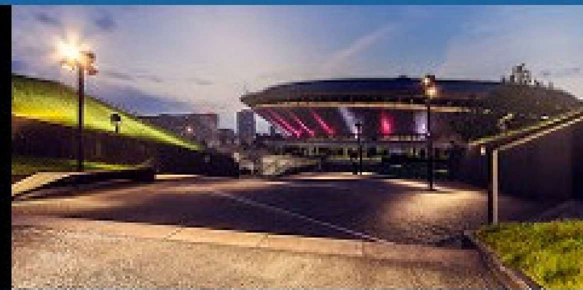
Matter To The Deepest 2021



Matter To The Deepest

15-17 September 2021

Europe/Warsaw timezone

17 SEPTEMBER:

# Fundamental properties of Nature: new opportunities for testing in the age of multi-messenger astronomy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NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

**Zong-Hong Zhu**

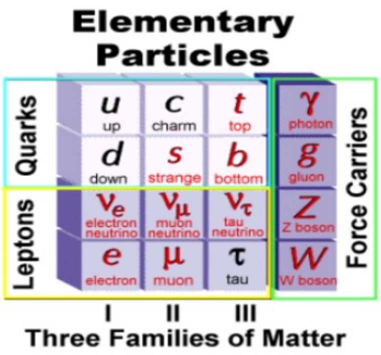
**Shuo Cao**

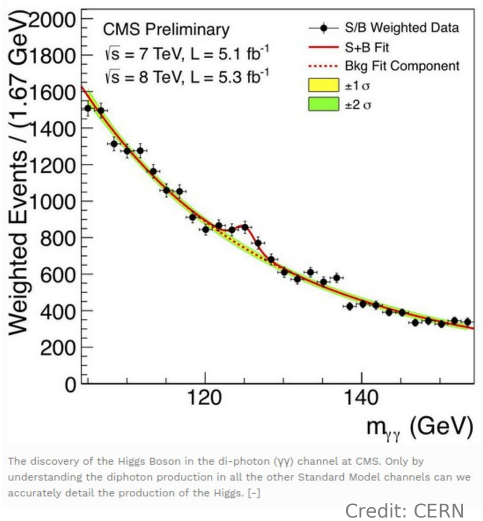
北京師範大學 BEIJING NORMAL UNIVERSITY

# testing Nature at fundamental level:

- motivations from SM:

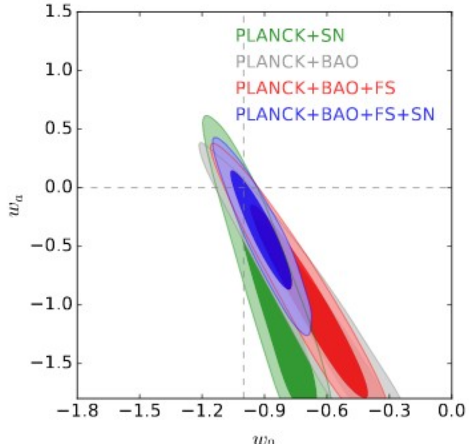
  **gravity should be mediated by a massless particle of spin 2** — **graviton**




Credit: CERN

- motivations from GR + observations:
  - dark matter
  - dark energy


Alam et al. 2016

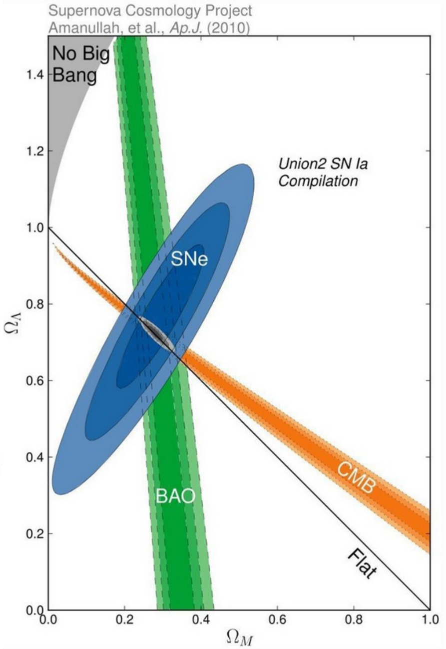
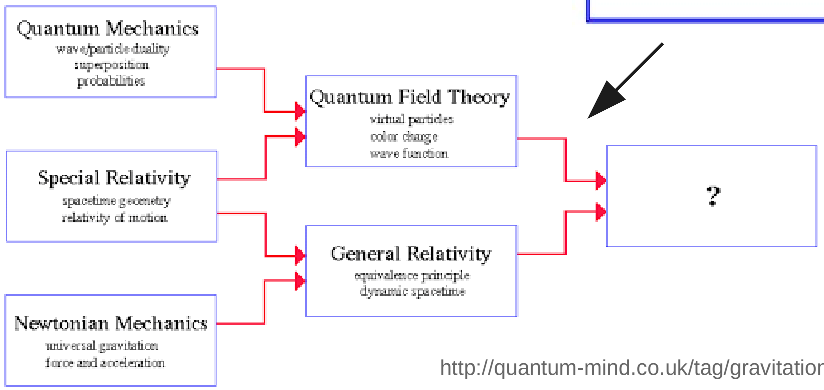




Image Source: https://slideplayer.com/slide/6061190

$$E_{Pl} \sim 10^{19}\,\mathrm{GeV}$$



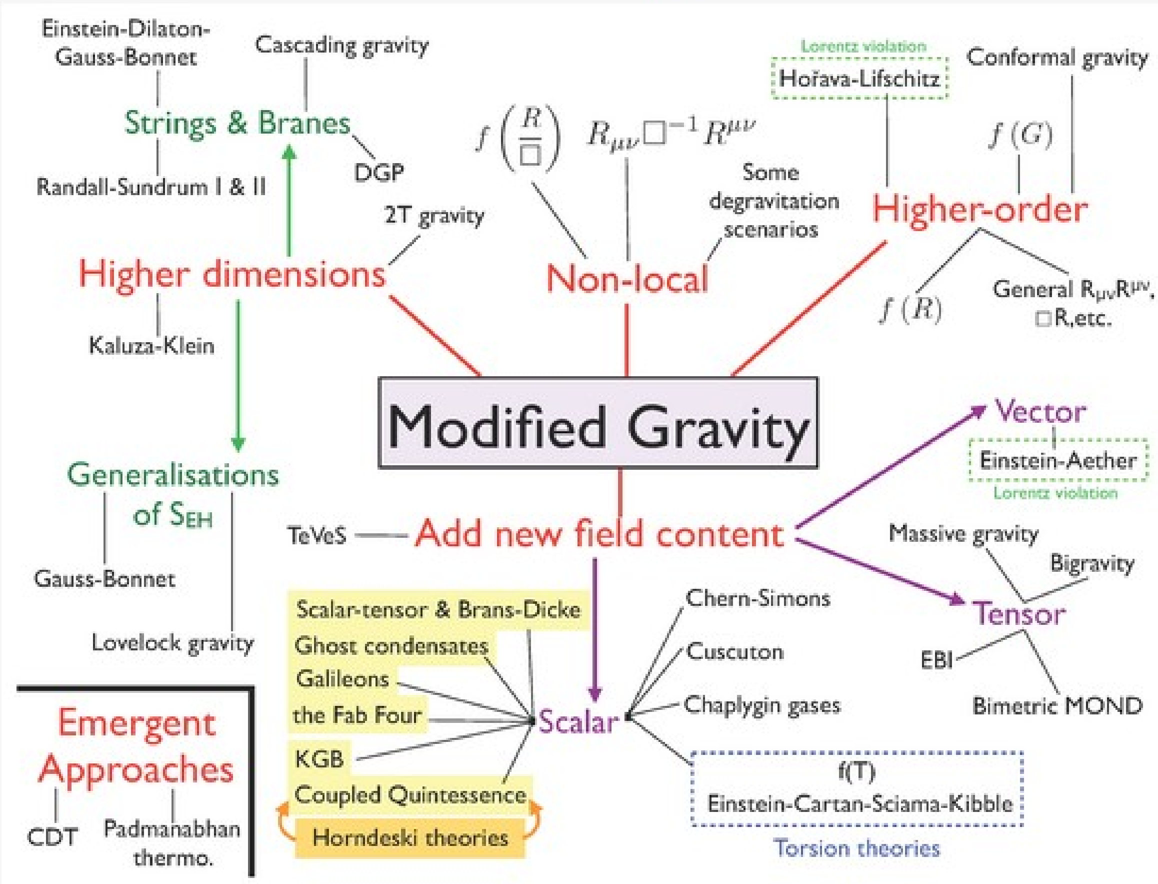

http://quantum-mind.co.uk/tag/gravitational-waves/

- motivations from QG:

**unification of GR and SM at high energies**

# Huge number of various aproaches to QG:

**Figure 11.** MGs tree diagram, reproduced from [358] (with permission from Tessa Baker).




Bull, P.; Akrami, Y.; Adamek, J.; Baker, T.; Bellini, E.; Beltrán Jiménez, J.; Bentivegna, E.; Camera, S.; Clesse, S.; Davis, J.H.; et al. Beyond Λ CDM: Problems, solutions, and the road ahead. *Phys. Dark Univ.* **2016**, *12*, 56–99.

GR naturally lose it's applicability at curvature singularities i.e. the Planck length

$$l_{Pl} = \sqrt{\hbar G/c^3} \sim 10^{-33}\text{cm}$$

or equivalently – Planck energy:

$$E_{PL} = \sqrt{\hbar c^3/G} \sim 10^{19}\text{GeV}$$

sensitivity requirements for tests are very strict:

an accuracy should be better than

$$\frac{E}{E_{Pl}} \sim 10^{-19}$$

**no experimental indication**

which way is correct ?

⇩

**effective phenomenology**


https://www.particlezoo.net

existence of massive gravitons

running nature of fundamental constants

violation of some basic principles

LIV

https://www.particlezoo.net

existence of massive gravitons

possible physical implications resulting from the fact that gravitons no longer travels at the speed of light

# MODIFIED DISPERSION RELATION

specific structure of deformation depends on a particular model

$$E^2 = m^2c^4 + \mathbf{p}^2c^2 \quad \Longrightarrow \quad E^2 = m^2 + p^2 + f(E, \mathbf{p}, m; E_{Pl})$$

Mattingly, 2005

Vucetich 2005

modification of relativistic dispersion relation may lead to **changes in travel time** of signals emitted from a astrophysical objects

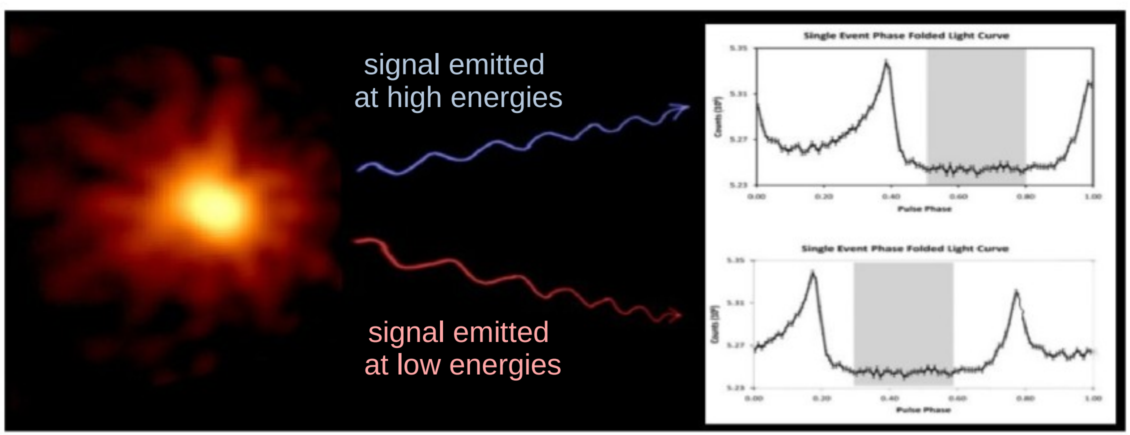
e.g. typical form of modification within LIV theories:

$$f_a(E, \mathbf{p}, m; E_{Pl}) \sim \eta_\alpha (\frac{E}{E_{Pl}})^\alpha$$

*a* represents particle species

free parameter $\alpha$ represents departure from ordinary case

# time-of-flight measurements




## high energy sources under consideration:

- pulsars
- GRBs
- AGNs
- DCO mergers

- photons
- neutrinos
- gravitons

within LIV models:

$$\Delta t_{LIV} = \frac{\Delta E}{E_{QG}} \int_0^z \frac{(1+z')dz'}{H(z')}$$

e.g. **time delay** between signals observed at high and low energies

**multi-messenger** astronomy

# Example: time delay technique in probing LIV effects

modified dispersion relation:

$$E^2 - p^2c^2 - m^2c^4 = \epsilon E^2 \left(\frac{E}{\xi_n E_{QG}}\right)^n$$

$\epsilon = \pm 1$ is 'sign parameter'

$\xi_n$ is a dimensionless parameter

$\xi_1 = 1$

$\xi_2 = 10^{-7}$

Rodriguez Martinez & Tsvi Piran, JCAP, 2006

Jacob & Piran, Nature Phys., 2007

Biesiada M. & Piórkowska A., Class. Quantum Grav. 26 125007, 2009

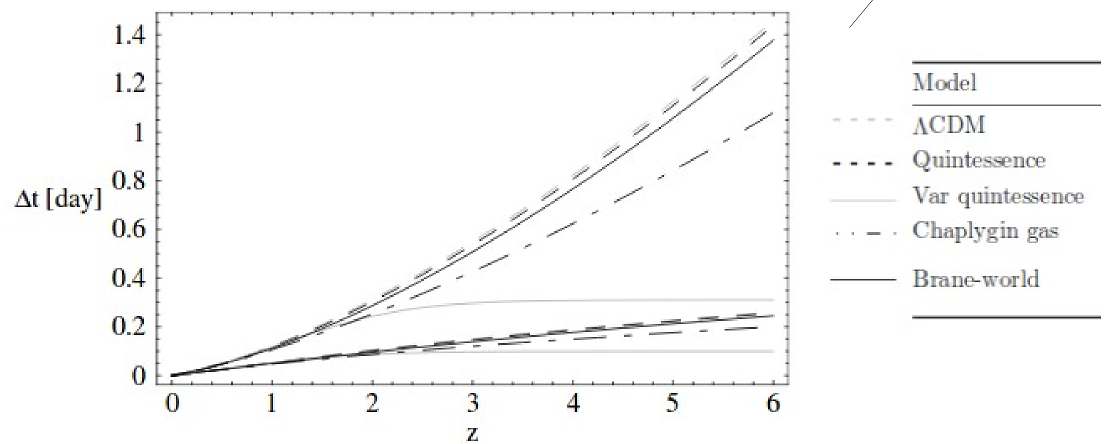
Biesiada M. & Piórkowska A., JCAP 0705:011, 2007

time delay between photon and a given particle emitted at the same time from a source to the Earth:

$$\Delta t = \int_0^z \left[\frac{m^2c^4}{2E_0}\frac{1}{(1+z)^2} - \epsilon\frac{n+1}{2}\left(\frac{E_0}{\xi_n E_{QG}}\right)^n (1+z)^n\right]\frac{dz}{H(z)}$$

for photons mass term vanishes

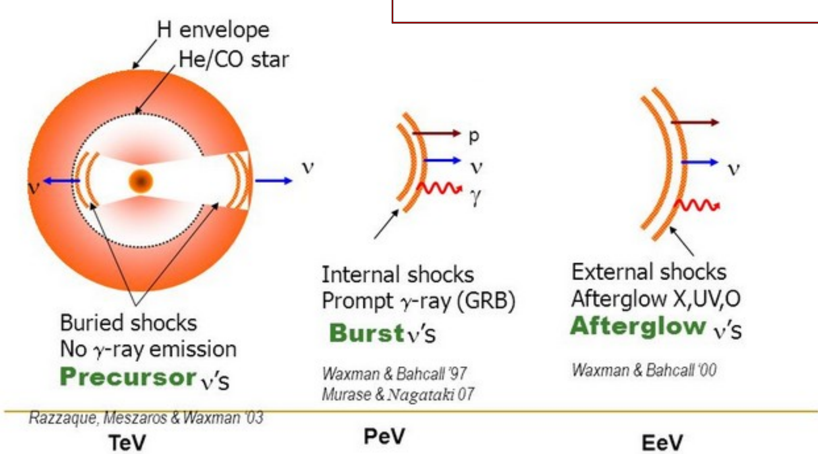
LIV term




## pair production

photons of energies above 10 TeV should annihilate with CMB photons via pair production

SOLUTION: **neutrinos**




E. Waxman and J. N. Bahcall, Phys. Rev. Lett. **78**, 2292 (1997), astro-ph/9701231.

our ignorance concerning cosmological models creates systematic effects!

**Problem: up to now no GRB neutrinos has been detected!**

Aartsen et al. (IceCube Collab.) 2017

**But we detected HE neutrino related with blazar TXS 0506+056**

Aartsen et al. (IceCube Collab.) Science 361, 1378, 2018

Biesiada M. & Piórkowska A., JCAP 0705:011, 2007

time delay between photon and a given particle emitted at the same time from a source to the Earth:

$$\Delta t = \int_0^z [\frac{m^2c^4}{2E_0}\frac{1}{(1+z)^2} - \epsilon\frac{n+1}{2}\left(\frac{E_0}{\xi_n E_{QG}}\right)^n (1+z)^n]\frac{dz}{H(z)}$$

for photons mass term vanishes — LIV term

$$\Delta t_{obs} = \Delta t_{LIV} + \Delta t_{intrinsic}$$

**linear fit** with assumption of $\Lambda$CDM

$$\frac{\Delta t_{obs}}{1+z} = a_{LIV} K(z) + b$$

$$a_{LIV} = \frac{\Delta E}{H_0 E_{QG}} \qquad K = \frac{1}{1+z}\int_0^z \frac{(1+z')dz'}{h(z')}$$

flat $\Lambda$CDM with $\Omega_\Lambda = 0.3$

## intrinsic time lags

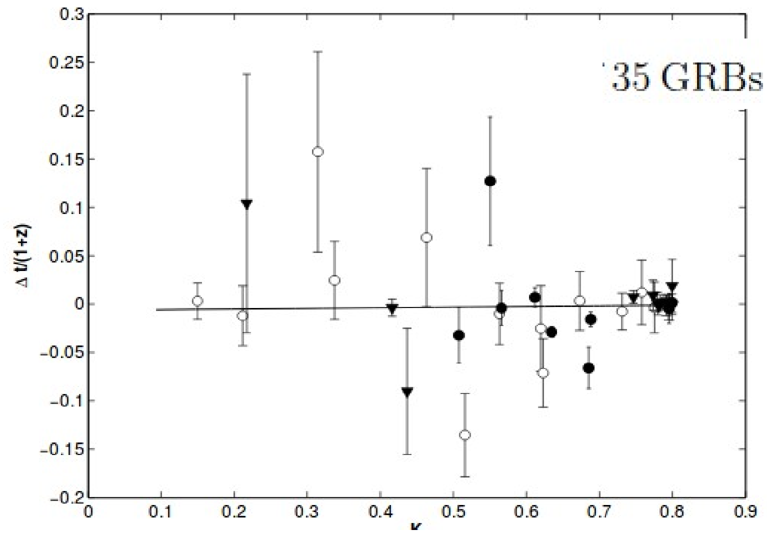
how to recognize QG effects from any delays created in the source

SOLUTION: **statistics**

Ellis et al. A&A 2003

Ellis et al. Astropart.Phys. 2006

Ellis et al. [arXiv:astro-ph/0712.2781] (Erratum)




$$\frac{\Delta t^{dw}_{obs}}{1+z} = (0.0068 \pm 0.0067)\,K - (0.0065 \pm 0.0046)$$

$$E_{QG} \geq 1.4 \times 10^{16}\ \mathrm{GeV}$$

## analysis for different cosmological scenarios:

Biesiada M. & Piórkowska A., Class. Quantum Grav. 26 125007, 2009

Table II. Regression coefficients (with $1\sigma$ ranges) for the time delay vs. $K(z)$ technique in the cosmological models tested. Akaike differences, Akaike weights

| Cosmological model | Regression coefficient $a_{LIV}$ | Intercept $b$ | $\Delta_i$ | $w_i$ | Odds against |
|---|---|---|---|---|---|
| $\Lambda$CDM | $a_{LIV} = -0.0794 \pm 0.0447$ | $b = 0.0494 \pm 0.0288$ | 1.645 | 0.152 | 2.276 |
| Quintessence | $a_{LIV} = -0.0806 \pm 0.0460$ | $b = 0.0489 \pm 0.0288$ | 1.712 | 0.147 | 2.354 |
| Var Quintessence | $a_{LIV} = -0.1510 \pm 0.0683$ | $b = 0.0735 \pm 0.0340$ | 0. | 0.347 | 1. |
| Chaplygin Gas | $a_{LIV} = -0.1201 \pm 0.0618$ | $b = 0.0627 \pm 0.0330$ | 1.042 | 0.206 | 1.684 |
| Braneworld | $a_{LIV} = -0.0866 \pm 0.0493$ | $b = 0.0501 \pm 0.0294$ | 1.704 | 0.148 | 2.344 |

quintessence model with varying EOS is the one which gives the best fit

PHYSICAL REVIEW LETTERS

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Speed of Gravitational Waves from Strongly Lensed Gravitational Waves and Electromagnetic Signals

Xi-Long Fan, Kai Liao, Marek Biesiada, Aleksandra Piórkowska-Kurpas, and Zong-Hong Zhu

Phys. Rev. Lett. **118**, 091102 – Published 2 March 2017

# time delay technique in probing graviton mass

See also:
T. E. Collett and D. Bacon, Phys. Rev. Lett.118, 091101 (2017)

In the case of massive graviton:

$$E_{GW}^2 - p_{GW}^2 c^2 = m_{GW}^2 c^4$$

for photons: $E_\gamma^2 - p_\gamma^2 c^2 = 0$

**assumption:**
GW travel along radial geodesics in flat FRW model

$$p_r = a^2 p^r$$

$$\frac{dr}{dt} = \frac{p^r c^2}{E} = \frac{p_r c^2}{a^2 E}$$

$$v_{GW} = \frac{dr}{dt} = \frac{c}{a}\left[1 - \frac{1}{2}\frac{m_{GW}^2 c^2 a^2}{p_r^2}\right]$$

$$r(t) = \int_{t_{emission}}^{t_0} v(t)dt$$

If the GW signal was emitted at the moment $t_e$ and detected (observed) at $t_0$, then the travel distance of GW is:

$$r_{GW} = r_\gamma - \Delta r_{GW}$$


comoving distance to the source:

$$r_\gamma = \int_{t_e}^{t_0} \frac{c}{a(t)}dt = c\int_0^z \frac{dz}{H(z)}$$

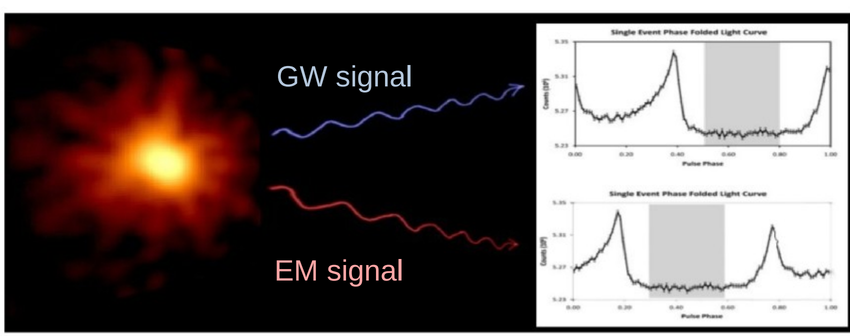
**GW signal registered later than electromagnetic counterpart**

$$\Delta t_{GW} = \Delta r_{GW}/c$$

and:

$$\Delta r_{GW} = \frac{1}{2}\frac{m_{GW}^2 c^3}{p_r^2}\int_{t_e}^{t_0} a(t)dt$$

$$= \frac{1}{2}\frac{c}{H_0}\frac{m_{GW}^2 c^4}{E^2}(1+z)^2 I_2(0,z)$$




one should placed here a characteristic 'chirping' shape of GW signal

Modified dispersion relation

$$E^2 = p^2c^2 + m_g^2c^4$$

$$\lambda_g = \frac{h}{m_g c}$$

$$v_g^2/c^2 \equiv c^2p^2/E^2 \simeq 1 - h^2c^2/(\lambda_g^2E^2)$$

**energy/frequency dependent speed of graviton !**

**Bounding the mass of the graviton using gravitational-wave observations of inspiralling compact binaries**


Clifford M. Will*
*McDonnell Center for the Space Sciences, Department of Physics, Washington University, St. Louis, Missouri 63130*


difference in the propagation speed:

lower frequency GW signal (emitted earlier)
travel slightly slower than
higher frequency GW signal (emitted later)

First ever laboratory detection of GW signal:

the tail of the signal will travel faster than the front - **signal should be ''squeezed''**

**shape (or phasing) distorsion** of the observed GW waveform

extra phase term:

$$\Phi_{MG}(f) = -D/[4\pi\lambda_g^{\,2}(1+z)f]$$

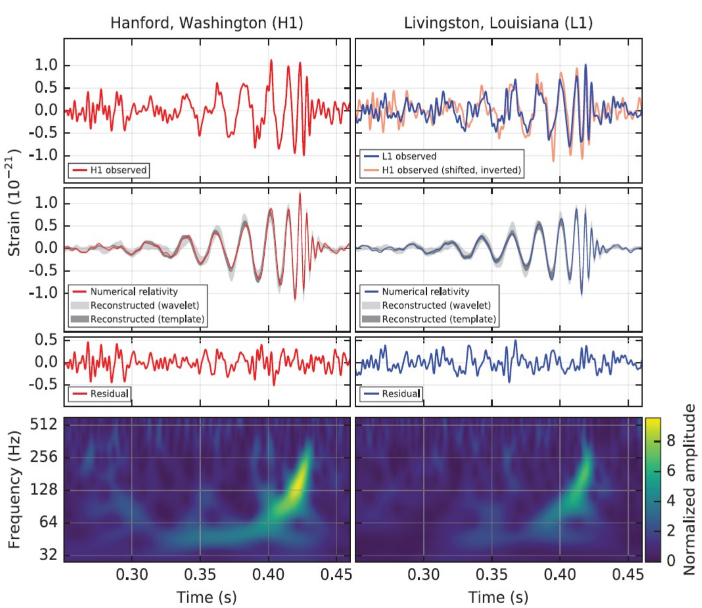

Selected for a Viewpoint in *Physics*
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016


**Observation of Gravitational Waves from a Binary Black Hole Merger**


B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)



(Received 21 January 2016; published 11 February 2016)


**GW150914**

$$\lambda_g > 10^{13}\ \mathrm{km}$$

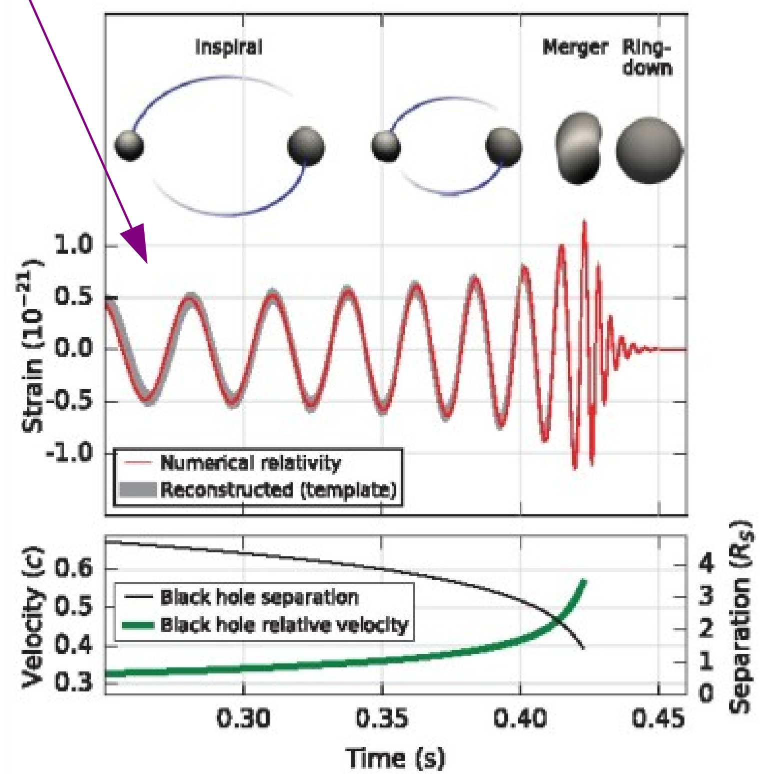
$$m_g \le 1.2 \times 10^{-22}\ \mathrm{eV/c^2}$$

at 90% confidence

confirmed by

also for **GW151226**

N.Yunes, K. Yagi, F. Pretorius, Phys. Rev D 94, 084002, 2016



LIGO Scientific Collaboration

VIRGO Listening to the cosmic whisper

scientific runs:

O1 from 12 September 2015 to 19 January 2016,

O2 from 30 November 2016 to 25 August 2017,

O3a from 1 April to 30 September 2019

O3b from 1 November 2019 suspended in March 2020

KAGRA

observation run started on 25 February 2020

LIGO@Hanford

LIGO@Livingston

https://www.ligo.caltech.edu/

VIRGO

KAGRA

A2 A bird's eye view image of KAGRA. The 3-km arms and the center part are illustrated.

https://gwcenter.icrr.u-tokyo.ac.jp/

**More than 50**
GW signals
registered so far !

**GW150914** — the first GW signal
**GW151012**
**GW151226**
**GW170104**
**GW170608**
**GW170729**
**GW170814**
**GW170809**
**GW170817** — the first NS-NS merger
**GW170818**
**GW170823**
**GW190412**
**GW190425**
**GW190814** — probably the first mixed BH-NS merger
...

B.P.Abbott et al. [LSC, Virgo Collab.], Phys. Rev. X 9, 031040 (2019)
R.Abbott et al. [LSC, Virgo Collab.], arXiv:2010.14527 [gr-qc] (2020)
R.Abbott et al. [LSC, Virgo Collab.], arXiv:2010.14533 [astro-ph] (2020)

a rule-of-thumb estimate for the graviton Compton wavelength:

C. de Rham et al., Rev. Mod. Phys. 89 (2017) 2, 025004
Clifford M. Will, Phys.Rev.D57:2061-2068,1998

$$\lambda_g > 5 \times 10^{11}\ \mathrm{km} \left( \frac{D}{200\ \mathrm{Mpc}} \frac{100\ \mathrm{Hz}}{f} \frac{1}{f \Delta t} \right)^{\frac{1}{2}}$$

phase distortion $\sim 1/\rho$

**GW150914**

$D \sim 400$ Mpc

$f \sim 100$ Hz

$\rho \sim 23$

signal-to-noise ratio

$$\lambda_g \gtrsim 10^{12}\ \mathrm{km}$$

in agreement with

B.P..Abbott et al. [LSC], PRL 116, 061102 (2016)

**GWs propagate without dispersion and that the graviton is massless**

- 24 GW events from O3a
- median of D ~ 1.6 Gpc
- two evens with SNR ~25

$$m_g \le 1.76 \times 10^{-23}\ \mathrm{eV}/c^2$$

at 90% confidence

R.Abbott et al. [LSC, Virgo Collab.] arXiv:2010.14529 [gr-qc] (2020)

# Prospects: probing graviton mass in future GW detectors

C. de Rham et al., Rev. Mod. Phys. 89 (2017) 2, 025004
Clifford M. Will, Phys.Rev.D57:2061-2068,1998

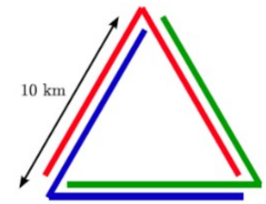
$$\lambda_g > 5 \times 10^{11}\ \text{km} \left( \frac{D}{200\ \text{Mpc}} \frac{100\ \text{Hz}}{f} \frac{1}{f\Delta t} \right)^{\frac{1}{2}}$$

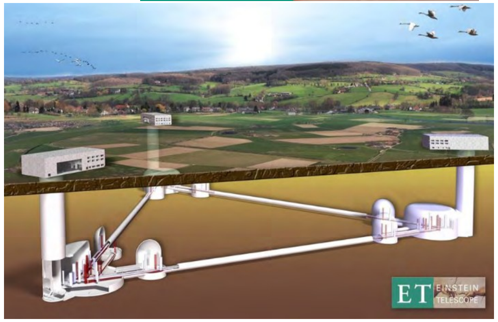
$\sim 1/\rho$ phase distortion

| | |
|---|---|
| ET: | $r_0$ = 1917 Mpc |
| DECIGO | $r_0$ = 6709 Mpc |
| B-DECIGO | $r_0$ = 535 Mpc |

broadening the GW spectrum to lower frequencies (lower than 1 Hz)

inaccessible from the ground due to irremovable **seismic noise**



http://www.et-gw.eu/

Goldstein, A., et al., *ApJL* **2017**, *848*, L14.

single triangular detector unit is equivalent for two standard L-shaped interferometers rotated by 45°

Yagi, K. & Seto, N. 2011, PRD, 83, 044011

https://lisa.nasa.gov/

LISA — Laser Interferometer Space Antenna

f: 0.1 mHz – 100 mHz

eLISA | $D \sim 3$ Gpc, $\rho \sim 10^3$, $f \sim 10^{-3}$ Hz

$$m_g < 10^{-26}\ \text{eV}, \quad \lambda_g > 10^{16}\ \text{km}$$

DECIGO — Space Gravitational Wave Antenna

f: 1 mHz – 100 Hz

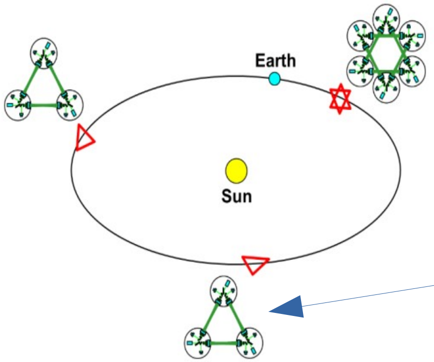
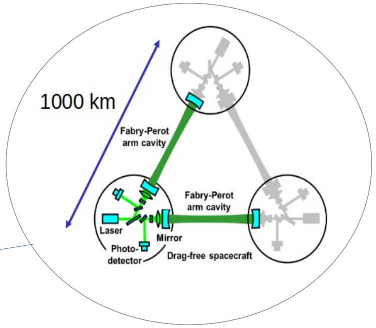



Fig. 1. Orbit of DECIGO. Four clusters of DECIGO are put in the heliocentric orbit: two at the same position and the other two at different positions.

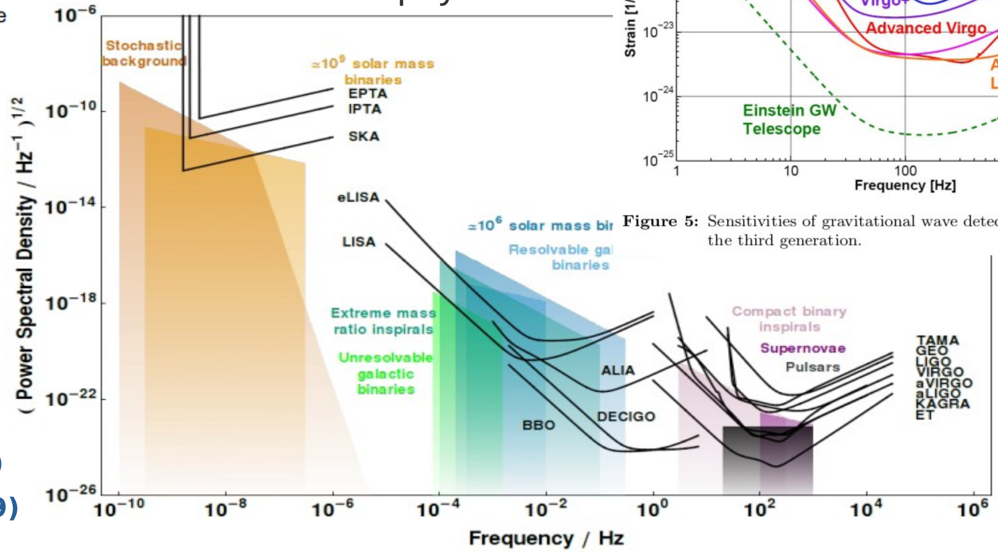
https://decigo.jp/index_E.html

Fig. 2. Conceptual design of DECIGO. One cluster of DECIGO consists of three drag-free spacecraft. FP cavities are used to measure a change in the arm length.




Nakamura T., et al. (2016)
Kawamura, S., et al. (2019)

**Multifrequency** GW astrophysics !



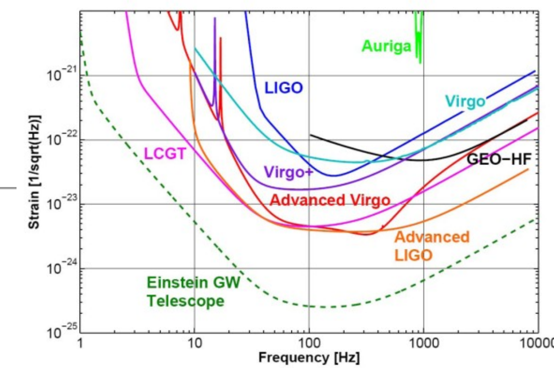




**Figure 5:** Sensitivities of gravitational wave detectors from the first to the third generation.

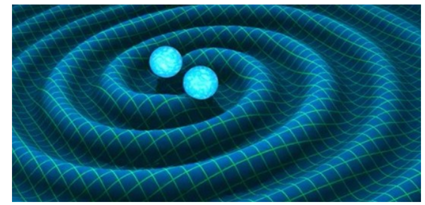
EINSTEIN TELESCOPE

DECIGO

Big catalogs of inspiral events up to cosmological distances ⇒ Some of them would be gravitationally lensed

## GW lensing – motivations from theory ⇒

GW experience the same geometric-optics effects as EM waves:


https://scienceline.org

**cosmological redshift**

**gravitational redshift**

**gravitational lensing**

EM field equations

$$\partial_\mu F^{\mu\nu} = k j^\nu$$

EM field tensor

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

4-vector 'potential'

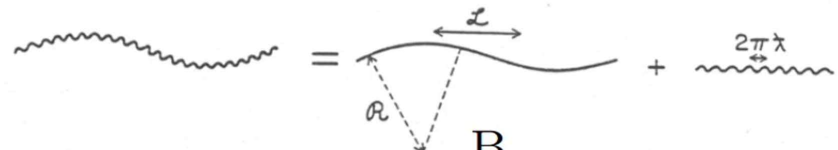
Lorentz gauge

$$\partial_\mu A^\mu = 0$$

EM field equations in terms of Lorentz gauge

$$\Box^2 A_\mu = \mu_0 j_\mu$$

$$\lambdabar = \lambda/2\pi \ll \mathcal{L} = (\text{lengthscale on which background metric varies}) \lesssim \mathcal{R}$$




$$g_{\alpha\beta} = g^{\mathrm{B}}_{\alpha\beta} + h_{\alpha\beta}$$

$g^{\mathrm{B}}_{\alpha\beta} \equiv \langle g_{\alpha\beta} \rangle$, $h_{\alpha\beta} \equiv g_{\alpha\beta} - \langle g_{\alpha\beta} \rangle$

Kip S. Thorne, Lorentz Lectures, University of Leiden, September 2009

https://www.lorentz.leidenuniv.nl/lorentzchair/thorne/Thorne1.pdf

Einstein field equations:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$\kappa$

weak-field metric

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \qquad \text{where } |h_{\mu\nu}| \ll 1,$$

+ Lorentz gauge $\partial_\mu \bar{h}^{\mu\nu} = 0$

$$\bar{h}_{\mu\nu} \equiv h_{\mu\nu} - \tfrac{1}{2}\eta_{\mu\nu} h.$$

$$\Box^2 \bar{h}^{\mu\nu} = 2\kappa T^{\mu\nu}$$

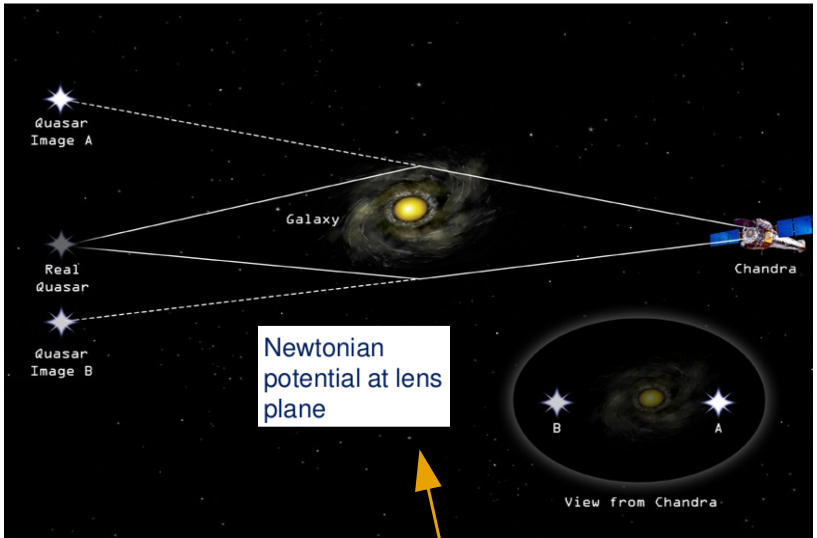
**basic field equations of linearised GR in terms of metric perturbation**

$$\Box^2 \bar{h}^{\mu\nu} = 0$$

**in vacuum**

# Strong gravitational lensing:

light traveling along null geodesics bends
in the vicinity of massive bodies




https://chandra.harvard.edu/

effective lesing
(Fermat) potential

$$\phi(\boldsymbol{\theta}) = \frac{D_{ls}}{D_l D_s} \frac{2}{c^2} \int \Phi(D_l \boldsymbol{\theta}, z) dz$$

Travel time of light rays from images → time delay:

$$\Delta t = \frac{1+z_1}{c} \frac{D_{\rm ol} D_{\rm os}}{D_{\rm ls}} \left[ \frac{(\boldsymbol{\theta} - \boldsymbol{\beta})^2}{2} - \phi(\boldsymbol{\theta}) \right]$$

$t_{\rm geom}$ $t_{\rm grav}$

Massimo Meneghetti, Introduction to Gravitational Lensing; Lecture scripts

Schneider, Ehlers, Falco, ‘Gravitational Lenses’

Schneider, Kochanek, Wambsganss, ‘Gravitational Lensing: Strong, Weak and Micro’

in the **light ray formalism**
- thin screen approximation:

$$\boldsymbol{\eta} = \frac{D_{\rm s}}{D_{\rm d}} \boldsymbol{\xi} - D_{\rm ds} \hat{\boldsymbol{\alpha}}(\boldsymbol{\xi})$$

In terms of angular coord.:

$$\boldsymbol{\eta} = D_{\rm s} \boldsymbol{\beta}$$
$$\boldsymbol{\xi} = D_{\rm d} \boldsymbol{\theta}$$

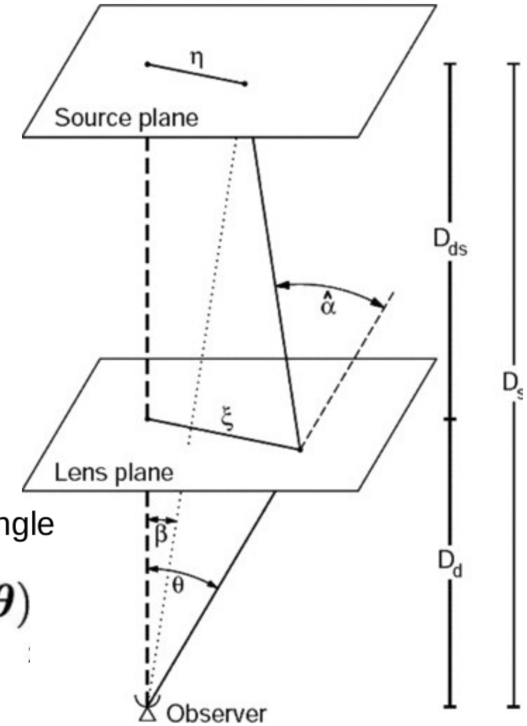
$$\boldsymbol{\beta} = \boldsymbol{\theta} - \boldsymbol{\alpha}(\boldsymbol{\theta})$$

**lens equation**

reduced deflection angle

$$\boldsymbol{\alpha} = \nabla_{\boldsymbol{\theta}} \phi \qquad \frac{D_{\rm ds}}{D_{\rm s}} \hat{\boldsymbol{\alpha}}(D_{\rm d} \boldsymbol{\theta})$$

$$\boldsymbol{\theta} - \boldsymbol{\beta} - \nabla_{\boldsymbol{\theta}} \phi = 0$$




Bartelmann& Schneider, 2001
Schneider, 2006

S. Suyu; lectures XXIV Canary Islands Winter School of Astrophysics 2012

## Fermat Principle

$$\nabla_{\boldsymbol{\theta}} \Delta t = 0$$

Images are located at points where the total time delay function is stationary

## magnification

$$\mu(\boldsymbol{\theta}) = \frac{1}{\det A(\boldsymbol{\theta})}$$

$$A(\boldsymbol{\theta}) = \frac{\partial \boldsymbol{\beta}}{\partial \boldsymbol{\theta}}$$

# Singular Isothermal Sphere (SIS) model

three-dimensional density distribution

one-dimensional velocity dispersion

$$\rho(r) = \frac{\sigma_v^2}{2\pi G}\frac{1}{r^2}$$

Source-Lens-Observer perfectly aligned

## Einstein radius

$$\theta_E = 4\pi\left(\frac{\sigma}{c}\right)^2 \frac{d_A(z_l,z_s)}{d_A(z_s)}$$

two images form on the opposite side of the lens

$$\theta_\pm = \theta_E \pm \beta$$

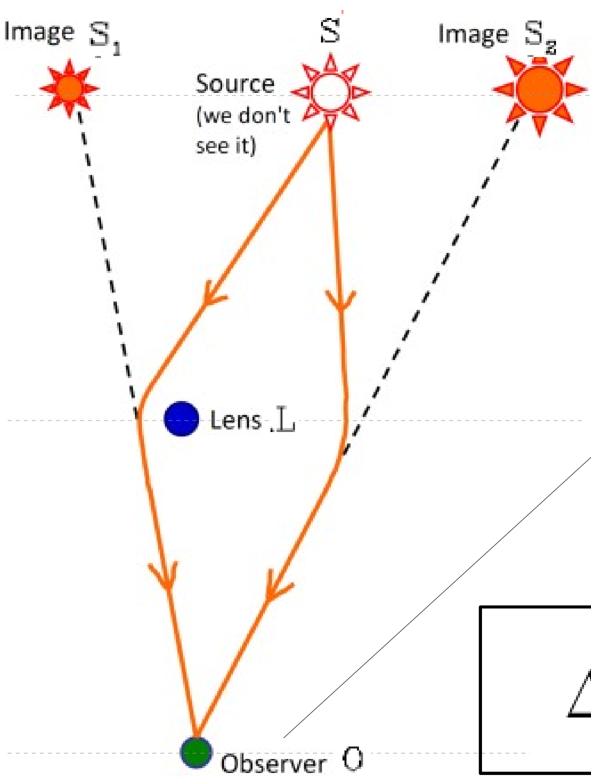
angle between directions to the lens and to the source

$$x_\pm = \frac{\theta_\pm}{\theta_E} \qquad y = \frac{\beta}{\theta_E}$$

misalignment of the source wrt optical axis of the lens

$$x_\pm = 1 \pm y$$

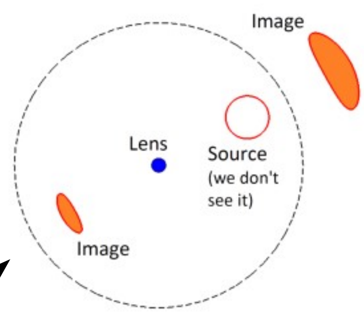
Typical angular scale of image separation for galaxy lens = 1”




*Universe* **2017**, 3, 57

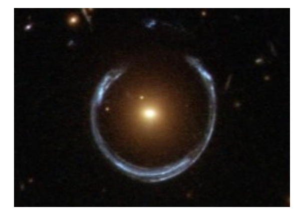
magnification

$$\mu_\pm = \frac{1}{y} \pm 1$$




**‘Horseshoe Lens’**

SDSS J114833.14+193003.2




NASA, ESA, Bolton (SLACS Team)

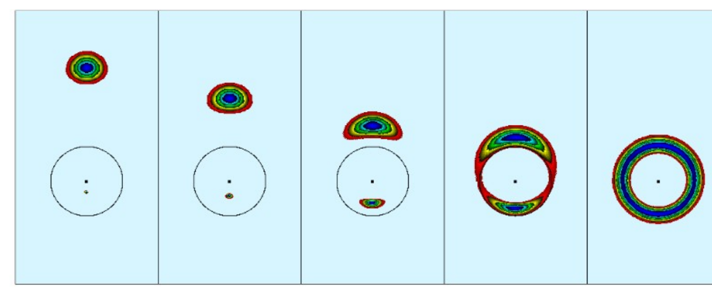


Figure 19: Five snapshots of a gravitational lens situation: From left to right the alignment between lens and source gets better and better, until it is perfect in the rightmost panel. This results in the image of an “Einstein ring”.

J.Wambsganss, Living Reviews in Relativity volume 1, Article number: 12 (1998)

**time delay** between signals:

Schneider, Ehlers, Falco, ‘Gravitational Lenses’

$$\Delta t_{SIS} = \frac{1+z_l}{2c}\frac{D_l D_s}{D_{ls}}\left(\theta_+^2 - \theta_-^2\right) = \frac{2(1+z_l)}{c}\frac{D_l D_s}{D_{ls}}\theta_E \beta$$

Schneider, Kochanek, Wambsganss, ‘Gravitational Lensing: Strong, Weak and Micro’

PHYSICAL REVIEW LETTERS

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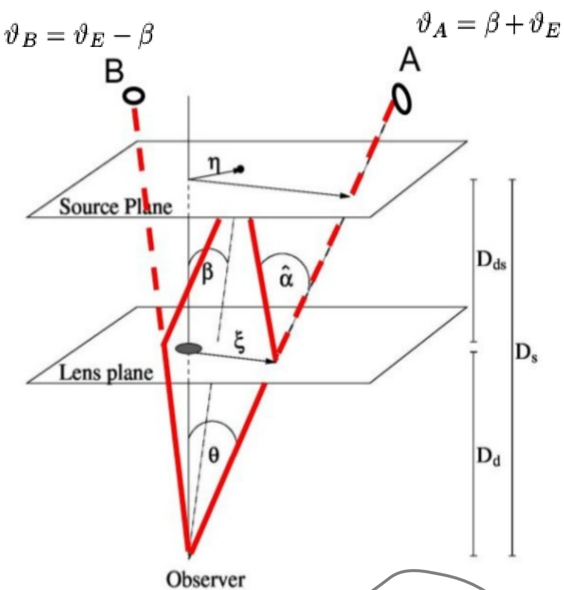
## Speed of Gravitational Waves from Strongly Lensed Gravitational Waves and Electromagnetic Signals

Xi-Long Fan, Kai Liao, Marek Biesiada, Aleksandra Piórkowska-Kurpas, and Zong-Hong Zhu
Phys. Rev. Lett. **118**, 091102 – Published 2 March 2017

# constraining directly speed of GWs with SL

See also:
T. E. Collett and D. Bacon, Phys. Rev. Lett.118, 091101 (2017)




[Schneider et al. 2006]

$\beta < \vartheta_E$
lensing is strong

**SIS model:**

$$\vartheta_E = 4\pi \frac{D_{ls}}{D_s}\frac{\sigma_v^2}{c^2}$$

$$\vartheta_{E,GW} = \vartheta_E\left(1 + \frac{m_{GW}^2 c^4}{2E^2}\right)$$

Lowenthal, PRD, 1973

$$\Delta t_{SIS} = \frac{32\pi^2}{H_0}\left(\frac{\sigma}{c}\right)^4 y \frac{\tilde{r}(z_l)\tilde{r}(z_l, z_s)}{\tilde{r}(z_s)}$$

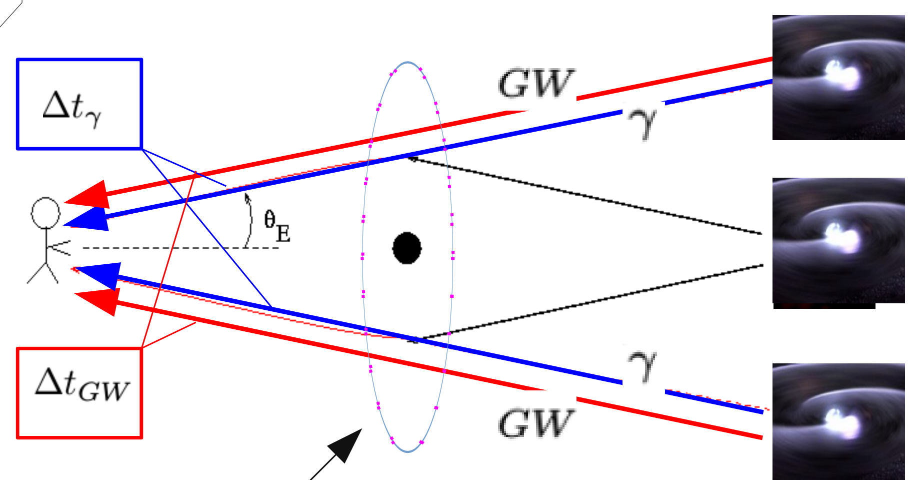
source-lens misalignment $y = \beta/\vartheta_E$

$$\Delta t_{GW} \neq \Delta t_\gamma$$

difference between time delays measured **independently** in **GW and EM windows**

$$\Delta t_\gamma - \Delta t_{GW}$$

- method based on modified dispersion relation and thus **independent of a particular non-standard model of gravity**
- method is differential in nature and thus - **free from any assumptions regarding intrinsic timelag between EM and GW signal emission**




time delay is produced at lens location
– **results doesn't depend strongly on cosmology**

general form for bound on $v_{GW}$ valid for a broad set lens models

timing accuracy

$$1 - \left(\frac{v_{GW}}{c}\right)^2 \leq \frac{\delta T}{\Delta t_\gamma F_{\rm lens}(z_l, z_s)}$$

factor related to lens model and cosmology $F_{\rm lens}(z_l, z_s) \sim O(1)$

## perspectives:

for galaxy-galaxy strong lensing with $z_l = 1$ and $z_s = 2$

$$1 - \left(\frac{v_{GW}}{c}\right)^2 \leq 4.26 \times 10^{-10} \left(\frac{\delta T}{1\ ms}\right) \left(\frac{\sigma}{250\ km/s}\right)^{-4} \left(\frac{y}{0.1}\right)^{-1}$$

with assumed ΛCDM cosmology:
$H_0 = 68\ km\ s^{-1}\ Mpc^{-1}$,
$\Omega_m = 0.3$

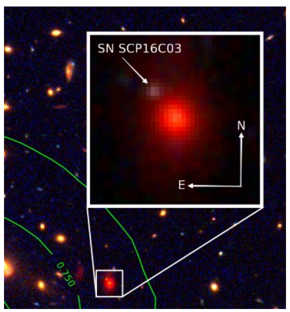
**accuracy of time delay measurements**
sets constraints on GW speed

strongly lensed transient events

**PS1-10afx** **2014**
controversial case

**SCP16C03**
**29.02.2016**

massive galaxy cluster
MOO J1014+0038
at z =1.3
SNIa at z =2.22




D.Rubin et al., ApJ 866, 65 (2018)

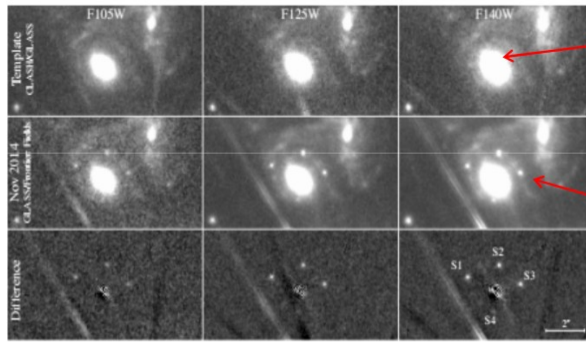



**Fig. 1:** *HST* WFC3-IR images showing the simultaneous appearance of four point sources around a cluster member galaxy. From left to right the columns show imaging in the *F105W* filter (*Y* band), *F125W* (*J*), and *F140W* (*JH*). From top to bottom the

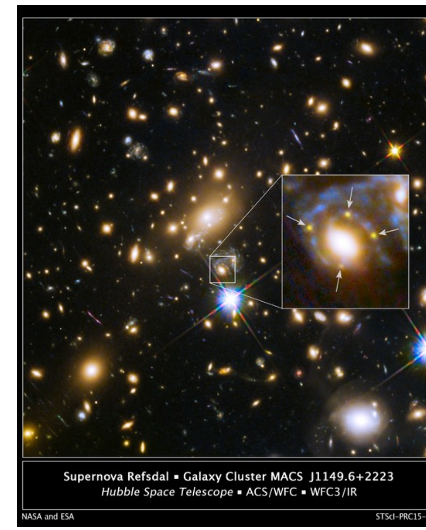
Kelly et al., ApJL 2016

**Refsdal Supernova** **11.11.2014**
identified as core-collapse supernova

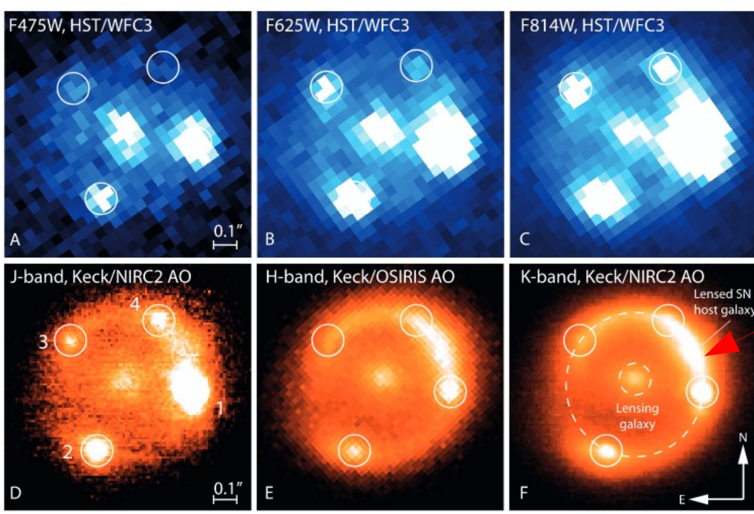
**lens**:
elliptical galaxy from
MACS J1149.6+2223
galaxy cluster at z=0.54

**source:**
spiral galaxy at z=1.49
host galaxy of SN

Kelly et al., Science 2015




reappearance
of Refsdal SN
**11.12.2015**




normal SN Ia at $z = 0.409$

**IPTF16geu**
**(SN 2016geu)**

**5.09.2016**

A.Goobar et al., Science, 356, 291-295 (2017)

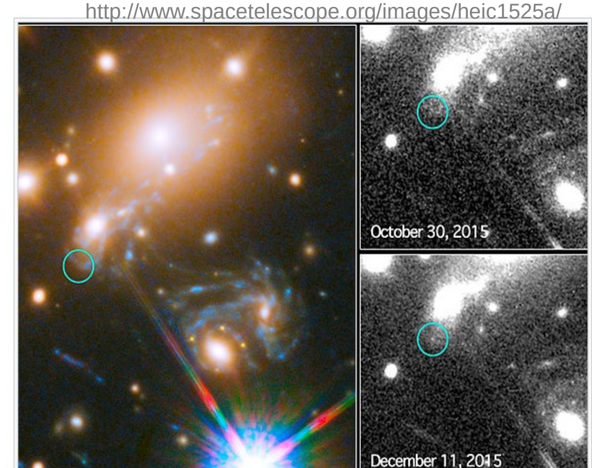
$z = 0.216$
$\mu \sim 52$

for SX image:

$$1 - \left(\frac{v_{GW}}{c}\right)^2 \leq 3.2 \times 10^{-11}$$

reappearance
predicted
in about one year
in one of
lensed
images
of host galaxy

http://www.spacetelescope.org/images/heic1525a/



## perspectives:

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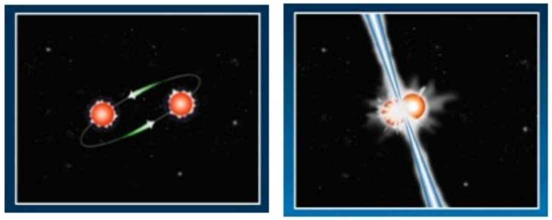
$$1-\left(\frac{v_{GW}}{c}\right)^2 \leq 4.26\times10^{-10}\left(\frac{\delta T}{1\ ms}\right)\left(\frac{\sigma}{250\ km/s}\right)^{-4}\left(\frac{y}{0.1}\right)^{-1}$$

$$\Delta t_{\gamma,GW} = \frac{1}{2H_0}(1+z_s)^2 I_2(0,z_s) \Rightarrow \boxed{1-\left(\frac{v_{GW}}{c}\right)^2 \leq 9.92\times10^{-22}}$$

## lensed NS-NS or NS-BH mergers

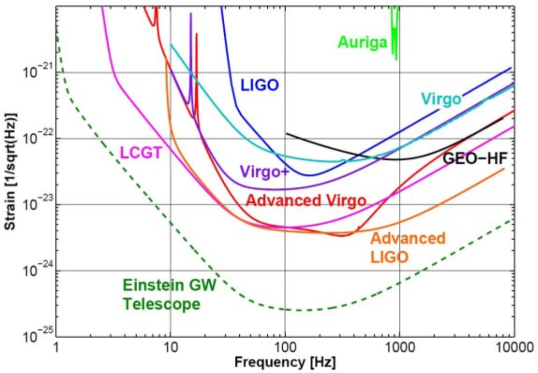


jet collimation:

~10% of NS-NS systems will be aligned as to give observable SGRBs

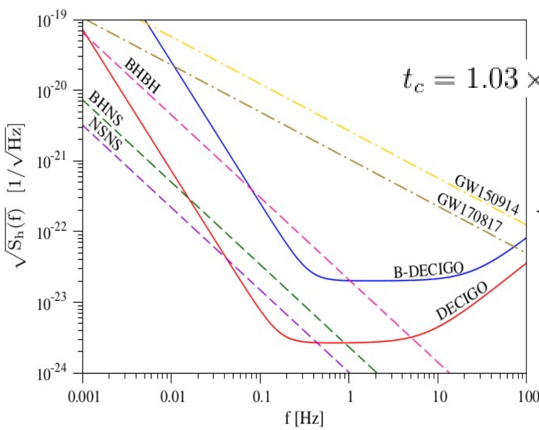
EM counterpart of NS-NS or NS-BH mergers visible as:

- kilonovae — duration of order of days — P.S.Cowperthwaite and E.Berger, ApJ 814, 25 (2015)
- short GRBs — duration of order of 0.1 - 1s — D.B. Fox et al., Nature 437, 845 (2005)
- FRB — duration of order of ms — D. J. Champion et al., MNRAS 10.1093 (2016) D.Thornton et al., Science 341, 53 (2013)




## NS-NS systems planned to be routinely detected by GW detectors

**DECIGO/B-DECIGO** ← Big catalogs of inspiral events up to cosmological distances → **ET, aLIGO/aVirgo**




$$t_c = 1.03\times10^6\ \mathrm{s}\ (\mathcal{M}_z/30.1\ M_\odot)^{-5/3}(f/0.1\ \mathrm{Hz})^{-8/3}$$

Isoyama, S. et al., Prog. Theor. Exp. Phys. 073E01 (2018)

GW150914 and GW170817 could have been visible in (B-)DECIGO band for ~ 10 days and ~ 7 yrs prior to coalescence with large numbers of GW cycles

DECIGO sensitivity **significantly affected** by unresolved BH-BH systems; B-DECIGO affected much less

**A. Piórkowska-Kurpas et al, ApJ 908 196 (2021)**

**respective rates for B-DECIGO**: $10^3$ (NS-NS), $10^4$ (BH-NS), $10^5$ (BH-BH)

| Source | BNS | NS-BH | BBH |
|---|---|---|---|
| Rate (Mpc$^{-1}$ Myr$^{-1}$) | 0.1–6 | 0.01–0.3 | $2\times10^{-3}$–0.04 |
| Event Rate (yr$^{-1}$) in aLIGO | 0.4–400 | 0.2–300 | 2–4000 |
| Event Rate (yr$^{-1}$) in ET | $\mathcal{O}(10^3$–$10^7)$ | $\mathcal{O}(10^3$–$10^7)$ | $\mathcal{O}(10^4$–$10^8)$ |

ET Science Team, ''Einstein gravitational wave Telescope conceptual design study'' https://zenodo.org/record/3911261

Yearly detection rate for DECIGO

| Evolutionary scenario | standard | optimistic CE | delayed SN | high BH kicks |
|---|---|---|---|---|
| NS-NS | | | | |
| low-end metallicity | 233.1 | 119. | 335.5 | 3054.4 |
| high-end metallicity | 439.6 | 203.9 | 707.3 | 8807.7 |
| BH-NS | | | | |
| low-end metallicity | 2688.9 | 1239.5 | 1838.6 | 1877.6 |
| high-end metallicity | 2000. | 1314.6 | 1614.5 | 1613.7 |
| BH-BH | | | | |
| low-end metallicity | 207755.2 | 384698. | 178991.7 | 20125.8 |
| high-end metallicity | 166436. | 360001.5 | 145583.5 | 15379.5 |
| TOTAL | | | | |
| low-end metallicity | 210677.2 | 386056.5 | 181165.8 | 25057.8 |
| high-end metallicity | 168875.6 | 361520 | 147905.3 | 25800.9 |

## perspectives:

## First Multimessenger Transient

**GW170814** — GWs LIGO/VIRGO

⇩ ~1.7 s

**GRB 170817A** — γ-rays Fermi/GBM

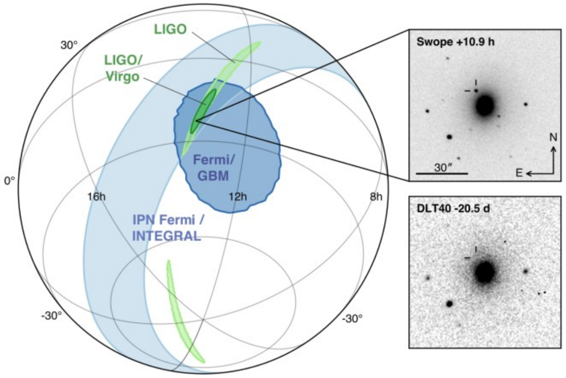
⇩ 11 hours after the merger

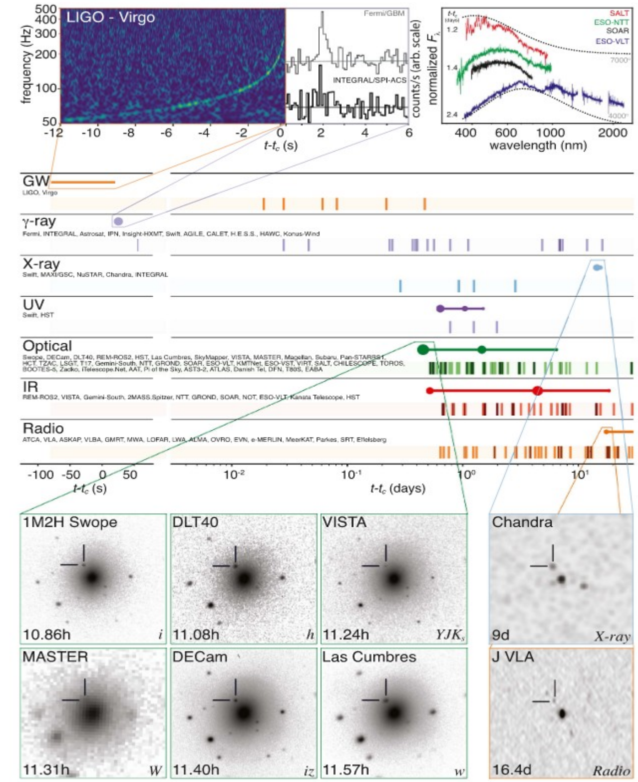
**SSS17a / AT 2017gfo** — bright optical transient in NGC 4993

⇩ multi-wavelength evolution within the first 12–24 hr

**Follow-up observations:**

| | |
|---|---|
| UV-blue transient | ~15h after merger |
| X-ray emission | ~9 days after merger |
| radio emission | ~16 days after merger |




Multi-messenger Observations of a Binary Neutron Star Merger; ApJL, 848:L12, 2017

⇨ **lensed** NS-NS or NS-BH mergers

**GW lensing in ET** discussed in papers:

A. Piórkowska et al. **JCAP10(2013)022** (NS-NS only)

M. Biesiada et al. **JCAP10(2014)080** (full DCO: NS-NS, BH-NS, BH-BH)

X. Ding et al. **JCAP12(2015)006** (relaxing intrinsic SNR=8 demand; magnification bias)

robust prediction: **50-100 lensed DCO events per year**

BH-BH systems contribute 91 – 95%;
NS-NS systems 1 – 4%

**~a few lensed NS-NS /yr**

ET EINSTEIN TELESCOPE

## Einstein Telescope

- *Increased sensitivity great expectations*
- *Big catalogs of inspiral events up to cosmological distances*
- *Multi-messenger astrophysics*
- *Some of them would be gravitationally lensed*

results corrected for Earth's rotation effect:
L. Yang et al. **ApJ 874, 139 (2019)**

THE ASTROPHYSICAL JOURNAL

SNR above threshold of 8

Yagi & Seto 2011
Isoyama et al. 2018

# Inspiraling Double Compact Object Detection and Lensing Rate: Forecast for DECIGO and B-DECIGO

Aleksandra Piórkowska-Kurpas[1,2], Shaoqi Hou[3], Marek Biesiada[1,4], Xuheng Ding[3,5], Shuo Cao[1], Xilong Fan[3], Seiji Kawamura[6], and Zong-Hong Zhu[1,3]

Published 2021 February 24 • 

The Astrophysical Journal, Volume 908, Number 2

**Citation** Aleksandra Piórkowska-Kurpas *et al* 2021 *ApJ* **908** 196

optical depth corrected for finite duty cycle of detector

$$\dot{N}_{lensed}(z_s) = \int_0^{z_s} \tau_{\Delta t}(z_s, y_{max}, T_{surv}) \frac{d\dot{N}(>\rho_0)}{dz} dz$$

merger rates according to **Dominik et al. 2013**

`https://www.syntheticuniverse.org`

StarTrack code

**50 lensed events per year**
**few lensed events per year**

⇒ confusion noise of unresolved systems influence our ability to detect inspiraling DCO systems

! only BH-BH systems

**4 binary evolution scenarios:**

2 galaxy metallicity evolution models
„high-end" „low-end"

1. Standard
2. Optimistic Common Envelope (OCE)
3. Delayed SN explosion
4. High BH kick

expected numbers of lensed GW events from inspiraling DCOs

$T_{surv} = 4\ yrs.$

DECIGO

| Evolutionary scenario | standard | optimistic CE | delayed SN | high BH kicks |
|---|---|---|---|---|
| NS-NS | | | | |
| low-end metallicity | 0. | 0. | 0. | 0.07 |
| high-end metallicity | 0. | 0. | 0. | 0.29 |
| BH-NS | | | | |
| low-end metallicity | 0.2 | 0.02 | 0.15 | 0.38 |
| high-end metallicity | 0.21 | 0.03 | 0.2 | 0.39 |
| BH-BH | | | | |
| low-end metallicity | 66.91 | 58.12 | 62.86 | 10.04 |
| high-end metallicity | 65.07 | 71.28 | 61.41 | 8.46 |

B-DECIGO

| Evolutionary scenario | standard | optimistic CE | delayed SN | high BH kicks |
|---|---|---|---|---|
| NS-NS | | | | |
| low-end metallicity | 0. | 0. | 0. | 0. |
| high-end metallicity | 0. | 0. | 0. | 0. |
| BH-NS | | | | |
| low-end metallicity | 0.2 | 0.02 | 0.15 | 0.38 |
| high-end metallicity | 0.21 | 0.03 | 0.2 | 0.39 |
| BH-BH | | | | |
| low-end metallicity | 9.25 | 5.42 | 9.2 | 2.73 |
| high-end metallicity | 13.66 | 10.94 | 14.78 | 2.25 |

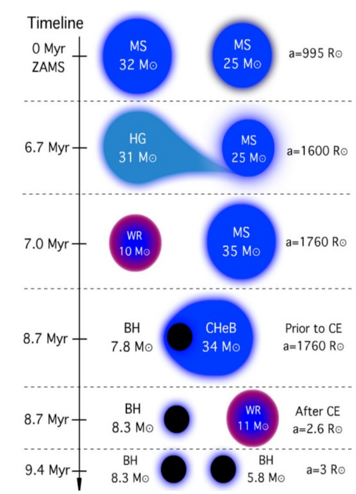
DECIGO

| standard 4yrs | optimistic CE 4yrs | delayed SN 4yrs | high BH kicks 4yrs |
|---|---|---|---|
| 6.1 | 53.4 | 6.4 | 6.1 |
| 6.0 | 56.7 | 6.5 | 6.2 |
| 6.2 | 9.4 | 2.9 | 0.7 |
| 5.7 | 9.8 | 2.7 | 0.7 |
| 146.4 | 324.0 | 125.2 | 11.4 |
| 125.6 | 312.0 | 106.4 | 9.4 |

B-DECIGO

| standard 4yrs | optimistic CE 4yrs | delayed SN 4yrs | high BH kicks 4yrs |
|---|---|---|---|
| 0.0001 | 0.0004 | 0.0001 | 0.0001 |
| 0.0002 | 0.0004 | 0.0002 | 0.0001 |
| 0.07 | 0.2 | 0.04 | 0.006 |
| 0.03 | 0.1 | 0.02 | 0.005 |
| 48.8 | 134.1 | 40.3 | 3.1 |
| 38.3 | 121.2 | 31.3 | 2.4 |

lensing rates calculated if all accessible sources were resolvable ...




existence of massive gravitons → weakening of the gravitational force at large distance due to

https://www.particlezoo.net

# YUKAWA-like POTENTIAL

Poisson's equation for gravity

$$\nabla^2 \phi = 4\pi G \rho$$

$$\Downarrow$$

$$(\nabla^2 - m^2)\phi = 4\pi G \rho$$

$\mathbf{g} = -\nabla\phi$

$$g_Y(r) = \frac{GM^Y_{\text{tot}}(< r)}{r} \exp\left[-\frac{r}{\lambda_g}\right]\left(\frac{1}{\lambda_g} + \frac{1}{r}\right)$$

$$\lambda_g = \frac{h}{m_g c}$$

C.M. Will, Phys. Rev.D 57 (1998) 2061-2068.
C. de Rham et al., Rev. Mod. Phys. 89 (2017), 025004.

$$m_g \to 0 \Rightarrow \lambda_g \to \infty \Rightarrow g_Y(r) \to g_N(r) = \frac{GM_{tot}(<r)}{r^2}$$

At small lenght scales (e.g. Solar System scales) departure from Newtonian case is very tiny;
**One need galactic and extragalactic scales to put strong constraints on graviton mass.**

**F. Zwicky**, Publ. Astron. Soc. Pac. 73, 314, **1961**:

COSMIC AND TERRESTRIAL TESTS FOR THE REST MASS OF GRAVITONS*

F. Zwicky

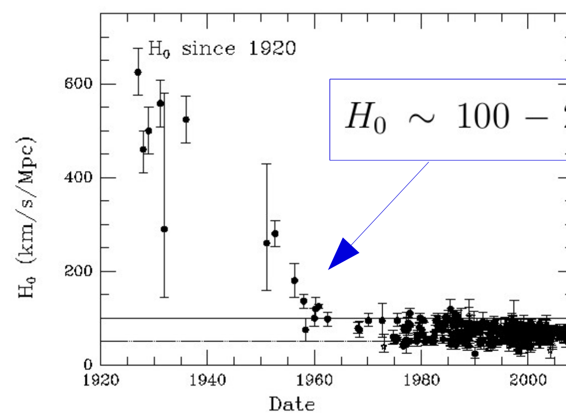
Mount Wilson and Palomar Observatories
Carnegie Institute of Washington
California Institute of Technology

one relates to the fact that the rich globular clusters of galaxies are the largest statistically stationary aggregates of matter and that among more than 20,000 clusters of galaxies there is no cluster of clusters. There is not even a single bona fide double system that consists of two distinct globular or elliptical compact clusters of galaxies. Furthermore, the large velocity dispersion expected among neighboring clusters of galaxies if Newton's law were strictly correct is nonexistent. From these observations we may conclude that the *indicative absolute range*† of gravitational forces Λ is of the order of 20 million parsecs. This leads to a rest mass of the graviton $m_G$ of the order of h/cΛ or 5.65 × $10^{-64}$ grams.

$$m_g < 5.65 \cdot 10^{-64}\text{g}$$

$$\Downarrow$$

$$m_g < 3.2 \cdot 10^{-31}\ \text{eV}$$




$$H_0 \sim 100 - 200\ km\ s^{-1} Mpc^{-1}$$

improved estimation:

$$m_g < 1.1 \cdot 10^{-29}\text{eV}$$

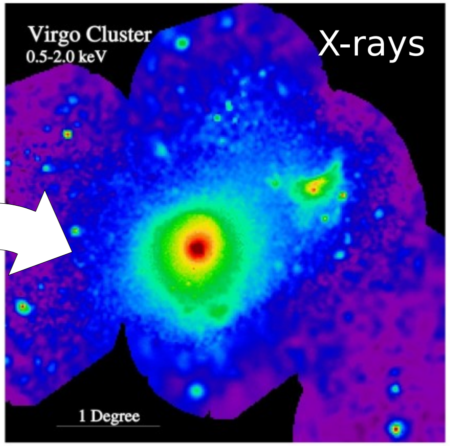
**Goldhaber** and **Nieto**, Phys. Rev. D 9, 1119 (**1974**).

Gravitational acceleration in the case of non-zero graviton mass:

$$g_Y(r) = \frac{G M_{\rm tot}^Y(<r)}{r} \exp\left[-\frac{r}{\lambda_g}\right]\left(\frac{1}{\lambda_g} + \frac{1}{r}\right)$$

massive gravitons modify cluster mass estimates !


Optical image: Virgo cluster (largest galaxy M87)
Credit: NOAO




ROSAT image, credit S. L. Snowden

R. W. Schmidt, ITP, 11 Jan 2012

(galaxies account for only about 2–3% of the total mass of the clusters)

Assumptions:

- spherical symmetry distribution
- perfect gas
- **hydrostatic equilibrium** with cluster gravitational potential

**Hot intracluster gas (ICG)**
thermal Bremsstrahlung emission of electrons with energies up to several keV

$(20\text{–}100)\times 10^6\,{\rm K}$

only **relaxed** clusters !

$$P_{\rm gas} = n_{\rm gas} k_B T_{\rm gas} = \frac{\rho_{\rm gas}(r)}{\mu m_u} k_B T_{\rm gas}$$

$\mu \sim 0.6$ - mean molecular weight of ionized plasma

(in atomic mass unit $m_u = 1.66 \times 10^{-24}$g)

$$\frac{dP_{\rm gas}}{dr} = -\rho_{\rm gas}(r) g(r)$$

total dynamical mass of cluster:

$$M_{\rm tot}(<r) = -\frac{r}{G\rho_{\rm gas}(r)} \frac{dP_{\rm gas}}{dr}$$

$g_N(r)$

$g_Y(r)$

in the presence of non-standard Yukawa potential

in Newtonian case: $M_{\rm tot}(<r) = -\frac{k_B}{\mu m_u}\frac{r T_{\rm gas}(r)}{G}\left(\frac{d\ln\rho_{\rm gas}(r)}{d\ln r} + \frac{d\ln T_{\rm gas}(r)}{d\ln r}\right)$

**from cluster surafce brightness measurements in X-rays:**

$$S_X = \frac{1}{4\pi(1+z)^4}\int n_e^2 \Lambda_{ee}(T_e, A) dl.$$

**supported by SZ observations:** $\frac{\Delta T_{\rm CMB}}{T_{\rm CMB}} = f(x) y$

dimensionless **Compton parameter** : $y = \frac{\sigma_T k_B}{m_e c^2}\int T_e(l) n_e(l) dl = \frac{\sigma_T}{m_e c^2}\int P_e(l) dl$

$$M_{\rm tot}^Y(<r) = M_{\rm tot}(<r)\exp\left[\frac{r}{\lambda_g}\right]\left(\frac{\lambda_g}{r+\lambda_g}\right)$$


S.Gupta, S.Desai, Class. Quantum Grav. 36, 105001 (2019)
A.Piórkowska-Kurpas, S.Cao and M.Biesiada, submitted to Class.Quantum Grav.

# Graviton mass from X-COP galaxy clusters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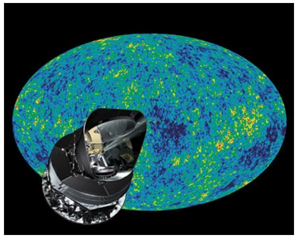
(submitted)

the *XMM-Newton* Cluster Outskirts Project

X-ray observations combined with SZ effect

**XMM-Newton Telescope**

+



**Planck Mission**

**12 massive galaxy clusters**
(with redshifts 0.04 < z < 0.1 )

\+ non-thermal pressure fraction taken into account

especially good quality of **M_tot (< r) estimates**
(relative uncertainties remains at around 5%)

the highest signal-to-noise ratio for Planck SZ signal

**D. Eckert et al. (2018)**

**S. Ettori et al., Astron. Astrophys. 621, A39 (2019)**

we are looking for a minimum of the $\chi^2$ objective function

$$\chi^2 = \sum_{i=1}^{n} \left( \frac{M^Y_{\mathrm{tot},i}(r;\lambda_g) - M^{obs}_{\mathrm{tot},i}(r)}{\sigma_{M^{obs}_{\mathrm{tot},i}}} \right)^2$$

$$M^Y_{\mathrm{tot}}(<r) = M_{\mathrm{tot}}(<r)\exp\left[\frac{r}{\lambda_g}\right]\left(\frac{\lambda_g}{r+\lambda_g}\right)$$

**Table 4** from
D. Eckert et al., Astron. Astrophys. 621, A40 (2018)

$M_{tot,500}$ / $M_{tot,200}$

$M_\Delta$ and $R_\Delta$ are defined as the mass and the radius of a given cluster corresponding to the density of the cluster which is $\Delta$ times critical density of the Universe $\rho_c = \frac{3H_0^2}{8\pi G}$.

$$\lambda_g = \frac{h}{m_g c}$$

lower limits on the Compton wavelength $\lambda_g$ ⇒ upper limits on graviton mass $m_g$

# Results

**Table 1.** Lower limits on the Compton wavelength $\lambda_g$ (in km) associated with massive graviton and corresponding upper limits on graviton mass $m_g$ (in eV) obtained on the basis of the X-COP galaxy cluster total masses reconstructed with non-thermal contribution to ICM pressure [46].

| | $\lambda_g^{\rm fit}$ [a] | $m_g^{\rm fit}$ [b] | $\lambda_g^{68\%c.l.}$ [c] | $m_g^{68\%c.l.}$ [c] | $\lambda_g^{95\%c.l.}$ [d] | $m_g^{95\%c.l.}$ [d] |
|---|---|---|---|---|---|---|
| Results for $M_{tot,500}$: [e] | $6.22 \cdot 10^{34}$ | $1.99 \cdot 10^{-44}$ | $2.61 \cdot 10^{19}$ | $4.77 \cdot 10^{-29}$ | $1.83 \cdot 10^{19}$ | $6.79 \cdot 10^{-29}$ |
| Results for $M_{tot,200}$: [f] | $2.44 \cdot 10^{34}$ | $5.10 \cdot 10^{-44}$ | $3.55 \cdot 10^{19}$ | $3.49 \cdot 10^{-29}$ | $2.49 \cdot 10^{19}$ | $4.99 \cdot 10^{-29}$ |

[a] $\lambda_g^{\rm fit}$ is graviton Compton wavelength understood as best fit value obtained via minimization procedure of $\chi^2$ function given by Eq.(10); [b] $m_g^{\rm fit}$ is best fit value expressing upper limit on graviton mass directly linked to $\lambda_g^{\rm fit}$ through $\lambda_g = \frac{h}{m_g c}$; [c] estimated 68% c.l. limits on the graviton Compton wavelength and mass; [d] 95% c.l. limits on the graviton Compton wavelength and mass; [e] results obtained with using X-COP cluster total masses estimated within $r = R_{500}$; [f] results obtained with using X-COP cluster total masses estimated within $r = R_{200}$.

One can see that 68% C.L. for graviton mass of about $m_g < (3.49 - 4.77) \times 10^{-29}\ eV$ obtained from X-COP sample is among stringest available.

## other dynamical tests of Yukawa term:

- bounds from the **Solar System**: $m_g < 10^{-23}\ eV$ C.M. Will (1998) Phys. Rev. D 57, 2061–2068.
- bounds from the **S2 (or Source 2) star orbit at the Galactic Center**: $m_g < 2.9 \times 10^{-21}\ eV$ A.F. Zakharov, P. Jovanovic, D. Borka and V. Borka Jovanovic, JCAP05(2016)045.
- bounds from **galaxy clusters**: $m_g < 10^{-29} - 10^{-30}\ eV$

S. Gupta and S. Desai (2018) Annals of Physics 399, 85.

S. Gupta and S. Desai (2019) Class. Quantum Grav. 36, 105001.

A. Rana, D. Jain, S. Mahajan and A. Mukherjee (2018) Phys. Lett. B 781, 220.

# Summary:

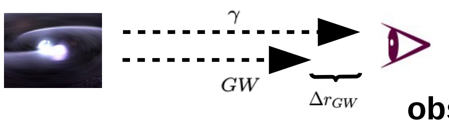
- effective phenomenology based on the modification of relativistic dispersion relation for massive graviton:

  ⇨ non-zero graviton mass may cause **shape (or phasing) distorsion** of the observed GW waveform

  $$m_g \leq 1.76 \times 10^{-23}\ \mathrm{eV}/c^2 \quad \text{at } 90\% \text{ confidence}$$

  ⇨ non-zero graviton mass may cause **changes in travel time of GW signals** emitted from a distant astrophysical objects

  time delay between GW and EM signals emitted form the same source




**intrinsic time-lag problem!**

  ⇨ strong lensing of GW signals from NS-NS or NS-BH systems can be used to directly constrain speed of GWs:

difference between time delays measured **independently** in **GW and EM windows**

$$\Delta t_\gamma - \Delta t_{GW}$$

ET EINSTEIN TELESCOPE robust prediction: **few lensed NS-NS /yr**

THESEUS mission will complement ET GW detections in EM window

HE transient events, accurate sky position, source characteristics

- dynamical tests based on Yukawa potential:

  ⇨ non-zero graviton mass influence **cluster mass estimates**

$$m_g < (3.49-4.77)\times 10^{-29}\ eV \quad 68\%\ \text{C.L.}$$

from X-COP galaxy clusters (X-ray + SZ effect)

upcoming X-ray missions

eROSITA

ATHENA

Thank you for attention!