Simplification of Tensor Interactions

New Paths in Dark Matter, Flavor Violation, Neutrino Scattering, and β-Decays

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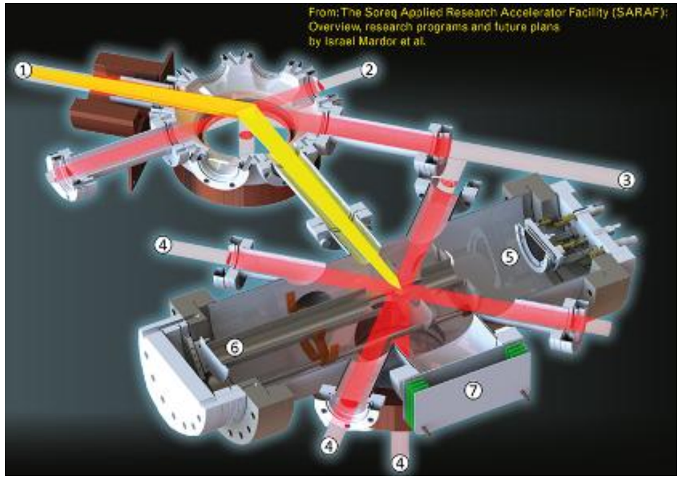
CIPANP 2025

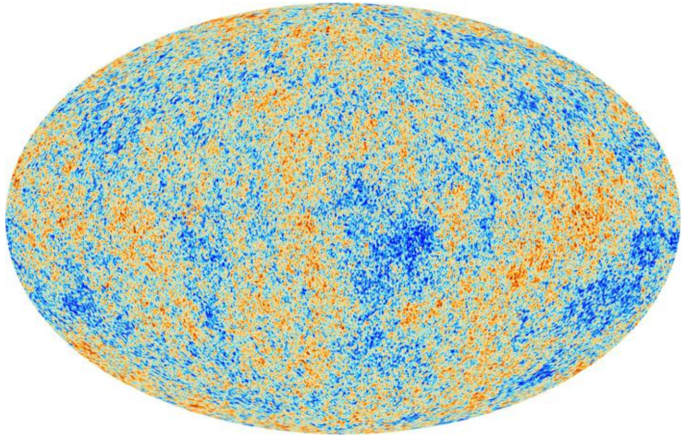
Searches for BSM physics

Nuclear Physics



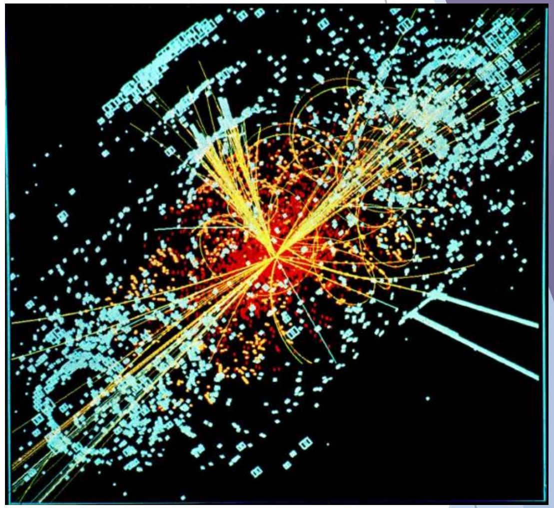
Mardor *et al.*, Eur. Phys. J. A 54, 91 (2018)

Astrophysics & Cosmology



https://www.esa.int/ESA_Multimedia/Images/2013/03/Planck_CMB

Particles Physics



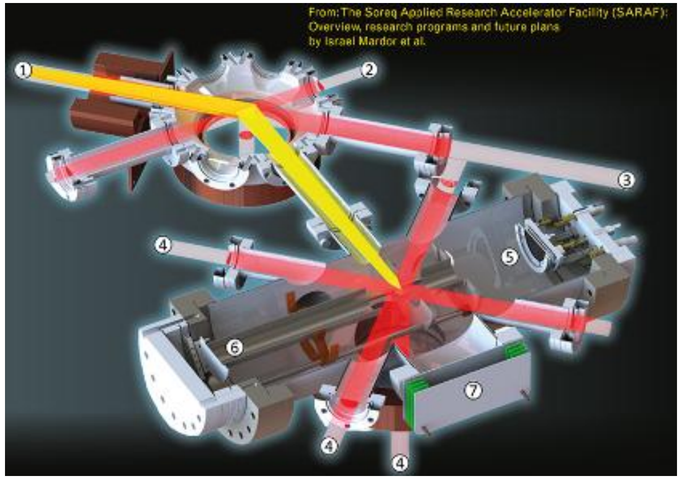
Lucas Taylor / CERN - http://cdsweb.cern.ch/record/628469

E.g.,

- β-decays
- Dark Matter
- Neutrinos & $\mu \to e$

Searches for BSM physics

Nuclear Physics



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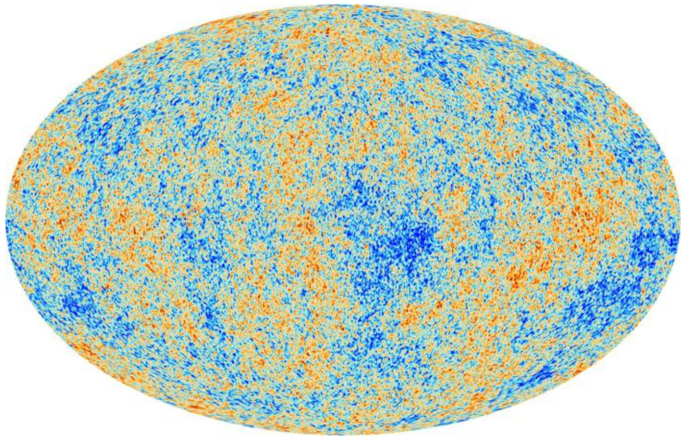

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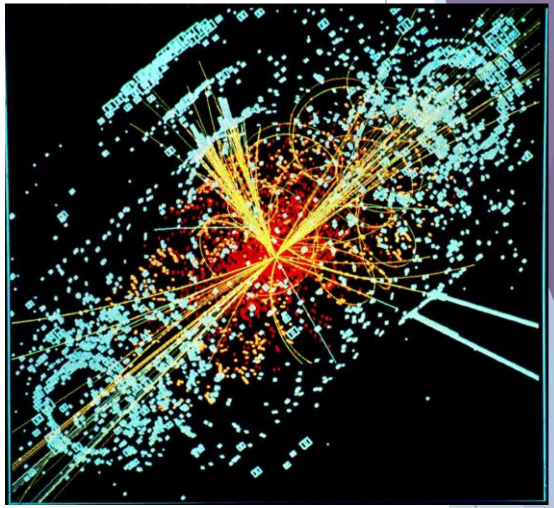

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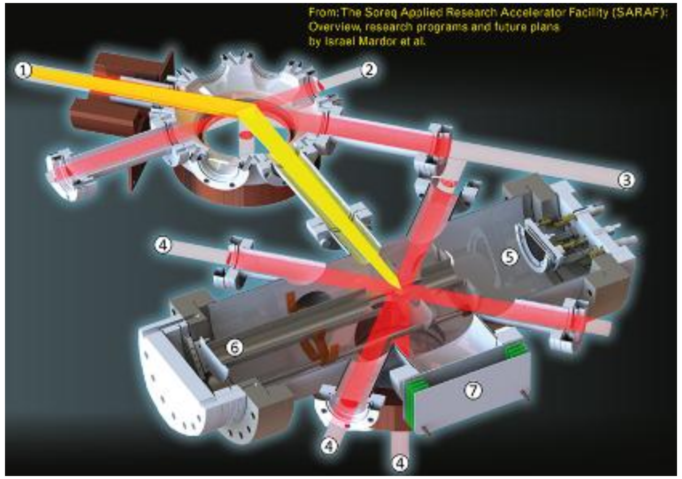
E.g.,

- β-decays
- Dark Matter
- Neutrinos & $\mu \to e$

with nuclei… (low energy)

✓ Tensor decomposition

Nuclear Physics



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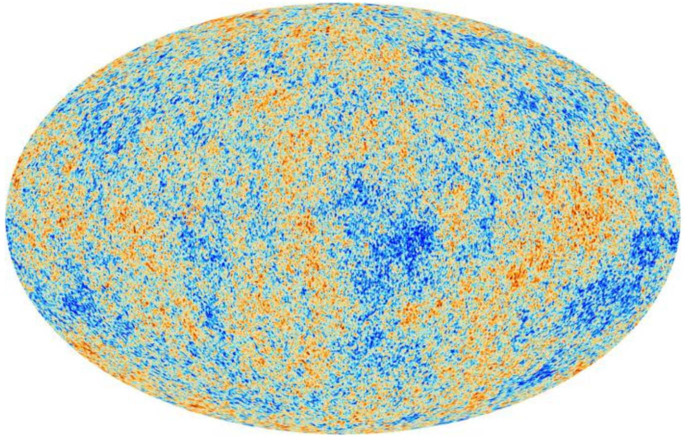

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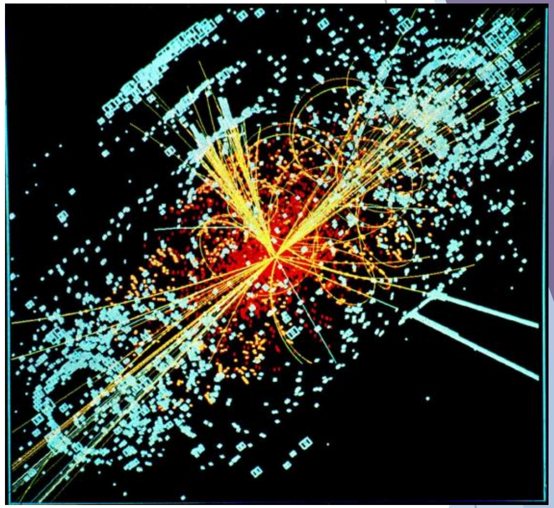

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E.g.,

- **β-decays**
- **Dark Matter**
- **Neutrinos & $\mu \to e$**

- **Summary**

The Fundamental Symmetries approach

How to describe interactions with Nuclei @Low Energy?

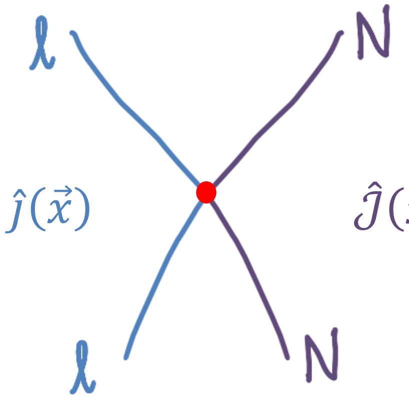
QCD is nonperturbative @Low Energies

- **Effective Theories**
  - The structure of the coupling is determined only by ***symmetry*** considerations

The Fundamental Symmetries approach

Low energy interaction of *something* with nuclei

Something's current $\hat{j}(\vec{x})$



$\hat{J}(\vec{x})$ nuclear current

$$\hat{\mathcal{H}}_W \sim \hat{j}(\vec{x}) \cdot \hat{J}(\vec{x})$$

And similar terms for the *something*

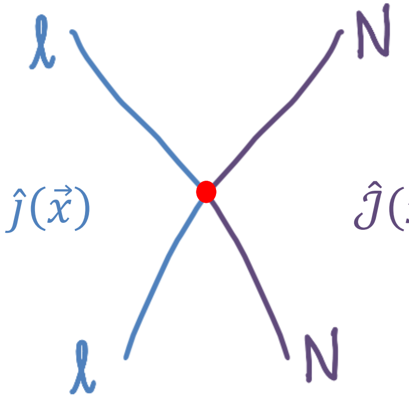
Nuclear current => bilinear covariants

- Scalar
- PseudoScalar
- Vector
- Axial vector
- Tensor

The Fundamental Symmetries approach

Low energy interaction of *something* with nuclei

Something's current $\hat{\jmath}(\vec{x})$



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$$\hat{\mathcal{H}}_W \sim \hat{\jmath}^{\mu\nu}(\vec{x})\,\hat{J}_{\mu\nu}(\vec{x})$$

And similar terms for the *something*

Nuclear current => bilinear covariants

- Scalar
- PseudoScalar
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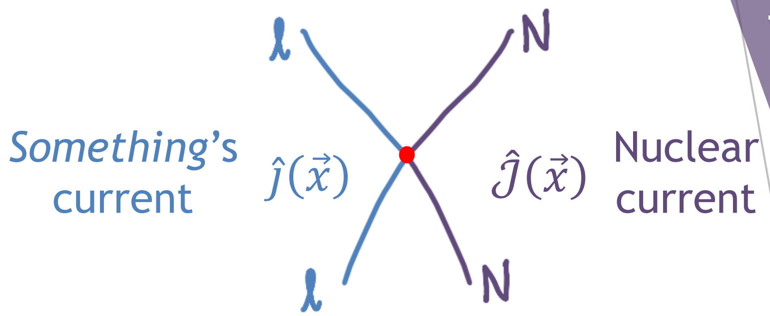
$$J_{\mu\nu} = \begin{pmatrix} J_{00} & J_{01} & J_{02} & J_{03} \\ J_{10} & J_{11} & J_{12} & J_{13} \\ J_{20} & J_{21} & J_{22} & J_{23} \\ J_{30} & J_{31} & J_{32} & J_{33} \end{pmatrix}$$

Tensor



$$\hat{\mathcal{H}}_W \sim \hat{j}^{\mu\nu}(\vec{x})\,\hat{J}_{\mu\nu}(\vec{x})$$

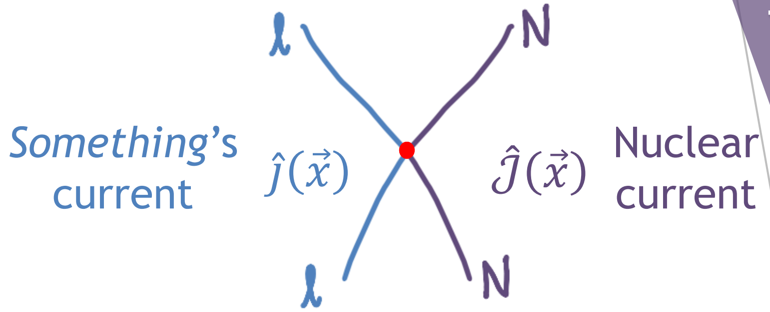
Tensor interactions

- ~~Symmetric:~~
  - ~~A space-time-metric and the~~ stress-energy tensor
- Antisymmetric
  - Fermionic probes

$$J_{\mu\nu} = \begin{pmatrix} J_{00} & J_{01} & J_{02} & J_{03} \\ J_{10} & J_{11} & J_{12} & J_{13} \\ J_{20} & J_{21} & J_{22} & J_{23} \\ J_{30} & J_{31} & J_{32} & J_{33} \end{pmatrix}$$

AGM & Gazit, PRD 2023

Tensor



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Time-only

mixed space-time

$$J_{\mu\nu} = \begin{pmatrix} J_{00} & \left(\leftarrow \quad \vec{J}_{0\cdot} \quad \rightarrow \right) \\ \begin{pmatrix} \uparrow \\ \\ \vec{J}_{\cdot 0} \\ \\ \downarrow \end{pmatrix} & \begin{pmatrix} \\ \\ J_{ij} \\ \\ \\ \end{pmatrix} \end{pmatrix}$$

Space-only

mixed space-time

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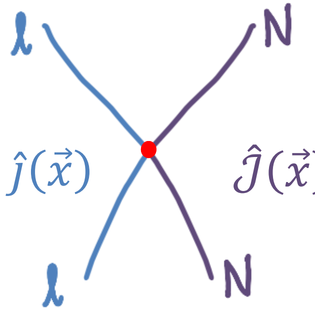
Tensor



Something's current $\hat{j}(\vec{x})$ $\hat{J}(\vec{x})$ Nuclear current

$$\hat{\mathcal{H}}_W \sim \hat{j}^{\mu\nu}(\vec{x})\,\hat{J}_{\mu\nu}(\vec{x})$$

Tensor interactions

- ~~Symmetric:~~
  - ~~A space-time-metric and the~~ stress-energy tensor
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$$\Longrightarrow J_{00} = 0$$

Time-only — mixed space-time

$$J_{\mu\nu} = \begin{pmatrix} \cancel{J_{00}} & \left(\leftarrow \quad \vec{J}_{0\cdot} \quad \rightarrow \right) \\ \begin{pmatrix} \uparrow \\ \vec{J}_{\cdot 0} \\ \downarrow \end{pmatrix} & \begin{pmatrix} \\ J_{ij} \\ \\ \end{pmatrix} \end{pmatrix}$$

Space-only

mixed space-time

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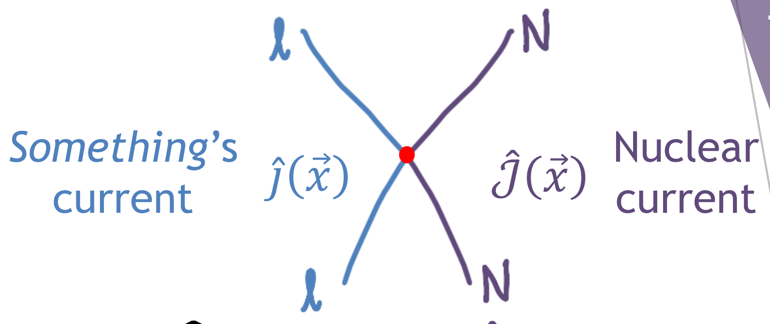
Tensor



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Tensor interactions

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$$\Rightarrow J_{00} = 0$$

$$\Rightarrow J_{\cdot 0} = -J_{0\cdot}$$

Time-only

mixed space-time

$$J_{\mu\nu} = \begin{pmatrix} \cancel{J_{00}} & \left(\leftarrow \quad \vec{J}_{0\cdot} \quad \rightarrow \right) \\ \begin{pmatrix} \uparrow \\ -\vec{J}_{0\cdot} \\ \downarrow \end{pmatrix}^{T'} & \begin{pmatrix} \\ J_{ij} \\ \\ \end{pmatrix} \end{pmatrix}$$

Space-only

mixed space-time

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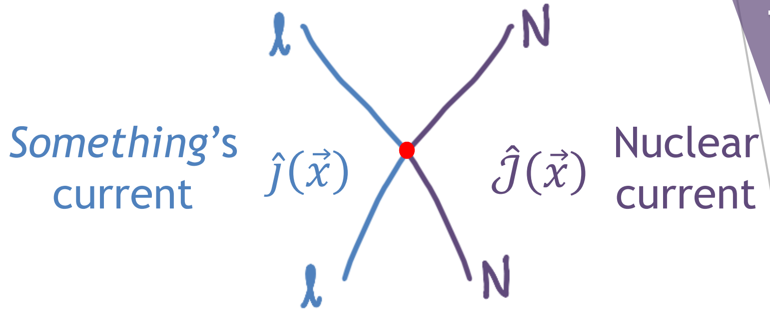
Tensor
$\rightarrow$ vector-like objects



$$\hat{\mathcal{H}}_W \sim \hat{j}^{\mu\nu}(\vec{x})\,\hat{J}_{\mu\nu}(\vec{x})$$
$$= -\left[\vec{j}^{T}\cdot\vec{J}^{T} + \vec{j}^{T'}\cdot\vec{J}^{T'}\right]$$

Tensor interactions

- ~~Symmetric:~~
  - ~~A space-time-metric and the~~ stress-energy tensor
- Antisymmetric
  - Fermionic probes

$$\Longrightarrow J_{00} = 0$$
$$\Longrightarrow J_{\cdot 0} = -J_{0\cdot}$$
$$\Longrightarrow J_{ij} \longrightarrow [J_{ij}]^{(1)}$$

Time-only | mixed space-time

$$J_{\mu\nu} = \begin{pmatrix} \cancel{J_{00}} & \left(\leftarrow \quad \vec{J}_{0\cdot} \quad \rightarrow\right) \\ \begin{pmatrix} \uparrow \\ \overset{T'}{-\vec{J}_{0\cdot}} \\ \downarrow \end{pmatrix} & \begin{pmatrix} \overset{T}{\vec{J}^{(1)}} \end{pmatrix} \end{pmatrix}$$

mixed space-time | Space-only

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Tensor → vector-like objects

Tensor "vector-like" nuclear currents with an **identified parity**

BSM currents **identify** with the well-known SM currents!

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Tensor → vector-like objects

Tensor "vector-like" nuclear currents with an **identified parity**

- Mixed space-time "Vector–like" tensor current:

$$\vec{J}^{T'} \propto -\frac{1}{\sqrt{2}}\frac{\vec{\nabla}+\vec{\sigma}\times\vec{P}}{2m_N}g_T\tau^i$$

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- Space-only “Axial-vector-like” tensor current:

$$\vec{J}^{T} = -\frac{i}{\sqrt{2}} \frac{g_T}{g_A} \vec{J}^{A} + \mathcal{O}\left(\frac{p^2}{m_N^2}\right)$$

BSM current

Well known SM current

BSM currents **identify** with the well-known SM currents!

$\frac{g_T}{g_A} \sim 1$ nuclear charges (lattice)

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Well known SM current

- No time-only tensor current (the scalar $l_{00} = 0$)

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BSM current

Well known SM current

- No time-only tensor current (the scalar $l_{00}=0$)

"vector-like" $$\mathcal{J}^{S} = -\frac{i}{\sqrt{2}}\frac{g_S}{g_V}\mathcal{J}_0^{V} + \mathcal{O}\left(\frac{p^2}{m_N^2}\right)$$

"Axial-vector-like" $$\mathcal{J}^{P} = -\frac{g_P}{g_A}\vec{\mathcal{J}}^{A}\cdot\frac{i\vec{\nabla}}{2m_N} + \mathcal{O}\left(\frac{p^2}{m_N^2}\right)$$

BSM currents identify with the well-known SM currents!

$\frac{g_S}{g_V}, \frac{g_T}{g_A} \sim 1$

$\frac{g_P}{g_A} \sim 300$

nuclear charges (lattice)

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Tensor → vector-like objects

Tensor "vector-like" nuclear currents with an **identified parity**

- Mixed space-time "Vector–like" tensor current:

$$\vec{J}^{T'} \propto -\frac{1}{\sqrt{2}}\frac{\vec{\nabla}+\vec{\sigma}\times\vec{P}}{2m_N}g_T\tau^i$$

- Space-only "Axial-vector-like" tensor current:

$$\vec{J}^{T} = -\frac{i}{\sqrt{2}}\frac{g_T}{g_A}\vec{J}^{A} + \mathcal{O}\left(\frac{p^2}{m_N^2}\right)$$

BSM current

Well known SM current

- No time-only tensor current (the scalar $l_{00}=0$)

"vector-like"

$$J^{S} = -\frac{i}{\sqrt{2}}\frac{g_S}{g_V}J_0^{V} + \mathcal{O}\left(\frac{p^2}{m_N^2}\right)$$

"Axial-vector-like"

$$J^{P} = -\frac{g_P}{g_A}\vec{J}^{A}\cdot\frac{i\vec{\nabla}}{2m_N} + \mathcal{O}\left(\frac{p^2}{m_N^2}\right)$$

$\frac{g_S}{g_V},\frac{g_T}{g_A}\sim 1$

$\frac{g_P}{g_A}\sim 300$

nuclear charges (lattice)

BSM currents **identify** with the well-known SM currents!

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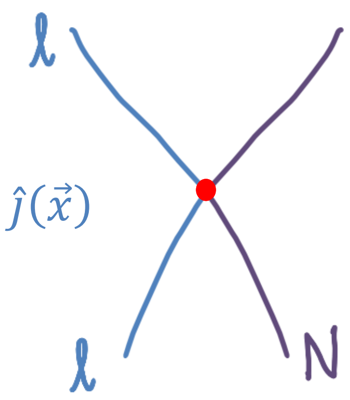
Weak interaction

β-decays

Weak interaction

Low energy reaction of
leptons with nucleons

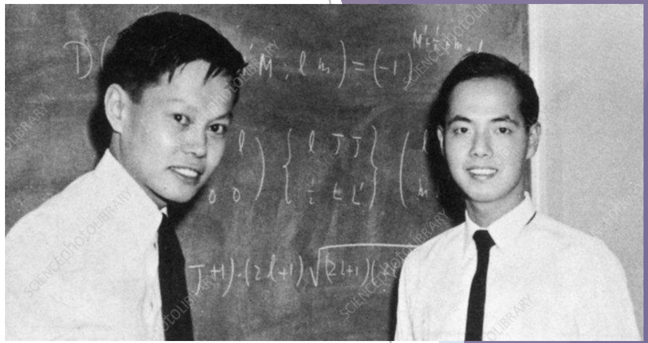
lepton current $\hat{\jmath}(\vec{x})$



$\hat{\mathcal{J}}(\vec{x})$ nuclear current

$$\hat{\mathcal{H}}_W \sim C\, \hat{\jmath}(\vec{x}) \cdot \hat{\mathcal{J}}(\vec{x})$$

A-priori:
- Scalar (C_S)
- PseudoScalar (C_P)
- Vector (C_V)
- Axial-vector (C_A)
- Tensor (C_T)



Theory: C.N. Yang and T.D. Lee (Nobel 1957)

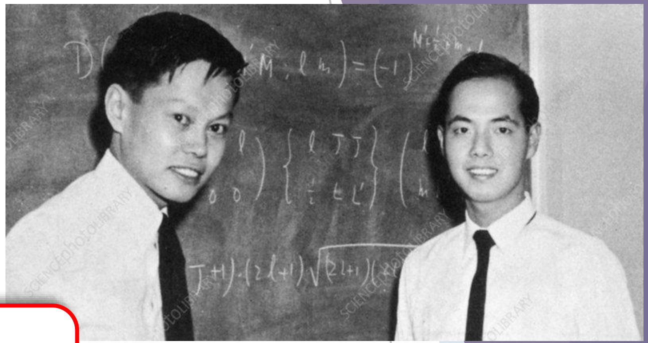
Experiment: C.S. Wu:
Parity violation in ***nuclear β-decays***

$\Rightarrow$ **Weak SM structure:**

"$V - A$"

Weak interaction

Low energy reaction of



C.N. Yang and T.D. Lee (Nobel 1957)

The SM is incomplete

>> Ongoing searches for C_S, C_P, C_T
in precision ***nuclear β-decay*** experiments

Experiment: C.S. Wu:
Parity violation in ***nuclear β-decays***

$$\hat{\mathcal{H}}_W \sim C\, \hat{j}(\vec{x}) \cdot \hat{J}(\vec{x})$$

A-priori:
- Scalar (C_S)
- PseudoScalar (C_P)
- Vector (C_V)
- Axial-vector (C_A)
- Tensor (C_T)

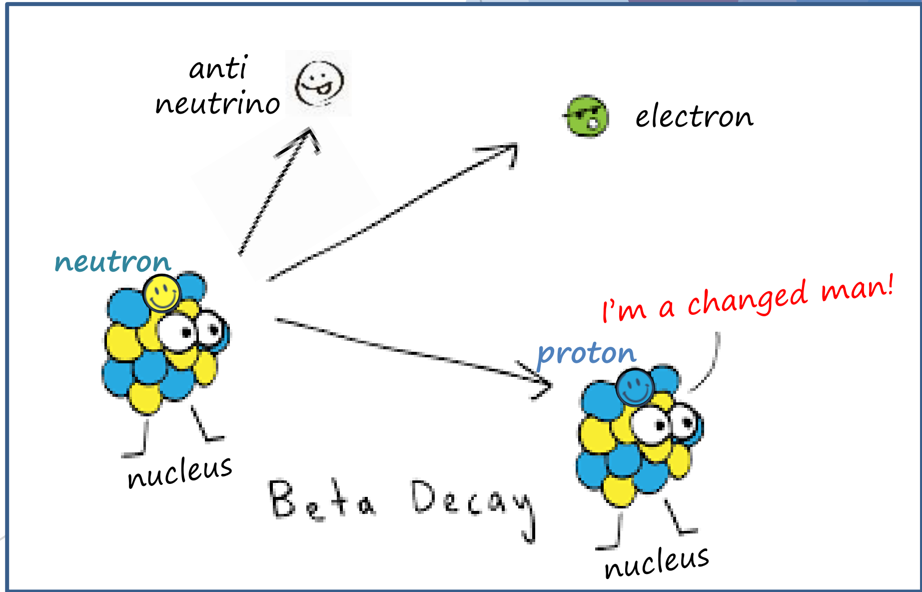
$\Rightarrow$ **Weak SM structure:**

“$V - A$”

Nuclear β-decay

Low momentum transfer: $q \sim 0 - 10\ \mathrm{MeV/c}$

Beta decay, Khan Academy, cdn.kastatic.org/ka-perseus-images/8d978444f15f9bbc3bcadb0549816bc7e264b977.svg



Nuclear β-decay

Low momentum transfer: $q \sim 0 - 10\ \mathrm{MeV/c}$

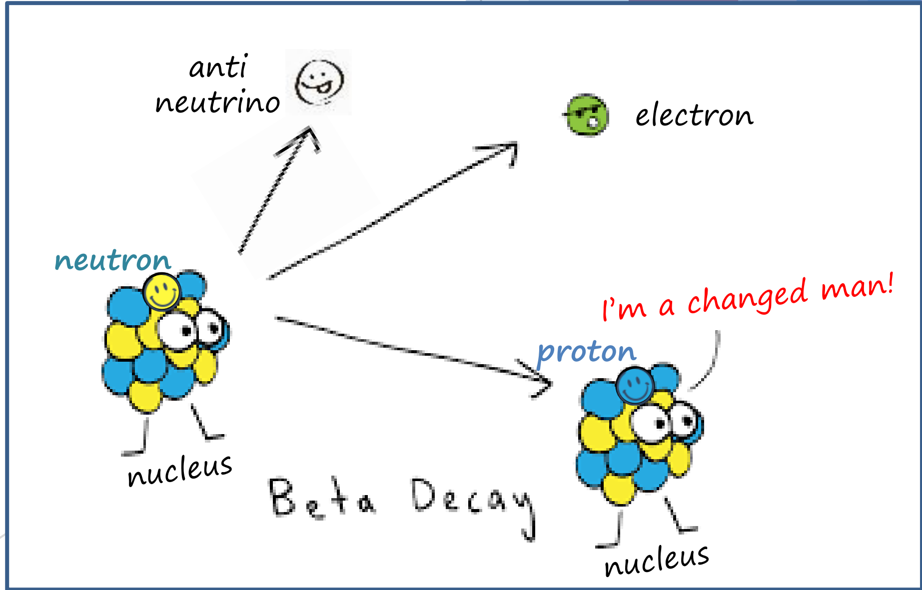
angular momentum

parity

Transitions $J^{\Delta\pi}$:

"Allowed" (when $q \to 0$)	• 0^+: Fermi • 1^+: Gamow-Teller
"Forbidden" (vanish for $q \to 0$)	All the rest $J^{\Delta\pi}$

Beta decay, Khan Academy, cdn.kastatic.org/ka-perseus-images/8d978444f15f9bbc3bcadb0549816bc7e264b977.svg



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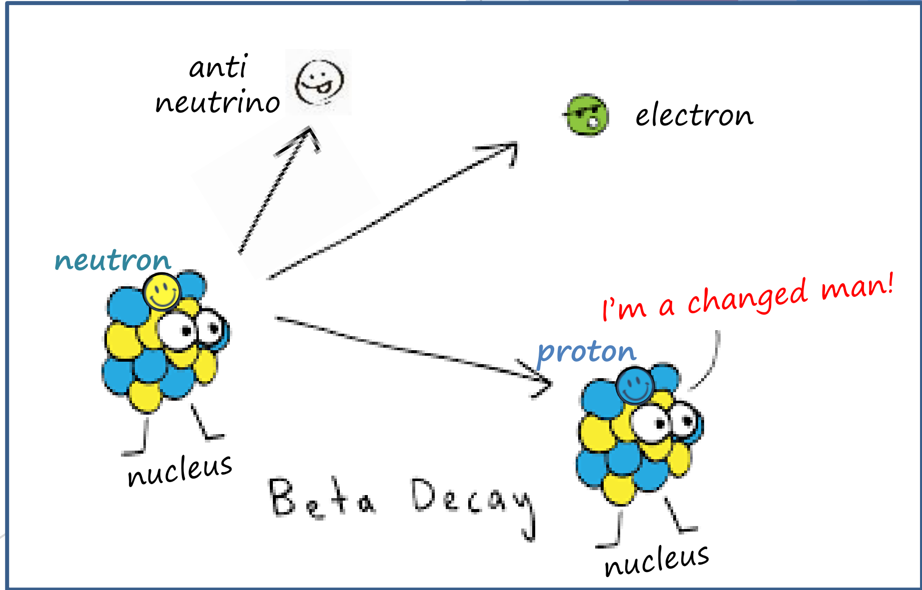
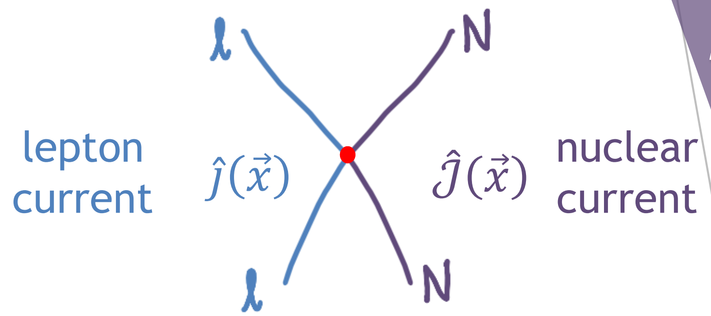
"Forbidden" (van...	... the rest $J^{\Delta\pi}$

Missing theory for tensor!

Beta decay, Khan Academy, cdn.kastatic.org/ka-perseus-images/8d978444f15f9bbc3bcadb0549816bc7e264b977.svg



SM Formalism



$$\hat{\mathcal{H}}_W \sim C_V\, \hat{j}^{\mu}(\vec{x})\hat{\mathcal{J}}_{\mu}(\vec{x})$$

- β-decay rate:

$$d\Gamma \propto \left|\langle\psi_f\|\hat{H}_W\|\psi_i\rangle\right|^2 \propto \sum_{J=0}^{\infty} f^V(\vec{\beta},\hat{\nu})\, \langle\psi_f\|\hat{O}_J^V\|\psi_i\rangle\langle\psi_f\|\hat{Q}_J^V\|\psi_i\rangle^*$$

Observables

Multipole operators

$$\hat{\mathcal{H}}_W \sim C_V\, \hat{j}^{\mu}(\vec{x})\hat{\mathcal{J}}_{\mu}(\vec{x})$$

Vector coupling constant

Vector lepton current

Vector nuclear current

4 Multipole Operators $\hat{C}_{JM}^V$, $\hat{L}_{JM}^V$, $\hat{E}_{JM}^V$, $\hat{M}_{JM}^V$:

$$\hat{C}_{JM}^V = \int d^3x\, j_J(qx)Y_{JM}(\hat{x})\hat{\mathcal{J}}_0^V(\vec{x})$$

$$\hat{L}_{JM}^V = \frac{i}{q}\int d^3x\{\vec{\nabla}[j_J(qx)Y_{JM}(\hat{x})]\}\cdot\vec{\mathcal{J}}^V(\vec{x})$$

$$\hat{E}_{JM}^V = \frac{i}{q}\int d^3x\{\vec{\nabla}\times[j_J(qx)\,\vec{Y}_{JJ1}^M(\hat{x})]\}\cdot\vec{\mathcal{J}}^V(\vec{x})$$

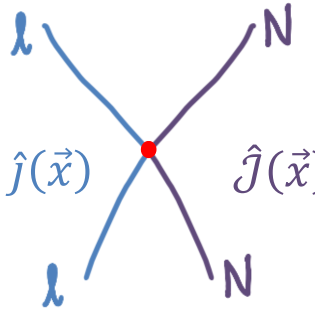
$$\hat{M}_{JM}^V = \int d^3x[j_J(qx)\,\vec{Y}_{JJ1}^M(\hat{x})]\cdot\vec{\mathcal{J}}^V(\vec{x})$$

Vector nuclear current

Vector spherical harmonics

and the same for the Axial-vector (A) symmetry

SM Formalism



lepton current $\hat{j}(\vec{x})$ $\hat{\mathcal{J}}(\vec{x})$ nuclear current

$$\hat{\mathcal{H}}_W \sim C_T\, \hat{j}^{\mu\nu}(\vec{x})\hat{\mathcal{J}}_{\mu\nu}(\vec{x})$$

- β-decay rate:

$$d\Gamma \propto \left|\langle\psi_f\|\hat{H}_W\|\psi_i\rangle\right|^2 \propto \sum_{J=0}^{\infty} f^T\left(\vec{\beta},\hat{\nu}\right)\langle\psi_f\|\hat{O}_J^T\|\psi_i\rangle\langle\psi_f\|\hat{Q}_J^T\|\psi_i\rangle^*$$

Observables

Multipole operators

$$\hat{\mathcal{H}}_W \sim C_T\, \hat{j}^{\mu\nu}(\vec{x})\hat{\mathcal{J}}_{\mu\nu}(\vec{x})$$

Tensor coupling constant

Tensor lepton current

Tensor nuclear current

4 Multipole Operators $\hat{C}^T_{JM}$, $\hat{L}^T_{JM}$, $\hat{E}^T_{JM}$, $\hat{M}^T_{JM}$:

antisymmetric

The currents are tensors: $\hat{j}^{\mu\nu}$ $\hat{\mathcal{J}}_{\mu\nu}$

$$\hat{C}^T_{JM} = \int d^3x\, j_J(qx)\cancel{Y_{JM}(\hat{x})}\mathcal{J}^{\mu\nu}(\vec{x})$$

$$\hat{L}^T_{JM} = \frac{i}{q}\int d^3x\{\vec{\nabla}[j_J(qx)\cancel{Y_{JM}(\hat{x})}]\}\cdot\mathcal{J}^{\mu\nu}(\vec{x})$$

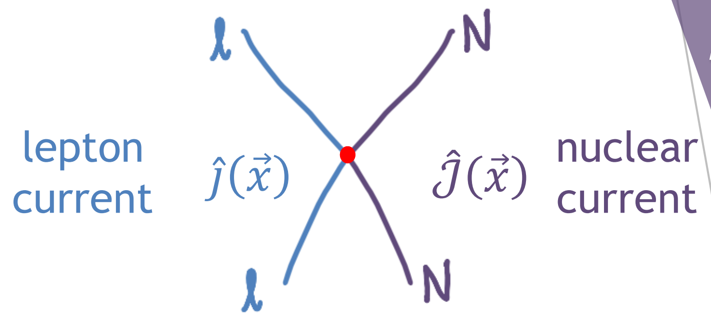
$$\hat{E}^T_{JM} = \frac{i}{q}\int d^3x\{\vec{\nabla}\times[j_J(qx)\,\cancel{\vec{Y}^M_{JJ1}(\hat{x})}]\}\cdot\mathcal{J}^{\mu\nu}(\vec{x})$$

$$\hat{M}^T_{JM} = \int d^3x[j_J(qx)\,\cancel{\vec{Y}^M_{JJ1}(\hat{x})}]\cdot\mathcal{J}^{\mu\nu}(\vec{x})$$

Tensor nuclear current

~~Vector~~ spherical harmonics

Tensor
$\rightarrow$ vector-like objects



$$\hat{\mathcal{H}}_W \sim C_T\, \hat{j}^{\mu\nu}(\vec{x})\hat{J}_{\mu\nu}(\vec{x})$$
$$= -C_T\left[\vec{j}^{T}\cdot\vec{J}^{T} + \vec{j}^{T'}\cdot\vec{J}^{T'}\right]$$

Tensor interactions

- ~~Symmetric:~~
  - ~~A space-time-metric and the~~ stress-energy tensor
- Antisymmetric
  - Fermionic probes

$$\Longrightarrow J_{00} = 0$$
$$\Longrightarrow J_{\cdot 0} = -J_{0\cdot}$$
$$\Longrightarrow J_{ij} \longrightarrow [J_{ij}]^{(1)}$$

Time-only | mixed space-time

$$J_{\mu\nu} = \begin{pmatrix} \cancel{J_{00}} & \left(\leftarrow \quad \vec{J}_{0\cdot} \quad \rightarrow\right) \\ \begin{pmatrix} \uparrow \\ T' \\ -\vec{J}_{0\cdot} \\ \downarrow \end{pmatrix} & \begin{pmatrix} T \\ \vec{J}^{(1)} \end{pmatrix} \end{pmatrix}$$

Space-only

mixed space-time

AGM & Gazit, PRD 2023

Tensor → vector-like objects

- Tensor "vector-like" ***Multipole Operators*** with an **identified parity**

Tensor

$$\hat{L}^T, \hat{E}^T, \hat{M}^T \approx -\frac{i}{\sqrt{2}}\frac{g_T}{g_A}\hat{L}^A, \hat{E}^A, \hat{M}^A$$

BSM operators

$\cancel{\hat{C}^T}(l_{00}=0)$

Well known SM operators

Scalar

$$\hat{C}^S \approx -\frac{i}{\sqrt{2}}\frac{g_S}{g_V}\hat{C}^V$$

Pseudoscalar

$$\hat{C}^P \approx \frac{q}{2m_N}\frac{g_P}{g_A}\hat{L}^A$$

BSM operators **identify** with the well-known SM operators

$\frac{g_S}{g_V}, \frac{g_T}{g_A} \sim 1$

$\frac{g_P}{g_A} \sim 300$

nuclear charges (lattice)

AGM & Gazit, PRD 2023

Multipole operator's matrix elements

$\hat{H}$

Nuclear Hamiltonian

$$\langle \psi_f || \quad || \psi_i \rangle$$

Nuclear wave functions

$\hat{\mathcal{J}}_\mu$

SM nuclear currents

$\hat{O}_J$

SM multipole operators

$$\langle \psi_f || \hat{O}_J || \psi_i \rangle$$

SM nuclear matrix elements

δ_a, δ_b

SM corrections

Numerical calculations of the nuclear structure

BSM operators **identify** with the well-known SM operators

AGM & Gazit, PRD 2023

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$\langle\psi_f\| \quad \|\psi_i\rangle$

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SM nuclear currents

$\hat{\mathcal{J}}^T_{\mu\nu}, \hat{\mathcal{J}}^S, \hat{\mathcal{J}}^P$

BSM nuclear currents

$\hat{O}_J$

SM multipole operators

$\langle\psi_f\|\hat{O}_J\|\psi_i\rangle$

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[AGM & Gazit, PRD 2023](#)

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- Predictions & Observables for forbidden decays for the first time

AGM & Gazit, PRD 2023

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SM nuclear matrix elements

Numerical calculations of the nuclear structure

δ_a, δ_b

SM corrections

BSM predictions

BSM operators **identify** with the well-known SM operators

Experiments @ ORNL, HUJI, SOREQ

- Predictions & Observables for forbidden decays for the first time

- ***5:00 PM @ Tests of Symmetries & EW: Unique forbidden β-decays at zero momentum transfer***

  Seng, AGM, Cirigliano, PRL 2025

  Forbidden decays are ***not*** *forbidden*

AGM & Gazit, PRD 2023

Neutrino-

Nucleus Scattering

Neutrino-nucleus scattering

PHYSICAL REVIEW D **102,** 074018 (2020)

Coherent elastic neutrino-nucleus scattering: EFT analysis and nuclear responses

Martin Hoferichter,[1,2,*] Javier Menéndez,[3,4,†] and Achim Schwenk[5,6,7,‡]

- Used the Tensor → vector-like decomposition:
  - The mixed space-time (T') $\propto \cancel{\frac{1}{m_N}}$
  - The space-only (T) response functions <u>identify</u> with the *Axial-vector* ones in leading order!

For the tensor operator, the most relevant contributions are expected from the spacelike components σ_{ij}, because only those are momentum independent and not suppressed by $1/m_N$ in the nonrelativistic expansion. For the same reason, the induced terms in Eq. (21) are subleading. The result of the multipole decomposition for tensor currents, see Appendix D, then leads to the following expressions: defining the couplings via

$$g_{T,1}^N(t) = \sum_{q=u,d,s} C_q^T F_{1,T}^{q,N}(t), \qquad g_{T,1}^N \equiv g_{T,1}^N(0), \qquad (106)$$

and

$$g_{T,1}^0 = \frac{g_{T,1}^p + g_{T,1}^n}{2}, \qquad g_{T,1}^1 = \frac{g_{T,1}^p - g_{T,1}^n}{2}, \qquad (107)$$

the cross section becomes

$$\begin{aligned}\frac{d\sigma_A}{dT}\bigg|_{\text{tensor}} &= \frac{8m_A}{2J+1}\left(2 - \frac{m_A T}{E_\nu^2} - \frac{2T}{E_\nu}\right)[(g_{T,1}^0)^2 \bar{\mathcal{S}}_{00}^{\mathcal{T}}(\mathbf{q}^2) \\ &\quad + g_{T,1}^0 g_{T,1}^1 \bar{\mathcal{S}}_{01}^{\mathcal{T}}(\mathbf{q}^2) + (g_{T,1}^1)^2 \bar{\mathcal{S}}_{11}^{\mathcal{T}}(\mathbf{q}^2)] \\ &\quad + \frac{32m_A}{2J+1}\left(1 - \frac{T}{E_\nu}\right)[(g_{T,1}^0)^2 \bar{\mathcal{S}}_{00}^{\mathcal{L}}(\mathbf{q}^2) \\ &\quad + g_{T,1}^0 g_{T,1}^1 \bar{\mathcal{S}}_{01}^{\mathcal{L}}(\mathbf{q}^2) + (g_{T,1}^1)^2 \bar{\mathcal{S}}_{11}^{\mathcal{L}}(\mathbf{q}^2)]. \qquad (108)\end{aligned}$$

Contrary to the axial-vector response, there is now also a contribution from the longitudinal multipoles, $\bar{\mathcal{S}}_{ij}^{\mathcal{L}}(\mathbf{q}^2)$. These response functions are identical to the ones derived for the axial-vector case only at leading order, i.e., the two-body corrections for the tensor current would take a different form and likewise the corrections from the induced pseudoscalar and the axial-vector radius need to be removed:

$$\bar{\mathcal{S}}_{ij}^{\mathcal{T}}(\mathbf{q}^2) = \mathcal{S}_{ij}^{\mathcal{T}}(\mathbf{q}^2)|_{\delta'(\mathbf{q}^2)=0}, \quad \bar{\mathcal{S}}_{ij}^{\mathcal{L}}(\mathbf{q}^2) = \mathcal{S}_{ij}^{\mathcal{L}}(\mathbf{q}^2)|_{\delta''(\mathbf{q}^2)=0}.$$

Neutrino-nucleus scattering

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  - The mixed space-time (T') $\propto \cancel{\frac{1}{m_N}}$
  - The space-only (T) response functions **identify** with the *Axial-vector* ones in leading order!

Tensor interaction in coherent elastic neutrino-nucleus scattering

Jiajun Liao,[1,*] Jian Tang,[1,†] and Bing-Long Zhang[1,‡]

[1] *School of Physics, Sun Yat-sen University, Guangzhou, 510275, China*

arXiv:2502.10702

Neutrino tensor interactions have gained prominence in the study of coherent elastic neutrino-nucleus scattering (CEνNS) recently. We perform a systematical examination of the nuclear effect, which plays a crucial role in evaluating the cross section of CEνNS in the presence of tensor interactions. Our analysis reveals that the CEνNS cross section induced by tensor interactions is not entirely nuclear spin-suppressed and can be enhanced by a few orders of magnitude compared to the conventional studies. The neutrino magnetic moment induced by the loop effect of tensor interactions, is also taken into account due to its sizable contribution to the CEνNS cross section. We also employ data from the COHERENT experiment and recent observations of solar ^{8}B neutrinos from dark matter direct detection experiments to scrutinize the parameter space of neutrino tensor interactions.

For the tensor operator, the most relevant contributions are expected from the spacelike components σ_{ij}, because only those are momentum independent and not suppressed by $1/m_N$ in the nonrelativistic expansion. For the same reason, the induced terms in Eq. (21) are subleading. The result of the multipole decomposition for tensor currents, see Appendix D, then leads to the following expressions: defining the couplings via

$$g^N_{T,1}(t) = \sum_{q=u,d,s} C^T_q F^{q,N}_{1,T}(t), \qquad g^N_{T,1} \equiv g^N_{T,1}(0), \tag{106}$$

and

$$g^0_{T,1} = \frac{g^p_{T,1} + g^n_{T,1}}{2}, \qquad g^1_{T,1} = \frac{g^p_{T,1} - g^n_{T,1}}{2}, \tag{107}$$

the cross section becomes

$$\begin{aligned}\frac{d\sigma_A}{dT}\bigg|_{\text{tensor}} &= \frac{8m_A}{2J+1}\left(2 - \frac{m_A T}{E_\nu^2} - \frac{2T}{E_\nu}\right)[(g^0_{T,1})^2\bar{S}^{\mathcal{T}}_{00}(\mathbf{q}^2) \\ &\quad + g^0_{T,1}g^1_{T,1}\bar{S}^{\mathcal{T}}_{01}(\mathbf{q}^2) + (g^1_{T,1})^2\bar{S}^{\mathcal{T}}_{11}(\mathbf{q}^2)] \\ &\quad + \frac{32m_A}{2J+1}\left(1 - \frac{T}{E_\nu}\right)[(g^0_{T,1})^2\bar{S}^{\mathcal{L}}_{00}(\mathbf{q}^2) \\ &\quad + g^0_{T,1}g^1_{T,1}\bar{S}^{\mathcal{L}}_{01}(\mathbf{q}^2) + (g^1_{T,1})^2\bar{S}^{\mathcal{L}}_{11}(\mathbf{q}^2)].\end{aligned} \tag{108}$$

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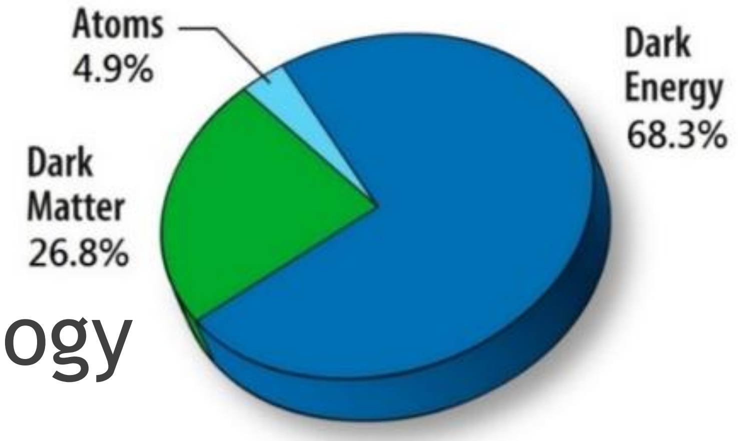
Dark Matter

direct detection

Dark matter direct detection



- A major puzzle in Astrophysics and Cosmology
- Leading candidates – **WIMPs**:
  Weakly-**I**nteracting **M**assive **P**articles
- Direct detection:
  - Measuring WIMP scattering off nuclei on detectors
  - Detection capabilities: $q \sim 100\ \mathrm{MeV/c}$

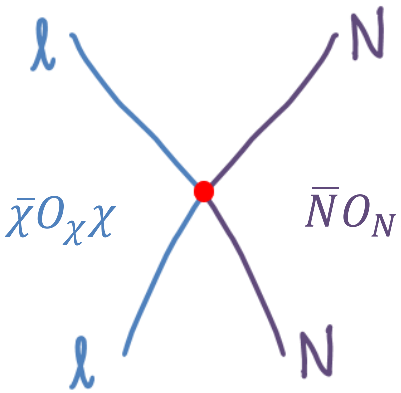
q - momentum transfer

WIMPs scattering off nuclei

Low energy interaction of WIMPs with nucleons

WIMP current

$\bar{\chi} O_\chi \chi$



$\bar{N} O_N N$

nuclear current

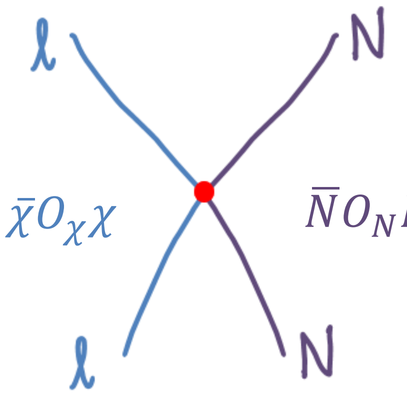
$$\mathcal{L} \sim \bar{\chi} O_\chi \chi \, \bar{N} O_N N$$

WIMPs scattering off nuclei

Low energy interaction of
WIMPs with nucleons

WIMP
current

$\bar{\chi} O_\chi \chi$



$\bar{N} O_N N$

nuclear
current

$$\mathcal{L} \sim \bar{\chi} O_\chi \chi \, \bar{N} O_N N$$

And similar terms
for the WIMP

Nuclear current:

- Scalar
- PseudoScalar
- Vector
- Axial vector
- Tensor

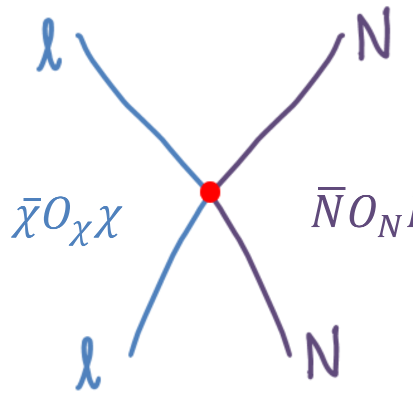
Anand, Fitzpatrick, Haxton, PRC 2014
Fitzpatrick, Haxton, Katz, Lubbers, Xu, JCAP 2013

WIMPs scattering off nuclei

Low energy interaction of WIMPs with nucleons

Non-Relativistic Effective Field Theory

WIMP current $\bar{\chi} O_\chi \chi$



$\bar{N} O_N N$ nuclear current

$$\mathcal{L} \sim \bar{\chi} O_\chi \chi \, \bar{N} O_N N \quad \rightarrow \quad \sum_{i=1}^{16} c_i O_i$$

And similar terms for the WIMP

Nuclear current:

- Scalar
- PseudoScalar
- Vector
- Axial vector
- Tensor

Anand, Fitzpatrick, Haxton, PRC 2014
Fitzpatrick, Haxton, Katz, Lubbers, Xu, JCAP 2013

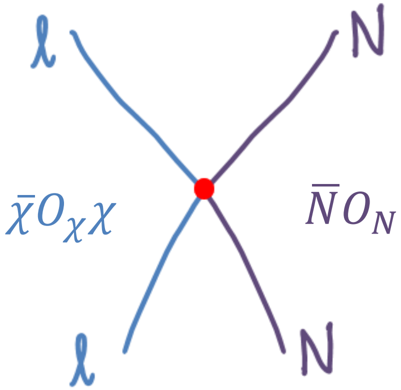
$\{O_i\}_{i=1}^{16}$ non-relativistic operators

WIMPs scattering off nuclei

Low energy interaction of WIMPs with nucleons

Non-Relativistic *Effective Field Theory*

WIMP current $\bar{\chi} O_\chi \chi$



$\bar{N} O_N N$ nuclear current

built of 4 vectors:

$$\frac{i\vec{q}}{m_N}$$

$$\vec{v}^{\perp} \equiv \frac{\vec{P}}{2m_\chi} - \frac{\vec{K}}{2m_N}$$

$$\vec{S}_\chi \qquad \vec{S}_N$$

$$\mathcal{L} \sim \bar{\chi} O_\chi \chi \, \bar{N} O_N N \rightarrow \sum_{i=1}^{16} c_i O_i$$

And similar terms for the WIMP

Nuclear current:
- Scalar
- PseudoScalar
- Vector
- Axial vector
- Tensor

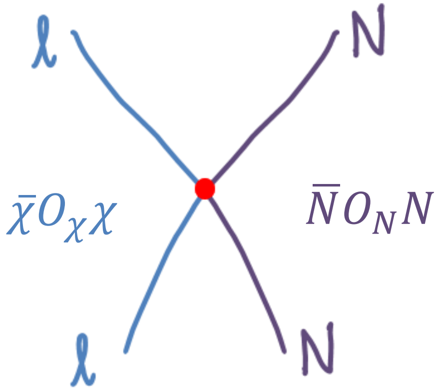
	$\dagger$	T	P
$\vec{S}$	$+1$	-1	$+1$
$i\vec{q}$	$+1$	$+1$	-1
$\vec{v}^{\perp}$	$+1$	-1	-1

Anand, Fitzpatrick, Haxton, PRC 2014
Fitzpatrick, Haxton, Katz, Lubbers, Xu, JCAP 2013

WIMPs scattering off nuclei

Low energy interaction of WIMPs with nucleons

WIMP current



nuclear current

Non-Relativistic Effective Field Theory

$$\mathcal{L} \sim \bar{\chi}O_\chi\chi\ \bar{N}O_N N \rightarrow \sum_{i=1}^{16} c_i O_i$$

And similar terms for the WIMP

Nuclear current:
- Scalar
- PseudoScalar
- Vector
- Axial vector
- Tensor Missing tensor couplings

$\{O_i\}_{i=1}^{16}$ non-relativistic operators

built of 4 vectors:

$$\frac{i\vec{q}}{m_N}$$

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$\vec{S}_\chi$ $\vec{S}_N$

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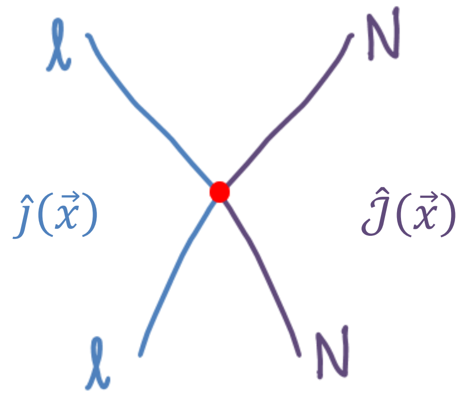
Anand, Fitzpatrick, Haxton, PRC 2014
Fitzpatrick, Haxton, Katz, Lubbers, Xu, JCAP 2013

Why do we need the Tensor?
We already have 16-operator basis

Weak interaction: Low energy interaction of leptons with nucleons

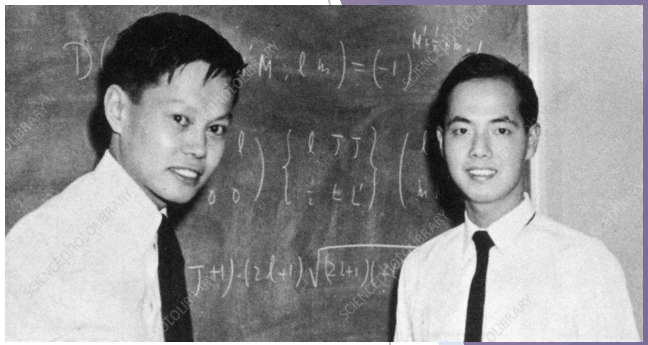
lepton current



nuclear current

$$\hat{\mathcal{H}}_W \sim C\, \hat{j}(\vec{x}) \cdot \hat{J}(\vec{x})$$

A-priori:
- Scalar (C_S)
- PseudoScalar (C_P)
- $\boxed{\text{Vector } (C_V)}$
- $\boxed{\text{Axial vector } (C_A)}$
- Tensor (C_T)



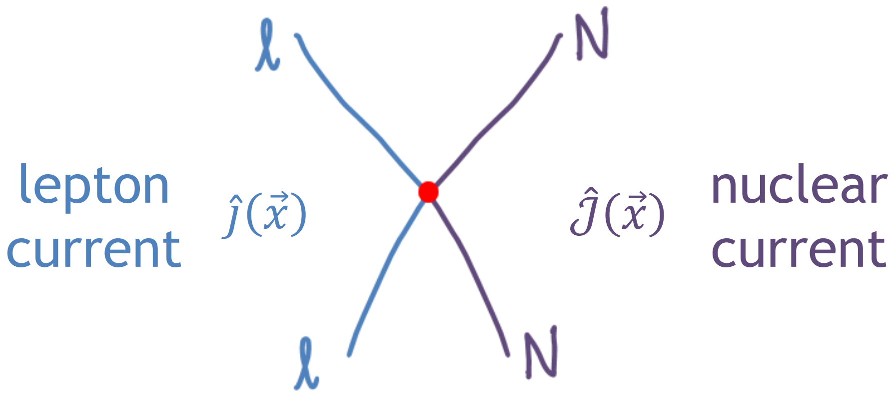
Theory: C.N. Yang and T.D. Lee (Nobel 1957)

Experiment: C.S. Wu:
Parity violation in ***nuclear β-decays***

⇒ **Weak SM structure: "$V - A$"**

Why do we need the Tensor? We already have 16-operator basis

Weak interaction: Low energy interaction of leptons with nucleons



$$\hat{\mathcal{H}}_W \sim C\, \hat{j}(\vec{x}) \cdot \hat{J}(\vec{x})$$

A-priori:
- Scalar (C_S)
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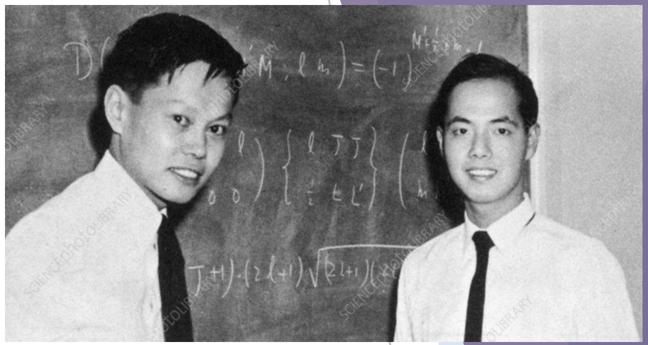

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⇒ **Weak SM structure: "$V - A$"**

To identify the interaction's nature, we need to know the operators & symmetries involved in each of S, P, V, A, T

How can we find the Tensor NREFT?

Low energy interaction of WIMPs with nucleons

Non-Relativistic *Effective Field Theory*

$\overset{12}{\cancel{4\times 4}} \times 2 = 24$

$\sigma_{\mu\nu}$

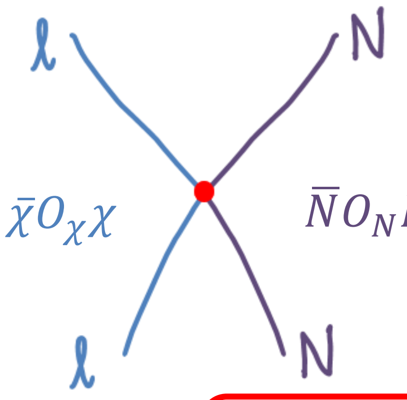
$\frac{q_\mu}{m_N}\gamma_\nu$

$\frac{q_\mu}{m_N}\frac{K_\nu}{m_N}$

$\gamma_\mu \frac{\not{q}}{m_N}\gamma_\nu$

γ^5 variations

WIMP current $\bar{\chi}O_\chi\chi$



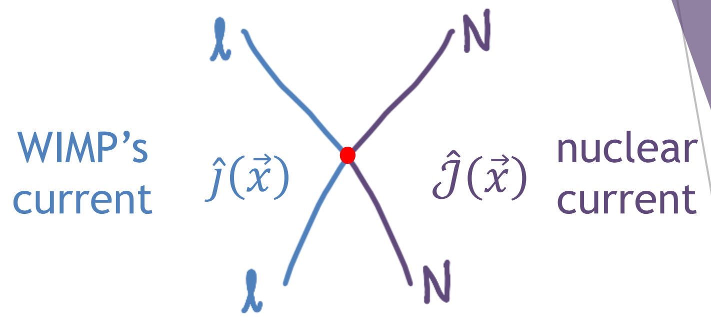
$\bar{N}O_N N$ nuclear current

$$\mathcal{L}\sim\bar{\chi}O_\chi\chi\,\boxed{\bar{N}O_N N}$$

Nuclear current:

$$\langle k_f\left|\mathcal{J}^a_{\mu\nu}\right|k_i\rangle=\bar{u}\left(k_f\right)\frac{1}{2}\left[g_T\left(q^2\right)\sigma_{\mu\nu}+\tilde{g}_T^{(1)}\left(q^2\right)\left(\frac{q_\mu}{m_M}\gamma_\nu-\frac{q_\nu}{m_M}\gamma_\mu\right)+\right.$$
$$\left.+\tilde{g}_T^{(2)}\left(q^2\right)\left(\frac{q^\mu}{m_M}\frac{K^\nu}{m_M}-\frac{q^\nu}{m_M}\frac{K^\mu}{m_M}\right)+\tilde{g}_T^{(3)}\left(q^2\right)\left(\gamma_\mu\frac{\not{q}}{m_M}\gamma_\nu-\gamma_\nu\frac{\not{q}}{m_M}\gamma_\mu\right)\right]\tau^a u\left(k_i\right)$$

And similar terms for the WIMPs $\bar{\chi}O_\chi\chi$



$$\hat{\mathcal{L}} \sim \hat{j}^{\mu\nu}(\vec{x})\, \hat{J}_{\mu\nu}(\vec{x})$$
$$= -\left[\vec{j}^{T} \cdot \vec{J}^{T} + \vec{j}^{T'} \cdot \vec{J}^{T'}\right]$$

Tensor
→ vector-like objects

- ~~Symmetric:~~
  - ~~A space-time-metric and the~~ stress-energy tensor
- Antisymmetric
  - Fermionic probes

$$\Longrightarrow j_{00} = 0$$
$$\Longrightarrow j_{i0} = -j_{0i}$$
$$\Longrightarrow j_{ij} \longrightarrow \left[j_{ij}\right]^{(1)}$$

$$l_{\mu\nu} = \begin{pmatrix} \cancel{l_{00}} & \begin{pmatrix} \leftarrow & \vec{l}_{0\cdot} & \rightarrow \end{pmatrix} \\ \begin{pmatrix} \uparrow \\ -\vec{l}_{0\cdot} \\ \downarrow \end{pmatrix} & \begin{pmatrix} & & \\ & \vec{l}^{(1)} & \\ & & \end{pmatrix} \end{pmatrix}$$

[AGM & Gazit, PRD 2023](#)

Tensor

$\overset{12}{\cancel{4 \times 4}} \times 2 = 24$

$\sigma_{\mu\nu}$

$\frac{q_\mu}{m_N}\gamma_\nu$

$\frac{q_\mu}{m_N}\frac{K_\nu}{m_N}$

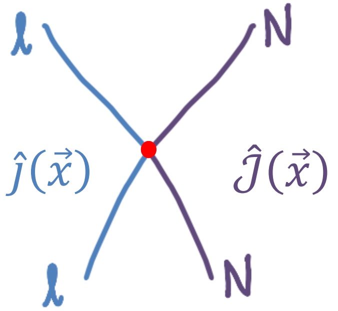
$\gamma_\mu \frac{\not{q}}{m_N} \gamma_\nu$

γ^5 variations

E.g.,

$$\bar{\chi}\sigma^{\mu\nu}\chi \, \bar{N}\left(\frac{q_\mu}{m_N}\frac{K_\nu}{m_N} - \frac{q_\nu}{m_N}\frac{K_\mu}{m_N}\right)\gamma_5 N$$

WIMP's current



nuclear current

$$\hat{\mathcal{L}} \sim \hat{j}^{\mu\nu}(\vec{x})\,\hat{J}_{\mu\nu}(\vec{x})$$

20 couplings were known from Scalar & Vector, 24 new Tensor couplings!

To identify the interaction's nature, we need to know the operators & symmetries involved in each of S, P, V, A, T

AGM, PRD letter 2024

$$\overset{12}{\cancel{4\times 4}}\times 2 = 24$$

$\sigma_{\mu\nu}$

$\frac{q_\mu}{m_N}\gamma_\nu$

$\frac{q_\mu}{m_N}\frac{K_\nu}{m_N}$

$\gamma_\mu \frac{\not{q}}{m_N}\gamma_\nu$

γ^5 variations

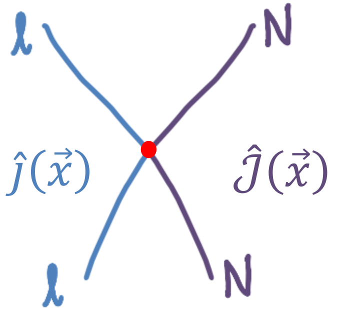
Tensor

E.g., $\bar{\chi}\sigma^{\mu\nu}\chi\,\bar{N}\left(\frac{q_\mu}{m_N}\frac{K_\nu}{m_N}-\frac{q_\nu}{m_N}\frac{K_\mu}{m_N}\right)\gamma_5 N$

Tensor decomposition

vector-like objects

WIMP's current



nuclear current

$\hat{j}(\vec{x})$ $\hat{J}(\vec{x})$

$$\hat{\mathcal{L}} \sim \hat{j}^{\mu\nu}(\vec{x})\,\hat{J}_{\mu\nu}(\vec{x})$$
$$= -\left[\vec{j}^{T}\cdot\vec{J}^{T}+\vec{j}^{T'}\cdot\vec{J}^{T'}\right]$$

20 couplings were known from Scalar & Vector, 24 new Tensor couplings!

To identify the interaction's nature, we need to know the operators & symmetries involved in each of S, P, V, A, T

AGM, PRD letter 2024

$$\overset{12}{\cancel{4\times 4}}\times 2 = 24$$

$$\sigma_{\mu\nu}$$
$$\frac{q_\mu}{m_N}\gamma_\nu$$
$$\frac{q_\mu}{m_N}\frac{K_\nu}{m_N}$$
$$\gamma_\mu \frac{\not{q}}{m_N}\gamma_\nu$$

γ^5 variations

Tensor

E.g.,
$$\bar{\chi}\sigma^{\mu\nu}\chi\,\bar{N}\left(\frac{q_\mu}{m_N}\frac{K_\nu}{m_N}-\frac{q_\nu}{m_N}\frac{K_\mu}{m_N}\right)\gamma_5 N$$

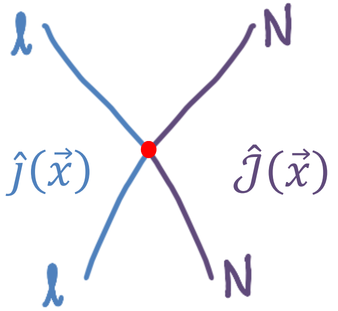
Tensor decomposition

vector-like objects

NREFT

$$-i\frac{q^2}{m_N^2}\left(\frac{\vec{q}}{m_\chi}\cdot\vec{\sigma}_N\right)+2\left(\vec{\sigma}_\chi\times\vec{v}^\perp\right)\cdot\frac{\vec{q}}{m_N}\left(\vec{\sigma}_N\cdot\frac{\vec{q}}{m_N}\right)+O\left(\frac{1}{m^5}\right)$$

WIMP's current



nuclear current

$$\hat{\mathcal{L}}\sim\hat{\jmath}^{\mu\nu}(\vec{x})\,\hat{\mathcal{J}}_{\mu\nu}(\vec{x})$$
$$=-\left[\vec{\jmath}^{T}\cdot\vec{\mathcal{J}}^{T}+\vec{\jmath}^{T'}\cdot\vec{\mathcal{J}}^{T'}\right]$$

20 couplings were known from Scalar & Vector, 24 new Tensor couplings!

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AGM, PRD letter 2024

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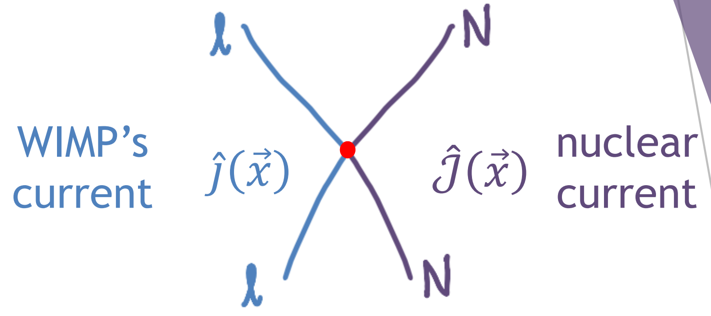
Tensor

E.g.,

$$\bar{\chi}\sigma^{\mu\nu}\chi\,\bar{N}\left(\frac{q_\mu}{m_N}\frac{K_\nu}{m_N} - \frac{q_\nu}{m_N}\frac{K_\mu}{m_N}\right)\gamma_5 N$$

Tensor decomposition

vector-like objects



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NREFT

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operators

$$-2\frac{q^2}{m_\chi m_N}O_{10} - 8O_{16}$$

To identify the interaction's nature, we need to know ... involved

Now we know all operators involved in Tensor couplings

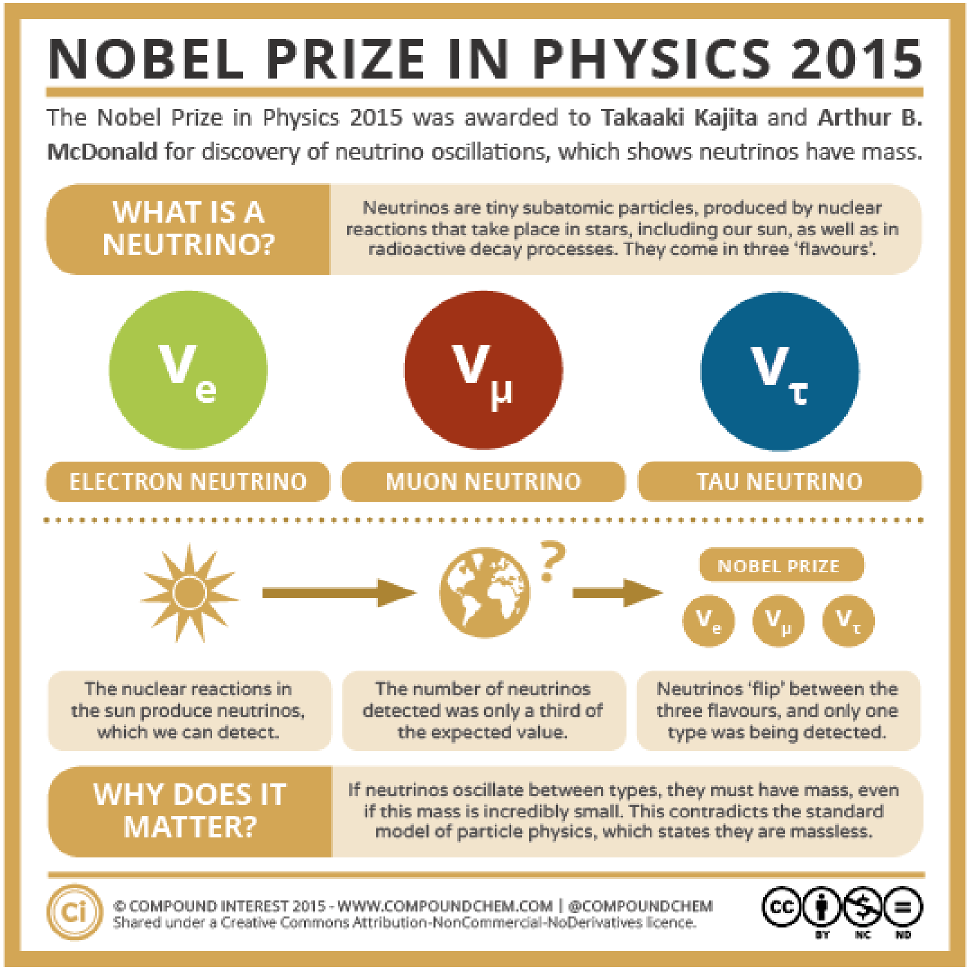
AGM, PRD letter 2024

Relevant also for…

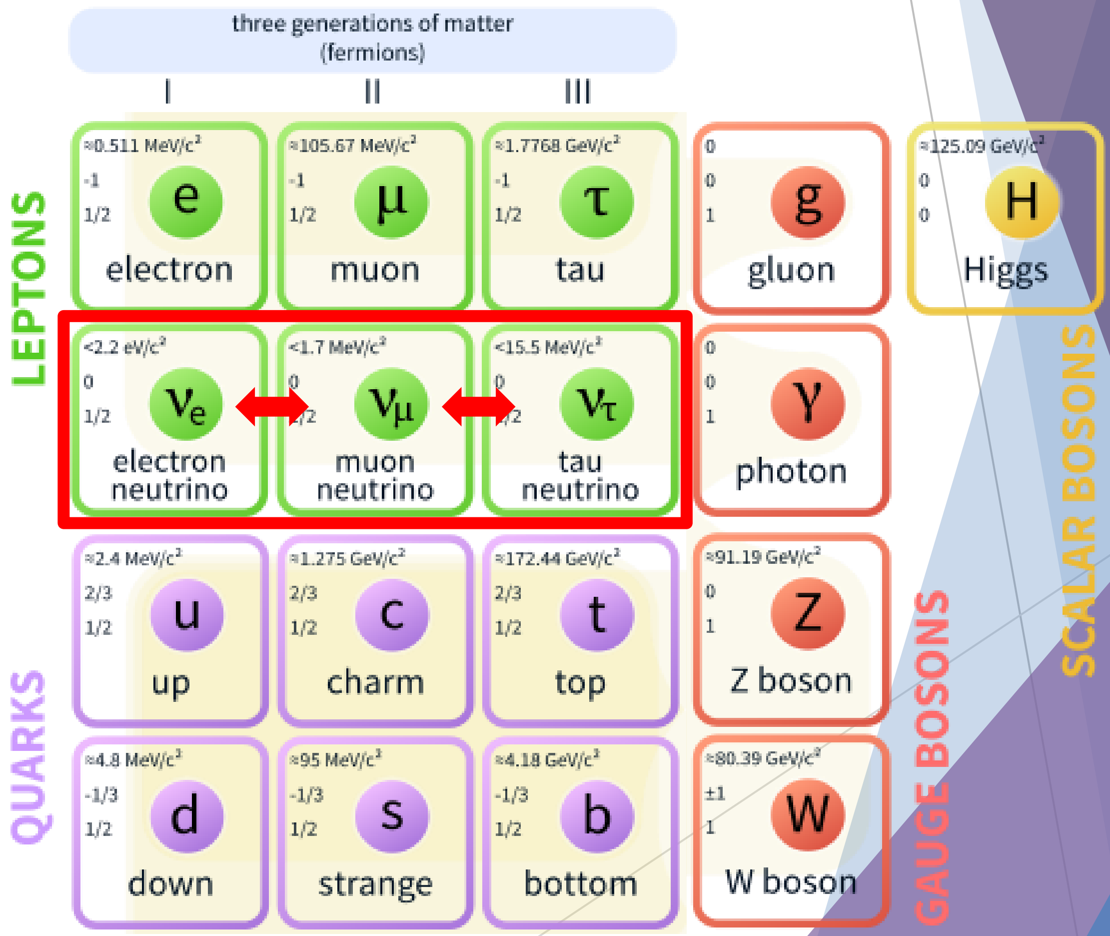
Lepton Flavor Violation

$\mu \to e$ conversion

Beyond Standard Model (BSM)



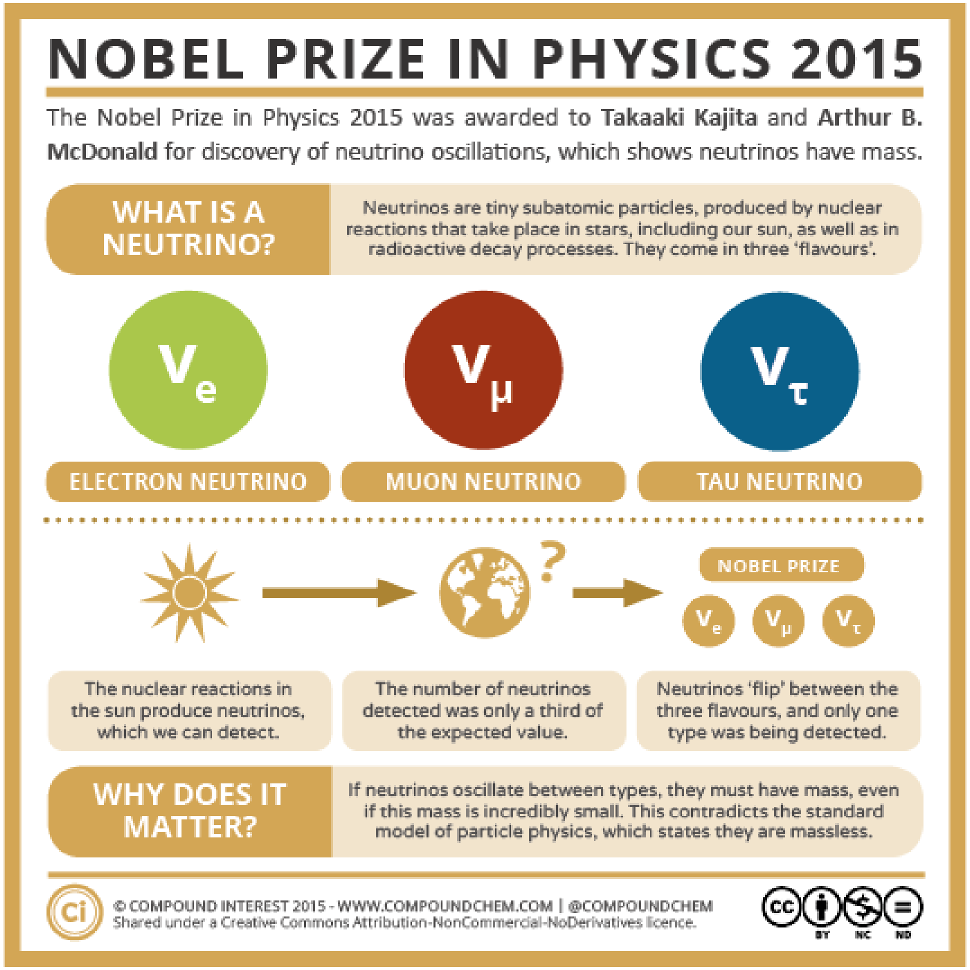
Elementary Particles



Lepton Flavor Violation

(Credit: Wikipedia)

Beyond Standard Model (BSM)



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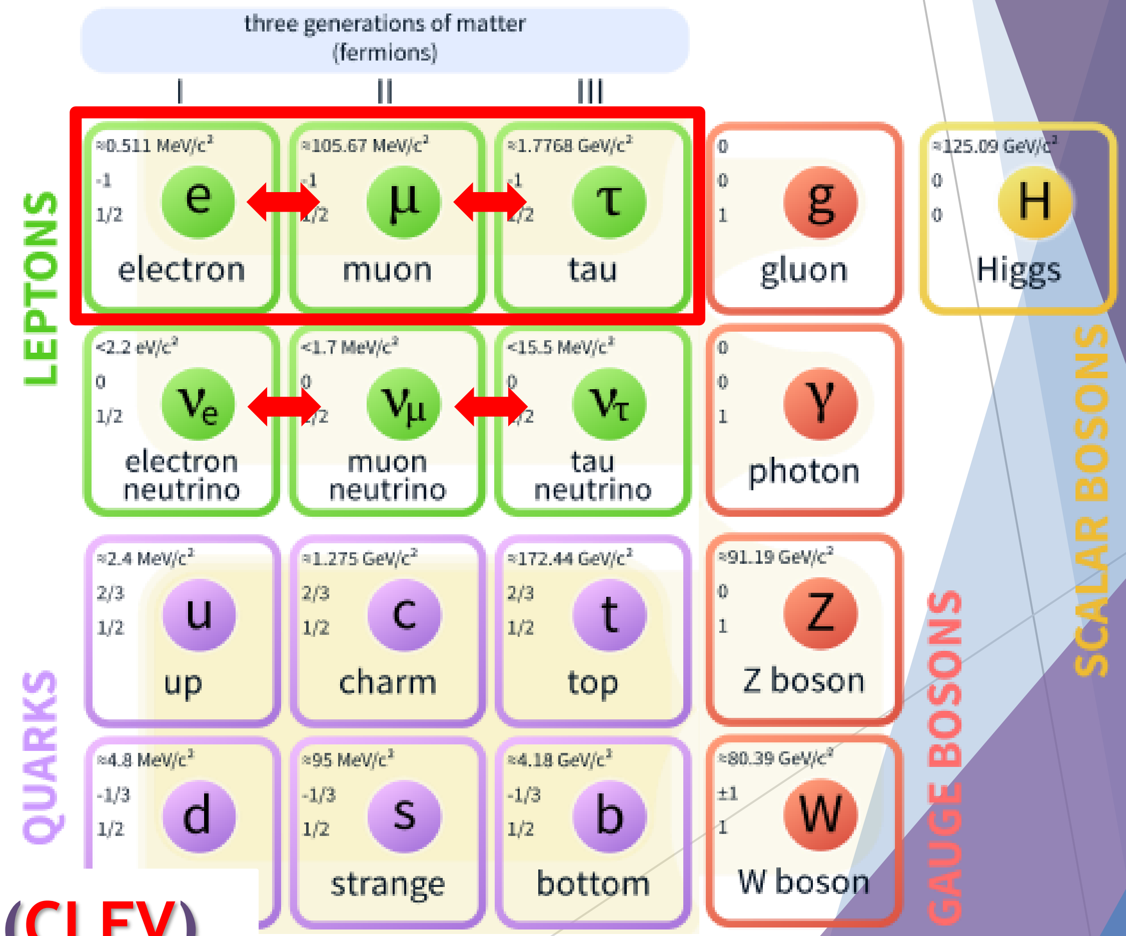
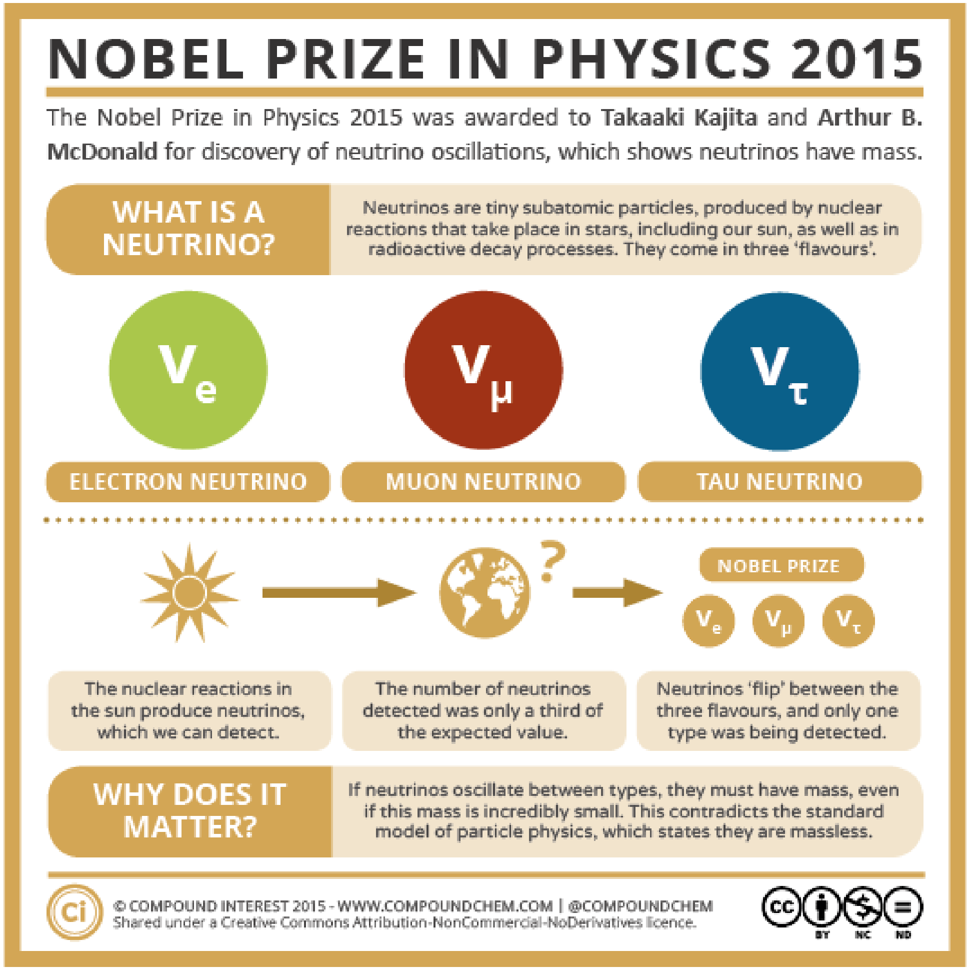
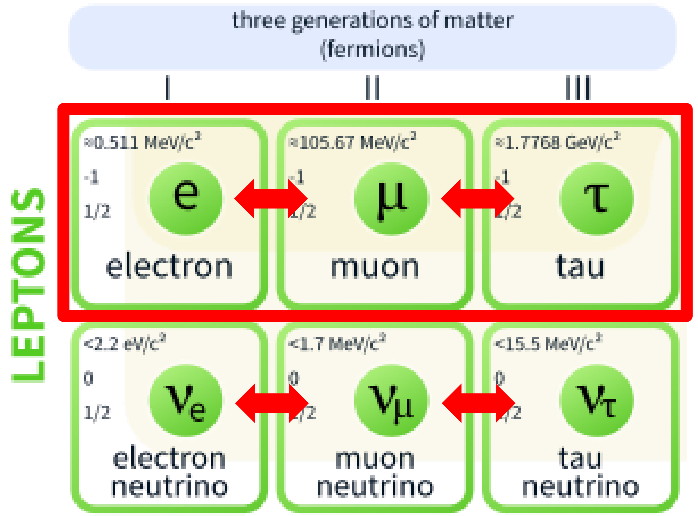


Charged Lepton Flavor Violation (CLFV)

Beyond Standard Model (BSM)

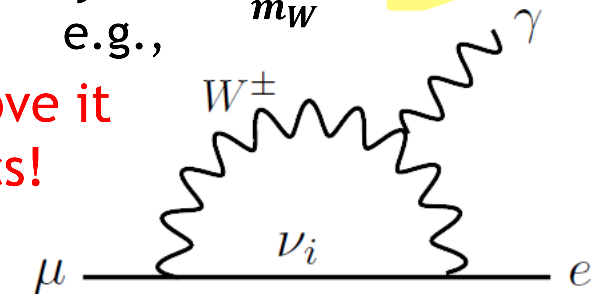


Elementary Particles



CLFV can occur through neutrino mixing, but is suppressed by $\mathbf{BR} \sim \frac{m_\nu}{m_W} \lesssim 10^{-50}$

e.g.,



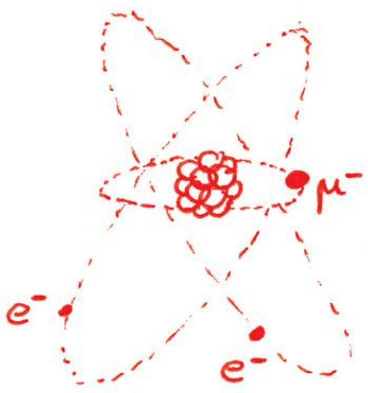
$\Longrightarrow$ Anything above it is New Physics!

Charged Lepton Flavor Violation (CLFV)

Beyond Standard Model (BSM)

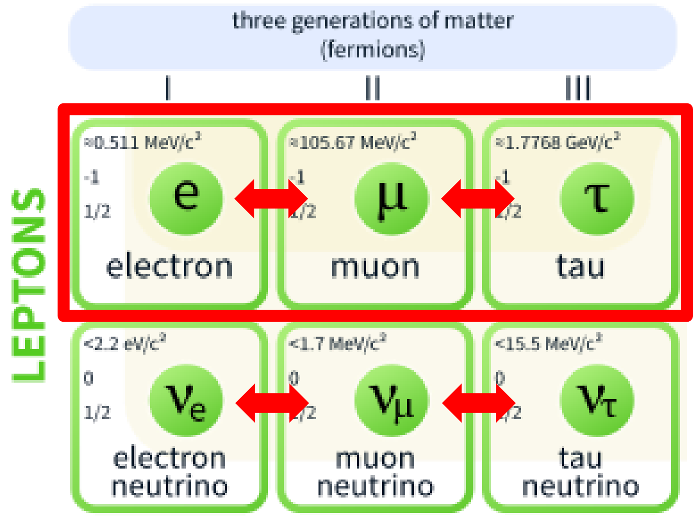
with nuclei…

This is what we start with.



(Credit: symmetry magazine)

Elementary Particles



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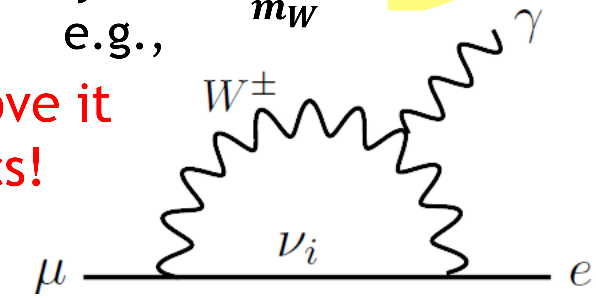


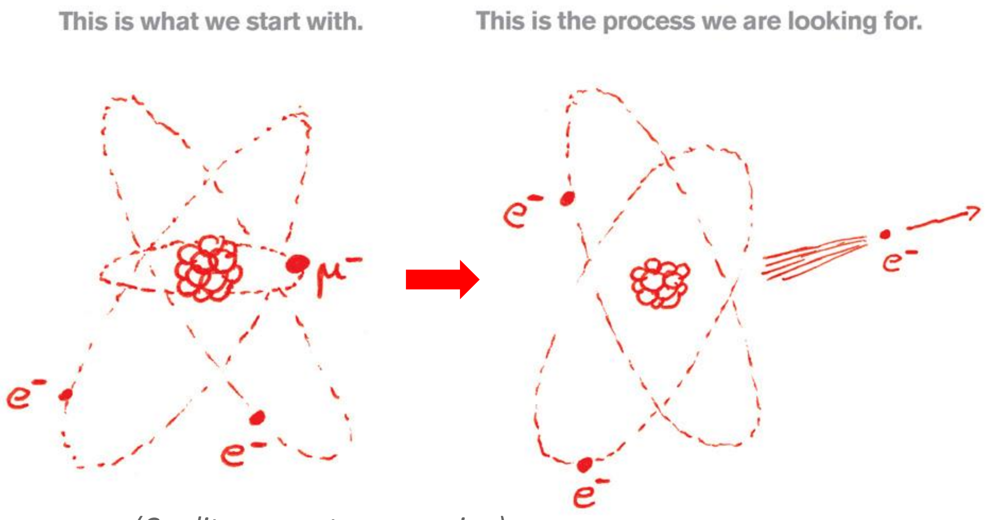
⟹ Anything above it is New Physics!

Charged Lepton Flavor Violation (CLFV)

Beyond Standard Model (BSM)

with nuclei…

$\mu \to e$ conversion



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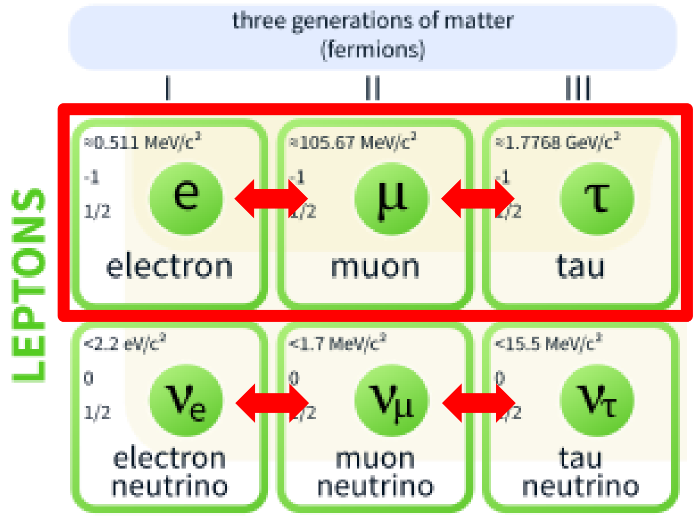
Elementary Particles



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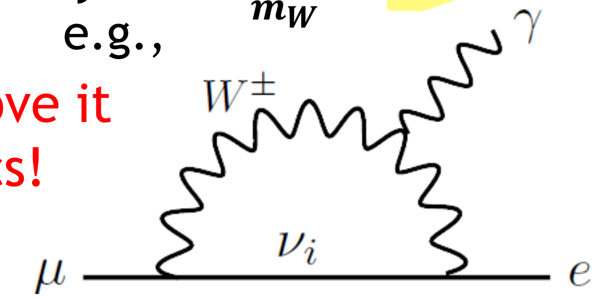

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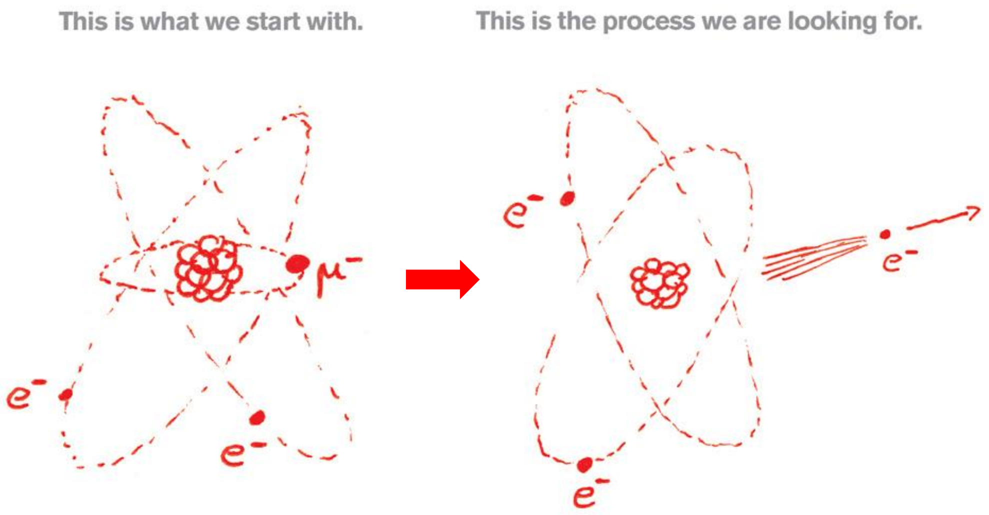
Charged Lepton Flavor Violation (CLFV)

Beyond Standard Model (BSM)

with nuclei…

$\mu \to e$ conversion



(Credit: symmetry magazine)

TABLE IX. Existing limits on branching ratios for $\mu \to e$ conversion, taken from the tabulation of [75].

Process	Limit	Lab/Reference
$\mu^- + {}^{32}S \to e^- + {}^{32}S$	7×10^{-11}	SIN [76]
$\mu^- + Ti \to e^- + Ti$	1.6×10^{-11}	TRIUMF [77]
$\mu^- + Ti \to e^- + Ti$	4.6×10^{-12}	TRIUMF [78]
$\mu^- + Ti \to e^- + Ti$	4.3×10^{-12}	PSI [79]
$\mu^- + Ti \to e^- + Ti$	6.1×10^{-13}	PSI [80]
$\mu^- + Cu \to e^- + Cu$	1.6×10^{-8}	SREL [81]
$\mu^- + Au \to e^- + Au$	7×10^{-13}	PSI [82]
$\mu^- + Pb \to e^- + Pb$	4.9×10^{-10}	TRIUMF [78]
$\mu^- + Pb \to e^- + Pb$	4.6×10^{-11}	PSI [83]

Haxton, Rule, McElvain, Ramsey-Musolf, PRC 2023

CLFV can occur through neutrino mixing, but is suppressed by $\mathbf{BR} \sim \frac{m_\nu}{m_W} \lesssim 10^{-50}$

- Future experiments: mu2e @ Fermilab, COMET @ J-PARC

$$({}^{27}\mathrm{Al}) \sim 10^{-17}$$

4 orders of magnitude enhancement!

$\Longrightarrow$ Observation of CLFV is **New Physics beyond νSM** (SM + neutrino mass)

NREFT – Similar, but different

$$\mathcal{L} \sim \bar{e} O_L \mu \, \bar{N} O_N N \quad \rightarrow \quad \sum_{i=1}^{15} c_i O_i$$

- $q \sim m_\mu$
- The electron is "fully relativistic"

$$y \equiv \left(\frac{qb}{2}\right)^2 > |\vec{v}_N| > |\vec{v}_\mu|$$

$$i\hat{q} = \frac{i\vec{q}}{|\vec{q}\,|}, \quad \vec{v}, \quad \vec{\sigma}_L, \quad \vec{\sigma}_N$$

	$\dagger$	T	P
$\vec{\sigma}_L, \vec{\sigma}_N$	$+1$	-1	$+1$
$i\hat{q}$	$+1$	$+1$	-1
$\vec{v}$	$+1$	-1	-1

Rule, Haxton, McElvain, PRL 2023
Haxton, Rule, McElvain, Ramsey-Musolf, PRC 2023

Non-**R**elativistic **E**ffective **F**ield **T**heory

15 NREFT operators
only 11 were obtained

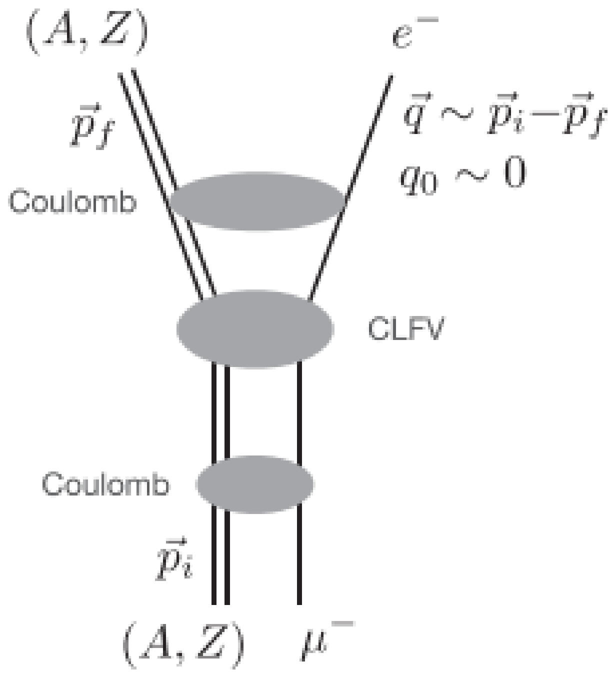


FIG. 1. Depiction of elastic $\mu \to e$ conversion. The nuclear Coulomb potential binds the $1s$ initial-state muon and distorts the outgoing electron wave function. Neglecting nuclear recoil, the electron's energy is the muon mass minus its Coulomb binding.

NREFT – Similar, but different

Non-Relativistic Effective Field Theory

15 NREFT operators

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$$i\hat{q} = \frac{i\vec{q}}{|\vec{q}\,|}, \quad \vec{v}, \quad \vec{\sigma}_L, \quad \vec{\sigma}_N$$

Missing tensor couplings

	$\dagger$	T	P
$\vec{\sigma}_L, \vec{\sigma}_N$	$+1$	-1	$+1$
$i\hat{q}$	$+1$	$+1$	-1
$\vec{v}$	$+1$	-1	-1

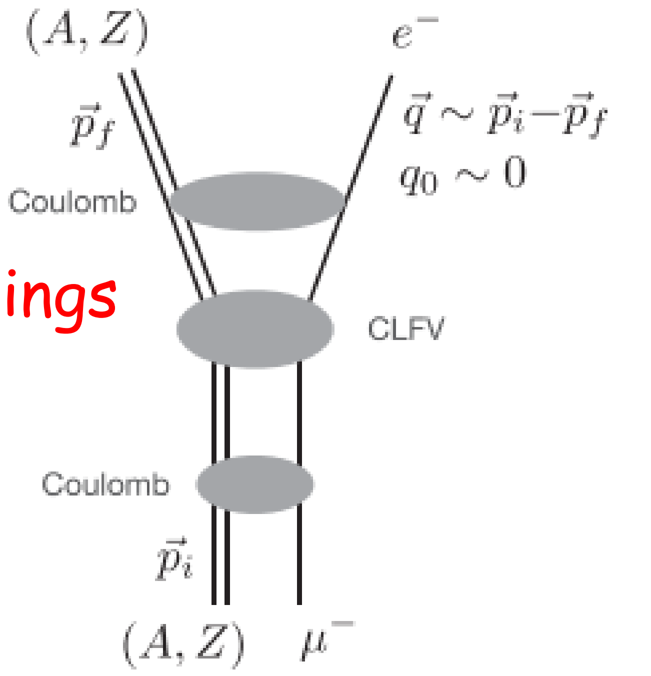

FIG. 1. Depiction of elastic $\mu \rightarrow e$ conversion. The nuclear Coulomb potential binds the $1s$ initial-state muon and distorts the outgoing electron wave function. Neglecting nuclear recoil, the electron's energy is the muon mass minus its Coulomb binding.

Rule, Haxton, McElvain, PRL 2023
Haxton, Rule, McElvain, Ramsey-Musolf, PRC 2023

Tensor $\mu \rightarrow e$ conversion: NREFT

Non-**R**elativistic
***E**ffective **F**ield **T**heory*

E.g.,

$$\bar{\chi}_e \left(\hat{q}^\mu \gamma^\nu - \hat{q}^\nu \gamma^\mu\right) \chi_\mu N \sigma_{\mu\nu} \gamma_5 N$$

Tensor decomposition

vector-like objects

NREFT

$$i1_L \left(\hat{q} \cdot \vec{\sigma}_N\right) - 2\vec{\sigma}_L \cdot \left(\vec{v}_N \times \vec{\sigma}_N\right) + 2\left(\hat{q} \cdot \vec{\sigma}_L\right) \hat{q} \cdot \left(\vec{v}_N \times \vec{\sigma}_N\right)$$
$$-\hat{q} \cdot \left(\vec{v}_\mu \times \vec{\sigma}_L\right) \left(\hat{q} \cdot \vec{\sigma}_N\right) + i\left(\hat{q} \cdot \vec{v}_\mu\right) \left(\hat{q} \cdot \vec{\sigma}_N\right) + O\left(\frac{q^2}{m_N^2}\right)$$

operators

$$2\left(\tfrac{1}{2}\mathcal{O}_{10} - \mathcal{O}_{12} - \mathcal{O}_{15} + \mathcal{O}_{15}^{f} - i\mathcal{O}_{16}^{f'}\right)$$

To identify the interaction's nature, we need to know
involved

Now we know all operators involved in Tensor couplings

AGM, PRD letter 2024

Tensor $\mu \to e$ conversion: NREFT

Non-**R**elativistic
***E**ffective **F**ield **T**heory*

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Tensor decomposition

vector-like objects

NREFT

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operators

$$2\left(\tfrac{1}{2}\mathcal{O}_{10} - \mathcal{O}_{12} - \mathcal{O}_{15} + \mathcal{O}_{15}^{f} - i\mathcal{O}_{16}^{f'}\right)$$

4 New operators!
Easier for identifying the nature of the CLFV

Matching data
$\Rightarrow$ Must be Tensor

entify the interaction's nature, we
to know
involved

Now we know all operators involved in Tensor couplings

AGM, PRD letter 2024

Tensor $\mu\to e$ conversion: SMEFT

Standard Model Effective Field Theory

$$\mathcal{L}_{\mathrm{SMEFT}} \sim \mathcal{L}_{\mathrm{SM}} + \frac{1}{M^2}\sum_i \tilde{c}_i O_{6i} + \frac{1}{M^4}\sum_i \tilde{d}_i O_{8i} + \cdots$$

$$\bar{l}_L^{J\alpha}\sigma_{\mu\nu}e_R^{\beta}\epsilon_{JK}\bar{q}_L^{Km}\sigma^{\mu\nu}u_R^{n}$$

AGM, PRD letter 2024

Tensor $\mu\rightarrow e$ conversion: SMEFT

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$$l_L^\alpha = \begin{pmatrix} \nu_L^\alpha \\ e_L^\alpha \end{pmatrix} \qquad \epsilon = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \qquad q_L^m = \begin{pmatrix} u_L^m \\ d_L^m \end{pmatrix}$$

$$\bar{l}_L^{J\alpha}\sigma_{\mu\nu}e_R^\beta \epsilon_{JK}\bar{q}_L^{Km}\sigma^{\mu\nu}u_R^n$$

$$= \bar{\nu}_L^\alpha \sigma_{\mu\nu} e_R^\beta \bar{d}_L^m \sigma^{\mu\nu} u_R^n - \bar{e}_L^\alpha \sigma_{\mu\nu} e_R^\beta \bar{u}_L^m \sigma^{\mu\nu} u_R^n$$

AGM, PRD letter 2024

Tensor $\mu \rightarrow e$ conversion: SMEFT

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$$\downarrow$$

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E.g., β-decay

$$l_L^\alpha = \begin{pmatrix} \nu_L^\alpha \\ e_L^\alpha \end{pmatrix}$$

$$\epsilon = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

$$q_L^m = \begin{pmatrix} u_L^m \\ d_L^m \end{pmatrix}$$

AGM, PRD letter 2024

Tensor $\mu\to e$ conversion: SMEFT

Standard **M**odel
***E**ffective **F**ield **T**heory*

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$$l_L^\alpha = \begin{pmatrix} \nu_L^\alpha \\ e_L^\alpha \end{pmatrix} \qquad \epsilon = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \qquad q_L^m = \begin{pmatrix} u_L^m \\ d_L^m \end{pmatrix}$$

$$\bar{l}_L^{J\alpha}\sigma_{\mu\nu}e_R^\beta \epsilon_{JK}\bar{q}_L^{Km}\sigma^{\mu\nu}u_R^n$$

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E.g., β-decay

μ_R

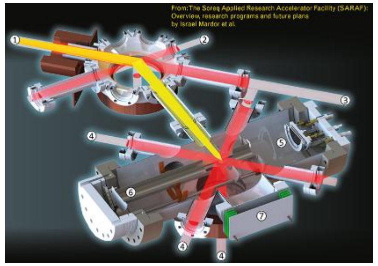
$\Longrightarrow$ can only occur with **up**, **charm**, or **top quarks** $(m, n = 1, 2, 3)$

AGM, PRD letter 2024

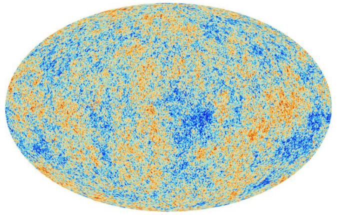
Fermionic Tensor → vector-like objects

BSM Tensor missing theory:

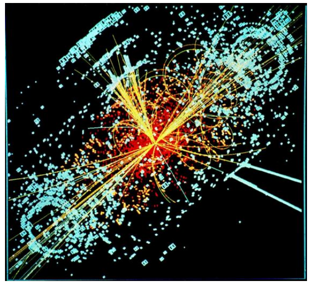
- ➤ *5:00 PM @ Tests of Symmetries & EW:*
  Unique forbidden β-decays
  at zero momentum transfer
  [Seng, AGM, Cirigliano, PRL 2025]
  Forbidden decays are ***not*** *forbidden*



- β**-decays**
  - **BSM matrix elements identify** with the **well-known SM** ones
  - **Predictions & Observables** for **forbidden decays** for the first time
    - **New experiments** @ ORNL, HUJI, SOREQ [AGM & Gazit, PRD 2023]



- **Dark Matter (WIMPs)**
  - **New terms**
    - **Identification** of the tensor symmetry involved **is now possible**



- $\mu \longrightarrow e$
  - **New Operators**
    - **Matching data $\Longrightarrow$ Must be Tensor!**
      [AGM, PRD letter 2024]

Summary

Thanks!

UC Berkeley
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Michael Hass

TRIUMF
Ish Mukul

U.S. DOE Topical Collaboration "Nuclear Theory for New Physics"
U.S. DOE Office of Science, Office of Nuclear Physics
Israel Academy of Sciences and Humanities
Israel Ministry of Science & Technology
Israel Science Foundation (ISF)

Nuclear Theory for New Physics

U.S. DEPARTMENT OF ENERGY | Office of Science

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Maria Dawid

FNAL
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ANL
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Leon Friedrich

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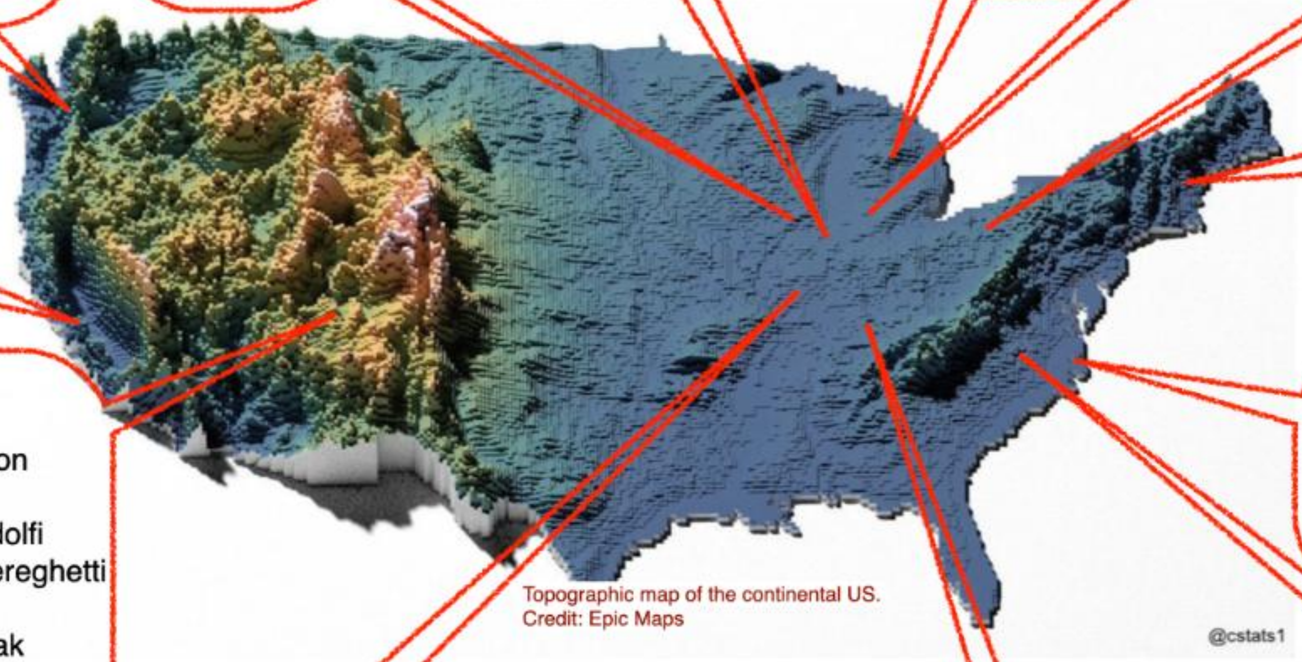
Wick Haxton
André Walker-Loud
Andrea Shindler
Lukáš Gráf
Zack Hall



Topographic map of the continental US.
Credit: Epic Maps

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Lucas Platter
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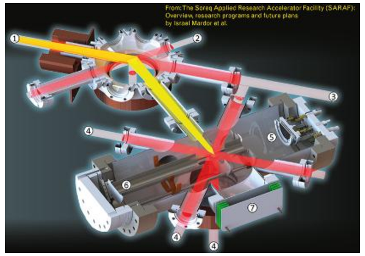
Jon Engel
Amy Nicholson
Zack Hall
Joeseph Moscoso

Fermionic Tensor → vector-like objects

BSM Tensor missing theory:



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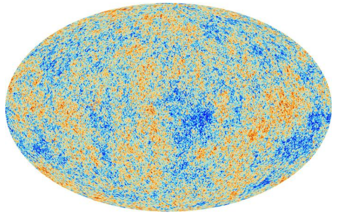
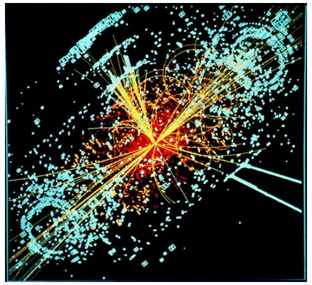
    - **New experiments** @ ORNL, HUJI, SOREQ

Glick-Magid & Gazit, PRD 2023



- **Dark Matter (WIMPs)**
  - **New terms**
    - **Identification** of the tensor symmetry involved **is now possible**



- ***μ*→*e***
  - **New Operators**
    - **Matching data ⟹ Must be Tensor!**

Glick-Magid, PRD letter 2024

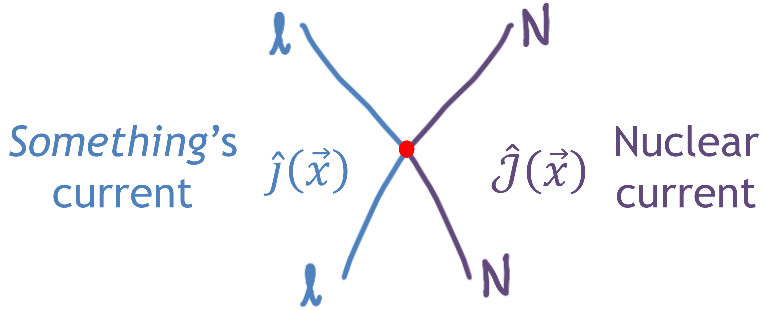
Time-only

mixed space-time

$$J_{\mu\nu} = \begin{pmatrix} \cancel{J_{00}} & \left(\leftarrow \quad \vec{J}_{0\cdot} \quad \rightarrow \right) \\ \begin{pmatrix} \uparrow \\ T' \\ -\vec{J}_{0\cdot} \\ \downarrow \end{pmatrix} & \begin{pmatrix} T \\ \vec{J}^{(1)} \end{pmatrix} \end{pmatrix}$$

mixed space-time

Space-only



$$\hat{\mathcal{H}}_W \sim \hat{j}^{\mu\nu}(\vec{x})\, \hat{J}_{\mu\nu}(\vec{x})$$

$$= -\left[\vec{j}^{T} \cdot \vec{J}^{T} + \vec{j}^{T'} \cdot \vec{J}^{T'}\right]$$