

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

ICONOCLASTS

## Toppling the Giant

SCIENTIFIC AMERICAN

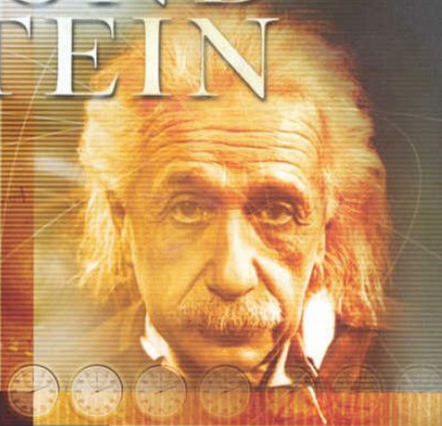
SPECIAL ISSUE

SEPTEMBER 2004  
WWW.SCIAM.COM

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

# BEYOND EINSTEIN

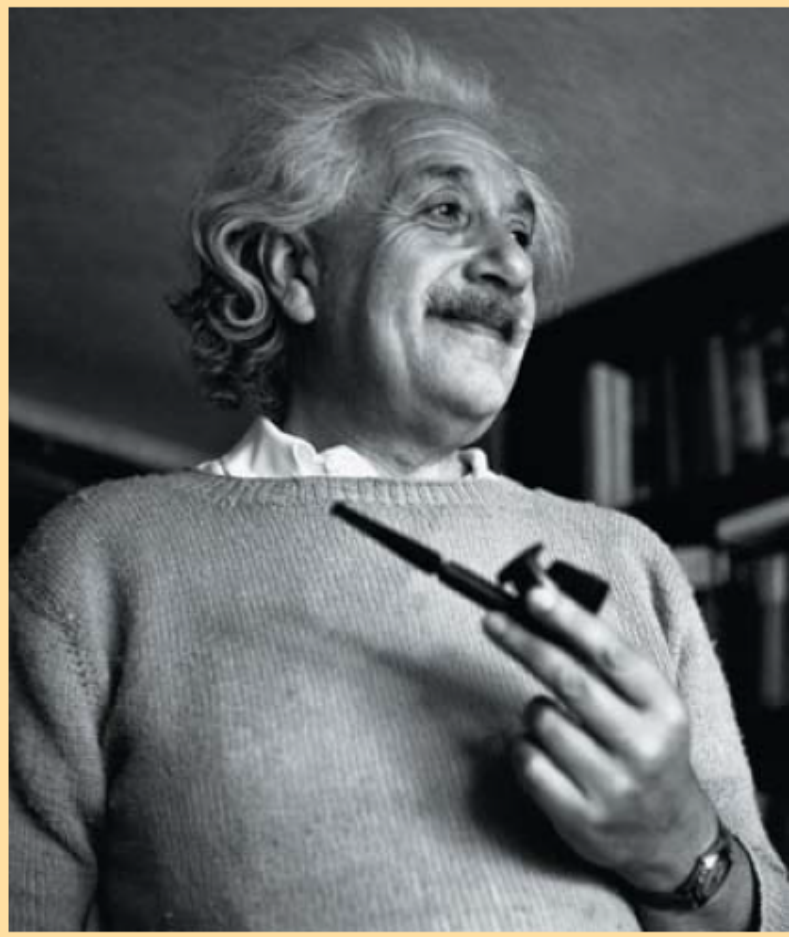
- Toward a Theory of Everything
- Energy That Expands the Cosmos
- Different Physics, Infinite Universes
- Does the Speed of Light Change?
- Computing with Relativity
- Einstein vs. Newton
- And More ...



Of the three most important physics theories of the 20th century, relativity and quantum mechanics have proved his ideas wrong. Perpetual-motion machines and other fringe pursuits are being pursued by misguided amateurs who seem to believe that they will acquire all his secrets. The only way to prove them wrong is to prove their own

... Many serious and ... and Einstein, in the way ... accompanying article ... search for departures ... cusses is based on a ... ll plausible relativity- ... article physics. This ... deviation that could ... -energy pinnacle of the

... have attracted specific ... me "doubly special ... i Amelino-Camelia of ... y Lee Smolin of the ... ntario, João Magueijo



Teppei Katori  
Queen Mary University of London  
Feb. 1, 2017



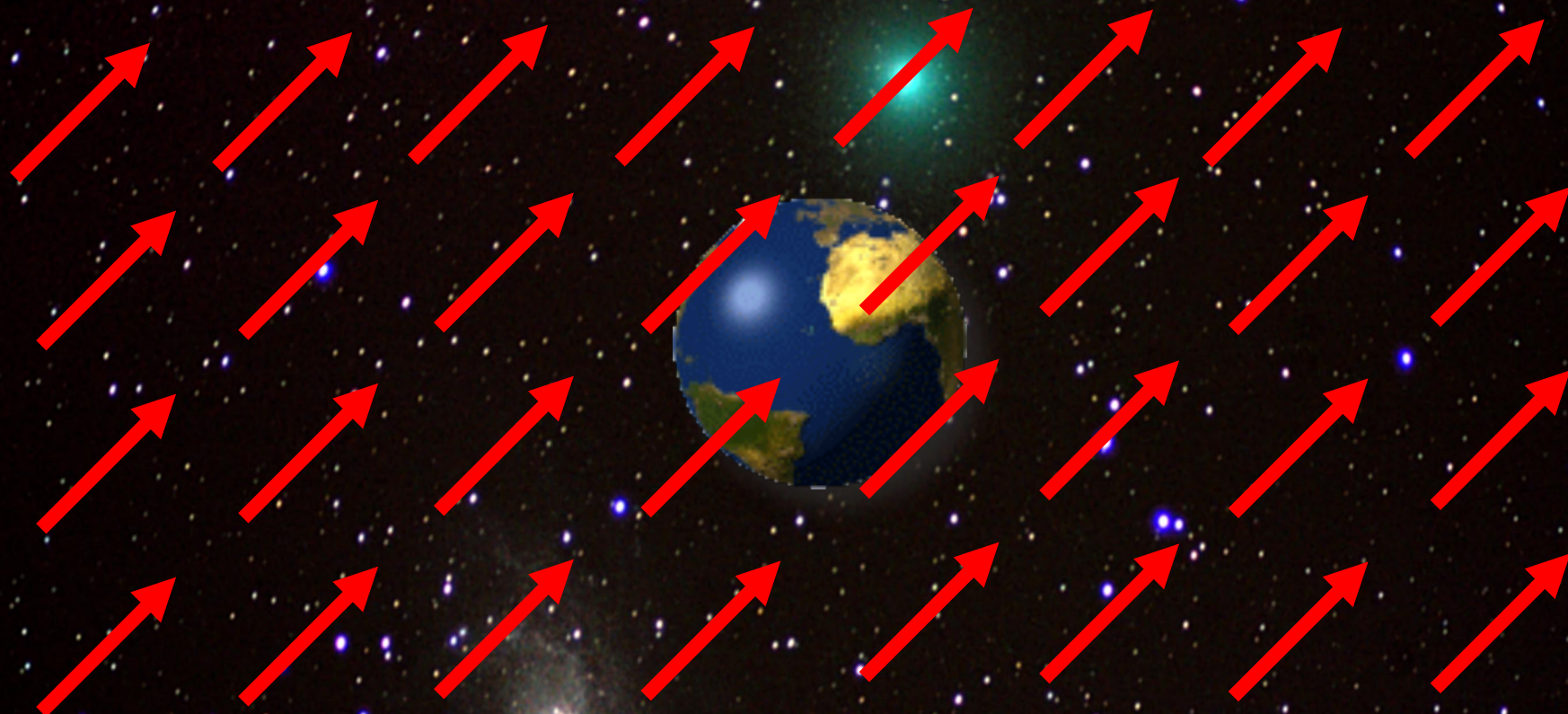
# Search of Space-Time Defect: The Race to Defeat Einstein



Teppei Katori  
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Feb. 1, 2017



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



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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

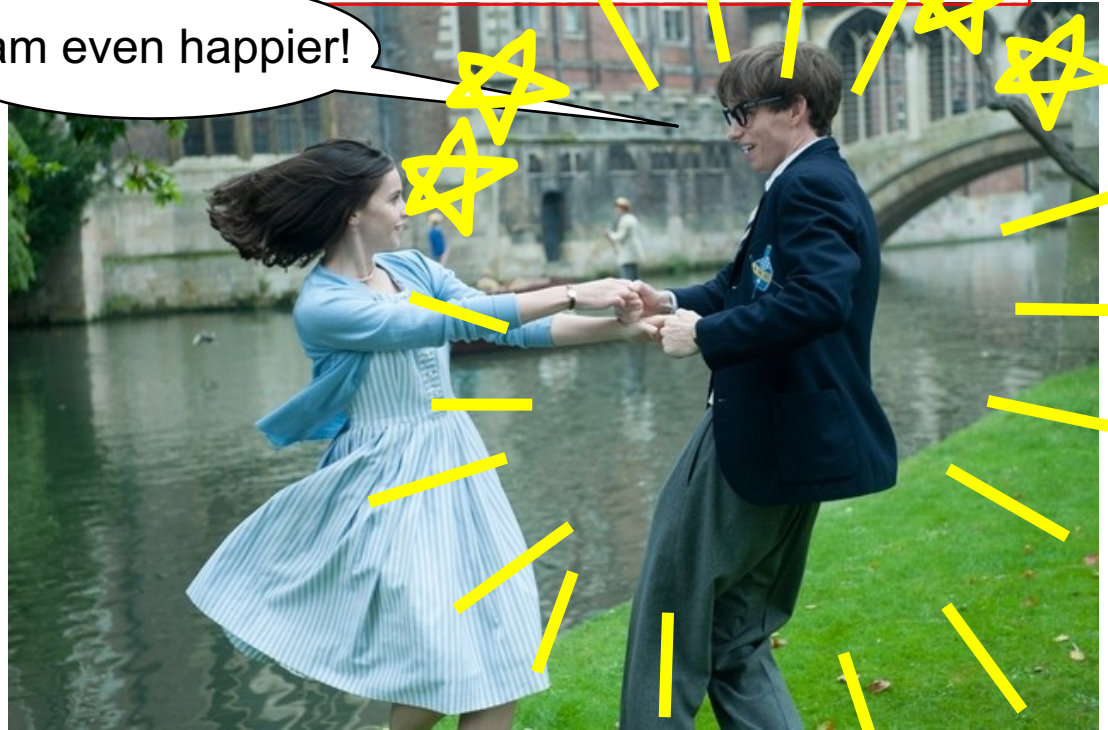
→ Discovery of Lorentz violation could be the first evidence of Theory of Everything!

Einstein and Lorentz



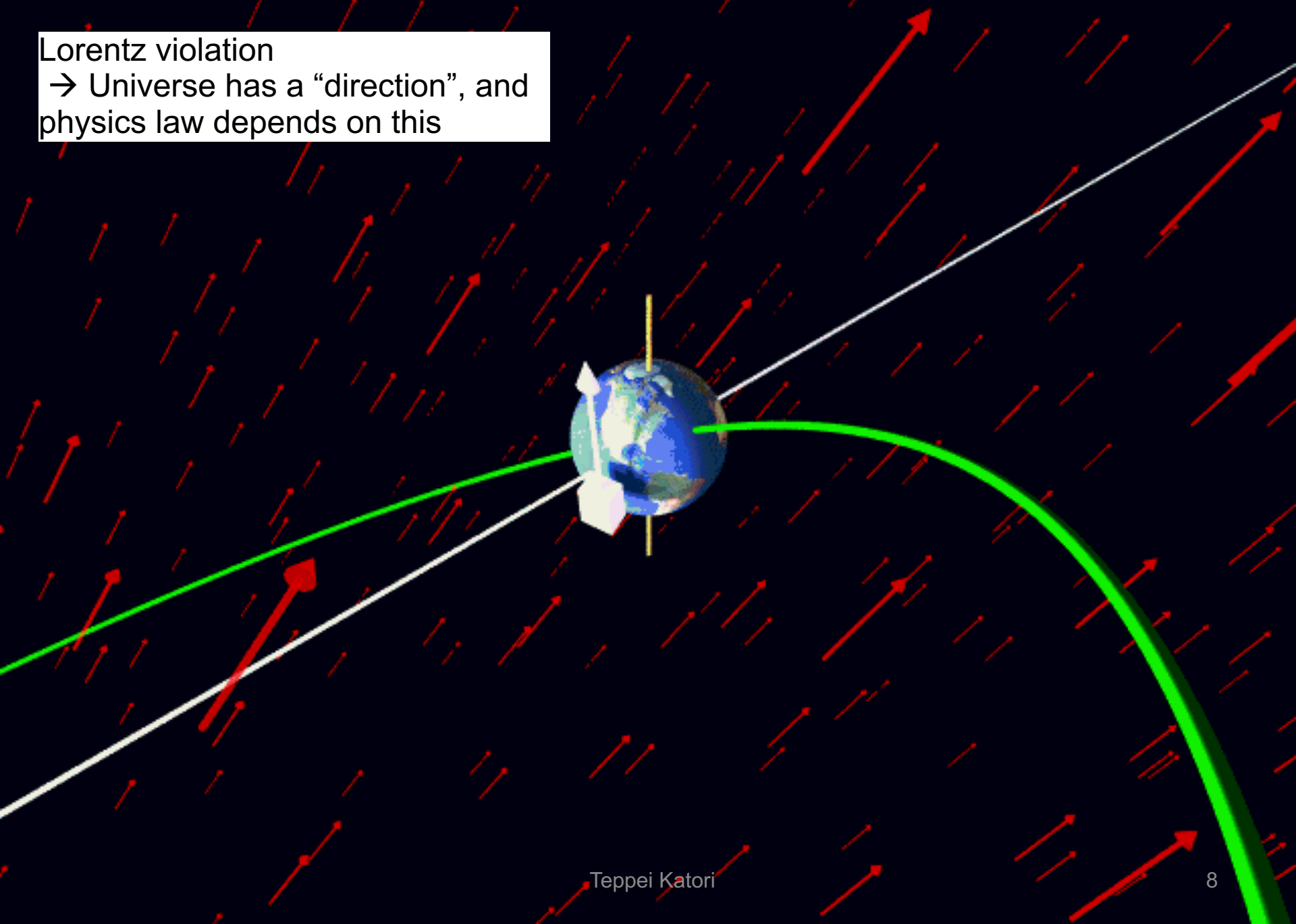
Stephen Hawking imposter and someone

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



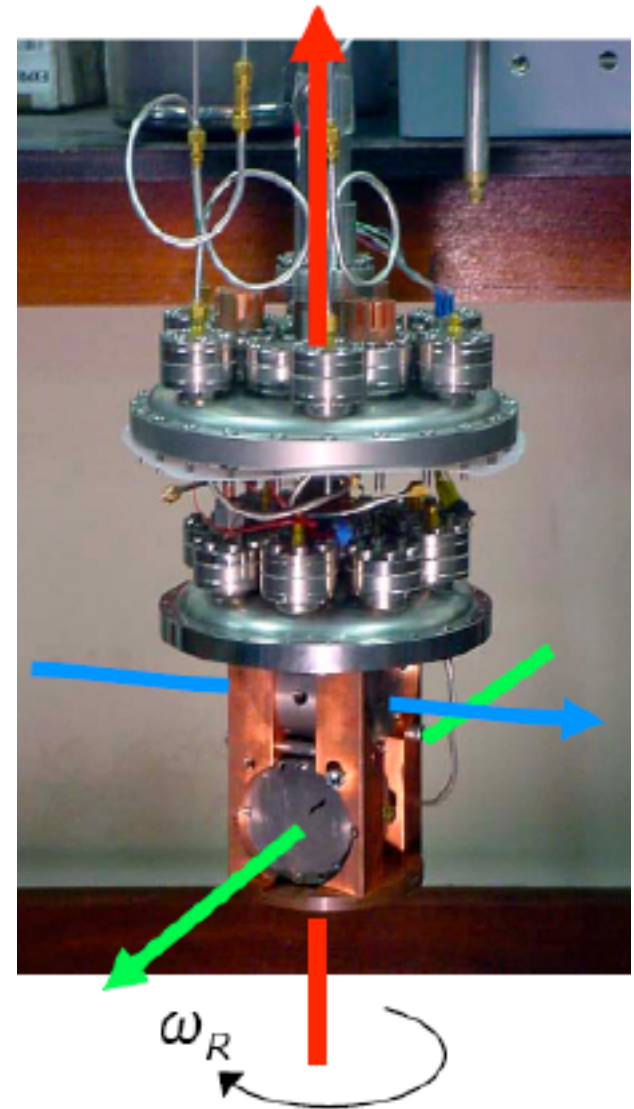
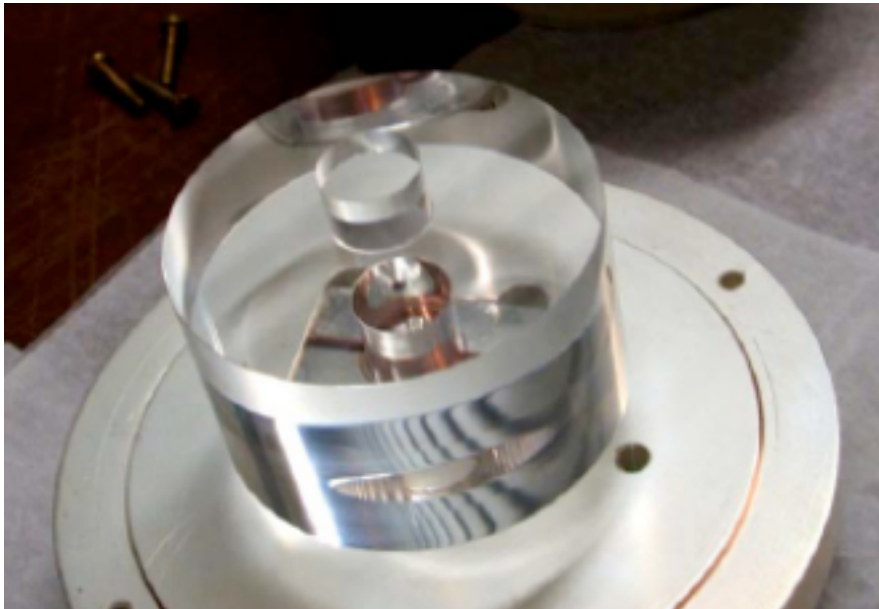
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# Cryogenic Sapphire Crystal Resonator

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

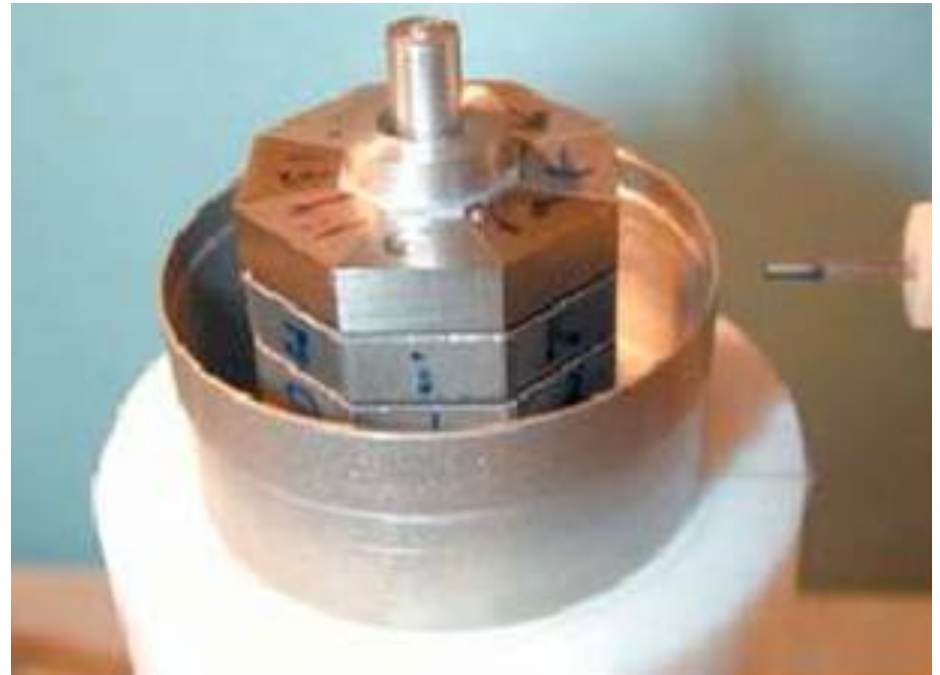
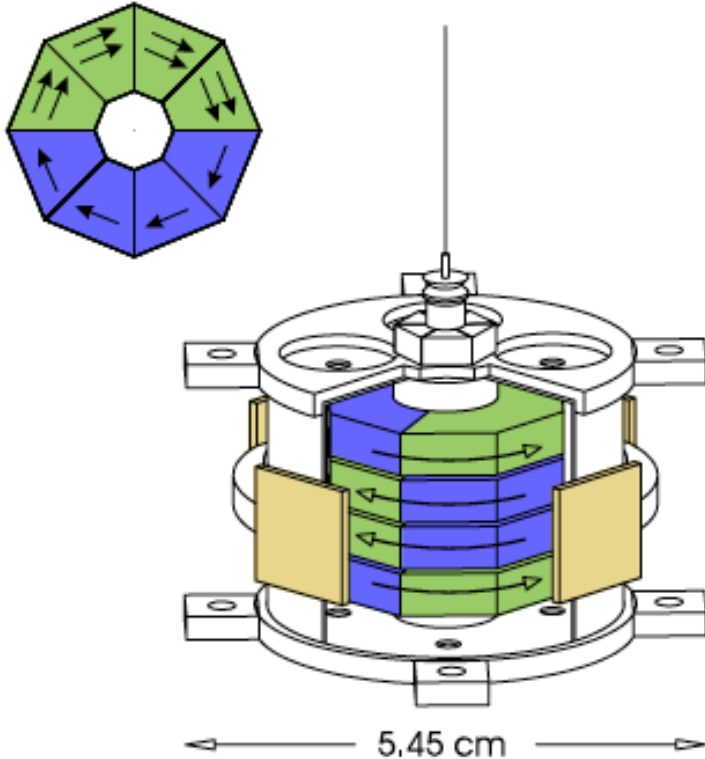
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# Double Alloy Spin Torsion Pendulum

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

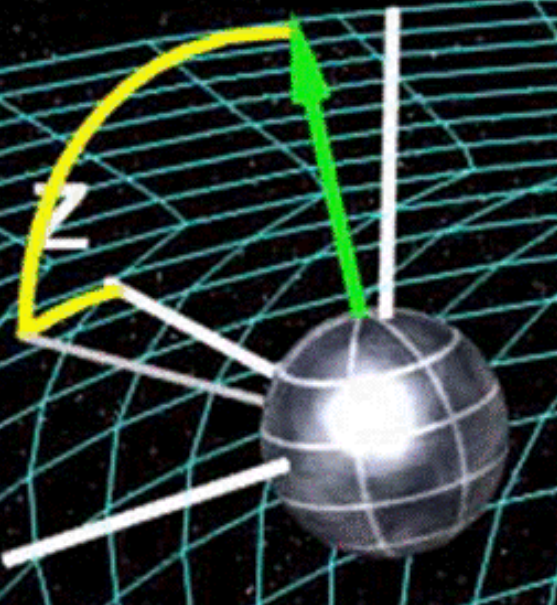


Geodetic effect  
6.6 arcsec/yr

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



CERN

Spin pendulum

Cryogenic crystal resonator

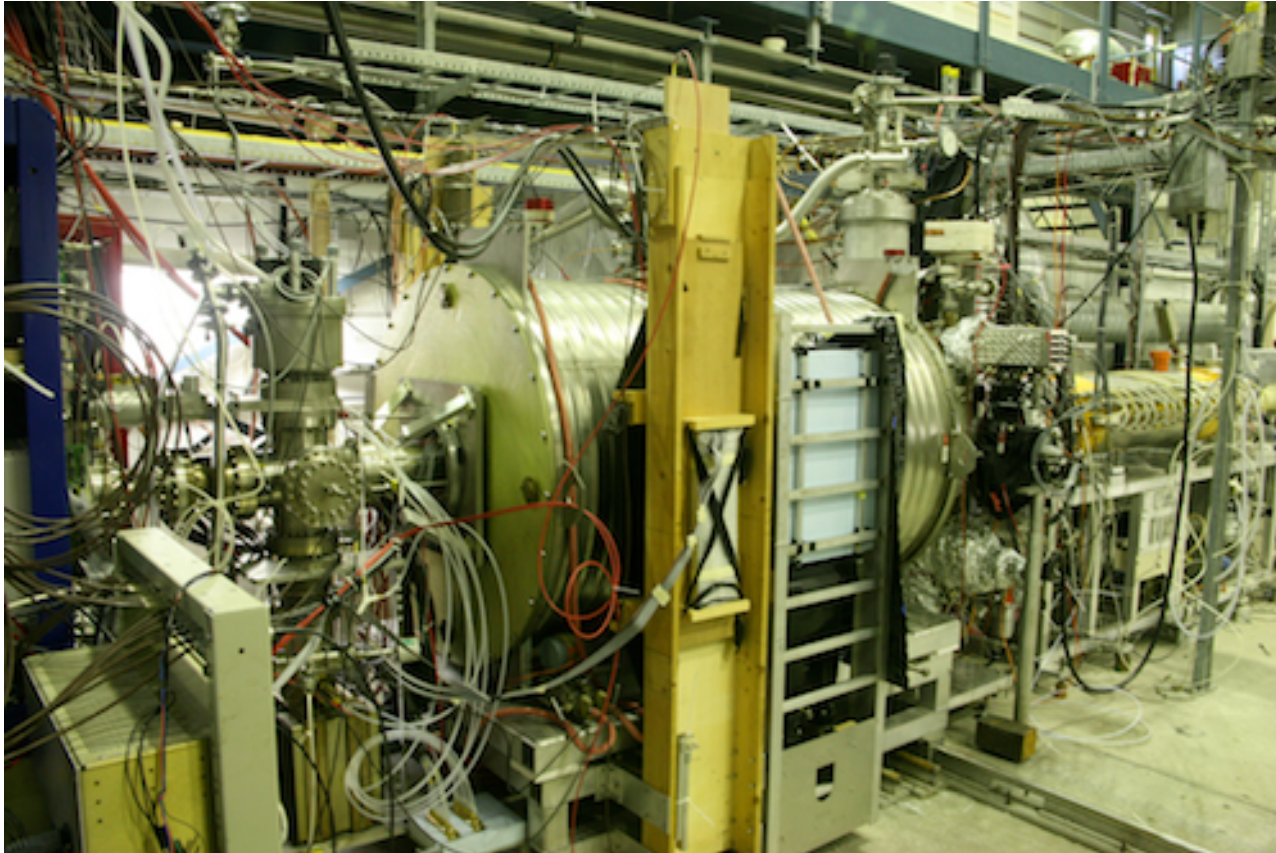
Space test



# Antiproton decelerator at CERN

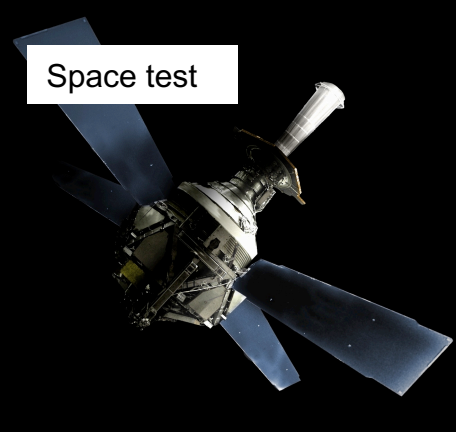
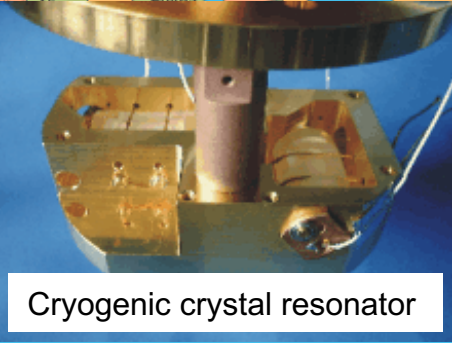
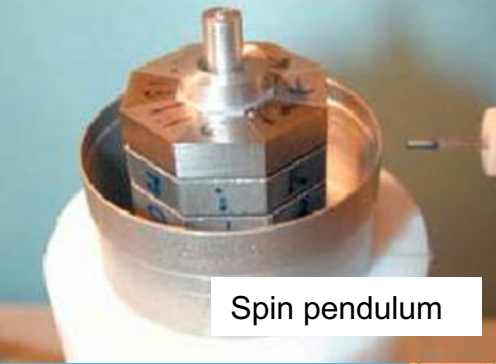
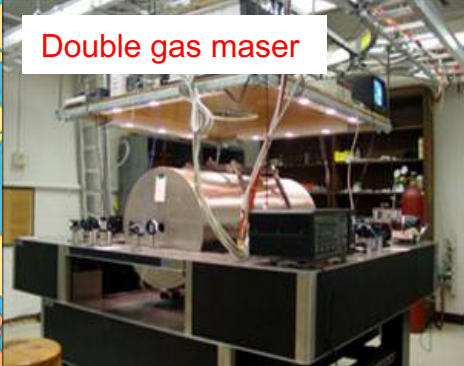
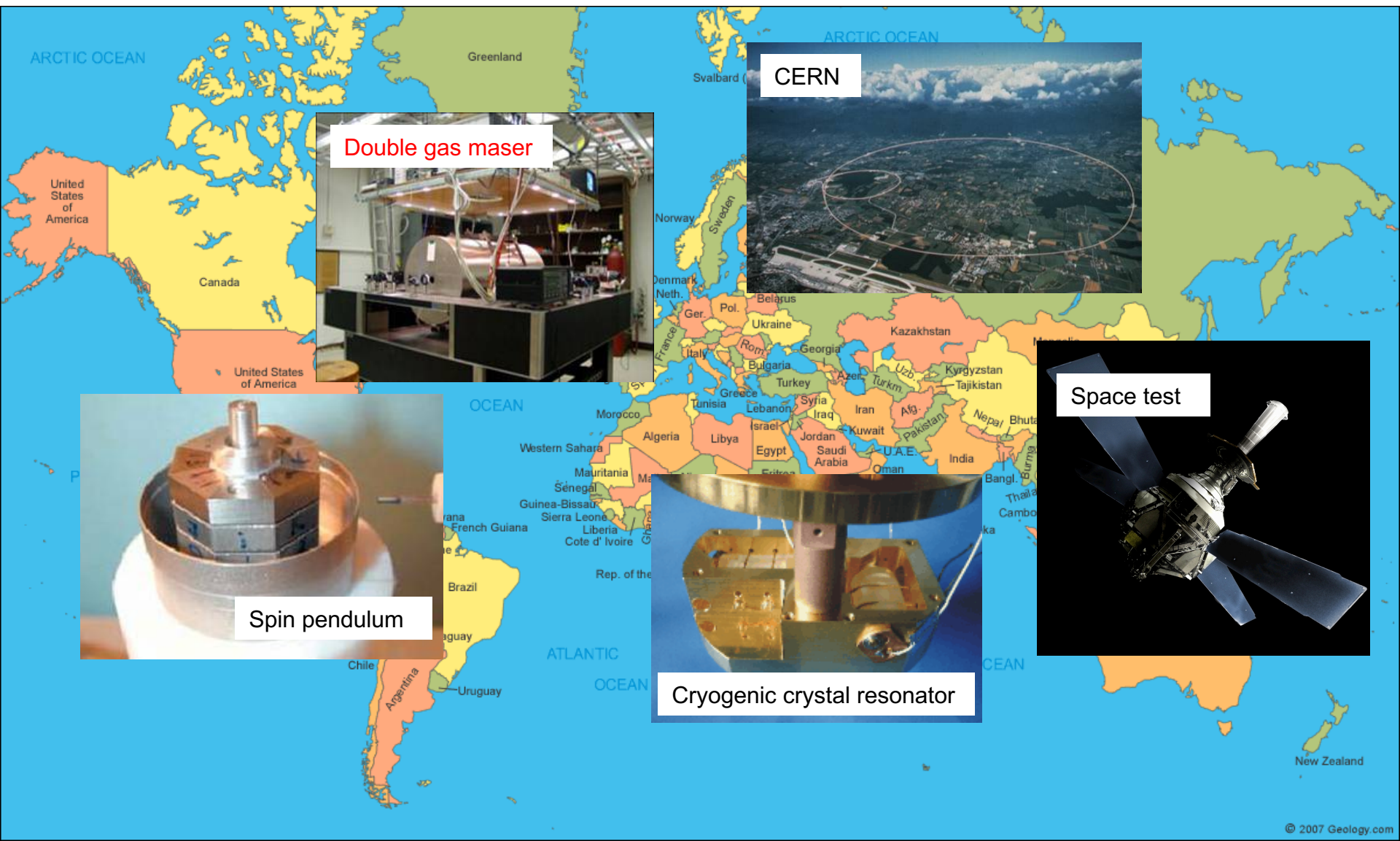
CERN has an ability to perform the highest precision antimatter test (matter-antimatter asymmetry induces Lorentz violation)

→ Lorentz violation is not discovered



# The race to defeat Einstein

Most precise magnetic field measurement

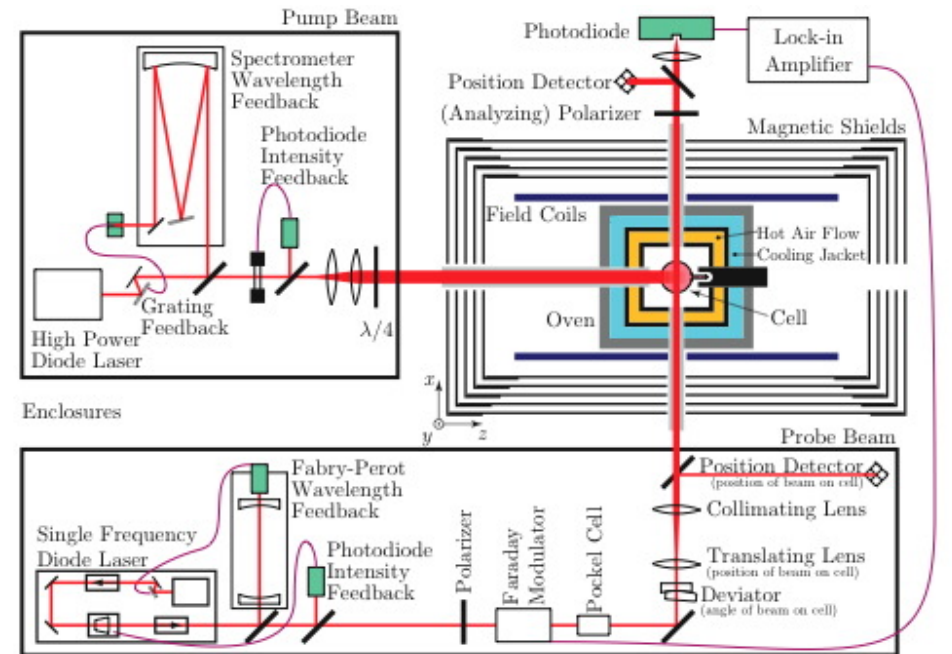




# Double Noble Gas Maser

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

→ Lorentz violation is not discovered





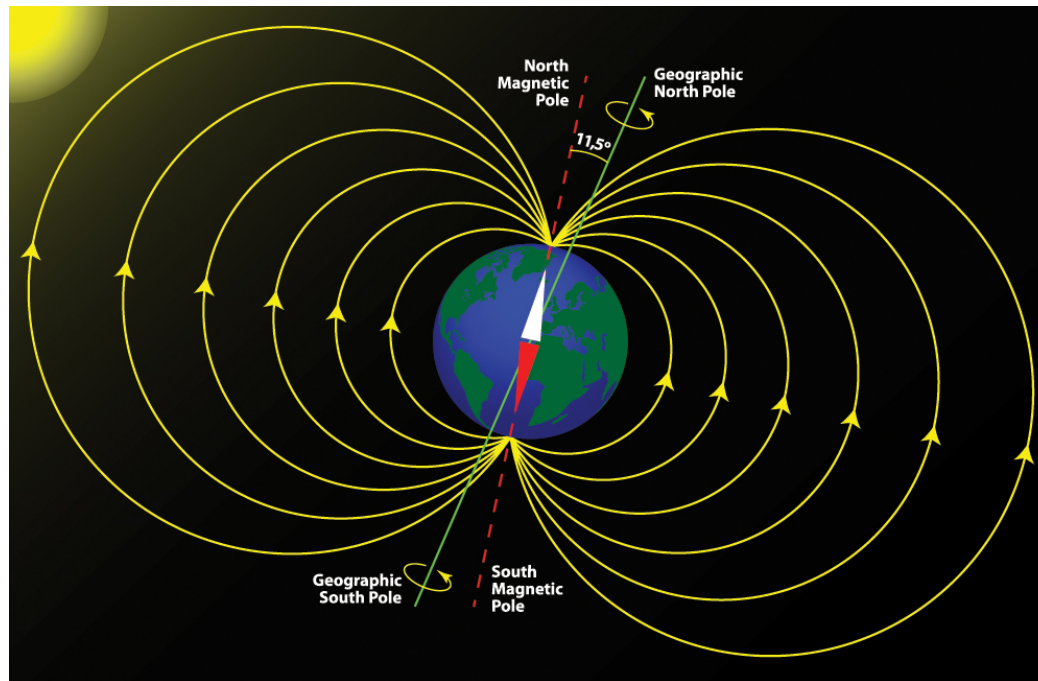
# Double Noble Gas Maser

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



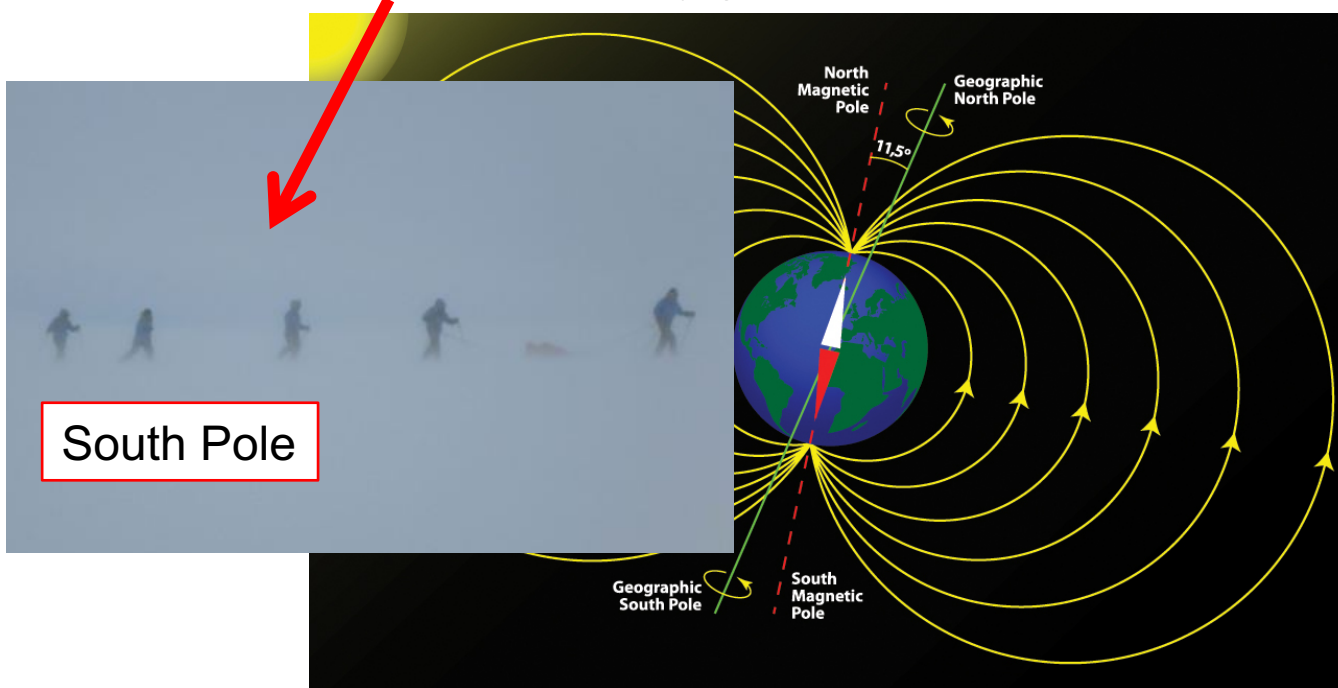
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# Double Noble Gas Maser

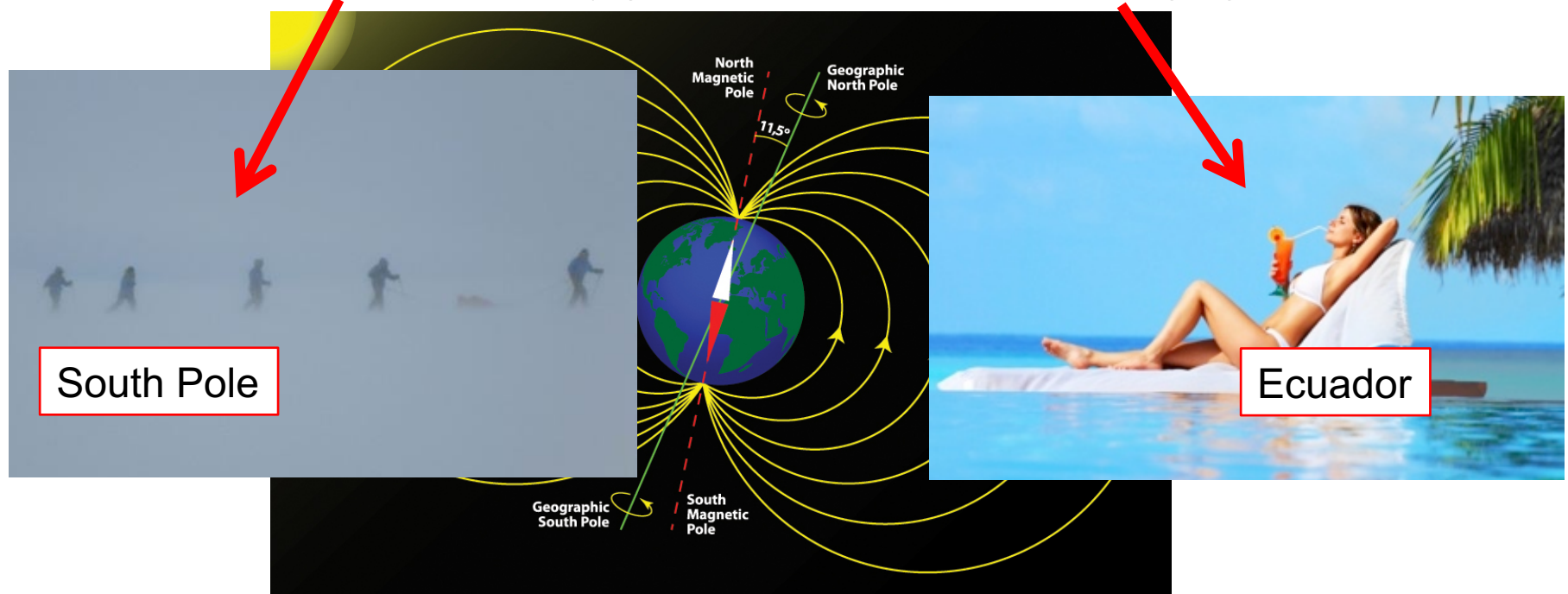
A type of atomic clock very sensitive to a tiny magnetic field

→ 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

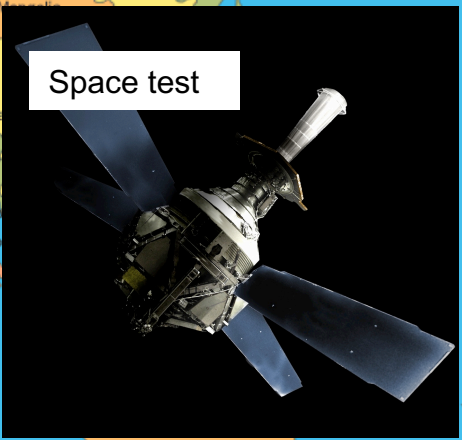
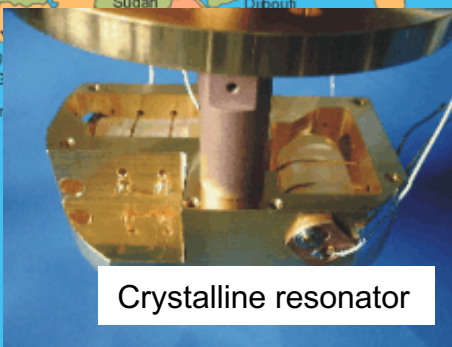
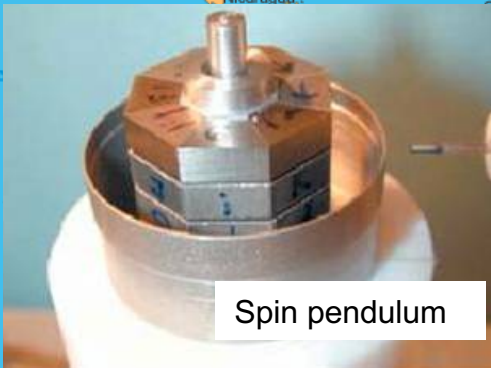
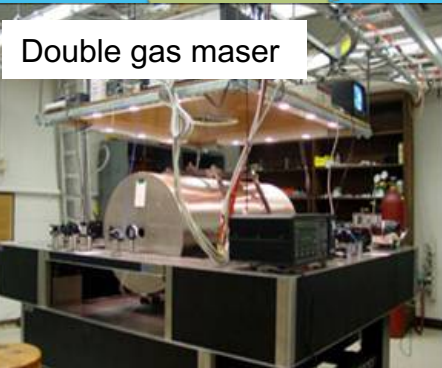
vs. Amherst college group





# The race to defeat Einstein

Most precise something



# 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	
$\tilde{g}_Q$		
$\tilde{g}_-$		
$\tilde{g}_J, (J = X, Y, Z)$		
$\tilde{g}_{XY}$	$10^{-17}$ 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
	$(\tilde{\kappa}_{e+})^{XY}$	$10^{-32}$	$(\tilde{\kappa}_{e-})^{XY}$	$10^{-17}$
	$(\tilde{\kappa}_{e+})^{XZ}$	$10^{-32}$	$(\tilde{\kappa}_{e-})^{XZ}$	$10^{-17}$
	$(\tilde{\kappa}_{e+})^{YZ}$	$10^{-32}$	$(\tilde{\kappa}_{e-})^{YZ}$	$10^{-17}$
	$(\tilde{\kappa}_{e+})^{XX} - (\tilde{\kappa}_{e+})^{YY}$	$10^{-32}$	$(\tilde{\kappa}_{e-})^{XX} - (\tilde{\kappa}_{e-})^{YY}$	$10^{-17}$
	$(\tilde{\kappa}_{e+})^{ZZ}$	$10^{-32}$	$(\tilde{\kappa}_{e-})^{ZZ}$	$10^{-16}$
	$(\tilde{\kappa}_{e-})^{XY}$	$10^{-32}$	$(\tilde{\kappa}_{o+})^{XY}$	$10^{-13}$
	$(\tilde{\kappa}_{e-})^{XZ}$	$10^{-32}$	$(\tilde{\kappa}_{o+})^{XZ}$	$10^{-14}$
	$(\tilde{\kappa}_{e-})^{YZ}$	$10^{-32}$	$(\tilde{\kappa}_{o+})^{YZ}$	$10^{-14}$
	$(\tilde{\kappa}_{e-})^{XX} - (\tilde{\kappa}_{e-})^{YY}$	$10^{-32}$		
	$(\tilde{\kappa}_{e-})^{ZZ}$	$10^{-32}$	$\tilde{\kappa}_{st}$	$10^{-14}$

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
	$\tilde{c}^{(4)}$	$10^{-9}$	$\tilde{c}_{\mu\mu}^{(4)}$	$10^{-10}$
	$\tilde{a}_{\mu\mu}^{(5)}$	$10^{-18}$ GeV <sup>-1</sup>	$\tilde{a}_{\mu\mu}^{(5)}$	$10^{-19}$ GeV <sup>-1</sup>
	$\tilde{c}^{(6)}$	$10^{-9}$ GeV <sup>-2</sup>	$\tilde{c}_{\mu\mu}^{(6)}$	$10^{-19}$ GeV <sup>-2</sup>
	$\tilde{a}_{\mu\mu}^{(7)}$	$10^{-29}$ GeV <sup>-3</sup>	$\tilde{a}_{\mu\mu}^{(7)}$	$10^{-19}$ GeV <sup>-3</sup>
	$\tilde{c}^{(8)}$	$10^{-11}$ GeV <sup>-4</sup>	$\tilde{c}_{\mu\mu}^{(8)}$	$10^{-18}$ GeV <sup>-4</sup>
	$\tilde{a}_{\mu\mu}^{(9)}$	$10^{-40}$ GeV <sup>-5</sup>	$\tilde{a}_{\mu\mu}^{(9)}$	$10^{-18}$ GeV <sup>-5</sup>
	$\tilde{c}^{(10)}$	$10^{-14}$ GeV <sup>-6</sup>	$\tilde{c}_{\mu\mu}^{(10)}$	$10^{-18}$ GeV <sup>-6</sup>

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]*			

New Zealand

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# So far no experiments find Lorentz violation...

most precise something

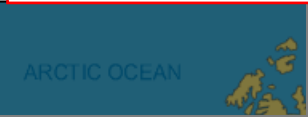


Table S2. Maximal sensitivities for the photon sector

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	
$\tilde{g}_{XZ}$	$10^{-17}$ 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
	$k_{(V)00}^{(3)}$	$10^{-43}$ 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
	$(\tilde{\kappa}_{e+})^{XY}$	$10^{-32}$	$(\tilde{\kappa}_{e-})^{XY}$	$10^{-17}$
	$(\tilde{\kappa}_{e+})^{XZ}$	$10^{-32}$	$(\tilde{\kappa}_{e-})^{XZ}$	$10^{-17}$
	$(\tilde{\kappa}_{e+})^{YZ}$	$10^{-32}$	$(\tilde{\kappa}_{e-})^{YZ}$	$10^{-17}$
	$(\tilde{\kappa}_{e+})^{XX} - (\tilde{\kappa}_{e+})^{YY}$	$10^{-32}$	$(\tilde{\kappa}_{e-})^{XX} - (\tilde{\kappa}_{e-})^{YY}$	$10^{-17}$
	$(\tilde{\kappa}_{e+})^{ZZ}$	$10^{-32}$	$(\tilde{\kappa}_{e-})^{ZZ}$	$10^{-16}$
	$(\tilde{\kappa}_{e-})^{XY}$	$10^{-32}$	$(\tilde{\kappa}_{o+})^{XY}$	$10^{-13}$
	$(\tilde{\kappa}_{e-})^{XZ}$	$10^{-32}$	$(\tilde{\kappa}_{o+})^{XZ}$	$10^{-14}$
	$(\tilde{\kappa}_{e-})^{YZ}$	$10^{-32}$	$(\tilde{\kappa}_{o+})^{YZ}$	$10^{-14}$
	$(\tilde{\kappa}_{e-})^{XX} - (\tilde{\kappa}_{e-})^{YY}$	$10^{-32}$		
	$(\tilde{\kappa}_{e-})^{ZZ}$	$10^{-32}$	$\tilde{\kappa}_{lt}$	$10^{-14}$

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
	$\tilde{a}_{\mu\mu}^{(3)}$	$10^{-7}$ GeV	$\tilde{a}_{\mu\mu}^{(2)}$	$10^{-20}$ GeV
	$\tilde{c}^{(4)}$	$10^{-9}$	$\tilde{c}_{\mu\mu}^{(4)}$	$10^{-10}$
	$\tilde{c}^{(5)}$	$10^{-18}$ GeV <sup>-1</sup>	$\tilde{c}_{\mu\mu}^{(5)}$	$10^{-19}$ GeV <sup>-1</sup>
	$\tilde{c}^{(6)}$	$10^{-9}$ GeV <sup>-2</sup>	$\tilde{c}_{\mu\mu}^{(6)}$	$10^{-10}$ GeV <sup>-2</sup>
	$\tilde{c}^{(7)}$	$10^{-29}$ GeV <sup>-3</sup>	$\tilde{c}_{\mu\mu}^{(7)}$	$10^{-19}$ GeV <sup>-3</sup>
	$\tilde{c}^{(8)}$	$10^{-11}$ GeV <sup>-4</sup>	$\tilde{c}_{\mu\mu}^{(8)}$	$10^{-18}$ GeV <sup>-4</sup>
	$\tilde{c}^{(9)}$	$10^{-40}$ GeV <sup>-5</sup>	$\tilde{c}_{\mu\mu}^{(9)}$	$10^{-18}$ GeV <sup>-5</sup>
	$\tilde{c}^{(10)}$	$10^{-14}$ GeV <sup>-6</sup>	$\tilde{c}_{\mu\mu}^{(10)}$	$10^{-18}$ GeV <sup>-6</sup>



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]*

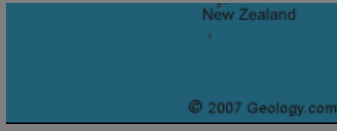
Table D6. Electron sector,  $d = 3, 4$  (part 2 of 3)

Combination	Result	System	Ref.
$\tilde{a}^{\text{UR}(4)}$	$< 1.5 \times 10^{-15}$	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]*

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]
$i \text{ to } 1.5) \times 10^{-15}$	"	[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]*
	"		$\times 10^{-14}$	"	[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

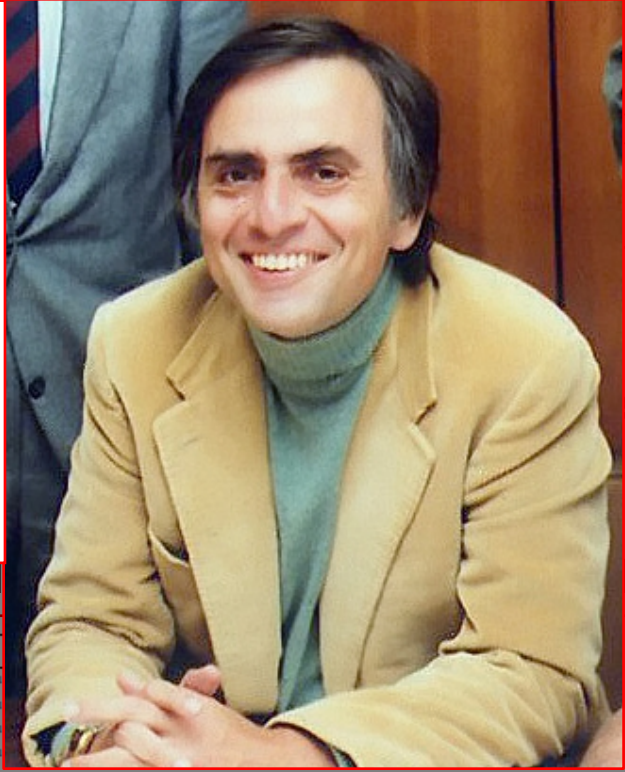
*“Extraordinary discovery requires extraordinary evidence”*

- Carl Sagan



*“Extraordinary discovery requires extraordinary particles”*

- Teppei



...but nobody

Table S3. Maximal sensitivities for the photon sector				Table D6. Electron sector, $d=3,4$ (part 1 of 3)			
Coefficient		Sensitivity		Combination	Result	System	Ref.
$\tilde{b}_X$	$10^{-26}$ GeV	$\text{Re}(a_L)^X$	$10^{-26}$ GeV	$\epsilon\mu$	$10^{-27}$ GeV		[41]*, [18]*
$\tilde{b}_Y$	$10^{-26}$ GeV	$\text{Re}(a_L)^Y$	$10^{-21}$ GeV	$\epsilon\tau$	$10^{-19}$ GeV		[42]*, [18]*
$\tilde{b}_Z$	$10^{-26}$ GeV	$\text{Re}(a_L)^Z$	$10^{-19}$ GeV	$\mu\tau$	$10^{-23}$ GeV		[43]*, [18]*
$\tilde{b}_T$	$10^{-26}$ GeV						[44]*, [18]*
$\tilde{c}_-$							
$\tilde{c}_Q$							
$\tilde{c}_X$							
$\tilde{c}_Y$							
$\tilde{c}_Z$							
$\tilde{c}_{TX}$							
$\tilde{c}_{TY}$							
$\tilde{c}_{TZ}$							
$\tilde{c}_{TT}$							
$\tilde{d}_+$							
$\tilde{d}_-$	$10^{-26}$ GeV						
$\tilde{d}_Q$	$10^{-26}$ GeV						
$\tilde{d}_{XY}$	$10^{-26}$ GeV						
$\tilde{d}_{YZ}$	$10^{-26}$ GeV						
$\tilde{d}_{ZX}$	$10^{-26}$ GeV						
$\tilde{d}_X$	$10^{-22}$ GeV						
$\tilde{d}_Y$	$10^{-22}$ 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						
$\tilde{g}_c$	$10^{-26}$ 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						
$\tilde{g}_{DY}$	$10^{-22}$ GeV						
$\tilde{g}_{DZ}$	$10^{-22}$ GeV						

New Zealand

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# So far no experiments find Lorentz violation...

most precise something

*“Extraordinary discovery requires extraordinary evidence”*

- Carl Sagan



*“Extraordinary discovery requires extraordinary particles”*

- Teppei



**Neutrino!**

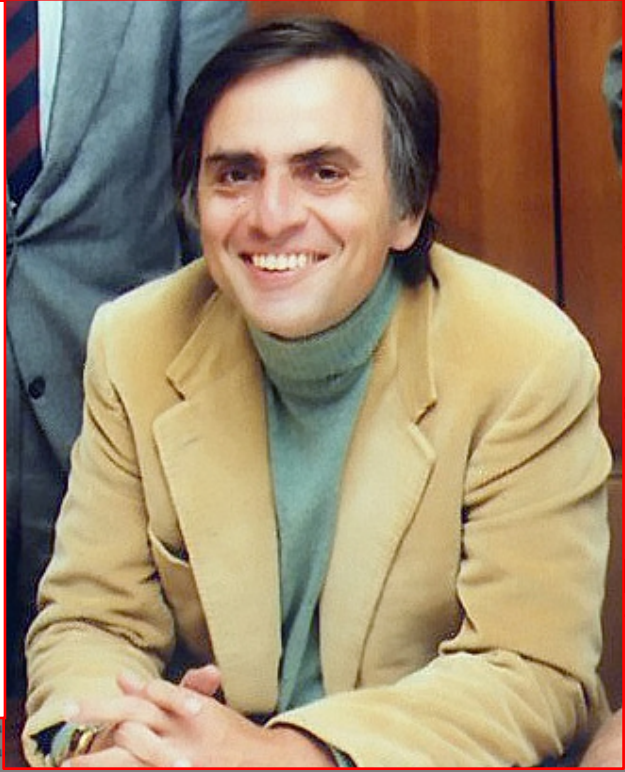
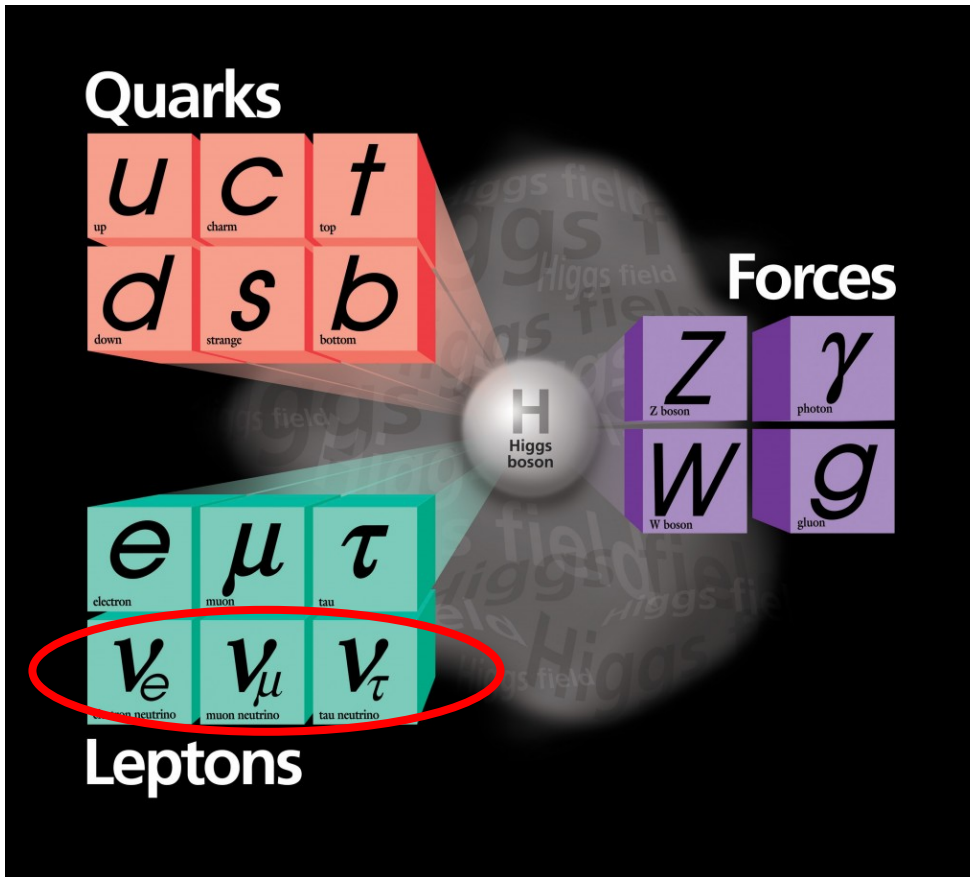


Table S3. Maximal sensitivities for the photon sector				Table D6. Electron sector, $d=3,4$ (part 1 of 3)			
Coefficient		Sensitivity		Coefficient		Sensitivity	
$\tilde{b}_X$	$10^{-19}$ GeV			$\text{Re}(c_L)^{YZ}$	$10^{-21}$	$10^{-16}$	$10^{-23}$
$\tilde{b}_Y$				$\text{Im}(c_L)^{YZ}$	$10^{-21}$	$10^{-16}$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

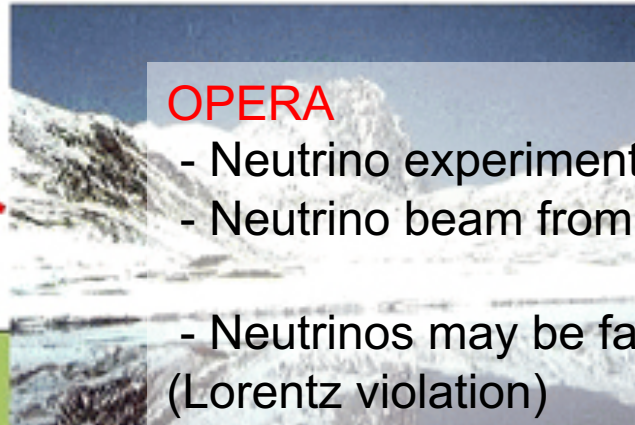
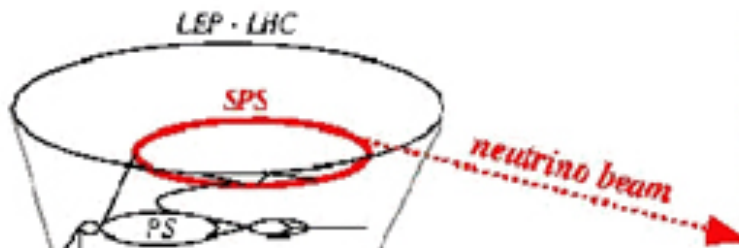
Neutrinos are mysterious particles, and we still don't know much about neutrinos  
→ Maybe neutrinos have better chance to find Lorentz violation?

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?

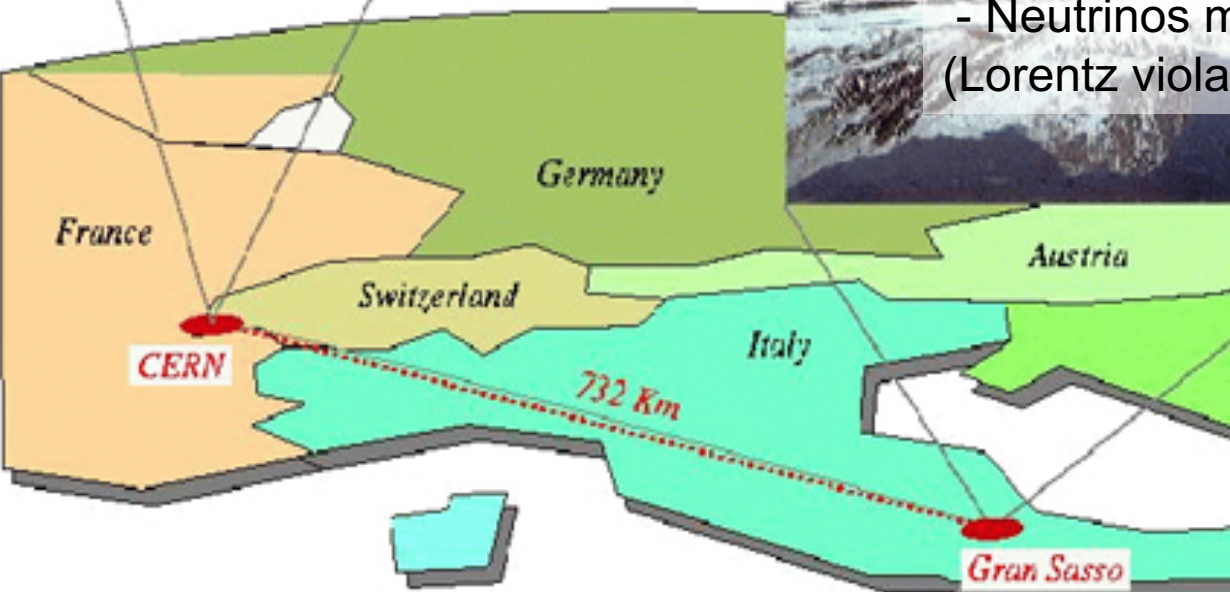


## OPERA

- 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 experiment  
about neutrinos

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?

RECOMMEND  
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The Washington Post

## OPERA

Posted  
Faster  
By Ale



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

The New York Times

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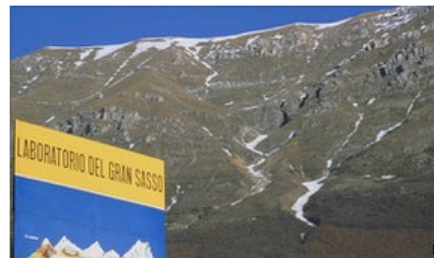
### Faster-than-light neutrinos could be down to bad wiring

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

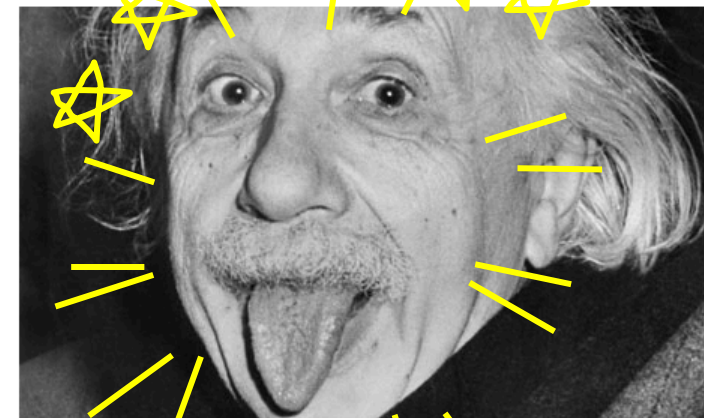


The neutrinos are fired deep under the Italian mountain range. The experiment is now being rewritten.

### 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?

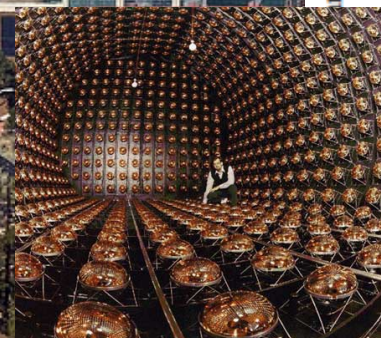
Especially, many neutrino data show some anomaly, it could be Lorentz violation?



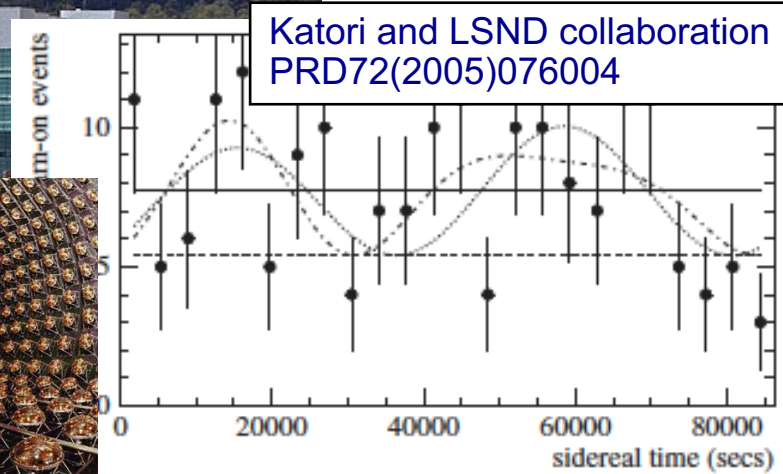
## LSND

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

→ This is not due to Lorentz violation



Inside of LSND detector





# Search of Lorentz Violation with Neutrino

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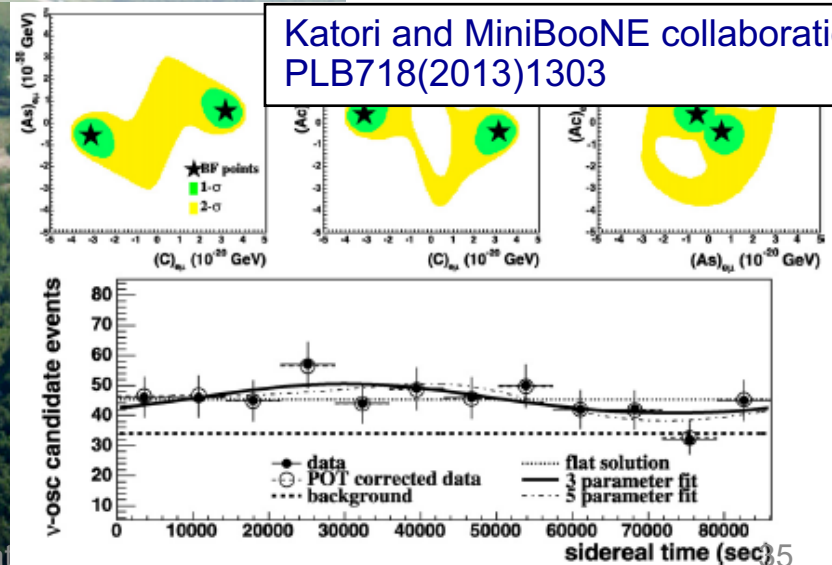
## MiniBooNE

- Neutrino experiment at Fermilab, USA
- Data show some anomaly

→ This is not due to Lorentz violation



Katori and MiniBooNE collaboration  
 PLB718(2013)1303



# Search of Lorentz Violation with Neutrino

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## Double Chooz

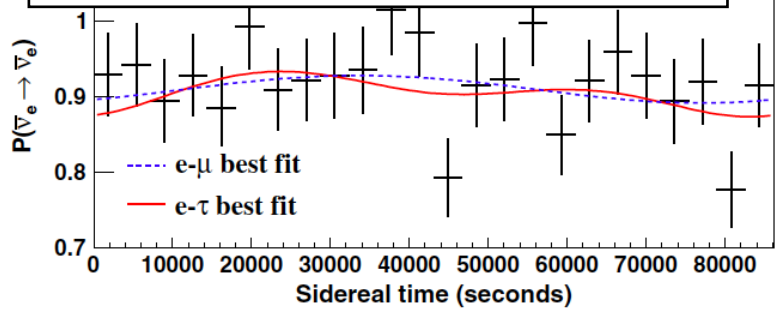
- Neutrinos from nuclear reactor in France
- Data show new type of neutrino oscillation, could be new physics

→ Lorentz violation is not discovered



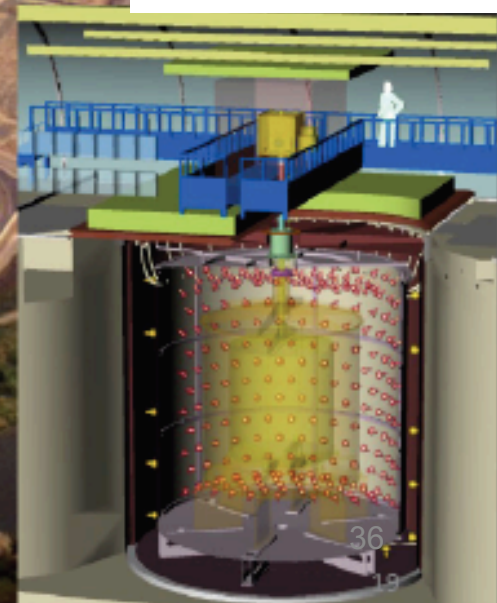
Double Chooz detector

Katori and Double Chooz collaboration  
 PRD86(2012)112009



## Chooz-B Power Plant

• 2 cores, 8.6 GW<sub>th</sub>





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

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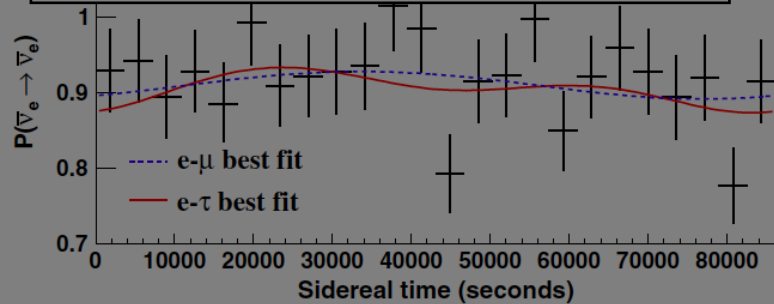
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Katori and Double Chooz collaboration  
PRD86(2012)112009





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

*“Extraordinary discovery requires extraordinary evidence”*

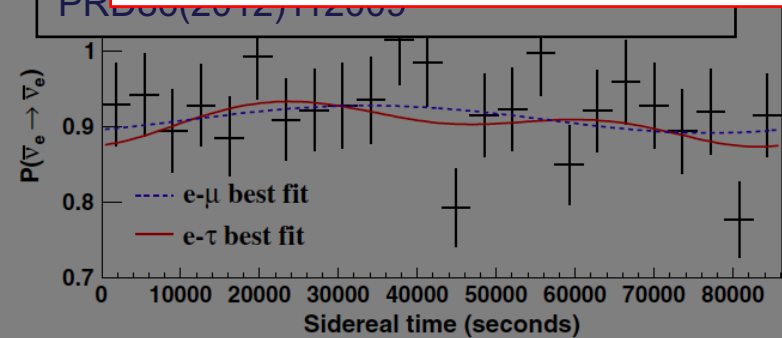
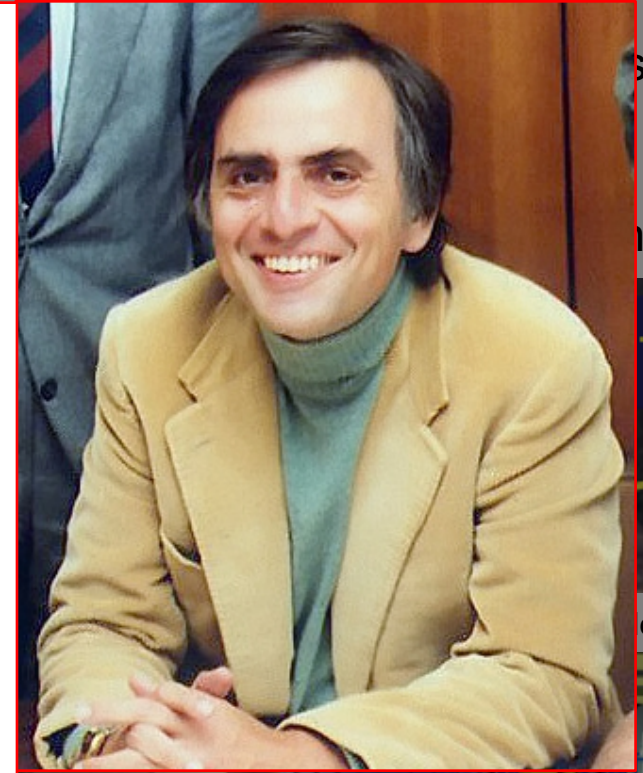
- Carl Sagan



*“Extraordinary discovery requires extraordinary particles”*

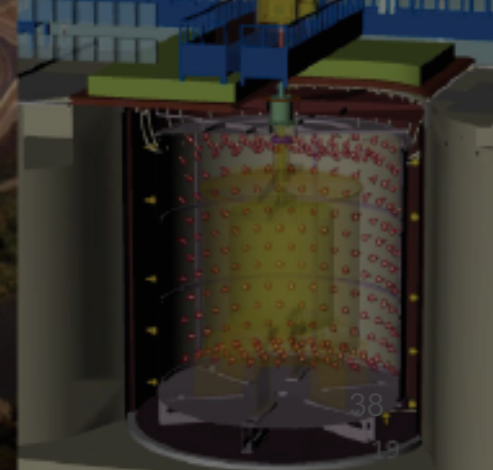
- Teppei

*...may be this is not extraordinary enough?*



**Chooz-B Power Plant**

• 2 cores, 8.6 GW<sub>th</sub>



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

*“Extraordinary discovery requires extraordinary evidence”*

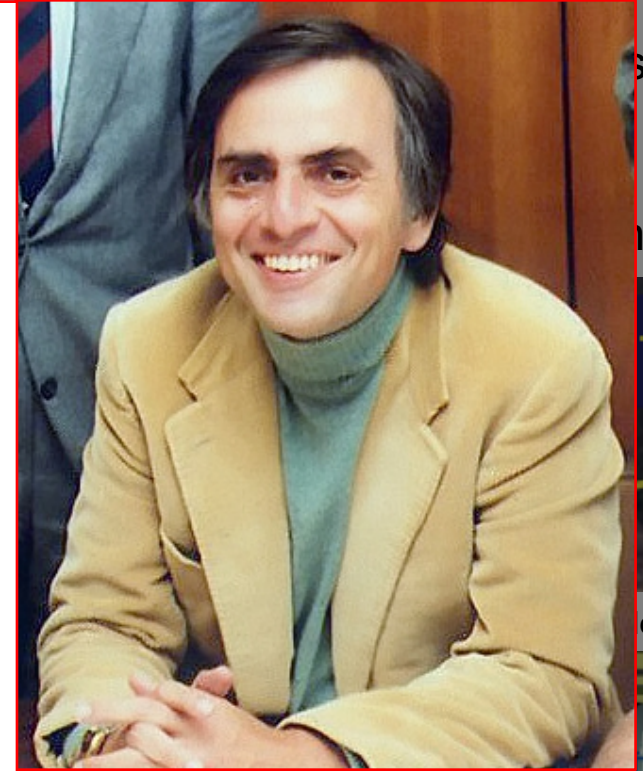
- Carl Sagan



*“Extraordinary discovery requires extraordinary particles”*

- Teppei

*...may be this is not extraordinary enough?*



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

- Teppei

→ 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.

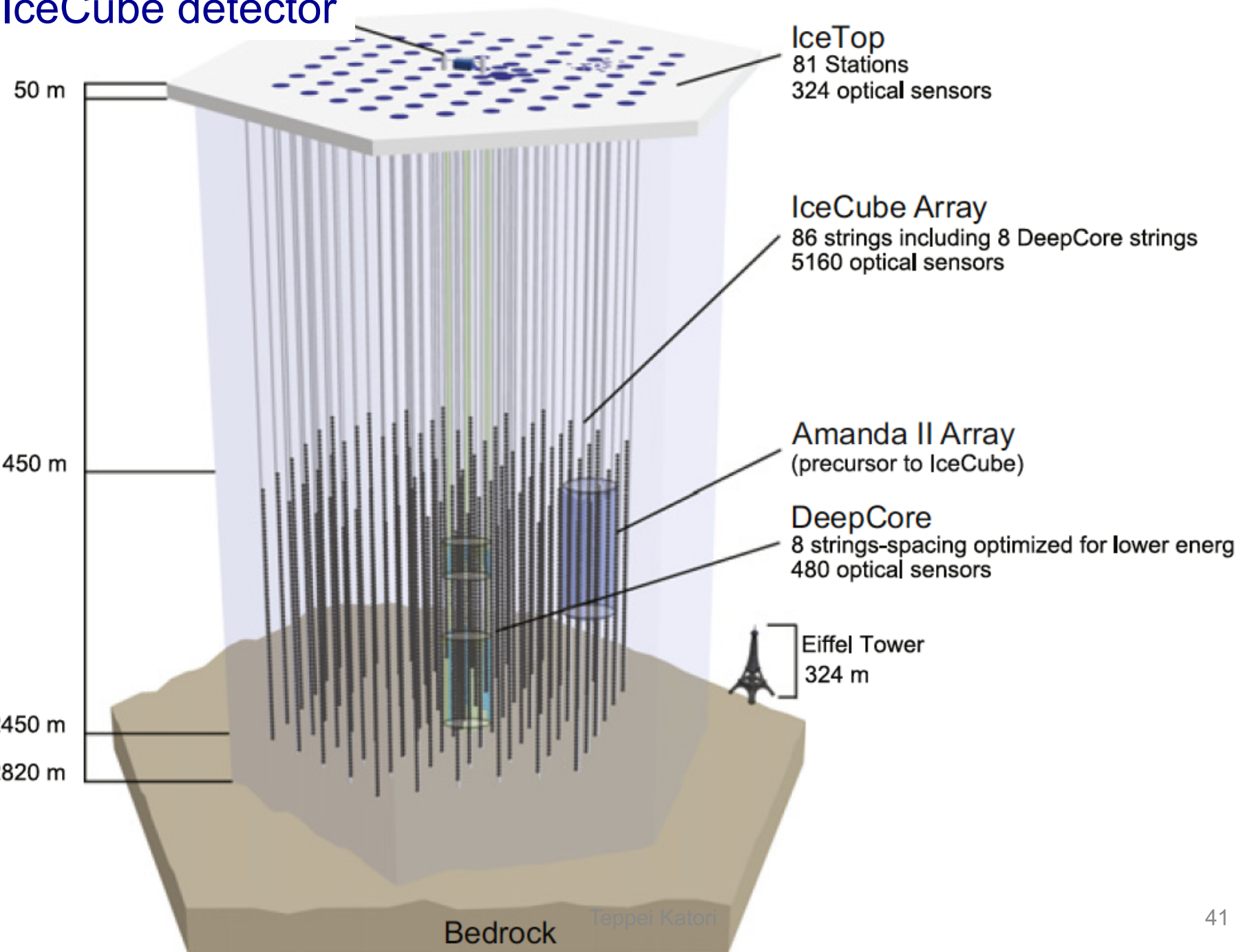
## IceCube Neutrino Observatory (Antarctica)

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

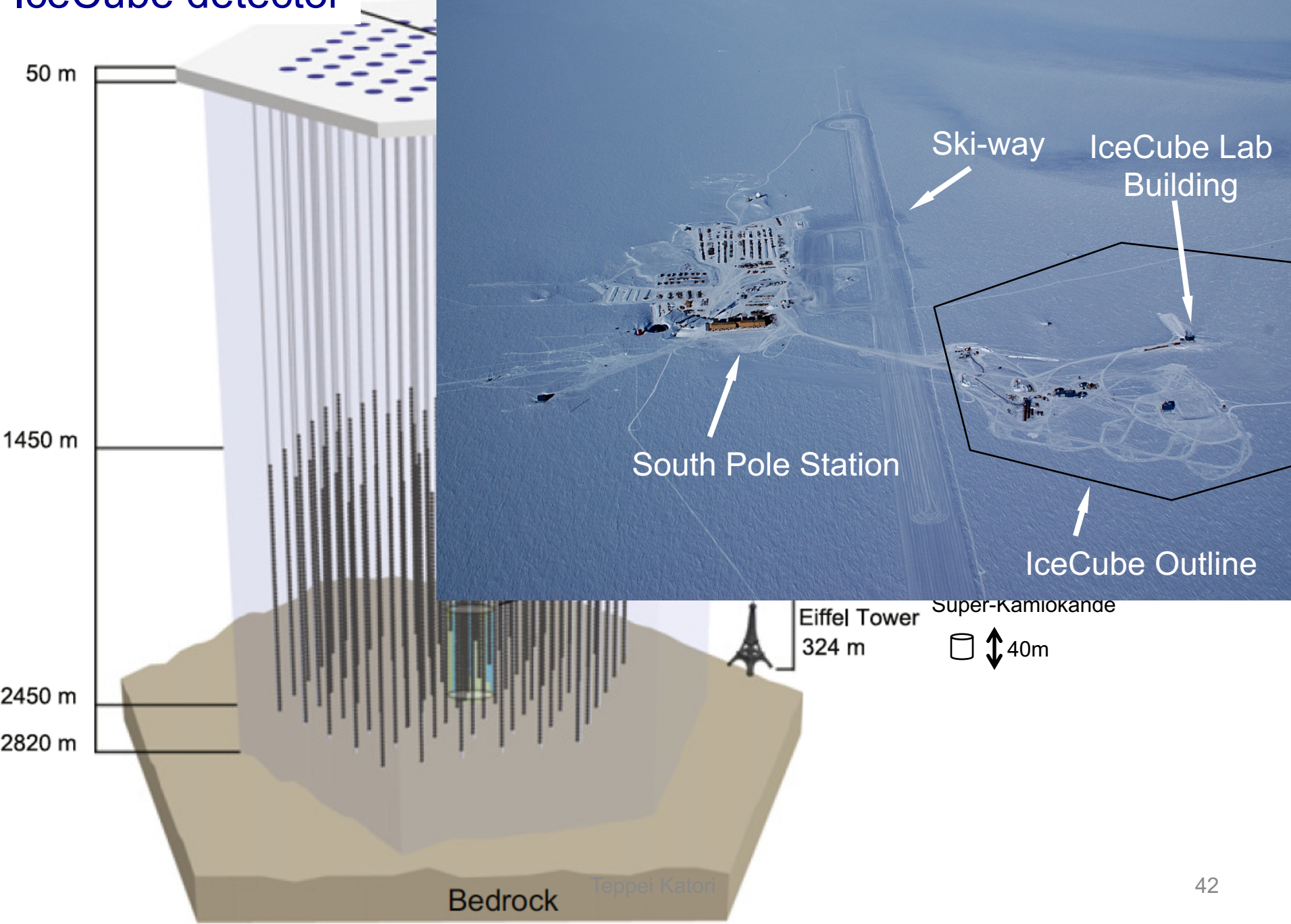
• 2 cores, 8.6 GW<sub>th</sub>



# IceCube detector

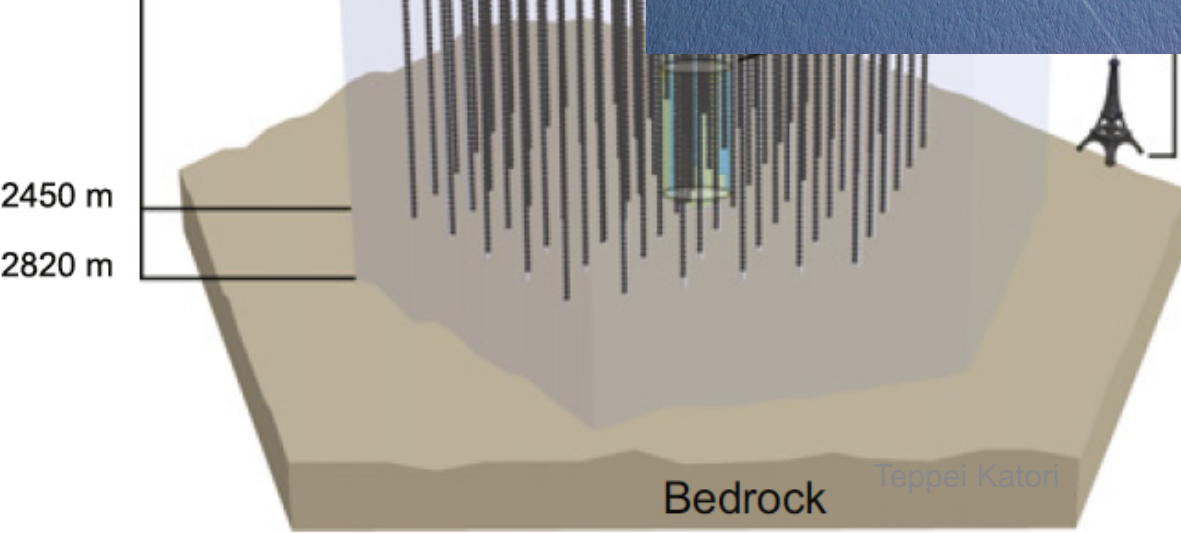
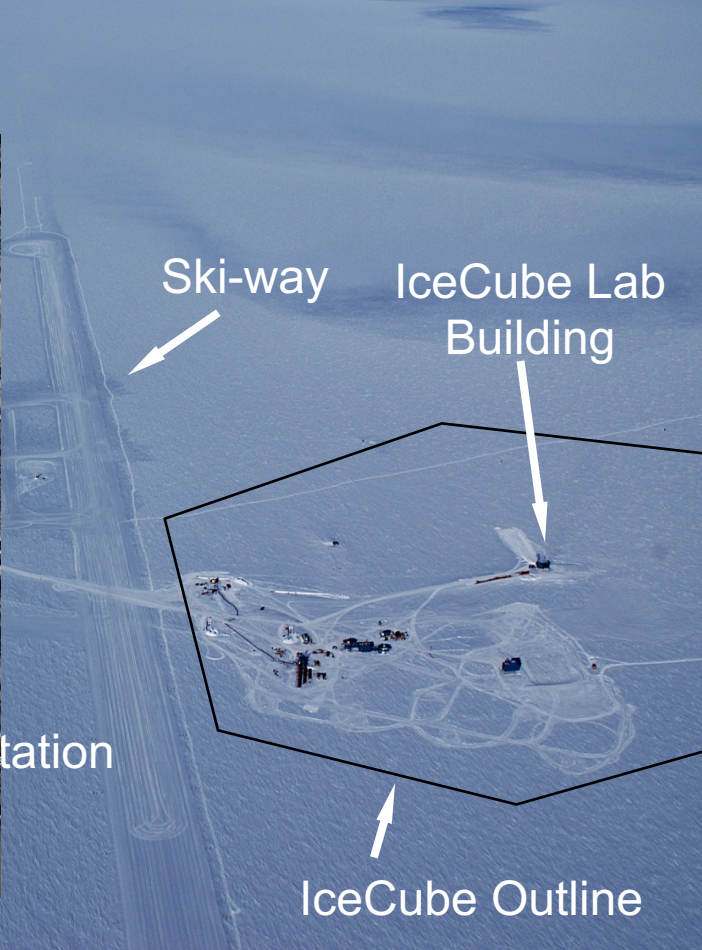
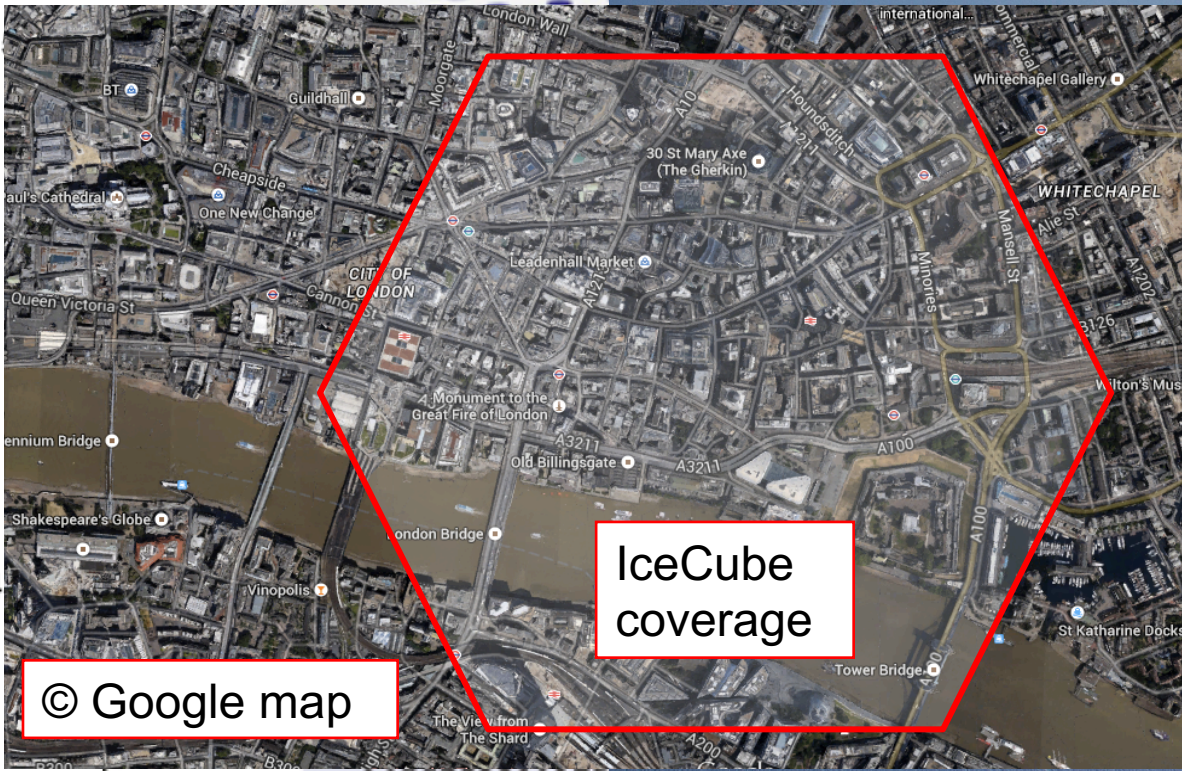



# IceCube detector





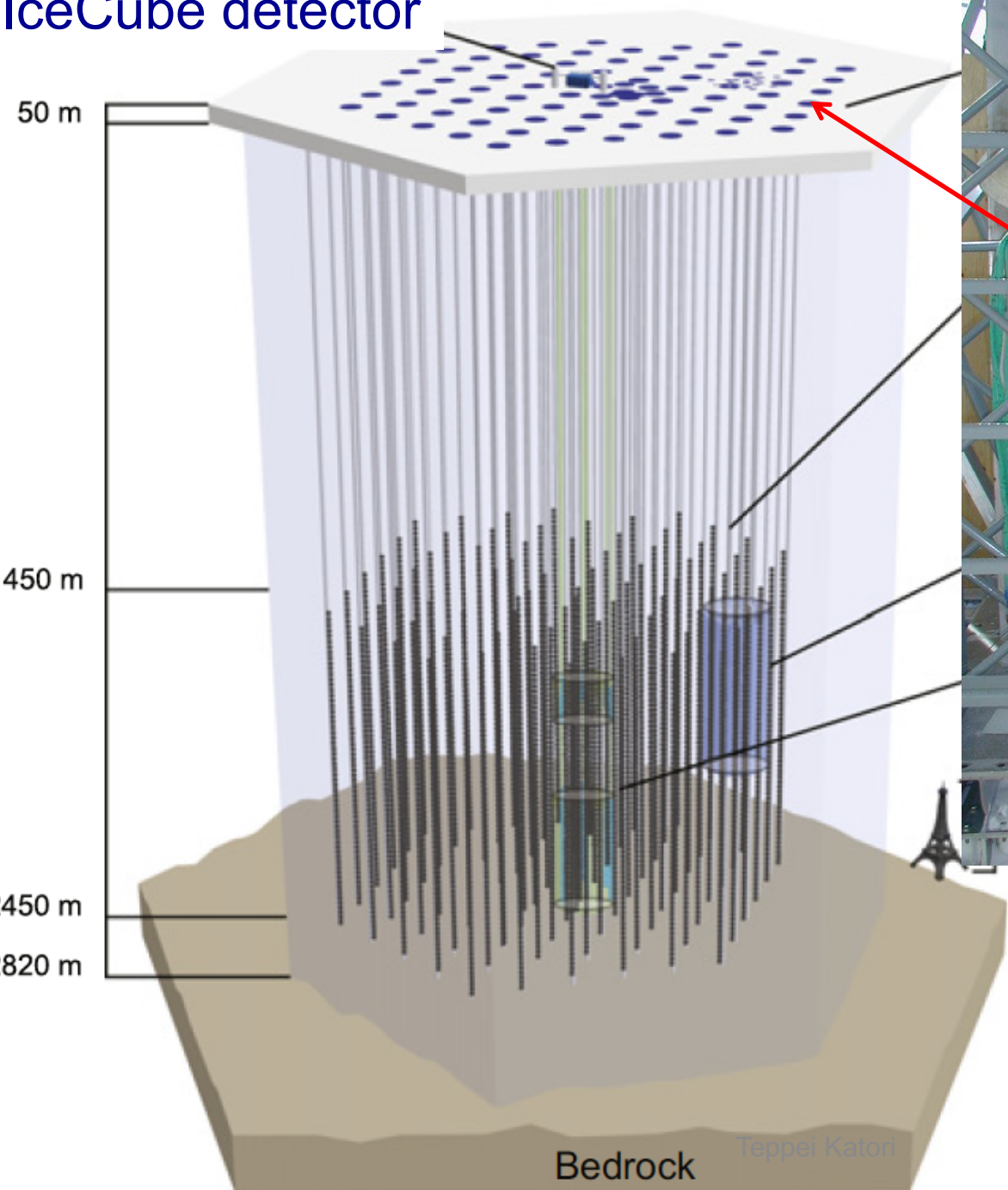
# IceCube detector



Super-Kamiokande  
 40m



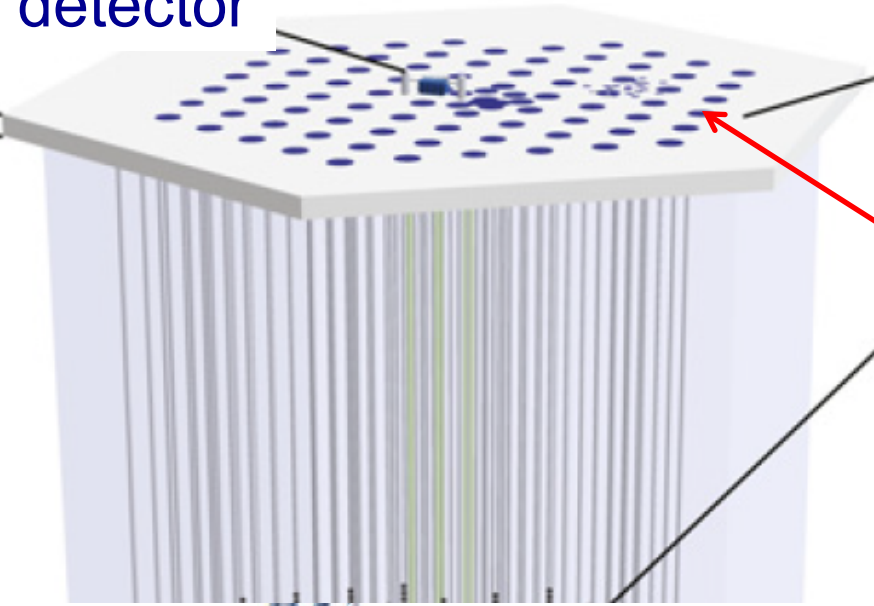
# IceCube detector



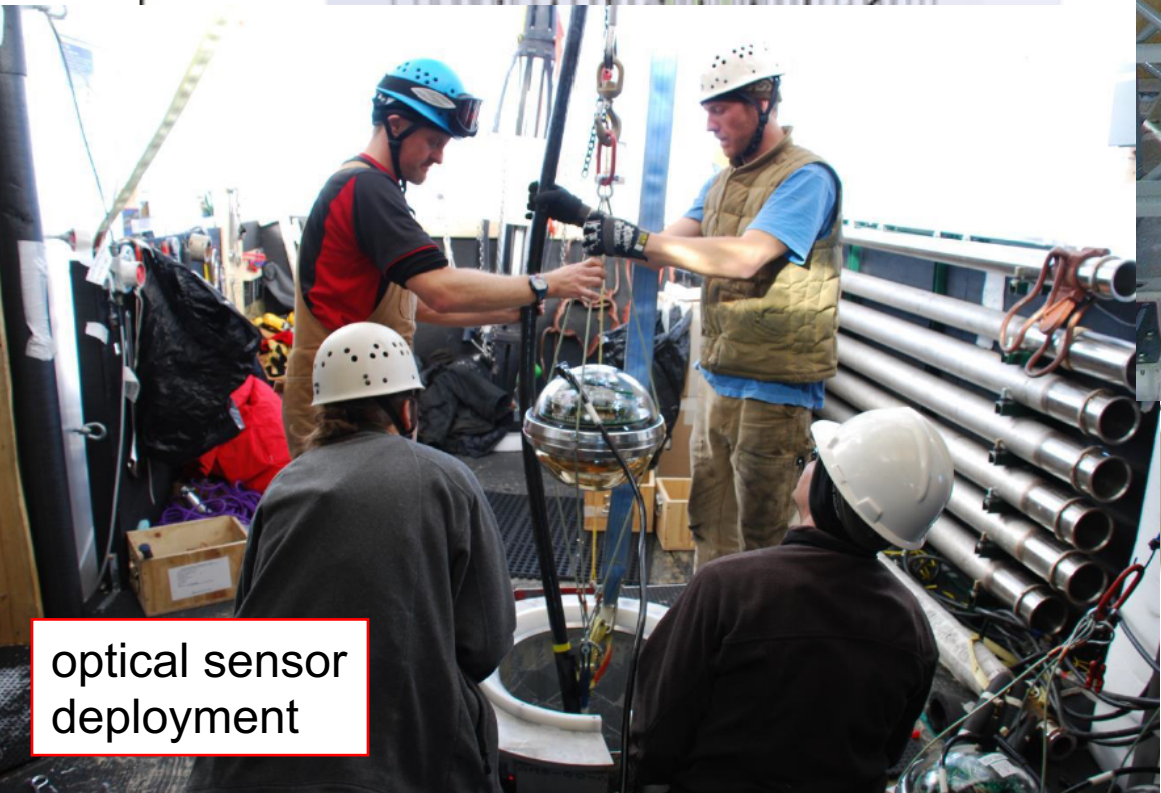
Bedrock Teppei Katori

# IceCube detector

50 m



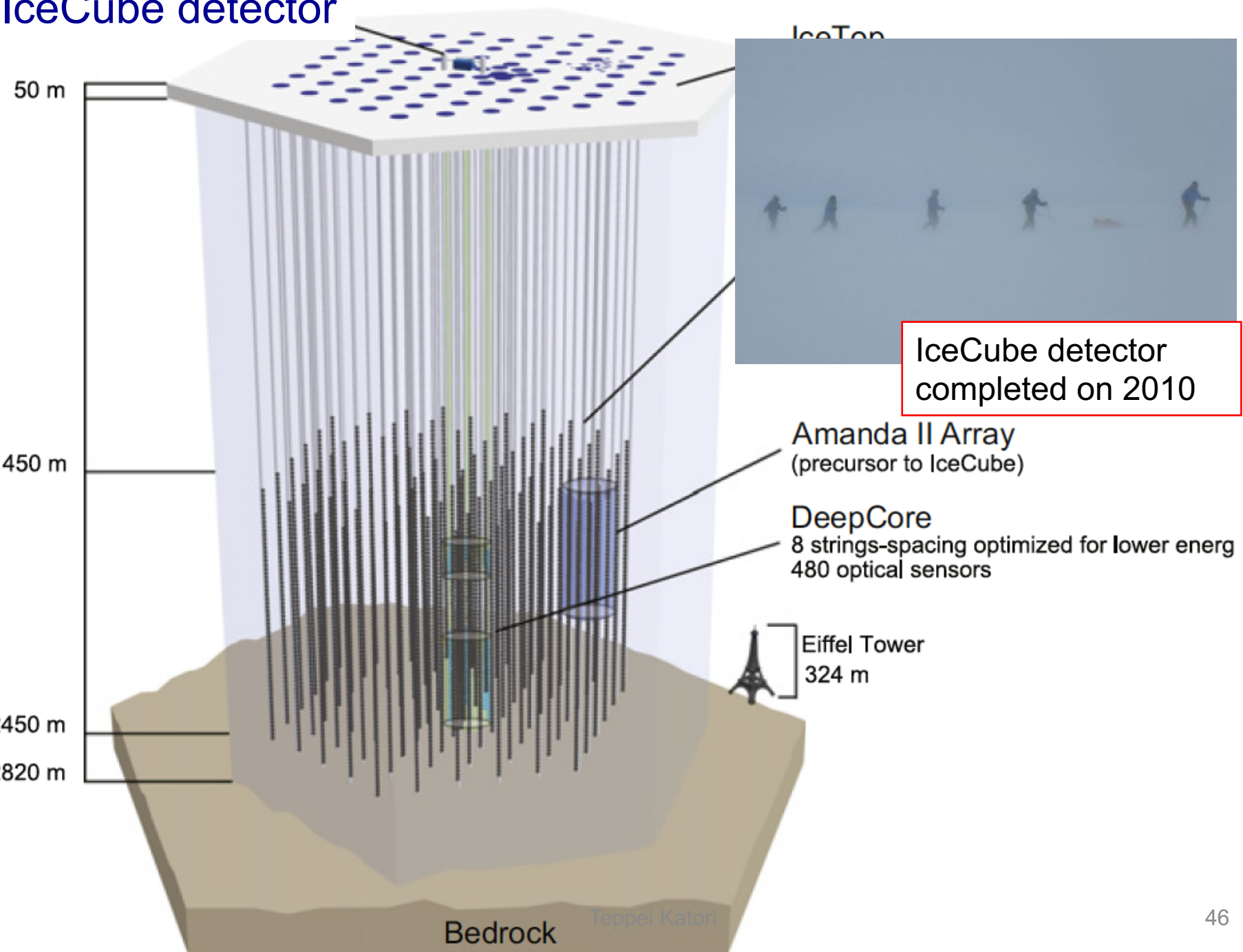
hot water drill



optical sensor deployment



# IceCube detector





# IceCube detector

50



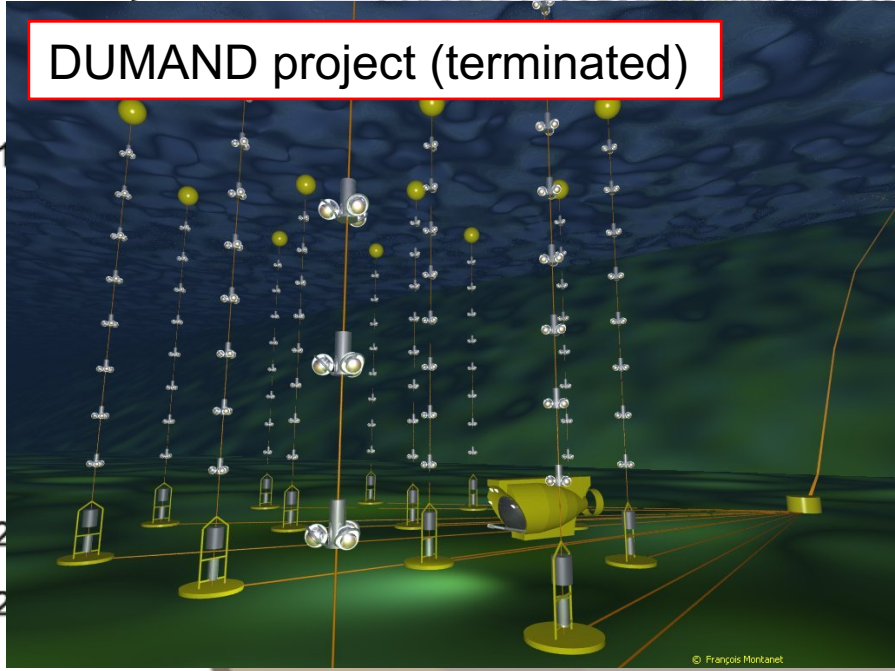
Hawaii

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

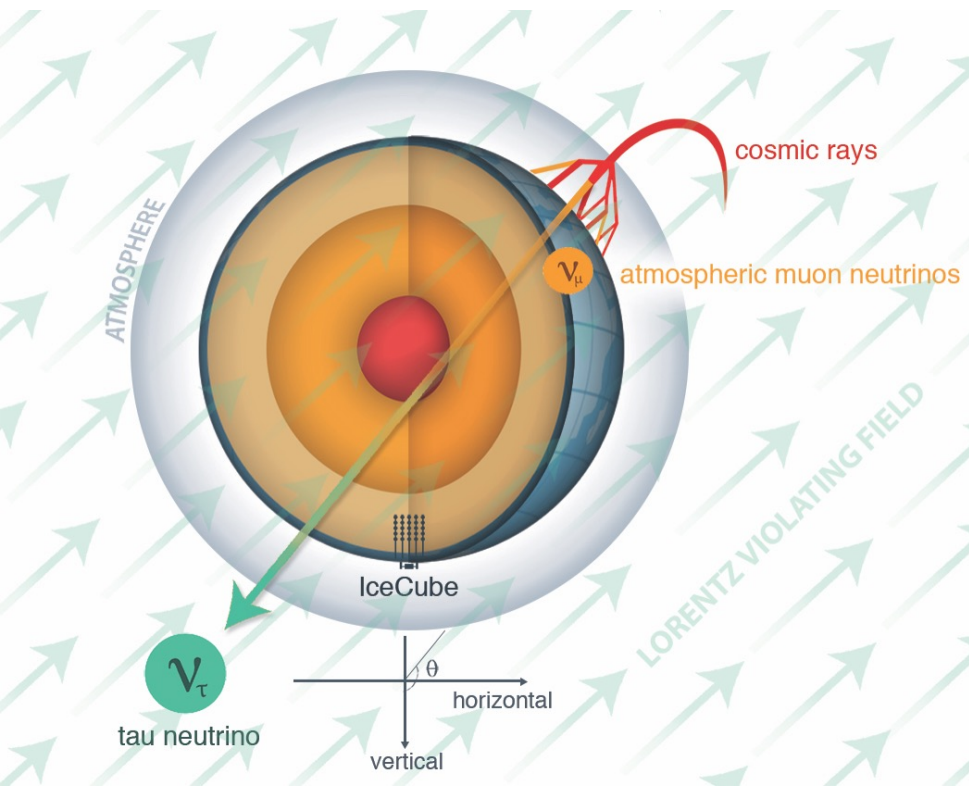
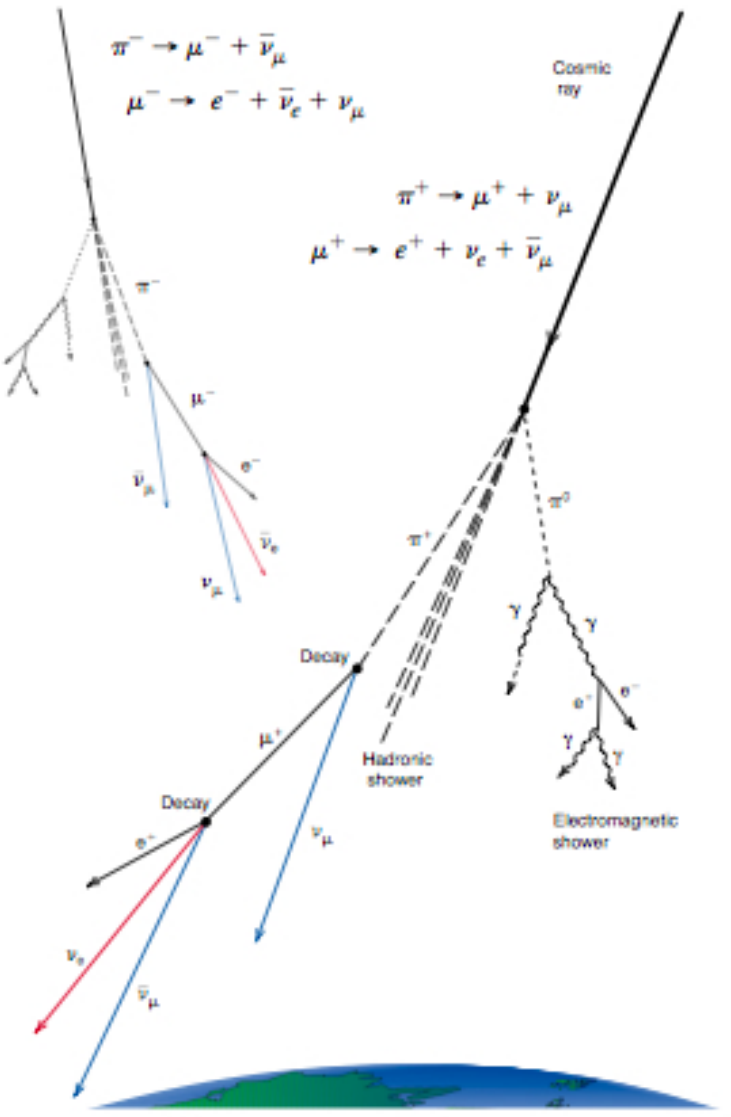
100/446 shown, max  $E$  (GeV) == 56675.77

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



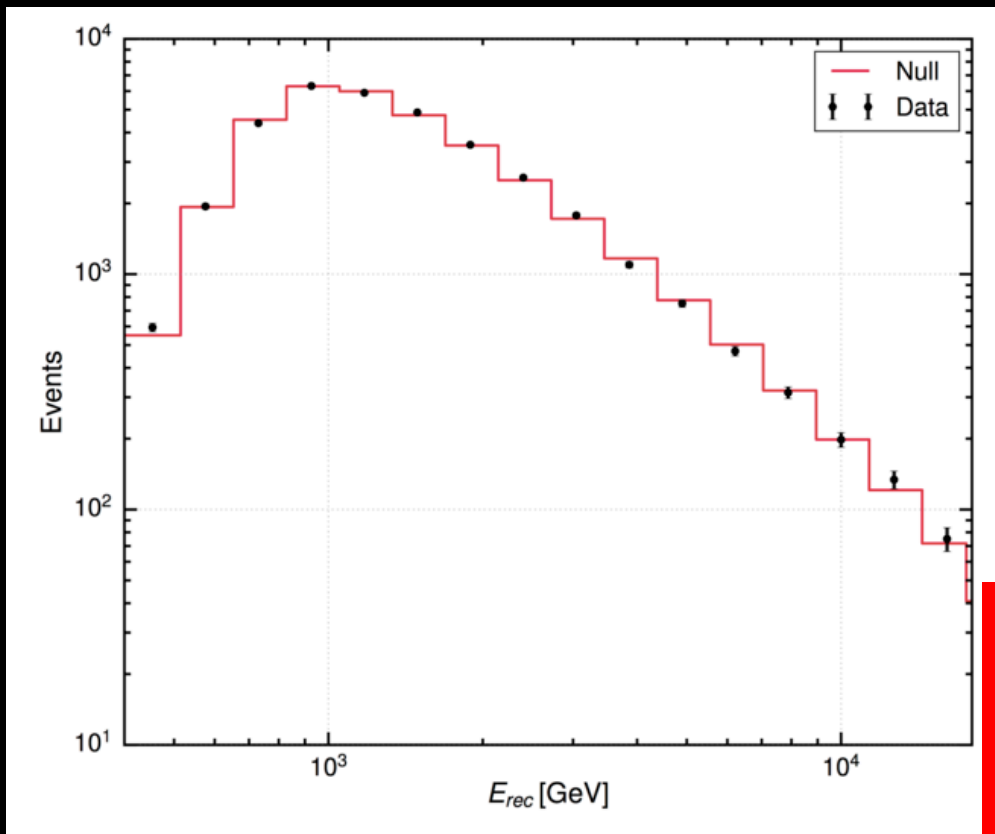
Shivesh Mandalia  
Queen Mary  
U. of London

# 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<sup>-2</sup>



We need much higher energy neutrinos...

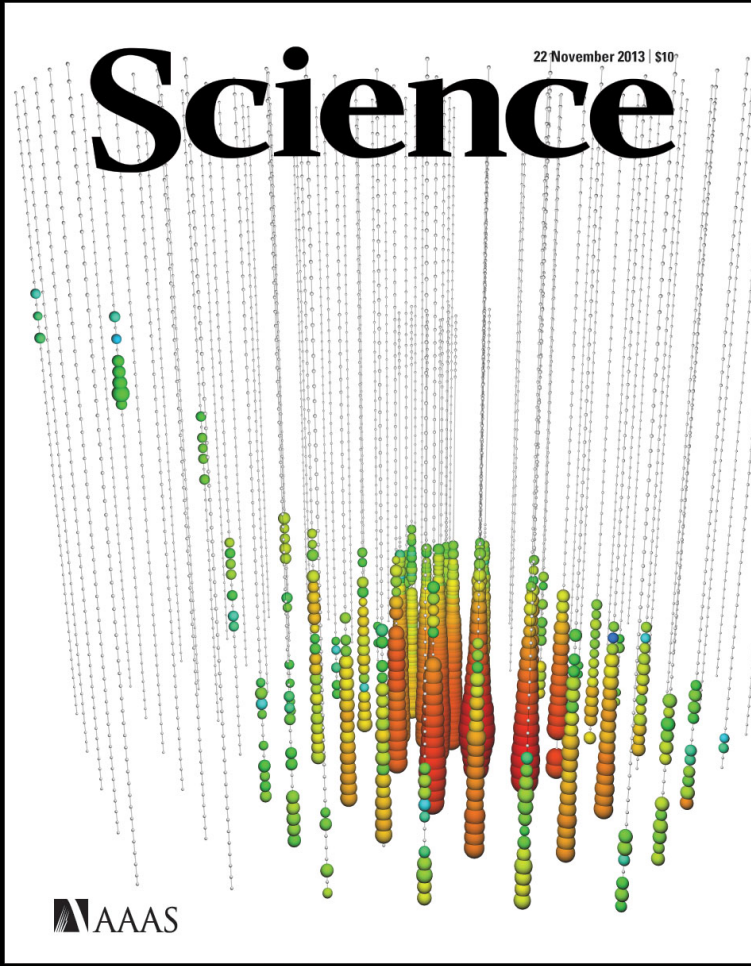
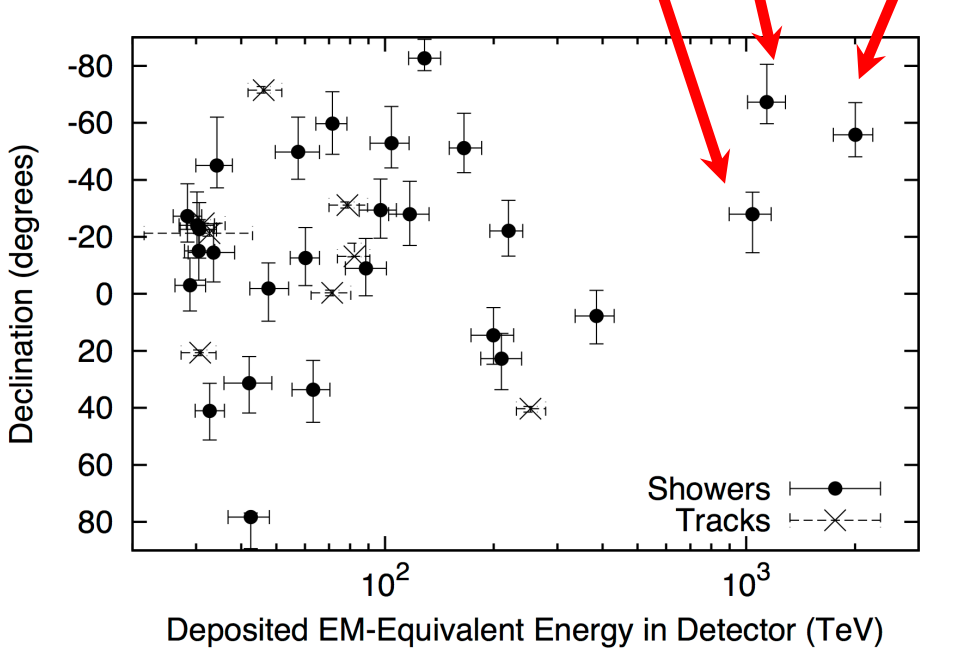
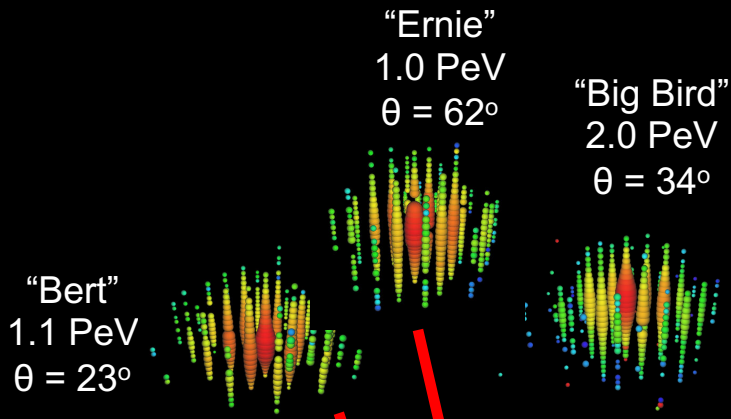


Shivesh Mandalia  
Queen Mary  
U. of London

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

# Discovery of High-Energy Astrophysical Neutrinos (2012)

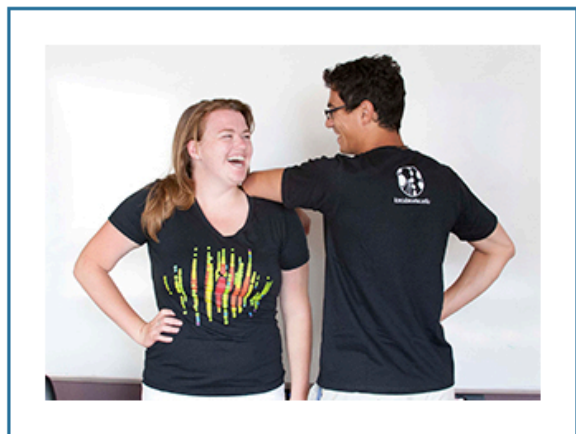
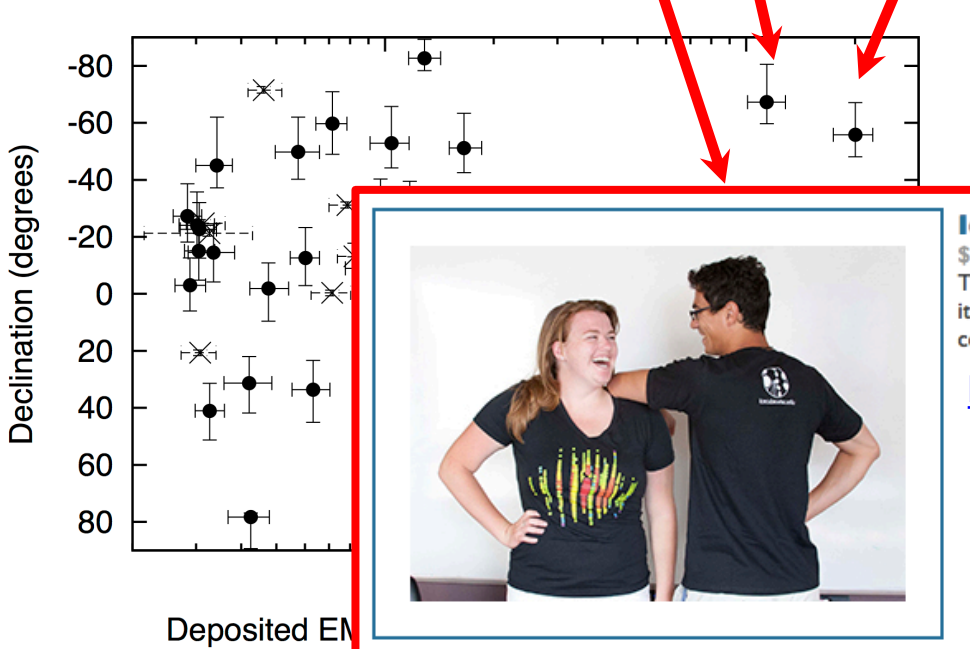
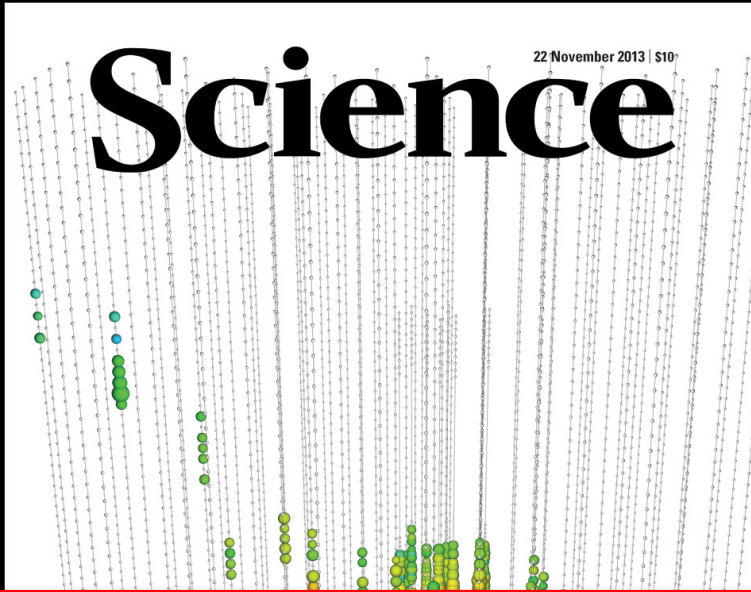
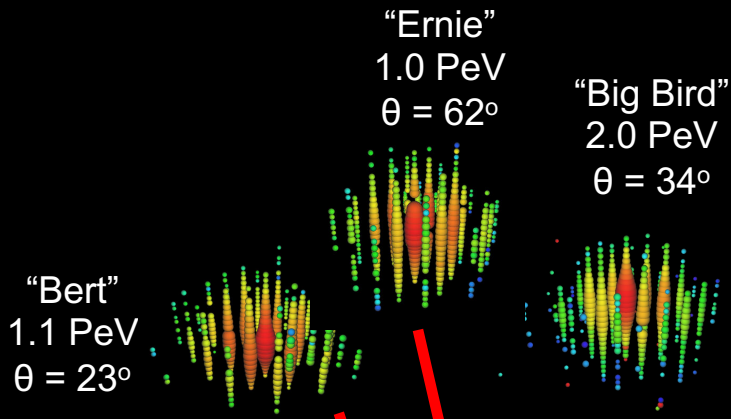
30 TeV to 2000 TeV very-high-energy neutrinos (Large Hadron Collider ~ 7 TeV)





# 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](https://charge.wisc.edu/icecube/wipac_store.aspx)

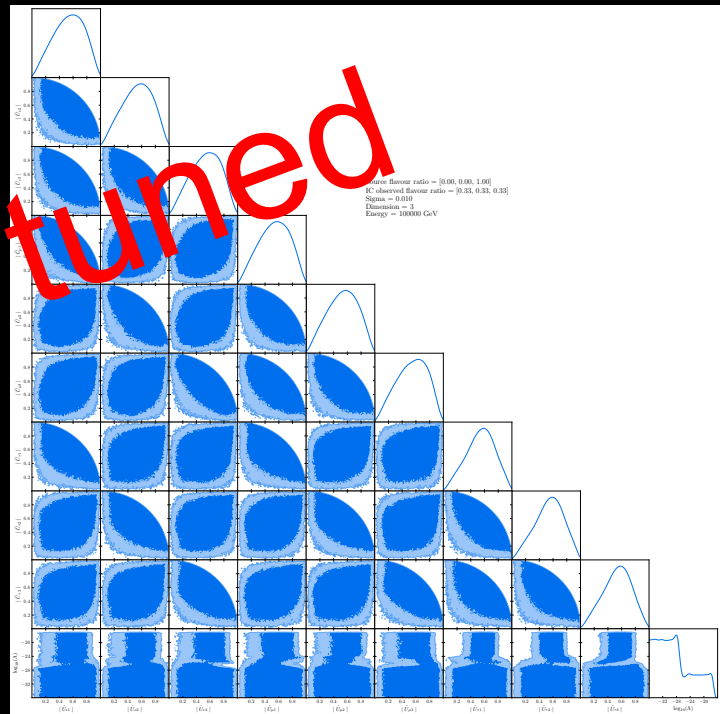
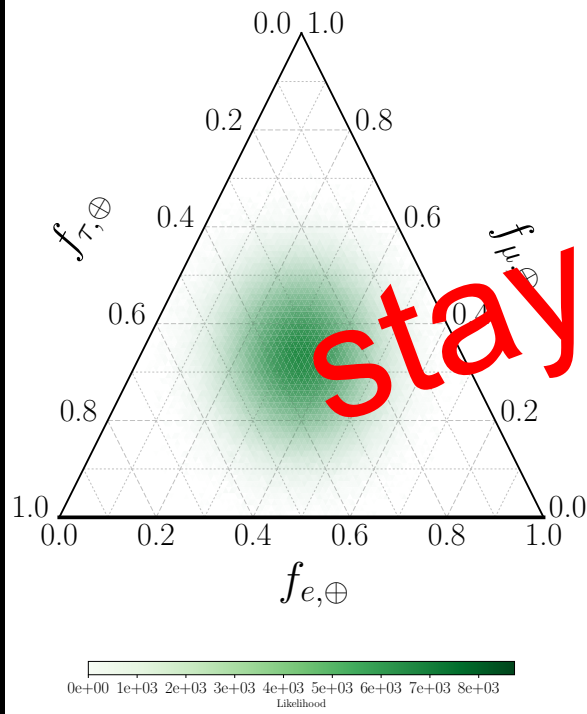
Support IceCube!

# Discovery of High-Energy Astrophysical Neutrinos (2012)

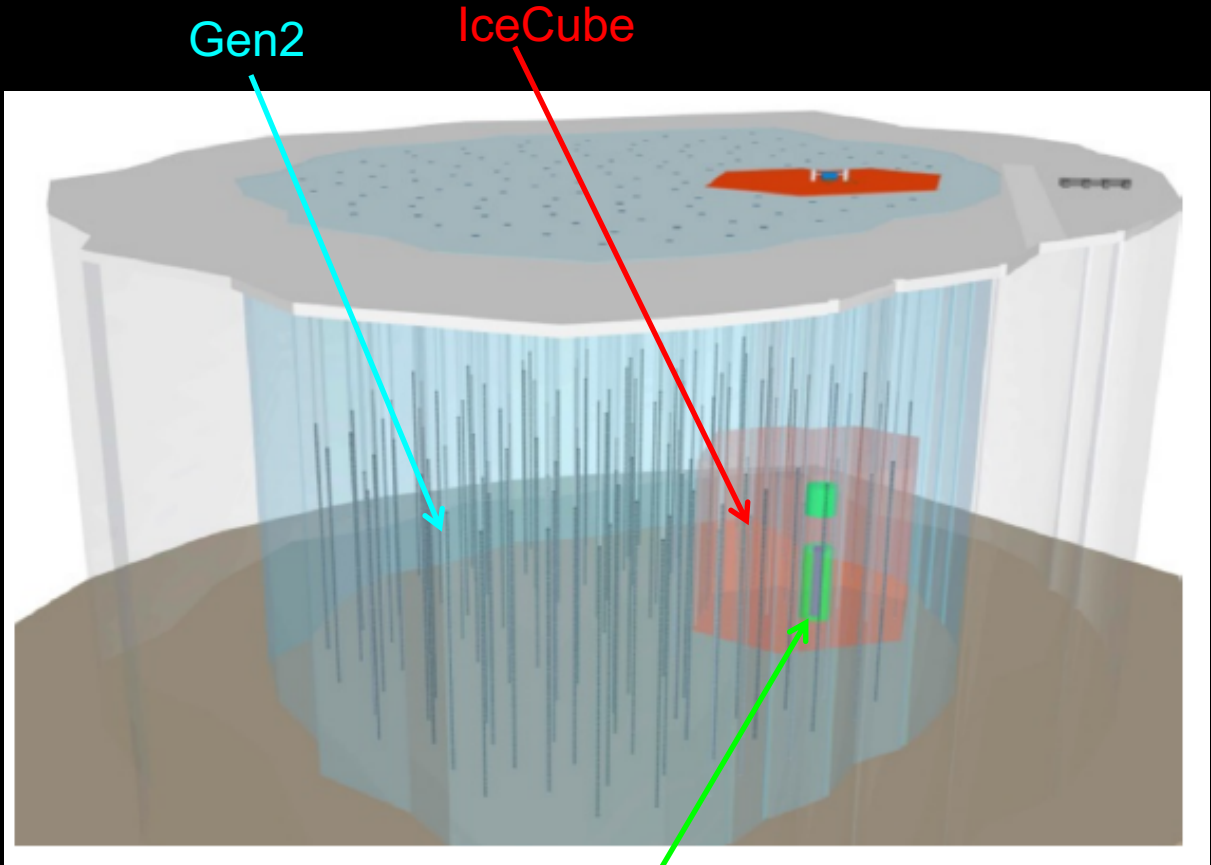
30 TeV to 2000 TeV very-high-energy neutrinos (Large Hadron Collider ~ 7 TeV)

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**

### Gen2

Larger string separations to cover larger area

**PINGU**: special region to study low energy neutrino

UK members: Queen Mary  
Oxford, Manchester



## 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!**

