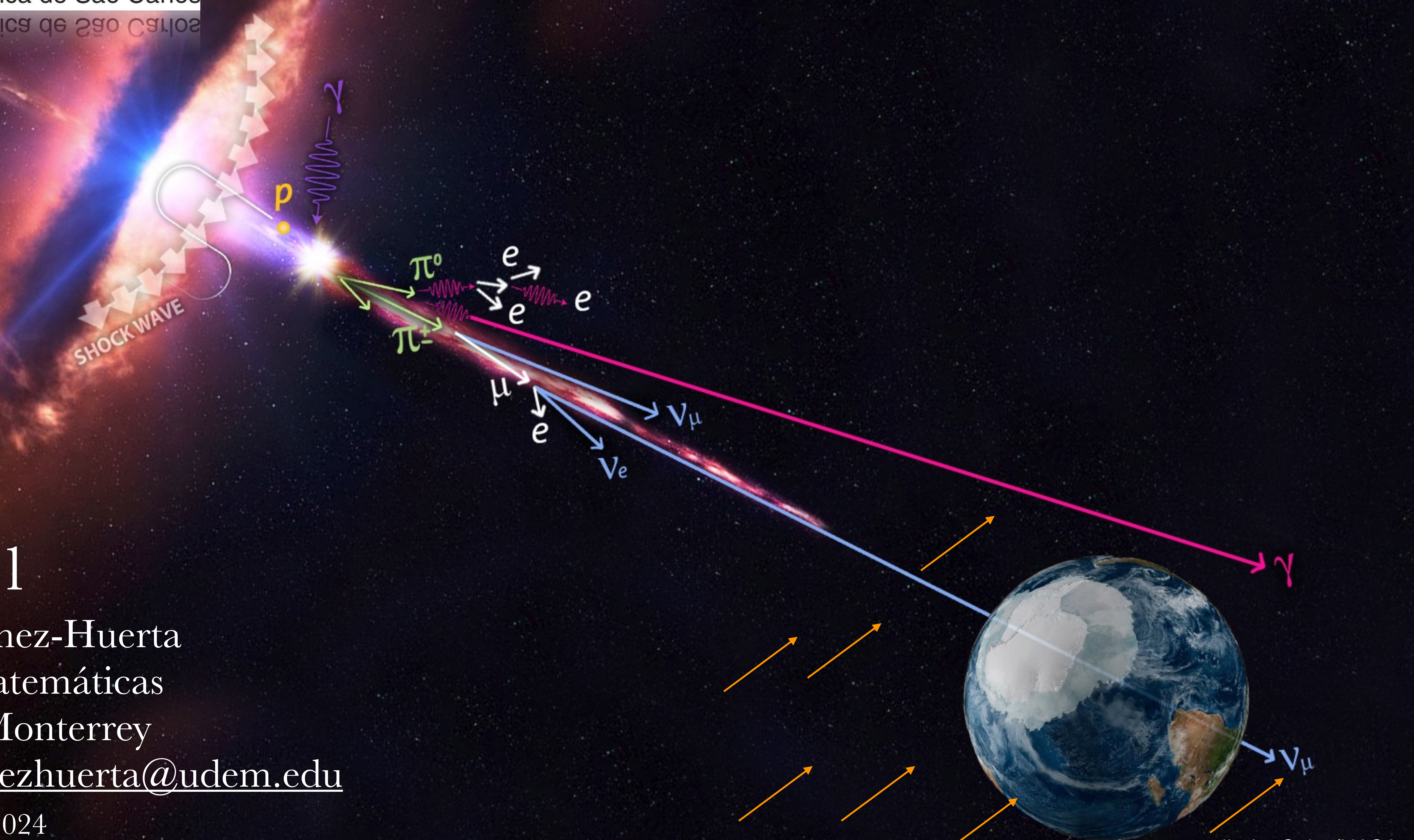

LIV Class 1

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Universidad de Monterrey
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IFSC-USP - 20 Feb, 2024

Image credit: IceCube/NASA

Theory ⟷ Phenomenology ⟷ Experiment

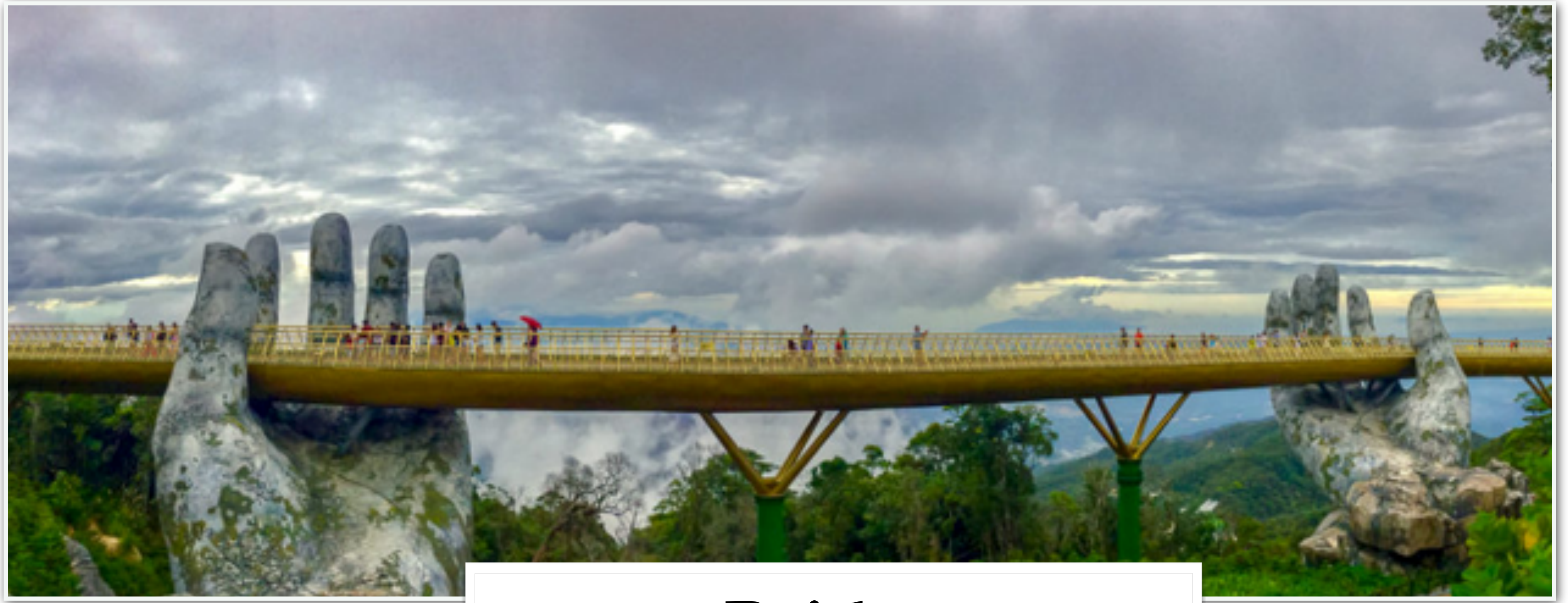
+Particle physics

+Effective Field Theories

+Standard Model Extension

+Double Special Relativity

…



Bridge

+Data Analysis (cosmic,gamma-ray,..)

+Programing (python, Gammapy…)

+Field experience (HAWC/Auger)

…

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Module 1: Introduction to Lorentz Symmetry and Violation

1.1 Lorentz Symmetry Recap

- A brief review of Lorentz symmetry in the context of special relativity
- Key principles, transformations, and their significance
- Four-Vectors
- Dispersion Relation |1→2 | 2→2|

1.2 Motivation for Lorentz Invariance Violation

- Motivations for exploring violations
- Modified Dispersion Relation | 2→2|

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Module 2: Theoretical Frameworks for Lorentz Symmetry Violation

2.1 Standard Model Extension (SME)

- Introduction to the Standard Model Extension as a framework for incorporating Lorentz symmetry violation
- Parameters, implications and comparison with MDR

2.2 Alternative Theories

- Overview of alternative theories proposing Lorentz symmetry violation
- String theory, quantum gravity, and other beyond-the-Standard-Model approaches

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Module 3: Phenomenological Implications and Experimental Constraints

3.1 Observable Effects

- Discussion on observable effects of Lorentz symmetry violation in different physical phenomena

3.2 Experimental Tests:

- Review of experimental methods for testing Lorentz symmetry violation and their implications

3.2 Current Constraints

- Overview of the current bounds on Lorentz symmetry violation from various experiments
- Comparison with theoretical predictions

3.3 Hands-on block

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Course Overview

Module 1: Introduction to Lorentz Symmetry and Violation

1.1 Lorentz Symmetry Recap

- A brief review of Lorentz symmetry in the context of special relativity
- Key principles, transformations, and their significance
- Four-Vectors
- Dispersion Relation |1→2 | 2→2|

1.2 Motivation for Lorentz Symmetry Violation

- Motivations for exploring violations
- Overview of scenarios where Lorentz symmetry might be broken
- Modified Dispersion Relation |1→2 | 2→2|

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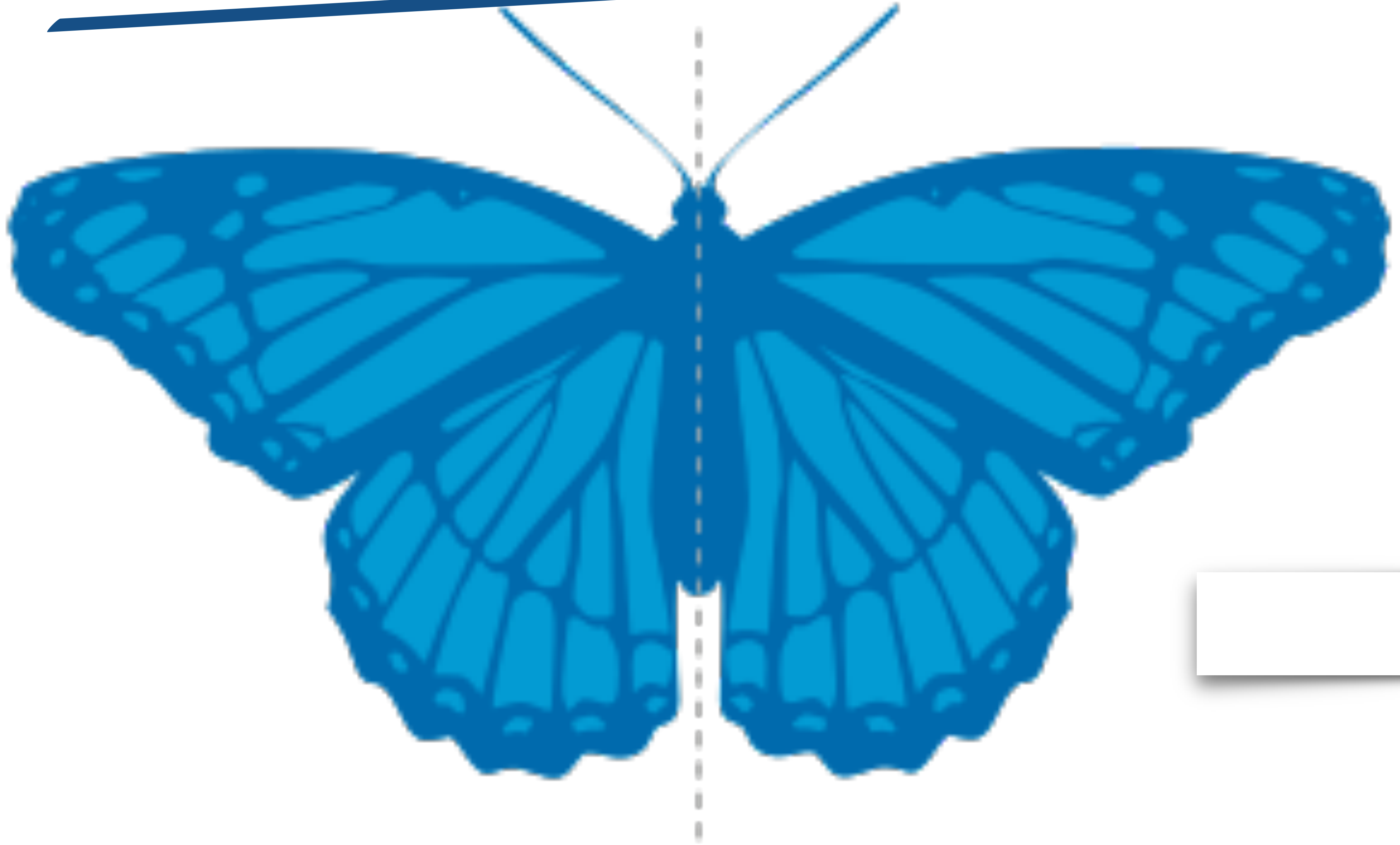
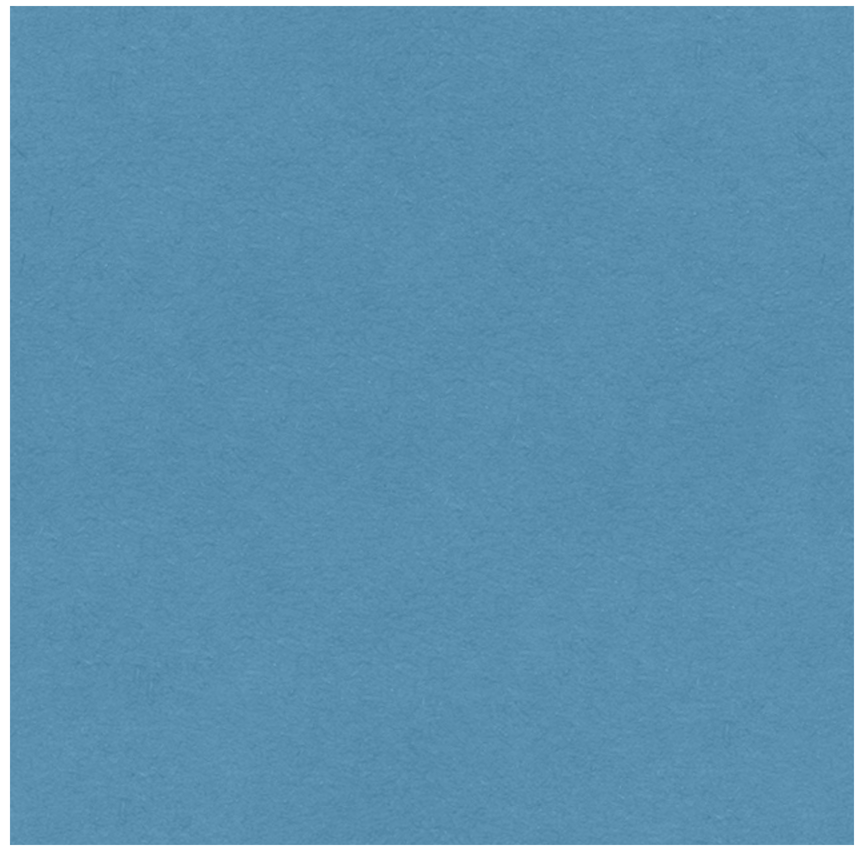
Symmetries

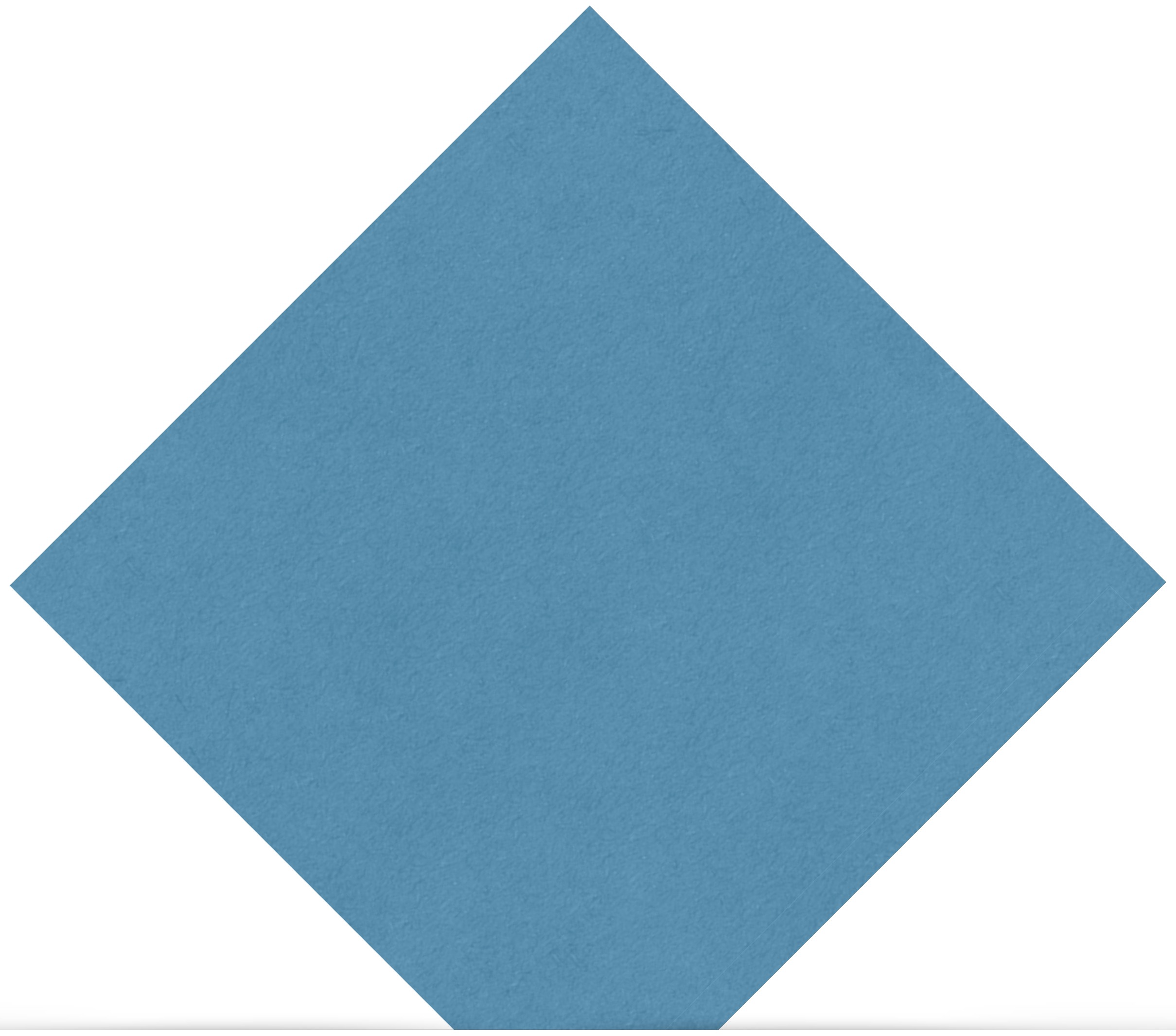




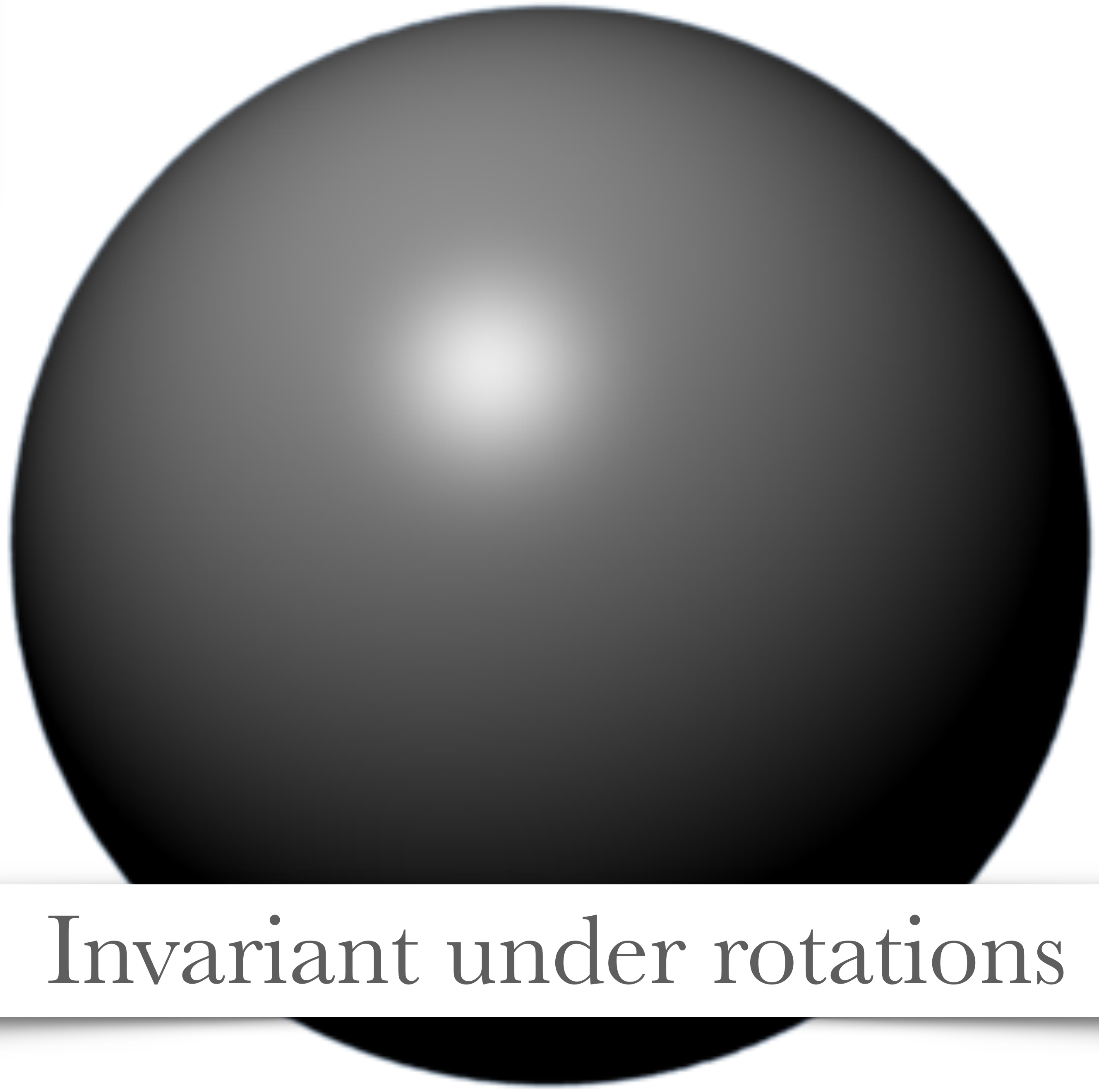
Invariant under?

Symmetries

Invariant under left-right reverse

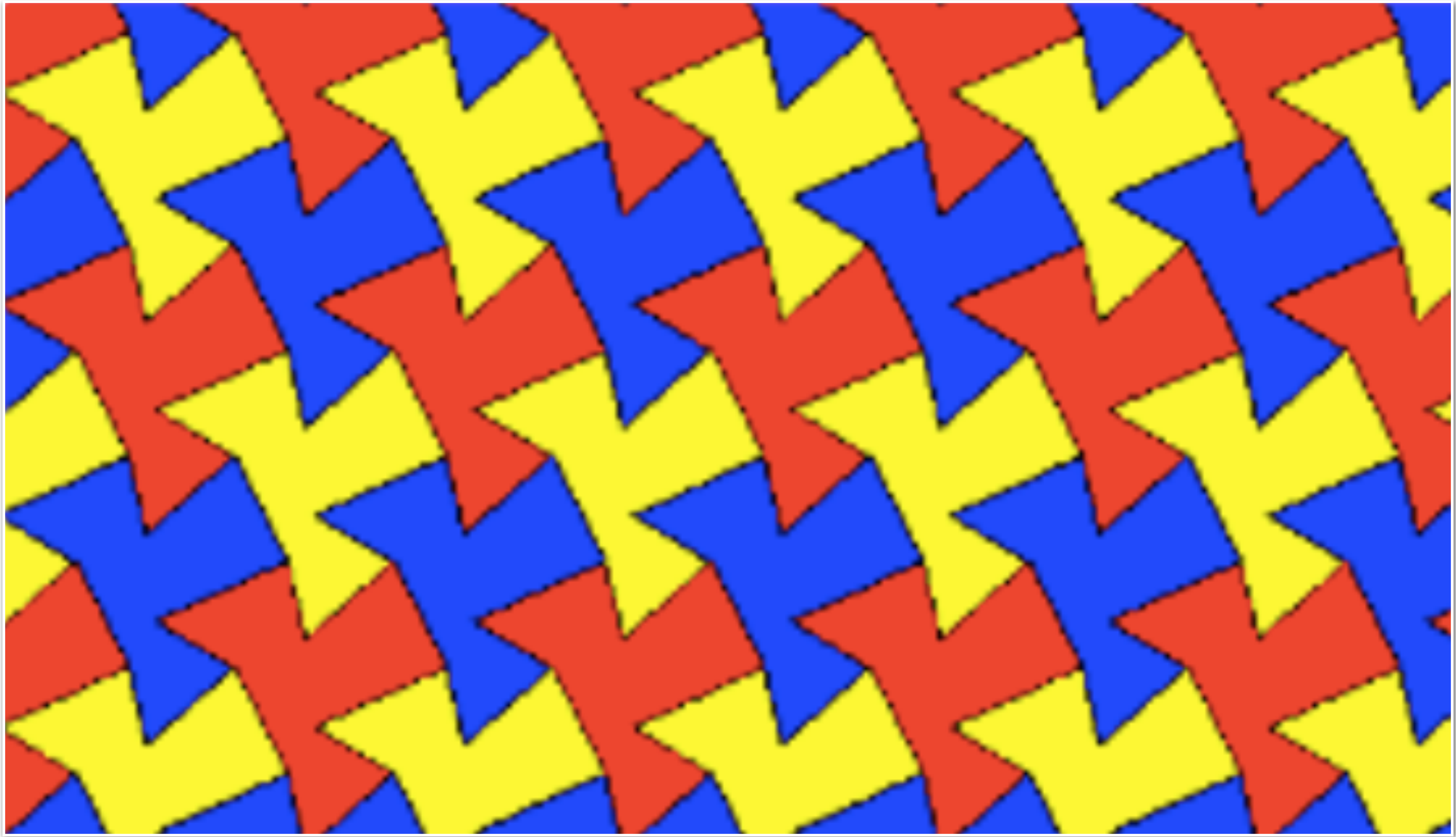


Invariant under rotations: 90° ($\pi/2$)

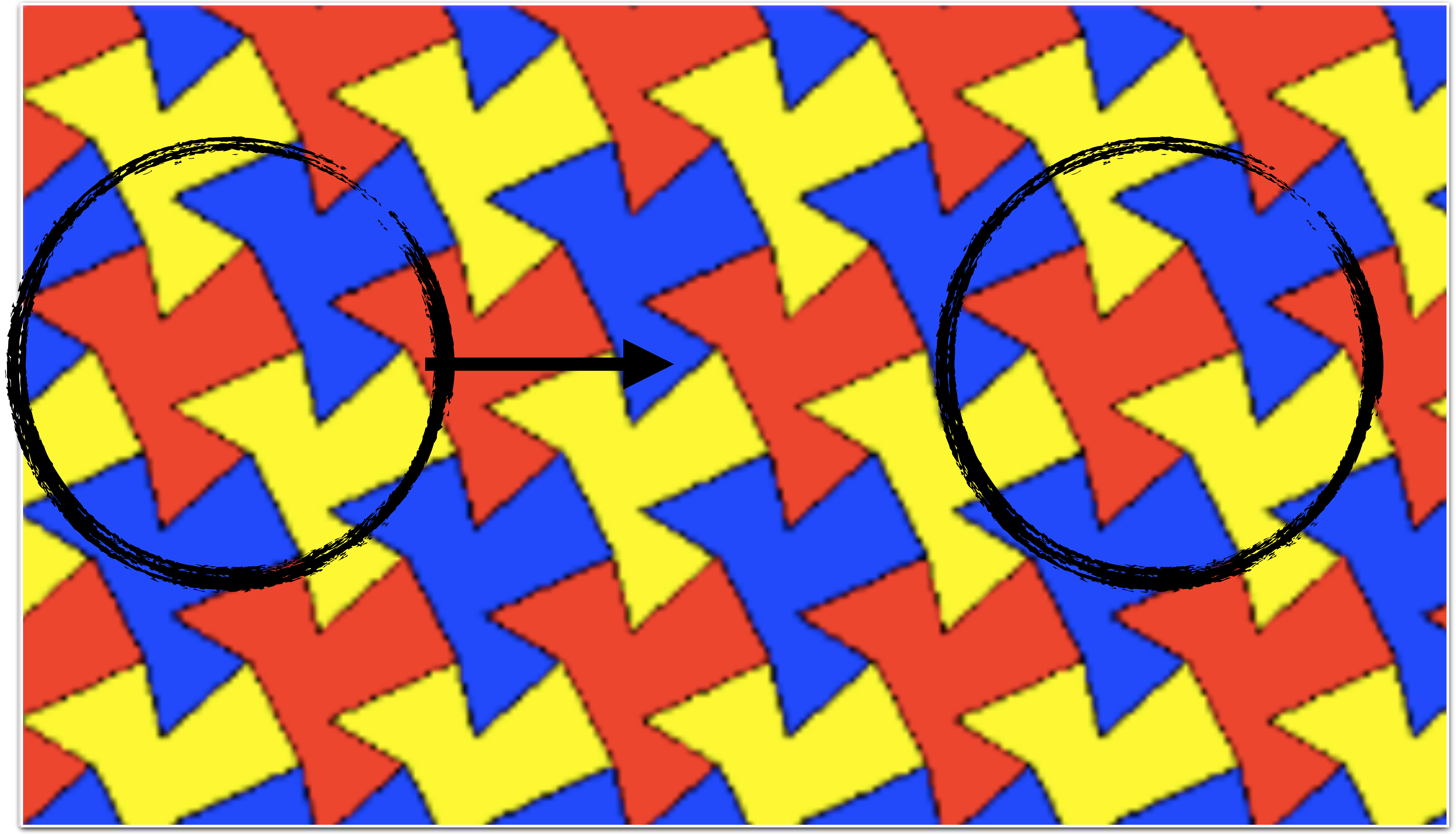


Invariant under rotations

Symmetries

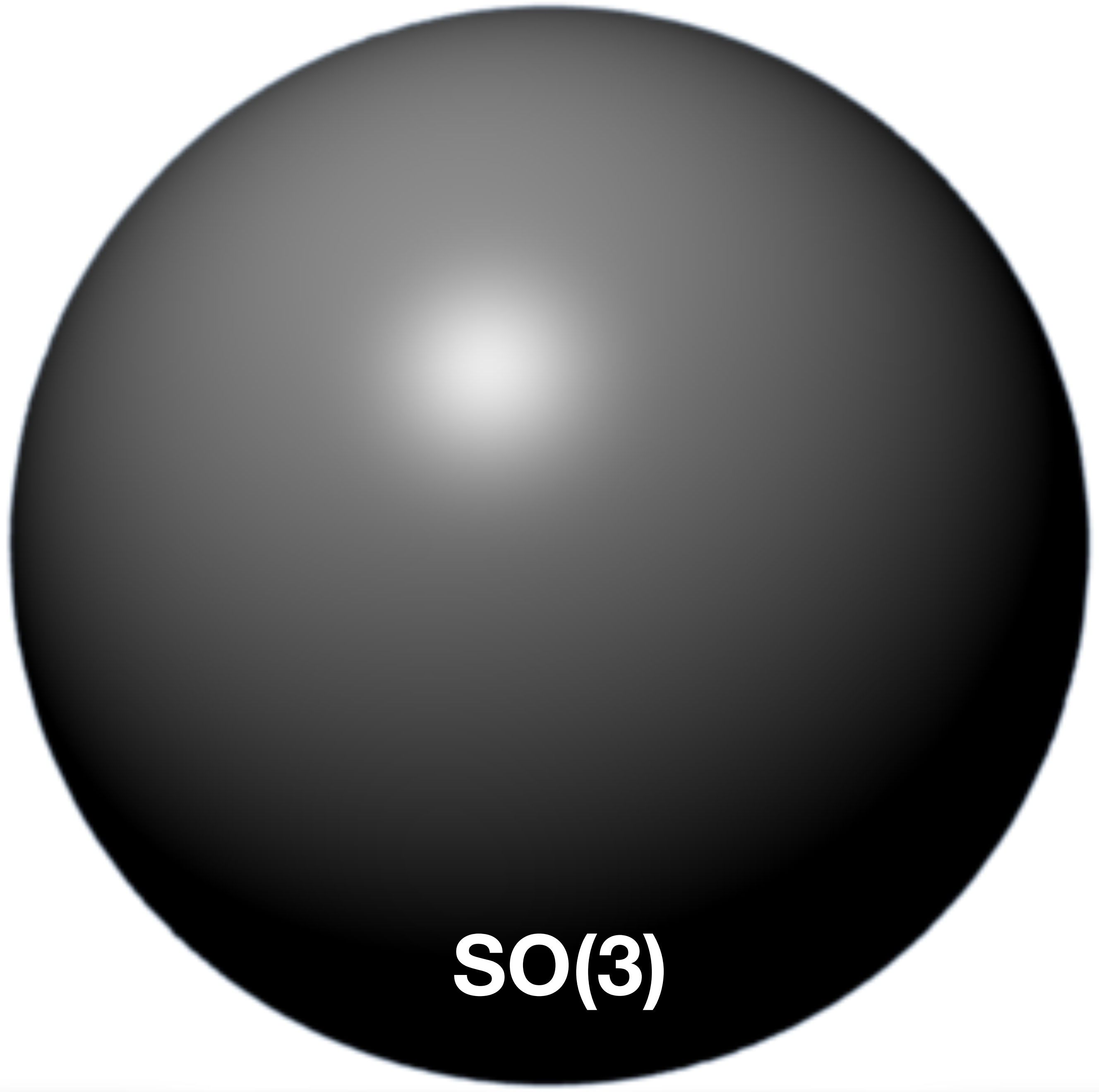


Symmetries



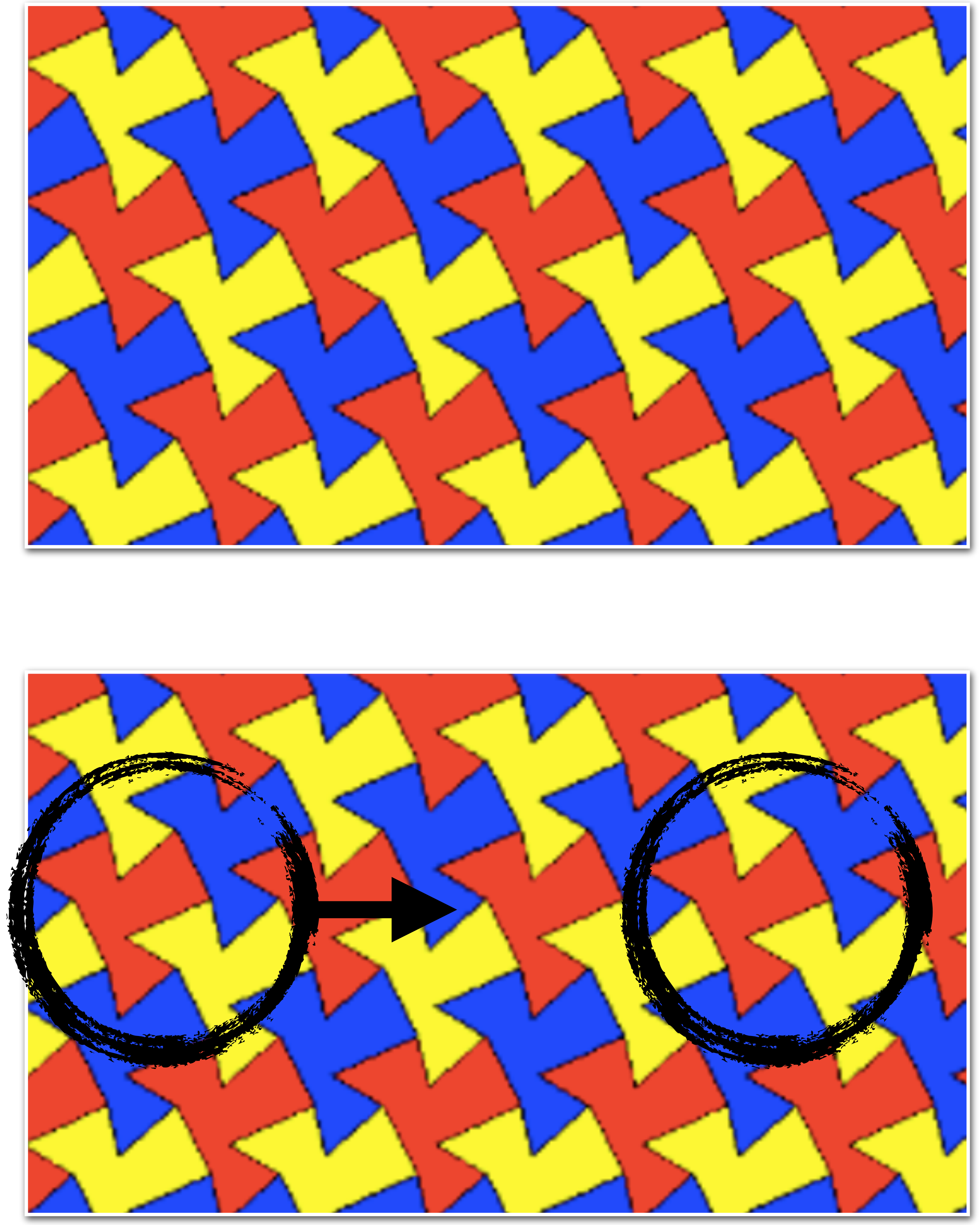
Invariant under?

Symmetries



Invariant under rotations

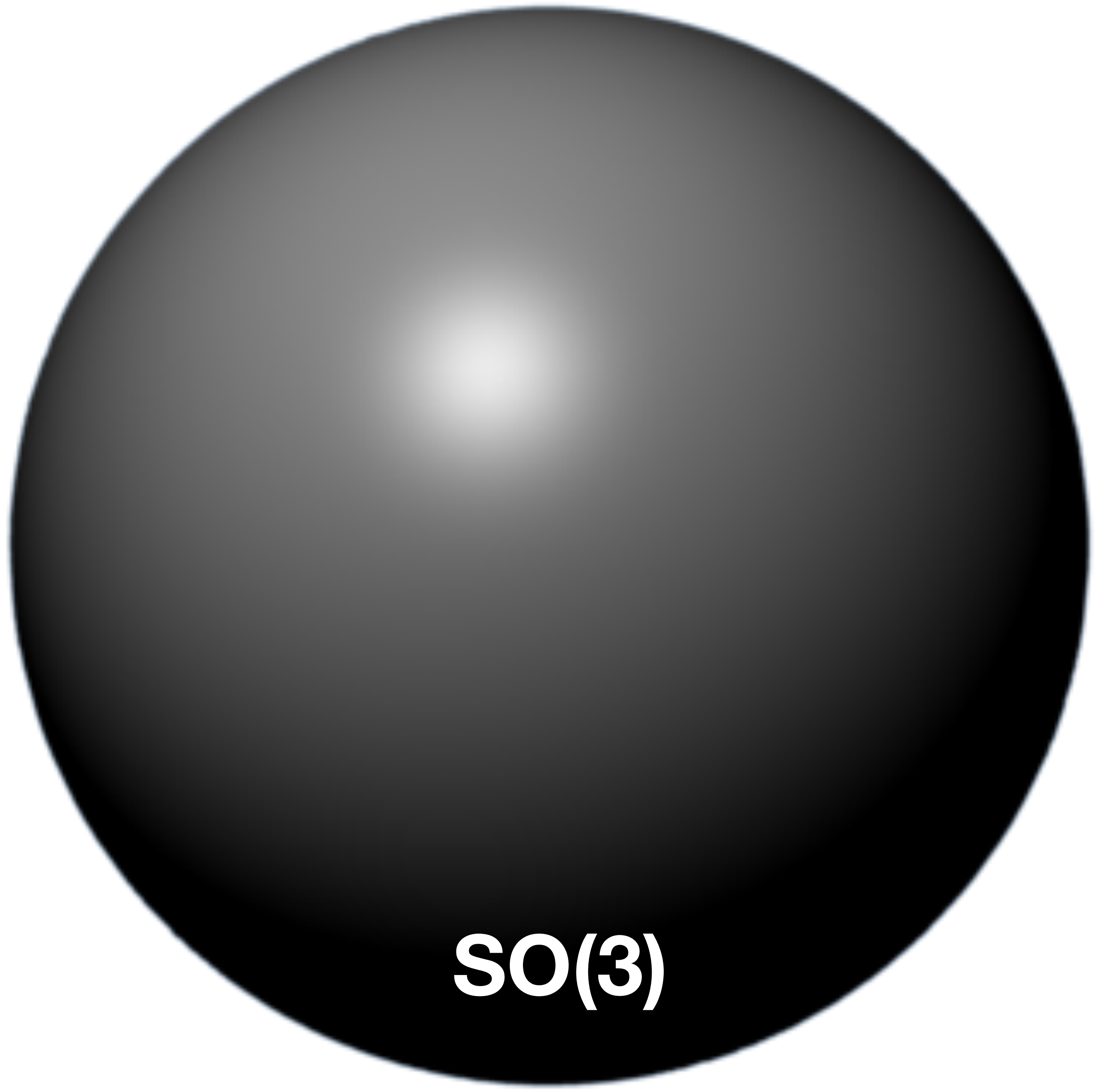
$$R_z(\varphi) = \begin{bmatrix} \cos\varphi & -\sin\varphi & 0 \\ \sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



Invariant under translation

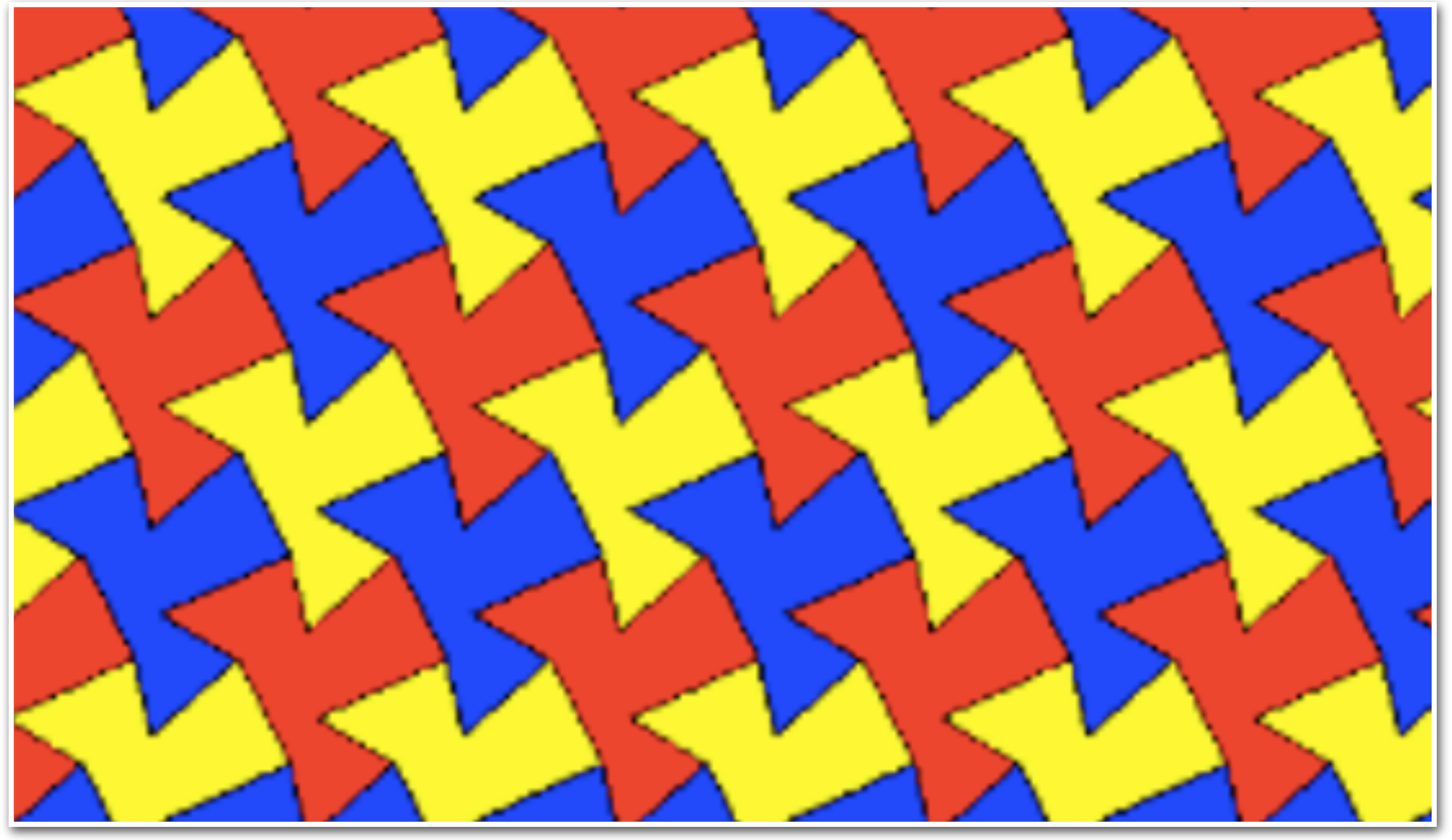
x -> x + δx

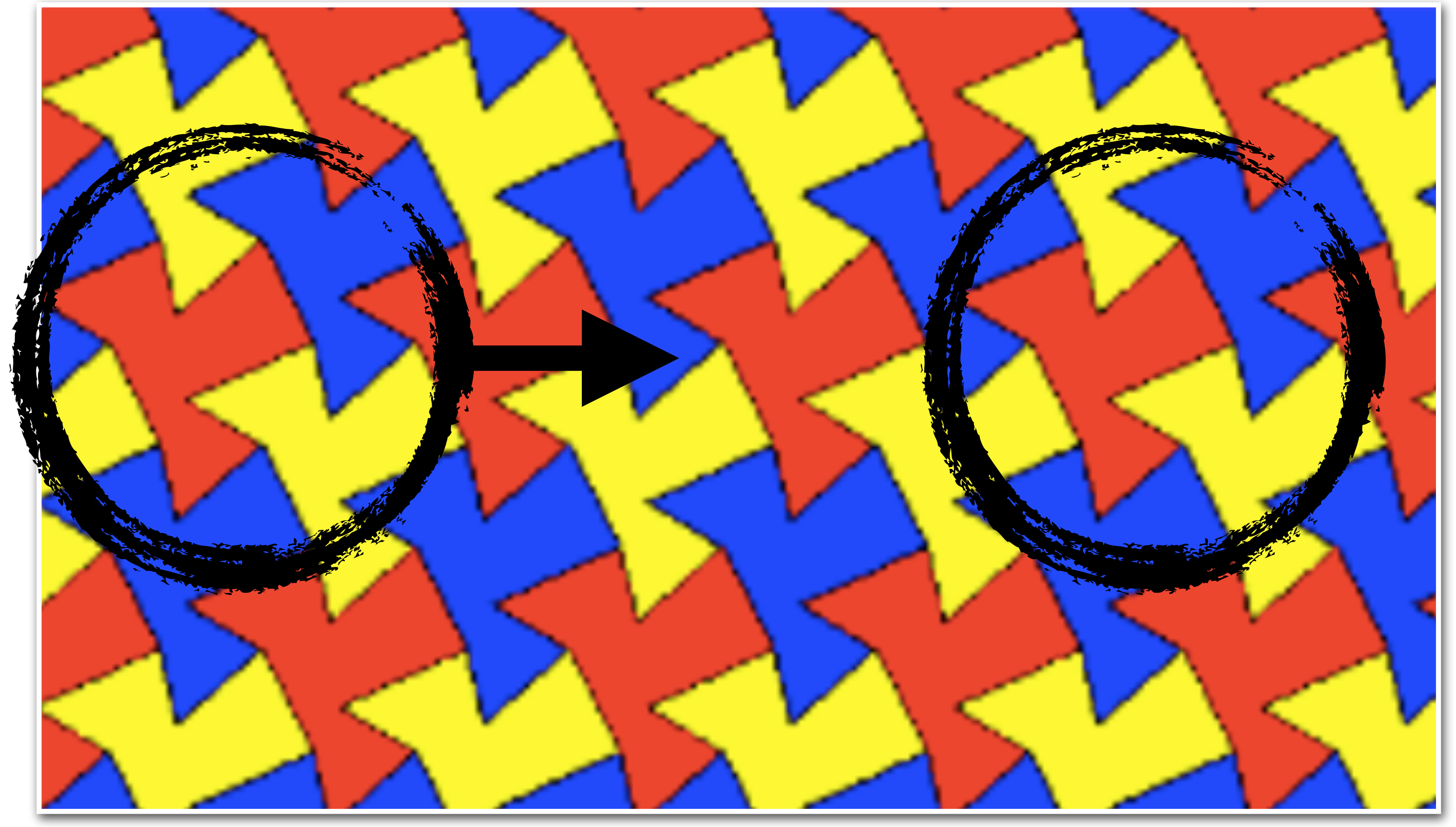
Symmetries



Invariante ante rotaciones

$$\begin{bmatrix} p'_x \\ p'_y \\ p'_z \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \bullet \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix}$$

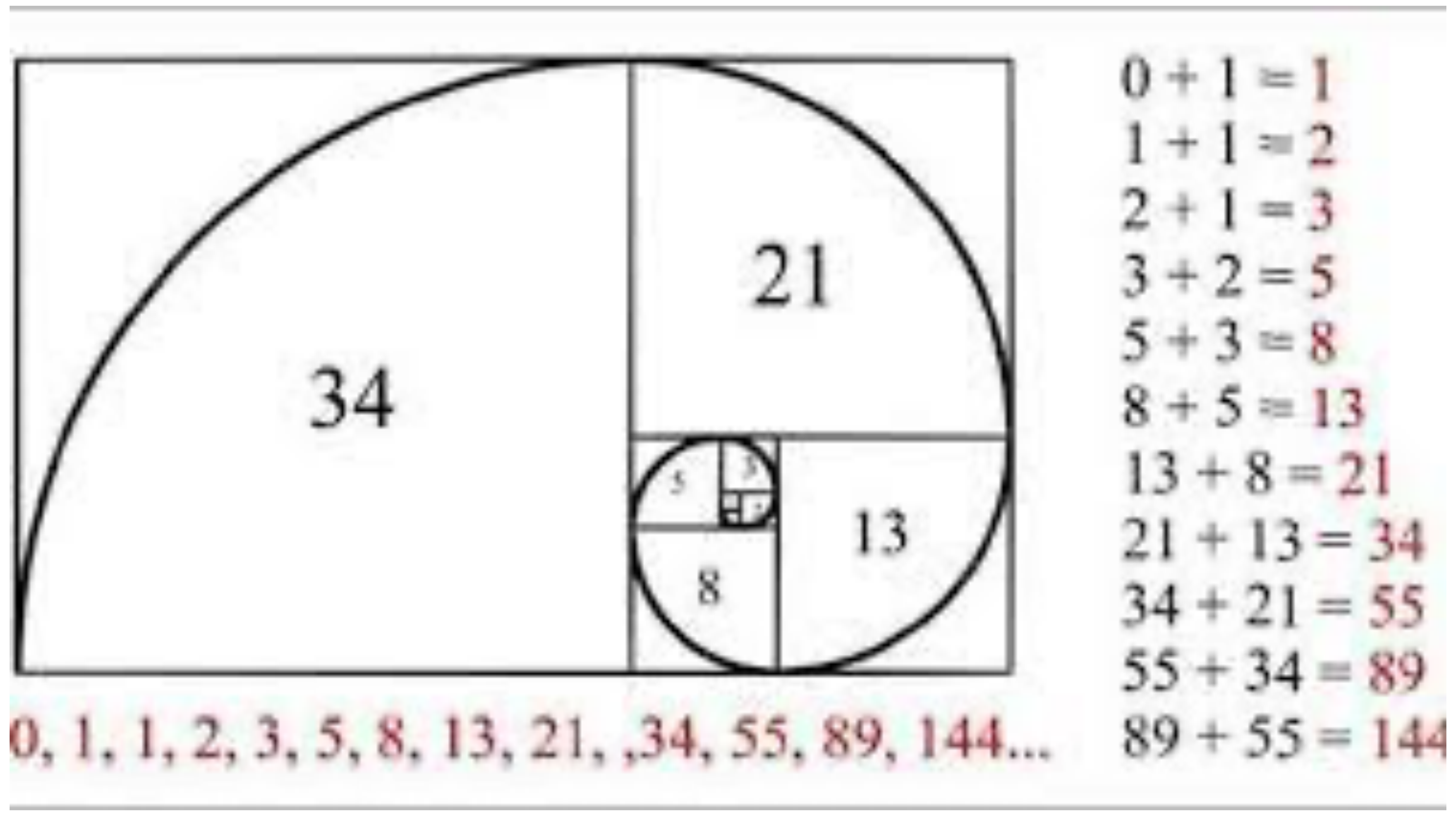




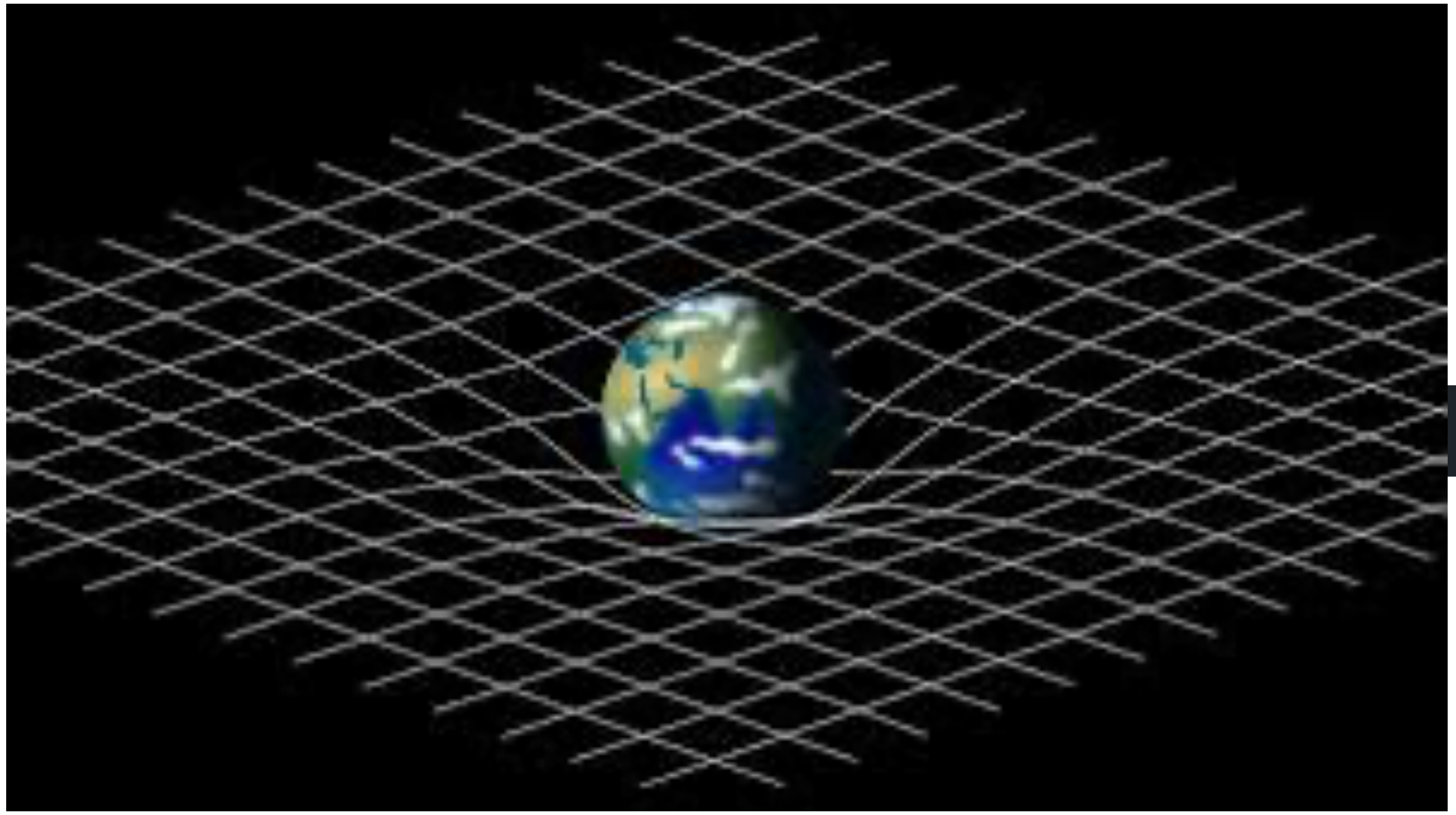
Invariante ante translaciones

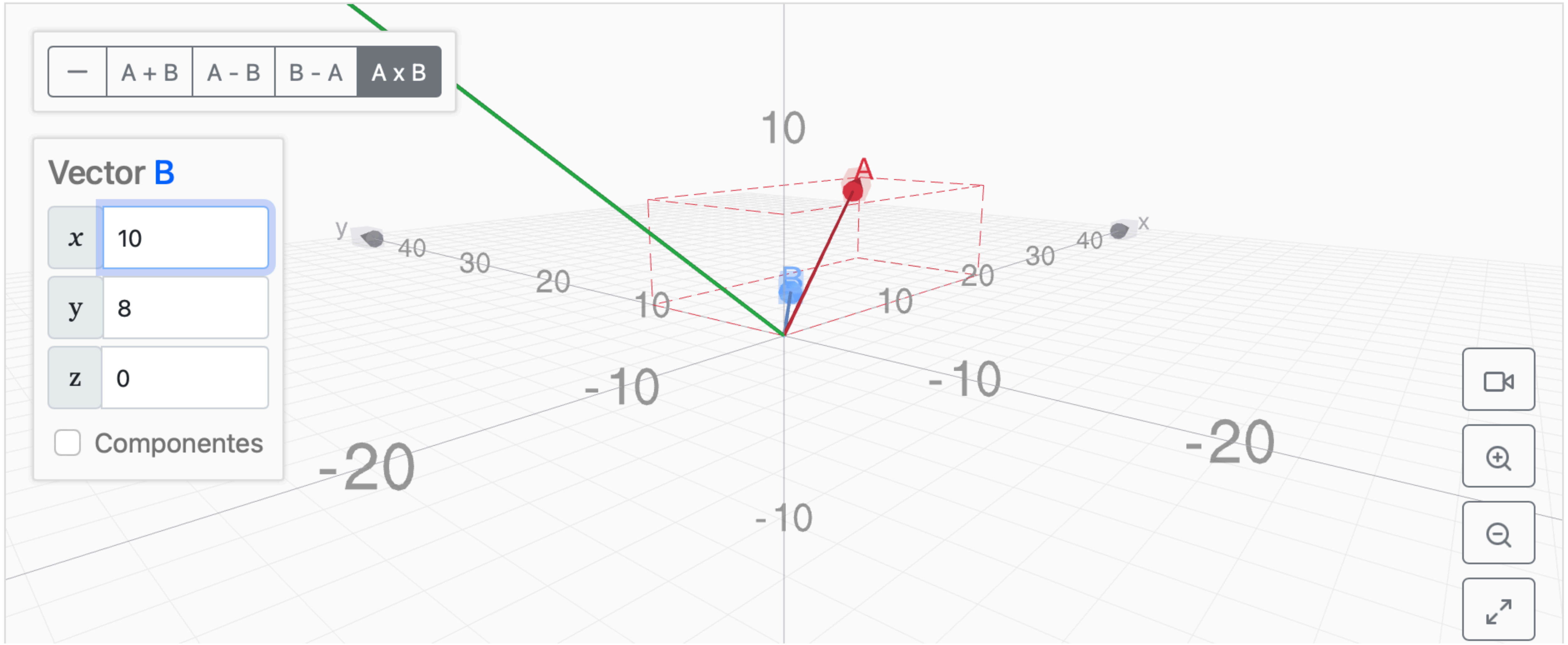
$x \;\; \text{->} \;\; x + \delta x$

Symmetries


34
21
13
8
5
0, 1, 1, 2, 3, 5, 8, 13, 21, ,34, 55, 89, 144...
0 + 1 = 1
1 + 1 = 2
2 + 1 = 3
3 + 2 = 5
5 + 3 = 8
8 + 5 = 13
13 + 8 = 21
21 + 13 = 34
34 + 21 = 55
55 + 34 = 89
89 + 55 = 144

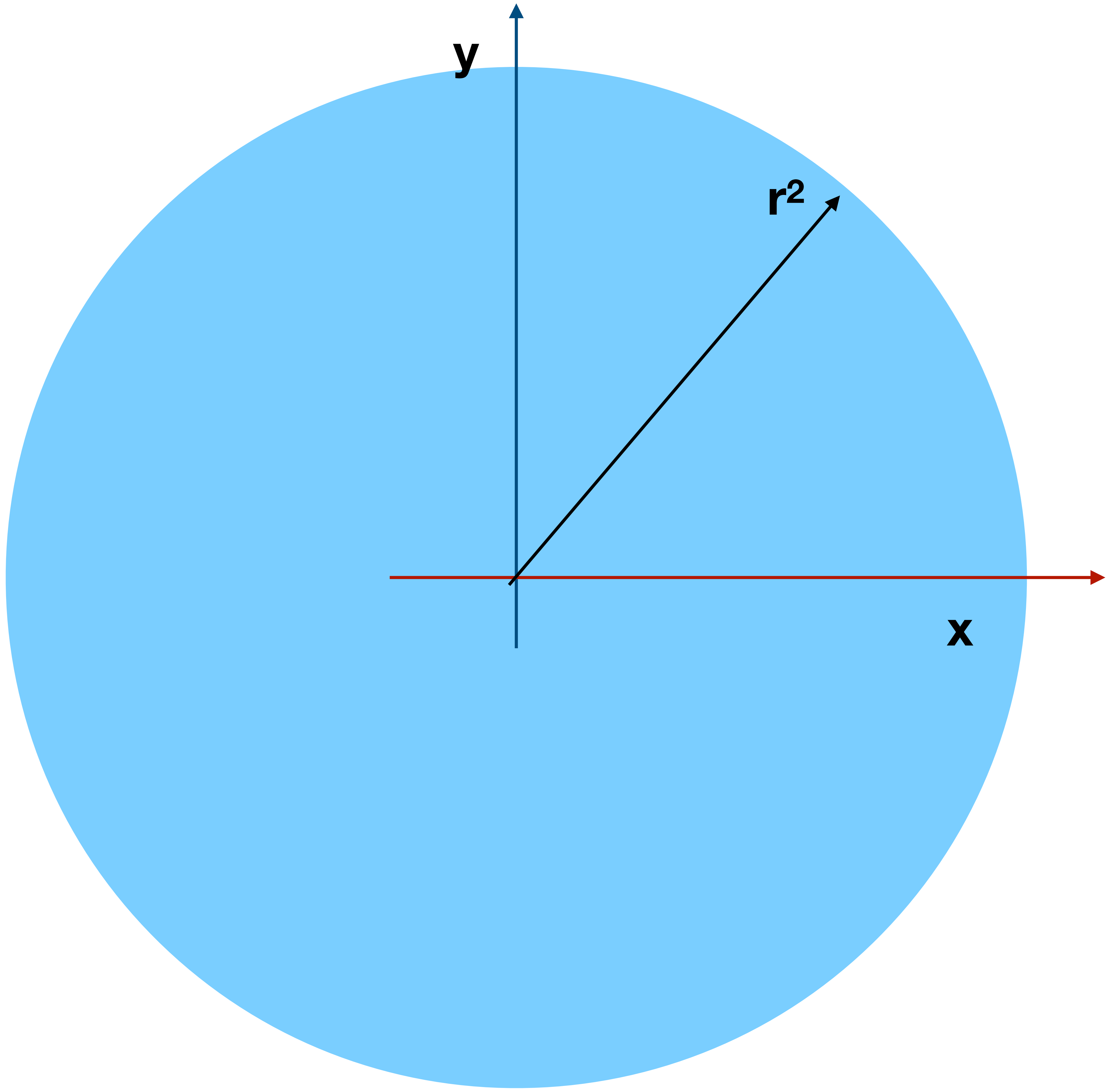
Space





Space

What is constant?

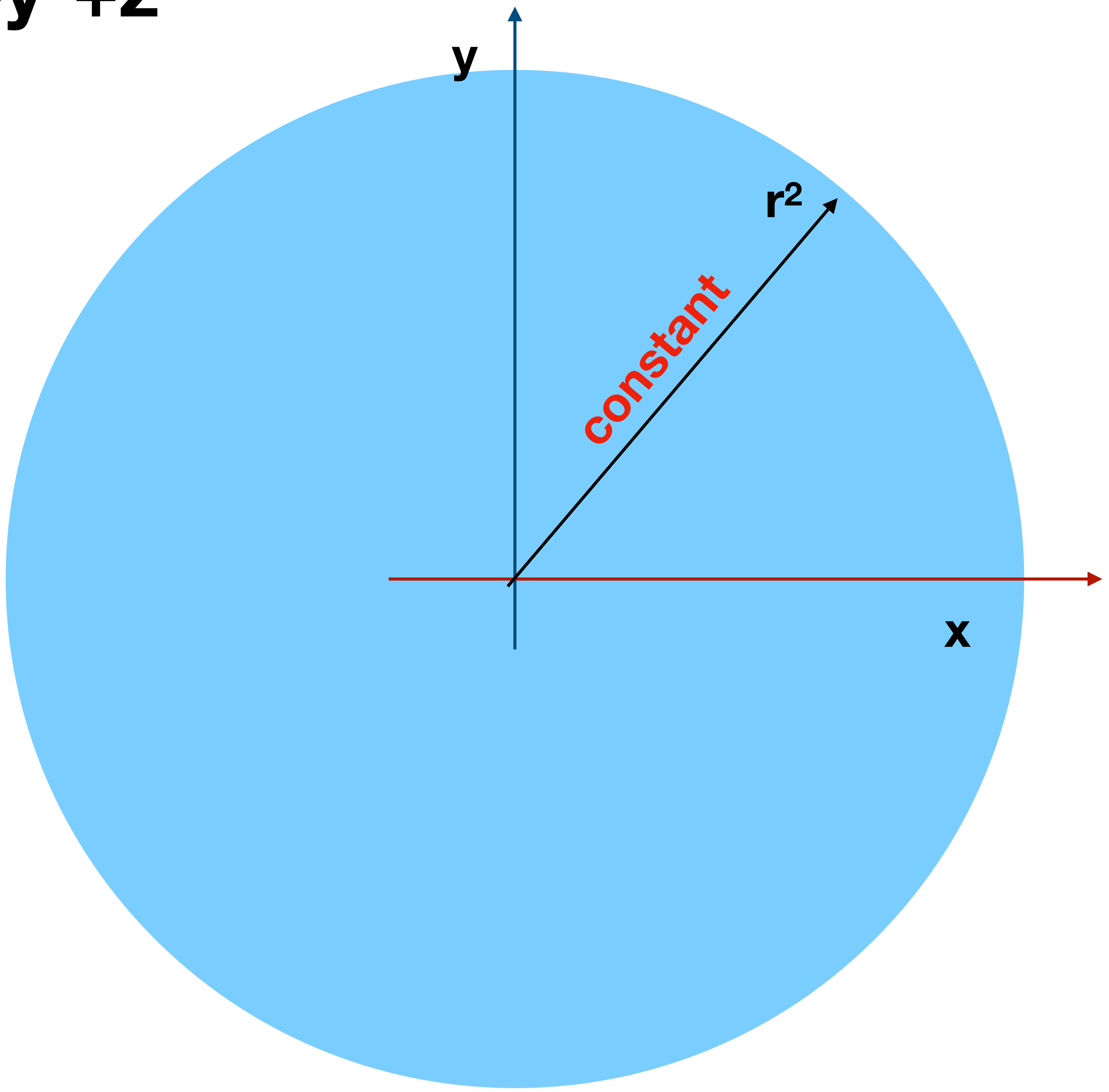


Space

We like constants!!

$$h^2 = x^2 + y^2$$

$$r^2 = x^2 + y^2 + z^2$$

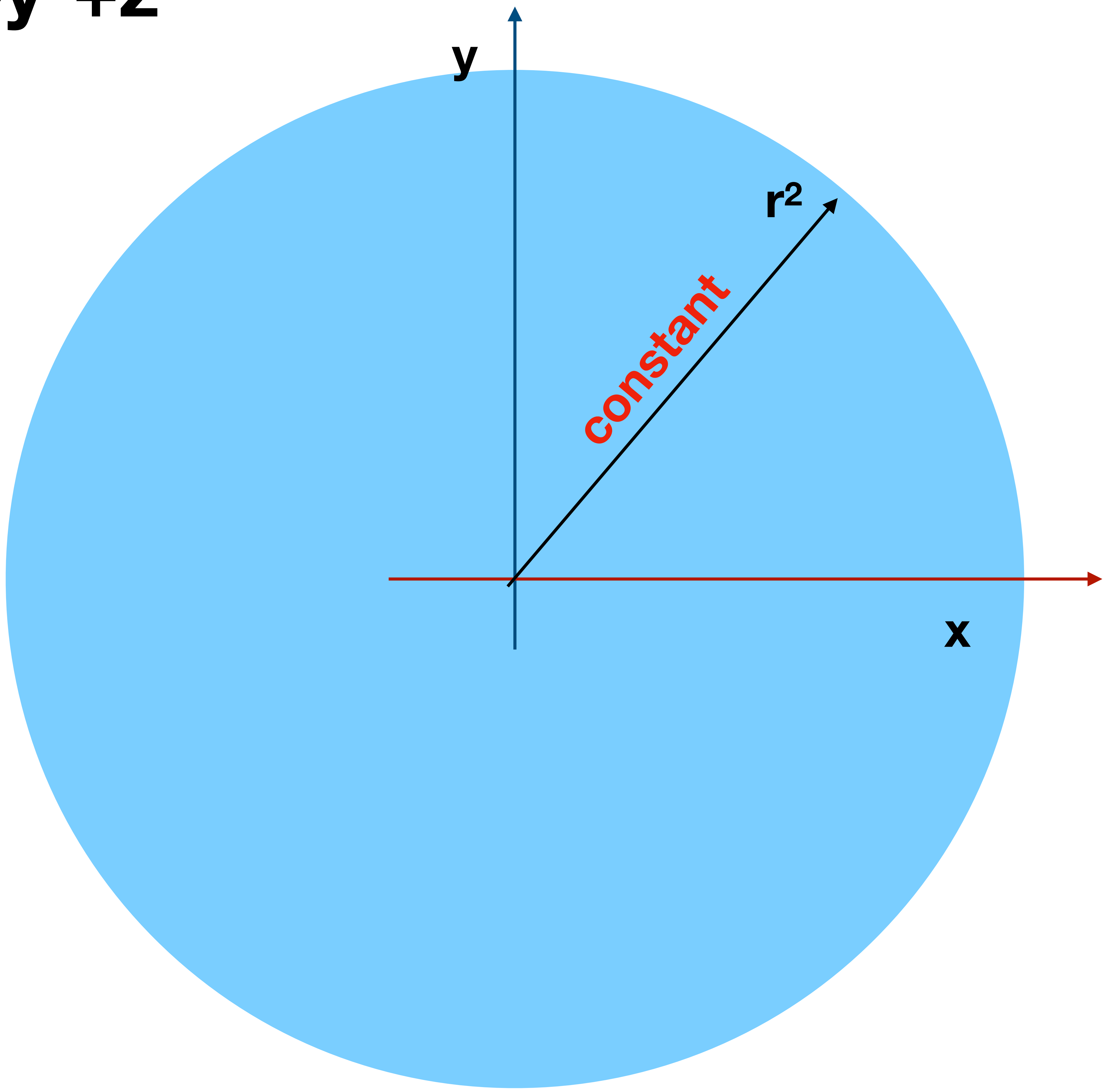


Space

We like constants!!
(physical constants)

$h^2 = x^2 + y^2$

$r^2 = x^2 + y^2 + z^2$



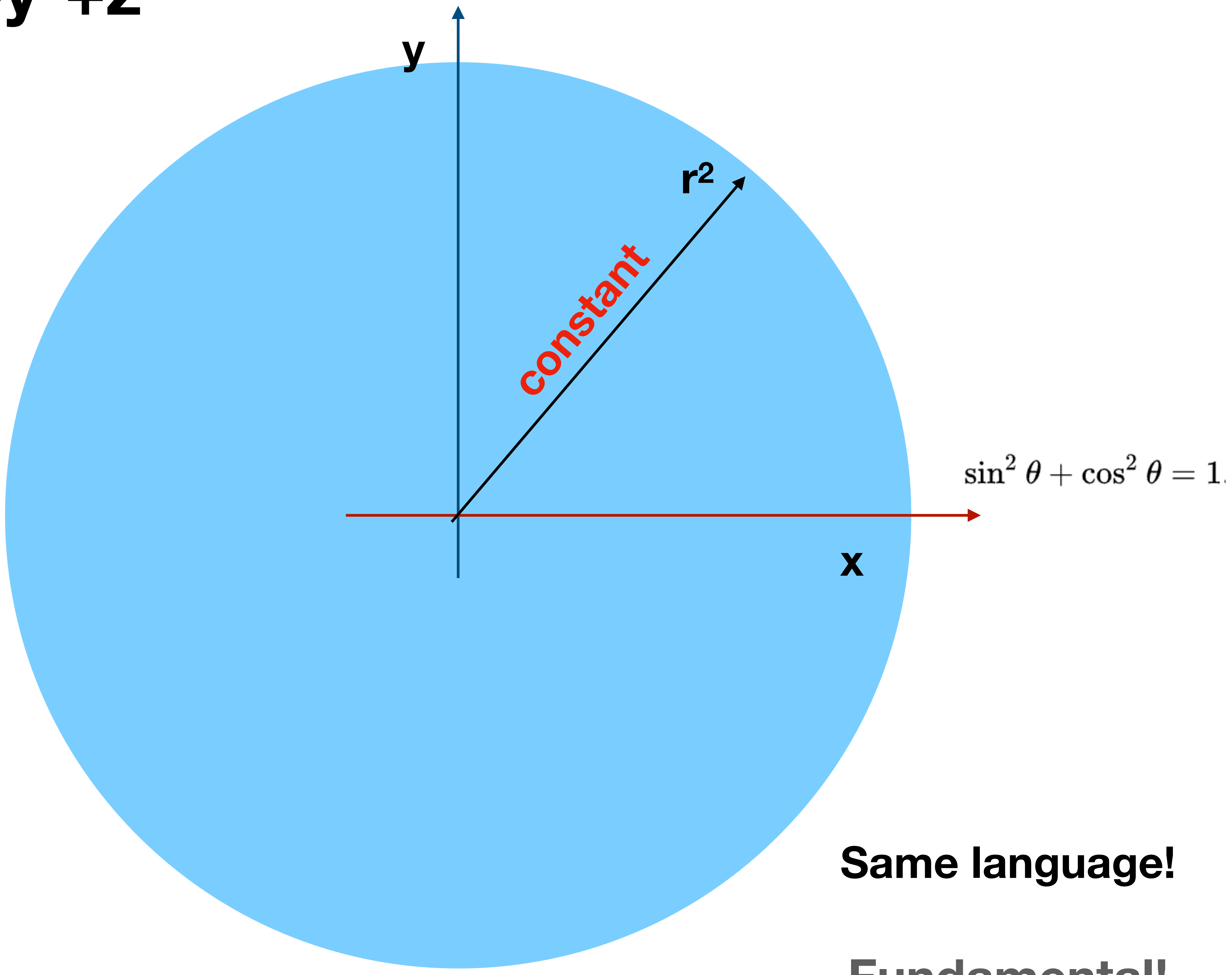
Space

We like constants!!
(physical constants)

$h^2 = x^2 + y^2$

$r^2 = x^2 + y^2 + z^2$

Constants
=
physical quantities conserved



Linear Momentum

$$P^2 = p_x^2 + p_y^2 + p_x^2$$

Angular Momentum

$$L^2 = l_x^2 + l_y^2 + l_z^2$$

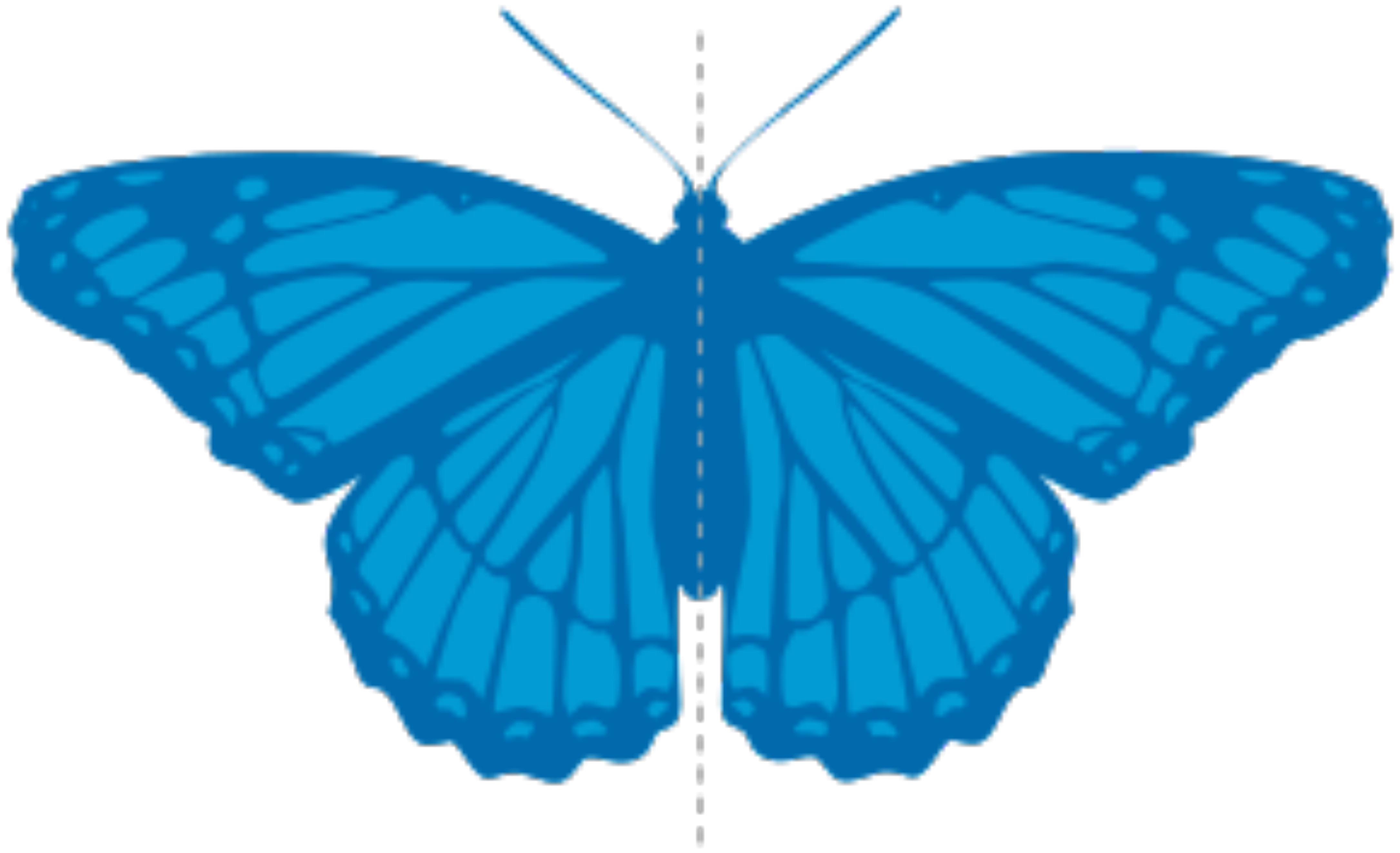
Energy

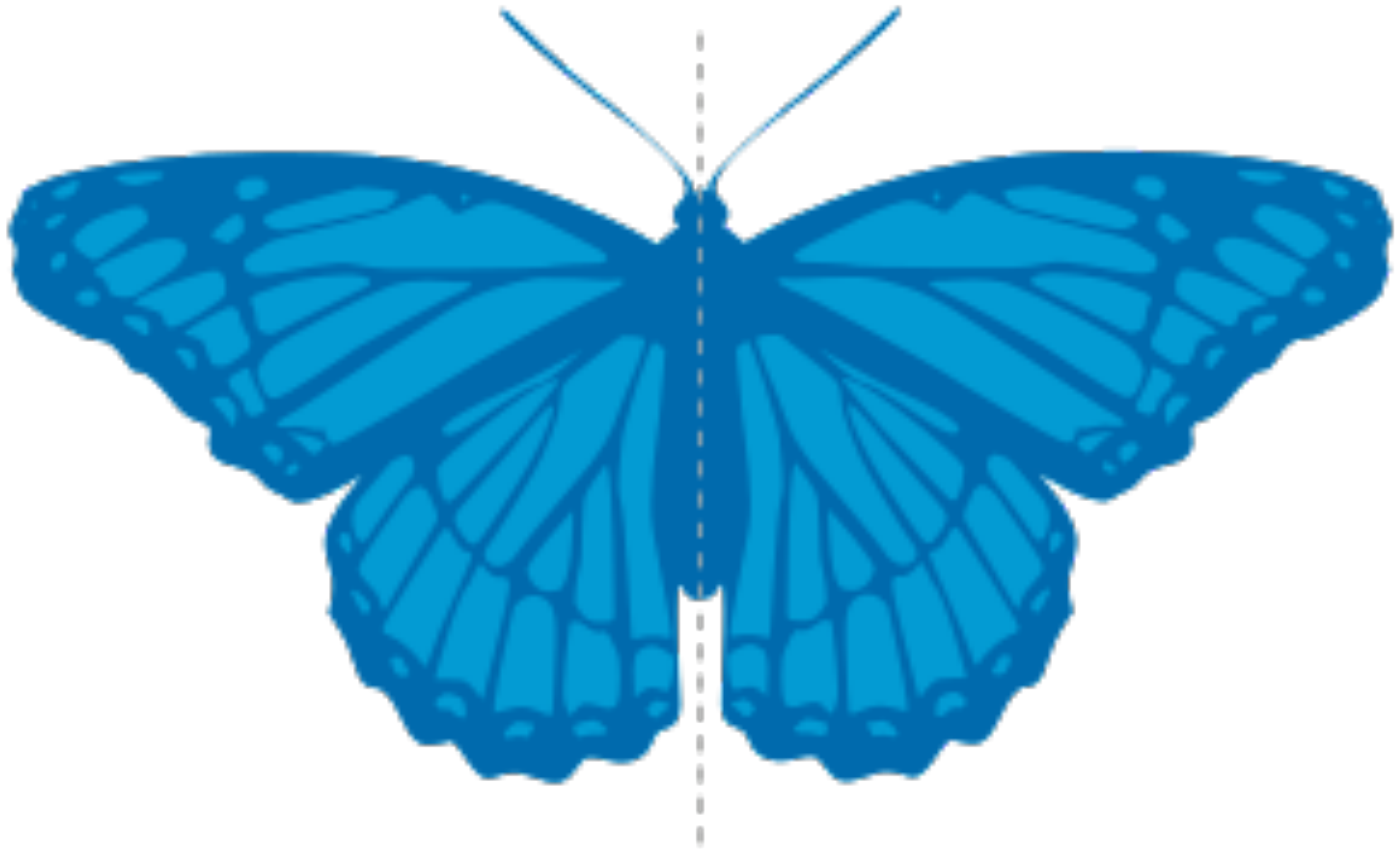
$$E$$

Same language!

Fundamental!

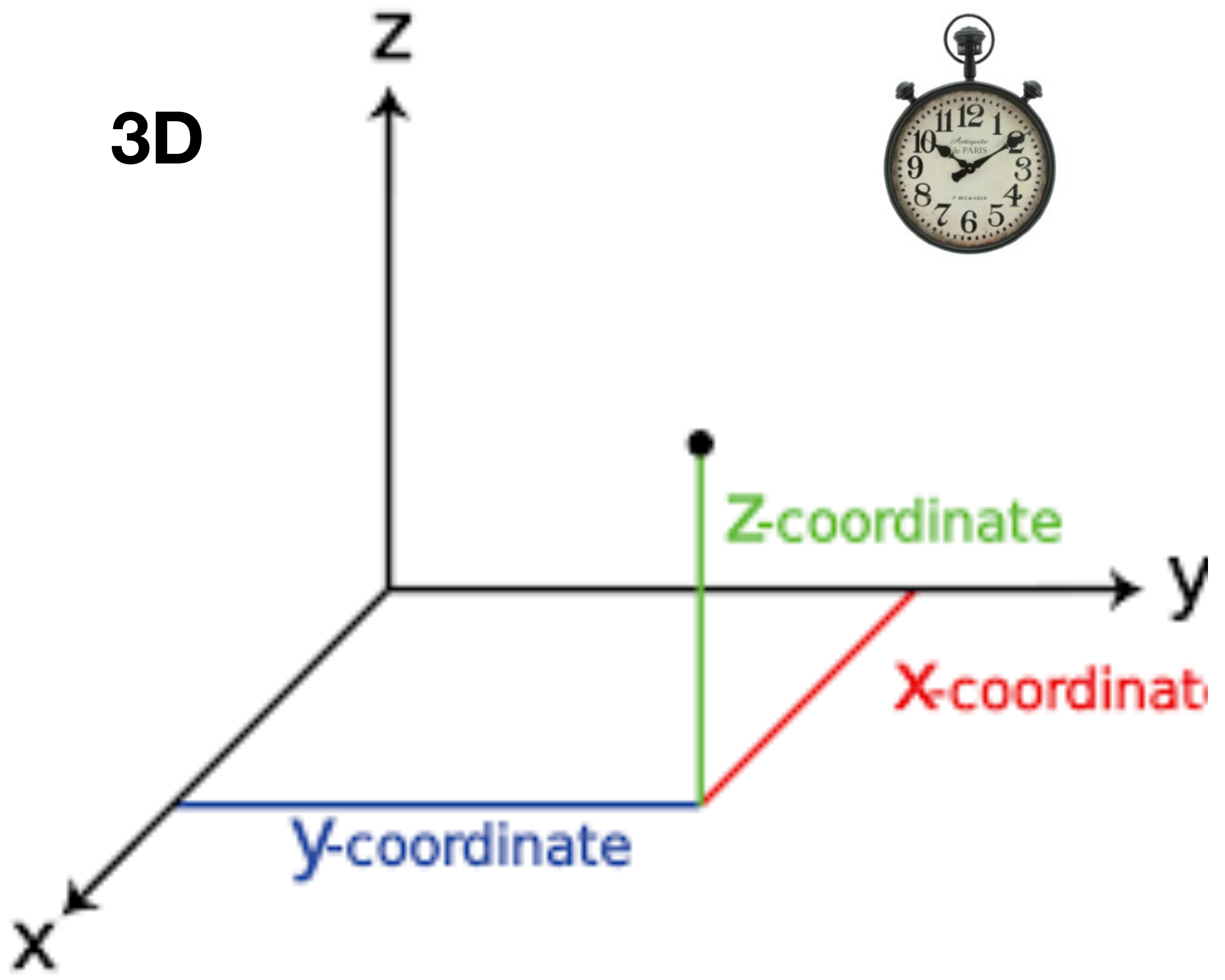
(Fundamental Physics)



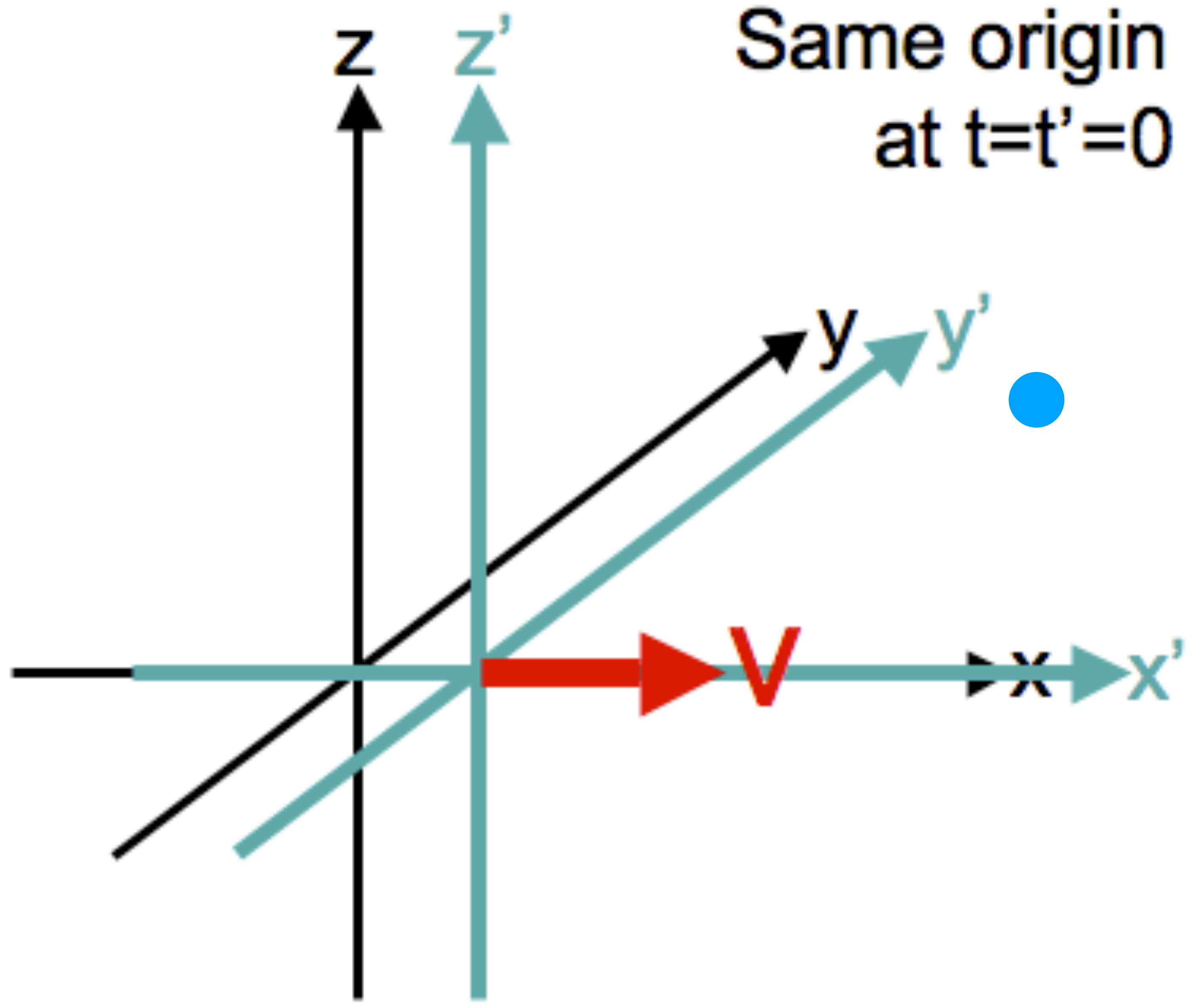


$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} \mapsto \begin{pmatrix} -x \\ +y \\ +z \end{pmatrix}$$

Space-time: v<<c



v<<c

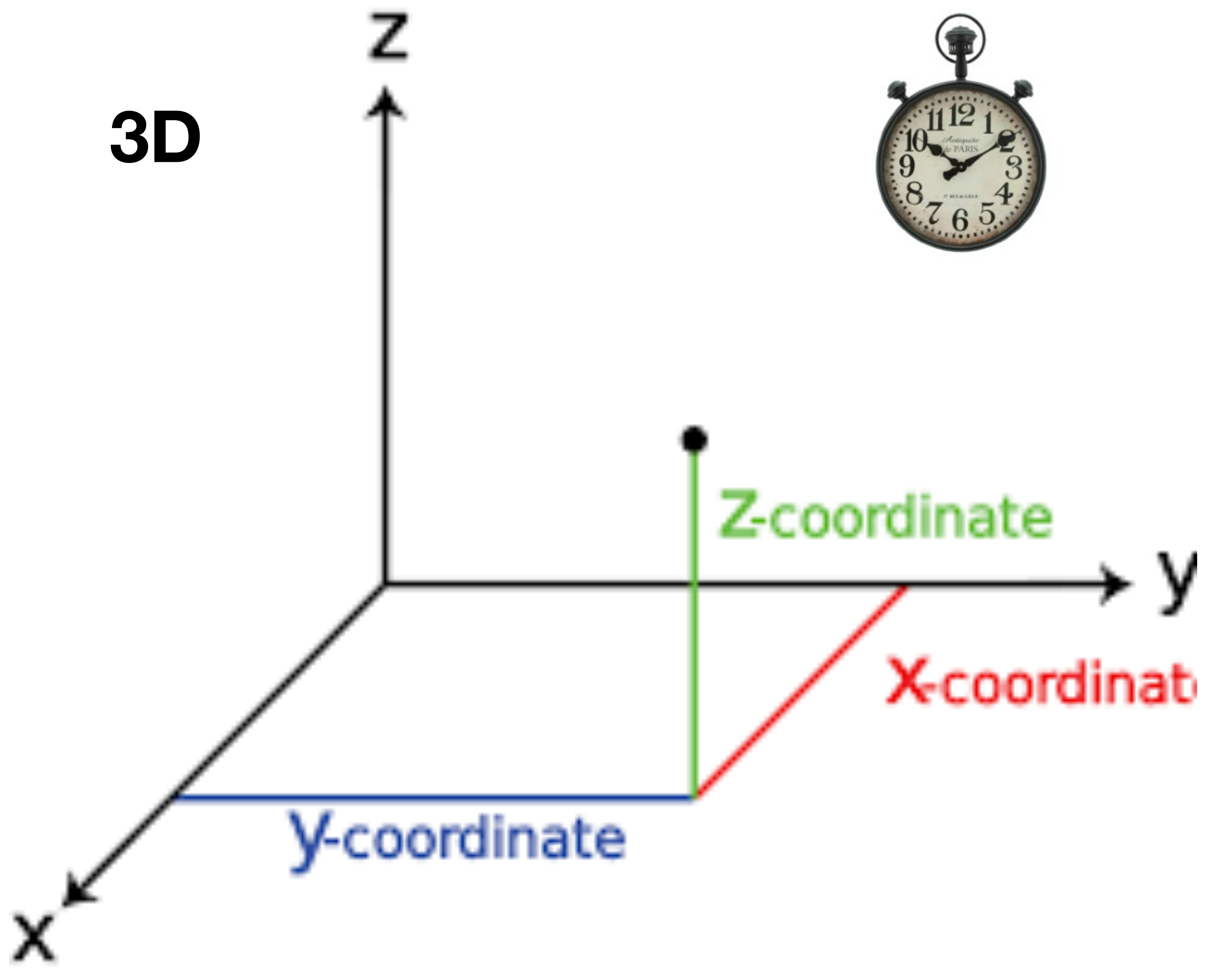


Galilean transformations

We can use them to move on reference frames

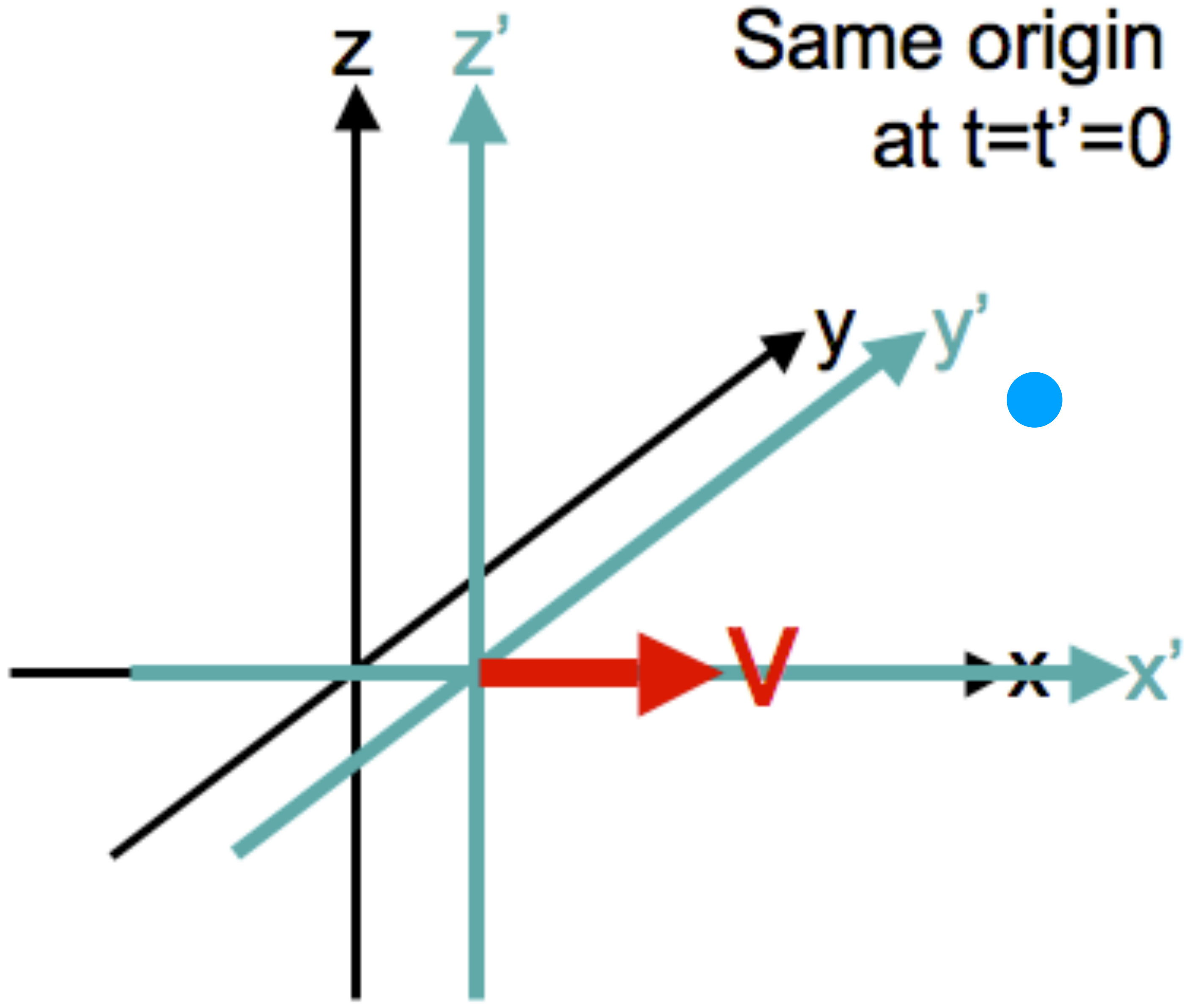
Space-time: v<<c

3D



We can use them to move on reference frames

v<<c



Galilean transformations

t' = t

x'= ? + x

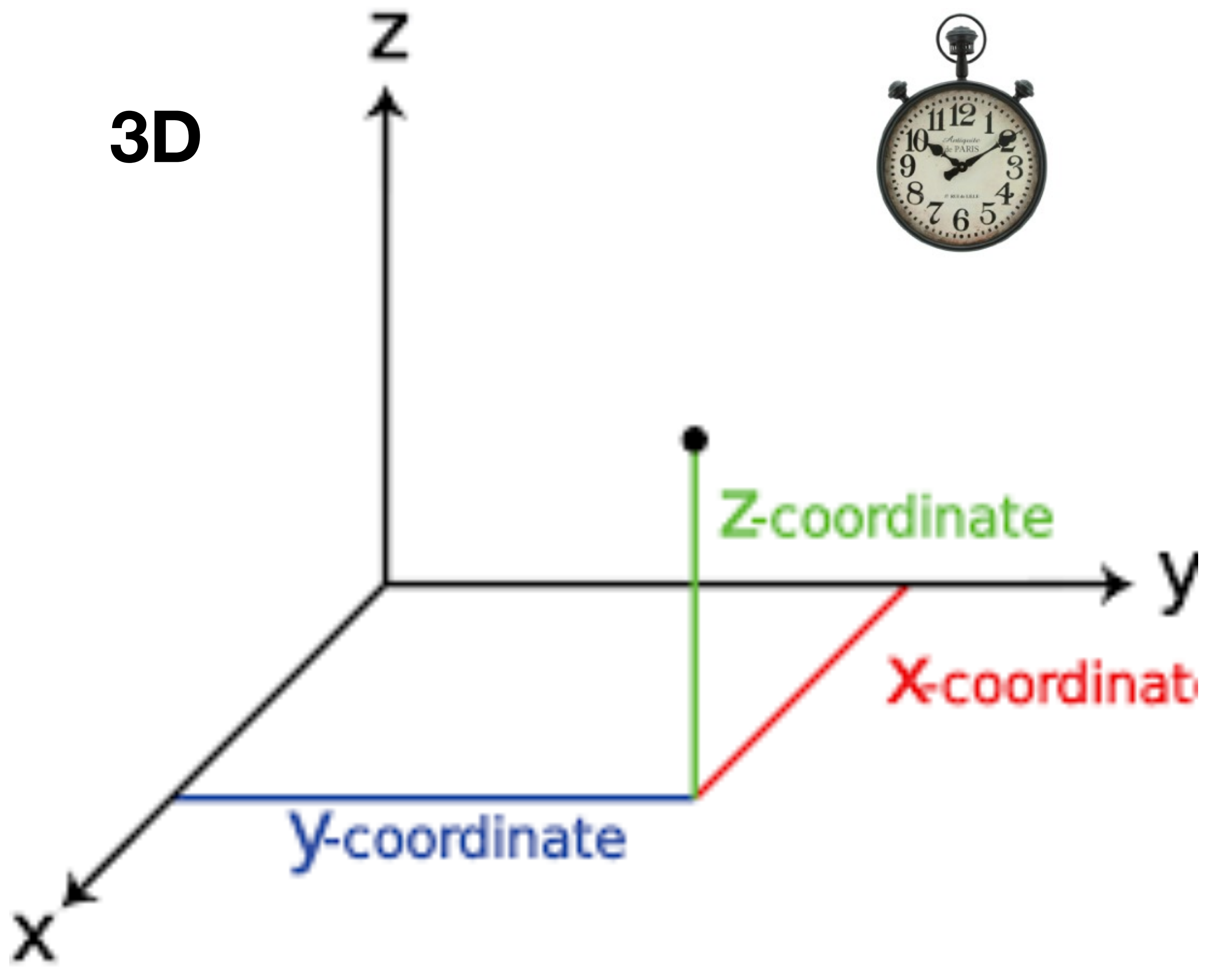
y'= y

z' = z

d = +/- Vt

Space-time: v<<c

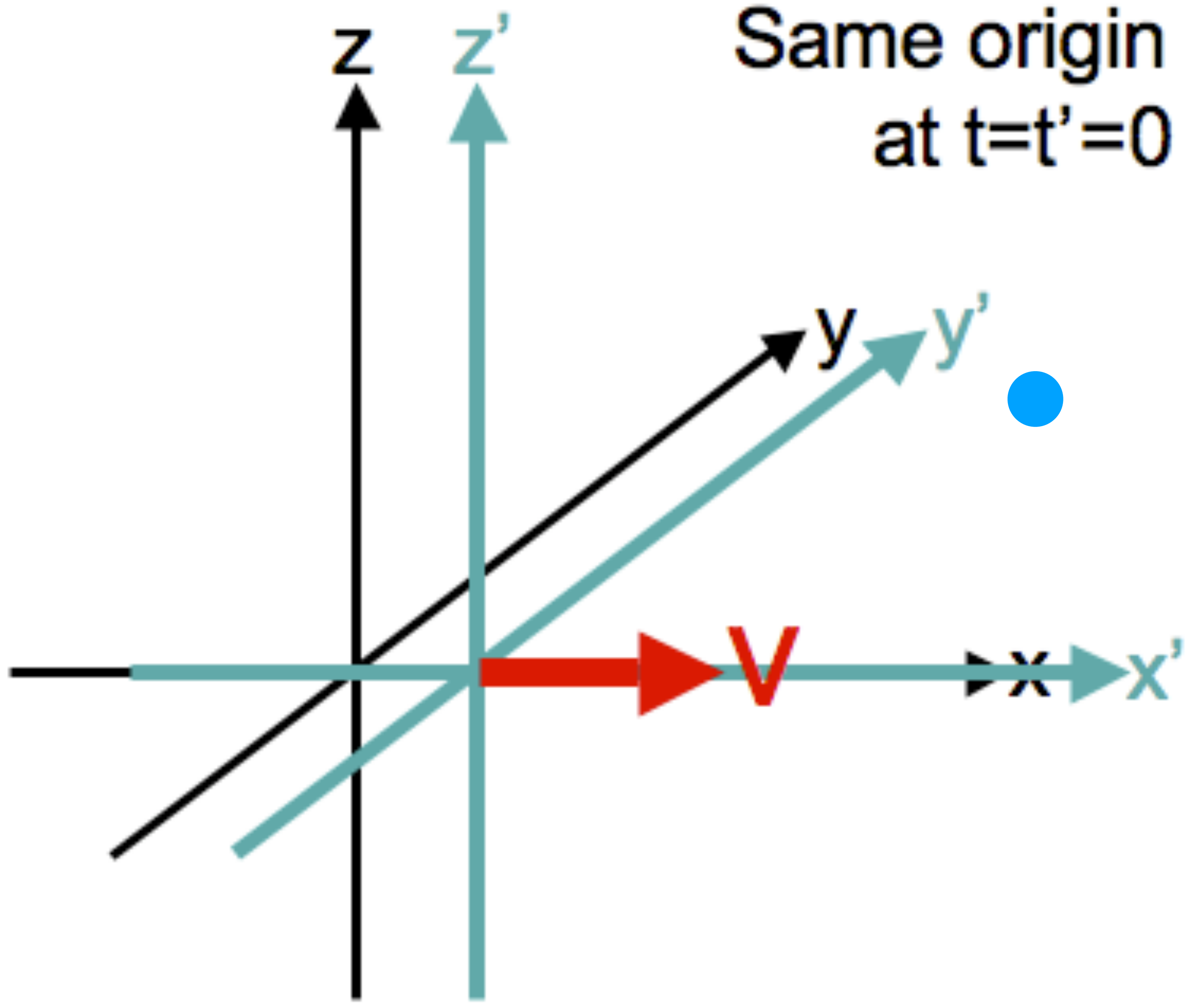
3D



We can use them to move on reference frames

v<<c

Same origin
at t=t'=0



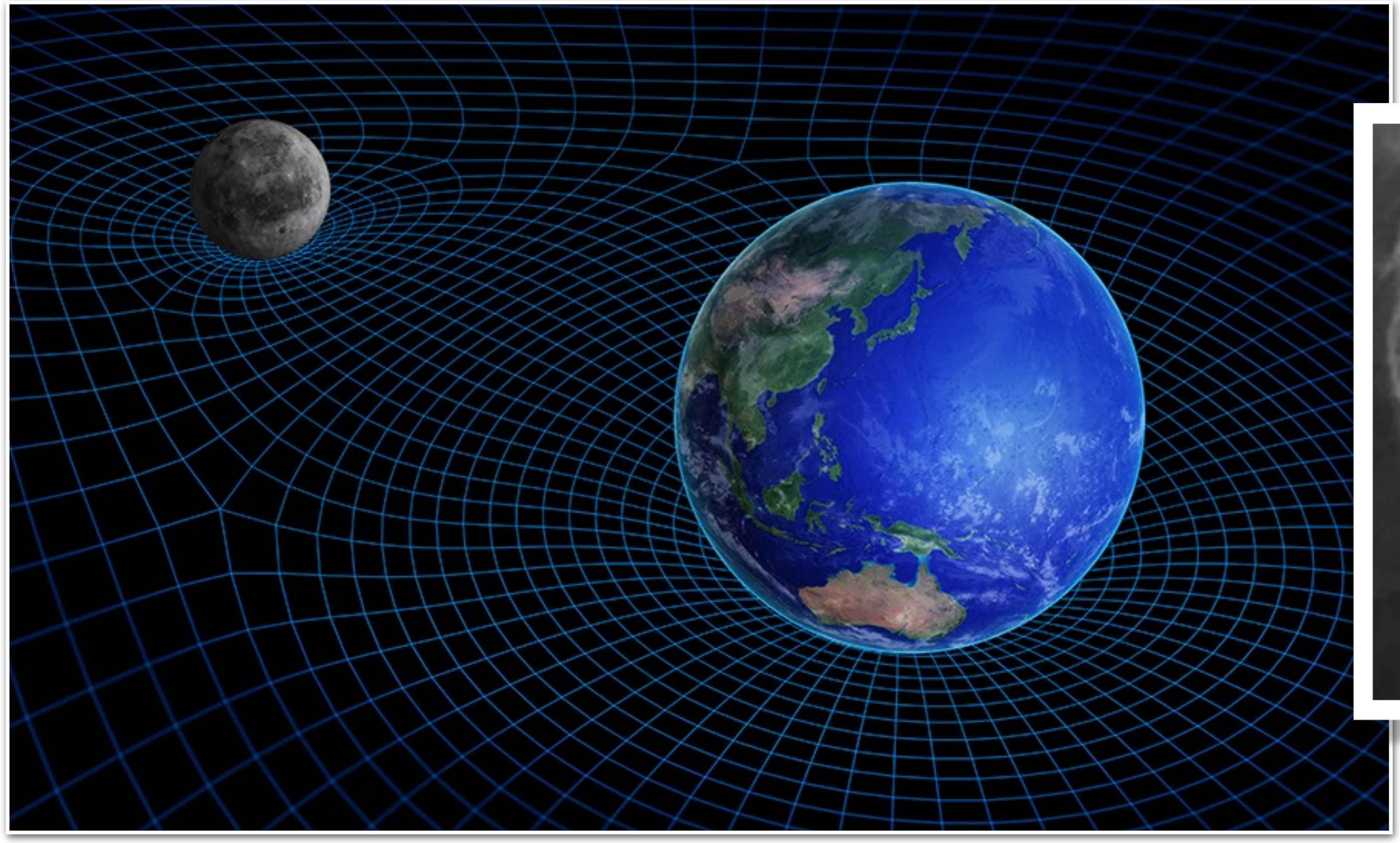
Galilean transformations

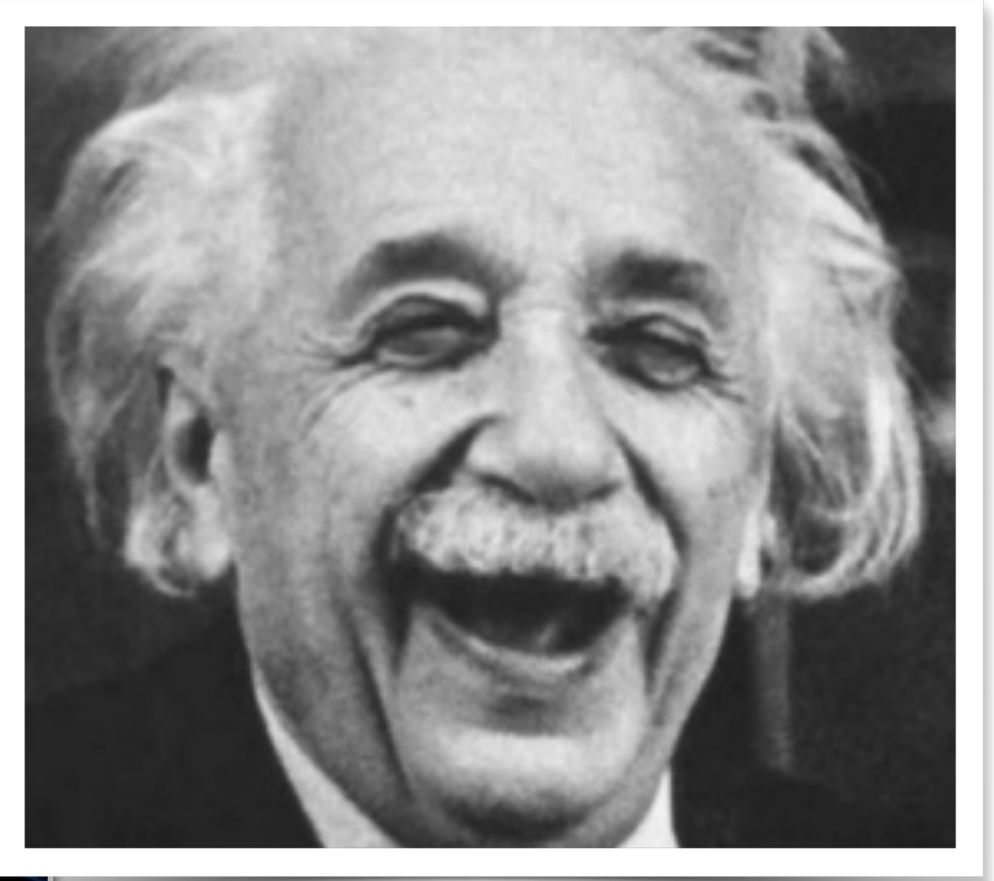
$$\begin{bmatrix} t' \\ x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ -V_x & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} t \\ x \\ y \\ z \end{bmatrix}$$

$$t' = t$$

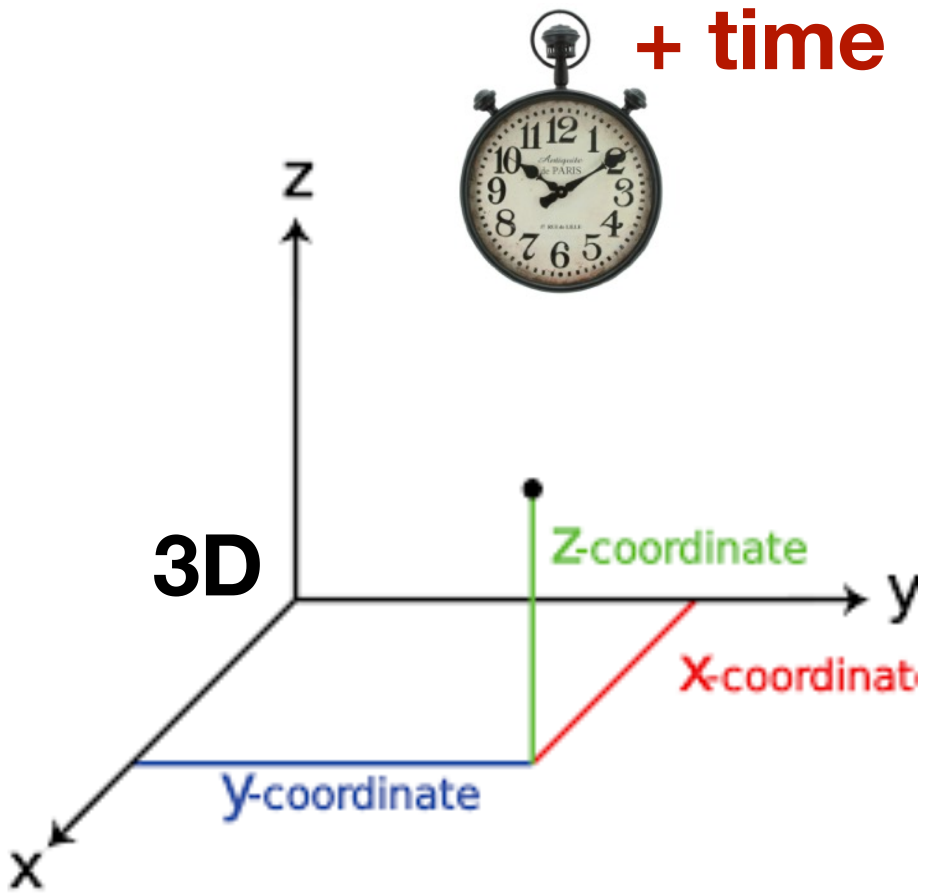
Same language!

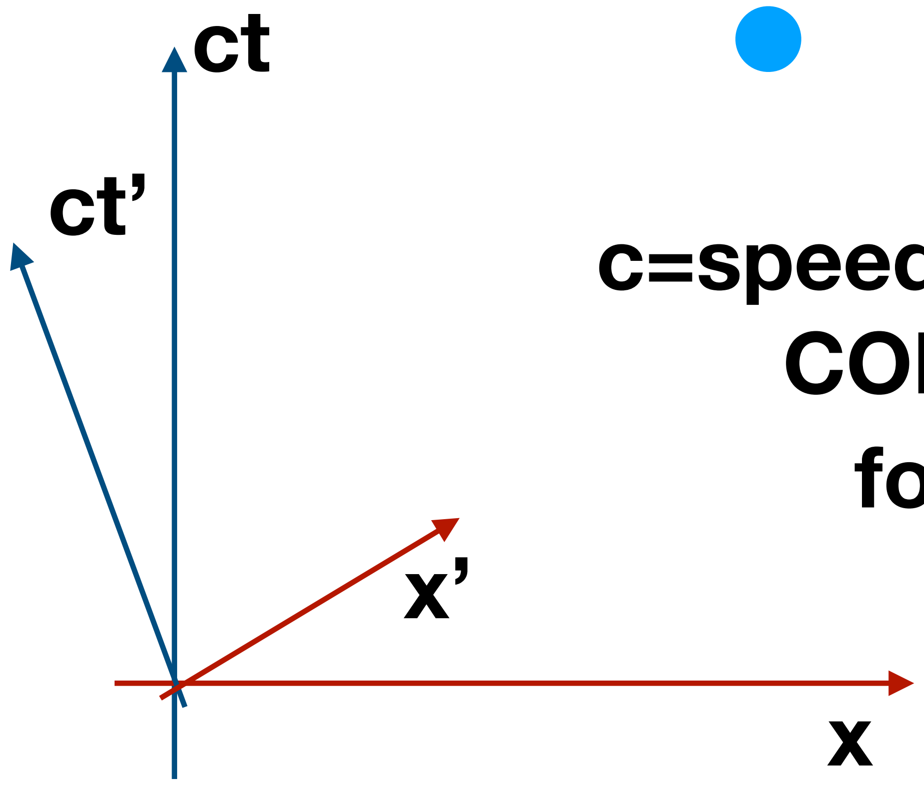
Space-time: v~c





v~c





c=speed of light
CONSTANT
for all inertial frames

$\cosh^2 x - \sinh^2 x = 1$

$$x^\mu x_\mu = ct^2 - x^2 = ct'^2 - x'^2 = x'^\mu x'_\mu$$

↓

Lorentz transformations

$$\begin{bmatrix} c\bar{t} \\ \bar{x} \\ \bar{y} \\ \bar{z} \end{bmatrix} = \begin{bmatrix} \gamma & -\beta\gamma & 0 & 0 \\ -\beta\gamma & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} ct \\ x \\ y \\ z \end{bmatrix}$$

$$\gamma = \frac{1}{\sqrt{1 - \frac{V^2}{c^2}}} \qquad \beta = \frac{V}{c}$$

Same Language: Fundamental!

Four-vectors

A Lorentz transformation is a four-dimensional transformation

$$x'^{\mu} = \Lambda^{\mu}{}_{\nu}\, x^{\nu},$$

satisfied by four-vectors x^{ν}, where $\Lambda^{\mu}{}_{\nu}$ is a so-called Lorentz tensor

Position

$$\begin{bmatrix} ct' \\ x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} \gamma ct - \beta\gamma x \\ -\beta\gamma ct + \gamma x \\ y \\ z \end{bmatrix}$$

$$\beta = \frac{v}{c}$$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

4-momentum

$$\vec{P} = \begin{bmatrix} E \\ p_x c \\ p_y c \\ p_z c \end{bmatrix} = \begin{bmatrix} E \\ \vec{p}c \end{bmatrix}$$

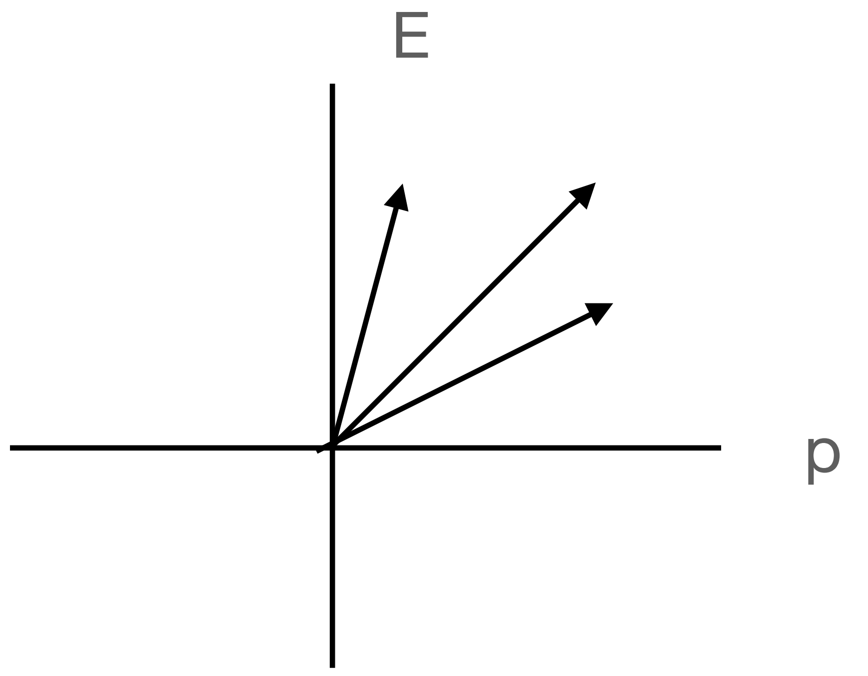
$$|P|^2 = (m_0 c)^2$$

$$|P|^2 = \eta_{\mu\nu} P^{\mu} P^{\nu} = \frac{E^2}{c^2} - p_x^2 - p_y^2 - p_z^2 = \frac{E^2}{c^2} - p^2$$

$$\Rightarrow (m_0 c)^2 = \frac{E^2}{c^2} - p^2$$

$$\Rightarrow E^2 = p^2 c^2 + m_0^2 c^4$$

$$E^2 - p^2 = m^2$$



Four-vectors

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Position

$$\begin{bmatrix} ct' \\ x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} \gamma ct - \beta\gamma x \\ -\beta\gamma ct + \gamma x \\ y \\ z \end{bmatrix}$$

$$\beta = \frac{v}{c}$$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Momentum

$$P = \begin{bmatrix} E \\ p_x c \\ p_y c \\ p_z c \end{bmatrix} = \begin{bmatrix} E \\ \vec{p}c \end{bmatrix}$$

$$|P|^2 = (m_0 c)^2$$

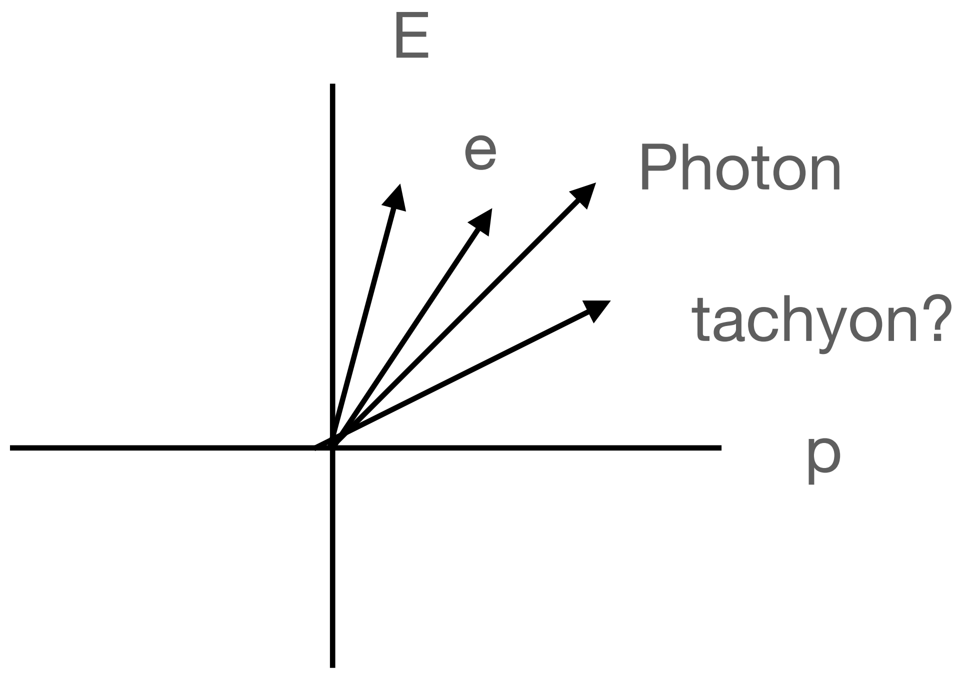
$$|P|^2 = \eta_{\mu\nu} P^{\mu} P^{\nu} = \frac{E^2}{c^2} - p_x^2 - p_y^2 - p_z^2 = \frac{E^2}{c^2} - p^2$$

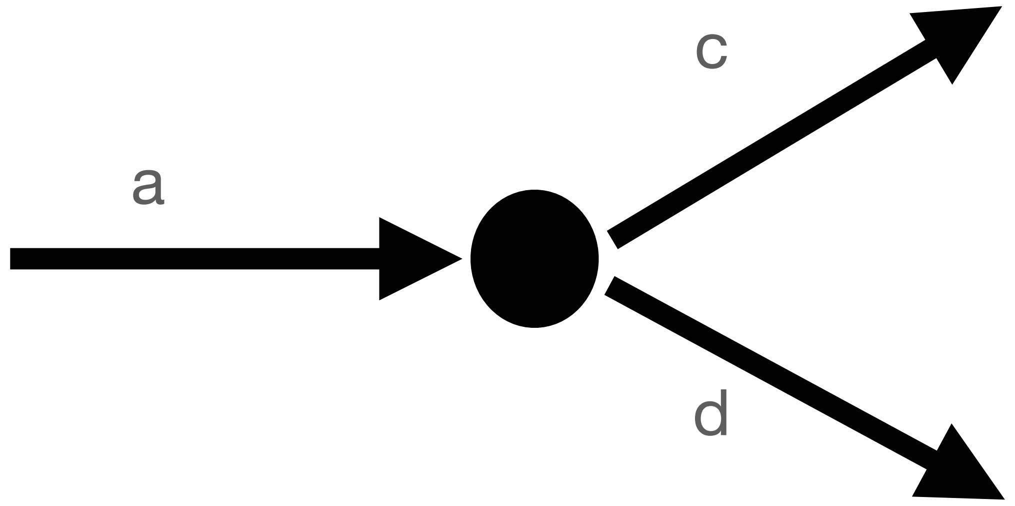
$$\Rightarrow (m_0 c)^2 = \frac{E^2}{c^2} - p^2$$

$$\Rightarrow E^2 = p^2 c^2 + m_0^2 c^4$$

$$E^2 - p^2 = m^2$$

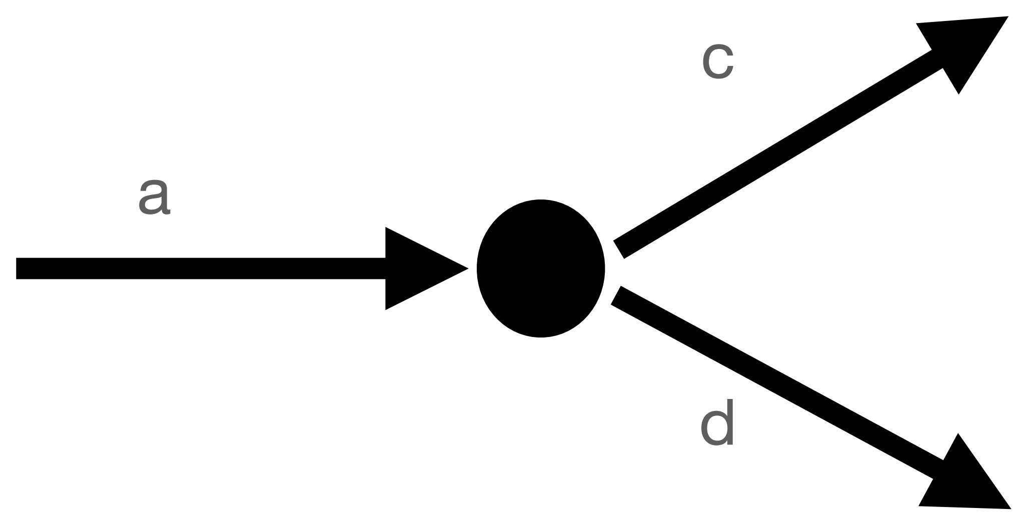
Dispersion Relation





$$P_a = P_c + P_d$$

$$|P|^2 = \eta_{\mu\nu} P^\mu P^\nu = E_a^2 - p_a^2 = m_a^2$$



$$P_a = P_c + P_d$$

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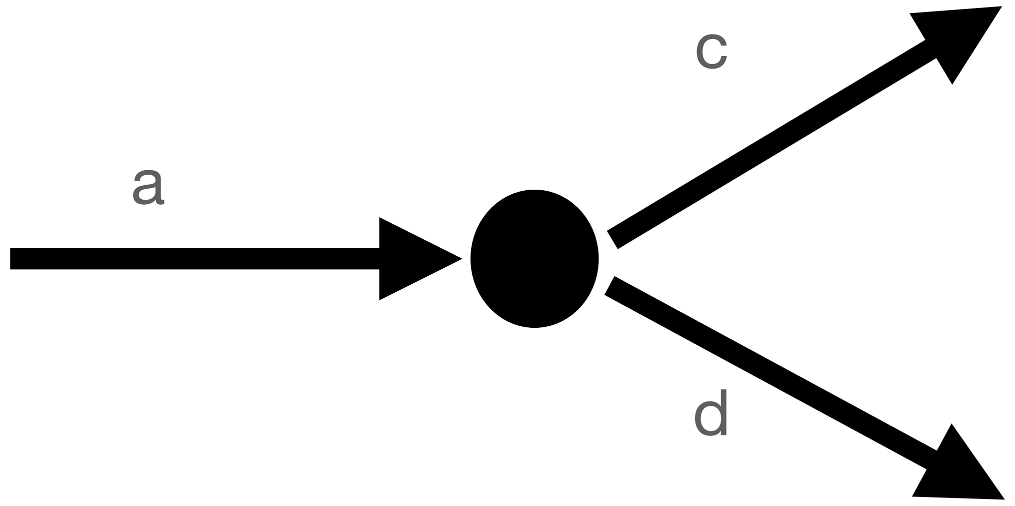
$$P_d = P_a - P_c$$

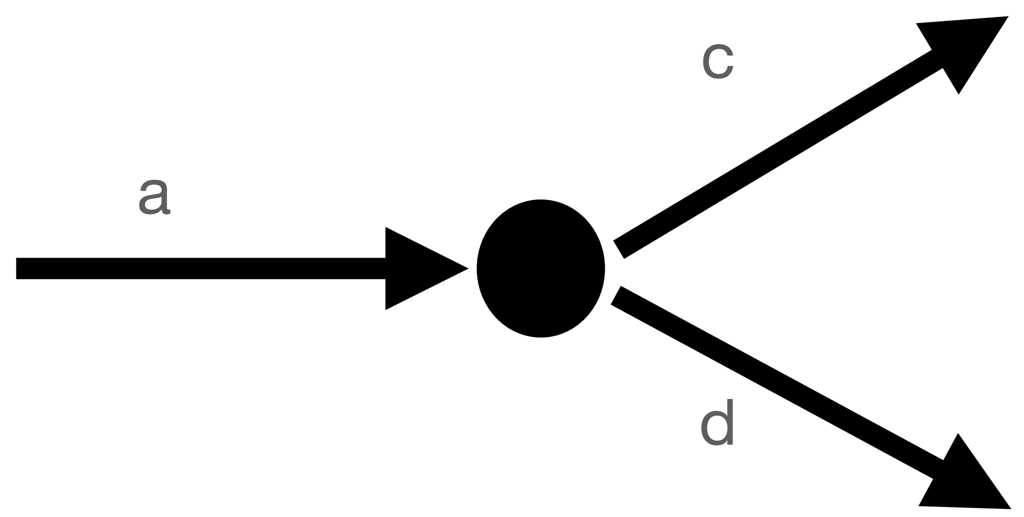


$$P_a = P_c + P_d$$

$$|P|^2 = \eta_{\mu\nu} P^\mu P^\nu = E_a^2 - p_a^2 = m_a^2$$

$$P_d = P_a - P_c$$

$$P_d^2 = (P_a - P_c)^2$$



$$P_a = P_c + P_d$$

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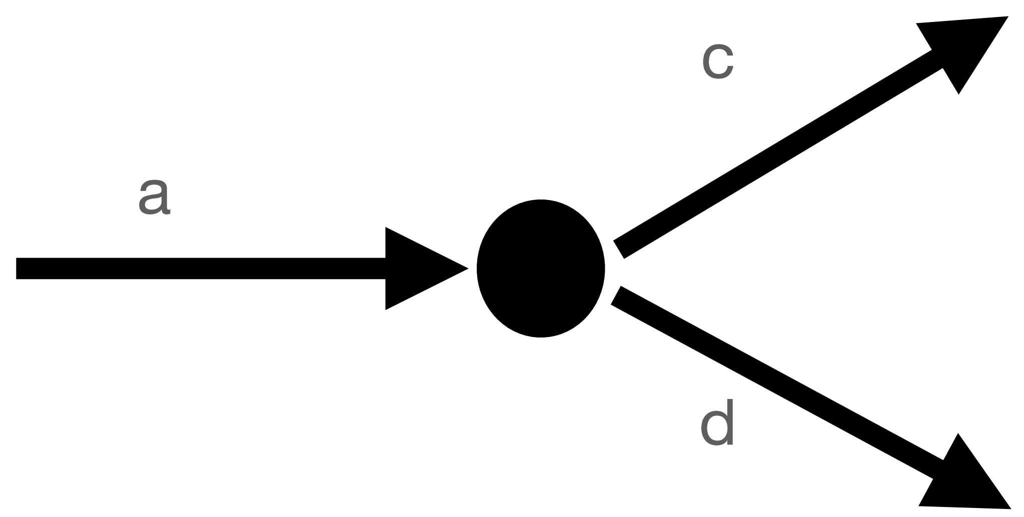
$$P_d = P_a - P_c$$

$$P_d^2 = (P_a - P_c)^2$$

$$m_d^2 = m_a^2 + m_c^2 - 2P_a P_c$$



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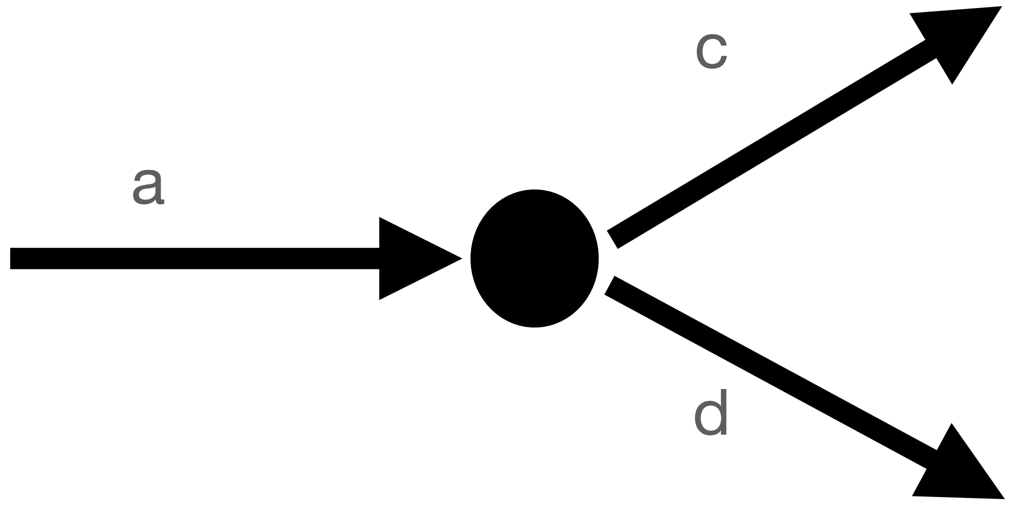
$$P_d^2 = (P_a - P_c)^2$$

$$m_d^2 = m_a^2 + m_c^2 - 2P_aP_c$$

$$m_d^2 = m_a^2 + m_c^2 - 2(E_aE_c - \vec{p}_a.\vec{p}_c)$$

$$p_a = 0$$



$$P_a = P_c + P_d$$

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$$P_d = P_a - P_c$$

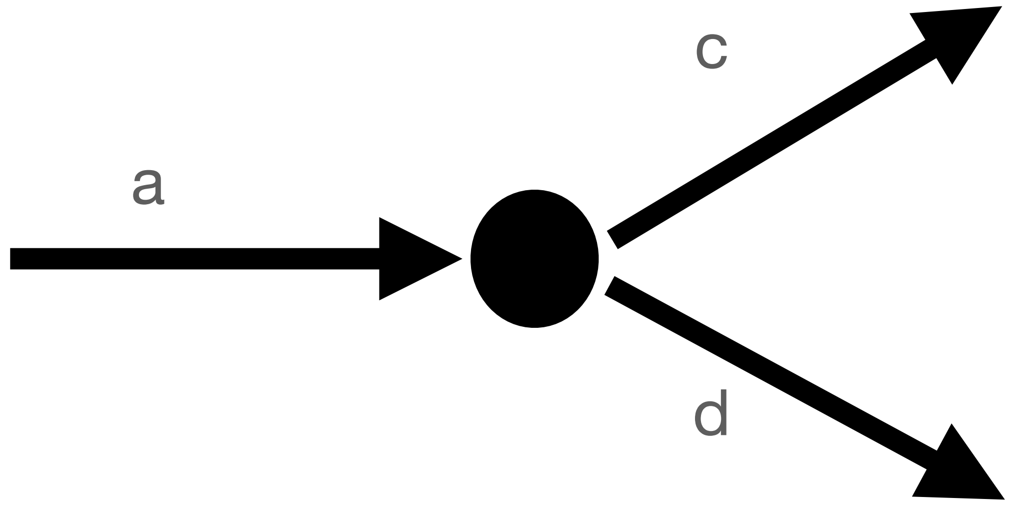
$$P_d^2 = (P_a - P_c)^2$$

$$m_d^2 = m_a^2 + m_c^2 - 2P_a P_c$$

$$m_d^2 = m_a^2 + m_c^2 - 2(E_a E_c - \vec{p}_a . \vec{p}_c)$$

$$p_a = 0$$

$$m_d^2 = m_a^2 + m_c^2 - 2m_a E_c$$



$$P_a = P_c + P_d$$

$$|P|^2 = \eta_{\mu\nu} P^\mu P^\nu = E_a^2 - p_a^2 = m_a^2$$

$$P_d = P_a - P_c$$

$$P_d^2 = (P_a - P_c)^2$$

$$m_d^2 = m_a^2 + m_c^2 - 2P_a P_c$$

$$m_d^2 = m_a^2 + m_c^2 - 2(E_a E_c - \vec{p}_a . \vec{p}_c)$$

$$p_a = 0$$

$$m_d^2 = m_a^2 + m_c^2 - 2m_a E_c$$

$$E_c = \frac{m_a^2 + m_c^2 - m_d^2}{2m_a}$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$m_\pi = 0.1396 \ \text{GeV}$$

$$m_\mu = 0.1057 \ \text{GeV}$$

$$m_\nu = 0$$

$E_\mu =$

$E_\nu =$

$p_\mu = p_\nu =$

$$E_c = \frac{m_a^2 + m_c^2 - m_d^2}{2m_a}$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e$$

$$m_\pi = 0.1396 \text{ GeV}$$

$$m_\mu = 0.1057 \text{ GeV}$$

$$m_\nu = 0$$

$$m_\mu = 0.1057 \text{ GeV}$$

$$m_e = 0.000511 \text{GeV}$$

$$m_\nu = 0$$

$$E_\mu = \frac{m_\pi^2 + m_\mu^2}{2m_\pi} = 0.1098 \text{ GeV}$$

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2m_\pi} = 0.0298 \text{ GeV}$$

$$p_\mu = p_\nu = E_\nu = 0.0298 \text{ GeV}$$

$$E_{e^+} =$$

$$E_\nu =$$

$$p_e =$$

$$E_c = \frac{m_a^2 + m_c^2 - m_d^2}{2m_a}$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$m_\pi = 0.1396 \text{ GeV}$$

$$m_\mu = 0.1057 \text{ GeV}$$

$$m_\nu = 0$$

$$E_\mu = \frac{m_\pi^2 + m_\mu^2}{2m_\pi} = 0.1098 \text{ GeV}$$

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2m_\pi} = 0.0298 \text{ GeV}$$

$$p_\mu = p_\nu = E_\nu = 0.0298 \text{ GeV}$$

$$\mu^+ \rightarrow e^+ + \nu_e$$

$$m_\mu = 0.1057 \text{ GeV}$$

$$m_e = 0.000511 \text{GeV}$$

$$m_\nu = 0$$

$$E_{e^+} = \frac{m_\mu^2 + m_e^2}{2m_\mu} = 0.0529 \text{ GeV}$$

$$E_\nu = \frac{m_\mu^2 - m_e^2}{2m_\mu} = 0.0529 \text{ GeV}$$

$$p_e = p_\nu = E_\nu \sim 53 \text{ MeV}$$

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

$$m_e = 0.000511 \text{GeV}$$

$$m_\gamma = 0$$

$$E_c = \frac{m_a^2 + m_c^2 - m_d^2}{2m_a}$$

$$\pi^+ \to \mu^+ + \nu_\mu$$

$m_\pi = 0.1396$ GeV

$m_\mu = 0.1057$ GeV

$m_\nu = 0$

$$E_\mu = \frac{m_\pi^2 + m_\mu^2}{2m_\pi} = 0.1098 \text{ GeV}$$

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2m_\pi} = 0.0298 \text{ GeV}$$

$$p_\mu = p_\nu = E_\nu = 0.0298 \text{ GeV}$$

$$\mu^+ \to e^+ + \nu_e$$

$m_\mu = 0.1057$ GeV

$m_e = 0.000511$GeV

$m_\nu = 0$

$$E_{e^+} = \frac{m_\mu^2 + m_e^2}{2m_\mu} = 0.0529 \text{ GeV}$$

$$E_\nu = \frac{m_\mu^2 - m_e^2}{2m_\mu} = 0.0529 \text{ GeV}$$

$$p_e = p_\nu = E_\nu \sim 53 \text{ MeV}$$

$$e^- \to e^- + \gamma$$

$m_e = 0.000511$GeV

$m_\gamma = 0$

$E_{e^+} =$

$E_\gamma =$

$p_e =$

$$E_c = \frac{m_a^2 + m_c^2 - m_d^2}{2m_a}$$

$$e^- \to e^- + \gamma$$

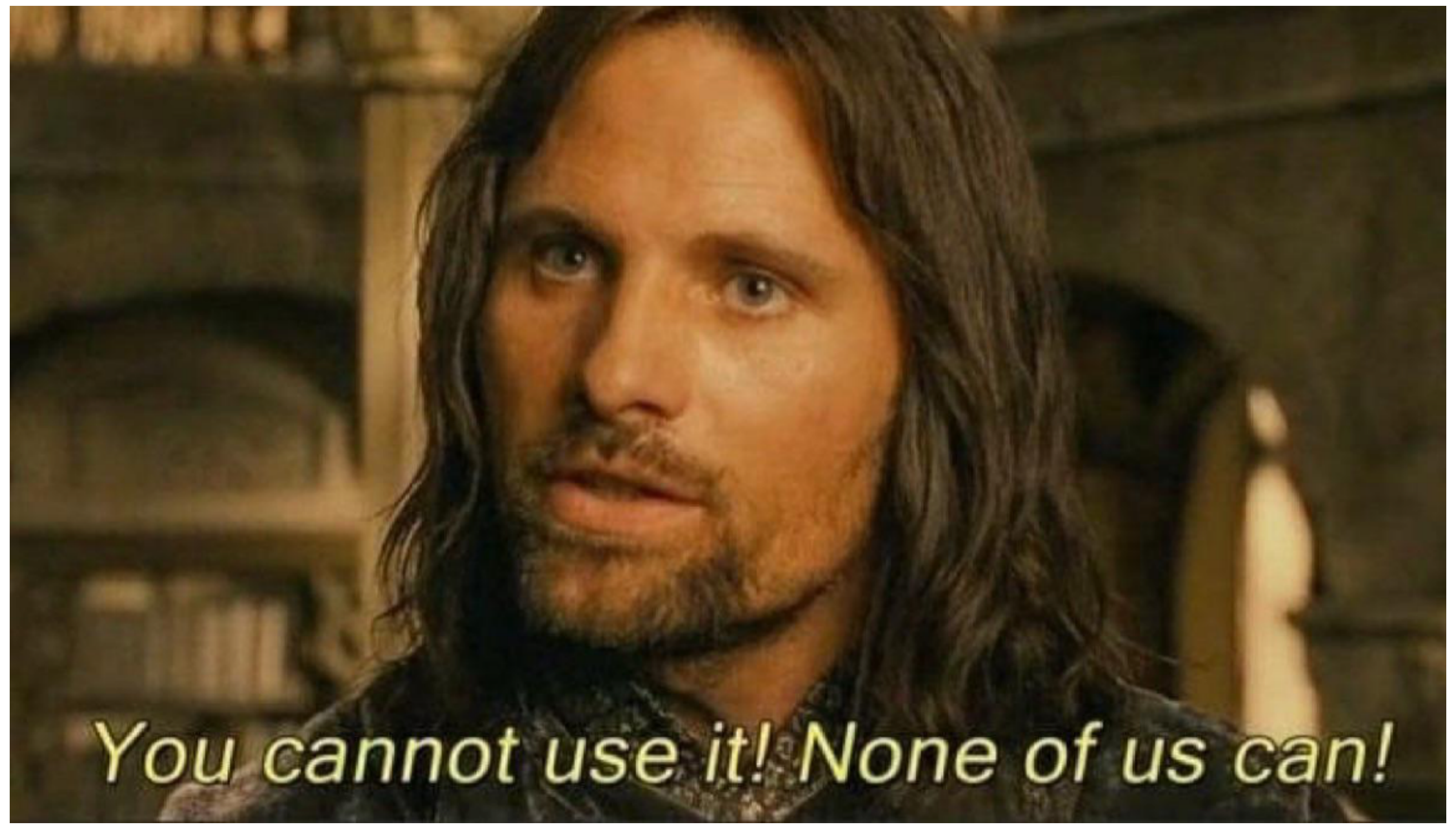
$$P_d = P_a - P_c$$

$$P_{e'}^2 = (P_e - P_\gamma)^2 = m_e^2 + 0 - 2P_eP_\gamma$$

$$m_{e'}^2 = (P_e^2 - P_\gamma)^2 = m_e^2 + 0 - 2P_eP_\gamma$$

$$0 = 2P_eP_\gamma = 2E_eE_\gamma - 2p_eE_\gamma\cos\theta = 2E_\gamma(E_e - p_e\cos\theta)$$

$$e^- \to e^- + \gamma$$



$$\gamma \to e^+ e^-$$

$$P_d = P_a - P_c$$

$$P_{e'}^2 = (P_e^2 - P_\gamma)^2 = m_e^2 + 0 - 2P_eP_\gamma$$

$$m_{e'}^2 = (P_e^2 - P_\gamma)^2 = m_e^2 + 0 - 2P_eP_\gamma$$

$$0 = 2P_eP_\gamma = 2E_eE_\gamma - 2p_eE_\gamma \cos\theta = 2E_\gamma(E_e - p_e \cos\theta)$$

$$E_\gamma = 0!$$

2→2

$$(P_a + P_b)^2 = (P_c + P_d)^2$$

$$P_a^2 + P_b^2 + 2P_aP_b = (P_c + P_d)^2$$

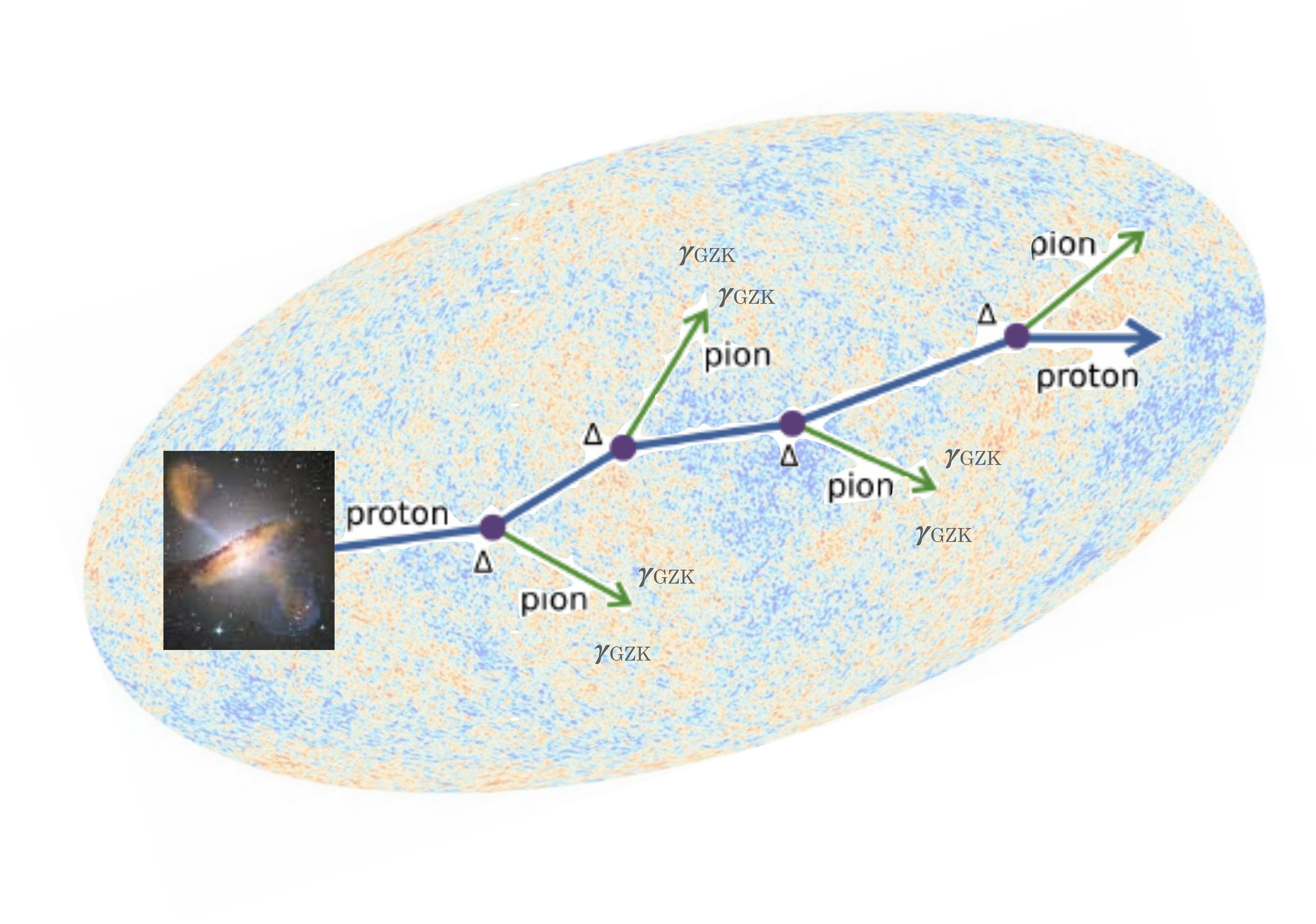
What would be the minimum energy Ea to produce c and d?

$$m_a^2 + m_b^2 + 2E_aE_b - 2p_ap_b\cos\theta = (m_c + m_d)^2 \quad \Big| \quad p_c^*, p_d^* \to 0$$

$$m_a^2 + m_b^2 + 2E_aE_b(1 - \frac{p_ap_b}{E_aE_b}\cos\theta) = (m_c + m_d)^2 \qquad E >> m$$

$$E_{a,\mathrm{th}} > \frac{(m_c + m_d)^2 - m_a^2 - m_b^2}{2E_b(1 - \cos\theta)} \xrightarrow{\cos\theta = -1} \frac{(m_c + m_d)^2 - m_a^2 - m_b^2}{4E_b}$$

$$p\ \gamma \rightarrow \Delta^+ \rightarrow p + \pi^0$$



$$\cos\theta = -1$$

$2.70 k_B T$ $\quad E_{\gamma_b} = 6.35\times10^{-4}$ eV

$$m_p = 0.938\ \text{GeV}$$

$$m_\Delta = 1.232\ GeV$$

$$m_\Delta^2 \downarrow$$

$$E_p = \frac{(m_c + m_d)^2 - m_a^2 - m_b^2}{4E_b}$$

$$= \frac{1.232^2 - 0.938^2}{4\times\left(0.635\times10^{-12}\right)} = 2.5\times10^{11}\ \text{GeV}$$

$$= 2.5\times10^{20}\ \text{eV}$$

$$p\,\gamma \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$

$$E_{\gamma_b} = 2.70 k_B T = 6.35\times10^{-4}\ \text{eV}$$

$$m_p = 0.938\ \text{GeV}$$

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$$E_p = \frac{(m_c + m_d)^2 - m_a^2 - m_b^2}{4E_b}$$

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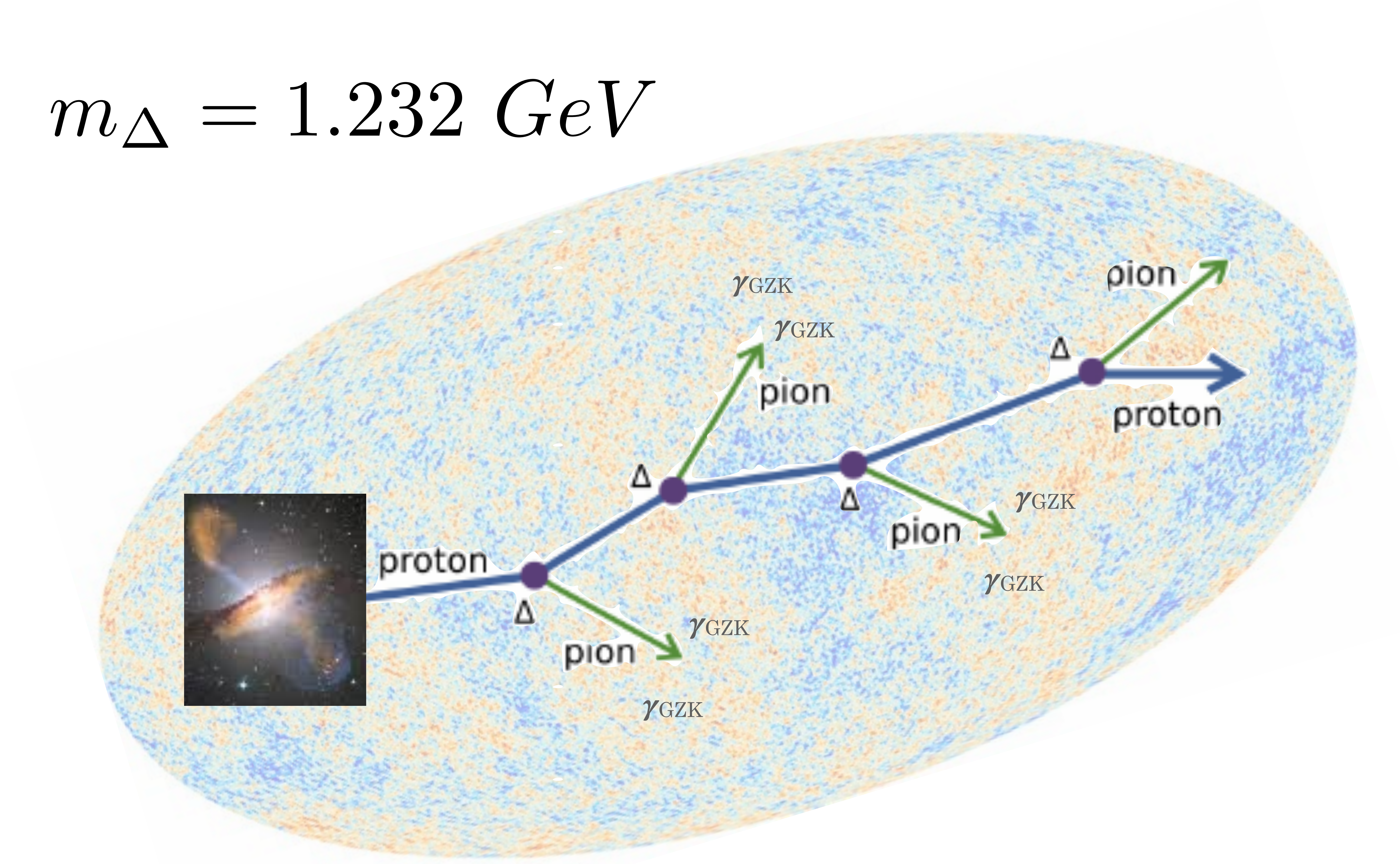
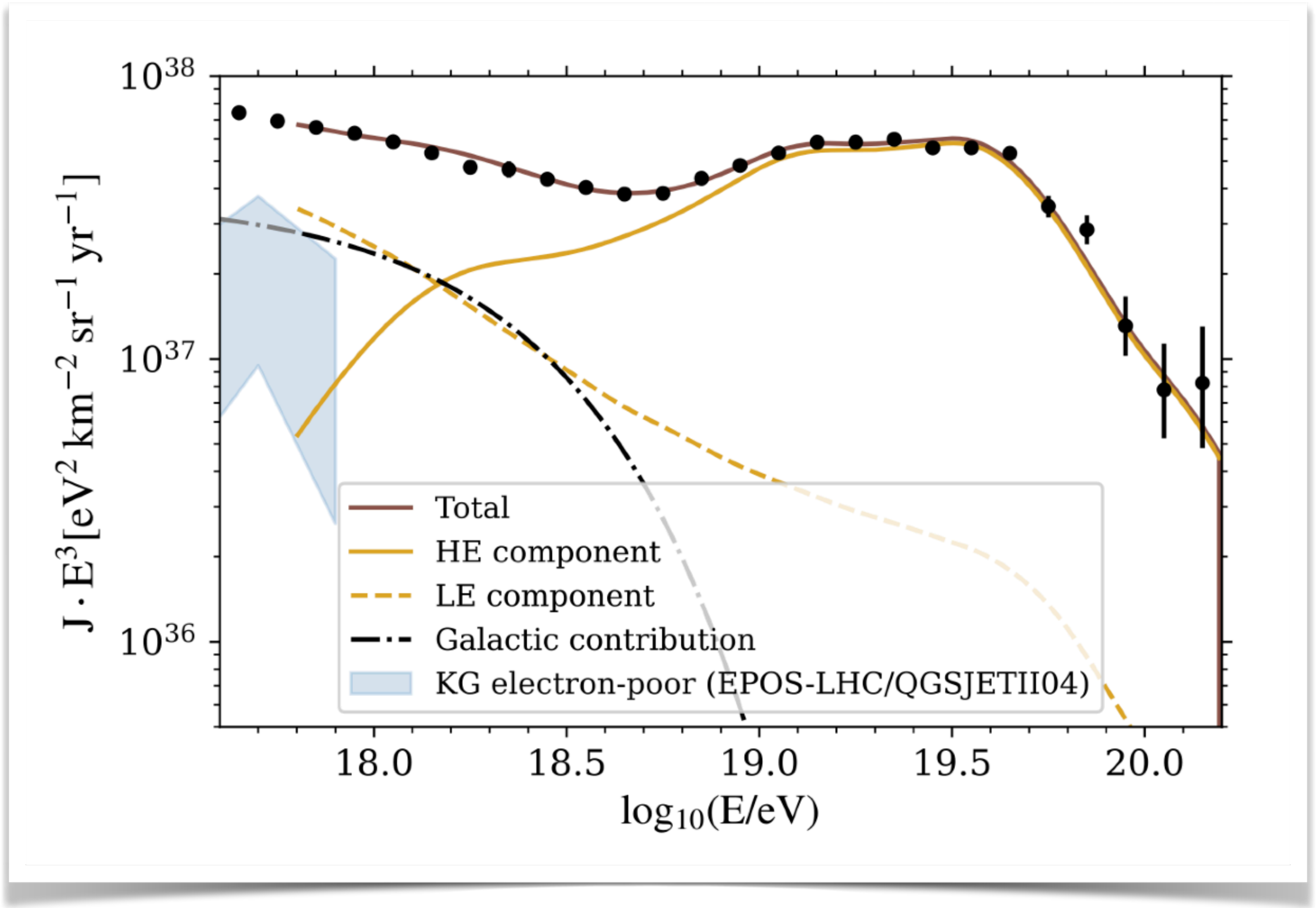
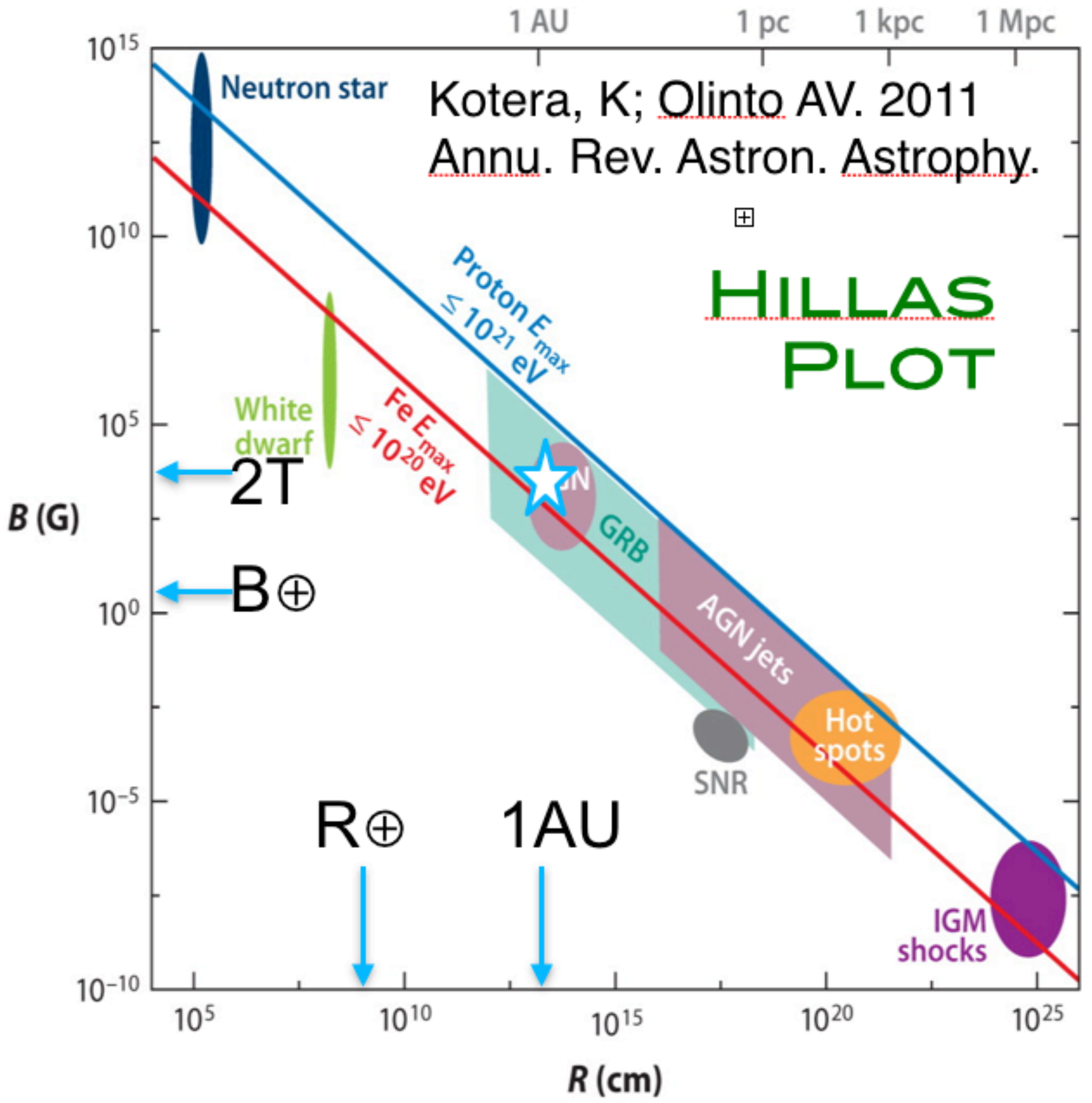


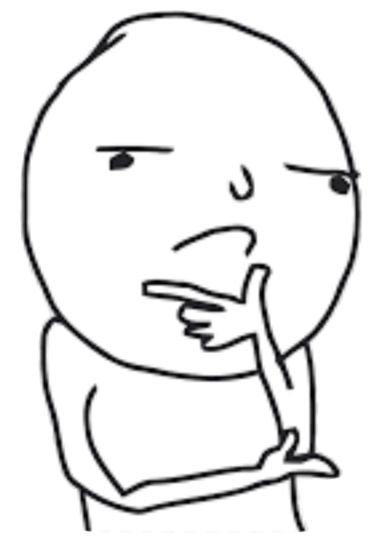




What if… there are sources that we do not understand or know

What if… we do not understand the acceleration mechanisms

What if… there are some unknown propagation effects … **will there be some mechanism that bypasses** the threshold?



Lorentz Invariance

Space - Time symmetry

Fundamental symmetry in Physics

Lorentz scalars are invariants

$$p_\mu p^\mu = -(mc)^2 \qquad E^2 - p^2 = m^2$$

$$\frac{1}{4} F_{\mu\nu} F^{\mu\nu} = \frac{1}{2}\left(\mathbf{E}^2 - \mathbf{B}^2\right)$$

If Lorentz invariant, there is CPT

But, LI may not be an **exact symmetry of Nature**

Like any other **fundamental principle**

exploring the limits of validity of **LI** has been

an essential motivation for theoretical and

experimental research

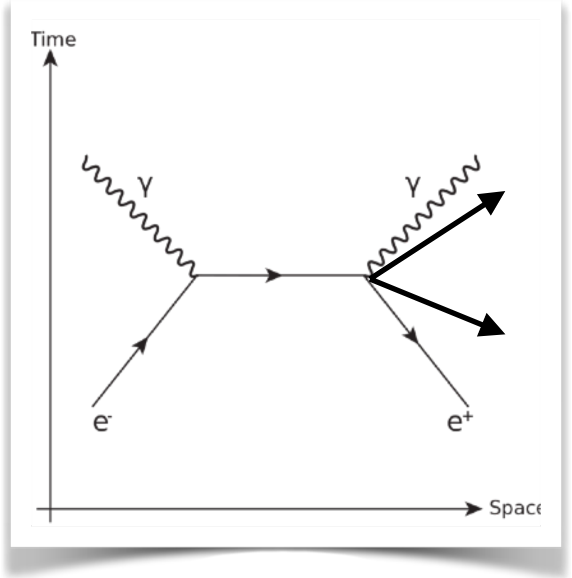
Paradigms:

-v<c

-x<compton length

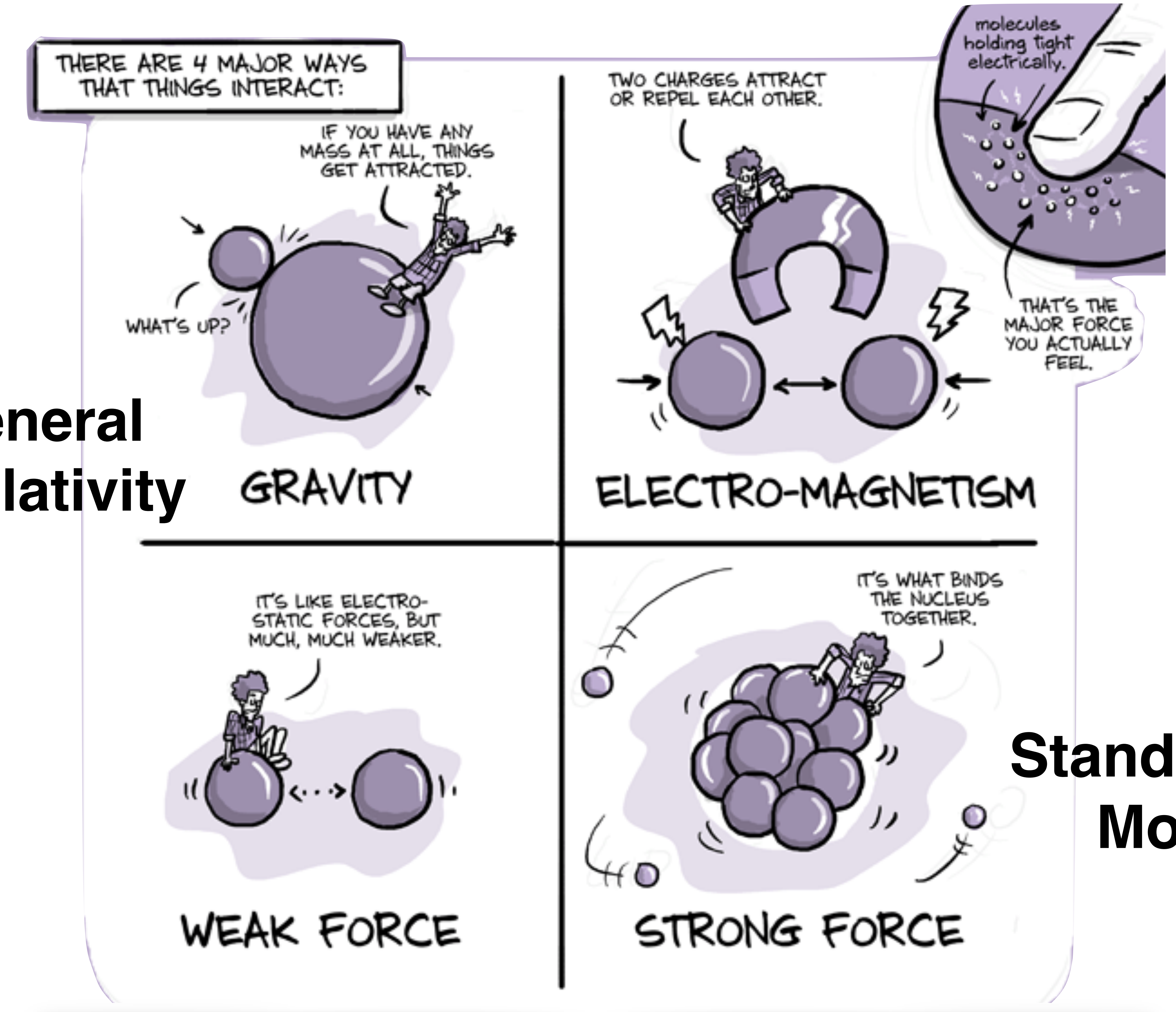
-Universal Time

...



…**will there be some mechanism that bypasses the threshold**?

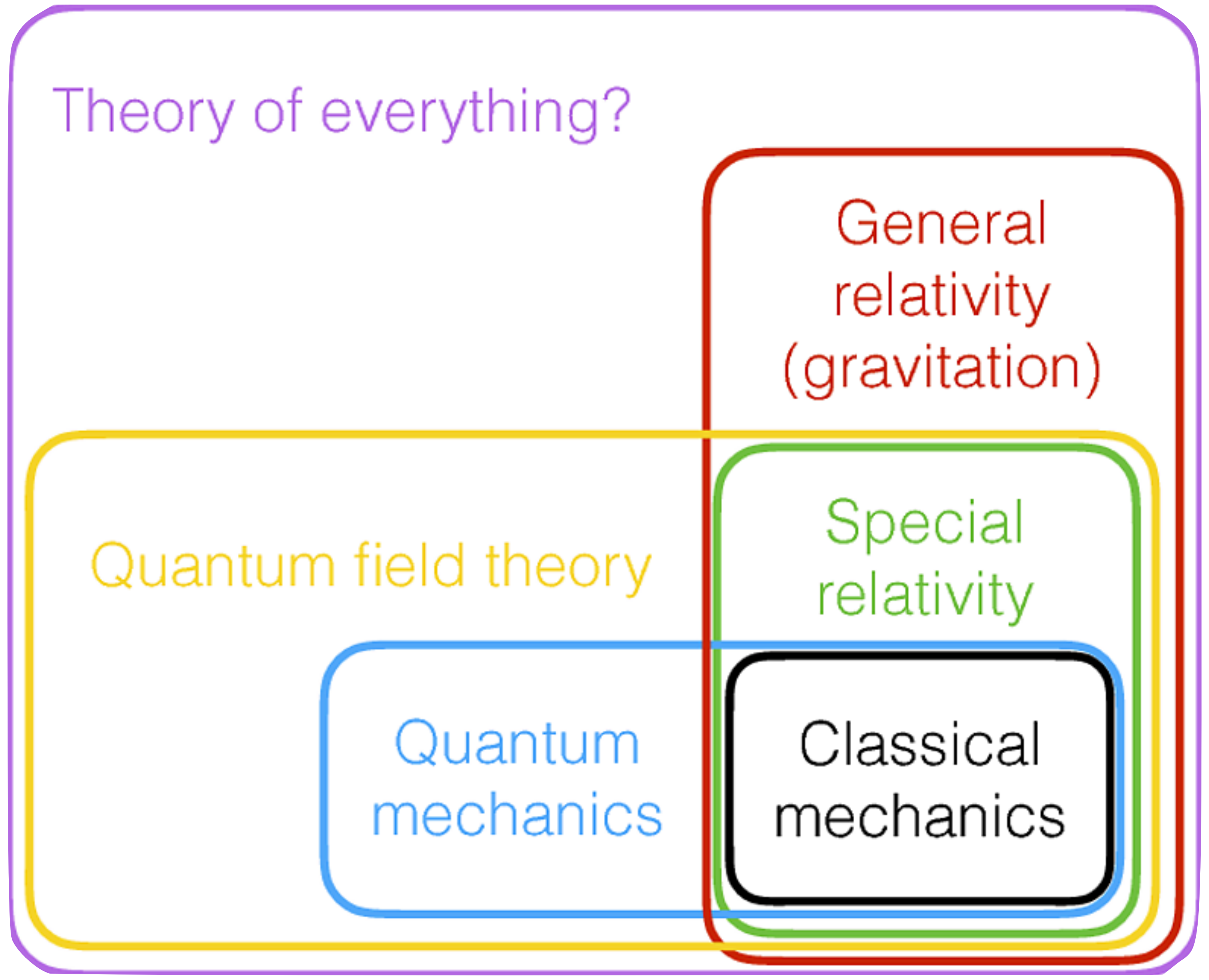
LIV



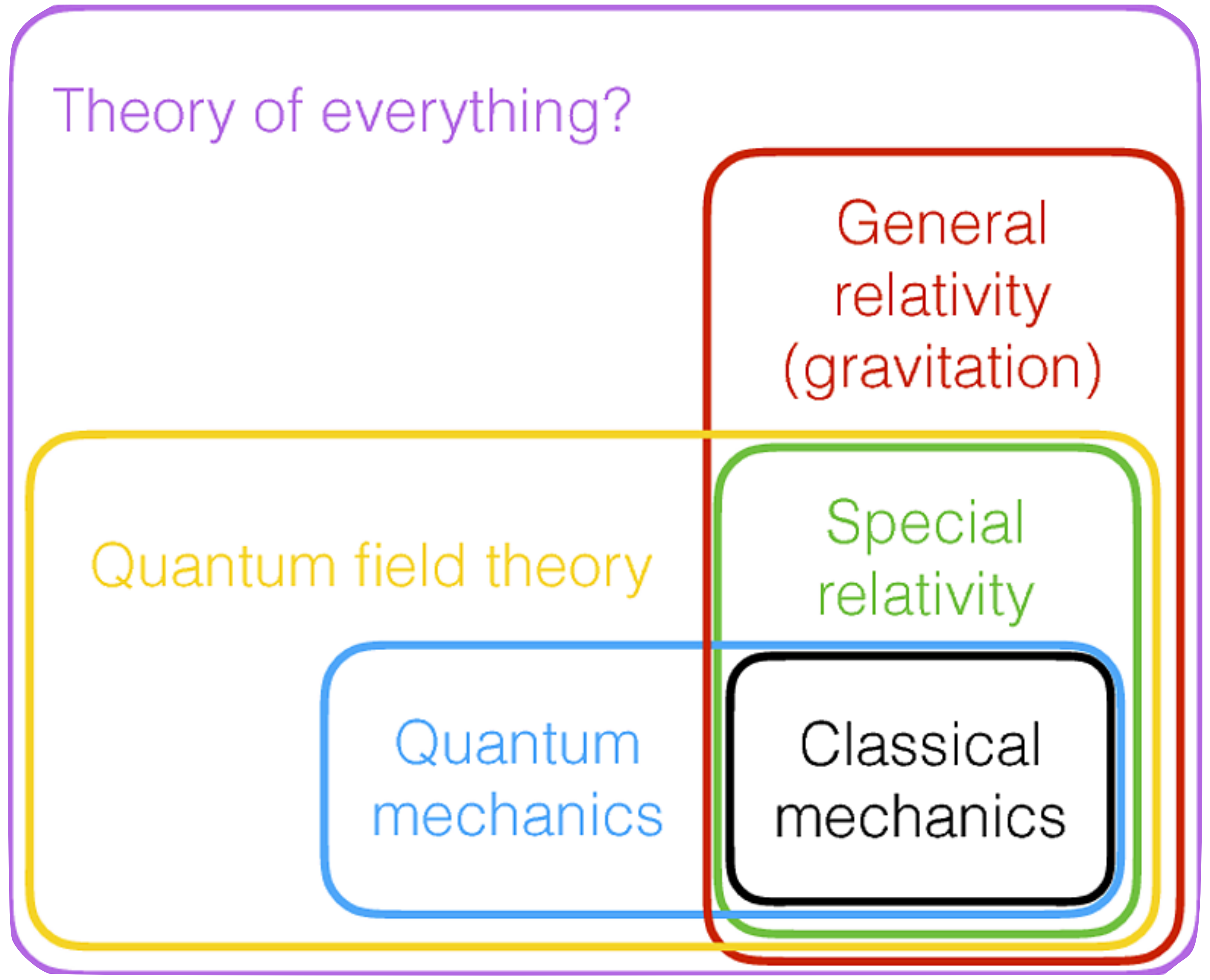
General Relativity

Standard Model

- SM & GR: the best theories describing the 4-fundamental Forces.
- No conflict with predictions from either of them.
- **They are fundamentally different.**



LIV



Quantum Theory of Gravity?

String Theory … Loop Quantum Gravity ?

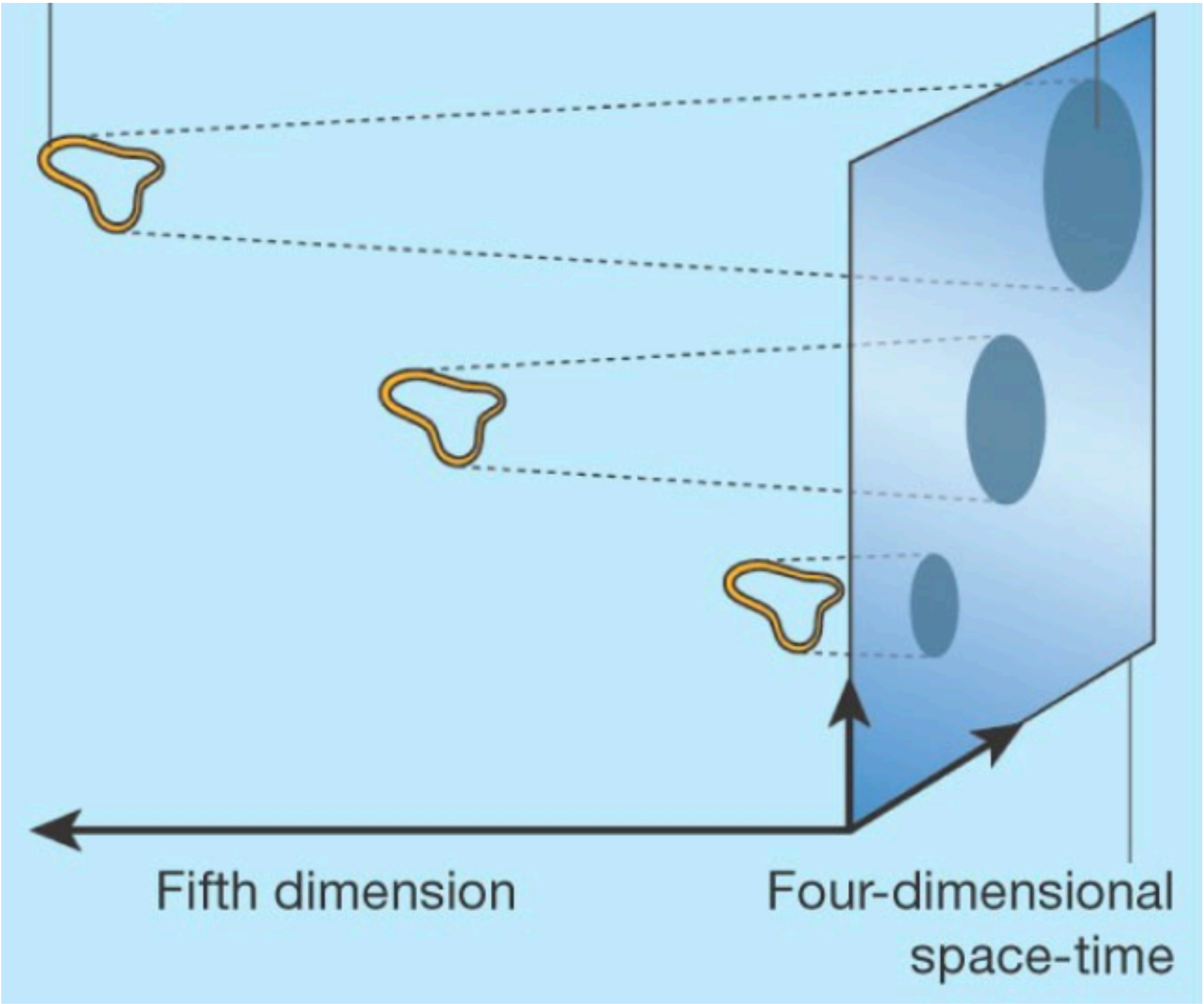
New Physics involves new features, such as:

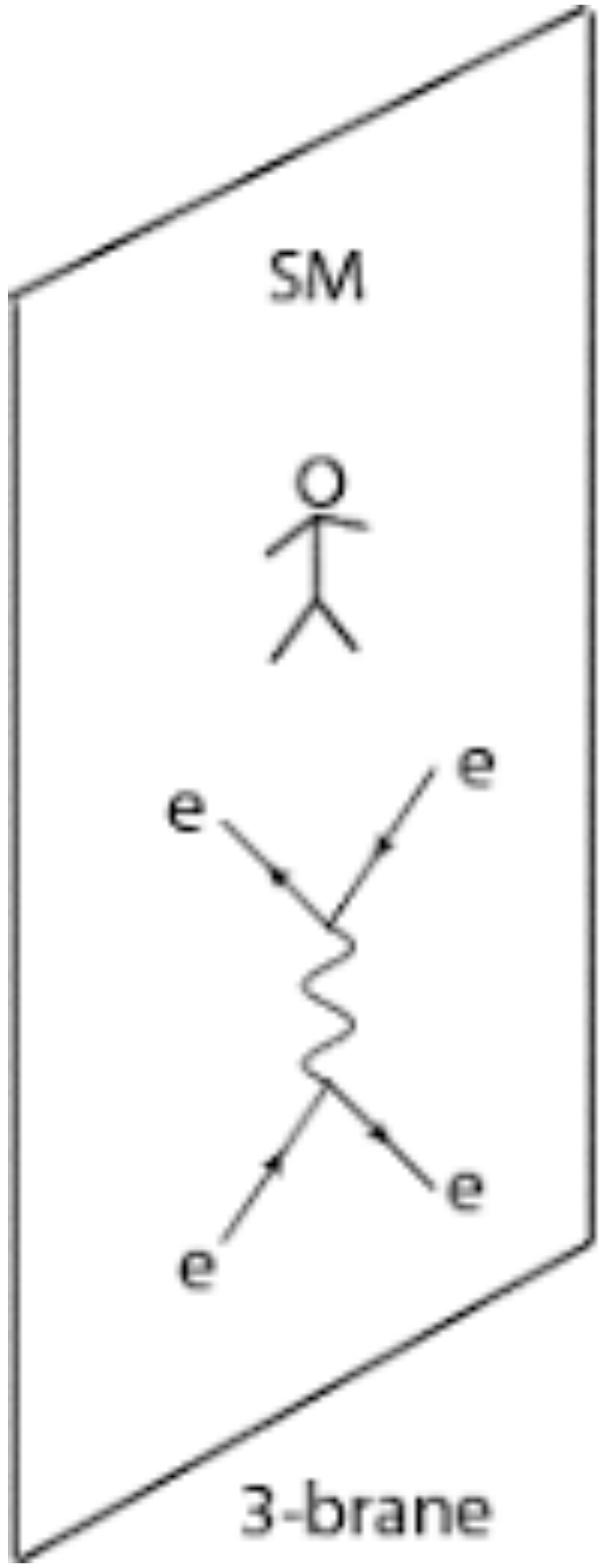
- ☐ Higher dimensions of space and time
- ☐ …
- ☑ The law of relativity might not hold exactly at all energy scales: **SME**, Effective-Theories,…

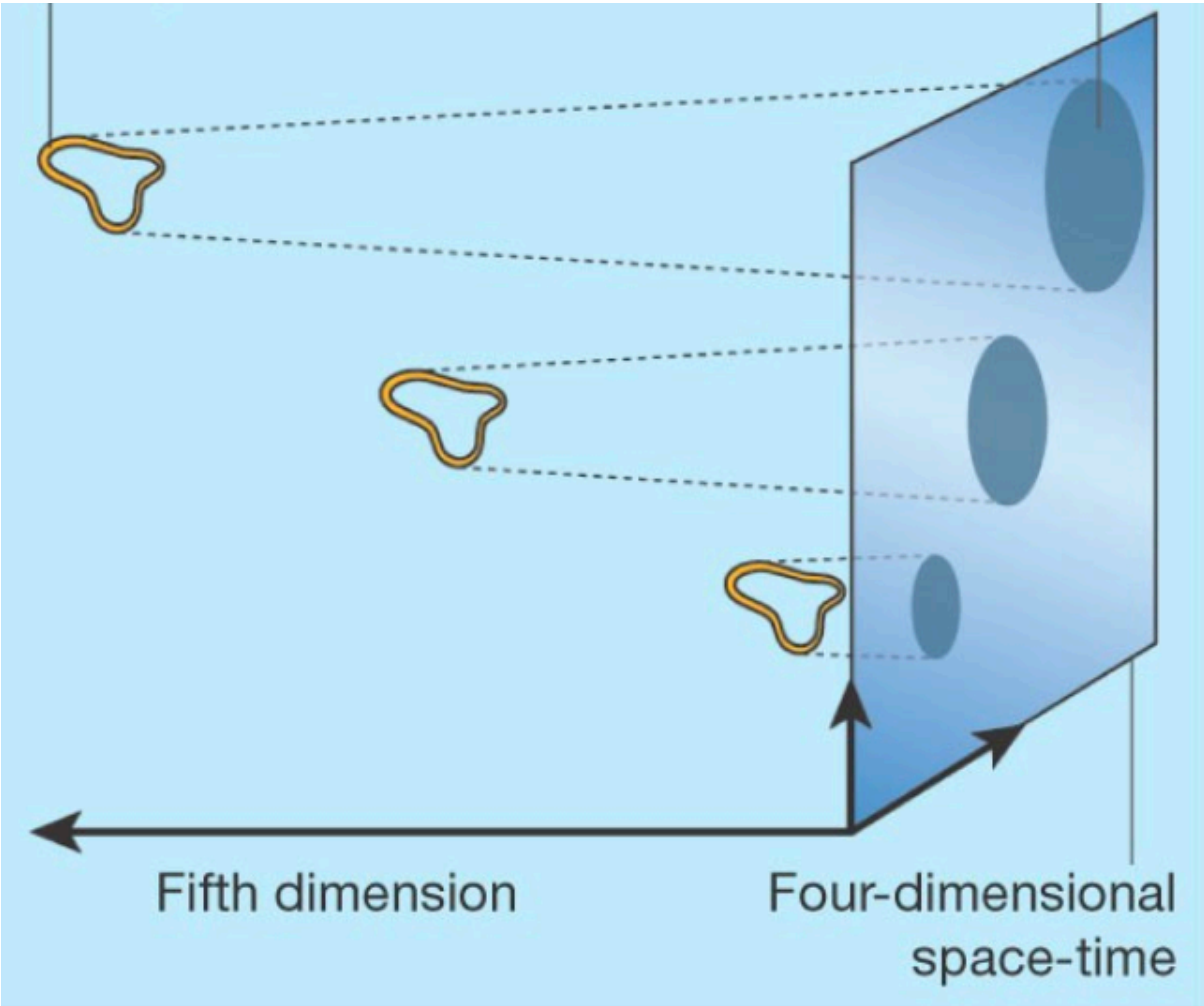
… **LI** may not be an **exact symmetry of Nature**

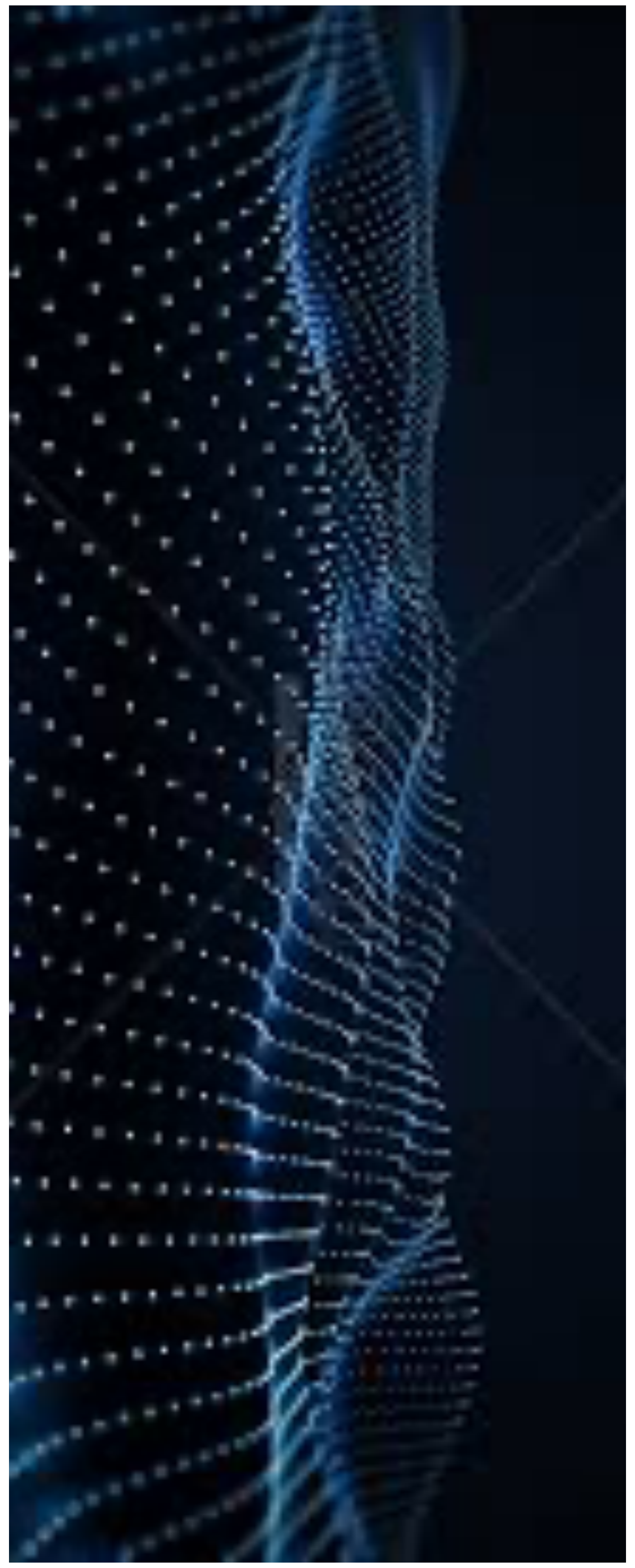
Lorentz Invariance Violation (LIV)

Like any other **fundamental principle** exploring the limits of validity of **LI** has been an essential motivation for theoretical and experimental research

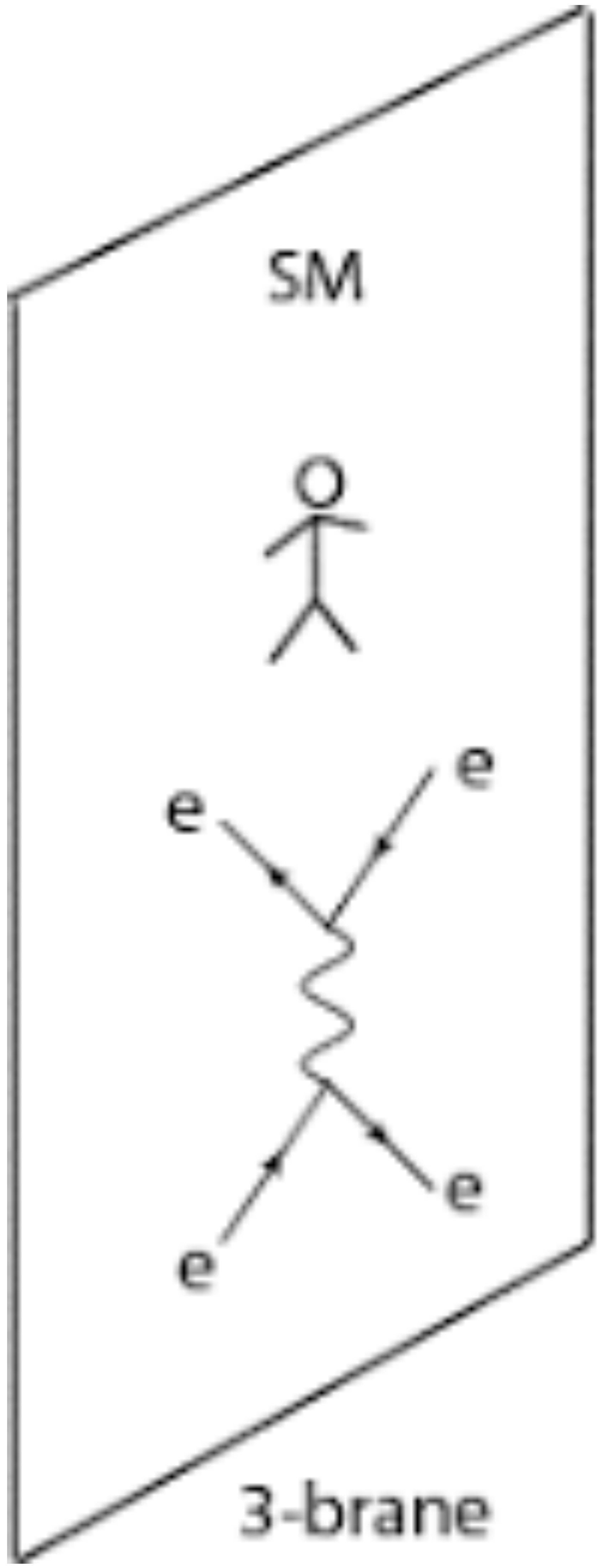

Fifth dimension
Four-dimensional space-time

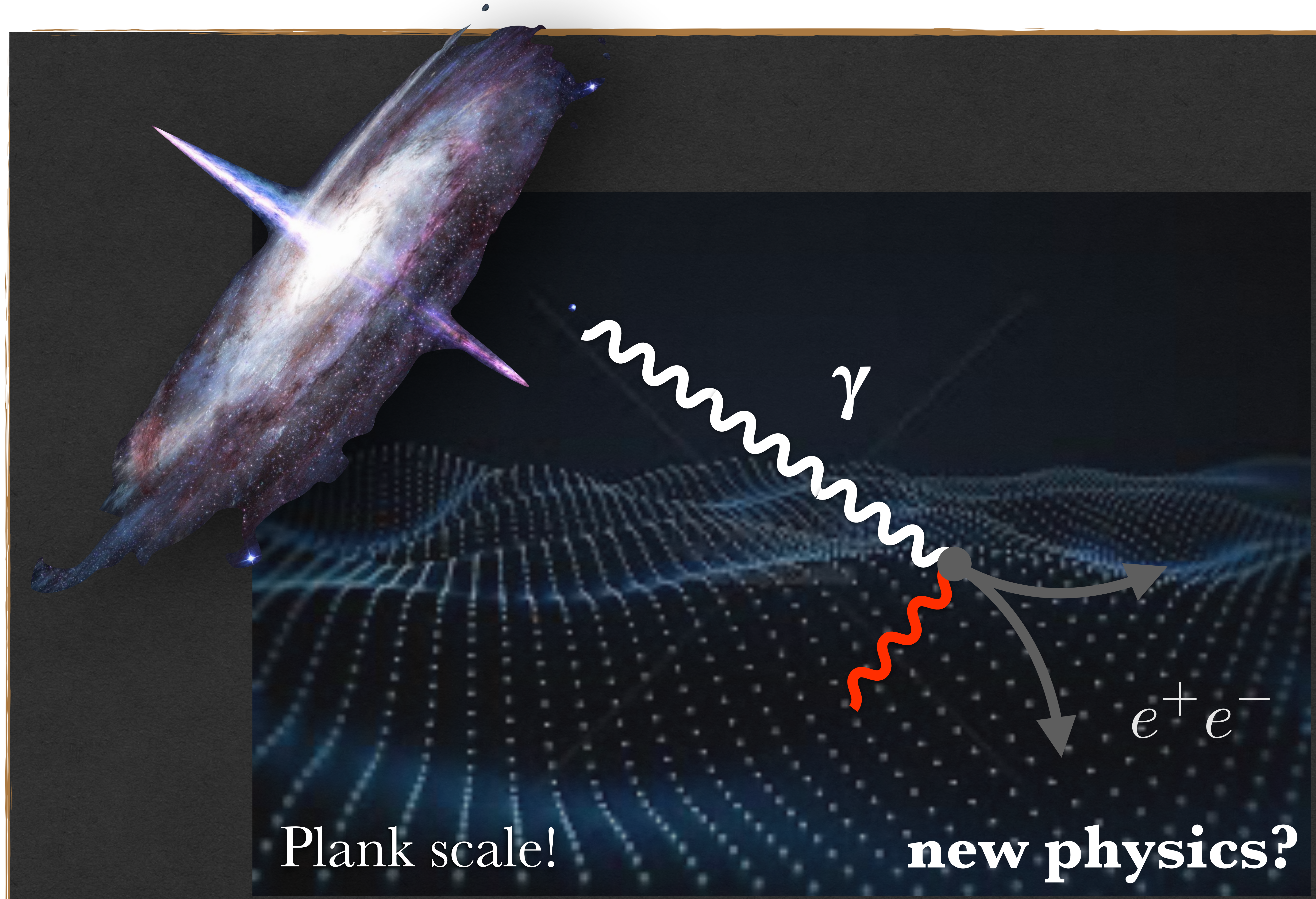

SM
e
e
e
e
3-brane


Fifth dimension
Four-dimensional
space-time



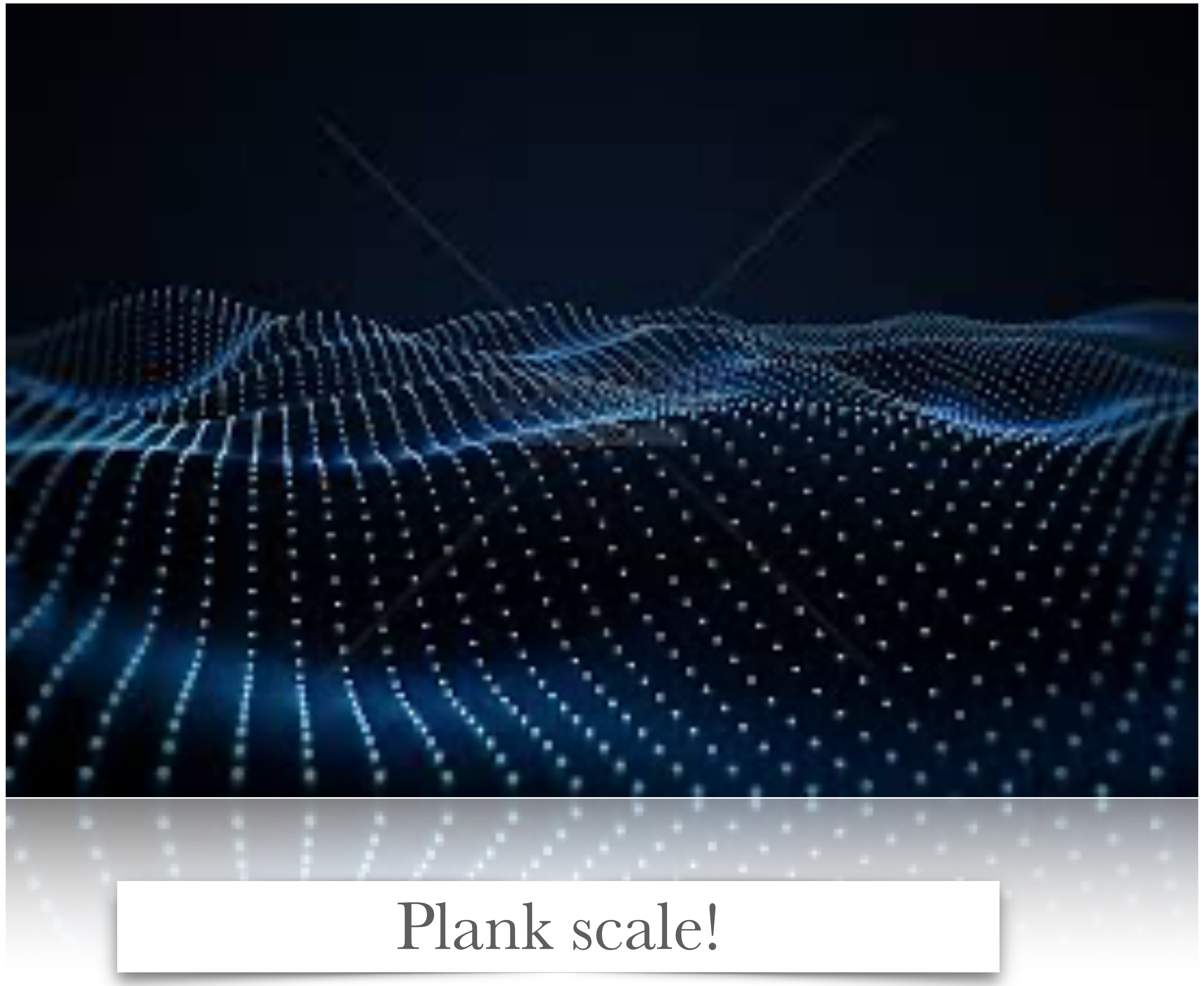
Plank scale!

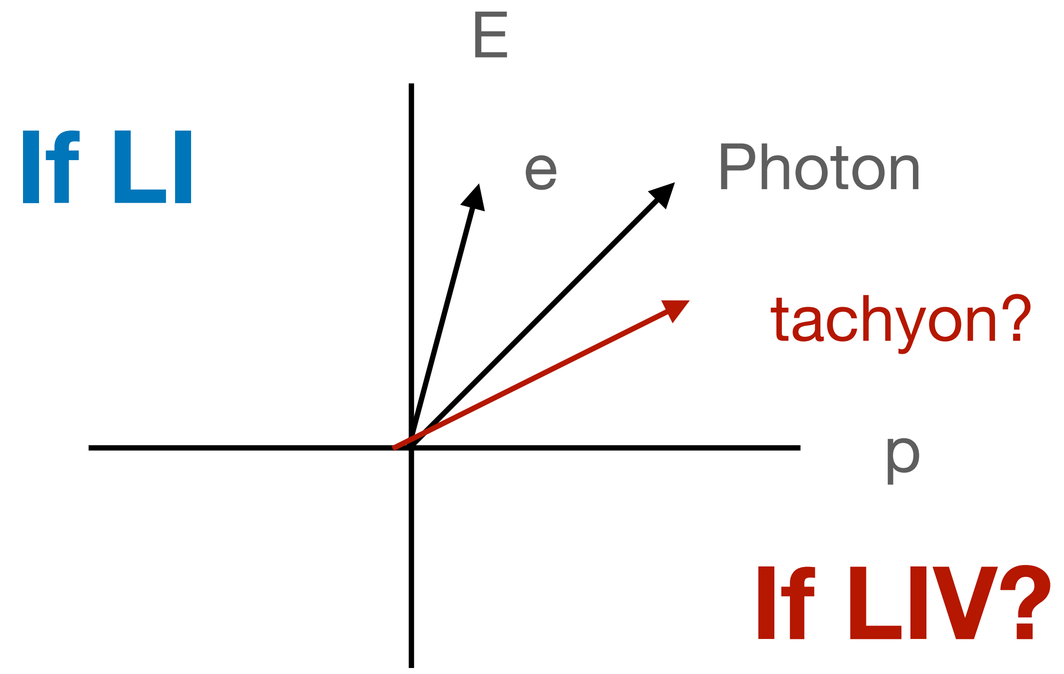

SM
e
e
e
e
3-brane



$$p\gamma \to \Delta$$

$$\gamma\gamma_b \to e^+e^-$$


Plank scale!

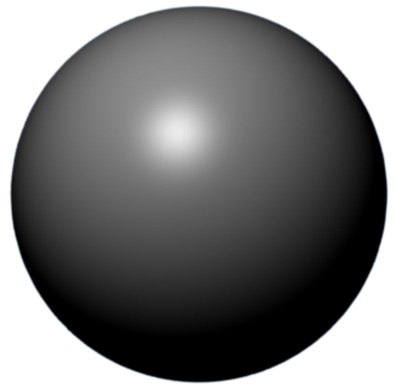

If LI
E
e
Photon
tachyon?
p
If LIV?


ASUME A
SPHERICAL
COW
IN A VACUUM

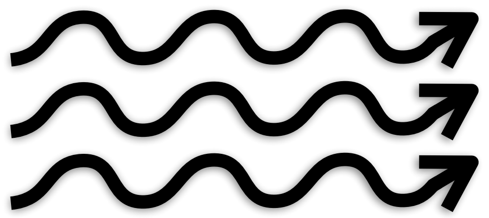

ASUME A
SPHERICAL
COW
IN A VACUUM
Something

LIV: Introduction

Theory ⟶ Phenomenology ⟶ Experiment



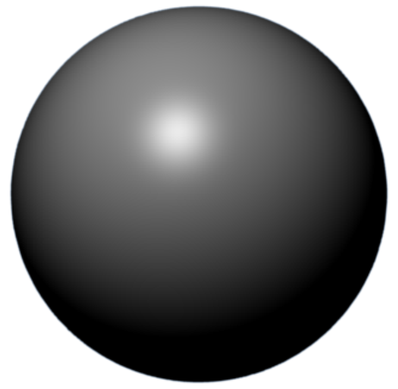
γ

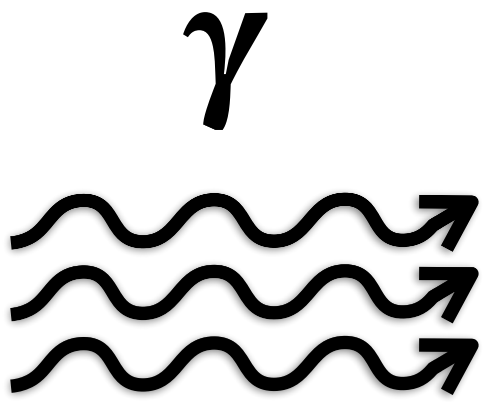


$$c = 3 \times 10^8 \ \mathrm{m/s}$$

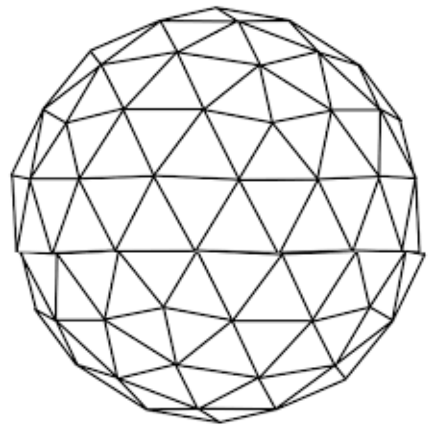
Introduction

Theory ⟶ Phenomenology ⟶ Experiment





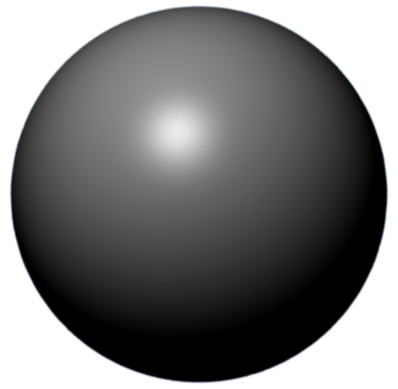
$c = 3 \times 10^8$ m/s

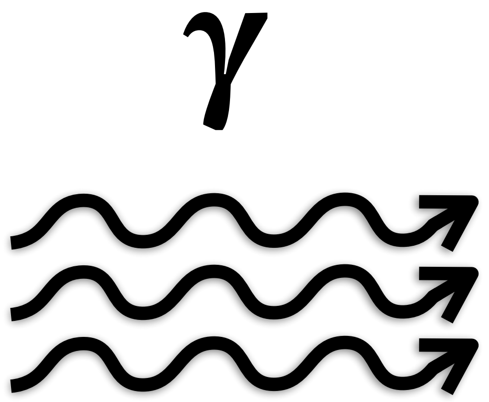


$c \neq 3 \times 10^8$ m/s

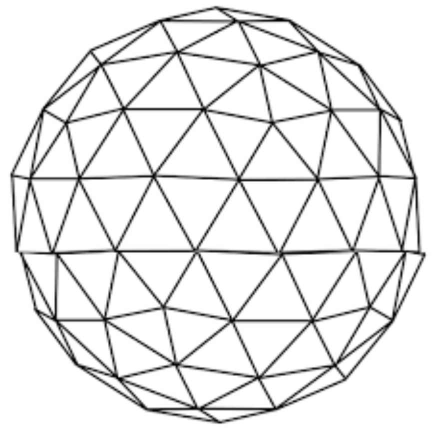
Introduction

Theory ⟶ Phenomenology ⟶ Experiment





$c = 3 \times 10^8 \text{ m/s}$



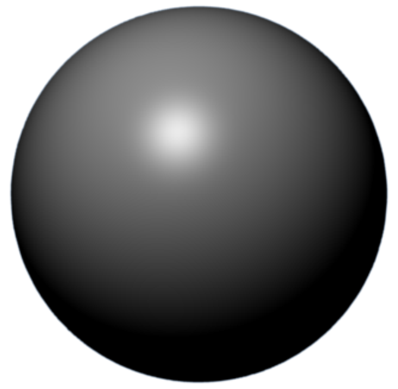
$c \neq 3 \times 10^8 \text{ m/s}$

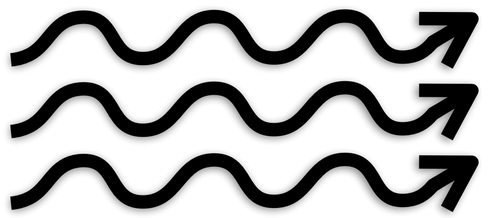
$c' = (1 \pm \delta)c$

Introduction

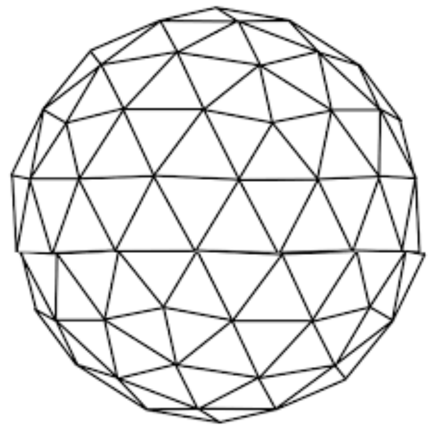
Theory $\longrightarrow$ Phenomenology $\longrightarrow$ Experiment

γ





$c = 3 \times 10^8$ m/s



$c \neq 3 \times 10^8$ m/s

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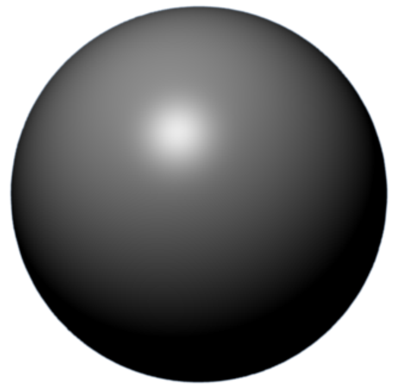
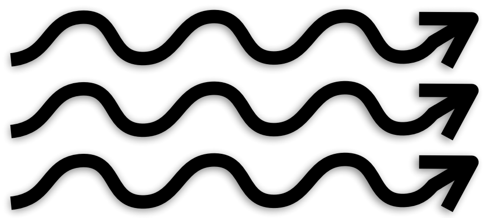
Fundamental Energy Scale $E_{QG} : E_{Pl} : E_{LIV}$

Introduction

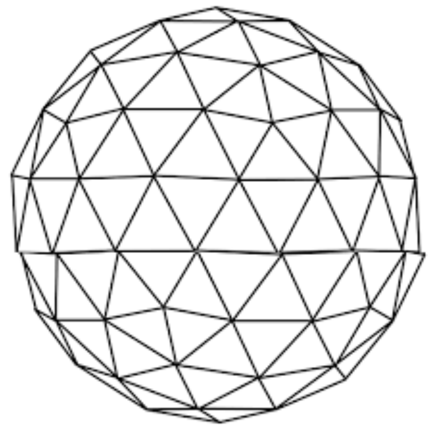
Theory ⟶ Phenomenology ⟶ Experiment



γ



$c = 3 \times 10^8 \ \mathrm{m/s}$



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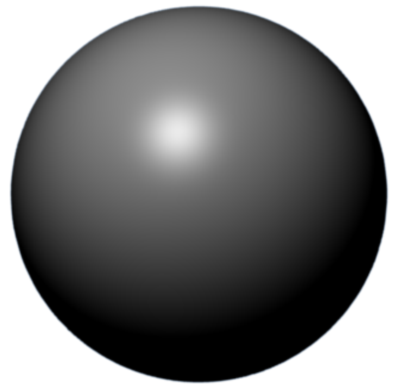
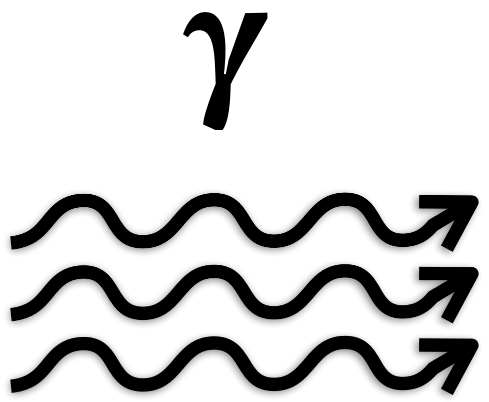
$$c' = \left[1 \pm f \left(\frac{E_\gamma}{E_{\rm LIV}} \right) \pm \ldots \right] c$$

Introduction

Theory $\longrightarrow$ Phenomenology $\longrightarrow$ Experiment





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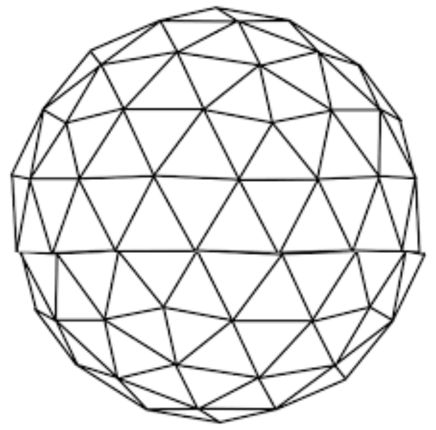

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$$c' = \left[1 \pm f\left(\frac{E_\gamma}{E_{\text{LIV}}}\right) \pm \ldots\right] c \longrightarrow E_\gamma^2 - p_\gamma^2 \left[1 \pm f\left(\frac{E_\gamma}{E_{\text{LIV}}}\right) \pm \ldots\right]^2$$

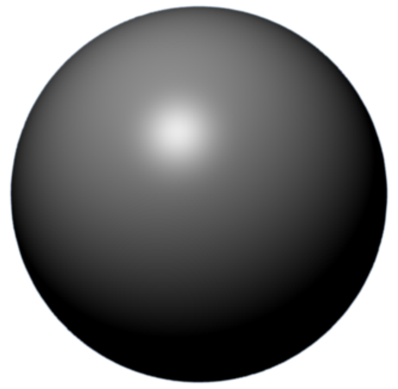
$$E^2 - p^2 \pm \epsilon A^2$$

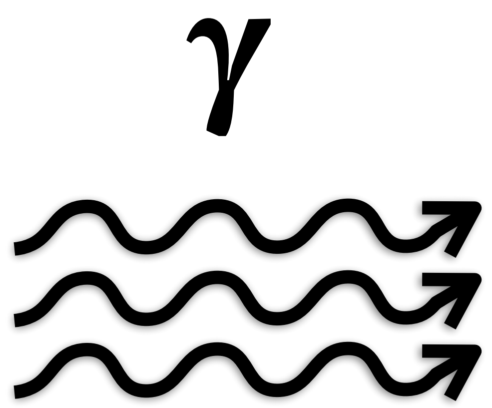
$A = p$

$$\epsilon(A)A^2 = \epsilon(0)A^2 + \epsilon'(0)A^{(2+1)} + \frac{\epsilon''(0)}{2!}A^{(2+2)} + \frac{\epsilon'''(0)}{3!}A^{(2+3)} + \ldots$$

Introduction

Theory $\longrightarrow$ Phenomenology $\longrightarrow$ Experiment





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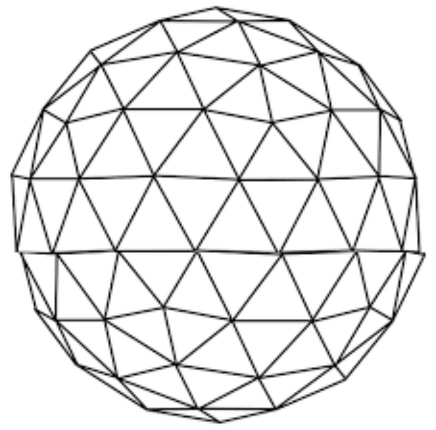

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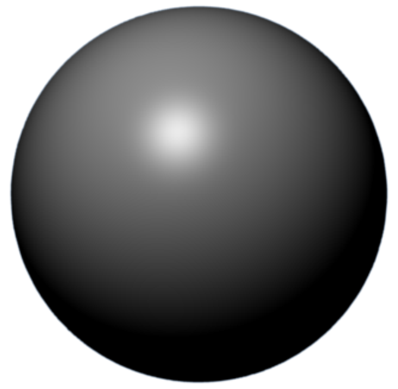
$$E^2 - p^2 \pm \epsilon A^2$$

n=1

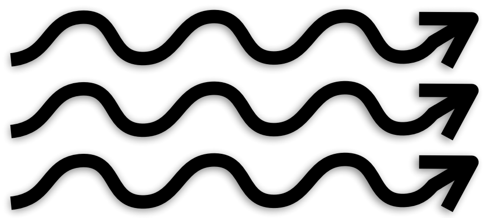
$A = p$

$$\epsilon(A)A^2 = \epsilon(0)A^2 + \boxed{\epsilon'(0)A^{(2+1)}} + \frac{\epsilon''(0)}{2!}A^{(2+2)} + \frac{\epsilon'''(0)}{3!}A^{(2+3)} + \ldots$$

Theory → Phenomenology → Experiment



$\boldsymbol{\gamma}$



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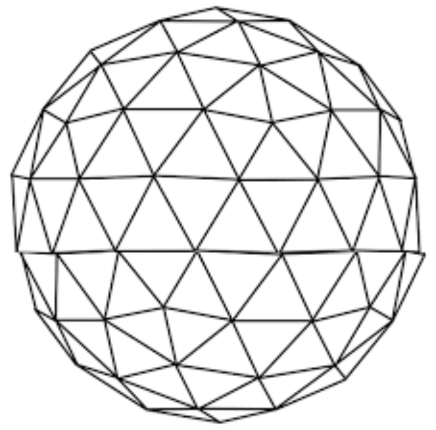

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$$c' = \left[1 \pm f\left(\frac{E_\gamma}{E_{\mathrm{LIV}}}\right) \pm \ldots\right] c \longrightarrow E_\gamma^2 - p_\gamma^2 \left[1 \pm f\left(\frac{E_\gamma}{E_{\mathrm{LIV}}}\right) \pm \ldots\right]^2$$

$$E^2 - p^2 \pm \epsilon A^2$$

n=2

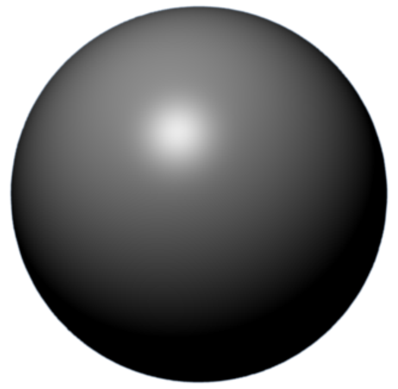
$A = p$

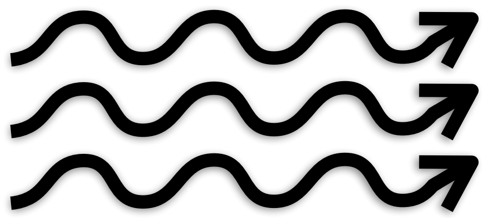
$$\epsilon(A)A^2 = \epsilon(0)A^2 + \epsilon'(0)A^{(2+1)} + \boxed{\frac{\epsilon''(0)}{2!}A^{(2+2)}} + \frac{\epsilon'''(0)}{3!}A^{(2+3)} + \ldots$$

Introduction

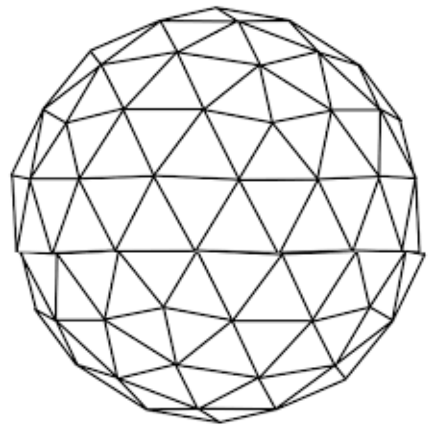
Theory ⟶ Phenomenology ⟶ Experiment

$\boldsymbol{\gamma}$





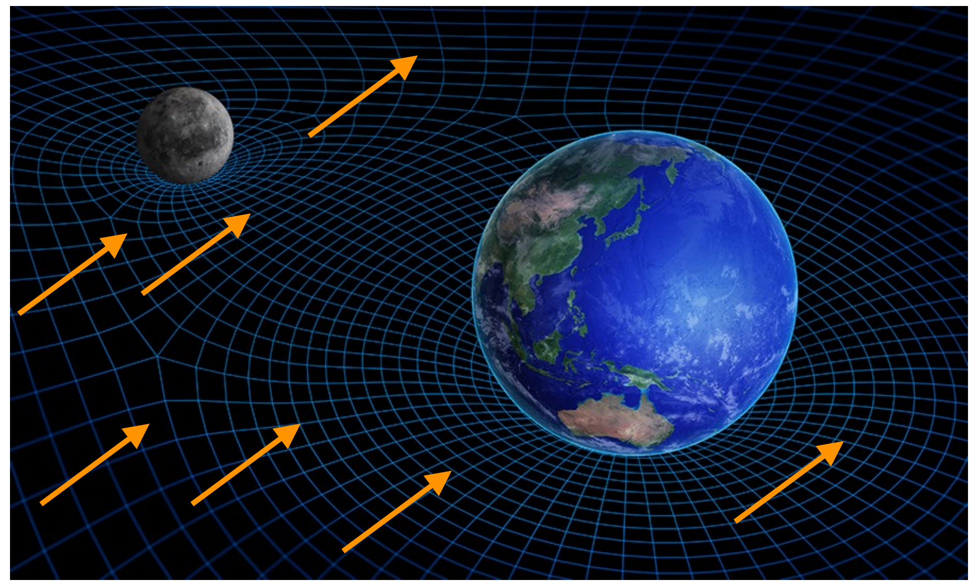
$$c = 3 \times 10^8 \text{ m/s}$$



$$c \neq 3 \times 10^8 \text{ m/s}$$

$$c' = (1 \pm \delta) c$$

Fundamental Energy Scale $E_{QG} : E_{Pl} : E_{LIV}$



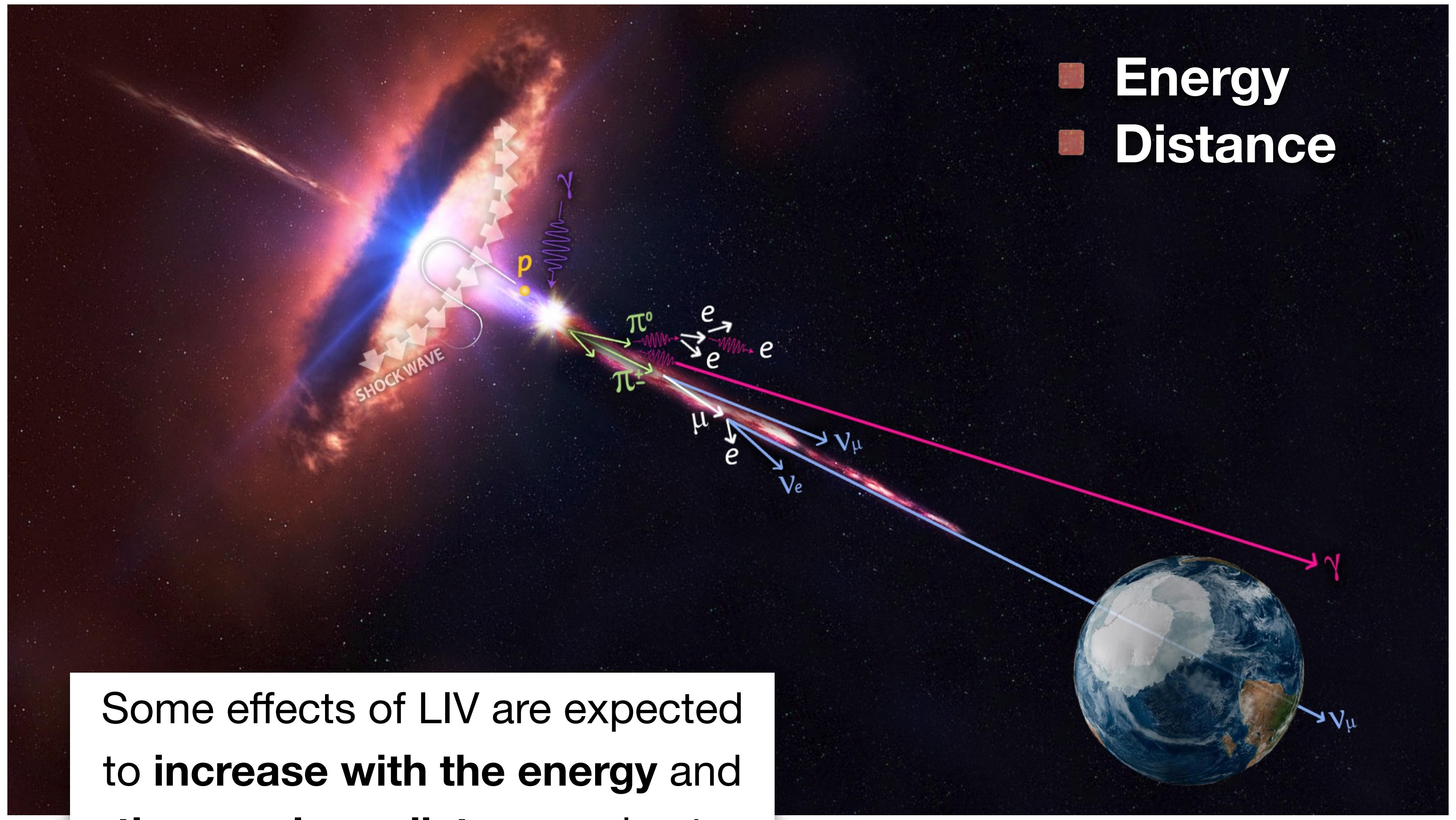
$$c' = \left[1 \pm f \left(\frac{E_\gamma}{E_{\mathrm{LIV}}} \right) \pm \ldots \right] c$$

$$E_\gamma^2 - p_\gamma^2 = \delta_{\gamma,n} \; p_\gamma^2 \approx \frac{E_\gamma^{n+2}}{\left(E_{\mathrm{LIV}}^{(n)} \right)^n}$$

Family of LIV-modified dispersion relations that may lead to similar phenomenology!

n = 0, 1, 2, ...

it is not necessarily bound to a particular LIV-model, which allows to generalize to some point the search of LIV-signatures.



Some effects of LIV are expected to **increase with the energy** and **the very long distances** due to cumulative processes

Examples LIV Dispersion Relation

$$\mathcal{L}_{modM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}\kappa^{\mu\nu}{}_{\rho\lambda}F_{\mu\nu}F^{\rho\lambda} \quad ; \quad \omega_{modM}(\mathbf{k}) = \sqrt{\frac{1-\widetilde{\kappa}_{tr}}{1+\widetilde{\kappa}_{tr}}}\,k, \quad k = |\mathbf{k}|,$$

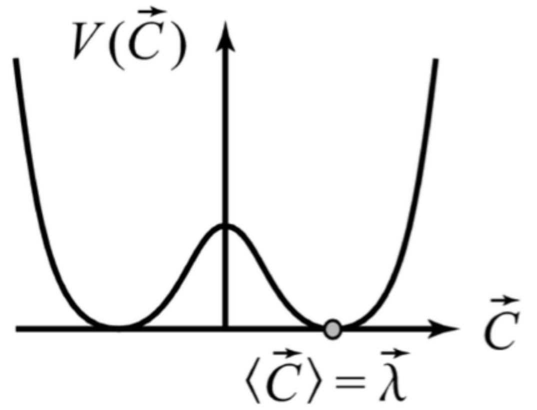
F. Klinkhamer and M. Schreck, Phys. Rev. D 78, 085026 (2008)

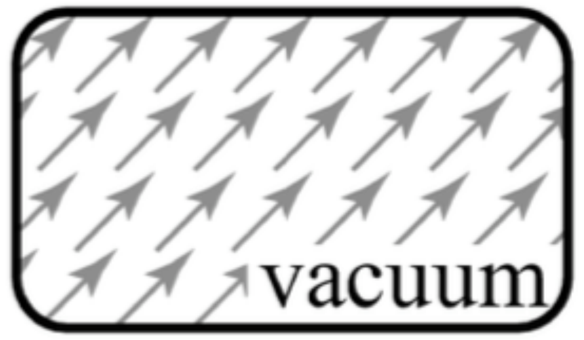
$$\mathcal{L}_\gamma = \frac{\xi}{M_{Pl}} n^a F_{ad} n \cdot \partial n_b \tilde{F}^{bd} \quad ; \quad \left(E^2 - p^2 \pm \frac{2\xi}{M_{Pl}} p^3\right)(\epsilon_x \pm i\epsilon_y) = 0$$

Robert C. Myers and Maxim Pospelov Phys.Rev. Lett 90 21 (2003)

$$\xi_n^+ = (-1)^n \xi_n^- \quad \text{for} \quad \mathrm{n} = 1, 2 \; ; \quad \omega_\pm^2 = k^2 + \xi_n^\pm k^2 \left(\frac{k}{M_{Pl}}\right)^n$$

Matteo Galaverna and Günter Sigl Phys.Rev. D78 (2008) 063003





$$E^2 \approx p^2 \left[1 - \sum_{n=1}^{\infty} s_\pm \left(\frac{E}{E_{QG}}\right)^n\right]$$

V. Vasileiou, A. Jacholkowska, F. Piron, J. Bolmont, C. Couturier, J. Granot, F. W. Stecker, J. Cohen-Tanugi, and F. Longo Phys. Rev. D 87, 122001

$$E^2 \approx p^2 \left(1 + \xi_n \left(\frac{p}{E_{QG}}\right)^n\right)$$

Lukas Nellen for the HAWC collaboration, ICRC'2015

SME

M. Hohensee, R. Lehnert, D. Phillips, R. Walsworth
Phys. Rev. D **80**, 036010 (2009)

D. Colladay and V. A. Kostelecký, Phys. Rev. D 58, 116002 (1998).

d= 4+n

$$E_\gamma^2 - p_\gamma^2 = \delta_{\gamma,n}\, p_\gamma^2 \approx \frac{E_\gamma^{n+2}}{\left(E_{\mathrm{LIV}}^{(n)}\right)^n}$$

n = 0, 1, 2, …

Generic LIV dispersion relation

$$E^2 - p^2 \pm \epsilon A^2 = m^2,$$

$$A = p$$

$$\epsilon \to \epsilon(A)$$

A general modification to the dispersion relation would rather involve a general function of energy and momentum

$$\epsilon(A)A^2 = \epsilon(0)A^2 + \epsilon'(0)A^{(2+1)} + \frac{\epsilon''(0)}{2!}A^{(2+2)} + \frac{\epsilon'''(0)}{3!}A^{(2+3)} + \ldots$$

The dispersion relation:

$$E^2 - p^2 \pm \delta_n A^{n+2} = m^2,$$

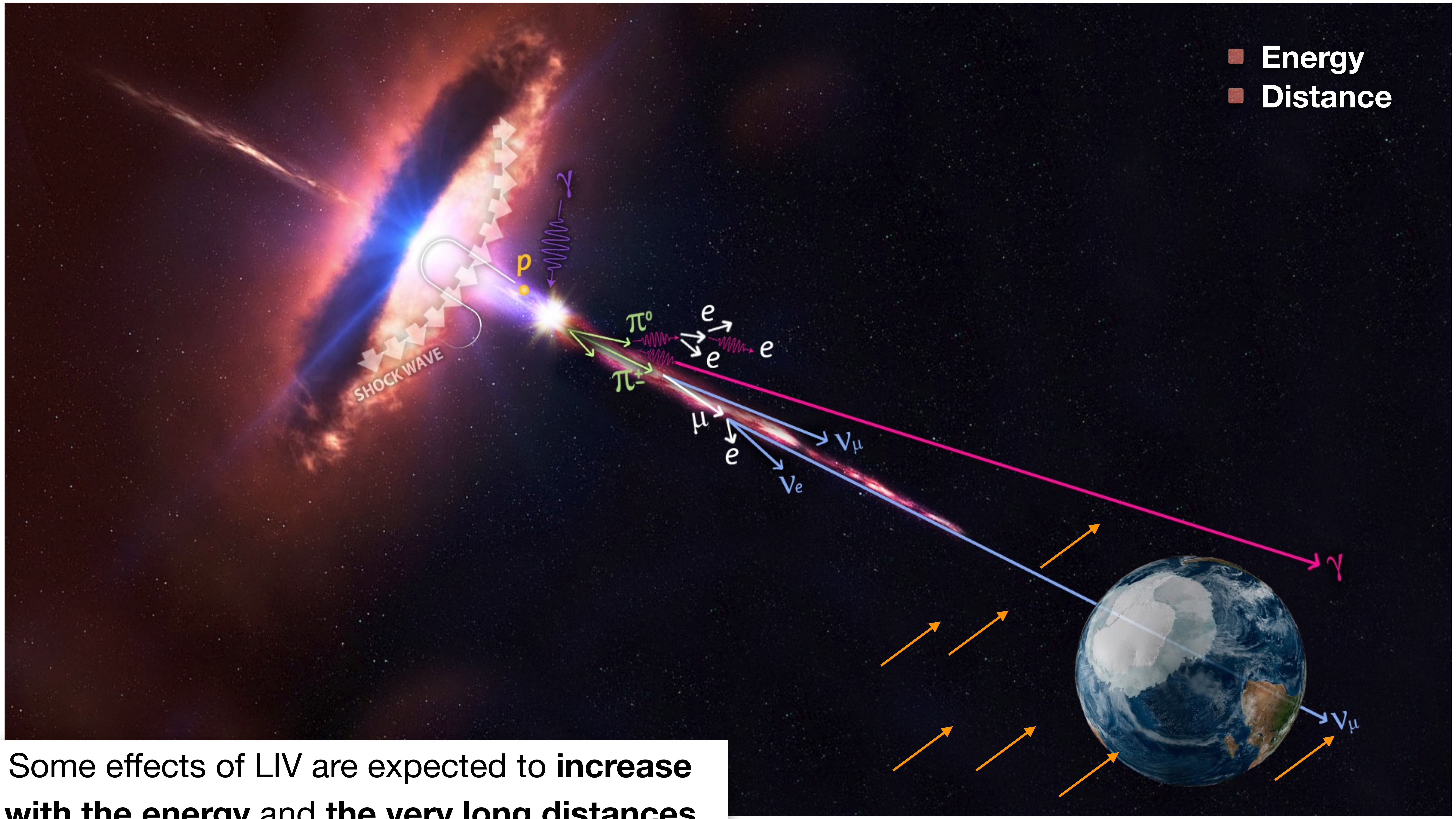
$$\delta_n \overset{n \geq 1}{=} \epsilon^{(n)}/M^n = 1/(E_{LIV}^{(n)})^n$$

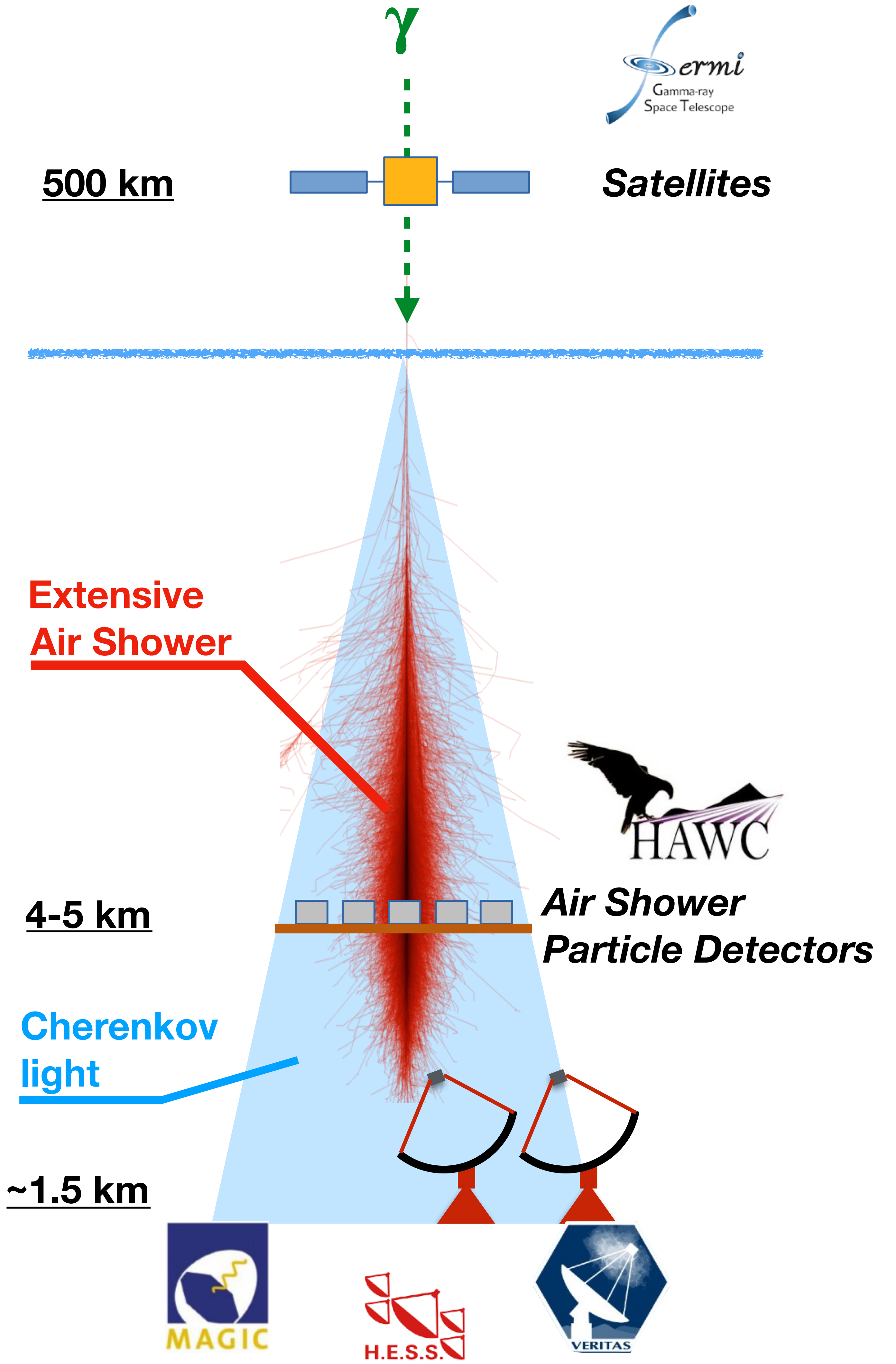
it is not necessarily bound to a particular LIV-model, which allows to generalize to some point the search of LIV-signatures.

LIV negligible at the standard energies

Astroparticle Physics: Lab to test Fundamental Physics

Theory ⟷ Phenomenology ⟷ Experiment



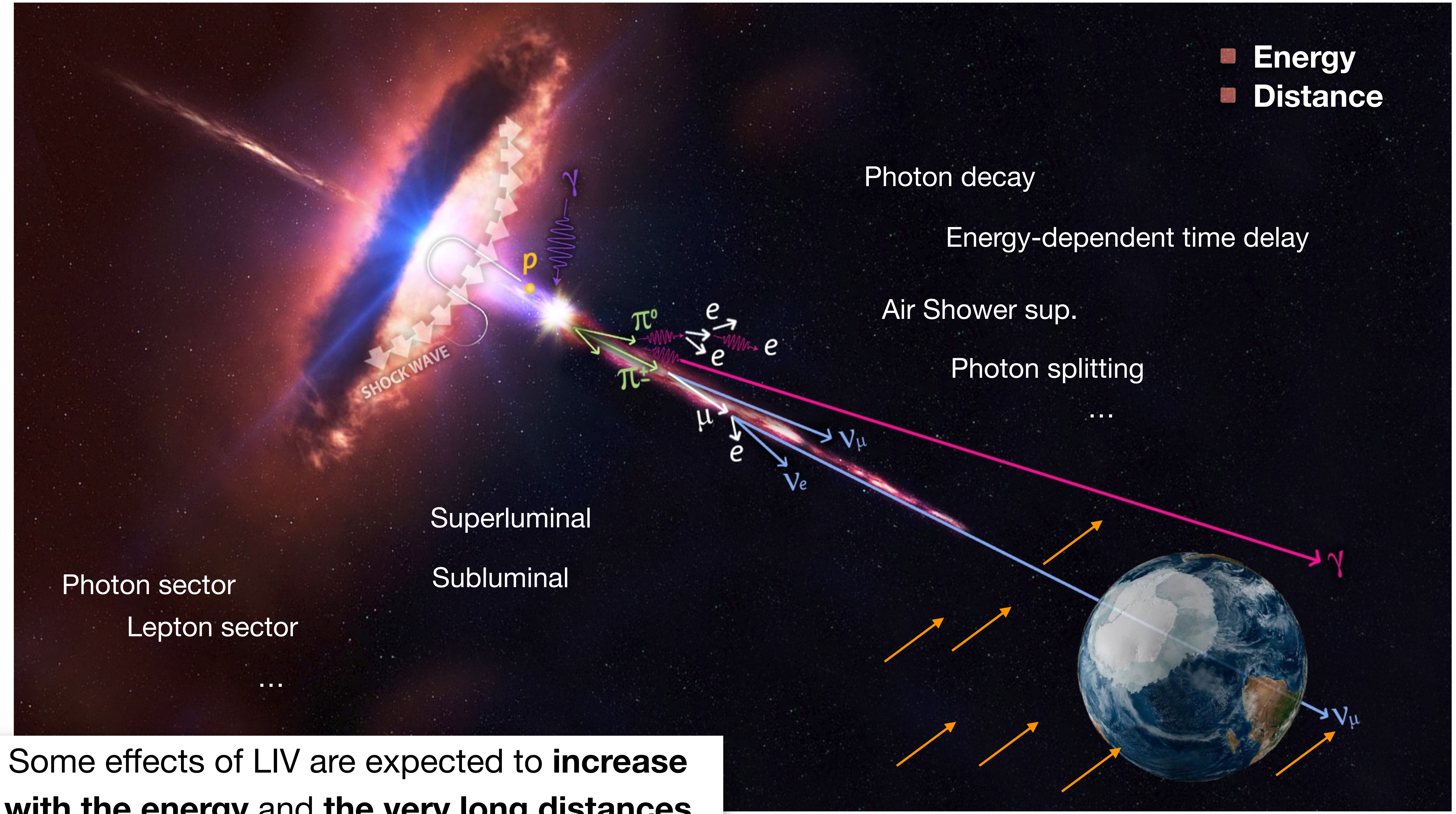


Some effects of LIV are expected to **increase with the energy** and **the very long distances** due to cumulative processes

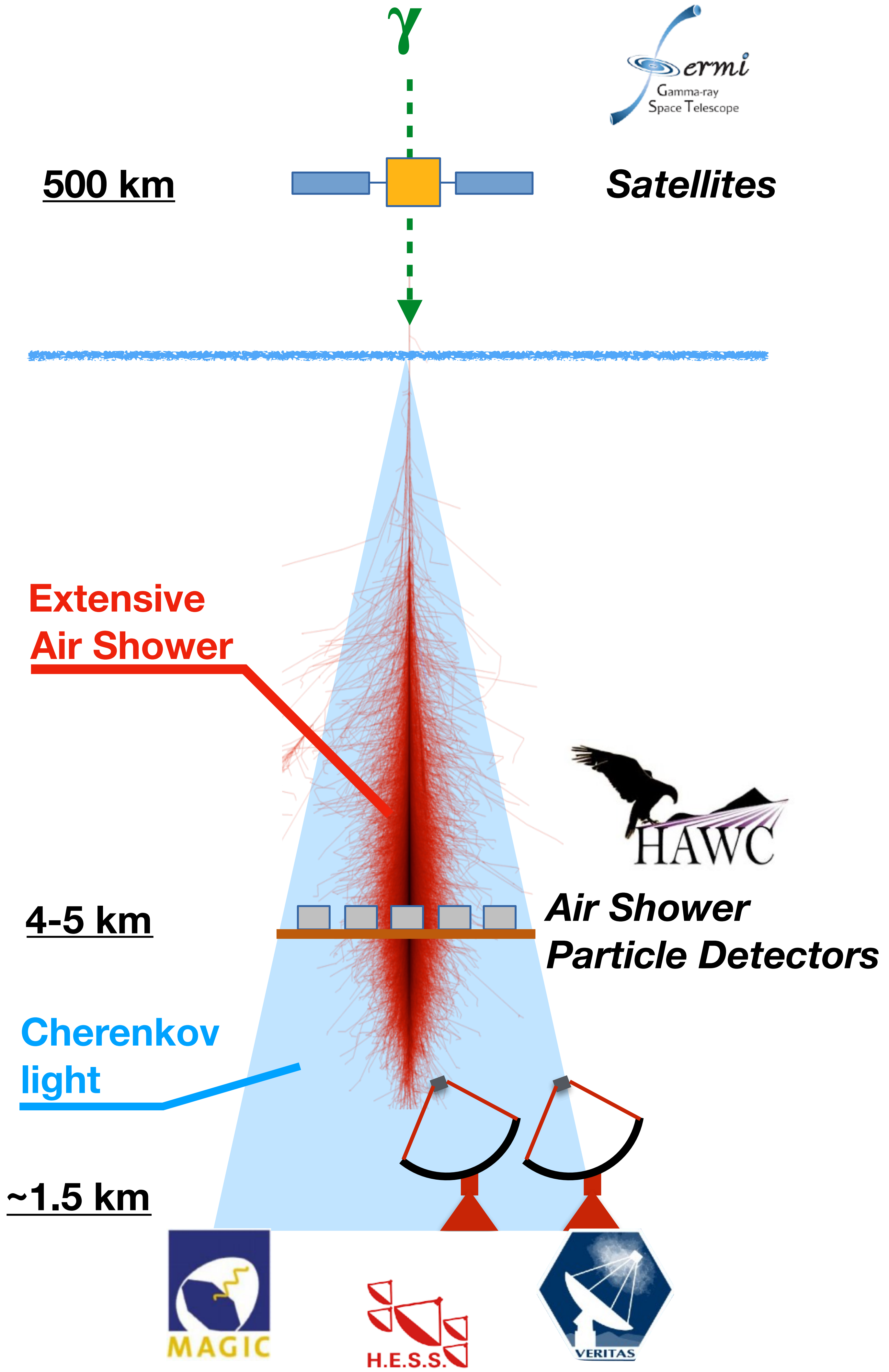

3 DORITOS LATER

Astroparticle Physics: Lab to test Fundamental Physics **and LIV tests**

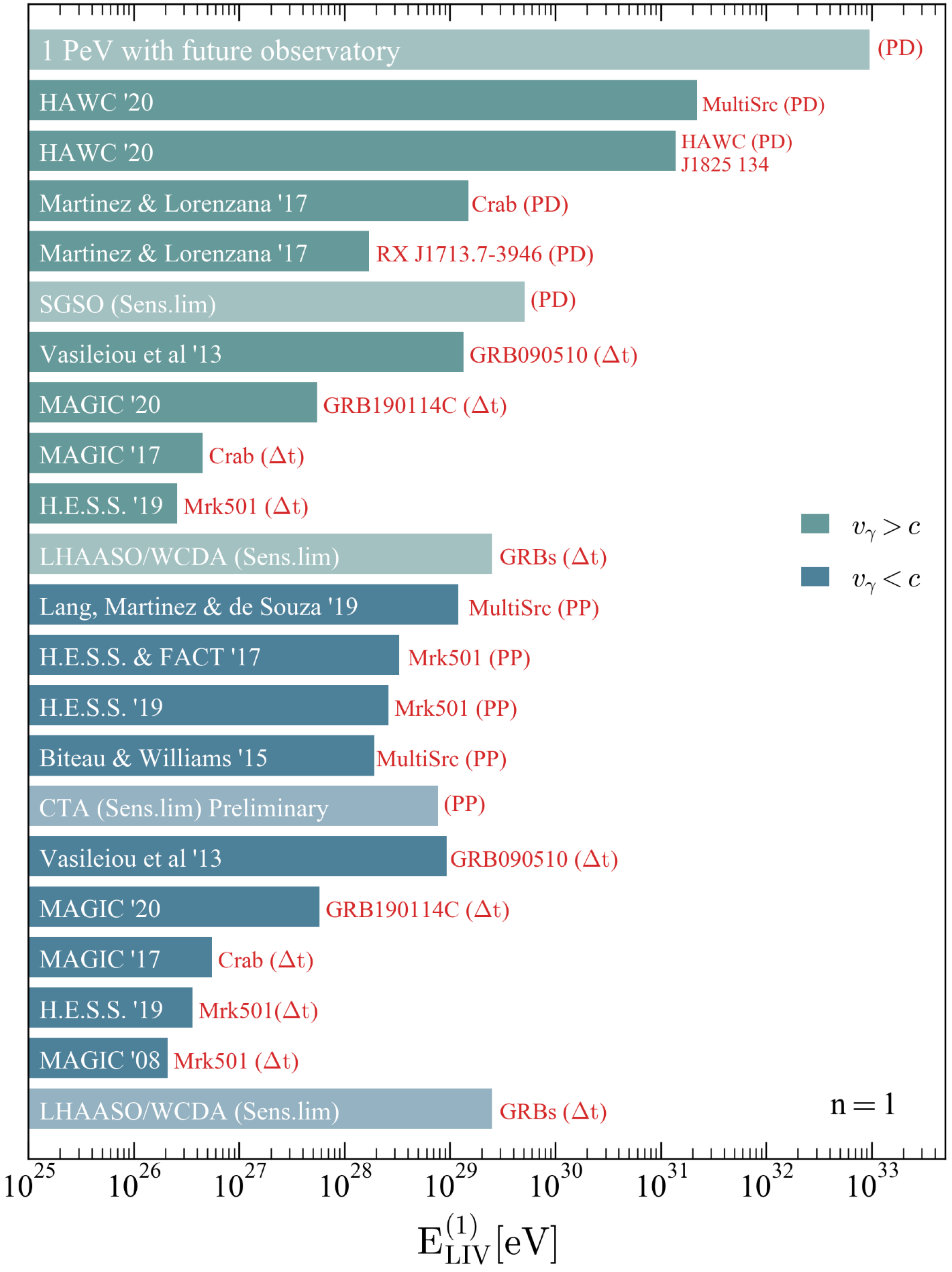
Theory ⟷ Phenomenology ⟷ Experiment (E_{LIV}?)

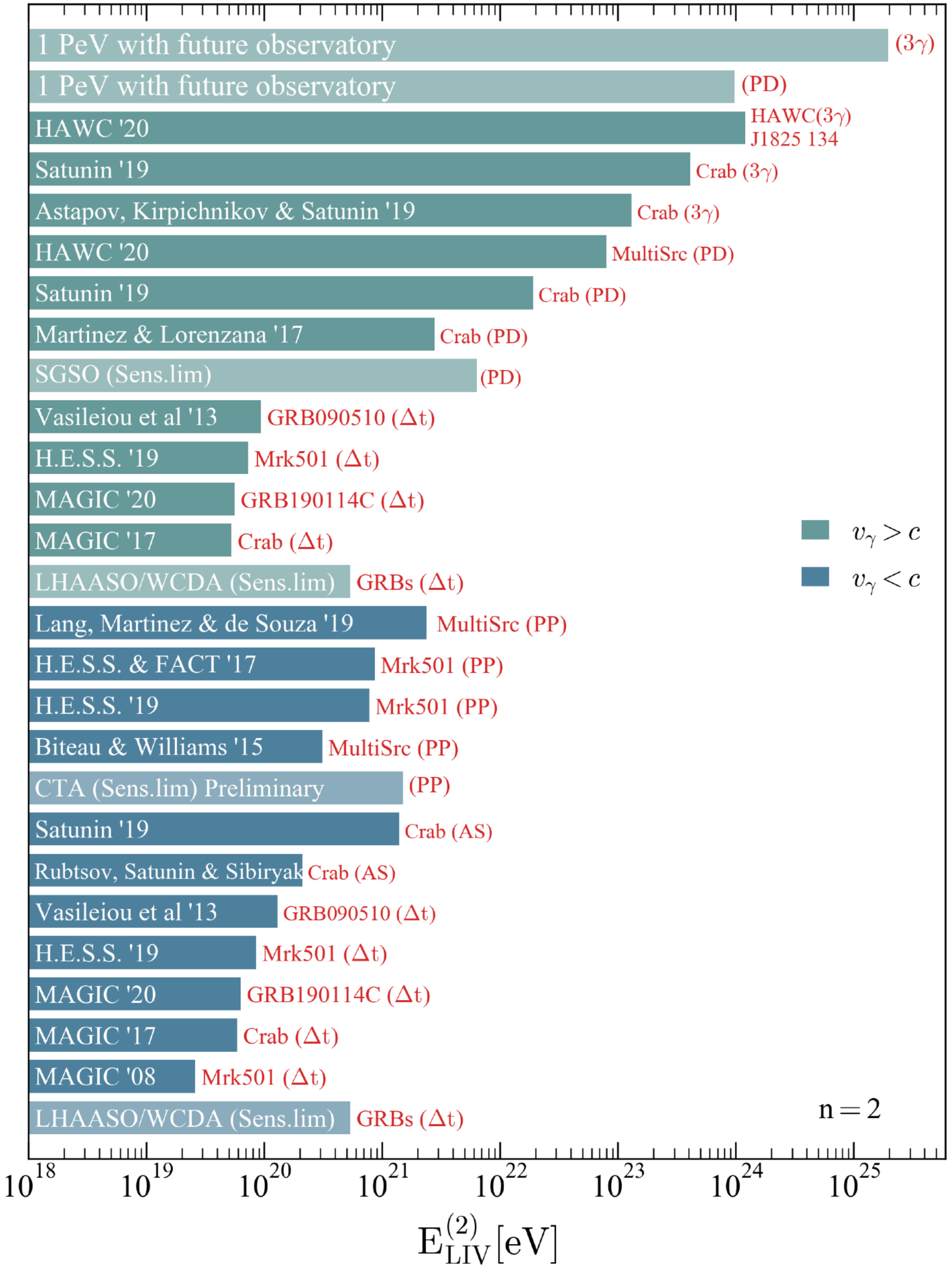


Some effects of LIV are expected to **increase with the energy** and **the very long distances** due to cumulative processes



Strong LIV Exclusion limits in the photon sector by astroparticle tests





Based on:
Symmetry 2020, 12, 1232.

Strong LIV Exclusion limits in the photon sector by astroparticle tests

Photon splitting

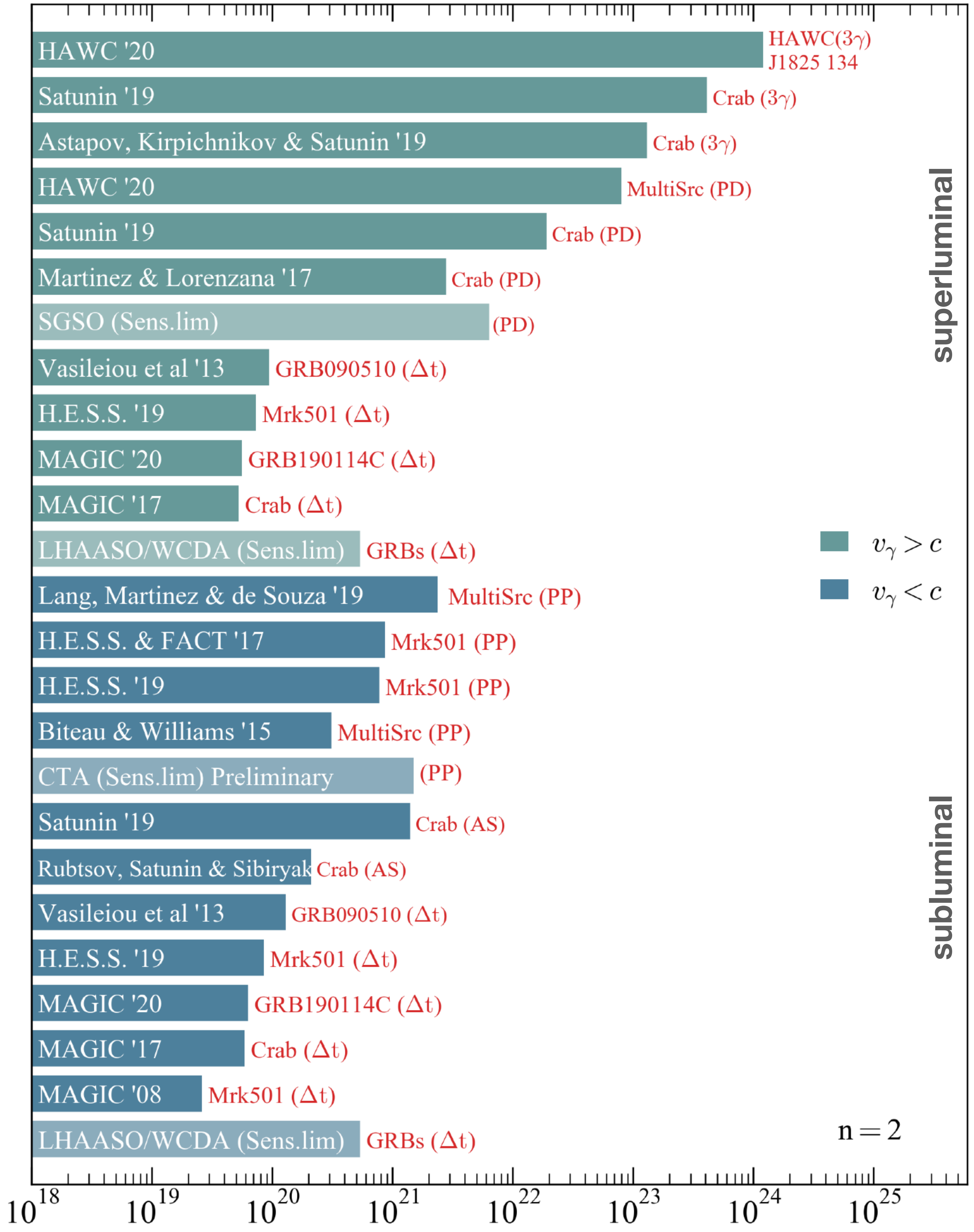
Photon decay

Energy-dependent time delay

Pair production threshold shifts

Suppression of Air Shower

Energy-dependent time delay



Strong LIV Exclusion limits in the photon sector by astroparticle tests

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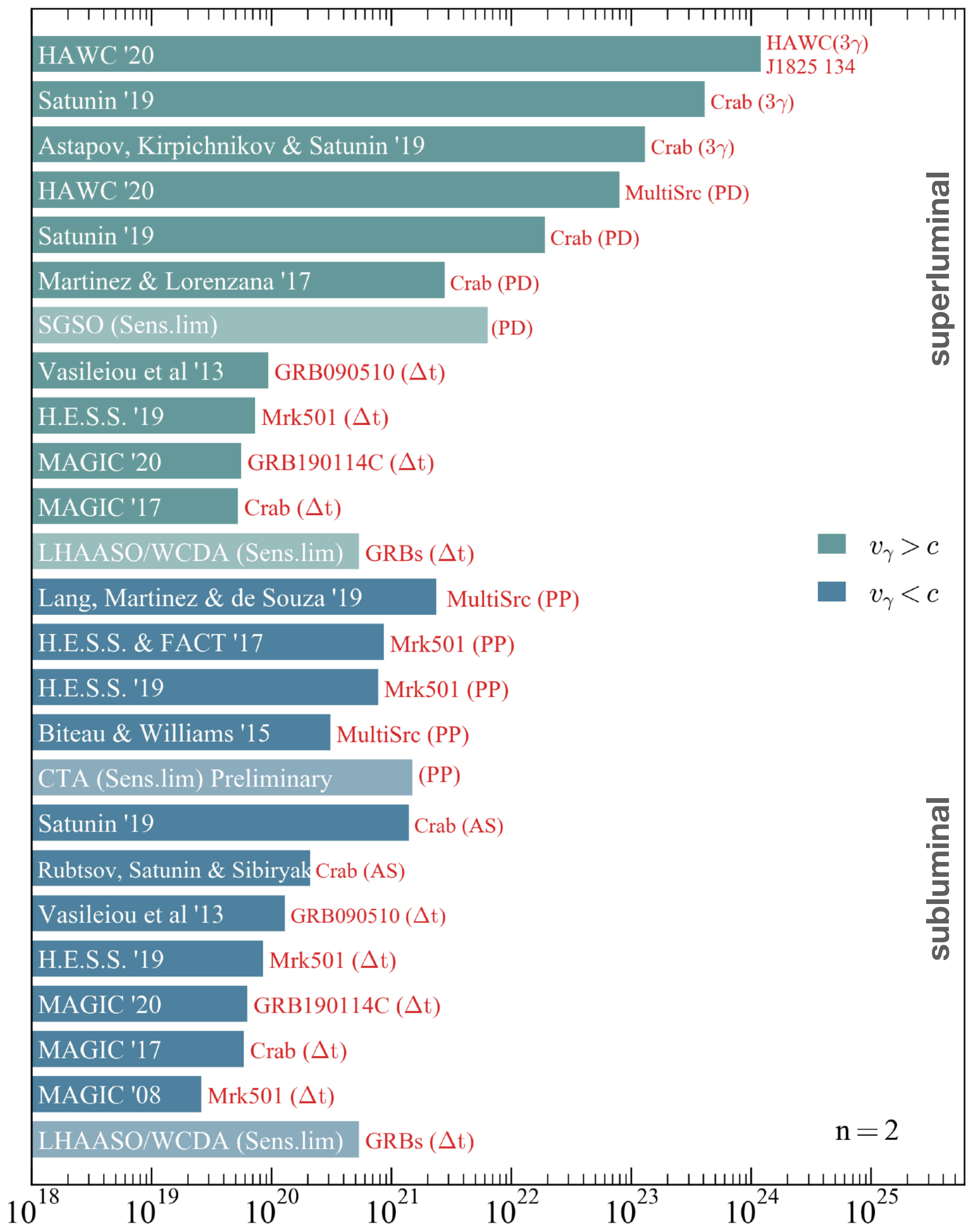


Constraints on Lorentz invariance violation using HAWC observations above 100TeV
HAWC Collaboration,
Phys Rev Lett. 124,131101 (2020)

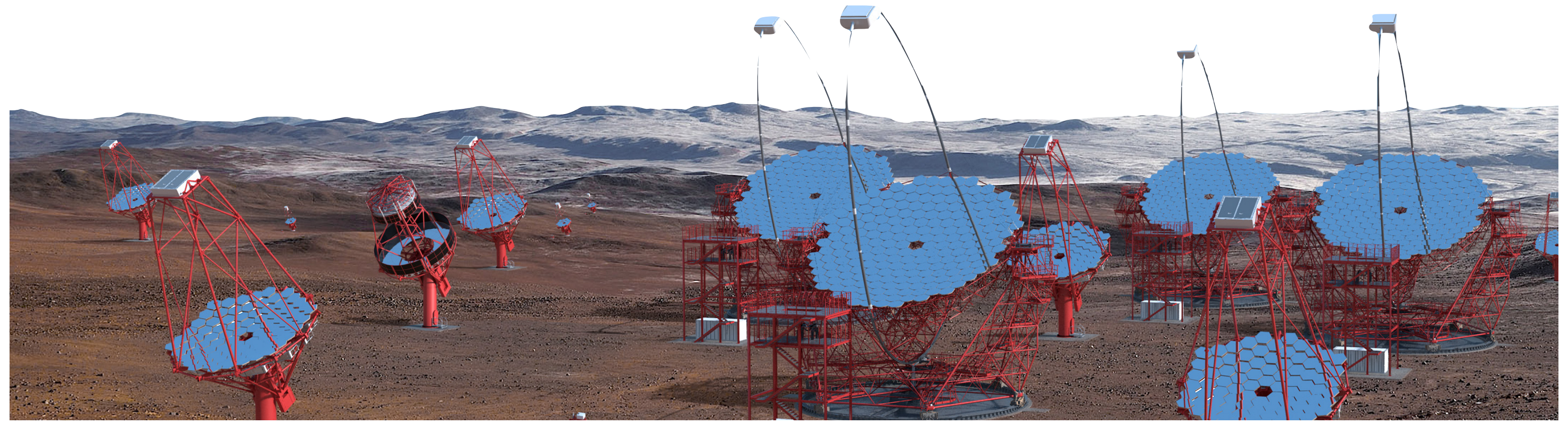
H. Martínez-Huerta, A. Pérez-Lorenzana.
Physical Review D 95, 063001 (2017)

SGSO Alliance arXiv:1902.08429
SWGO arXiv:1907.07737

phenomenology for different techniques and instruments

Lang, Martínez-Huerta and de Souza
Phys.Rev. D99 (2019) no.4.
***Lang, Martínez-Huerta and de Souza**
Astrophys.J. 853 (2018) no.1, 23

Sensitivity of the Cherenkov Telescope Array for probing cosmology and fundamental physics with gamma-ray propagation
CTA Consortium. (arXiv:**2010**.01349)



2→2

with LIV

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

LI: $E_a^2 - p_a^2 = m_a^2$ ⟶ **LIV** $S_{foton} = \omega^2 - k^2 = -\alpha_n\omega^{n+2};$ $(+\alpha_n k^{n+2})$

$$S_\pm = E_\pm^2 - p_\pm^2 = m_e^2 - \alpha_{n\pm}E_\pm^{n+2} \quad (+\alpha_{(n,\pm)}p_\pm^{n+2})$$

$$\omega\omega_b \approx m_e^2$$

$E >> m$

$E \sim p$

$$S_{inicial}^{VIL} = -\alpha\omega^{n+2} - \alpha_b^{n+2} + 2\omega\omega_b - 2kk_b\cos\theta_i,$$

$$S_{final}^{VIL} = -\alpha_{n+}E_+^{n+2} - \alpha_{n-}E^{n+2} + 2m_e^2 + 2E_+E_- - 2p_+p_-\cos\theta_f,$$

$$\begin{aligned}
&4\omega\omega_b - m_e^2\left(2 + \frac{(2K^2-2K)+1}{K(1-K)} - \frac{m_e^2}{2K(1-K)(\omega+\omega_b+\Xi)^2}\right)\\
&= \alpha_n\omega^{n+2}\left[1 + \frac{\omega_b^{n+2}}{\omega^{n+2}} - \frac{\omega_b}{\omega}\left(1+\frac{\omega_b^n}{\omega^n}\right)\right]\\
&+ \alpha_{n+}K^{n+1}(\omega+\omega_b+)^{n+2}\left[-K-(1-K)+\frac{m_e^2}{2}\frac{1}{(1-K)(\omega+\omega_b)^2}\right]\\
&+ \alpha_{n-}(1-K)^{n+1}(\omega+\omega_b)^{n+2}\left[-(1-K)-K+\frac{m_e^2}{2}\frac{1}{K(\omega+\omega_b)^2}\right].
\end{aligned}$$

$$E_+ + E_- := \omega + \omega_b + \Xi,$$

$$E_+ := K(\omega+\omega_b+\Xi),$$

$$E_- := (1-K)(\omega+\omega_b+\Xi).$$

$$m_e,\ \omega_b,\ \Xi \ll \omega$$

$\gamma\gamma_b \to e^+e^-$

LI: $E_a^2 - p_a^2 = m_a^2$ $\longrightarrow$ **LIV** $S_{foton} = \omega^2 - k^2 = -\alpha_n \omega^{n+2};$ $(+\alpha_n k^{n+2})$

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$$4\omega\omega_b - m_e^2\left(2 + \frac{(2K^2 - 2K) + 1}{K(1-K)} - \frac{m_e^2}{2K(1-K)(\omega + \omega_b + \Xi)^2}\right)$$
$$= \alpha_n\omega^{n+2}\left[1 + \frac{\omega_b^{n+2}}{\omega^{n+2}} - \frac{\omega_b}{\omega}\left(1 + \frac{\omega_b^n}{\omega^n}\right)\right]$$
$$+ \alpha_{n+}K^{n+1}(\omega + \omega_b +)^{n+2}\left[-K - (1-K) + \frac{m_e^2}{2}\frac{1}{(1-K)(\omega+\omega_b)^2}\right]$$
$$+ \alpha_{n-}(1-K)^{n+1}(\omega+\omega_b)^{n+2}\left[-(1-K) - K + \frac{m_e^2}{2}\frac{1}{K(\omega+\omega_b)^2}\right].$$

$$E_+ + E_- := \omega + \omega_b + \Xi,$$

$$E_+ := K(\omega + \omega_b + \Xi),$$

$$E_- := (1-K)(\omega + \omega_b + \Xi).$$

$m_e,\ \omega_b,\ \Xi \ll \omega$

$\gamma\gamma_b \to e^+e^-$

$$\frac{m_e}{\omega} \ll 1, \quad \frac{\omega_b}{\omega} \ll 1,$$

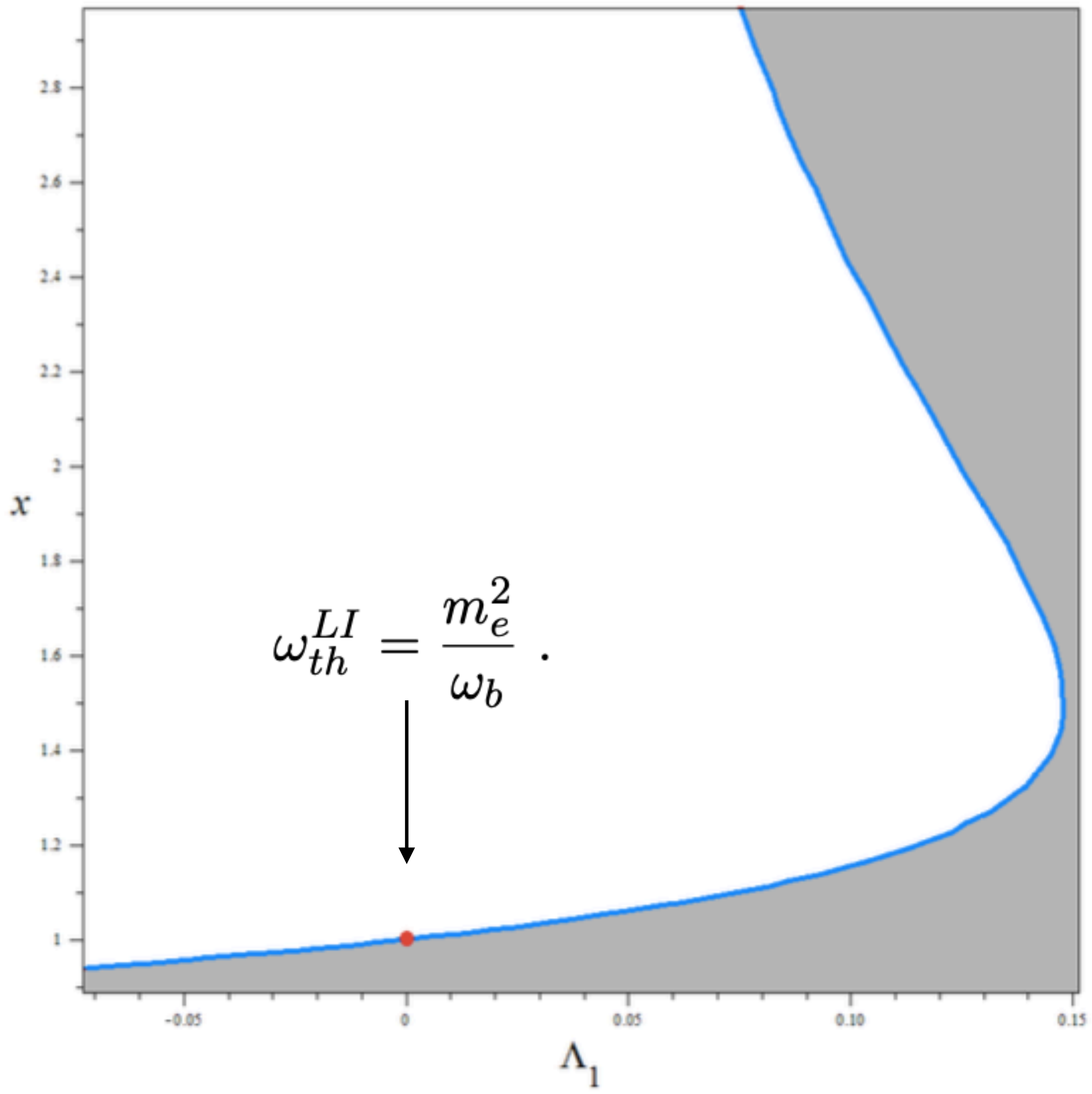
$$\boxed{4\omega\omega_b - \frac{m_e^2}{K(1-K)} = \left[\alpha_n - \alpha_{n+}K^{n+1} - \alpha_{n-}(1-K)^{n+1}\right]\omega^{n+2}.}$$

Let be:

$$x = \frac{4\omega_b K(1-K)}{m_e^2}\omega := \frac{1}{\omega_0}\omega,$$

$$\Lambda_n := \frac{\omega_0^{n+1}}{4\omega_b}\left[\alpha_n - \alpha_{n+}K^{n+1} - \alpha_{n-}(1-K)^{n+1}\right],$$

$$\boxed{\Lambda_n x^{n+2} - x + 1 = 0,}$$



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

$$\frac{m_e}{\omega} \ll 1, \quad \frac{\omega_b}{\omega} \ll 1,$$

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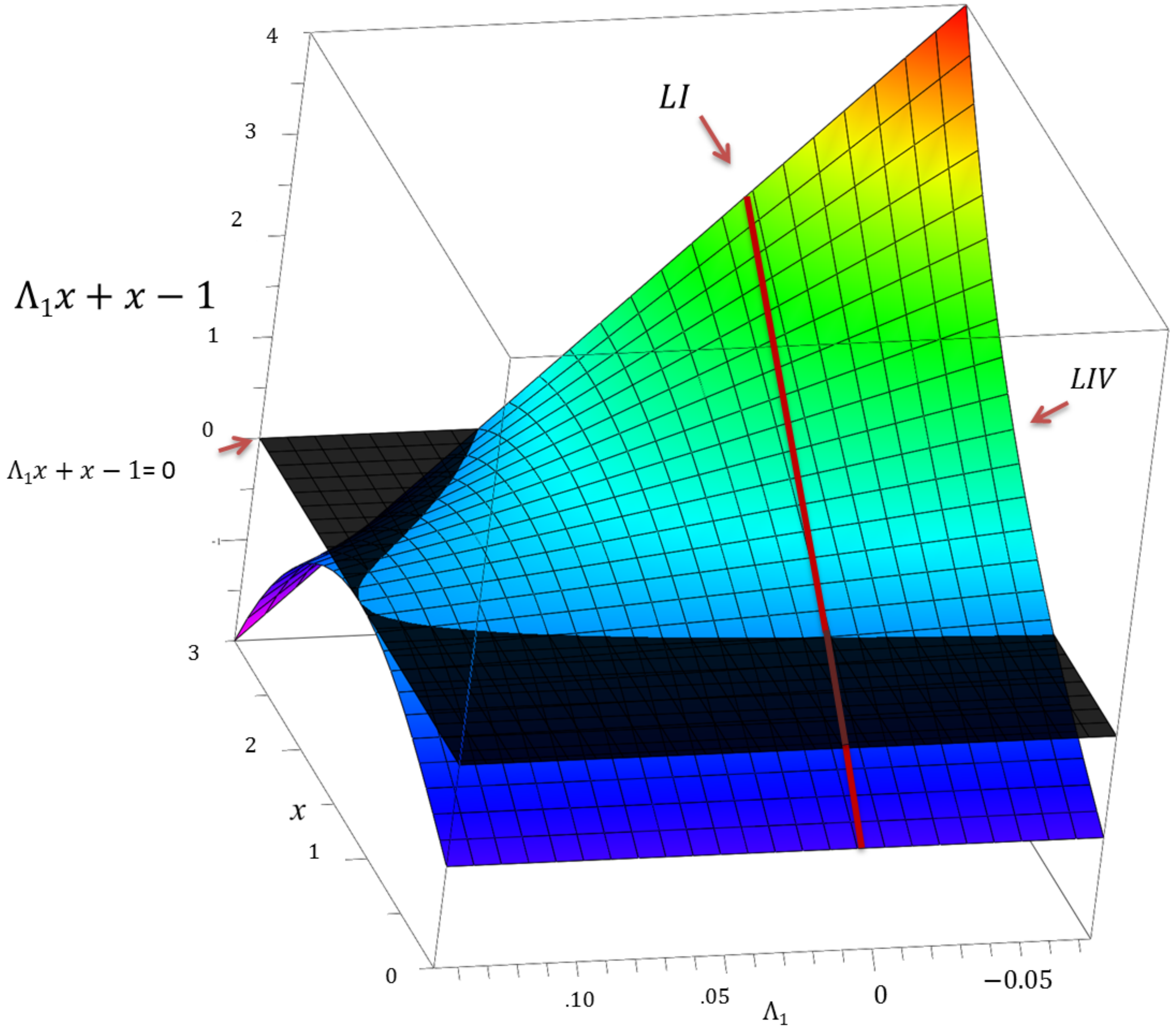


$\gamma\gamma_b \to e^+e^-$

$$\Lambda_{\gamma,n} x_\gamma^{n+2} + x_\gamma - 1 = 0$$

$$x_\gamma = \frac{E_\gamma}{E_\gamma^{\mathrm{LI}}}, \qquad \Lambda_{\gamma,n} = \frac{E_\gamma^{\mathrm{LI}\,(n+1)}}{4\epsilon}\delta_{\gamma,n}.$$

The threshold equation

$$\delta_{\gamma,n} E_\gamma^{n+2} + 4E_\gamma\epsilon - m_e^2 \frac{1}{K(1-K)} = 0$$

Critical point

$$\delta_{\gamma,n}^{lim} = -4\frac{\epsilon}{E_\gamma^{LI\ (n+1)}}\frac{(n+1)^{n+1}}{(n+2)^{n+2}}$$

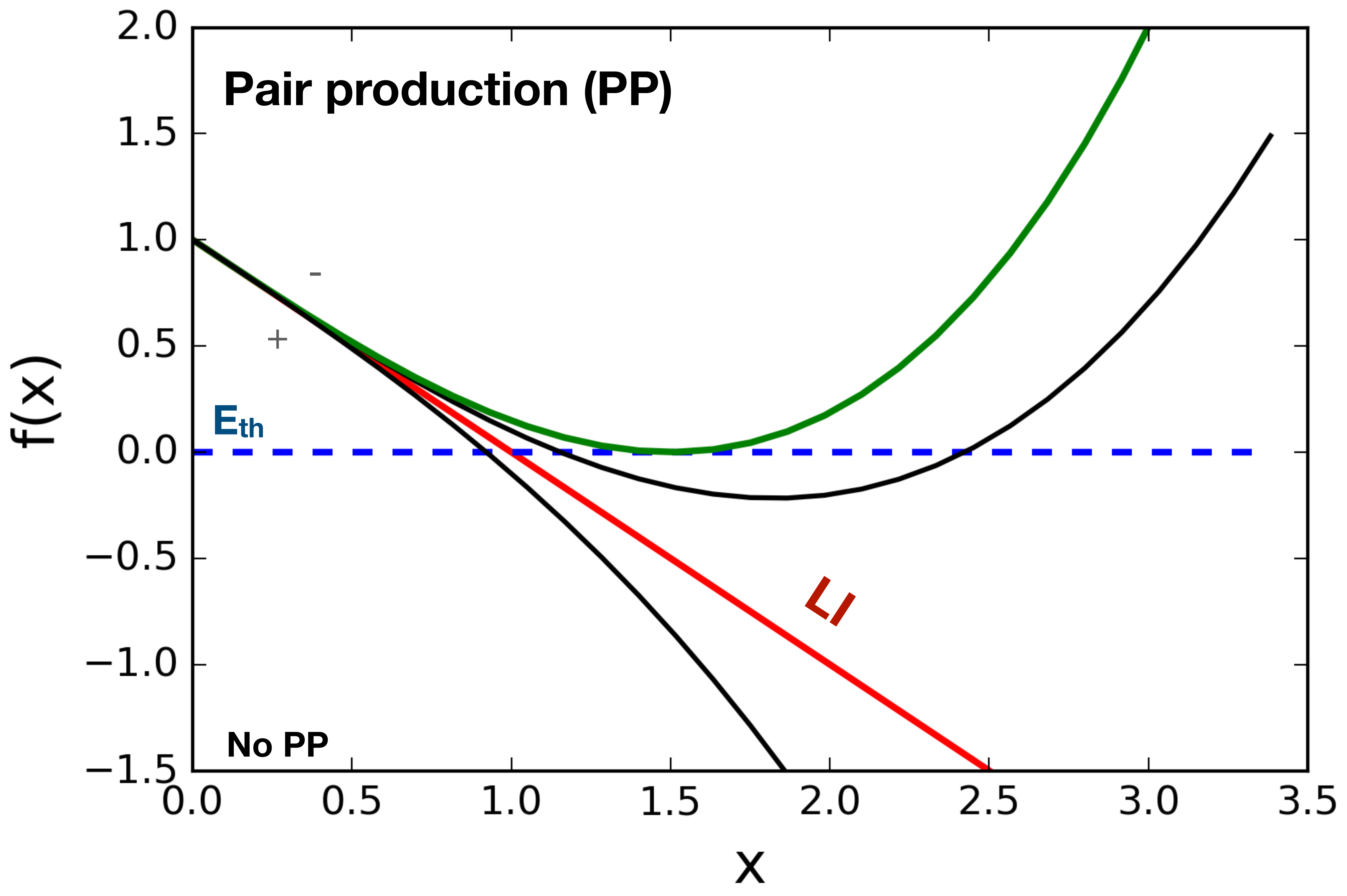
Background:

$$\epsilon_{th}^{\mathrm{LIV}} = \frac{m_e^2}{4E_\gamma K(1-K)} - \frac{\delta_{\gamma,n} E_\gamma^{n+1}}{4}$$

$\Lambda_n < 0$ Threshold-shifts

$\Lambda_n = 0$ LI scenario

$\Lambda_n > 0$ +2nd Threshold



H. Martínez-Huerta, A. Pérez-Lorenzana.
Phys. Rev. D 95, 063001 (2017)

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

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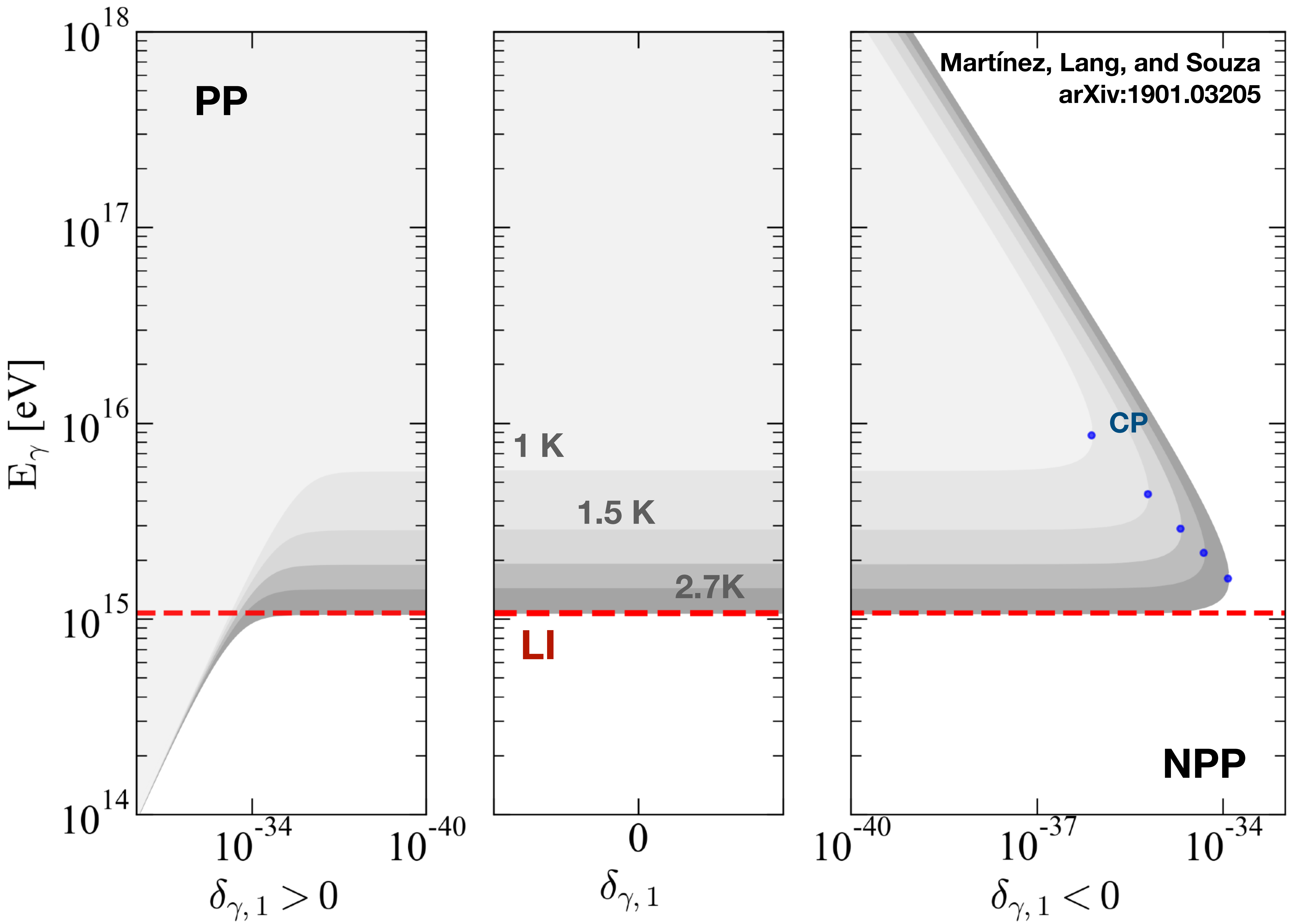
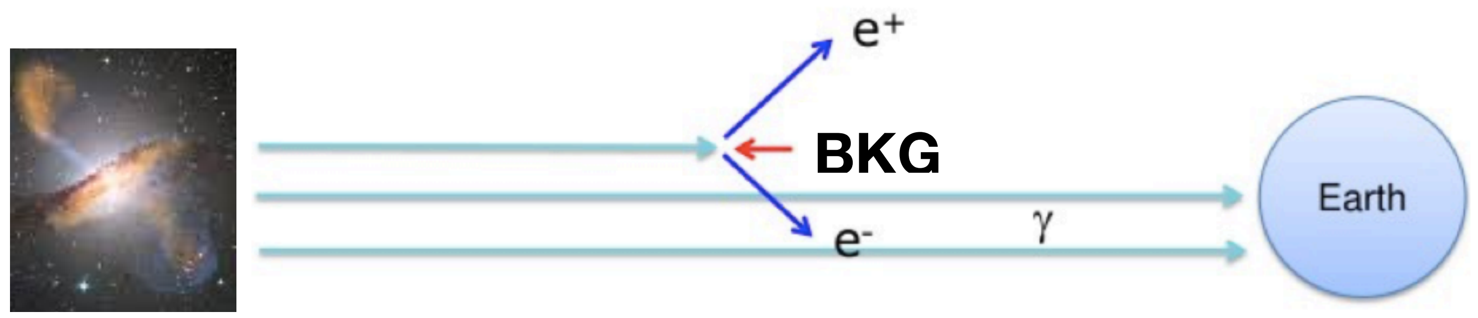
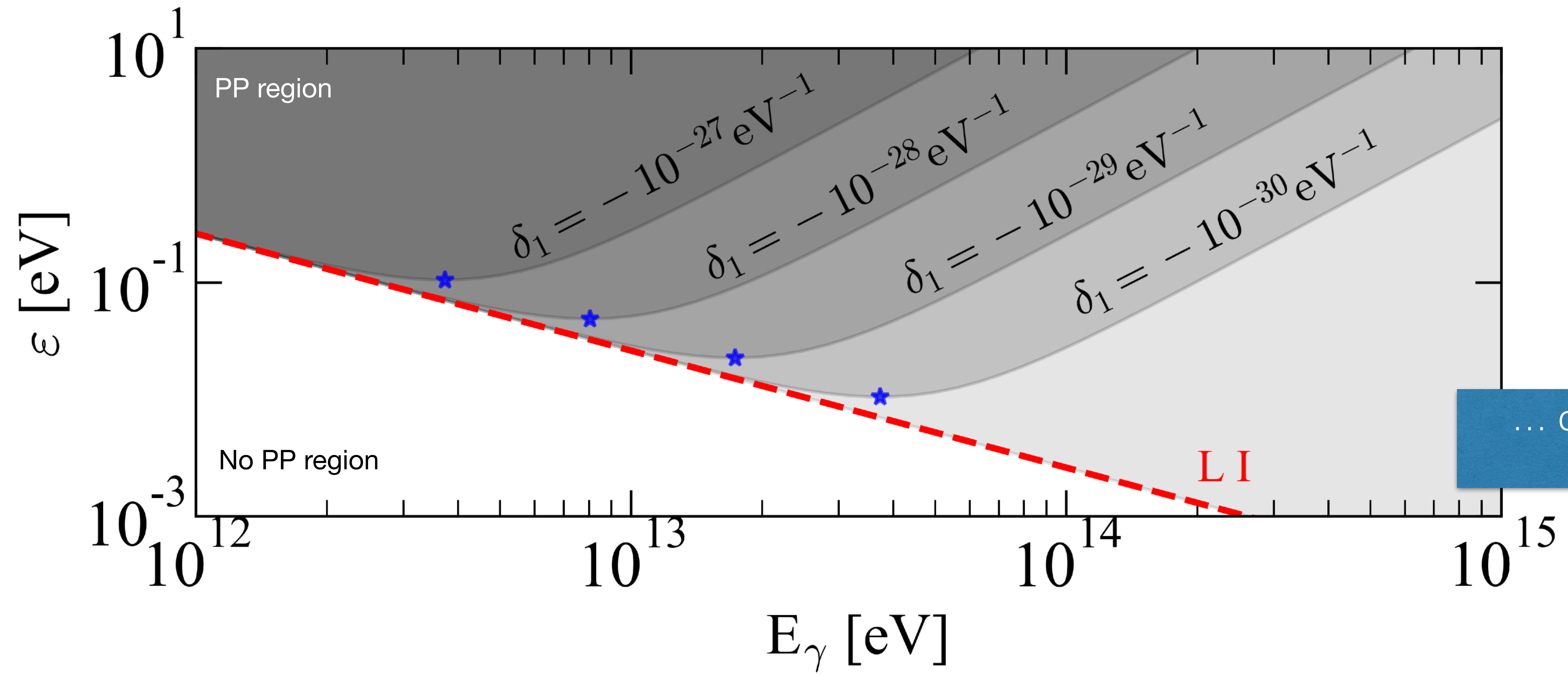


$\gamma\gamma_b \to e^+e^-$

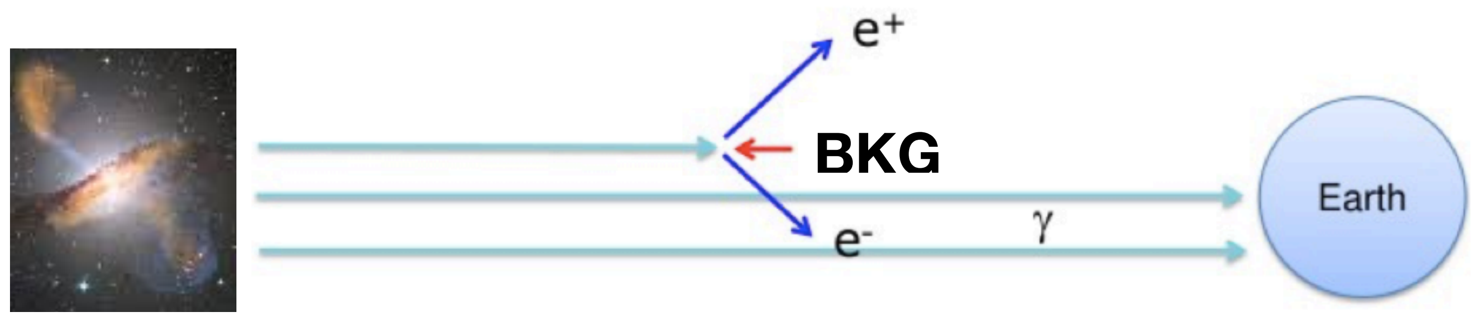


$$\epsilon_{th}^{\rm LIV} = \frac{m_e^2}{4E_\gamma K(1-K)} - \frac{\delta_{\gamma,n}E_\gamma^{n+1}}{4}$$

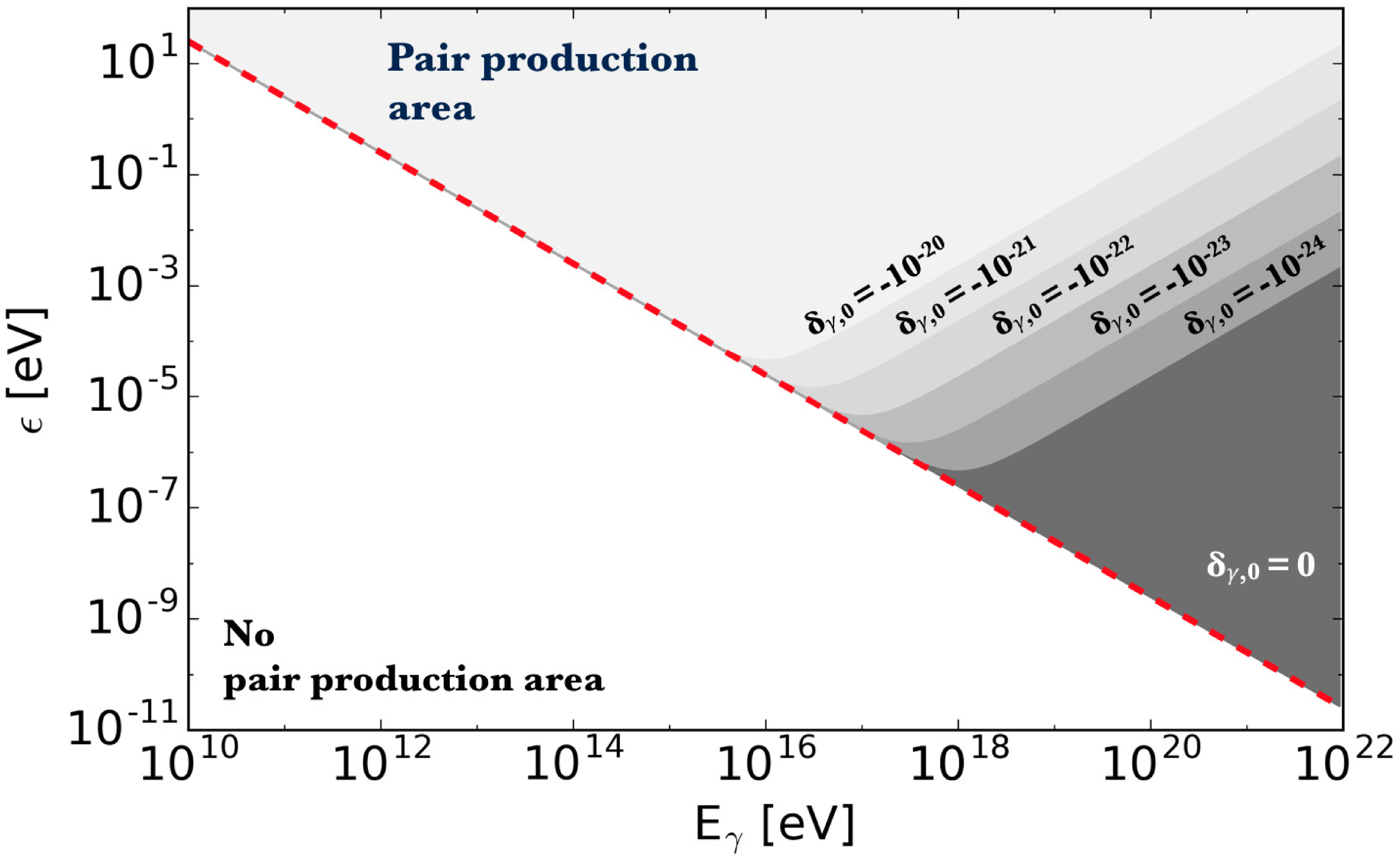


… deeper LIV effects

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

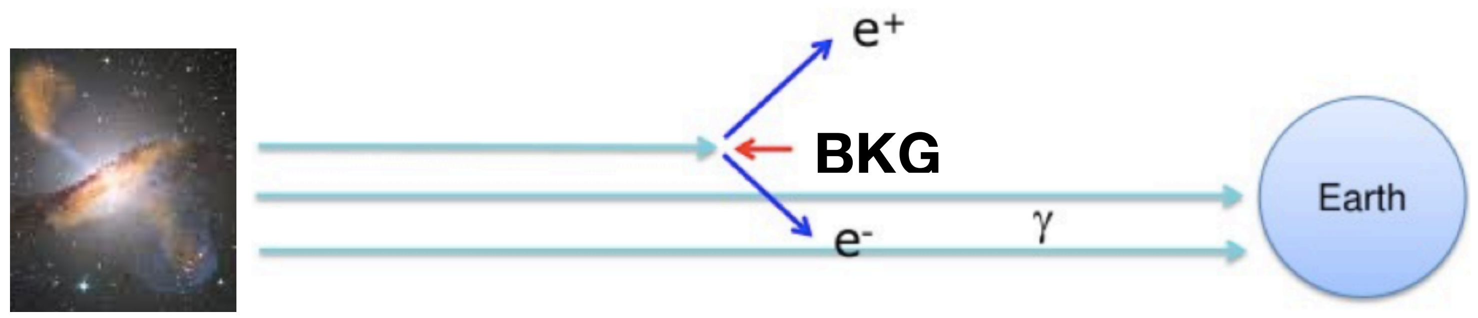


$$\epsilon_{th}^{\mathrm{LIV}} = \frac{m_e^2}{4E_\gamma K(1-K)} - \frac{\delta_{\gamma,n}E_\gamma^{n+1}}{4}$$

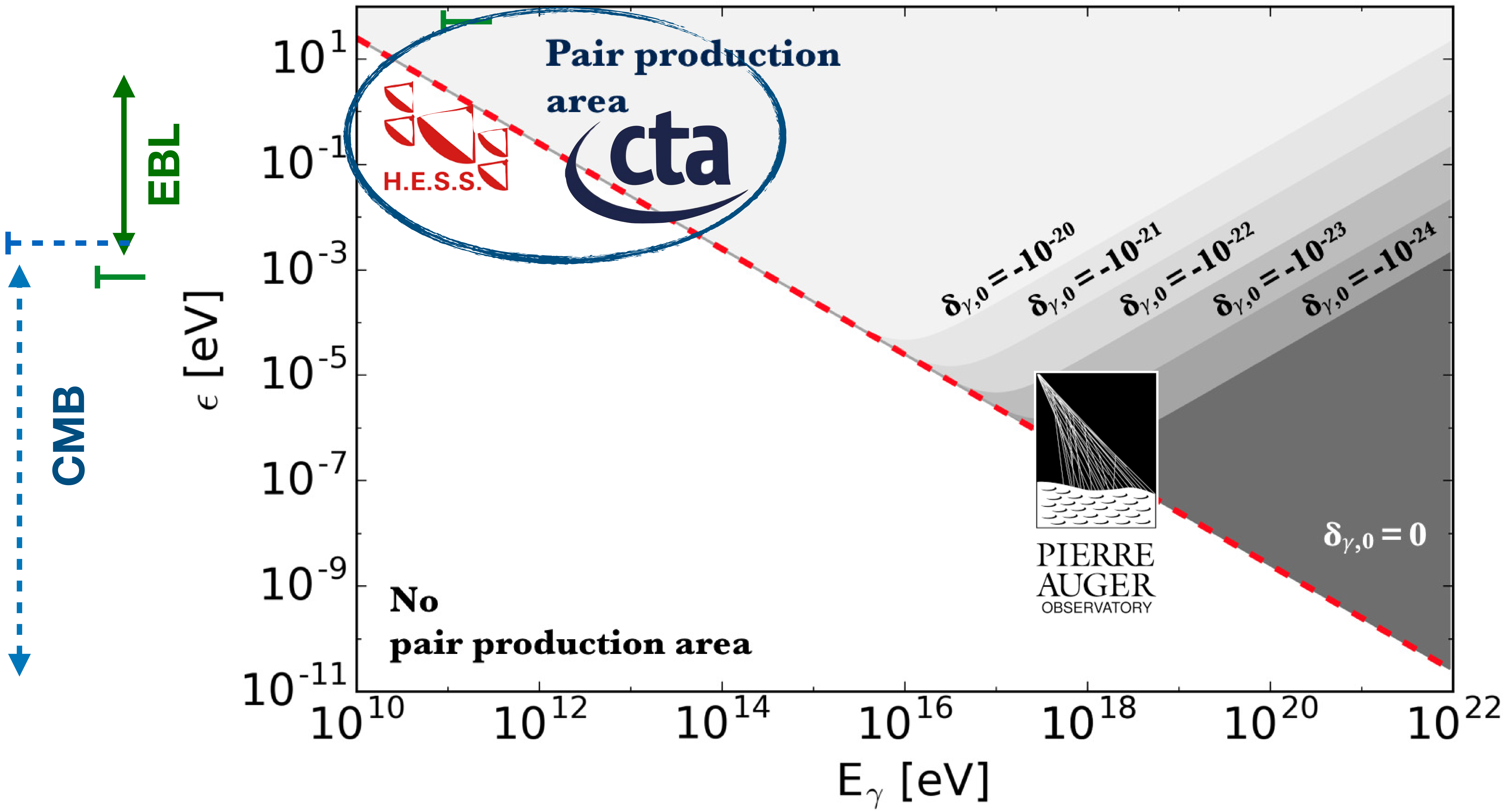


Allowed region change with the LIV parameter and the Energy

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



$$\epsilon_{th}^{\rm LIV} = \frac{m_e^2}{4E_\gamma K(1-K)} - \frac{\delta_{\gamma,n}E_\gamma^{n+1}}{4}$$



… deeper LIV effects

What is the minimum energy that a background photon must have to interacts with a 50 TeV gamma ray to produce an e+ e- pair?

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

$1\ \mathrm{TeV} = 1 \times 10^{12}\mathrm{eV}$

$m_e = 0.511\ \mathrm{MeV}$

What is the minimum energy that a background photon must have to interacts with a 50 TeV gamma ray to produce an e+ e- pair?

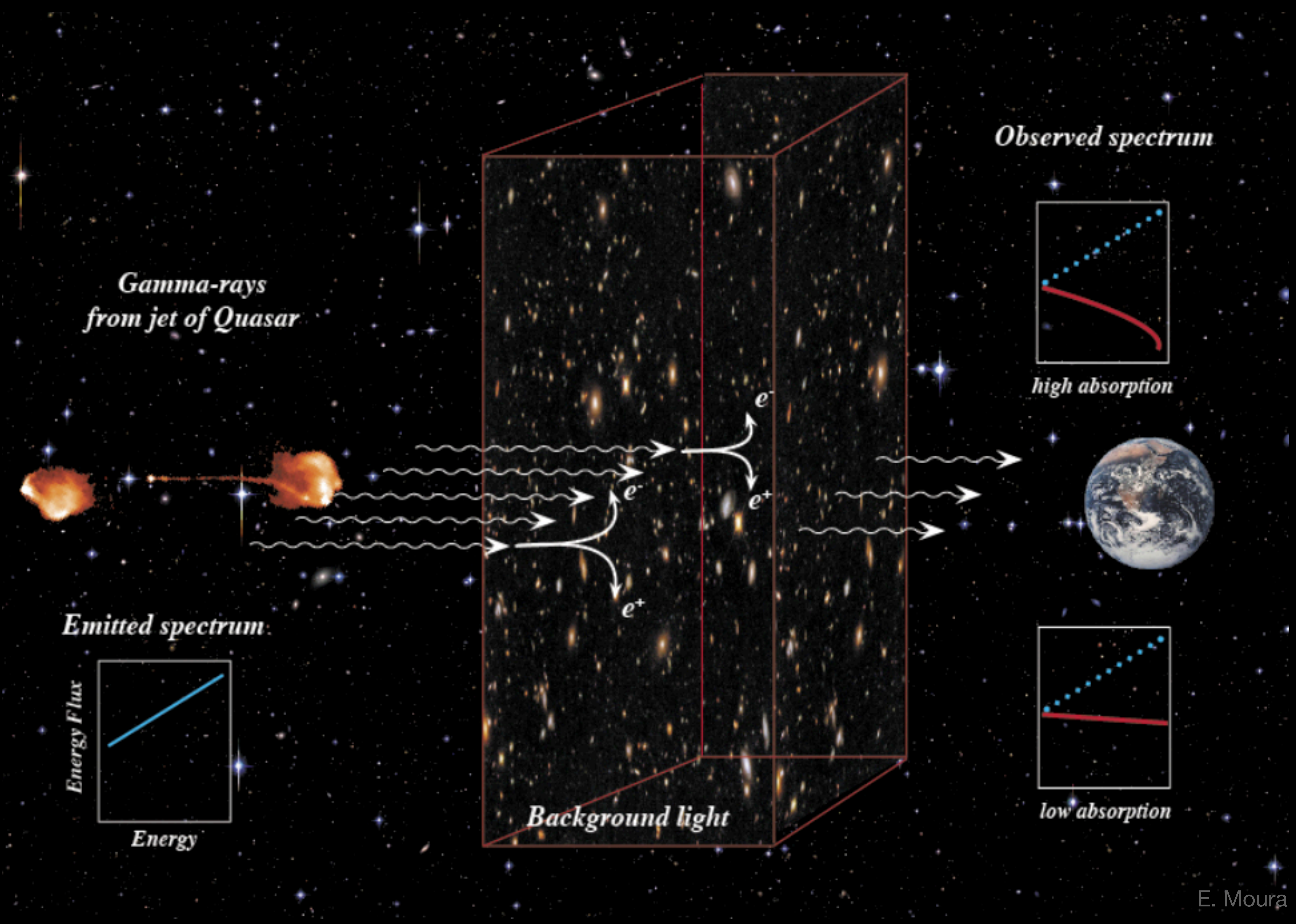
$$\gamma\gamma_b \rightarrow e^+e^-$$

$$\delta_{\gamma,n} = 10^{-26,-28,-29} eV^{-1}$$

$$K = 1/2$$

$$1\ \text{TeV} = 1 \times 10^{12}\text{eV}$$
$$m_e = 0.511\ \text{MeV}$$

-> Compare with LI case



Gamma-rays
from jet of Quasar
Emitted spectrum
Energy Flux
Energy
e⁻
e⁺
e⁻
e⁺
Background light
Observed spectrum
high absorption
low absorption
E. Moura