theseus
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

THESEUS CONFERENCE 2021, VIRTUAL - 23-26 March 2021

New perspectives for testing physics at fundamental level with multimessenger astronomy.

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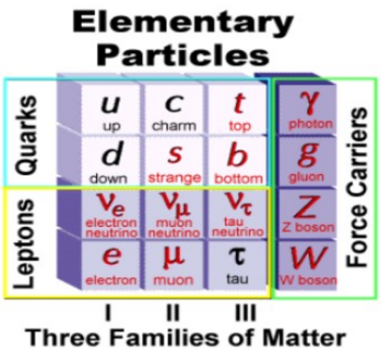
Faculty of Science and Technology,
University of Silesia in Katowice, Poland

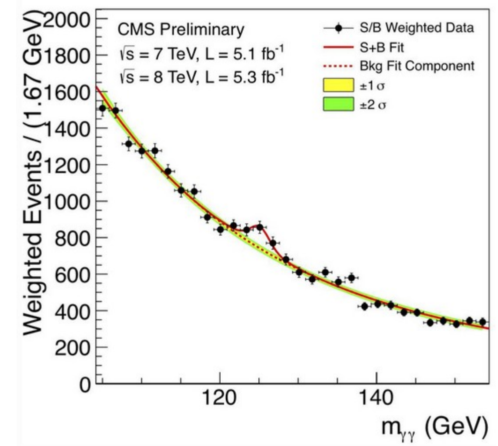
UNIVERSITY OF SILESIA
IN KATOWICE

testing physics at fundamental level:

- motivations from SM:

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





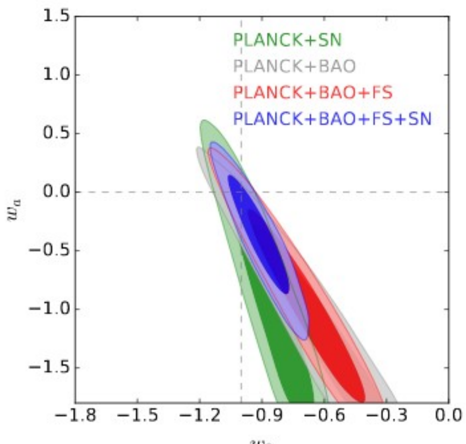
The discovery of the Higgs Boson in the di-photon (γγ) channel at CMS. Only by understanding the diphoton production in all the other Standard Model channels can we accurately detail the production of the Higgs. [-]

Credit: CERN

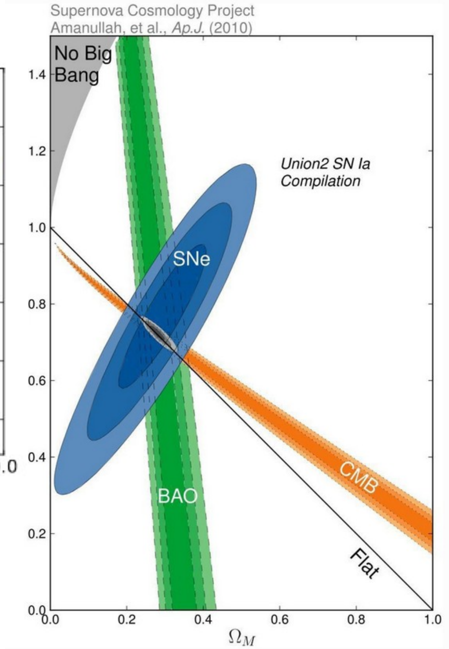
- motivations from GR + observations:

  dark energy and **dark matter** phenomena to be explained

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



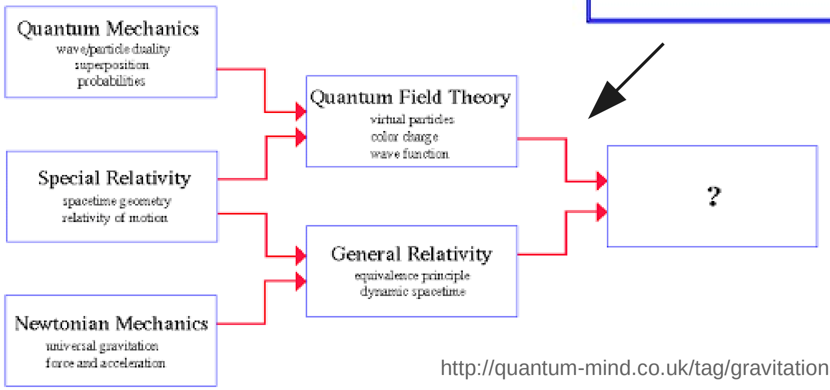
Alam et al. 2016



$$E_{Pl} \sim 10^{19}\text{GeV}$$

- motivations from QG:

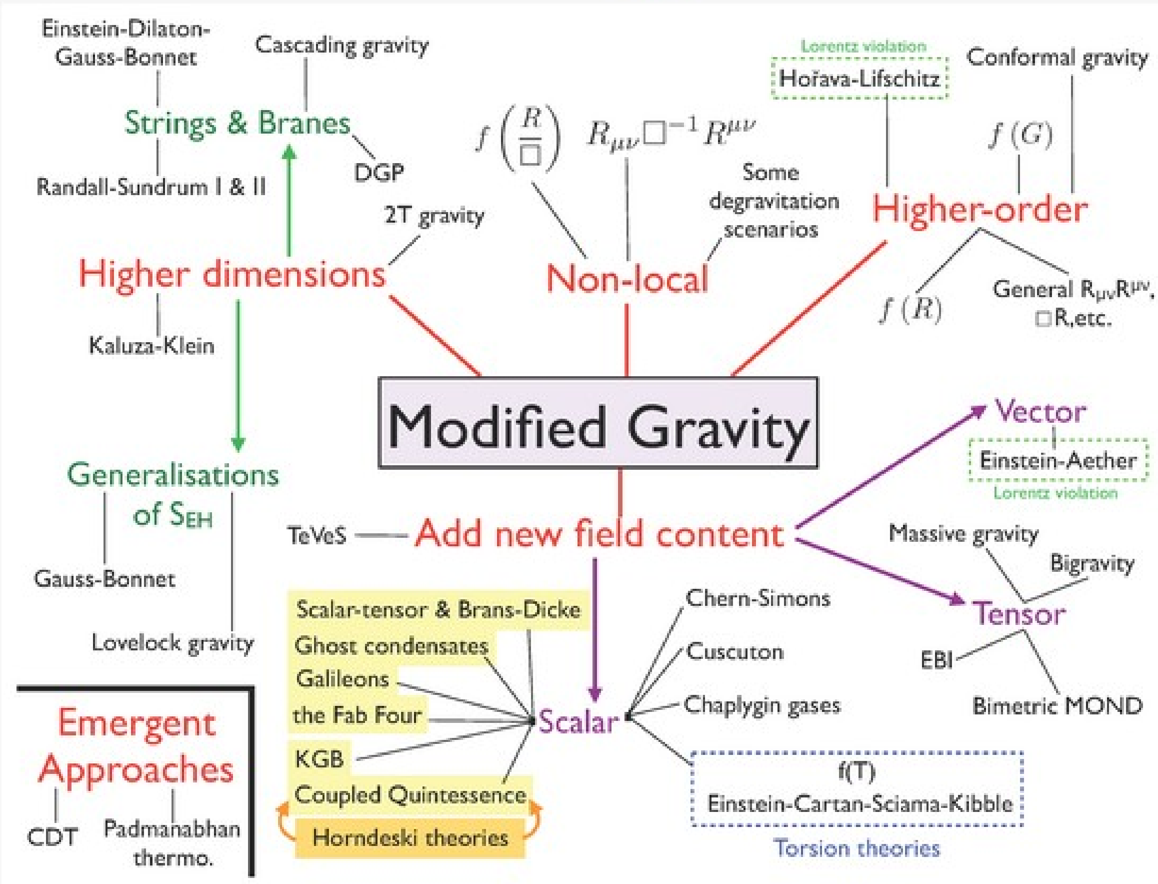
unification of GR and SM at high energies



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

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

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

no experimental indication

which way is correct ?

effective phenomenology

existence of massive gravitons

running nature of fundamental constants

violation of some basic principles

LIV

https://www.particlezoo.net

phenomenological approach:

standard theory considered as effective one, with all possible corrections necessary to describe physical phenomena possibly present at low energies as experimental puzzles

+ enough predictive power to be applicable in experimental analysis

MODIFIED DISPERSION RELATION

standard relativistic dispersion relation may be modified leading to changes in travel time of signals emitted from a distant astrophysical objects

Vucetich 2005

Mattingly, Living Rev. Rel., 2005

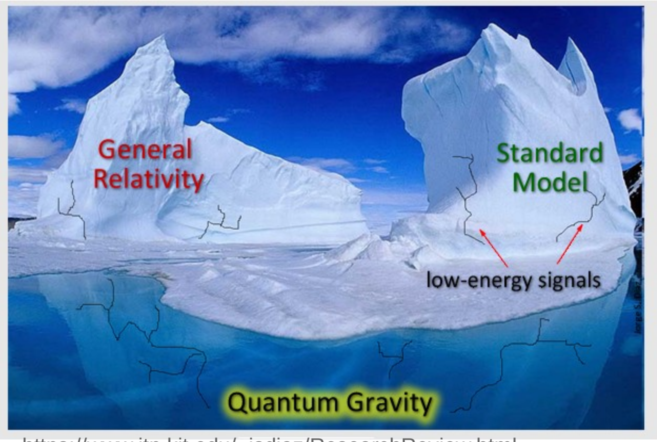
$$E^2 = m^2c^4 + \mathbf{p}^2c^2 \xrightarrow[\sim 10^{19}\mathrm{GeV}]{} \boxed{E^2 = F(\mathbf{p}, m)}$$

at low energies

specific structure of deformation can differ from model to model

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

should be written as $f_a(E, \mathbf{p}; E_{Pl})$, where a represents particle species



https://www.itp.kit.edu/~jsdiaz/ResearchReview.html

typical form of modification

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

where α and η are free parameters characterizing departure from ordinary case

Applicabillity:

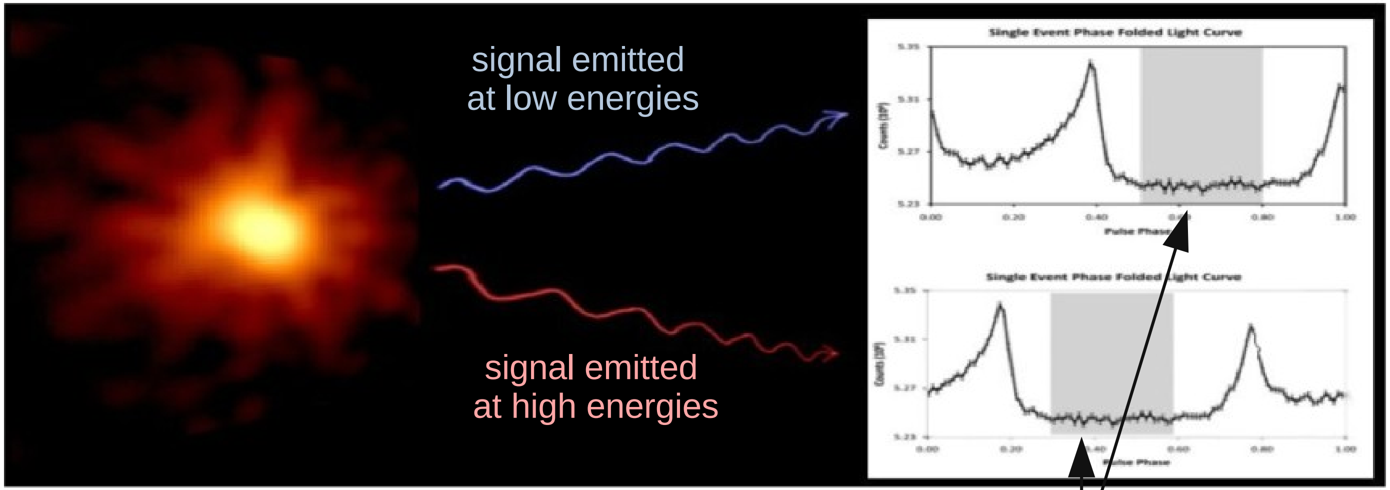
any departure from the well-known form of dispersion relation will be a clear signal of non-standard physics at low energies astrophysical tests may play an essential role in QG testing:

$$E^2 = m^2 + p^2 + f(E, \mathbf{p}, m; E_{Pl}) \Longrightarrow$$ **time-of-flight measurements**

modified dispersion relation may lead to changes in travel time of signals emitted from a distant astrophysical objects

high energy astrophysical sources

- pulsars
- AGNs
- GRBs
- DCO mergers

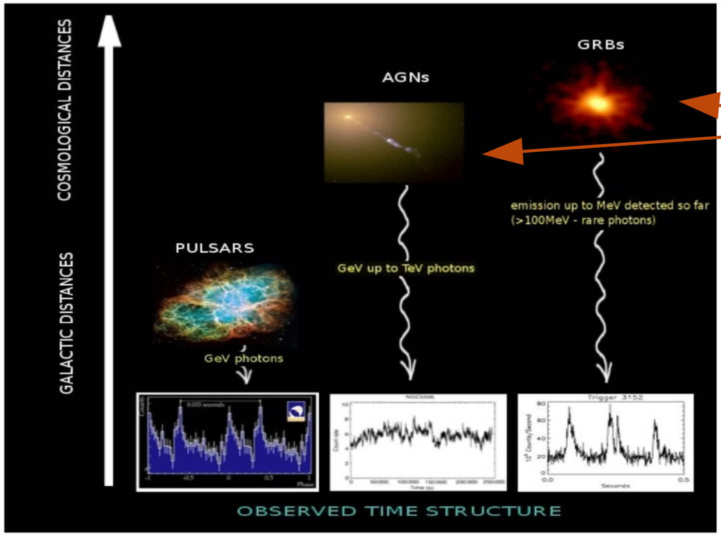


time delay between signals observed at high and low energies

multi-messenger astronomy

- photons
- neutrinos
- gravitons

multi-wavelength astronomy



HE sources
- usually at **cosmological distances**

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

Amelino-Camelia et al. Nature, 1998

HE sources
- **fine-scale time structure**

millisecods or better

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'
ξ_n is a dimensionless parameter

$\xi_1 = 1$
$\xi_2 = 10^{-7}$

Rodriguez Martinez & Tsvi Piran, JCAP, 2006

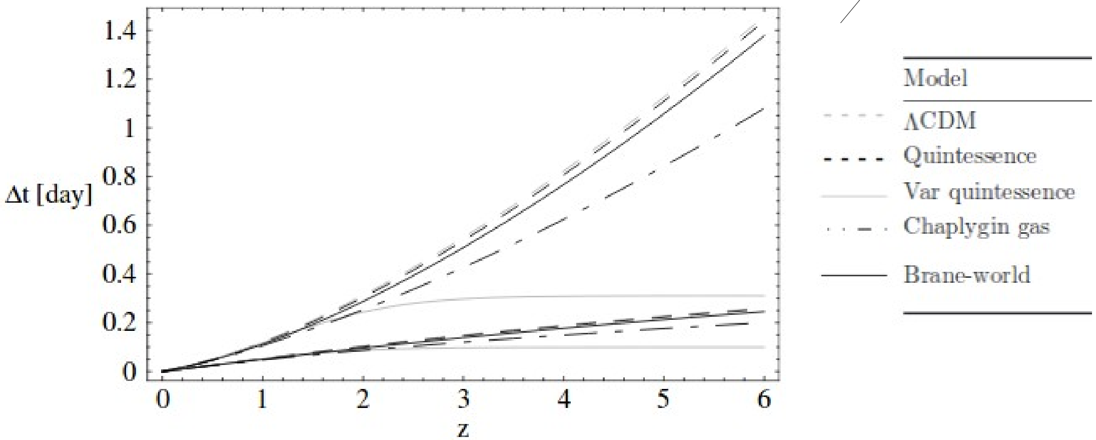
Jacob & Piran, Nature Phys., 2007

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:

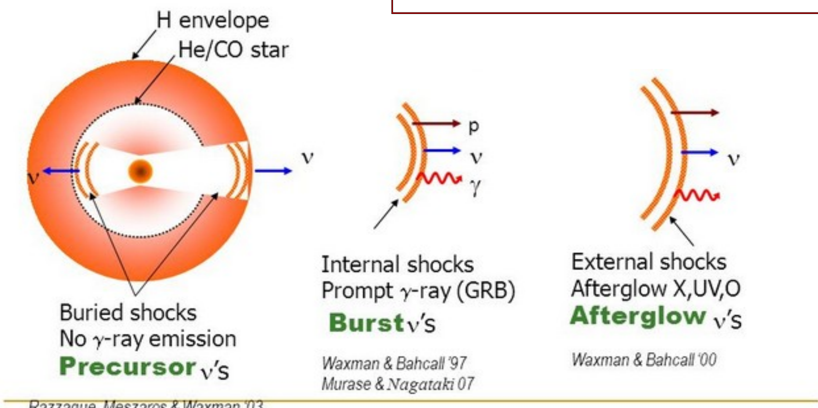
$$\boxed{\Delta t = \int_0^z [\underbrace{\frac{m^2c^4}{2E_0}\frac{1}{(1+z)^2}}_{\text{for photons mass term vanishes}} \underbrace{- \epsilon\frac{n+1}{2}\left(\frac{E_0}{\xi_n E_{QG}}\right)^n (1+z)^n}_{\text{LIV term}}]\frac{dz}{H(z)}}$$



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:

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

linear fit with assumption of ΛCDM

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

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

flat ΛCDM with $\Omega_\Lambda = 0.3$

intrinsic time lags

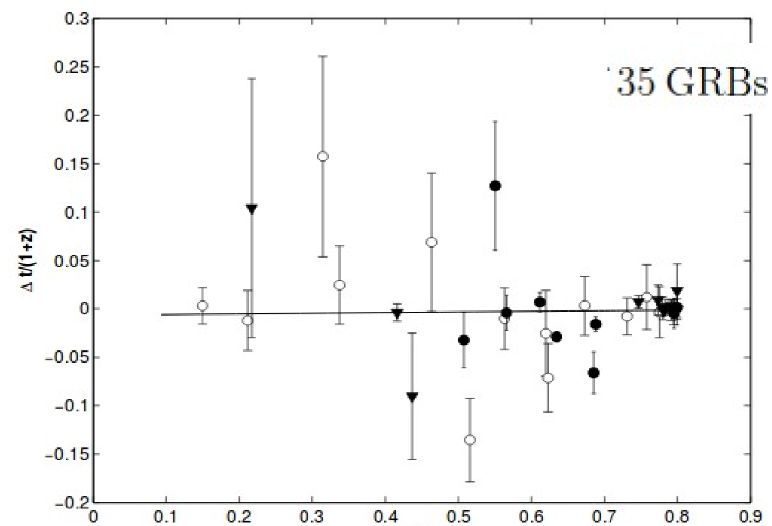
how to recognize QG effects from any delays created in the source

SOLUTION: **statistics**

Ellis et al. A&A 2003

Ellis et al. Astropart.Phys. 2006

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



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

$$\Downarrow$$

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

analysis for different cosmological scenarios:

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

Table II. Regression coefficients (with 1σ 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	Δ_i	w_i	Odds against
ΛCDM	$a_{LIV} = -0.0794 \pm 0.0447$	$b = 0.0494 \pm 0.0288$	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

Example: time delay technique in probing graviton mass

tests of gravity in its strong-field, dynamical regime !

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)

shape (or phasing) distorsion
of the observed GW waveform

extra phase term:

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

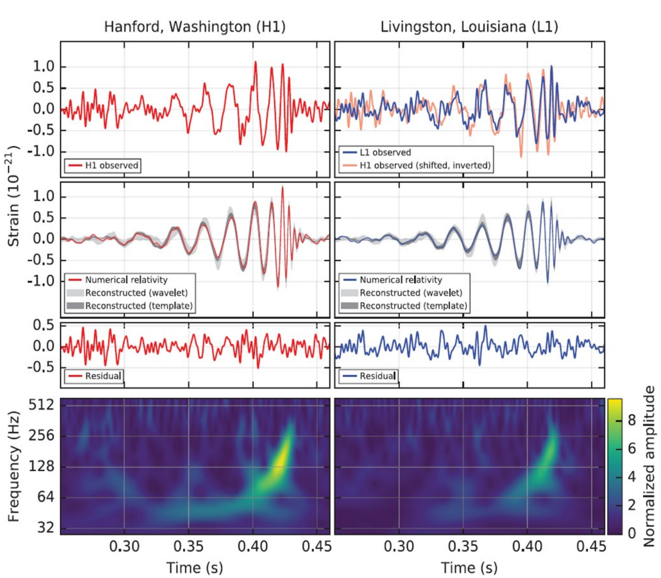
First ever laboratory detection of GW signal:

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

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

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

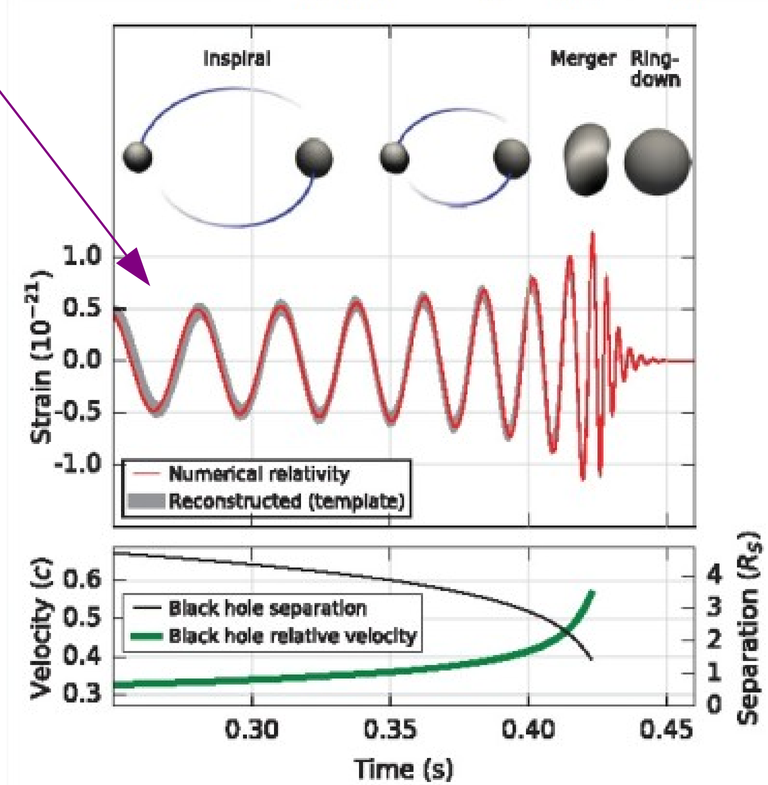
$$m_g \le 1.2 \times 10^{-22}\ \mathrm{eV/c^2}$$

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

$$D \sim 400\ \mathrm{Mpc}$$

$$f \sim 100\ \mathrm{Hz}$$

$$\rho \sim 23$$

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

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

at 90% confidence

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

Prospects: probing graviton mass in future GW detectors

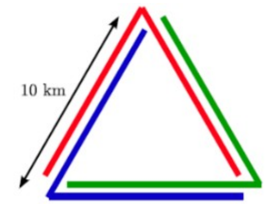
C. de Rham et al., Rev. Mod. Phys. 89 (2017) 2, 025004
Clifford M. Will, Phys.Rev.D57:2061-2068,1998

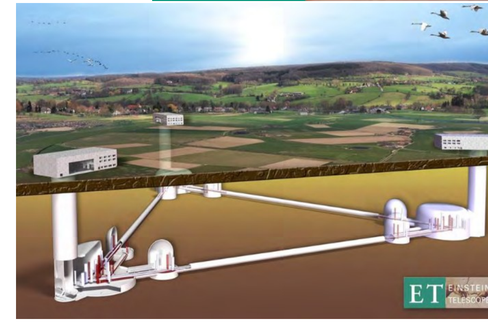
$$\lambda_g > 5\times10^{11}\ \mathrm{km}\left(\frac{D}{200\ \mathrm{Mpc}}\frac{100\ \mathrm{Hz}}{f}\frac{1}{f\Delta t}\right)^{\frac{1}{2}}$$

$\sim 1/\rho$ 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)





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

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

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

https://lisa.nasa.gov/

f: 0.1 mHz – 100 mHz

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

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

single triangular detector unit is equivalent for two standard L-shaped interferometers rotated by 45 ^{o}

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

f: 1 mHz – 100 Hz

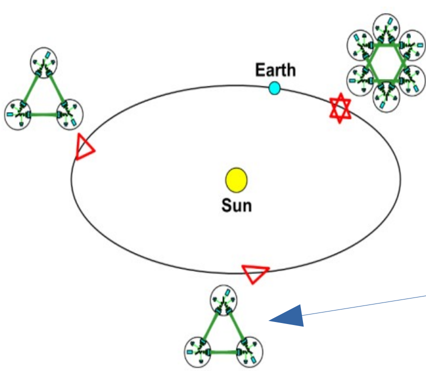
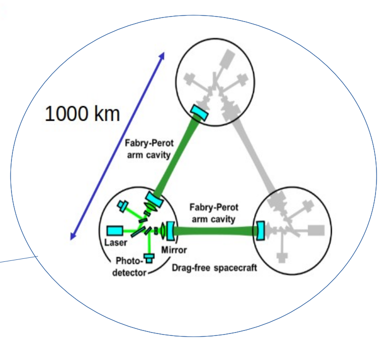


Fig. 1. Orbit of DECIGO. Four clusters of DECIGO are put in the heliocentric orbit: two at the same position and the other two at different positions.

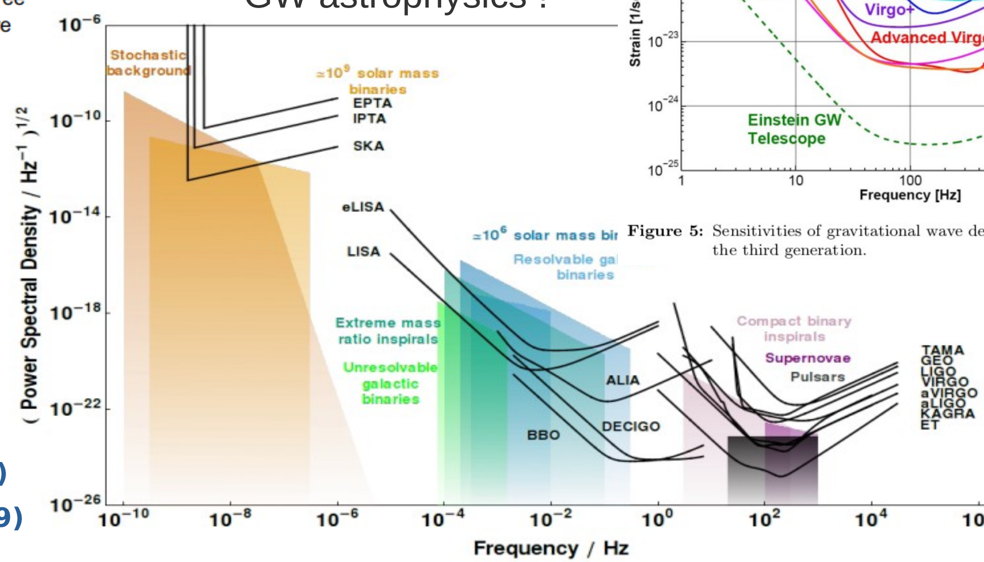
https://decigo.jp/index_E.html

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 !



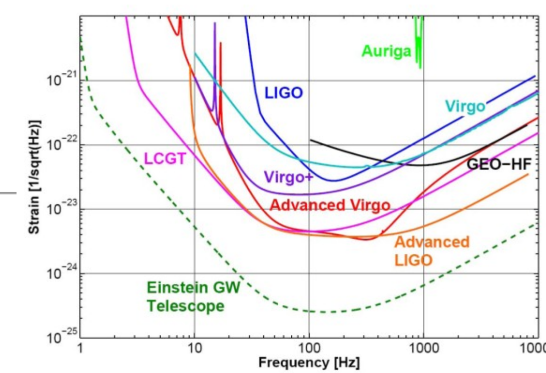


Figure 5: Sensitivities of gravitational wave detectors from the first to the third generation.

QG testing in the era of multimessenger astronomy

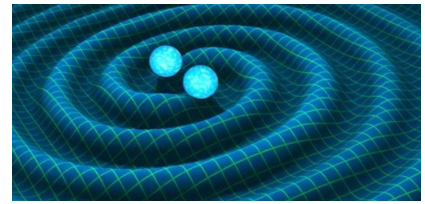
IDEA:
use gravitational lensing phenomenon !

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

cosmological redshift

gravitational redshift

gravitational lensing



https://scienceline.org

EM field equations

$$\partial_\mu F^{\mu\nu} = kj^\nu$$

EM field tensor

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

4-vector ‘potential’

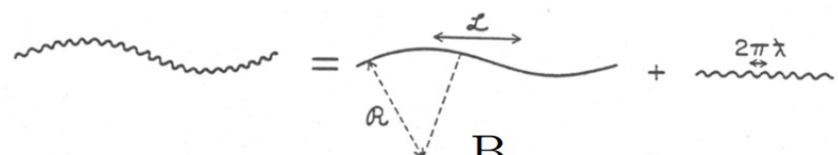
Lorentz gauge

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

EM field equations
in terms of Lorentz gauge

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

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



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

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

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

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

Einstein field equations:

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

κ

weak-field metric

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

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

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

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

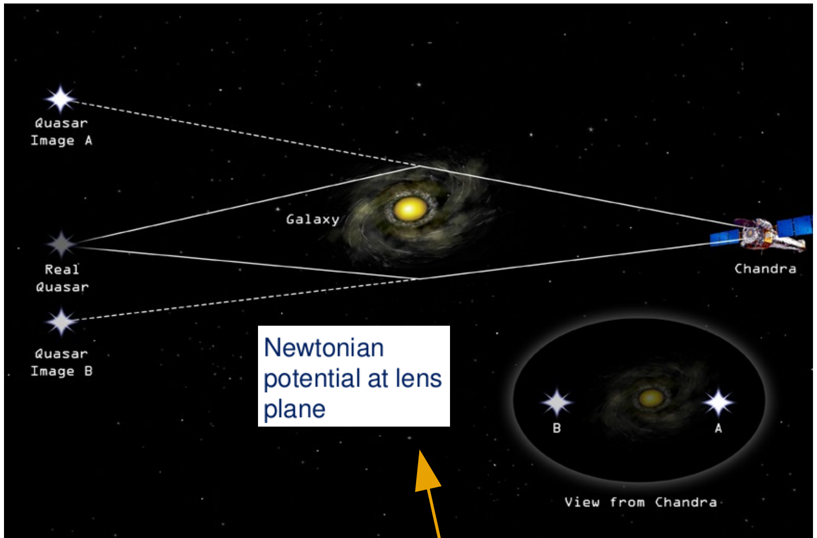
basic field equations of linearised GR
in terms of metric perturbation

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

in vacuum

Strong gravitational lensing:

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



Newtonian potential at lens plane

https://chandra.harvard.edu/

effective lesing (Fermat) potential

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

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

$$\boldsymbol{\eta} = \frac{D_s}{D_d}\boldsymbol{\xi} - D_{ds}\hat{\boldsymbol{\alpha}}(\boldsymbol{\xi})$$

In terms of angular coord.:

$$\boldsymbol{\eta} = D_s\boldsymbol{\beta}$$

$$\boldsymbol{\xi} = D_d\boldsymbol{\theta}$$

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

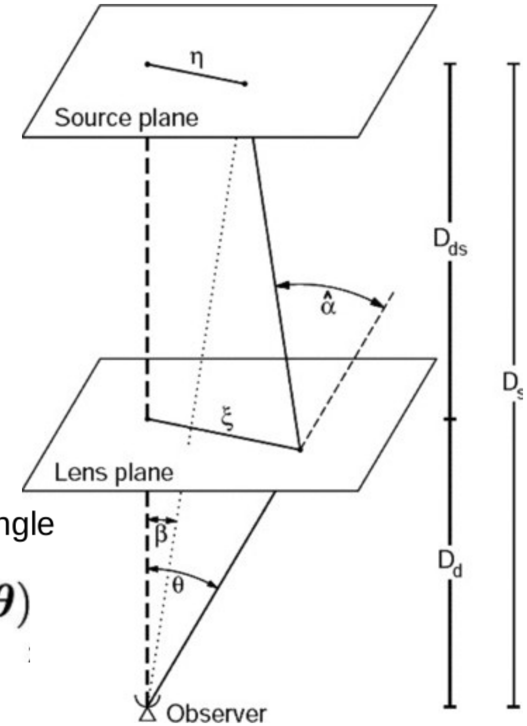
lens equation

reduced deflection angle

$$\frac{D_{ds}}{D_s}\hat{\boldsymbol{\alpha}}(D_d\boldsymbol{\theta})$$

$$\boxed{\boldsymbol{\alpha} = \nabla_{\boldsymbol{\theta}}\phi}$$

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



Bartelmann& Schneider, 2001
Schneider, 2006

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

Travel time of light rays from images → time delay:

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

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

Fermat Principle

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

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

magnification

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

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

Massimo Meneghetti, Introduction to Gravitational Lensing; Lecture scripts

QG testing with SL in the era of multimessenger astronomy

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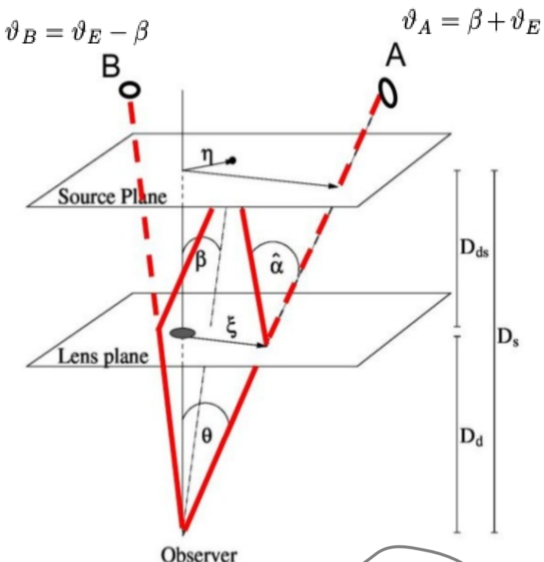
Speed of Gravitational Waves from Strongly Lensed Gravitational Waves and Electromagnetic Signals

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

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



[Schneider et al. 2006]

$\beta < \vartheta_E$
lensing is strong

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

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

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 $y = \beta/\vartheta_E$

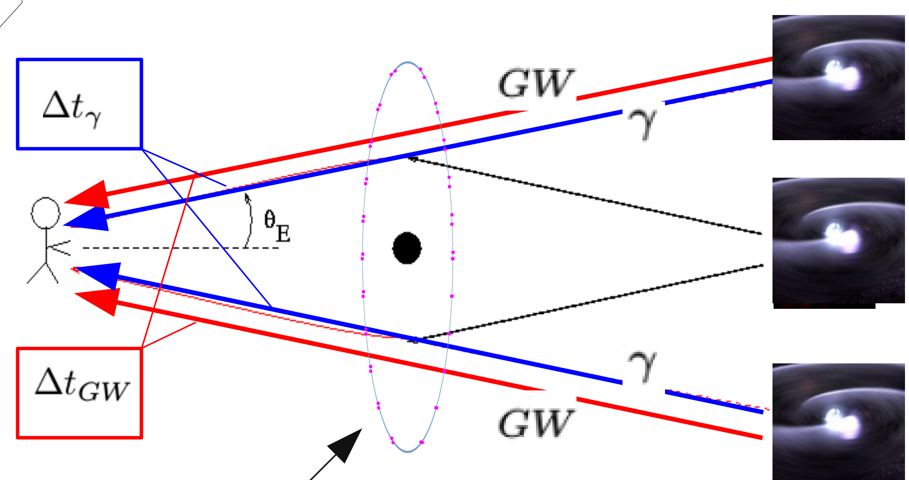
$$\boxed{\Delta t_{GW} \neq \Delta t_\gamma}$$

direct constraining speed of GW with SL

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

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

- 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

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

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

QG testing with SL in the era of multimessenger astronomy

detailes of the idea:

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

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

assumption:
GW travel along
radial geodesics
in flat FRW model

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

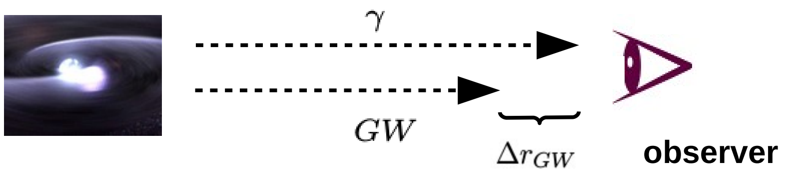
$$\frac{dr}{dt} = \frac{p^r c^2}{E} = \frac{p_r c^2}{a^2 E}$$

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

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

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

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



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

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

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

$$\vartheta_E$$

$$\boxed{\Delta t_{SIS,GW} - \Delta t_{SIS,\gamma} = \Delta t_{SIS,\gamma}\frac{m_{GW}^2 c^4}{E^2} F_{\text{lens}}(z_l, z_s)}$$

$$F_{\text{lens}}(z_l,z_s) = 1 + \frac{(1+z_s)I_2(0,z_s)}{2\widetilde{r}(z_l,z_s)} - \frac{(1+z_l)I_2(0,z_l)}{2\widetilde{r}(z_l)} - \frac{(1+z_l)I_2(0,z_l)}{\widetilde{r}(z_l,r_s)}$$

$$I_n(z_1,z_2) := \int_{z_1}^{z_2} \frac{dz'}{(1+z')^n h(z')}$$

comoving distance to the source

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

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

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

$$\frac{m_{GW}^2 c^4}{E^2} = 1 - \left(\frac{v_{GW}}{c}\right)^2$$

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

General bound:

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

QG testing with SL in the era of multimessenger astronomy

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

Refsdal Supernova **11.11.2014**

identified as core-collapse supernova

Kelly et al., Science 2015

PS1-10afx **2014**

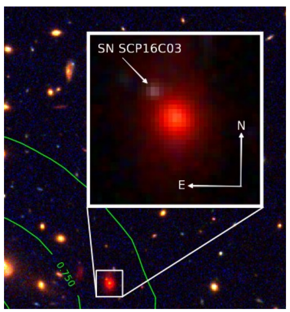
controversial case

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)

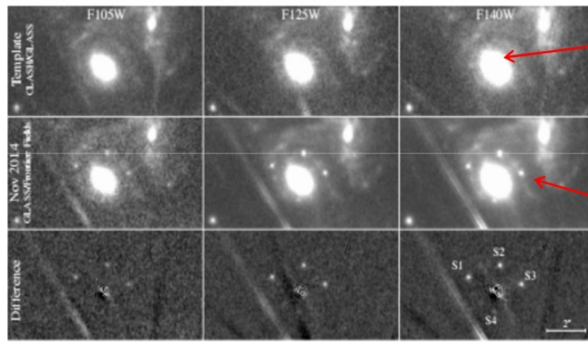


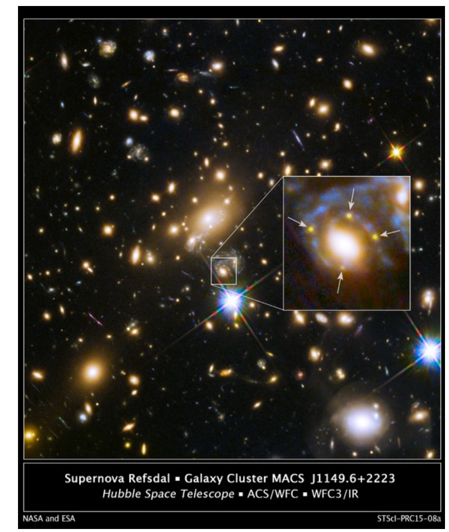
Fig. 1: *HST* WFC3-IR images showing the simultaneous appearance of four point sources around a cluster member galaxy. From left to right the columns show imaging in the *F105W* filter (*Y* band), *F125W* (*J*), and *F140W* (*JH*). From top to bottom the

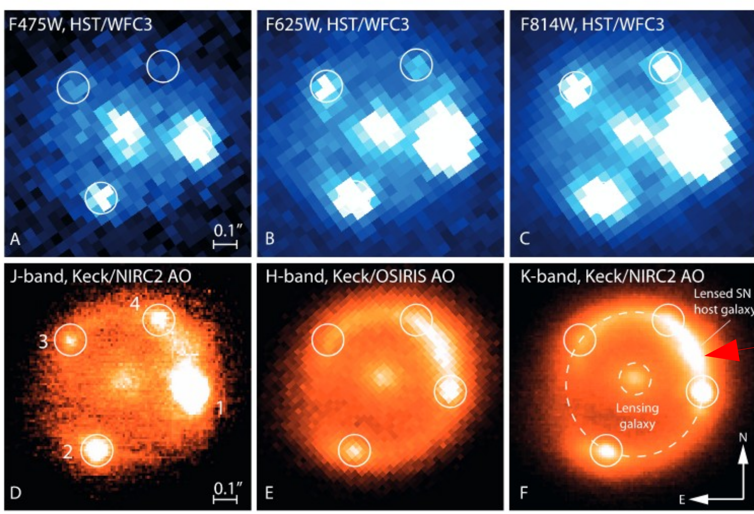
lens:
elliptical galaxy from
MACS J1149.6+2223
galaxy cluster at z=0.54

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

reappearance
of Refsdal SN

Kelly et al., ApJL 2016 **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)

$z = 0.216$

$\mu \sim 52$

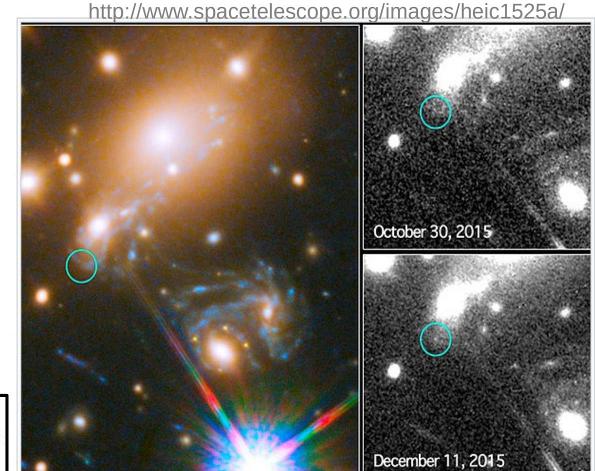
reappearance
predicted
in about one year
in one of
lensed
images
of host galaxy

⇩

for SX image:

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

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



QG testing with SL in the era of multimessenger astronomy

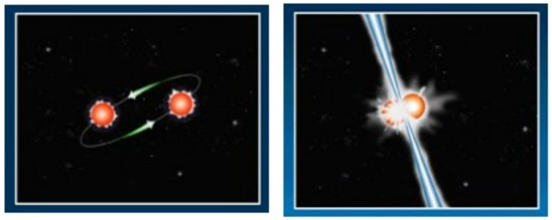
perspectives:

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

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

$$\Delta t_{\gamma,GW} = \frac{1}{2H_0}(1+z_s)^2 I_2(0,z_s) \Rightarrow \boxed{1-\left(\frac{v_{GW}}{c}\right)^2 \leq 9.92\times 10^{-22}}$$

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)

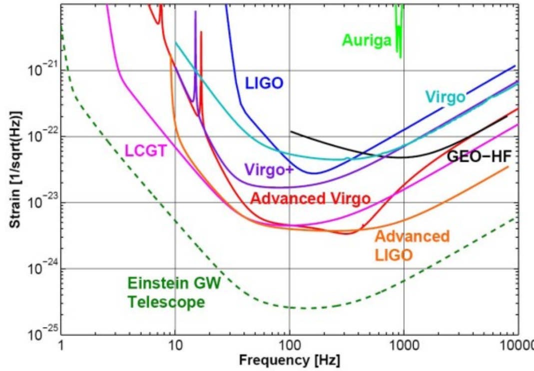


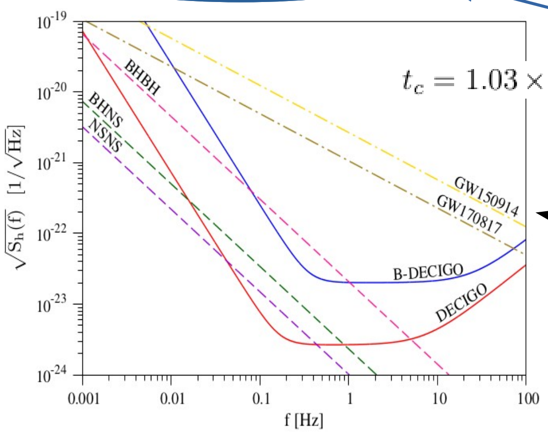
Figure 5: Sensitivities of gravitational wave detectors from the first to the third generation.

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



$$t_c = 1.03\times 10^6\ \mathrm{s}\ (\mathcal{M}_z/30.1\ M_\odot)^{-5/3}(f/0.1\ \mathrm{Hz})^{-8/3}$$

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

Aleksandra Piórkowska-Kurpas et al, ApJ 908 196 (2021)

Source	BNS	NS-BH	BBH
Rate (Mpc^{-1} Myr^{-1})	0.1–6	0.01–0.3	2×10^{-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

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

QG testing with SL in the era of multimessenger astronomy

perspectives:

First Multimessenger Transient

GW170814 GWs LIGO/VIRGO

$\sim$1.7 s

GRB 170817A γ-rays Fermi/GBM

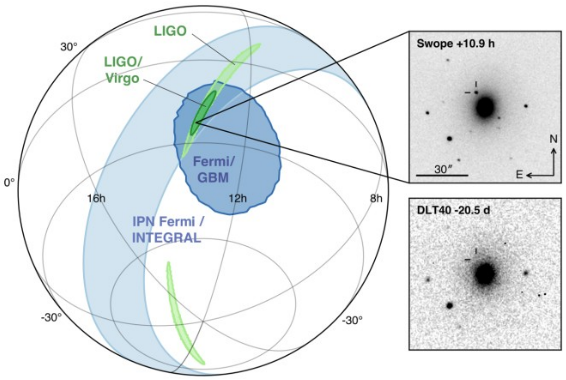
11 hours after the merger

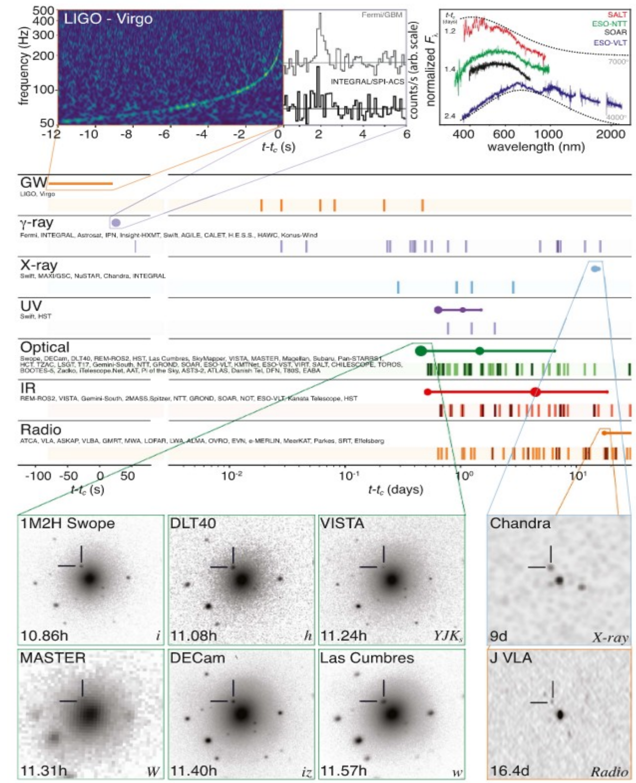
SSS17a / AT 2017gfo bright optical transient in NGC 4993

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

$\boxed{\textbf{lensed}}$ 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)

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*

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

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

~few NS-NS /yr

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

QG testing in the era of multimessenger astronomy

SNR above threshold of 8

Yagi & Seto 2011
Isoyama et al. 2018

perspectives:

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

DECIGO
Space Gravitational Wave Antenna

Yearly detection rates of **lensed**, **resolvable** DCO systems:

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

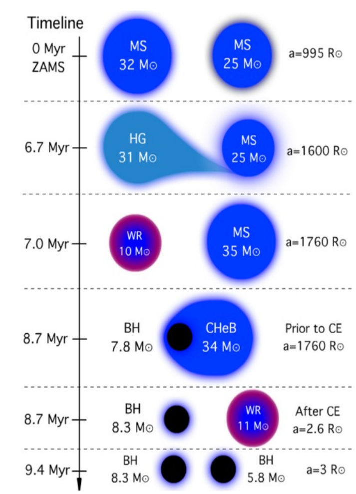
DECIGO

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 ...



Summary and Conclusions:

- Fundamental physics can be tested via effective phenomenology: standard relativistic dispersion relation may be modified leading to changes in travel time of signals emitted from a distant astrophysical objects.

  time-of-flight measurements for LIV, graviton mass etc.

- GW signals can be used to obtain constraints on non-zero graviton mass

  modified dispersion relation distort shape of observed GW waveform

- Future GW detectors (e.g. ET, DECIGO) are promising from QG testing perspective: triangular geometry will translate into better sensitivity.

  better constraints on graviton mass

  big catalogue of DCO GW events in the inspiral phase up to cosmological distances

  ET and DECIGO will probe smaller GW frequency bands and thus will be able to register GW signals for days to months before LIGO/VIRGO

- **Strong lensing of GW signals from NS-NS or NS-BH systems can be used to directly constrain speed of GWs.**

  This will create new opportunities: we expect that ET with consderably enlarge statistics of GW events will be able to 'see' 50-100 lensed GWs per year!

  mainly binary BHs and about **1-4% lensed NS-NS systems**

- Due to contamination of unresolved systems, either DECIGO or B- DECIGO will not be able to register any lensed NS-NS or BH-NS.

  however, they could register up to O(10) lensed BH-BH in the inspiral phase

- **THESEUS will complement ET GW detections in EM window**

  HE transient events, accurate sky position, source characteristics

Thank you for attention!