testing
Lorentz Invariance Violation
in VHE $\gamma$-rays

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Facts which at first seem improbable will, even on scant explanation, drop the cloak which has hidden them and stand forth in naked and simple beauty.

Galileo Galilei
VHE (E>10GeV) photons are best detected with Imaging Atmospheric Cherenkov Telescopes

VHE particle enters atmosphere

Interactions lead to an Extensive Air Shower
Which causes Cherenkov radiation

Multiple telescopes:
- improve angular resolution
- improve energy resolution
- reduce background

* not to scale
The Cherenkov Telescope Array

A factor 10 more sensitive than current instruments
+ much wider energy coverage, substantially better angular and energy resolution &
  wider field of view, and full sky coverage from two sites

A ~€200M international project
~1000 scientists in >120 institutes spread over 27 countries (EU, US, Japan, India, Brazil,...)

Construction due to start 2016 and science verification phase observations from 2018.

Low energy section
energy threshold 20-30GeV
4xLST - 23m telescopes

Medium energy section
mCrab sensitivity 100GeV-10TeV
~25 MSTs - 12m telescopes

High energy section
10km² collection area at multi-TeV
40-70 SSTs - 4m telescopes
Goal CTA Sensitivity

exploring the cut-off regime of cosmic accelerators...

CTA

high z AGN, pulsars

MAGIC-I

10% Crab

Fermi

1% Crab

Crab

population studies, extended sources, precision measurements

NOW2014 - Otranto - 09/09/2014
Lorentz invariance violation

Motivation: The assumption of Lorentz invariance is one of the founding principles of modern physics and violation of that would have profound implications to our understanding of the universe. The theoretical unification of quantum mechanics, that governs the smallest scales, and gravity, governing the largest scales, is one of the most serious challenges in modern physics.

As Quantum Gravity is only expected to manifest at extremely high energies (likely the Planck scale $E_{Pl} \sim 10^{19}$ GeV) it makes it difficult to assess directly in the laboratory.

There are a number of theories that predict QG would lead to an effective refractive index of the vacuum (eg loop quantum gravity, space-time foam,...) leading to an energy dependent dispersion. The exact form of the energy dependent photon momentum will vary according to the theory adopted, but given the effect is very small at accessible energies it can be treated perturbatively leading to a form like

$$c^2 p^2 = E_g^2 \left[ 1 \pm \xi_1 E_g / E_{QG} \pm \xi_2 \left( E_g^2 / E_{QG}^2 \right) \pm \ldots \right]$$

The small scale effects are cumulative and so can become noticeable to sensitive measurements when the photons have travelled astronomical distances ($L$).

$$\delta t \simeq \left( \frac{\Delta E}{\xi \alpha E_{Pl}} \right)^\alpha \frac{L}{c}$$

To first order, the magnitude of the time delays expected from QG variations of $c$ are $\delta t \sim 10s/TeV/Gpc$ for Planck scale QG.

Galileo Galilei

Infinities and indivisibles transcend our finite understanding, the former on account of their magnitude, the latter because of their smallness; Imagine what they are when combined.
Why LIV? space-time effects under quantum gravity

On the large scale a road is smooth, but zoom in and you feel the roughness of the asphalt.

Quantum fluctuations could similarly introduce small structure to the vacuum

If the wheels (ie wavelength) are large compared to the roughness you don't notice the bumps much (but there is still the coefficient of friction of course ;-)

Probing small features best done with small wavelengths: smallest wavelengths = very highest energies
**Lorentz invariance violation**

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$$c^2 p^2 = E_y^2 \left[ 1 \pm \xi_1 \frac{E_y}{E_{QG}} \pm \xi_2 \left( \frac{E_y^2}{E_{QG}^2} \right) \pm \ldots \right]$$

The small scale effects are **cumulative** and so can become noticeable to sensitive measurements when the photons have travelled **astronomical distances** ($L$).

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**Greatest sensitivity when sources have**

- **fast** variability
- **high energy** component
- **large distance** for photons to travel

(nb often mutually exclusive, eg EBL attenuates highest energies most)

\[ \sim 10^{-15}c @ 1\text{TeV} \]
At its simplest:

✔ We do know that for an energy dependent dispersion in propagation a skewness is introduced into the light curve shape.

✗ We do not know the intrinsic shape/width/duration/energy dependent effects of the light curve at origin.

Under the assumption of the high & low energy photons being emitted contemporaneously and co-spatially we can “de-disperse” the light curve until the low and high energy lightcurves match again.

If we see a common dispersion in multiple objects of different types and/or a dispersion that scales with distance then the case for LIV becomes stronger...

Need:
- multiple sources and/or
- multiple source types
A negative co-efficient implies "superluminal" propagation can occur. If this happens as many times as “sub-luminal” then lightcurve is broadened, but the net dispersion is zero!

Nature is relentless and unchangeable, and it is indifferent as to whether its hidden reasons and actions are understandable to man or not.

Galileo Galilei
There are many different schemes of testing for the presence of a dispersion,

Minimise width:
e.g. DisCan

Maximise power:
e.g. Energy Cost Function

Compare CDF:
e.g Barres de Almeida & Daniel *APh* **35**, 850 (2012).

Photon Pair Lags:

but most boil down to:
apply an energy dependent correction factor $\tau$ to the event arrival time

$$\delta t_i = \pm \tau E_i^\alpha$$

where $\alpha$ defines the energy scale and $\alpha=1$ is linear dispersion, $\alpha=2$ is quadratic dispersion...

after propagation

Minimise width:

de-disperse

recover original

test – do they match?
Sources of VHE photons suitable for testing LIV effects

If dispersion were to be detected it would need to be present in a wide variety of sources to be sure it was due to LIV.

<table>
<thead>
<tr>
<th>object</th>
<th>fast</th>
<th>far</th>
<th>High Energy</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRBs</td>
<td>Y</td>
<td>Y</td>
<td>GeV</td>
<td>serendipity required</td>
</tr>
<tr>
<td>AGN flares</td>
<td>Y</td>
<td>N</td>
<td>TeV</td>
<td>still serendipitous, but know where to look</td>
</tr>
<tr>
<td>AGN Monitoring</td>
<td>N</td>
<td>Y</td>
<td>TeV</td>
<td>good redshift coverage</td>
</tr>
<tr>
<td>gamma-ray horizon</td>
<td>N</td>
<td>-</td>
<td>TeV++</td>
<td>hard spectrum AGN required</td>
</tr>
<tr>
<td>pulsars</td>
<td>Y</td>
<td>N</td>
<td>?</td>
<td>better for higher order effects</td>
</tr>
</tbody>
</table>

*transient*: need a healthy dose of luck
Gamma Ray Bursts are the most distant fast photon sources available to us.

<2s it is a short duration GRB
>2s a long duration GRB

GRB090510 was a short duration GRB at a redshift z=0.903 and with emission up to a 31 GeV photon within a second of the main emission.

CTA will have >30,000x the effective area at >10GeV energies...

Currently most constraining limits set by GRB observations by Fermi satellite

Fermi-GBM:
- 10keV->25MeV
- all sky

Fermi-LAT:
- 20MeV-300GeV
- >2sr fov
- ~1m² eff. area


Best limits come from short duration GRBs – only way to catch those is serendipitously with a survey or wide field of view instrument.

\[ \alpha = 1 \]

Best limits come from short duration GRBs – only way to catch those is serendipitously with a survey or wide field of view instrument.

\[ \alpha = 2 \]

All truths are easy to understand once they are discovered; the point is to discover them.

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AGN: Flares

The highest energy fast photon sources are AGN flares.

CTA will resolve flares to greater precision than ever before.

Catch flares from known sources with monitoring programme or ToO triggers.

Get new sources (e.g. hard spectrum, high redshift) from survey in unbiased fashion.

Figure 3.2: Minimal distinguishable separation of two Gaussian peaks as a function of their width, in case of a H.E.S.S.-like measurement (open circles), a CTA-like measurement (crosses) and an ideal situation where a ten times more photons than in the CTA measurement could be collected.


*The sun, with all those planets revolving around it and dependent on it, can still ripen a bunch of grapes as if it had nothing else in the universe to do.*

*Galileo Galilei*
**AGN: Flares**

Using the spectrum & flux from the historically recorded highest known flux states

PKS2155 $z \sim 0.117$ $\delta t = 4.26\text{s/TeV for } \alpha = 1$

Add in some fancy statistical methods, eg non-parametric unbinned method of de Almeida & Daniel *ApJ* 35, 850 (2012) for $>E_{\text{pl}}$ limits on linear term

requires 10 photons at $E > 10$ TeV for flare FWHM $\leq 3 \times$ dispersion $= 120\text{s for PKS2155-304}$

within a factor two of currently resolved flares
Whilst the normal lightcurve may not be sufficient to determine dispersion for any single flare, if LIV is present the High Energy Lightcurve will always be shifted wrt Low Energy Lightcurve...

accumulate the 15-30 minute pointings taken over days/weeks/months/years.


Monitor a number of sources at a number of redshifts will disentangle intrinsic source physics delays from external propagation induced dispersion: LIV will scale with redshift, AGN physics should not.

We must say that there are as many squares as there are numbers.

*Galileo Galilei*
**Pulsars**

Crab pulsar limits within factor 10-100 of GRB limits on quadratic term if well understood shape then potentially also good limits on “superluminal” term

![Pulse profile of the Crab pulsar at γ-ray energies with VERITAS. All quality data between 2007 and 2011 is included, the exact data set used for [4]. The Fermi-LAT pulse profile is also shown below the VERITAS pulse profile.](image1.png)

![Preliminary performance of the $Z_{20}^2$ DisCan method on the VERITAS Crab Pulsar data between 2007 and 2011. Trial values of $\theta$ are plotted against $Z_{20}^2$. The green dashed line is the maximum $Z^2$ value at $\theta_{max} = -0.49 \mu s/GeV$.](image2.png)

if Crab pulsar spectrums cuts off $<400$ GeV – no improvement on current limits
Crab cutoff $\sim 1$ TeV: $\sim 2x$ current PKS2155-304 limits
MSP with 10% Crab IC component at 1TeV: $\sim M_{pl}$ on linear term; $10^{11}$GeV on quadratic term in 100 hours

*Otte (2014)*

*Epur si muove*
Pulsars

What pulsars lack in distance for limits on the linear term, they can make up for in energy for limits on the quadratic term.

They would also have completely different intrinsic source physics processes to GRBs/AGN.

inverse Compton upscattered curvature radiation from pair creation across the outer gap could generate photons of a few TeV and possibly be detected by CTA

Gamma Ray Horizon effects

A change in the $\gamma-\gamma \rightarrow e^+e^-$ pair production cross-section could arise due to broken Lorentz symmetry, eg
Fairbairn et al *JCAP* **06**, 005 (2014) CMB

Could this reduce the optical depth for the highest energy photons?

* arXiv:1401.8178

Measure what is measurable, and make measurable what is not so.

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Summary

If energy dependent dispersion is detected it would need to be present in a wide variety of sources to be sure it was due to LIV.

The science reach of CTA has sufficient breadth to test LIV in a model independent fashion in the photon sector.

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<tr>
<td>GRBs</td>
<td>Y</td>
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<td>N</td>
<td><strong>extragalactic survey</strong></td>
<td>serendipity</td>
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<td>AGN flares</td>
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<td>N</td>
<td>Y</td>
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<td>flaring AGN</td>
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<tr>
<td>AGN Monitoring</td>
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<td>Y</td>
<td>Y</td>
<td><strong>extragalactic AGN Monitoring</strong></td>
<td>AGN at various z</td>
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<tr>
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<td><strong>galactic Pulsars</strong></td>
<td>Crab, Vela ++</td>
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*transient*: need a healthy dose of luck
Extra Slides
Some quantum gravity models (see APh 43, 50 (2013) for further references)

Loop Quantum Gravity

Lifshitz-type quantum field theories

doubly (or deformed) special relativity

string theory: non-perturbative structures existing in various dimensions, eg D-branes & D-particles
  Our universe being a 3 dimensional membrane in higher dimensional bulk space.
  D-particles crossing 'our' brane show up as space-time events
  If propagating photon interacts via absorption and subsequent re-emission, photon slows
    → much like photon interacting with electron in glass
  Interaction of other particle types would not be universal, so would have different refractive indices
  Photon has no conserved quantum number to inhibit absorption/re-emission
    eg D-particle has no electric charge so an electron could not be simply absorbed/re-emitted
    ibid proton
  Neutrino has no electric charge and lepton number not expected to be absolutely conserved @E_{Pl}
    but as a fermion can not be absorbed/emitted by space-time defect unless it occurs in
    boson-fermion doublets as in supersymmetry.

… etc … etc …
Not always straightforward!
Forward & Backward in time? Fuzzy dispersion: propagation through “foamy” space-time

\[ E \approx p + \frac{m^2}{2p} - s_{\pm 1} \left( \frac{1}{2} \frac{E^{\alpha+1}}{M_{QG}^\alpha} \right), \nu(E) \approx 1 - \xi \frac{E}{M_{Pl}} \pm \xi \frac{E}{M_{Pl} \Delta \tau \pm \xi \frac{E}{M_{Pl}}} \]

can be positive or negative

Amelino-Camelia & Smolin *PRD* 80, 084017 (2009).
One observatory with two sites operated by a single consortium

Candidate sites under review now, selection should be made by end of 2013 (S) ~10km² flat area, 1.5-4.0 km altitude, minimum cloud cover, easy access.
Space Based Instrumentation

Fermi LAT:
20MeV->300GeV $\Delta E/E \leq 10\%$
3.5°(100MeV)->0.15°(10GeV)
~8000cm² effective collection area
Surveys whole sky every ~3hrs
has a bright diffuse background to contend with

pair conversion in satellite gives photon energy and direction
anti-coincidence shield removes cosmic ray events

also Fermi GBM for gamma-ray burst detection 8keV<E<40MeV
An exceptional gamma-ray flare from PKS 2155-304

Current catalogue of gamma-ray AGN


- **E>100 MeV emitters**
  - >600 objects, including 10 radio-quiet associations

- **E>100 GeV emitters**
  - >60 objects all radio loud
    - BL Lacs mainly HBL, with some IBL, LBL, FSRQ
    - 2 radio galaxies
    - (+2 starburst galaxies)

E>100 MeV emitters

E>100 GeV emitters

http://tevcat.uchicago.edu
The $\gamma$-ray Horizon

due to photon-photon pair production

$\gamma + \gamma \rightarrow e^+ + e^-$

Threshold

$E_\gamma E_T > m_e^2 c^4$

sensitive to the diffuse photon density of the universe, but this diffuse emission can be hard to measure directly due to foreground emission

CTA

(can be used to measure EBL, EG magnetic fields and search for axions!)

Mean Free Path

1 Gpc

100 Mpc

10 Mpc

1 Mpc

100 kpc

10 kpc

10 GeV

100 GeV

1 TeV

10 TeV

100 TeV

1 PeV

10 PeV

100 PeV

1 EeV

3C 279

Mrk 421

Cen A

M 31

Galactic Centre
Using the spectrum & flux from the historically recorded highest known flux states


Mrk 421 $z \sim 0.03$ $\Delta T \leq 30s$

**BUT**, these sims are 20 degrees, a northern hemisphere source will have high energy effective area boost at LZA when observed from the southern hemisphere SST array...
Using the spectrum & flux from the historically recorded highest known flux states


**3C279 z~0.536 ΔT≤630s**

IFAE.20130919.60s.3C279

DESY.20130901.3C279

Flaring AGN are not the best way to go to look for dispersion in very distant sources, instead better to go for the very fast flaring in the lower energy GRBs (not covered here).
**Pulsars**

Simulations are extrapolation of VERITAS Crab spectrum above 100GeV and at 2kpc. CTA will not detect spectrum >400GeV.

Aharonian model 1 TeV cut-off to the spectrum 100(50)hrs:
- limits at 800GeV thresh. linear $\to 5\times10^{18}$GeV ($3\times10^{18}$GeV); quadratic $\to 7.4\times10^{10}$GeV ($6\times10^{10}$GeV)

MSP Scenario CTA North 10% Crab flux power law of -3.8 Crab pulsar profile with peak at 60 GeV period of 3ms, 100 hrs obs linear $<1.4\times10^{18}$GeV; quadratic $<1\times10^{10}$GeV

IC component @1TeV is 10% flux at 100GeV (order of magnitude below present limits).

PSR 300ms 100hrs: linear $\to M_{\text{pl}}$; quadratic $\to 1\times10^{11}$GeV
PSR 3ms 100hrs: linear $\to M_{\text{pl}}$; quadratic $\to 3\times10^{11}$GeV

Otte (2014).
Not just which is best, but also when is best

Selecting harder sources rather than brighter sources, may be better for some LIV studies

Achievable limits depends on where the cut-off in the spectrum occurs – source list for some LIV KSP needs to come as a follow-up after the initial AGN observations have been made?

Which KSPs are for years 1-10 versus 1-5/5-10?

Could use science verification phase observations to lead KSP selections