Neutrinos as a key to a unified theory of particle physics and cosmology

Oleg Ruchayskiy
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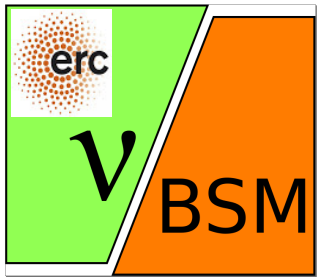

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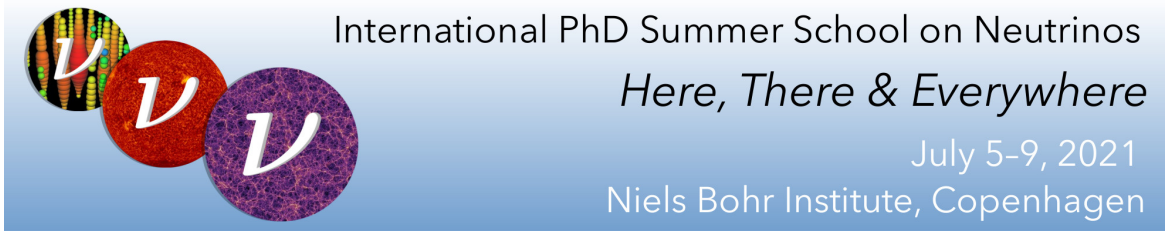
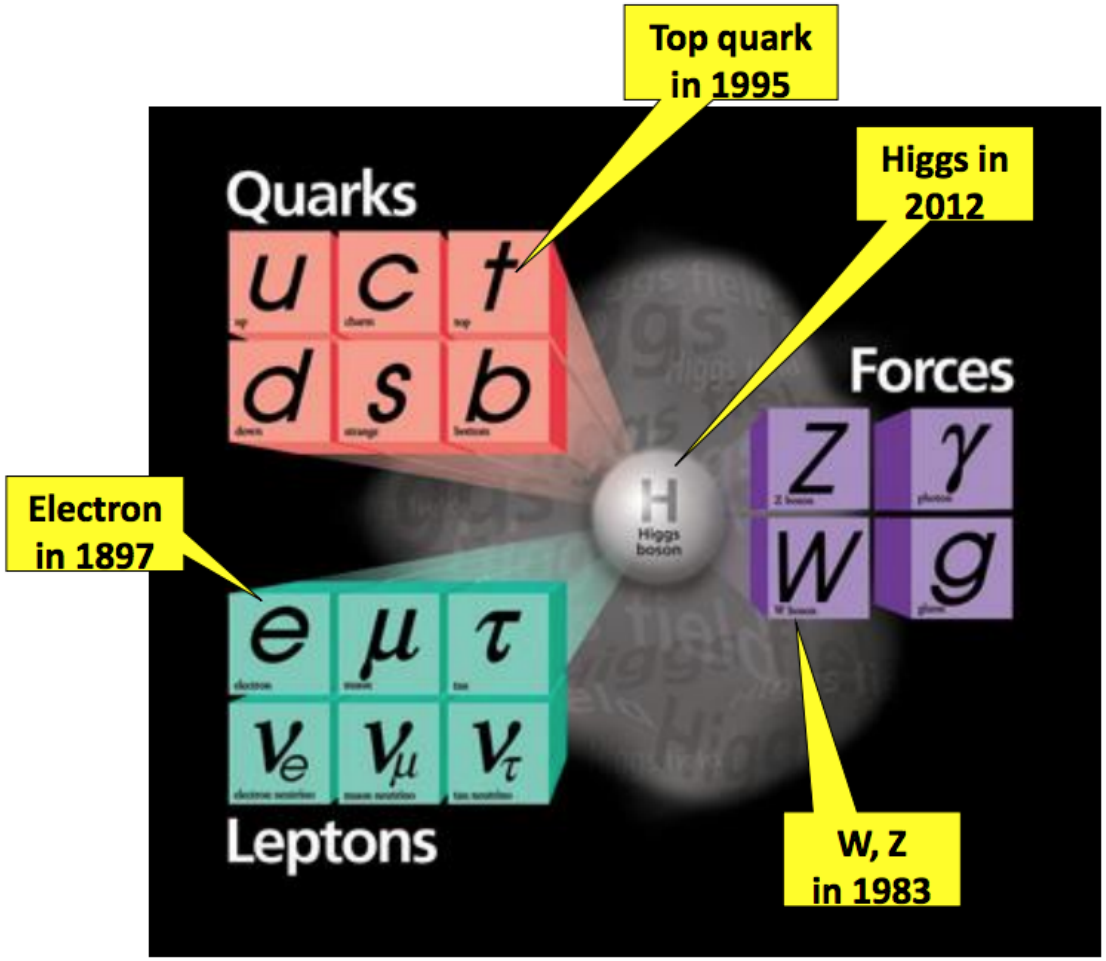
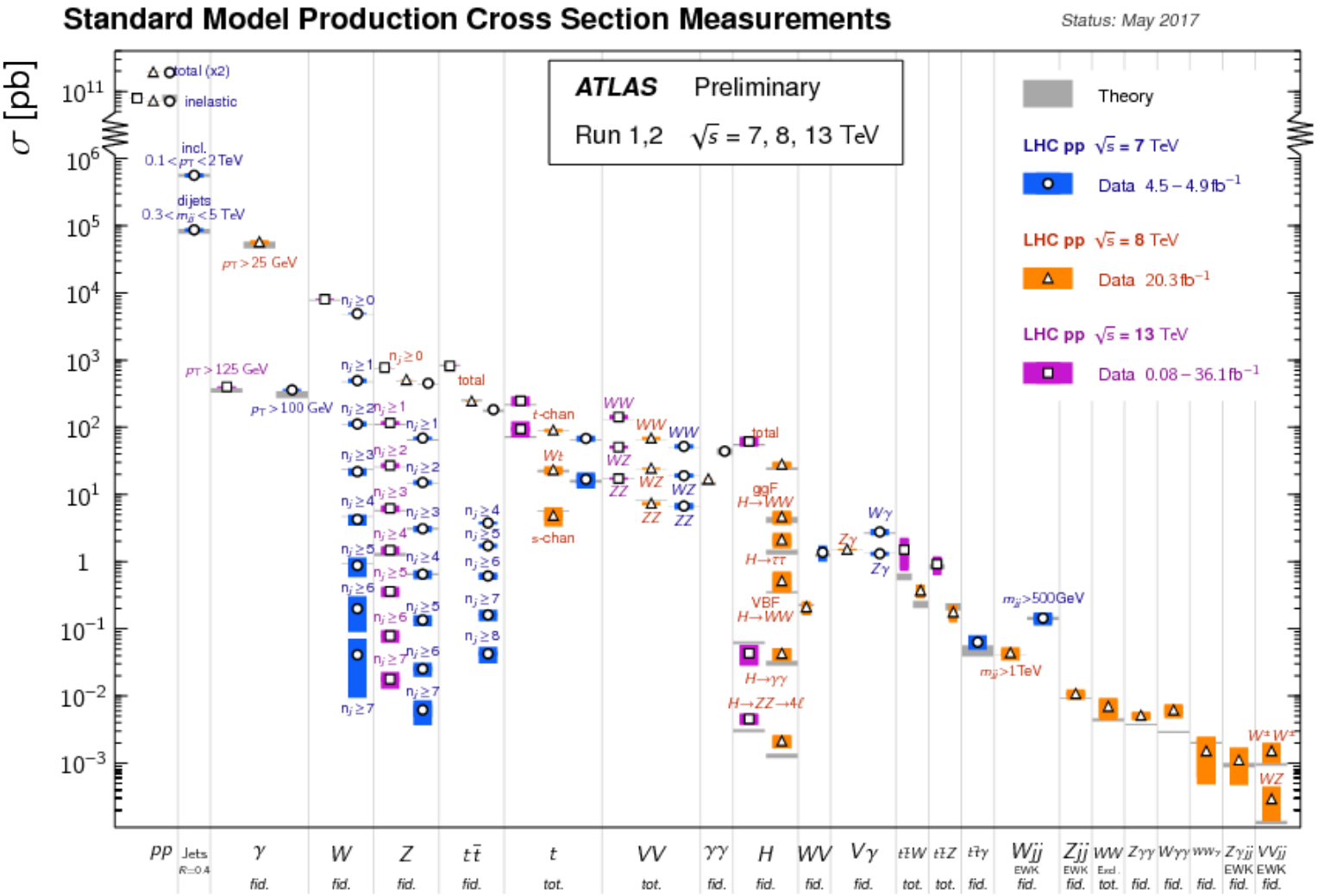


More than a century long history

Our quest to understand radioactivity took **hundred years** and culminated in the discovery of **Higgs boson**



"Stairway to heaven"



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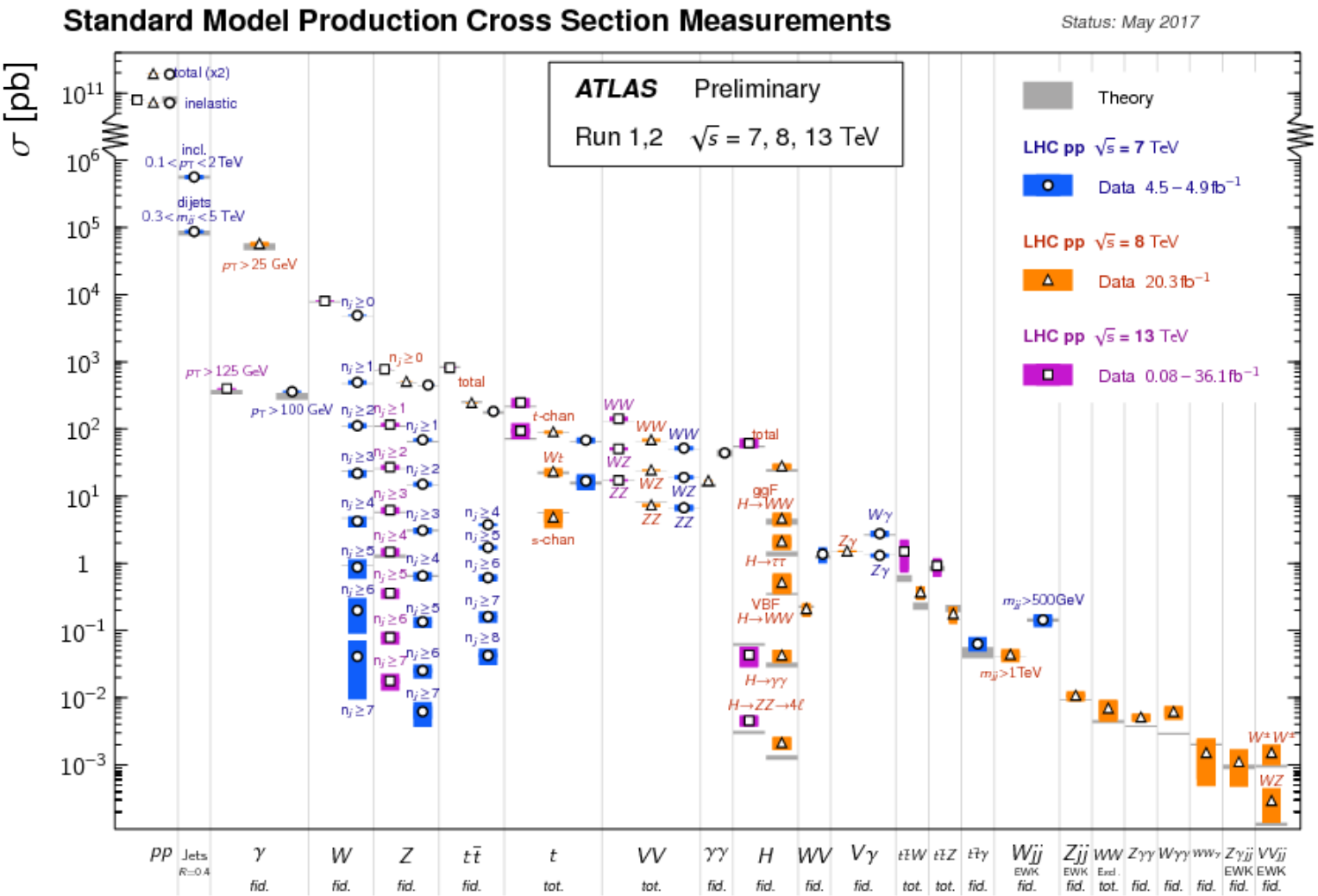
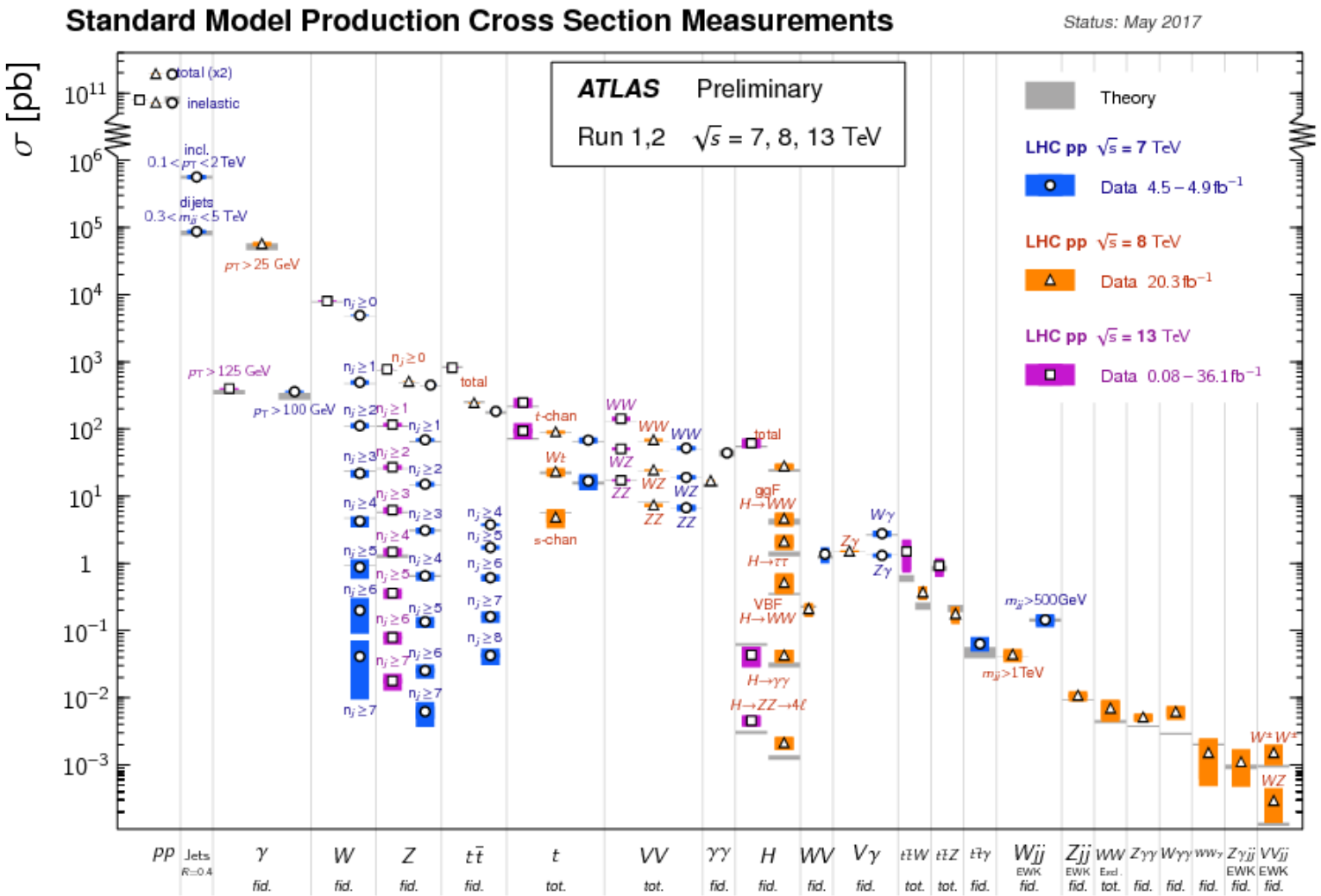


Various particles/types of interactions

"Stairway to heaven"

← Rare ..... Frequent →



Various particles/types of interactions

We find nothing "beyond the Standard Model" at colliders

. . . and destroy expectations of the past generations

Slide by J. Pinfold

Is there anything beyond the Standard Model?

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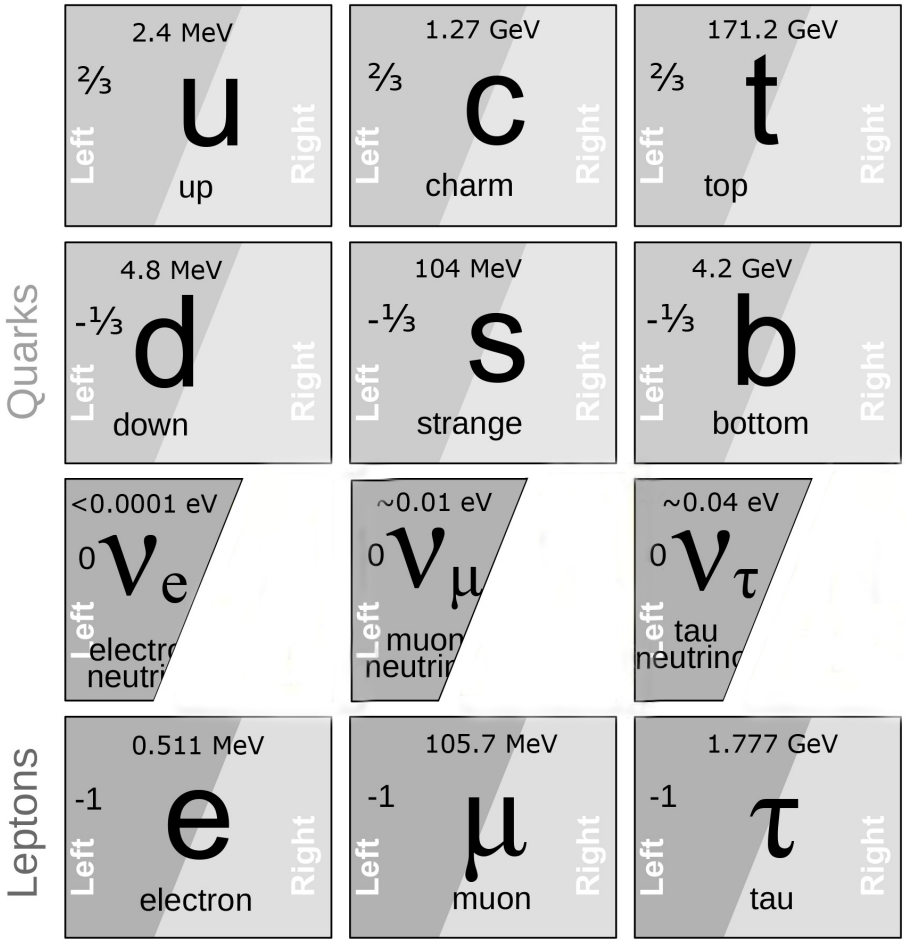
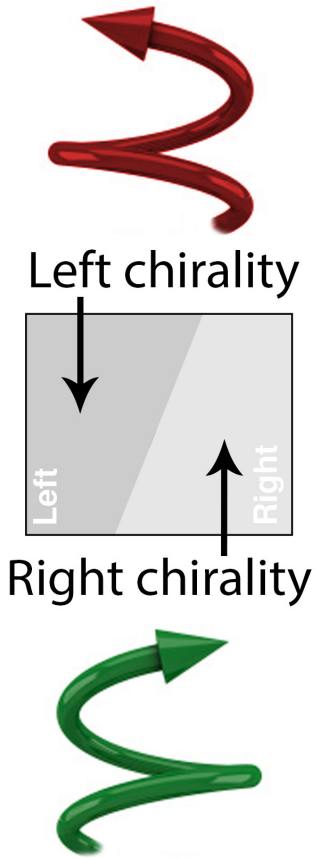
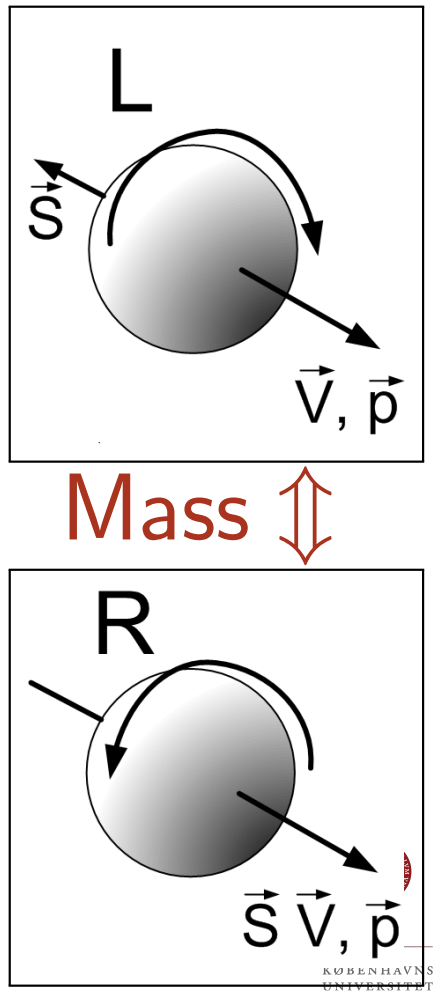
Neutrinos are only "half of the particle"

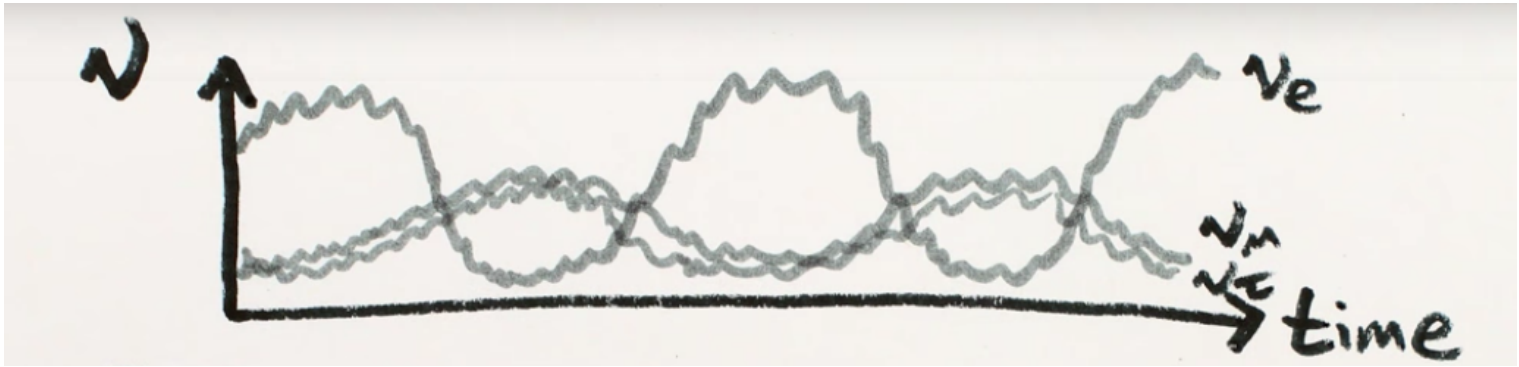
. . . and therefore they are necessarily massless



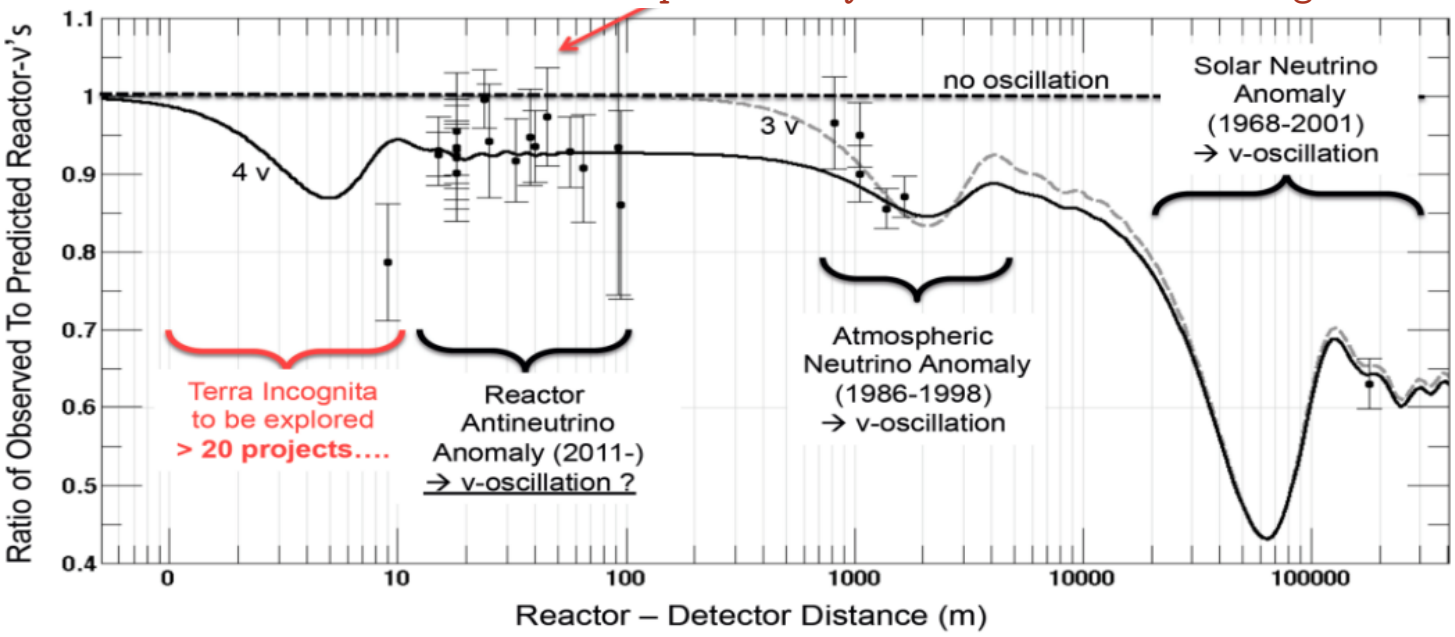




Neutrino "oscillate" – change flavour in flight



https://www.youtube.com/watch?v=7fgKBJDM054



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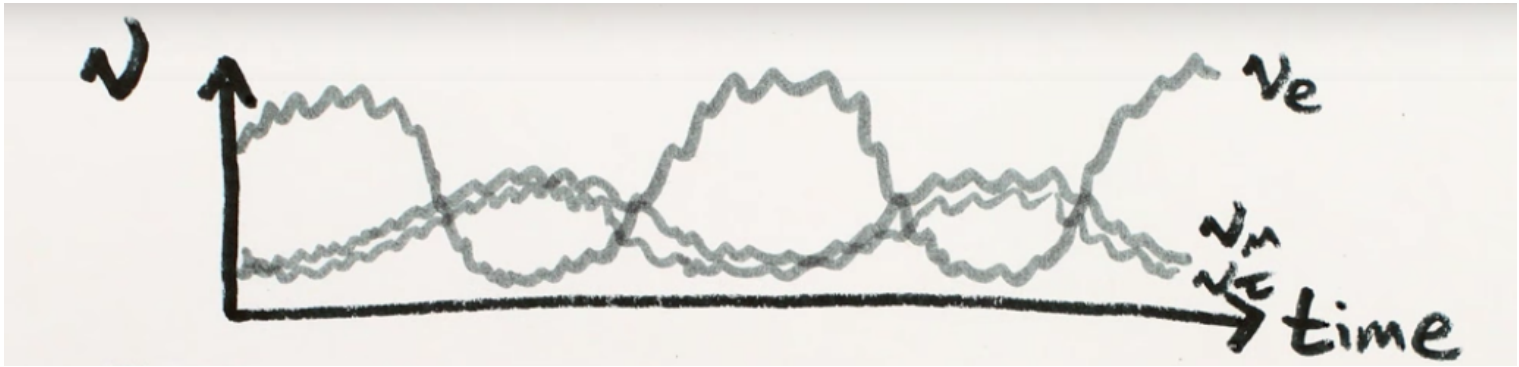
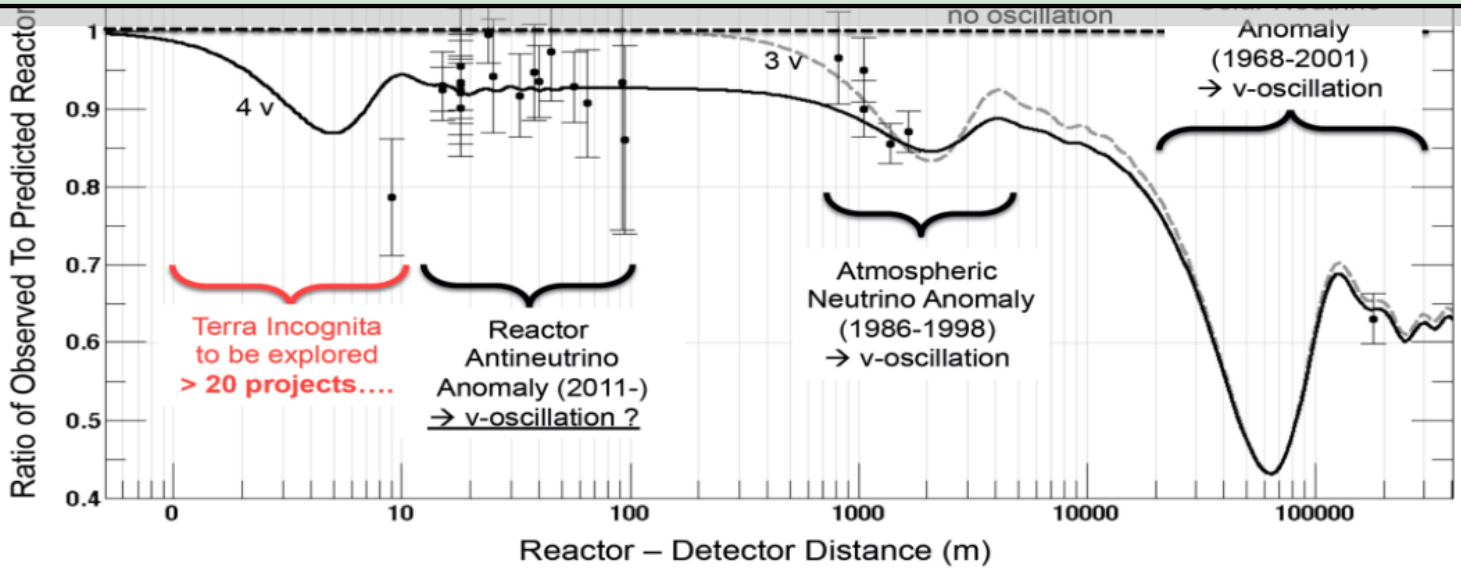
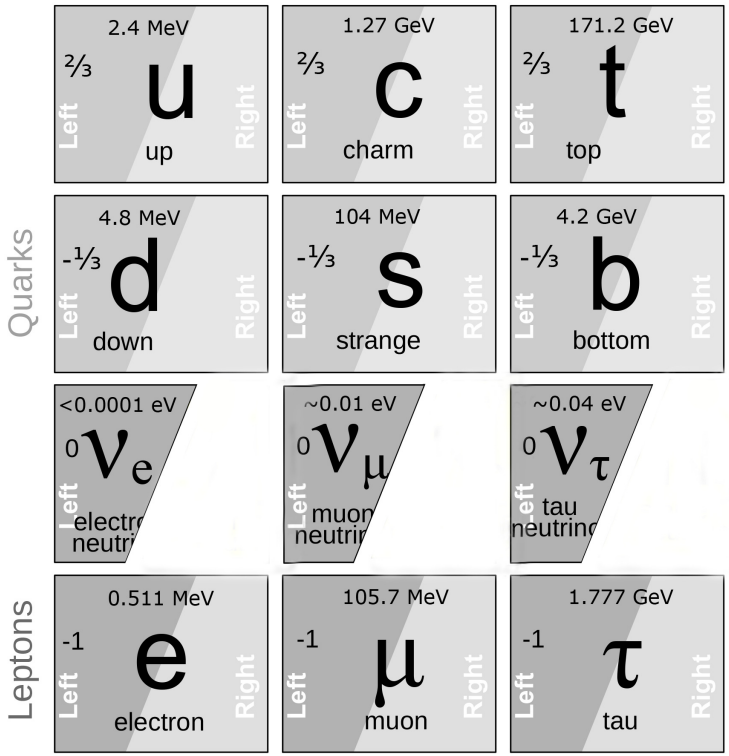
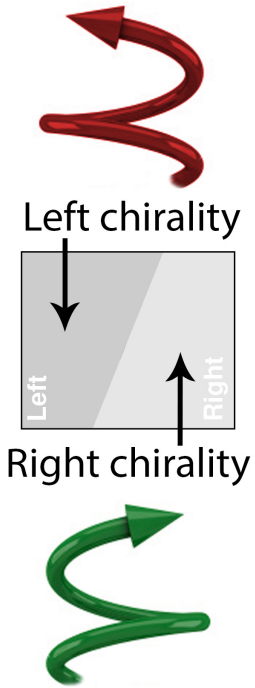


Neutrino oscillations imply mass



Idea: add the second half to neutrinos





- If mass requires two chiralities . . .

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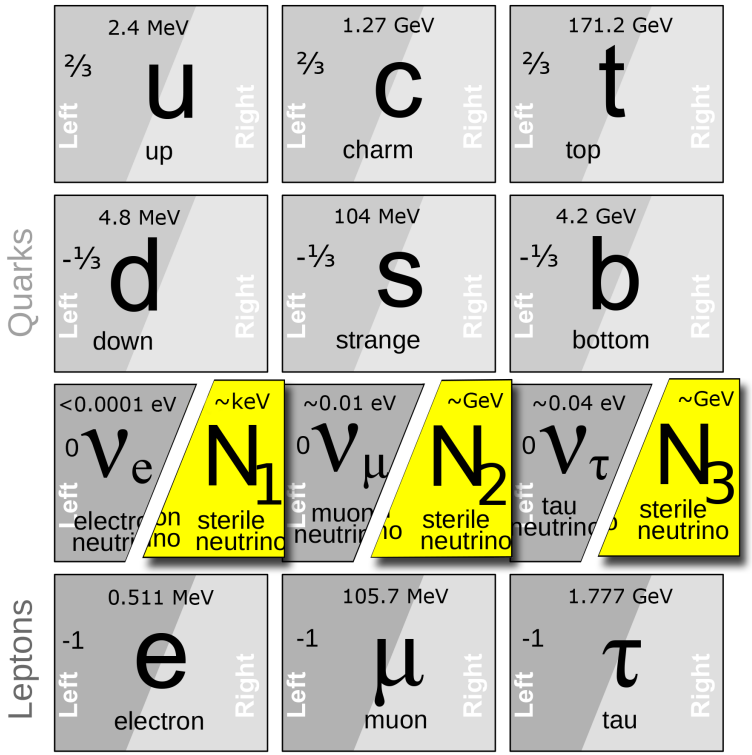

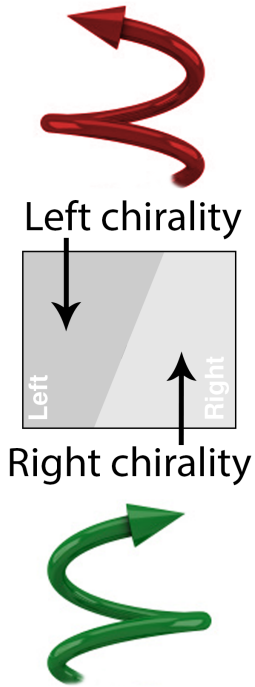

- If mass requires two chiralities . . .
- . . . postulate the "second half to neutrinos"

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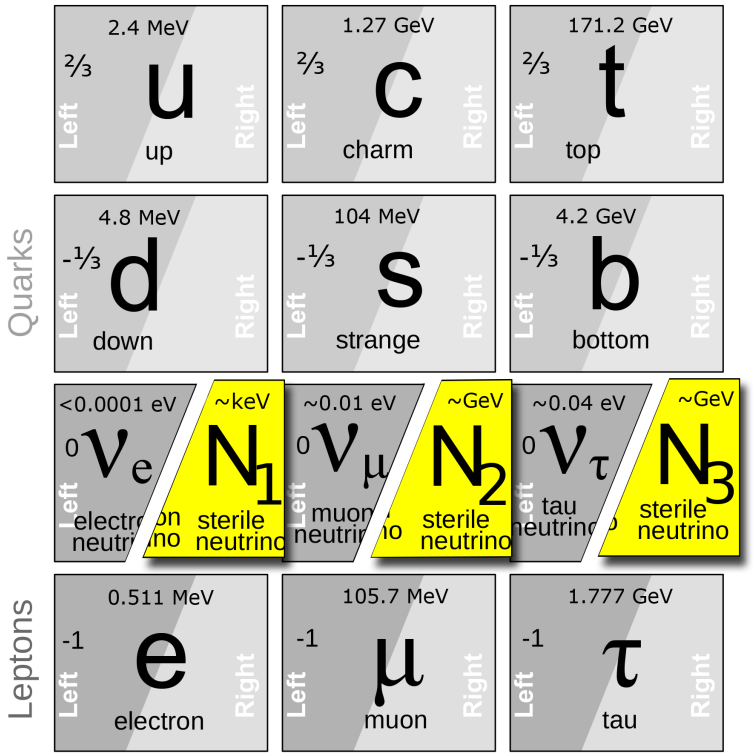
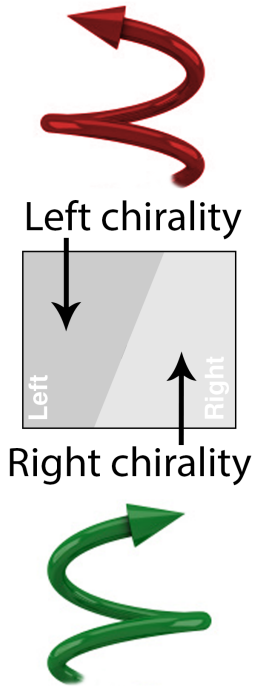
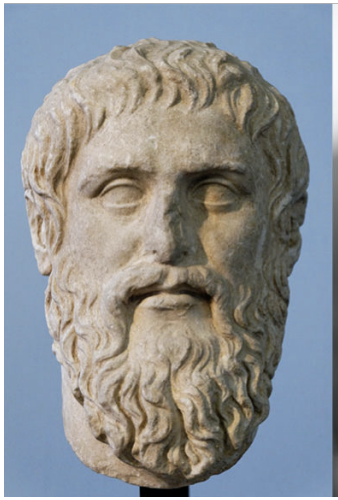




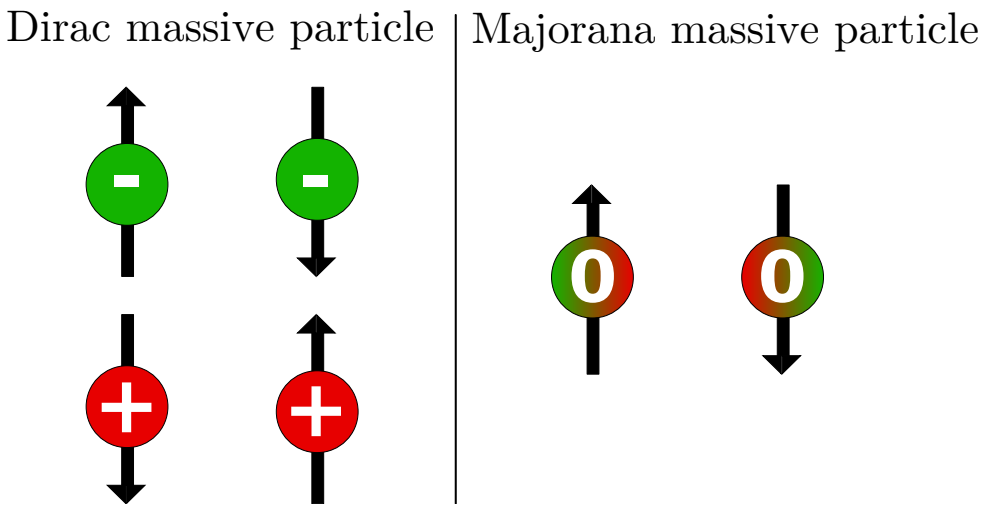
- If mass requires two chiralities . . .
- . . . postulate the "second half to neutrinos"
- Does this assumption bear consequences beyond a simple mass term?

Totalitarian principle



"Everything that can exist — must exist"

"Everything not forbidden is compulsory (in the quantum world)"



- Right-chiral neutrinos carry no Standard Model charges (not even weak)
- They **can** (must?) have their own **Majorana mass**
- Unlike any other fermion in the Standard Model, right-chiral neutrinos can be thought of as **separate particles**

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Same particle — many names

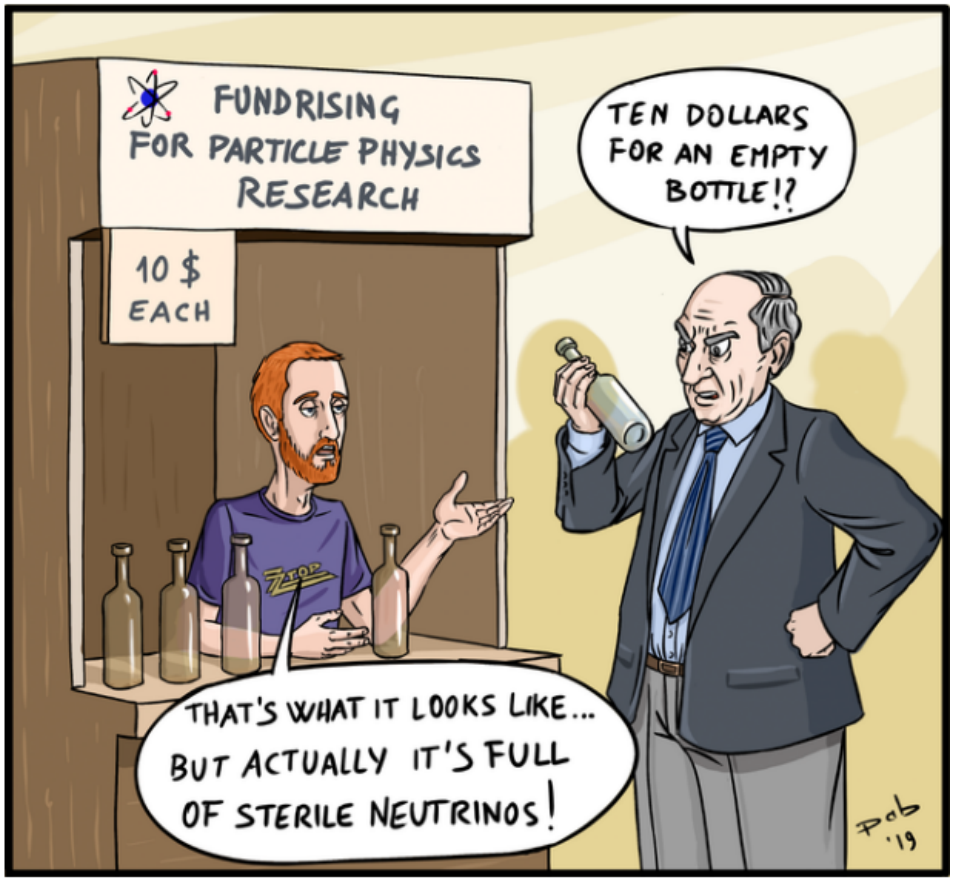

Image credit: @pab.ink

These new particles are called **sterile neutrinos**

They also have many alternative names (adopted by different communities)

- Heavy neutral lepton (HNL)
- Heavy (Majorana) neutrino
- Right-handed neutrino
- (Gauge) singlet neutrino

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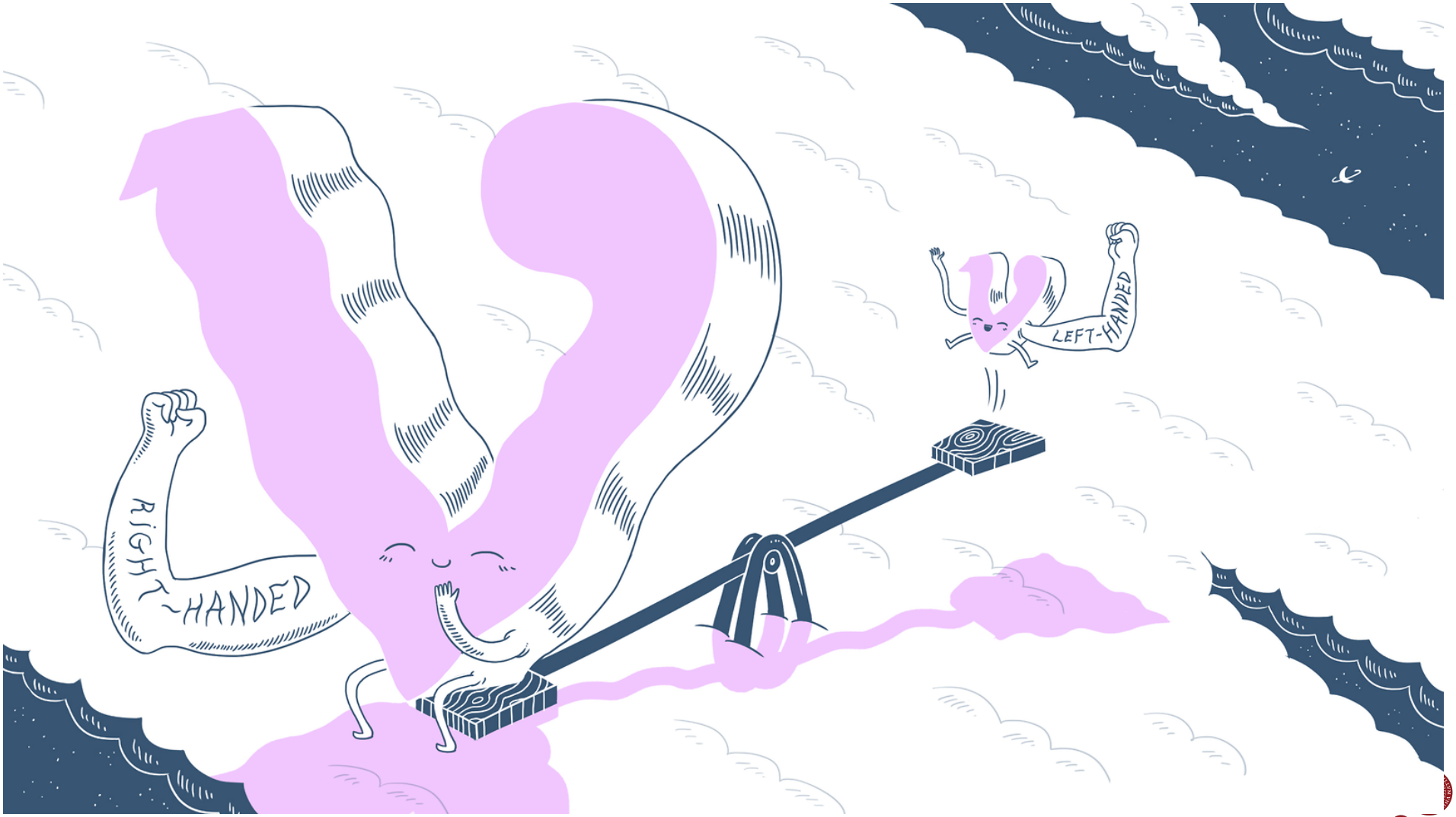
Idea: small mass comes from "seesaw mechanism"



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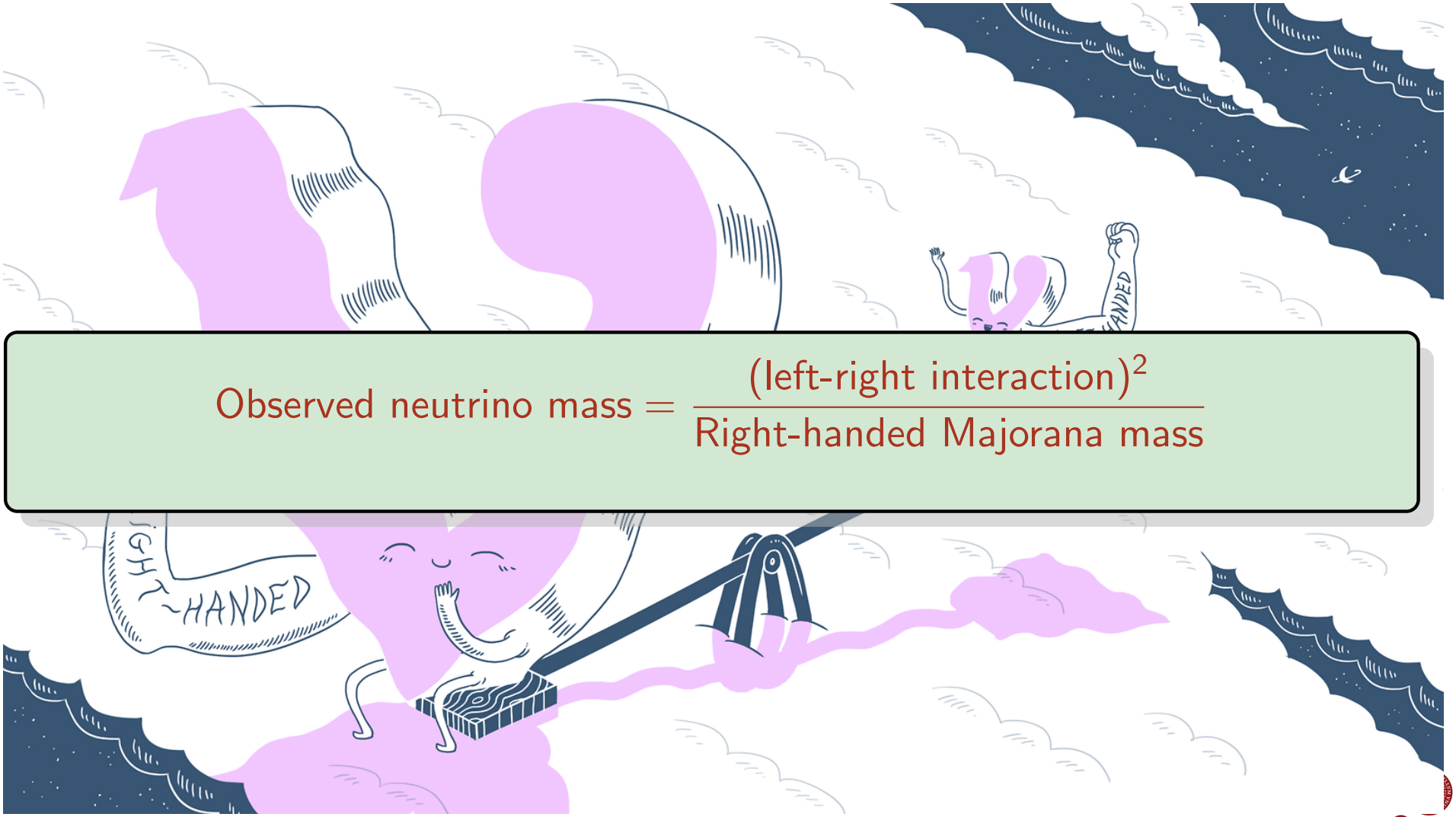

$$\text{Observed neutrino mass} = \frac{(\text{left-right interaction})^2}{\text{Right-handed Majorana mass}}$$

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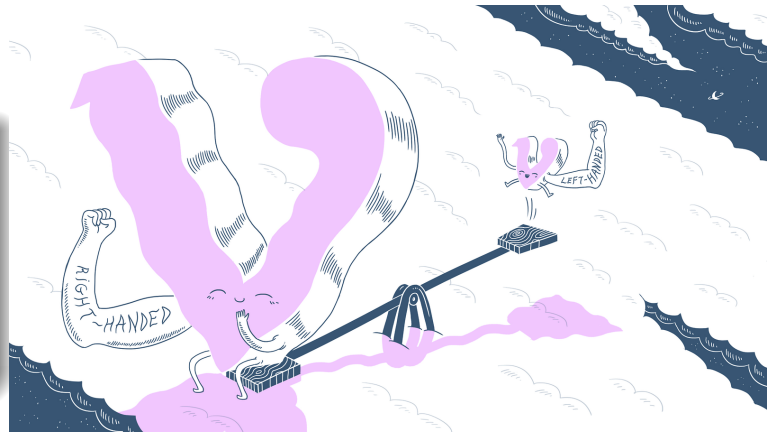
How mass works in the seesaw mechanism

Left-chiral ν_e

Massless

Neutrinos have a small probability to become massive sterile neutrinos (and then go back to themselves) $\Rightarrow$ propagate through space slower than speed of light (have mass)



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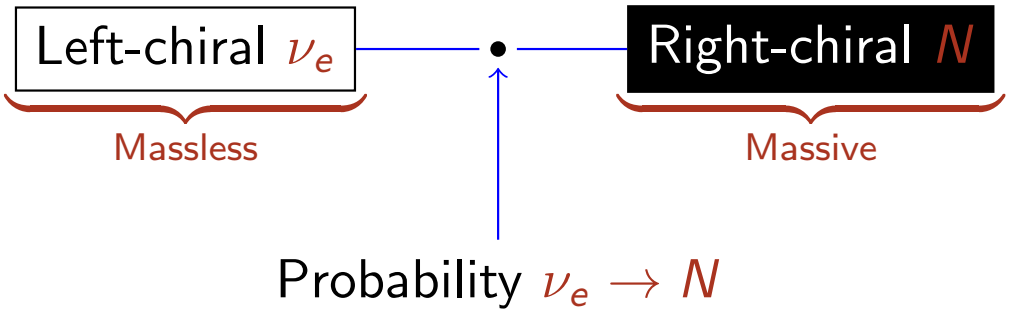

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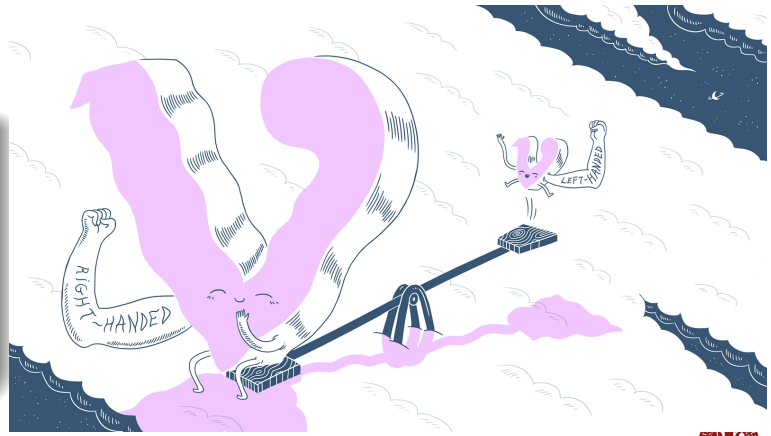

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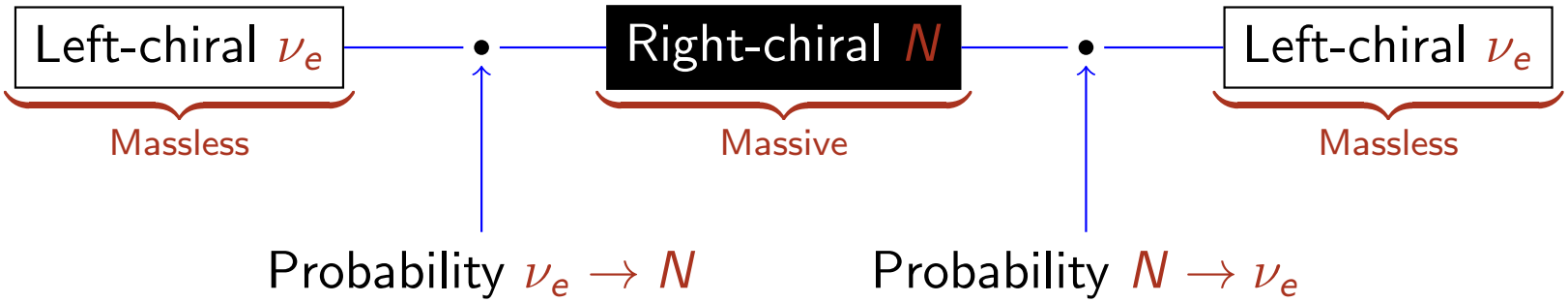

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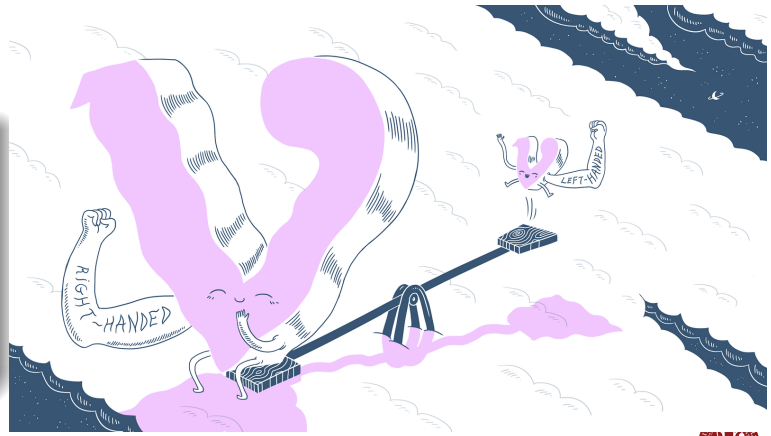
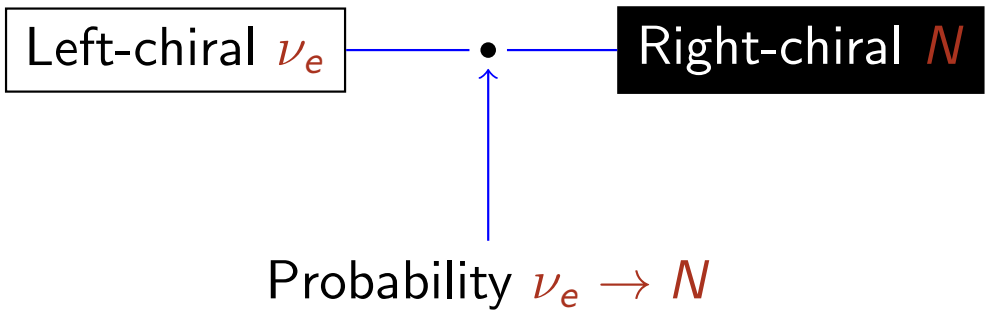


How oscillations work

Left-chiral ν_e

Neutrino oscillations are actually active-sterile-active neutrino oscillations

How oscillations work



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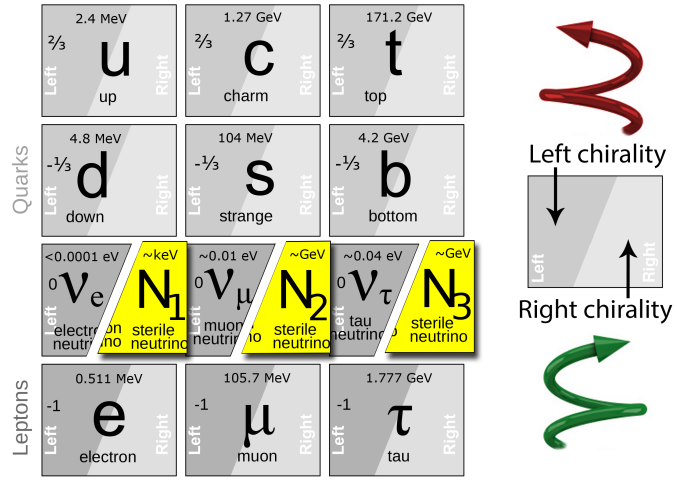

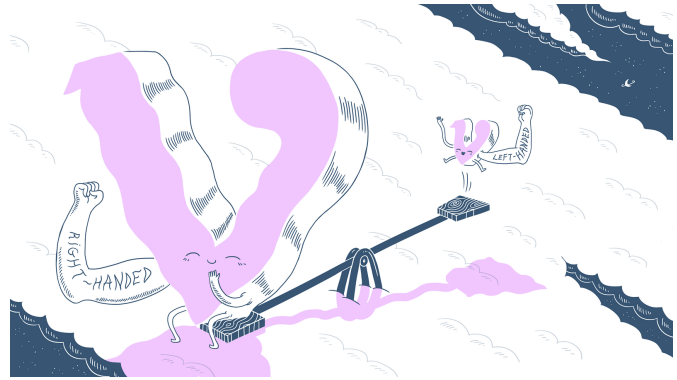

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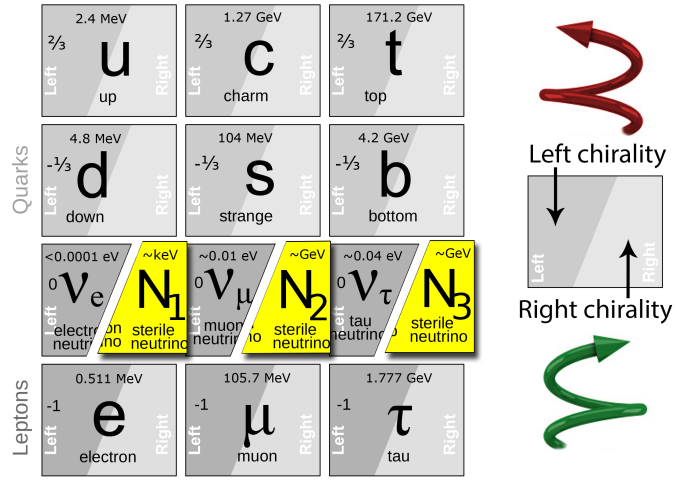

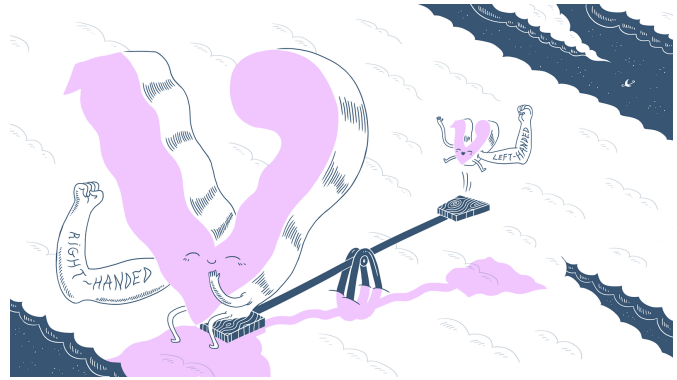

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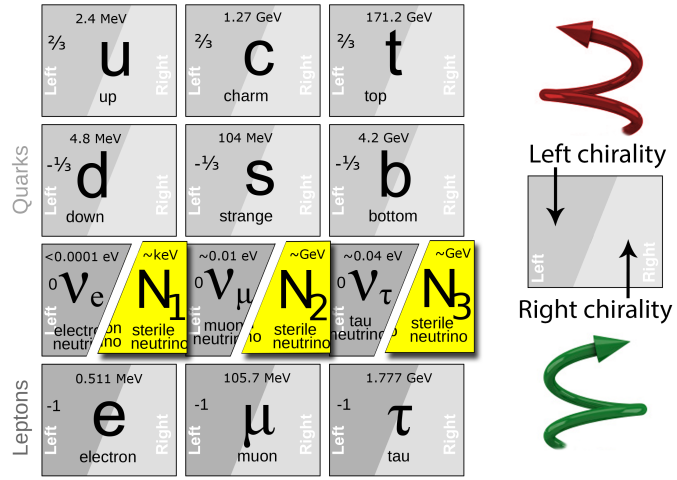

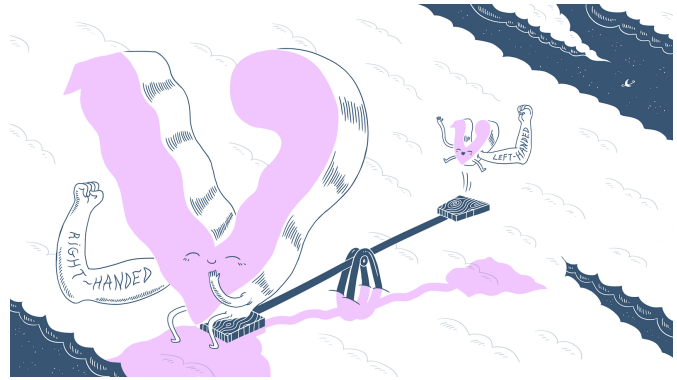

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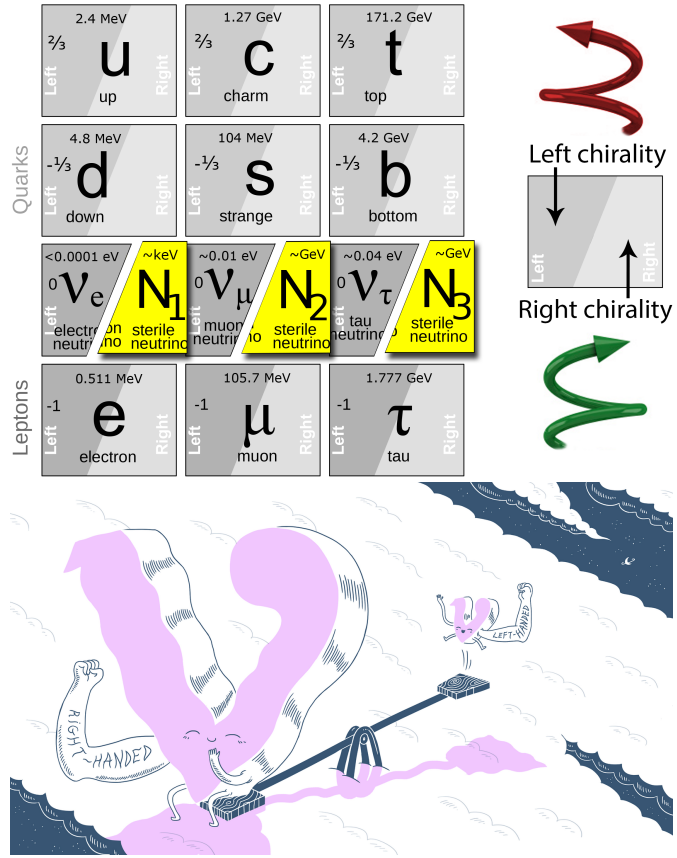

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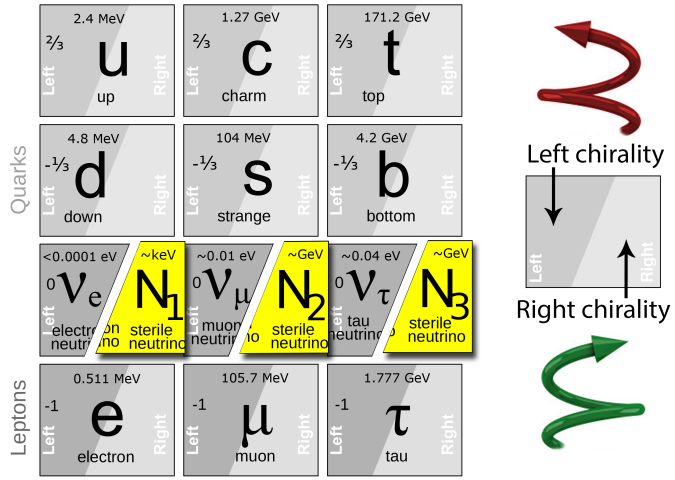

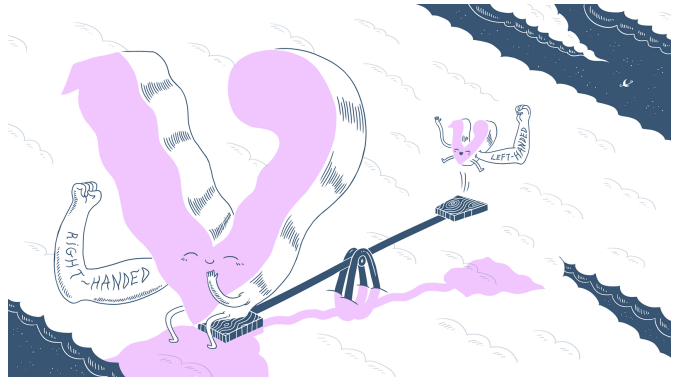

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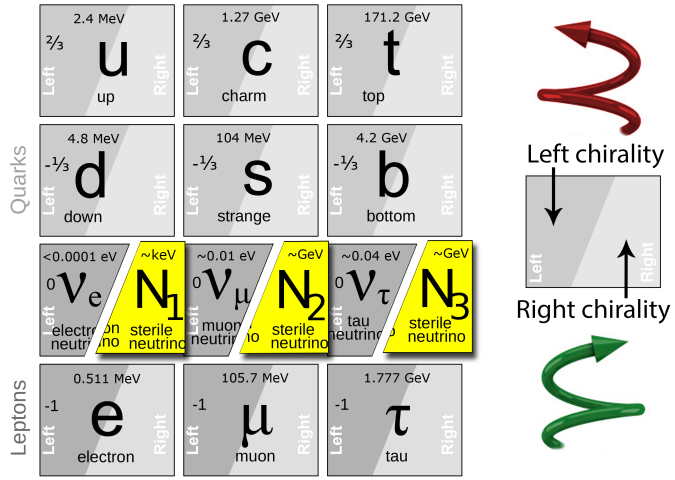

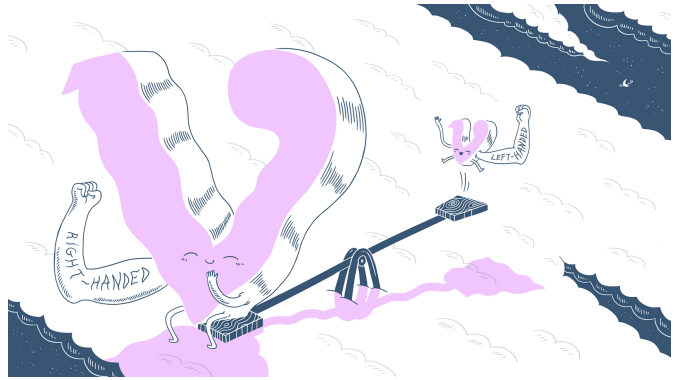

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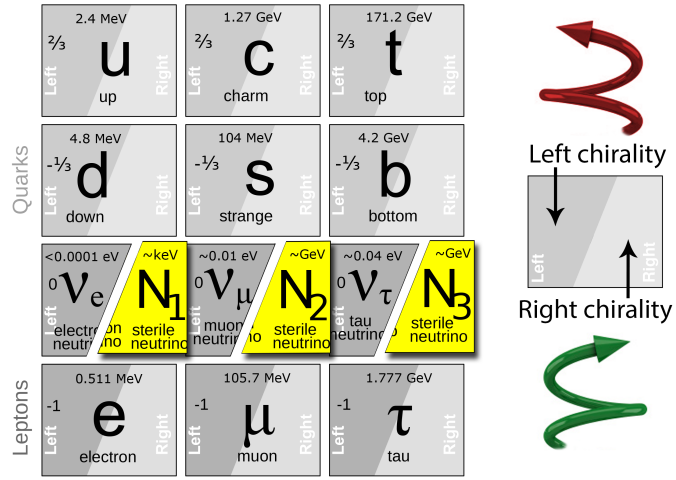

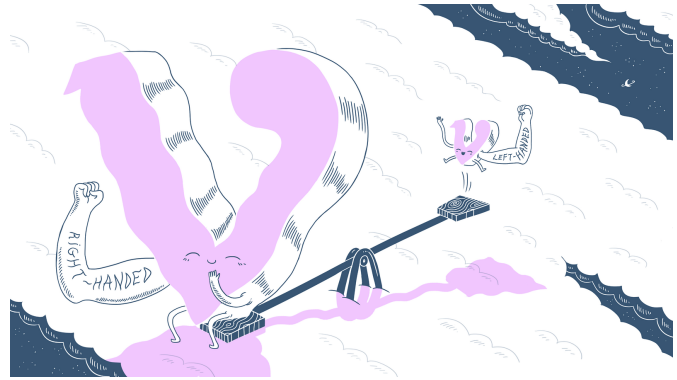

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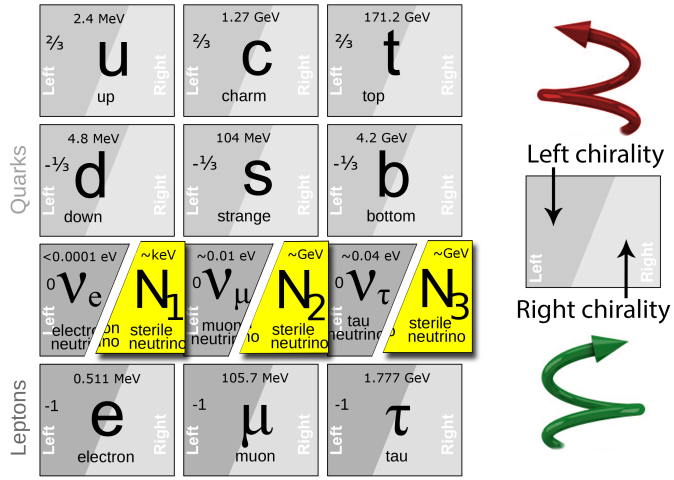

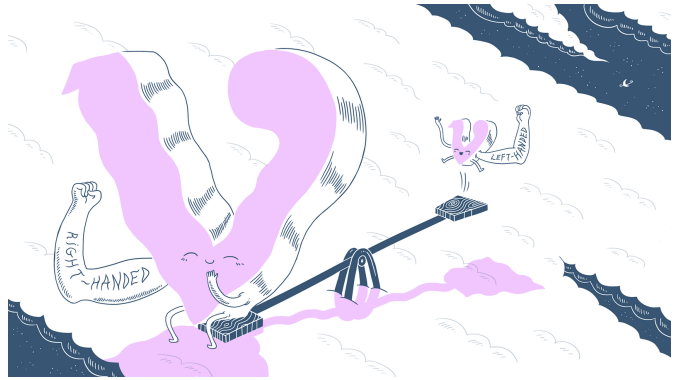

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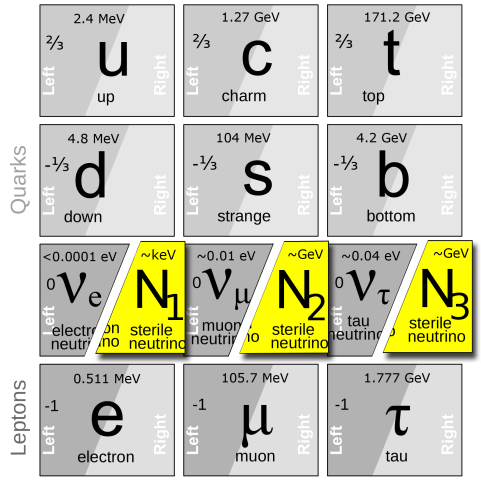

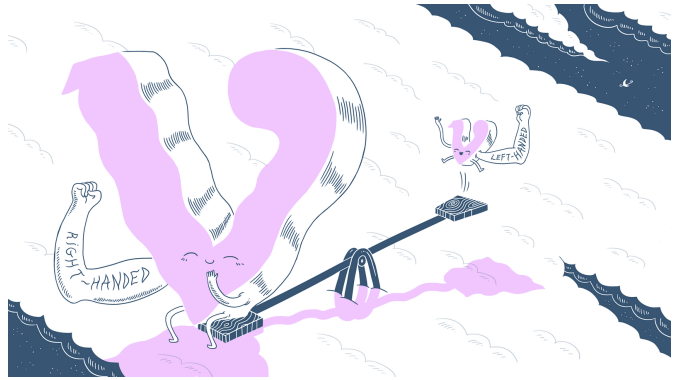

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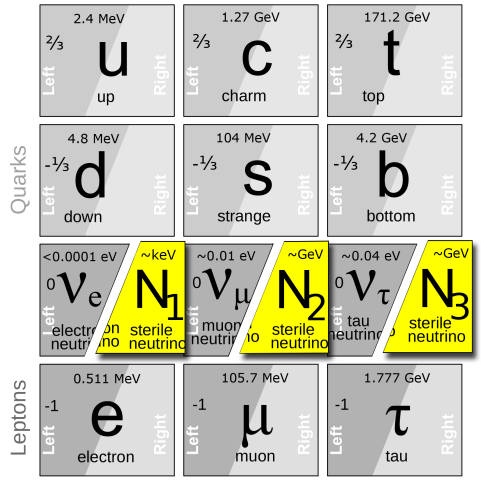
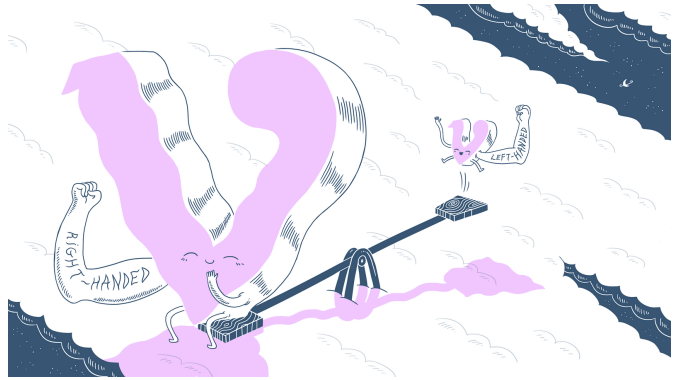
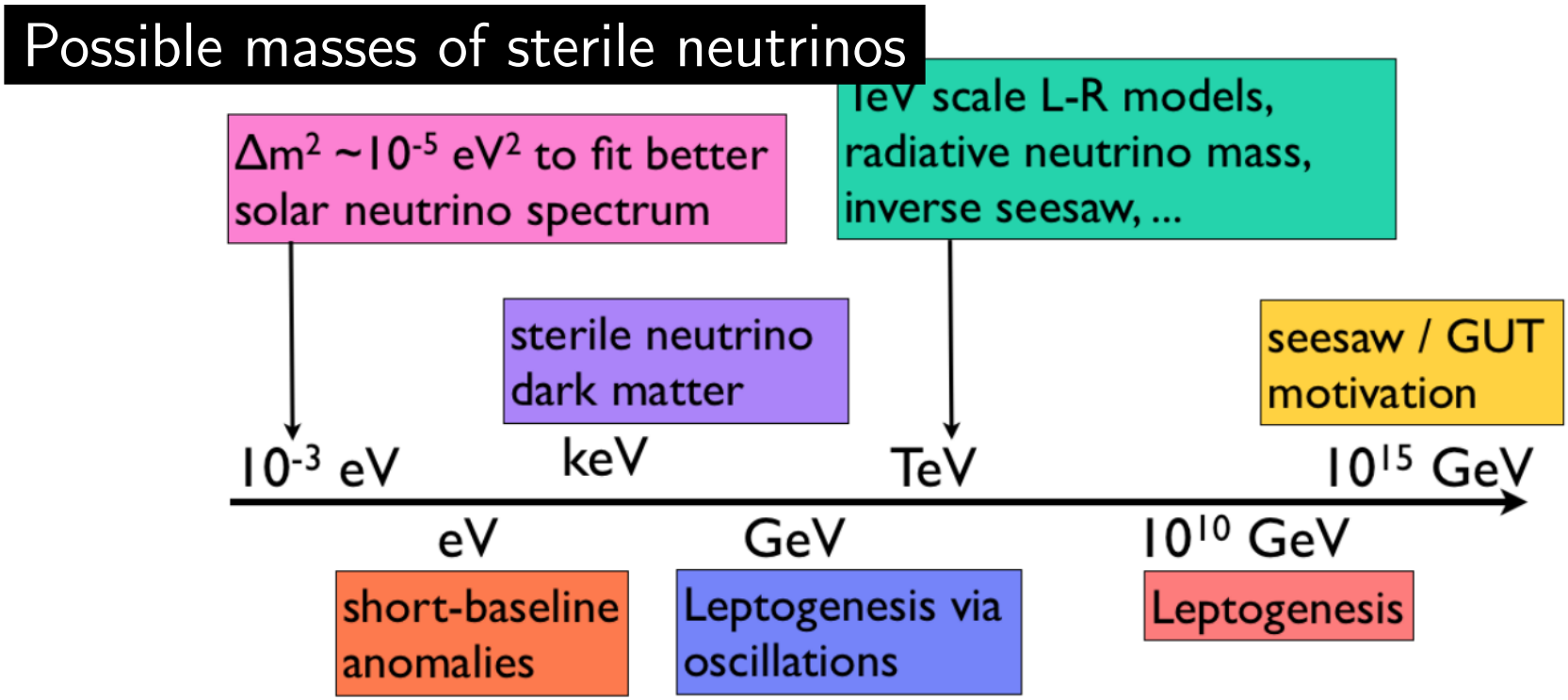
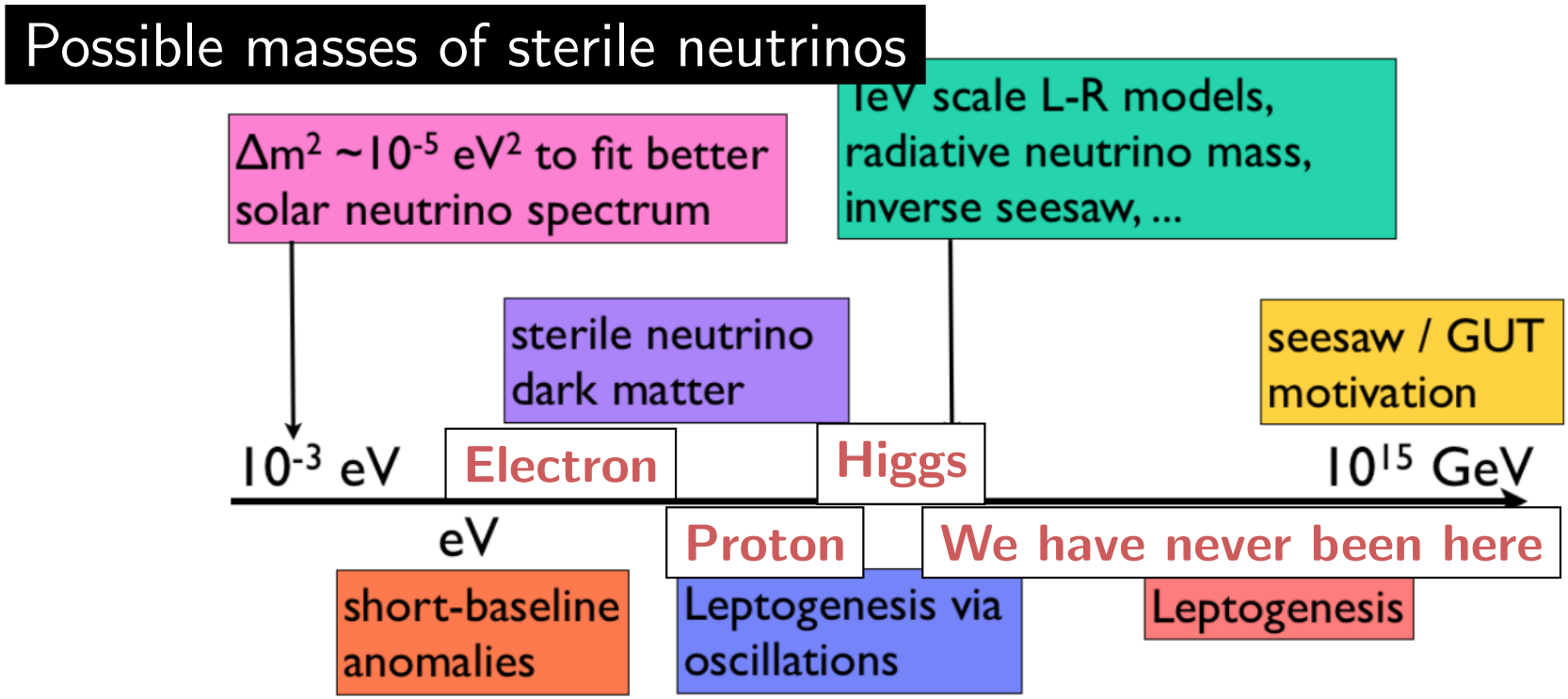




Scales and applications



Scales and applications



Particle physics applied to the whole **Universe**

Ya. Zel'dovich ("father" of modern cosmology)

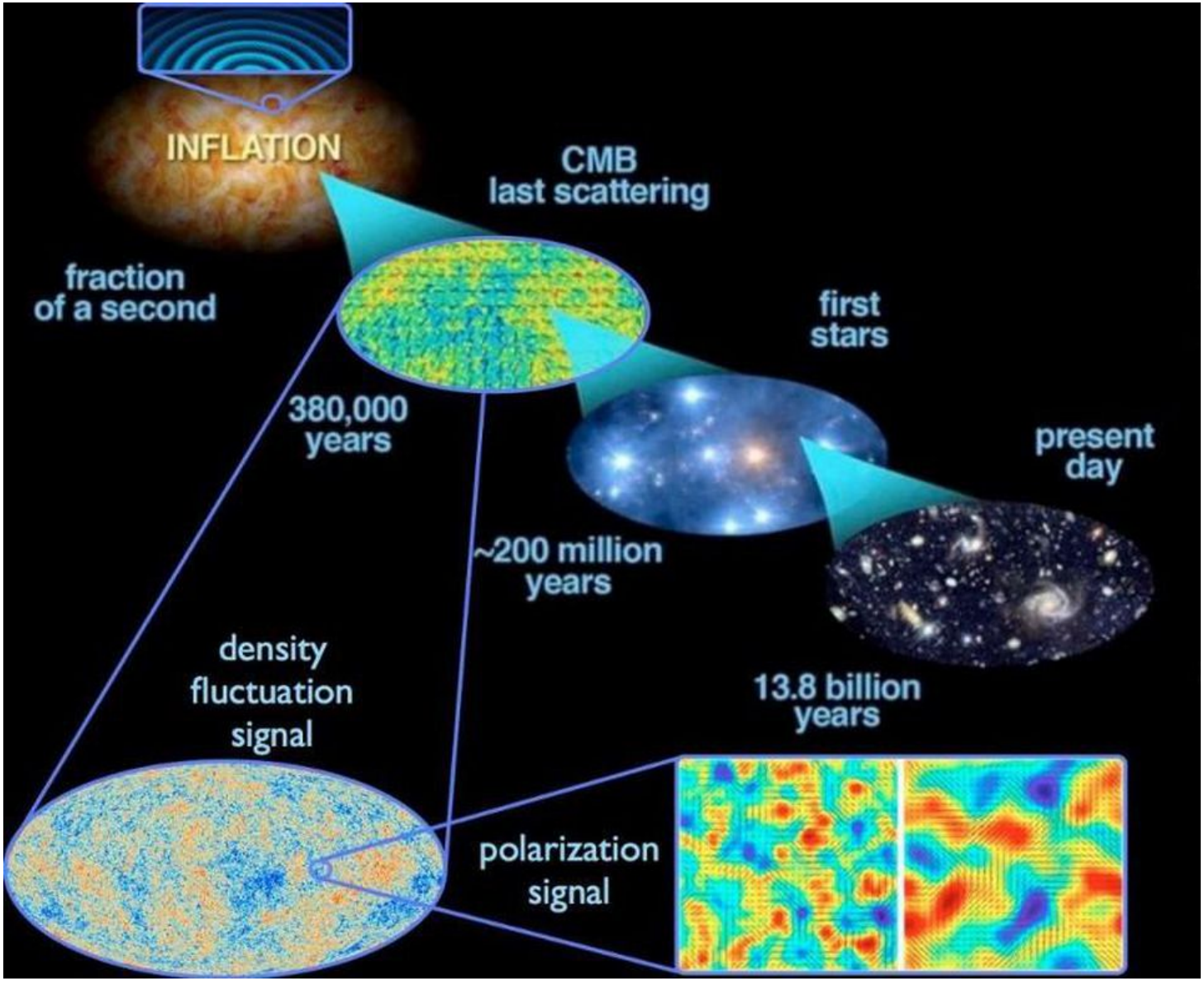
The Universe is the poor man's accelerator: experiments don't need to be funded, and all we have to do is to collect the experimental data and interpret them properly

Unfortunately, the experiment has been done only once

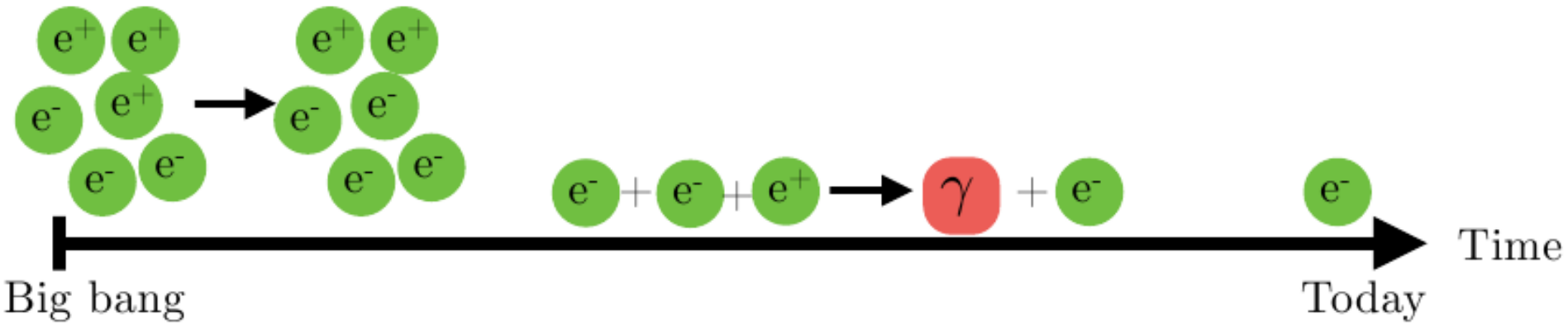
Physics of the Universe

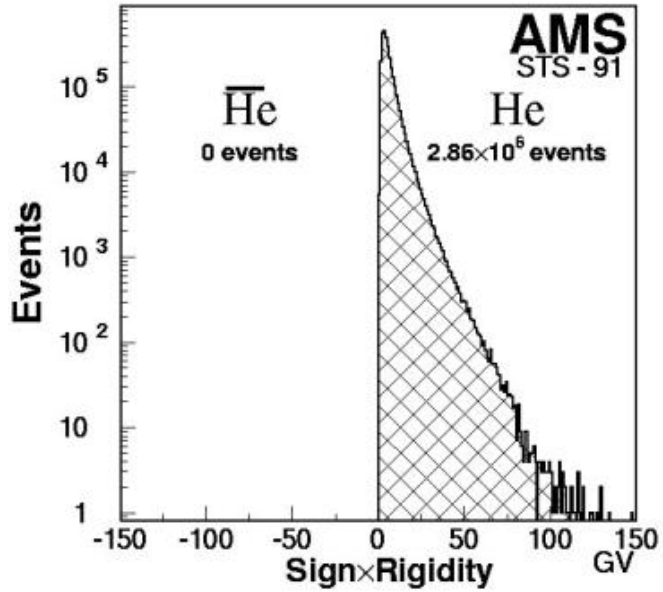
- Universe expands ..... **Hubble law** ..... **gravitation**
- In the past the Universe was hotter and denser ..... **thermodynamics**
- Atoms ionize ..... **cosmic microwave background** ..... **atomic physics**
- Nuclei dissolve ..... **primordial element abundance** ..... **nuclear physics**
- protons and neutrons dissolve into "quark soup" ..... **ALICE**
- all particles lose mass ..... **ATLAS**

We describe the Universe with a high precision



Matter-antimatter asymmetry





Immediate questions

Q: Can sterile neutrinos help to create matter-antimatter asymmetry

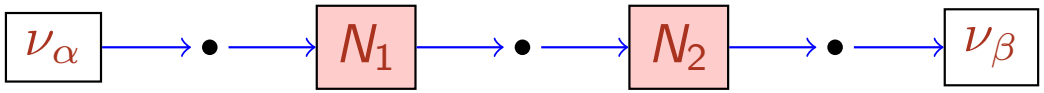
A: Yes!

Immediate questions

Q: Can sterile neutrinos help to create matter-antimatter asymmetry

A: Yes!

- In the early Universe probability of the processes



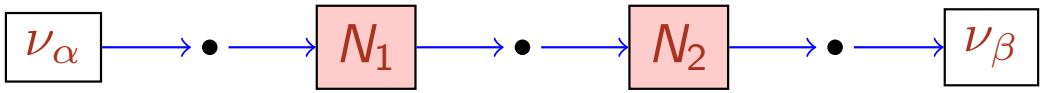
Particles

Immediate questions

Q: Can sterile neutrinos help to create matter-antimatter asymmetry

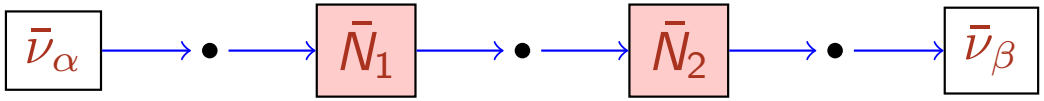
A: Yes!

- In the early Universe probability of the processes



Particles

- . . . is **not the same** as the probability of the processes



Anti-Particles

Immediate questions

Q: Can sterile neutrinos help to create matter-antimatter asymmetry

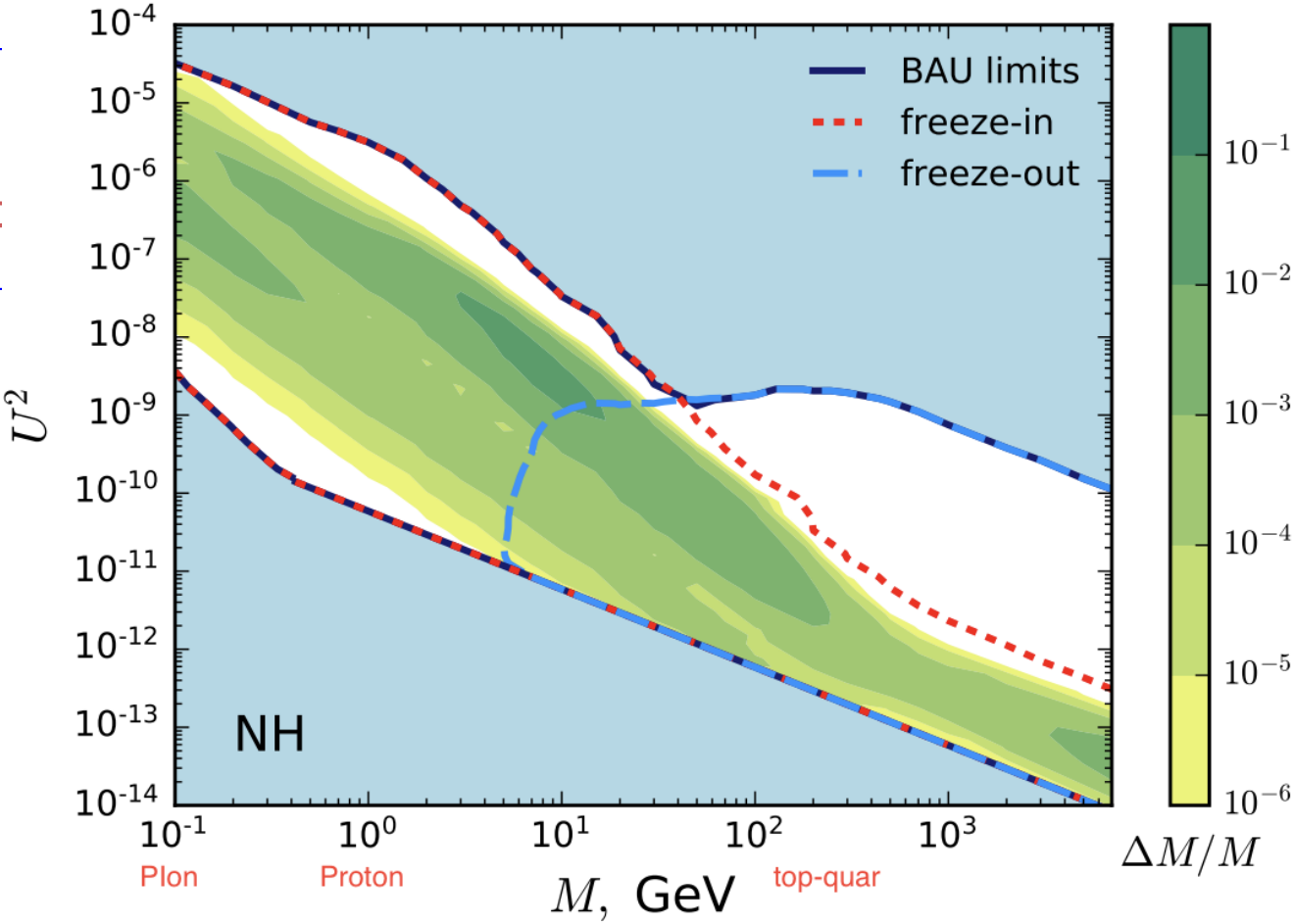
A: Yes!

- In the e

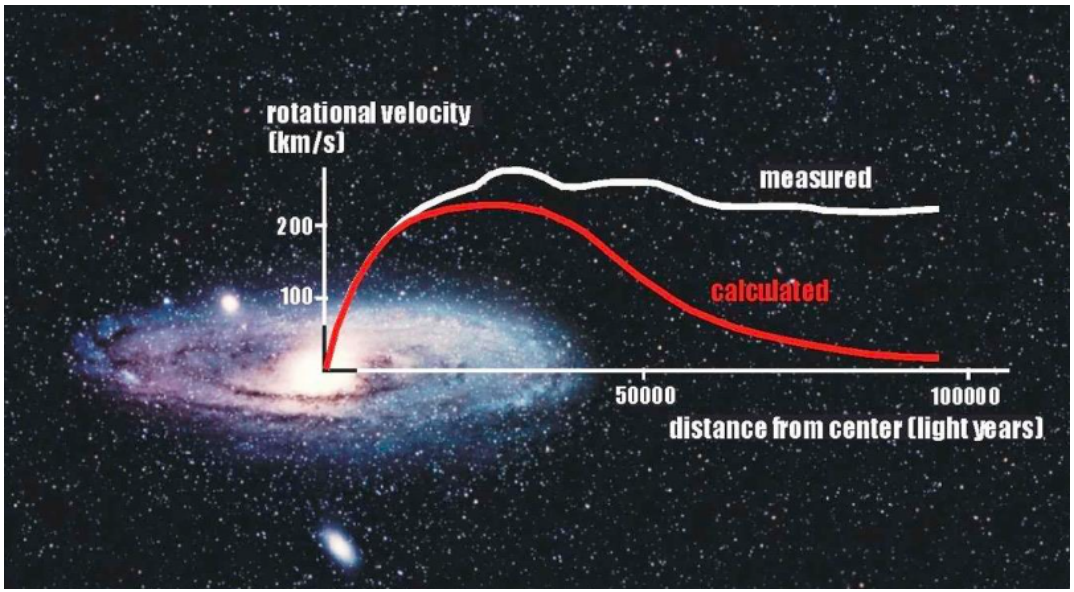
ν_α

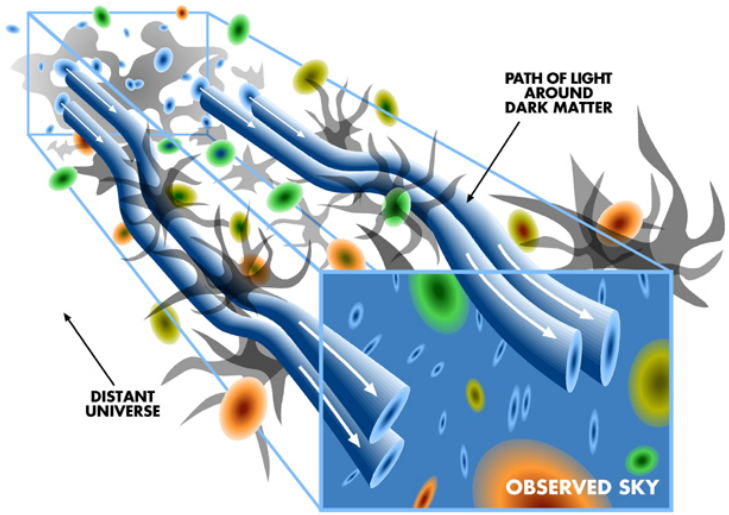
- . . . is nc

$\bar{\nu}_\alpha$

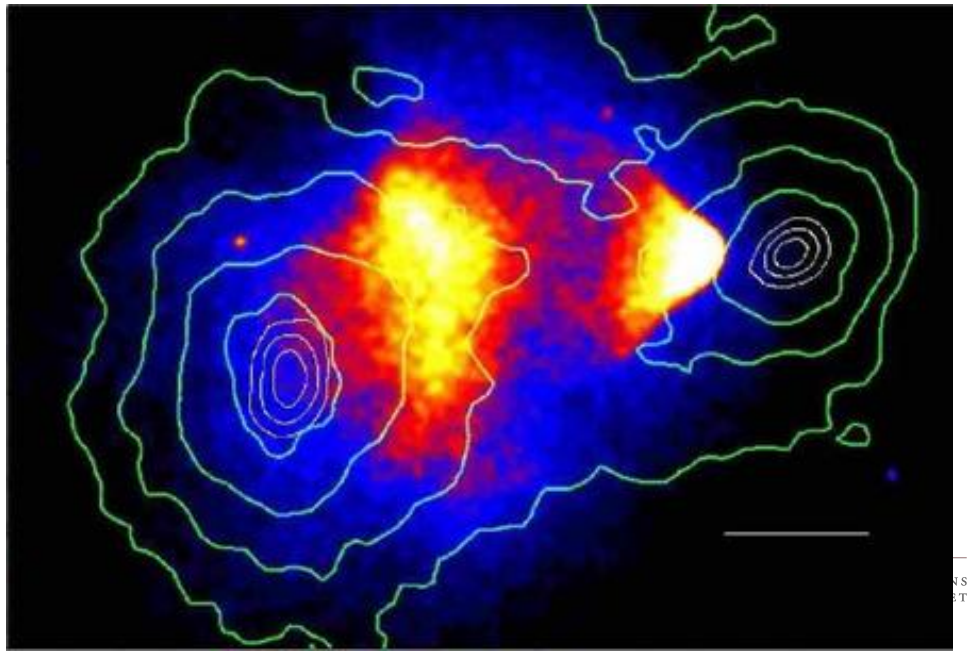


The phenomenon of dark matter



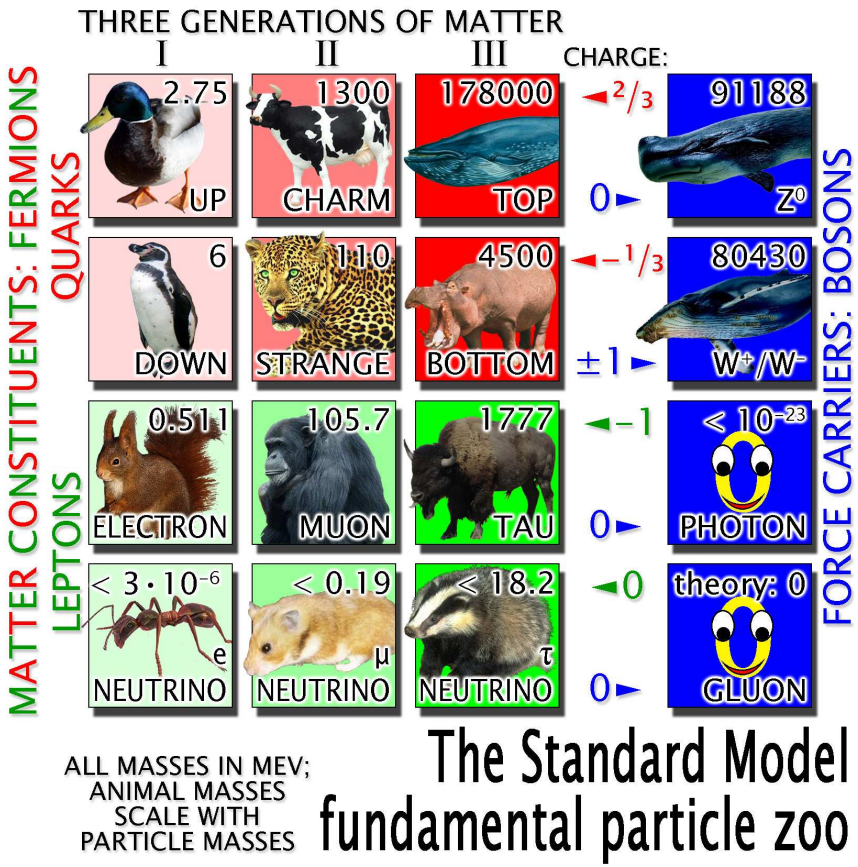


- On scales from smallest galaxies to largest super-clusters we see **missing mass** – there is much more gravitating
- Crucially important – there are many **classes** of observations that confirm this



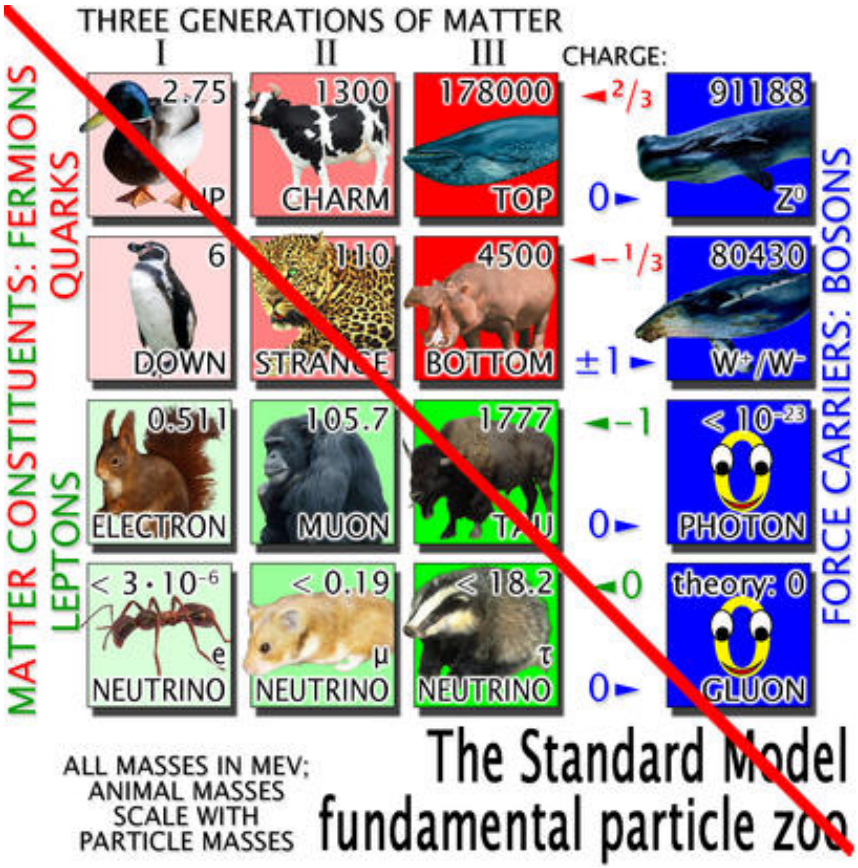
Why is dark matter important?

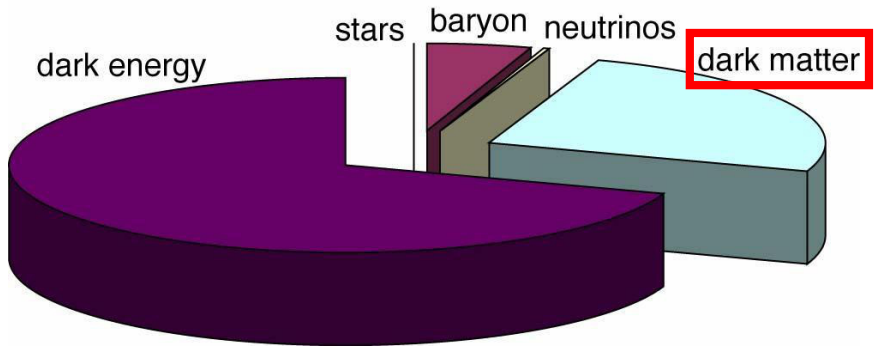
- If dark matter is made of particles —



Why is dark matter important?

- If dark matter is made of particles — this is some **unknown** particle



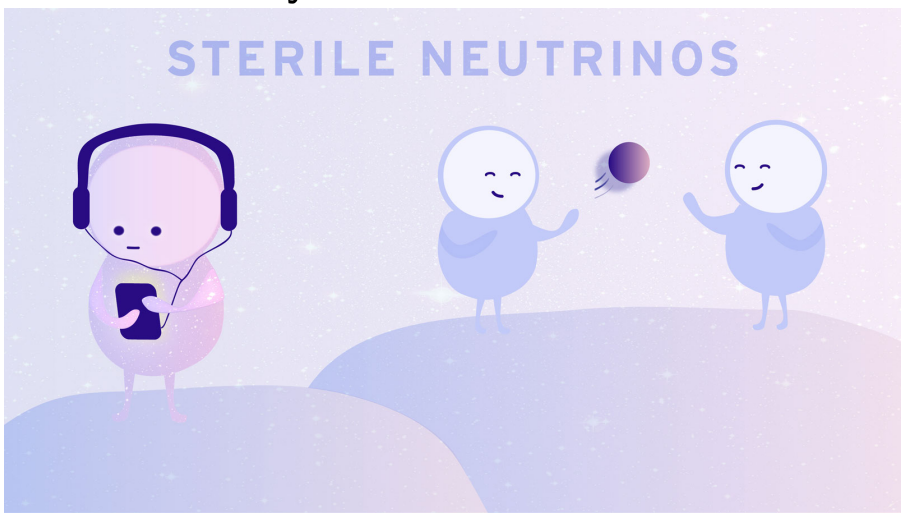


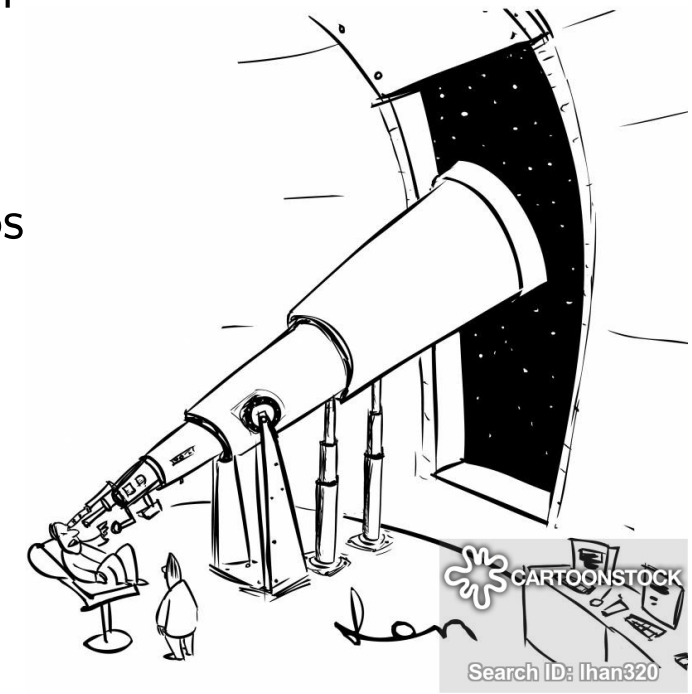
FAQ on sterile neutrinos

Q: Can sterile neutrinos help to explain dark matter of the Universe

A: Yes!

- Seesaw mechanism predicts that sterile neutrinos interact **weaker** than ordinary neutrinos by as much as they are heavier





"I've either discovered dark matter, or I've left the lens cap on."

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History of sterile neutrinos

Q: Is all this a new idea?

A: No! This has been growing slowly

- It has been known since 1970s that sterile neutrinos can explain **neutrino oscillations**

  Bilenky & Pontecorvo'76; Minkowski'77; Yanagida'79; Gell-Mann et al.'79; Mohapatra & Senjanovic'80; Schechter & Valle'80

- Its has been known since 1980s that sterile neutrinos can explain **matter-antimatter asymmetry**

  Fukugita & Yanagida'86; Akhmedov, Smirnov & Rubakov'98; Pilaftsis & Underwood'04-05; Shaposhnikov+'05–

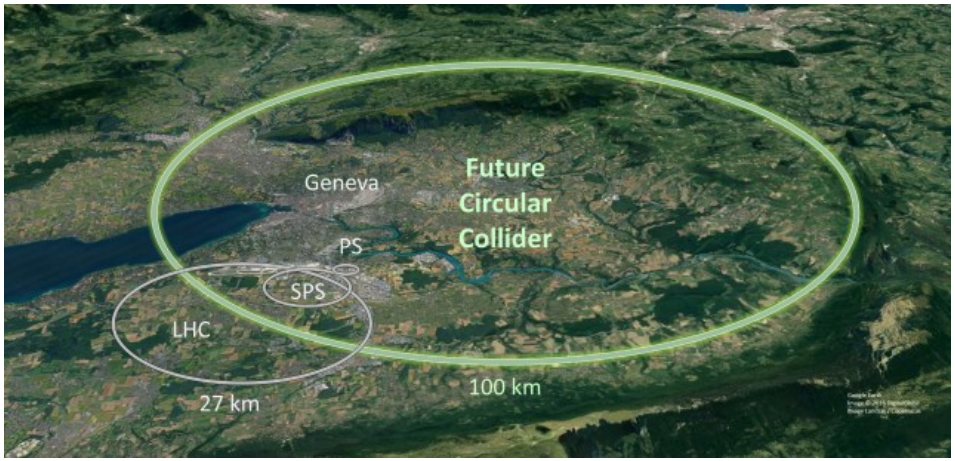
- Its has been known since 1990s that sterile neutrinos can explain **dark matter** Dodelson & Widrow'93; Shi & Fuller'99; Dolgov & Hansen'00; Abazajian+; Asaka, Shaposhnikov, Laine'06 –

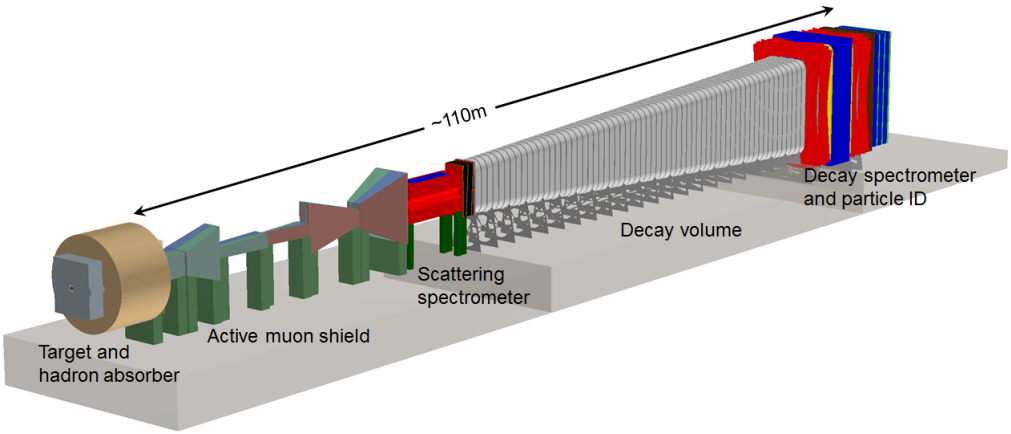
- Its has been understood in 2005 that sterile neutrinos can explain **all of the above** M. Shaposhnikov and collaborators'05 – ...

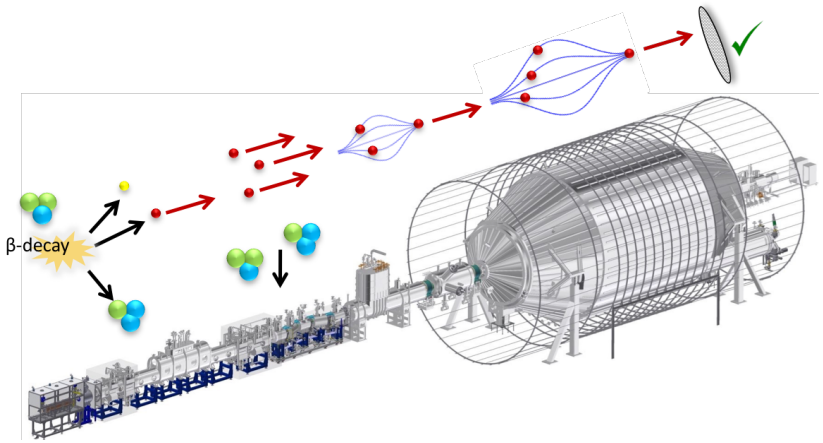
Discovery of sterile neutrinos in the lab

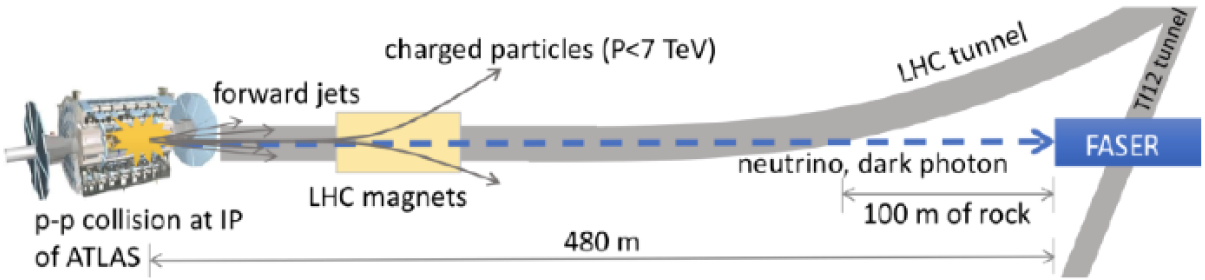
Q: Can sterile neutrinos be discovered?

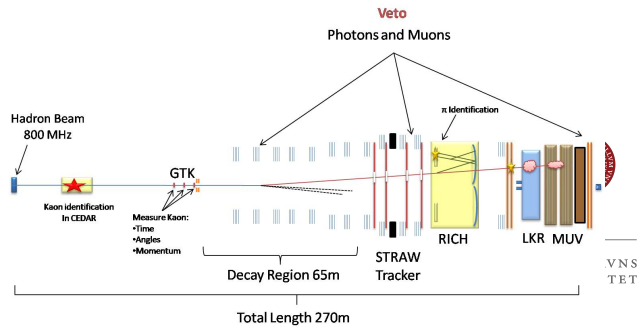
A: Yes!





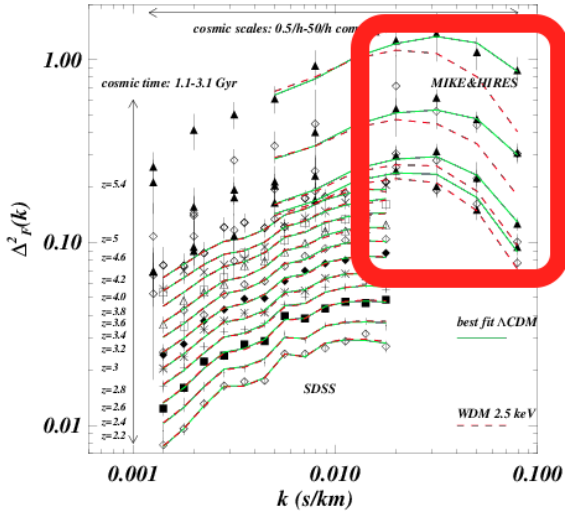


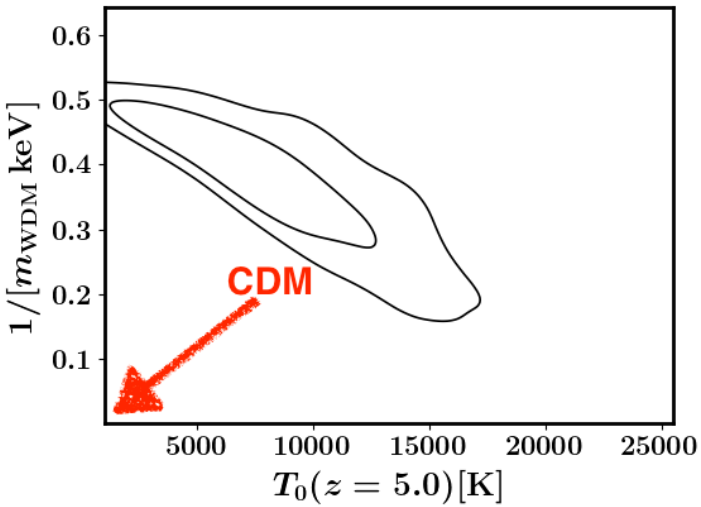


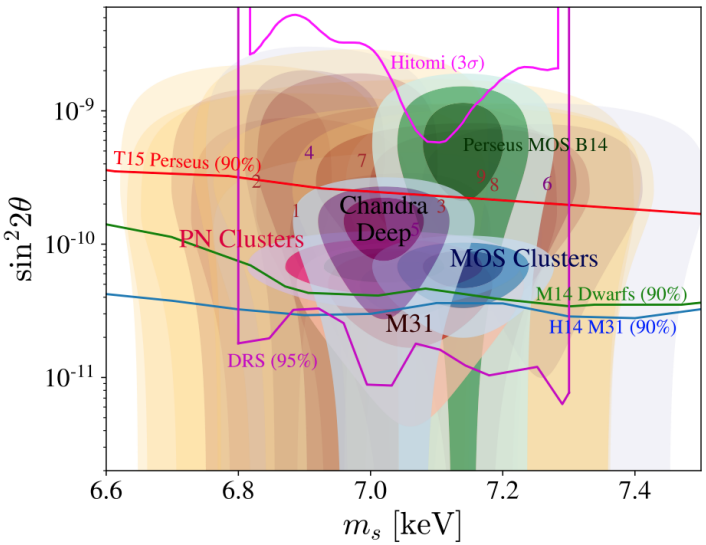


Discovery of sterile neutrinos in the sky

See review [1807.07938] and subsequent works [1812.10488], [1912.09397]







Profile	Significance in σ	Line position [keV]	Decay width $\Gamma\ [10^{-28}\ \mathrm{sec}^{-1}]$
NFW [19] $r_s = 20\,\mathrm{kpc}$	7σ	$3.494^{+0.002}_{-0.010}$	0.39 ± 0.04
Burkert $r_B = 9\,\mathrm{kpc}$	6.4σ	$3.494^{+0.003}_{-0.014}$	$0.57^{+0.05}_{-0.08}$
Einasto $r_s = 14.8\ \mathrm{kpc}$ $\alpha = 0.2$	6.9σ	$3.494^{+0.002}_{-0.009}$	$0.40^{+0.04}_{-0.06}$

TABLE II. Combined spectral modeling of spatial regions Reg1–Reg5 with the same position of the line and relative normalizations in different regions fixed in accordance with a DM density profile. Two parameters of the line fit are: the energy and the intrinsic decay

Things to think about

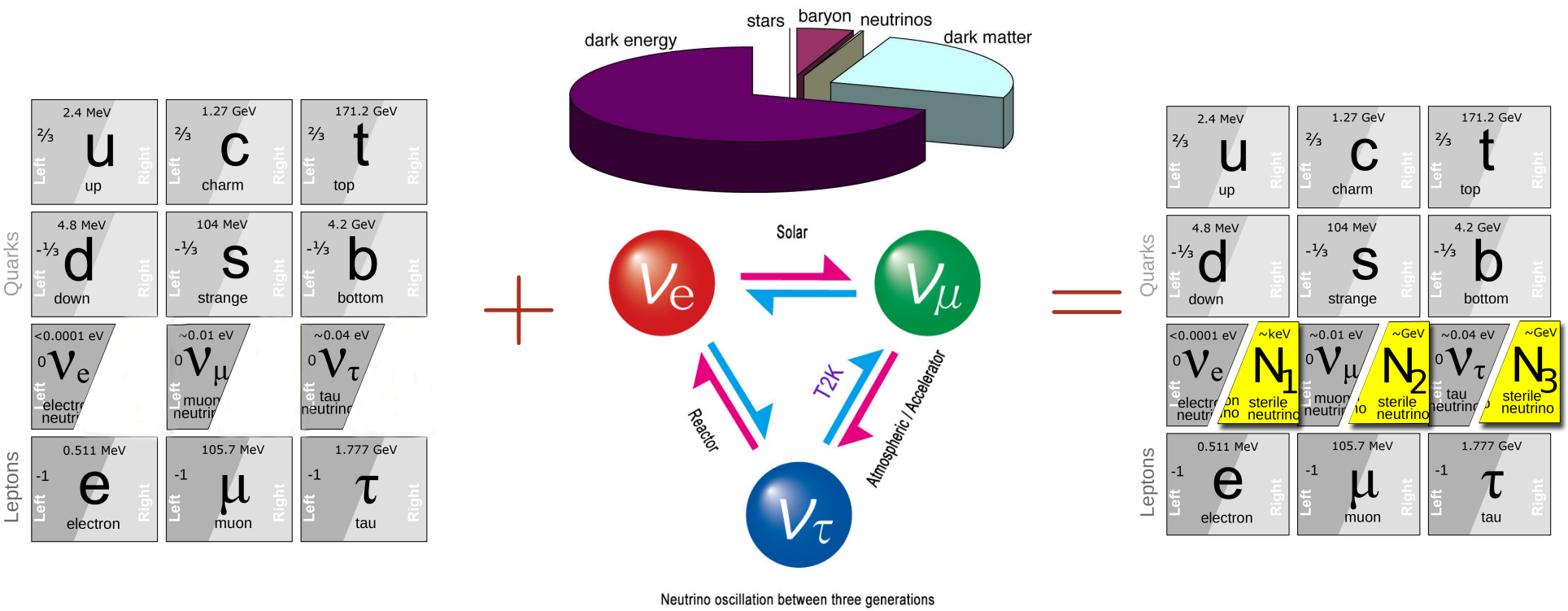
1. How many sterile neutrinos can be added to the Standard Model?
2. How many new parameters such a model will have?
3. How many parameters are fixed by fitting neutrino oscillation data?
4. Other types of seesaw models

- Type-III seesaw (**Foot et al. Z. Phys. C44 (1989)**)
- Inverse seesaw (**Mohapatra PRL 56 (1986); Mohapatra & Valle PRD34 (1986)**)
- Radiative seesaw (**Pilaftsis Z. Phys. C55 (1992)**)
- Left-right symmetric models
  (**Pati & Salam (1974); Mohapatra & Pati (1975); Mohapatra & Senjanovic (1981)**)
- HNLs will carry charge w.r.t. $U(1)_{B-L}$ – can be produced via off-shell $B-L$ boson (couples to protons) **See e.g. Mohapatra & Marshak (1980); del Aguila & Aguilar-Saavedra [0705.4117]; Huitu et al. [0803.2799]; Batell et al. [1604.06099]**
- Majorana mass of HNL can be generated via coupling with a new singlet scalar S
  (**Shaposhnikov & Tkachev (2006); Shoemaker et al. (2010)**)

$$M\bar{N}^c N \to f_N S \bar{N}^c N \tag{1}$$

where S develops vev

Conclusions



I am extremely grateful to https://www.symmetrymagazine.org where many of these pictures (along with beautiful texts) are can be found

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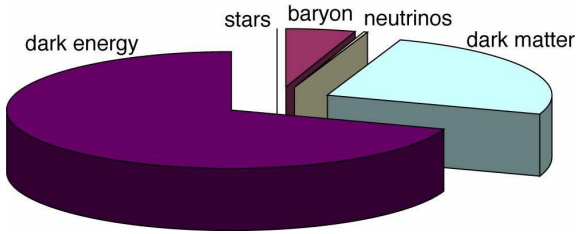
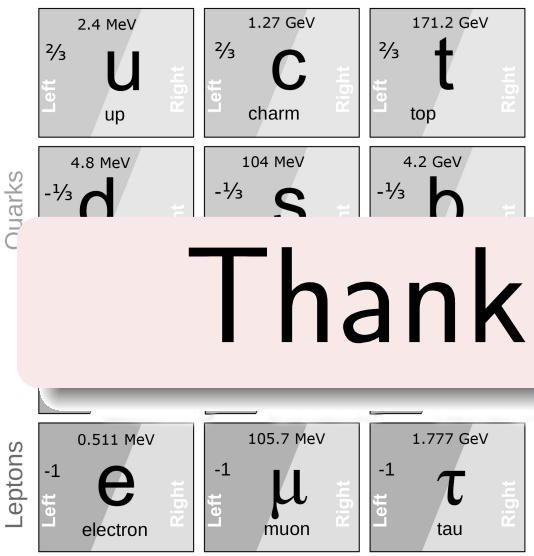
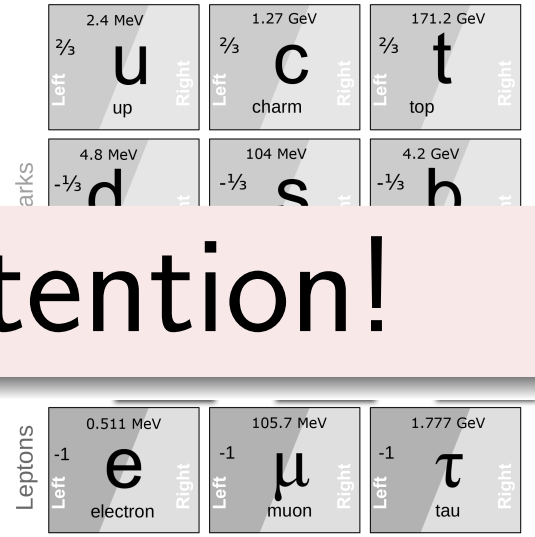
Conclusions







Neutrino oscillation between three generations

Thank you for your attention!

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