Fundamental physics tested on extra-galactic objects

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UNIWERSYTET ŚLĄSKI W KATOWICACH

a few philosophical remarks :

- our understanding of nature is based on certain abstract statements (principles)

- a principle cannot be considered as absolute
  - it is rather a convenient way of description, emerging from a large number of observations made by a particular method

- a principle can be used as a basis for a theory, but its predictions must be verified

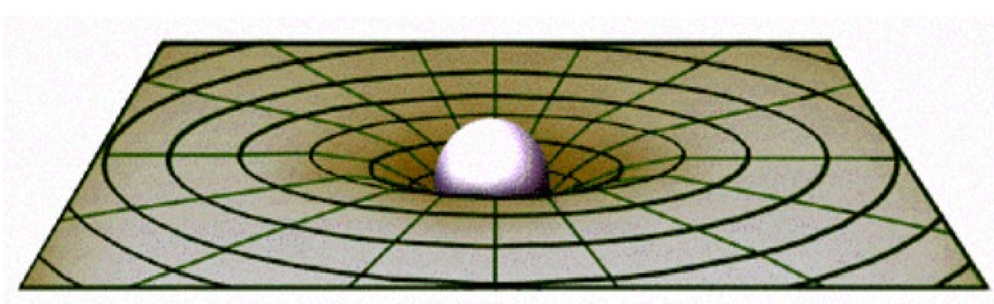
principles should be regarded as the properties of nature available through experiment rather, than of nature alone very few of all principles can refer to all physical phenomena and they are known as 'general' principles

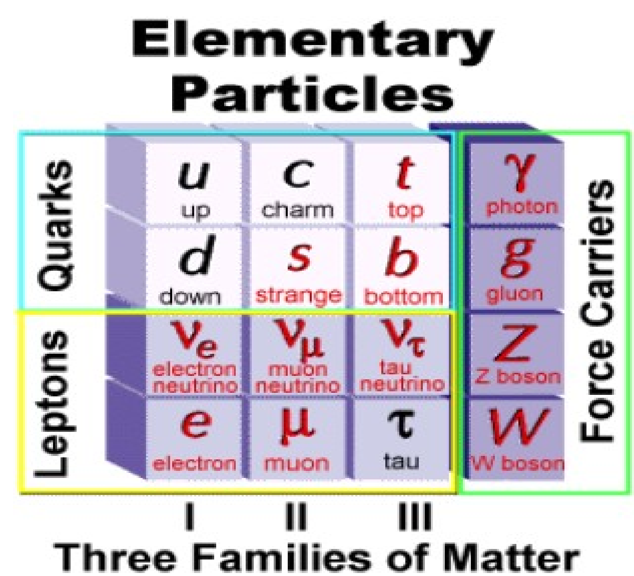
the **Principle of Relativity**

play a crucial role in the development of theory - practically all dynamical laws have the origin in the invariance of theory under a given kind of transformation

have the laws of mechanics the same mathematical form in all inertal frames?

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



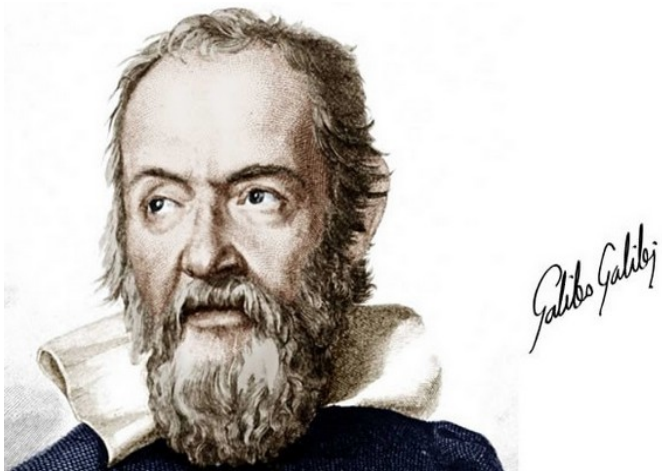


... a principle cannot be considered **as absolute**...

what does really move?

Galilean Relativity:

motion is not a property
of a moving body but
a state of the body



motion does not differ from the state of rest

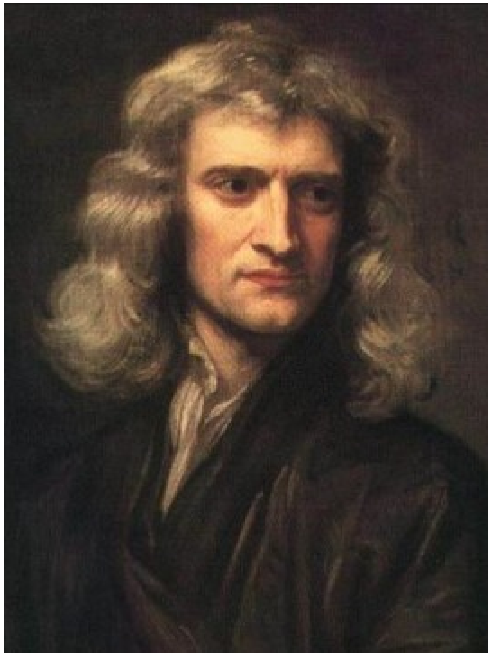
in contradiction to Aristotle's belief that the 'natural' state of matter is at rest...

M. Heller, 'Galileo's Relativity', 1985

... a principle cannot be considered **as absolute**...

Galilean Relativity: velocity is not absolute!

any two observers moving at constant speed and direction with respect to one another will obtain the same results for all mechanical experiments



Classical Relativity:

the laws of mechanics have the same mathematical form in all inertal frames

there is no privileged reference system !

... a principle cannot be considered **as absolute**...

up to 1904: puzzling properties of light

- the speed of light did not depend on the motion of the observer
- medium in which light propagates (aether) cannot be described consistently

Maxwell's equations:

$$(1)\quad \nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t} \qquad (2)\quad \nabla.\mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$(3)\quad \nabla\times\mathbf{B} = \mu_0\varepsilon_0\frac{\partial\mathbf{E}}{\partial t} + \mu_0\mathbf{J} \qquad (4)\quad \nabla.\mathbf{B} = 0$$

$$c = \frac{1}{\sqrt{\varepsilon_0\mu_0}}$$

$c = 3\times10^8$ meters per second

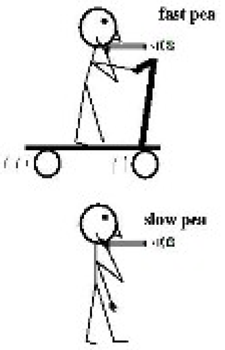
privileged reference frame ?!

… a principle cannot be considered **as absolute**…

a series of experiments based on Michelson's idea showed **no signal related to the aether**

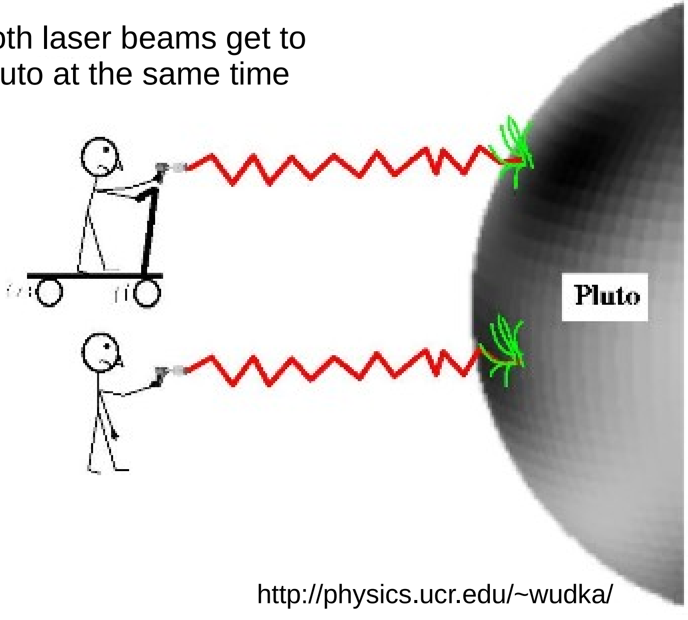
Einstein’s answer:

- the aether doesn't exist
- c is constant for all inertial observers



the pea shot from the scooter moves faster

both laser beams get to Pluto at the same time



Maxwell’s equations contain the speed of light c, which is given **without** reference to any inertial observer

http://physics.ucr.edu/~wudka/

... a principle cannot be considered **as absolute**...

1905 The **Principle of Relativity**

all the laws of physics are the same for all inertial observers.

if we accept the Principle of Relativity
and trust Maxwell's equations
we must conclude that
c is the same for all inertial observers

$c = 3\times10^8$ meters per second - measured as an absolute value, not relative to sth

⬇

there is no need to introduce privileged reference system !

… a principle cannot be considered **as absolute**…

Special Theory of Relativity
(STR hereafter)

based on two fundamental postulates:

1. All the laws of physics (including the light phenomena) have the same form in all inertial frames;

2. The velocity of light is a universal constant (has the same value in all inertial frames in all directions).

instead of the Newtonian postulate of an absolute time…

the principle of relativity
- one of the most general principle in nature

- goes deep into the foundations of standard theory
- implies a broad spectrum of features

  - a direct implications: the conservation laws of energy-momentum and angular momentum
  - other effect: the angular momentum in general case has two components, the ’orbital’ and ’spin’ parts; the latter one is simply the effect of the Lorentz transformations on the (spinor) field

- makes the all theory consistent not only from the mathematical point of view, but also with the experimental data

the principle of relativity
in the standard model of elementary particles

standard model automatically satisfies the relativity principle with all its consequences

the lagrangian is simply a sum of the free field lagrangians and the interactions terms - all being a Lorentz scalars

a **sophisticated construction** from:

- $\bar{\psi}\psi$ - Lorentz scalar
- $\bar{\psi}\gamma_5\psi$ - Lorentz pseudo-scalar
- $\bar{\psi}\gamma_\mu\psi$ - Lorentz vector
- $\bar{\psi}\gamma_5\gamma_\mu\psi$ - Lorentz pseudo-vector
- $\bar{\psi}(\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu)\psi$ - Lorentz antisymmetric tensor

$$\bar{\psi} = (\psi^*)^T$$

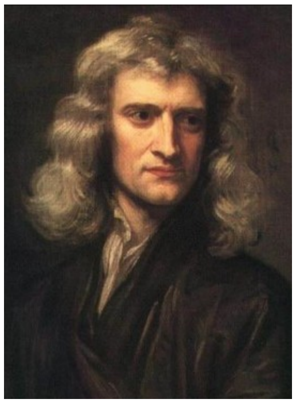
hermitian conjugation

gamma/Dirac's matrices

$$\gamma_5 = \gamma_1\gamma_2\gamma_3\gamma_4$$

the principle of relativity in the theory of gravity

Newtonian gravity is not consistent with special relativity



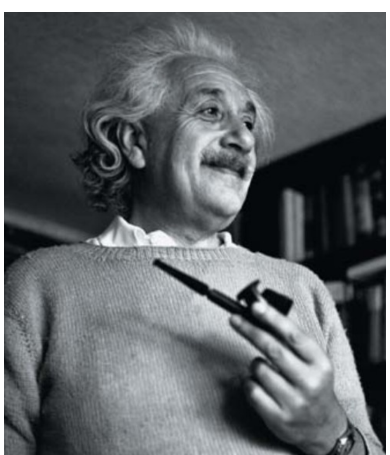
$$\boxed{\vec{\nabla}^2\Phi = 4\pi G\rho}$$

no explicit time dependence
- gravitational force responds instantaneously to a disturbance

the first LIV theory ever !

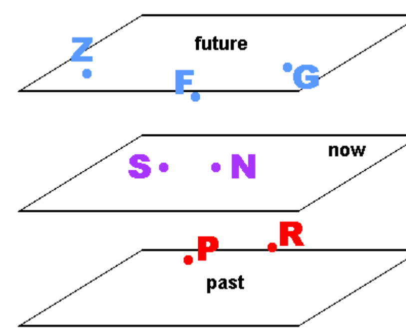
should be a Lorentz scalar BUT IS NOT

this violates the special-relativistic requirement that **signals cannot propagate faster than c**

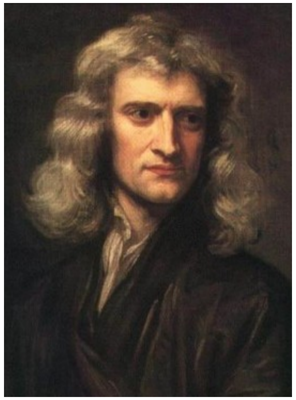


source of the problem:

Newtonian conception of **absolute time**!



the principle of relativity in the theory of gravity



the equation of motion of a particle in a gravitational field is given by

$$\frac{d^2\vec{x}}{dt^2} = -\frac{m_G}{m_I}\vec{\nabla}\Phi$$

this ratio is the same for all particles

The **Equivalence principle**

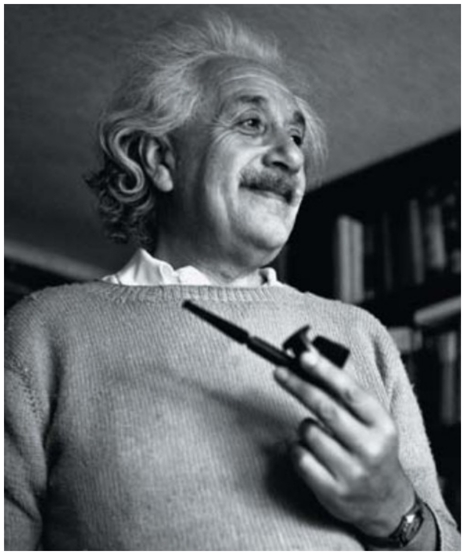
equality of the gravitational and inertial masses

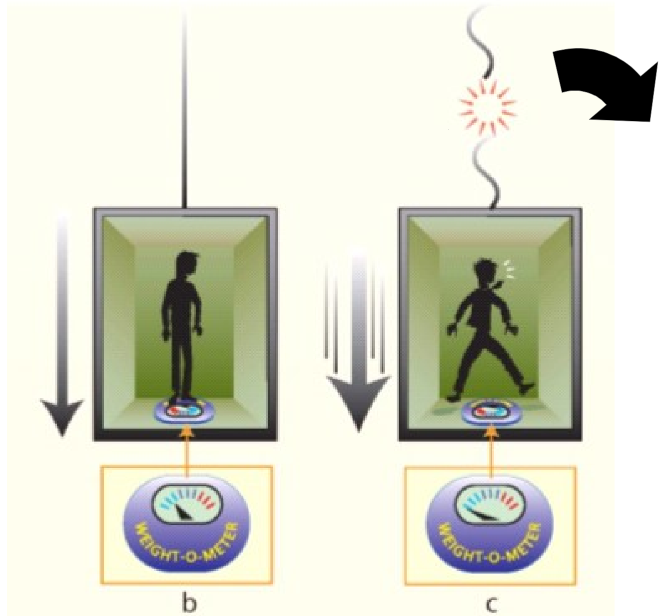
a truly remarkable **coincidence** in the Newtonian theory

there is no a-priori reason why the quantity that determines the magnitude of the gravitational force on the particle should equal the quantity that determines the particle’s ‘resistance’ to an applied force in general

the principle of relativity in the theory of gravity

Einstein's classic ‘elevator’ thought experiment:





the particle and the elevator cabin have the same acceleration relative to the Earth as a result of the equivalence of gravitational and inertial mass

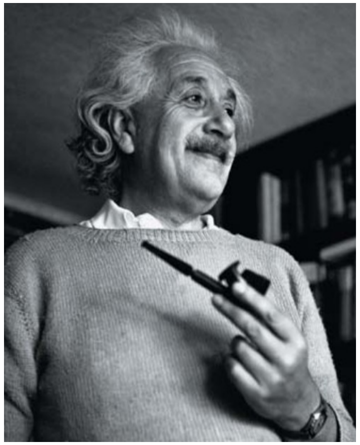
the **laws of special relativity hold** inside the elevator - a (local) inertial frame

The (strong) **Equivalence principle**:

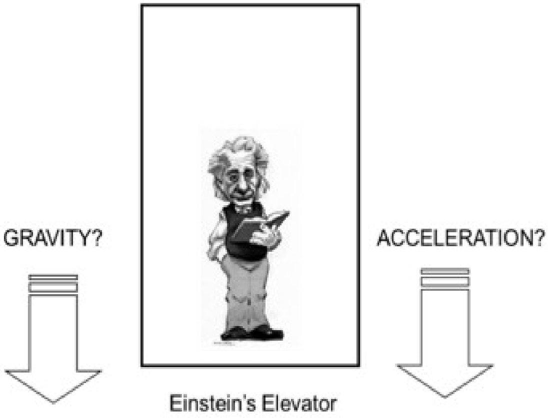
in a freely falling (non-rotating) laboratory occupying a small region of spacetime, the laws of physics are those of special relativity

all the Laws of physics

the principle of relativity in the theory of gravity



one can not tell whether it is gravity
or elevator's acceleration that is
causing to stick to the floor

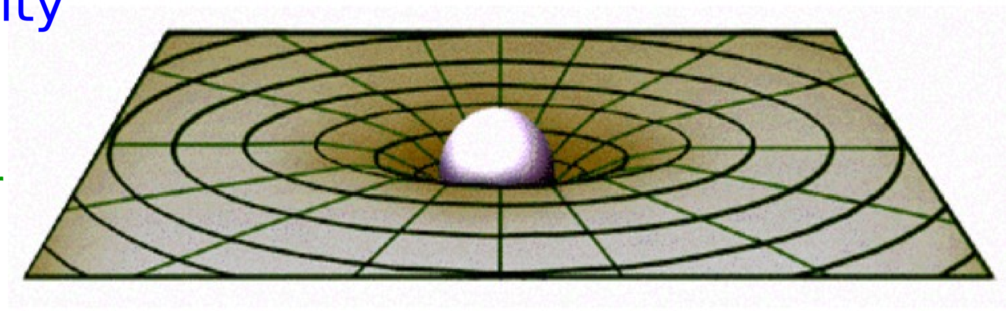


a **relativistic** description of gravity:

gravity should no longer be regarded as a force
in the conventional sense but rather as
a manifestation of the curvature of the spacetime
induced by the presence of matter

the **central idea** of general relativity

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



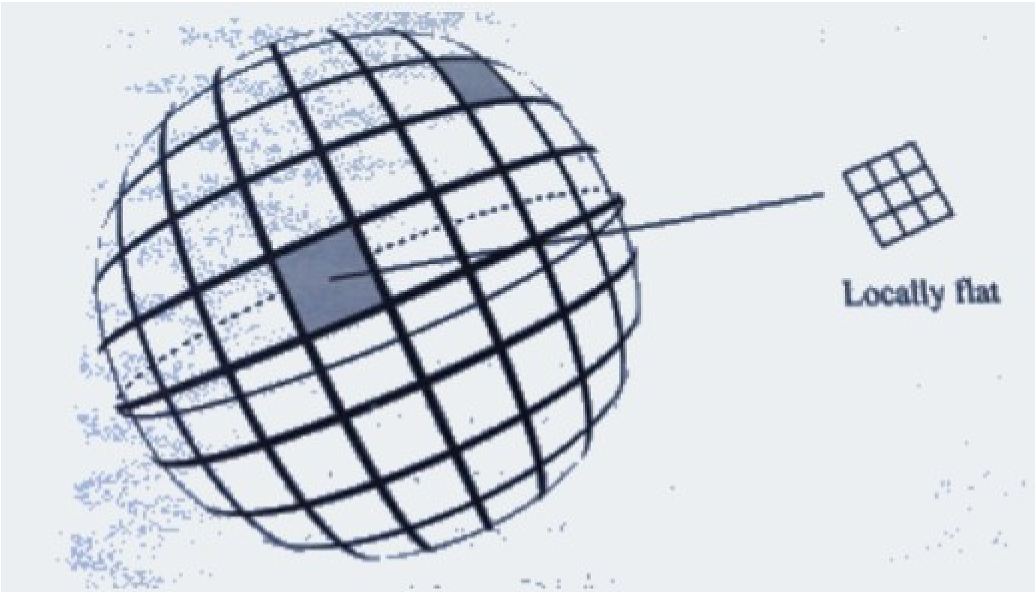
the principle of relativity in the theory of gravity

coordinate transformations in general relativity:

$\mathcal{M}$:

$$\boxed{\begin{array}{c} \xi^\mu \\ g_{\mu\nu}(\xi) \end{array}} \Rightarrow \boxed{\begin{array}{l} \xi'^\mu = \xi^\mu + \epsilon^\mu(\xi) \\ g'_{\mu'\nu'}(\xi') = \dfrac{\partial \xi^\mu}{\partial \xi'^{\mu'}} \dfrac{\partial \xi^\nu}{\partial \xi'^{\nu'}} g_{\mu\nu}(\xi) \end{array}}$$

Local Inertial Frame:



$$\boxed{g_{\mu\nu} = \eta_{\alpha\beta} \frac{\partial \xi^\alpha}{\partial x^\mu} \frac{\partial \xi^\beta}{\partial x^\nu}}$$

the free falling referential in which gravity seems to disappear locally

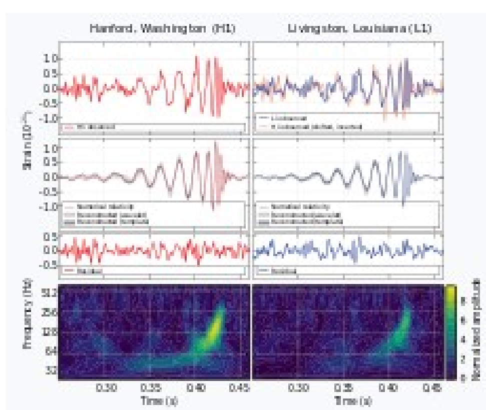
standard model **general relativity**

two **great pillars** of modern physics
and also
the most fundamental theories that are currently available...

- seem to explain almost all basic phenomena of physics known today
- experimental data show excellent agreement with their theoretical predictions

Photo: CERN

ESA/Hubble & NASA

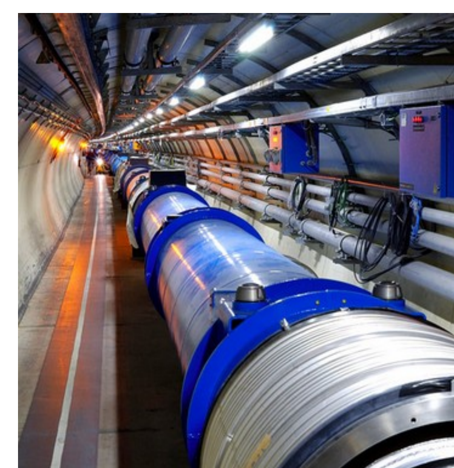


B. P. Abbott et al.2016

gravitational lensing

gravitational waves

precision electroweak data



... but no-one finds SM and GR satisfactory and complete!

the most obvious theoretical problems for which the standard theory does not offer any explanation:

- there are only three generations but so many different types of matter particles and so many different parameters
- the origin of the CP violation and flavour mixing
- ’the little hierarchy problem’ related with the finetuning in parameters to have appriopriate cancellations
- the problem of neutrino masses
- ’the hierarchy problem’: why the weak force is 10^{32} times stronger than gravity
- matter-antimatter assymetry in the Universe

… but no-one finds SM and GR satisfactory and complete!

the most obvious theoretical problems for which the standard theory does not offer any explanation:

- the nature of non-baryonic dark matter
- black holes and several problems related with them, e.g. information-loss paradox linked to black holes thermal evaporation
- a gigantic naturalness problem between dark energy and the energy of the vacuum state
- the nature of dark energy
- the origin of exponential expansion in the early Universe

all these strongly suggest that there should exist
a **richer and more complete theory**...

... having SM and GR as it's low-energy aproximations

the history teaches us is that the more fundamental theory lies always at higher energies or shorter distances than the scale of the problem

SM is valid down to energies smaller than the vacuum expectation value of the Higgs field

$$v = \sqrt{1/\sqrt{2}G_F} \sim 250\mathrm{GeV}$$

Fermi constant

equivalent to the distance scale:

$$d = \hbar c/v \sim 10^{-16}\mathrm{cm}$$

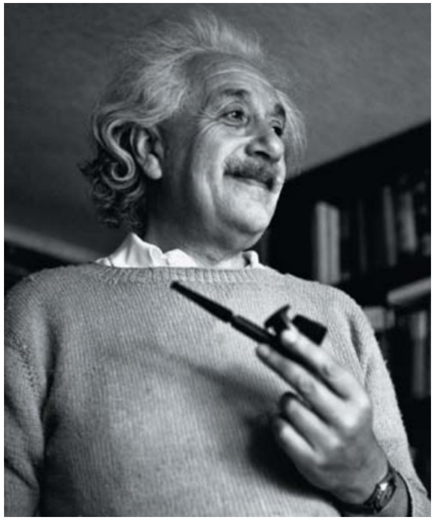
GR naturally lose it's applicability at curvature singularities i.e. the Planck length

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

or equivalently – Planck energy:

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

The idea of **’quantum gravity’** has more than 70 years...



aesthetic reasons:

remove ’artificial’ duality between curvature of spacetime and matter

$$\underbrace{G_{\mu\nu}}_{\text{geometry}} = \frac{8\pi G}{c^4} \underbrace{T_{\mu\nu}}_{\text{matter}}$$

search for geometrical representation of EM field, within general theory of gravity including spacetime with torsion

other approaches: Kaluza&Klein theory - not succesful...

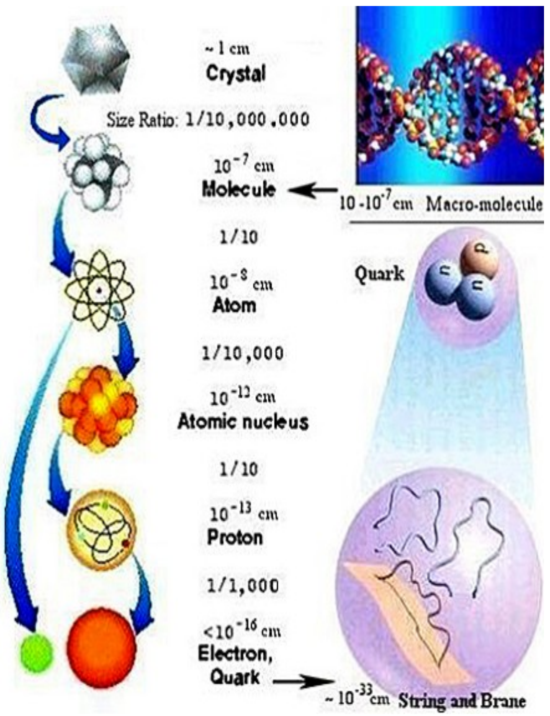
scepticism about unification:

one cannot simply merge gravity and quantum mechanics - these two theories are based on different assumptions and different mathematical formalisms now, we are still in the exploratory phase...

a huge number of
various approaches to 'quantum gravity'

ways from QFT ,
e.g. 'string theories'

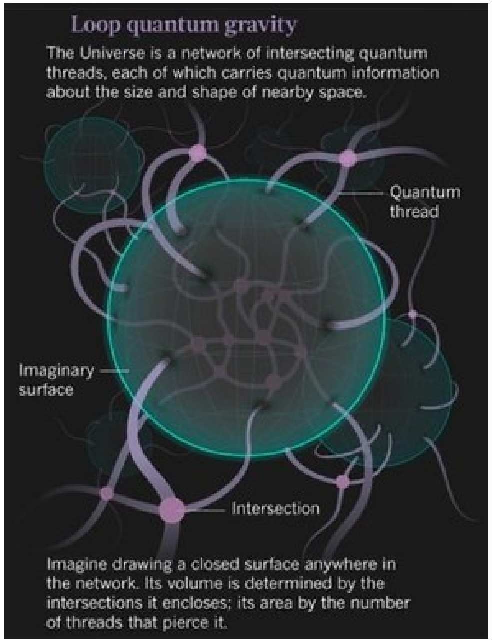
ways from GR
e.g. 'loop quantum gravity'
Lee Smolin et. al



http://www.particlecentral.com/strings_page.html

theories created
directly from
fundamental priciples
and new mathematical
formalisms, like
noncommutative
geometry,
twistors theory

Roger Penrose
Alain Connes



https://altexploit.wordpress.com/2017/03/27/
loop-quantum-gravity-and-nature-of-reality-briefer/

some comments:

- construction and analysis of any new theory beyond the standard one is very ambitious and difficult - there is **no experimental guidance** how to identify the correct theoretical framework

energies/distances of order of the Planck scale are far beyond our present-day capabilities

we need experimental confirmation !

- there is a chance to test Planck-scale effects: we can propose **phenomenological models** sensitive to non-standard properties from 'new physics'

effective phenomenology is the only way to obtain any information about the more fundamental theory

- **phenomenological approach:** standard theory is considered as an effective one, that includes all possible corrections necessary to describe physical phenomena, possibly occurring at low energies as experimental puzzles

+ enough predictive power to be applicable in experimental analysis

... a principle cannot be considered **as absolute**...

what if Lorentz symmetry is not an exact one ?

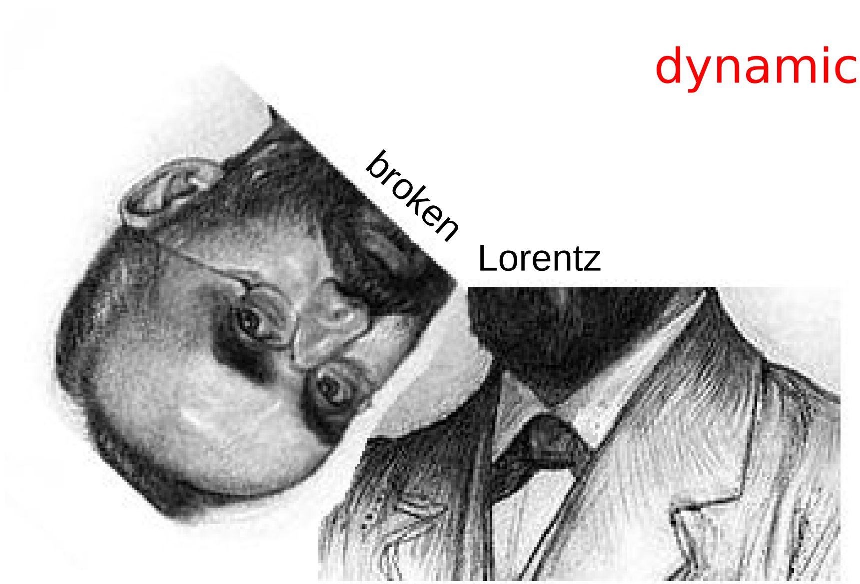
LIV

there are three main possibilities of Lorentz invariance violation:
’hard’, ’soft’ and spontaneous symmetry breaking

- a dozens of test models; most of them are only kinematical

Caution!

dynamics is essential for the complete theory



- most often LIV is introduced in a systematic manner, where the deviation is constant in time or space

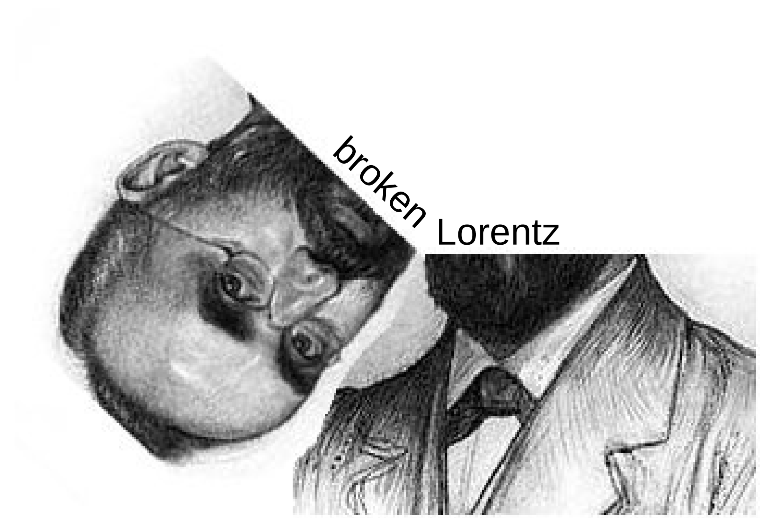
there are also works
dealing with stochastic LIV

what if Lorentz symmetry is not an exact one ?

- a great number of **technical difficulties** e.g. the problem of causality or stability within LIV field theory

- there should be also **some mechanism protecting it at low energies** and keeping it as an excellent approximation (since, there is no evidence for such violation)

something like 'fine tuning'?



the **presence of another symmetry**
(or partial symmetry)
may cause the absence
of LIV operators of
lower dimension

supersymmetry
or
extra dimensions ?

what if Lorentz symmetry is not an exact one ?

the problem with a reliable approximation limit for the energies where QG effects become relevant:

from dimensional analysis such threshold energy can be: $\boxed{E_{Pl} \sim 10^{19}\mathrm{GeV}}$

but is not Lorentz invariant !

- the border between classical and quantum gravity is not well defined
- it should have the same value for all inertial observers

'hard' violation:

there is a preferred frame relative to which Planck energy is the absolute limit for the QG effects

'soft' violation:

there a possibility that the Lorentz transformations must be changed to leave EP l invariant

'Hard' breaking of Lorentz invariance

breakdown of both STR postulates

'new aether' theories

Mattingly, Living Rev.Rel. 2005

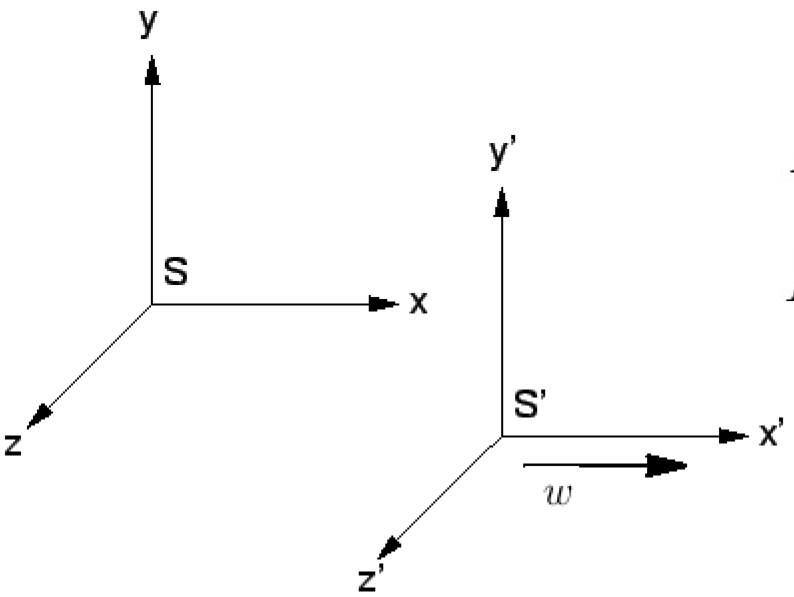
Smolin, 2003

introduce the preferred frame
(usually identified with CMBR)

the Robertson (Robertson–Mansouri–Sexl) model

a suitable generalization of the Lorentz transformations between two inertial frames S and S' of the form:

$$\begin{aligned} x^1 &= Ax'^1 + Bx'^0 \\ x^0 &= B'x'^0 + A'x'^1 \\ x^2 &= Cx'^2 \\ x^3 &= Cx'^3 \end{aligned}$$



where:

$$\begin{aligned} A' &= \frac{w}{c}A \\ B' &= \frac{w}{c}B \end{aligned}$$

the Robertson (Robertson–Mansouri–Sexl) model

- preferred frame S_0 is chosen to hold the Maxwell equations unchanged
- in this distinguished rest frame, metric has its usual Minkowski form

$$\boxed{ds^2 = dx_0^2 - (dx_1^2 + dx_2^2 + dx_3^2)}$$

S_0

... but in any frame S', moving with the velocity w in respect to the S_0, metric will change its form, as a result of modified Lorentz transformations

$$\boxed{ds'^2 = k_0^2 dx_0'^2 - k_1^2 dx_1'^2 - k_2^2 (dx_2'^2 + dx_3'^2)}$$

S'

$$\boxed{k_0(w) \;=\; \sqrt{1 - \frac{w^2}{c^2} B}}$$

$$\boxed{k_1(w) \;=\; \sqrt{1 - \frac{w^2}{c^2} A}}$$

$$\boxed{k_2(w) \;=\; C}$$

- Lorentz symmetry is recovered if $k_i(w) = 1, i = 0, 1, 2$

more general (bimetric) approach

the 'matter' metric $\hat{g}_{\mu\nu}$

the 'spacetime' metric for gravity $g_{\mu\nu}$

Jacobson & Mattingly, Phys. Rev. D, 2001

Clayton & Moffat, Phys. Lett. B, 2001

In the simplest case: $\boxed{\hat{g}_{\mu\nu} = g_{\mu\nu} + \tilde{B}\partial_\mu\phi\partial_\nu\phi}$

the total action is then:

ϕ - scalar field connecting two frames

$$S = S_g(g_{\mu\nu}) + S_\phi(g_{\mu\nu}, \phi) + \hat{S}_m(\hat{g}_{\mu\nu}, \phi, \psi)$$

usual matter fields

- the Lorentz symmetry is replaced by two copies of the SO(3,1) group
- each of two frames has its own light cone (different, in general, for each particle of the standard model)
- to make a correct description of any phenomenon, one of these frames should be selected; otherwise, physics will be interpreted differently, depending on the particular frame

more general (bimetric) approach

considering a cosmological scenario for homogeneous and isotropic spacetime one can find two metrics:

for gravity: $$ds^2 = v_g^2(t)dt^2 - a(t)^2[\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin\theta^2 d\phi^2]$$

for matter: $$d\hat{s}^2 = c^2(t)dt^2 - a(t)^2[\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin\theta^2 d\phi^2]$$

where: $$c(t) = c_0\sqrt{1 + \frac{B}{c_0^2}\dot{\phi}^2}$$ - the speed of light

$$v_g(t) = c_0\sqrt{1 - \frac{B}{c_0^2}\dot{\phi}^2}$$ - the speed of gravitational waves

- in the frame with varying speed of light, the universe appears to be decelerating (the speed of light increasing with the redshift) while in the second frame universe appears to be accelerating and the supernovae seem to be farther

Moffat, Int. J. Mod. Phys. D, 2003

'Soft' breaking of Lorentz invariance

breakdown of the second STR postulate

Amelino-Camelia, Int. J. Mod. Phys. D, 2001

Amelino-Camelia, Class. Quant. Grav. , 2003

- all inertial observers are equivalent, but the speed of light is not a constant

'deformed' special relativity (DSR)

'non-linear', 'double' or 'deformed' (depending on the authors)

modified postulates:

J. Magueijo, Rept. Prog. Phys., 2003

1. The laws of physics take the same form in all inertial frames.
2. There is a fundamental velocity scale c (measured by each inertial observer as a speed of light), the same for all inertial observers in the limit $E/E_{Pl} \to 0$.
3. There is a fundamental energy scale E_{Pl} the same for all inertial observers.

'deformed' special relativity (DSR)

- two limits:

  Kowalski-Glikman, Phys. Lett. A, 2001

  1. the well-known, relativistic limit for $E/E_{Pl} << 1$ and $v/c << 1$

  2. new limit associated with the transition to the Planck regime for $E/E_{Pl} \sim 1$

- to keep these two limits, the Lorentz group is replaced by an appriopriate, non-linear representation

Bruno & Kowalski-Glikman, Phys. Lett. B, 2001

rotational invariance has been proved with a high degree of accuracy, so it is reasonably to consider only with the 'boost' deformations:

$$\boxed{\tilde{B}_i = B_i + \frac{p_i}{E_{Pl}} D}$$

classical 'boost' generator

$$\boxed{B_i = p_i \frac{\partial}{\partial p_0} - p_0 \frac{\partial}{\partial p_i}}$$

$$\boxed{D = p_\mu \frac{\partial}{\partial p_\mu}}$$

'dilatation' generator related with non-linear deformations

’deformed’ special relativity (DSR)

- for such constuction one can find transformation rules for the position and time coordinates:

$$\begin{aligned} x'^0 &= \gamma(x^0 - \frac{vx^1}{c^2})(1 + (\gamma - 1)\frac{E}{E_{Pl}} - \gamma\frac{vp_1}{E_{Pl}}) \\ x'^1 &= \gamma(x^1 - vx^0)(1 + (\gamma - 1)\frac{E}{E_{Pl}} - \gamma\frac{vp_1}{E_{Pl}}) \\ x'^2 &= x^2(1 + (\gamma - 1)\frac{E}{E_{Pl}} - \gamma\frac{vp_1}{E_{Pl}}) \\ x'^3 &= x^3(1 + (\gamma - 1)\frac{E}{E_{Pl}} - \gamma\frac{vp_1}{E_{Pl}}). \end{aligned}$$

Magueijo & Smolin, Phys. Rev. D, 2003

a highly non-trivial task

- one can see that the metric tensor becomes energy dependent

$$s^2 = g_{\mu\nu}(dx^\mu)^2(dx^\nu)^2$$

this is equivalent to the fact that there is no single classical geometry at the Planck scale

a ’rainbow’ metric

Magueijo & Smolin, Class. Quant. Grav., 2004

https://www.thinkgeek.com

’deformed’ special relativity (DSR)

- main consequence of the 'rainbow' metric:

https://www.thinkgeek.com

the light cones are also deformed at a Planck regime, so the speed of light is a variable

but, unlike other theories with variable speed of light,
c does not evolve with time, but is rather a function of energy $c(E)$

- DSR was introduced in order to preserve not only E_{Pl} but also structure of the Lorentz algebra

Magueijo & Smolin, Class. Quant. Grav., 2004

other approach: non-commutative geometry

non-commutative spacetimes can arise in the context of quantum gravity frameworks

non-commuting spacetime operators related with the **κ-Poincare algebra**

non-commutative geometry

- Lorentz subalgebra of κ-Poincare algebra is not deformed and the generators of rotations and 'boosts' has its standard commutation relations; the only modification is the way how the boost act on four-momentum generator:

$$
\begin{aligned}
[B_i, P_j] &= i\delta_{ij}\left(\frac{\kappa}{2}(1 - \exp^{-2P_0/\kappa}) + \frac{\vec{P}^2}{2\kappa}\right) - i\frac{1}{\kappa}P_iP_j \\
[B_i, P_0] &= iP_i.
\end{aligned}
$$

Kowalski-Glikman, Lect. Notes Phys., 2005

- consequences:

1. such structure preserves the two fundamental constants and keeps the algebra stable - it cannot be transformed to the standard Poincare algebra by change of variables

2. spacetime is non-commutative with the following commutation relations of the coordinates:

$$
\begin{aligned}
[x_0, x_i] &= -\frac{1}{\kappa}x_i \\
[x_i, x_j] &= 0
\end{aligned}
$$

Freidel, Kowalski-Glikman, Nowak, Phys. Lett. B, 2007

the ambiguity in the prediction of DSR concerning the speed of light !

Spontaneous symmetry breaking

- the most elegant way of introducing the LIV into theory

symmetry is spontaneously broken when **the symmetry of the lagrangian is not the symmetry of the vacuum** (the vacuum 'feels' the transformation)

- it was used for the first time 50 years ago in solid-state physics and then adapted to the particle physics

Ginsburg-Landau theory:

ground state is at

$$\vec{M}(\alpha_1 + 2\alpha_2 \vec{M}\cdot\vec{M}) = 0$$

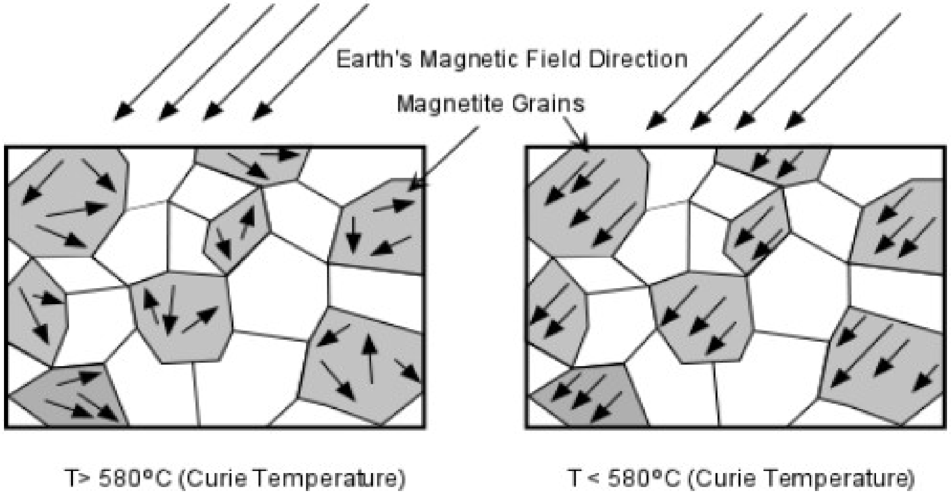
$$\alpha_2 > 0, \qquad \alpha_1 = \alpha\,(T - T_C) \qquad \alpha > 0$$

$T > T_C$ minimum at $\vec{M} = 0$

$T < T_C$ minimum at $\left|\vec{M}\right| = \sqrt{\dfrac{-\alpha_1}{2\alpha_2}} \neq 0$

If we choose $\vec{M}$ to be in some direction the rotational symmetry is broken

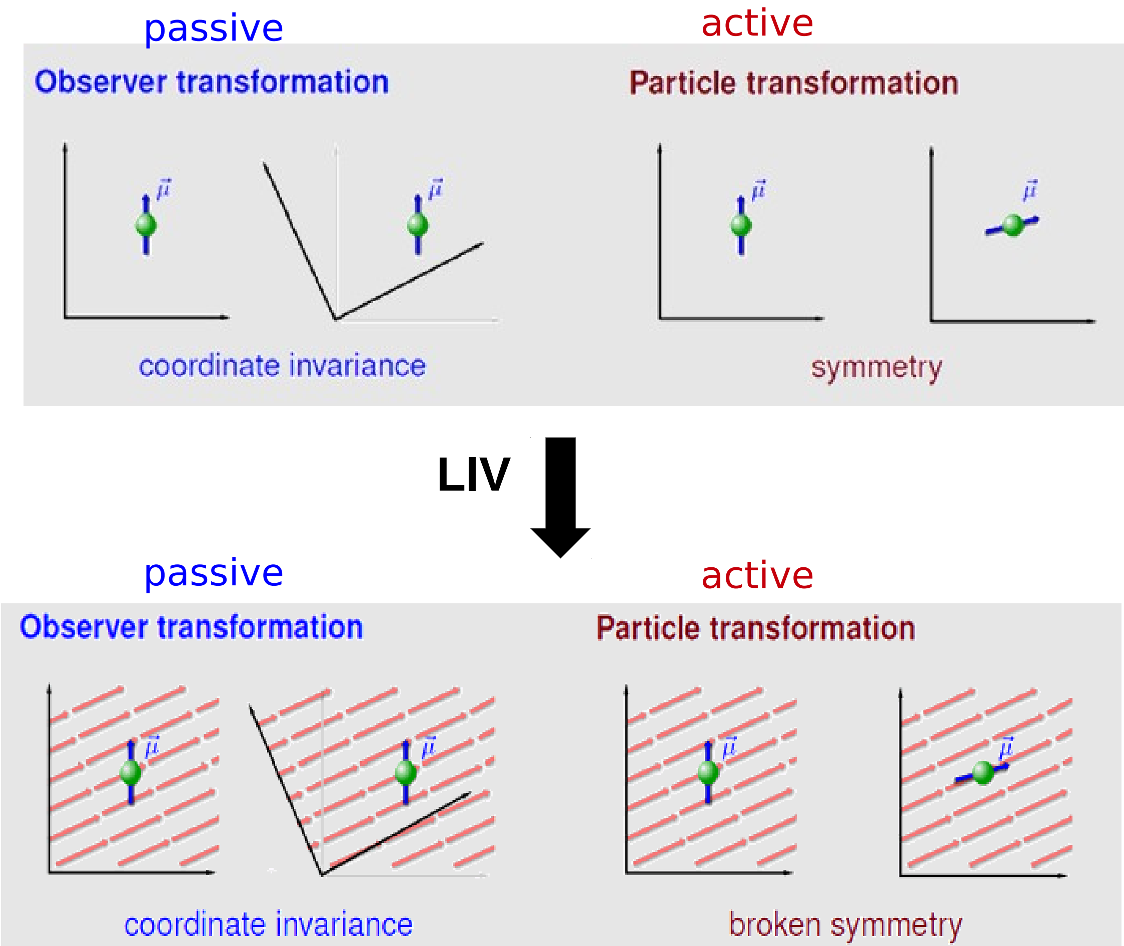
$T > T_C$ (Curie Temp) all magnetic dipoles are randomly oriented–rotational symm
$T < T_C$ all magnetic dipoles are in the same direction-not invariant under rotation



http://galileo.phys.virginia.edu/~pqh/Li.pdf

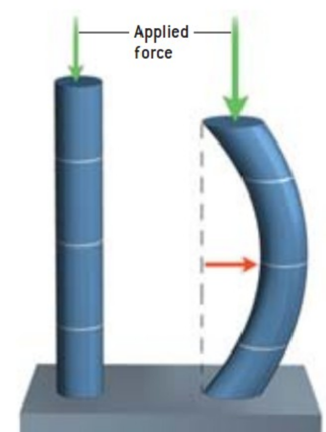
https://www.tulane.edu/~sanelson/eens1110/pltect.htm

Spontaneous breaking of Lorentz Invariance



SPONTANEOUS SYMMETRY BREAKING occurs when a completely symmetric set of conditions or underlying equations gives rise to an asymmetric result. For example, consider a cylindrical stick with a force applied vertically (*left*). The system is completely symmetrical with respect to rotations around the axis of the stick. If a large enough force is applied, however, the system becomes unstable and the stick will bend in some direction (*right*). The symmetry breaking can be represented by a vector, or an arrow (*red*), that indicates the direction and magnitude of the bending.

Lorentz violation involves the emergence of such vector quantities throughout spacetime.



invariance under coordinate transformations is unrelated to any physics; whereas, the invariance under particle transformations corresponds to the physical symmetry of the system

http://www.physics.indiana.edu/%7Ekostelec/lay/04sciam.pdf

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

Spontaneous breaking of Lorentz Invariance

- spontaneous breaking of the Lorentz invariance is attractive,
  - it leaves unaffected the underlying fundamental theory and its properties (like causality and the conservation principles)

- the essence of such framework:

Moffat, Int. J. Mod. Phys. D, 2003

1. there exist a preferred frame which can be specified by a unit, timelike vector field ϕ^μ

2. matter and gauge fields couple not only to the usual metric but also to the preferred frame:

$$S = S_g + S_m + S_\phi$$

standard action for gravity

standard action for matter

$$\boxed{S_\phi = \int d^4x\sqrt{-g}[-\frac{1}{4}g^{\mu\nu}g^{\alpha\beta}B_{\mu\alpha}B_{\nu\beta} - V(\phi)]}$$

where $B_{\mu\nu} = \partial_\mu\phi_\nu - \partial_\nu\phi_\mu \;\; (g = det(g_{\mu\nu}))$

assuming the abelian case

Spontaneous breaking of Lorentz Invariance

according to the spontaneous symmetry breaking in the standard model of particle physics, the potental $V(\phi)$ can be chosen as

$$V(\phi) = -\frac{1}{2}\mu^2\phi_\mu\phi^\mu + \lambda(\phi_\mu\phi^\mu) + V_0$$

with $\phi_\mu\phi^\mu$, λ and μ^2 are positive so the potential is bounded from below

(a 'Mexican hat' form)

Lorentz symmetry of the action S becomes spontaneously broken when $V(\phi)$ has its minimum at:

$$\frac{\partial V}{\partial \phi} = 0 \longrightarrow \quad < \phi_\mu >_0 \equiv \phi^0_\mu = \delta_{\mu 0} v$$

$$v = \sqrt{\frac{\mu^2}{4\lambda}}$$

construction similar to the 'unitary gauge' of electroweak theory

homogeneous Lorentz group is broken down to the rotation group - only three rotation generators leave the vacuum invariant

Spontaneous breaking of Lorentz Invariance

considering solutions close to the absolute minimum,
small values of the new field variables appear -
time and space parts of ϕ^μ are replaced by four fields:

$$\theta_i(x), i = 1, 2, 3 \qquad \text{and} \quad \chi(x)$$

paramerize position of ϕ^μ
around the minimum

measures distance of ϕ^μ
from the minimum

three massless Nambu-Goldstone modes

further studies required:

which is not observed

1. Goldstone fields may produce long-range ’fifth force’

2. the influence of Goldstone modes on the graviton propagator

should be massive...

...

Kostelecky & Potting, Phys. Rev. D, 2009

Spontaneous breaking of Lorentz Invariance

Colladay & Kostelecky, Phys. Rev. D, 1998

an alternative approach – a low-energy effective theory:

the **Standard Model Extension**

lagrangian contains not just well known Lorentz invariant terms but also all possible LIV operators created from standard model fields and derivatives operators coupled to tesor fields with non-zero vacuum expectation values responsible for LIV:

of dimension 4

$$S^{SME}_{TOT} = (S_G + S_G^{LIV}) + (S_{SM} + S_{SM}^{LIV}) + S_{LIV}$$

standard action for gravity

LIV corrections to gravity sector

standard action for matter

LIV corrections to matter sector

the action for LIV fields

- when gravity is taken into account, LIV terms should have dynamical form; otherwise it is sufficient to consider only constant operators

  minimal SME

- SME preserves:
  - minimal $SU(3) \times SU(2) \times U(1)$ gauge symmetry
  - power-counting renormalizability

http://www.physics.indiana.edu/~kostelec/

minimal SME

- modified Lagrangian for a Dirac particle takes the form:

$$L_D = \frac{1}{2} i\bar{\psi}\Gamma^\mu \partial_\mu \psi - \bar{\psi} M \psi$$

where

$$\begin{aligned}\Gamma^\mu &= \gamma^\mu + c^{\mu\nu}\gamma_\nu + d^{\mu\nu}\gamma_5\gamma_\nu + e^\mu + if^\mu\gamma_5 + \frac{1}{2} i g^{\lambda\nu\mu}\sigma_{\lambda\nu} \\ M &= m + a_\mu\gamma^\mu + b_\mu\gamma_5\gamma^\mu + \frac{1}{2} H^{\mu\nu}\sigma_{\mu\nu}\end{aligned}$$

- modified Lagrangian for quantum electrodynamics:

$$L_{\text{photon}} = -\frac{1}{4}(k_F)_{\kappa\lambda\mu\nu} F^{\kappa\lambda} F^{\mu\nu} + \frac{1}{2}(k_{AF})^\kappa \epsilon_{\kappa\lambda\mu\nu} A^\lambda F^{\mu\nu}$$

all LIV operators are real and have well defined transformation properties under CPT symmetry:

$(k_F)_{\kappa\lambda\mu\nu}$, $c^{\mu\nu}$, $d^{\mu\nu}$ and $H^{\mu\nu}$ are $\boxed{\text{CPT-even}}$

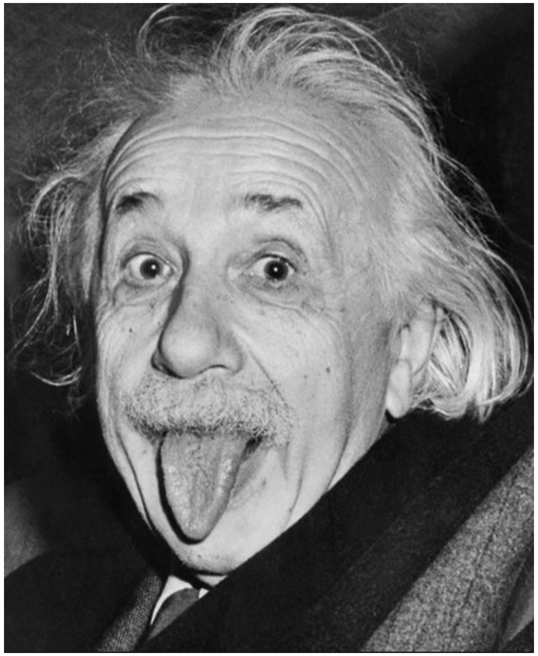
$(k_{AF})^\kappa$, e^μ, f^μ, $g^{\lambda\nu\mu}$ and b_μ are $\boxed{\text{CPT-odd}}$

observational status of LIV

... a principle can be used as a basis for a theory,
but its predictions must be verified...

sensitivity requirements for tests of Lorentz invariance are very strict:
one should have an accuracy better than

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



are we able to achieve that ?

... or **maybe LIV cannot be veryfied at all** ...?

observational status of LIV

but one has to remember that history is a great teacher...

... and a donor of hope...

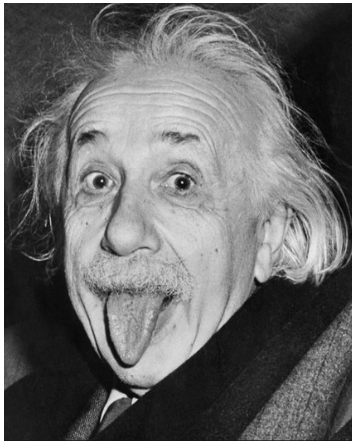
- **from strong gravitational lensing history of discovery:**

small value of deflection angle and the unlikely
alignment requirement for lensing by a single star

⬇

"there is no great chance of observing this phenomenon"

[Einstein, 1936]



observational status of LIV

F.Zwicky (1937): multiple images can be detected if one consider deflector as more massive than stars, e.g. galaxies

The first observation: Walsh, Carswell & Weynmann 1979 QSO-0957+561A,B

Now we know **more than 300 strong lenses** – massive galactic surveys

present:

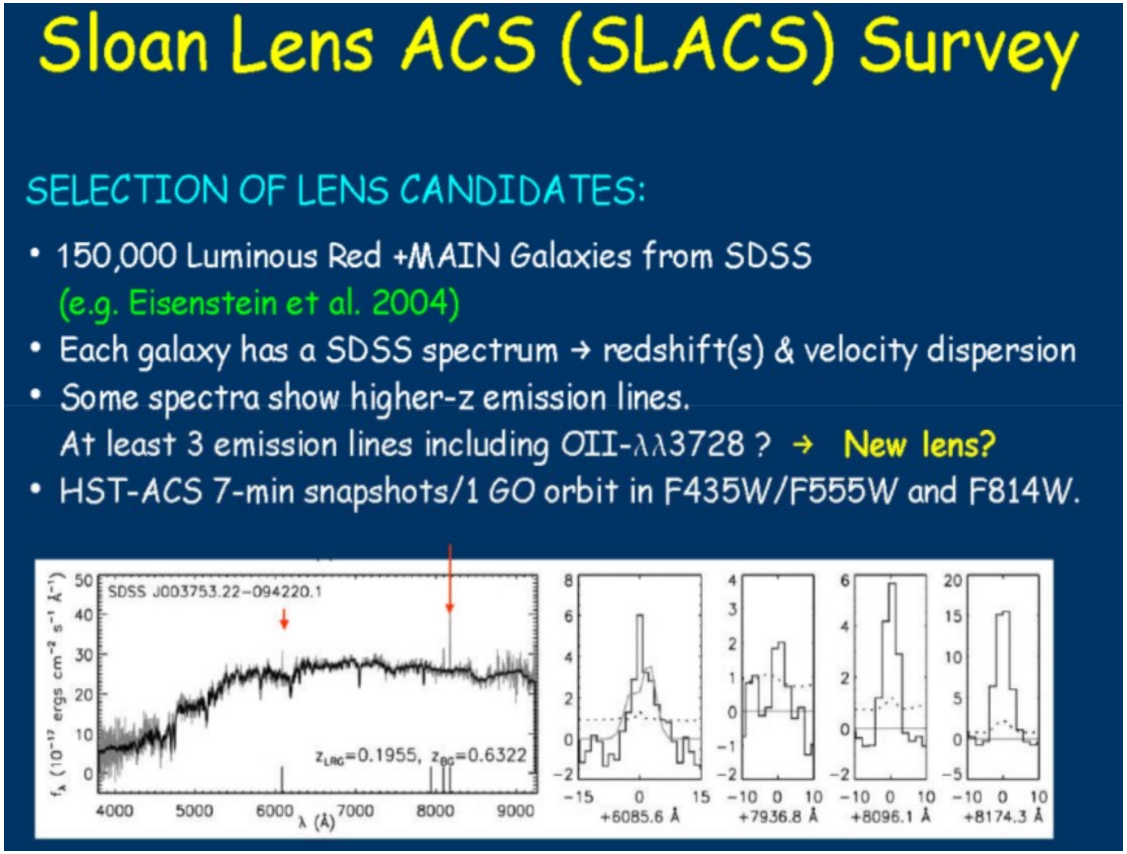
SLACS, BELLS, CFHT – SL2S,
CLASS, SQLS, HAGGLeS,
AEGIS, COSMOS, CASSOWARY

and future:

Pan-STARRS, LSST, JDES, SKA

spectroscopic searches concentrated on sources!

+ microlensing!



observational status of LIV

- **and also from gravitational waves history of discovery:**

do GWs really exist and, if yes, can we detect them directly ?

analogy to the Hooke's Law:

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

stress tensor

strain tensor

elastisity modulus

$$\boxed{\frac{c^4}{8\pi G} \approx 10^{43} N}$$

physical effect of gravitational wave:

$$h = \Delta L / L$$

$$\boxed{\Delta L \sim 10^{-16} \left(\frac{h}{10^{-21}} \right) \left(\frac{L}{km} \right) cm}$$

the proton radius is ~ 10^{-13} cm ...

observational status of LIV

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)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

2017 Nobel Prize in Physics

"for decisive contributions to the LIGO detector and the observation of gravitational waves".

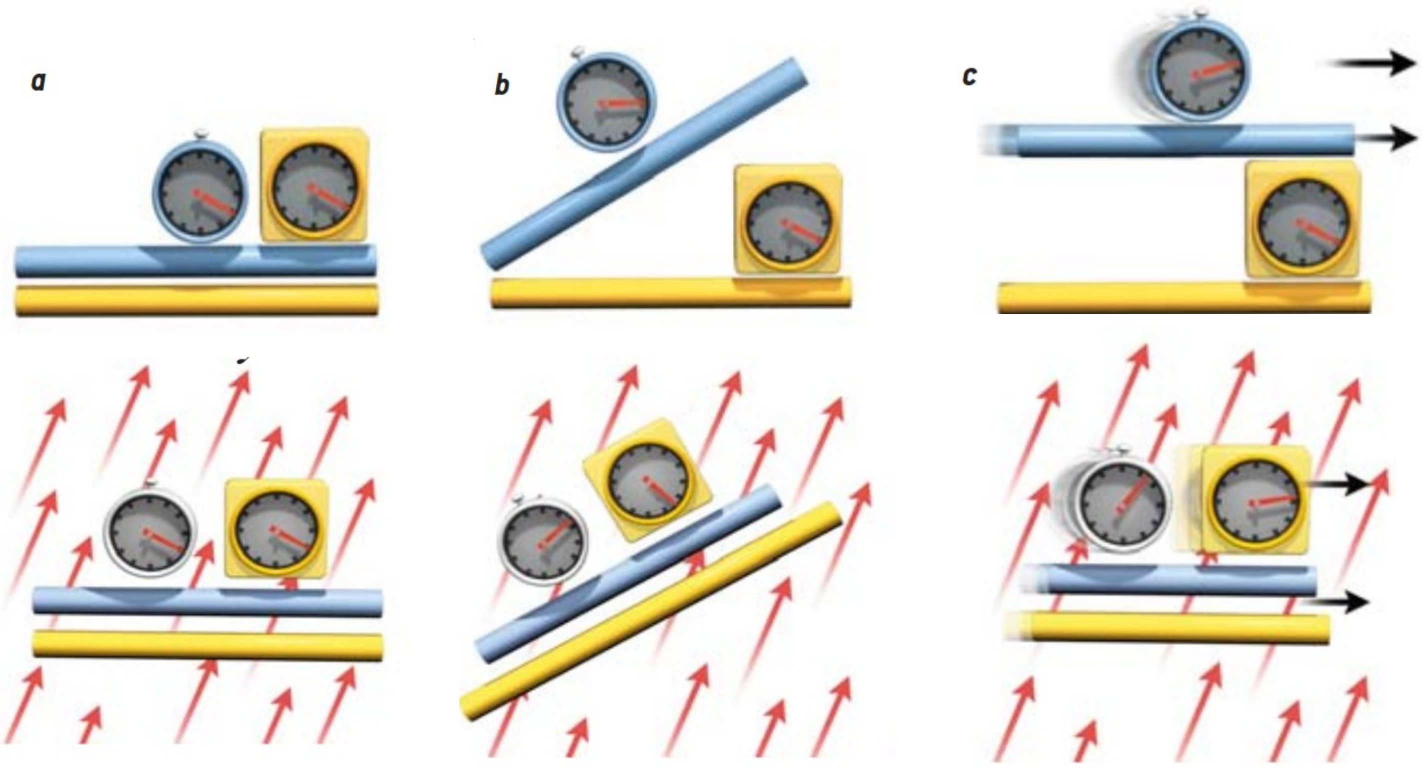
observational status of LIV

all tests of the Lorentz invariance should be
of **ultra-high precision** and **carefully selected**

a number of phenomena which can be used to search for LIV:

1. violation of local rotational symmetry

2. violation of Lorentz 'boosts' invariance



http://www.physics.indiana.edu/%7Ekostelec/lay/04sciam.pdf

traditional tests of SR

Michelson-Morley

? $\boxed{c(\theta) = c}$

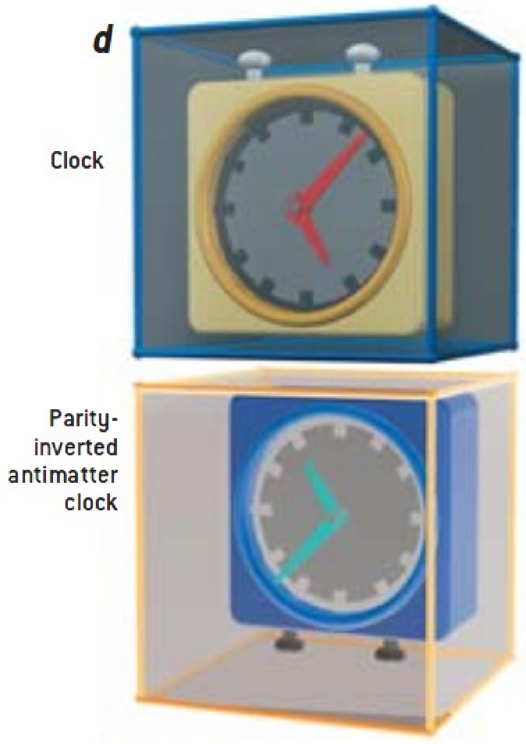
Kennedy-Thorndike

? $\boxed{c(v) = c}$

observational status of LIV

3. breakdown of descrete symmetries

in particular – **CPT symmetry**



http://www.physics.indiana.edu/%7Ekostelec/lay/04sciam.pdf

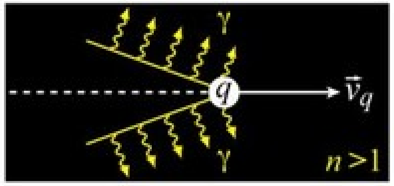
4. shift of thresholds

particle **reactions at high energies can be changed**

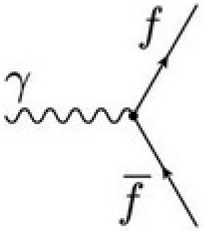
occurence of the forbidden processes

5. modification of particle propagation in vacuum

vacuum Cherenkov radiation



photon decay



energy-dependent photon polarization changes (vacuum birefringence)

6. possible violation of the Equivalence Principle

different gravitational coupling to the background field

observational status of LIV

two classes of experiments with sesitivity high enough to probe LIV

extremely precise laboratory tests
searching for a small deviations from standard values of specific quantities

modern Michelson's type tests

precision spectroscopy
(in fermionic sector)

atomic tests
(mainly: QED sector)

pendulum experiment

high precision

astrophysical tests
searching for anomalous processes and new propagation phenomena for relativistic particles from distant sources

threshold effects

dispersive processes
in vacuum

high energy

observational status of LIV

- **optical (or microwave) cavity tests**:

interferometers → resonators

Michelson-Morley

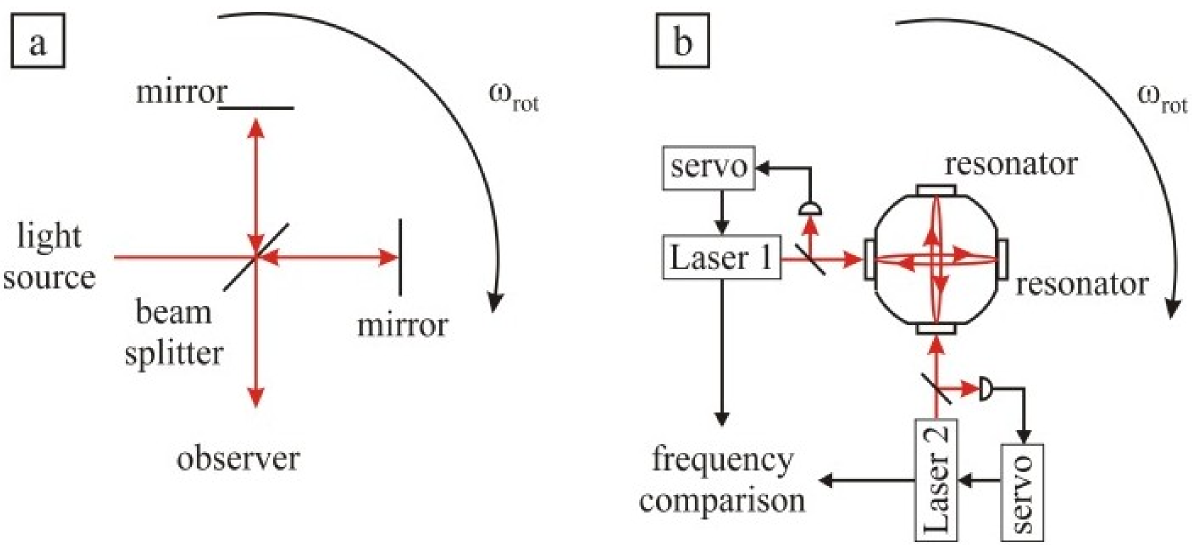
? $\boxed{c(\theta) = c}$

  - testing the isotropy of the speed of light
  - comparing the resonance frequency of two orthogonal **cavities** rotated on a turntable

$$\boxed{\nu_0 = \frac{mc}{2nL}}$$

a cristal cooled to liquid He temperatures

https://www.physics.hu-berlin.de/en/qom/research/michelson




photography (c) by Ernst Fesseler

$$\boxed{\Delta c/c = (0.6 \pm 1.2) \cdot 10^{-17}}$$

test theory – photon sector of SME:

$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} \; - \; \frac{1}{4} (k_F)_{\kappa\lambda\mu\nu} F^{\kappa\lambda} F^{\mu\nu}$$

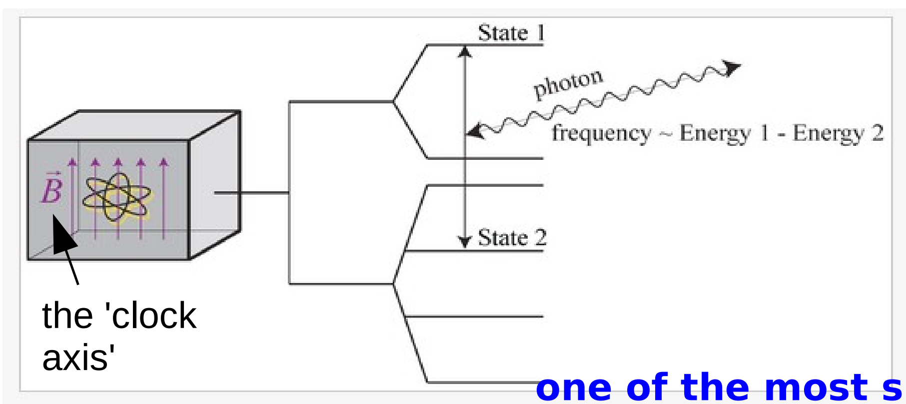
Rotating optical cavity experiment testing Lorentz invariance at the 10^{-17} level
S. Herrmann, A. Senger, K. Möhle, M. Nagel, E. V. Kovalchuk, A. Peters
Phys. Rev. D **80**, 105011 (2009)

observational status of LIV

- **precision spectroscopy – clock-comparision tests**
  - comparing energy levels of two atomic transition frequencies (**’atomic clocs’**) co-located at some point in laboratory and rotating as the Earth rotates aroud its axis
  - typically use hyperfine or Zeeman transitions

V. Hughes et al. 1960

R. Drever 1961



the clock frequency should be independent of the clock axis and the clock velocity if Lorentz symmetry is unbroken

LIV

anisotropy effects:
a tiny difference between those frequencies should be measured, with the period of a sidereal day (~ 23.93 hours)

one of the most sharp tests !

http://www.mdpi.com/2073-8994/9/10/245/htm

Experiment	Ref.	Atom(s)	Coefficients Bounded	$\log_{10}\left(\frac{\text{Bound}}{\text{GeV}}\right)$
Gemmel et al. 2010	[21]	$^{3}He, ^{129}Xe$	$n: \tilde{b}_X, \tilde{b}_Y$	−32
Smiciklas et al. 2011	[22,23]	^{21}Ne, Rb	$p: \tilde{c}_X, \tilde{c}_Y, \tilde{c}_Z, \tilde{c}_-$	−29
	[22]	^{21}Ne, Rb	$n: \tilde{c}_X, \tilde{c}_Y, \tilde{c}_Z, \tilde{c}_-$	−29
Peck et al. 2012	[24]	$^{199}Hg, ^{133}Cs$	$p: \tilde{b}_X, \tilde{b}_Y$	−30
Hohensee et al. 2013	[25]	Dy	$e: \tilde{c}_-, \tilde{c}_X, \tilde{c}_Y, \tilde{c}_Z$	−17
			$e: \tilde{c}_{TX}, \tilde{c}_{TY}, \tilde{c}_{TZ}$	−14
			$e: \tilde{c}_{TT}$	−8
			$p: \tilde{b}_Z, \tilde{d}_X, \tilde{d}_Y, \tilde{g}_{DX}, \tilde{g}_{DY}$	−28
			$n: \tilde{b}_Z, \tilde{d}_X, \tilde{d}_Y, \tilde{g}_{DX}, \tilde{g}_{DY}$	−29
			$n: \tilde{b}_X, \tilde{b}_Y$	−31
Allmendinger et al. 2014	[26]	$^{3}He, ^{129}Xe$	$n: \tilde{b}_X, \tilde{b}_Y$	−34

observational status of LIV

- **other atomic tests:**
  - measure various specific physical quantities like: masses, g factors, charge-to-mass ratios

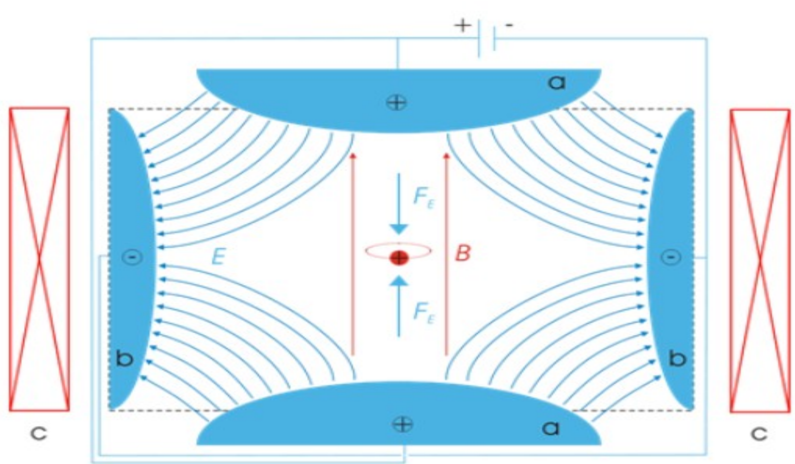
a direct high-precision CPT test ...

High-precision comparison of the antiproton-to-proton charge-to-mass ratio

S. Ulmer , C. Smorra, A. Mooser, K. Franke, H. Nagahama, G. Schneider, T. Higuchi, S. Van Gorp, K. Blaum, Y. Matsuda, W. Quint, J. Walz & Y. Yamazaki

Nature **524**, 196–199 (13 August 2015)

$$\boxed{\frac{(q/m)_{\bar{p}}}{(q/m)_{p}} - 1 = 1(64)(26) \times 10^{-12}}$$



measure of the cyclotron frequencies of single trapped protons and antiprotons in a Penning trap with magnetic field

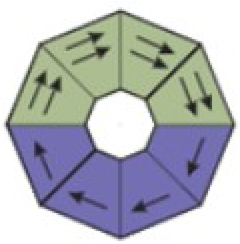
$$\omega_c = \frac{qB}{m}$$

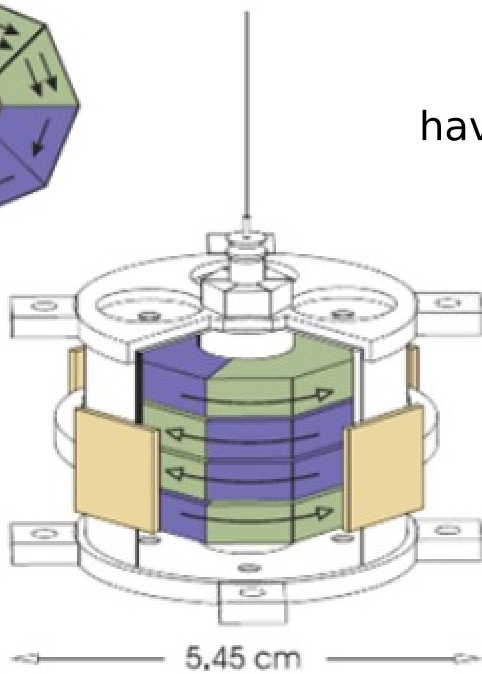
observational status of LIV

- **pendulum experiment**

the pendulum hangs from a fiber on a turntable
inside a set of magnetic shields in a vacuum chamber

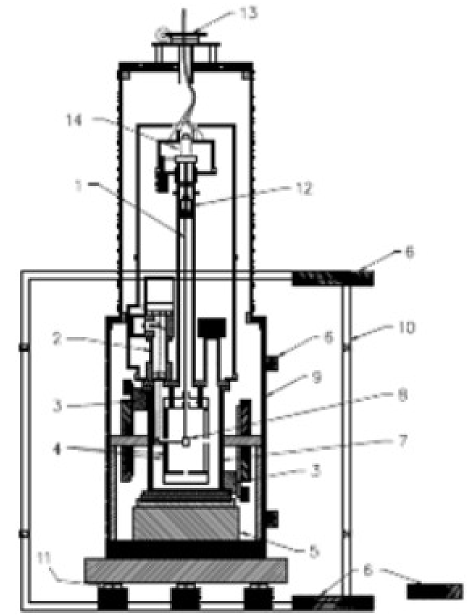
toroidal pendulum consists of
two different types of magnets





have a negligible magnetic field
but large net electron spin

a combined effect of
a large number of
aligned electron spins



LIV should induce a torque on the pendulum
and thus, additional time variations
with a sidereal period caused by Earth rotation

the best limit on LIV for electrons

$$|\tilde{b}^e_J| \lesssim 10^{-31}\ \text{GeV for } J = X, Y,$$

$$|\tilde{b}^e_Z| \lesssim 10^{-30}\ \text{GeV}$$

R.Potting talk on DISCRETE 2012

observational status of LIV

- **astrophysical tests:** dispersive processes in vacuum

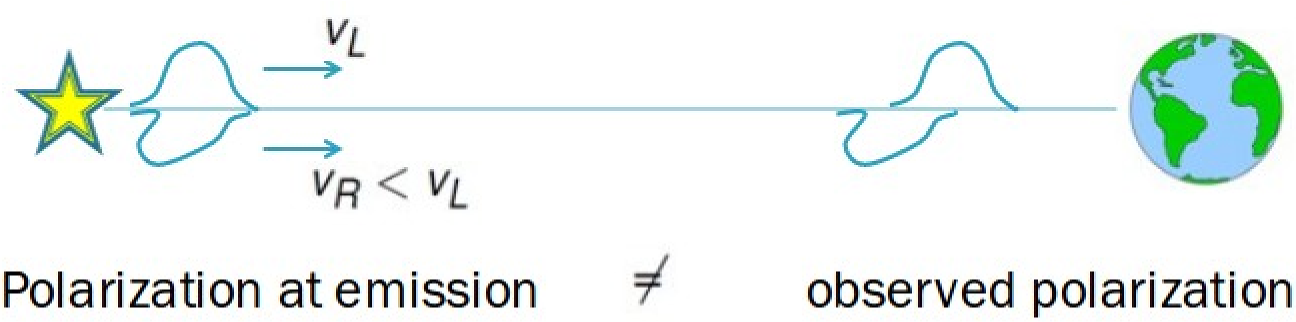
LIV effects on propagation of high energy particles form distant sources

Example: **vacuum birefringence of light**:

Shao & Ma, PRD, 2011

Laurent et al, PRD, 2011

different photon polarizations travel with slightly different velocities



change in the net polarization of light: $\boxed{\Delta\phi \sim \Delta v E L}$

spectropolarymetry of cosmological sources

Warning!

we need cosmological sources with known polarization

other possibilities:

threshold effects

- new processes (normally forbidden)
- threshold shifts for known processes
- change of final distribution of momenta (asymmetric pair prod.)

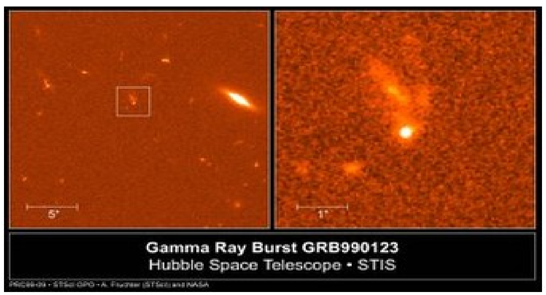
observational status of LIV

astrophysical tests may play an essential role in LIV testing:

can give one of the most stringent bounds on LIV parameters

- photons of highest energies (TeV energy range) reported from X-ray binaries and active galactic nuclei (AGN's):

in particular from blazars (BL Lac objects)



Amelino-Camelia et al., Nature, 1998

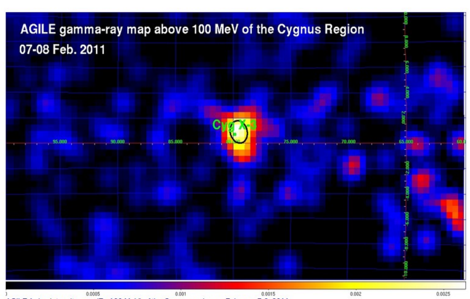
The H.E.S.S. Collaboration, A&A, 2006

Chadwick et al., ApJ 1999

Abdo et al., Nature, 2009

Wagner, AIP Conf. Proc., 2009

Tavani et al., Nature, 2009



Abramowski et al. (H.E.S.S. Collab.), Astropart. Phys, 2011

Greiner et al., A&A 2009

Vasileiou et al., Phys.Rev D, 2013

Albert et al., (MAGIC Collab.) Phys. Lett. B, 2008

Ahnen et al., (MAGIC Collab.) 2017

- high energy astrophys. sources usually are at cosmological distances and this would allow a tiny effects to accumulate

strong enhencement of intrinsically weak LIV signals

observational status of LIV

lower bounds on QG energy scale (linear contribution)

[Ahnen et. al (MAGIC), 2017]

$E_{\mathrm{QG}_1} > 5.5 \cdot 10^{17}$ GeV $(4.5 \cdot 10^{17}$ GeV$)$

best limits

Crab pulsar (EGRET) [Philip Kaaret, (1999)]	$E_{QG} > 1.8 \times 10^{15}$ GeV
Mkn 421 (Whipple) [S.D. Biller et al., (1999)]	$E_{QG} > 6 \times 10^{16}$ GeV
Mkn 501 (MAGIC) [J. Albert et al., (2007)]	$E_{QG} > 0.17 \times 10^{18}$ GeV
Combined analysis of 35 GRBs (BATSE, HETE, and SWIFT) [John Ellis et al., (2006)]	$E_{QG} > 0.9 \times 10^{16}$ GeV
GRB 051221A (Swift-BAT and Konus-Wind) [M. Rodriguez Martinez, Tsvi Piran and Yonatan Oren, (2006)]	$E_{QG} \gtrsim 0.66 \times 10^{17}$ GeV

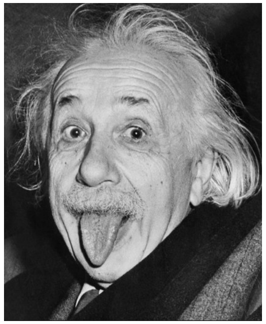
observational status of LIV

lower bounds on QG energy scale (linear contribution)

best limits

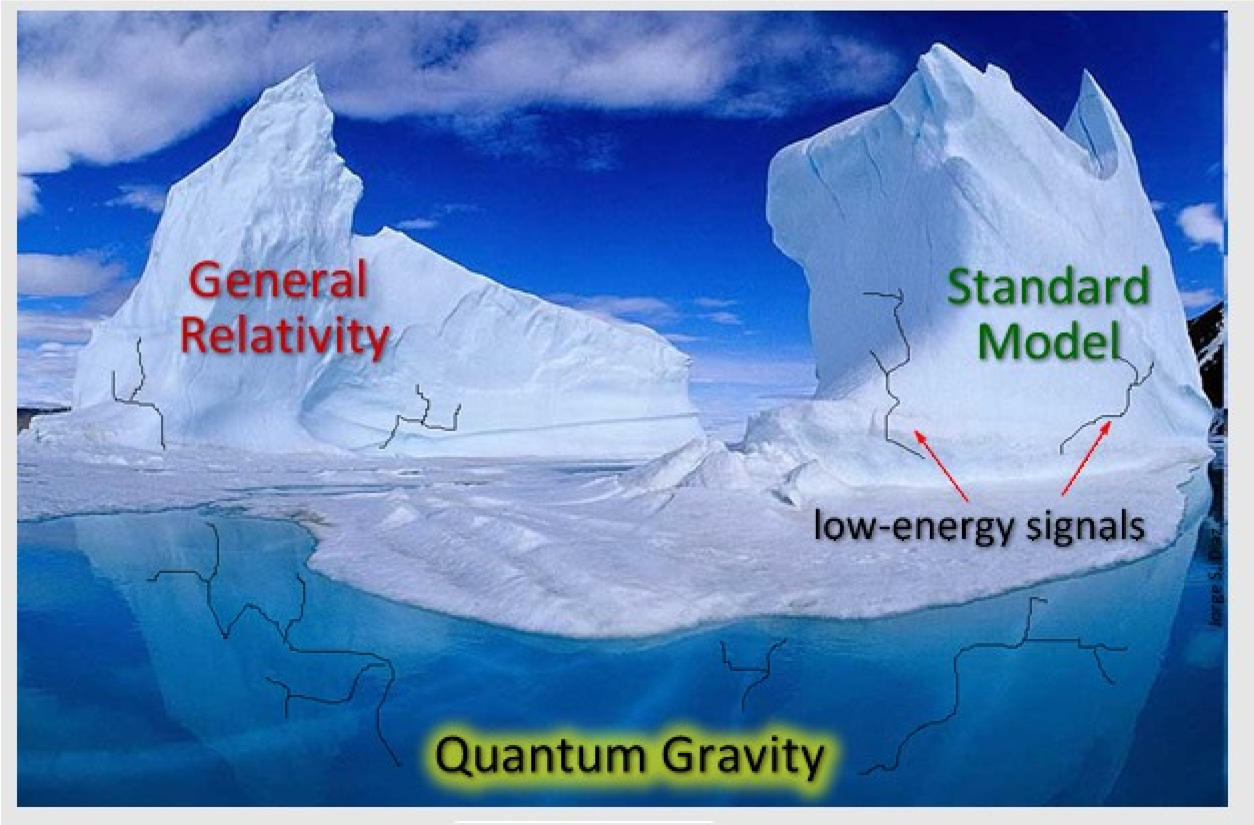
GRB 090510 (Fermi) [Vasileiou et al. (2013)]	$E_{\rm QG} > 7.6\ E_{\rm Pl}$
GRB 080916C (Fermi) [Abdo et al. (2009)]	$E_{\rm QG} > 1.5 \times 10^{18}$ GeV
PKS 2155 (H.E.S.S.) [Abramowski et al. (2011)]	$E_{\rm QG} > 2.1 \times 10^{18}$ GeV
Statistical analysis of 8 GRBs (Fermi) [Ellis et al. (2018)]	$E_{\rm QG} > 2.4$ to 8.4×10^{17} GeV

observational status of LIV



a sharp bounds on LIV parameters have been obtained,
finding no deviations from the standard physics

… but still there is a room for improvement, and in fact, many experimental groups continue to provide data with increasing precision …



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

https://www.serishirts.com/

Modified dispersion relation

- very useful framework for astrophysical test of LIV

one of the most important consequences of the theory of relativity:

relation between mass and energy

$$E^2 = m^2c^4 + \mathbf{p}^2c^2$$

Vucetich 2005

Mattingly, Living Rev. Rel., 2005

$\sim 10^{19}\mathrm{GeV}$

$$\boxed{E^2 = F(\mathbf{p}, m)}$$

any departure from its conventional form should be a clear signal of LIV:

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

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

Modified dispersion relation

- this approach may seem shallow (lack of dynamics and deeper analysis), but in its simplicity is very useful from the experimental point of view

- specific structure of the deformation can differ from model to model, but typically QG leading-order pieces of more complicated analytic structure should be of the form:

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

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

thus, low-energy modified dispersion relation is:

$$\boxed{E^2 = p^2c^2 + m^2c^4 + \eta_1 E^2 (\frac{E}{E_{Pl}}) + \eta_2 E^2 (\frac{E}{E_{Pl}})^2 + \ldots .}$$

time delay technique for LIV testing

- LIV induced time delays

MDR for any massive particle from distant cosmological source:

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

$$H = \sqrt{(p^2c^2 + m^2c^4)\left[1 + \epsilon \left(\frac{E}{\xi_n E_{QG}}\right)^n\right]}$$

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

ξ_n is a dimensionless parameter

$$\xi_1 = 1$$

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

because of the expansion of the Universe,
particle's momentum and energy should be rescaled:

Rodriguez Martinez & Tsvi Piran, JCAP, 2006

Jacob &Piran, Nature Phys., 2007

$$p = p(t) \longrightarrow p(t) = \frac{p(t_0)}{a(t)}$$

$$E = E(t) \longrightarrow E(t) = \frac{E(t_0)}{a(t)}$$

time delay technique for LIV testing

time dependent velocity is: $v(t) = \frac{\partial H}{\partial p}$

$$H = \sqrt{(p^2c^2 + m^2c^4)\,[1 + \epsilon \left(\frac{E}{\xi_n E_{QG}}\right)^n]}$$

$$v\,(t) \simeq \frac{c}{a(t)}[1 - \frac{1}{2}\frac{m^2c^4}{E_0^2}a^2(t) + \frac{1}{2}(n+1)\epsilon\left(\frac{E_0}{\xi_n E_{QG}}\right)^n \frac{1}{a^n(t)}]$$

comoving distance travelled by particle from a source to the Earth is:

$$r(t) = \int_{t_{emission}}^{t_0} v(t)dt \xrightarrow[a(t) = \frac{1}{1+z}]{} r(z) = \int_0^z v(z)\frac{dz}{H(z)(1+z)}$$

(comoving distance measured in light years)

time of flight from cosmological source to the Earth is then

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

time delay technique for LIV testing

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

well-known time of flight for photons

implies time delay due to particle's mass

implies time delay due to LIV effects

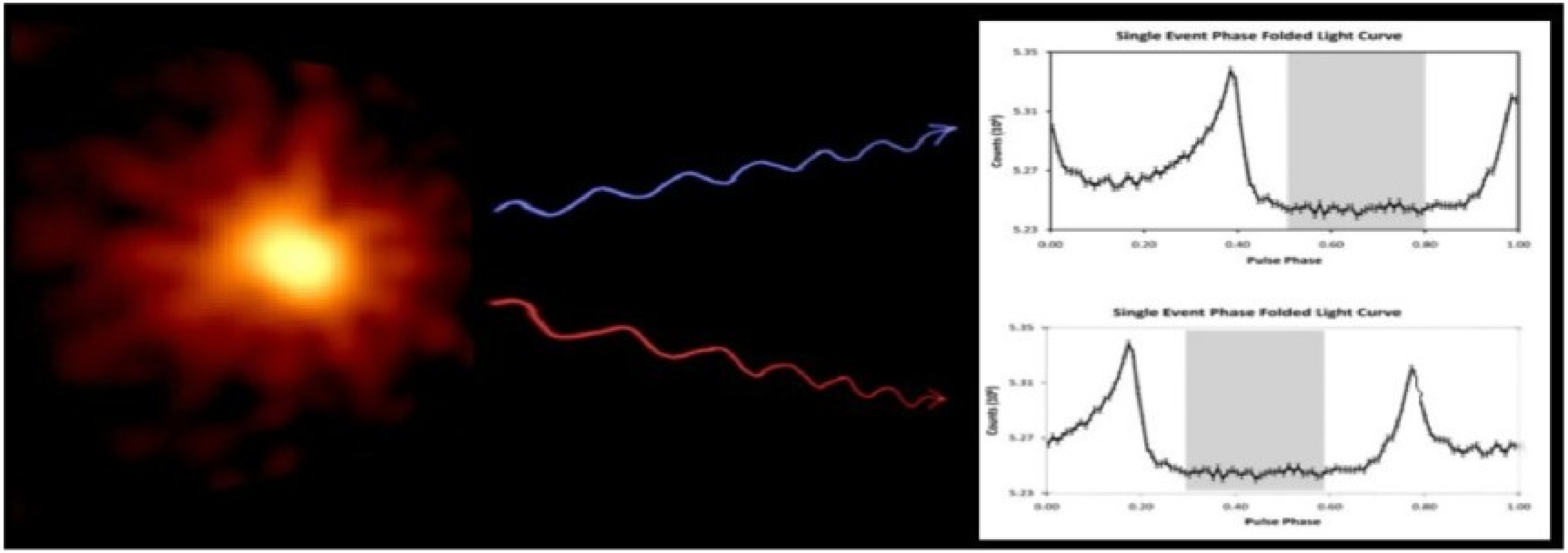
$$\boxed{\Delta t = \int_0^z [\underbrace{\frac{m^2c^4}{2E_0}\frac{1}{(1+z)^2}}_{\text{for photons mass term vanishes}} \underbrace{- \epsilon\frac{n+1}{2}\left(\frac{E_0}{\xi_n E_{QG}}\right)^n (1+z)^n]}_{\text{LIV term}}\frac{dz}{H(z)}}$$

IDEA:

searching for time delay by comparison between the arrival times of photons from distant, transient sources in different energy bands

time delay technique for LIV testing

Simple experimental setting for LIV testing:



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

$n = 1$ term

$\epsilon = +1$

fine-scale time structure

milliseconds or better

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

Amelino-Camelia et al.
Nature, 1998

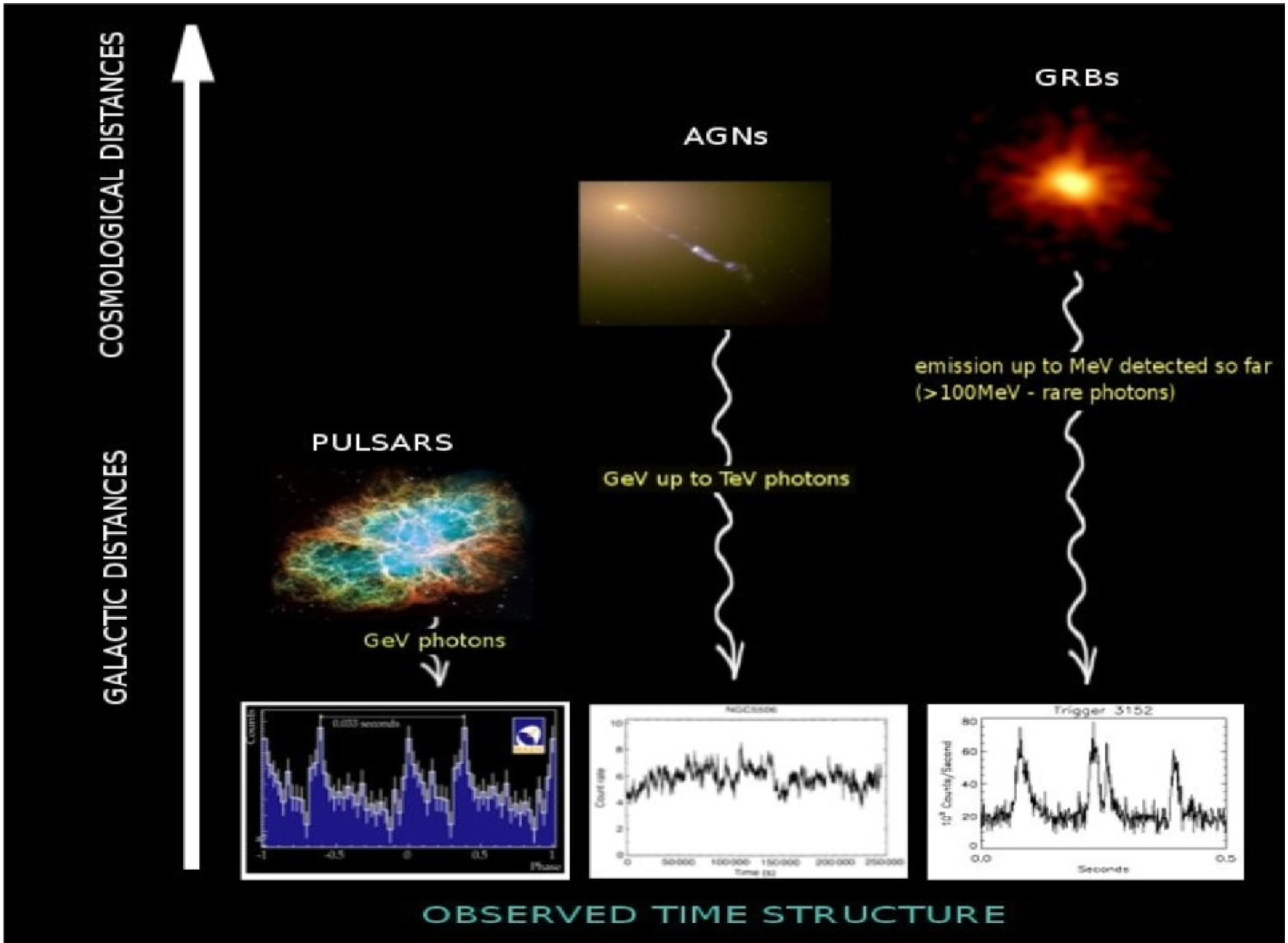
high-energy spectrum

20 MeV and more

cosmological distances

time delay technique for LIV testing

… but nature offers us fairly good astrophysical tools:



time delay technique for LIV testing

- Challenges:

1. HIGHER ENERGIES

The problem of pair production:	photons with energies above 10 TeV (like this from Mkn 501 BL Lac object) should have been annihilated with CMBR background photons via pair production.

2. BETTER TEMPORAL RESOLUTION

Intrinsic time lags problem:	how to distinguish LIV effects from any intrinsic (source) delay?

3. MORE DISTANT SOURCES

Cosmological impact problem:	does cosmological model matter for time delay analysis?

time delay technique for LIV testing

1. HIGHER ENERGIES

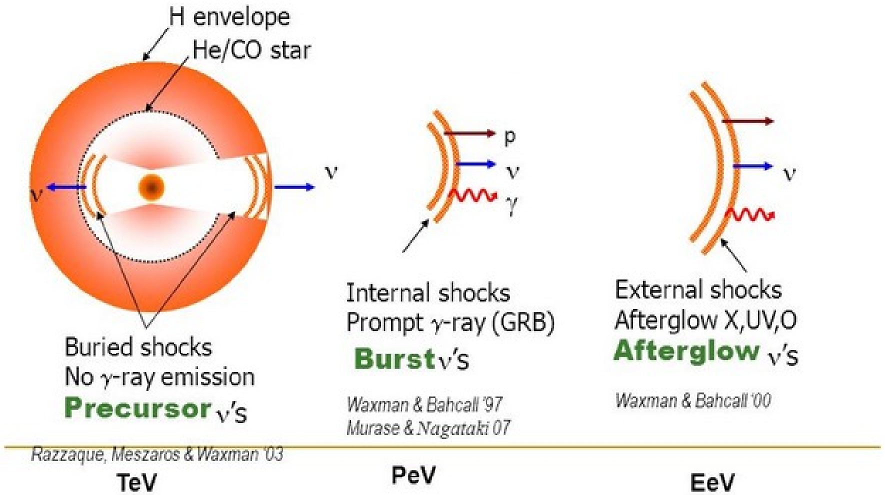
The problem of pair production: photons with energies above 10 TeV (like this from Mkn 501 BL Lac object) should have been annihilated with CMBR background photons via pair production.

SOLUTION:

one can use very high energy (100 TeV up to 10 000 TeV) neutrinos from GRB's instead of photons

Jacob & Piran, Nature Phys. 2007

Biesiada & Piórkowska, JCAP 2007



Xiang-Yu Wang talk on Liverpool GRB meeting, 2012

EXTRA PROFIT:

- energies of such neutrinos are order of magnitude higher than GRB's photons
- neutrino detectors like Ice Cube are extremely quiet in this energy range

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

Aartsen et al. (IceCube Collab.) 2017

time delay technique for LIV testing

3. MORE DISTANT SOURCES

Cosmological impact problem: does cosmological model matter for time delay analysis?

Cosmology is inherently built into the Hubble function H(z)

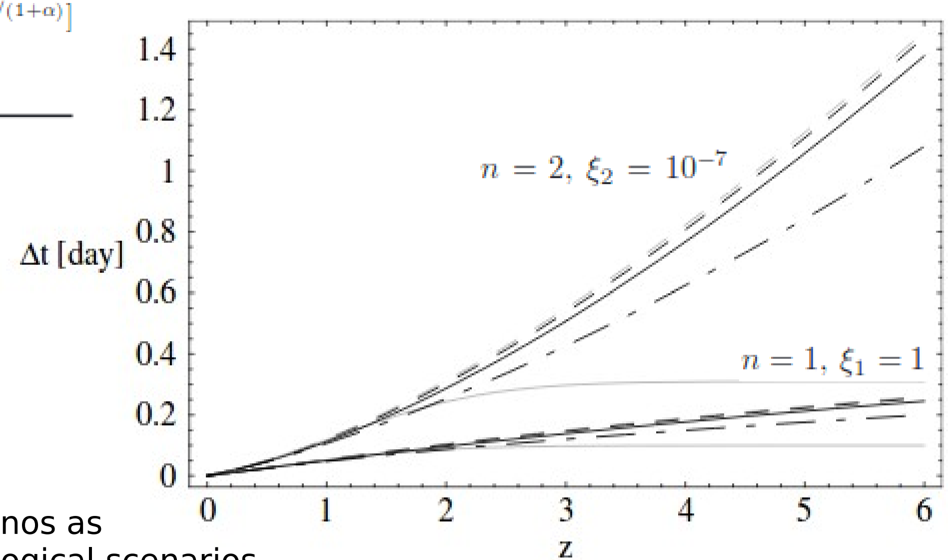
$$\Delta t = \int_0^z \left[\frac{m^2c^4}{2E_0}\frac{1}{(1+z)^2} - \epsilon\frac{n+1}{2}\left(\frac{E_0}{\xi_n E_{QG}}\right)^n (1+z)^n\right]\frac{dz}{H(z)}$$

Model	$H^2(z)$
ΛCDM	$\Omega_m = 0.3,\ \Omega_\Lambda = 0.7$
Quint.	$w = -0.87$
Var. Quint.	$w_0 = -1.5$ and $w_1 = 2.1$
Chap. Gas	$\alpha = 1$ and $A_0 = 0.83$
Brane	$r_c = 1.4H_0^{-1}$ and $\Omega_{r_c} = \frac{1}{4}(1-\Omega_m)^2$

Model	Cosmological expansion rate $H(z)$ (the Hubble function)
ΛCDM	$H^2(z) = H_0^2[\Omega_m\,(1+z)^3 + \Omega_\Lambda]$
Quintessence	$H^2(z) = H_0^2[\Omega_m\,(1+z)^3 + \Omega_Q\,(1+z)^{3(1+w)}]$
Var quintessence	$H^2(z) = H_0^2[\Omega_m\,(1+z)^3 + \Omega_Q\,(1+z)^{3(1+w_0-w_1)}\,\exp(3w_1 z)]$
Chaplygin gas	$H(z)^2 = H_0^2[\Omega_m(1+z)^3 + \Omega_{Ch}(A_0 + (1-A_0)(1+z)^{3(1+\alpha)})^{1/(1+\alpha)}]$
Brane-world	$H(z)^2 = H_0^2\left[\left(\sqrt{\Omega_m(1+z)^3 + \Omega_{r_c}} + \sqrt{\Omega_{r_c}}\right)^2\right]$

our ignorance concerning cosmological models creates systematic effects!

Biesiada & Piórkowska, JCAP 2007



observed time delays for 100 TeV neutrinos as a function of redshift in different cosmological scenarios

time delay technique for LIV testing

2. BETTER TEMPORAL RESOLUTION

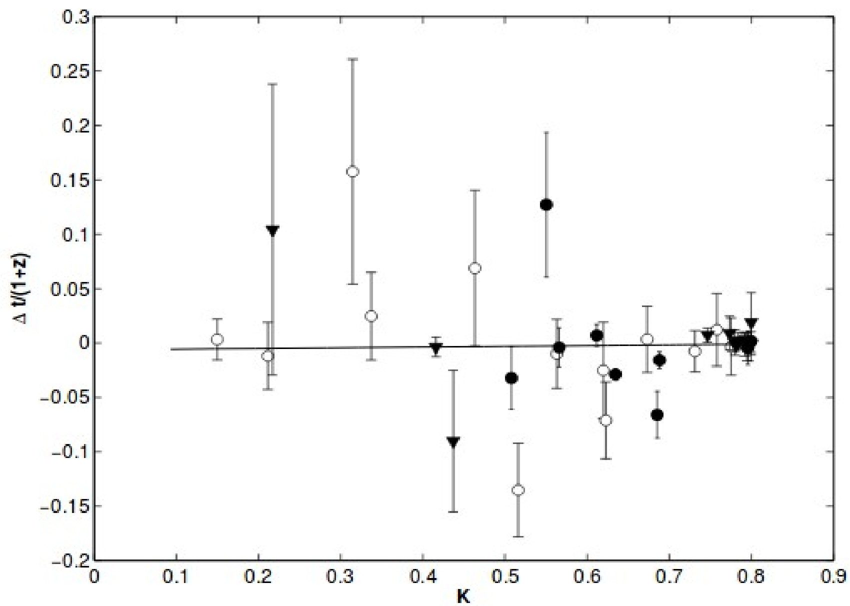
Intrinsic time lags problem:	how to distinguish LIV effects from any intrinsic (source) delay?

SOLUTION:

I. Statistical analysis of a sample of sources with known distance distribution

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

linear fit with assumption of **ΛCDM**



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

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

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

Ellis et al. Astropart.Phys. 2006

Ellis et al. A&A 2003

analysis for different cosmological scenarios:

Biesiada & Piórkowska, Class.Quant.Grav. 2009

time delay technique for LIV testing

II. Observe $\boxed{\text{time delays between lensed images in different energy channels}}$

MONTHLY NOTICES
of the Royal Astronomical Society

Gravitational lensing time delays as a tool for testing Lorentz-invariance violation FREE

Marek Biesiada, Aleksandra Piórkowska

Monthly Notices of the Royal Astronomical Society, Volume 396, Issue 2, 21 June 2009, Pages 946–950, https://doi.org/10.1111/j.1365-2966.2009.14748.x
Published: 10 June 2009 **Article history** ▾

$$\psi_{2D} = \frac{D_{LS}}{D_S} \int_{observer}^{source} \frac{2\Phi_{3D}}{c^2} \frac{d\ell}{D_L}$$

'time delay surface'

$$t(\boldsymbol{\theta};\boldsymbol{\beta}) = \underbrace{\frac{1+z_L}{c}\frac{D_L D_S}{D_{LS}}}_{t_{geom}} \left[\frac{1}{2}(\vec{\theta}-\vec{\beta})^2 - \psi_{2D}(\vec{\theta})\right]$$

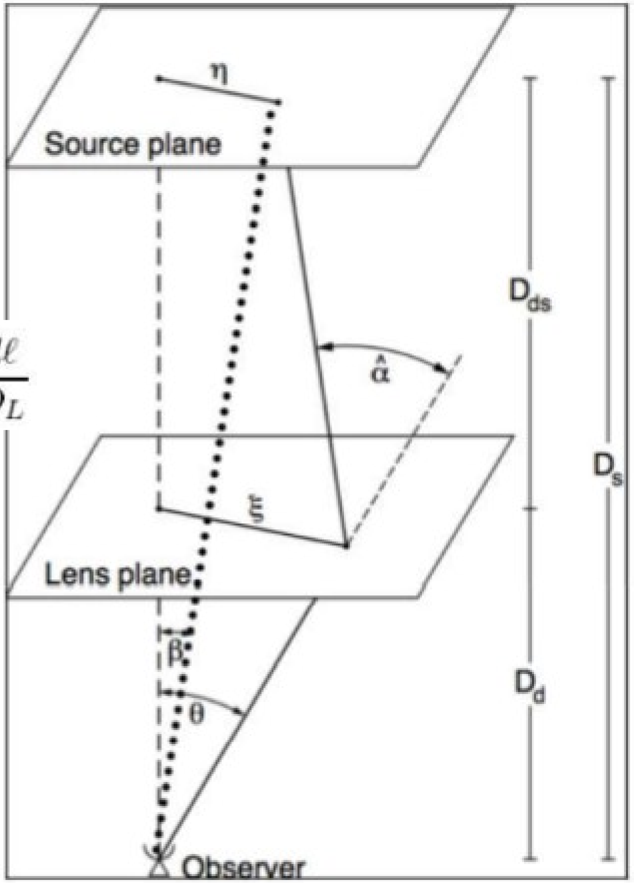
t_{grav}

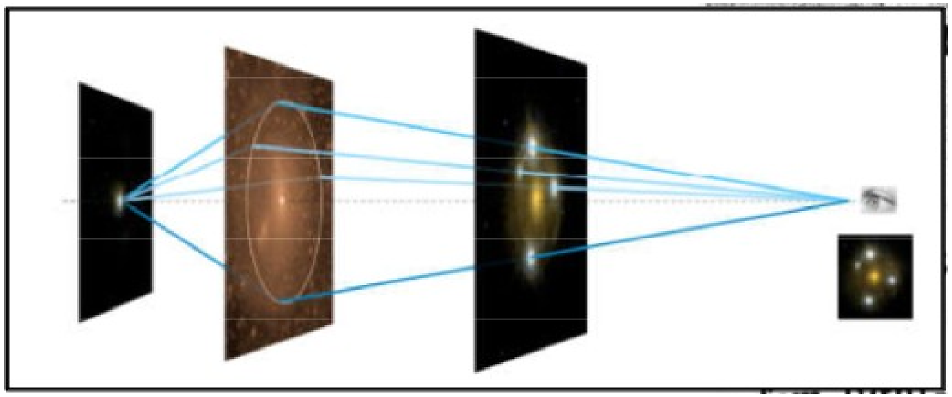
Fermat potential

$\tau(\boldsymbol{\theta};\boldsymbol{\beta})$

geometric part
(due to bending light rays)

Shapiro effect
(gravitational field)





Fermat principle: $\nabla\tau(\boldsymbol{\theta};\boldsymbol{\beta}) = 0$

extrema of time delay surface

$$\vec{\theta} - \vec{\beta} - \frac{\partial\psi_{2D}}{\partial\vec{\theta}} = 0$$

lensing equation

time delay technique for LIV testing

II. Observe time delays between lensed images in different energy channels

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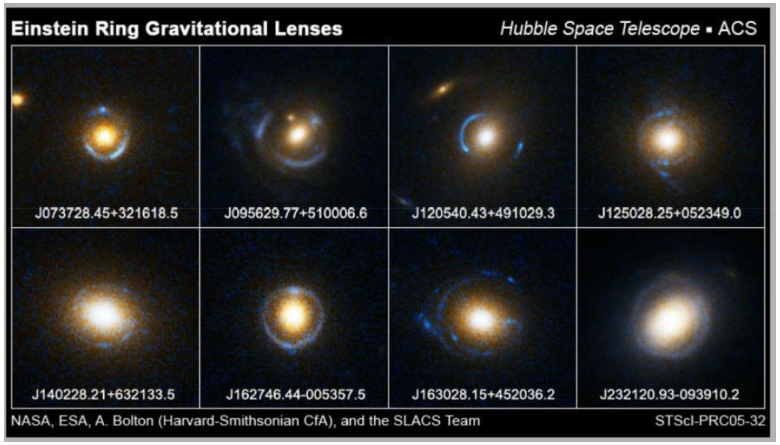
For SIS model of the lens potential:

the simplest realistic case

majority of cases the lens is a late-type E/SO galaxy

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

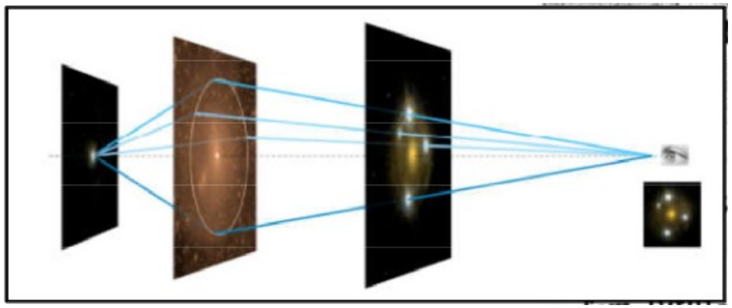


time delay between images in SIS model

$$\boxed{\Delta t_{SIS} = \frac{2(1+z_l)}{c} \frac{D_l D_s}{D_{ls}} \vartheta_E \beta}$$

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

Einstein radius
characterisctic angular scale of each lens



ACHROMATIC in well known lorentz invariant physics

time delay technique for LIV testing

II. Observe $\boxed{\text{time delays between lensed images in different energy channels}}$

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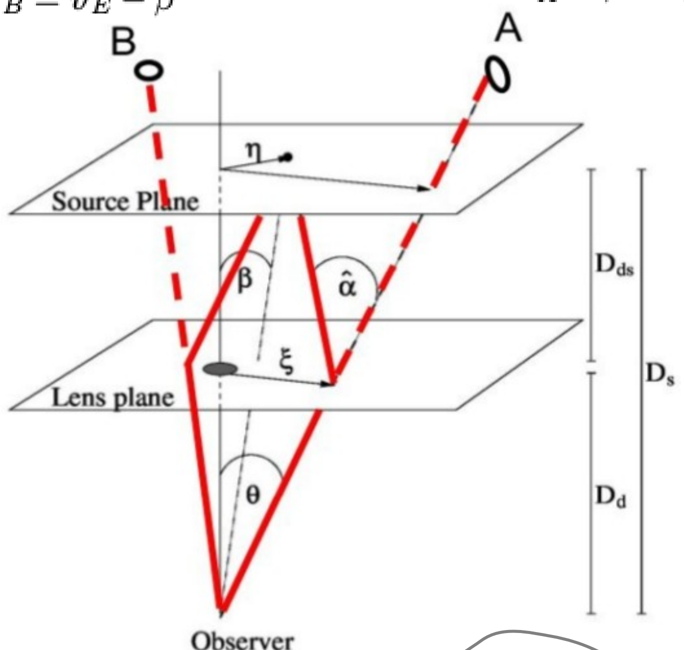
$\vartheta_B = \vartheta_E - \beta$ $\vartheta_A = \beta + \vartheta_E$



[Schneider et al. 2006]

$\beta < \vartheta_E$
lensing is strong

reduced comoving distance to lens $\boxed{\int_0^z \frac{dz'}{h(z';\mathbf{p})}}$

$$\Delta t_{SIS} = \frac{2(1+z_l)}{c}\frac{D_l D_s}{D_{ls}}\vartheta_E \beta = \frac{8\pi}{H_0}\tilde{r}_l \beta \frac{\sigma^2}{c^2}$$

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

LIV

$$\Delta t_{LIV,SIS} = \frac{8\pi}{H_0}\tilde{r}_{LIV}(z_l)\beta\frac{\sigma^2}{c^2}$$

$$\boxed{\tilde{r}_{LIV}(z_l) = \tilde{r}_l + H_0 \frac{E}{E_{QG}} \int_0^{z_l} \frac{(1+z')dz'}{H(z')}}$$

with LIV time delay is **no longer achromatic !!!**

$$\boxed{\Delta t_{LIV,SIS} - \Delta t_{SIS} = \frac{8\pi}{H_0}\beta\frac{\sigma^2}{c^2}\frac{E}{E_{QG}}\int_0^{z}\frac{(1+z')dz'}{H(z')}}$$

time delay technique for LIV testing

II. Observe $\boxed{\text{time delays between lensed images in different energy channels}}$

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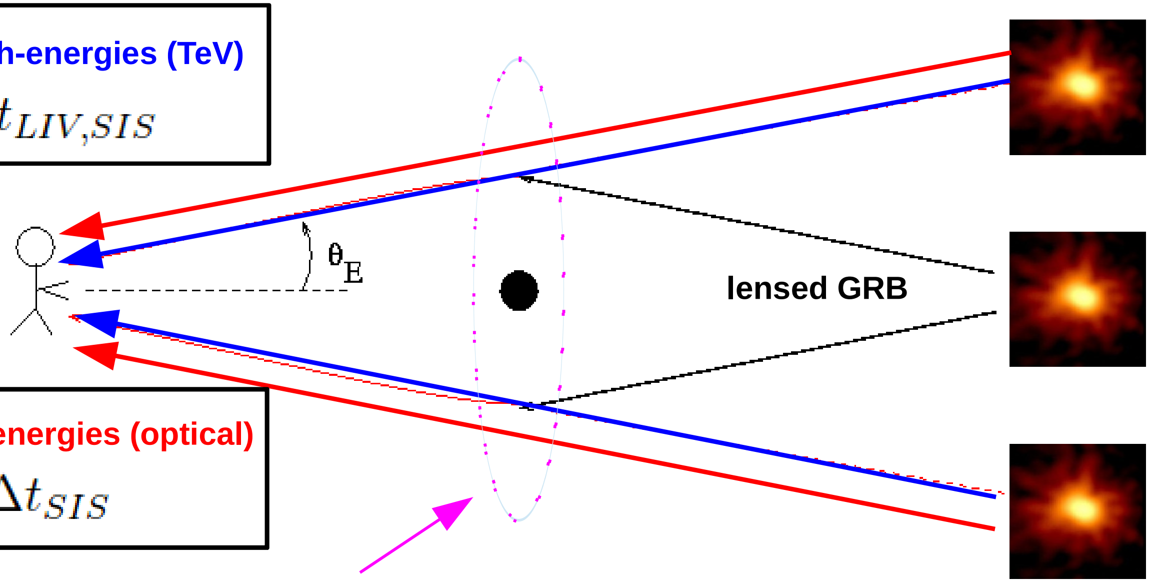
experimental setting:

$$\Delta t_{LIV,SIS} - \Delta t_{SIS} = \frac{8\pi}{H_0}\beta\frac{\sigma^2}{c^2}\frac{E}{E_{QG}}\int_0^z \frac{(1+z')dz'}{H(z')}$$

in LIV high energy photons should come at different times comparing with low energy ones

in high-energies (TeV)

$\Delta t_{LIV,SIS}$



in low-energies (optical)

Δt_{SIS}

method is
differential in nature

- it **gets rid of the assumptions about intrinsic time delays** of signals at different energies

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

time delay technique for LIV testing

II. Observe time delays between lensed images in different energy channels

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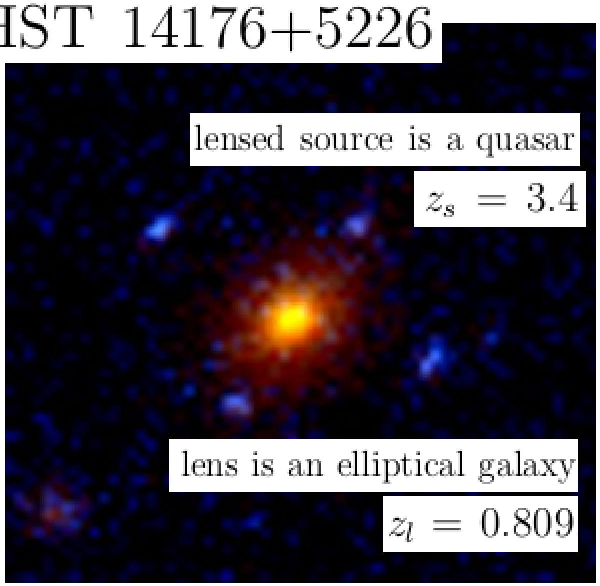
$$\Delta t_{LIV,SIS} - \Delta t_{SIS} = \frac{8\pi}{H_0}\beta\frac{\sigma^2}{c^2}\frac{E}{E_{QG}}\int_0^z \frac{(1+z')dz'}{H(z')}$$

- $3.7 \times 10^{-9}\ s$ for $5\ TeV$ photons
- $1.5 \times 10^{-8}\ s$ for $20\ TeV$ photons

HST 14176+5226



Colours & filters

Band	Wavelength	Telescope
Infrared I	814 nm	Hubble Space Telescope WFPC2
Optical V	606 nm	Hubble Space Telescope WFPC2

Ratnatunga et al., Astrophys. J. 1995

Crampton et al., A&A 1996

SIE model:

$$\theta_E = 1''.489$$

$$\beta = 0''.13 = 8.4 \times 10^{-7}\ rad$$

Ratnatunga et al., Astron. J. 1999

spectroscopy:

$$\sigma = 290 \pm 8\ km/s.$$

Ohyama et al., Astron.J. 2002

Treu & Koopmans, Astrophys. J. 2004

HST 14176+5226 is the first, and brightest lens system discovered in 1995 with the Hubble telescope. This lens candidate has now been confirmed spectroscopically using large ground-based telescopes. The elliptical lensing galaxy is located 7 billion light-years away, and the lensed quasar is about 11 billion light-years distant.

Credit: Kavan Ratnatunga (Carnegie Mellon Univ.) and NASA/ESA

time delay technique for LIV testing

II. Observe $\boxed{\text{time delays between lensed images in different energy channels}}$

one may ask if appropriate lensing systems exist ...

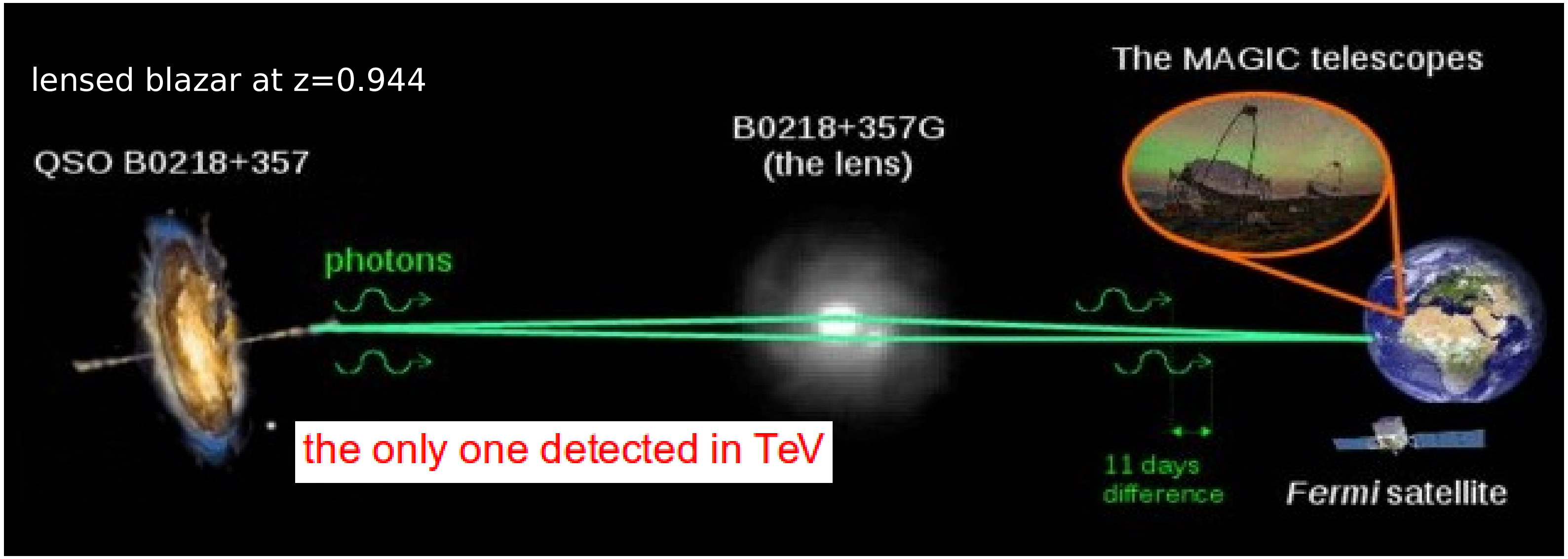
sources emitting both low and high energy photons

... quasars are in fact the sources in almost all known strong lensing systems

it is a matter of coordinating strong lensing surveys
with experiments in high energy astrophysics:

QSO B0218+357

a violent flare observed by the *Fermi*-LAT and followed by the MAGIC telescopes



Cheung et al., ApJL 2014

Ahnen et al. (MAGIC Collab.), A&A 2016

the farest object detected in TeV   observed emission spans the energy range from 65 to 175 GeV.

time delay technique for LIV testing

II. Observe time delays between lensed images in different energy channels

what about strong lensed GRBs?

Refsdal Supernovae

11.11.2014

Kelly et al., Science 2015

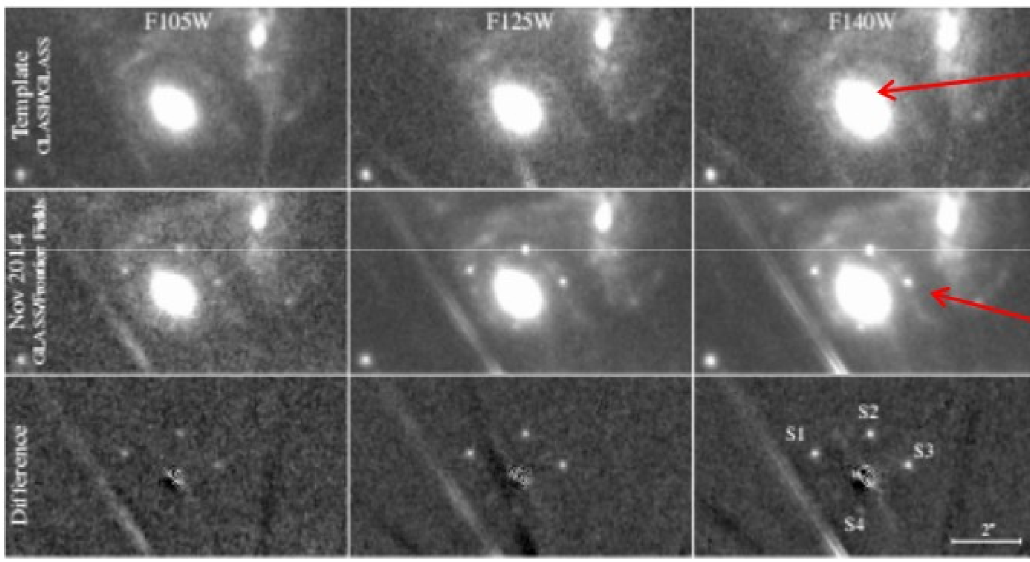
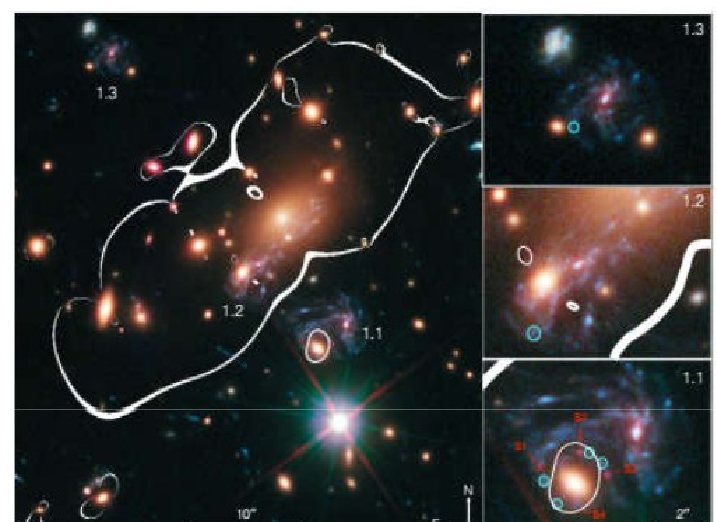


Fig. 1: *HST* WFC3-IR images showing the simultaneous appearance of four point sources around a cluster member galaxy. From left to right the columns show imaging in the *F105W* filter (*Y* band), *F125W* (*J*), and *F140W* (*JH*). From top to bottom the

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

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

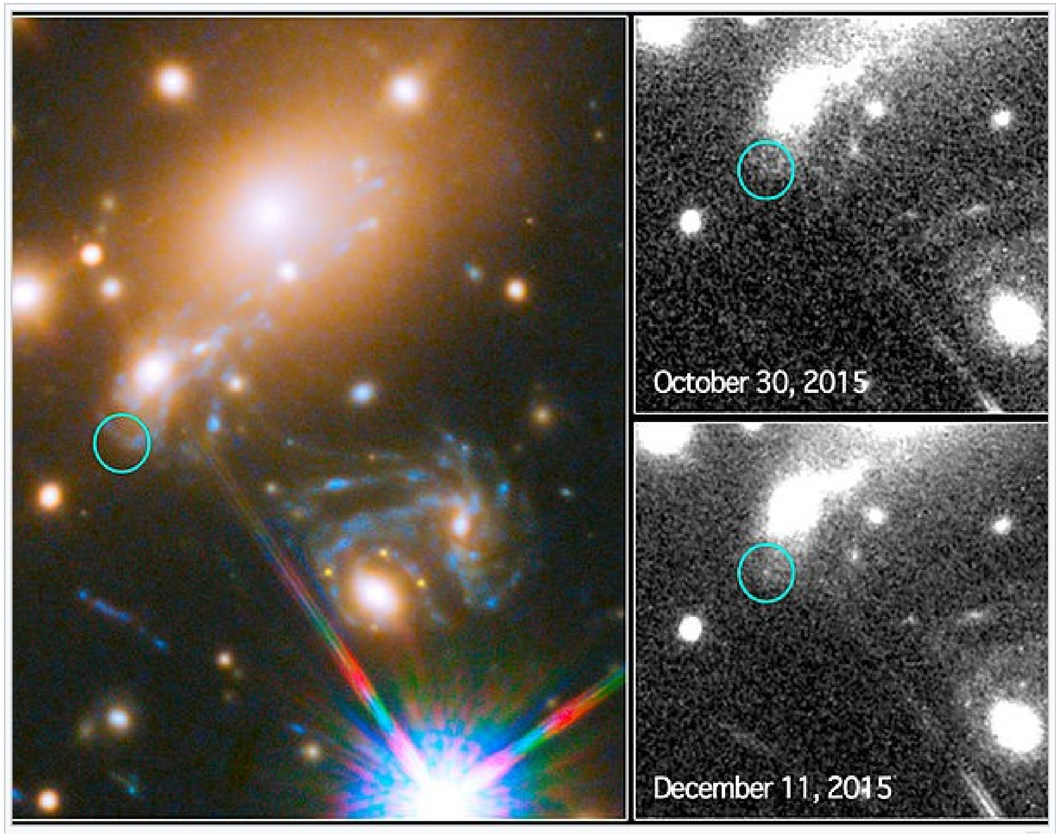
SNII reappearance predicted in about one year
in one of lensed images of host galaxy



time delay technique for LIV testing

II. Observe $\boxed{\text{time delays between lensed images in different energy channels}}$

what about strong lensed GRBs?



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

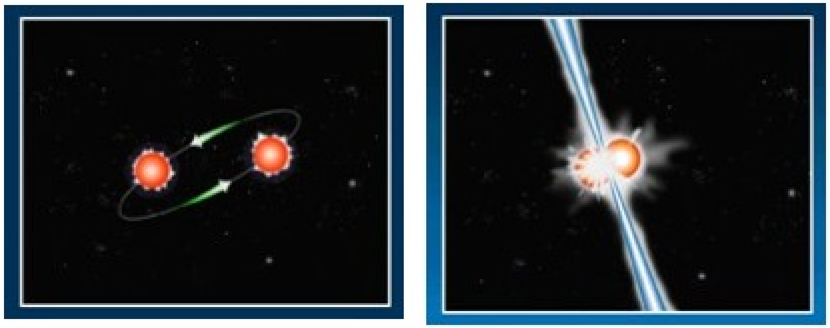
Reappearance of Refsdal SN

11.12.2015

Kelly et al., ApJL 2016

we are starting discover transient events lensed by a cluster !

NS-NS mergers

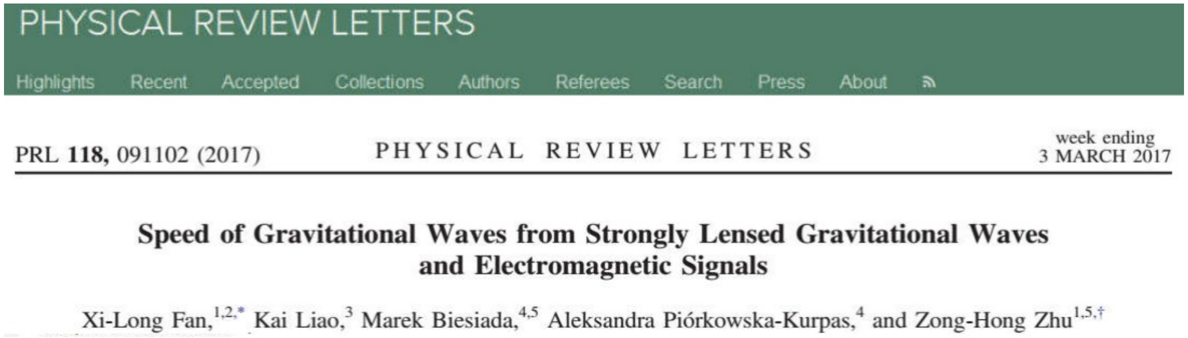


Rotation -> collimation of the ejecta

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

time delay technique for LIV testing

II. Observe time delays between lensed images **for two independent signals: GW + EM**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PRL **118,** 091102 (2017) PHYSICAL REVIEW LETTERS week ending 3 MARCH 2017

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

Xi-Long Fan,[1,2,*] Kai Liao,[3] Marek Biesiada,[4,5] Aleksandra Piórkowska-Kurpas,[4] and Zong-Hong Zhu[1,5,†]

a method to
directly constrain the speed of GW

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

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

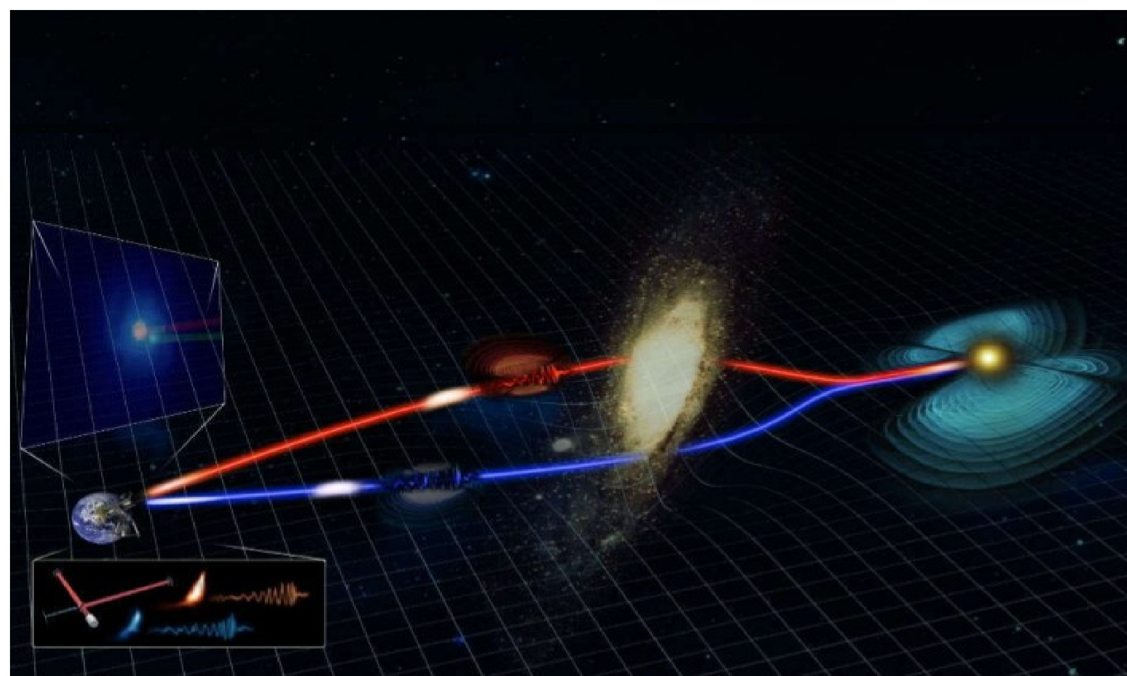
$$1 - \left(\frac{v_{GW}}{c}\right)^2 \leq \frac{\delta T}{\Delta t_\gamma F_{\mathrm{lens}}(z_l, z_s)}$$

δT is timing accuracy

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

---

the difference between gravitational lensing time delays
measured independently in GW detectors and EM window



perspectives for observing strongly lensed GWs from merging DCOs:

~2-10/yr NS-NS, NS-BH

Biesiada et al. JCAP 2014

Ding et al. JCAP 2015

time delay technique for LIV testing

II. Observe $\boxed{\text{time delays between lensed images } \textbf{for two independent signals: GW + EM}}$

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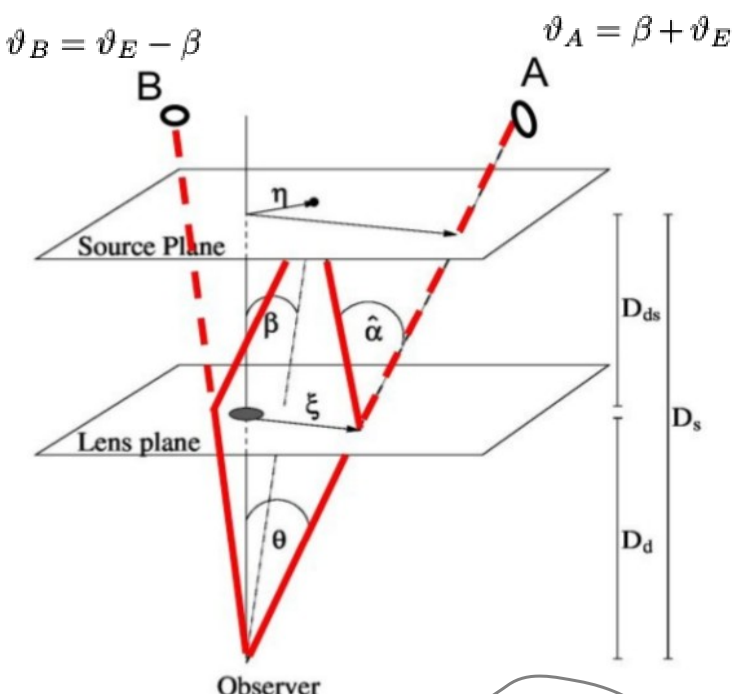

[Schneider et al. 2006]

$\beta < \vartheta_E$
lensing is strong

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

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

Lowenthal, PRD, 1973

$$\Delta t_{SIS} = \frac{1+z_l}{2c}\frac{D_l D_s}{D_{ls}}(\vartheta_A^2 - \vartheta_B^2)$$

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

$y = \beta/\vartheta_E$

source-lens misalignment

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

the difference between image time delays observed in GW detectors and in the EM domain is

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

time delay technique for LIV testing

II. Observe $\boxed{\text{time delays between lensed images } \textbf{for two independent signals: GW + EM}}$

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propagation of **massive gravitons**:

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

$$\boxed{p_r = a^2 p^r}$$

assumption:

GW travel along radial geodesics in flat FRW model

velocity of gravitons is

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

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

for photons:

$$E_\gamma^2 - p_\gamma^2 c^2 = 0$$

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

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

usual comoving distance to the GW source

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

$$a(t) = \frac{1}{1+z}$$

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

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

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the travel distance of GW

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

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

$$p_r = a(t_e)\frac{E}{c}$$

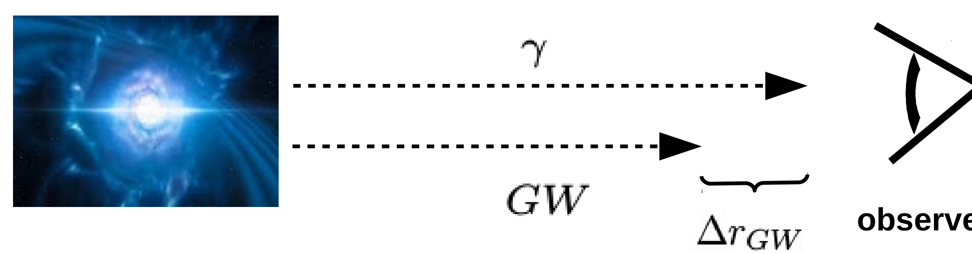
$$\int_{t_{emission}}^{t_0} a\ dt \xrightarrow[a(t)=\frac{1}{1+z}]{} \int_0^z \frac{dz}{H(z)(1+z)^2}$$

$$H(z) = H_0 h(z)$$

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

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

The above formulae should be understood in the following way: if the emission time t_e and detection time t_0 are fixed, i.e. the same for the GW and electromagnetic sources then the GW source is by Δr_{GW} closer than electromagnetic source. On the other hand if they are emitting from the same location the GW signal would come by $\Delta t_{GW} = \Delta r_{GW}/c$ later than electromagnetic counterpart. In other words, travel time for GW would be by Δt_{GW} longer, as if the source was located by Δr_{GW} farther.



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we specify the speed of GW using the information from the lensed GW-EM system:

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

the accuracy of time delay measurements sets constraints on the v_{GW}

If one would be able to measure such a difference in time delays this would also be a proof that gravitons are massive (i.e. that GR needs to be modified).

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

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

with assumed ΛCDM cosmology:

$$H_0 = 68\ km\ s^{-1}\ Mpc^{-1},$$

$$\Omega_m = 0.3$$

- taking the value of time delay for the Refsdal SN image SX (reappeared as predicted one):

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

assuming $1ms$ timing accuracy.

- strong lensing of transient source seen both in EM and GW offers additional possibility to compare the moments of arrival of the same image seen in the EM and GW respectively:

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

a bit of philosophy once again ...

the end of XIX century:

- why are the stars shining?
- Universe is static and eternal
- Milky Way = the entire Universe
- what causes the radioactivity of chemical elements?
- what is the smallest component of matter?

STR

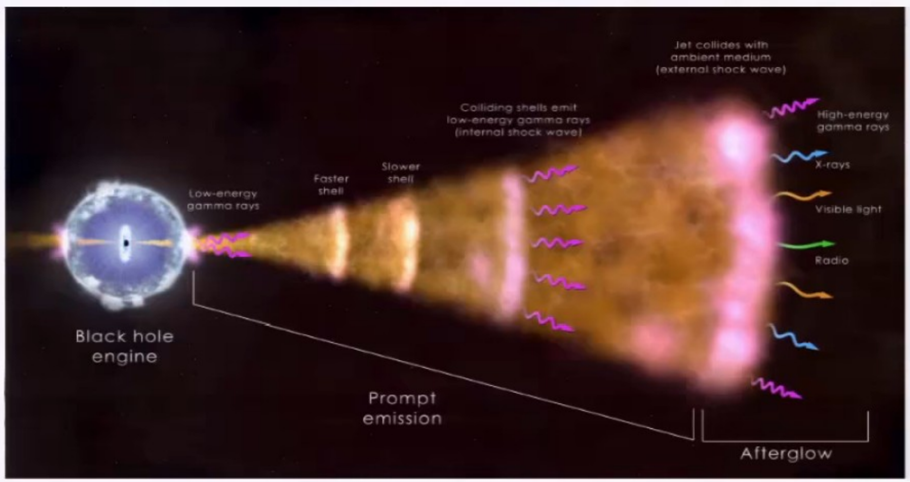
now:

- a consistent model of stellar structure and evolution
- relativistic model of the expanding Universe with flat spatial geometry
- a consistent model of nucleosynthesis in the universe (primordial + stellar)
- a consistent model of large scale structure in the Universe
- a consistent model of elementary particles

spectacular development of particle physics, astrophysics and cosmology as an empirical sciences

a bit of philosophy once again ...

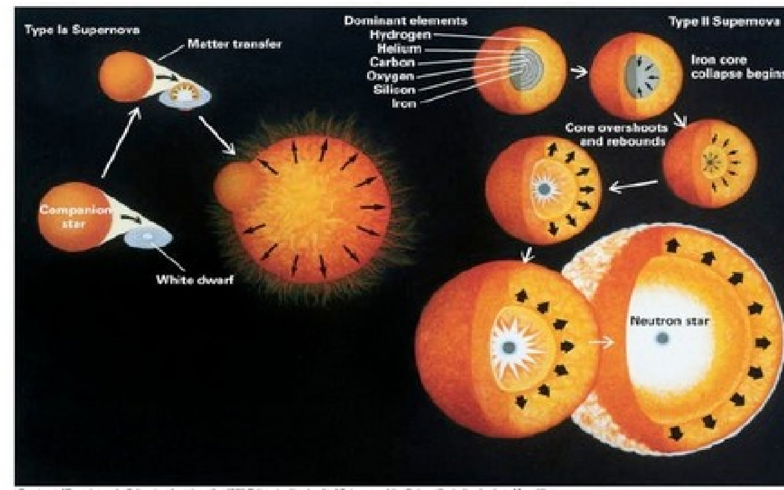
in particular: fundamental physics has contributed to our understanding of the nature of distant astrophysical objects, e.g.:



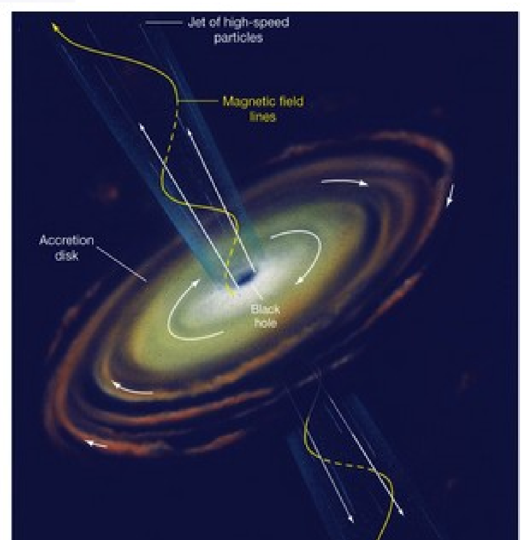
artist's conception (NASA)

GRBs

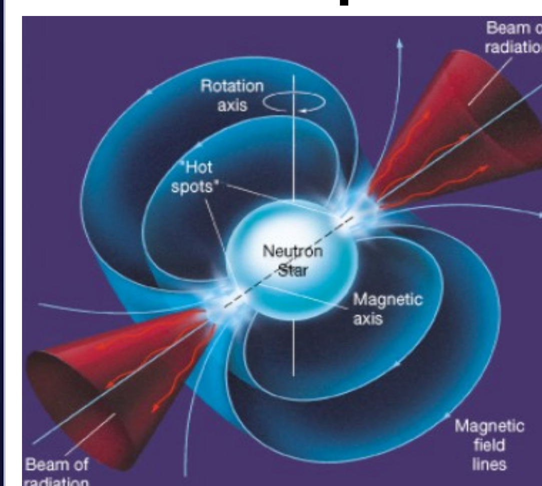
SNs



AGNs



pulsars



compact binary mergers

a bit of philosophy once again ...

and now, such extra-galactic sources
starts to reveal its potential to allow us to
understand nature better at its fundamental level

SnowCrystals.com

thank you for your attention!