भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

Part I: Bound on graviton mass using galaxy clusters

Shantanu Desai
IIT, Hyderabad

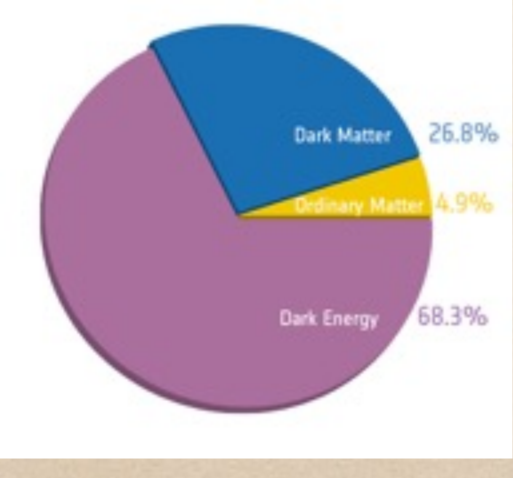
Kavli IPMU seminar
June 26, 2018

Based on arXiv:1708.06502 , PLB 778, 325 (2018)

Why Modify General Relativity?

(Experimentalist/Observer Perspective)

- Cosmological Issues :

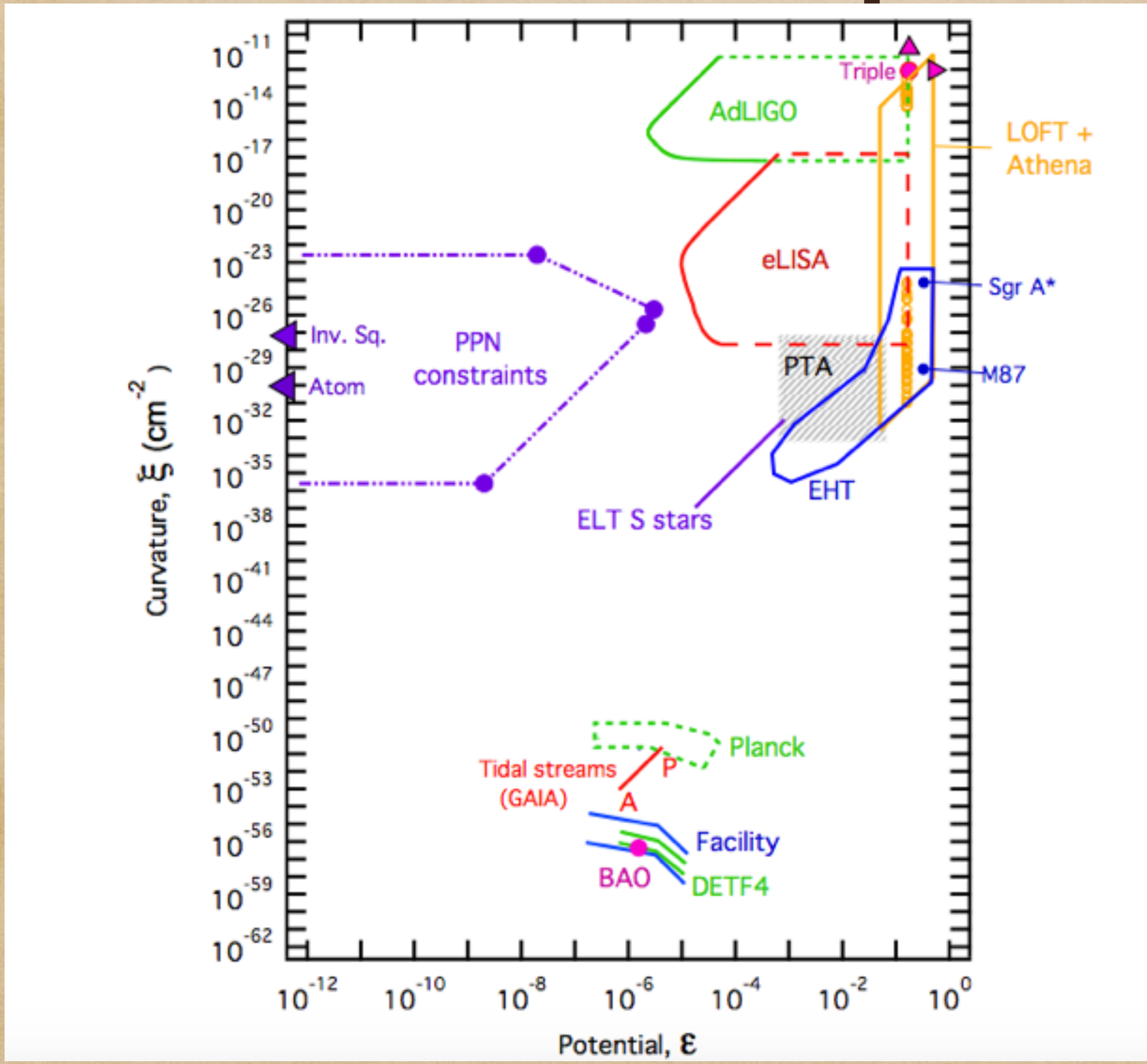


  - Dark Energy, Dark Matter, Baryogenesis
  - Inflation cf.model based on Einstein-Cartan gravity:

    Gasperini 86, SD+Poplawski 2016

- Conceptual Issues :
  - Expansion of Universe problem Peacock (1999) Padmanabhan (2010)
  - Big-Bang Singularity Hawking and Penrose (1970)
  - Quantization of gravity String theory , LQG, etc

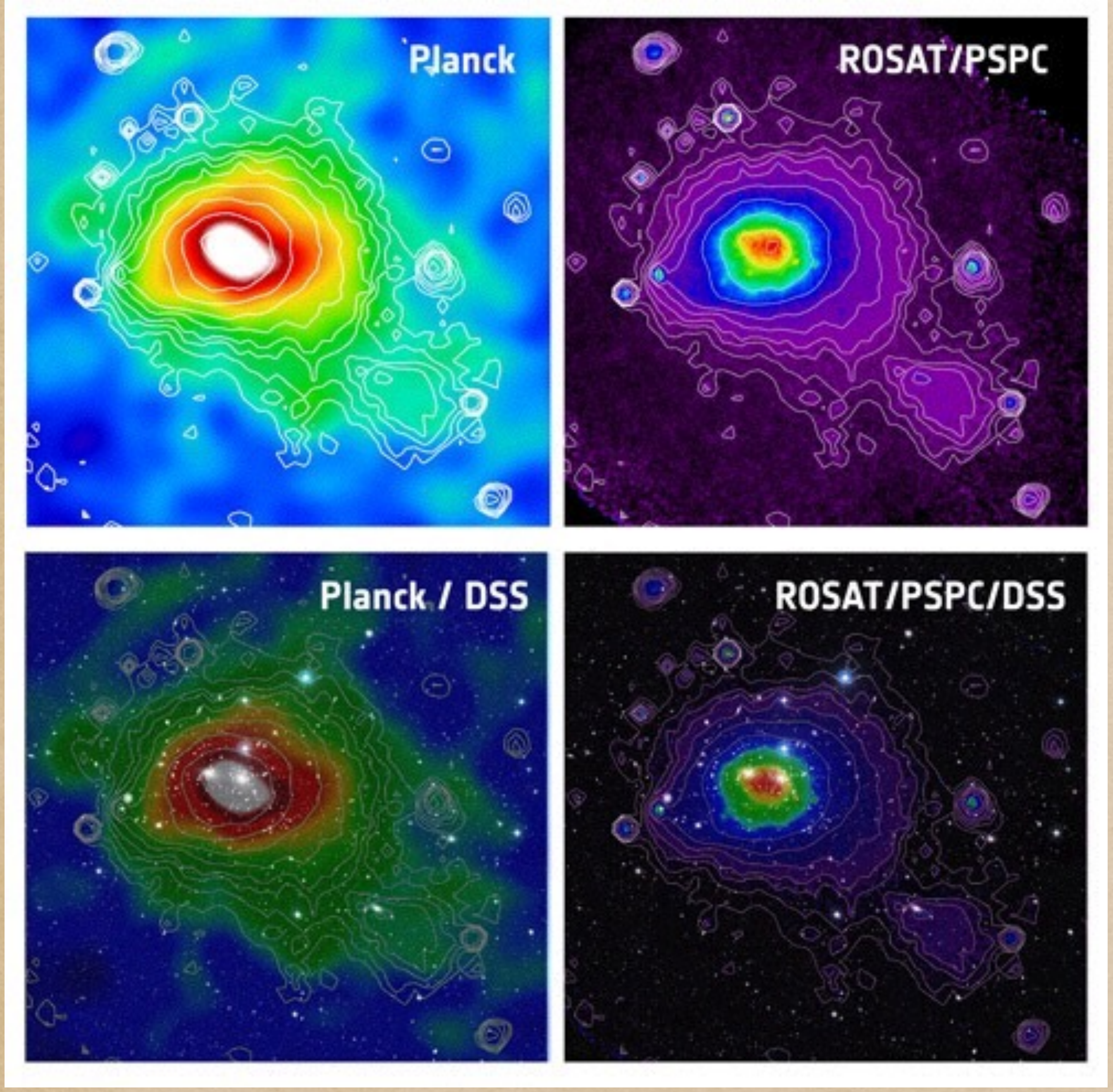
Observational probes of GR



Baker,Skordis,Psaltis 1412.3455

Cosmology, solar system, binary pulsar, LIGO probe test GR in different regimes

Galaxy Clusters Primer



- Most massive gravitationally collapsed objects with masses $>10^{14} M_{sun}$
- Typical Sizes = 1- 10 Mpc
- Composition :

  Galaxies : 2%

  Gas/Baryons : 13%

  Dark Matter : 85%
- Seen at all (nearly) wavelengths from radio to hard x-rays

Coma Cluster :

Credit : ESA / LFI and HFI Consortia (Planck image); MPI (ROSAT image); NASA/ESA/DSS2 (visible image).

Acknowledgement: Davide De Martin (ESA/Hubble).

Tests of GR using Clusters

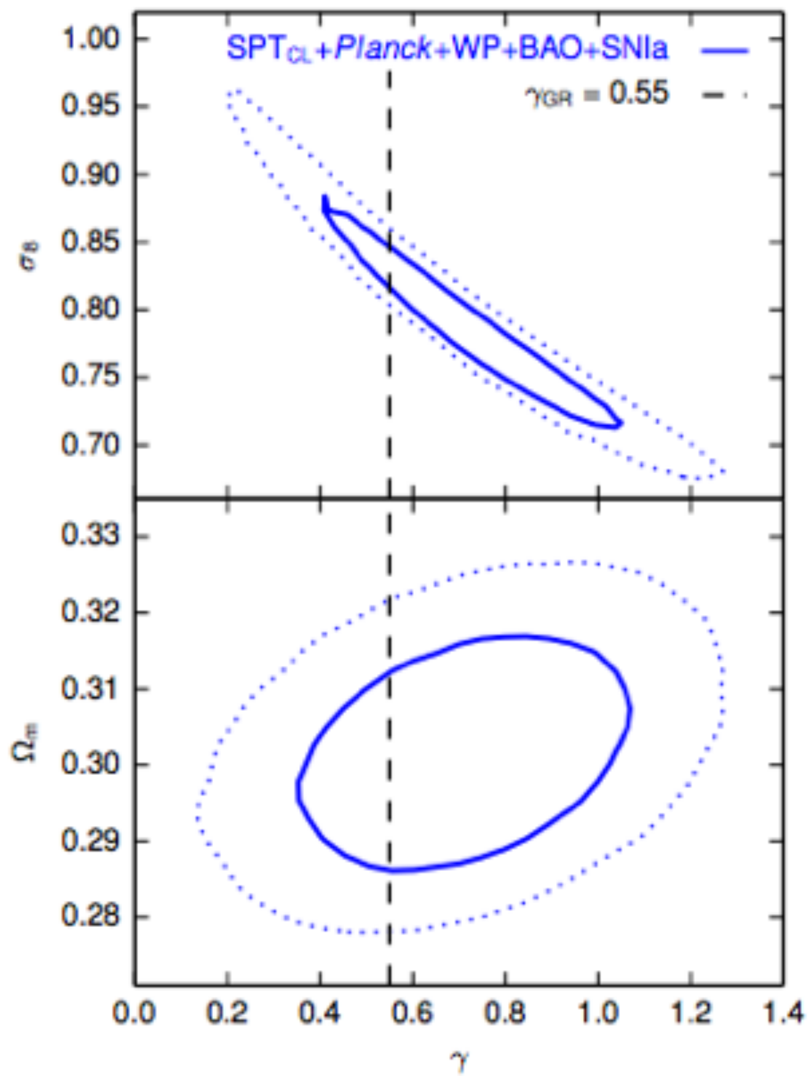


Figure 5. γ+ΛCDM: Likelihood contours (68% and 95%) for the growth index γ and σ_8 (top), and γ and Ω_m (bottom). The prediction by GR $\gamma_{GR} = 0.55$ is indicated by the dashed line. The strong degeneracy between γ and σ_8 is clear. We measure $\gamma = 0.72 \pm 0.24$, indicating no tension with the growth rate predicted by GR.

SPT collab. 1407.2942 (720 deg^2)

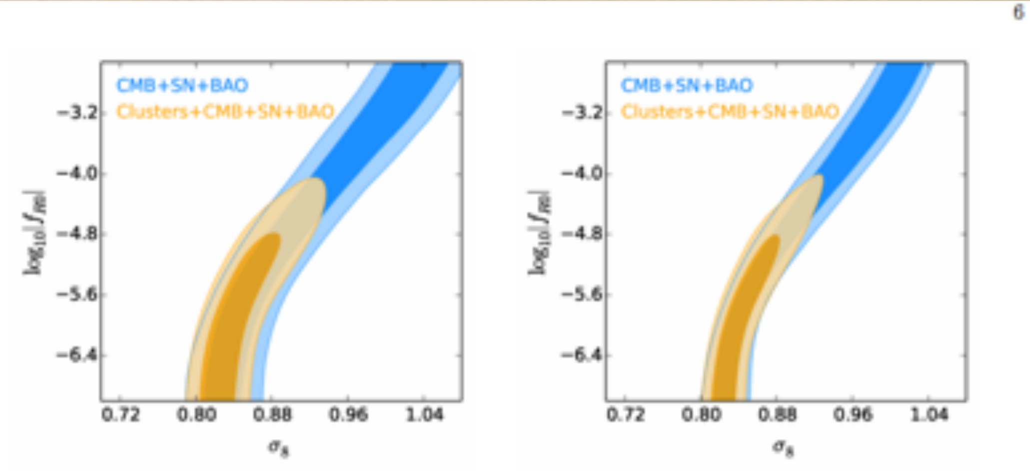


FIG. 1. Constraints on the HS model with $n = 1$. Dark and light shadings indicate the 68.3 and 95.4 per cent confidence regions (accounting for systematic uncertainties) from the following data sets: the CMB combined with SNIa+BAO (blue), and the combination of all these with clusters (gold). In the left panel, we use WMAP+ACT+SPT as CMB data, and *Planck*+WP+lensing+ACT+SPT in the right panel.

Cataneo et al 1412.0133

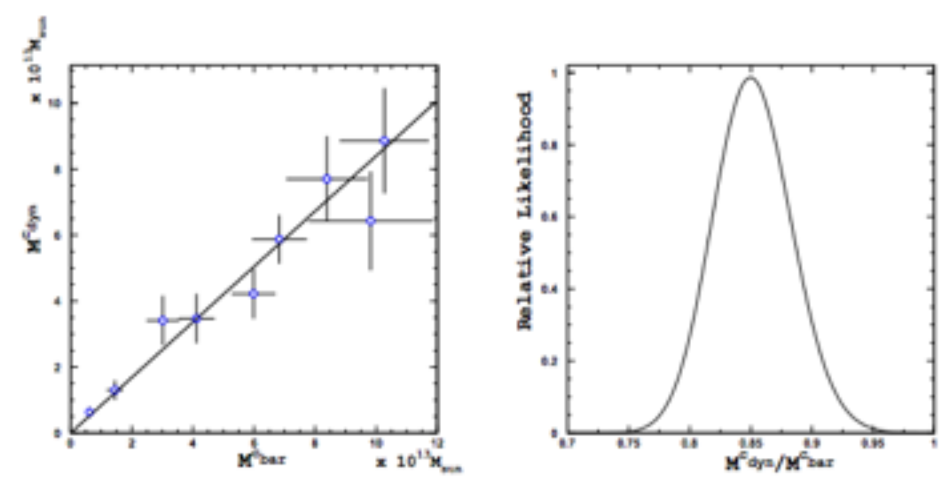
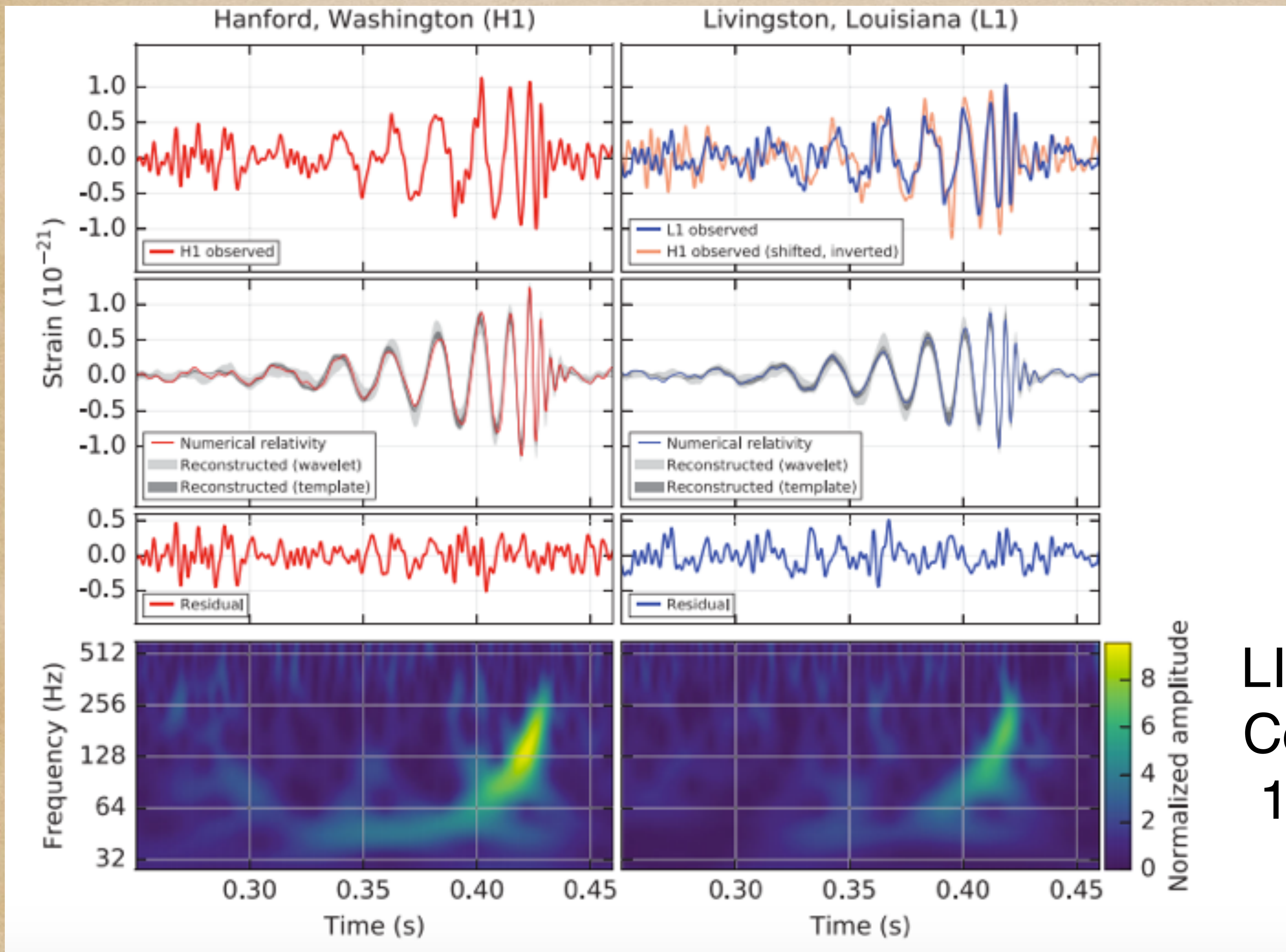


FIG. 6: Left panel: The best linear fit to the relation between the dynamical masses according to nonlocal gravity and the observed baryonic masses of the ten *Chandra* X-ray clusters of Table V. Here the best-fitting slope is $M^c_{dyn}/M^c_{bar} = 0.84 \pm 0.04$. Right panel: The likelihood function for parameter $\mathcal{M} = M^c_{dyn}/M^c_{bar}$.

Rahvar & Mashoon 1401.4819

GW150914



LIGO-VIRGO
Collaboration
1602.03837

Tests of GR From GW150914

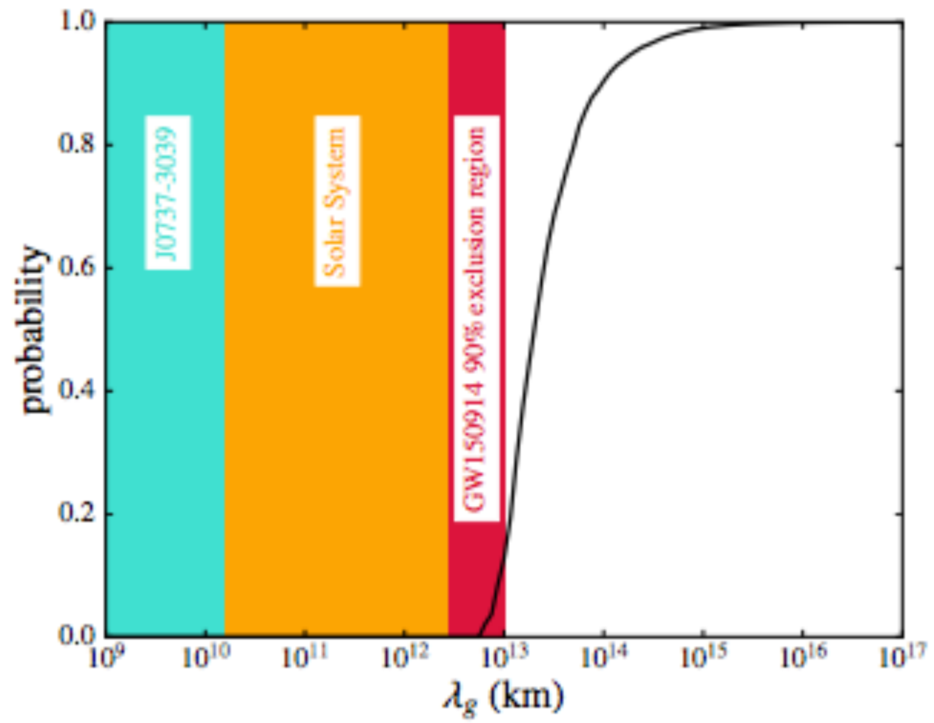


FIG. 8. Cumulative posterior probability distribution for λ_g (black curve) and exclusion regions for the graviton Compton wavelength λ_g from GW150914. The shaded areas show exclusion regions from the double pulsar observations (turquoise), the static Solar System bound (orange) and the 90% (crimson) region from GW150914.

1602.03841
LIGO, VIRGO Collaboration
See however,
S. Deser 1604.04015

$$\lambda_G > 10^{13}\text{km} \quad m_g \leq 1.2 \times 10^{-22}\text{eV}$$

$$m_g \leq 7.7 \times 10^{-23}\text{eV} \;\; (\text{GW170104})$$

GW170817 : $m_g < 10^{-22}$ eV (Baker et al 1710.06394)

Other Bounds on Graviton Mass

$m_g < 1.2 \times 10^{-22}$ eV$/c^2$. This improves on Solar System and binary pulsar bounds [98,99] by factors of a few and a thousand, respectively, but does not improve on the model-dependent bounds derived from the dynamics of Galaxy clusters [100] and weak lensing observations [101]. In

arXiv:1602.03837

Existing bounds on λ_g that do not probe the propagation of gravitational interactions (i.e., the so-called *static* bounds), come from Solar System observations [92, 93] (which probe the above Yukawa-corrected Newtonian potential), the non-observation of superradiant instabilities in supermassive black holes [94], model-dependent studies of the large-scale dynamics of galactic clusters [95], and weak lensing observations [96]; these bounds are 2.8×10^{12} km, 2.5×10^{13} km, 6.2×10^{19} km and 1.8×10^{22} km, respectively. We note that the bound from superradiance relies on the assumption that the very massive, compact objects in the centers of galaxies are indeed supermassive Kerr black holes, as opposed to other, more exotic objects. As also stressed in Ref. [93], the model-dependent bounds from clusters and weak lensing should be taken with caution, in view of the uncertainties on the amount of dark matter in the Universe and its spatial distribution. The only *dynamical* bound to date comes from binary-pulsar ob-

arXiv:1602.03841

.Comprehensive review on graviton mass bounds in

De Rham et al Rev. Mod. Phys. 89, 025004 (2017)

Galaxy Cluster Limit on graviton mass

PHYSICAL REVIEW D VOLUME 9, NUMBER 4 15 FEBRUARY 1974

Mass of the graviton*

Alfred S. Goldhaber† and Michael Martin Nieto
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico 87544
(Received 30 May 1973)

After emphasizing that it remains an open question whether one should try to quantize gravity theory (which would mean gravitational force is propagated by a graviton particle), we nevertheless ask whether a limit can be set on the rest mass (μ_g) of the "graviton." By recalling that gravitational force is clearly exerted over large distances in systems of galaxies and is not eliminated by a graviton-mass Yukawa cutoff, we find a limit. So, although it is not known if the graviton exists, one can still say that its rest mass is less than 2×10^{-42} g.

- Uses the fact that galaxy cluster orbits are closed and bound.
- Orbits of Holmberg galaxy cluster catalog extend upto 580 kpc.

$$e^{-1} \leq \exp(-\mu_g r)$$

$$m_g <= 10^{-29} eV$$

No other limit on graviton mass using galaxy clusters since 1974 !!

Non-Newtonian (including Yukawa potential) can also produce closed orbits 1705.02444

Abell 1689 Cluster

Located in VIRGO constellation
z= 0.18

Credit: ESA/Hubble

Acceleration data for Abell 1689

1610.01543 Nieuwenhuizen

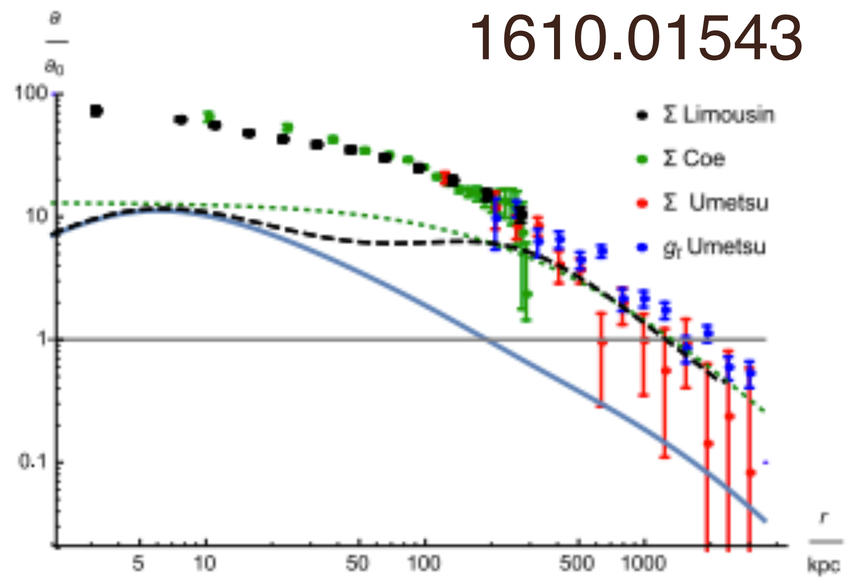


Figure 2: Full line: the Newton acceleration a, normalized to a_0, as function of the radius, as induced by the gas and galaxies in A1689. Beyond 200 kpc it is an order of magnitude smaller than the other indicators, which points at the need for dark matter already at 50 kpc. In the absence of it, modifications of Newton's law for $a < a_0$ are unlikely capable to bridge the gap. Data points: estimate (13) for a, based on data of Σ in[38–40], and the estimate (15) based on data of g_t[40].
Dotted: a in the optimal NFW fit (finite at $r = 0$), and dashed: in our neutrino model, governed below 30 kpc by the BCG[37].

- Strong lensing data between 3-271 Kpc from Limousin (2006) and Coe (2010)

- Weak Lensing shear data between 200 Kpc and 3 Mpc from Umetsu et al (2015)

Mass models for Abell 1689

- Dark Matter $$M_{dm} = 4\pi\rho_s r_s^3 \left[\log\left(\frac{r_s + r}{r_s}\right) - \frac{r}{r_s + r}\right], \qquad (2)$$
- Gas Mass $$\rho_{gas} = 1.167 m_p n_{e0} \exp\left\{k_g - k_g\left(1 + \frac{r^2}{R_g^2}\right)^{1/(2n_g)}\right\},$$
- BCG Mass $$\rho_{gal}(r) = \frac{M_{cg}(R_{co} + R_{cg})}{2\pi^2(r^2 + R_{co}^2)(r^2 + R_{cg}^2)},$$

Ref : 1610.01543 Nieuwenhuizen 1703.10219 Hodson & Zhao

Caveat: Some of the above models (such as NFW) assume Newtonian gravity

Acceleration Profiles

$$a_{Newt} = \frac{GM}{R^2}$$

$$a_{yukawa} = \frac{GM}{R} \exp(-\frac{R}{\lambda_G}) \left(\frac{1}{\lambda_G} + \frac{1}{R} \right)$$

$$\chi^2 = \sum_{i=1}^{N} \left(\frac{a_{newt} - a_{yukawa}}{\sigma_a} \right)^2$$

To calculate 90% c.l. limit on graviton mass find m_g for which

$$\Delta\chi^2 > 2.71$$ (Ref: Numerical Recipes)

Modification from physical boundary

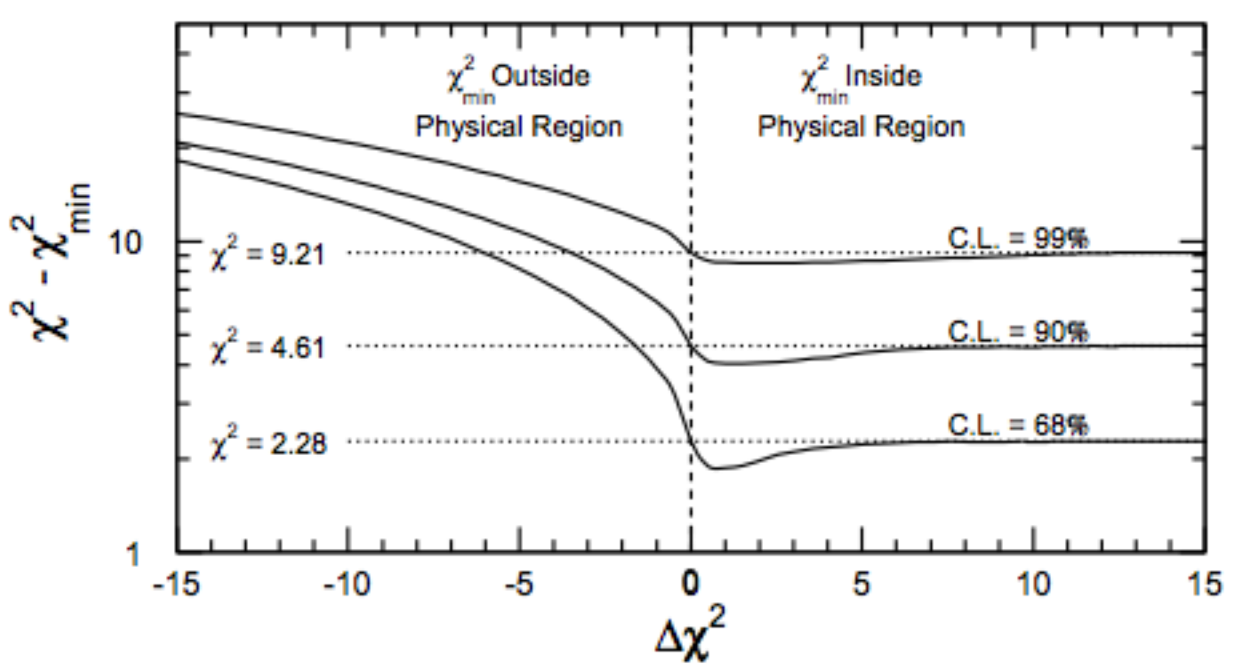


Figure 8.14: The χ^2 differences corresponding to the 68%, 90%, and 99% confidence intervals for a bounded physical region. $\Delta\chi^2$ is the difference between the value of χ^2_{min} and the value of χ^2 on the physical boundary; it is taken positive if χ^2_{min} occurs inside the physical region and negative if outside the physical region.

Mark Messier Ph.D thesis (Boston Univ. 1999)

$\Delta\chi^2$ interval unchanged due to physical boundary

Results

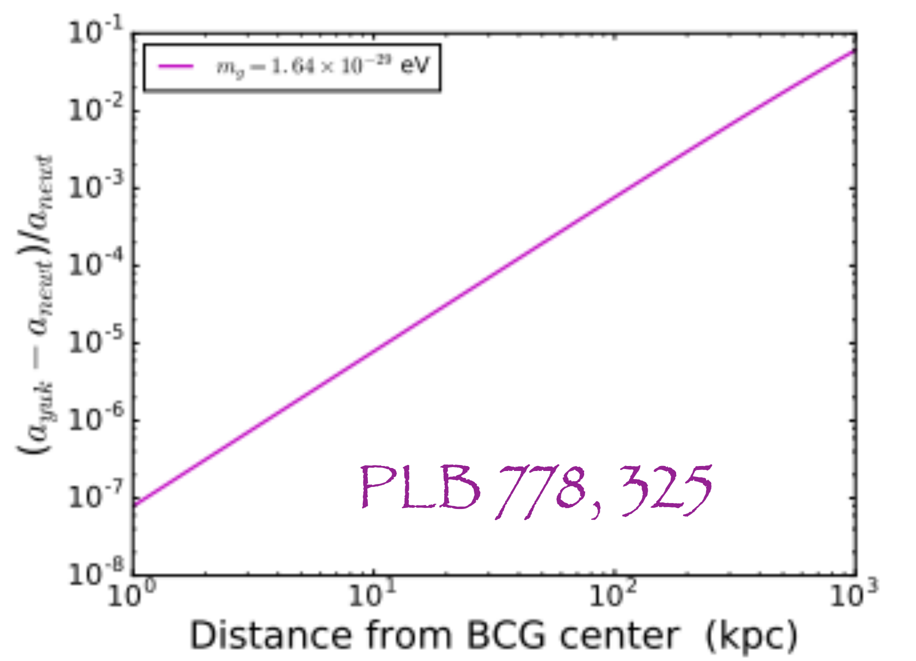


FIG. 2: Fractional absolute deviation between acceleration computed assuming Yukawa gravity (for a graviton mass of $m_g = 1.37 \times 10^{-29}$ eV, corresponding to the 90% cl upper limit) as a function of distance from the center of the central galaxy of the cluster (usually referred to as BCG). The fractional deviation is about 10% at 1 Mpc.

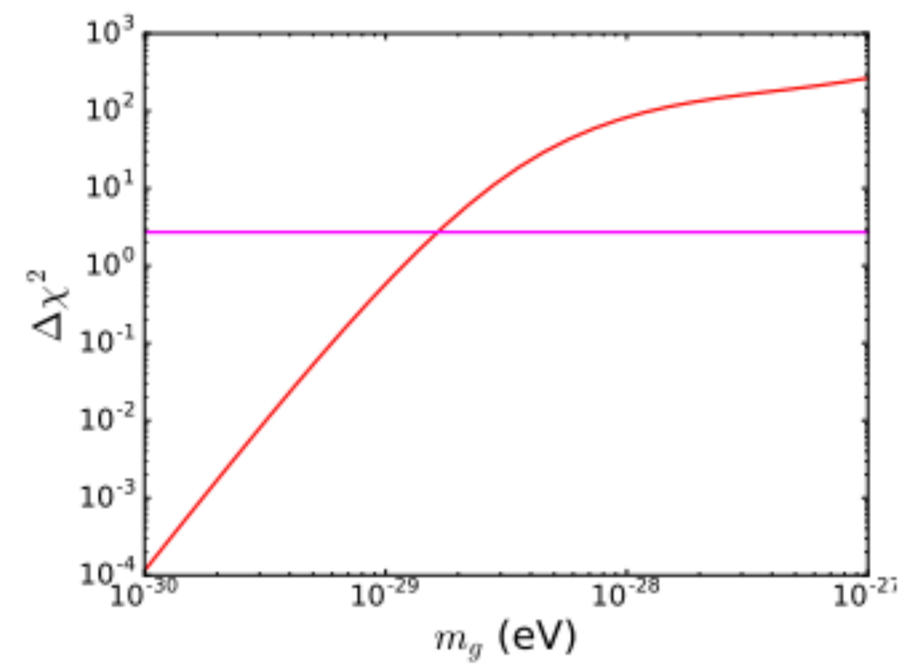


FIG. 1: $\Delta\chi^2$ as a function of graviton mass. The horizontal line at $\Delta\chi^2 = 2.71$ gives the 90% c.l. upper limit on graviton mass of 1.37×10^{-29} eV or a lower limit on the Compton wavelength of $\lambda_g > 9.1 \times 10^{19}$ km. We note that since $\chi^2_{min} = 0$ for $m_g = 0$, this is mathematically equivalent to the χ^2 functional defined in Eq. 7.

$$m_g < 1.37 \times 10^{-29} \text{eV}$$

$$\lambda_G > 9.1 \times 10^{19} \text{km}$$

at 90% confidence level

Limit from stacking Cluster Catalogs

Rana et al arXiv:1801.3309

$$a_n(z, M_\Delta) = (GM_\Delta)^{1/3}\left(\frac{H^2(z)\Delta}{2}\right)^{2/3}$$

$$a_y(z, M_\Delta, \lambda_g) = (GM_\Delta)^{2/3}\left(\frac{H^2(z)\Delta}{2}\right)^{1/3} \times \exp\left[-\frac{1}{\lambda_g}\left(\frac{2M_\Delta G}{H^2(z)\Delta}\right)^{1/3}\right]\left[\frac{1}{\lambda_g} + \left(\frac{H^2(z)\Delta}{2M_\Delta G}\right)^{1/3}\right] \quad (6)$$

Once the acceleration corresponding to the Newtonian potential and Yukawa potential are known, we define a chi-square χ^2 as;

$$\chi^2 = \sum_i \left[\frac{a_{n,i}(z, M_\Delta) - a_{y,i}(z, M_\Delta, \lambda_g)}{\sigma_{a,i}}\right]^2 \quad (7)$$

where σ_a gives the error in acceleration obtained by adding the errors of mass estimate, σ_{M_Δ} and Hubble parameter σ_H in quadrature, given by,

$$\sigma_a = \frac{a_n}{3}\sqrt{\left(\frac{\sigma_{M_\Delta}}{M_\Delta}\right)^2 + 16\left(\frac{\sigma_H}{H(z)}\right)^2} \quad (8)$$

Two catalogs were used for this analysis:

- WL catalog from LoCuSS collaboration
- SZ catalog from ACT

Bounds on graviton mass

Rana et al arXiv:1801.3309

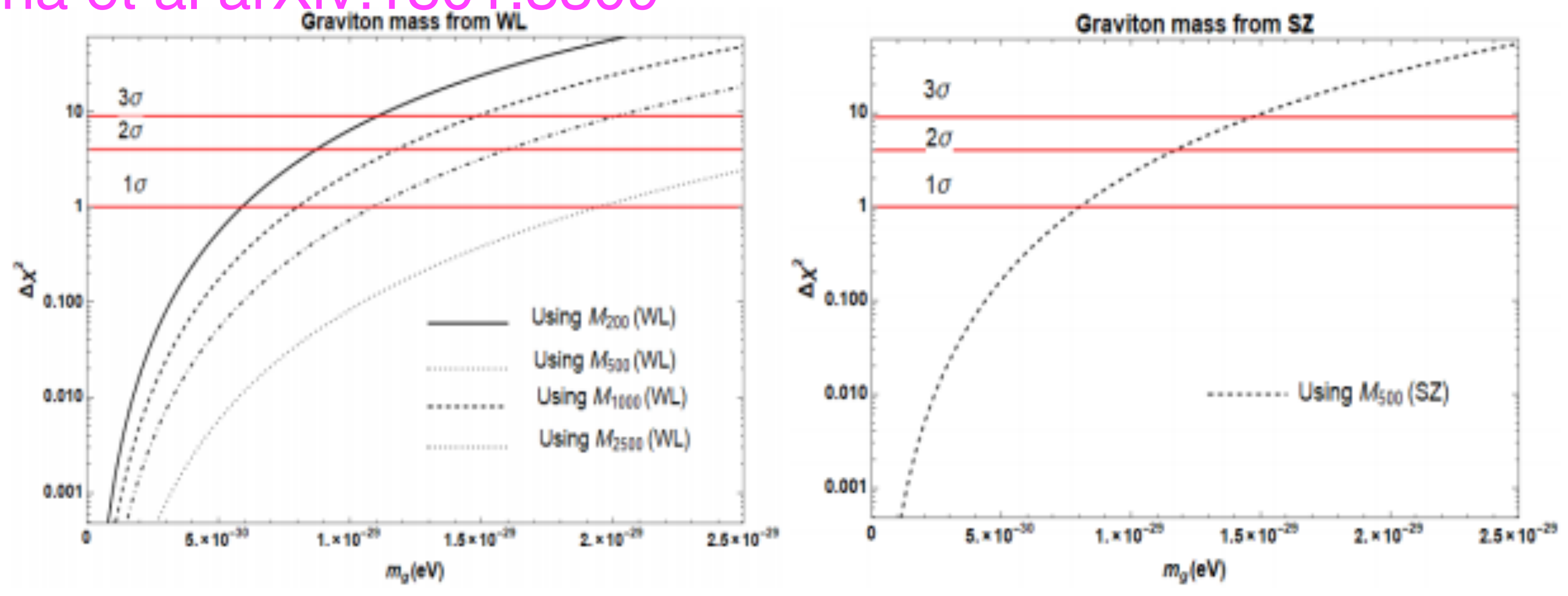
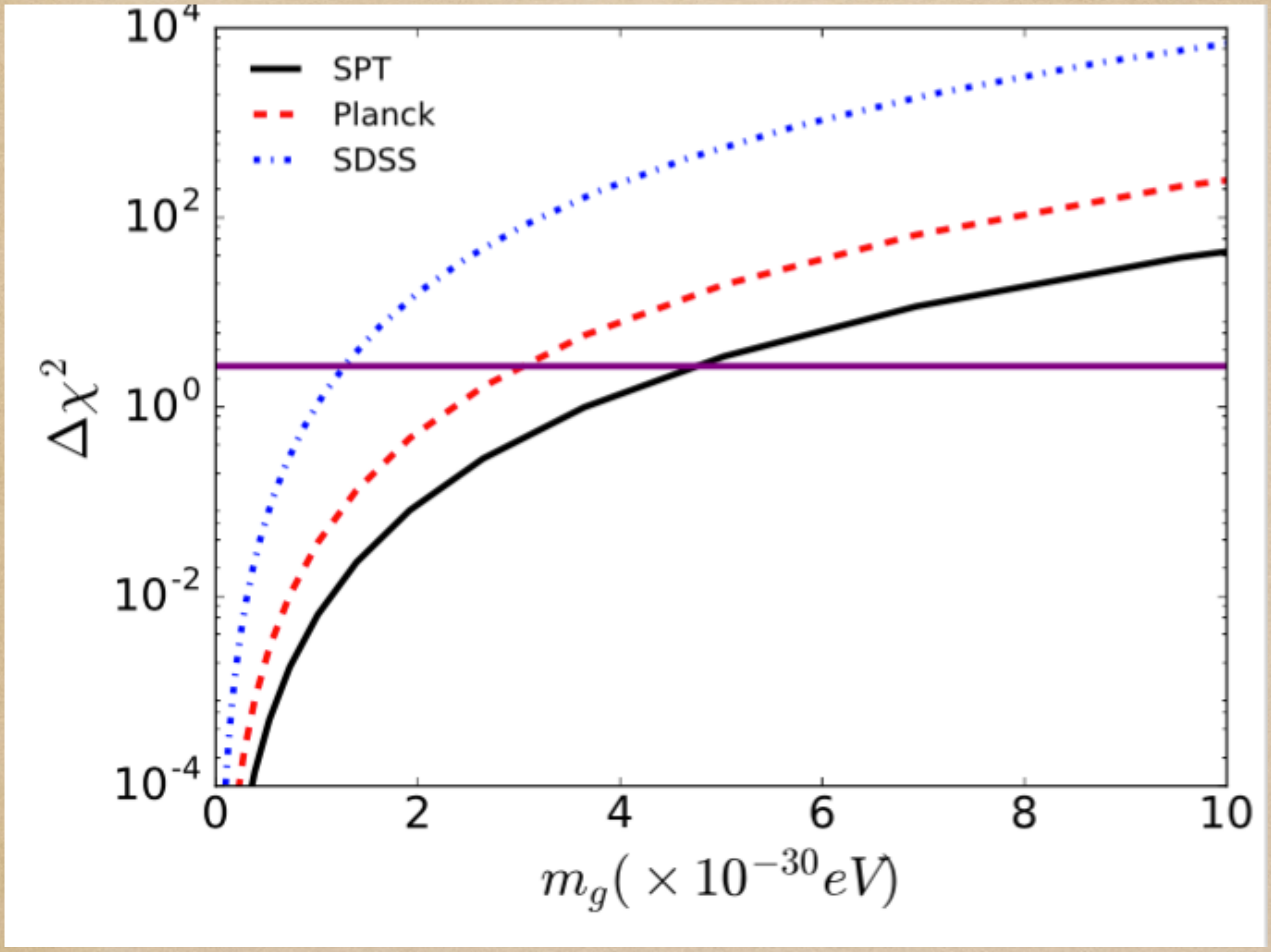


Figure 1: $\Delta\chi^2$ is plotted as a function of m_g (in eV) obtained by using the mass of galaxy clusters with weak lensing and SZ effect. The horizontal red lines at $\Delta\chi^2 = 1, 4$ and 9 represent the 1σ, 2σ and 3σ confidence limits. **Left panel** curves have been plotted by using the M_{200}^{WL}, M_{500}^{WL}, M_{1000}^{WL} and M_{2500}^{WL} estimates of 50 galaxy clusters studied by using weak lensing. In the **Right panel**, the black dashed line is plotted by using the M_{500}^{SZ} mass estimate of 182 galaxy clusters studied by using SZ effect. (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)

Upper Bound on Graviton mass m_g (in eV) and lower bound on λ_g (in Mpc)					
Data	Parameter	1 σ (68.3%)	1.64 σ (90%)	2 σ (95.5%)	3 σ (99.7 %)
M_{200}^{WL}	$m_g <$ (in eV)	5.902 $\times 10^{-30}$	7.849 $\times 10^{-30}$	8.715 $\times 10^{-30}$	1.105 $\times 10^{-29}$
	$\lambda_g >$(Mpc)	6.822	5.132	4.622	3.643
M_{500}^{WL}	$m_g <$ (in eV)	8.003 $\times 10^{-30}$	1.053 $\times 10^{-29}$	1.175 $\times 10^{-29}$	1.48 $\times 10^{-29}$
	$\lambda_g >$(in Mpc)	5.033	3.824	3.427	2.713
M_{1000}^{WL}	$m_g <$ (in eV)	1.088 $\times 10^{-29}$	1.427 $\times 10^{-29}$	1.598 $\times 10^{-29}$	2.017 $\times 10^{-29}$
	$\lambda_g >$(in Mpc)	3.700	2.821	2.520	1.997
M_{2500}^{WL}	$m_g <$ (in eV)	1.952 $\times 10^{-29}$	2.583 $\times 10^{-29}$	2.894 $\times 10^{-29}$	3.641 $\times 10^{-29}$
	$\lambda_g >$(in Mpc)	2.060	1.560	1.390	1.100
M_{500}^{SZ}	$m_g <$ (in eV)	8.307 $\times 10^{-30}$	1.051 $\times 10^{-29}$	1.169 $\times 10^{-29}$	1.461 $\times 10^{-29}$
	$\lambda_g >$(Mpc)	5.012	3.831	3.443	2.747



Sajal Gupta (IISER undergrad)

Best limit from SDSS-Redmapper of $< 1.27 \times 10^{-30}$ eV

Conclusions

- A new limit on graviton mass using a galaxy cluster (44 years after the previous paper!) now available.

$$m_g < 1.37 \times 10^{-29}\mathrm{eV}$$

$$\lambda_G > 9.1 \times 10^{19}\mathrm{km}$$

- A follow-up paper using stacked measurements of galaxy clusters gets a limit of 7.8×10^{-30} eV using LoCuSS WL catalog and 1.27×10^{-30} eV using SDSS RedMapper clusters

Part II : Shapiro Delay of Gravitational Waves

Collaborators:

Sibel Boran (Istanbul Technical Univ)
Emre Kahya (Istanbul Technical Univ.)
Richard Woodard (Univ. of Florida)

Line of Sight Shapiro Delay

References:

0804.3804 SD, Kahya, Woodard
1001.0725 Kahya
1510.08828 SD, Kahya
1602.04779 Kahya, SD
1612.02532 SD, Kahya
1710.06618 Boran, SD, Kahya, Woodard

Related/Similar work by other authors:

Sivaram 1999; Gao et al 1509.00150 ; Wu et al 1602.01566 ; Wu et al 1604.06668 ; Liu et al ;1604.02566 Luo et al 1601.00180 Li et al ; 1602.04460 ; Li et al 1601.03636 Nusser 1606.00458 Takahashi 1703.09935; Wu et al 1710.05834; LVC, Fermi, Integral Collaborations; 1710.05860 ; Wei et al; 1710.05805 Wang et al; Shoemaker and Murase 1710.06427 ; etc

Shapiro Delay

Irwin Shapiro (1964)

FOURTH TEST OF GENERAL RELATIVITY

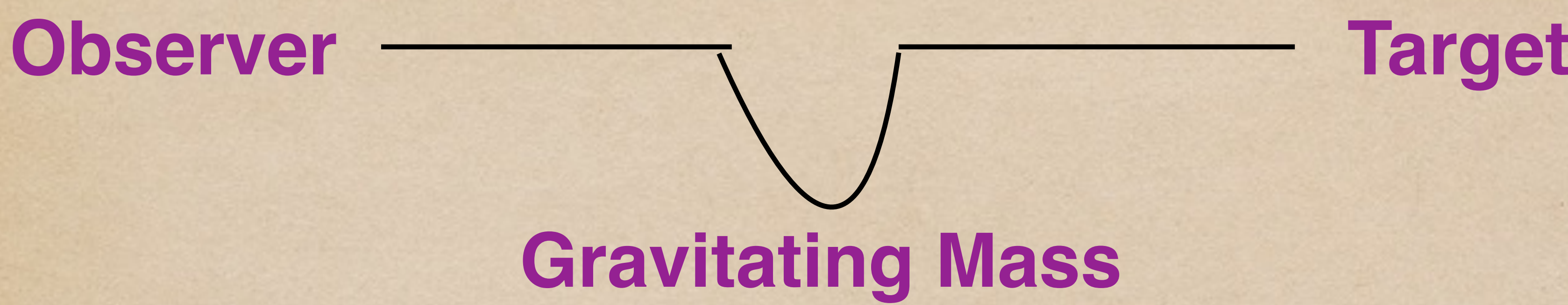
Irwin I. Shapiro
Lincoln Laboratory,* Massachusetts Institute of Technology, Lexington, Massachusetts
(Received 13 November 1964)

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

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

Formula for Shapiro Delay



Time delay due to light traveling around a single mass [edit]

For a signal going around a massive object, the time delay can be calculated as the following:[citation needed]

$$\Delta t = -\frac{2GM}{c^3} \log(1 - \mathbf{R} \cdot \mathbf{x})$$

Here **R** is the unit vector pointing from the observer to the source, and **x** is the unit vector pointing from the observer to the gravitating mass *M*. The dot denotes the usual Euclidean dot product.

Using $\Delta x = c\Delta t$, this formula can also be written as

$$\Delta x = -R_s \log(1 - \mathbf{R} \cdot \mathbf{x}),$$

which is the extra distance the light has to travel. Here R_s is the Schwarzschild radius.

In PPN parameters,

$$\Delta t = -(1+\gamma)\frac{R_s}{2c} \log(1 - \mathbf{R} \cdot \mathbf{x}),$$

which is twice the Newtonian prediction (with $\gamma = 0$).[3]

Source: wikipedia

First Shapiro Delay Measurement

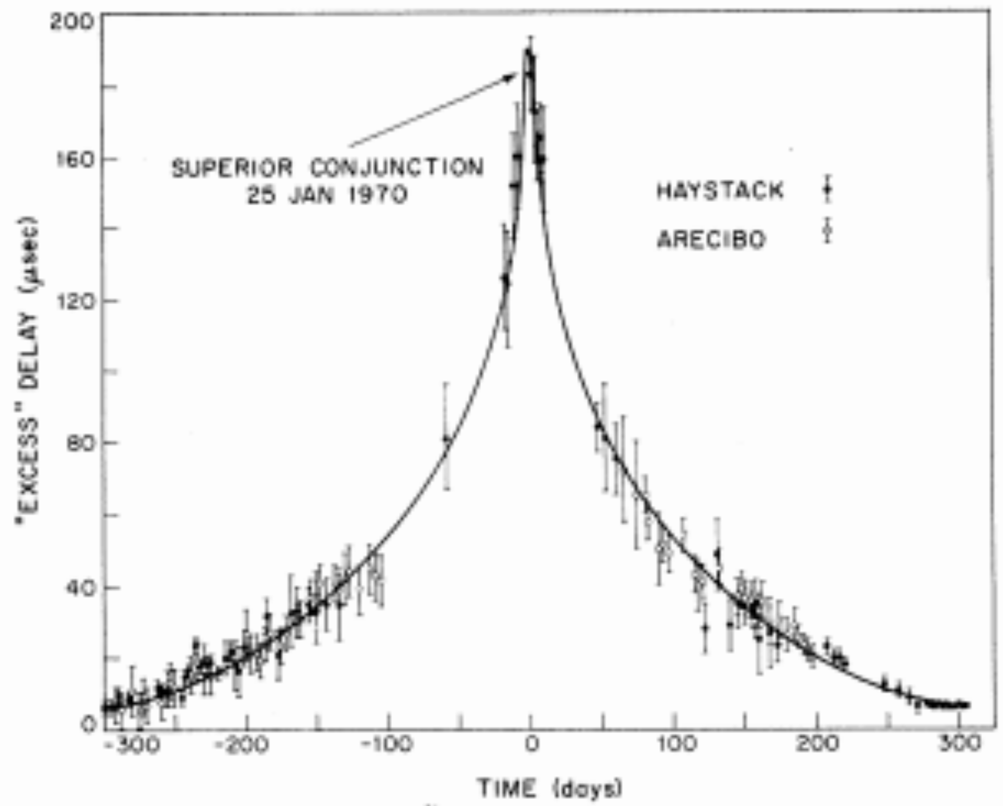
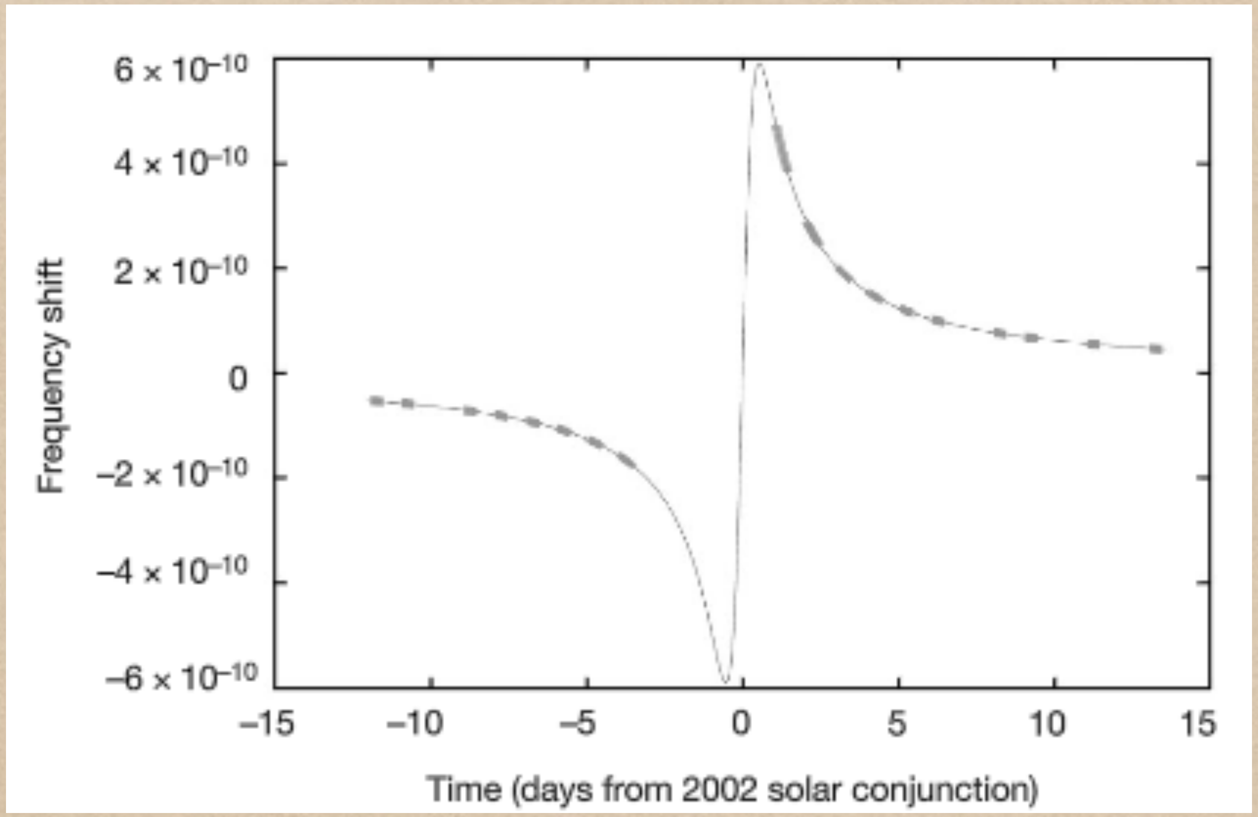


FIG. 1. Typical sample of post-fit residuals for Earth-Venus time-delay measurements, displayed relative to the "excess" delays predicted by general relativity. Corrections were made for known topographic trends on Venus. The bars represent the original estimates of the measurement standard errors. Note 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

Delay ~ 200 microsecond

Best solar system measurement



Cassini satellite

Bertotti et al Nature 2003

Shapiro Delay in Binary Pulsars

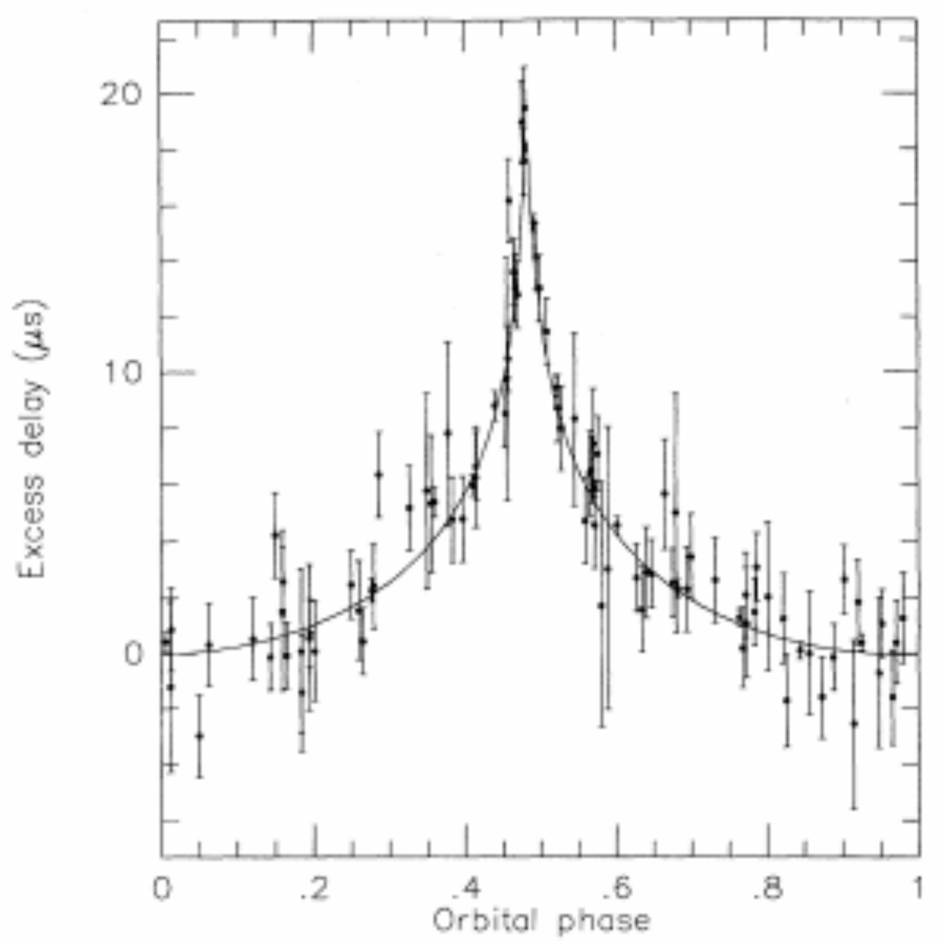
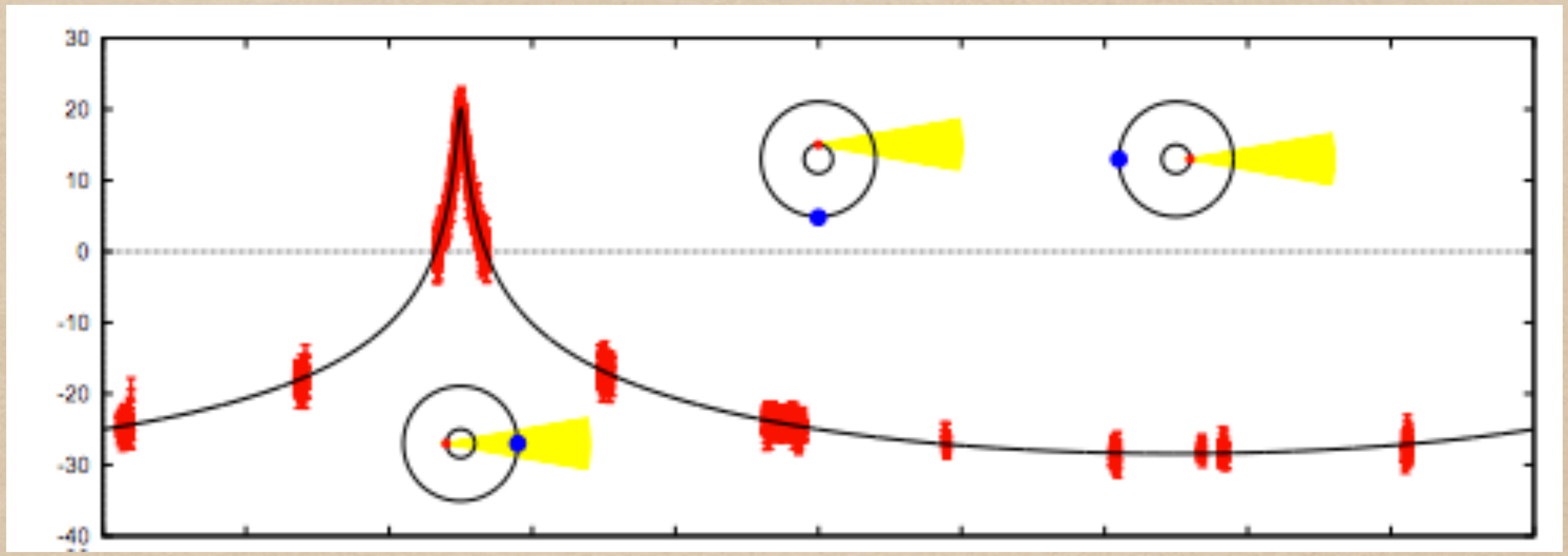


FIG. 8. Measurements of the Shapiro time delay in the PSR 1855+09 system. The theoretical curve corresponds to Eq. (10), and the fitted values of *r* and *s* can be used to determine the masses of the pulsar and companion star.

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

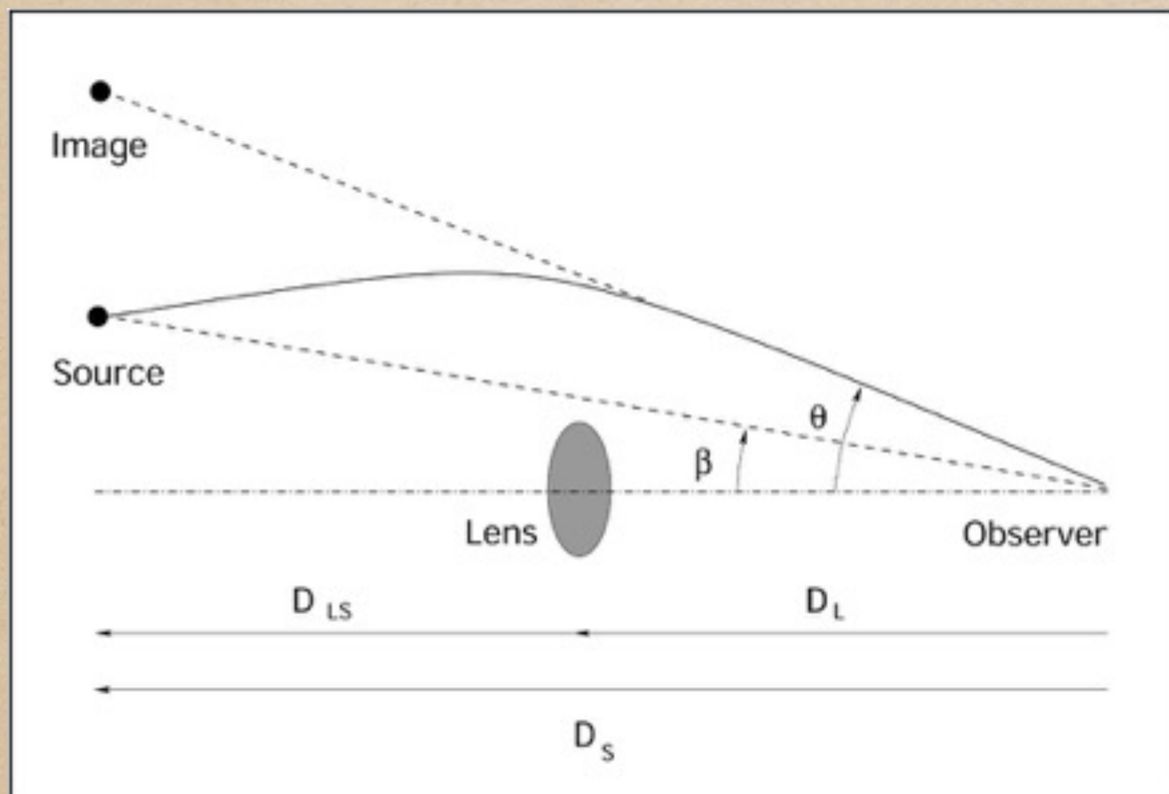
Mass Measurement using Shapiro Delay



arxiv:1010.5788

Discovery of 2 solar mass Neutron Star PSR J1614-2230

Effect of Shapiro Delay in Time Delay Measurements of Lensed Quasars



0.08 x 0.08 arc minute
ESA/Hubble

$$t_{\rm tot} = t_{\rm geom} + t_{\rm grav},$$

Each contribution to the total time-delay writes as:

$$t_{\rm geom}(\vec{\theta}) = (1+z_{\rm L})\frac{D_{\rm L}D_{\rm S}}{cD_{\rm LS}}(\vec{\theta}-\vec{\beta})^2,$$

$$t_{\rm grav}(\vec{\theta}) = (1+z_{\rm L})\frac{8\pi G}{c^3}\nabla^{-2}\Sigma(\vec{\theta}).$$

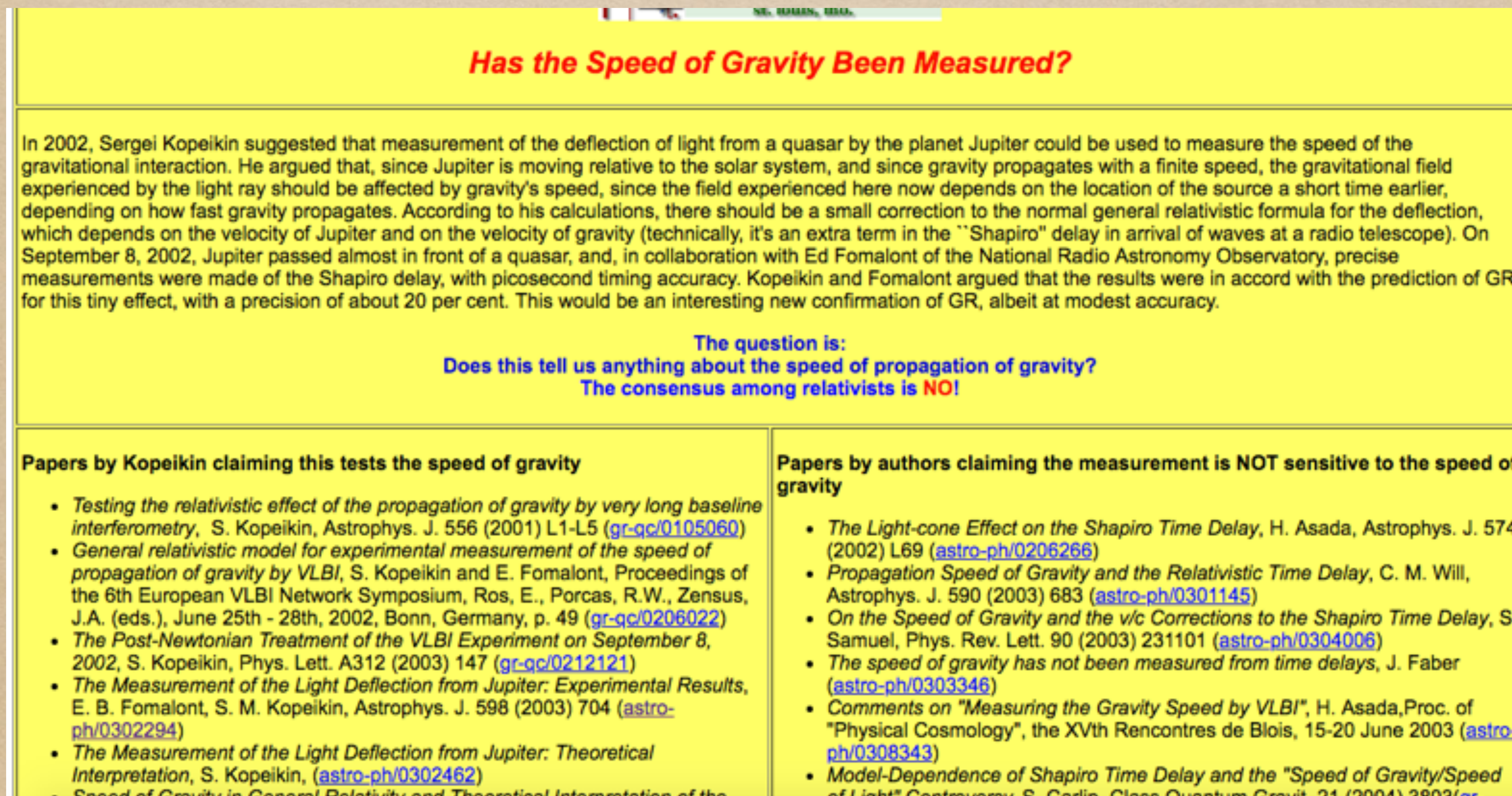
Time-delays between lensed images for a variable source used to measure Hubble constant

astro-ph/0304497

Similar idea for GWs proposed in 1602.05882

Shapiro delay for a moving source

Measured by Kopeikin and Fomalont (2003) for Jupiter by measuring light deflection of quasar and used to obtain speed of gravity (result disputed)



Has the Speed of Gravity Been Measured?

In 2002, Sergei Kopeikin suggested that measurement of the deflection of light from a quasar by the planet Jupiter could be used to measure the speed of the gravitational interaction. He argued that, since Jupiter is moving relative to the solar system, and since gravity propagates with a finite speed, the gravitational field experienced by the light ray should be affected by gravity's speed, since the field experienced here now depends on the location of the source a short time earlier, depending on how fast gravity propagates. According to his calculations, there should be a small correction to the normal general relativistic formula for the deflection, which depends on the velocity of Jupiter and on the velocity of gravity (technically, it's an extra term in the ``Shapiro" delay in arrival of waves at a radio telescope). On September 8, 2002, Jupiter passed almost in front of a quasar, and, in collaboration with Ed Fomalont of the National Radio Astronomy Observatory, precise measurements were made of the Shapiro delay, with picosecond timing accuracy. Kopeikin and Fomalont argued that the results were in accord with the prediction of GR for this tiny effect, with a precision of about 20 per cent. This would be an interesting new confirmation of GR, albeit at modest accuracy.

The question is:
Does this tell us anything about the speed of propagation of gravity?
The consensus among relativists is NO!

Papers by Kopeikin claiming this tests the speed of gravity

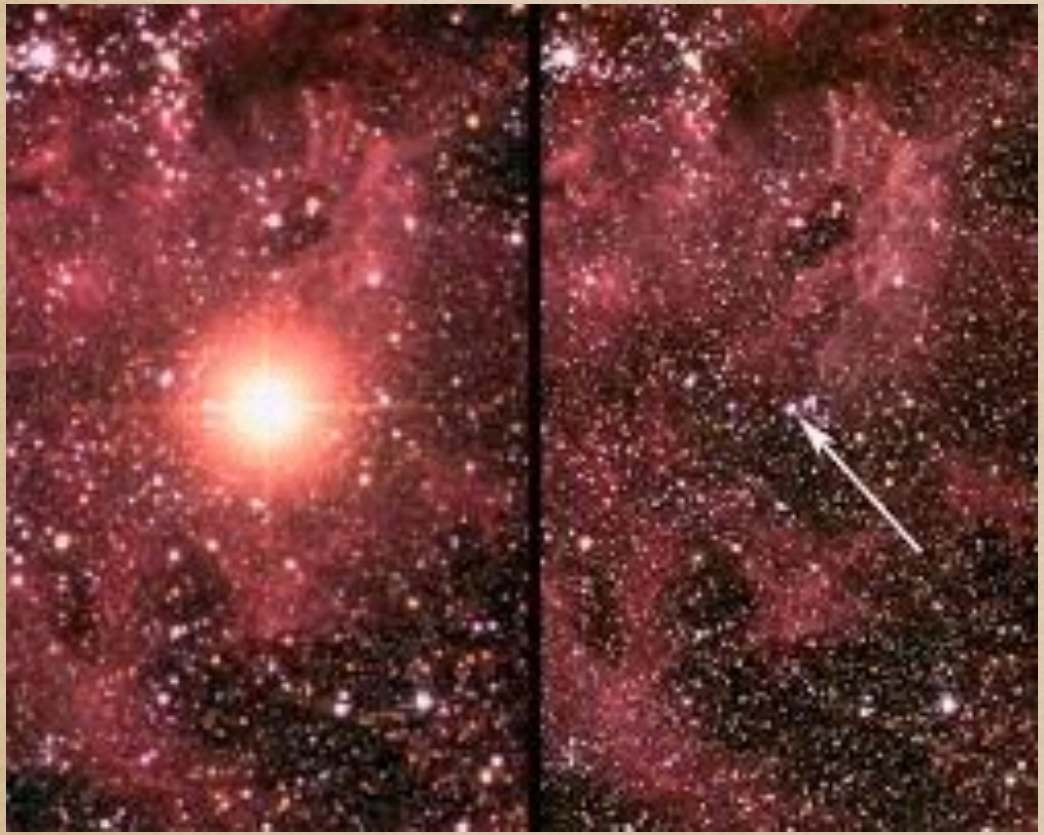
- *Testing the relativistic effect of the propagation of gravity by very long baseline interferometry*, S. Kopeikin, Astrophys. J. 556 (2001) L1-L5 (gr-qc/0105060)
- *General relativistic model for experimental measurement of the speed of propagation of gravity by VLBI*, S. Kopeikin and E. Fomalont, Proceedings of the 6th European VLBI Network Symposium, Ros, E., Porcas, R.W., Zensus, J.A. (eds.), June 25th - 28th, 2002, Bonn, Germany, p. 49 (gr-qc/0206022)
- *The Post-Newtonian Treatment of the VLBI Experiment on September 8, 2002*, S. Kopeikin, Phys. Lett. A312 (2003) 147 (gr-qc/0212121)
- *The Measurement of the Light Deflection from Jupiter: Experimental Results*, E. B. Fomalont, S. M. Kopeikin, Astrophys. J. 598 (2003) 704 (astro-ph/0302294)
- *The Measurement of the Light Deflection from Jupiter: Theoretical Interpretation*, S. Kopeikin, (astro-ph/0302462)
- *Speed of Gravity in General Relativity and Theoretical Interpretation of the*

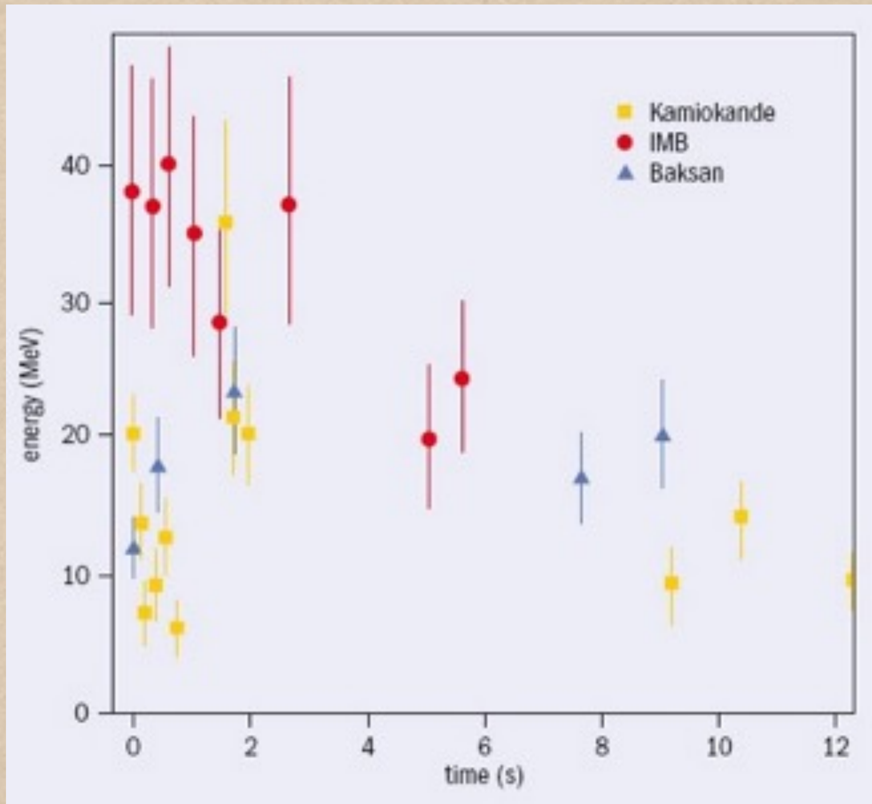
Papers by authors claiming the measurement is NOT sensitive to the speed of gravity

- *The Light-cone Effect on the Shapiro Time Delay*, H. Asada, Astrophys. J. 574 (2002) L69 (astro-ph/0206266)
- *Propagation Speed of Gravity and the Relativistic Time Delay*, C. M. Will, Astrophys. J. 590 (2003) 683 (astro-ph/0301145)
- *On the Speed of Gravity and the v/c Corrections to the Shapiro Time Delay*, S. Samuel, Phys. Rev. Lett. 90 (2003) 231101 (astro-ph/0304006)
- *The speed of gravity has not been measured from time delays*, J. Faber (astro-ph/0303346)
- *Comments on "Measuring the Gravity Speed by VLBI"*, H. Asada, Proc. of "Physical Cosmology", the XVth Rencontres de Blois, 15-20 June 2003 (astro-ph/0308343)
- *Model-Dependence of Shapiro Time Delay and the "Speed of Gravity/Speed of Light" Controversy*, S. Carlip, Class.Quantum Gravit. 21 (2004) 3803(gr-

http://www.phy.ufl.edu/~cmw/SpeedofGravity.html

Birth of multi-messenger Astronomy



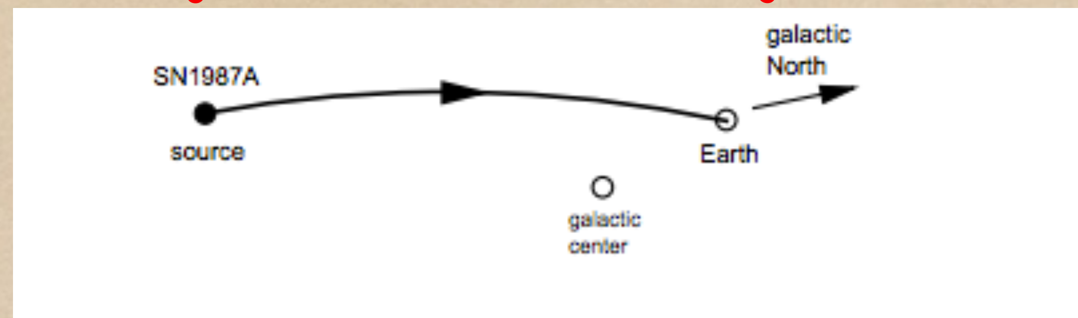


Detection of neutrinos from SN 1987 A (@50 kpc) followed by flash of optical light (4 hours later)

IMB, Kamiokande, Baksan (disputed)

2002 Nobel Prize to Masatoshi Koshiba

Shapiro delay for neutrinos



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

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

PPN gamma quantifying violation of WEP

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

More results from SN 1987A

Shapiro Delay CP invariant (LoSecco 1988)

The test of the equivalence principle pointed out by Longo and by Krauss and Tremaine can be easily extended to comparing the infall velocities of matter and antimatter. The very close coincidence in arrival times for neutrinos and antineutrinos places strong constraints on the coupling of gravitational interactions to matter and antimatter. The relative difference in gravitational delay is less than $5{\times}10^{-6}$.

Non-0 neutrino mass does not change the delay
(Bose & McGlinn 1988)

QED corrections to Shapiro delay can explain anomalous events seen in Mt Blanc detector.

(Franson, arXiv:1111.6986)

From Shapiro delay ⟶ bounds on EEP

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

TABLE I: Upper bounds on the differences of the γ values from the Shapiro time delay measurements.

Author (year)	Source	Messengers	Gravitational field	$\Delta\gamma$	References
Krauss & Tremaine (1988)	Supernova 1987A	eV photons and MeV neutrinos	Milky Way	5.0×10^{-3}	[3]
Longo (1988)	Supernova 1987A	eV photons and MeV neutrinos	Milky Way	3.4×10^{-3}	[4]
	Supernova 1987A	7.5–40 MeV neutrinos	Milky Way	1.6×10^{-6}	[4]
Gao *et al.* (2015)	GRB 090510	MeV–GeV photons	Milky Way	2.0×10^{-8}	[5]
	GRB 080319B	eV–MeV photons	Milky Way	1.2×10^{-7}	[5]
Wei *et al.* (2015)	FRB 110220	1.2–1.5 GHz photons	Milky Way	2.5×10^{-8}	[8]
	FRB/GRB 100704A	1.23–1.45 GHz photons	Milky Way	4.4×10^{-9}	[8]
Tingay & Kaplan (2016)	FRB 150418	1.2–1.5 GHz photons	Milky Way	$(1\text{–}2)\times 10^{-9}$	[9]
Nusser (2016)	FRB 150418	1.2–1.5 GHz photons	Large-scale structure	10^{-12}–10^{-13}	[16]
Wei *et al.* (2016a)	Blazar Mrk 421	keV–TeV photons	Milky Way	3.9×10^{-3}	[10]
	Blazar PKS 2155-304	sub TeV–TeV photons	Milky Way	2.2×10^{-6}	[10]
Wang *et al.* (2016)	Blazar PKS B1424-418	MeV photons and PeV neutrino	Virgo Cluster	3.4×10^{-4}	[11]
	Blazar PKS B1424-418	MeV photons and PeV neutrino	Great Attractor	7.0×10^{-6}	[11]
Wei *et al.* (2016b)	GRB 110521B	keV photons and TeV neutrino	Laniakea supercluster of galaxies	1.3×10^{-13}	[6]
Wu *et al.* (2016a)	GW 150914	35–150 Hz GW signals	Milky Way	$\sim 10^{-9}$	[14]
Yang & Zhang (2016)	Crab pulsar	8.15–10.35 GHz photons	Milky Way	$(0.6\text{–}1.8)\times 10^{-15}$	[12]
Wu *et al.* (2016b)	GRB 120308A	Polarized optical photons	Laniakea supercluster of galaxies	1.2×10^{-10}	This paper
	GRB 100826A	Polarized gamma-ray photons	Laniakea supercluster of galaxies	1.2×10^{-10}	This paper
	FRB 150807	Polarized radio photons	Laniakea supercluster of galaxies	2.2×10^{-16}	This paper

Wu et al arxiv:1703.09935

Constrains on violation of PPN gamma parameter

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

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

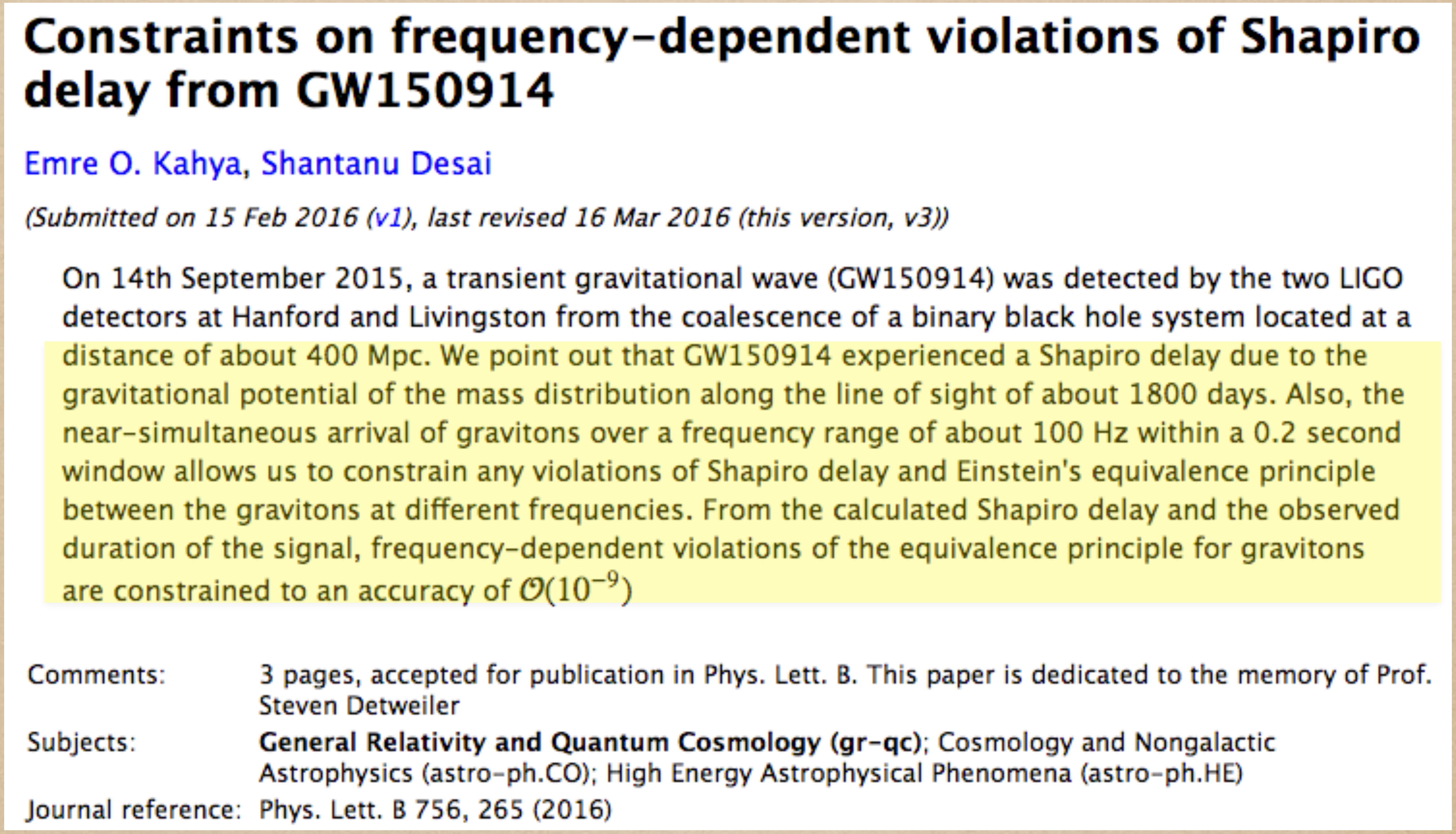
Thus γ_{ray} and optical photons 'see' the same gravitationally induced time delay to about 4 parts in 10^7 and the difference between gamma and radio photons is about one part in 10^3 (as here $\delta t \sim 1$day). If future detectors are able to register simultaneously neutrino and gravitational waves 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 From GW150914


Constraints on frequency-dependent violations of Shapiro delay from GW150914

Emre O. Kahya, Shantanu Desai

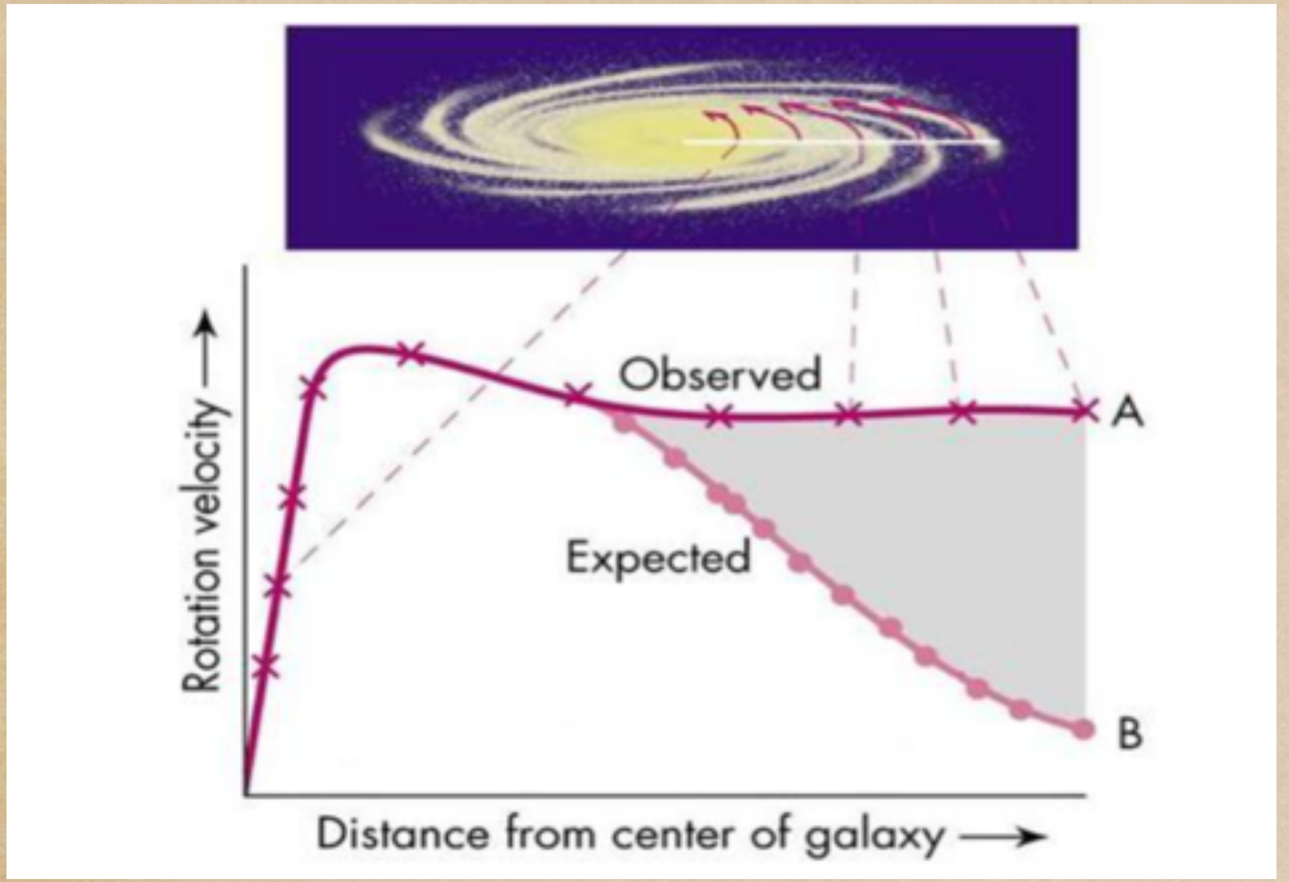
(Submitted on 15 Feb 2016 (v1), last revised 16 Mar 2016 (this version, v3))

On 14th September 2015, a transient gravitational wave (GW150914) was detected by the two LIGO detectors at Hanford and Livingston from the coalescence of a binary black hole system located at a distance of about 400 Mpc. We point out that GW150914 experienced a Shapiro delay due to the gravitational potential of the mass distribution along the line of sight of about 1800 days. Also, the near-simultaneous arrival of gravitons over a frequency range of about 100 Hz within a 0.2 second window allows us to constrain any violations of Shapiro delay and Einstein's equivalence principle between the gravitons at different frequencies. From the calculated Shapiro delay and the observed duration of the signal, frequency-dependent violations of the equivalence principle for gravitons are constrained to an accuracy of $\mathcal{O}(10^{-9})$

Comments:	3 pages, accepted for publication in Phys. Lett. B. This paper is dedicated to the memory of Prof. Steven Detweiler
Subjects:	**General Relativity and Quantum Cosmology (gr-qc)**; Cosmology and Nongalactic Astrophysics (astro-ph.CO); High Energy Astrophysical Phenomena (astro-ph.HE)
Journal reference:	Phys. Lett. B 756, 265 (2016)

Similar paper by Wu et al 1602.01566 with same conclusions

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)**

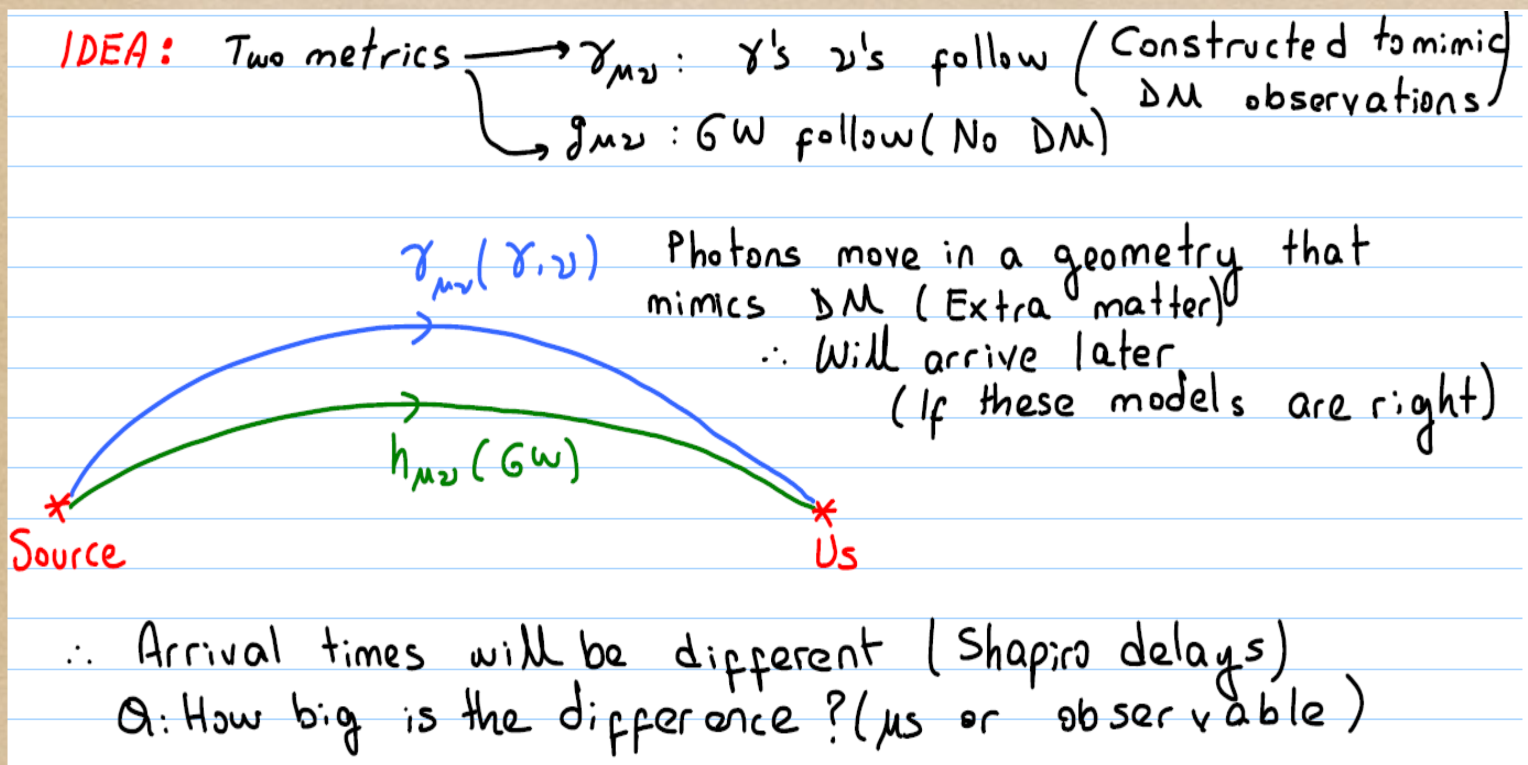
$$a = a_{\rm newt}(a_{\rm newt}/a_0)^{-1/2} \text{ for } \mathrm{a} < \mathrm{a}_0$$

- **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.

Differential Shapiro delay

Profile	GRB 070201	SN 1987a	Sco–X1
Isothermal	742 days	78.2 days	4.98 days
NFW	804 days	74.8 days	4.88 days
Moore	811 days	74.5 days	4.97 days

arXiv:0804.3804

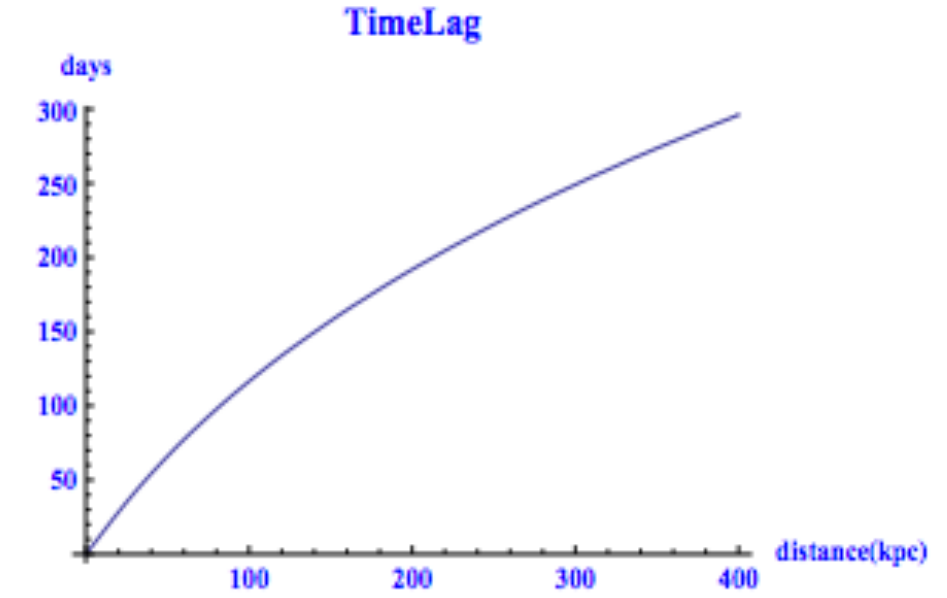


FIG. 1: Shapiro delays for sources located in Milky Way.

arXiv:1001.0725

GW170817: First BNS merger with EM counterparts

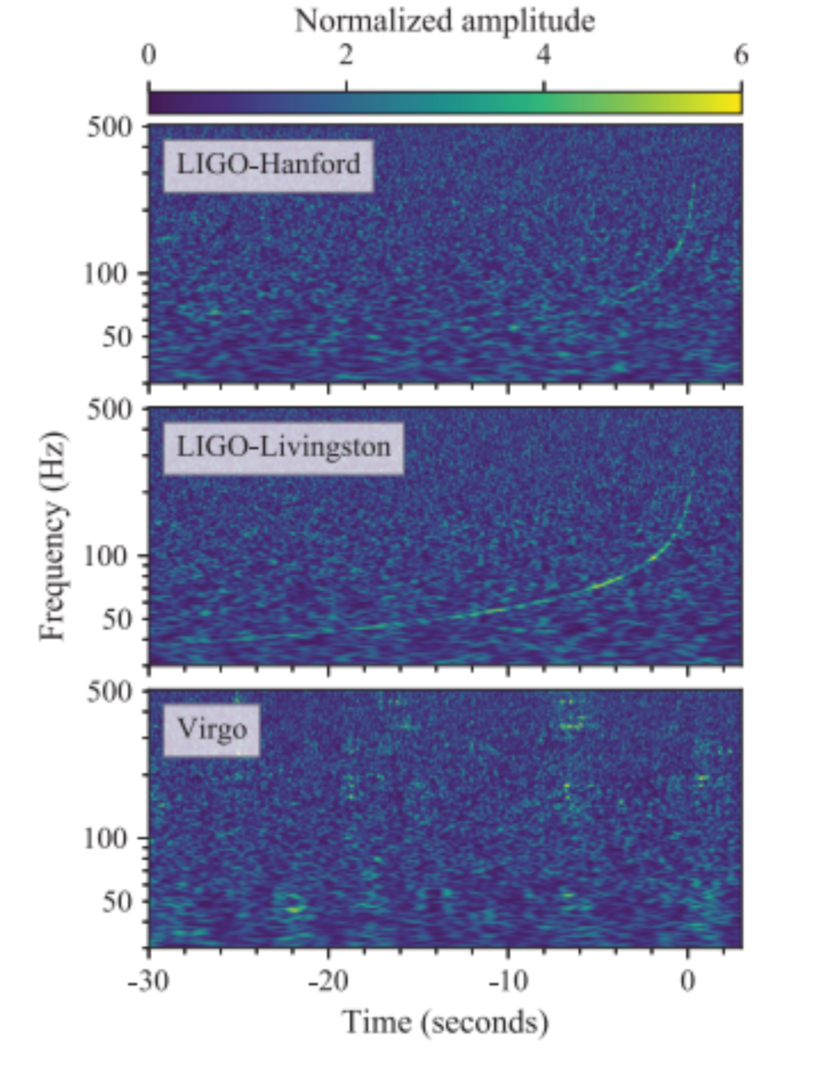
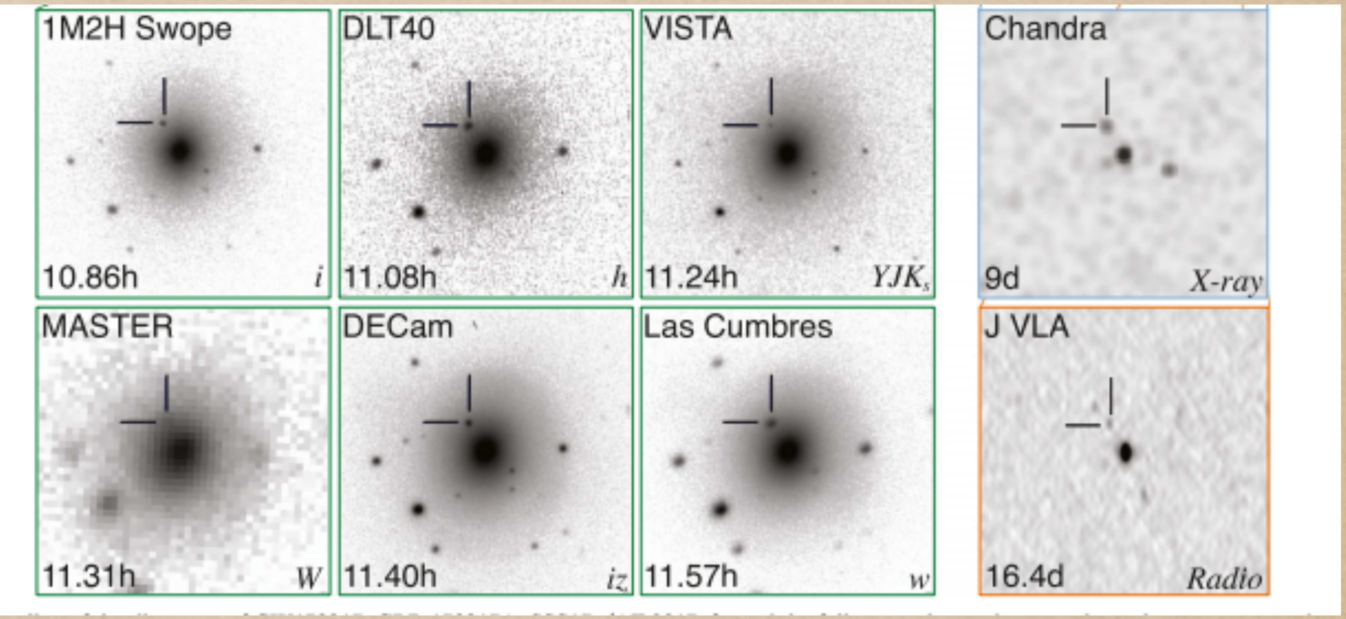


TABLE I. Source properties for GW170817: we give ranges encompassing the 90% credible intervals for different assumptions of the waveform model to bound systematic uncertainty. The mass values are quoted in the frame of the source, accounting for uncertainty in the source redshift.

	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 of GW170817

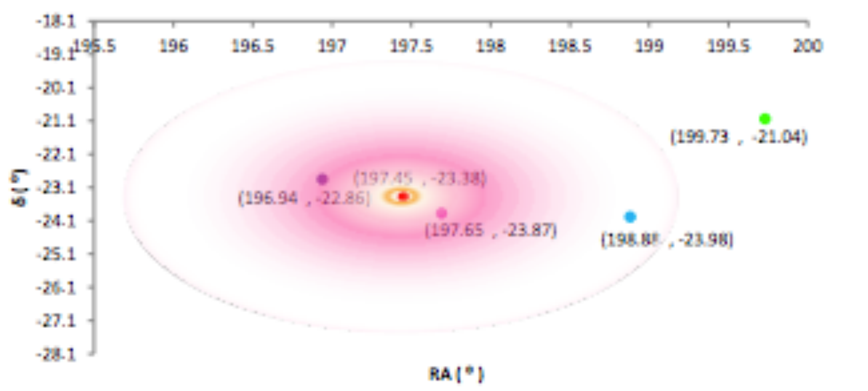


FIG. 1: The angular locations of galaxies which affect the Shapiro delay of any cosmic messenger coming from NGC 4993

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

- GW150914 observations show that Shapiro delay of gravitational waves is frequency independent.

- 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"

Thank you for your time and attention!!