

Search of Space-Time Defect: The Race to Defeat Einstein

ICONOCLASTS

Toppling the Giant

SCIENTIFIC AMERICAN

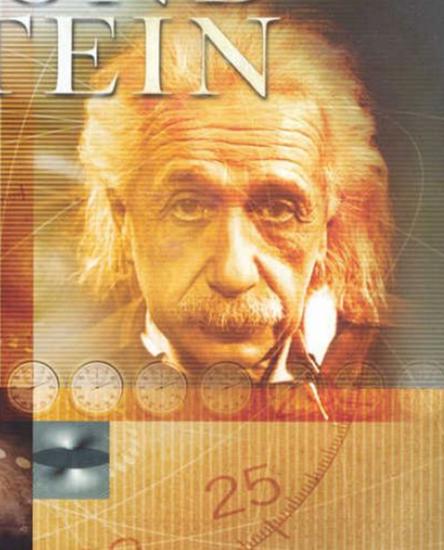
SPECIAL ISSUE

SEPTEMBER 2004
WWW.SCIAM.COM

For a century, his ideas have reshaped the world. But discover how physicists are now venturing

BEYOND EINSTEIN

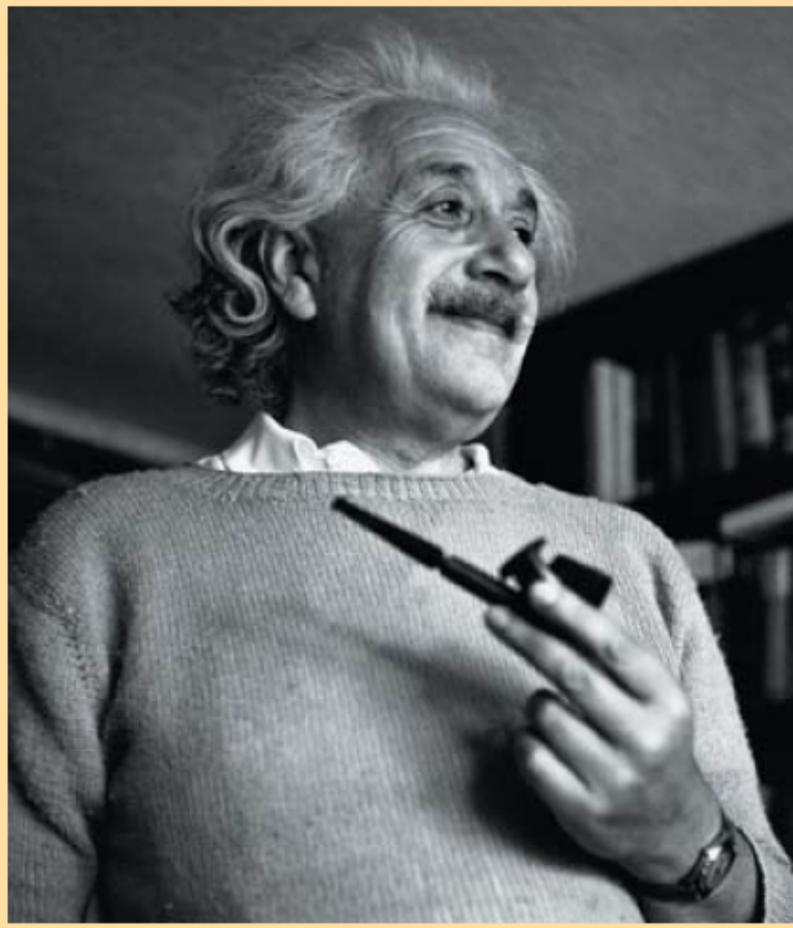
- Toward a Theory of Everything
- Energy That Expands the Cosmos
- Different Physics, Infinite Universes
- Does the Speed of Light Change?
- Computing with Relativity
- Einstein vs. Newton
- And More ...



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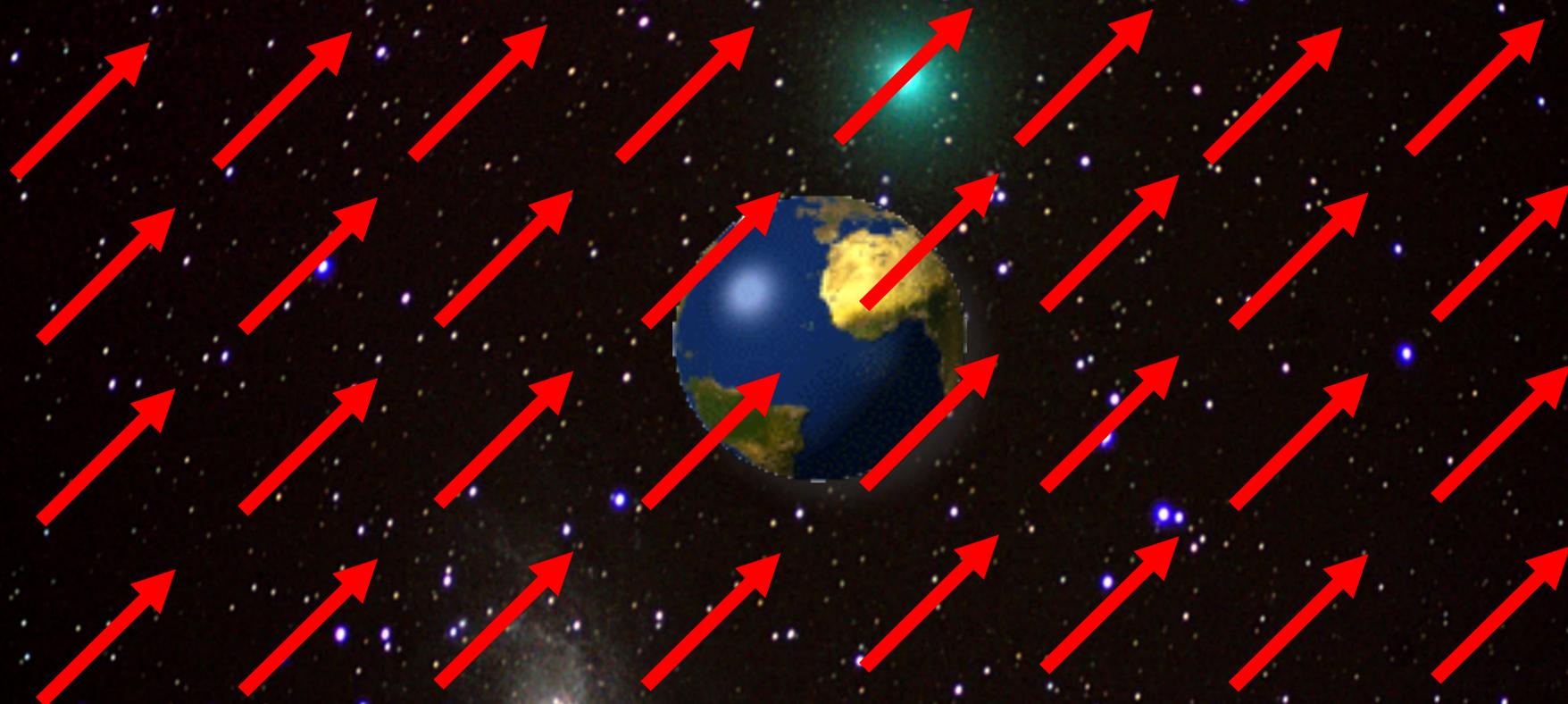
Teppei Katori
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Feb. 1, 2017

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Emmy Noether (1882-1935)

Mathematician from Germany

Noether's Theorem

“Every conservation law is a consequence of corresponding symmetry”

- conservation of energy
- conservation of electric charge
- prediction of Higgs boson

etc



Conservation of Angular Momentum

Rotating object keep rotating

Conservation of angular momentum



Yulia Lipnitskaya (Russia)

Isaac Newton
Emmy Noether



Universe has no special direction
→ Universe has rotation symmetry
(Lorentz symmetry)



Isotropy of the Space
(no directionality)

Lorentz Symmetry and Special Relativity

Einstein's **theory of special relativity** is based on the **Lorentz symmetry**

Lorentz symmetry assumes isotropic space-time

Einstein and Lorentz



If the universe has a special direction
Space doesn't have Lorentz symmetry
→ Lorentz transformation is violated, or **Lorentz violation**

Angular momentum is not conserved,
so Yulia Lipnitskaya cannot spin so much!

Since Yulia Lipnitskaya CAN spin so much,
Lorentz violation is very weak effect, even if existed

→ you need very precise machines to find it

Lorentz Symmetry and Theory of Everything

Quantum Gravity or “Theory of Everything” (such as superstring theory, quantum loop gravity, etc) allow tiny amount of Lorentz violation

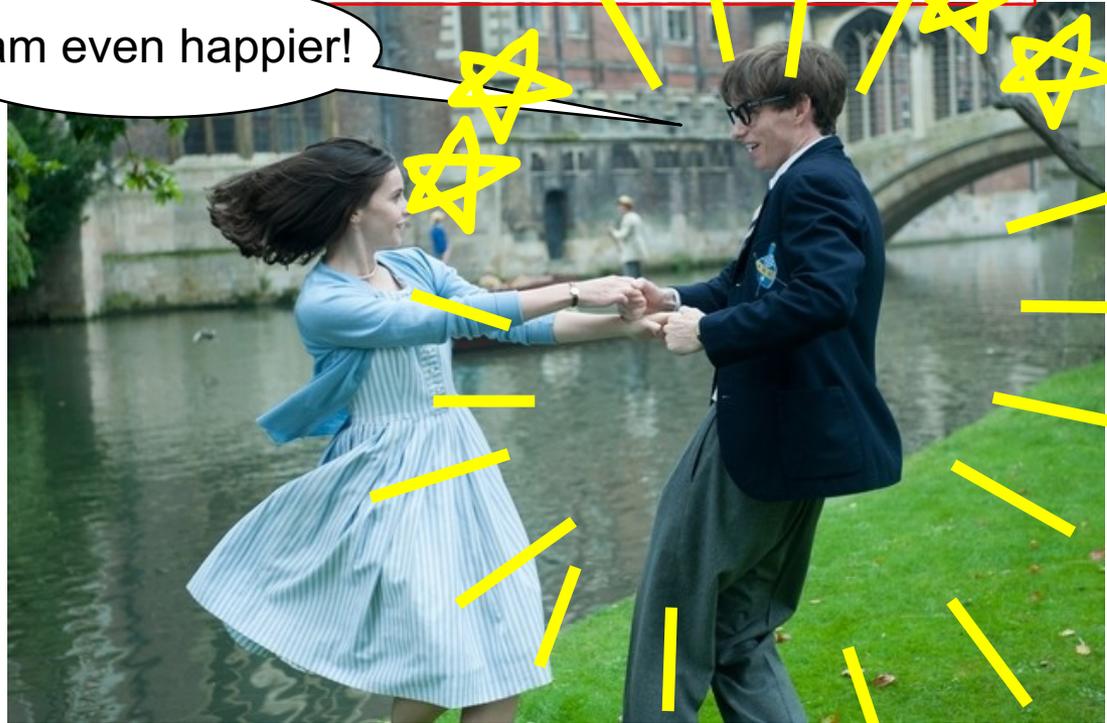
→ Discovery of Lorentz violation could be the first evidence of Theory of Everything!

Einstein and Lorentz

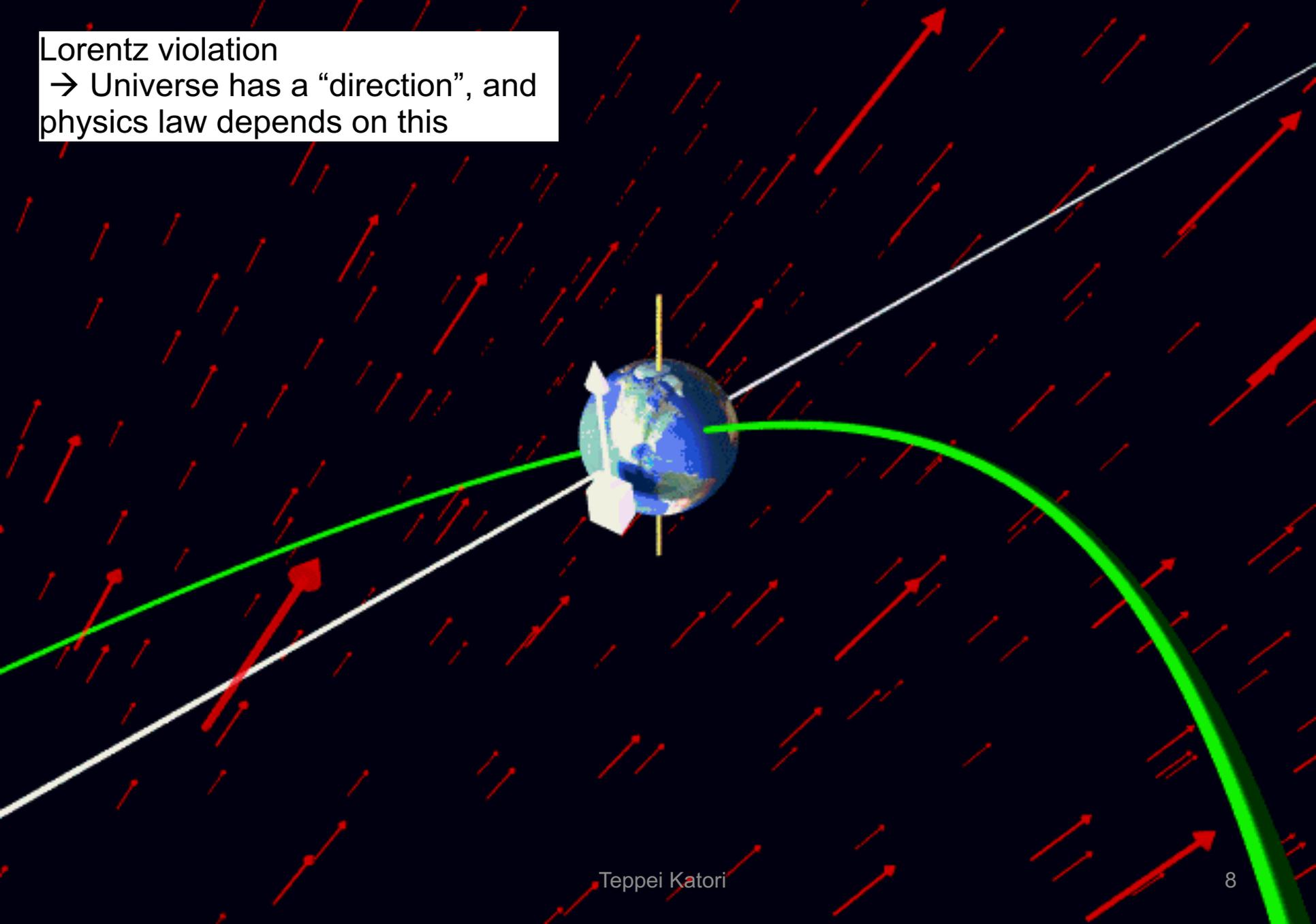


Stephen Hawking imposter and someone

I am even happier!



Lorentz violation
→ Universe has a “direction”, and physics law depends on this



The race to defeat Einstein

Most precise something



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The race to defeat Einstein

Most precise speed of light measurement

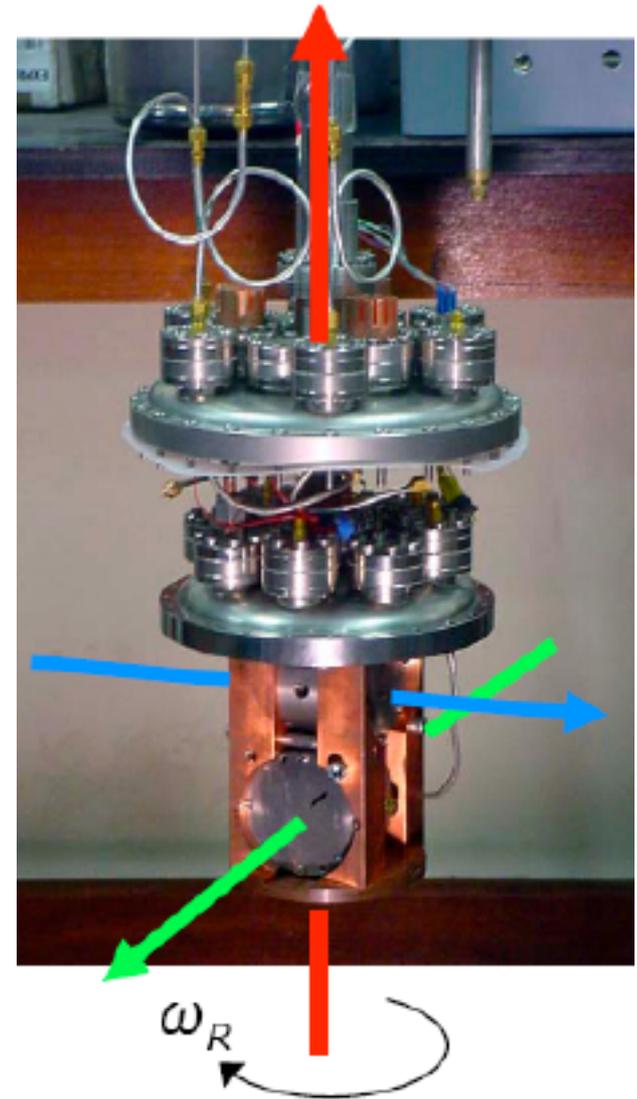
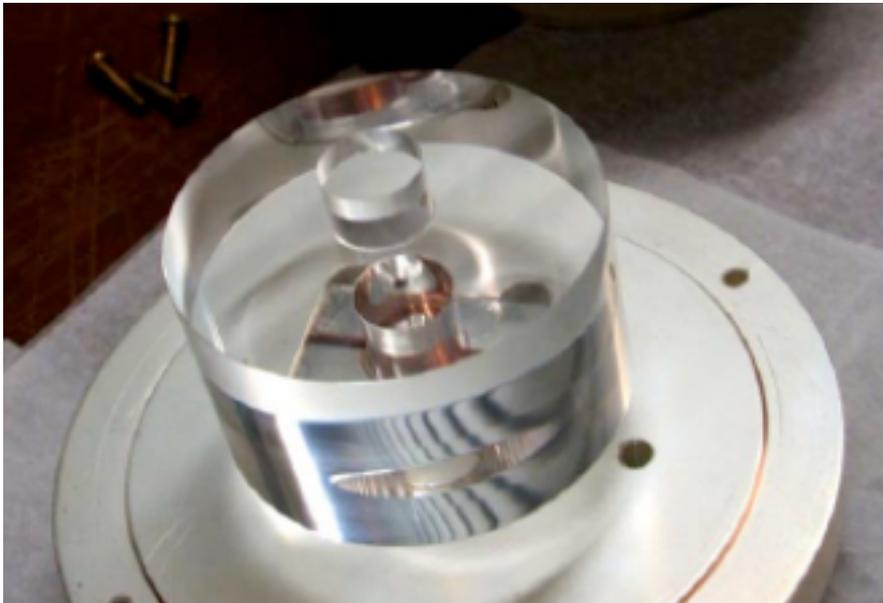


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Cryogenic Sapphire Crystal Resonator

Group from University of Western Australia can measure speed of light with the highest accuracy by this device

→ Lorentz violation is not discovered



The race to defeat Einstein

Most precise pendulum



Spin pendulum

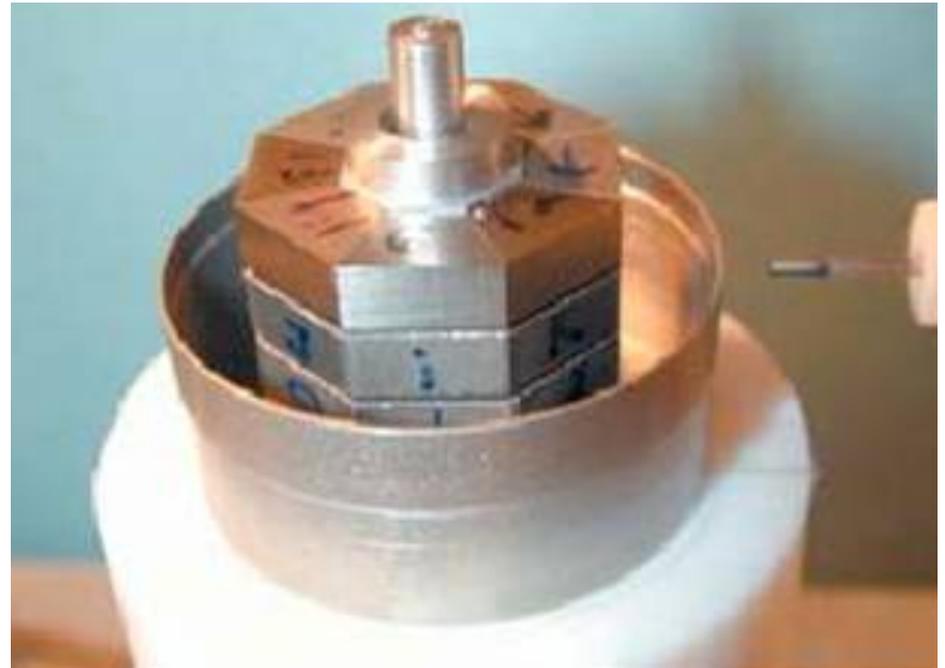
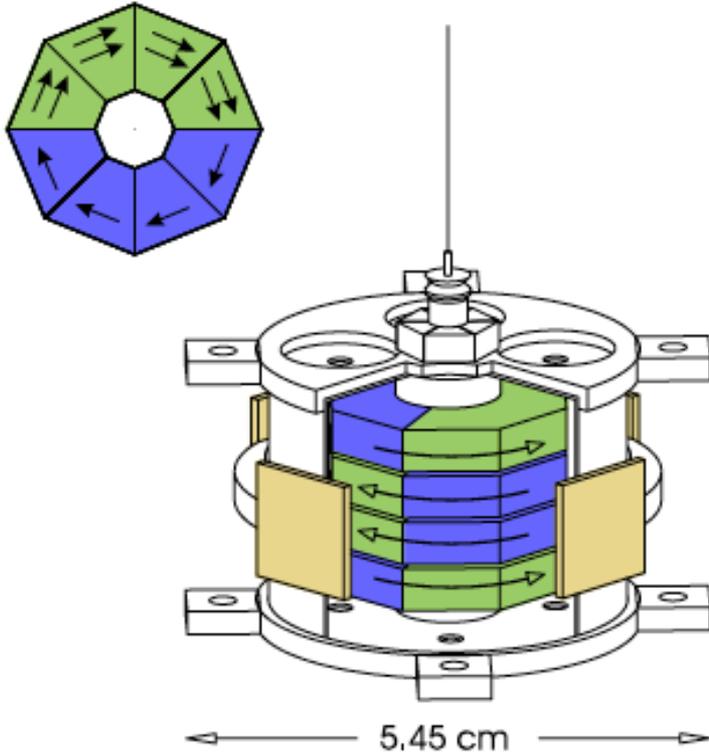
Cryogenic crystal resonator

© 2007 Geology.com

Double Alloy Spin Torsion Pendulum

University of Washington has a technology to make the highest precision pendulum. The pendulum made of clever combination of special alloys is very sensitive of Lorentz violation of atomic electrons

→ Lorentz violation is not discovered



The race to defeat Einstein

Most precise gyroscope



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Highest precision gravity test in the space

IM Pegasi

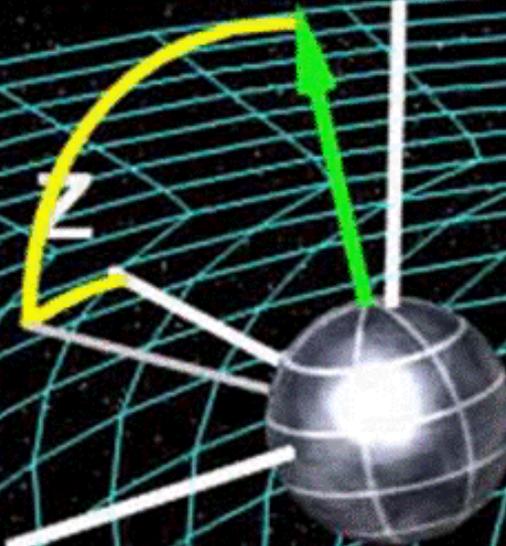


Geodetic effect
6.6 arcsec/yr

X

Frame dragging
0.041 arcsec/yr

Y



Gravity Probe B tests tiny special gravitational effect in a satellite by the gyroscope, according to Guinness record “the most spherical man-made object”

→ Lorentz violation is not discovered

The race to defeat Einstein

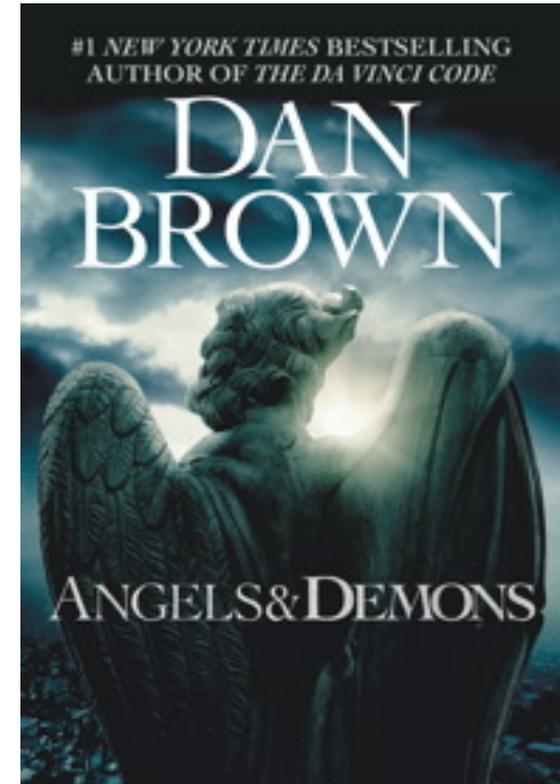
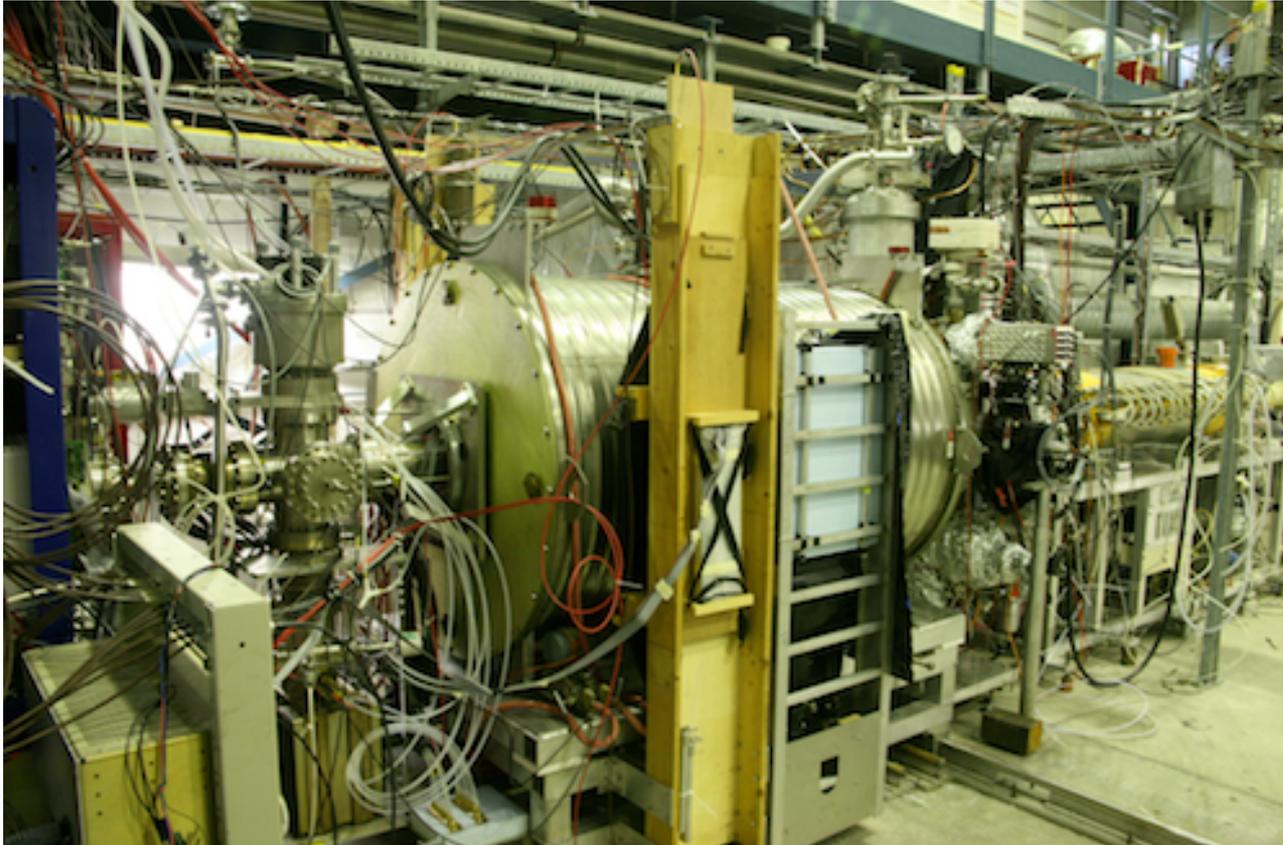
Largest amount of anti-hydrogen



Antiproton decelerator at CERN

CERN has an ability to perform the highest precision antimatter test (matter-antimatter asymmetry induces Lorentz violation)

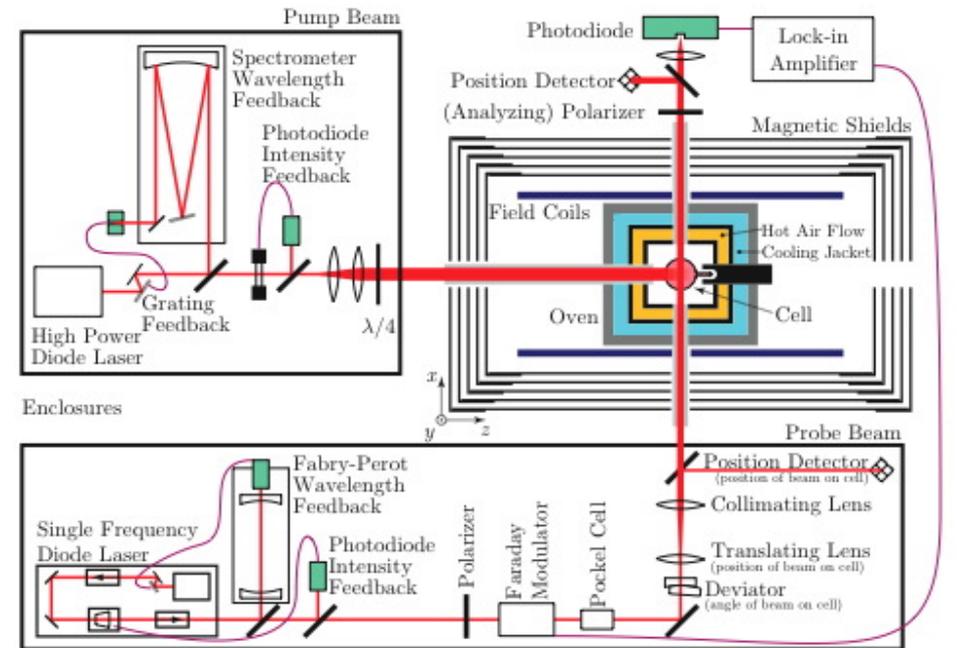
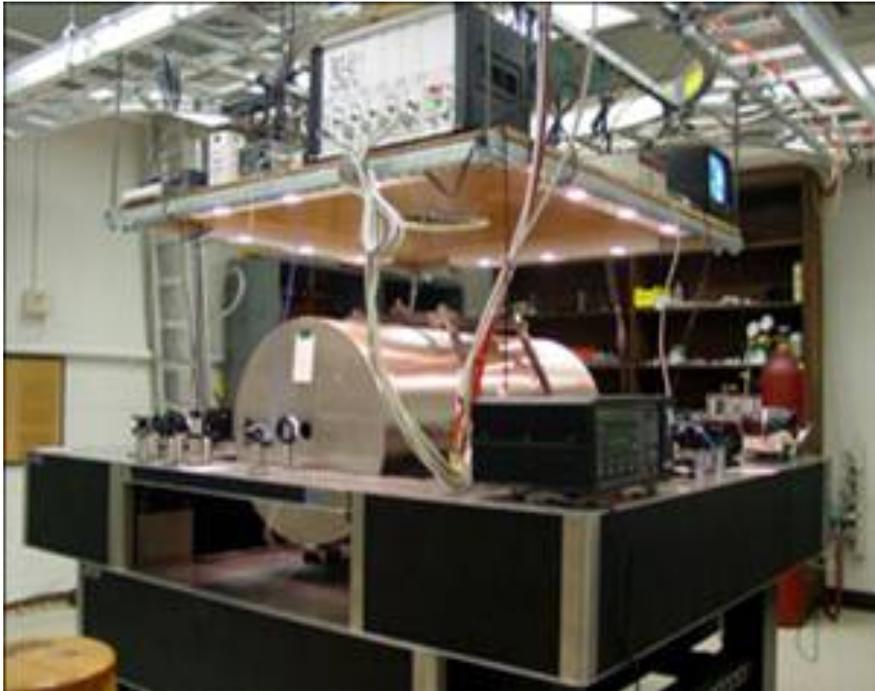
→ Lorentz violation is not discovered



Double Noble Gas Maser

A type of atomic clock very sensitive to a tiny magnetic field

→ Lorentz violation is not discovered



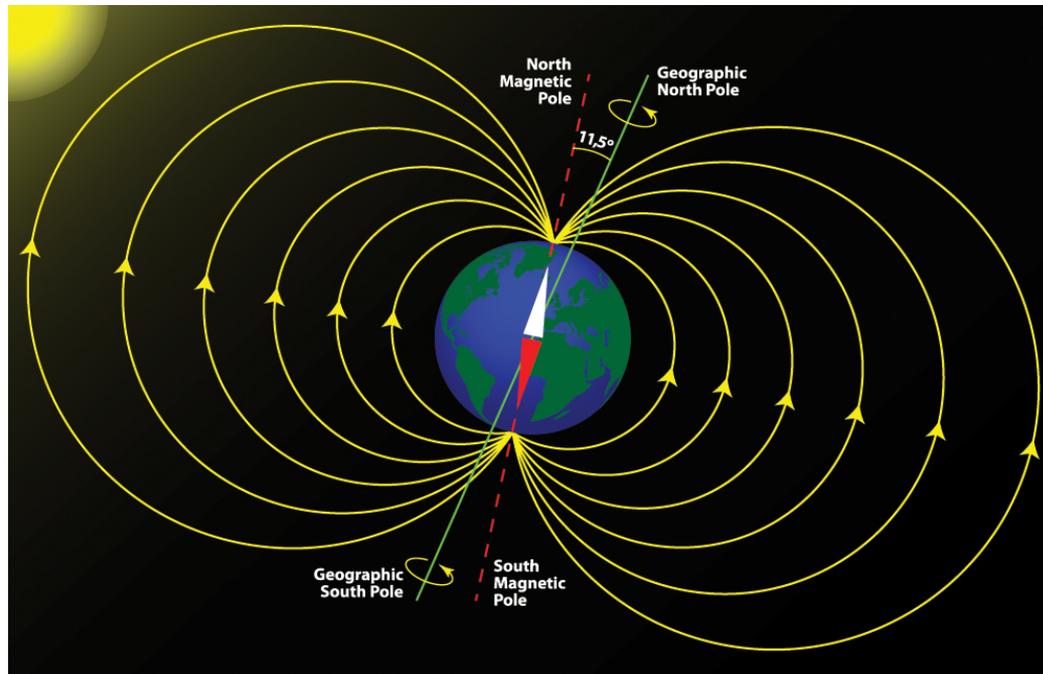
Double Noble Gas Maser

A type of atomic clock very sensitive to a tiny magnetic field

→ Lorentz violation is not discovered

The earth magnetic field gives error. To improve sensitivity, scientists want to repeat the measurement at special location on the earth (special earth magnetic field configuration)

Princeton university group vs. Amherst college group



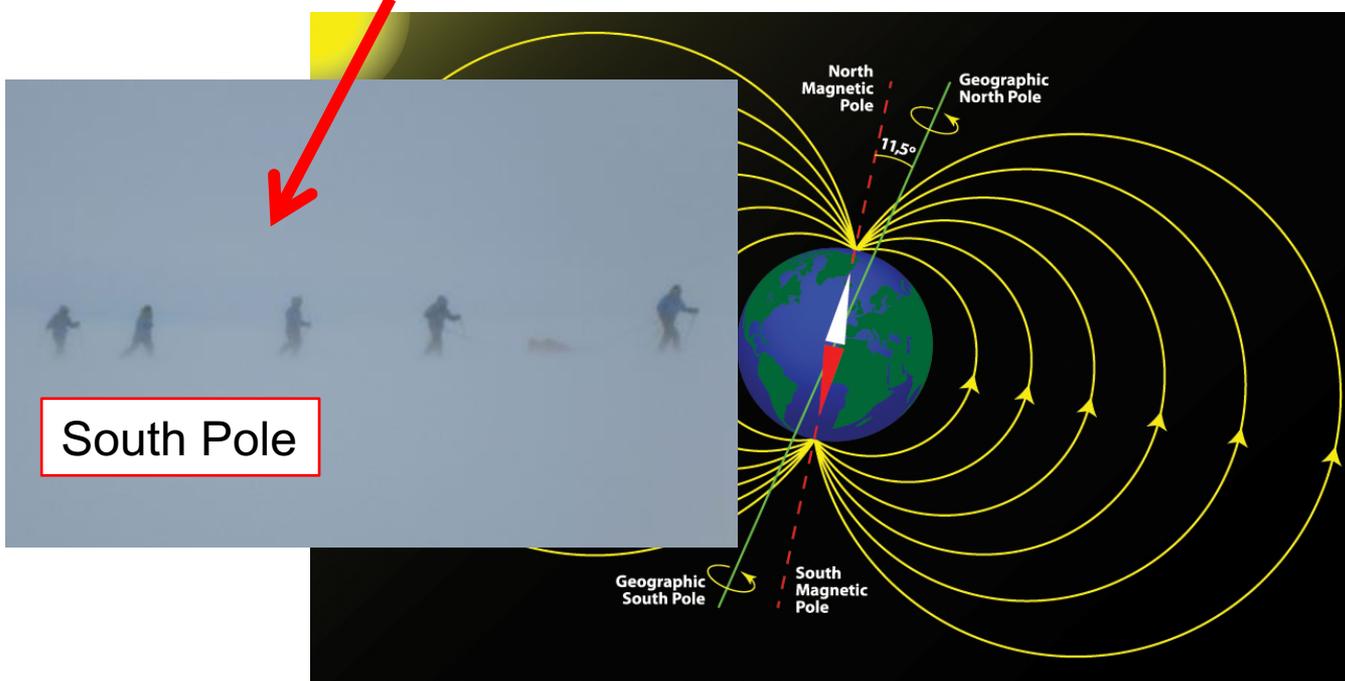
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Double Noble Gas Maser

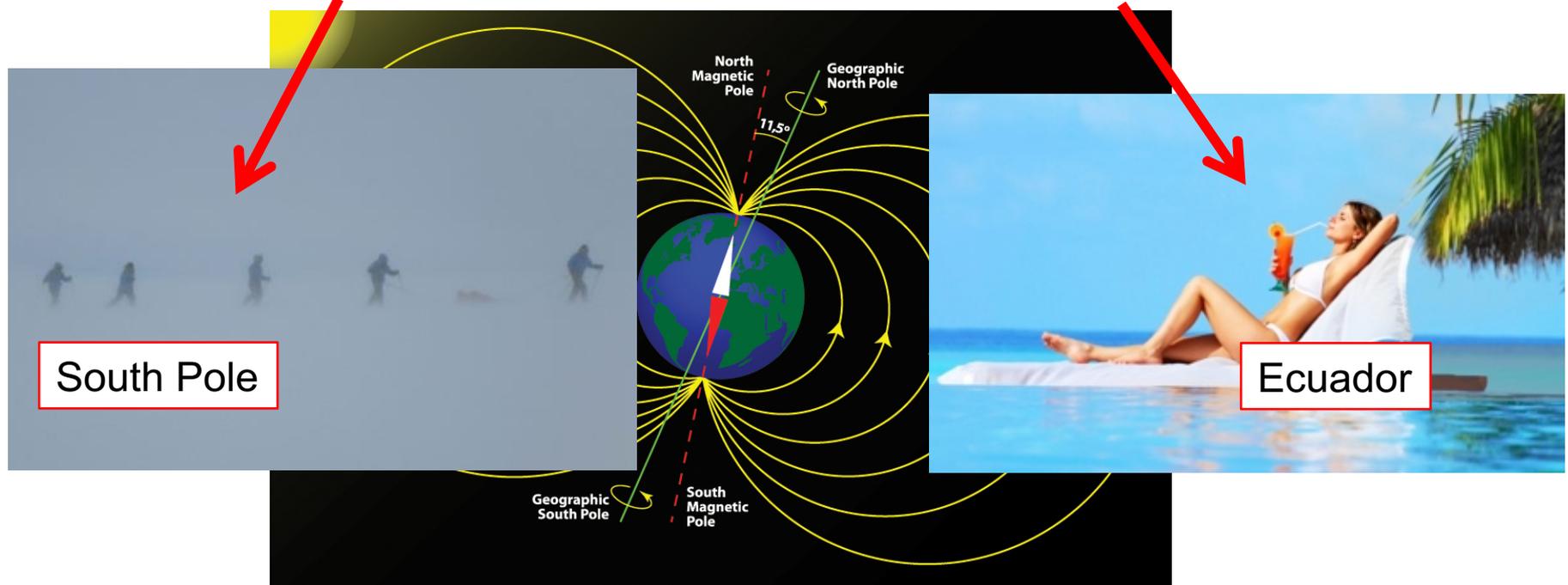
A type of atomic clock very sensitive to a tiny magnetic field

→ Lorentz violation is not discovered

The earth magnetic field gives error. To improve sensitivity, scientists want to repeat the measurement at special location on the earth (special earth magnetic field configuration)

Princeton university group

vs. Amherst college group



The race to defeat Einstein

Most precise something



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The race to defeat Einstein

Most precise something

ARCTIC OCEAN

Table S2. Maximal sensitivities for the photon sector

Coefficient	Electron	Proton
\tilde{b}_X	10^{-31} GeV	10^{-33}
\tilde{b}_Y	10^{-31} GeV	10^{-33}
\tilde{b}_Z	10^{-29} GeV	10^{-28}
\tilde{b}_T	10^{-26} GeV	10^{-7}
$\tilde{b}_J, (J = X, Y, Z)$	10^{-22} GeV	
\tilde{c}_-	10^{-20} GeV	10^{-24}
\tilde{c}_Q	10^{-17} GeV	10^{-21}
\tilde{c}_X	10^{-21} GeV	10^{-25}
\tilde{c}_Y	10^{-21} GeV	10^{-25}
\tilde{c}_Z	10^{-20} GeV	10^{-24}
\tilde{c}_{TX}	10^{-18} GeV	10^{-20}
\tilde{c}_{TY}	10^{-18} GeV	10^{-20}
\tilde{c}_{TZ}	10^{-20} GeV	10^{-20}
\tilde{c}_{TT}	10^{-18} GeV	10^{-11}
\tilde{d}_+	10^{-27} GeV	10^{-7}
\tilde{d}_-	10^{-26} GeV	
\tilde{d}_Q	10^{-26} GeV	10^{-7}
\tilde{d}_{XY}	10^{-26} GeV	
\tilde{d}_{YZ}	10^{-26} GeV	
\tilde{d}_{ZX}	10^{-26} GeV	
\tilde{d}_X	10^{-22} GeV	10^{-27} GeV
\tilde{d}_Y	10^{-22} GeV	10^{-27} GeV
\tilde{d}_Z	10^{-19} GeV	
\tilde{H}_{XT}	10^{-26} GeV	
\tilde{H}_{YT}	10^{-26} GeV	
\tilde{H}_{ZT}	10^{-26} GeV	
\tilde{g}_T	10^{-27} GeV	10^{-7} GeV
\tilde{g}_c	10^{-26} GeV	
\tilde{g}_Q		
\tilde{g}_-		
$\tilde{g}_{TJ}, (J = X, Y, Z)$		
\tilde{g}_{XY}	10^{-17} GeV	
\tilde{g}_{YX}	10^{-17} GeV	
\tilde{g}_{ZX}	10^{-18} GeV	
\tilde{g}_{XZ}	10^{-17} GeV	
\tilde{g}_{YZ}	10^{-17} GeV	
\tilde{g}_{ZY}	10^{-18} GeV	
\tilde{g}_{DX}	10^{-22} GeV	10^{-27} GeV
\tilde{g}_{DY}	10^{-22} GeV	10^{-27} GeV
\tilde{g}_{DZ}	10^{-22} GeV	

Table S3. Maximal sensitivities for the photon sector

$d = 3$	Coefficient	Sensitivity
	$k_{(V)00}^{(2)}$	10^{-43} GeV
	$k_{(V)10}^{(2)}$	10^{-42} GeV
	$\text{Re} k_{(V)11}^{(2)}$	10^{-42} GeV
	$\text{Im} k_{(V)11}^{(2)}$	10^{-42} GeV

$d = 4$	Coefficient	Sensitivity	Coefficient	Sensitivity
	$(\tilde{\kappa}_{e+})^{XY}$	10^{-32}	$(\tilde{\kappa}_{e-})^{XY}$	10^{-17}
	$(\tilde{\kappa}_{e+})^{XZ}$	10^{-32}	$(\tilde{\kappa}_{e-})^{XZ}$	10^{-17}
	$(\tilde{\kappa}_{e+})^{YZ}$	10^{-32}	$(\tilde{\kappa}_{e-})^{YZ}$	10^{-17}
	$(\tilde{\kappa}_{e+})^{XX} - (\tilde{\kappa}_{e+})^{YY}$	10^{-32}	$(\tilde{\kappa}_{e-})^{XX} - (\tilde{\kappa}_{e-})^{YY}$	10^{-17}
	$(\tilde{\kappa}_{e+})^{ZZ}$	10^{-32}	$(\tilde{\kappa}_{e-})^{ZZ}$	10^{-16}
	$(\tilde{\kappa}_{e-})^{XY}$	10^{-32}	$(\tilde{\kappa}_{o+})^{XY}$	10^{-13}
	$(\tilde{\kappa}_{e-})^{XZ}$	10^{-32}	$(\tilde{\kappa}_{o+})^{XZ}$	10^{-14}
	$(\tilde{\kappa}_{e-})^{YZ}$	10^{-32}	$(\tilde{\kappa}_{o+})^{YZ}$	10^{-14}
	$(\tilde{\kappa}_{e-})^{XX} - (\tilde{\kappa}_{e-})^{YY}$	10^{-32}		
	$(\tilde{\kappa}_{e-})^{ZZ}$	10^{-32}	$\tilde{\kappa}_{et}$	10^{-14}

Table S4. Maximal sensitivities for the neutrino

$d = 3$	Coefficient	$e\mu$	$e\tau$	$\mu\tau$	Coeff
	$\text{Re}(a_L)^T$	10^{-20} GeV	10^{-19} GeV	-	$\text{Im}(a_L)$
	$\text{Re}(a_L)^X$	10^{-20} GeV	10^{-19} GeV	10^{-23} GeV	$\text{Im}(a_L)$
	$\text{Re}(a_L)^Y$	10^{-21} GeV	10^{-19} GeV	10^{-23} GeV	$\text{Im}(a_L)$
	$\text{Re}(a_L)^Z$	10^{-19} GeV	10^{-19} GeV	-	$\text{Im}(a_L)$

$d = 4$	Coefficient	$e\mu$	$e\tau$	$\mu\tau$	Coefficient	$e\mu$	$e\tau$	$\mu\tau$
	$\text{Re}(c_L)^{XY}$	10^{-21}	10^{-17}	10^{-23}	$\text{Im}(c_L)^{XY}$	10^{-21}	10^{-17}	10^{-21}
	$\text{Re}(c_L)^{XZ}$	10^{-21}	10^{-17}	10^{-23}	$\text{Im}(c_L)^{XZ}$	10^{-21}	10^{-17}	10^{-21}
	$\text{Re}(c_L)^{YZ}$	10^{-21}	10^{-16}	10^{-23}	$\text{Im}(c_L)^{YZ}$	10^{-21}	10^{-16}	10^{-21}
	$\text{Re}(c_L)^{XX}$	10^{-21}	10^{-16}	10^{-23}	$\text{Im}(c_L)^{XX}$	10^{-21}	10^{-16}	10^{-21}
	$\text{Re}(c_L)^{YY}$	10^{-21}	10^{-16}	10^{-23}	$\text{Im}(c_L)^{YY}$	10^{-21}	10^{-16}	10^{-21}
	$\text{Re}(c_L)^{ZZ}$	10^{-19}	10^{-16}	-	$\text{Im}(c_L)^{ZZ}$	-	10^{-16}	-
	$\text{Re}(c_L)^{TT}$	10^{-19}	10^{-17}	-	$\text{Im}(c_L)^{TT}$	-	10^{-17}	-
	$\text{Re}(c_L)^{TX}$	10^{-22}	10^{-17}	10^{-27}	$\text{Im}(c_L)^{TX}$	10^{-22}	10^{-17}	10^{-22}
	$\text{Re}(c_L)^{TY}$	10^{-22}	10^{-17}	10^{-27}	$\text{Im}(c_L)^{TY}$	10^{-22}	10^{-17}	10^{-22}
	$\text{Re}(c_L)^{TZ}$	10^{-20}	10^{-16}	-	$\text{Im}(c_L)^{TZ}$	-	10^{-16}	-

Isotropic	Coefficient	Sensitivity	Coefficient	Sensitivity
	$\tilde{a}_{\mu\mu}^{(2)}$	10^{-7} GeV	$\tilde{a}_{\mu\mu}^{(2)}$	10^{-20} GeV
	$\tilde{c}_{\mu\mu}^{(4)}$	10^{-9}	$\tilde{c}_{\mu\mu}^{(4)}$	10^{-10}
	$\tilde{a}_{\mu\mu}^{(5)}$	10^{-18} GeV ⁻¹	$\tilde{a}_{\mu\mu}^{(5)}$	10^{-19} GeV ⁻¹
	$\tilde{c}_{\mu\mu}^{(6)}$	10^{-9} GeV ⁻²	$\tilde{c}_{\mu\mu}^{(6)}$	10^{-19} GeV ⁻²
	$\tilde{a}_{\mu\mu}^{(7)}$	10^{-29} GeV ⁻³	$\tilde{a}_{\mu\mu}^{(7)}$	10^{-19} GeV ⁻³
	$\tilde{c}_{\mu\mu}^{(8)}$	10^{-11} GeV ⁻⁴	$\tilde{c}_{\mu\mu}^{(8)}$	10^{-18} GeV ⁻⁴
	$\tilde{a}_{\mu\mu}^{(9)}$	10^{-40} GeV ⁻⁵	$\tilde{a}_{\mu\mu}^{(9)}$	10^{-18} GeV ⁻⁵
	$\tilde{c}_{\mu\mu}^{(10)}$	10^{-14} GeV ⁻⁶	$\tilde{c}_{\mu\mu}^{(10)}$	10^{-18} GeV ⁻⁶

Table D6. Electron sector, $d = 3, 4$ (part 1 of 3)

Combination	Result	System	Ref.
$ b_0 $	$< 2 \times 10^{-14}$ GeV	Cs spectroscopy	[30]*, [31]*
"	$< 2 \times 10^{-12}$ GeV	Tl spectroscopy	[30]*, [31]*
"	$< 7 \times 10^{-15}$ GeV	Dy spectroscopy	[30]*, [31]*

Table D6. Electron sector, $d = 3, 4$ (part 2 of 3)

Combination	Result	System	Ref.
$\tilde{c}^{UR(4)}$	$< 1.5 \times 10^{-15}$	Astrophysics	[41]*, [18]*
"	$> -5 \times 10^{-13}$	"	[42]*, [18]*
"	$(-1.3 \text{ to } 0.2) \times 10^{-15}$	"	[43]*, [18]*
"	$> -1.2 \times 10^{-16}$	"	[44]*, [18]*

There are tons of experiments to look for Lorentz violation all over the world, and just the summary of all results makes 50 page documents!

...but nobody found Lorentz violation (so far)

$-7 \text{ to } 4) \times 10^{-15}$	"	[58]*	$\times 10^{-9}$	"	[49]
$1 \text{ to } 1.5) \times 10^{-15}$	"	[58]*	$\times 10^{-9}$	"	[49]
$-4 \text{ to } 2) \times 10^{-17}$	"	[58]*	$\times 10^{-6}$	Nuclear binding energy	[50]
$< 1.3 \times 10^{-15}$	"	[59]*	$\times 10^{-6}$	Cs interferometer	[51]
	"		$\times 10^{-15}$	Collider physics	[52]*
	"		$\times 10^{-14}$	"	[52]*
$< 2.5 \times 10^{-15}$	"	[59]*	$\times 10^{-15}$	"	[52]*
	"		$\times 10^{-13}$	"	[52]*
	"		$\times 10^{-11}$	1S-2S transition	[53]*
$.8) \times 10^{-27}$ GeV	Torsion pendulum	[32]	$\times 10^{-16}$	Optical, microwave resonators	[54]*
$.4) \times 10^{-27}$ GeV	"	[32]	$\times 10^{-16}$	"	[54]*
$.9) \times 10^{-27}$ GeV	"	[32]	$\times 10^{-16}$	"	[54]*
$.2) \times 10^{-27}$ GeV	"	[32]	$\times 10^{-16}$	"	[54]*
$< 2 \times 10^{-14}$	Astrophysics	[60]*	$\times 10^{-16}$	"	[54]*
$< 3 \times 10^{-15}$	"	[60]*	$\times 10^{-16}$	"	[54]*
$< 2 \times 10^{-15}$	"	[60]*	$\times 10^{-16}$	"	[54]*
$< 2 \times 10^{-14}$	"	[60]*	$\times 10^{-16}$	"	[54]*
$< 7 \times 10^{-15}$	"	[60]*	$\times 10^{-16}$	"	[54]*
$< 5 \times 10^{-14}$	"	[60]*	$\times 10^{-16}$	"	[54]*
$< 5 \times 10^{-15}$	"	[60]*	$\times 10^{-16}$	"	[54]*
$< 8 \times 10^{-17}$	"	[60]*	$\times 10^{-16}$	"	[54]*
$< 10^{-22}$ GeV	Hg/Cs comparison	[39], [40]*			
$< 10^{-19}$ GeV	Astrophysics	[28]*			
$< 10^{-17}$ GeV	Astrophysics	[28]*			
$< 10^{-17}$ GeV	"	[28]*			
$< 10^{-18}$ GeV	"	[28]*			
$< 10^{-22}$ GeV	Penning trap	[28]*			
$< 10^{-22}$ GeV	Hg/Cs comparison	[39], [40]*			

So far no experiments find Lorentz violation...

most precise something

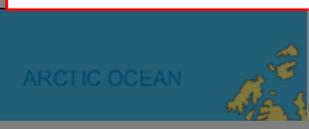


Table S2. Maximal sensitivities for the photon sector

Coefficient	Electron	Proton
\tilde{b}_X	10^{-31} GeV	10^{-33}
\tilde{b}_Y	10^{-31} GeV	10^{-33}
\tilde{b}_Z	10^{-29} GeV	10^{-28}
\tilde{b}_T	10^{-26} GeV	10^{-7}
$\tilde{b}_J, (J = X, Y, Z)$	10^{-22} GeV	
\tilde{c}_-	10^{-20} GeV	10^{-24}
\tilde{c}_Q	10^{-17} GeV	10^{-21}
\tilde{c}_X	10^{-21} GeV	10^{-25}
\tilde{c}_Y	10^{-21} GeV	10^{-25}
\tilde{c}_Z	10^{-20} GeV	10^{-24}
\tilde{c}_{TX}	10^{-18} GeV	10^{-20}
\tilde{c}_{TY}	10^{-18} GeV	10^{-20}
\tilde{c}_{TZ}	10^{-20} GeV	10^{-20}
\tilde{c}_{TT}	10^{-18} GeV	10^{-11}
\tilde{d}_+	10^{-27} GeV	10^{-7}
\tilde{d}_-	10^{-26} GeV	
\tilde{d}_Q	10^{-26} GeV	10^{-7}
\tilde{d}_{XY}	10^{-26} GeV	
\tilde{d}_{YZ}	10^{-26} GeV	
\tilde{d}_{ZX}	10^{-26} GeV	
\tilde{d}_X	10^{-22} GeV	10^{-27} GeV
\tilde{d}_Y	10^{-22} GeV	10^{-27} GeV
\tilde{d}_Z	10^{-19} GeV	
\tilde{H}_{XT}	10^{-26} GeV	
\tilde{H}_{YT}	10^{-26} GeV	
\tilde{H}_{ZT}	10^{-26} GeV	
\tilde{g}_T	10^{-27} GeV	10^{-7} GeV
\tilde{g}_c	10^{-26} GeV	
\tilde{g}_Q		
\tilde{g}_-		
$\tilde{g}_{TJ}, (J = X, Y, Z)$		
\tilde{g}_{XY}	10^{-17} GeV	
\tilde{g}_{YZ}	10^{-17} GeV	
\tilde{g}_{ZX}	10^{-18} GeV	
\tilde{g}_X	10^{-17} GeV	
\tilde{g}_Y	10^{-17} GeV	
\tilde{g}_{ZY}	10^{-18} GeV	
\tilde{g}_{DX}	10^{-22} GeV	10^{-27} GeV
\tilde{g}_{DY}	10^{-22} GeV	10^{-27} GeV
\tilde{g}_{DZ}	10^{-22} GeV	

Table S3. Maximal sensitivities for the photon sector

$d = 3$	Coefficient	Sensitivity
	$k_{(V)00}^{(3)}$	10^{-43} GeV
	$k_{(V)10}^{(3)}$	10^{-42} GeV
	$\text{Re} k_{(V)11}^{(3)}$	10^{-42} GeV
	$\text{Im} k_{(V)11}^{(3)}$	10^{-42} GeV

$d = 4$	Coefficient	Sensitivity	Coefficient	Sensitivity
	$(\tilde{\kappa}_{e+})^{XY}$	10^{-32}	$(\tilde{\kappa}_{e-})^{XY}$	10^{-17}
	$(\tilde{\kappa}_{e+})^{XZ}$	10^{-32}	$(\tilde{\kappa}_{e-})^{XZ}$	10^{-17}
	$(\tilde{\kappa}_{e+})^{YZ}$	10^{-32}	$(\tilde{\kappa}_{e-})^{YZ}$	10^{-17}
	$(\tilde{\kappa}_{e+})^{XX} - (\tilde{\kappa}_{e+})^{YY}$	10^{-32}	$(\tilde{\kappa}_{e-})^{XX} - (\tilde{\kappa}_{e-})^{YY}$	10^{-17}
	$(\tilde{\kappa}_{e+})^{ZZ}$	10^{-32}	$(\tilde{\kappa}_{e-})^{ZZ}$	10^{-16}
	$(\tilde{\kappa}_{o-})^{XY}$	10^{-32}	$(\tilde{\kappa}_{o+})^{XY}$	10^{-13}
	$(\tilde{\kappa}_{o-})^{XZ}$	10^{-32}	$(\tilde{\kappa}_{o+})^{XZ}$	10^{-14}
	$(\tilde{\kappa}_{o-})^{YZ}$	10^{-32}	$(\tilde{\kappa}_{o+})^{YZ}$	10^{-14}
	$(\tilde{\kappa}_{o-})^{XX} - (\tilde{\kappa}_{o-})^{YY}$	10^{-32}		
	$(\tilde{\kappa}_{o-})^{ZZ}$	10^{-32}	$\tilde{\kappa}_{lt}$	10^{-14}

Table S4. Maximal sensitivities for the neutrino

$d = 3$	Coefficient	$e\mu$	$e\tau$	$\mu\tau$	Coeff
	$\text{Re}(a_L)^T$	10^{-20} GeV	10^{-19} GeV	-	$\text{Im}(a_L)$
	$\text{Re}(a_L)^X$	10^{-20} GeV	10^{-19} GeV	10^{-23} GeV	$\text{Im}(a_L)$
	$\text{Re}(a_L)^Y$	10^{-21} GeV	10^{-19} GeV	10^{-23} GeV	$\text{Im}(a_L)$
	$\text{Re}(a_L)^Z$	10^{-19} GeV	10^{-19} GeV	-	$\text{Im}(a_L)$

$d = 4$	Coefficient	$e\mu$	$e\tau$	$\mu\tau$	Coefficient	$e\mu$	$e\tau$	$\mu\tau$
	$\text{Re}(c_L)^{XY}$	10^{-21}	10^{-17}	10^{-23}	$\text{Im}(c_L)^{XY}$	10^{-21}	10^{-17}	10^{-21}
	$\text{Re}(c_L)^{XZ}$	10^{-21}	10^{-17}	10^{-23}	$\text{Im}(c_L)^{XZ}$	10^{-21}	10^{-17}	10^{-21}
	$\text{Re}(c_L)^{YZ}$	10^{-21}	10^{-16}	10^{-23}	$\text{Im}(c_L)^{YZ}$	10^{-21}	10^{-16}	10^{-21}
	$\text{Re}(c_L)^{XX}$	10^{-21}	10^{-16}	10^{-23}	$\text{Im}(c_L)^{XX}$	10^{-21}	10^{-16}	10^{-21}
	$\text{Re}(c_L)^{YY}$	10^{-21}	10^{-16}	10^{-23}	$\text{Im}(c_L)^{YY}$	10^{-21}	10^{-16}	10^{-21}
	$\text{Re}(c_L)^{ZZ}$	10^{-19}	10^{-16}	-	$\text{Im}(c_L)^{ZZ}$	-	10^{-16}	-
	$\text{Re}(c_L)^{TT}$	10^{-19}	10^{-17}	-	$\text{Im}(c_L)^{TT}$	-	10^{-17}	-
	$\text{Re}(c_L)^{TX}$	10^{-22}	10^{-17}	10^{-27}	$\text{Im}(c_L)^{TX}$	10^{-22}	10^{-17}	10^{-22}
	$\text{Re}(c_L)^{TY}$	10^{-22}	10^{-17}	10^{-27}	$\text{Im}(c_L)^{TY}$	10^{-22}	10^{-17}	10^{-22}
	$\text{Re}(c_L)^{TZ}$	10^{-20}	10^{-16}	-	$\text{Im}(c_L)^{TZ}$	-	10^{-16}	-

Isotropic	Coefficient	Sensitivity	Coefficient	Sensitivity
	$\tilde{a}^{(3)}$	10^{-7} GeV	$\tilde{a}_{qu}^{(2)}$	10^{-20} GeV
	$\tilde{c}^{(4)}$	10^{-9}	$\tilde{c}_{qu}^{(4)}$	10^{-10}
	$\tilde{c}^{(5)}$	10^{-18} GeV ⁻¹	$\tilde{c}_{qu}^{(5)}$	10^{-19} GeV ⁻¹
	$\tilde{c}^{(6)}$	10^{-9} GeV ⁻²	$\tilde{c}_{qu}^{(6)}$	10^{-10} GeV ⁻²
	$\tilde{c}^{(7)}$	10^{-29} GeV ⁻³	$\tilde{c}_{qu}^{(7)}$	10^{-19} GeV ⁻³
	$\tilde{c}^{(8)}$	10^{-11} GeV ⁻⁴	$\tilde{c}_{qu}^{(8)}$	10^{-18} GeV ⁻⁴
	$\tilde{c}^{(9)}$	10^{-40} GeV ⁻⁵	$\tilde{c}_{qu}^{(9)}$	10^{-18} GeV ⁻⁵
	$\tilde{c}^{(10)}$	10^{-14} GeV ⁻⁶	$\tilde{c}_{qu}^{(10)}$	10^{-18} GeV ⁻⁶



There are tons of experiments to look for Lorentz violation all over the world, and just the summary of all results makes 50 page documents!

...but nobody found Lorentz violation (so far)

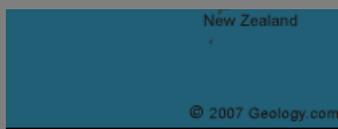
Table D6. Electron sector, $d = 3, 4$ (part 1 of 3)

Combination	Result	System	Ref.
$ b_0 $	$< 2 \times 10^{-14}$ GeV	Cs spectroscopy	[30]*, [31]*
"	$< 2 \times 10^{-12}$ GeV	Tl spectroscopy	[30]*, [31]*
"	$< 7 \times 10^{-15}$ GeV	Dy spectroscopy	[30]*, [31]*

Table D6. Electron sector, $d = 3, 4$ (part 2 of 3)

Combination	Result	System	Ref.
$\tilde{a}^{UR(4)}$	$< 1.5 \times 10^{-15}$	Astrophysics	[41]*, [18]*
"	$> -5 \times 10^{-13}$	"	[42]*, [18]*
$\frac{1}{2}(\tilde{b}_T + \tilde{d}_- - 2\tilde{g}_c - 3\tilde{g}_T + \dots)$	$(-1.3 \text{ to } 0.2) \times 10^{-15}$	"	[43]*, [18]*
$\frac{1}{2}(2\tilde{g}_c - \tilde{g}_T - \tilde{b}_T + 4\tilde{d}_+ - \dots)$	$> -1.2 \times 10^{-16}$	"	[44]*, [18]*

$-7 \text{ to } 4) \times 10^{-15}$	"	[58]*	$\times 10^{-9}$	"	[49]
$i \text{ to } 1.5) \times 10^{-15}$	"	[58]*	$\times 10^{-9}$	"	[49]
$-4 \text{ to } 2) \times 10^{-17}$	"	[58]*	$\times 10^{-6}$	Nuclear binding energy	[50]
$< 1.3 \times 10^{-15}$	"	[59]*	$\times 10^{-6}$	Cs interferometer	[51]
	"		$\times 10^{-15}$	Collider physics	[52]*
$< 2.5 \times 10^{-15}$	"	[59]*	$\times 10^{-14}$	"	[52]*
	"		$\times 10^{-15}$	"	[52]*
	"		$\times 10^{-13}$	"	[52]*
	"		$\times 10^{-11}$	1S-2S transition	[53]*
$.8) \times 10^{-27}$ GeV	Torsion pendulum	[32]	$\times 10^{-16}$	Optical, microwave resonators	[54]*
$.4) \times 10^{-27}$ GeV	"	[32]	$\times 10^{-16}$	"	[54]*
$.9) \times 10^{-27}$ GeV	"	[32]	$\times 10^{-16}$	"	[54]*
$.2) \times 10^{-27}$ GeV	"	[32]	$\times 10^{-16}$	"	[54]*
$< 2 \times 10^{-14}$	Astrophysics	[60]*	$\times 10^{-16}$	"	[54]*
$< 3 \times 10^{-15}$	"	[60]*	$\times 10^{-16}$	"	[54]*
$< 2 \times 10^{-15}$	"	[60]*	$\times 10^{-16}$	"	[54]*
$< 2 \times 10^{-14}$	"	[60]*	$\times 10^{-16}$	"	[54]*
$< 7 \times 10^{-15}$	"	[60]*	$\times 10^{-16}$	"	[54]*
$< 5 \times 10^{-14}$	"	[60]*	$\times 10^{-16}$	"	[54]*
$< 5 \times 10^{-15}$	"	[60]*	$\times 10^{-16}$	"	[54]*
$< 8 \times 10^{-17}$	"	[60]*	$\times 10^{-16}$	"	[54]*
$< 10^{-22}$ GeV	Hg/Cs comparison	[39], [40]*			
$< 10^{-19}$ GeV	Astrophysics	[28]*			
$< 10^{-17}$ GeV	Astrophysics	[28]*			
$< 10^{-17}$ GeV	"	[28]*			
$< 10^{-18}$ GeV	"	[28]*			
$< 10^{-22}$ GeV	Penning trap	[28]*			
$< 10^{-22}$ GeV	Hg/Cs comparison	[39], [40]*			

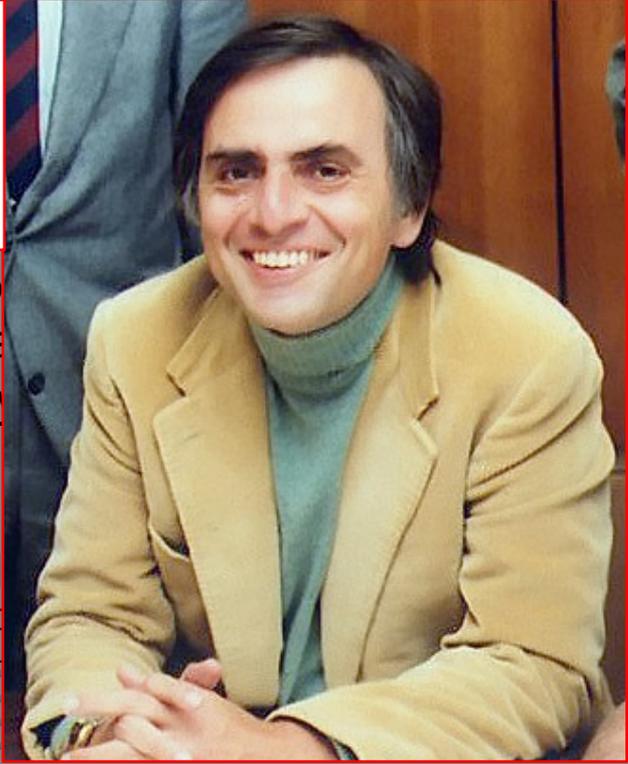


New Zealand © 2007 Geology.com

So far no experiments find Lorentz violation...

most precise something

“Extraordinary discovery requires extraordinary evidence”
 - Carl Sagan



There are tons of Lorentz violation experiments, but no one has published a summary document!
 ...but nobody

Table S3. Maximal sensitivities for the photon sector				Table D6. Electron sector, $d=3,4$ (part 1 of 3)			
Coefficient	Energy	Sensitivity	Ref.	Combination	Result	System	Ref.
\tilde{b}_X							
\tilde{b}_Y							
\tilde{b}_Z							
\tilde{b}_T							
$\tilde{b}_J, (J=X,Y,Z)$	10^{-22} GeV	10^{-22} GeV	[41]*, [18]*				[41]*, [18]*
\tilde{c}_-	10^{-20} GeV	10^{-24}					[42]*, [18]*
\tilde{c}_Q	10^{-17} GeV	10^{-21}					[43]*, [18]*
\tilde{c}_X	10^{-21} GeV	10^{-25}					[44]*, [18]*
\tilde{c}_Y	10^{-21} GeV	10^{-25}					[44]*, [18]*
\tilde{c}_Z	10^{-20} GeV	10^{-24}					[44]*, [18]*
\tilde{c}_{TX}	10^{-18} GeV	10^{-20}					[44]*, [18]*
\tilde{c}_{TY}	10^{-18} GeV	10^{-20}					[44]*, [18]*
\tilde{c}_{TZ}	10^{-20} GeV	10^{-20}					[44]*, [18]*
\tilde{c}_{TT}	10^{-18} GeV	10^{-11}					[44]*, [18]*
\tilde{d}_+	10^{-27} GeV	10^{-7}					[49]
\tilde{d}_-	10^{-26} GeV						[49]
\tilde{d}_Q	10^{-26} GeV	10^{-7}					[50]
\tilde{d}_{XY}	10^{-26} GeV						[51]
\tilde{d}_{YZ}	10^{-26} GeV						[52]*
\tilde{d}_{ZX}	10^{-26} GeV						[52]*
\tilde{d}_X	10^{-22} GeV	10^{-27} GeV					[52]*
\tilde{d}_Y	10^{-22} GeV	10^{-27} GeV					[52]*
\tilde{d}_Z	10^{-19} GeV						[52]*
\tilde{H}_{XT}	10^{-26} GeV						[52]*
\tilde{H}_{YT}	10^{-26} GeV						[52]*
\tilde{H}_{ZT}	10^{-26} GeV						[52]*
\tilde{g}_T	10^{-27} GeV	10^{-7} GeV					[54]*
\tilde{g}_c	10^{-26} GeV						[54]*
\tilde{g}_Q							[54]*
\tilde{g}_-							[54]*
\tilde{g}_{XY}	10^{-17} GeV						[54]*
\tilde{g}_{YX}	10^{-17} GeV						[54]*
\tilde{g}_{ZX}	10^{-18} GeV						[54]*
\tilde{g}_{XZ}	10^{-17} GeV						[54]*
\tilde{g}_{YZ}	10^{-17} GeV						[54]*
\tilde{g}_{ZY}	10^{-18} GeV						[54]*
\tilde{g}_{DX}	10^{-22} GeV	10^{-27} GeV					[54]*
\tilde{g}_{DY}	10^{-22} GeV	10^{-27} GeV					[54]*
\tilde{g}_{DZ}	10^{-22} GeV						[54]*

So far no experiments find Lorentz violation...

most precise something

“Extraordinary discovery requires extraordinary evidence”

- Carl Sagan



“Extraordinary discovery requires extraordinary particles”

- Teppei



Neutrino!

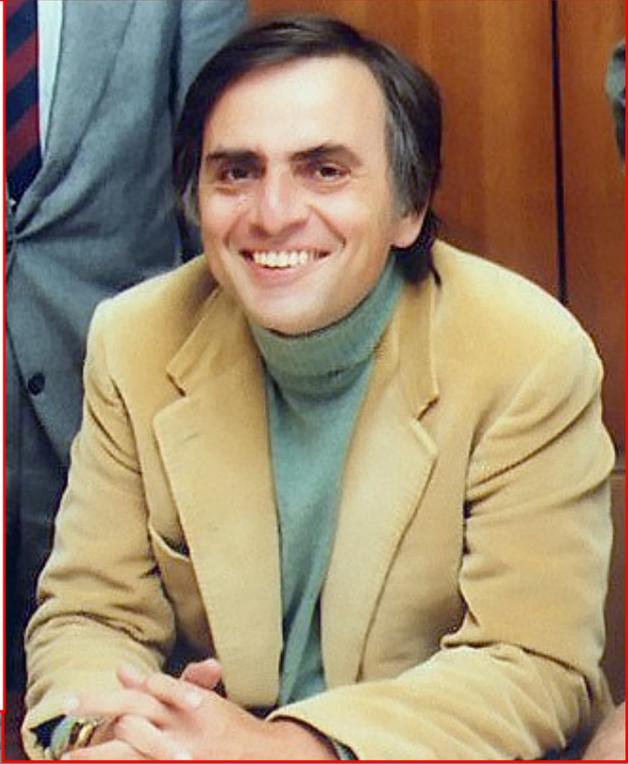
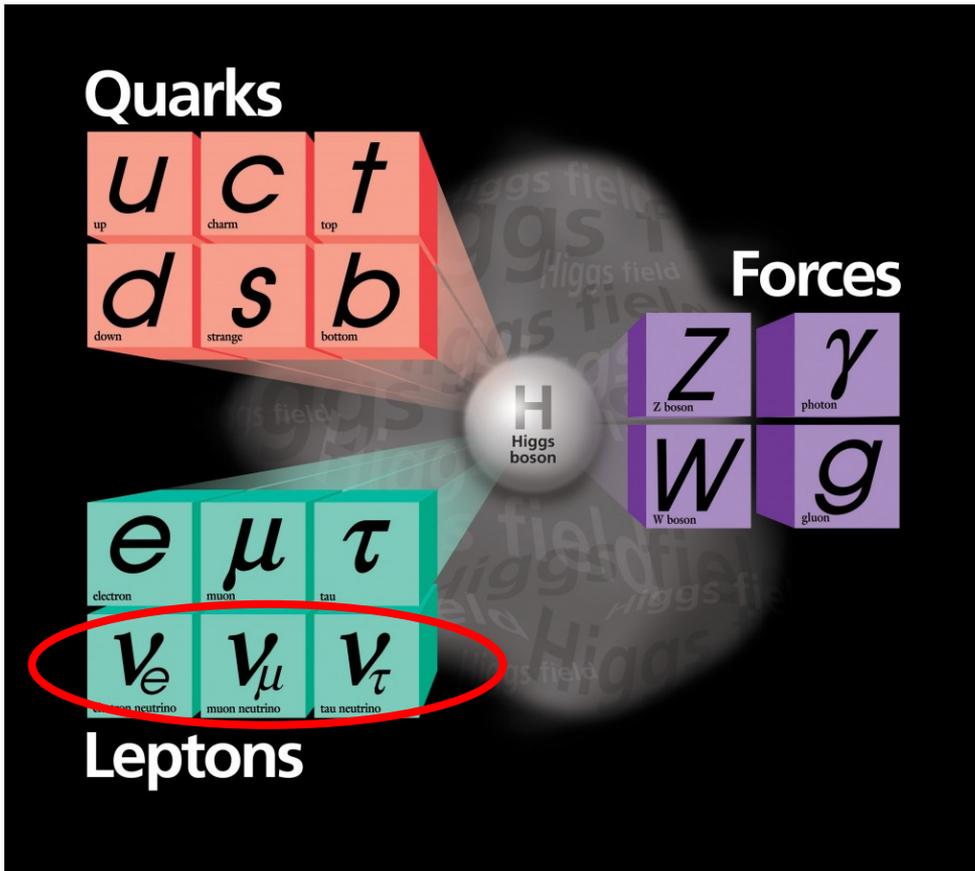


Table S3. Maximal sensitivities for the photon sector				Table D6. Electron sector, $d=3,4$ (part 1 of 3)			
Coefficient		Sensitivity		Coefficient		Sensitivity	
\tilde{b}_X	10^{-19} GeV			$\text{Re}(c_L)^{YZ}$	10^{-21}	10^{-16}	10^{-23}
\tilde{b}_Y				$\text{Im}(c_L)^{YZ}$	10^{-21}	10^{-16}	10^{-21}
\tilde{b}_Z				$\text{Re}(c_L)^{XX}$	10^{-21}	10^{-16}	10^{-23}
\tilde{b}_T				$\text{Im}(c_L)^{XX}$	10^{-21}	10^{-16}	10^{-21}
$\tilde{b}_J, (J=X, Y, Z)$				$\text{Re}(c_L)^{YY}$	10^{-21}	10^{-16}	10^{-23}
\tilde{c}_-				$\text{Im}(c_L)^{YY}$	10^{-21}	10^{-16}	10^{-21}
\tilde{c}_Q				$\text{Re}(c_L)^{ZZ}$	10^{-19}	10^{-16}	
\tilde{c}_X				$\text{Im}(c_L)^{ZZ}$		10^{-16}	
\tilde{c}_Y				$\text{Re}(c_L)^{TT}$	10^{-19}	10^{-17}	
\tilde{c}_Z				$\text{Im}(c_L)^{TT}$		10^{-17}	
\tilde{c}_{TX}				$\text{Re}(c_L)^{TX}$	10^{-22}	10^{-17}	10^{-22}
\tilde{c}_{TY}				$\text{Im}(c_L)^{TX}$	10^{-22}	10^{-17}	10^{-22}
\tilde{c}_{TZ}				$\text{Re}(c_L)^{TY}$	10^{-22}	10^{-17}	10^{-22}
\tilde{c}_{TT}				$\text{Im}(c_L)^{TY}$	10^{-22}	10^{-17}	10^{-22}
\tilde{d}_+				$\text{Re}(c_L)^{TZ}$	10^{-20}	10^{-16}	
\tilde{d}_-				$\text{Im}(c_L)^{TZ}$		10^{-16}	
\tilde{d}_Q							
\tilde{d}_{XY}							
\tilde{d}_{YZ}							
\tilde{d}_{ZX}							
\tilde{d}_X							
\tilde{d}_Y							
\tilde{d}_Z							
\tilde{H}_{XT}	10^{-26} GeV						
\tilde{H}_{YT}	10^{-26} GeV						
\tilde{H}_{ZT}	10^{-26} GeV						
\tilde{g}_T	10^{-27} GeV	10^{-7} GeV					
\tilde{g}_c	10^{-26} GeV						
\tilde{g}_Q							
\tilde{g}_-							
$\tilde{g}_{TJ}, (J=X, Y, Z)$							
\tilde{g}_{XY}	10^{-17} GeV						
\tilde{g}_{YX}	10^{-17} GeV						
\tilde{g}_{ZX}	10^{-18} GeV						
\tilde{g}_{XZ}	10^{-17} GeV						
\tilde{g}_{YZ}	10^{-17} GeV						
\tilde{g}_{ZY}	10^{-18} GeV						
\tilde{g}_{DX}	10^{-22} GeV	10^{-27} GeV					
\tilde{g}_{DY}	10^{-22} GeV	10^{-27} GeV	10^{-28} GeV				
\tilde{g}_{DZ}	10^{-22} GeV						

Search of Lorentz Violation with Neutrino

People use ordinary particles to look for Lorentz violation, but cannot find
→ Maybe we should use extraordinary particles, such as neutrinos



Neutrinos

- 3 types
- neutral (no electric charge)
- extremely tiny mass
- second most abundant particles in the universe (after photon)

- neutrinos interact very very weakly with matters, so extremely difficult to detect

ex) Neutrinos from the Sun
~1 trillion neutrinos pass through your body every second, **and you have 25% chance to hit one neutrino in 80 years**

Search of Lorentz Violation with Neutrino

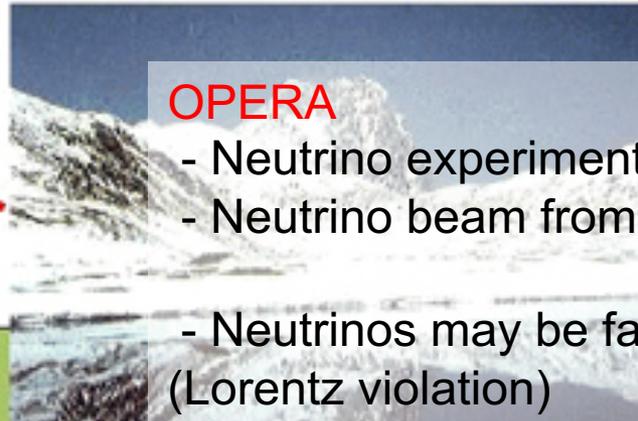
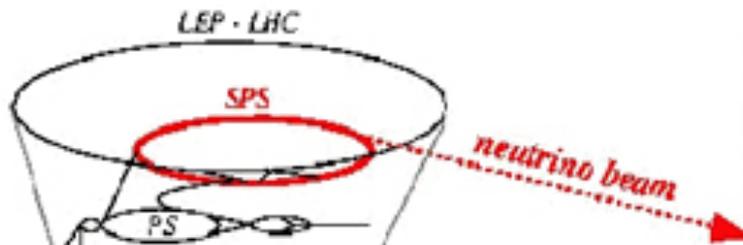
Neutrinos are mysterious particles, and we still don't know much about neutrinos
→ Maybe neutrinos have better chance to find Lorentz violation?

Especially, many neutrino data show some anomaly, it could be Lorentz violation?

Search of Lorentz Violation with Neutrino

Neutrinos are mysterious particles, and we still don't know much about neutrinos
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In particular, many neutrino data show anomalies, it could be Lorentz violation?



OPERA

- Neutrino experiment at Gran Sasso, Italy
- Neutrino beam from CERN, Switzerland
- Neutrinos may be faster than the light?! (Lorentz violation)



OPERA detector at Gran Sasso



Search of Lorentz Violation

theguardian

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Neutrinos are mysterious particles
→ Maybe neutrinos have better
Neutrinos still faster than light in latest version of experiment

Finding that contradicts Einstein's theory of special relativity is repeated with fine-tuned procedures and equipment

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The Washington Post

Posted at 08:25 AM ET, 09/23/2011

Neutrinos may have traveled faster than the speed of light

By Elizabeth Flock

Scientists at CERN, the world's largest physics lab, announced a startling finding yesterday that would be enough to make Albert Einstein roll over in his grave: Subatomic particles, called [neutrinos](#), have been found to be traveling faster than the speed of light.

Monday 06 February 2012

The Telegraph

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Speed of light broken again as scientists test neutrino result

The speed of light appears to have been broken again after scientists carried out a new set of experiments to test measurements that could require the laws of physics to be rewritten.

In particular, many neutrino data

LEP - LHC

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The New York Times

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Scientists Report Second Sighting of Faster-Than-Light Neutrinos

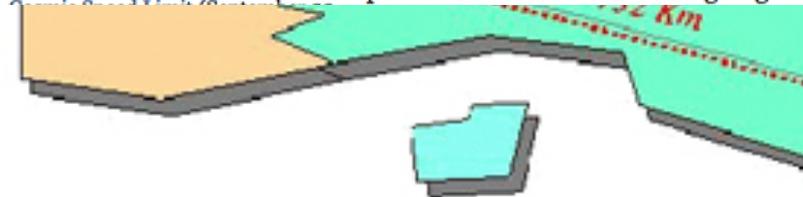
By DENNIS OVERBYE
Published: November 18, 2011

Few scientists are betting against Einstein yet, but the phantom neutrinos of Opera are still eluding explanation.

Related

Tiny Neutrinos May Have Broken

Two months after scientists reported that they had clocked subatomic particles known as neutrinos going



Search of Lorentz Violation

The New York Times

Science

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Two Technical Problems Leave Neutrinos' Speed in Question

By KENNETH CHANG
Published: February 23, 2012

Remember those faster-than-light neutrinos that supposedly defied Einstein's speed limit?

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The

OPERA

- Neutrinos may be faster than the light?!
(Lorentz violation)

→ experimental error
(Lorentz violation is not discovered)

We should take a look other neutrino data

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Faster-than-light neutrinos could be down to bad wiring

By Jason Palmer
Science and technology reporter, BBC News

What might have been the biggest physics story of the past century may instead be down to a faulty connection.

In September 2011, the Opera experiment reported it had seen particles called neutrinos evidently travelling faster than the speed of light.

The team has now found two problems that may have affected their test in opposing ways: one in its timing gear and one in an optical fibre

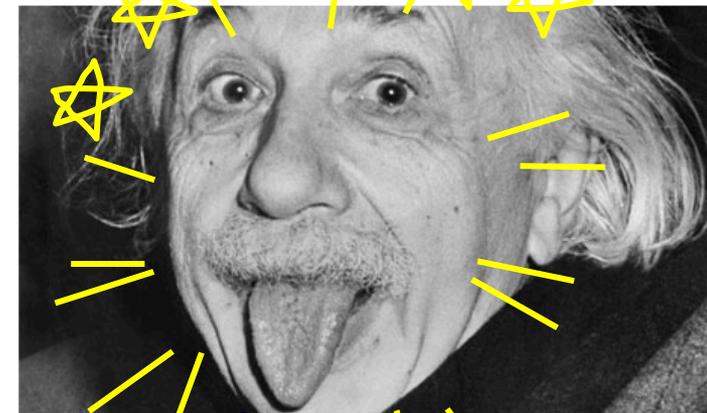


The neutrinos are fired deep under the Italian
rewritten.

Faster-than-light neutrinos: was a faulty connection to blame?

A dodgy optical fibre connection may have skewed results that appeared to show neutrinos travelling faster than light

Alok Jha, science correspondent
guardian.co.uk, Thursday 23 February 2012 11:05 EST
Article history



Faster-than-light neutrinos would breach Einstein's theory of special relativity.

Search of Lorentz Violation with Neutrino

Neutrinos are mysterious particles, and we still don't know much about neutrinos
→ Maybe neutrinos have better chance to find Lorentz violation?

Especially, many neutrino data show some anomaly, it could be Lorentz violation?



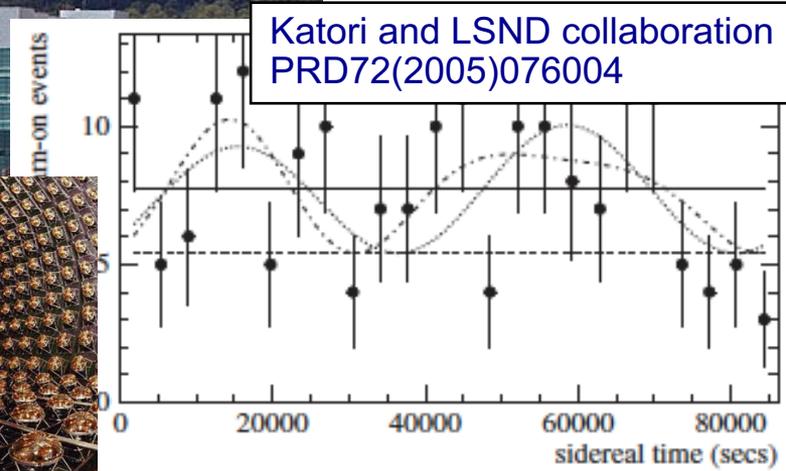
LSND

- Neutrino experiment at Los Alamos laboratory, USA
- Data show some anomaly

→ This is not due to Lorentz violation



Inside of LSND detector



Katori and LSND collaboration
PRD72(2005)076004

Search of Lorentz Violation with Neutrino

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MiniBooNE

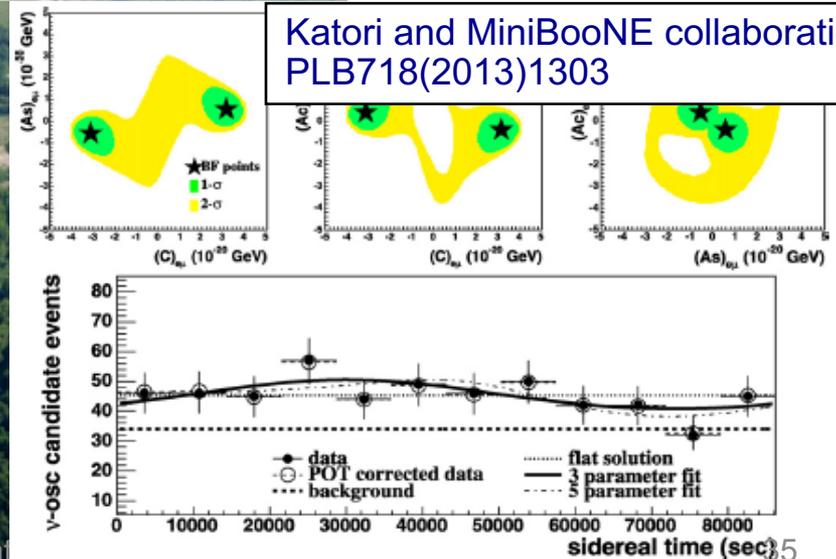
- Neutrino experiment at Fermilab, USA
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MiniBooNE detector

Katori and MiniBooNE collaboration
PLB718(2013)1303



Search of Lorentz Violation with Neutrino

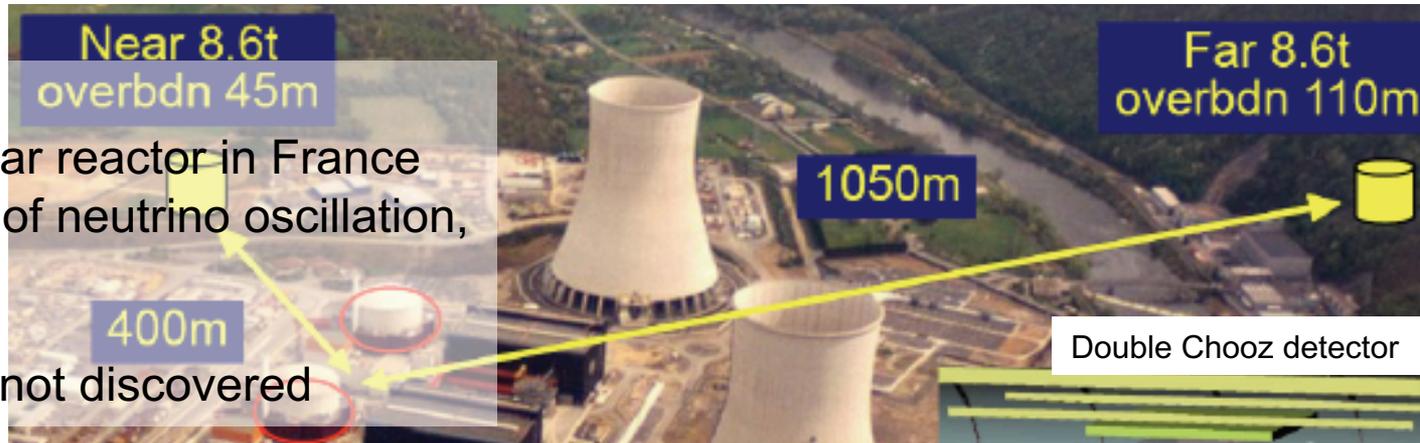
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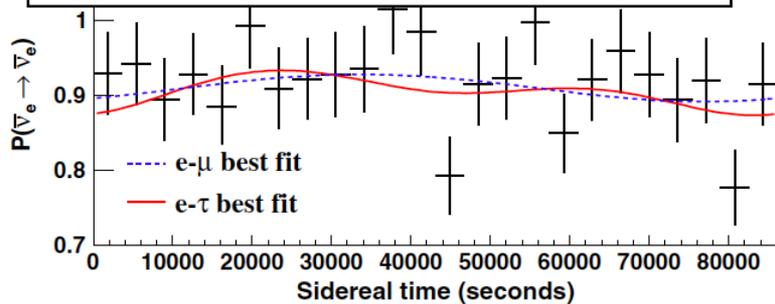
Double Chooz

- Neutrinos from nuclear reactor in France
- Data show new type of neutrino oscillation, could be new physics

→ Lorentz violation is not discovered

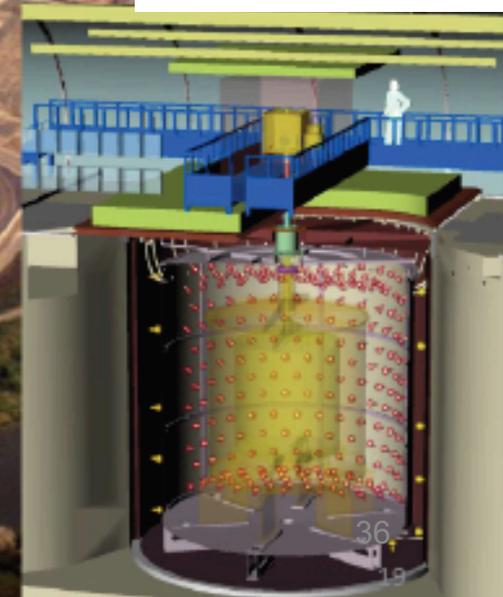


Katori and Double Chooz collaboration
 PRD86(2012)112009



Chooz-B Power Plant

• 2 cores, 8.6 GW_{th}



So far, no neutrino experiments find Lorentz violation...

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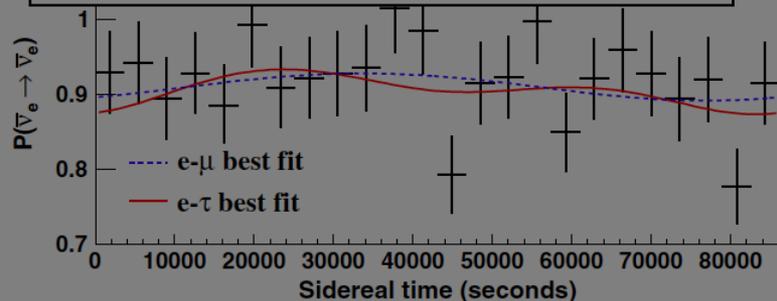
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Katori and Double Chooz collaboration
PRD86(2012)112009



So far, no neutrino experiments find Lorentz violation...

“Extraordinary discovery requires extraordinary evidence”

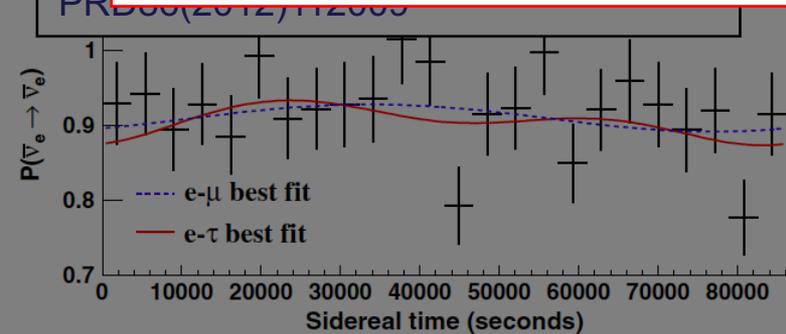
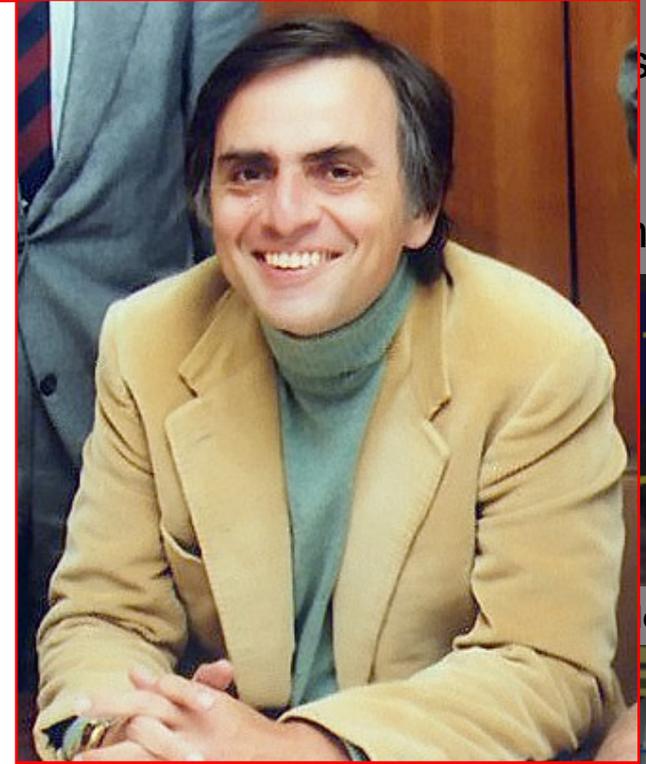
- Carl Sagan



“Extraordinary discovery requires extraordinary particles”

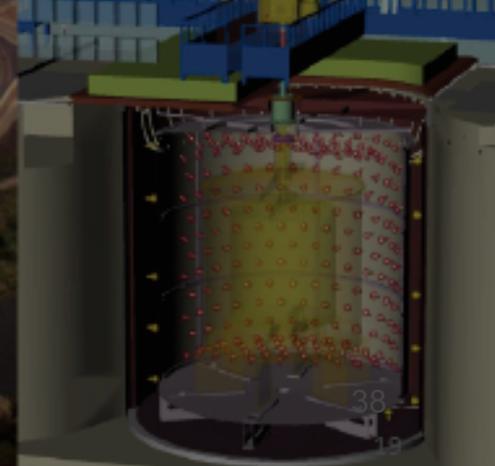
- Teppei

...may be this is not extraordinary enough?



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“Extraordinary discovery requires extraordinary evidence”

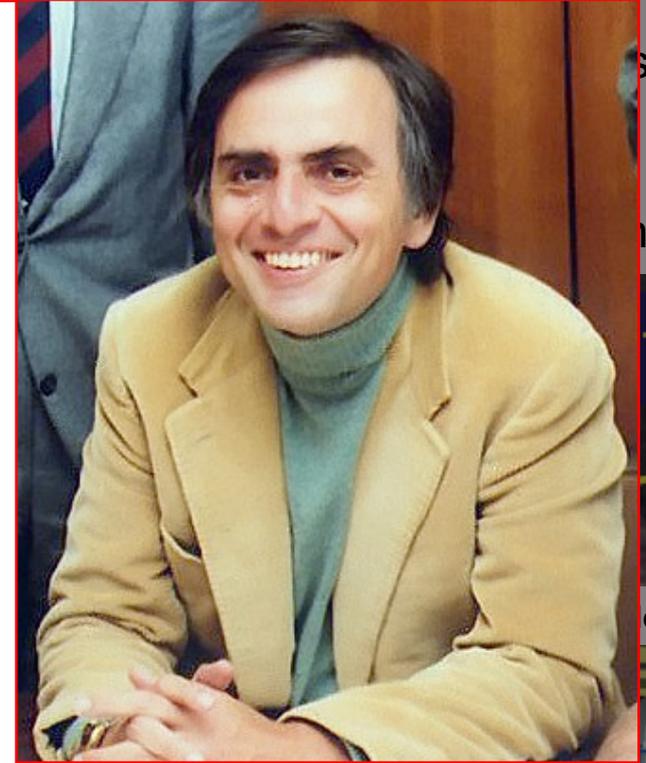
- Carl Sagan



“Extraordinary discovery requires extraordinary particles”

- Teppei

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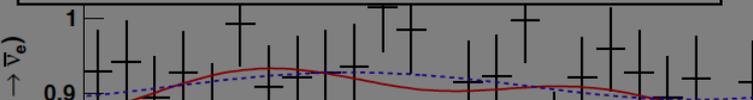
*“Extraordinary discovery requires extraordinary particles with **the extraordinary energy** and **extraordinary propagation distance**”*

- Teppei

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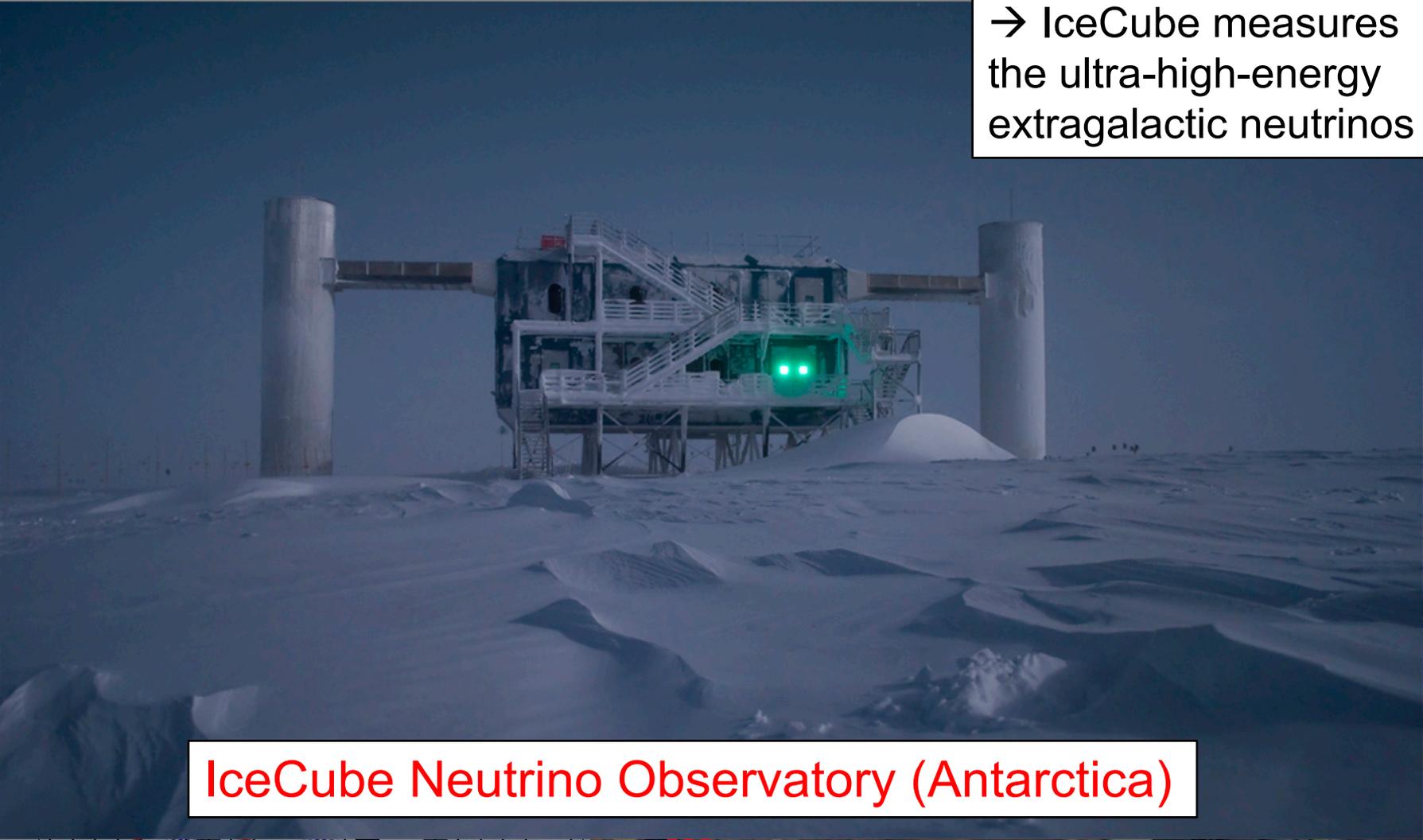
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etector

• 2 cores, 8.6 GW_{th}

→ IceCube measures the ultra-high-energy extragalactic neutrinos

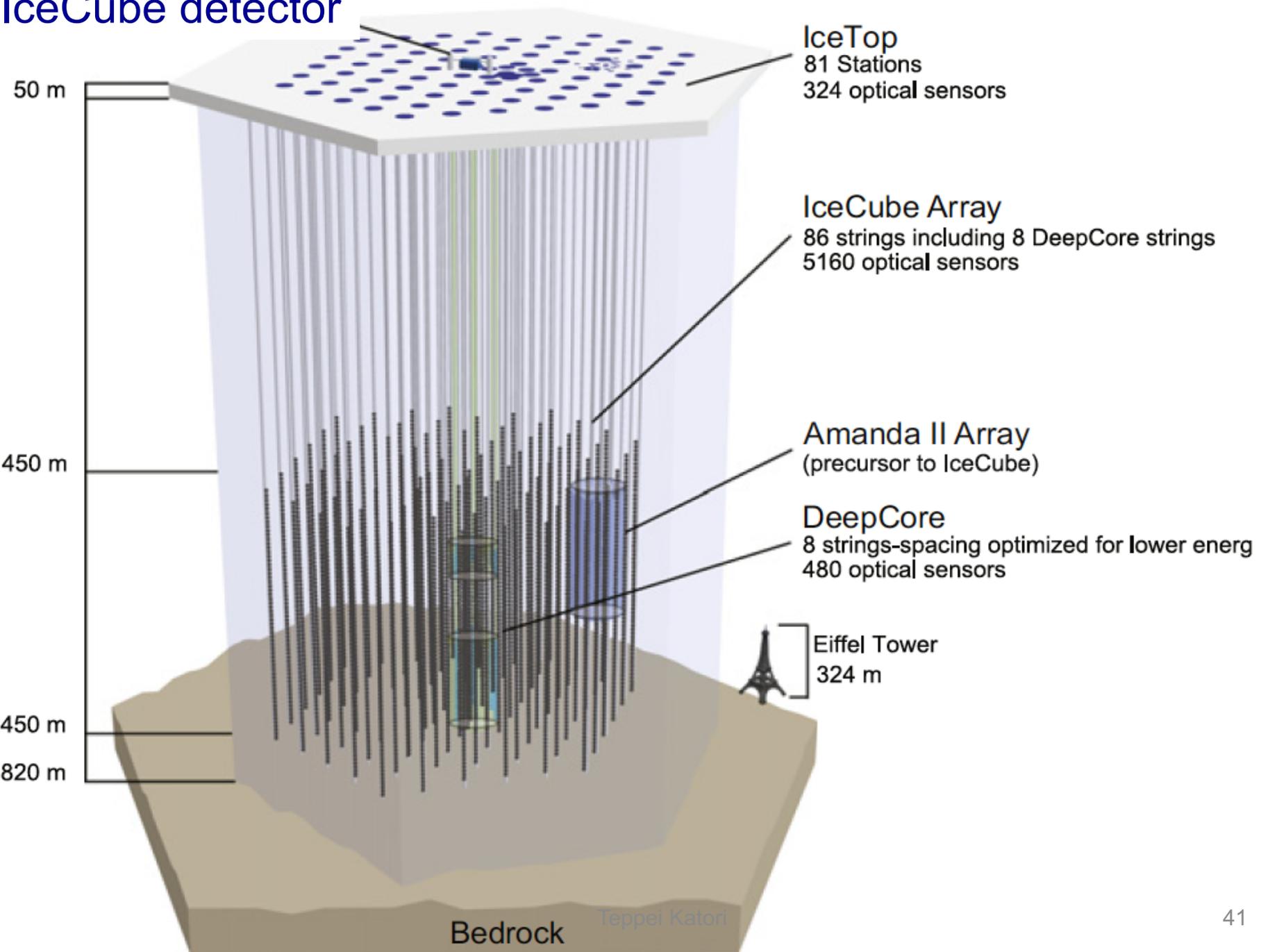
A photograph of the IceCube Neutrino Observatory in Antarctica. The structure is a complex of metal scaffolding and platforms built on a vast, flat, snow-covered landscape. Two large, white cylindrical pillars stand on either side of the central structure. A bright green light is visible on the central platform. The sky is a clear, pale blue.

IceCube Neutrino Observatory (Antarctica)

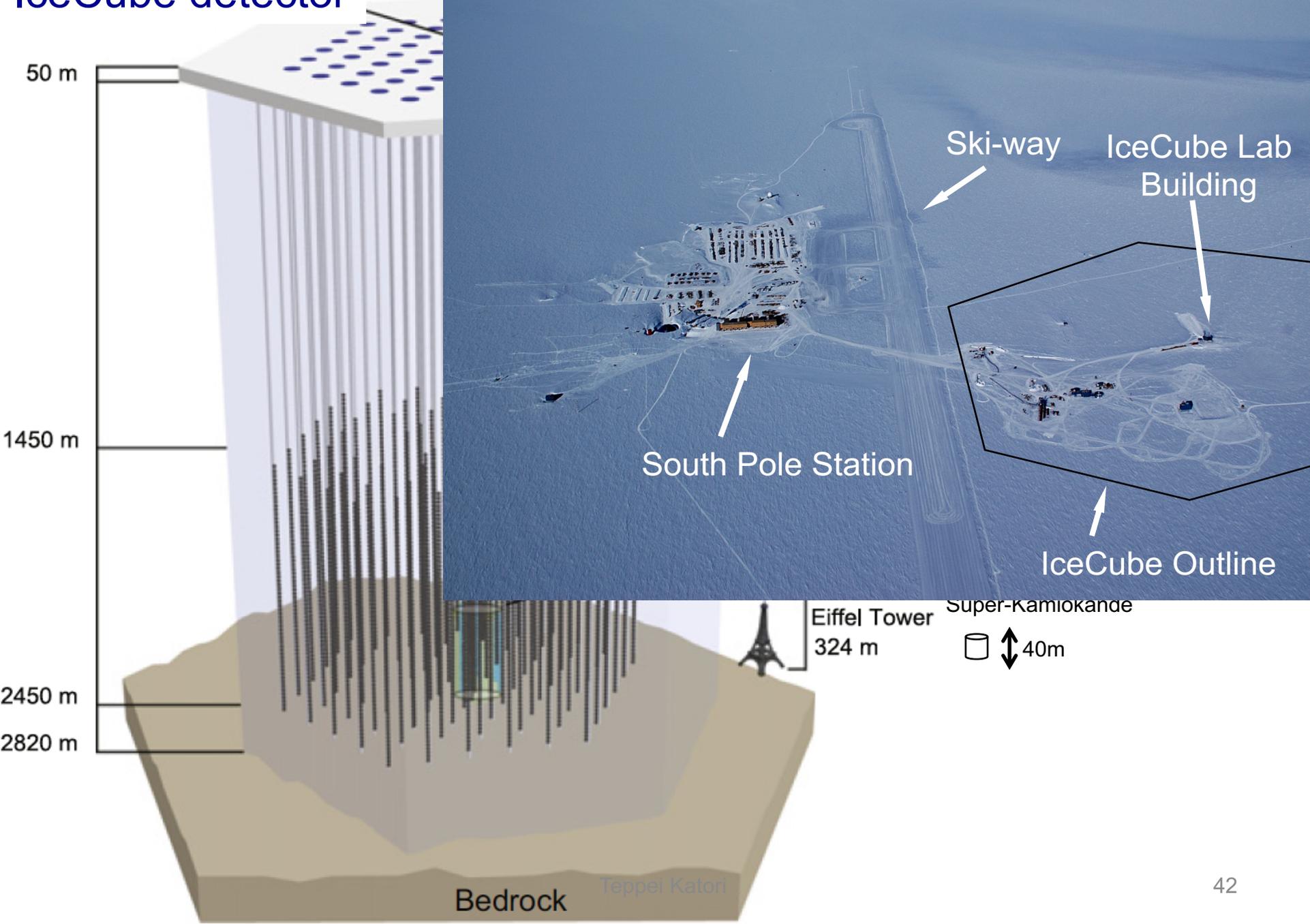
*“Extraordinary discovery requires extraordinary particles with **the extraordinary energy and extraordinary propagation distance**”*
- Teppei

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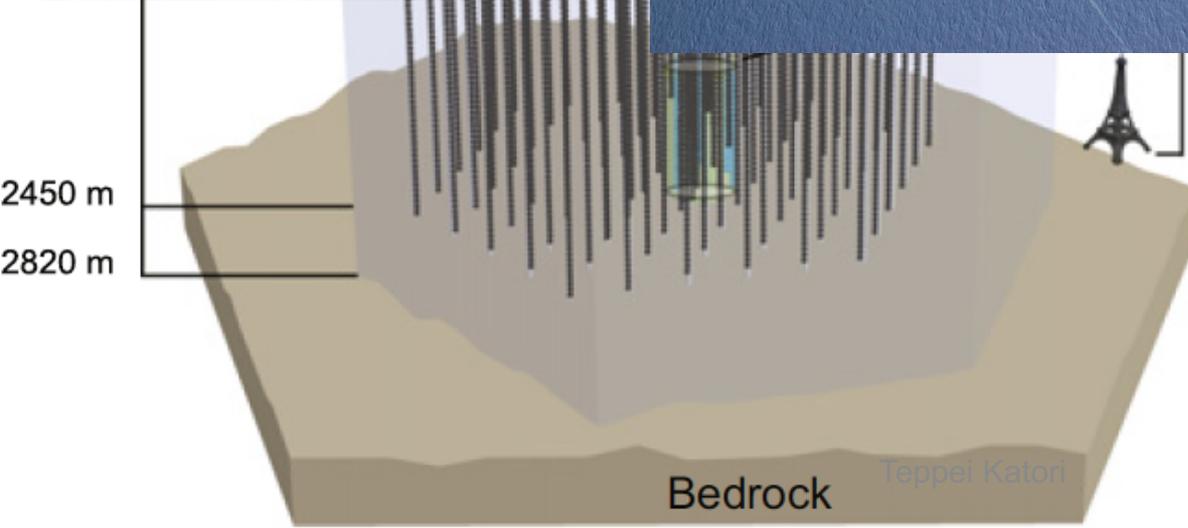
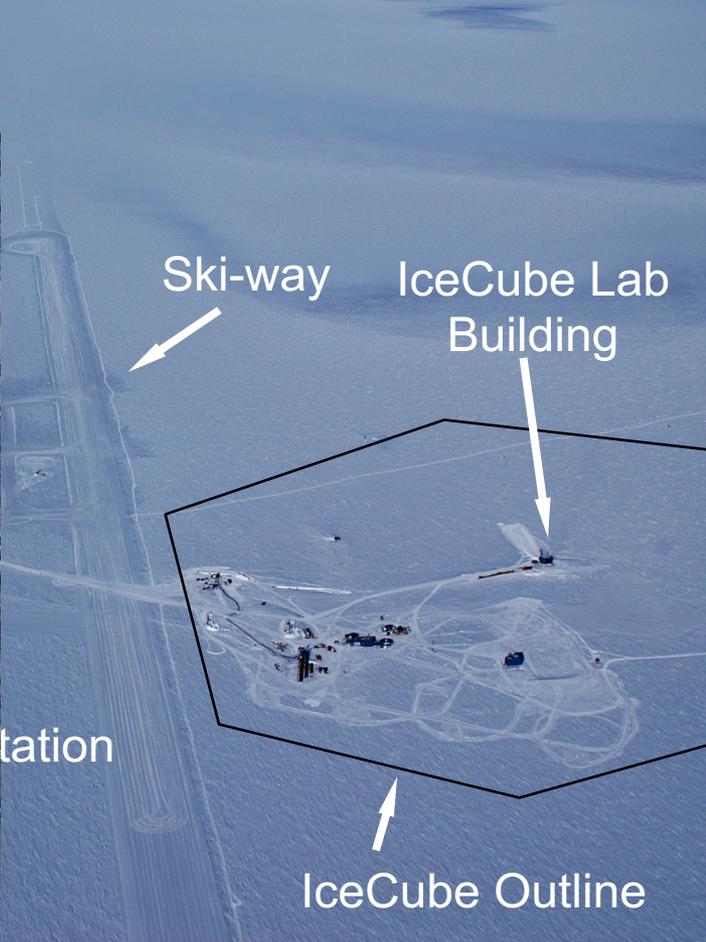
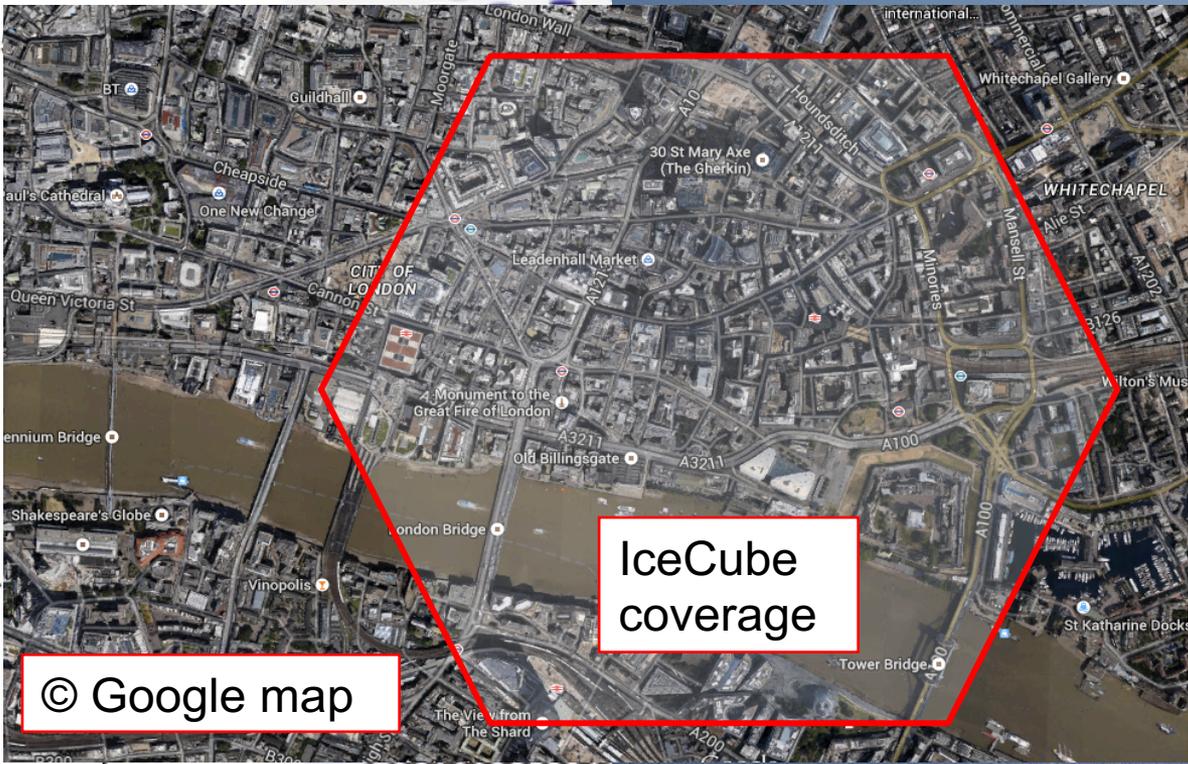
IceCube detector



IceCube detector



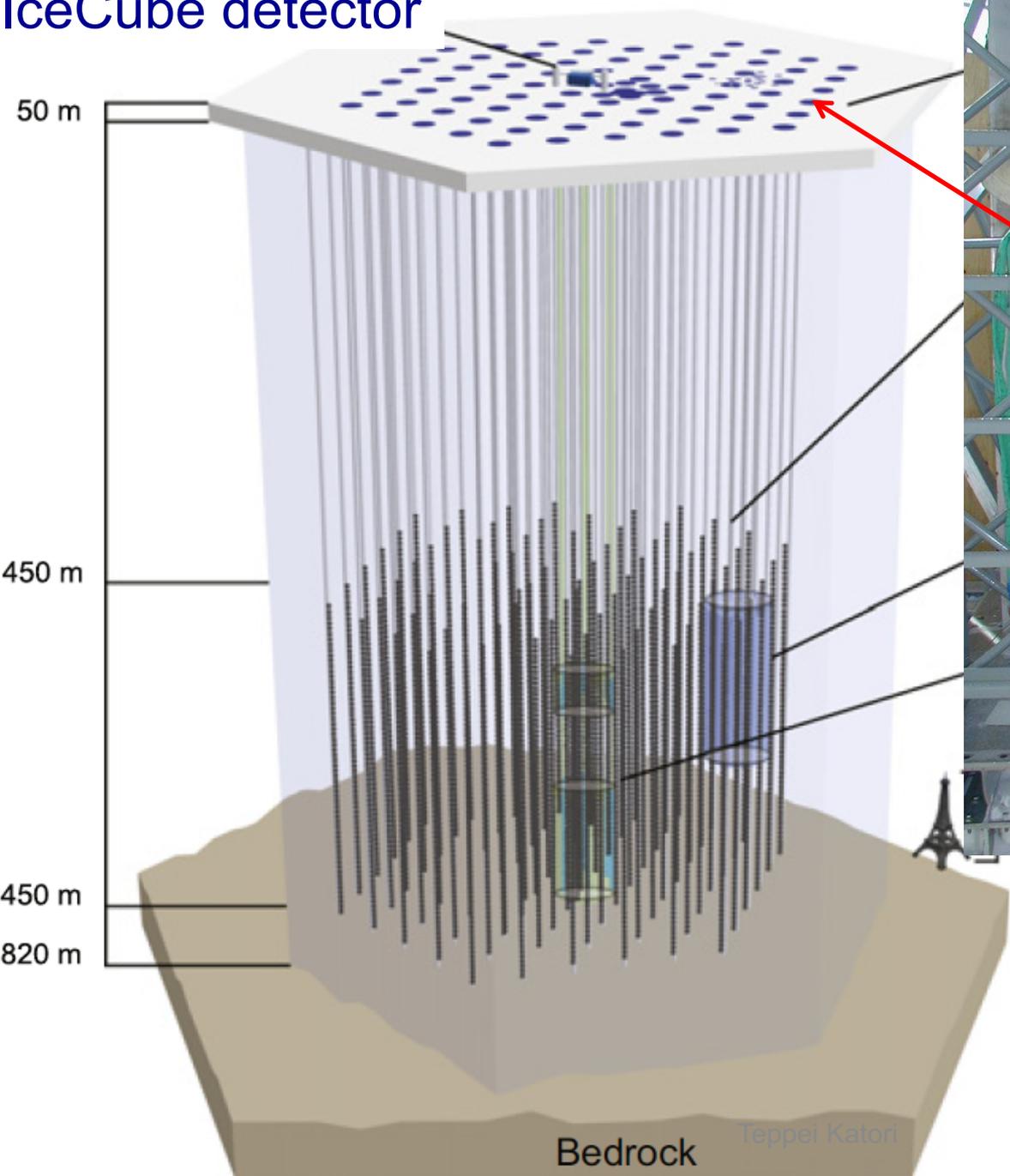
IceCube detector



Super-Kamiokande
 40m

Teppei Katori

IceCube detector

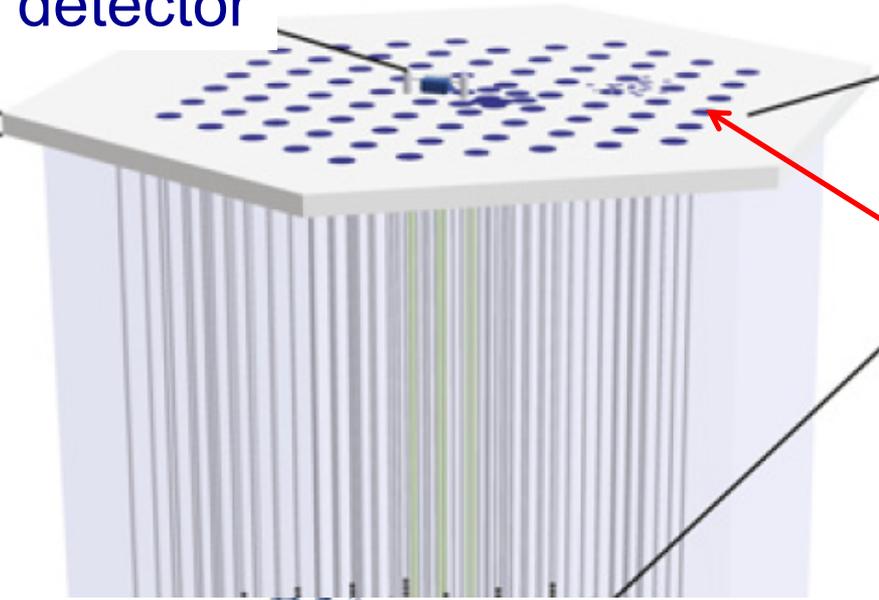


hot water drill

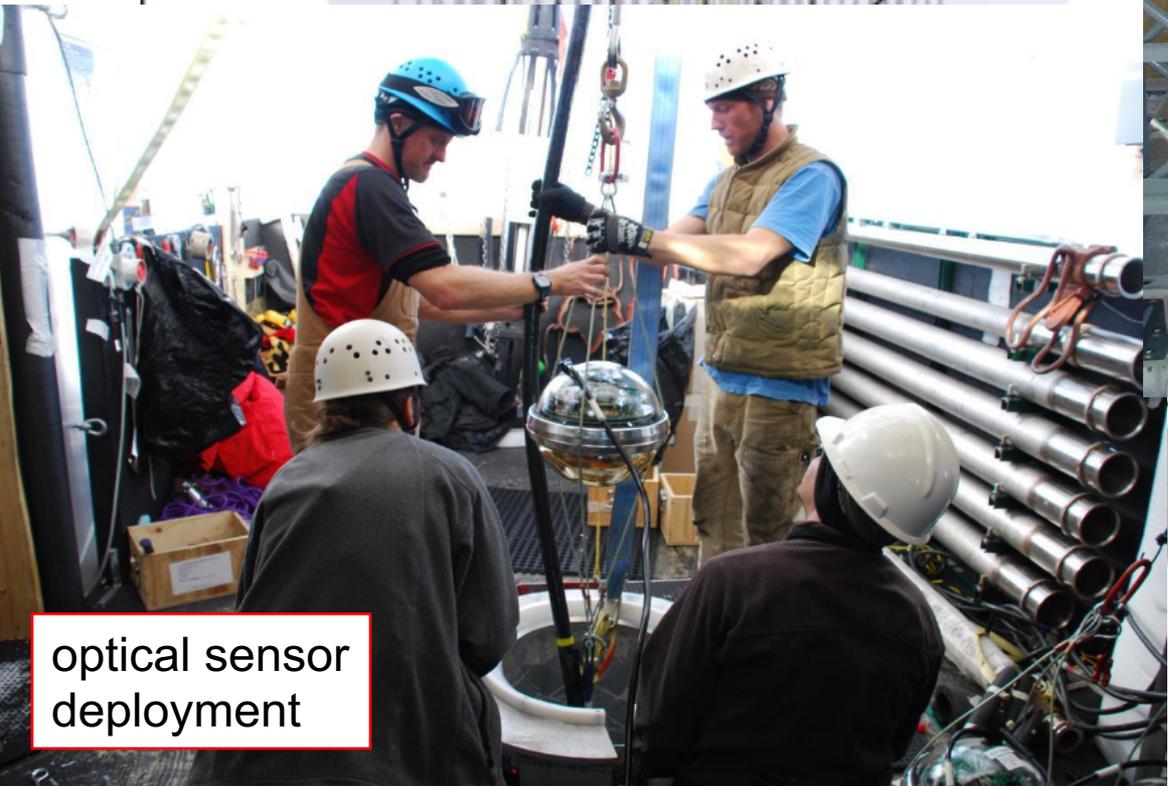
Bedrock Teppei Katori

IceCube detector

50 m

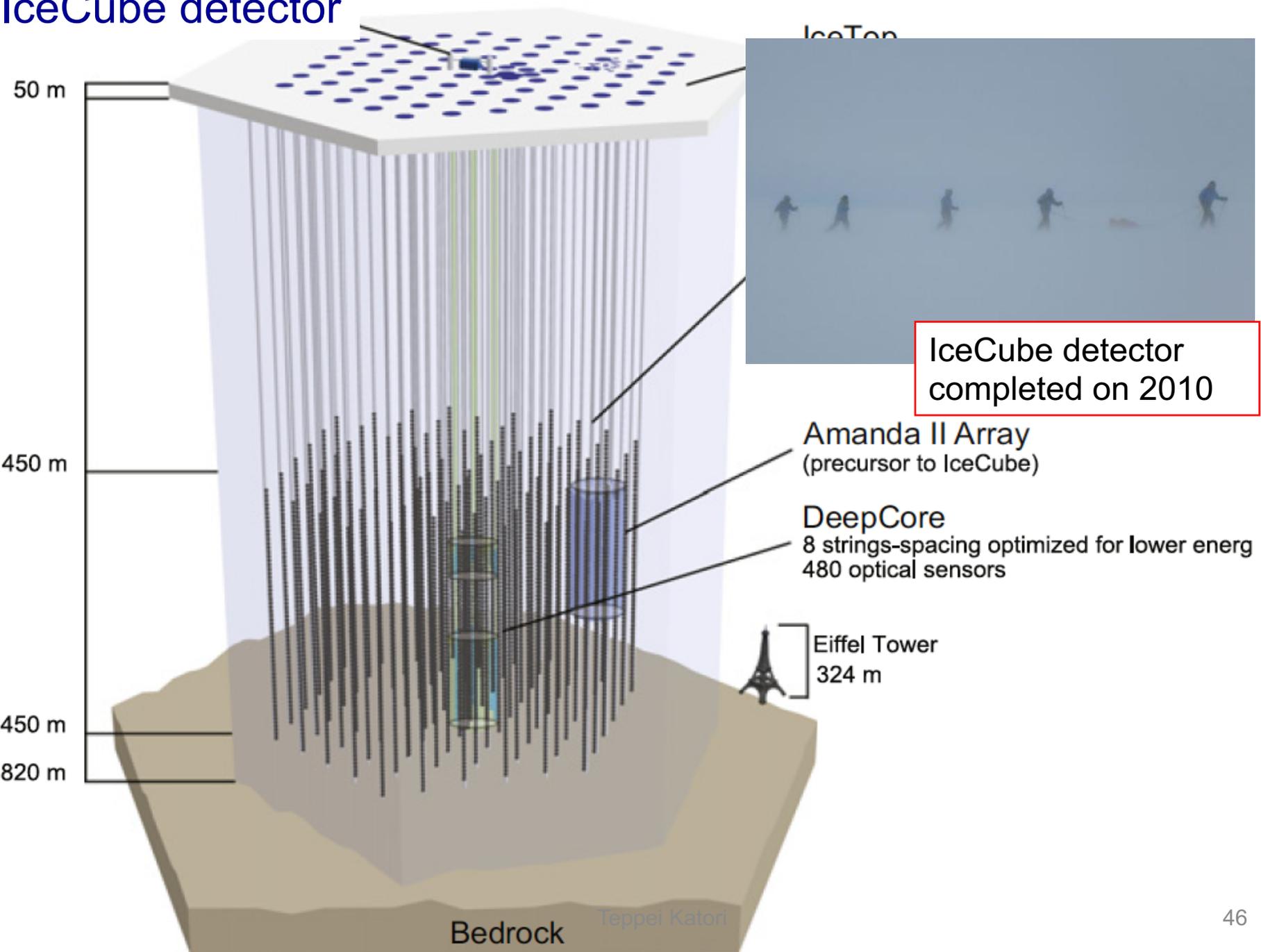


hot water drill



optical sensor deployment

IceCube detector



IceCube detector

50



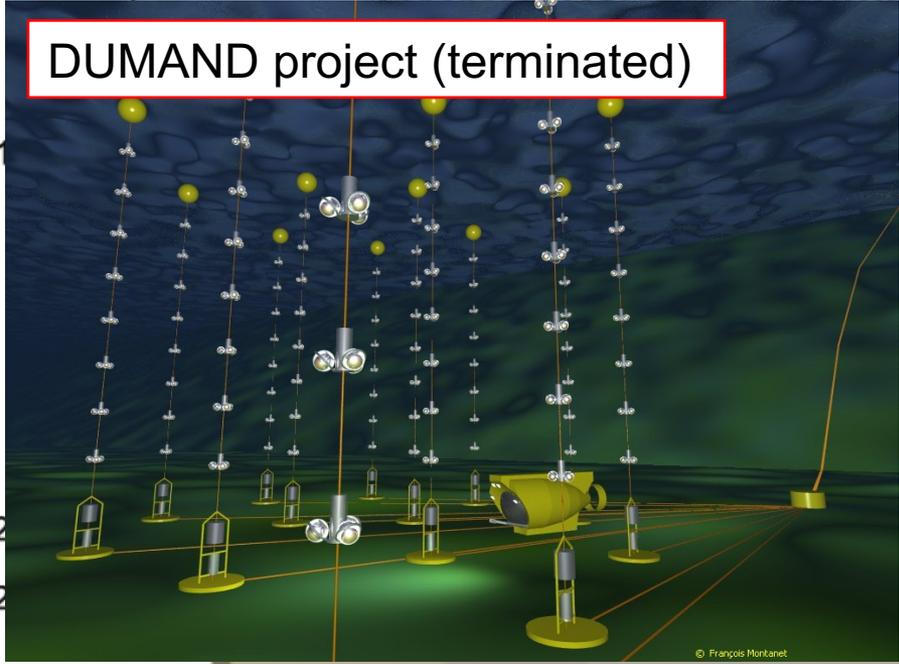
Hawaii

VS.



IceCube detector completed on 2010

DUMAND project (terminated)



Amanda II Array (precursor to IceCube)

DeepCore 8 strings-spacing optimized for lower energy 480 optical sensors

Eiffel Tower 324 m

Bedrock

Teppei Katori

NuMu

6.08e+04

44.43 deg

357.53 deg

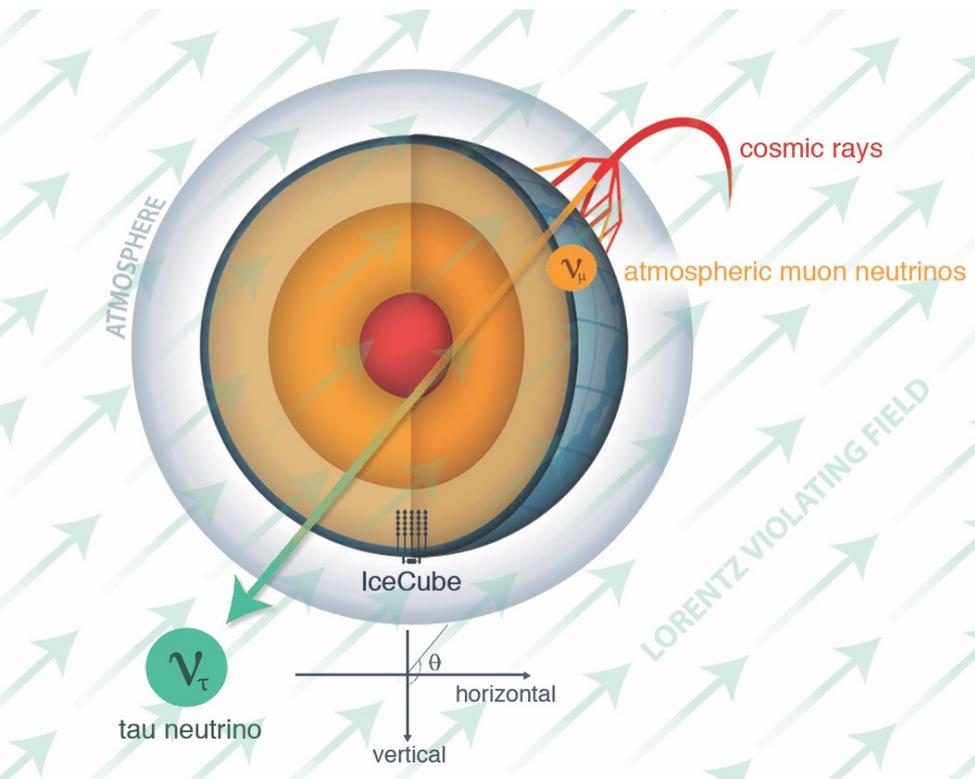
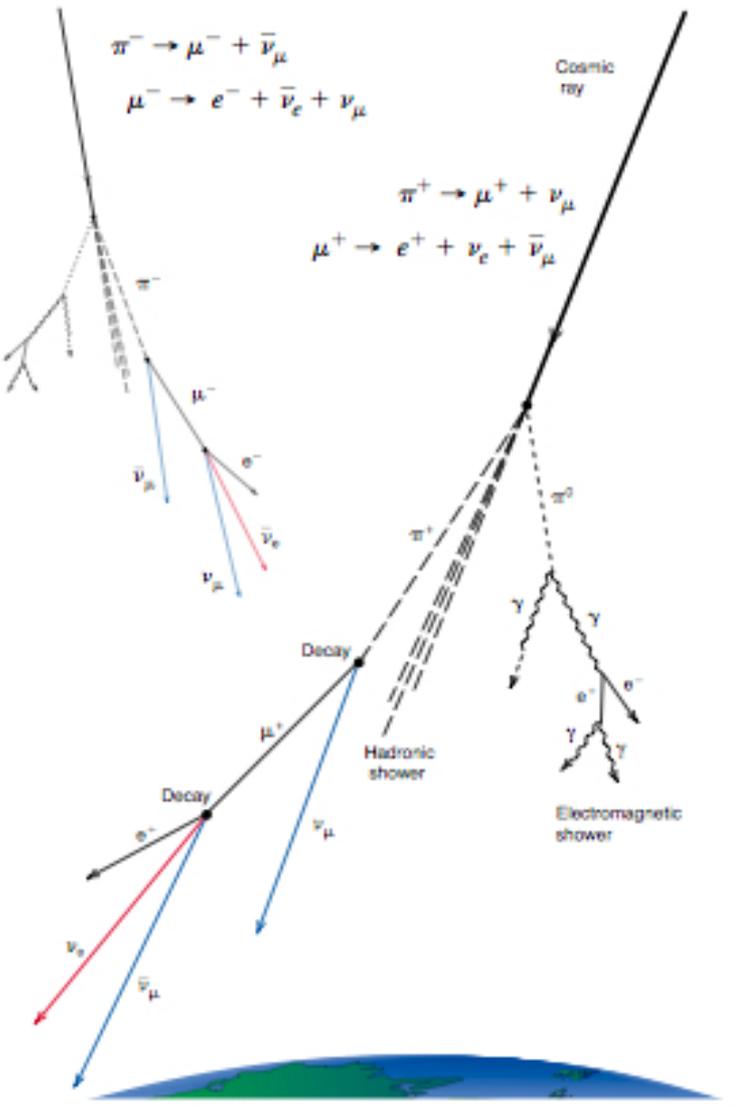
100/446 shown, max E (GeV) == 56675.77

100/444 shown, max E (GeV) == 1.58

Test of Lorentz violation with Atmospheric neutrino at IceCube

We start to look for Lorentz violation from abundant atmospheric neutrinos

Lorentz violation may change the signal of **neutrino oscillations (Nobel prize 2015)**



Test of Lorentz violation with Atmospheric neutrino at IceCube



Carlos Argüelles



Gabriel Collin



Janet Conrad

MIT



Ali Kheirandish
U. Wisconsin,
Madison



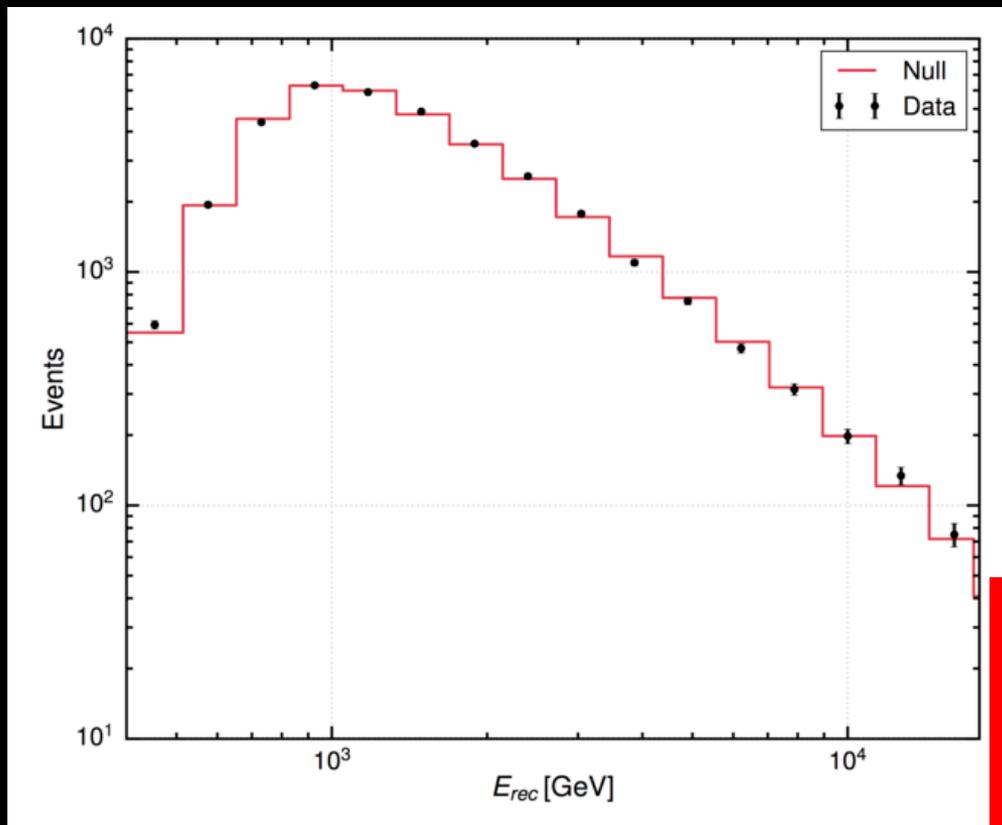
Shivesh Mandalia
Queen Mary
U. of London

Test of Lorentz violation with Atmospheric neutrino at IceCube

1 to 20 TeV high energy neutrinos (Large Hadron Collider ~ 7 TeV)

Neutrino signal looks normal..., Lorentz violation is not discovered

→ We set limit on dimension-6 new physics operator down to 10^{-36} GeV⁻²



We need much higher energy neutrinos...

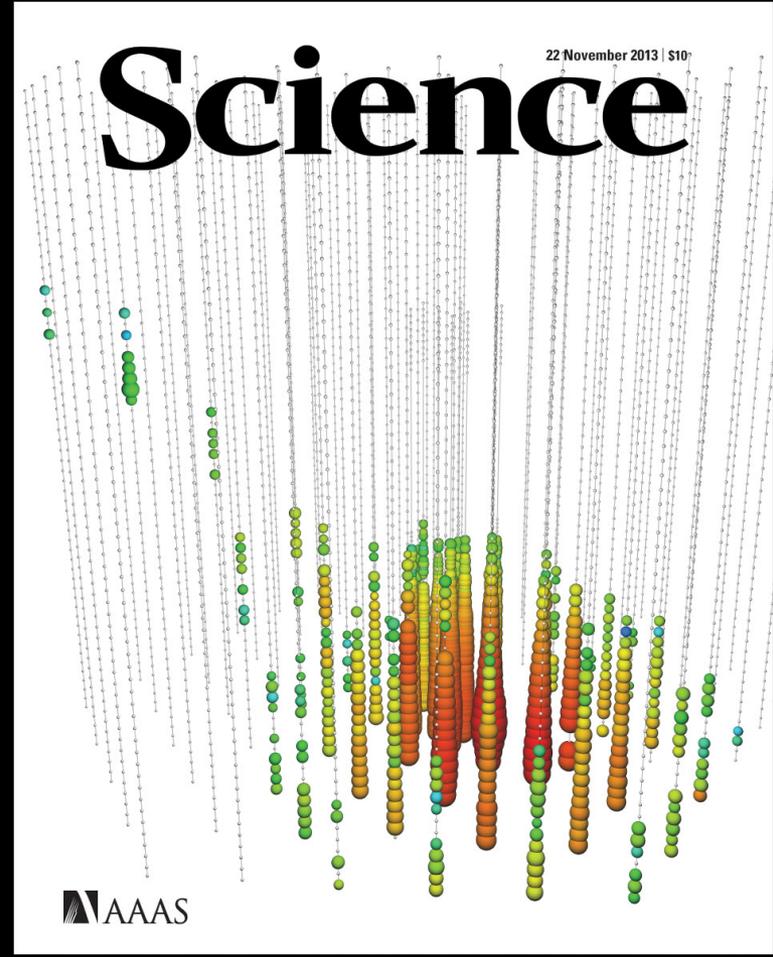
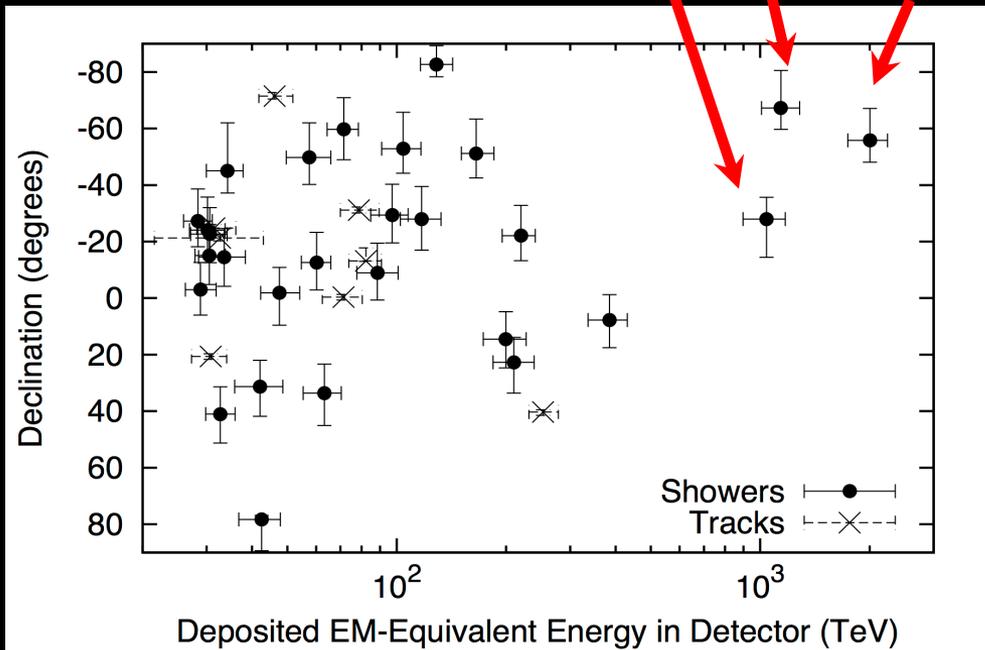
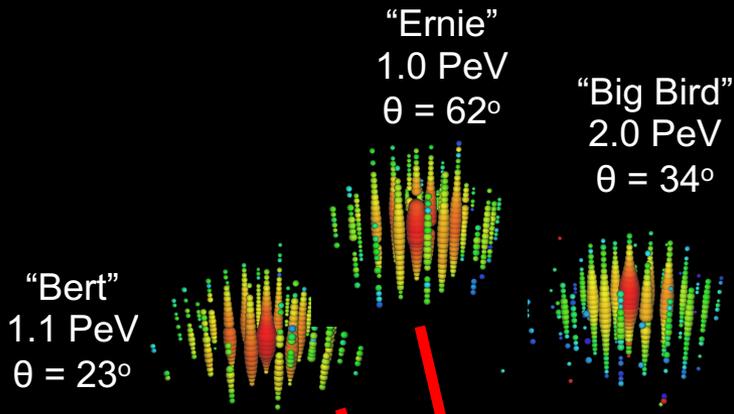


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this is the existing highest precision test of Lorentz violation! (to be published)

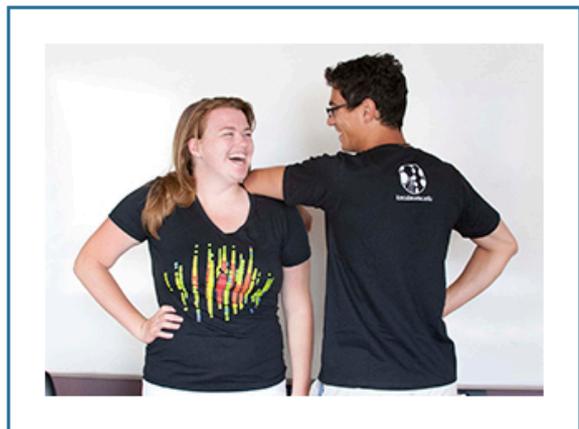
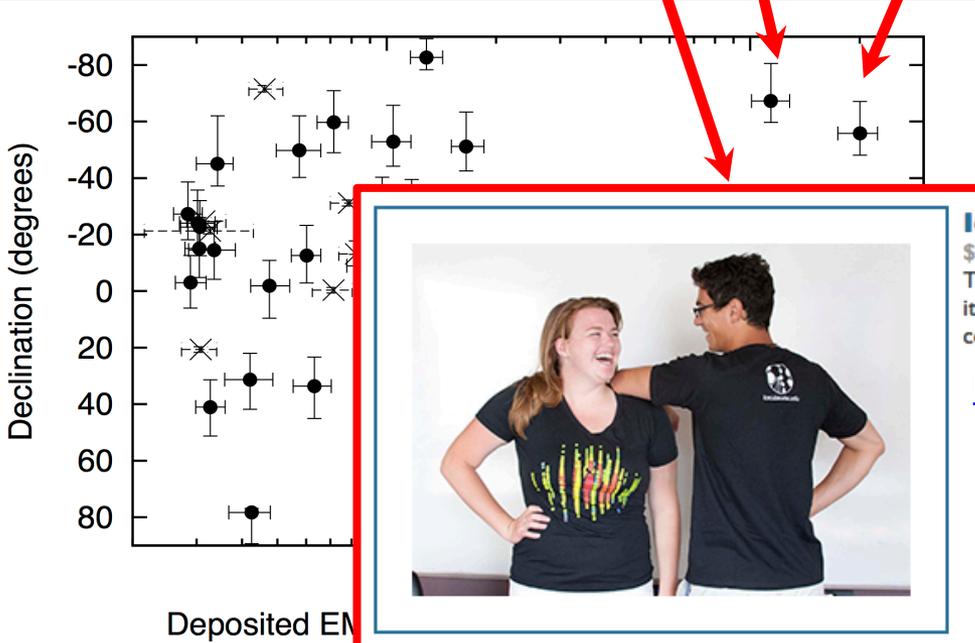
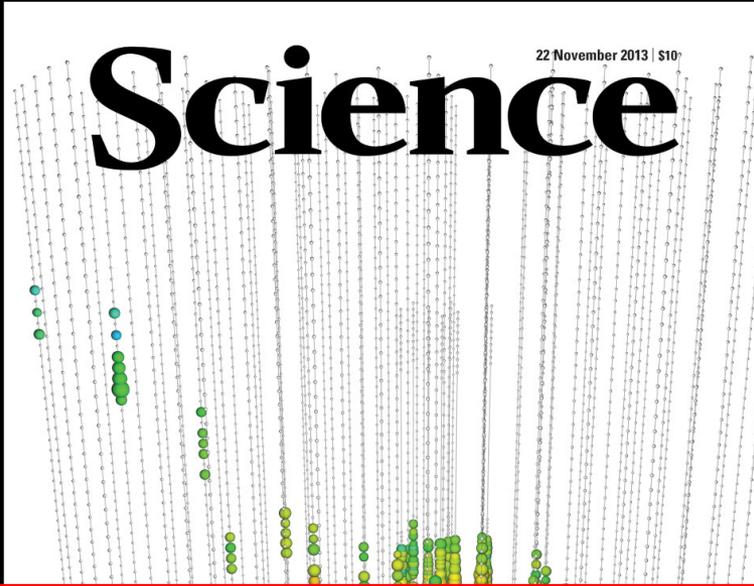
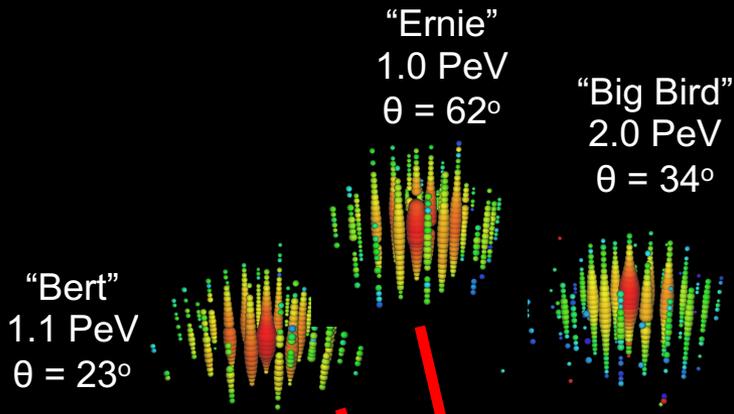
Discovery of High-Energy Astrophysical Neutrinos (2012)

30 TeV to 2000 TeV very-high-energy neutrinos (Large Hadron Collider ~ 7 TeV)



Discovery of High-Energy Astrophysical Neutrinos (2012)

30 TeV to 2000 TeV very-high-energy neutrinos (Large Hadron Collider ~ 7 TeV)



IceCube V-neck high energy neutrino t-shirt
\$15.00
The "Bertshirt" in V-neck style. Soft, 100% ring spun cotton with a longer torso length makes it comfortable for all wearers. IceCube logo on the back. Black, V-neck, pre-shrunk 3.2 oz cotton. Available in sizes S-2XL.
https://charge.wisc.edu/icecube/wipac_store.aspx

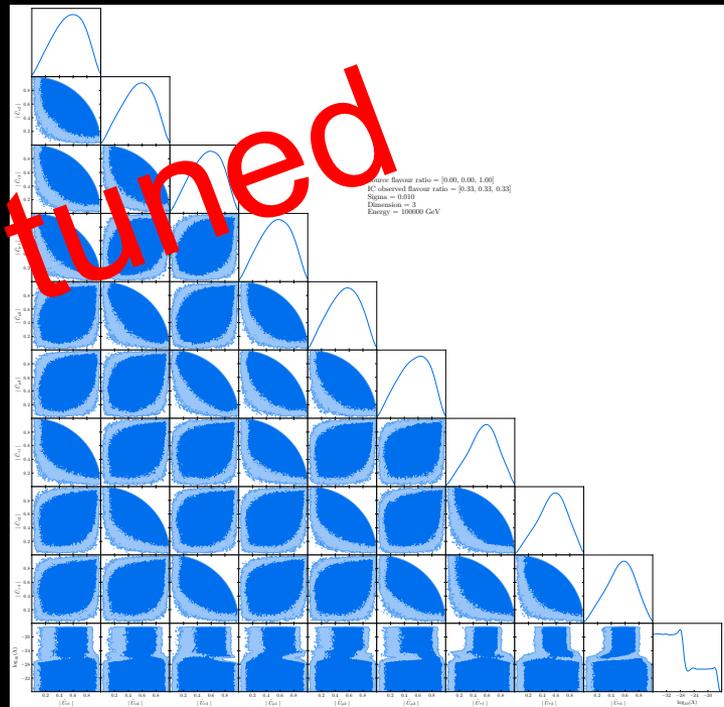
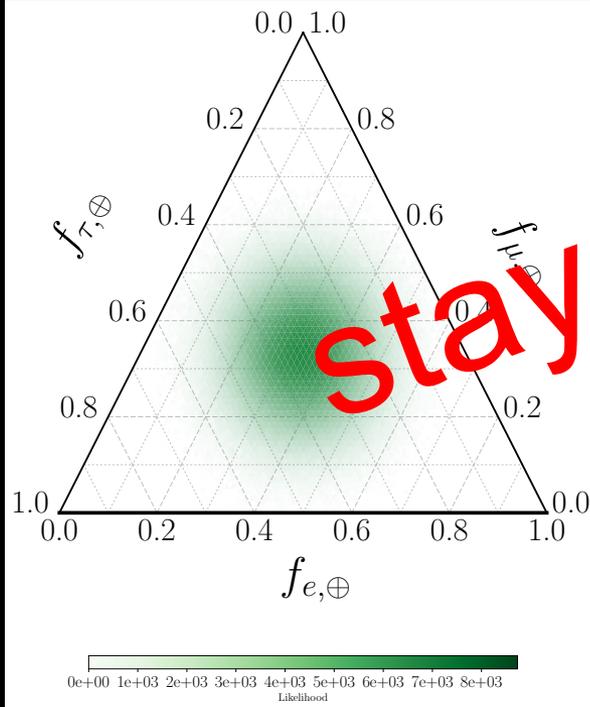
Support IceCube!

Discovery of High-Energy Astrophysical Neutrinos (2012)

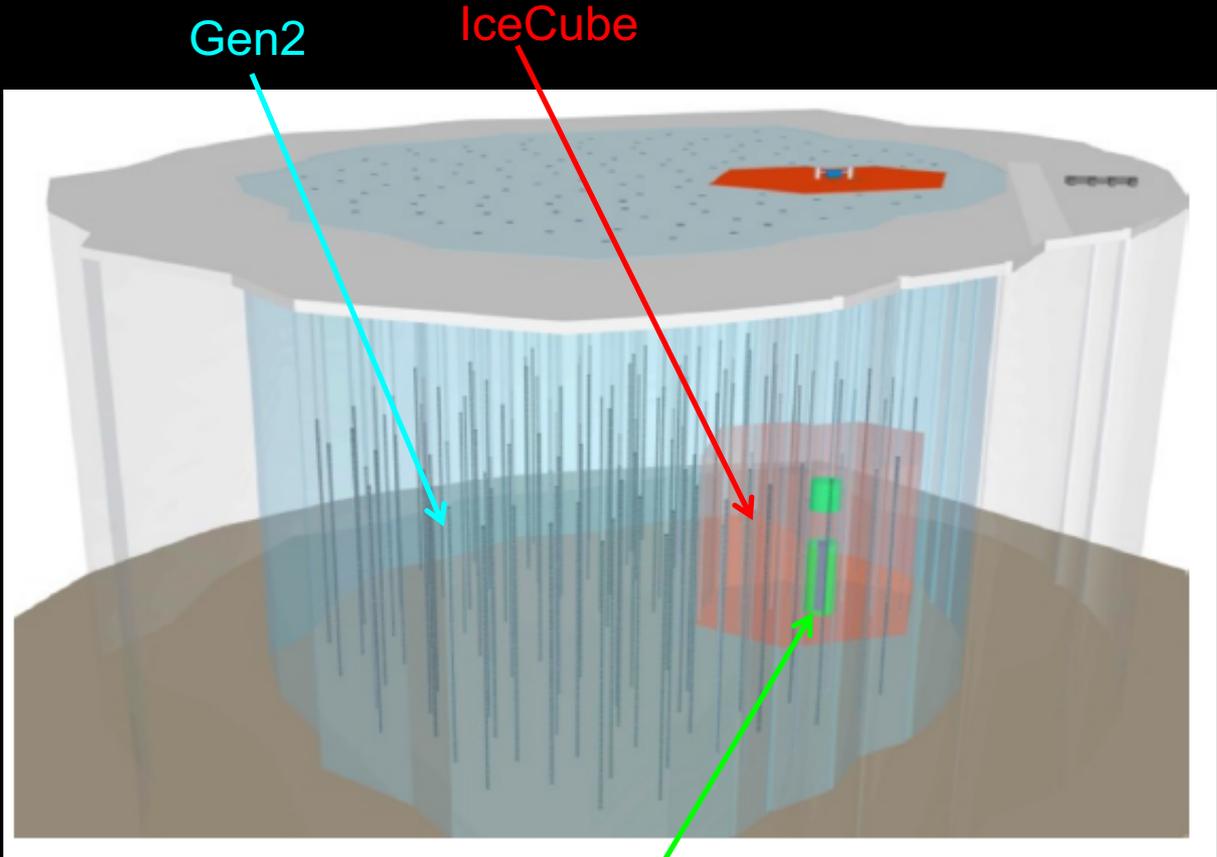
30 TeV to 2000 TeV very-high-energy neutrinos (Large Hadron Collider ~ 7 TeV)

Currently, Queen Mary IceCube group is looking for Lorentz violation from astrophysical neutrinos using Markov Chain Monte Carlo (MCMC) based analysis. The result will be presented in 2018.

MARKOV



IceCube-Generation 2 (Gen2)



To study astrophysical neutrinos more carefully, we need a bigger **IceCube**

Gen2
Larger string separations to cover larger area

PINGU: special region to study low energy neutrino

PINGU

UK members: Queen Mary
Oxford, Manchester



IceCube-Generation 2 (Gen2)

IceCube-Gen2 collaboration



To study astrophysical neutrinos more carefully, we need a bigger **IceCube**

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Conclusion

Lorentz violation may be the first evidence of Theory of Everything

There is a worldwide effort to look for Lorentz violation, using various state-of-the-art techniques, but so far nobody found Lorentz violation

Neutrinos, especially ultra-high-energy astrophysical neutrinos have a great potential to discover Lorentz violation



Thank you for your attention!

