Fundamental Interactions

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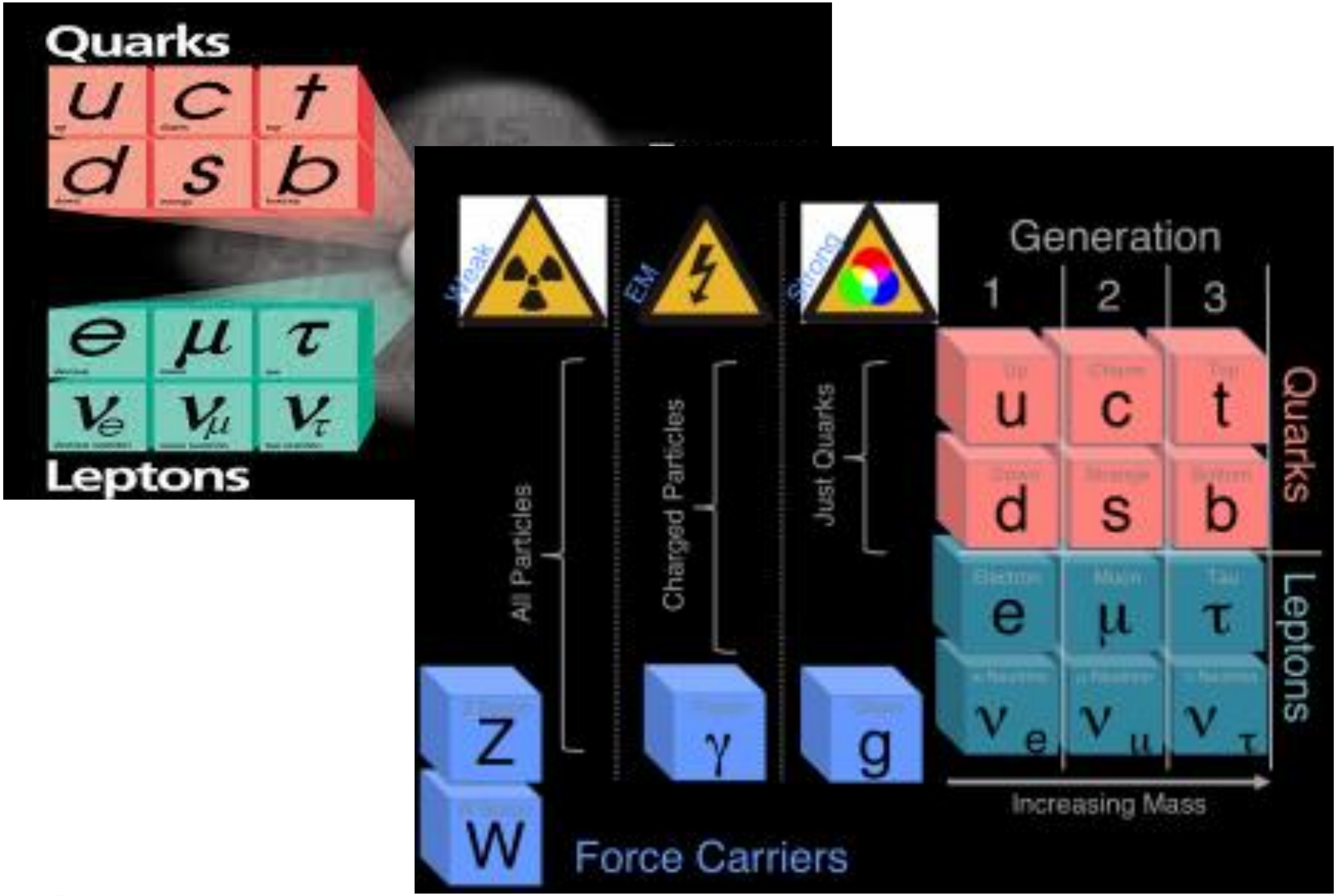
Outline of 2 lectures

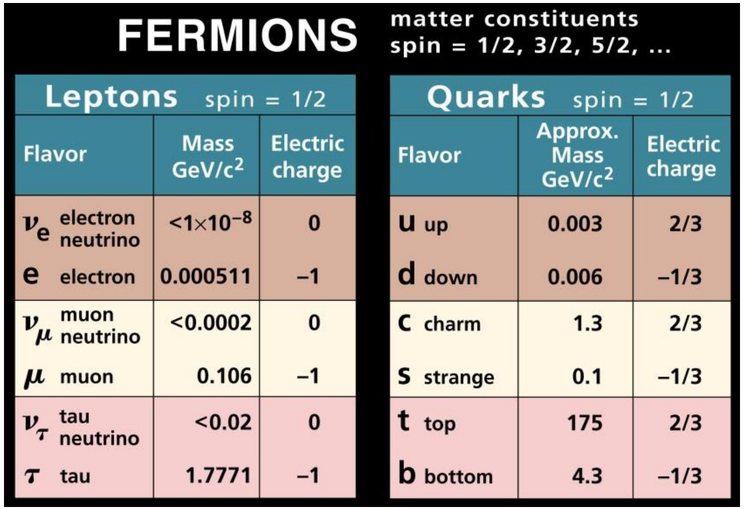
- **Standard Model**
  - Very basic introduction
  - Recent changes
- **Fundamental interactions at low energy**
  - General approach
    - Symmetries, conservation laws
    - Nuclei as laboratory
    - Tools → traps
  - Detailed look at present and planned work
    - Superallowed Fermi decay
    - Angular correlations in β-decay
    - PNC in atoms
    - EDM
    - Others …
- **FRIB and fundamental interactions**

2nd lecture

Standard Model constituents



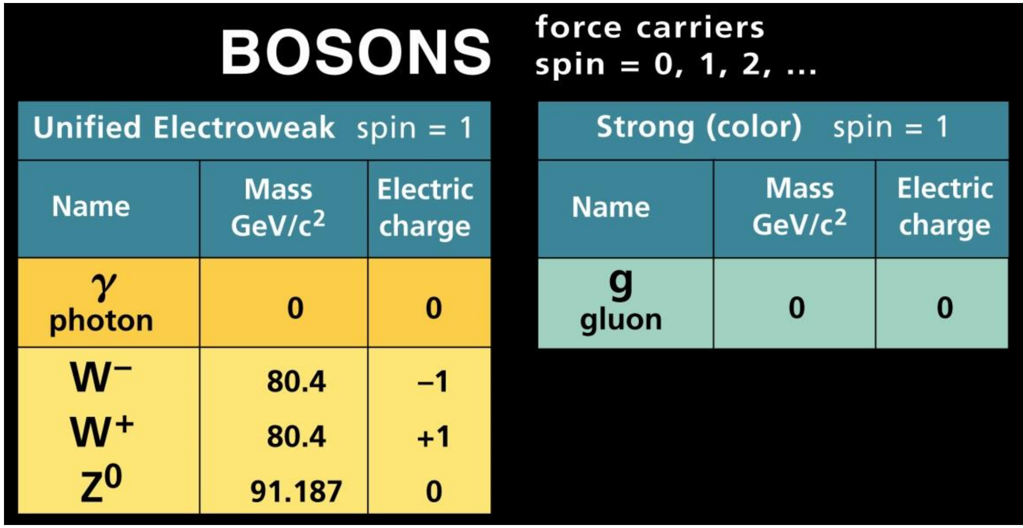
Fundamental particles and interactions



FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3



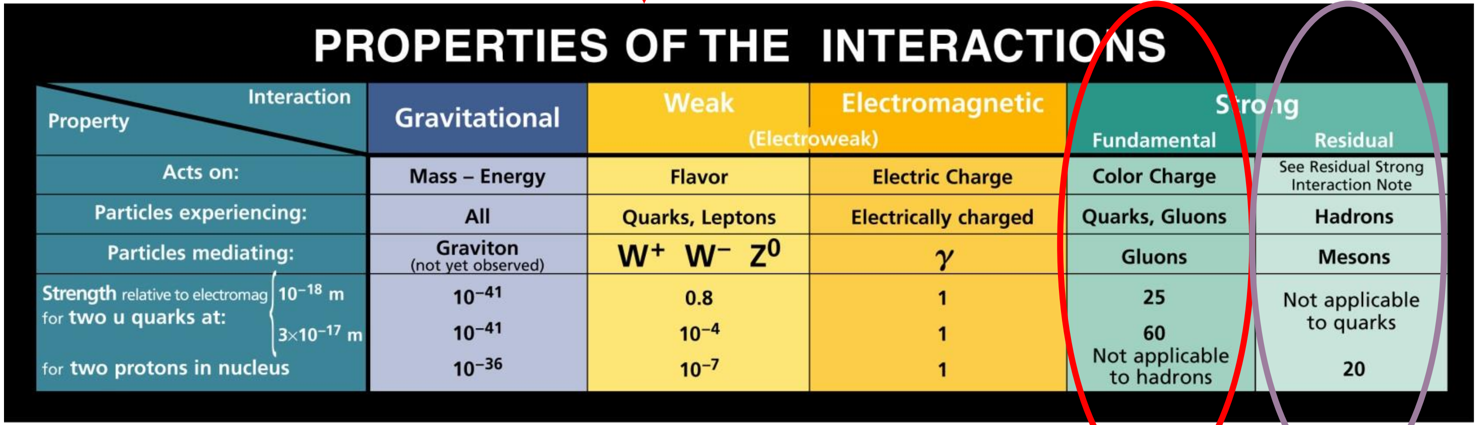
BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

High energy

Low energy



PROPERTIES OF THE INTERACTIONS

Interaction / Property		Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong Fundamental	Strong Residual
Acts on:		Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:		All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:		Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at:	10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
	3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus		10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Resulting composite particles

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

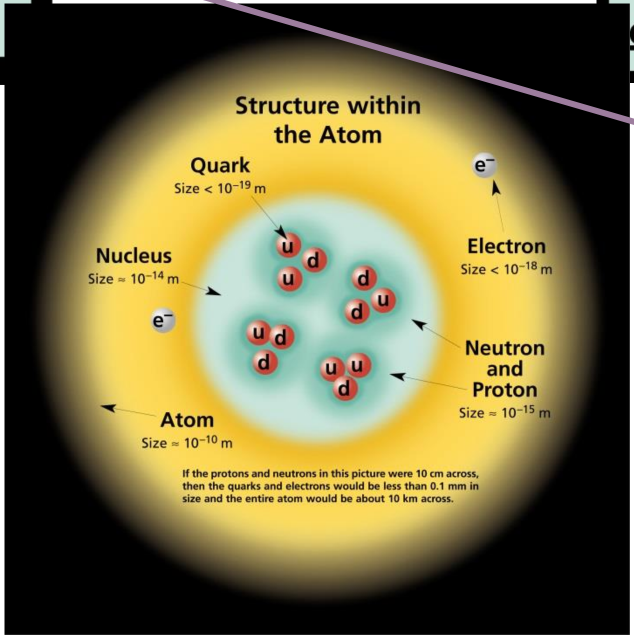
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	−1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Composite particles must be colour neutral

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	−1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	−1	1.672	3/2

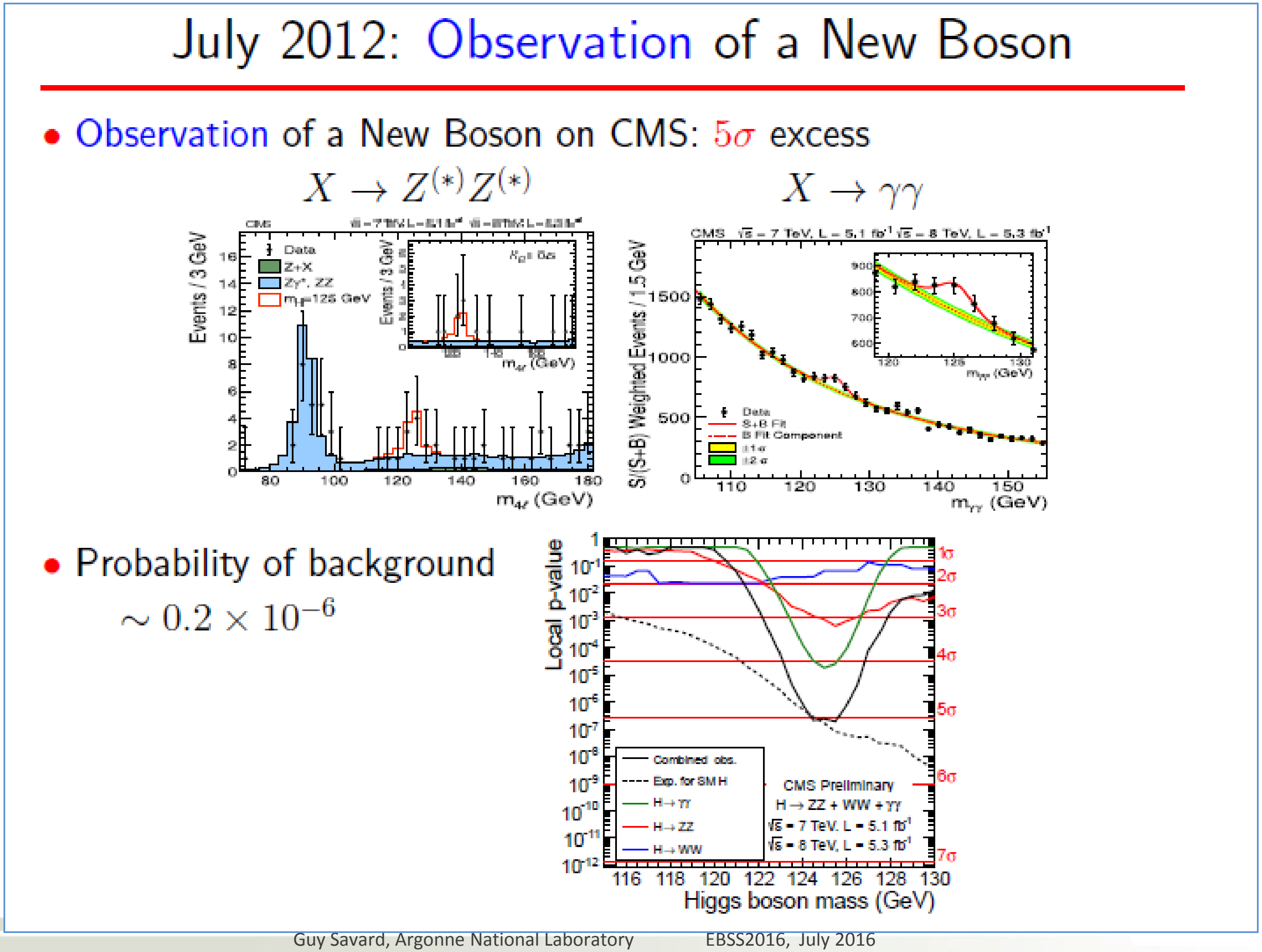


If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

Composite particles are mostly "fields" … distinction between particles and fields not so simple.

Recent SM update --- Higgs boson discovery

… actually not an update, more of a confirmation … fully consistent with SM



July 2012: Observation of a New Boson

- Observation of a New Boson on CMS: 5σ excess

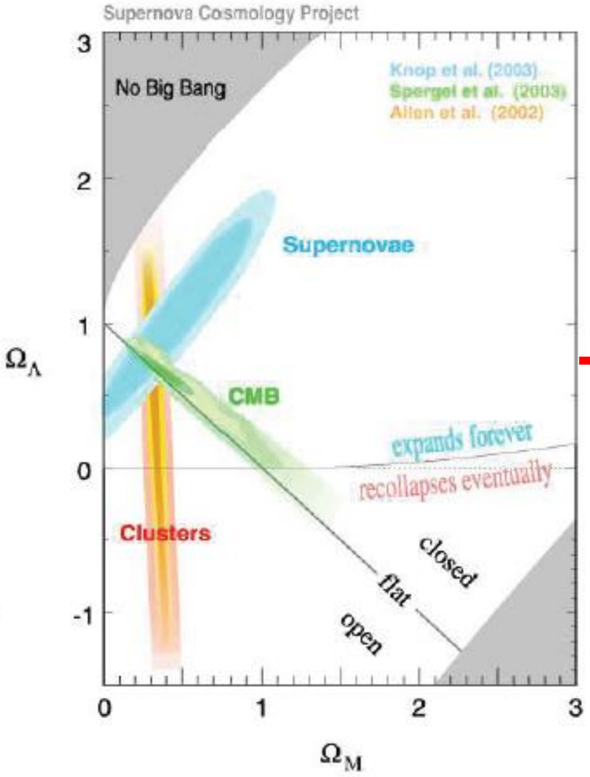
$X \to Z^{(*)}Z^{(*)}$ $\qquad$ $X \to \gamma\gamma$

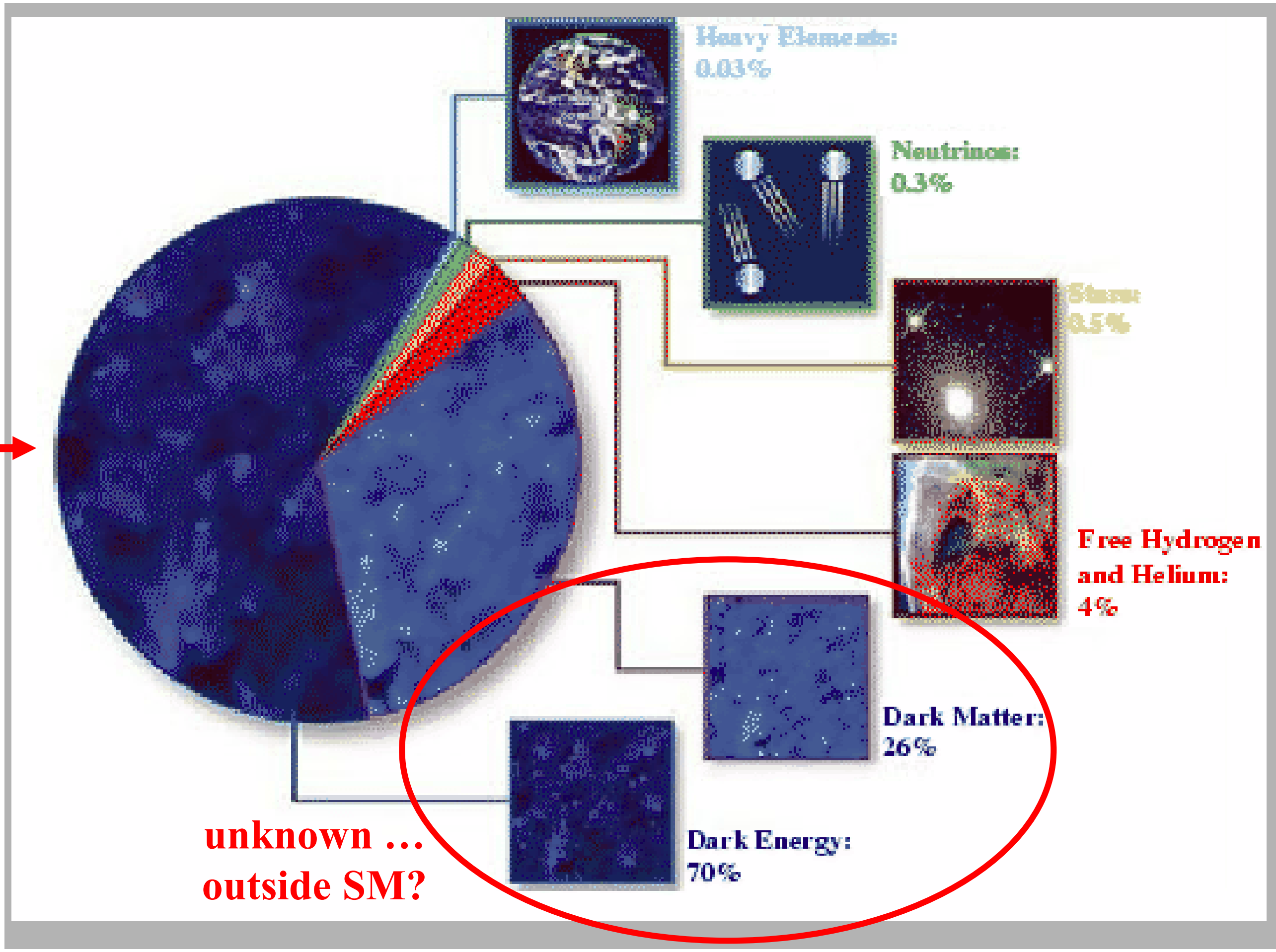
- Probability of background

$\sim 0.2 \times 10^{-6}$

Recent SM update --- Dark matter and Dark Energy

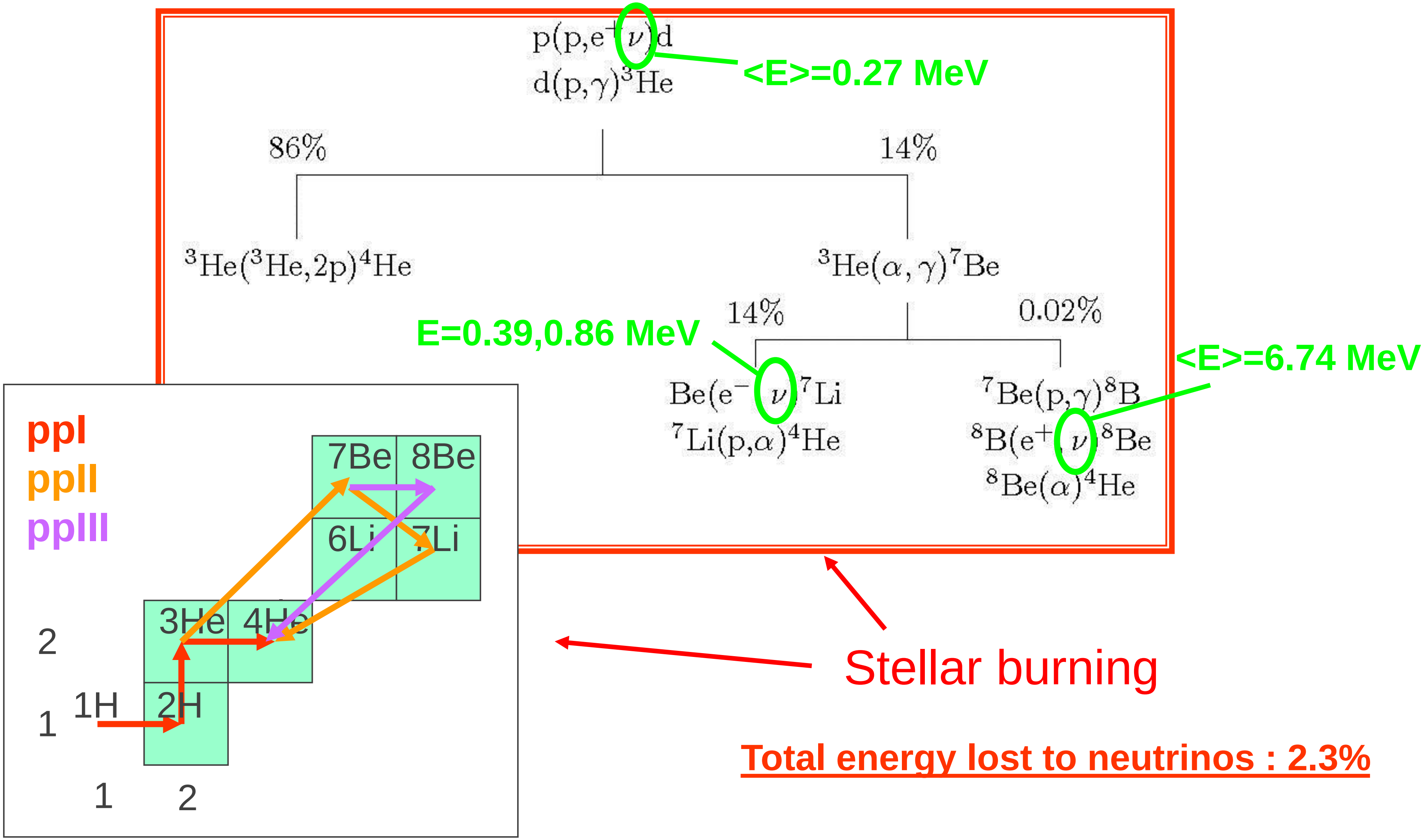
The Standard Model only explains 5% of what makes up our universe





unknown …
outside SM?

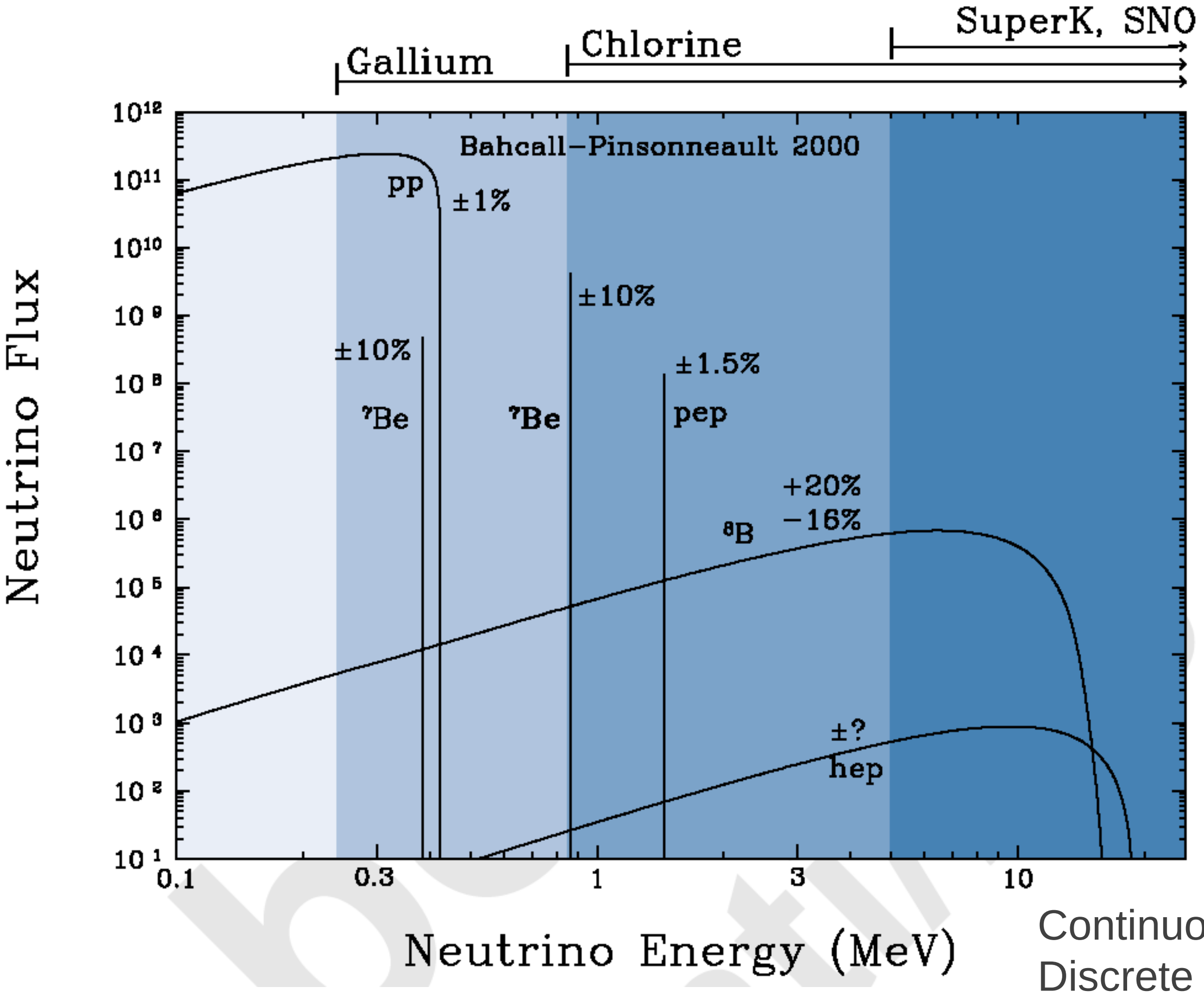
Recent SM update --- Neutrino oscillations: Solar neutrinos



Stellar burning

Total energy lost to neutrinos : 2.3%

Recent SM update --- Neutrino oscillations: Solar neutrinos

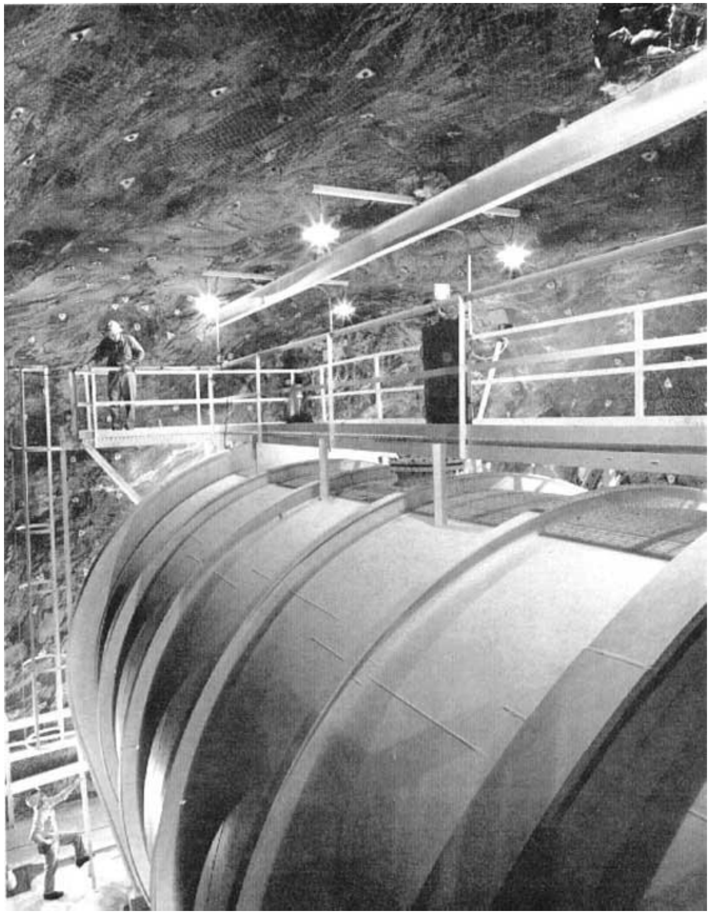


Continuous fluxes in /cm^2/s/MeV
Discrete fluxes in /cm^2/s

Recent SM update --- Neutrino oscillations: Solar neutrino detection

- **1964** John Bahcall and Ray Davis have the idea to detect solar neutrinos using the reaction:

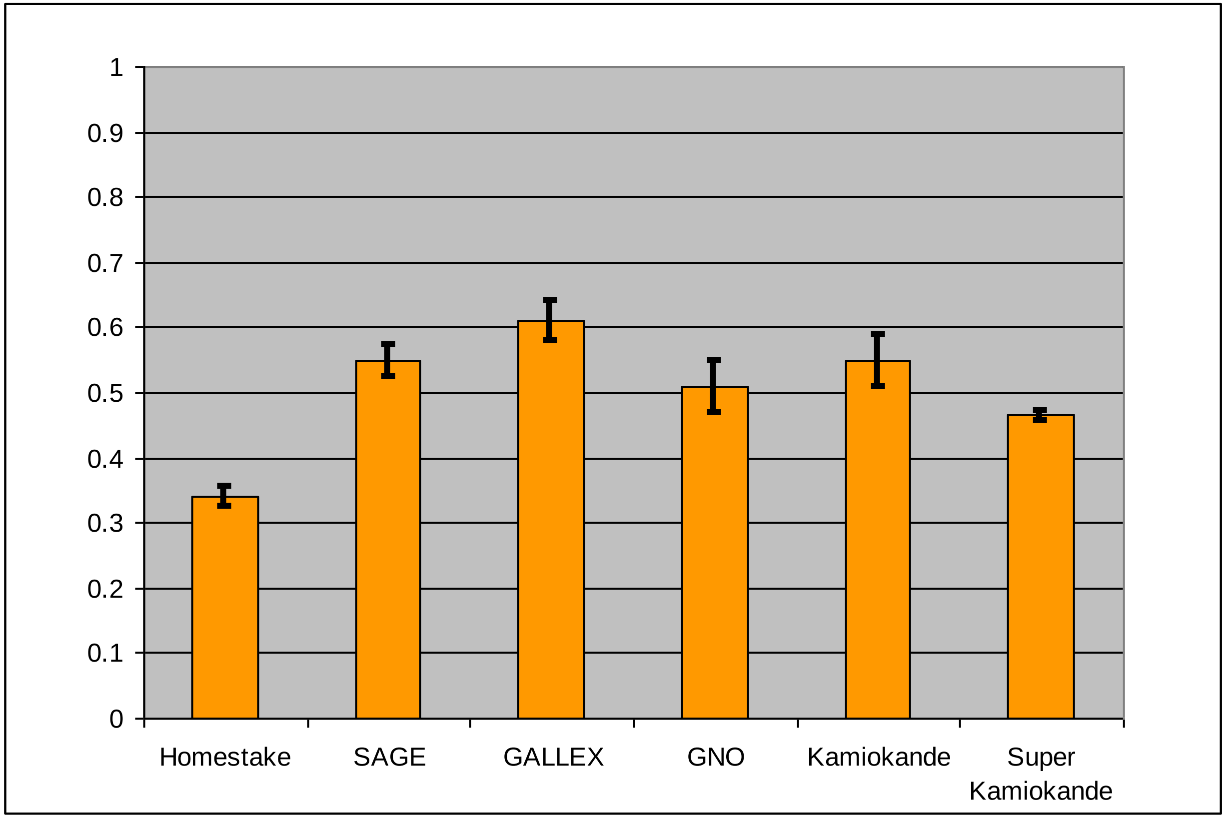
$$^{37}Cl + \nu_e \longrightarrow {}^{37}Ar + e^-$$



- **1967 Homestake experiment starts taking data**
  - 100,000 Gallons of cleaning fluid in a tank 4850 feet underground
  - ^{37}Ar extracted chemically every few months (single atoms !) and decay counted in counting station (35 days half-life)
  - event rate: ~1 neutrino capture per day !
- **1968 First results: only 34% of predicted neutrino flux !**

  solar neutrino problem is born - for next 20 years there is no other detector !

Recent SM update --- Neutrino oscillations: Solar neutrino detection



many more experiments over the years with very different energy thresholds:
all show a deficit vs standard solar model

ν_e only

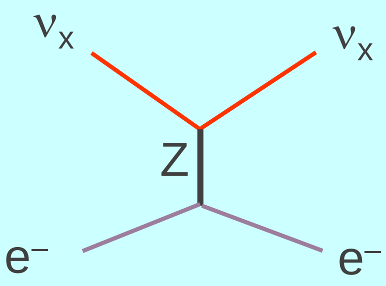
all flavors, but
ν_τ,ν_μ only 16% of
ν_e cross section because
no CC, only NC

Recent SM update --- Neutrino oscillations: Solar neutrino detection

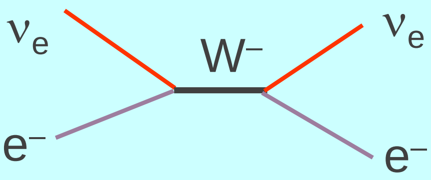
Water Cherenkov detector:

$$\upsilon + e^- \longrightarrow \upsilon + e^-$$

high energy (compared to rest mass) - produces Cherenkov radiation when traveling in water **(can get direction)**

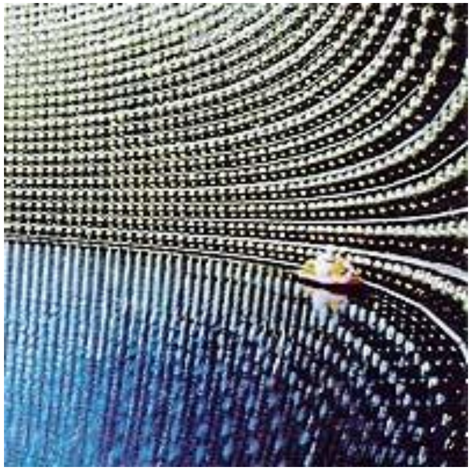


neutral current (NC)



charged current (CC)

Super-Kamiokande Detector



Recent SM update --- Neutrino oscillations: Solar neutrino detection

Possible explanation: neutrinos can change flavor while traveling from sun to earth

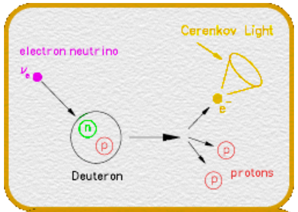
SNO solar neutrino experiment

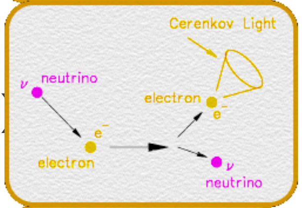
three reactions in heavy water:

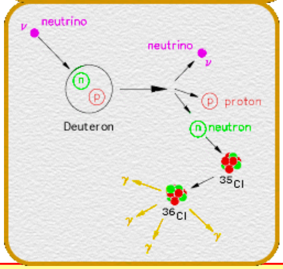
CC $\upsilon_e + d \longrightarrow p + p + e^-$ (only ν_e)

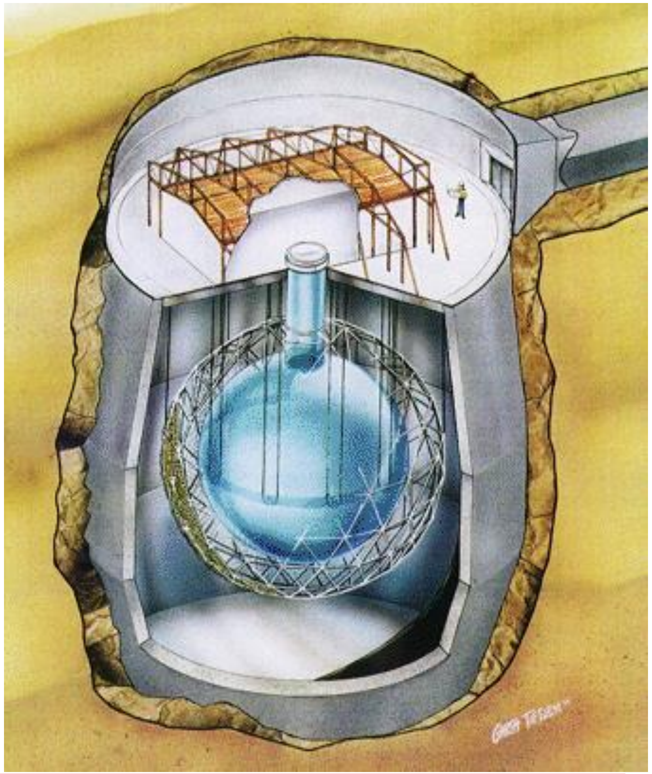
ES $\upsilon + e^- \longrightarrow \upsilon + e^-$ (mostly ν_e)

NC $\upsilon + d \longrightarrow p + n + \upsilon$ (all ν)



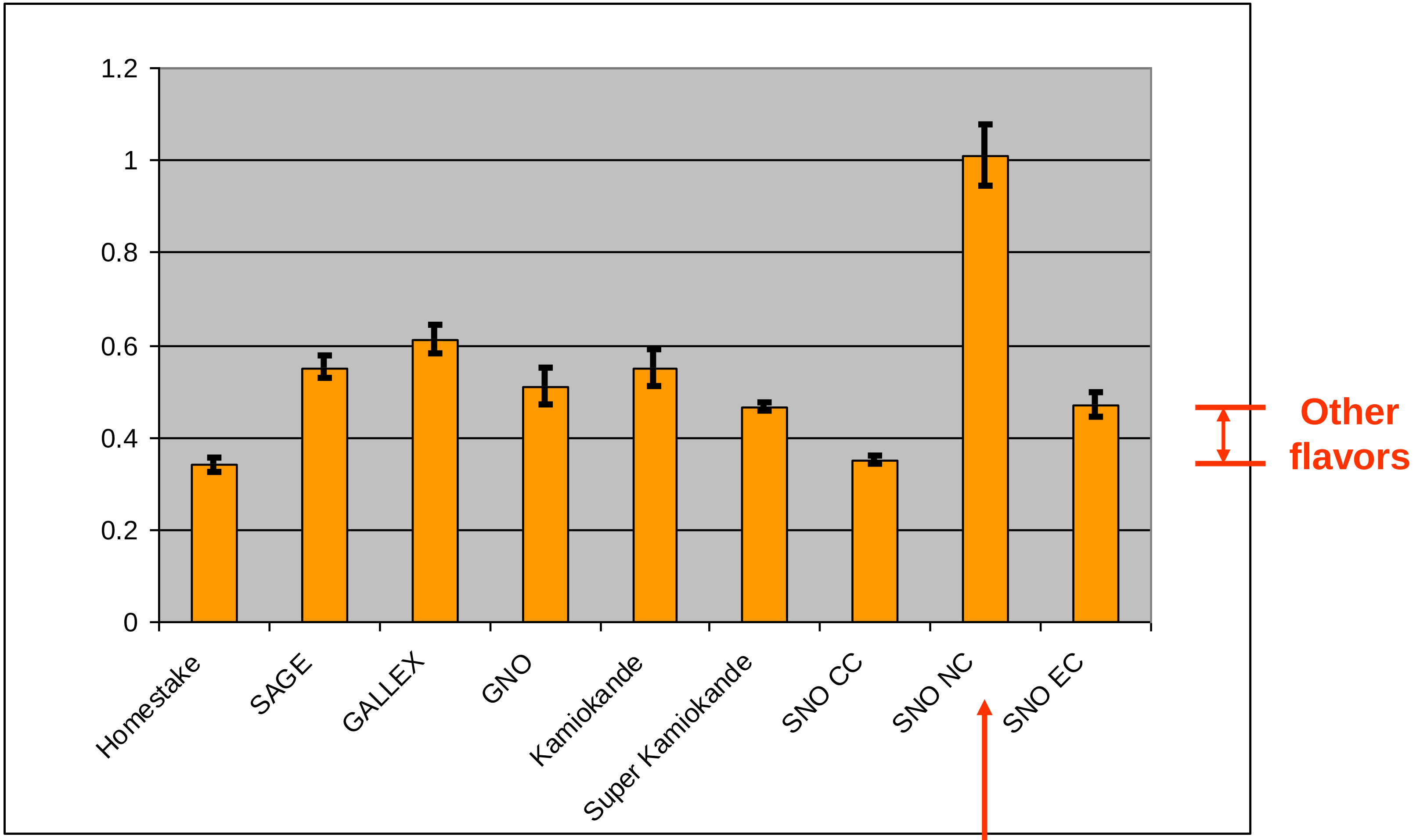






signature:
- **NC independent of flavor - should always equal solar model prediction if oscillations explain the solar neutrino problem**
- **Difference between CC and ES indicates additional flavors present**

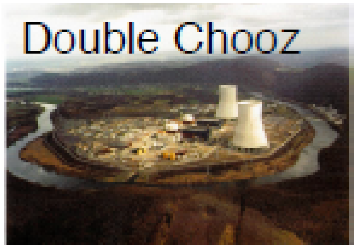
Recent SM update --- Neutrino oscillations: Solar neutrino detection

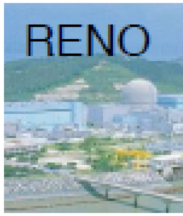


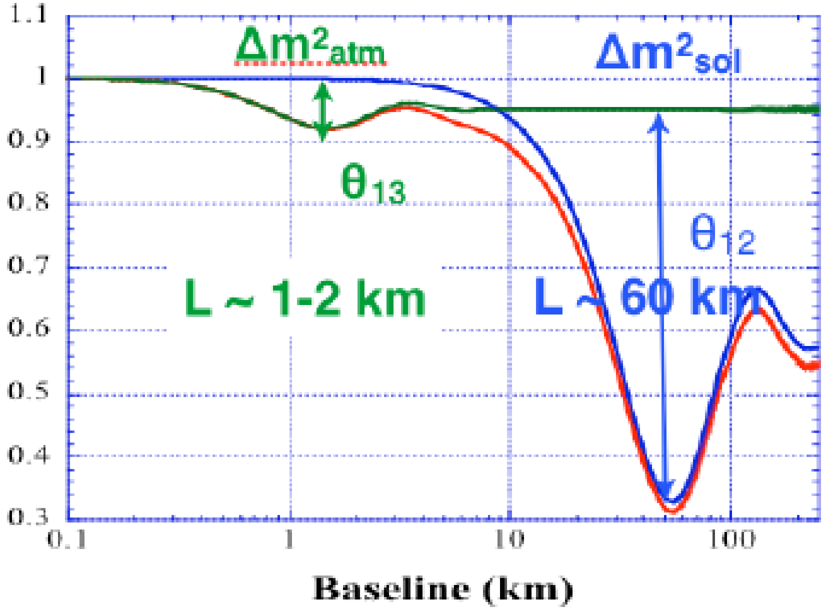
Other flavors

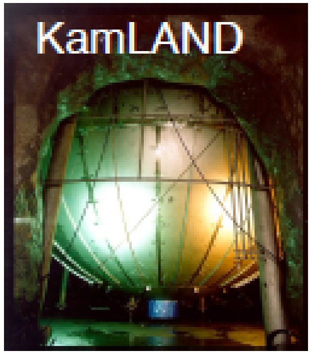
Total neutrino flux

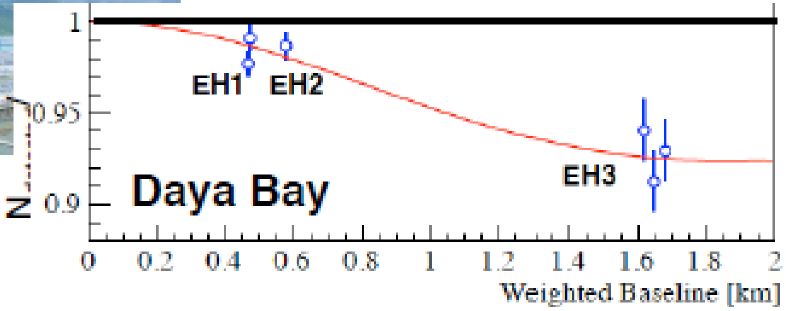
Recent SM update --- Neutrino oscillations: Reactor neutrino

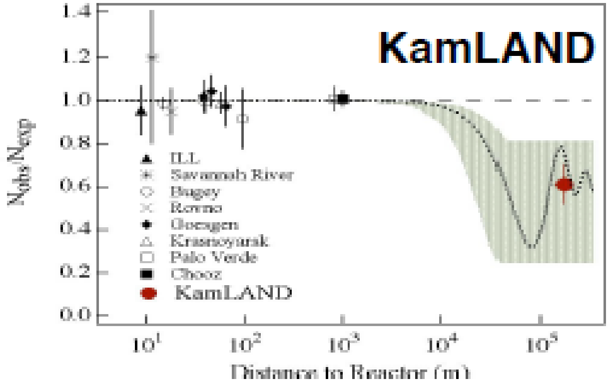












Beginning of era of precision neutrino physics :

$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

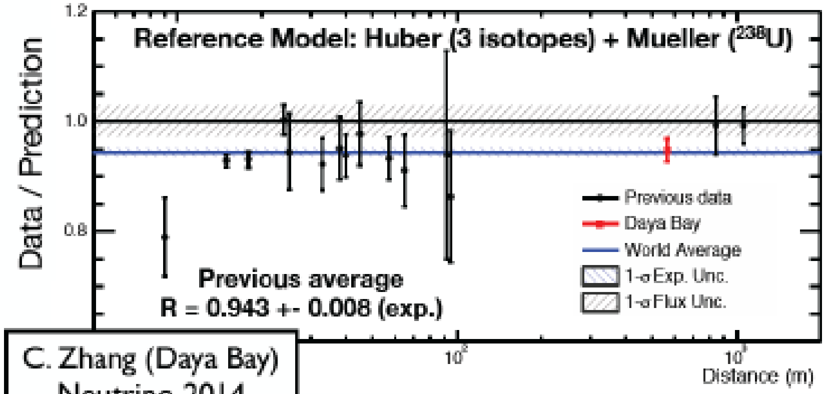
$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3}\mathrm{eV}^2$$

Recent SM update --- but not all is perfect in neutrino land

Reactor Flux and Spectrum "Anomalies"

Flux Deficit

Consistent with previous experiments

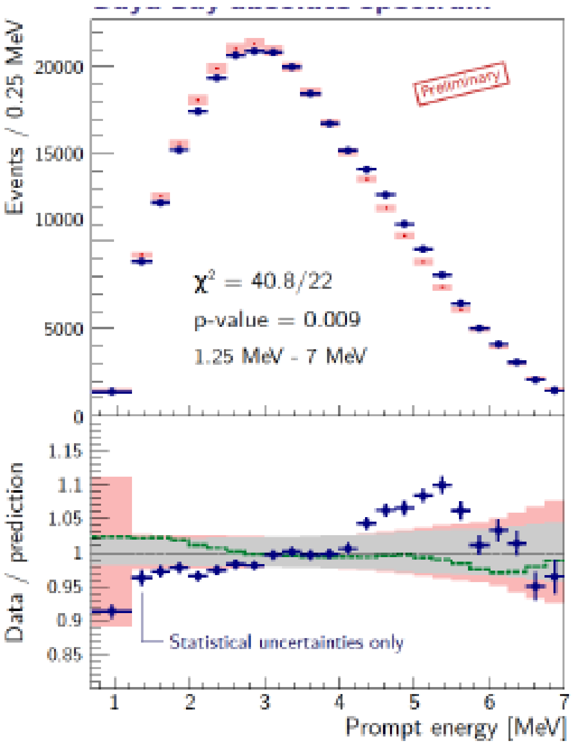


C. Zhang (Daya Bay)
Neutrino 2014

Extra neutrino oscillations or artifact of flux predictions?

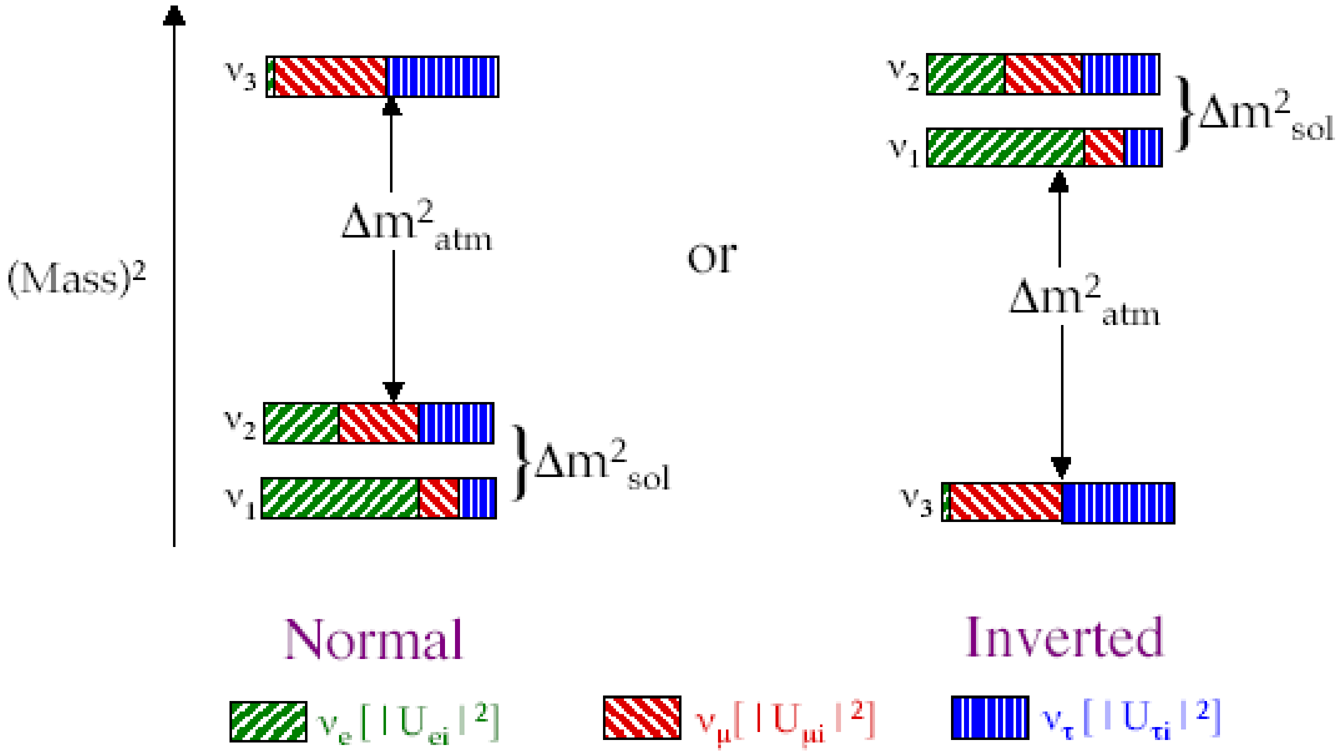
More data needed to better understand these observations

Spectral Deviation



New feature in 4-6 MeV region of spectrum. Seen by Daya Bay, Double Chooz, and Reno.

Recent SM update --- Neutrino oscillations: Neutrino mass status



Don't know yet absolute offset for m:

$$\langle m_\beta \rangle = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \, m_i^2} < 2.2\,\mathrm{eV}$$ (direct searches from tritium β-decay)

$$\sum m_i < (0.4-1.0)\,\mathrm{eV}$$ (cosmological data+model)

Recent SM update --- Neutrino oscillations: Neutrino nature status

Neutrinos not quite like other leptons:

- ν mass requires addition of new fields to SM Lagrangian

e.g. $L \sim m_D \overline{\nu_L} \nu_R$

- ν mass allows $\overline{\nu_i} = \nu_i$ (Majorana neutrinos)

Which in turn allows new CP-violating phases:

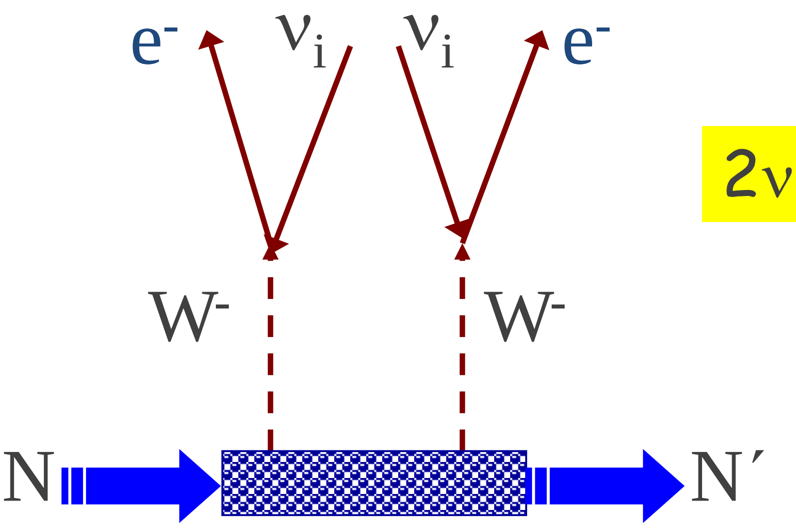
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{atmospheric, K2K}} \times \overbrace{\underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{reactor and accelerator}}}^{\text{Dirac phase}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{SNO, solar SK, KamLAND}} \times \overbrace{\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{0\nu\beta\beta}}^{\text{Majorana phases}}$$

$\sin^2\theta_{23}$ $\sin^2\theta_{13}$ $\sin^2\theta_{12}$

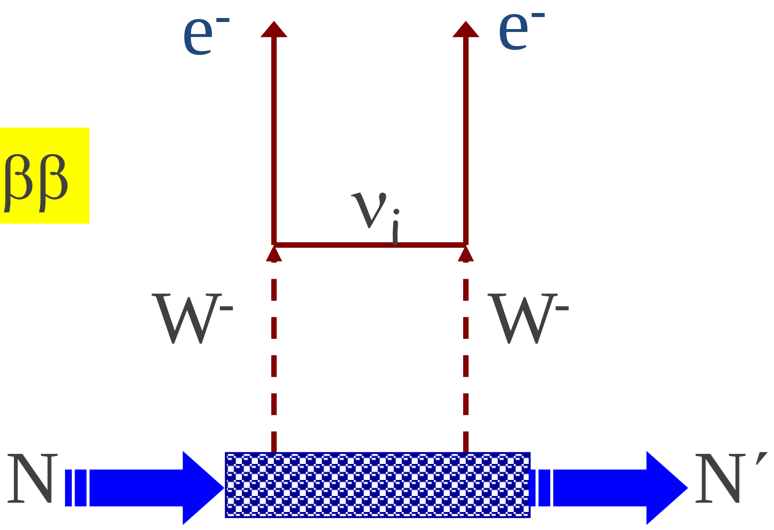
Recent SM update --- Neutrino oscillations: Testing neutrino nature (Majorana vs Dirac)

2νββ vs. 0νββ



$$\Gamma_{2\nu} = G_{2\nu}\left|M_{2\nu}\right|^2$$

$$\langle m_\beta \rangle = \sqrt{\sum_{i=1}^{3} \left|U_{ei}\right|^2 m_i^2}$$



Nuclear matrix element (~ OK)

Phase space (OK)

$$T_{1/2} \propto m_\nu^2$$

$$\Gamma_{0\nu} = G_{0\nu}\left|M_{0\nu}\right|^2 m_\nu^2$$

Mass is mixed average

$$\langle m_{\beta\beta} \rangle = \sum_{i=1}^{3} \left|U_{ei}\right|^2 m_i \,\varepsilon_i$$

observed   not seen yet

S. Elliott, SLAC Summer Inst. (2004)

Recent SM update --- Neutrino oscillations: Testing neutrino nature

Cosmology

$$\Sigma = m_1 + m_2 + m_3$$

Oscillations

$$\delta m_{ij}^2 = m_j^2 - m_i^2$$

Beta decay

$$\langle m_\beta \rangle = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$

ββ

$$\langle m_{\beta\beta} \rangle = \sum_{i=1}^{3} |U_{ei}|^2 m_i \varepsilon_i$$

	Absolute Mass Scale	Relative Mass Scale	Mixing Matrix Elements	CP nature of ν
ββ	✓			✓
β, cosm	✓			
Oscil.		✓	✓	

Slide by S. Elliott

Standard Model as it stands now

The Standard Model has been very successful at describing the world around us in terms of its basic constituents and interactions.

Recent changes have however made the number of free parameters in the SM grow to at least 26:

12 Fermion masses: $m_{e,} m_{\mu}, m_{\tau,}$ neutrino masses, quark masses
2 Gauge boson masses: M_Z and M_W (2 parameters)
2 Coupling constants: $\alpha_{\text{strong},}$ $\alpha_{\text{electroweak}}$
2 Vacuum energies: Higgs mass, θ_{QCD}
4 quark mixing angles ($\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}$) Cabibbo-Kobayashi-Maskawa
4 lepton mixing angles ($\theta_{e\tau}, \theta_{e\mu}, \theta_{\mu\tau}, \delta$) (neutrino oscillations, etc.)

more if the neutrinos are Majorana particles or if sterile neutrinos. It does not tell us what dark energy is and cannot accommodate us being here (not enough CP violation to explain the dominance of matter over antimatter).

A more complete (and elegant) scheme must exist.

Low energy tests of the Standard Model: accurate physics in an inaccurate system

The nucleus is a complex quantum system not generally amenable to an exact description.

However, by a proper choice of nuclear system and observable, specific physical processes can be isolated and determined to high precision.

e.g.: 0^+ to 0^+ superallowed decays or PNC in atoms

Requirements are:

- An identifiable and separable observable (e.g.: a P-violating signal in an otherwise P-conserving experiment)
- A suitable laboratory (nucleus where the specific observable is enhanced and unperturbed)
- The proper experimental tools

Testing the Standard Model at low energy: use the symmetries

For **H** an Hamiltonian obeying a symmetry **S** :

$$[\mathbf{H},\mathbf{S}] = 0$$

If $|\Psi\rangle$ is an eigenstate of **H** with eigenvalue E, then

$$(\mathbf{HS}-\mathbf{SH})\,|\Psi\rangle = 0 \quad \rightarrow \quad \mathbf{H}\,(\mathbf{S}\,|\Psi\rangle) = E\,(\,\mathbf{S}\,|\Psi\rangle)$$

Thus $\mathbf{S}|\Psi\rangle$ is an eigenstate with the same energy E and if the spectrum is nondegenerate, $\mathbf{S}|\Psi\rangle = s\,|\Psi\rangle$ with s a number.

→ $|\Psi\rangle$ is an eigenstate of **S** if **H** obeys the symmetry **S.**

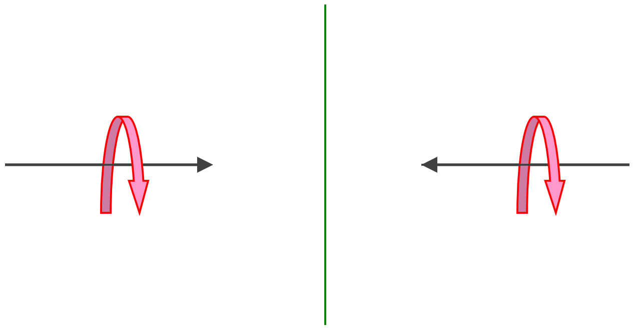
You can learn about the properties of the interactions by studying the wavefunction properties.

Symmetry example : Parity

Under the parity operation:

- **r → -r**
- **p → -p**
- **r×p → r×p**
- **J → J**

Parity Mirror

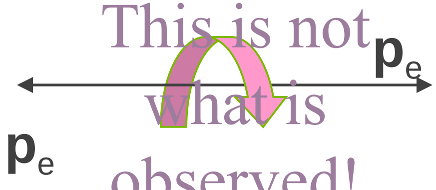


If you call the two states $|\Psi_R\rangle$ and $|\Psi_L\rangle$, neither is an eigenstate of an inversion symmetric H. The proper states are:

$$|\Psi_S\rangle = (2)^{-1/2}\,(|\Psi_L\rangle + |\Psi_R\rangle)$$
$$|\Psi_A\rangle = (2)^{-1/2}\,(|\Psi_L\rangle - |\Psi_R\rangle)$$

Madame Wu’s experiment:
Polarize ^{60}Co and look at the direction of the emitted β’s.

In a parity-symmetric world we would see as many electrons emitted in the direction of **J** as opposite **J**.



This is not what is observed!

Other useful fundamental symmetries

Other useful fundamental symmetries:

- P (space reversal)
- T (time reversal)
- C (charge conjugation …. particle ←→ antiparticle)
- CP … must be broken for us to exist
- CPT … this one must be conserved … Lorentz invariance
- …

Other symmetries can be useful … even the non-exact ones

A useful approximate symmetry:

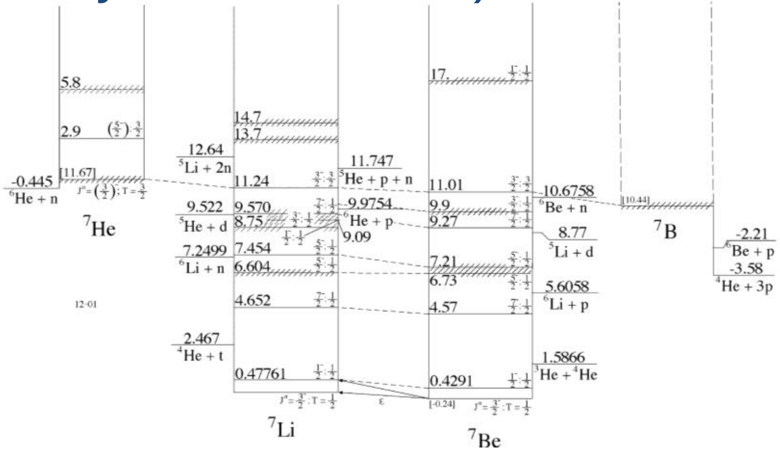
- isospin
  - up and down quarks form an isospin doublet

$$|u\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \qquad |d\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \qquad \textit{with } I^+|d\rangle = |u\rangle$$

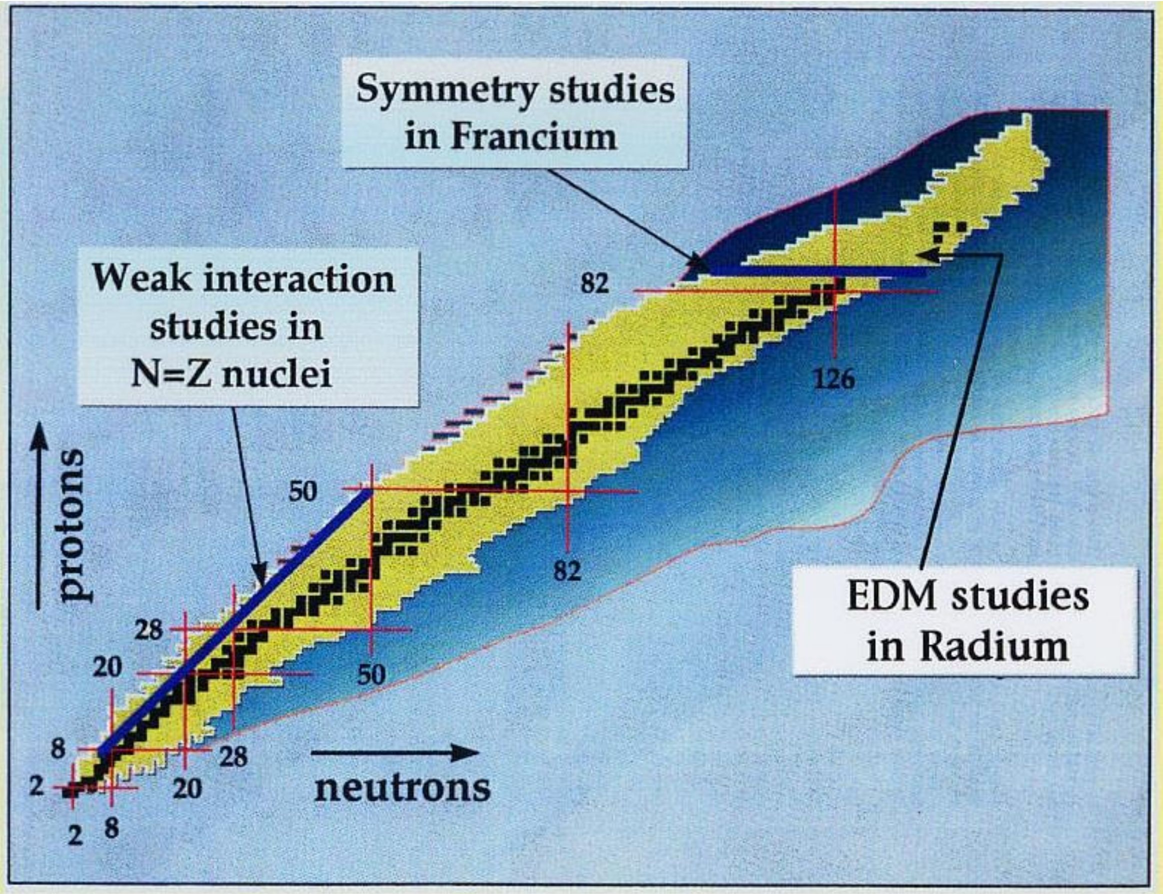
  - nucleons (protons and neutrons) also form a doublet

$$t_{nucleon} = \frac{1}{2} \oplus \frac{1}{2} \oplus \frac{1}{2} = \frac{1}{2} \qquad |p\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \qquad |n\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \qquad \textit{with } I^+|n\rangle = |p\rangle$$

  - isospin symmetry fairly good in light nuclei (broken by E&M and somewhat by nuclear forces)



Testing fundamental symmetries at low energy: the laboratory



Specific nuclei have advantages: good isospin symmetry, enhanced effects because of relativity or deformation … just by statistics, you would expect most of the best candidates will be radioactive.

Testing fundamental symmetries at low energy: traps … the precision tools

Traps allow the confinement of particles in a well-controlled environment, free from outside perturbations, where they are available for precision measurements.

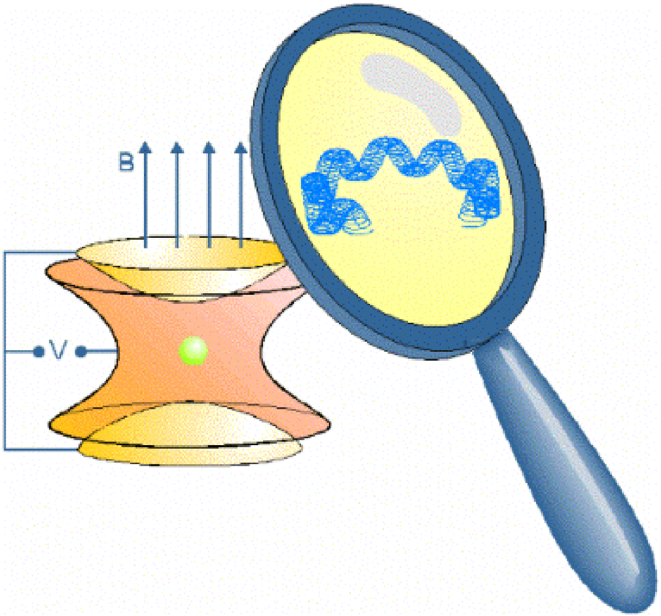
A large variety of traps is available:

- Penning trap
- Optical trap
- Magnetic trap
- Dipole trap
- FORT trap
- Radio-frequency trap
- Magneto-optical trap
- Cyclotron trap
- …

Conception of experiment:

Physics
↓
Observable
↓
Trap

Measurements in traps

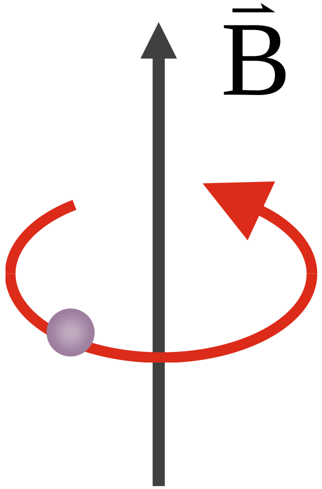


Traps can be used as a storage device where the intrinsic properties of the confined particle can be studied under optimal conditions

- or -

Information on the captured species can be obtained from the eigenmodes of the trapped particules in a precision trap

Most simple trap: 2d-confinement of charged particle in a magnetic field

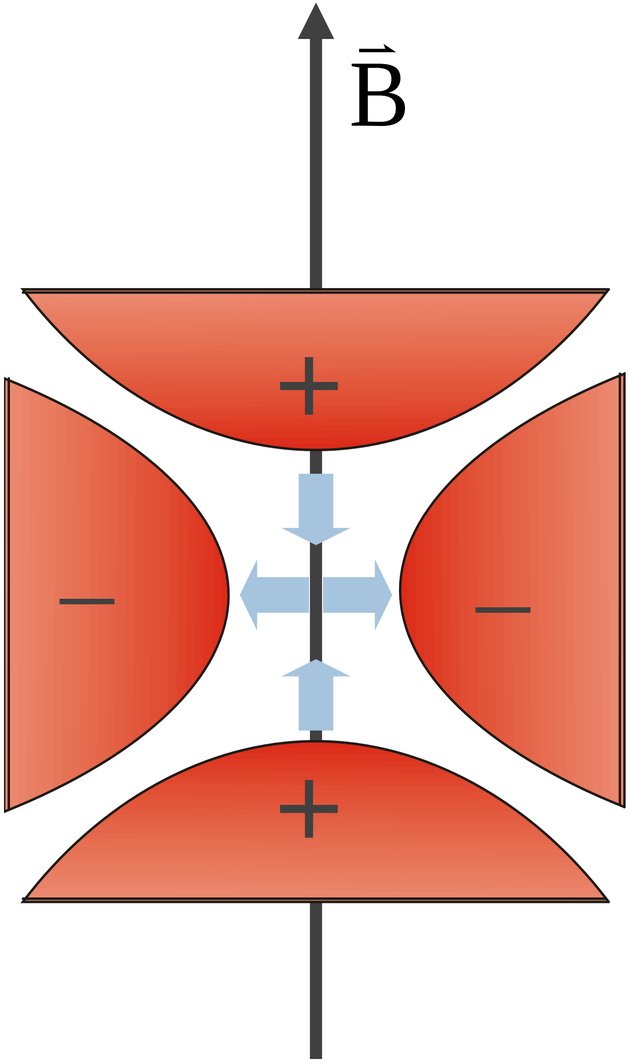


- Constant axial magnetic field
- particle orbits in horizontal plane

$$\omega_c = \frac{qB}{m}$$

- free to escape axially

Most simple trap: 3d-confinement in the Penning trap



- Add an axial harmonic electric field to confine particles
- axial oscillations:

$$\omega_z = \sqrt{\frac{eV}{md^2}}$$

- Radial motion split into two components by electric field:

→ω_+ : reduced cyclotron freq.

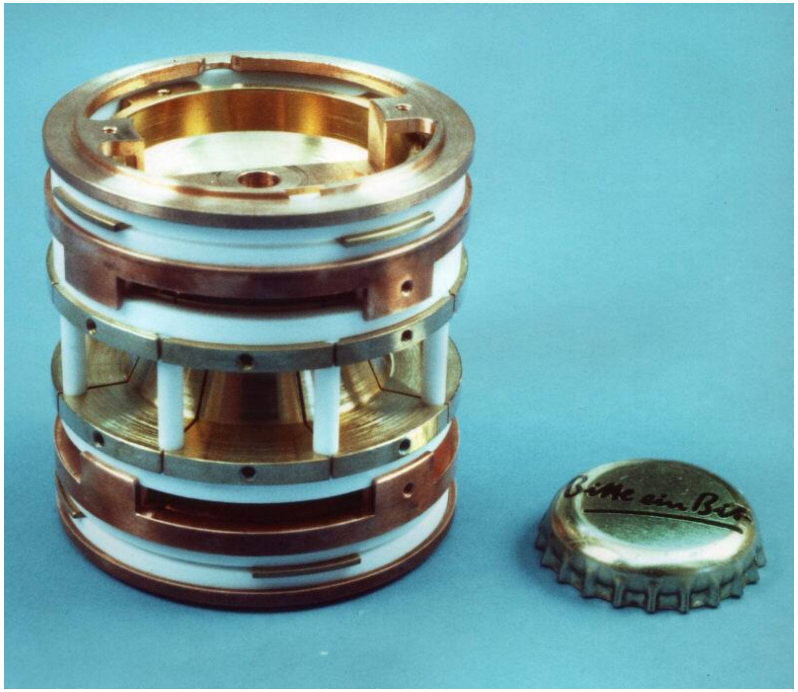
→ω_-: magnetron frequency

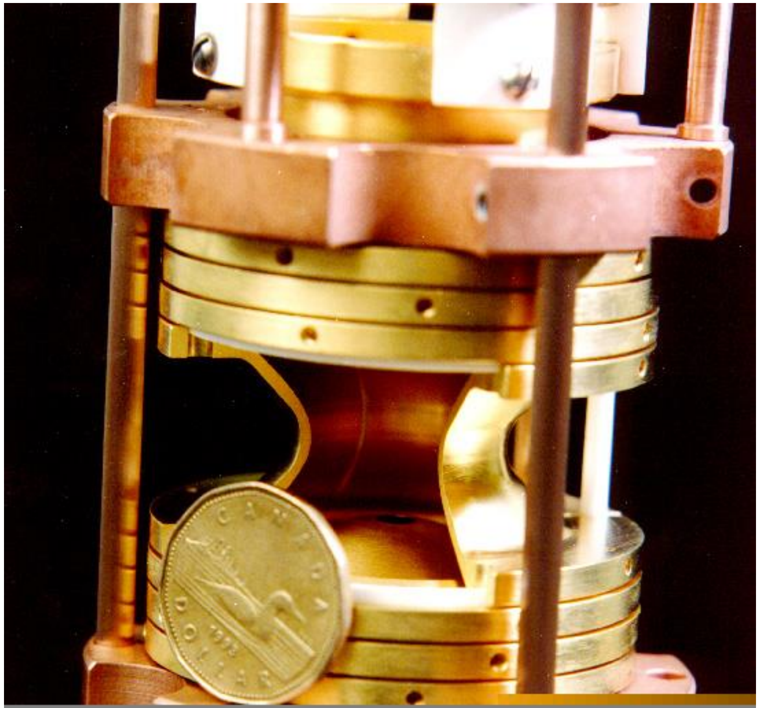
with:

$$\omega_+ + \omega_- = \omega_c$$

Can trap any charged species!

Early on-line Penning traps





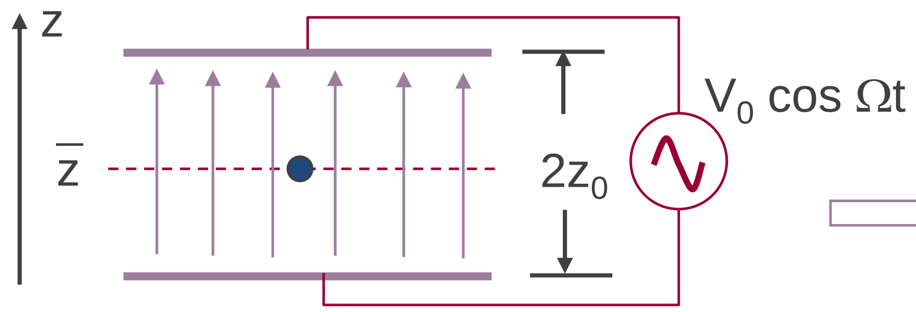
ISOLTRAP at CERN

CPT at Argonne

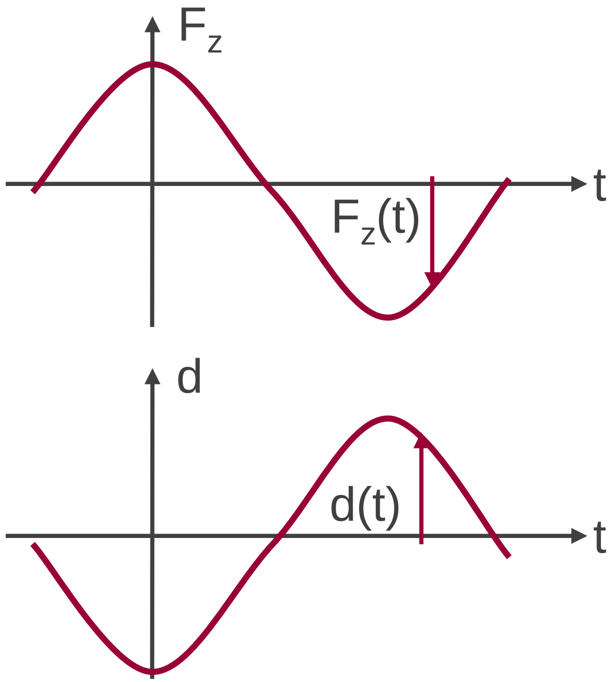
… now a lot more of them

RF focusing(1)

Uniform RF field



$$\Rightarrow \quad E_0(z) = E_0(\bar{z})$$



Basic harmonic motion

$$m\ddot{z} = F_z(t) = eE_0(z)\cos\Omega t$$
$$z(t) = \bar{z} + d(t)$$
$$d(t) = -d_0 \cos\Omega t$$

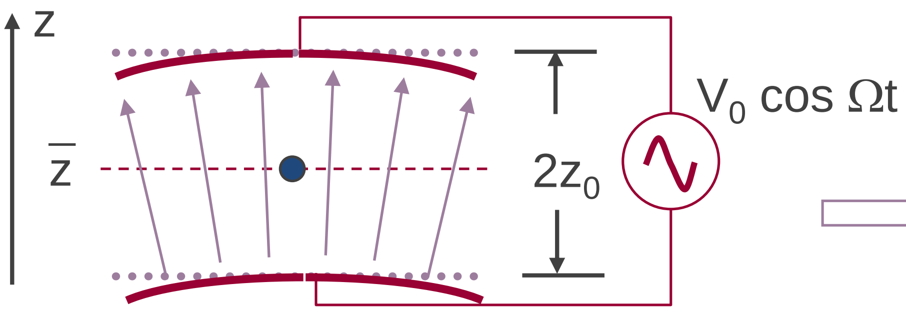
$$\boxed{d_0 = \frac{eE_0(\bar{z})}{m\Omega^2}}$$

$$< F_z(t) >_{av} = eE_0(\bar{z}) < \cos\Omega t >= 0$$

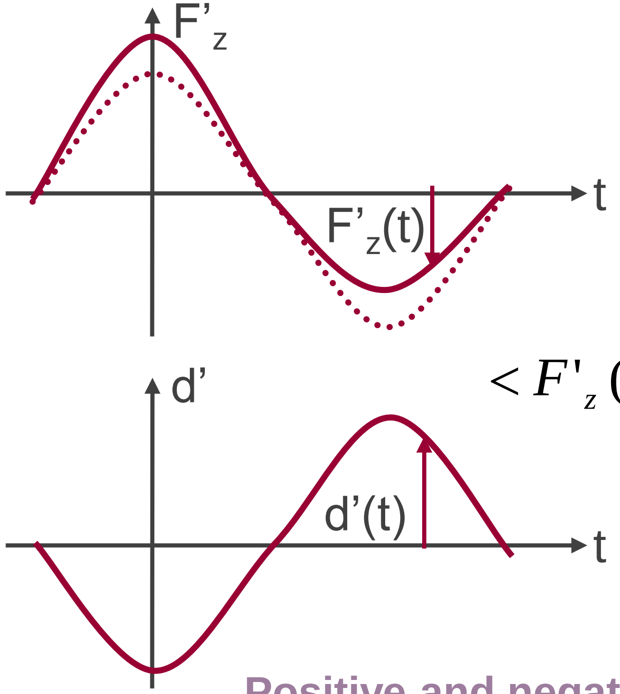
No net force when averaged over full RF cycle!

RF focusing(2)

Non-Uniform RF field



$$E_0(z) = E_0(\bar{z}) + \left(\frac{\partial E_0(\bar{z})}{\partial \bar{z}}\right) d$$



$$m\ddot{z} = F'_z(t) = eE_0(z)\cos\Omega t$$

$$z(t) = \bar{z} + d'(t)$$

$$d'(t) \cong d(t) = -d_0 \cos\Omega t$$

$$\boxed{d_0 = \frac{eE_0(\bar{z})}{m\Omega^2}}$$

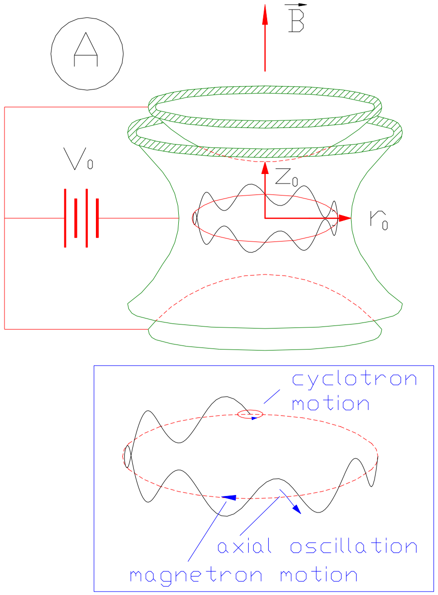
$$< F'_z(t) >_{av} = e\left(\frac{\partial E_0(\bar{z})}{\partial \bar{z}}\right) < d'\cos\Omega t >= \frac{-e^2 E_0(\bar{z})}{2m\Omega^2}\left(\frac{\partial E_0(\bar{z})}{\partial \bar{z}}\right)$$

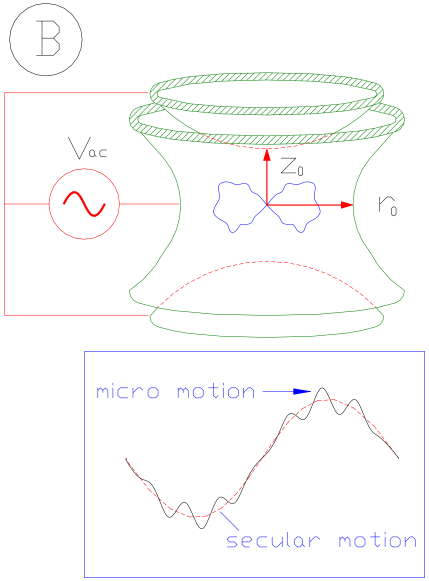
$$\boxed{F' = -e\frac{\partial V_{ps}}{\partial z} \Rightarrow V_{ps} = \frac{eE_0^2(z)}{4m\Omega^2}}$$

Positive and negative charges attracted to regions of lower RF amplitude!

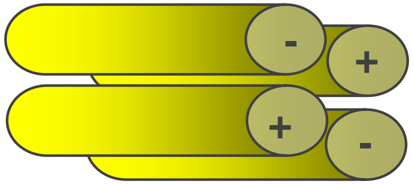
Guiding/trapping structures

Penning Trap

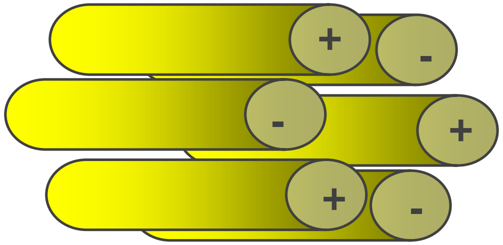




RFQ Trap

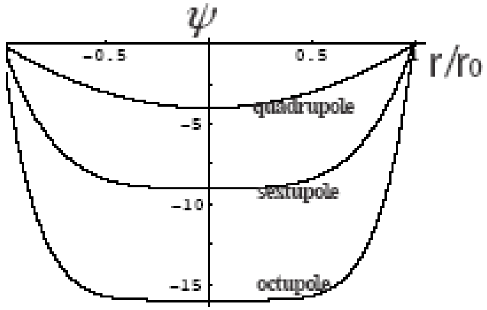


RF quadrupole



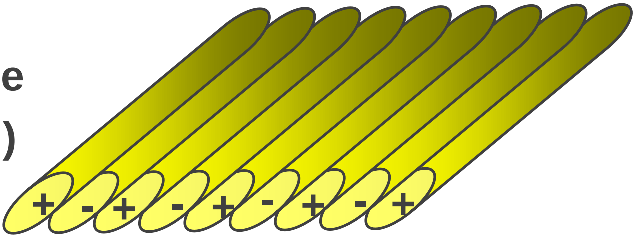
RF hexapole

Pseudo Potential

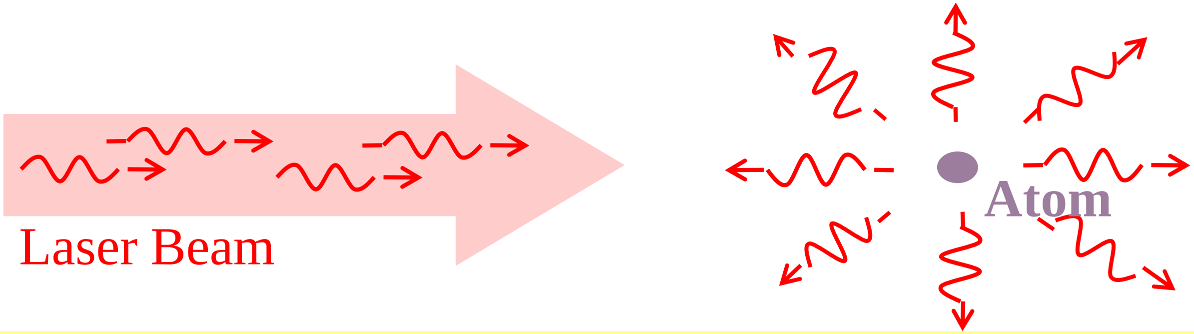


$$\varphi = \frac{qN^2}{4m\Omega^2}\left(\frac{V}{r_0}\right)^2\left(\frac{r}{r_0}\right)^{2(N-1)}$$

Centipole
(RF wall)



Optical traps: spontaneous scattering light force … resonance and repetition



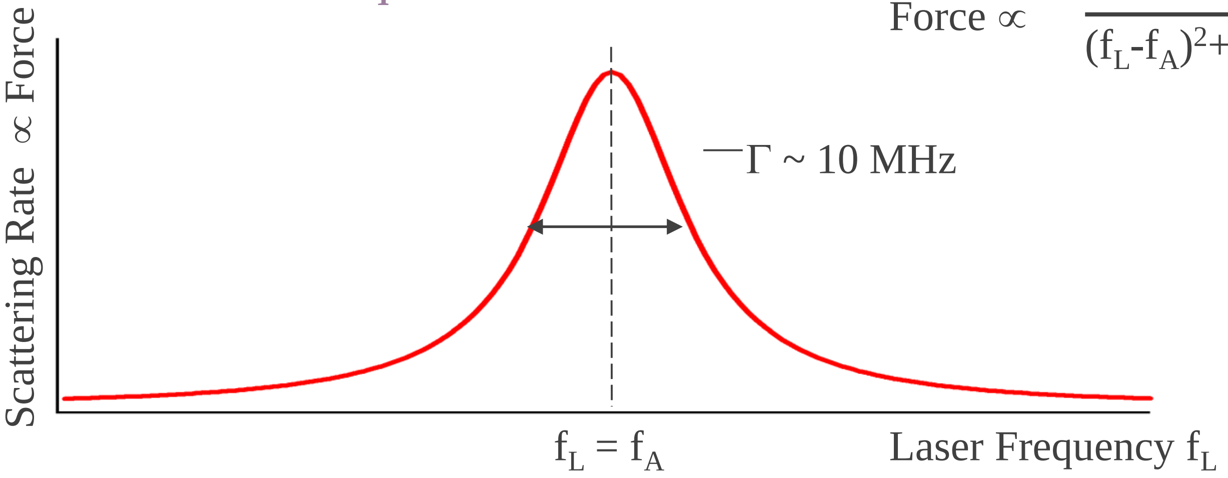
Krypton Atom:

$1s_5$ -- $2p_9$ wavelength = 811 nm Single photon kick δv = 6 mm/sec

Transition rate ~ 1×10^7 /sec Acceleration ~ 6×10^4 m/sec^2

Resonance Requirement

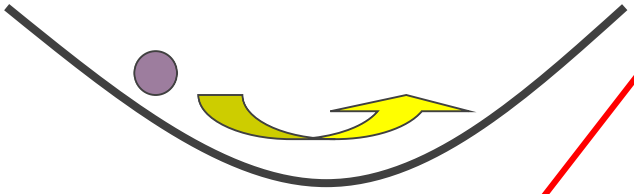
$$\text{Force} \propto \frac{1}{(f_L - f_A)^2 + (\Gamma/2)^2}$$



Optical traps: requirements

Trapping

F = -kx



Magnetic Field B(x)

↓

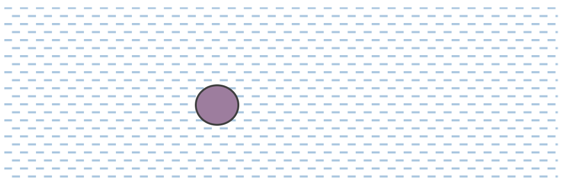
$f_A(x)$

Zeeman Shift

position dependent

Cooling

F = -av



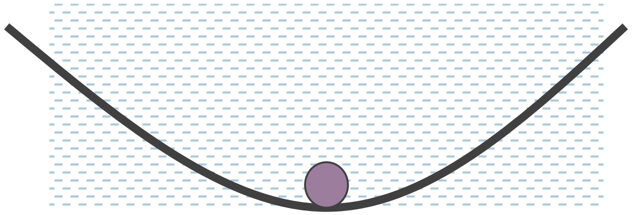
Atom Velocity

↓

$f_L(v)$

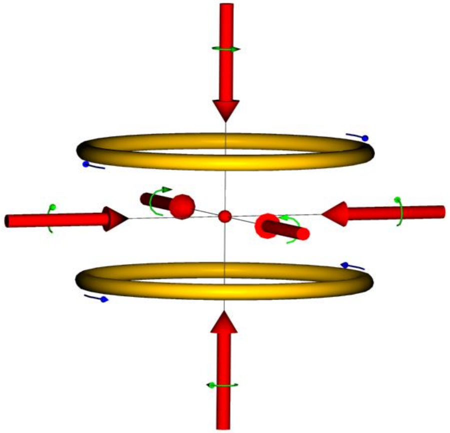
Doppler Shift

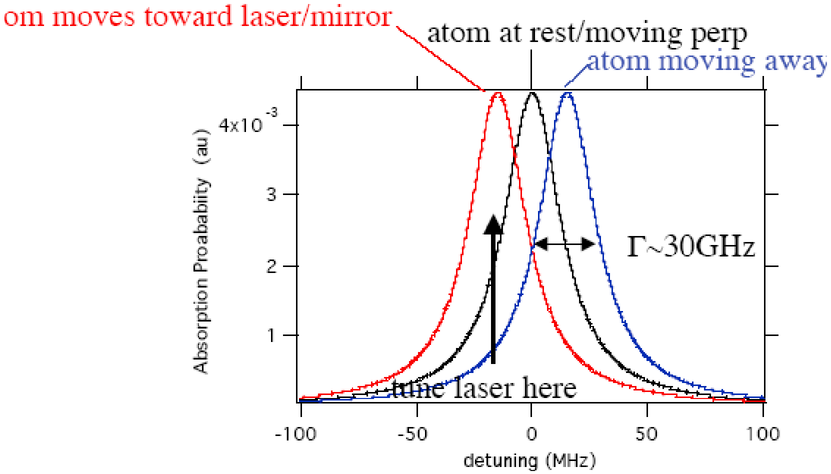
A Trap with Cooling



Magneto-Optical Trap (MOT)

Raab, Prentiss, Cable, Chu, Pritchard, Bell Lab & MIT, 1987





$$R = \int d\sigma(\nu)\, \Phi_\gamma(\nu)\, d\nu$$

Ingredients:

Laser beams --- alignment, frequency, polarization;

Quadrupole B-field --- 20 G/cm, anti-Helmholtz;

Ultra-high vacuum --- τ_{trap} ~ 1 sec @ $1\text{x}10^{-8}$ Torr.

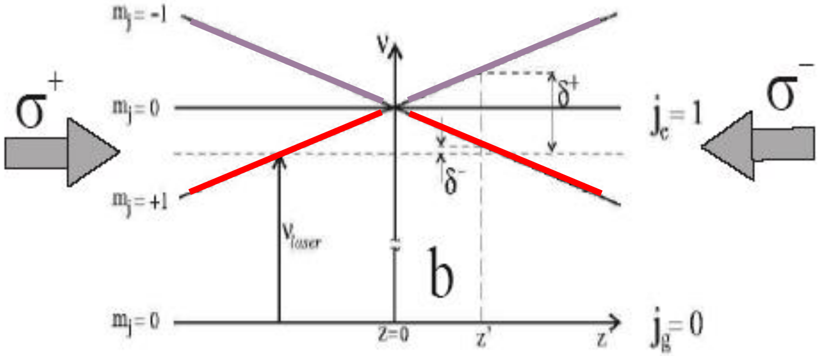
Typical Parameters:

Number --- 10^{10};

Density --- 10^{8} mm^{-3};

Temperature --- ~mK, < 1 m/sec;

Capture speed --- 20 m/sec.



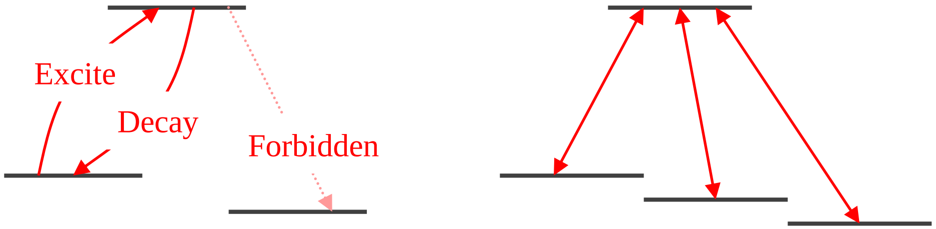
Trappable Atoms

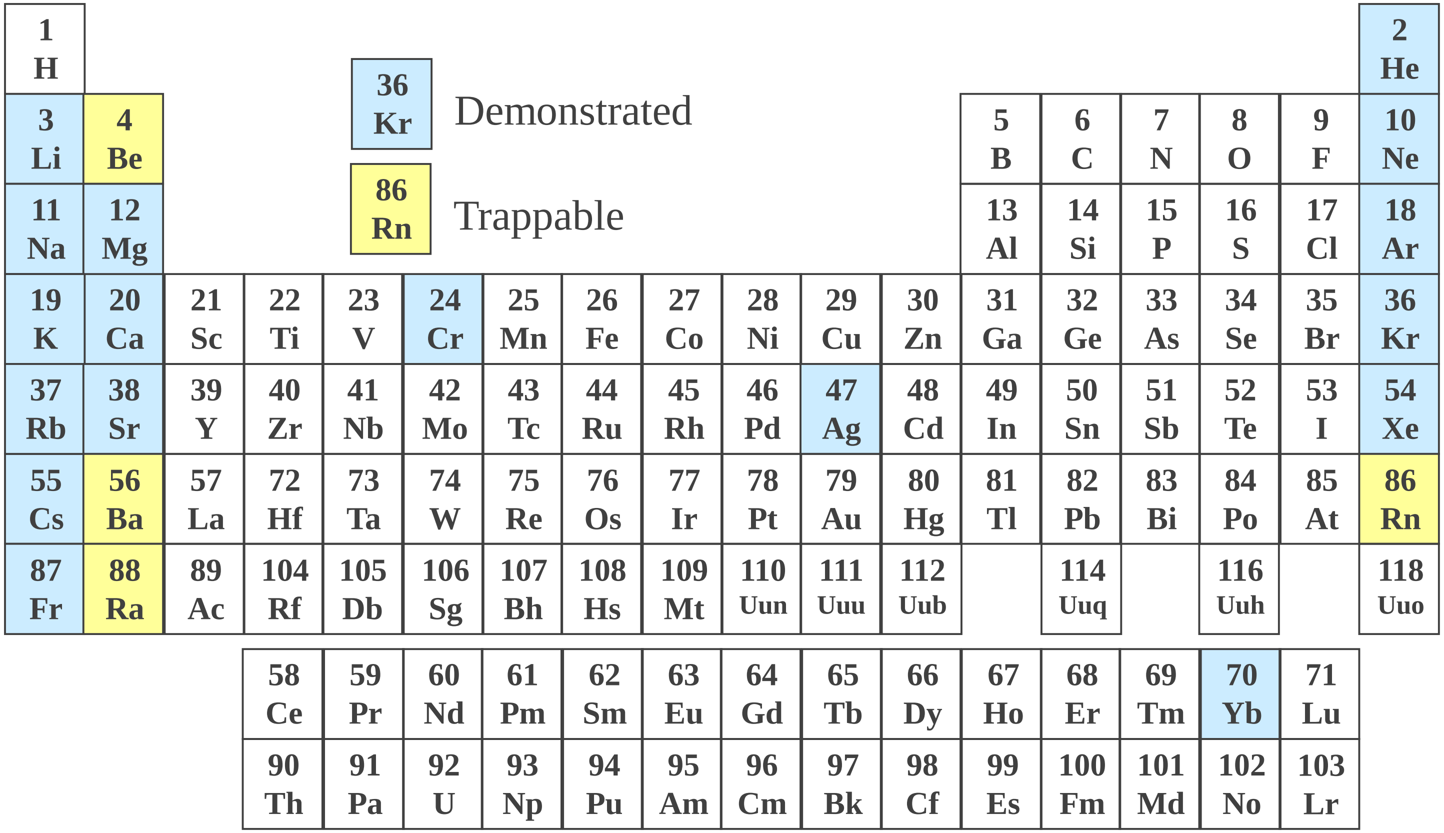
Transition Requirements:

Cycling transition

High transition rate (10^7 sec^{-1}, allowed E1)

Practical wavelength ($\lambda > 200$ nm)





36 Kr Demonstrated

86 Rn Trappable

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun	111 Uuu	112 Uub		114 Uuq		116 Uuh		118 Uuo
			58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
			90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

Two-sigma user's guide to traps

- **Penning trap**
  - Trapping potential ~ 1-1000 eV
  - Universal
  - Precision device
  - Space-charge limitation
  - Expensive

- **Radio-frequency trap**
  - Trapping potential ~ 1-1000 eV
  - Universal
  - Storage device
  - Space-charge limitation
  - Inexpensive

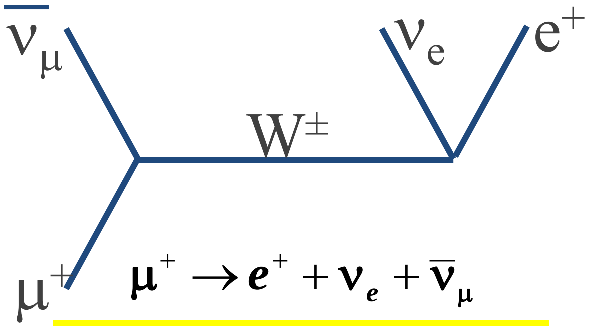
- **Magneto-optical trap**
  - Trapping potential ~ μeV
  - Alcali with good efficiency, others with more difficulty
  - Not a precision device, but a great cooler
  - No space-charge limitation
  - Expensive

Example of low energy “opportunities”

- Detailed look at present and planned work
    - Superallowed Fermi decay
    - Angular correlations in β-decay
    - PNC in atoms
    - EDM
    - others …

CKM matrix and universality of weak interaction

purely leptonic decay



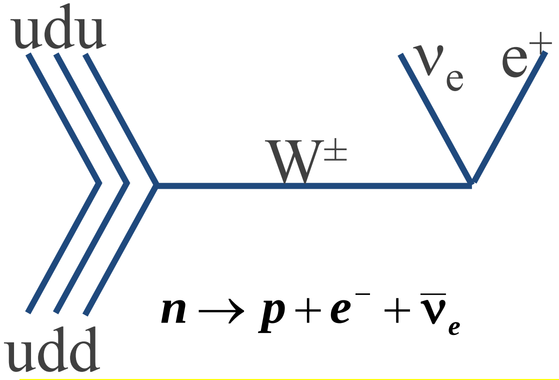
$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$

$G_V = G_F = G_\mu$

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

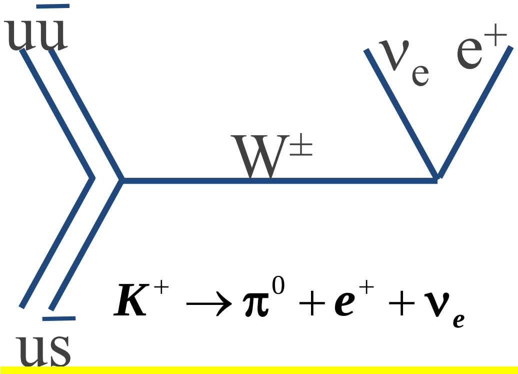
weak eigenstates **rotation matrix** **mass eigenstates**

semileptonic decays



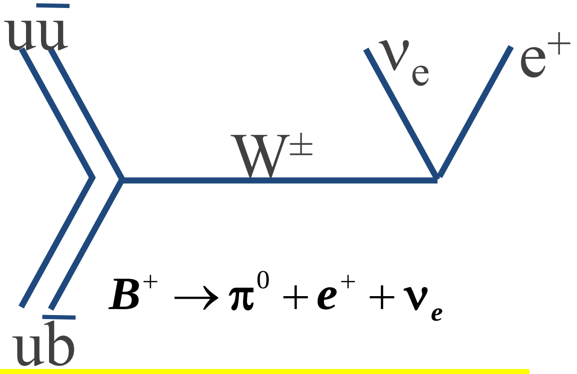
$n \to p + e^- + \bar{\nu}_e$

$G_V = G_F|V_{ud}| = G_F \cos\theta_C$



$K^+ \to \pi^0 + e^+ + \nu_e$

$G_V = G_F|V_{us}| = G_F \sin\theta_C$



$B^+ \to \pi^0 + e^+ + \nu_e$

$G_V = G_F|V_{ub}|$

Superallowed Beta Decay

- » **Precision tests of CVC**
- » **Determination of weak vector coupling constant and V_{ud}**
- » **Unitary tests of the CKM matrix**

- Basic β-decay rate equation for allowed decay

$$ft = \frac{K}{G_V^2\left(|M_F|^2 + g_A^2|M_{GT}|^2\right)}$$

- Superallowed transitions between 0^+ T=1 states
  - $0^+ \rightarrow 0^+$ is a pure vector (Fermi) decay within SM
  - CVC tells us that all such decays should have same ft value

$$ft_{0+\rightarrow 0+} = \frac{K}{G_V^2|M_F|^2} = \text{const.}$$

with, within isospin symmetry, $|M_F|^2 = T(T+1) = 2$ for T=1 analog states.

Weak interaction rates

Rate by Fermi's golden rule:

$$d\lambda(E) = \left(\frac{2\pi}{\hbar}\right)\left|H_{fi}\right|^2 \rho(E)$$

density of final states strongly influences rate.

- **beta decay (3 bodies in the final state):**

$$\lambda(p_e) = \frac{g^2\left|M_{if}\right|^2}{2\pi^3\hbar^7 c^3} p_e^2 F(Z,E_e)(E_0 - E_e)\left[(E_0 - E_e)^2 - (m_\nu c^2)^2\right]^{1/2} dp_e$$

$$\boxed{\lambda = \frac{\ln 2}{t_{1/2}} = \frac{m_e^5 g^2 c^4\left|M_{if}\right|^2}{2\pi^3\hbar^7} f(Z,E_0)} \quad (\text{with } f \sim E^5)$$

- **neutrino capture (2 bodies in final state):**

$$\boxed{\sigma_\nu = \frac{g^2\left|M_{if}\right|^2 F(Z,E) p_e E_e}{\pi\hbar^4 c^3}} \quad (\sigma \sim E^2)$$

Superallowed Beta Decay

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with, within isospin symmetry, $|M_F|^2 = T(T+1) = 2$ for T=1 analog states.

Superallowed Beta Decay

- Demonstrating that all such ft values (accounting for small corrections) are constant tests CVC, puts stringent limits on scalar currents, and yields best value of G_V.

- Basic test for physics beyond the standard model

  G_v together with G_μ yield

  the V_{ud} quark mixing element

  of the CKM matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- If matrix is not unitary then we need new physics

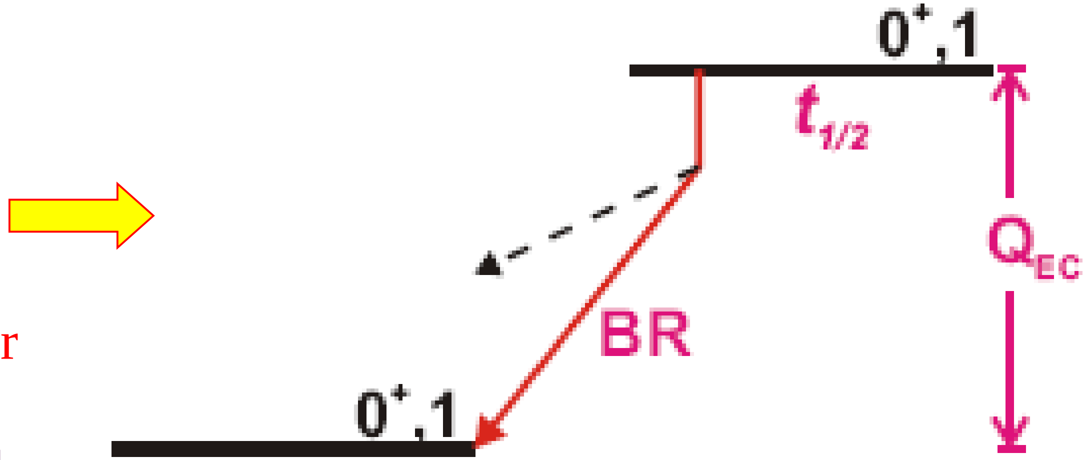
  Additional Z bosons, Right-handed currents, …

Experimental inputs to Superallowed Fermi Decay

We require:

- Q-value
- lifetime
- branching ratio

Goal is for ft value at better than 0.1%. Last two measurements are required to that level, first one to 5 times better. All are at the limit of what present technology allows.



Theoretical inputs to Superallowed Fermi Decay

WEAK DECAY EQUATION

$$ft = \frac{K}{G_V^2 \langle \tau \rangle^2}$$

$f = f(Z, Q_{EC})$

$t = f(t_{1/2}, BR)$

G_V = coupling constant

$\langle \tau \rangle$ = matrix element

RADIATIVE CORRECTIONS

$$t \longrightarrow t(1 + \delta'_R + \delta_{NS})$$

$$G_V^2 \longrightarrow G_V^2(1 + \Delta_R)$$

$\delta'_R = f(Z, Q_{EC})$

$\delta_{NS} = f$(nuclear structure)

$\Delta_R = f$(interaction)

T SYMMETRY-BREAKING CORRECTIONS

$$\langle \tau \rangle^2 \longrightarrow 2(1 - \delta_C)$$

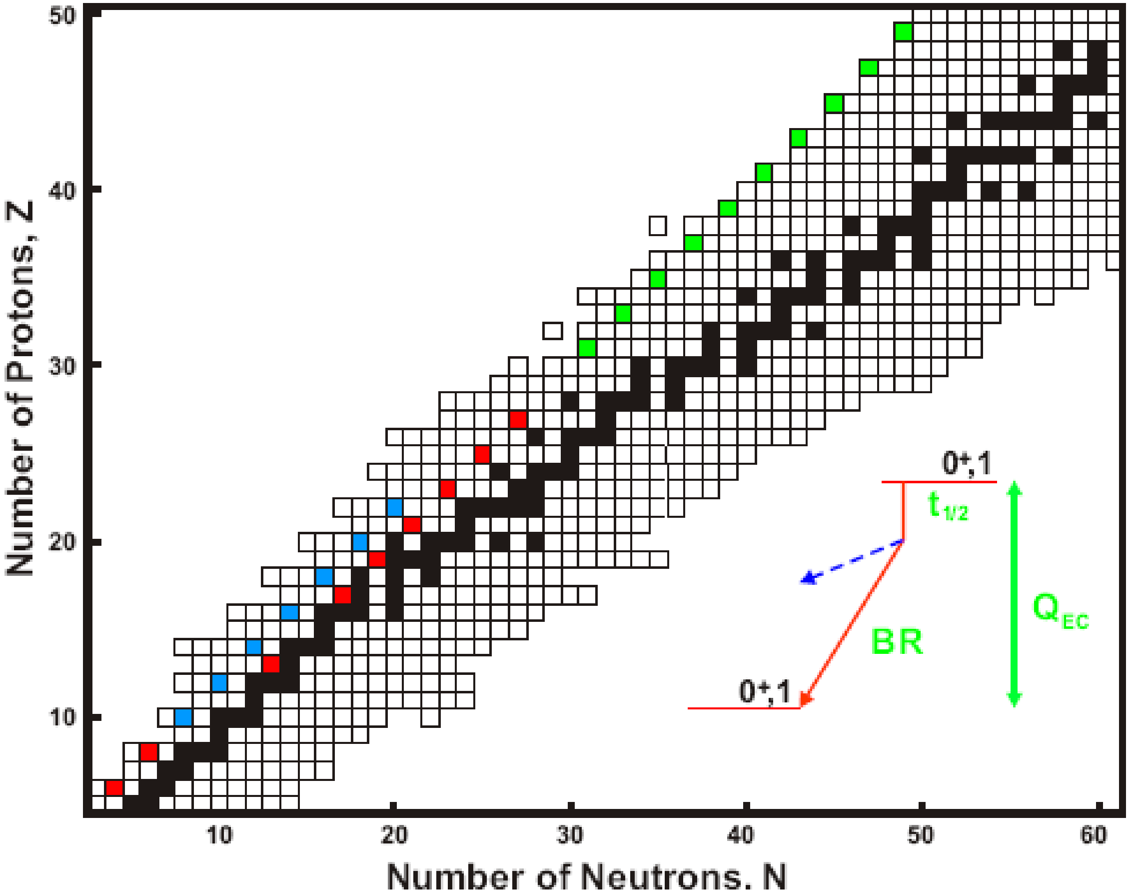
$\delta_C = f$(nuclear structure)

CVC

$$\mathcal{F}t = ft(1 + \delta'_R + \delta_{NS})(1 - \delta_C) = \frac{K}{2G_V^2(1 + \Delta_R)}$$

CONSTANT

Superallowed Fermi decay candidates



8 “golden” cases:

^{14}O to ^{54}Co

- superallowed Fermi branch > 99%
- daughter is a stable nucleus

- And a whole bunch of good but difficult cases

Precision measurements --- lifetime

- In principle simplest measurement there is … yet this is where the biggest mistakes have been made

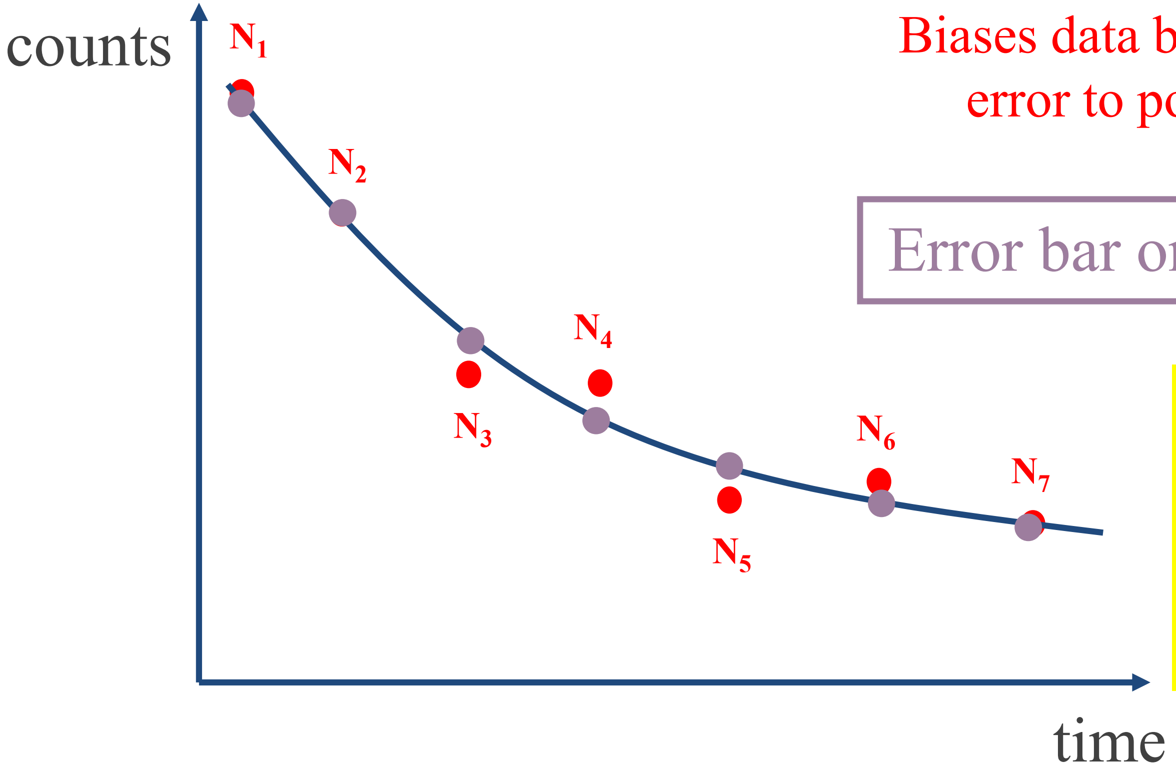
- At the required accuracy of about 0.05%, no measurement done before 1970 (maximum likelihood introduced) is correct. Analysis procedure needs to be tested with pseudo-data and Poisson statistics.

- This is not high energy: signature is one low energy β … backgrounds are present. Need to collect data for about 14 to 20 lifetimes to fix background … analysis cannot do it reliably otherwise.

- In practice, use mass separated samples if available, almost 100% efficient detector (to eliminate pile-up), and fixed deadtime in the electronics (we often used two parallel acquisitions with different deadtime to check systematics).

Precision lifetime measurements can easily be corrupted in the experiment or the analysis

N_i is number of counts per time interval



~~Error bar on N_i → $(N_i)^{1/2}$~~

Biases data by assigning smaller error to point below curve

Error bar on N_i → $(N_{i\text{-fit}})^{1/2}$

Difference in extracted lifetime can be many σ !

Precision measurements --- lifetime

- In principle simplest measurement there is … yet this is where the biggest mistakes have been made
- At the required accuracy of about 0.05%, no measurement done before 1970 (maximum likelihood introduced) is correct. Analysis procedure needs to be tested with pseudo-data and Poisson statistics.
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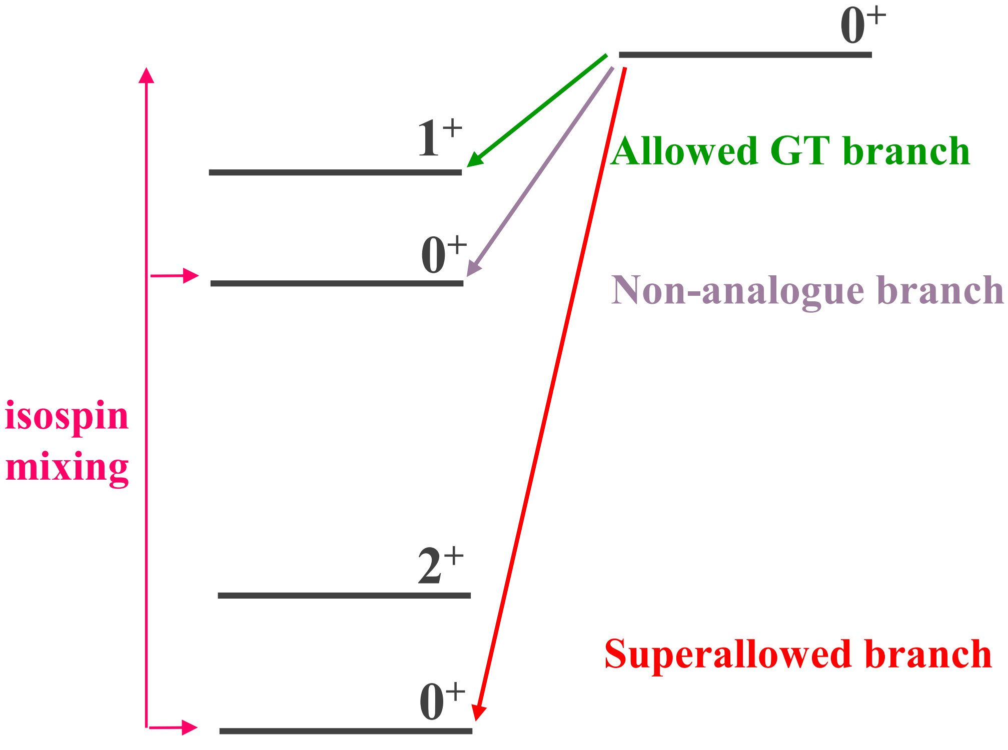
- In practice, use mass separated samples if available, almost 100% efficient detector (to eliminate pile-up), and fixed deadtime in the electronics (we often used two parallel acquisitions with different deadtime to check systematics).

Precision measurements --- branching ratio

- parent and daughter are not perfect analogues
  - measured rate lower than expected
  - isospin mixing one contributing factor

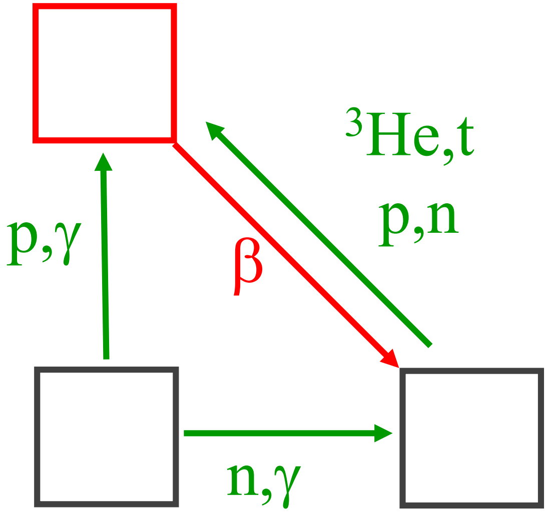
- necessary experimental quantity

- aid theory (calculated correction terms)



Precision measurements --- Q-value

- required precision (0.1 – 1 keV) cannot be reached by endpoint measurement
- Use reaction threshold (neutron yield vs energy for p,n reaction) or gamma-ray energy
- Difficulty then lies in proton energy calibration
- Can only be applied to nuclei whose daughter is a stable target



For Isotopes whose daughter is not stable: Precision measurements in a Penning trap

Can use:

$$\omega_c = \omega_+ + \omega_-$$

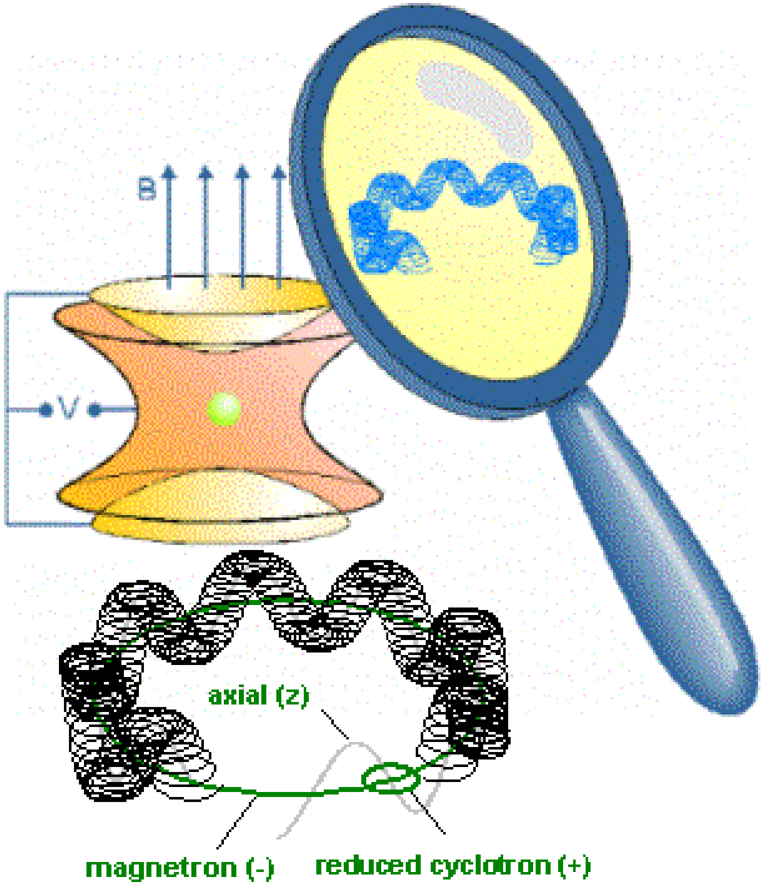
$$\omega_c^2 = \omega_+^2 + \omega_-^2 + \omega_z^2$$

Recall:

$$\omega_c = \frac{qB}{\gamma m}$$

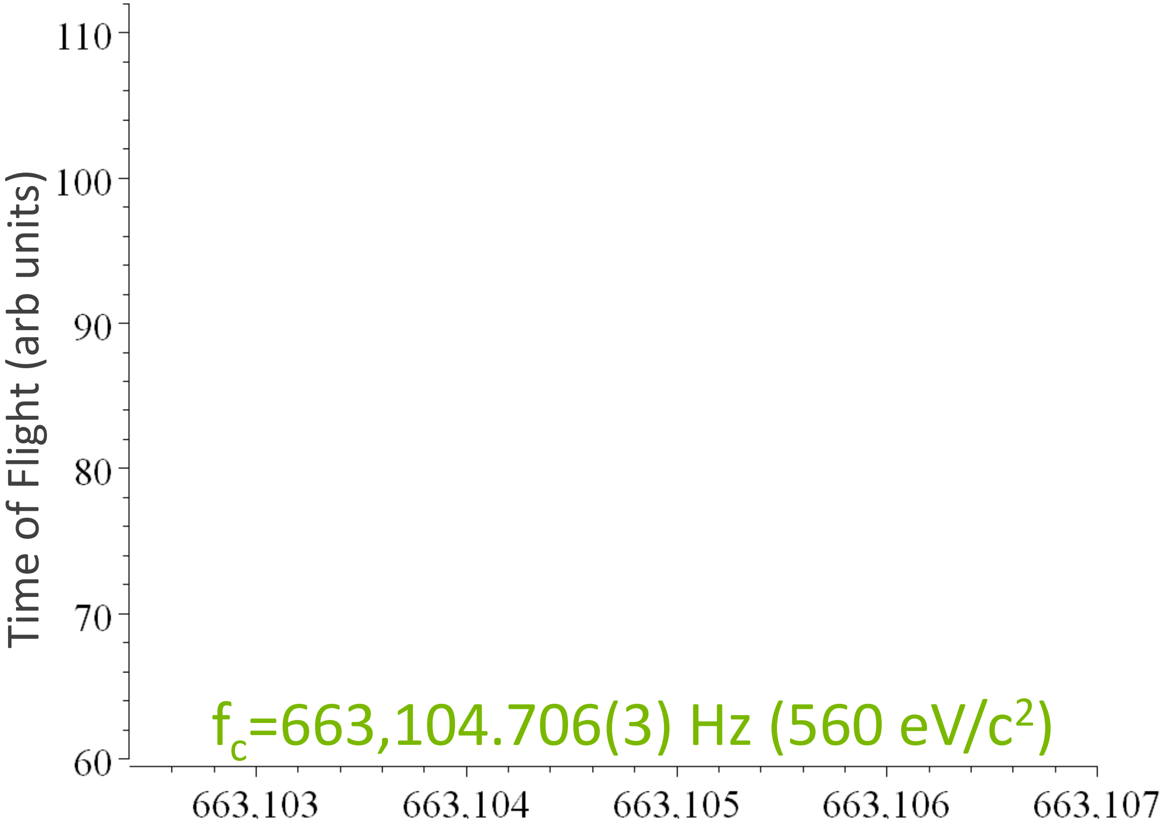
ω_c depends only on:

- the mass
- the magnetic field
- not on the electric fields or the energy as long as γ is small



Can use ω_c to make accurate and precise mass measurements

Sample time-of-flight (TOF) spectrum



f_c=663,104.706(3) Hz (560 eV/c^2)

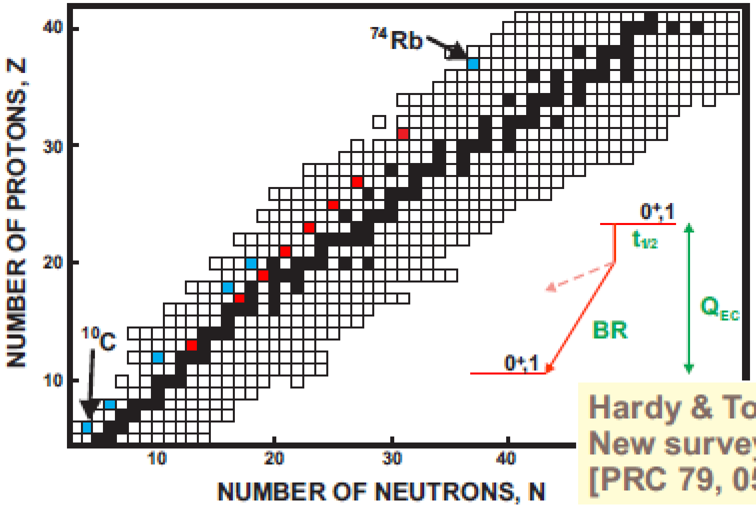
$$\omega_c = \frac{q_c B_c}{m_c}$$

Unknown: $\omega_? = \frac{q_? B_c}{m_?}$

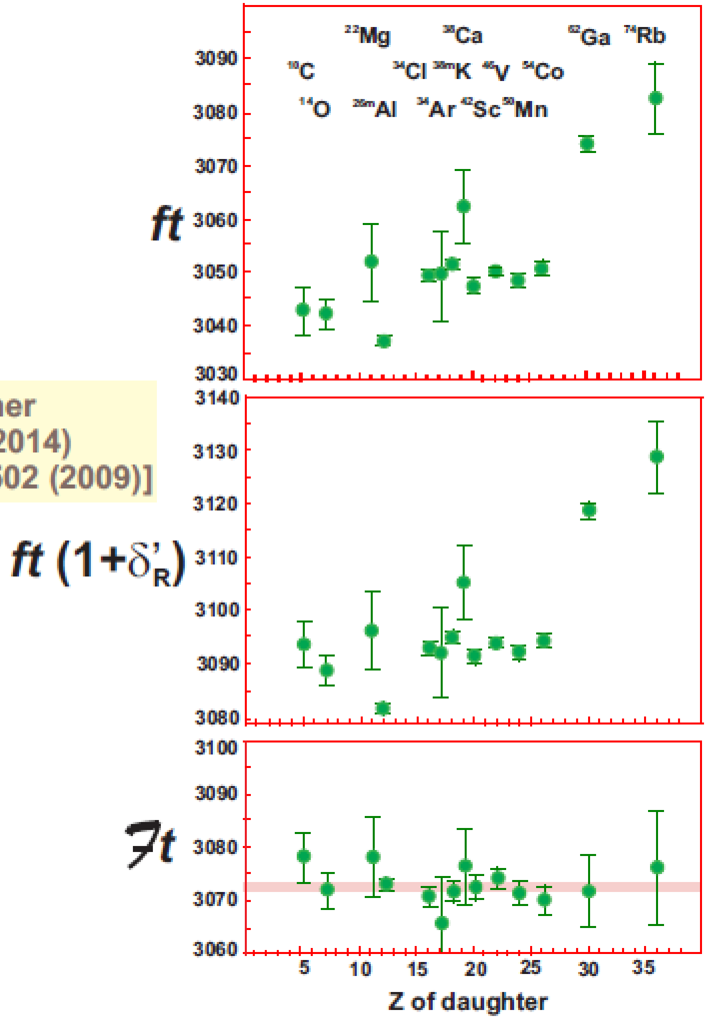
$$\frac{Unknown}{Calibration} \Rightarrow m_? = \frac{q_?}{q_c}\frac{\omega_c}{\omega_?} m_c$$

Well-known calibrant mass is a requirement for accurate measurements, use ^{133}Cs (known to ~ 0.01 keV) in this region.

0+ → 0+ status as of 2014



Hardy & Towner
New survey (2014)
[PRC 79, 055502 (2009)]



- 8 cases with *ft*-values measured to <0.05% precision; 6 more cases with 0.05-0.3% precision.
- ~220 individual measurements with compatible precision

$$\mathcal{F}t = ft\,(1 + \delta'_R)[1 - (\delta_C - \delta_{NS})] = \frac{K}{2G_V^2\,(1 + \Delta_R)}$$

Results from 0+ →0+ decays

FROM A SINGLE TRANSITION

Experimentally determine $G_V^2(1 + \Delta_R)$

$$\mathcal{F}t = ft\,(1 + \delta'_R)[1 - (\delta_C - \delta_{NS})] = \frac{K}{2G_V^2\,(1 + \Delta_R)}$$

FROM MANY TRANSITIONS

Test Conservation of the Vector current (CVC)

G_V constant to ± 0.013%

Validate correction terms ✓

Test for Scalar current

limit, $C_S/C_V = 0.0014\,(13)$

WITH CVC VERIFIED

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

weak eigenstates

mass eigenstates

Cabibbo-Kobayashi-Maskawa matrix

Obtain precise value of $G_V^2(1 + \Delta_R)$

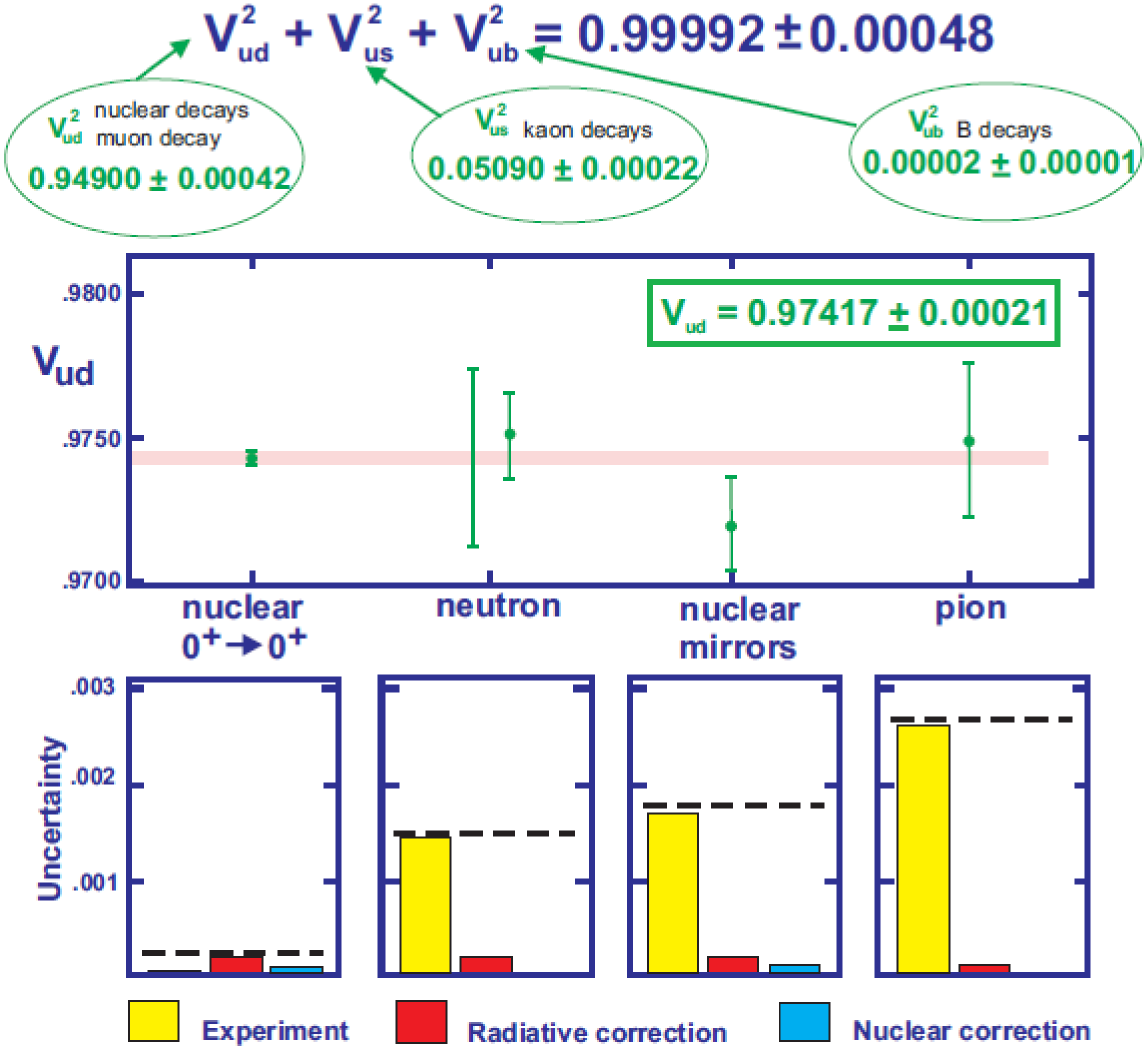
Determine V_{ud}^2

$$V_{ud}^2 = G_V^2/G_\mu^2 = 0.94900 \pm 0.00042$$

Test CKM unitarity

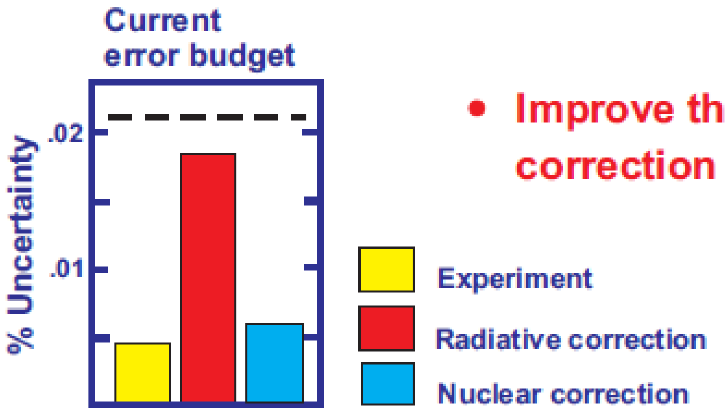
$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.99992 \pm 0.00048$$

Status of CKM unitarity



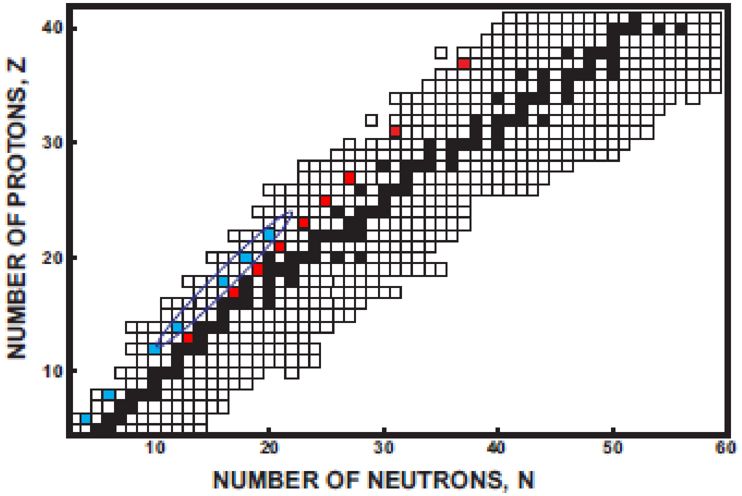
Courtesy of J.C. Hardy

Next step: Improving V_{ud} and CKM matrix unitarity



- Improve the calculation of the “inner” radiative correction Δ_R.

Currently Δ_R = 2.361(38) %
Marciano & Sirlin, PRL **96,** 032002 (2006)



- Potentially improve nuclear correction by completing the pairs of mirror superallowed decays with A ≤ 42.

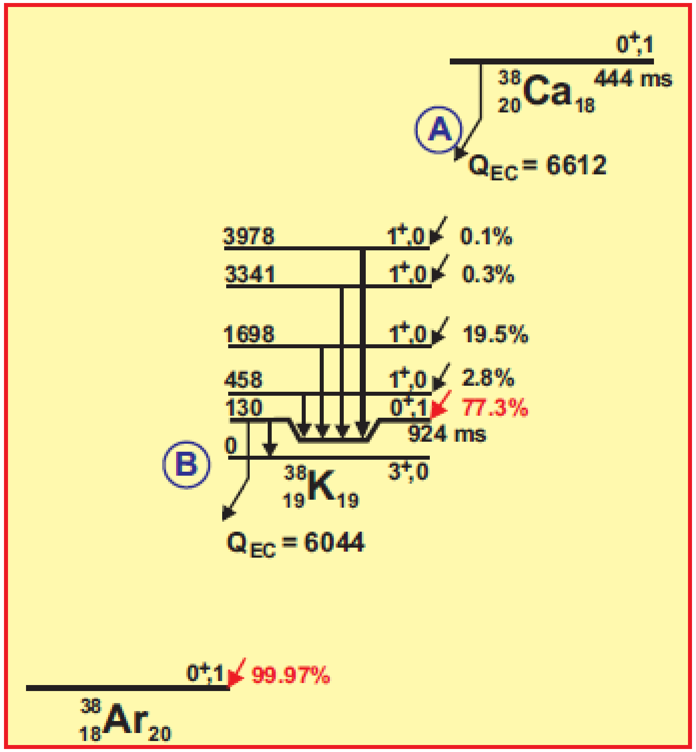
^{38}Ca done
H.I. Park *et al.*, PRL **112,** 102502 (2014)

^{26}Si, ^{34}Ar and ^{42}Ti remain

- If theory improves, broadly improve all experimental *ft* values

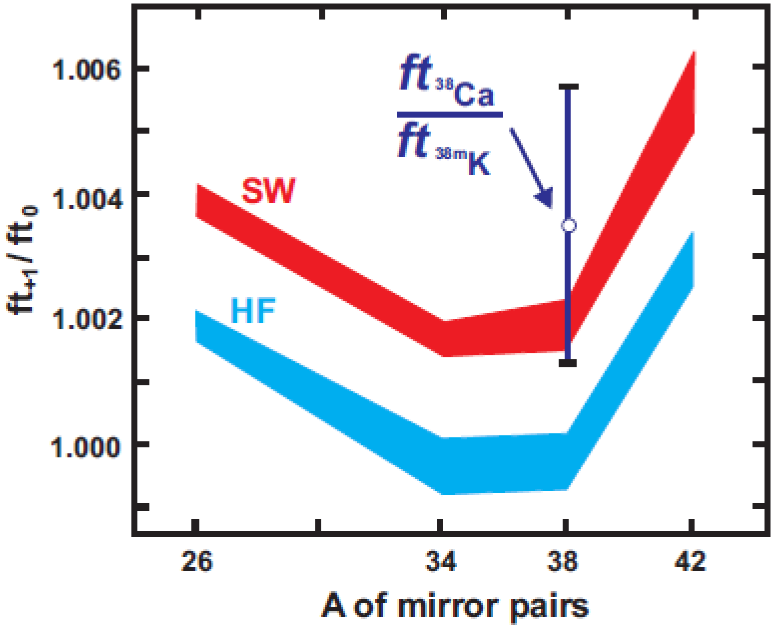
Testing δ_c calculations with measurements of mirror superallowed transitions

$$\mathcal{F}t = ft\,(1 + \delta'_R)[1 - (\delta_C - \delta_{NS})]$$



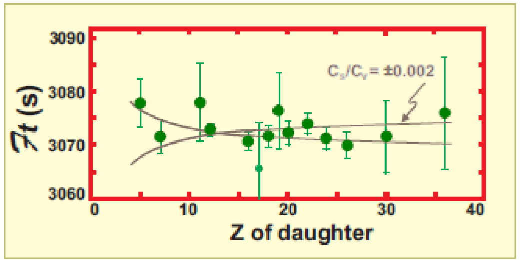
$$\frac{ft_A}{ft_B} = \frac{(1 + \delta'^B_R)[1 - (\delta^B_C - \delta^B_{NS})]}{(1 + \delta'^A_R)[1 - (\delta^A_C - \delta^A_{NS})]}$$

$$= 1 + (\delta'^B_R - \delta'^A_R) + (\delta^B_{NS} - \delta^A_{NS}) - (\delta^B_C - \delta^A_C)$$



Further progress coming at low-energy

Search for scalar currents

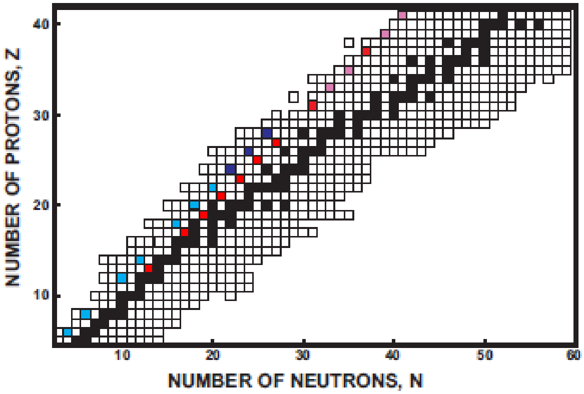


limit, $C_s/C_v = 0.0014\ (13)$

- Tighten uncertainties on the *ft* values for ^{10}C and ^{14}O

Require (order of priority):
^{10}C branching ratio
^{14}O branching ratio
^{14}O Q_{EC} value
^{10}C half-life

Adding new transitions



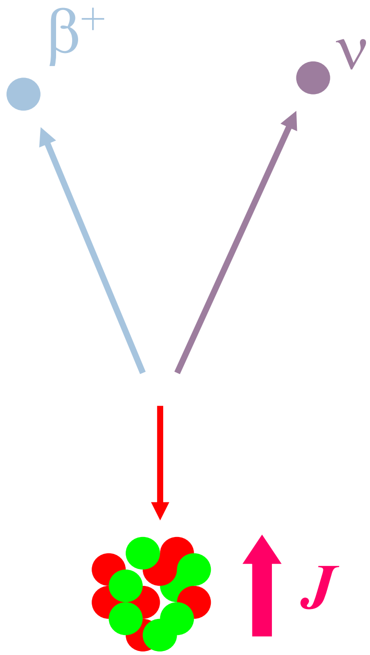
- Potential FRIB measurements

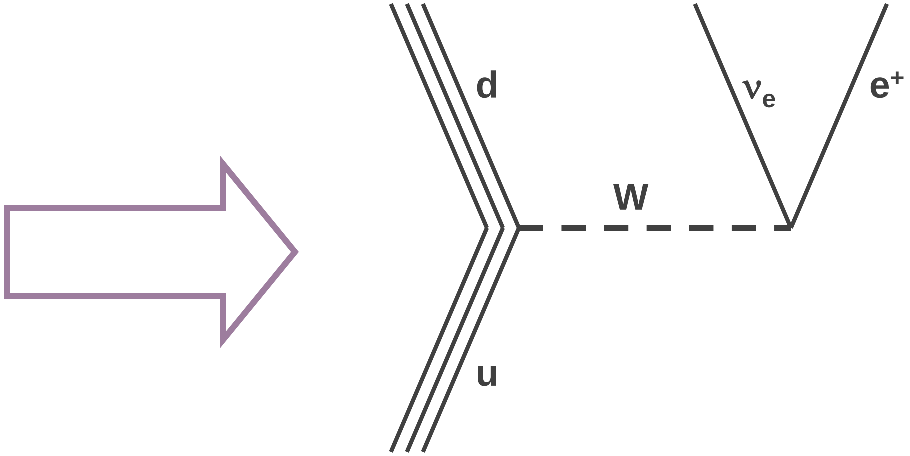
- Complete more pairs of mirror superallowed transitions: ^{46}Cr, ^{50}Fe, ^{54}Ni ...

Tests δ_C, δ_{NS} calculations in $f_{7/2}$ shell nuclei

- Add new heavy $T_z = 0$ superallowed emitters: ^{66}As, ^{70}Br, ^{78}Y ...

Correlations in nuclear β-decay





- exchanged boson properties determine character of interaction (must conserve energy, momentum, angular momentum, etc …)

  e.g. vector boson in an allowed Fermi decay (no angular momentum for emitted particles) implies that the lepton spins must anti-align (since no spin change) … i.e. neutrino and positron (opposite chirality) emitted preferentially in the same direction in Fermi decay

- interaction best studied in decay selected to limit other contributions

Basic rules for getting form of Γ

Take neutron beta decay as an example $n \rightarrow p + e^- + \bar{\nu}_e$

Available vectors: $\vec{\sigma}_n, \vec{p}_n, \vec{\sigma}_p, \vec{p}_p, \vec{\sigma}_e, \vec{p}_e, \vec{\sigma}_\nu, \vec{p}_\nu$

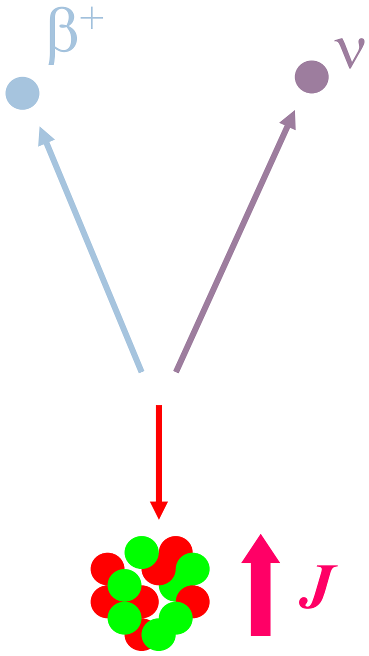
Γ is invariant under rotation so scalar or pseudoscalar and can therefore contain terms like

$$\begin{array}{lll} \vec{\sigma}_n \bullet \vec{\sigma}_p & \vec{\sigma}_n \bullet \vec{p}_e & \longleftarrow \textbf{P-violating} \\ \vec{p}_p \bullet \vec{p}_e & \vec{\sigma}_n \bullet \left(\vec{p}_e \times \vec{p}_\nu\right) & \leftarrow \textbf{T-violating} \\ \vec{p}_\nu \bullet \vec{p}_e & \cdots\cdot & \end{array}$$

Using as independent vectors $\vec{\sigma}_n, \vec{p}_e, \vec{p}_\nu$:

$$\Gamma \propto 1 + \alpha\left(\vec{p}_e \bullet \vec{p}_\nu\right) + \vec{\sigma}_n \bullet \left[A\,\vec{p}_e + B\,\vec{p}_\nu + D\,\vec{p}_e \times \vec{p}_\nu\right]$$

Angular correlations in β-decay



Angular correlations between momentum and spin vectors of the particle emitted in beta-decay yield information about the nature of the interaction.

- 🟦 Compare experimental values to SM predictions
- 🟧 Put limits on terms “forbidden” by SM

$$dW = dW_o\varepsilon\left[1+\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu}a+\frac{\Gamma m_e}{E_e}b+\vec{J}\cdot\left(\frac{\vec{p}_e}{E_e}A+\frac{\vec{p}_\nu}{E_\nu}B+\frac{\vec{p}_e\times\vec{p}_\nu}{E_eE_\nu}D\right)+\dots\right]$$

Boson mass range that can be probed

If you observe a nuclear beta-decay,
even in a table top experiment,
you are already at 80.4 GeV/c^2.

How high can you go?

Coupling ~ $(M^2 – q^2)^{-1}$ $\longrightarrow$ M^{-2} (as $q \rightarrow 0$)
Observable ~ $(\text{Coupling})^2$ $\longrightarrow$ M^{-4} (as $q \rightarrow 0$)

1 % expt $\longrightarrow$ $(0.01)^{-4}\, M_W \sim 260$ GeV/c^2
0.1% expt $\longrightarrow$ $(0.001)^{-4}\, M_W \sim 460$ GeV/c^2

Sensitivity is also different than for other experiments, eg: non-manifest left-right model (assuming $\zeta=0$ and ν_R much lighter than M_R), we get the following sensitivities:

nuclear β-decay

$$\left(\frac{g_R}{g_L}\right)^4\left(\frac{V_{ud_R}}{V_{ud_L}}\right)^2\left(\frac{M_L}{M_R}\right)^4$$

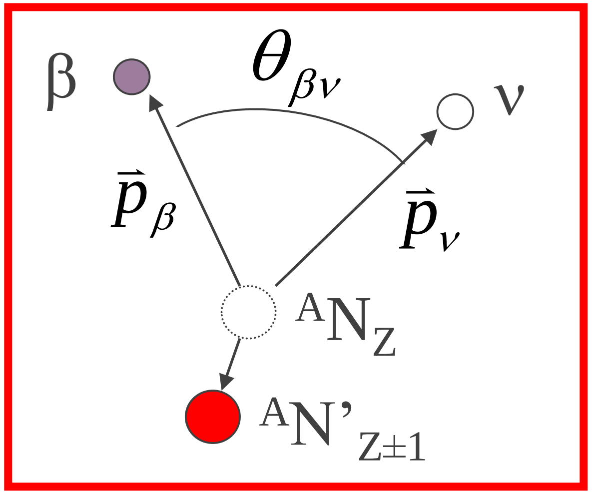
μ decay

$$\left(\frac{g_R}{g_L}\right)^4\left(1-\left(\frac{V_{ud_R}}{V_{ud_L}}\right)^2\right)\left(\frac{M_L}{M_R}\right)^4$$

pp collider

$$\left(\frac{g_R}{g_L}\right)^2\left(\frac{V_{ud_R}}{V_{ud_L}}\right)^2 function\left(\frac{M_L}{M_R}\right)$$

β–ν Correlation



$$\Gamma \propto 1 + a_{\beta\nu} \frac{\vec{p}_\beta \cdot \vec{p}_\nu}{E_\beta E_\nu}$$
$$\propto 1 + a_{\beta\nu} \frac{v}{c} \cos\theta_{\beta\nu}$$

Experiments difficult – correlation inferred from recoil of nucleus

a > 0 leads to larger average recoil energies

Recoil energy ~ 100 eV

1) requires acceleration of daughters
2) infer recoil from energy shift in subsequent particle decay

Continuous energy spectra in all particles

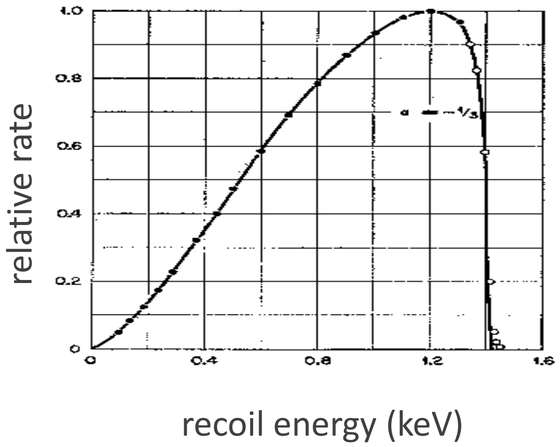
sensitive to detector thresholds and resolution
sensitive to approximations made about underlying physics

Correlation easily perturbed by molecular effects, scattering, etc…

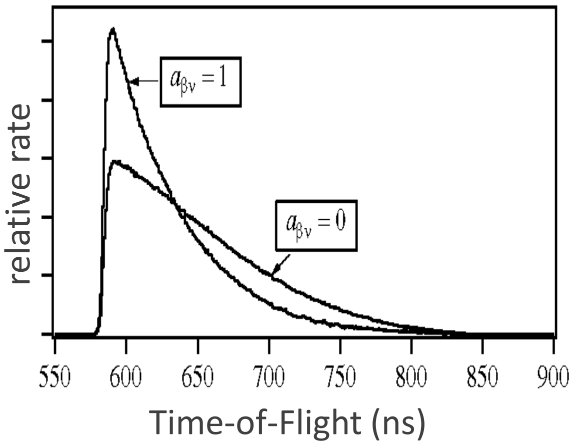
How to measure?

Avoid detecting neutrino, measure other observables related to $\theta_{(\beta\nu)}$.

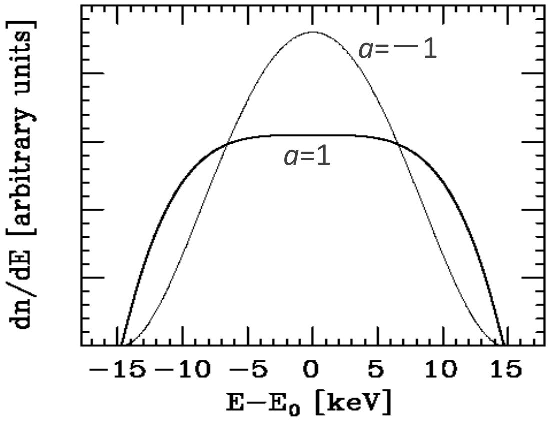
Measure decay product energy directly	Measure TOF of recoil nucleus	Measure delayed particle emission
n, ^{19}Ne, ^{23}Ne, ^{35}Ar, ^{60}Co(β) ^{6}He	n, ^{6}He, ^{38M}K ^{21}Na, ^{37}K, ^{19}Ne	^{8}Li, ^{11}Be, ^{14}O ^{18}Ne, ^{20}Na, ^{32}Ar(p)



C.H. Johnson *et al*. Phys. Rev. 132, 1149



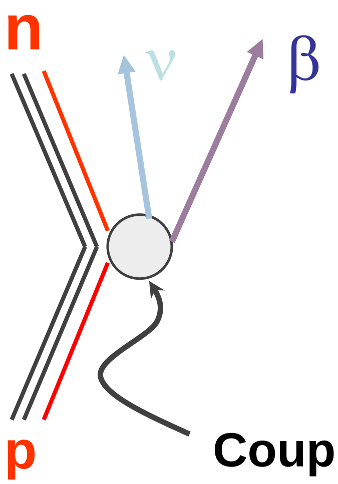
N. D. Scielzo *et al.* PRL.93,102501, 2004



0+ → 0+ delayed proton for *a*=1 & *a*=-1

E.G. Adelberger *et al.* PRL.83, 1299 (1999).

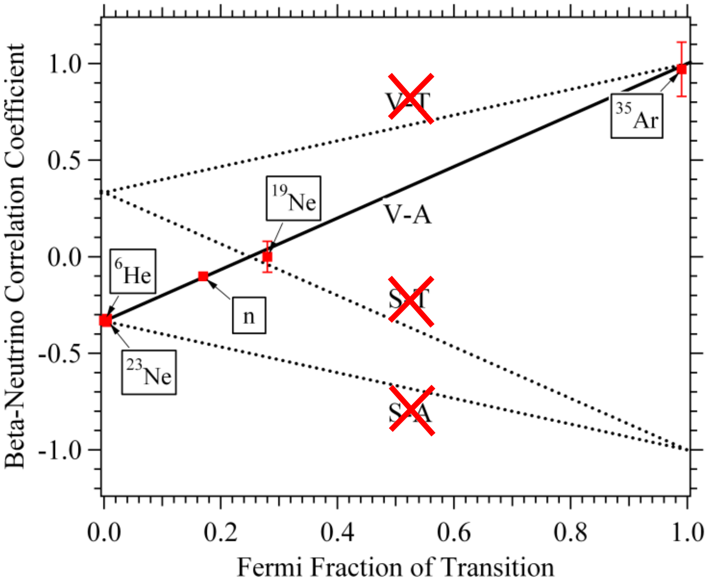
Measurements of β-decay angular correlations helped establish the V-A structure of the electroweak interaction



Coupling constants:
C_V, C_A, $\cancel{C_S}$, $\cancel{C_T}$

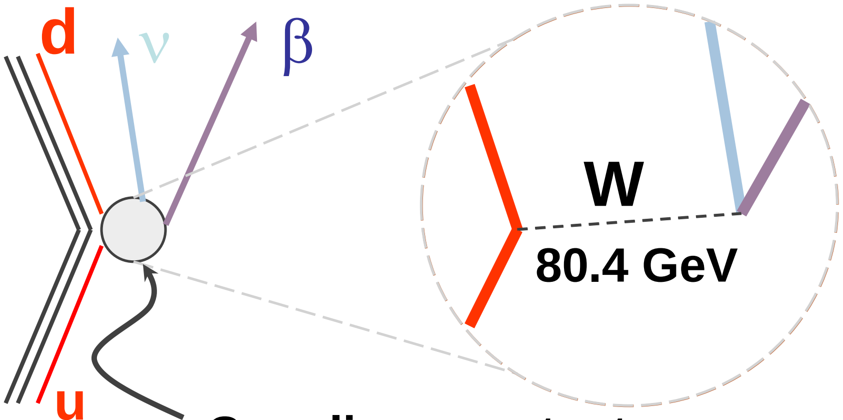
$$\boxed{dW = dW_o\left[1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} + b\frac{\Gamma m_e}{E_e}\right]}$$

In the 1960's, the *V-A* structure of the weak interaction was determined by measurements of the beta-neutrino correlation, ***a***, in noble gas nuclei



Fermi decay → C_V, C_S
Gamow-Teller decay → C_A, C_T

Measurements of β-decay angular correlations helped establish the V-A structure of the electroweak interaction

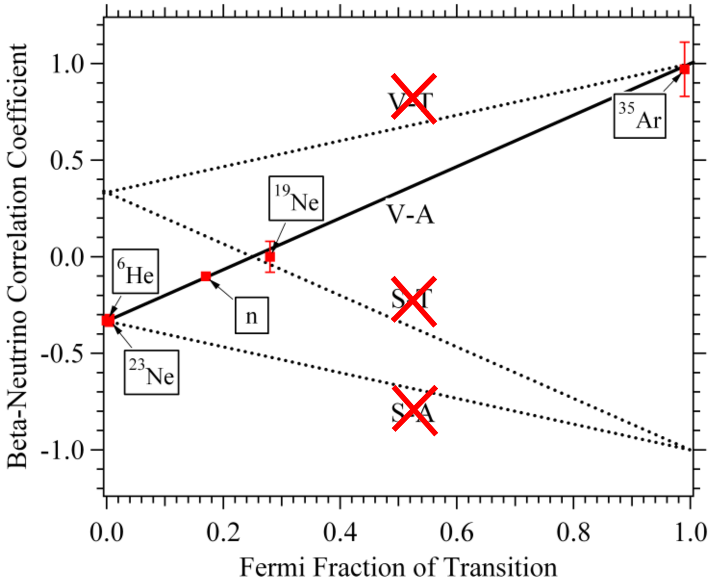


Coupling constants:

$C_V, C_A, \cancel{C_S}, \cancel{C_T}$

$$dW = dW_o\left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{\Gamma m_e}{E_e}\right]$$

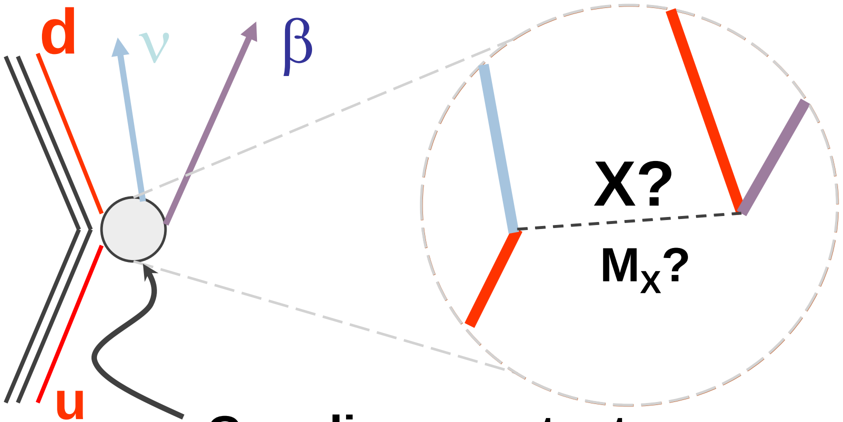
We now know β decay is mediated by the W boson with well known properties



Fermi decay → C_V

Gamow-Teller decay → C_A

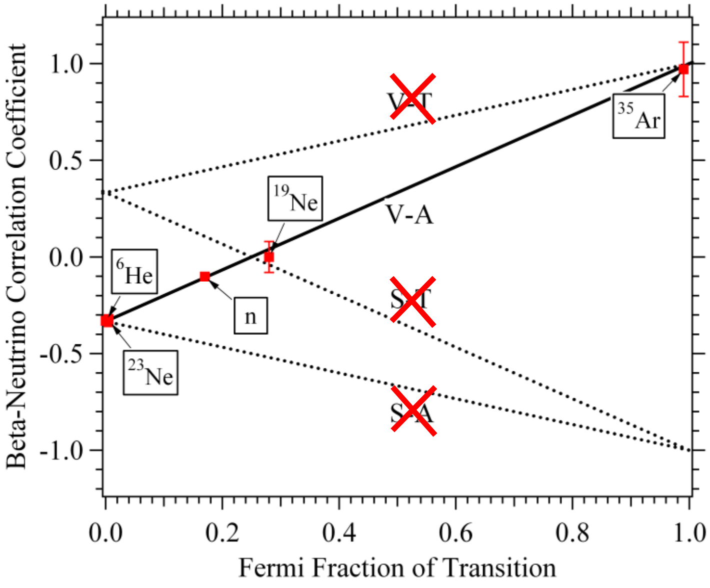
Measurements of β-decay angular correlations helped establish the V-A structure of the electroweak interaction



Coupling constants:
C_V, C_A, C_S?, C_T?

$$dW = dW_o\left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{\Gamma m_e}{E_e}\right]$$

But perhaps there is more to discover if we look closely enough…



Fermi decay → C_V, C_S?

Gamow-Teller decay → C_A, C_T?

At higher precision, have to contend with recoil-order terms, which are sensitive to additional SM symmetries

Give rise to small *E*

$$\boxed{dW \sim \left[\boxed{1} + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e}\right]}$$

Plus additional correlations:

$$g_{10}(E_e) = -\frac{E_e}{M}\left(1+d \mp b_{wm}\right)\cdot\cos^2\theta_{e\alpha}$$

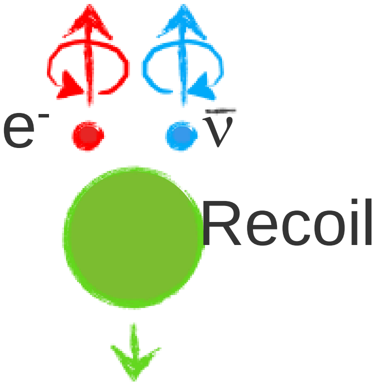
$$\xrightarrow{\quad}\left(1-\frac{2E_0}{3M}\left(1+d\pm b_{wm}\right)+\frac{2E_e}{3M}\left(5\pm 2b_{wm}\right)\right)$$

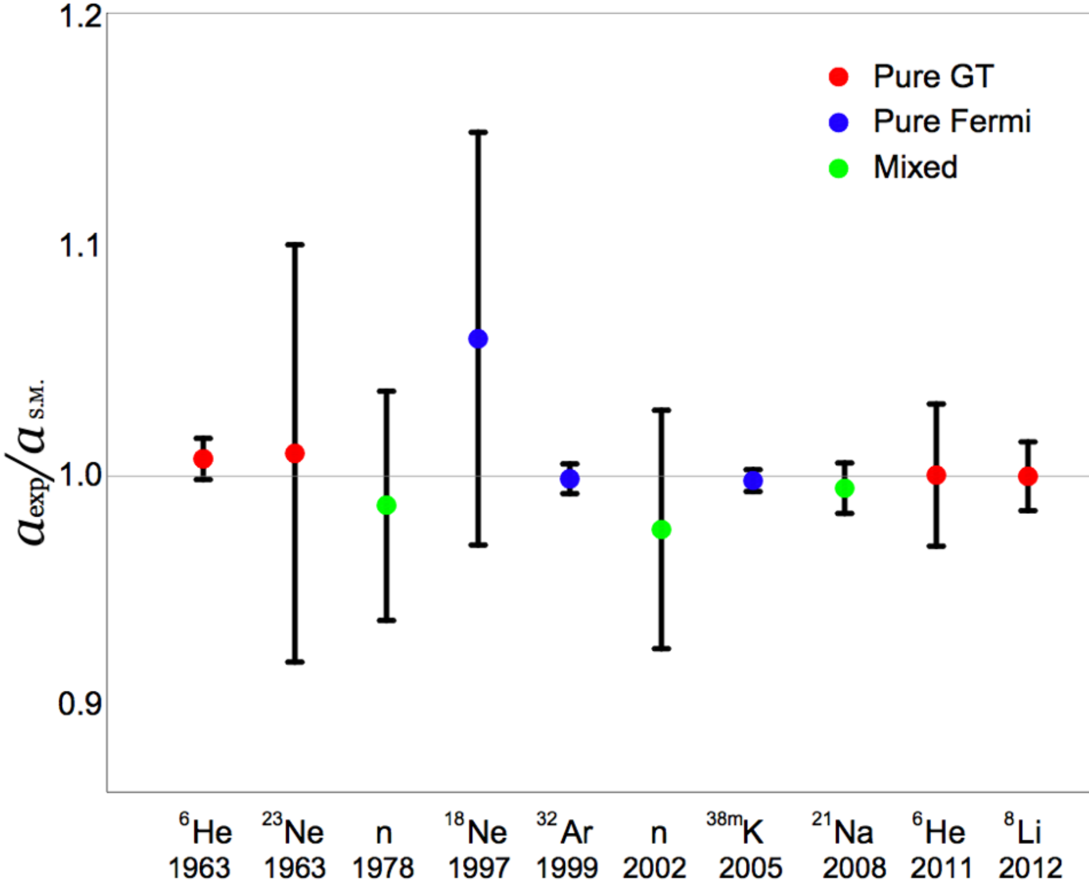
- b_{wm} (changes sign with $\beta^{\pm}$)
  - CVC hypothesis – weak vector coupling constant is not renormalized in the nucleus
- d (independent of $\beta^{\pm}$)
  - Second-class currents – induced terms that do not obey same symmetries as strong interaction

Need to study mirror nuclei to disentangle, e.g. both ^{8}Li and ^{8}B

Intuitive Picture

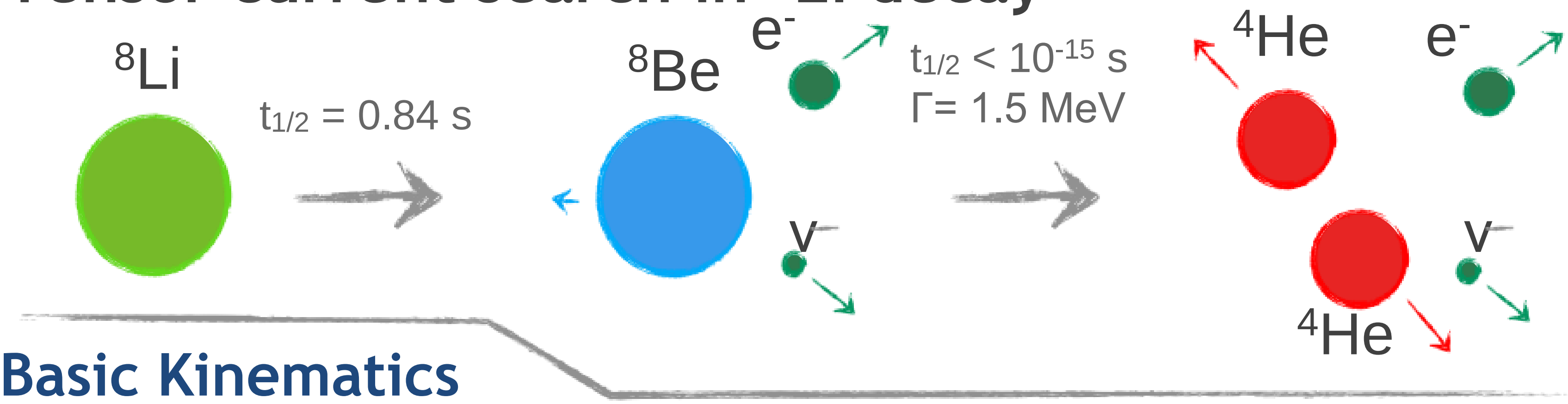
- Fermi Decay
  - ΔJ=0 -> spins anti-align in singlet state
  - e^- & $\bar{\nu}$ couple with opposite helicity
  - e^- & $\bar{\nu}$ are preferentially emitted in same direction → ***a***=+1





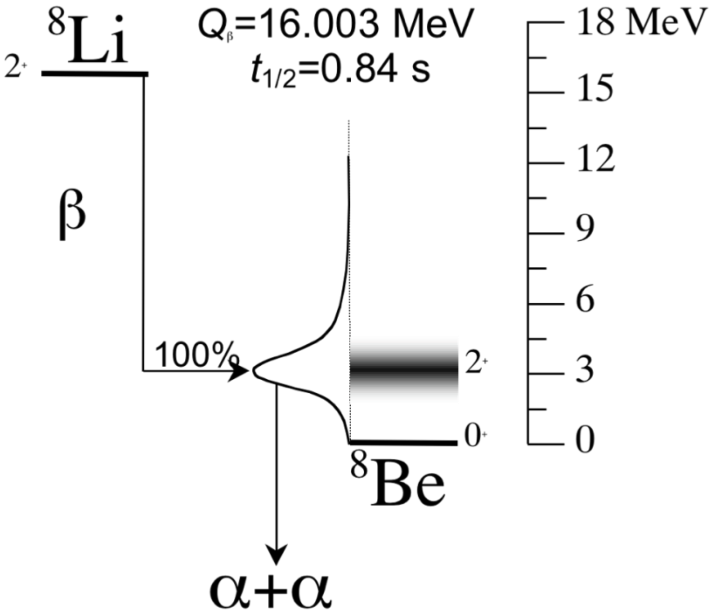
- GT Decay
  - ΔJ=0,±1 -> spins are in triplet
  - same reasoning → ***a***=-1/3

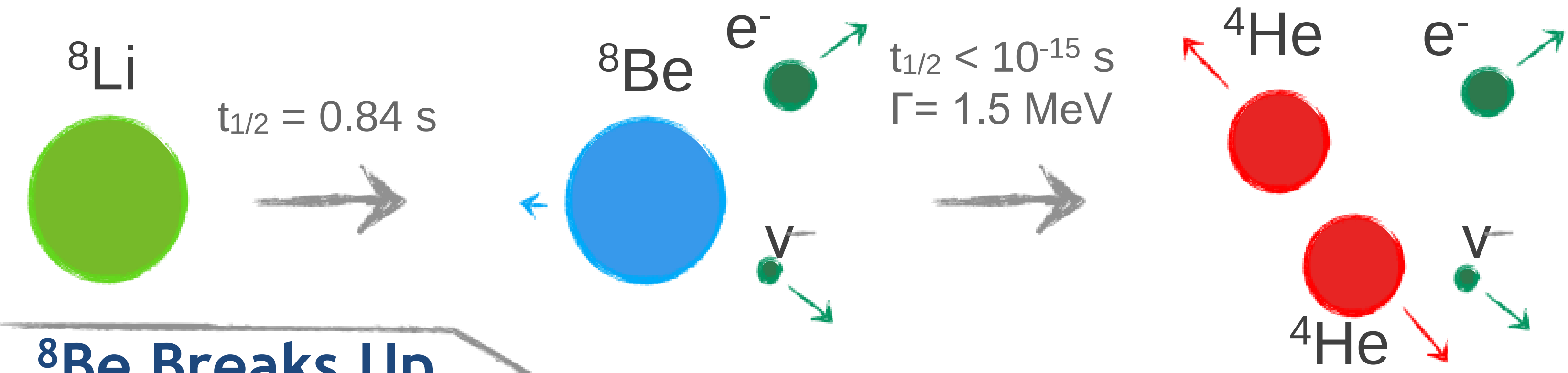
Tensor current search in ^{8}Li decay



Basic Kinematics

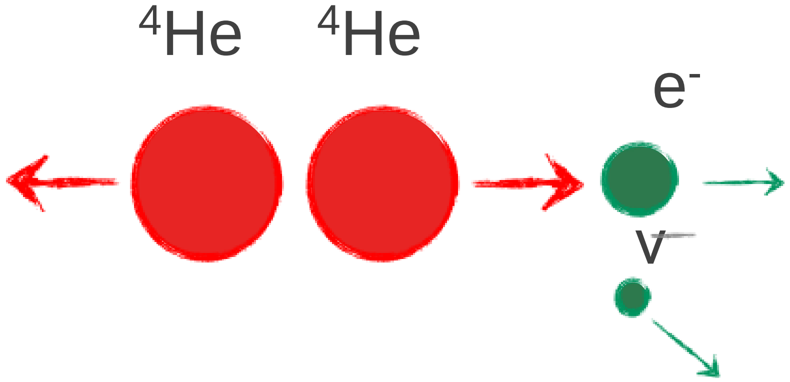
- "Pure" GT decay
- Large Q value and light nucleus gives large recoil energy up to 12 keV
- Immediate breakup to two α's gives coincident constraint providing strong background suppression
- α's are emitted back to back in ^{8}Be rest frame leading to large shifts in lab frame



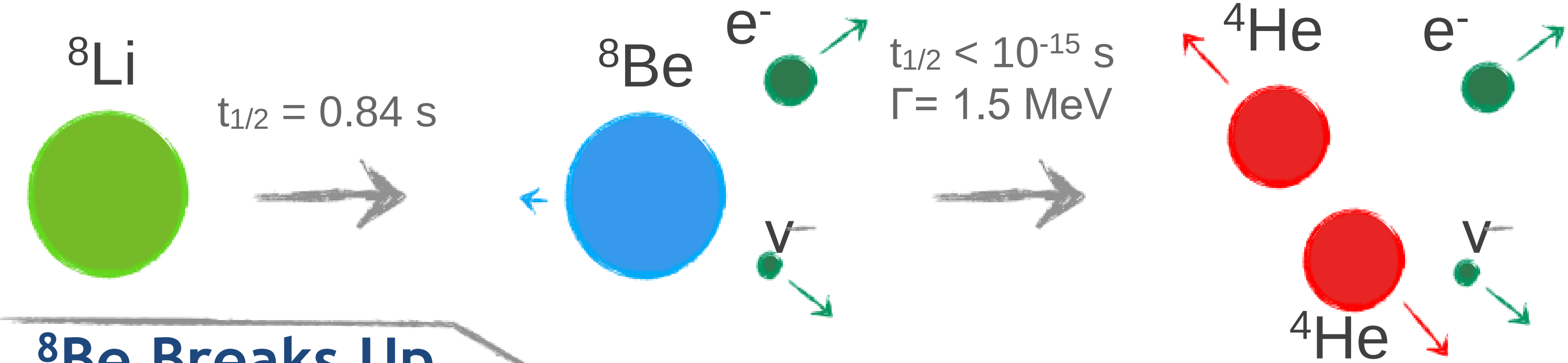


^{8}Be Breaks Up Parallel to e^{-}

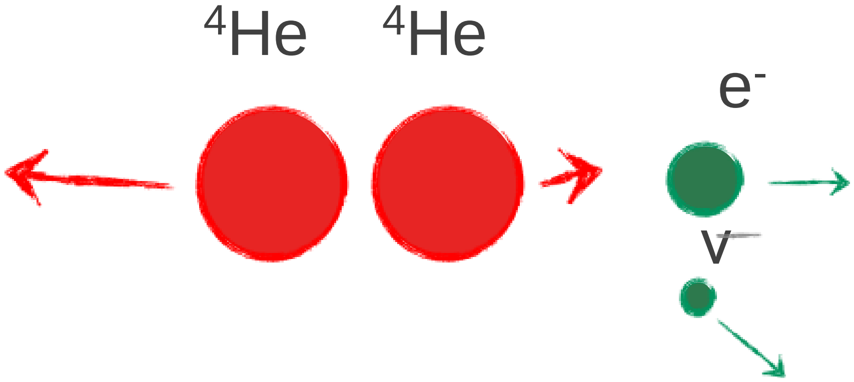
Reference Frame of Recoiling ^{8}Be

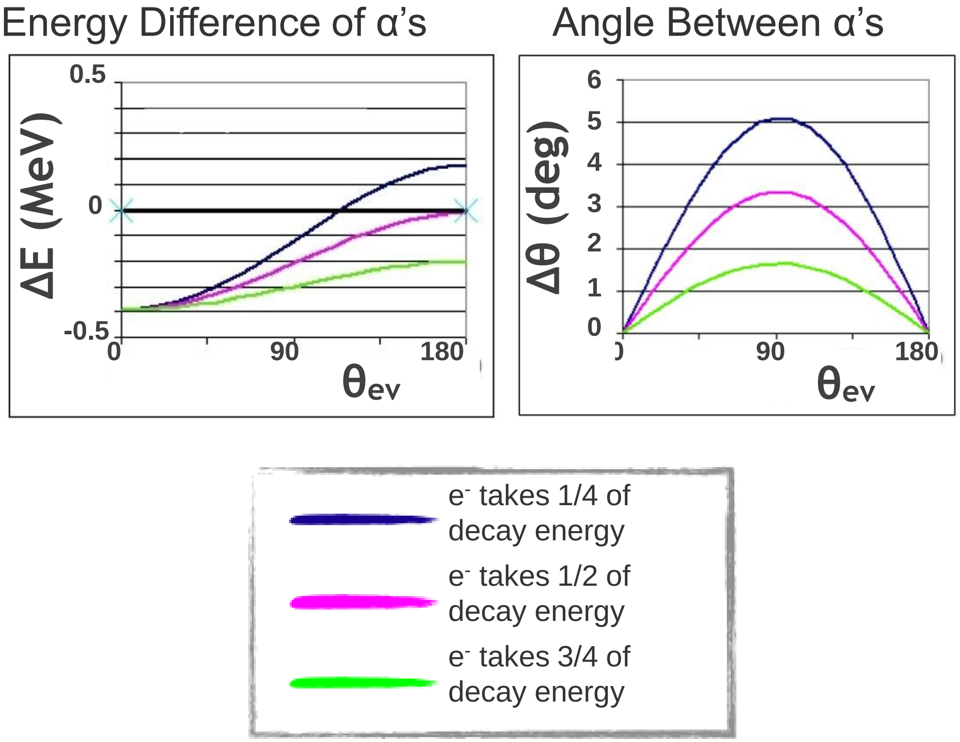


^{8}Be Breaks Up Parallel to e$^-$



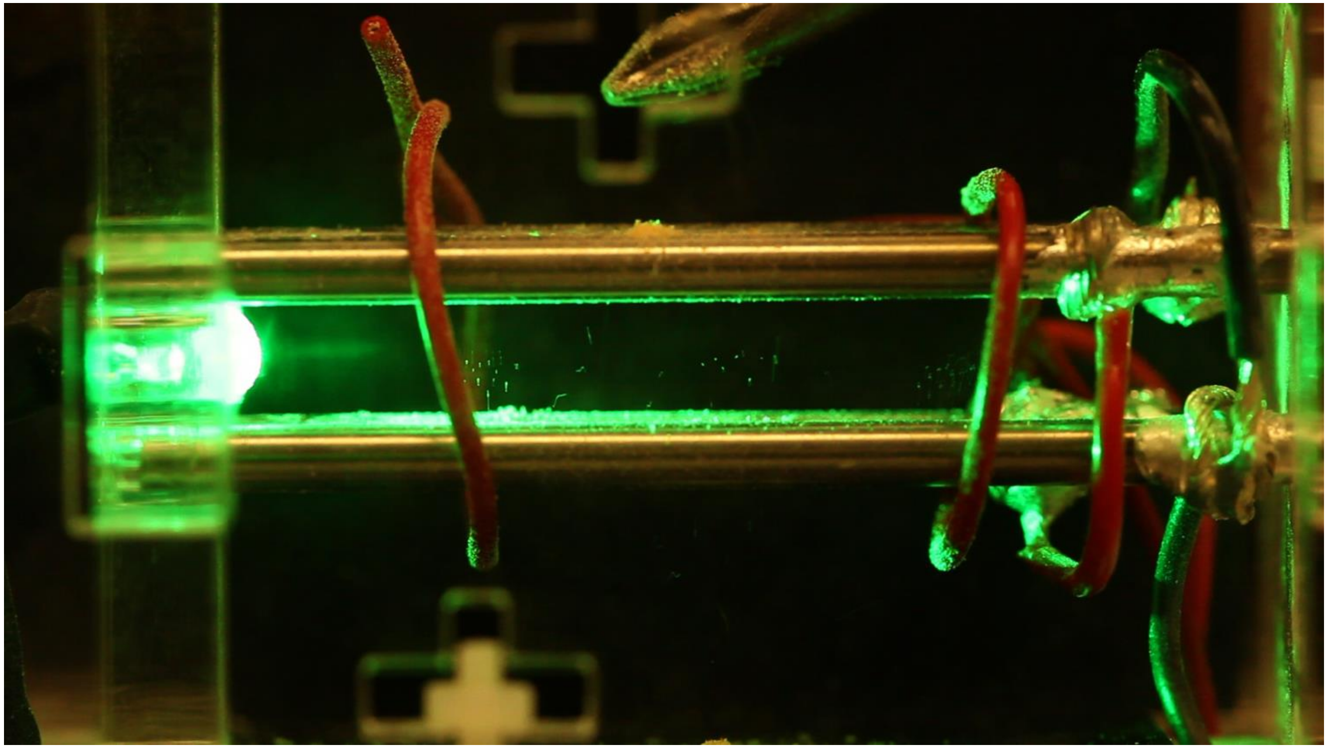
Reference Frame of Laboratory

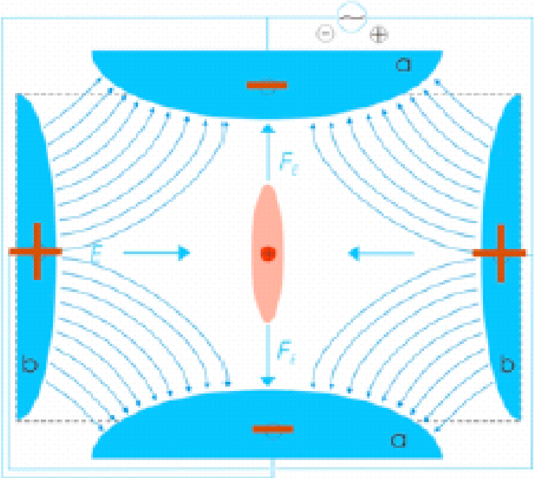



Energy Difference of α's

Angle Between α's

Paul Traps

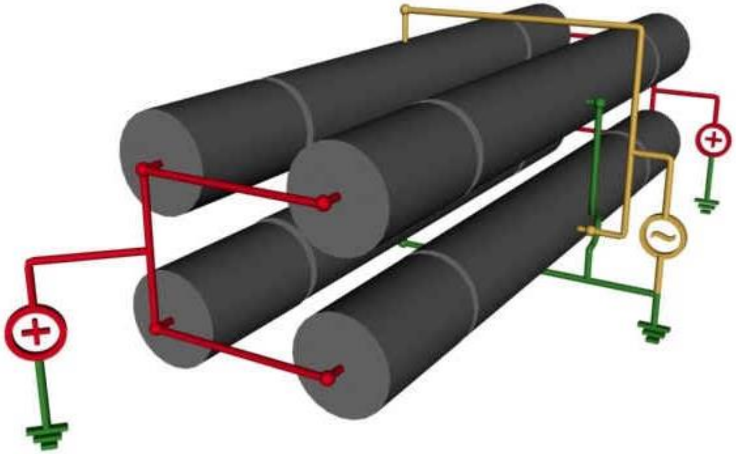




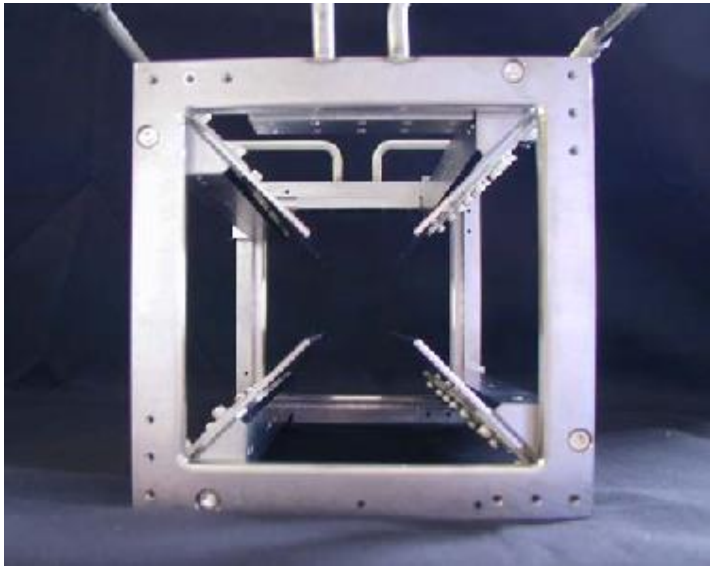
Trap Geometry

To get open geometry

- Standard Linear Paul Trap:
  Hyperbolic electrodes

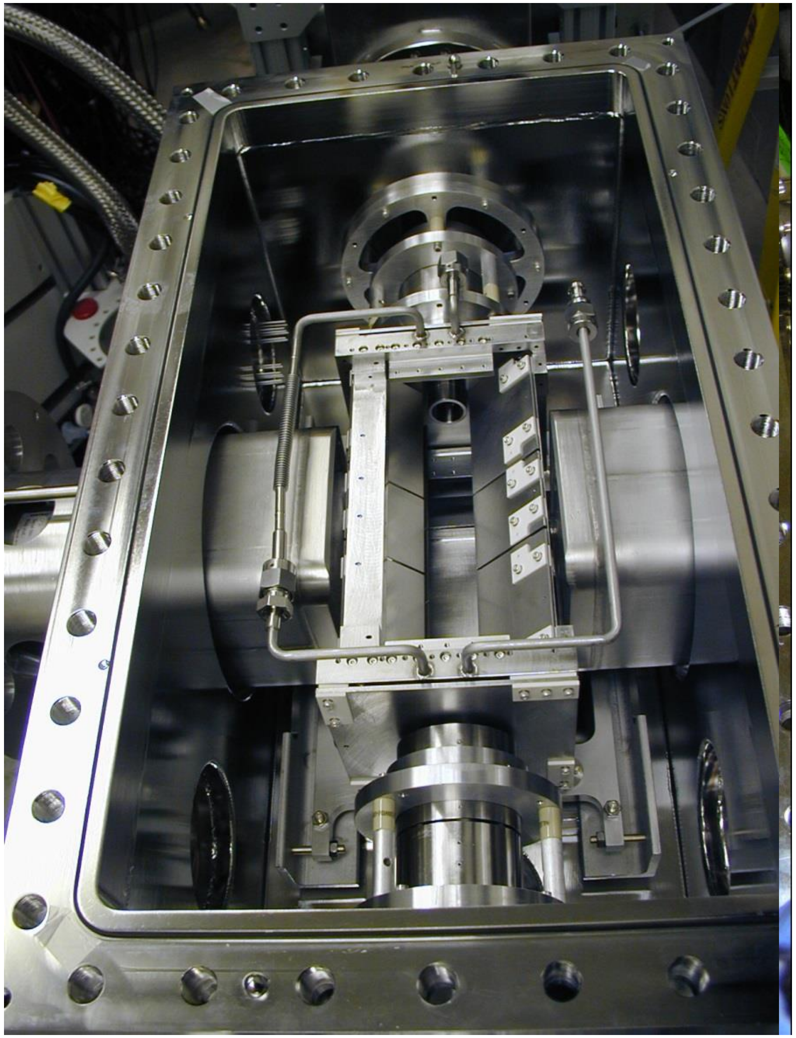


- Planar Linear Ion Trap



The Beta-decay Paul Trap

N.D. Scielzo *et al.*, NIM A **681**, 94 (2012)



- Confine up to ~10^6 ions at once
- Hold for >200 sec
- Accessible half-life > 50 ms
- Confine in ~1-mm^3 volume
- DC fields of ~100V
- RF fields of 200-1000 V_{pp} at 0.2-1.3 MHz
- He buffer gas cools ions to ~0.1 eV

Correlations determined from β-α-α coincidences

Double-sided silicon strip detectors (DSSDs) used to determine:

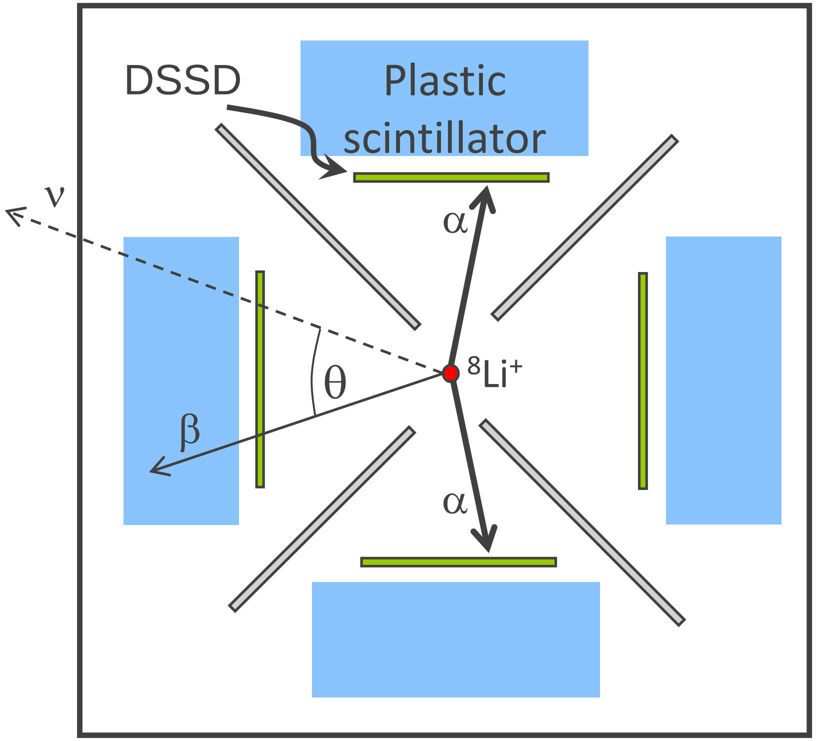
- β momentum direction
- Momentum and energy for both α particles

This is sufficient to fully reconstruct the decay kinematics

- $E_{\alpha 1} + E_{\alpha 2}$: ^{8}Be excitation energy
- $p_{\alpha 1} + p_{\alpha 2}$: nuclear recoil

Additional measurement of β energy not required… but overconstrains the kinematics

trapped ions surrounded by DSSDs and plastic scintillators

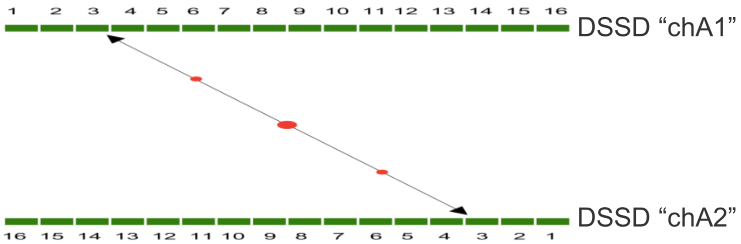


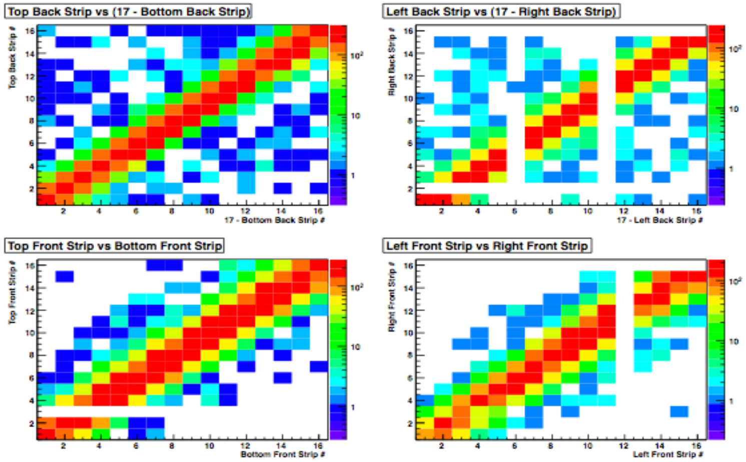
DSSDs:

- 1-mm thick, 64x64-mm^2 detector, 2-mm strips
- ~100-nm dead layer
- Continuous *in situ* calibration using ^{148}Gd and ^{244}Cm α sources

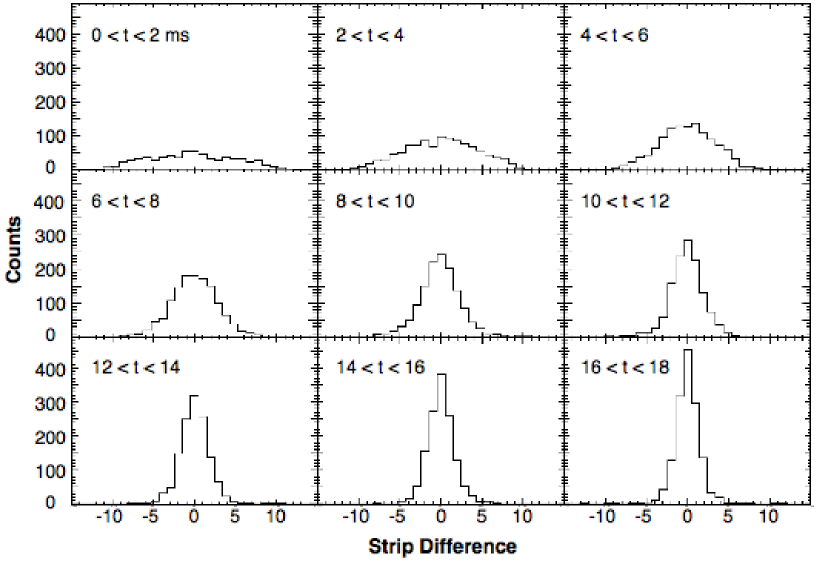
First Results with β-α-α Coincidences

- **Imaging the ion cloud with back-to-back α's**

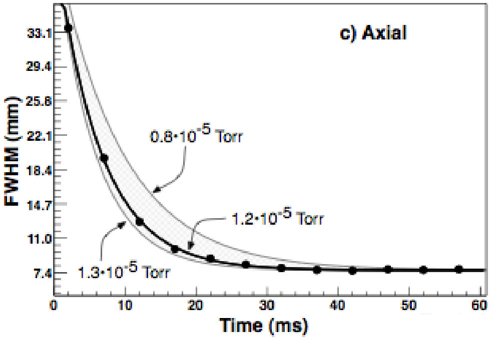


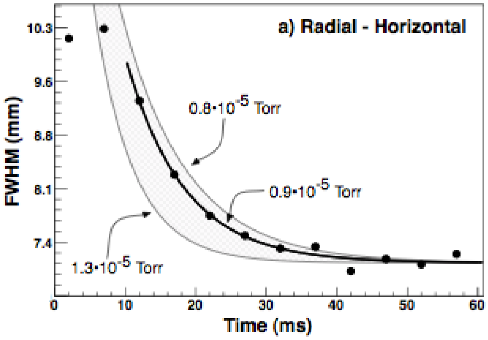


- Looking at the strip differences over time we can watch the ion cloud cool



- Slight broadening due to resolution of strips & angular broadening of α's from recoil
- Image is consistent with ion cloud ~1 mm^3
- Finer strips will provide more precise imaging





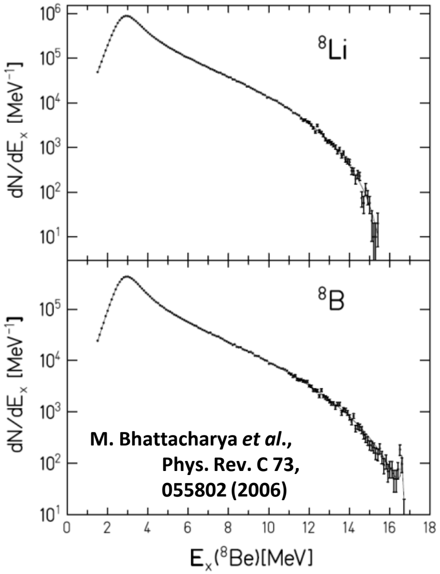
Analysis depends on high-fidelity simulations…

Beta-decay Event Generator

- Beta-decay phase space and angular correlations
- Final-state distribution of ^{8}Be*
- Recoil-order terms and radiative corrections
- Ion cloud distribution

$$
\begin{aligned}
d^7\Gamma = {}& F_{\mp}(Z,E)\,\frac{G_v{}^2\cos^2\theta_c}{2(2\pi)^6}\,(E_0-E)^2 pE\,dE\,d\Omega_e\,d\Omega_\nu\,d\Omega_n \\
&\times\Bigg(g_1(E) + g_2(E)\,\frac{\mathbf{p}}{E}\cdot\hat{k} + g_3(E)\left[\left(\frac{\mathbf{p}}{E}\cdot\hat{k}\right)^2 - \frac{1}{3}\,\frac{\mathbf{p}^2}{E^2}\right] \\
&+ \delta_1(E, v^*, \tau_{J',J''}(L))\,\frac{\hat{n}\cdot\mathbf{p}}{E} \\
&+ \delta_2(E, v^*, \tau_{J',J''}(L))\,\hat{n}\cdot\frac{\mathbf{p}}{E}\,\frac{\mathbf{p}}{E}\cdot\hat{k} \\
&+ \delta_3(E, v^*, \tau_{J',J''}(L))\,\hat{n}\cdot\hat{k} \\
&+ \delta_4(E, v^*, \tau_{J',J''}(L))\,\hat{n}\cdot\hat{k}\,\frac{\mathbf{p}}{E}\cdot\hat{k} \\
&+ \tfrac{1}{10}\tau_{J',J''}(L)\,T^{(2)}(\hat{n}):\Big\{ g_{10}(E)[\mathbf{p}/E, \mathbf{p}/E] \\
&+ g_{11}(E)[\mathbf{p}/E, \mathbf{p}/E]\,\frac{\mathbf{p}}{E}\cdot\hat{k} + g_{11}(E)[\mathbf{p}/E, \hat{k}] \\
&+ g_{12}(E)[\mathbf{p}/E, \hat{k}]\,\frac{\mathbf{p}}{E}\cdot\hat{k} + g_{13}(E)[\hat{k}, \hat{k}] \\
&+ g_{15}(E)[\hat{k}, \hat{k}]\,\frac{\mathbf{p}}{\mathrm{E}}\cdot\hat{k} + g_{16}(E)\left[\frac{\mathbf{p}}{E}, \frac{\mathbf{p}}{E}\times\hat{k}\right] \\
&+ g_{17}(E)\left[\hat{k}, \frac{\mathbf{p}}{E}\times\hat{k}\right]\Big\} \\
&+ \delta_8(E, v^*, \tau_{J'J''}(L))\,T^{(3)}(\hat{n}):[\mathbf{p}/E, \mathbf{p}/E, \hat{k}] \\
&+ \delta_9(E, v^*, \tau_{J'J''}(L))\,T^{(3)}(\hat{n}):[\mathbf{p}/E, \hat{k}, \hat{k}] \\
&+ \tfrac{1}{10}\omega_{J'J''}(L)\,T^{(4)}(\hat{n}):\{ g_{25}(E)[\mathbf{p}/E, \mathbf{p}/E, \mathbf{p}/E, \hat{k}] \\
&+ g_{26}(E)[\mathbf{p}/E, \mathbf{p}/E, \hat{k}, \hat{k}] \\
&+ g_{27}(E)[\mathbf{p}/E, \hat{k}, \hat{k}, \hat{k}]\}\Bigg). \qquad (53)
\end{aligned}
$$

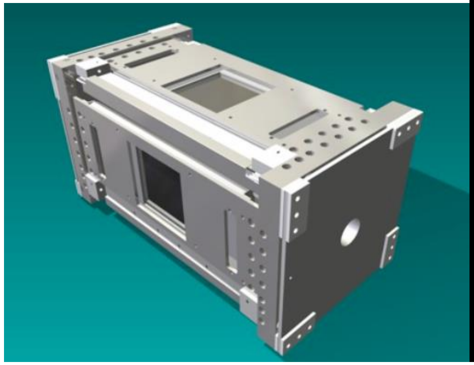
B.R. Holstein, RMP 46, 789 (1974)

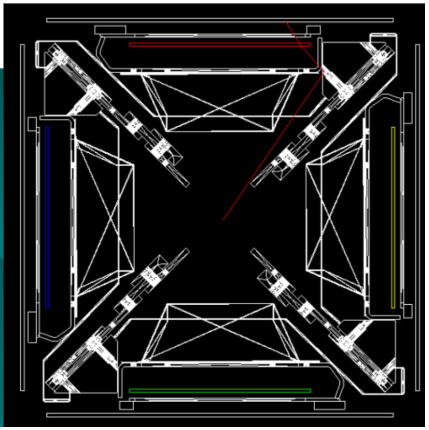


M. Bhattacharya *et al.*, Phys. Rev. C 73, 055802 (2006)

Apparatus Simulation

- Propagate β particles through experimental geometry using GEANT4
- DSSD detector response (resolution and dead layer) incorporated



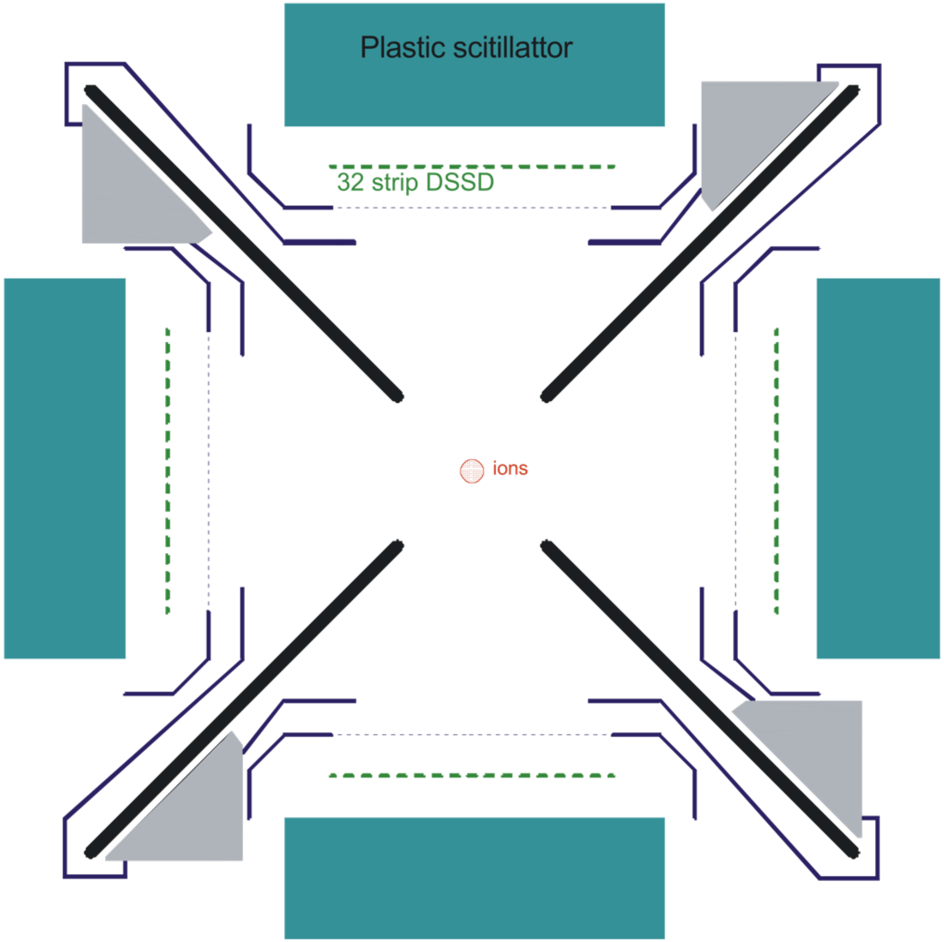


Autodesk Inventor → GE

2011 Detector System

- 64 mm X 64 mm - 32 X 32 strips
  - ~30% solid angle
  - 1 mm thick
  - 100 nm Dead Layer
  - Angular resolution - 3 degrees
  - 10% efficiency for β-α-α
- Scintillating Plastic for β’s
- Modified RF shielding
- Modified electrode design
  - Solid electrode design blocks source alphas at large angles
  - RF is only applied at tip of electrode to reduce pickup on DSSD

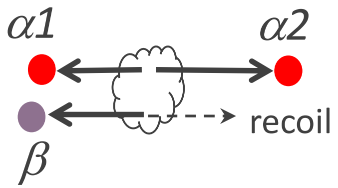
- There are 8 degrees of freedom
- We measure 9 - system is over constrained!

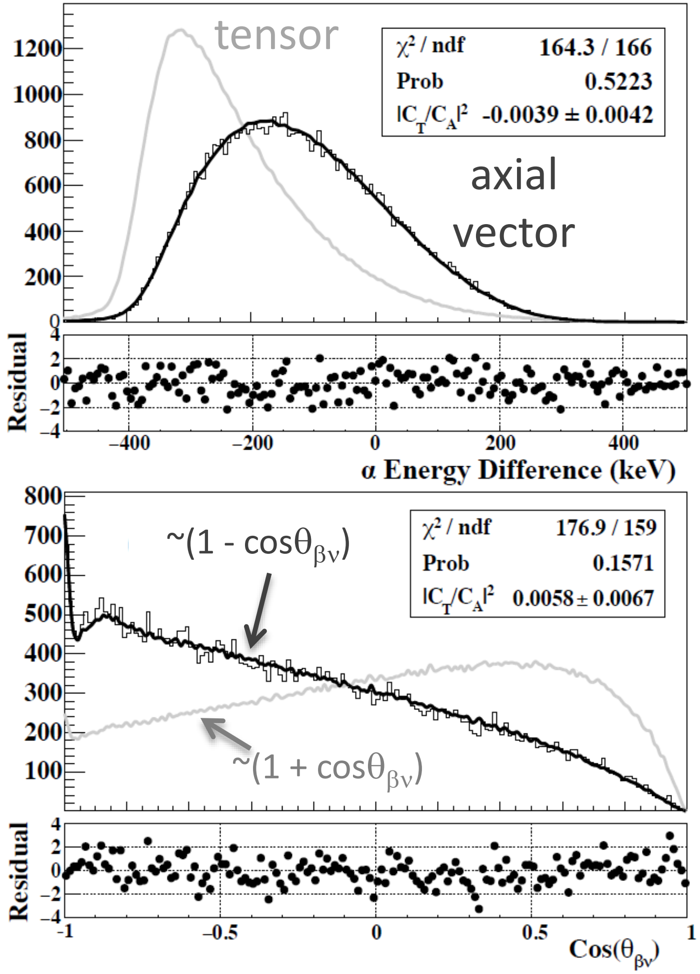


^{8}Li: 1st improved limits on $|C_T/C_A|^2$ from β decay in 50 years

M.G. Sternberg *et al.*, PRL **115**, 182501 (2015)

Most sensitive measure of correlation from E_α difference when β parallel to α





Axial vector: leptons preferentially emitted in opposite directions
→ smaller recoil, smaller ΔE_α

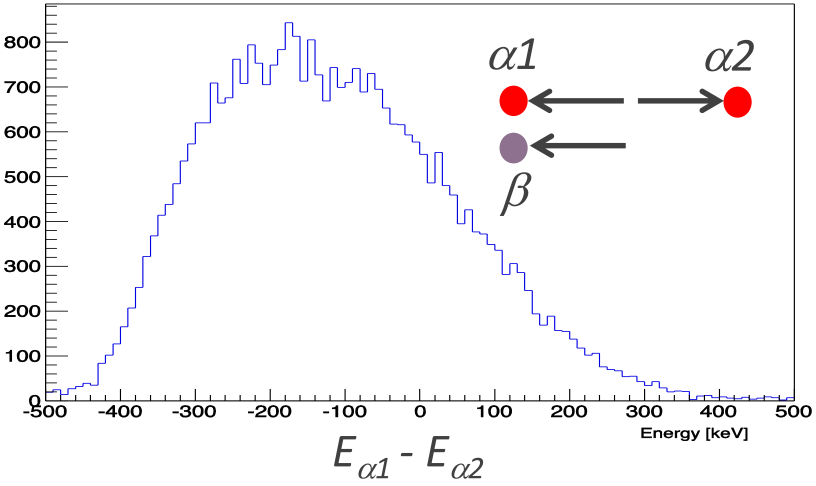
Tensor: leptons preferentially emitted in same direction
→ larger recoil, larger ΔE_α

$$a_{\beta\nu} = -0.3342 \pm 0.0026_{stat} \pm 0.0029_{syst}$$

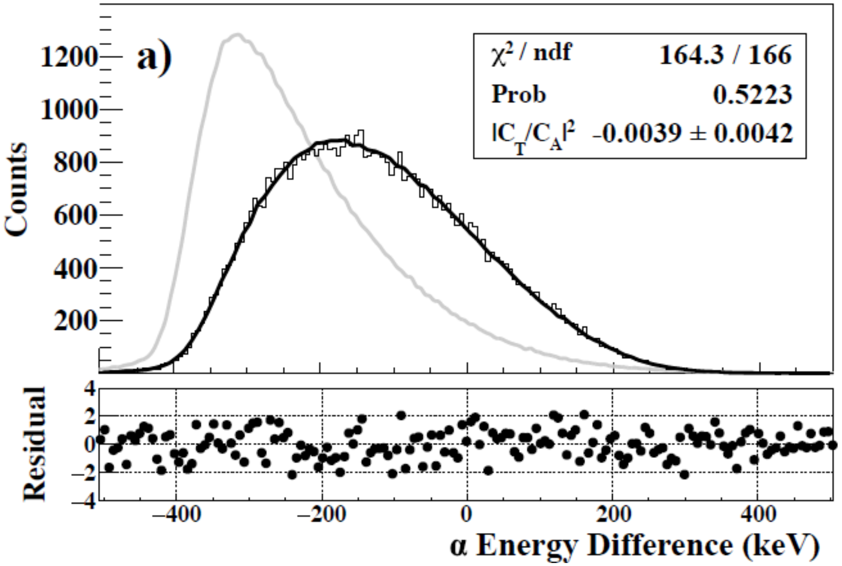
$$|C_T/C_A|^2 = -0.0013 \pm 0.0038_{stat} \pm 0.0043_{syst}$$

β-α-α coincidences from ^{8}B decay under analysis

$^{8}B \rightarrow {}^{8}Be^{*} + \beta^{+} + \nu_e$



$^{8}Li \rightarrow {}^{8}Be^{*} + \beta^{-} + \overline{\nu}_e$



β-decay angular correlations comparable to earlier ^{8}Li

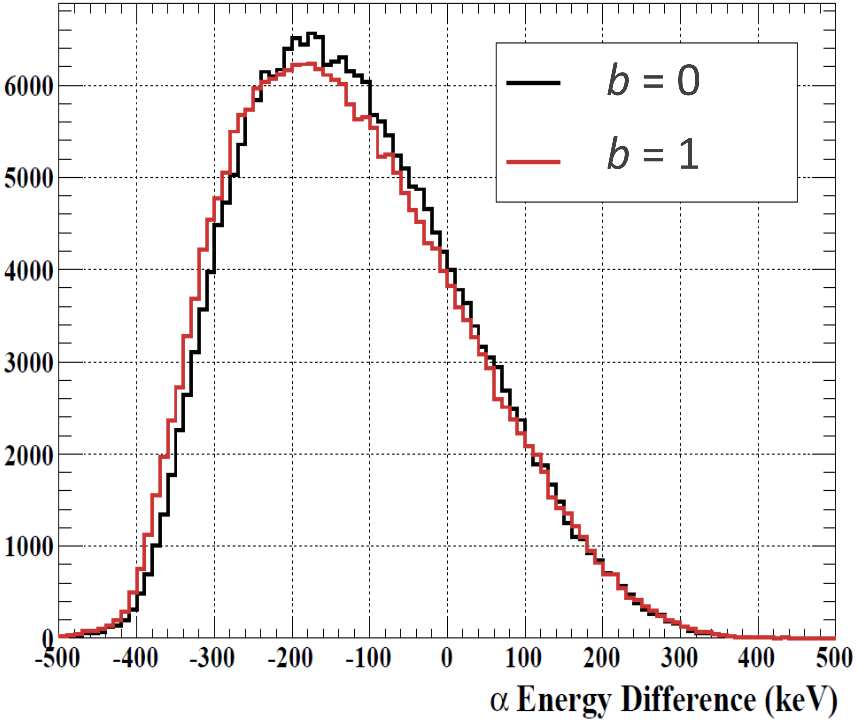
Precise determination of ^{8}B solar neutrino spectrum

Comparison to ^{8}Li data → recoil-order terms (small E_e dependence)

- Weak magnetism (change sign with $\beta^{\pm}$)
- Second-class currents (independent of $\beta^{\pm}$)

Fully-reconstructed ^{8}Li/^{8}B decays allows determination of recoil-order terms in several correlations

Also on the horizon…
A search for the Fierz interference term



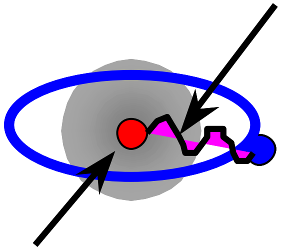
$$dW \sim \left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e}\right]$$

~0.001 **~0.01**

Sensitivity to Fierz interference term is ~10× less than for tensor contribution

Systematics need to be carefully investigated

The weak interaction between the outer electron and the nucleus is predicted by the Standard Model

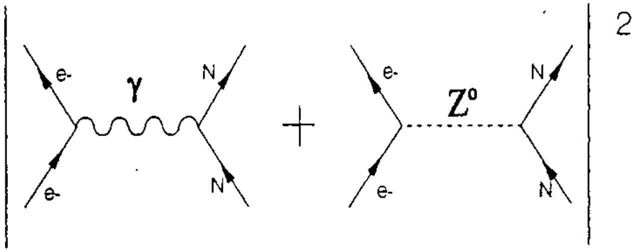


weak interaction

valence electron

nucleus

alkali atom



$$|nS\rangle' = |nS\rangle + \delta |nP\rangle$$

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

$$Q_W = \rho\left[-N + Z\left(\underbrace{1-4\sin^2\theta_W}_{\sim 0}\right)\right]$$

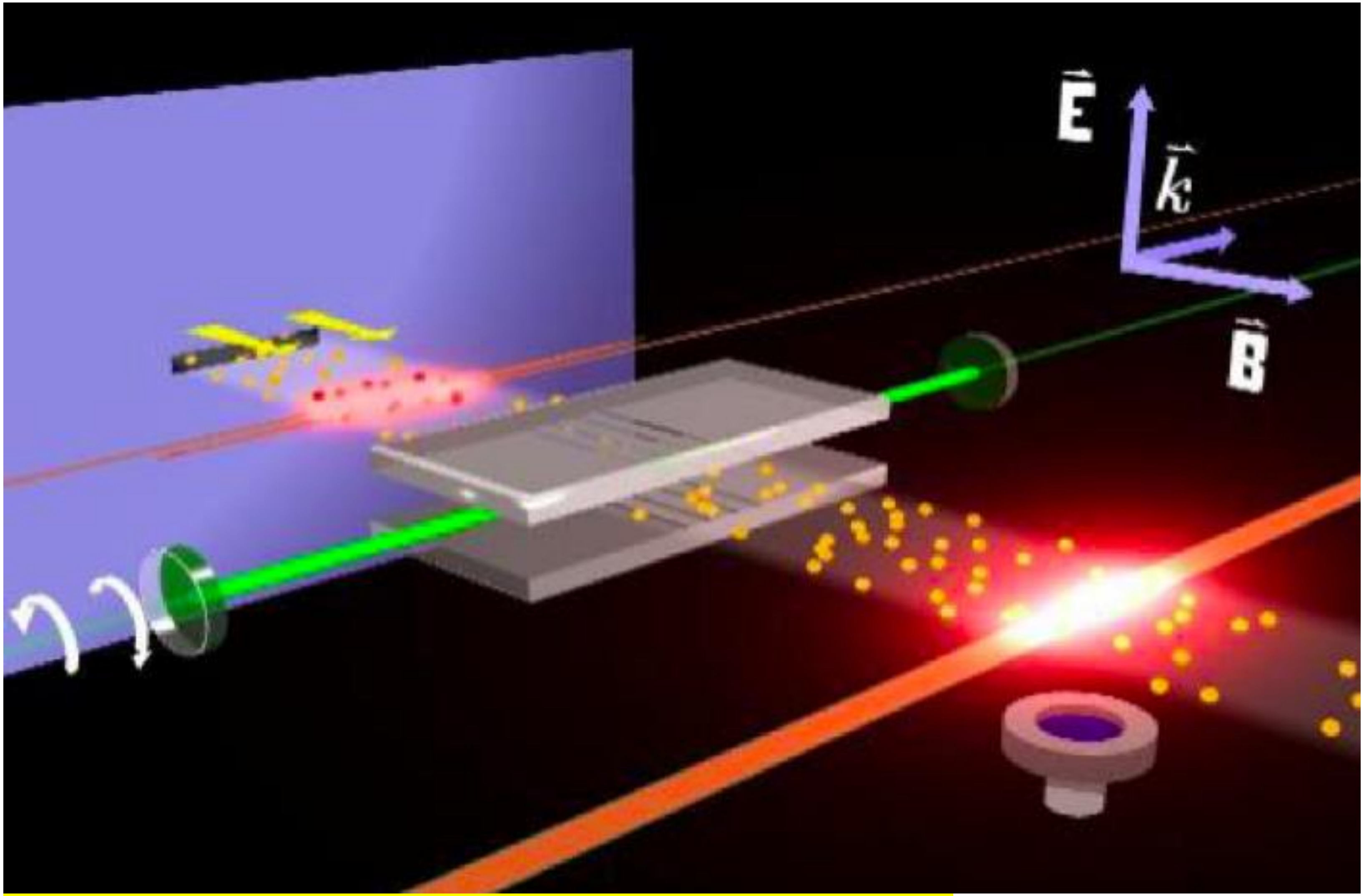
Q_W(Experiment)*=-72.06±0.28_{exp}±0.34_{th}

Q_W(Standard Model)= -73.20

*PRL 82 (1999) 2484

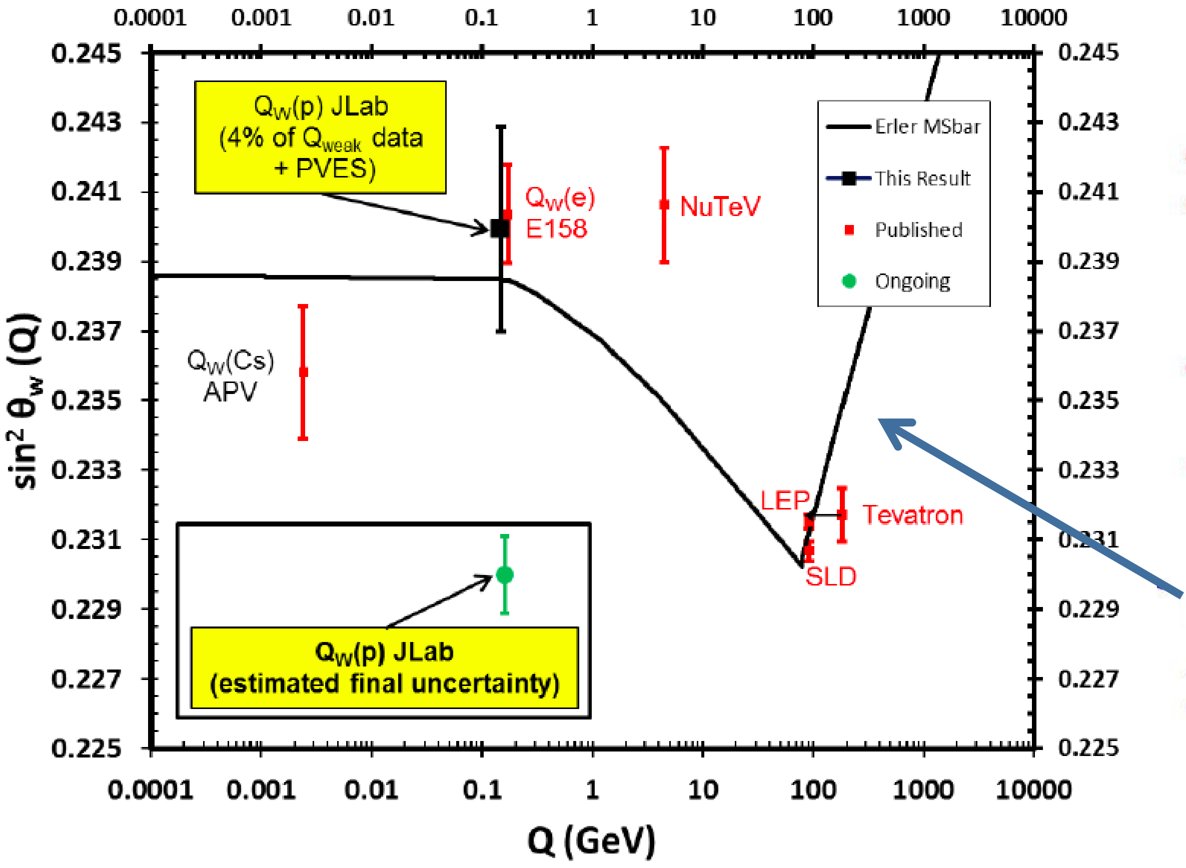
The Boulder Cs PNC Experiment

1982-1999



- P-odd, T-even correlation: $\boldsymbol{\sigma} \cdot [\boldsymbol{E} \times \boldsymbol{B}]$
- 5 reversals to distinguish PNC from systematics

Parity non-conservation in atoms



An example of the so called running of fundamental constants.

Prediction of the Standard Electro-Weak Theory

A credible path to necessary improvements on parity non-conservation in atoms requires an intense source of Fr atoms:

- **X18 larger signal**
- **atomic structure independent**
- **neutron distribution …. ^{208}Pb at JLAB and hyperfine anomaly**

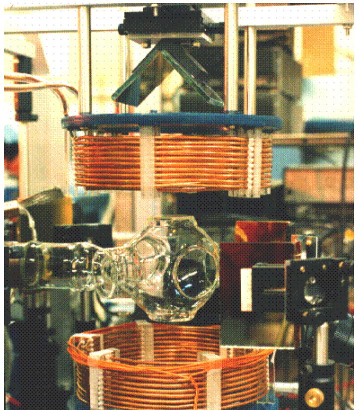
Francium-a new laboratory for fundamental symmetry tests

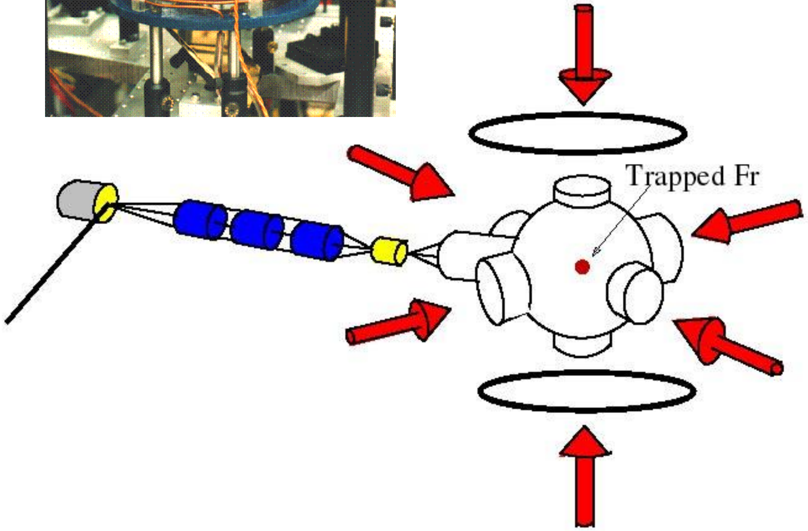
87 Fr 27°
2 8 18 32 18 8 1
+1
[223]

Fr200	Fr201	Fr202	Fr203	Fr204	Fr205	Fr206	Fr207	Fr208	Fr209	Fr210	Fr211	Fr212
	48 ms	0.34 s	0.55 s	1.7 s	3.85 s	15.9 s	14.8 s	59.1 s	50.0 s	3.18 m	3.10 m	20.0 m
	(9/2-)		(9/2-)	(3+) *	(9/2-)	(5+) *	9/2-	7+	9/2-	6+	9/2-	5+
	EC,α	EC,α	EC,α	EC,α	EC,α	EC,α	EC,α	EC,α	EC,α	EC,α	EC,α	EC,α

Fr213	Fr214	Fr215	Fr216	Fr217	Fr218	Fr219	Fr220	Fr221	Fr222
34.6 s	5.0 ms	86 Ns	0.70 Us	22 Us	1.0 ms	20 ms	27.4 s	4.9 m	14.2 m
9/2-	(1-) *	9/2-	(1-)	9/2-	1- *	9/2-	1+	5/2-	2-
EC,α	α	α	EC,α	α	α	α	β^-,α	α	β^-

Fr223	Fr224	Fr225	Fr226	Fr227	Fr228	Fr229	Fr230	Fr231	Fr232
21.8 m	3.33 m	4.0 m	49 s	2.47 m	38 s	50 s	19.1 s	17.5 s	5 s
3/2(-)	1-	3/2-	1-	1/2+	2-				
β^-,α	β^-	β^-	β^-	β^-	β^-	β^-	β^-	β^-	β^-





A systematic study of Parity non-conservation for different isotopes in Francium would lead to greatly enhanced sensitivity to new physics, complementing high energy physics studies. To study a wide range of isotopes requires ISAC or FRIB.

A possible experimental approach:

1. **Capture** Fr atoms in a MOT
2. **Accumulate** and cool in the MOT
3. **Transfer** to a second trap (purely optical)
4. Establish a “**coordinate system**” by dc electric field, dc magnetic field, k vector of the exciting laser
5. **Excite** 7S to 8S using a build up cavity and detect using the 7S to 7P transition.
6. **Reverse** the **coordinate** axis.
7. **Change isotope**.

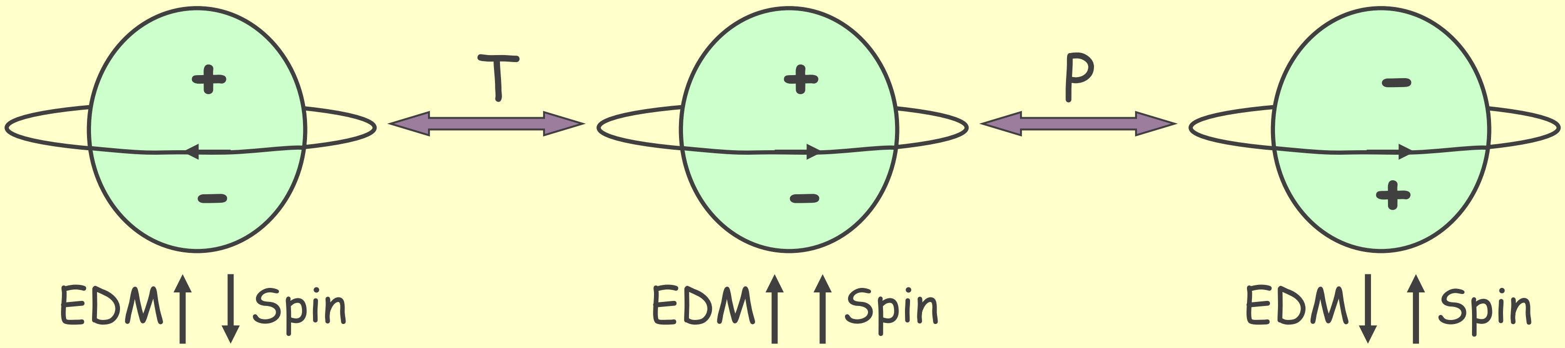
From Luis Orozco Les Houche 2000

CP Violation

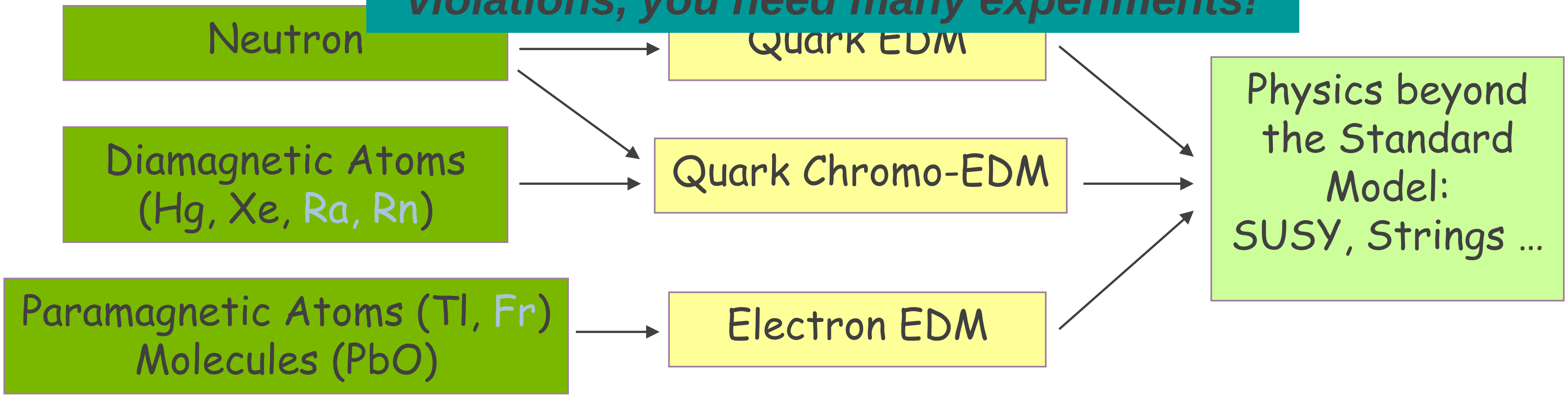
- Astronomical Observations indicate that the universe is dominated by matter.
- The CP violation observed in K and B decays is not sufficient to explain the observed asymmetry of matter.
- There are many proposed theoretical models with CP violation.
- The most stringent test for models is the Electric Dipole Moments they predict for the neutron, the electron and for nuclei.
- RIB facilities allow these measurements of particular nuclei in which the moments are greatly enhanced.

Search for an electric dipole moment and physics beyond the standard model

A permanent EDM violates both time-reversal symmetry and parity



To understand the origin of the symmetry violations, you need many experiments!


Neutron

Diagamagnetic Atoms (Hg, Xe, Ra, Rn)

Paramagnetic Atoms (Tl, Fr) Molecules (PbO)

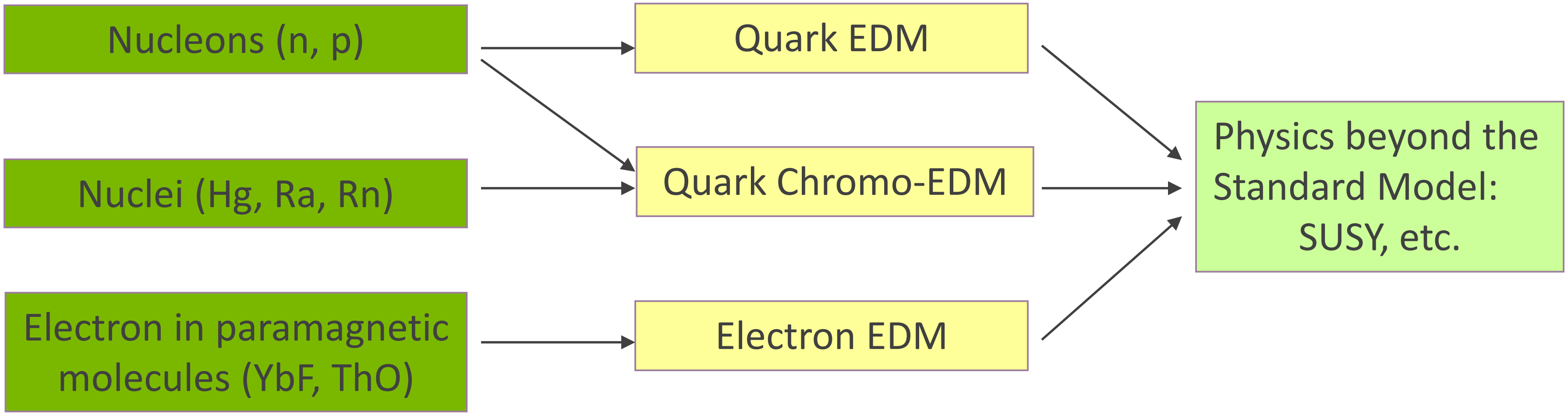
Quark EDM

Quark Chromo-EDM

Electron EDM

Physics beyond the Standard Model: SUSY, Strings …

EDM Searches in Three Sectors



Nucleons (n, p)

Nuclei (Hg, Ra, Rn)

Electron in paramagnetic molecules (YbF, ThO)

Quark EDM

Quark Chromo-EDM

Electron EDM

Physics beyond the Standard Model: SUSY, etc.

Sector	Exp Limit (e-cm)	Method	Standard Model
Electron	9×10^{-29}	ThO in a beam	10^{-38}
Neutron	3×10^{-26}	UCN in a bottle	10^{-31}
^{199}Hg	3×10^{-29}	Hg atoms in a cell	10^{-33}

M. Ramsey-Musolf (2009)

Neutron EDM; Ramsey,

Dress et al. Phys. Rep. 43, 410 (1978).

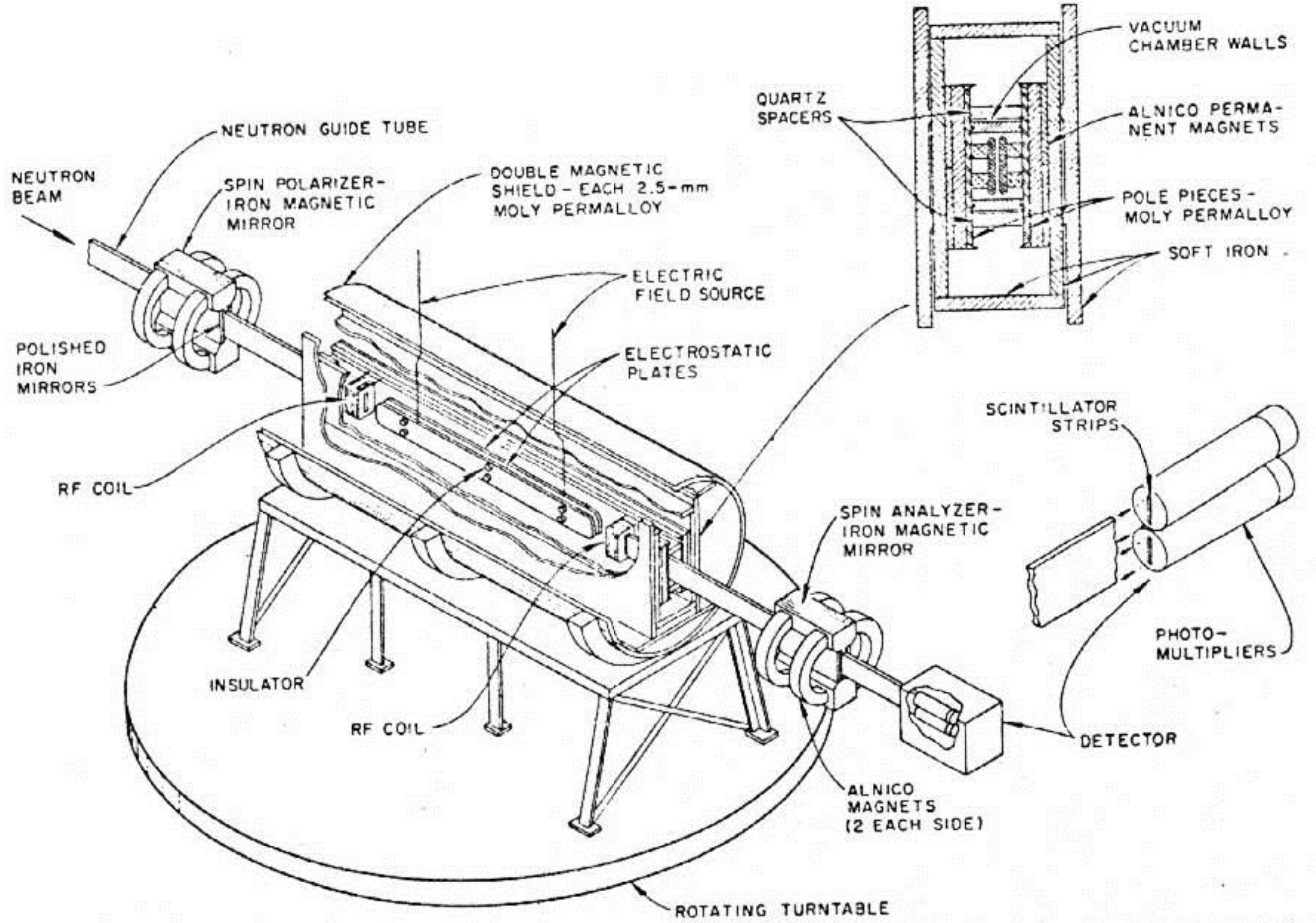


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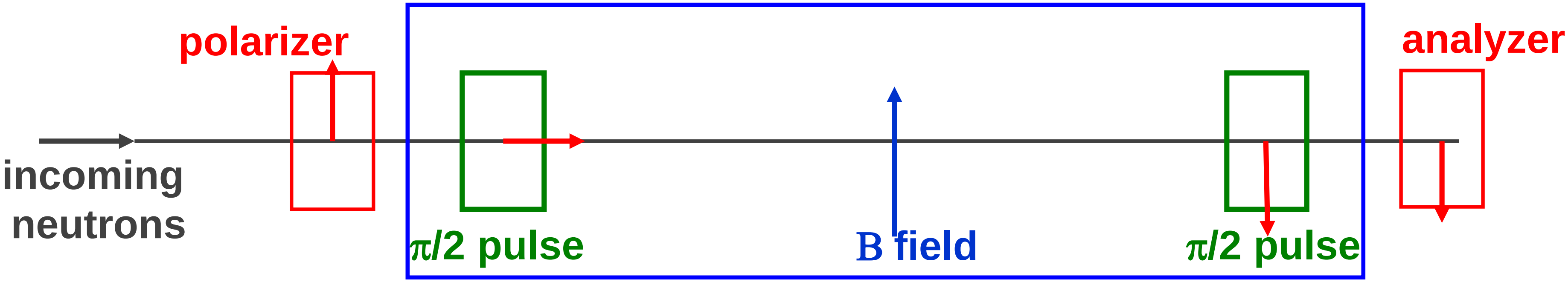
FIGURE 1 Pictorial representation of the neutron-beam spectrometer. The insert, upper right, is a cross-sectional view through the midpoint of the apparatus indicating various materials used in construction. The gap between the magnetic poles in 9 cm.

Neutron EDM; Ramsey,

Dress et al. Phys. Rep. 43, 410 (1978).

Simplified version



Neutron EDM; Ramsey,

Dress et al. Phys. Rep. 43, 410 (1978).

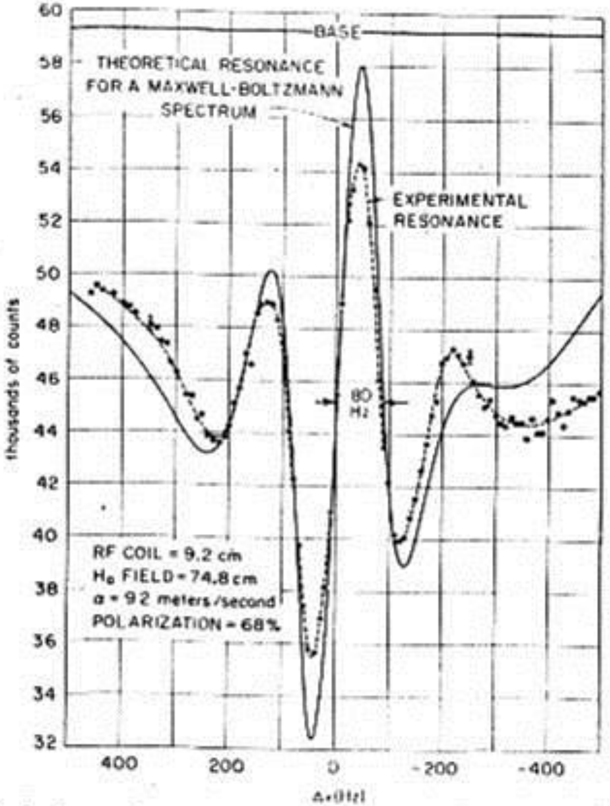
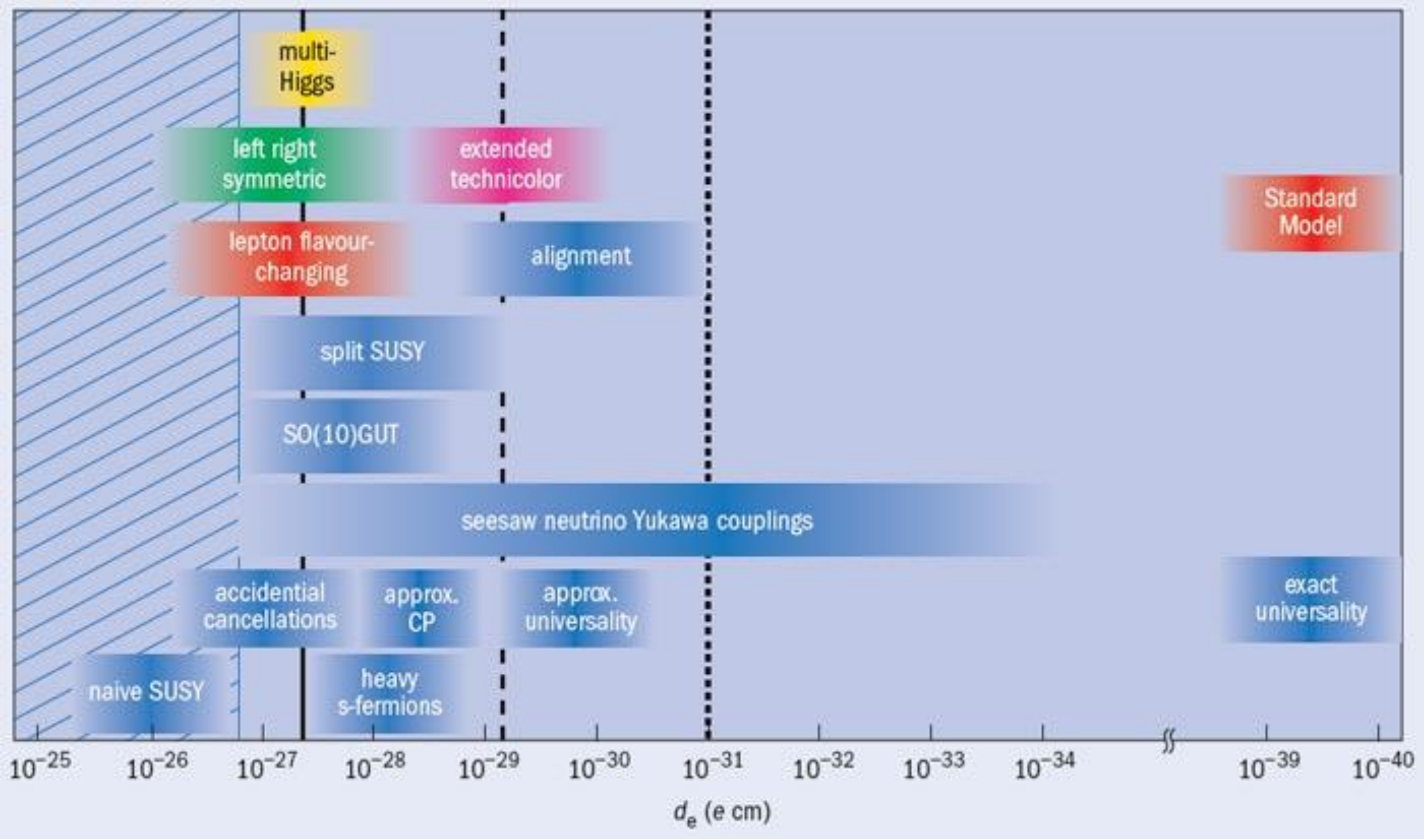


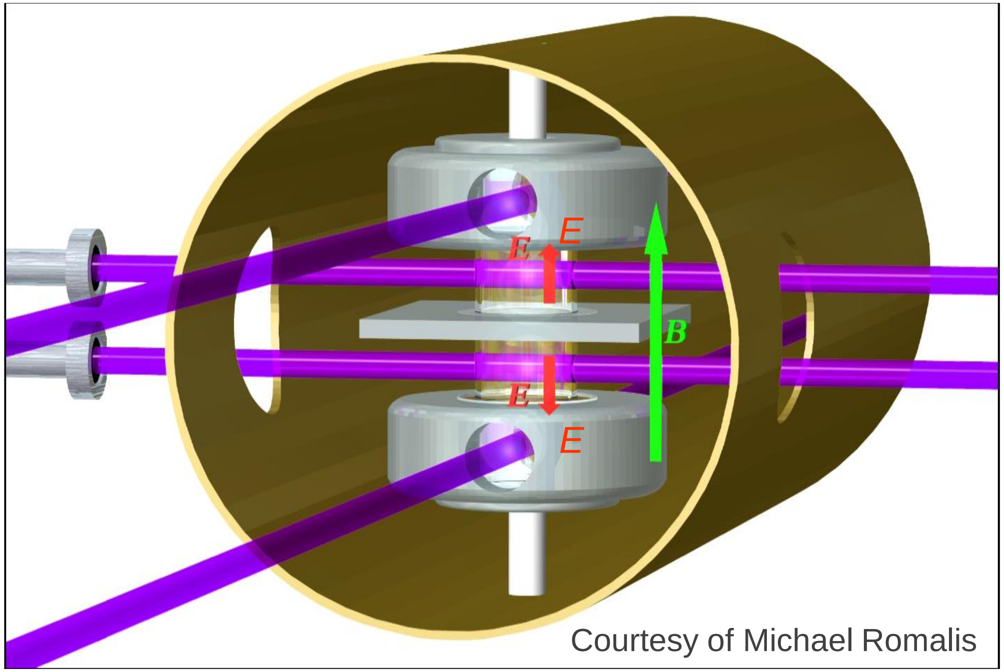
FIGURE 2 Typical magnetic resonance with the neutron-beam apparatus for a phase shift of $\pi/2$ between the two oscillatory fields. The calculated transition probability for a Maxwell-Boltzmann distribution characterized by a temperature of 1 K is shown by the solid curve. The departure of the experimental curve from theory when far from resonance is to be expected from the known departure of the beam velocity from a Maxwell–Boltzmann distribution.

EDM … the Standard Model extension slayer



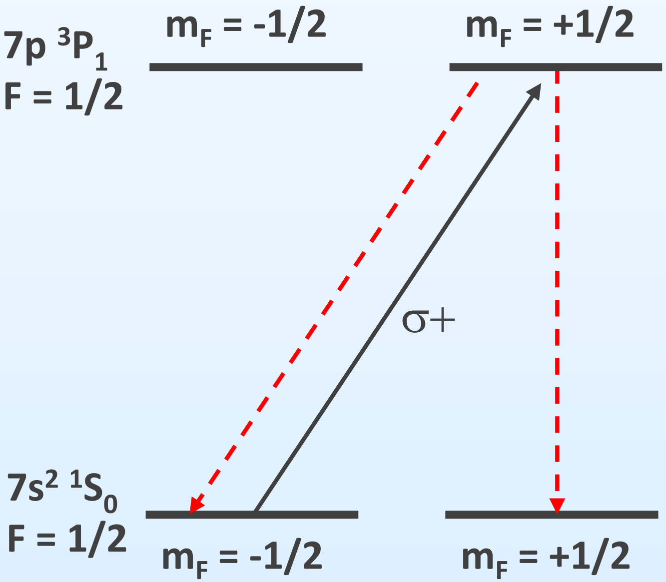
The Seattle EDM Measurement

^{199}Hg stable, high Z, groundstate $^{1}S_{0}$, I = ½, high vapor pressure



Courtesy of Michael Romalis

Optical Pumping



7p $^{3}P_{1}$
F = 1/2

$m_F = -1/2$ $m_F = +1/2$

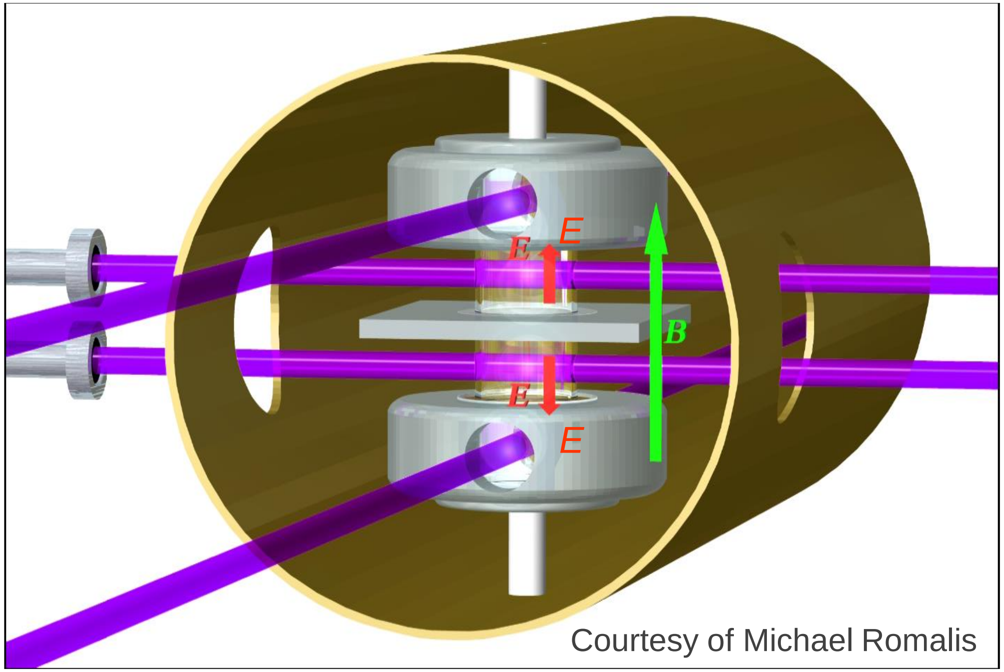
$\sigma+$

7s^{2} $^{1}S_{0}$
F = 1/2

$m_F = -1/2$ $m_F = +1/2$

The Seattle EDM Measurement

^{199}Hg stable, high Z, groundstate $^1S_0$, I = ½, high vapor pressure

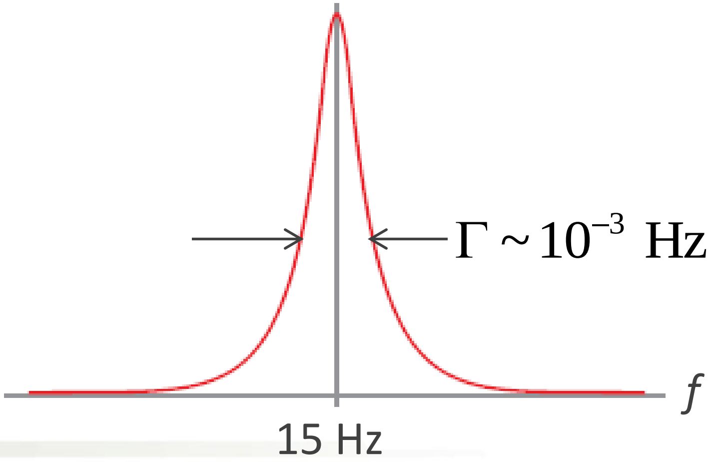


Courtesy of Michael Romalis

$$f_+ = \frac{2\mu B + 2dE}{h} \approx 15 \text{ Hz}$$

$$f_- = \frac{2\mu B - 2dE}{h} \approx 15 \text{ Hz}$$

$$\left| f_+ - f_- \right| < 1 \times 10^{-10} \text{ Hz}$$



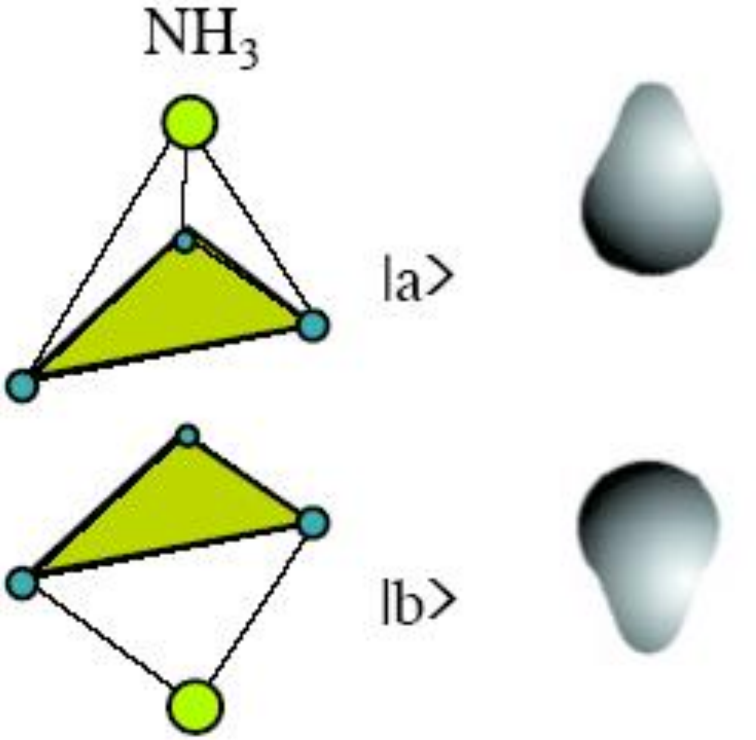
Limits and Sensitivities

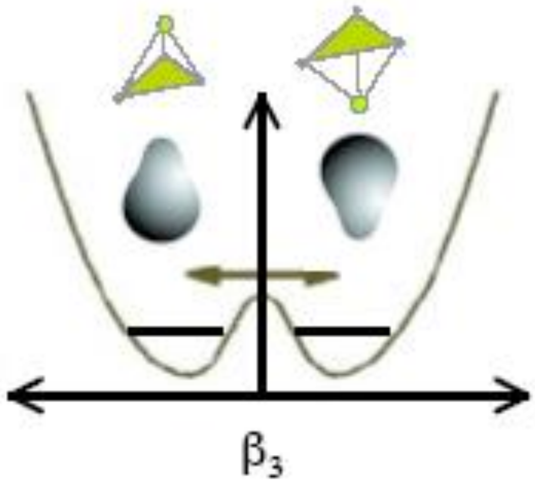
- Current: < 3 x 10^{-29} e-cm

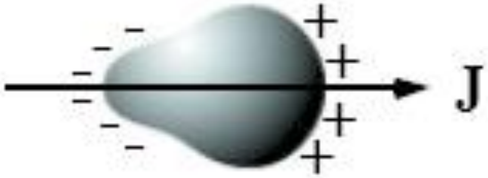
  -- Griffith *et al.*, PRL (2009)

- Next 5 years: 3 x 10^{-30} e-cm
- Beyond 2020: 6 x 10^{-31} e-cm

Enhancement of nuclear EDM sensitivity in octupole deformed parity doublets







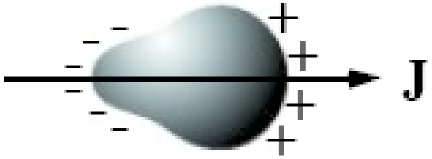
$$|\psi_\pm\rangle = \frac{1}{\sqrt{2}}\left(|a\rangle \pm |b\rangle \right)$$

$$S \sim \frac{\langle + | \eta r^3 \cos\theta | - \rangle}{E_+ - E_-} \sim \frac{\eta \beta_2 \beta^2_3 Z A^{2/3} r_0^3}{E_+ - E_-}$$

Nuclei with Octupole Deformation/Vibration

(Haxton & Henley; Auerbach, Flambaum, Spevak; Engel, Hayes & Friar, etc.)

$$S \sim \frac{\langle + | \eta r^3 \cos\theta | - \rangle}{E_+ - E_-} \sim \frac{\eta \beta_2 \beta_3^2 Z A^{2/3} r_0^3}{E_+ - E_-}$$



	223Rn	223Ra	225Ra	223Fr	225Ac	229Pa	199Hg	129Xe
t_{1/2}	23.2 m	11.4 d	14.9 d	22 m	10.0 d	1.5 d		
I	7/2	3/2	1/2	3/2	3/2	5/2	1/2	1/2
ΔE_{th}* (keV)	37†	170	47	75	49	5		
ΔE_{exp} (keV)	--	50.2	55.2	160.5	40.1	0.22		
10^5 S (efm^3)	1000	400	300	500	900	12000	-1.4	1.75
10^{28} d_A (e-cm)	**3300**	**3300**	**2500**	**2800**			-5.6	0.8

Ref: Dzuba PRA66, 012111 (2002) - Uncertainties of 50%

*Based on Woods-Saxon Potential

† Nilsson Potential Prediction is 137 keV

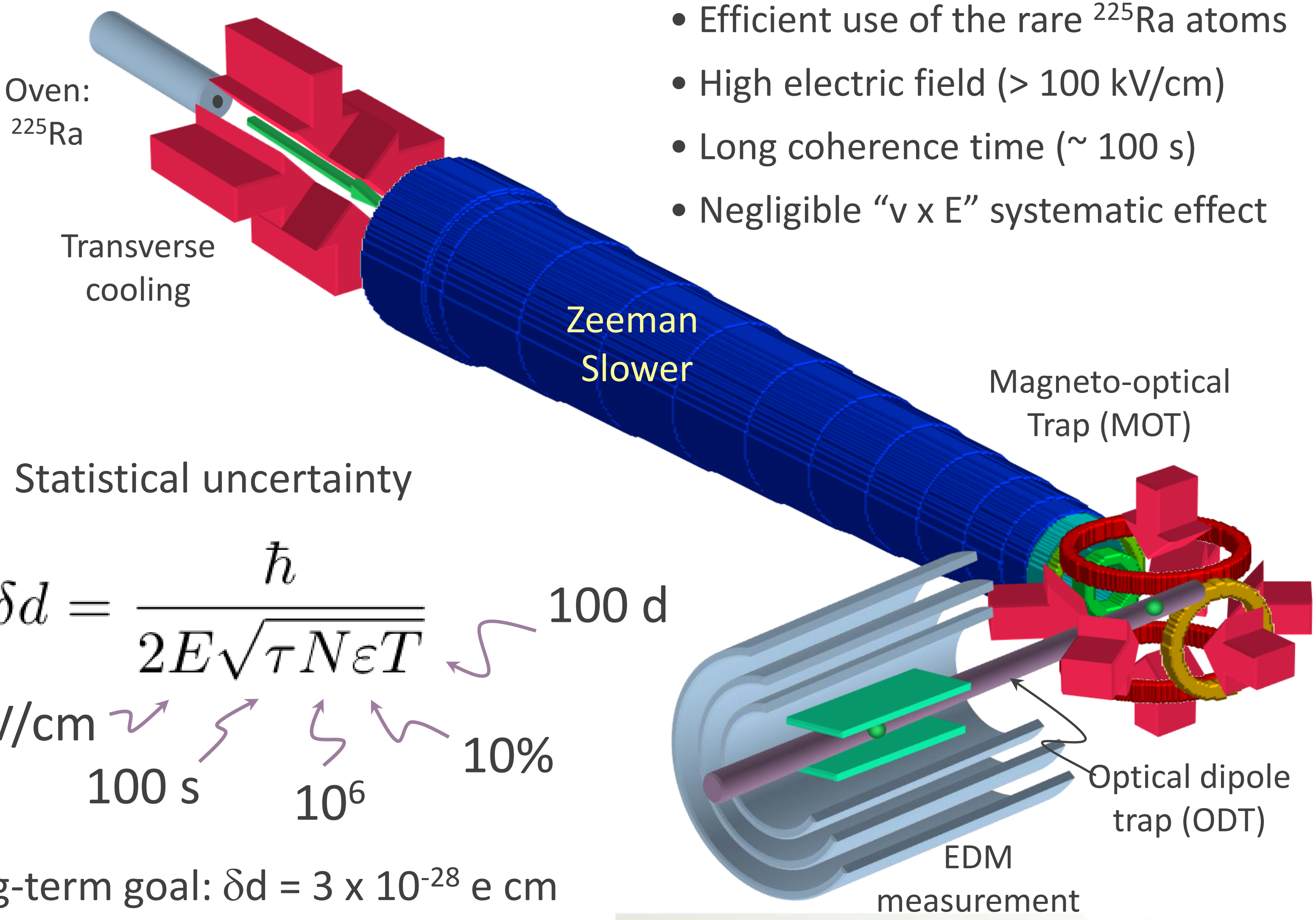
NOTES:
Ocutpole Enhancements
Engel et al. agree with Flambaum et al.
Even octupole vibrations enhance S (Engel, Flambaum& Zelevinsky)

EDM measurement on ^{225}Ra in a trap

Collaboration of Argonne, Kentucky, Michigan State

^{225}Ra:
$I = ½$
$t_{1/2}$ = 15 d

- Efficient use of the rare ^{225}Ra atoms
- High electric field (> 100 kV/cm)
- Long coherence time (~ 100 s)
- Negligible “v x E” systematic effect



Statistical uncertainty

$$\delta d = \frac{\hbar}{2E\sqrt{\tau N \varepsilon T}}$$

100 kV/cm

100 s

10^6

10%

100 d

Long-term goal: $\delta d = 3 \times 10^{-28}$ e cm

Nuclear EDM outlook

- First results
  - 2015: 5×10^{-22} e cm
  - 2016: 1.4×10^{-23} e cm
- 2015-2018, blue upgrade – more efficient trap;
- Five-year goal (before FRIB): 10^{-26} e cm;
- 2020 and beyond (at FRIB): 3×10^{-28} e cm;
- Far future: search for EDM in diatomic molecules
  - Effective E field is enhanced by a factor of 10^3;
  - Reach the Standard Model value of 10^{-30} e cm.

Low energy fundamental symmetry tests

- a number of opportunities, exploiting special features of low energy systems and symmetries of the interactions, are being pursued

→ A few presented here … many more ongoing

- most require pure sources of isotopes with specific intrinsic properties and beam preparation

→ High intensity rare isotopes

- these studies are competitive with and complementary to higher energy experiments

- new technologies enhance our capabilities to pursue these opportunities but to take full advantage of them we need FRIB.