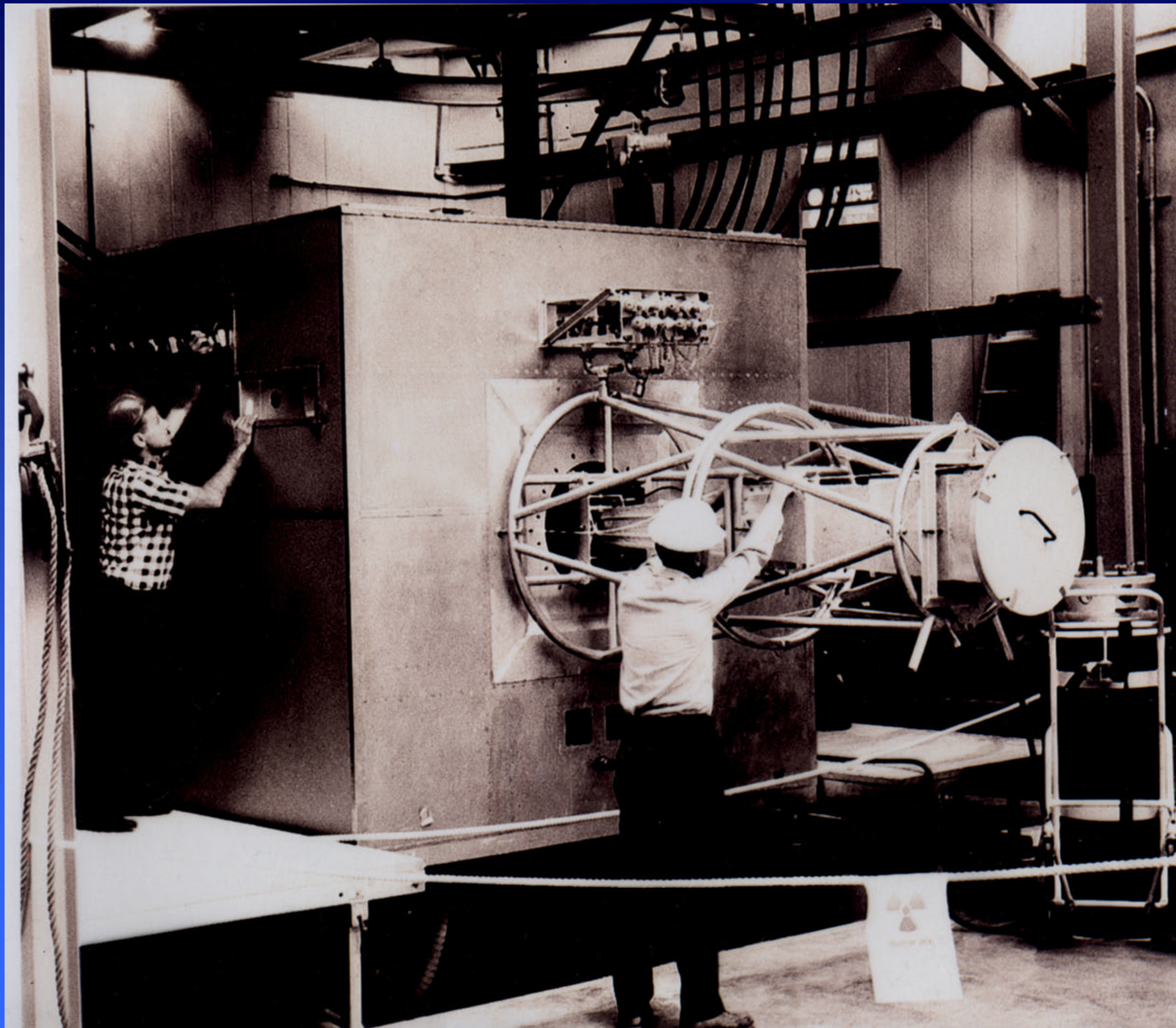
- Echo strength depends on inverse fourth power of distance of target planet (for Venus at its closest, this factor is < 10^{-7} for Moon)

- Continuous wave transmitted for equivalent of round-trip time to target planet (~5 to ~30min, depending on Earth-planet separation)

- Phase of pure (monotonic) transmitted signal encoded via pseudo-random code to allow reconstruction of round-trip travel time from received echo

- Echo signal spread in frequency and delay due to properties of target planet. "Template matching" used to determine round-trip time

- Analogy on Echo Power



Model of Solar System

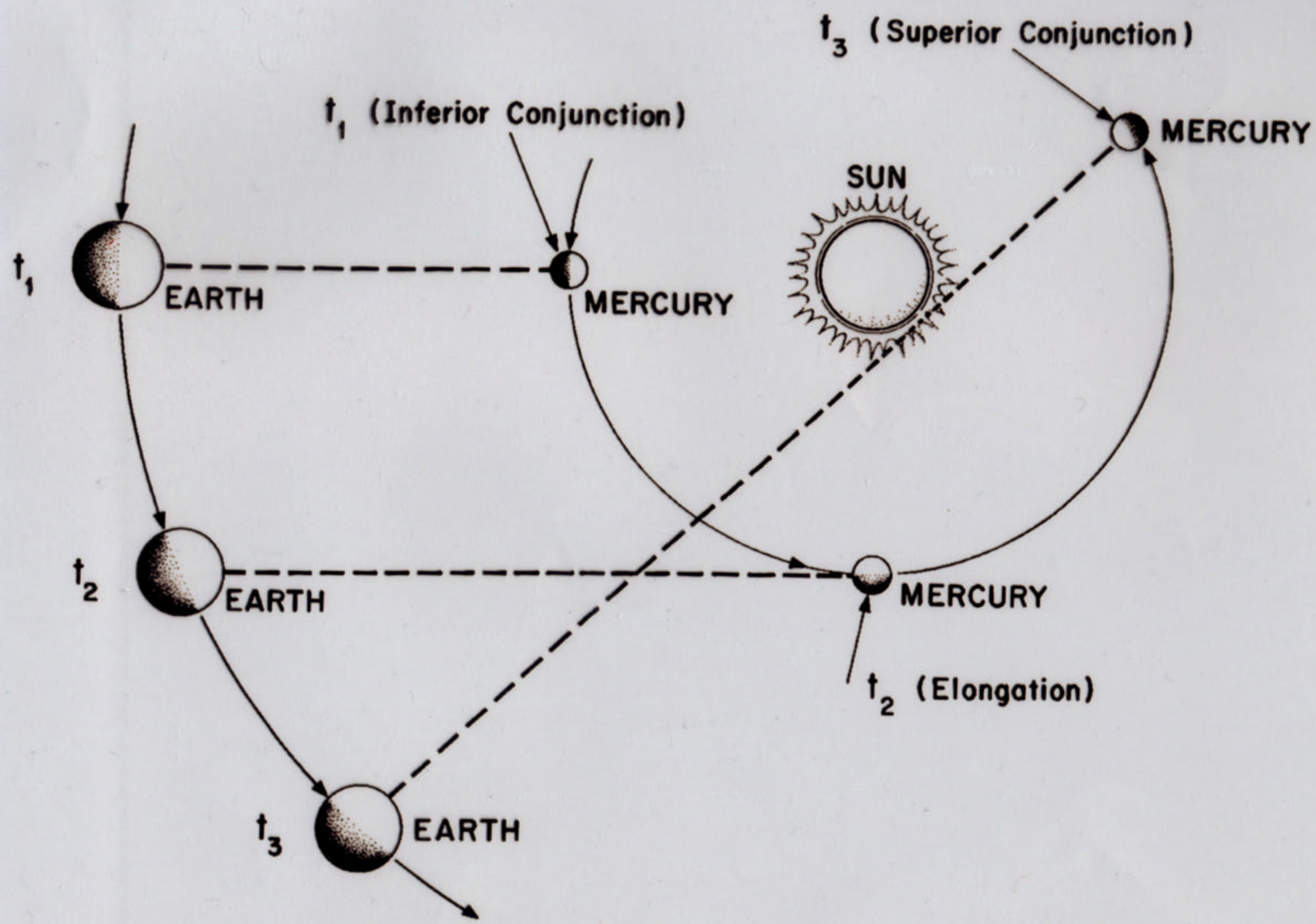
Equations of motion of planets and Moon in post Newtonian approximation to GR. (Equations, too, of partial derivatives of motion equations with respect to relevant masses and initial conditions.) Solutions carried out wholly numerically, based on "first guesses" of initial conditions.

Motions of Earth:

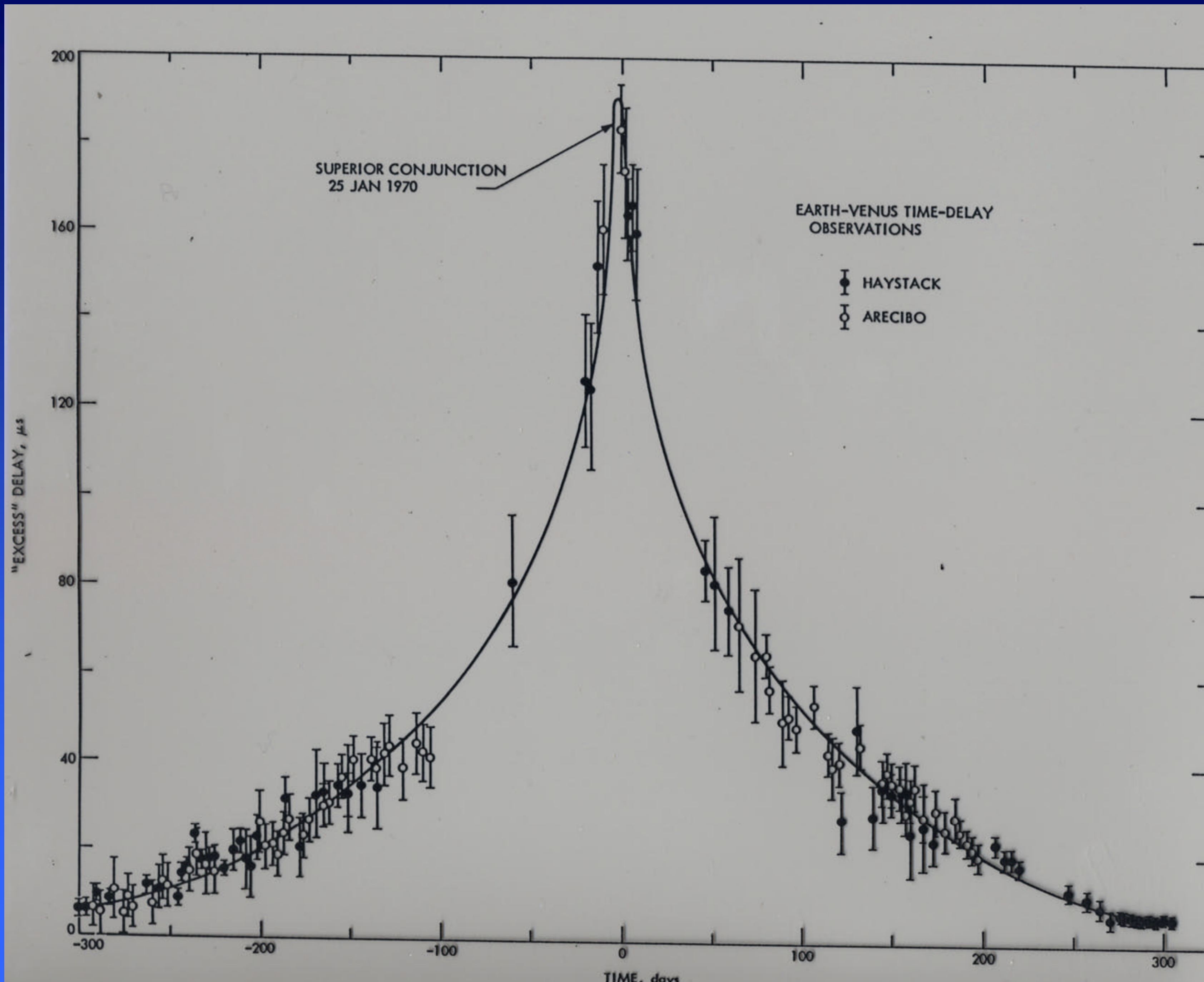
- precession and nutation
- polar motion and Earth rotation

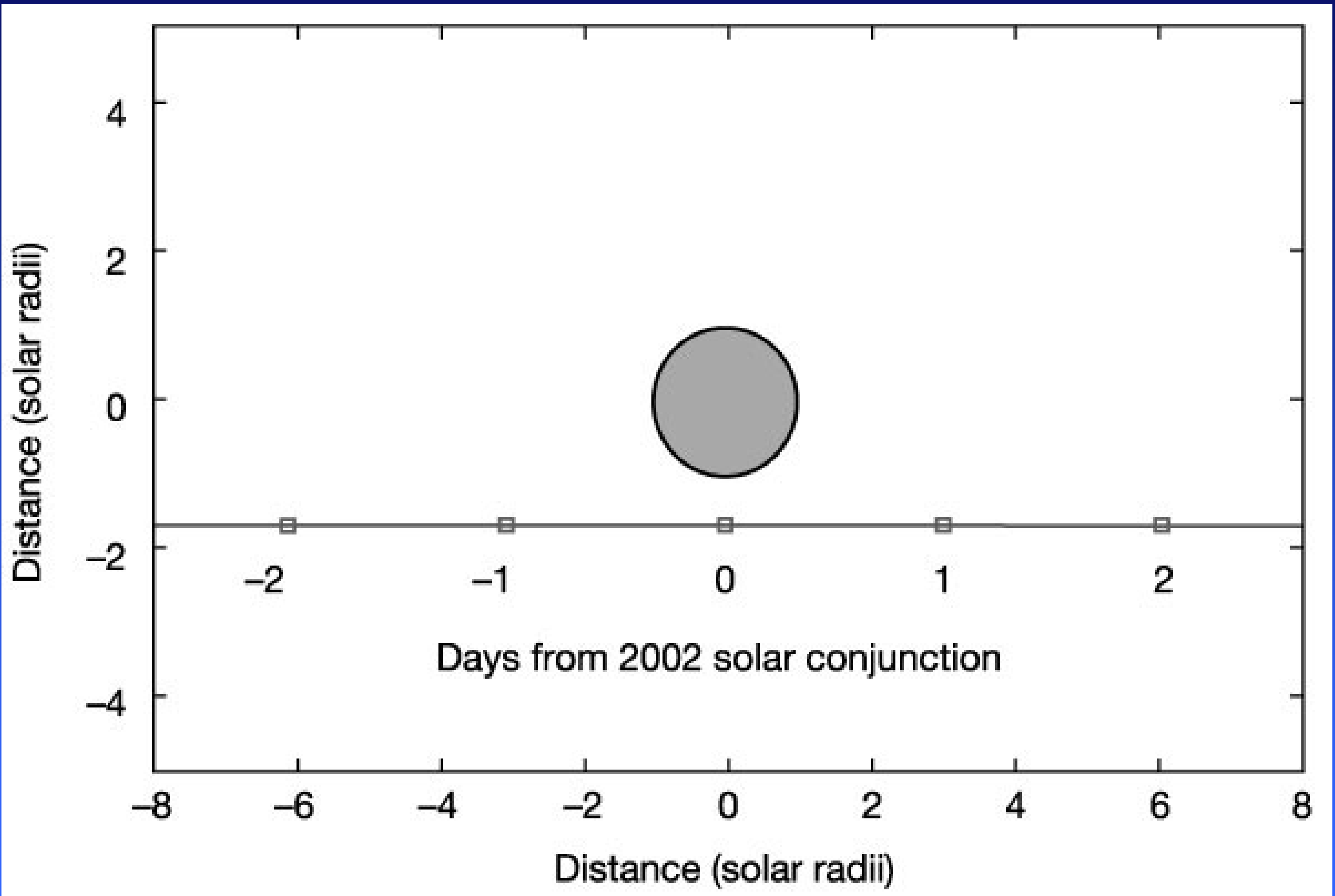
Effects on Signal:

- topography and scattering properties of target planet
- atmosphere of Earth
- plasma along propagation path (inverse square dependence on frequency)

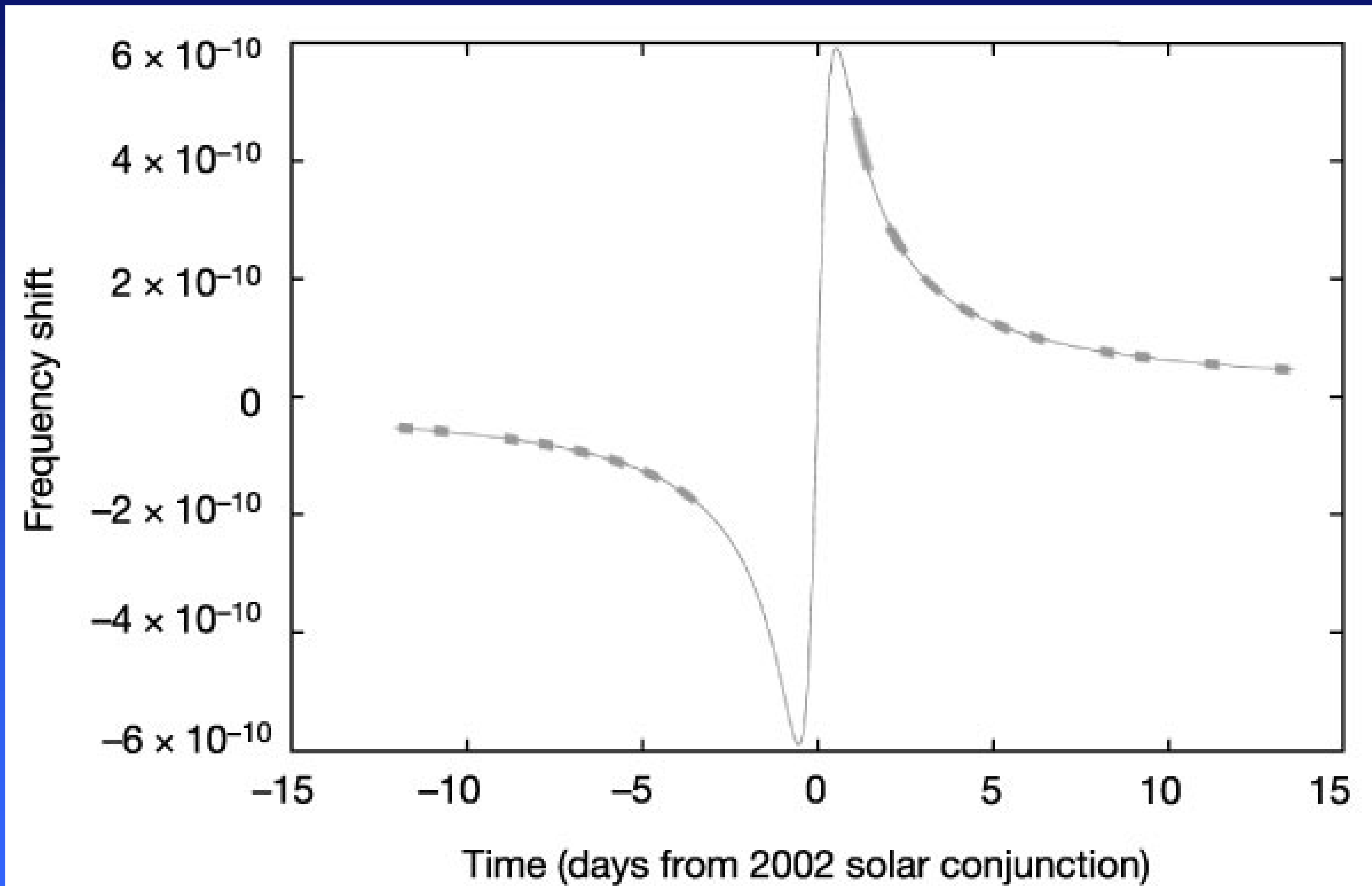


EFFECTS OF GENERAL RELATIVITY
ON INTERPLANETARY TIME-DELAY MEASUREMENTS

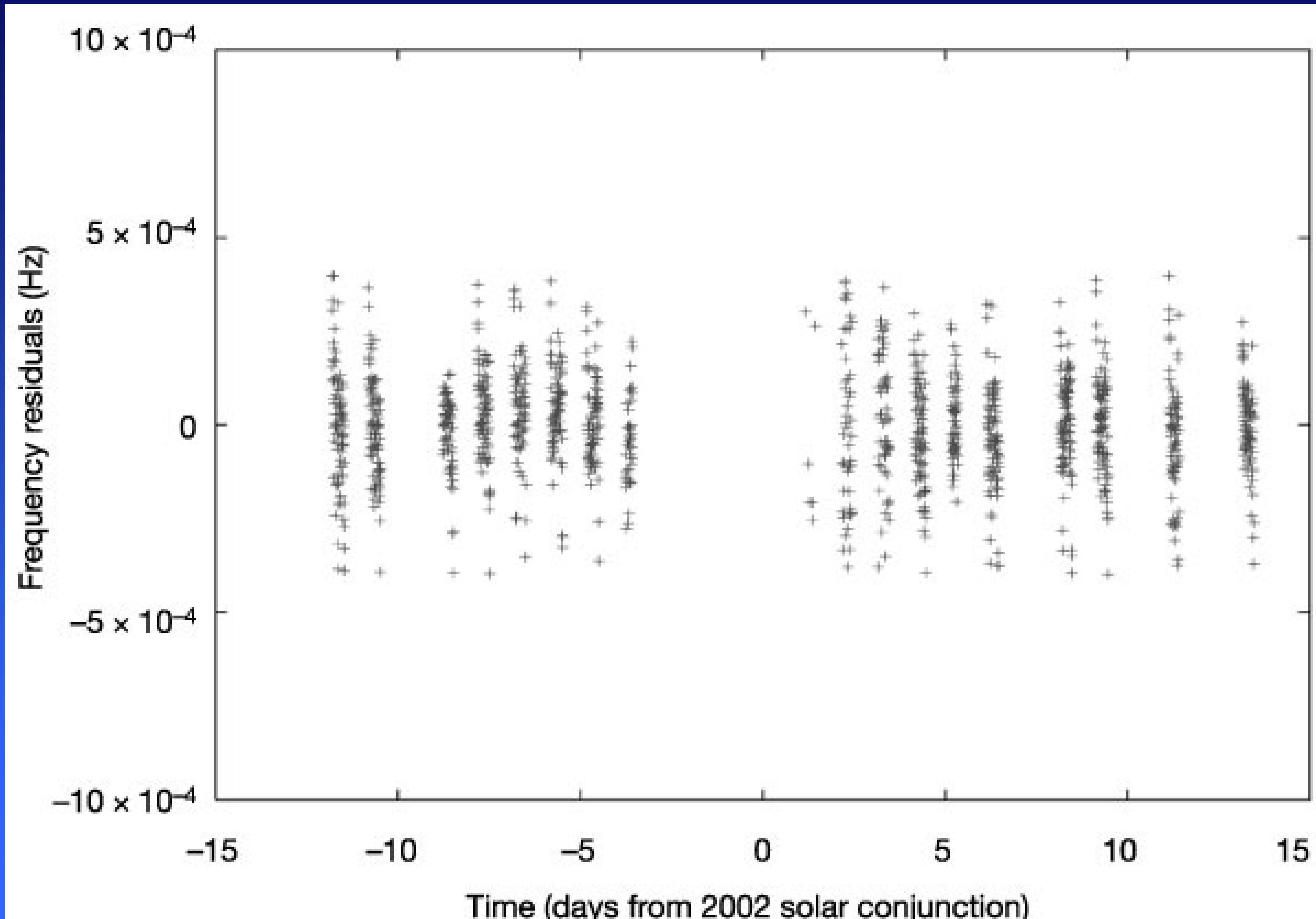

SUPERIOR CONJUNCTION
25 JAN 1970
EARTH-VENUS TIME-DELAY
OBSERVATIONS
HAYSTACK
ARECIBO
"EXCESS" DELAY, μs
TIME, days
200
160
120
80
40
0
-300
-200
-100
0
100
200
300



4
2
0
–2
–4
Distance (solar radii)
–2
–1
0
1
2
Days from 2002 solar conjunction
–8
–6
–4
–2
0
2
4
6
8
Distance (solar radii)



Frequency shift
6 × 10−10
4 × 10−10
2 × 10−10
0
−2 × 10−10
−4 × 10−10
−6 × 10−10
−15
−10
−5
0
5
10
15
Time (days from 2002 solar conjunction)



10 × 10⁻⁴
5 × 10⁻⁴
0
−5 × 10⁻⁴
−10 × 10⁻⁴
Frequency residuals (Hz)
−15
−10
−5
0
5
10
15
Time (days from 2002 solar conjunction)

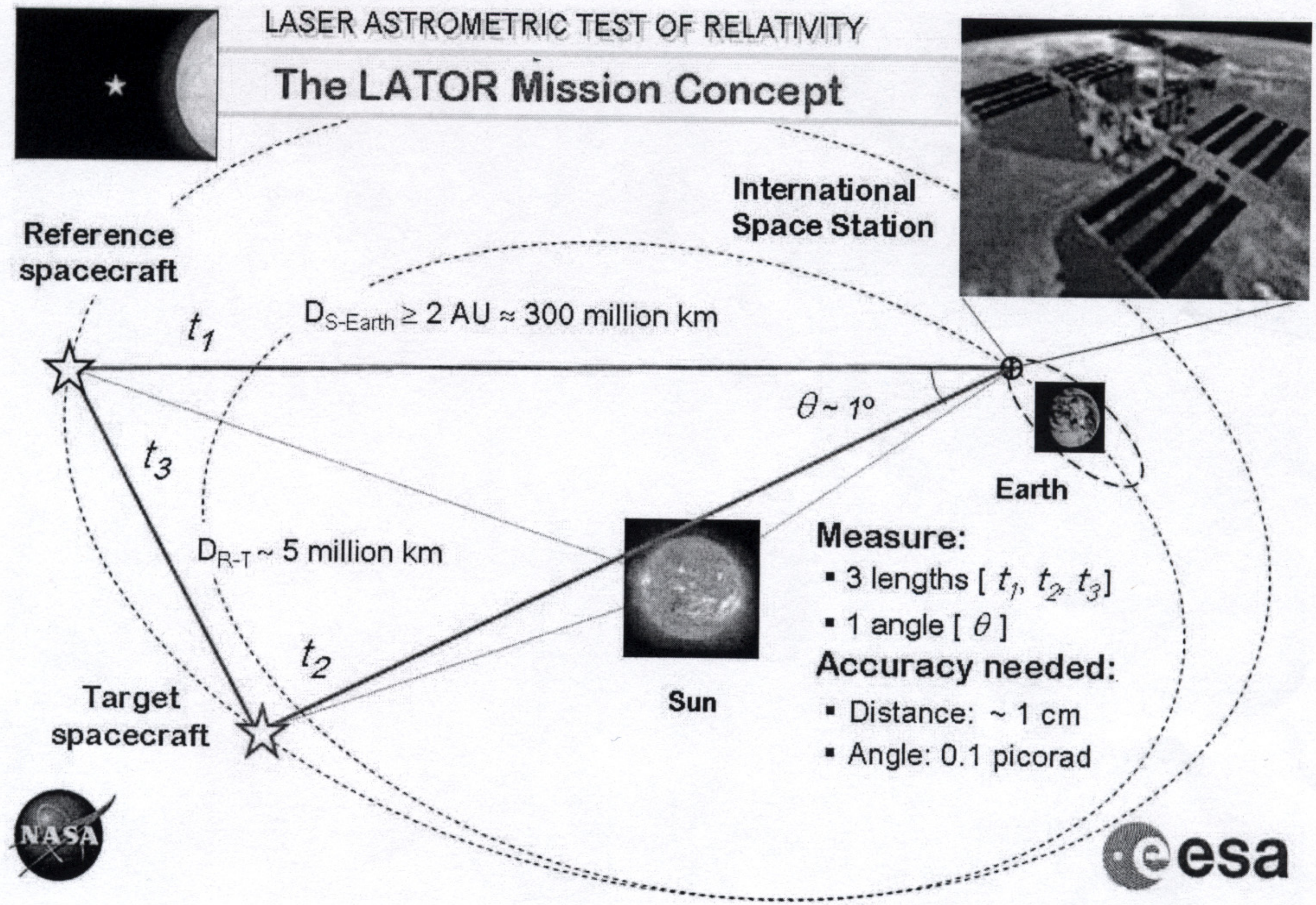


Figure 1. The overall geometry of the LATOR experiment.

Imaging of Black Holes

- **Evidence for Existence of Black Holes**

  - Monster Holes:

    NGC 4258 (Water-vapor masers, Kinematic Evidence from VBLI, and Results for Mass and Distance)

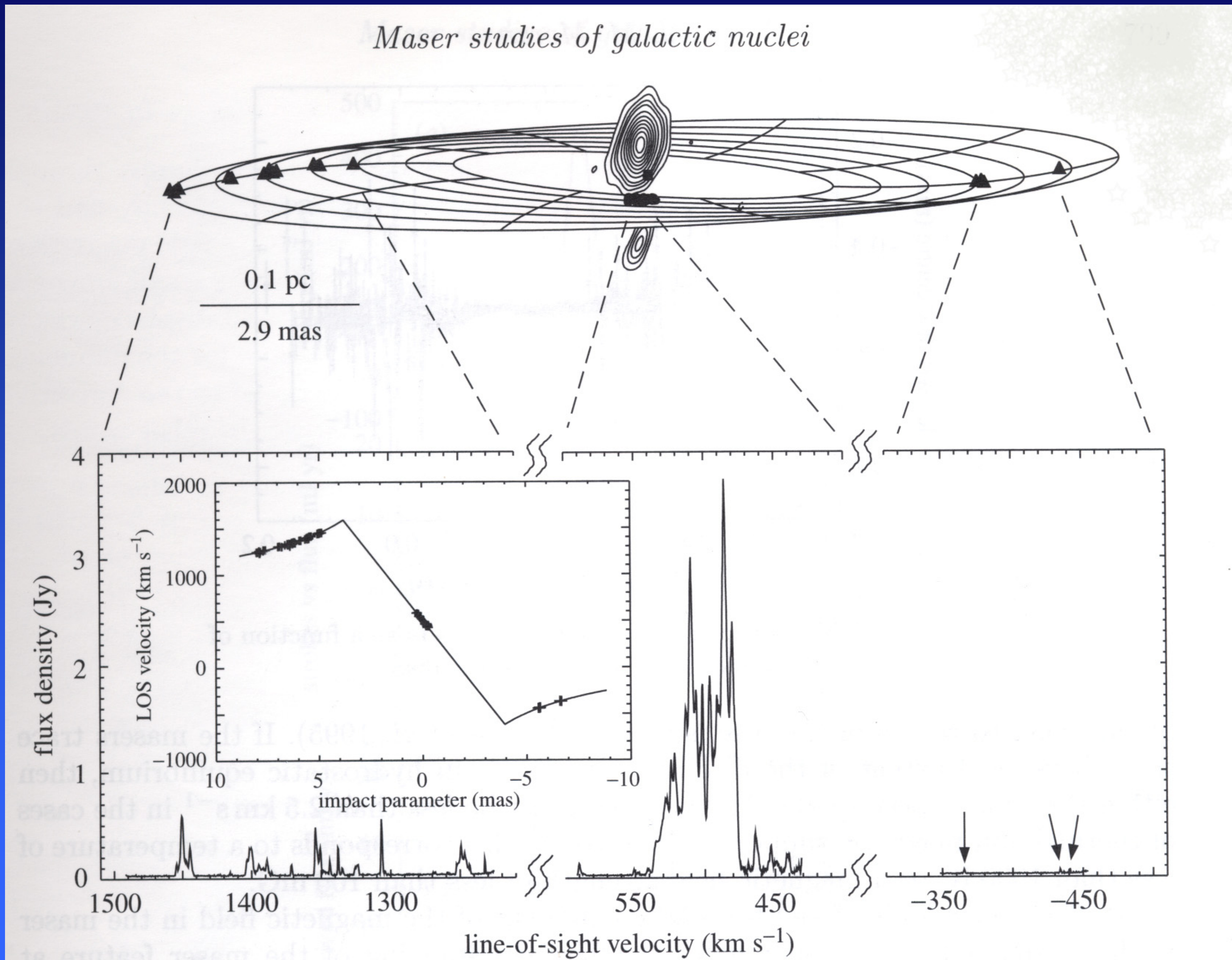
  - Moderate Holes:

    Center of Milky Way (Stars, Infrared Astrometry, and Results for Mass and Distance)

  - Mini Holes:

    Neutron Star Luminosity vs. Black Hole Luminosity

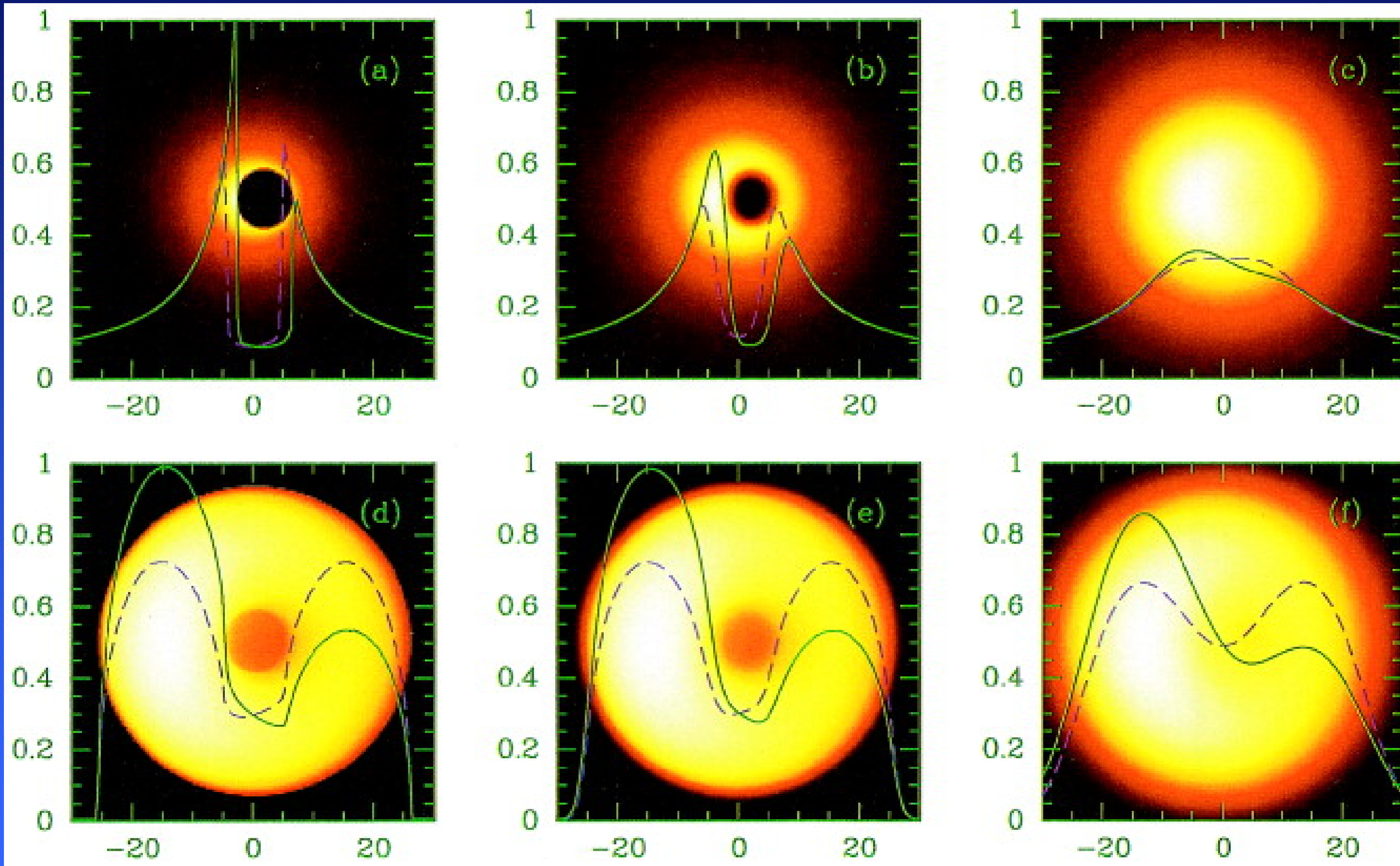
    Mass of Member of Compact Binary



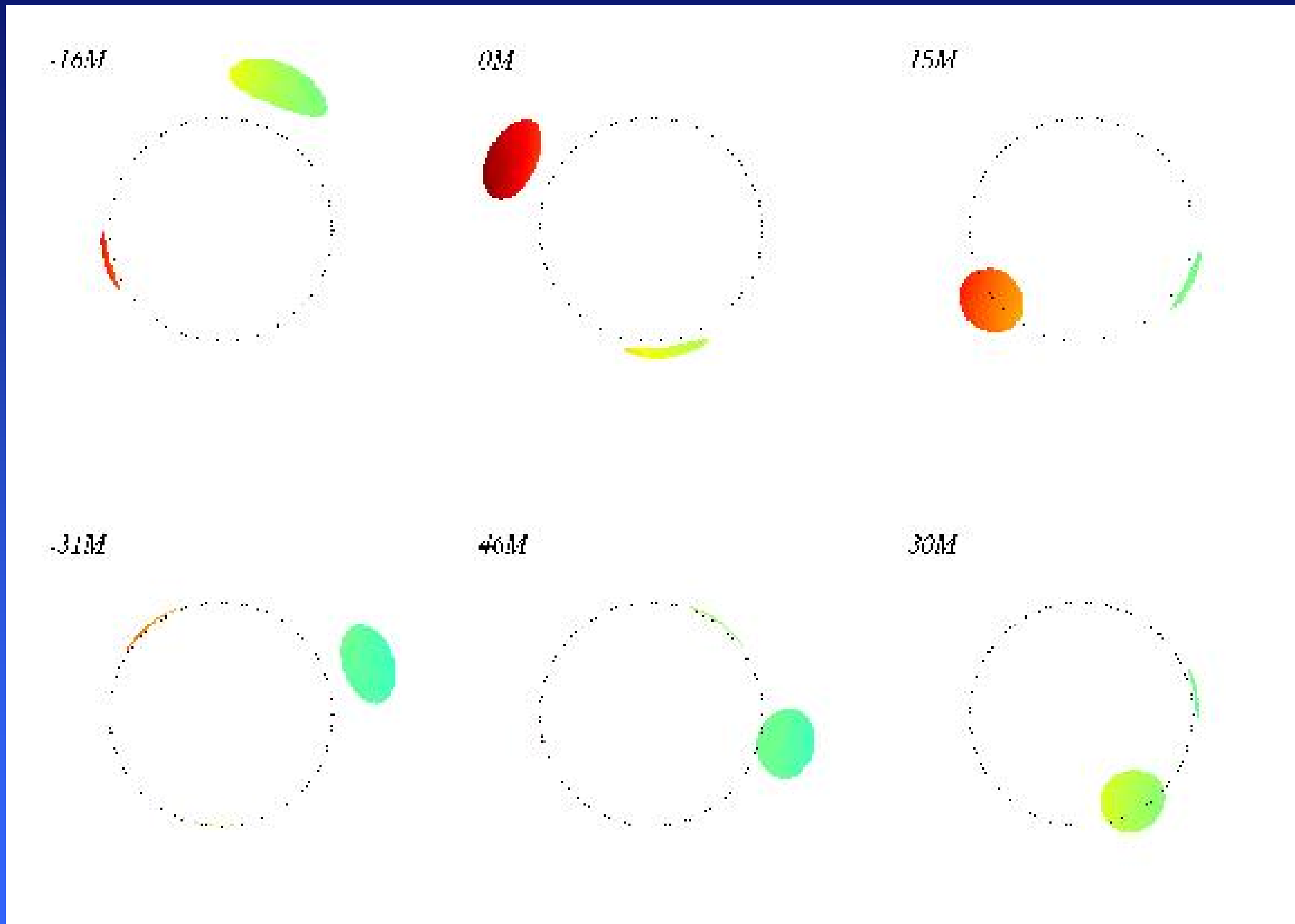
Maser studies of galactic nuclei
0.1 pc
2.9 mas
flux density (Jy)
LOS velocity (km s^{-1})
impact parameter (mas)
line-of-sight velocity (km s^{-1})

Imaging of Black Holes (cont'd)

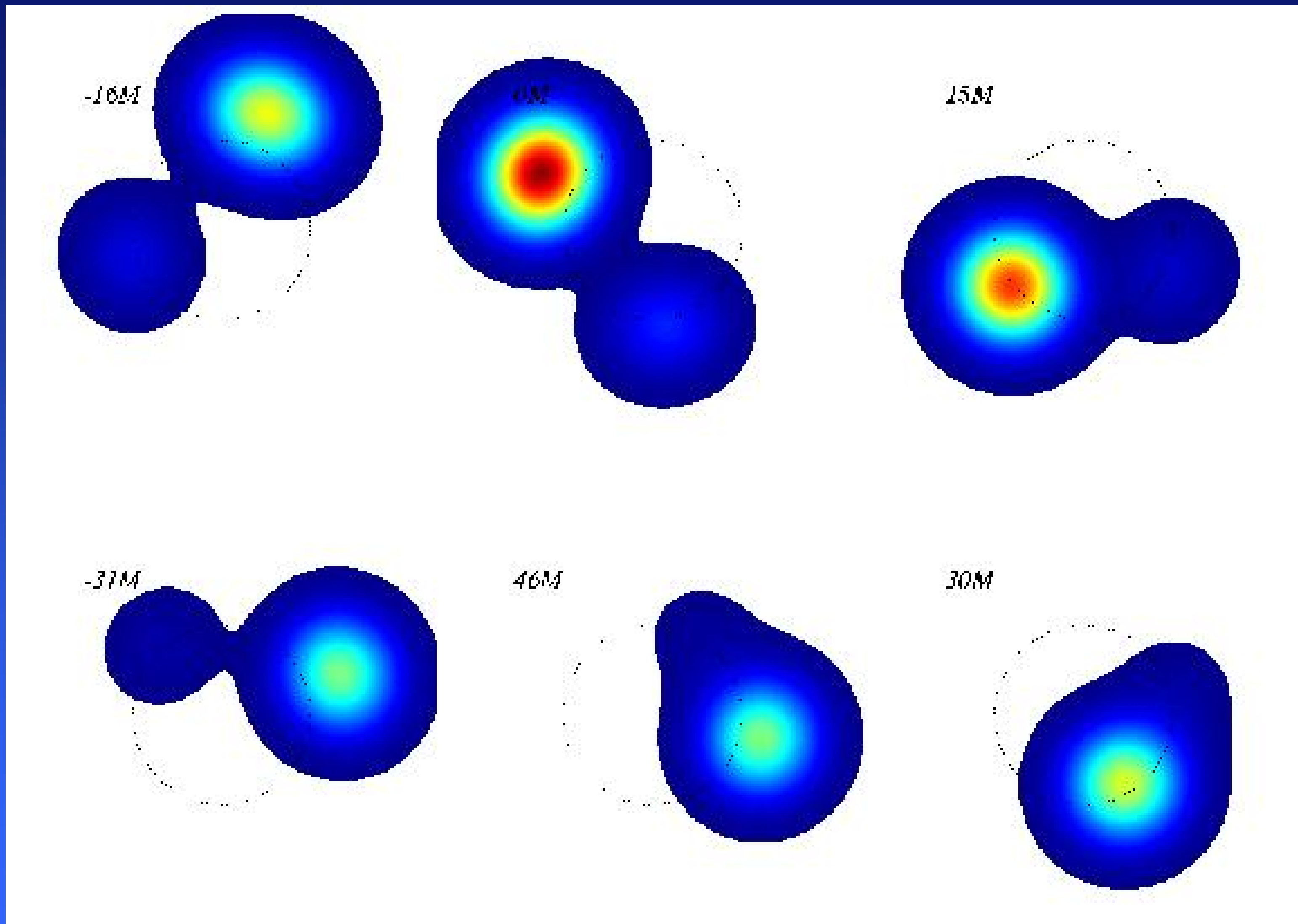
- **Imaging Possibilities:**
  - Basic Idea (Formation of "Shadows")
  - Choice of Galactic Center
  - "Match" of Shadow Region Size and VBLI Resolution
  - Need for Observations at Submillimeter Wavelengths
  - Optically Thin Source Surrounding Black Hole
    (H. Falcke et al., 2000)
  - Optically Thick Bright Spot(s) Orbiting Black Hole
    (A. Broderick and A. Loeb, 2005)
  - Practical Considerations:
    VBLI Array (Not Yet Extant)
    Weather (Need for Dynamic Scheduling)
    Funding

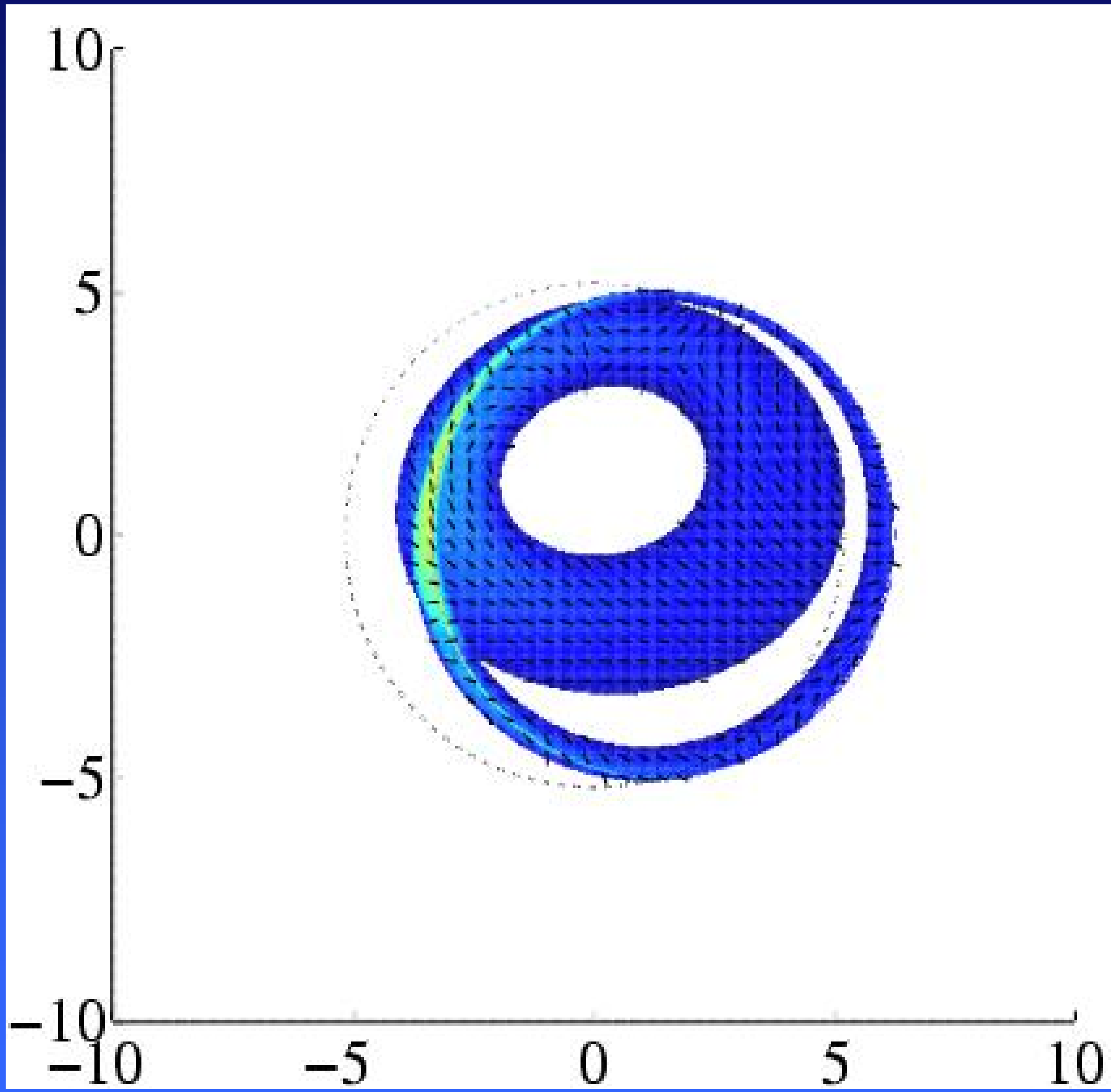


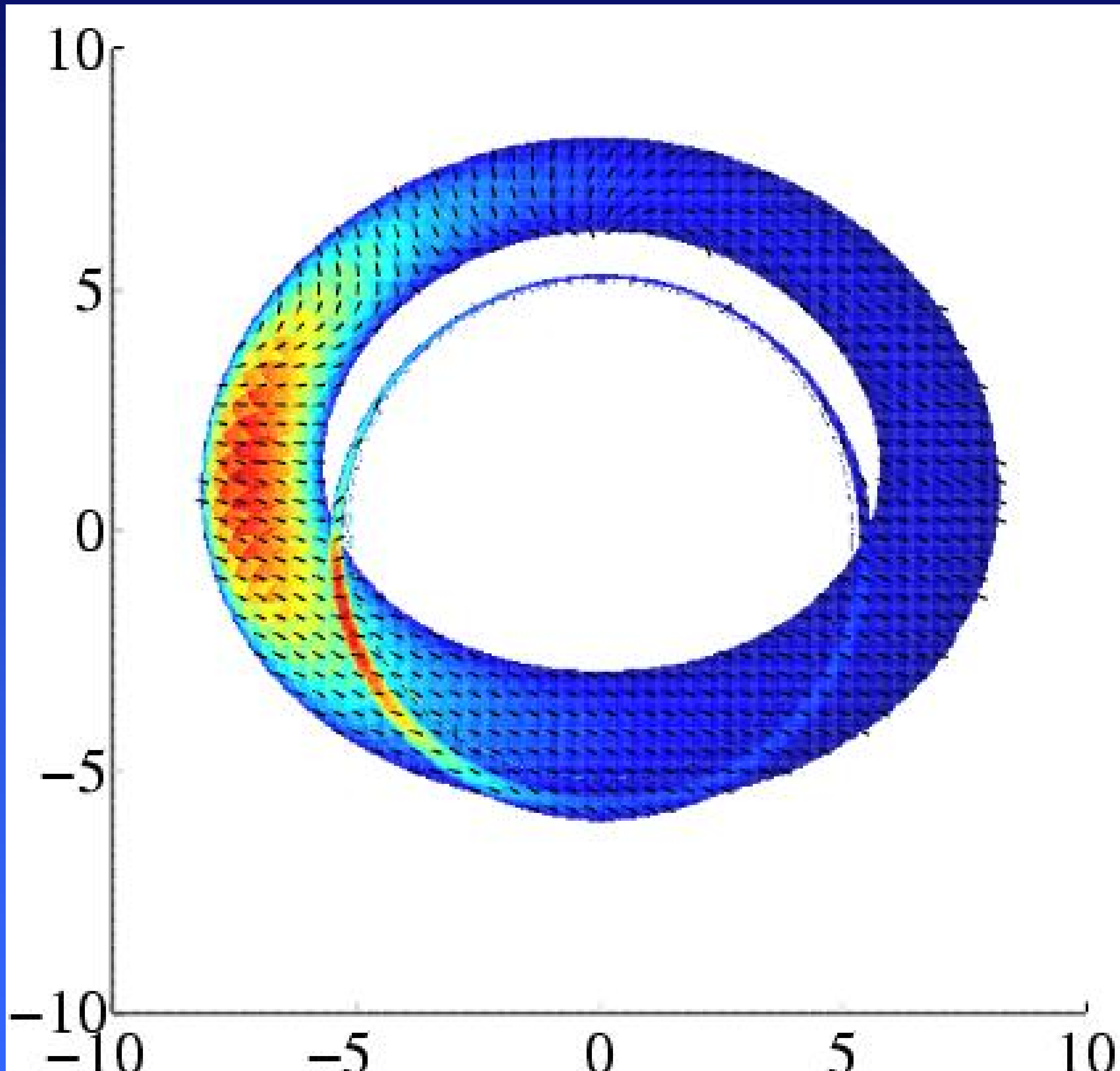
(a)
(b)
(c)
(d)
(e)
(f)
1
0.8
0.6
0.4
0.2
0
−20
0
20



-16M
0M
15M
-31M
46M
30M


-16M
0M
15M
-31M
46M
30M


10
5
0
−5
−10
−10
−5
0
5
10



10
5
0
−5
−10
−10
−5
0
5
10

Conclusion

- Scientific-Technical Prospects are Bright

- Funding Prospects are Dim

- Time Scales are Protracted