Recent Progress and Future Developments in Gravitational Physics

Gerhard Schäfer

Institute for Theoretical Physics
Friedrich-Schiller-University Jena
www.tpi.uni-jena.de

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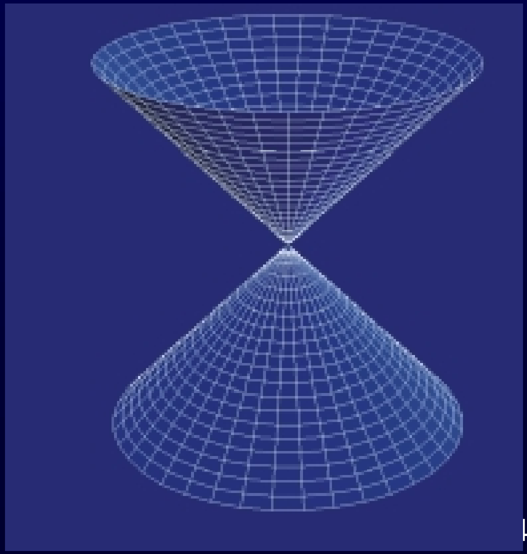
Fundamental Principles in Physics

❖ **The Principle of Lorentz Invariance**

- Universal constant: c speed of light
- Resulting framework: Special Theory of Relativity
- Unification of space and time:

spacetime

$$ds^2 = -c^2 dt^2 + dx^2 + dy^2 + dz^2$$

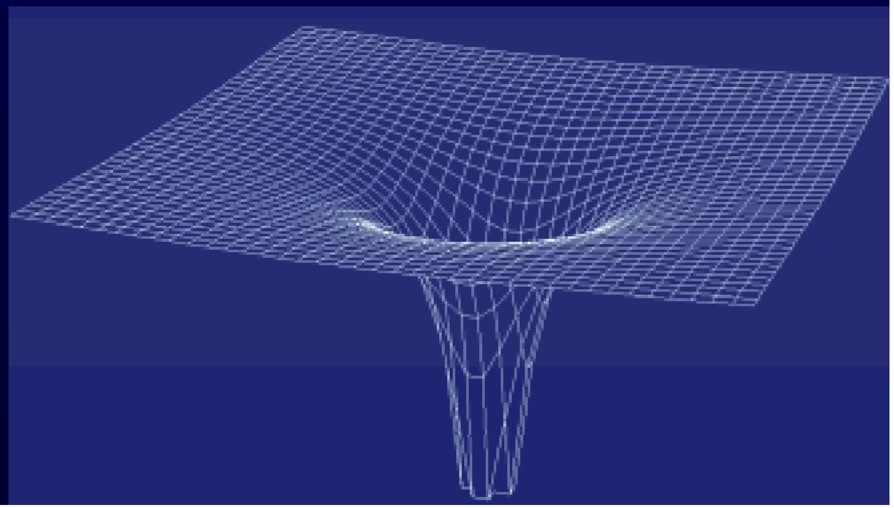


Fundamental Principles in Physics

- **The Principle of Equivalence of Gravitation and Inertia**
  - Universal constant: G/c^4
  - Resulting framework: General Theory of Relativity
  - Unification of inertia and gravity:

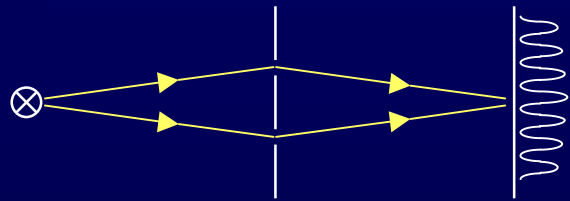
curved spacetime

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$



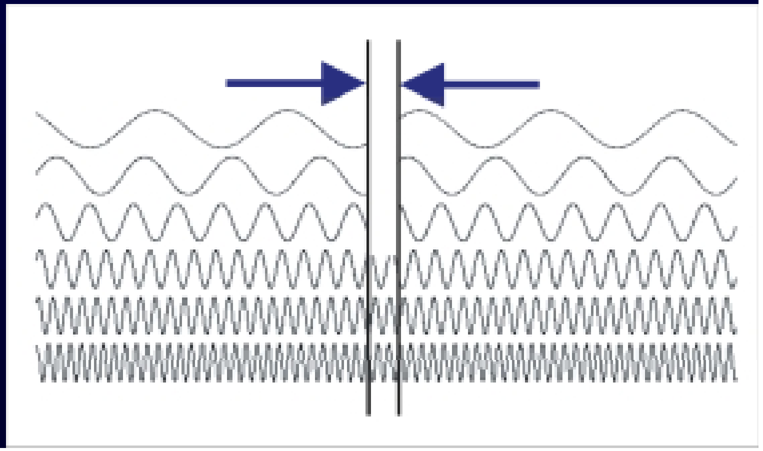
Fundamental Principles in Physics

❖ **The Principle of Superposition of Microscopic States**



- Universal constant: $\hbar$
- Resulting framework: Quantum Theory
- Unification of particles and fields: quantum fields

$$i\hbar\dot{\psi} = H\psi$$



Principle of Lorentz Invariance

- Robertson-Mansouri-Sexl line element (for $\vec{v}$ $\vec{e}_x$)

$$ds^2 = -g_0(v)c^2dt^2 + g_1(v)dx^2 + g_2(v)\left(dy^2 + dz^2\right)$$

- Propagation of light: $ds^2 = 0$

- $g_1 \neq g_2 \quad \Rightarrow$ anisotropy: Michelson-Morley
- $g_1 \neq g_0 \quad \Rightarrow$ velocity dependence: Kennedy-Thorndike
- $g_0 \neq 1 \quad \Rightarrow$ anomal time dilation: Doppler shift

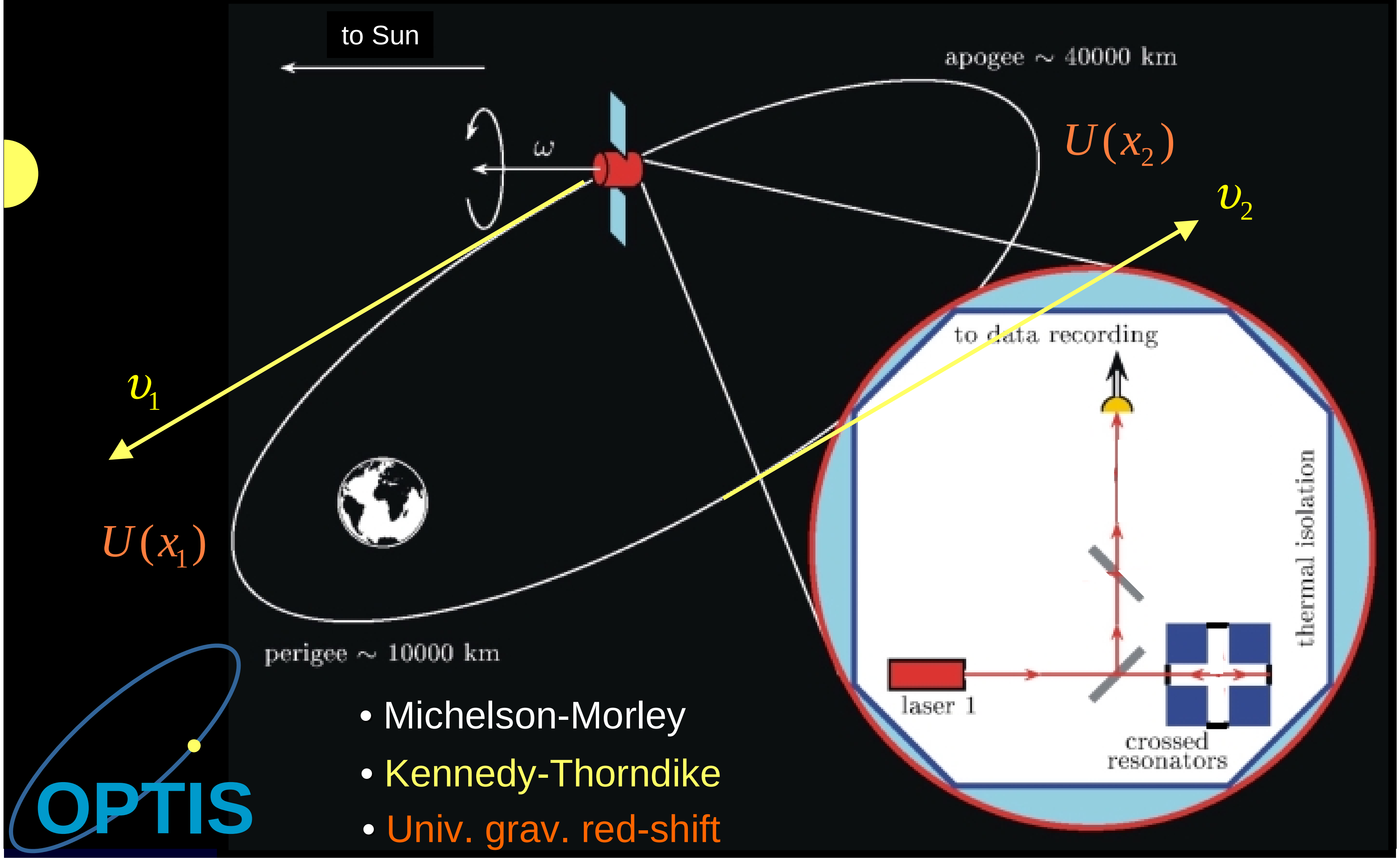
$$g_i(v) = 1 + g_i^0 \frac{v^2}{c^2} + \ldots$$

Principle of Lorentz Invariance

	Method	Accuracy	Experiment
Isotropy	cavity	$\left\|g_1^0 - g_2^0\right\| \leq 2 \cdot 10^{-9}$	Müller et al 2002
Velocity independence	cavity	$\left\|g_1^0 - g_0^0\right\| \leq 2 \cdot 10^{-5}$	Braxmaier et al 2002
Time dilation	2 beam spectroscopy	$\left\|g_0^0 - 1\right\| \leq 8 \cdot 10^{-7}$	Grieser et al 1994

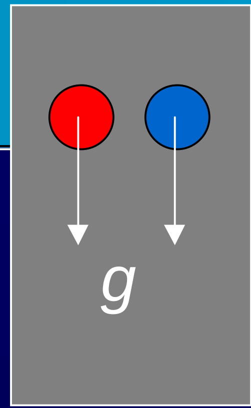
Future: OPTIS / DLR and SUMO / NASA:
MM and KT 3 orders improvement

OPTIS



- Michelson-Morley
- Kennedy-Thorndike
- Univ. grav. red-shift

Universality of Free Fall



- Action of point mass $\quad -mc\int \underbrace{\sqrt{-g_{\mu\nu}dx^{\mu}dx^{\nu}}}_{c\,d\tau}$

- Violation of EP: $\quad m = m[\phi], \quad \phi =$ fundamental field

$$g_{\mu\nu} = A^2(\phi)\,\bar{g}_{\mu\nu}$$

- Acceleration of mass 1:

$$a_1 = \frac{(m_{\mathrm{g}})_1}{(m_{\mathrm{i}})_1}\frac{G(m_{\mathrm{g}})_3}{r_{13}^2} = G_{13}\frac{(m_{\mathrm{i}})_3}{r_{13}^2}$$

$$m_{\mathrm{i}} = m[\phi_0], \quad \phi = \phi_0 + \psi, \quad \phi_0 = \text{ cosmological value}$$

Universality of Free Fall

- Composition-dependent gravitational constant:

$$\frac{G_{13}}{G} = \frac{(m_{\mathrm{g}})_1}{(m_{\mathrm{i}})_1}\frac{(m_{\mathrm{g}})_3}{(m_{\mathrm{i}})_3} \approx 1 + \alpha_1\alpha_3 \quad \text{with} \quad \alpha = \frac{\partial \ln m[\phi_0]}{\partial \phi_0}$$

- Eötvös coefficient:

$$\eta = 2\frac{a_1 - a_2}{a_1 + a_2} = 2\frac{G_{13} - G_{23}}{G_{13} + G_{23}} \approx (\alpha_1 - \alpha_2)\alpha_3$$

$$r_{13} \approx r_{23}$$

Loránd Eötvös (1848 - 1919)

Universality of Free Fall

Method	Accuracy η	Experiment
Pendula	10^{-3}	Newton (1686)
Pendula	2×10^{-5}	Bessel (1832)
Torsion balance	5×10^{-9}	Eötvös, Pekar, Fekete (1922)
Torsion balance	10^{-11}	Roll, Krotkov, Dicke (1964)
Torsion balance	10^{-12}	Braginski, Panov (1972)
Torsion balance	10^{-12}	Adelberger et al. (1994)
Earth-Moon motion	5×10^{-13}	Williams et al. (1996)

future

Free fall in orbit	10^{-15}	MICROSCOPE (2005)
Free fall in orbit	10^{-17}	GG
Free fall in orbit	10^{-18}	STEP

Universality of Gravitational Red Shift

- **Gravitational Red shift:**
  Clocks at larger distances from gravitating objects go faster than nearby clocks.

$$\nu(x) = \left(1 + \frac{U(x_0) - U(x)}{c^2}\right)\nu(x_0) \qquad U = \frac{GM}{r}$$

- **Universality of Gravitational Red Shift:**
  All kinds of clocks show the same behaviour.

  Interpretation: Universality of coupling of gravity to **all** kinds of particles and fields; constancy of the basic coupling parameters.

Universality of Gravitational Red Shift

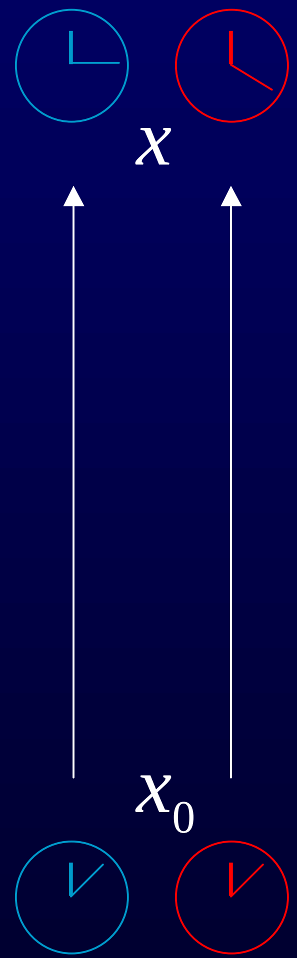
- No universality (absolute measurement):

$$\nu(x) = \left(1 + \alpha_{\text{clock}} \frac{U(x_0) - U(x)}{c^2}\right) \nu(x_0)$$

- Comparison of two clocks (differential mmt.):

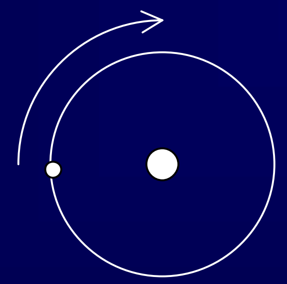
$$\Delta_x \left(\frac{\nu_{\text{clock 1}}}{\nu_{\text{clock 2}}}\right) = \left(\alpha_{\text{clock 2}} - \alpha_{\text{clock 1}}\right) \frac{\Delta U}{c^2} \frac{\nu_{\text{clock 1}}}{\nu_{\text{clock 2}}}$$

Zero in GR: Null test



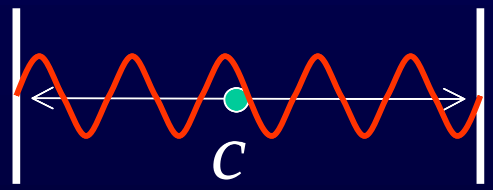
Universality of Gravitational Red Shift

- Atomic (hf) clock
  - H-maser
  - Cs atomic clock
  - Ion clock
  - Atomic fountain clock



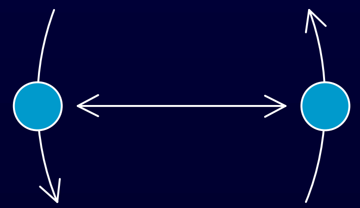
$$E \quad \alpha^2 f(\alpha)$$

- Cavity clock



$$L \quad \alpha$$

- Molecule clock (rotation, vibration)



$$E_{\mathrm{rot,vib}} \quad f_{\mathrm{rot,vib}}\left(\frac{m_e}{m_p}, \alpha\right)$$

Universality of Gravitational Red Shift

Comparison	Accuracy $\alpha_2 - \alpha_1$	Experiment
Red Shift (H-maser) am	(7×10^{-5})	GP-A, Vessot et al 1980 (ACES: 2 ord. impr. pos.)
Mg – Cs (fine structure) dm	7×10^{-4}	Godone et al 1995
Resonator – I_2 (electronic) dm	4×10^{-2}	Braxmaier et al 2002
Cs – H-Maser (hf) dm	2.1×10^{-5}	Bauch et al 2002

The Consequence: General Relativity

- Lorentz Invariance
- Universality of Free Fall
- Universality of Grav. Red Shift

$\Rightarrow$ Gravity is Geometry (Riemann Geometry) $g_{\mu\nu}$

Equations for the metric: Einstein field equations

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

geometry matter

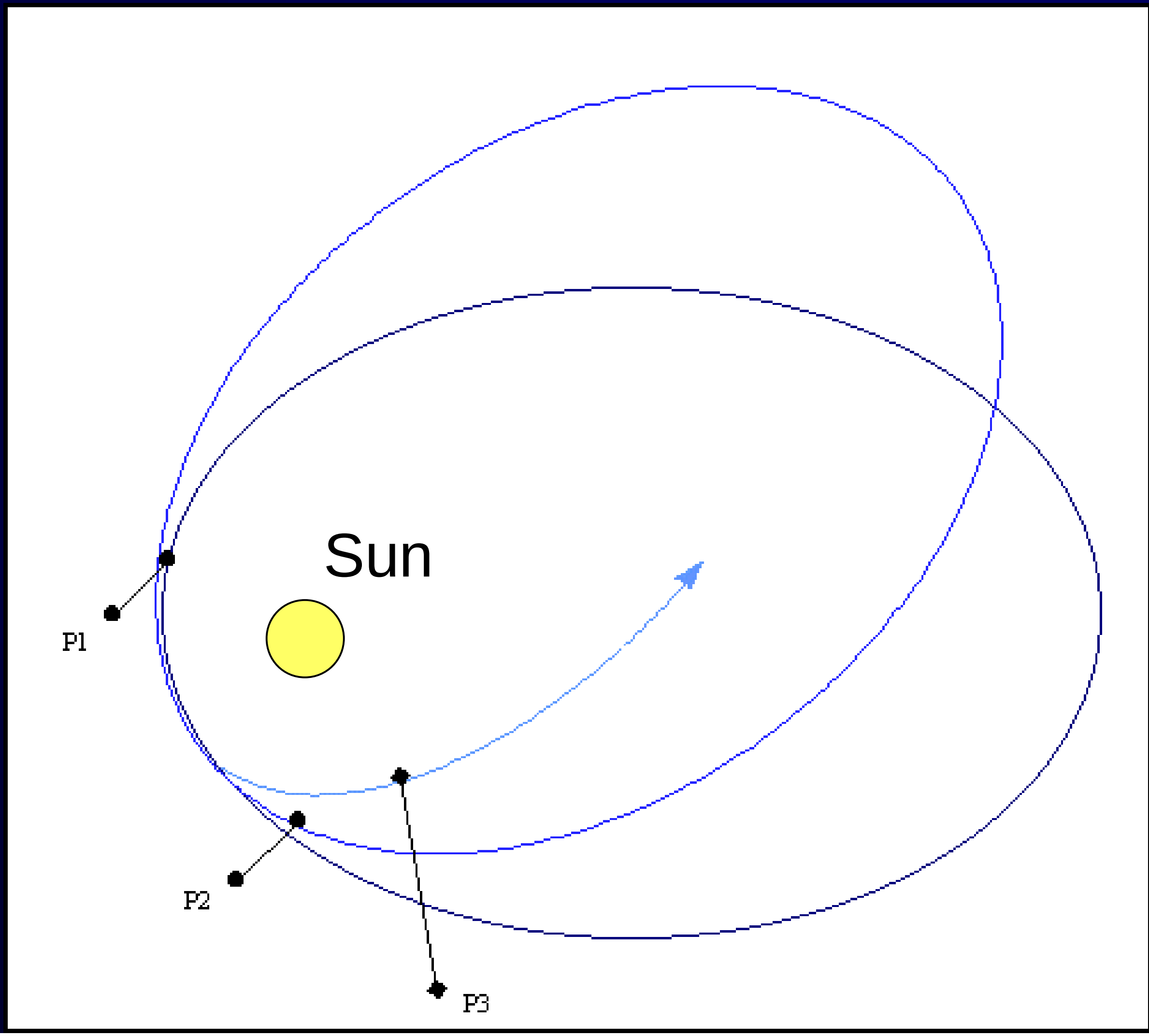
Predictions of General Relativity

- 1843: Perihelion shift (Mercury orbit)

  1915: General Theory of Relativity
- 1919: Deflection of light (solar eclipse)
- 1960: Gravitational redshift (Mössbauer effect)
- 1967: Shapiro time delay (radar ranging to Mercury)
- 1974: Periastron shift (binary pulsar)
- 1978: Gravitational radiation damping (binary pulsar)
- 1987: Geodetic precession (Earth-Moon gyroscope)
- 1997: Lense-Thirring effect (LAGEOS satellites)

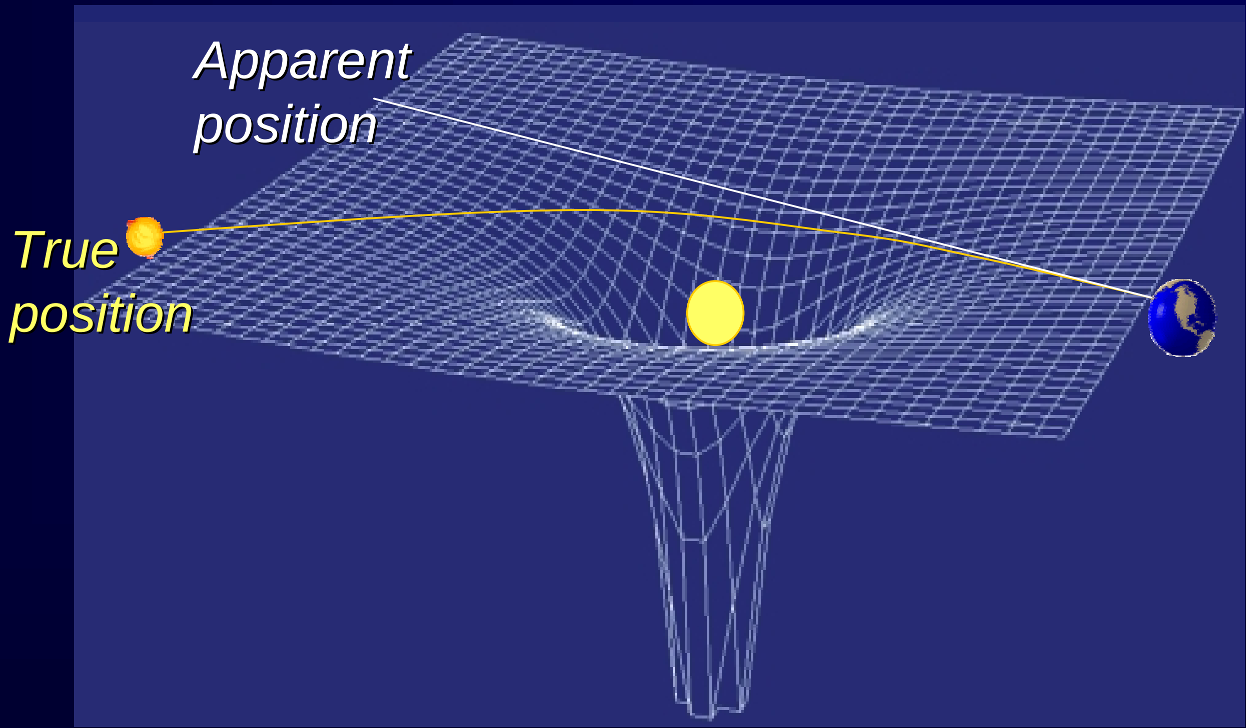
Predictions of General Relativity

- Perihelion shift



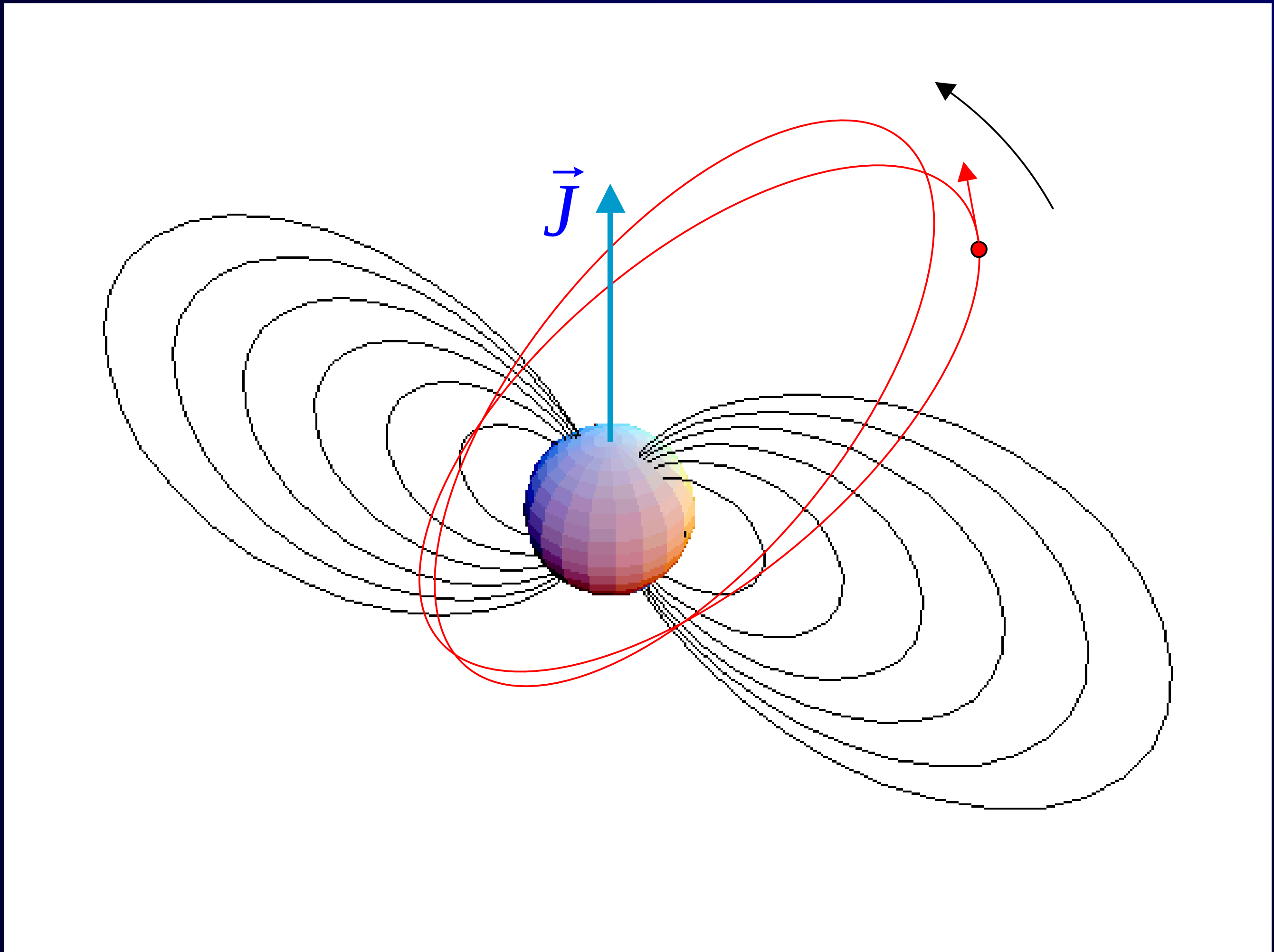
Predictions of General Relativity

- Deflection of light
- Shapiro time delay



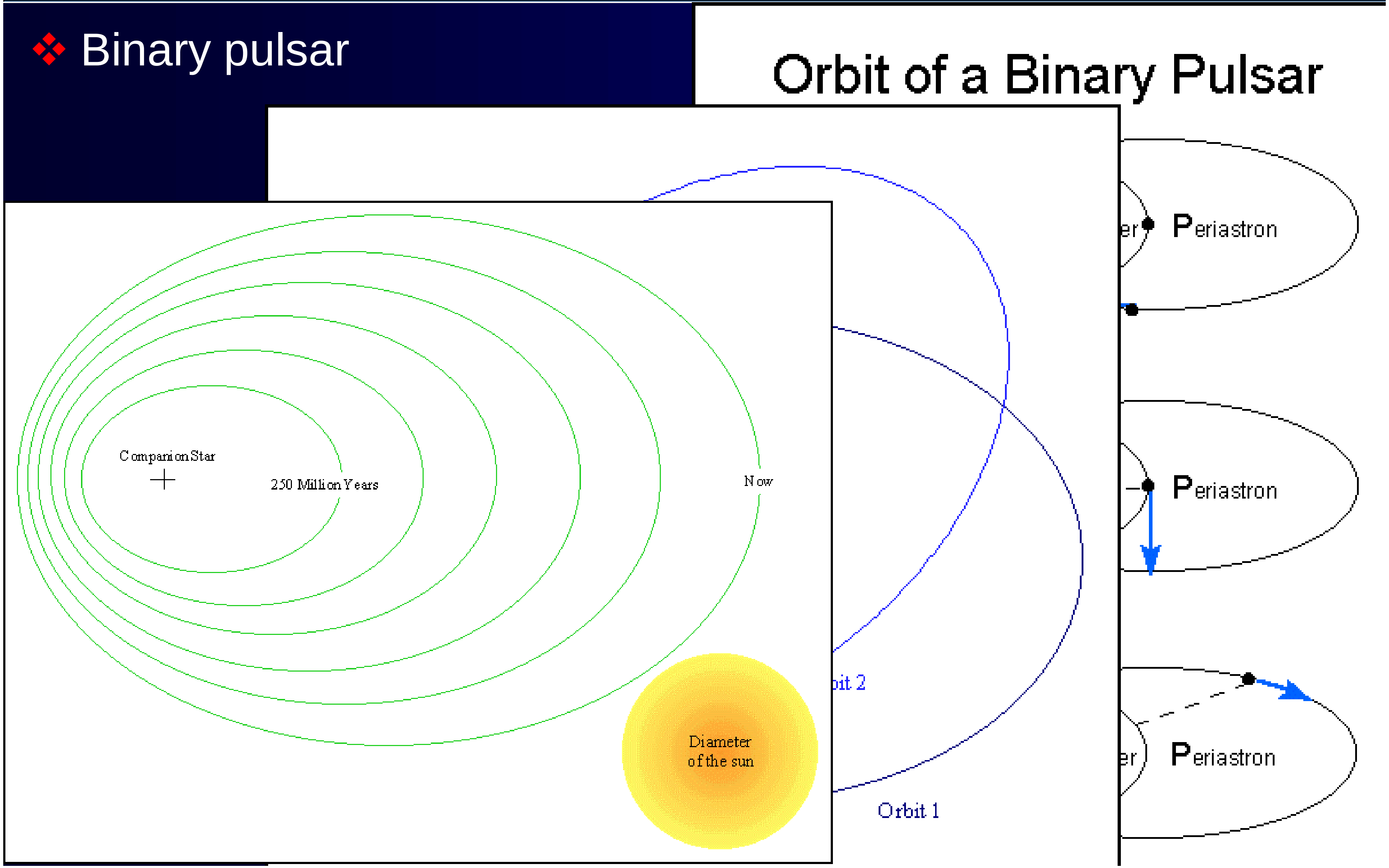
Predictions of General Relativity

- Gravitomagnetism (Lense-Thirring effect)



Predictions of General Relativity

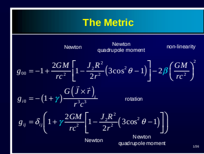
- Binary pulsar



Predictions of General Relativity

Effect	Method	Reference
Perihelion shift	Mercury orbital motion	Shapiro (1990)
Periastron shift	binary pulsar	Taylor (1993)
Deflection of light	VLBI	Lebach et al (1995)
Shapiro time delay	Viking radar ranging	Reasenberg et al (1979)
Geodetic precession	lunar laser ranging	Williams et al (1996)
Lense-Thirring effect	satellite ranging	Ciufolini et al (1997)
Gravitational radiation damping	binary pulsar	Taylor (1993)

$\gamma = 0.9996 \pm 0.0017 \qquad \beta = 0.9997 \pm 0.0005$

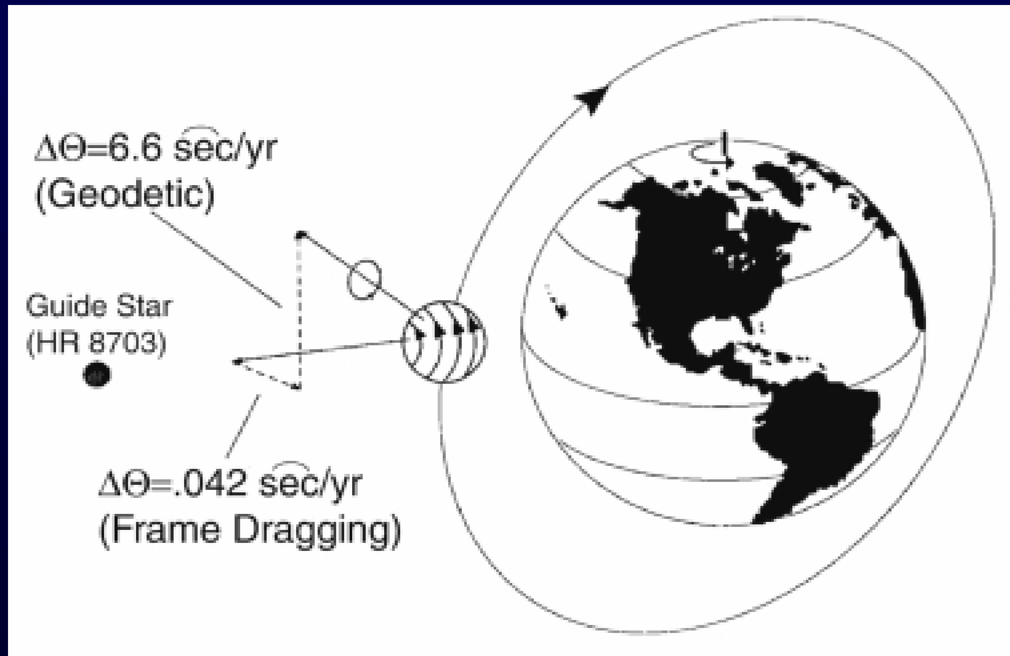


accuracy for strong field effects: 0.03%

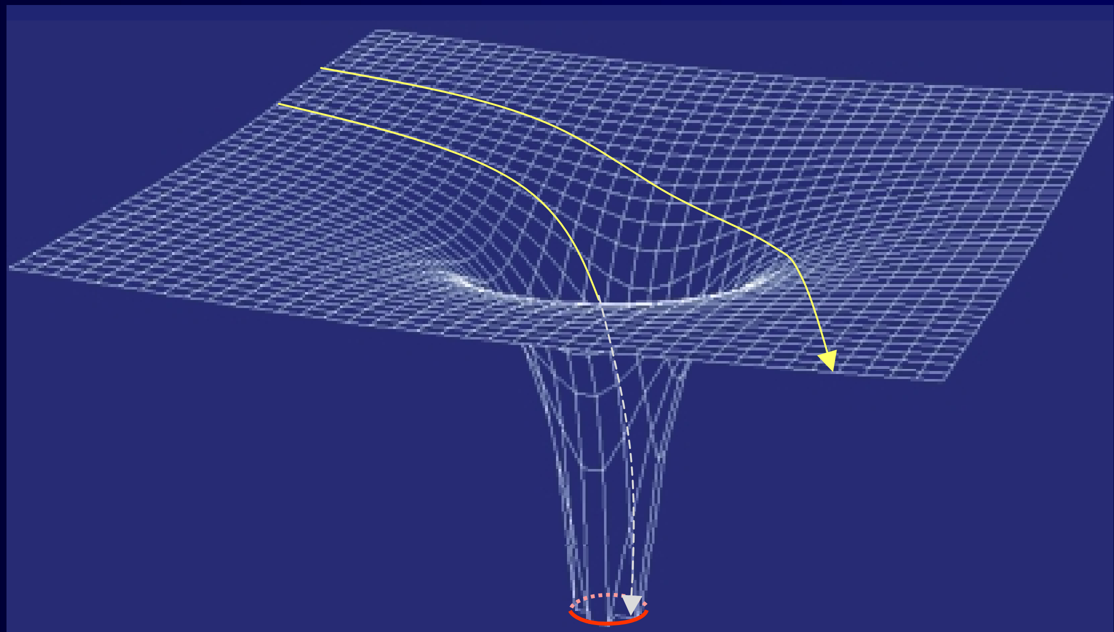
$\Rightarrow$ evidence for gravitational waves

Future Test: GP-B (NASA)

- Scientific objectives
  - Test of frame dragging to 0.1% accuracy
  - Test of geodetic precession to 0.001% accuracy
- Launch: 2003



Evidence for Black Holes



Black Hole horizon

Evidence for Black Holes

Stellar Black Hole Candidates in the Milky Way		
X-Ray Source Name	**Mass of Companion**	**Mass of Black Hole**
Cygnus X-1	24 – 42	11 – 21
V404 Cygni	~ 0.6	10 –15
GS 2000+25	~ 0.7	6 – 14
H 1705-250	0.3 – 0.6	6.4 – 6.9
GRO J1655-40	2.34	7.02
A 0620-00	0.2- 0.7	5 – 10
GS 1124-T68	0.5 – 0.8	4.2 – 6.5
GRO J042+32	~ 0.3	6 – 14
4U 1543-47	~ 2.5	2.7 – 7.5

Mass in units of M

R. Blandford & N. Gehrels (1999)

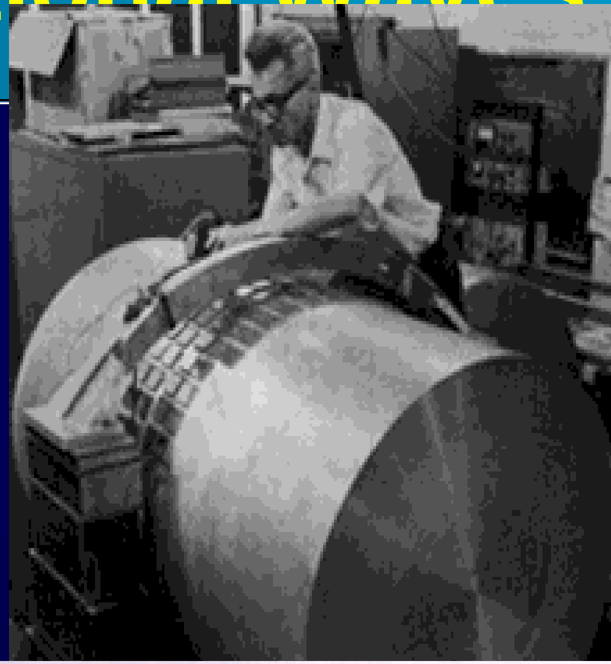
Evidence for Black Holes

Supermassive Black Hole Candidates		
Name	**Mass**	**Method**
M87	2×10^9	stars + optical disc
NGC 3115	10^9	stars
NGC 4486 B	5×10^8	stars
NGC 4594 (Sombrero)	5×10^8	stars
NGC 3377	8×10^7	stars
NGC 3379	5×10^7	stars
NGC 4258	4×10^7	masing H_2O disc
M 31 (Andromeda)	3×10^7	stars
M 32	3×10^6	stars
Galactic Centre	2.5×10^6	stars + (3-D motions)

Mass in units of M

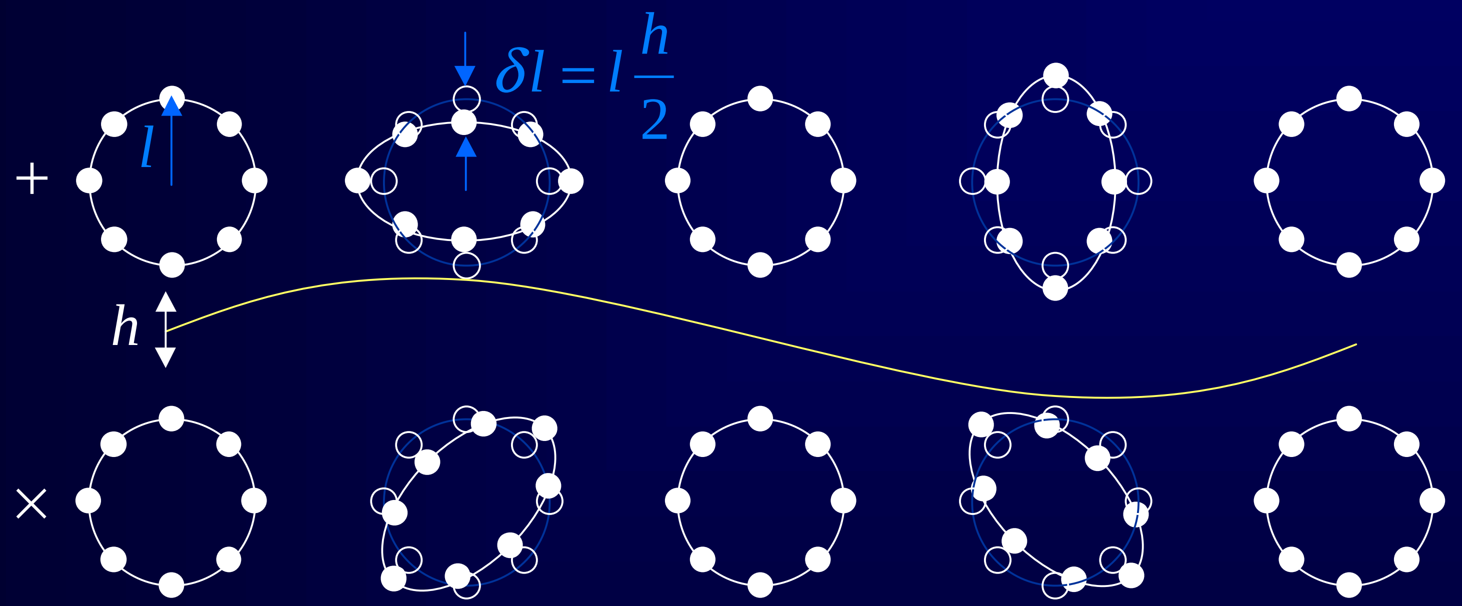
M.J. Rees (1997)

Detection of Gravitational Waves



- Resonant bar detectors
  - ALLEGRO (Louisiana/USA)
  - AURIGA (Legnaro/Italy)
  - NAUTILUS (Frascati/Italy)
  - EXPLORER (CERN)
  - NIOBE (Perth/Australia)
- Laserinterferometric detectors
  - Earth-based
    - LIGO (USA)
    - VIRGO (France - Italy)
    - GEO600 (Germany - UK)
    - TAMA300 (Japan)
  - Space-borne
    - LISA (ESA - NASA)

Detection of Gravitational Waves



$$\delta l \quad \frac{r_{\text{proton}}}{1000}$$

Detection of Gravitational Waves

Country: *Institute:*	**USA** MIT, Caltech	**FRA** CNRS	**ITA** INFN	**GER** MPQ	**GBR** Glasgow	**JPN** NAO, U-Tokyo, ICRR

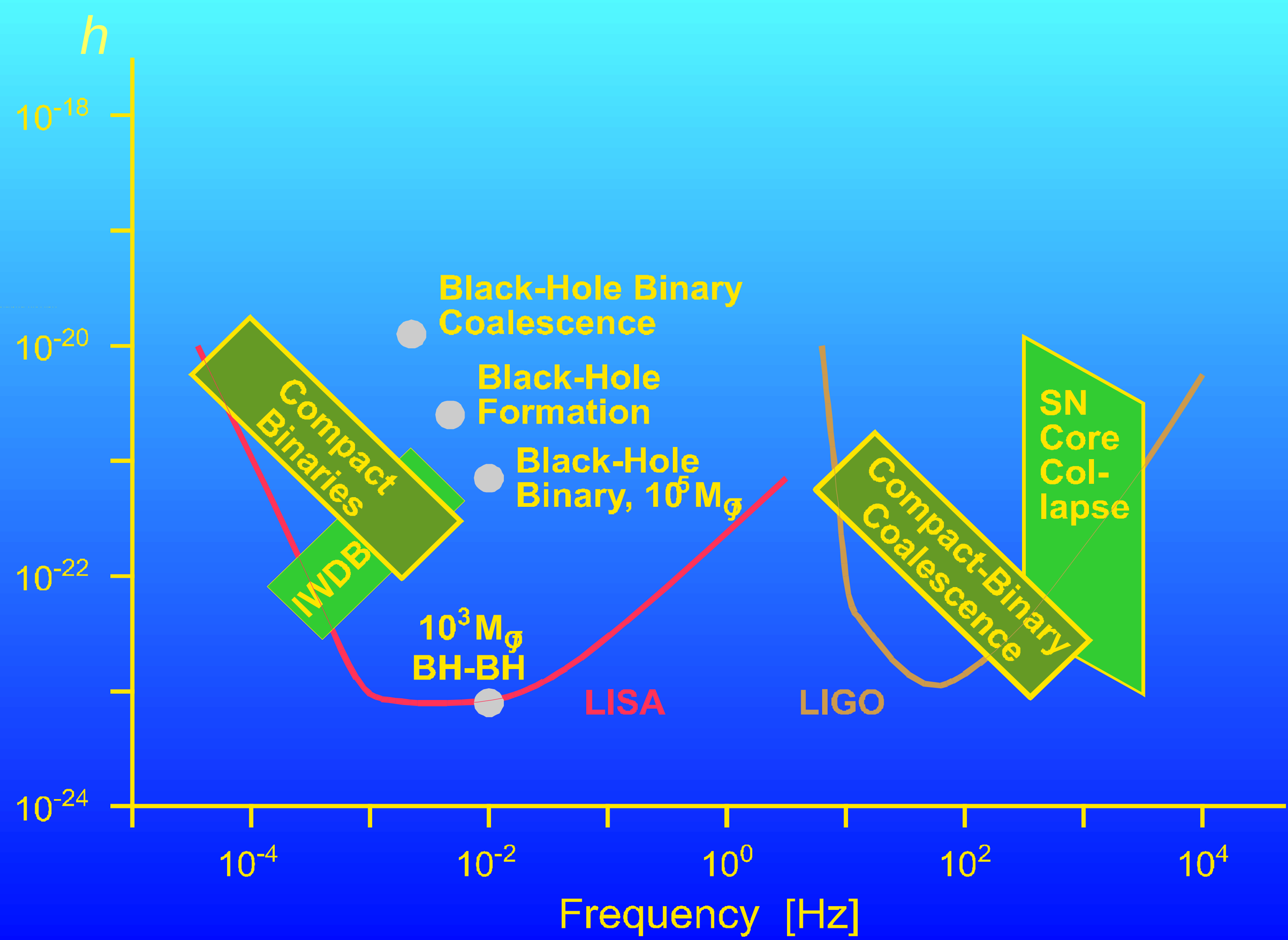
Large Interferometric Detectors: the current generation

Project name:	**LIGO**		**VIRGO**	**GEO 600**	**TAMA 300**
Arm length ℓ:	4 km 2 km	4 km	3 km	600 m	300 m
Site *(State)*	Hanford (WA)	Livingston (LA)	Pisa ITA	Hannover GER	Mitaka JPN

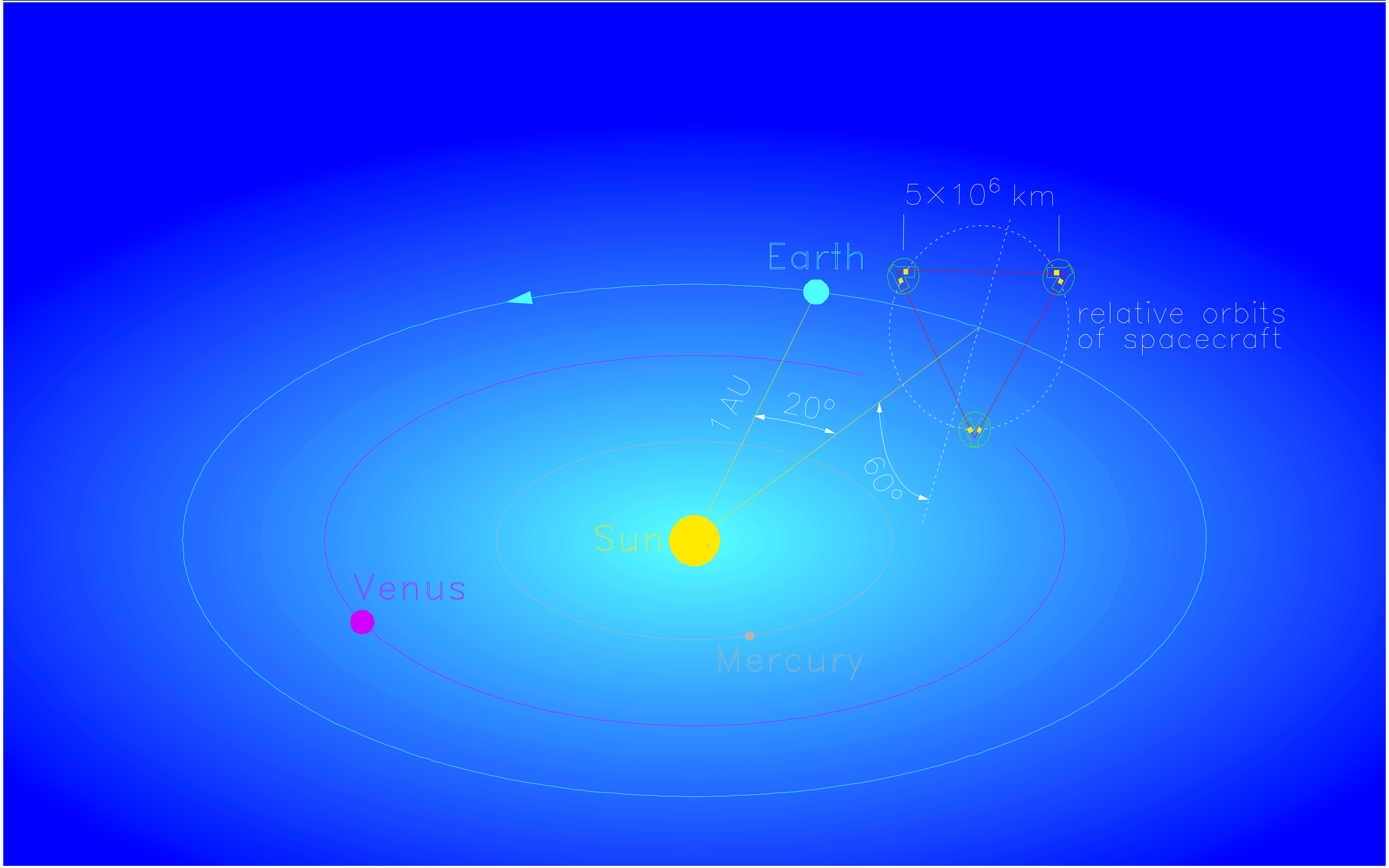
Large Interferometric Detectors: the bright future

Planning (start):	1995		1999	1998
Arm length ℓ:	4 km	4 km	3 km	3 km
Site *(State)*	Hanford (WA)	Livingston (LA)	EUROPE	Kamioka JPN
Project name:	**LIGO II**		**EURO**	**LCGT**
special features:	suspension RSE		super-attenuator; cryogenic diffractive optics, tunable	cryogenic underground

Detection of Gravitational Waves



ESA-NASA mission: LISA



Cosmology

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

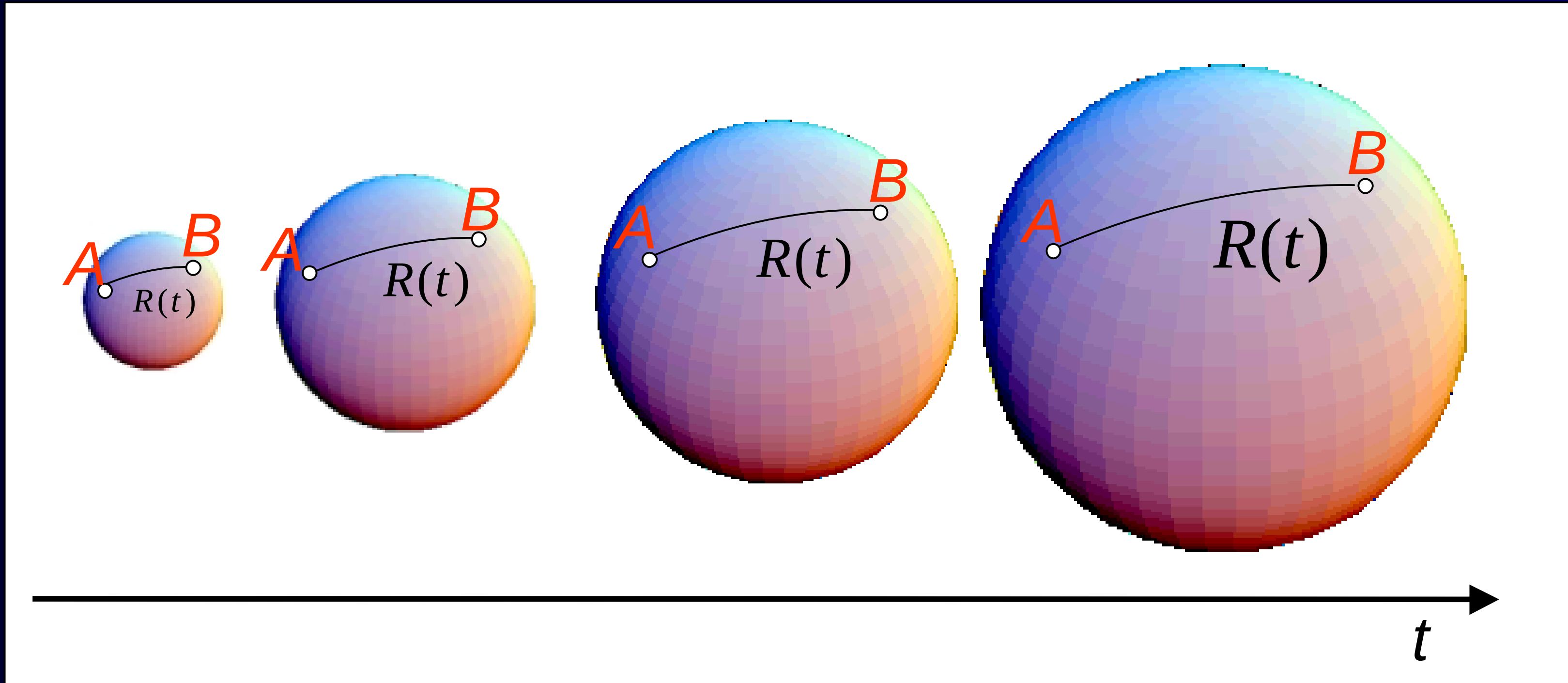
↑

Cosmological Constant

- Friedmann-Lemaître Universes:

$$ds^2 = -c^2 dt^2 + R^2(t) d\sigma^2$$

Cosmology



- Curvature $K = k / R^2 \qquad (k = 0, \pm 1)$
- Hubble parameter $H = \dot{R} / R$
- Deceleration parameter $q = -\ddot{R} / RH^2$

Cosmology

$$\Omega_M + \Omega_\Lambda + \Omega_K = 1 \qquad q = \frac{1}{2}\Omega_M - \Omega_\Lambda$$

$$(p \approx 0)$$

$$\Omega_\mathrm{M} = \rho / \rho_\mathrm{crit}$$

$$\Omega_\Lambda = \Lambda / 3H^2$$

$$\Omega_K = -K / H^2$$

$$H \approx 65 \text{ km/s Mpc}$$

$$\rho_\mathrm{crit} = 3H^2 / 8\pi G \approx 10^{-29} \text{ g/cm}^3$$

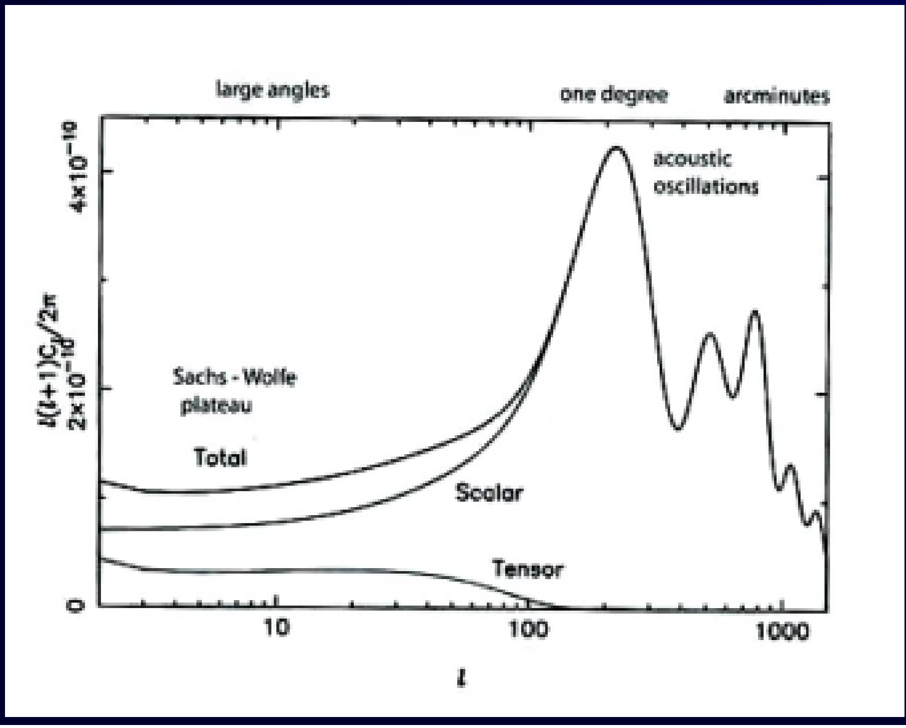
Cosmology

- Present values CMB and GRS

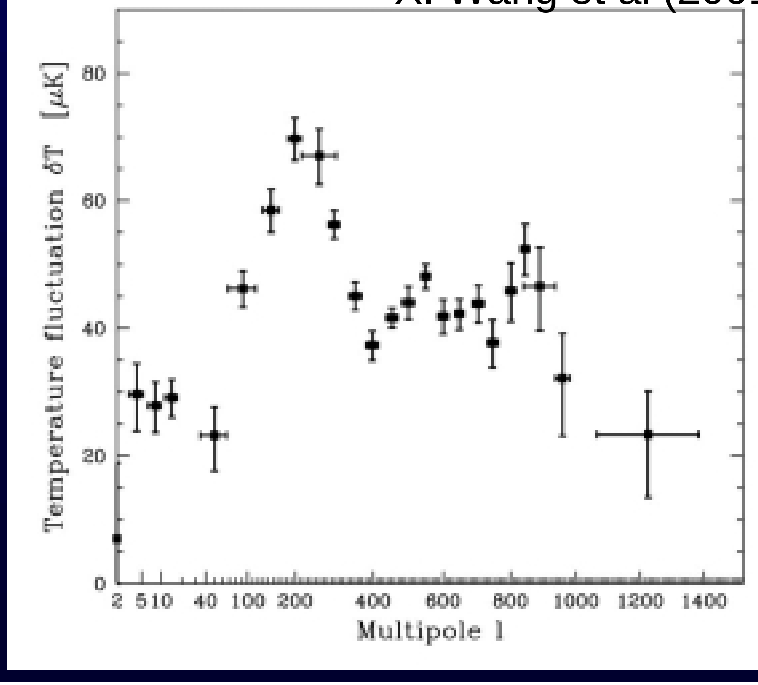
$$\Omega_M = 0.11 - 0.40$$
$$\Omega_\Lambda = 0.65 - 0.85$$
$$\Omega_K = (-0.05) - (+0.04)$$
$$q = (-0.79) - (-0.45)$$

Efstathiou et al (2001)

Accelerating Universe !

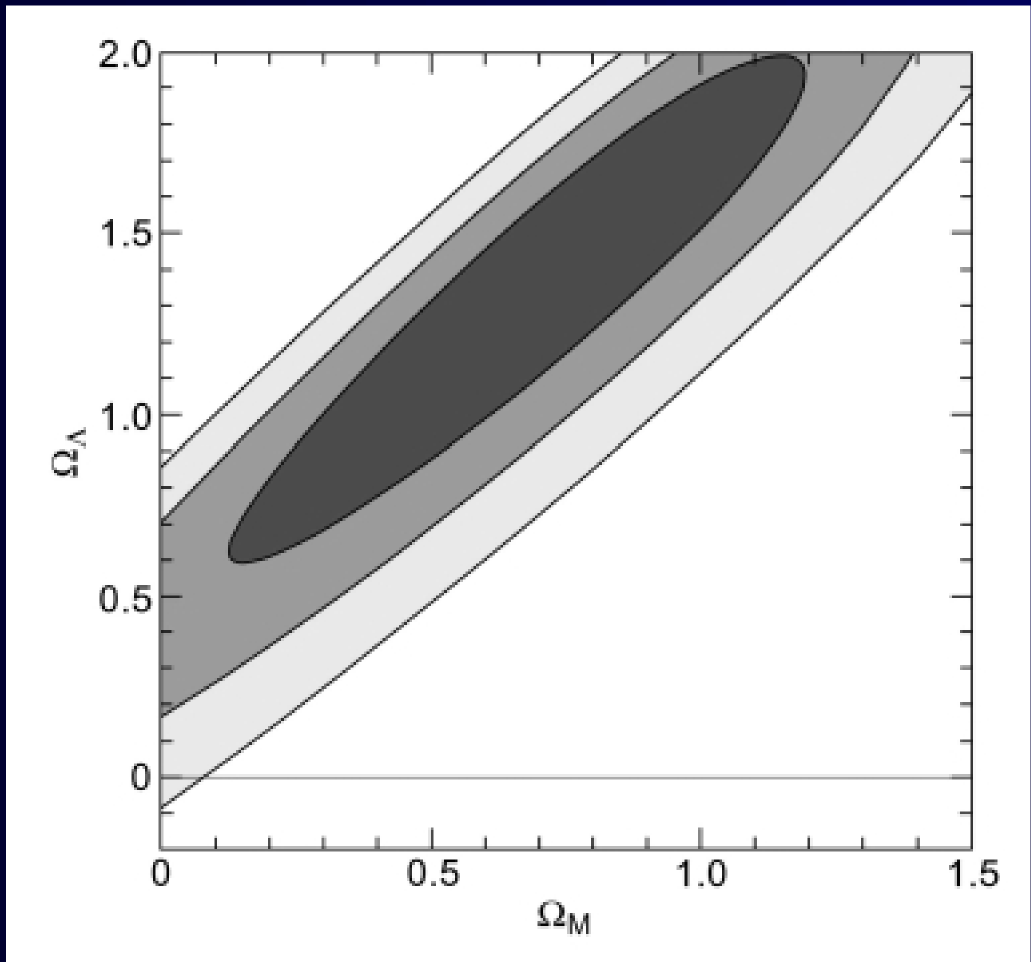


X. Wang et al (2001)



Cosmology

- SN -Ia: $\Omega_\Lambda \approx 1.3\,\Omega_M + 0.45$



Leibundgut (2001)

Beyond General Relativity

- Unification of Gravity with Electro-Weak and Strong Interactions
- Observation: General Relativity

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

is effective theory (low-energy limit): $\Lambda[\phi_0],\ G[\phi_0]$

$\phi_0 = \langle 0|\phi|0\rangle$: vacuum-expectation value of fundamental field ϕ at the present epoch

- Λ- term is of vacuum-energy type $\rho_{\text{vac}} c^2$ with pressure

$$p_{\text{vac}} = -\rho_{\text{vac}} c^2 \qquad \Lambda = \frac{8\pi G}{c^2} \rho_{\text{vac}}$$

Beyond General Relativity

- Unification-Ansatze: String and brane theories in higher-dimensional spacetimes with non-trivial topologies

- However, the effective cosmological constant is infinitesimal by particle-physics standards

$$\rho_\Lambda c^2 \leq \rho_{\mathrm{crit}} c^2 = 10^{-46} \left(\mathrm{GeV}\right)^4 \Big/ \left(\hbar c\right)^3$$

$$\rho_\Lambda = \Lambda c^2 \Big/ 8\pi G$$

- Quintessence scenarios (ad hoc)

The Future: Summary and Outlook

M I S S I O N S and E X P E R I M E N T S

- Special Relativity and Foundations of General Relativity:

  SUMO, OPTIS, PHARAO/ACES, HYPER;
  MICROSCOPE, GG, STEP

- General Relativity:

  GP-B; Gravitational Wave Detectors; GAIA

- Cosmology:

  Planck (CMB), SNAP (SN-Ia), DEEP (Redshift)