Probing (Beyond) the Standard Model physics
On heaven & earth

Future vision

Wouter Dekens

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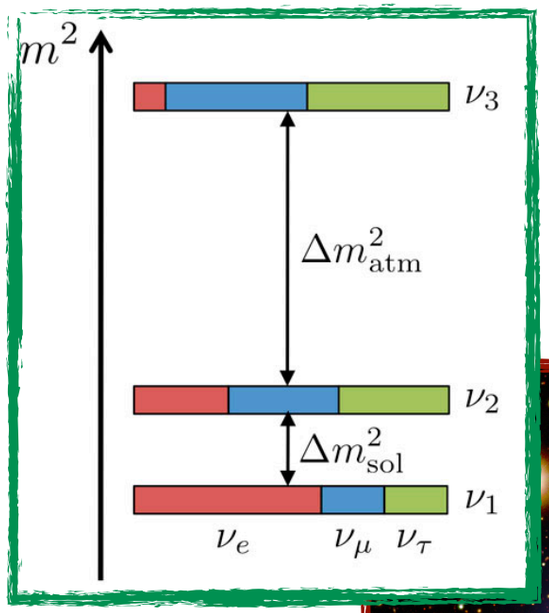
INSTITUTE for NUCLEAR THEORY

The Standard Model

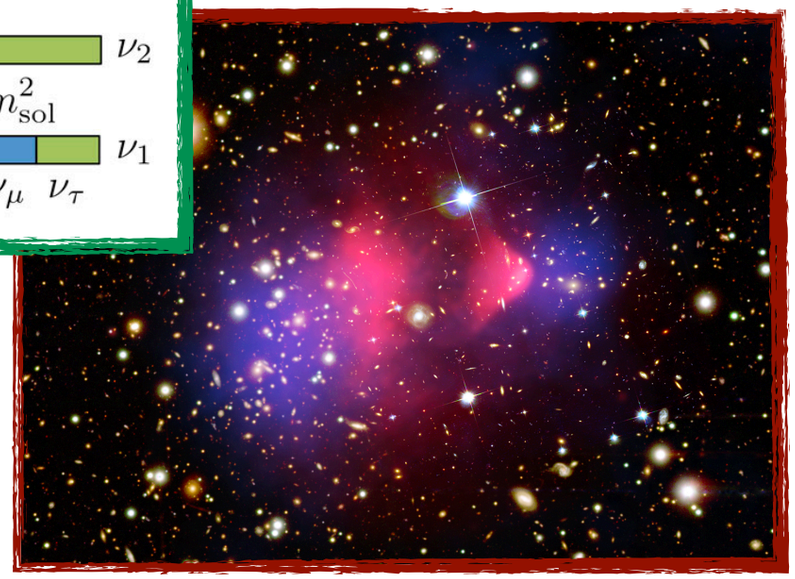
Open questions

Neutrino masses



Credit: JUNO Collaboration

Dark Matter



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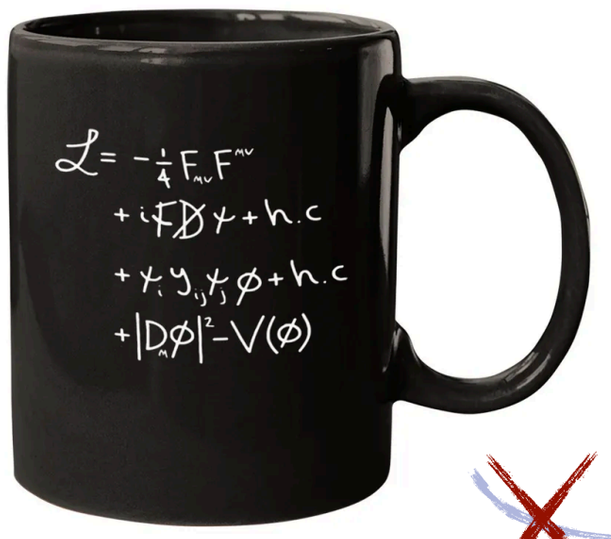
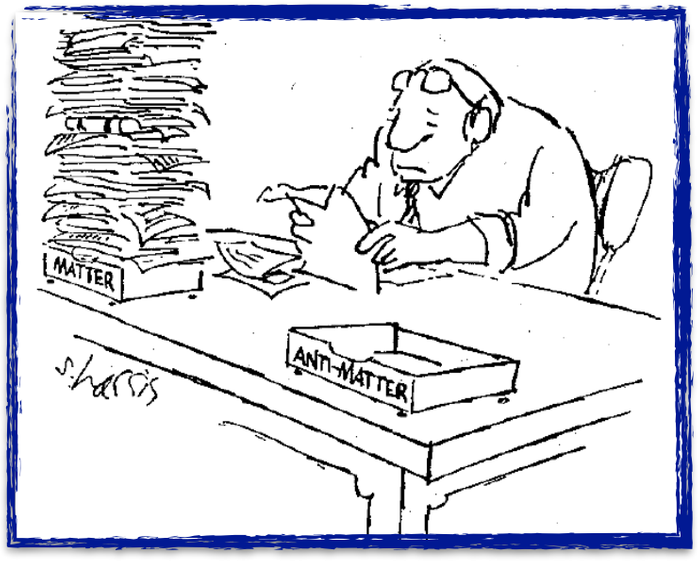




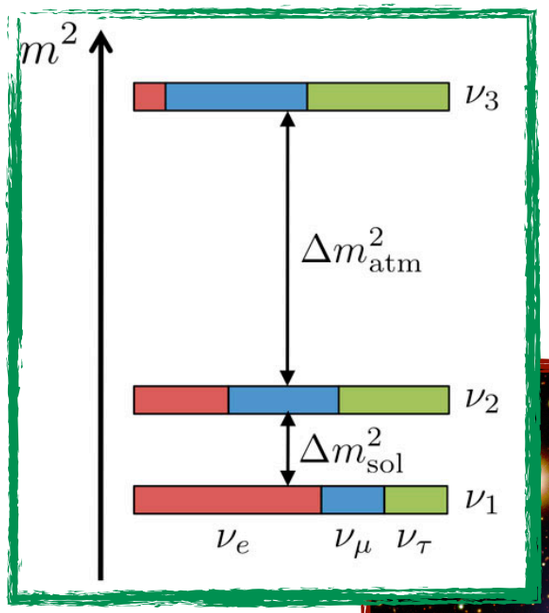
Why there's matter

Are there more than the known 4 forces?

The Standard Model

Open questions

Neutrino masses



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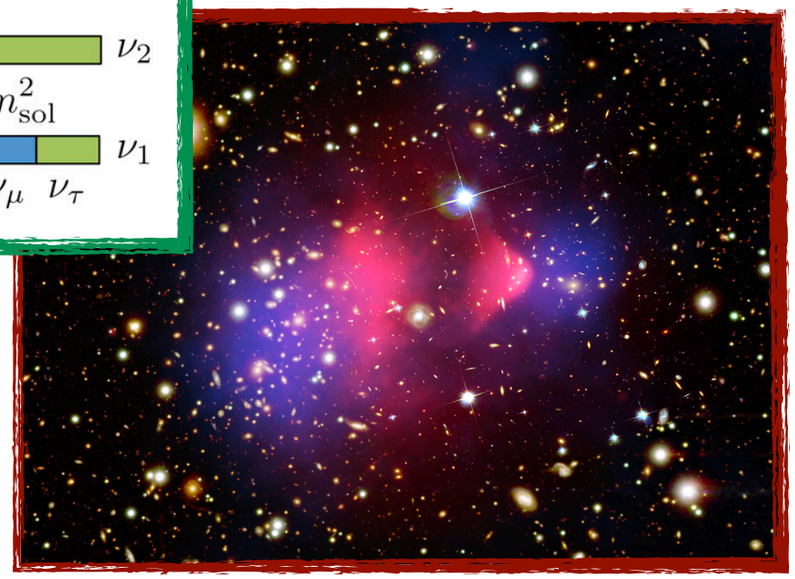

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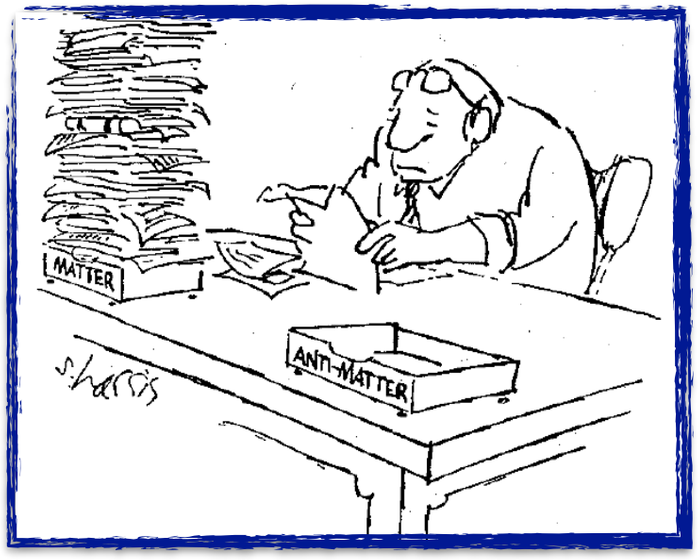
Answers require

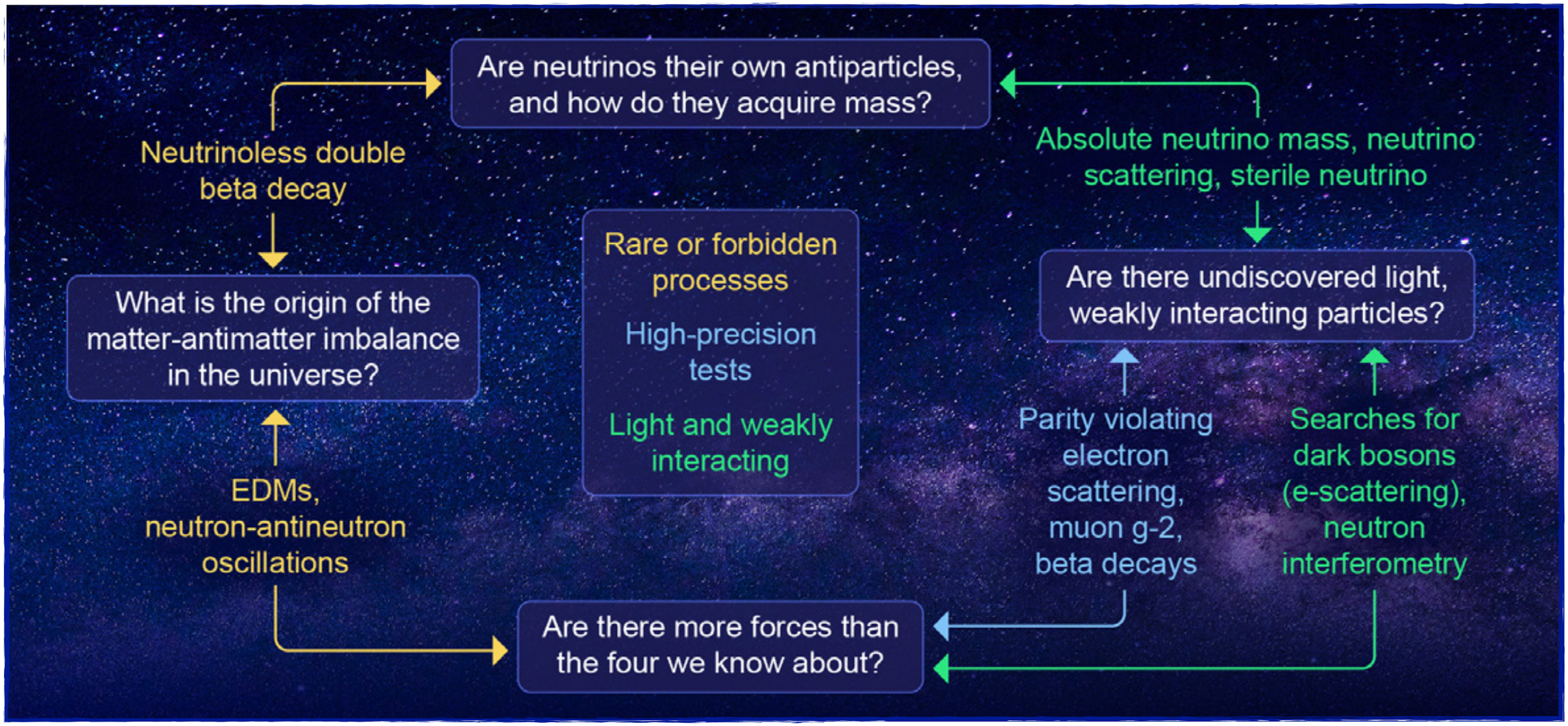
new particles and interactions

Are there more than the known 4 forces?



Why there's matter

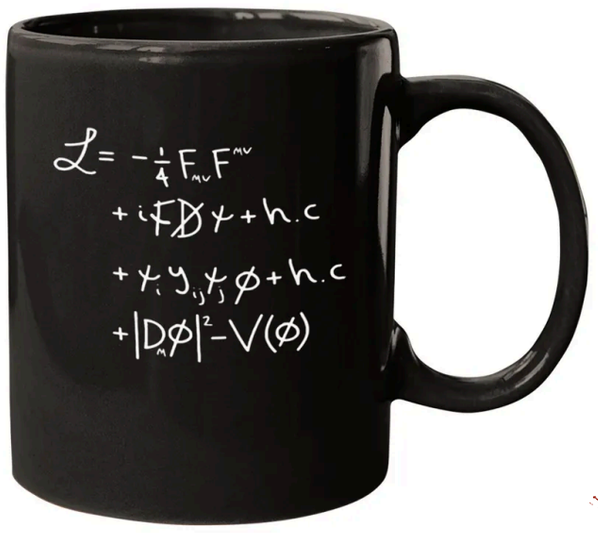
How to find new physics



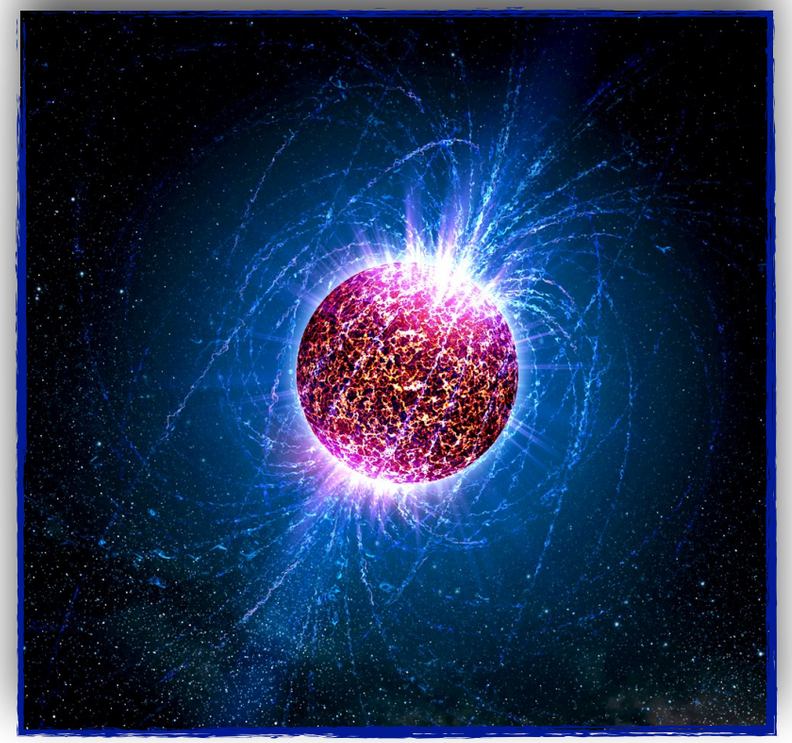
2023 Long Range Plan for Nuclear Science

The Standard Model

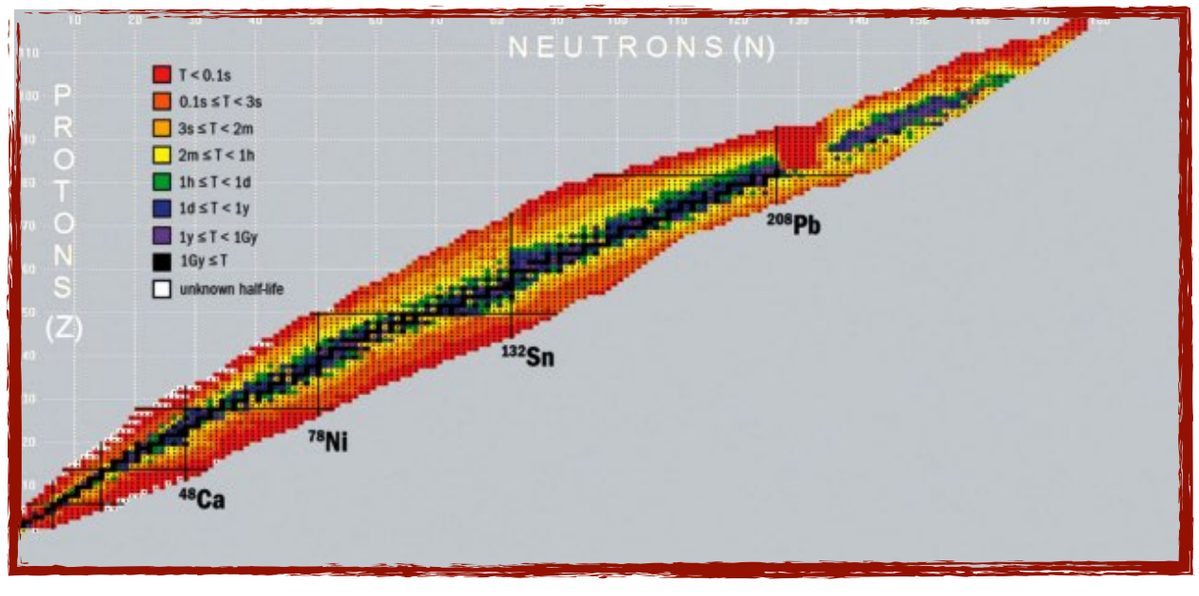
Hard questions



Neutron Stars



Nuclei



The Standard Model

Hard questions

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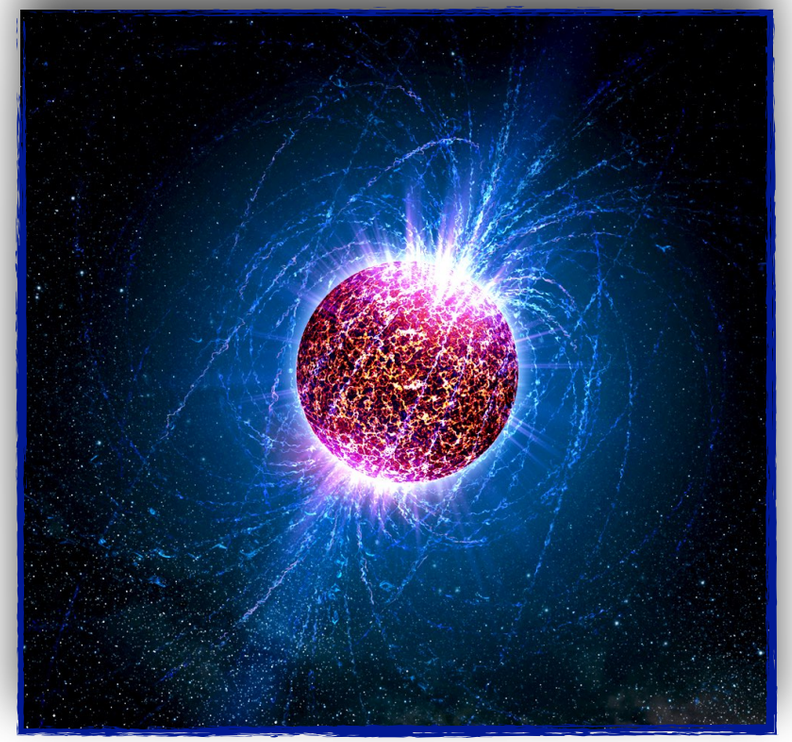
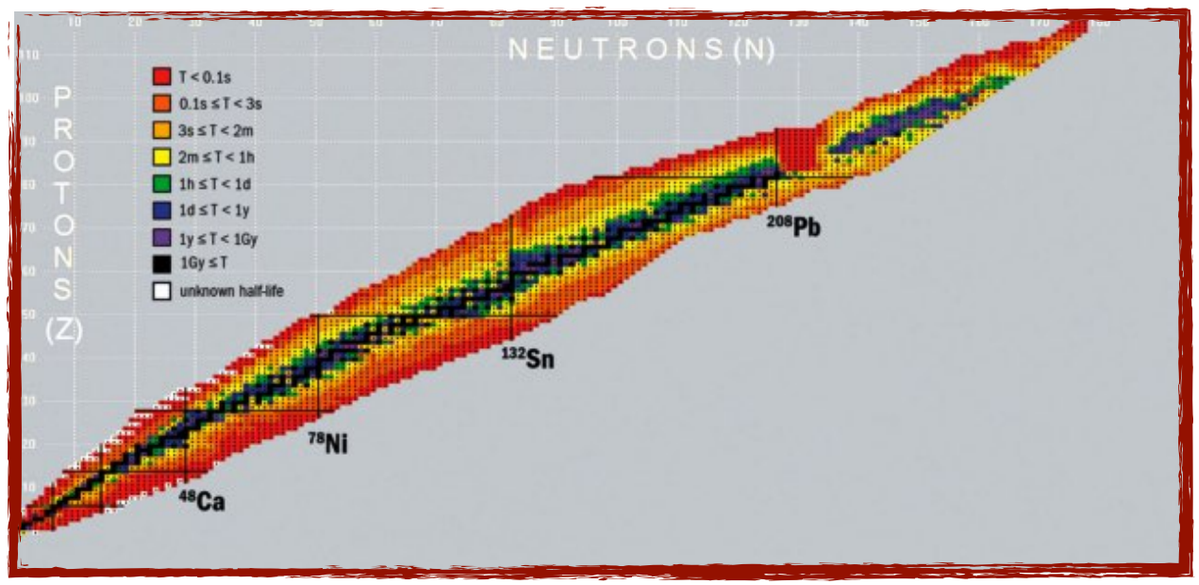


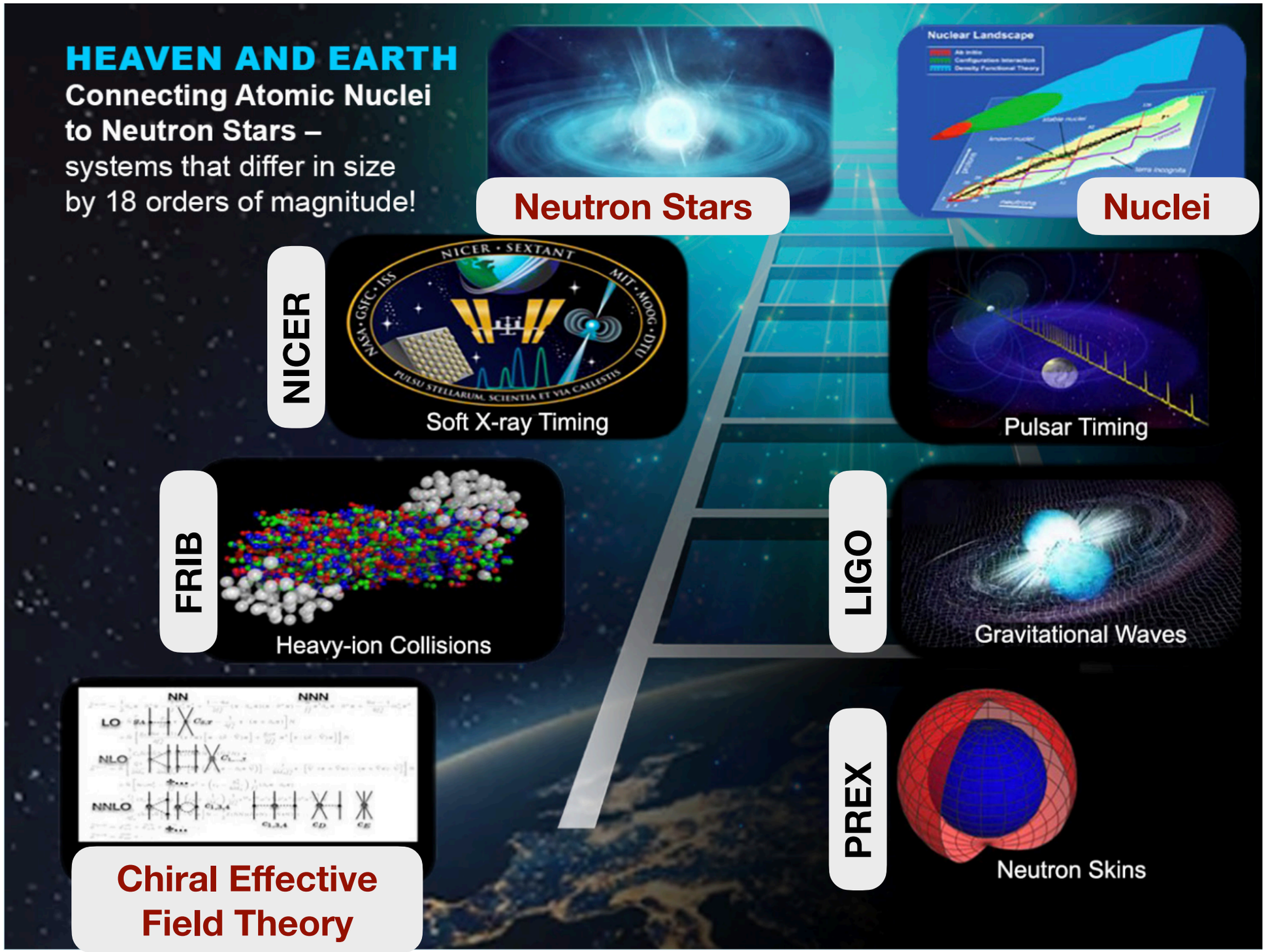
Requires accurate

description of Nuclear Forces

Nuclei



Connecting nuclei to the cosmos



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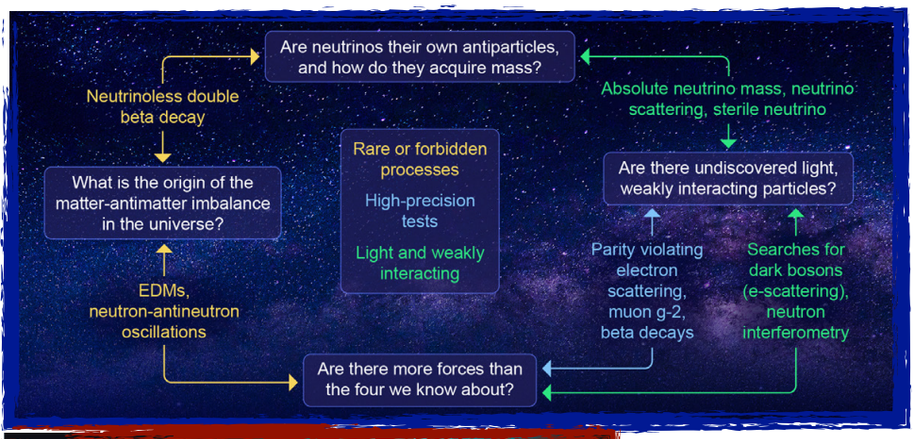
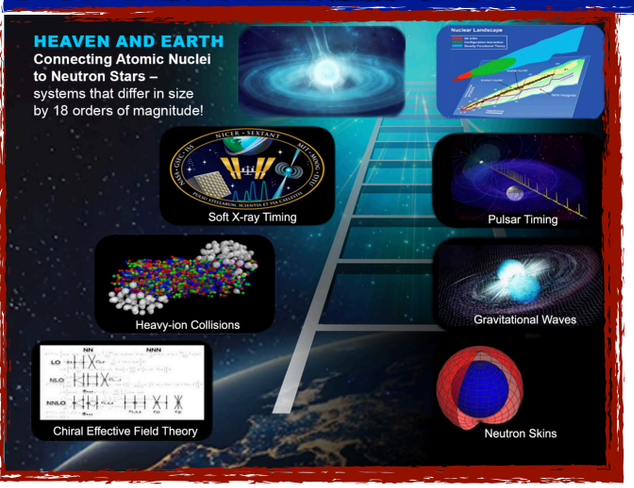
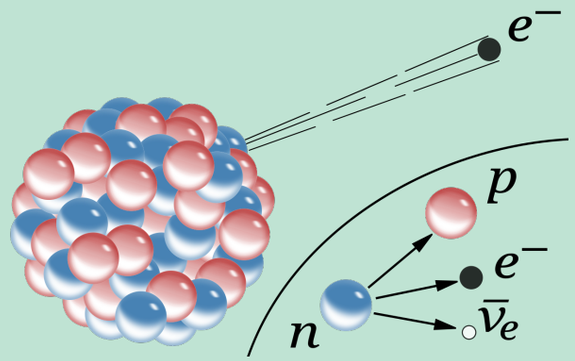




Precision frontier

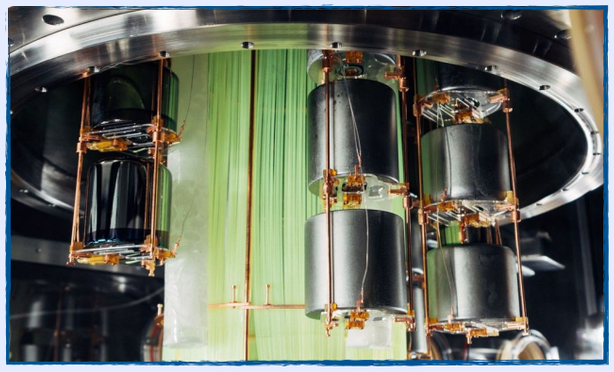
- Cabibbo Angle Anomaly & β decays



Effectively probing (Beyond) the SM physics

Fundamental Symmetries

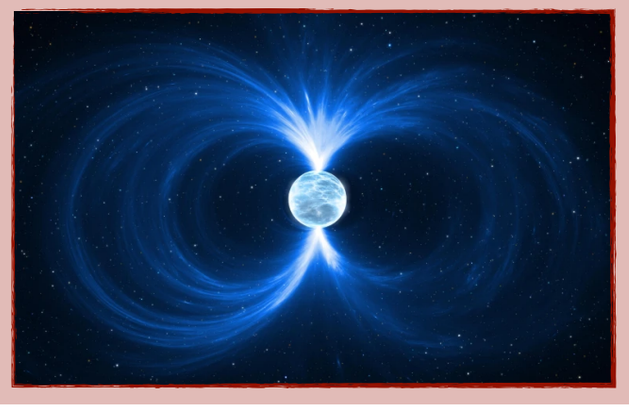
- Lepton number & Sterile Neutrinos

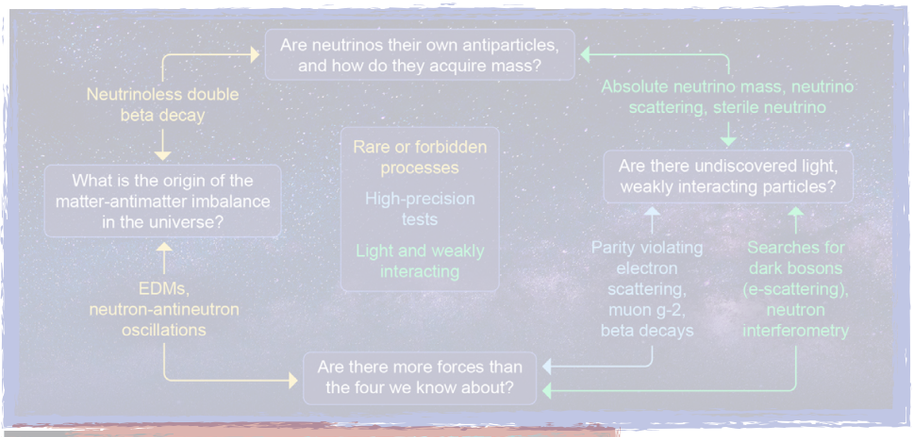


$0\nu\beta\beta$ LEGEND (ORNL lead US lab)

Connecting nuclei to the cosmos

- Dense matter & Neutron stars





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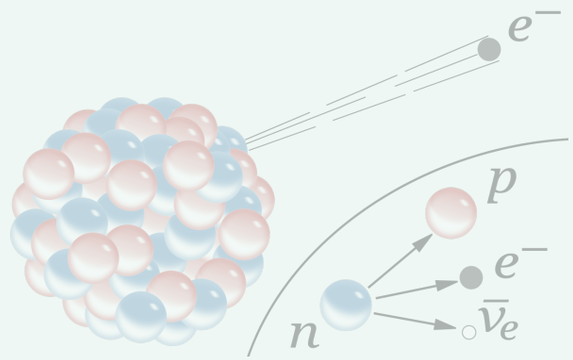

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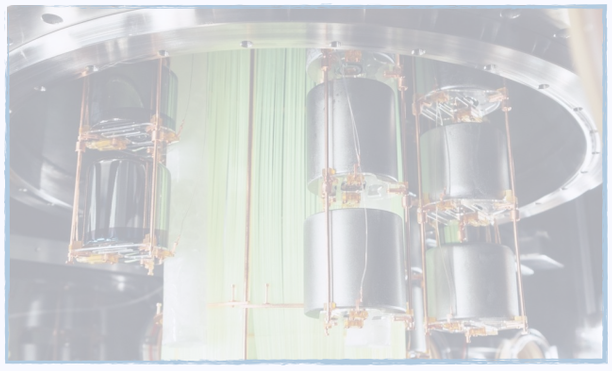

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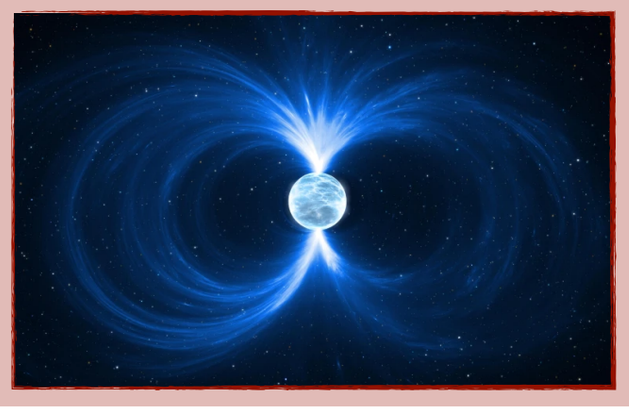
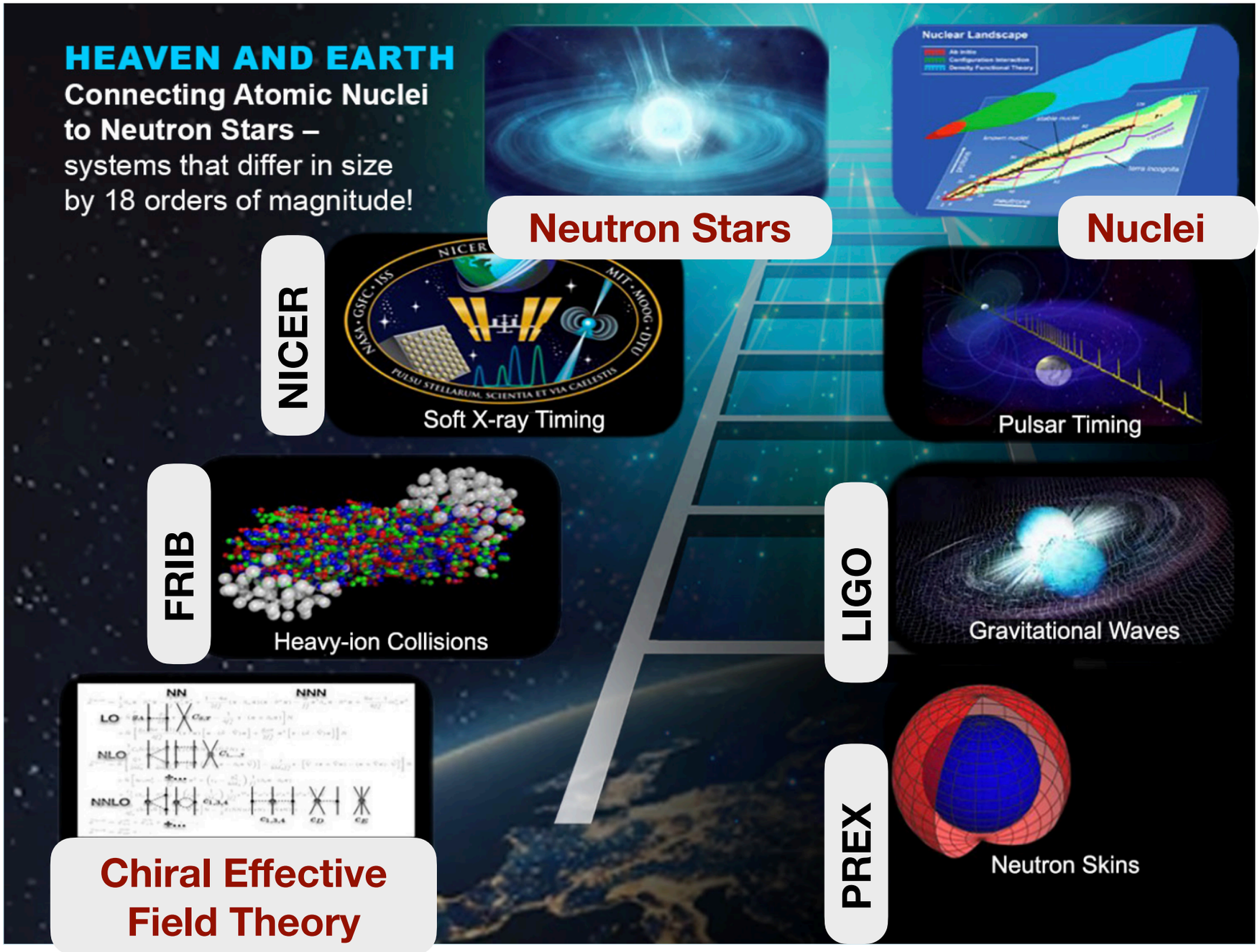


Nuclear forces

2023 Long Range Plan for Nuclear Science



- Upcoming laboratory & astrophysics experiments will probe nuclear physics of
  - Neutron Stars
  - Nuclei
- ***Connection requires understanding of nuclear forces***

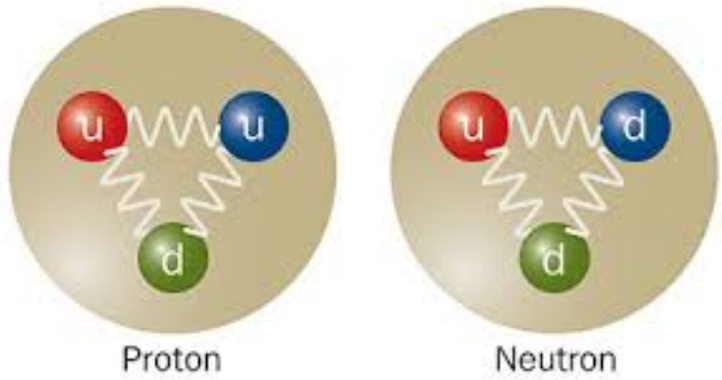
From quarks to nucleons

Modern view of nucleon forces

M_{QCD}
1 GeV

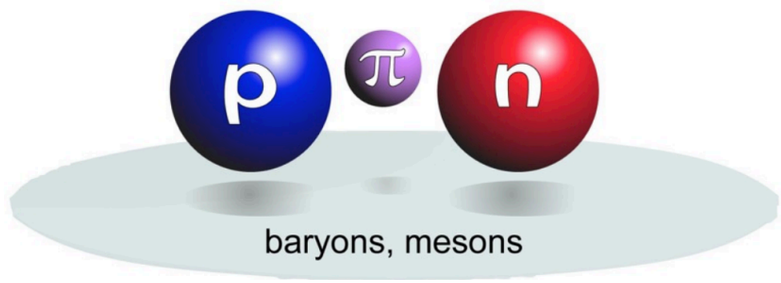
SM (QCD)

In terms of quarks, gluons, leptons



Chiral Effective Theory

In terms of nucleons, pions, leptons



- Possible hadronic interactions determined by (chiral) symmetries
- Interaction strengths determined by (unknown) coupling constants
- Expansion in $Q/\Lambda_\chi \sim m_\pi/\Lambda_\chi$, where $\Lambda_\chi \sim 1$ GeV

Manohar, Georgi, `84; Weinberg, `90, `91

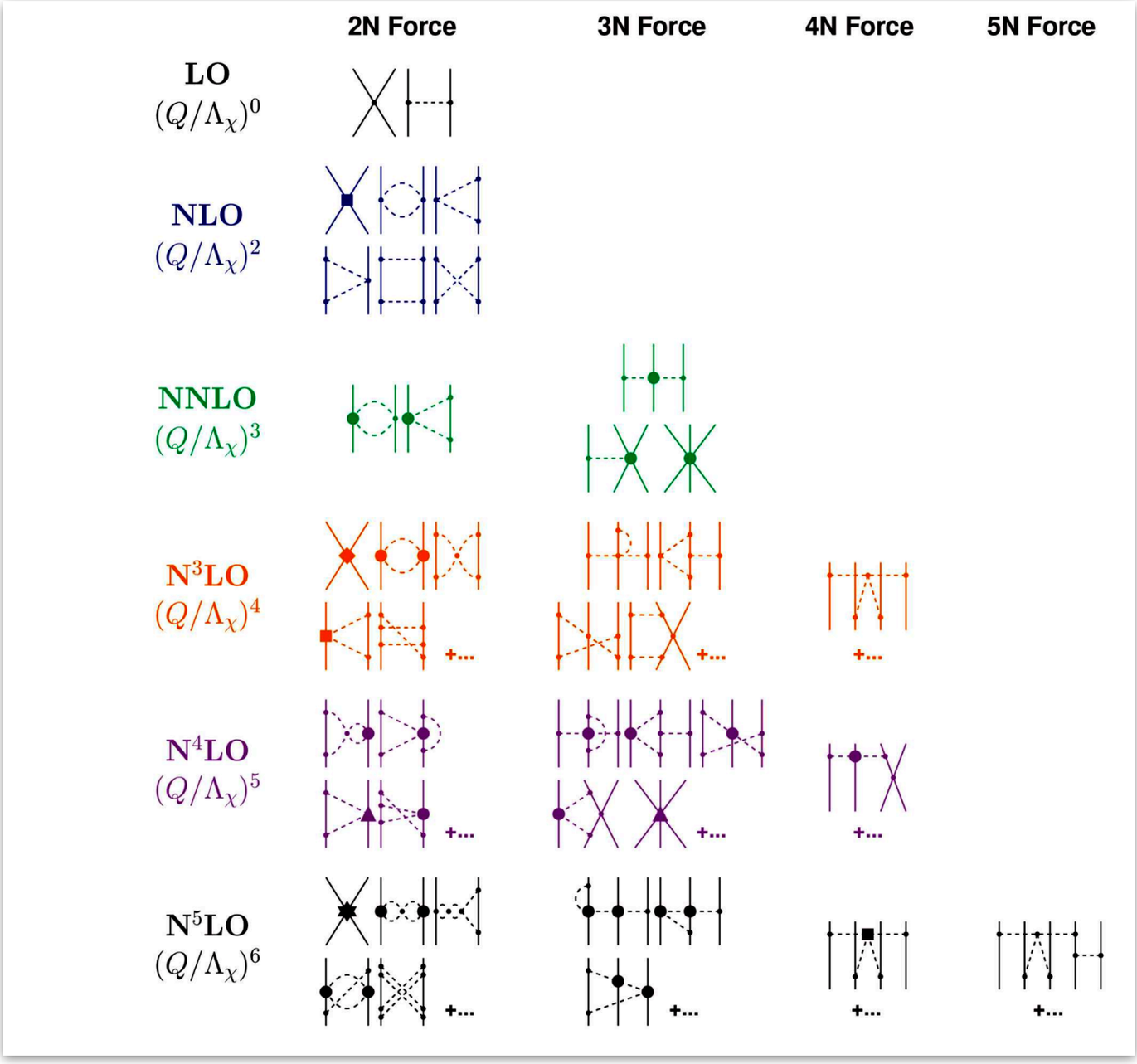
Chiral Effective Theory

Modern view of nucleon forces

- Chiral EFT is an expansion in
  - $Q/\Lambda_\chi \sim m_\pi/\Lambda_\chi$, where $\Lambda_\chi \sim 1$ GeV
- Leads to a hierarchy of nuclear forces

- Relies on “power counting”
  - Determines the importance of vertices
- Weinberg’s counting is widely used
  - Known to have inconsistencies

Requires re-ordering three-nucleon forces

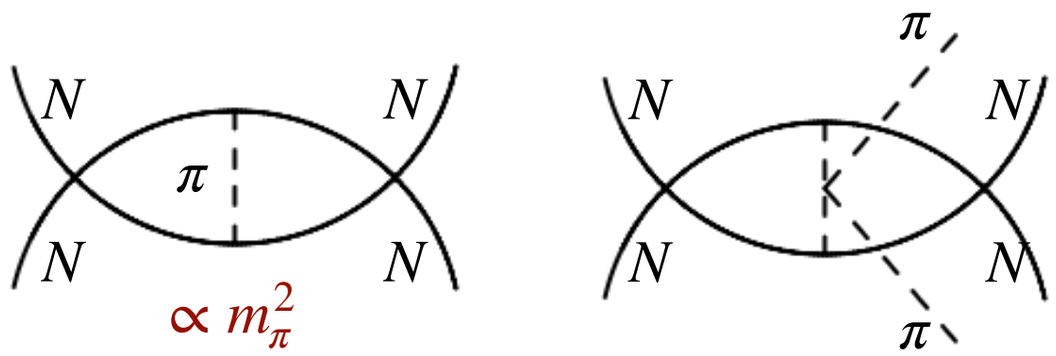


Hierarchy of nuclear forces up to N5 LO in ChiPT. Solid lines represent nucleons and dashed lines pions. Entem, Machleidt, Y. Nosyk, (arXiv:1703.05454)

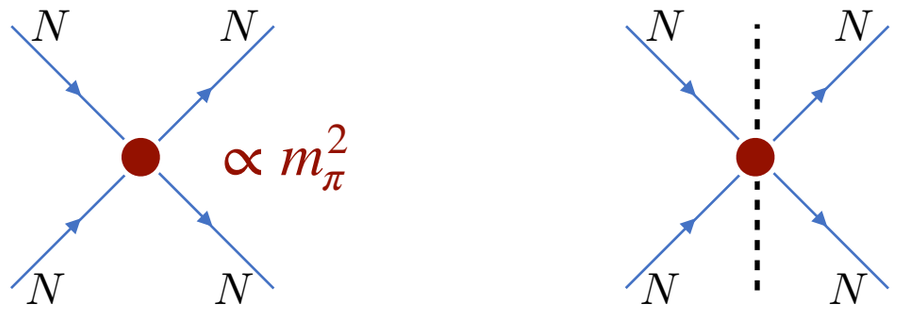
New class of three-nucleon forces

Failure of Weinberg's counting

- Certain diagrams lead to divergences
  - Generate short-distance interactions

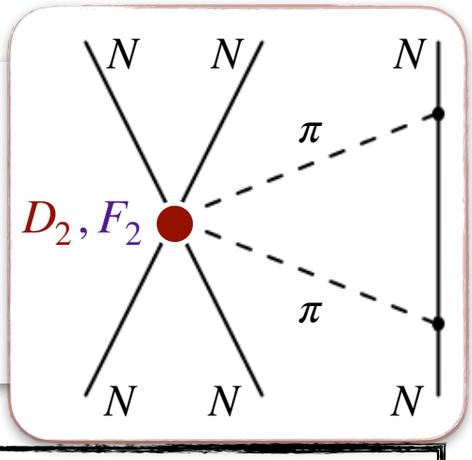


- ***Consistency requires leading-order interactions***
  - N2LO in Weinberg's counting



Kaplan, Savage, Wise, '96;

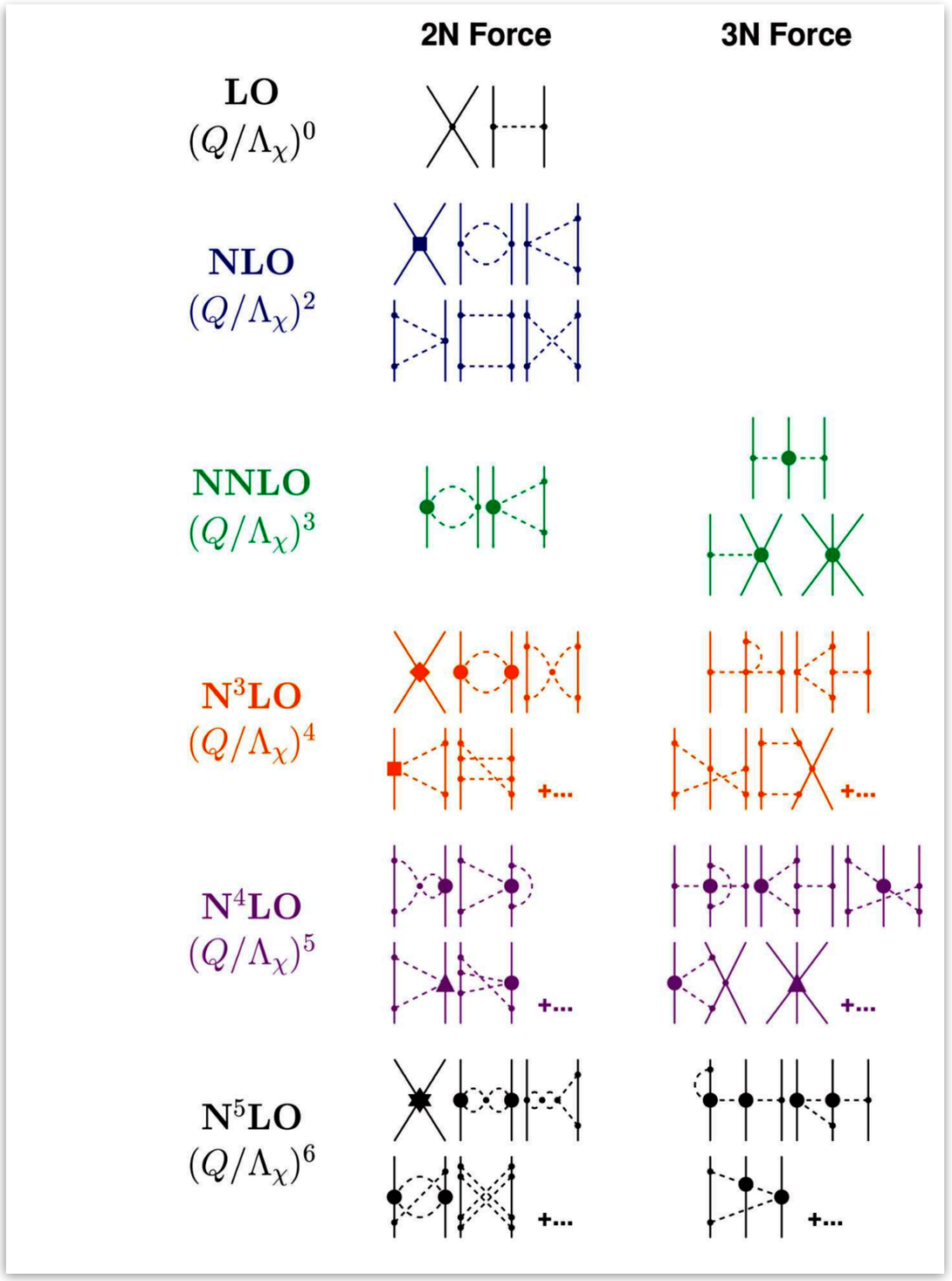
- These interactions generate a new class of 3N forces
- ***Cannot*** be absorbed into LO contact terms like in 2-nucleon sector



WD, M. Dawid, V. Cirigliano, S. Reddy

New class of three-nucleon forces

Relearning how to count



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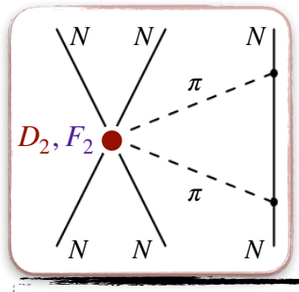

Weinberg's counting

New class of three-nucleon forces

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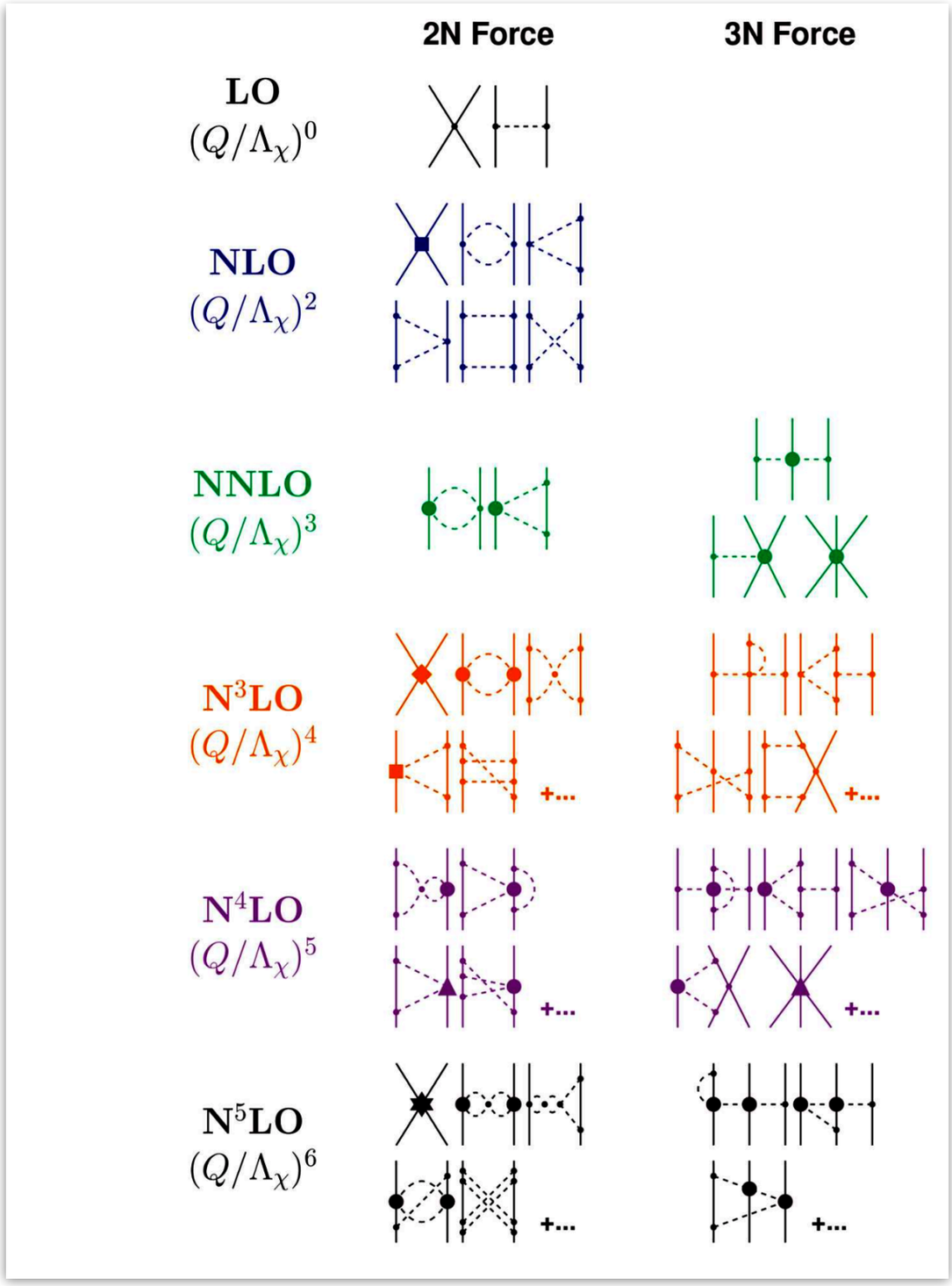

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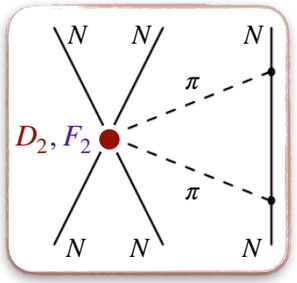
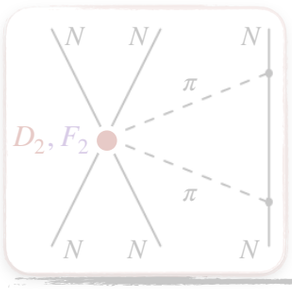


Consistency requirement

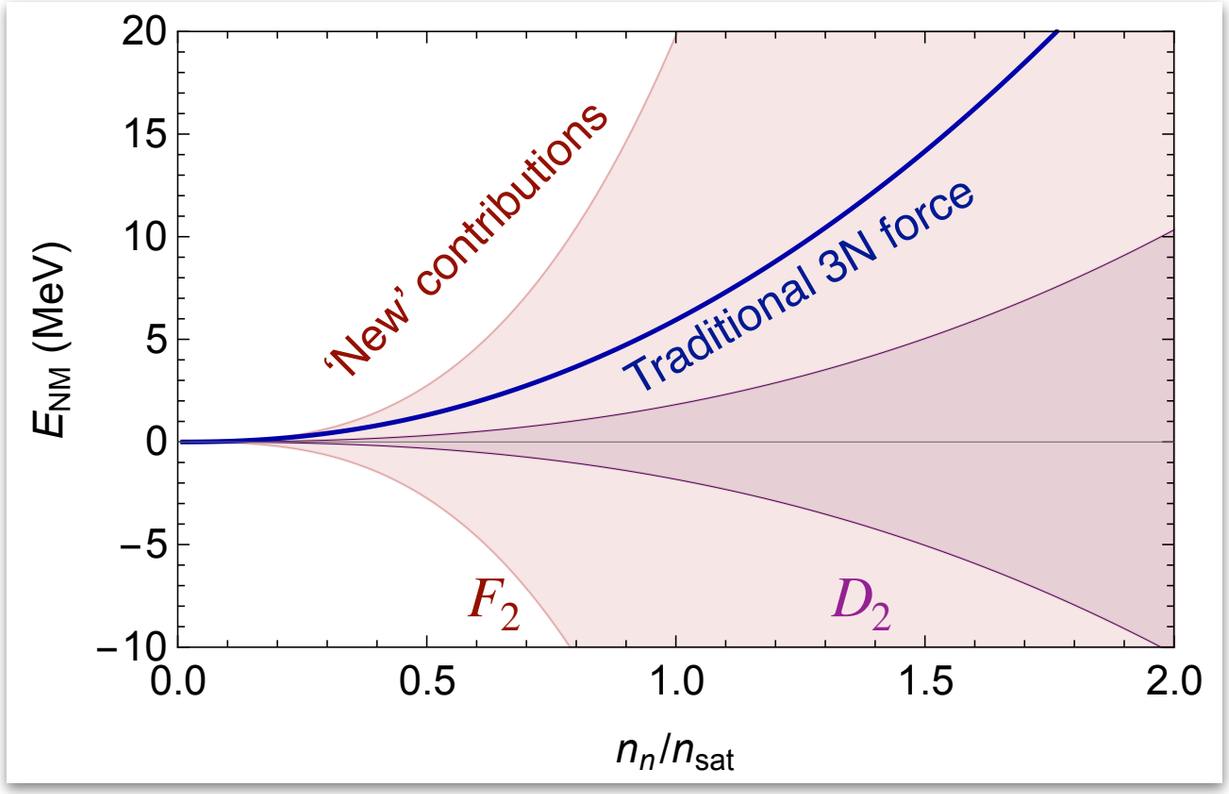


Weinberg's counting

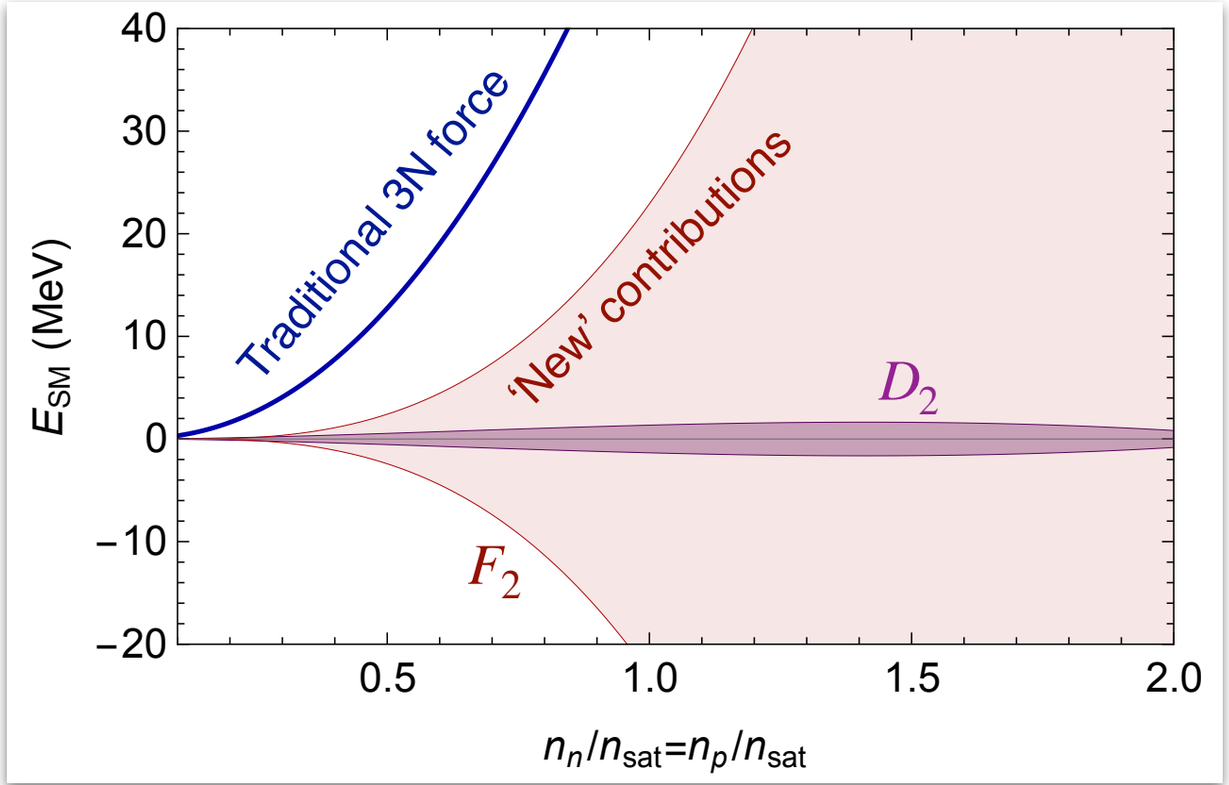
New class of three-nucleon forces

Effects in dense matter

Neutron Matter



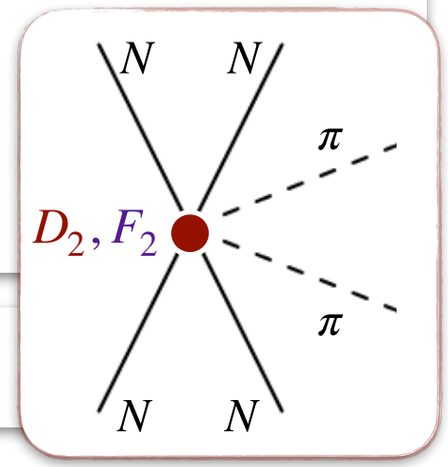
Symmetric Matter



- Significant contribution in Neutron & symmetric matter
  - Larger than currently quoted uncertainties

- **Affects our understanding of nuclei and Neutron Stars**
  - Equation of State in Neutron stars & mass-radius relation

- Depends on poorly known 2pion-4nucleon couplings



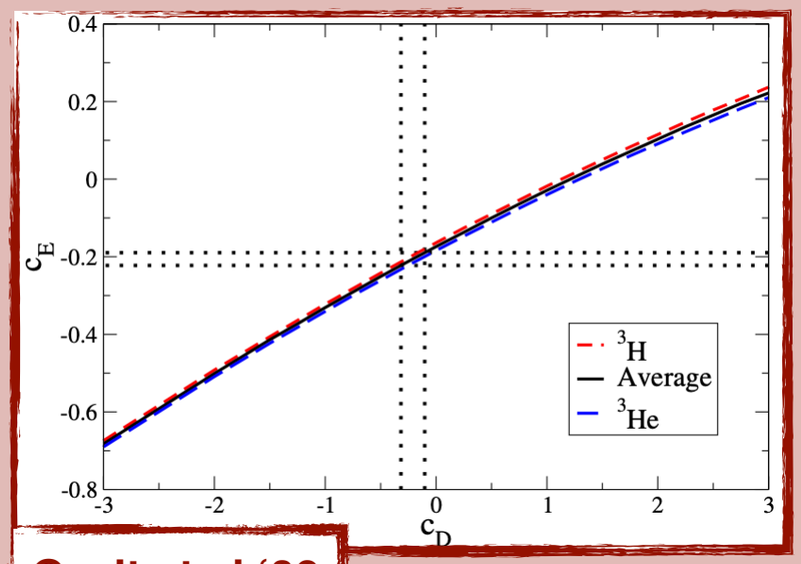
From Nuclei to the Cosmos

Future projects

Connecting nucleons to neutron stars

Determining the hadronic couplings

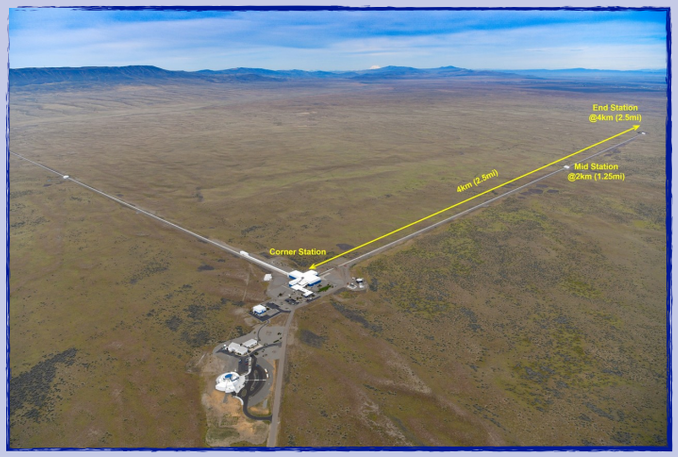
- Fit to light nuclei



Gazit et al ‘09

Impact on dense matter

- Nuclei
- Neutron Star Equation of State



LIGO

Spin-off:
Effect on axions

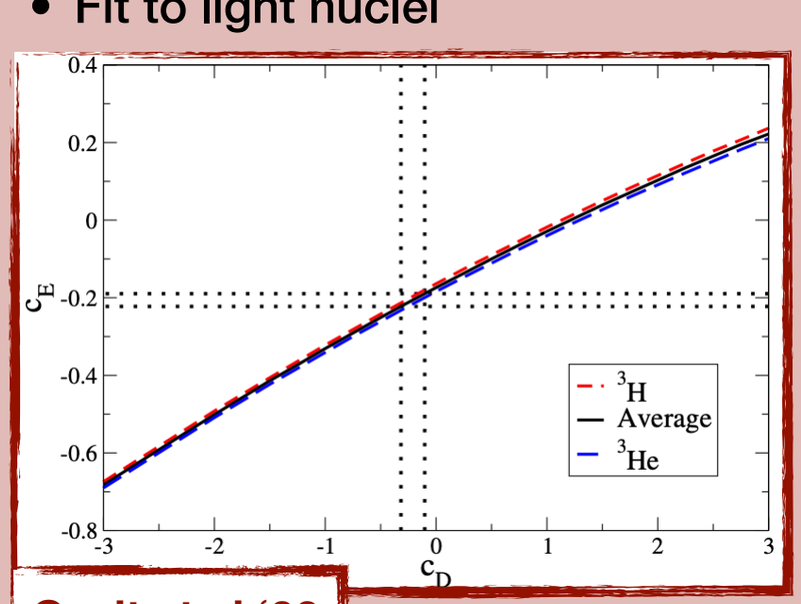
Affected by the same hadronic couplings in dense matter

Connecting nucleons to neutron stars

Overlap with Nuclear Theory Group

Determining the hadronic couplings

- Fit to light nuclei



Gazit et al '09

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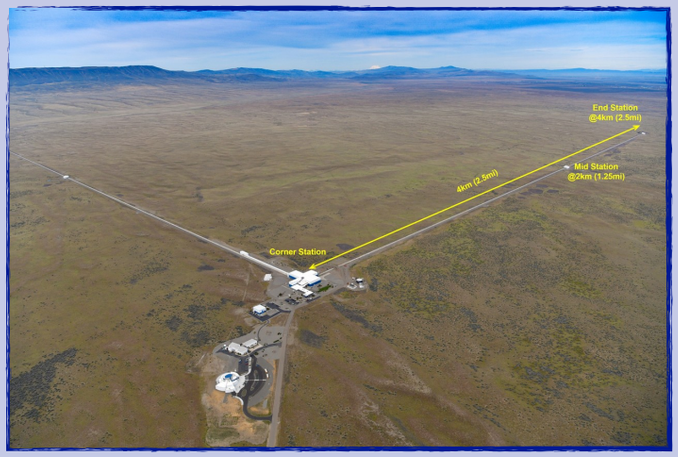

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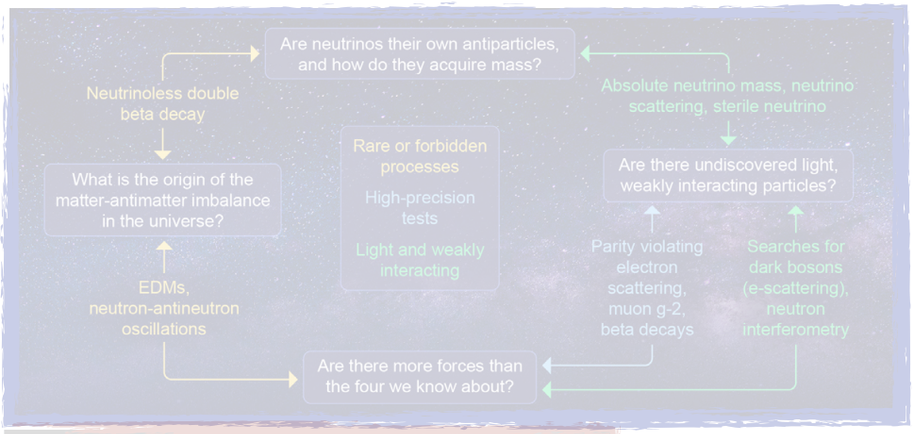
Astrophysics Group



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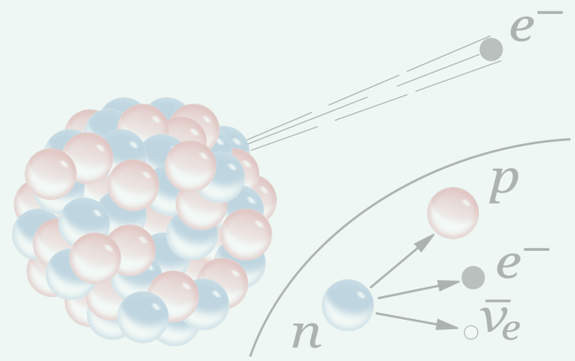

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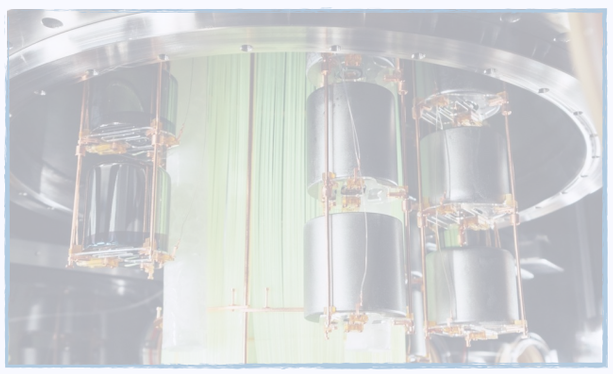
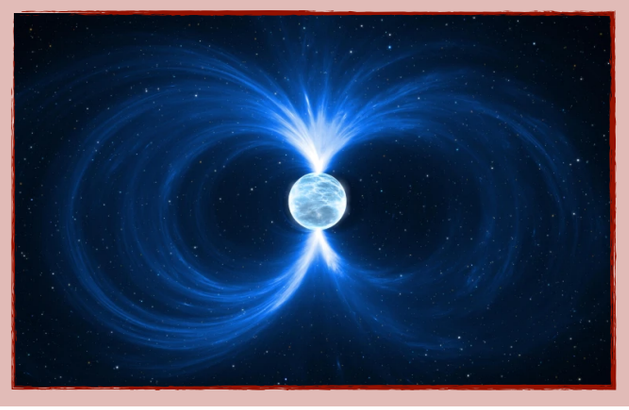
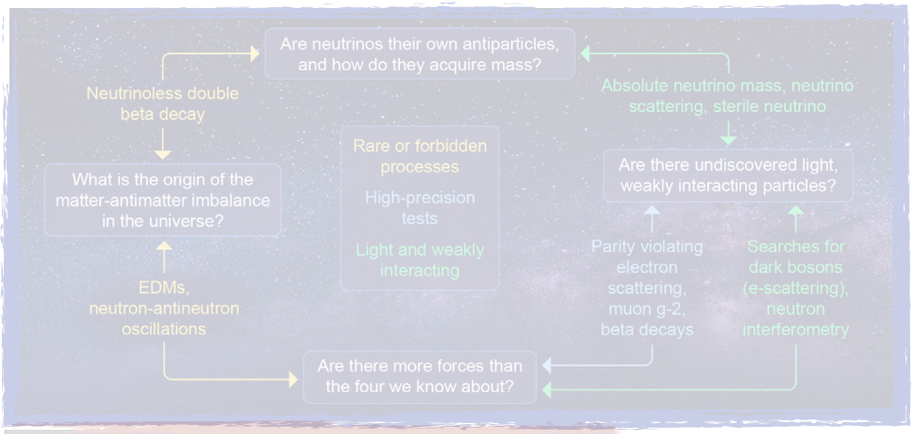


$0\nu\beta\beta$ LEGEND (ORNL lead US lab)

Connecting nuclei to the cosmos

- Dense matter & Neutron stars





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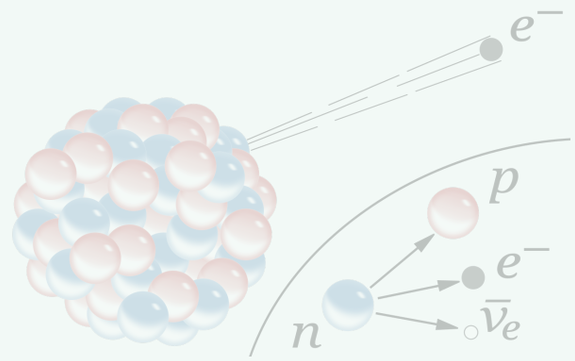

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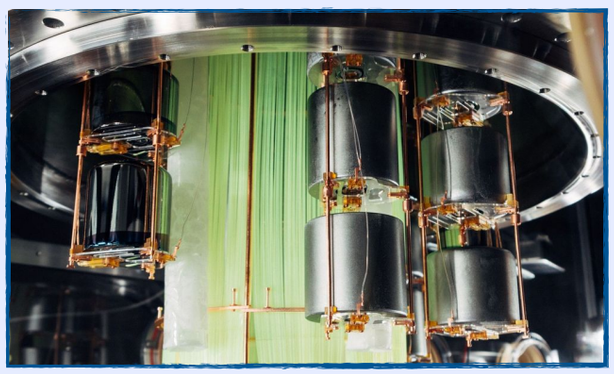

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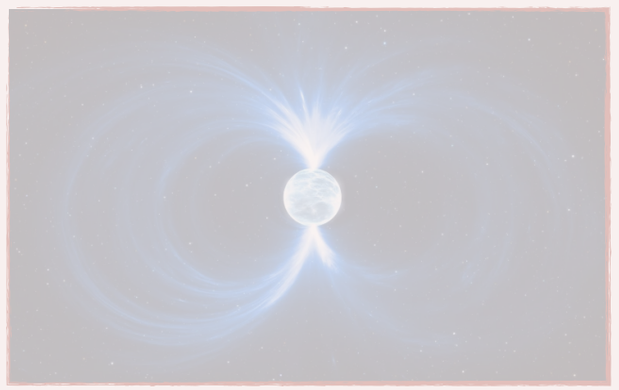
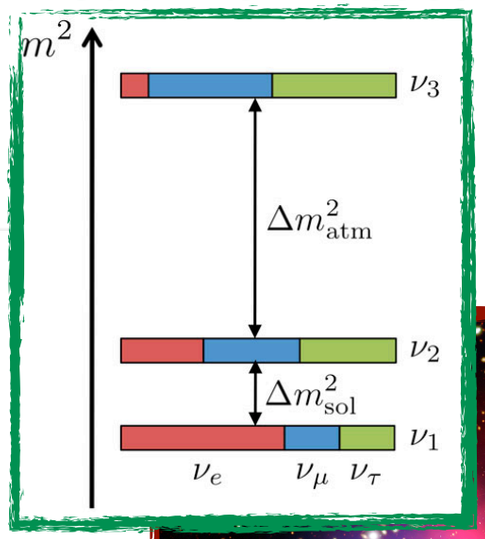


Sterile neutrinos & $0\nu\beta\beta$

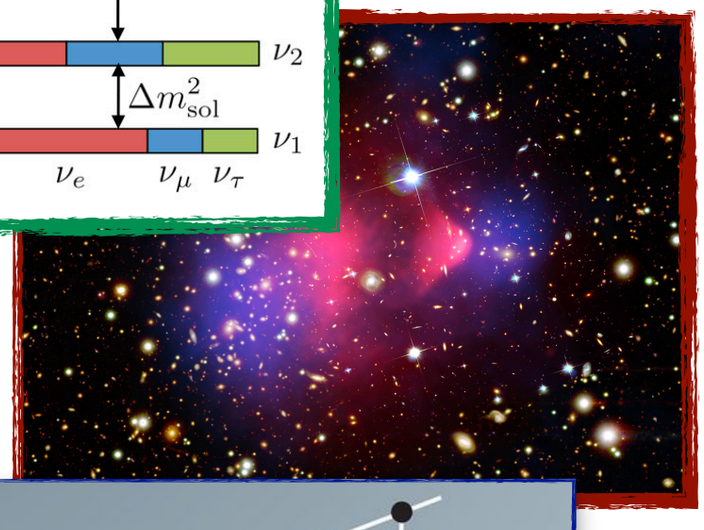
- Sterile neutrinos can answer open questions:
  - **Neutrino masses**
  - **Dark matter candidate**
  - **Matter-antimatter Asymmetry**

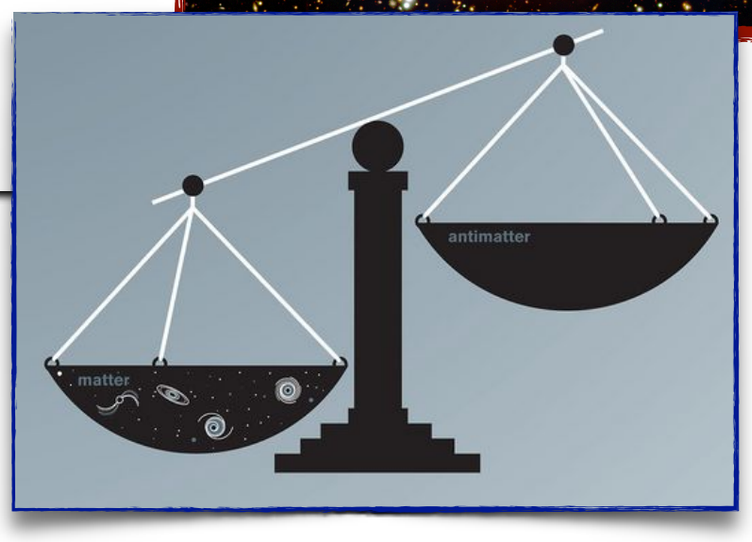
- Appear in many BSM scenarios: Left-Right/GUTs…

Neutrino masses



Dark Matter





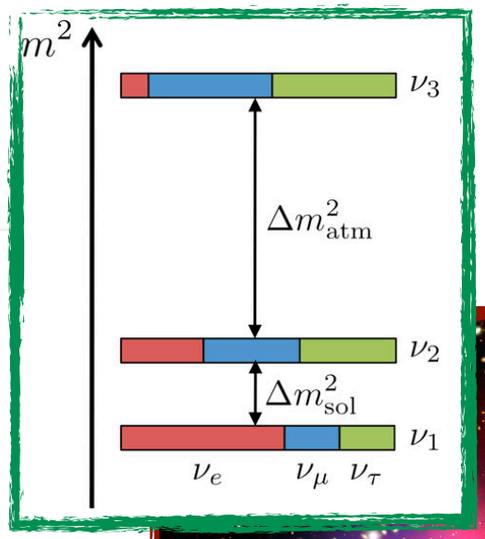
Why there's matter

Sterile neutrinos & $0\nu\beta\beta$

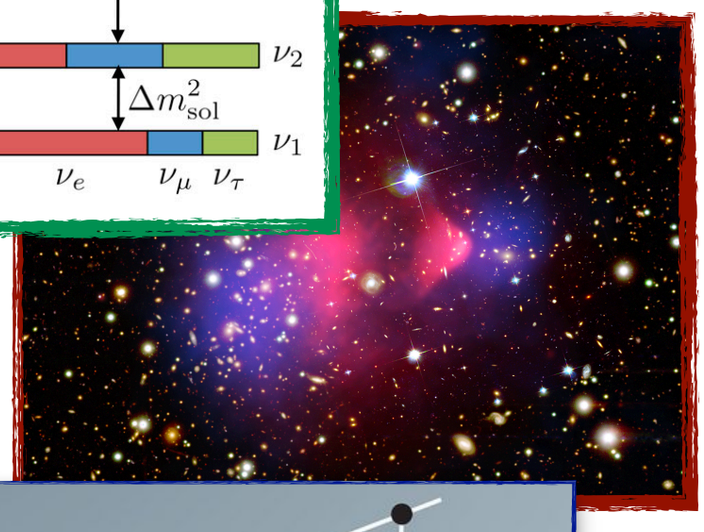
- Sterile neutrinos can answer open questions:
  - **Neutrino masses**
  - **Dark matter candidate**
  - **Matter-antimatter Asymmetry**

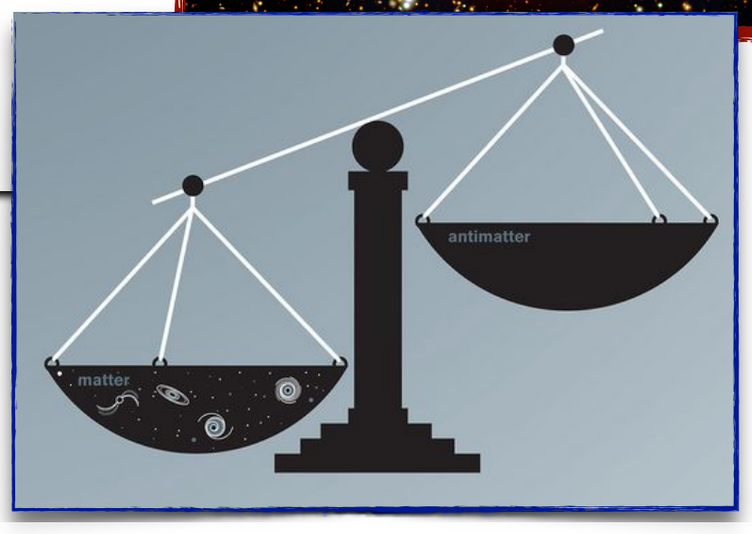
- Appear in many BSM scenarios: Left-Right/GUTs…

Neutrino masses



Dark Matter





Why there's matter

Generally leads to Lepton-Number Violation

$$\Longrightarrow 0\nu\beta\beta$$

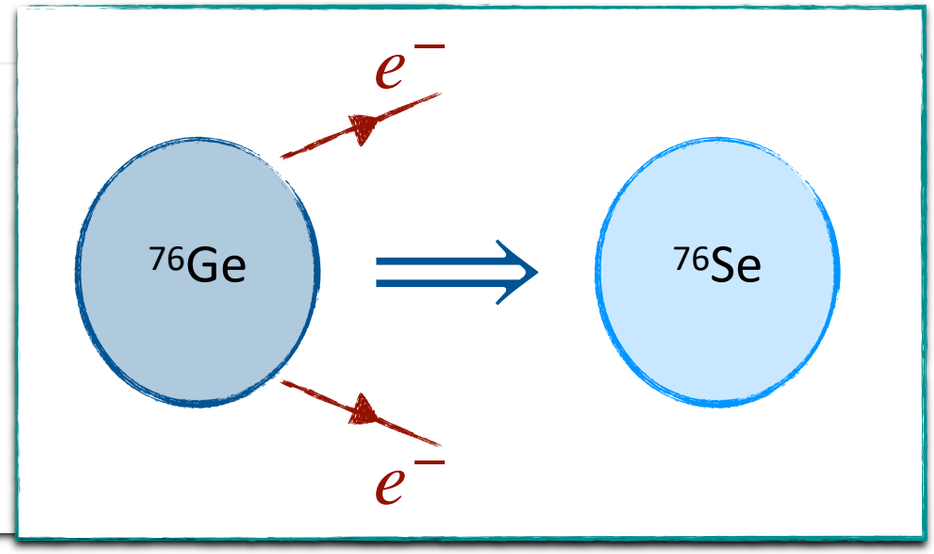
Neutrinoless Double beta decay

What & why?

What is $0\nu\beta\beta$?

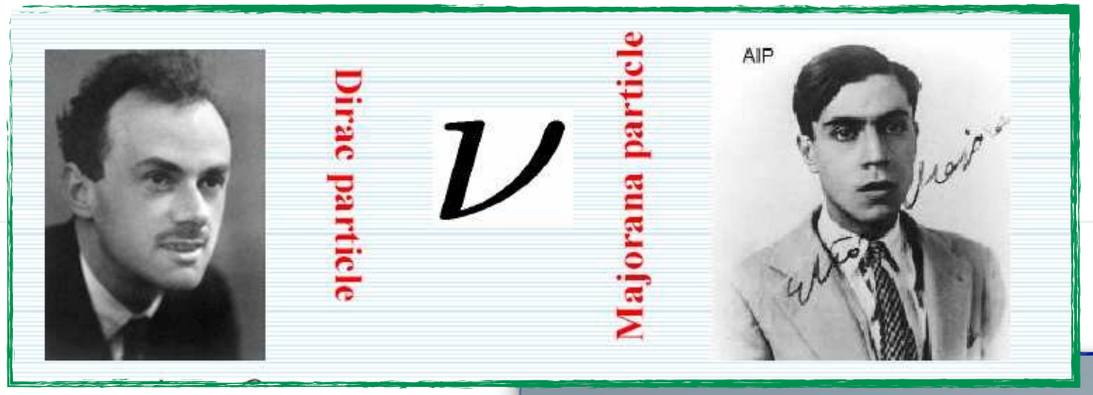
- $A(Z,N) \rightarrow A(Z+2,N-2) + 2e^- + 0\,\bar{\nu}$

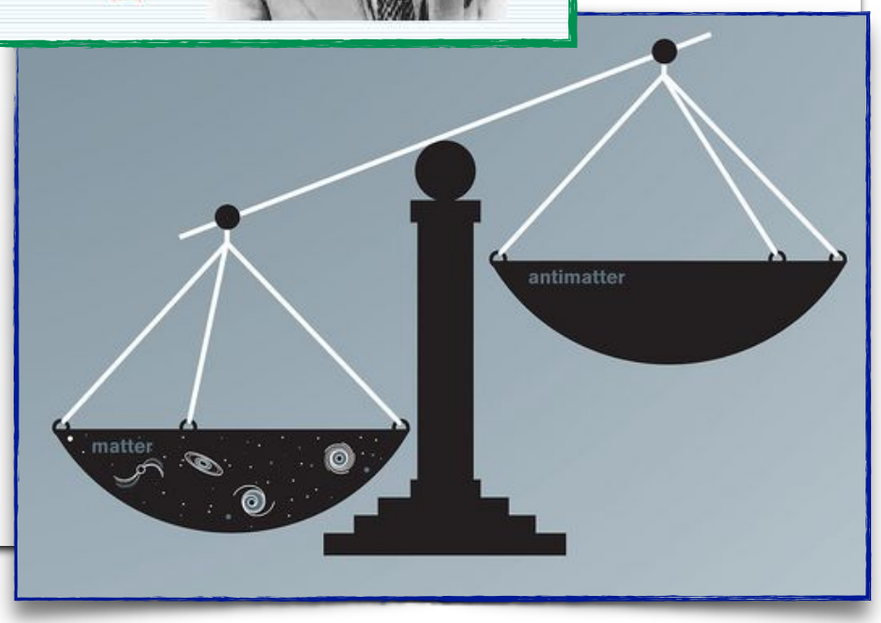
- Lepton Number Violating (LNV)



Why look for $0\nu\beta\beta$?

- Detection sheds light on:
  - **Neutrino masses**
    - **Observation would show that ν's are Majorana particles**
  - **Matter-antimatter asymmetry**





Schechter, Valle, `82

Neutrinoless Double beta decay

What & why?

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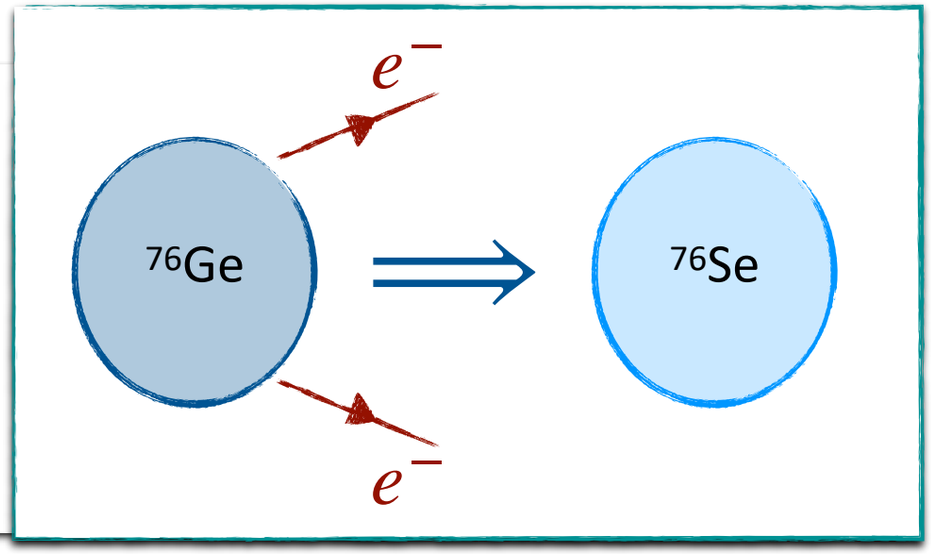
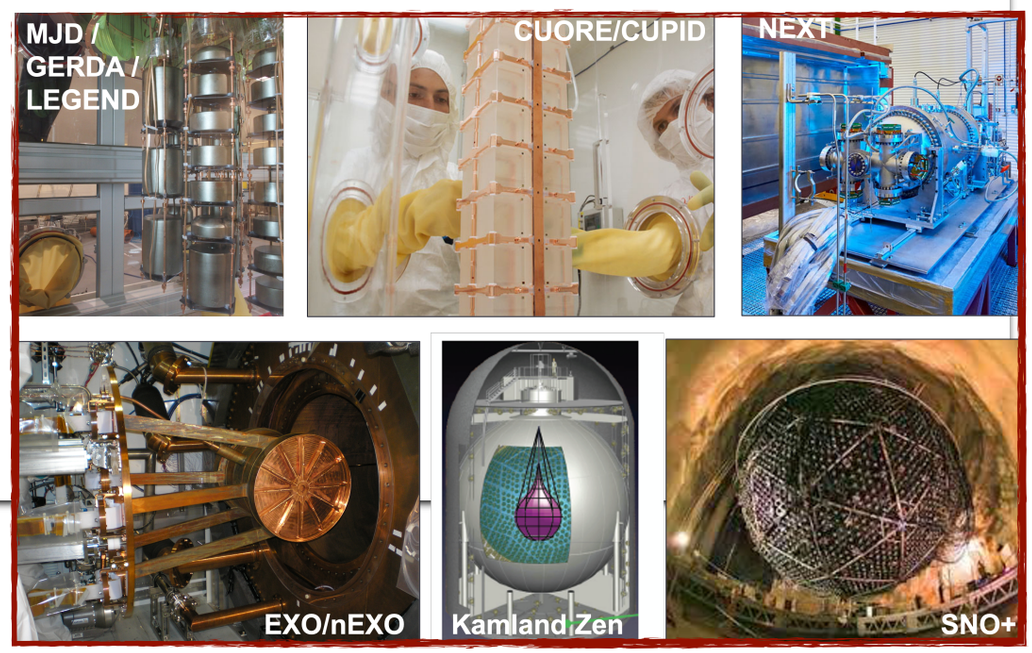


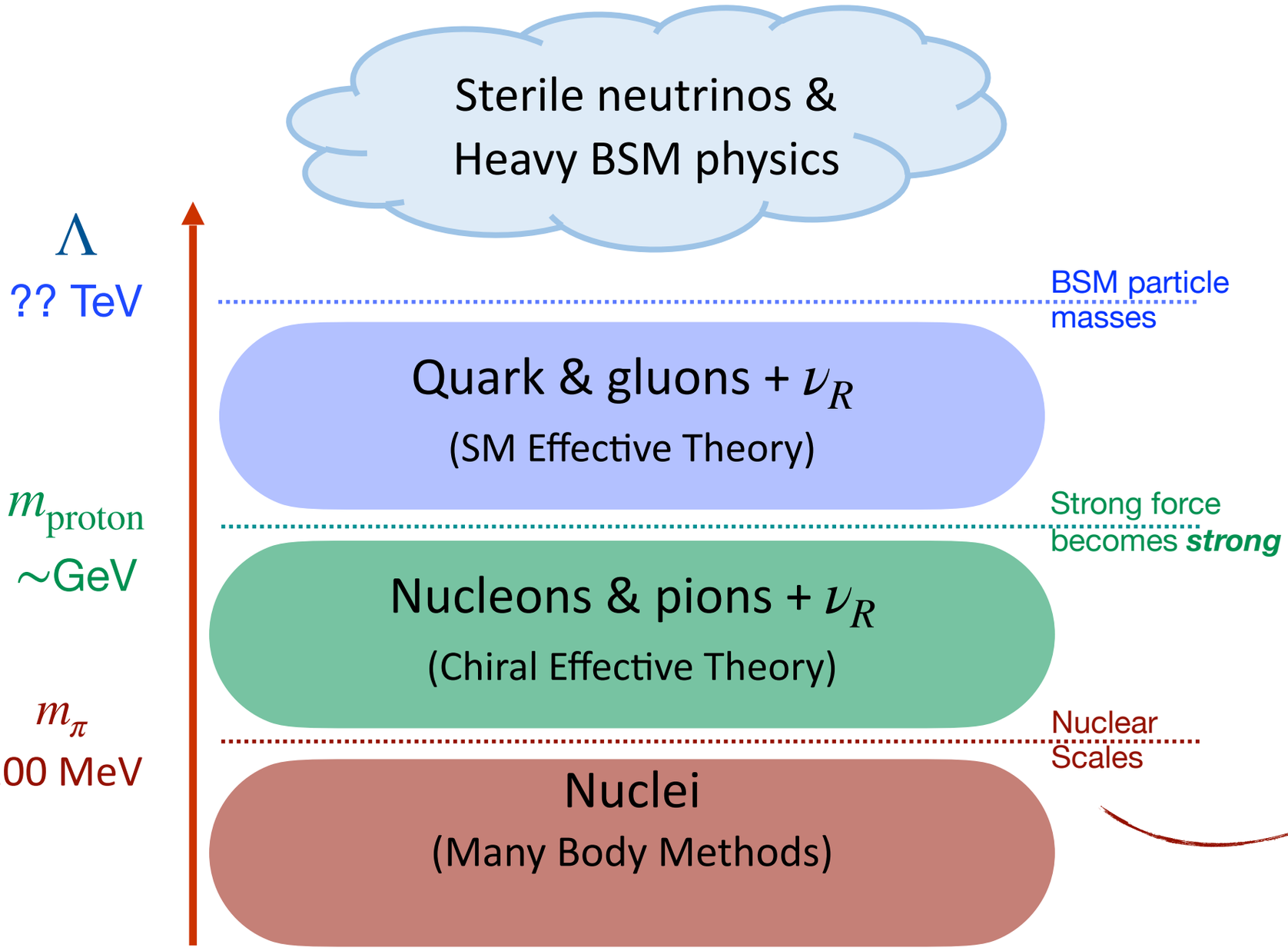
- Large scale experimental program underway
  - *Highest priority in Long Range Plan for Nuclear Science*

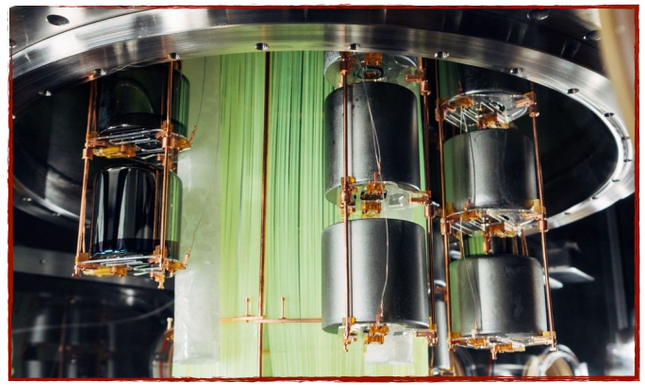
- ***Theory is needed to connect to the underlying physics***
  - ***Sterile neutrinos***



Developed EFT framework for ν_R in $0\nu\beta\beta$

From BSM scales to nuclear scales





$0\nu\beta\beta$ **LEGEND**
(ORNL US lead lab)

Developed EFT framework for ν_R in $0\nu\beta\beta$

From BSM scales to nuclear scales

Sterile neutrinos &
Heavy BSM physics

Λ
?? TeV

BSM particle masses

Quark & gluons + ν_R
(SM Effective Theory)

m_{proton}
~GeV

Strong force becomes ***strong***

Nucleons & pions + ν_R
(Chiral Effective Theory)

m_π
100 MeV

Nuclear Scales

Nuclei
(Many Body Methods)

PHYSICAL REVIEW C **108**, 045501 (2023)

Neutrinoless double-β decay in the neutrino-extended standard model

Wouter Dekens,[1,*] Jordy
Pab

JHEP

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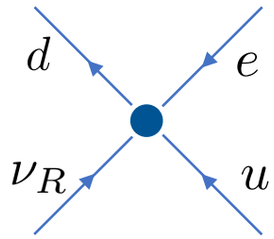
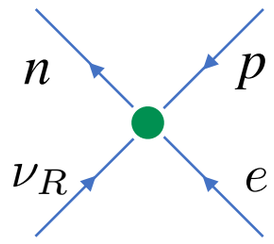
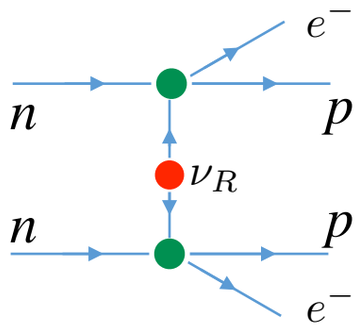
Sterile neutrinos and neutrinoless double beta decay in effective field theory

W. Dekens,[a] J. de Vries,[b,c] K. Fuyuto,[b,d] E. Mereghetti[d] and G. Zhou[b]







Neutrinoless double beta decay

Example for heavy ν_R: Majorana-mass mechanism

- **Fundamental Physics**
  - *Effective neutrino mass*
- **Theory input: Nuclear Matrix Element**

$$\Gamma_{0\nu\beta\beta} \propto M_\nu{}^2 m_{\beta\beta}^2$$

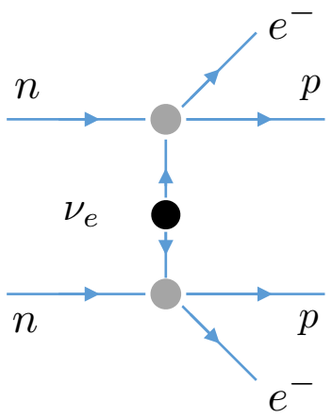
PHYSICAL REVIEW LETTERS **120,** 202001 (2018)

Editors' Suggestion | Featured in Physics

New Leading Contribution to Neutrinoless Double-β Decay

Vincenzo Cirigliano,[1] Wouter Dekens,[1] Jordy de Vries,[2] Michael L. Graesser,[1] Emanuele Mereghetti,[1] Saori Pastore,[1] and Ubirajara van Kolck[3,4]

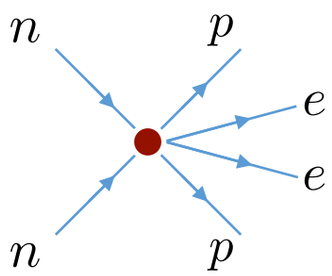
$M_\nu \sim$



Previous literature

+

g_ν



New interaction
Needed at *leading order*

- Provided first estimate of g_ν

PHYSICAL REVIEW LETTERS **126,** 172002 (2021)

Toward Complete Leading-Order Predictions for Neutrinoless Double β Decay

Vincenzo Cirigliano,[1] Wouter Dekens,[2] Jordy de Vries,[3,4,5,6] Martin Hoferichter,[7] and Emanuele Mereghetti[1]

Neutrinoless double beta decay

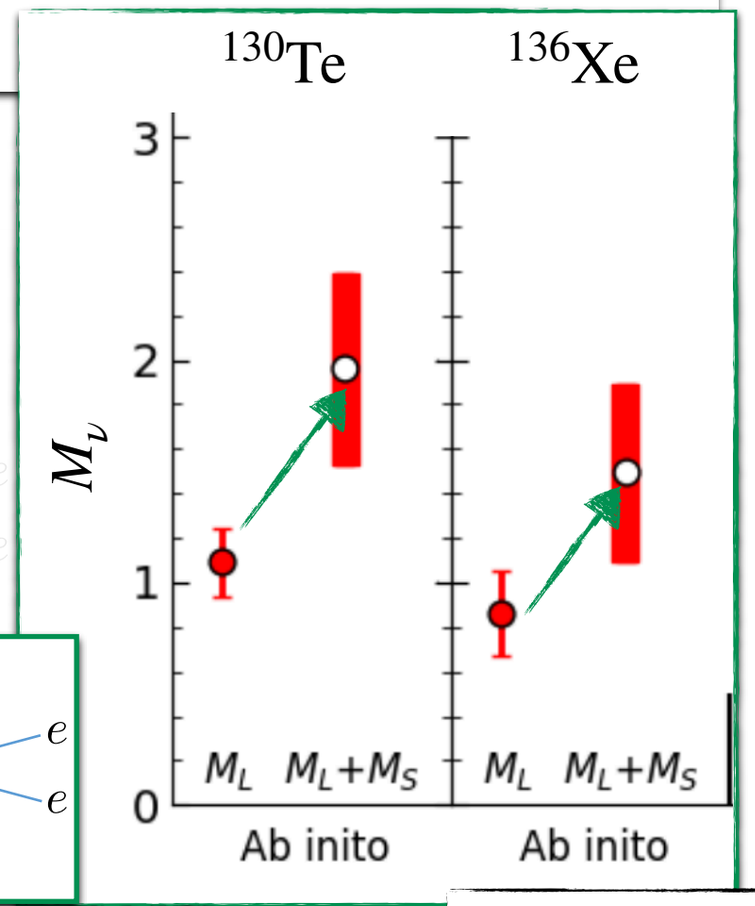
Example for heavy ν_R: Majorana-mass mechanism

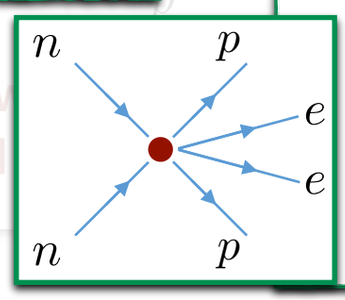
- **Fundamental Physics**
  - *Effective neutrino mass*

$$\Gamma_{0\nu\beta\beta} \propto |M_\nu|^2 m_{\beta\beta}^2$$

- **Theory input: Nuclear Matrix Element**

- Changed the way many-body calculations of M_ν are done
- Resulted in $\mathcal{O}(40-90\%)$ *increase of* M_ν
  - Means experiments have more sensitivity to $m_{\beta\beta}$!



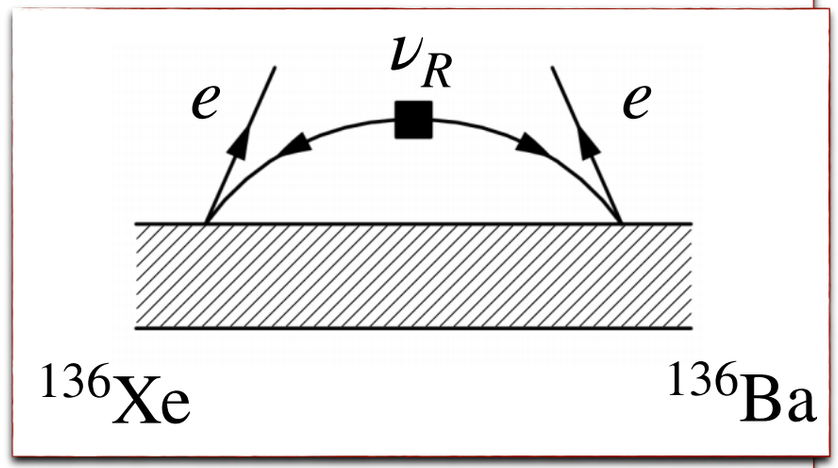


Belley et al, '23;

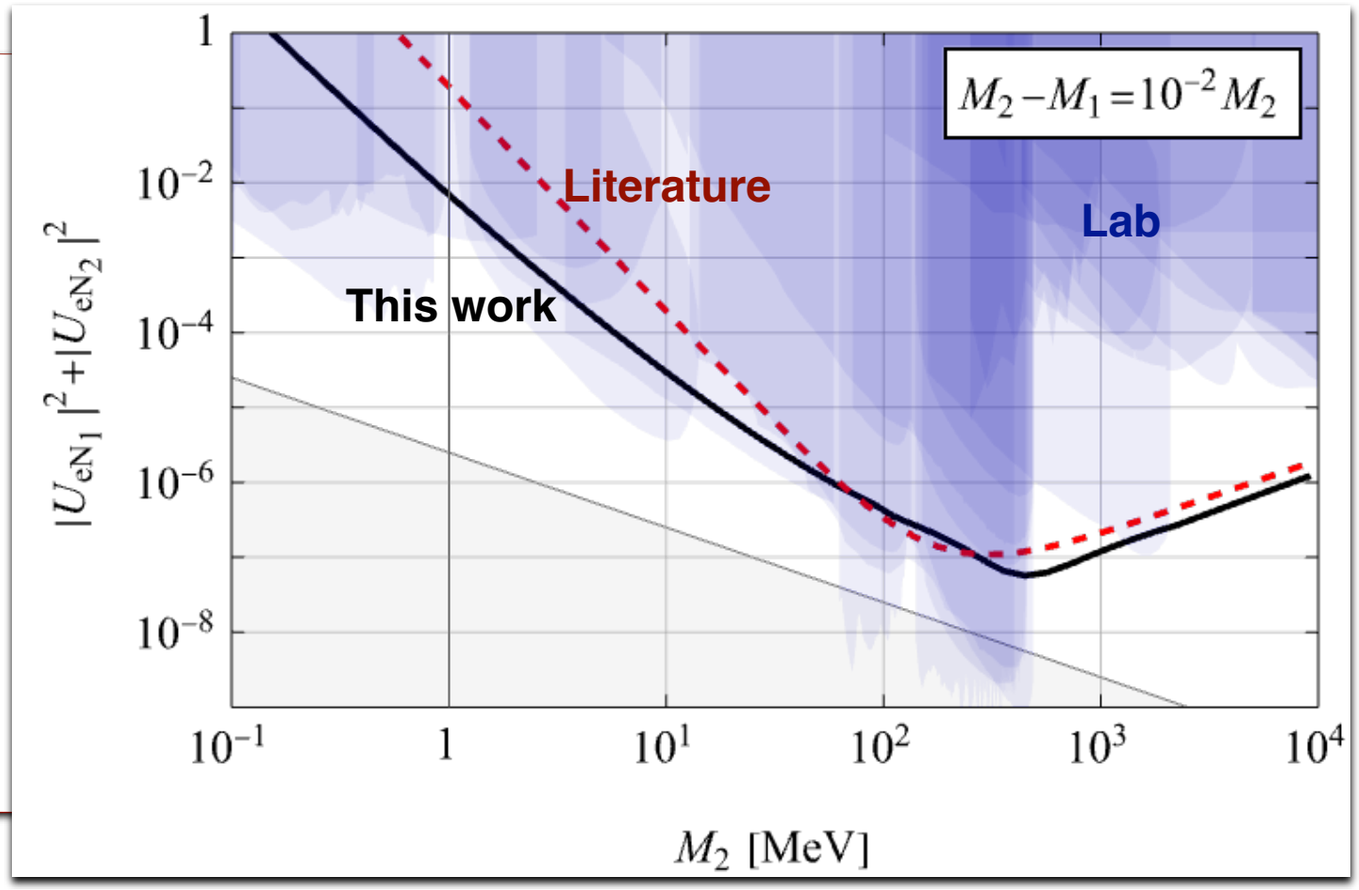
Neutrinoless double beta decay

Example: Light ν_R

- Need to keep sterile neutrinos (ν_R) in the hadronic theory
- Leads to new effects from ν_R with small momenta $\sim \mathrm{MeV}$
  - These ν_R couple to the nucleus as a whole
- ***This contribution was missed in the literature***



- Impact in a toy model
  - "1+1+1" scenario
- **Is the leading contribution for light ν_R**
- ***Systematic EFT description crucial***



Fundamental Symmetries

Future projects

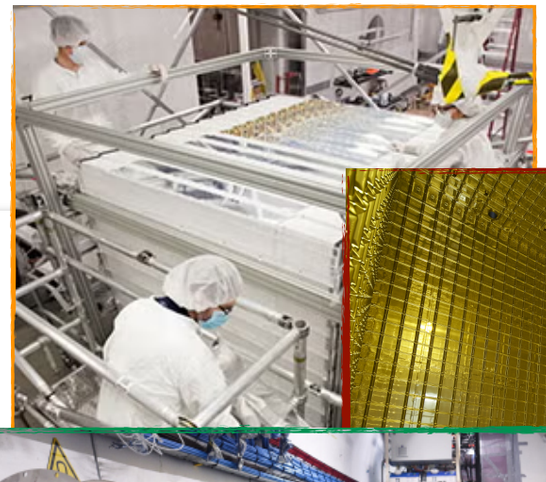
Lepton Number Violation and Sterile neutrinos

Future work

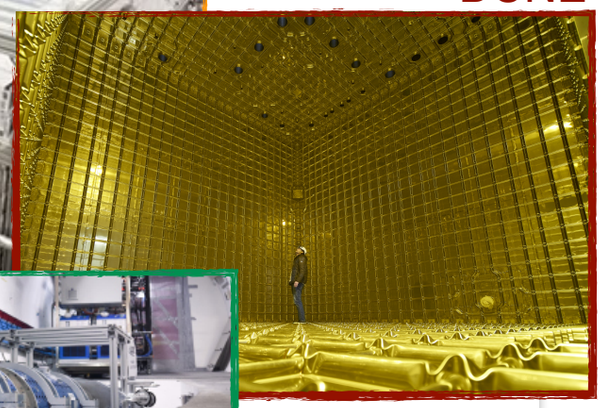
Future work

- Combine $0\nu\beta\beta$ with other probes in the same EFT framework
  - Colliders, reactor, oscillation experiments, astrophysical probes…
- **Needed to assess viability of sterile-neutrino scenarios**

PROSPECT @ ORNL



DUNE



CERN: SHiP, FASER

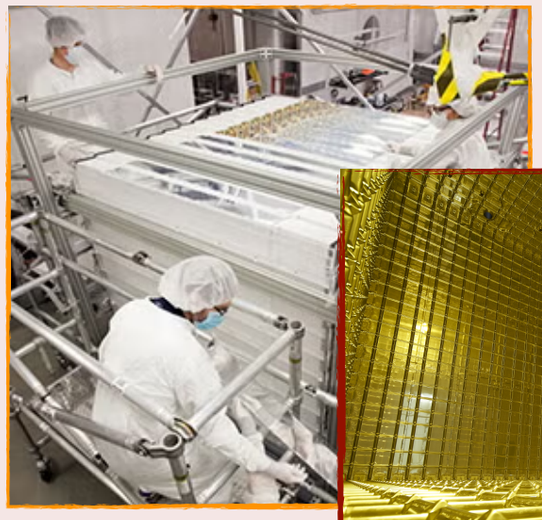
COHERENT @ ORNL

Lepton number & Sterile Neutrinos

Global Analysis of ν_R interactions

- Combine $0\nu\beta\beta$ with Colliders, reactor, oscillation experiments, astrophysical probes…

PROSPECT @ ORNL



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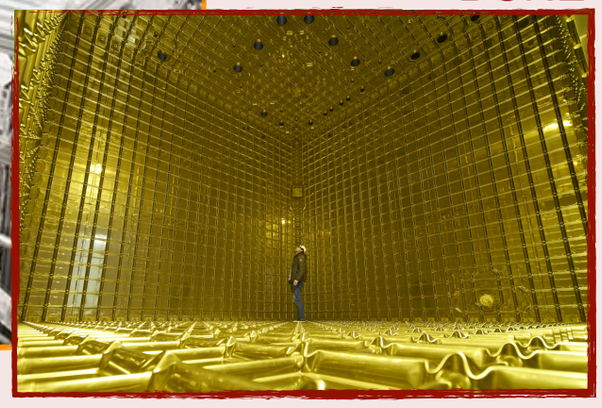


Overlap with the Astrophysics & HEP Groups

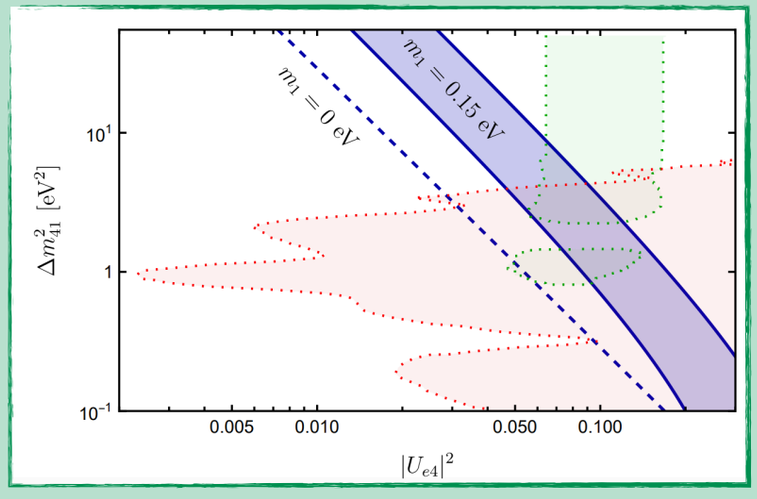
ν cross sections in reactor experiments

Currently involve anomalies

- Can be interpreted as light sterile neutrinos

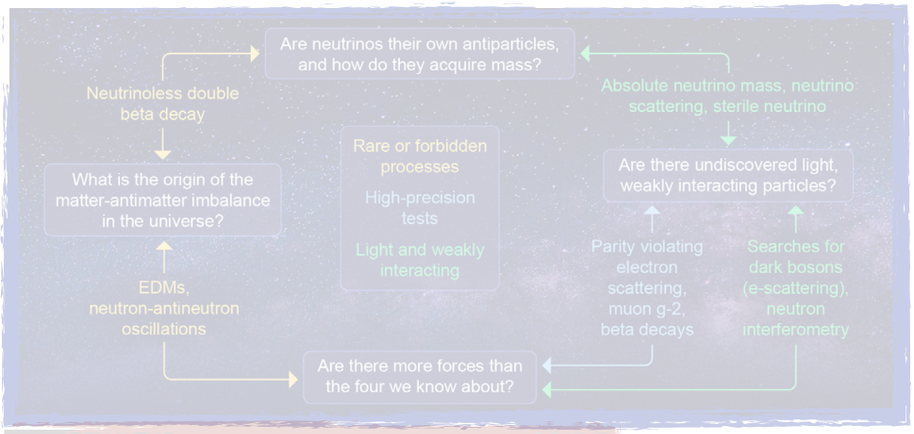
SM prediction using Chiral EFT framework

- Interplay with “Precision Frontier” direction



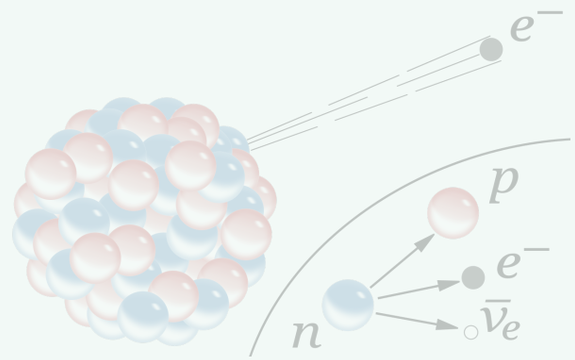
Gallium anomaly

Overlap with the Nuclear Theory Group



Precision frontier

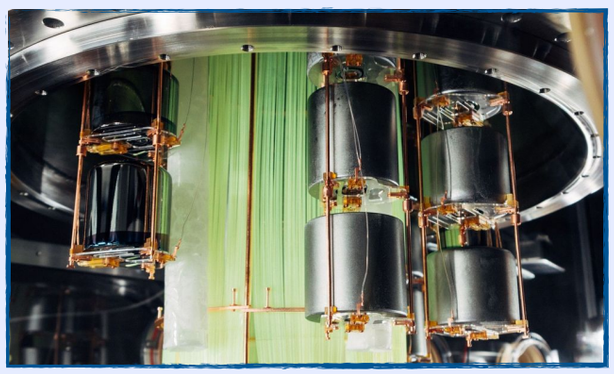
- Cabibbo Angle Anomaly & β decays



Effectively probing (Beyond) the SM physics

Fundamental Symmetries

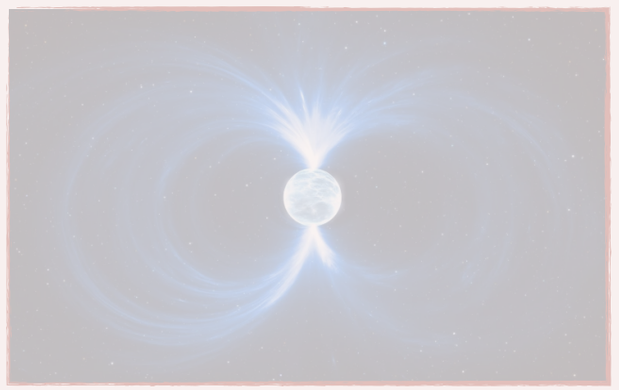
- Lepton number & Sterile Neutrinos

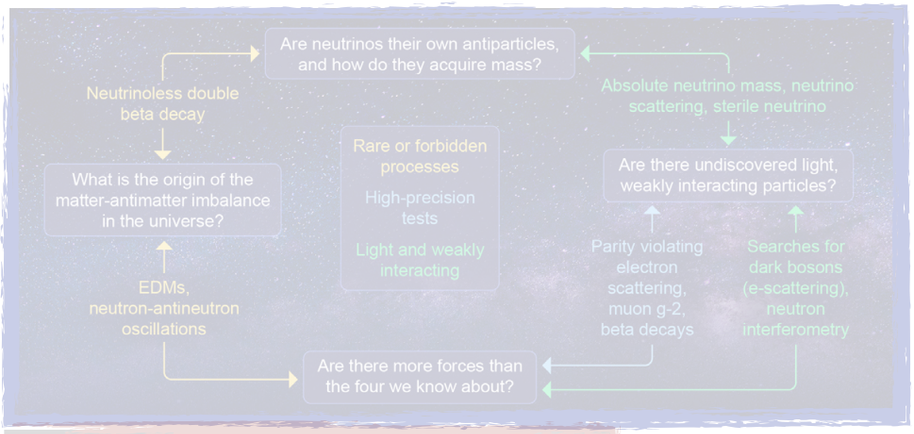


$0\nu\beta\beta$ LEGEND (ORNL lead US lab)

Connecting nuclei to the cosmos

- Dense matter & Neutron stars





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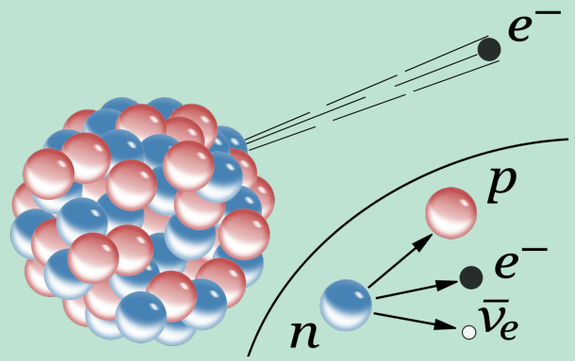

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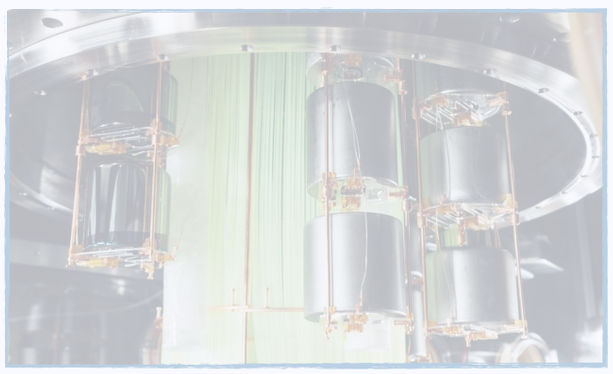

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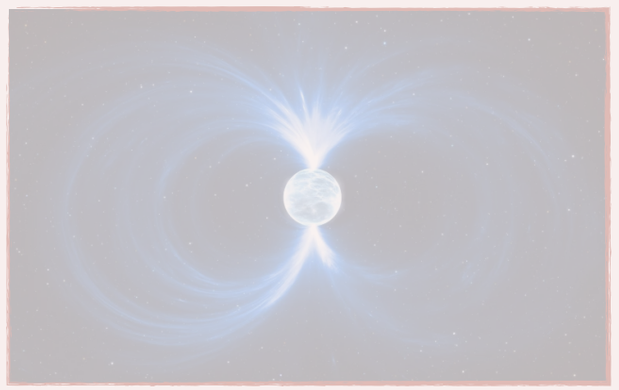
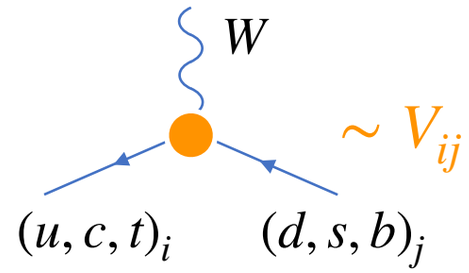


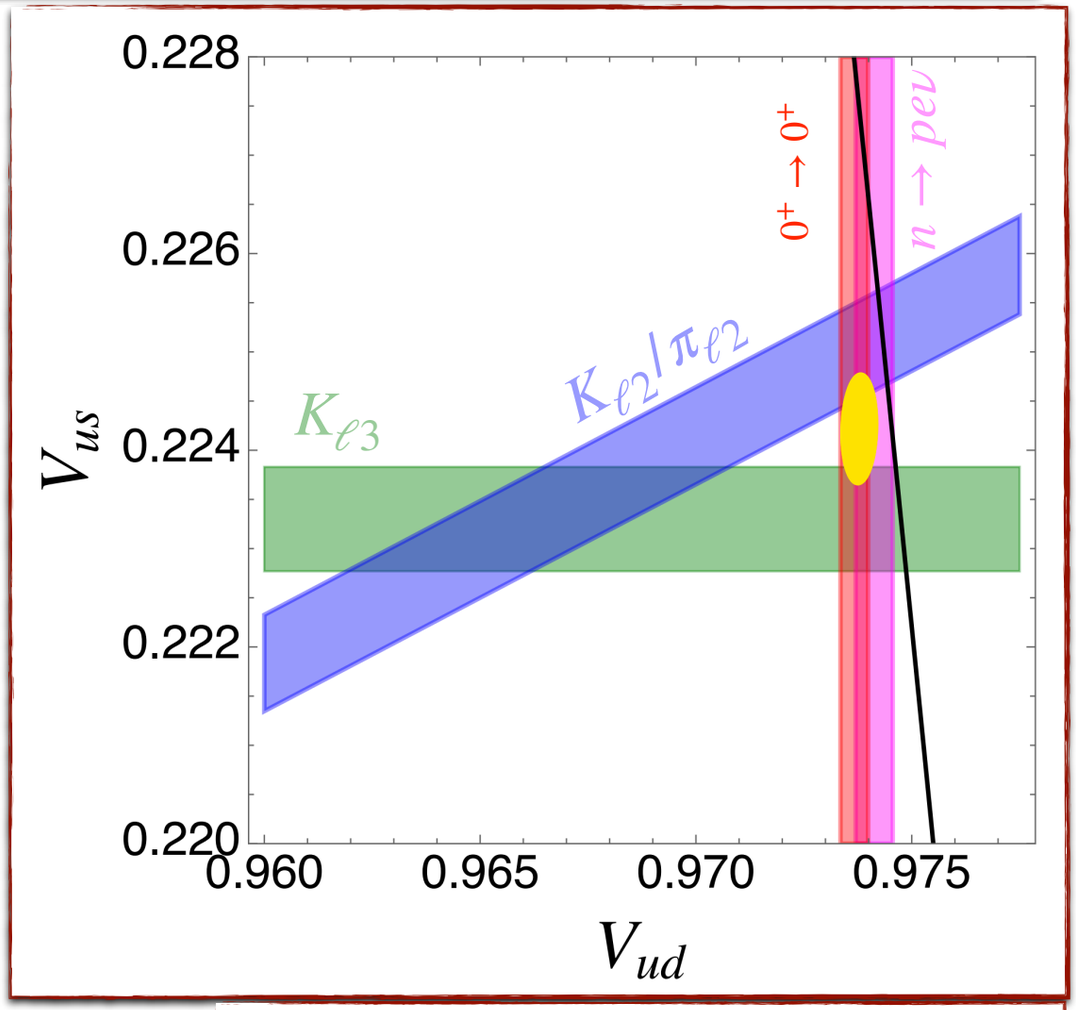
β decays

- Helped build the SM, probe $O(10)$ TeV BSM scales
- Determine V_{ud} very precisely $\delta V_{ud} \sim \text{few} \times 10^{-4}$
- CKM unitarity test: $\Delta = |V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} - 1 = 0$



Unitarity test

- Experimentally determined
  - V_{ud} from neutron & nuclear β decays
  - V_{us} from Kaon/pion decays
- Disagrees with unitarity by $\sim 3\sigma$
  - Issue with SM predictions/uncertainties?
  - BSM physics?



Cirigliano, Crivellin, Moulson, Hoferichter '23

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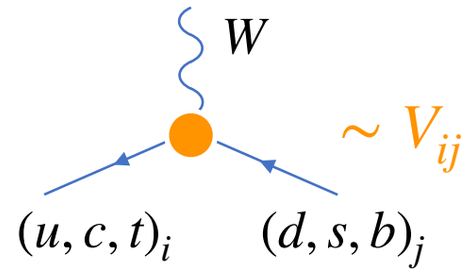

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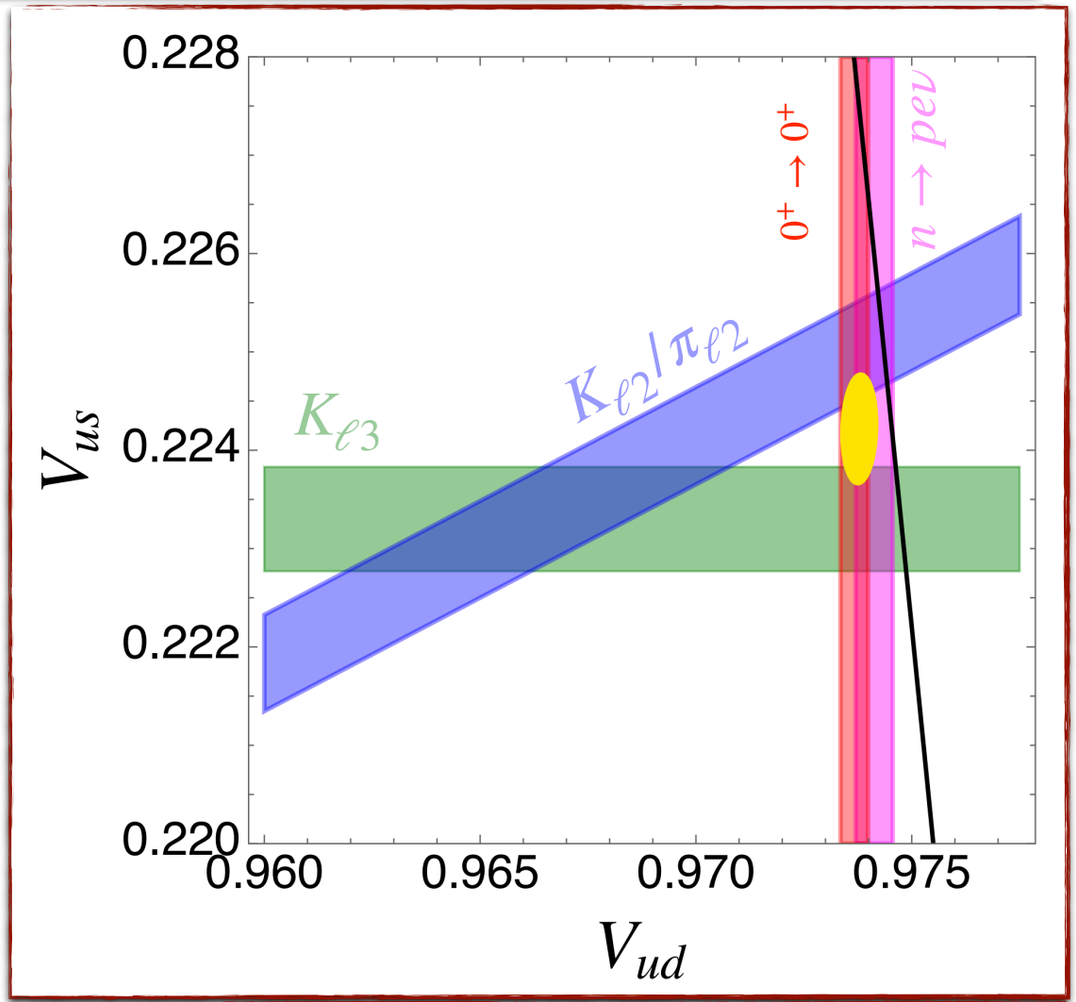
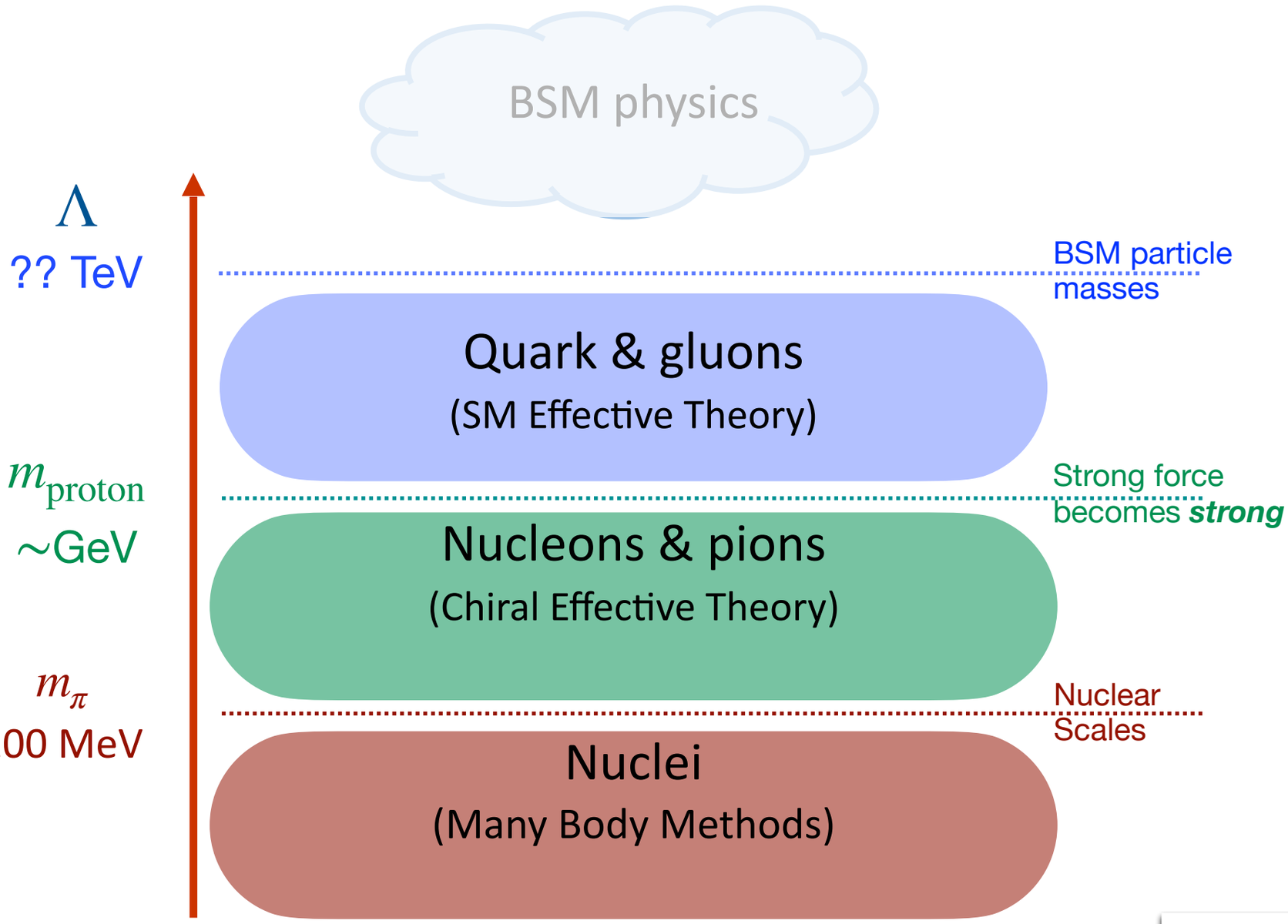


Cirigliano, Crivellin, Moulson, Hoferichter '23

Developed EFT framework for nuclear β decays

From BSM scales to nuclear scales



Nuclear β decays

- 10^{-4} accuracy requires corrections
  - $\mathcal{O}(\alpha\, m_\pi/m_N)$
  - $\mathcal{O}(\alpha\, m_e/m_\pi)$

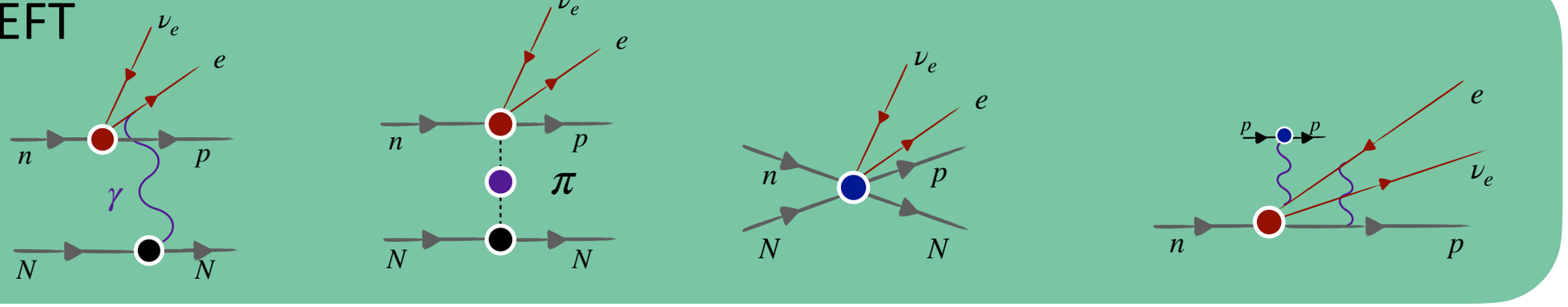
Developed EFT framework for one & two nucleon effects

PHYSICAL REVIEW LETTERS **133,** 211801 (2024)

Radiative Corrections to Superallowed β Decays in Effective Field Theory

Vincenzo Cirigliano,[1] Wouter Dekens,[1] Jordy de Vries,[2,3] Stefano Gandolfi,[4]

Chiral EFT



100 MeV

$\mathcal{O}(\alpha m_\pi/m_N)$ & $\mathcal{O}(\alpha m_e/m_\pi)$ two-nucleon terms

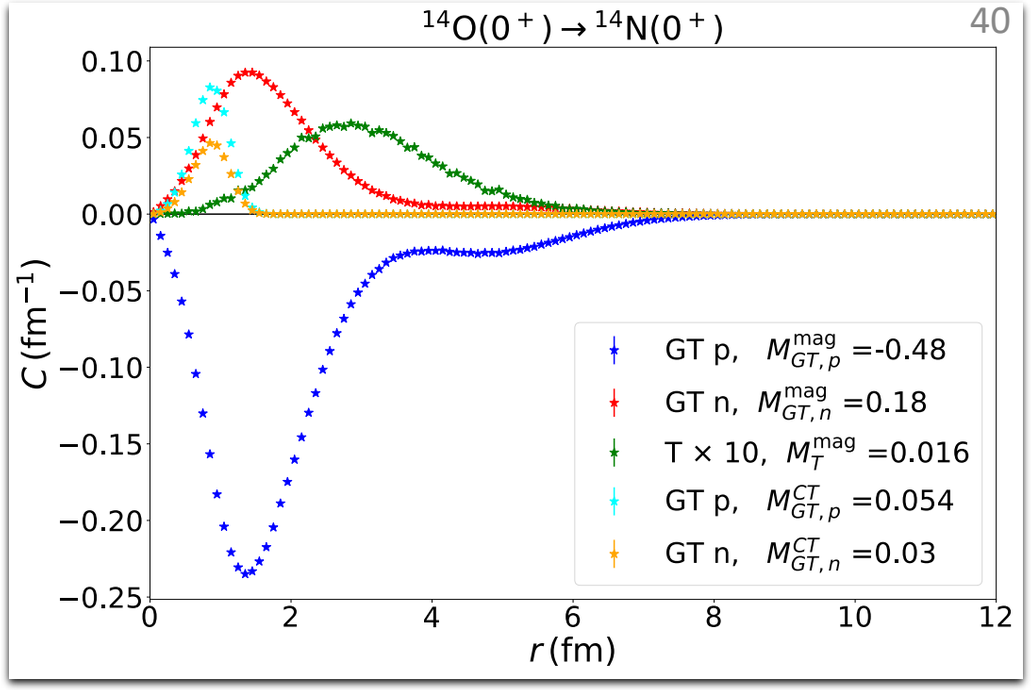
$\mathcal{O}(\alpha^2 Z)$ two-nucleon terms

Nuclear-structure dependence, "δ_{NS}"

- Source of largest uncertainty
- In EFT described by $\langle \psi_i \ \ V \ \ \psi_i \rangle$

Half Life

$^{14}\mathrm{O} \rightarrow {}^{14}\mathrm{N}$



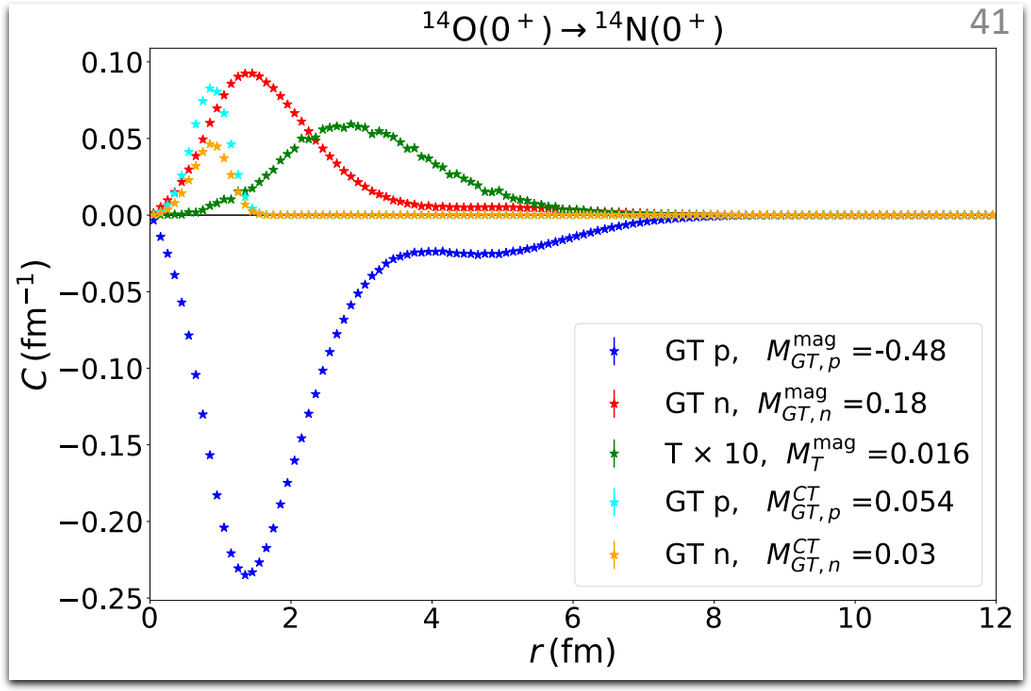
Nuclear Matrix Elements

- All combined: $V_{ud} = 0.97364(12)_{g_V}(10)_{\mathrm{exp}}(22)_{\bar{f}}(13)_{\delta_{NS}^{\mathrm{non-LEC}}}(44)_{\delta_{NS}^{\mathrm{LEC}}}(12)_{\delta_c}[55]_{\mathrm{total}}$
- Compatible with traditional approach $V_{ud} = 0.97405(37)_{\mathrm{total}}$

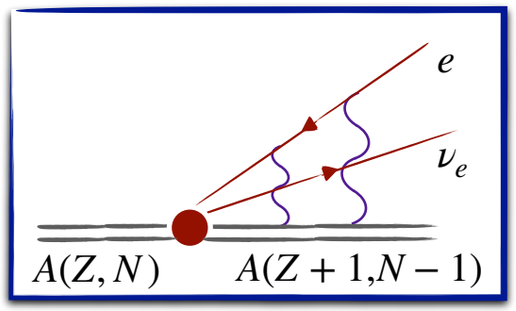
Hardy & Towner, ‘20

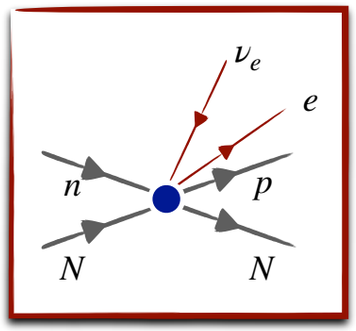
Half Life

$^{14}\mathrm{O} \rightarrow {}^{14}\mathrm{N}$



Nuclear Matrix Elements





- All combined: $V_{ud} = 0.97364(12)_{g_V}(10)_{\mathrm{exp}}(22)_{\bar{f}}(13)_{\delta^{\mathrm{non-LEC}}_{NS}}(44)_{\delta^{\mathrm{LEC}}_{NS}}(12)_{\delta_c}[55]_{\mathrm{total}}$
- Compatible with traditional approach $V_{ud} = 0.97405(37)_{\mathrm{total}}$

Hardy & Towner, ‘20

- ***But larger uncertainty***

Precision frontier

Future projects

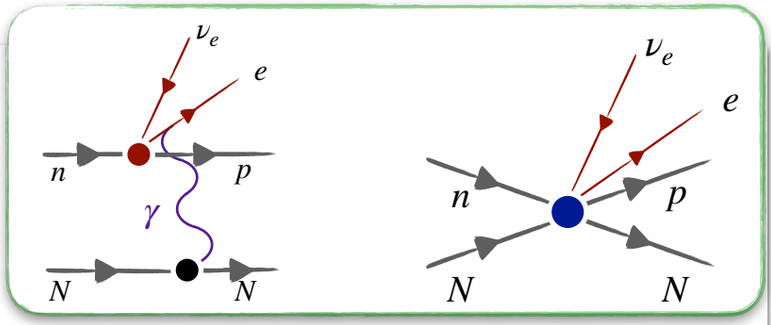
Precision frontier

Future work

Controlling theory uncertainties

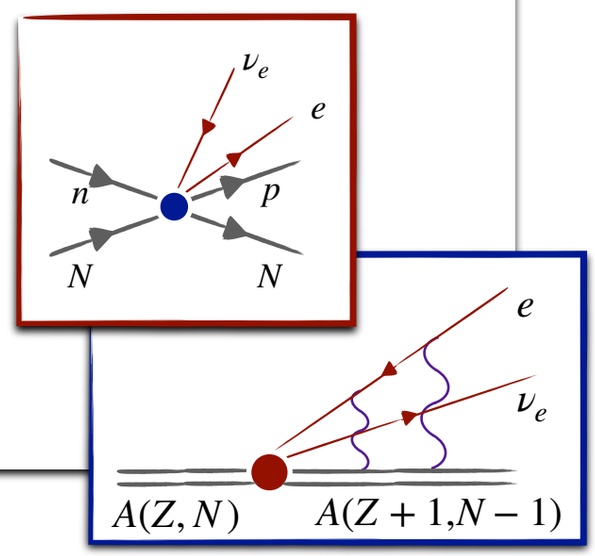
- Nuclear β decays measured to $\mathcal{O}(10^{-4})$ precision

- Obtain same level of precision using EFT framework
  - ***Needed to unlock the full BSM reach of experiments***



Radiative corrections in EFT

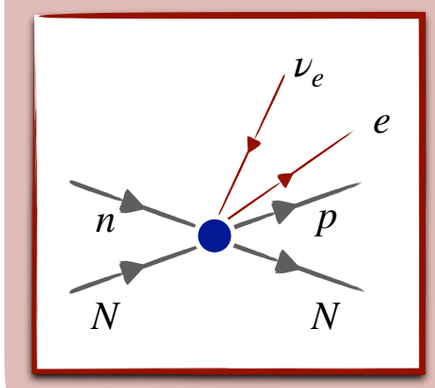
- Requires control of:
  - Unknown short-distance interactions
  - Missing $O(\alpha^2 Z)$ contributions
- ***EFT allows for systematic improvements***



Uncertainties at the precision frontier

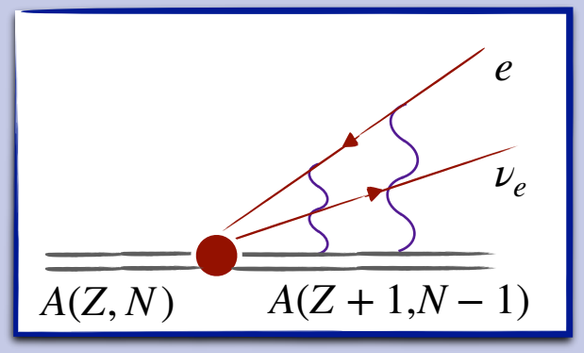
Short-distance couplings

- Fit to measurements
- Obtain from theory



$O(\alpha^2 Z)$ corrections

- Compute two-loop diagrams



Isospin breaking effects

Develop EFT framework for "δ_C"

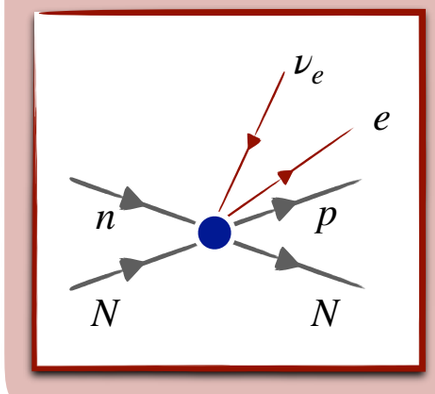
$$\langle \psi_f \ \ \tau^+ \ \ \psi_i \rangle = \sqrt{2}(1 - \delta_C/2)$$

Uncertainties at the precision frontier

Overlap with Nuclear Theory Group

Short-distance couplings

- Fit to measurements
- Obtain from theory



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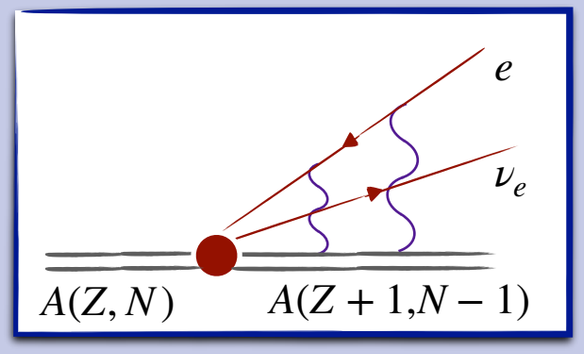
- Compute two-loop diagrams



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Uncertainties at the precision frontier

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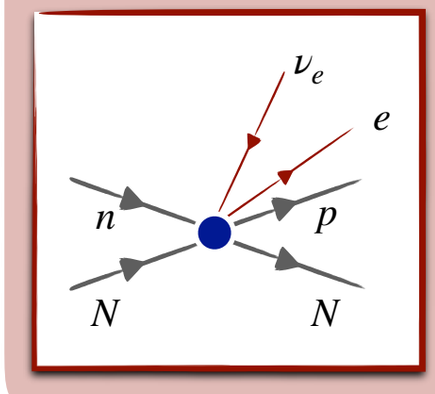

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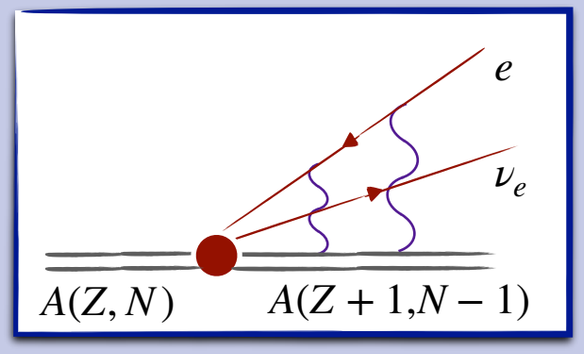
- Compute two-loop diagrams



Isospin breaking effects

Develop EFT framework for "δ_C"

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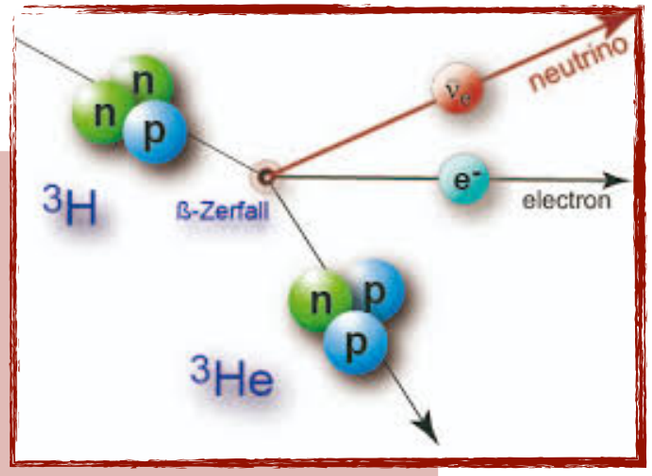
NTNP topical collaboration

Uncertainties at the precision frontier

Spin off: beyond $0^+ \rightarrow 0^+$ decays



Generalize to decays of tritium

- Help determine three-nucleon forces
  - Could be affected by radiative corrections
  - Interplay with “Connecting nuclei to the Cosmos”

Funding strategies

Funding strategies

Initially

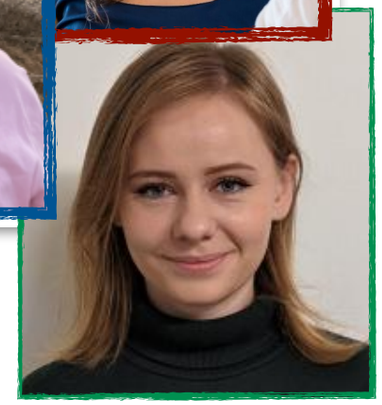
- Possible start-up funds
  - A student & postdoc
- Apply for
  - DOE: Early Career Award, regular FOAs
  - NSF: CAREER program, regular FOAs

Other sources of funding

- Lead and/or participate in collaborative grant applications
  - DOE topical collaborations
  - NSF hubs
- Explore
  - Departmental grants
  - RENEW / FAIR
- Sources of funding in related fields
- E.g. machine learning has applications to
  - BSM fits for sterile neutrinos
  - Effects of three-nucleon forces in Neutron Stars

Mentoring

- Recent/current mentorship
  - Thomas Cepollina (undergraduate)
  - Maria Dawid (Graduate student)
  - Sebastián Urrutia Quiroga (Postdoc)
  - Heleen Mulder (Master student, Nikhef/Amsterdam)



INTURN
INSTITUTE FOR NUCLEAR THEORY UNDERGRADUATE RESEARCH NETWORK

- The INT's Undergraduate Research Network
  - Provides research opportunities to undergraduates from diverse backgrounds
  - Aimed at ensuring they are able to stay in physics

- Part of organization/selection committee
- I currently mentor Thomas Cepollina (3rd-year student) on a research project

At UTK

- Act as a mentor in the Nuclear Physics Eastern Tennessee Fellowship

- Outreach: High School Lecture Series

Summary

- Exciting portfolio of (upcoming) experiments
- Will probe
  - **Beyond the SM physics to**
  - **Nuclear physics of dense matter**
- Nuclear theory is needed to
  - Connect different measurements
  - Unlock their full BSM reach

- Addressed by research program with 3 pillars
  - **Sterile neutrinos & Lepton number**
  - **β decays & the Cabibbo Angle**
  - **Connecting Nuclei to Neutron Stars**

Each has opportunities for collaboration with
- ***UTK Nuclear Theory***
- ***UTK Astrophysics & HEP***
- ***NTNP***

Finding new physics using nuclei