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

Aleksandra Piórkowska-Kurpas

August Chełkowski Institute of Physics, Faculty of Science and Technology, University of Silesia in Katowice, Poland
testing physics at fundamental level:

- motivations from SM: 
  - gravity should be mediated by a massless particle of spin 2
  - dark energy and dark matter phenomena to be explained

- motivations from GR + observations:

- motivations from QG:
  - unification of GR and SM at high energies
Huge number of various approaches to QG:

- Einstein-Dilaton-Gauss-Bonnet
- Cascading gravity
- Strings & Branes
- DGP
- 2T gravity
- Some degravitation scenarios
- Conformal gravity
- Higher-order
- General $R_{\mu\nu}R^{\mu\nu}$, R, etc.
- Lorentz violation
- Hořava-Lifschitz
- Vector
- Einstein-Aether
- Bigravity
- Massive gravity
- Tensor
- Chern-Simons
- Cuscuton
- Chaplygin gases
- EBI
- Bimetric MOND
- Scalar
- Scalar-tensor & Brans-Dicke
- Ghost condensates
- Galileons
- the Fab Four
- KGB
- Coupled Quintessence
- Horndeski theories
- $f(T)$
- Einstein-Cartan-Sciama-Kibble
- Torsion theories

**Modified Gravity**

- **Add new field content**
- **Emergent Approaches**
  - CDT
  - Padmanabhan thermo.
  - Huge number of various approaches to QG

**Sensitivity requirements for tests are very strict:**

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

**no experimental indication**

**which way is correct?**

**Effective phenomenology**

- existence of massive gravitons
- running nature of fundamental constants
- violation of some basic principles

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

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

or equivalently – Planck energy:

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

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

\[ E^2 = m^2 c^4 + p^2 c^2 \]

\[ E^2 \approx 10^{19} \text{GeV} \]

\[ E^2 = F(p, m) \]

Vucetich 2005
Mattingly, Living Rev. Rel., 2005

at low energies

specific structure of deformation can differ from model to model

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

typical form of modification

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

\[ f_a(E, p, m; E_{Pl}) \sim \eta \alpha \left( \frac{E}{E_{Pl}} \right)^\alpha \]

where \( \alpha \) and \( \eta \) are free parameters characterizing departure from ordinary case

Applicability:

any departure from the well-known form of dispersion relation will be a clear signal of non-standard physics at low energies

https://www.itp.kit.edu/~jsdiaz/ResearchReview.html
astrophysical tests may play an essential role in QG testing:

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

\[ \Rightarrow \quad \text{time-of-flight measurements} \]

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

**multi-messenger astronomy**
- photons
- neutrinos
- gravitons

**multi-wavelength astronomy**

**time delay** between signals observed at high and low energies

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


HE sources
- **fine-scale time structure**
  - millisecods or better

HE sources
- usually at **cosmological distances**
Example: time delay technique in probing LIV effects

modified dispersion relation:

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

\( \epsilon = \pm 1 \) is 'sign parameter'
\( \xi \) is a dimensionless parameter
\( \xi_1 = 1 \)
\( \xi_2 = 10^{-7} \)

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

Rodriguez Martinez & Tsvi Piran, JCAP, 2006
Jacob & Piran, Nature Phys., 2007

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

pair production

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

SOLUTION: neutrinos

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

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

for photons mass term vanishes

LIV term

\[ \Delta t_{\text{obs}} = \Delta t_{\text{LIV}} + \Delta t_{\text{intrinsic}} \]

linear fit with assumption of $\Lambda$CDM

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

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

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

**SOLUTION:** statistics

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

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.**

<table>
<thead>
<tr>
<th>Cosmological model</th>
<th>Regression coefficient (a_{\text{LIV}})</th>
<th>Intercept (b)</th>
<th>(\Delta_j)</th>
<th>(w_i)</th>
<th>Odds against $E_{QG}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACDM</td>
<td>(a_{\text{LIV}} = -0.0794 \pm 0.0414)</td>
<td>(b = 0.0494 \pm 0.0288)</td>
<td>1.645</td>
<td>0.152</td>
<td>2.276</td>
</tr>
<tr>
<td>Quintessence</td>
<td>(a_{\text{LIV}} = -0.0806 \pm 0.0460)</td>
<td>(b = 0.0489 \pm 0.0288)</td>
<td>1.712</td>
<td>0.147</td>
<td>2.354</td>
</tr>
<tr>
<td>Var Quintessence</td>
<td>(a_{\text{LIV}} = -0.1510 \pm 0.0683)</td>
<td>(b = 0.0735 \pm 0.0340)</td>
<td>0</td>
<td>0.347</td>
<td>1.00</td>
</tr>
<tr>
<td>Chaplygin Gas</td>
<td>(a_{\text{LIV}} = -0.1201 \pm 0.0618)</td>
<td>(b = 0.0627 \pm 0.0330)</td>
<td>1.042</td>
<td>0.206</td>
<td>1.684</td>
</tr>
<tr>
<td>Braneworld</td>
<td>(a_{\text{LIV}} = -0.0866 \pm 0.0483)</td>
<td>(b = 0.0501 \pm 0.0294)</td>
<td>1.704</td>
<td>0.148</td>
<td>2.344</td>
</tr>
</tbody>
</table>
Example: time delay technique in probing graviton mass tests of gravity in its strong-field, dynamical regime!

Modified dispersion relation

\[ E^2 = p^2 c^2 + m_g^2 c^4 \]

\[ \lambda_g = \frac{h}{m_g c} \]

\[ \frac{v_g^2}{c^2} \equiv \frac{c^2 p^2}{E^2} \simeq 1 - \frac{h^2 c^2}{(\lambda_g^2 E^2)} \]

energy/frequency dependent speed of graviton!

First ever laboratory detection of GW signal: the tail of the signal will travel faster than the front - signal should be “squeezed”

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) distortion of the observed GW waveform
extra phase term:

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

GW150914

\[ \lambda_g > 10^{13} \text{ km} \]

\[ m_g \leq 1.2 \times 10^{-22} \text{ eV/c}^2 \]

at 90% confidence

confirmed by also for GW151226

More than 50 GW signals registered so far!

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

GW190412 the first mixed BH-NS merger
GW190425 probably the first NS-NS merger

KAGRA observation run started on 25 February 2020

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

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

GW150914

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

GW151012
GW151226
GW170104
GW170608
GW170729
GW170814
GW170809
GW170817
GW170818
GW170823
GW190412
GW190425
GW190814
GW190817
GW190818
GW190823

GWs propagate without dispersion and that the graviton is massless

\[ m_g \leq 1.76 \times 10^{-23} \text{ eV}/c^2 \]

at 90% confidence
Prospects: probing graviton mass in future GW detectors

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

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

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

inaccessible from the ground due to irremovable seismic noise

Kawamura, S., et al. (2019)

Nakamura T., et al. (2016)

ET: \( r_0 = 1917 \text{ Mpc} \)
DECIGO: \( r_0 = 6709 \text{ Mpc} \)
B-DECIGO: \( r_0 = 535 \text{ Mpc} \)


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

https://lisa.nasa.gov/

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.

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.

Multifrequency GW astrophysics!
QG testing in the era of multimessenger astronomy

IDEA:
use gravitational lensing phenomenon!

GW experience the same geometric-optics effects as EM waves:
- cosmological redshift
- gravitational redshift
- gravitational lensing

EM field equations

\[ \partial_\mu F^{\mu \nu} = k j^\nu \]

EM field tensor

\[ F_{\mu \nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \]

Lorentz gauge

\[ \partial_\mu A^\mu = 0 \]

4-vector 'potential'

\[ \Box^2 A_\mu = \mu_0 j_\mu \]

EM field equations in terms of Lorentz gauge

Einstein field equations:

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

weak-field metric

\[ g_{\mu \nu} = \eta_{\mu \nu} + h_{\mu \nu} \quad \text{where} \quad |h_{\mu \nu}| \ll 1, \]

basic field equations of linearised GR in terms of metric perturbation

\[ \Box^2 h^{\mu \nu} = 0 \]

in vacuum

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

Strong gravitational lensing:
light traveling along null geodesics bends in the vicinity of massive bodies

https://chandra.harvard.edu/

Newtonian potential at lens plane

Effective lensing (Fermat) potential

\[ \phi(\theta) = \frac{D_{ls}}{D_{l} D_{S}} \frac{2}{c^2} \int \Phi(D_{l} \theta, z) dz \]

Travel time of light rays from images → time delay:

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

massimo meneghetti, introduction to gravitational lensing; lecture scripts

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

\[ \eta = \frac{D_{s}}{D_{d}} \xi - D_{ds} \hat{\alpha}(\xi) \]

In terms of angular coord.:

\[ \eta = D_{s} \beta \]
\[ \xi = D_{d} \theta \]

\[ \beta = \theta - \alpha(\theta) \]

\[ \alpha = \nabla_{\theta} \phi \]

\[ \frac{D_{ds}}{D_{s}} \frac{\hat{\alpha}(D_{d} \theta)}{\hat{\alpha}(D_{d})} \]

\[ \theta - \beta - \nabla_{\theta} \phi = 0 \]

**Fermat Principle**

\[ \nabla_{\theta} \Delta t = 0 \]

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

\[ \mu(\theta) = \frac{1}{\det A(\theta)} \]

\[ A(\theta) = \frac{\partial \beta}{\partial \theta} \]

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

Massimo Meneghetti, Introduction to Gravitational Lensing; Lecture scripts

Bartelmann & Schneider, 2001

Schneider, 2006

S. Suyu; lectures XXIV Canary Islands Winter School of Astrophysics 2012
QG testing with SL in the era of multimessenger astronomy

Speed of Gravitational Waves from Strongly Lensed Gravitational Waves and Electromagnetic Signals
Xi-Liang Fan, Kai Liao, Marek Biesiada, Aleksandra Płorkowska-Kurpas, and Zong-Hong Zhu
Phys. Rev. Lett. 118, 091102 – Published 2 March 2017

\[ \theta_B = \theta_E - \beta \]
\[ \theta_A = \beta + \theta_E \]
\[ \theta_E = 4\pi \frac{D_{ls}}{D_s} \frac{c^2}{c^2} \]
\[ \theta_{E, GW} = \theta_E (1 + \frac{m_{GW}^2 c^4}{2E^2}) \]

Lowenthal, PRD, 1973

\[ \Delta t_{SI} = \frac{32\pi^2}{H_0} \left( \frac{\sigma}{c} \right) \frac{1}{y} \bar{r}(z_l) \bar{r}(z_l, z_s) \]

source-lens misalignment \( y = \beta / \theta_E \)

general form for bound on \( v_{GW} \)
valid for a broad set lens models

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

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

direct constraining speed of GW with SL

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


\( \Delta t_{\gamma} \) - \( \Delta t_{GW} \)
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: \[ E_\gamma^2 - p_\gamma^2 c^2 = 0 \]

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

assumption:
GW travel along radial geodesics in flat FRW model

\[ p_r = a^2 p_r \]

\[ \frac{dr}{dt} = \frac{p_r c^2}{E} = \frac{p_r c^2}{a^2 E} \]

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

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

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

\[ r_{GW} = r_\gamma - \Delta r_{GW} \]

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

\[ \Delta r_{GW} = \frac{1}{2} \frac{m_{GW}^2 c^4}{p_r^2} \int_{t_e}^{t_0} a(t) dt \]

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

\[ \Delta t_{GW} = \Delta r_{GW} / c \]

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

\[ F_{lens}(z_l, z_s) = 1 + \frac{(1 + z_s) I_2(0, z_s)}{2 \tilde{r}(z_l, z_s)} - \frac{(1 + z_l) I_2(0, z_l)}{2 \tilde{r}(z_l)} - \frac{(1 + z_l) I_2(0, z_l)}{2 \tilde{r}(z_l, r_s)} \]

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

General bound:

\[ 1 - \left( \frac{v_{GW}}{c} \right)^2 \leq \frac{\delta T}{\Delta t_{\gamma} F_{lens}(z_l, z_s)} \]
QG testing with SL in the era of multimessenger astronomy

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

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

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

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 $z = 1.3$
SN Ia at $z = 2.22$

IPTF16geu (SN 2016geu) 5.09.2016
reappearance predicted in about one year in one of lensed images of host galaxy

normal SN Ia at $z = 0.409$

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

for SX image:
QG testing with SL in the era of multimessenger astronomy

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

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

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

**lensed** NS-NS or NS-BH mergers

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

**Jet collimation:**

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

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

**Big catalogs of inspiral events up to cosmological distances**

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

QG testing with SL in the era of multimessenger astronomy

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

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%

~few NS-NS /yr

results corrected for Earth’s rotation effect:


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
QG testing in the era of multimessenger astronomy


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

\[
\dot{N}_{lensed}(z_\text{s}) = \int_0^{z_\text{s}} \frac{\tau\Delta t(z_\text{s}, y_{\text{max}}, T_{\text{surv}}) d\dot{N}(>\rho_0)}{dz} dz
\]

- Sensitivity: SNR above threshold of 8
- Merger rates according to Dominik et al. 2013
- Optical depth corrected for finite duty cycle of detector
- StarTrack code
- Isoyama et al. 2018

Merger rates according to Dominik et al. 2013

- Yagi & Seto 2011
- Isoyama et al. 2018

50 lensed events per year

few lensed events per year

Only BH-BH systems

Confusion noise of unresolved systems influence our ability to detect inspiraling DCO systems

**4 binary evolution scenarios:**

- Standard
- Optimistic
- Common Envelope (OCE)
- Delayed SN explosion
- High BH kick

<table>
<thead>
<tr>
<th>Evolutionary scenario</th>
<th>DECIGO</th>
<th>B-DECIGO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>standard</td>
<td>optimistic</td>
</tr>
<tr>
<td>NS-NS low-end metallicity</td>
<td>0.</td>
<td>0.</td>
</tr>
<tr>
<td>high-end metallicity</td>
<td>0.</td>
<td>0.</td>
</tr>
<tr>
<td>BH-NS low-end metallicity</td>
<td>0.2</td>
<td>0.02</td>
</tr>
<tr>
<td>high-end metallicity</td>
<td>0.21</td>
<td>0.03</td>
</tr>
<tr>
<td>BH-BH low-end metallicity</td>
<td>66.91</td>
<td>55.12</td>
</tr>
<tr>
<td>high-end metallicity</td>
<td>65.07</td>
<td>71.28</td>
</tr>
<tr>
<td>NS-NS low-end metallicity</td>
<td>0.</td>
<td>0.</td>
</tr>
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<td>0.21</td>
<td>0.03</td>
</tr>
<tr>
<td>BH-BH low-end metallicity</td>
<td>9.25</td>
<td>5.42</td>
</tr>
<tr>
<td>high-end metallicity</td>
<td>13.66</td>
<td>10.94</td>
</tr>
</tbody>
</table>

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.  
  
- GW signals can be used to obtain constraints on non-zero graviton mass  
  
- Future GW detectors (e.g. ET, DECIGO) are promising from QG testing perspective: triangular geometry will translate into better sensitivity.  
  
- 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 considerably enlarge statistics of GW events will be able to ‘see’ 50-100 lensed GWs per year!  
  
- Due to contamination of unresolved systems, either DECIGO or B-DECIGO will not be able to register any lensed NS-NS or BH-NS.  
  
- THESEUS will complement ET GW detections in EM window  
  
  HE transient events, accurate sky position, source characteristics  
  
Thank you for attention!