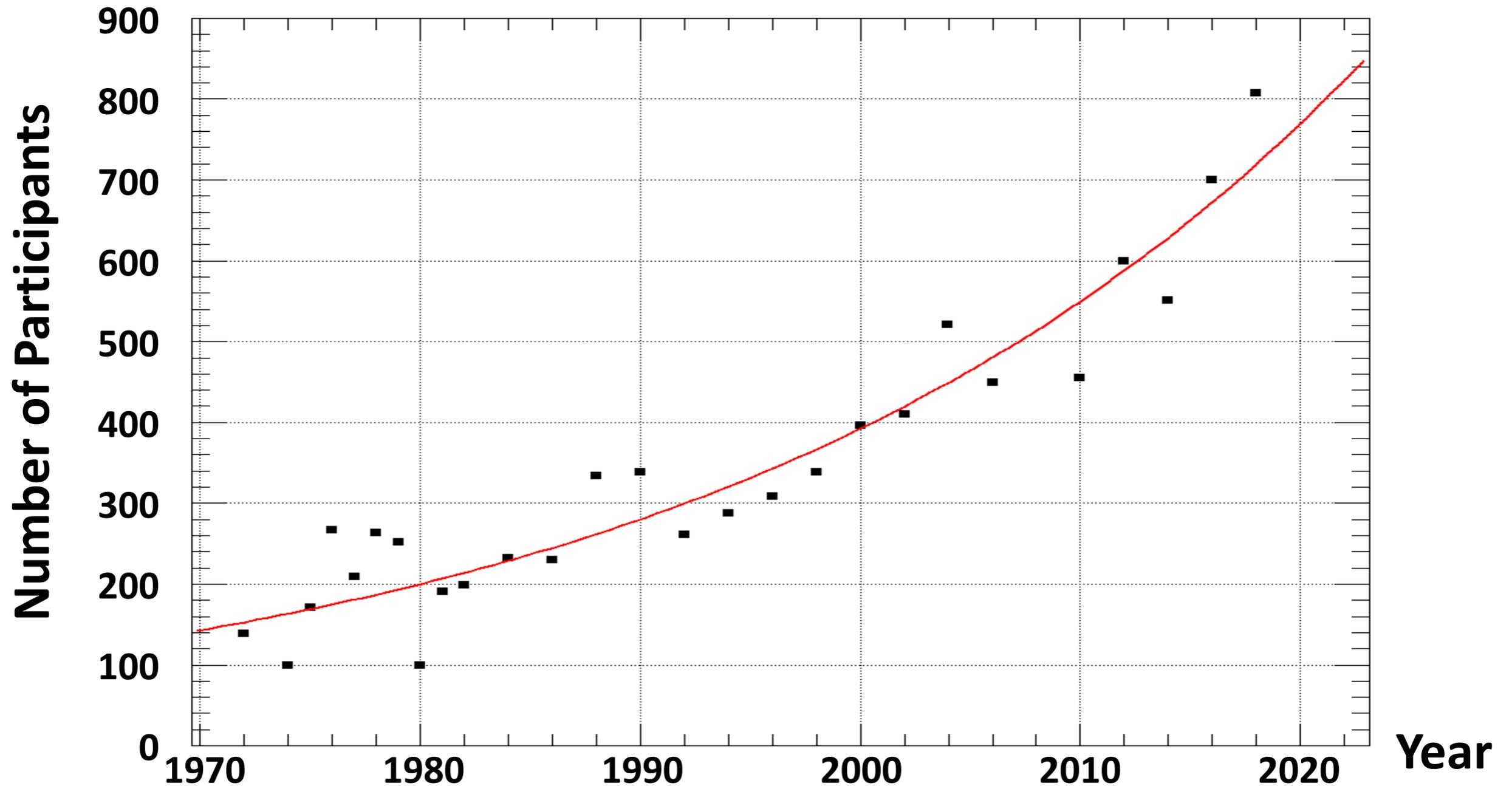


Current Challenges in Neutrino Physics

Joachim Kopp (CERN & JGU Mainz)
Fermilab Neutrino University, June 9, 2022

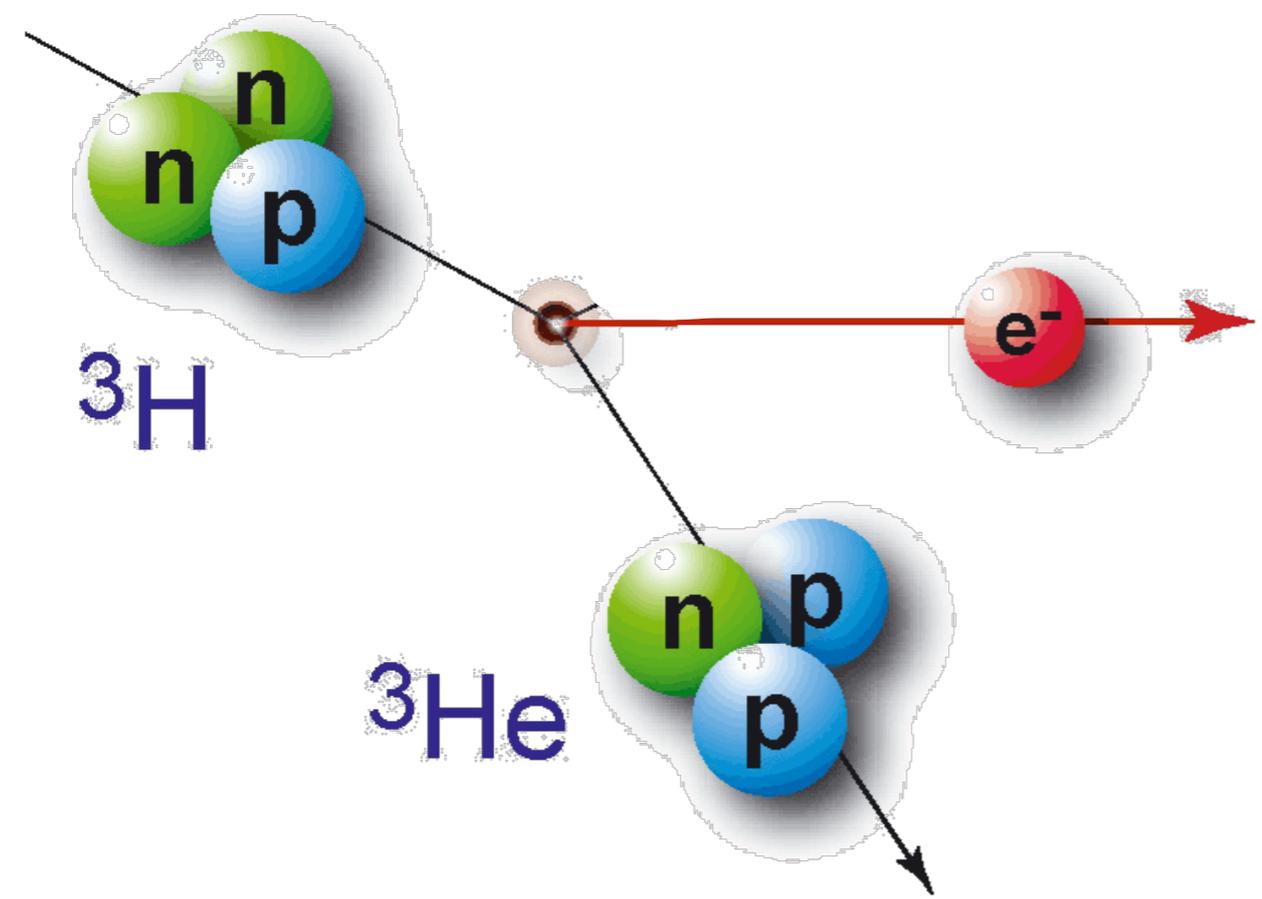


Neutrino Conference Series





Wolfgang Pauli



Original - Photocopy of PLC 0393
Abschrift/15.12.30 PW

Offener Brief an die Gruppe der Radioaktiven bei der
Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst
ansuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich
angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie
des kontinuierlichen beta-Spektrums auf einen verweifelten Ausweg
verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz
zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale
Teilchen, die ich Neutronen nennen will, in den Kernen existieren,
welche den Spin $1/2$ haben und das Ausschliessungsprinzip befolgen und
sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie
nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen
müsste von derselben Grössenordnung wie die Elektronenmasse sein und
jedemfalls nicht grösser als $0,01$ Protonenmasse.- Das kontinuierliche
beta-Spektrum wäre dann verständlich unter der Annahme, dass beim
beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert
wird, derart, dass die Summe der Energien von Neutron und Elektron
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Nun handelt es sich weiter darum, welche Kräfte auf die
Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint
mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer
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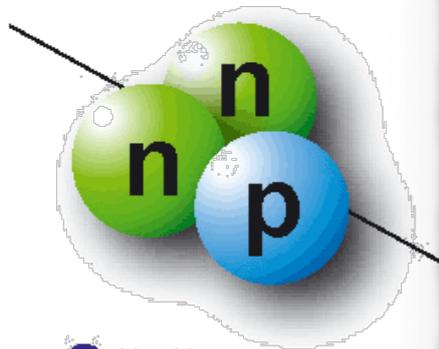
Ich traue mich vorläufig aber nicht, etwas über diese Idee
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Radioaktive, mit der Frage, wie es um den experimentellen Nachweis
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Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat:
"O, daran soll man am besten gar nicht denken, sowie an die neuen
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Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht
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ges. W. Pauli



Wolfgang Pauli



3H

3H

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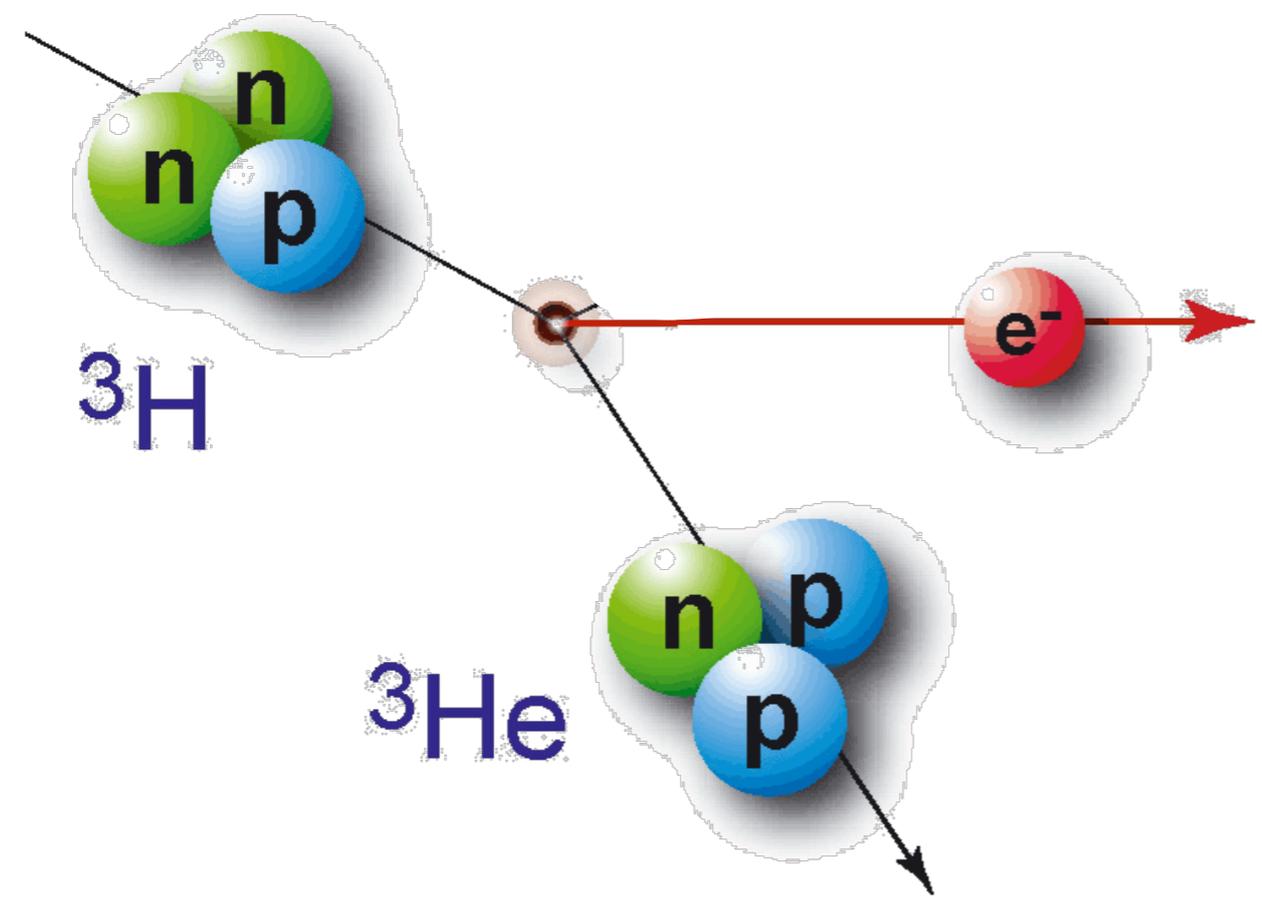
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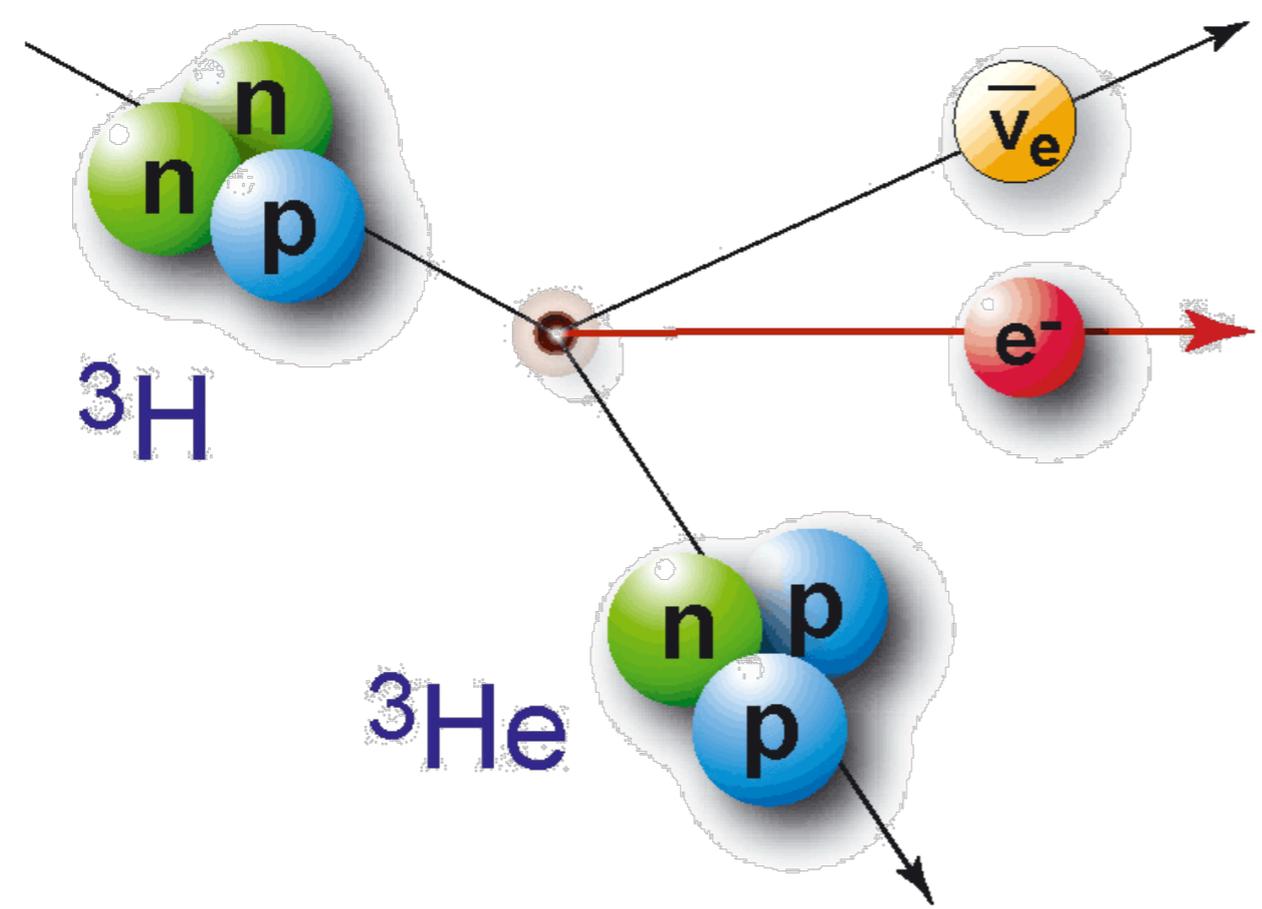


Wolfgang Pauli

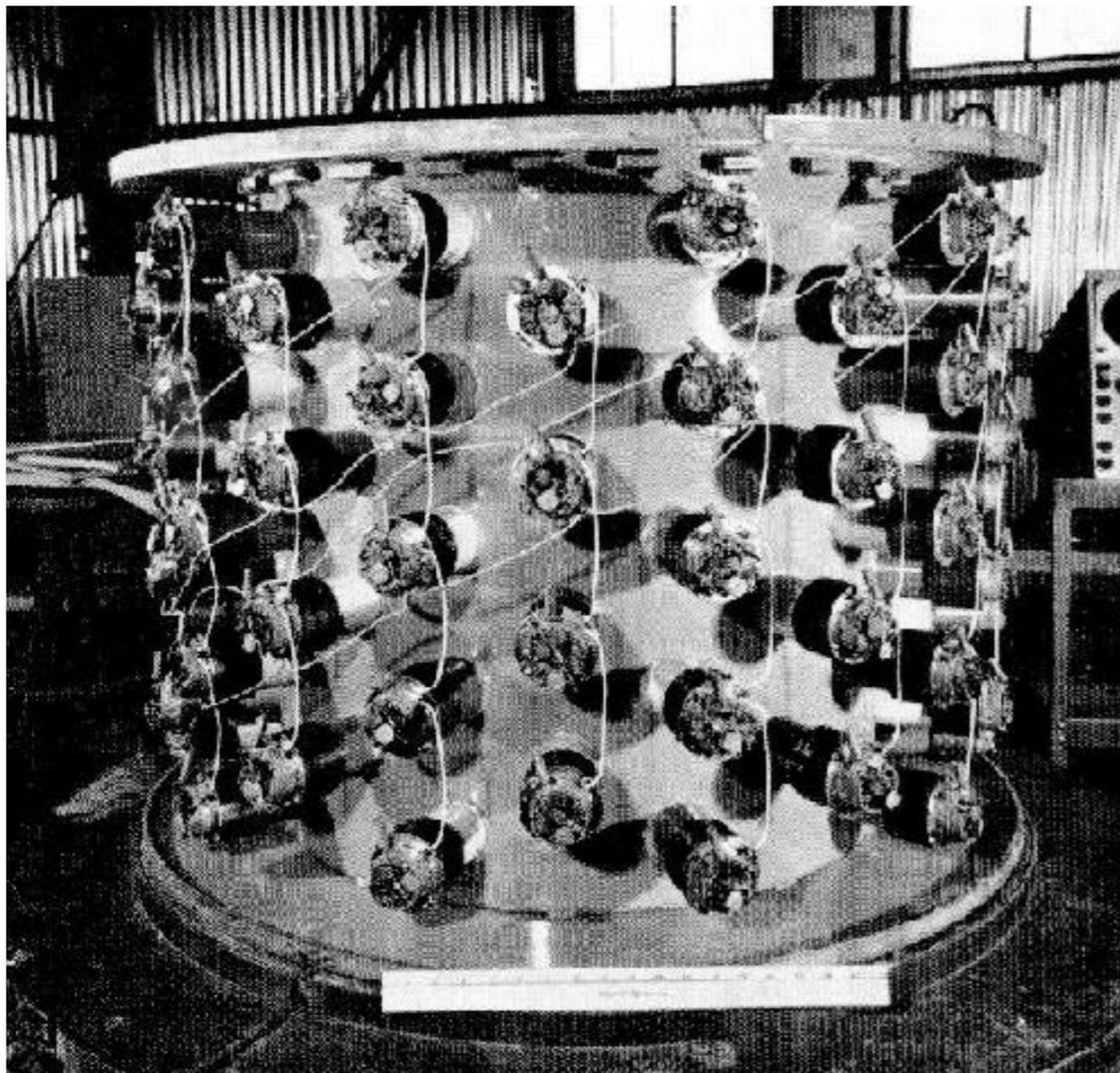




Wolfgang Pauli



First Detection of Neutrinos

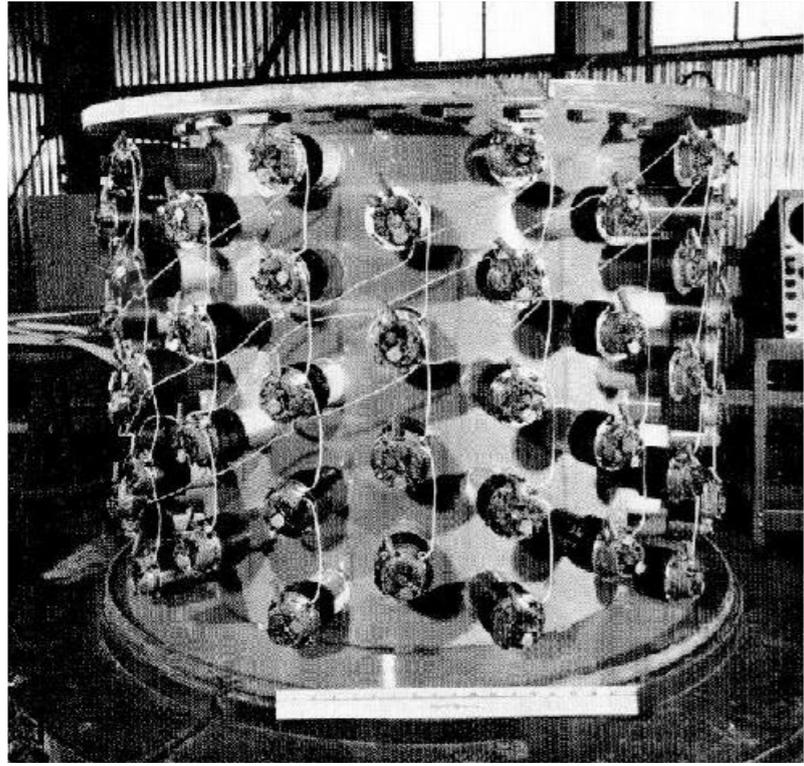


Poltergeist (1956)

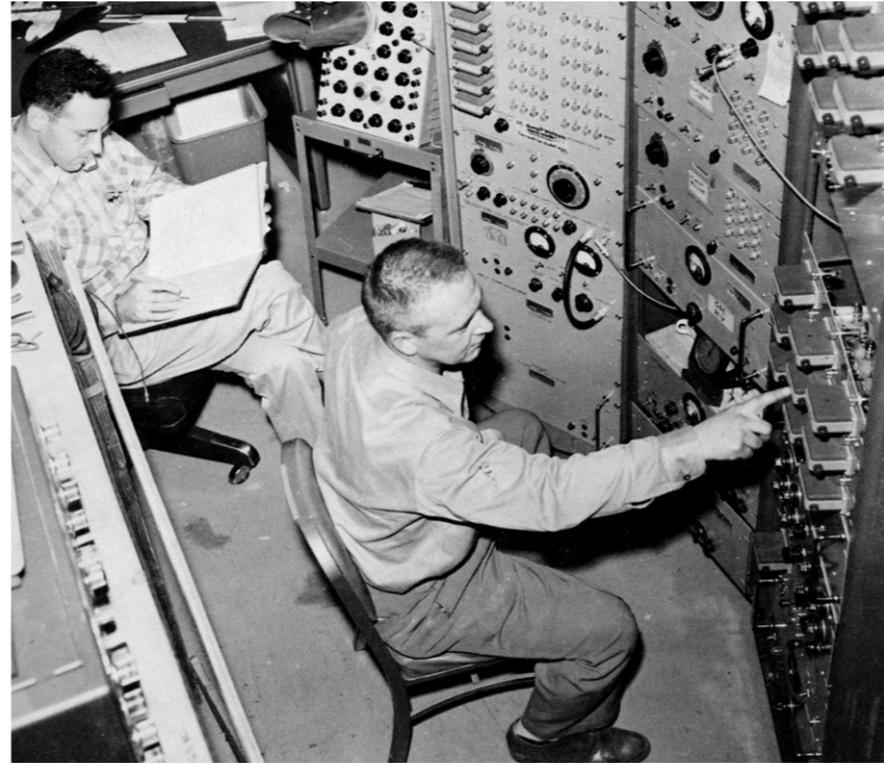


Fred Reines, Clyde Cowan

First Detection of Neutrinos

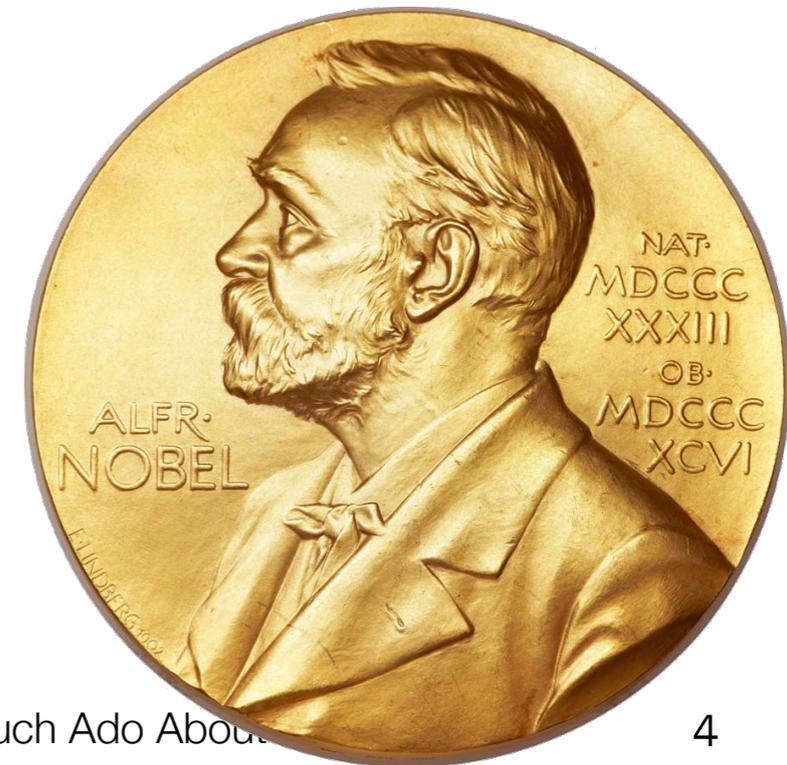


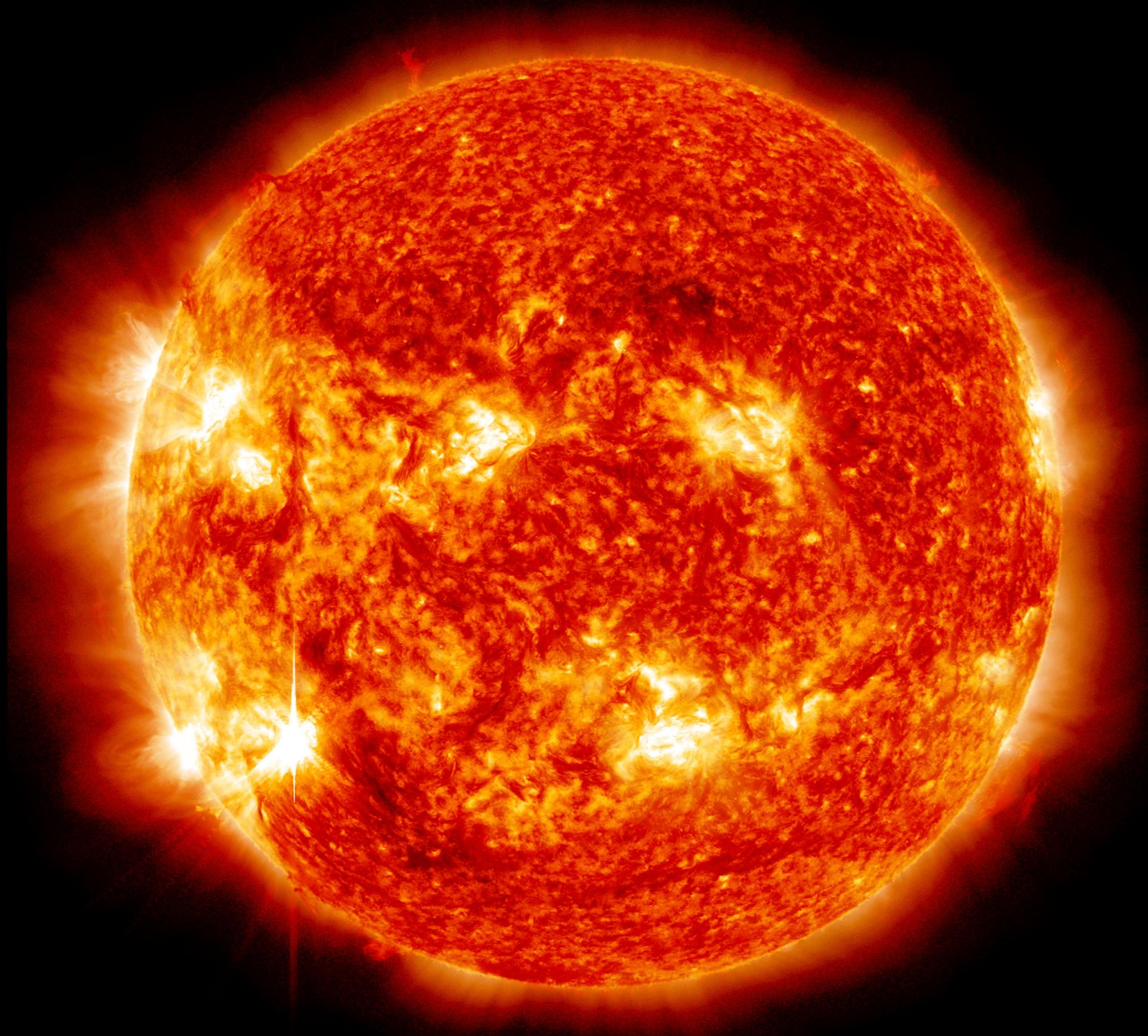
Poltergeist (1956)



Fred Reines, Clyde Cowan

Nobel Prize in Physics 1995
“for the detection of the neutrino”





Homestake Neutrino Experiment

Raymond Davis

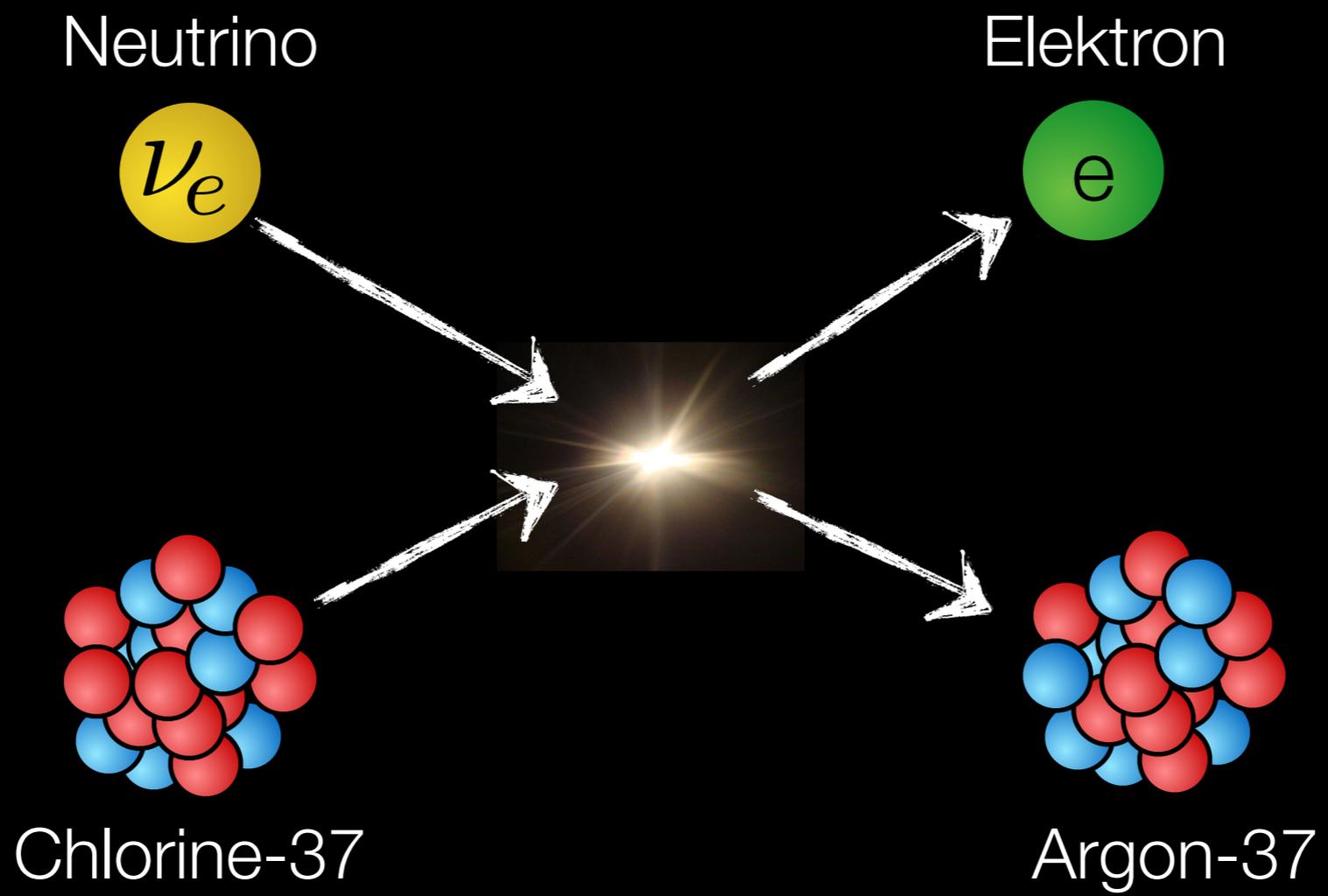


Homestake Neutrino Experiment

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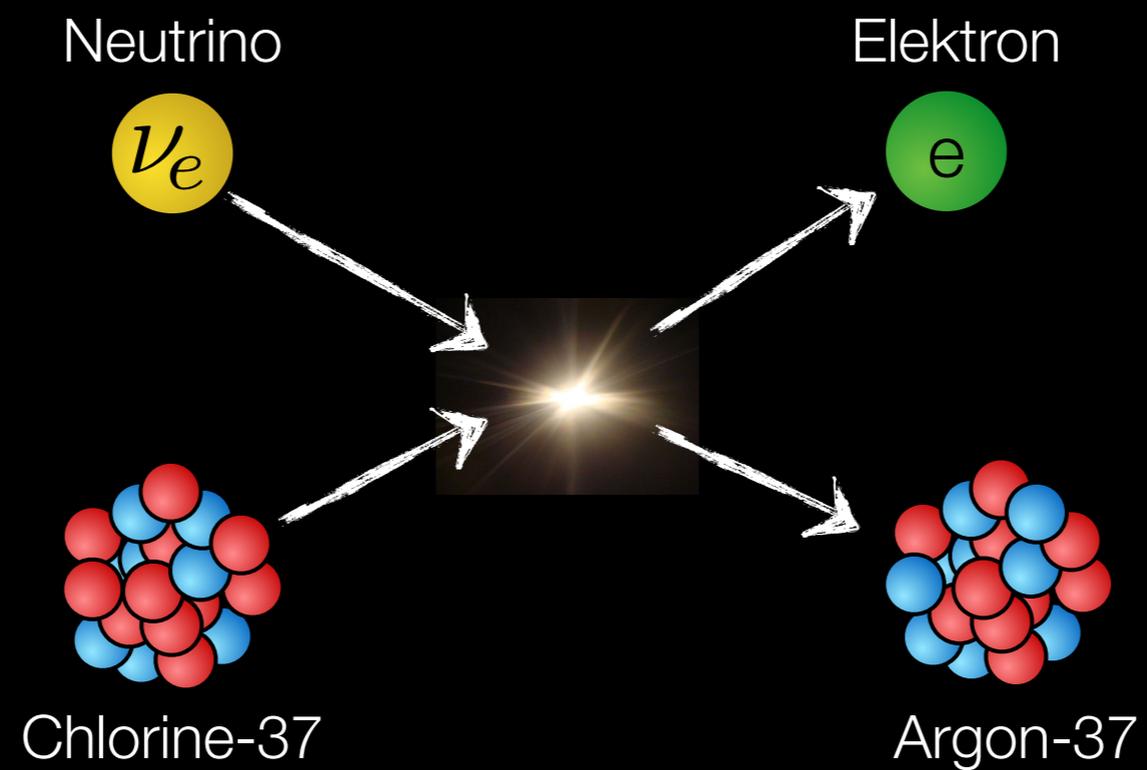
Nobel Prize in Physics 2002
“for pioneering contributions
to astrophysics,
in particular for the detection
of cosmic neutrinos”







Ray Davis

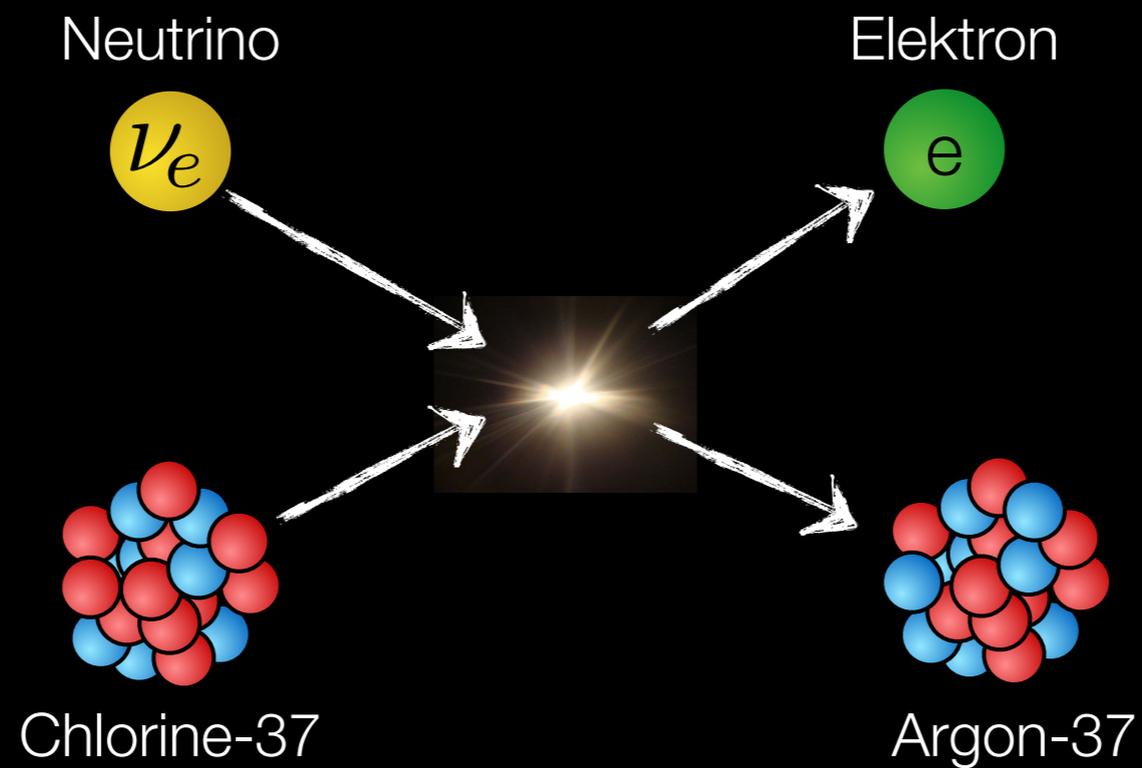




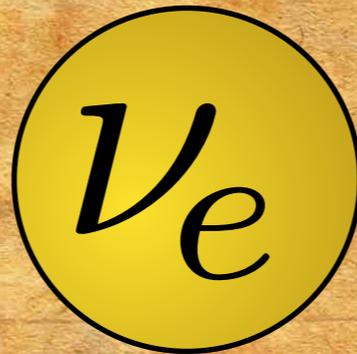
John Bahcall



Ray Davis



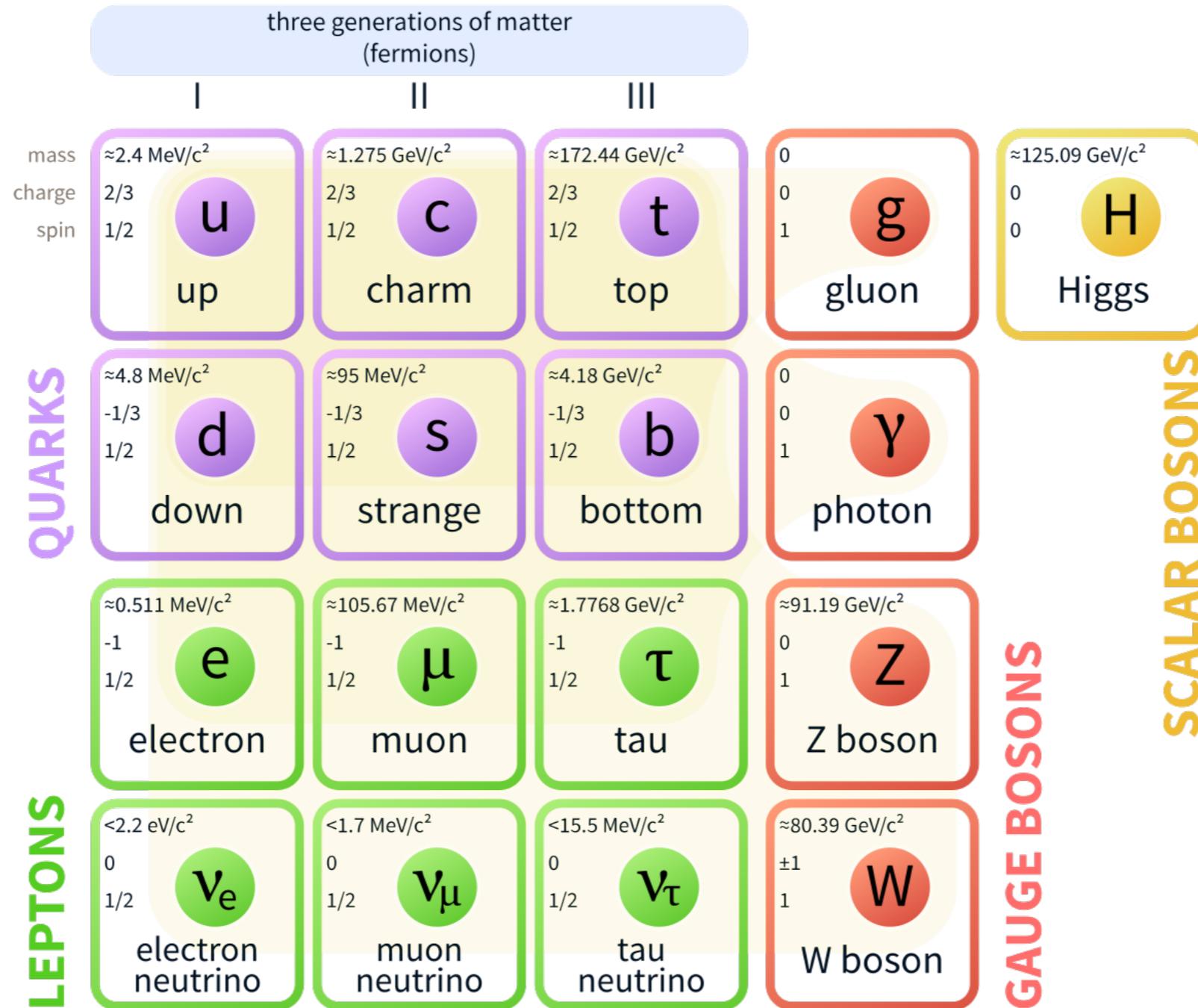
WANTED



**THE MISSING
NEUTRINOS**

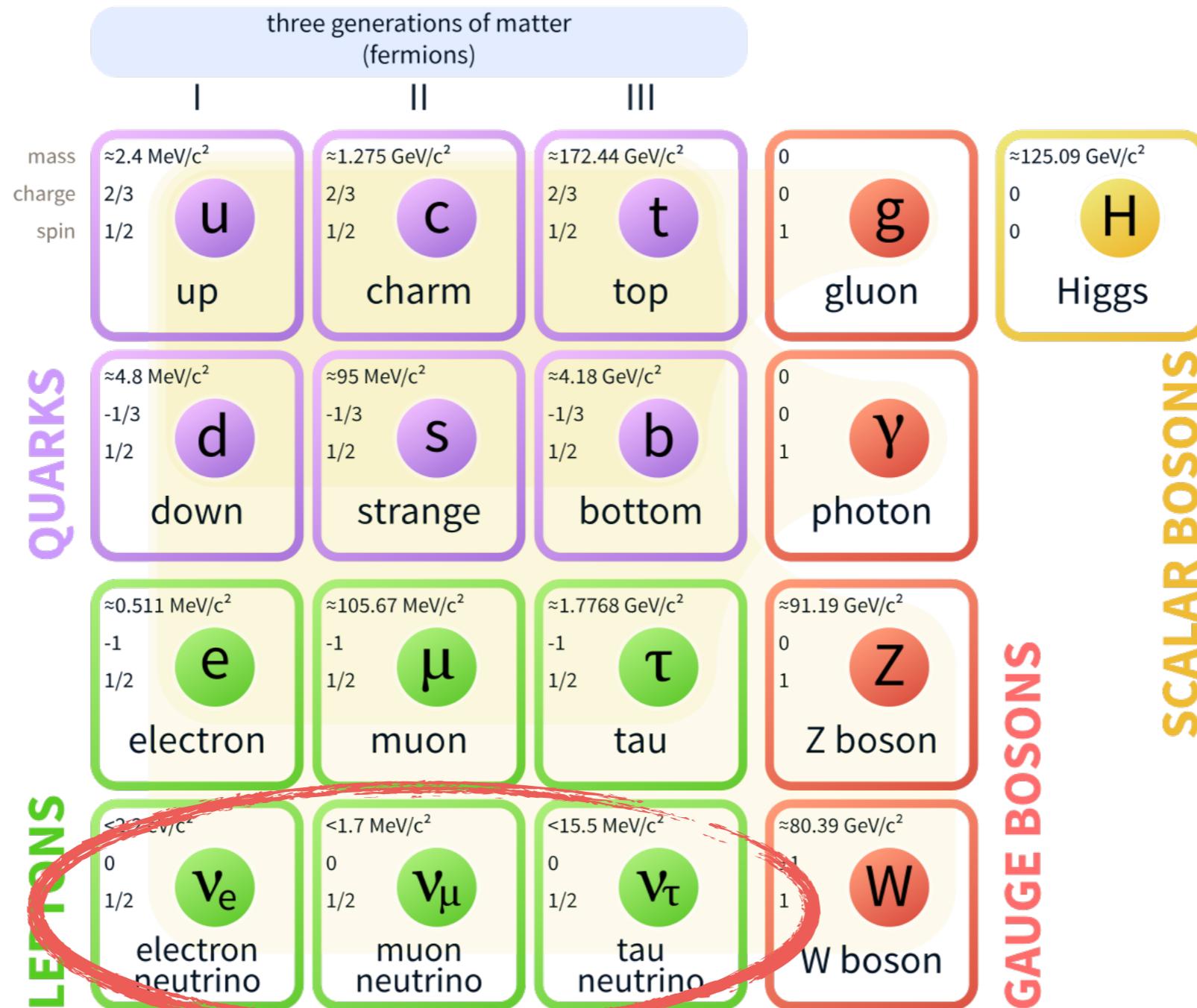
Particle Physicist's View of Neutrinos

Standard Model of Elementary Particles



Particle Physicist's View of Neutrinos

Standard Model of Elementary Particles



Neutrino Mixing

$$|\nu_\alpha\rangle = \sum_j U_{\alpha j}^* |\nu_j\rangle$$

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Flavor Eigenstate
(well-defined coupling)

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Flavor Eigenstate
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$$|\nu_\alpha\rangle = \sum_j U_{\alpha j}^* \nu_j$$

Mass Eigenstate
(well-defined energy)

Mixing Matrix
(3x3, unitary)

Neutrino Mixing

The diagram shows the equation $|\nu_\alpha\rangle = \sum_j U_{\alpha j}^* |\nu_j\rangle$ enclosed in a white box. Red handwritten circles highlight $|\nu_\alpha\rangle$, $U_{\alpha j}^*$, and $|\nu_j\rangle$. Red arrows point from the text labels to these circled terms.

Flavor Eigenstate
(well-defined coupling)

Mass Eigenstate
(well-defined energy)

Mixing Matrix
(3x3, unitary)

- ☑ ν_j run out of phase over time
→ interference patterns (neutrino oscillations)

Neutrino Oscillations

☑ Initial state

$$|\nu_\alpha\rangle = \sum_j U_{\alpha j}^* |\nu_j\rangle$$

☑ Transition probability

$$\begin{aligned} P_{\alpha \rightarrow \beta} &= |\langle \nu_\beta | e^{-i\hat{H}T} | \nu_\alpha \rangle|^2 \\ &= \sum_{j,k} U_{\alpha j}^* U_{\beta j} U_{\alpha k} U_{\beta k}^* \exp[-i(E_j - E_k)T] \end{aligned}$$

☑ Two flavor approximation

$$U = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \quad P_{\alpha \rightarrow \beta} \simeq \sin^2 2\theta \sin^2 \frac{\Delta m^2 T}{4E}$$

Neutrino Oscillations

- ☑ Initial state

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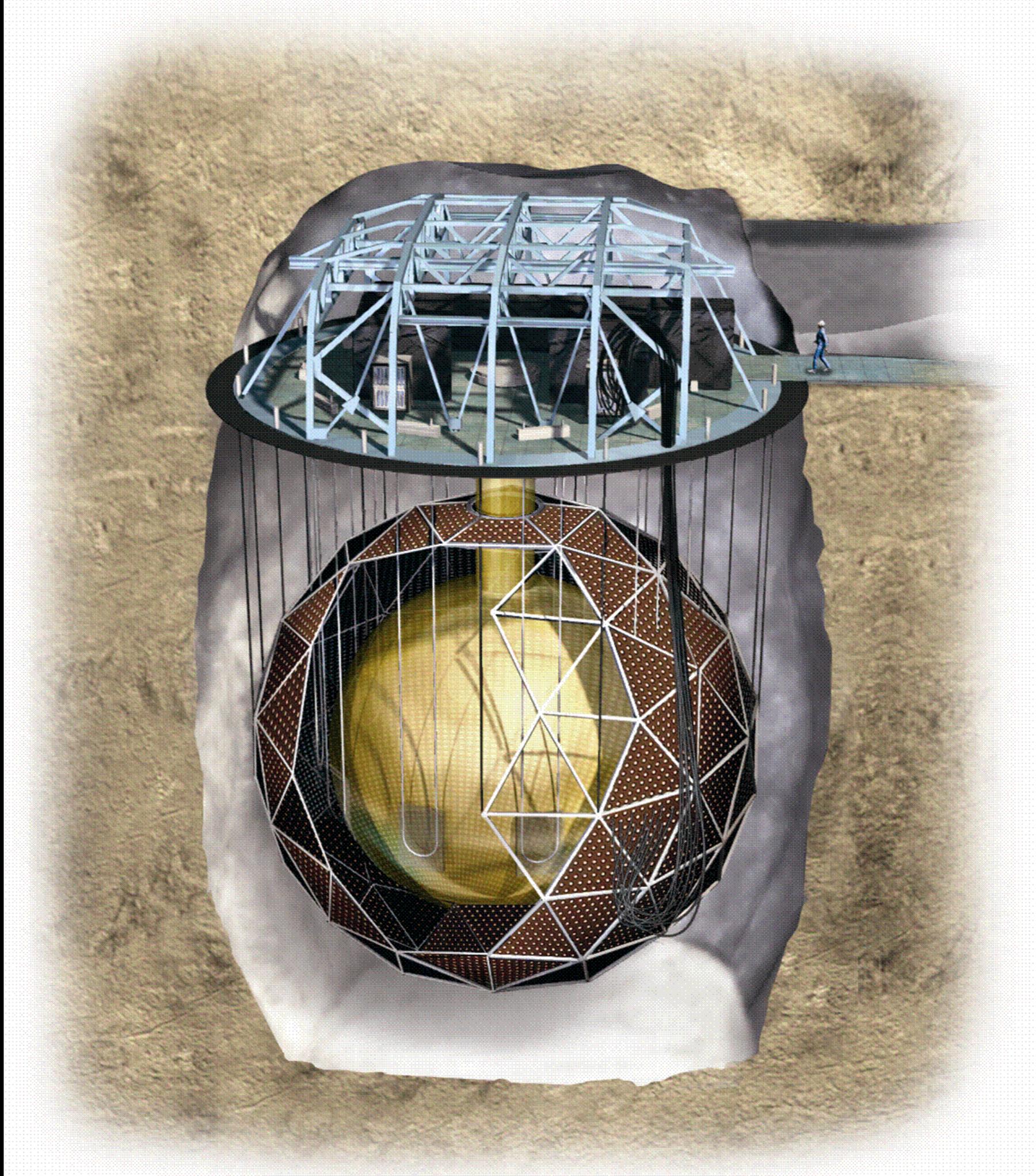
- ☑ Transition probability

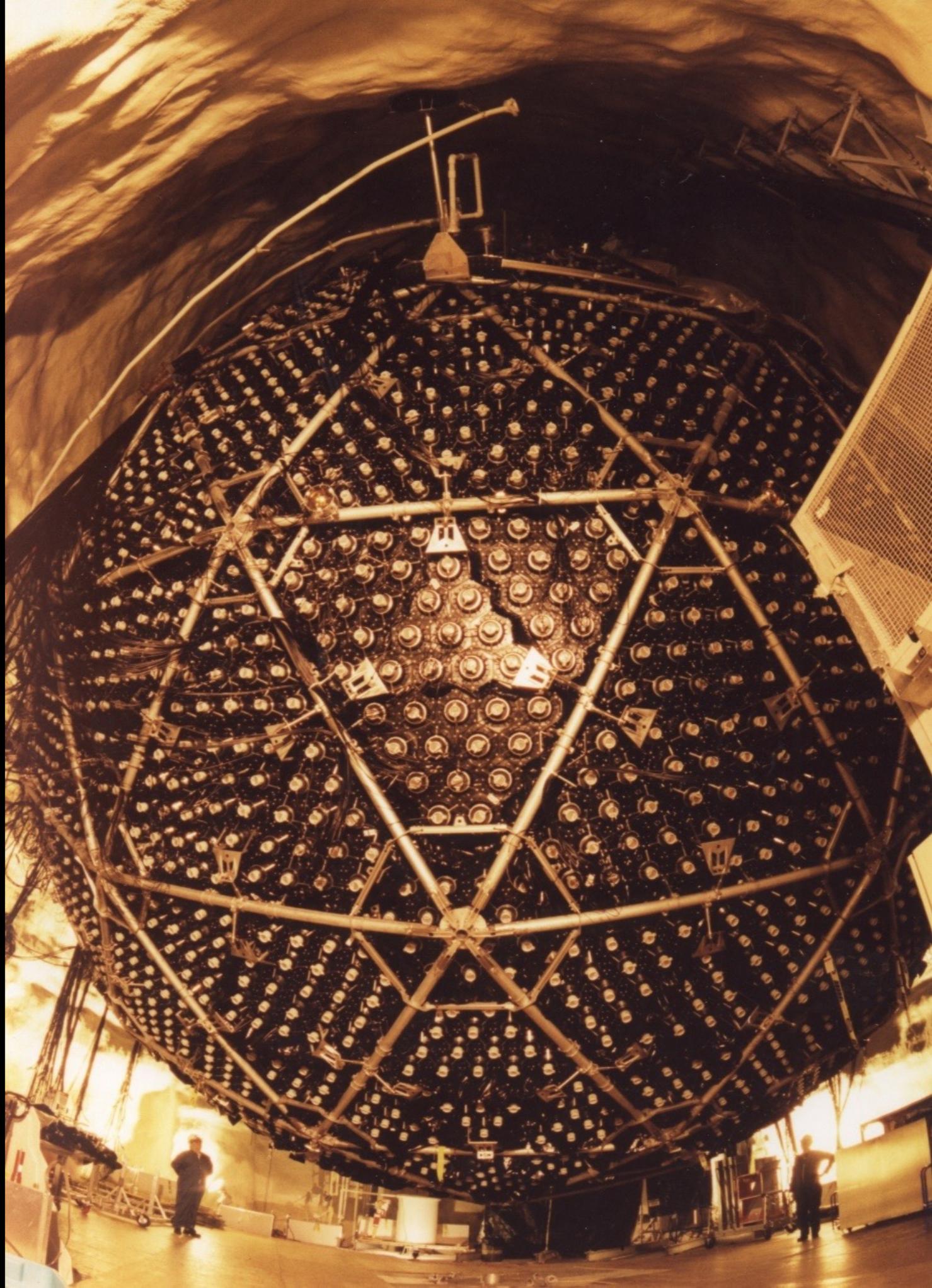
Oscillation length $\sim E/\Delta m^2$

- ☑ Two flavor approximation

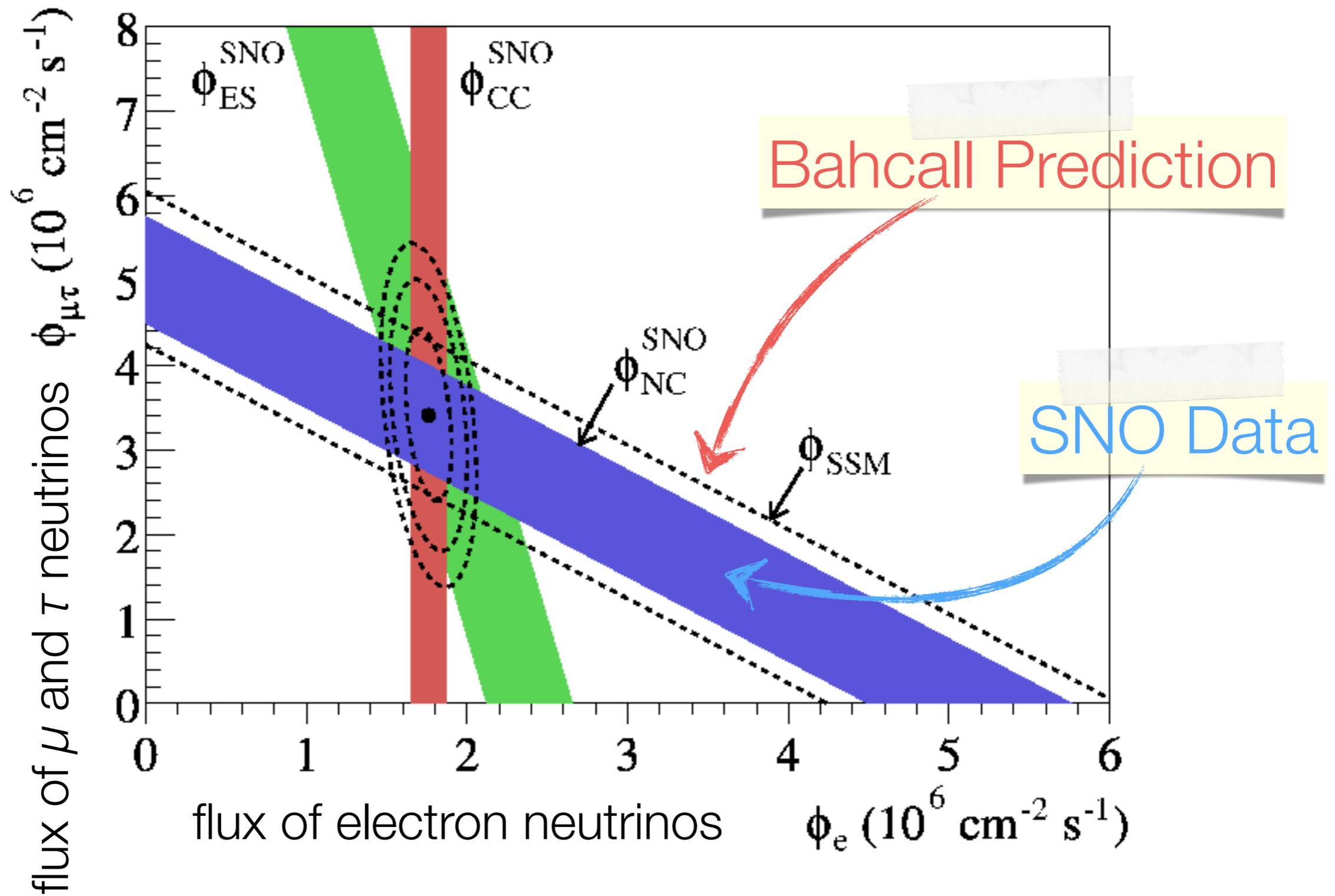
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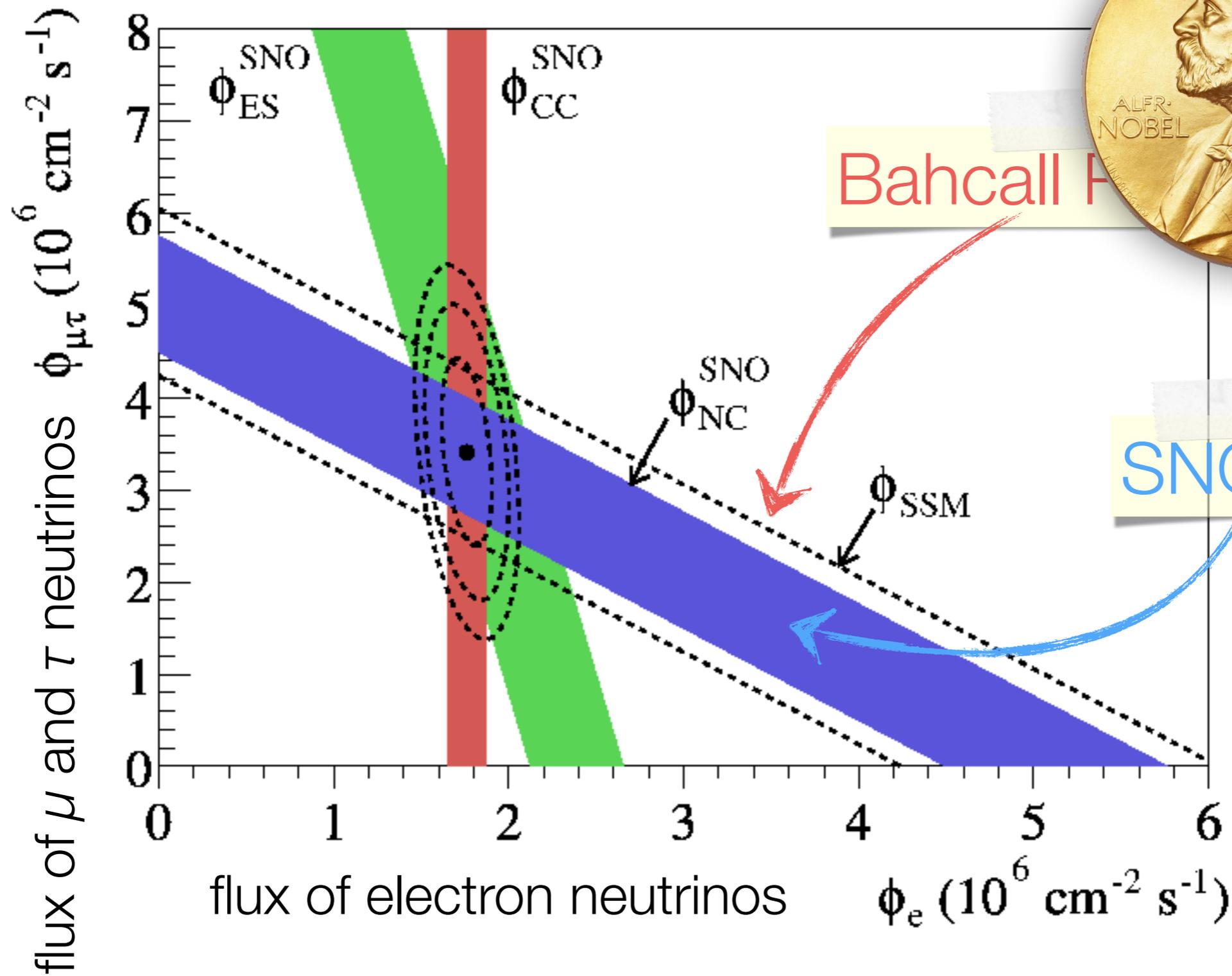




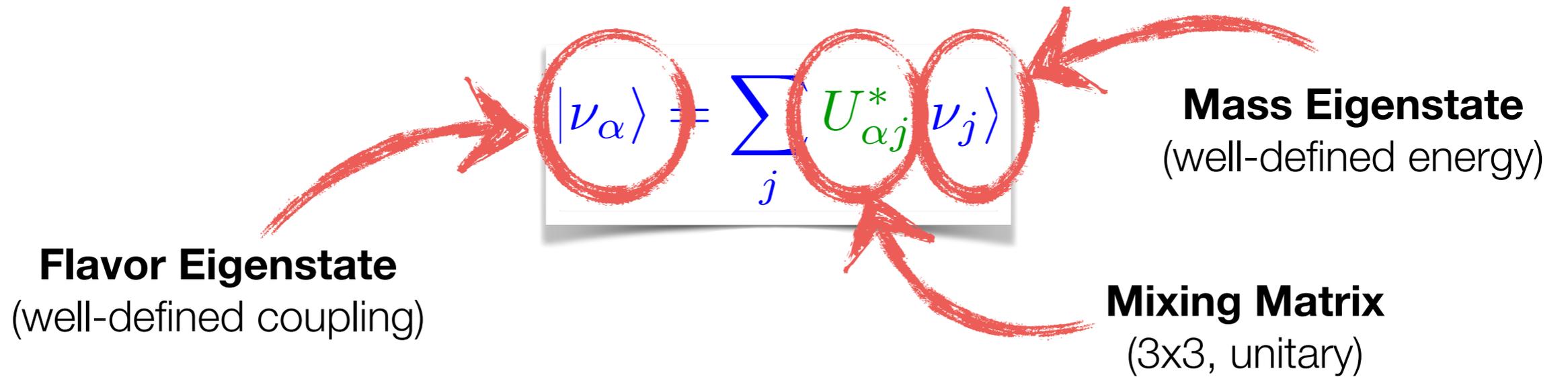
SNO (Sudbury Neutrino Observatory) Results



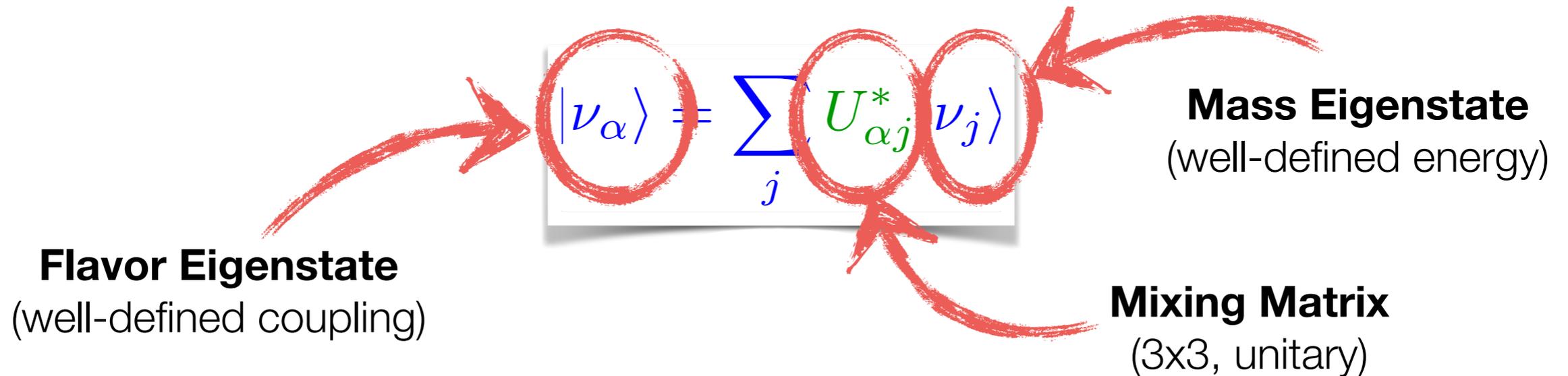
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Neutrino Mixing



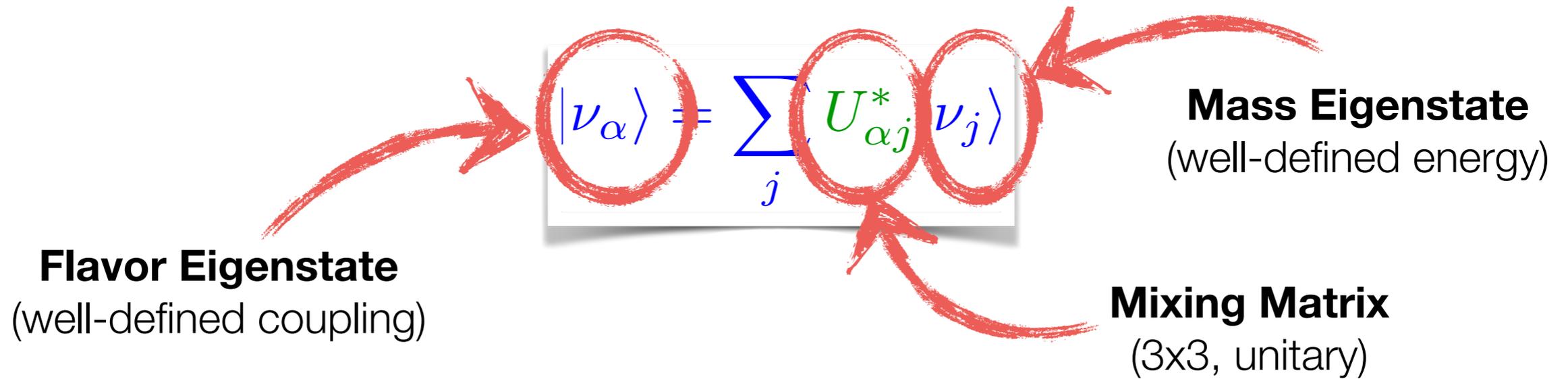
Neutrino Mixing



☑ Mixing Matrix:

$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

Neutrino Mixing

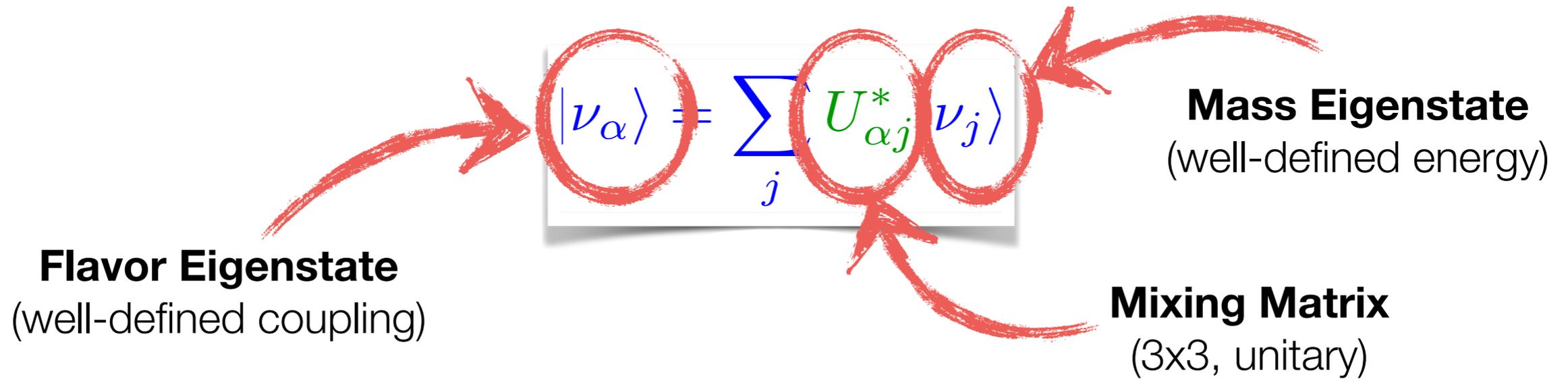


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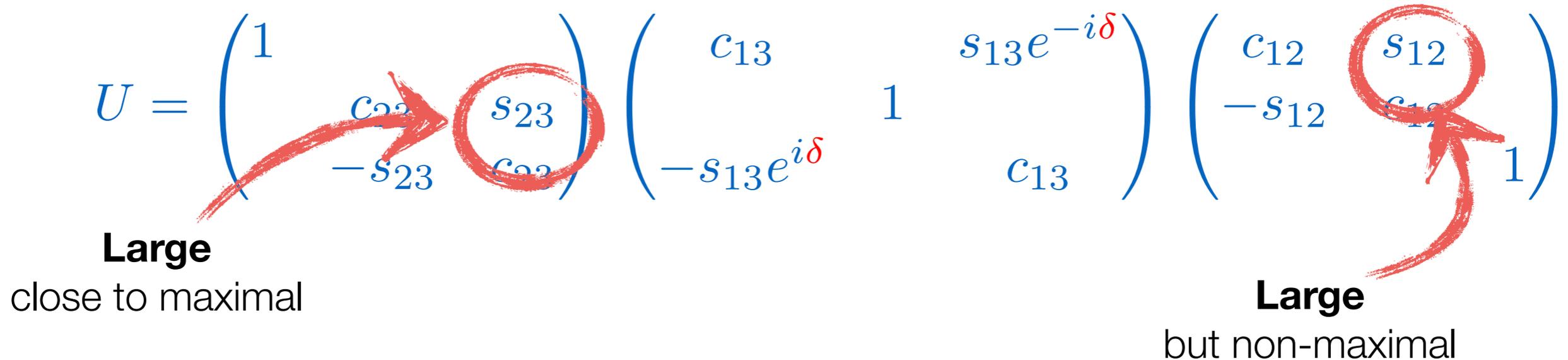
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Large
close to maximal

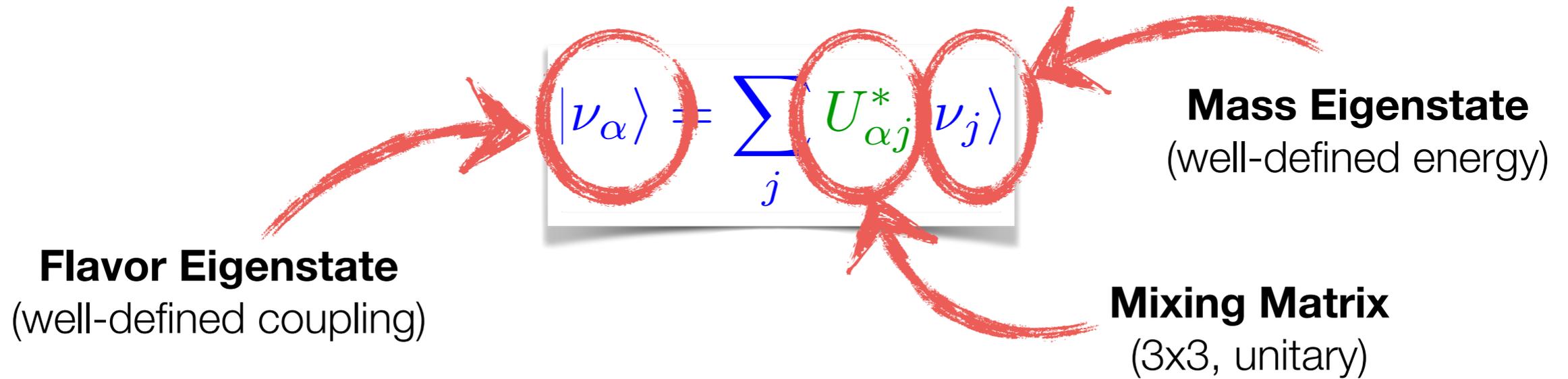
Neutrino Mixing



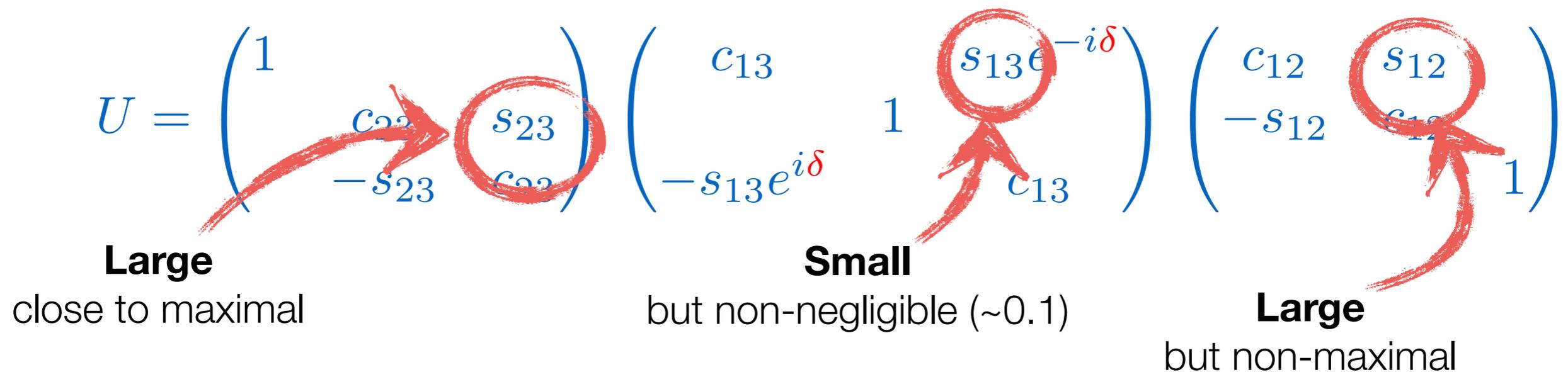
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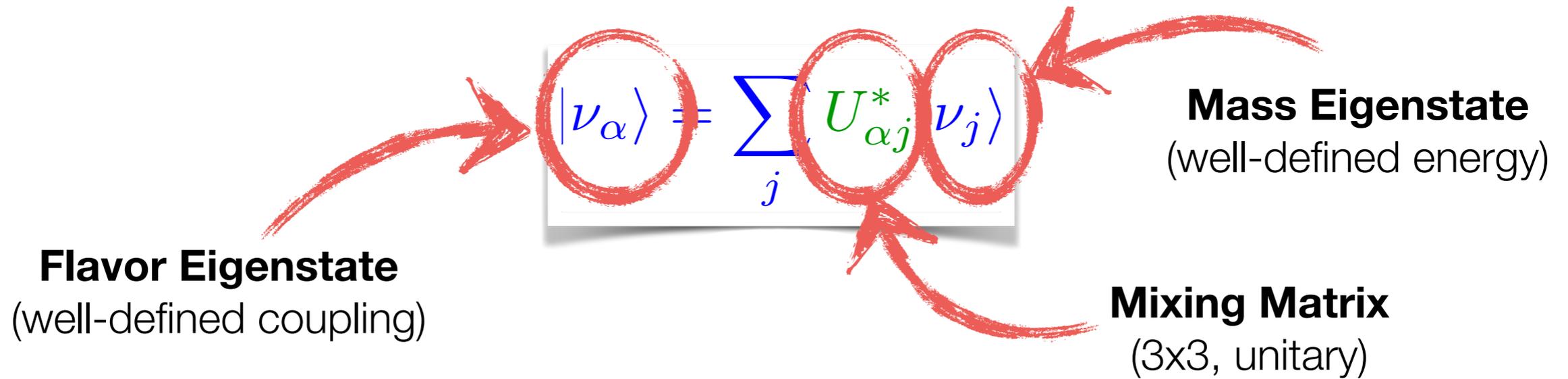
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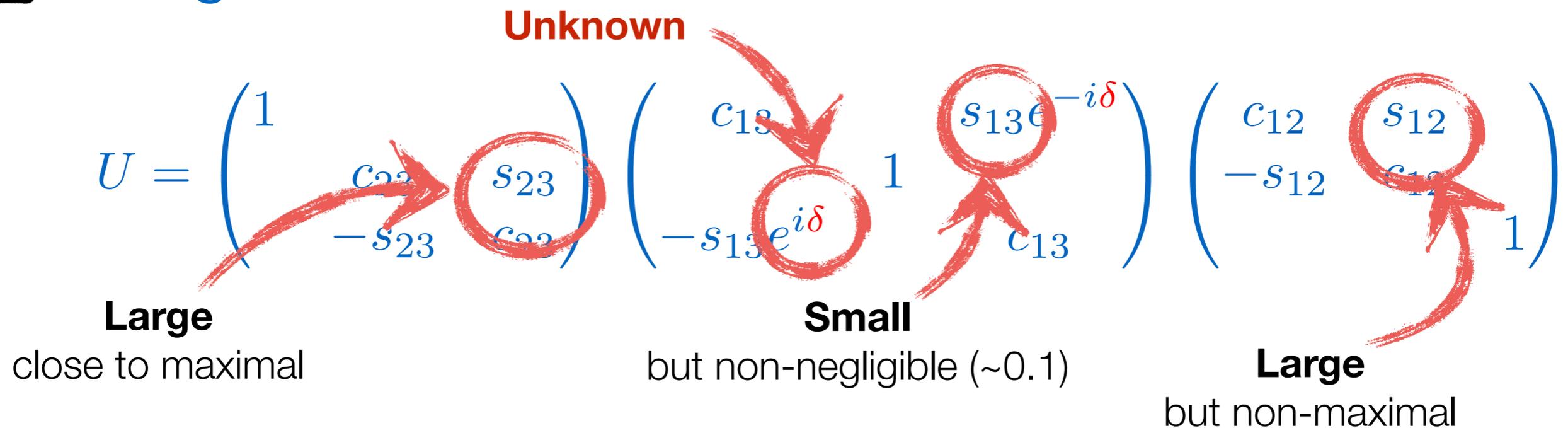
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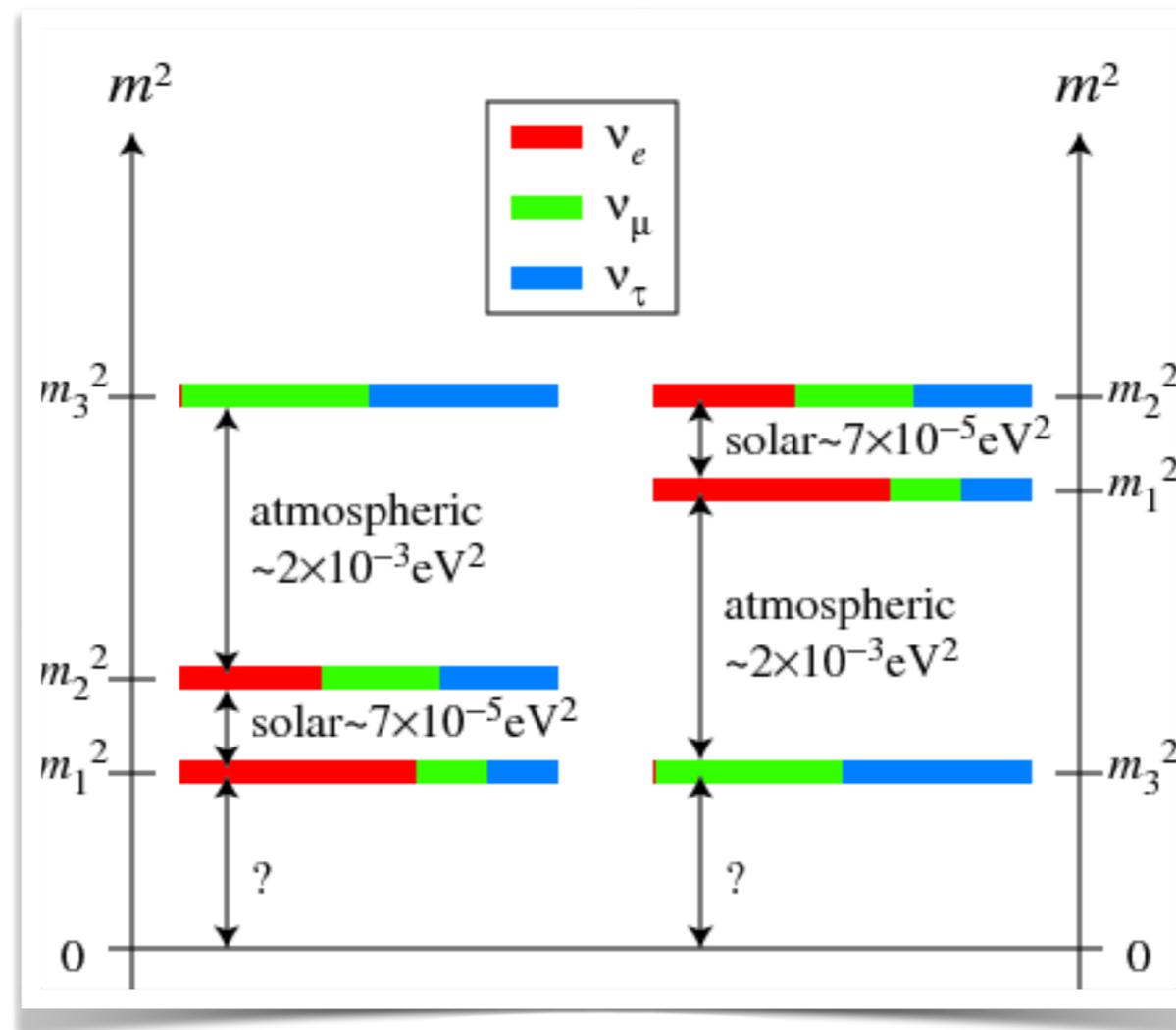


☑ Mixing Matrix:



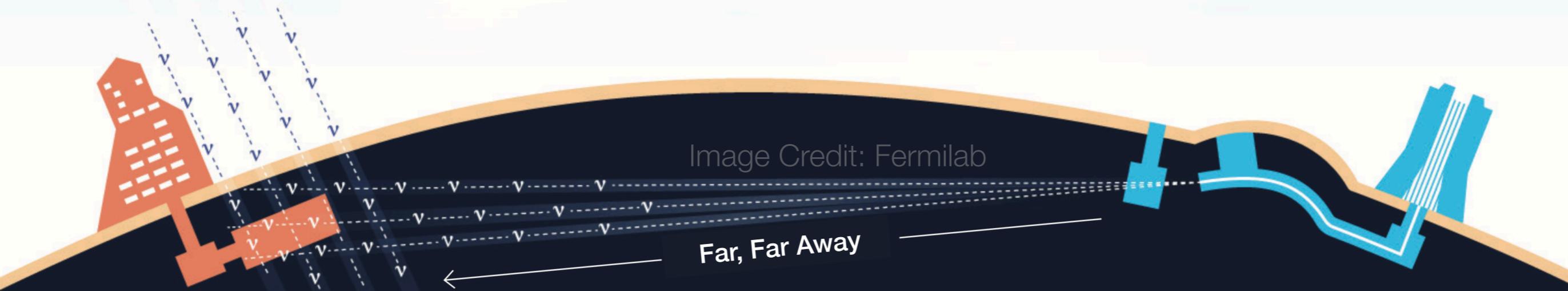
The Known Unknowns

- ☑ Is θ_{23} exactly maximal? (new symmetry?)
- ☑ What is the value of δ ? (leptogenesis?)
- ☑ What is the ordering of the ν_j ? ($0\nu 2\beta$; constraints on models)



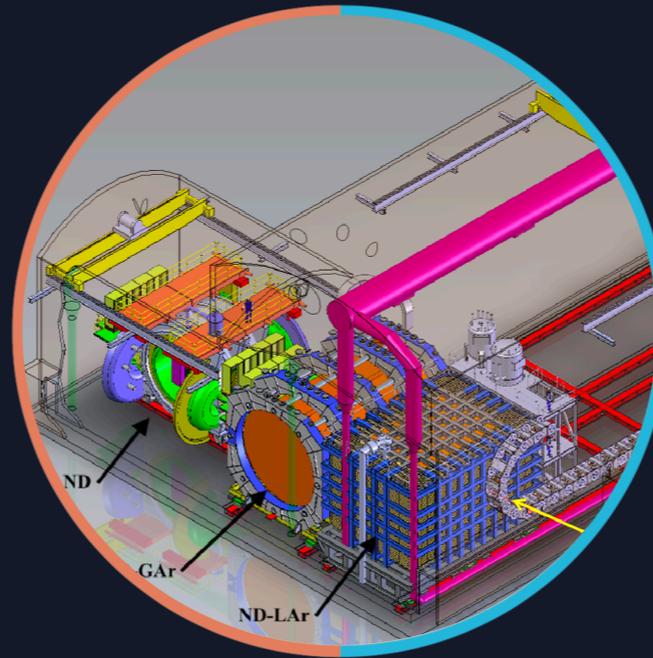
King Luhn 1301.1340

Next-Generation Long-Baseline Experiments



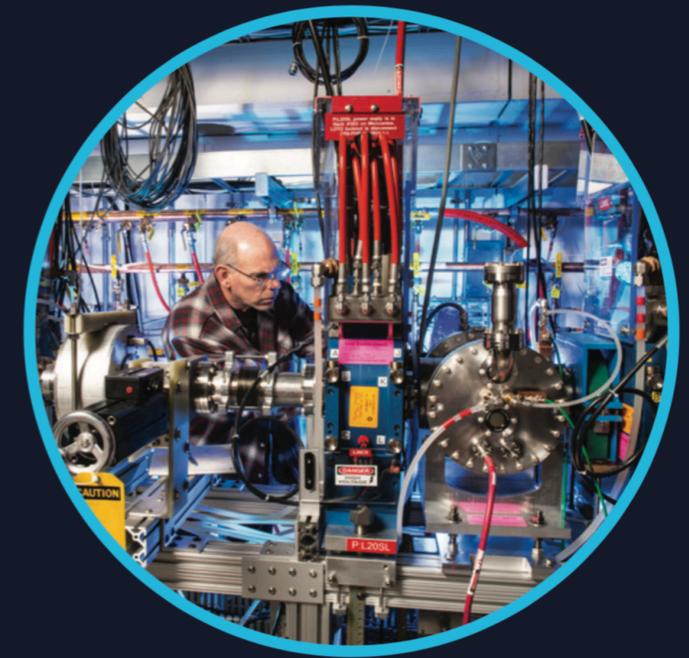
Far Detectors

measure oscillated spectrum



Near Detectors

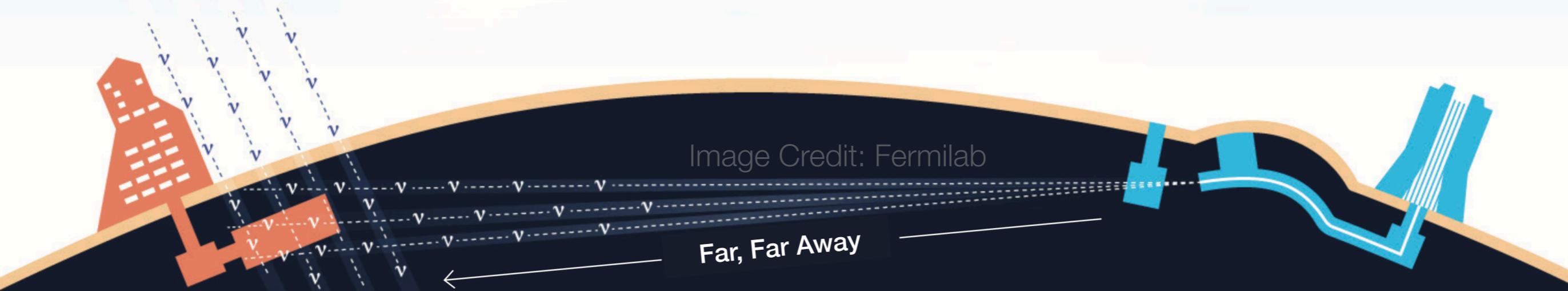
measure unoscillated spectrum
(reduce flux & x-sec uncertainties)



Neutrino Source

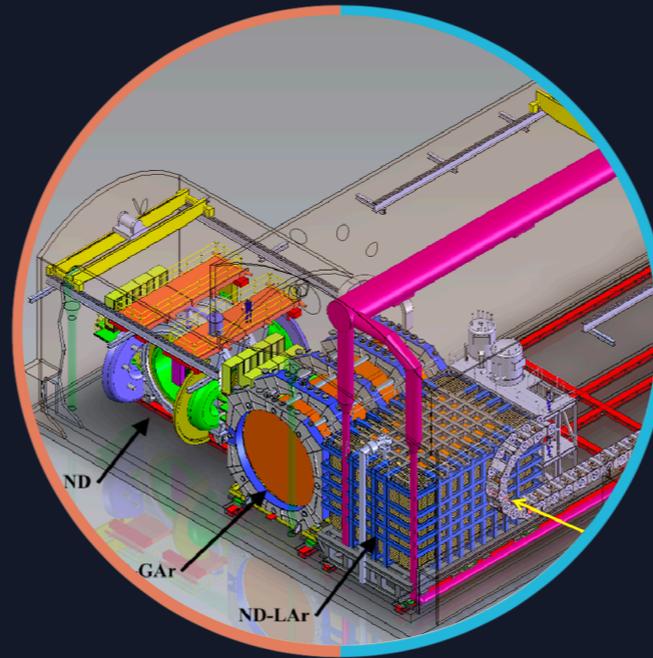
create focused pion beam,
pions decay to neutrinos

Next-Generation Long-Baseline Experiments



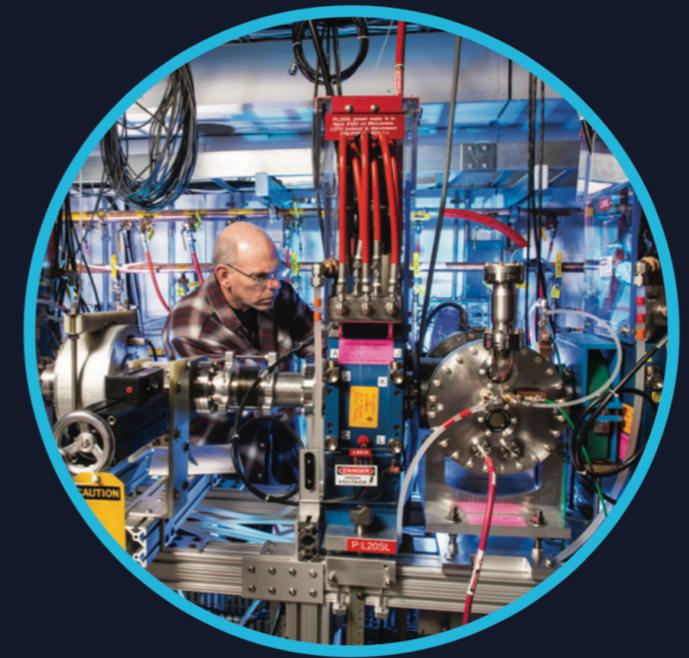
Far Detectors

measure oscillated spectrum



Near Detectors

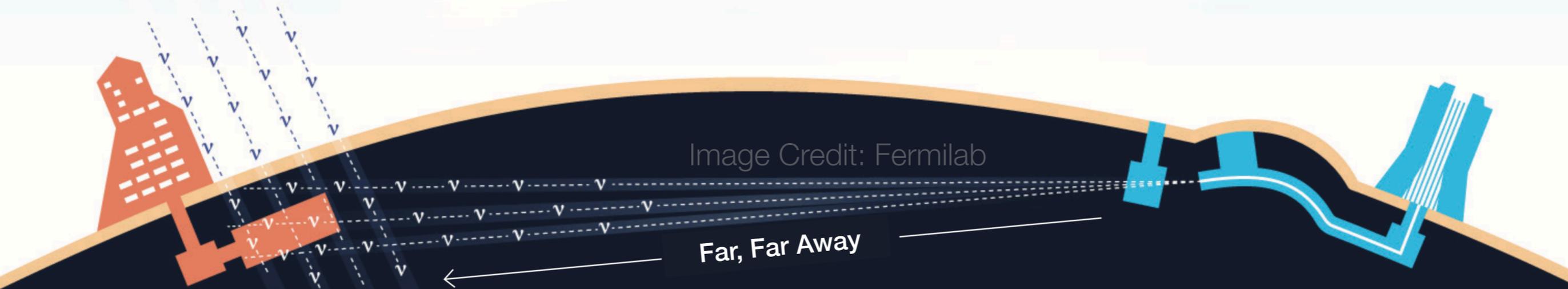
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MACARONI

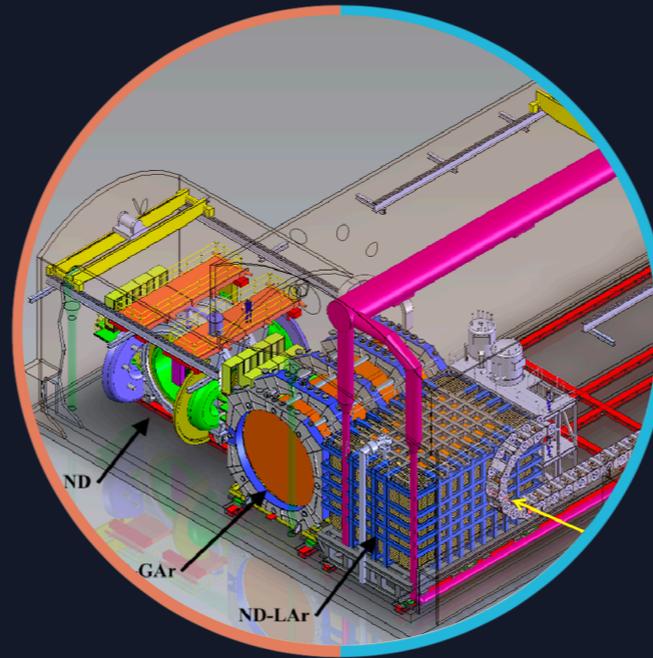
(**M**egawatt **A**ccelerator for **C**reating
Abundant **R**adiation **O**f **N**eutrin**I**)

Next-Generation Long-Baseline Experiments



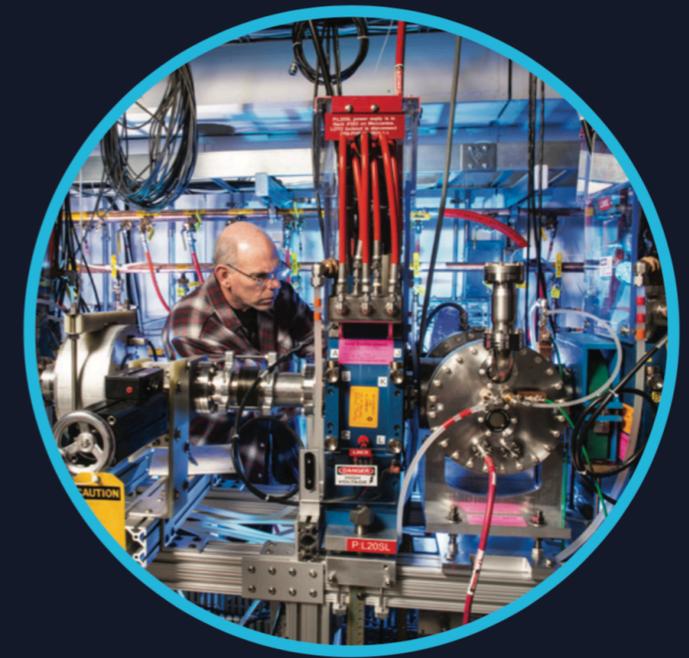
Far Detectors

measure oscillated spectrum



ENTRECOTE

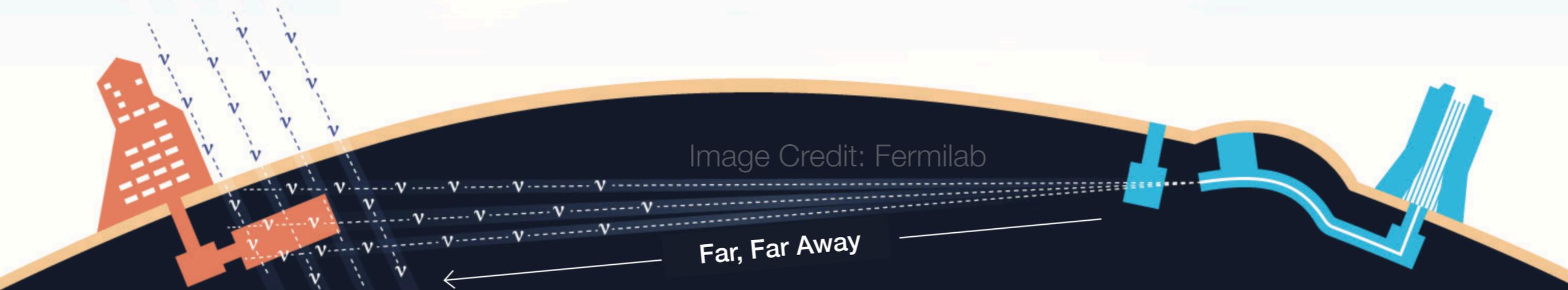
(Experiments **N**eeded for **T**ackling
Reliably the **E**xtrême **C**onundrum
Originating from **T**heory **E**rrors)



MACARONI

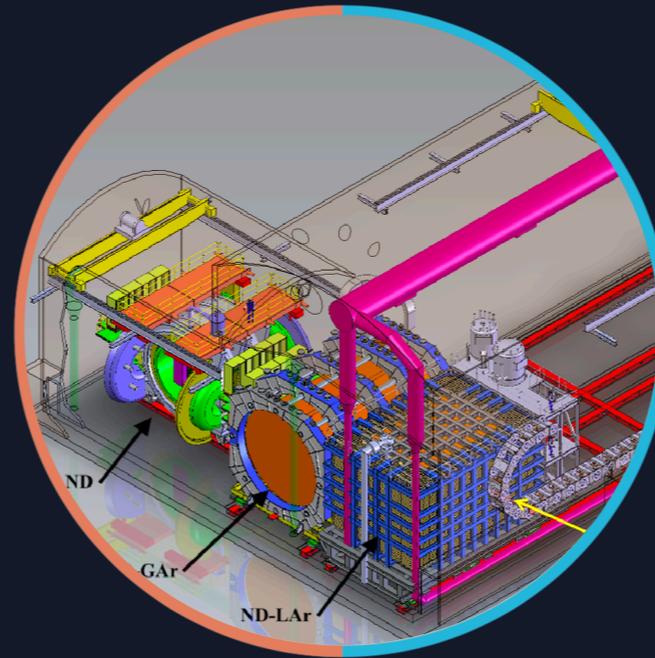
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Next-Generation Long-Baseline Experiments



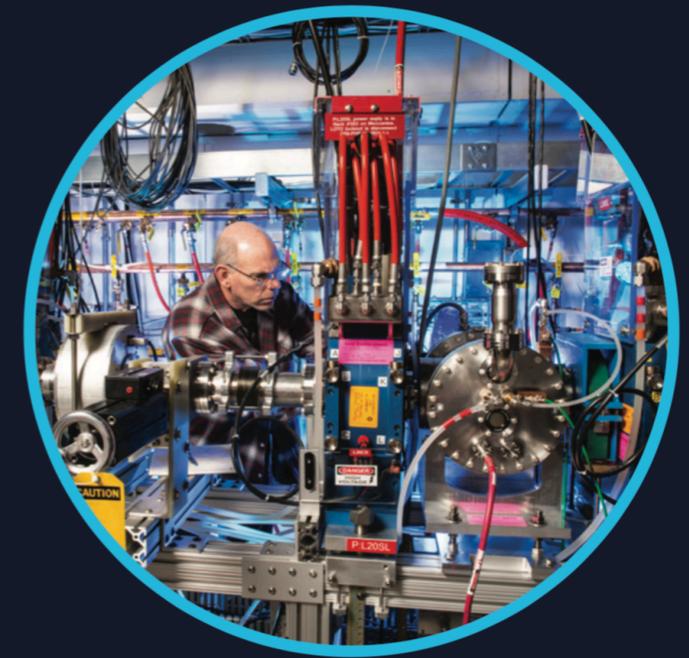
GELATO

(**G**inormous **E**xperiment at **L**ong-Baseline **A**iming to **T**est **O**scillations)



ENTRECOTE

(**E**xperiments **N**eeded for **T**ackling **R**eliably the **E**xtrême **C**onundrum **O**riginating from **T**heory **E**rrors)



MACARONI

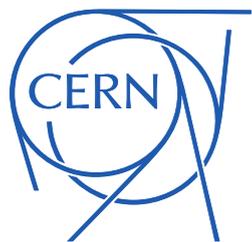
(**M**egawatt **A**ccelerator for **C**reating **A**bundant **R**adiation **O**f **N**eutrin**I**)

Yes, but why?

- ✓ Precise knowledge of particle physics parameters is indispensable for using **neutrinos as messengers**
- ✓ Connection between **leptonic CP violation** and **baryogenesis**
- ✓ Hints for the **origin of flavor**
- ✓ **Multi-purpose detectors** with lots of secondary opportunities
(proton decay, supernova neutrinos, light dark sectors, ...)
- ✓ Portal to **new physics**
- ✓ ...

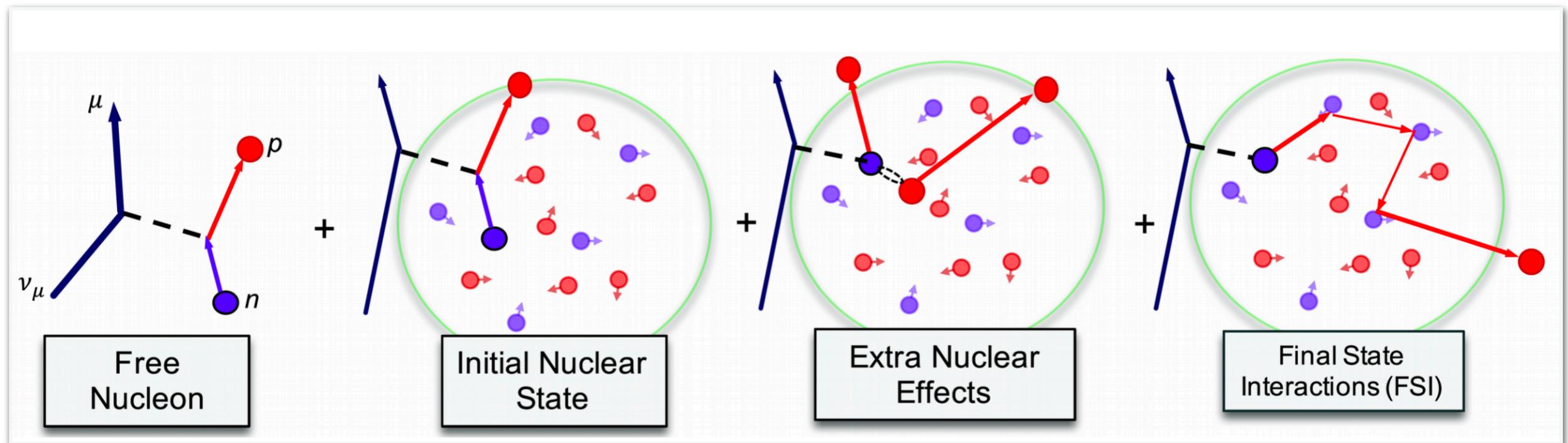
Challenge 1

Understanding Neutrino Interactions

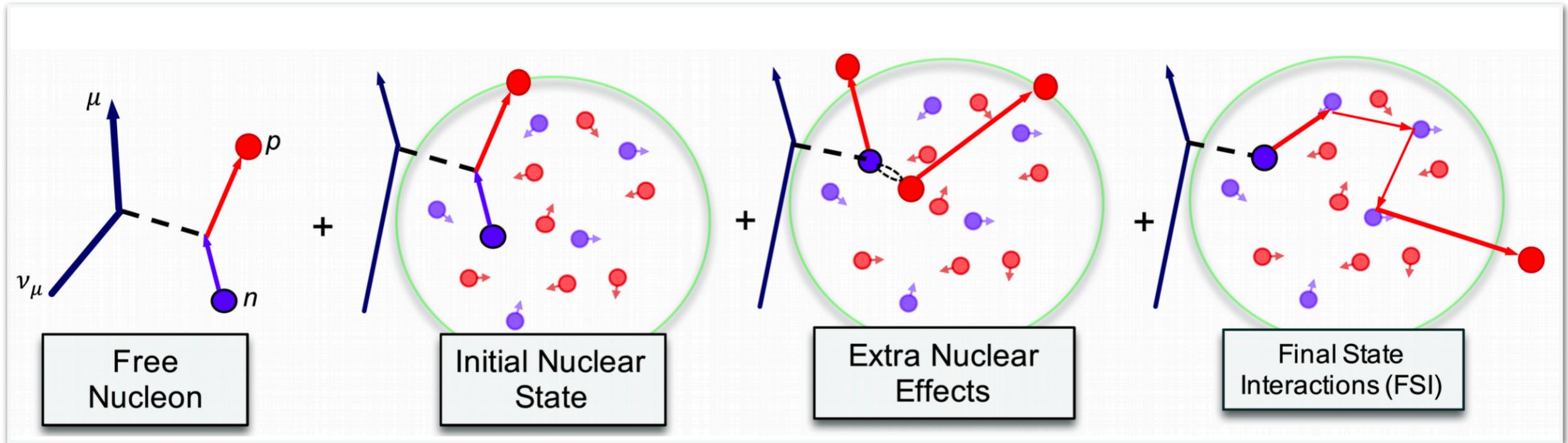


Understanding Neutrino Interactions

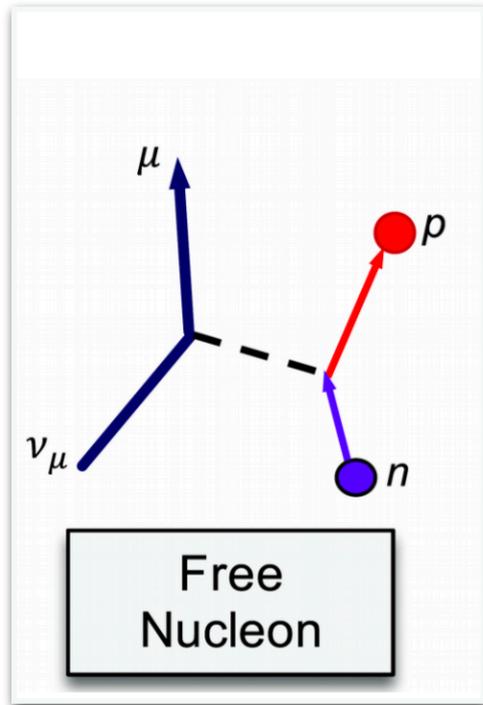
- ☑ Large systematic / theoretical uncertainties in Neutrino Interaction Cross Sections



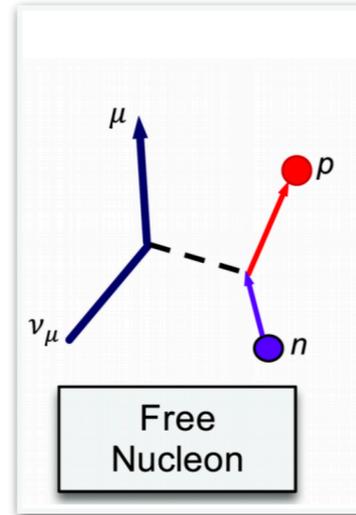
Understanding Neutrino Interactions



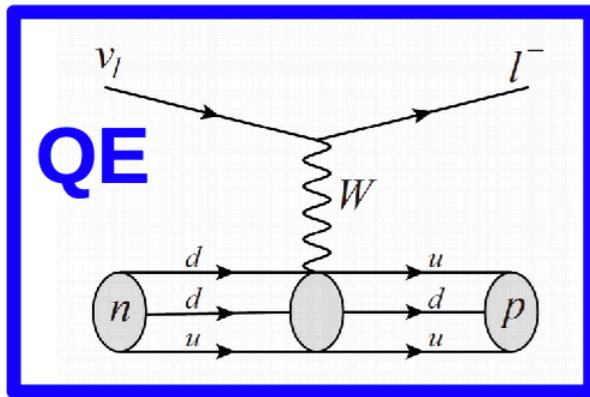
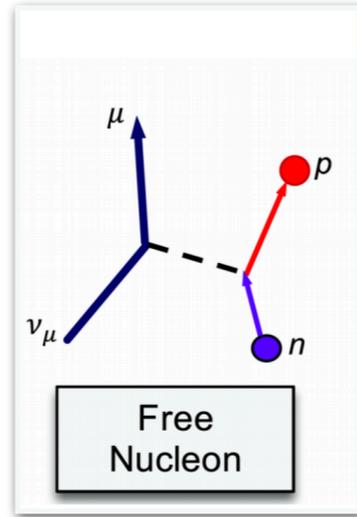
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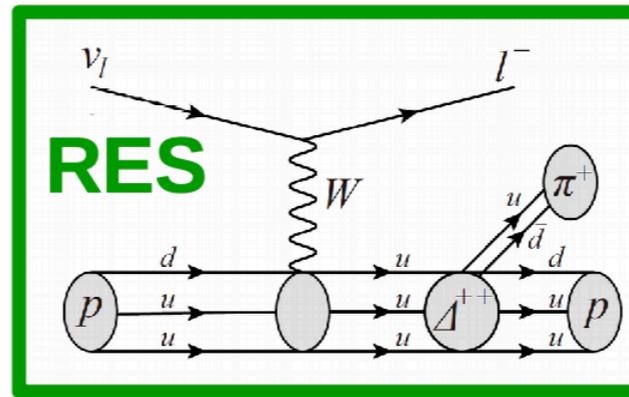
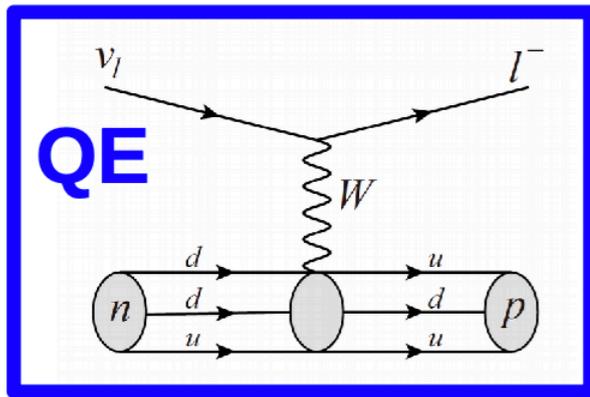
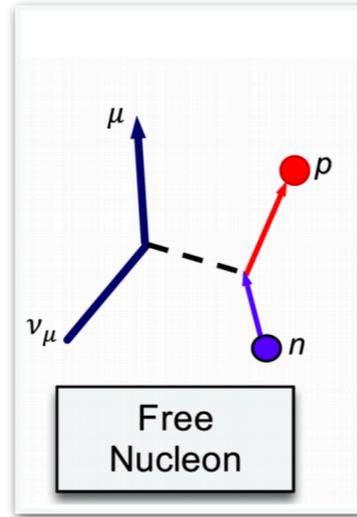
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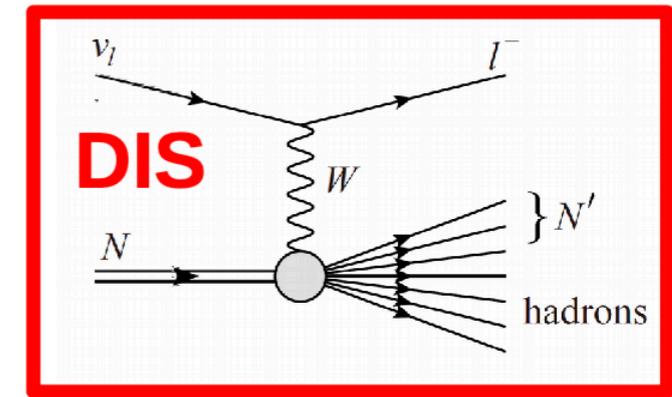
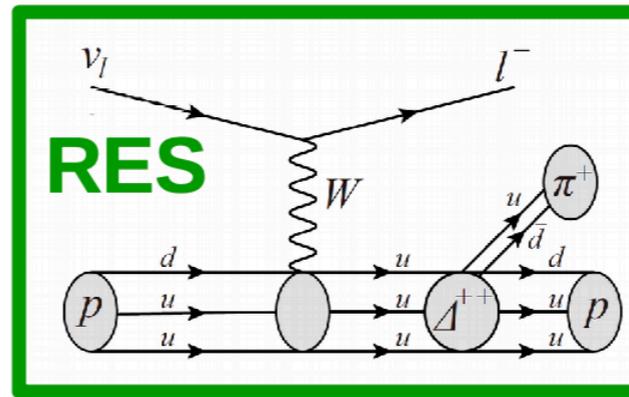
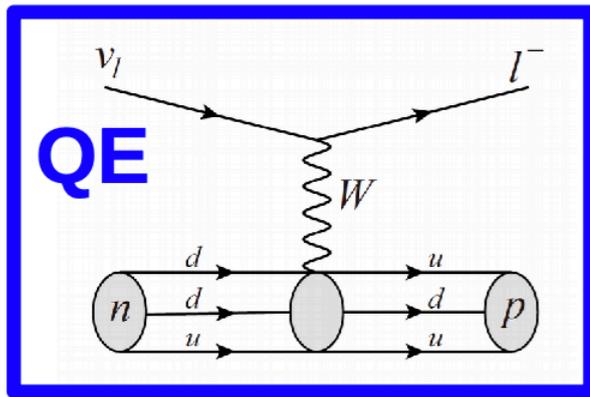
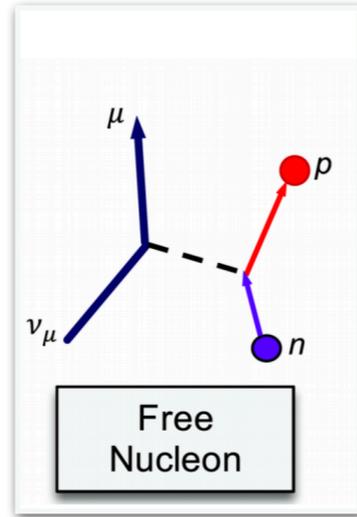
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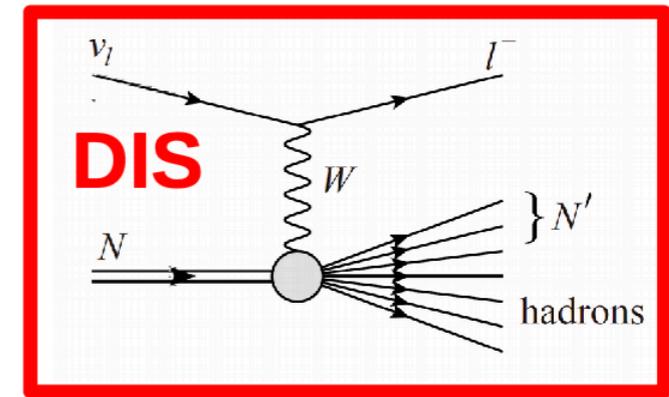
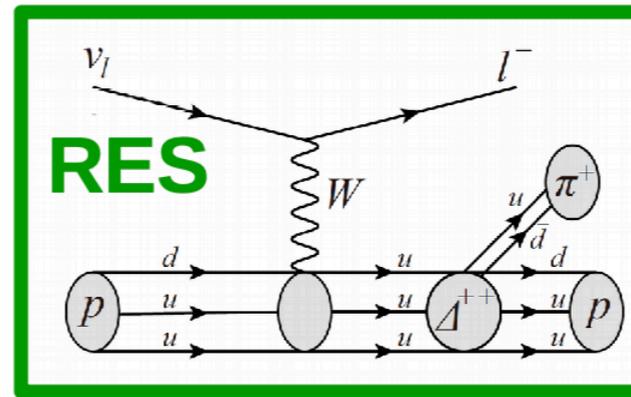
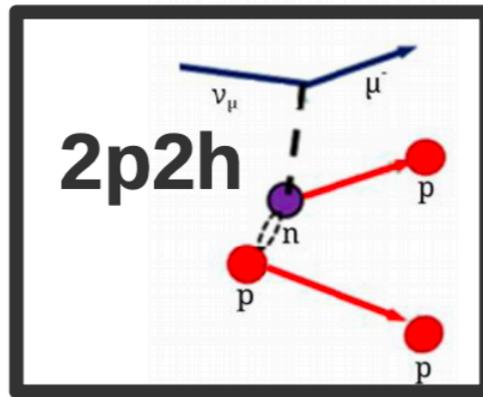
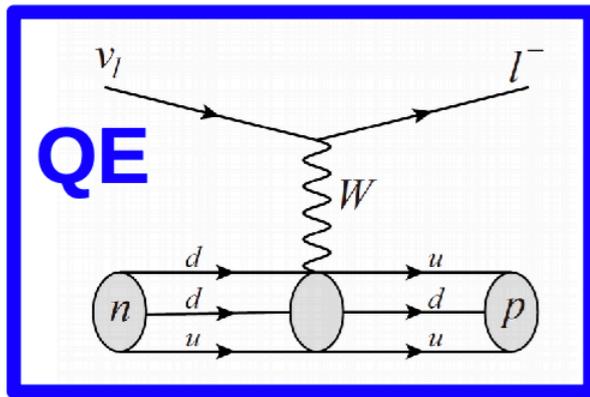
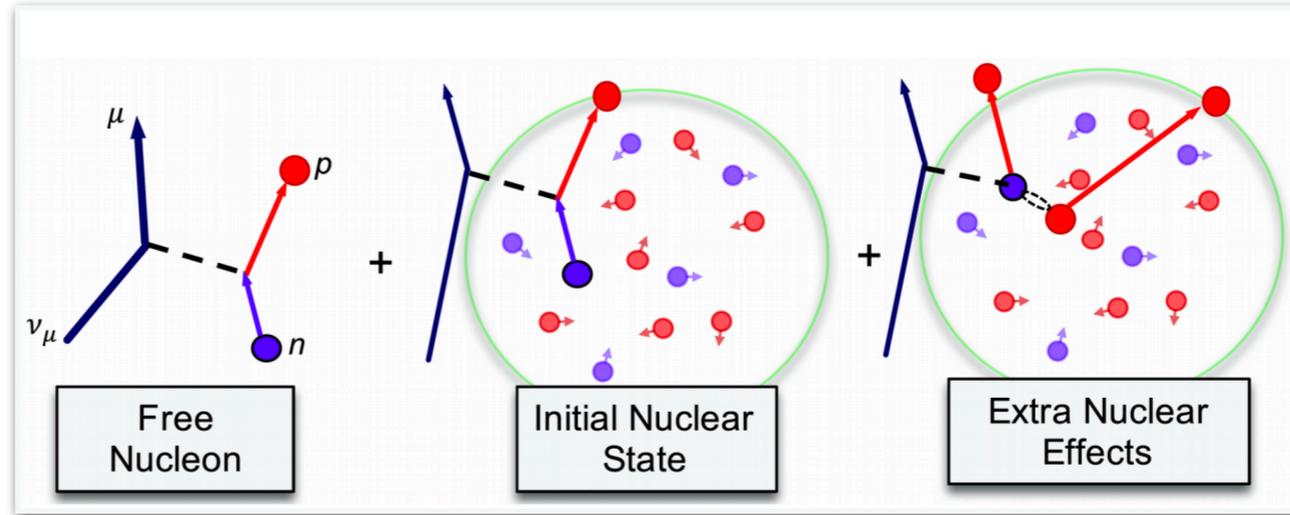
Understanding Neutrino Interactions



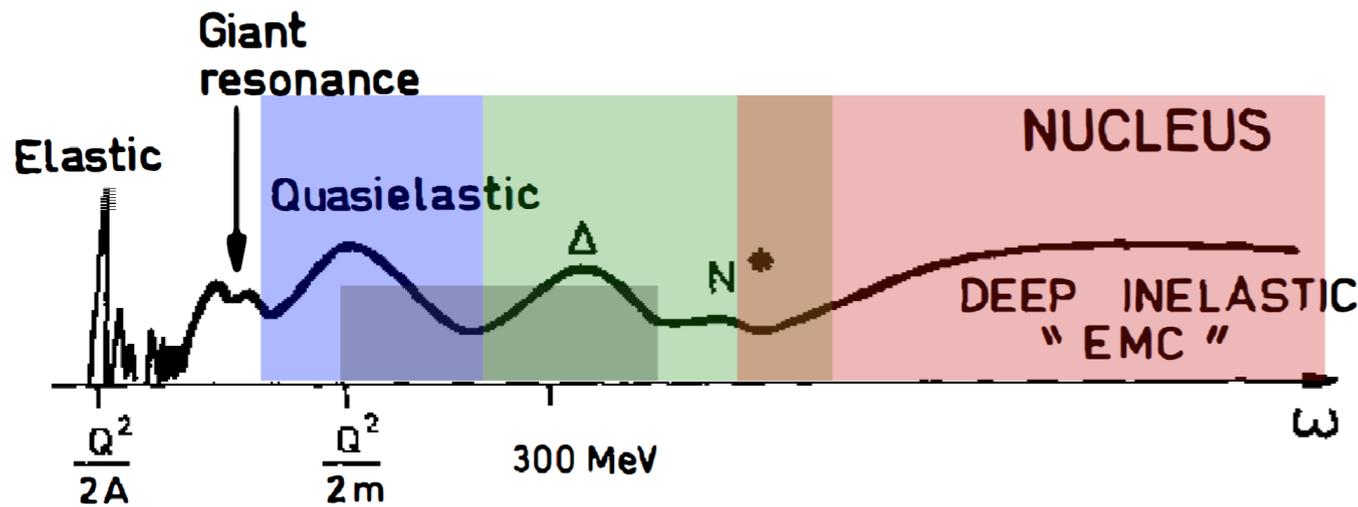
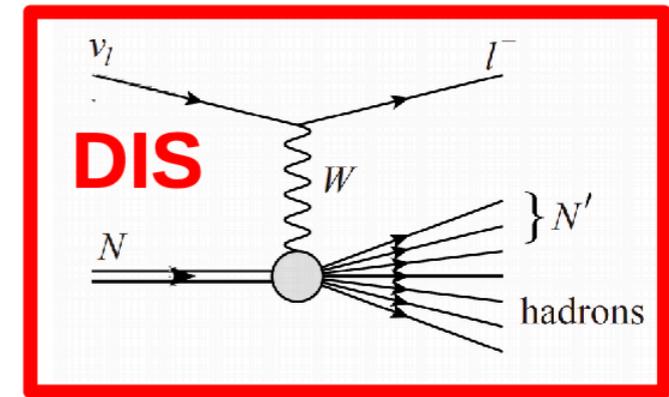
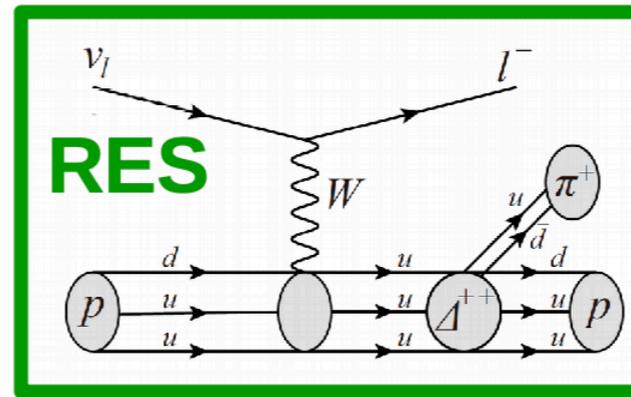
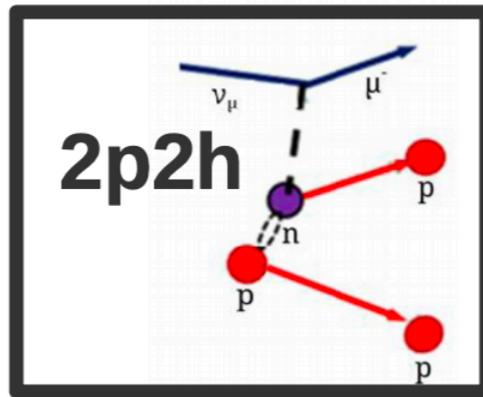
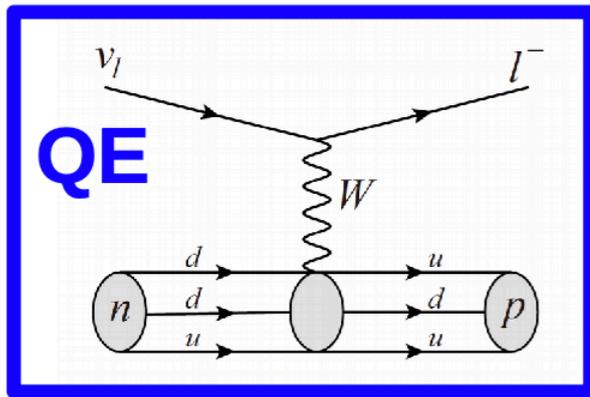
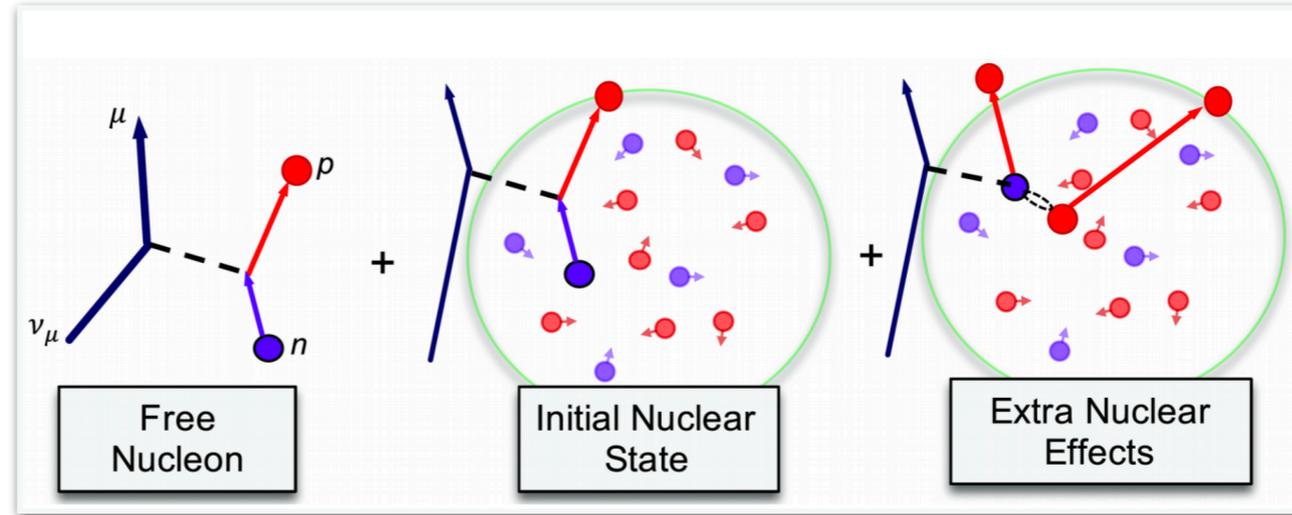
Understanding Neutrino Interactions



Understanding Neutrino Interactions



Understanding Neutrino Interactions



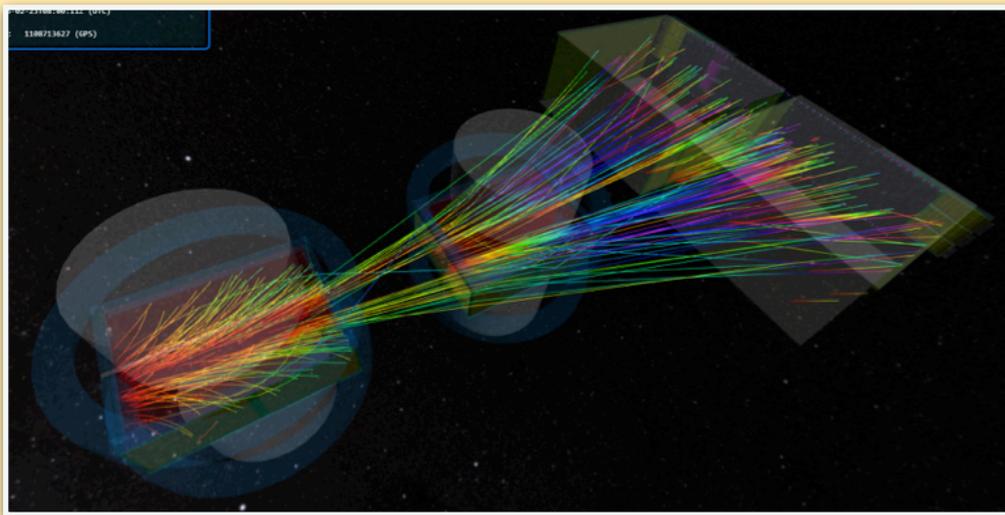
multi-nucleon effects are crucial

Understanding Neutrino Interactions

- ☑ Large systematic / theoretical uncertainties in Neutrino Interaction Cross Sections

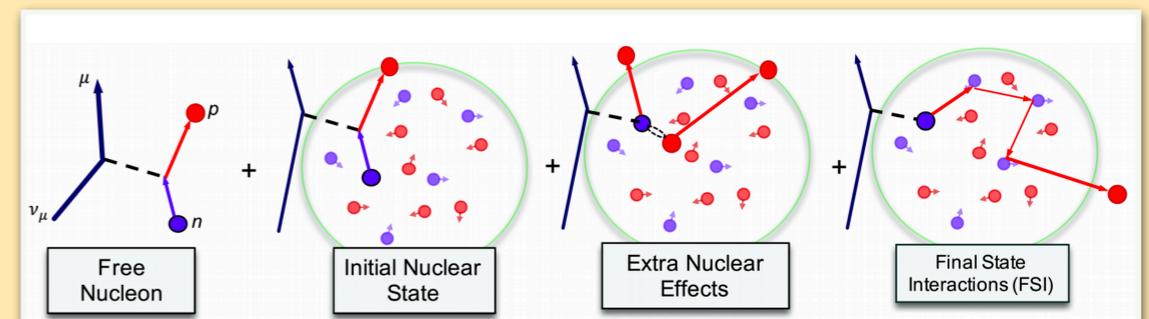
Experimental Mitigation

- ☑ near detectors (on-axis and off-axis)
- ☑ hadroproduction experiments (e.g. NA61/SHINE)



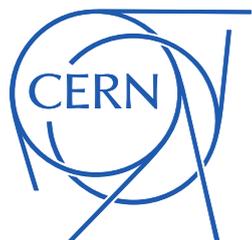
Theory Needs

- ☑ better modelling of neutrino interactions
- ☑ new strategies for optimally exploiting near detector data (in particular DUNE-PRISM)

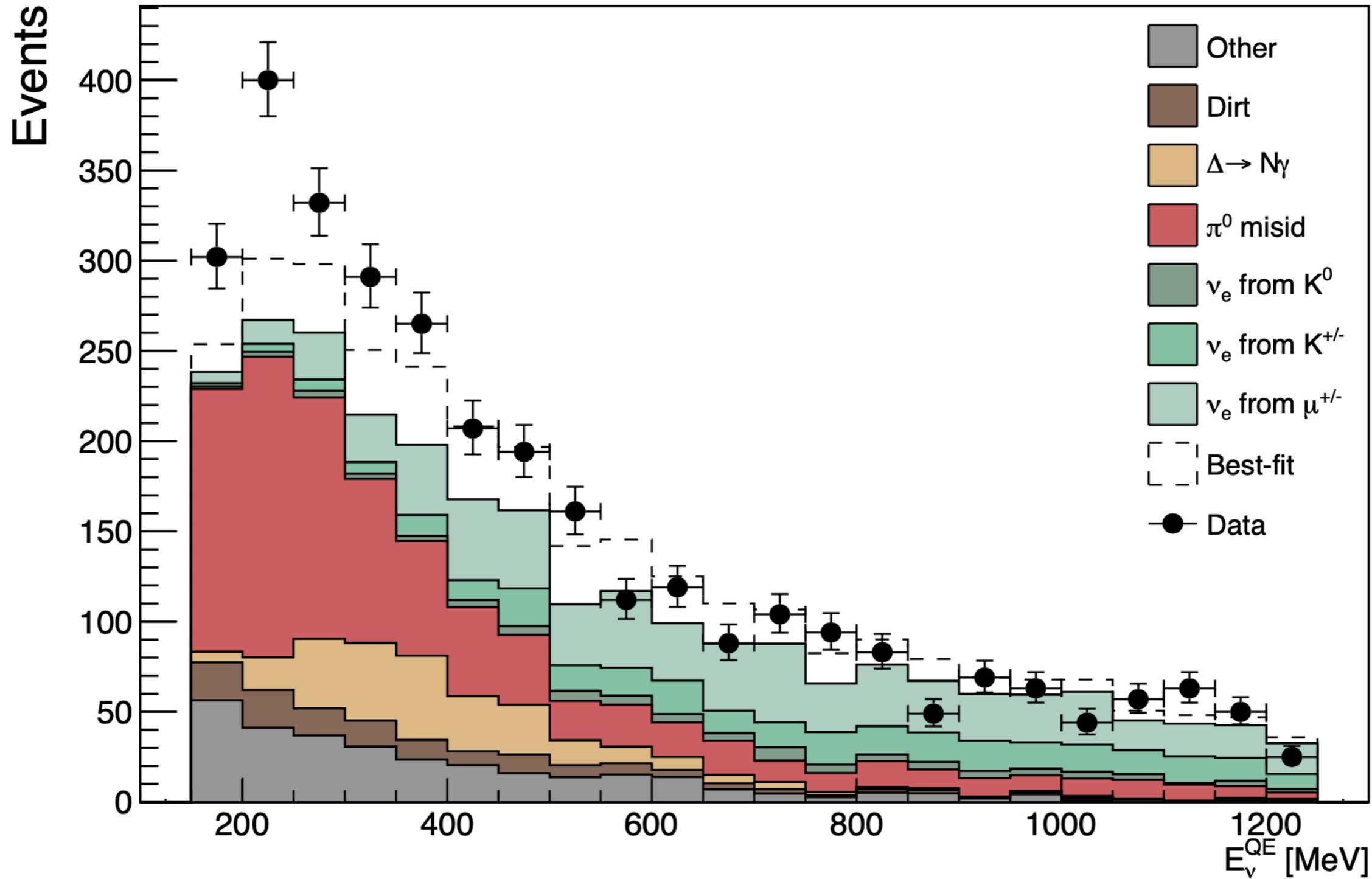


Challenge 2

Neutrino Anomalies



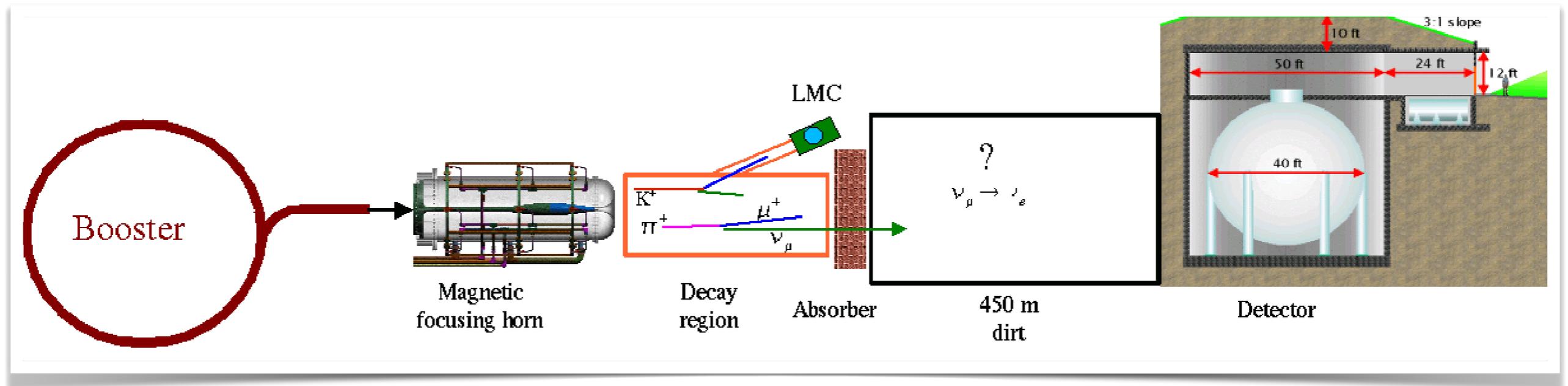
The MiniBooNE Anomaly



MiniBooNE 2020



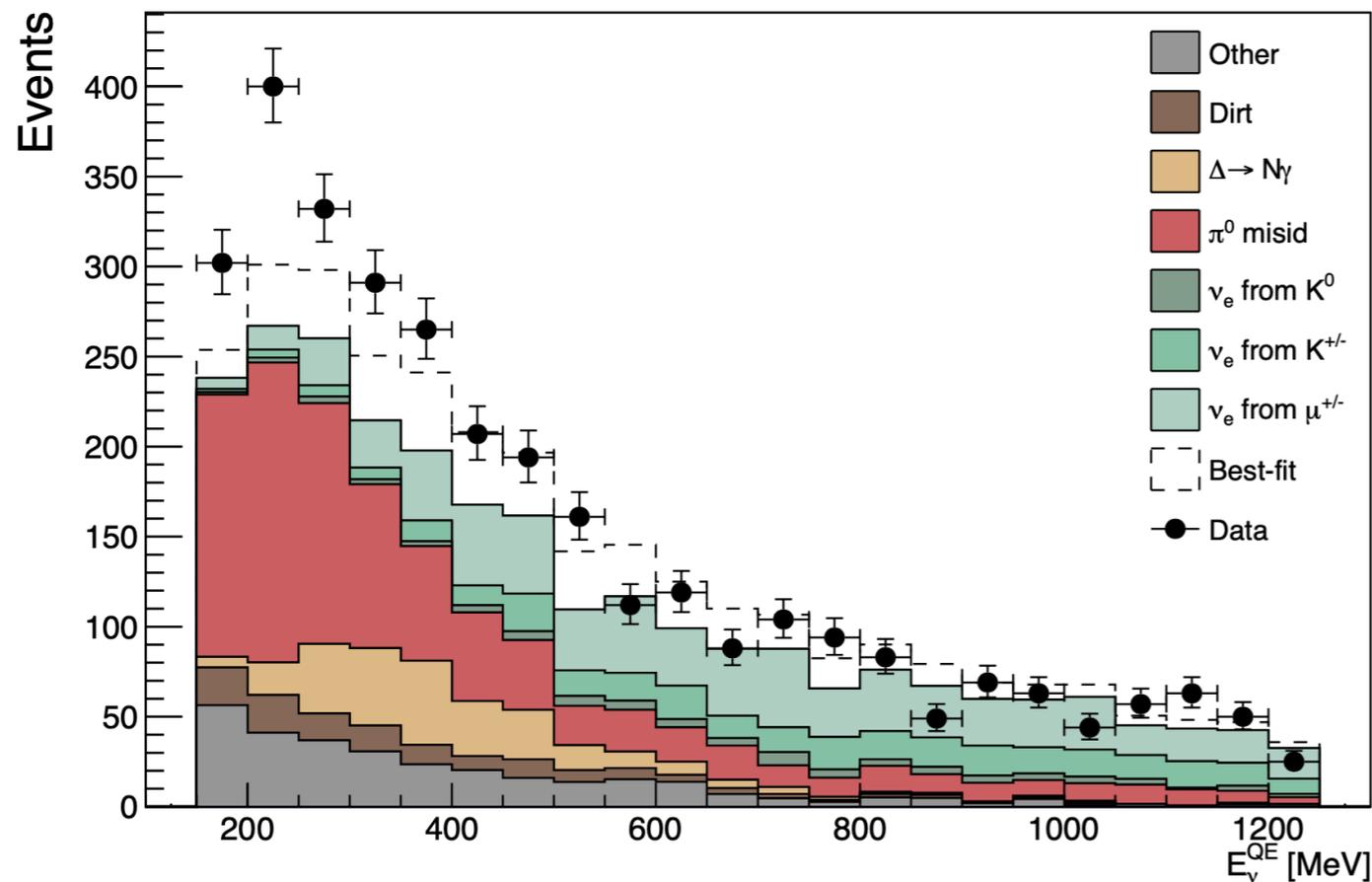
The MiniBooNE Anomaly



The MiniBooNE Anomaly

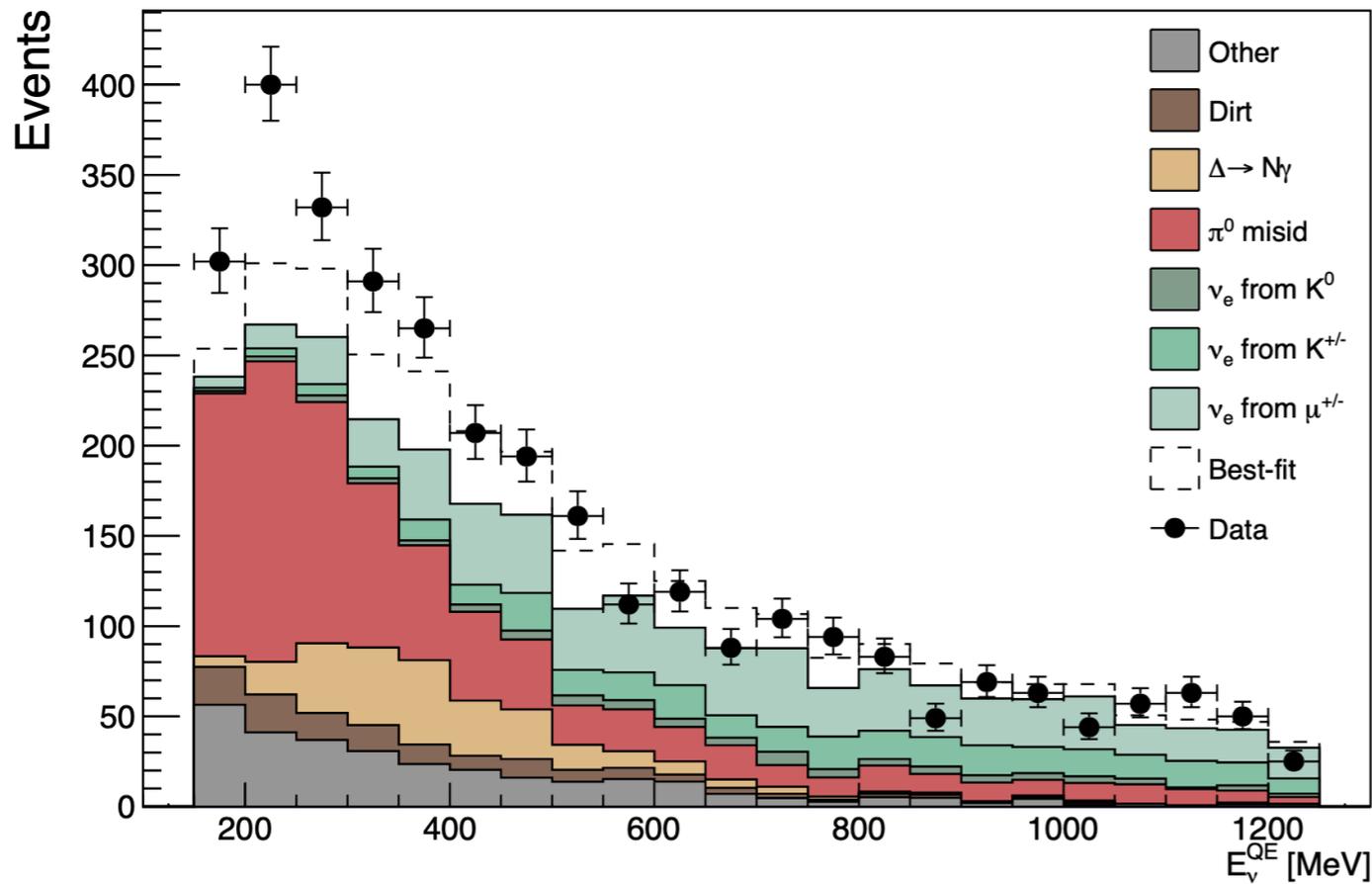
MiniBooNE Collaboration arXiv:2006.16883

- ✓ Excess of ν_e in ν_μ beam (4.8σ)
- ✓ baseline too short for standard oscillations
- ✓ a 4th neutrino flavour (“sterile neutrino”)?

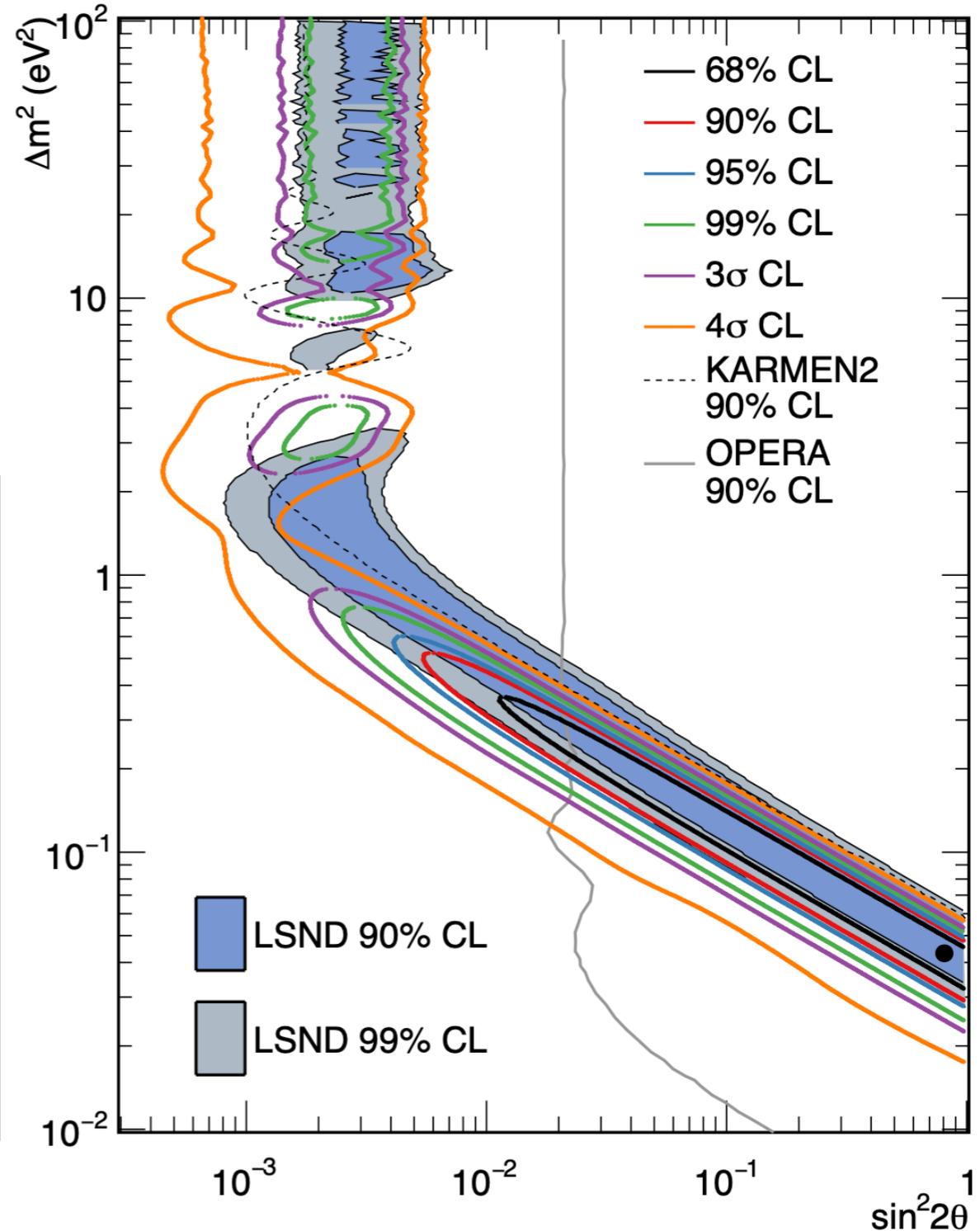


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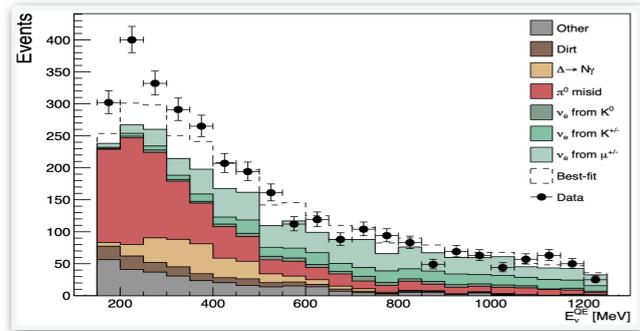
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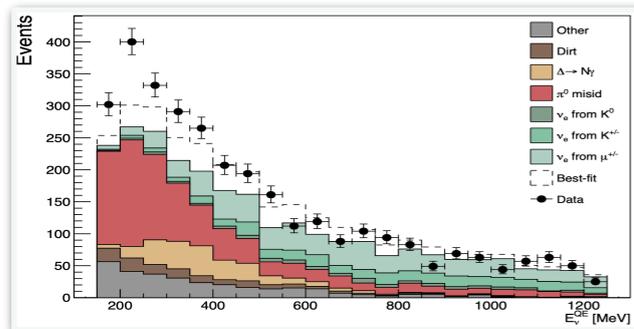
Short-Baseline Anomalies



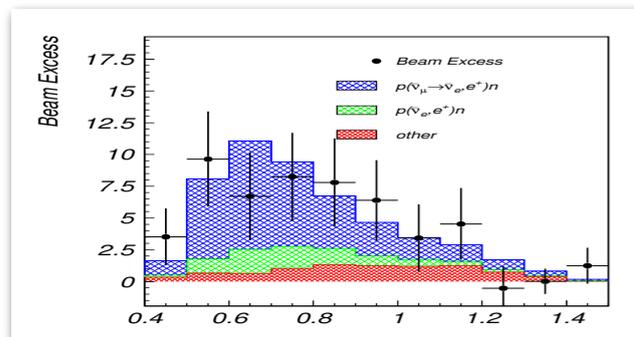
MiniBooNE
unresolved



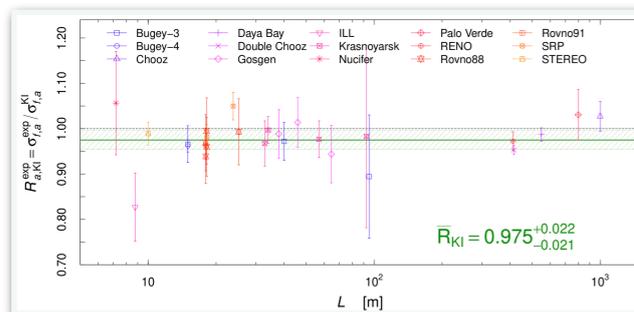
Short-Baseline Anomalies



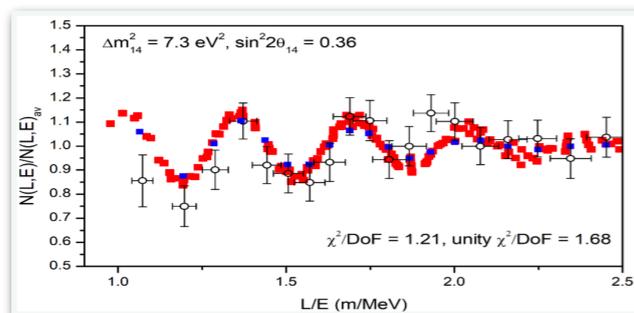
MiniBooNE
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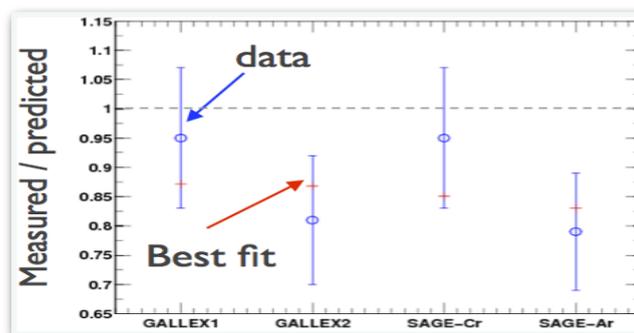
LSND
unresolved



reactor flux anomaly
resolved with new input data
to flux calculation



reactor spectra
is there really an anomaly?



gallium anomaly
unresolved, recently reinforced



Light Sterile Neutrinos?

☑ Add extra neutrino flavor, promote mixing matrix to 4×4

☑ Oscillation channels are related:

$$P_{\nu_e \rightarrow \nu_e} \simeq 1 - 2|U_{e4}|^2(1 - |U_{e4}|^2)$$

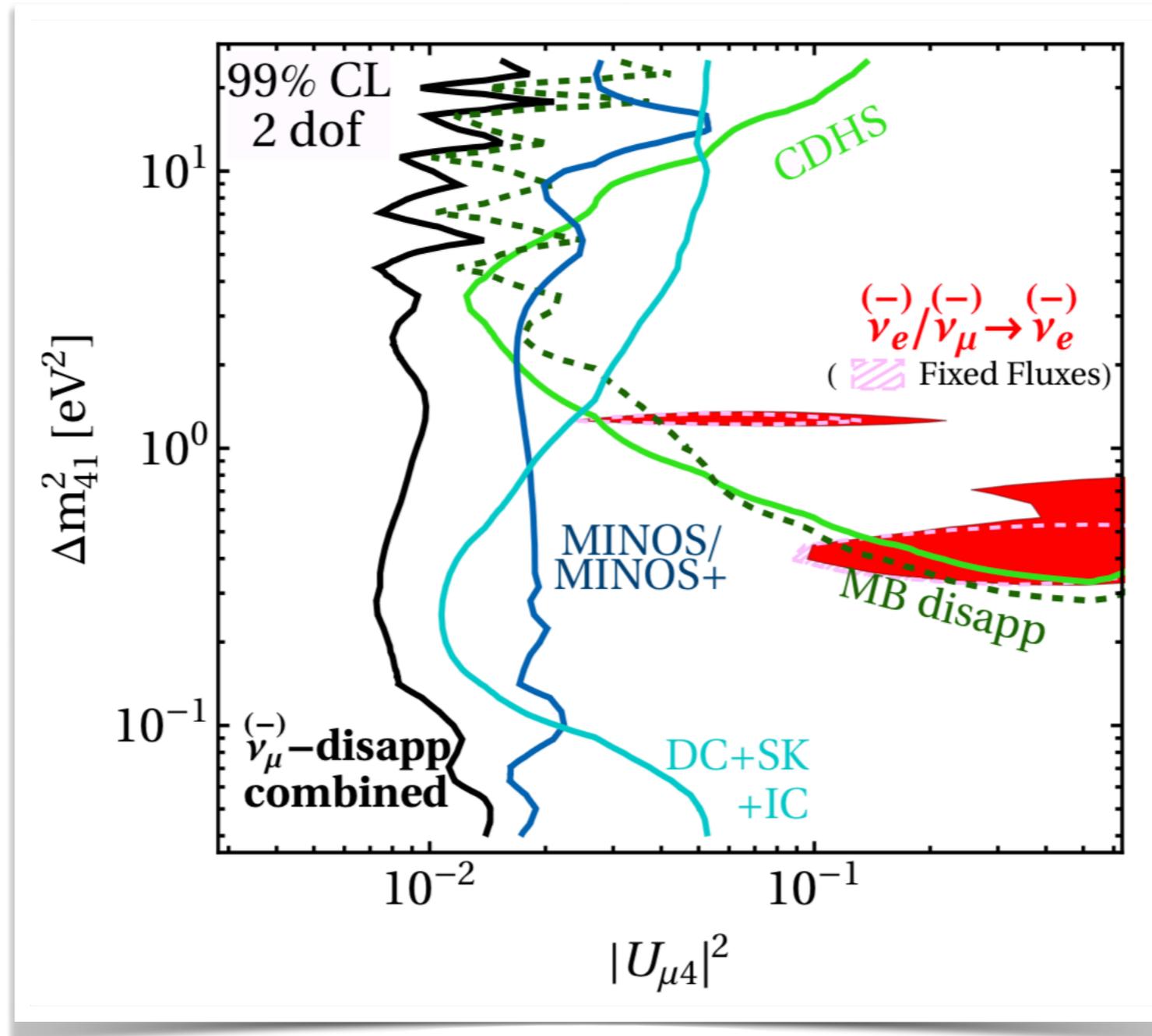
$$P_{\nu_\mu \rightarrow \nu_\mu} \simeq 1 - 2|U_{\mu4}|^2(1 - |U_{\mu4}|^2)$$

$$P_{\nu_\mu \rightarrow \nu_e} \simeq 2|U_{e4}|^2|U_{\mu4}|^2$$

(for $4\pi E / \Delta m_{41}^2 \ll L \ll 4\pi E / \Delta m_{31}^2$)

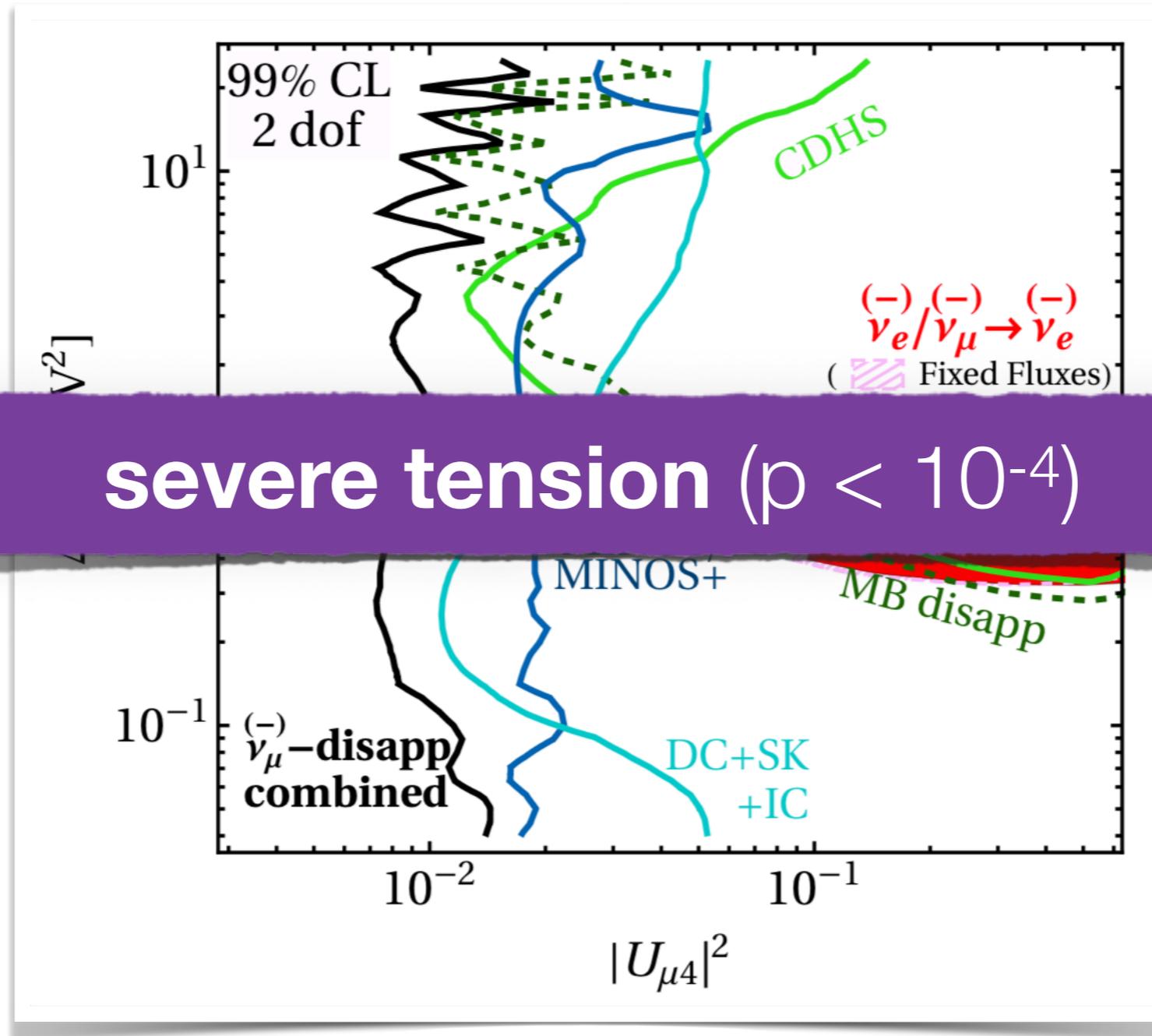
☑ Models can be **over-constrained**.

Global Fit in 3+1 Model



Dentler Hernandez JK Machado Maltoni Martinez Schwetz, [1803.10661](#)
 see also works by Collin Argüelles Conrad Shaevitz, [1607.00011](#)
 Gariazzo Giunti Laveder Li, [1703.00860](#)

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Sterile Neutrinos in Cosmology

Problems don't end here.

An extra neutrino species is in **severe tension with cosmology**.

Standard picture: ν_s production via oscillation at $T \gtrsim \text{MeV}$

$$N_{\text{eff}} \approx 3.38 \quad \text{⚡}$$

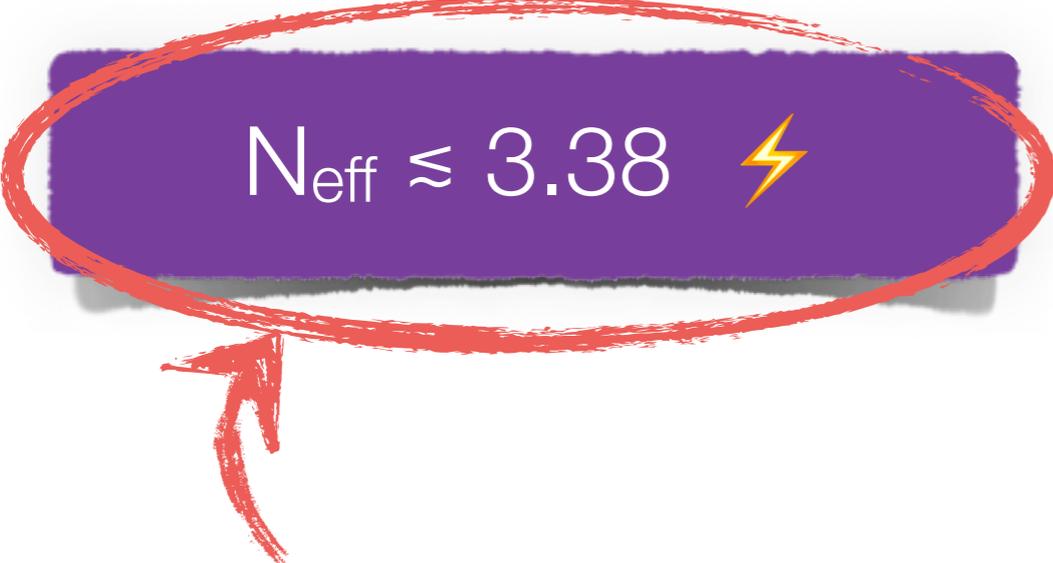
$$\Sigma m_\nu \approx 0.23 \text{ eV} \quad \text{⚡}$$

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measure for the

energy density in relativistic particles

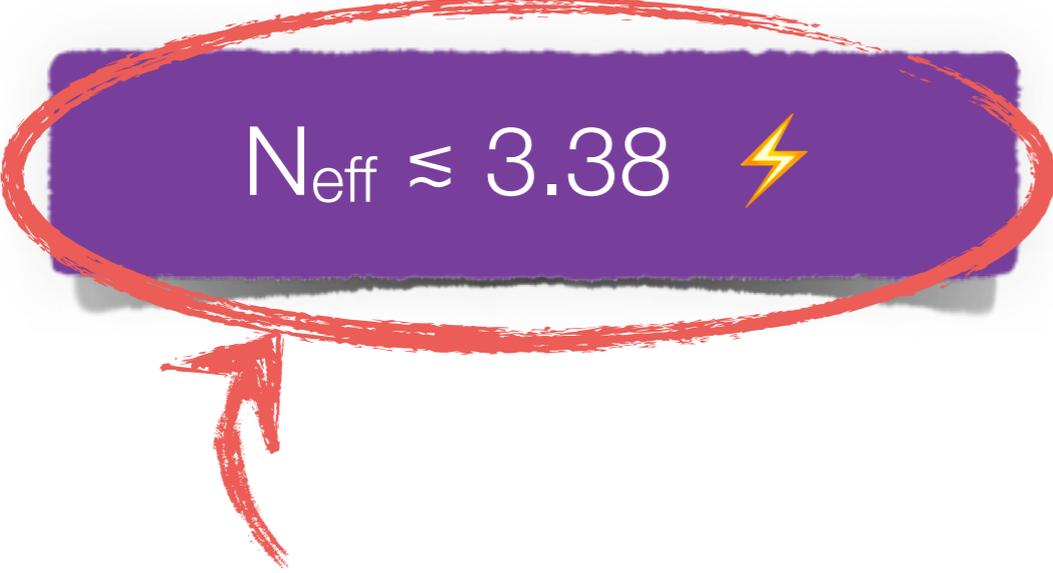
extra neutrino species would imply $N_{\text{eff}} \sim 4$

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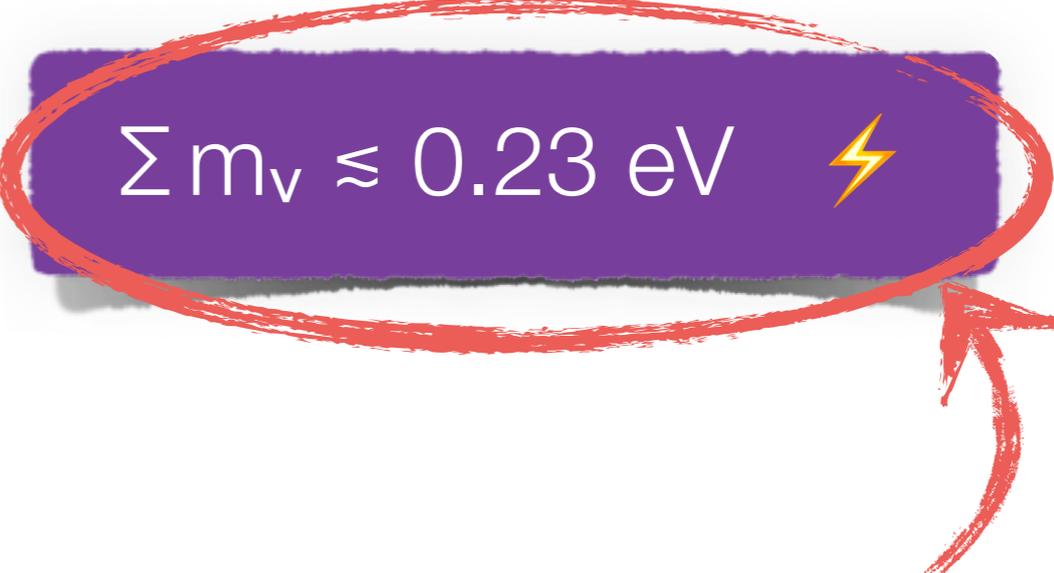
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measure for the

energy density in relativistic particles

extra neutrino species would imply $N_{\text{eff}} \sim 4$


$$\Sigma m_{\nu} \approx 0.23 \text{ eV} \quad \text{⚡}$$

sum of neutrino masses

affects structure formation

sterile neutrino compatible with anomalies

would imply $\Sigma m_{\nu} \sim 1 \text{ eV}$

Other Proposals (1)

- ☑ Decay of $O(\text{keV})$ sterile neutrinos to active neutrinos
Dentler Esteban JK Machado [1911.01427](#)
de Gouvea Peres Prakash Stenico [1911.01447](#)
Hostert Pospelov [2008.11851](#)
- ☑ New resonance matter effects from neutrinophilic Higgs
Asaadi Church Guenette Jones Szelc [1712.08019](#)
- ☑ Altered dispersion relations
Döring Päs Sicking Weiler [1808.07460](#)
Barenboim Martinez-Mirave Ternes Tortola [1911.02329](#)
- ☑ Sterile ν + non-standard interactions
Liao Marfatia Whisnant [1810.01000](#)
- ☑ Mixed $O(1 \text{ eV})$ ν_s oscillation and $O(100 \text{ MeV})$ ν_s decay
Vergani Kamp Diaz Argüelles Conrad Shaevitz Uchida [2105.06470](#)

Other Proposals (2)

- Decay of heavy ν_s produced in beam
 - Palomares-Ruiz Pascoli Schwetz [hep-ph/0505216](#)
 - Gninenko [1101.4004](#)
 - Bai Lu Lu Salvado Stefanek [1512.05357](#)
 - Hernandez-Cabezudo Schwetz [1909.09561](#)
 - Magill Plestid Pospelov Tsai [1803.03262](#)

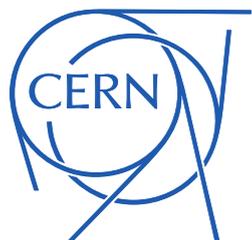
- Decay of ν_s or new scalars produced in the detector
 - Alvarez-Ruso Saul-Sala [1705.00353](#)
 - Bertuzzo Jana Machado Zukanovich-Funchal [1807.09877](#)
 - Abdullahi Hostert Pascoli [2007.11813](#)
 - Ballett Pascoli Ross-Lonergan [1808.02915](#)
 - Dutta Ghosh Li [2006.01319](#)
 - Abdallah Gandhi Roy [2010.06159](#)

- Decay of axion-like particles
 - Chang Chen Ho Tseng [2102.05012](#)

- A model-independent approach
 - Brdar Fischer Smirnov [2007.14411](#)

- ...

Challenge 3: Collective Oscillations



Collective Neutrino Oscillations

☑ flavor evolution described by von Neumann equation

$$i(\partial_t + \vec{v} \cdot \vec{\nabla}_{\vec{r}}) \rho_{\vec{r}, \vec{p}} = [H_{\text{vac}} + H_{\text{MSW}} + H_{\nu\nu}, \rho_{\vec{r}, \vec{p}}]$$

Collective Neutrino Oscillations

- ☑ flavor evolution described by Schrödinger-like equation

density matrix
in flavour space

$$i(\partial_t + \vec{v} \cdot \vec{\nabla}_{\vec{r}}) \rho_{\vec{r}, \vec{p}} = [H_{\text{vac}} + H_{\text{MSW}} + H_{\nu\nu}, \rho_{\vec{r}, \vec{p}}]$$

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vacuum oscillations

$$H_{\text{vac}} = \frac{1}{2E} U_{\text{PMNS}} M^2 U_{\text{PMNS}}^\dagger$$

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matter effects

$$H_{\text{MSW}} = \sqrt{2} G_F n_e \begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix}$$

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self-interactions

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- ✓ at large n_ν :

- same equation for all energies \Rightarrow synchronization
- non-trivial angular dependence

- ✓ non-linear equation \Rightarrow all kinds of instabilities

Collective Neutrino Oscillations

- ★ pure **Standard Model** problem
- ★ solution will be crucial for the next **Galactic supernova**
- ★ **the neutrinos are already on their way**

Challenge 4: New ν Physics



Example: New Neutrino Interaction

Coloma Esteban Gonzalez-Garcia Maltoni [arXiv:1911.09109](https://arxiv.org/abs/1911.09109)
Biggio Blenow Fernandez-Martinez [arXiv:0907.0097](https://arxiv.org/abs/0907.0097)



Example: New Neutrino Interaction

☑ EFT below the electroweak scale

$$\mathcal{L}_{\text{NSI,NC}} = \sum_{f,\alpha,\beta} 2\sqrt{2}G_F \varepsilon_{\alpha\beta}^{f,P} (\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta) (\bar{f} \gamma^\mu P f) + \text{h.c.}$$

$$\mathcal{L}_{\text{NSI,CC}} = \sum_{f,f',\alpha,\beta} 2\sqrt{2}G_F \varepsilon_{\alpha\beta}^{ff',P} (\bar{\nu}_\alpha \gamma_\mu P_L \ell_\beta) (\bar{f}' \gamma^\mu P f) + \text{h.c.}$$

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Example: New Neutrino Interaction

dim-6 operators

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dimensionless coefficients

(strength of new interactions
relative to SM weak interactions)

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dimensionless coefficients

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☑ NC: non-standard **matter effects**

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dim-6 operators

☑ EFT below the electroweak scale

$$\mathcal{L}_{\text{NSI,NC}} = \sum_{f,\alpha,\beta} 2\sqrt{2}G_F \varepsilon_{\alpha\beta}^{f,P} (\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta) (\bar{f} \gamma^\mu P f) + \text{h.c.}$$

$$\mathcal{L}_{\text{NSI,CC}} = \sum_{f,f',\alpha,\beta} 2\sqrt{2}G_F \varepsilon_{\alpha\beta}^{ff',P} (\bar{\nu}_\alpha \gamma_\mu P_L \ell_\beta) (\bar{f}' \gamma^\mu P f) + \text{h.c.}$$

dimensionless coefficients

(strength of new interactions
relative to SM weak interactions)

☑ NC: non-standard **matter effects**

☑ CC: anomalous **production and detection**
(near detectors!)

Coloma Esteban Gonzalez-Garcia Maltoni [arXiv:1911.09109](https://arxiv.org/abs/1911.09109)

Biggio Blenow Fernandez-Martinez [arXiv:0907.0097](https://arxiv.org/abs/0907.0097)

Example: New Neutrino Interactions

- ☑ EFT below the electroweak scale

$$\mathcal{L}_{\text{NSI,NC}} = \sum_{f,\alpha,\beta} 2\sqrt{2}G_F \varepsilon_{\alpha\beta}^{f,P} (\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta)$$

$$\mathcal{L}_{\text{NSI,CC}} = \sum_{f,f',\alpha,\beta} 2\sqrt{2}G_F \varepsilon_{\alpha\beta}^{ff',P} (\bar{\nu}_\alpha \gamma_\mu P_L \ell_\beta)$$

not covered by EFT:

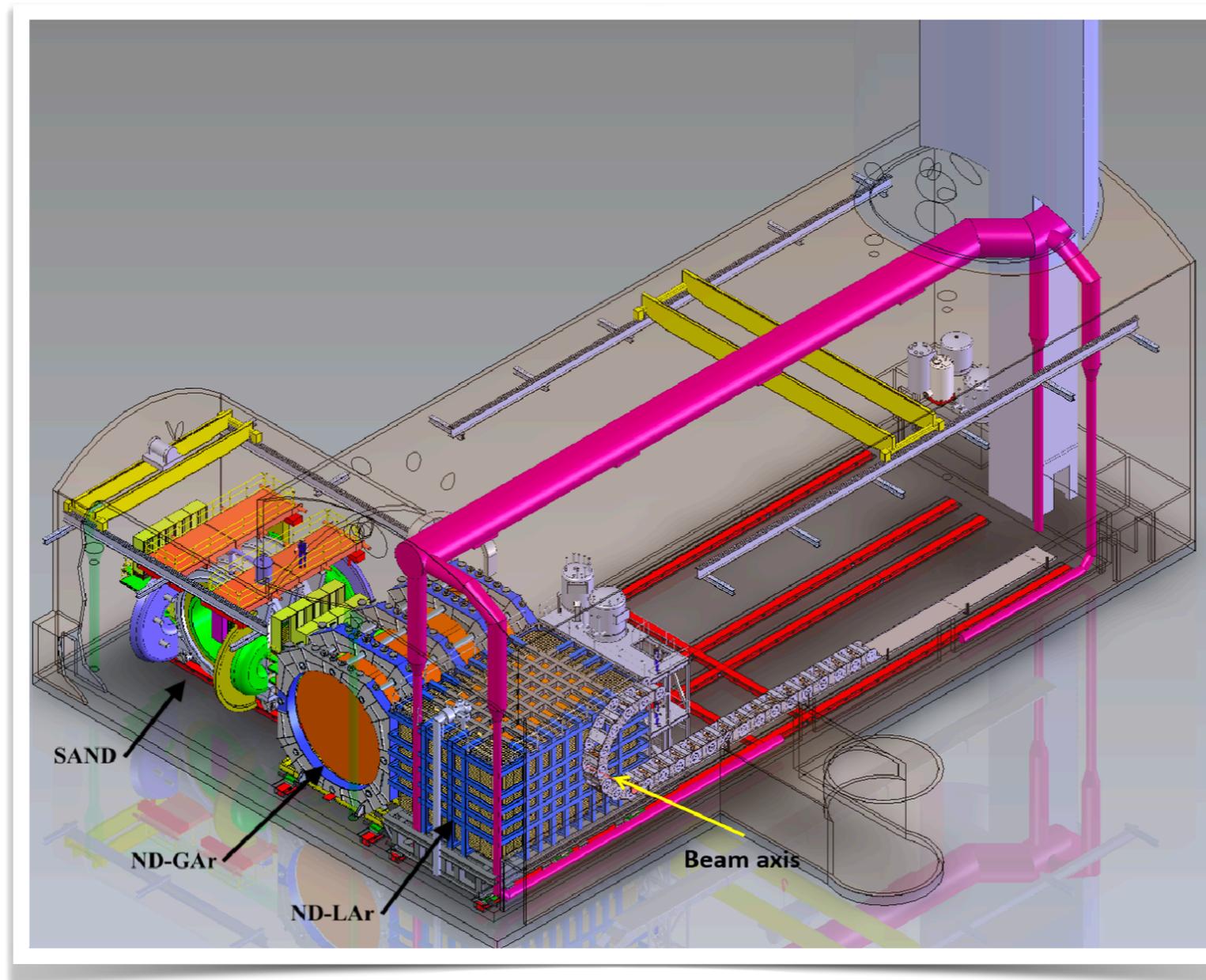
- ☑ light sterile neutrinos
- ☑ magnetic moments
- ☑ “secret” interactions
- ☑ neutrino–DM interactions
- ☑ ...

- ☑ NC: non-standard matter effects

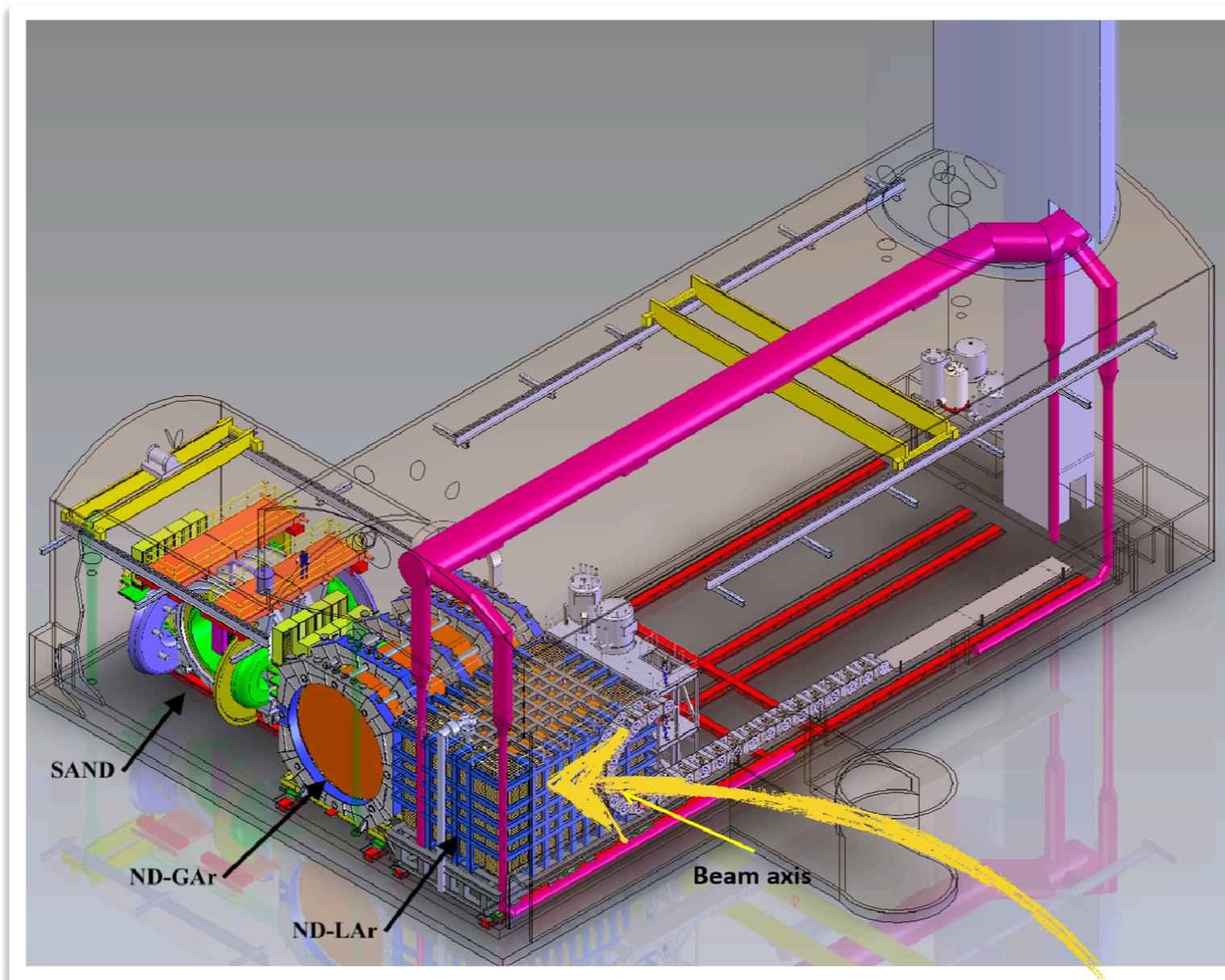
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New Physics at Near Detectors

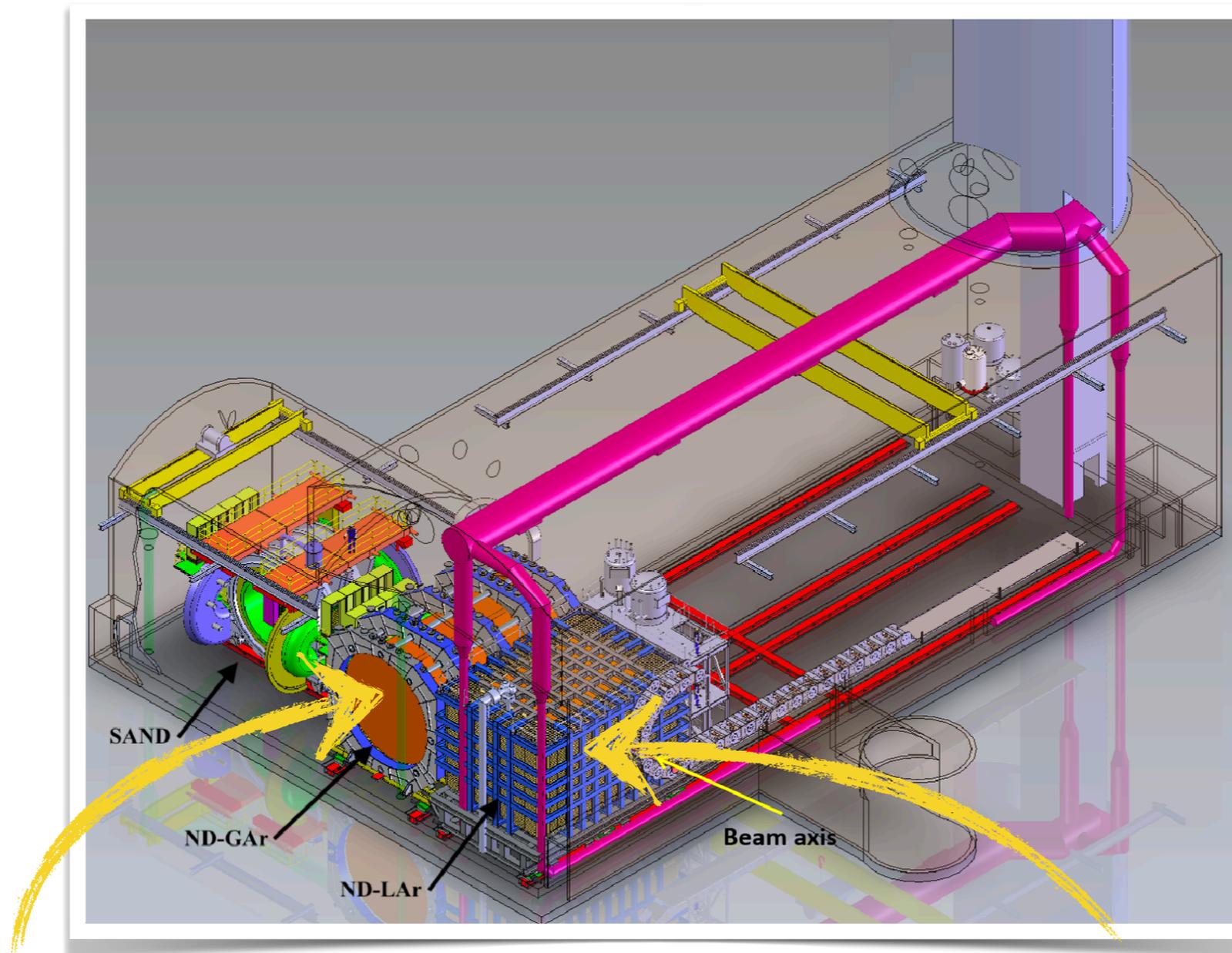


New Physics at Near Detectors



Liquid Argon TPC (“ND-LAr”)

New Physics at Near Detectors

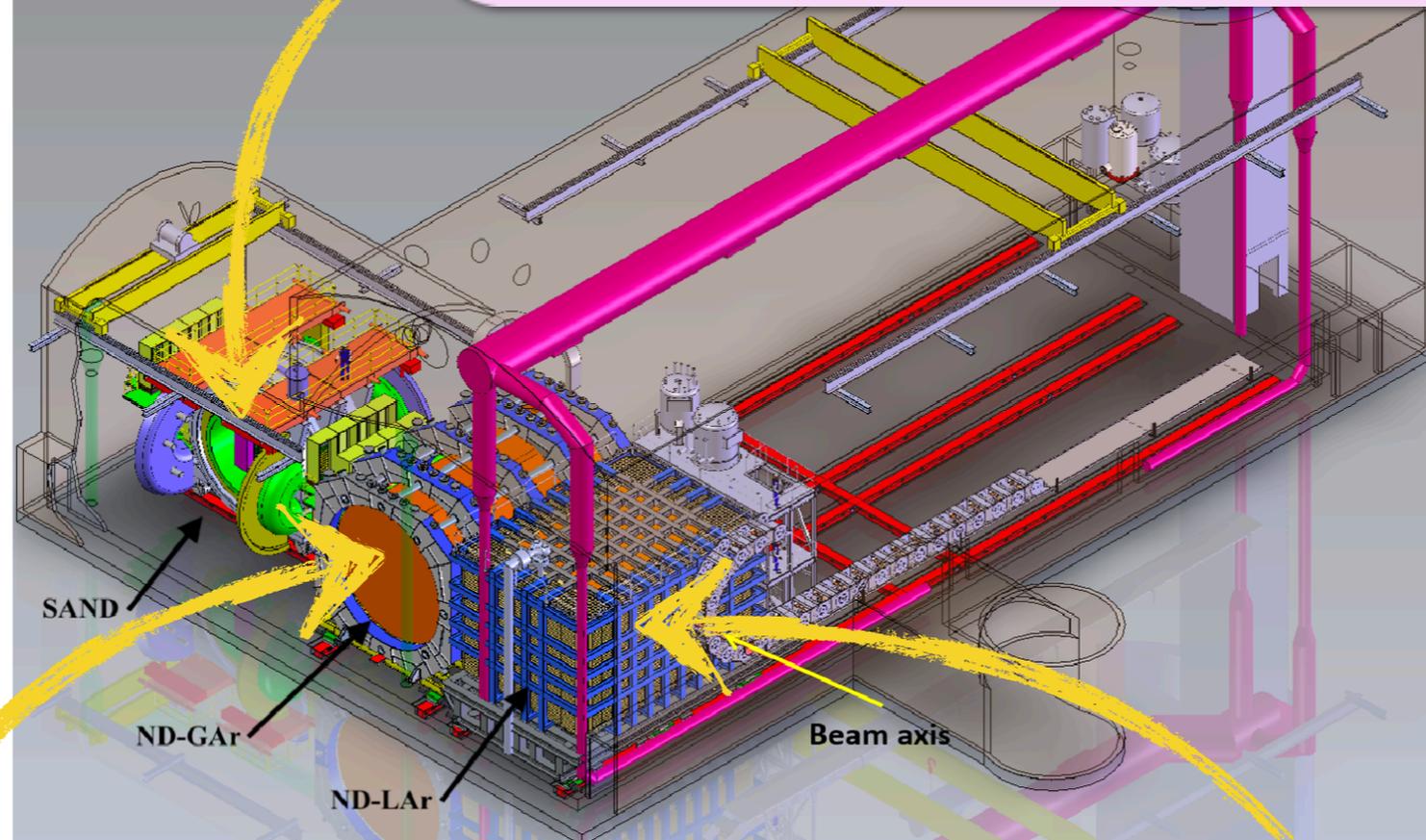


HP Gas TPC + ECal (“ND-GAr”)

Liquid Argon TPC (“ND-LAr”)

New Physics at Near Detectors

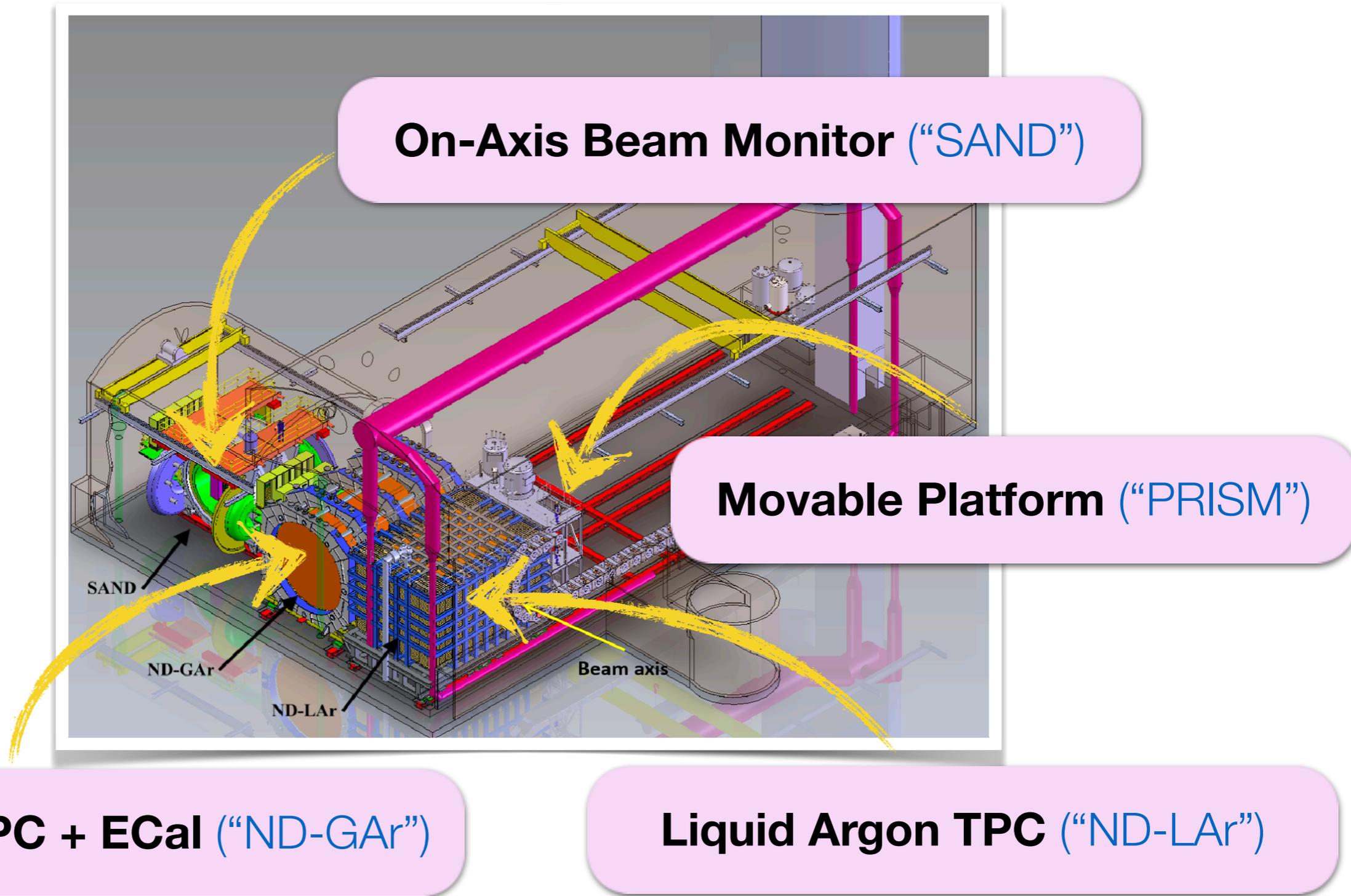
On-Axis Beam Monitor (“SAND”)



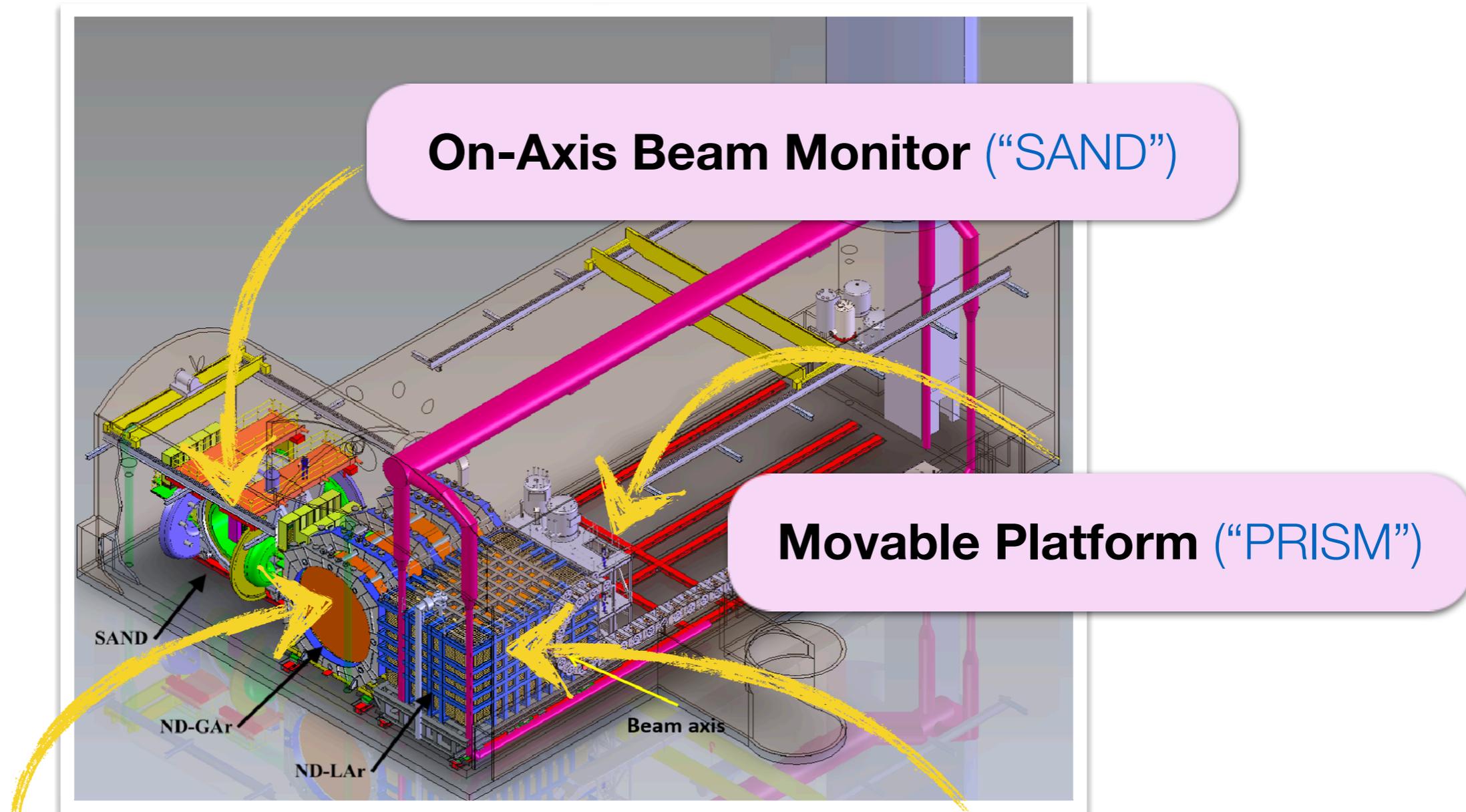
HP Gas TPC + ECal (“ND-GAr”)

Liquid Argon TPC (“ND-LAr”)

New Physics at Near Detectors



New Physics at Near Detectors



On-Axis Beam Monitor (“SAND”)

Movable Platform (“PRISM”)

SAND

ND-GAr

ND-LAr

Beam axis

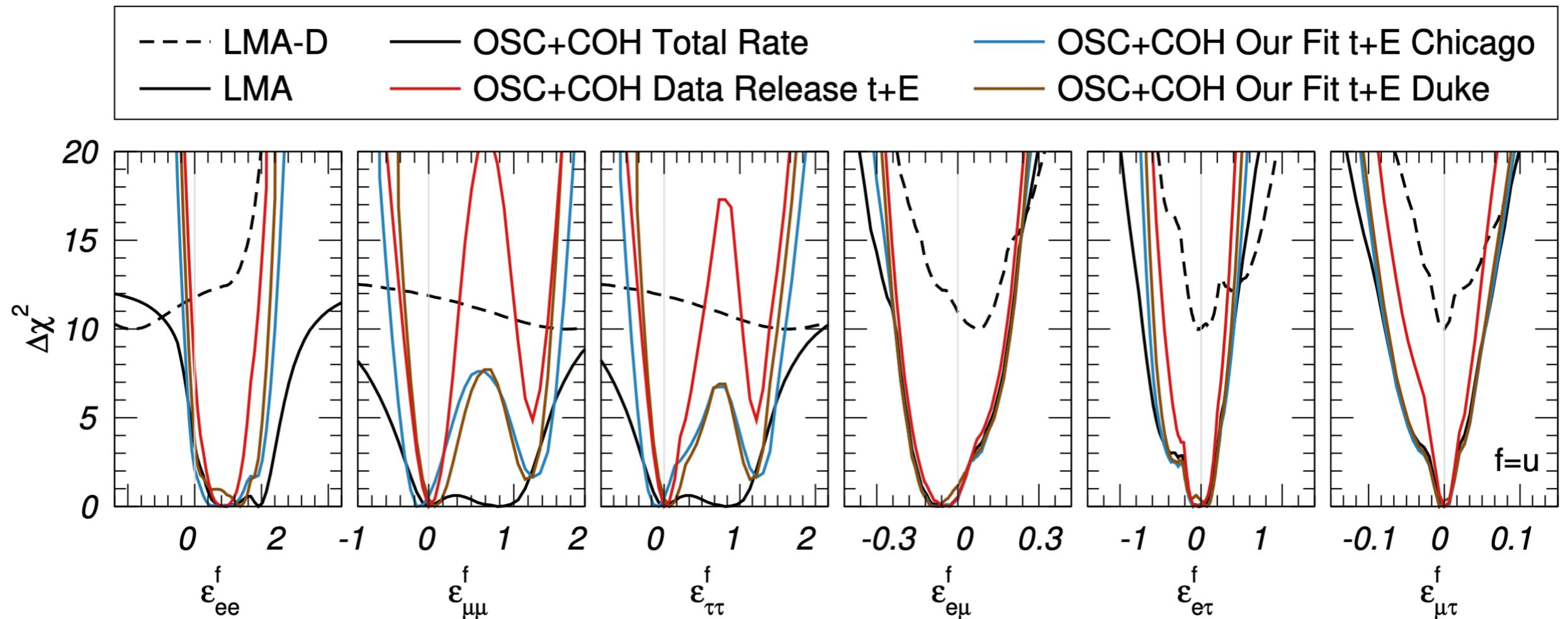
HP Gas TPC + ECal (“SEASIDE”)

(**S**ystem of **E**vaporated **A**rgon for **S**ystematics, **I**nteractions, and **D**etailed **E**vent Topologies)

Liquid Argon TPC (“LAGOON”)

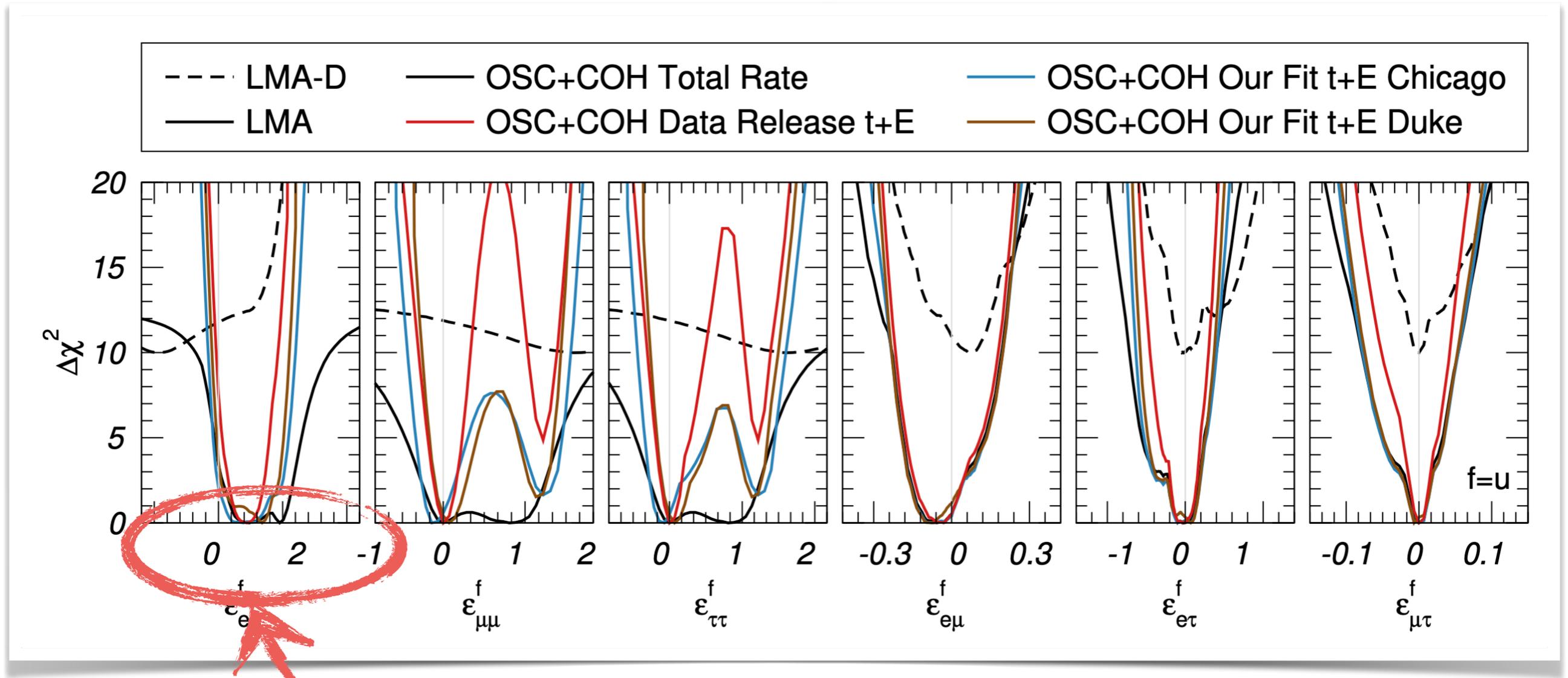
(**L**iquid **A**rgon **G**adget for **O**n-axis and **O**ff-axis **N**eutrinos)

Anomalous Neutral Currents in Oscillations



Coloma Esteban Gonzalez-Garcia Maltoni arXiv:1911.09109

Anomalous Neutral Currents in Oscillations

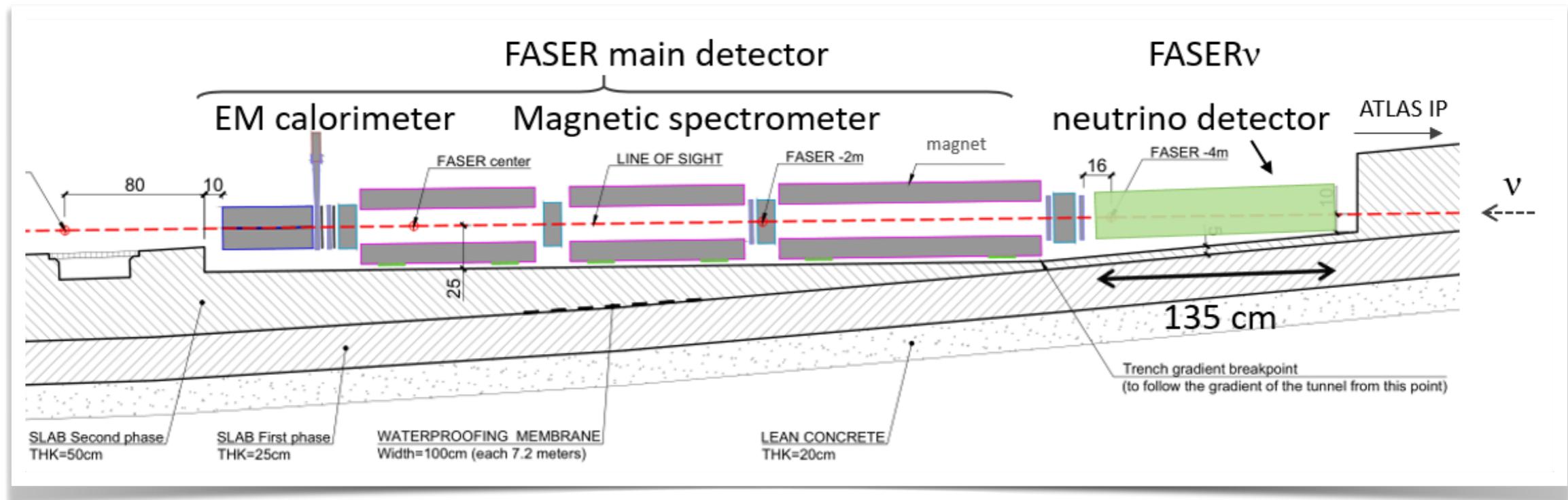


Coloma Esteban Gonzalez-Garcia Maltoni arXiv:1911.09109

sensitivity to interactions
similar in strength to
SM weak interactions

Anomalous Charged Currents

☑ Interesting new opportunity: **FASERv** at the **LHC**



<https://faser.web.cern.ch/about-the-experiment/detector-design/fasernu>

Example: Neutrino Magnetic Moments

$$\mathcal{L} \supset \frac{1}{2} \mu_\nu^{\alpha\beta} \bar{\nu}_L^\alpha \sigma^{\mu\nu} \nu_R^\beta F_{\mu\nu}$$

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electromagnetic
field strength tensor

Example: Neutrino Magnetic Moments

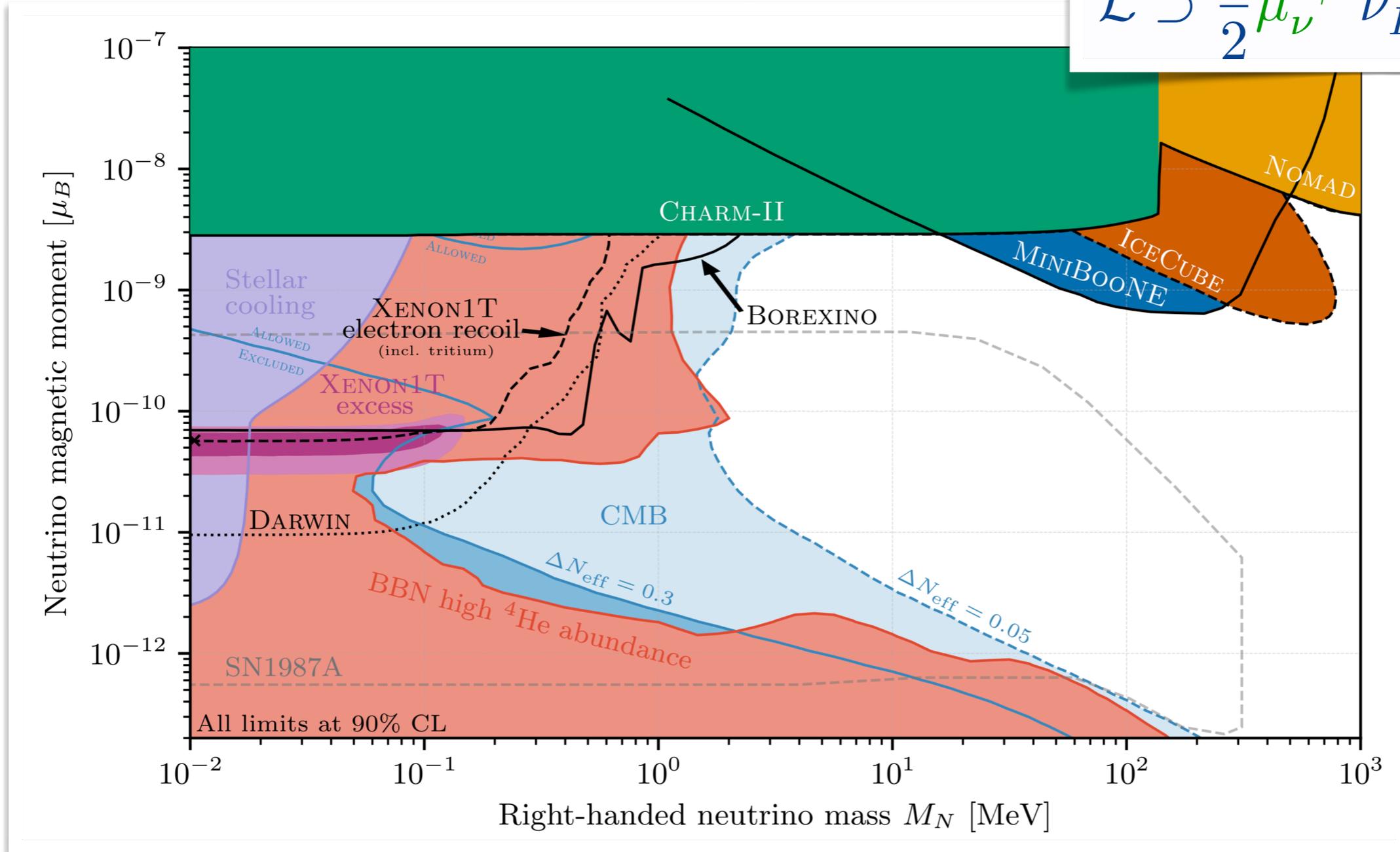
Couples LH and RH neutrinos

$$\mathcal{L} \supset \frac{1}{2} \mu_\nu^{\alpha\beta} \bar{\nu}_L^\alpha \sigma^{\mu\nu} \nu_R^\beta F_{\mu\nu}$$

electromagnetic
field strength tensor

Example: Neutrino Magnetic Moments

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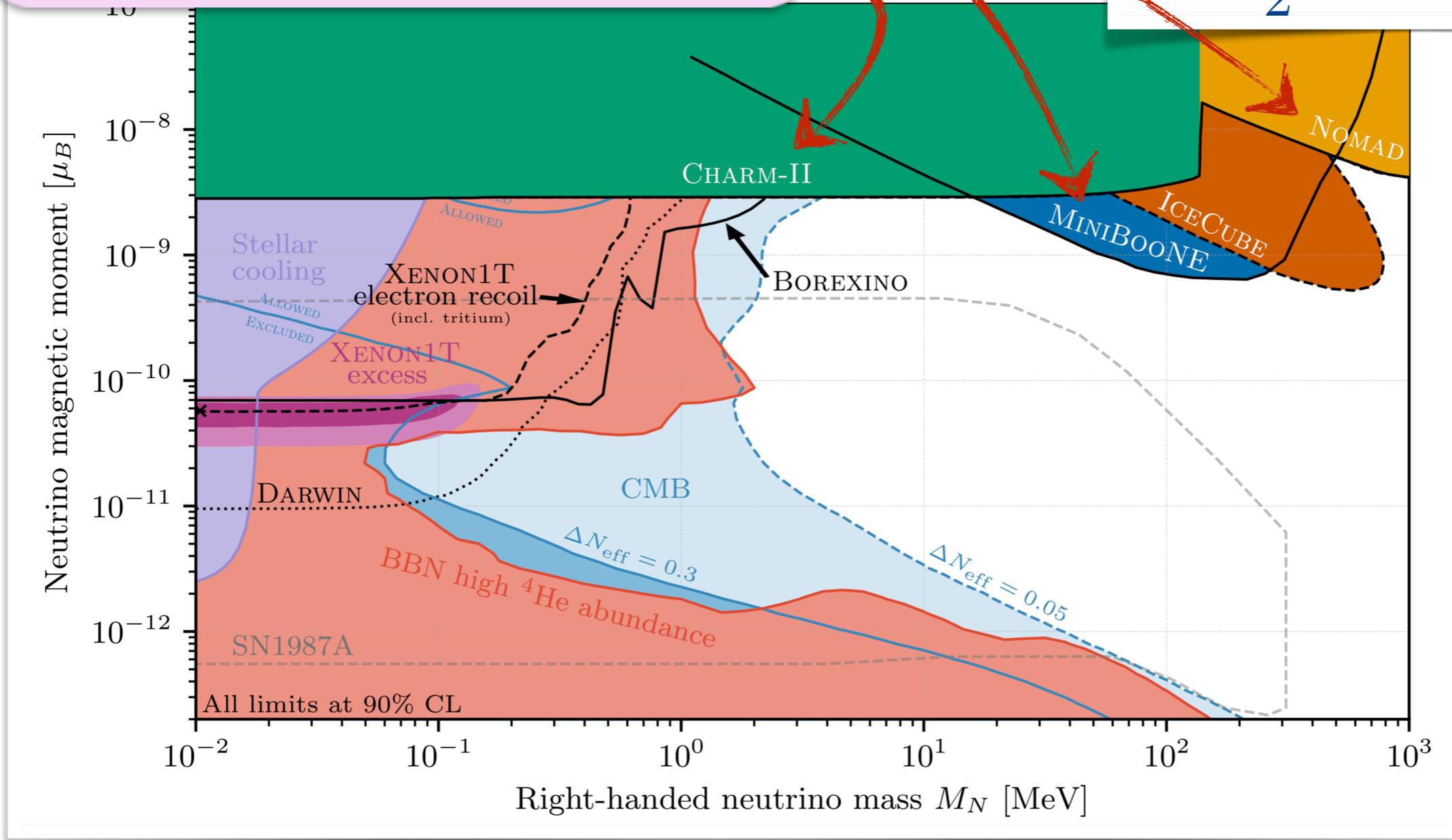
Coloma Machado Martinez-Soler Shoemaker [1707.08573](#), Magill Plestid Pospelov Tsai [1803.03262](#)
 Shoemaker Wyenberg [1811.12435](#), Brdar Greljo JK Opferkuch [arXiv:2007.15563](#), Greljo Stangl Thomsen [2103.13991](#)



Example: Neutrino Magnetic Moments

constraints from accelerator experiments

$$\mathcal{L} \supset \frac{1}{2} \mu_{\nu}^{\alpha\beta} \bar{\nu}_L^{\alpha} \sigma^{\mu\nu} \nu_R^{\beta} F_{\mu\nu}$$



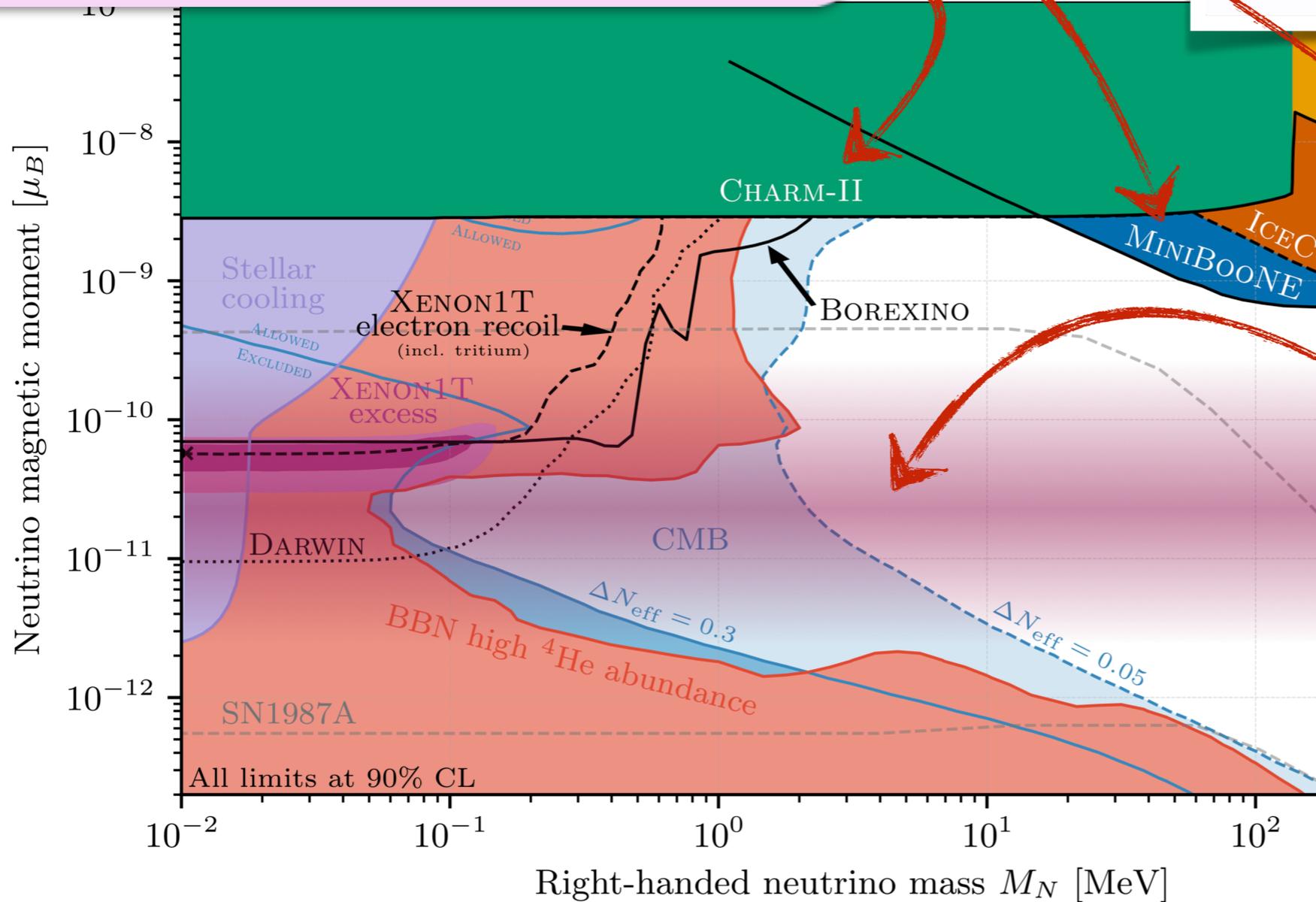
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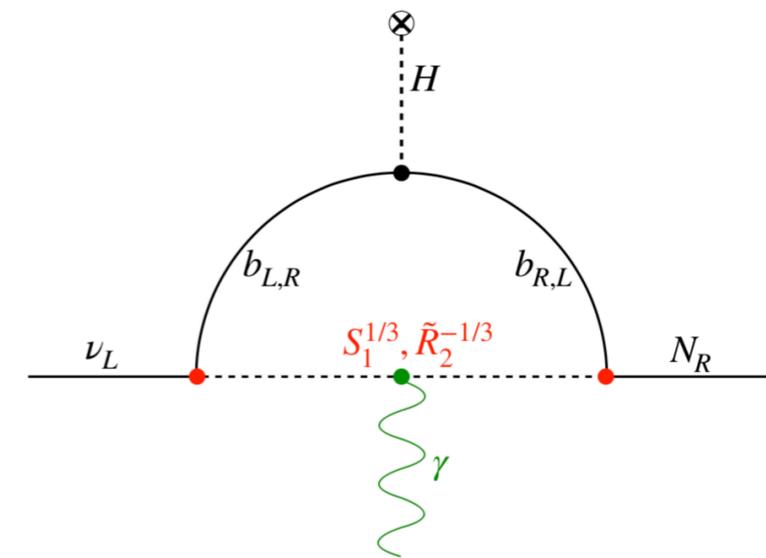
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leptoquark model, inspired by flavor anomalies



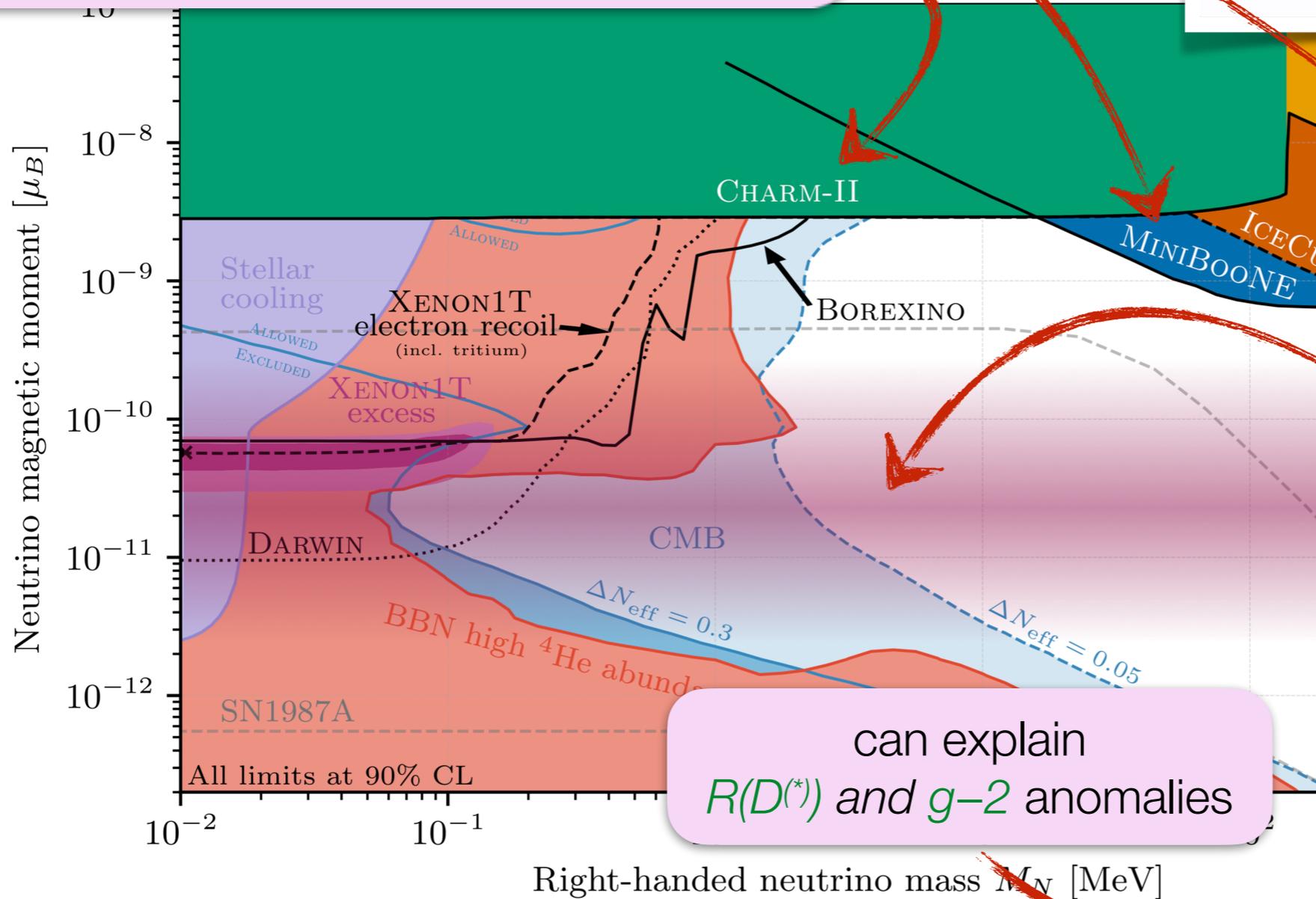
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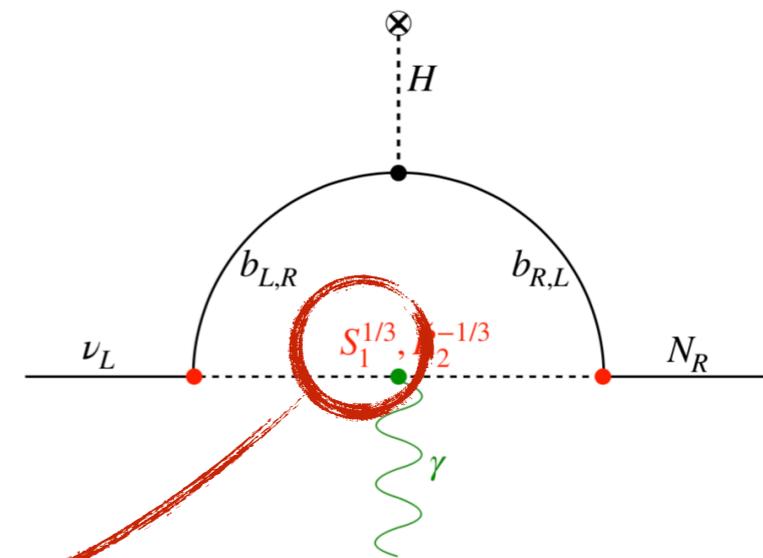
Example: Neutrino Magnetic Moments

constraints from accelerator experiments

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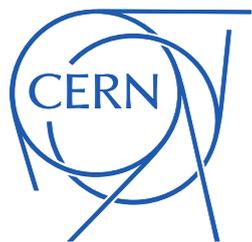
leptoquark model, inspired by flavor anomalies



Coloma Machado Martinez-Soler Shoemaker [1707.08573](#), Magill Plestid Pospelov Tsai [1803.03262](#)
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Summary



Summary

- ☑ Neutrino physics has come a long way
 - well-established 3-flavor picture
 - tremendous experimental & theoretical progress
- ☑ But some serious dents remain in this picture
 - neutrino interactions poorly understood
 - unresolved anomalies
 - neutrinos in extreme environments
 - physics beyond the Standard Model?

Beyond this Talk

- Neutrino Cosmology**
(crucial role in evolution of the Universe, probe of new physics)
- Neutrino Astrophysics**
(learn about neutrinos by looking at the stars,
learn about the stars by looking for neutrinos)
- Neutrinoless Double Beta Decay**
(are neutrinos Dirac or Majorana particles?)
- Absolute Neutrino Masses**
(from terrestrial experiments and/or from cosmology)
- ...