# Theoretical Perspective on Neutrino Physics

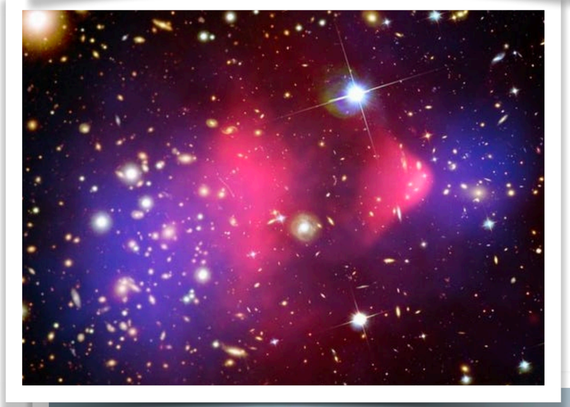
Pedro Machado

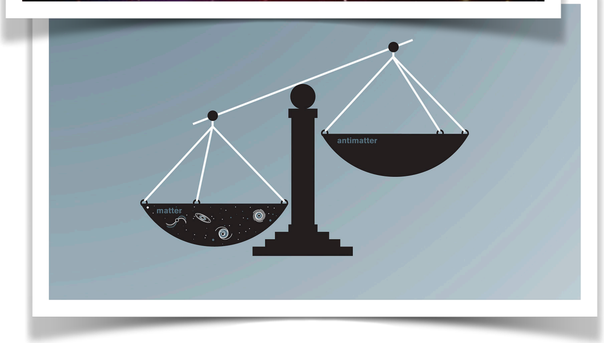
November 28th, 2023

ICFA

*Disclaimer: I am a member of SBND and DUNE, but this talk only conveys my personal opinion and science. Mistakes are mine!

# The outstanding questions in neutrino physics and beyond, guided by neutrino experiments




The mechanism of neutrino masses
The nature of neutrinos
The unification of all forces
The matter-antimatter asymmetry
Neutrinos as a portal to new physics
CP violation in the leptonic sector
The absolute masses of neutrinos
Neutrino mixings: patterns and symmetries
Existence of extra neutrino species

The nature of dark matter
CP violation in strong interactions
The existence of dark sectors

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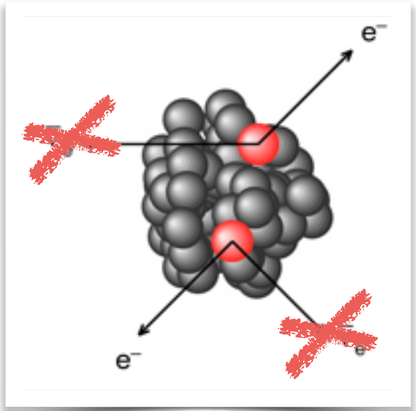


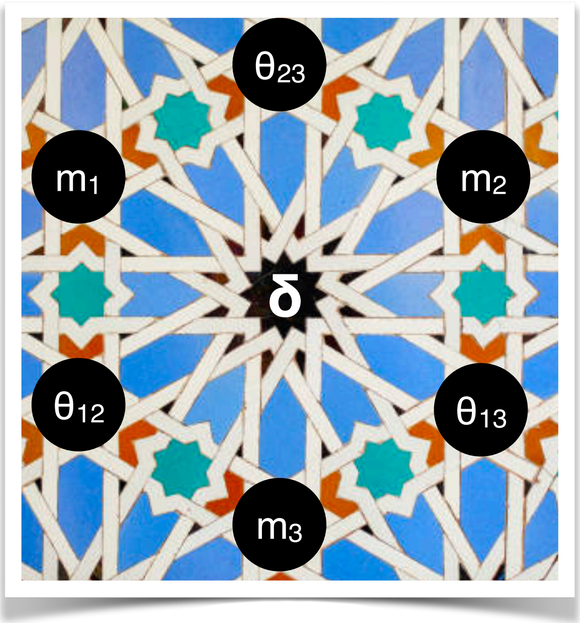


**Where does the standard model break?**



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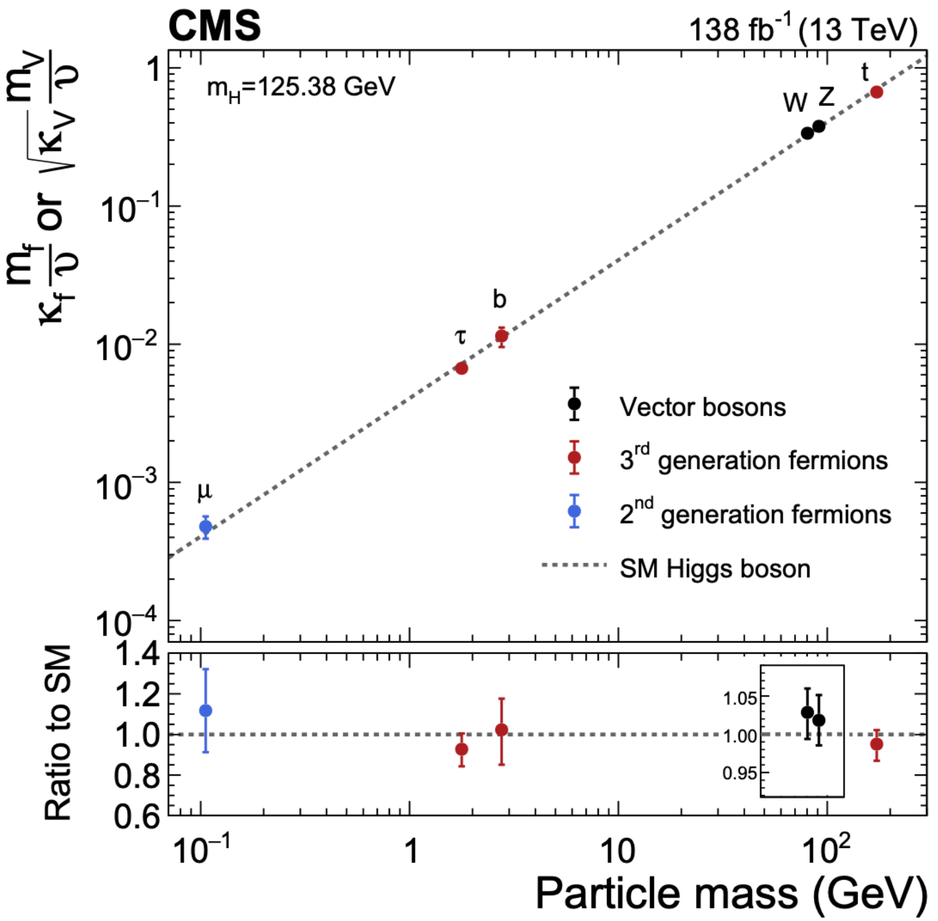
# The mechanism of neutrino masses

**The mechanism of neutrino masses is qualitatively different from charged fermions**

All particles within the framework of the standard model, except for neutrinos, get their masses directly and exclusively from the Higgs mechanism

Data points in that direction, at least for charged fermions of the 2nd and 3rd families and gauge bosons

But neutrinos are very different





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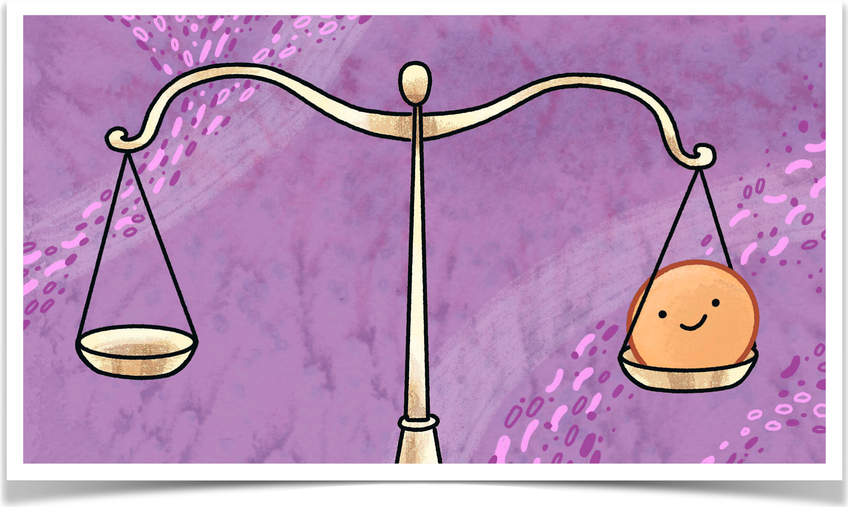
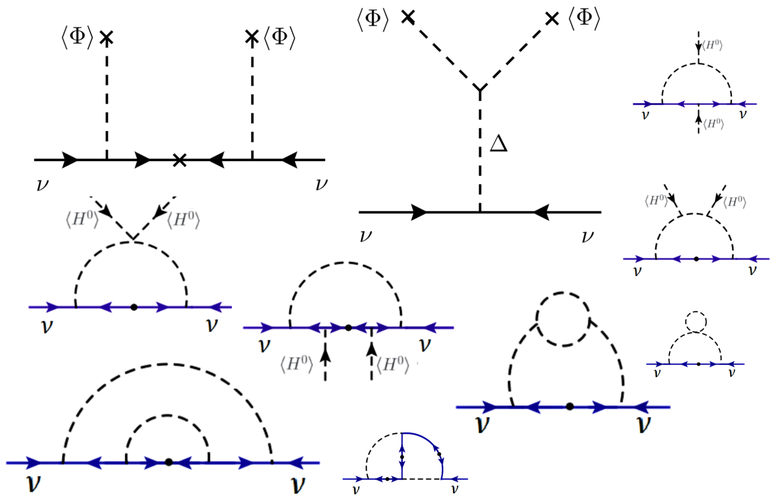
# The mechanism of neutrino masses

Just repeating the Higgs mechanism for neutrinos (invoking a right-handed neutrino) would **predict a particle that is completely different from all observed particles**: its mass has nothing to do with electroweak symmetry breaking

Possible realizations of the neutrino mass mechanism span at least 20 orders of magnitude in scale, from the sub-eV to grand unification, and there is little to no experimental guidance on the right energy scale

**Theory landscape is wide open**





Miranda Valle 1602.00864
Babu et al 1907.09498



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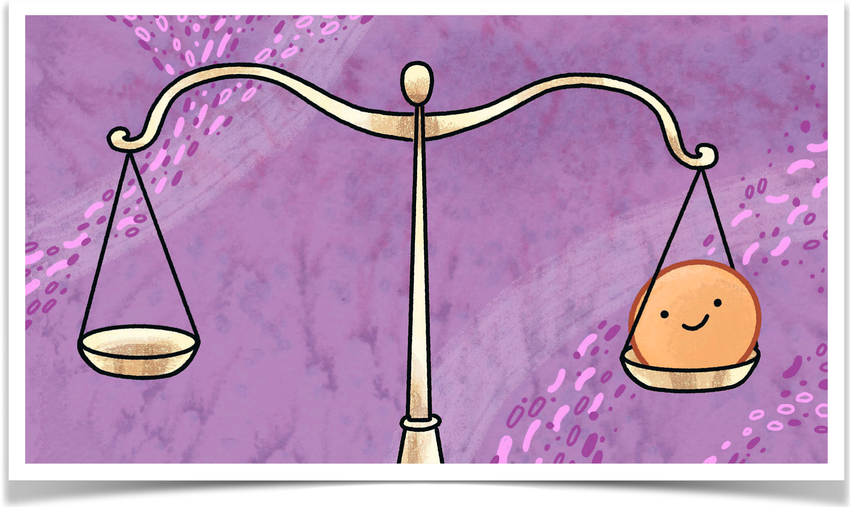
# The mechanism of neutrino masses

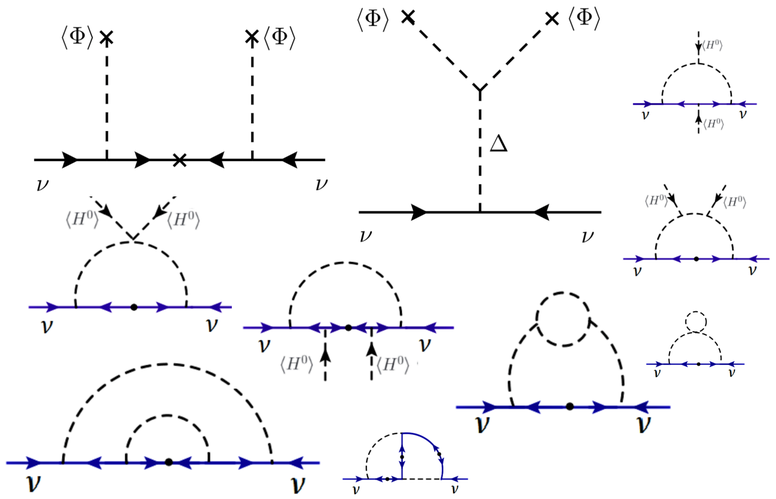
One key point:
**The neutrino mass mechanism is much more than neutrino masses**,
just as electroweak symmetry breaking is much more than the Fermi constant

Of course, we need to determine neutrino masses and the nature of neutrinos, but it is crucial that we go beyond these measurements

We need to approach the problem from many sides

We need a precision neutrino physics program





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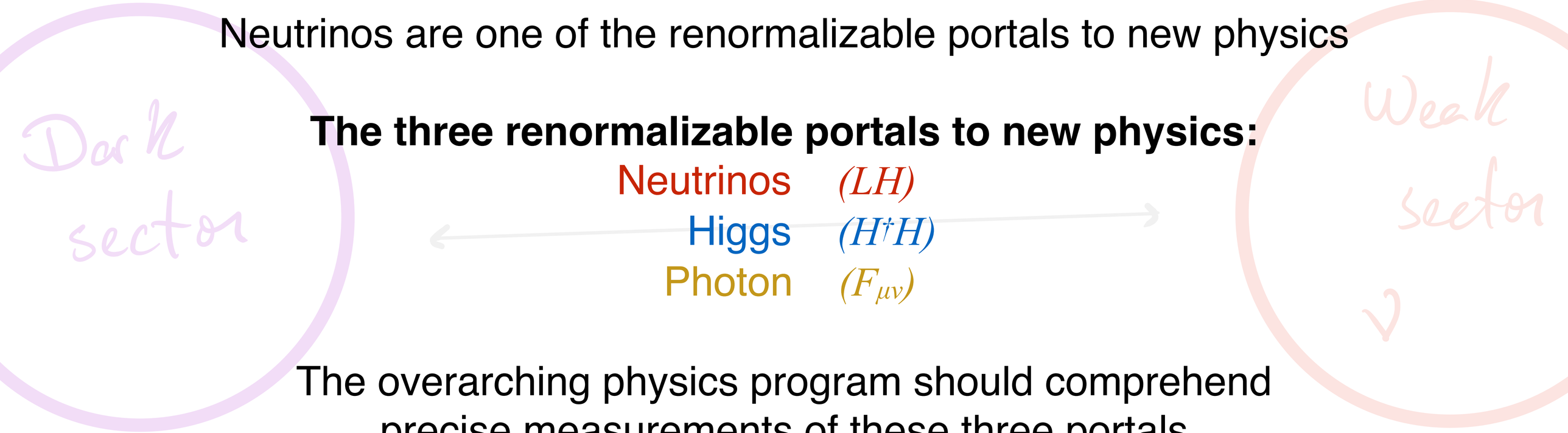
# Exploring the unknown through the lens of neutrinos

From a theory perspective, $(LH)$ is special: it is a gauge-singlet

Neutrinos are one of the renormalizable portals to new physics




**The three renormalizable portals to new physics:**

Neutrinos $(LH)$

Higgs $(H^\dagger H)$

Photon $(F_{\mu\nu})$

The overarching physics program should comprehend precise measurements of these three portals

**We need a precision neutrino physics program**



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**Precision physics program**

Measure same parameters with different observables

Test predictions of the model, given previous measurements

Example:

$M_Z$ at LEP with good precision is great,

but the model is really tested when we e.g. measure the *weak mixing angle*

and compare with the prediction given $M_Z$ and $M_W$ measurements

Currently, the closest we get to a precision neutrino physics program is encoded in the measurements of $\delta_{cp}$ and the atmospheric mixing and mass splitting



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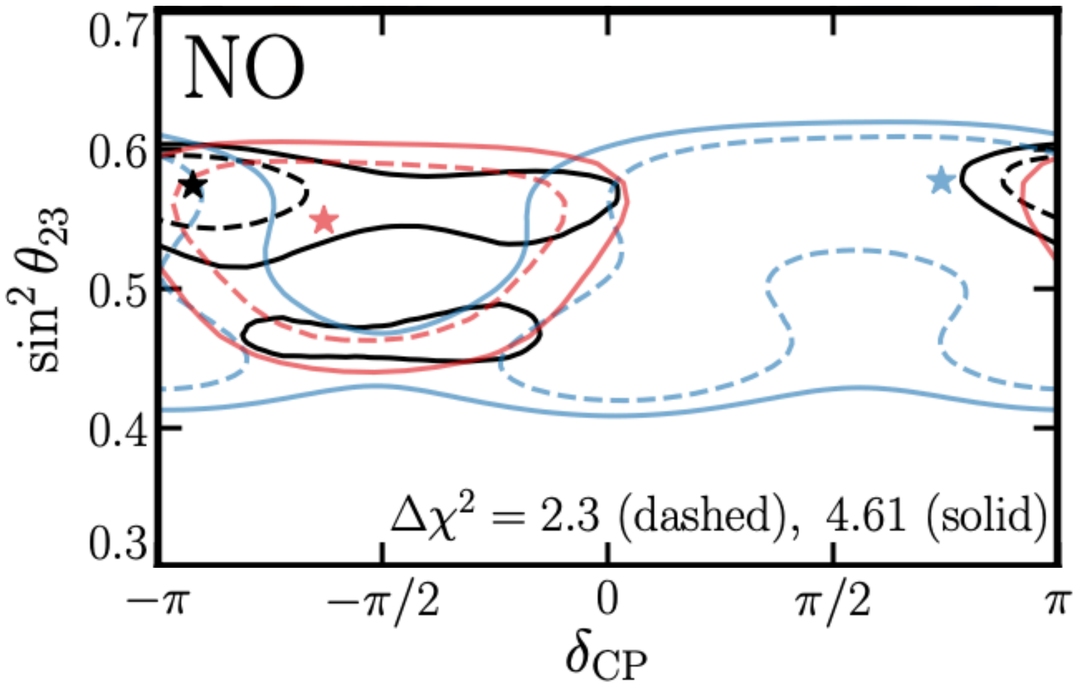
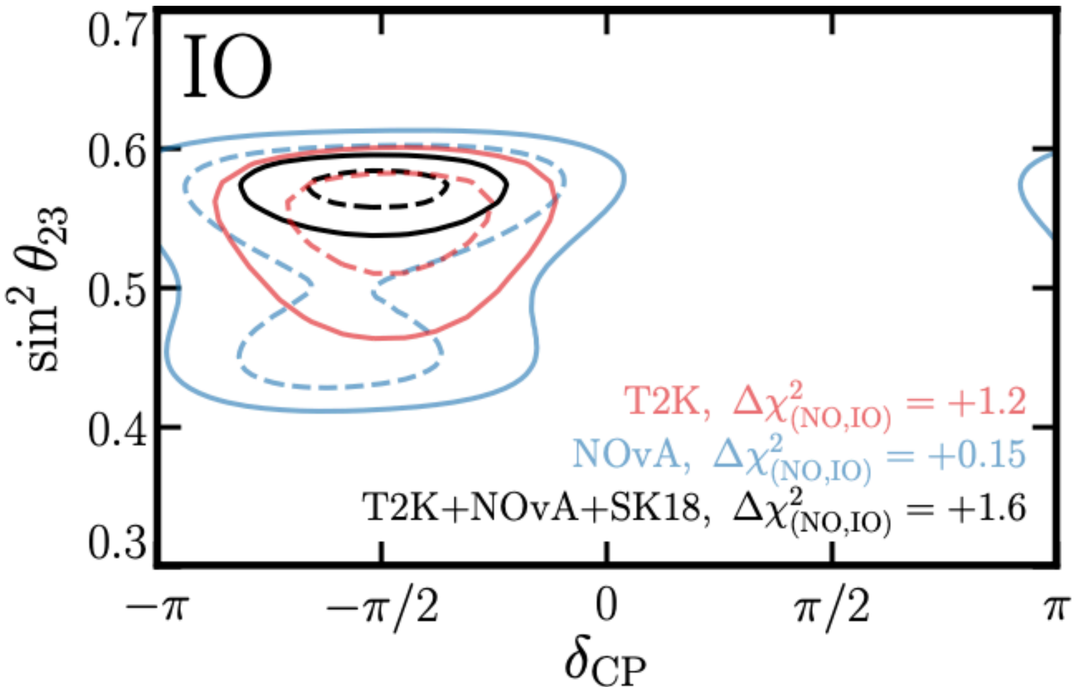
# Exploring the unknown through the lens of neutrinos

| Parameter | Measurements | Values | Uncertainty |
|---|---|---|---|
| $\theta_{13}$ | Daya Bay/RENO, T2K/NOvA, solar | 8.5° | 1.7% |
| $\theta_{12}$ | Solar neutrinos, KamLAND | 33° | 2.5% |
| $\theta_{23}$ | T2K/NOvA, atm (SK/IceCube) | 49° | 2.3% |
| $\Delta m^2_{21}$ | KamLAND, solar | $7.4\ 10^{-5}$ eV$^2$ | 2.8% |
| $\Delta m^2_{atm}$ | T2K/NOvA, atm | $2.5\ 10^{-5}$ eV$^2$ | 1.1% |
| $\delta_{CP}$ | T2K/NOvA, atm | -π/2?π? | 30%? |
| MO | T2K/NOvA, atm | Normal?Inverted? | 100%? |



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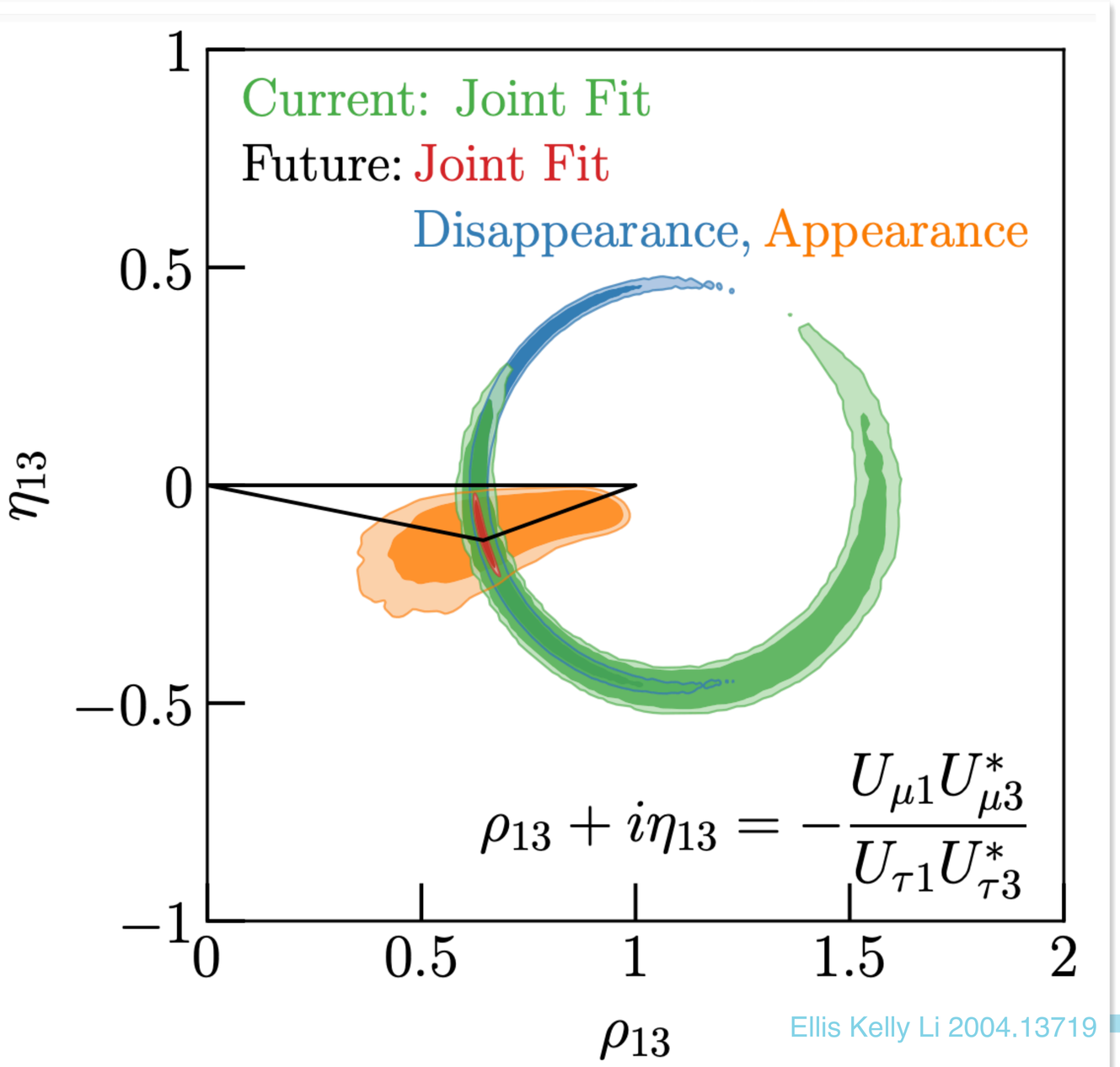
# Exploring the unknown through the lens of neutrinos




Ellis Kelly Li 2004.13719

**DUNE, HK, JUNO, and neutrino observatories will enable a bona fide precision physics program in the neutrino sector**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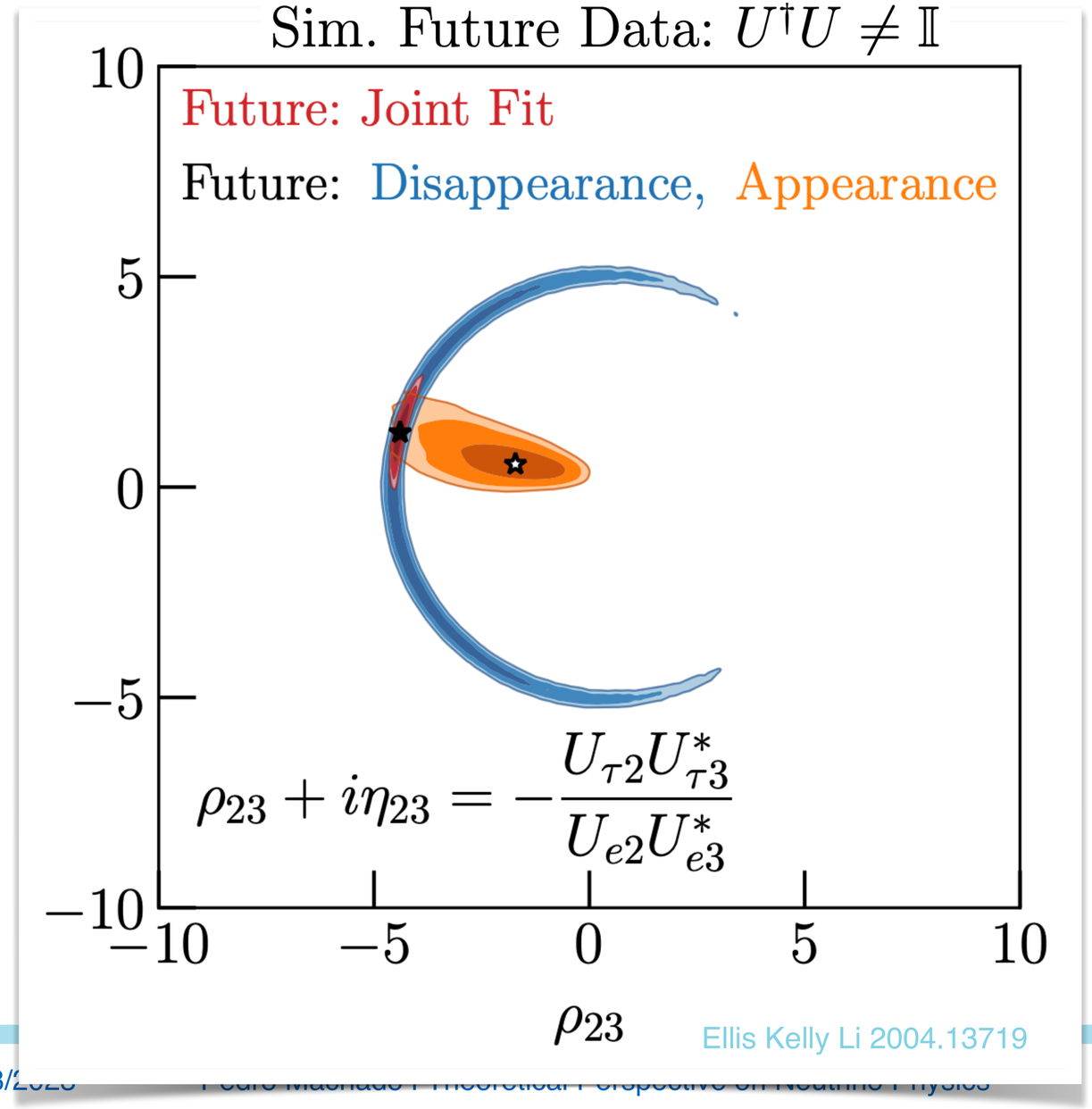
# Exploring the unknown through the lens of neutrinos

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**DUNE, HK, JUNO, and neutrino observatories will enable a bona fide precision physics program in the neutrino sector**



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# Break to apologize

It is impossible to cover the entire field of neutrino physics in one talk

**Here are some of the topics I am omitting**

Neutrino-nucleus interaction modeling
Neutrino in cosmology
Astrophysical neutrinos
Ultrahigh energy neutrinos
Neutrinoless double beta decay experiments and physics program
Direct mass measurements
Cosmic neutrino background
Neutrinos in high energy colliders
…


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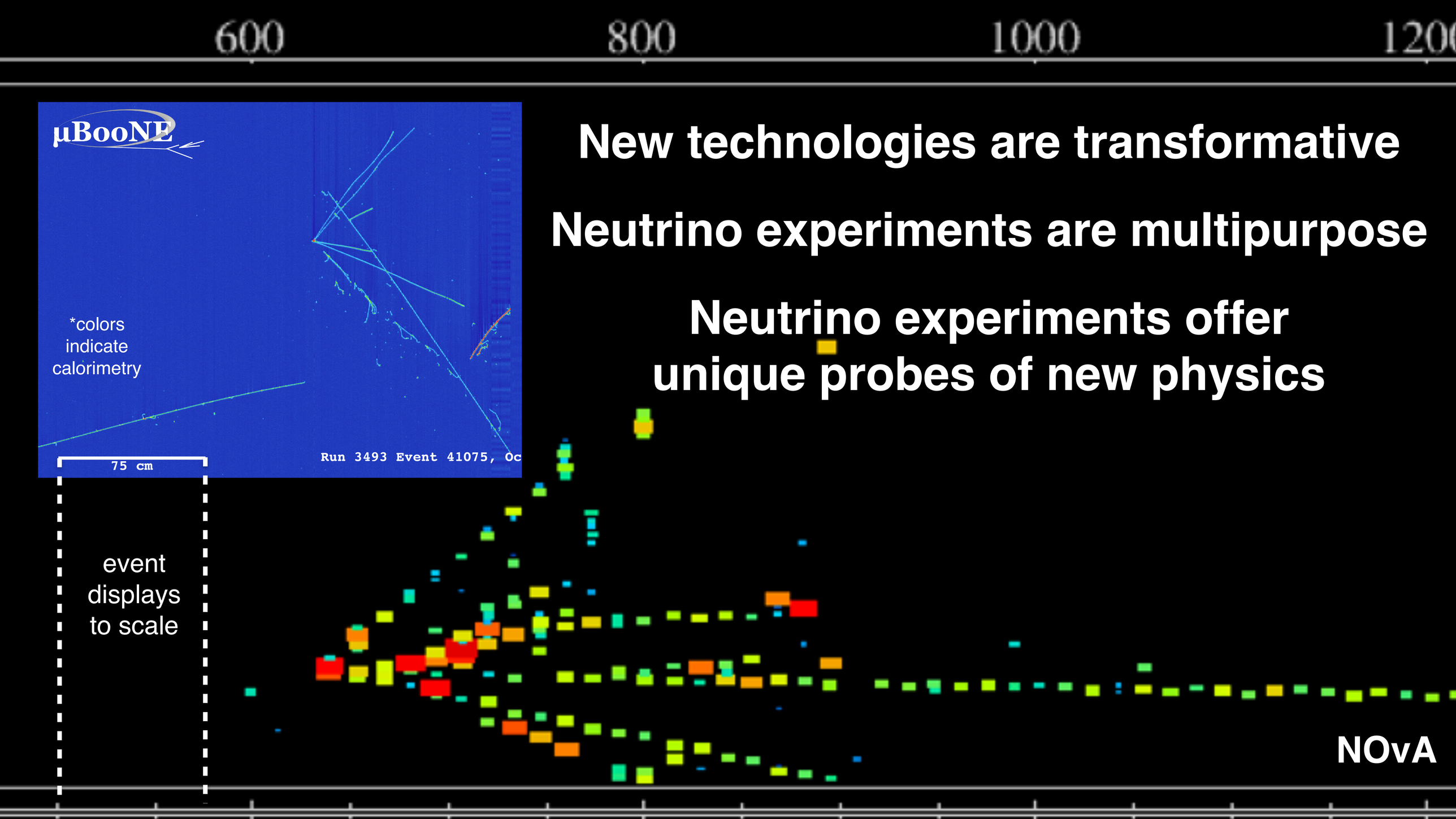


**New technologies are transformative**

**Neutrino experiments are multipurpose**

**Neutrino experiments offer unique probes of new physics**

# Near detector physics

Neutrino detectors are made to detect weakly coupled physics, including neutrinos.

There is a variety of physics that can be probed in near detectors,
such as the DUNE-ND or the Short Baseline Program,
which could help us answer the outstanding questions of the standard model.

| | |
|---|---|
| Light dark matter | Nature of dark matter |
| Axions | Strong CP, existence of PNGBs |
| Heavy neutral leptons | Mechanism of neutrino masses |
| Millicharged particles | Quantization of charge |
| Neutrino tridents | Precision physics |
| Dark photons | Existence of dark sectors |
| Light scalars | Existence of dark sectors |
| Dark neutrinos | Mechanism of neutrino masses |
| … | … |


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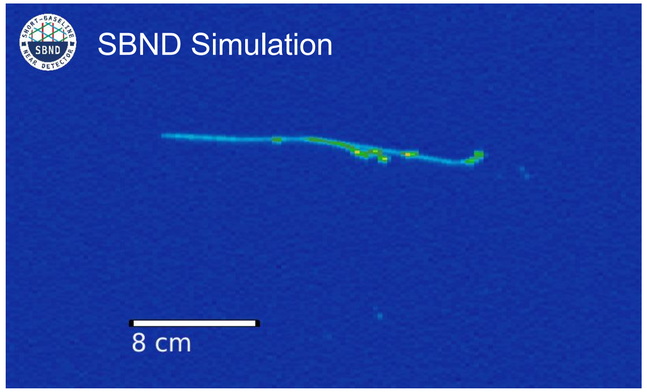
# Near detector physics

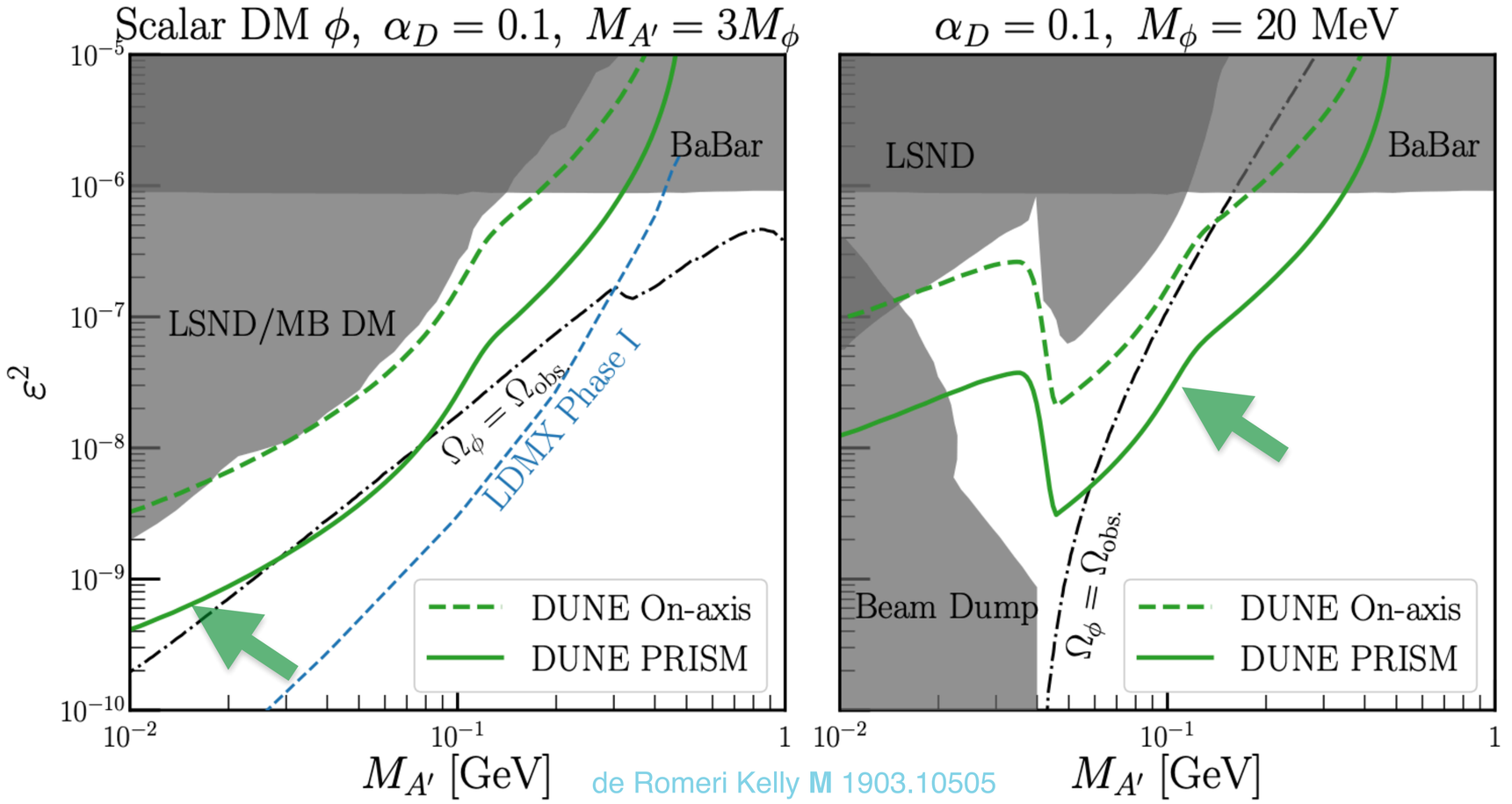
Light Dark Matter




nade to detect weakly coupled physics, including neutrinos.

ty of physics that can be probed in near detectors

**Light dark matter**
Axions
Heavy neutral leptons
Millicharged particles
Neutrino tridents
Dark photons
Light scalars
Dark neutrinos
…




de Romeri Kelly **M** 1903.10505



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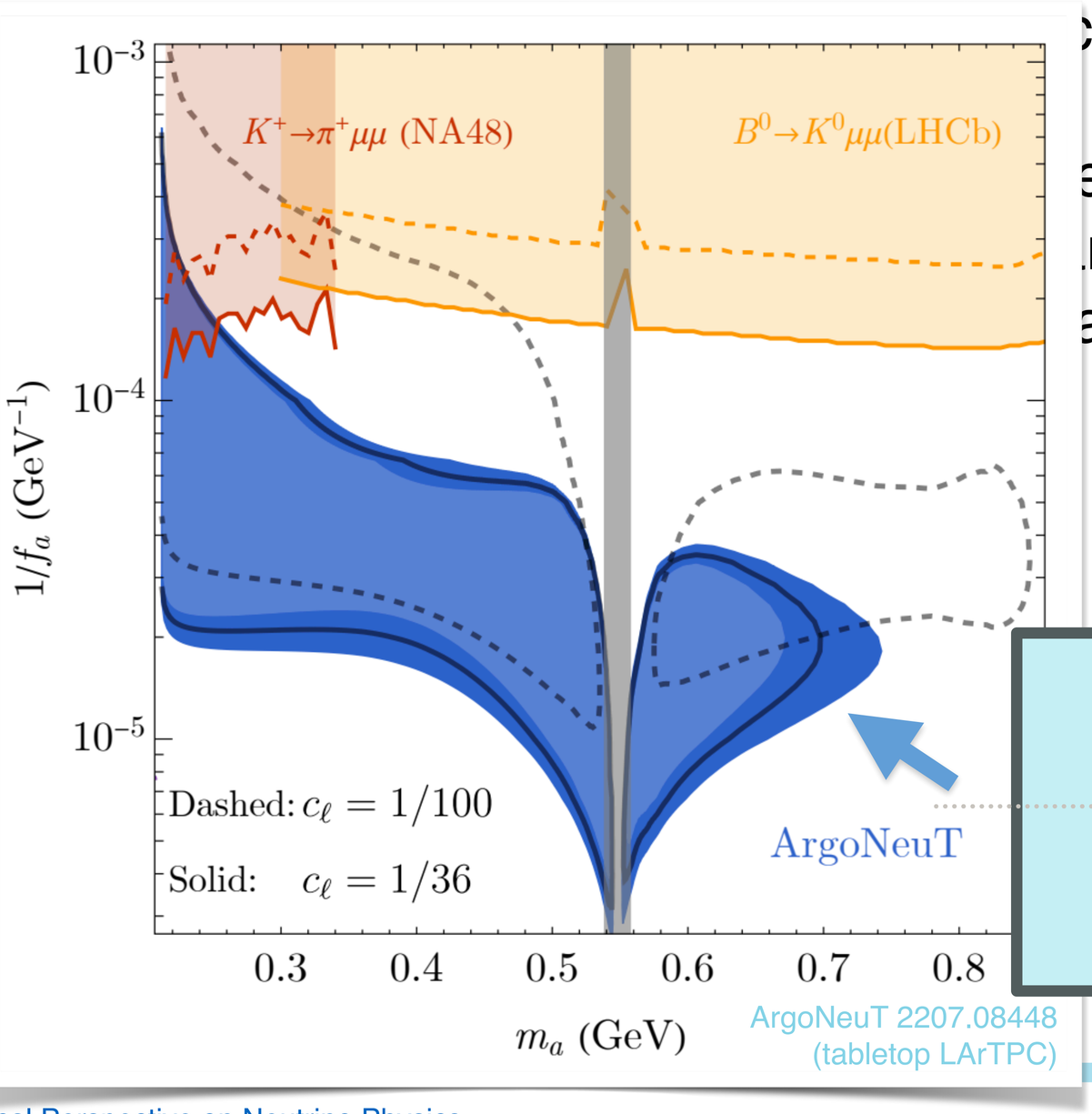
# Near detector physics

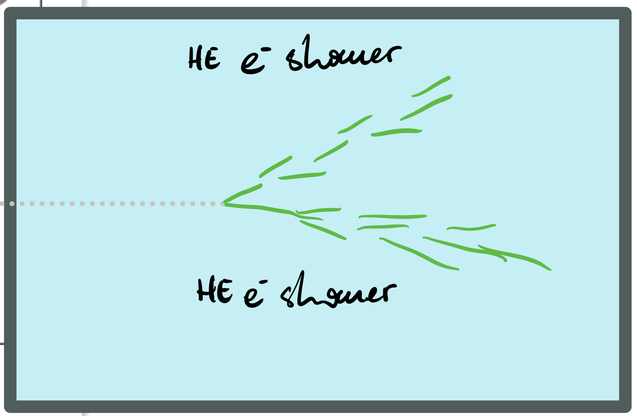
Neutrino detectors are ma cluding neutrinos.

There is a variety etectors,
such as the m,
which could help us ar andard model.

Light dark matter
**Axions**
Heavy neutral leptons
Millicharged particles
Neutrino tridents
Dark photons
Light scalars
Dark neutrinos
…




ArgoNeuT 2207.08448
(tabletop LArTPC)

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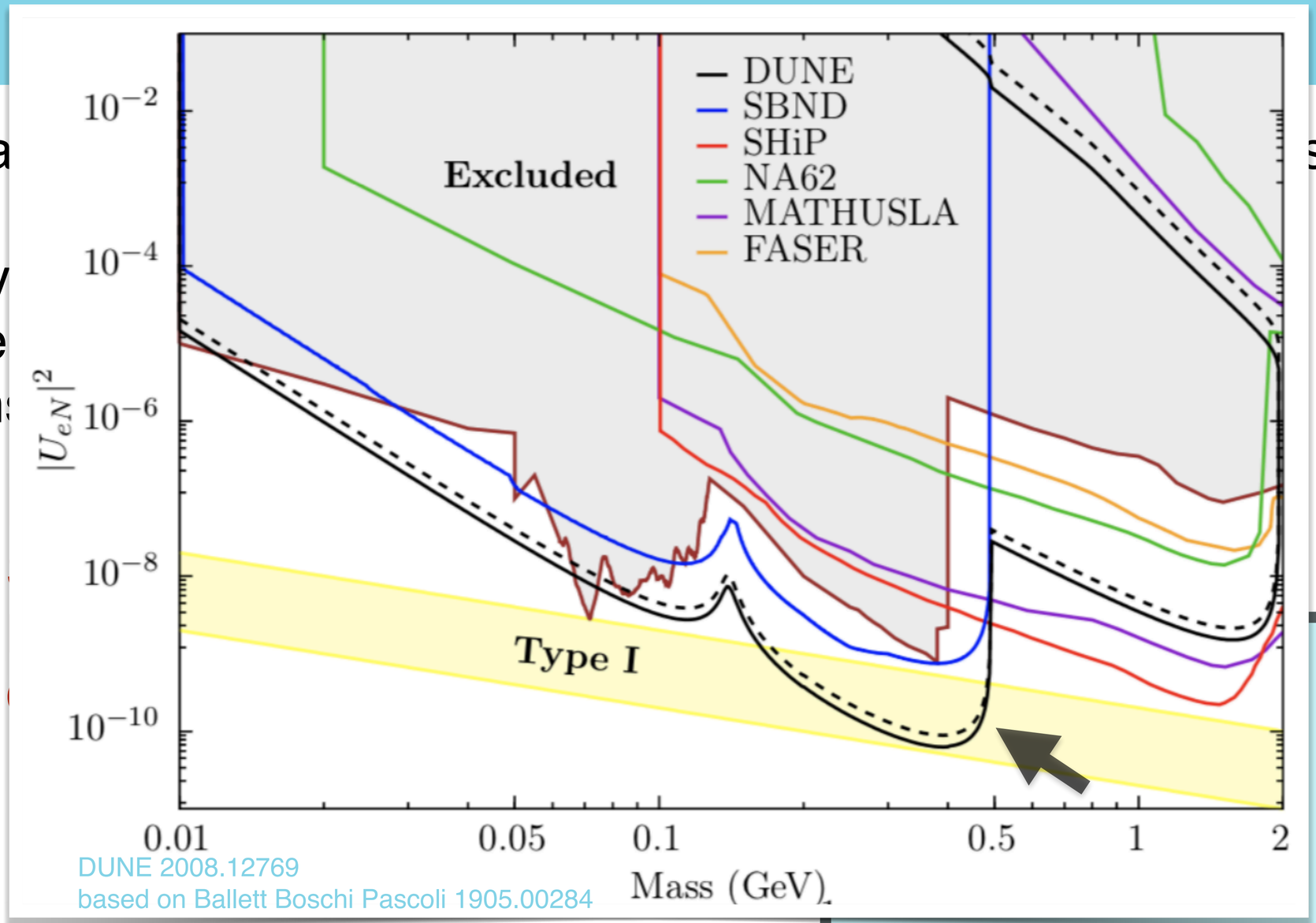
Neutrino detectors are ma s.

There is a variety
such as the
which could help us an

Light dark matter
Axions
**Heavy neutral leptons**
Millicharged particles
Neutrino tridents
Dark photons
Light scalars
Dark neutrinos
… …




DUNE 2008.12769
based on Ballett Boschi Pascoli 1905.00284

Mechanism of neutrino masses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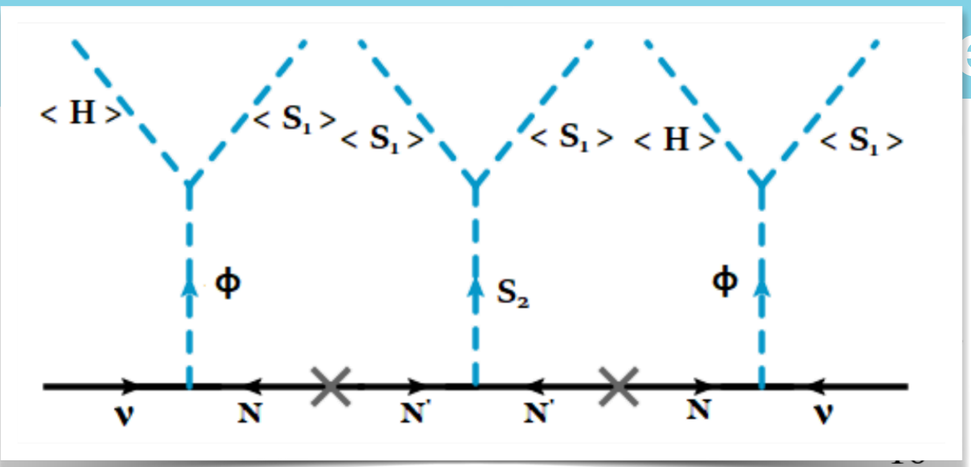
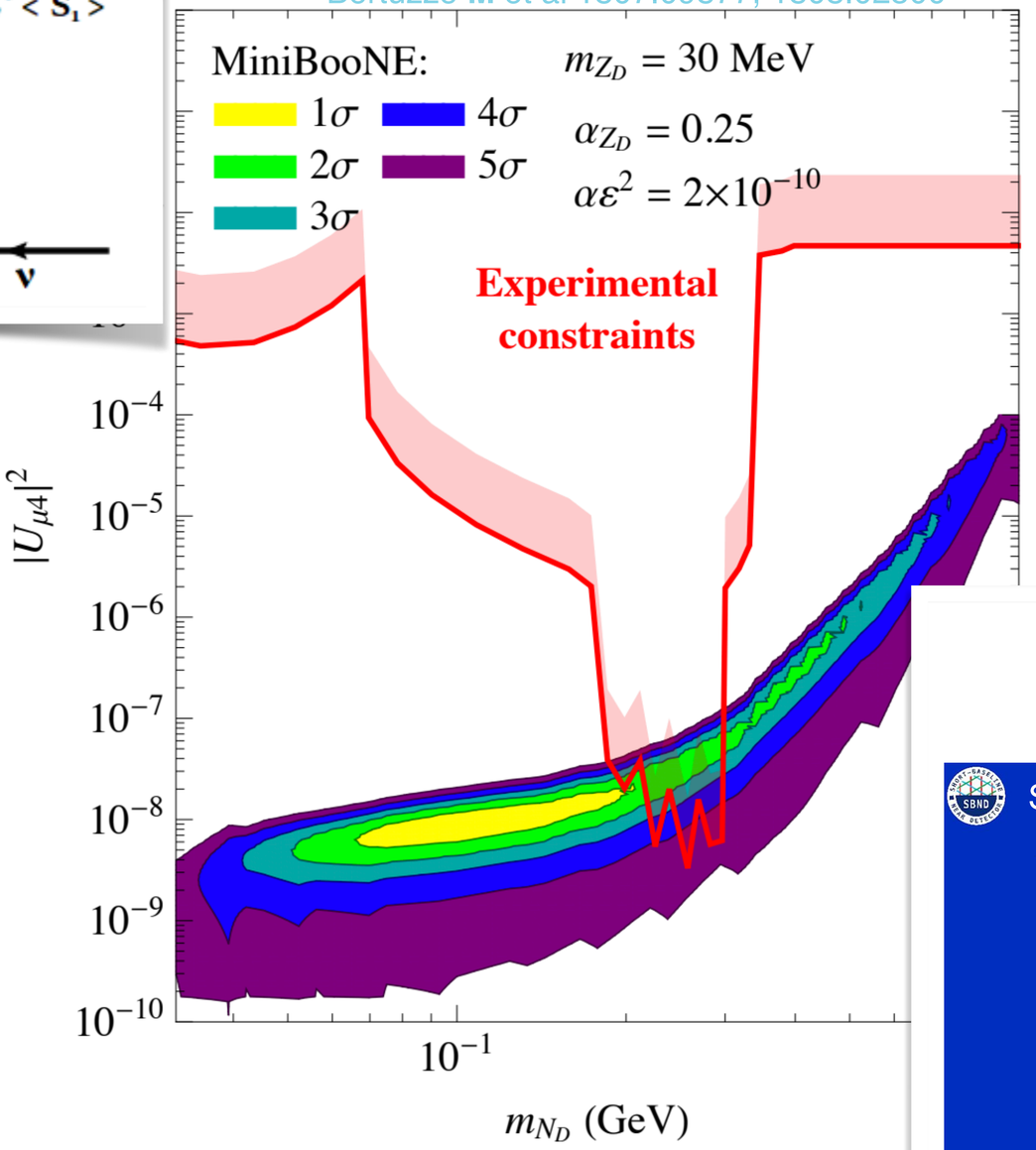
# ear detector physics

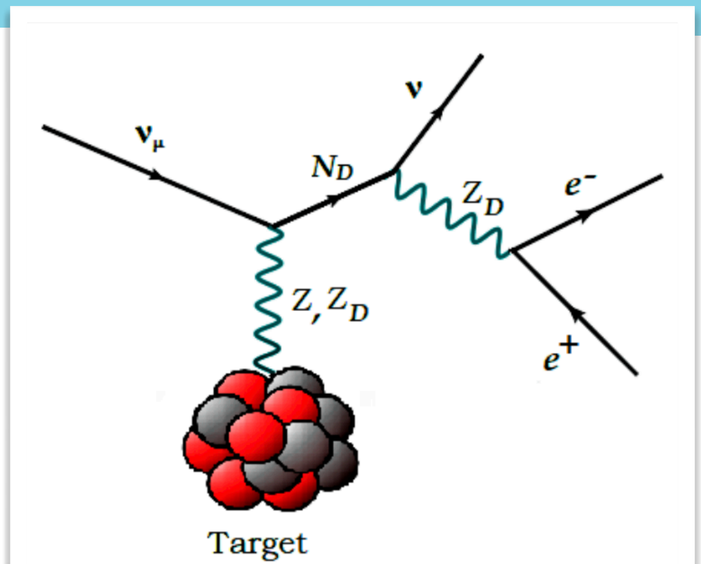



which could help us a

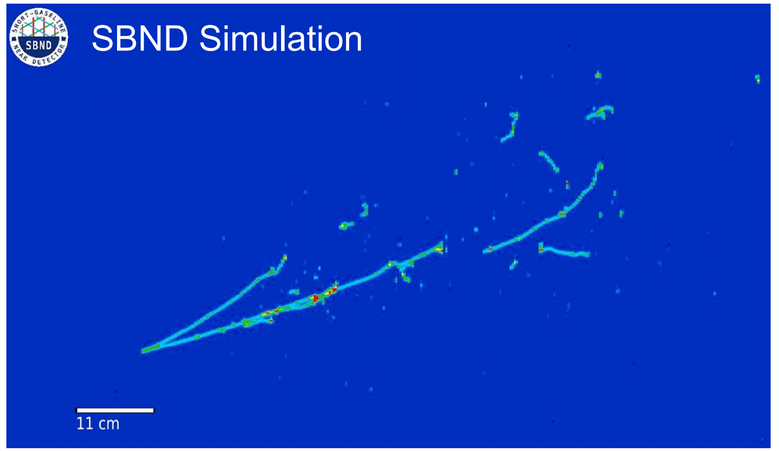
- Light dark matter
- Axions
- Heavy neutral leptons
- Millicharged particles
- Neutrino tridents
- Dark photons
- Light scalars
- **Dark neutrinos**
- …

Bertuzzo M et al 1807.09877, 1808.02500



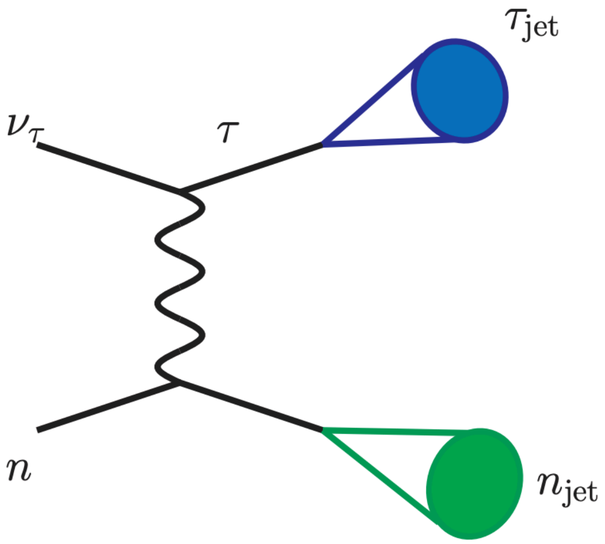

## Dark Neutrinos

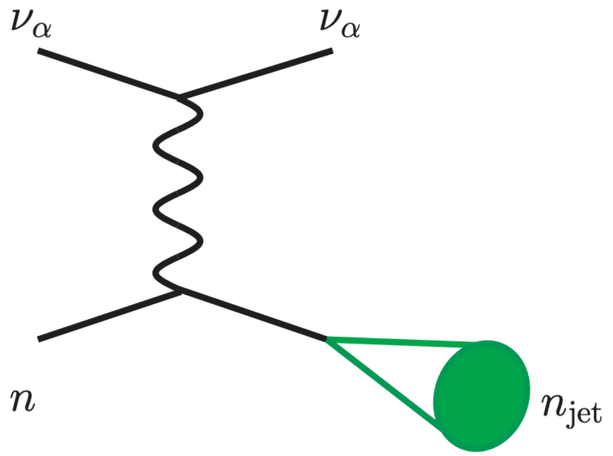


# Far detector physics

Far detectors on the other hand are gigantic, but far from the beam.
The weakly coupled physics they probe is either non-beam related or neutrino-related

| | |
|---|---|
| $p^+$ decay and n-nbar osc. | Unification of forces |
| Supernova dynamics | Astrophysics in extreme environments |
| Ultralight scalar fields | Dark matter |
| New interactions | Neutrino portal to new physics |
| Precision neutrino physics | Consistency of the standard model |
| … | … |



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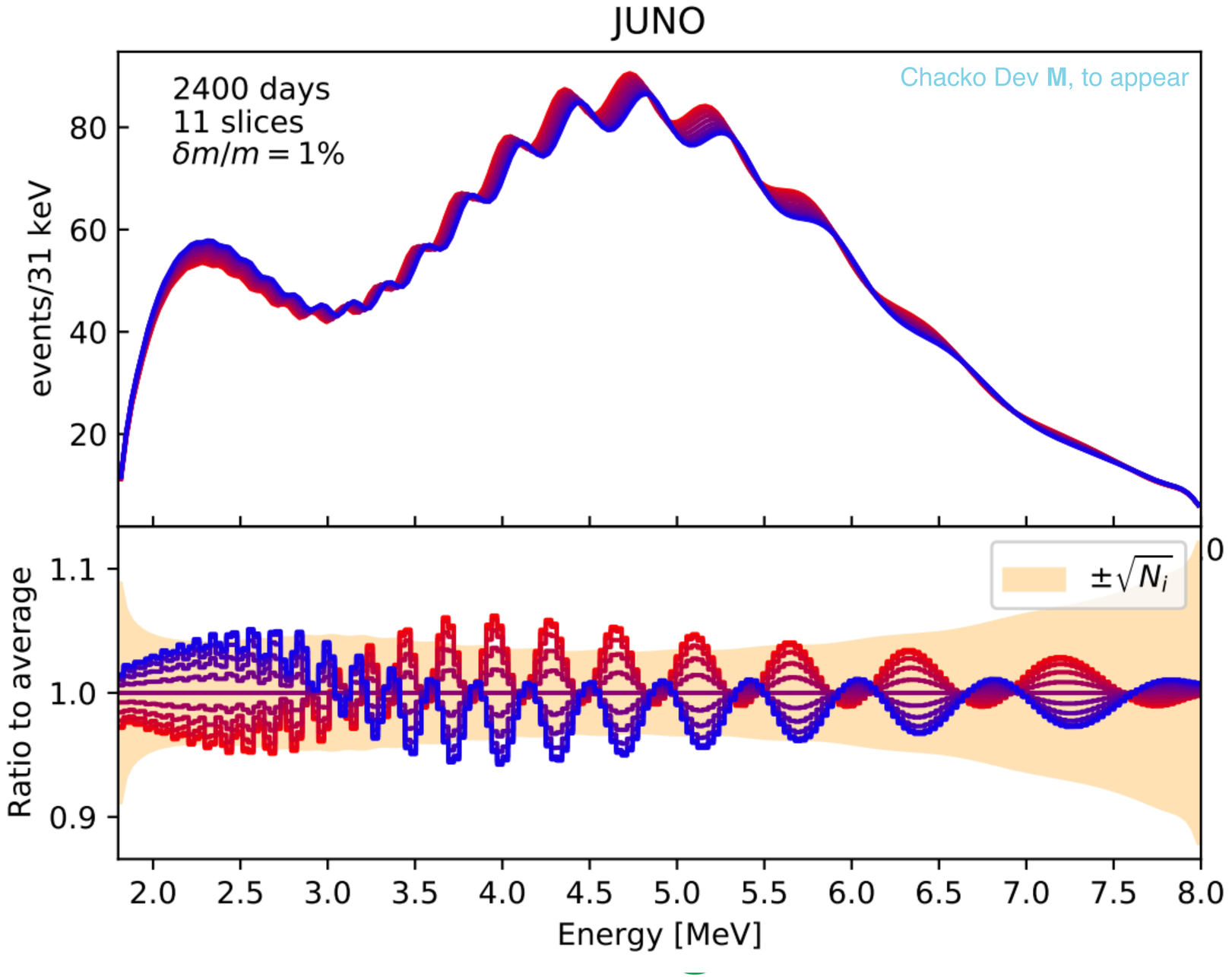
# Far detector physics

Far detectors on the
The weakly coupled physics t

$p^+$ decay and n-nbar osc.
Supernova dynamics
**Ultralight scalar fields**
New interactions
Precision neutrino physics
…

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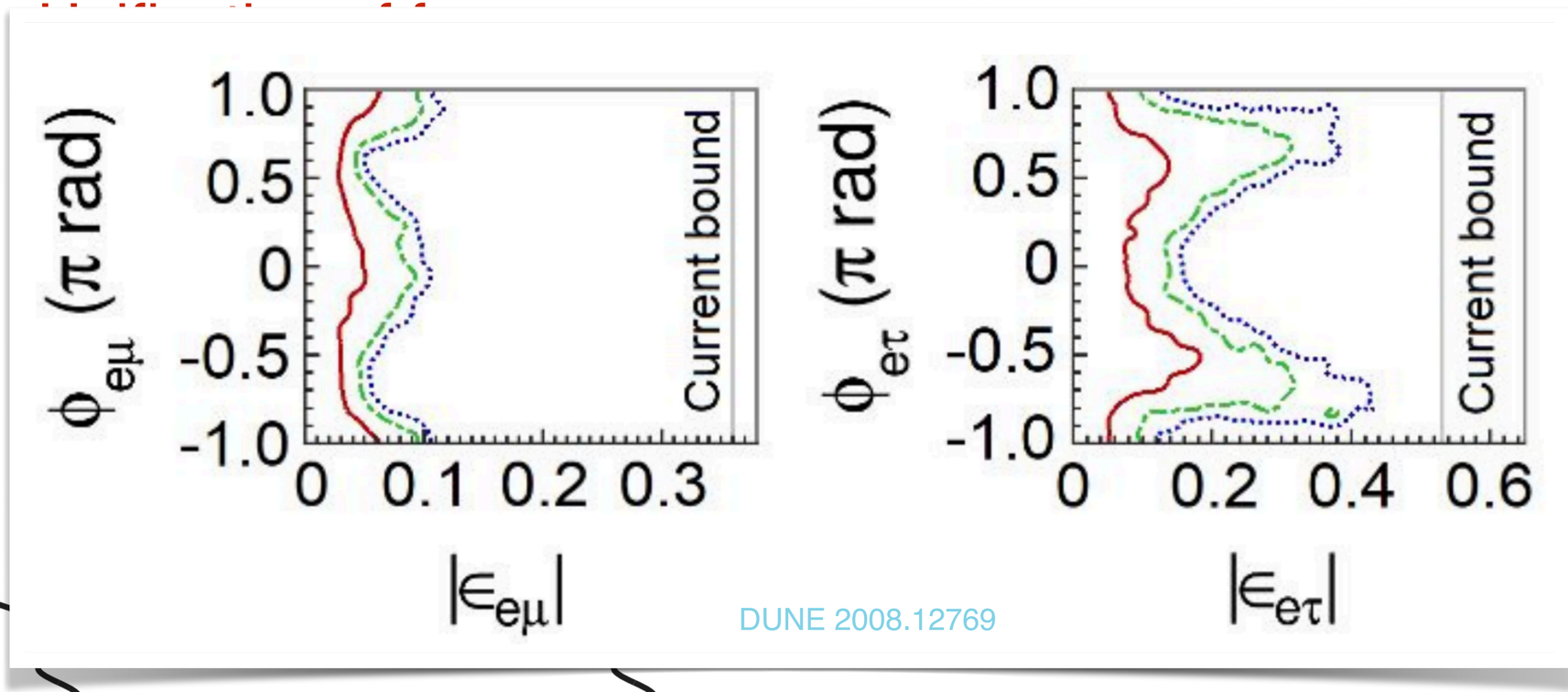
Far detectors on the other hand are gigantic, but far from the beam.
The weakly coupled physics they probe is either non-beam related or neutrino-related

- $p^+$ decay and n-nbar osc.
- Supernova dynamics
- Ultralight scalar fields
- **New interactions**
- Precision neutrino physics
- …

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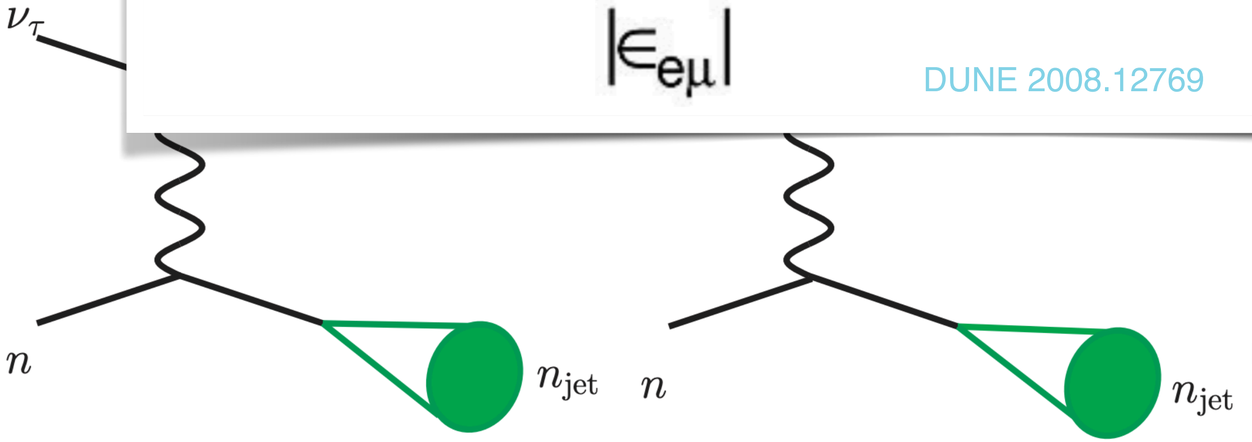







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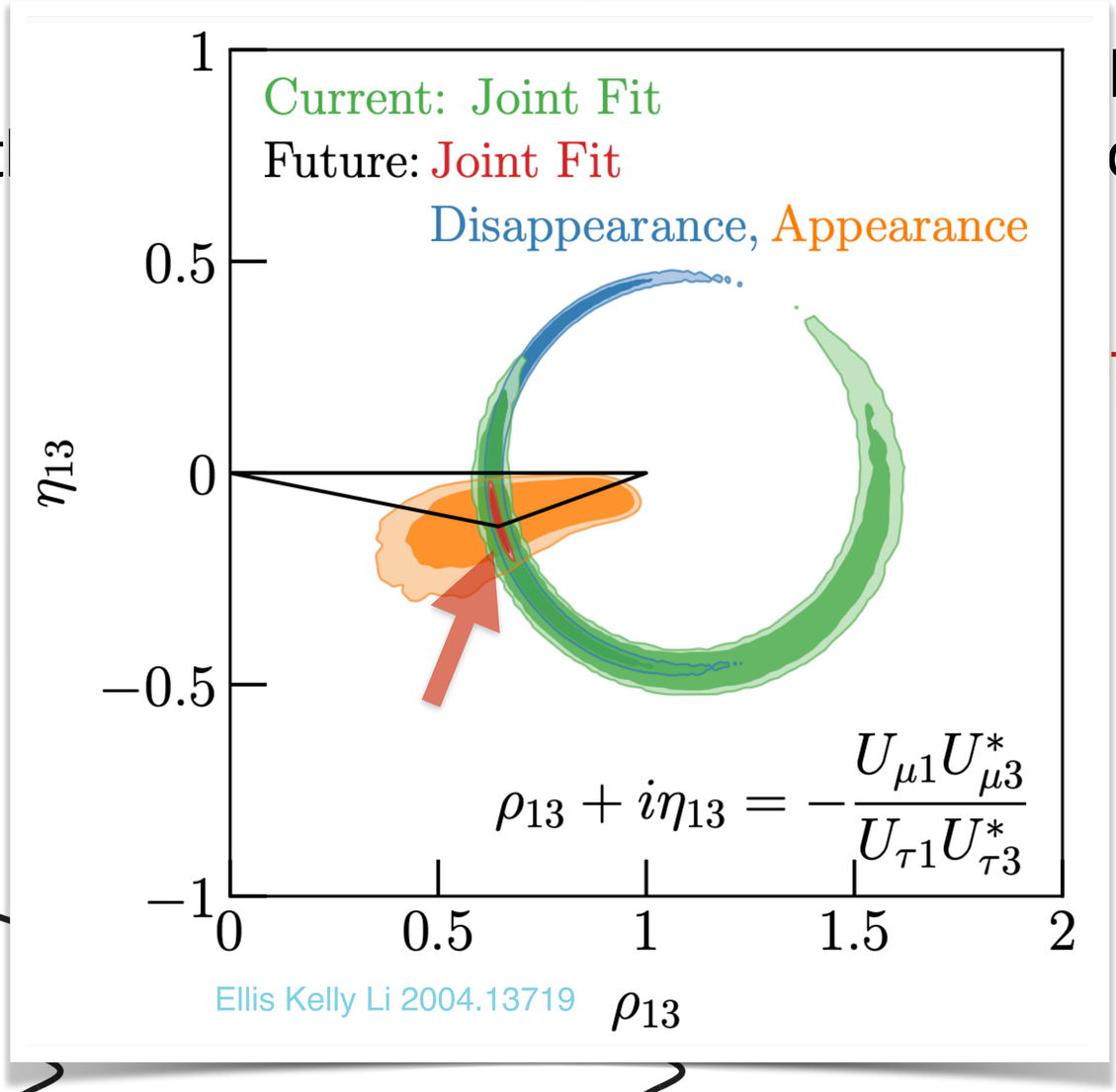
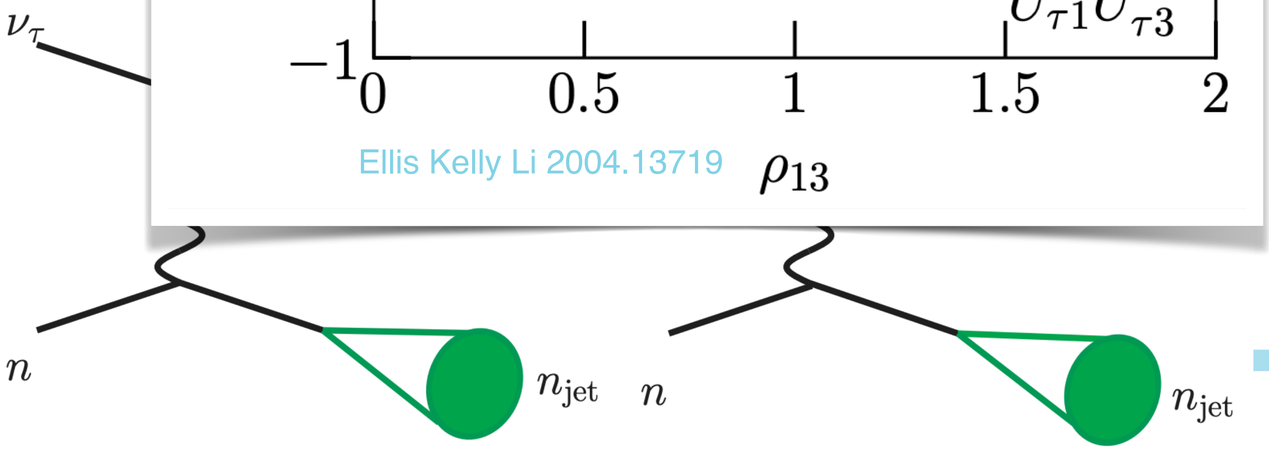
# Far detector physics

Far detectors on the [illegible] he beam.
The weakly coupled physics t[illegible] or neutrino-related [illegible]ts

- $p^+$ decay and n-nbar osc.
- Supernova dynamics
- Ultralight scalar fields
- New interactions
- **Precision neutrino physics**
- …



Ellis Kelly Li 2004.13719





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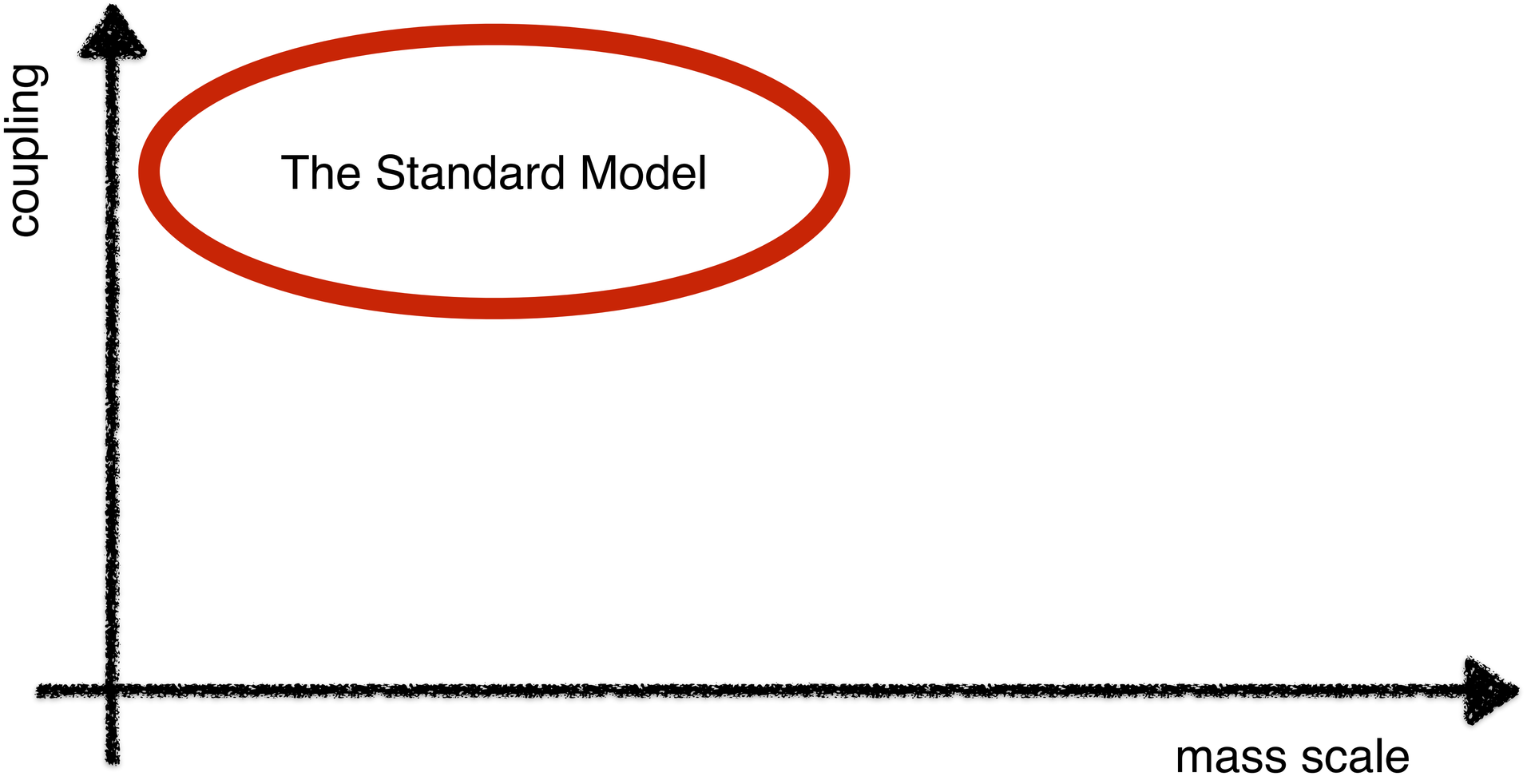
# How do neutrino experiments help probing new physics?





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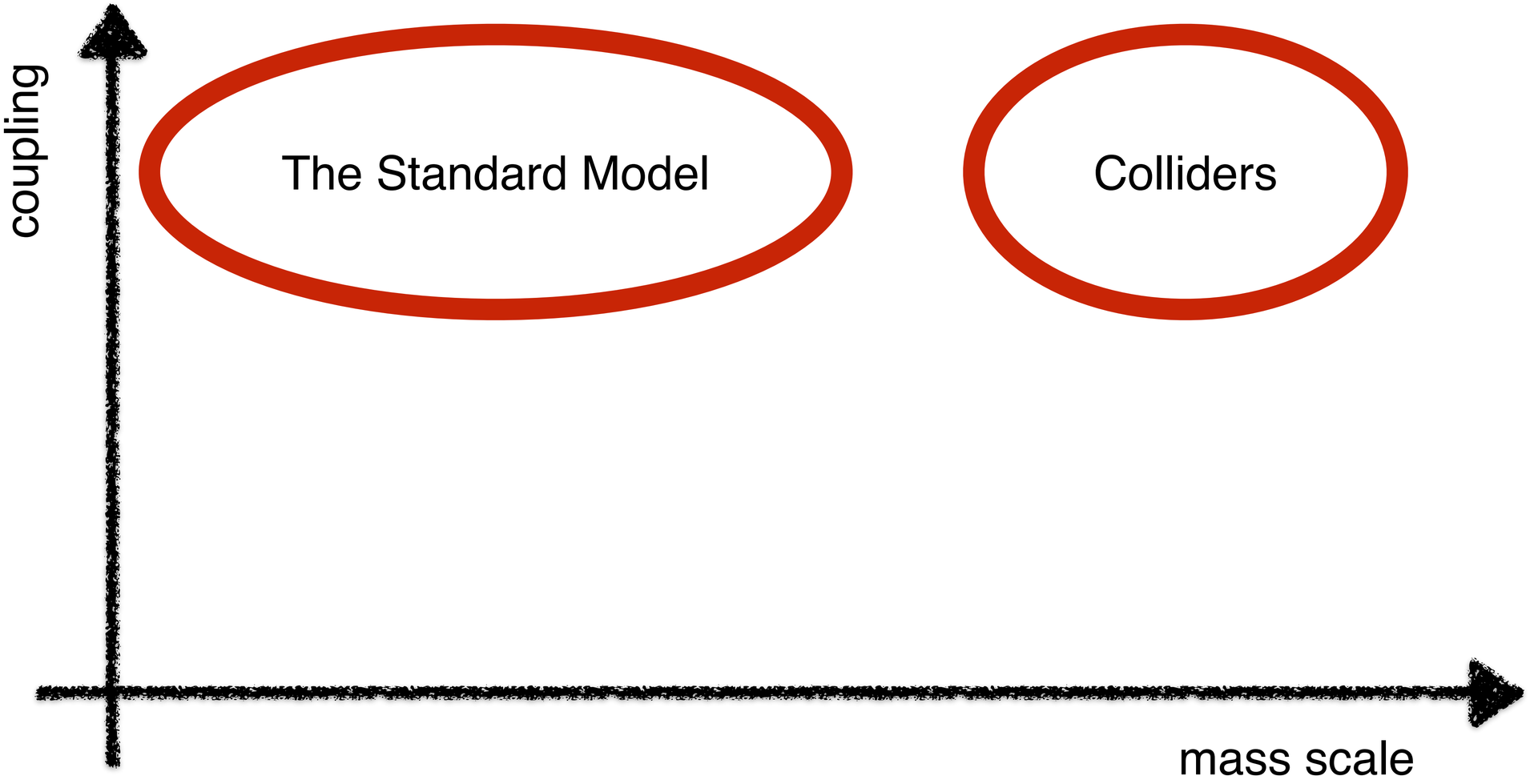



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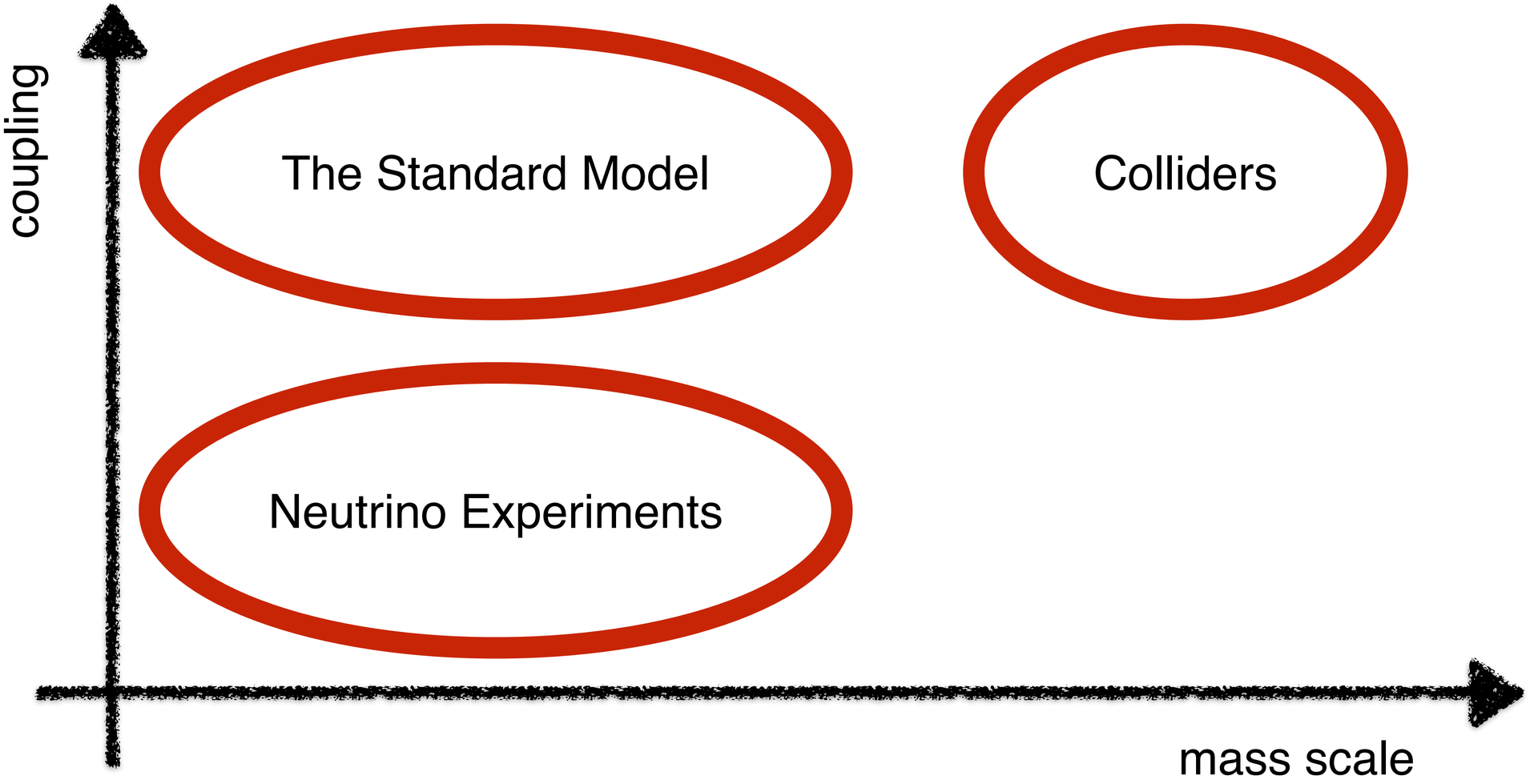



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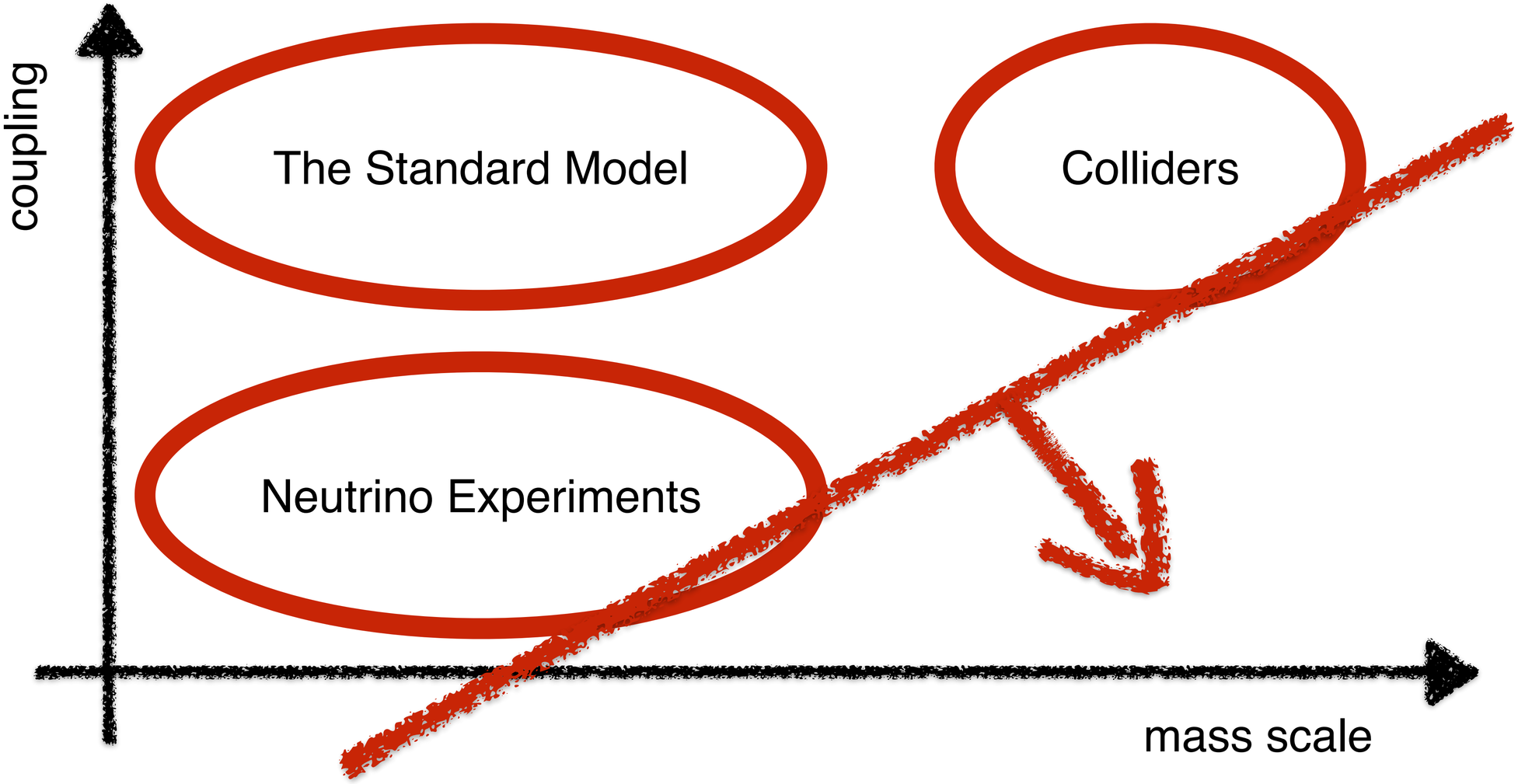



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# Conclusions

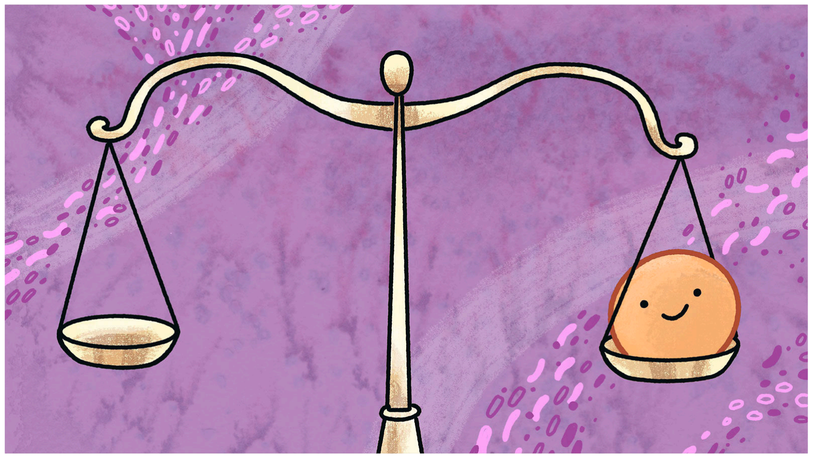
**We do not know where new physics is**

But we know that **there needs to be new physics** that address the outstanding questions of the standard model, in particular the **mechanism of neutrino mass generation**

Neutrino experiments are multipurpose experiments
***neutrino experiments >> neutrinos***

Neutrino physics cut across several traditional areas in physics: from nuclear to cosmo to high energy and beyond

A **precision neutrino physics program** will scrutinize the least known sector of the standard model,
with **broad BSM discovery potential**

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