Probing symmetries of the weak interaction via the $\beta$ decay of laser-cooled, polarized $^{37}$K

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Overview

1. Fundamental symmetries
   - what is our current understanding?
   - what lies beyond?

2. $V_{ud}$ and CKM unitarity
   - $0^+ \rightarrow 0^+$ decays
   - neutron decay: a complementary test
   - mirror transitions are like “heavy neutrons”

3. Angular correlations using laser-cooled atoms
   - trapping short-lived neutral atoms
   - polarizing the atom cloud
   - angular correlations of polarized $^{37}$K
Scope of fundamental physics

from the very smallest scales . . .
Scope of fundamental physics

The atom from the very smallest scales . . .

d . . . to the very largest
All of the *known* elementary particles and their interactions are described within the framework of the *new* STANDARD MODEL.
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**THE new STANDARD MODEL**

- **quantum** + **special rel** \(\Rightarrow\) **quantum field theory**
All of the known elementary particles and their interactions are described within the framework of

THE new STANDARD MODEL

- quantum + special rel \implies quantm field theory
- Noether’s theorem: symmetry \iff conservation law
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- **quantum + special rel** ⇒ quantum field theory
- Noether’s theorem: symmetry ⇔ conservation law

Maxwell’s eqns invariant under changes in vector potential ⇔ conservation of electric charge, $q$
All of the *known* elementary particles and their interactions are described within the framework of the *new* Standard Model.

- **quantum** + **special rel** $\Rightarrow$ **quantum field theory**
- Noether’s theorem: symmetry $\Leftrightarrow$ conservation law

Maxwell’s eqns invariant under changes in vector potential $\Leftrightarrow$ conservation of electric charge, $q$

and there’s other symmetries too:

- time $\Leftrightarrow$ energy
- space $\Leftrightarrow$ momentum
- rotations $\Leftrightarrow$ angular momentum
  
- :
All of the *known* elementary particles and their interactions are described within the framework of

**THE new STANDARD MODEL**

- **quantum** + **special rel** $\Rightarrow$ **quantum field theory**
- Noether’s theorem: symmetry $\Leftrightarrow$ conservation law

$$SU(3) \times SU(2)_L \times U(1)$$

- **strong**
- **weak**
- E & M

**electroweak**

- **gravitational force**

$+$ (classical general rel)
All of the known elementary particles and their interactions are described within the framework of

**THE new STANDARD MODEL**

- **quantum + special rel** $\Rightarrow$ quantum field theory
- Noether’s theorem: symmetry $\Leftrightarrow$ conservation law
- $SU(3) \times SU(2)_L \times U(1)$: strong + electroweak
- **12 elementary particles** and **4 fundamental forces**

<table>
<thead>
<tr>
<th></th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>$Q$</th>
<th>mediator force</th>
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<tbody>
<tr>
<td>leptons</td>
<td>$(\nu_e, \nu_\mu, \nu_\tau)$</td>
<td>$(\nu_e, \nu_\mu, \nu_\tau)$</td>
<td>$(\nu_e, \nu_\mu, \nu_\tau)$</td>
<td>0, -1</td>
<td>$g$, $W^\pm$, $Z^\circ$</td>
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<tr>
<td>quarks</td>
<td>$(u, d)$</td>
<td>$(c, s)$</td>
<td>$(t, b)$</td>
<td>$+2/3$, $-1/3$</td>
<td>$\gamma$</td>
</tr>
</tbody>
</table>

**mediator force**
- **strong** $g$
- **weak** $W^\pm$, $Z^\circ$
- **EM** $\gamma$
That’s all fine and dandy, but…

Does the Standard Model work??
That’s all fine and dandy, but…

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- predicted the existence of the $W^\pm$, $Z_0$, $g$, $c$ and $t$
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- is a **renormalizable** theory
- GSW $\Rightarrow$ **unified** the weak force with **electromagnetism**
- QCD **explains** quark confinement

$$a_\mu \equiv \frac{1}{2}(g - 2)$$

$$a_\mu(\text{exp}) = 11659208(6) \times 10^{-10}$$

$$a_\mu(\text{SM}) = 11659181(8) \times 10^{-10}$$

$\pm 1$ **part-per-million**!!

(PRL 92 (2004) 161802)
Does the Standard Model work??

- **predicted** the existence of the $W^\pm$, $Z_0$, $g$, $c$ and $t$
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(PRL 92 (2004) 161802)

Wow ... this is the most precisely tested theory ever conceived!
But there are still questions . . .

- **values of parameters**: does our “ultimate” theory really need 25 arbitrary constants? Do they change with time?
- **dark matter**: SM physics makes up only 4% of the energy-matter of the universe!
- **baryon asymmetry**: why more matter than anti-matter?
- **strong CP**: do axions exist? Fine-tuning?
- **neutrinos**: Dirac or Majorana?
- **fermion generations**: why three families?
- **weak mixing**: Is the CKM matrix unitary?
- **parity violation**: is parity maximally violated in the weak interaction? No right-handed currents?
- **EW symmetry breaking**: how do the fermions acquire mass? Mass hierarchy?
- **gravity**: of course can’t forget about a quantum description of gravity!
At our energy scales, we see four distinct forces . . .
But these coupling ‘constants’ aren’t really constant: $\alpha_i \rightarrow \alpha_i(Q)$

- electromagnetic and weak strengths equal at $\approx 10^{13}$ GeV
- strong force gets weaker, but doesn’t unify with EW...
But what if there is new physics we haven’t seen yet?

the running of the coupling constants would be affected; maybe they converge at some GUT scale?

Are the three theories of E & M, weak and strong interactions all low-energy limits of one unifying theory?
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What is the CKM matrix?

**Cabibbo**

- **flavour mixing**
  \[
  |d'\rangle = \cos \theta_C |d\rangle + \sin \theta_C |s\rangle \\
  |s'\rangle = -\sin \theta_C |d\rangle + \cos \theta_C |s\rangle
  \]

- **mass eigenstates** ≠ **weak eigenstates**

- **purely leptonic**
  \[
  \sqrt{G_F} W^+ \rightarrow e^+ \nu_e \\
  \sqrt{G_F} \mu^+ \rightarrow e^+ \nu_\mu \\
  \sqrt{G_F} = \text{strength of lepton coupling to } W
  \]

- **semi-leptonic**
  \[
  \sqrt{G_F} \cos \theta_C d \rightarrow e^+ \nu_e \\
  \sqrt{G_F} \cos \theta_C u \rightarrow W^+ d \\
  \sqrt{G_F} \cos \theta_C = \text{strength of quark coupling to } W
  \]
**What is the CKM matrix?**

**Cabibbo**

Mass eigenstates ≠ weak eigenstates

\[
\begin{pmatrix}
\sqrt{G_F} \\
W^+ \\
\sqrt{G_V}
\end{pmatrix}
\]

\[
\left(\begin{array}{c}
d' \\
s' \\
b'
\end{array}\right)
= \left(\begin{array}{ccc}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{array}\right)
\left(\begin{array}{c}
d \\
s \\
b
\end{array}\right)
\]

\[
V_{ud} = G_V / G_F
\]
What is the CKM matrix?

Cabibbo

Kobayashi

Maskwawa

mass eigenstates \neq \text{weak eigenstates}

\sqrt{G_F} \nu_e \quad \sqrt{G_V} \quad \text{weak eigenstates}

\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}

\text{mass mixing matrix}

\text{mass eigenstates}

\boxed{V_{ud} = \frac{G_V}{G_F}}

If no missing strength:

\boxed{|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1}
The unitarity test

\[ |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1? \]

\[
\begin{pmatrix}
 d' \\
 s' \\
 b'
\end{pmatrix}
= \begin{pmatrix}
 0.974 & 0.225 & 0.004 \\
 0.224 & 0.973 & 0.04 \\
 0.01 & 0.04 & 0.999
\end{pmatrix}
\begin{pmatrix}
 d \\
 s \\
 b
\end{pmatrix}
\]

\[ \sum |V_{u,i}|^2 = 0.9999(6) \]

\begin{align*}
|V_{ud}| &= 0.97425(22) \quad \text{Hardy&Towner PRC79 (2009)} \\
|V_{us}| &= 0.2252 \quad (9 ) \quad \text{PDG 2010} \\
|V_{ub}| &= 0.00393(35) \quad \text{negligible}
\end{align*}

A 0.1% constraint on new physics!
Pure Fermi $0^+ \rightarrow 0^+$ decays

The comparative half-life of $\beta$ decay is:

$$ f_t = \left( \frac{\text{phase space}}{} \right) \left( \frac{\text{partial half-life}}{} \right) = \frac{K}{G_V^2 |M_F|^2 + G_A^2 |M_{GT}|^2} $$

$$ K/(\hbar c)^6 = 2\pi^3 \hbar \ln 2/(m_e c^2)^5 $$

and

$$ G_V = G_F V_{ud} $$

For pure Fermi $T=1$ decays

$$ (T_3 \equiv \frac{1}{2}(N-Z) = \text{“isospin”}) $$

$$ M_F = \sqrt{2} $$

$$ M_{GT} = 0 $$
Pure Fermi $0^+ \rightarrow 0^+$ decays

The comparative half-life of $\beta$ decay is:

$$f t = \left( \frac{\text{phase space}}{\text{partial half-life}} \right) = \frac{K}{G^2_V |M_F|^2 + G^2_A |M_{GT}|^2}$$

$$K/(\hbar c)^6 = 2\pi^3 \hbar \ln 2/(m_e c^2)^5$$

and by CVC, $G_V = G_F V_{ud}$

For pure Fermi $T=1$ decays

$$(T_3 \equiv \frac{1}{2}(N-Z) = \text{“isospin”})$$

$M_F = \sqrt{2}$

$M_{GT} = 0$

$ft = \frac{K}{2G^2_F |V_{ud}|^2}$ should be constant

$Q_{EC} \Rightarrow f$

$t_{1/2} \quad BR$ \quad $Q_{EC}$

$0^+ \quad T = 1$

$BR$
Corrected $Ft$ value

We must account for the fact that the decay occurs within the nuclear medium.

\[
Ft \equiv ft \left(1 + \delta'_R \right) \left(1 + (\delta_{NS} - \delta_C) \right) = \frac{K}{G_F^2 |V_{ud}|^2 |M_F|^2 (1 + \Delta^V_R)}
\]

(really should be constant)

- $\delta'_R = E_{e}^{\text{max}}$ and $Z$ dependent radiative correction
- $\delta_{NS}$ = nuclear structure dependent radiative correction
- $\delta_C$ = isospin symmetry-breaking correction
- $\Delta^V_R$ = transition independent radiative correction
$\mathcal{F}t$ values of $0^+ \rightarrow 0^+$ decays

![Graph of $\mathcal{F}t$ values vs. $Z$ of parent.](image_url)
$\mathcal{F}t$ values of $0^+ \rightarrow 0^+$ decays

\[ \langle \mathcal{F}t \rangle = 3072.1(8) \text{ s} \]
\[ \chi^2 / 12 = 0.28 \]

**corrected $\mathcal{F}t$ values constant to 3 parts in $10^4$!**

Hardy and Towner, PRC 79, 055502 (2009)
The comparative half-life of $\beta$ decay is:

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and

$$G_V = G_F V_{ud} \text{ (CVC)}$$

$$G_A \approx -1.27 G_F V_{ud} \text{ (PCAC)}$$

For neutron decay: $M_F = 1$ and $M_{GT} = \sqrt{3}$

Gamow-Teller component $\Rightarrow$ have to measure $\lambda \equiv G_A / G_V$
The comparative half-life of $\beta$ decay is:

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Theoretically simpler 3-quark system:

$\rightarrow$ no isospin corrections
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$$K/(\hbar c)^6 = \frac{2\pi^3 \hbar \ln 2}{(m_e c^2)^5}$$ and $$G_V = G_F V_{ud} \ (\text{CVC})$$

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Gamow-Teller component $\Rightarrow$ have to measure $\lambda \equiv G_A/G_V$

$$ft = \frac{K}{G_F^2 |V_{ud}|^2 (1 + 3\lambda^2)} \iff |V_{ud}|^2 = \frac{4903.7 \pm 3.8 \text{ s}}{\tau_n (1 + 3\lambda^2)}$$

Theoretically simpler 3-quark system:

$\rightarrow$ no isospin corrections
How to get the Gamow-Teller part?

\[
\frac{d^5 W}{dE_\beta d\Omega_\beta d\Omega_\nu} = \frac{G_F^2}{(2\pi)^5} |V_{ud}|^2 p_e E_e (E_\circ - E_e)^2 \xi \left[ 1 + a_{\beta\nu} \frac{p_\beta \cdot p_\nu}{E_\beta E_\nu} + b \frac{m_e}{E_\beta} \right]
\]

unpolarized decay rate

\[\beta - \nu\] correlation

Fierz interference

neutron spin

\[\beta\] asymmetry

\[\nu\] asymmetry
time-reversal violating
How to get the Gamow-Teller part?

\[
\frac{d^5W}{dE_\beta d\Omega_\beta d\Omega_\nu} = \frac{G_F^2}{(2\pi)^5} |V_{ud}|^2 p \frac{E_e (E_\circ - E_e)^2}{E_\beta E_\nu} \xi \left[ 1 + a_{\beta\nu} \frac{p_\beta \cdot p_\nu}{E_\beta E_\nu} + b \frac{m_e}{E_\beta} \right] + \sigma_n \cdot \left( A_\beta \frac{p_\beta}{E_\beta} + B_\nu \frac{p_\nu}{E_\nu} + D \frac{p_\beta \times p_\nu}{E_\beta E_\nu} \right)
\]

Within the Standard Model and in terms of \( \lambda \equiv G_A/G_V \):

\[
A_\beta = -2 \frac{|\lambda|^2 + \Re(\lambda)}{1 + 3|\lambda|^2}
\]

\[
= -0.1173(13)
\]

\[\Leftrightarrow \lambda = -1.2694(28) \quad \text{PDG2010}\]
How to get the Gamow-Teller part?

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\]

\[
+ \sigma_n \cdot \left( A_\beta \frac{p_\beta}{E_\beta} + B_\nu \frac{p_\nu}{E_\nu} + D \frac{p_\beta \times p_\nu}{E_\beta E_\nu} \right)
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= -0.1173(13) \quad \Rightarrow \lambda = -1.2694(28) \quad \text{(UCNA)}
\]

\[
PRL 102 (2009)
\]

\[
= -0.1138(46)(21) \quad \Rightarrow \lambda = -1.2603(134) \quad \{ \text{UCNA} \}
\]
How to get the Gamow-Teller part?

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\frac{d^5 W}{dE_\beta d\Omega_\beta d\Omega_\nu} = \frac{G_F^2}{(2\pi)^5} |V_{ud}|^2 p_e E_e (E_\circ - E_e)^2 \xi \left[ 1 + a_{\beta\nu} \frac{p_\beta \cdot p_\nu}{E_\beta E_\nu} + b \frac{m_e}{E_\beta} \right]
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\[
= -0.1173(13) \quad \text{PRL 102 (2009)} \quad -0.1138(46)(21) \quad -0.1197(9)(^{+12}_{-14}) \quad \text{PRL 105 (2010)} \quad -1.2694(28)
\]

\[
\Leftrightarrow \lambda = -1.2694(28) \quad -1.2603(134) \quad -1.2759(^{+41}_{-45}) \quad \text{UCNA}
\]
| $V_{ud}$ | from neutron decay |

1. PDG 2010 average of $\lambda$ from $A_\beta$ measurements
2. PDG 2010 average of lifetime measurements
3. PERKEO II $A_\beta$ (Abele, PRL 88 (2002))
4. UCNA $A_\beta$ (Liu, PRL 105 (2010))
5. most recent lifetime (Serebrov, PLB 605 (2005))
6. $|V_{ud}|$ from pure Fermi decays (Hardy and Towner, PRC 79 (2009))
7. $\sqrt{1 - |V_{us}|^2 - |V_{ub}|^2}$ from FlaviaNet 2010
The $\beta^+$-decay of $^{37}\text{K}$

$$f^t = \left( \text{phase space} \right) \left( \text{partial half-life} \right) = \frac{K}{G_V^2 |M_F|^2 + G_A^2 |M_{GT}|^2}$$
The $\beta^+$-decay of $^{37}$K

$$f t = \left( \text{phase space} \right) \left( \text{partial half-life} \right) = \frac{K}{G_V^2 |M_F|^2 + G_A^2 |M_{GT}|^2}$$

For isobaric analogue decay: $M_F = 1$ and $M_{GT} = ???$

GT component $\Rightarrow$ have to measure $\rho \equiv G_A M_{GT} / G_V M_F$

$$f t = \frac{K}{G_F^2 |V_{ud}|^2 (1 + \frac{f_A}{f_V} \rho^2)}$$

$Q_{EC} = 6.14746(20)$ MeV
$B.R. = 0.9799(14)$
and $t_{1/2} = 1.225(7)$ s

$^{37}$K $\beta^+$$^{37}$Ar

$^{37}$Ar $\beta^+$$^{37}$K

$^{37}$K $^1$S0 $^{37}$Ar $^1$D3

$^{37}$K $^1$S0 $^{37}$Ar $^3$S1

$^{37}$K $^1$S0 $^{37}$Ar $^5$S1

$^{37}$K $^1$S0 $^{37}$Ar $^7$S1

$^{37}$K $^1$S0 $^{37}$Ar $^9$S1

$Q_{EC} = 6.14746(20)$ MeV
$B.R. = 0.9799(14)$
and $t_{1/2} = 1.225(7)$ s
Present status of $^{37}$K’s $ft$ value

\[ Q_{EC}: \pm 0.003\% \]
\[ BR: \pm 0.14\% \]
\[ t_{1/2}: \pm 0.57\% \]

\[
ft = 4533(28) + \delta'_R: \pm 0.04\%
\]
\[
\delta'^{V}_{NS} - \delta^{V}_{C}: \pm 0.06\%
\]

\[ \mathcal{F}t = 4562(28) \]

Lifetime limits the $\mathcal{F}t$ value
Present status of $^{37}$K’s $ft$ value

$$
\begin{align*}
Q_{EC} & : \pm 0.003\% \\
BR & : \pm 0.14\% \\
t_{1/2} & : \pm 0.57\%
\end{align*}
\right\}
\begin{align*}
ft & = 4533(28) + \delta'_{NS} - \delta_{C}' \pm 0.57\% \\
\delta'_{R} & : \pm 0.04\% \\
\delta_{NS} & : \pm 0.06\%
\right\}
\begin{align*}
\mathcal{F}t & = 4562(28)
\end{align*}

Lifetime limits the $\mathcal{F}t$ value

$^{38}$Ar$(p, 2n)^{37}$K at CI:

Produced $\approx 20,000$ pps; $t_{1/2}$ measurement last fall
Preliminary result

Agreement between analysis schemes:

Set #4: $t_{1/2} = 1237.6 \pm 1.7 \text{ ms}; \quad \chi^2/488 = 0.962$

Finalizing systematics:

- contaminant levels
- analyses
- detector bias
- deadtime
- threshold

Set #4: $t_{1/2} = 1238.5 \pm 2.0 \text{ ms}; \quad \chi^2/6858 = 1.025$
Preliminary result

Agreement between analysis schemes:

Finalizing systematics:
- contaminant levels
- analyses
- detector bias
- deadtime
- threshold

all-but-final result is:

\[ t_{1/2} = 1236.1(3)_{\text{stat}}(7)_{\text{syst}} \text{ ms} \]

vs \[ 1224.8 \pm 7.3 \text{ ms} \]

\[ \sigma_t = 0.57\% \rightarrow 0.06\% \]

\[ \mathcal{F}t = 4562(28) \rightarrow 4604(8) \]

limited by branching ratio
An improved $|V_{ud}|$?
An improved $|V_{ud}|$?

Not yet . . . to get $V_{ud}$, still need $\rho \equiv G_A M_{GT}/G_V M_F$

$$|V_{ud}|^2 = \frac{5831.3 \pm 2.3 \text{ secs}}{\mathcal{F} t_{\text{mirror}} (1 + \frac{f_A}{f_V} \rho^2)}$$

see Naviliat-Cuncic and Severijns, PRL 102, 142302 (2009)
An improved $|V_{ud}|$?

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**FIG. 1.** $\mathcal{F}t_0$ values deduced for five mirror transitions as a function of the mass number of the mirror nuclei. The horizontal band shows the $\pm 1\sigma$ limits of the result from the fit.
An improved $|V_{ud}|$?

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see Naviliat-Cuncic and Severijns, PRL 102, 142302 (2009)
Angular distribution of $\frac{3}{2}^+ \rightarrow \frac{3}{2}^+$ decay

$$
dW \sim 1 + a_{\beta\nu} \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \Gamma \frac{m}{E_e} + \frac{\vec{I}}{I} \cdot \left[ A_{\beta} \frac{\vec{p}_e}{E_e} + B_{\nu} \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right] + c_{\text{align}} \frac{\vec{p}_e \cdot \vec{p}_\nu}{3E_e E_\nu} - \frac{(\vec{p}_e \cdot \hat{i})(\vec{p}_\nu \cdot \hat{i})}{E_e E_\nu} \left[ \frac{I(I+1) - 3\langle(\vec{I} \cdot \hat{i})^2 \rangle}{I(2I-1)} \right]
$$

Just like the neutron, need to measure a correlation parameter (e.g. $A_{\beta}$) to determine $\rho$
Angular distribution of $^{3/2} \rightarrow ^{3/2} \text{ decay}$

\[ dW \sim 1 + c_{\beta \nu} \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \Gamma \frac{m}{E_e} + \frac{I}{I} \cdot \left[ A_{\beta} \frac{\vec{p}_e}{E_e} + B_{\nu} \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right] \\
+ c_{\text{align}} \left[ \frac{\vec{p}_e \cdot \vec{p}_\nu}{3E_e E_\nu} - \frac{(\vec{p}_e \cdot \hat{i})(\vec{p}_\nu \cdot \hat{i})}{E_e E_\nu} \right] \left[ \frac{I(I+1) - 3\langle (\vec{I} \cdot \hat{i})^2 \rangle}{I(2I-1)} \right] \]

<table>
<thead>
<tr>
<th>Correlation</th>
<th>SM prediction with $\rho = 0.5770(20)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta - \nu$ correlation:</td>
<td>$a_{\beta \nu} = \frac{1-\rho^2/3}{1+\rho^2}$ = 0.6670(18)</td>
</tr>
<tr>
<td>Fierz interference parameter:</td>
<td>$b_{\text{Fierz}} = 0$ (sensitive to scalars and tensors)</td>
</tr>
<tr>
<td>$\beta$ asymmetry:</td>
<td>$A_{\beta} = \frac{-2\rho}{1+\rho^2} \left( \sqrt{\frac{3}{5}} - \frac{\rho}{5} \right) = -0.5707(7)$</td>
</tr>
<tr>
<td>$\nu$ asymmetry:</td>
<td>$B_{\nu} = \frac{-2\rho}{1+\rho^2} \left( \sqrt{\frac{3}{5}} + \frac{\rho}{5} \right) = -0.7705(17)$</td>
</tr>
<tr>
<td>Alignment parameter:</td>
<td>$c_{\text{align}} = \frac{4\rho^2/5}{1+\rho^2}$ = 0.1998(11)</td>
</tr>
<tr>
<td>Time-violating $D$ coefficient:</td>
<td>$D = 0$ (sensitive to imaginary couplings)</td>
</tr>
<tr>
<td>a $\beta$–recoil observable specific to our geometry</td>
<td>$R_{\text{slow}} \sim \frac{1-a_{\beta \nu}-2c_{\text{align}}/3 - (A_{\beta}-B_{\nu})}{1-a_{\beta \nu}-2c_{\text{align}}/3 + (A_{\beta}-B_{\nu})} = 0$</td>
</tr>
</tbody>
</table>
1. Fundamental symmetries
   - what is our current understanding?
   - what lies beyond?

2. $V_{ud}$ and CKM unitarity
   - $0^+ \rightarrow 0^+$ decays
   - neutron decay: a complementary test
   - mirror transitions are like “heavy neutrons”

3. Angular correlations using laser-cooled atoms
   - trapping short-lived neutral atoms
   - polarizing the atom cloud
   - angular correlations of polarized $^{37}$K
The gameplan

\[
\frac{Z}{A}X \rightarrow \frac{Z+1}{A}Y + e^\pm + \nu_e
\]

- perform a β decay experiment on short-lived isotopes
The gameplan

- perform a $\beta$ decay experiment on short-lived isotopes
- make a precision measurement of the angular correlation parameters

\[ \frac{Z}{A}X \rightarrow \frac{Z+1}{A}Y + e^\pm + \nu_e \]

\[ \vec{p}_X = 0 \]
The gameplan

- perform a $\beta$ decay experiment on short-lived isotopes
- make a precision measurement of the angular correlation parameters

1. deduce $\rho$ and measure $|V_{ud}|$
The gameplan

- perform a $\beta$ decay experiment on short-lived isotopes
- make a precision measurement of the angular correlation parameters

1. deduce $\rho$ and measure $|V_{ud}|$

2. $\mathcal{F}t + \text{SM} \rightarrow$ predict correlation parameters

With new $t_{1/2}$, $\mathcal{F}t + V_{ud}^{0+} \rightarrow 0^+ \Rightarrow \rho = 0.5770(20)$

$\Leftrightarrow A_\beta = -0.5707(7)$

vs. $A_\beta^{\text{obs}}$
The gameplan

- perform a $\beta$ decay experiment on short-lived isotopes
- make a **precision** measurement of the angular correlation parameters

1. deduce $\rho$ and measure $|V_{ud}|$
2. $\mathcal{F}t + \text{SM} \rightarrow$ predict correlation parameters

With new $t_{1/2}$, $V_{ud}$ either interpretation is a search for **new physics**

$|V_{ud}| = 0.9719(18)$ $\pm$ $0.0065$

$\chi^2/4 = 0.587$

C.L. = 67%

$0^+ \rightarrow 0^+$

$\Rightarrow A_\beta = -0.5707(7)$

vs. $A_{\beta}^{\text{obs}}$
The **Standard Model**: \( \text{SU}(2)_L \times \text{U}(1) \Rightarrow W^\pm_L, Z^0, \gamma \)

Built upon **maximal** parity violation:

- **Vector** \( \hat{P} |\Psi\rangle = + |\Psi\rangle \)

\[
H_\beta = G_F V_{ud} \bar{e} \left( \gamma_\mu - \gamma_\mu \gamma_5 \right) \nu_e \bar{u} \gamma^\mu \left( \gamma^\mu \gamma_5 \right) d
\]

- **Axial-vector** \( \hat{P} |\Psi\rangle = - |\Psi\rangle \)
The **Standard Model**: $SU(2)_L \times U(1) \Rightarrow W^\pm_L, Z^0, \gamma$

Built upon **maximal** parity violation:

$$H_\beta = G_F V_{ud} \bar{e}(\gamma_\mu - \gamma_\mu \gamma_5) \nu_e \bar{u}(\gamma^\mu - \gamma^\mu \gamma_5)d$$

Vector \( \hat{P}\ket{\Psi} = + \ket{\Psi} \)

Axial – vector \( \hat{P}\ket{\Psi} = - \ket{\Psi} \)

**low-energy limit of a deeper** $SU(2)_R \times SU(2)_L \times U(1)$ theory?
Eg: Right-handed currents

The **Standard Model**: \( SU(2)_L \times U(1) \Rightarrow W^\pm_L, Z^\circ, \gamma \)

Built upon **maximal** parity violation:

\[
H_\beta = G_F V_{ud} \left( e^{-i \frac{\gamma_\mu}{2}} - e^{i \frac{\gamma_\mu}{2}} \right) \nu_e \left( \bar{u} \gamma^\mu - i\gamma^5 \gamma^\mu \right) d
\]

**Vector** \( \hat{P}|\Psi\rangle = +|\Psi\rangle \)

**Axial-vector** \( \hat{P}|\Psi\rangle = -|\Psi\rangle \)

low-energy limit of a **deeper** \( SU(2)_R \times SU(2)_L \times U(1) \) theory?

\( \Rightarrow 3 \) more vector bosons: \( W^\pm_R, Z' \)

Simplest extensions: **manifest left–right symmetric models**

\( \quad \rightarrow \quad \) only new parameters are the \( W_2 \) mass and a mixing angle, \( \zeta \):

\[
|W_L\rangle = \cos \zeta |W_1\rangle - \sin \zeta |W_2\rangle
\]

\[
|W_R\rangle = \sin \zeta |W_1\rangle + \cos \zeta |W_2\rangle
\]
RHCs would affect correlation parameters

\[ A_\beta = \frac{-2\rho}{1+\rho^2} \left( \sqrt{\frac{3}{5}} - \frac{\rho}{5} \right) \]

\[ B_\nu = \frac{-2\rho}{1+\rho^2} \left( \sqrt{\frac{3}{5}} + \frac{\rho}{5} \right) \]

and \[ R_{\text{slow}} = 0 \]
RHCs would affect correlation parameters

In the presence of new physics, the angular distribution of $\beta$ decay will be affected.

\[
A_\beta = \frac{-2\rho}{1+\rho^2} \left( \sqrt{\frac{3}{5}} - \frac{\rho}{5} \right) \rightarrow \frac{-2\rho}{1+\rho^2} \left[ (1-xy) \sqrt{\frac{3(1+x^2)}{5(1+y^2)}} - \frac{\rho(1-y^2)}{5(1+y^2)} \right]
\]

\[
B_\nu = \frac{-2\rho}{1+\rho^2} \left( \sqrt{\frac{3}{5}} + \frac{\rho}{5} \right) \rightarrow \frac{-2\rho}{1+\rho^2} \left[ (1-xy) \sqrt{\frac{3(1+x^2)}{5(1+y^2)}} + \frac{\rho(1-y^2)}{5(1+y^2)} \right]
\]

and \( R_{\text{slow}} = 0 \rightarrow y^2 \)

where \( x \approx (M_L/M_R)^2 - \zeta \) and \( y \approx (M_L/M_R)^2 + \zeta \)

are RHC parameters that are zero in the SM.
RHCs would affect correlation parameters

In the presence of new physics, the angular distribution of $\beta$ decay will be affected.

\[
A_\beta = \frac{-2\rho}{1+\rho^2} \left( \sqrt{\frac{3}{5}} - \frac{\rho}{5} \right) \quad \rightarrow \quad \frac{-2\rho}{1+\rho^2} \left[ (1-x y) \sqrt{\frac{3(1+x^2)}{5(1+y^2)}} - \frac{\rho(1-y^2)}{5(1+y^2)} \right]
\]

\[
B_\nu = \frac{-2\rho}{1+\rho^2} \left( \sqrt{\frac{3}{5}} + \frac{\rho}{5} \right) \quad \rightarrow \quad \frac{-2\rho}{1+\rho^2} \left[ (1-x y) \sqrt{\frac{3(1+x^2)}{5(1+y^2)}} + \frac{\rho(1-y^2)}{5(1+y^2)} \right]
\]

and

\[
R_{\text{slow}} = 0 \quad \rightarrow \quad y^2
\]

where \( x \approx (M_L/M_R)^2 - \zeta \) and \( y \approx (M_L/M_R)^2 + \zeta \) are RHC parameters that are zero in the SM.

\[\Rightarrow\] Precision measurements test the SM

Goal must be \( \lesssim 0.1\% \)

(see Profumo, Ramsey-Musolf and Tulin, PRD 75 (2007))
The $\beta$ asymmetry

\[ A_\beta = \frac{-2\rho \left( \sqrt{\frac{3}{5}} - \frac{\rho}{5} \right)}{1 + \rho^2} \]

- **recoil order corrections** under control
- value sensitive to **RHC** parameters $\delta$ and $\zeta$
- energy-dependence sensitive to **SCCs**
Many groups around the world realize the potential of using traps for precision weak interaction studies.
Any type of trap requires a velocity-dependent force to cool an object.
Any type of trap requires a velocity-dependent force to cool an object . . . as well as a position-dependent force that defines $\vec{x} = 0$. 
Any type of trap requires a velocity-dependent force to cool an object . . . as well as a position-dependent force that defines $\vec{x} = 0$.
Any type of trap requires a velocity-dependent force to cool an object... as well as a position-dependent force that defines $\vec{x} = 0$.

Laser light $\rightarrow$ velocity-dependent force

Zeeman effect $\rightarrow$ position-dependent force

$\Rightarrow$ atom trap = damped harmonic oscillator
How can light seriously affect a thermal atom?

\[ \hbar \vec{k} \approx 1.6 \text{ eV/c} \quad \text{vs.} \quad \vec{M} \vec{v} \approx 45 \text{ keV/c} \]
Atom-photon interactions

Cycling Transitions!

\[ \hbar \vec{k} \times 30,000 \approx M \vec{v} \]
cycling transition $\Rightarrow$ not everything trappable
However... cycling transition $\Rightarrow$ not everything trappable

and *still* the trap is shallow...
Still, gotta love it!!

neutralizer

ion beam

\[
\sigma^+ \quad I \quad \sigma^-
\]

\[
\sigma^- \quad I \quad \sigma^+
\]

Raab PRL 59 (1987)

iso\textit{merically} selective!
Still, gotta love it!!

- isomERICALLY selective!
- point-like source!
  \((\lesssim 1 \text{ mm}^3 \text{ FWHM})\)

Raab PRL 59 (1987)
Still, gotta love it!!

- isomerically selective!
- point-like source! ($\lesssim 1 \text{ mm}^3 \text{ FWHM}$)
- cold atoms! ($\lesssim 1 \text{ mK}$)

Raab PRL 59 (1987)
Still, gotta love it!!

- \textit{isomerically} selective!
- \textit{point-like} source! ($\lesssim 1 \, \text{mm}^3$ FWHM)
- \textit{cold} atoms! ($\lesssim 1 \, \text{mK}$)
- backing-free source!

Raab PRL 59 (1987)
Still, gotta love it!!

- isomerically selective!
- point-like source! ($\lesssim 1 \text{ mm}^3$ FWHM)
- cold atoms! ($\lesssim 1 \text{ mK}$)
- backing-free source!

Raab PRL 59 (1987)

an ideal source of radioactives for $\beta$-decay experiments!
Coupling a MOT to ISAC-I

\[ \sigma^+ + \sigma^- + K^+ \text{ ion beam} \]

Zr neutralizer

$^{37}$K yield with 40 $\mu$A on TiC #1: $6 \times 10^7$/s
Double-MOT system

Ion beam

Push beam

Neutralizer

Collection chamber

15 cm

MCP

Electrostatic hoops

DSSSD

BC408

β detector

Detection chamber
Traps provide a backing-free, cold ($\lesssim 1$ mK), localized ($\lesssim 1$ mm$^3$) source of short-lived radioactive atoms.

Detect $\vec{p}_\beta$ and $\vec{p}_{\text{recoil}} \Rightarrow$ deduce $\vec{p}_\nu$!
The TRINAT lab
The TRINAT lab
Optical pumping

\[ \hat{z} = \text{MCP} - \beta\text{-telescope axis} \]

\[ \hat{x} = \text{phoswich detector axis} \]
Optical pumping

\[ \hat{z} = \text{MCP} - \beta\text{-telescope axis} \]
\[ \hat{x} = \text{phoswich detector axis} = \text{polarization axis} \]

\[ \vec{F} = \vec{I} + \vec{J} \]
\[ I = \frac{3}{2} \]
\[ J = \frac{1}{2} \]

\[ m_F = -2 \quad -1 \quad 0 \quad 1 \quad 2 \]
\[ B_{\text{op}} = 2.5 \text{ G} \]
Optical pumping

\[ \hat{z} = \text{MCP} - \beta \text{-telescope axis} \]
\[ \hat{x} = \text{phoswich detector axis} = \text{polarization axis} \]

Can monitor atomic fluorescence via photoions

\[ \vec{F} = \vec{I} + \vec{J} \]
\[ I = \frac{3}{2} \]
\[ J = \frac{1}{2} \]

\[ \vec{B}_{\text{op}} = 2.5 \text{ G} \]

\[ m_F = -2 \quad -1 \quad 0 \quad 1 \quad 2 \]
Atomic measurement of $P$

$P_{1/2}$

$S_{1/2}$

$m_F = -2 \quad -1 \quad 0 \quad 1 \quad 2$

- deduce $P$ based on a model of the excited state populations:

$P_{\text{nucl}} = 96.74 \pm 0.53^{+0.19}_{-0.73}$

$I = 124 \pm 22 \ \mu W/cm^2$

$B_{\text{bad}} = 210.3 \pm 40.5 \ \text{mG}$

$\Delta = -4.50 \ \text{MHz}$

$b = 0.085 \ \text{counts/10\mu s}$

$\chi^2/128 = 1.362$

$C.L. = 0.4\%$

$\Rightarrow \langle P \rangle = -97.0 \pm 0.9\%$
Trap/optical pumping cycle

- re-trap atoms before they expand too far
- MCP–laser coinc. and position cuts \( \Rightarrow \) high \( S/N \)
- Gaussian fits \( \Rightarrow \hat{x}, \hat{y}, \hat{z} \) characterization

![Graph showing cycle time vs. number of photoions and position/width data.](chart)

Position:
- \( x^2/4 = 1.63 \)
- \( x^2/2 = 1.11 \)
- \( x_0 = 2.59 \pm 0.15 \text{ mm} \)
- \( v_x = -40 \pm 37 \text{ cm/s} \)
- \( \sigma_x = 2.89 \pm 0.06 \text{ mm} \)
- \( v_{\text{therm}} = -75 \pm 8 \text{ cm/s} \)

Width:
- \( \sigma_0 = 1.268 \pm 0.053 \text{ mm} \)
- \( \nu_{\text{therm}} = 181 \pm 7 \text{ cm/s} \)
- \( T = 7.46 \pm 0.61 \text{ mK} \)
Asymmetry = \frac{N(\sigma^+) - N(\sigma^-)}{N(\sigma^+) + N(\sigma^-)}
\sim PA_\beta \left\langle \frac{p_e}{E_e} \right\rangle

\begin{align*}
A = 81.3(1.0)\% \\
A = -79.2(1.5)\% \\
A = (0.28 \pm 0.49)\% \\
A = (-0.87 \pm 0.61)\%
\end{align*}
$A_\beta$ – phoswich asymmetries

Asymmetry = \frac{N(\sigma^+) - N(\sigma^-)}{N(\sigma^+) + N(\sigma^-)}

\sim P A_\beta \langle \frac{p_e}{E_e} \rangle

atoms can get sprayed onto the thin mirrors and walls . . .
recoil coincidences cleaner!
Measuring $B_\nu$ (and $D$)

\[ d\Gamma \sim PB_\nu \hat{p}_\nu \cdot \hat{i} + PD \frac{\hat{i} \cdot (\vec{p}_\beta \times \hat{p}_\nu)}{E_\beta} \]

\[ \hat{p}_\beta \approx \hat{z} \implies \vec{p}_\nu \approx -\vec{p}_{Ar} \]
Measuring $B_\nu$ (and $D$)

\[ d\Gamma \sim P B_\nu \hat{p}_\nu \cdot \hat{i} + P D \frac{\hat{i} \cdot (\vec{p}_\beta \times \hat{p}_\nu)}{E_\beta} \]

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d\Gamma \sim PB_\nu \hat{p}_\nu \cdot \hat{i} + PD \frac{\hat{i} \cdot (\vec{p}_\beta \times \hat{p}_\nu)}{E_\beta}
\]

\[
\hat{p}_\beta \approx \hat{z} \quad \Rightarrow \quad \vec{p}_\nu \approx -\vec{p}_{Ar}
\]

$\hat{x}$ asymmetry $\sim PB_\nu$

$\hat{y}$ asymmetry $\sim PD$
The neutrino asymmetry measurement

1\textsuperscript{st} : \( \langle B_\nu \rangle = (0.995 \pm 0.040) B_\nu^{\text{SM}} \) (stat)

2\textsuperscript{nd} : \( \langle B_\nu \rangle = (0.975 \pm 0.031) B_\nu^{\text{SM}} \) (stat)

\[ B_\nu = 0.981(26)(17) B_\nu^{\text{SM}} \]

(Melconian, PLB \textbf{649} (2007) 370)
The new chamber

- Shake-off $e^-$ detection
- Better control of OP beams
- Increased $\beta$/recoil solid angles
- Stronger $E$-field
- Eddy currents: AC-MOT (Harvey & Murray, PRL 101 (2008))
The new chamber

for MOT currents rapidly switched to zero, the induced eddy currents continue to produce B fields until they too reduce to zero.

In practice the B field due to the MOT takes \( \sim 10 \) ms to reduce to \( < 10^{-7} \) T, this time depending on the proximity of conductors to the coils, their shape, and resistivity. During this time, a large fraction of trapped atoms escape, resulting in a cold atom density that rapidly falls to zero. Losses can be reduced by leaving the cooling lasers on to create an optical molasses (if this does not interfere with the experiment); however, the loss problems remain. The comparatively long time taken for the B field to decay also reduces data accumulation rates, since the repetition rate is then only \( \sim 50 \) Hz.

It is clearly advantageous to eliminate these constraints. Several methods have been attempted, including shaping the dc MOT driving current at switchoff to try to cancel fields due to eddy currents [10]. This technique is complicated and requires different currents when spectrometer

Dan Melconian

\[ \text{BC408} \]

500\( \mu \text{m} \) thick Be foil

\[ \text{(anti)Helmholtz coils} \]

\[ \text{electrostatic hoops} \]

\[ \text{BB1 Si-strip detector} \]

\[ 40 \times 40 \text{mm} \times 300 \mu \text{m} \]

\[ 40 \times 40 \text{mm} \times 300 \mu \text{m} \]

\[ 500 \mu \text{m} \text{ thick Si-coated mirror} \]

\[ 500 \mu \text{m} \text{ thick Be foil} \]

04/29/2011 – 40
Goal, in terms of RHCs

Expected limits if $A_\beta$, $B_\nu$ and $R_{\text{slow}}$ all measured to 0.1%

see Profumo, Ramsey-Musolf and Tulin, PRD 75 (2007) 075017
Beyond the minimal L-R symmetric model

(adapted from Thomas et al., Nucl Phys A 694; see also Severijns, Beck and Naviliat-Cuncic, Rev Mod Phys 78 (2006))

different experiments are complementary
● SM is fantastic, but incomplete
● many exciting avenues to find more complete model
● $|V_{ud}|$ from mirror decays complement $0^+ \rightarrow 0^+$
● $t_{1/2}$ of $^{37}$K no longer limits $\mathcal{F}t$
● needed: precision measurement of correlation parameters
● MOT + opt. pumping = cool physics
● two interpretations of precision experiments:

1. $\mathcal{F}t + \rho_{obs} \rightarrow |V_{ud}|$
2. $\mathcal{F}t + |V_{ud}^{0^+ \rightarrow 0^+}| \rightarrow \rho_{SM}$ vs. $\rho_{obs}$

Thank you for your attention!
Main collaborators/thanks


Tel Aviv: D. Ashery, I. Cohen

Manitoba: G. Gwinner
A 1D optical molassis

\[ I = 0 \text{ case: } ^{38}\text{mK} \]

\[ F' = \frac{3}{2} \quad \Delta \quad P_{3/2} \]

\[ F = \frac{1}{2} \quad \omega_L \quad S_{1/2} \]
a 1D magneto-optical trap

$I = 0$ case: $^{38}\text{mK}$

$F' = 3/2$

$\sigma^+$

$\sigma^-$

$F = 1/2$

$B(z)$

$z = 0$

$z, B < 0$

$z, B > 0$

$B(z)$

$z = B = 0$

$F' = 3/2$

$F' = 1/2$

$F' = -1/2$

$F' = -3/2$

$m_F = 1/2$

$m_F = -1/2$

$m_{F'} = 3/2$

$m_{F'} = 1/2$

$m_{F'} = -1/2$

$m_{F'} = -3/2$
**$B_\nu$ error budget**

<table>
<thead>
<tr>
<th>Source</th>
<th>$\langle \Delta B_\nu \rangle / B_\nu^{SM}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st</td>
</tr>
<tr>
<td>Asymmetry fit</td>
<td>±4.0</td>
</tr>
<tr>
<td>Polarization</td>
<td>±0.7</td>
</tr>
<tr>
<td>stat</td>
<td></td>
</tr>
<tr>
<td>syst</td>
<td>+0.7</td>
</tr>
<tr>
<td>cloud position/velocity</td>
<td>+1.5</td>
</tr>
<tr>
<td></td>
<td>−1.0</td>
</tr>
<tr>
<td>cloud size/temperature</td>
<td>+0.5</td>
</tr>
<tr>
<td></td>
<td>−0.0</td>
</tr>
<tr>
<td>binning</td>
<td>+0.4</td>
</tr>
<tr>
<td></td>
<td>−0.1</td>
</tr>
<tr>
<td>MCP efficiency/calibration</td>
<td></td>
</tr>
<tr>
<td>MCP rotation</td>
<td>+1.1</td>
</tr>
<tr>
<td></td>
<td>+0.4</td>
</tr>
</tbody>
</table>

With $B_\nu^{SM} = -0.7791$

$$B_\nu = -0.765 \pm 0.020 \pm 0.013$$

(stat) \hspace{2cm} (syst)
Are they constant?

The most precisely measured $0^+ \rightarrow 0^+ ft$ values

1st forbidden
allowed
super-allowed

$Z$ of parent

$\log_{10} ft$
Are they constant?

The most precisely measured $0^+ \rightarrow 0^+ ft$ values
How do we test the SM?

colliders: CERN, SLAC, FNAL, BNL, KEK, DESY, . . . .

direct search for new particles

“go big or go home”

- large multi-national collabs
- billion $ price-tags
How do we test the SM?

**nuclear physics**: radioactive ion beam facilities (ISOL/frag)

- smaller collaborations
- contribute to all aspects
- “table-top” physics
How do we test the SM?

- **colliders**: CERN, SLAC, FNAL, BNL, KEK, DESY . . .
- **nuclear physics**: traps, exotic beams, neutron, EDMs, $0\nu\beta\beta$, . . .
- **cosmology/astrophysics**: SN1987a, Big Bang nucleosynthesis, . . .
- **muon decay**: Michel parameters: $\rho$, $\delta$, $\eta$, and $\xi$
- **atomic physics**: anapole moment, spectroscopy, . . .

All of these techniques are **complementary** and **important**.

- Different experiments probe different (new) physics.
- If a signal is seen, cross-checks are crucial!

**Often they are interdisciplinary**

(fun and a great basis for graduate students!)