STRAIGHT
OUTTA
COMPTON

Straight Outta Compton: Lorentz Invariance Tests with Compton Scattering

MISSISSIPPI STATE

Jefferson Lab
EXPLORING THE NATURE OF MATTER

Hall C

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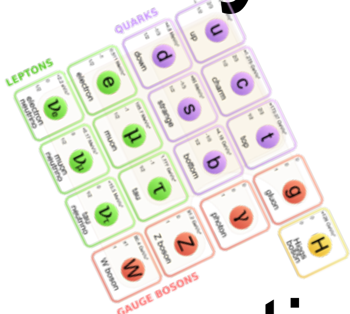
DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

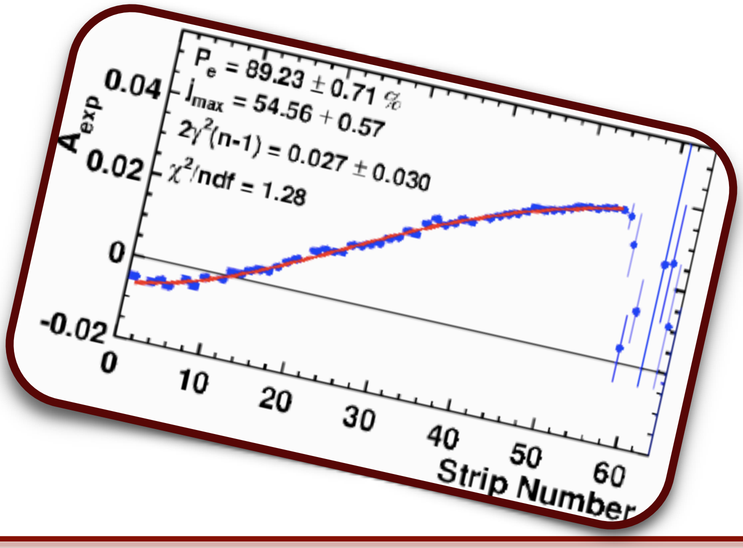
Outline

- Introduction (Why & What?)

- Over a century of Lorentz symmetry tests
  (How others did it?)



- A brief detour (An oblique connection to LI !)
- Lorentz invariance test with Compton asymmetry (How we did it?)



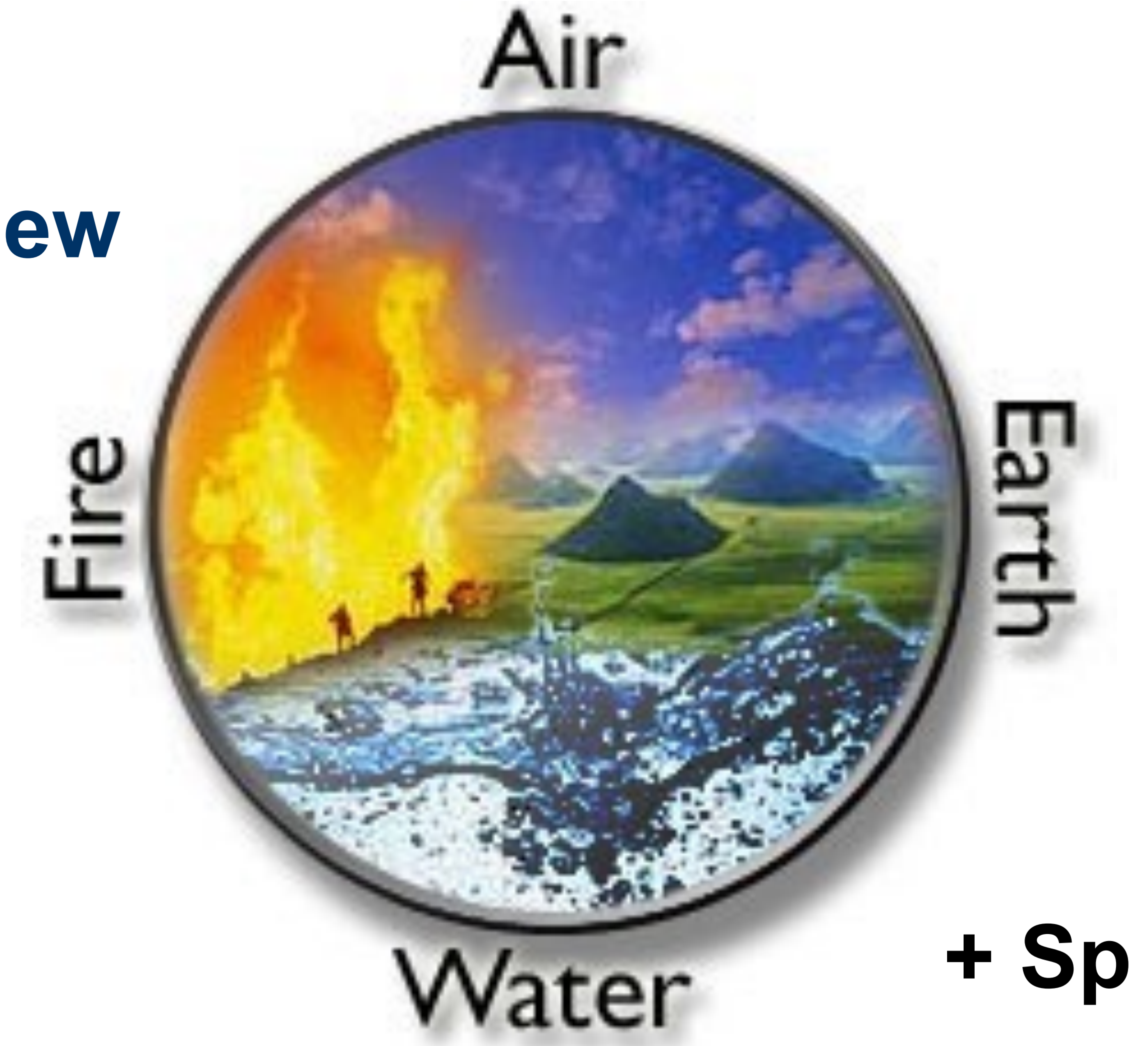
- Summary

Throughout history humans have wondered - what is matter made of, and what holds it together?

Reductionist reasoning → **all matter is made of few basic (i.e. fundamental) constituents.**

(nature of complex things can be understood by reducing them to simpler more fundamental things)

The Greek/ Aristotelian view

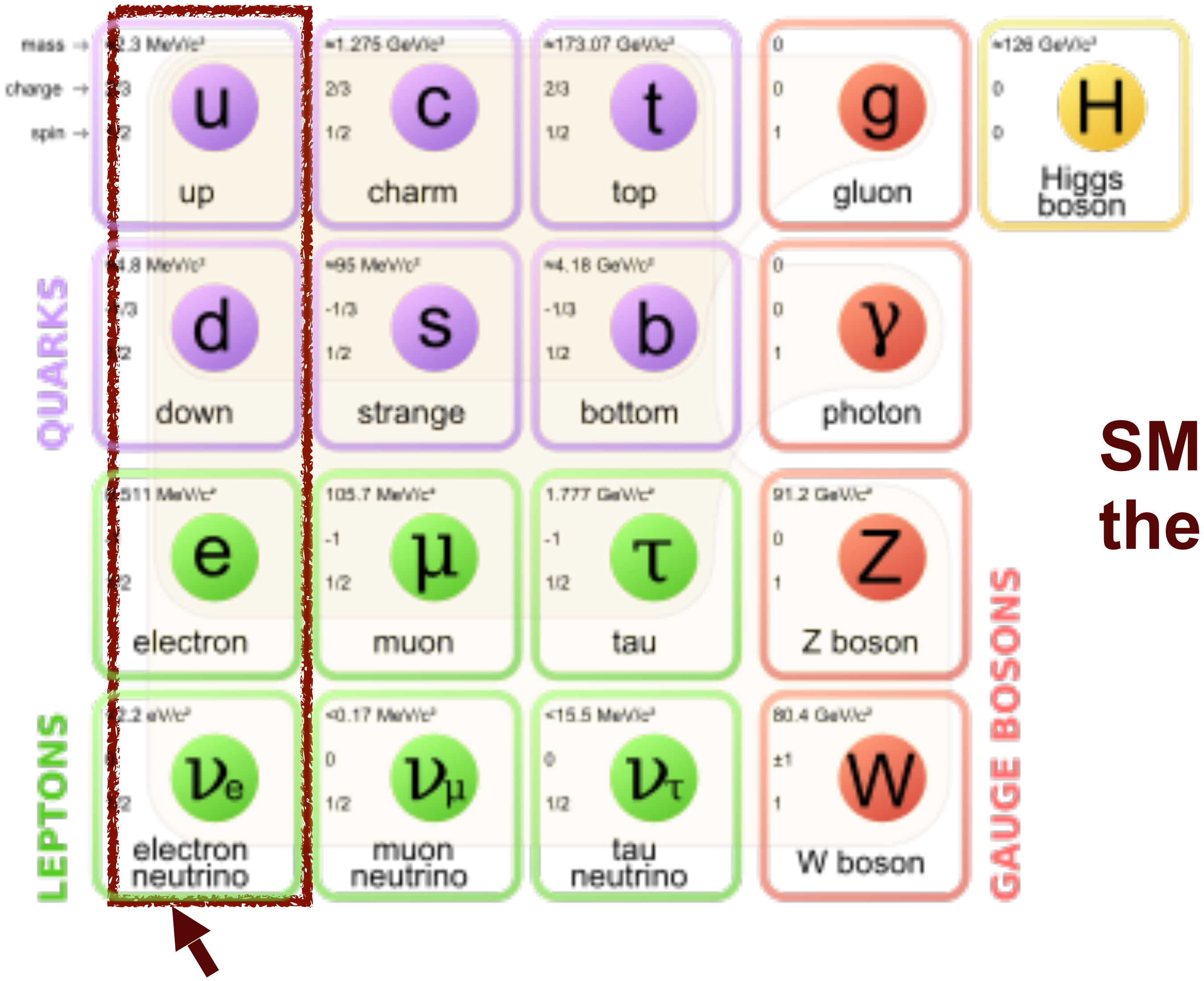


+ Space (the Indian view)[1]

[1] Samkhya-Karikas by Ishvarakrsna (circa 3rd century AD)

The Standard Model (SM) is the modern, scientific incarnation of this quest.

Standard Model



Ordinary matter

SM = The quantum field theory of the electro-weak and strong force

SM + Gravity = complete set of forces needed to describe nature

The Standard Model is a tremendous achievement but …

Too many free parameters!

No

GRAVITON

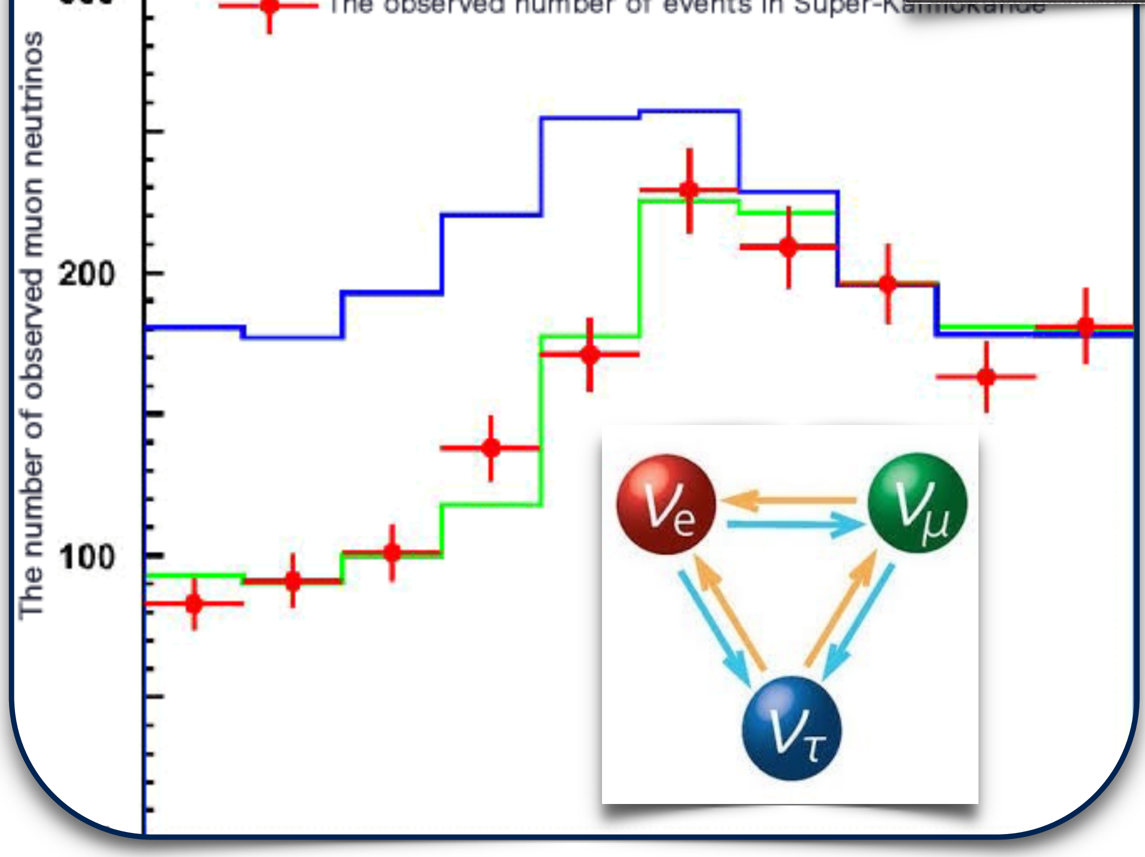
The **GRAVITON** is a particle not yet observed. It communicates the force of gravity and is the smallest bundle of the gravitational force field. Some theorists believe gravitons can travel between braneworlds. Lucky l'il fellas!

Acrylic felt with poly fill for minimum mass.

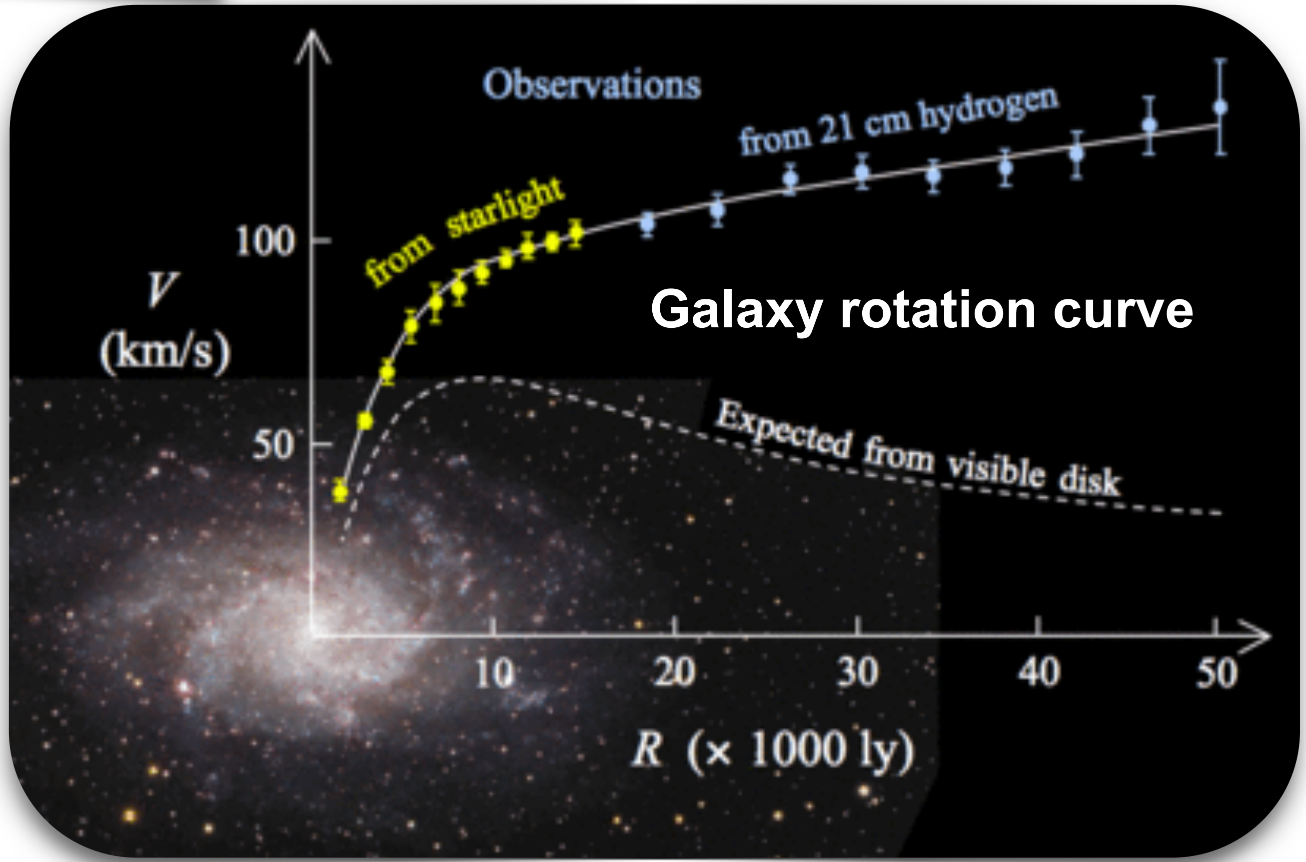
$10.49 PLUS SHIPPING

Why 3 generations?
Why mass hierarchy?

No neutrino mass



No dark matter, dark energy



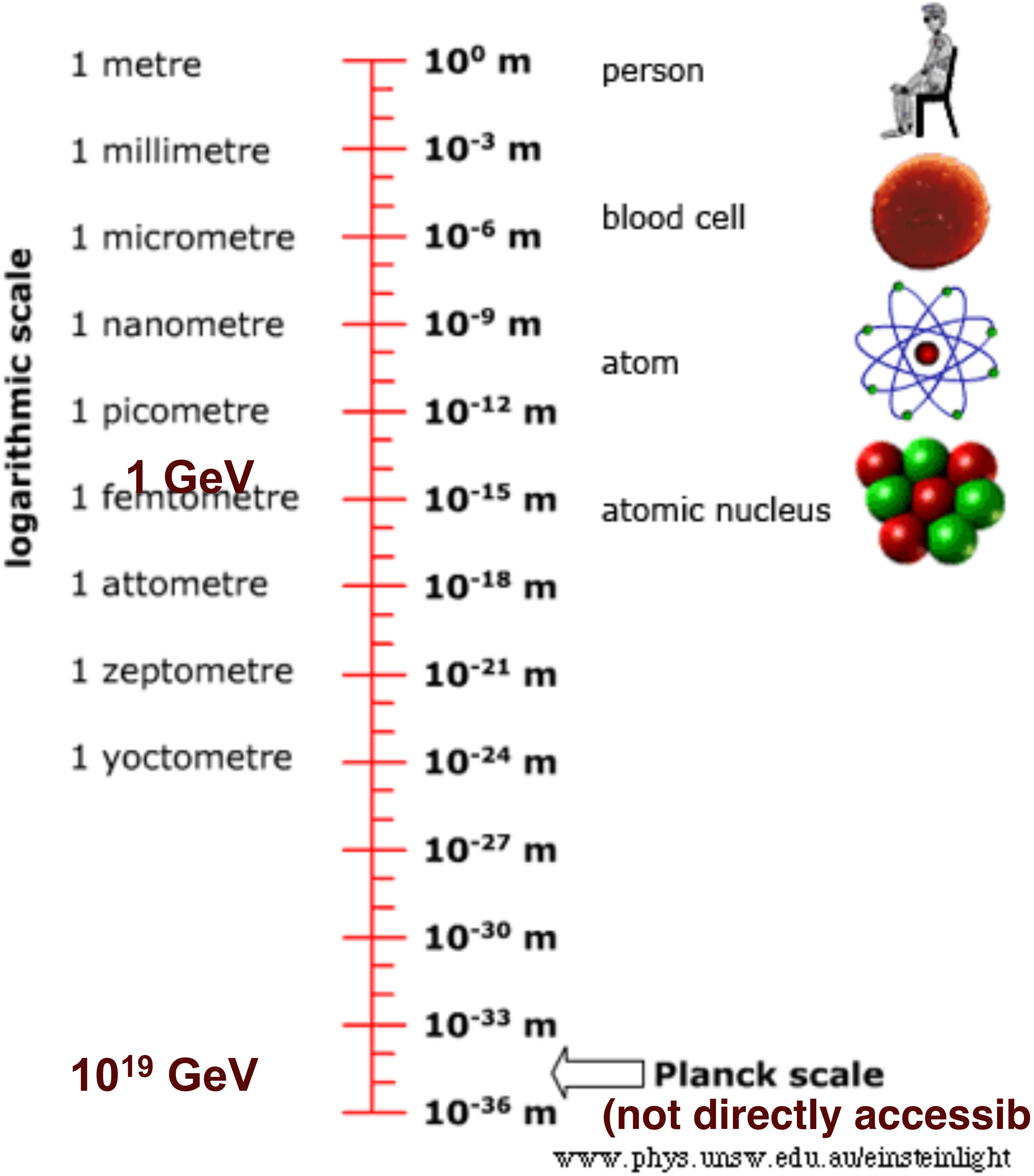
The current Standard Model + Gravity are most likely part of some larger model.

The Flammarion engraving: Flammarion, Camille (1888). L'atmosphère: météorologie populaire.

What's in the world 'Beyond Standard Model'?

To go beyond the current SM + Gravity, we need more direct evidence for new force(s).

SM and GR are expected to merge into a single elegant theory at the Planck scale



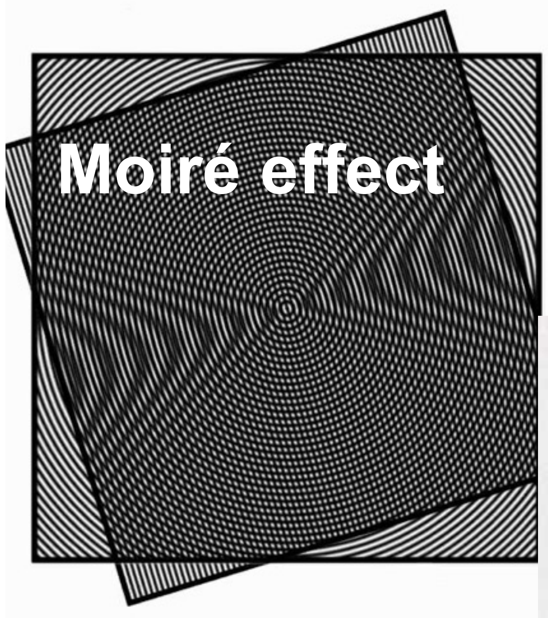
1 GeV

10^{19} GeV

(not directly accessible)

www.phys.unsw.edu.au/einsteinlight

Indirect effects effects of new forces at Planck scales may be detectable in sufficiently sensitive experiments



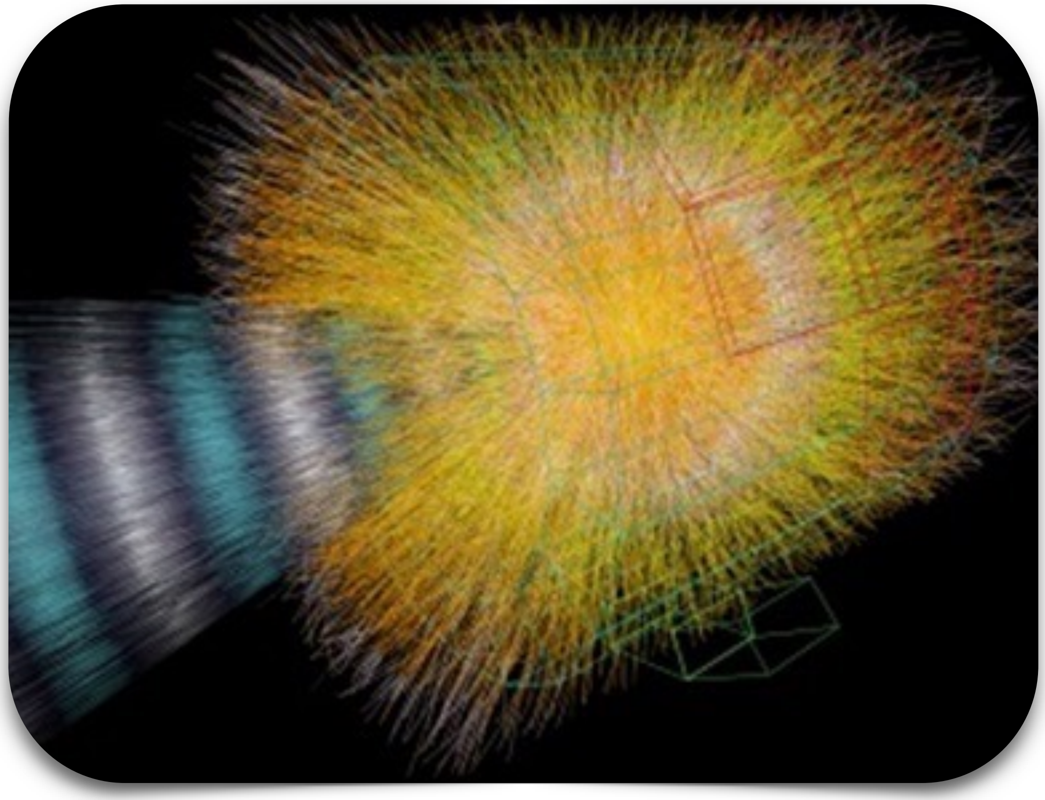
Moiré effect

Similar to how pixels of an image becomes evident when narrow stripes trigger “Moiré patterns”

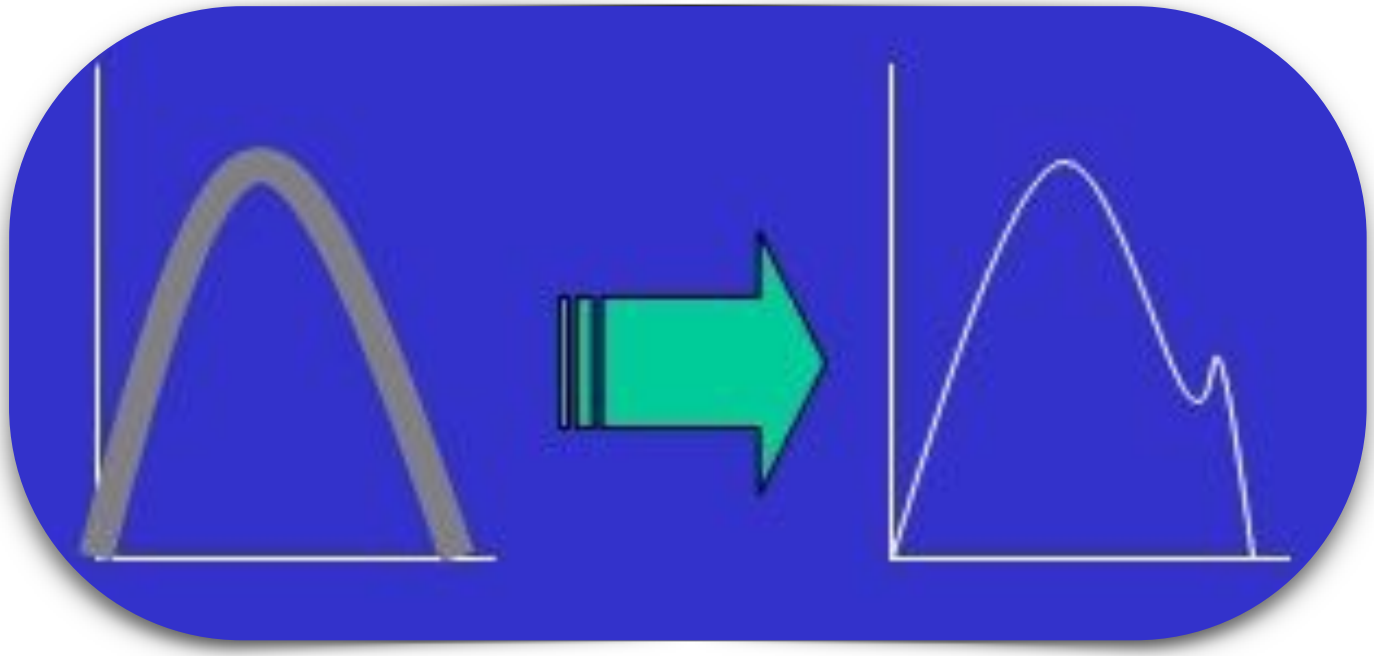
There are two routes to knowledge about new forces.

High energy frontier

High precision frontier



New phenomena
(new particles)
created when
"usable energy" > $2M_{new}c^2$



known phenomena
studied with
high precision may show
inconsistency with theory

High precision tests of fundamental symmetries is one of the most promising techniques.

The CPT symmetry in the cornerstone of the Standard Model.

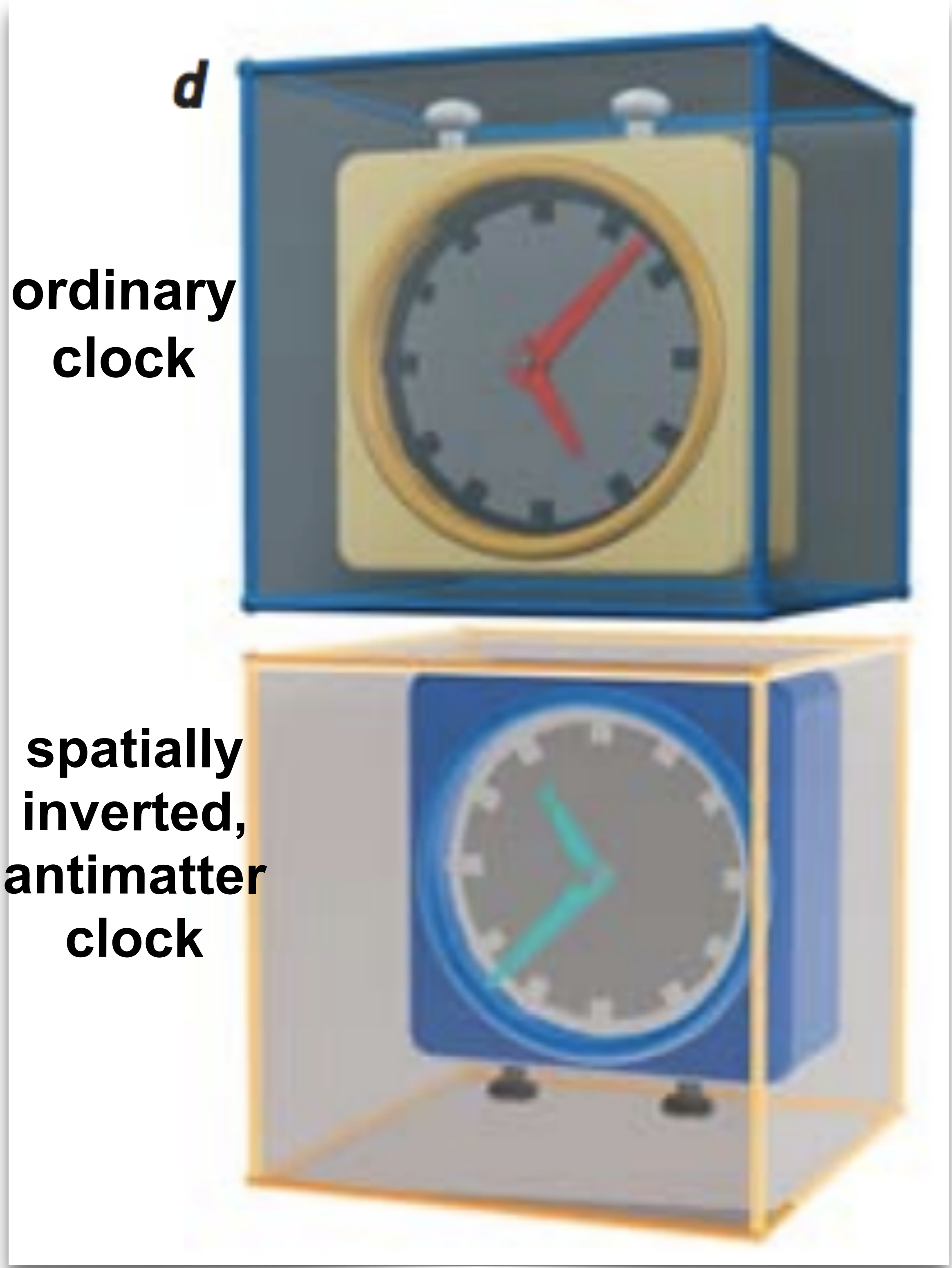
C- symmetry: laws of physics same for particles and anti-particles.

P- symmetry: laws of physics same under spatial inversion. (violated in weak interactions)

T- symmetry: laws of physics same when time is reversed.

P & CP & T symmetry violated in weak interactions

CPT theorem*:
Lorentz symmetry = CPT symmetry
also been shown:
~~CPT symmetry~~ = ~~Lorentz symmetry~~



*J. S. Bell, Ph.D. Thesis, Birmingham University (1954)

image courtesy of: A. Kostelecky, Sci. Am., Sept 2004, pg 93

Lorentz symmetry is the fundamental symmetry for both Gravity and SM.

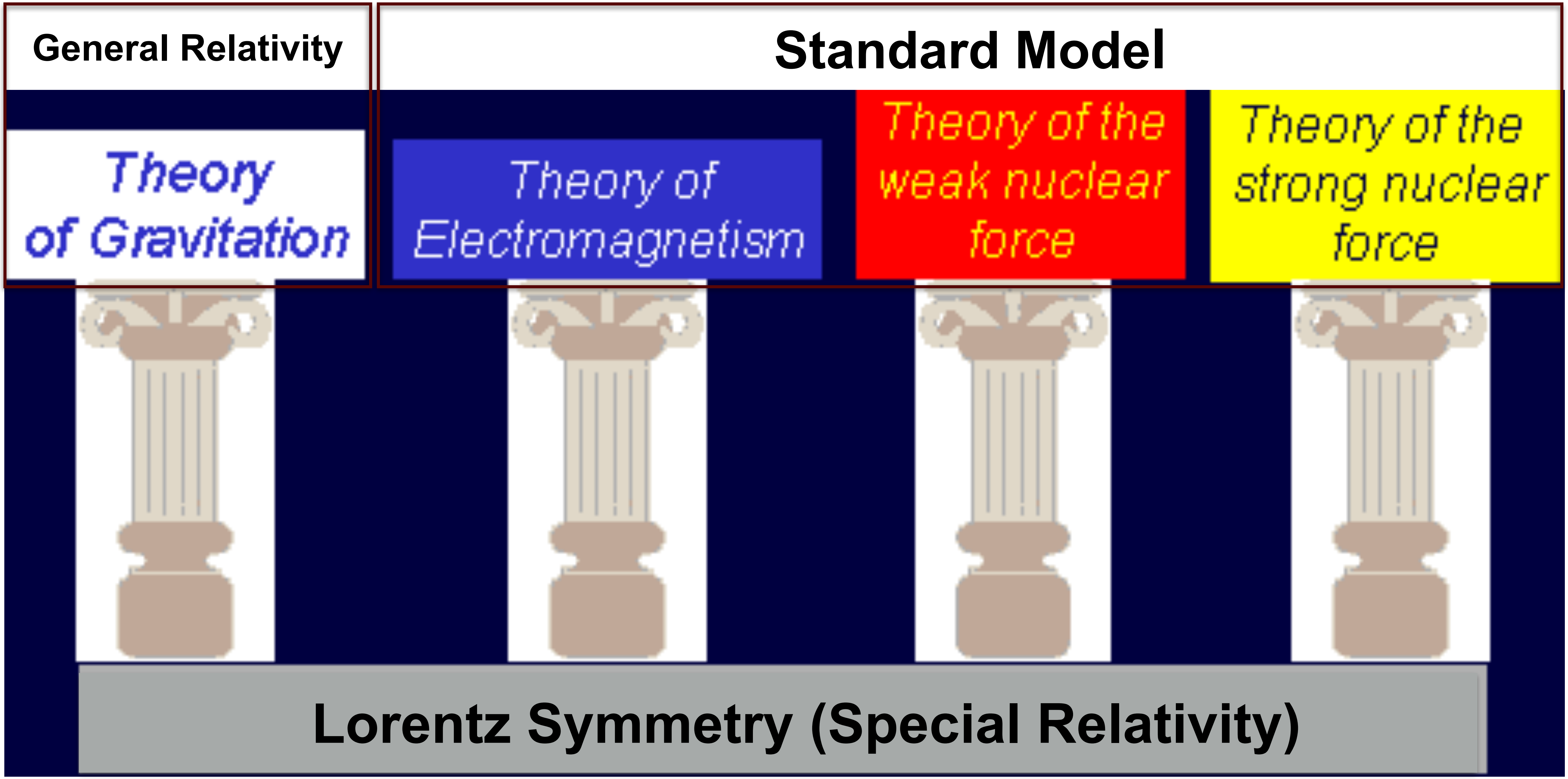


image courtesy of: http://www.exphy.uni-duesseldorf.de/ResearchInst/FundPhys.html

Sensitive searches for violations of Lorentz symmetry have provided the best limits on new physics (no conventional process can mimic Lorentz violation)

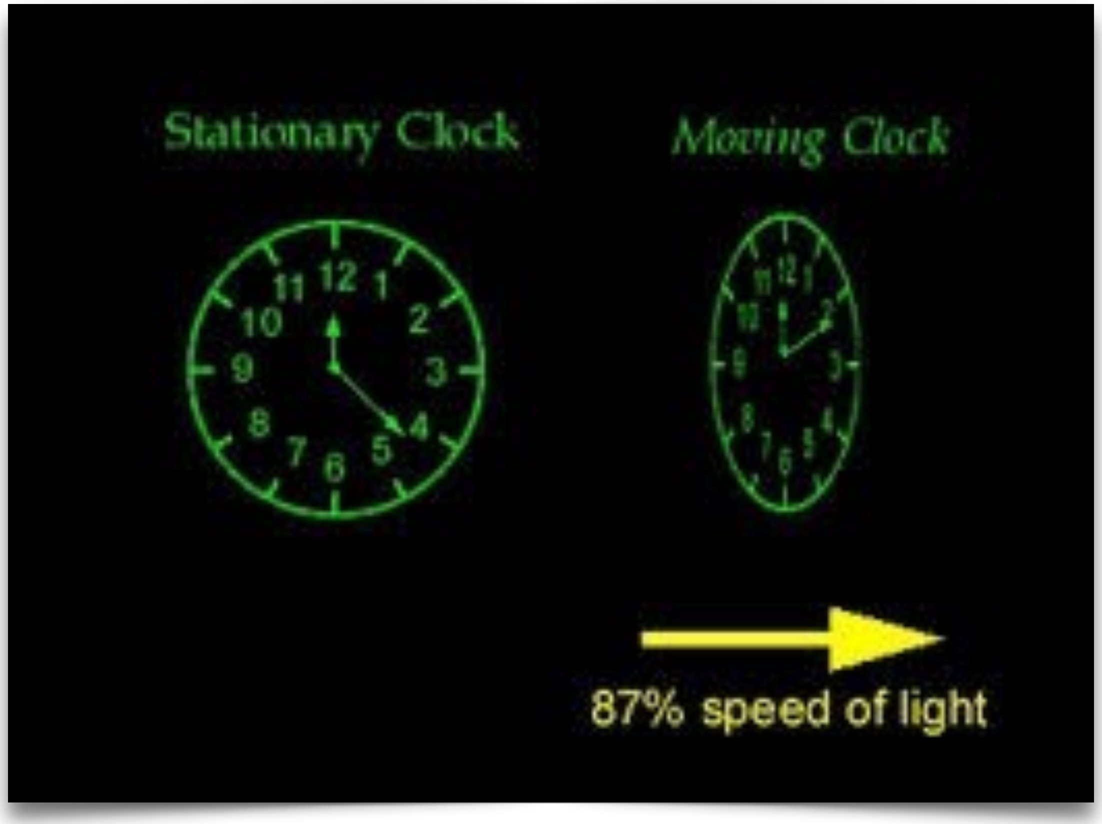
Lorentz symmetry has two parts: rotational symmetry and boost symmetry.

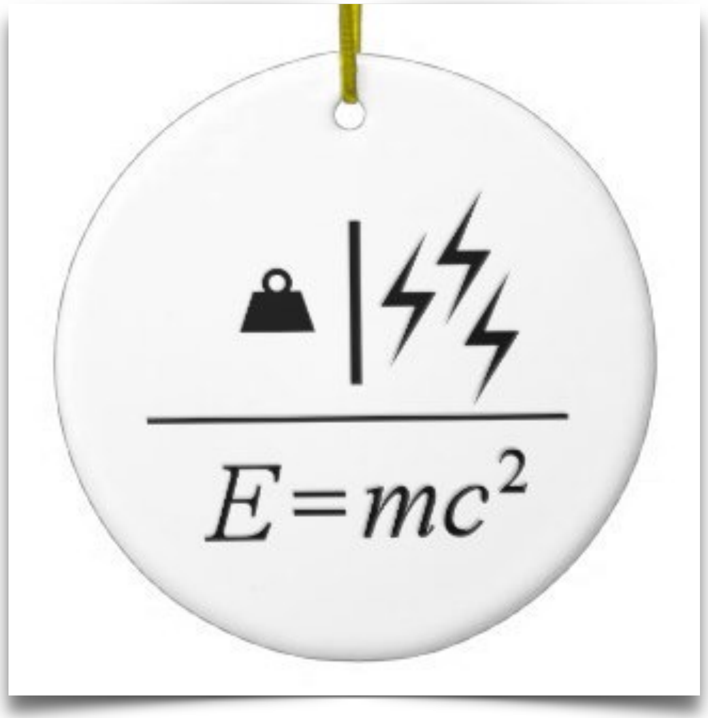
Lorentz symmetry: laws of physics are the same for all inertial frames.

Lorentz symmetry obeyed = Lorentz invariance

image courtesy of: A. Kostelecky, Sci. Am., Sept 2004, pg 93

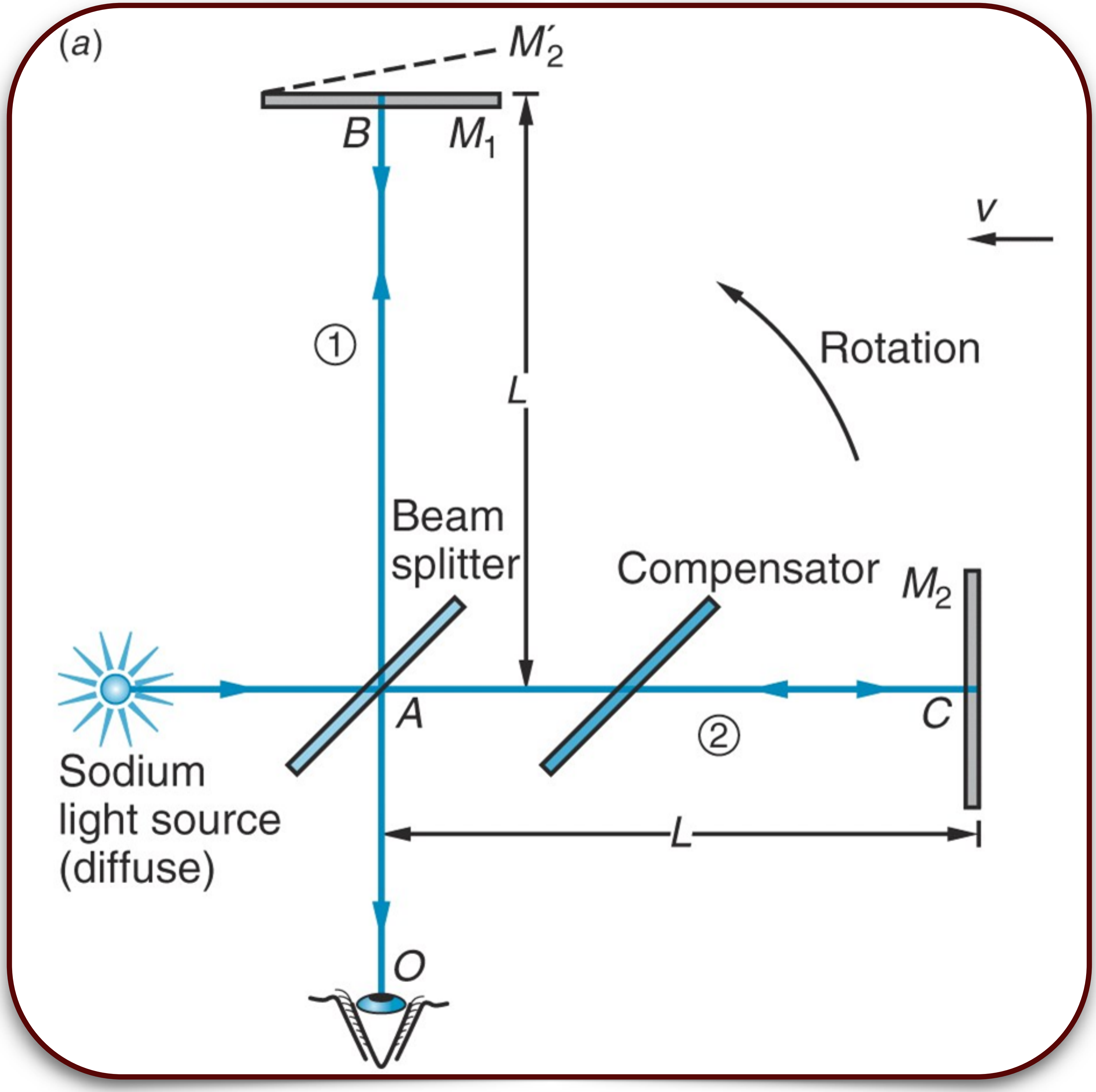
Lorentz invariance leads to several key precisely verified predictions.





GPS is an everyday application of relativity

The Michelson-Morley experiment was the first test of Lorentz symmetry



Original aim: to detect the influence of the mysterious 'ether' — the medium through which light waves were thought to travel

Null result led Einstein to postulate Lorentz Invariance

image courtesy of:
Tipler and Llewellyn, Modern Physics, W. H. Freeman

Lorentz symmetry could be violated via spontaneous symmetry breaking.

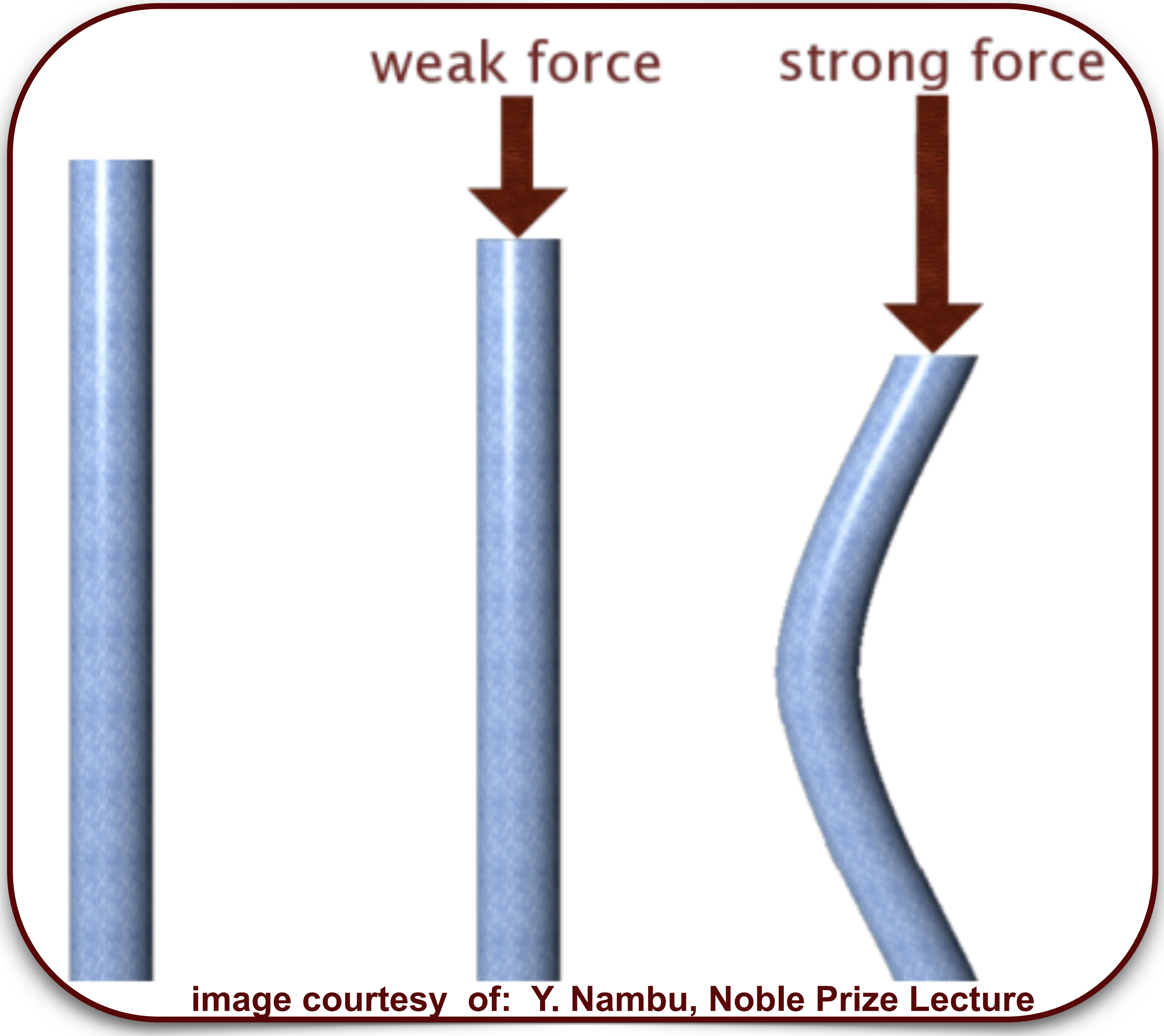
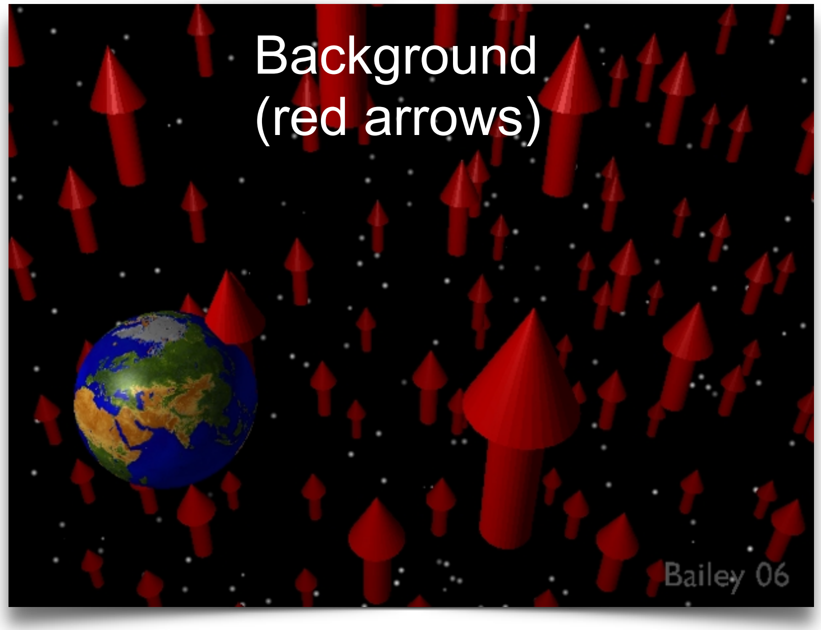


image courtesy of: Y. Nambu, Noble Prize Lecture

symmetric under rotation around axis

spontaneously broken rotational symmetry

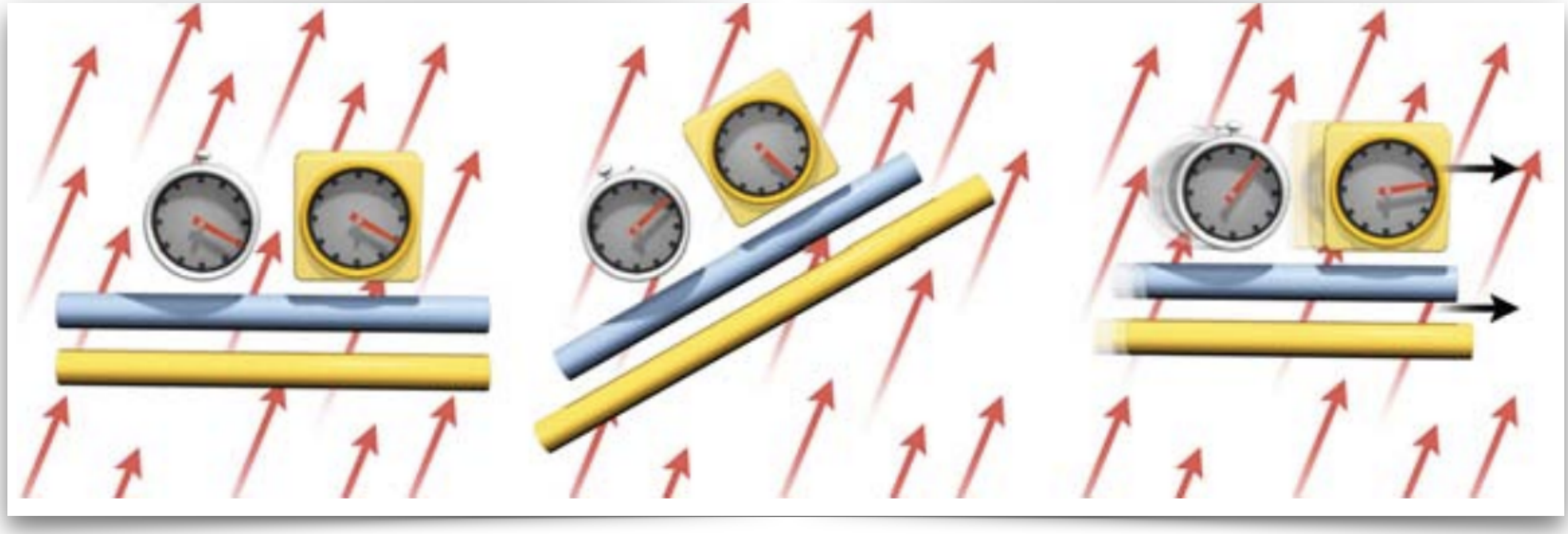
It has been shown that some beyond-SM theories can spontaneously break Lorentz symmetry.



Background fields can spontaneously acquire non-zero strength

(The theory is Lorentz invariant but certain solutions are not)

Spontaneous Lorentz symmetry violation implies a preferred direction



Background field has a direction (they are vectors/tensors) hence they break rotational symmetry (and boost symmetry)

A lab experiment will change direction relative to the background field, as the earth rotates.

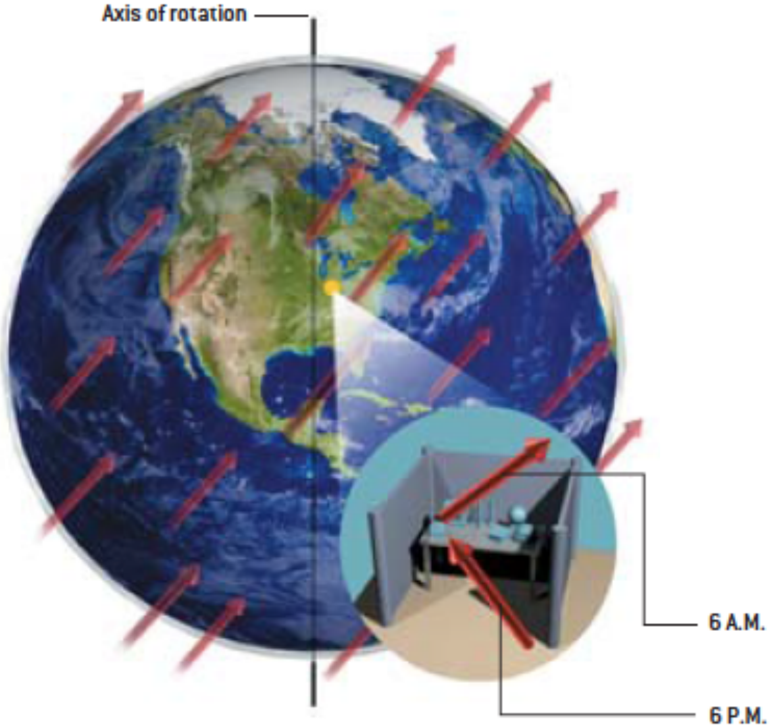
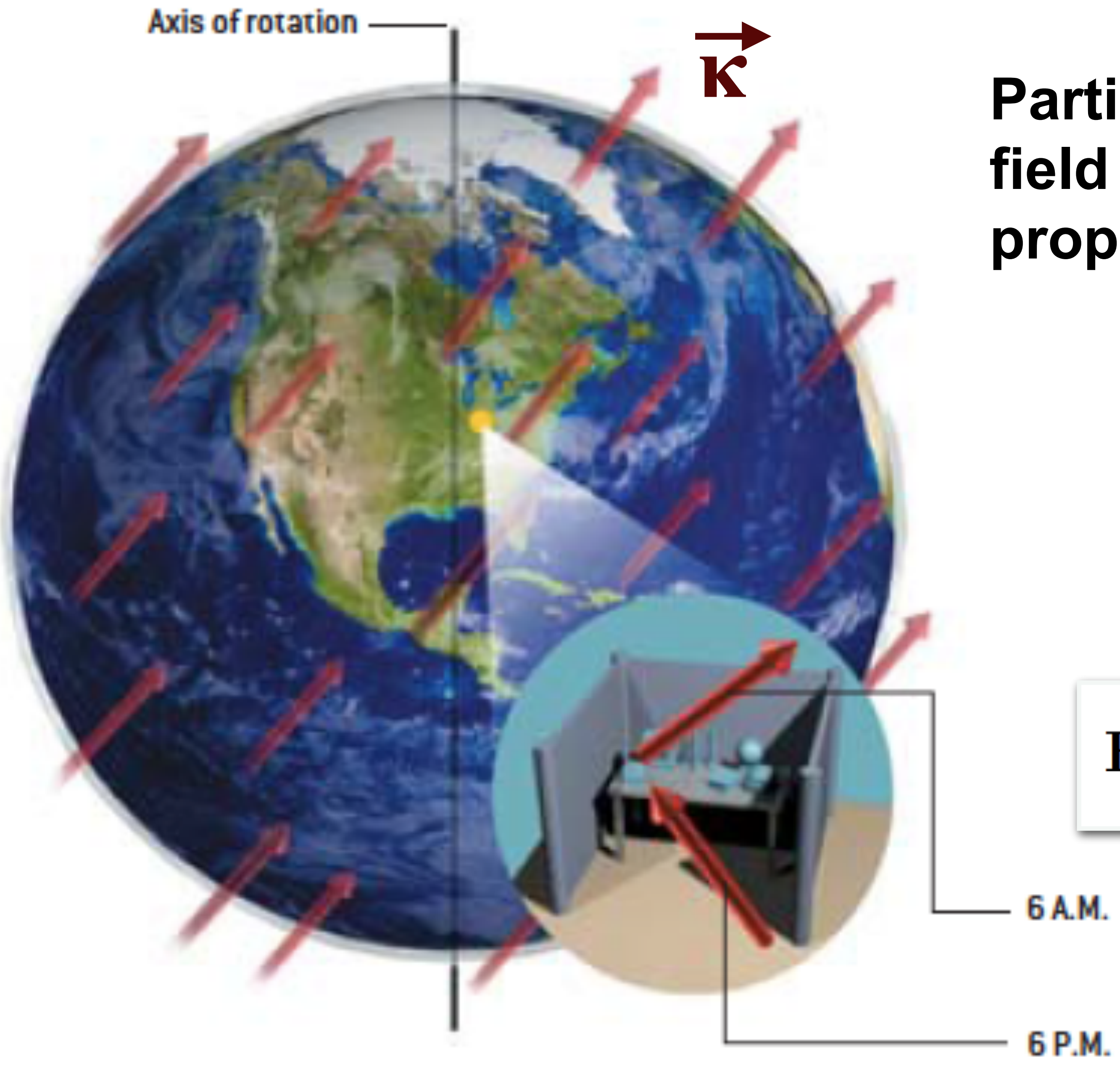


image courtesy of: A. Kostelecky, Sci. Am., Sept 2004, pg 93

Most laboratory based tests of Lorentz symmetry rely on the rotation of the Earth.

A Lorentz symmetry breaking background field $\vec{\kappa}$ will seem to change direction as the earth rotates



Particles that interacts with this background field will show variations in their physical properties as the earth rotates.

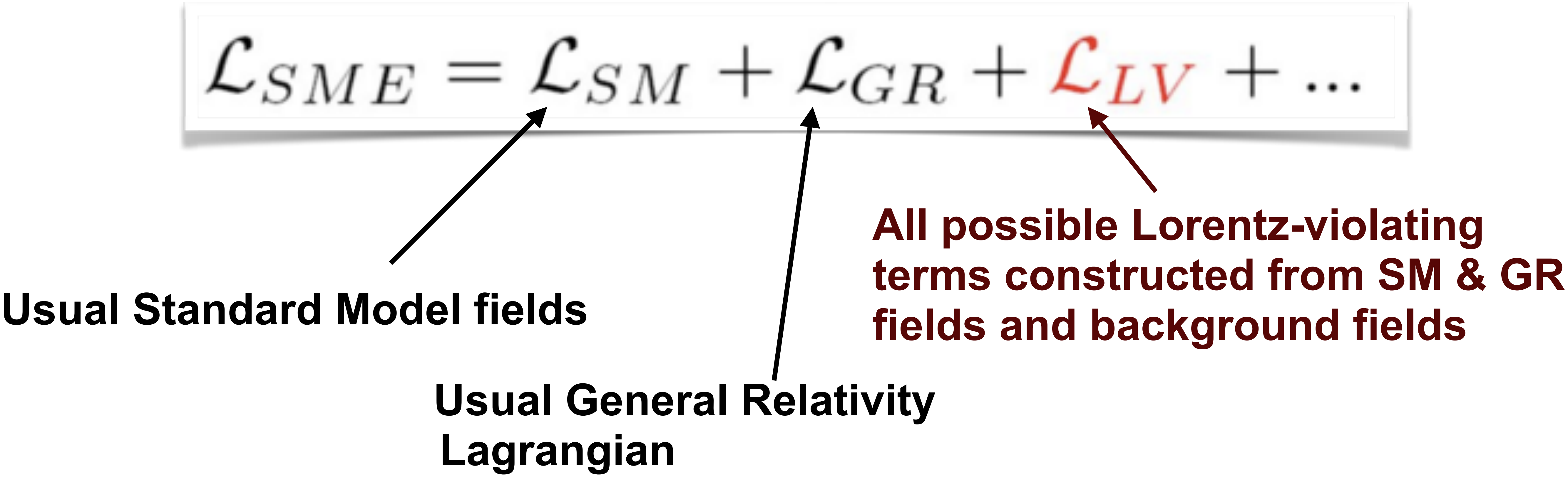
For example, according to SME the dispersion relation of a photon (for c=1) changes from -

$$\mathbf{E}_\gamma = \mathbf{p}_\gamma \quad \rightarrow \quad \mathbf{E}_\gamma = (\mathbf{1} - \vec{\kappa} \cdot \hat{\mathbf{p}})\mathbf{p}_\gamma + \mathcal{O}(\kappa^2)$$

a sidereal variation in Eγ is then a signal for Lorentz violation

The Standard Model extension (SME) is a general theoretical framework for studying Lorentz violation.

Based on effective field theory



$$\mathcal{L}_{SME} = \mathcal{L}_{SM} + \mathcal{L}_{GR} + \mathcal{L}_{LV} + \ldots$$

Usual Standard Model fields

Usual General Relativity Lagrangian

All possible Lorentz-violating terms constructed from SM & GR fields and background fields

Minimal SME restricts to gauge-invariant and renormalizable terms only

The SME provides a quantitative description of Lorentz and CPT violation, controlled by a set of coefficients whose values are to be determined or constrained by experiment.

Kostelecky & Potting, PRD 51, 3923 (1995), Colladay and Kostelcky, PRD 55, 6760 (1997), Kostelecky PRD 69, 105009 (2004)

The Standard Model extension (SME) is a general theoretical framework for studying Lorentz violation.

The coefficients in the minimal SME has been adopted by experimentalists as the standard for reporting bounds on Lorentz violation.

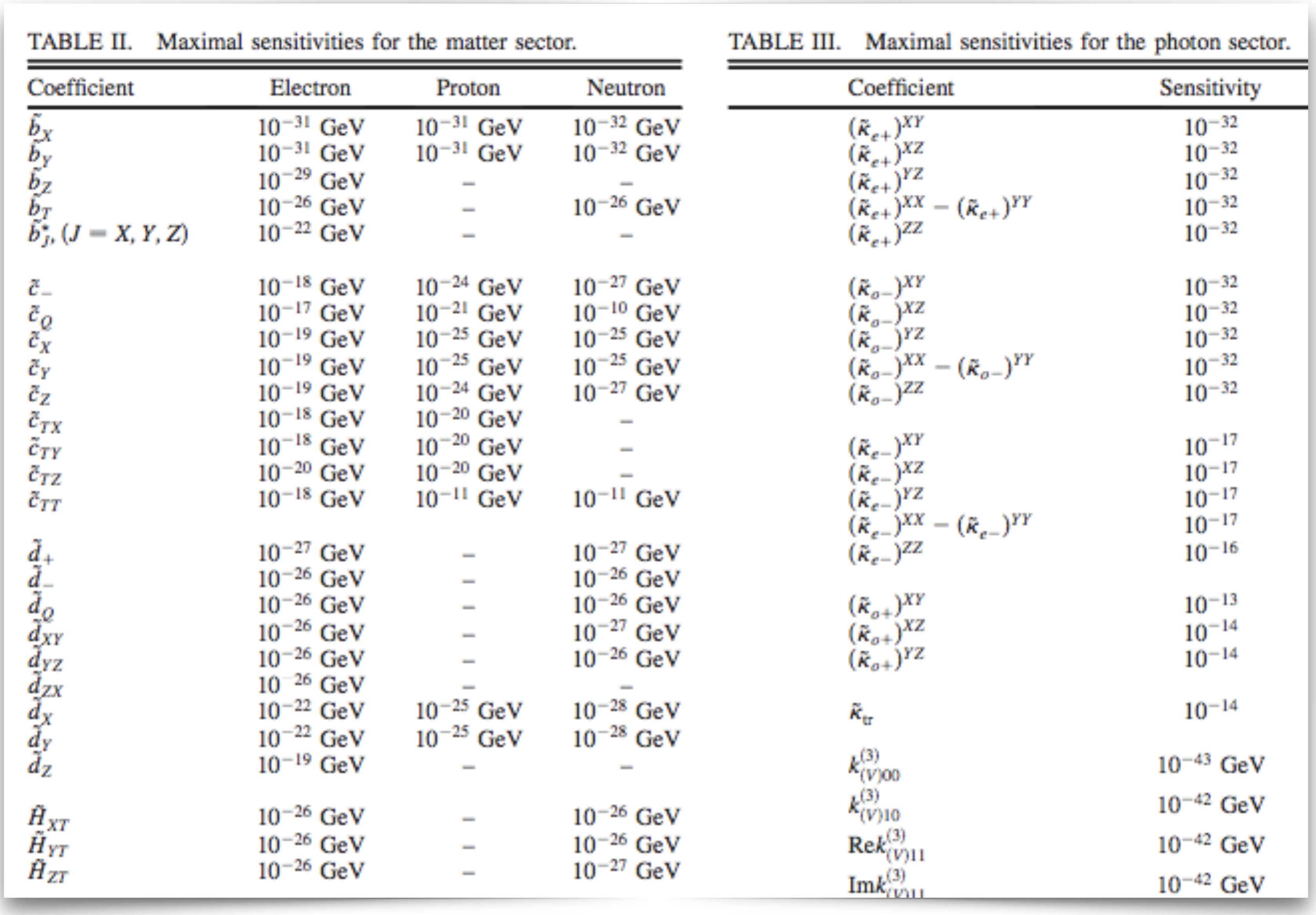


TABLE II. Maximal sensitivities for the matter sector.

Coefficient	Electron	Proton	Neutron
$\tilde{b}_X$	10^{-31} GeV	10^{-31} GeV	10^{-32} GeV
$\tilde{b}_Y$	10^{-31} GeV	10^{-31} GeV	10^{-32} GeV
$\tilde{b}_Z$	10^{-29} GeV	–	–
$\tilde{b}_T$	10^{-26} GeV	–	10^{-26} GeV
$\tilde{b}^*_J$, $(J = X, Y, Z)$	10^{-22} GeV	–	–
$\tilde{c}_-$	10^{-18} GeV	10^{-24} GeV	10^{-27} GeV
$\tilde{c}_Q$	10^{-17} GeV	10^{-21} GeV	10^{-10} GeV
$\tilde{c}_X$	10^{-19} GeV	10^{-25} GeV	10^{-25} GeV
$\tilde{c}_Y$	10^{-19} GeV	10^{-25} GeV	10^{-25} GeV
$\tilde{c}_Z$	10^{-19} GeV	10^{-24} GeV	10^{-27} GeV
$\tilde{c}_{TX}$	10^{-18} GeV	10^{-20} GeV	–
$\tilde{c}_{TY}$	10^{-18} GeV	10^{-20} GeV	–
$\tilde{c}_{TZ}$	10^{-20} GeV	10^{-20} GeV	–
$\tilde{c}_{TT}$	10^{-18} GeV	10^{-11} GeV	10^{-11} GeV
$\tilde{d}_+$	10^{-27} GeV	–	10^{-27} GeV
$\tilde{d}_-$	10^{-26} GeV	–	10^{-26} GeV
$\tilde{d}_Q$	10^{-26} GeV	–	10^{-26} GeV
$\tilde{d}_{XY}$	10^{-26} GeV	–	10^{-27} GeV
$\tilde{d}_{YZ}$	10^{-26} GeV	–	10^{-26} GeV
$\tilde{d}_{ZX}$	10^{-26} GeV	–	–
$\tilde{d}_X$	10^{-22} GeV	10^{-25} GeV	10^{-28} GeV
$\tilde{d}_Y$	10^{-22} GeV	10^{-25} GeV	10^{-28} GeV
$\tilde{d}_Z$	10^{-19} GeV	–	–
$\tilde{H}_{XT}$	10^{-26} GeV	–	10^{-26} GeV
$\tilde{H}_{YT}$	10^{-26} GeV	–	10^{-26} GeV
$\tilde{H}_{ZT}$	10^{-26} GeV	–	10^{-27} GeV

TABLE III. Maximal sensitivities for the photon sector.

Coefficient	Sensitivity
$(\tilde{\kappa}_{e+})^{XY}$	10^{-32}
$(\tilde{\kappa}_{e+})^{XZ}$	10^{-32}
$(\tilde{\kappa}_{e+})^{YZ}$	10^{-32}
$(\tilde{\kappa}_{e+})^{XX} - (\tilde{\kappa}_{e+})^{YY}$	10^{-32}
$(\tilde{\kappa}_{e+})^{ZZ}$	10^{-32}
$(\tilde{\kappa}_{o-})^{XY}$	10^{-32}
$(\tilde{\kappa}_{o-})^{XZ}$	10^{-32}
$(\tilde{\kappa}_{o-})^{YZ}$	10^{-32}
$(\tilde{\kappa}_{o-})^{XX} - (\tilde{\kappa}_{o-})^{YY}$	10^{-32}
$(\tilde{\kappa}_{o-})^{ZZ}$	10^{-32}
$(\tilde{\kappa}_{e-})^{XY}$	10^{-17}
$(\tilde{\kappa}_{e-})^{XZ}$	10^{-17}
$(\tilde{\kappa}_{e-})^{YZ}$	10^{-17}
$(\tilde{\kappa}_{e-})^{XX} - (\tilde{\kappa}_{e-})^{YY}$	10^{-17}
$(\tilde{\kappa}_{e-})^{ZZ}$	10^{-16}
$(\tilde{\kappa}_{o+})^{XY}$	10^{-13}
$(\tilde{\kappa}_{o+})^{XZ}$	10^{-14}
$(\tilde{\kappa}_{o+})^{YZ}$	10^{-14}
$\tilde{\kappa}_{\mathrm{tr}}$	10^{-14}
$k^{(3)}_{(V)00}$	10^{-43} GeV
$k^{(3)}_{(V)10}$	10^{-42} GeV
$\mathrm{Re}k^{(3)}_{(V)11}$	10^{-42} GeV
$\mathrm{Im}k^{(3)}_{(V)11}$	10^{-42} GeV

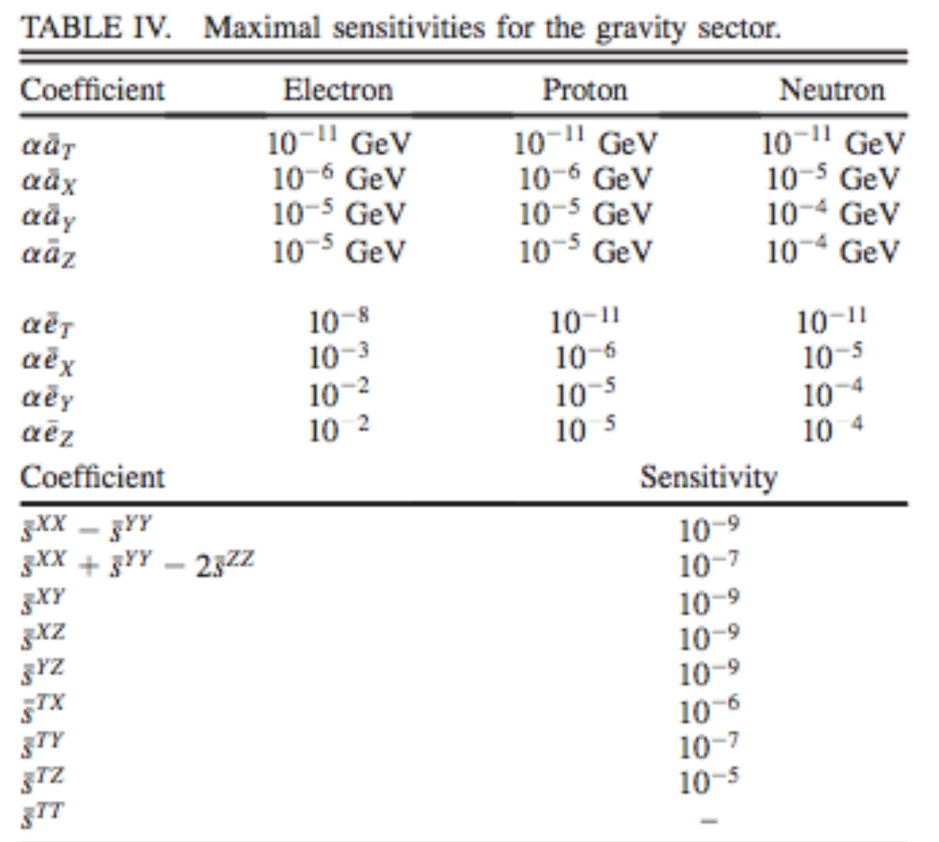


TABLE IV. Maximal sensitivities for the gravity sector.

Coefficient	Electron	Proton	Neutron
$\alpha\bar{a}_T$	10^{-11} GeV	10^{-11} GeV	10^{-11} GeV
$\alpha\bar{a}_X$	10^{-6} GeV	10^{-6} GeV	10^{-5} GeV
$\alpha\bar{a}_Y$	10^{-5} GeV	10^{-5} GeV	10^{-4} GeV
$\alpha\bar{a}_Z$	10^{-5} GeV	10^{-5} GeV	10^{-4} GeV
$\alpha\bar{e}_T$	10^{-8}	10^{-11}	10^{-11}
$\alpha\bar{e}_X$	10^{-3}	10^{-6}	10^{-5}
$\alpha\bar{e}_Y$	10^{-2}	10^{-5}	10^{-4}
$\alpha\bar{e}_Z$	10^{-2}	10^{-5}	10^{-4}

Coefficient	Sensitivity
$\bar{s}^{XX} - \bar{s}^{YY}$	10^{-9}
$\bar{s}^{XX} + \bar{s}^{YY} - 2\bar{s}^{ZZ}$	10^{-7}
$\bar{s}^{XY}$	10^{-9}
$\bar{s}^{XZ}$	10^{-9}
$\bar{s}^{YZ}$	10^{-9}
$\bar{s}^{TX}$	10^{-6}
$\bar{s}^{TY}$	10^{-7}
$\bar{s}^{TZ}$	10^{-5}
$\bar{s}^{TT}$	–

# of coefficients = 19 + n*48,
where n = number of elementary particles

Kostelecky & Russell RMP 83, 11 (2011)

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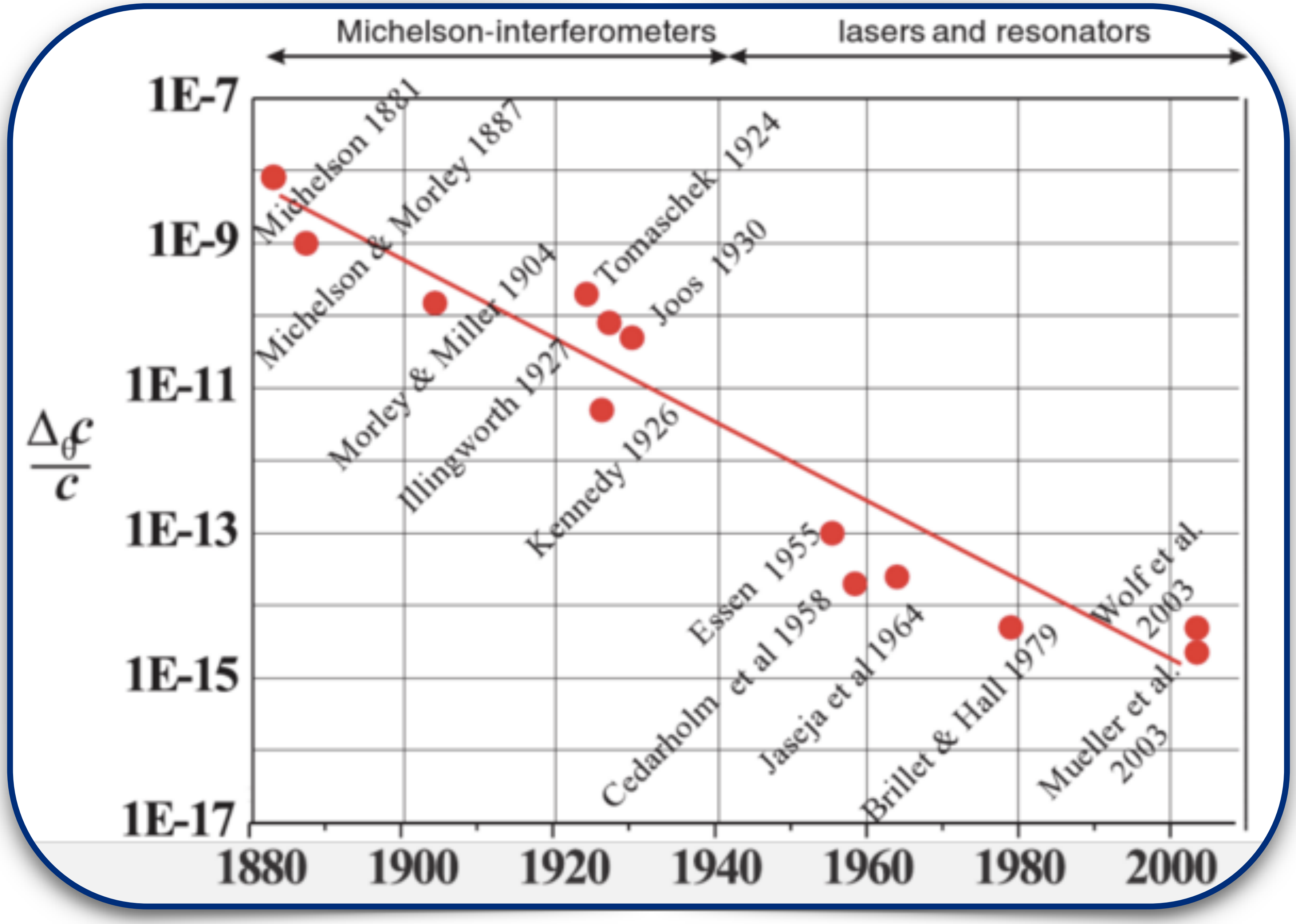
Lorentz symmetry has so far withstood over a century of testing with ever improving sensitivity.

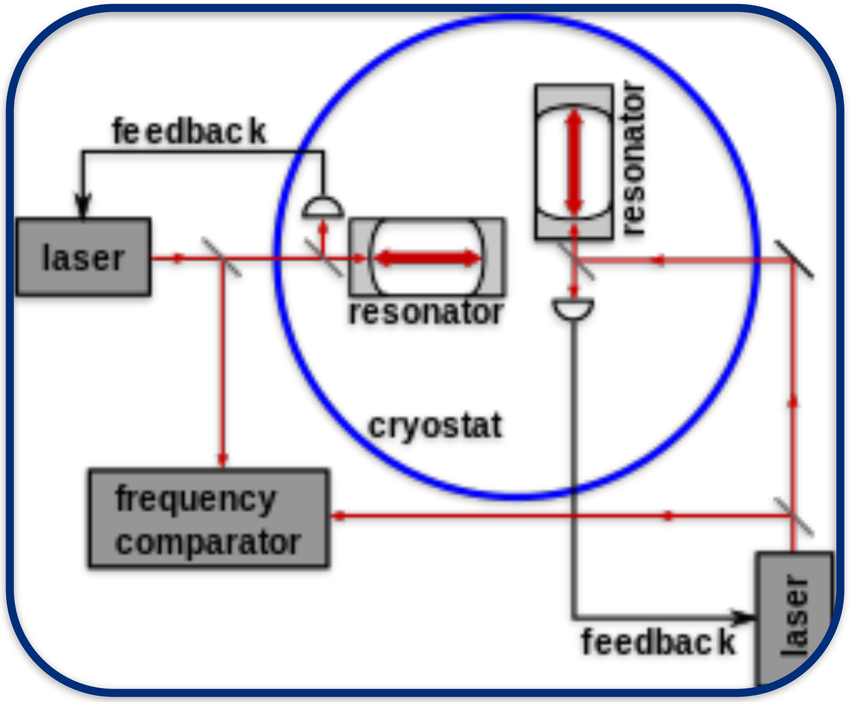
The isotropy of speed of light tested in (photon sector)

Michelson-Morley type experiments (rotating interferometer) &
Kennedy-Thorndike type experiments (uses the earth's motion).

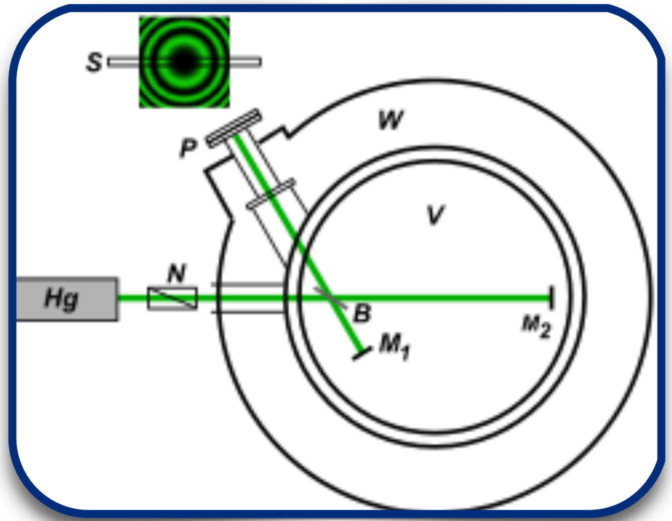


S. Herrmann et al., Lect. Notes Phys. 702, 385 (2006)

optical resonator based MM expt.

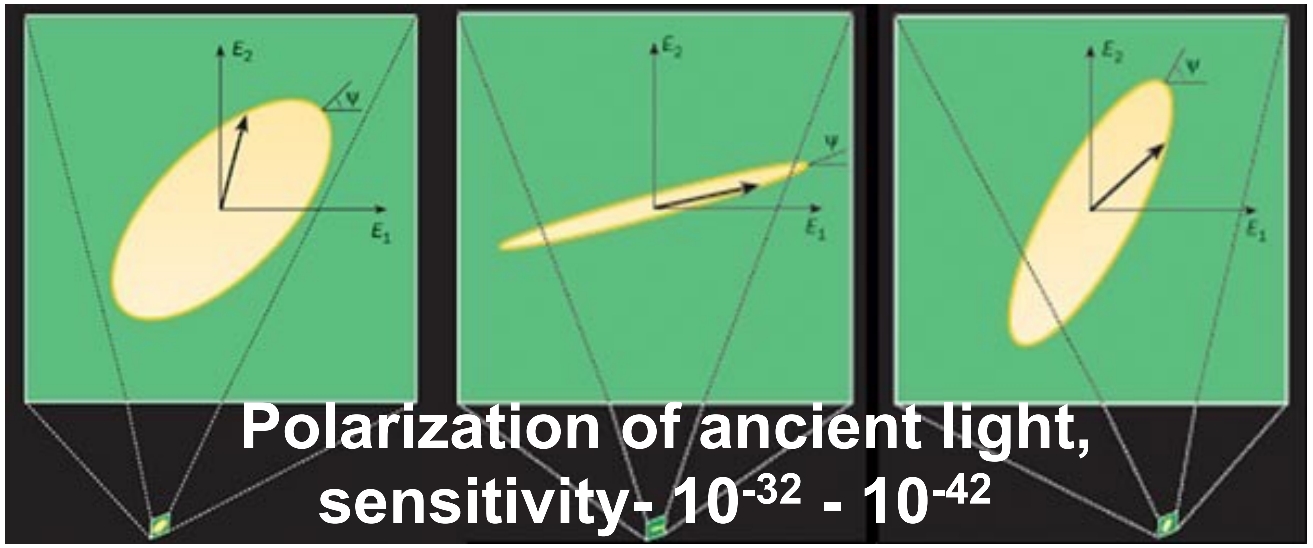


Kennedy-Thorndike type expt.



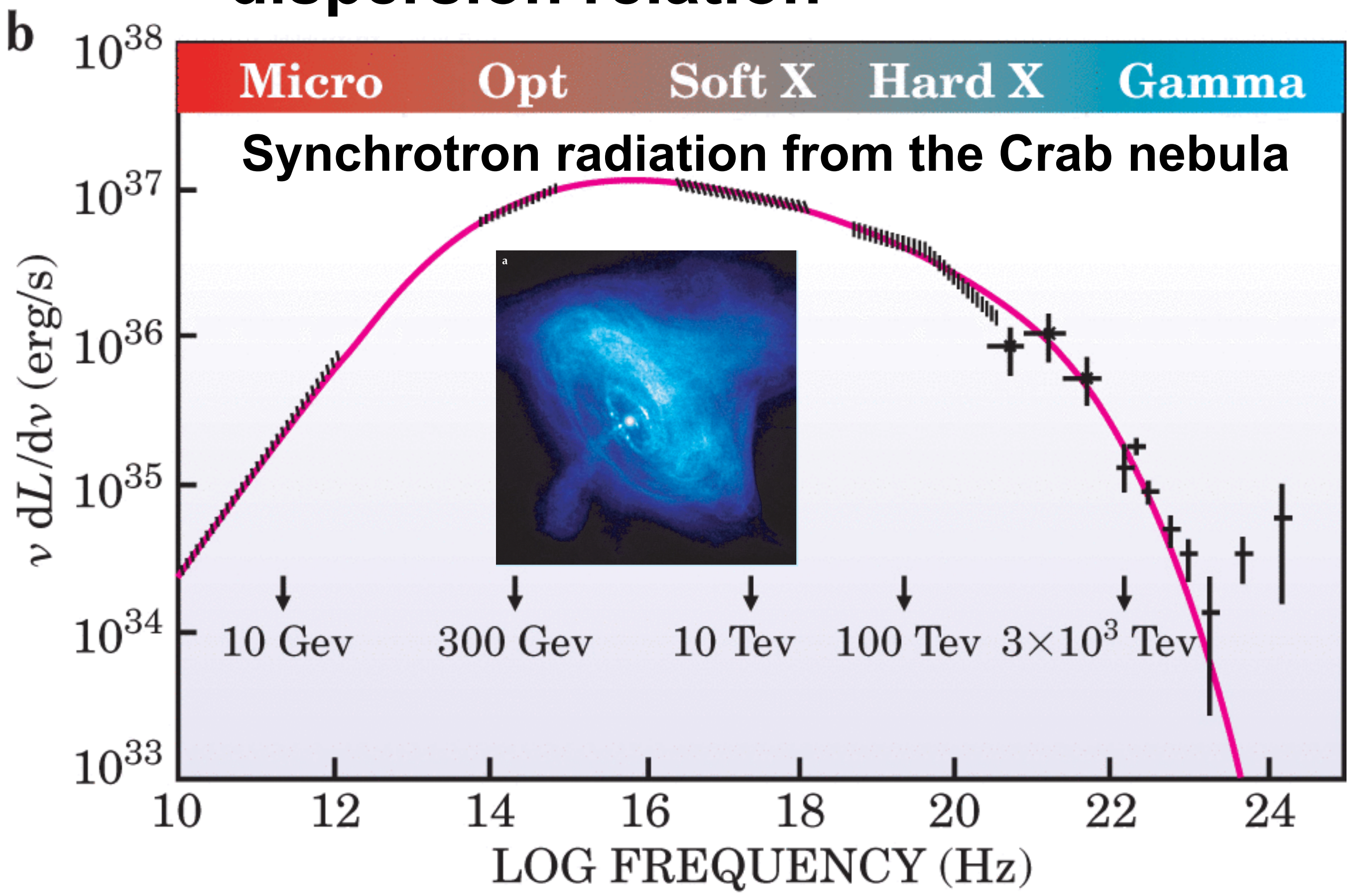
Lorentz symmetry has so far withstood over a century of testing with ever improving sensitivity.

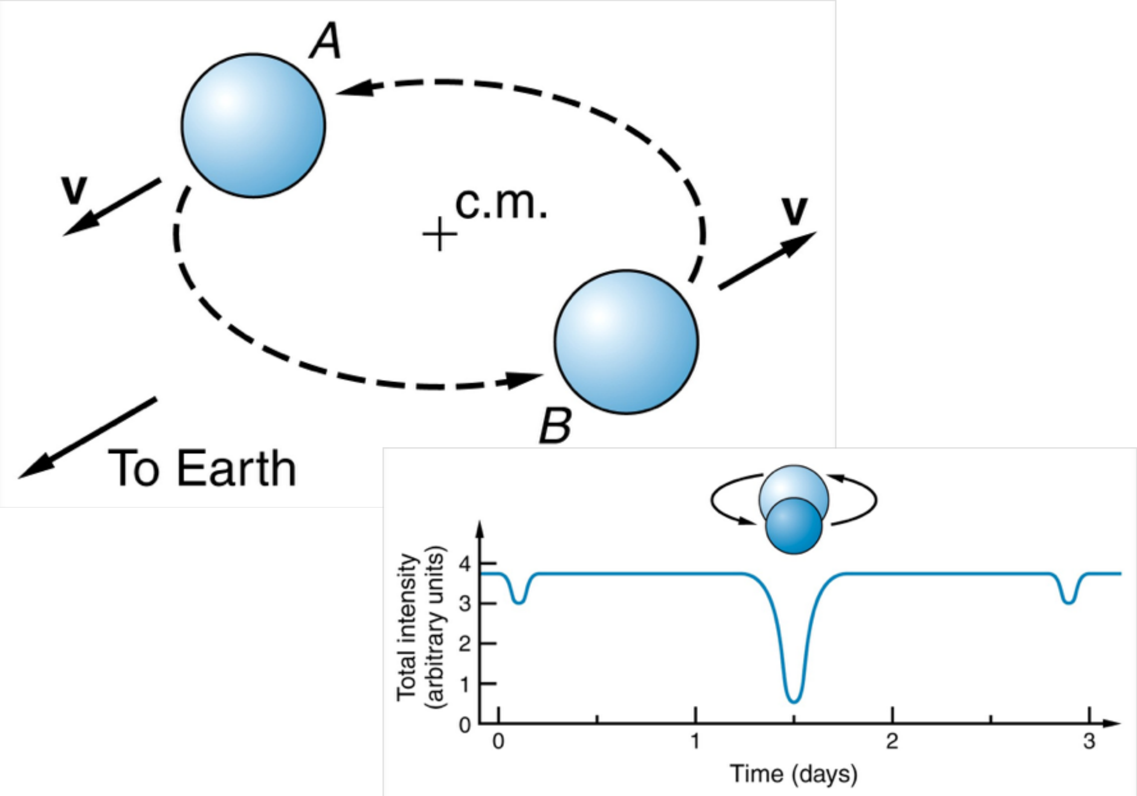
Astrophysical and Cosmological tests



Polarization of ancient light, sensitivity- 10^{-32} - 10^{-42}

Highest energy cosmic rays, constrains on modification of dispersion relation





Light from binary stars such as Algol and simultaneous arrival of all light from supernovae provide best limits for c being independent of velocity of source

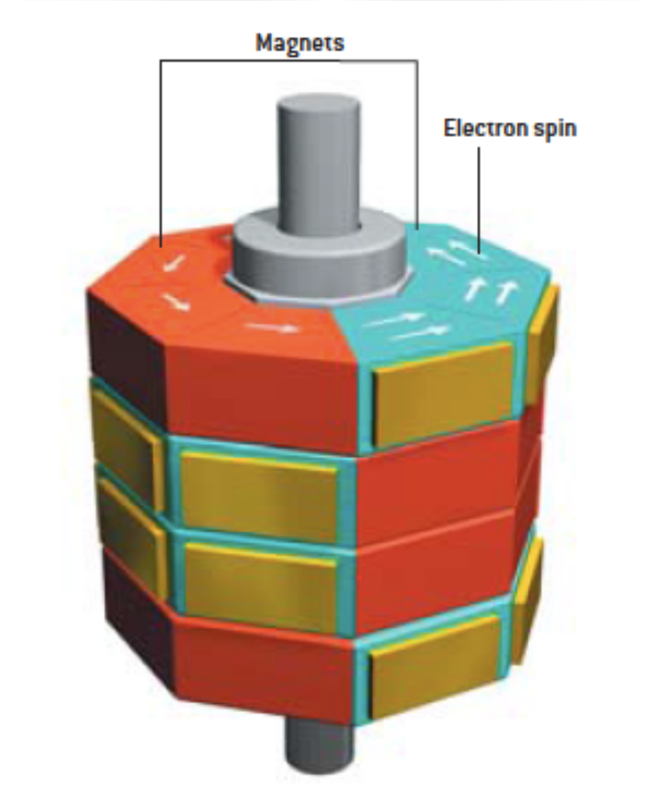
Lorentz symmetry has so far withstood over a century of testing with ever improving sensitivity.

clock comparison experiments

Search for variation in frequency of transitions in nuclei, atoms & molecules as they rotate with the earth or on the ISS

Best results: Walsworth et al. 10^{-31} sensitivity for neutrons

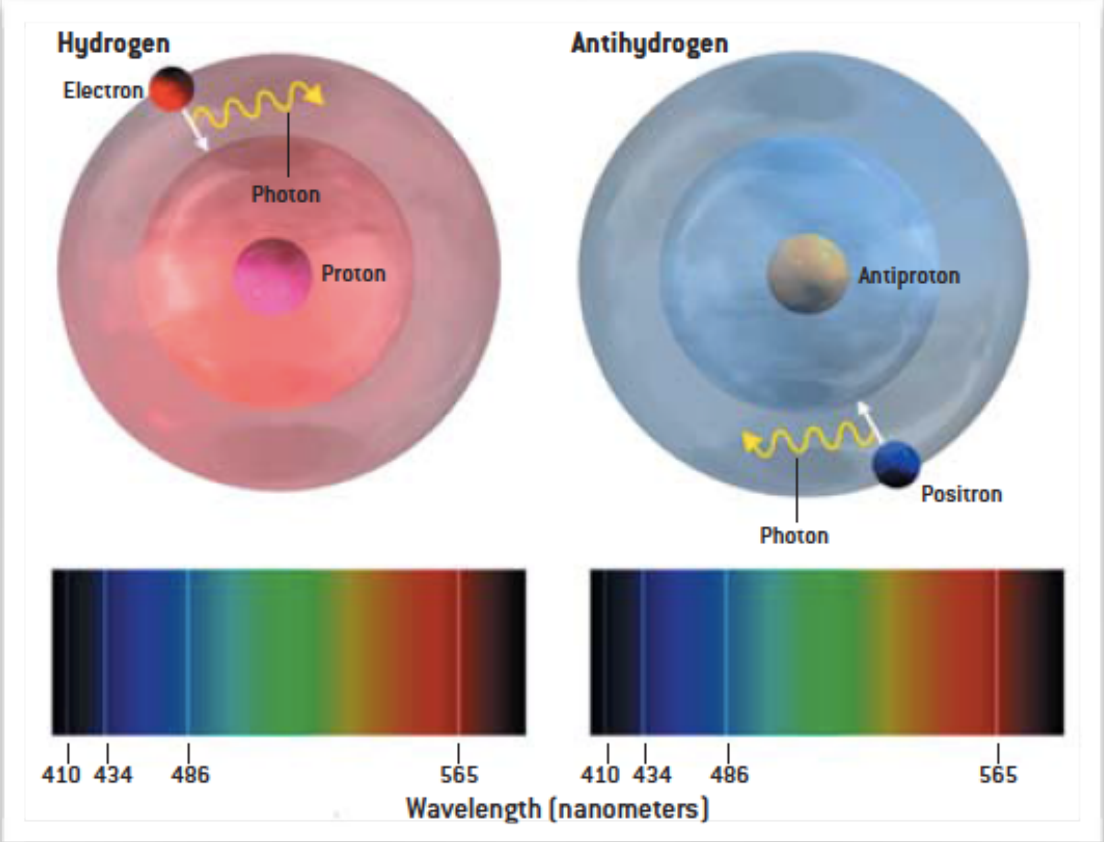
torsion pendulum



Bob made of closed loop of magnets with unbalanced electron spins.

Best results: Heckel et al. 10^{-29} sensitivity for electons

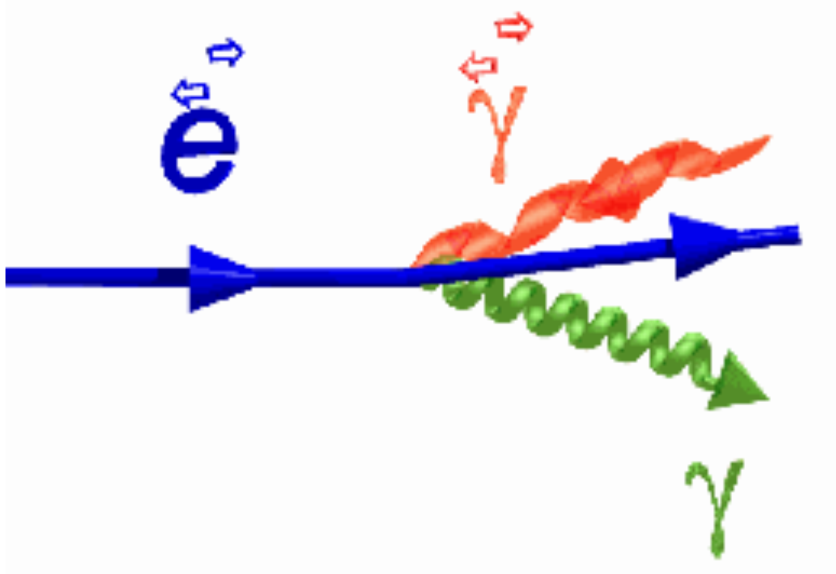
Anti-matter experiments



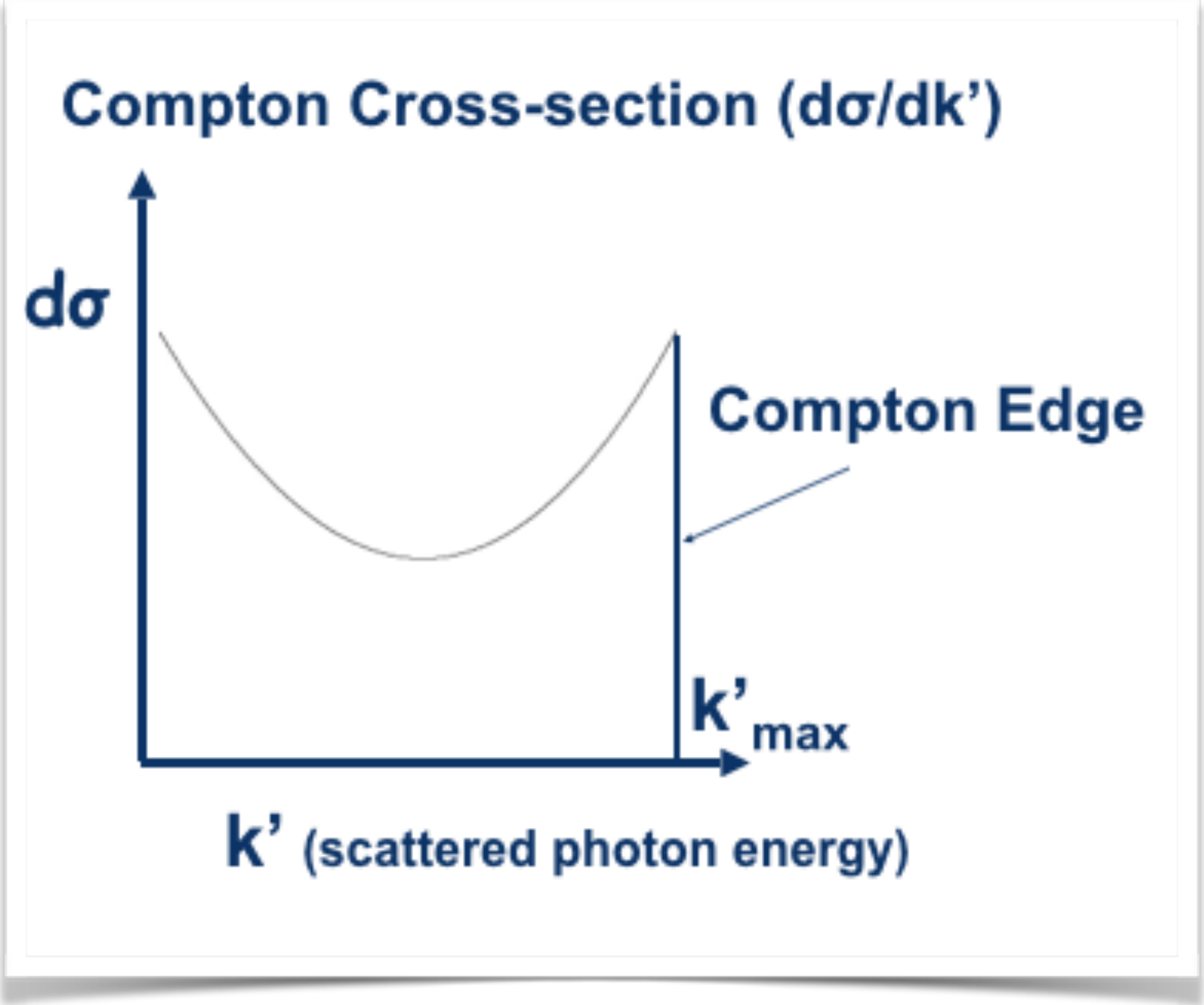
Test of CPT invariance

A large amplification at the kinematic edge in Compton scattering makes it sensitive to Lorentz violation.

Compton scattering: $e(E) + \gamma\,(k) \rightarrow e'(E') + \gamma(k')$



kinematic edge of Compton scattering can be used to precisely measure k’$_{max}$



The modified dispersion relation gives

$$p'_\gamma = p_\gamma^{CE}\left[1+\underbrace{\frac{2\gamma^2}{(1+4\gamma p_\gamma/m)^2}}\vec{\kappa}\cdot\hat{p}\right]$$

lorentz boost $\gamma = p/m$

conventional energy at CE

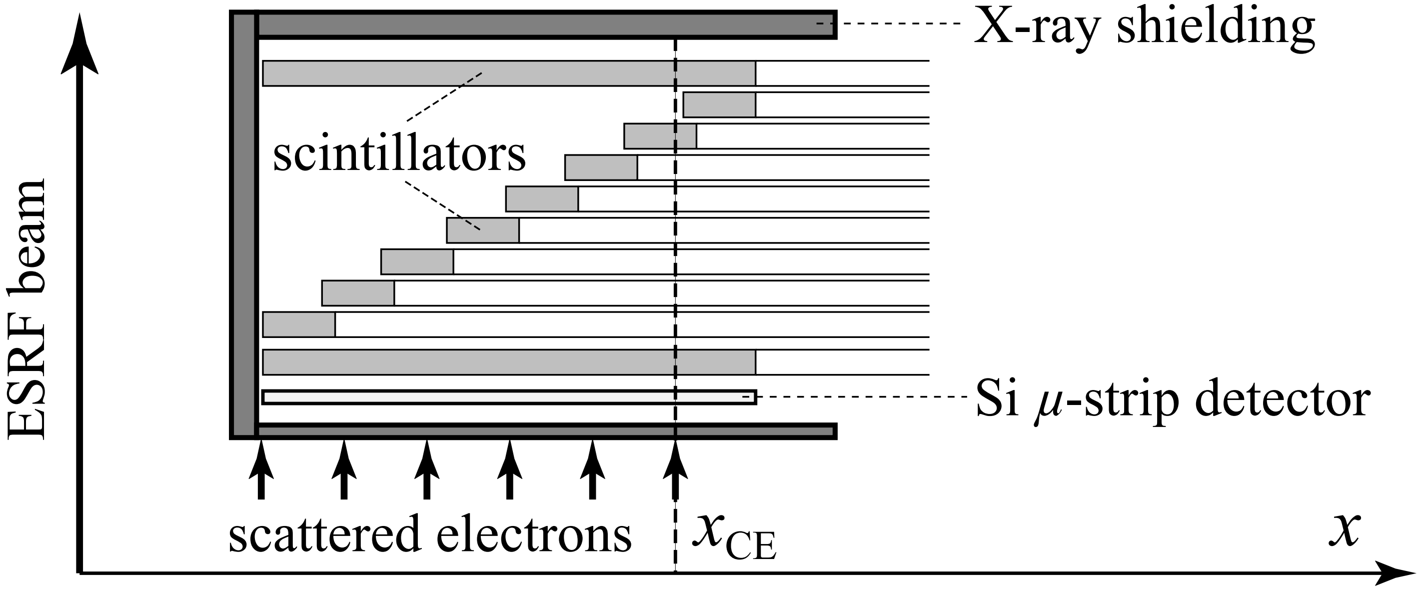
large amplification factor

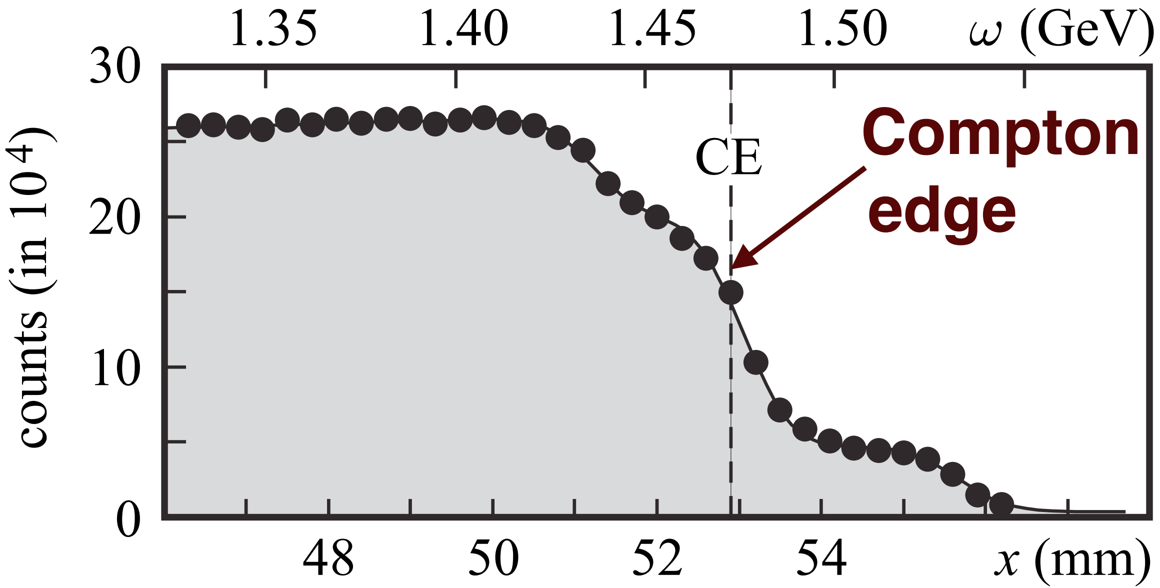
Current best limits for Lorentz violation from Compton scattering come from the GRAAL experiment at ESRF.

GRAAL γ-ray beam is produced by Compton scattering of a laser beam with the 6 GeV ESRF electron beam

Current best limits for Lorentz violation from Compton scattering come from the GRAAL experiment at ESRF.

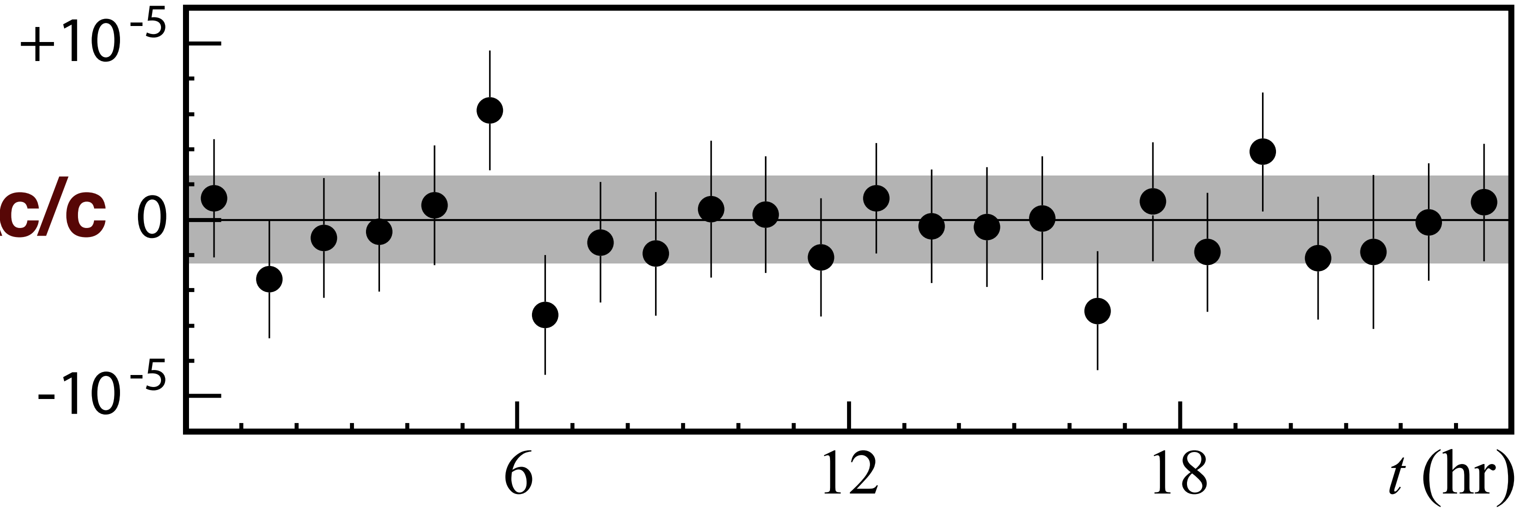
The position of the Compton scattered electron is detected by a Si μ-strip detector.





Compton edge

scattered electron position



Δc/c

sidereal hour

Sidereal variation of the position of the Compton edge provides a ~ 10^{-14} limit on Lorentz violating SME parameters in the electron-photon sector.

J. -P. Bocquet et al., Phys. Rev. Lett. 104, 241601 (2010)

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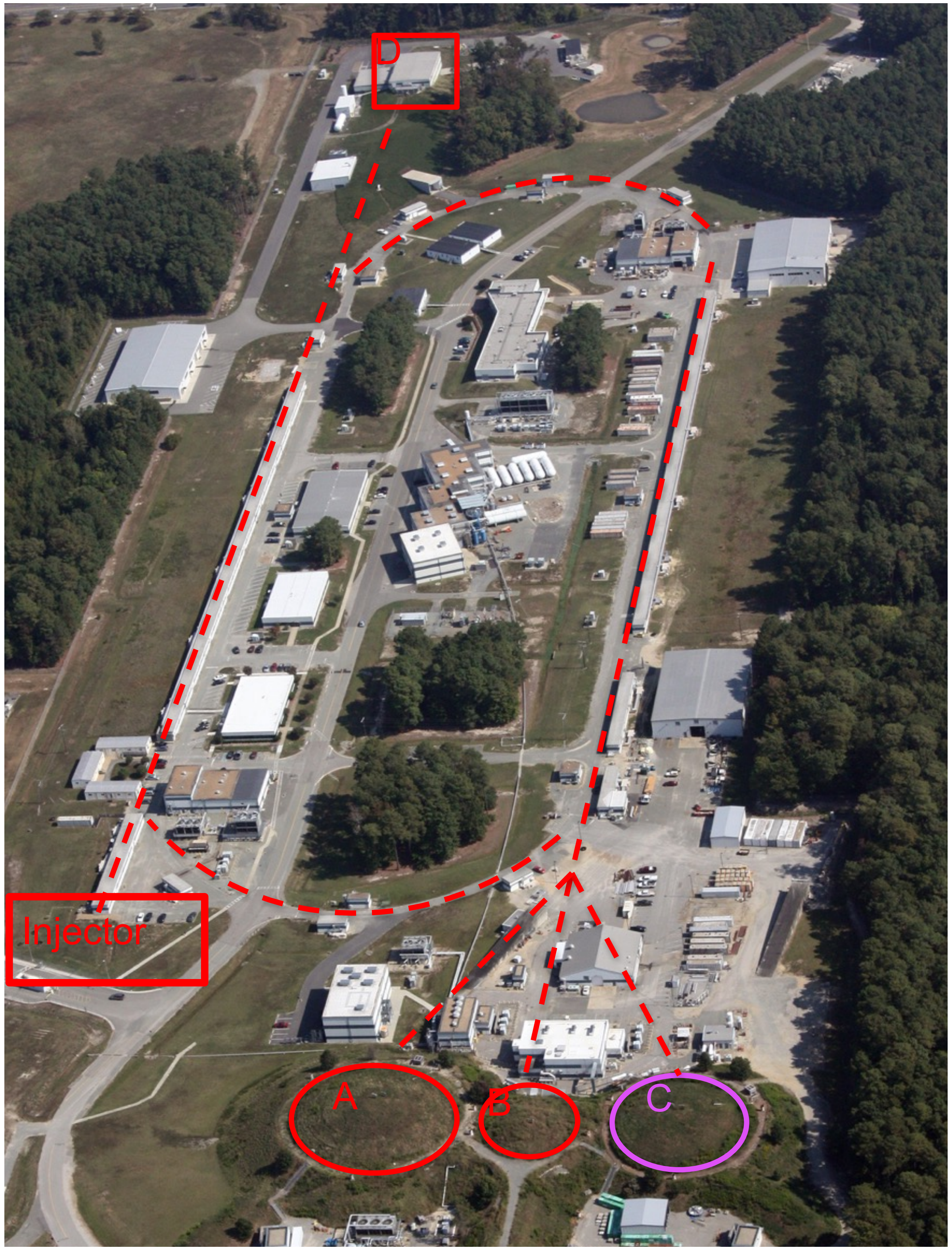
The Q-Weak experiment at Jefferson Lab measured parity- violating elastic ep scattering at low energies.



Installed and run in experimental Hall C at Jefferson Lab: 2010-2012

Aim: Measure PV asymmetry in elastic ep scattering at $Q^2 \sim 0.025$ GeV^2

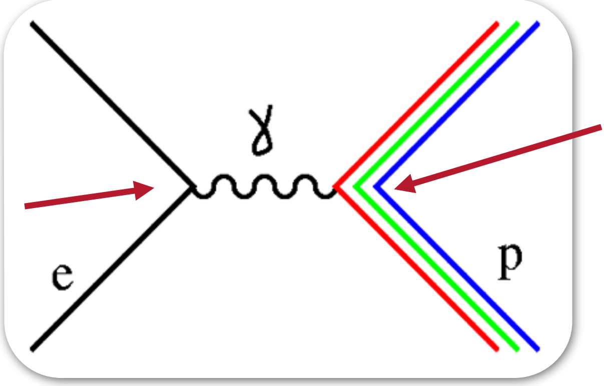
Nominal asymmetry ~ -230 ppb

Three distinct run periods:

1. Fall 2010-January 2011: Commissioning
2. January-Spring 2011: Run 1
3. Fall 2011-Spring 2012: Run 2

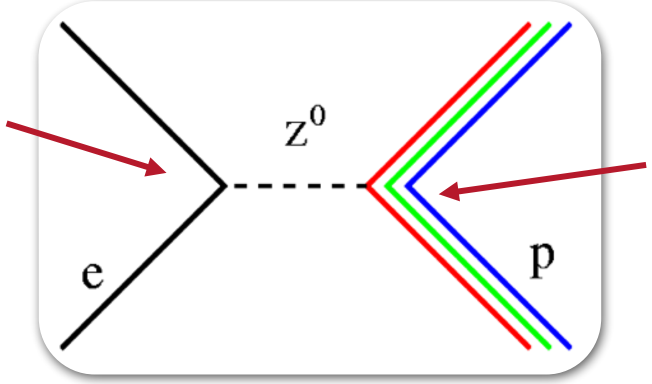
The Q-Weak experiment is a measurement of the weak charge of the proton using parity-violating electron scattering.

$\sqrt{\alpha} = \frac{e}{\sqrt{hc}}$



EM Charge

$\frac{e}{\sqrt{hc}}$



Weak Charge

Q^p_W , G^p_W

q^{up}	$+2/3$	$1 - \frac{8}{3}\sin^2\theta_W \approx 1/3$
q^{down}	$-1/3$	$-1 + \frac{4}{3}\sin^2\theta_W \approx -2/3$
$Q^p = 2q^{up} + 1q^{down}$	$+1$	$1 - 4\sin^2\theta_W = .048$
$Q^n = 1q^{up} + 2q^{down}$	0	-1

$Q_w{}^p$ is the neutral-weak analog of the proton's electric charge

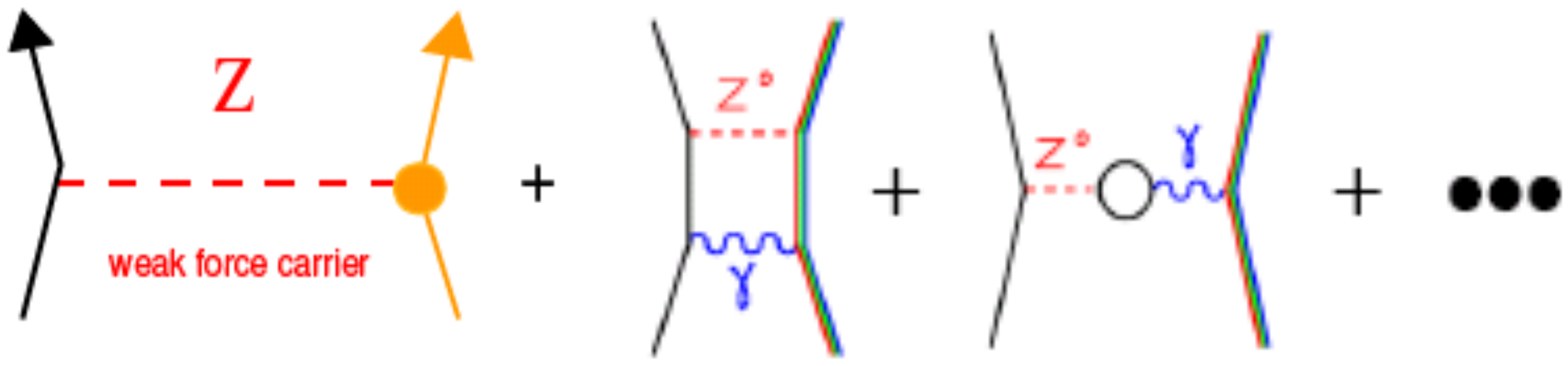
neutron weak charge is dominant, proton weak charge is almost zero.

The θ_W parametrizes the relative strength of the EM and Weak interaction

This suppression allows a sensitive measurement of **$\sin^2\theta_W$ at low energies,** and a search for **new PV interactions** between electrons and light quarks.

The suppression of the proton's weak charge in the SM makes it a sensitive probe of BSM interactions.

The weak charge is not constant



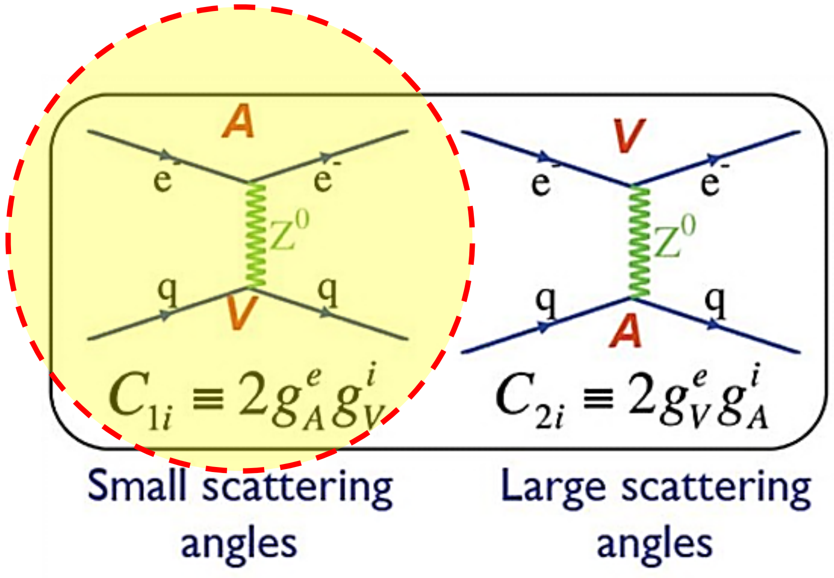
If large mass particle is exchanged among these virtual particles, $\sin^2\theta_W$ would deviate from the SM prediction.

$$\delta\, Q_W^p = \pm 4\% \;\Rightarrow\; \delta(\sin^2\theta_W) = \boxed{\pm\ 0.3\%}$$

Sensitive to "New Physics" at the TeV scale

Parity- violating elastic ep scattering can provide access to the proton's weak charge and thereby $\sin^2\theta_W$.

Parity violation in electron scattering arises from V x A couplings of the Z.



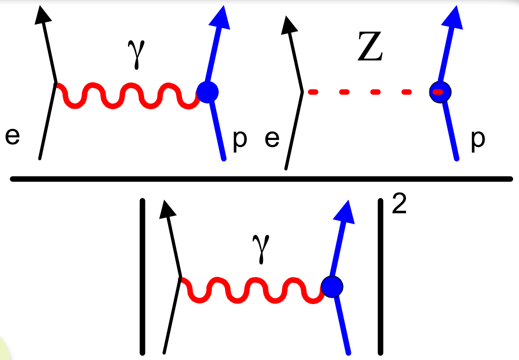
$C_{1i} \equiv 2g_A^e g_V^i$ $C_{2i} \equiv 2g_V^e g_A^i$

Small scattering angles

Large scattering angles

We want A(e) x V(q) to dominate.

$$A_{PV} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} =$$



We isolate the small EM x WEAK interference term, normalized to $|EM|^2$, thru the PV asymmetry.

depends on proton form factors

At low momentum transfer and forward kinematics, the leading order term for elastic scattering contains the weak charge:

- Recast $A_{ep} = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left[Q_w^p + Q^2 B(Q^2,\theta)\right]$ **(~ -200 ppb)**
  - So in a plot of $A_{ep}/\left[\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\right]$ vs Q^2:
    - **Q_w^p is the *intercept*** (anchored by precise data near Q^2=0)
    - $B(Q^2,\theta)$ is the ***slope*** (determined from higher Q^2 PVES data)

At our chosen kinematics, Q_w^p is ~2/3 of the asymmetry

How Small is the 200 ppb Q-weak PV Signal?

It is same as measuring the width of a single hair from the end of a regular soccer field.

And we had to measure it with a few % precision.

Source of error	Contribution to $\Delta A_{phys}/A_{phys}$	Contribution to $\Delta Q_w^p \,/Q_W^p$
Counting Statistics	2.1%	3.2%
Hadronic structure	—	1.5%
Beam polarimetry	1.0%	1.5%
Absolute Q^2	0.5%	1.0%
Backgrounds	0.7%	1.0%
Helicity-correlated beam properties	0.5%	0.8%
TOTAL:	2.5%	4.2%

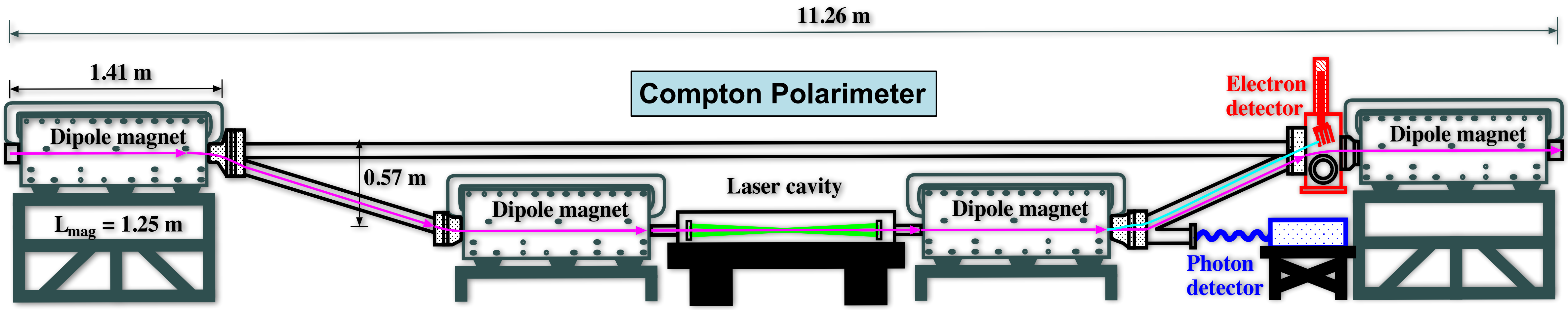
$\delta A_{PV} \approx \pm 2.5\%$

$\Rightarrow \delta Q^p_W \approx \pm 4.2\%$

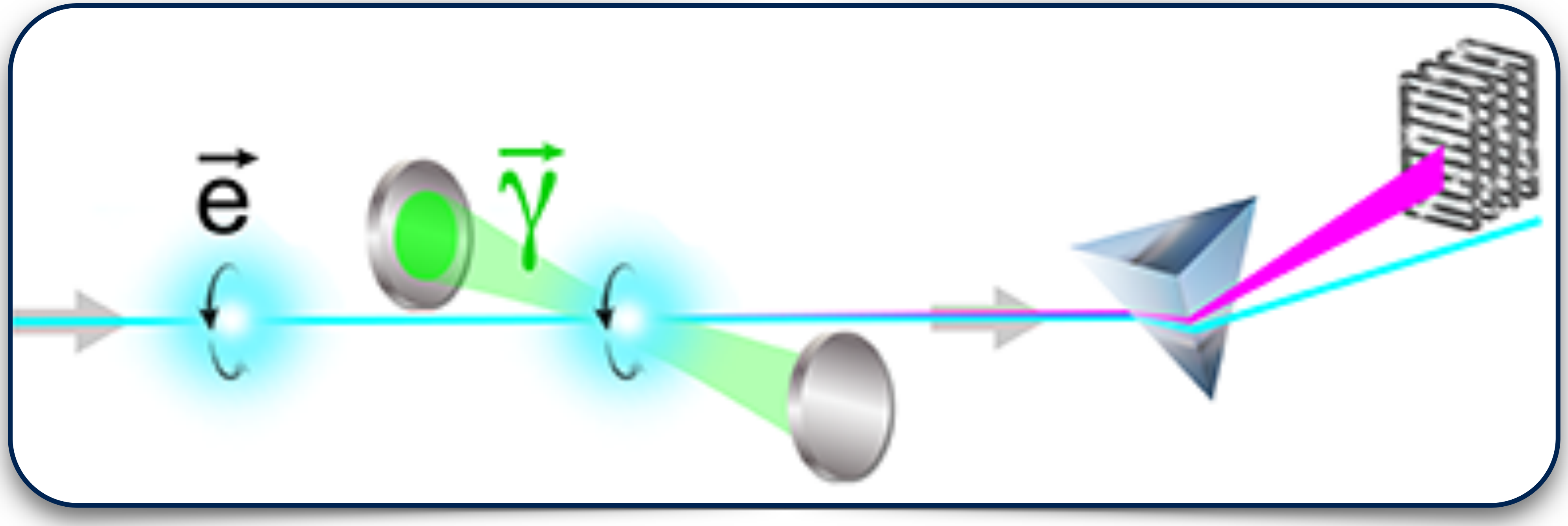
$\Rightarrow \delta(\sin^2\theta_W) \approx \pm 0.3\%$

at the chosen kinematics

A new Compton polarimeters was used to provide sub-1% polarimetry.



Compton scattering: $e(E) + \gamma\ (k) \rightarrow e'(E') + \gamma(k')$



The Compton scattering cross section and asymmetry are very precisely known in QED.

Compton scattering: $e(E) + \gamma\ (k) \rightarrow e'(E') + \gamma(k')$

cross-section

$$\frac{d\sigma}{dk'} = \frac{d\sigma_0}{dk'}[1 + P_\gamma P_e A_Z]$$

$$= A_{expt} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$

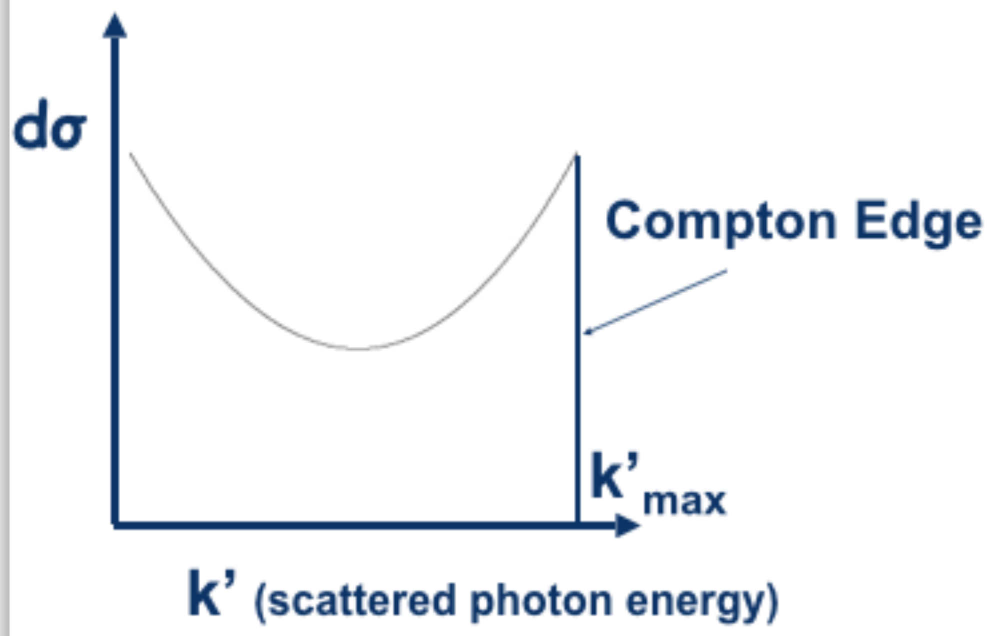
$$\boxed{\therefore P_e = \frac{A_{expt}}{P_\gamma A_z}}$$

$\frac{d\sigma_0}{dk'}, A_z$ (known precisely from QED)

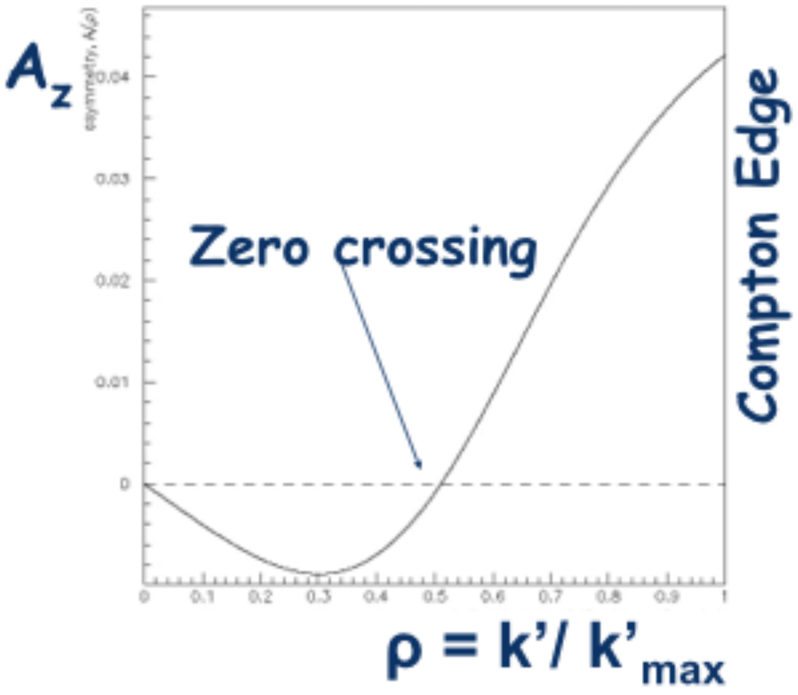
P_γ = circular polarization of photon (~100%)

P_e = longitudinal polarization of electrons

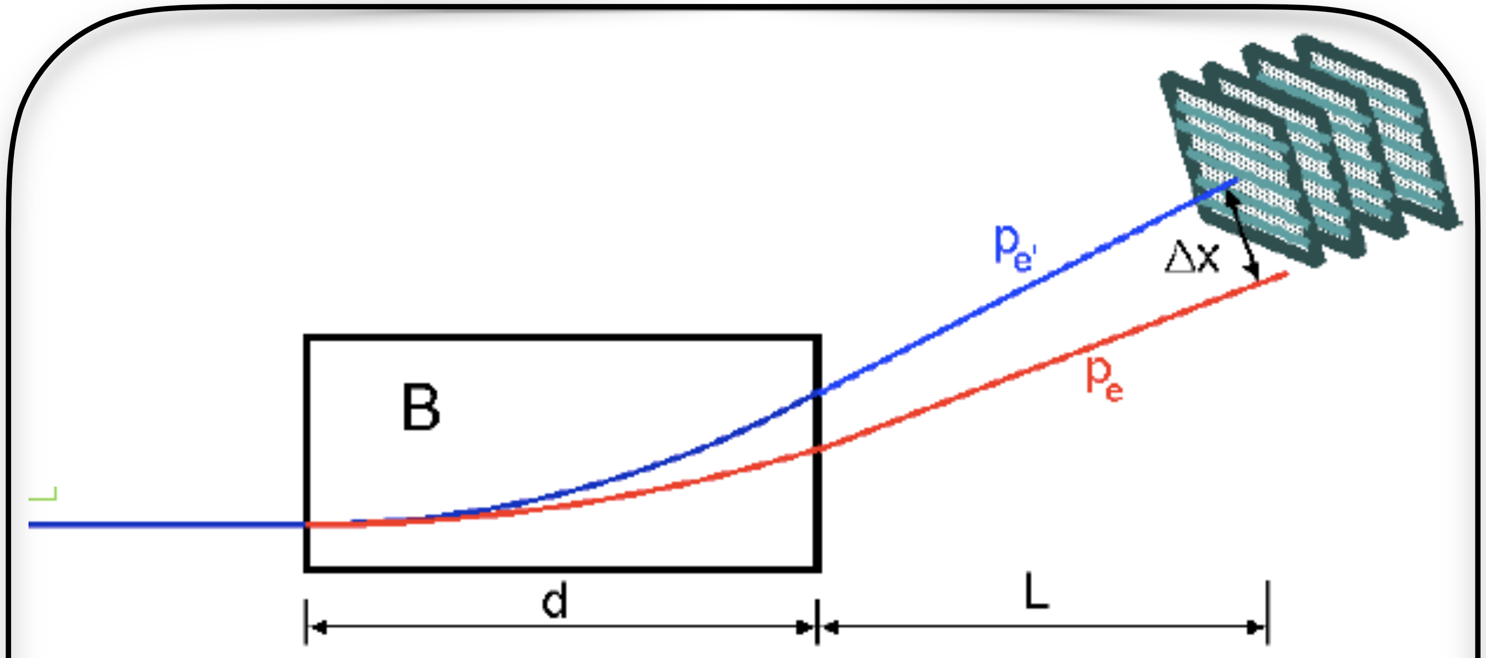
Compton Cross-section (dσ/dk')



Compton Asymmetry



Polarization of electron beam is extracted by fitting the measured asymmetry to the QED calculation.



$$\Delta x_{\text{measured}} \xrightarrow[(p_e,\, B_{\text{map}},\, L)]{} p_{e'} \longrightarrow \rho = k'/k$$

$$A(\rho)_{\text{Theory}} \longrightarrow A(\Delta x)_{\text{Theory}}$$

electron polarization

photon polarization

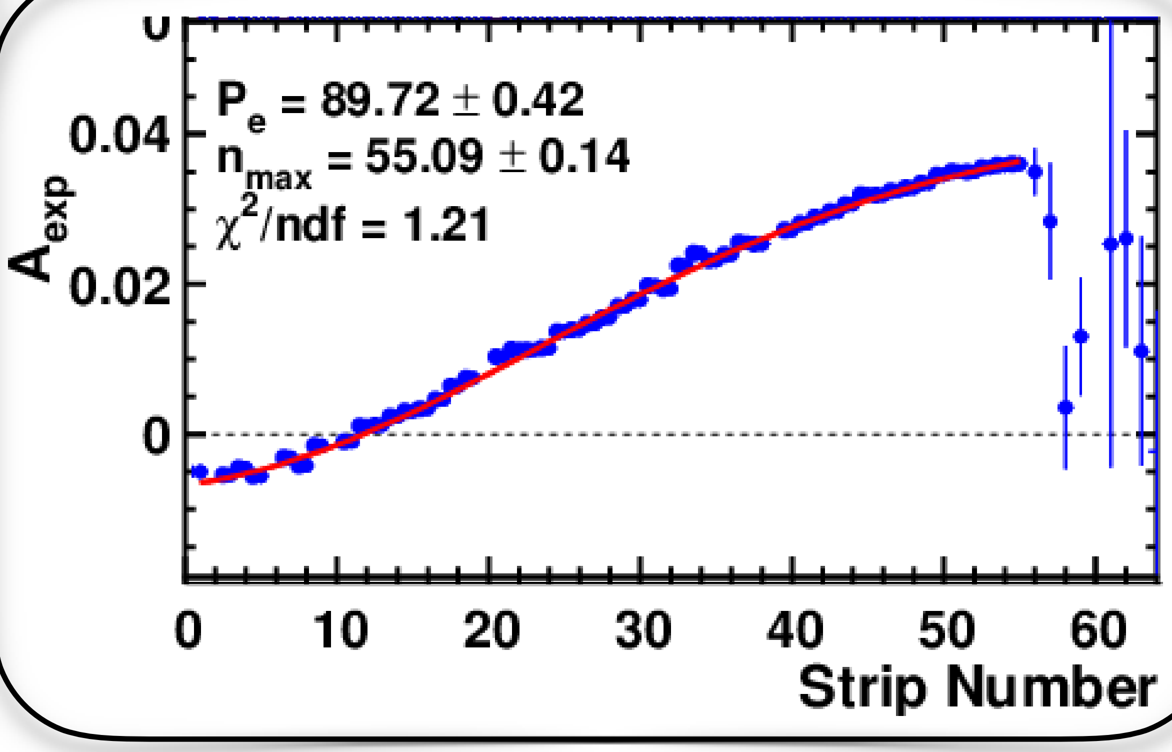
$$A^{n}_{\text{exp}} = P_e P_\gamma A^{n}_{\text{th}}$$

measured asymmetry on nth strip

calculated asymmetry for nth strip

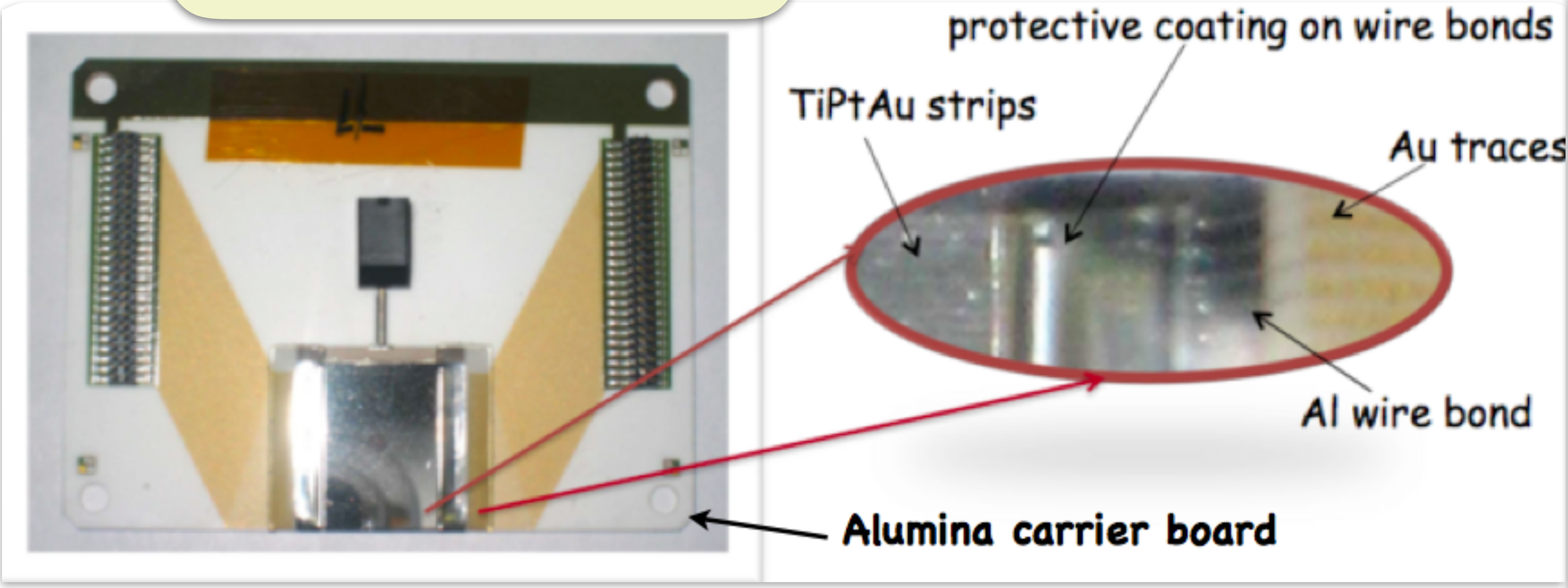
fit of measured to calculated asymmetry with P_e and n_{max} as parameters

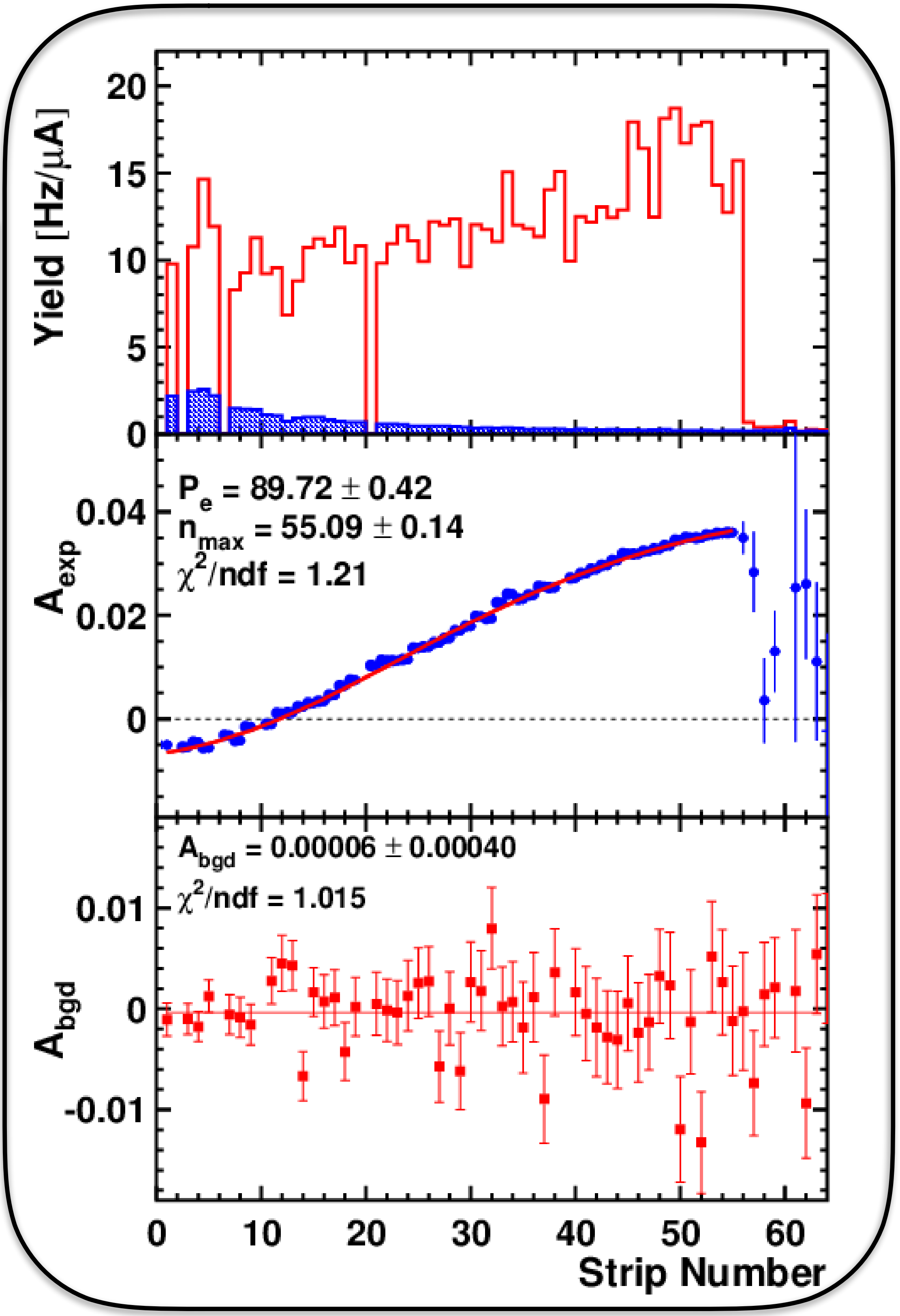
n_{max} is the strip with the Compton edge



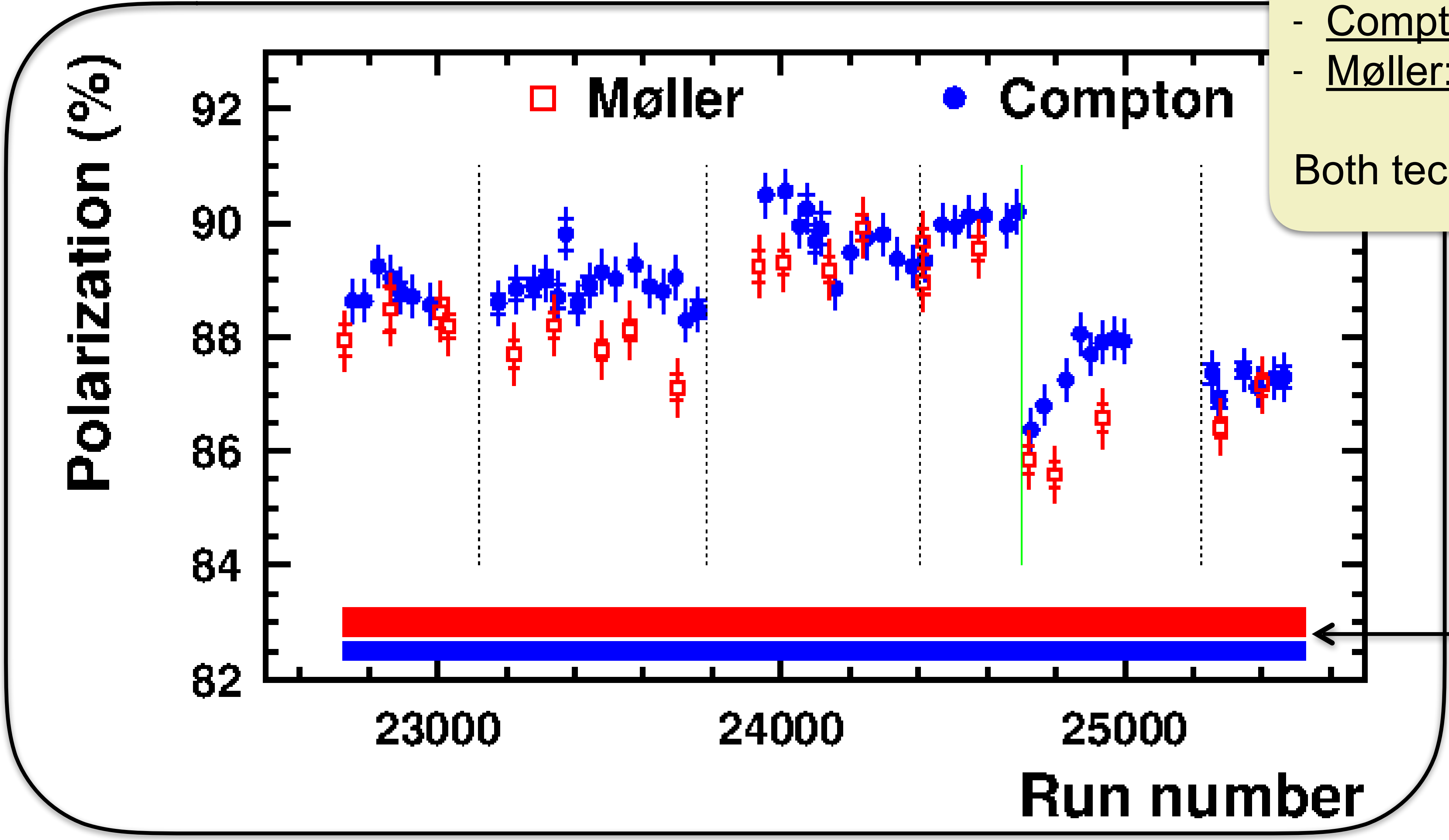
MSU group led the Compton electron detector effort

Compton e-detector: First use of a diamond micro-strip detector in an experiment.





Moller and Compton polarimeters together provided sub-1% polarimetry.



Systematic uncertainties
- Compton: dP/P = 0.59%
- Møller: dP/P = 0.84%

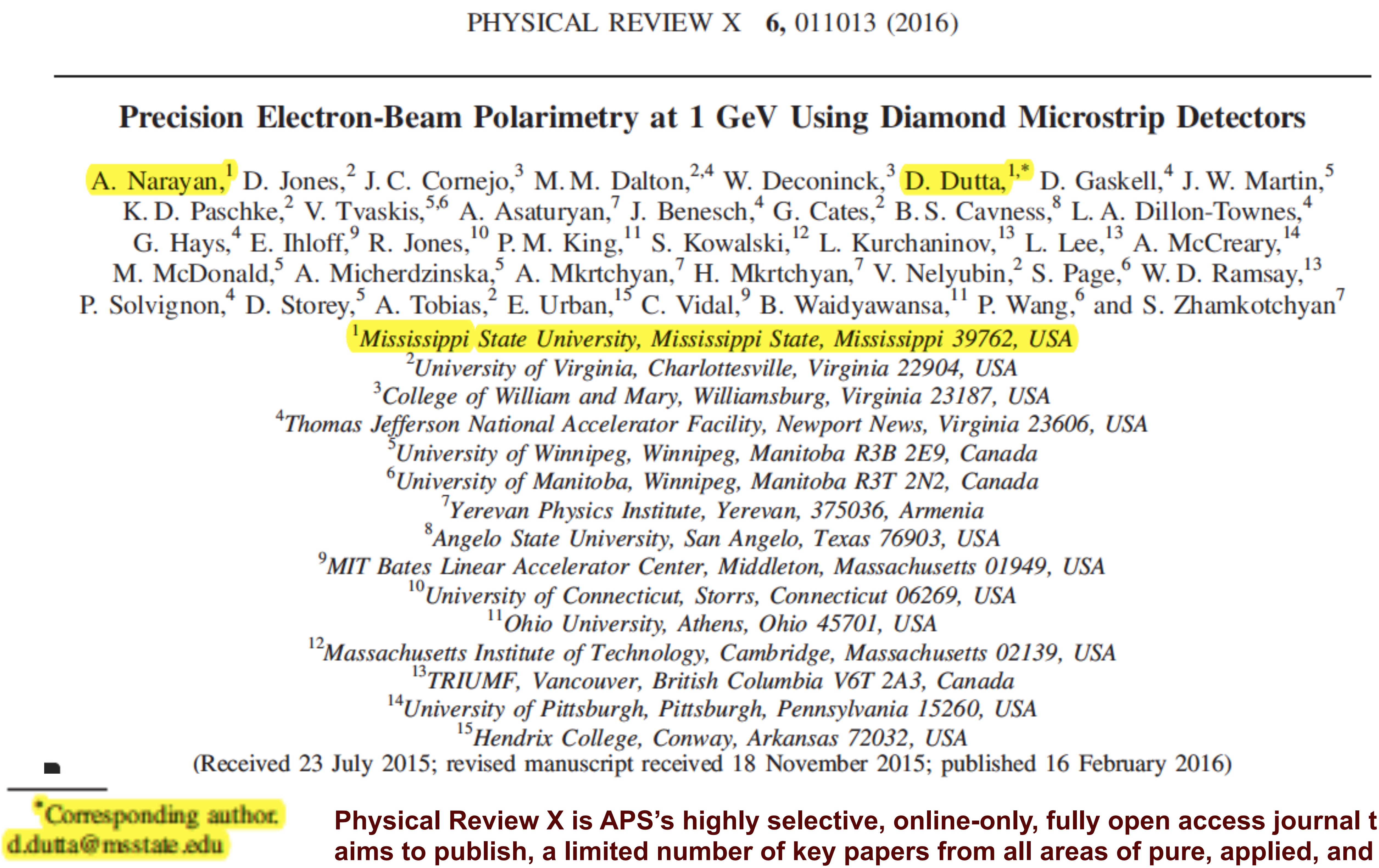
Both techniques agree to < 0.8%

Normalization uncertainties

***P_{Moller}* +/- stat (inner) +/- point-to-point systematic (0.53%)**

***$P_{Compton}$* +/- stat +/- point-to-point syst. (0.41%)**

The Compton polarimetry results were recently published in PRX.



PHYSICAL REVIEW X **6,** 011013 (2016)

Precision Electron-Beam Polarimetry at 1 GeV Using Diamond Microstrip Detectors

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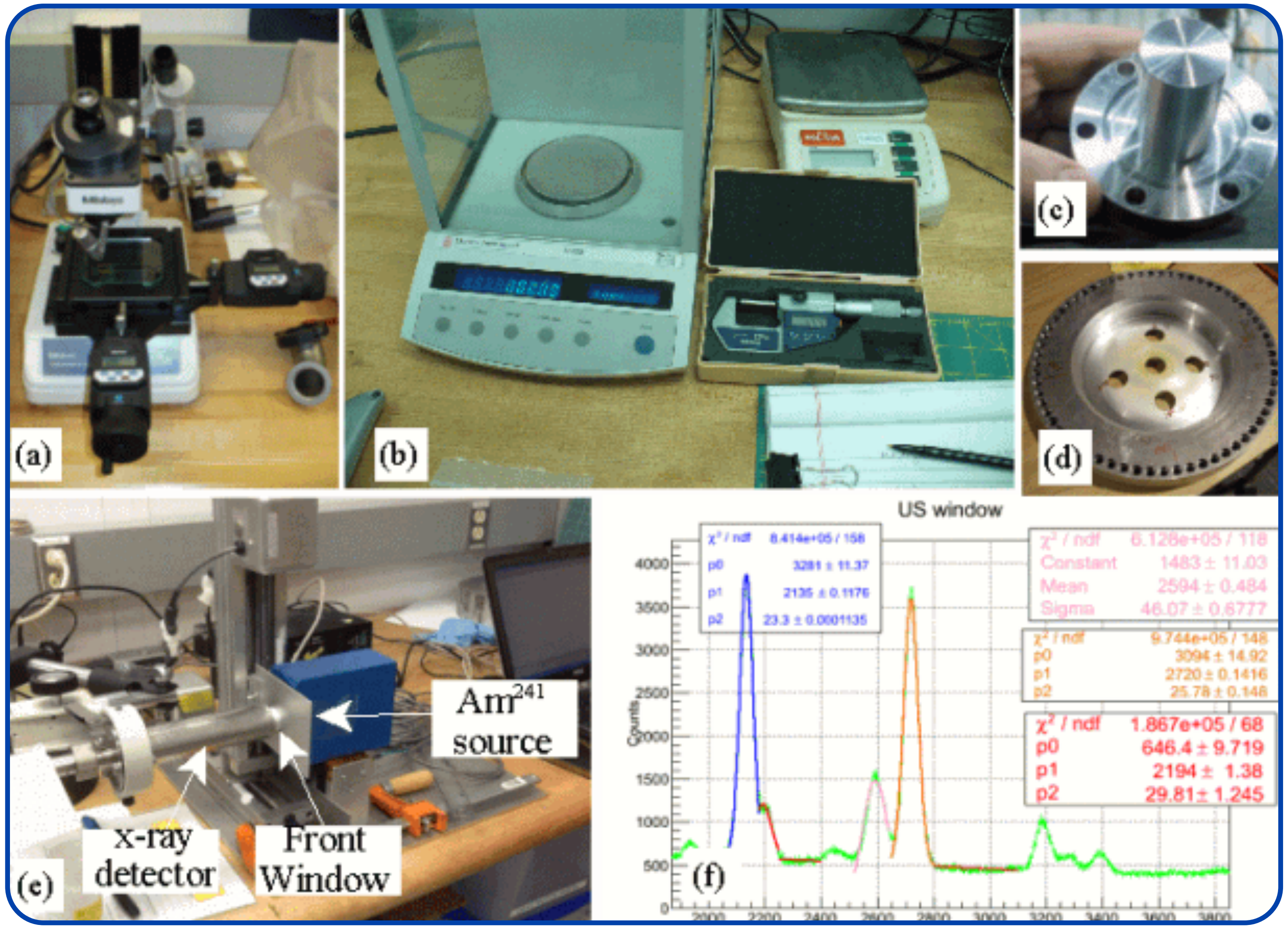
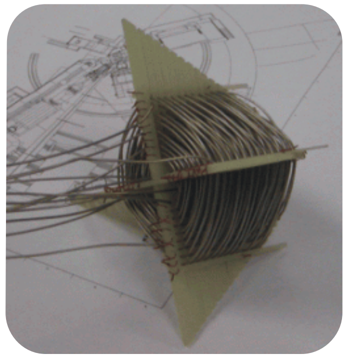
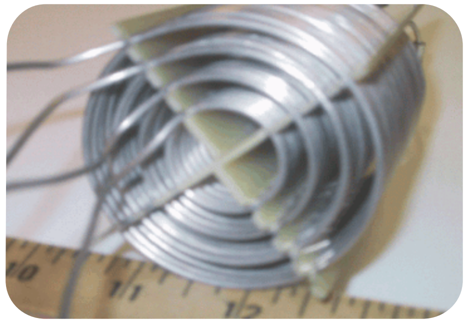
Physical Review X is APS's highly selective, online-only, fully open access journal that aims to publish, a limited number of key papers from all areas of pure, applied, and interdisciplinary physics, that merit broad dissemination and high visibility.

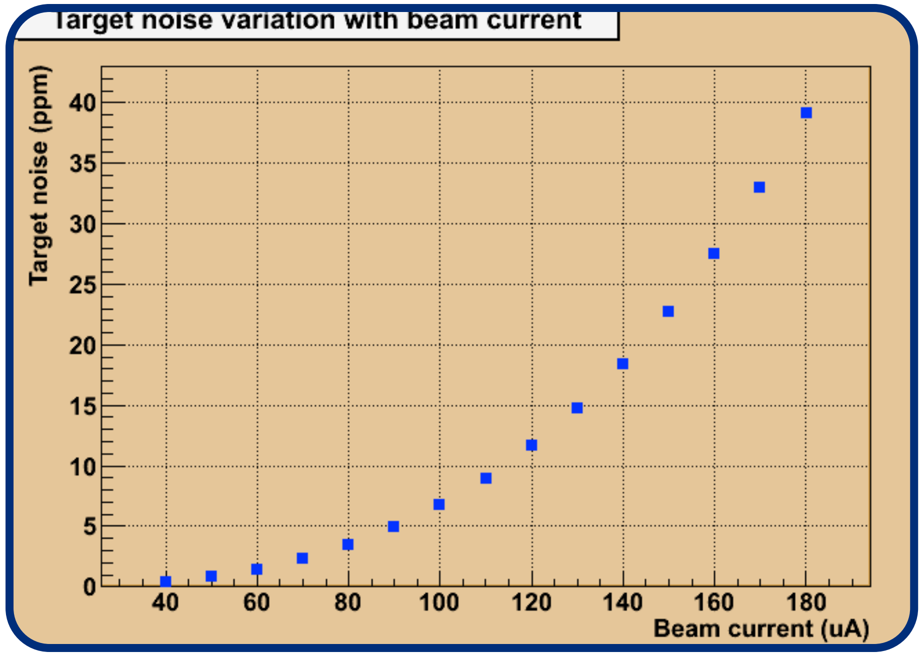
MSU group (Jim Dunne) along with JLab led the cryogenic target effort for QWeak

Miss. State group also designed and built the high power heater, the solid target ladder, the target motion system and parts of the control software



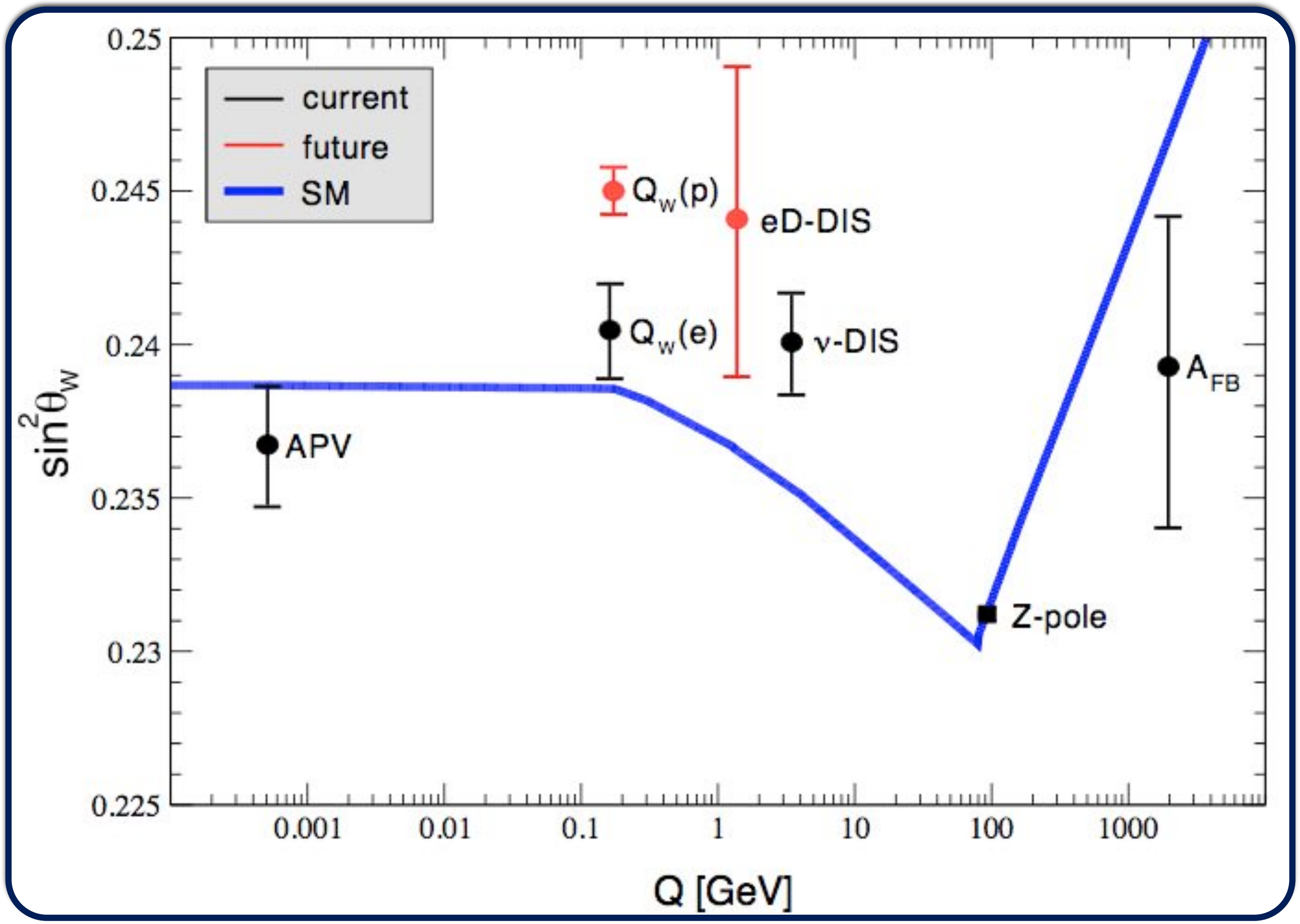






It was the highest power liquid Hydrogen target in the world (35 cm long, 2.5KW)

Miss. State was a major player in the successful running of the QWeak experiment.



- 2 Miss. State students were QWeak thesis students, they were experts on call for the Compton (Amrendra Narayan) and the liquid hydrogen target (Adesh Subedi).
- Jim Dunne and DD were run coordinators several times
- DD spend 6-mo on sabbatical leave during installation and commissioning
- A third grad student and post-doc also participated

MSU group took cumulative 260 shifts and we are deeply involved in the analysis. Adesh Subedi won the JLab thesis prize in 2015.

Outline

- Introduction (What & Why?)
- Over a century of Lorentz symmetry tests (How others did it?)
- A brief detour (An oblique connection to LI !)
- Lorentz invariance test with Compton asymmetry (How we did it?)
- Summary

The Compton asymmetry is sensitive to Lorentz violation because of the kinematic amplification factor.

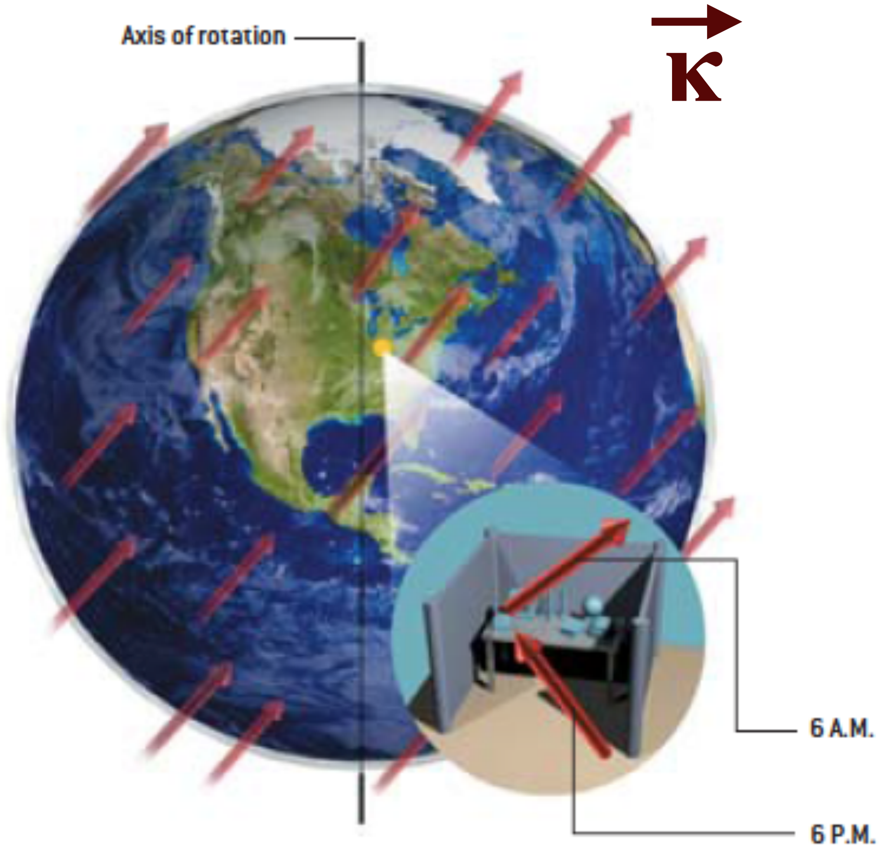
The Compton asymmetry is calculated as a function of a dimensionless variable

$$\rho = \frac{E_\gamma}{E_\gamma^{\mathrm{max}}}$$

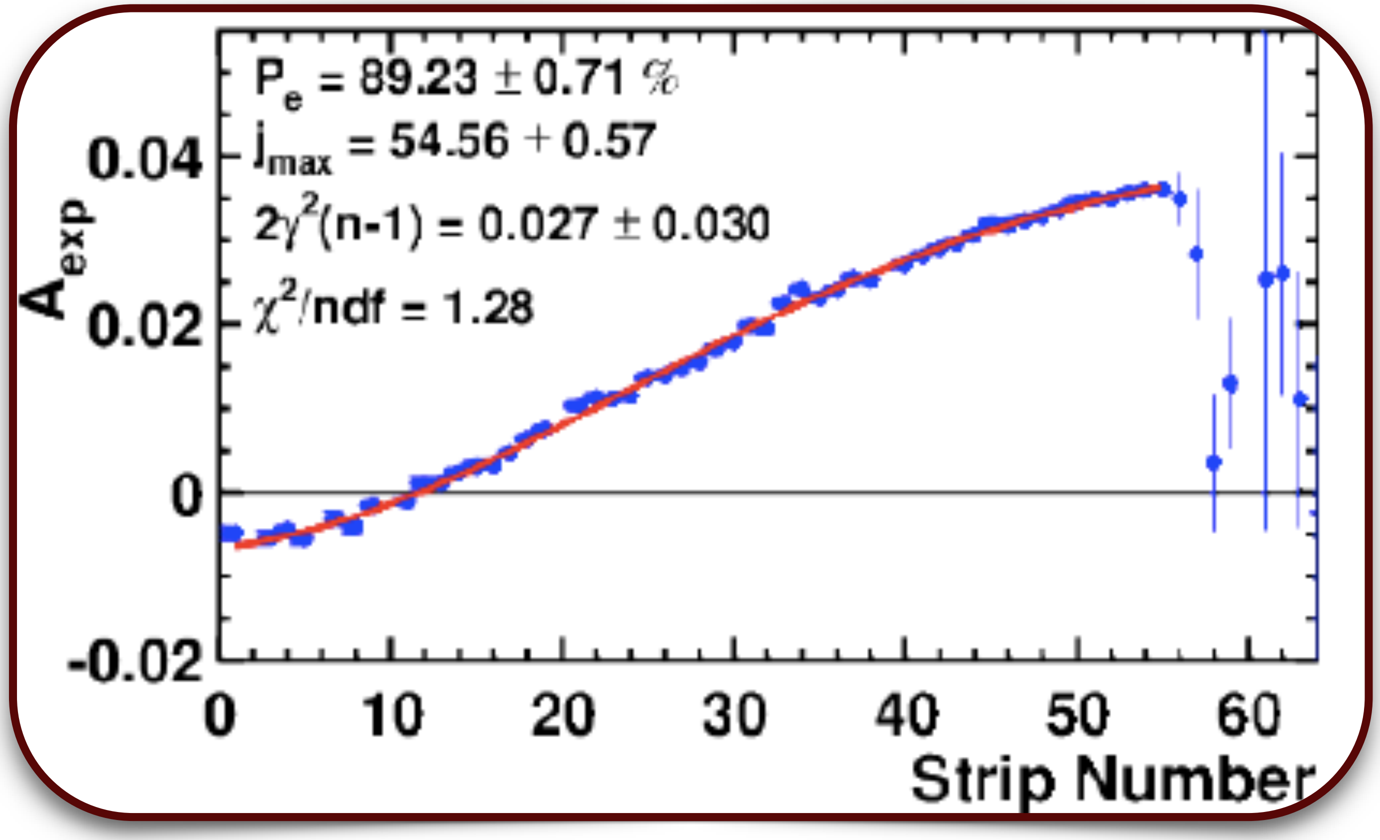
The modified dispersion relation leads to

$$\rho(n) = \rho\left[1 + \underbrace{2\gamma^2(n-1)f(x,\theta)}_{\text{large amplification factor}}\right]$$

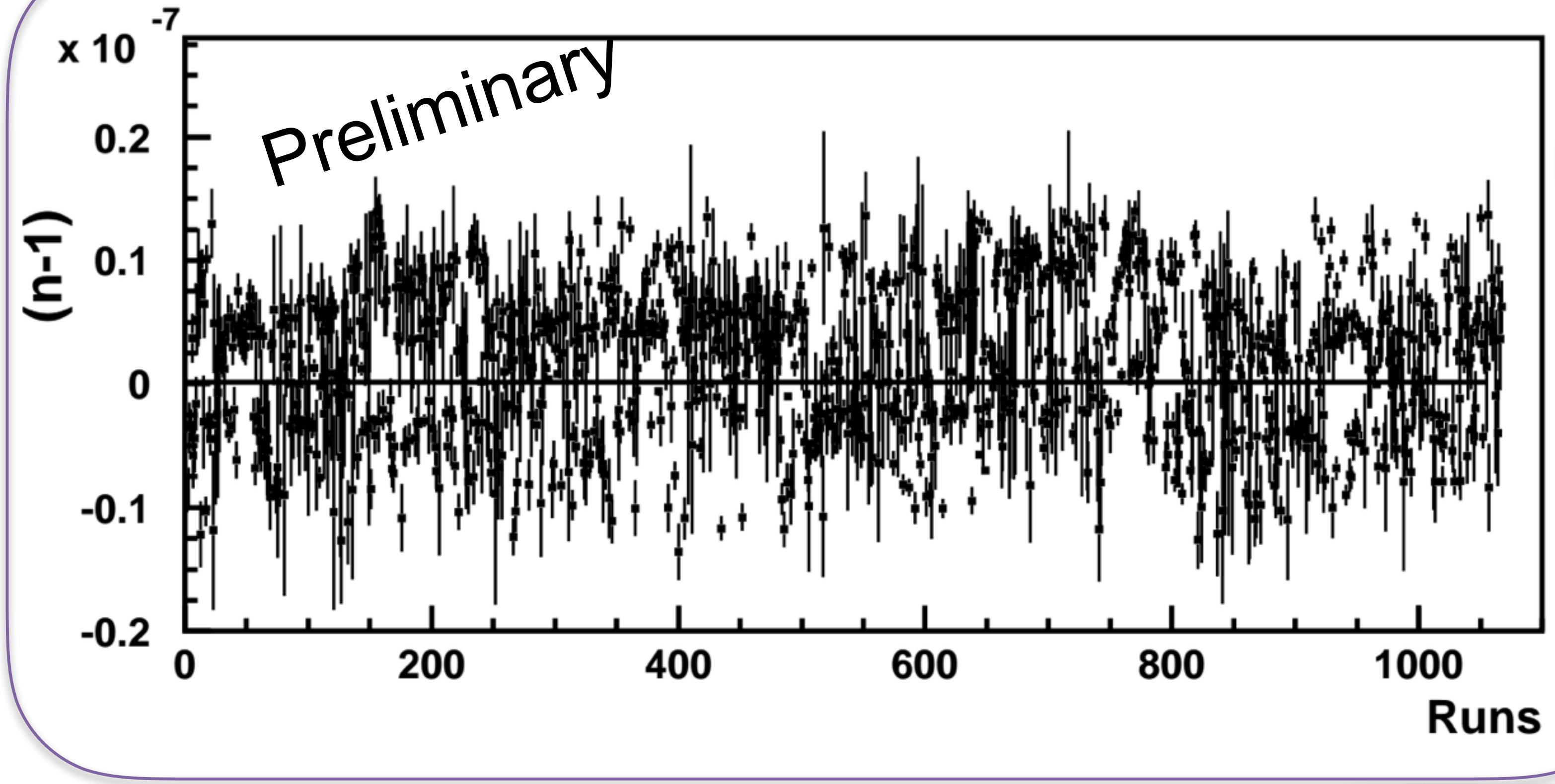
where the vacuum refractive index is $\mathrm{n} \approx [1 + \vec{\kappa}\cdot\hat{\mathrm{p}}]$



Asymmetry data is refit with electron polarization, CE and $2\gamma^2$(n-1) as parameters



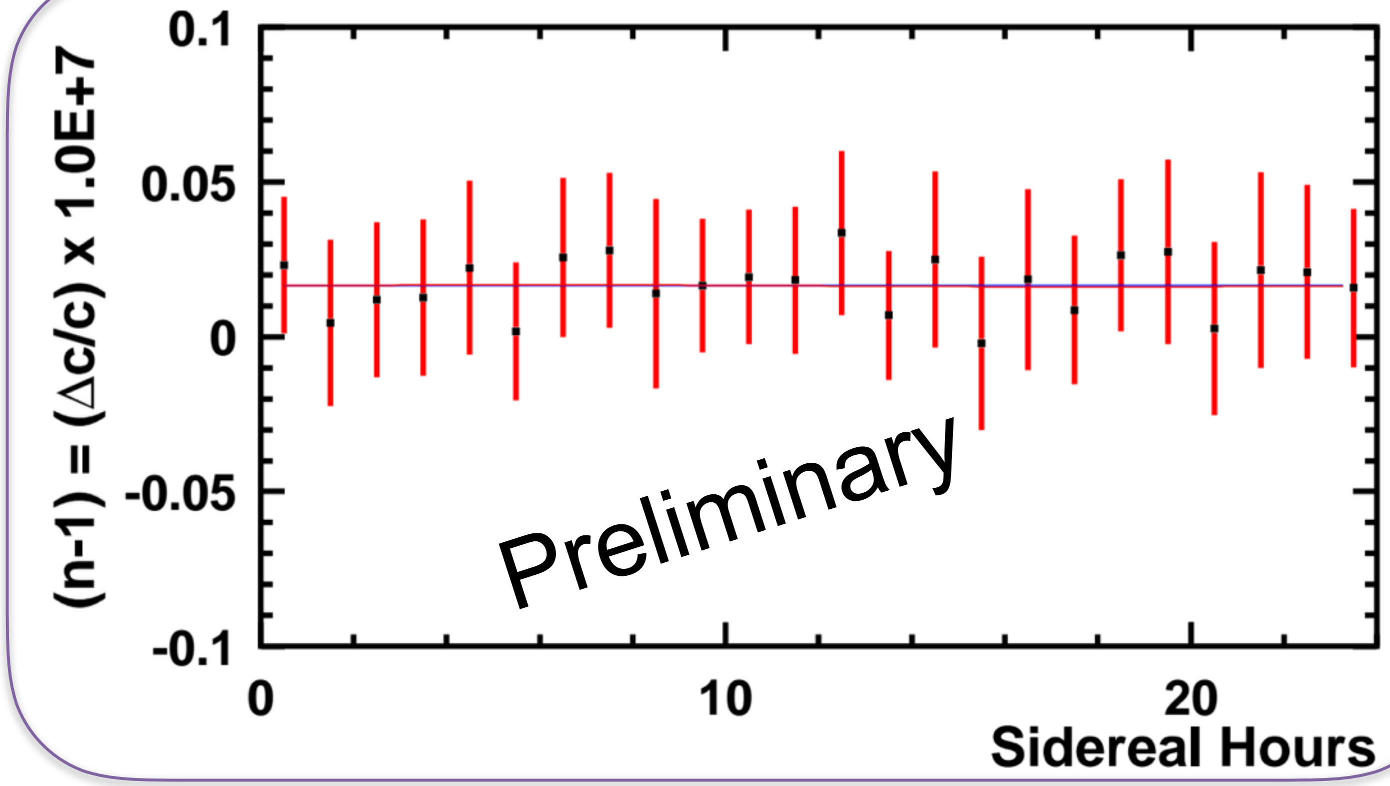
Asymmetry data was used to look at the sidereal variation of the speed of light, as a test of Lorentz invariance.



n - 1 = $\Delta c/c = 2.4 \pm 6.8 \times 10^{-9}$

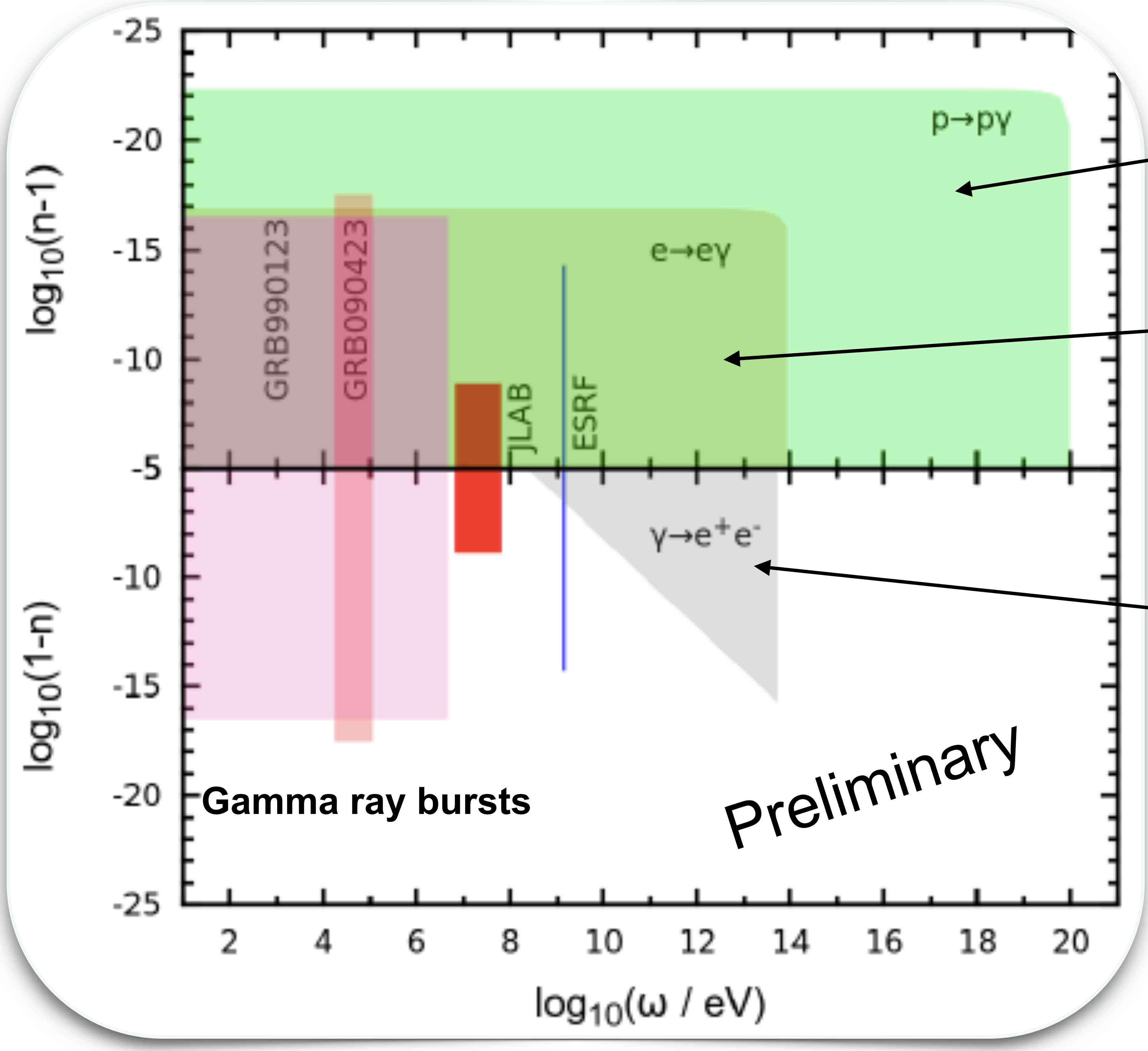
about 6 months of ~ 1 hr long runs were binned in sidereal hours to look for sidereal variation.

When interpreted within the minimal SME we get constrains on the combined photon and electron parameters ~10^{-9}



Future JLab experiments with higher beam energies will provide much higher sensitivity and stronger constraints.

Asymmetry data also provide new constraints on the photon energy dependence of the speed of light.



Highest energy cosmic ray protons

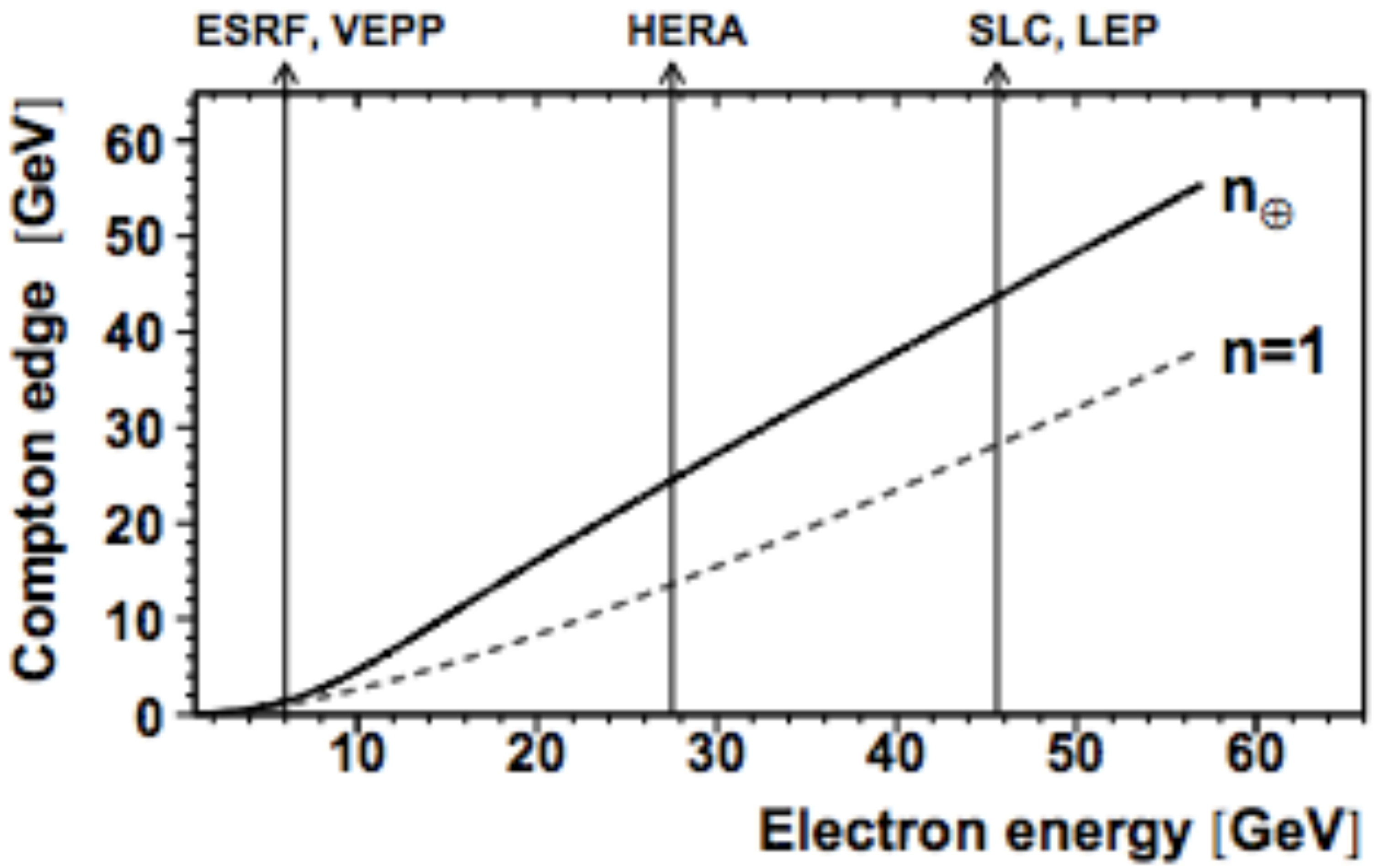
Highest energy cosmic ray electrons

Highest energy cosmic ray photons

Future Compton data will be sensitive to GR effects as well

The bending of light in Earth's gravitational field cause a few times 10^{-9} shift in the vacuum refractive index

$$n_\oplus = 1 + \frac{2GM_\oplus}{c^2 R_\oplus}.$$



Summary

- Sensitive tests of Lorentz invariance are one of the bests ways to look for new forces beyond the standard model.

- The SME formalism provides a framework to quantify such tests

- Lorentz symmetry has withstood over a century of testing.

- Compton scattering provides another mechanism to test Lorentz symmetry, the energy at the Compton edge as well as the Compton asymmetry provide sensitivity.

- Future experiments that use the higher energy beam at JLab will be able to set much more stringent limits.