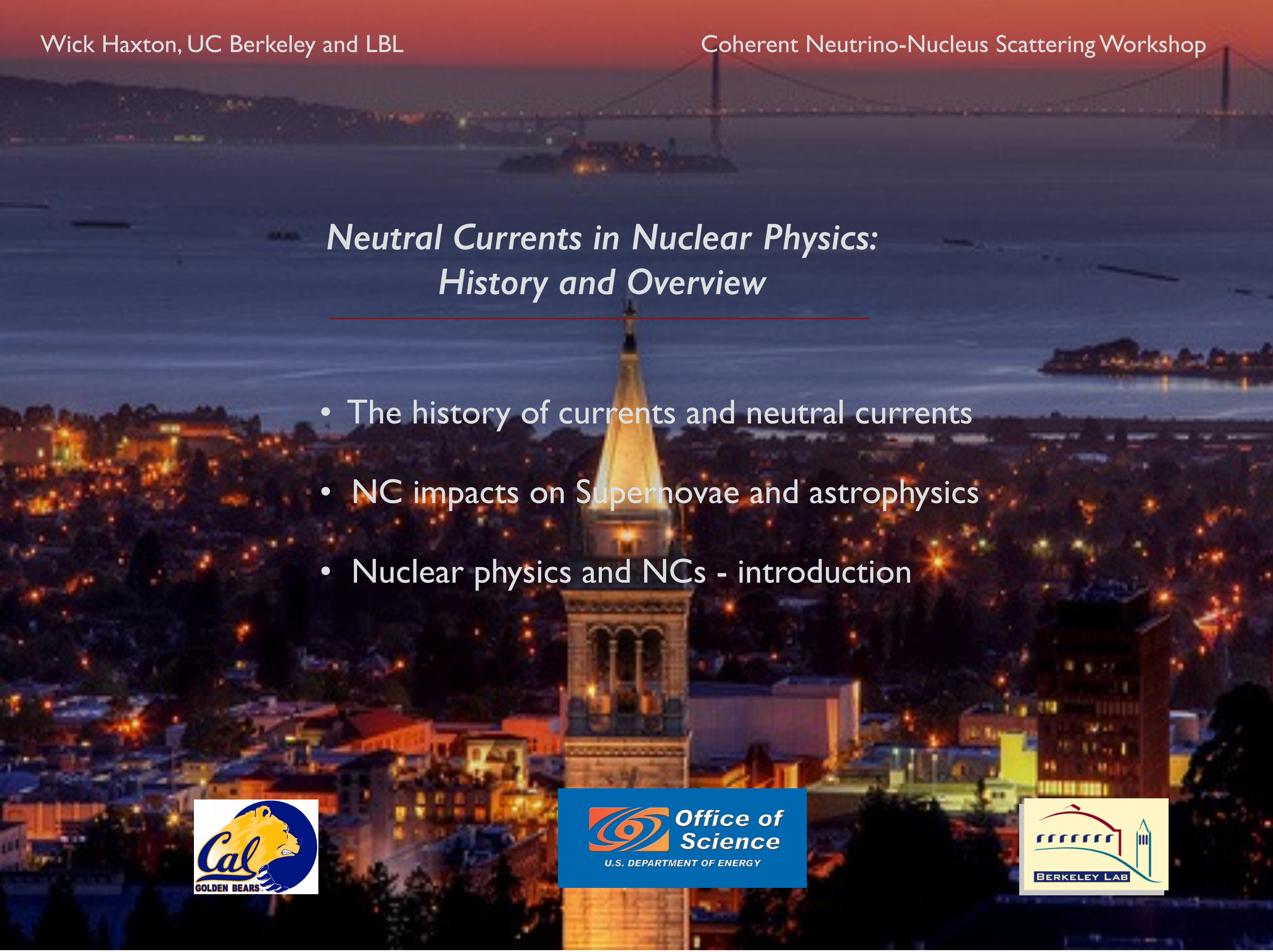


Neutral Currents in Nuclear Physics: History and Overview

- The history of currents and neutral currents
- NC impacts on Supernovae and astrophysics
- Nuclear physics and NCs - introduction

Introduction

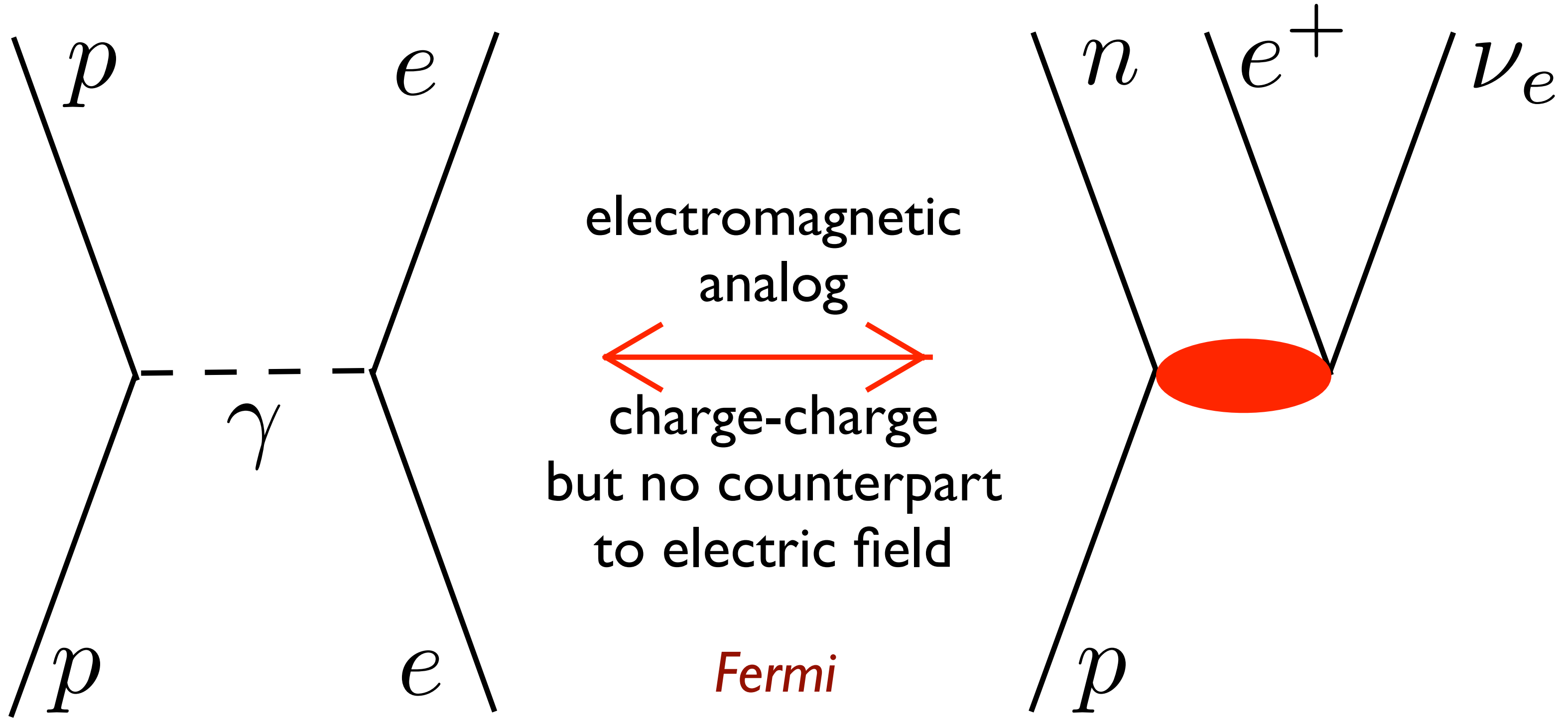
Rather remarkable that the neutral current of the standard model was not uncovered earlier than the 1970s

- 1930: Pauli's suggests a "neutrino" accompanies the electron in β decay
- 1932: Chadwick's discovery of the "neutron"
- 1934: Fermi's incorporation of both in his "effective theory" of β decay

$$n_{\text{bound}} \to p_{\text{bound}} + e^- + \bar{\nu}_e$$

- 1937: Majorana notes that the neutrino may or may not carry a additive charge $\nu_e \equiv \bar{\nu}_e$

Fermi’s treatment of beta decay was based on an analogy with the neutral electromagnetic interaction between static charges, modified to yield a point-like interaction



electromagnetic analog

charge-charge but no counterpart to electric field

Fermi


© Instituts Internationaux de Physique

1933 7th Solvay Conference: Pauli’s first public presentation of the neutrino

Russian authorities yielded to Gamow’s insistence that his physicist wife Lyubov Vokmintseva also be granted a visa for the meeting

Unknown to the authorities, the couple had twice previously tried to escape Russia (via kayak!)

Did not return: Curie Institute → Univ. London → Univ. Michigan → George Washington University to join Teller

We can look at this from a modern isospin context $p = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad n = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

so e-neutron or e-proton interaction vs. weak interaction

$$[e] \; \frac{1}{r} \; \left[e \frac{1+\tau_3}{2} \right] \qquad \Leftrightarrow \qquad [e] \; \frac{\delta(\vec{r})}{M^2} \; \left[\mp \frac{1}{\sqrt{2}} e \tau_\pm \right]$$

E&M: $\rho^{S} + \rho^{V(0)}$ weak $\rho^{V(\pm)}$

makes sense: Fermi used the “missing” components of isovector charge —

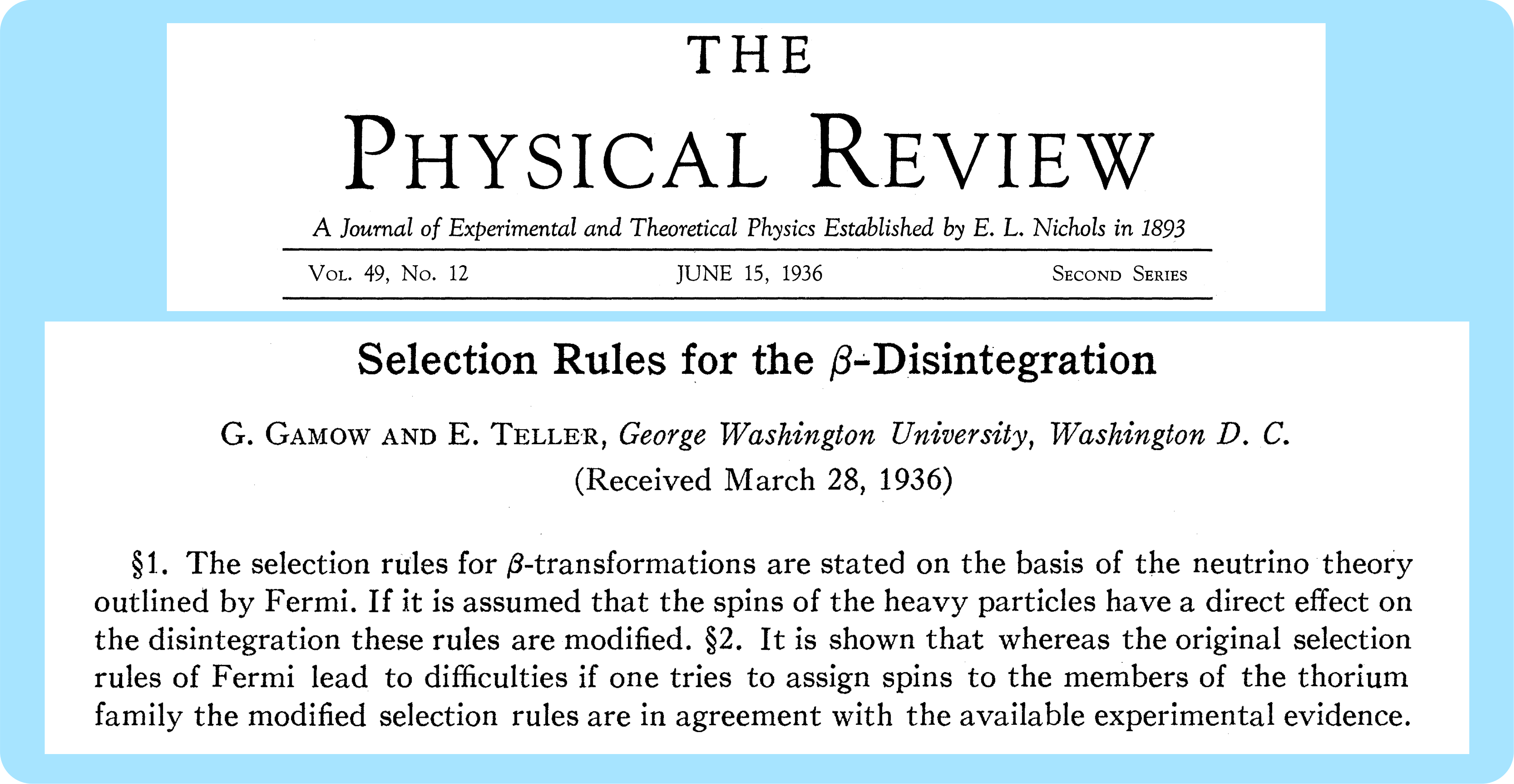
but did not consider using the electromagnetic
neutral current itself in the weak interaction

Fermi later recognized that Lorentz invariance meant that this relation must extend to currents (moving charges), $\rho \rightarrow j^{\mu} = (\rho, \vec{j}) = e(1, \vec{p}/M_N)$

$$j^{E\&M} = j_{\mu}^{V;S} + j_{\mu}^{V;V(0)} \qquad \Leftrightarrow \qquad j^{Weak} = j_{\mu}^{V;V(\pm)}$$

Weak current a space-spin vector and an isospin isovector:
E&M and the weak interaction made use of all three isospin components of the vector hadronic current: basic idea of CVC

Then:



THE
PHYSICAL REVIEW
A Journal of Experimental and Theoretical Physics Established by E. L. Nichols in 1893
VOL. 49, NO. 12 JUNE 15, 1936 SECOND SERIES

Selection Rules for the β-Disintegration

G. GAMOW AND E. TELLER, *George Washington University, Washington D. C.*
(Received March 28, 1936)

§1. The selection rules for β-transformations are stated on the basis of the neutrino theory outlined by Fermi. If it is assumed that the spins of the heavy particles have a direct effect on the disintegration these rules are modified. §2. It is shown that whereas the original selection rules of Fermi lead to difficulties if one tries to assign spins to the members of the thorium family the modified selection rules are in agreement with the available experimental evidence.

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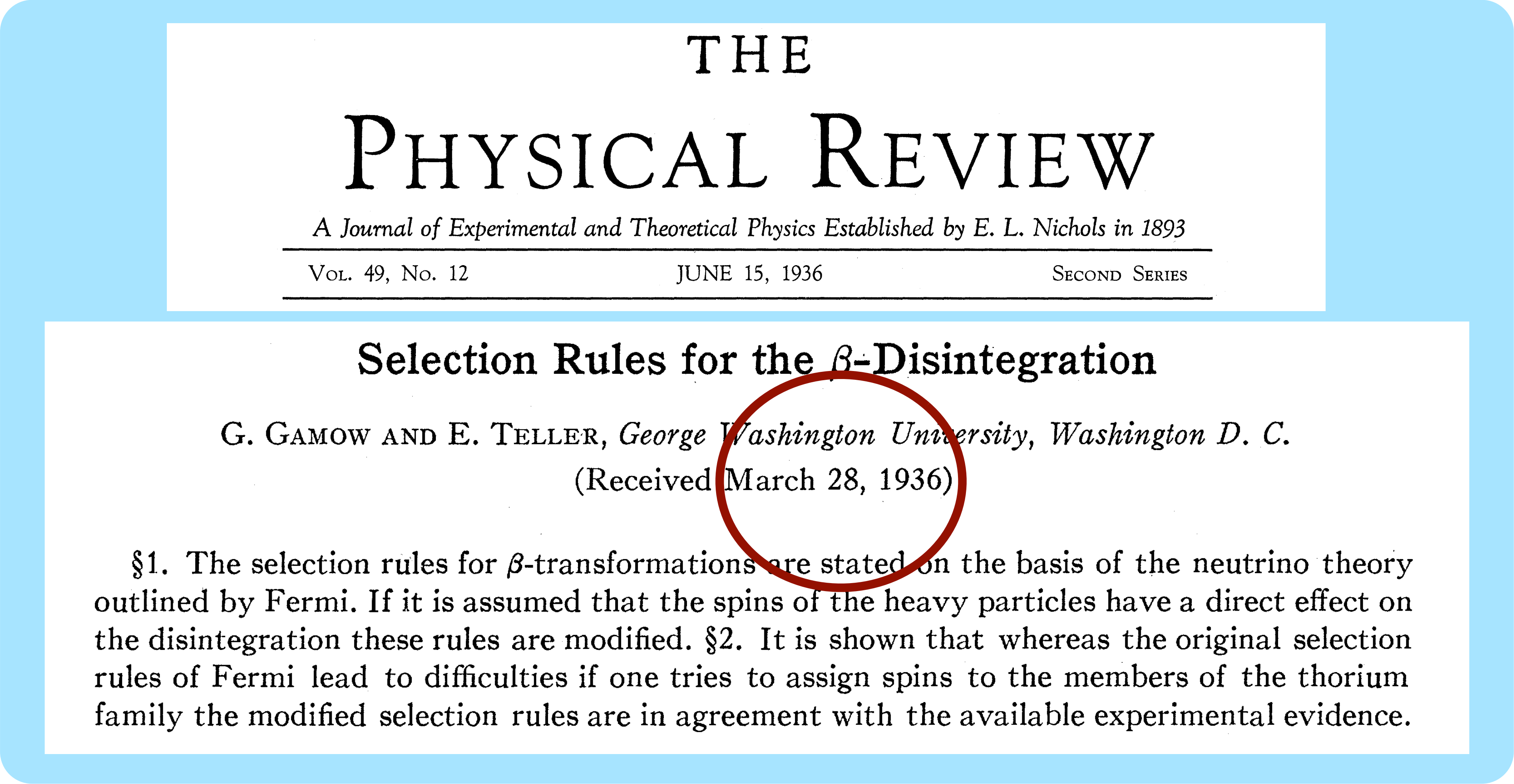
$$j^{E\&M} = j_{\mu}^{V;S} + j_{\mu}^{V;V(0)} \qquad \Leftrightarrow \qquad j^{Weak} = j_{\mu}^{V;V(\pm)}$$

Weak current a space-spin vector and an isospin isovector:
E&M and the weak interaction made use of all three isospin components of the vector hadronic current: a step toward unification!

Then:



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Fermi's β-decay ↔ electromagnetism analogy ↔ vector weak current ⇒

	$\mu = 0$	$\mu = 1, 2, 3$
$j_\mu^{weak} = j_\mu^{V;V\pm}$	$1\ \tau_\pm$	$\vec{p}/m_N\ \tau_\pm$

Fermi's relativistic correction, noted by G and T

⇒ selection rules for "allowed" decays of

$\Delta J = 0 \quad \Delta\pi = 0$, e.g., $0^+ \rightarrow 0^+$ decays

with relativistic corrections

$\Delta J = 0, \pm 1$ (but no $0 \rightarrow 0$) $\quad \Delta\pi = 1$, e.g., $1^- \rightarrow 0^+$ decays: suppressed by $(v/c)^2$ in transition probabilities

GT added an axial contribution to Fermi's interaction

	$\mu = 0$	$\mu = 1, 2, 3$
$j_\mu^{weak} = j_\mu^{V;V\pm}$	$1 \ \tau_\pm$	$\vec{p}/m_N \ \tau_\pm$
$+j_\mu^{A;V\pm}$	$\vec{\sigma} \cdot \vec{p}/m_N \ \tau_\pm$	$\vec{\sigma} \ \tau_\pm$

ordinary vector

$\sim \vec{r} \times \vec{p}$

carries opposite parity

pseudo- or axial-vector

So that one could obtain in lowest order (allowed)

Fermi: ΔJ = 0 Δπ = 0, e.g., $0^+ \rightarrow 0^+$ decays and

Gamow-Teller: ΔJ = 0, ±1 (but no 0→0) Δπ = 0, e.g., $1^+ \rightarrow 0^+$

"Either the matrix element M_1 or the matrix element M_2 or finally a linear combination of M_1 and M_2 will have to be used to calculate the probabilities of the β-disintegrations. If the third possibility is the correct one, and the two coefficients in the linear combination have the same order of magnitude, then all transitions [satisfying the selection rules] would now [be strong allowed ones]"

- They had deduced the correct rate for beta decay

$$\omega \sim |\langle 1\rangle|^2 + g_A^2 |\langle \vec{\sigma}\rangle|^2$$

- They obtained this result by generalizing Fermi's interaction into a sum of four-fermion interactions

$$j_\mu^{lep\ V;\mp} j_\mu^{nucl\ V;\pm} \Leftrightarrow j_\mu^{lep\ V;\mp} j_\mu^{nucl\ V;\pm} + j_\mu^{lep\ A;\mp} j_\mu^{nucl\ A;\pm}$$

- But failed to comment on a second possible generalization

$$H_{\rm weak} \sim \frac{G_F}{\sqrt{2}} \left(j_\mu^{lep\ V;\mp} - j_\mu^{lep\ A;\mp}\right) \left(j_\mu^{nucl\ V;\pm} - j_\mu^{nucl\ A;\pm}\right)$$

This alternative gives the same β-decay formula, but implies parity violation, which presumably was so outlandish to GT that it was not worth a comment

Fermi’s construction has already introduced the idea implicitly of using all components of an isovector

$$j^{E\&M} = j_\mu^{V;S} + j_\mu^{V;V(0)} \qquad \Leftrightarrow \qquad j^{Weak} = j_\mu^{V;V(\pm)}$$

Had GT considered their current from the same perspective of efficiency, they would have encountered a puzzle

$$j_\mu^{A;V(0)} \qquad \Leftrightarrow \qquad j^{Weak} = j_\mu^{A;V(\pm)}$$

Where is the neutral axial current - the third component of the isovector?

20 years before PNC, 35 years before the SM & neutral weak currents

Neutral Currents

1958 the V-A theory was formulated:

Feynman and Gell-Mann “Theory of the Fermi Interaction”
Sudarshan and Marshak “Chiral Noninvariance and the Universal Fermi Interaction”

in which only charged currents appeared

1967 Weinberg published his electroweak unification paper in which a neutral partner Z to the W was introduced, so that both charged and neutral currents appeared

Citation record: 0 (1967), 0 (1968), 0 (1969), 1 (1970), 4 (1971), 64 (1972), 162 (1973), …

By the end of 1971 both the Higgs mechanism, to generate massive intermediate bosons, and the theory’s renormalizability (Veltman and ’t Hooft) had been established

In 1960s neutrino experiments — to isolate the weak interaction from others — were begun at both BNL and CERN

Included the construction of a large bubble chamber at CERN, by a French collaboration led by Andre Lagarrigue: Gargamelle

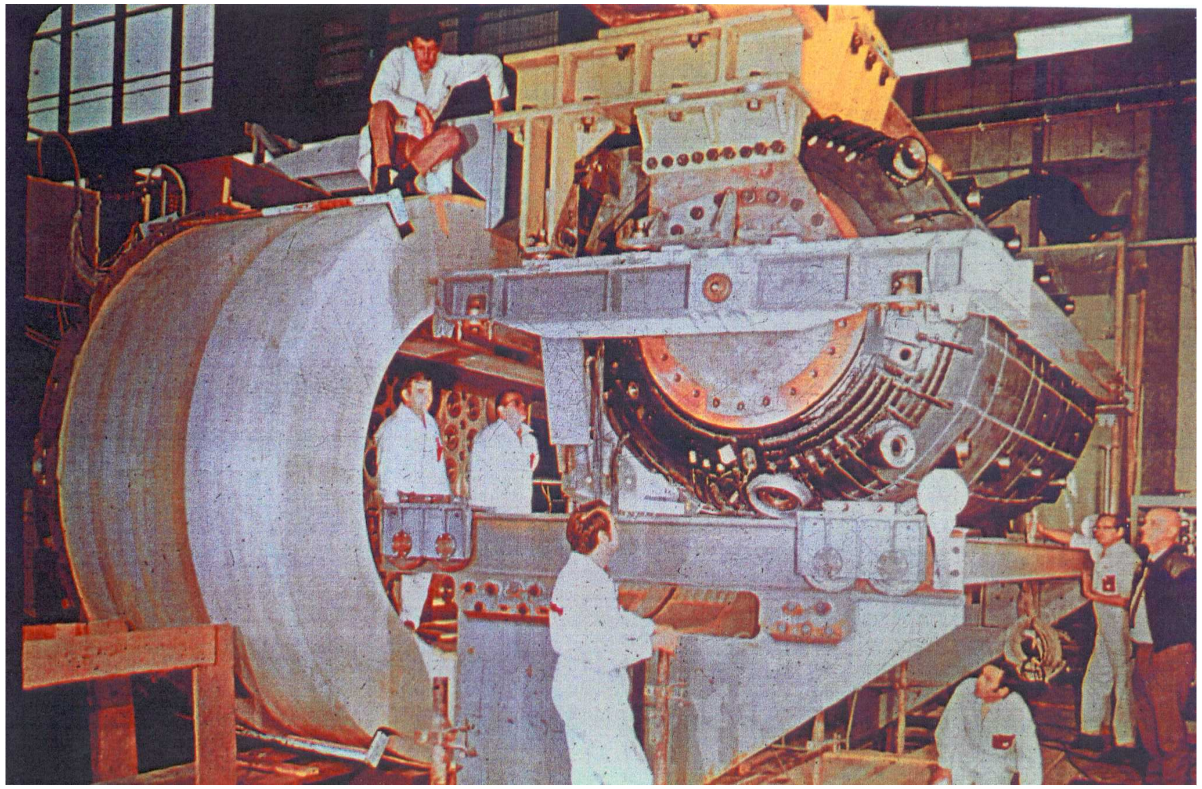
Gargamelle’s target region consisted of 18 tons of freon

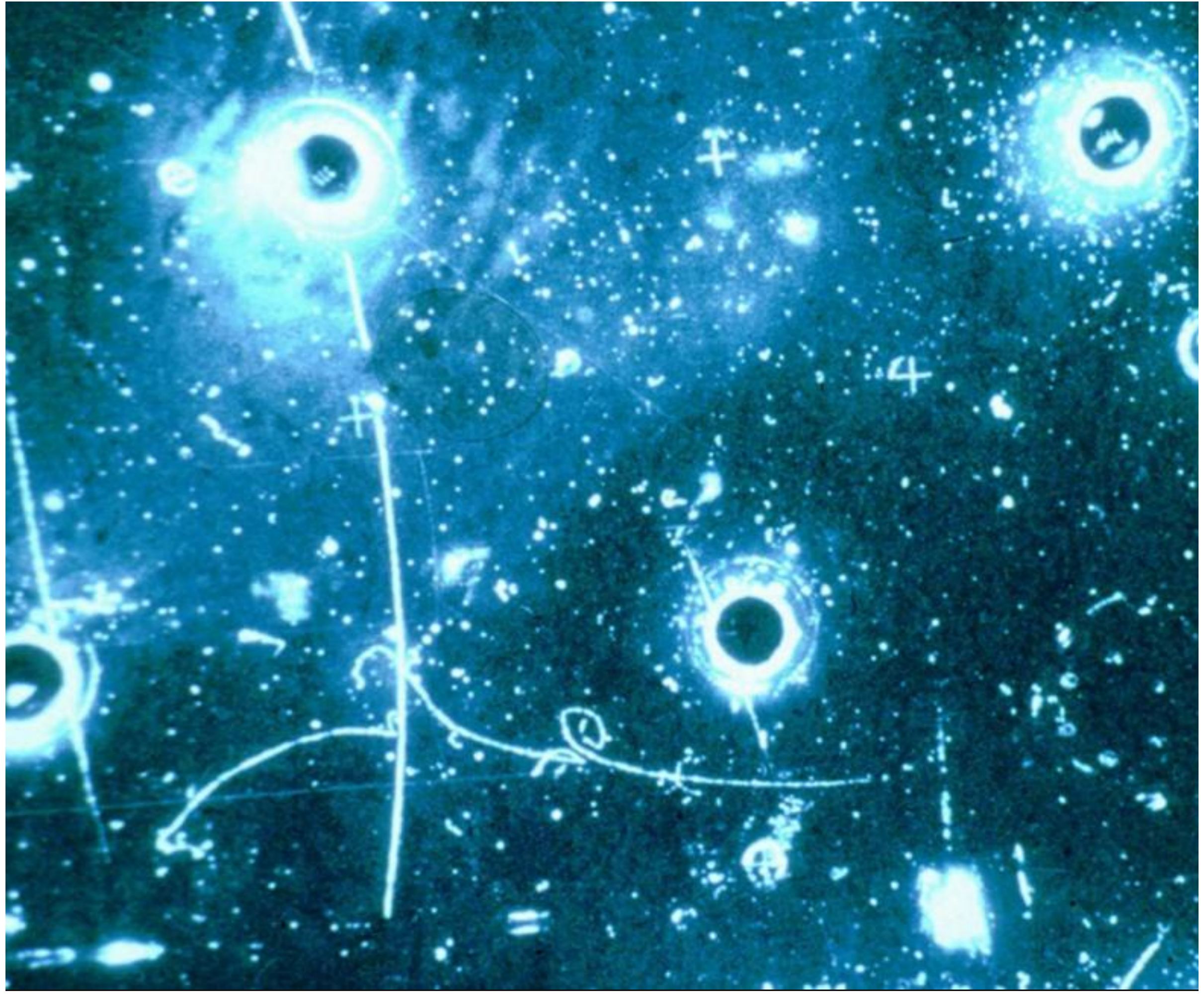
Construction was completed in 1971 and the first neutrino exposures in the CERN PS neutrino beam line were carried out in 1972

The experimentalist expected charged current events producing a muon: Gargamelle’s class A events

Background events consisting of a charged hadron were class B events — arising from interactions in the target of neutrons produced upstream

In December 1972 an isolated electron track was found in the antineutrino class B data





Gargamelle’s first neutral current event

	ν-exposure	$\overline{\nu}$-exposure
# NC	102	64
# CC	428	148

The flat distribution of the NC events followed that of the CC events, and thus was “neutrino-like” The spatial distribution of the NC/CC event ratios showed no anomalies

Yet there was concern that neutrons might be mimicking an NC signal

- neutrino flux radial distribution extended well beyond the fiducial volume, so associated neutrons could enter from the sides
- the neutrons could cascade: number of background neutrons were not governed by an interaction length, but by a longer, energy-dependent cascade length

A neutron background characterization was carried out, ending in mid 1973.
The conclusion: few background events contaminated the NC signal.
The claim for NC discovery was published in Phys Lett in July

Alternating NCs: In 1972 the NAL (FermiLab) started operation, at 10 times CERN's energy. The Harvard/Penn/Wisconsin neutrino experiment was mounted, using relatively coarse-grained tracking. Initially the detector made hardware and electronic cuts to record only muon events

Revised to trigger on hadrons: allowed detection of muons with charged hadrons, in sum constituting a NC event: "escaping muons" a concern.

Monte Carlos suggested such events were not able to account for the HPW NC signal: news communicated to CERN, reinforced Gargamelle decision to publish. HPW also submitted a NC-discovery paper.

HPW mid-1973 data set showed a smaller NC signal; froze their paper in refereeing stage, re-configured their detector to record a large fraction of the muons, and found a very much smaller signal than Gargamelle, consistent with zero. A new, no-NC paper was drafted.

But the detector modifications reduced the shielding, potential increasing the possibility that neutrons could punch through, mimicking muons, and thus driving the NC/CC ratio to zero by enhancing the CC rate

By mid-1974 estimates of the punch-through neutron flux had doubled, yielding a NC/CC ratio that agreed with Gargamelle

Initial paper and two others published

In fact it was subsequently recognized that NC events were apparent in CERN bubble chamber experiments as early as 1967: a anomalous number of muon-less hadron events had been recorded

Musset and Vialle, “Neutrino Physics with Gargamelle”
Barish, “Experimental Aspects of High Energy Astrophysics"

The trigger for the searches at CERN and NAL/FermiLab came from the theory community in 1971, with the Veltman/’t Hooft completion of the SM

CERN theorists lobbied Gargamelle to look for NC then
Weinberg helped convince HPW of the need to trigger on hadrons, too

Nuclear weak current: This and subsequent work tested and verified the first-generation currents governing low-energy nuclear weak interactions. In addition to the charged hadronic current

$$J_\mu^+ = \cos\theta_C\ \bar{u}\gamma_\mu(1-\gamma_5)d + \sin\theta_C\ \bar{u}\gamma_\mu(1-\gamma_5)s$$

we have the neutral contribution

$$J_\mu^0 = \bar{u}\gamma_\mu(1-\gamma_5)u - \ \bar{d}\gamma_\mu(1-\gamma_5)d - 4\sin^2\theta_W J_\mu^{em}$$

which includes contributions

isoscalar vector $\sim -4\sin^2\theta_W\ \frac{1}{2}$

isovector vector $\sim \left(2-4\sin^2\theta_W\right)\ \frac{\tau_3}{2}$

isovector axial-vector $\sim -2\ \frac{\tau_3}{2}$

Consequently there is a low-energy coherent vector charge contribution proportional to

$$\sim -4\sin^2\theta_W \frac{Z+N}{2} + \left(2-4\sin^2\theta_W\right)\frac{Z-N}{2}$$

$$\sim -N + (1-4\sin^2\theta_W)Z \sim -N$$

Astrophysics

In the 1960s (as today!) the mechanism responsible for core-collapse supernovae was under debate

A star proceeds through its burning stages, forming an onion-like shell structure, with the last stage of explosive Si burning rapidly forming an iron core, supported by electron degeneracy pressure

As the core reaches the Chandrasekhar mass of about 1.4, the electron gas EoS can no longer support the core, leading to rapid collapse and compression and heating of the core by the gravitational work

Every volume element of the star is initially bound, so the fundamental issue is that mechanism by which energy is preferentially transported from the core to the mantle, allowing ejection of the latter

In 1966 Colgate and White proposed that the thermonuclear SNII mechanism proposed by BBFH was much too weak to power an explosion

Instead proposed a hydrodynamic explosion: core bounce and a shock wave that is driven by neutrino diffusion and neutrino energy deposition

This deposition occurred through inverse beta decay on free neutrons, governed by a luminosity connected with the diffusion rate

The discovery of coherent neutrino scattering had a significant effect on this prompt neutrino-driven mechanism

J. R. Wilson, 1976
Freedman, Schramm, and Tubbs, "The Weak NC and its Effects in Stellar Collapse" (1977)

The coherent scattering off nuclei and off density fluctuations lengthens the diffusion time

As the energy in neutrinos is fixed (3 10^{53} ergs) and the Eddington luminosity for neutrinos to mechanically drive material off the star is 10^{54} ergs/s, the necessary diffusion time require for the Colgate and White prompt neutrino mechanism is known

Concluded that with NCs, missed by a factor of 3 the needed luminosity

A large number of other stellar observables were shown altered by the discovery of neutral currents

— pair processes that control stellar cooling:
one celebrated case is the plasmon → $\nu\bar{\nu}$ rate that controls the core temperature and thus the time of He ignition in a red giant

— NCs contribute to many of the neutrino scattering processes that control the temperature hierarchy of the supernova flavors (which we hope to exploit in the next galactic supernova)

— NCs dominate most of the important neutrino process channels in SN, such as the production of F from Ne or or ^{11}B from C

Nuclear physics: where we stand today

Hadronic and semileptonic NC weak interactions:

Hadronic weak interaction: $L = \frac{G_F}{\sqrt{2}} \left(J_W^\dagger J_W + J_Z^\dagger J_Z \right) + \text{h.c.}$

$$J_W = \cos\theta_C J_W^{\Delta I=1, \Delta S=0; u \to d} + \sin\theta_C J_W^{\Delta I=1/2, \Delta S=1; u \to s}$$

The neutral current is diagonal in strangeness — indeed the c quark was introduced to avoid a current construction in which $\Delta S \neq 0$ currents arose — and as noted contains $\Delta I = 0$ and $\Delta I = 1$ components

$$J_Z = J_Z^{\Delta I=0, \Delta S=0} + J_Z^{\Delta I=1, \Delta S=0}$$

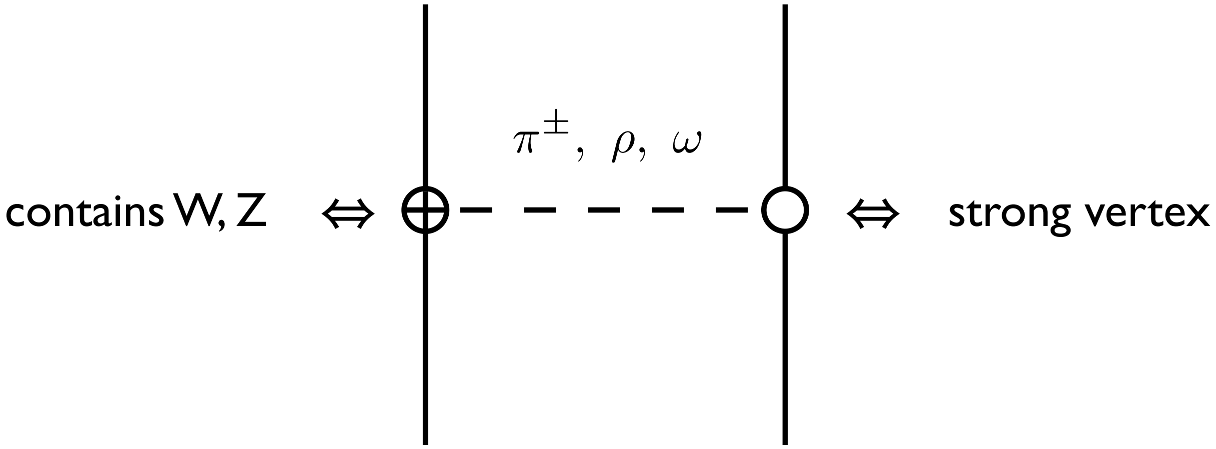
Symmetric products of $\Delta I = 1$ currents carry $\Delta I = 0, 2$ while symmetric products of $\Delta I = 1/2$ carry $\Delta I = 1$. Consequently

$$L^{\Delta S=0} = \frac{G_F}{\sqrt{2}} \left(\cos^2\theta_C J_W^{\dagger\, 1,0} J_W^{1,0} + \sin^2\theta_C J_W^{\dagger\, 1/2,-1} J_W^{1/2,1} + J_Z^{\dagger\; 0,0} J_Z^{0,0} + J_Z^{\dagger\, 1,0} J_Z^{1,0} + J_Z^{\dagger\, 1,0} J_Z^{0,0} + J_Z^{\dagger\, 0,0} J_Z^{1,0} \right)$$

$\Delta I = 0, 2$ $\Delta I = 1$ $\Delta I = 0$ $\Delta I = 0, 2$ $\Delta I = 1$

Cabibbo suppressed

We can measure the NC in hadronic interactions by exploiting parity violation and by isolating the $\Delta I = 1$ interaction



The $\Delta I = 1$ corresponds to long-range pion exchange

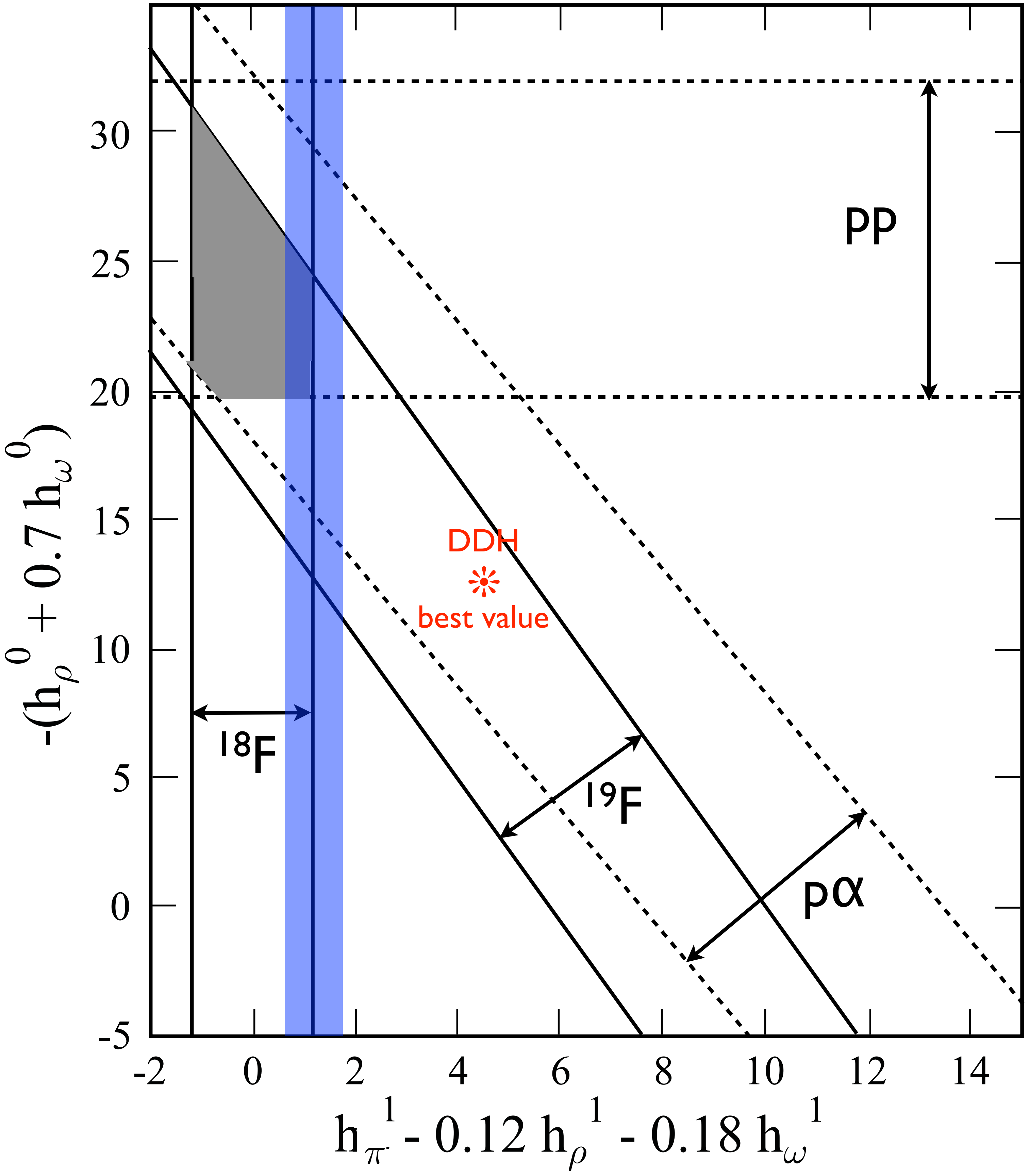
It has been known since the early 1980s that this interaction is weaker than one would expect based on the underlying quark-level currents: upper bound established in ^{18}F

Major effort underway at SNS to measure $h_\pi^1 : \ \vec{n} + p \rightarrow d + \gamma$

Lattice QCD estimate has been made

But we have yet to isolate this current

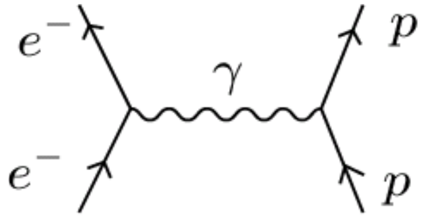
This is the long-range $\pi^{\pm}$ exchange

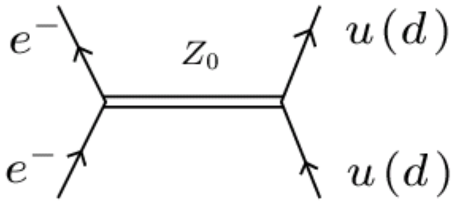


Semi-leptonic: electron-nucleus electroweak interference

Bill Donnelly will address electron scattering PNC in the next talk
Atomic PNC complements these measurements with ones at very low q

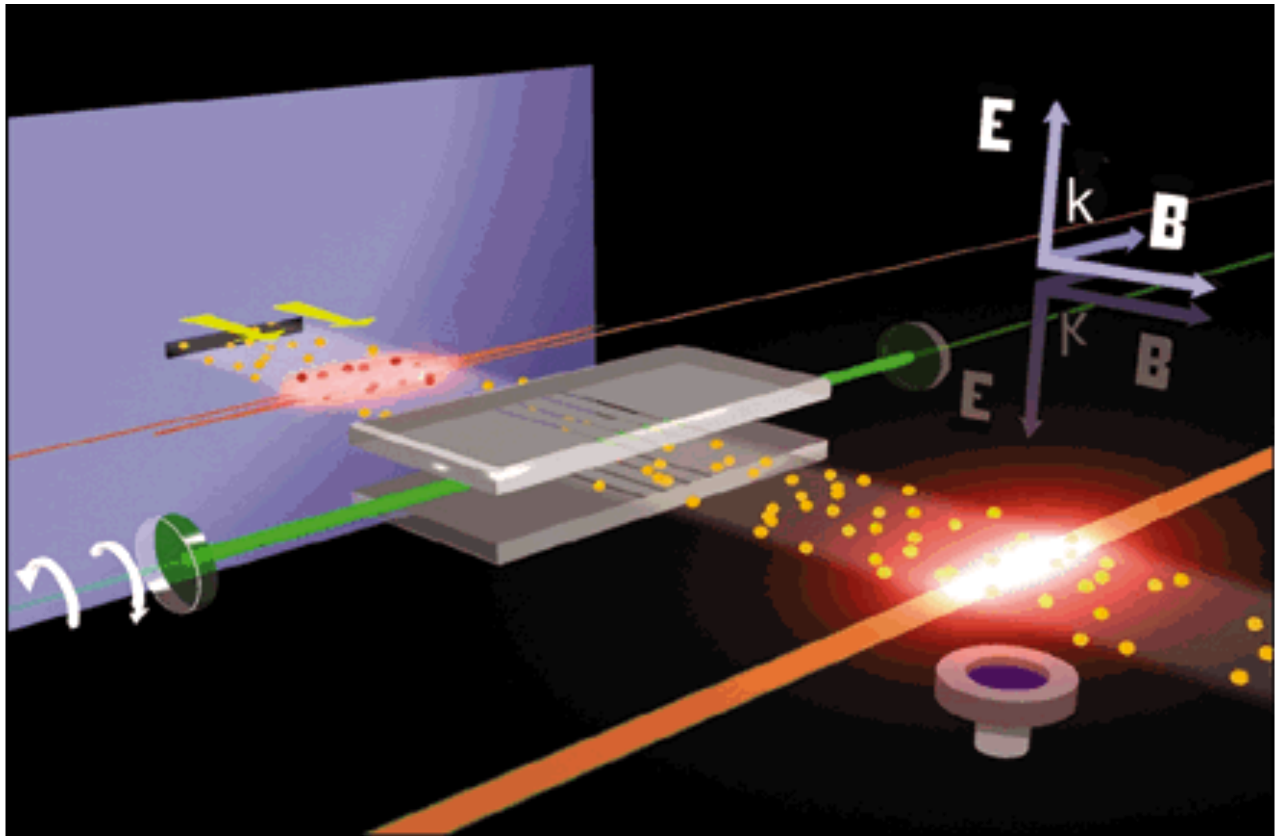
State-of-the-art measurement remains the JILA 1999 measurement of Woods, Weiman, et al.





Dominant interaction is
A(e) - V(N)

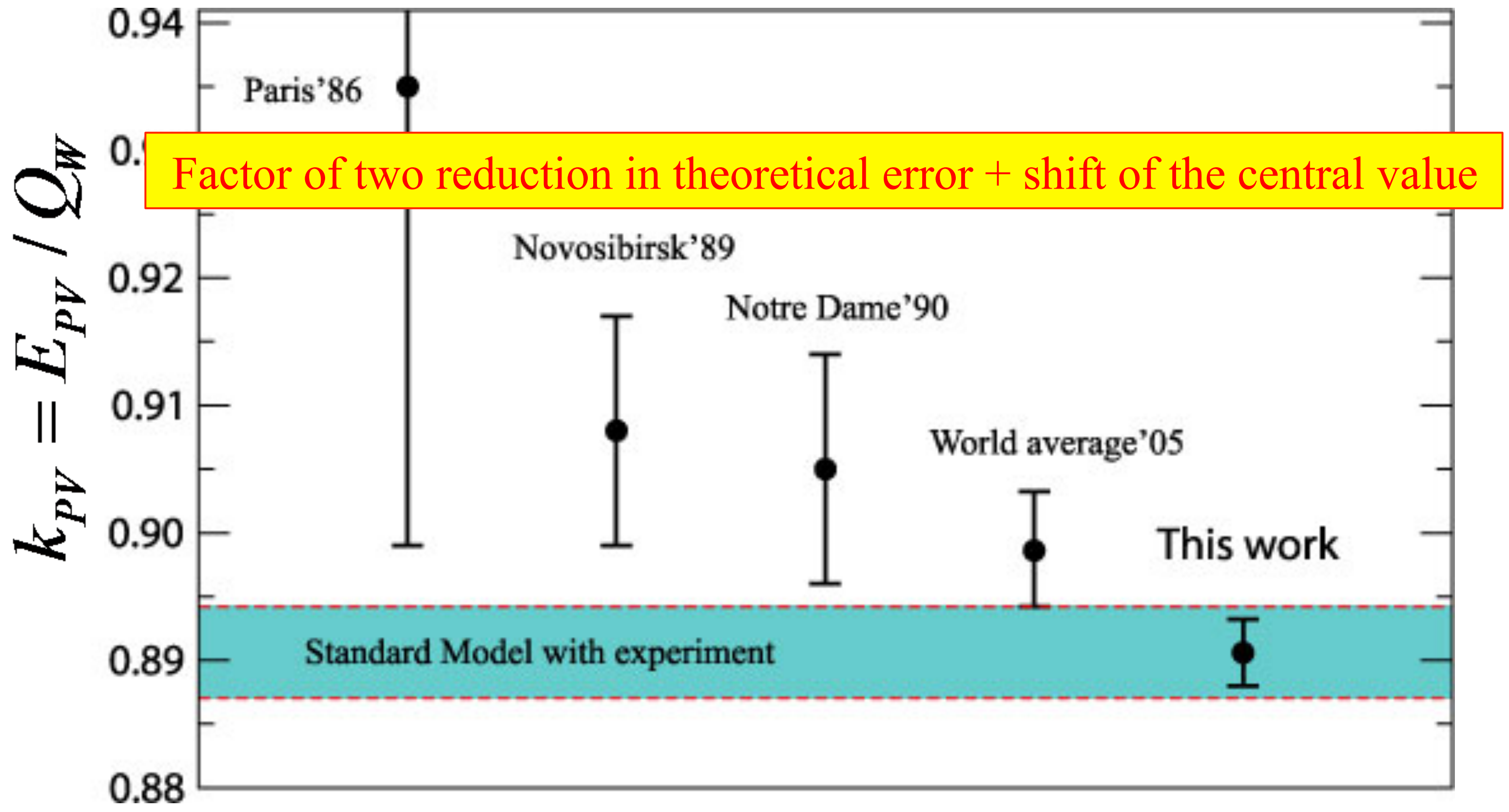
$$|6S_{1/2}\rangle_{NC} = |6S_{1/2}\rangle + \sum_m |mP_{1/2}\rangle \frac{\langle mP_{1/2}|H_W|6S_{1/2}\rangle}{E_{6S} - E_{mP_{1/2}}}$$



$$H_W = Q_W \frac{G_F}{\sqrt{8}} \gamma_5 \rho_n(r)$$

PNC w.f. admixtures are ~ 10^{-11}

resulting energy shift measured to 0.3%



Factor of two reduction in theoretical error + shift of the central value

S. G. Porsev, K. Beloy and A. Derevianko, *Phys. Rev. Lett. 102, 181601 (2009)*
S. G. Porsev, K. Beloy and A. Derevianko, *Phys. Rev. D 82, 036008 (2010)*

But polarizability "tail" contributions evaluated by Dzuba et al in 2012 have moved the latest number back to the 05 average

Now 15+ years since this measurement was reported. Successors?

- Purdue effort on Cs
- Berkeley effort on Dy
- TRIUMF efforts on Fr
- KVI on Ra^+

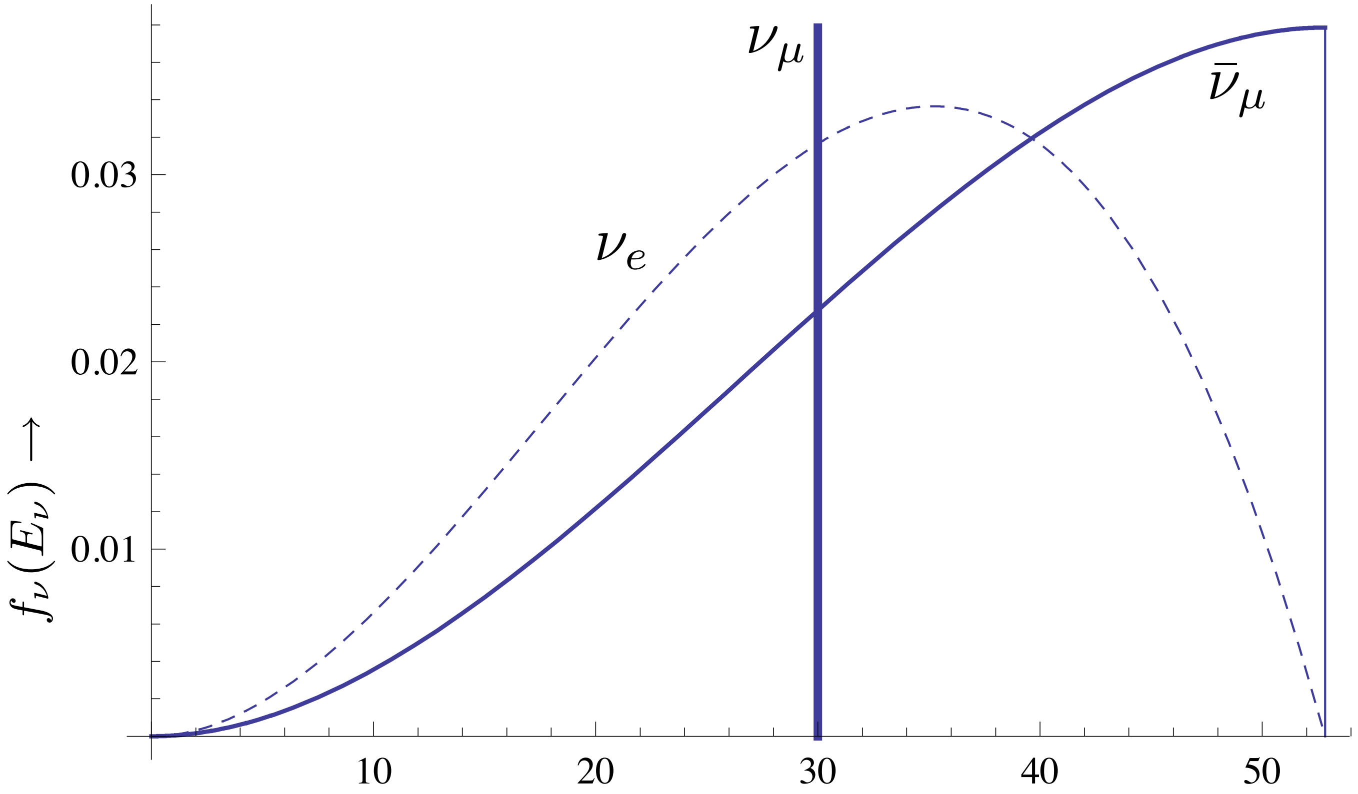
Semi-leptonic: neutrino-nucleus scattering - our main workshop topic

Interest has been driven in part by stopped pion neutrino sources like that of the SNS, which operates at 1.4 MW and could be upgraded to 3.0

Pulses delivered at 60 Hz, with a width of 695 ns: decays are prompt

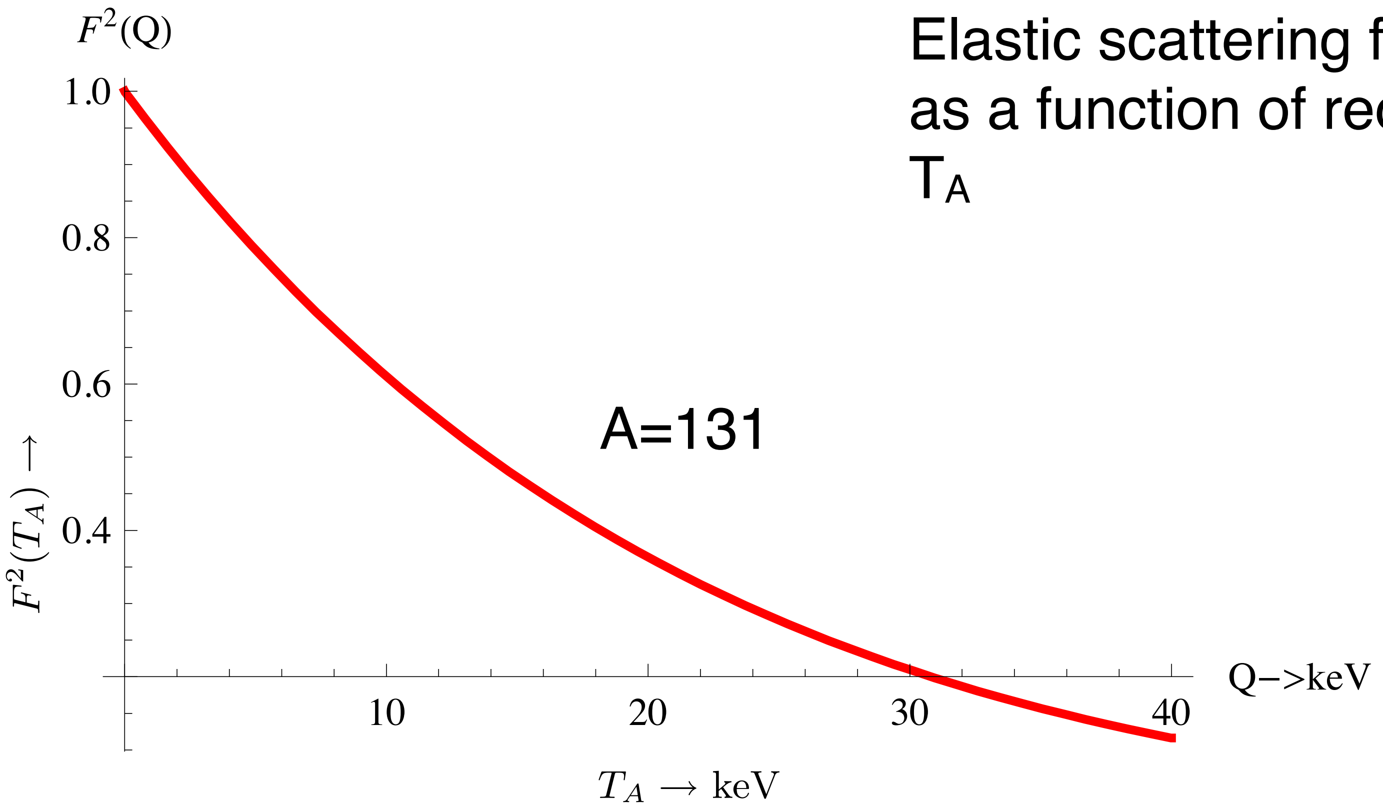
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad \tau = 26 \text{ ns} \qquad \text{followed by}$$
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \quad \tau = 2.2\ \mu\text{s}$$

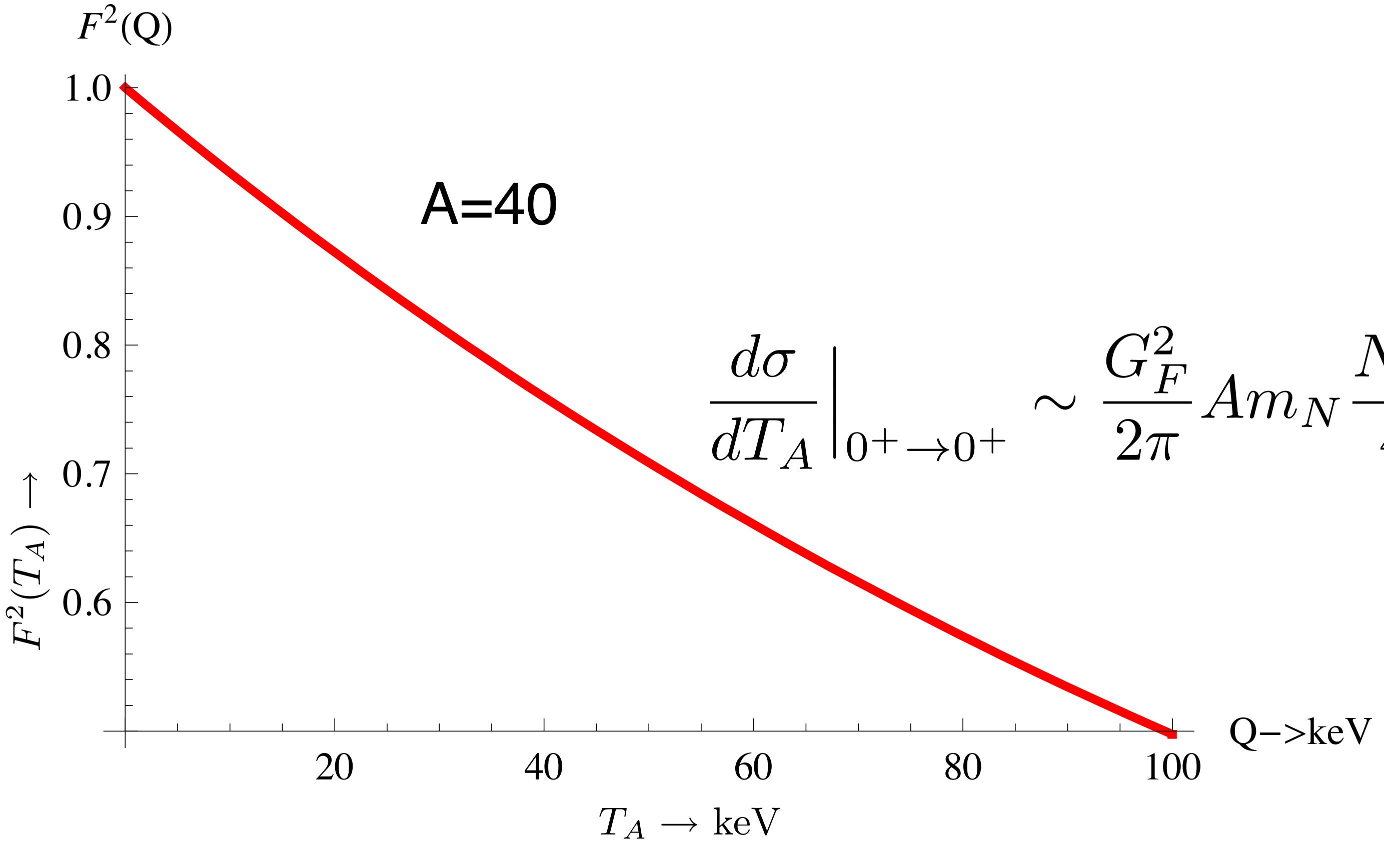
With these parameters, a detector buried under 25m of standard rock would have background rates comparable to a “continuous beam” detector that has an overburden of 2.0 ($\nu_\mu s$) to 2.8 ($\bar{\nu}_\mu s$) km w.e.



Vergados et al. 2013

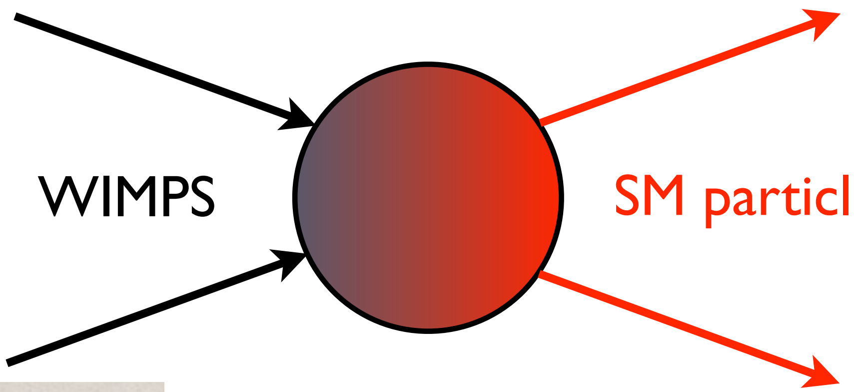
Elastic scattering form factor as a function of recoil energy T_A



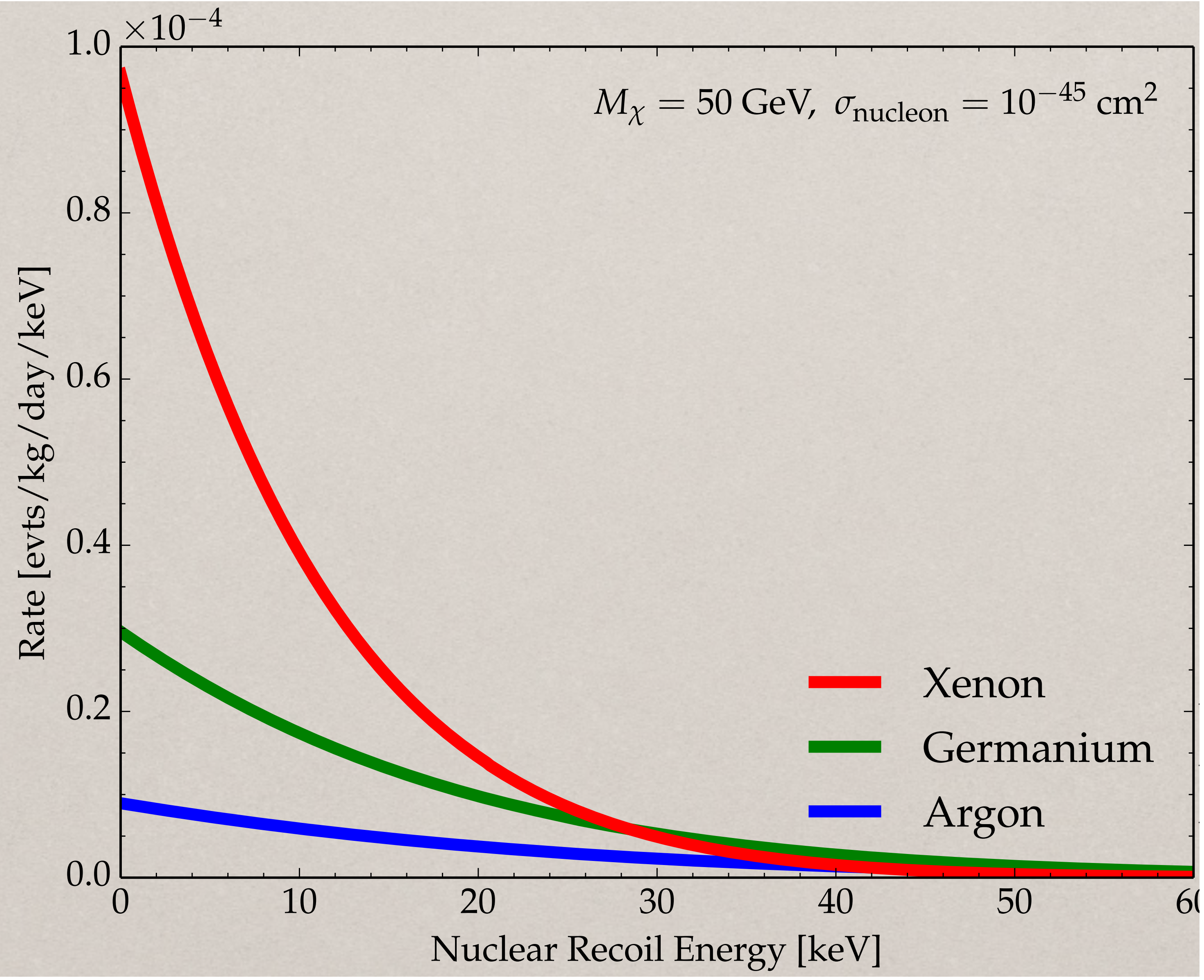


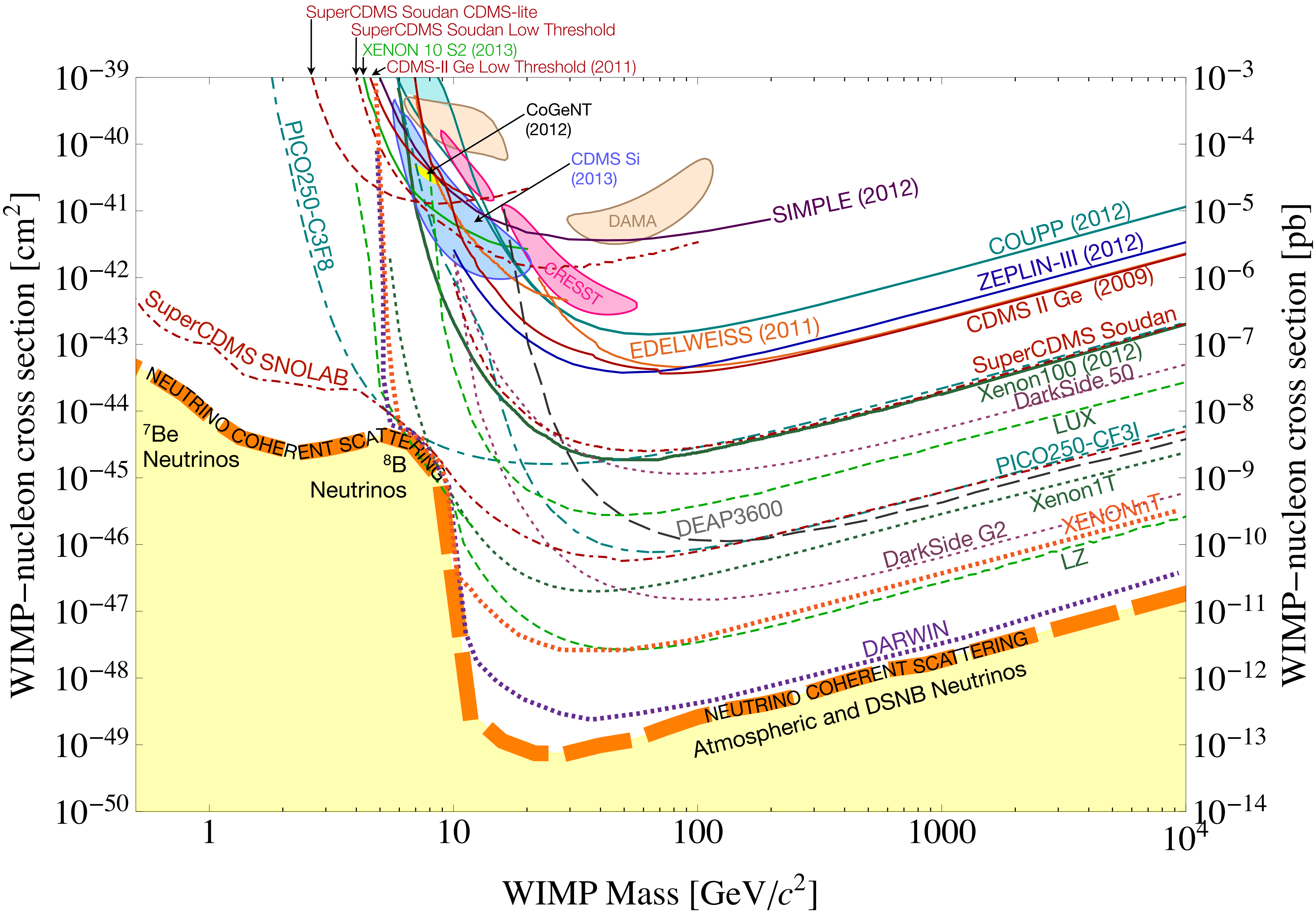
$$\frac{d\sigma}{dT_A}\bigg|_{0^+\rightarrow 0^+} \sim \frac{G_F^2}{2\pi} A m_N \frac{N^4}{4} F^2(T_A, E_\nu)$$

Large investments being made in DM detectors capable of measuring nuclear recoils in this range


WIMPS

SM particles




SuperCDMS Soudan CDMS-lite
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
CRESST
EDELWEISS (2011)
SuperCDMS Soudan
Xenon100 (2012)
DarkSide 50
LUX
PICO250-CF3I
PICO250-C3F8
DEAP3600
Xenon1T
XENONnT
DarkSide G2
LZ
DARWIN
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos
WIMP–nucleon cross section [cm^2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c^2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
1
10
100
1000
10^4

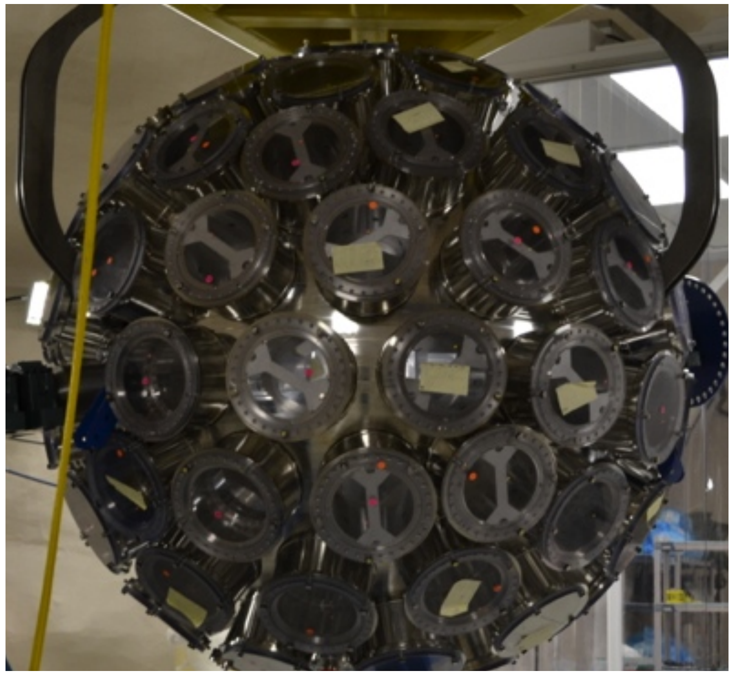
NOBLE GASSES

Single-phase detectors (SCINTILLATION LIGHT)

- Challenge: ultra-low absolute backgrounds
- LAr: pulse shape discrimination, factor 10^9-10^{10} for gammas/betas

XMASS-RFB at Kamioka:

835 kg LXe (100 kg fiducial),
single-phase, 642 PMTs
unexpected background found
detector refurbished (RFB)
new run this fall -> 2013



CLEAN at SNOLab:

500 kg LAr (150 kg fiducial)
single-phase open volume
under construction
to run in 2014

DEAP at SNOLab:

3600 kg LAr (1t fiducial)
single-phase detector
under construction
to run in 2014

Time projection chambers (SCINTILLATION & IONIZATION)

XENON100 at LNGS:

161 kg LXe
(~50 kg fiducial)

242 1-inch PMTs
taking new science data

LUX at SURF:

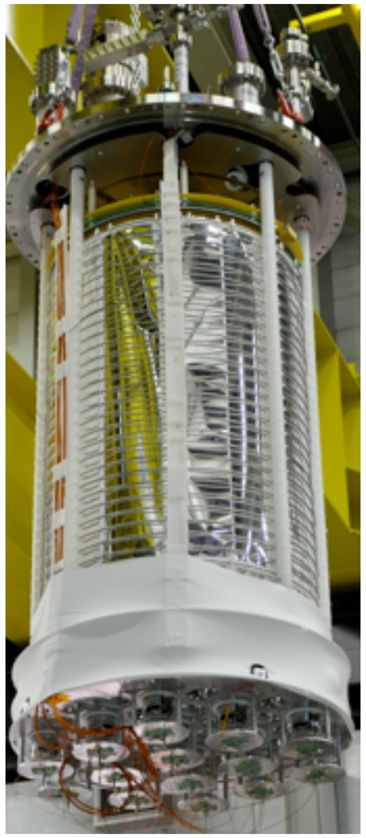
350 kg LXe
(100 kg fiducial)

122 2-inch PMTs
physics run since spring 2013

PandaX at CJPL:

125 kg LXe
(25 kg fiducial)

143 1-inch PMTs
37 3-inch PMTs
started in 2013



ArDM at Canfranc:

850 kg LAr
(100 kg fiducial)

28 3-inch PMTs
in commissioning
to run 2014

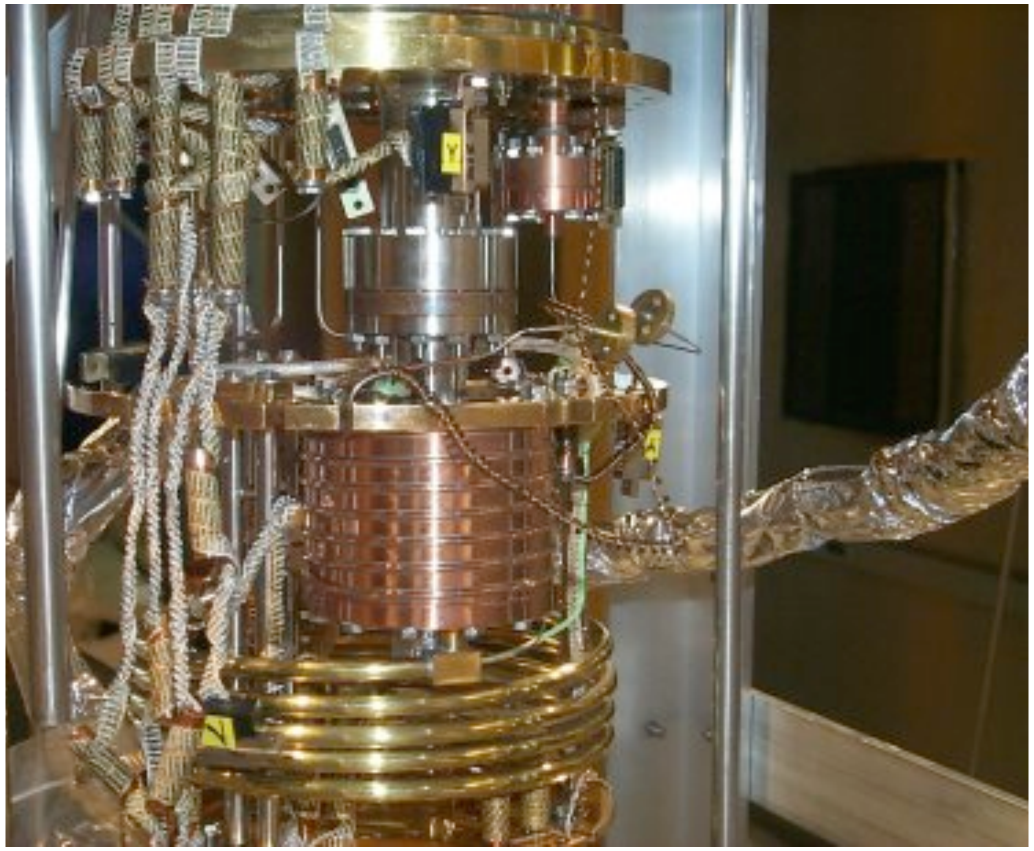
DarkSide at LNGS

50 kg LAr (dep in ^{39}Ar)
(33 kg fiducial)

38 3-inch PMTs
in commissioning
since May 2013
to run in fall 2013

CRYSTALS, BUBBLE CHAMBERS, ...

DAMA/LIBRA NaI



CDMS Si, Ge
CoGENT Ge

COUP CF_3I

So perhaps there is a v opportunity, too

Interest in hearing, over the next two days, what ideas the participants have for moving forward