Galactic and Extra-galactic Shapiro delay

Shantanu Desai

IIT Hyderabad

Collaborators:

Sibel Boran (Istanbul Technical Univ)

Emre Kahya (Istanbul Technical Univ.)

Richard Woodard (Univ. of Florida)

IPTA Catch-up Meeting 2020

arXiv:1602.04779 Phys. Lett. B 756, 265

arXiv:1710.06168 Phys. Rev. D, 97, 041501

arXiv:1807.05201 EPJC 79, 85

Shapiro Delay

Irwin Shapiro (1964)

FOURTH TEST OF GENERAL RELATIVITY

Irwin I. Shapiro
Lincoln Laboratory,* Massachusetts Institute of Technology, Lexington, Massachusetts
(Received 13 November 1964)

Recent advances in radar astronomy have made possible a fourth test of Einstein's theory of general relativity. The test involves measuring the time delays between transmission of radar pulses towards either of the inner planets (Venus or Mercury) and detection of the echoes. Because, according to the general theory, the speed of a light wave depends on the strength of the gravitational potential along its path, these time delays should thereby be increased by almost 2×10^{-4} sec when the radar pulses pass near the sun.[1] Such a change, equivalent to 60 km in distance, could now be measured over the required path length to within about 5 to 10% with presently obtainable equipment.[2]

Measurements over
last 5 decades
at all scales from
solar system to
binary pulsars to Cosmology

Used as tests of GR
and also as an
astrophysics probe
to measure masses of
neutron stars in binary
systems and also to measure H_0

Examples of Shapiro Delay Measurements

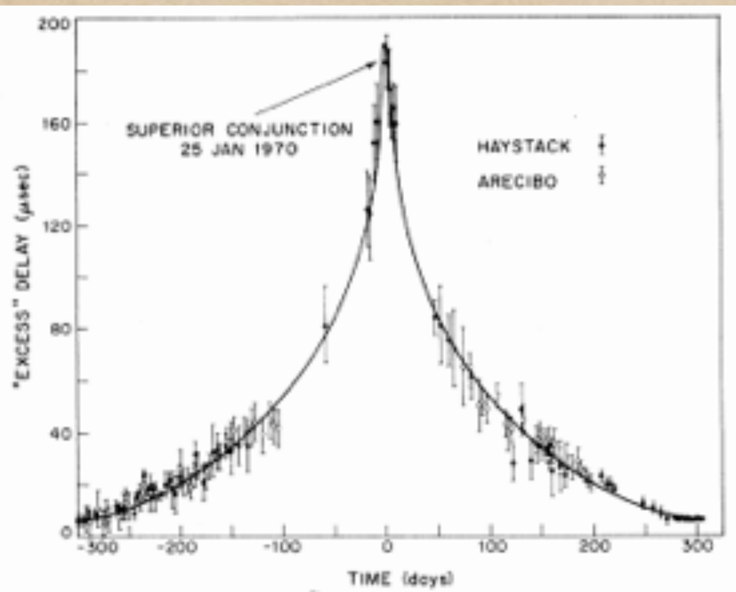
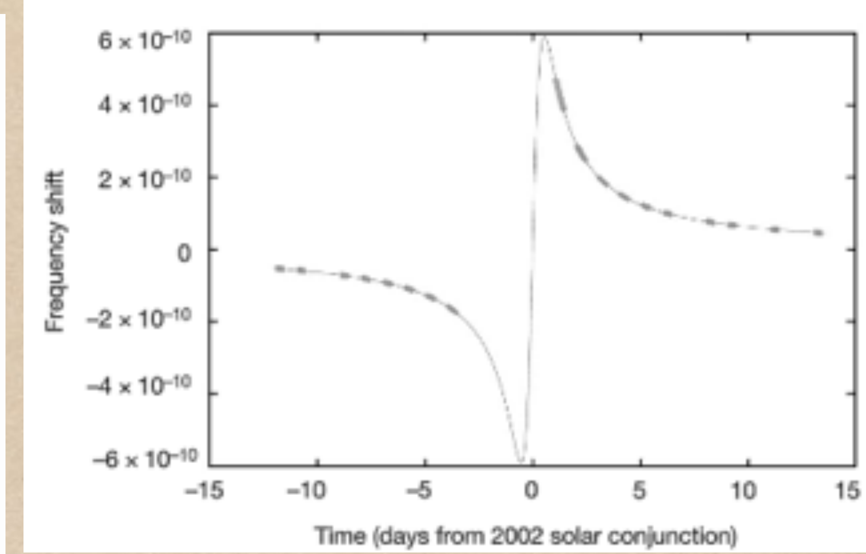


FIG. 1. Typical sample of post-fit residuals for Earth-Venus time-delay measurements, displayed relative to the "excess" delays predicted by general relativity. Corrections were made for known topographic trends on Venus. The bars represent the original estimates of the measurement standard errors. Note the dramatic increase in accuracy that was obtained with the radar-system improvements incorporated at Haystack just prior to the inferior conjunction of November 1970.

Shapiro et al, 1971
PRL 26,1132



Bertotti et al 2003
Nature 425, 374
Cassini Satellite

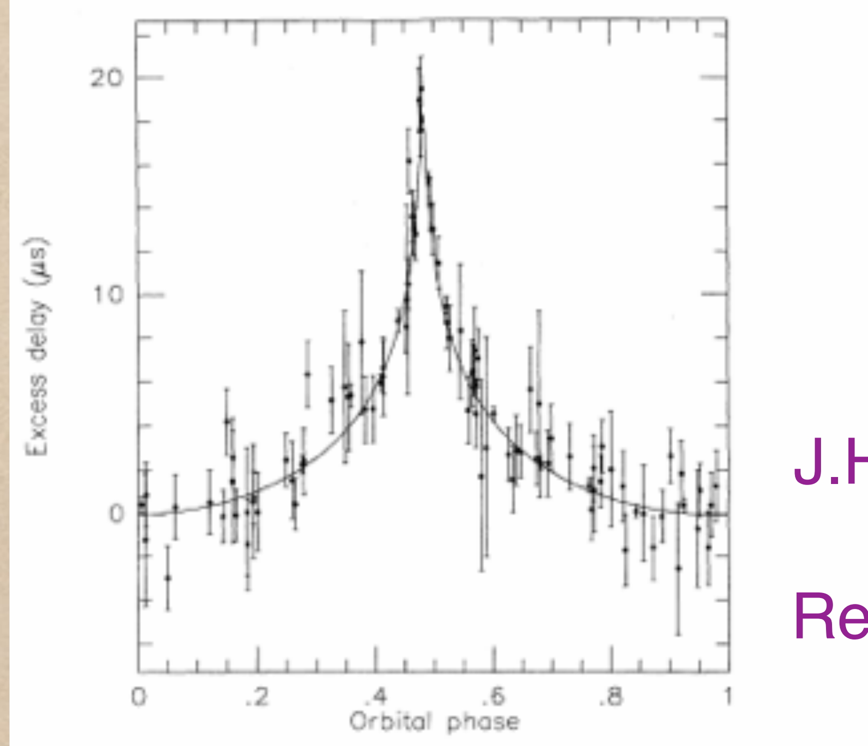


FIG. 8. Measurements of the Shapiro time delay in the PSR 1855+09 system. The theoretical curve corresponds to Eq. (10), and the fitted values of r and s can be used to determine the masses of the pulsar and companion star.

J.H. Taylor, Nobel Prize lecture
Rev. Mod. Phys. 66,711
1994

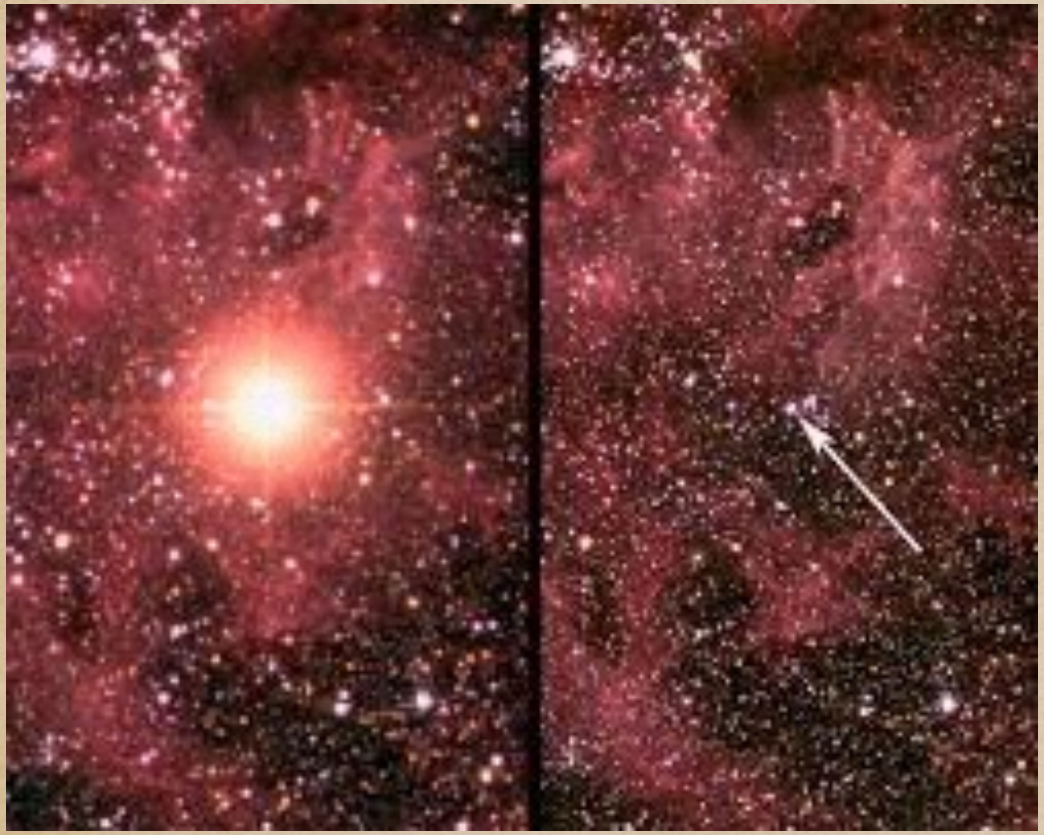
Also Shapiro delay from Sun, Jupiter, Venus, Uranus, Neptune used in MSP timing model

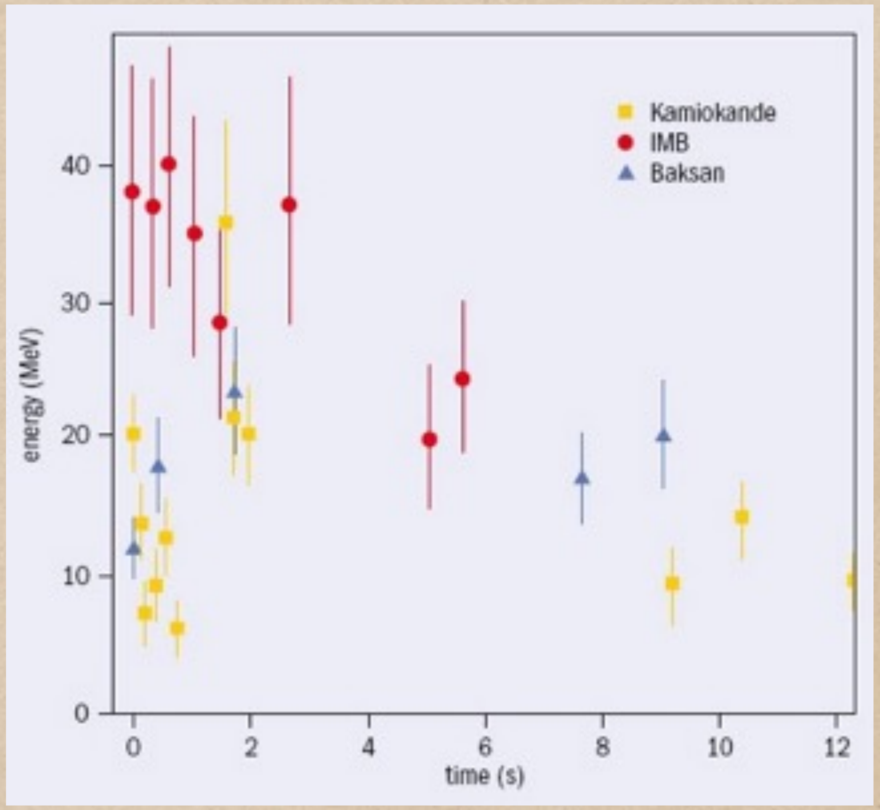
First mention of Galactic Shapiro delay in literature

D.C Backer and R.W. Hellings
Ann. Rev. of Astronomy and Astrophysics 24, 537 (1986)

where $\mathbf{r}_{pN}$ is the position of the receiver relative to the pth solar system body at the time of closest approach of the photon to that body, and $\mathbf{R}_{pN}$ is the pulsar's position relative to body p at time T_N (Shapiro 1964). The vector $\mathbf{n}$ is a unit vector in the direction of the pulsar. In principle, the sum in Equation 4.3 extends over all bodies along the photon path from the pulsar to the Earth, including interstellar objects. However, except in the case of a pulsar whose line of sight lies particularly close to some intervening star, the delay produced by interstellar gravitational fields will be essentially constant over tens of years of data and need not be modeled. The delay produced by the pulsar's own gravitational field will also be constant and may be neglected. The effects produced by the planets may need to be included, since a signal passing by Jupiter, for instance, may be delayed by as much as 200 ns by Jupiter's gravitational field.

Birth of multi-messenger Astronomy



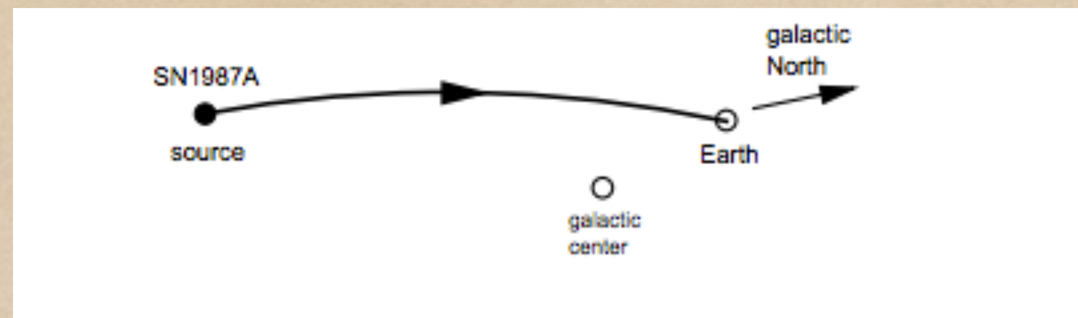


Detection of neutrinos from SN 1987 A (@50 kpc) followed by flash of optical light (4 hours later)

IMB, Kamiokande, Baksan

2002 Nobel Prize to Masatoshi Koshiba

First Galactic Shapiro delay calculation



New Precision Tests of the Einstein Equivalence Principle from SN1987A

Michael J. Longo
University of Michigan, Ann Arbor, Michigan 48109

(Received 14 September 1987)

As is shown below, the gravitational field of our galaxy causes a significant time delay, ≃5 months, in the transit time of photons from SN1987A. (This is the delay relative to the transit time expected if the gravitation of the galaxy could be "turned off.") The fact that the arrival time of the neutrinos from SN1987A was the same as that for the first optical photons from the supernova to within several hours allows an accurate comparison of the general-relativistic time delay of the photons and neutrinos. The arrival time of the neutrinos is known to

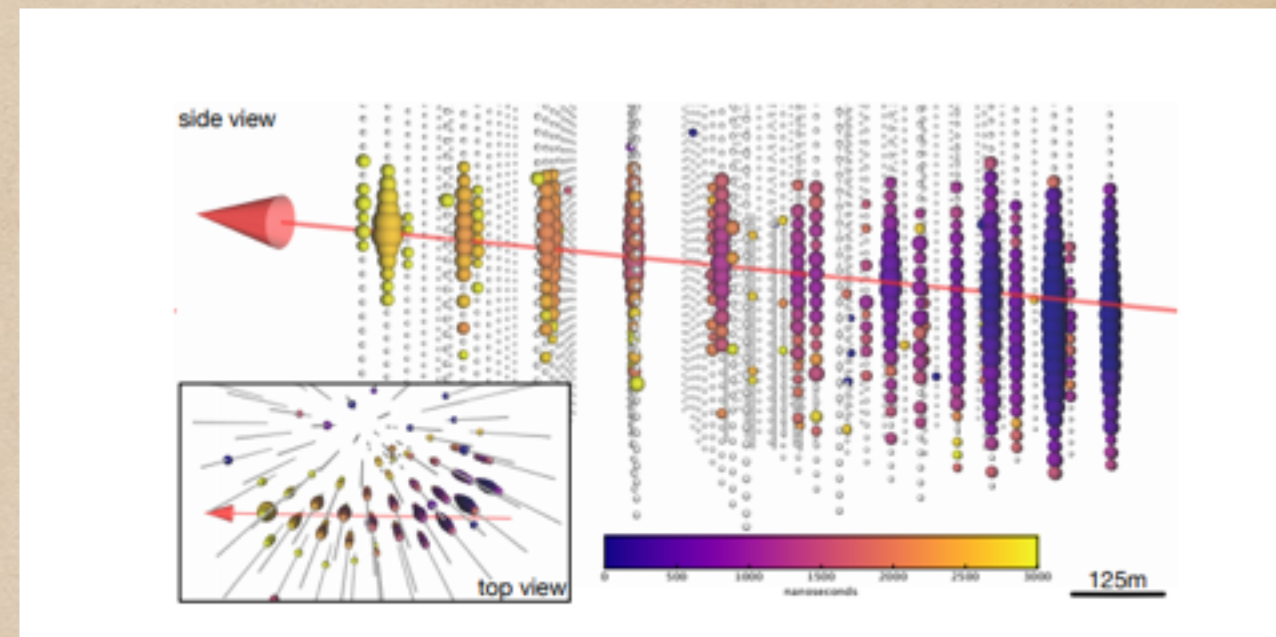
PRL 60, 173 (1988)
Also, Krauss & Tremaine (1988)
same issue of PRL next paper
First mention of this effect in
Becker & Hellings 86

$$\Delta\gamma \leq 2\,\frac{\Delta t}{\Delta t_{\rm shapiro}}\,.$$

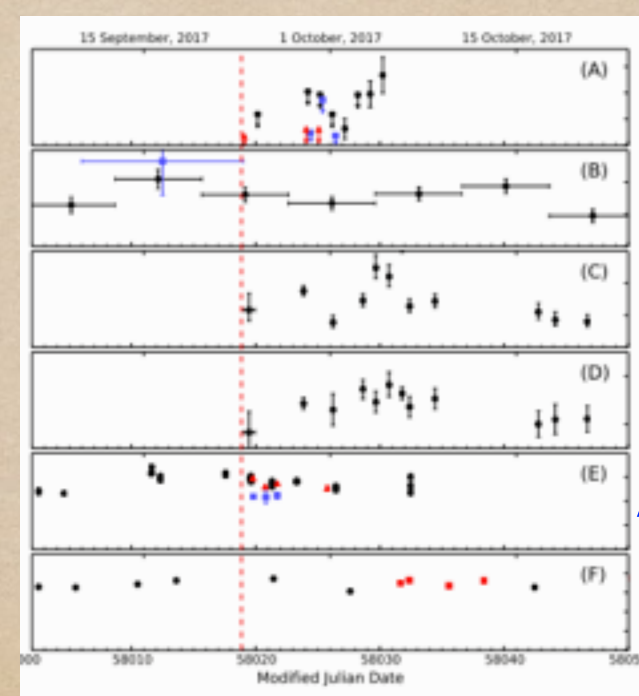
PPN gamma quantifying violation of WEP

Only direct proof that neutrinos are affected by gravity and obey equivalence principle (to within 0.2%)

IceCube coincident detection from TXS0506+056



E_ν = 290 TeV $\Delta\Theta$ ~ 0.1 deg



MAGIC, HESS, Veritas

Fermi-LAT, AGILE

SWIFT XRT

ASAS-SN. KISO/KWFC, kanata/HONIR

OVRO/VLA

Credit : IceCube

Significance ~ 3σ IceCube Coll. 1807.08816

Shapiro delay for IceCube-070922A

Constraints on differential Shapiro delay between neutrinos and photons from IceCube-170922A

Sibel Boran, Shantanu Desai, Emre O. Kahya

On 22nd September 2017, the IceCube Collaboration detected a neutrino with energy of about 290 TeV from the direction of the gamma-ray blazar TXS 0506+056, located at a distance of about 1.75 Gpc. During the same time, enhanced gamma-ray flaring was also simultaneously observed from multiple telescopes, giving rise to only the second coincident astrophysical neutrino/photon observation after SN 1987A. We point out that for this event, both neutrinos and photons encountered a Shapiro delay of about 6300 days along the way from the source. From this delay and the relative time difference between the neutrino and photon arrival times, one can constrain violations of Einstein's Weak Equivalence Principle (WEP) for TeV neutrinos. We constrain such violations of WEP using the Parameterized Post-Newtonian (PPN) parameter γ, which is given by $|\gamma_\nu - \gamma_{\rm EM}| < 5.5 \times 10^{-2}$, after assuming time difference of 175 days between neutrino and photon arrival times.

Similar calculations for same event in R. Laha 1807.05621 ; Wei et al 1807.06504

TABLE I: The limits on violation of WEP between neutrinos and photons from previous literature, along with the result from this work.

Source	Messengers	Gravitational Field	$\Delta t = \|t_\nu - t_{\rm EM}\|$	$\Delta\gamma = \|\gamma_\nu - \gamma_{\rm EM}\|$
SN 1987A	ν(MeV) – EM(eV)	Milky Way	6 hrs [11]	3.4×10^{-3} [11]
SN 1987A	ν(MeV) – EM(eV)	Milky Way	10^4 s [12]	4×10^{-3} and 7×10^{-4} [12]
Blazar TXS 0506 + 056	ν(PeV) – EM(eV)	Laniakea supercluster of galaxies	7 days [44]	3.5×10^{-7} [44]
Blazar TXS 0506 + 056	ν(TeV) – EM(eV)	Laniakea supercluster of galaxies	15 days [45]	7.3×10^{-7} [45]
Blazar TXS 0506 + 056	ν(TeV) – EM(eV)	Laniakea supercluster of galaxies	175 days [45]	8.5×10^{-6} [45]
Blazar TXS 0506 + 056	ν(TeV) – EM(eV)	All Milky Way – like galaxies along line – of – sight	175 days	5.5×10^{-2} (This work)

arXiv:1807.05201

Shapiro delay For GWs

As

$$\frac{\delta t_\gamma(\gamma_{ray}) - \delta t_{opt}}{\delta t_\gamma} = ½\,(\gamma_\gamma - \gamma_{opt}) < 20/9 \times 10^7$$

(from the observed delay of 20 seconds)

This gives

$$\gamma_\gamma - \gamma_{opt} \leq 4 \times 10^{-7} \qquad (7)$$

Thus γ_{ray} and optical photons 'see' the same gravitationally induced time delay to about 4 parts in 10^7 and the difference between gamma and radio photons is about one part in 10^3 (as here $\delta t \sim 1$day). If future detectors are able to register simultaneously neutrino and gravitational waves during gamma rays bursts, all the above formulae would give similar constraints on their properties and limits on violation of EEP for them also.

First proposed test by C. Sivaram (1999)

Bulletin of Astronomical Society of India 27,627

Gravitational waves gravitate due to a static potential at infinity.

Shapiro delay for GW150914

Kahya, SD Phys. Lett. B 756, 265 (2016)

$$\Delta t^{MW}_{shapiro} = (1+\gamma)\frac{GM_{\rm MW}}{c^3}\ln\left(\frac{d}{b}\right) ,$$

Milky way contribution ~ 300 days @400 Kpc
Logarithmic enhancement of three @ 400 Mpc
Estimate total no of Milky way galaxies upto 400 Mpc

Consider a cylindrical line of sight with surface area from galaxy viral radius (250 kpc) and height determined by distance to the source and divide by volume of sphere of radius 400 Mpc x no of galaxies within spherical volume

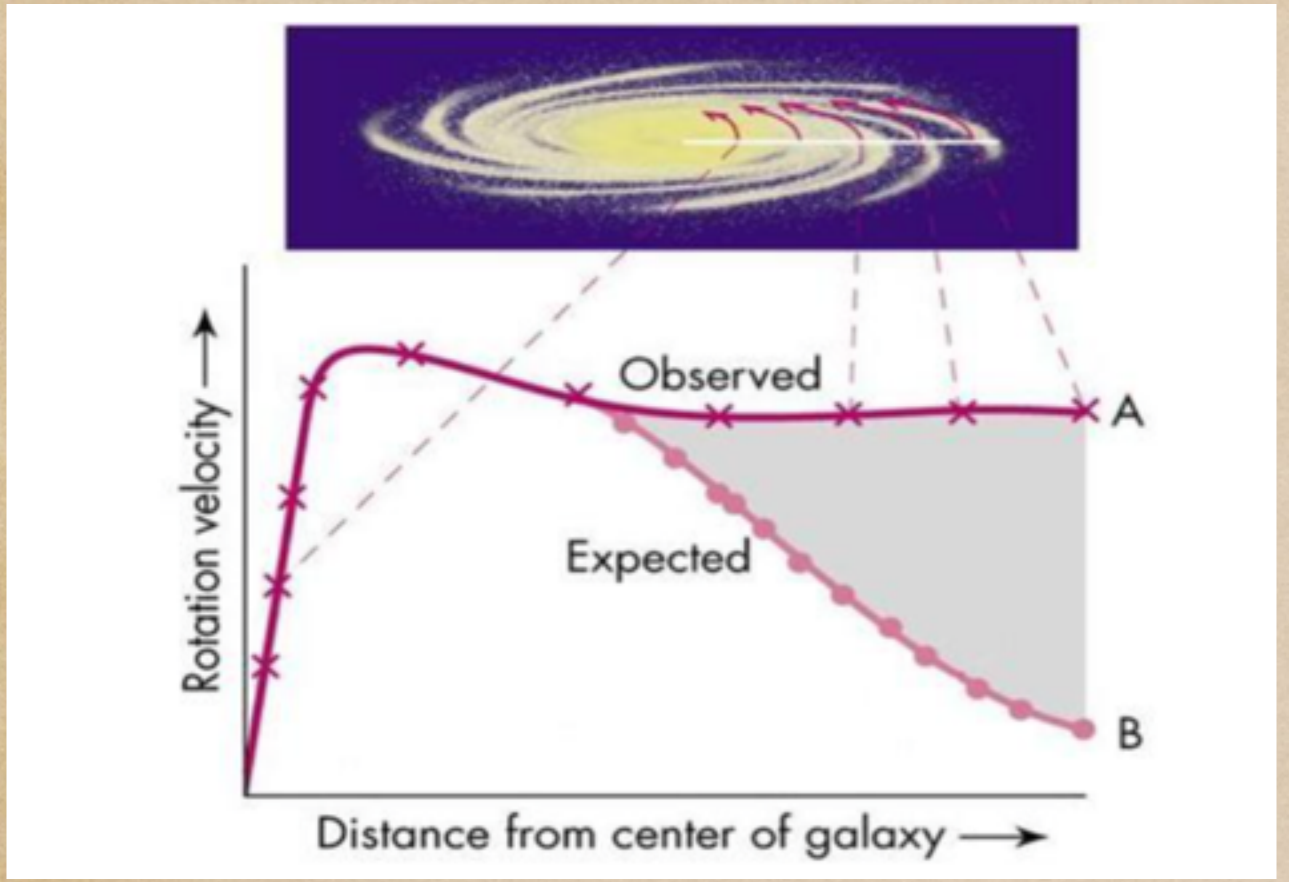
$\sim (r_{vir}/400\ \mathrm{Mpc})^2 \times N_{tot}$

For $N_{tot} = 3 \times 10^6$ & $r_{vir} = 250$ kpc ~ two

Total Shapiro delay = 300 x 6 ~ 1800 days

→ $|\Delta\gamma| < 10^{-9}$ for $\Delta t \sim 0.4$ secs

Galactic Rotation Curves



Conventional interpretation is most of mass of galaxy made up dark matter haloes.

Milgrom noticed (1983): ⟶ MOND

- **Need for D.M. arises below a fixed acceleration scale (10^{-8} m/s^2)**

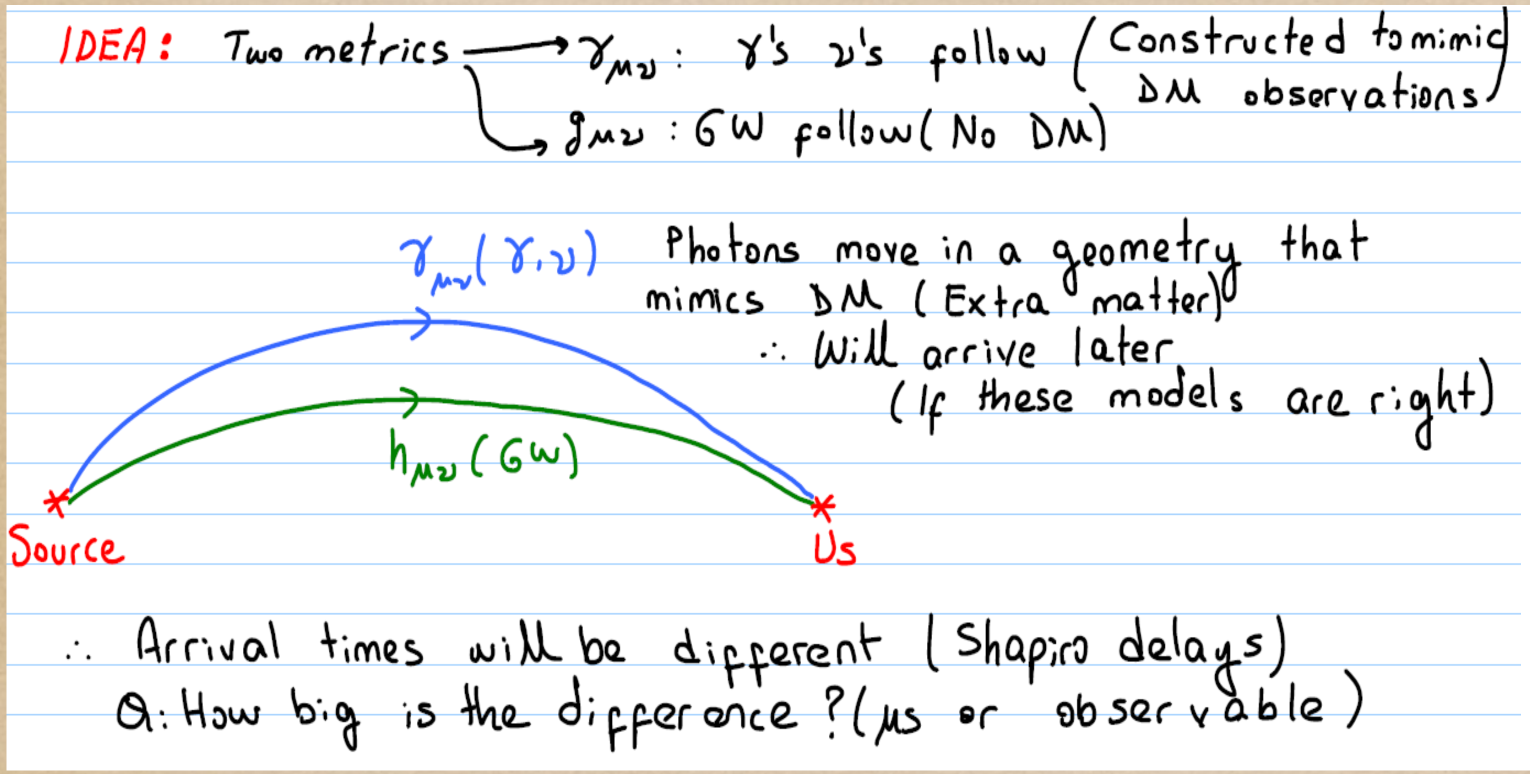
$$a = a_{\rm newt}(a_{\rm newt}/a_0)^{-1/2} \text{ for } a < a_0$$

- **Explains flat rotation curve and Tully-Fisher relation**

$$L \propto v^4$$

No-go theorem (Soussa/Woodard 2003)

Cannot construct metric theory of MOND and agree with solar system tests of GR and explain lensing without dark matter (astro-ph/0307358)



For a whole class of modified gravity models which avoid dark matter :

- Shapiro Delay for light/neutrinos = Potential of visible + dark matter.
- Shapiro Delay for gravity waves = Potential of visible matter only.

GW170817: First BNS merger with EM counterparts

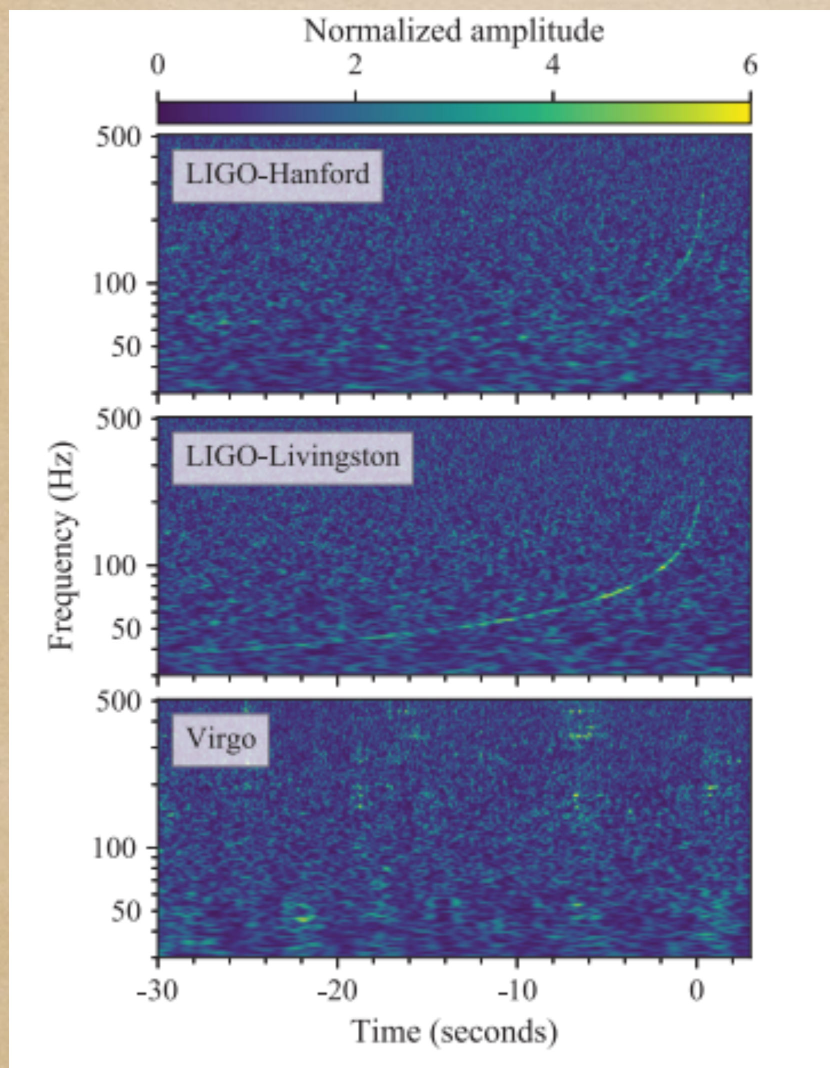
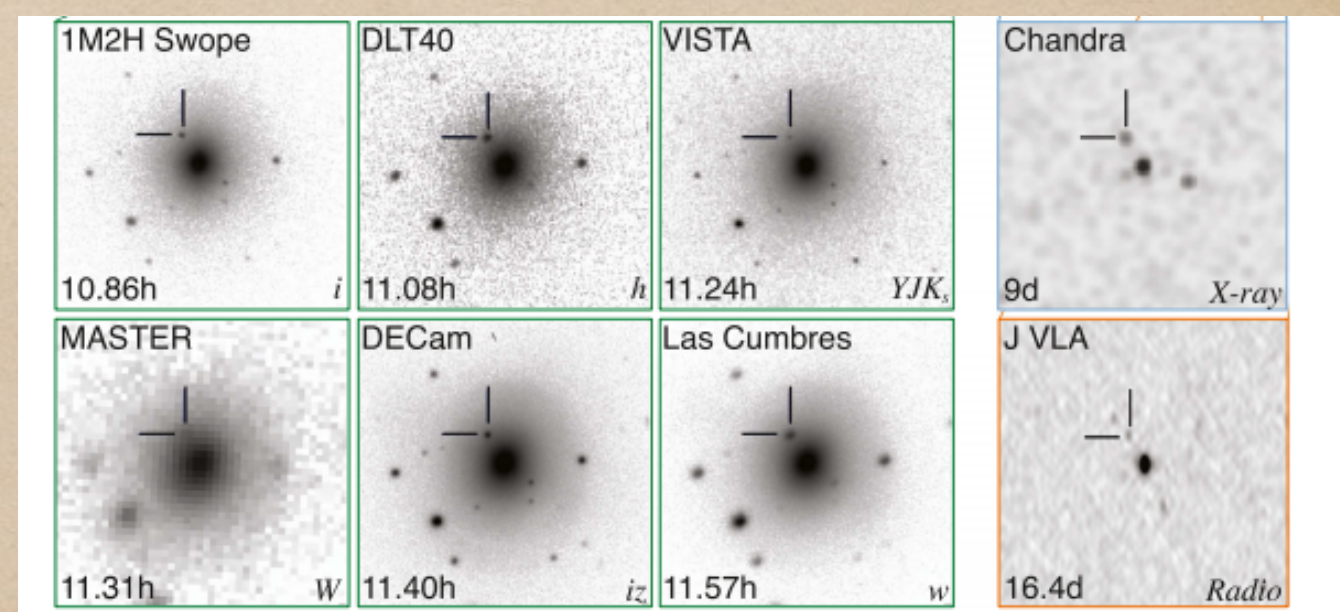


TABLE I. Source properties for GW170817: we give ranges encompassing the 90% credible intervals for different assumptions of the waveform model to bound systematic uncertainty. The mass values are quoted in the frame of the source, accounting for uncertainty in the source redshift.

	Low-spin priors ($\|\chi\| \leq 0.05$)	High-spin priors ($\|\chi\| \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance D_L	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400



Shapiro delay for GW170817

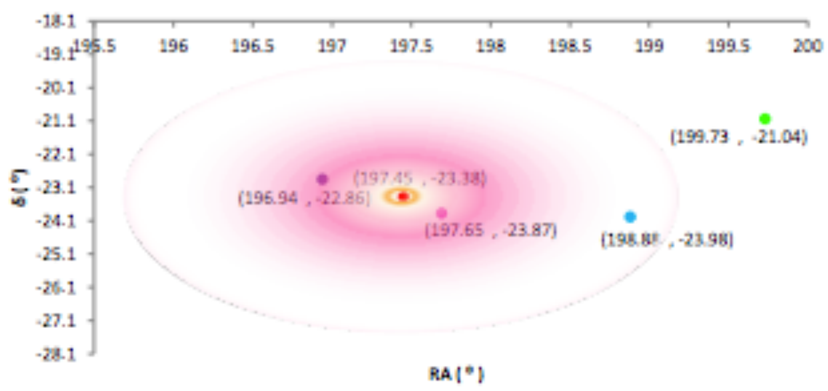


FIG. 1: The angular locations of galaxies which affect the Shapiro delay of any cosmic messenger coming from NGC 4993

Boran,SD, Kahya, Woodard, PRD 97, 041501

Shapiro delay for our galaxy

$$\Delta t_{\rm shapiro} = (1+\gamma)\frac{GM}{c^3}\ln\left(\frac{d}{b}\right) ,$$

For a cored isothermal profile T_{sh}~ 115 days for a source at 200 kpc
Taking into account contribution of NGC 4993 total delay ~ 400 days.

Observed delay between gamma rays and GWs < 2 seconds

→ **All Dark matter emulator models completely ruled out**

Conclusions

- **Line of Sight Galactic and Extra-Galactic Shapiro delay important probe of how different cosmic messengers couple to gravity, even though direct measurement not possible. They allow tests of WEP**

- **GW170817 results show that Shapiro delay of gravitational waves is same as that of photons, which rules out a whole class of modified gravity theories called "Dark Matter Emulators".**