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General Theory of Relativity & Gravitational Waves

GTR

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THE «SOUND» OF VACUUM







SPACE – TIME and GRAVITY

NEWTON

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Absolute Space & Time

ARISTOTLE & DESCARTES

There is no space in the absence of matter

Ernst Mach -> Einstein

SPACE is defined as the distance between bodies

TIME as the interval between events



$$F_1 = F_2 = G \frac{m_1 \times m_2}{r^2}$$

 $\nabla^2 U \approx \rho$

SPACE – TIME and GRAVITY



There is NO ABSOLUTE SPACE & TIME

The measurements

SPATIAL DISTANCES

and of

TIME INTERVALS

Are velocity dependent!

The measurements

SPATIAL DISTANCES

and of

TIME INTERVALS

Depend on the **PRESENCE of MATTER!**

SPECIAL THEORY 1905

GENERAL THEORY 1915

GENERAL THEORY OF RELATIVITY

matter tells spacetime how to curve

... and space tells matter how to move!



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



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There is no need of the notion of "gravitational force" Gravitational field can be expressed via the spacetime curvature.



HOW TO TEST IT?





GTR - RESOLVED

RESOLVED: PERIHELION SHIFT OF PLANETS

MERCURY: 43.1" - 42.98"/CENTURY
 VENUS: 8.65" - 8.62" /CENTURY
 EARTH: 3.85" - 3.84"/CENTURY
 PSR 1913+16 : 4.2°/YEAR

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GTR - PREDICTED

BENDING OF LIGHT





 $\delta \varphi \sim \frac{4 \mathrm{GM}}{c^2 r}$

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1919 : THE TRIUMPH



When a student asked Einstein:

what he would have done had the eclipse measurements not confirmed his theory

He replied:

"In that case, I would have to feel sorry for God, because the theory is correct."

ASTROPHYSICS : GRAVITATIONAL LENSING







TIME & GRAVITY

GRAVITATIONAL REDSHIFT

$$\Delta t \sim \frac{G}{c^2} \frac{M}{r}$$

Pound–Rebka Experiments 1959-65

Basic instrument for measuring the strength of the gravitational field of astronomical objects



GPS & RELATIVITY

- Satellite Orbit: 20.000 km
- Velocity: 14.000 km/h

-7 μsec/day due to STR
+45 μsec/day due to GTR
+38 μsec/day due in total



Error in position : 10 km/day

1970+ & Shapiro delay

200 microseconds = 0.0002 seconds





Shapiro delay: ASTROPHYSICS





2010 – The 1st Neutron Star with 2M_☉

GTR Prevails !!





gremlin, goblin (creature which according to Greek folklore lives underground and comes up on Christmas Day to cause minor mischief, disappearing back into the earth on the feast of the Epiphany)



GTR

GTR Prevails !!

| Parameter | Bound | Effect | Experiment |
|-----------|------------------------------|------------------------------------|-----------------------------------|
| γ-1 | 2.3x10 ⁻⁵ | Time delay, Light deflection | Cassini tracking |
| β-1 | 1.1x10 ⁻⁴ | Nordtvedt effect, Perihelion shift | Nordtvedt effect |
| ζ | 0.001 | Earth tides | Gravimeter data |
| α1 | 10 ⁻⁴ | Orbit polarization | Lunar laser ranging |
| α2 | 4x10 ⁻⁷ | Spin precession | Sun axis' alignment with ecliptic |
| α3 | 2.2x10 ⁻²⁰ | Self-acceleration | Pulsar spin-down statistics |
| ζ1 | 0.02 | | Combined PPN bounds |
| ζ2 | 4x10 ⁻⁵ | Binary pulsar acceleration | PSR 1913+16 |
| ζ3 | 10 ⁻⁸ | Newton's 3rd law | Lunar acceleration |
| ζ4 | 0.006 | | Kreuzer experiment |



 $\sim 2(1+\gamma)rac{M}{b}$ $\gamma = rac{1+\omega}{2+\omega}$

1960-70 & the Golden Decade

- > 1957: Pirani-Bondi+... demonstrate that gravitational waves carry energy
- > 1960- : Black Holes- (Finkelstein, Kruskal, Wheeler,...)
- > 1963: 1st & only solution of Einstein equations describing rotating black holes (Roy Kerr)
- > 1960-70 : Post-Newtonian Approximations (Chandrasekhar)
- > 1963: <u>Peter & Mathews</u>: gravitational radiation from binary systems
- > **1965-...**: First Equations of State for Neutron Stars (not yet detected!)
- 1966-...: Kip Thorne and collaborators engaged in the systematic study of gravitational wave sources
- > **1967**: Detection of the 1st pulsar <u>Jocelyn Bell Burnell</u> & Antony Hewish
- > 1960+: <u>Zel'dovich</u> and collaborators «Relativistic Cosmology »

1973: BINARY PULSAR

Binary Pulsar: PSR 1913+16

INDIRECT PROOF OF GRAVITATIONAL RADIATION EMISSION



GRAVITATIONAL WAVES: The CONFIRMATION







LIFE CYCLE OF STARS



WHITE DWARFS

 $\frac{\mathrm{GM}}{c^2 R} = 0.0002$

 $\frac{\text{GM}}{c^2 R} = 0.2$

 $\frac{\text{GM}}{c^2 R} = 0.5$

COSMIC ABYSS... (BLACK HOLES)

«INFNITE» SPACETIME DEFORMATION



BLACK HOLES IN THE LAB



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SCIENCE FICTION



GALACTIC BLACK HOLES

MOST GALAXIES HOST A SUPER-MASSIVE BLACK HOLE IN THEIR CENTER

- IN THE `60 : SUSPISIONS
- IN THE `70 : INDICATIONS
- IN THE `80 : PROOFS



The BH in the CENTER of our GALAXY

MASS = 2.000.000M_☉

RANGE: 10⁶ – 6.6x10¹⁰ M_•



NEUTRON STARS

- They are the most compact stars known to exist in the universe.
- They have densities equal to that of the early universe and gravity similar to that of a black hole.
- Most extreme magnetic fields known in the universe up to 10¹⁶ G.

| Conjectured | 1931 | |
|--------------------------------|------------------------------------|--|
| Discovered | 1967 | |
| • Known | 2500+ | |
| • Mass | 1.2–2M _☉ | |
| • Radius | 8-14 km | |
| Density | 10 ¹⁵ g/cm ³ | |
| • Spin | < 716 Hz | |
| • In our Galaxy | ~10 ⁸ | |
| | | |



quark gluon plasma?

THE MANY FACES of NEUTRON STARS









