Experimental General Relativity

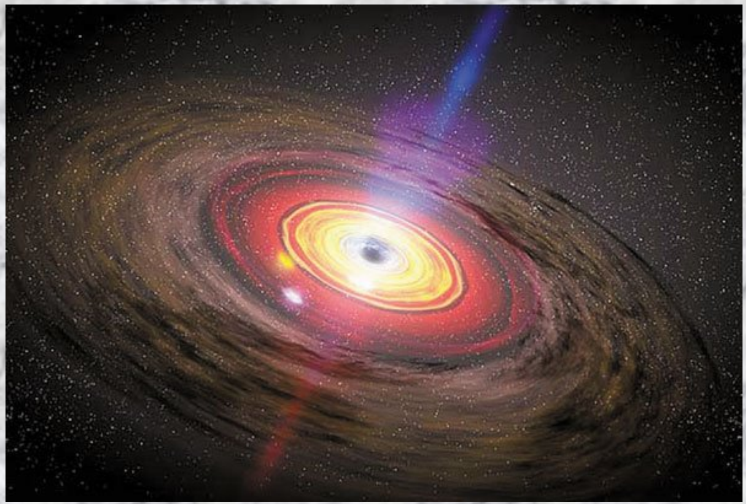
Barak Kol
Hebrew Un, Jerusalem
DESY June 09

"GR was a theorist's paradise
but an experimentalist's hell"
(Misner, Thorne, Wheeler)

Outline

- Past
- Present
- Future

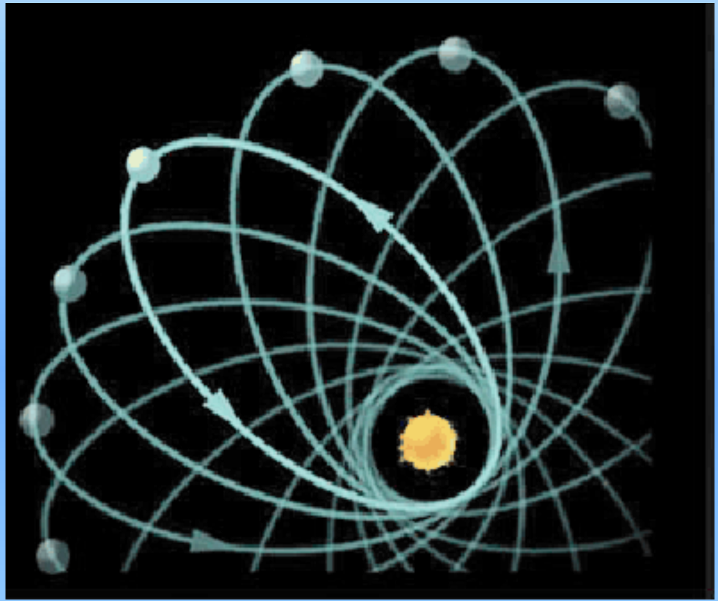
Review by Clifford Will



Past

- Perihelion shift
  (Mercury – Einstein 1915)

$$\Delta\theta = \frac{6\pi GM}{p}$$ per revolution

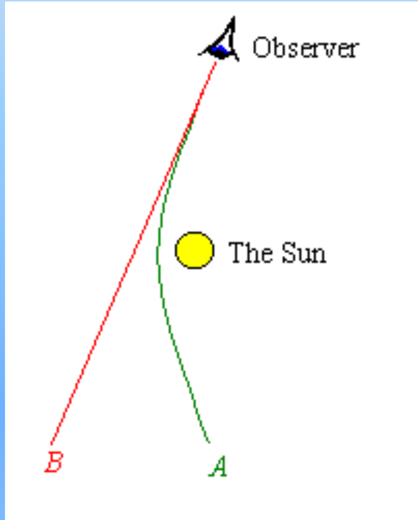


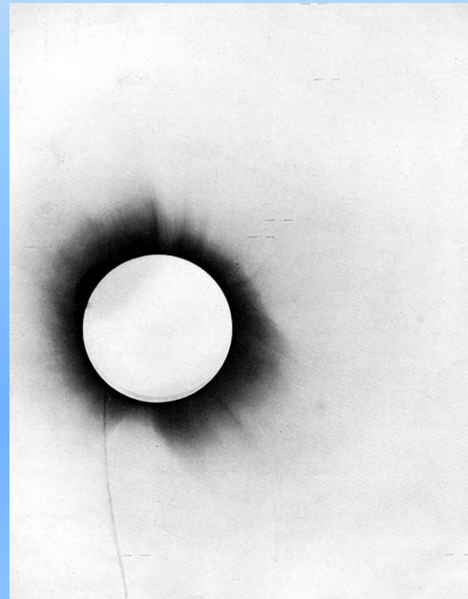
Where p is the ellipse's semi-latus rectum

$$r(\theta) = \frac{p}{1 + e\cos(\theta)}$$

43.0''/cent out of
5600.0''/cent observed

Deflection of light





(Einstein 1915)

Eddington's expedition (1919)

$$\delta\Theta = \frac{4GM_{sun}}{d}$$

$$= 1.75''$$

Sun grazing rays

Shapiro (1964) time delay

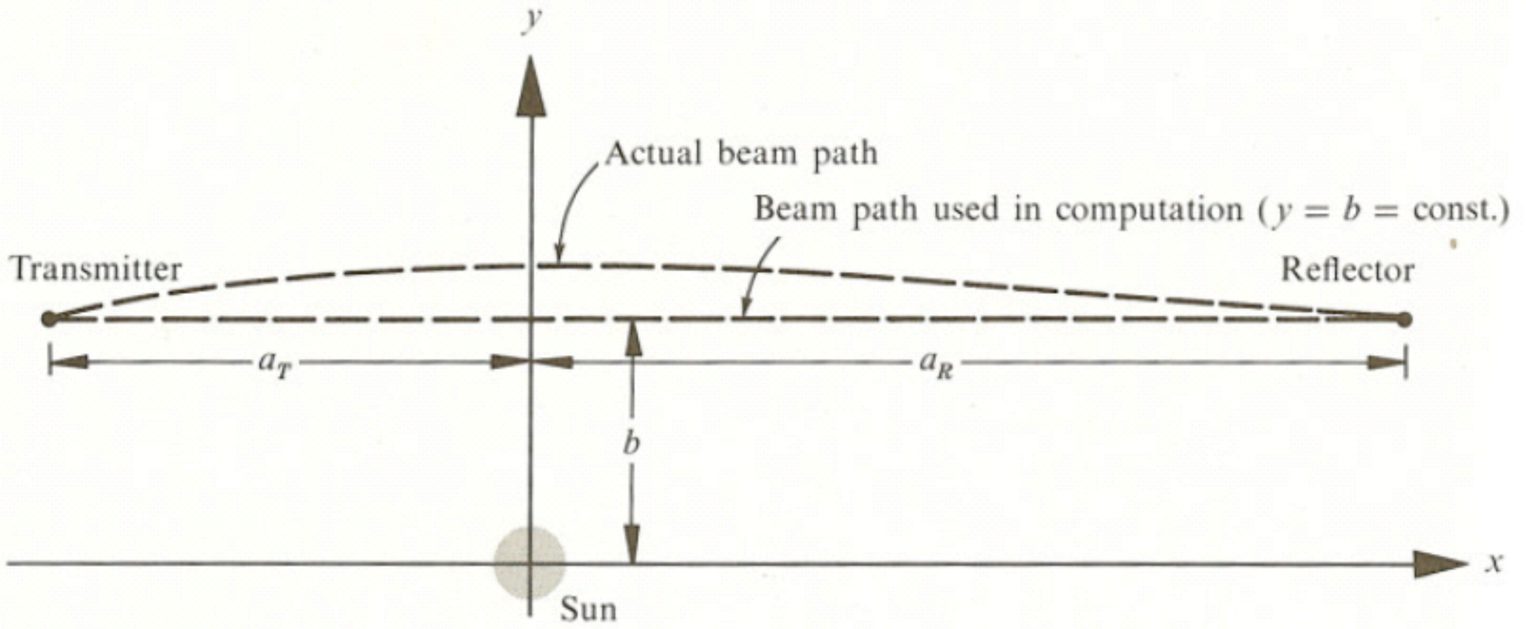


Figure 40.3.
Diagram, in the PPN coordinate system, for the calculation of the relativistic time delay.

$$\delta t = 4\,GM_{sun}\log\left[(r_{src} + \vec{x}_{src}\cdot\hat{n})(r_e + \vec{x}_e\cdot\hat{n})/d^2\right]$$

Actually measure the echo time
as it changes as the trajectory evolves.

Gravitational redshift

- Adams (1925) spectral shift from Sirius B
- Pound & Rebka (Jefferson labs Harvard,1959)
- Mössnauer effect

$$\Delta\nu / \nu = gh / c^2$$

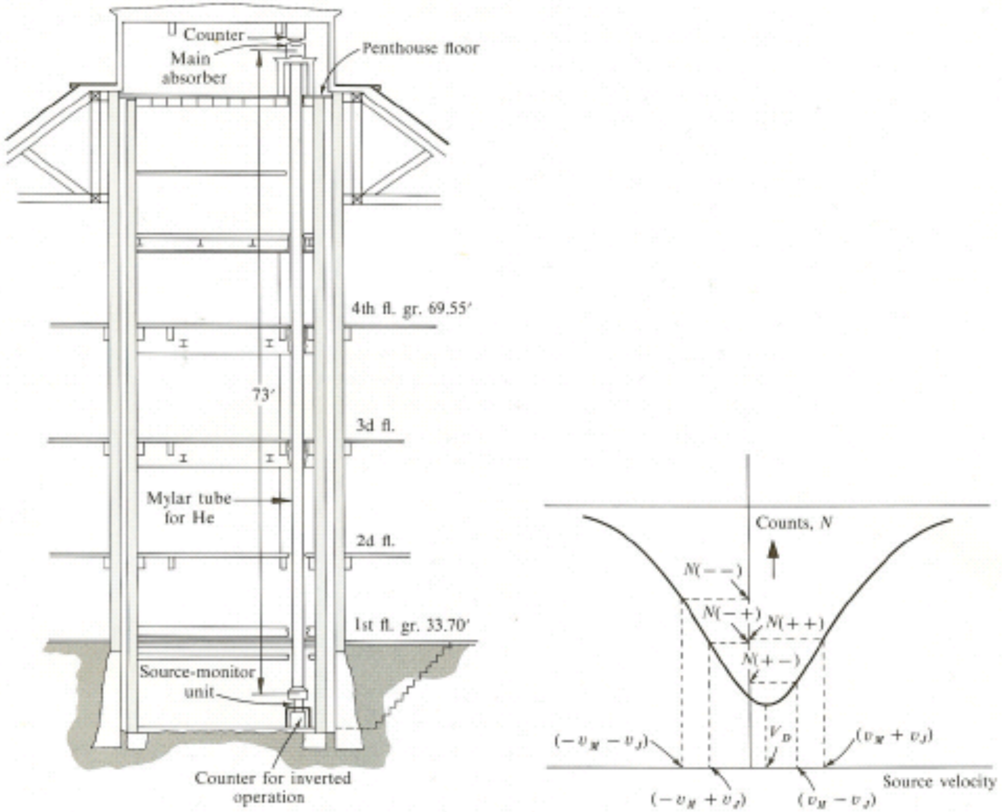
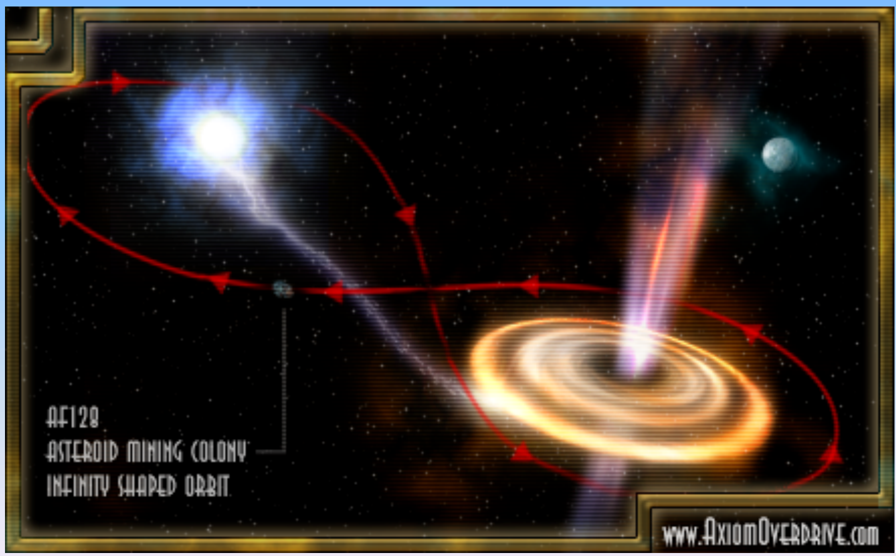
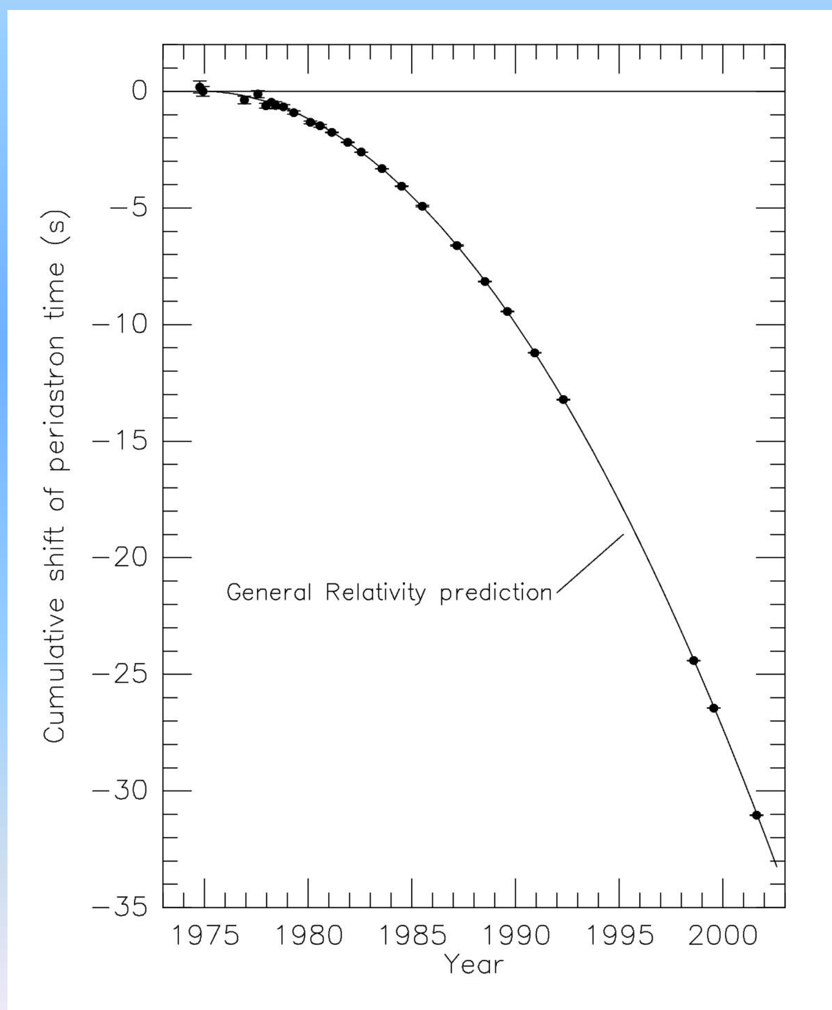


Figure 38.1.
The experiment of Pound and Rebka (1959) and Pound and Snider (1965) on the gravitational redshift of photons rising 22.5 meters against gravity through a helium-filled tube in a shaft in the Jefferson Physical Laboratory of Harvard University. The source of Co^{57} had an initial strength greater than a curie. The 14.4 keV gamma rays had to pass in through an absorber enriched in Fe^{57} to reach the large-window proportional counters. Both source and absorber were placed in temperature-regulated ovens. The velocity of the source consisted of two parts: one steady (v_M), to put the center of the emission line on the part of the transmission curve that is nearly straight; and the other alternating between $+v_s$ and $-v_s$, to sweep the transmission curve in this straight region; similarly when the steady velocity was $-v_M$. The departure from symmetry between the two cases $+v_M$ and $-v_M$ allows one to determine the offset v_D (effect of gravitational redshift) from the zero-gravity case of stationary emitter and stationary absorber. The final result for the redshift was (0.9990 ± 0.0076) times the value 4.905×10^{-15} of $2gh/c^2$ predicted from the principle of equivalence (difference between "up" experiment and "down" experiment). Diagrams adapted from Pound and Snider (1965).

The binary pulsar

- Hulse-Taylor (1974, Nobel 1993)
- B1913+16





Radio Telescope

Arecibo Radio Telescope (Puerto Rico)

An Australian radio-telescope array

Present

Strong gravity

- Black holes
- Gravitational waves
- Cosmology (CMB, ...)

Black hole candidates

A. Stellar Astro-ph/0612312

Obs… ss

4 J. Casares

Table 1. Confirmed black holes and mass determinations

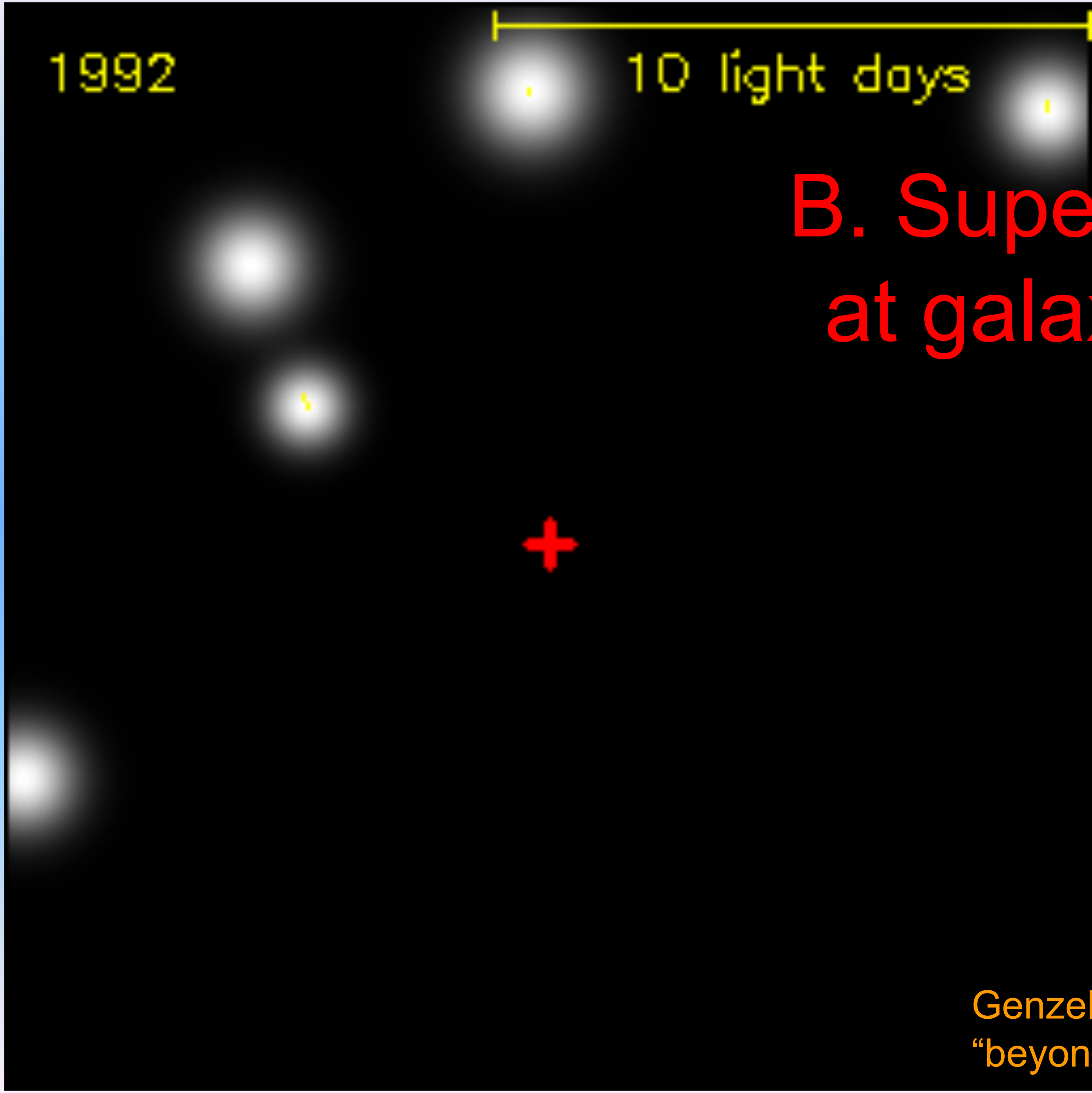
System	P_{orb} [days]	$f(M)$ [$M_{\odot}$]	Donor Spect. Type	Classification	M_x † [$M_{\odot}$]
GRS 1915+105[a]	33.5	9.5 ± 3.0	K/M III	LMXB/Transient	14 ± 4
V404 Cyg	6.471	6.09 ± 0.04	K0 IV	,,	12 ± 2
Cyg X-1	5.600	0.244 ± 0.005	09.7 Iab	HMXB/Persistent	10 ± 3
LMC X-1	4.229	0.14 ± 0.05	07 III	,,	> 4
XTE J1819-254	2.816	3.13 ± 0.13	B9 III	IMXB/Transient	7.1 ± 0.3
GRO J1655-40	2.620	2.73 ± 0.09	F3/5 IV	,,	6.3 ± 0.3
BW Cir[b]	2.545	5.74 ± 0.29	G5 IV	LMXB/Transient	> 7.8
GX 339-4	1.754	5.8 ± 0.5	–	,,	
LMC X-3	1.704	2.3 ± 0.3	B3 V	HMXB/Persistent	7.6 ± 1.3
XTE J1550-564	1.542	6.86 ± 0.71	G8/K8 IV	LMXB/Transient	9.6 ± 1.2
4U 1543-475	1.125	0.25 ± 0.01	A2 V	IMXB/Transient	9.4 ± 1.0
H1705-250	0.520	4.86 ± 0.13	K3/7 V	LMXB/Transient	6 ± 2
GS 1124-684	0.433	3.01 ± 0.15	K3/5 V	,,	7.0 ± 0.6
XTE J1859+226[c]	0.382	7.4 ± 1.1	–	,,	
GS2000+250	0.345	5.01 ± 0.12	K3/7 V	,,	7.5 ± 0.3
A0620-003	0.325	2.72 ± 0.06	K4 V	,,	11 ± 2
XTE J1650-500	0.321	2.73 ± 0.56	K4 V	,,	
GRS 1009-45	0.283	3.17 ± 0.12	K7/M0 V	,,	5.2 ± 0.6
GRO J0422+32	0.212	1.19 ± 0.02	M2 V	,,	4 ± 1
XTE J1118+480	0.171	6.3 ± 0.2	K5/M0 V	,,	6.8 ± 0.4

† Masses compiled by Orosz (2003) and Charles & Coe (2006).
[a] New photometric period of 30.8±0.2 days recently reported by Neil, Bailyn & Cobb (2006). The implied mass function, assuming constant velocity amplitude, would be 8.7 $M_{\odot}$.
[b] Updated after Casares et al (2007).
[c] Period is uncertain, with another possibility at 0.319 days (see Zurita et al 2002). This would drop the mass function to 6.18 $M_{\odot}$.

[1] I…

Abstract. R… existence of … masses in exc… gives us a hin… history of bla… …ice for the dynamical …ems which …narizes the

$$f(M_x) = K^3 P_{orb}/2\pi G = M_x^3 \sin^3 i/(M_x + M_c)^2$$



B. Super-massive at galaxy center

$M \cong 4.4 \cdot 10^6 \, M_{sun}$

$R \cong 8 \, Kpc \cong 25 \, K \, lyr$

$R_s \cong 0.1 AU \cong 9.3 \, \mu as$

Instrinsic diameter

@1.3mm waves

$35 \, \mu as$

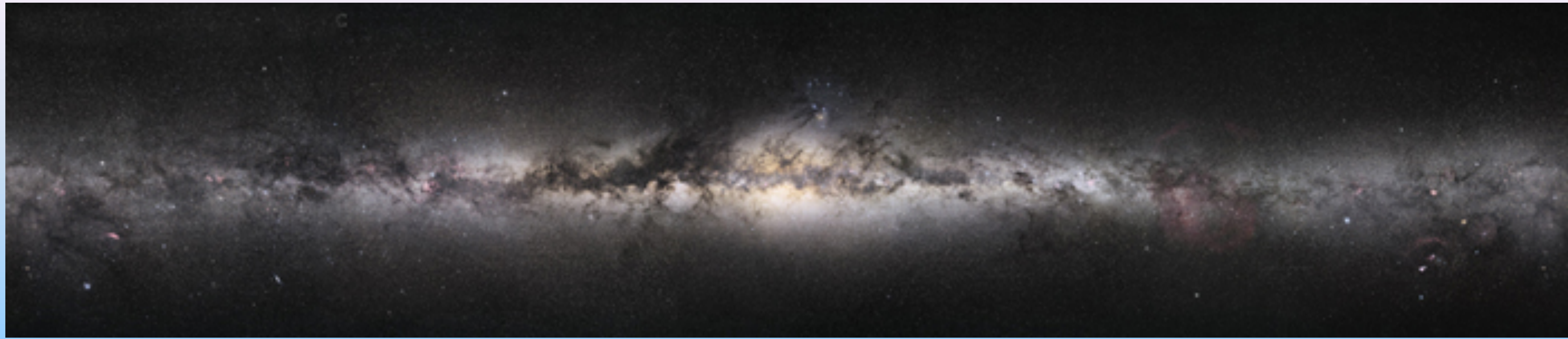
Doeleman et al (2008)

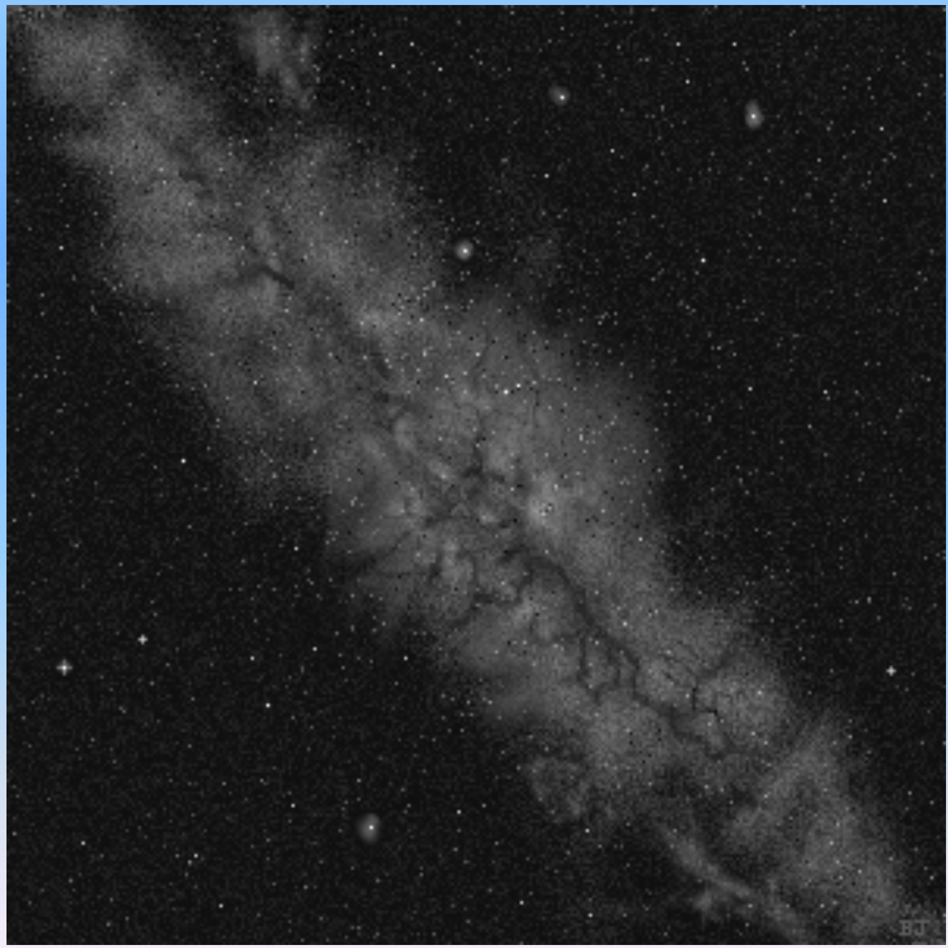
Genzel MPI Garching (2010)
“beyond reasonable doubt”

The zodiac

Sagittarius A*

The sun's location relative to the stars and as see from earth changes over the year

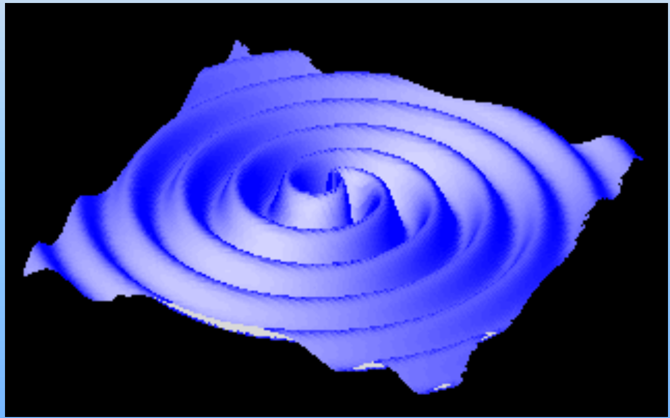


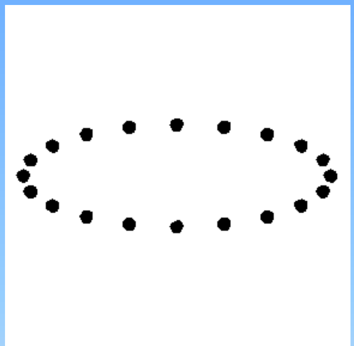


The milky way galaxy

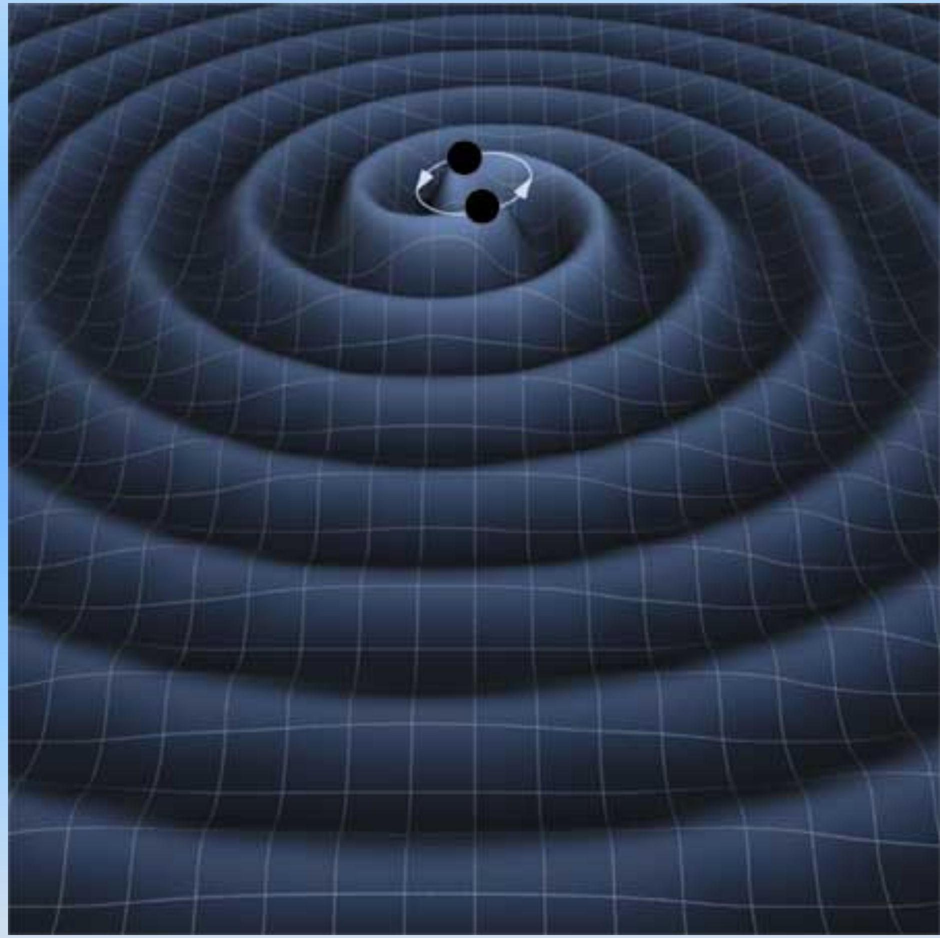
Name's origin

Gravitational waves



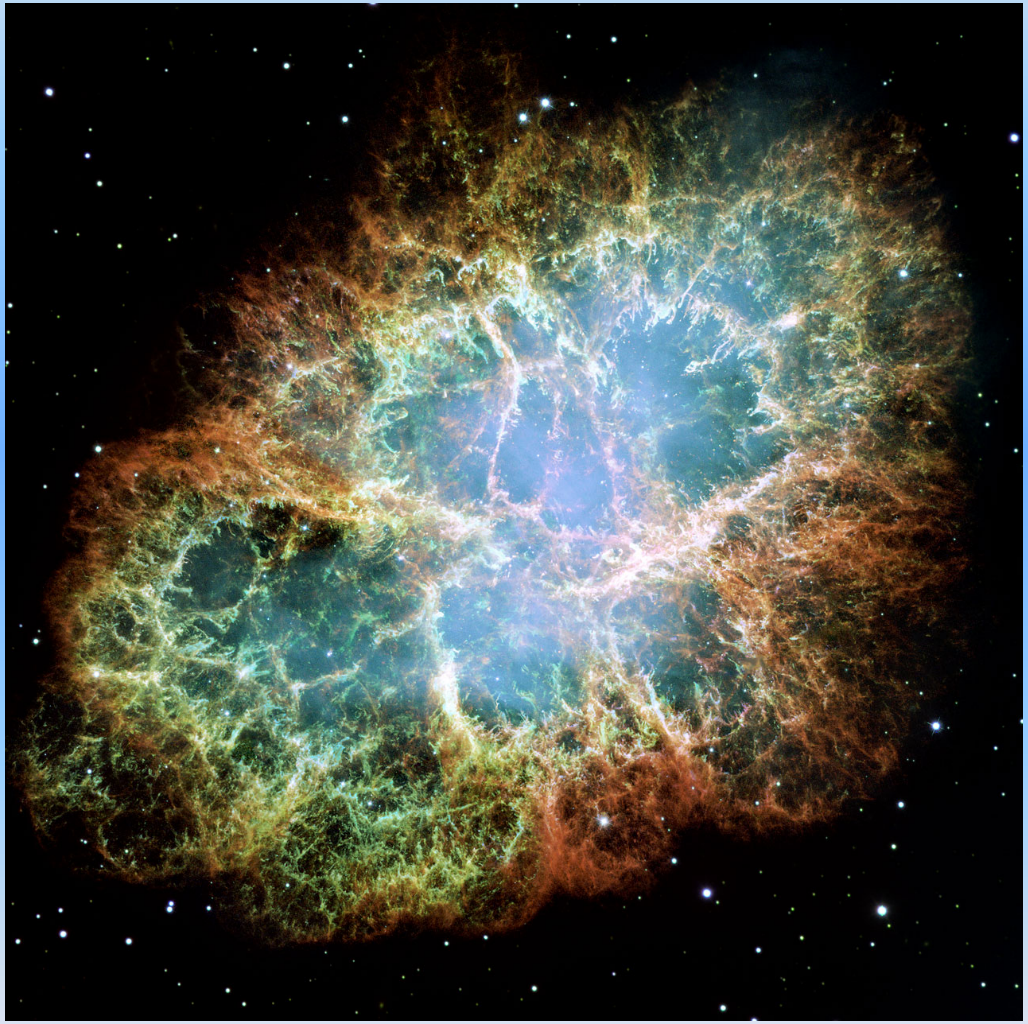


- Sources
- Detectors



Binary source

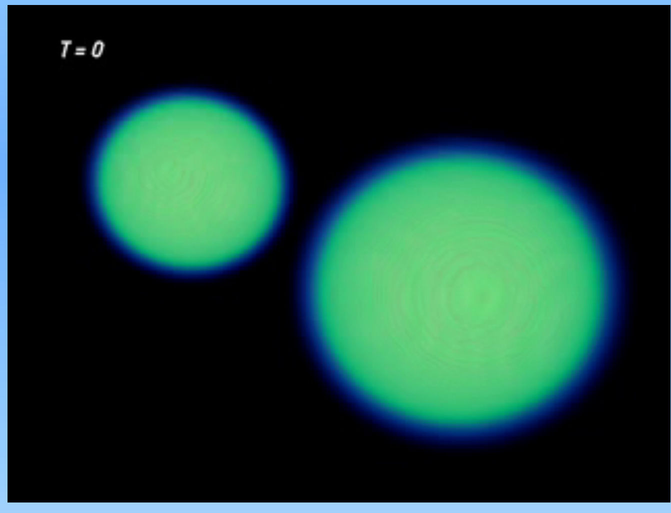
Collapse



Crab nabula –

Was created by a supernova

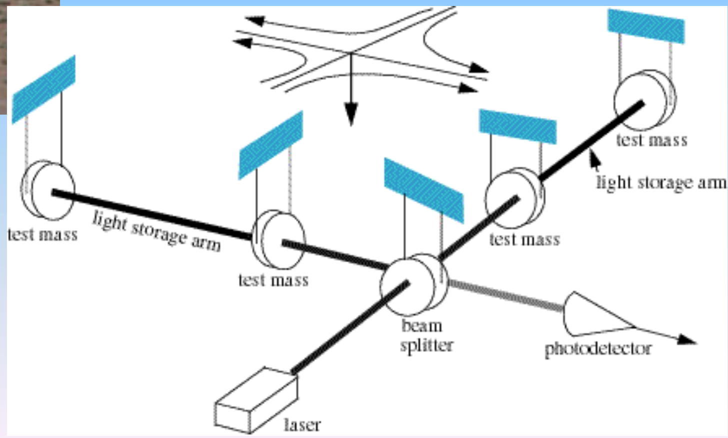
Merger of Neutron stars – computerized simulation (AEI Potsdam)



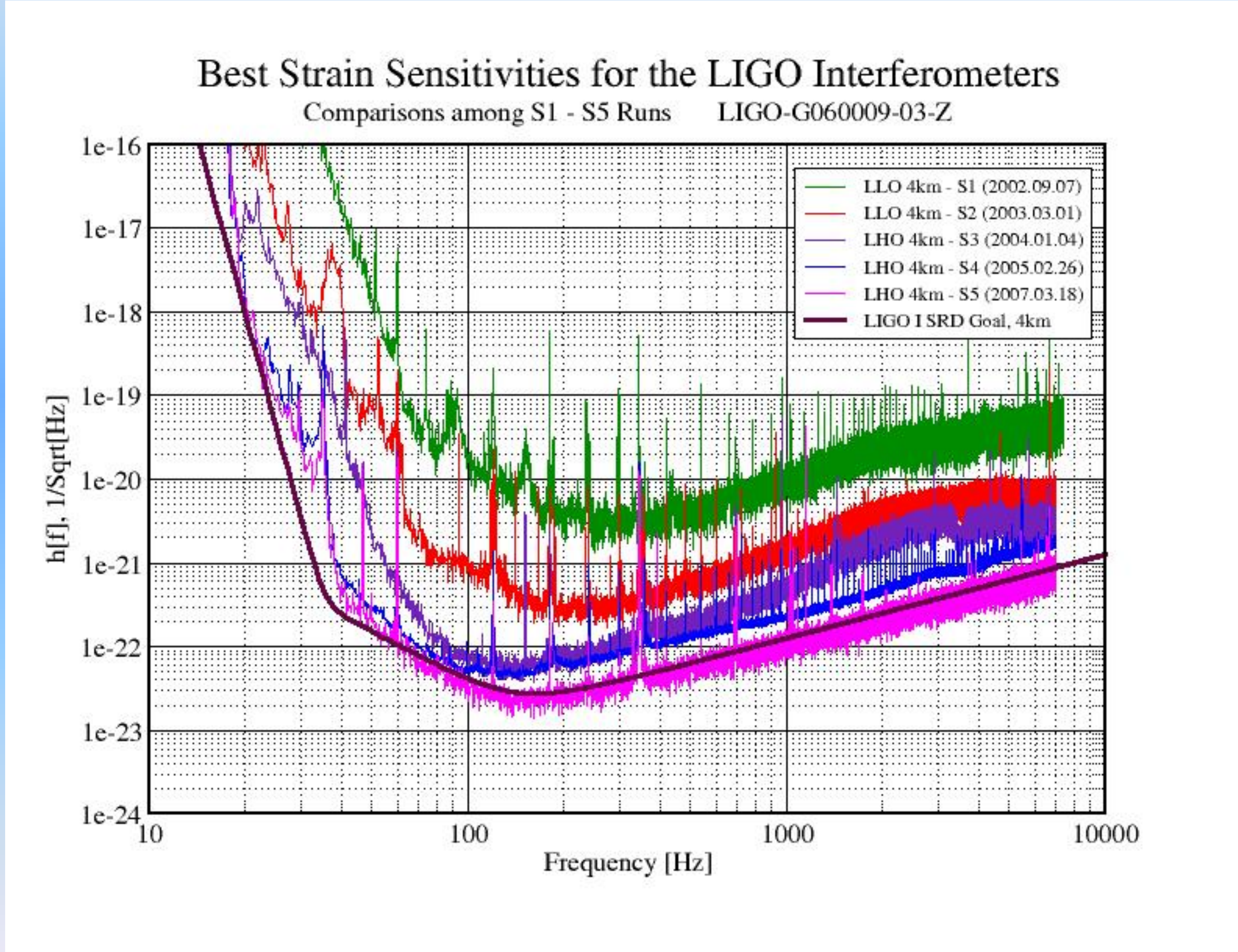
Initial conditions: nearby and at rest (unrealistic)

InterFerometer Observatories (IFOs)

LIGO (Washington, USA)



Sensitivity



VIRGO (Italy)

GEO600

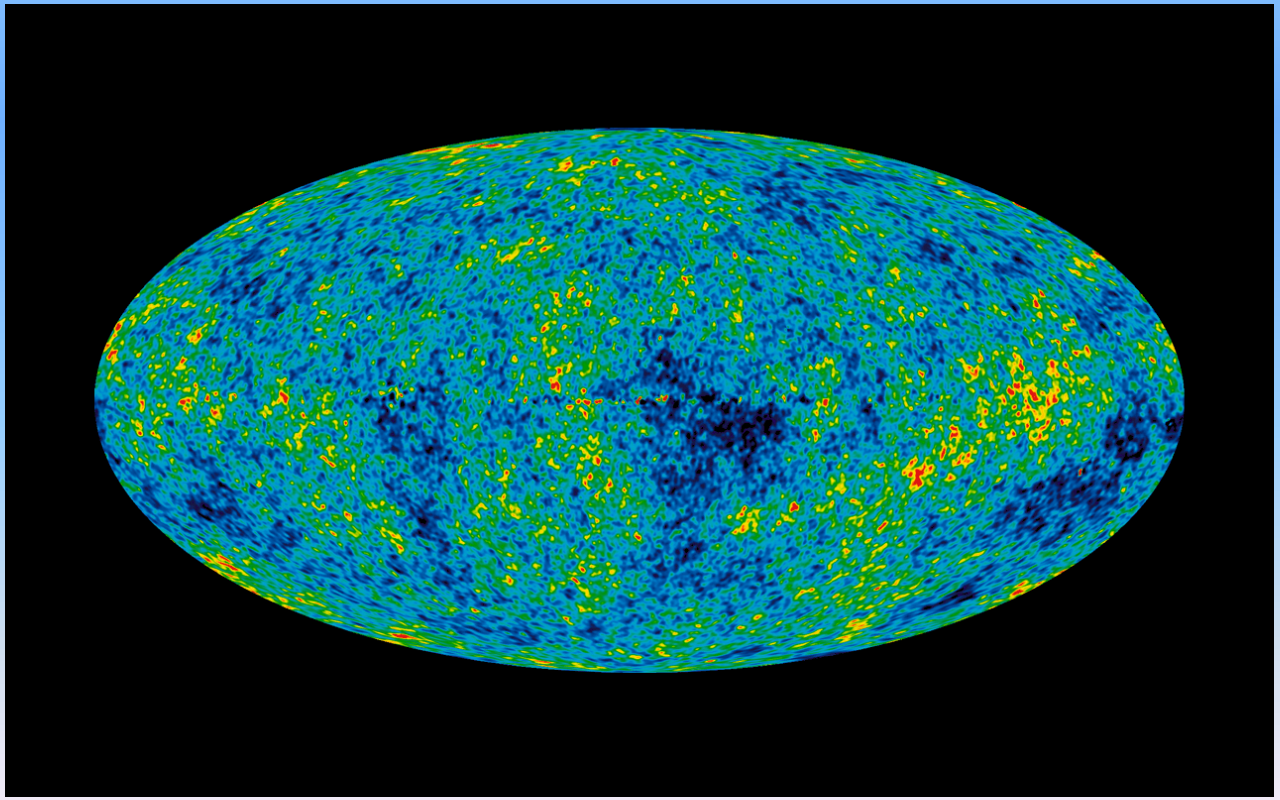
German-British collab
near Hanover

Bird's eye view

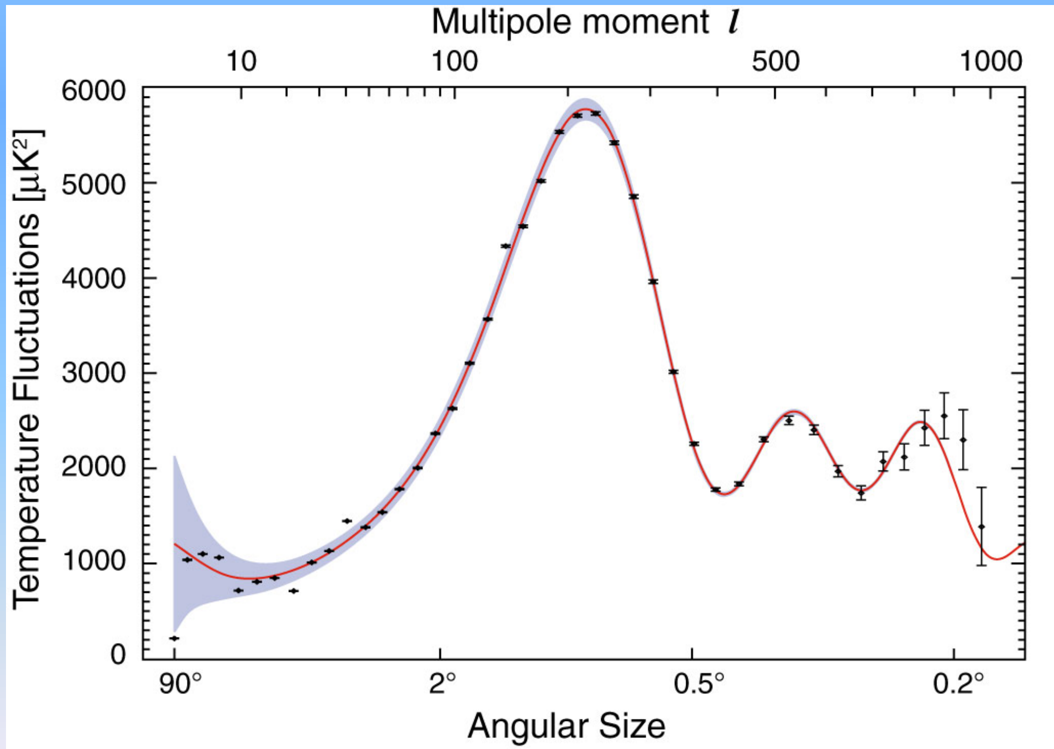
The trench

Cosmology

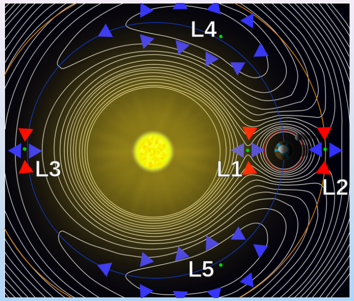
- Cosmic Microwave Background (CMB)
- WMAP (launched 2001, 7 year data)



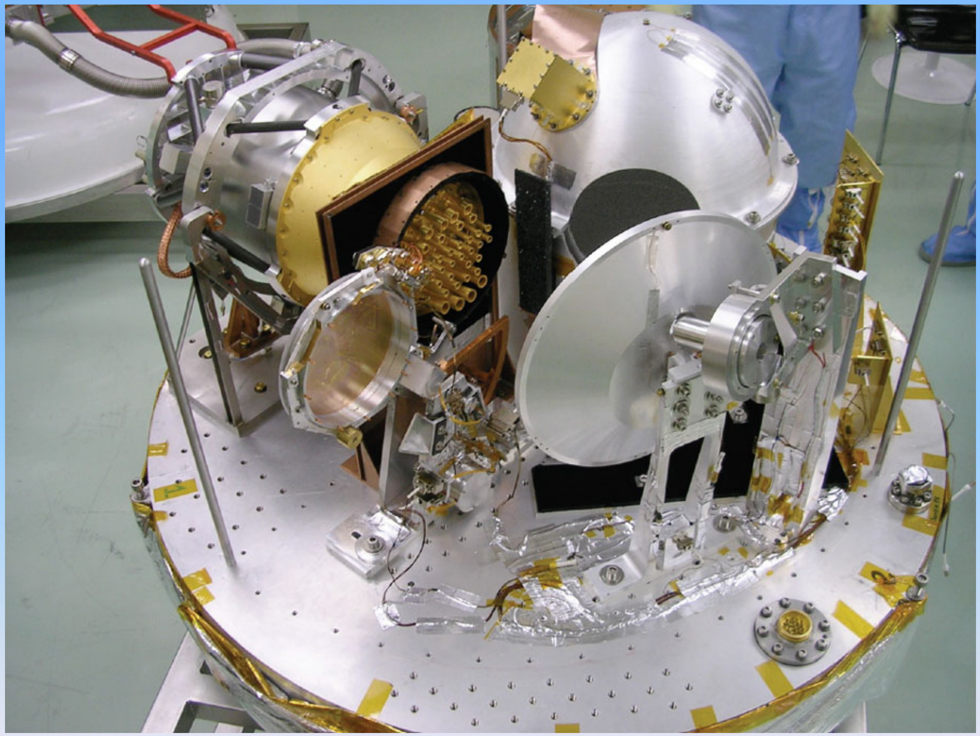
- Hubble const 70.5 km/s/Mpc, age 13.75 Gyr
- Matter content: 72% dark energy, 23% cold dark matter, 5% baryonic matter.

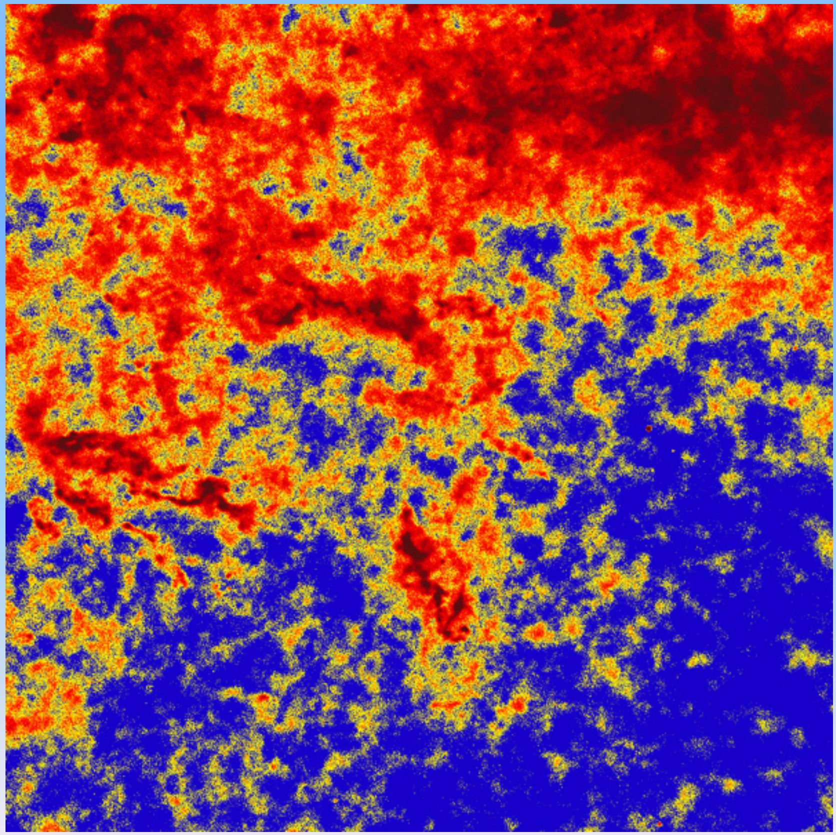


Planck

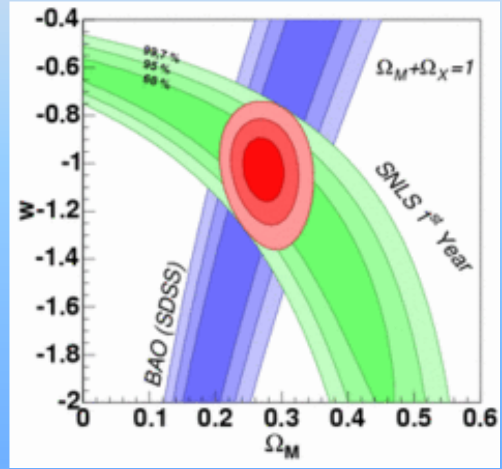


- Launched may 09 to L2 Lagrangian point.
- Prelim data Feb 10, Dec 10, final end 2012.





Supernovae survey



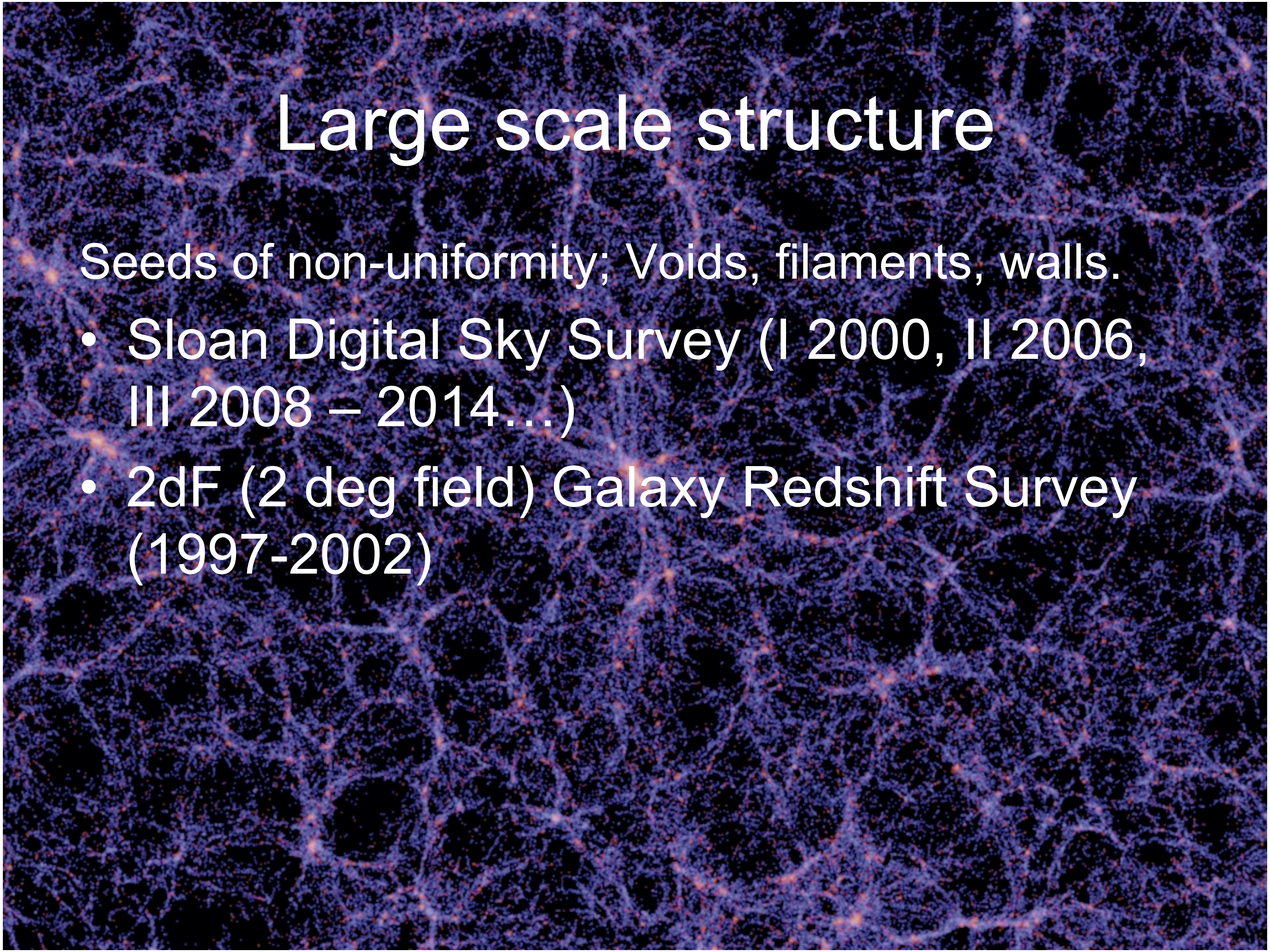
Distant supernovae are dimmer than expected – constrains cosmological parameters

- Supernova Cosmology project (Berkeley based , PI Perlmutter)
- SuperNova Legacy Project 2003-8

Large scale structure

Seeds of non-uniformity; Voids, filaments, walls.

- Sloan Digital Sky Survey (I 2000, II 2006, III 2008 – 2014….)
- 2dF (2 deg field) Galaxy Redshift Survey (1997-2002)



Short range Modifications of gravity

Hep-ph/0611184

Eöt-Wash

Fifth force

Extra dimensions

String theory motivated

Precision weak gravity

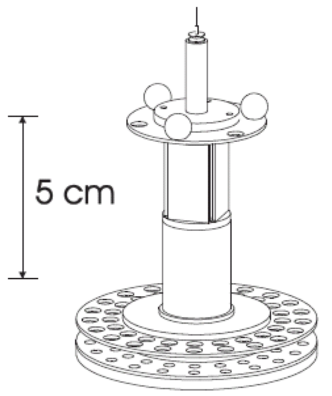


FIG. 1: Scale drawing of our detector and attractor. The 3 small spheres near the top of the detector were used for a continuous gravitational calibration of the torque scale. Four rectangular plane mirrors below the spheres are part of the twist-monitoring system. The detector's electrical shield is not shown.

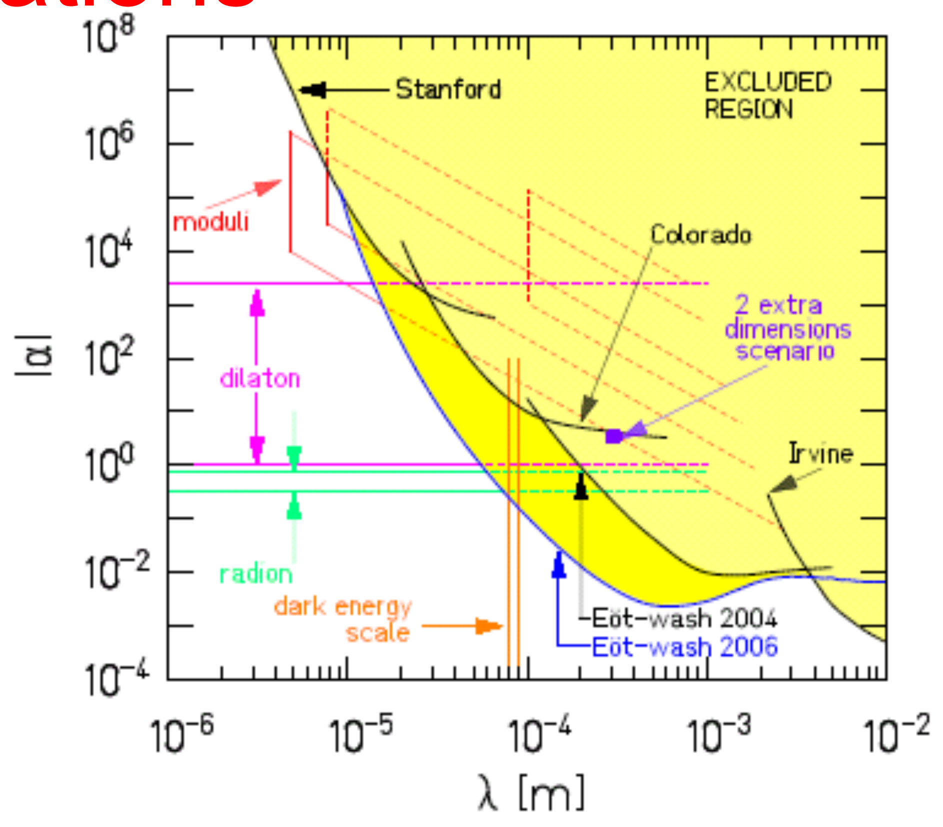


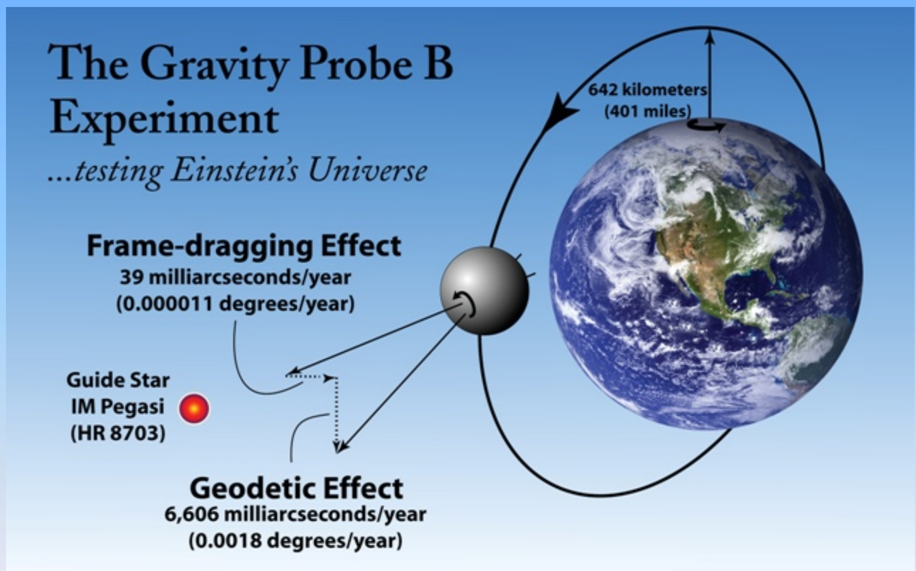
FIG. 6: [Color online] Constraints on Yukawa violations of the gravitational $1/r^2$ law. The shaded region is excluded at the 95% confidence level. Heavy lines labeled Eöt-Wash 2006, Eöt-Wash 2004, Irvine, Colorado and Stanford show experimental constraints from this work, Refs. [11], [14], [15] and [16, 17], respectively. Lighter lines show various theoretical expectations summarized in Ref. [9].

$$V(r) = -G\frac{m_1 m_2}{r}[1 + \alpha \exp(-r/\lambda)]$$

Spin

Gravity Probe B experiment

- Geodesic precession of spin
- Frame dragging effect (due to earth's rotation)

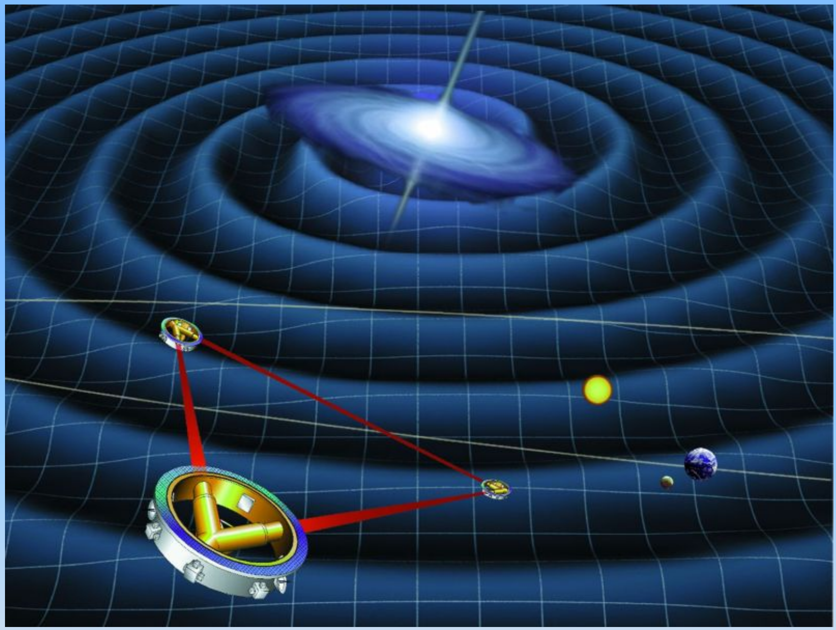


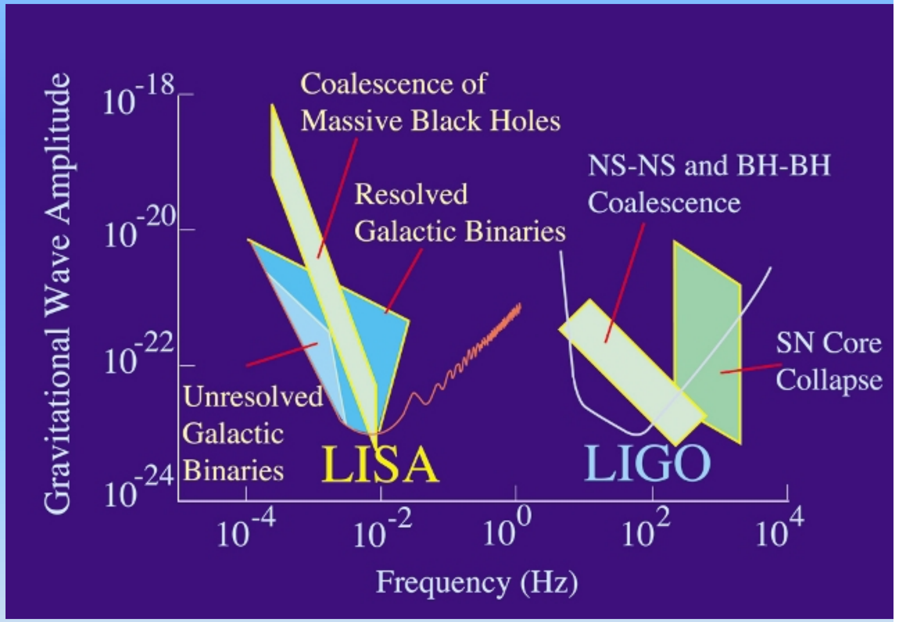
Future
NASA: Physics of the Cosmos (formerly Beyond Einstein)

- Joint Dark Energy Mission (JDEM)
- Laser Interferometer Space Antena (LISA)
- International X ray Observatory (IXO)
- Also post-included past missions: XMM-Newton,Chandra, Fermi, Planck

LISA

- Laser Interferometer Space Antenna





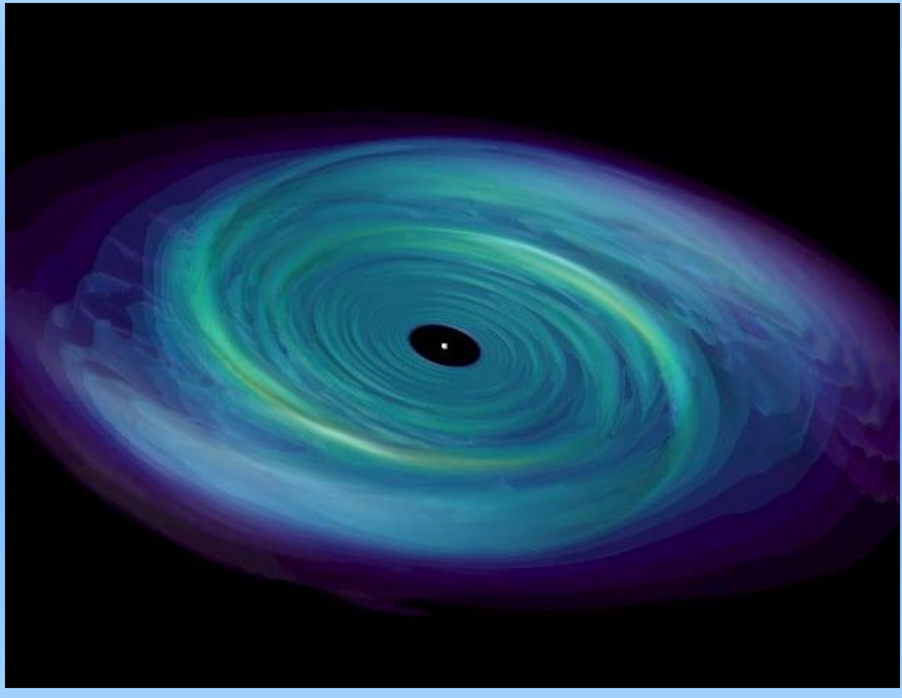
5 million km apart

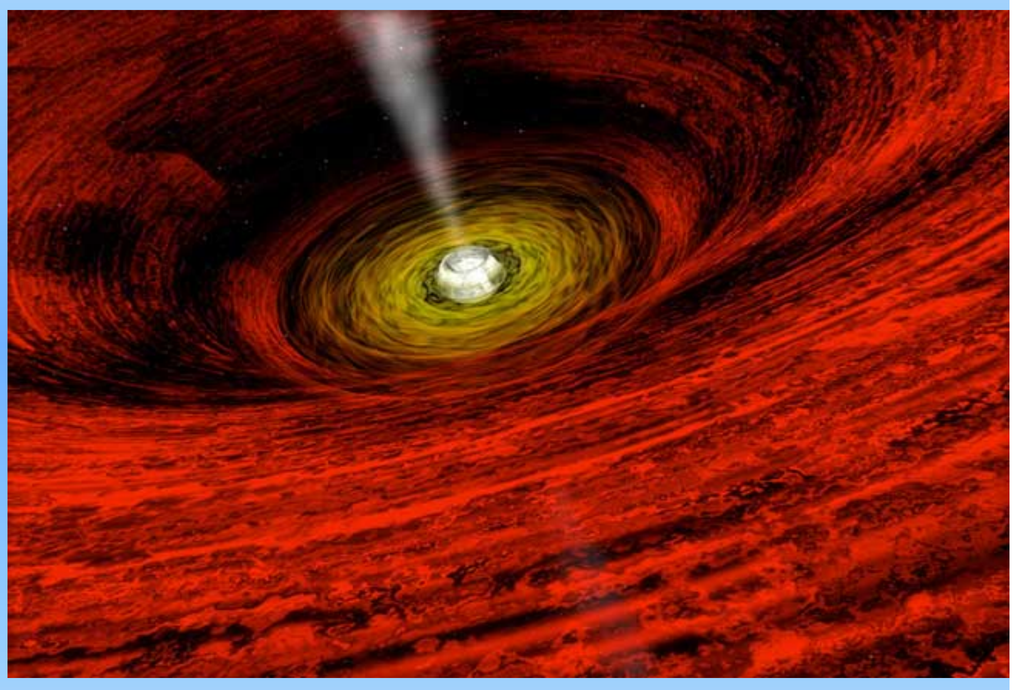
See also advanced LIGO (2014)

Near horizon

- X-ray from accretion disks
- Iron fluorescence from disks
- Quasi Periodic Oscillations (QPO)

Accretion disks



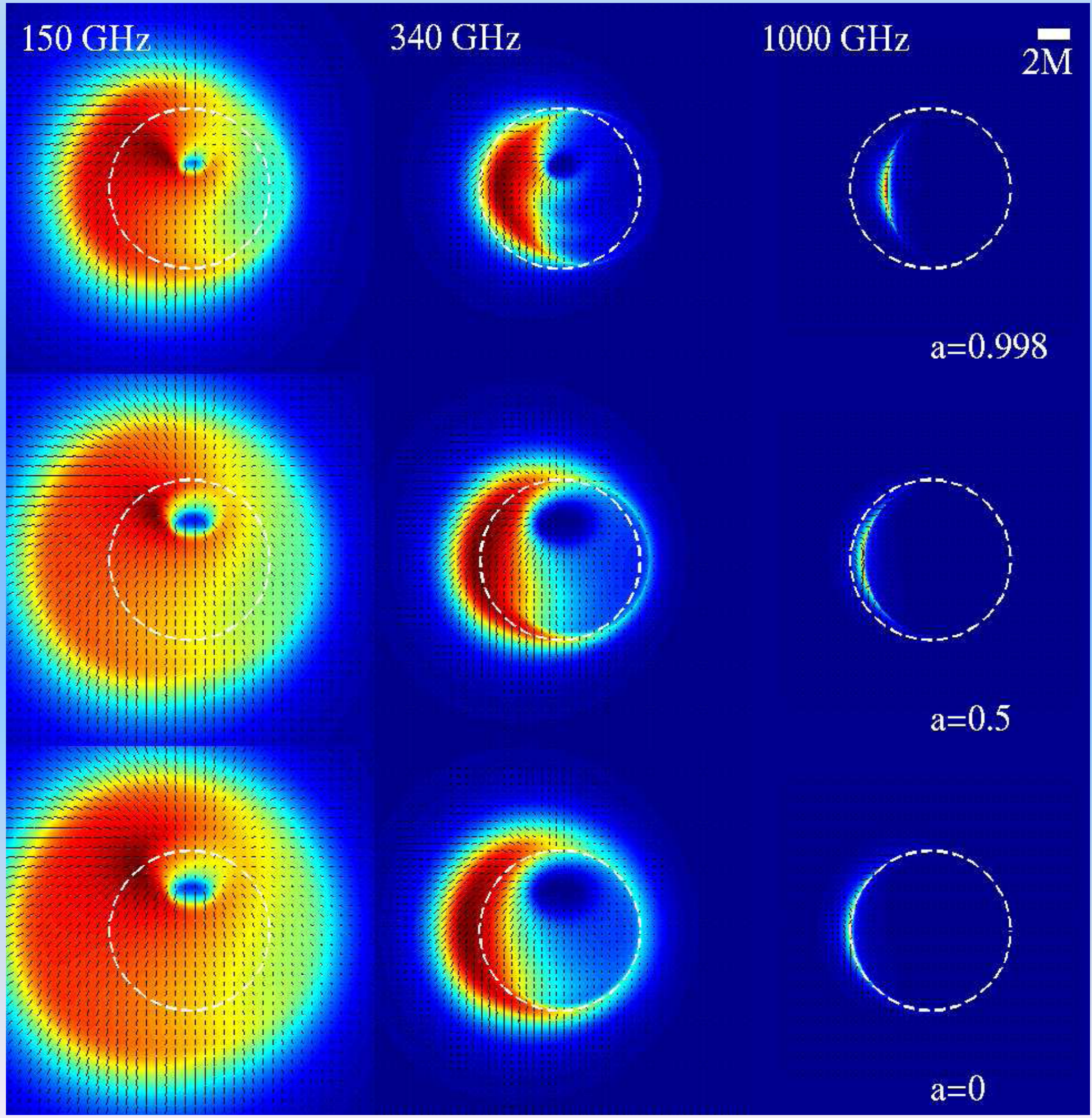


Shadow of horizon

Broderick & Loeb

arXiv:0508386.

System at 45º to line of sight.



Theoretical challenges

- Post-Newtonian approximation
- Effective Field theory approach
- Many of the deep concepts of Quantum Field Theory in a classical setting

EIH in CLEFT

Action

$$ds^2 = e^{2\phi}(dt - A_i\, dx^i)^2 - e^{-2\phi}\gamma_{ij}\, dx^i dx^j$$

$$S = -\frac{1}{16\pi G}\int dt\, dx^3 \sqrt{\gamma}\left[R[\gamma] + 2\,(\partial\phi)^2 - \frac{1}{4}e^{4\phi}F^2\right]$$

$$S \supset \frac{1}{16\pi G}\int dt\, dx^3\, 2\dot{\phi}^2$$

$$S_{pp} \equiv -m_0 \int d\tau = -m_0 \int dt\, e^{\phi}\sqrt{(1 - \vec{A}\cdot\vec{v})^2 - e^{-4\phi}\gamma_{ij}\, v^i v^j} =$$

$$= -m_0 \int dt\left(1 - \frac{1}{2}v^2 + \phi - \vec{A}\cdot\vec{v} + \frac{3}{2}\phi\, v^2 + \ldots\right)$$

- Feynman rules

φ $\delta(t)\, G/r$

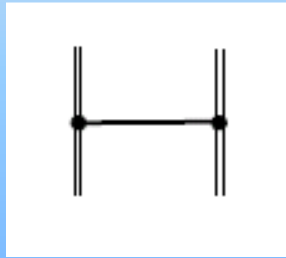
A_i $-4\,\delta(t)\,\delta_{ij}G/r$

$\frac{G\,r}{2}\delta''(t)$

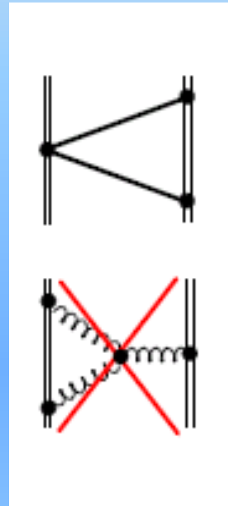
$-m$

$m\vec{v}$

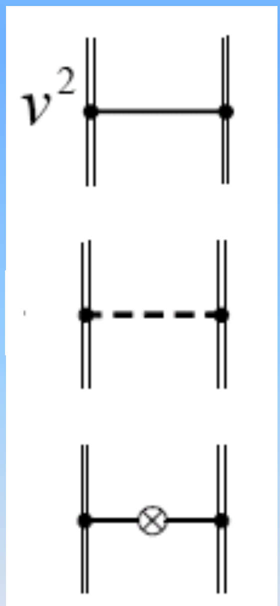
Feynman diagrams



$$(-m_1)(-m_2)\frac{G}{r}$$



$$\frac{1}{2}(-m_1)(-m_2)^2\left(\frac{G}{r}\right)^2$$



$$\frac{G\,m_1\,m_2}{r}\cdot\tfrac{3}{2}\,v_1{}^2$$

$$(m_1\vec{v}_1)\bullet(m_2\vec{v}_2)\left(-\frac{4G}{r}\right)$$

$$(-m_1)(-m_2)\left(\frac{G\,\vec{v}_{1\perp}\bullet\vec{v}_{2\perp}}{2r}\right),\quad \vec{v}_\perp := \vec{v}-\frac{\vec{r}_{12}\left(\vec{v}\bullet\vec{r}_{12}\right)}{r_{12}{}^2}$$

PN2 in CLEFT:
Gilmore, Ross 0810

Summary

- We discussed past, present and future gravitational experiments
- Central topics: weak Post-Newtonian corrections, Black holes, gravitational waves, cosmology
- Theoretical and experimental challenges


Danke!
Questions?
© ורה עציון