Neutrons and Fundamental Symmetries Experimental III: Other Symmetry Tests

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NNPSS 2018

Slides from J. Barrow, A. Young, M. Snow, H. Shimizu, M. Hurber, H. Abele, …

Topics I will cover:

Lecture 1: beta-decay

- A brief history of the electroweak theory---the precursor to the Standard Model.
- Neutron decay to test the V-A theory & beyond the SM interactions
- Current status with neutron experiments on gA & lifetime
- Physics is Symmetries

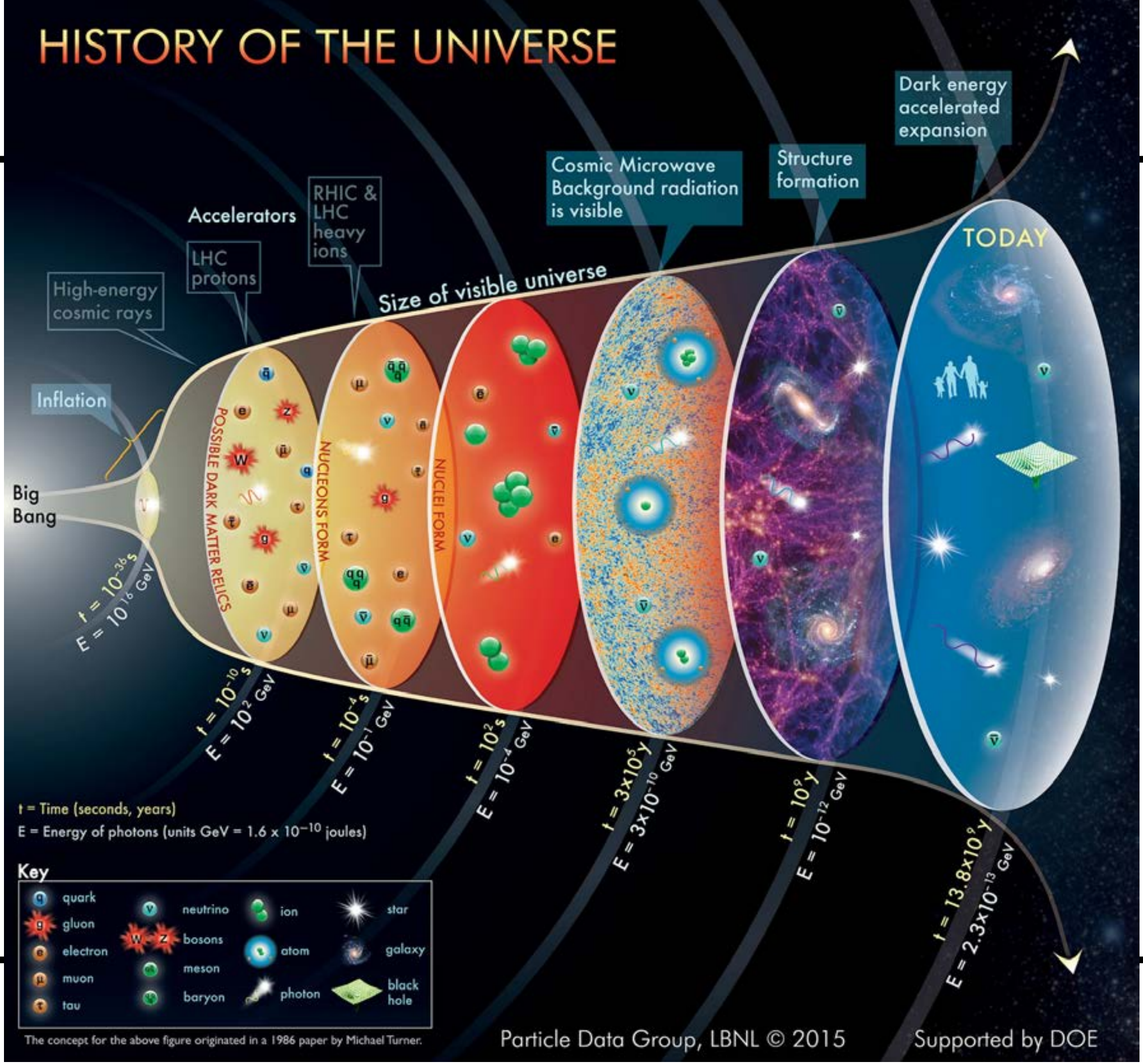
Lecture 2: EDM

- CP violation
- Electric Dipole Moments: Highly sensitive low-energy probes of new Physics
- muon- g-2

Lecture 3: other symmetry violation measurements/tests

- Baryogenesis & symmetry violations
- Nnbar oscillation: B violation
- Hadronic weak interactions: P violation
- NOPTREX: T violation
- Neutron interferometry: Lorentz symmetry violation

Q: What are the cosmological consequences of symmetry breaking?



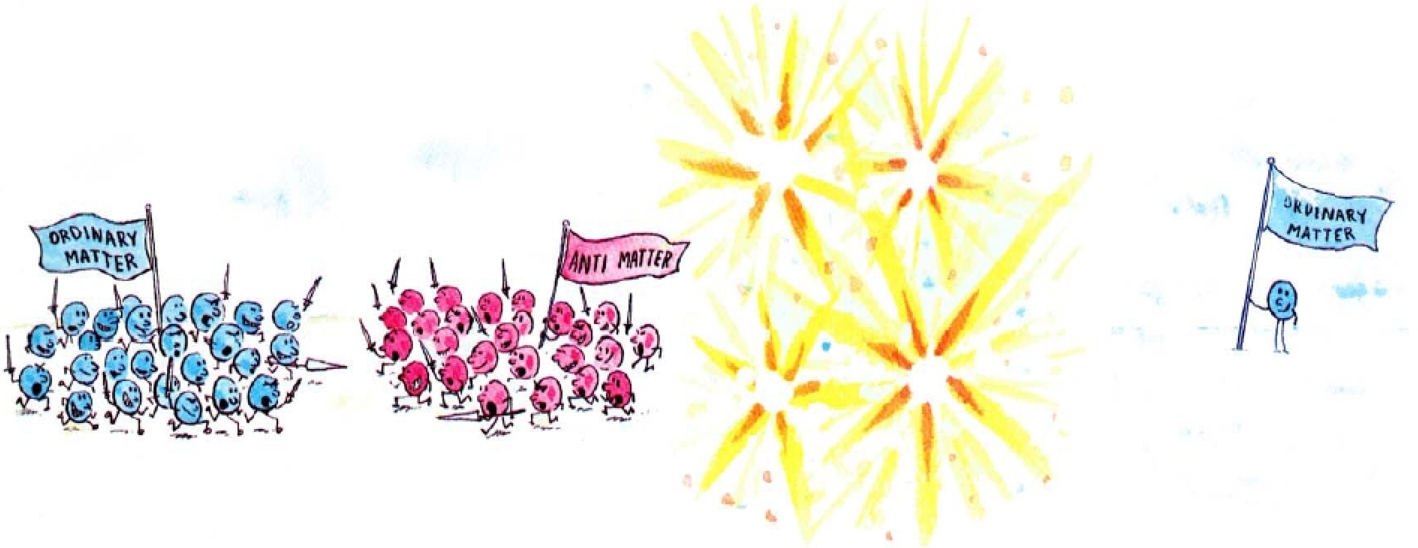
The concept for the above figure originated in a 1986 paper by Michael Turner.

Particle Data Group, LBNL © 2015

Supported by DOE

Matter-Antimatter Asymmetry of the Universe

(or Baryon Asymmetry of the Universe, BAU)



$$\eta \equiv \frac{\eta_B - \eta_{\overline{B}}}{\eta_\gamma}$$

η: baryon asymmetry of the universe (BAU)

$$2.6\times10^{-10} < \eta < 6.2\times10^{-10}$$

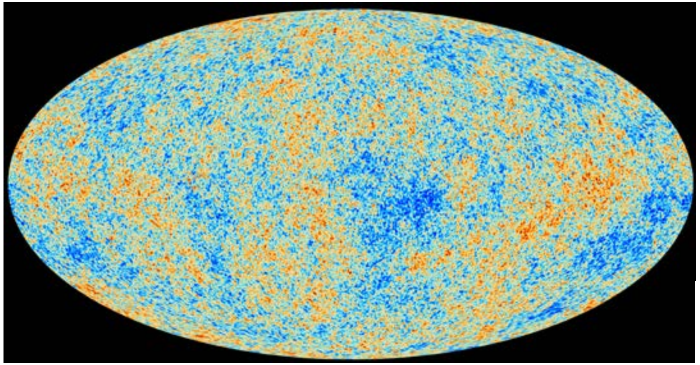
The Sakharov Conditions

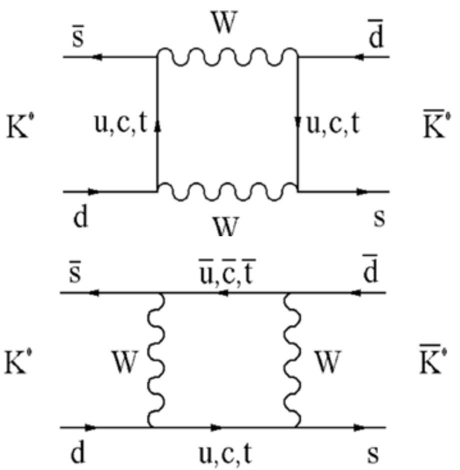
left-handed particle
under C → left-handed antiparticle
then P → right-handed antiparticle

The ***baryon asymmetry of the universe*** motivates **three hypotheses put forward by Sakharov in 1967**

Any model attempting to explain our universe must satisfy the following:

1. **CP violation** (& C non-conservation; different interactions of particles and antiparticles)
    - ***Exists in SM, but the degree of violation might be too small.***
2. **Departure from thermal equilibrium** (provided by the expansion of the universe)
    - ***Demonstrated from astronomical observations***
3. **Baryon number (charge) B violation**
    - ***Still never seen experimentally***





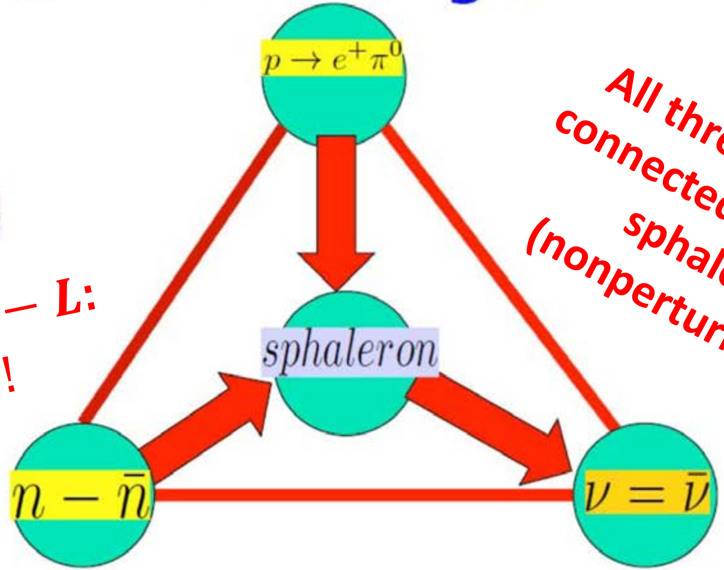
Adapted from Rabi Mohapatra

From NNbar to Majorana neutrino via sphalerons

- Sphaleron Op. rewrite

$$\underbrace{QQQQQQ}_{n-\bar{n}}\ \underbrace{QQQL}_{p\to e^+\pi^0}\ \underbrace{LL}_{m_\nu}$$

B-L Triangle:



All three are BSM; connected by the SM sphaleron (nonperturbative)

The sphaleron conserves $B-L$: IF $\Delta L_{0\nu 2\beta}=2 \Rightarrow \Delta B$!!!

Observe p-decay and nn-bar→Neutrino Majorana

n→nbar Oscillation

- Schrödinger equation

Unkown mixing interaction

$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix}\psi_n\\ \psi_{\bar n}\end{pmatrix}=\begin{pmatrix}E_n & \enclose{circle}{\varepsilon}\\ \varepsilon & E_{\bar n}\end{pmatrix}\begin{pmatrix}\psi_n\\ \psi_{\bar n}\end{pmatrix}\quad,\quad\begin{pmatrix}\psi_n(0)\\ \psi_{\bar n}(0)\end{pmatrix}=\begin{pmatrix}1\\ 0\end{pmatrix}$$

$$|\psi_{\bar n}(t)|^2=\frac{4\varepsilon^2}{\omega^2+4\varepsilon^2}\sin^2\left(\frac{1}{2}\sqrt{\omega^2+4\varepsilon^2}\,t/\hbar\right)$$

$$\omega=(E_n-E_{\bar n})=\left(m_n+\frac{p^2}{2m_n}+V_n\right)-\left(m_{\bar n}+\frac{p^2}{2m_{\bar n}}+V_{\bar n}\right)$$

- Transition Probability: (if ωt <<1)

$$P_{n\to\bar n}(t)=\psi_{\bar n}(t)^2=\varepsilon^2\cdot(t/\hbar)^2=\left(\frac{t}{\tau_{n\bar n}}\right)^2\qquad\tau_{n\bar n}=\frac{\hbar}{\varepsilon}$$

Suppression of n→nbar transition

$$|\psi_{\bar{n}}(t)|^2 = \frac{4\varepsilon^2}{\omega^2 + 4\varepsilon^2}\sin^2\left(\frac{1}{2}\sqrt{\omega^2 + 4\varepsilon^2}\,t/\hbar\right)$$

- Free neutron in a magnetic field

$$\omega = (E_n - E_{\bar{n}}) = (m_n + \frac{p^2}{2m_n} + V_n) - (m_{\bar{n}} + \frac{p^2}{2m_{\bar{n}}} + V_{\bar{n}}) = 2\mu \cdot B$$

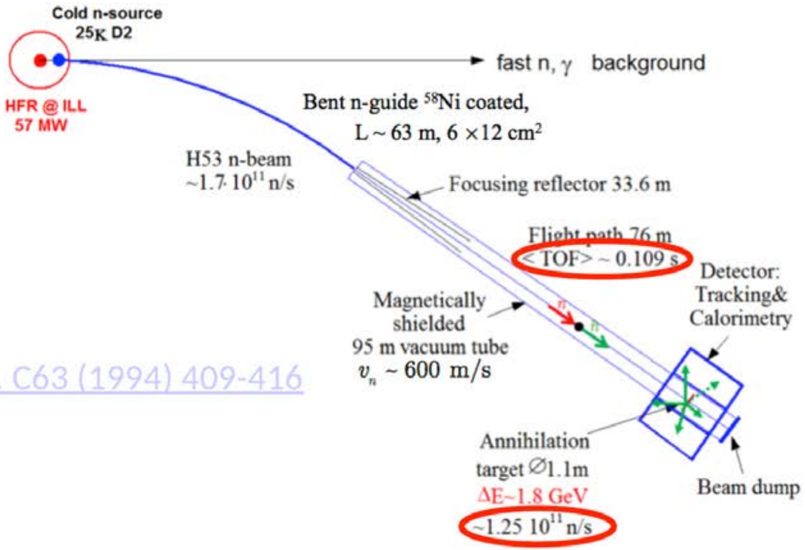
  - **Under earth field (0.5 gauss), $2\mu HB=6\times10^{-12}$eV**
  - $\varepsilon_{n\bar{n}} = \frac{\hbar}{\tau_{n\bar{n}}} < 10^{-23} eV$ with $\tau_{free}>1.2\times10^{8}$ s

$$|\psi_{\bar{n}}(t)|^2 = \frac{4\varepsilon^2}{\omega^2}\sin^2(t/\tau_{Larmor}) = 10^{-23}\sin^2(t/2\times10^{-4})$$

- To measure $\tau_{free}>1.2\times10^{8}$ s, the magnetic field has to be as small as 0.5×10^{-11}gauss!
- For the neutron time-in-flight t=0.1s,
  - B < 5 mgauss.

$$\varepsilon_{n\bar{n}} = \frac{\hbar}{\bar{t}} < 10^{-14} eV$$

Current Limits

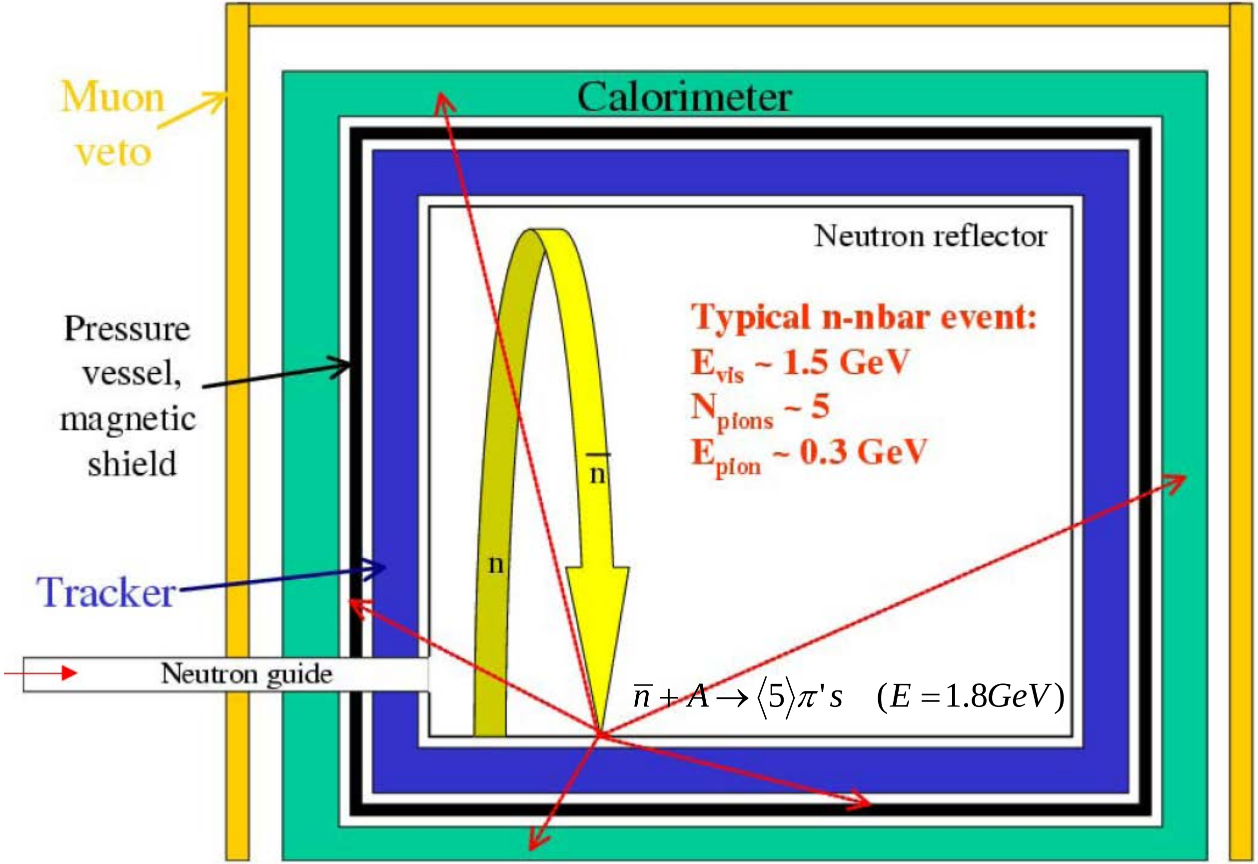


Baldo-Ceolin et al, Z.Phys. C63 (1994) 409-416

- $Nt^2 = 1.5\ 10^9 s^2$, $P < 1.6\ 10^{-18}$ (run lasted ~1 year) and $\tau > 0.86\ 10^8$s
  - Many subtle optimizations to minimize losses and backgrounds
  - CN integrated beam flux was 1.25×10^{11} n/s
  - Experiment was background-free
- Bound neutron limits ~3 times better
  - Many considerations make these measurements complementary to free neutron oscillations

Typical Detector for the UCN N→Nbar Experiment

Typical detector size:
height 2.5 m
diameter 5 m



Muon veto

Calorimeter

Neutron reflector

Pressure vessel, magnetic shield

Tracker

Neutron guide

Typical n-nbar event:

E_{vis} ~ 1.5 GeV

N_{pions} ~ 5

E_{pion} ~ 0.3 GeV

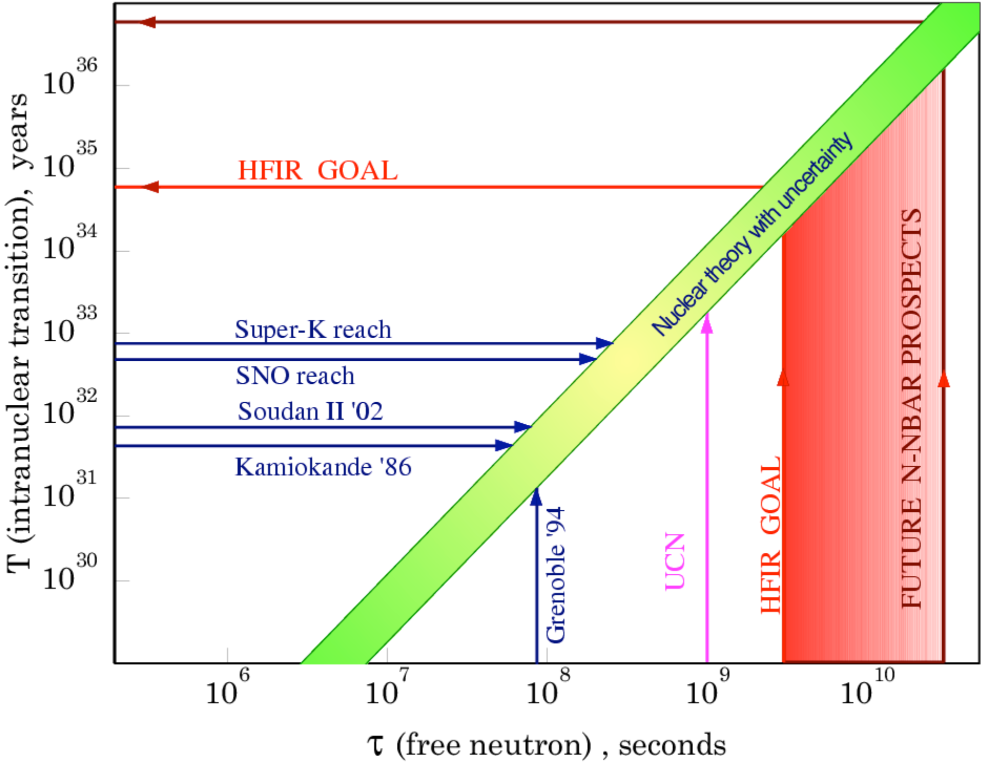
$\bar{n}$

n

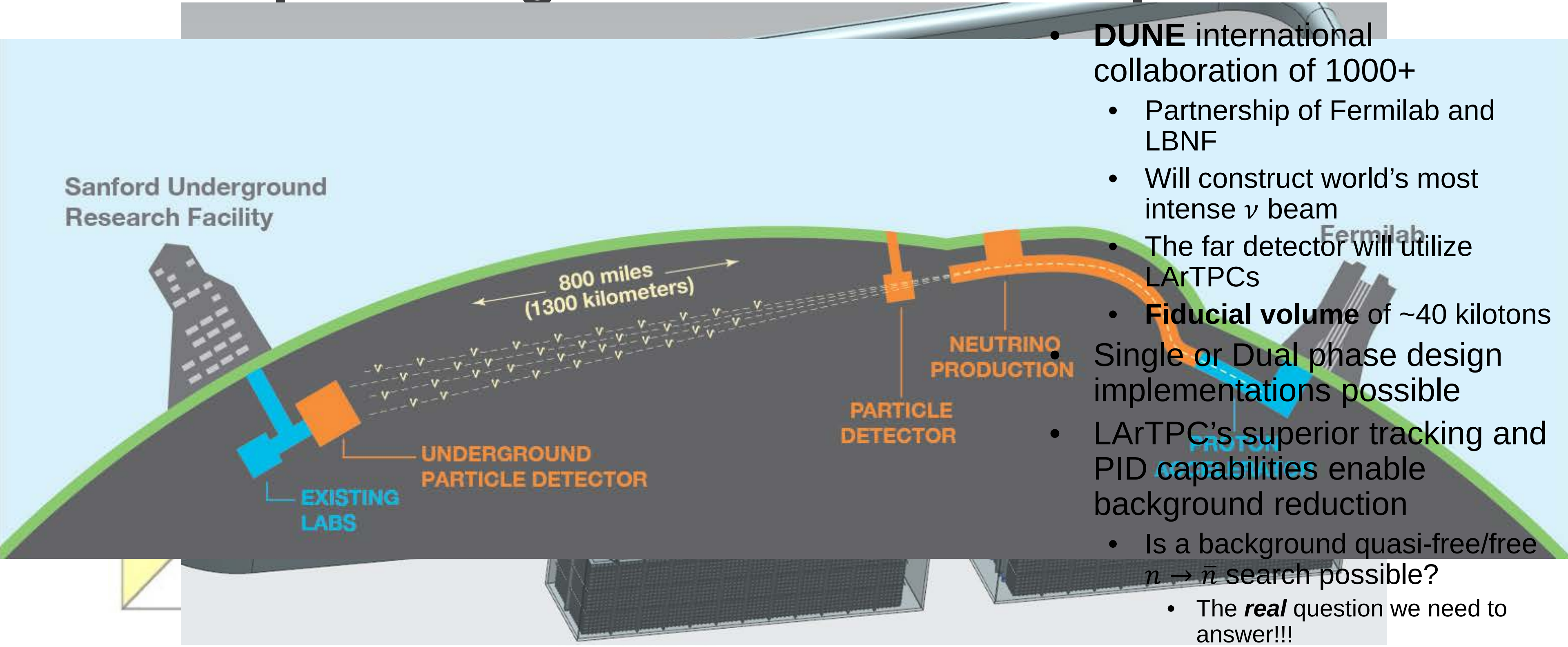
$\bar{n} + A \rightarrow \langle 5 \rangle \pi' s \quad (E = 1.8 GeV)$

Stability of matter from Neutron-Antineutron transition search

$T_A = R * (\tau_{free})^2$, where R is "nuclear suppression factor" in intranuclear transition



Bound Neutron Search at the Deep Underground Neutrino Experiment



- **DUNE** international collaboration of 1000+
  - Partnership of Fermilab and LBNF
  - Will construct world's most intense ν beam
  - The far detector will utilize LArTPCs
  - **Fiducial volume** of ~40 kilotons
- Single or Dual phase design implementations possible
- LArTPC's superior tracking and PID capabilities enable background reduction
  - Is a background quasi-free/free $n \rightarrow \bar{n}$ search possible?
    - The ***real*** question we need to answer!!!

Adapted from
Y. Kamyshkov

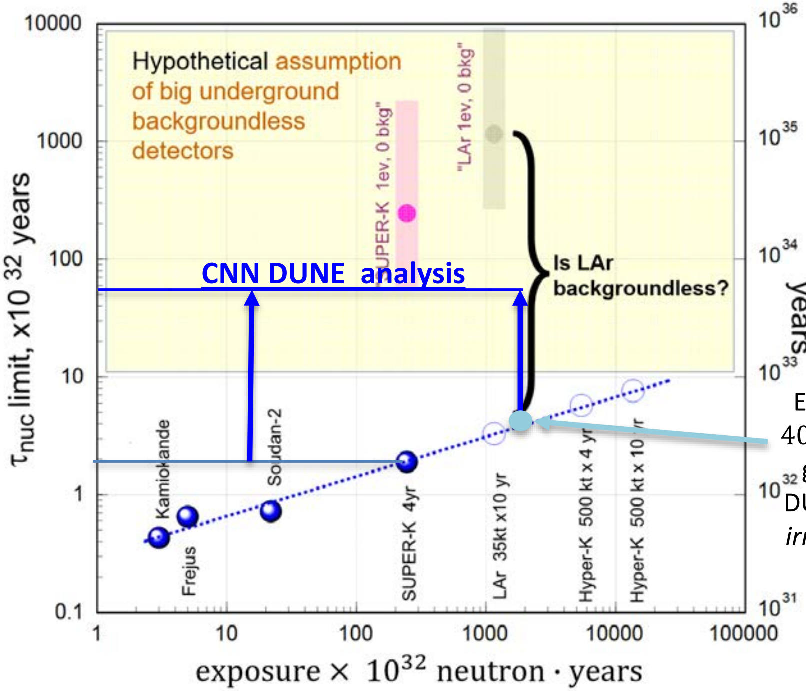
Atmospheric ν Backgrounds Impede Intranuclear $n \rightarrow \bar{n}$ Event Identification In Large Underground Experiments

Previous searches for $n \rightarrow \bar{n}$ suffered greatly from this!

- Super-Kamiokande: 24 candidate events
  - Expected $sig.eff:bkgrcount = \mathbf{12\%:24.1}$
- DUNE?
  - **Convolutional Neural Network**: $sig.eff:bkgrcount = \mathbf{14\%:3}$
    - Fully oscillated sample!
    - Important ν_τ interactions
  - **Truth**: $sig.eff:bkgrcount = \mathbf{27\%:0}$
    - Unoscillated sample! (a large grain of salt)

Theorists and computational physicists are working tirelessly to improve the accuracy of ν generators

- This is a requirement for understanding ν oscillation parameters precisely and atmospheric background properly
- GENIE is one of many used today
  - New cross section model from Pastore will be implemented soon
  - Implement explicit transformation radius dependence, spectral functions
- GIBUU and NuWRO getting great comparative results from MicroBooNE with their novel and unique techniques
- Plan to **run/re-run proper signal and background events** on all these platforms **for separability comparisons in the future**



Expected $400\ kt \cdot yr$ goal for DUNE with *irreducible* bkgr?

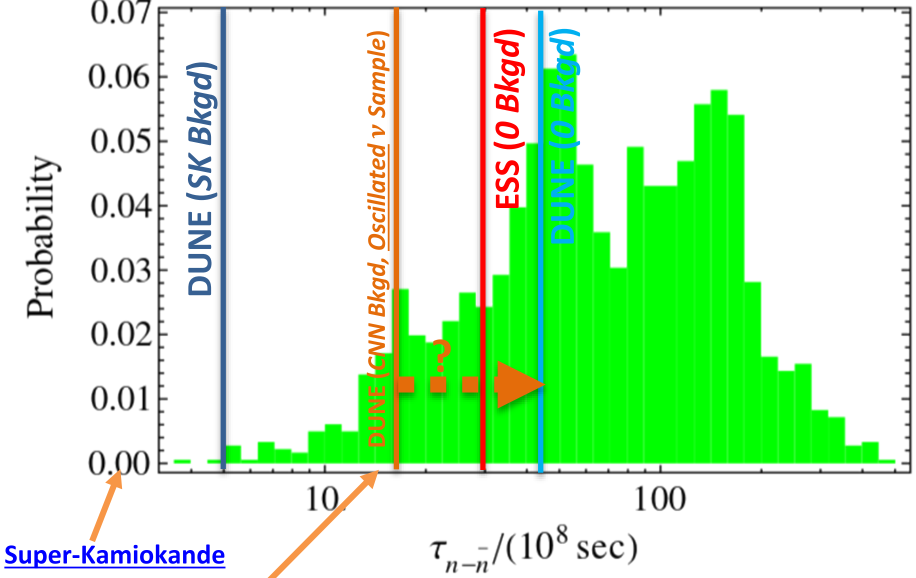
Theoretically Important Probability Parameter Space of $\tau_{n\to\bar{n}}$

Post-sphaleron baryogenesis can predict the free $n \to \bar{n}$ transformation time

- **Blue** shows converted limit from intranuclear transformation time
  - DUNE, 10 years, ~13,500x ILL sensitivity
  - **Assumes 25% efficiency**—*more possible*?
  - **Assumes no background**!
- **Red** line shows free neutron transformation time
  - ESS, 3 yr, *goal* of ~1000x ILL sensitivity
  - Assuming ILL-like *zero background*
    - Future work to show this definitively

$$\tau_M = R \cdot \tau_{n\to\bar{n}}^2$$

Babu, Dev, Fortes, and Mohapatra-DOI: 10.1103/PhysRevD.87.115019



Super-Kamiokande

$24:12\%$

Current DUNE Analysis

$\sim 3:14\%$

Improvements to be made

Summary on nnbar experiments

- Baryon number violation is a requirement for the existence of our universe
- Arguably the best way to look for this is BSM processes such as $n \rightarrow \bar{n}$ with pure $\Delta B \neq 0$
  - Ability to say something experimentally about this depends on further integration of efforts between the neutron and HEP community
- DUNE has significant reach potential to constrain popular baryogenesis theories
  - Need to take into account zeroth—first-order corrections in nuclear physics models to understand signals and backgrounds properly
    - Transformation/annihilation radius distribution, spectral functions, new ν cross section
- Free experiments (NNbar collaboration at ESS, see next talk from Albert) are also possible, and promise a similar reach
- Bound and free searches are ***incredibly complementary***, and, if $n \rightarrow \bar{n}$ is definitively observed, rate differences could hint at further important BSM physics

A New Limit on Time-Reversal-Invariance Violation in Beta Decay: Results of the emiT-II Experiment

T.E. Chupp, K.P. Coulter & R.L. Cooper
University of Michigan

S.J. Freedman & B.K. Fujikawa
University of California - Berkeley/
Lawrence Berkeley National Laboratory

G.L. Jones
Hamilton College

A. Garcia
University of Washington

H.P. Mumm, J.S. Nico, & A.K. Thompson
National Institute of Standards and Technology

C. Trull & F.E. Wietfeldt
Tulane University

J.F. Wilkerson
University of North Carolina

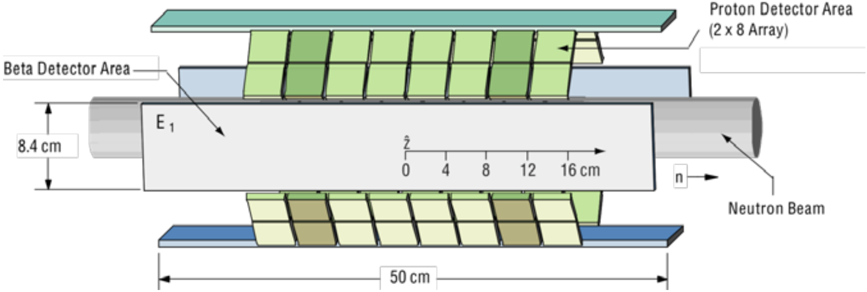
NEW RESULT: D=[-0.94±1.89(STAT)±0.97(SYS)]X10^{-4}

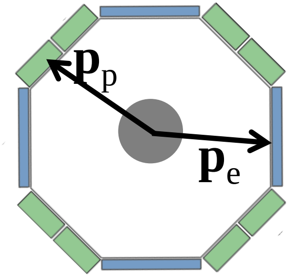
Phys. Rev. C **86**, 035505

$$\varphi_{AV} = 180.012 \pm 0.028 \qquad \frac{g_A}{g_V} = |\lambda| e^{i\varphi_{AV}}$$

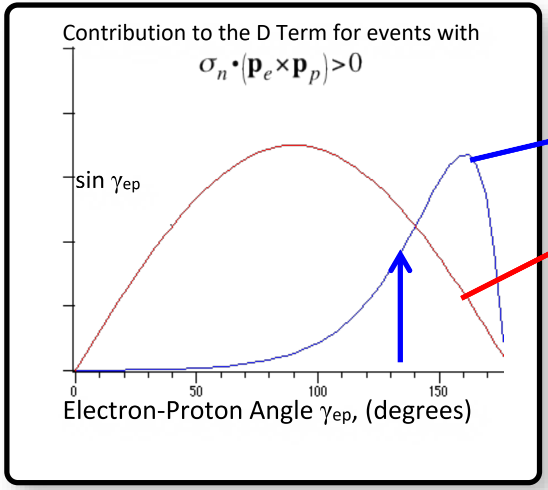
Work supported in part by NIST and grants from the DOE and NSF

emiT: 8-fold symmetry
64 proton SBDs/4 β scintillators





$$D \vec{J}_n \cdot (\vec{p}_p \times \vec{p}_e)$$

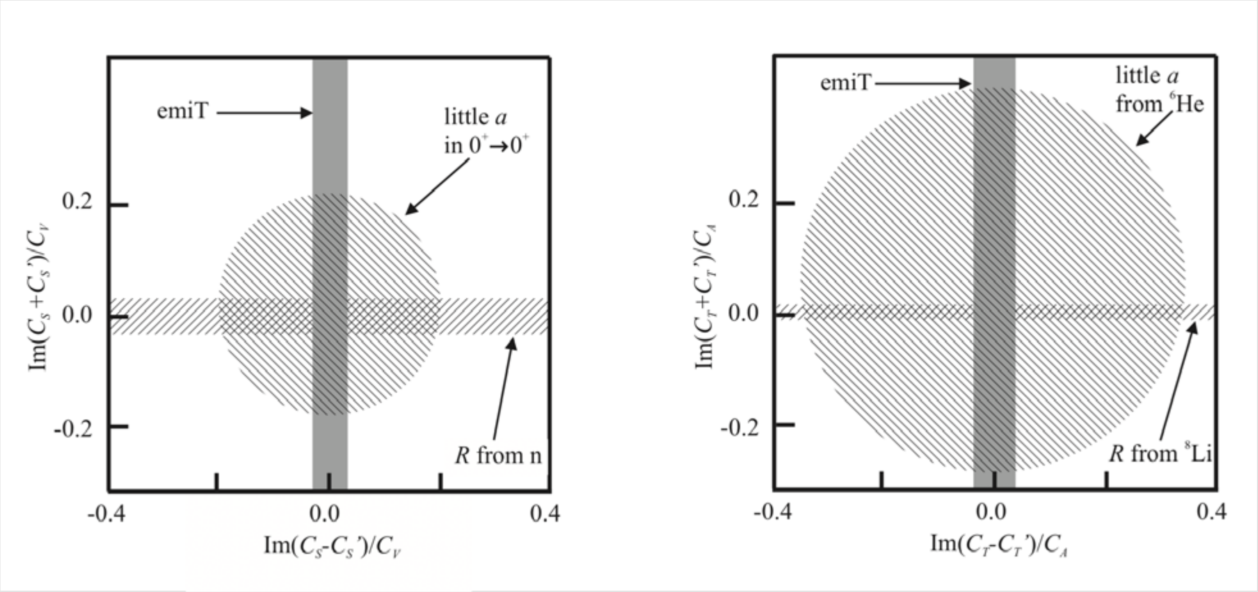


- Proton-electron momenta anticorrelated
  - Coincidence rate favors 180°
  - $\sin\theta_{ep}$ favors 90°
  - FOM ($1/\sigma^2$) 9x improved at 135°
- Symmetrical, segmented detector:
  - Minimize sensitivity to *A* and *B*
  - Investigate nonuniformities
  - Study systematic effects

Final emiT Result

$$D=(-0.94\pm1.89\ (\mathrm{stat})\pm0.97(\mathrm{sys}))\mathrm{x}10^{-4}$$

$$\phi_{AV} = 180.012^{\circ} \pm 0.028^{\circ}$$



This is the most sensitive measurement of D in nuclear β decay. The result can be interpreted as a measurement of the phase of the ratio of the axial-vector and vector coupling constants ($C_A/C_V=|\lambda|e^{i\varphi AV}$) with $\varphi_{AV}=180.012^{\circ}\pm0.028^{\circ}$ (68% confidence level). This result can also be used to constrain time-reversal-violating scalar and tensor interactions that arise in certain extensions to the Standard Model such as leptoquarks.

QCD in a nutshell

Quantum Chromo Dynamics = gauge theory of the strong interactions

Fritzsch, Gell-Mann & Leutwyler

$f = u, d, s, c, b, t$

SU$_c$(3) gauge group

$$\mathcal{L}_{QCD} = \sum_f \bar{q}_f \left(iD_\mu \gamma^\mu - m_f \right) q_f - \frac{1}{4} F^a_{\mu\nu} F^{a,\mu\nu}$$

$$q_f = \begin{pmatrix} q_{f,r} \\ q_{f,g} \\ q_{f,b} \end{pmatrix} \qquad q'_{f,\alpha} = U_{\alpha\beta}\, q_{f,\beta}$$

$$U \equiv \exp\left(-i\, \theta_a \frac{\lambda_a}{2} \right)$$

Eight non-commuting generators

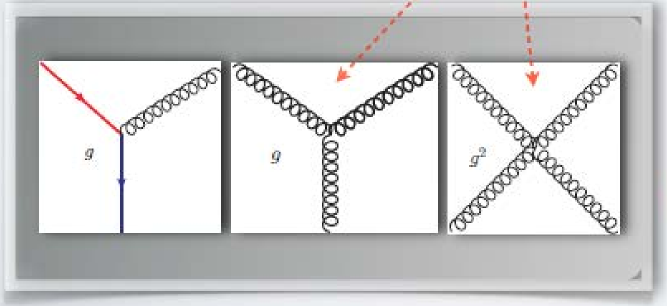
$$D_\mu q_f \equiv \left(\partial_\mu + ig\mathcal{A}_\mu \right) q_f \qquad \mathcal{A}_\mu = \mathcal{A}^a_\mu \frac{\lambda^a}{2}$$

$$\left[\frac{\lambda_a}{2}, \frac{\lambda_b}{2} \right] = i f^{abc} \frac{\lambda_c}{2}$$

$$F^a_{\mu\nu} = \partial_\mu \mathcal{A}^a_\nu - \partial_\nu \mathcal{A}^a_\mu - g f^{abc} \mathcal{A}^b_\mu \mathcal{A}^c_\nu$$

$$\mathcal{A}_\mu(x) \to \mathcal{A}_\mu(x) - \frac{1}{e} \partial_\mu \theta(x) \qquad \text{(QED)}$$

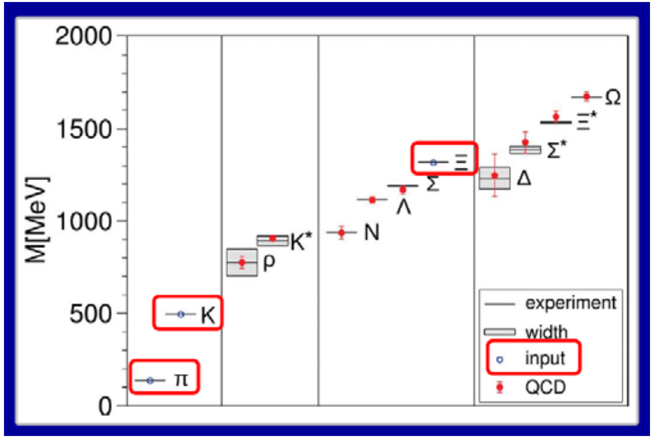
$$\mathcal{A}^a_\mu(x) \to \mathcal{A}^a_\mu(x) + \frac{1}{g} \partial_\mu \theta^a(x) + f^{abc} \mathcal{A}^c_\mu(x) \theta^b(x) \qquad \text{(QCD)}$$



Generators of the adjoint representation

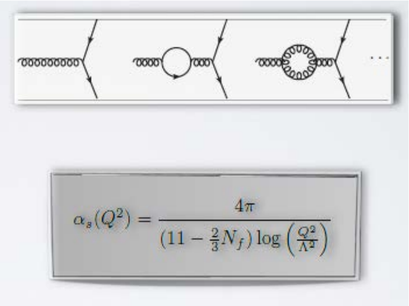
Gluons are in the adjoint representation

Non-perturbative QCD
Lattice QCD calculations

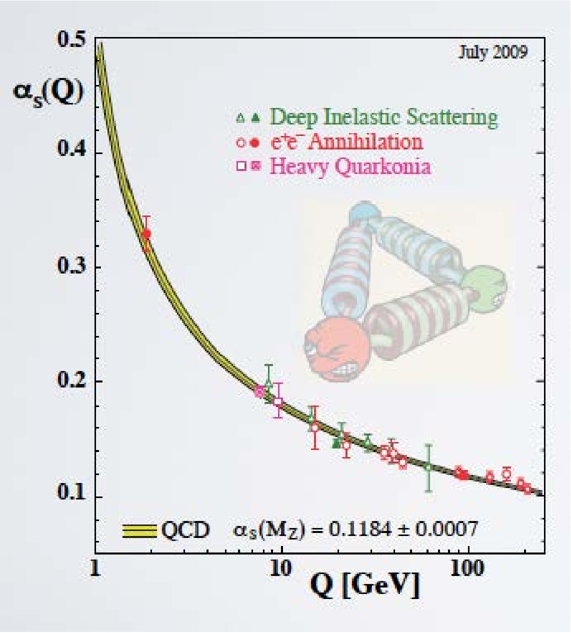


Supercomputers evaluate QCD correlation functions on a spacetime lattice.

Gets the right hadron spectrum once a few masses are supplied



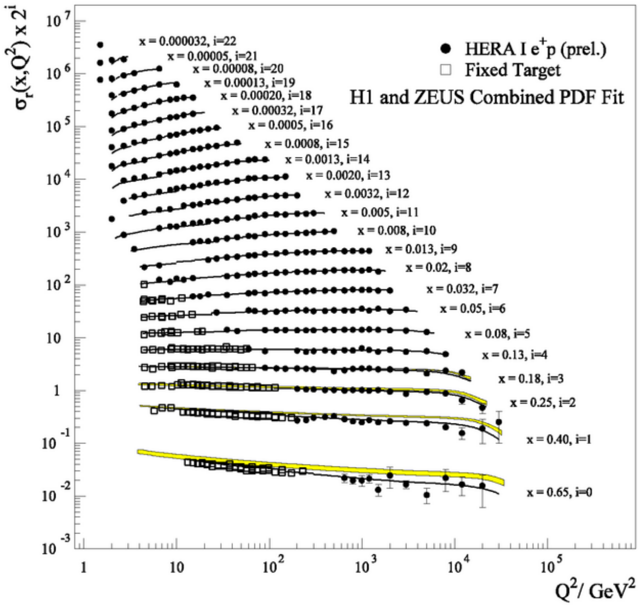
$$\alpha_s(Q^2) = \frac{4\pi}{(11-\frac{2}{3}N_f)\log\left(\frac{Q^2}{\Lambda^2}\right)}$$



Perturbative QCD

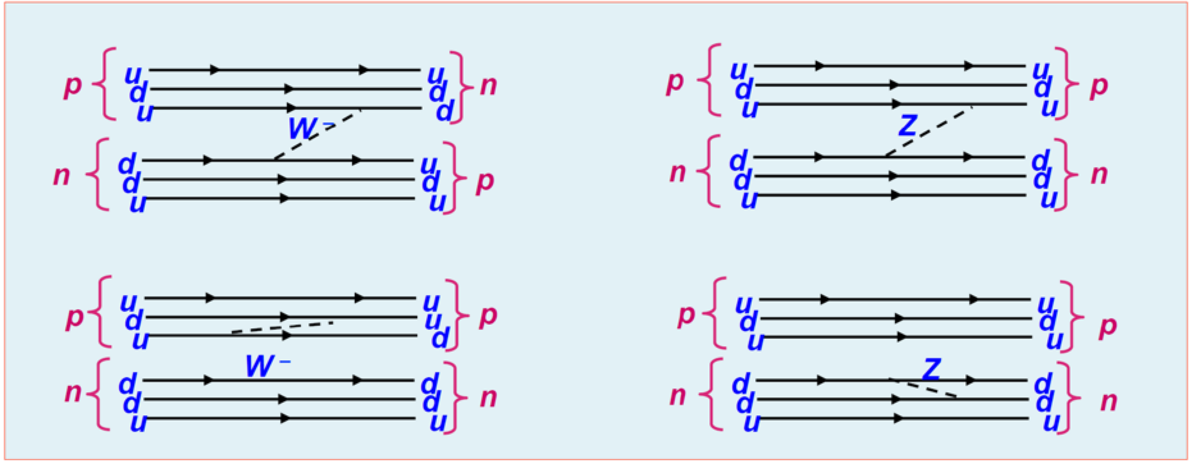
Asymptotic Freedom

David J. Gross, H. David Politzer & Frank Wilczek, 2004



NN Weak Interaction: use EW parity violation to probe QCD

In the Standard Model, the structure of the quark-quark weak interaction is known from the electroweak sector. However, strong QCD **confines color** and **breaks chiral symmetry**, thereby strongly correlating the quarks in both the *initial* and *final* nucleon ground states.



QCD contains only vector quark-gluon couplings → P is conserved.

Relative strength

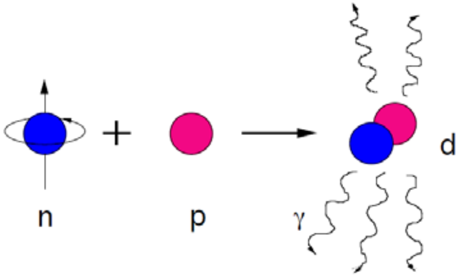
$$\frac{e^2}{M_W^2} / \frac{g^2}{m_\pi^2} \approx 10^{-7}$$

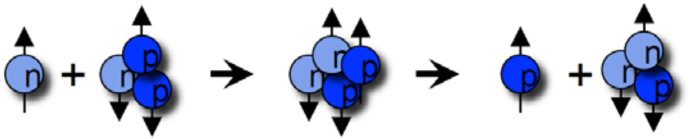
Two aspects of qq weak interaction make it useful as **an interesting probe of QCD**:

(1) Since it is weak, it probes the nucleons in their ground states without exciting them.

(2) Since it is short-ranged compared with the size of the nucleon, NN weak amplitudes should be first-order sensitive to **quark-quark correlation effects in the nucleon.**

Few-Body P-odd NN in progress: n-p, n-^{3}He, n-^{4}He





NPDγ
$A\gamma \sim 10^{-8}$

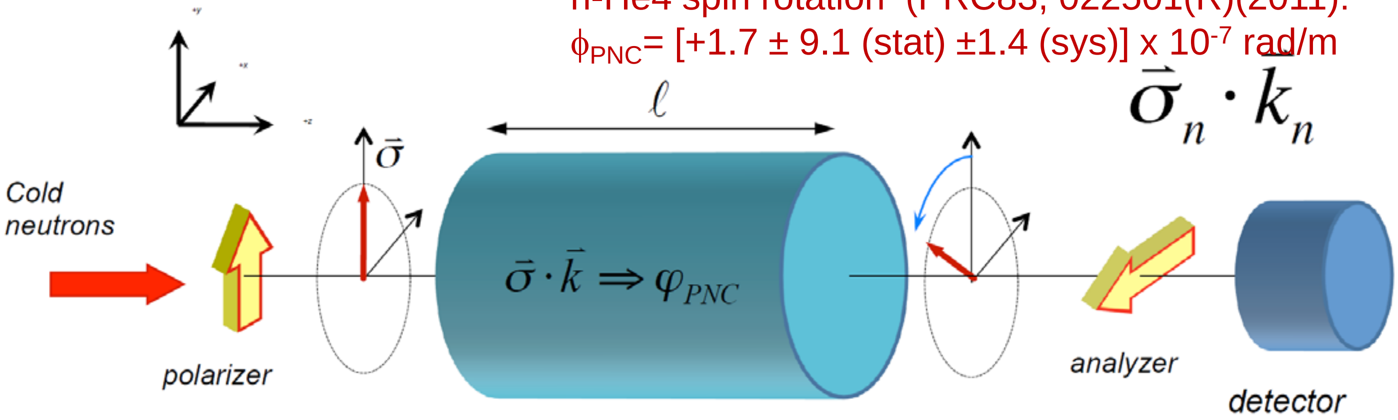
$$\vec{\sigma}_n \cdot \vec{k}_\gamma$$

$$\vec{\sigma}_n \cdot \vec{k}_p$$

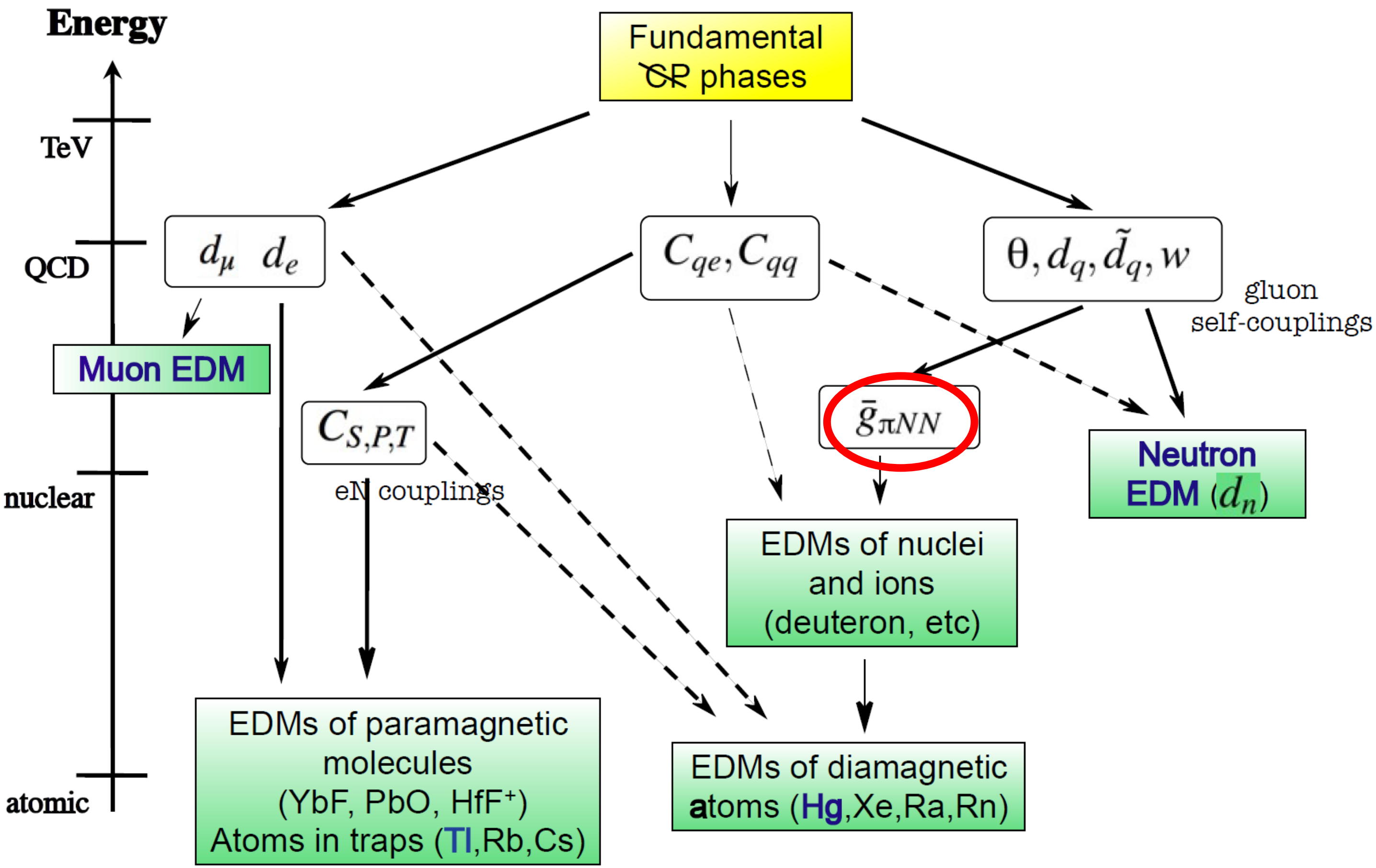
N-He3
$Ap \sim 2\text{x}10^{-8}$

n-He4 spin rotation (PRC83, 022501(R)(2011):
ϕ_{PNC}= [+1.7 ± 9.1 (stat) ±1.4 (sys)] x 10^{-7} rad/m

$$\vec{\sigma}_n \cdot \vec{k}_n$$



CP-violation in Low Energy Phenomena



Energy

TeV

QCD

nuclear

atomic

Fundamental $\not{C}\!P$ phases

$d_\mu \quad d_e$

C_{qe}, C_{qq}

$\theta, d_q, \tilde{d}_q, w$

gluon self-couplings

Muon EDM

$C_{S,P,T}$

eN couplings

$\bar{g}_{\pi NN}$

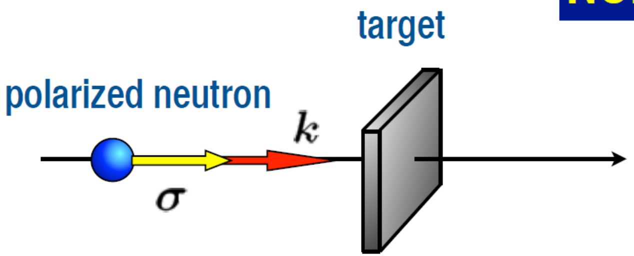
Neutron EDM (d_n)

EDMs of nuclei and ions (deuteron, etc)

EDMs of paramagnetic molecules (YbF, PbO, HfF$^+$) Atoms in traps (Tl,Rb,Cs)

EDMs of diamagnetic atoms (Hg,Xe,Ra,Rn)

Pospelov Ritz, Ann Phys 318 (05) 119

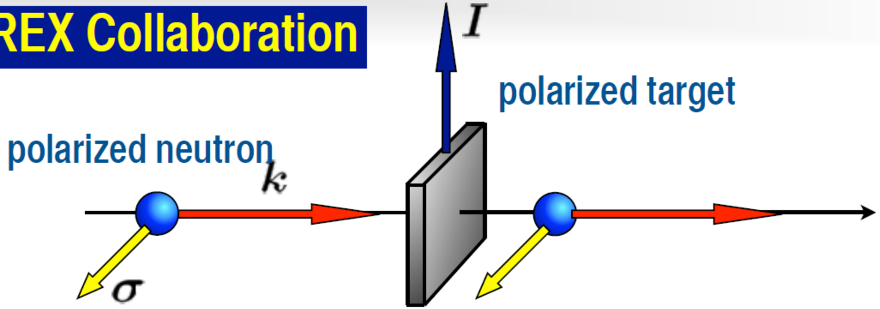


$$\boldsymbol{\sigma} \cdot \hat{\boldsymbol{k}}$$

$$P : \boldsymbol{\sigma} \cdot \hat{\boldsymbol{k}} \to \boldsymbol{\sigma} \cdot (-\hat{\boldsymbol{k}})$$

P-odd

$\cancel{P}$



$$\boldsymbol{\sigma} \cdot (\hat{\boldsymbol{k}} \times \hat{\boldsymbol{I}})$$

$$P : \boldsymbol{\sigma} \cdot (\hat{\boldsymbol{k}} \times \hat{\boldsymbol{I}}) \to \boldsymbol{\sigma} \cdot ((-\hat{\boldsymbol{k}}) \times \hat{\boldsymbol{I}})$$

$$T : \boldsymbol{\sigma} \cdot (\hat{\boldsymbol{k}} \times \hat{\boldsymbol{I}}) \to (-\boldsymbol{\sigma}) \cdot ((-\hat{\boldsymbol{k}}) \times (-\hat{\boldsymbol{I}}))$$

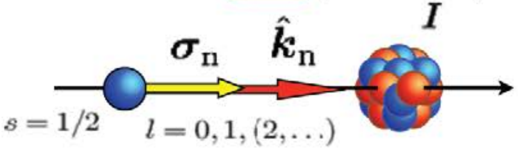
P-odd T-odd

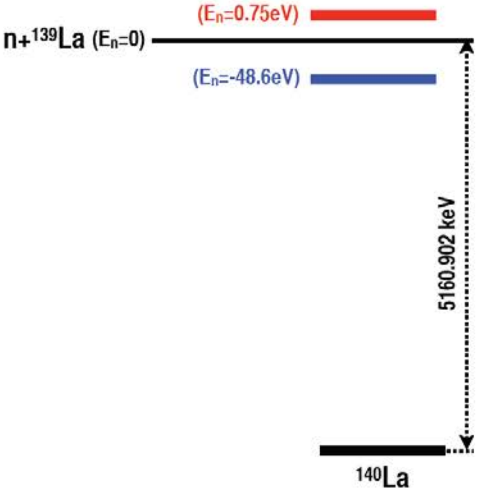
$\cancel{T}$

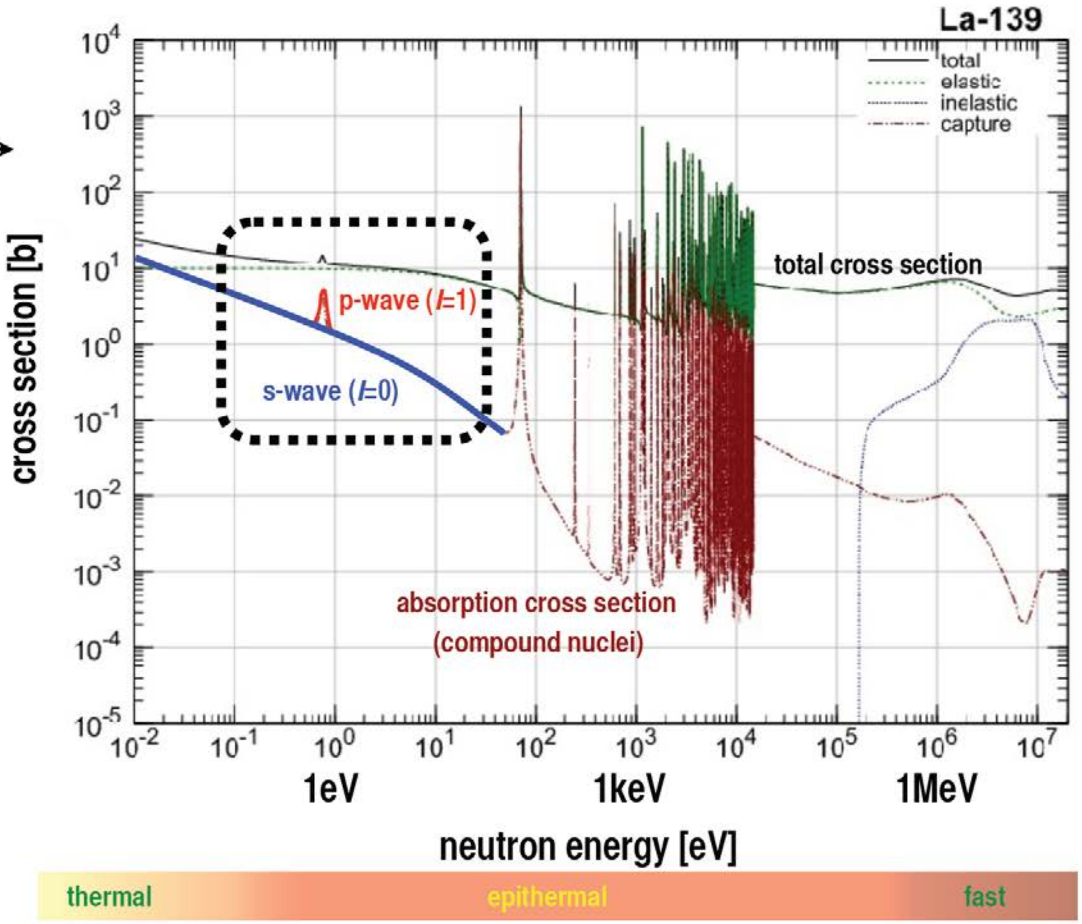
Compound States

P-violation

$$\sigma = \sigma_0 + \boxed{\Delta\sigma}(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_n)$$



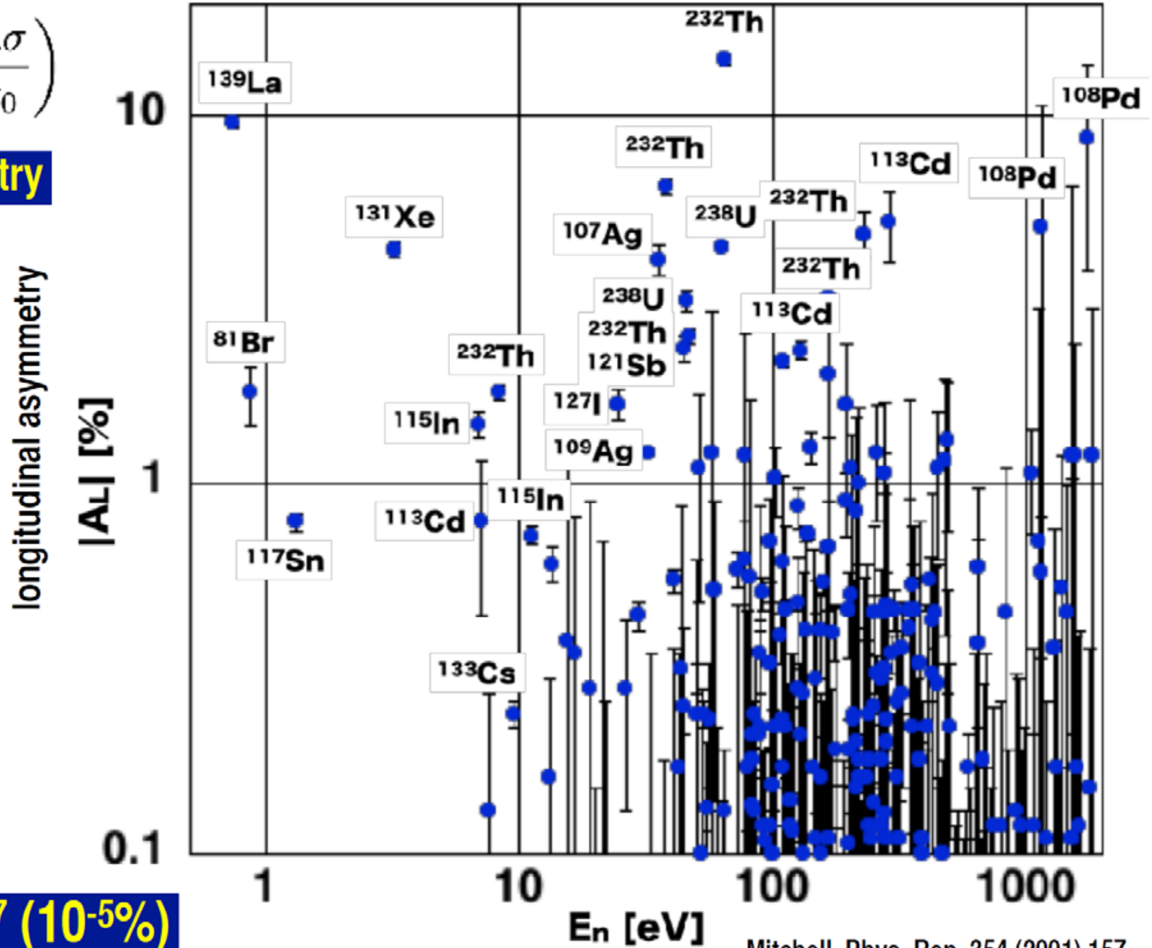




Enhanced P-violation in Compound States

$$A_{\mathrm{L}} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \left(= \frac{\Delta\sigma}{\sigma_0} \right)$$

Longitudinal Asymmetry

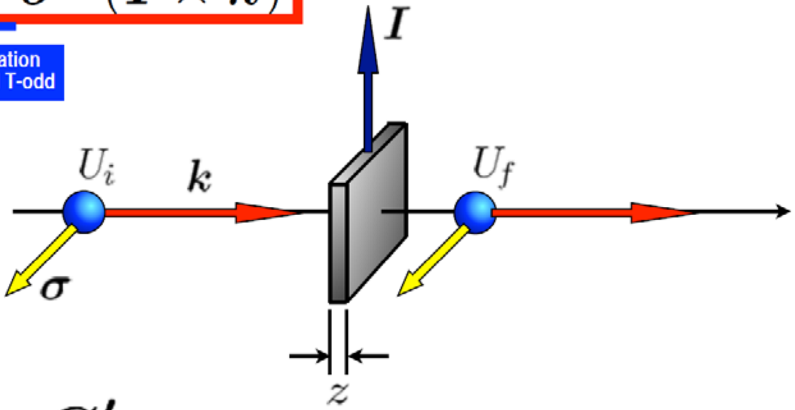


Mitchell, Phys. Rep. 354 (2001) 157

NN-interaction 10^{-7} (10^{-5}%)

T-violation in Neutron Optics

$$f = \underbrace{A'}_{\substack{\text{Spin Independent}\\ \text{P-even T-even}}} + \underbrace{B'}_{\substack{\text{Spin Dependent}\\ \text{P-even T-even}}}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + \underbrace{C'}_{\substack{\text{P-violation}\\ \text{P-odd T-even}}}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + \boxed{\underbrace{D'}_{\substack{\text{T-violation}\\ \text{P-odd T-odd}}}\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}})}$$



T-violating matrix element

$$\underbrace{\boxed{\Delta\sigma_{\rm CP} = \kappa(J)\frac{W_{\rm T}}{W}\overbrace{\Delta\sigma_{\rm P}}^{C'}}}_{}\quad D' — \Delta\sigma_{\rm CP}$$

T-violation

angular momentum factor

P-violation

P-violating matrix element

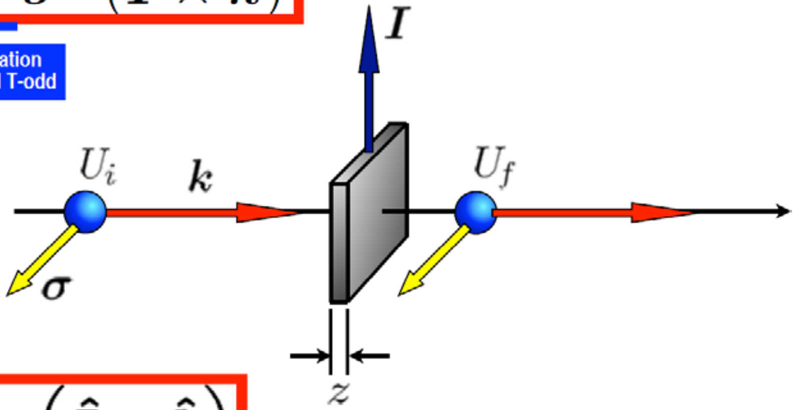
Gudkov, Phys. Rep. 212 (1992) 77

$$\kappa(J) = 0.99^{+0.88}_{-0.07},\ 4.84^{+5.58}_{-1.69}$$

$$\left|\frac{W_{\rm T}}{W}\right| < 3.9\times10^{-4}$$

T-violation in Neutron Optics

$$f = \underbrace{A'}_{\substack{\text{Spin Independent}\\ \text{P-even T-even}}} + \underbrace{B'}_{\substack{\text{Spin Dependent}\\ \text{P-even T-even}}}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + \underbrace{C'}_{\substack{\text{P-violation}\\ \text{P-odd T-even}}}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + \boxed{\underbrace{D'}_{\substack{\text{T-violation}\\ \text{P-odd T-odd}}}\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}})}$$



$$U_f = \delta U_i$$

$$\delta = e^{i(n-1)kz} \qquad n = 1 + \frac{2\pi\rho}{k^2} f$$

$$\delta = \underbrace{A}_{\substack{\text{Spin Independent}\\ \text{P-even T-even}}} + \underbrace{B}_{\substack{\text{Spin Dependent}\\ \text{P-even T-even}}}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + \underbrace{C}_{\substack{\text{P-violation}\\ \text{P-odd T-even}}}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + \boxed{\underbrace{D}_{\substack{\text{T-violation}\\ \text{P-odd T-odd}}}\boldsymbol{\sigma}\cdot\left(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}}\right)}$$

$$A = e^{iZA'}\cos b \qquad B = ie^{iZA'}\frac{\sin b}{b}ZB'$$

$$Z = \frac{2\pi\rho}{k}z \qquad C = ie^{iZA'}\frac{\sin b}{b}ZC'$$

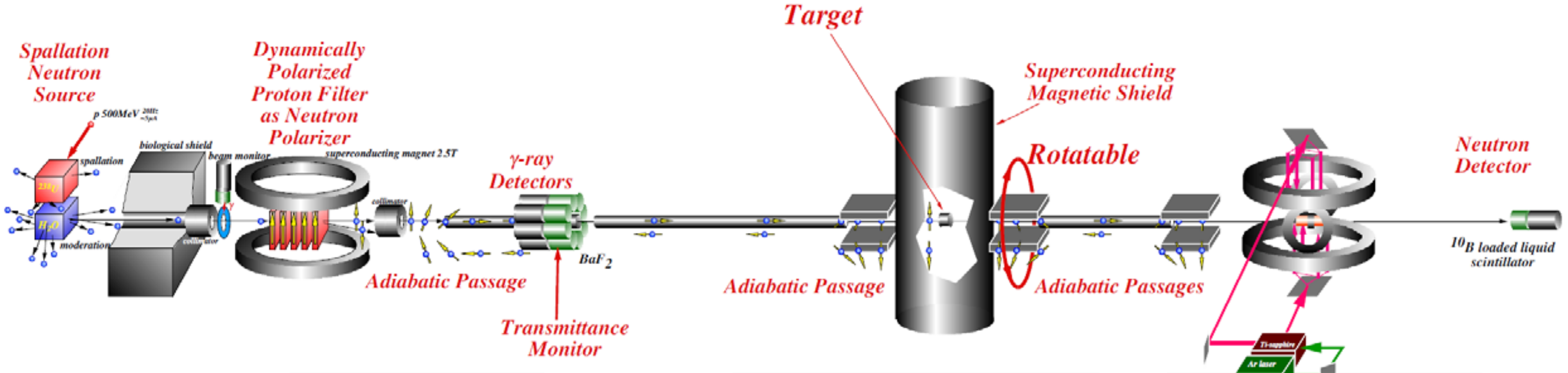
$$b = Z(B'^2 + C'^2 + D'^2)^{1/2} \qquad D = ie^{iZA'}\frac{\sin b}{b}ZD'$$

D≠0 ➡ D’≠0

KEK 2018S12

Neutron Optics for Parity and Time Reversal EXperiment

NOPTREX Collaboration



epithermal neutron polarizer

polarized target

spin control

epithermal neutron spin analyzer

Polarized Neutron Source

Target station

Neutron Spin Analyzer

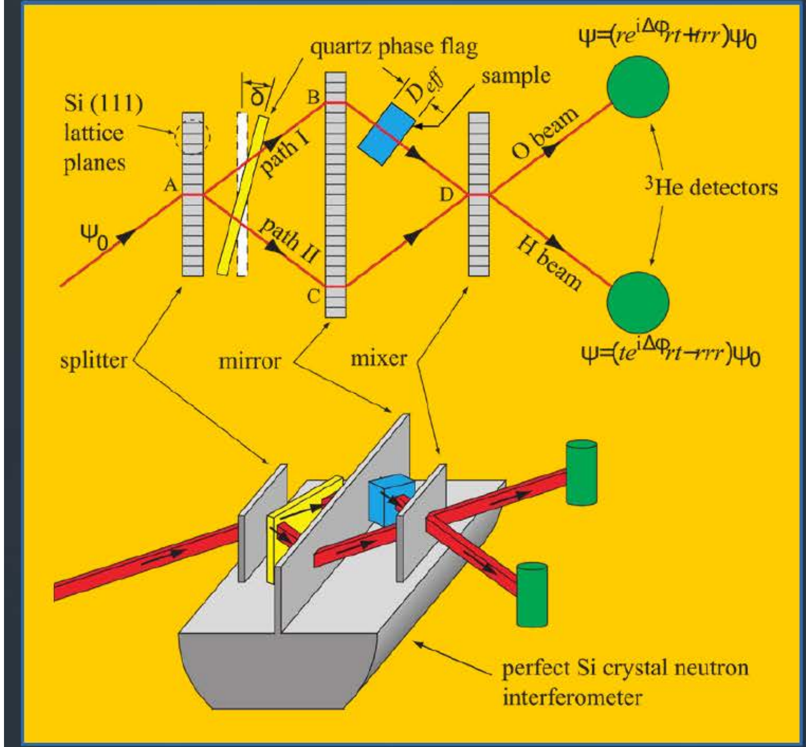
$\overrightarrow{{}^{3}\mathrm{He}}$ $\overrightarrow{\mathrm{p}}$

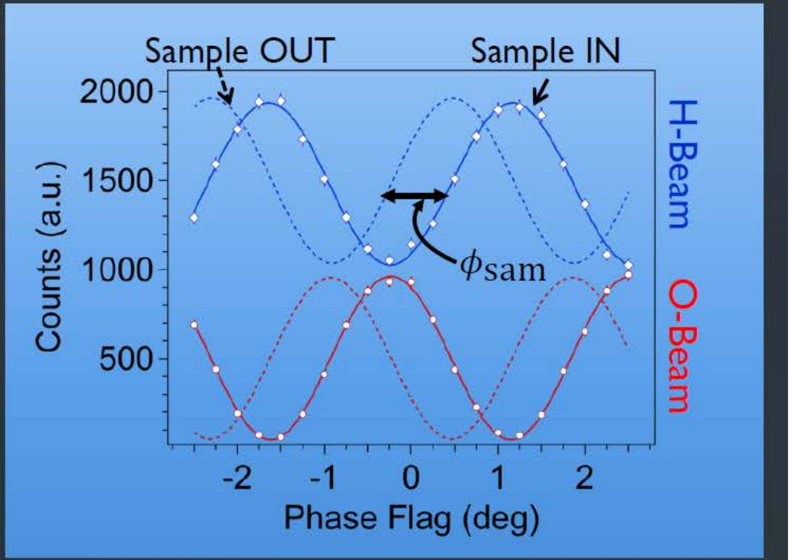
$\overrightarrow{{}^{139}\mathrm{La}}$ $\overrightarrow{{}^{131}\mathrm{Xe}}$

$\overrightarrow{{}^{81}\mathrm{Br}}, \overrightarrow{{}^{117}\mathrm{Sn}}, \overrightarrow{{}^{115}\mathrm{In}}, \overrightarrow{{}^{127}\mathrm{I}}, \overrightarrow{{}^{133}\mathrm{Cs}}, \overrightarrow{{}^{81}\mathrm{Br}}, \ldots$

$\overrightarrow{{}^{3}\mathrm{He}}$ $\overrightarrow{\mathrm{p}}$

Neutron Interferometer





Interferogram:

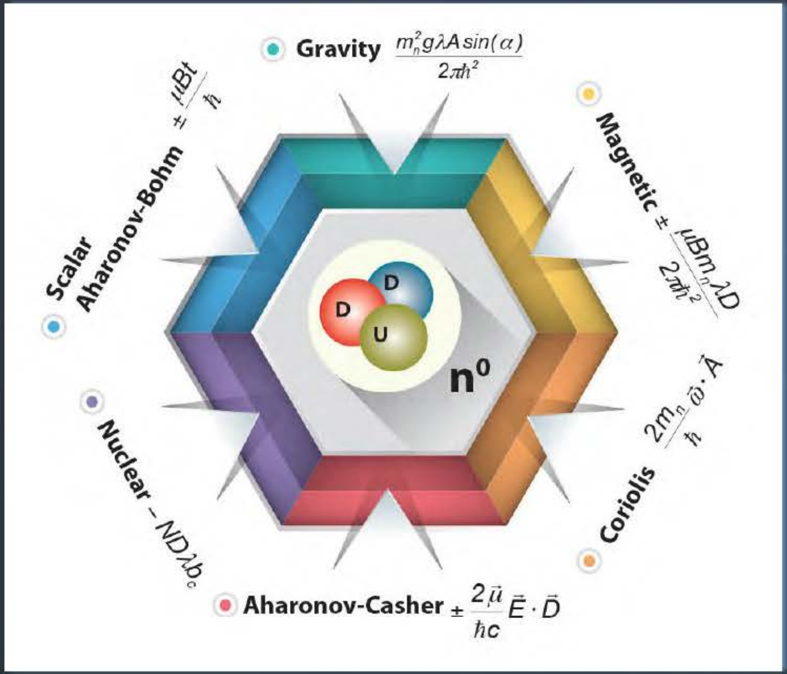
$$I_O = A\left[1 + C * \cos\left(\phi_{sam,1} + \phi_{sam,2}\left(d_{\text{eff}}\right) + \phi_0\right)\right]$$

$$I_H = A\left[\frac{B}{A} - C * \cos\left(\phi_{sam,1} + \phi_{sam,2}\left(d_{\text{eff}}\right) + \phi_0\right)\right]$$

The fringe visibility or contrast (C) is an important parameter as $\delta\phi \propto C^{-1}$ and is used to evaluate an interferometer's quality.

Phase Shifts

neutron interferometry
is a *diverse* instrument!



Nuclear: $\phi_{\mathbf{nuc}}$

$\phi_{nuc}\sim 135\pi$ for 1 cm of Al

Gravity: $\phi_{\mathbf{gravity}}$

$\phi_{gravity}\sim 50\pi$ for 0.002 m^2 Area

Magnetic: $\phi_{\mathbf{mag}}$

$\phi_{mag}\sim 15\pi$ for 1 cm of 100 G field

Aharonov-Casher: $\phi_{\mathbf{AC}}$

$\phi_{AC}\sim$ 1 mrad for 30kV field

Geometric: $\phi_{\mathbf{geo}}$

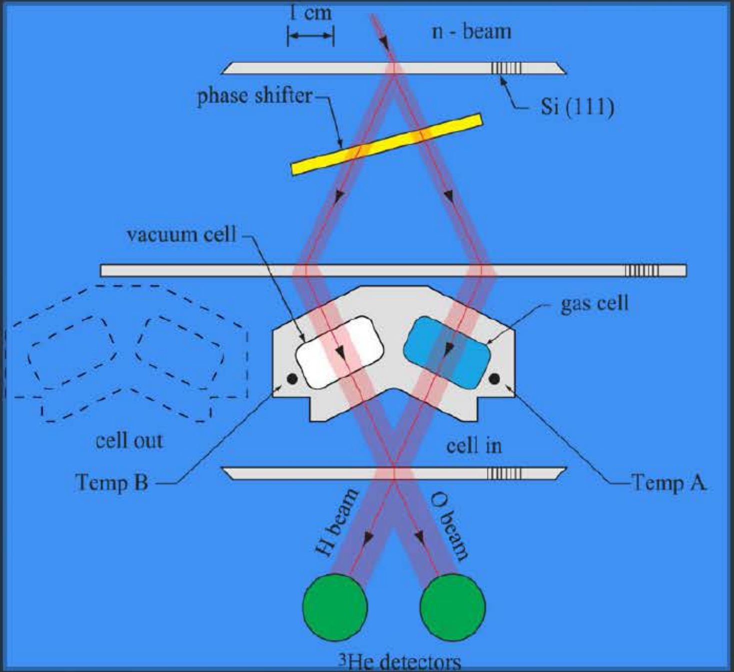
$\phi_{geo}\sim\pi$

Sagnac: ϕ_{sag}

$\phi_{sag}\sim\pi$ for 0.002 m^2 Area

Precision Scattering Lengths

- Tighter constraints for NN and few-nucleon potential models
- Neutron scattering lengths of light nuclei are benchmarks for chiral effective field theories and can be used to calculate low-energy coefficients required by the theory
- ^{4}He is often utilized in fundamental neutron experiments exploring physics beyond the standard model

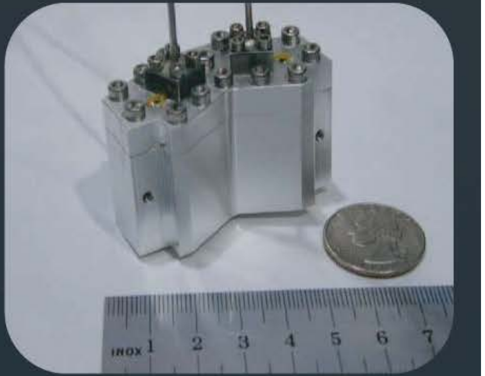


$$b = \frac{\varphi_{gas}}{N(T,P)\lambda D(T)}$$

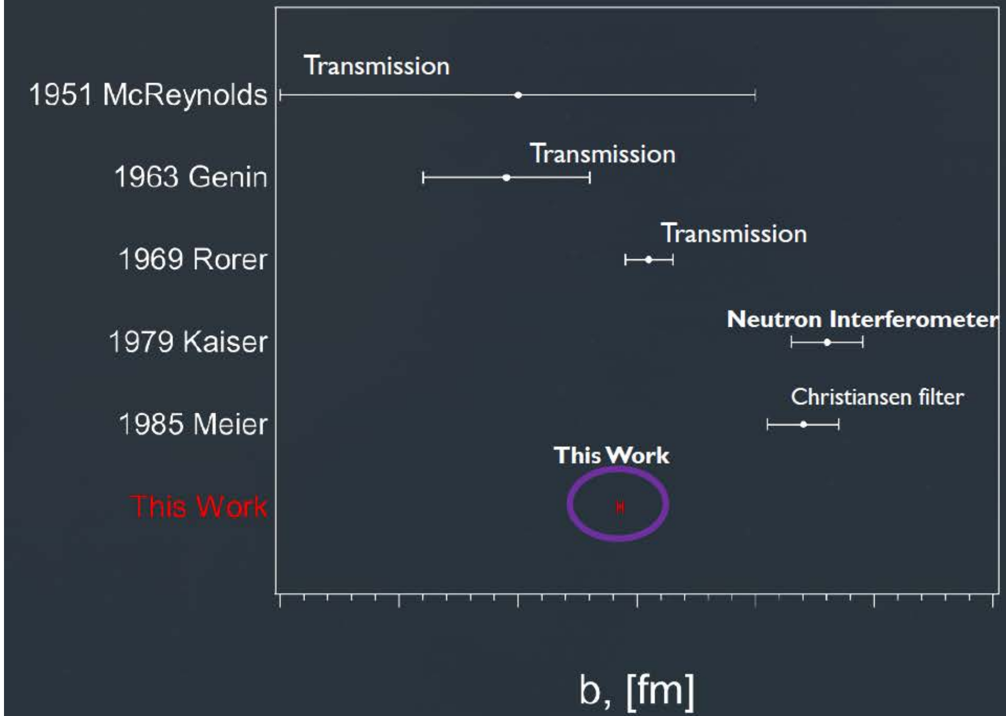
Path Length $D(T) = D_0[1 + \alpha(T - T_0)]$

Density $N(T,P) = \dfrac{P}{k_B T(1 + B_P P + C_P P^2)}$

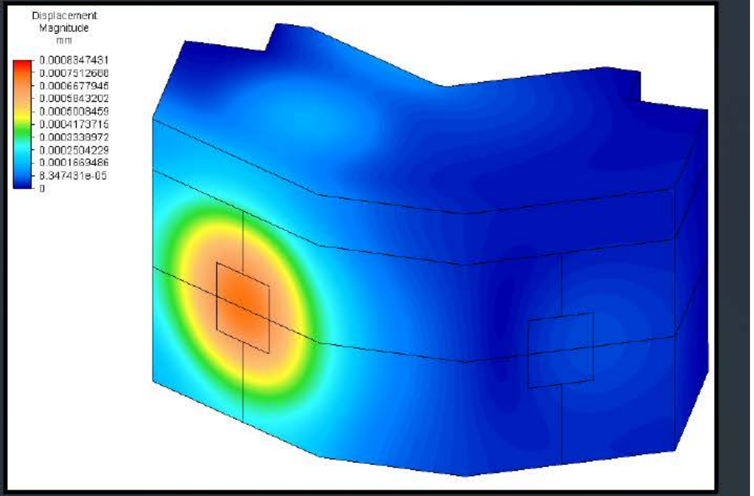
Wavelength $\lambda = 2.70913(15)$ Å

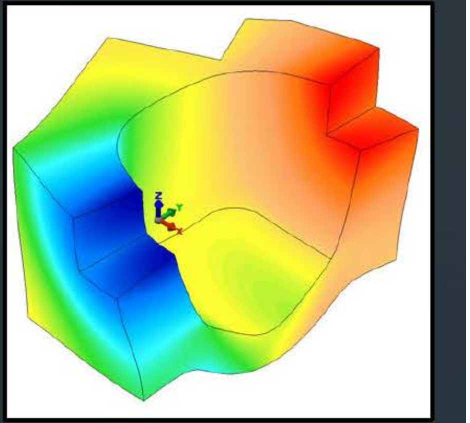


n-^{4}He Preliminary Results



10x more precise result and shifts the world average



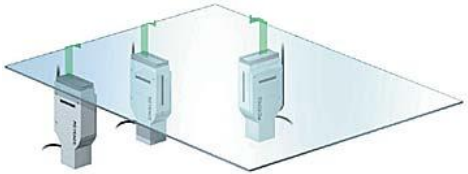


FEA calculations of the effects of cell deformation when pressurized will shift this result ~1σ are pending…

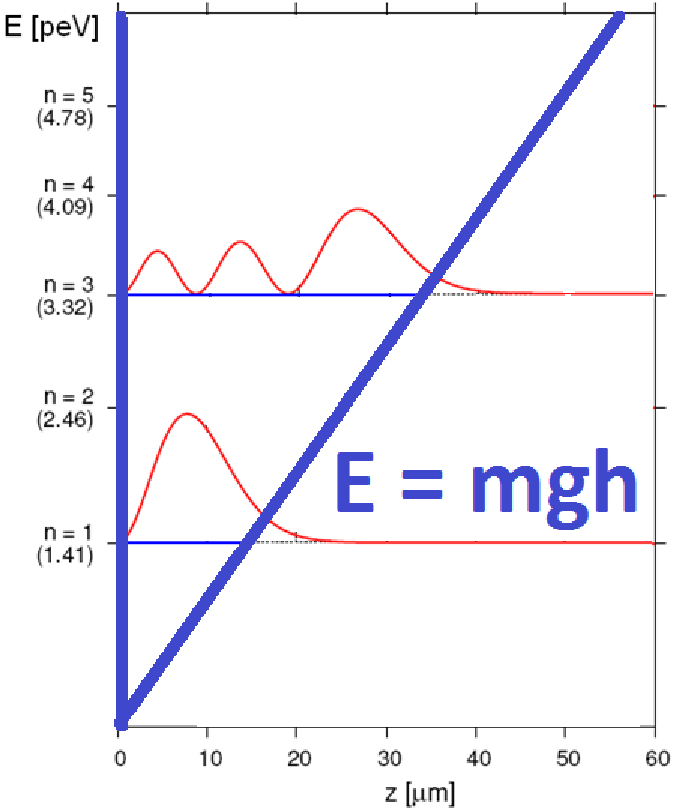
Quantum States in the Gravity Potential

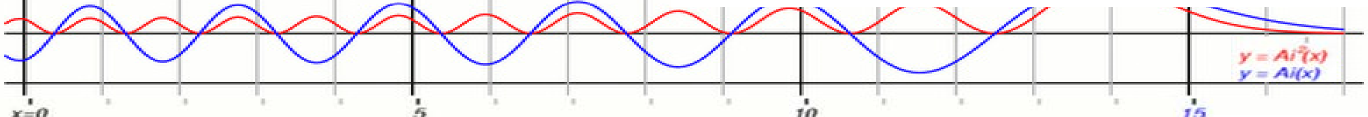
- Bound States
- Discrete energy levels
- Ground state 1.4 peV
- Airy-Functions

$$\left(-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial z^2}+mgz\right)\varphi_n(z)=E_n\varphi_n(z)$$

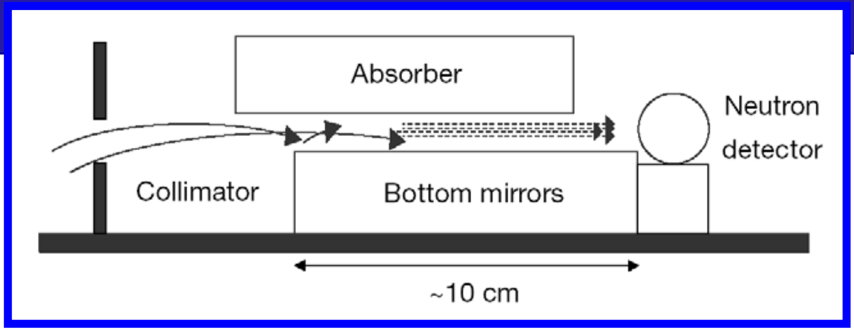


ψ^2

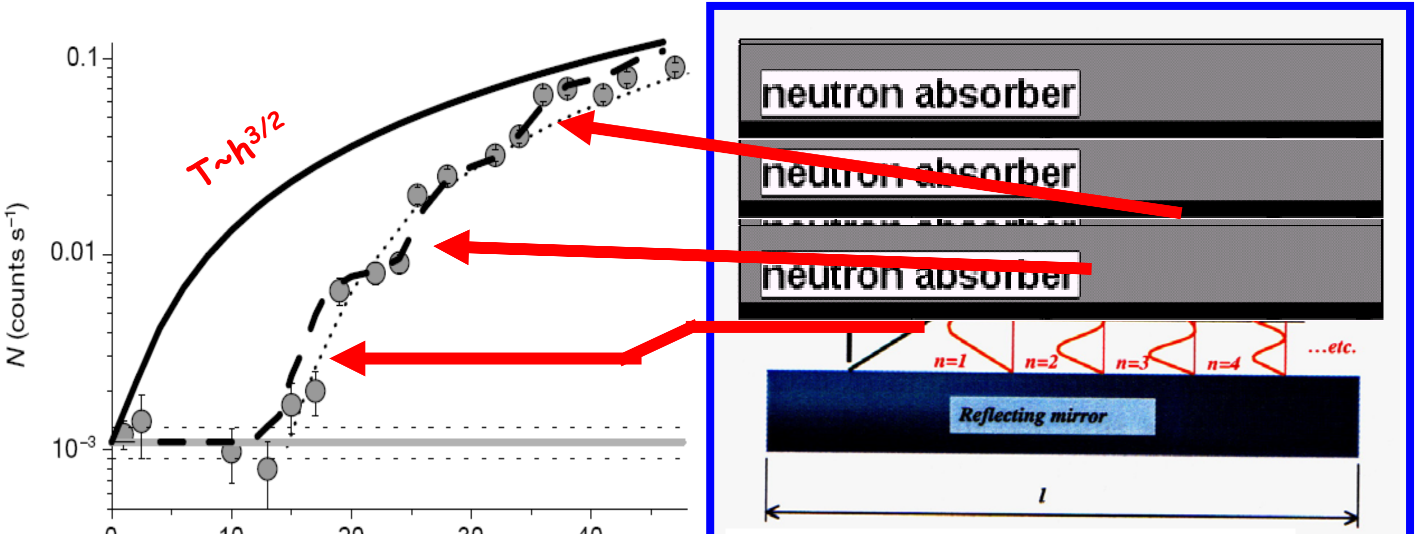




Nesvizhevsky et al. 2002: Observation of Bound Quantum States



Neutron mirror:
polished glass plate 10 cm long

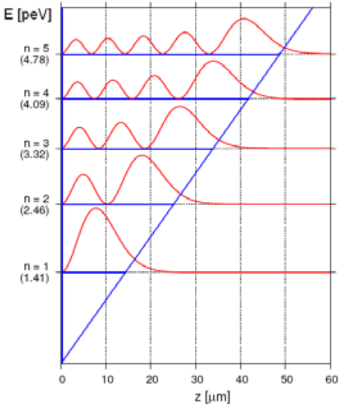


Nesvizhevsky et al. Nature 415 299 (2002)

Neutrons test Newton

$$\boxed{V(r) = G\frac{m_1 \cdot m_2}{r}(1 + \alpha \cdot e^{-r/\lambda})}$$

- **Strength α**
- **Range λ**



Hypothetical Gravity Like Forces

Extra Dimensions:
The string and D_p-brane theories predict the existence of extra space-time dimensions

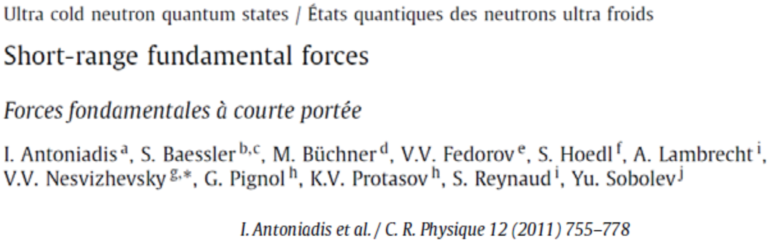
Infinite-Volume Extra Dimensions: Randall and Sundrum

Exchange Forces from new Bosons: a deviation from the ISL can be induced by the exchange of new (pseudo)scalar and (pseudo)vector bosons

- **Axion - - - - - - - - - - - - - - - - - - - → 0.2 μm < λ < 0.2 cm**
- **Scalar boson. Cosmological consideration**
- **Bosons from Hidden Supersymmetric Sectors**
- **Gauge fields in the bulk (ADD, PRD 1999) - - - - →$10^6 < \alpha < 10^9$**

Supersymmetric large Extra Dimensions (B.& C.) - - - - → $\alpha < 10^6$

Short range fundamental forces



Ultra cold neutron quantum states / États quantiques des neutrons ultra froids

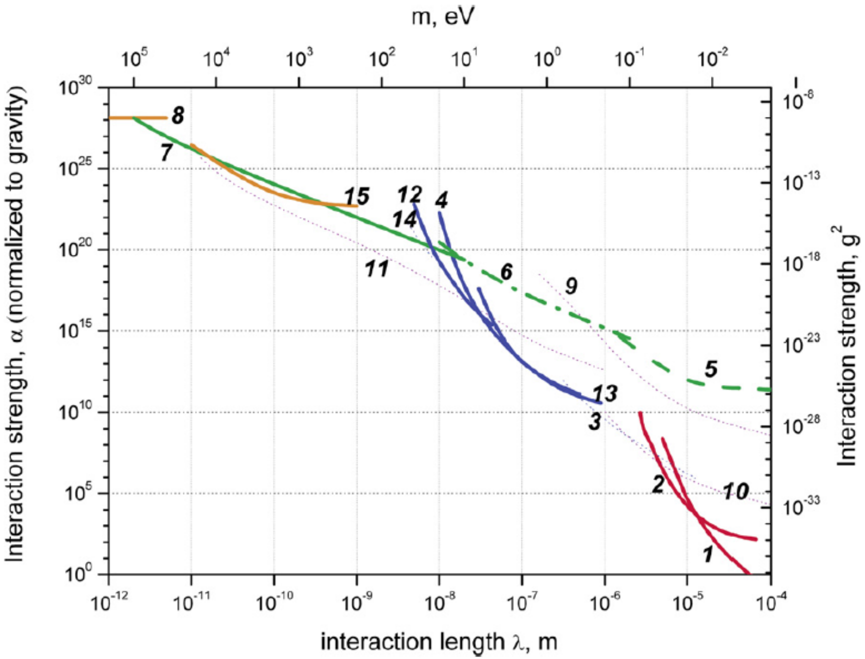
Short-range fundamental forces

Forces fondamentales à courte portée

I. Antoniadis[a], S. Baessler[b,c], M. Büchner[d], V.V. Fedorov[e], S. Hoedl[f], A. Lambrecht[i],
V.V. Nesvizhevsky[g,*], G. Pignol[h], K.V. Protasov[h], S. Reynaud[i], Yu. Sobolev[j]

I. Antoniadis et al. / C. R. Physique 12 (2011) 755–778

$$V(r) = G\frac{m_1 \cdot m_2}{r}\left(1+\alpha \cdot e^{-r/\lambda}\right)$$



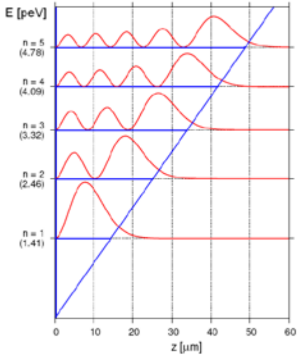
- Quantum interference:
  - sensitivity to fifth forces
  - coming from extra dimensions
  - string theories (higher dimensional field theories)
  - axion fields
- stroboscopic snapshots
  - spatial resolution 1µm
  - low background: 1 neutron every 100s

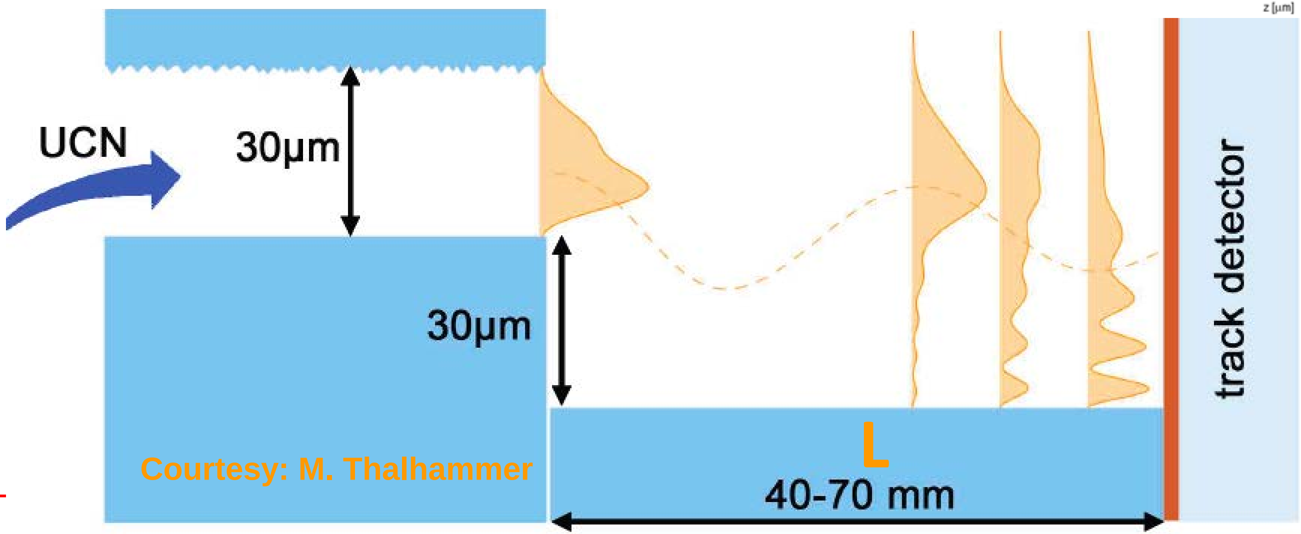
M. Thalhammer, T. Jenke et al.

- Snapshots with spatial resolution detectors ~ 1.5 μm

$$\Psi(z,t) = \sum_{n=0}^{\infty} c_n e^{-iE_n t/\hbar}\psi_n(z)$$

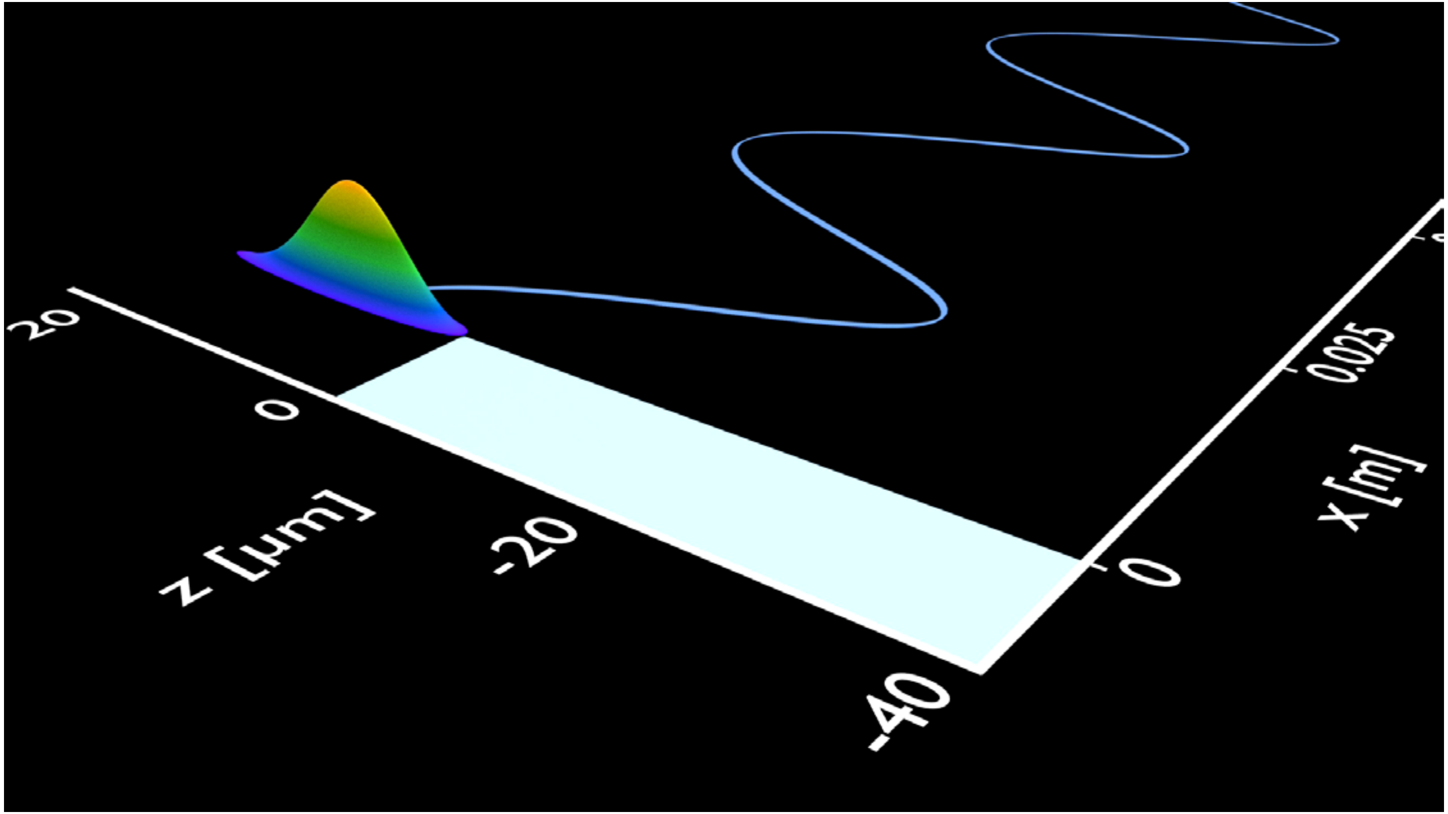
$$\psi_n(z) \sim Ai[\frac{z}{z_0} - \frac{E_n}{E_0}]; c_n = \int_0^{\infty} \Psi(z,0)\psi(z)dz$$



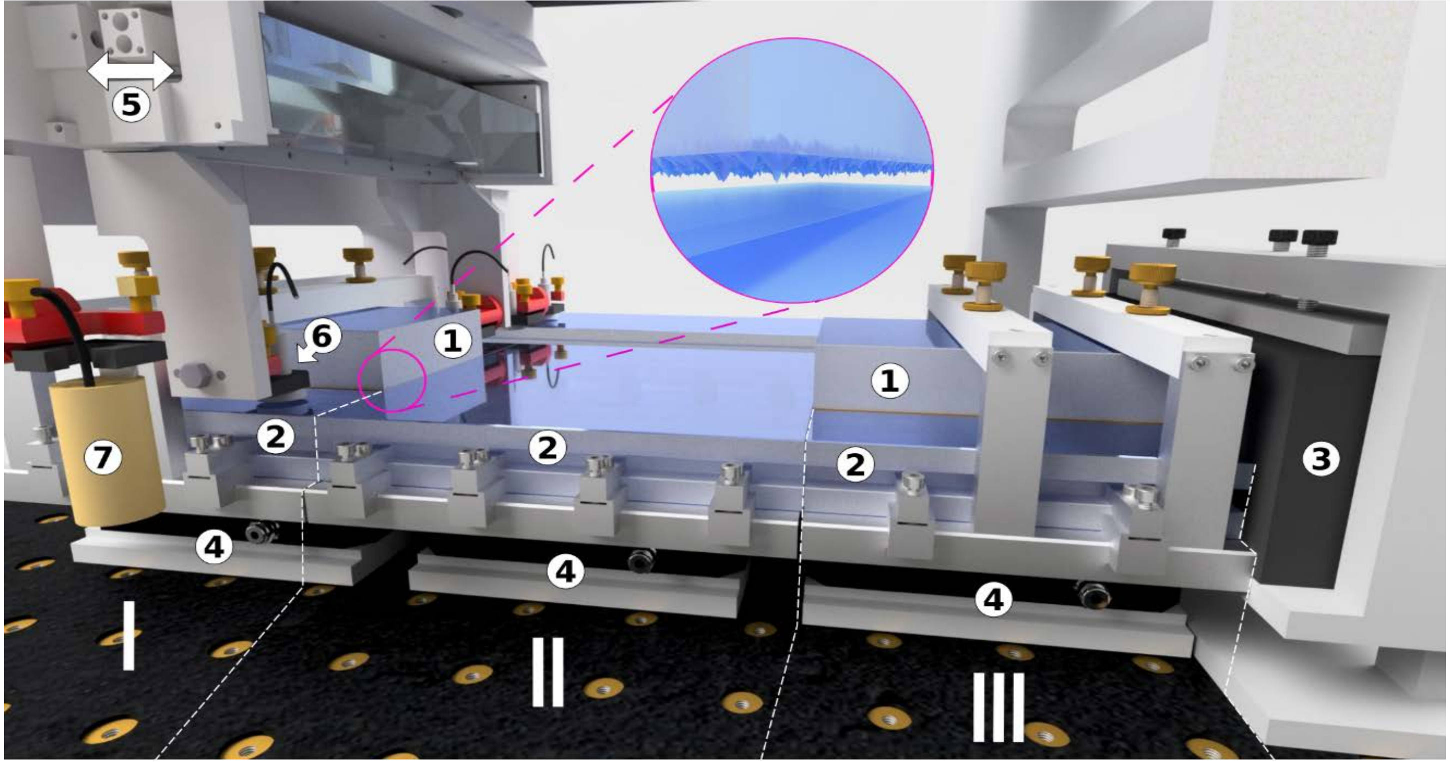


Courtesy: M. Thalhammer

*q*Bounce

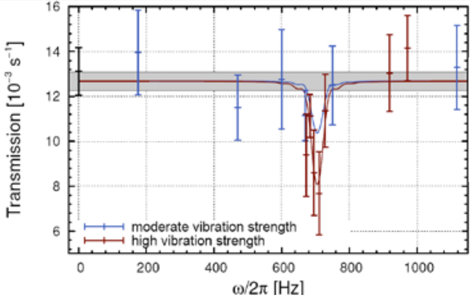


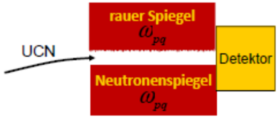
Acoustic Rabi Transitions



Three regions (marked I, II, III). rough neutron mirror on top (1) the neutron mirror (2) neutron detector (3) All neutron mirrors are mounted on nano-positioning tables (4). An optical system (parts in 5) controls the induced mirror oscillations. A movable system based on highly precise capacitive sensors (6) controls and levels steps between the regions. The experiment is shielded by μ-metal against the magnetic field of the Earth. Flux-gate magnetic field sensors (7) log the residual magnetic fields.

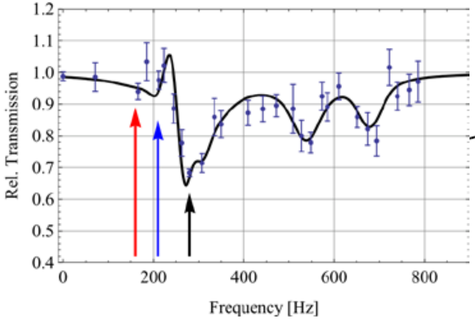
*q*Bounce – Gravity Resonance Spectroscopy

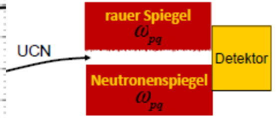




|1> ↔ |3>

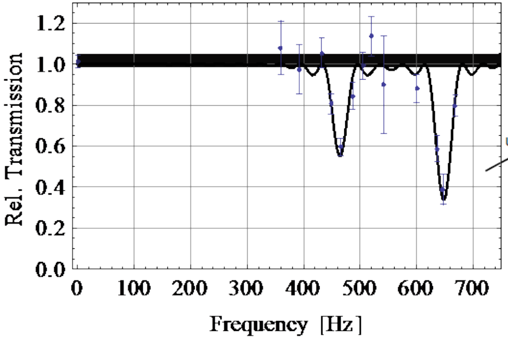
- **T. Jenke et al. NP 2011**

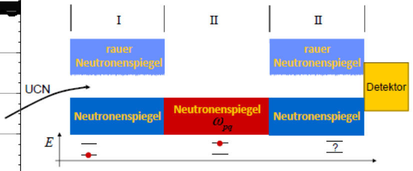




|1> ↔ |2> : 266 Hz
|1> ↔ |3> : 563 Hz
|2> ↔ |3> : 296 Hz
|2> ↔ |4> : 701 Hz

- **T. Jenke et al. PRL 2014**



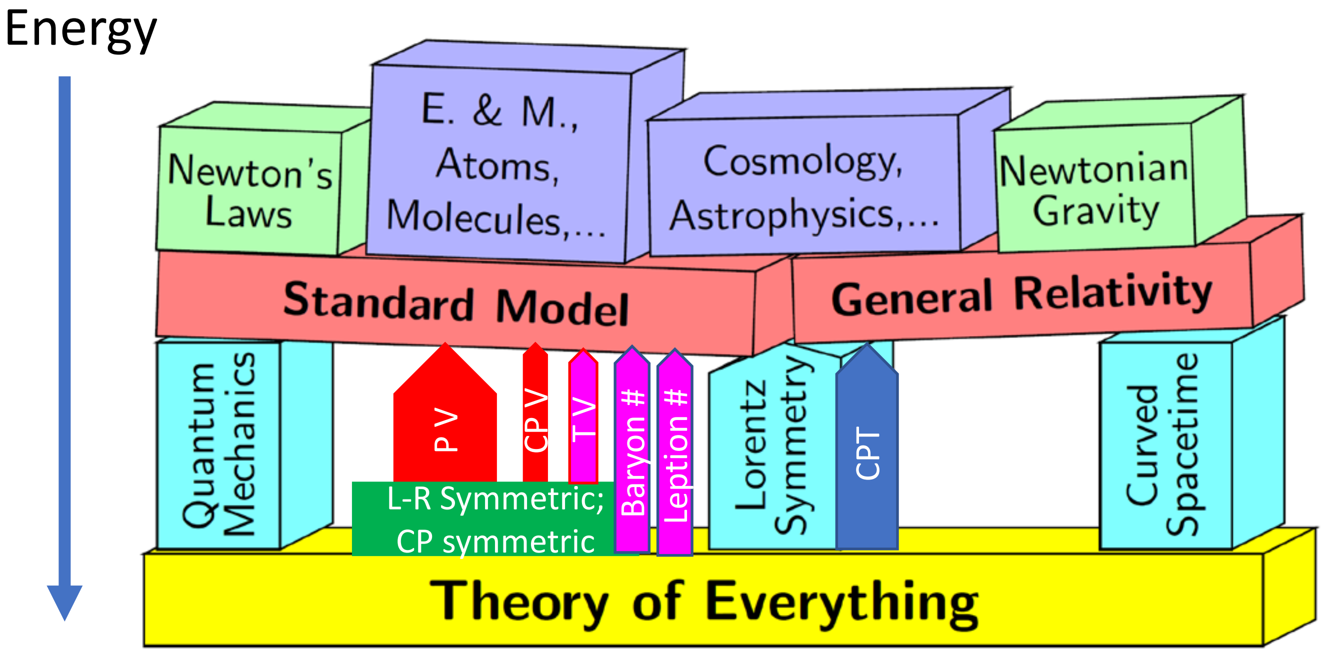


|1> ↔ |3> : 462 Hz
|1> ↔ |4> : 647 Hz

- **C. Cronenberg et al.**

Question: Why Lorentz Violation?

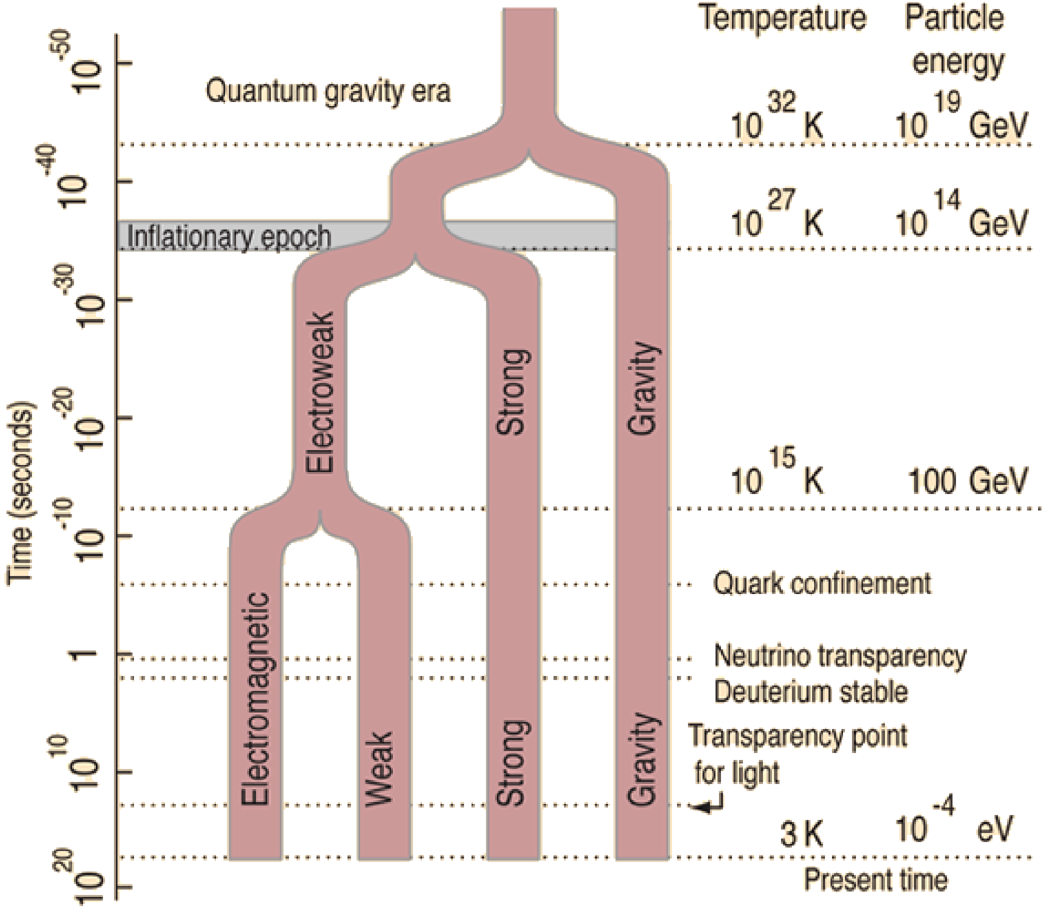
& Discrete Symmetries



Answer: Symmetry violations (at low E-scales) are evidences, pointing to new physics that unifies all forces at high E-scales.

Experimental Approach: **Precision measurements on small values of symmetry-violating observables.**

A (Possible) Unified Theory of Everything



History: Unifications through Symmetries

$$
\begin{aligned}
\nabla\times\nabla\times\mathbf{E} = -\nabla^2\mathbf{E} &= \\
&= -\mu\frac{\partial}{\partial t}(\nabla\times\mathbf{H}) \\
&= -\mu\frac{\partial}{\partial t}\left(\frac{\partial\mathbf{D}}{\partial t}+\mathbf{J}\right) \\
&= -\mu\varepsilon\frac{\partial}{\partial t}\left(\frac{\partial\mathbf{E}}{\partial t}\right)
\end{aligned}
$$

$$\Rightarrow \boxed{\nabla^2\mathbf{E} = \mu\varepsilon\frac{\partial^2\mathbf{E}}{\partial t^2}}$$

[The Vector wave equation]

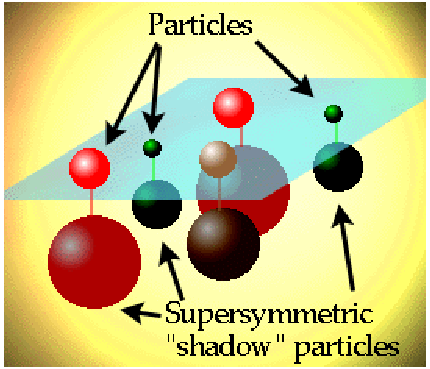
Light = Electromagnetic wave

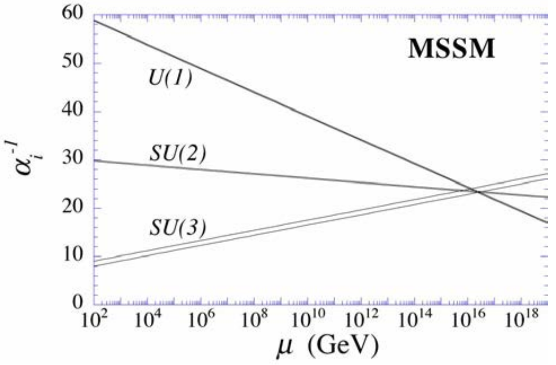
- **Stern and Gerlach:** Intrinsic spin, properties with respect to the rotation operator J doubles the number of electron states

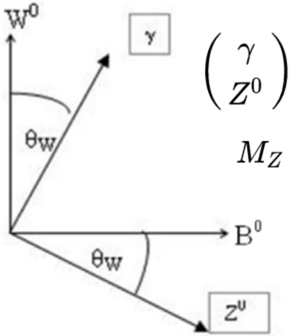
- **Dirac:** particle/antiparticle, properties with respect to the Lorentz boost generator, K, doubling the number of electron states: electron-positron

- **Supersymmetry:** introduces a new generator Q doubling the number of states once again: electron and scalar electron (selectron)

Mike Berger







$$\begin{pmatrix}\gamma\\ Z^0\end{pmatrix} = \begin{pmatrix}\cos\theta_W & \sin\theta_W\\ -\sin\theta_W & \cos\theta_W\end{pmatrix}\begin{pmatrix}B\\ W_3\end{pmatrix}$$

$$M_Z = \frac{M_W}{\cos\theta_W}.$$

Electro-weak

$$G_F^0 \simeq \frac{\pi\alpha}{\sqrt{2}\,M_W^2(1-M_W^2/M_Z^2)}$$

Questions?