Fundamental symmetries II

Leendert Hayen

EBSS22, Notre Dame, June 8th 2022

North Carolina State University & TUNL, USA

Image by Sandbox Studios

Waiting

If this was you yesterday...

Flow of these lectures

Lecture I

Introduction to symmetries & their description

Gauge theory & how symmetry $\rightarrow$ dynamics

Introduction to the Standard Model and its symmetries

Lecture II

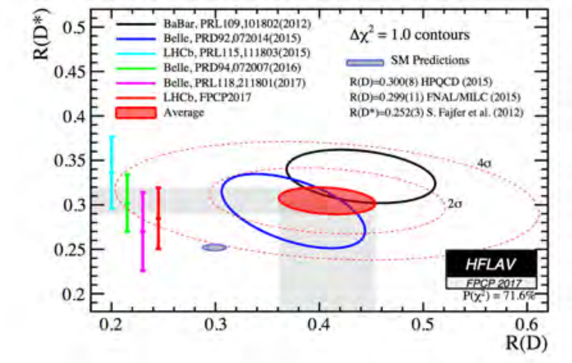
Beyond the Standard Model: Effective field theory

Examples

- Precision (nuclear) β decay
- Sterile neutrinos
- EDMs
- Leptogenesis

Standard Model anomalies

Several experiments 3-4 σ away from SM



B-meson anomalies @ LHCb, B factories

HFLAV FPCP 2017

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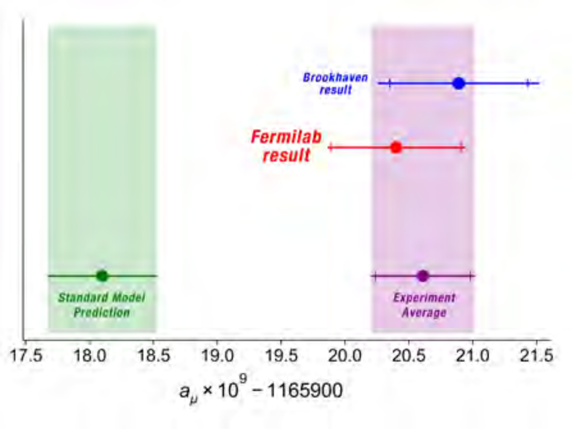

Muon $(g-2)_\mu$

fnal.gov, 2021

Standard Model anomalies

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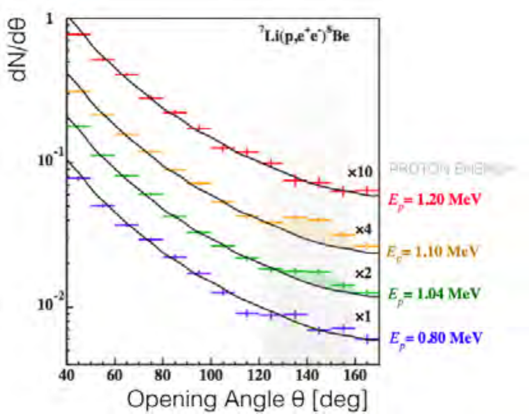

Atomki ^{8}Be anomaly

PRL 116 042501

Standard Model anomalies

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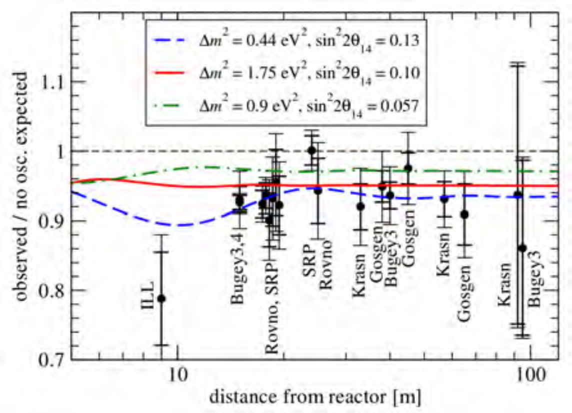


Reactor antineutrino anomaly

See also LH et al., PRC 100 054323

Standard Model anomalies

NEWS FEATURE

The Era of Anomalies

May 14, 2020 • *Physics* 13, 79

Particle physicists are faced with a growing list of "anomalies"—experimental results that conflict with the standard model but fail to overturn it for lack of sufficient evidence.

Littlewood's Law of Miracles, or something more?

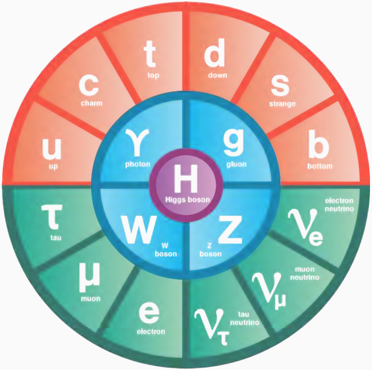
Introduction: Standard Model

Three out of four fundamental forces (no gravity): Standard Model

18 free parameters

Great (annoyingly so), consistent with constraints at $\sim 10^{0-2}$ TeV

Open questions: dark matter, gravity, neutrino masses, ...



Standard Model

According to a theorist

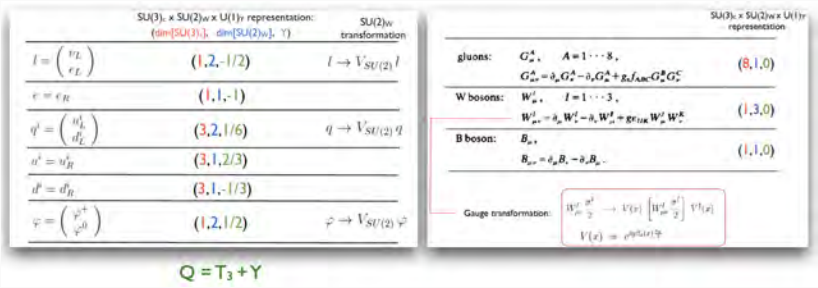


Figure by V. Cirigliano

Traditional paradigm

Based on earlier success, **gauge theory** seemed the way to go!

Just find the right symmetry groups, and off you go, right?

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Physicists' Nightmare Scenario: The Higgs and Nothing Else

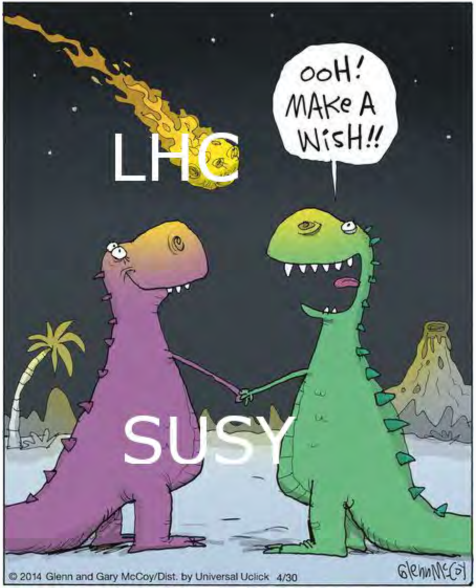
October 22, 2016

Has physics entered the nightmare scenario?

Saturday, August 06, 2016

The LHC “nightmare scenario” has come true.

SUSY vs LHC


OOH! MAKE A WISH!!
LHC
SUSY
© 2014 Glenn and Gary McCoy/Dist. by Universal Uclick 4/30
GlennMcCoy

What to do?

SM tests @ low energy: sensitive to off-shell exotic physics (footprints rather than actual beast)

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- CKM unitarity
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All of these can be probed using **(nuclear)** β **decay**

Introduction: Weak interaction & CKM matrix

Cabibbo-Kobayashi-Maskawa matrix relates weak and mass eigenstates

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

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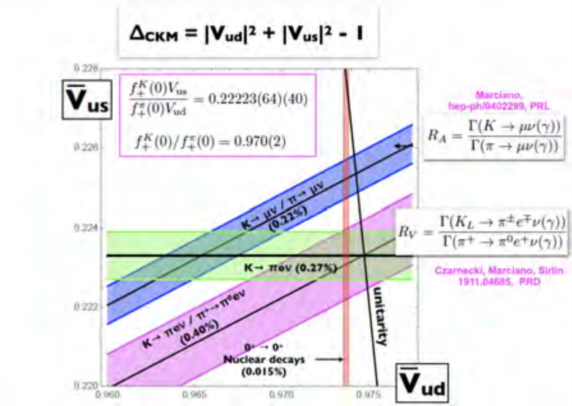
(nuclear) β decay, meson decay (π, K), $|V_{ub}|^2 \sim 10^{-5}$

Violations are sensitive to **TeV scale** new physics!

CKM unitarity: Current status

Signs of non-unitarity at few σ level...

Disagreement between $Kl2$ and $Kl3$ $|V_{us}|$

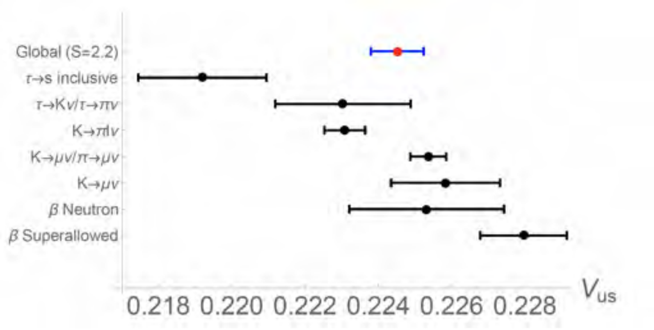


Early signs of new physics? Lattice QCD artifacts?

Figure by Vincenzo Cirigliano, DND 2020

CKM unitarity: Cabibbo Angle Anomaly

Things get even more interesting... (Falkowski CKM2021)



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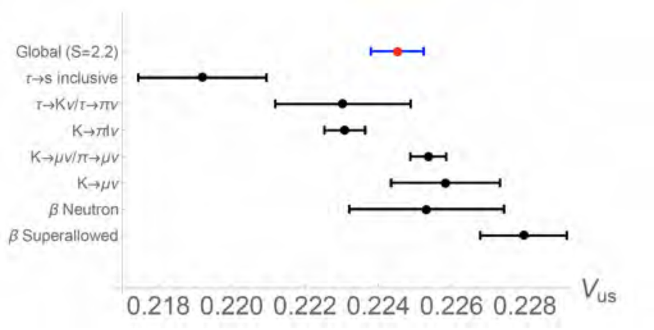

Takeaways assuming Standard Model physics:

- Most precise V_{ud} & V_{us} not consistent with unitarity
- Significant internal inconsistencies within V_{us}
- Taken at face value $\sim 3\sigma$ for new physics

Exotic contributions

What would electroweak Beyond Standard Model look like?

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Effective field theory: new physics at scale $\Lambda_{BSM} \gg$ LHC

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{i=1} c_i \frac{\mathcal{O}_{4+i}}{\Lambda^i_{BSM}}$$

effective operators $\mathcal{O}(i)$. Expansion in parameter $c_i/\Lambda^i_{BSM} \ll 1$

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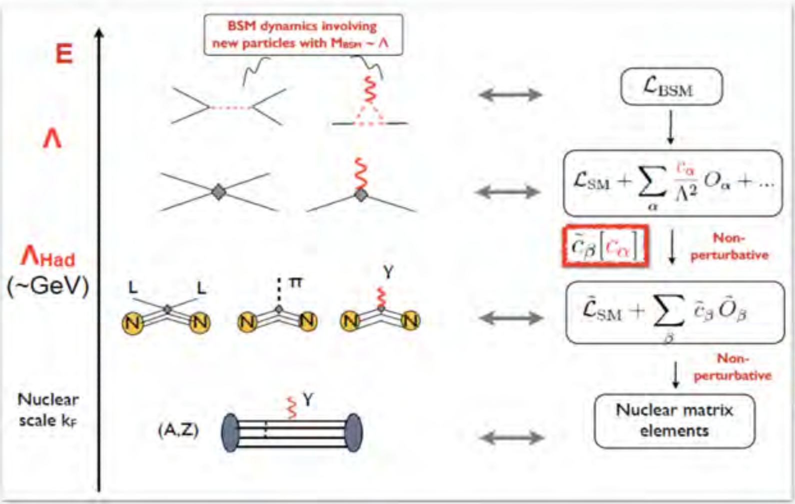
Phenomenological theories will give different $\{c_i\}$,

but agnostic experimental analysis

Effective field theory tower Slide by V. Cirigliano



Chiral EFT, Lattice QCD

Nuclear many-body methods

Effective field theory recipe Slide by V. Cirigliano

- In order to build L_{eff}, one needs to specify:
  - ★ Relevant low-E degrees of freedom: *assume* SM field content
    - ★ One Higgs doublet, no light ν_R and no other light fields
  - ★ Symmetries: L_{eff} must reflect symmetries of underlying theory
    - ★ Assume underlying theory respects SM gauge group $SU(3)_c \times SU(2)_W \times U(1)_Y$
    - ★ But not necessarily SM symmetries that result from keeping only terms of dimension ≤ 4
  - ★ Power counting in E/Λ, $v_{EW}/\Lambda << 1$ (recall $v_{EW} = G_F^{-1/2}$): organize analysis in terms of operators of increasing dimension (5,6,...)

$$\boxed{\mathcal{L}_{\text{eff}} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots}$$

- Dim 5: only one operator

Weinberg 1979

$$\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \quad \ell = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \quad \boxed{\hat{O}_{\text{dim}=5} = \ell^T C \epsilon \varphi \, \varphi^T \epsilon \ell} \quad \begin{array}{c} C = i\gamma_2\gamma_0 \\ \epsilon = i\sigma_2 \end{array}$$

- Violates total lepton number $\ell \to e^{i\alpha}\ell \qquad e \to e^{i\alpha} e$
- Generates Majorana mass for L-handed neutrinos (after EWSB)

$$\frac{1}{\Lambda}\hat{O}_{\text{dim}=5} \xrightarrow{\langle\varphi\rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}} \frac{v^2}{\Lambda}\nu_L^T C \nu_L$$

- "See-saw": $m_\nu \sim 1\,\text{eV} \;\to\; \Lambda \sim 10^{13}\,\text{GeV}$

Effective β decay

SM has V-A structure, but more generally

$$\mathcal{L}_{\text{eff}} = -\frac{G_F \tilde{V}_{ud}}{\sqrt{2}} \Big\{ \bar{e}\gamma_\mu \nu_L \cdot \bar{u}\gamma^\mu [c_V - (c_A - 2\epsilon_R)\gamma^5] d + \epsilon_S \, \bar{e}\nu_L \cdot \bar{u}d$$
$$- \epsilon_P \, \bar{e}\nu_L \cdot \bar{u}\gamma^5 d + \epsilon_T \, \bar{e}\sigma_{\mu\nu}\nu_L \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma^5) d \Big\} + \text{h.c.},$$

at the quark level

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at the quark level

All ϵ_i are proportional to $(M_W/\Lambda_{BSM})^2$, change kinematics

$\epsilon_i \lesssim 10^{-4} \rightarrow \Lambda_{BSM} \gtrsim 15$ TeV assuming natural couplings

CKM unitarity: V_{ud}

Let's break it down: How to obtain V_{ud}?

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Semi-leptonic up-down decay rate

$$\Gamma \propto G_F^2 |V_{ud}|^2 (1 + RC) |\langle O_{\mathrm{hadr}} \rangle|^2 \times \text{phase space}$$

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Things you need to know

- G_F (μ lifetime)
- Radiative corrections
- Hadronic theory
- For each β transition: $t_{1/2}, Q_\beta$, BR, (GT/F mixing)

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Everything to $\lesssim 0.01\%$! **Recent changes**

CKM unitarity: V_{ud} precision

Nuclear sandbox $\rightarrow$ make hadronic theory easy

- Pion
- Neutron
- Superallowed $0^+ \rightarrow 0^+$
- $T = 1/2$ mirrors

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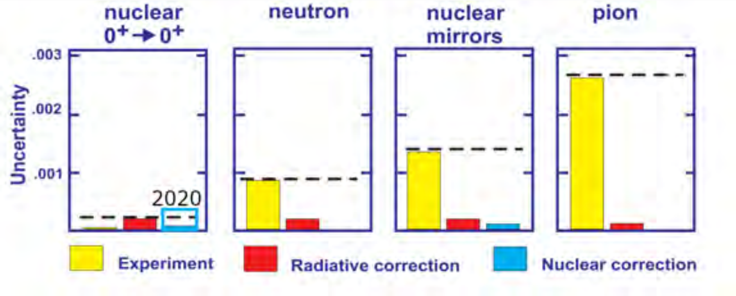

$\pi^+ \to \pi^0 e^+ \nu_e$ very hard (BR $\sim 10^{-8}$), SA new nuclear corrections!

Modified from J. Hardy, UMass Amherst May 2019

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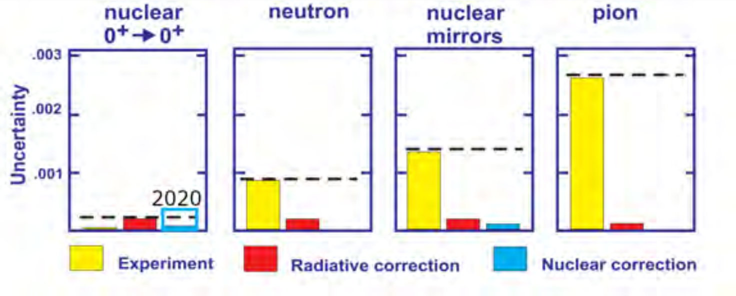

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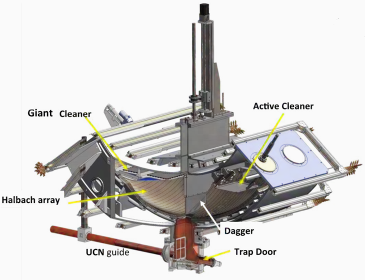
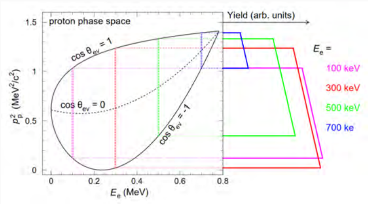
The neutron: Ongoing experiments

Neutrons are unique system, **trappable** when ultracold!

Currently involved in

UCNτ, LANL (bottle τ_n) & Nab, ORNL (g_A from $a_{\beta\nu}$)





UCNτ has current most precise determination of τ_n (0.04%), Nab is commissioning @ ORNL, aims $\mathcal{O}(0.1\%)$

Overview of β angular correlations

Several experiments worldwide

Figure by B. Maerkisch

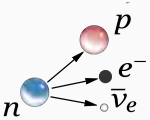
Biased, will focus on Nab

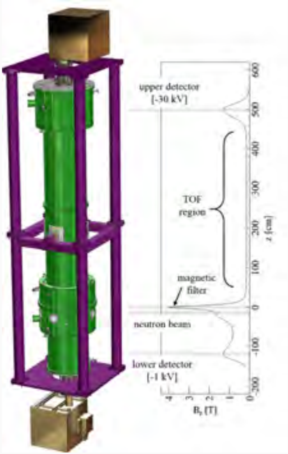
Nab - overview

Measurement of β-ν angular correlation

$$d\Gamma \propto d\Gamma_0 \left[1 + a_{\beta\nu} \beta \hat{p}_e \cdot \hat{p}_\nu\right]$$

in **neutron** β **decay** @ SNS (ORNL)





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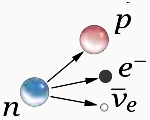
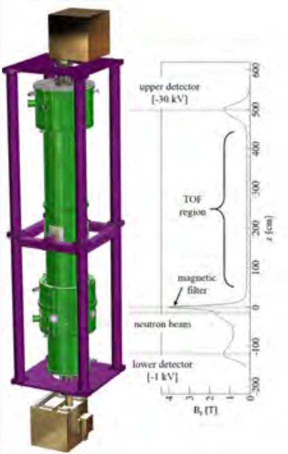




To leading order in SM

$$a_{\beta\nu} = \frac{1 - g_A^2}{1 + 3g_A^2}$$

and

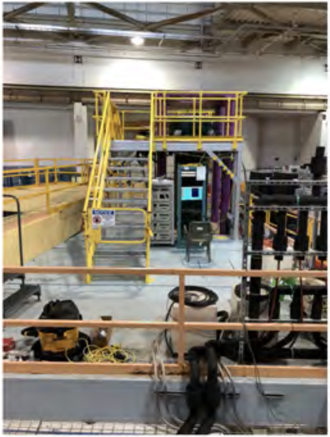
$$\frac{\delta a}{a} \approx 5 \frac{\delta g_A}{g_A}$$

meaning factor 5 sensitivity enhancement!

Nab installation

Largest (>1t) cryogen-free system in the world!

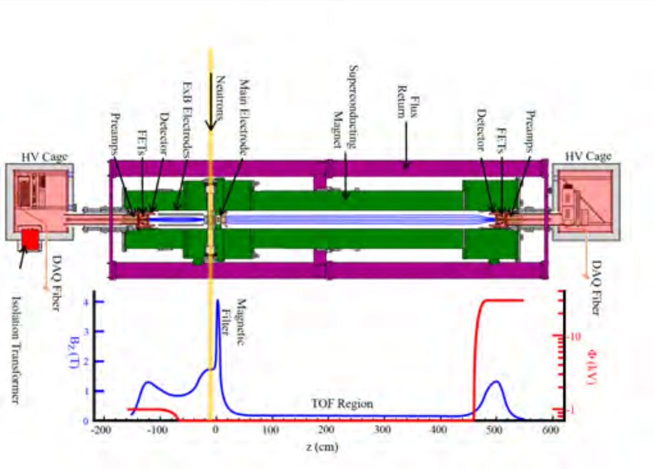
Spectrometer first mounted on the beamline in 2018



Shielding and stairs to upper detector in 2019

Nab spectrometer

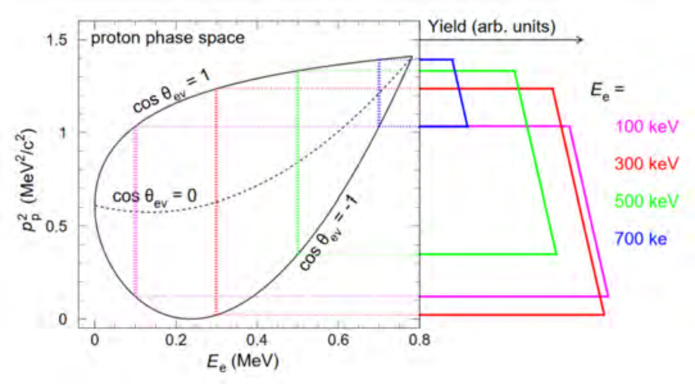
Salient features



(1) B pinch (2) Field expansion TOF (3) HV detector

Nab detection scheme

Measure p$^+$ instead of ν, $\vec{p}_p = -(\vec{p}_e + \vec{p}_\nu)$



For given slice of E_e, slope of $p_p^2 \propto a_{\beta\nu}$

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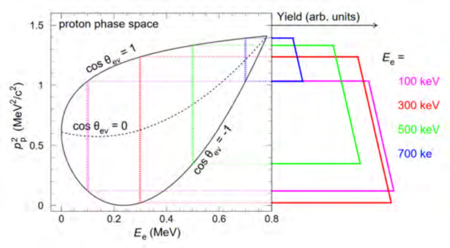

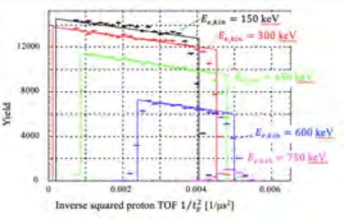

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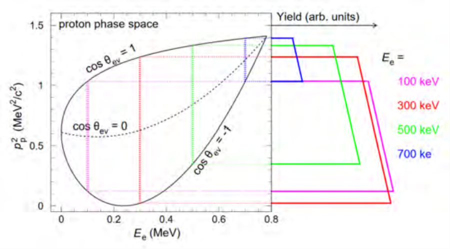

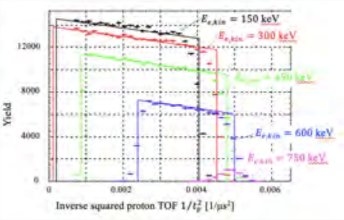

Get p_p from **time-of-flight**, need $\langle t_p \rangle$ better than **300ps**!

$$\frac{1}{t_p^2} = \frac{p^2}{m_P^2}\left[\int_{z_0}^{L} dl \left(1 - \frac{e(V - V_0)}{T_0} - \frac{B}{B_0}\sin\theta^2\right)^{-1/2}\right]^{-2} + \delta t_{\mathrm{det}}^{e-p}$$

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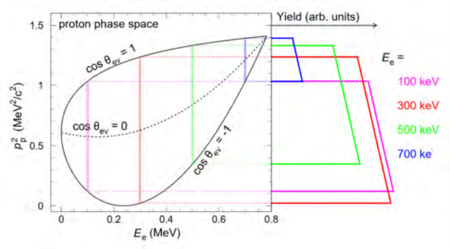

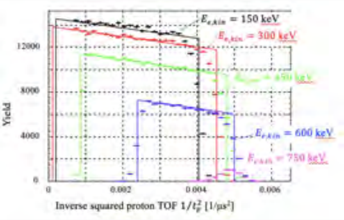

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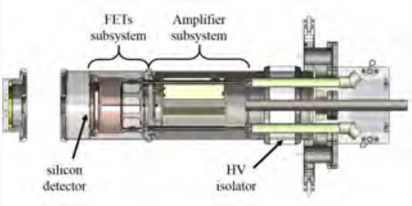
Need to map fields, but detector effects are plentiful!

Detector overview

Use highly-segmented, high-purity, large, floating Si detectors; all adjectives are great but **add complexity**



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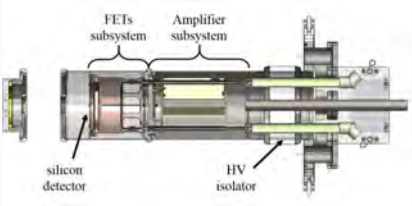
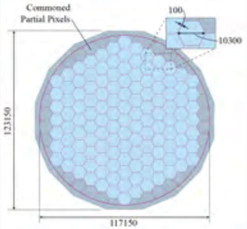
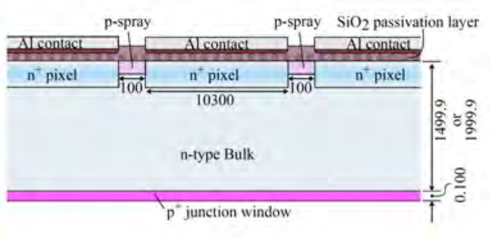


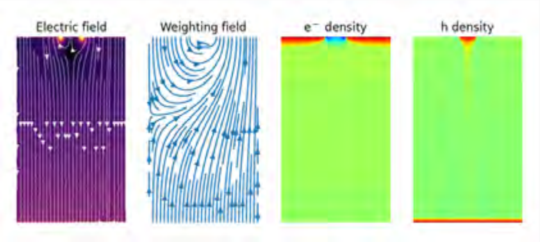
127 pixels separated with p-stop or p-spray, ∼100nm junction



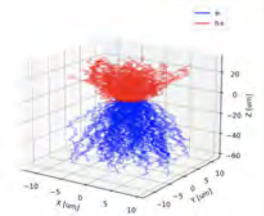


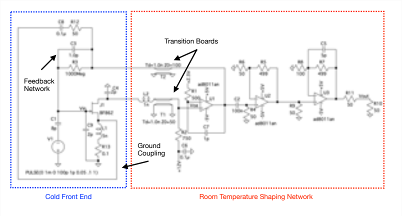
Edge effects

State of the art Silicon simulation



Plasma effects, SPICE electronics simulation, . . .





Nab hard at work

In parallel, working hard on having successful B field ramping tests!

First neutron β decay e^- seen, beam time this year!

Dark matter

Why dark matter: intuitive

For stars in circular orbits in galaxy, virial theorem says

$$v(r) = \sqrt{\frac{GM(r)}{r}}$$

so should be $\propto r^{-1/2}$ towards edge

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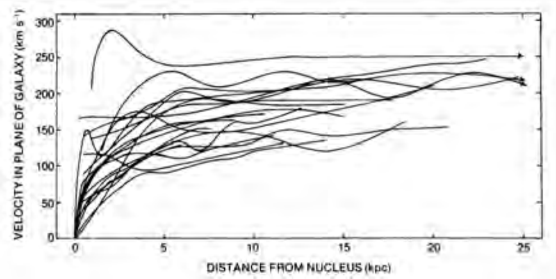
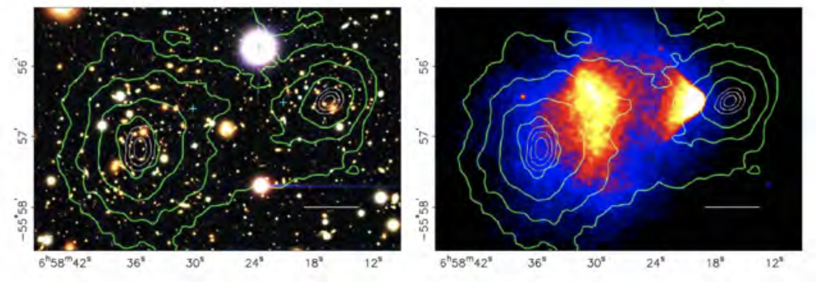


The need for dark matter

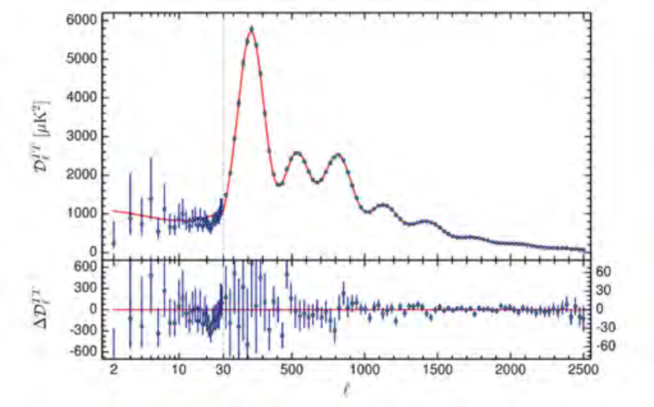
Discrepancy between weak gravitational lensing & X-ray



Most of gravitational mass $\neq$ visible mass!

Cosmic microwave background

Power spectrum of CMB



Best fit gives $\Omega_{DM}/\Omega_b \approx 5$ using ΛCDM

Why & what is dark matter

General assumed DM properties:

- Neutral
- Long-lived
- Non-baryonic

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Open questions: Thermal? Cold? Fermionic?

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Cosmic microwave background & more explained by ΛCDM (Cold Dark Matter)

What's a WIMP?

Standard candidate: **W**eakly **I**nteraction **M**assive **P**article

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Can do elastic scattering!

$$\sigma = C_{SI}(Zf_p + (A - Z)f_n)^2 + C_{SD}(a_p\langle S_p\rangle + a_n\langle S_n\rangle)^2$$

spin-independent or spin-dependent

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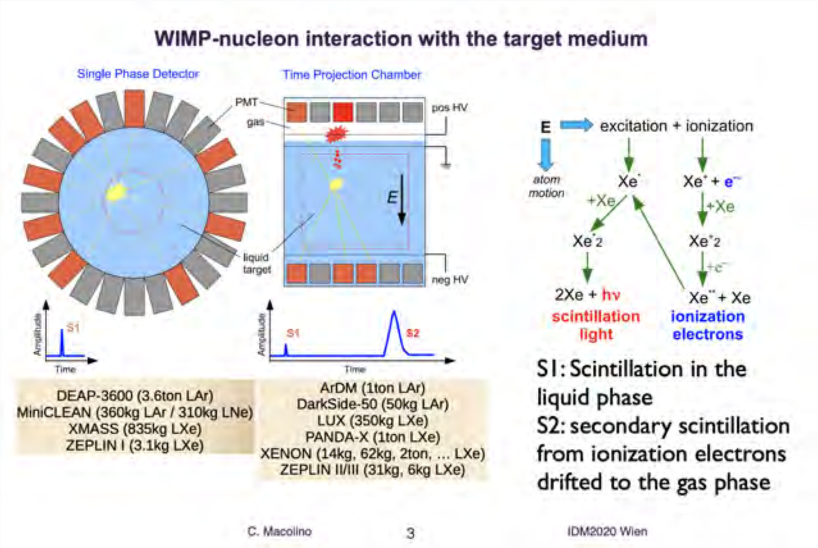
spin-independent or spin-dependent

Comes out naturally in early supersymmetry models: "WIMP miracle"

Searching for WIMPs



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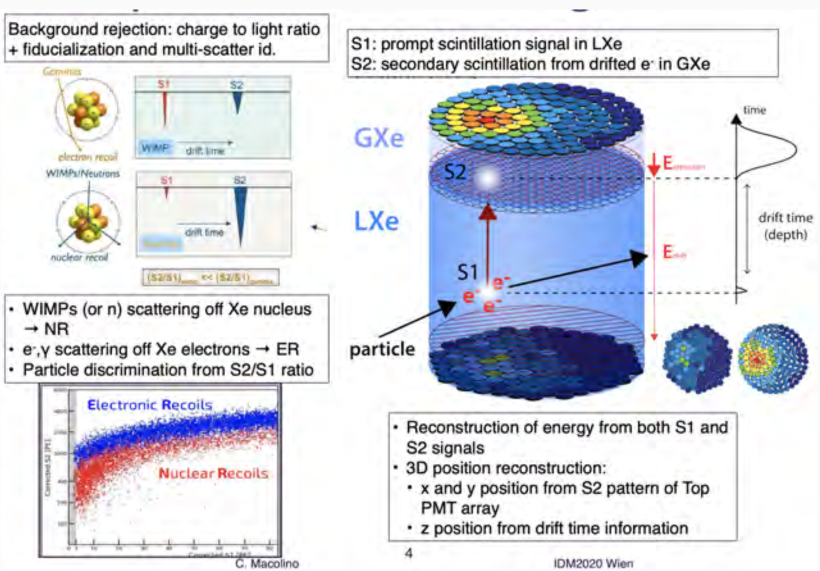
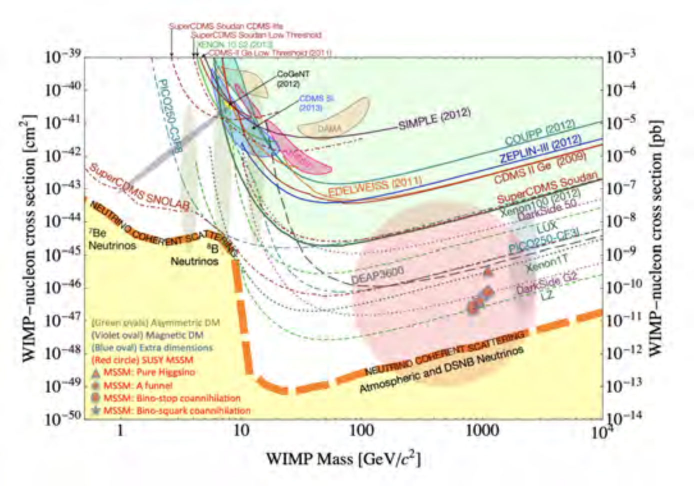


Dark matter candidates: WIMPs

Quite far below $\sigma \sim 1$ pb already...



and getting close to neutrino floor

- Sterile neutrinos are natural extensions to the SM
- To generate mostly sterile mass states on the keV-MeV scale, additional new physics is required
- ...however, mass states in this region have $\tau \approx \tau_{\text{universe}}$ and could thus serve as some fraction of the observed DM in our universe
  - Excellent candidates for warm dark matter

Dodelson and Widrow, PRL 72, 17 (1994)

Image Courtesy: Symmetry Magazine

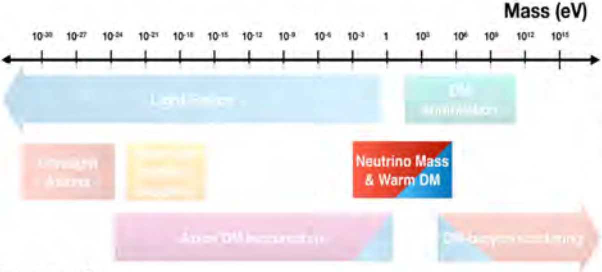
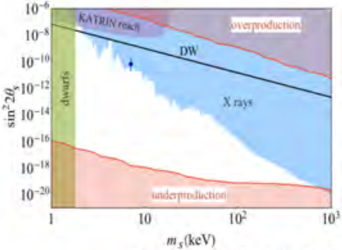


Image courtesy: CMB-S4



B. Dasgupta and J. Kopp, Phys. Rep. 928, 1-63 (2021)

What's a 'sterile' neutrino?

Transforms as a complete singlet under SM symmetries

$$SU(3)_c \times SU(2)_L \times U(1)_Y : (1,1,1) \qquad \text{essentially } \nu_R!$$

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$$\mathcal{L} = m_D(\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L)$$

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Or can go and make Majorana and explain smallness m_ν

$$\mathcal{L} = (\bar{\nu}_L \bar{\nu}_R) \begin{pmatrix} 0 & m_D \\ m_D & M_M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

if neutrino is own antiparticle, active $m_\nu = m_D^2/M_M$ seesaw!

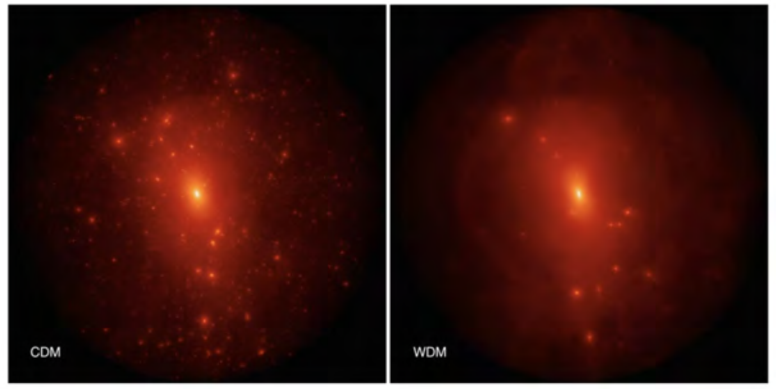
Sterile neutrino WDM

Explain *all* dark matter, must at least be $\mathcal{O}(\text{keV}) \rightarrow$ warm DM

Sterile neutrino WDM

Explain *all* dark matter, must at least be $\mathcal{O}(\text{keV}) \to$ warm DM

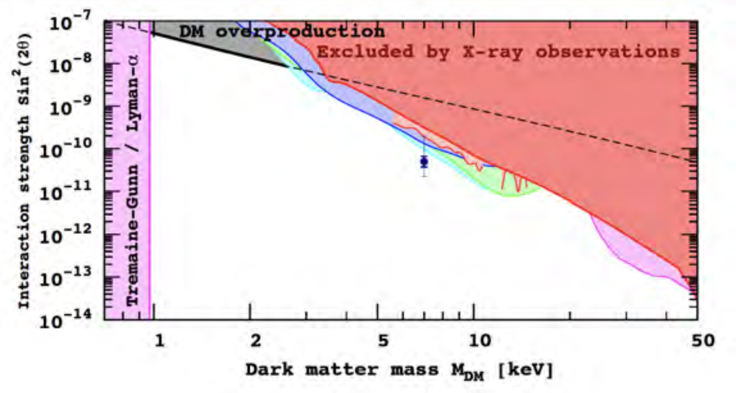
Warm DM washes out short-scale structure $\to$ easy to see?



Unfortunately, galaxy formation washes out signal . . .

Possible observation?

Sterile neutrino can decay $N \to \nu\gamma$

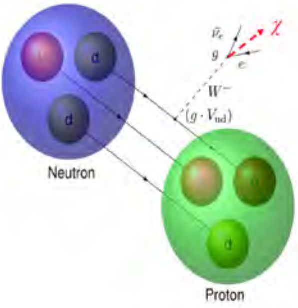


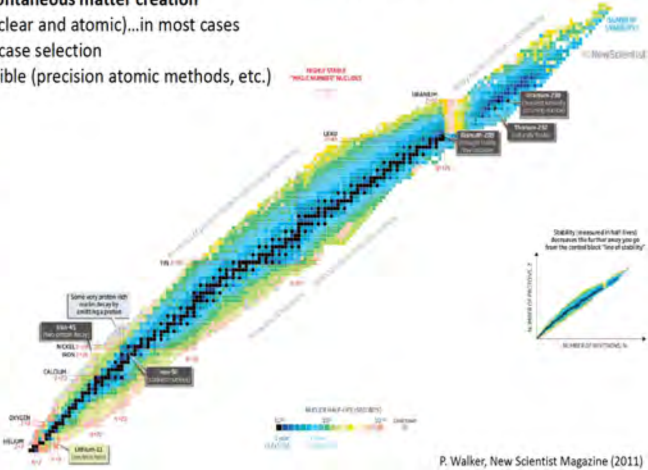
Still controversial!

Measuring sterile neutrinos using β decay Slide by K. Leach

Weak nuclear decay is among the most sensitive BSM physics probes – and particularly powerful for keV-MeV neutrinos

- Pure energy-to-matter conversion: **spontaneous matter creation**
- Complex, but understood systems (nuclear and atomic)…in most cases
- More than 3500 different systems for case selection
- Exceptional experimental control possible (precision atomic methods, etc.)



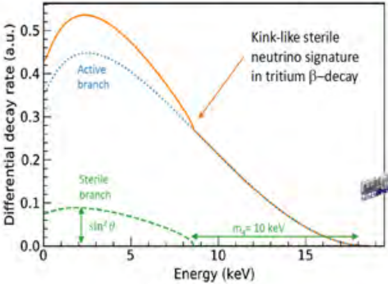


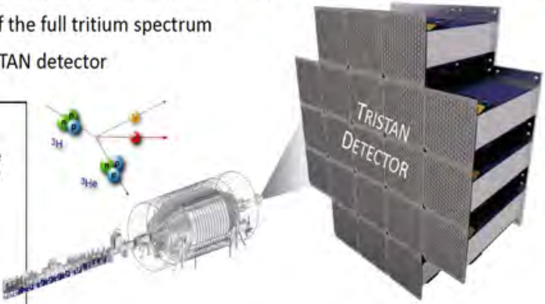
P. Walker, New Scientist Magazine (2011)

Measuring sterile neutrinos using β decay Slide by K. Leach

Idea:

- Make use of the strong KATRIN tritium source and beamline
- Perform a differential measurement of the full tritium spectrum
- Requires new detector system → TRISTAN detector



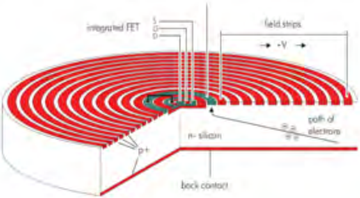


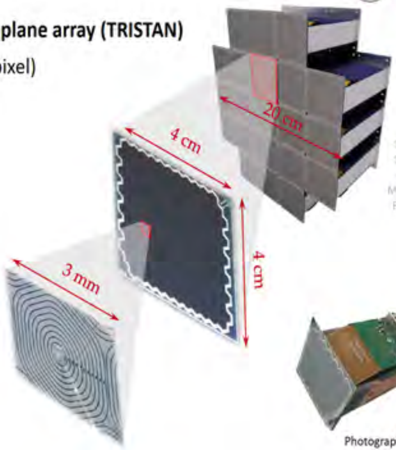
S. Mertens et al. JCAP 1502 (2015)
S. Mertens et al, PRD 91 (2015)

Measuring sterile neutrinos using β decay Slide by K. Leach

Multi-pixel (>1000) silicon drift detector focal plane array (TRISTAN)

- ✓ Capability of handling high rates (> 10^5 cps/pixel)
- ✓ Good energy resolution (300 eV @ 20 keV)
- ✓ Large focal plane area coverage

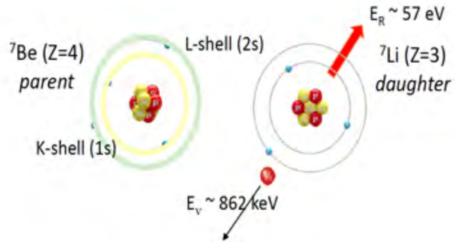


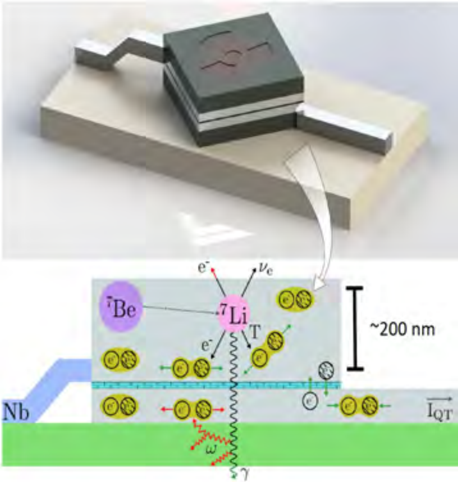


S. Mertens et al, J. Phys. G46 (2019)
S. Mertens et al, J. Phys. G48 (2020)
M. Gugiatti et al, NIM-A 979 (2020)
M. Biassoni et al, EPJ Plus 136 (2021)
P. King et al JINST 16 T07007 (2021)

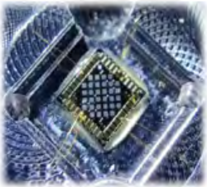
Photograph of TRISTAN module

Measuring sterile neutrinos using β decay Slide by K. Leach

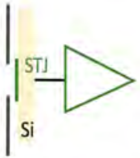




Superconducting Tunnel Junctions (STJs)

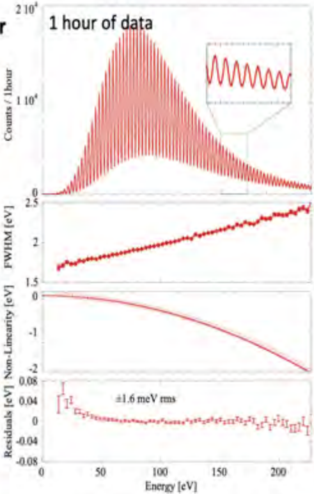


Superconducting tunnel junctions Slide by K. Leach



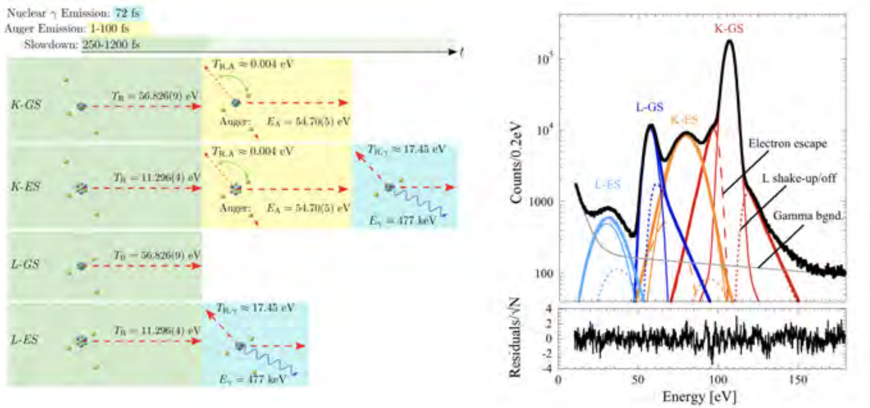
- Pulsed 355 nm (3.49965(15) eV) laser at 5 kHz fed through optical fiber to 0.1 K stage
- Illumination of STJ provides a comb of peaks at integer multiples of 3.5 eV
- Intrinsic resolution of our Ta-based devices is between ~1.5 and ~2.5 eV FWHM at ~10 – 200 eV
- Stable response and small quadratic non-linearity (10^{-4} per eV)

Adiabatic Demagnetization Refrigerator (ADR) – Base Temp ~70 mK



S. Friedrich et al., J. Low Temp. Phys. **200**, 200 (2020)

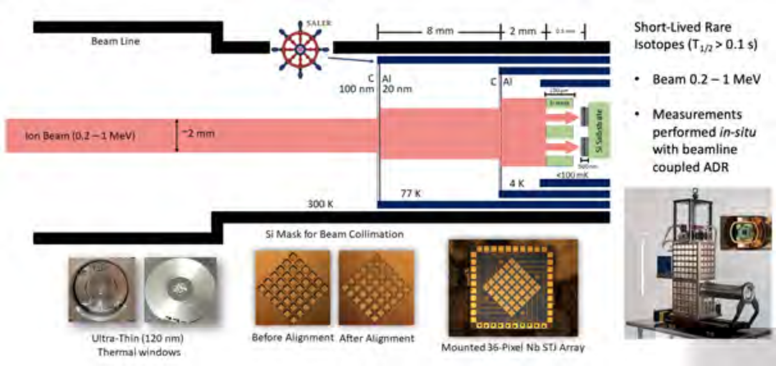
Superconducting tunnel junctions Slide by K. Leach



S. Fretwell et al., Phys. Rev. Lett. **125**, 032701 (2020)

Level-up: STJs @ RIB → SALER

Superconducting **A**rray for **L**ow **E**nergy **R**adiation



Bringing to RIB: TRIUMF, FRIB, ISOLDE, . . .

Level-up: STJs @ RIB → SALER

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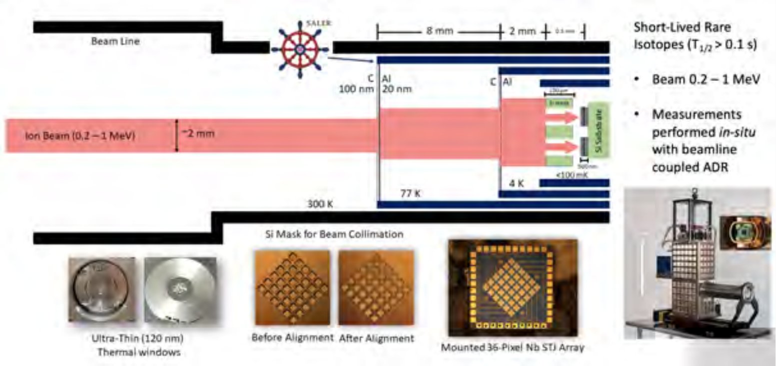
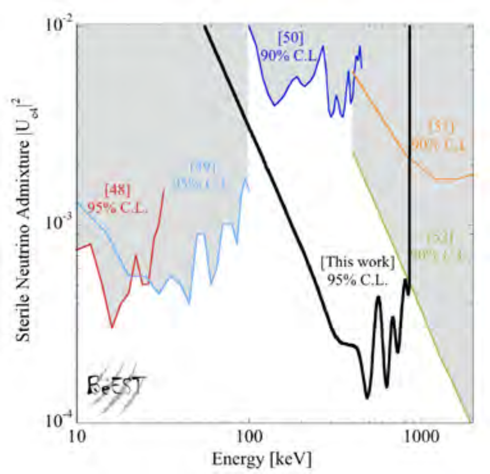


Bringing to RIB: TRIUMF, FRIB, ISOLDE, . . .

^{11}C first target, immediate physics reach for TeV scale new physics

In first physics run, already competitive



CP violation and EDMs

Baryon asymmetry

Already discussed baryon asymmetry:

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = \mathcal{O}(10^{-10})$$

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$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = \mathcal{O}(10^{-10})$$

Baryon asymmetry can arise **dynamically** on three conditions (Sakharov 1967)

- B-number violation
- CP violation
- Departure from equilibrium

First two present in SM but way too little,

Higgs too heavy for last

Look for other ways of *CP* violation: permanent electric dipole moments

$$\mathcal{H} = -\mu_{\mathrm{n}} \frac{\vec{\sigma}}{|\vec{\sigma}|} \vec{B} - d_{\mathrm{n}} \frac{\vec{\sigma}}{|\vec{\sigma}|} \vec{E}$$

Time reversal symmetry T is not conserved:

$$\mathrm{T}\mathcal{H} = -\mu_{\mathrm{n}} \frac{-\vec{\sigma}}{|\vec{\sigma}|} (-\vec{B}) - d_{\mathrm{n}} \frac{-\vec{\sigma}}{|\vec{\sigma}|} \vec{E} \neq \mathcal{H}$$

CPT theorem: T-violation $\Leftrightarrow$ CP-violation.

Neutron excellent system: neutral & $d_n^{SM} \sim \mathcal{O}(10^{-34}) e{\cdot}\mathrm{cm}$

Current limit on nEDM

Current limit is $d_n < 1 \times 10^{-26} e{\cdot}\mathrm{cm}$

If we blow up neutron to size of the earth

separation between + and - is less than width of a human hair!

How to measure an EDM? Slide by B. Franke

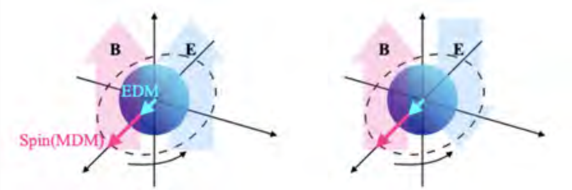
- Apply a magnetic field $\vec{B}$ and an electric field $\vec{E}$ $\uparrow\uparrow$ or $\uparrow\downarrow$

$$hf_{\mathrm{n}} = 2\mu_{\mathrm{n}}B \pm 2d_{\mathrm{n}}E$$

- Extract nEDM d_{n} from *the difference* of Larmor precession frequencies in $\uparrow\uparrow$ or $\uparrow\downarrow$ fields:

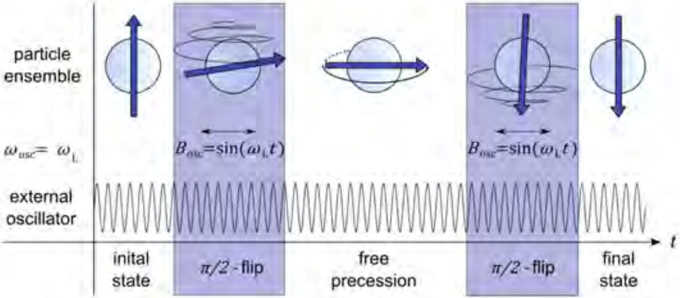
$$d_{\mathrm{n}} = \frac{h\left(f_{\mathrm{n}}^{\uparrow\uparrow} - f_{\mathrm{n}}^{\uparrow\downarrow}\right) - \mu_{\mathrm{n}}\left(B^{\uparrow\uparrow} - B^{\uparrow\downarrow}\right)}{2\left(E^{\uparrow\uparrow} + E^{\uparrow\downarrow}\right)}$$

$$\sigma(d_{\mathrm{n}})_{\mathrm{stat}} = \frac{\hbar}{2\alpha ET\sqrt{N}}$$



How to measure an EDM?

Ramsey's method of separated oscillatory fields

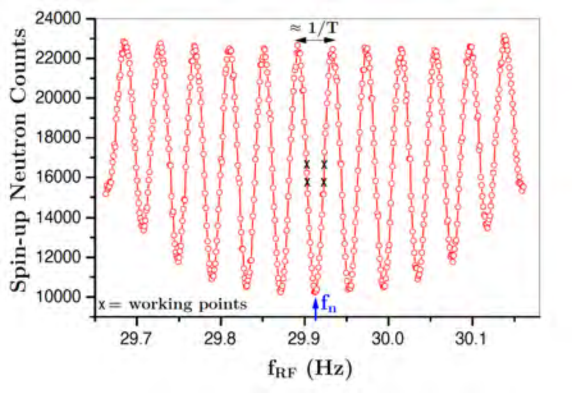


Ingredients to extract f_n via the Ramsey method of separated oscillatory fields:

- 100 % polarized ensemble
- Magnetic field, ideally on single homogeneous component
- very precise external clock
- count neutrons depending on polarization state

Ramsey fringes

Varying the RF frequency around the cyclotron frequency



Measure at steepest edges for maximum sensitivity

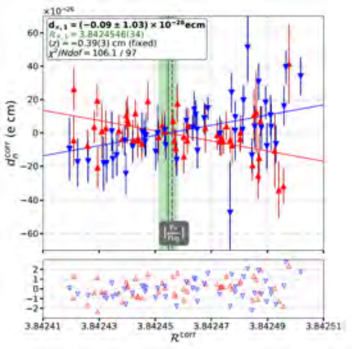
Final result

Best current result by

nEDM @ PSI

Total campaign of >10 years

$d_n =$
$(-0.09 \pm 1.03) \times 10^{-26} e{\cdot}\text{cm}$



Leptogenesis

Leptogenesis

Baryogenesis through electroweak condensation impossible,

not enough CP violation in quarks $\rightarrow$ maybe leptons?

$$J_{CP} = s_{12}c_{12}s_{13}c_{13}^2 s_{23}c_{23}\sin\delta$$

C. Jarlskog PRL 55, 1039 (1985)

1. Strong interaction: no observed EDM $\Rightarrow$ CP (nearly) **conserved**

$$\frac{\bar{\theta}}{2\pi} < 10^{-11}$$

J. Pendlebury, et al. 1509.04411

2. Quark mass matrix: non-zero but **small** CP violation

$$\frac{|J_{\rm CKM}|}{J_{\max}} = 3\times 10^{-4}$$

CKMfitter 1501.05013

3. Lepton mass matrix: **?**

$$\frac{|J_{\rm PMNS}|}{J_{\max}} < 0.34$$

PBD, J. Gehrlein, R. Pestes 2008.01110

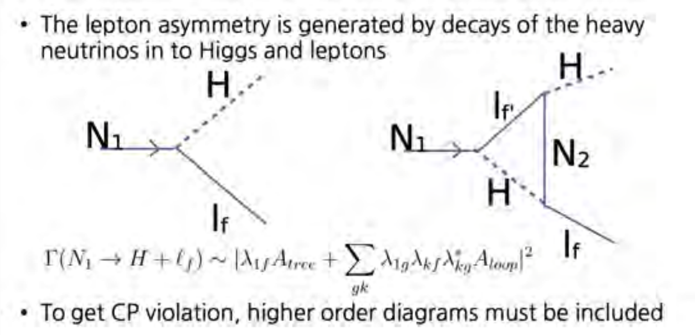
$J_{\max} = \frac{1}{6\sqrt{3}} \approx 0.096$

δ is complex phase ($\cancel{CP}$) in mixing matrix (CKM/PMNS)

Leptogenesis: possible scenario

Add heavy sterile neutrino N with Yukawa coupling

$$\mathcal{L} = \mathcal{L}_{SM} + MN_R^T N_R + (\nu_L^T H^0 - l_L H^-)\lambda N + h.c.$$



Hard to test, but if $0\nu\beta\beta$ is found plausible!

Leptogenesis

δ: what is it not?

$$\delta \not\Rightarrow \text{Baryogenesis}$$

The amount of leptogenesis is a function of:

1. the heavy mass scale
2. δ
3. α, β (Majorana phases)
4. CP phases in the RH neutrinos
5. ...

C. Hagedorn, et al. 1711.02866

K. Moffat, et al. 1809.08251

$$\boxed{\begin{array}{lcl} \text{Measuring } \delta = 0, \pi & \not\Rightarrow & \text{no leptogenesis} \\ \text{Measuring } \delta \neq 0, \pi & \not\Rightarrow & \text{leptogenesis} \end{array}}$$

Summary

Fundamental symmetries is a rich field

Low energy particle physics with neutrons & nuclei sandbox, cross-pollination

Tabletop-small room size experiments competitive and complementary with collider searches

Suggested reading

As always, contact me: lmhayen@ncsu.edu

Leptogenesis for pedestrians, hep-ph/0401240v1

BBN for pedestrians, astro-ph/0406320

A white paper on keV sterile neutrino dark matter, 1602.04816

The neutron and its role in cosmology and particle physics, 1105.3694

Electric dipole moments of atoms, molecules, nuclei, and particles

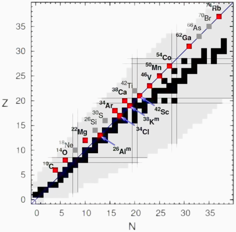
Nucleus: Superallowed $0^+ \to 0^+$

Pure Fermi transitions, $M_F = \sqrt{2}$

$$f_V t(1+\delta_R)(1-\delta_C+\delta_{NS}) = \frac{K}{2G_F^2 V_{ud}^2(1+\Delta_R^V)}$$

Few small $\mathcal{O}(0.1\% - 2.5\%)$ corrections

$\delta V_{ud}/V_{ud} \approx 0.04\%$



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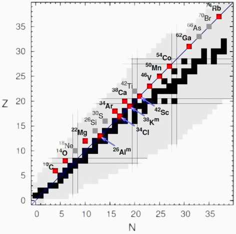

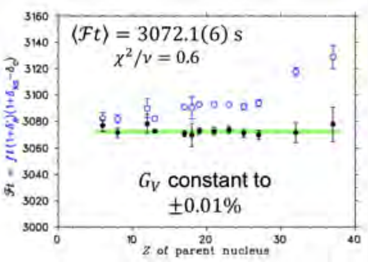

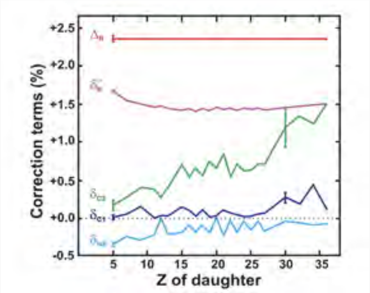

Towner & Hardy analysis; Plots by J. Hardy & D. Malconian

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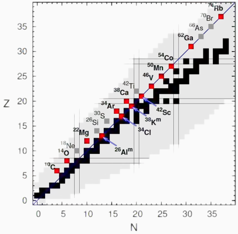
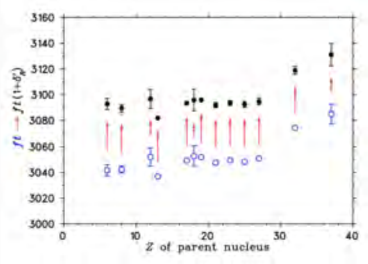
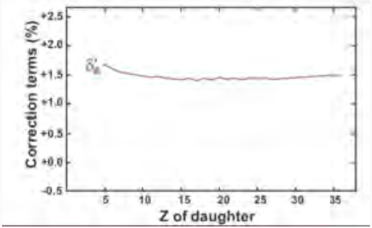






Additional photonic corrections

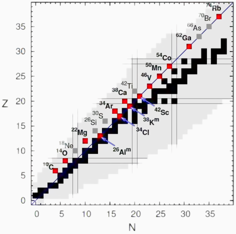
Nucleus: Superallowed $0^+ \to 0^+$

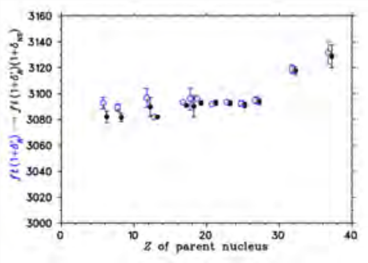
Pure Fermi transitions, $M_F = \sqrt{2}$

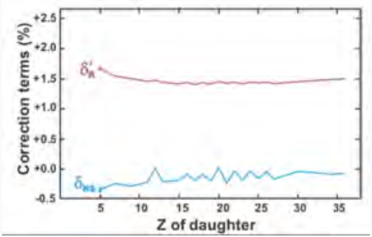
$$f_V t(1+\delta_R)(1-\delta_C+\delta_{NS}) = \frac{K}{2G_F^2 V_{ud}^2(1+\Delta_R^V)}$$

Few small $\mathcal{O}(0.1\% - 2\%)$ corrections

$\delta V_{ud}/V_{ud} \approx 0.04\%$







Nuclear effects in RC (2BC)

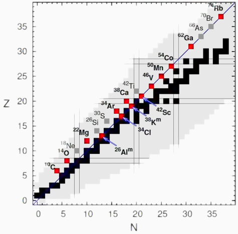
Nucleus: Superallowed $0^+ \to 0^+$

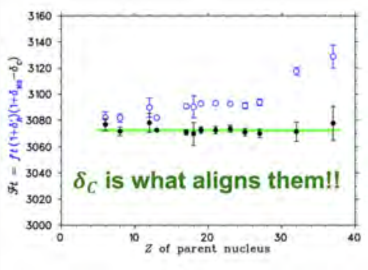
Pure Fermi transitions, $M_F = \sqrt{2}$

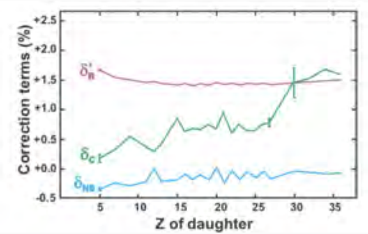
$$f_V t(1+\delta_R)(1-\delta_C+\delta_{NS}) = \frac{K}{2G_F^2 V_{ud}^2(1+\Delta_R^V)}$$

Few small $\mathcal{O}(0.1\% - 2\%)$ corrections

$\delta V_{ud}/V_{ud} \approx 0.04\%$







Isospin breaking. How sure are we of δ_C?