Gravitational Waves and the Validity of General Relativity

WUGRAV
WASHINGTON UNIVERSITY
GRAVITY GROUP

- INTRODUCTION
- TESTING GENERAL RELATIVITY: A MILLENNIAL UPDATE
- GRAVITATIONAL–WAVE TESTS OF GR
  - Polarization of Gravitational Waves
  - Speed of Gravitational Waves
  - Tests of Gravitational–wave Damping

Cliff Will 11/11/99 LIGO-G990127-01-M

THE EINSTEIN EQUIVALENCE PRINCIPLE

- Test bodies fall with the same acceleration
  Weak Equivalence Principle (WEP)

- In a local freely falling frame, non-gravitational physics is independent of the frame's velocity
  Local Lorentz Invariance (LLI)

- In a local freely falling frame, non-gravitational physics is independent of the frame's location
  Local Position Invariance (LPI)

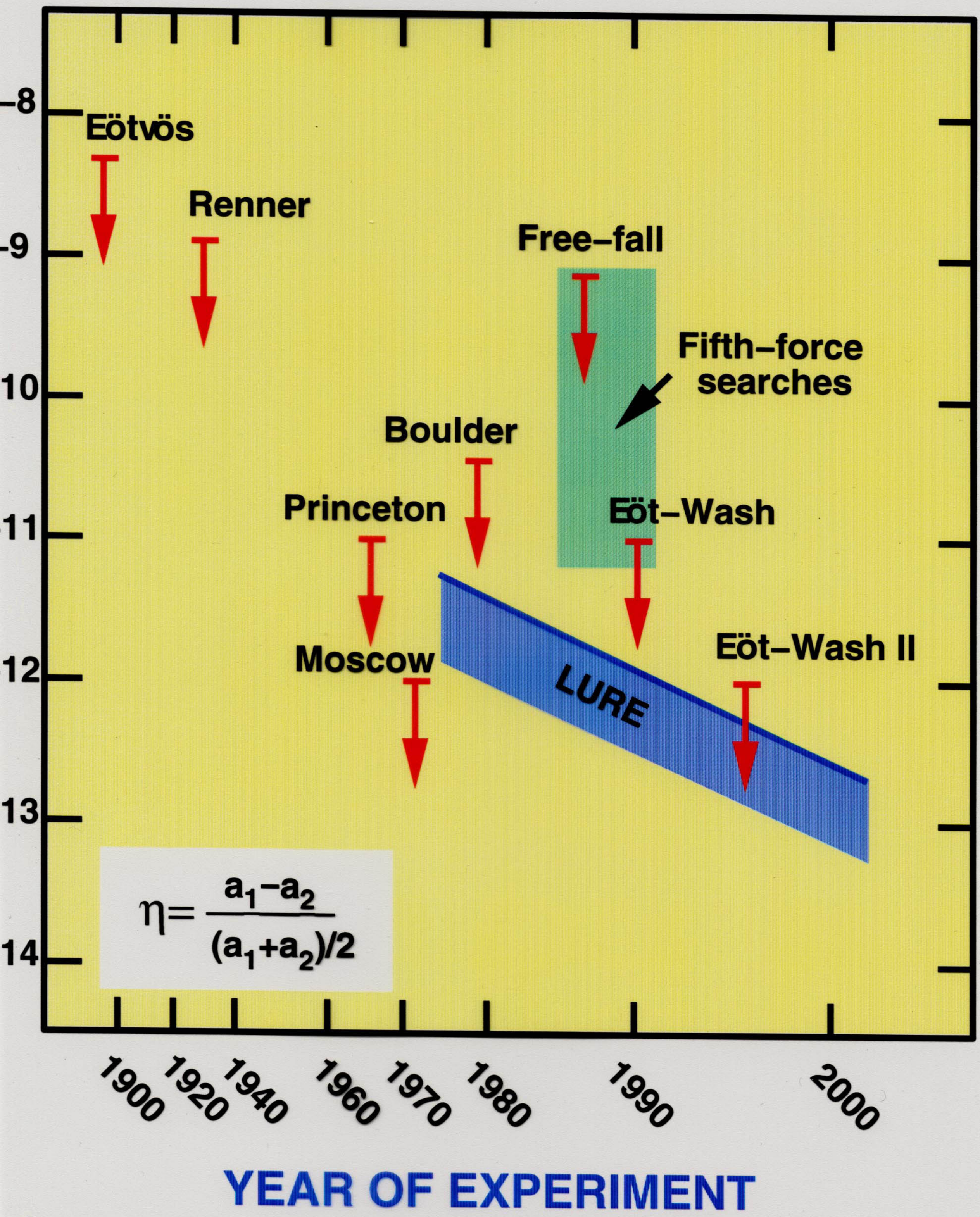
EEP $\longrightarrow$ Metric Theory of Gravity

- symmetric $g_{\mu\nu} \longleftrightarrow \eta_{\mu\nu}$ locally
- 'semicolon' $\longleftrightarrow$ 'comma'

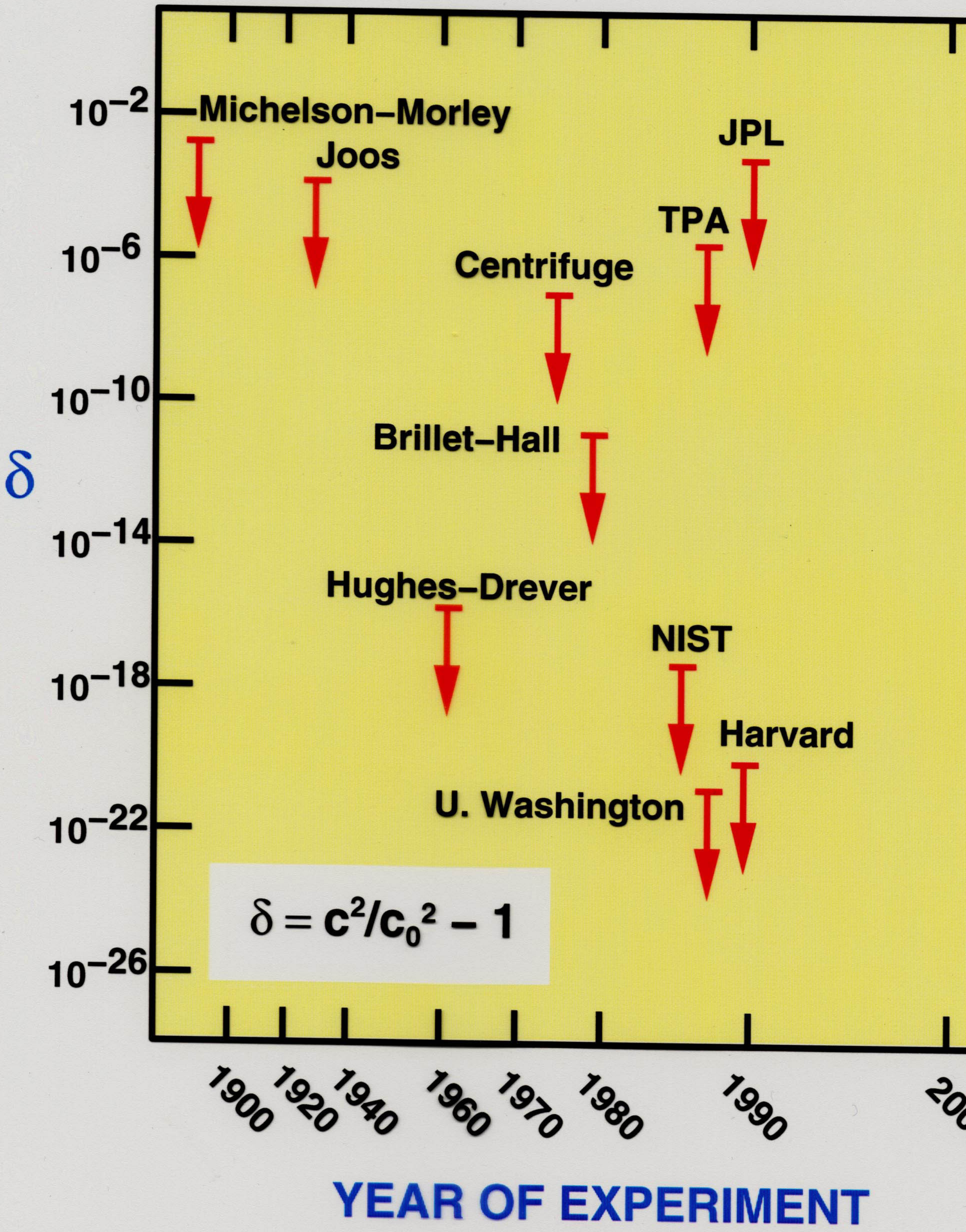
Metric Theories: *GR, Brans-Dicke, Rosen, ...*

Nonmetric Theories: *Moffat's NGT, String Theory ...*

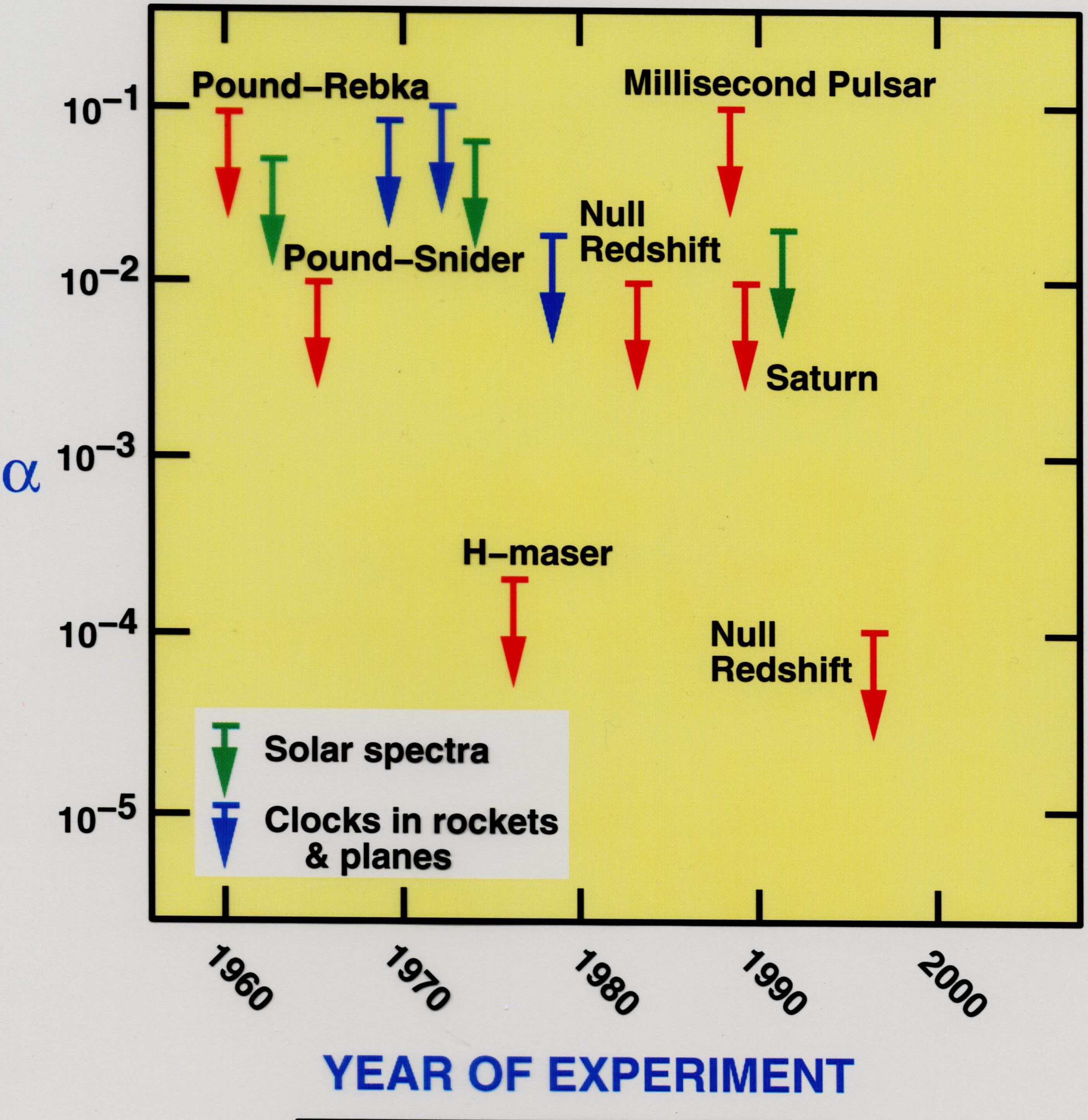
TESTS OF THE WEAK EQUIVALENCE PRINCIPLE



TESTS OF LOCAL LORENTZ INVARIANCE



TESTS OF LOCAL POSITION INVARIANCE



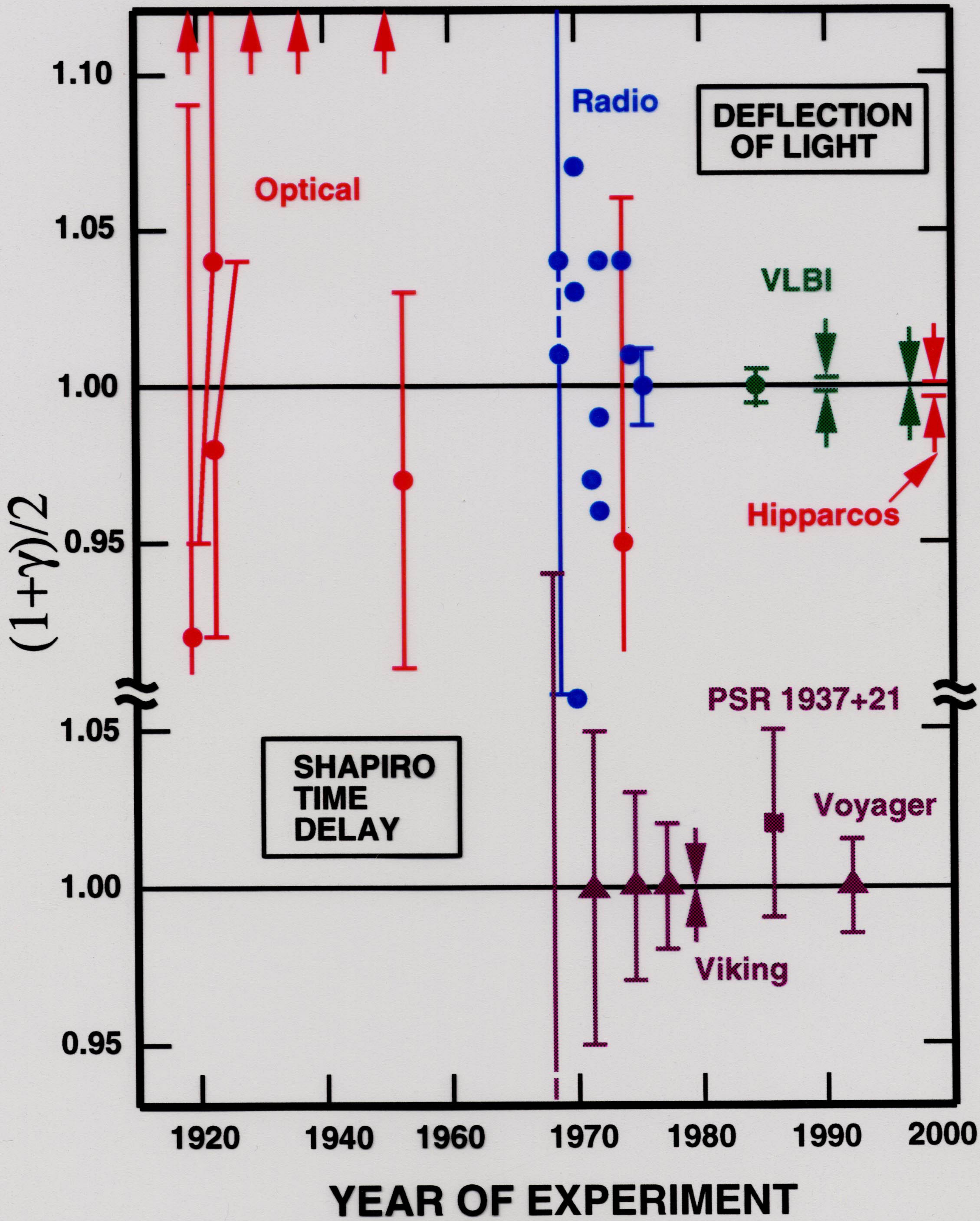
$$\Delta\nu/\nu = (1+\alpha)\Delta U/c^2$$

Table 1. The PPN Parameters and Their Significance*

Parameter	What it measures relative to general relativity	Value in general relativity	Value in semi-conservative theories	Value in fully-conservative theories
γ	How much space-curvature is produced by unit rest mass?	1	γ	γ
β	How much "nonlinearity" is there in the superposition law for gravity?	1	β	β
ξ	Are there preferred location effects?	0	ξ	ξ
α_1	Are there preferred-frame effects? (α_1, α_2, α_3)	0	α_1	0
α_2		0	α_2	0
α_3		0	0	0
ζ_1	Is there violation of conservation of total momentum? (α_3, ζ_1, ζ_2, ζ_3, ζ_4)	0	0	0
ζ_2		0	0	0
ζ_3		0	0	0
ζ_4		0	0	0

*For a compendium of PPN parameter values in alternative theories together with derivations, see TEGP, Chapter 5.

THE PARAMETER $(1+\gamma)/2$



Mercury's Perihelion: Triumph or Trouble?

- In 1915: triumph
- 1966–80: trouble
- 1980 – : resolution

$$\omega = 42''.98\,(\lambda_{REL} + \lambda_{QUAD})$$

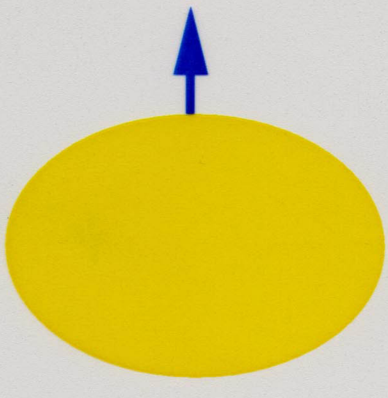
$$\lambda_{REL} = (2+2\gamma-\beta)/3 = 1 \text{ in GR}$$

*** Triumph**

$$\lambda_{OBS} = 1.000 \pm 0.001 \text{ (Mercury radar)}$$

*** Trouble and resolution**

$$\lambda_{QUAD} = 3 \times 10^{-4}\,(J_2 / 10^{-7})$$



Helioseismology ☛ $J_2 \cong 2 \times 10^{-7}$

CURRENT LIMITS ON THE PPN PARAMETERS

Parameter	Effect	Limit	Remarks
$\gamma - 1$	time delay	2×10^{-3}	Viking ranging
	light deflection	3×10^{-4}	VLBI
$\beta - 1$	perihelion shift	3×10^{-3}	$J_2 = 10^{-7}$ from helioseismology
	Nordtvedt effect	6×10^{-4}	$\eta = 4\beta - \gamma - 3$ assumed
ξ	Earth tides	10^{-3}	gravimeter data
α_1	orbital polarization	10^{-4}	Lunar laser ranging PSR J2317+1439
α_2	solar spin precession	4×10^{-7}	solar alignment with ecliptic
α_3	pulsar acceleration	2×10^{-20}	pulsar $\dot{P}$ statistics
η	Nordtvedt effect[1]	10^{-3}	Lunar laser ranging
ζ_1	–	2×10^{-2}	combined PPN bounds
ζ_2	binary self-boost	4×10^{-5}	$\ddot{P}$ for PSR 1913+16
ζ_3	Newton's 3rd law	10^{-8}	Lunar acceleration
ζ_4	–	–	not independent

[1] Here $\eta = 4\beta - \gamma - 3 - 10\xi/3 - \alpha_1 - 2\alpha_2/3 - 2\zeta_1/3 - \zeta_2/3$

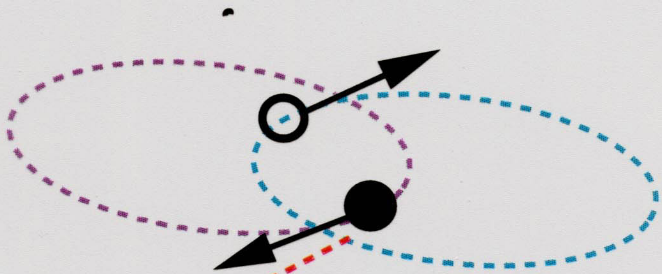
Bound on Scalar-tensor theory:

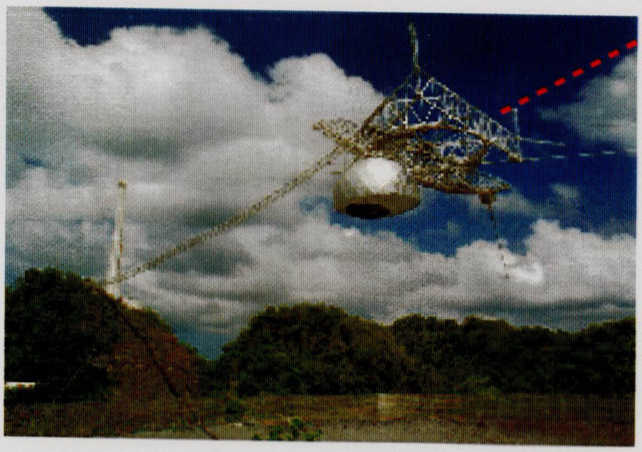
$\omega > 3000$

1979: Waves of Gravity

The Binary Pulsar

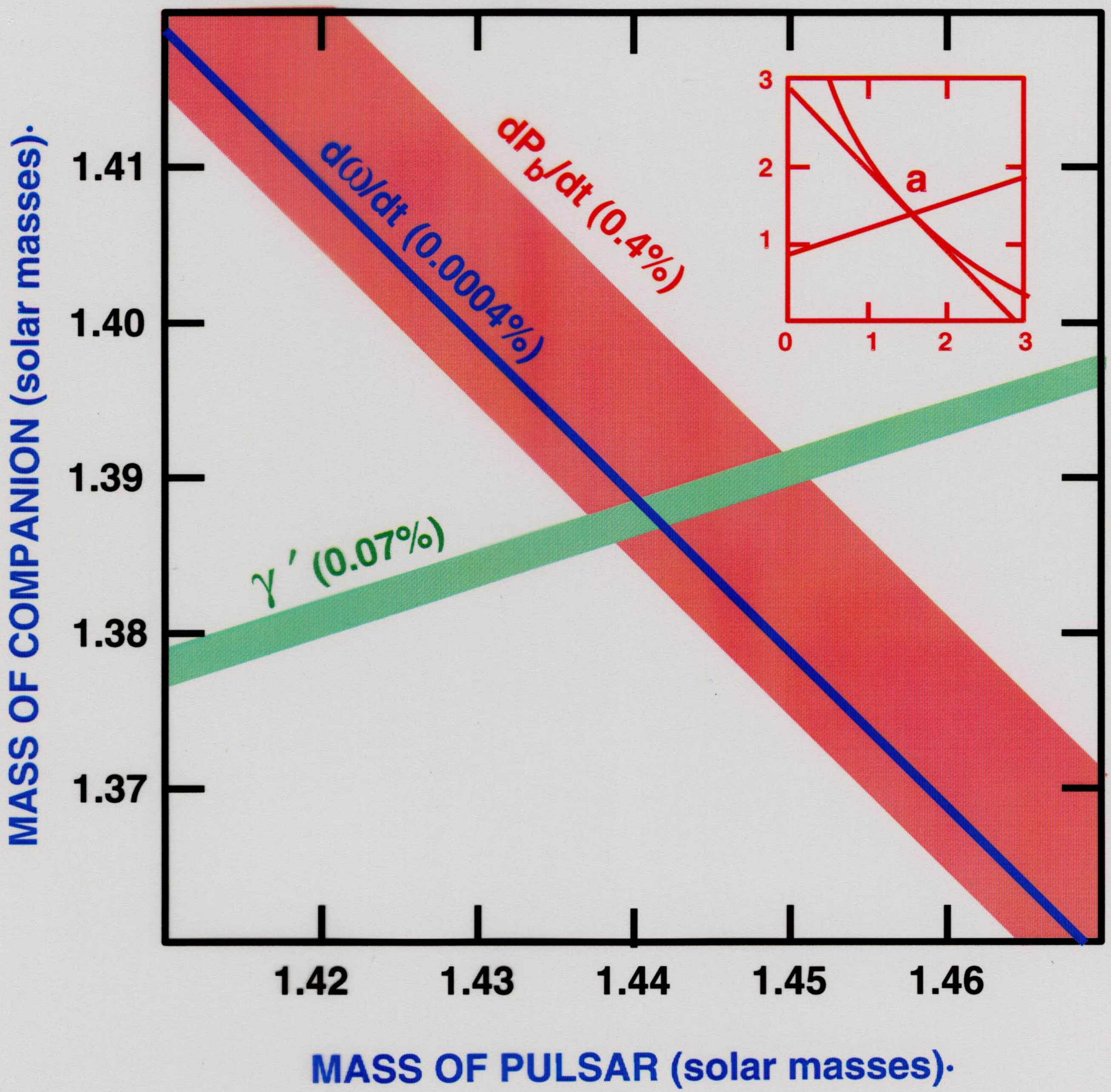
Discovery: 1974
Pulse Period: 59 ms (16 cps)
Orbit Period: 8 hours





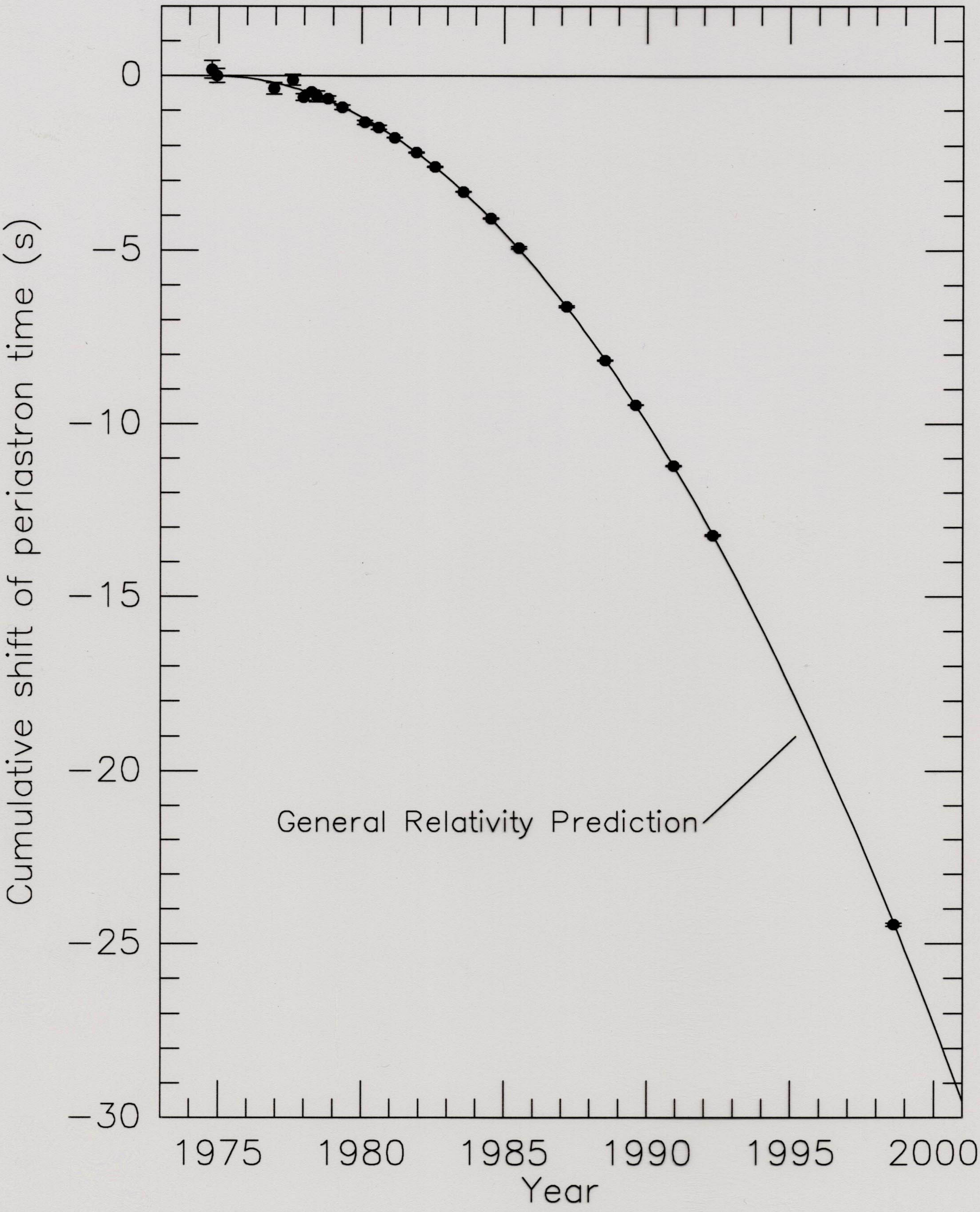
1993 Nobel Prize to Joe Taylor & Russell Hulse

Parameter	Value
Keplerian	
Pulse period (ms)	59.029997929613(7)
Orbit period (day)	0.322997462736(7)
Eccentricity	0.6171308(4)
Post–Keplerian	
Periastron shift ($d\omega/dt$ °/yr)	4.226621(11)
Pulsar clock shifts (γ ms)	4.295(2)
Orbit decay (dP_b/dt 10^{-12})	−2.422(6)



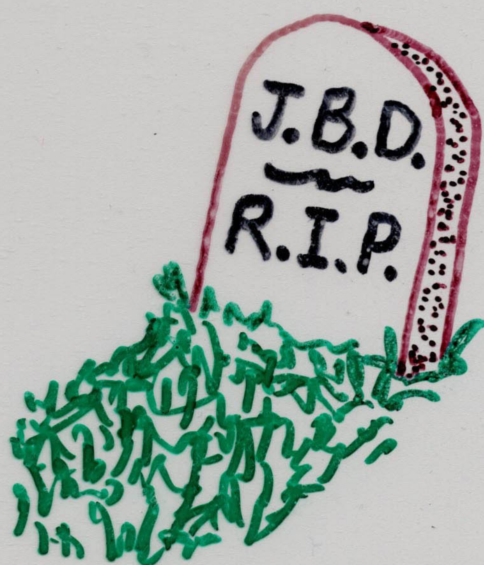
m_p = 1.4411(7) solar masses

m_c = 1.3874(7) solar masses



Cumulative shift of periastron time (s)
0
−5
−10
−15
−20
−25
−30
General Relativity Prediction
1975
1980
1985
1990
1995
2000
Year

THE DEMISE OF JORDAN-BRANS-DICKE GRAVITY

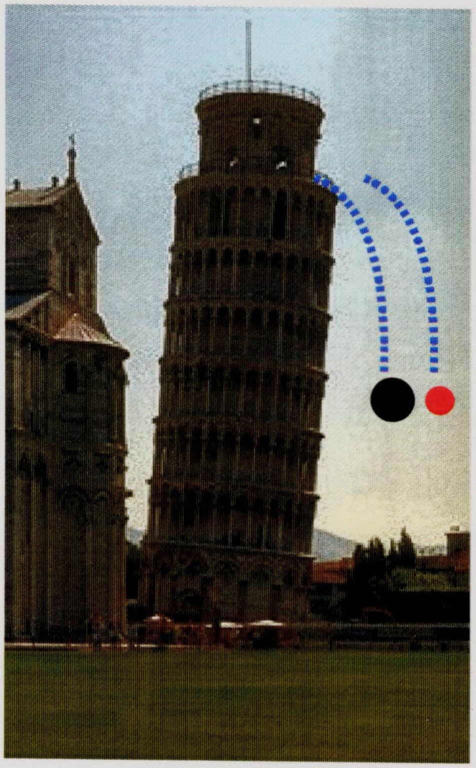


- GR coupled to scalar field
- Coupling constant ω (strength $\propto \omega^{-1}$)
- $G(\phi) \to G(t)$
- $\frac{GR-BD}{GR} \sim \omega^{-1}$
- PPN bounds $\to \omega > 3000$ $\left\{ \gamma = \frac{1+\omega}{2+\omega} \right\}$

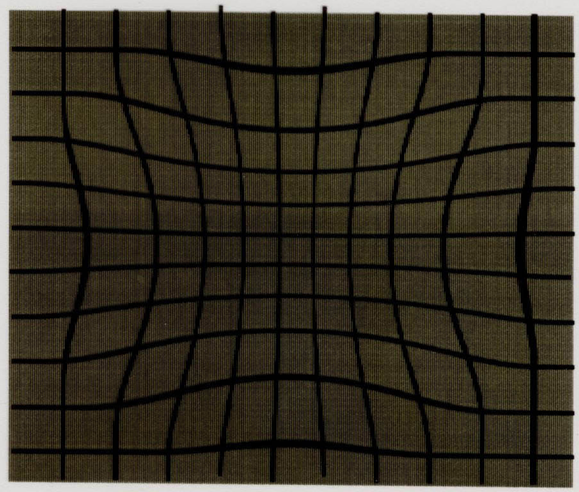
IT'S BAAAACCCKKKK ! ! !

- ⋆ Scalar fields in string-inspired theories
  - dilatons, moduli
  - weak violations of WEP
- ⋆ Extended inflation in cosmology
- ⋆ Biscalar and multi-scalar theories (Damour & Esposito-Farèse 1992)
- ⋆ Oscillating-G theories (Steinhardt, Accetta, Will, 1995)
- ⋆ GR as an "attractor" (Damour & Nordtvedt 1993)
  - $(1/\omega)_{\rm today} \to 10^{-4} - 10^{-7}$

The Equivalence Principle and General Relativity

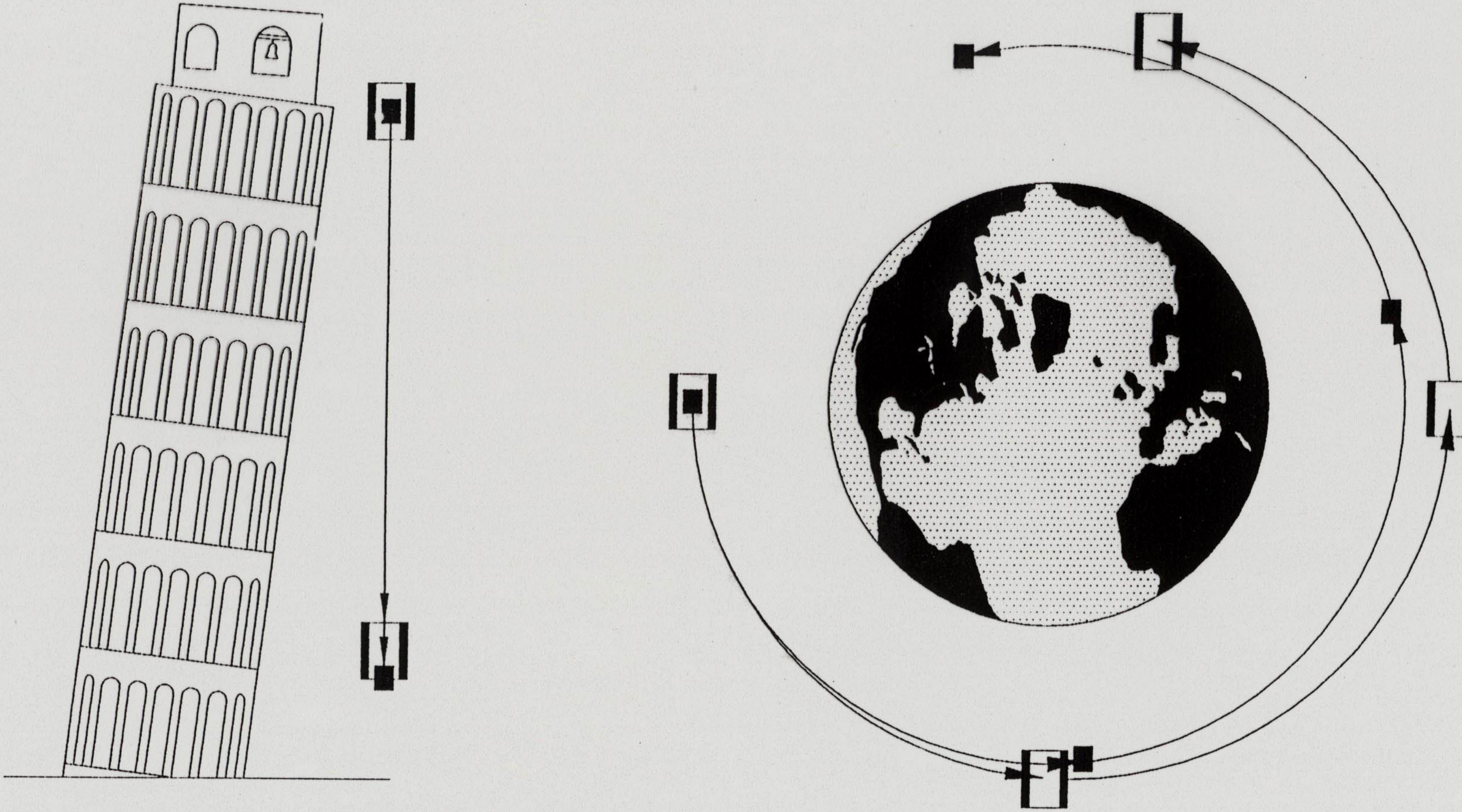


$\Rightarrow$



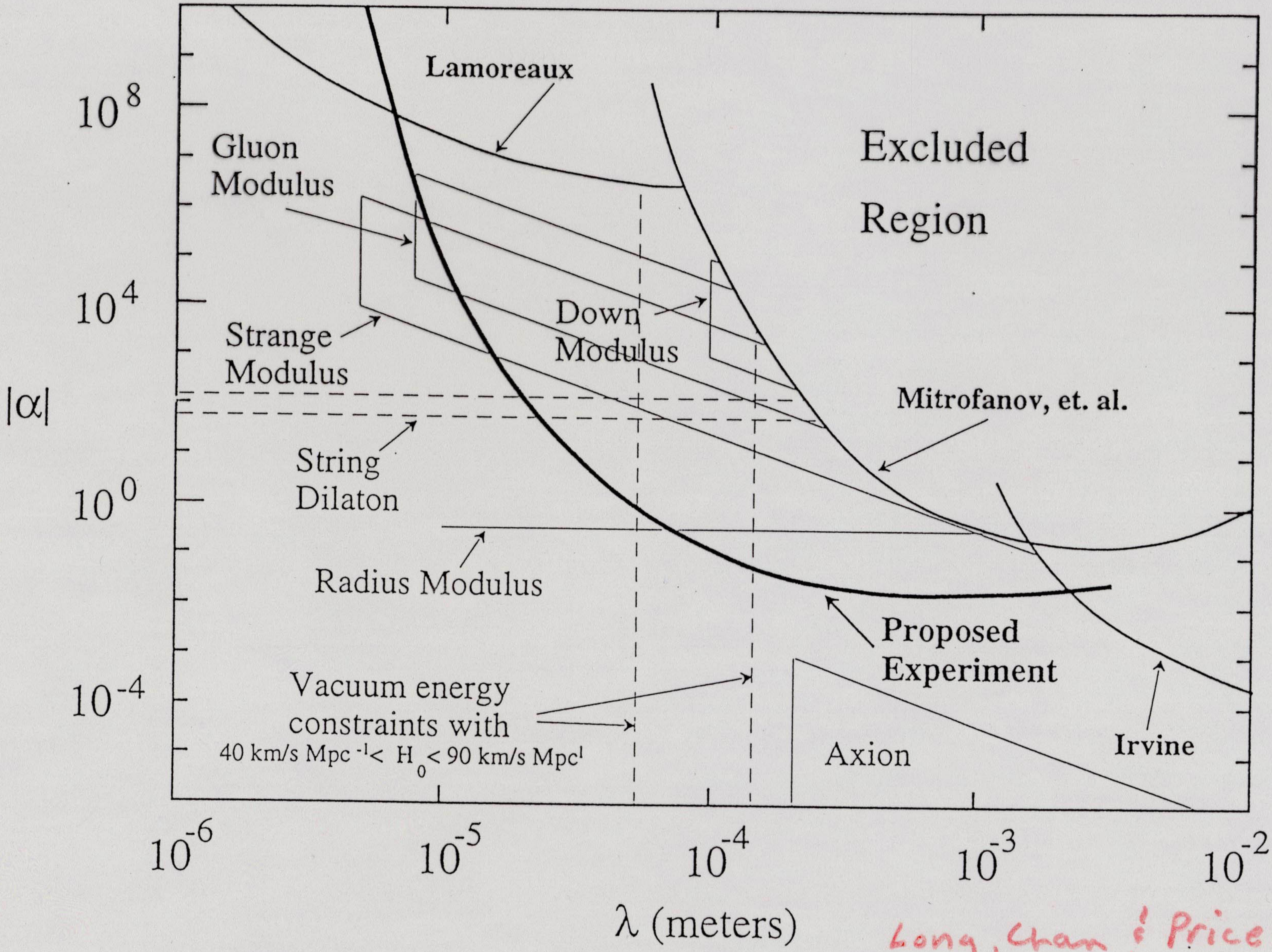
... but how good is it?

- Current experiments good to 10^{-12}
  - Lab tests
  - Lunar ranging
- Violations imply new physics
  - String theory predicts violation
  - New elementary particles
- Space experiment to reach 10^{-18}



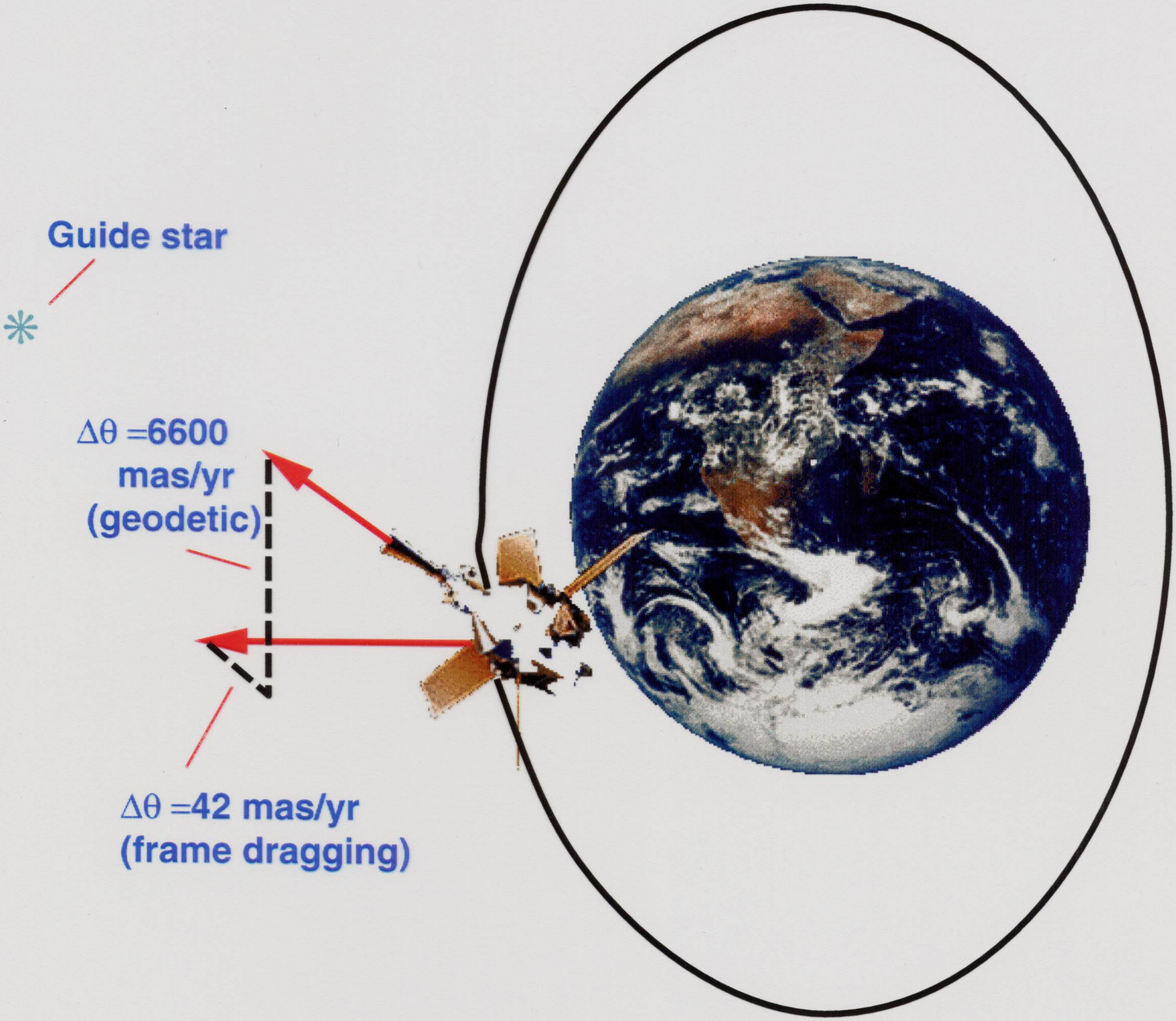
EFFECT OF EQUIVALENCE PRINCIPLE VIOLATION

Search for Forces at sub-mm Scales



Long, Chan & Price (1998)

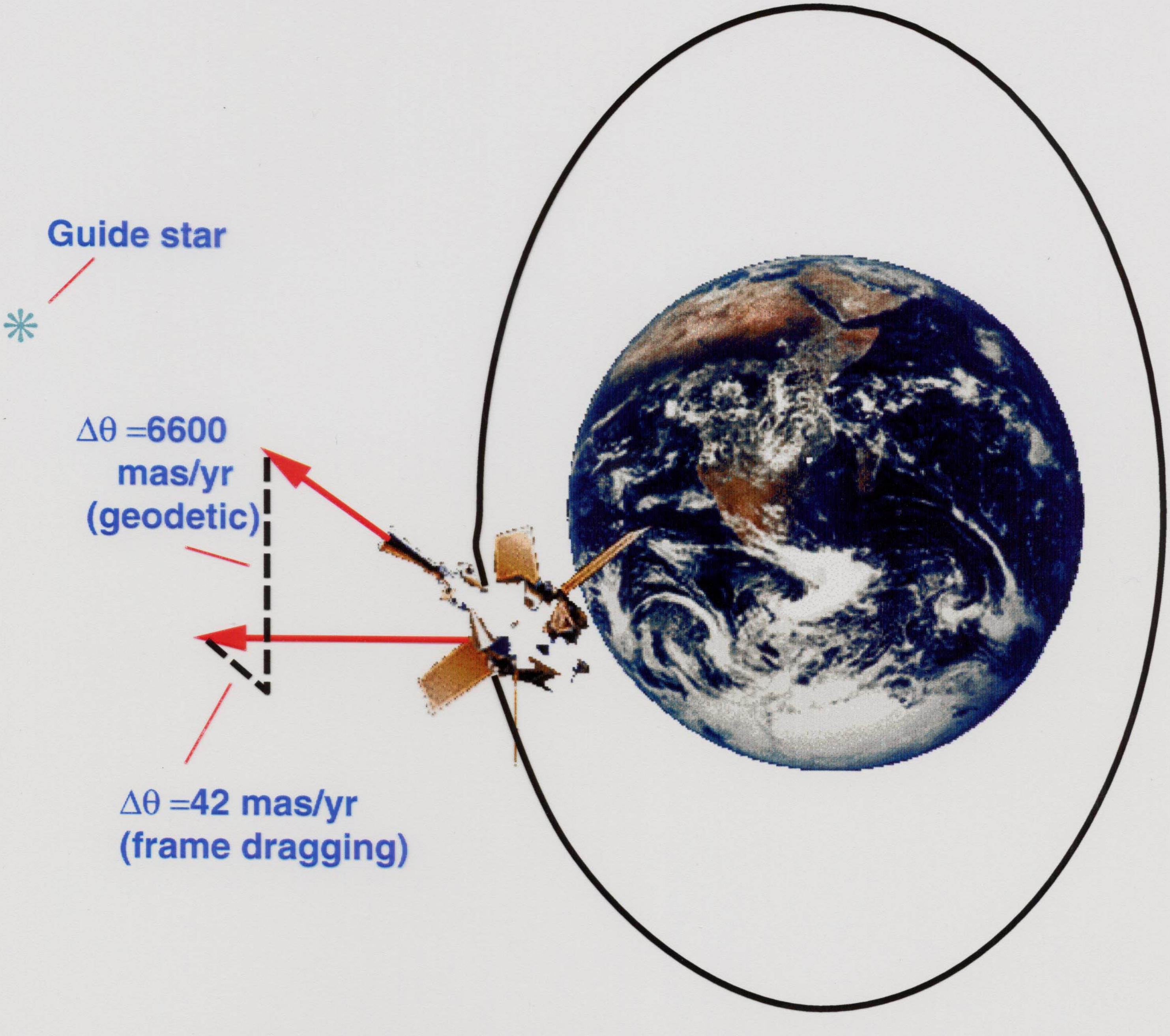
GRAVITY PROBE B



GOAL: 0.4 mas/yr

LAUNCH: Early 2001

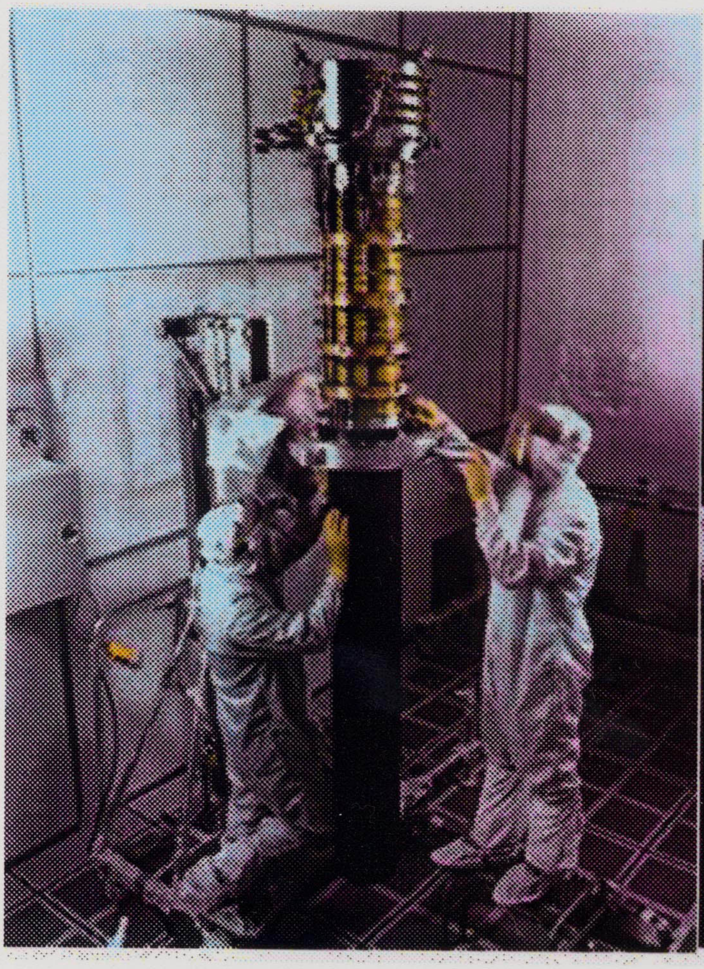
GRAVITY PROBE B

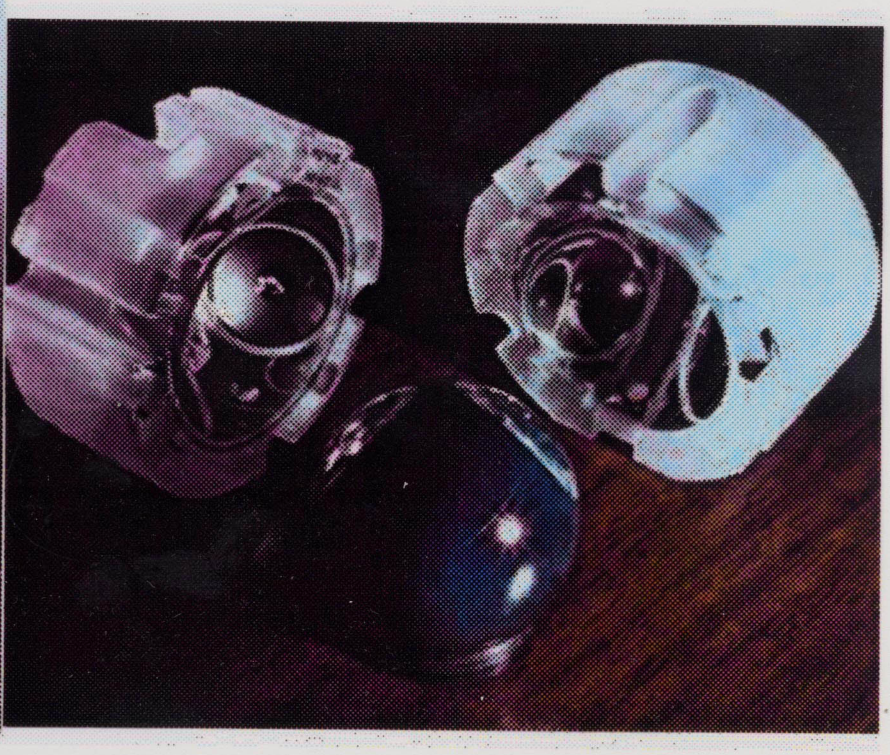


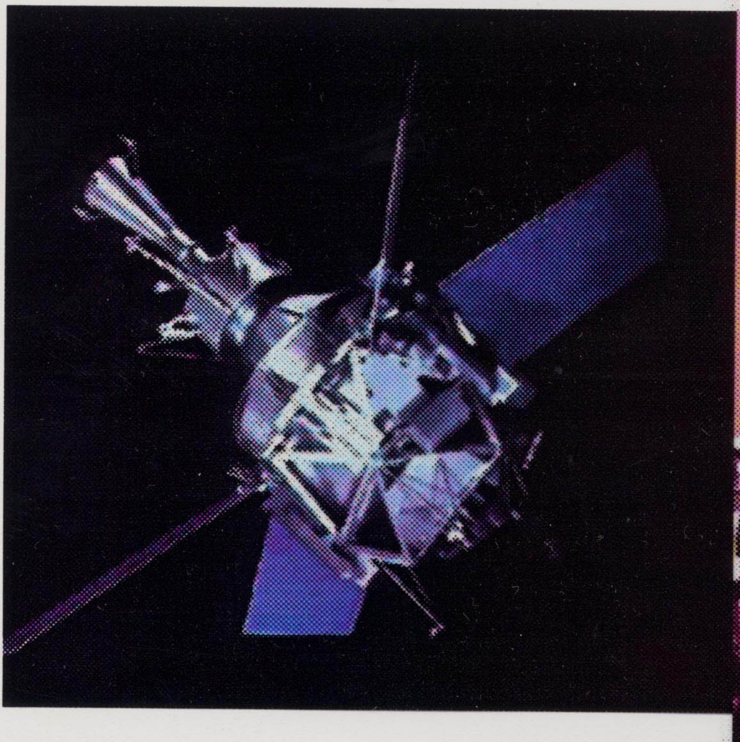
GOAL: 0.4 mas/yr

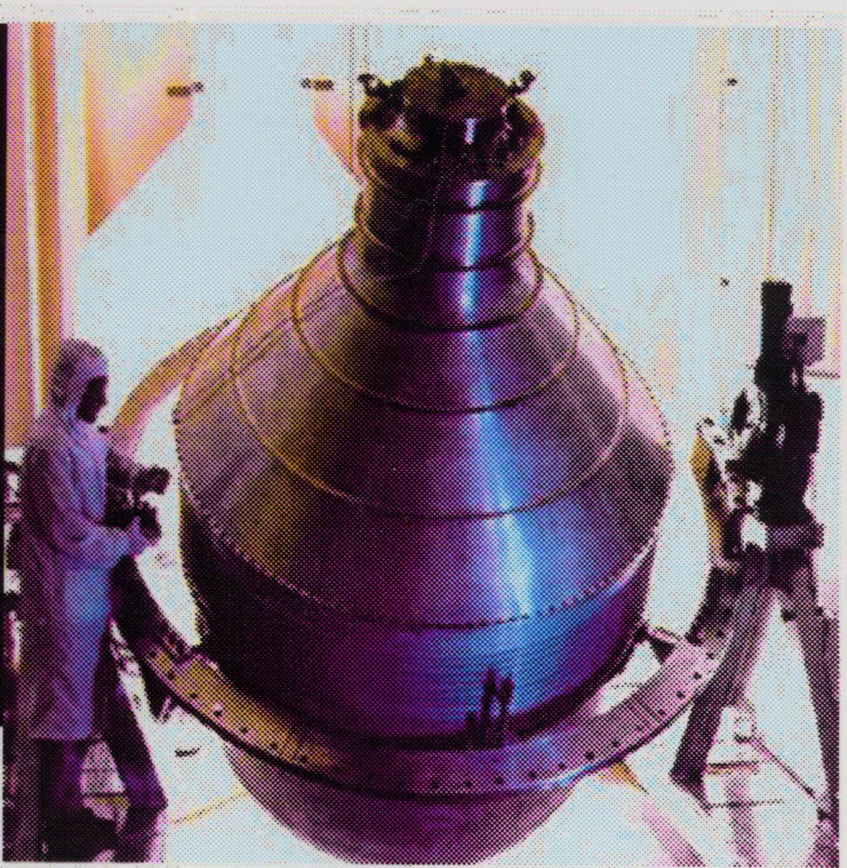
LAUNCH: Early 2001

GRAVITY PROBE-B

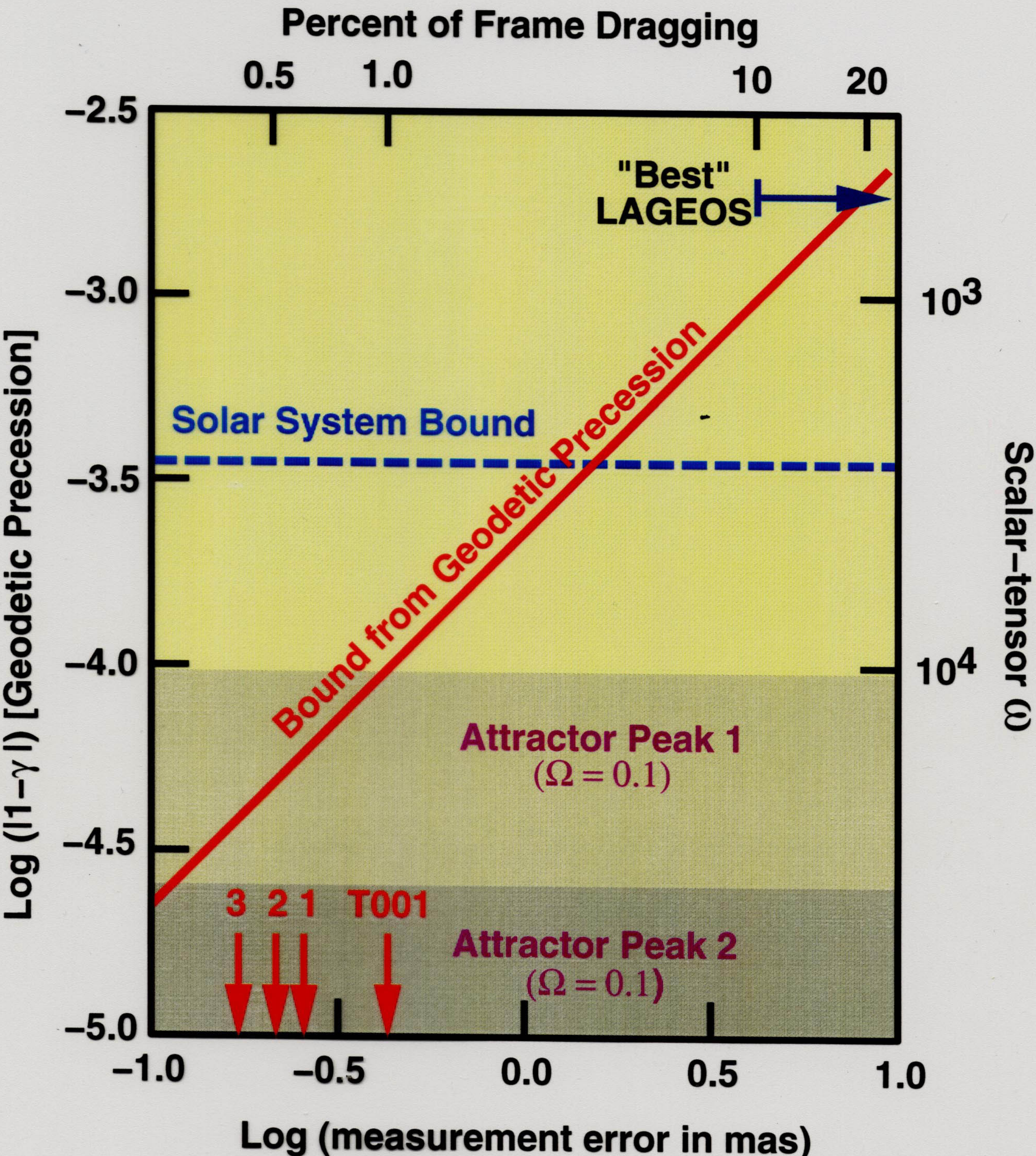








Implications of Gravity Probe B



WHAT CAN LIGO/VIRGO DO?

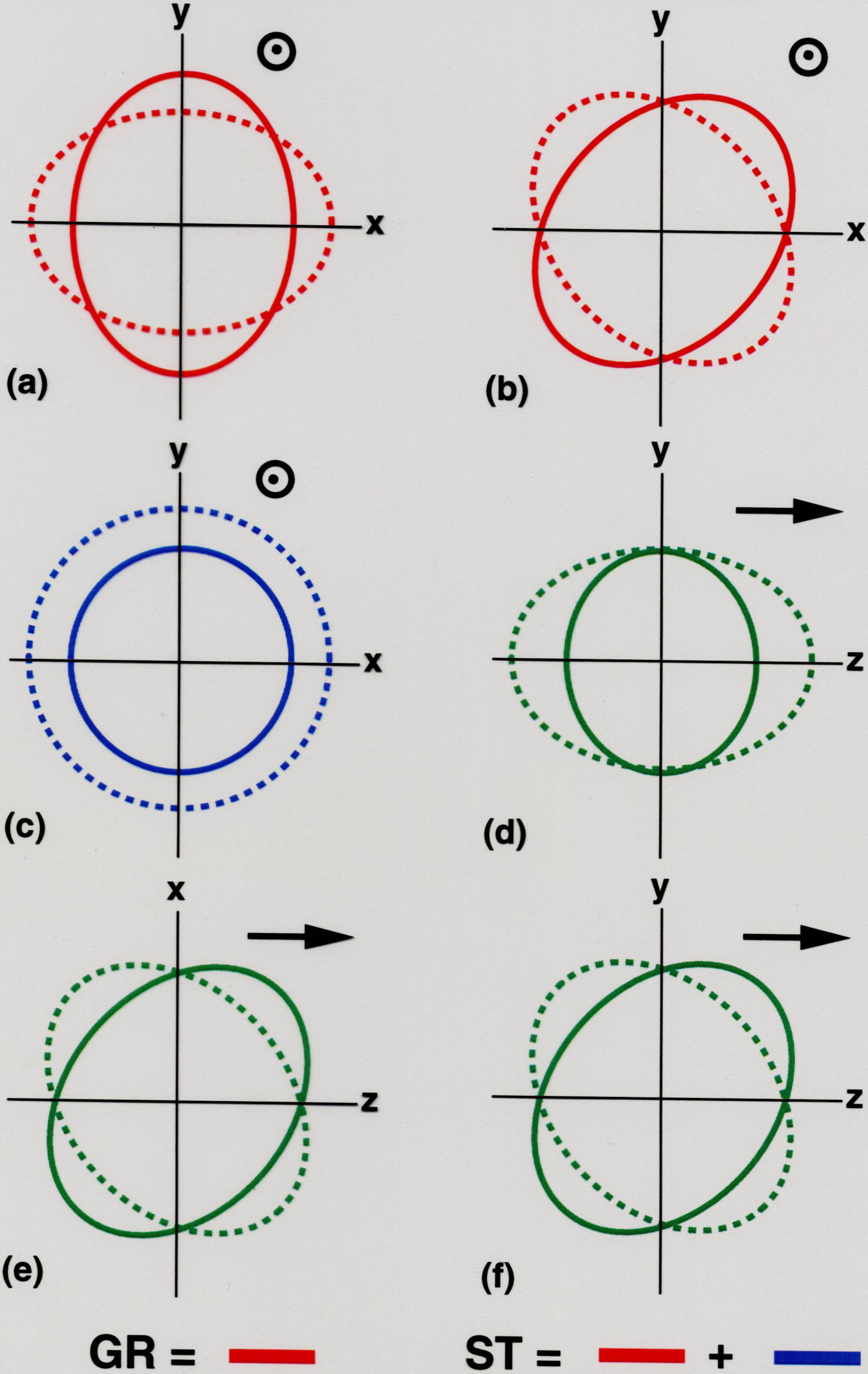
♦ Tests of General Relativity

- Speed of gravitational waves
- Polarization
- GR in strong field regime

♦ Observe and study sources of GW

- Supernovae
- Inspiralling binaries
  - NS–NS, BH–BH, NS–BH
  - Gamma ray bursts?
- New hot neutron stars
- Pulsars
- Cosmological background
- The unexpected

Gravitational–Wave Polarization



SPEED OF GRAVITATIONAL WAVES

WHY SPEED COULD BE DIFFERENT FROM LIGHT SPEED

- Massive graviton: $v_g^2 = 1 - \left(\frac{m_g}{E_g}\right)^2$
- Gravity coupling to "background" fields: $v_g = F(\phi, \vec{K}, \mathbf{H}, \ldots)$

EXAMPLES

- *General Relativity.* For $\lambda \ll \mathcal{R}$, GW move on null geodesics of background spacetime, as do photons. $v_g \equiv 1$.
- *Scalar Tensor Gravity.* Tensor waves have have $v_g \equiv 1$, even if scalar is massive.
- *Theories with background flat metric.* *Eg.* Rosen's Bimetric Theory (1970s). GW follow null cones of η, light follows cones of $\mathbf{g}$.

POSSIBLE LIMITS

$$\boxed{1 - v_g \approx 5 \times 10^{-17} \left(\frac{200\text{Mpc}}{D}\right) [\Delta t_a - (1+Z)\Delta t_e]}$$

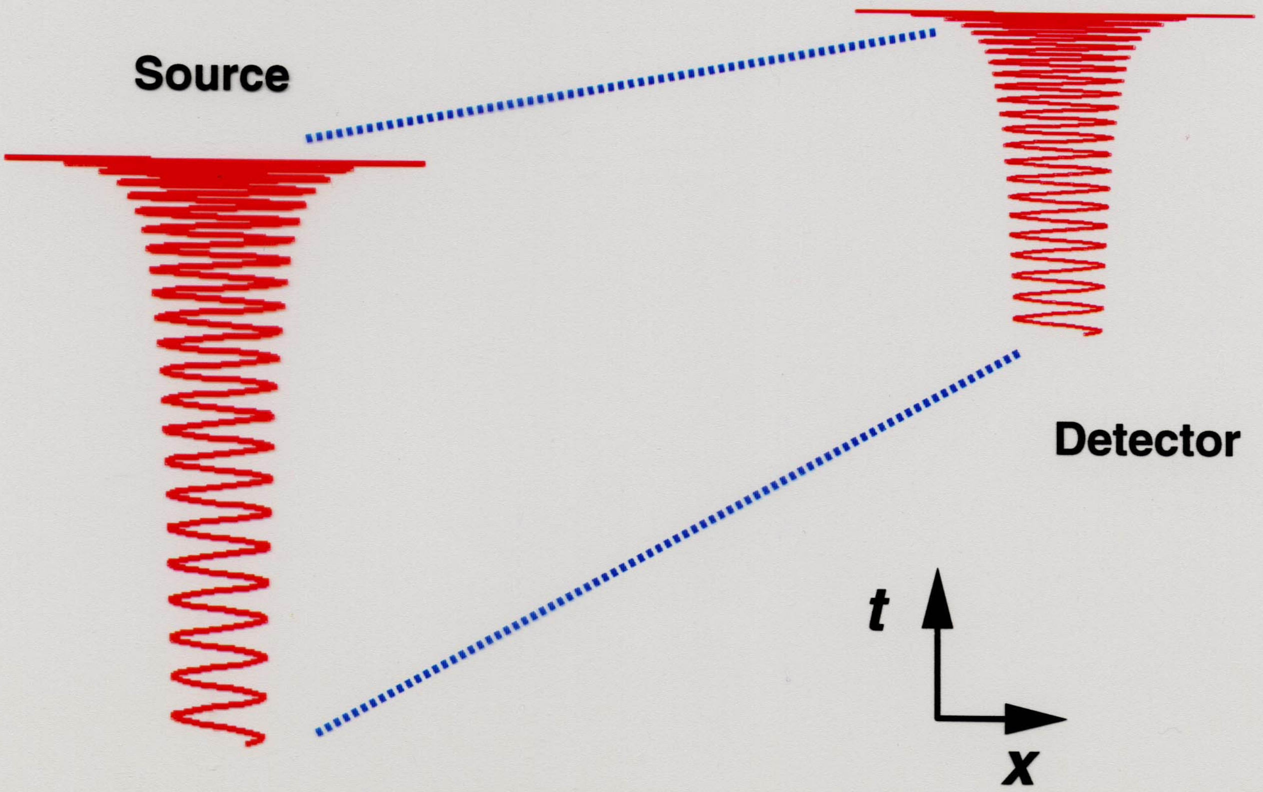
D = distance of source $\quad Z$ = redshift of source

Δt_a (Δt_e) = time difference, in seconds

$$\boxed{\lambda_g > 3 \times 10^{12}\ \text{km} \left(\frac{D}{200\text{Mpc}}\right)^{1/2} \left(\frac{100\text{Hz}}{f}\right)^{1/2} \left(\frac{1}{f\Delta t}\right)^{1/2}}$$

$$3 \times 10^{12}\ \text{km} = (4 \times 10^{-22}\ \text{eV})^{-1}$$

Bounding the Graviton Mass Using Inspiralling Compact Binaries



m_1	m_2	*Distance (Mpc)*	*Bound on λ_g (km)*
Ground Based (LIGO/VIRGO)			
1.4	1.4	300	4.6×10^{12}
10	10	1500	6.0×10^{12}
Space Based (LISA)			
10^6	10^6	3000	5.4×10^{16}
10^4	10^4	3000	0.7×10^{16}

Other Limits on the Graviton Mass

$\lambda_g > 3 \times 10^{12}$ km (solar system $1/r^2$ law)

$\lambda_g > 6 \times 10^{19}$ km (galaxy & cluster dynamics)

CMW, PRD '98

Testing Gravitational Radiation Reaction

$$\frac{df}{dt} = \frac{96}{5\pi \mathcal{M}^2}(\pi \mathcal{M} f)^{11/3}\Big[1$$

N — Measure chirp Mass $\mathcal{M}$

$$-\left(\frac{743}{336} + \frac{11}{4}\eta\right)(\pi M f)^{2/3}$$

1PN — Measure m_1 & m_2

"Tail" term: Test GR

$$+(4\pi - \beta)(\pi M f)$$

1.5PN — Measure spins

$$+\left(\frac{34103}{18144} + \frac{13661}{2016}\eta + \frac{59}{18}\eta^2 + \sigma\right)(\pi M f)^{4/3}$$

2PN — Test GR

$$+O[(\pi M f)^{5/3}]\Big]$$

$$M = m_1 + m_2\,; \qquad \eta = m_1 m_2/M^2\,; \qquad \mathcal{M} = \eta^{3/5} M$$

$$\beta = \text{Spin} - \text{Orbit Effect}\,; \qquad \sigma = \text{Spin} - \text{Spin Effect}$$

Testing Scalar Tensor Gravity with Advanced LIGO

- Requirement: NS–BH binary inspiral