# New opportunities in neutrino physics

Pedro A. N. Machado

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pmachado@fnal.gov

# Why neutrinos?

The mystery of neutrino masses




The nature of neutrinos



The least known sector of the SM



The darkest of all particles





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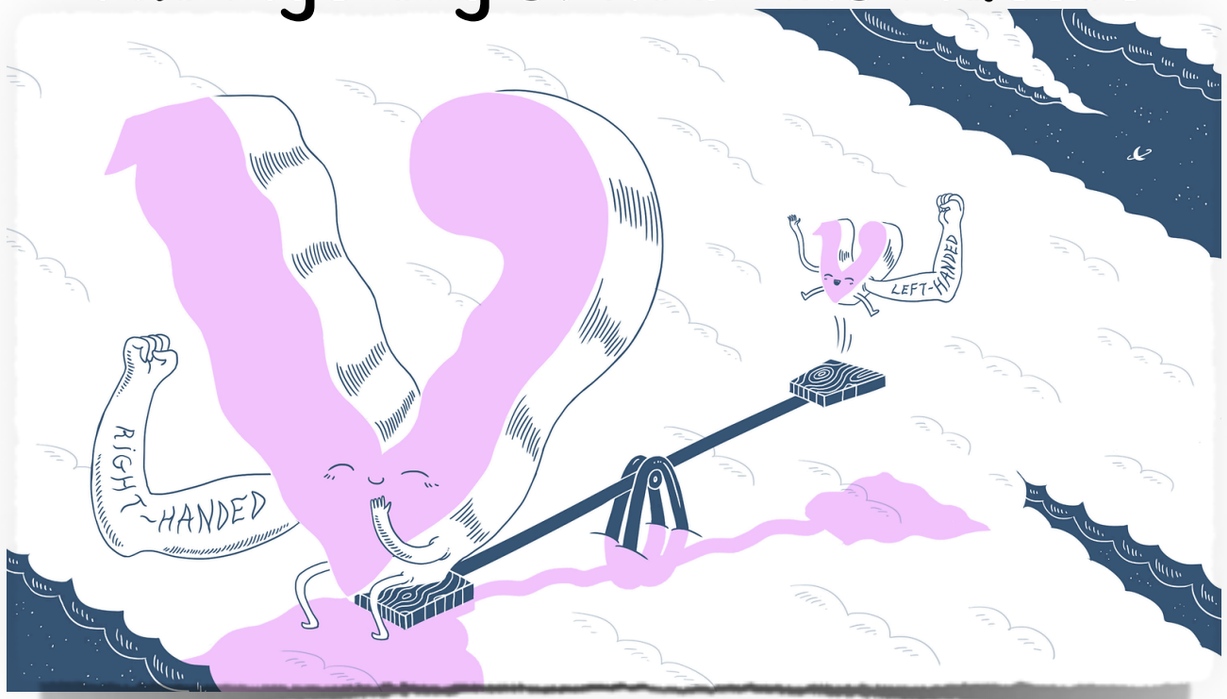
# Why neutrinos?

## The mystery of neutrino masses

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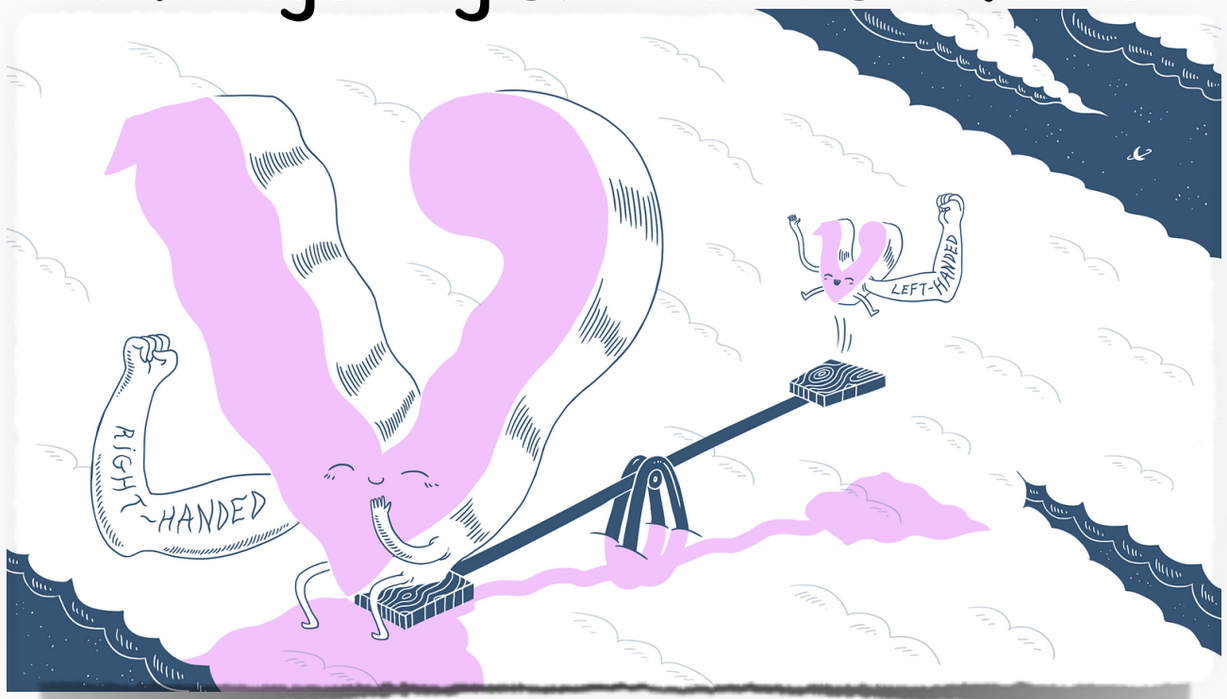


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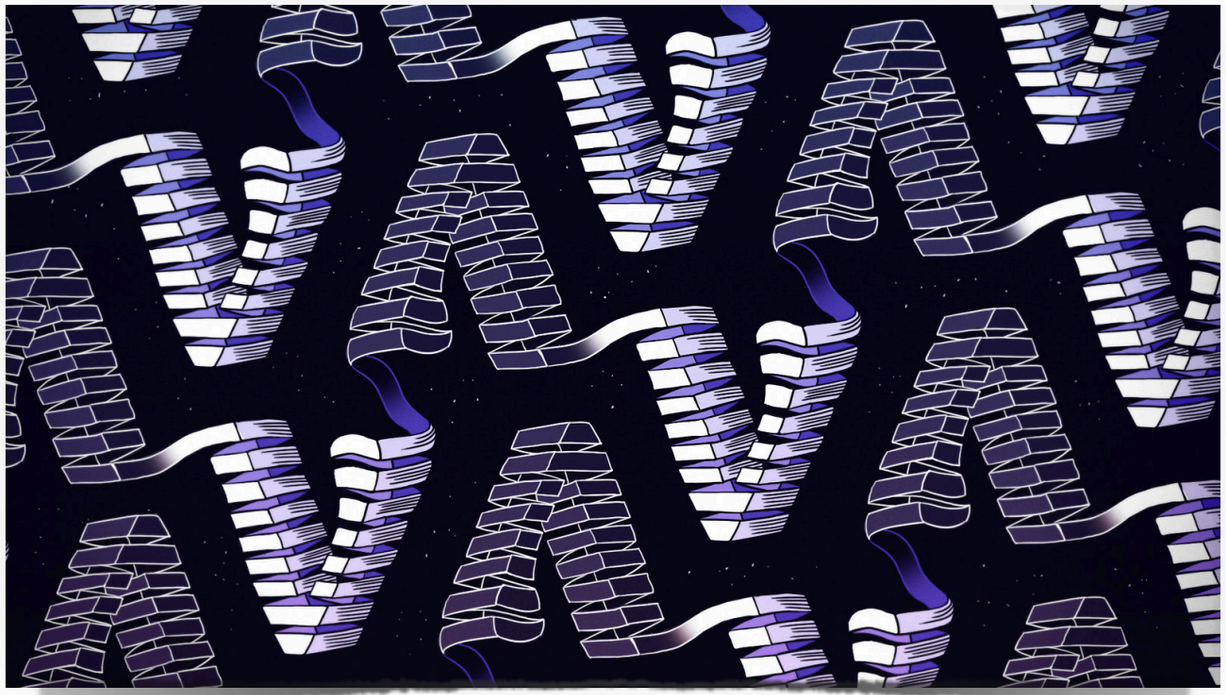

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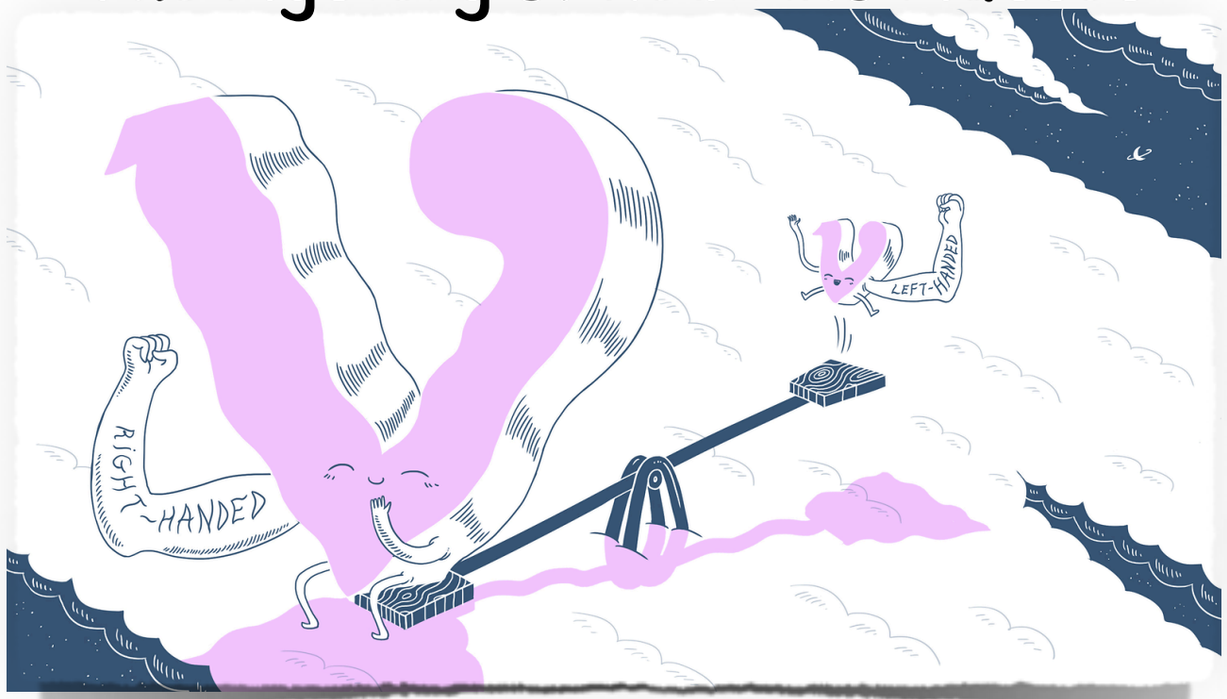


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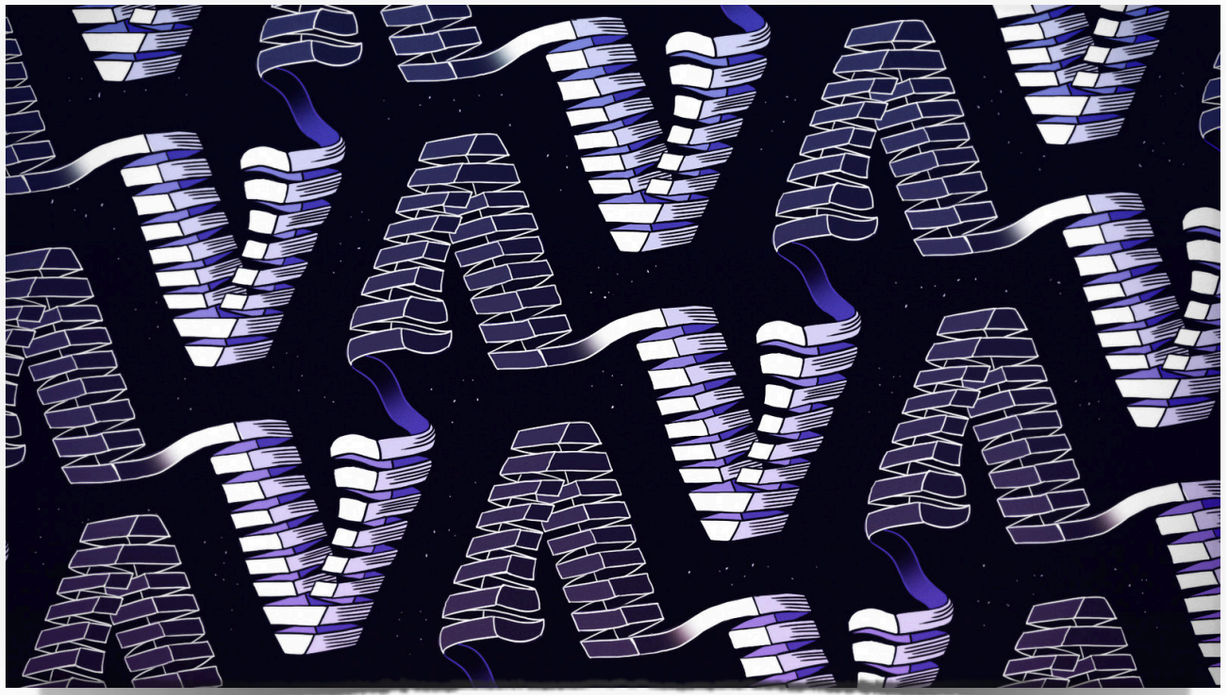

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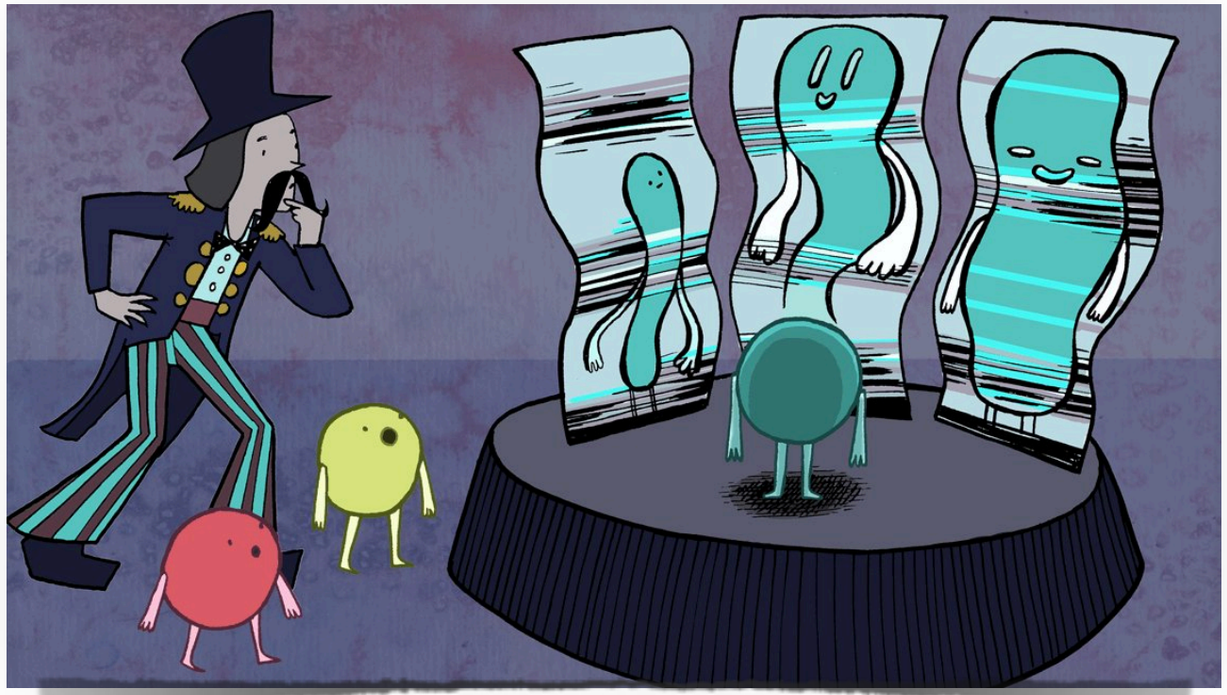

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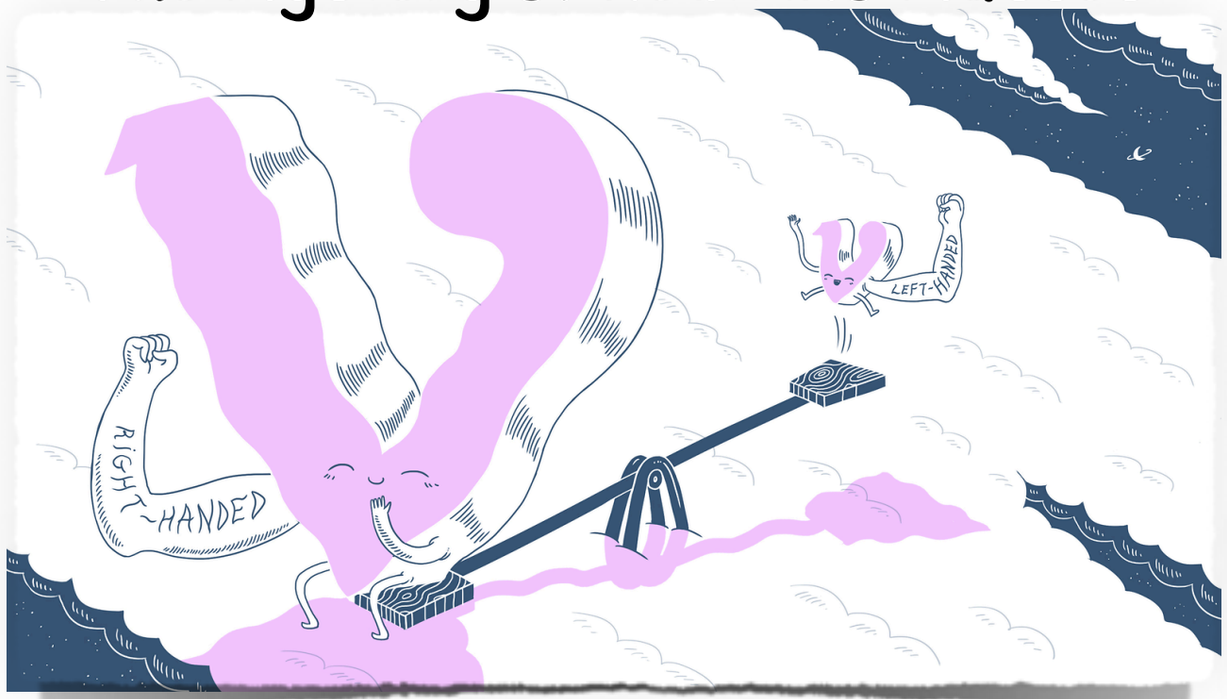


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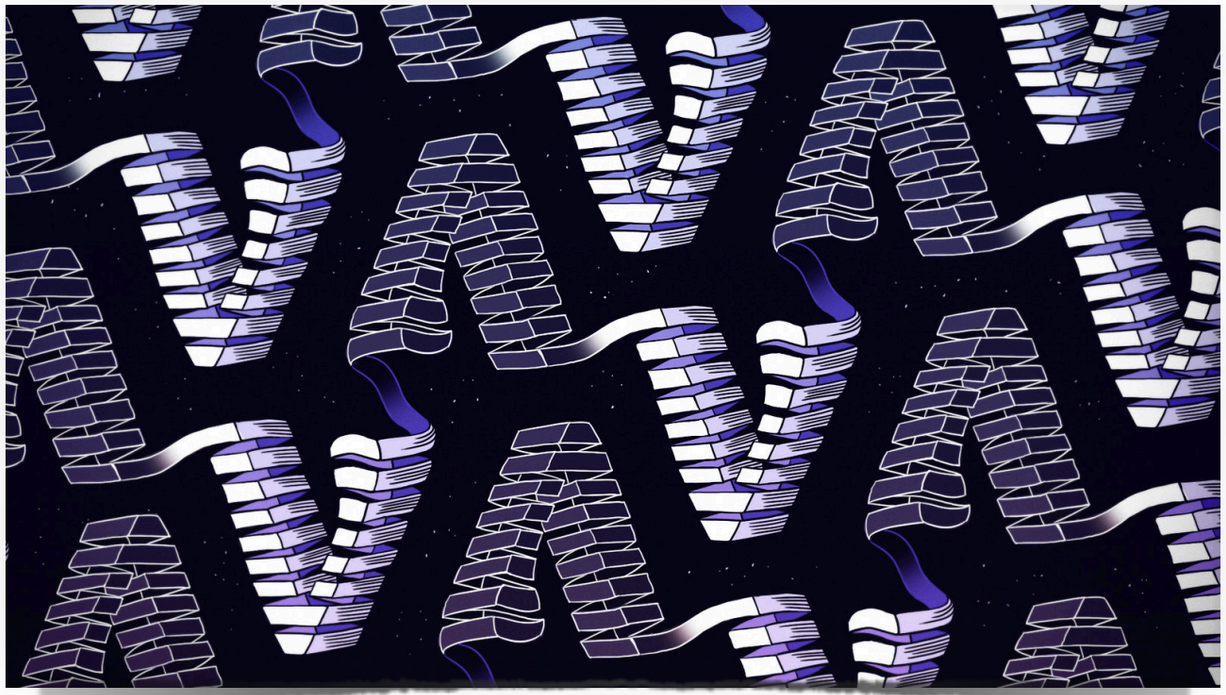

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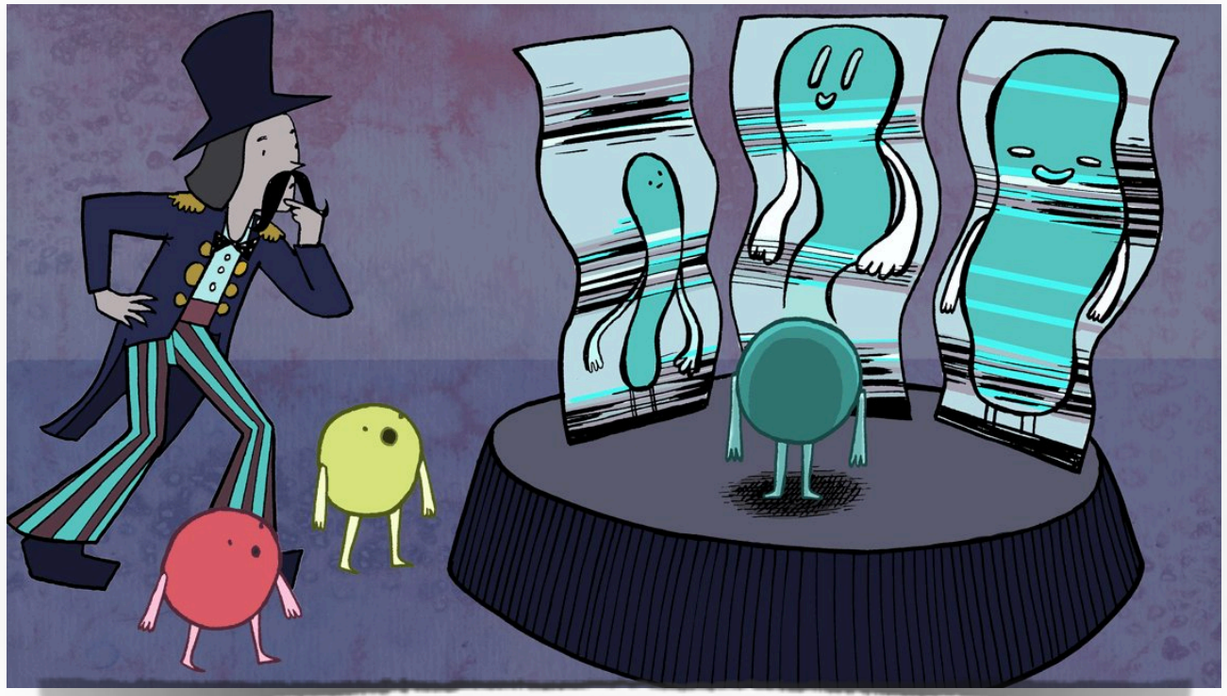

## The darkest of all particles



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# What do we know about neutrinos?

Neutrinos oscillate, therefore they have mass

We don't know neutrino masses, only the mass splittings

$m_\nu \sim$ smaller than about 1 $eV^2$



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What is the mechanism behind neutrino masses and mixings?

We understand oscillation physics, but there are unknowns:
mass ordering, CP violation, some flavor content, why so much mixing…


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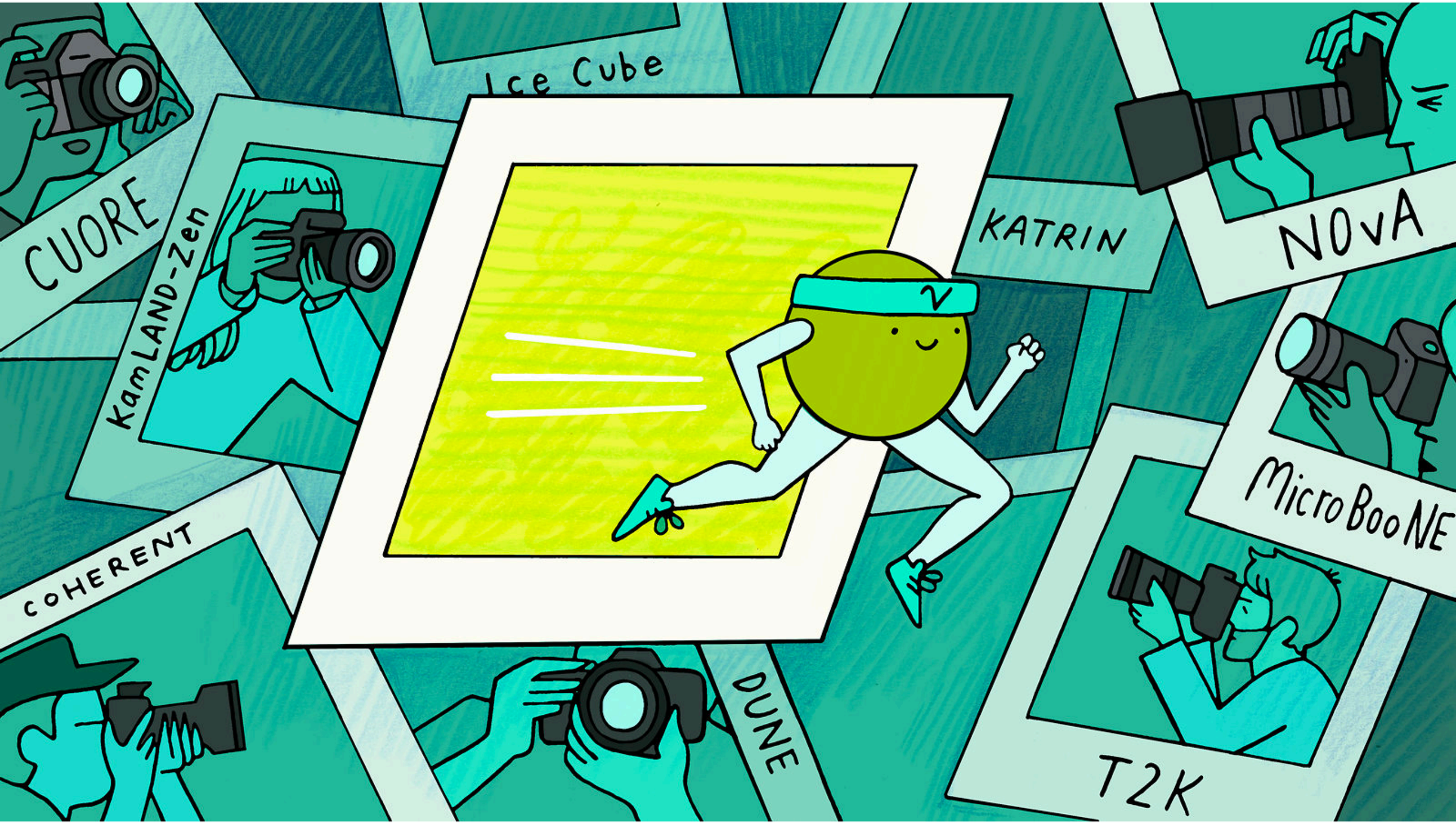
As far as we know, neutrinos only interact via weak interactions

There are only 3 light neutrinos with weak interactions. Are there sterile neutrinos? If so, at what scale?

Majorana or Dirac?

# Neutrino oscillations





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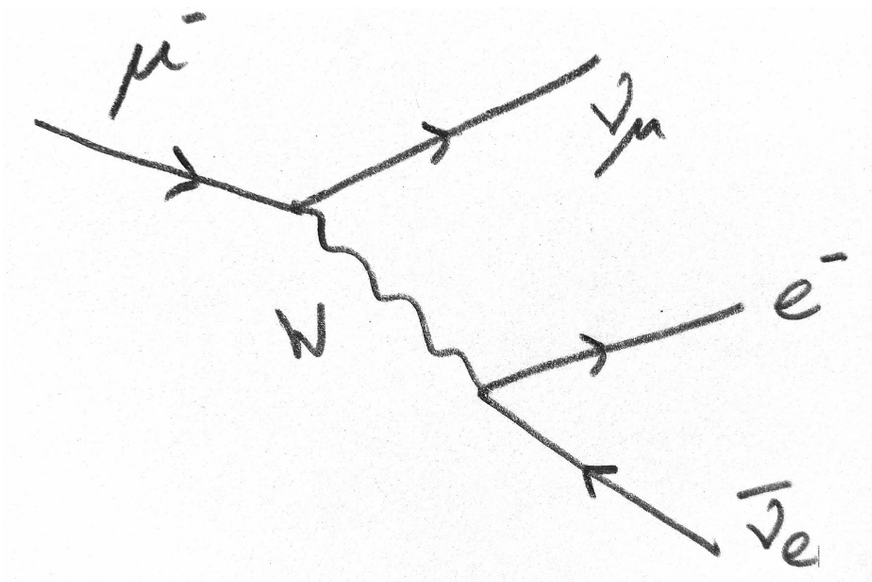
# Neutrino oscillations

Neutrinos are only produced by weak interactions




The state produced by
weak interactions
is a quantum superposition of
physical states

$$|\nu_e\rangle = U^*_{e1}|\nu_1\rangle + U^*_{e2}|\nu_2\rangle + U^*_{e3}|\nu_3\rangle$$
$$\vdots$$

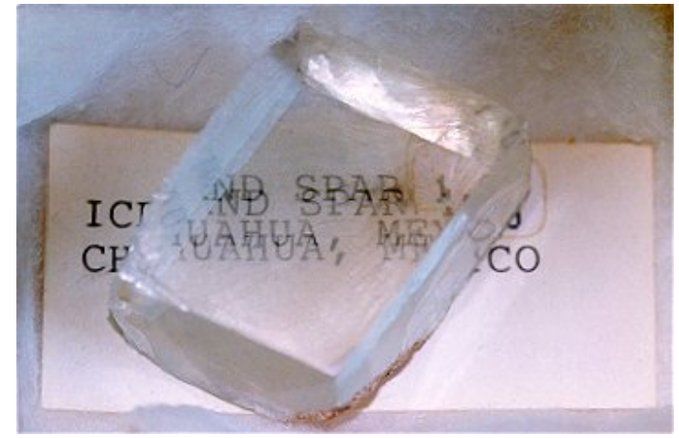
Flavor eigenstates: produced by weak interactions
Mass eigenstates: physical states with well-defined mass

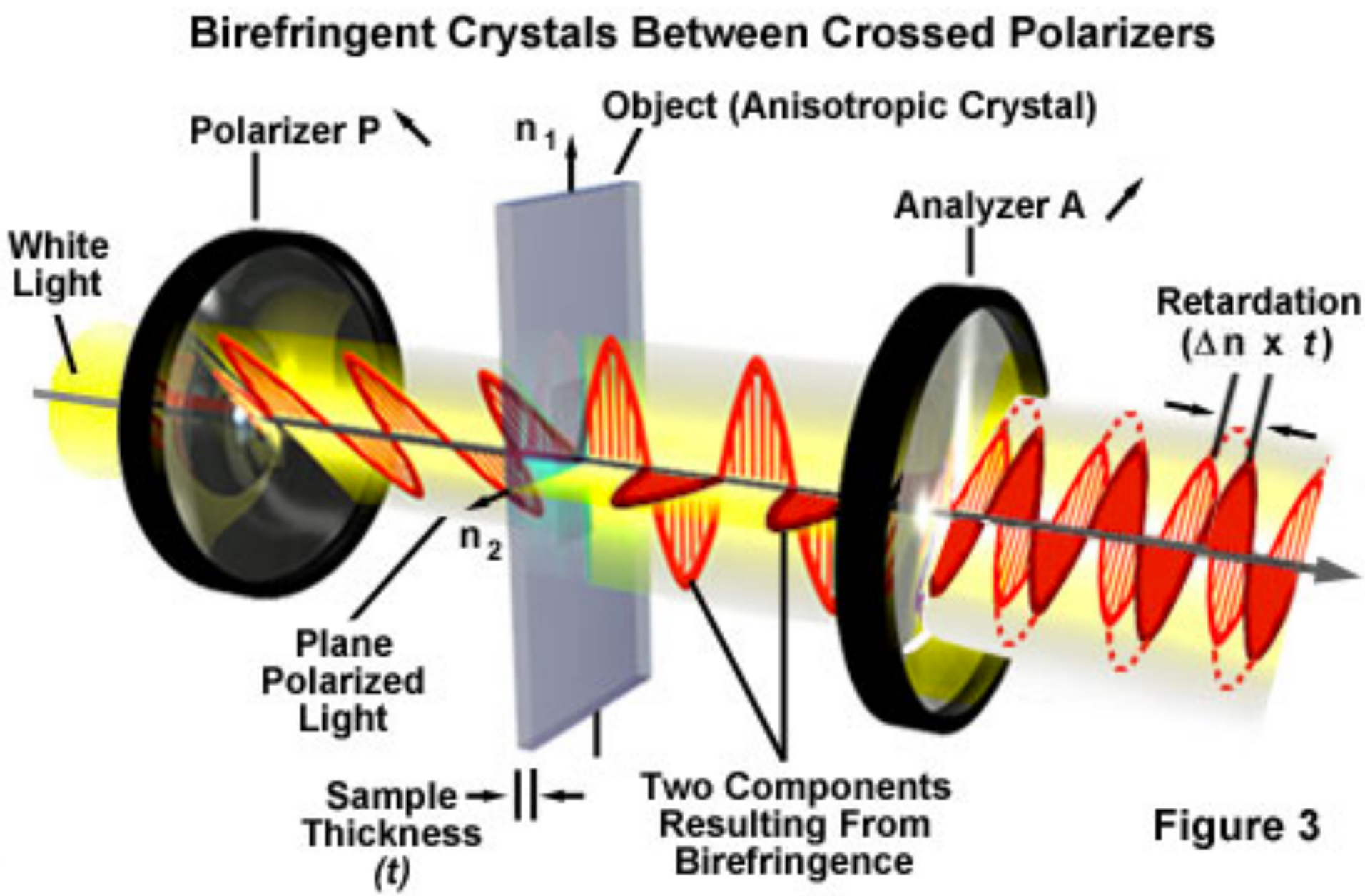
**Quantum Mechanics 101**

Evolution of flavor state is non-trivial, leading to neutrino oscillations

# Neutrino oscillations

Birefringent crystals have different index of refraction for light polarized parallel or perpendicular to its optical axis





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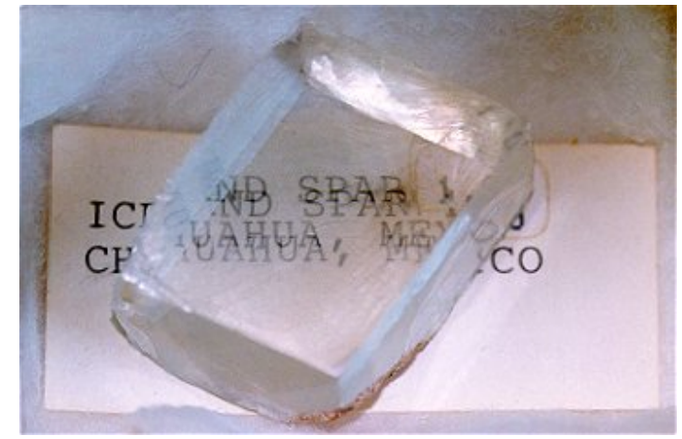
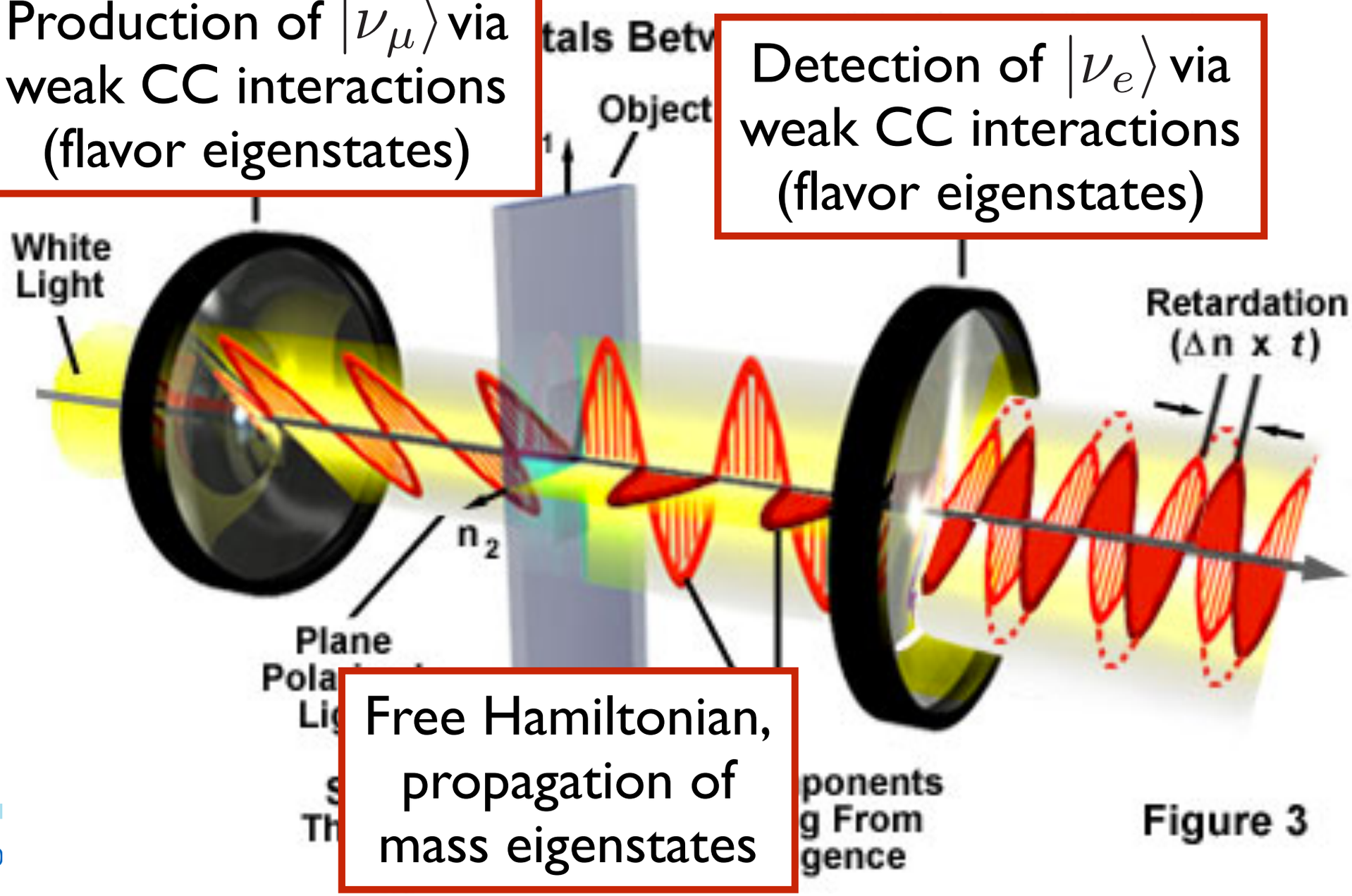


Production of $|\nu_\mu\rangle$ via weak CC interactions (flavor eigenstates)

Detection of $|\nu_e\rangle$ via weak CC interactions (flavor eigenstates)




Free Hamiltonian, propagation of mass eigenstates



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# Neutrino oscillations

A soccer example:

Say I have been ~~oscillating~~ changing teams over the years

2000

2003


2004


2009



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A soccer example:

Say I have been ~~oscillating~~ changing teams over the years

2000 2003 2004 2009

In reality,

~~teams propagate non-trivially~~

~~under the free Hamiltonian~~

I don't have a team, I am a fan of Marta!



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# Neutrino oscillations

A soccer example:
Say I have been ~~oscillating~~ changing teams over the years

Flavor eigenstates



2000 2003 2009

Mass eigenstates

In reality,
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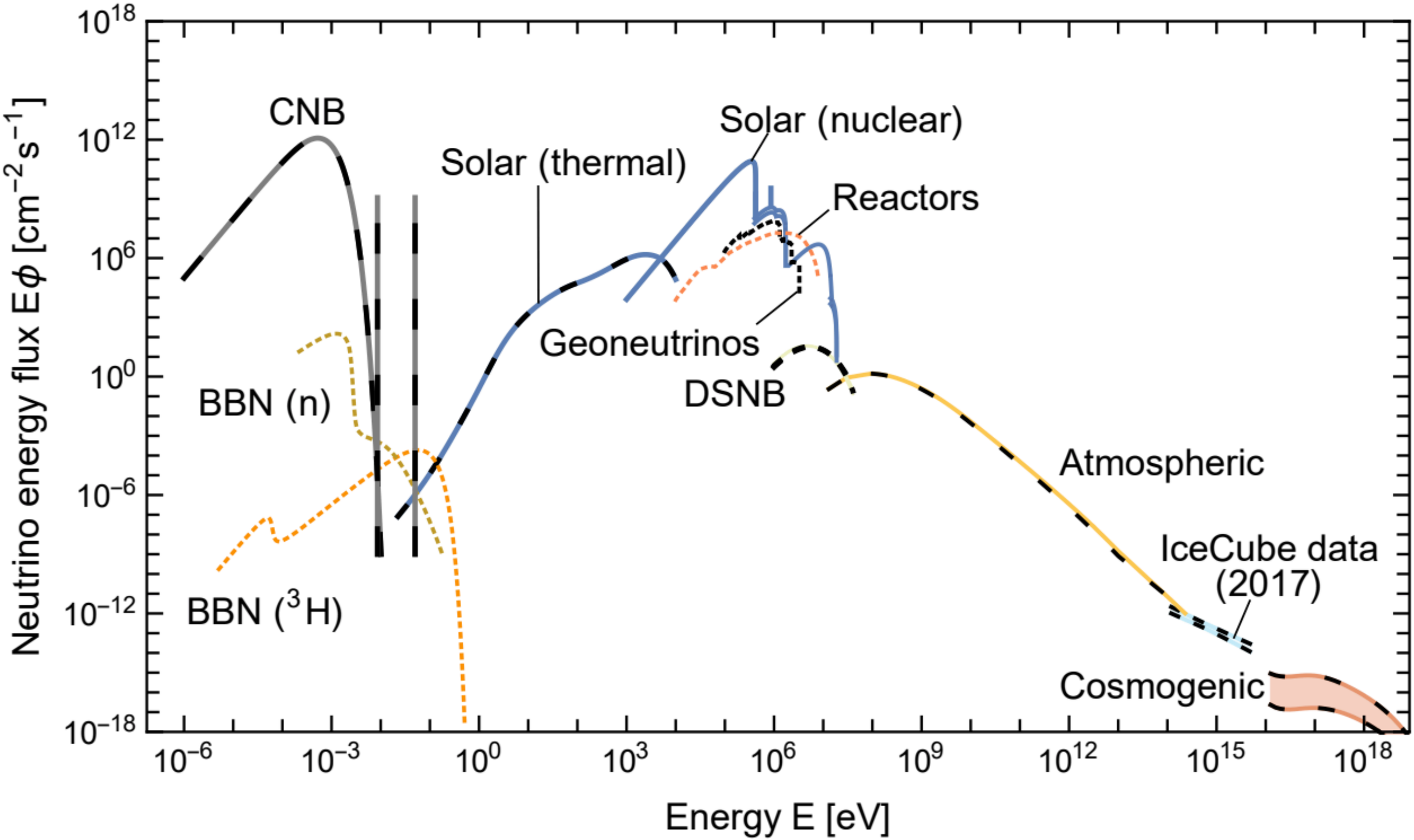
# Neutrinos are everywhere





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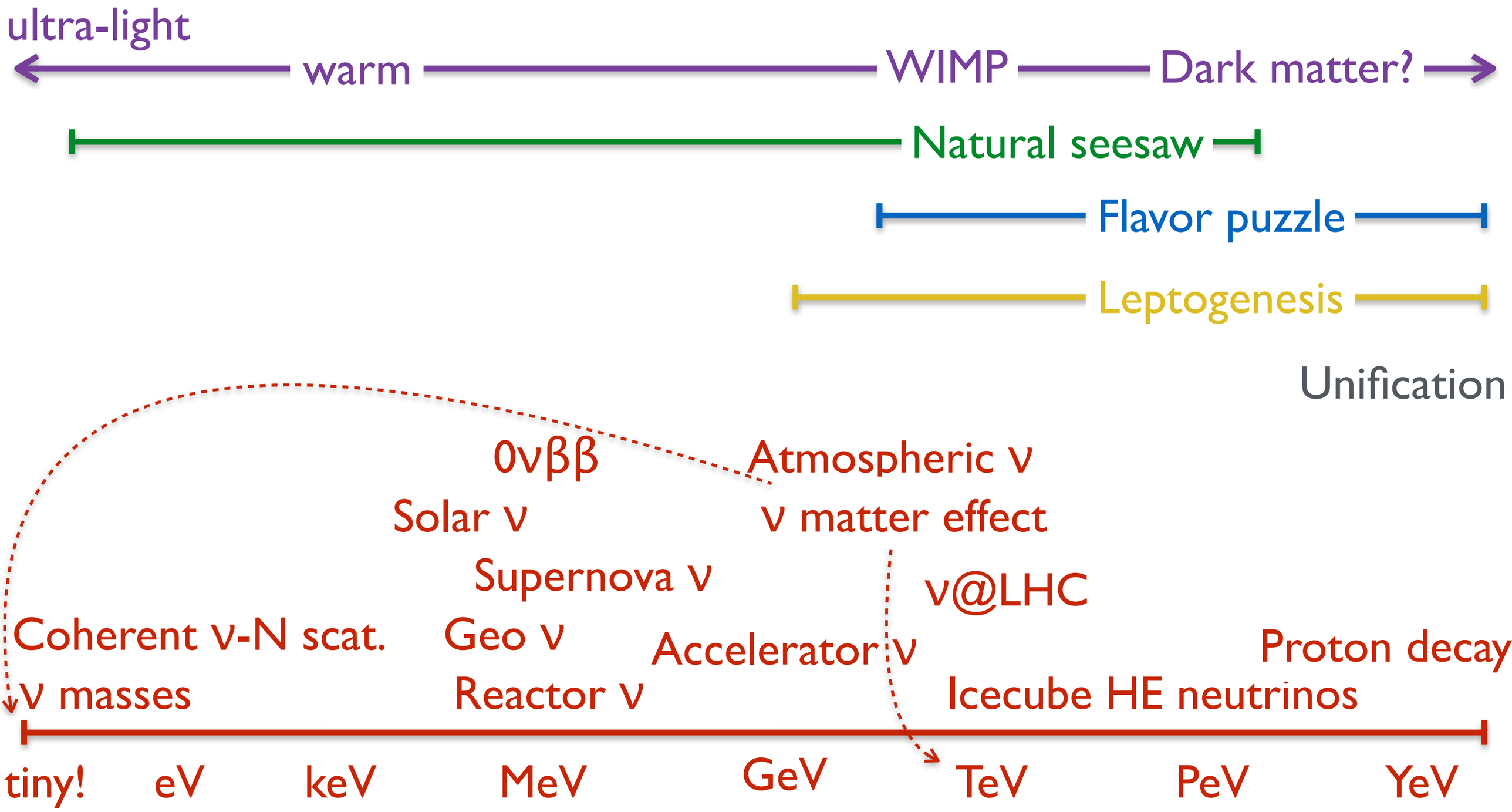



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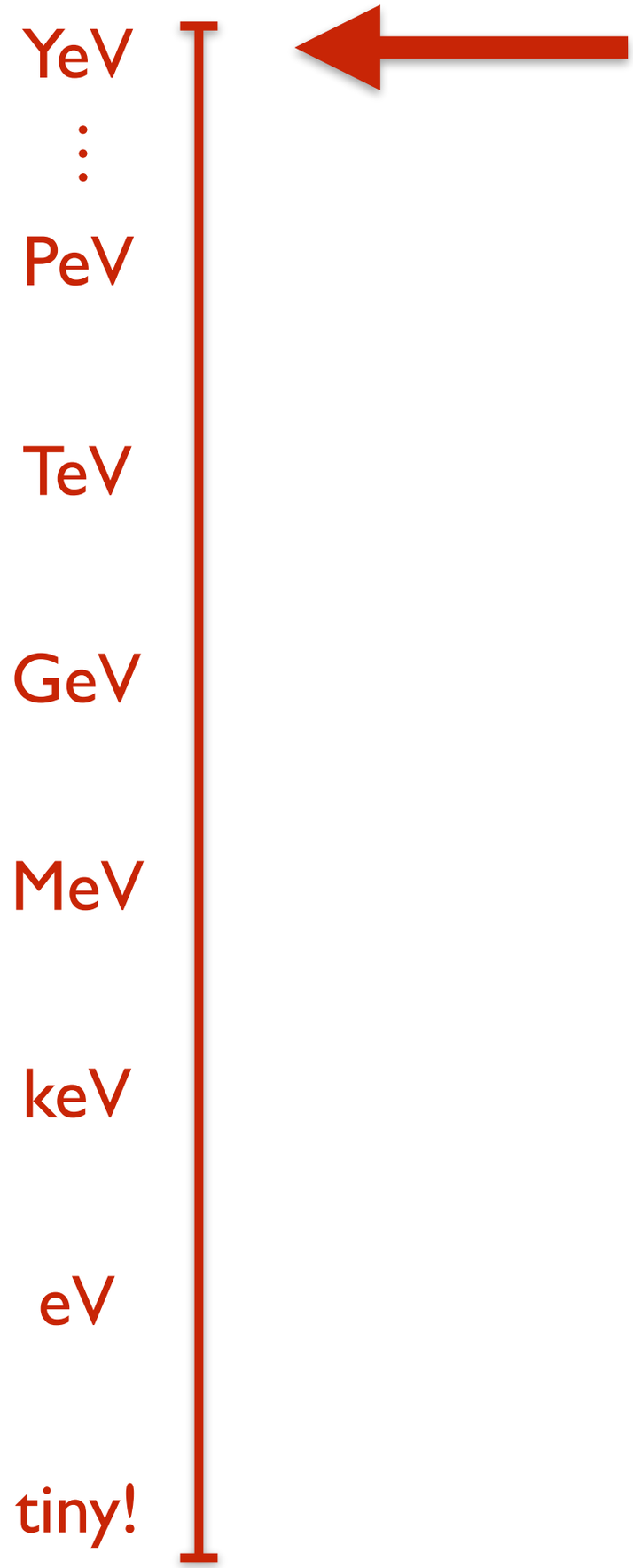



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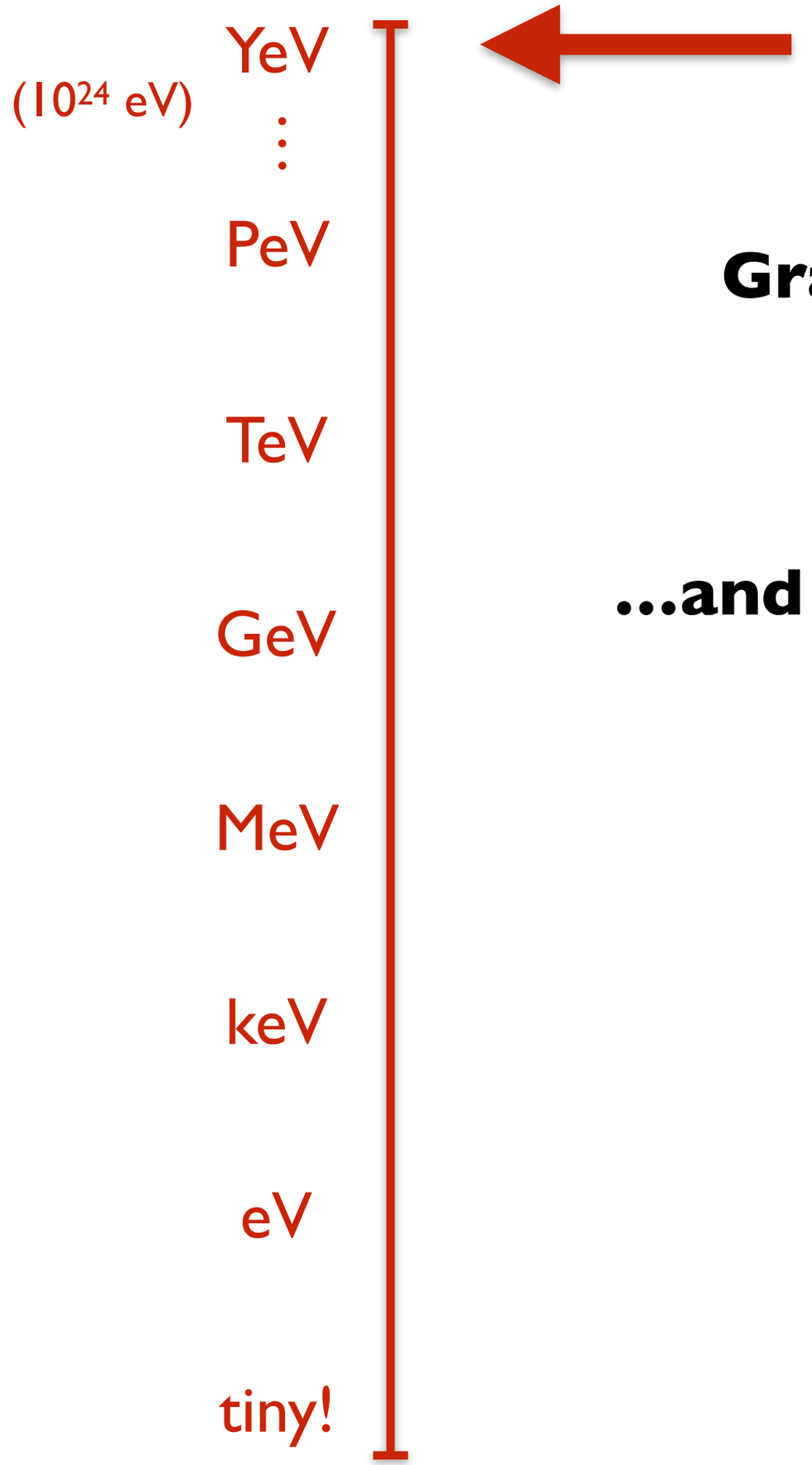


**Grand Unification**

**...and grand motivation!**


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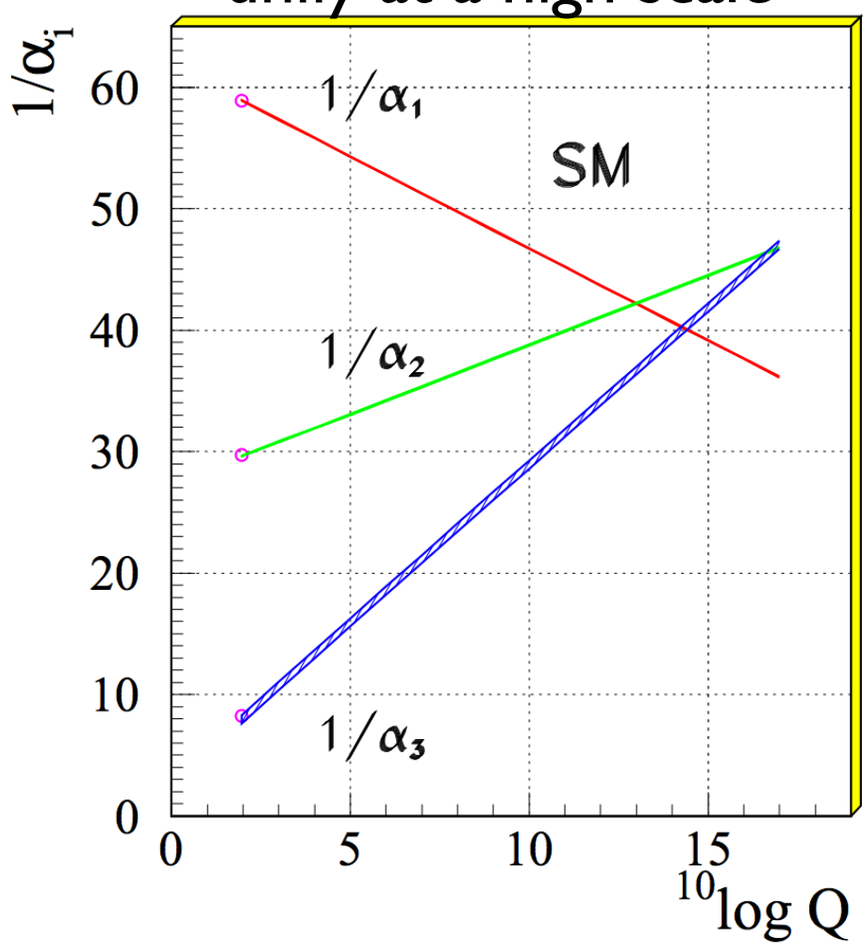
# Grand Unified Theories

Pati Salam 1973, Georgi Glashow 1974, Georgi Quinn Weinberg 1974

SM gauge couplings *almost* unify at a high scale



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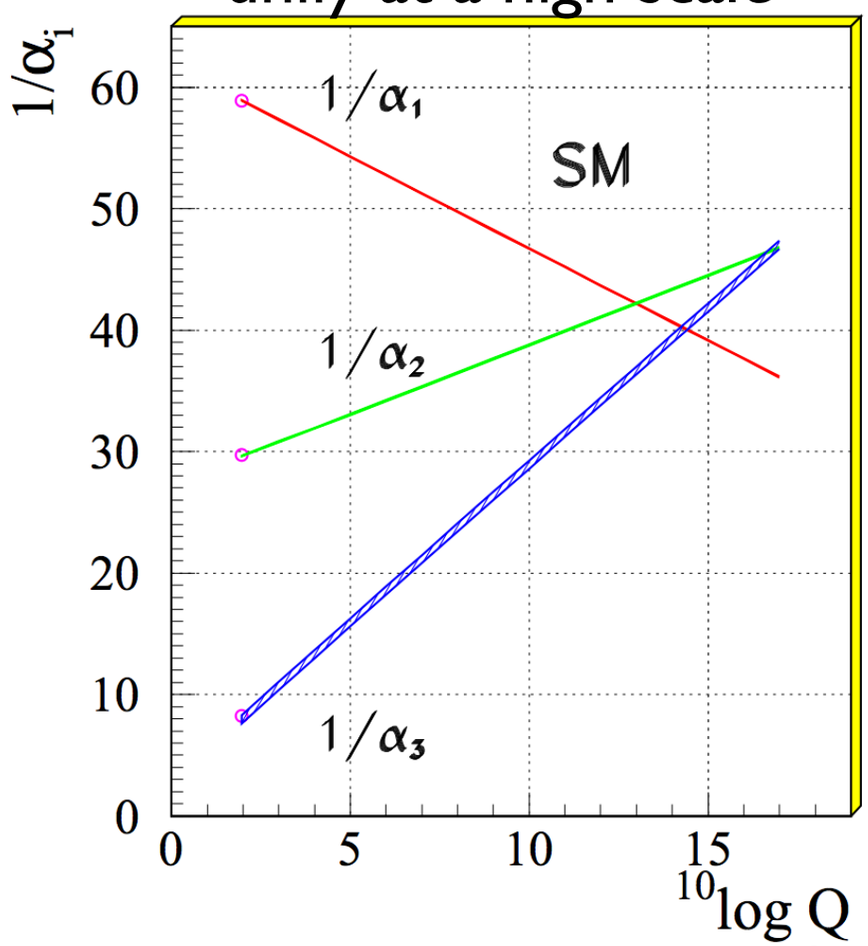


More interestingly, all SM fermions, with the addition of a sterile neutrino, fit perfectly in a **16** of SO(10)

**16** = ($u_L$ $u_L$ $u_L$ $u_R$ $u_R$ $u_R$ $d_L$ $d_L$ $d_L$ $d_R$ $d_R$ $d_R$ $e_L$ $e_R$ $\nu_L$ $\nu_R$)

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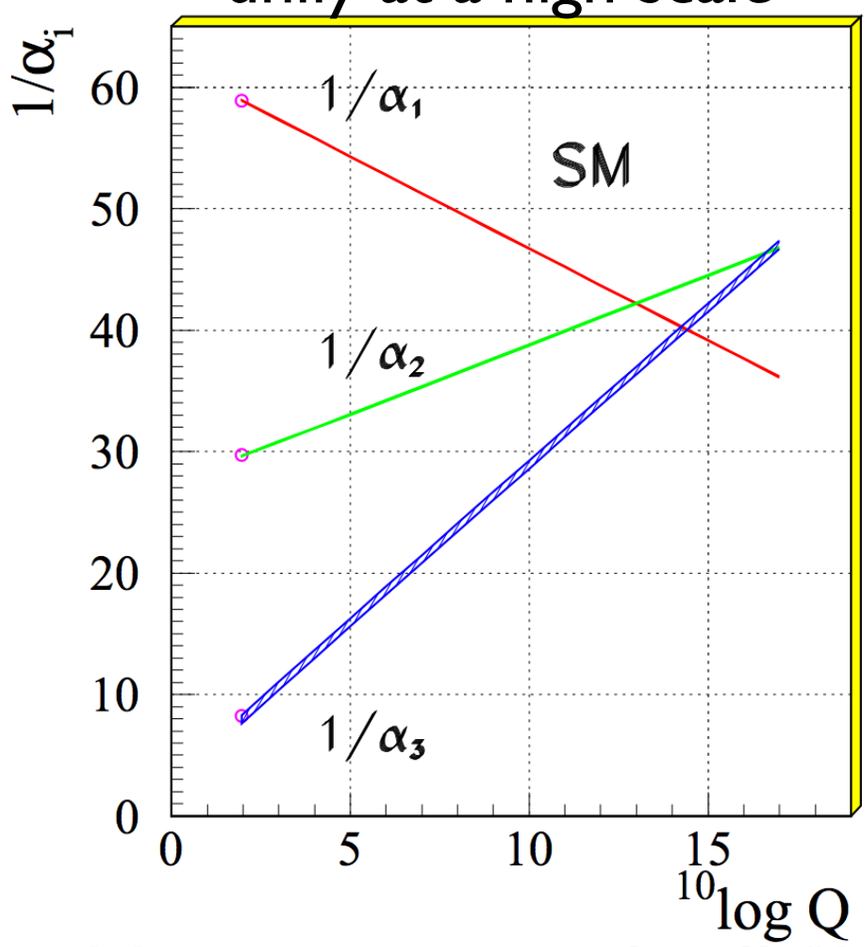


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## Deep consequences

Unification of all forces under a single gauge group

Proton decay

Majorana masses for neutrinos


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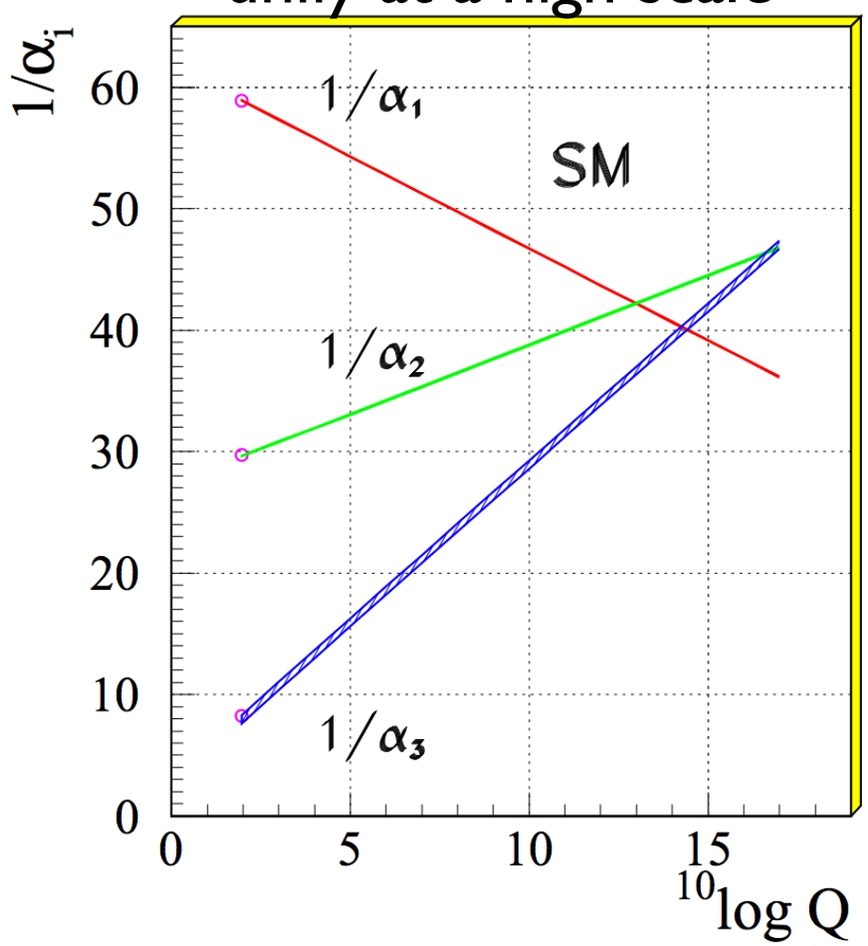


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# Are neutrinos Majorana or Dirac fermions?

## Charged fermions

4 degrees of freedom: ($e^+_L$ $e^+_R$ $e^-_L$ $e^-_R$)

Particle ≠ antiparticle


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## Charged fermions

4 degrees of freedom: $(e^+_L \;\; e^+_R \;\; e^-_L \;\; e^-_R)$

Particle ≠ antiparticle

## Neutral fermions

4 degrees of freedom $(\nu_L \;\; \nu_R \;\; \bar{\nu}_L \;\; \bar{\nu}_R)$???
Dirac

but $(\nu_L \;\; \nu^c_R)$ is enough for what we have observed…
Majorana

Particle ≠ antiparticle???


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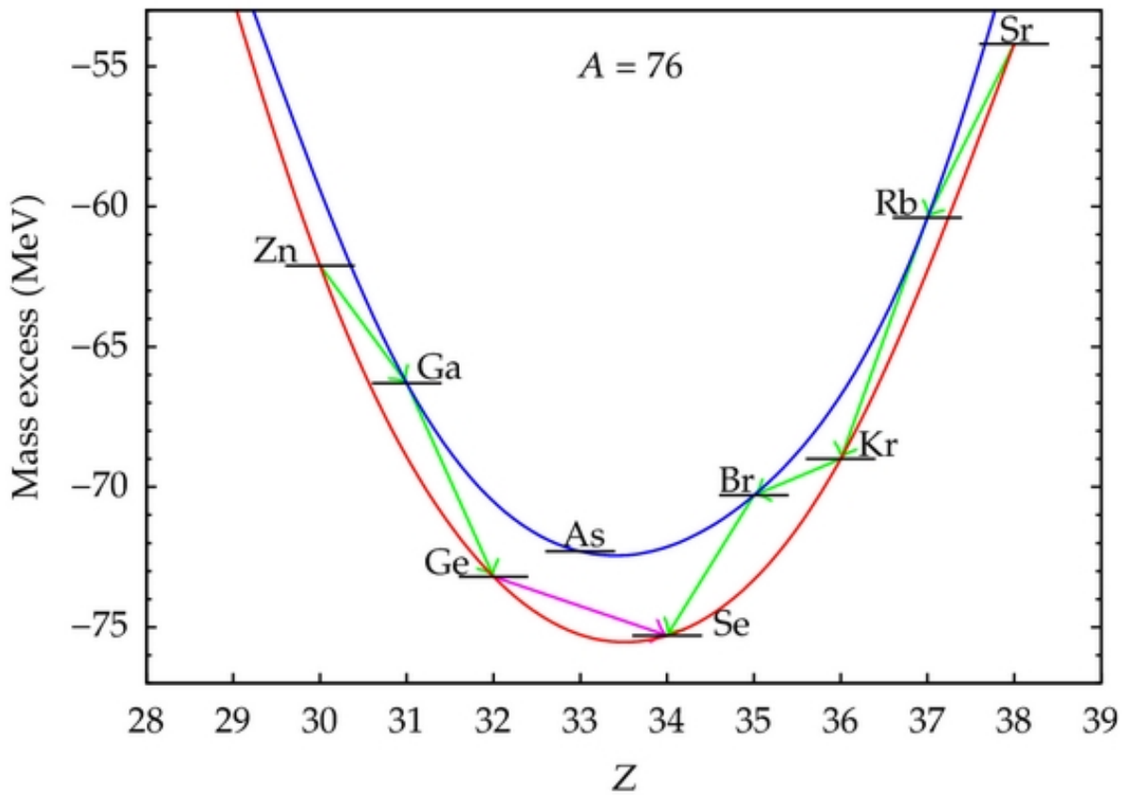
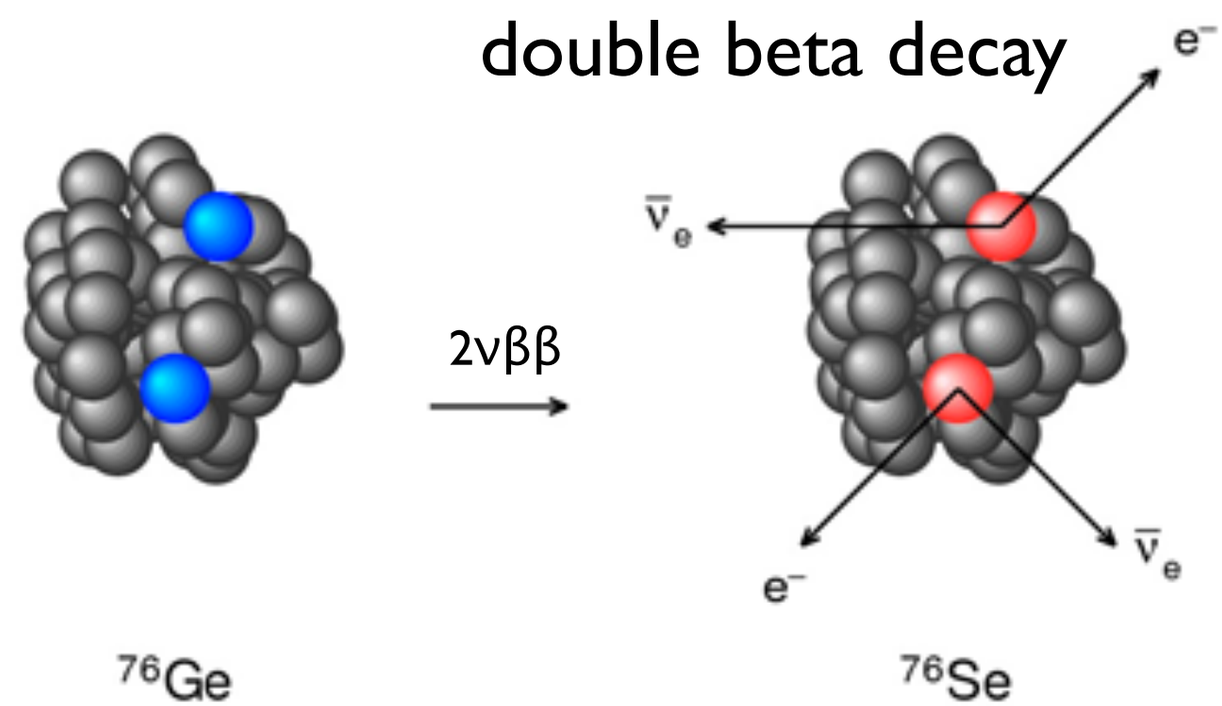
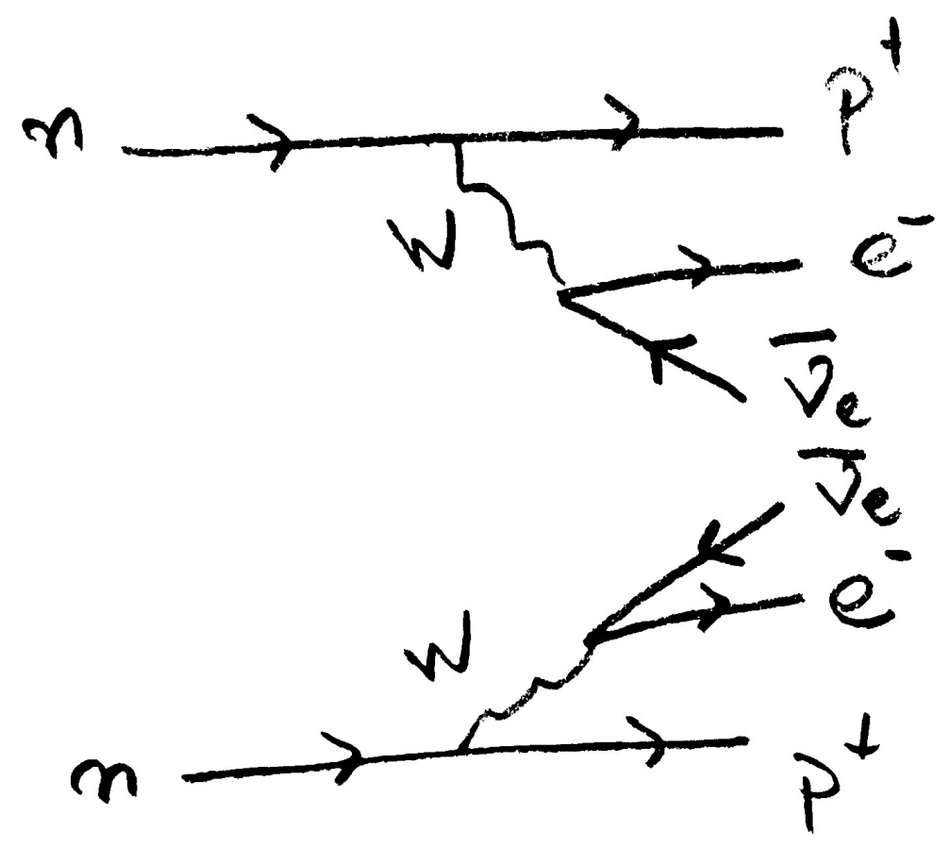



double beta decay



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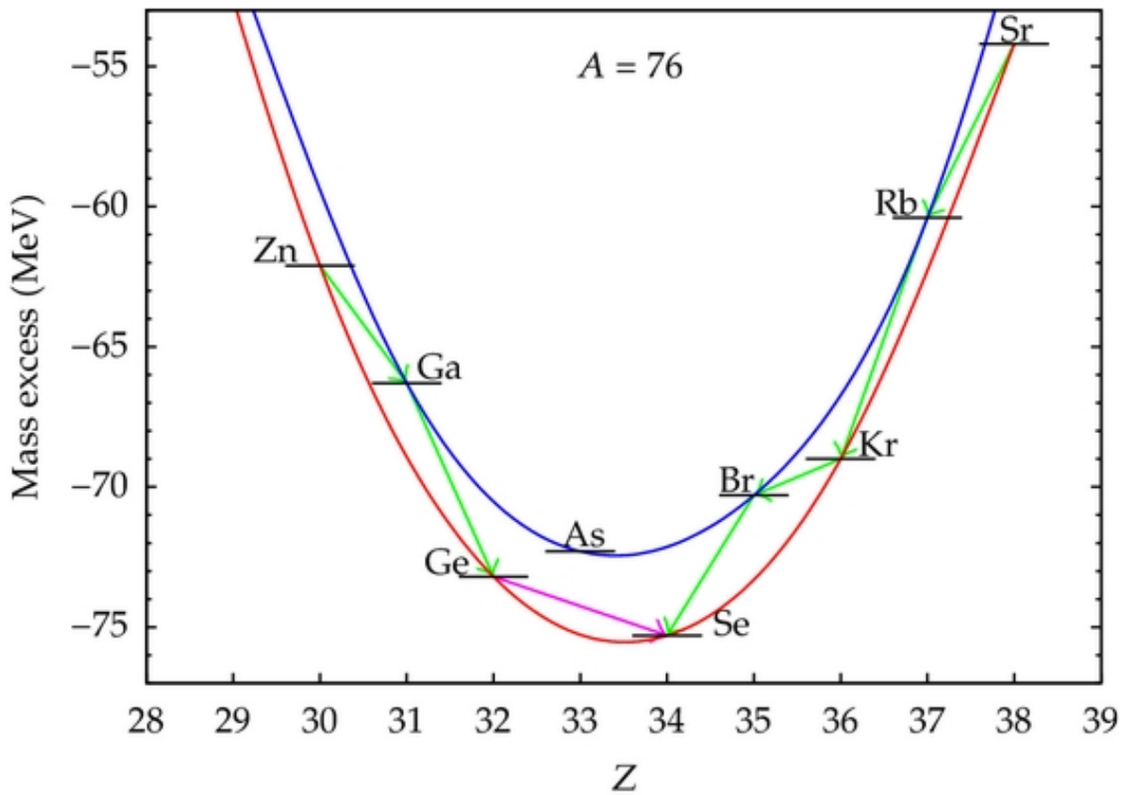
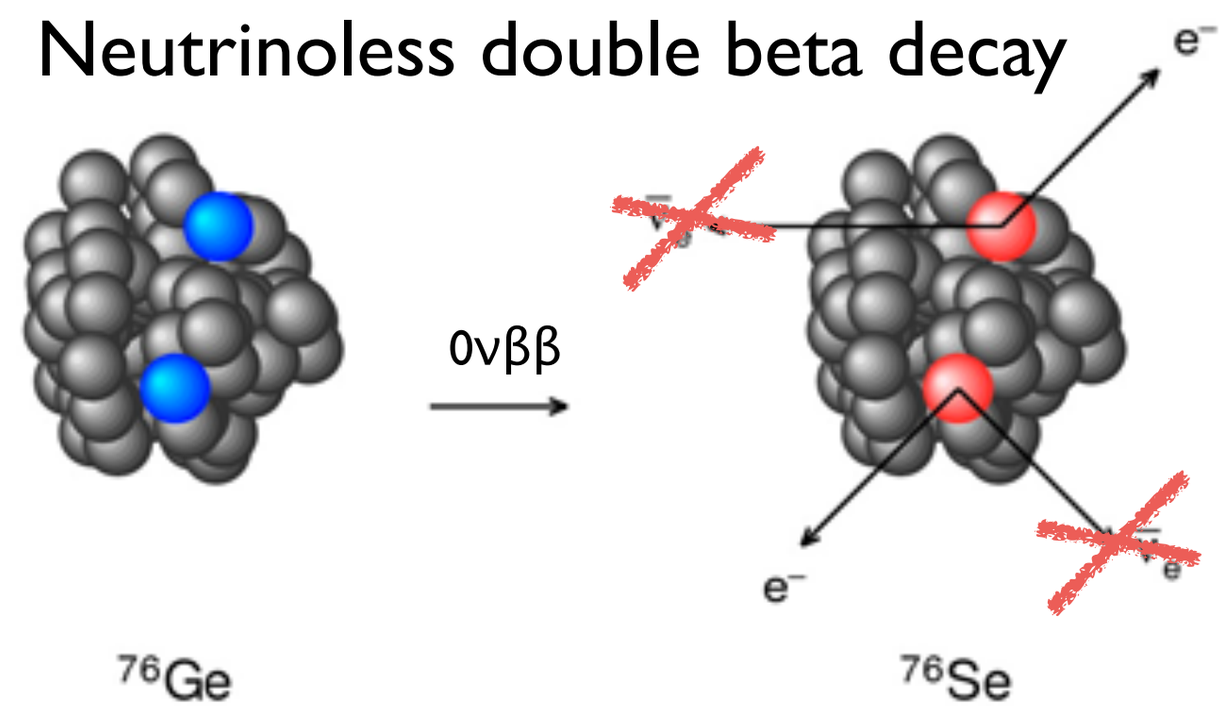
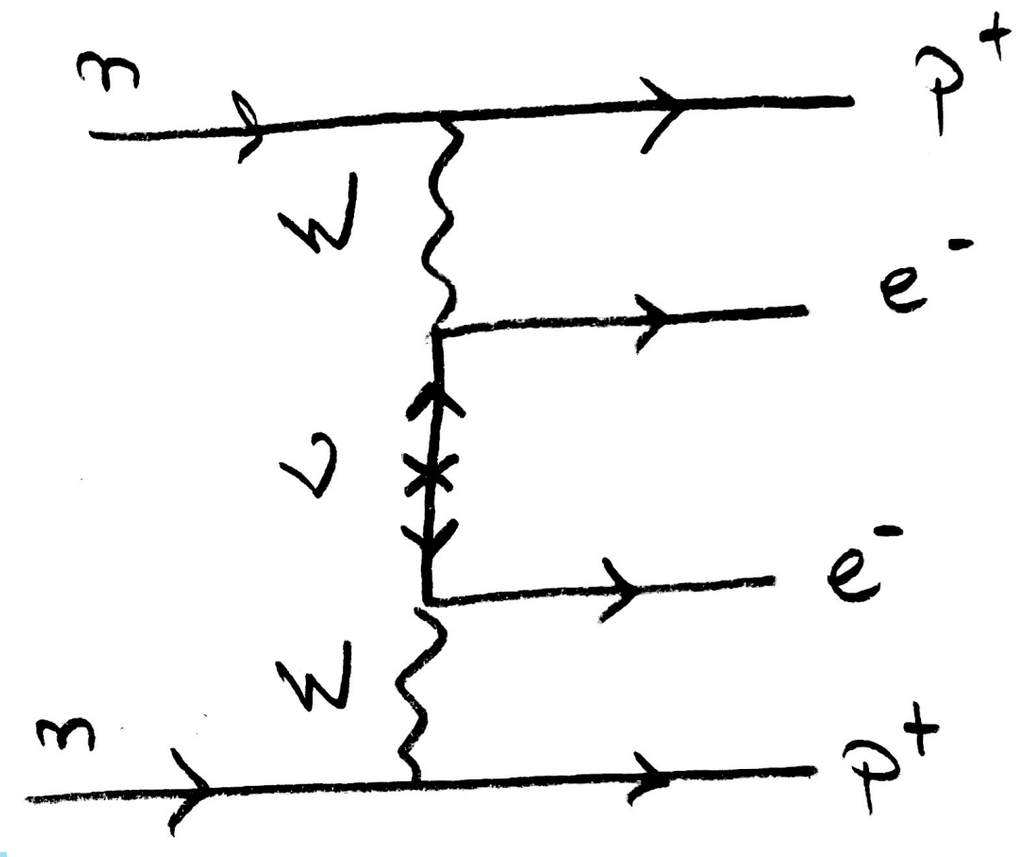



Neutrinoless double beta decay





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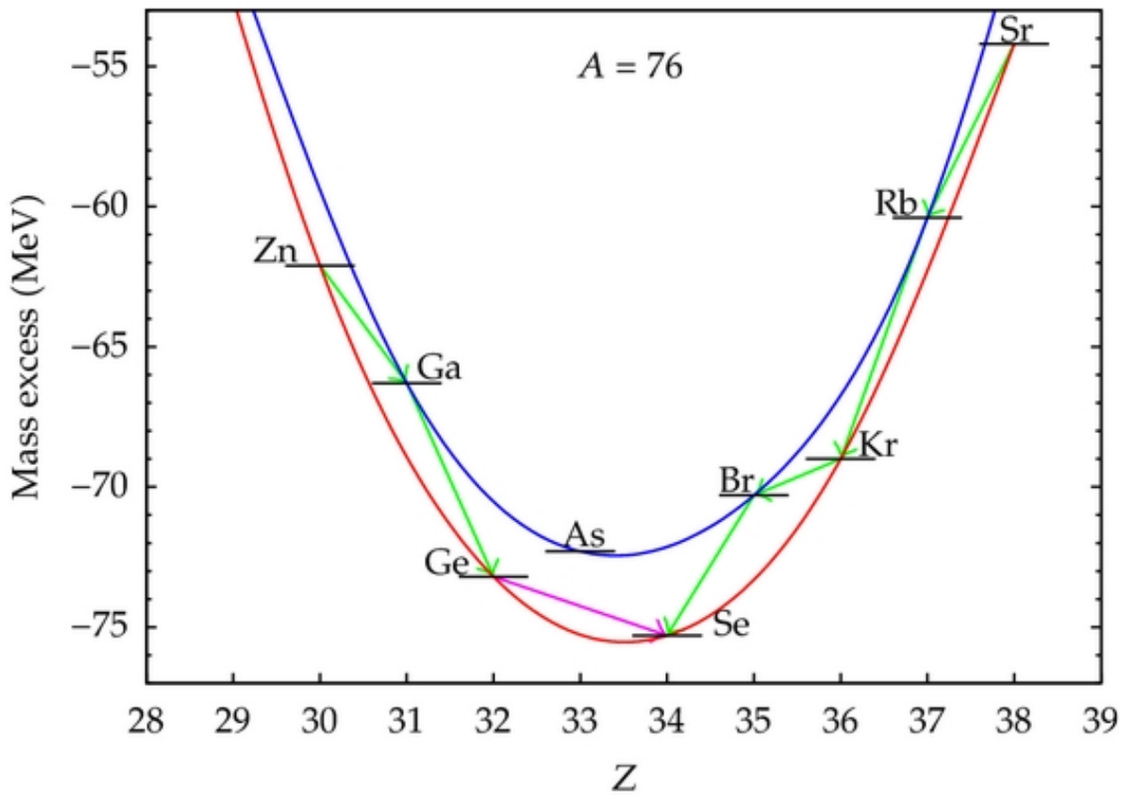


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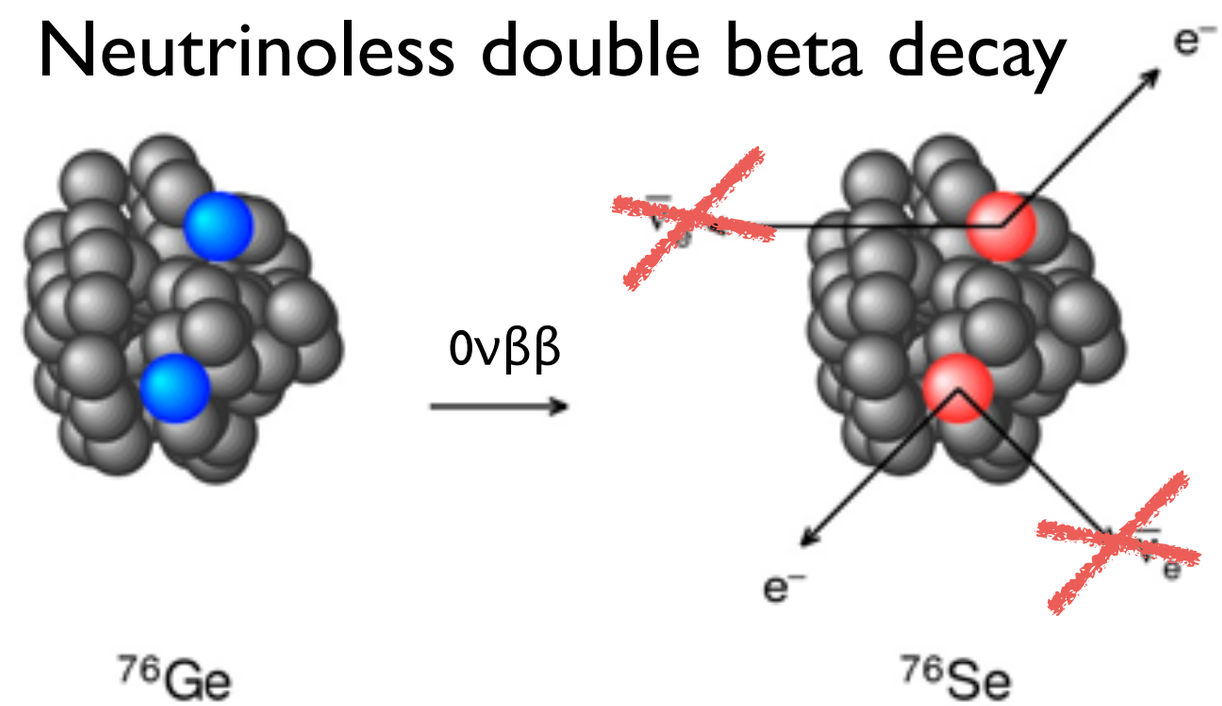
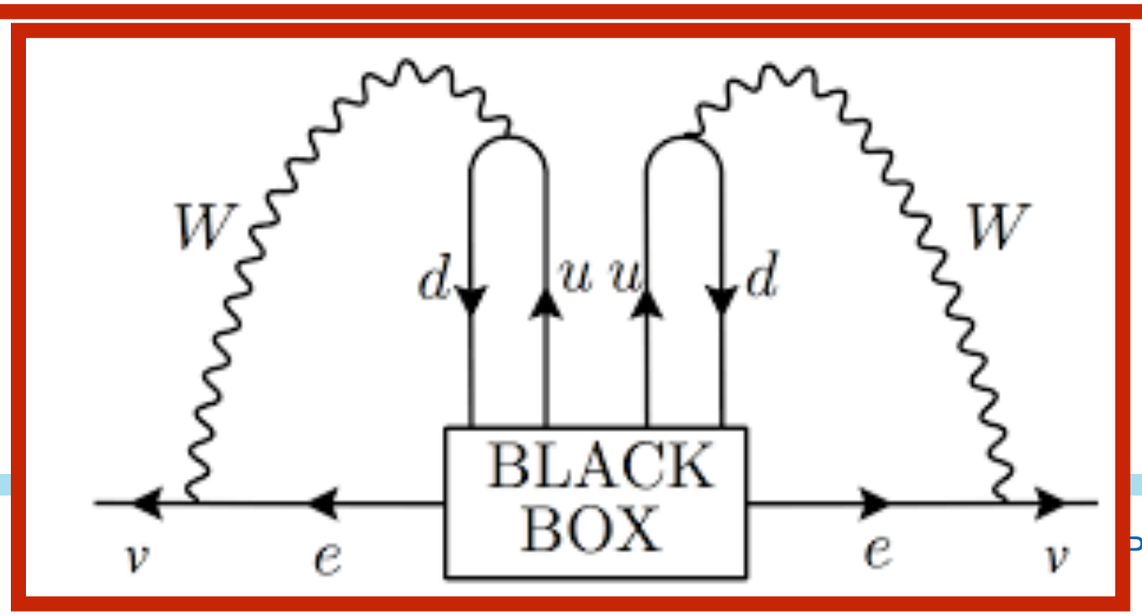
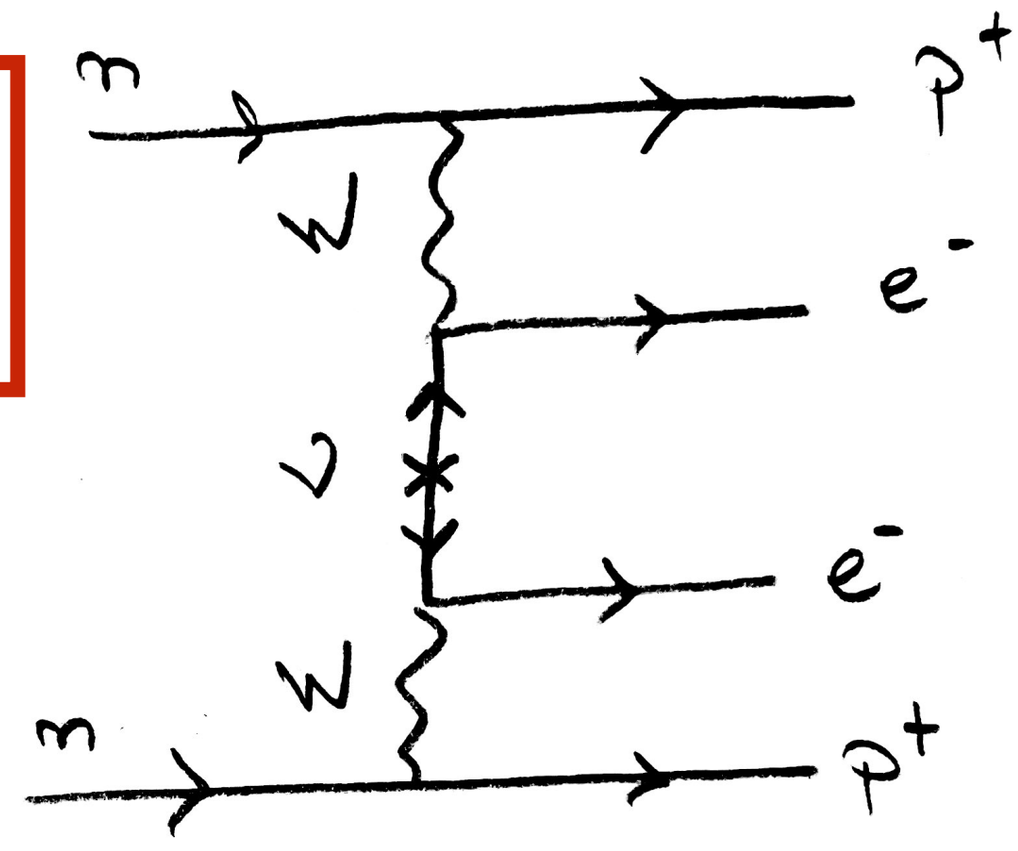



**The black box theorem**

If 0νββ is measured, neutrino masses necessarily have a Majorana component




Schechter Valle 1981



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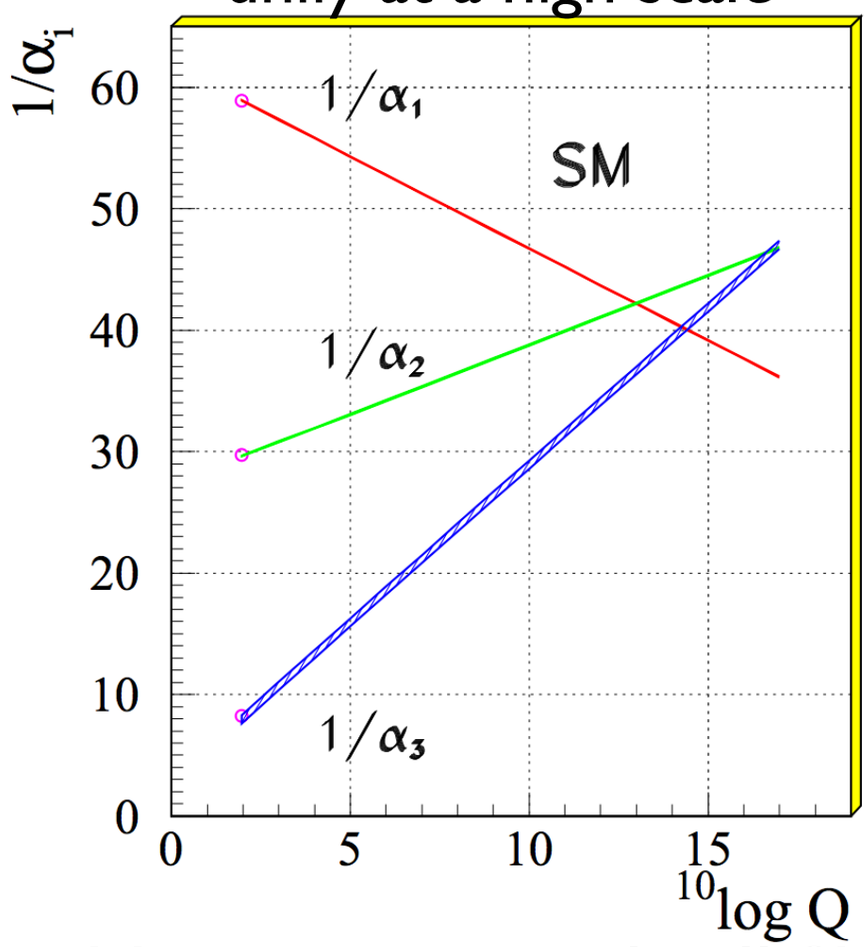


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**Proton decay**

Majorana masses for neutrinos



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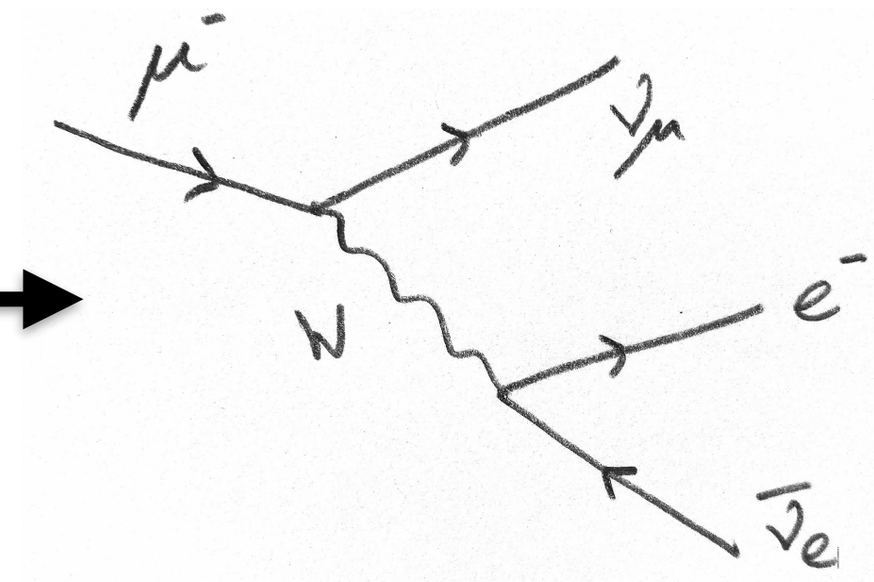
# Is the proton stable?

Weak interactions:
in $SU(2)_L$ we have **2** = ($\nu_L$ $\ell_L$)




Grand Unification Theories:
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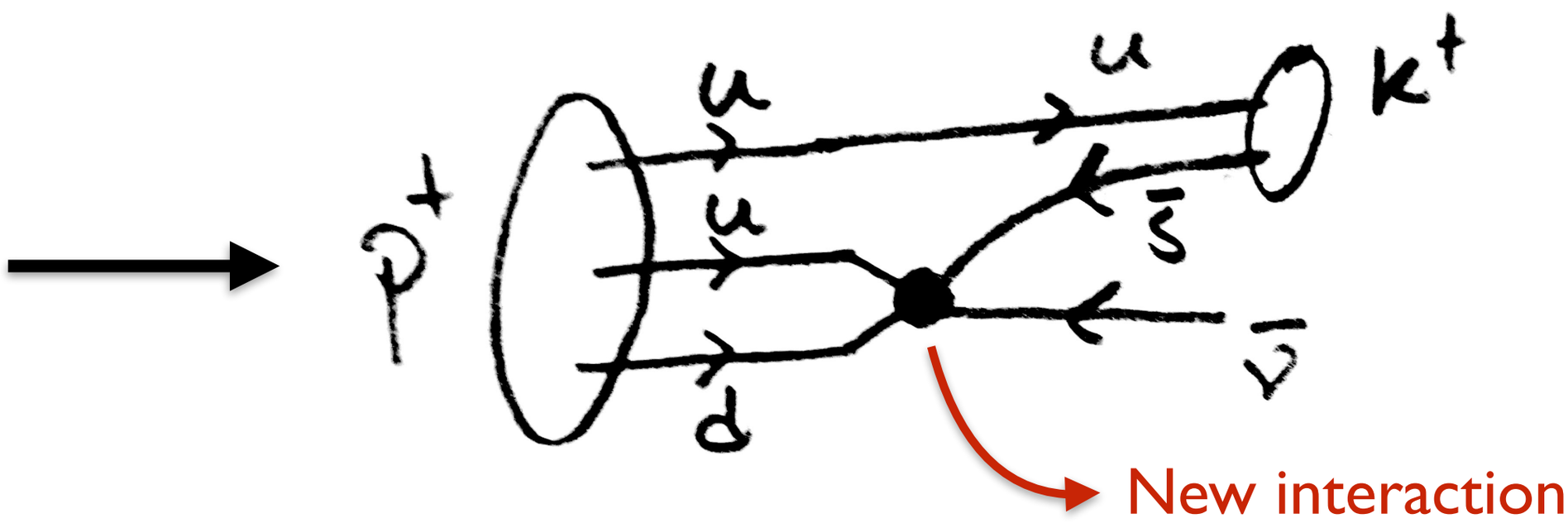
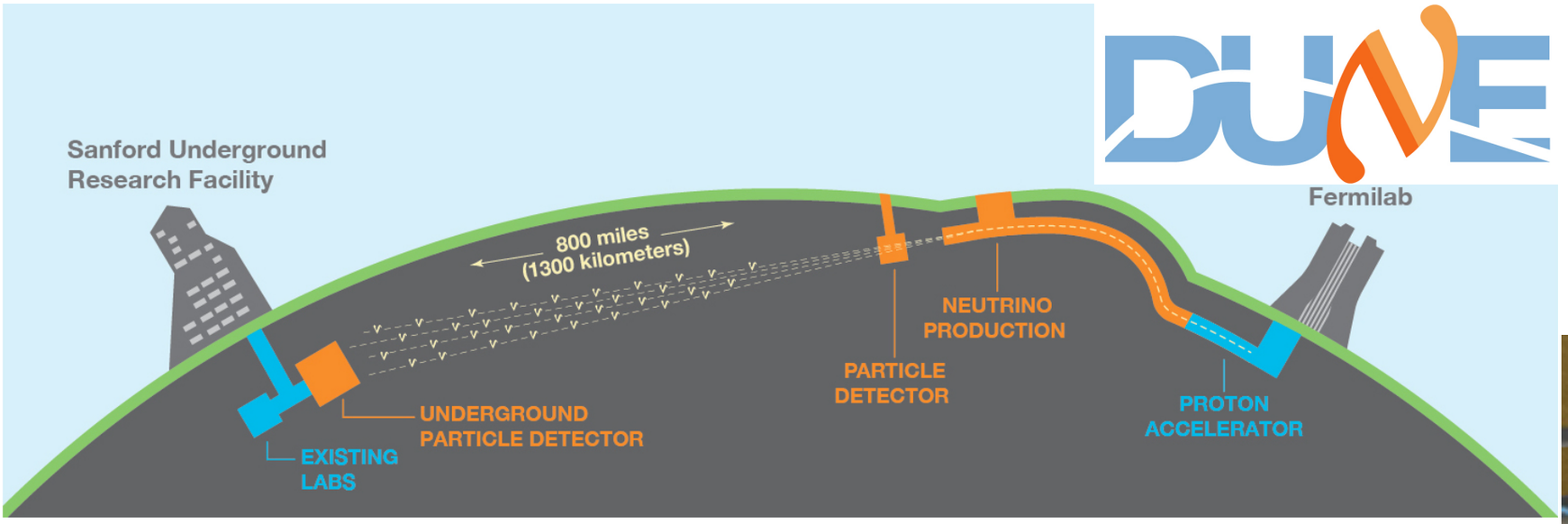
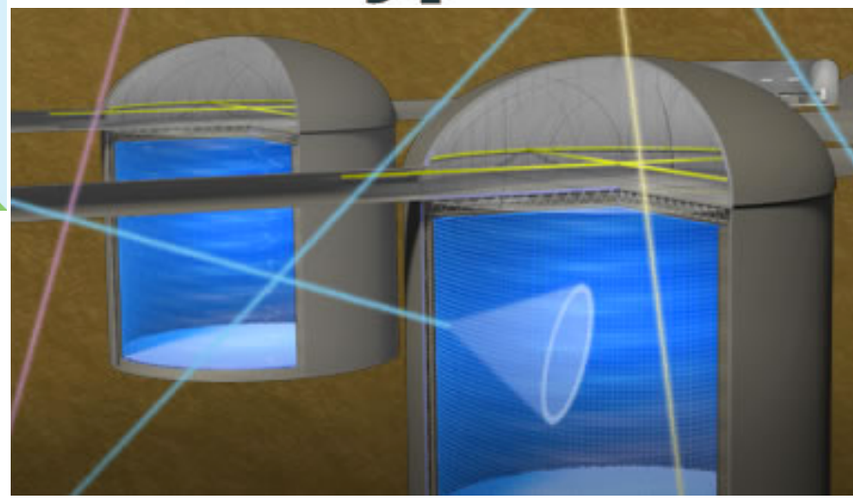
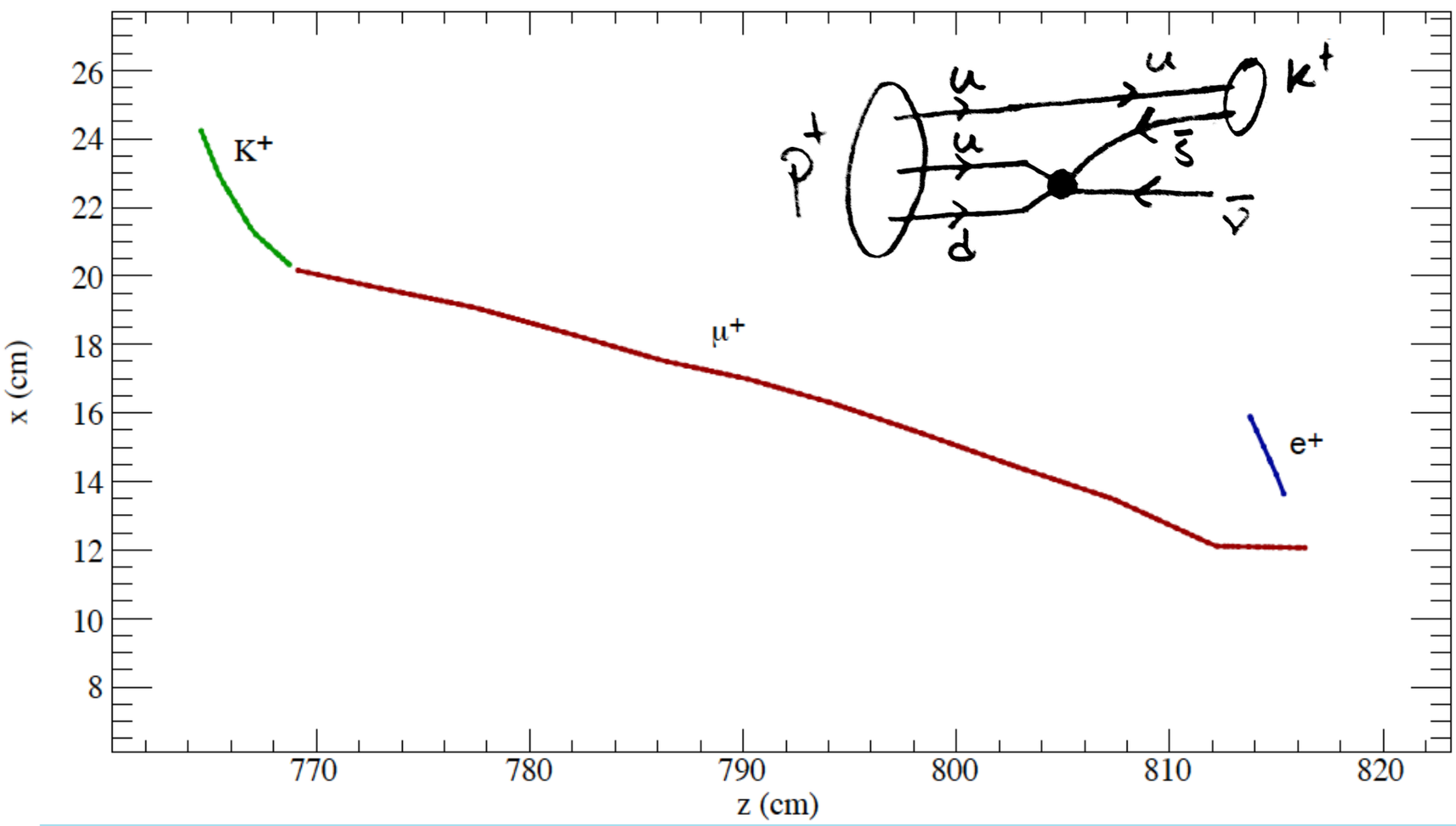


# Is the proton stable?






$\tau_{proton} > 2 \times 10^{29}$ years
Specific channels have much stronger constraints

For comparison
$T_{universe} \sim 1.4 \times 10^{10}$ years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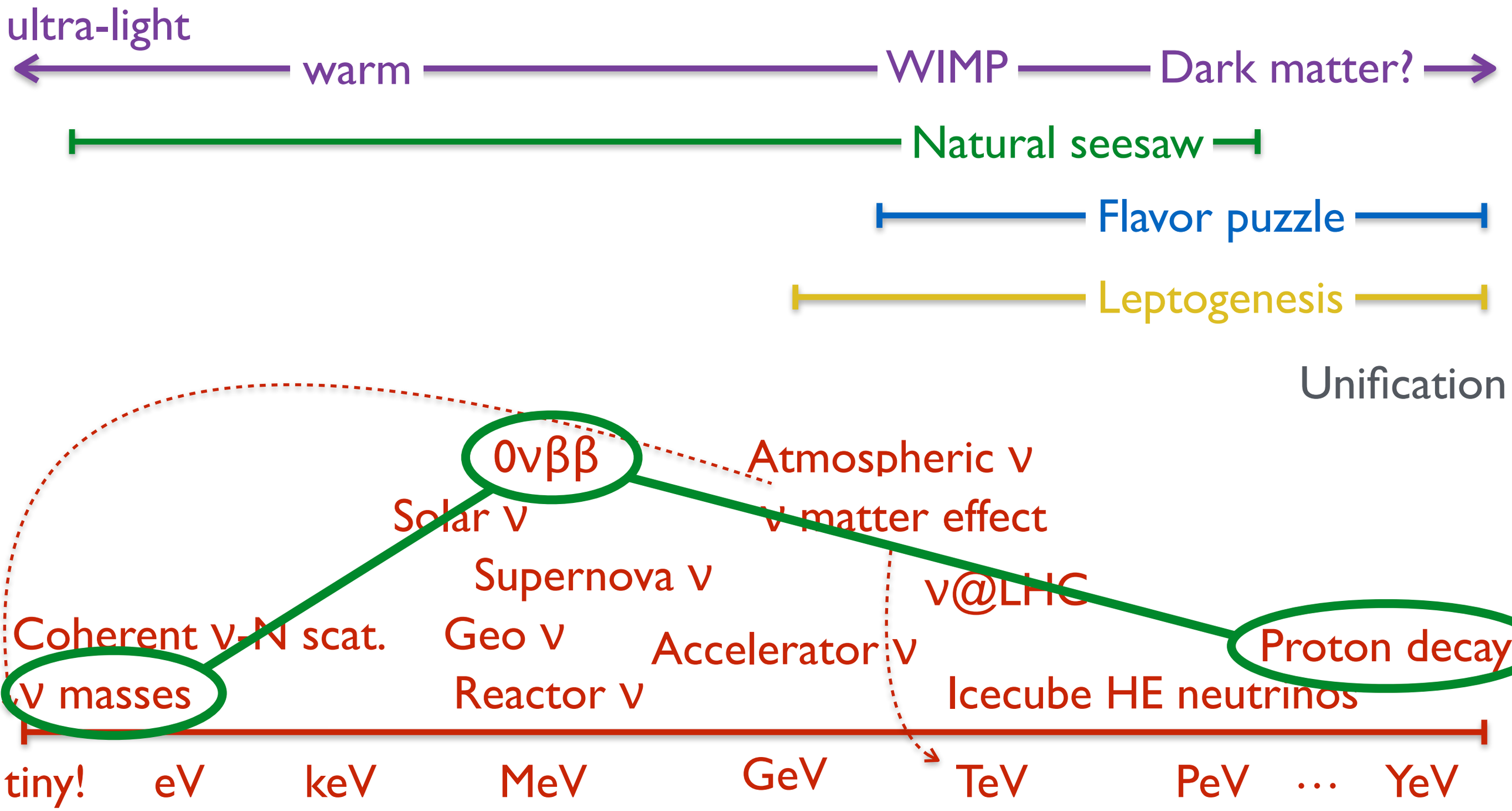
# Neutrinos are everywhere in nature





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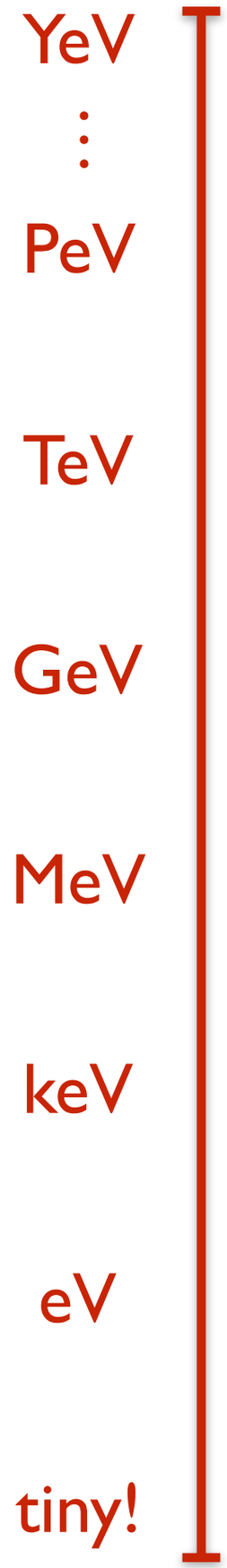


**New physics in neutrino oscillations**

-ish

**Theory developments**



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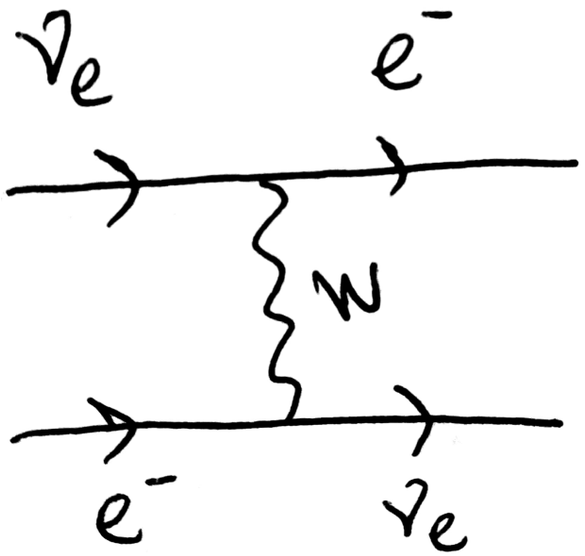
# Neutrino matter effects

Neutrinos of a given flavor only interact, via W boson, with charged leptons of the same flavor

Matter does not have $\mu^-$ or $\tau^-$

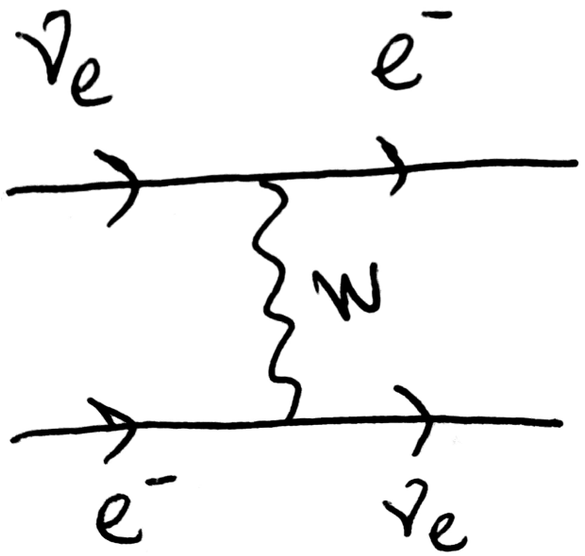
This induces a matter potential in neutrino propagation




$$V = \sqrt{2}\, G_F\, n_e = n_e/v^2$$

# Neutrino matter effects

Neutrinos of a given flavor only interact, via W boson, with charged leptons of the same flavor




Matter does not have $\mu^-$ or $\tau^-$

This induces a matter potential in neutrino propagation

$$V = \sqrt{2}\, G_F\, n_e = n_e/v^2$$

Neutrino matter effects are measuring the electroweak breaking scale (v = 246 GeV)

Determining matter effects at the 1% level translates into

v ~ 2.5 TeV <== LHC scales!

# Non-standard interactions

Start with something like this

$$\mathcal{L}_{NSI}^{NC} = -2\sqrt{2}G_F\epsilon(\bar{\nu}_L\gamma_\mu\nu_L)(\bar{f}\gamma^\mu f)$$

Check out *Neutrino non-standard interactions: a status report,* 1907.00991

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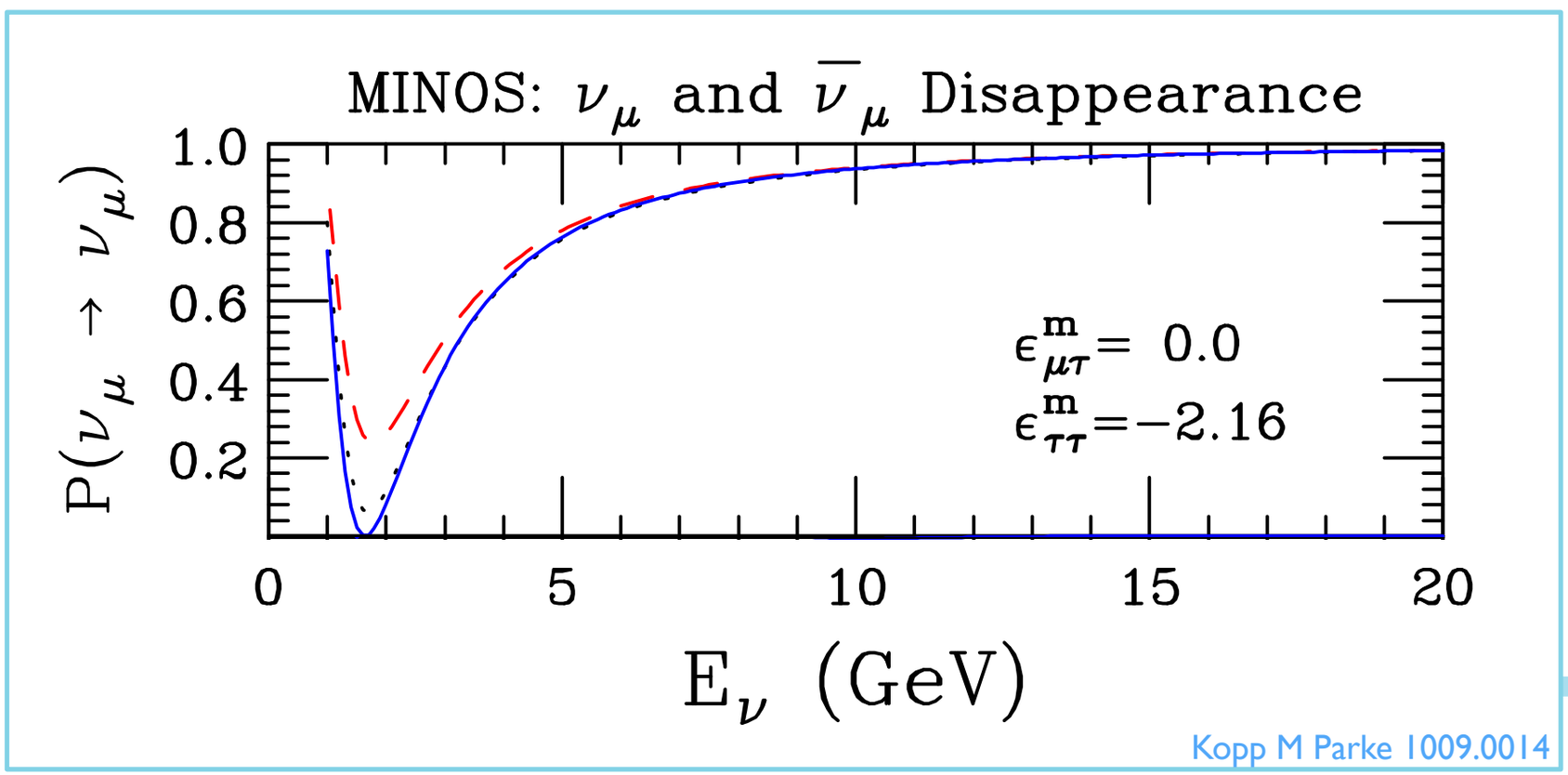
all this would be new

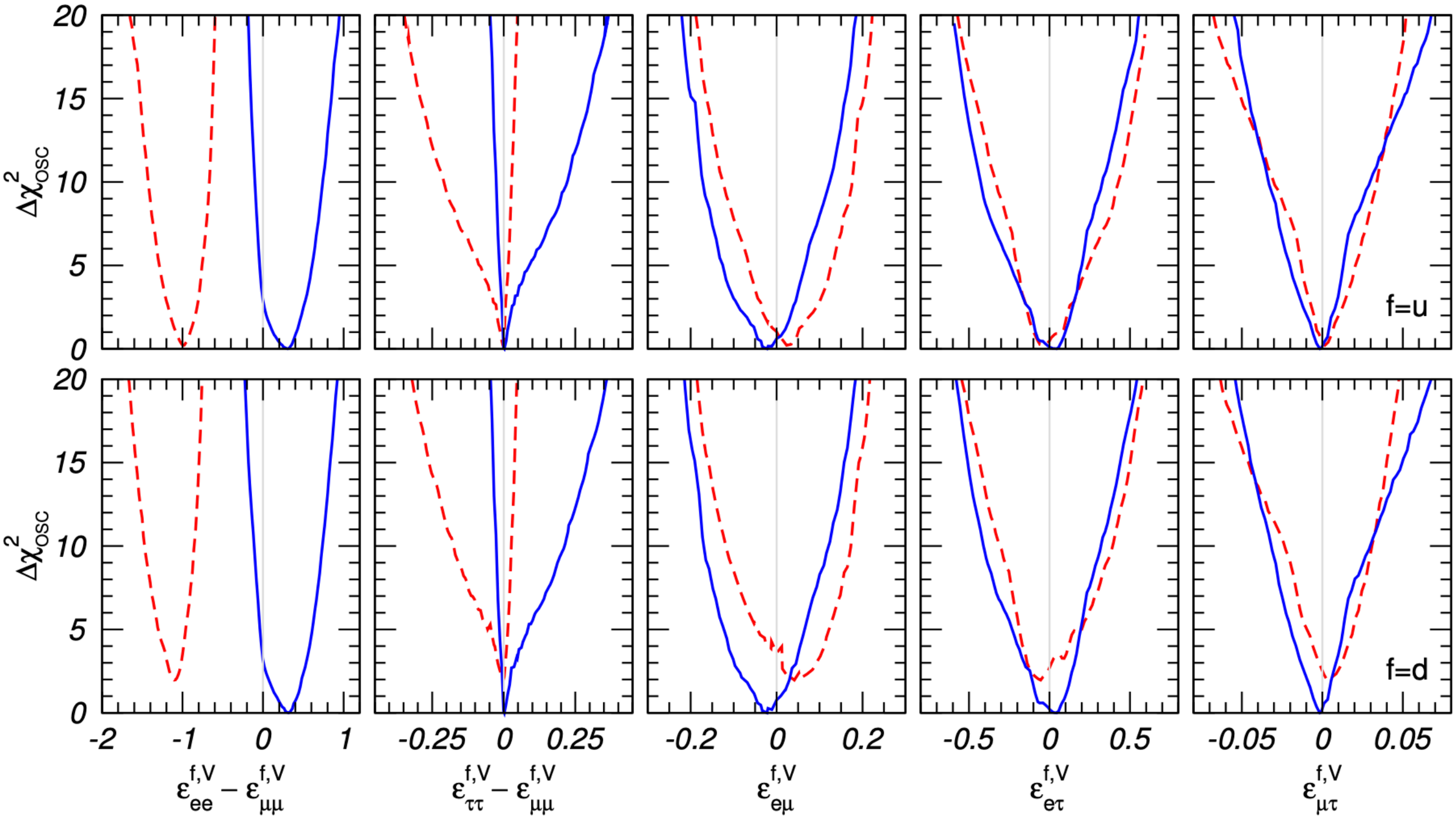



Kopp M Parke 1009.0014

Check out *Neutrino non-standard interactions: a status report*, 1907.00991

# Non-standard interactions

General way to parametrize new physics




Coloma et al 1701.04828

# Non-standard interactions - criticisms

$$\mathcal{L}_{NSI}^{NC} = -2\sqrt{2}G_F\epsilon(\bar{\nu}_L\gamma_\mu\nu_L)(\bar{f}\gamma^\mu f)$$

No SU(2) invariance

Other observables are likely to be much more stringent than neutrino oscillations

LHC monojet searches surpass sensitivity of neutrino exps

No model

Berezhiani Rossi hep-ph/0111137
Gavela et al 0809.3451
Davidson Sanz 1108.5320
Friedland et al 1111.5331
Farzan Shoemaker 1512.09147
Franzosi Frandsen Shoemaker 1507.07574
Choudhury Ghosh Niyogi 1801.01513
...

# Non-standard interactions - criticisms

And with the luminosity that the LHC is slated to deliver, continuing negative results would only strengthen the constraint to well beyond what even a next-generation neutrino experiment will be able to probe [14, 57–60]. This would indicate that the only role such facilities may play in this regard would be the confirmatory one.

the neutrino sector. Since any model of new physics has to recover the Standard Model at low energies, we have required gauge invariance under the SM gauge group and studied the possible effective theories. The focus is set on purely leptonic NSI, that is, on operators in

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# Non-standard interactions

**Theory developments:** realistic models with large NSIs

New insights on what NSI can teach us

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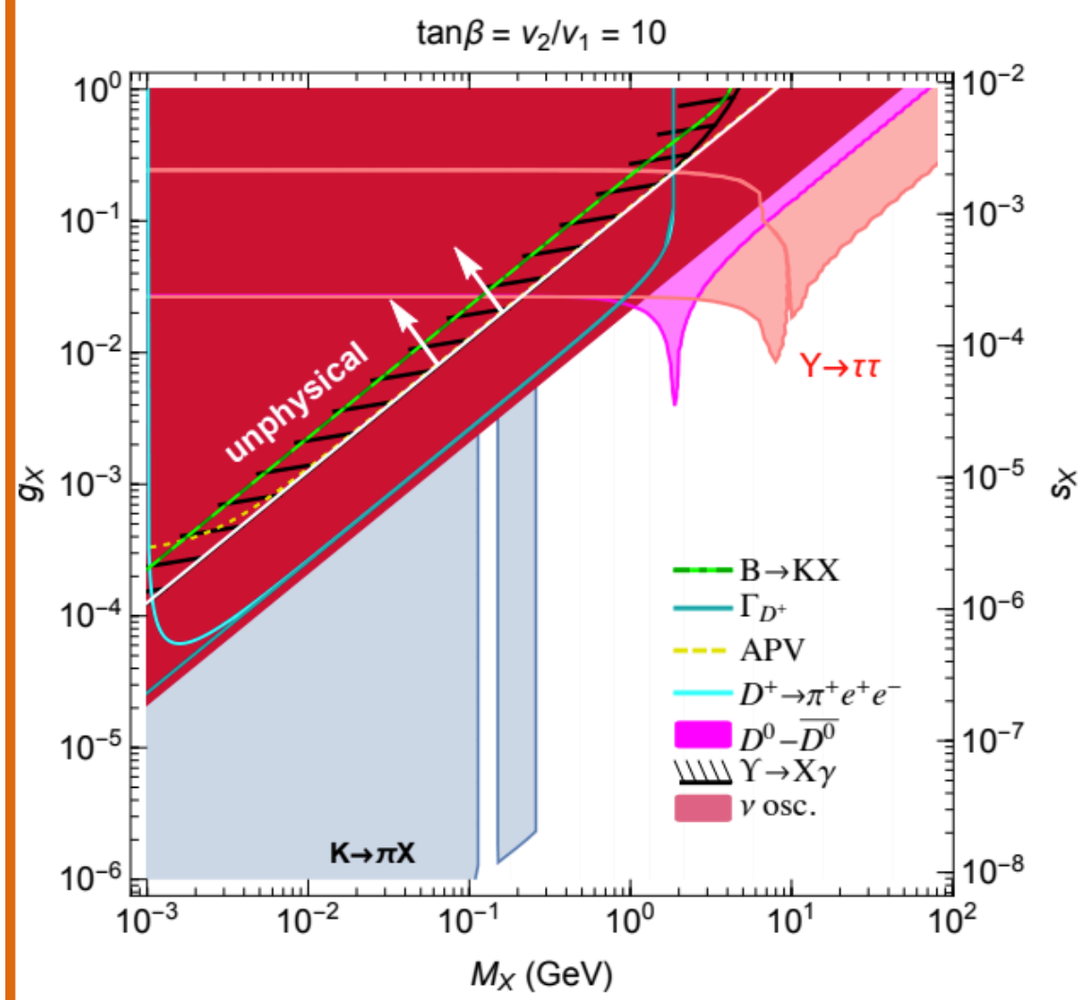
New insights on what NSI can teach us

Example 1: new force that acts only on 3rd family fermions




Complementarity between several observables: ν oscillations, meson decay and oscillation, parity violation, kaon physics…

Babu Friedland M Mocioiu 1705.01822



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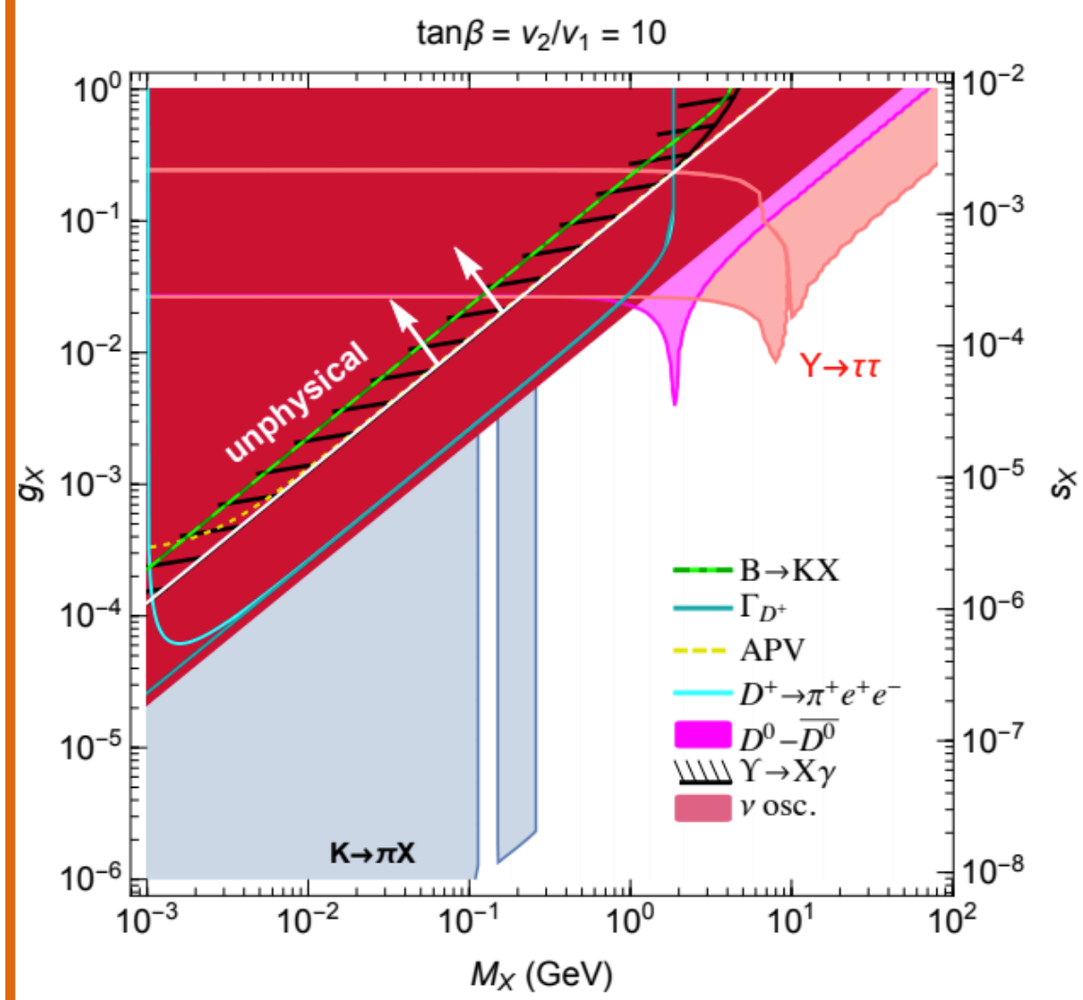


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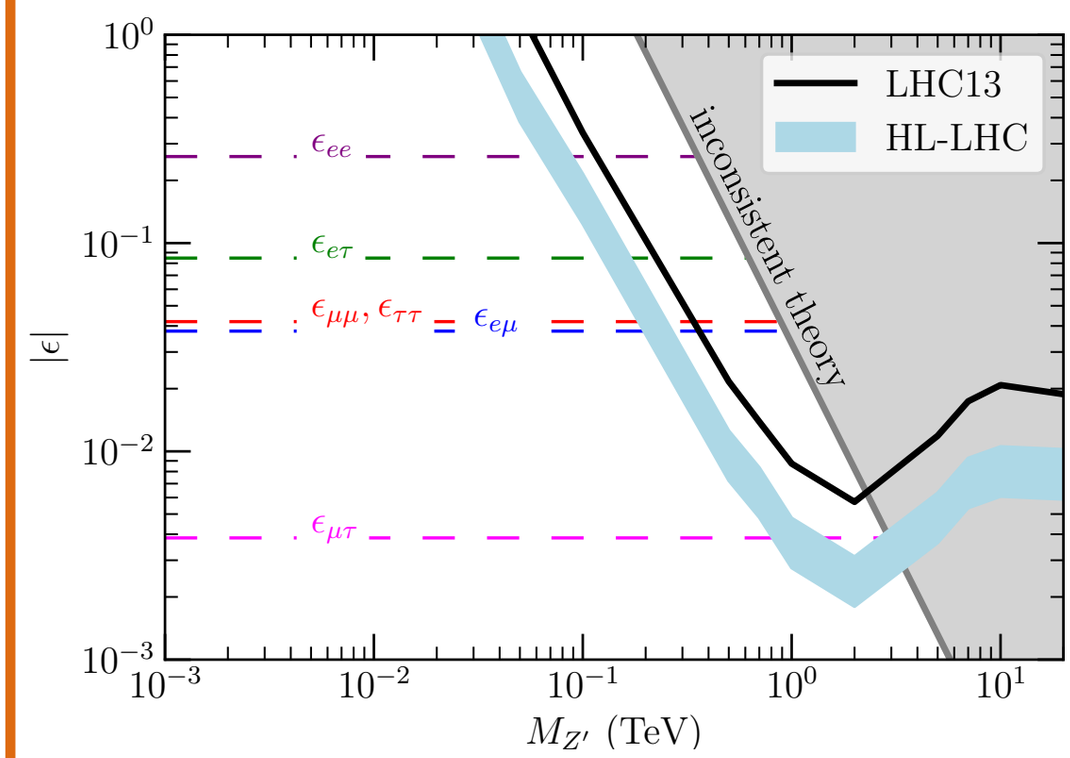
Example 2: LHC physics and NSIs in simplified models




Non-trivial complementarity between collider and oscillation measurements

Babu Gonçalves Jana M , to appear



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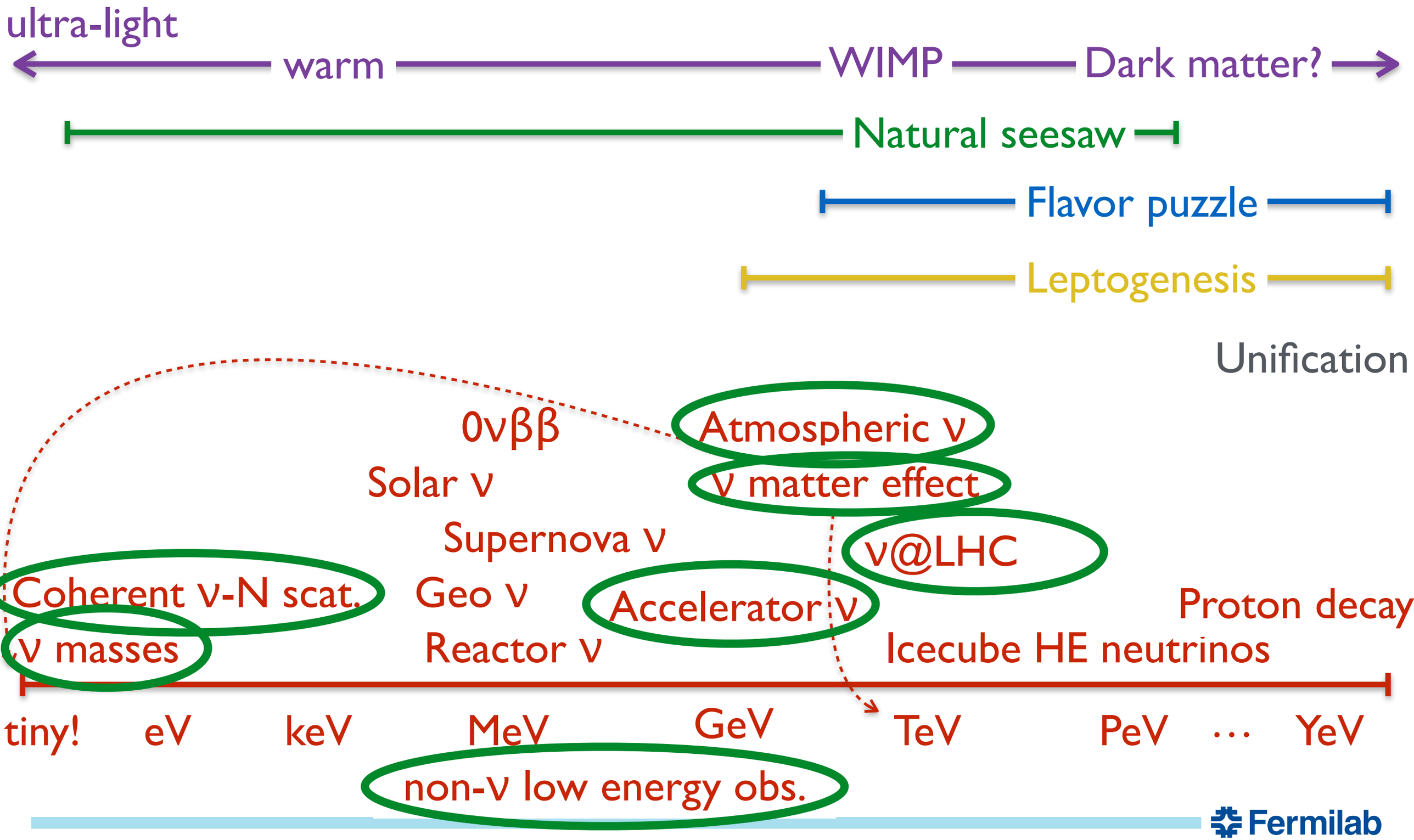
# Neutrinos are everywhere in nature





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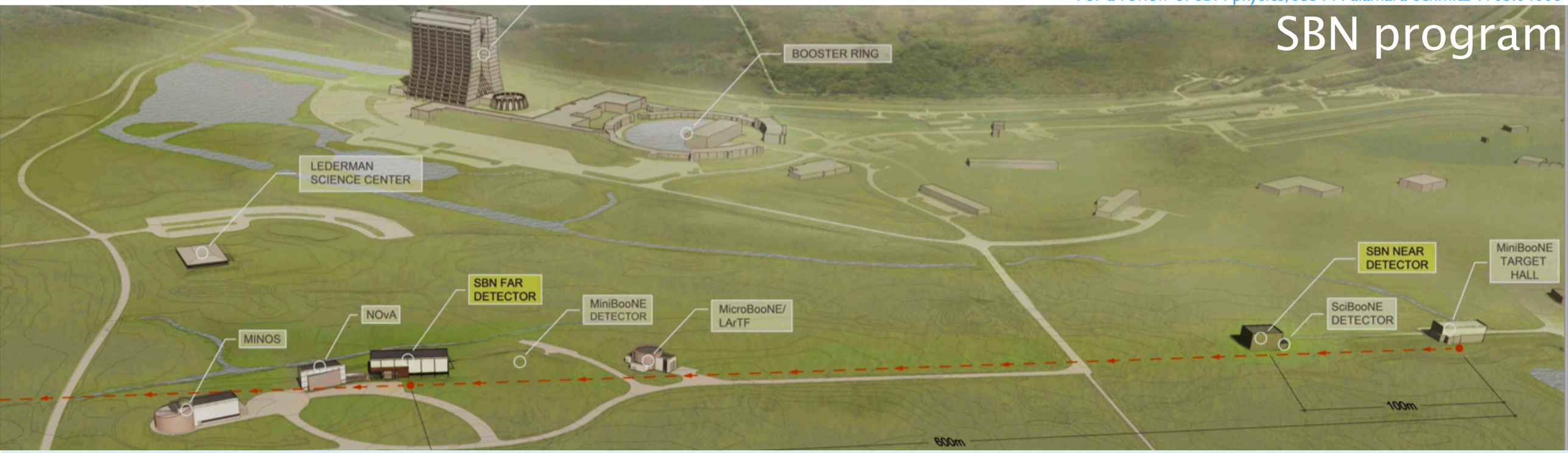
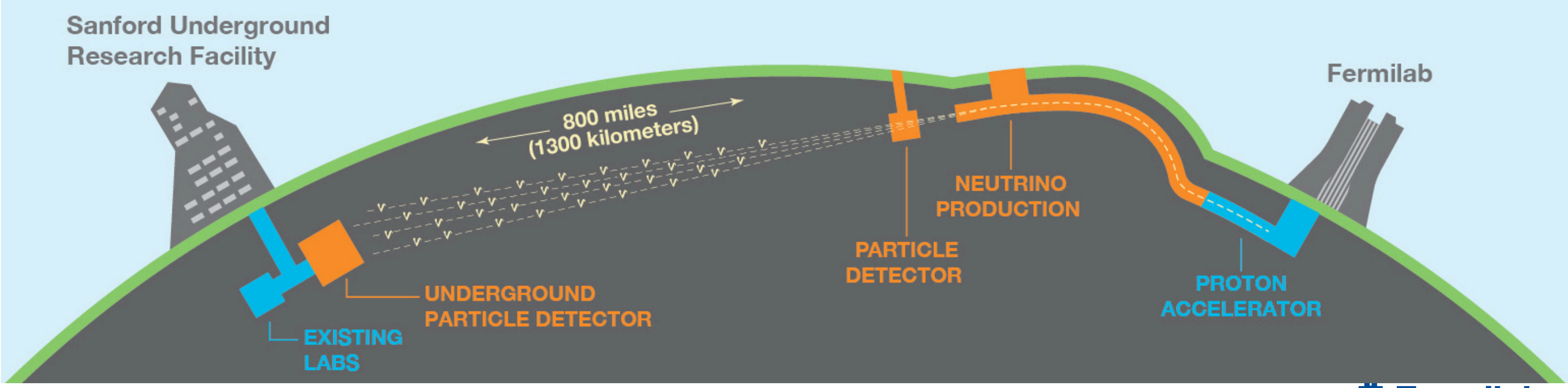
# The liquid argon program

For a review of SBN physics, see M Palamara Schmitz 1903.04608

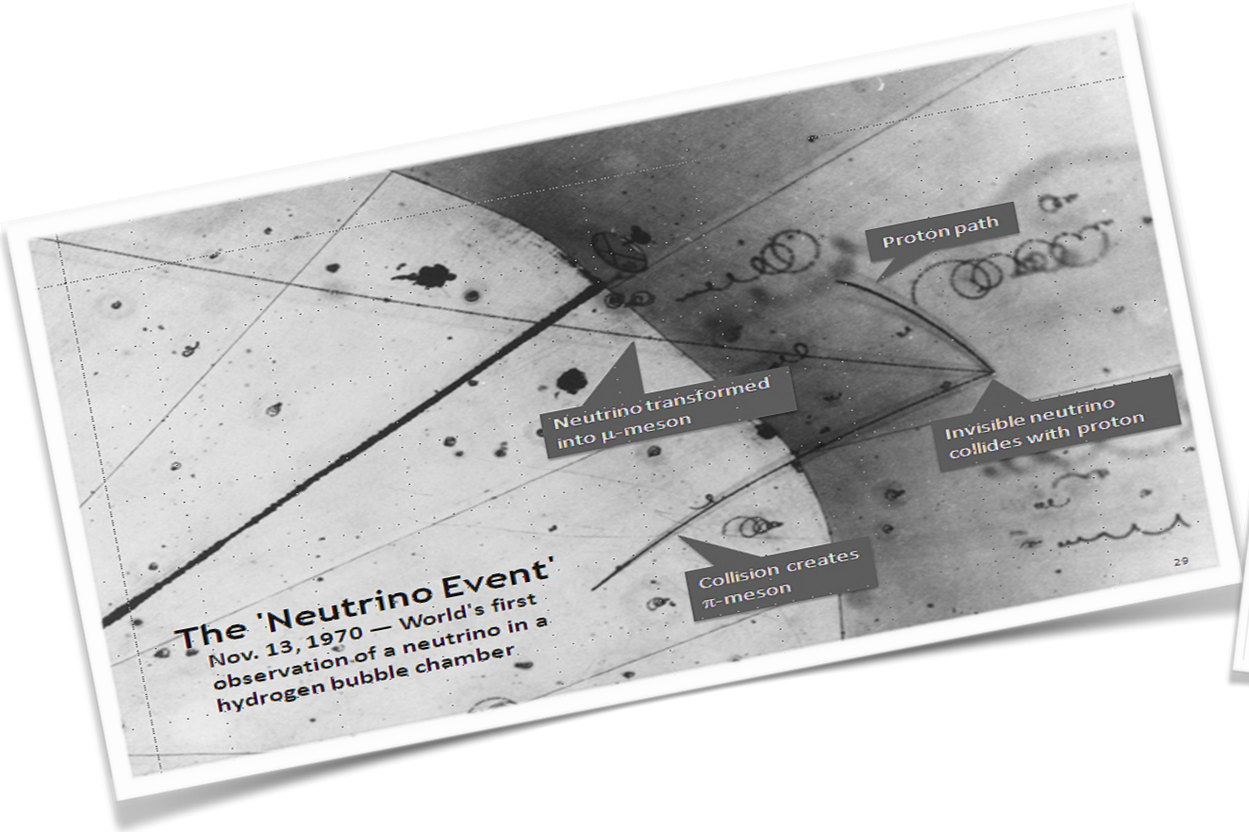
SBN program

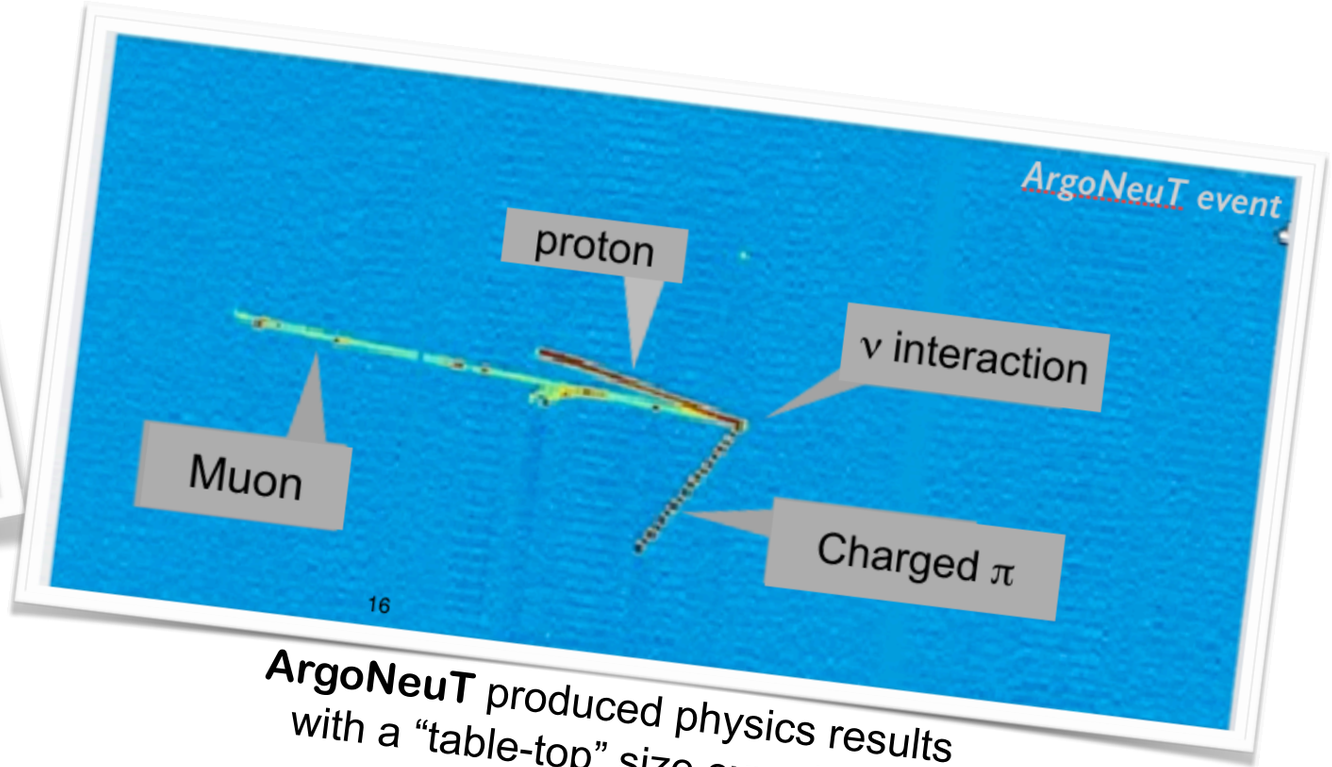



DUNE



# Why **Liquid Argon Time Projection Chamber**?




**ArgoNeuT** produced physics results with a "table-top" size experiment [240 Kg LArTPC]

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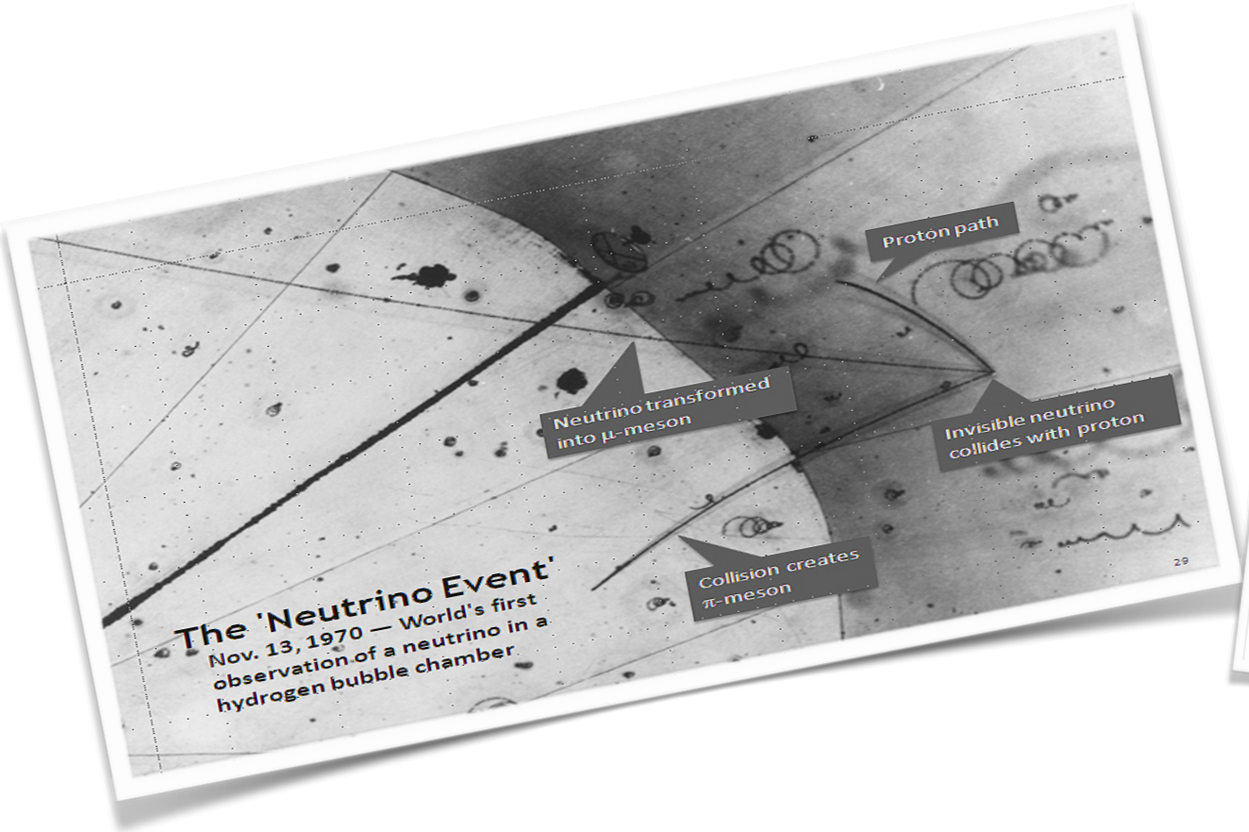


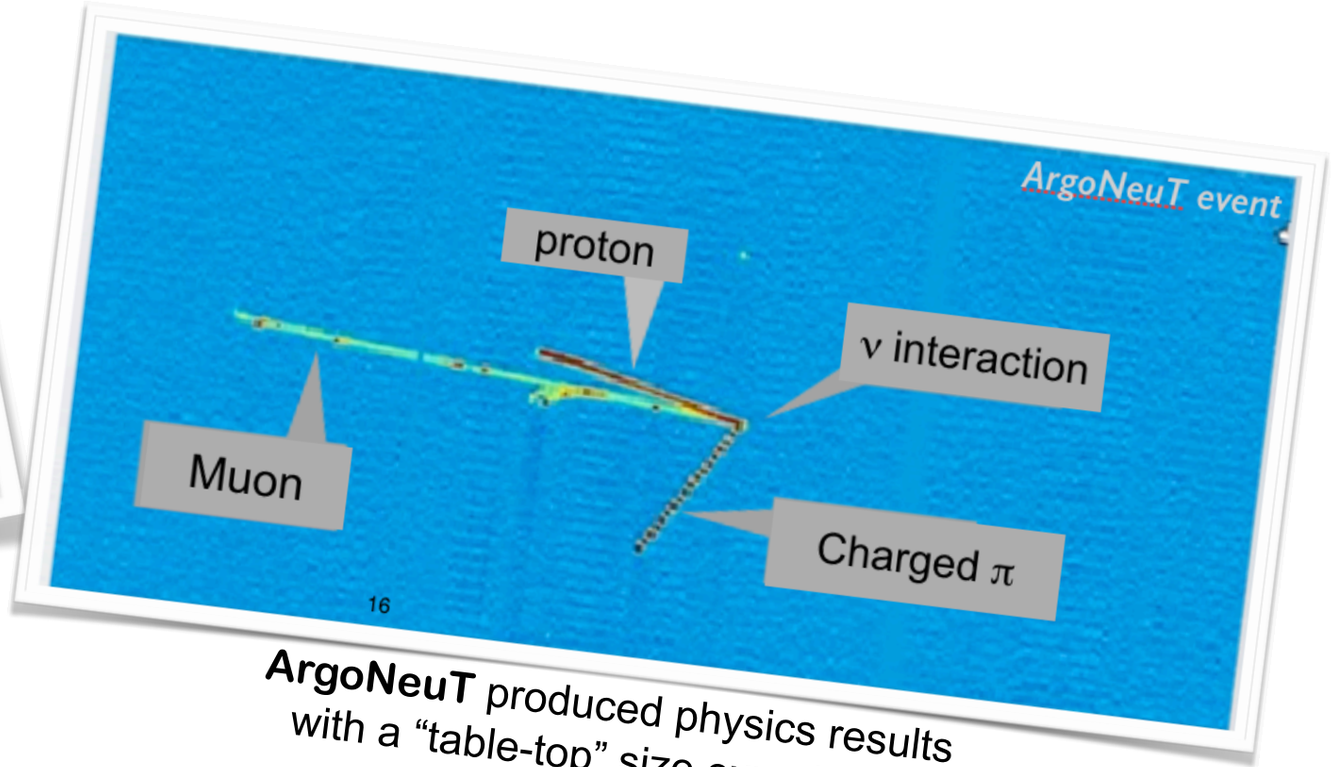


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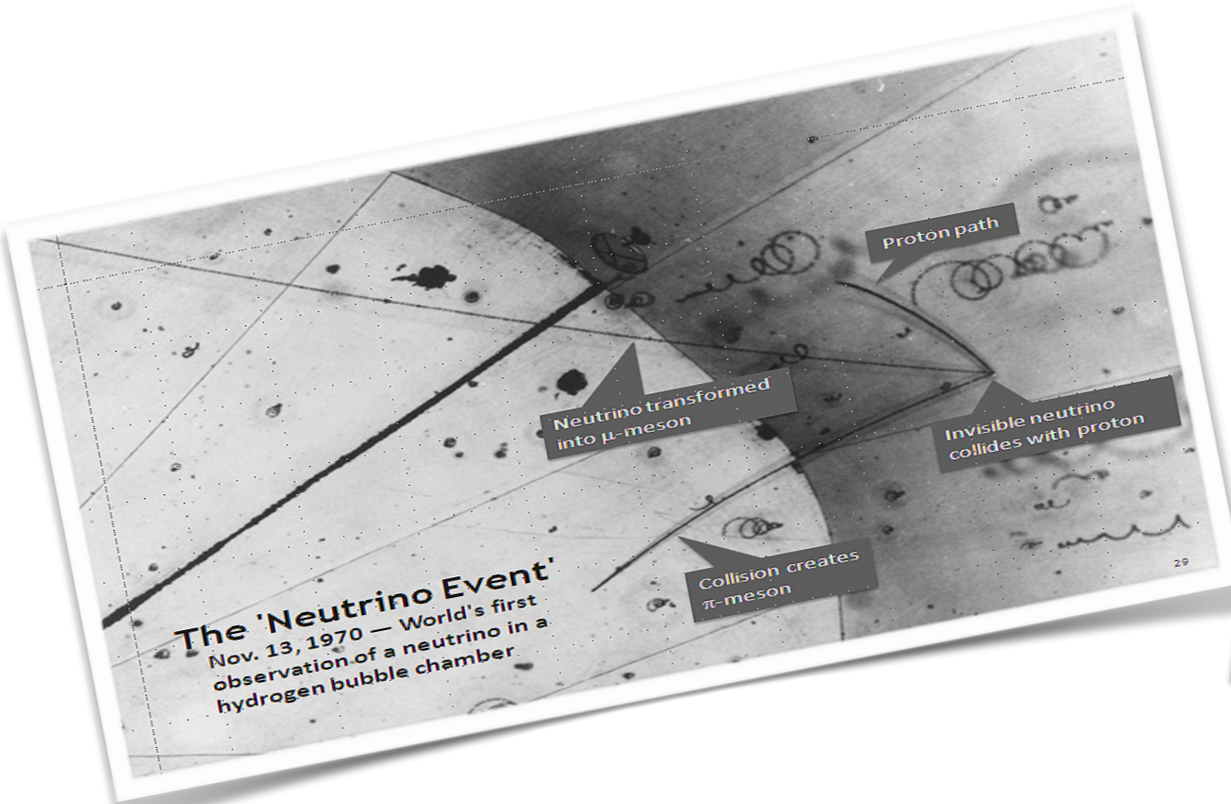
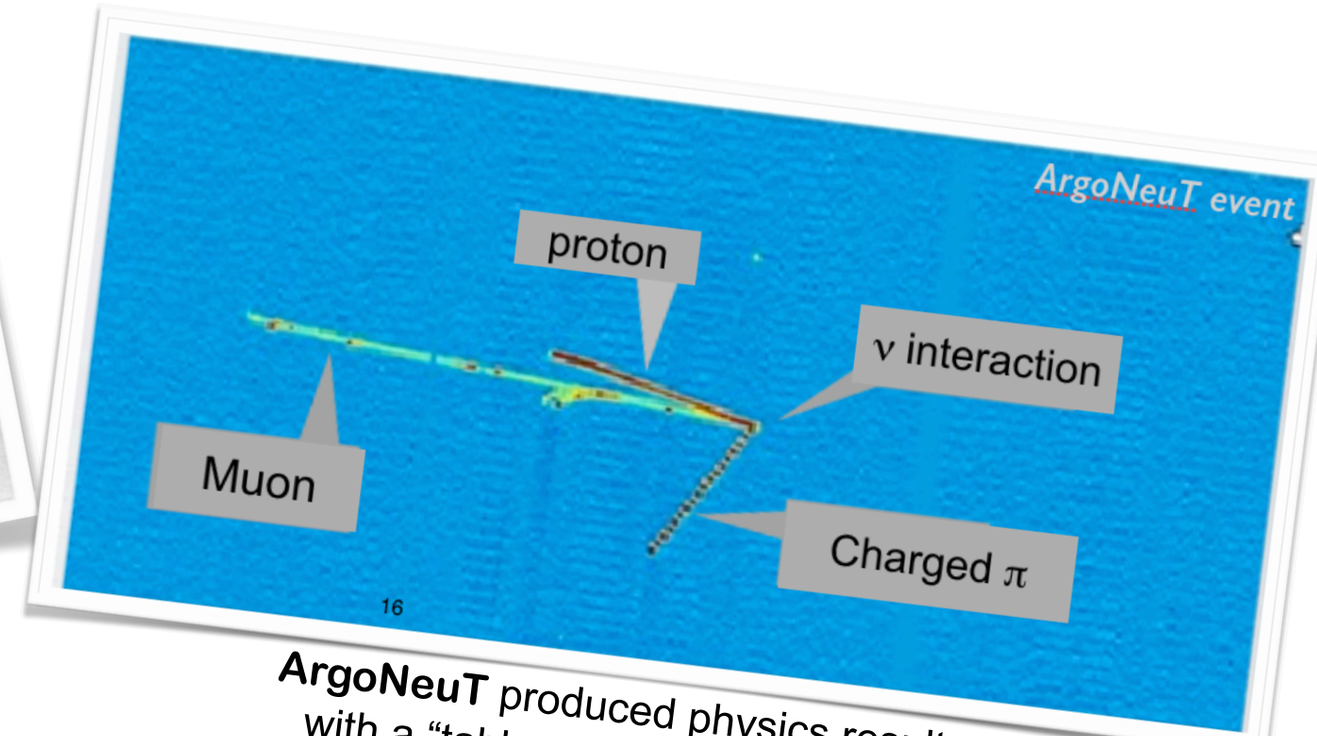


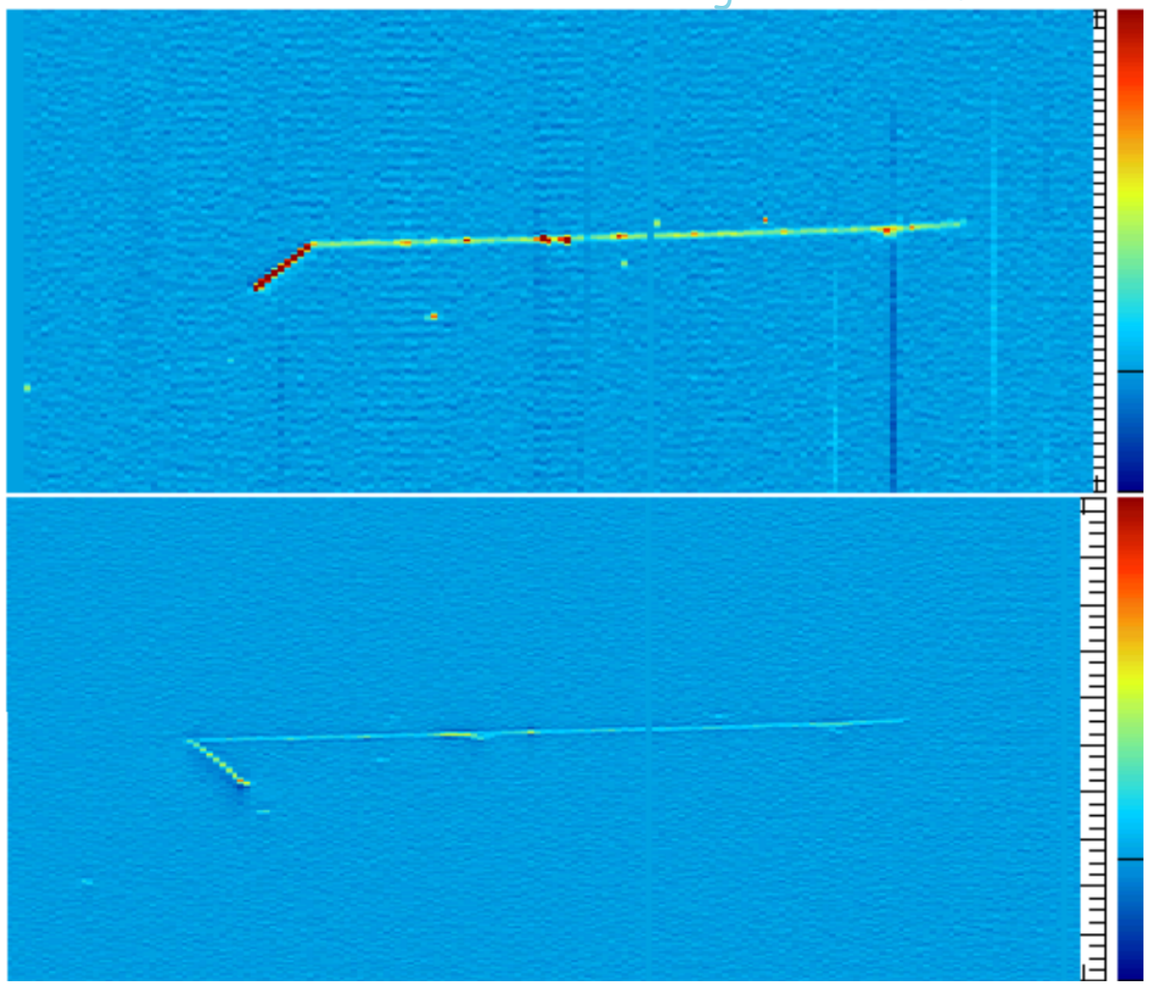




**ArgoNeuT** produced physics results with a "table-top" size experiment [240 Kg LArTPC]

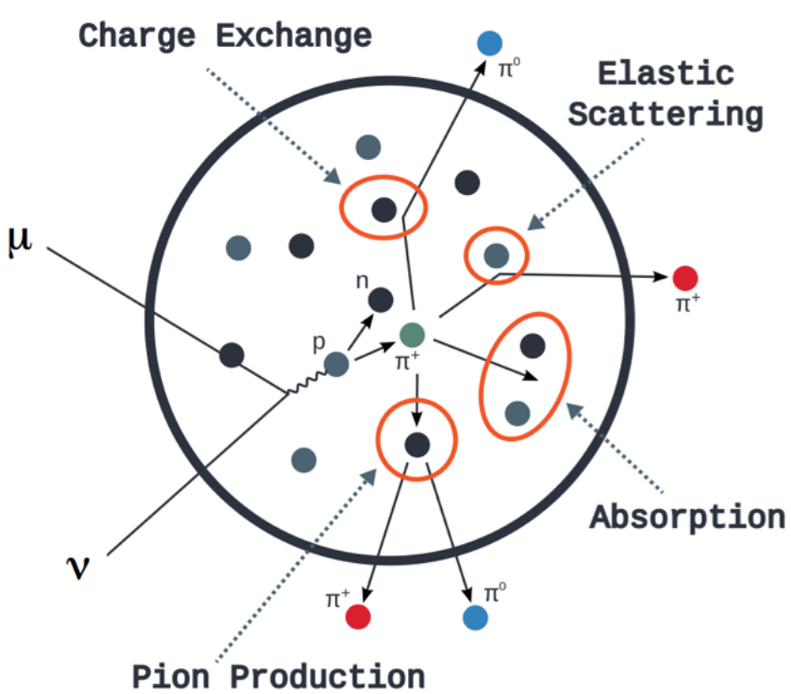
**LAr TPC: Bubble chamber quality of data with added calorimetry**

**...or LArTPC is "a "colored" bubble chamber" (theorist simplified view!)**

ArgoNeuT 1810.06502



ArgoNeuT demonstrated the LAr capability to detect 21 MeV recoil protons.

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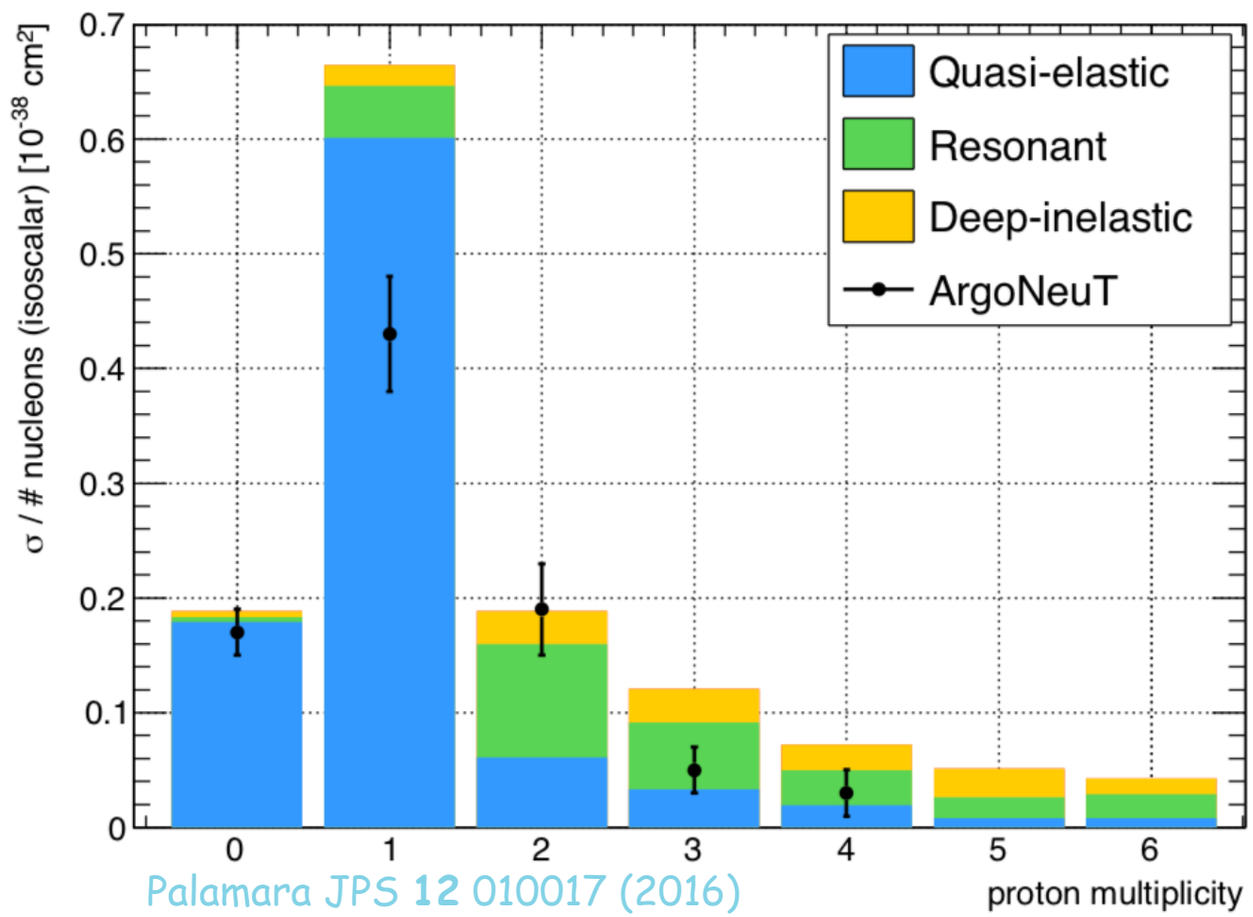


Palamara JPS **12** 010017 (2016)

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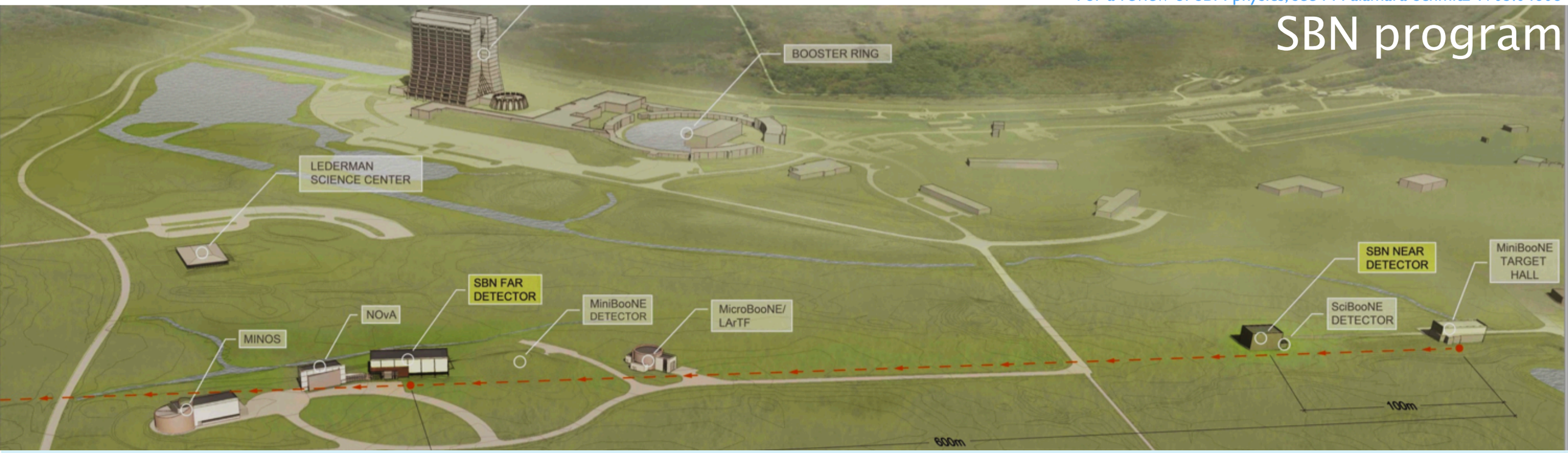
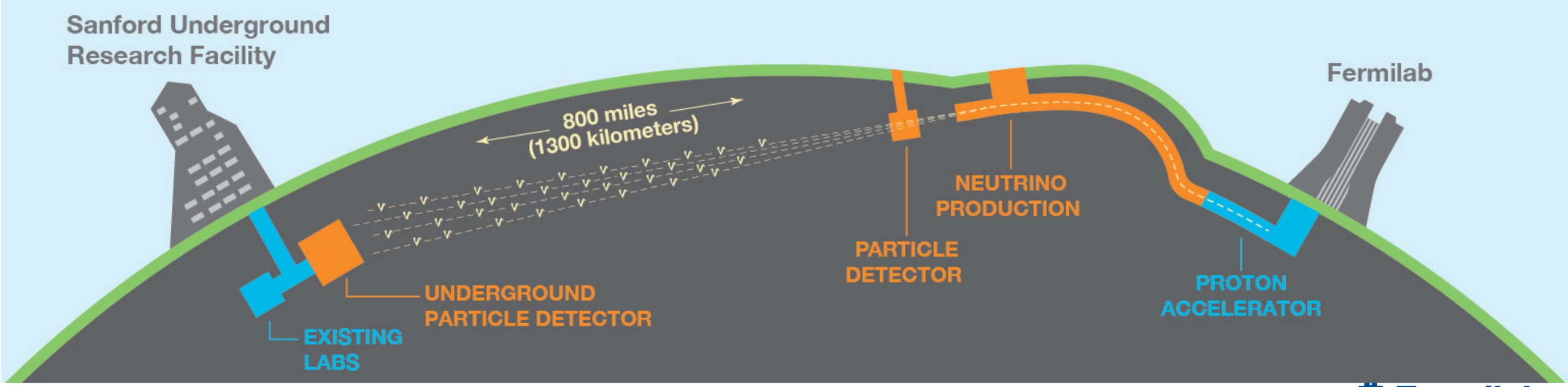
# SBN program




# DUNE



# What sort of new things can we do with that?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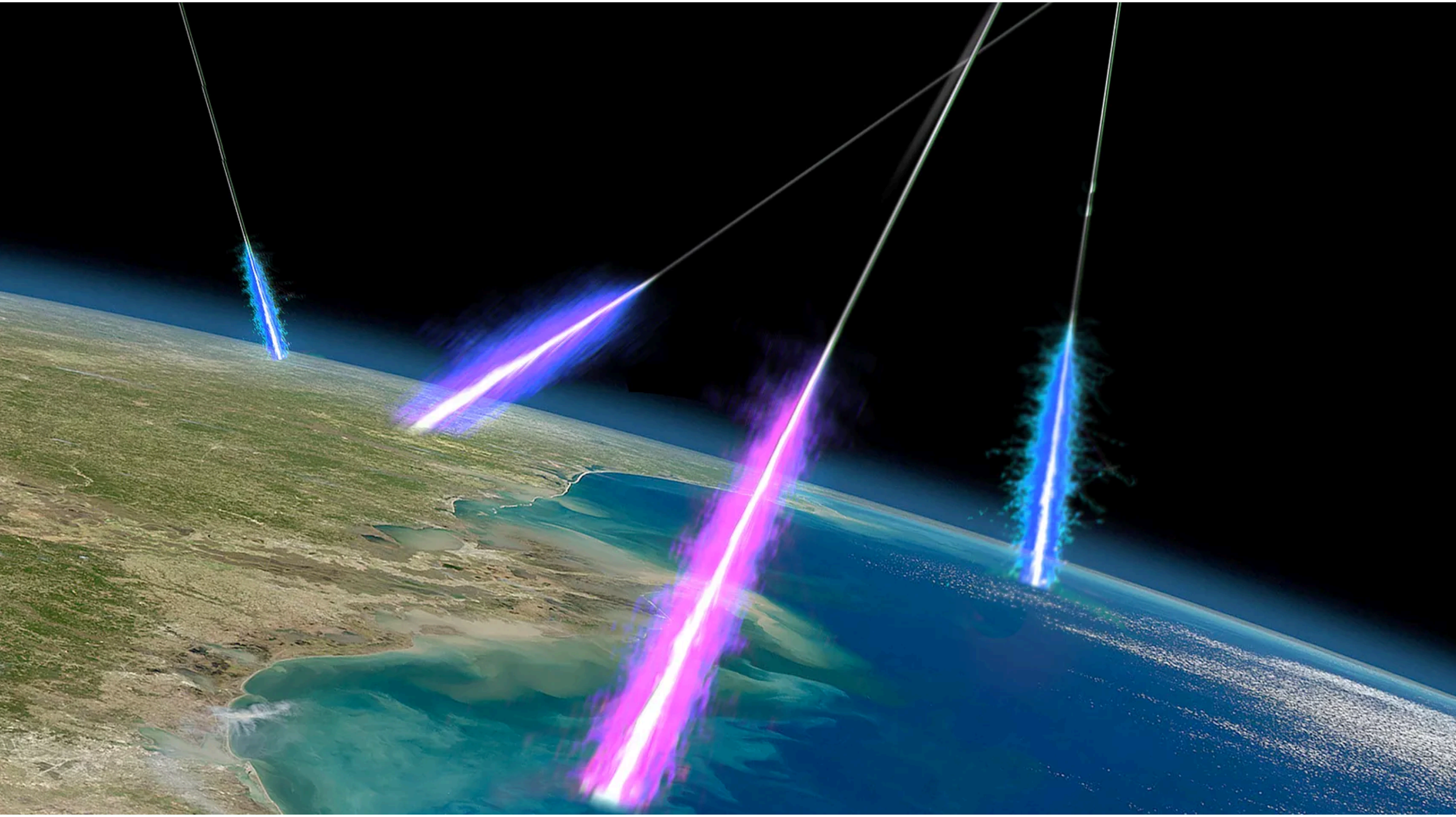
# Low energy atmospheric neutrinos





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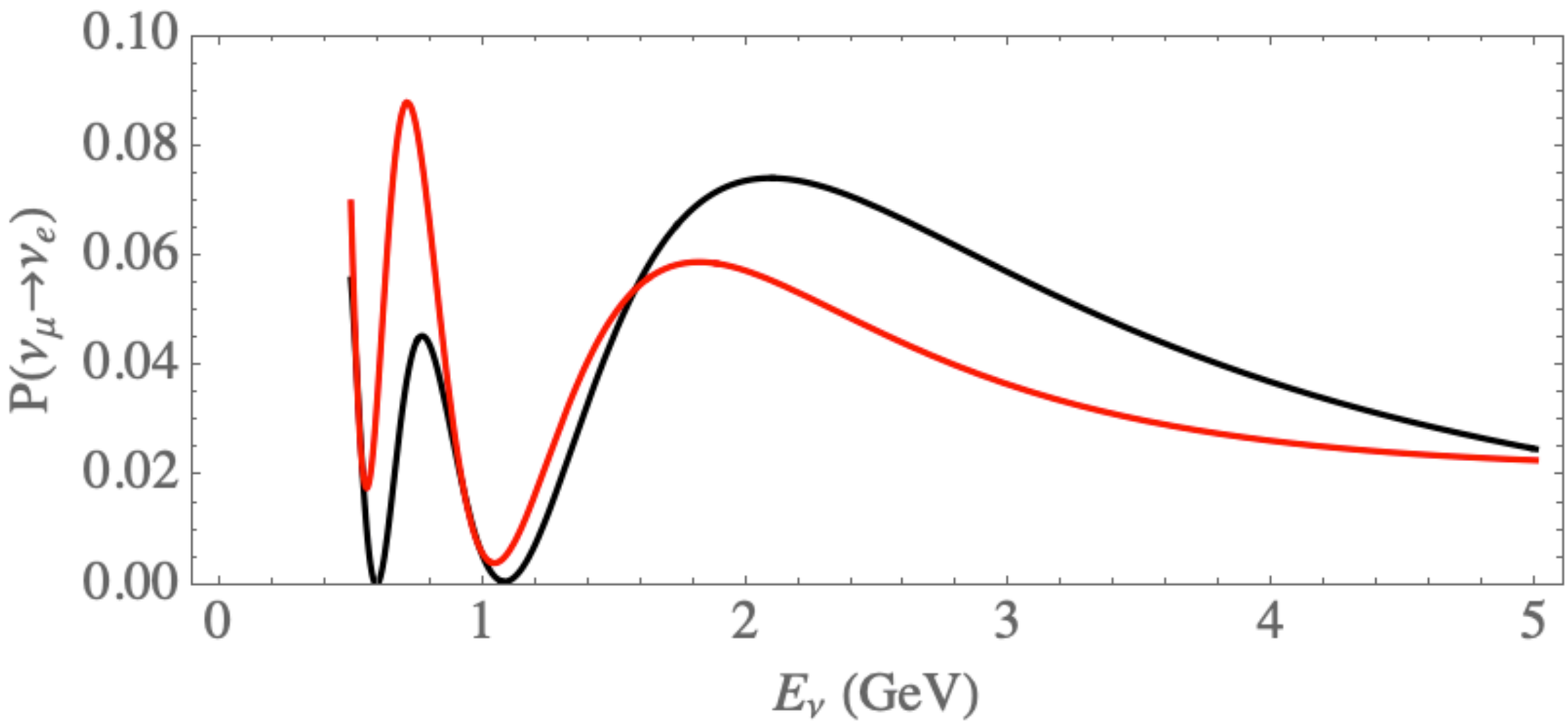
# Low energy atmospheric neutrinos

Kelly et al 1904.02751

The main goal of DUNE is to measure leptonic CP violation

For DUNE's beam, CP will be a small effect (few %)



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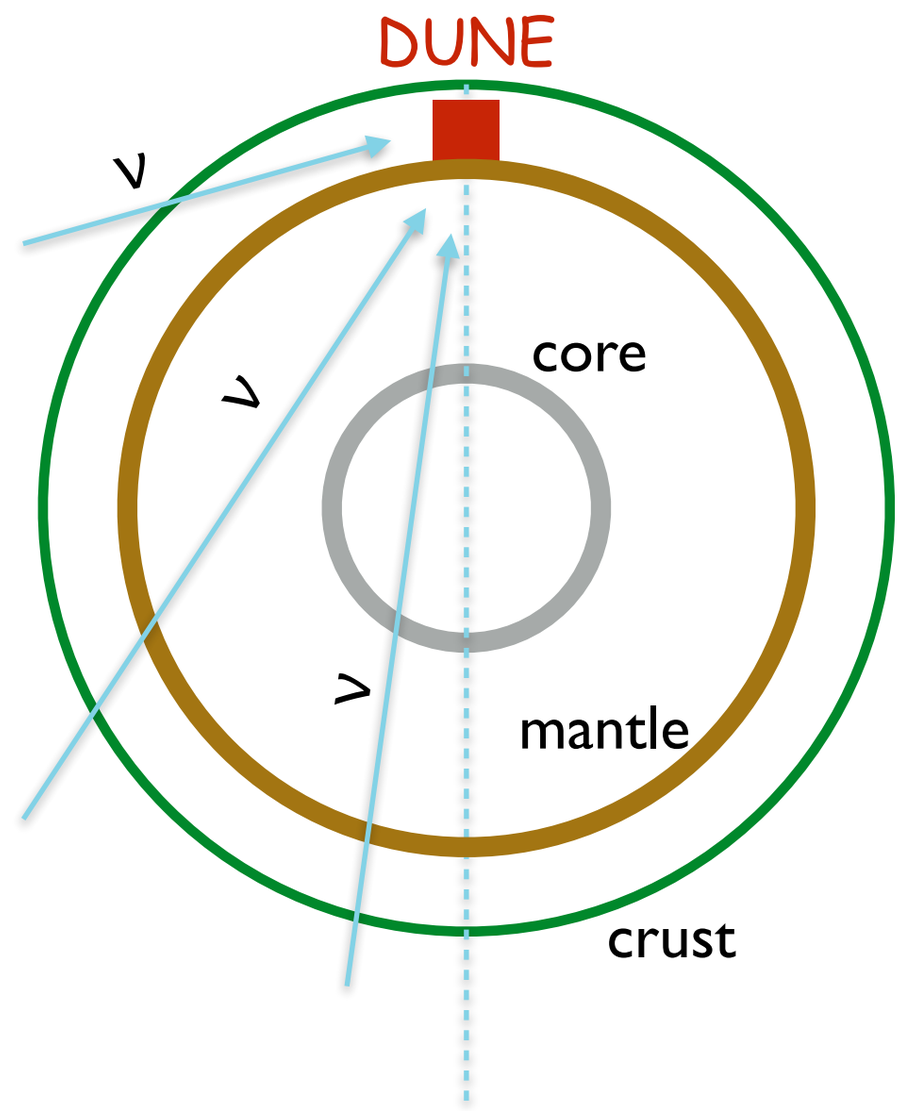



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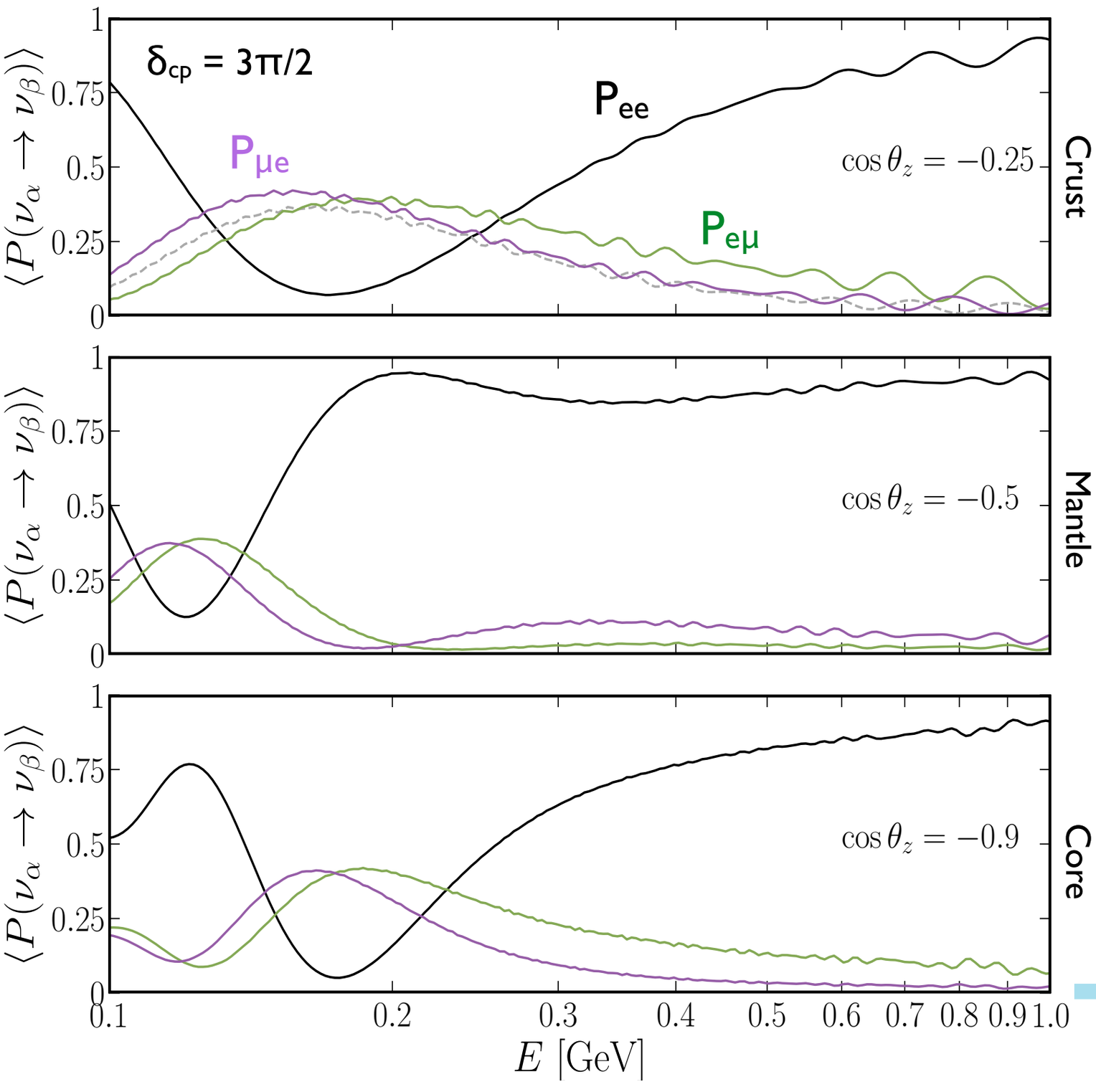
Sub-GeV atmospheric neutrinos are one of the richest neutrino samples we have access to.

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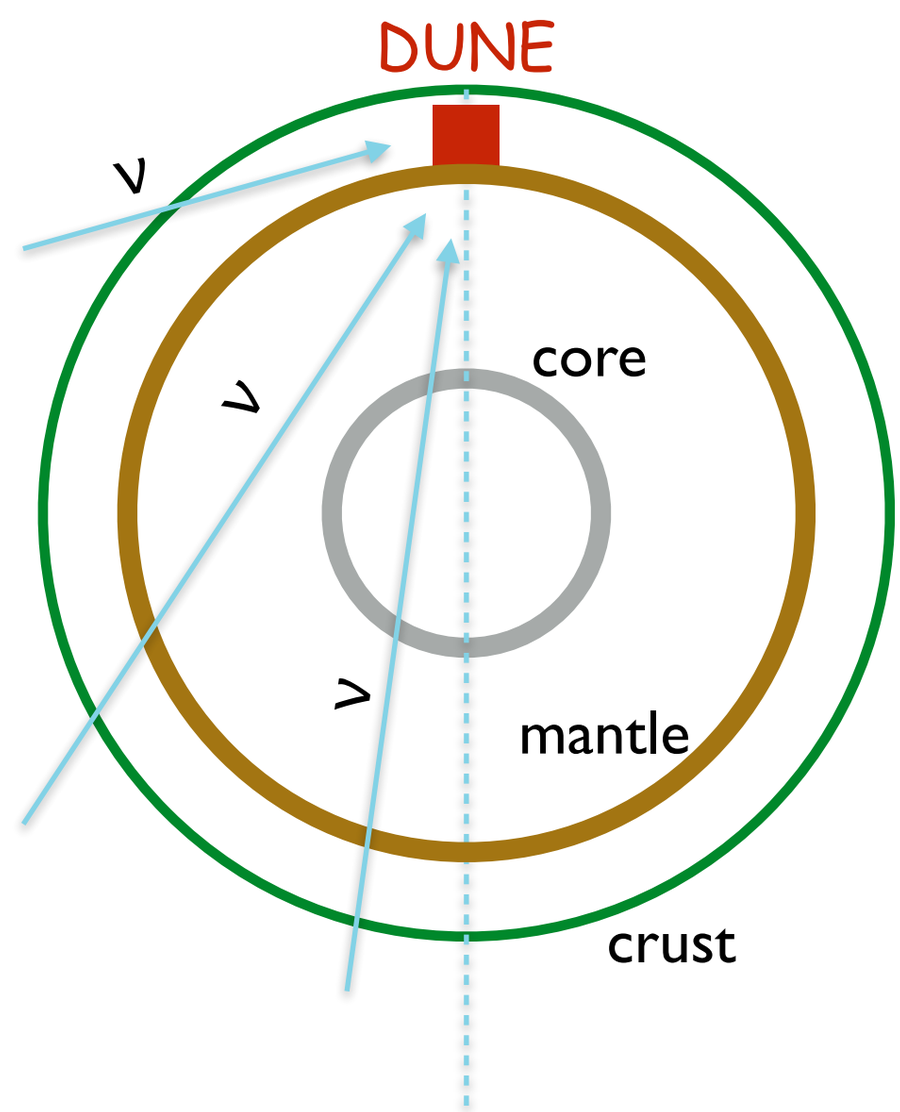


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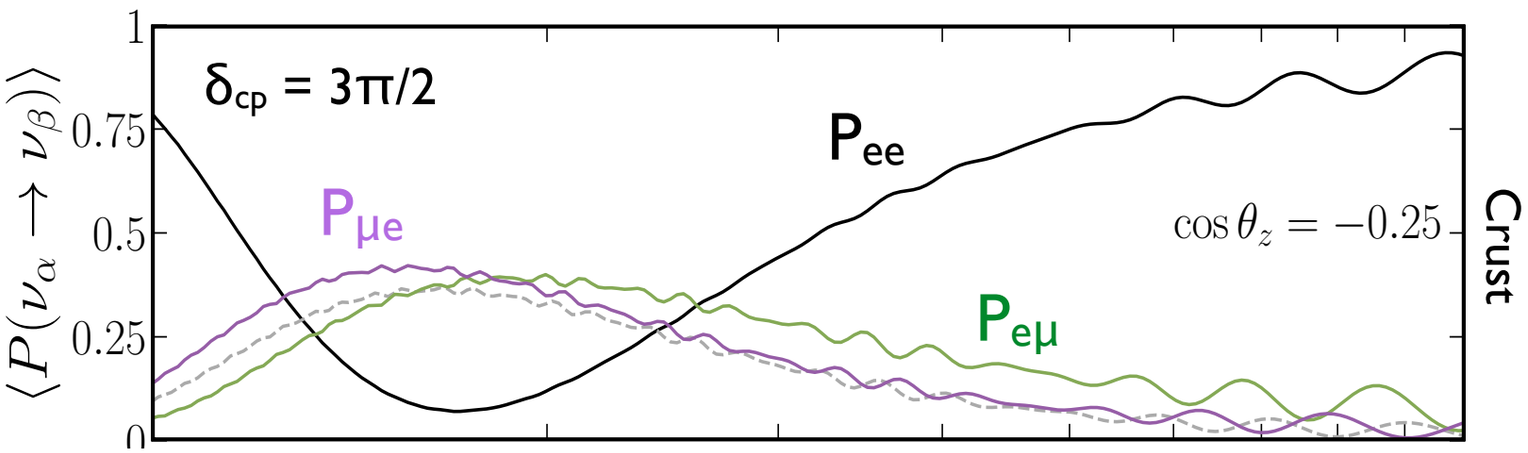


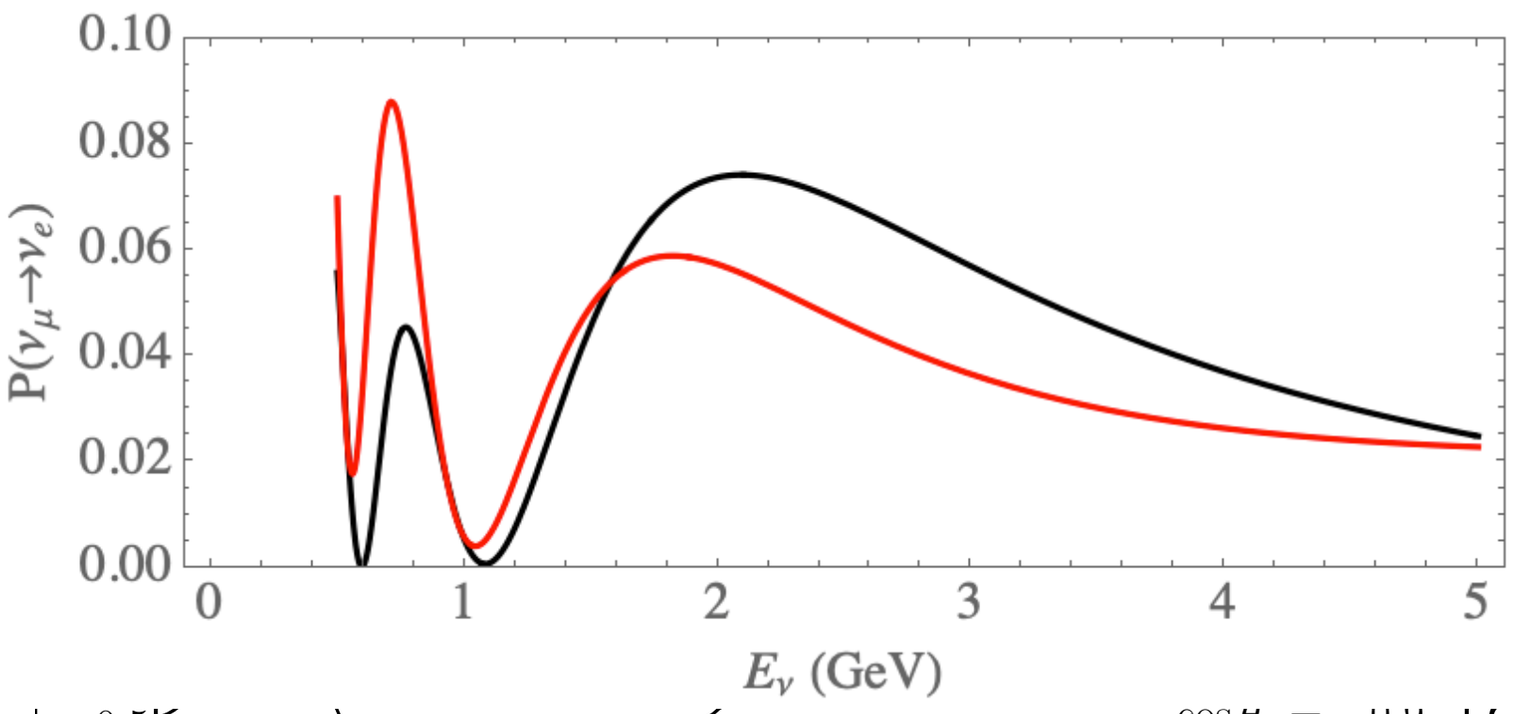


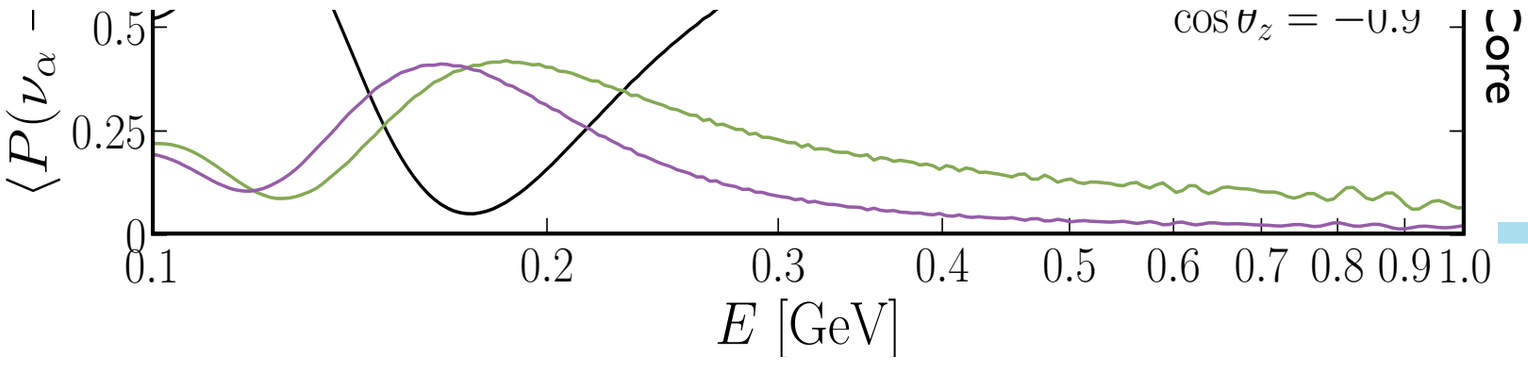


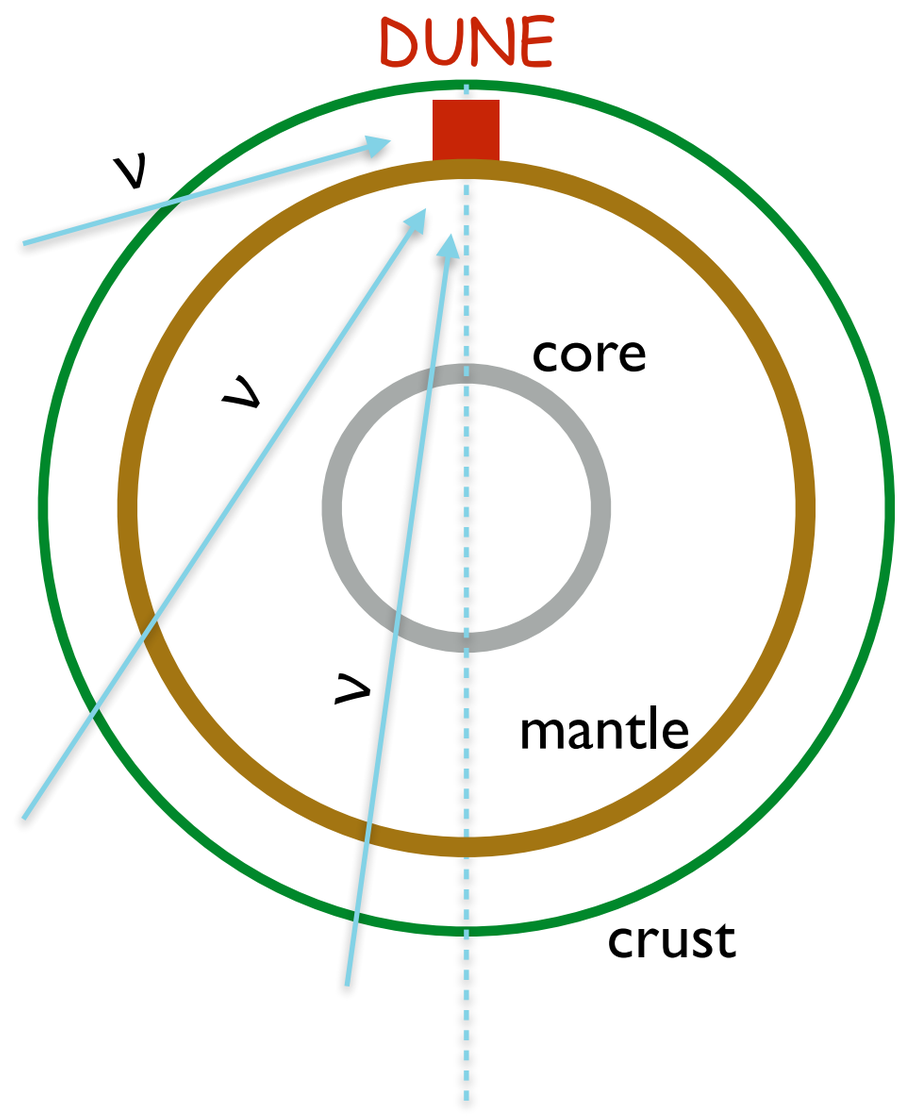



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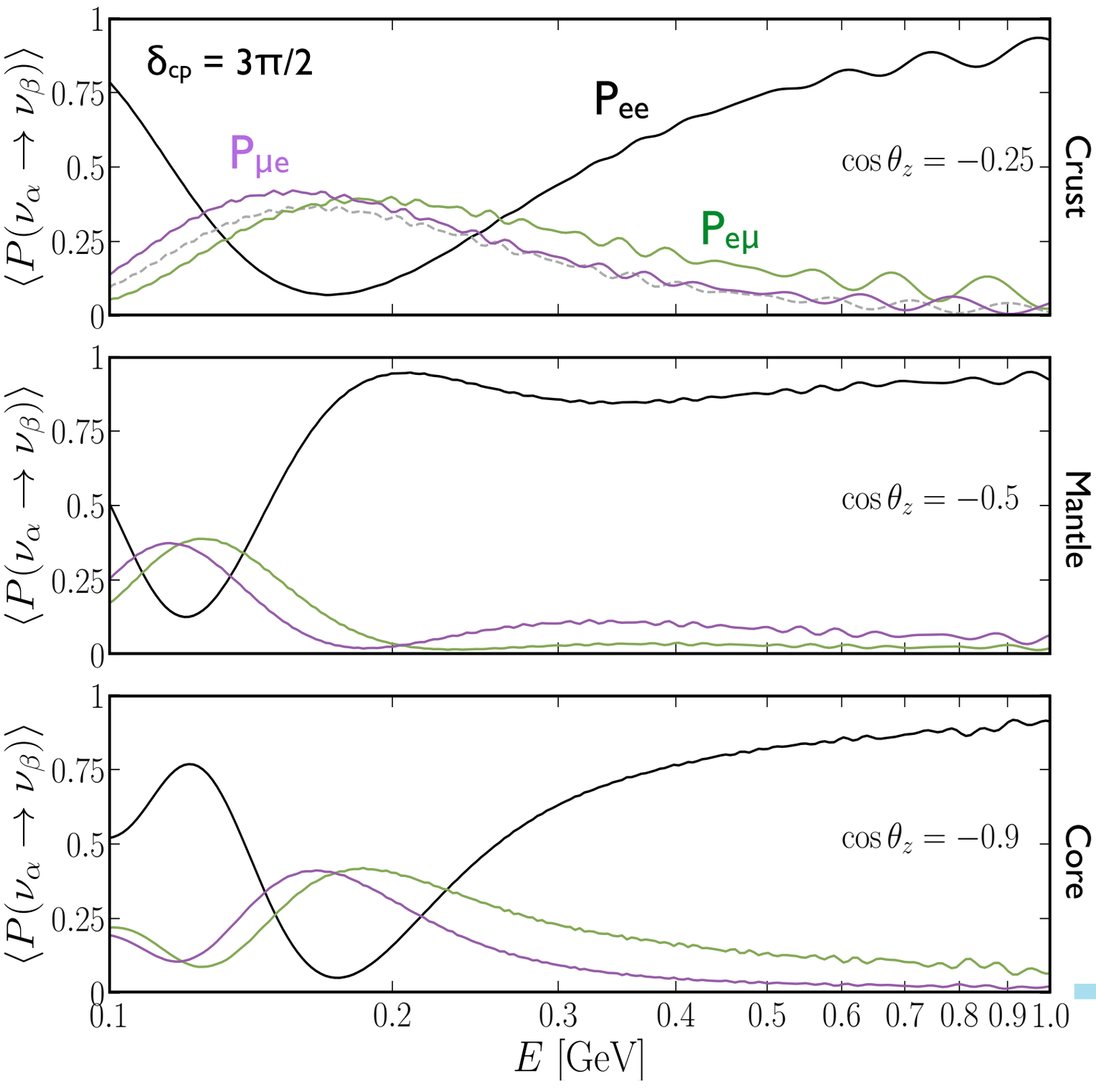


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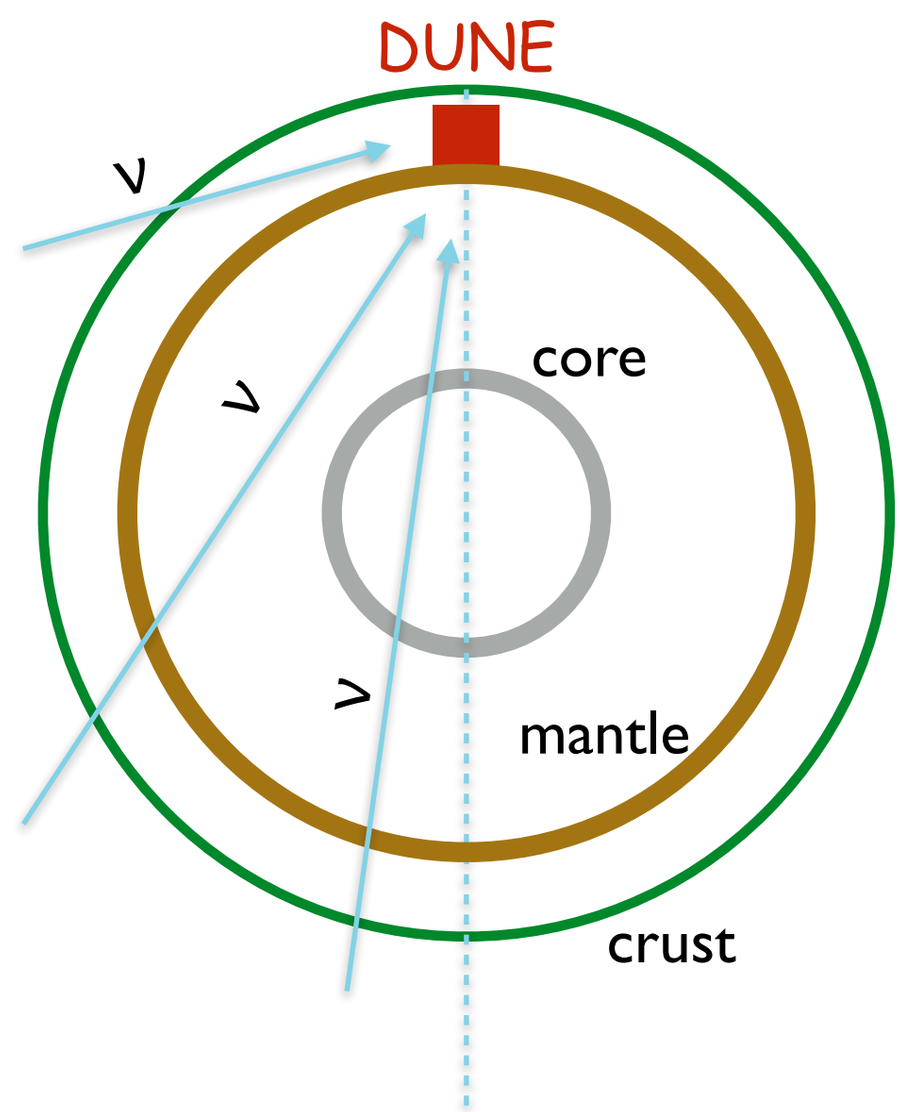


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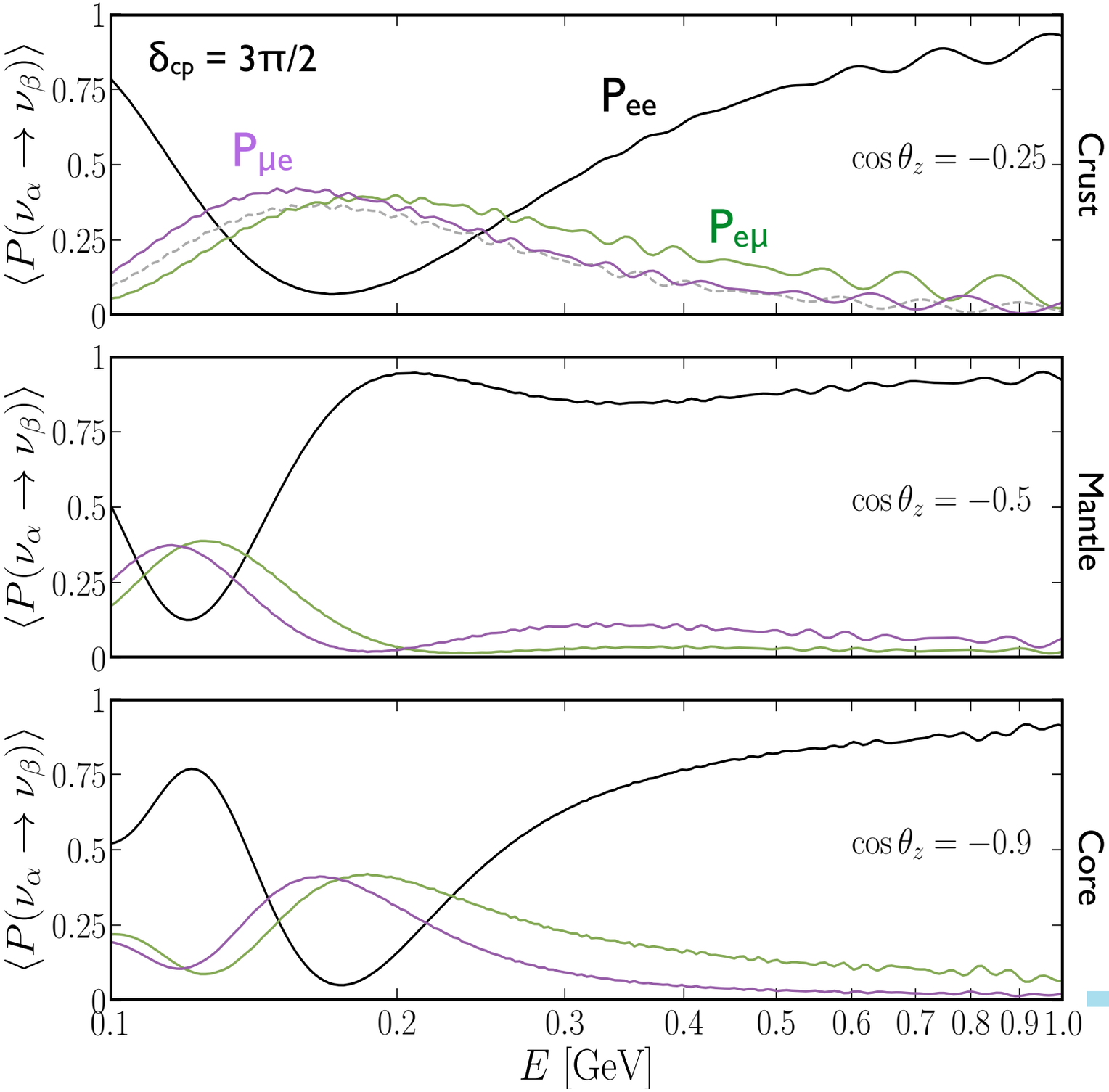
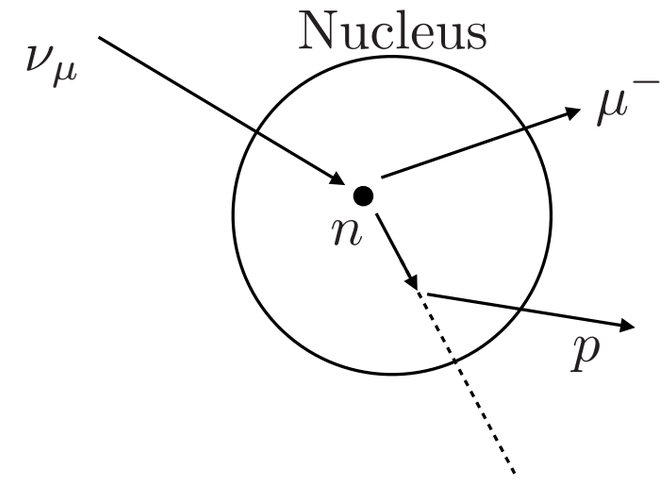



**But very difficult...**




Needs to know neutrino direction

Low E protons are invisible @ Cherenkov detectors

Liquid Argon TPCs can do it!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# Low energy atmospheric neutrinos

Kelly et al 1904.02751

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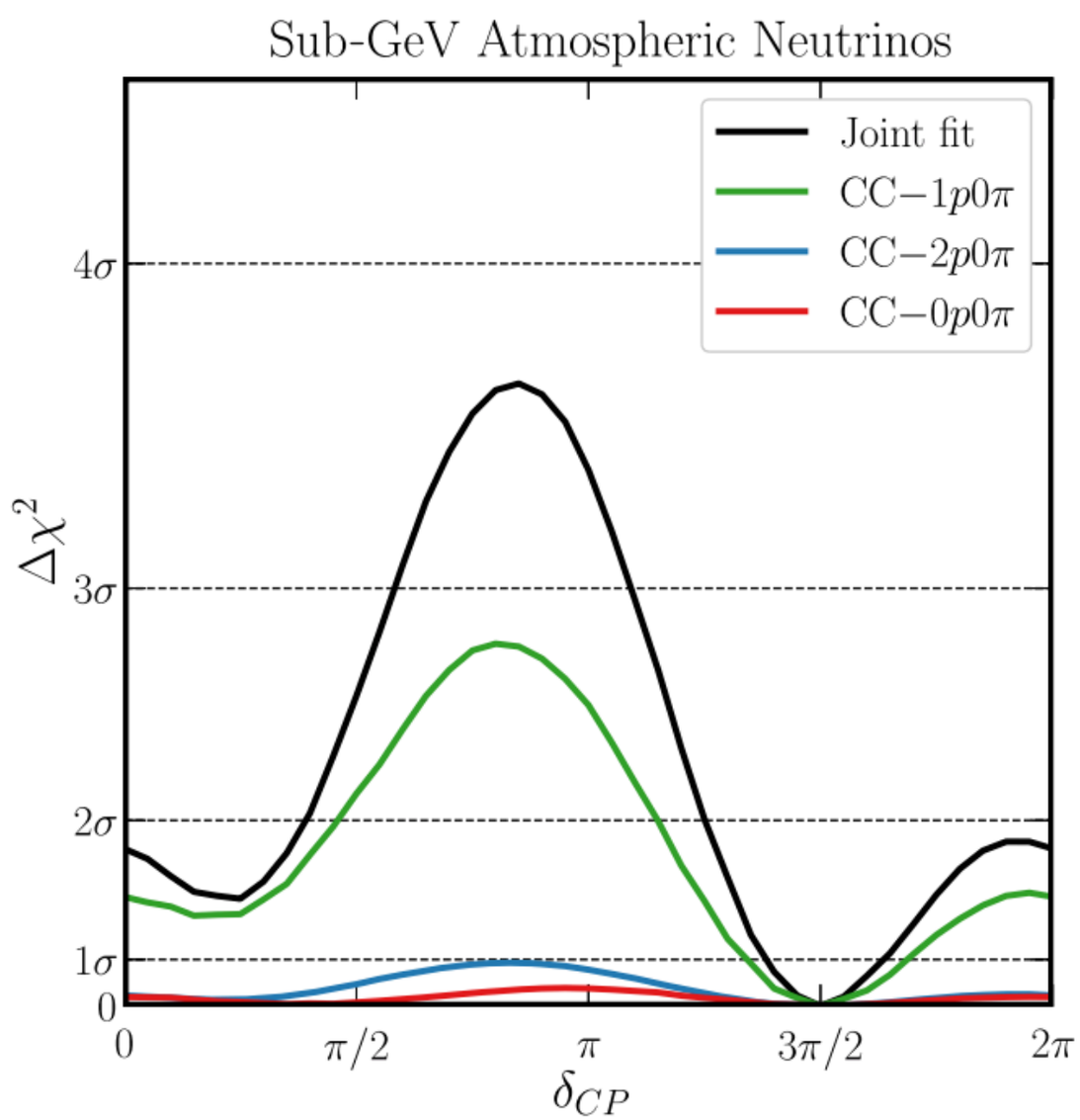


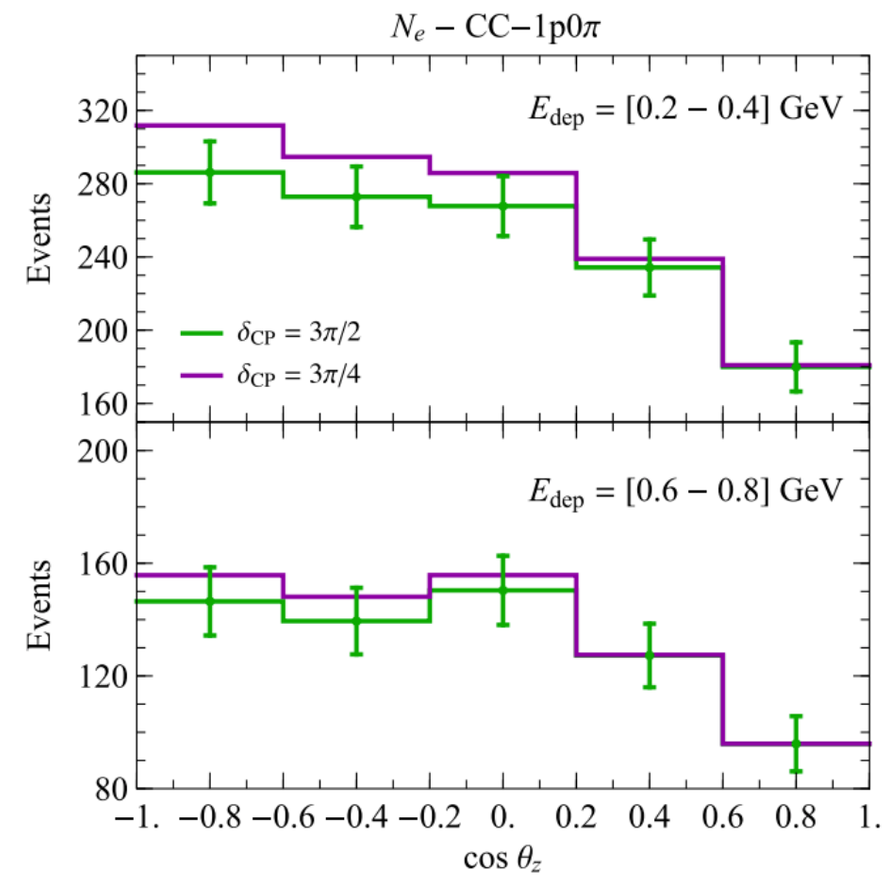


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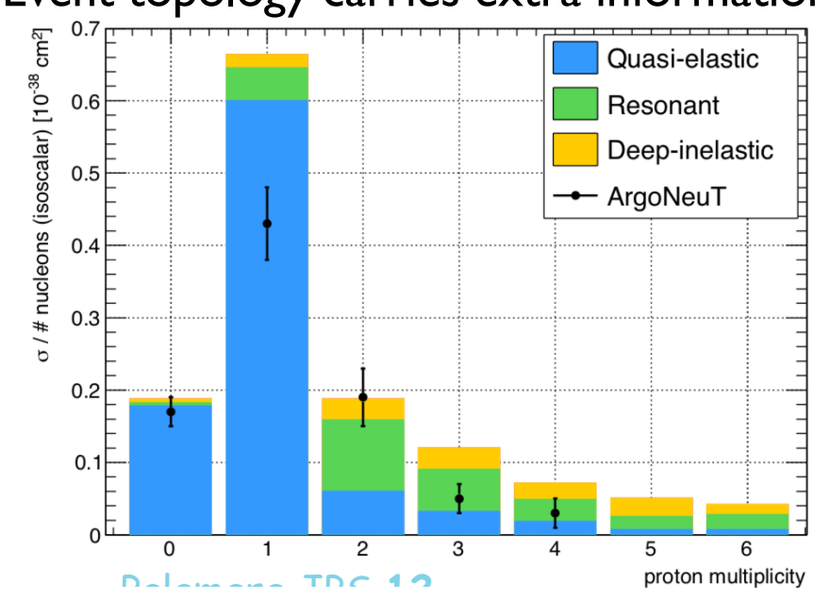




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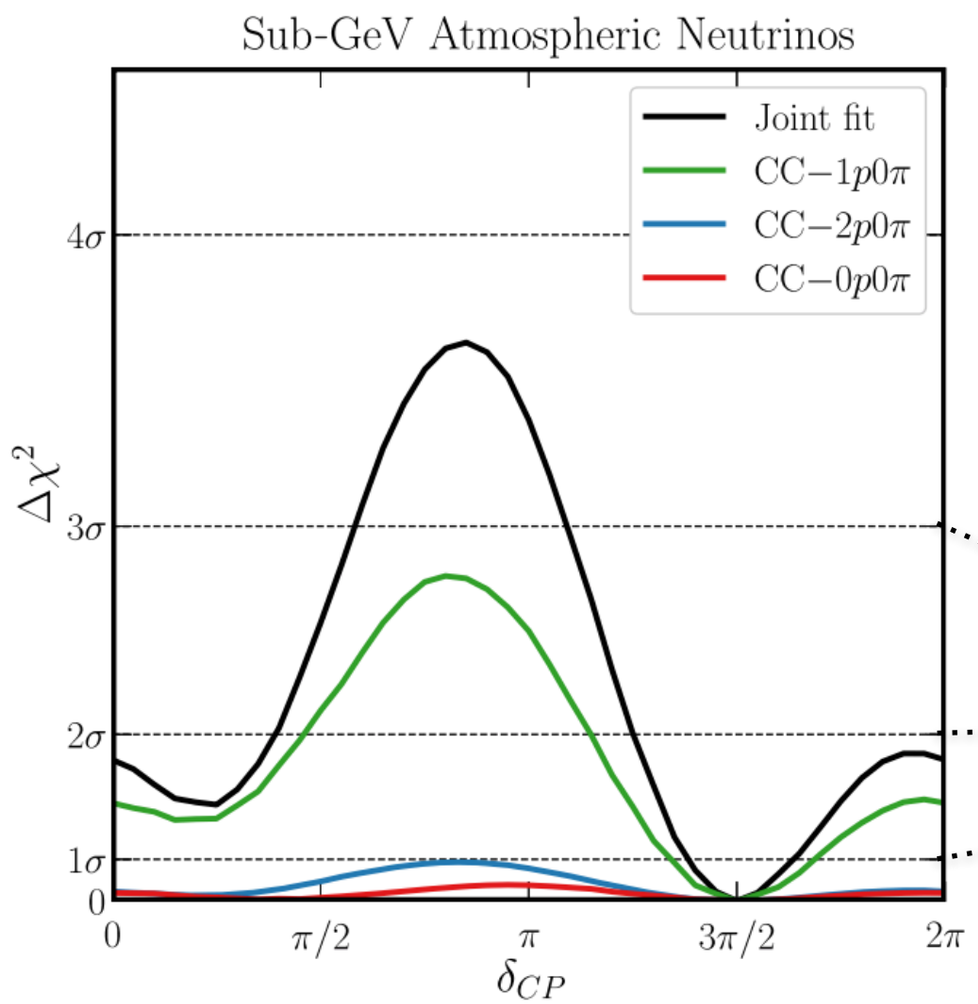
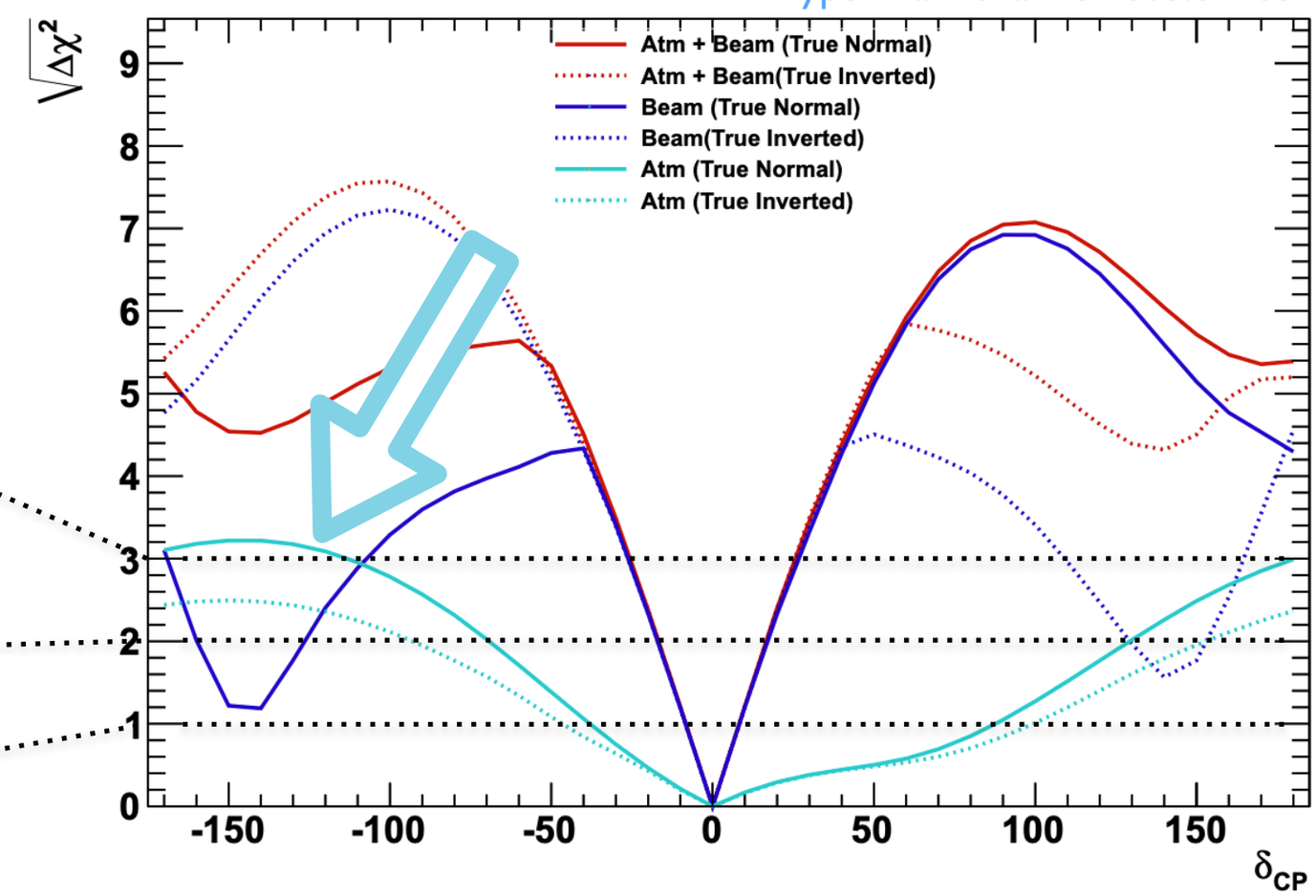



Hyper-Kamiokande 1805.04163




DUNE

40 kton, 10 years, only sub-GeV atm-ν

Hyper-Kamiokande

187 kton, 10 years, all atm-ν



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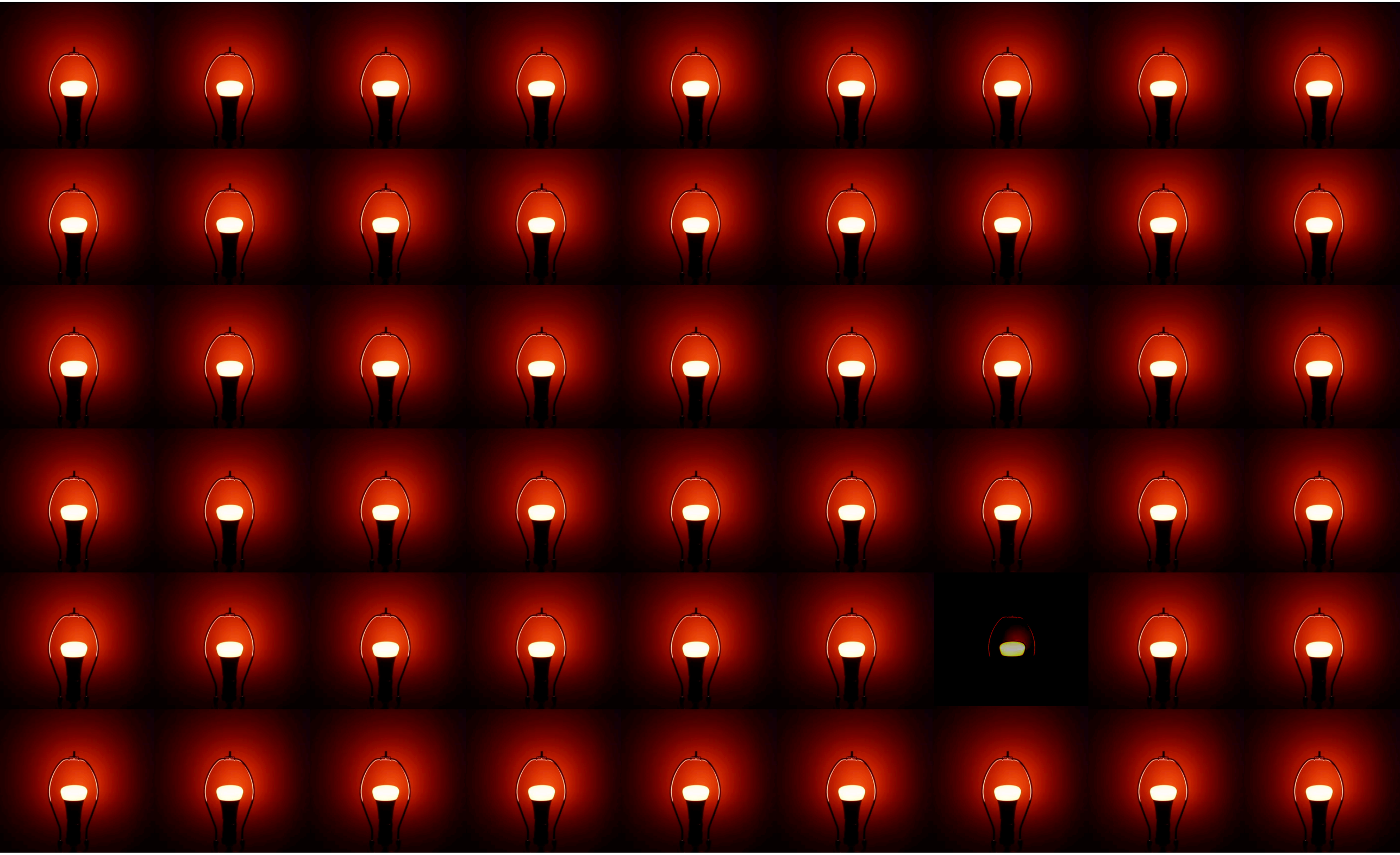
# Millicharged Particles

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# Millicharged particles

Harnik Liu Palamara 1902.03246

Q(down quarks) = -1/3 Q(up quarks) = +2/3 Q(e,μ,τ) = –1

Are there particles with tiny charges?

These can easily be there if there is "dark electromagnetism"

Low production, difficult detection



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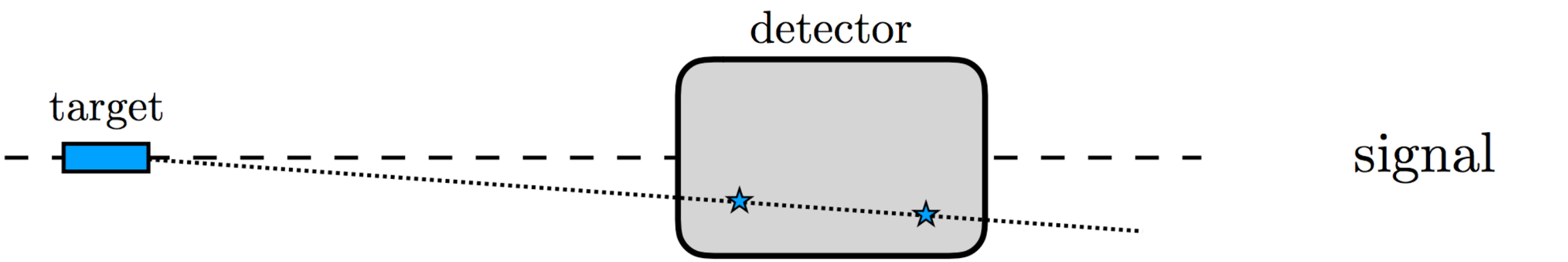


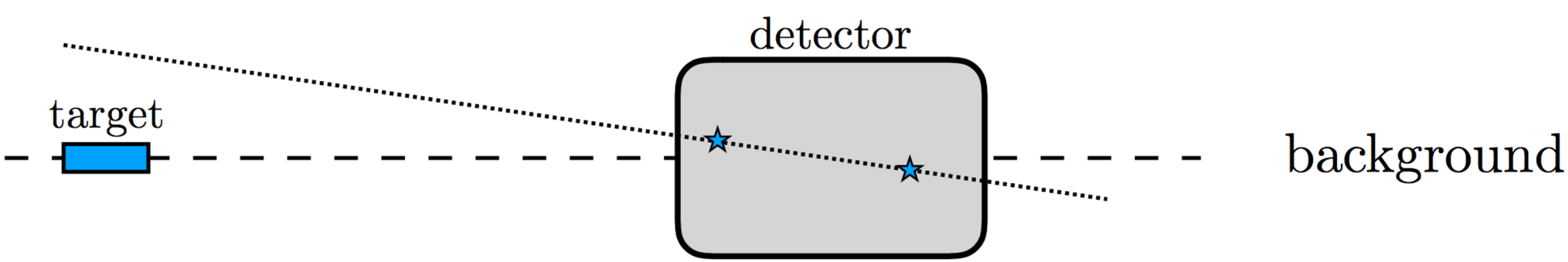

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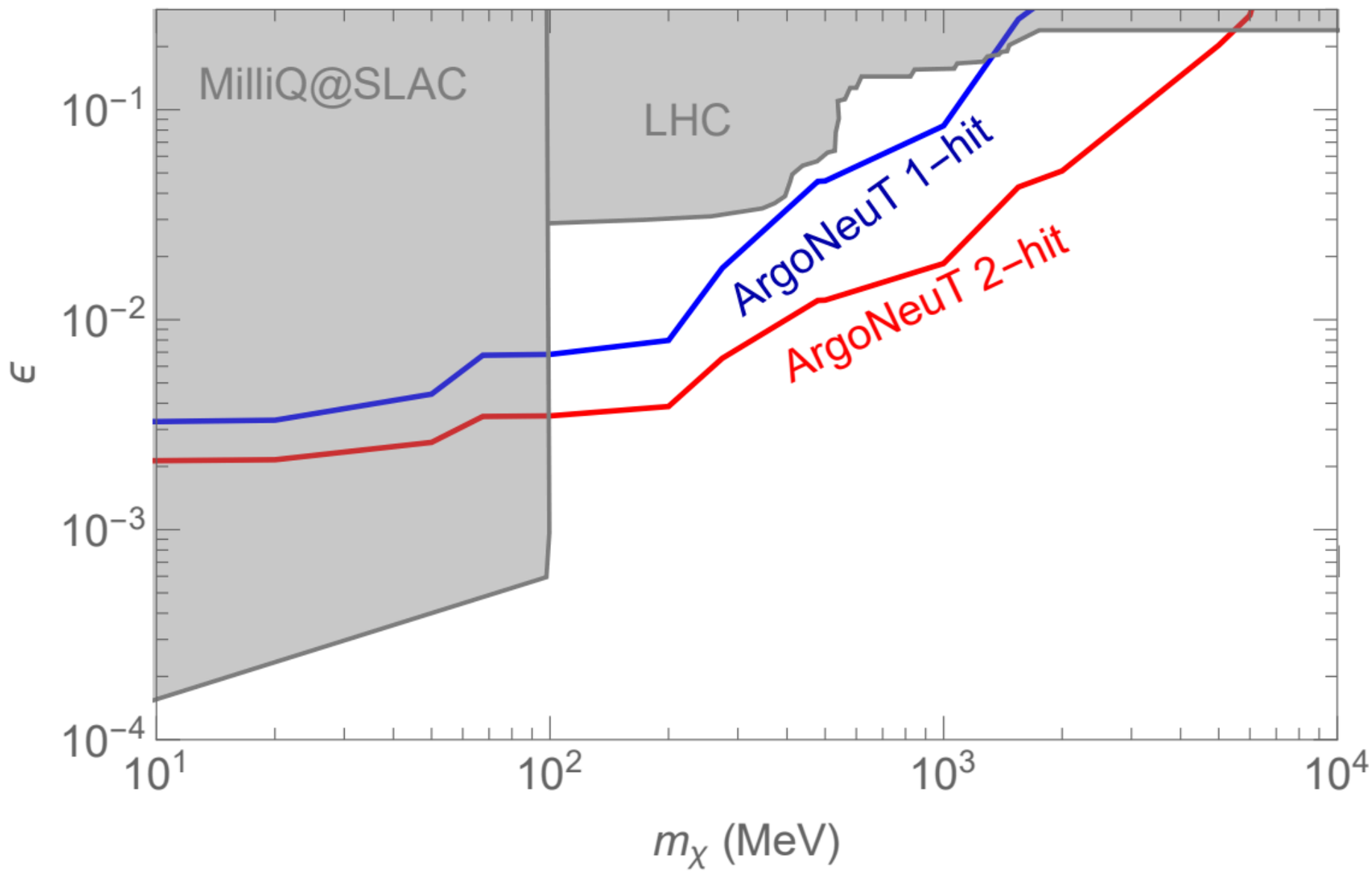




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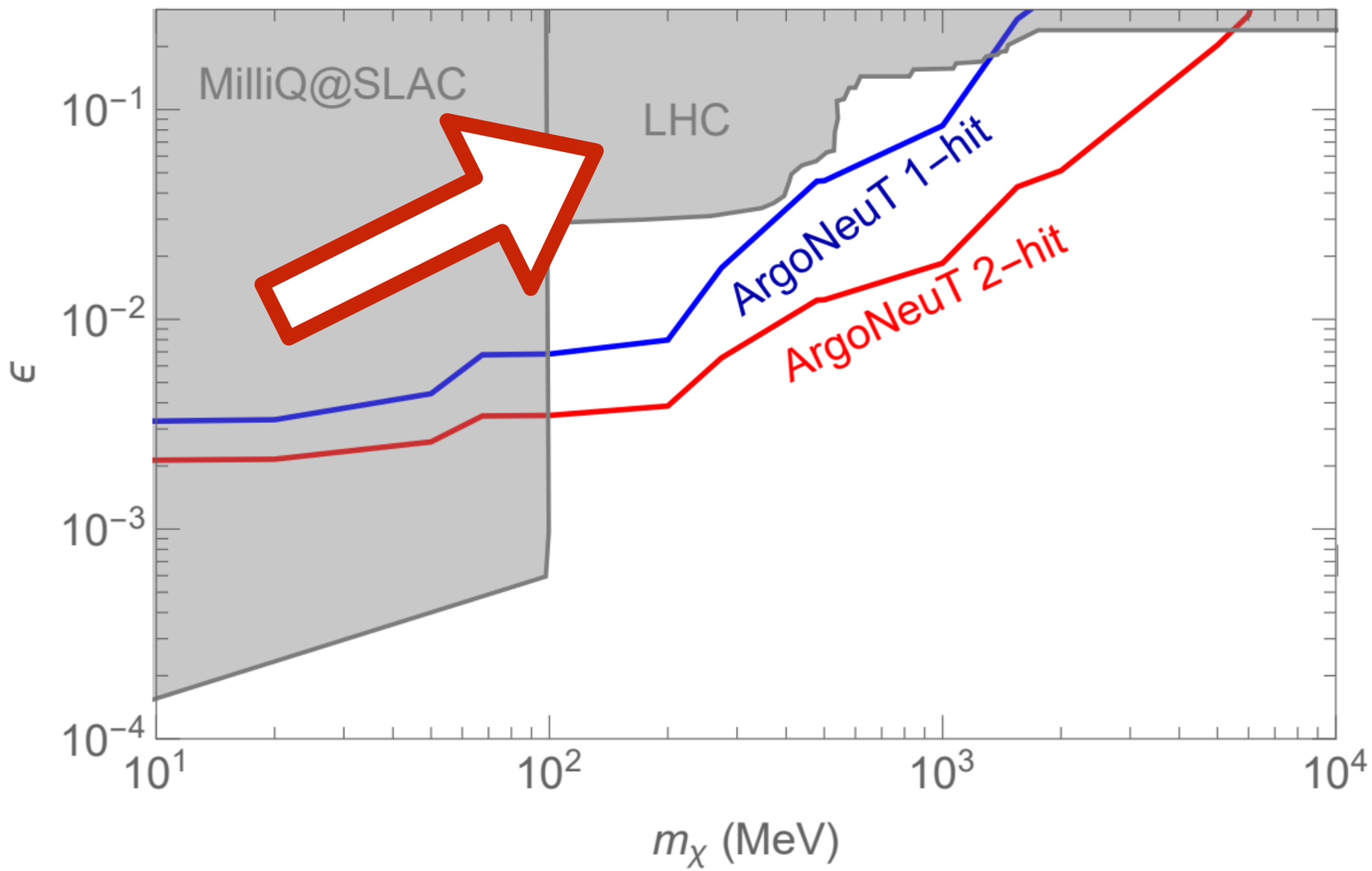
Are there particles with tiny charges?

These can easily be there if there is "dark electromagnetism"



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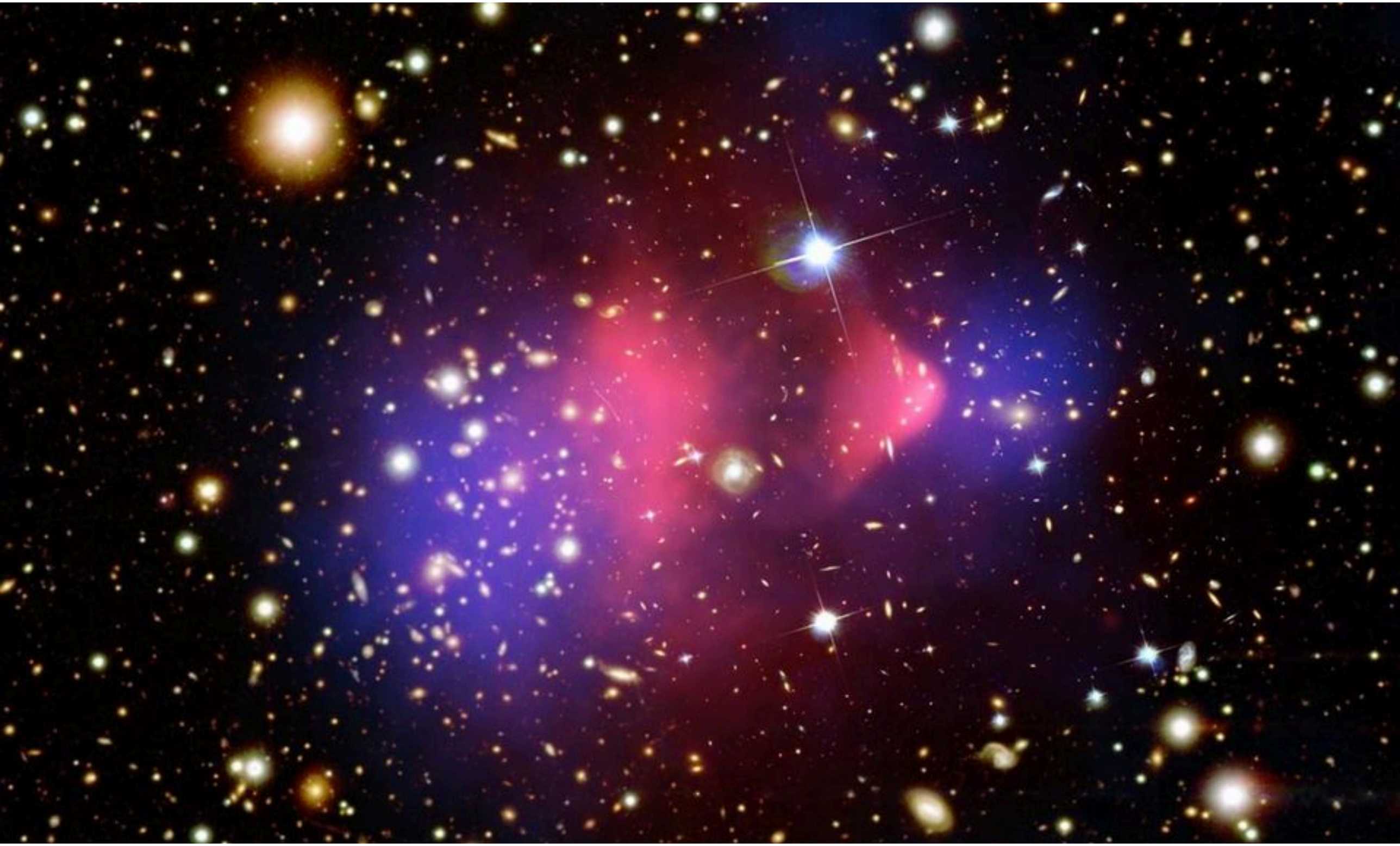
# Dark Matter

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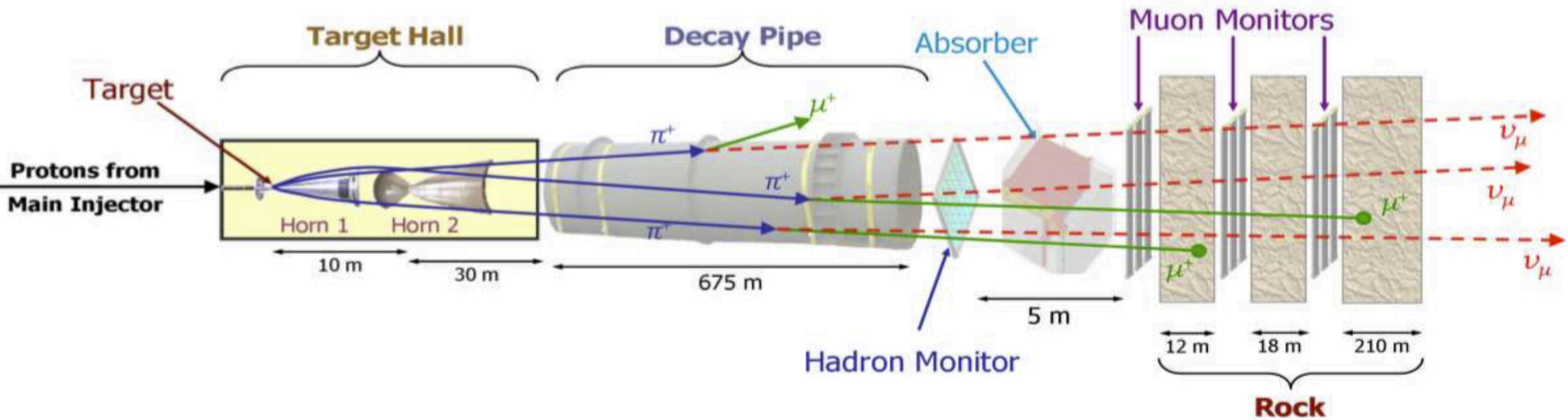
# Light dark matter

DM interacts with "dark electromagnetism" which has a "dark photon"

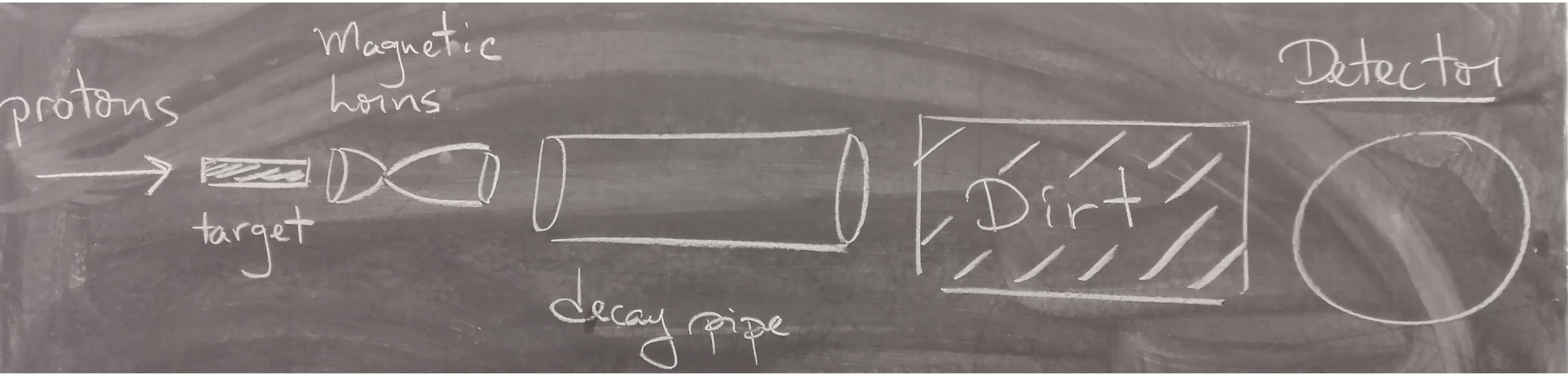
Whatever couples to the photon will couple to the dark photon
(kinetic mixing)

$$\pi^0 > A\,A' > A\,\chi\,\chi$$

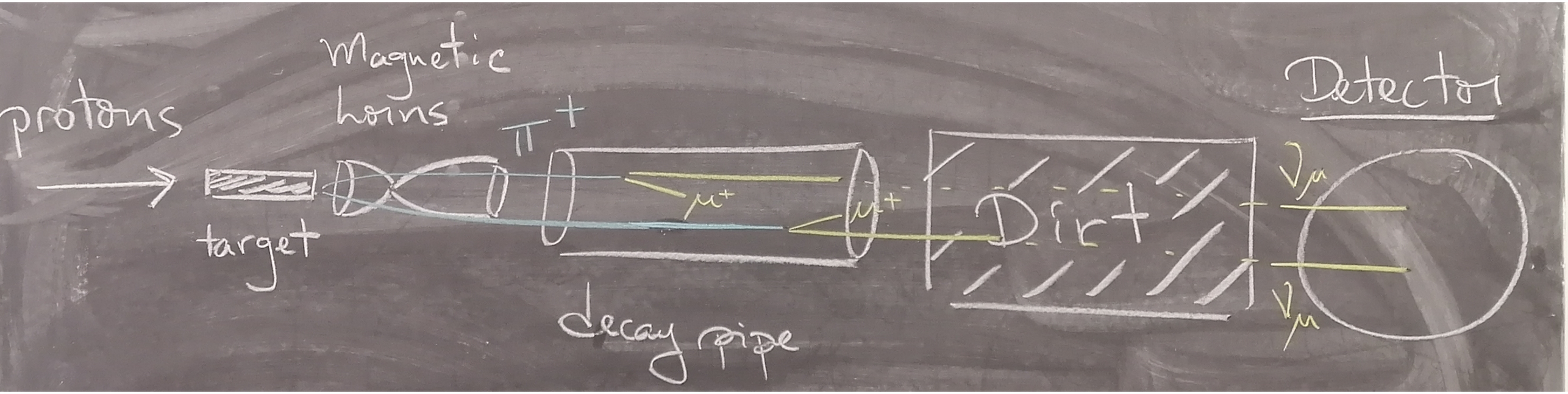
# Light dark matter



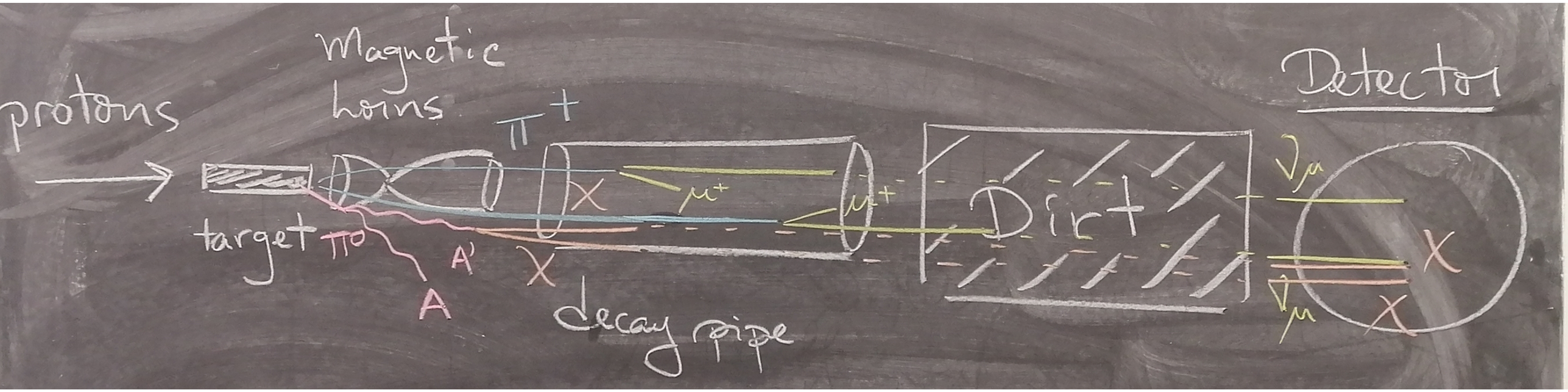
# Light dark matter



# Light dark matter

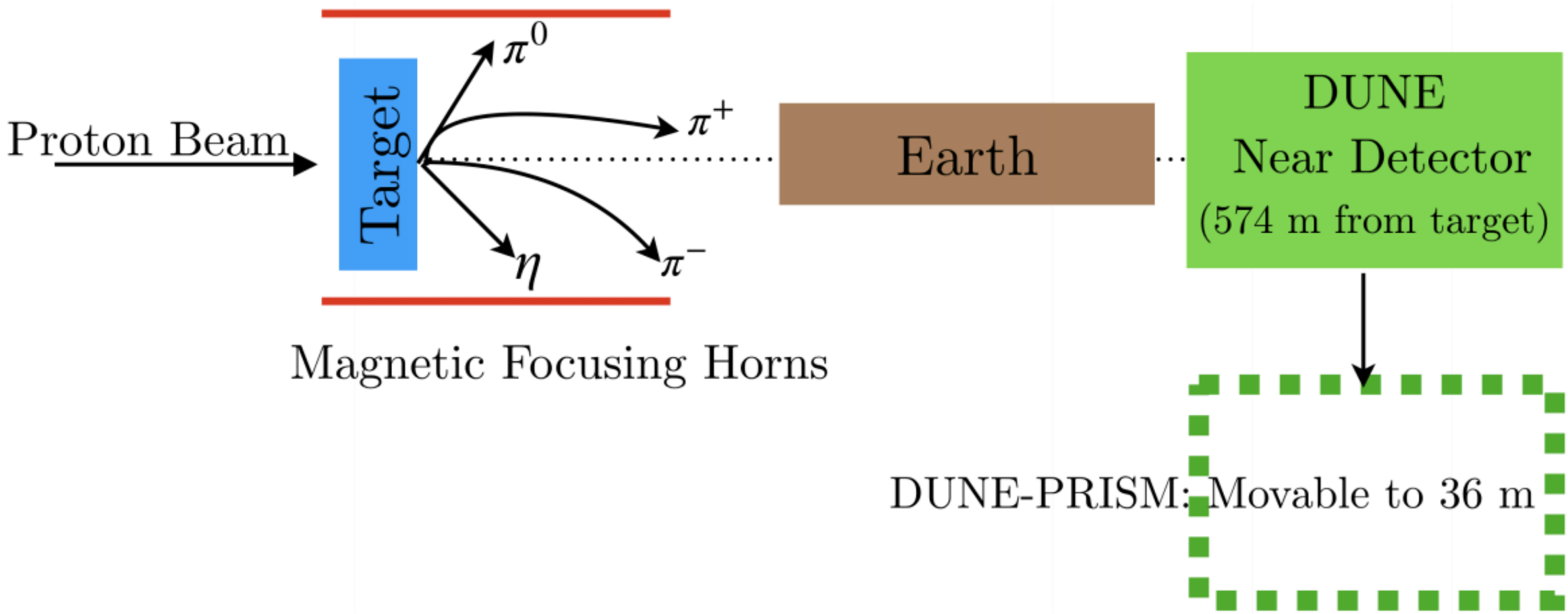


# Light dark matter



# Light dark matter

de Romeri Kelly M 1903.10505

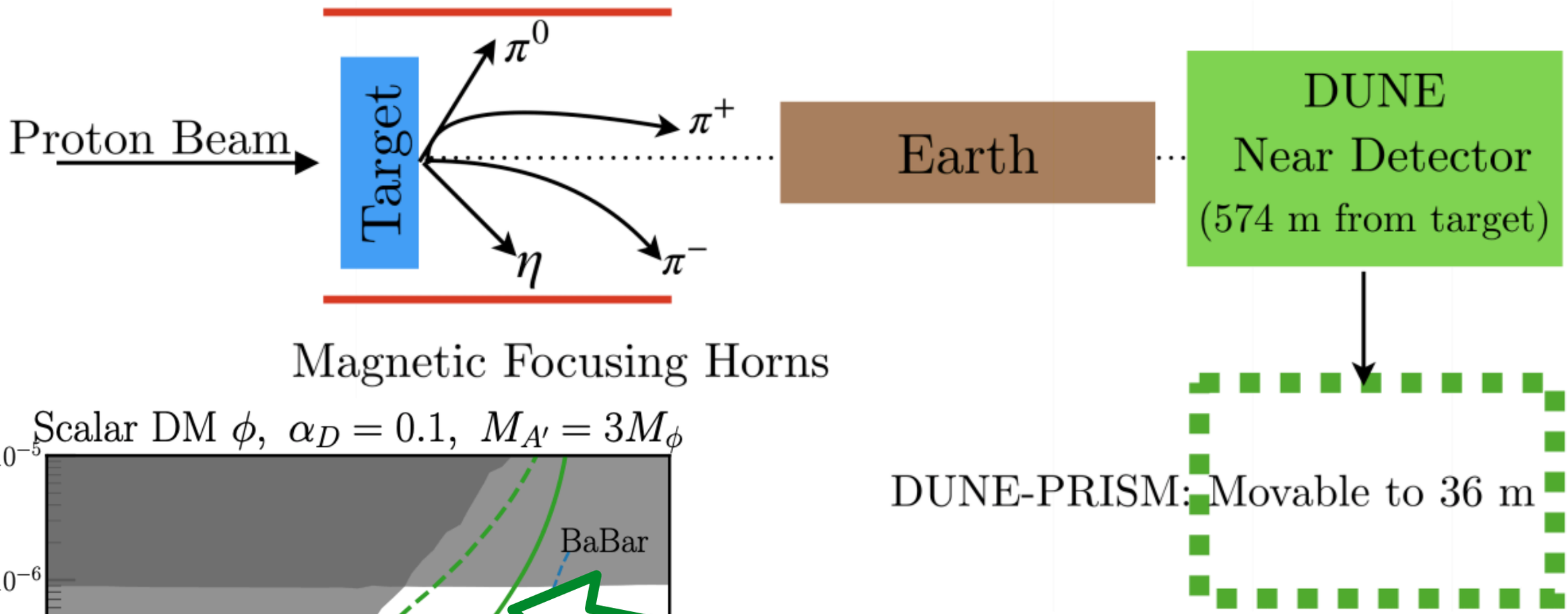


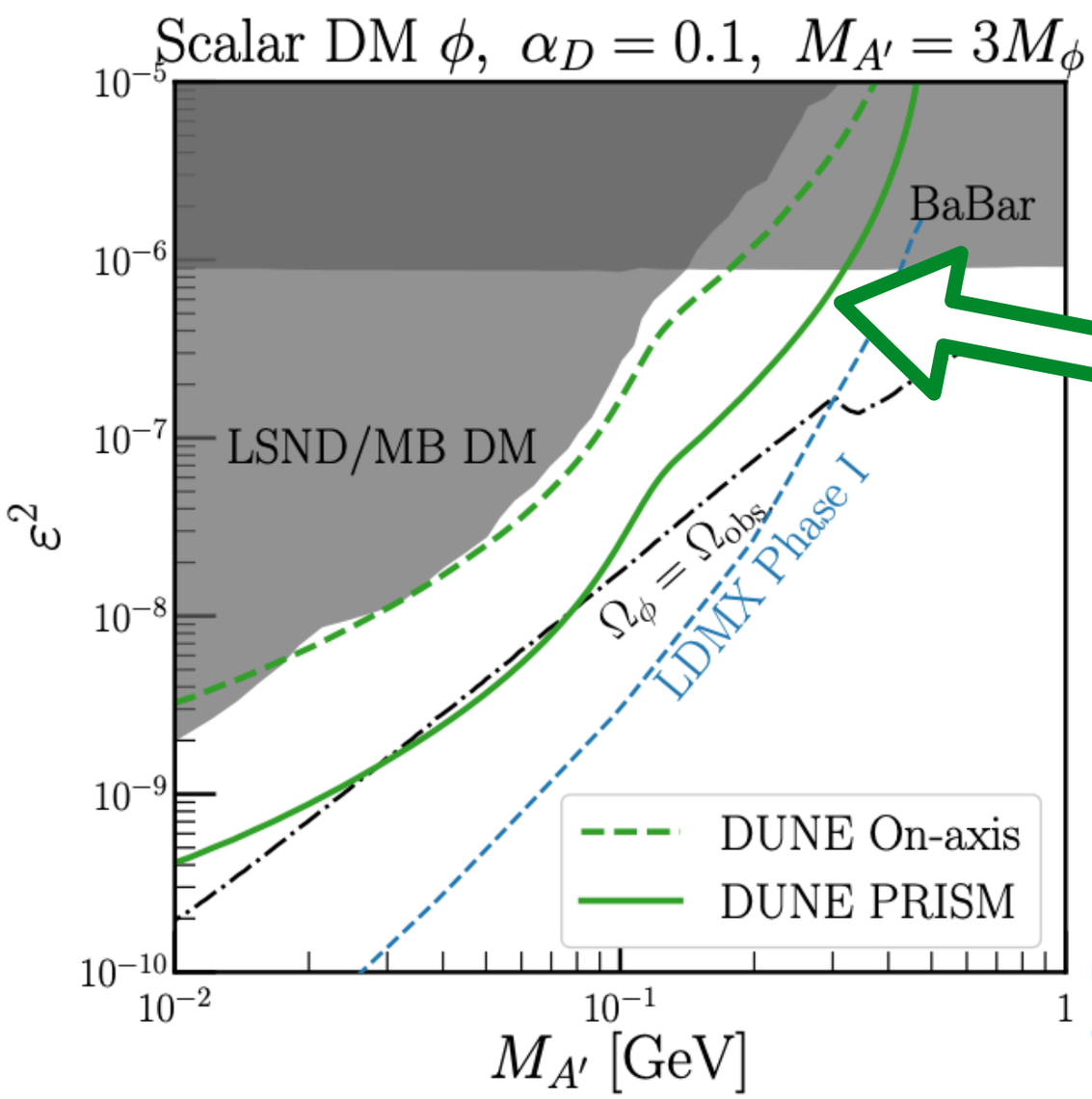

Neutrino flux is higher on-axis

DM flux is relatively higher off-axis

# Light dark matter

de Romeri Kelly M 1903.10505



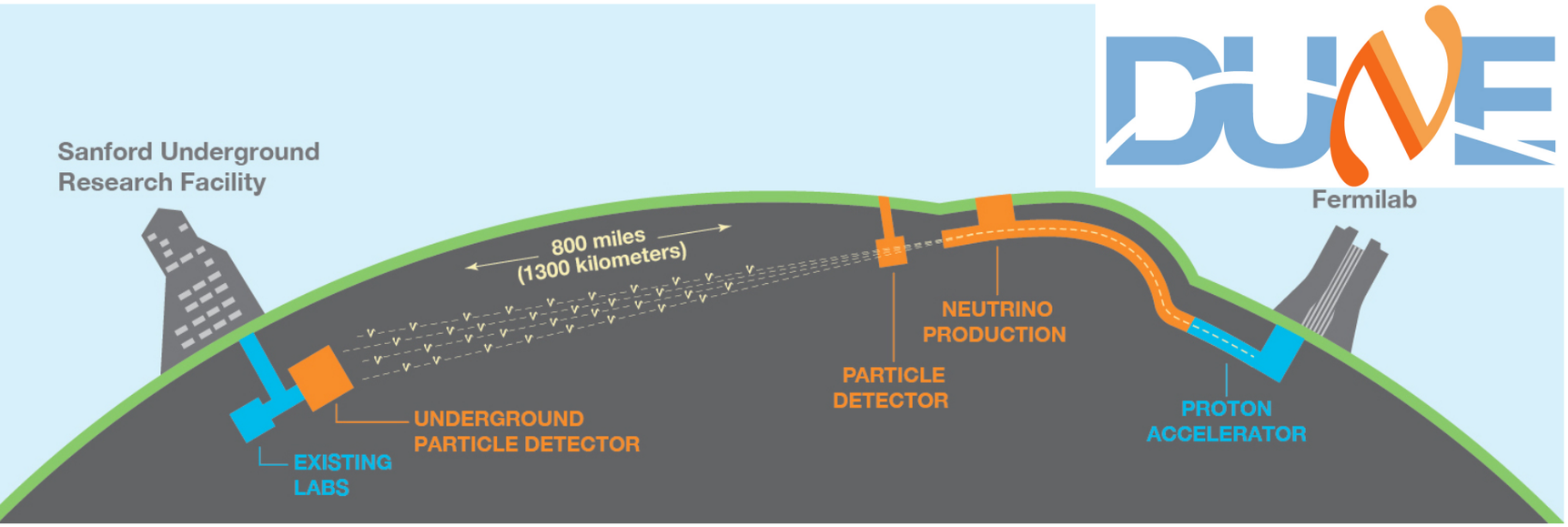



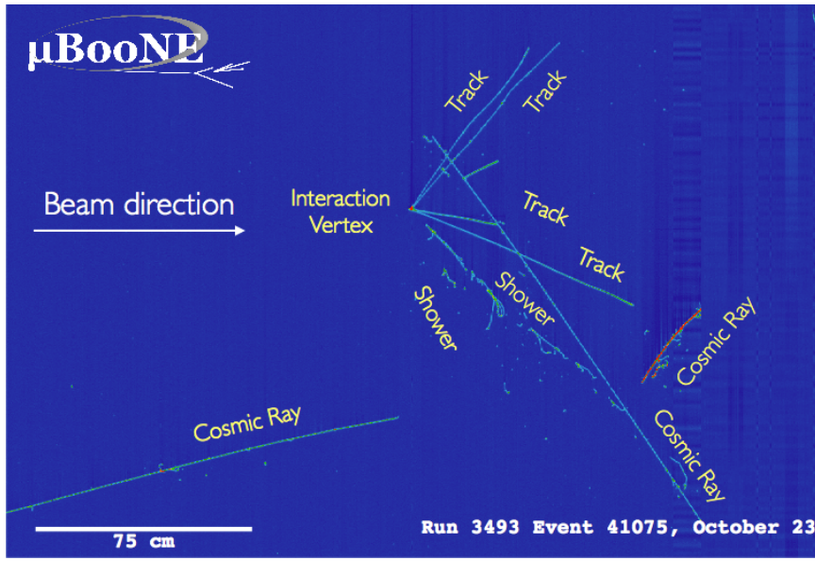

Neutrino flux is higher on-axis

DM flux is relatively higher off-axis

# Accelerator neutrinos at Fermilab

SBN program will set the stage for the future DUNE experiment




CP violation

Dark neutrinos

atmospheric neutrinos

Lorentz violation

Mass ordering

light dark matter

Precision oscillation physics

proton decay

sterile neutrinos

millicharged particles

unitarity of PMNS matrix

neutrino tridents

neutrino cross sections

ultra-light dark matter

low scale neutrino mass models



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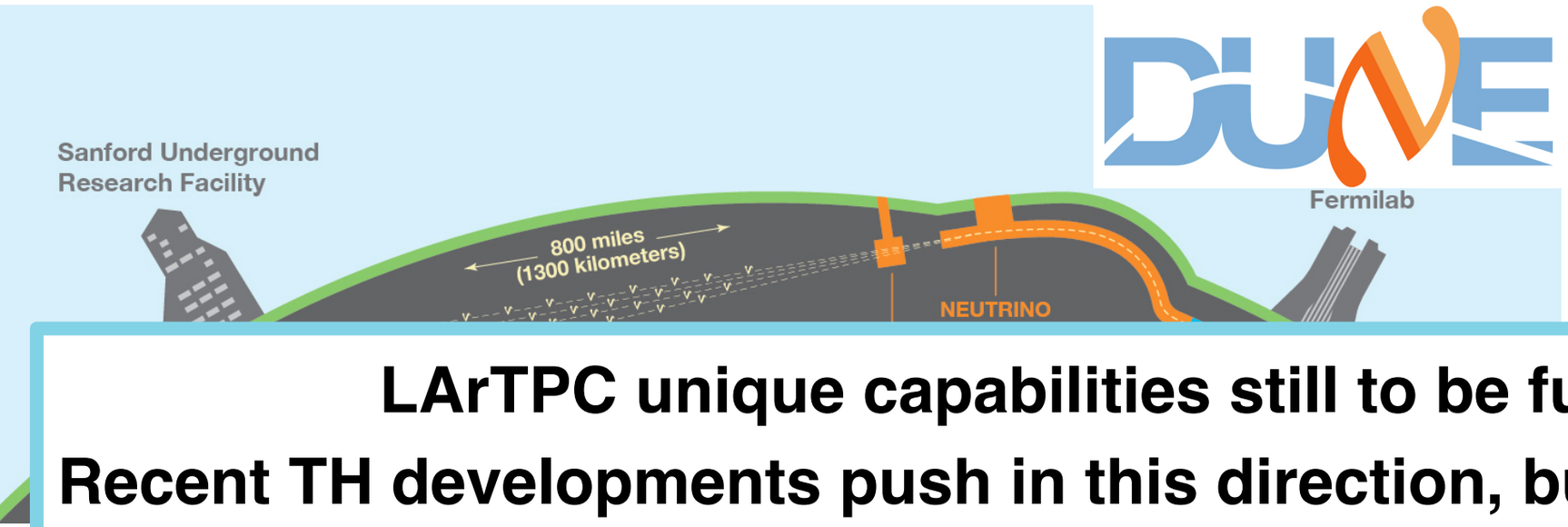
pmachado@fnal.gov

# Accelerator neutrinos at Fermilab

SBN program will set the stage for the future DUNE experiment





**LArTPC unique capabilities still to be fully exploited**

**Recent TH developments push in this direction, but still much work to do**

**SBN and DUNE will be multi-purpose experiments**

CP violation

Lorentz violation

Dark neutrinos

atmospheric neutrinos

Mass ordering

light dark matter

Precision oscillation physics

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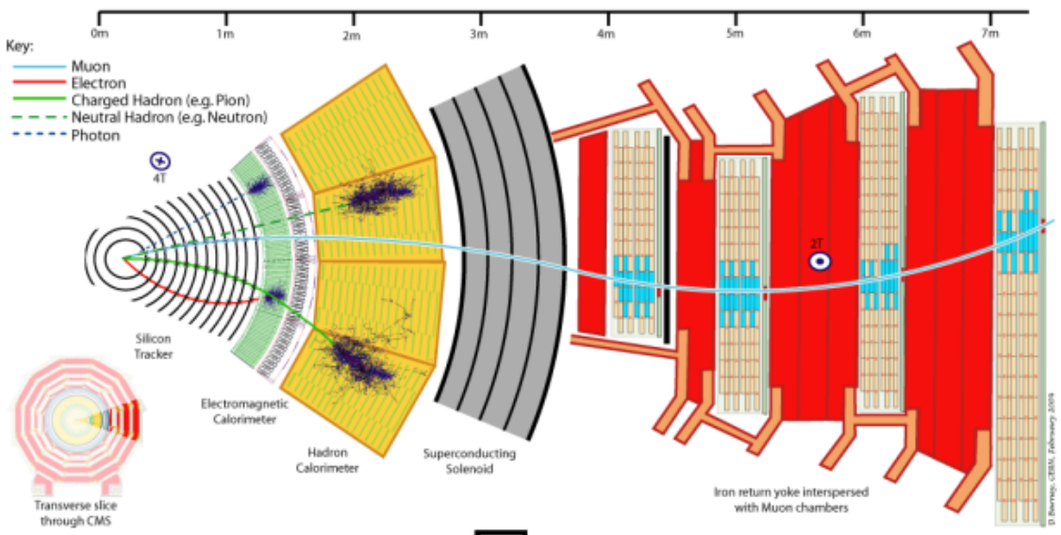
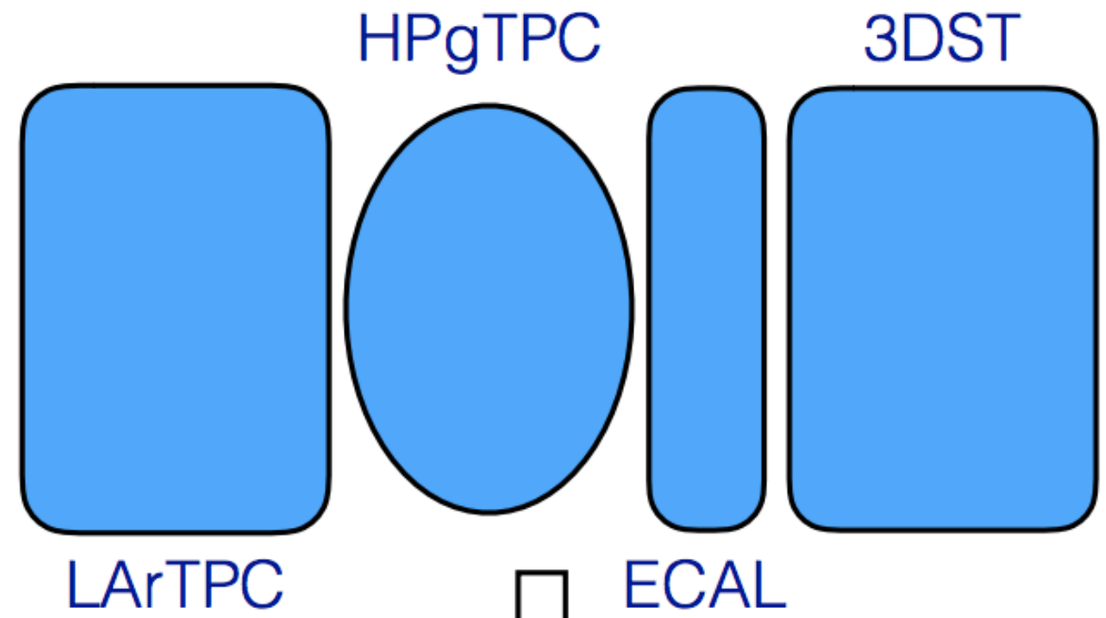
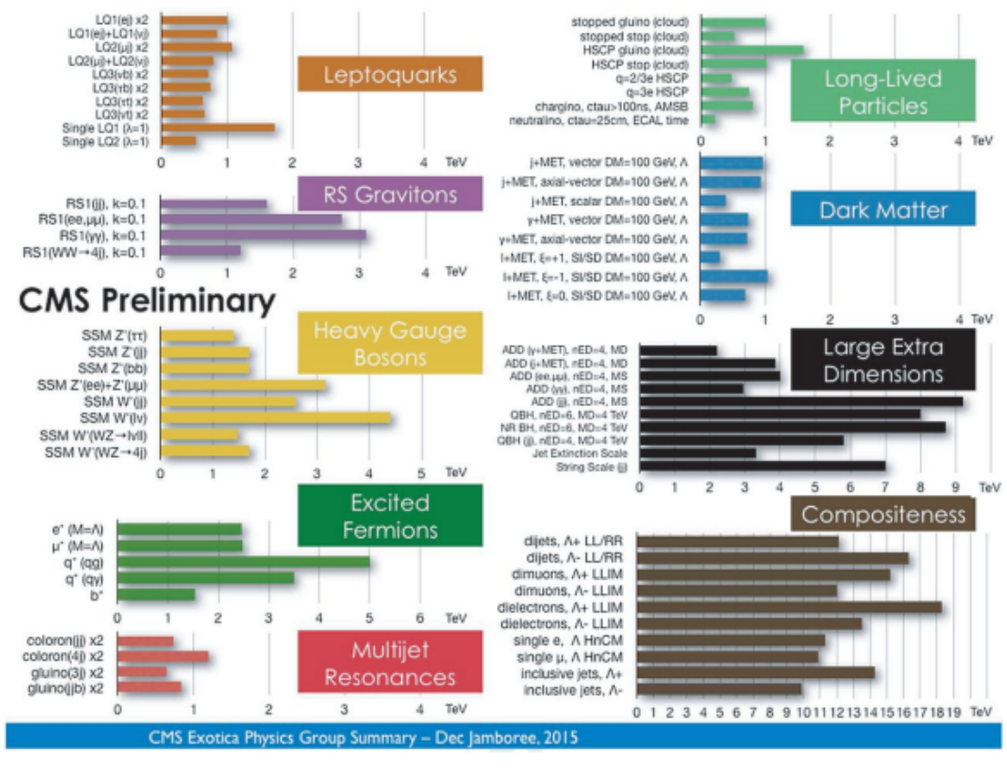
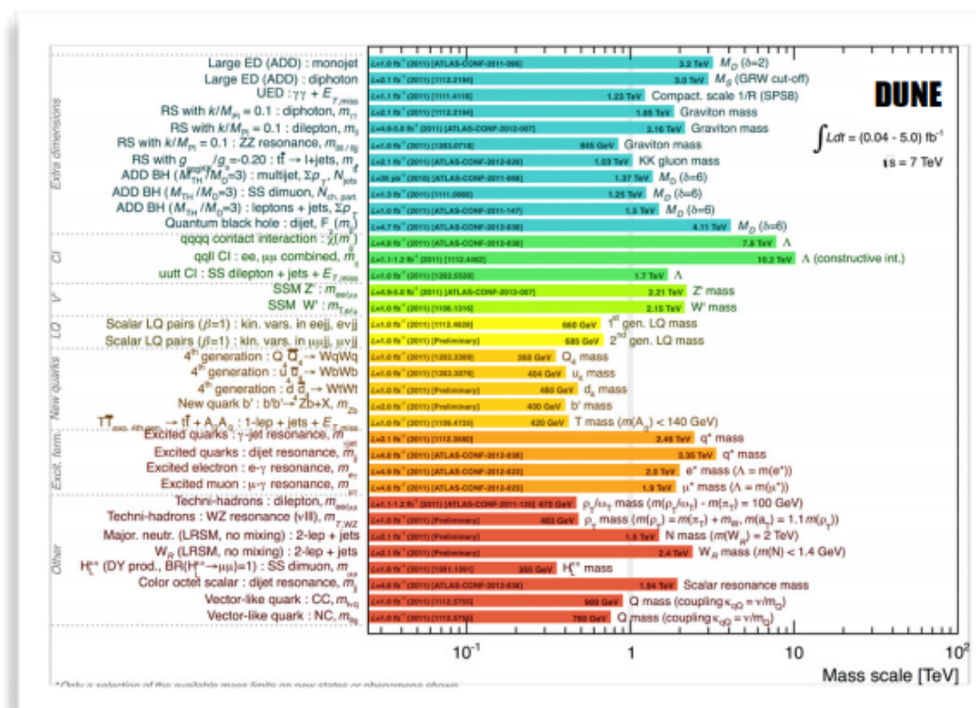
# Multi-Purpose Detectors

**Roni Harnik's slides in PONDD 2019**



# Conclusions?

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# Conclusions?

**In the standard model, neutrinos are still *terra incognita* to be explored**

**Is there CP violation in the lepton sector?**

**What is the neutrino mass spectrum?**

**What are the absolute values of neutrino masses?**

**What is the mechanism of neutrino masses?**

**Are neutrinos Dirac or Majorana?**

**Are there light sterile neutrinos?**

**Can we overcome the neutrino cross section challenge?**

**Can we overcome experimental challenges?**

**Is there a reason for the mass and mixing pattern of the SM?**

**Do protons decay?**

**Do the forces of nature unify?**

**...**

**What else may be hiding in the neutrino sector?**

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