General Relativity: Beyond insight and elegance to observations and astronomy

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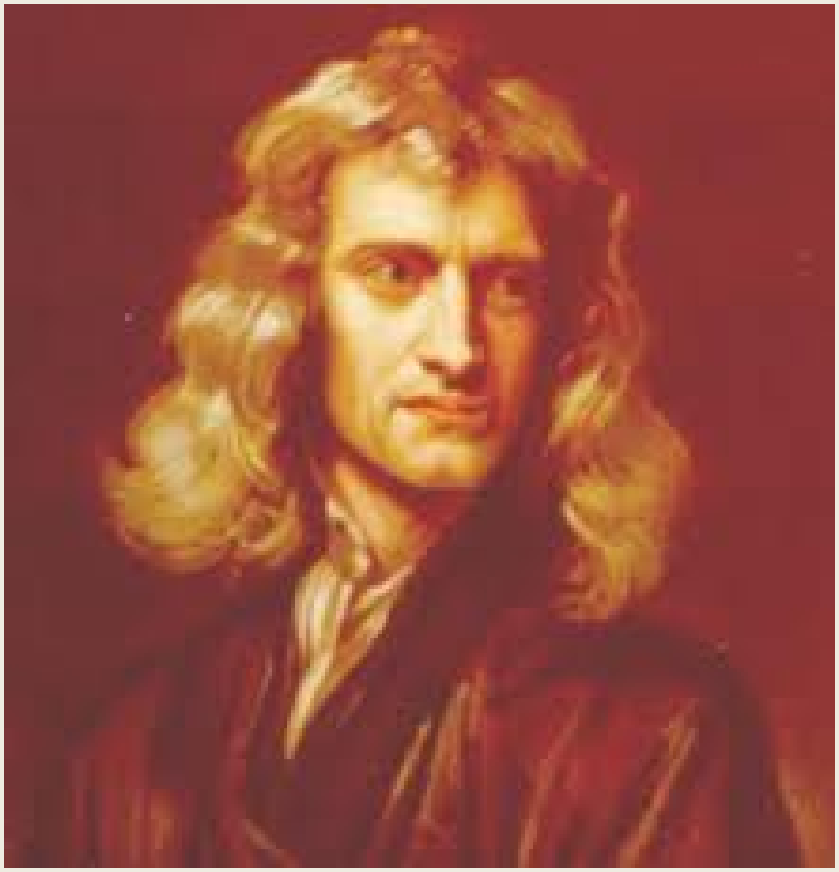
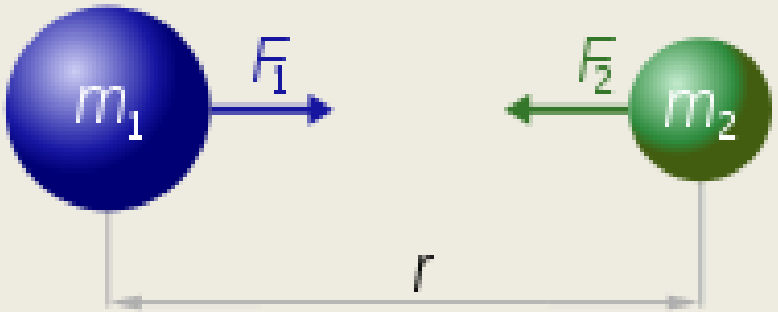
IndIGO
Indian **I**nitiative in **G**ravitational-wave **O**bservations

ICGC-2015, IISER, Mohali, Dec 2015

Newtonian Gravity (1687)



- Mass is source of gravity
- Inverse Square Law of Universal gravitation



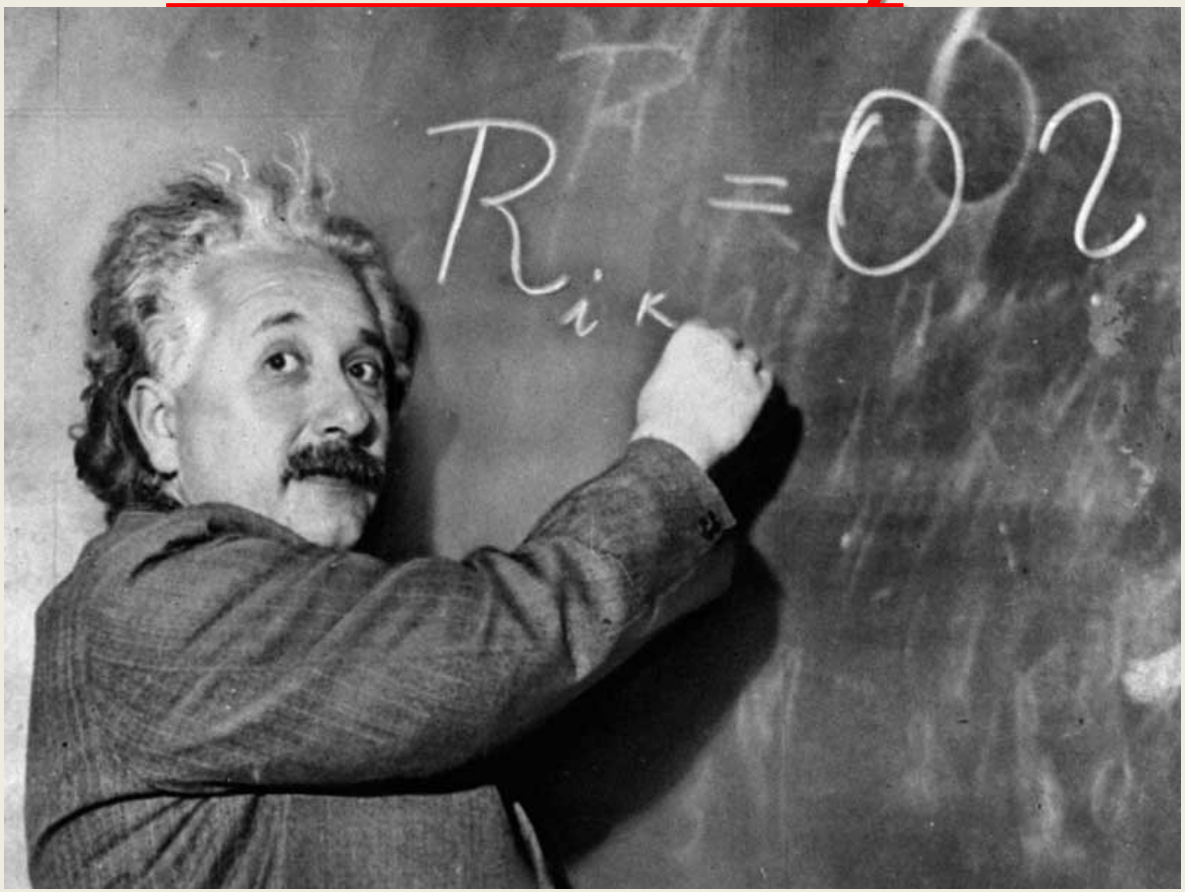
$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$

- Bodies on the Earth and Heavens follow the same LAWS
- Prediction, Discovery of the planet Neptune (Le Verrier)
- Instantaneous Action at a distance theory
- Gravitation propagates with infinite velocity

Special Relativity (1905)

- Maxwell's Eqns of Electromagnetism Consistent with Special Relativity.
- Electric and Magnetic fields are observer dependent decomposition of a **Combined** Electromagnetic Field and Space and Time of a **Combined** Spacetime
- No interaction can propagate faster than the Speed of light
- 1907 - Tension between the highly successful two century old Newtonian Gravity and his Newly discovered two year old Special Relativity

Einstein's Relativistic Gravity
General Relativity



Epitome of Mathematical elegance,
Conceptual depth, Observational success
25 Nov 2015: Centenary of General Relativity

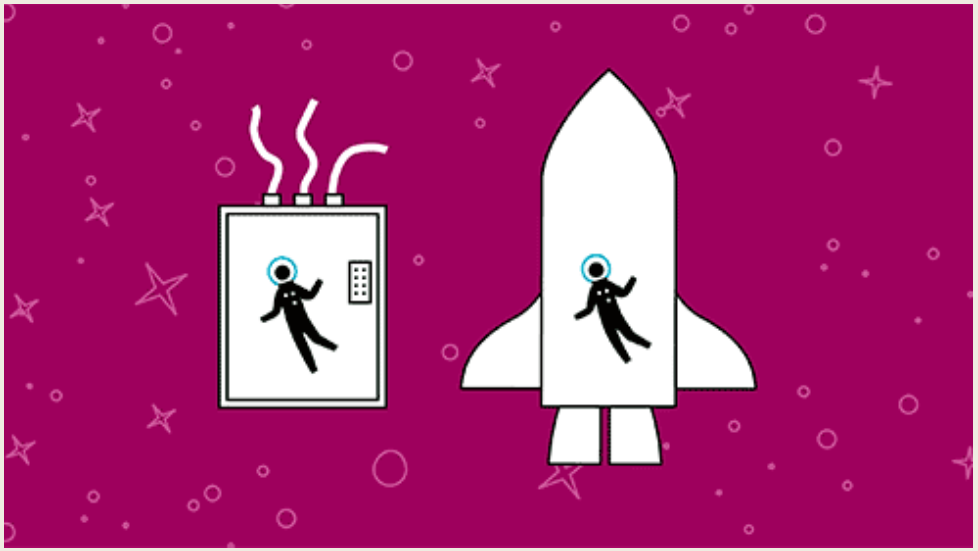
Plan

- The Discovery
  - Insight to Inspiration
- The Consolidation
  - Improved Understanding,
  - Conquering the Solar System
- The Renaissance
  - Birth of Relativistic Astrophysics
  - Towards Precision Cosmology
- The Future
  - Gravitational Waves: New window to the universe
  - Quantum Gravity: Ideas in search of an Experiment..

The Discovery

From Insight to Inspiration

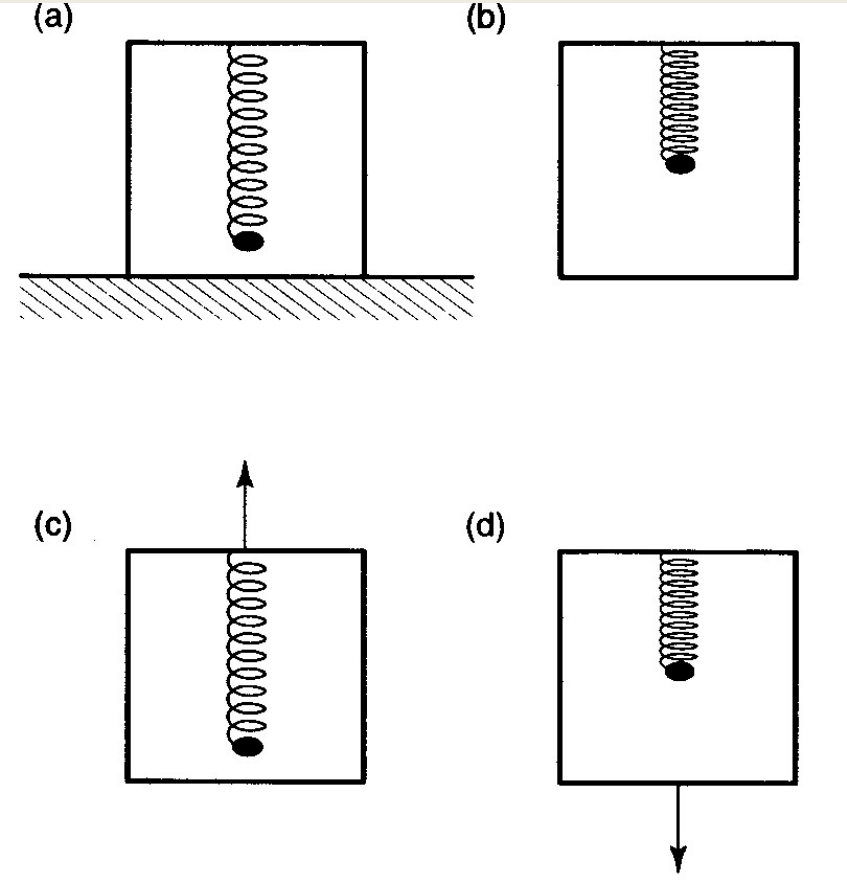
1907 Happiest Thought– Equivalence Principle



Credit: JONATHAN CORUM and JENNIFER DANIEL

Then occurred to me the happiest thought of my life in the following form. The gravitational field has only relative existence. Because for an observer falling freely from the roof of a house there exists at least in his immediate surroundings no gravitational field. If the observer drops some bodies these remain relative to him in a state of rest or uniform motion independent of their chemical or physical nature (ignoring air resistance). The observer has the right to interpret his state as at rest.

Einstein's Elevator



(b)~(d)

An uniform gravitational field can be eliminated locally by free fall.

(a)~(c)

An uniform gravitational field can be mimicked by acceleration.

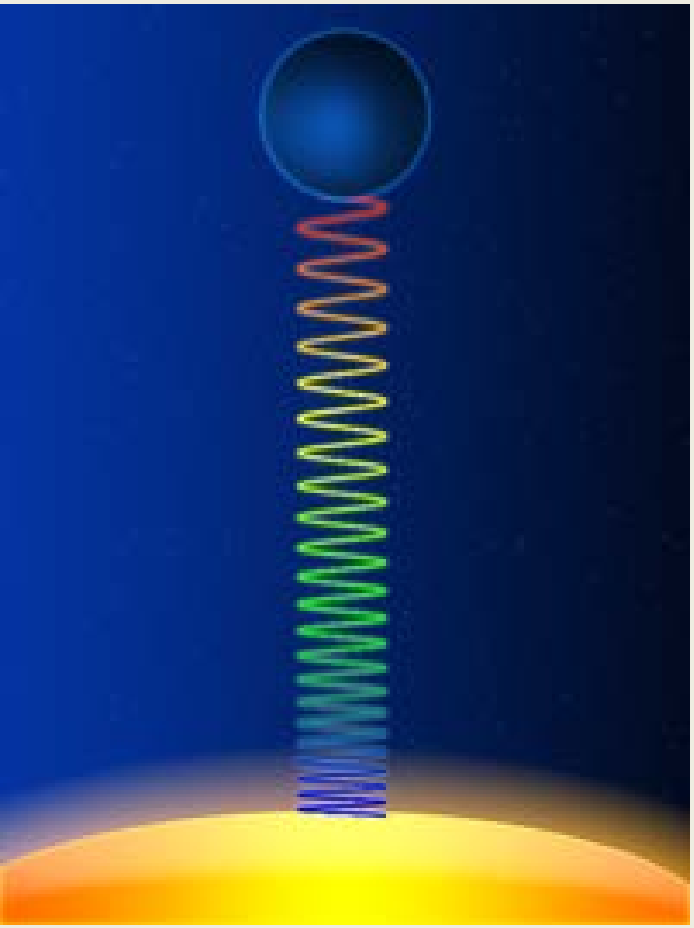
Einstein's unique Lodestone

- By a **mechanical** experiment one cannot distinguish an uniformly accelerated frame from an uniform gravitational field.
- Insight and conviction that Universality of the ratio of inertial mass to gravitational mass for all matter is remarkable and must have a critical role in the theory of gravitation rather than being a accidental coincidence..
- Today, One of the most accurately tested facts.

  Moon and earth fall towards sun with an accuracy 1.5×10^{-13}
- Einstein's Equivalence Principle is the idea that **no Experiment in physics** can distinguish it either.
- Experiments in a sufficiently small freely falling Lab over sufficiently small times give results indistinguishable from those of same Experiments in an inertial frame in empty space.

- Insights and Consequences from EP

Gravitational Redshift



Credit: jenszornsculpture.com

Time is warped in the presence of gravity

- Change in frequency or wavelength of light as it falls in a gravitational field

The gravitational redshift experiment. Let us first imagine performing an idealized experiment, first suggested by Einstein. (i) Let a tower of height h be constructed on the surface of Earth, as in Fig. 5.1. Begin with a

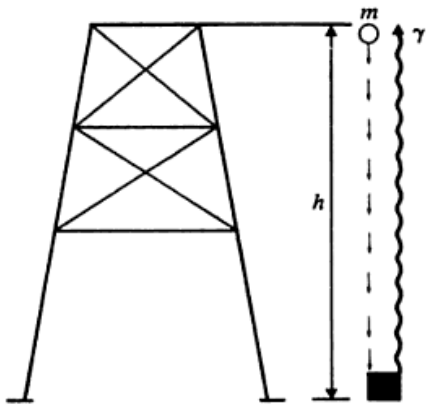


Fig. 5.1 A mass m is dropped from a tower of height h. The total mass at the bottom is converted into energy and returned to the top as a photon. Perpetual motion will be performed unless the photon loses as much energy in climbing as the mass gained in falling. Light is therefore redshifted as it climbs in a gravitational field.

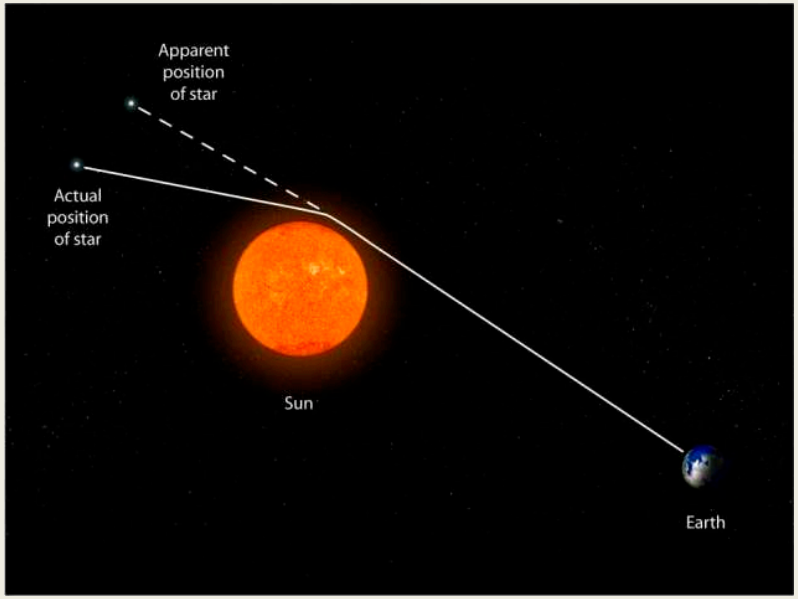
physics.stackexchange.com

- Earlier attempts at verification using observations in Sun and White dwarfs unsuccessful due to other uncertainties

Deflection of Light

- **Gravity affects light**
- An observer looking at a light ray in an accelerated frame of reference would see the path as curved. EP implies a gravitational field must curve path of light ray

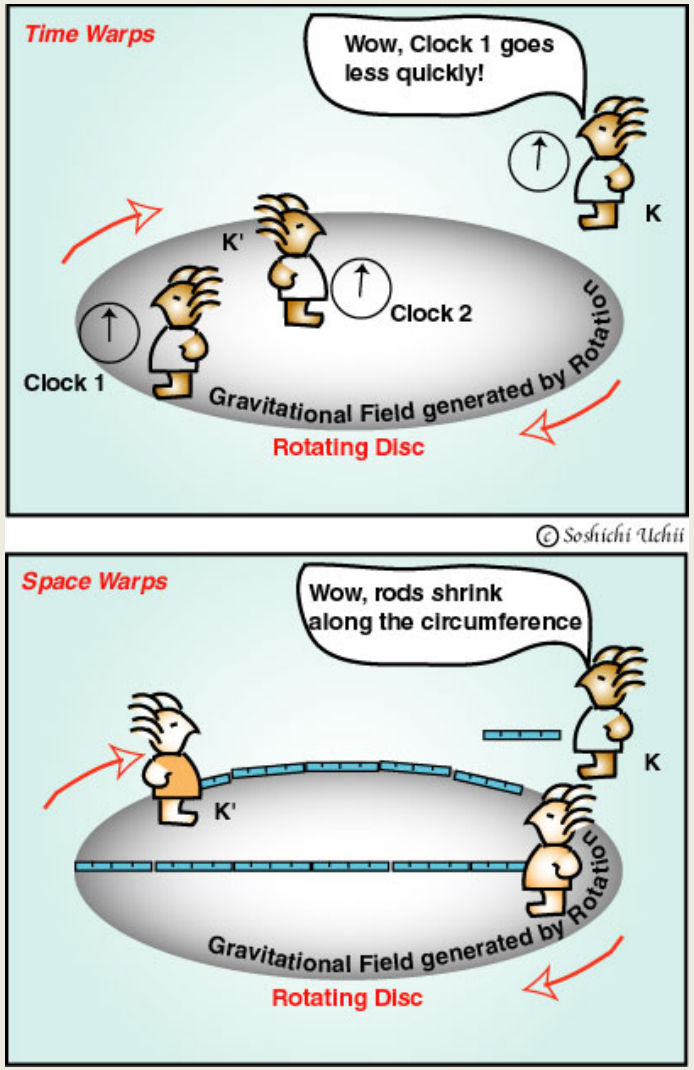
1911: Deflection of light by the Sun (0.875”) can be tested by Expt during solar eclipse by observing starlight passing close to Sun on way to earth.



Credit: www.sciencenews.org

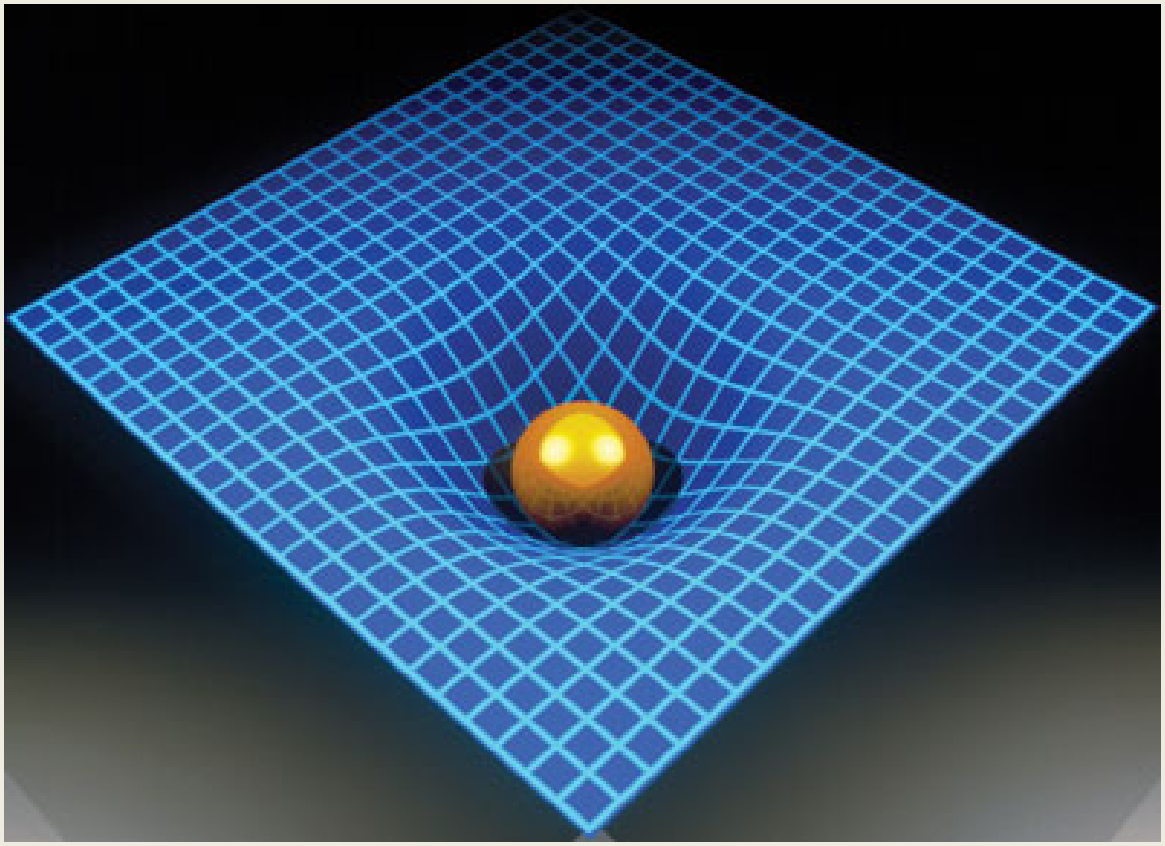
- 1914 Erwin Freundlich planned German Expt
- World War I aborted this..
- Fortunate since the predicted deflection was only half the story …
- 1803 Johann Soldner: Would gravity bend light?

Spacetime is Curved



- Application of EP to uniformly rotating frame of reference..

  A Rigidly rotating disk..
- Measuring rods at rest on such a rotating disk would show ratio of its circumference to diameter different from π due to Lorentz contraction along circumference but not radius
- A **non-Euclidean** geometry must hold in the disk frame of reference.
- By EP in presence of gravitational field measuring rods will map a **non-Euclidean** geometry.
- Equivalence Principle implies Spacetime is curved or distorted



credit: www.chicagonow.com

Einstein's view ~ Gravitation ~

~ Spacetime Geometry ~

Curvature or Distortion of Spacetime

1912

- Natural to Combine gravitational field and ST structure into one inertio-gravitational field so that the remarkable equality of inertial and gravitational mass inbuilt in GR
- Einstein's unique and most enduring legacy:

  Insight that Spacetime and Gravity be represented by the same structure
- Equivalence Principle implied Spacetime is curved
- Metric is non-euclidean physically determined by gravitation and hence by matter
- Gravitational field mathematically represented by the symmetric 2^{nd} rank tensor field determining the line element of 4 dimensional non-euclidean ST. Ten eqns instead of one in Newtonian gravity!!
- "Grossmann, you must help me or else I'll go crazy!!"

Based on Arch and Scaffold – Janssen and Renn

Marcel Grossman

Gauss, Riemann, Ricci, Levi-Civita

1913 -14 Einstein + Grossman

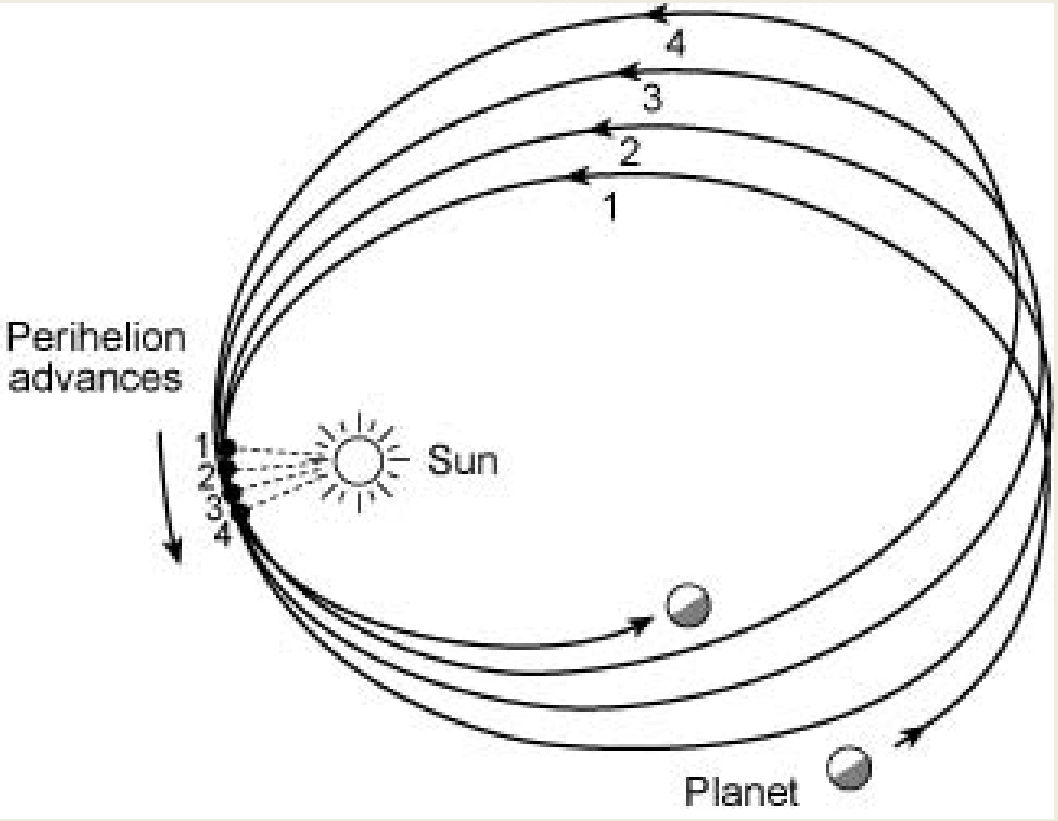
- 1913 - Relying on elaborate analogy between gravitational and EM fields produced Entwurf (draft or outline) field Eqns. To recover from 10 eqns, a single one in the Newtonian limit used for potential a simple expression resulting in covariance under limited transformations. He tried to justify it by his “hole” argument which also was later shown to be fallacious!
- 1914 - Derived Entwurf eqns from a variational principle. Easier to deal with Lagrangian than multi component FE.
- Lagrangian: EM like. Square of gravitational field which is gradient of metric (potential)
- Four conditions on metric and its derivatives ensure Energy Momentum conservation and class of transformations under which Lagrangian retains its form

Based on Arch and Scaffold – Janssen and Renn

Einstein + Michele Besso 1913

- Checked that rotating disk was solution of Entwurf eqns but there was a mistake in the calculation as he discovered in 1915!
- June 1913 - Besso and Einstein calculated precession of perhelion of Mercury in Entwurf theory…WHY???

Precession of Perhelion of Mercury



- Orbit of Mercury not a closed ellipse..
- Not a simple two body but Perturbed by other planets ..
- Le Verrier - 1843/59 Problem with motion of Mercury.
- Orbit not an ellipse fixed in space but precessing by 574” per century not auditable..

Precession of Perhelion of Mercury

- 574” per century accounted by..
- Venus: 277",
- Jupiter: 153",
- Earth: 90",
- Rest:10"
- Adding to 531" ;
- 43" MISSING..
- Maybe a new planet Vulcan beyond Mercury???
- Entwurf gave: Only 18” per century

Planck to Einstein - 1913

1913: Planck visits Einstein in Zurich

As an older friend, I must advice you against it, for, in the first place you will not succeed, and even if you succeed, no one will believe you

Early 1915

- 1915 Discovered to his horror rotation metric NOT solution of Entwurf theory
- Motivated to consider different Lagrangian keeping general formalism of 1914.
- Changed definition of gravitational field.. Redefinition of gravitational field in terms of Christoffel symbols was the key to the solution.

Based on Arch and Scaffold – Janssen and Renn

- By the fall of 1915, Albert Einstein was a bit grumpy.
- And why not? Cheered on, to his disgust, by most of his Berlin colleagues, Germany had started a ruinous world war. He was living alone… A friend, Janos Plesch, said,
  - "He sleeps until he is awakened; he stays awake until he is told to go to bed; he will go hungry until he is given something to eat; and then he eats until he is stopped."
- Worse, he had discovered a fatal flaw in his new theory of gravity, propounded with great fanfare only a couple of years before. And now he no longer had the field to himself. The German mathematician David Hilbert was breathing down his neck.

credit: Denis Overbye

- Einstein's Talk at Gottigen inspired Hilbert to work on this given the mathematics
- 4 Short Papers on 4 consecutive Thursdays

  (4, 11, 18, 25 Nov 1915)
- Used elaborate framework built around FE of Entwurf, theory as a **Scaffold** on which he placed fresh **Arch** stones of his 1915 FE

Nov 2015

- 4 Nov: Replaced Entwurf FE of 1913 with limited covariance with Eqns that retain their form under a broader class of coordinate transformations.
- 11 Nov: Obtained Eqns that were generally covariant by choosing restrictions on nature of matter
- 18 Nov: Based on above FE accounted for 43” per century perhelion precession of Mercury correctly!
- 25 Nov: Obtained generally covariant eqn by changing FE of 4 Nov. Energy Mom conservation provided independent argument for addition of trace term
- (Precession calculation was unaffected by this change)

Based on Arch and Scaffold – Janssen and Renn

Einstein's Eqns

credit: www.mrhalliday.com

Nov 28 1915 - Einstein to Sommerfeld

During the last month, I experienced one of the most exciting and most exacting times of my life, true enough also one of the most successful...

Now the marvellous thing which I experienced was the fact that not only did Newton's theory result as first approximation but also the perhelion of Mercury (43" per century) as second approximation.

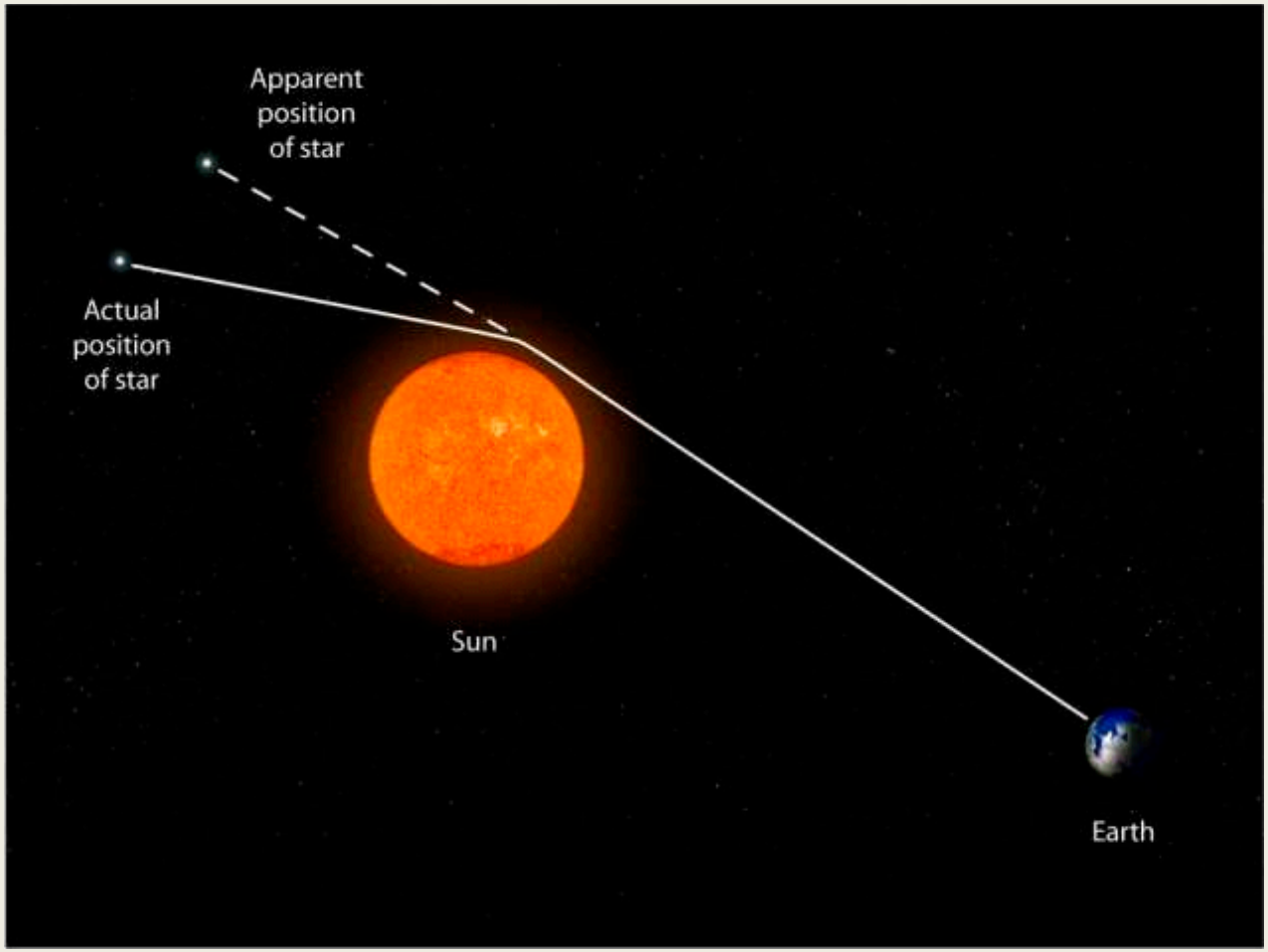
General Relativity, Einstein's Eqns

- GR is the current best description of gravitation which unifies special relativity and Newton's law of universal gravitation, and describes gravity as a geometric property of spacetime.
- The curvature or distortion of spacetime is directly related to the Energy-Momentum tensor of matter and radiation. The relation is specified by the Einstein field equations, a system of ten non-linear partial differential equations.
- Spacetime not just a passive background stage as in SR with fields as actors but ST also a part of the cast acting on matter and in turn being acted upon by it.
- MTW: Matter tells Spacetime how to curve;
  Spacetime tells matter how to move!

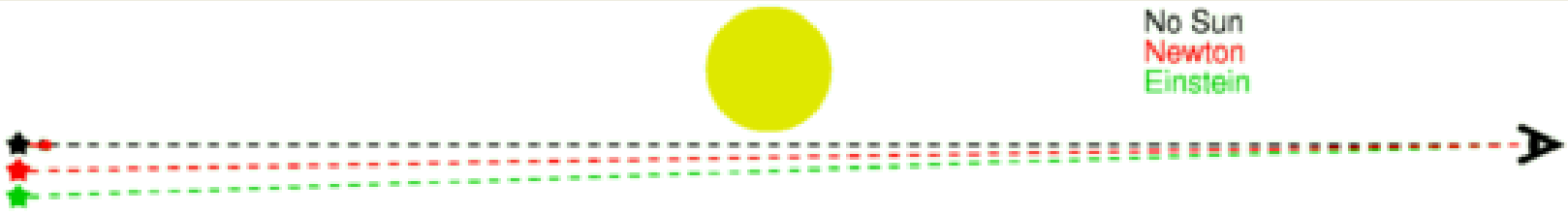
The Consolidation

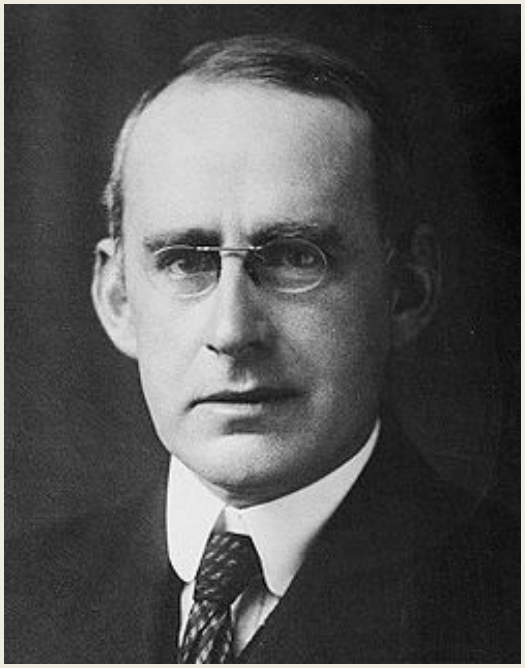
Conquering the Solar system
Improved Understanding
Interplanetary Space Programs

Deflection of Light



Credit: www.sciencenews.org





- 1915: GR Deflection:1.75”
- .875” (Newtonian, EP). Deflection relative to local straight lines
- .875”

(Space Curvature + nonlinearity in GR). Local straight lines bent relative to straight lines far away. Different in alternate theories.

- Confirmed in 1919 by British team under Eddington*

*A British government permitting a pacifist scientist to avoid wartime military duty so that he could go off and try to verify a theory produced by an enemy scientist.!!!! – Cliff Will

LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

No More in All the World Could

DON'T WORRY OVER NEW LIGHT THEORY

Physicists Agree That It Can Be Disregarded for Practical Purposes.

NEWTON'S LAW IS SAFE

At Most It Suffers Only Slight Correction, Says Prof. Bumstead of Yale University.

OTHER PROFESSORS' VIEWS

EINSTEIN EXPOUNDS HIS NEW THEORY

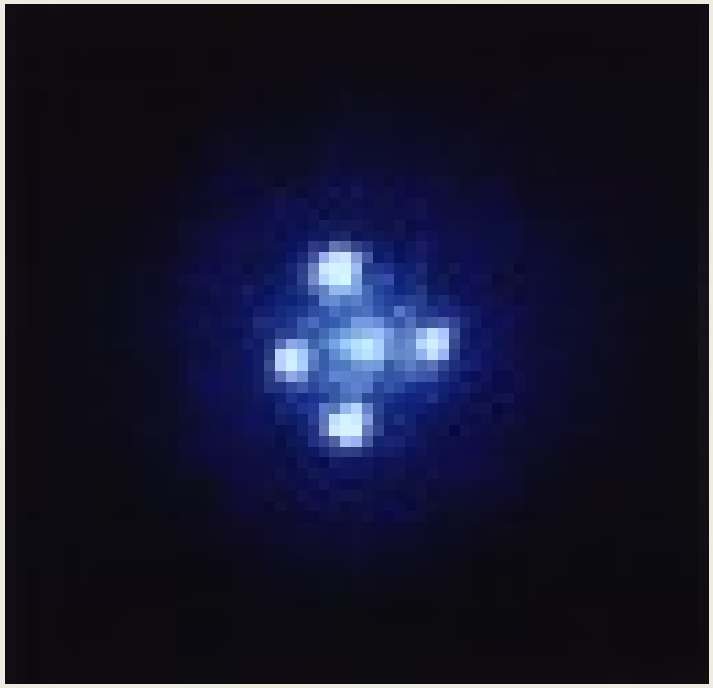
It Discards Absolute Time and Space, Recognizing Them Only as Related to Moving Systems.

IMPROVES ON NEWTON

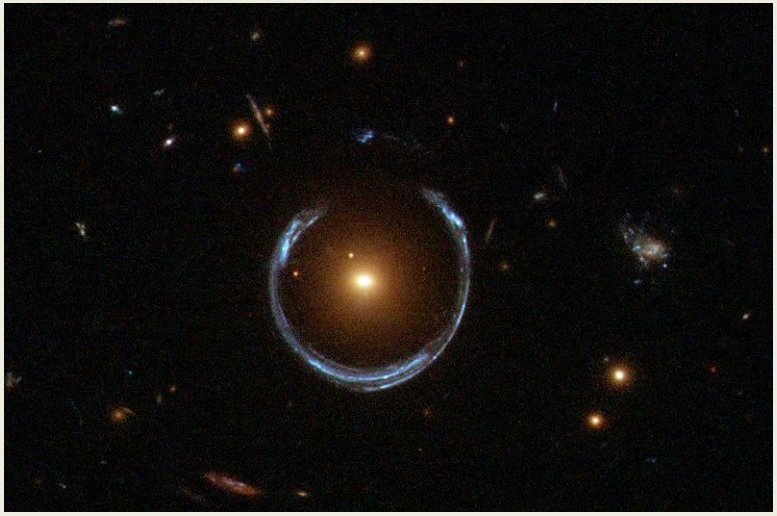
Whose Approximations Hold for Most Motions, but Not Those of the Highest Velocity.

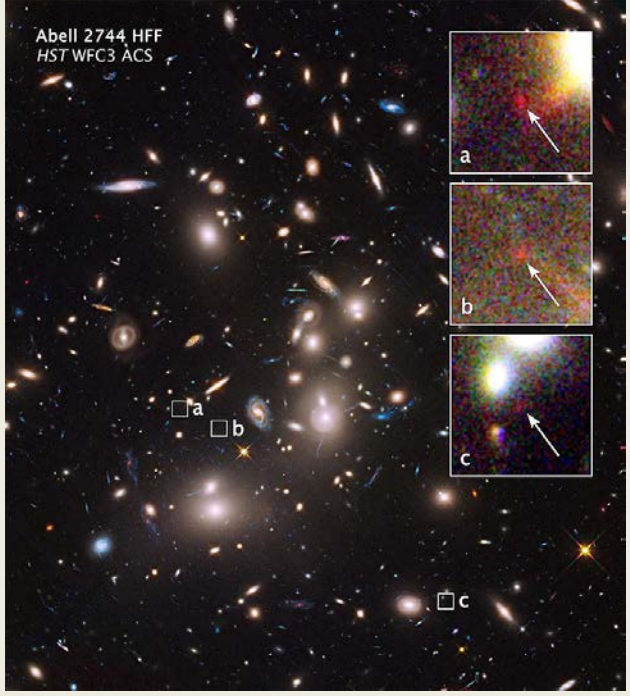
- **Einstein and GR became overnight sensations.**
- **Einstein aura not abated since…**
- What if observations had not confirmed predictions?
- Then I would have been sorry for the dear Lord.. the theory is correct! - Einstein
- Quasar Radio Wave Deflection (Seventies) 1%

Gravitational Lensing

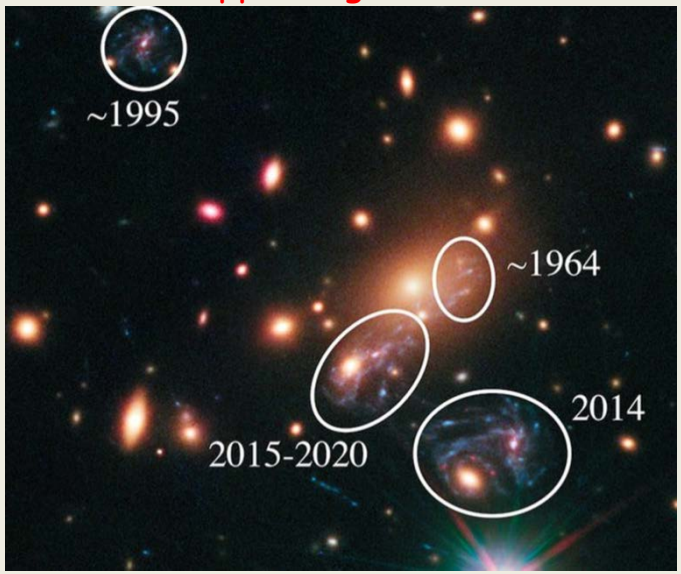


Einstein cross by NASA, ESA, and STScI



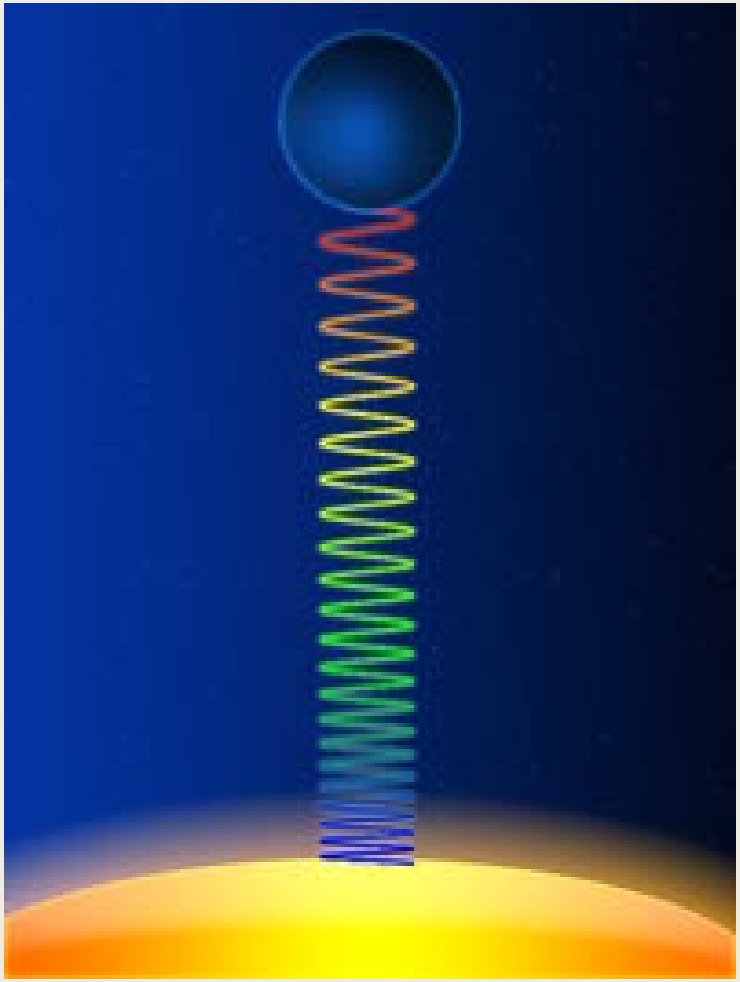


Multiple images of the Supernova Refsdal, appearing over time.



Credit NASA and European Space Agency

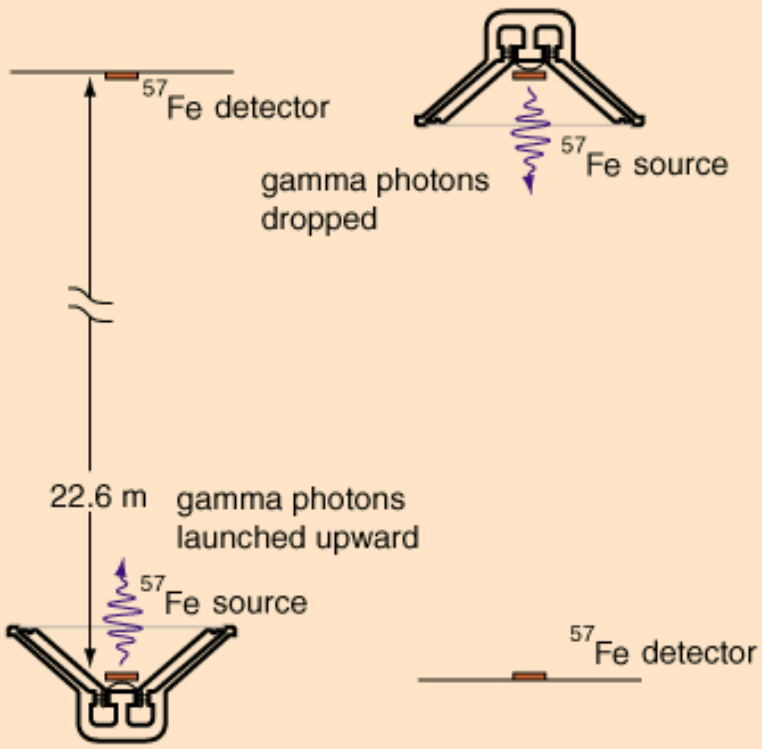
Gravitational Redshift



- Change in frequency or wavelength of light as it falls in a gravitational field
  - 1960 - Pound and Rebka demonstrated it..
  - 1965 – 1% accuracy

Credit: jenszornsculpture.com

Harvard Tower Experiment

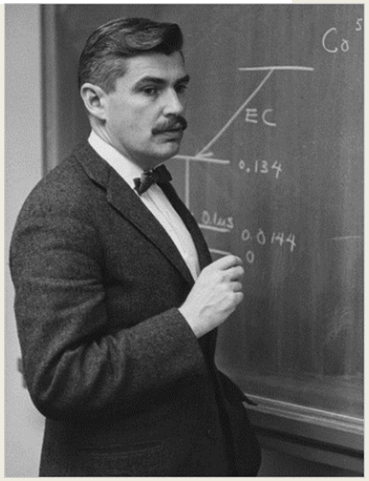


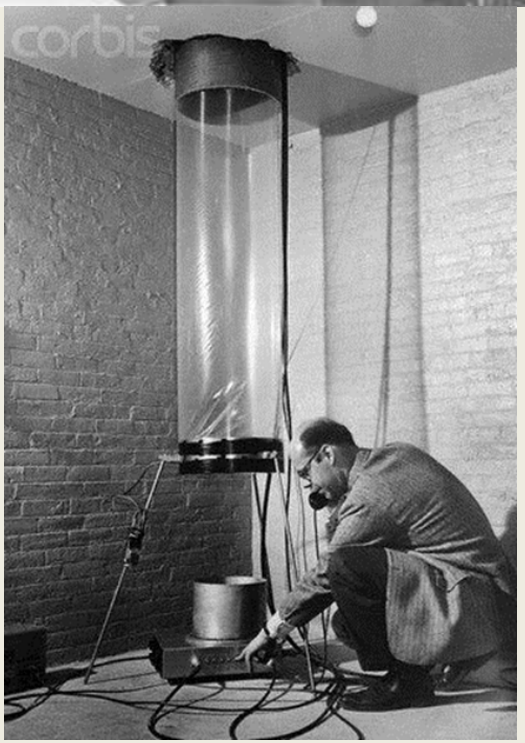
In just 22.6 meters, the fractional gravitational red shift given by

$$\nu = \nu_0 \left[1 + \frac{gh}{c^2} \right]$$

is just 4.92 x 10^-15 , but the Mossbauer effect with the 14.4 keV gamma ray from iron-57 has a high enough resolution to detect that difference. In the early 60's physicists Pound, Rebka,and Snyder at the Jefferson Physical Laboratory at Harvard measured the shift to within 1% of the predicted shift.

Credit: hyperphysics.phy-astr.gsu.edu





- Critically uses Mossbauer effect. Expt finds mention in Nobel Prize of Mossbauer
- Consequence of the Equivalence Principle

The new push for GR

- Programs of Soviet and American space travel of sixties were the drivers. Improved tracking of planets was integral part of inter planetary exploration*.
- Interplanetary space programs of sixties made radar ranging to planets and satellites a vital new probe of relativistic effects
- New technologies: H maser, Atomic clocks, Radar tracking of planets, radio interferometry of quasars, space platforms,..

*Accuracy was a part in 1000 leading in closest approach of a planet (40 million km) error of 40,000km.

How Politics shaped GR – David Kaiser

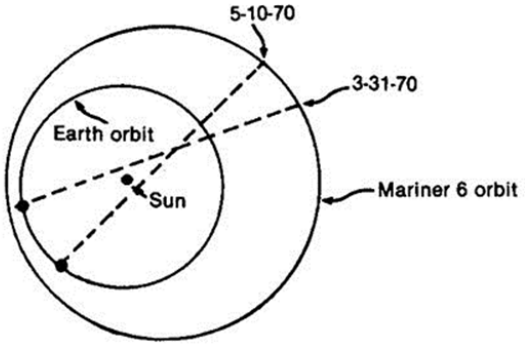
- Physicists and engineers working on enormous radar arrays to detect incoming Soviet missiles calibrated and fine tuned new system by sending radar pulses to nearby planets. Realized if they timed return echo from planets with unprecedented accuracy, they could test a subtle prediction of Einstein's GR: Gravity slows speed of light as well as bending its path. For decades, this time delay test provided most precise measurements available that Space-time behaved as Einstein predicted

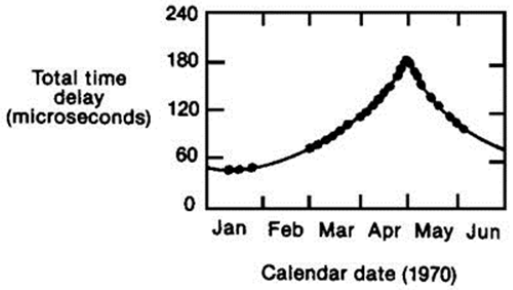
- Even the most abstract scientific research can be buffeted, derailed and even propelled by the most potent force of all: Politics!!

Stuart Shapiro

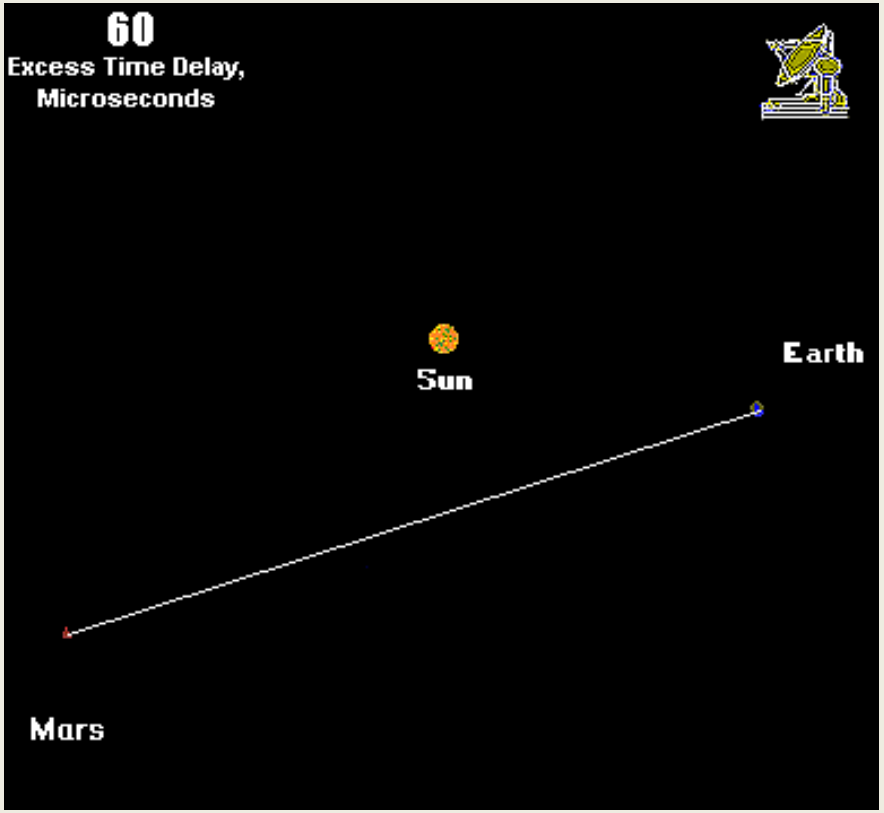
Shapiro time delay

- GR is relevant for radar ranging.. Radar signal takes longer to make round trip than based on Newtonian theory and constant speed of light. Additional delay depends on how close the signal gets to the sun. Smaller the distance larger the effect. In round trip to Mars of 42 mins, effect is 200 microsec at superior conjunction.
- 1967: ½ from EP+1/2 from curvature/nonlinearity of Space
- 1970-72 – Mariner 6: 3%-2%; Viking lander on Mars .1%

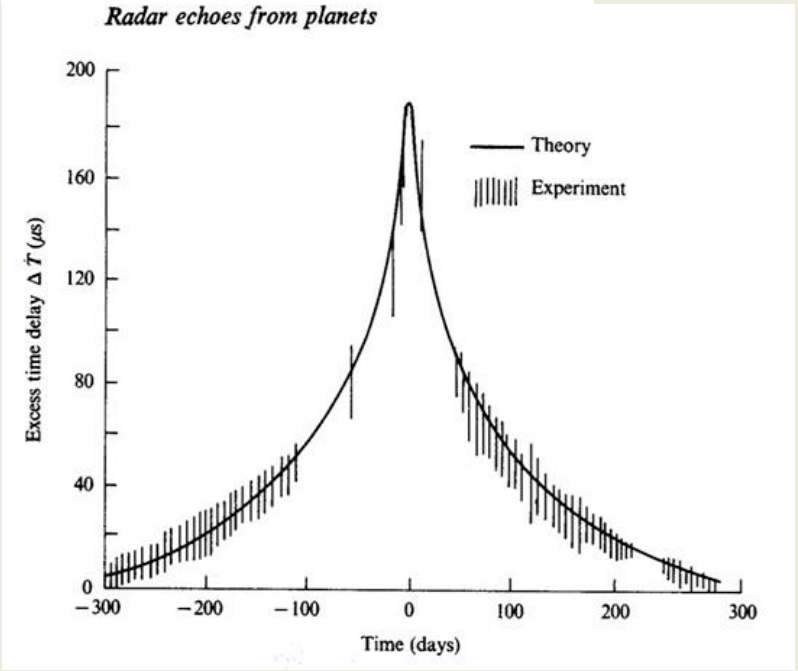




credit: www.lchr.org



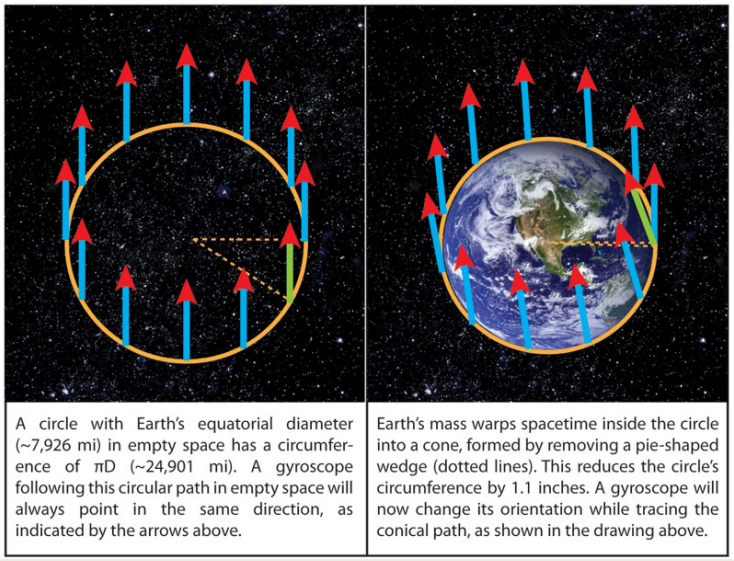
Credit: www.deceptiveuniverse.com



credit: www.deceptiveuniverse.com

Gravimagnetism, Lense-Thirring ..

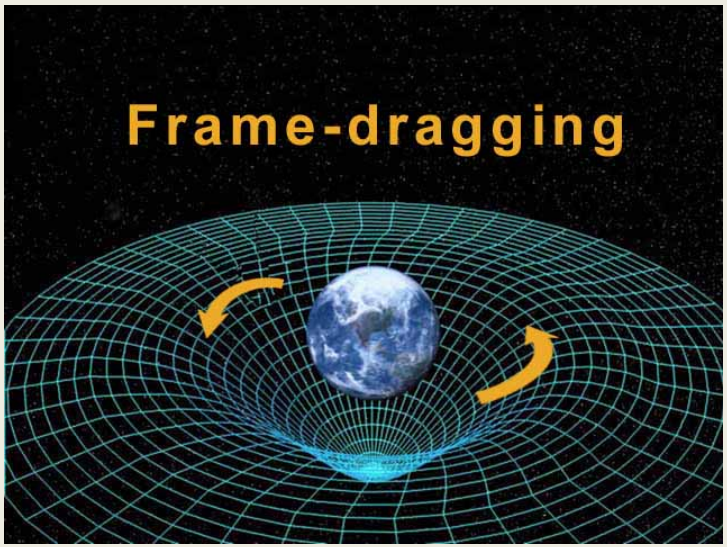
Geodetic Precession



A circle with Earth's equatorial diameter (~7,926 mi) in empty space has a circumference of πD (~24,901 mi). A gyroscope following this circular path in empty space will always point in the same direction, as indicated by the arrows above.

Earth's mass warps spacetime inside the circle into a cone, formed by removing a pie-shaped wedge (dotted lines). This reduces the circle's circumference by 1.1 inches. A gyroscope will now change its orientation while tracing the conical path, as shown in the drawing above.

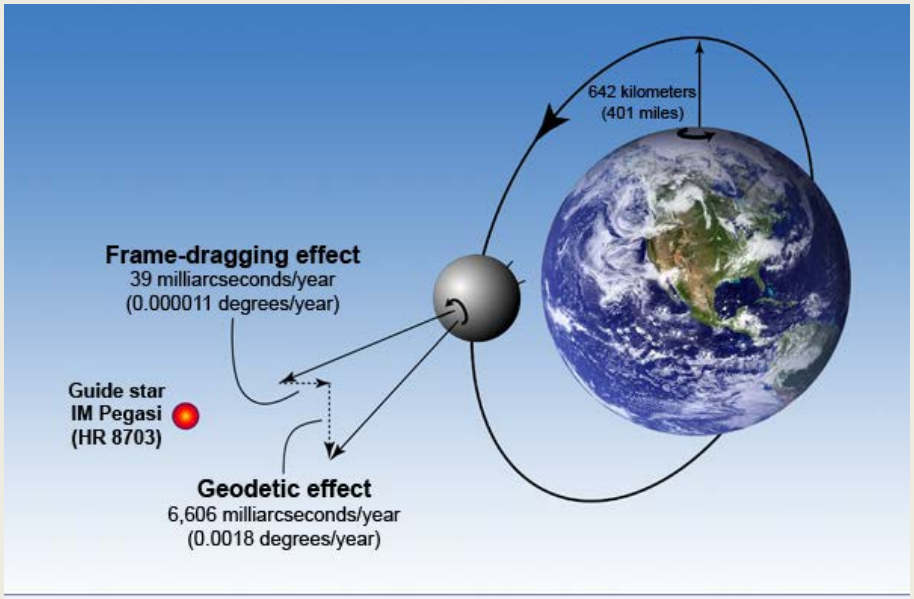
Credit: einstein.stanford.edu



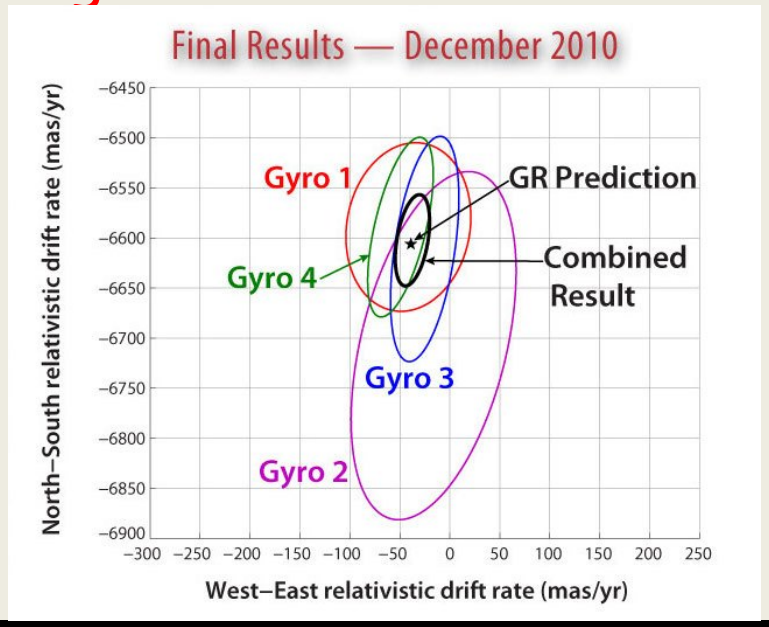
- Einstein had the first idea that dragging effect should result from a relativistic, tensorial theory of gravity. Introduced extremely useful model of a rotating mass shell and calculated (Entwurf-theory) Coriolis force field inside a rotating shell and the motion of the nodes of planets due to sun's rotation.
- Achieved with minimum calculational expense (first order w) a maximum of physical insight and practical results. Einstein-Thirring-Lense effect (credit: Herbert Pfister)

Gravity Probe B

Verifying Gravimagnetism

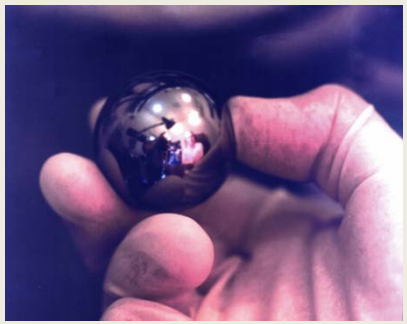


	Measured	Predicted
Geodetic precession (mas)	6602 ± 18	6606
Frame-dragging (mas)	37.2 ± 7.2	39.2



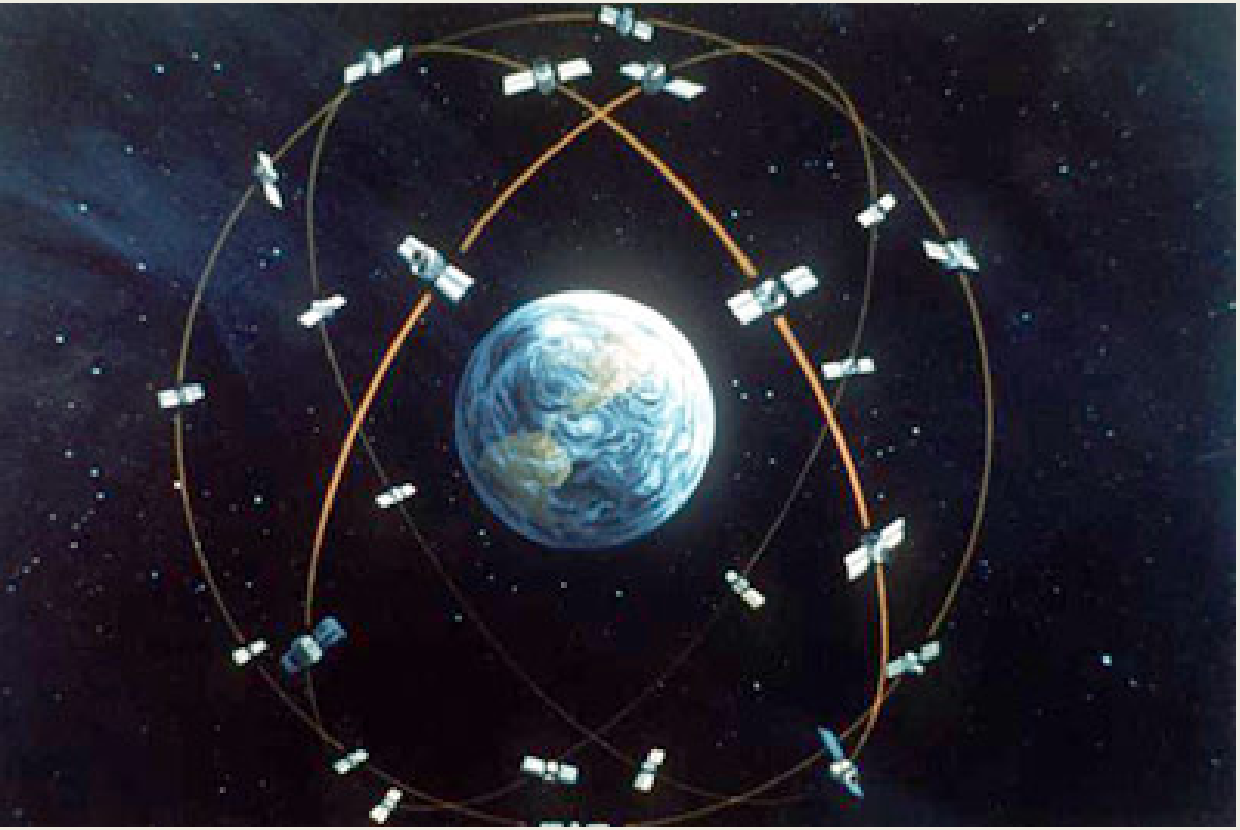
Credit: asterisk.apod.com

Goal: 0.4 mas/yr
Launch April 20, 2004
Mission ends: Sept 2005
Final Results: 2010



GR in Daily Life
Global Positioning System

- No better example of impact and influence of Einstein's relativity on daily life involving abstract theory and high precision technology



- **24 Satellites**
- **Stable Atomic clocks,**
- **Synchronised, running at well calibrated rates**
- **15 m Absolute position accuracy, 1 cm level Relative position**
- **50 ns time transfer**

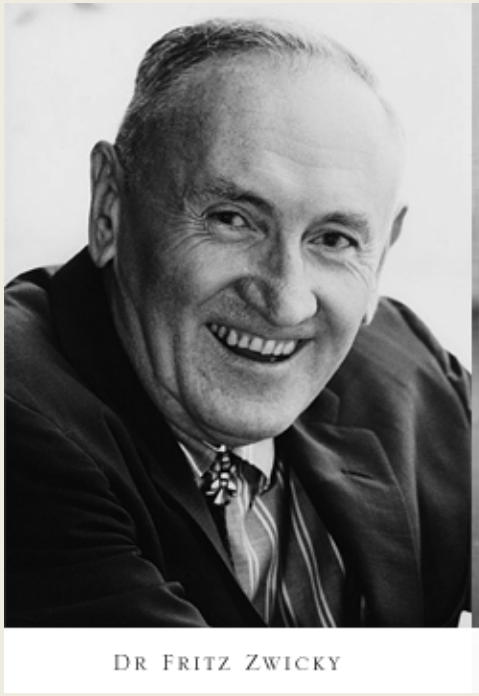
GR: Clocks at altitude tick faster than clocks on ground. (+ 46,000 ns/day).
SR: Moving clocks tick slower than stationary clocks (- 7000 ns).
Unless corrected for, GPS would fail in about half an hour

The Renaissance

Birth of Relativistic Astrophysics

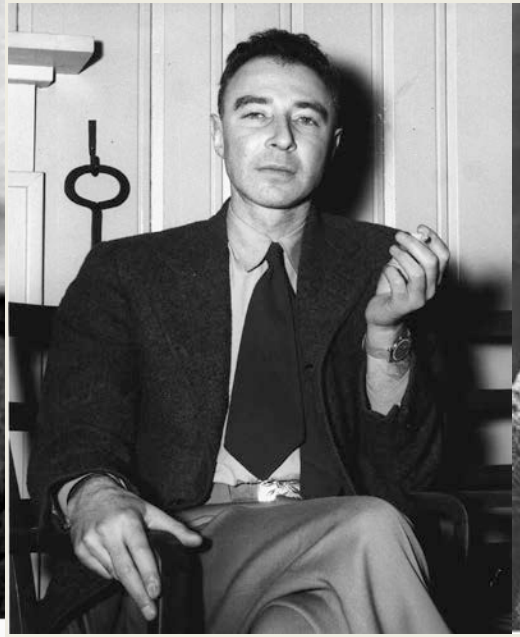
Neutron Stars

- 1933: Baade and Zwicky hypothesized existence of stars composed of neutrons as possible end states of a supernova explosion
- 1939 : Oppenheimer and Volkoff published theory of neutron stars. Radius: 10 km. Mass less than Msun.



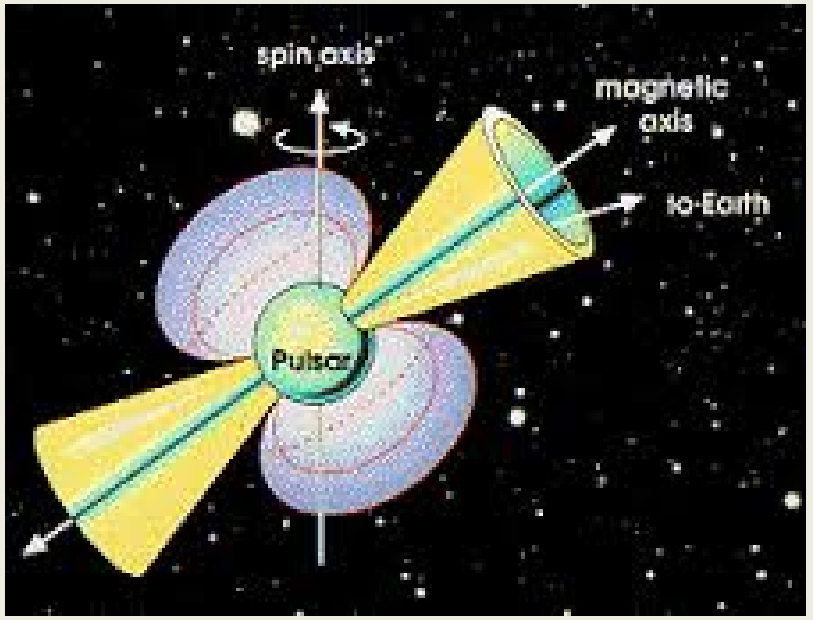
DR FRITZ ZWICKY

WALTER BAADE, FIZIKUS

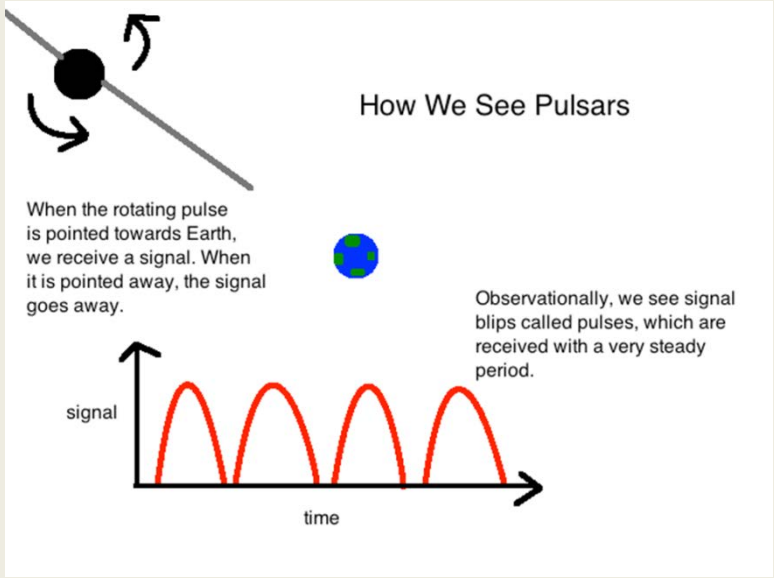


Pulsars

www.mpifr-bonn.mpg.de



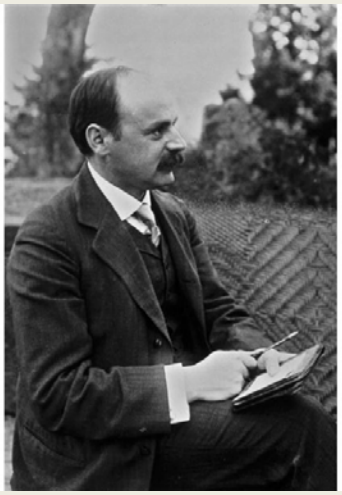
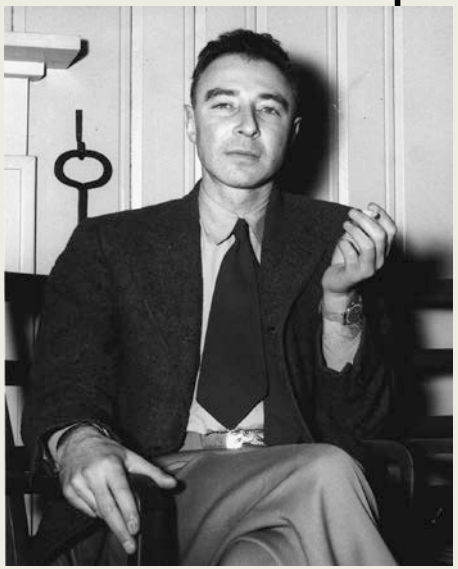
- 1967: Pulsars discovered by Jocelyn Bell and Tony Hewish
- Cosmic light houses
- Pulsars are Rotating Neutron stars.
- GR + Nuclear matter EOS: Determine structure
- NS Mass limit: 3 Msun.

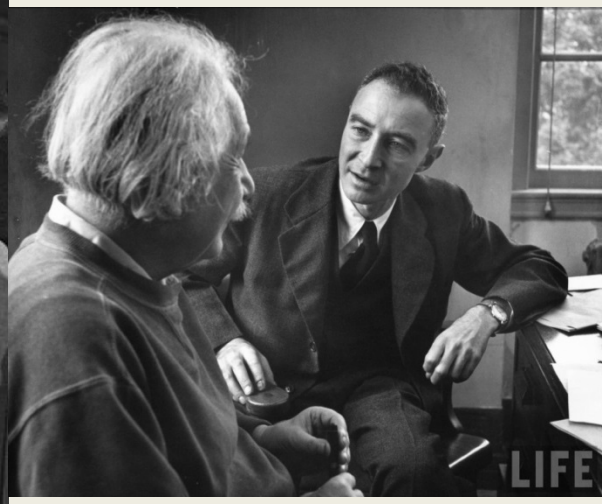


Millisecond Pulsars: Celestial Clocks

Black Holes – Extreme warping of ST

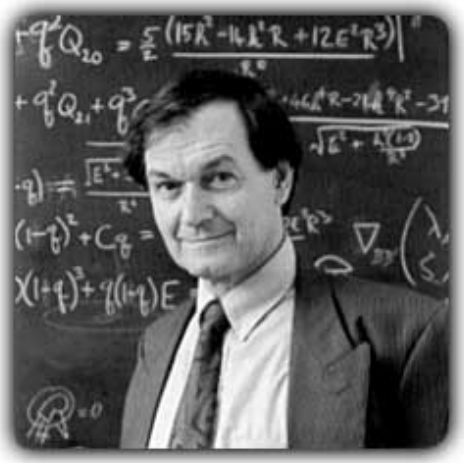
- 1783 – John Michell. How much larger than the Sun should a body be so that light cannot escape from its surface?
- 1798 Laplace revisited this question
- 1916 - K. Schwarzschild publishes 1st exact soln of EFE

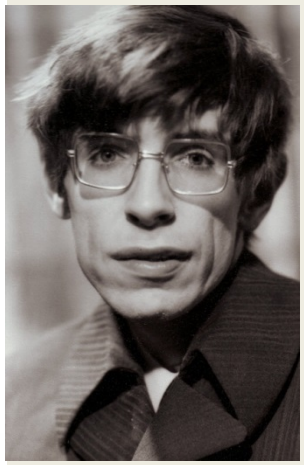



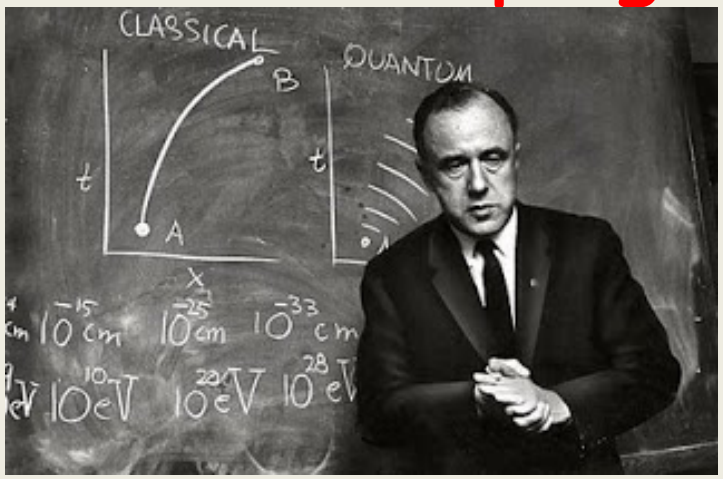


- 1939: Oppenheimer and Snyder showed SS collapse of dust due to gravitational self-attraction leads to Ap. BH
- Not considered physical due to idealizations of SS and dust

Black Holes – Extreme warping of ST





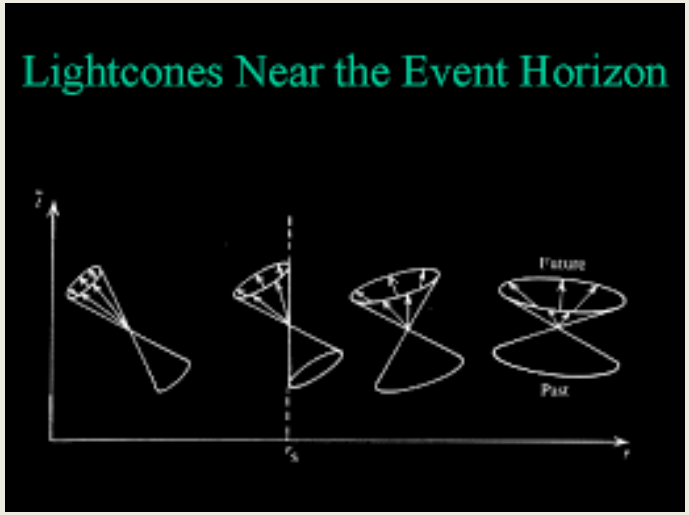


- Classical differential geometry adequate starting point for the initial studies of GR. Later developments required careful understanding of the **Global structure of spacetime, singularities and asymptotics** to interpret these solutions and formalisms to disentangle physical effects from coordinate or gauge dependent ones.
- Penrose: If appropriate causality conditions hold and matter and fields satisfy suitable energy conditions then closed trapped surfaces will form leading to singularities in gravitational collapse. “Greatest Crisis in Physics for all time”

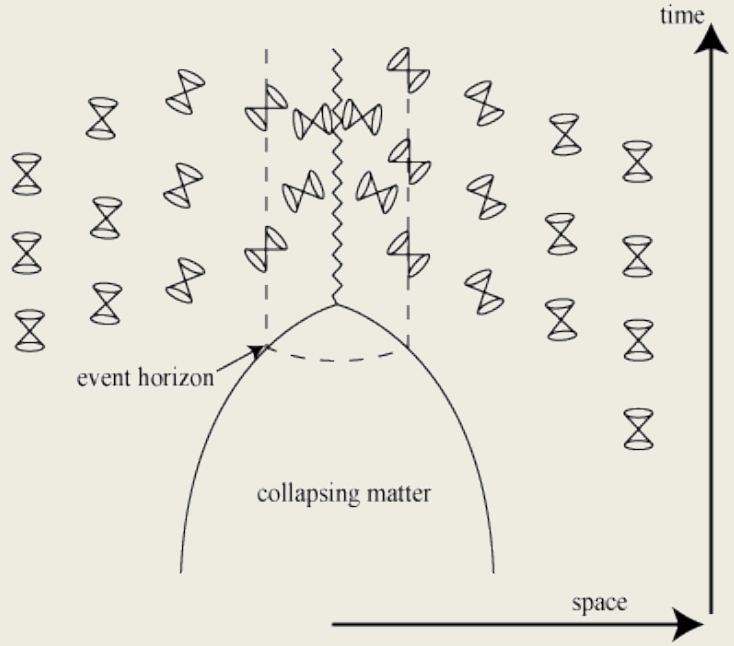
Black Holes – Extreme warping of ST

- R=2M; Schwarzschild singularity: Coordinate singularity
- Infinite red-shift surface,
- One way membrane or Event horizon..

Schwarzschild (non-rotating) Black Hole



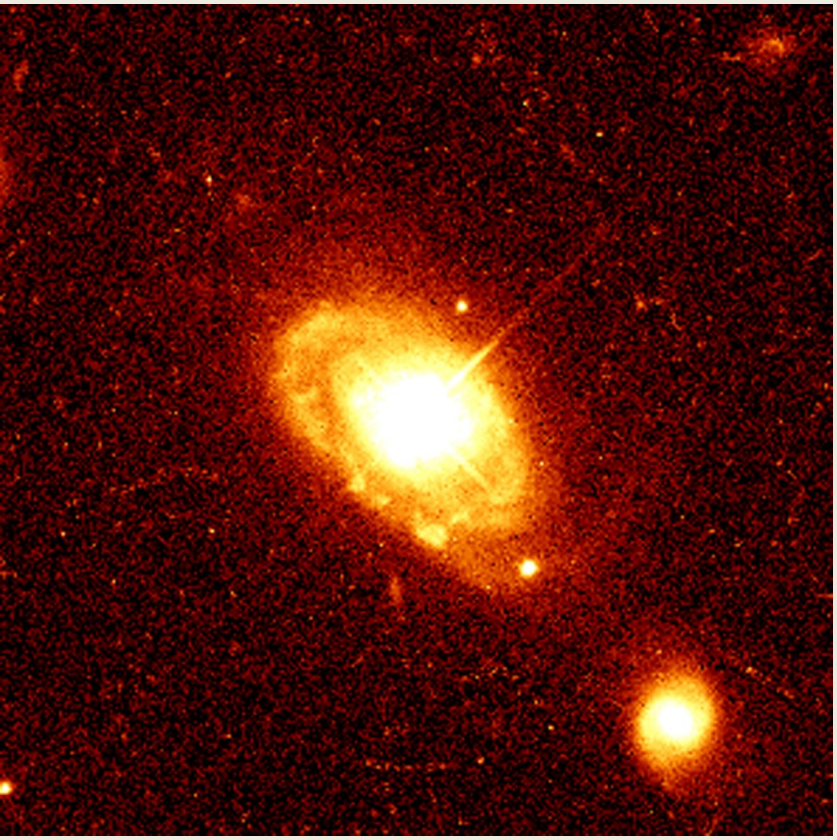
credit: www.scienceforums.net



credit: plato.stanford.edu

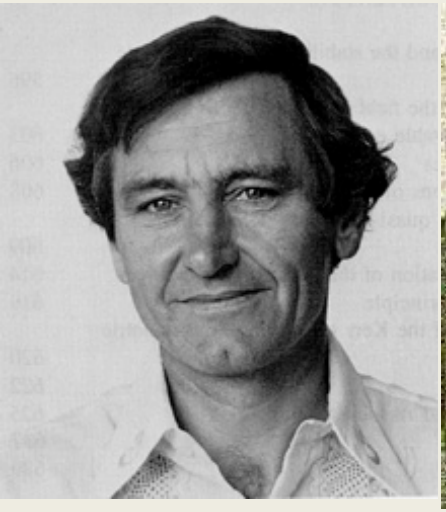
- R=0 Physical Singularity; Infinite Tidal forces, Curvature..
- Considered just Interesting Mathematical solutions until…

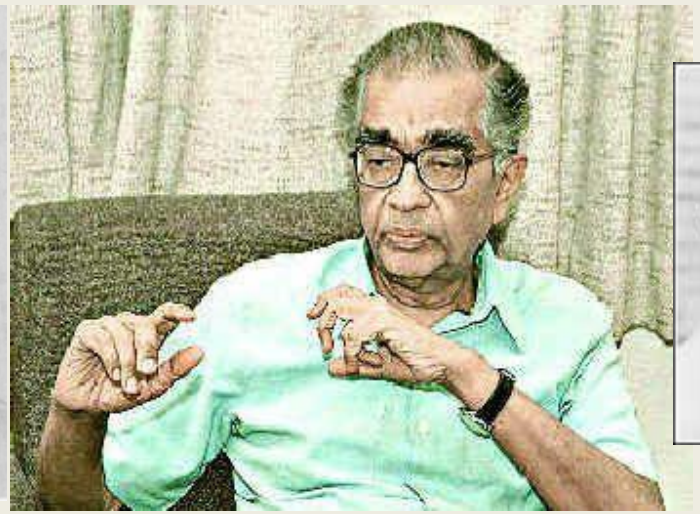
Quasars

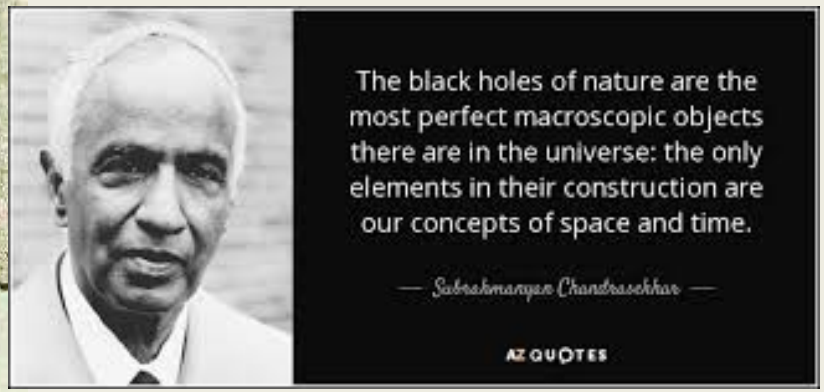


- 1963 Existence of very distant and powerfully radiating objects – Quasars.
- Soon associated with Black holes.
- First celestial objects that can only be described by GR.
- Birth of Relativistic Astrophysics
- x-ray source like Cyg-X1..

Source (www.spacetelescope.org)





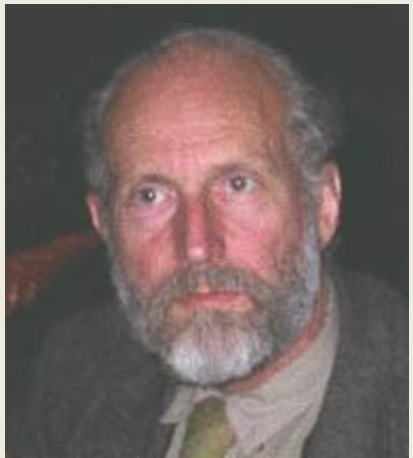


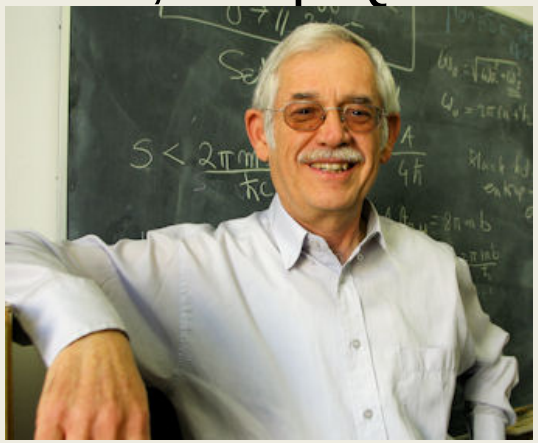
1963 – Kerr or Rotating BH

1970 - Vishveshwara (Linear Stability of Schwarzschild BH, Quasi normal modes of BH)

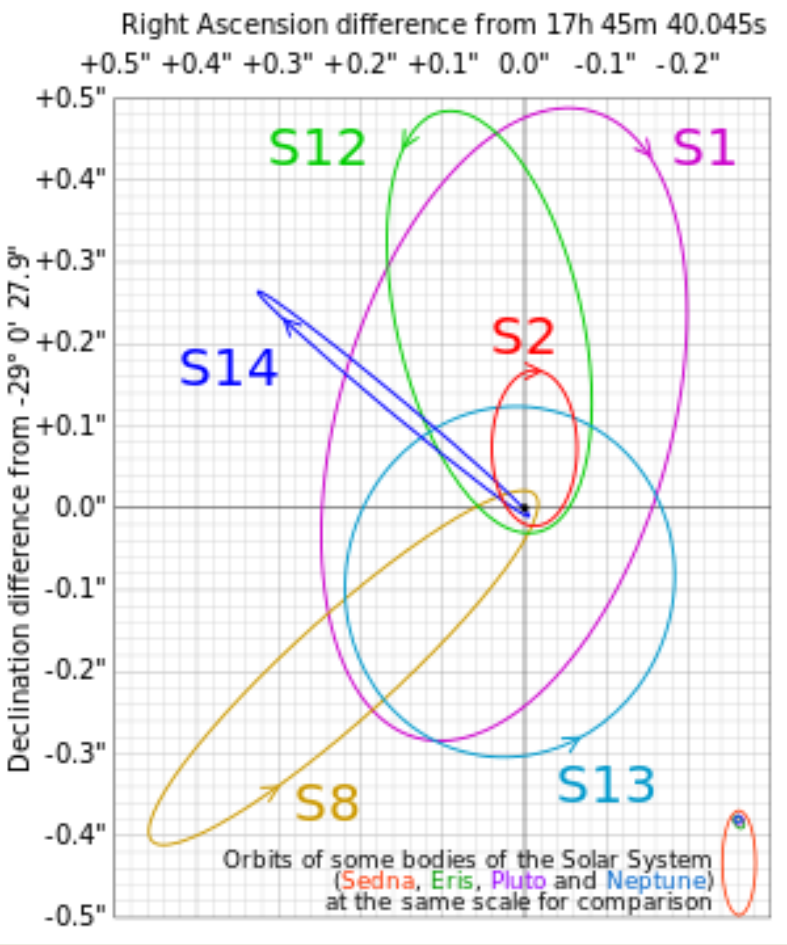
1974 – BH mechanics, Thermodynamics, Hawking radiation.

Today… ??? Cosmic Censorship, Non-linear stability, Naked singularities, ADS-CFT, Loop Quantum Cosmology????





Supermassive BH exists in centre of Milky way..



- Supermassive BH at centers of galaxies
- Stellar Mass Black Holes
- Do Intermediate mass Black Holes exist???

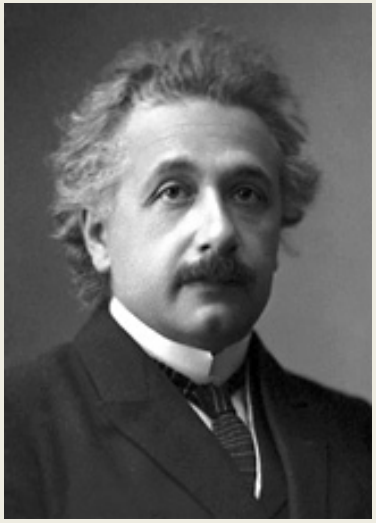
The Renaissance

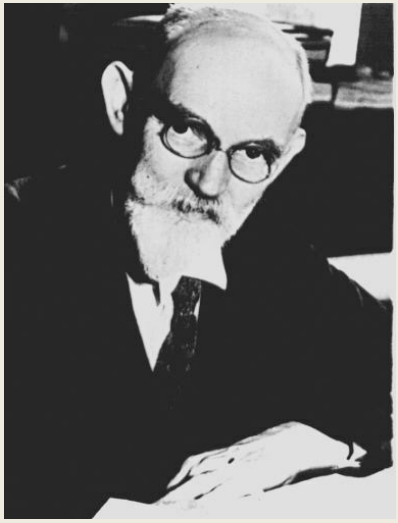
The First Three Minutes of the Universe

Towards Precision Cosmology

Birth of Relativistic Cosmology

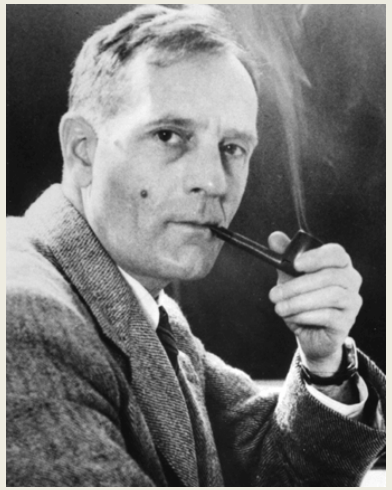
- 1917 Einstein applied GR to universe as a whole founding Relativistic Cosmology. Found Homogeneous and isotropic universe is dynamical not static. Introduced cosmological constant (long range repulsive force) to achieve a static universe. Imagine his cult status if he accepted the expansion and made instead the prediction that universe expands !!!
- De Sitter discovered a solution with no matter flying far apart
- “It would be unsatisfactory, in my opinion, if a world without matter were possible.” - Einstein



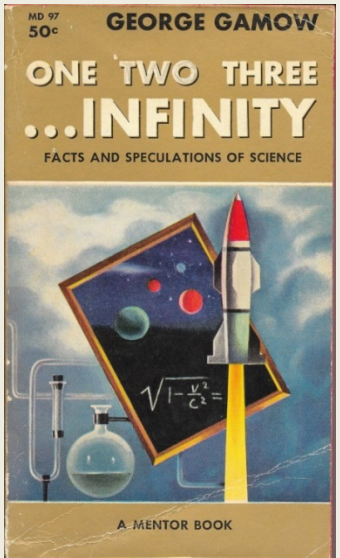


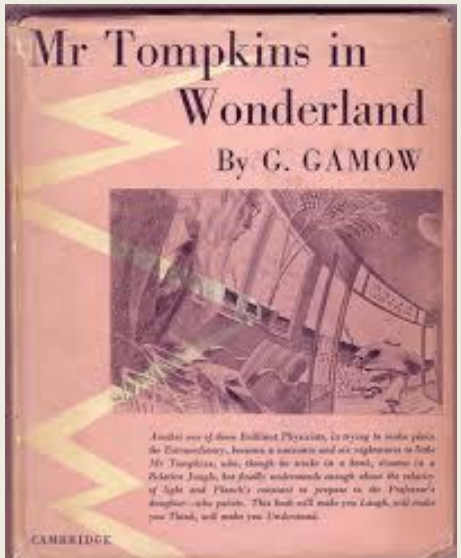
- 1922 Friedmann: solution of the Einstein field equations that describe a homogeneous and isotropic universe was an expanding universe that contained moving matter
- 1927 Georges Lemaitre: non-static solns of EE describing expanding universe. (Derives Hubble's law...)
- 1929 – Edwin Hubble discovered empirical law according to which extragalactic objects are receding from us at speed proportional to distance. First observational confirmation that universe is expanding.
- 1933 Robertson-Walker – Maximally symmetric Space

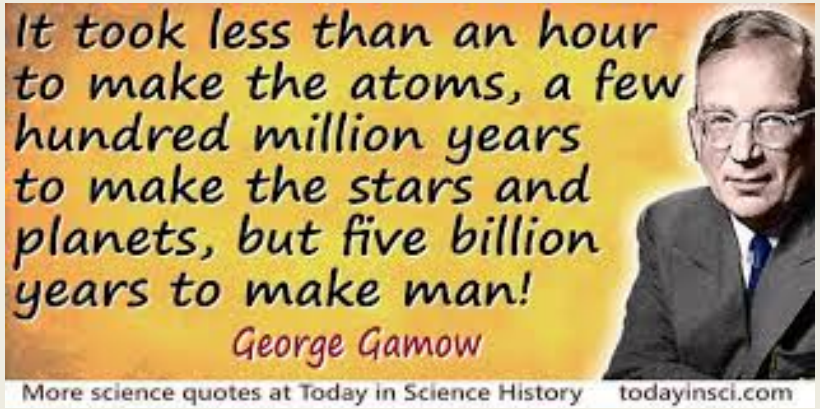


- 1946-48: Universe should be filled with remnant radiation from Big Bang.. Few degree K







The Origin of Chemical Elements

R. A. ALPHER*
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland

AND

H. BETHE
Cornell University, Ithaca, New York

AND

G. GAMOW
The George Washington University, Washington, D. C.

February 18, 1948

AS pointed out by one of us,[1] various nuclear species must have originated not as the result of an equilibrium corresponding to a certain temperature and density, but rather as a consequence of a continuous building-up process arrested by a rapid expansion and cooling of the primordial matter. According to this picture, we must imagine the early stage of matter as a highly compressed neutron gas (overheated neutral nuclear fluid) which started decaying into protons and electrons when the gas

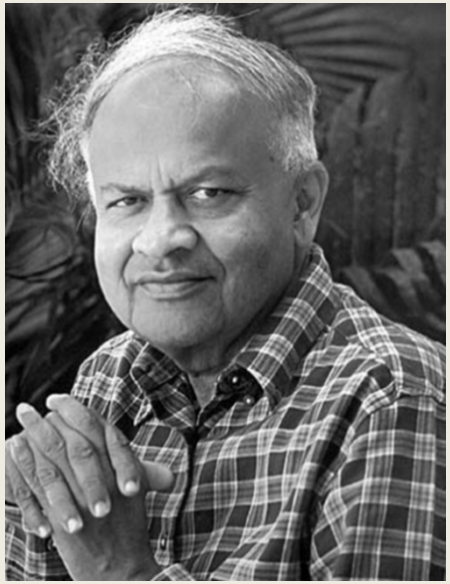
Big Bang Nucleosynthesis

sis. Gamow, in typical fashion, even coined the following passage, written in biblical style. In the beginning, when God was creating the elements,

> In the excitement of counting, He missed calling for mass five and so, naturally no heavier elements could have been formed. God was very much disappointed, and wanted first to contract the Universe again, and to start all over from the beginning. But it would be much too simple. Thus, being almighty, God decided to correct His mistake in a most impossible way. And God said, "Let there be Hoyle." And there was Hoyle. And God looked at Hoyle . . . And told him to make heavy elements in any way he pleased. And Hoyle decided to make heavy elements in stars, and to spread them around by supernova explosions.

The Steady State
Bondi, Gold, Hoyle, Narlikar

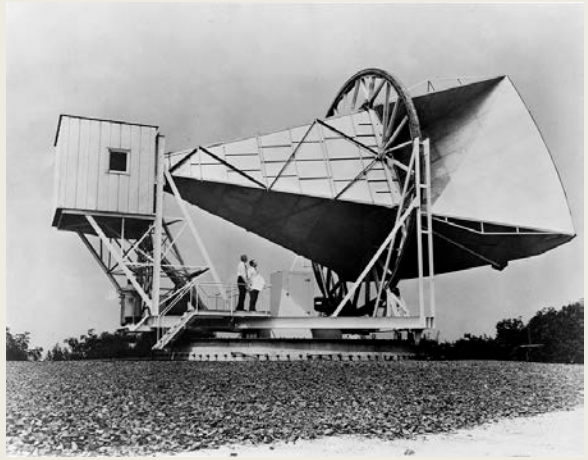
- **De Sitter**
- **Maximally Symmetric ST**
- **More Beautiful but observations have the decisive veto!!**



Relativistic Cosmology

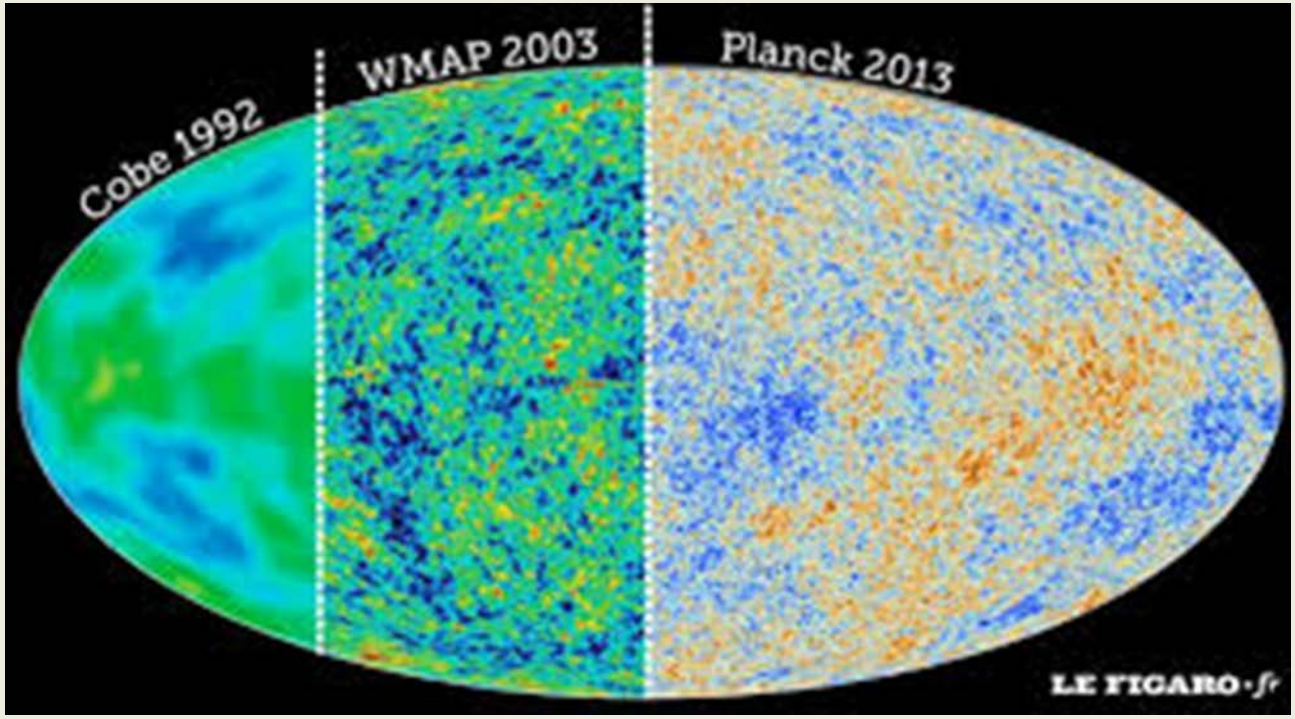
- 1955 – Raychaudhuri eqn
- Crucial role in Singularity Thms

- 1965 – A. Penzias and R. Wilson discover Cosmic microwave background radiation at 3 K serendipitously. Interpreted as afterglow of Big Bang. Dicke was preparing to look for it. Proof universe had origin in time and not expanding forever as in steady state. Big Bang coined by Hoyle in amusement!!



Towards precision Cosmology

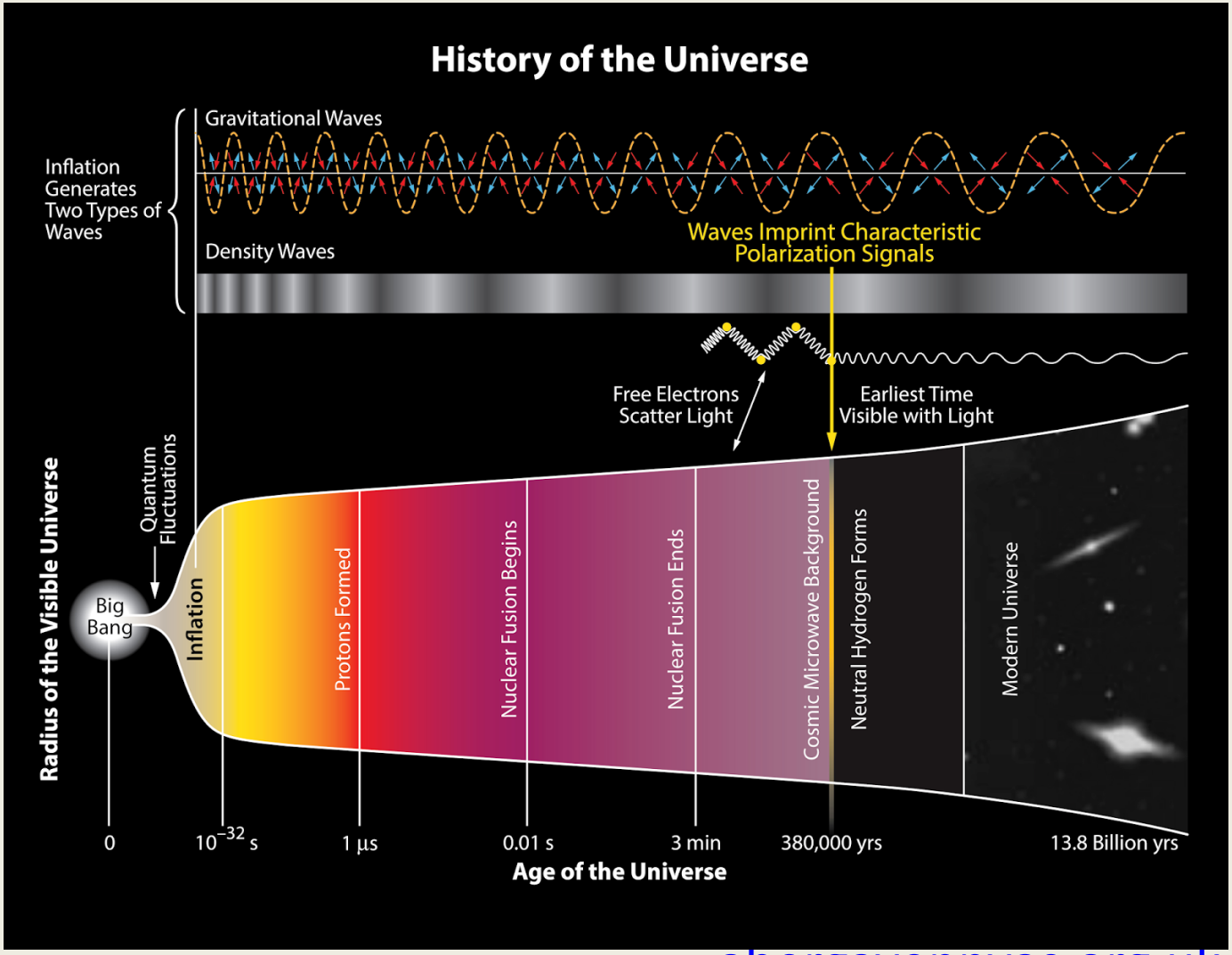
- 1980: Inflationary Cosmology (Starobinsky, Guth)
- 1990: COBE measures CMB and pins temp at 2.725 K
- 1992: COBE data reveal miniscule variations in CMB temp.. Sign of density fluctuations in EU that would later condense to galaxies
- 2003: NASA WMAP charts CMB in increased detail
- 2013: Planck..



Dark Energy

- 1998 – Observations of distant supernovae lead to conclusion universe is accelerating. Dark Energy
- 2006 Nobel: Saul Perlmutter, Adam Reiss, Brian Schmidt

History of the Universe



abergavennyas.org.uk

We have a STANDARD Model of the Universe!!

The Future

The Last Three minutes of CCB

Gravitational Waves: Towards a New Astronomy

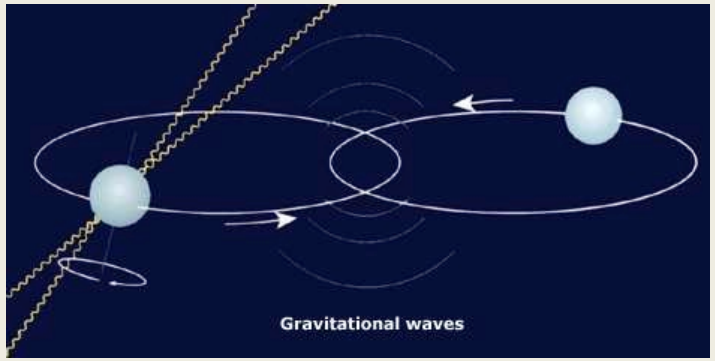
Relativistic Gravitation and Gravitational Waves

- Any relativistic theory of Gravitation (like General Relativity) must be consistent with Principle of Special Relativity.
- Effect of Gravity cannot be transmitted Faster that Light
- If Gravitational Field of an object changes, the changes propagate thro' space and take a Finite time to reach other objects. Propagating oscillations of gravitational fields are Gravitational Radiation or Gravitational Waves. Ripples of space-time curvature in GR.
- They are produced by accelerated motion of "masses"
- They carry away Energy, Angular momentum and Linear Momentum from the system.
- GW propagate essentially unperturbed thro space as they interact weakly with matter ..
- In GR, as in EM, GW travel with speed of light, are transverse and have two states of polarization (+, x)

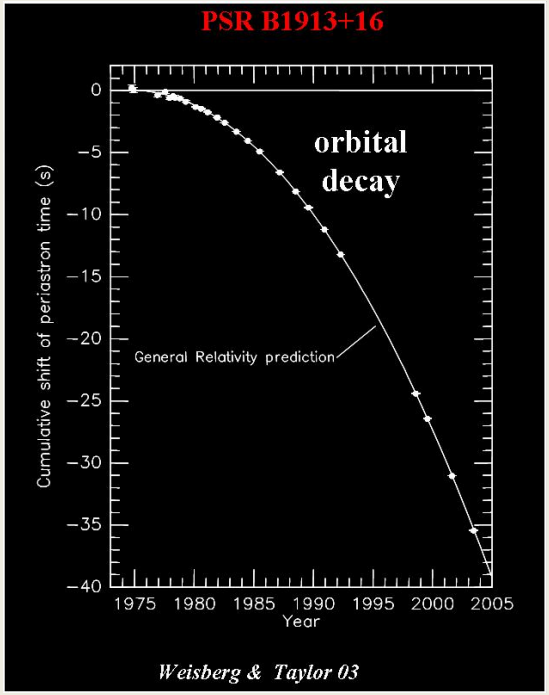
A Century long Wait

- GW predicted by Einstein in 1916 as an important consequence of General Relativity.. No experimental confirmation a la Hertz .
- Reason is connected to two fundamental differences between EM and Gravitation: The weakness of the gravitational interaction relative to EM (10^{-39}) and the spin two nature of gravitation compared to the spin one nature of EM that forbids dipole radiation in GR.
- Implies low efficiency for conversion of mechanical energy to gravitational radiation except in strong fields and at relativistic velocities. And feeble effects of GW on any potential detector.
- Likely sources: Signals produced by astrophysical systems where there are potentially huge masses accelerating very strongly
- E.g. Chirps from coalescing neutron star binaries and black holes, bursts from supernovae and gamma ray bursts, GW from isolated neutron stars and stochastic murmurs from the big bang ..

Gravitational Waves exist



- 1974 Hulse and Taylor, discovered Binary Pulsar 1913+16
- If General relativity is right the system must emit GW



- Orbital period slowly decreasing at just the rate predicted by GR for emission of GW!!! Indeed, Orbit shrinks by 0.0000758 secs/year
- Precession: 4.2 degree/year
- Mercury 43”/century
- $v/c=10^{-3}$
- Hulse and Taylor received Nobel Prize for this (1993).

Insights into GR and GW from Binary Pulsars

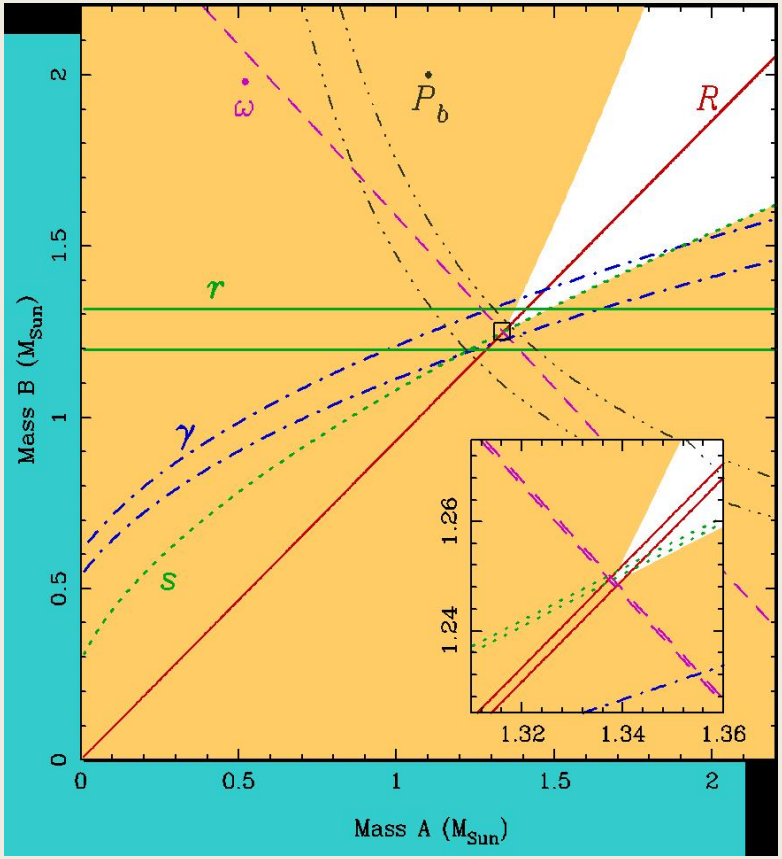
- Binary pulsars like 1913+16 provide direct observational proof that gravity propagates at velocity of light and has a quadrupolar structure

- About a dozen relativistically interesting: Double Pulsar, system with White Dwarf companions, system with most massive NS known, system with two WD companions..

- Stringent limits on Dipole Radn (test of quadrupolar structure of Grav Radn Damping) exist currently from Pulsar-WD systems. Best PSR J1738+0333

- GR valid beyond quasi-stationary weak-field regime. Probed for first time in regimes involving radiative effects and strong fields

Double Pulsar provides accurate tests of the strong field regime of relativistic gravity



- GR passed all binary pulsar tests with flying colors

- Existence of binary neutron stars emitting GW for hundreds of million years before coalescing spectacularly in sensitivity BW of detectors like LIGO/Virgo.
- Estimated number of GW events for LIGO.

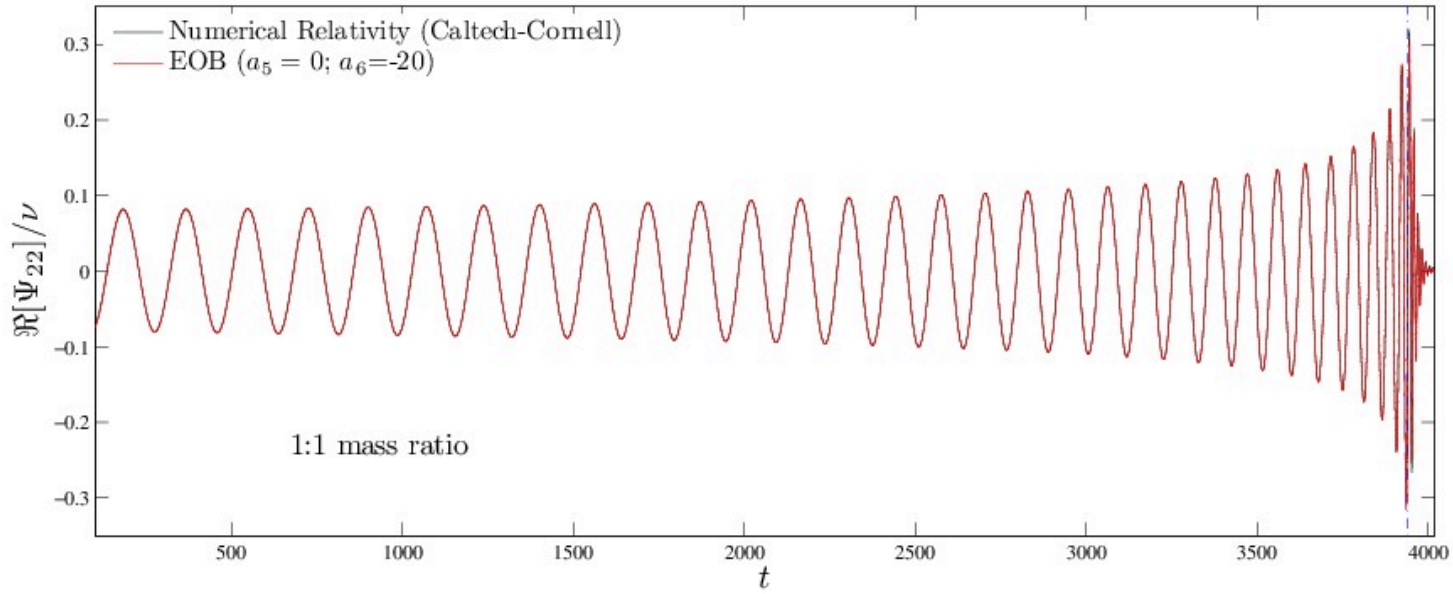
Gravitational Machines for Interstellar communication

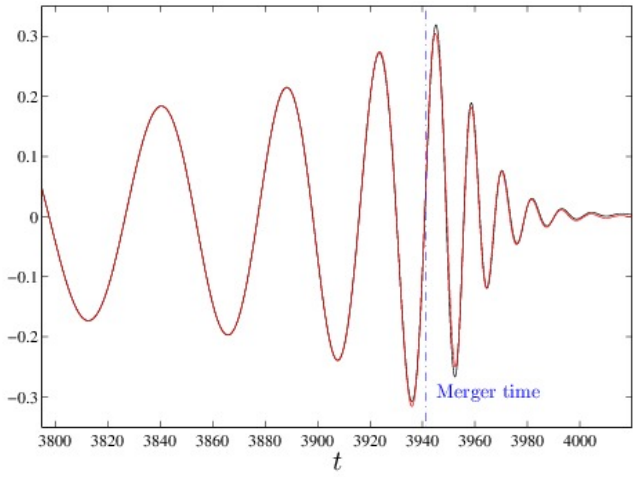
- 1963 Freeman Dyson: Possible use of gravitational energy by advanced civilizations by creation of binary neutron star systems to accelerate spacecraft to enormous speeds!
- `If a close binary system could ever be formed from a pair of neutron stars, these systems would emit sufficient quantities of gravitational radiation (on account of the intense fields produced at short range by such highly condensed bodies) to cause the system to decay on a relatively short timescale until its components plunged into each other in a final immensely strong burst of GW at frequency suitable for detection by Weber's instrument to distance of order 100 Mpc (100 million galaxies) .. would be worthwhile to maintain a watch for events of this kind..
- Prescient ..Pulsars were discovered by Jocelyn Bell and Tony Hewish in 1967 and Binary pulsars in 1974!

Towards direct detection of GW and beyond

- **Direct detection of GW -**
  - **1st mandate of Laser Interferometric GW detectors**
- **Promised and Real Excitement -**
  - **New Observational Window into the Dark Universe;**
  - **Tool for Astrophysics and Cosmology;**
  - **Experimental Probe for Basic Physics**
- **Challenges..**
  - **NS-NS system in Virgo cluster produces strain of $h \approx 10^{-21}$ or a miniscule 10^{-18} m displacement in Km scale Interferometer**
  - **v/c~0.4 near merger. Challenge in GW detection reqd & led to Progress in Two Body Problem in GR .**
  - **Experiment leads Theory**

The triumph of GR…

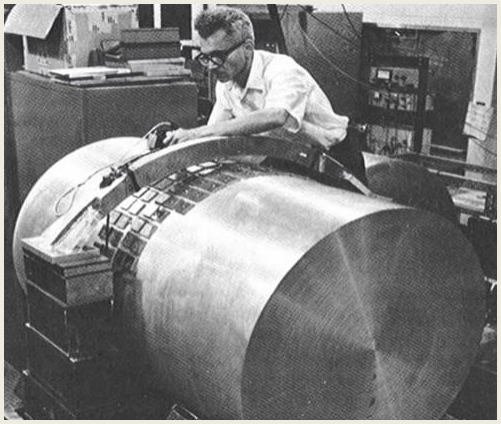




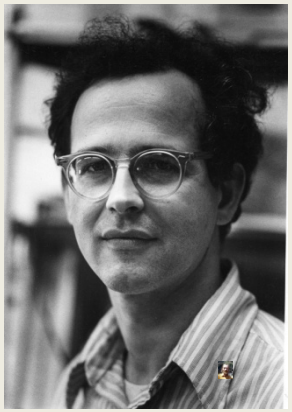
- Corrections to Newtonian Gravity to orders (v/c)^7 computed Analytically for Inspiral, Merger and Ringdown by Numerical Relativity, Ringdown by BH Perturbation

Damour, Nagar

The League of Extraordinary Gentlemen.. Gerstenstein & Pustovoit; Forward, Billing and Winkler, Meers..



Joe Weber



Ray Weiss

Ray Weiss

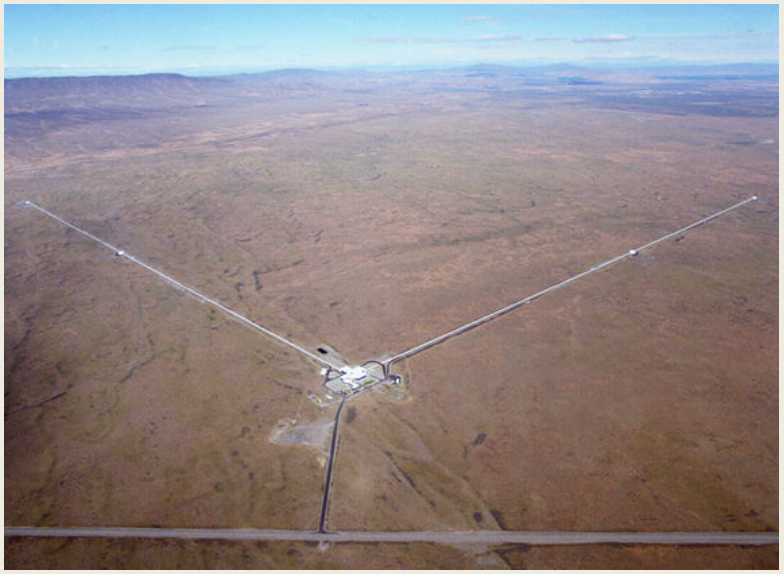
Ron Drever

Kip Thorne

Kip Thorne

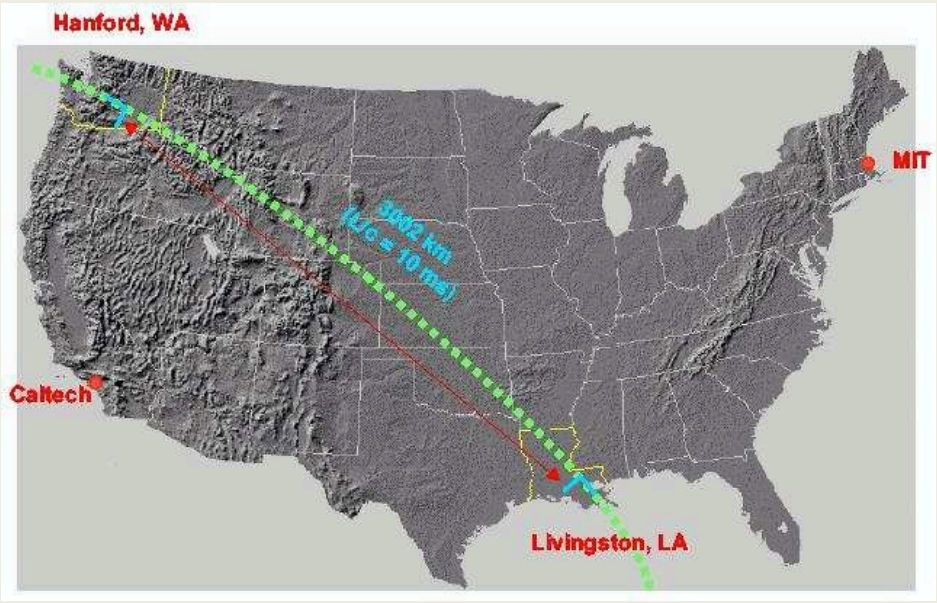
Alain Brillet

Adalberto Giazotto

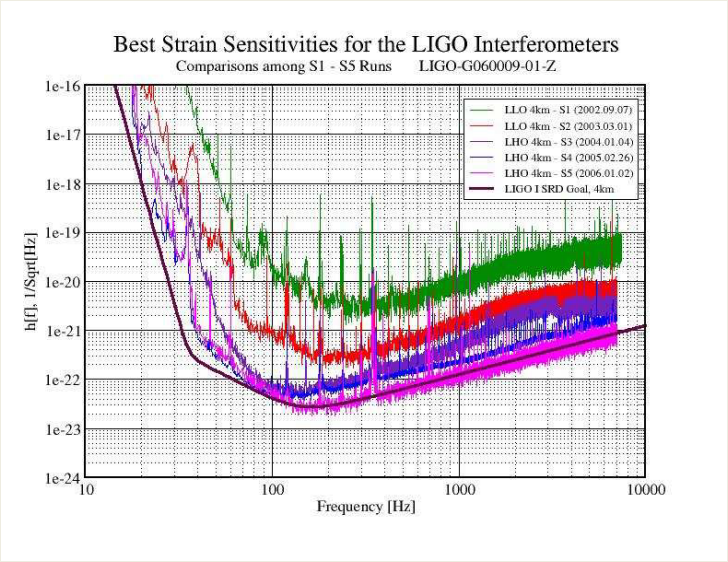


Hanford: Two Laser Interferometers in same beam tube

Livingston: One Laser Interferometer

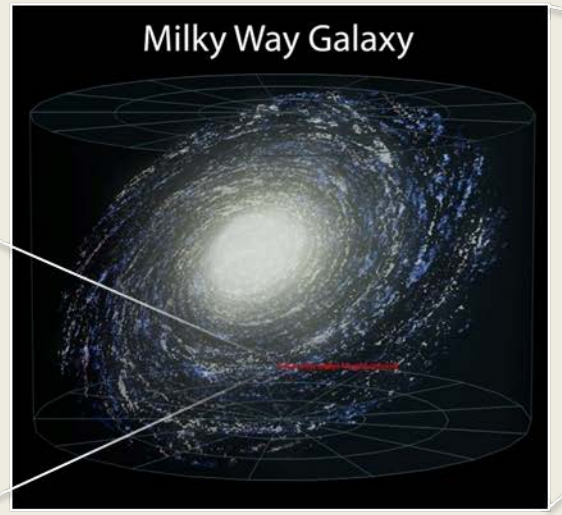


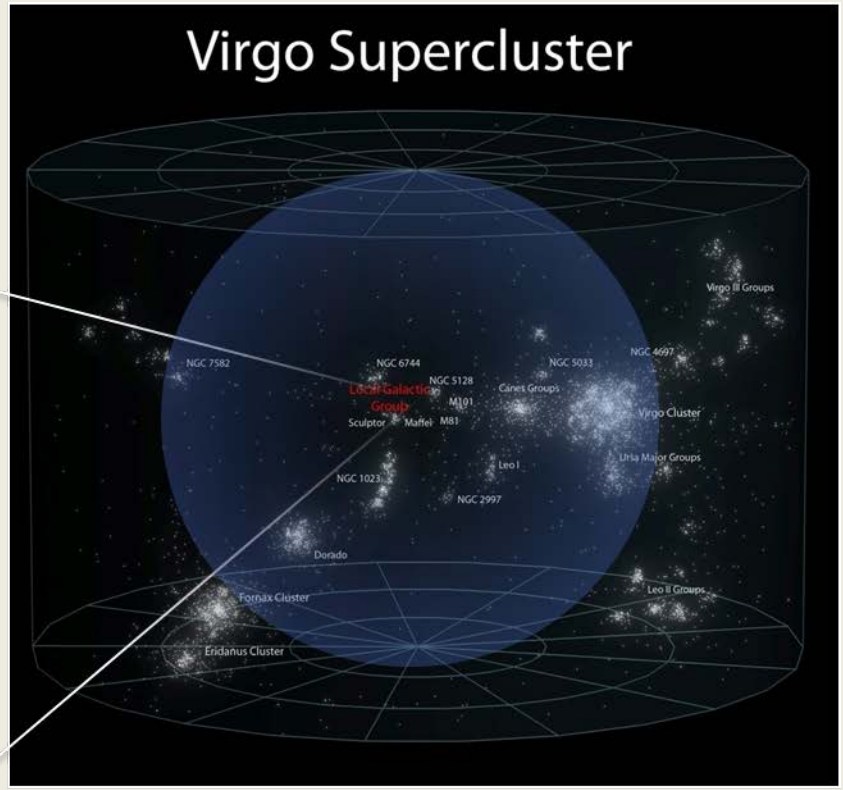
Cascina: Virgo



$$\Delta L \sim 10^{-19}\, m/\sqrt{Hz} \text{ (Achieved)} \rightarrow$$

Credit: M. Evans



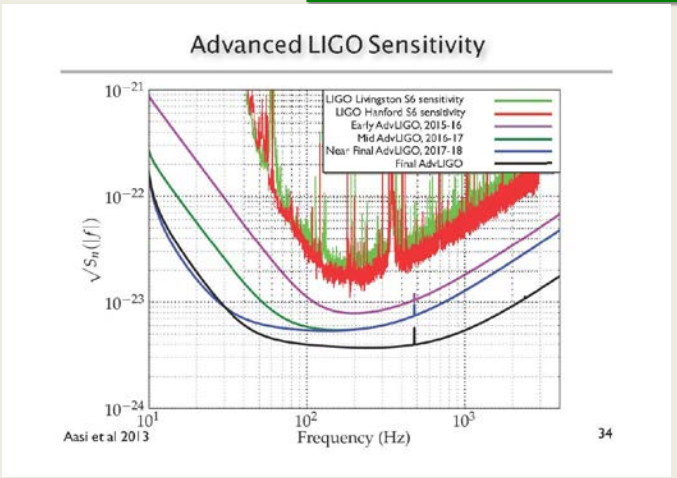


Not surprising we have not detected any GW event in Initial LIGO

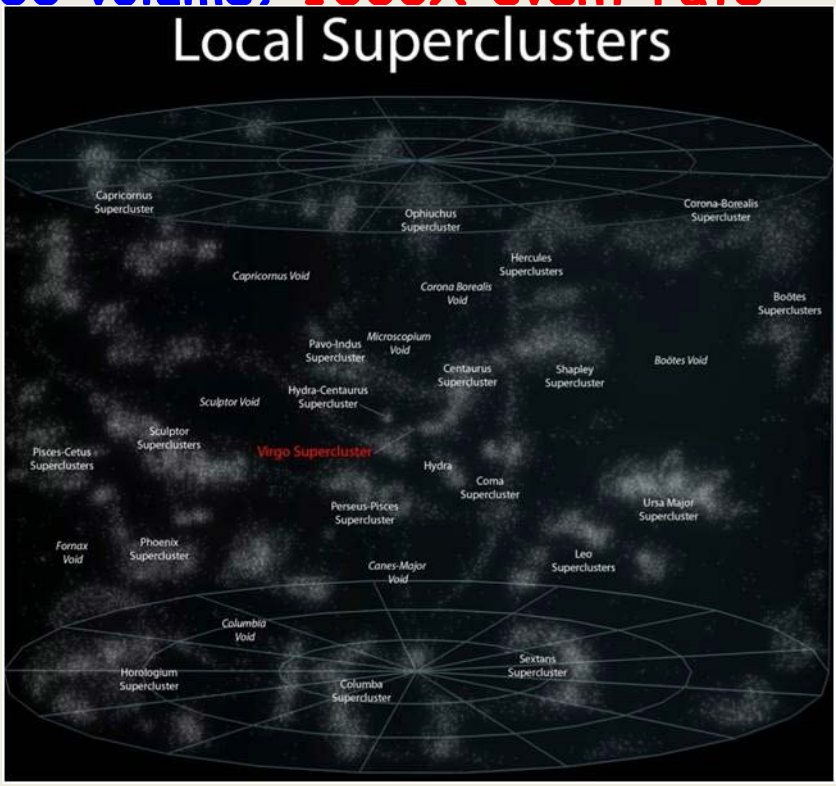
Rate is 1 NS-NS per galaxy per 10,000 years

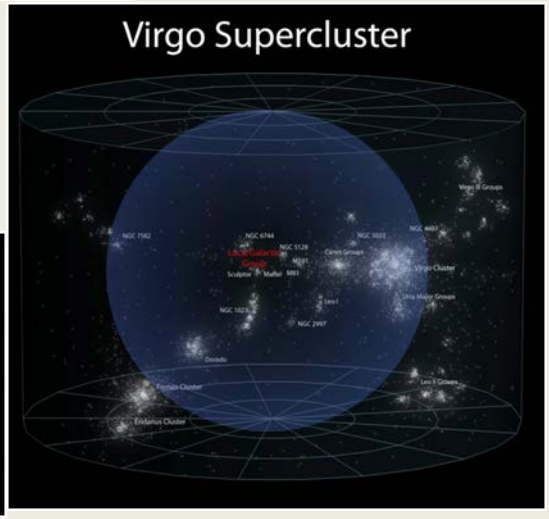
Initial LIGO's reach up to 100 galaxies

Era of Advanced GW detectors: 2015+



- Adv LIGO: 4×10^{-20} m/√Hz
- 10x sensitivity; 10x Distance);
- 1000 volume: 1000X event rate





Very surprising if we did NOT detect anything with Advanced LIGO!!! With rate of 1 NS-NS per galaxy per 10,000 yrs and aLIGO reaching up to 100,000 galaxies , we could see 1 event per month!!

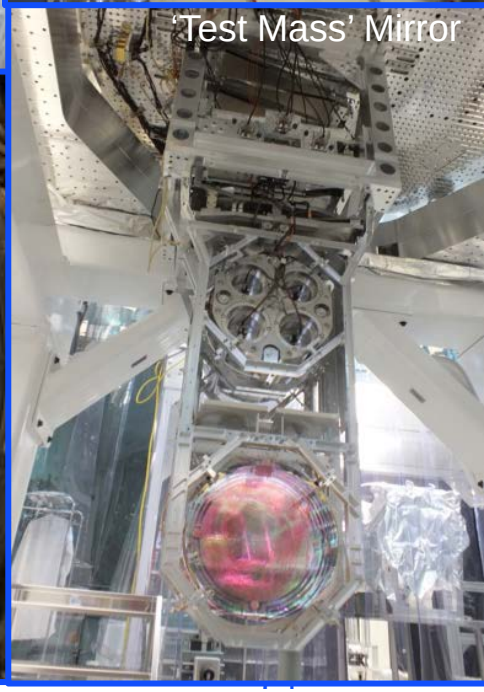
Advanced LIGO anticipated to be a Discovery machine..

First Science run O1 began in Sept and will end in Jan..

LIGO

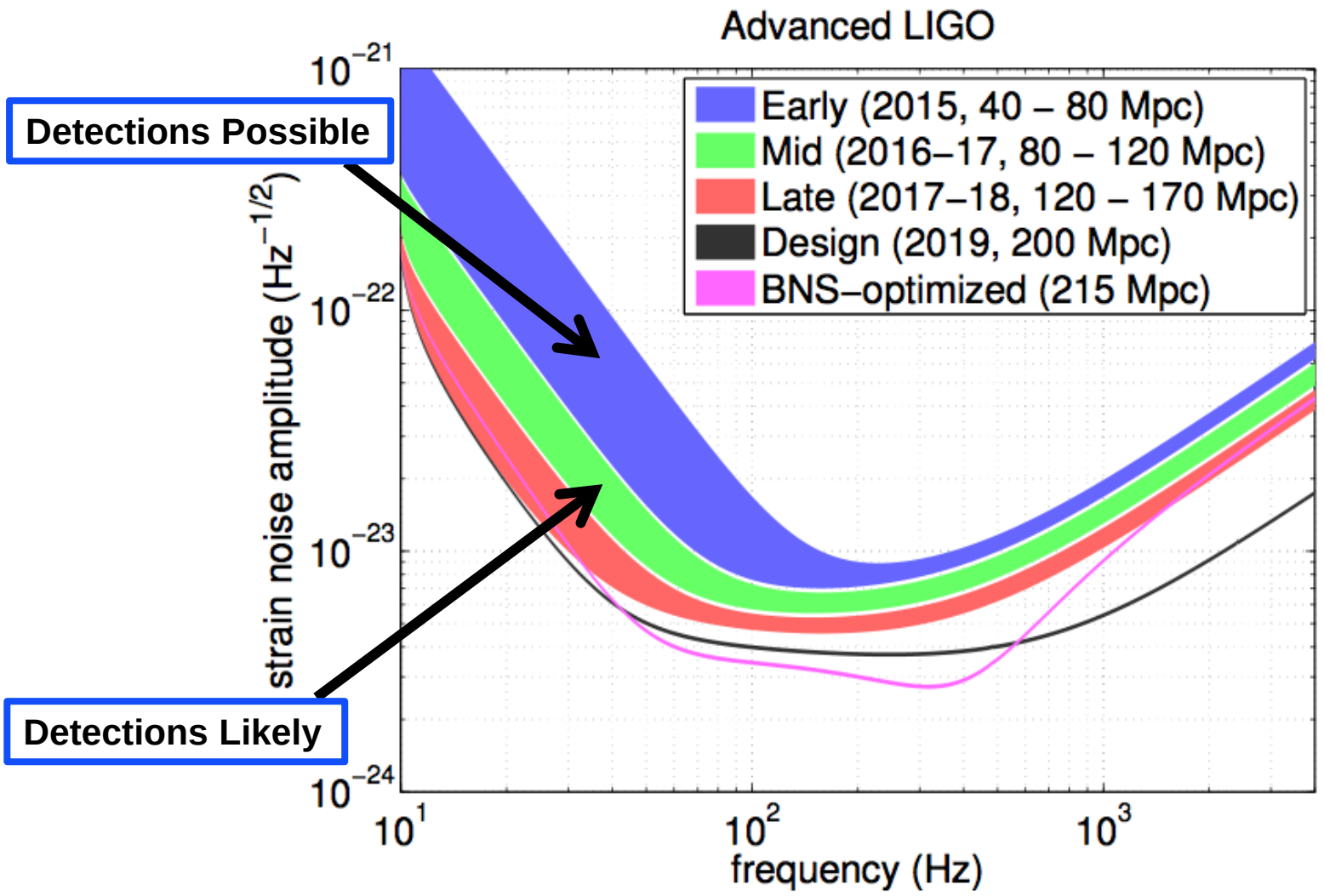
Courtesy: D. Reitze

Advanced LIGO in Pictures



LIGO

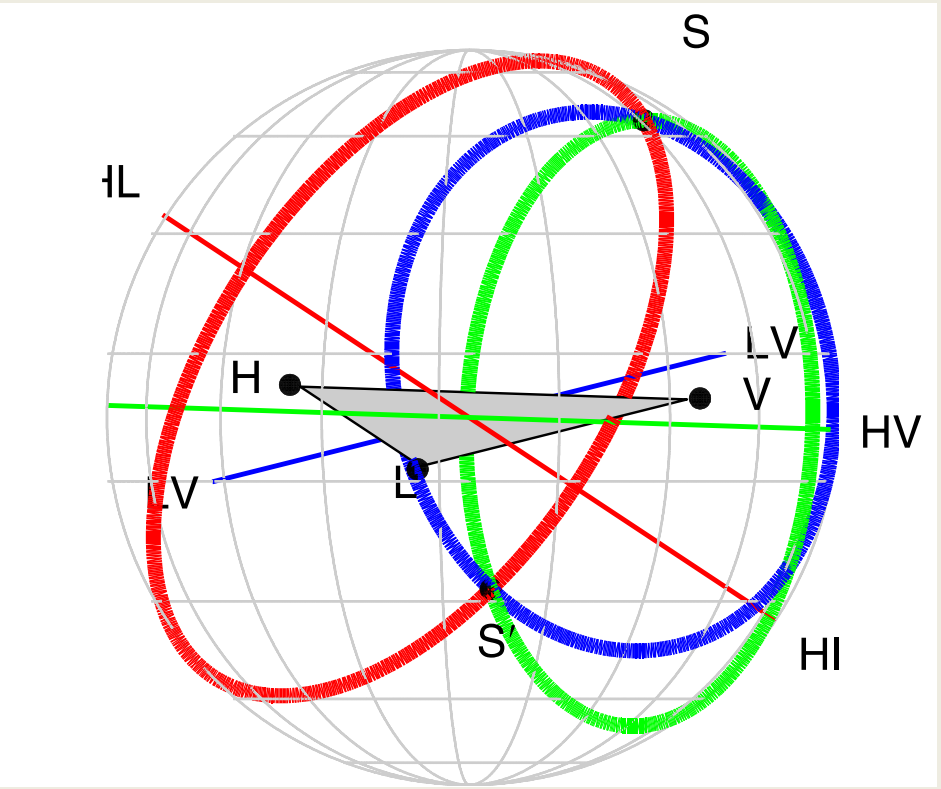
A look at the near future of Observations – when do we think we can see something?



Courtesy Shoemaker

Where do Einstein's Messengers (GW) come from and what are they???

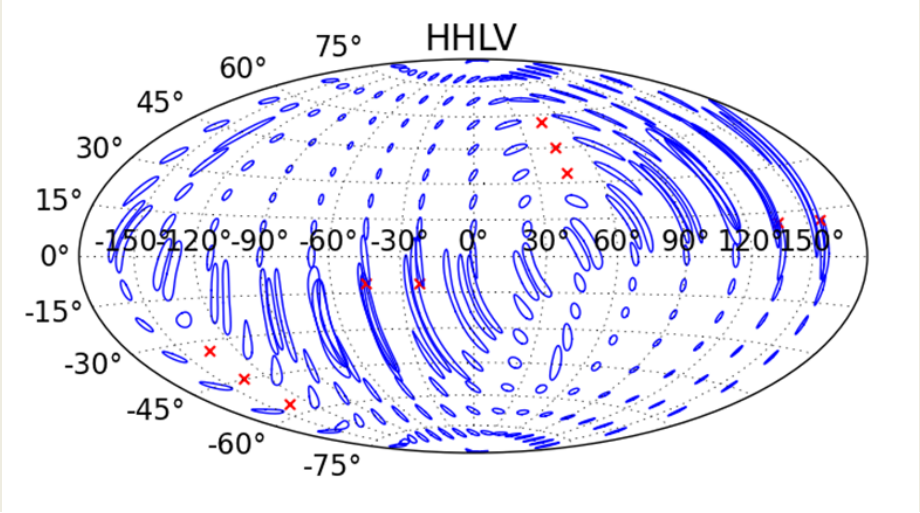
LOCALIZATION

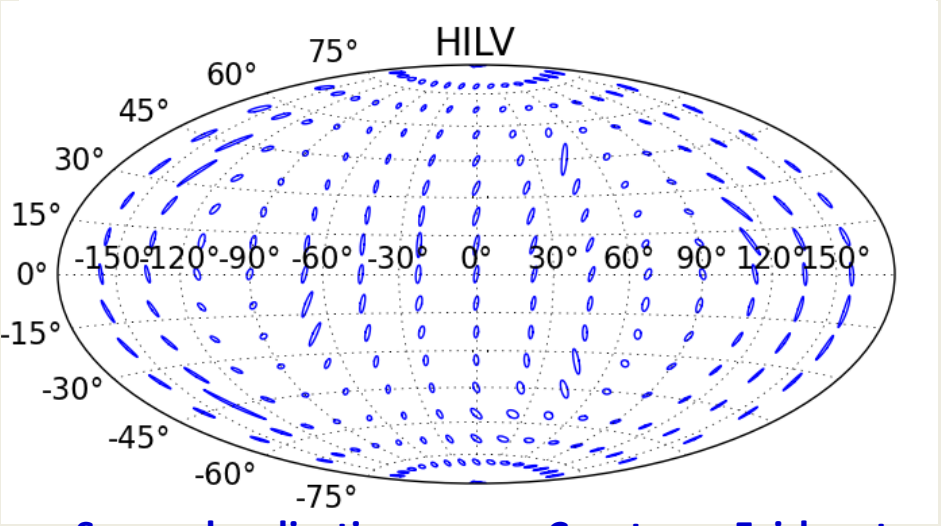


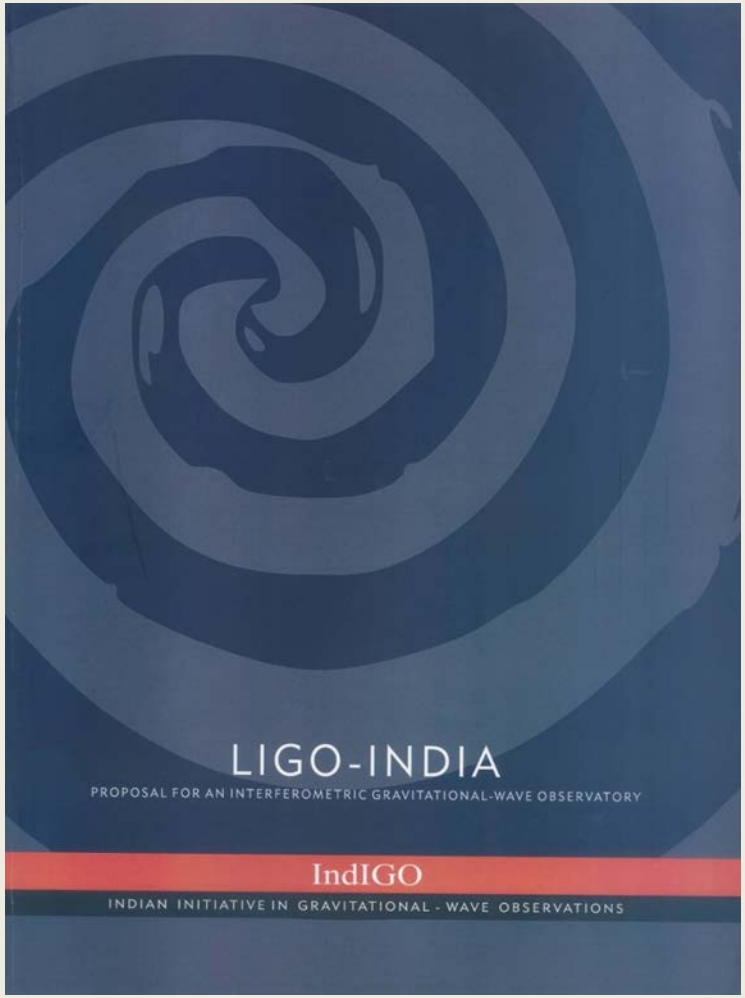
Courtesy: LIGO-G1200972-v3

- ✓ Triangulation using measured Time delays between sites
- ✓ Errors on TOA and Site location determine sky location uncertainty
- ✓ 2 sites – 1 time delay Localized Ring in Sky
- ✓ 3 Sites – 2 Time delays – Mirror images in Detector Plane
- ❑ Localization poor for sources in and close to plane

LIGO-India
Towards GW Astronomy





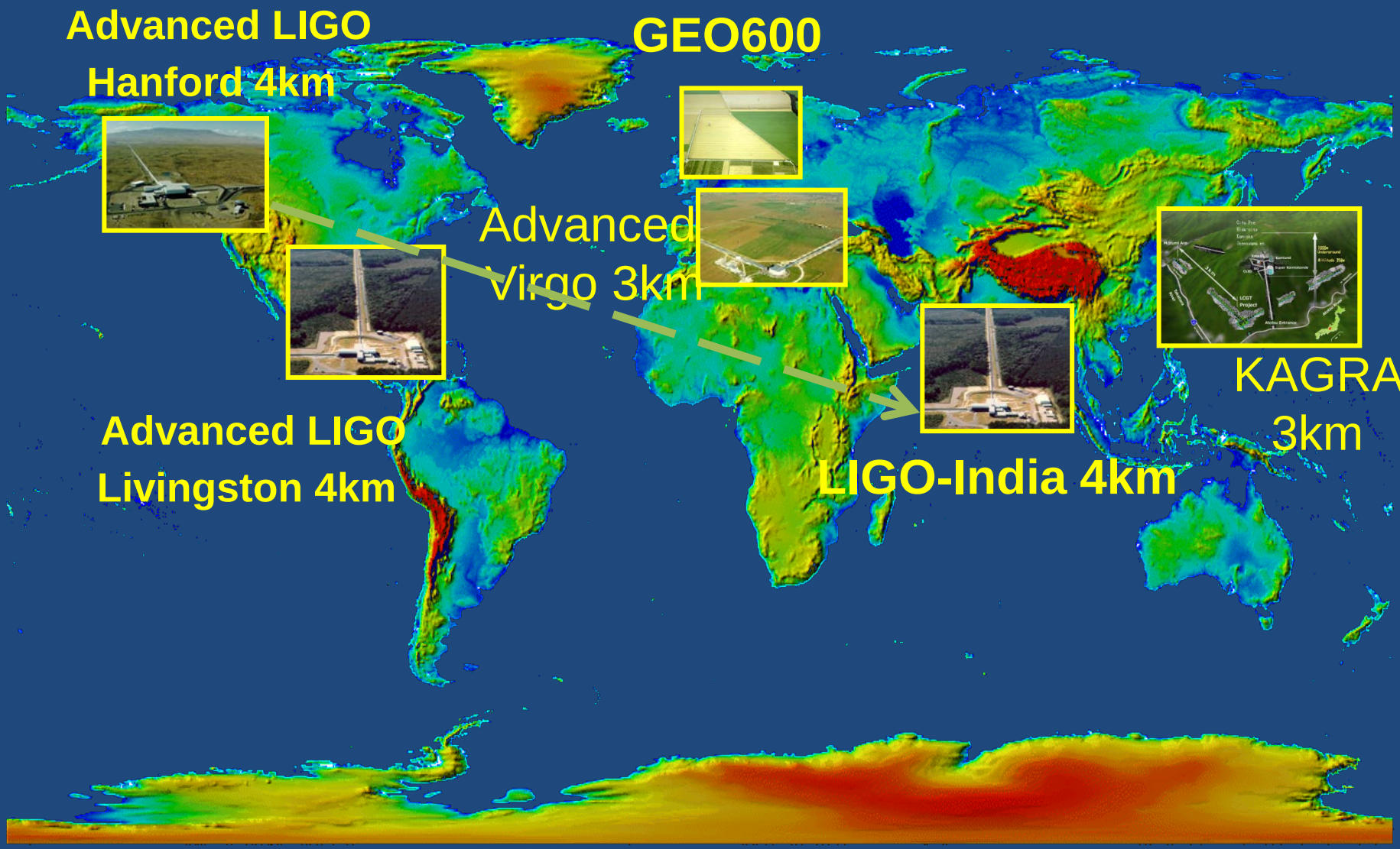


Source localization error – Courtesy: Fairhurst

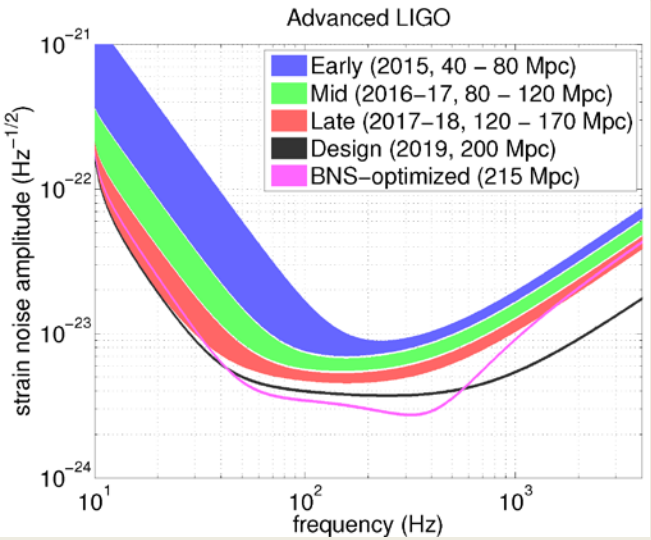
Similar results: Sathyaprakash;

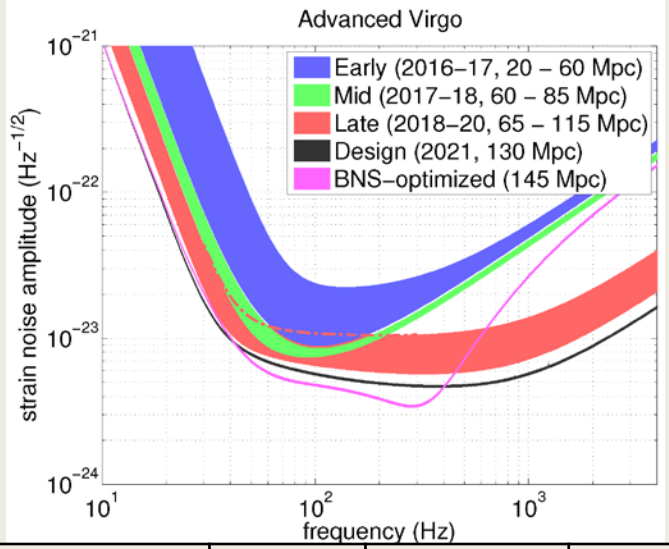
Klimenko & Vedovato

The GW Detector Network ~ 2022



The road to detections…



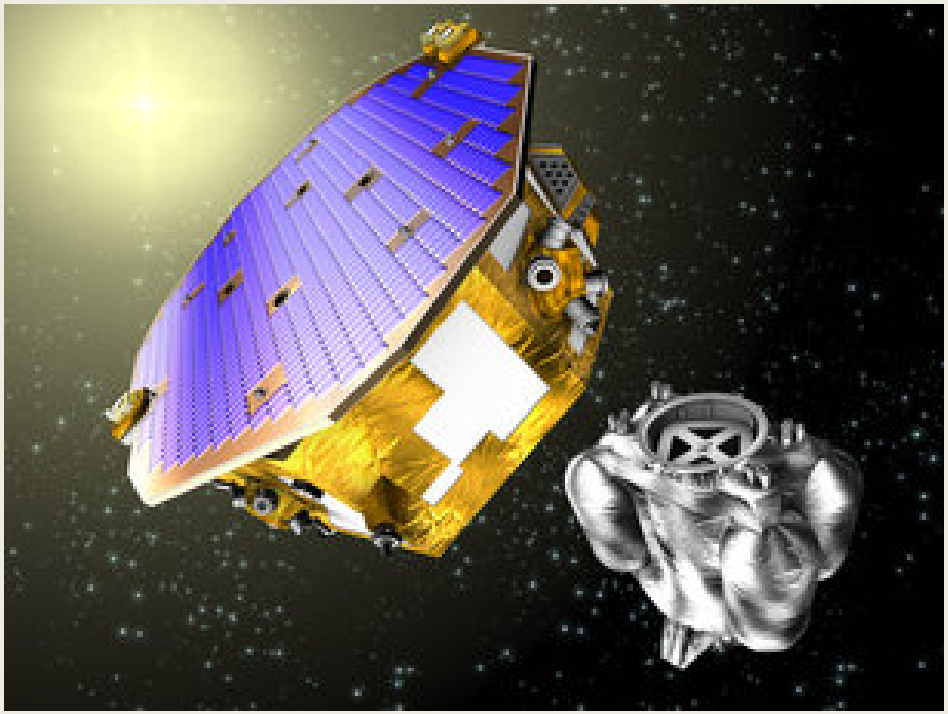


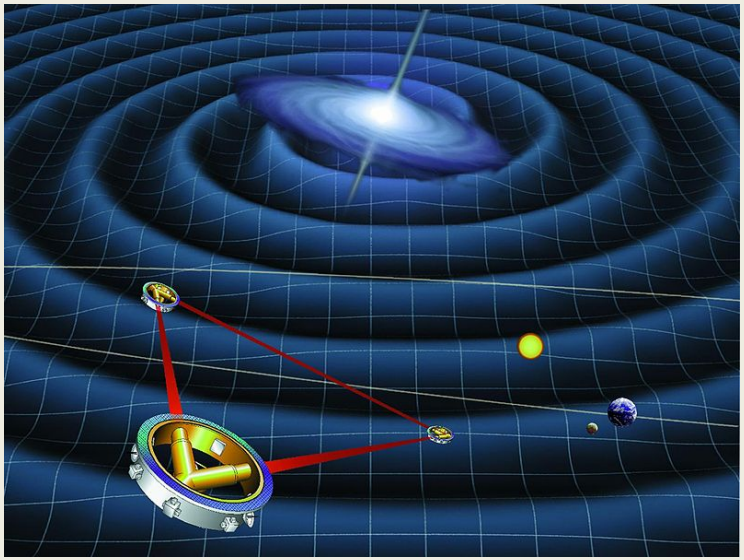
Aasi et al 2013 arXiv 1304. 0670

Epoch	Run Duration	BNS Range (Mpc) LIGO	BNS Range (Mpc) Virgo	Number of BNS Detections	Median Area Sq.Deg	% BNS Localized in 5 Sq. deg	%BNS Localized in 20 Sq.deg
2015	3 months	40 - 80	-	.0004 – 3	2000	-	-
2016-17	6 months	80 - 120	20 – 40	.006 - 20	70	2	5 - 12
2017-18	9 months	120 -170	40 - 50	.04 - 100	84	1 - 2	10 - 12
2019+	Per year	200	40 -80	0.2 - 200	31	3 - 8	8 - 28
2022+ **LIGO-India**	Per year	200	80	0.4 - 400	11	**17**	**48**

Successful operation of Advanced Detectors will transform the field from GW Detection to GW Astronomy when LIGO-India joins the global GW detector network

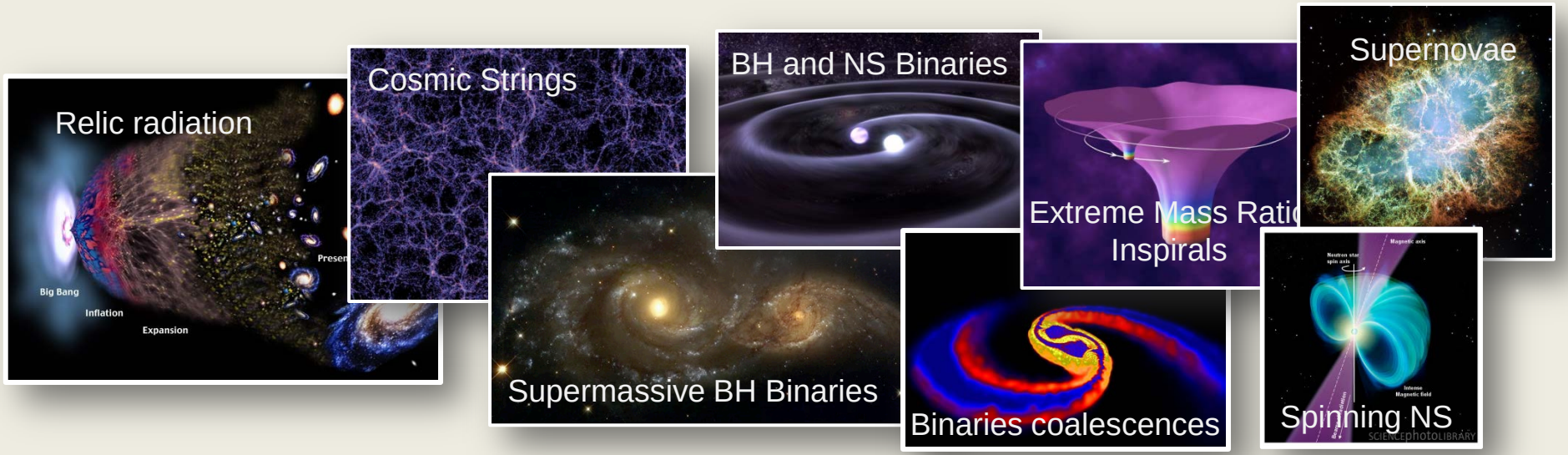
Towards eLISA – LISA Pathfinder





- LISA Pathfinder: Test in flight concept of low-frequency GW detection
- Put two test masses in a near-perfect gravitational free-fall, control and measure their motion with unprecedented accuracy.
- Use inertial sensors, a laser metrology system, a drag-free control system and an ultra-precise micro-propulsion system.
- **Launched: 3 Dec 2015**
- eLISA 2034

The GW Spectrum



10^{-16} Hz — 10^{-9} Hz — 10^{-4} Hz — 10^{0} Hz — 10^{3} Hz

Inflation Probe | Pulsar timing | Space detectors | Ground interferometers

Courtesy: M. Evans,

The Future

Quantum Gravity: Ideas in search of an Experiment

Profound Impact But Deeper Problems

In spite of intense work over half a century by many brilliant minds we do not know how to consistently put together Quantum Mechanics and General Relativity:

Quantum Gravity is still an open problem. Insights mainly from mathematical structure..

Loop quantum gravity, Superstrings, Causal Sets, ….

No clear unambiguous inputs from observations or experiments..

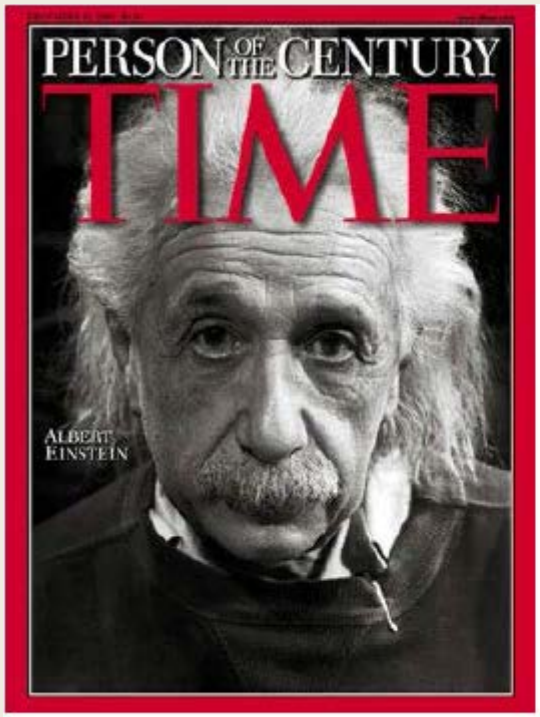
GR – A hundred years later

- General Relativity is Characterized not only by mathematical elegance and conceptual depth but amazing observational success over the century
- Has revealed unforseen facets and gone far beyond the initial traditional mathematics connections to symbiotic exchanges with new emerging areas like geometric analysis, numerical computations, high energy physics and gravitational wave astronomy.
- Exhibits Increasing mathematical sophistication; Uses Advances in Technology & precision measurement techniques
- Four centuries after Galileo's Telescope launched Optical Astronomy and a century after Einstein's inspired discovery of general relativity, a MAJOR revolution in astronomy is round the corner with a facility in India, LIGO-India, having the opportunity to play a key role.

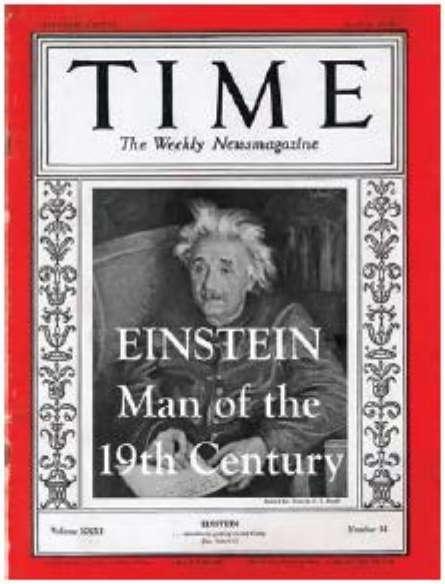
GR – A hundred years later

- Though Einstein seems to be right, Is he 100% **Right??**
- In spite of its spectacular success, even Newtonian gravity had to change after 200 years; Neutrino properties that received the Nobel Prize this year after seventy..
- Many Enigmatic aspects of Gravity still remain. Decoding Gravitation is the holy grail and the Odyssey encompasses the whole universe most of it dark but inevitably gravitating
- GR has become an integral part of the core toolkit every physicist must be equipped with to investigate and comprehend the universe we live in…
- And what about Einstein..

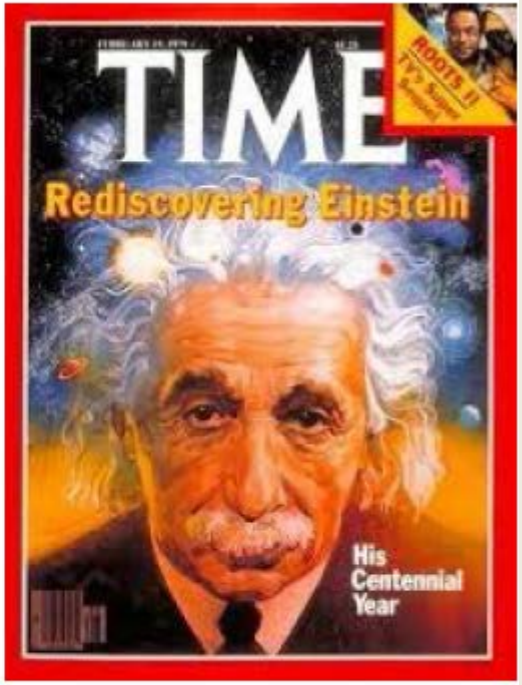
Timeless…



Time magazine cover (1999)

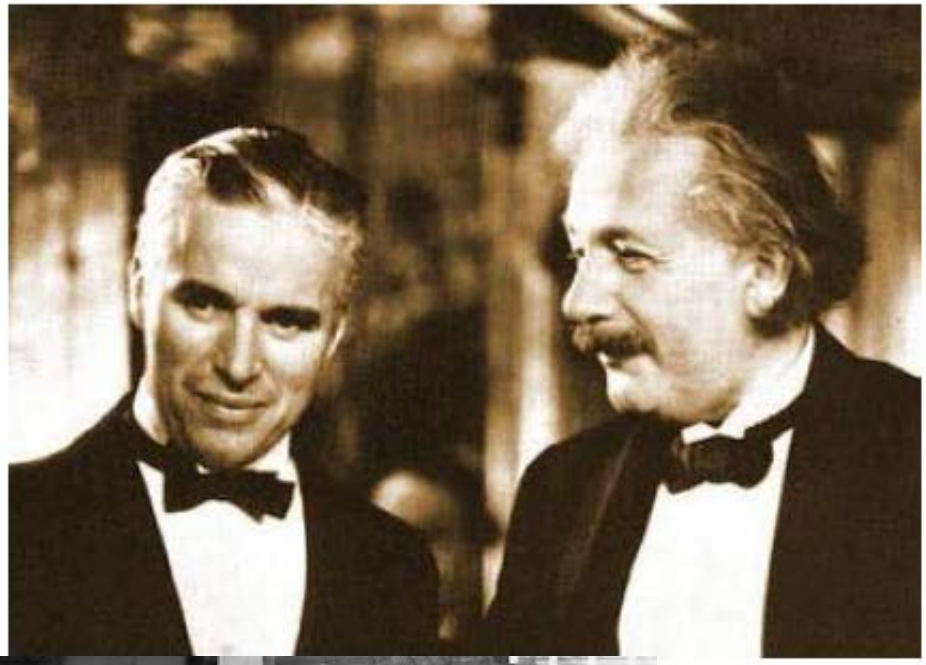


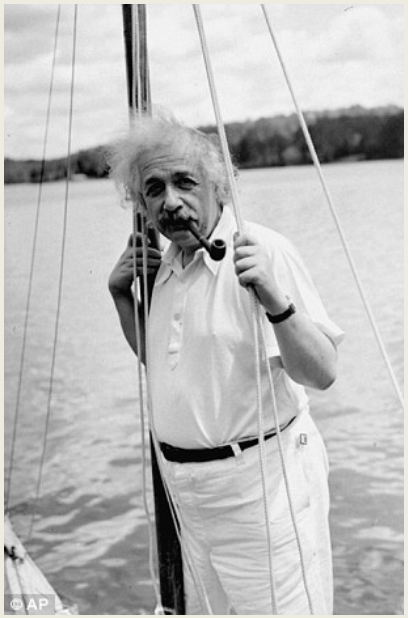
Time magazine cover (1922)

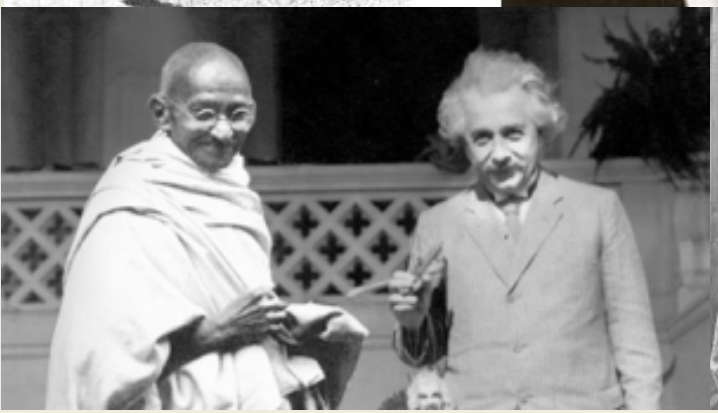


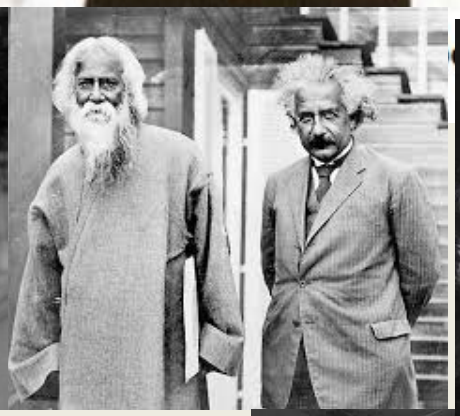
Time magazine cover (2005)

Man of 19th Century in 1922,
Centenary of whose 1905 Annus Mirabilis
was declared Year of Physics,
Who was voted Person of the Century in 1999

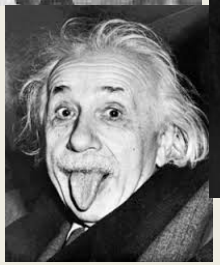




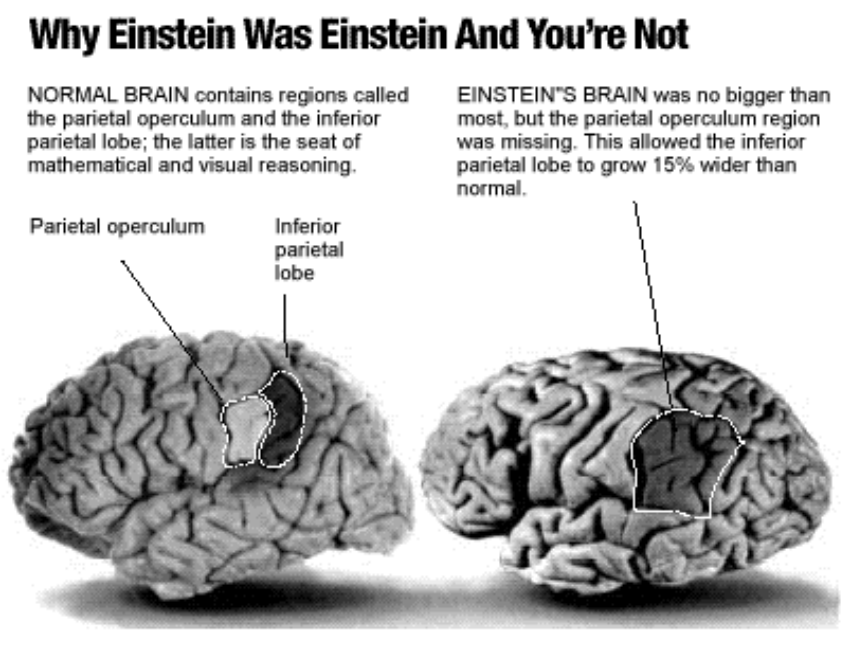


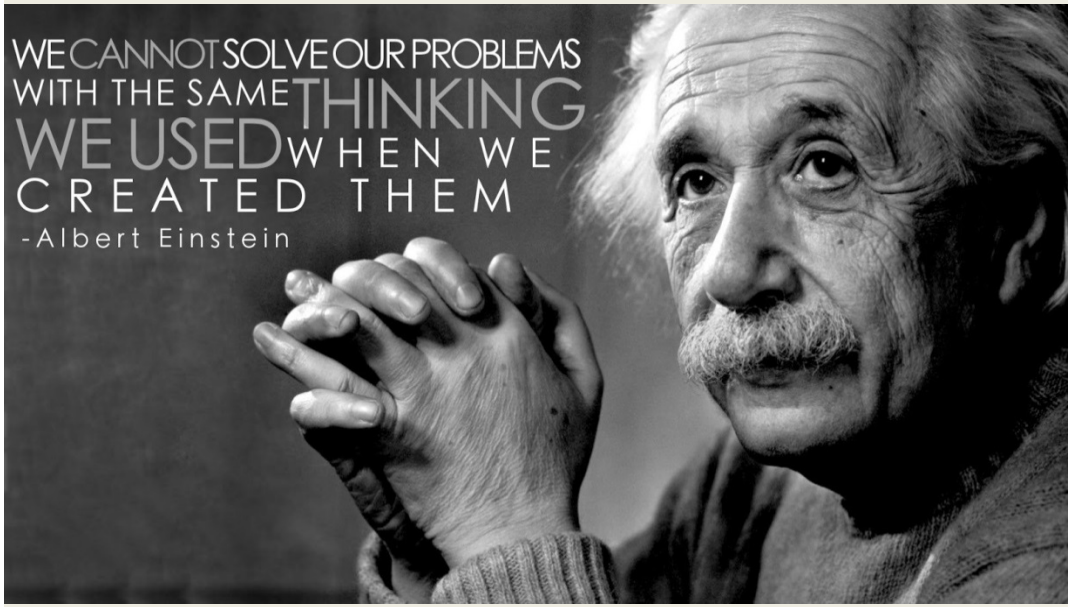


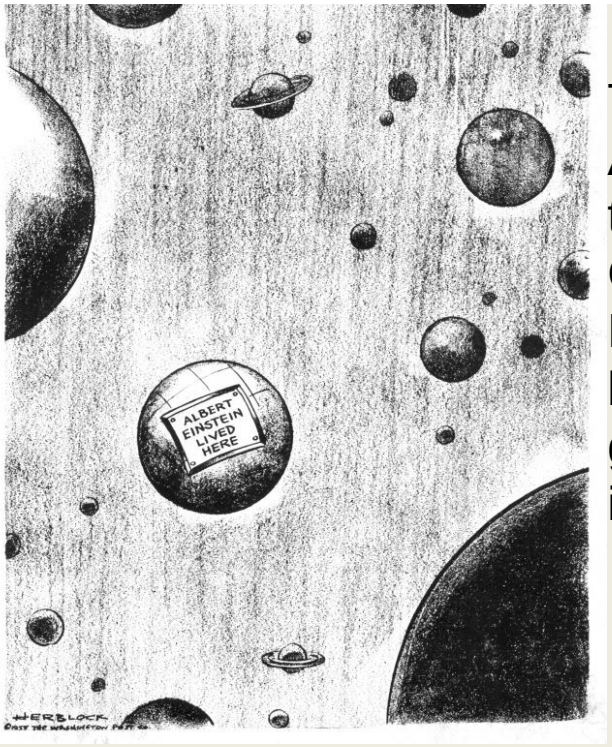
Unique was his science
And insight, But
Personally always
connected to the
humanity around him



Nothing inspires more than advice U did not expect







The Ideal to aspire for,
And the epitaph for
the Earth and our
Civilization ..
Not just In science
but in the Complex
grey times We live in,
it is good To remember
that..

ThanqFyA