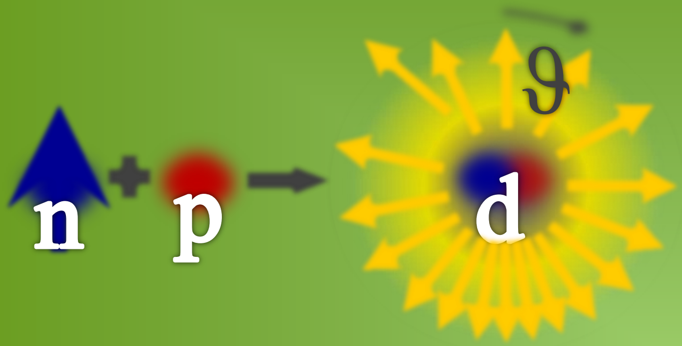
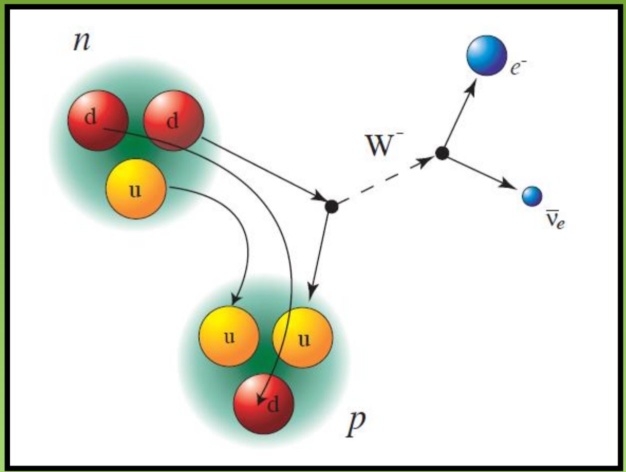
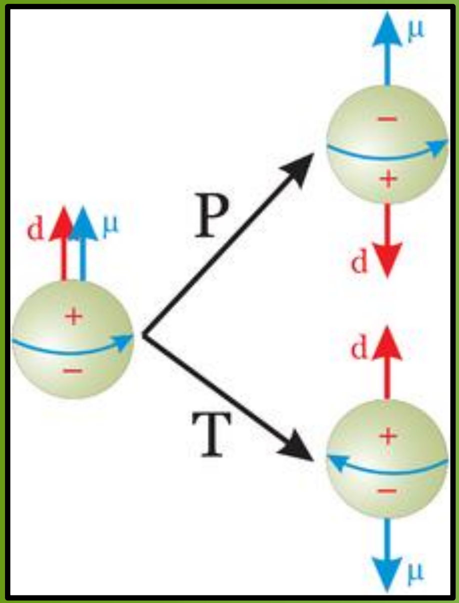
Nuclear and Particle Physics using Cold Neutrons



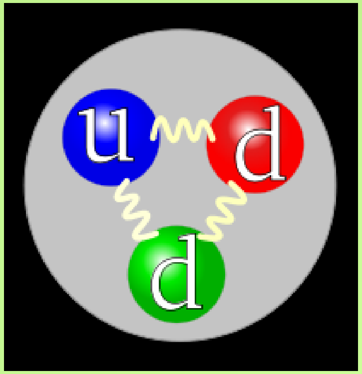




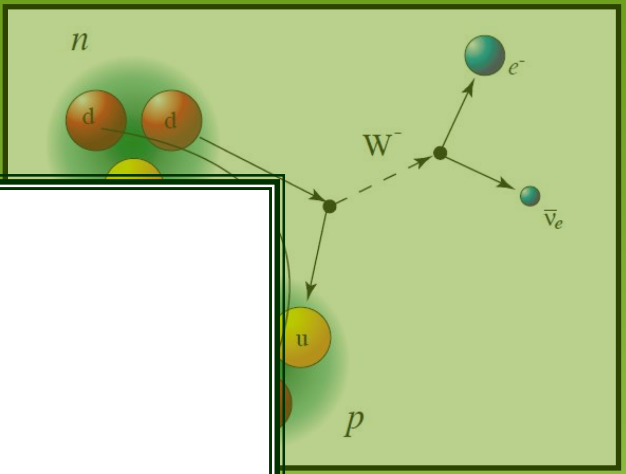
Nadia Fomin

University of Tennessee

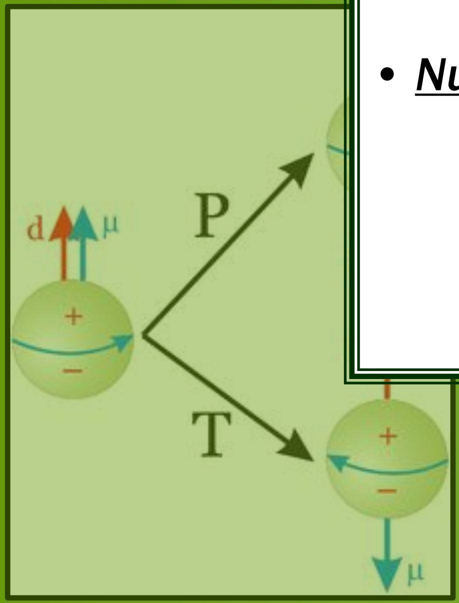
October 4th, 2013

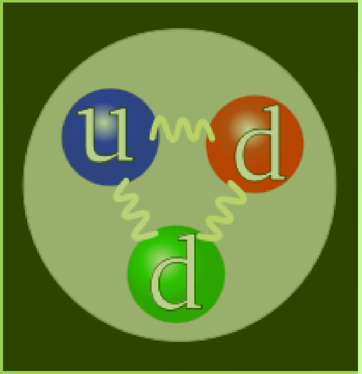


Nuclear and Particle Physics using Cold Neutrons



- ***Neutron***
  - History
  - Properties
  - Neutron sources
- ***Nuclear physics with neutrons***
  - nEDM
  - *β*-decay
  - Hadronic weak interaction - NPDGamma



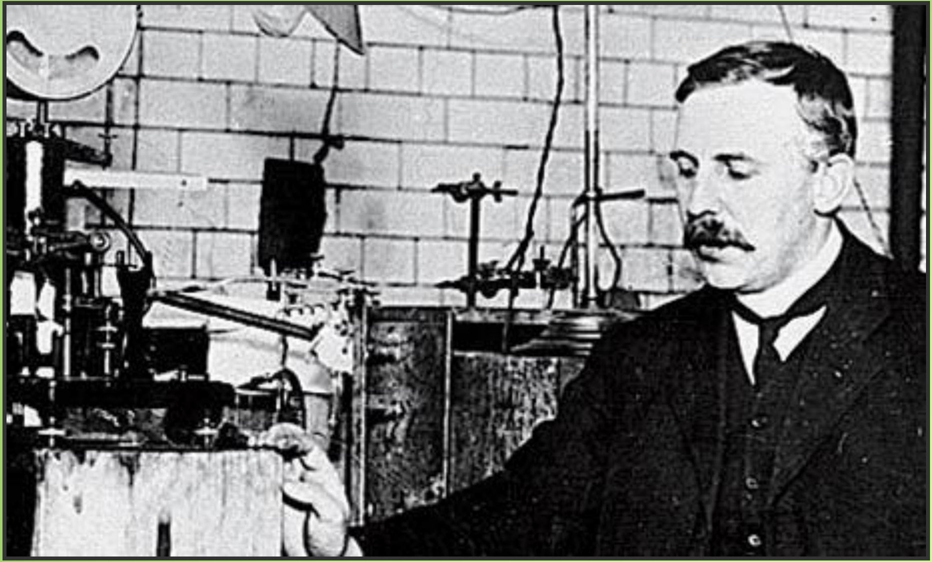


Why so neutral and unstable?

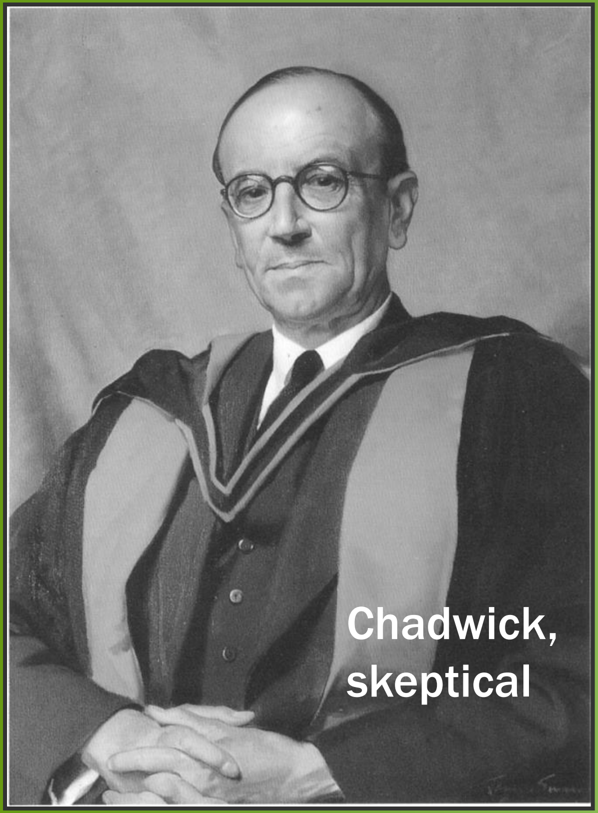
- Rutherford (1920) observed that atomic mass differs from atomic number and that electromagnetism would not bind a group of positively charged protons.
- Suggested the existence of a heavy neutral particle that was a tightly bound combination of an electron and proton, meaning:

$$M_n < M_p + M_e$$

If true, would be impossible for the neutron to spontaneously decay into a proton and electron



Idea of neutron as an elementary particle was met with skepticism



"It is, of course, possible to suppose that the neutron may be an elementary particle. This view has little to recommend it at present."

-Chadwick, 1932 (same year as he discovered the neutron)

1935:

- **M_n=1.0090 amu**
- **M_H=1.00081 amu**

$$\longrightarrow \quad M_n > M_p + M_e$$

- first serious suggestion of neutron decay

Precision τ_n (neutron lifetime) measurements had to wait

Technological hurdle → the only source of neutrons were simple nuclear reactions:

$$\alpha + {}^{9}Be \rightarrow {}^{12}C + n$$

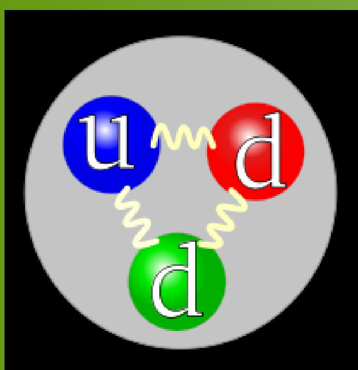
A τ_n measurement requires:

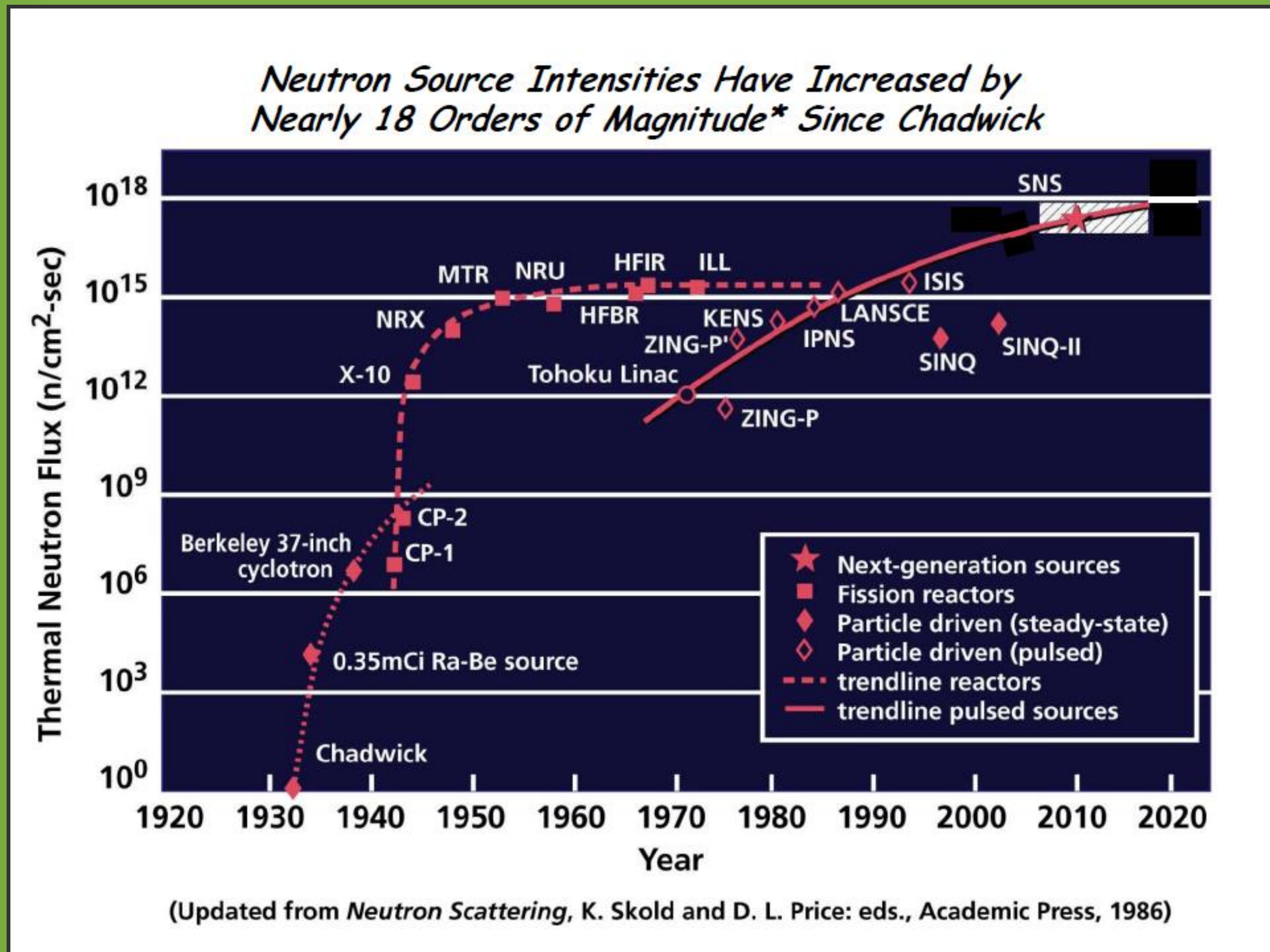
1. **Reasonable activity per unit volume of beam, i.e. a fairly high flux**
   - **Graphite Reactor at ORNL, 1943**
2. **Low and well understood background**
   - **Especially for early experiments at reactors, near the core**

Mining neutrons

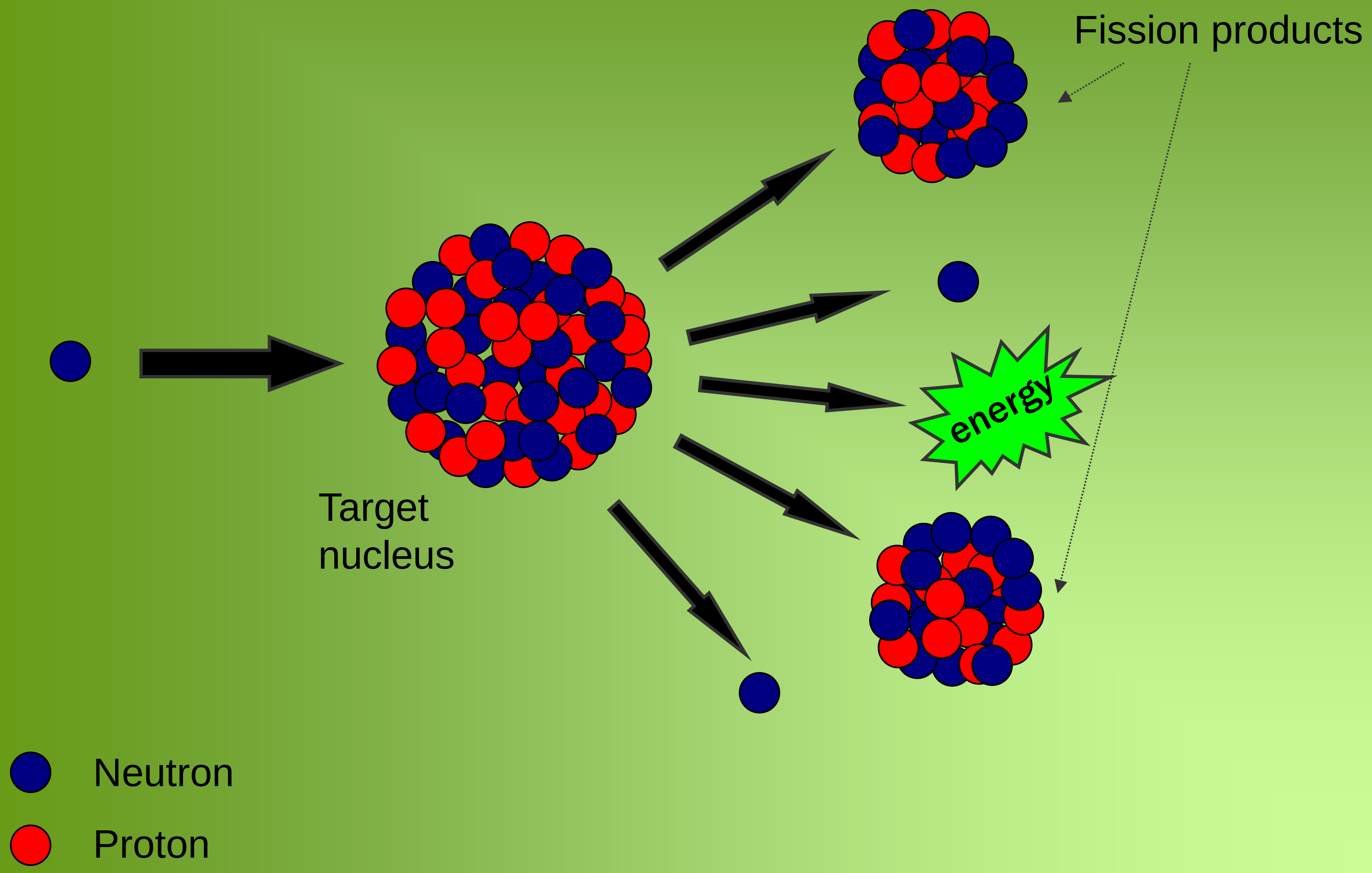
<u>2 types of modern high flux facilities:</u>

- High Flux Fission reactor
- Spallation Sources (accelerator-based)

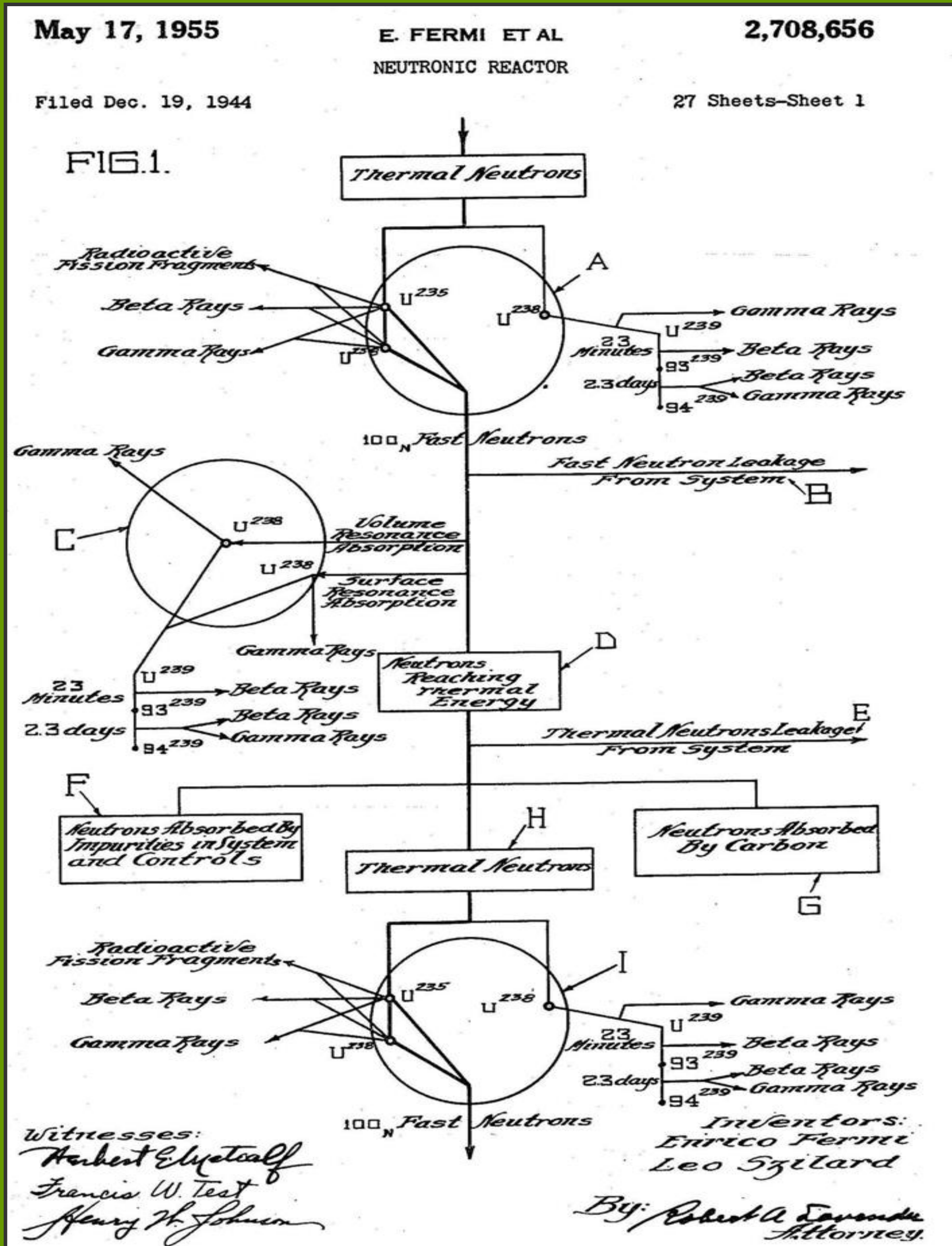


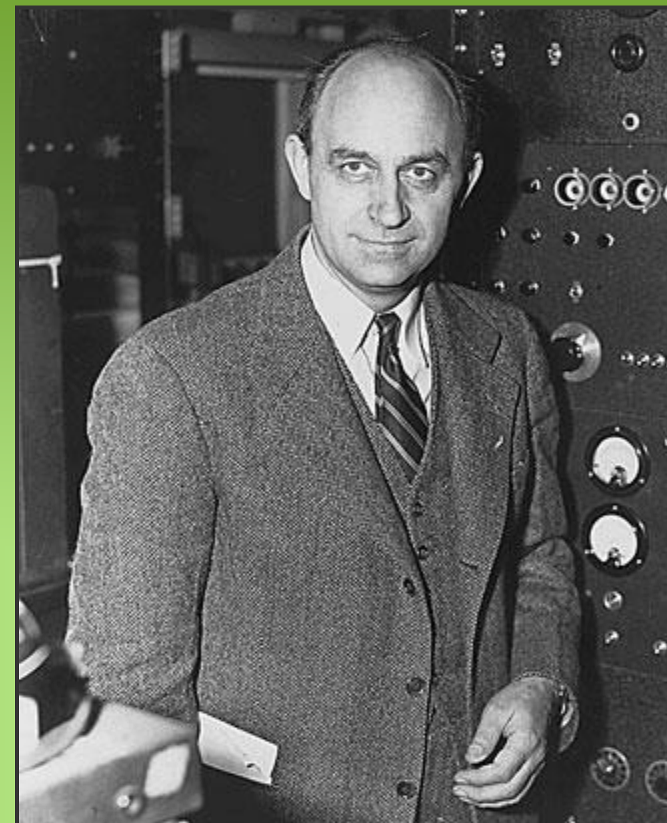


Fission: 1-2 neutrons released

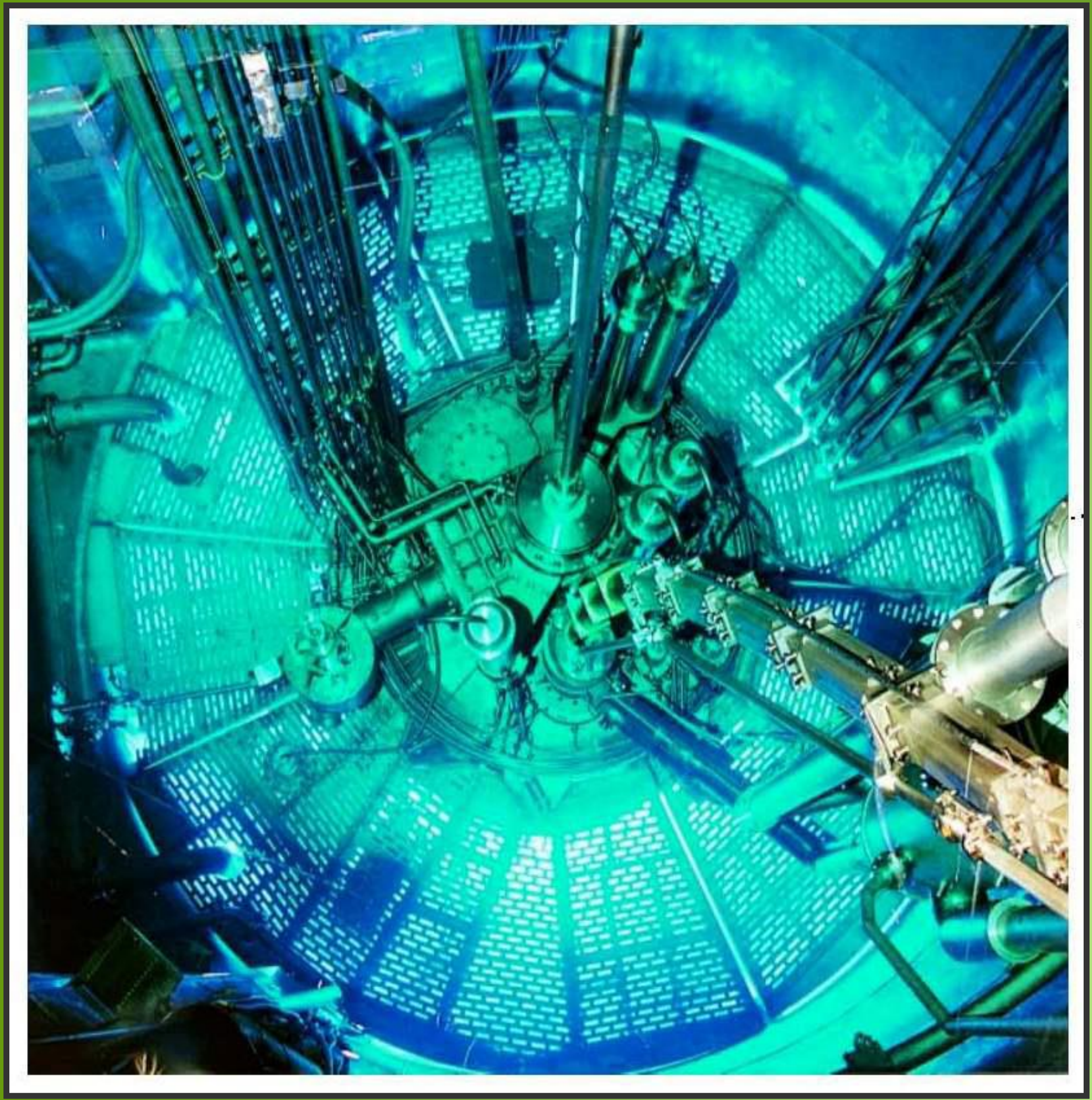


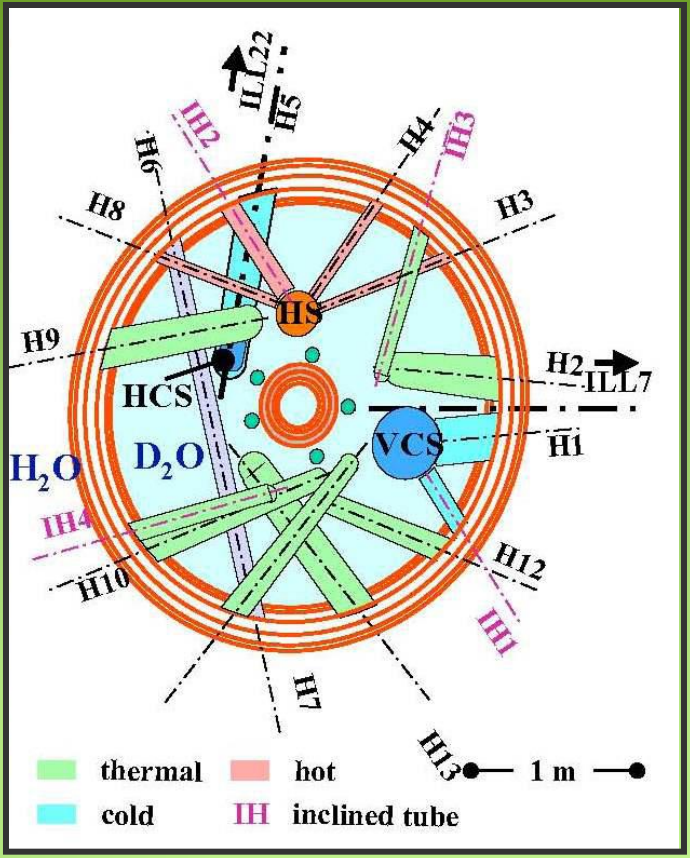
Fermi said it best





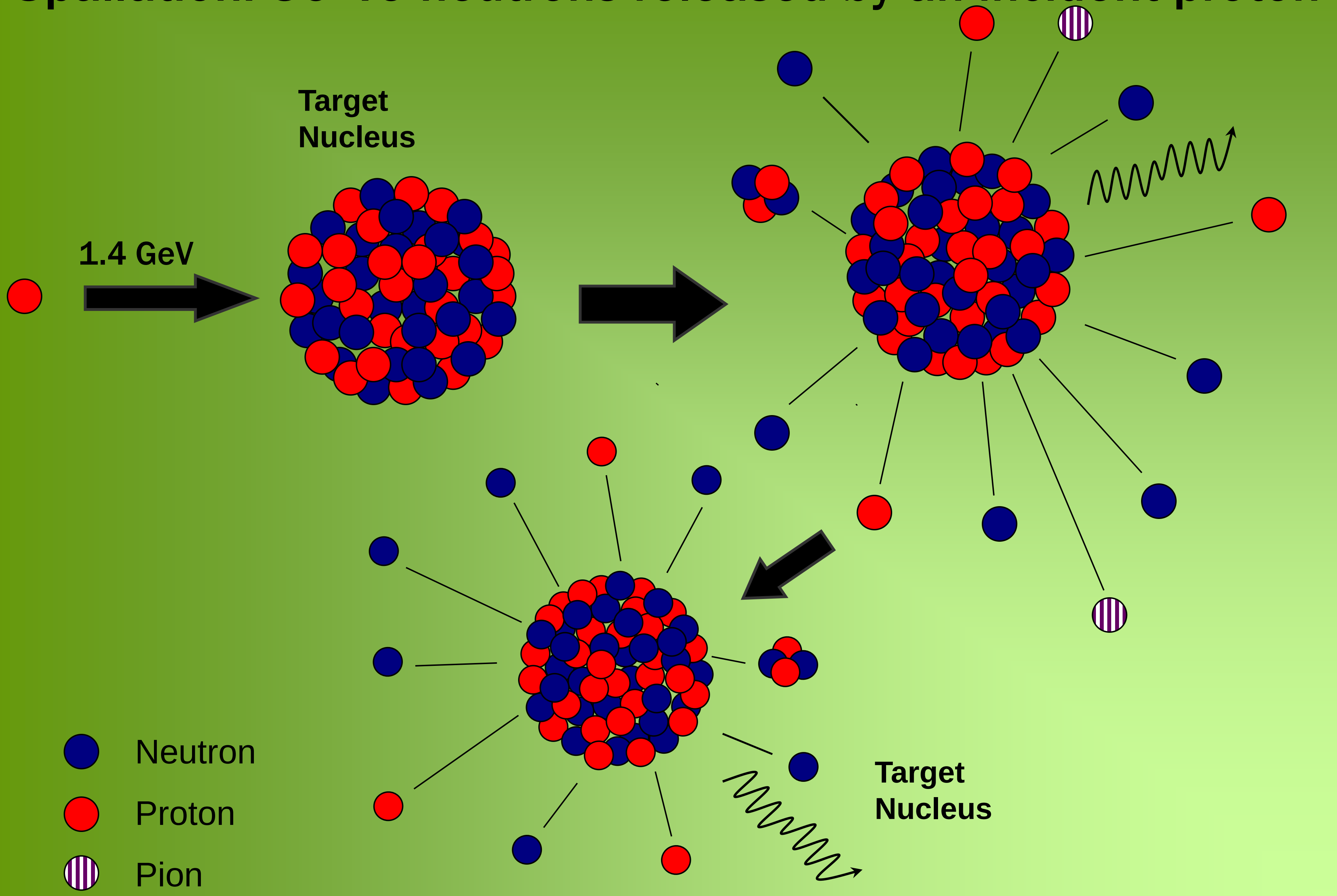
High flux neutron reactor at ILL – 57 MW





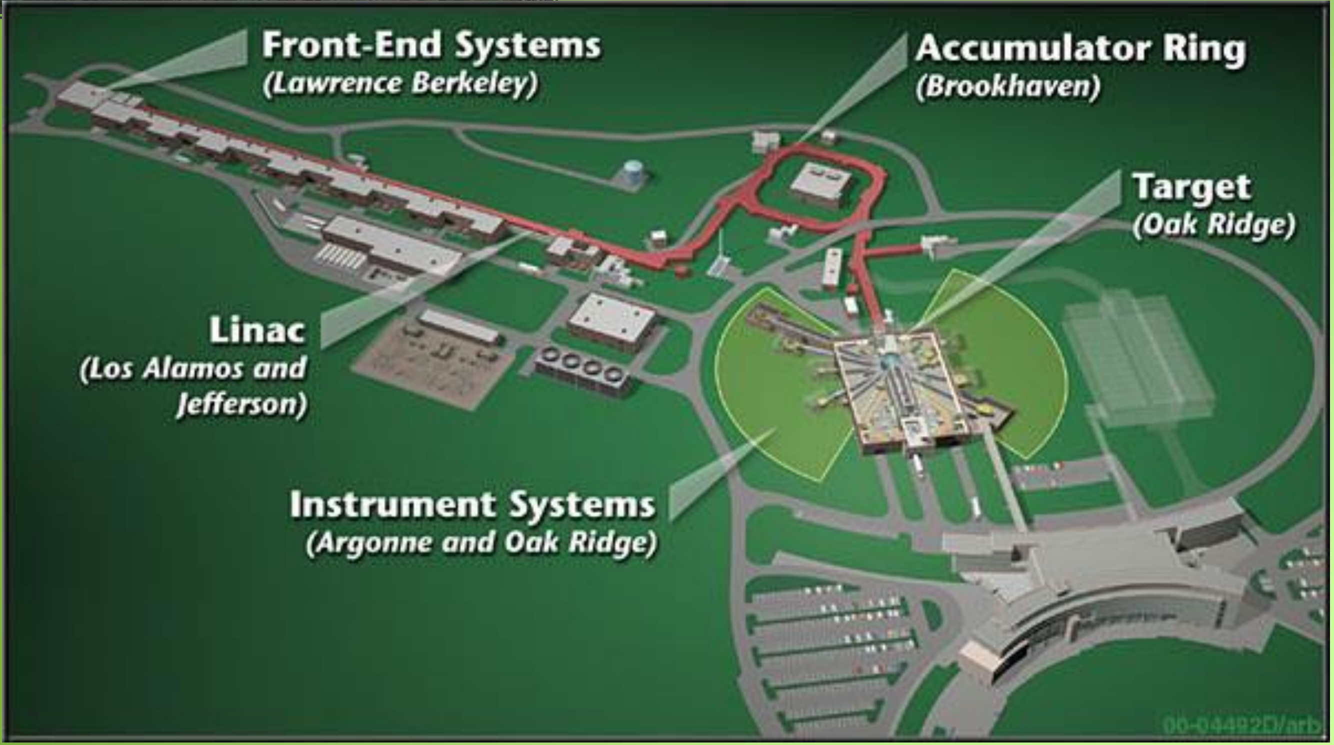
The glowing is fine, it’s just Čerenkov light

Spallation: 30-40 neutrons released by an incident proton

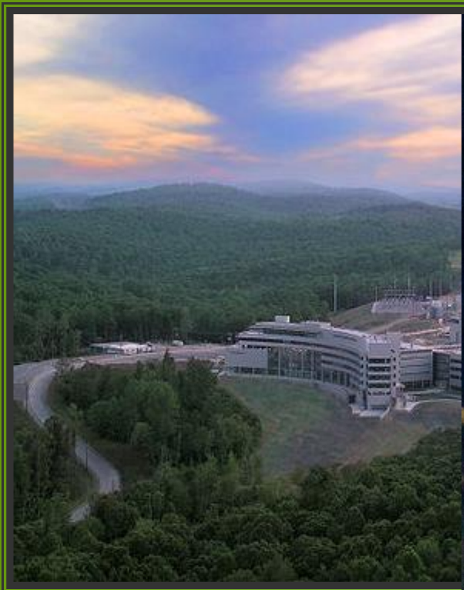


Spallation Neutron Source at ORNL

- 1.4 GeV protons, 60Hz
- Hg Spallation target → neutrons
- H_2 moderator
- 17 m SM guide, curved



Spallation Neutron Source at ORNL



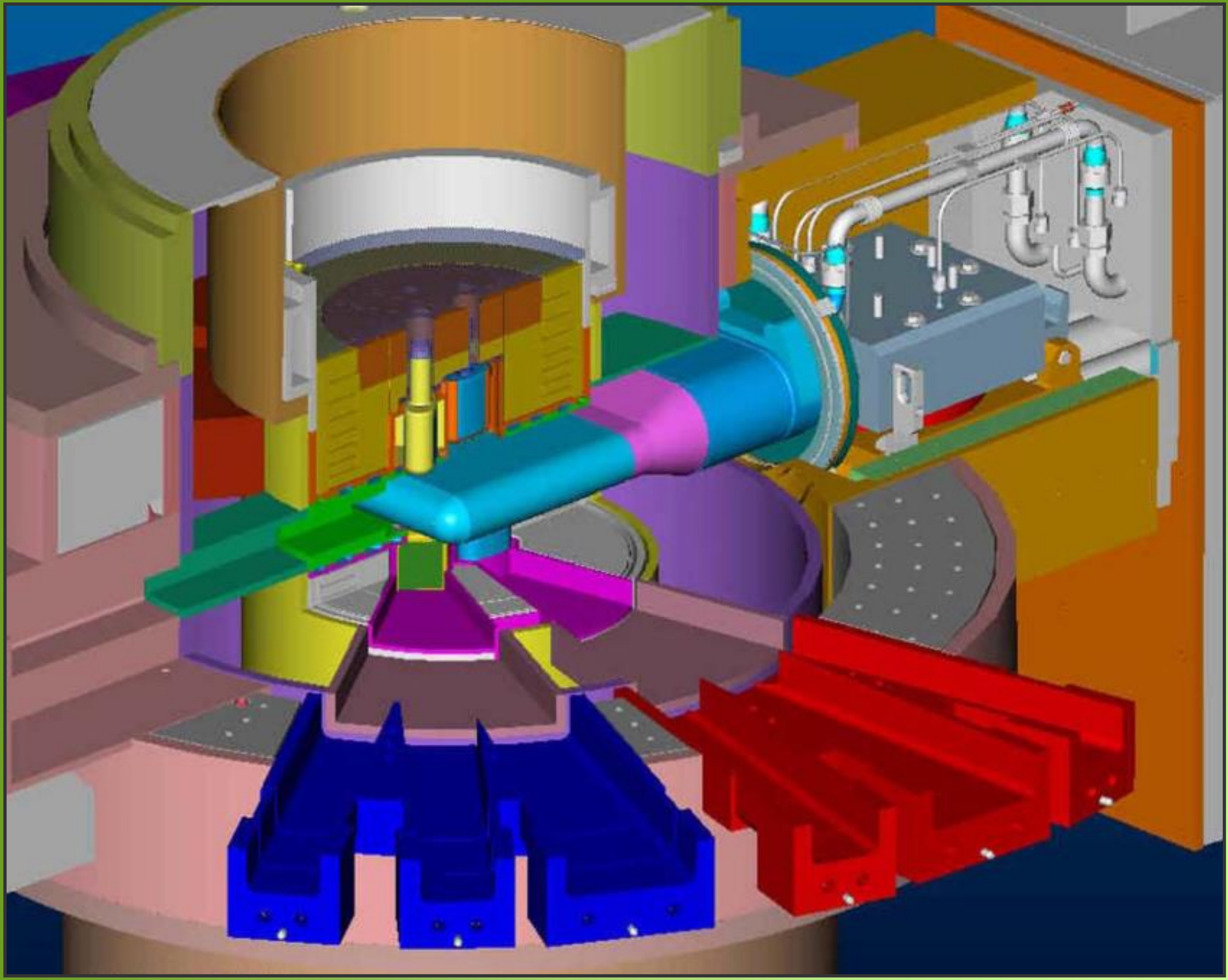
ons, 60Hz

n target → neutrons

r

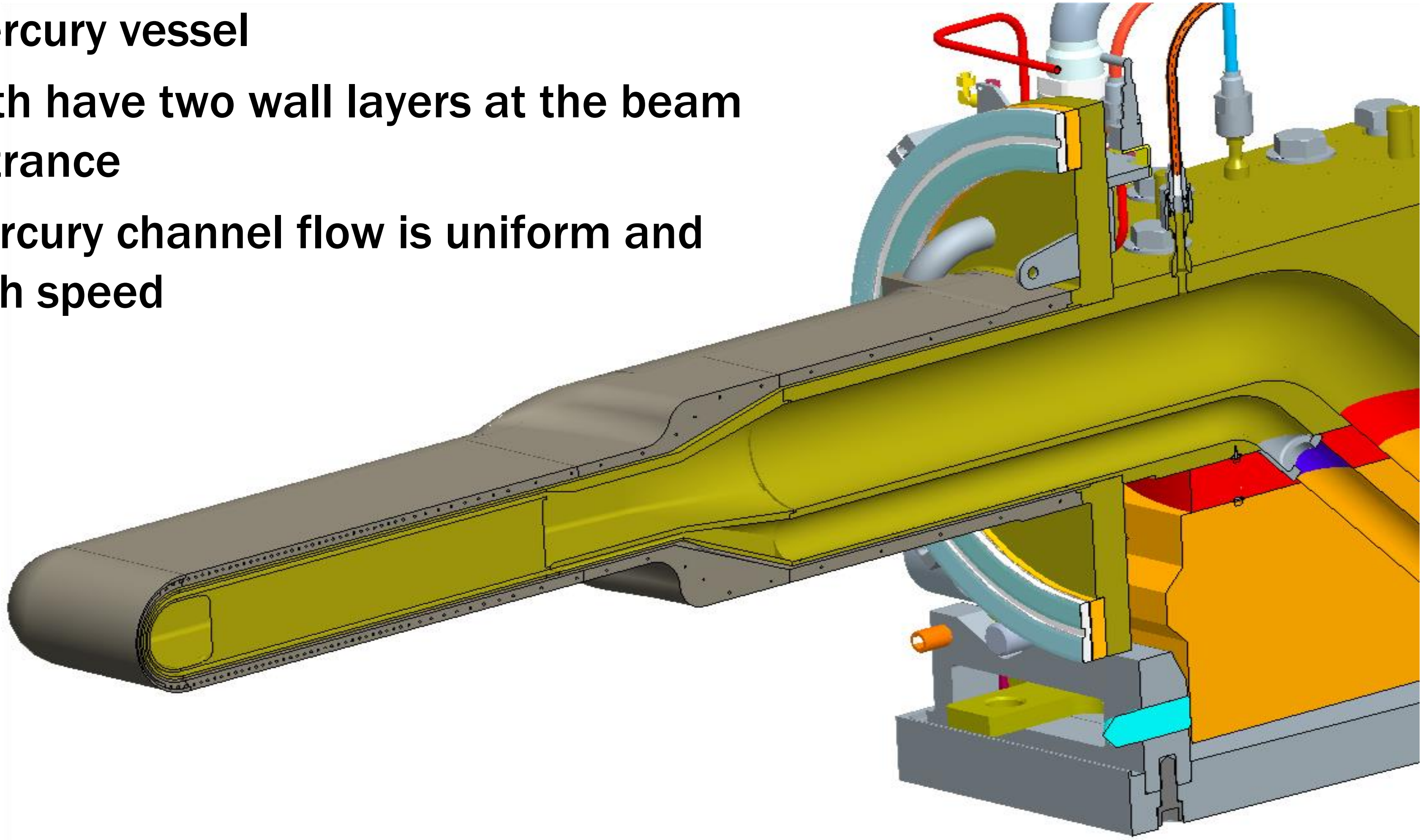
de, curved

Spallation Neutron Source



Present SNS Target Module Design

- Water cooled shroud surrounds mercury vessel
- Both have two wall layers at the beam entrance
- Mercury channel flow is uniform and high speed



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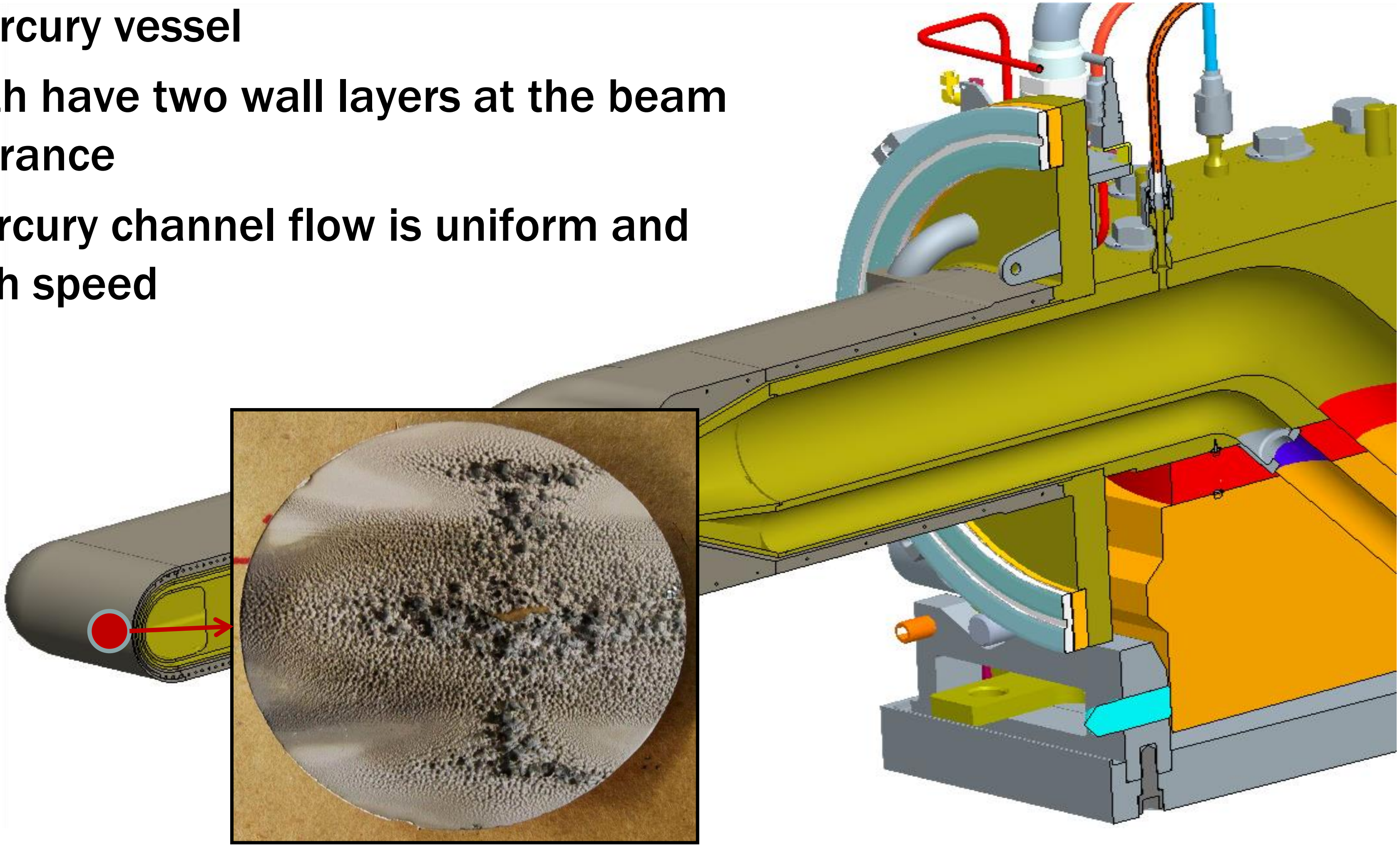
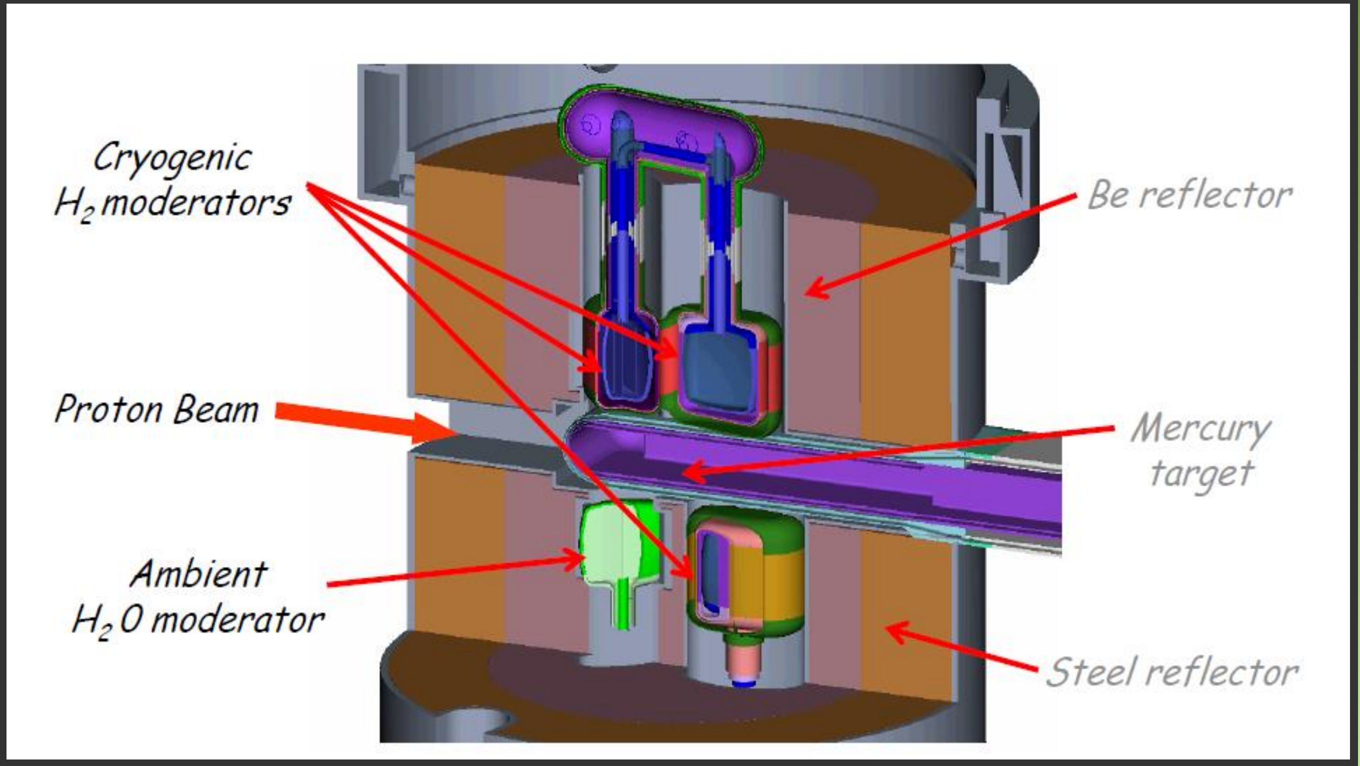


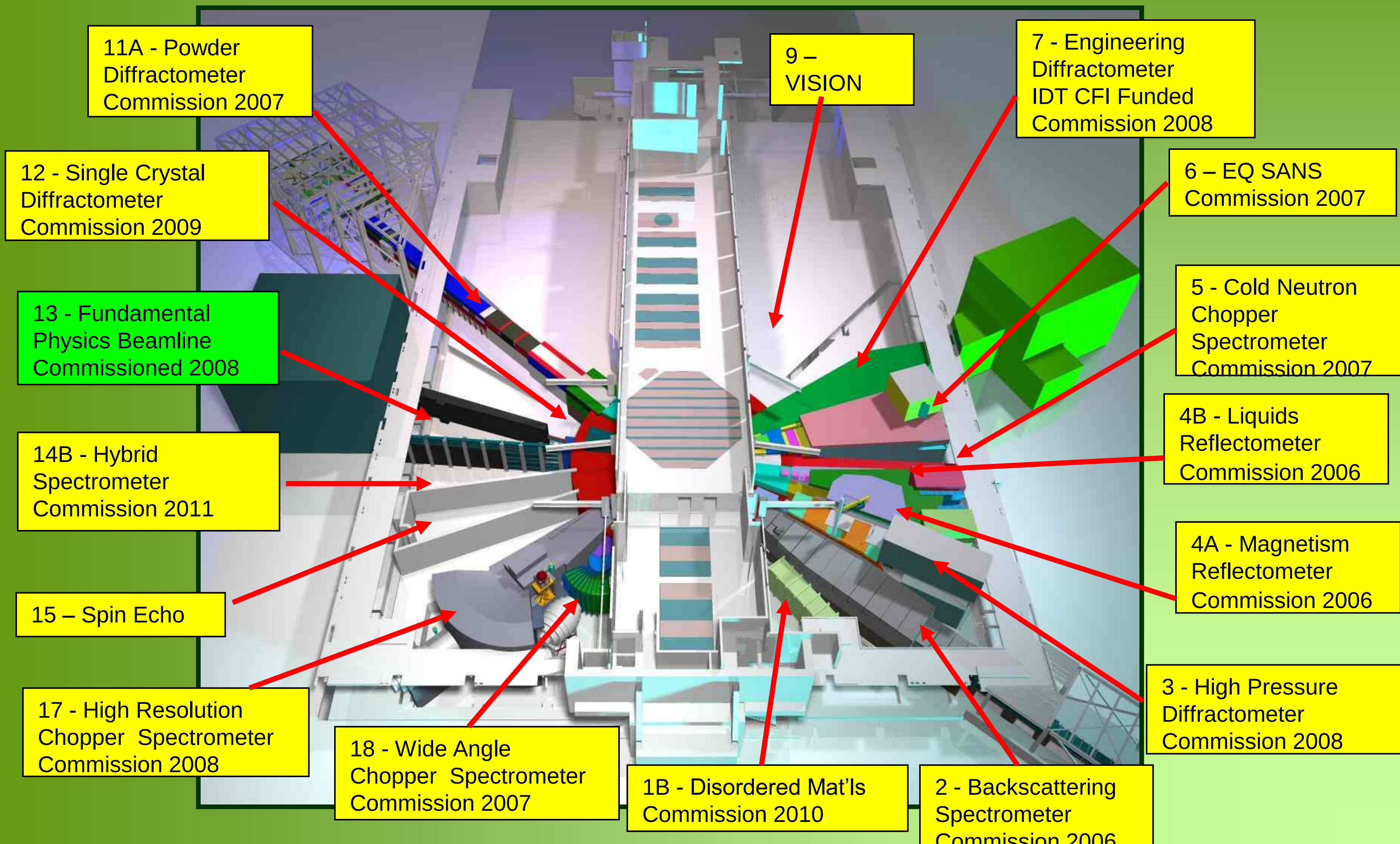
A closer look at the Mercury Target



- Thermal ~25meV (2200m/s, λ_T=1.8Å)
- Cold 50μeV-25meV
- Very cold 2×10^{-7} - 5×10^{-5} eV
- Ultra cold $<2\times10^{-7}$eV

Spallation Neutron Source at ORNL

Reached 1MW of power – September, 2009

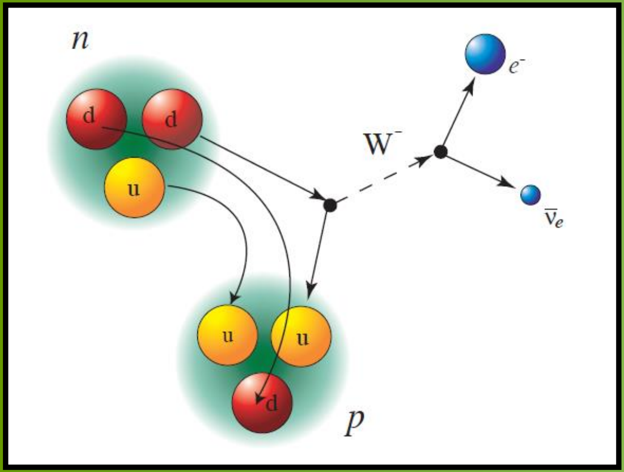


Now that we have our neutrons, what can we do with them?

Bright Future of the FnPB – 10 years

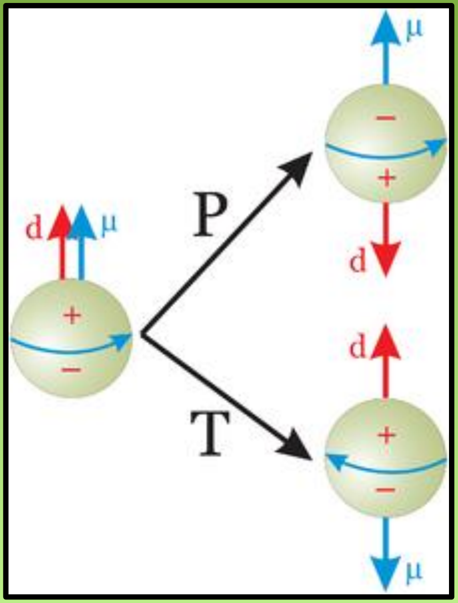
Neutron β-decay

Tests of the standard model



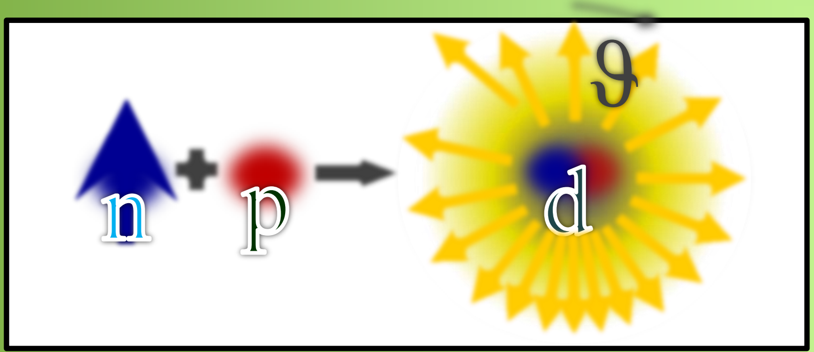
nEDM search

Why is there a matter/antimatter imbalance?

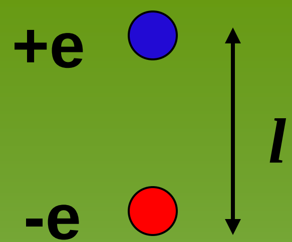


Hadronic Weak Interaction

Strength of the weak force between nucleons



nEDM



$d = el$

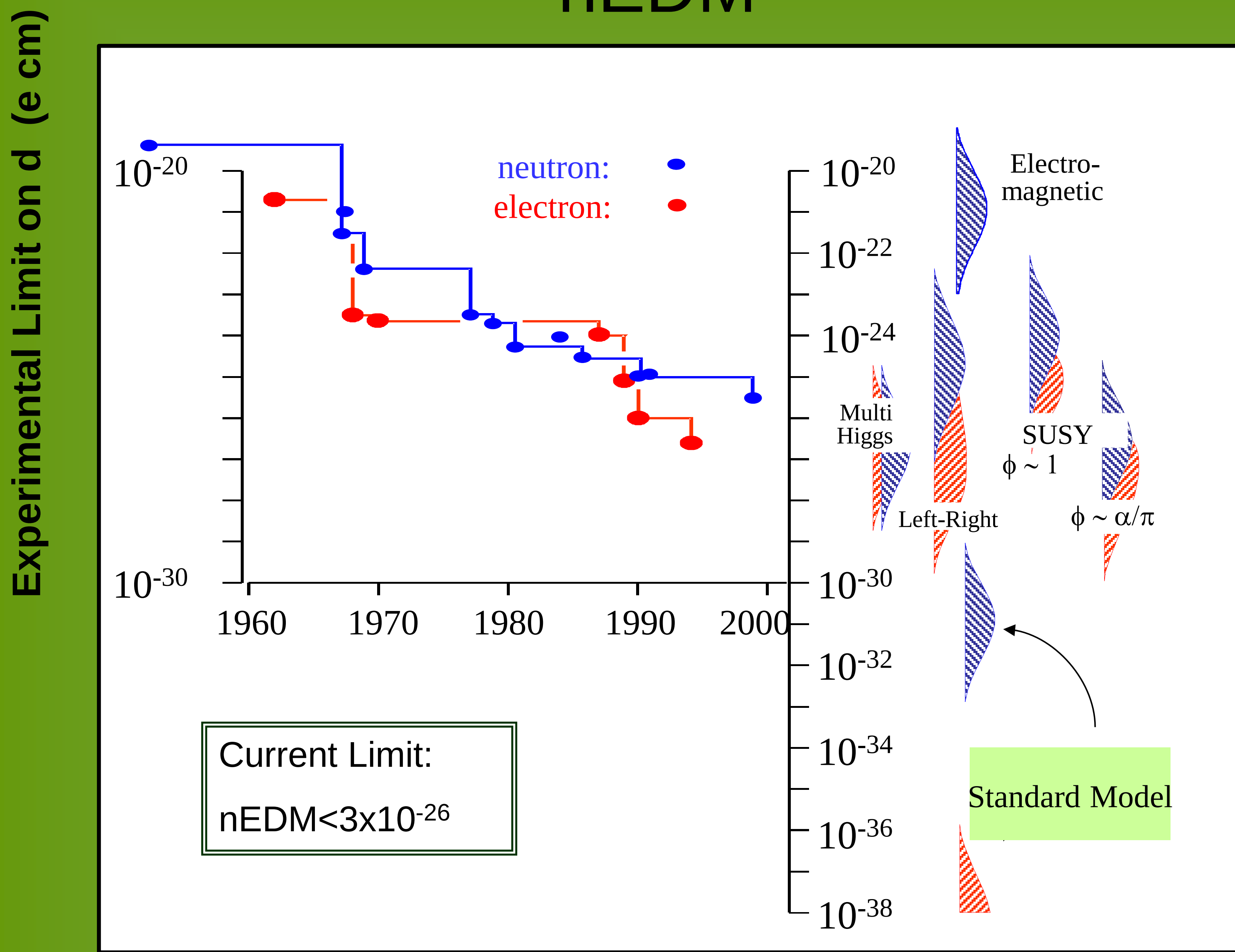
- Early in the big bang, there were equal amounts of matter/anti-matter (SM)
- Symmetry-breaking process creates a small imbalance
- As the universe cooled, matter/anti-matter annihilation left some baryons behind

$$\frac{N_{Baryon}}{N_{\gamma}} \approx 10^{-10}$$

- Violation of Baryon Number Conservation
- A period of Non-Thermal Equilibrium
- **T-violation**

Same process would give rise to a **nEDM** **(~10^{-28})**

nEDM

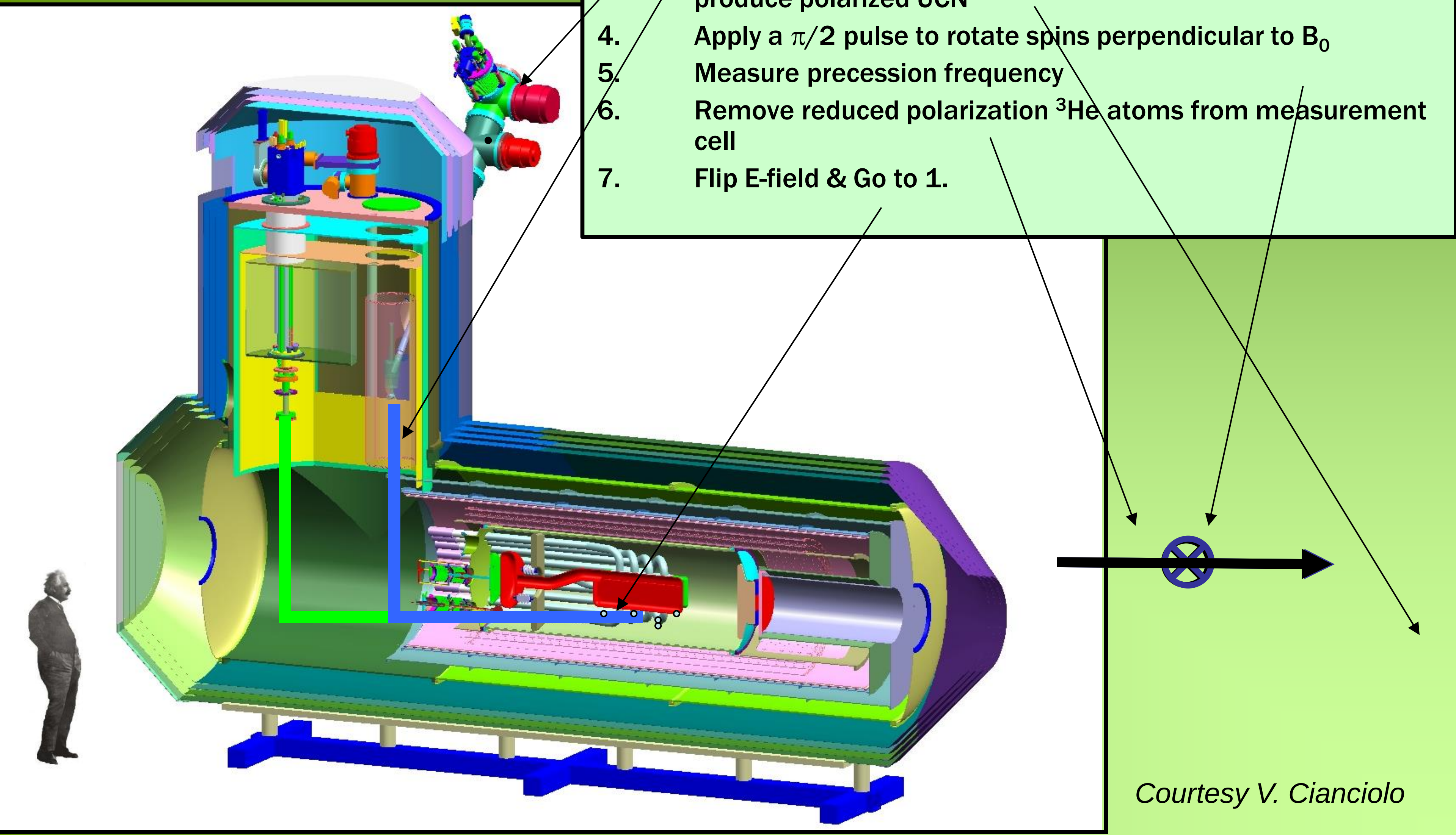


Current Limit:

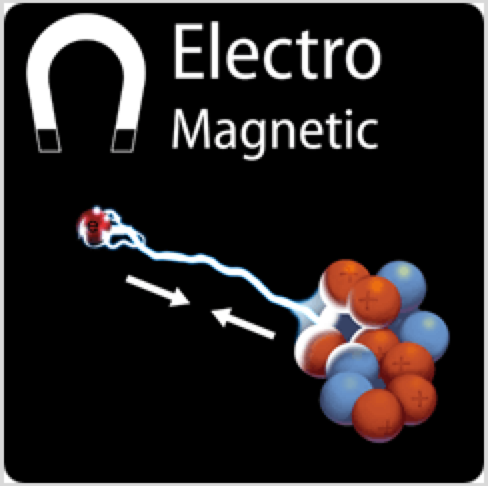
nEDM<$3x10^{-26}$

SNS nEDM Measurement Cycle

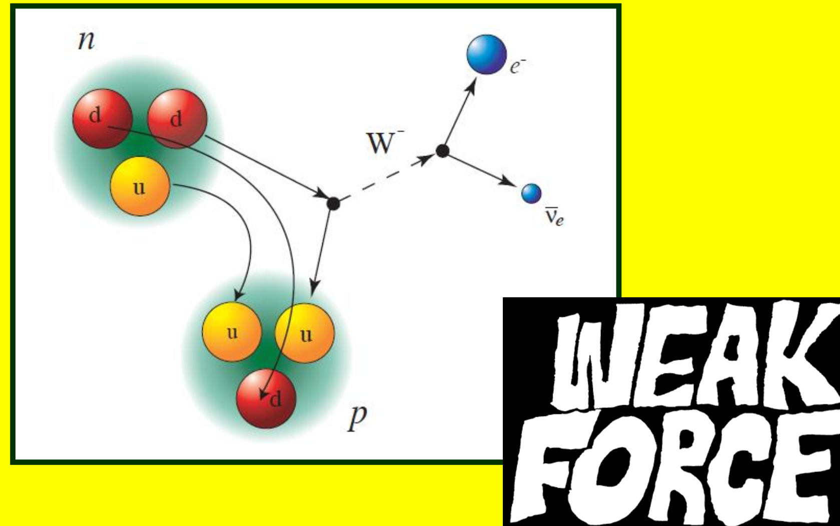
1. Load collection volume with polarized ^{3}He atoms
2. Transfer polarized ^{3}He atoms into the measurement cell
3. Illuminate measurement cell with polarized cold neutrons to produce polarized UCN
4. Apply a $\pi/2$ pulse to rotate spins perpendicular to B_0
5. Measure precession frequency
6. Remove reduced polarization ^{3}He atoms from measurement cell
7. Flip E-field & Go to 1.



Courtesy V. Cianciolo



Mediated by virtual photons



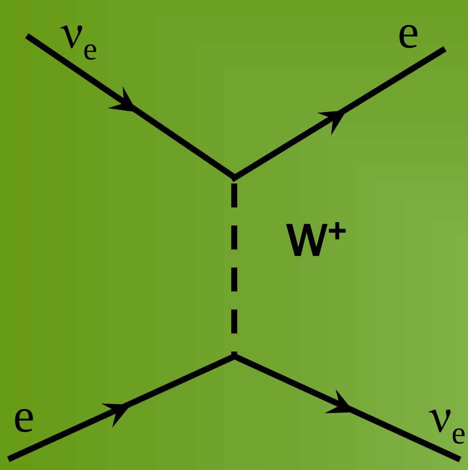
Mediated by W,Z bosons

Gravity

Mediated by gravitons

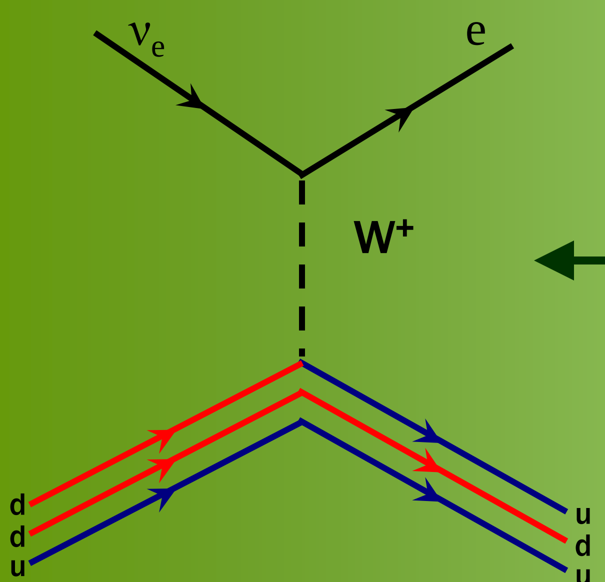
Mediated by gluons

The Weak Force

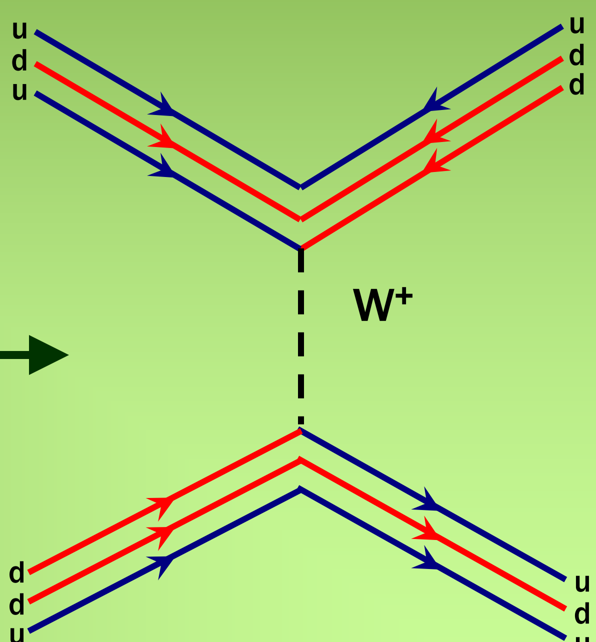


Leptonic weak Interaction

- Neutrons aren't helpful here



Enter: Neutrons

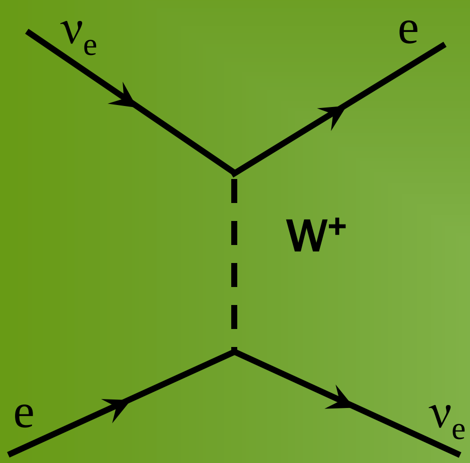


Semi-Leptonic weak Interaction

Hadronic weak Interaction

--strong force makes it tricky

The Weak Force



__Leptonic weak Interaction__

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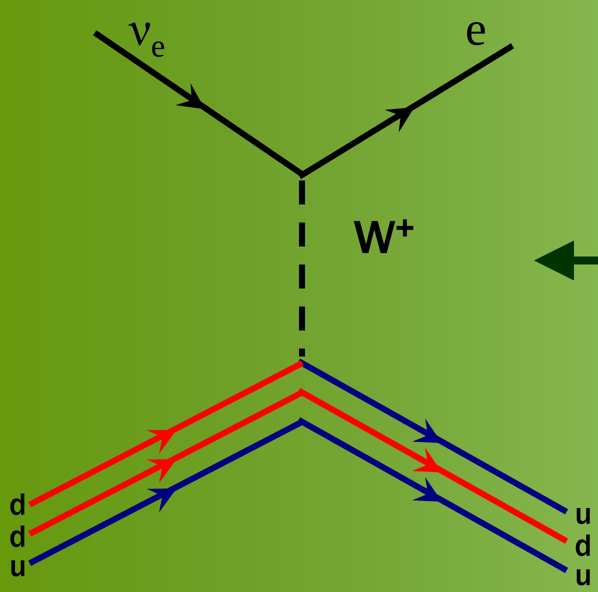


__What experiments can we do?__

- ***Neutron lifetime***
- **Free neutron β−decay**

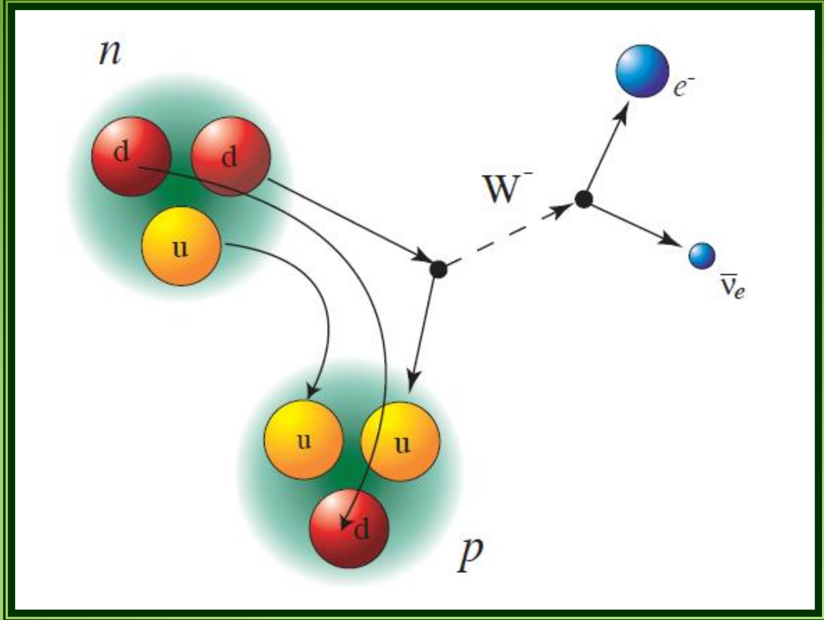
Semi-Leptonic weak Interaction

Free neutron β-decay

Prototype for all weak decays of hadrons and leptons

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

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$



V_{ud} – determined from neutron lifetime and free neutron decay

V_{us} – determined from semi-leptonic decays of K mesons and hyperon β decays

V_{ub} – expected to be negligibly small

Neutron lifetime also a window into Big Bang Nucleosynthesis

1ms

Thermal equilibrium
(T > 1 MeV)

$$\frac{n}{p} \propto e^{-Q/T}$$

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

$$n + \nu_e \leftrightarrow p + e^-$$

1s

After freezeout
n/p decreases due to
neutron decay

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

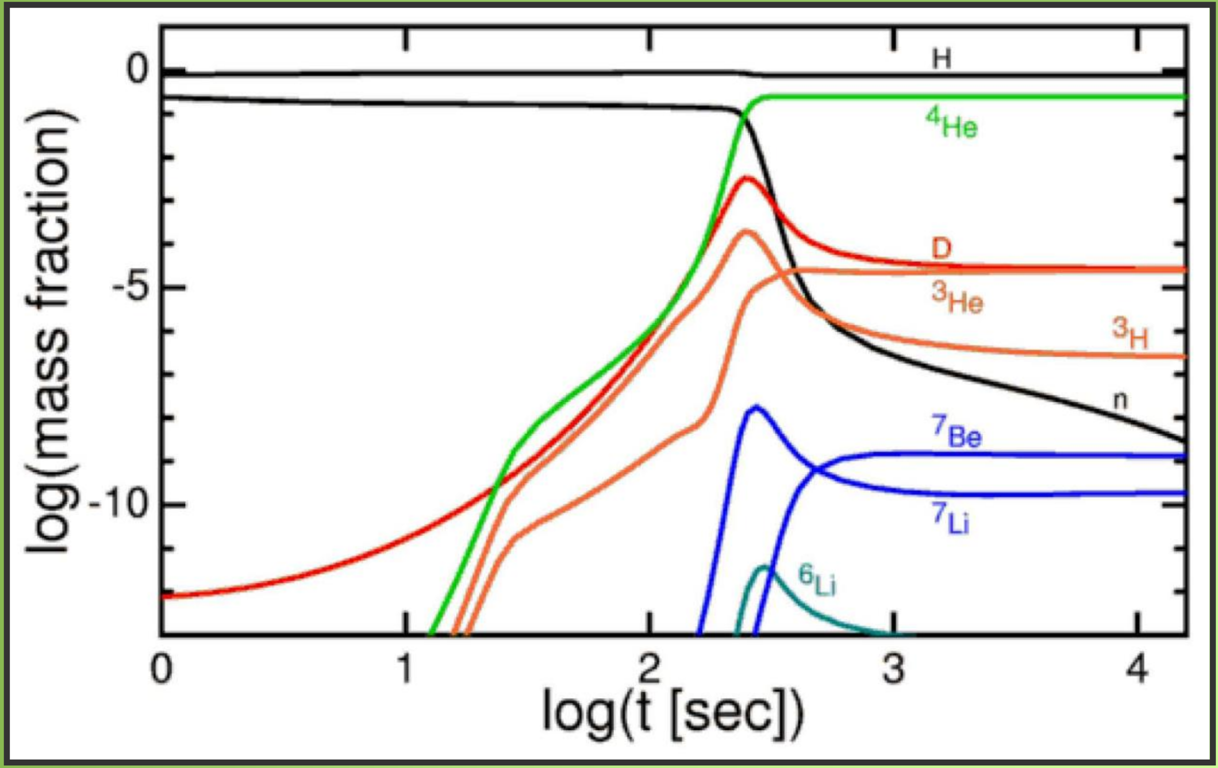
100s

Nucleosynthesis (T~0.1 MeV)
Light elements are formed

$$p + n \rightarrow d + \gamma$$

$$d + d \rightarrow {}^4\mathrm{He} + \gamma$$

Neutron lifetime dominates the theoretical uncertainty of ^{4}He abundance.



Slide: Courtery of A. Yue

Neutron Lifetime

$$\tau_n^{-1} = \frac{2\pi}{\hbar} G_F^{\,2} V_{ud}^{\,2} (1 + 3|\lambda|^2) \int \rho(E_e)$$

- In-Beam measurements

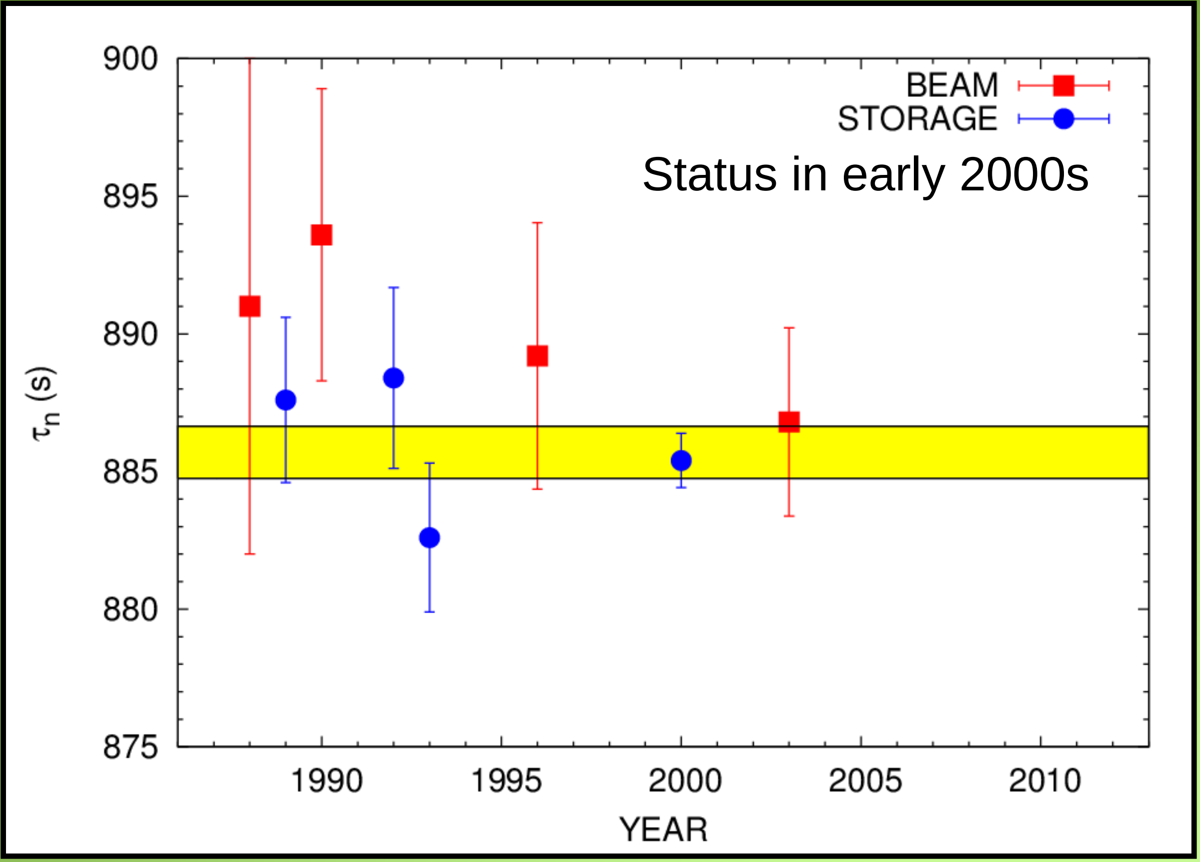
  → Number of decays is recorded (usually by detecting protons and electrons)

$$\frac{dN(t)}{dt} = \frac{-N(t)}{\tau_n}$$

- Bottle Experiments

  → Measure the number of neutrons that survive after some time ***t***

$$N(t) = N(0)\exp[-t/\tau_n]$$



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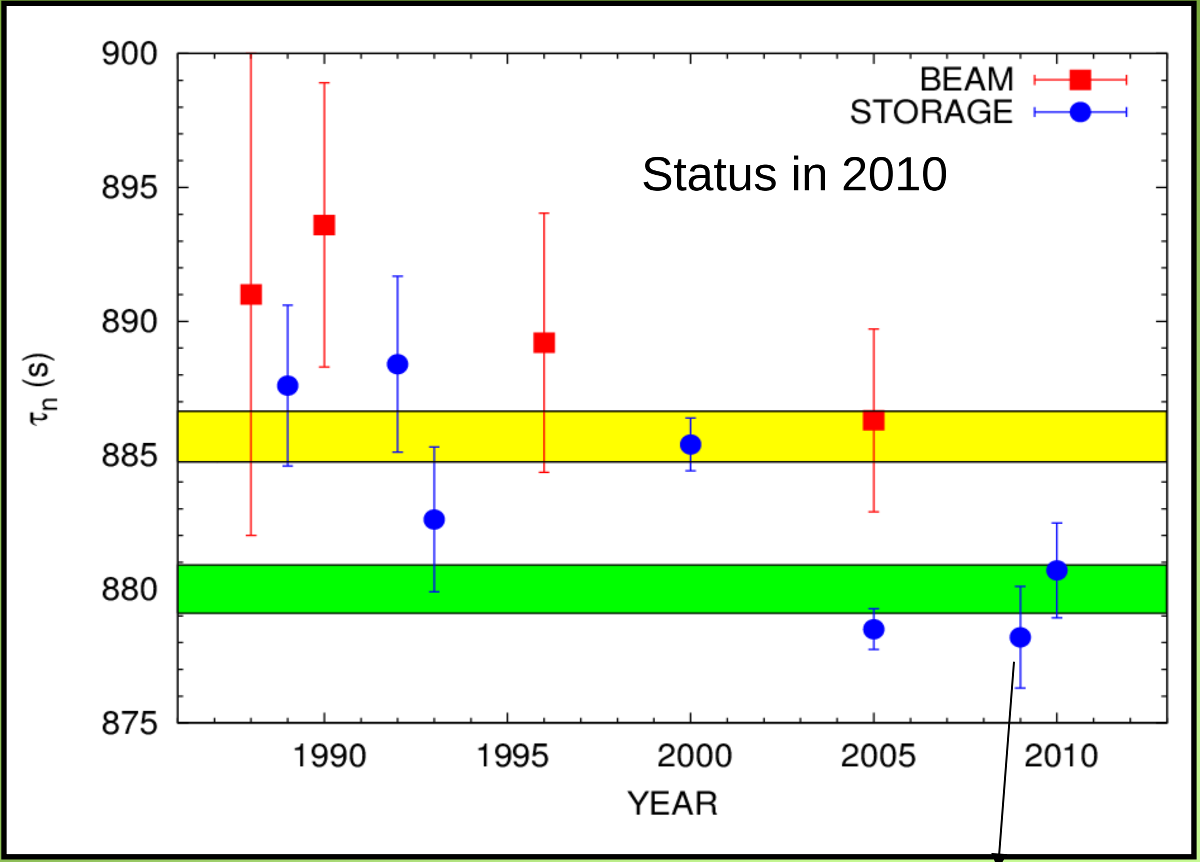

*unpublished

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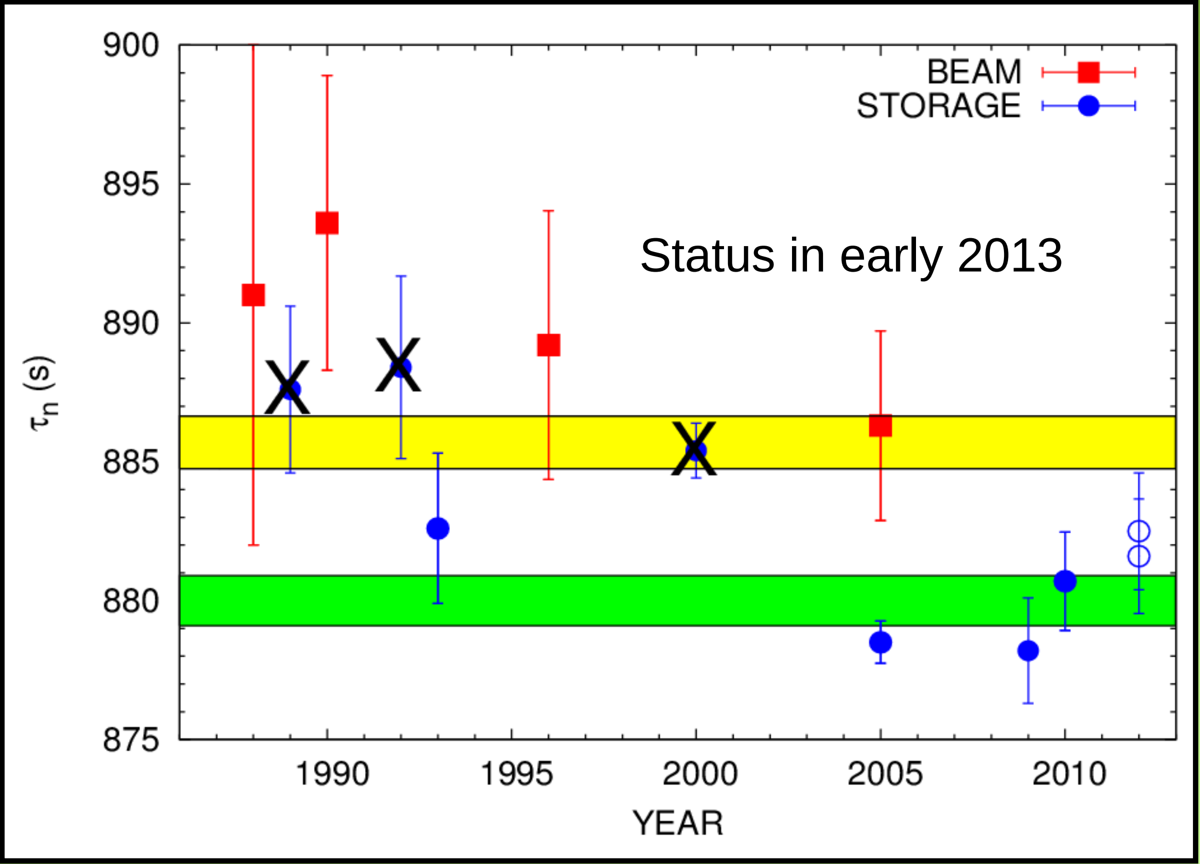
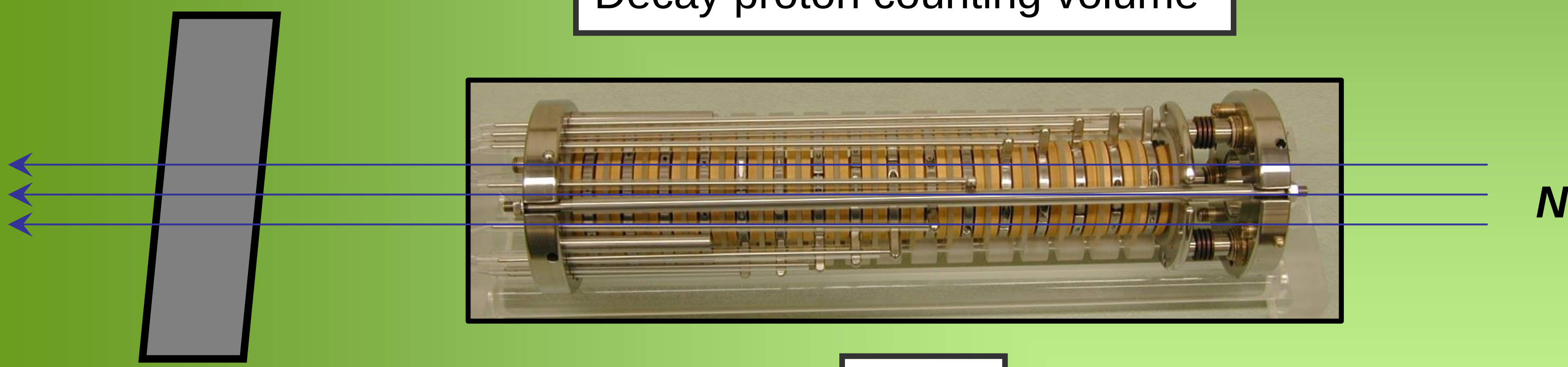


Beam lifetime measurement

$$\frac{dN(t)}{dt} = \frac{-N(t)}{\tau_n}$$

Neutron flux

Decay proton counting volume

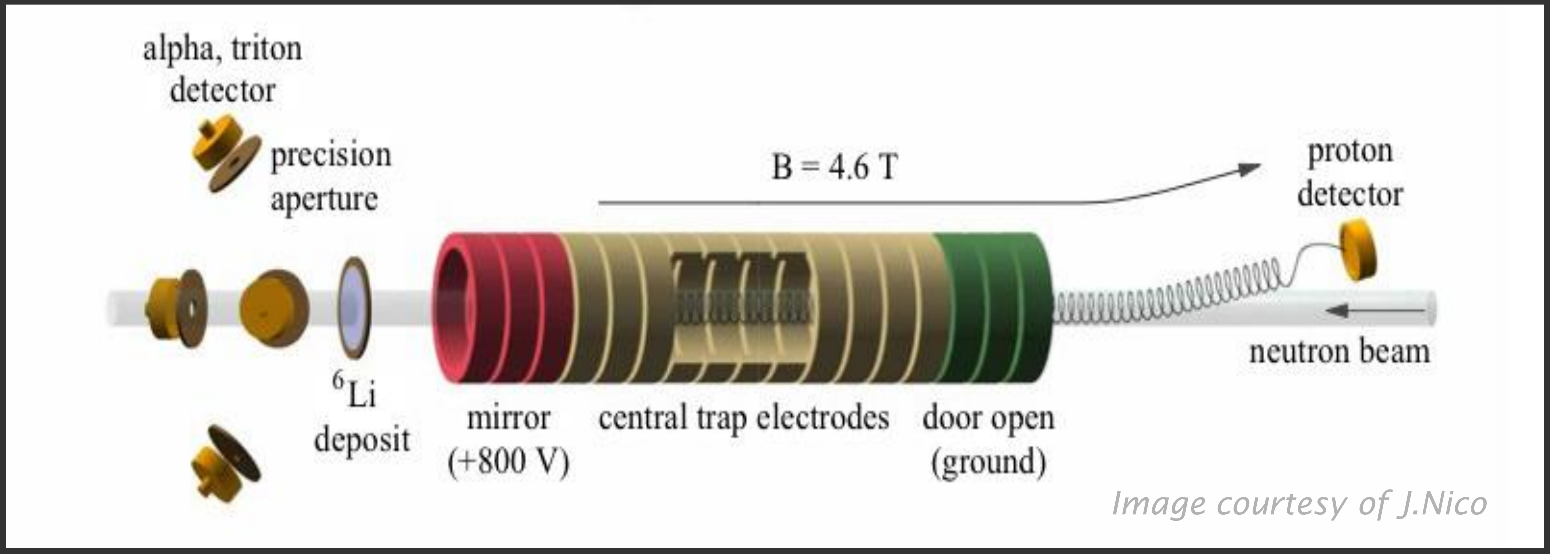


$$N(t)$$

$$\frac{dN(t)}{dt}$$

Must have knowledge of neutron detection and proton trapping/detection efficiencies

Neutron lifetime at NIST – an "in-beam" measurement



- Absolute neutron counting is important
- Current precision measurements are from bottle experiments – sensitive to different systematic effects

$$\tau_n = 886.3 \pm 1.2 \pm 3.2$$

Critical Improvements over previous measurement

Source of correction	Correction (s)	Uncertainty (s)
^{6}LiF deposit areal density		2.2
^{6}Li cross section		1.2
Neutron detector solid angle		1.0
Absorption of neutrons by ^{6}Li	+5.2	0.8
Neutron beam profile and detector solid angle	+1.3	0.1
Neutron beam profile and ^{6}Li deposit shape	−1.7	0.1
Neutron beam halo	−1.0	1.0
Absorption of neutrons by Si substrate	+1.2	0.1
Scattering of neutrons by Si substrate	−0.2	0.5
Trap nonlinearity	−5.3	0.8
Proton backscatter calculation		0.4
Neutron counting dead time	+0.1	0.1
Proton counting statistics		1.2
Neutron counting statistics		0.1
Total	−0.4	3.4

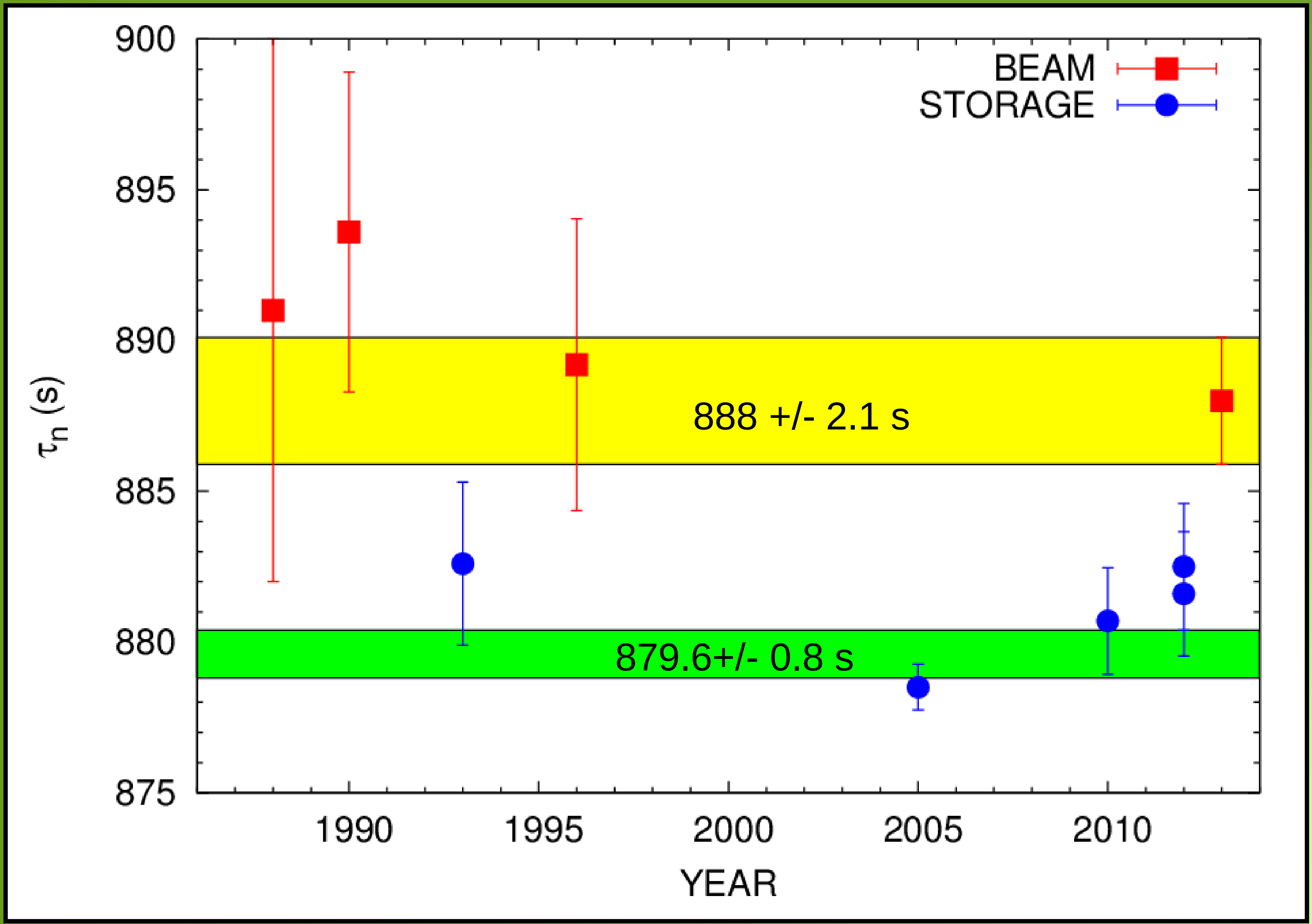
2.7s

- **Recent work by Andrew Yue will yield a result with <0.5s uncertainty**
- **Powerful motivation to run the experiment again with ~1s uncertainty**

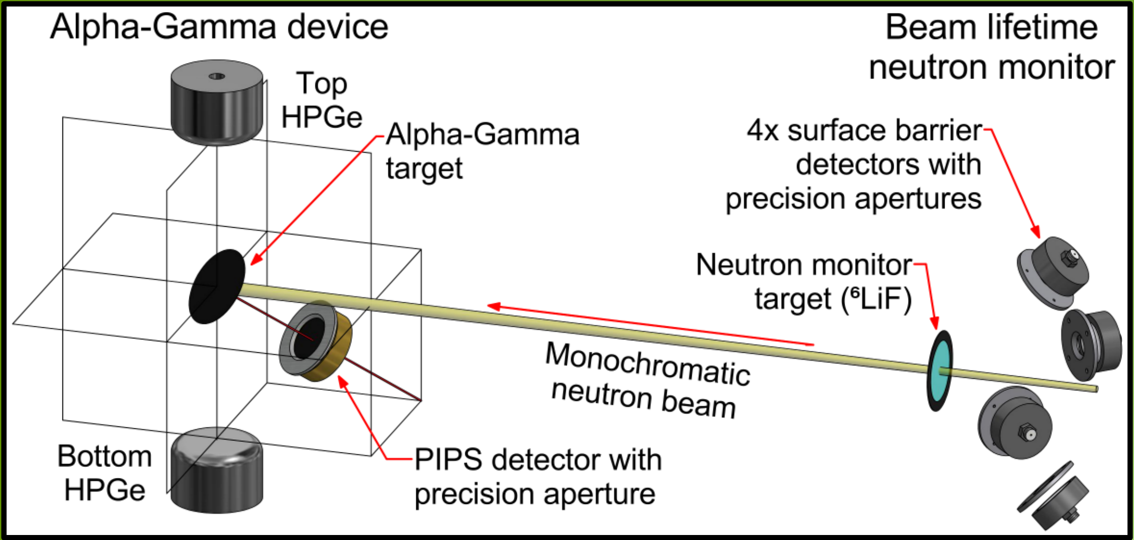
(~2014 at NIST)

Jonathan Mulholland leading the new effort

4σ disagreement

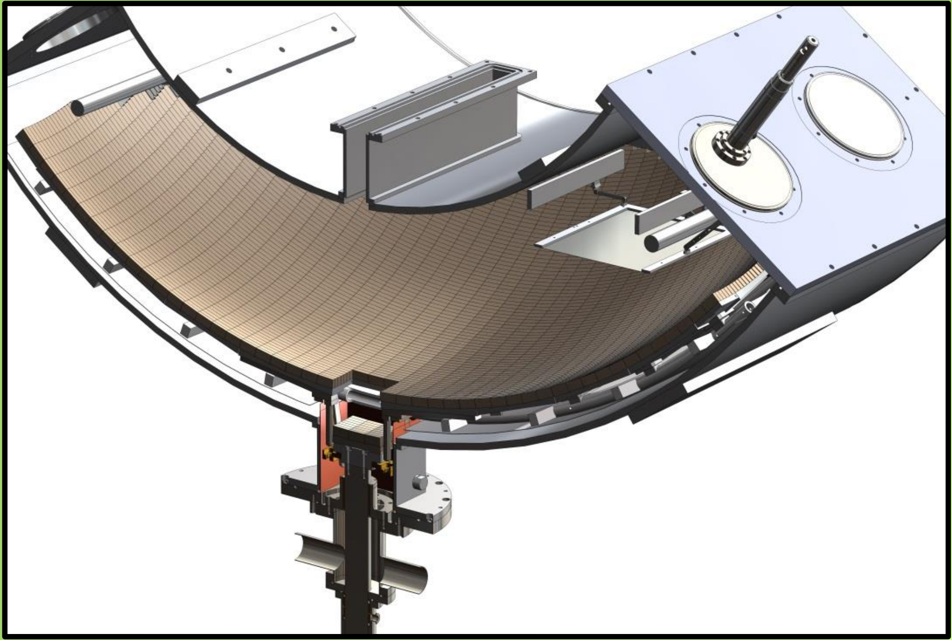


More measurements to come

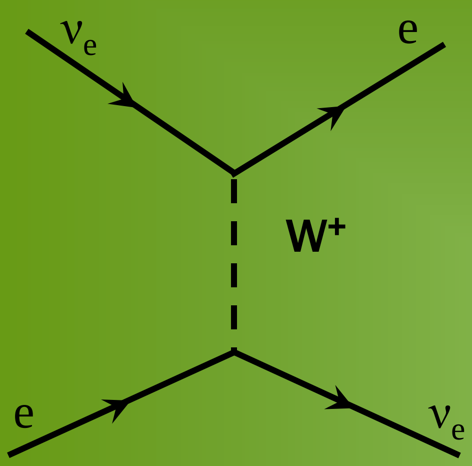


Improved absolute neutron counting via Alpha-Gamma device allows a ~1s beam measurement
arXiv:1309.2623

Asymmetric Halbach array magnetic trap – proof of concept run completed at LANSCE → results coming soon

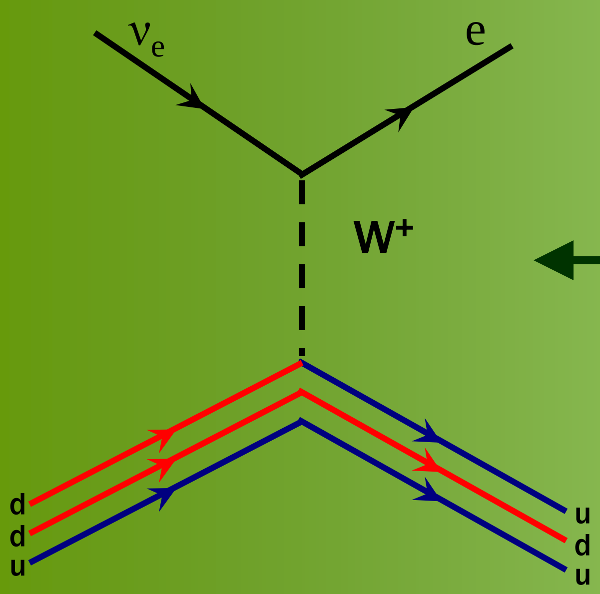


The Weak Force



Leptonic weak Interaction

- Neutrons aren't helpful here



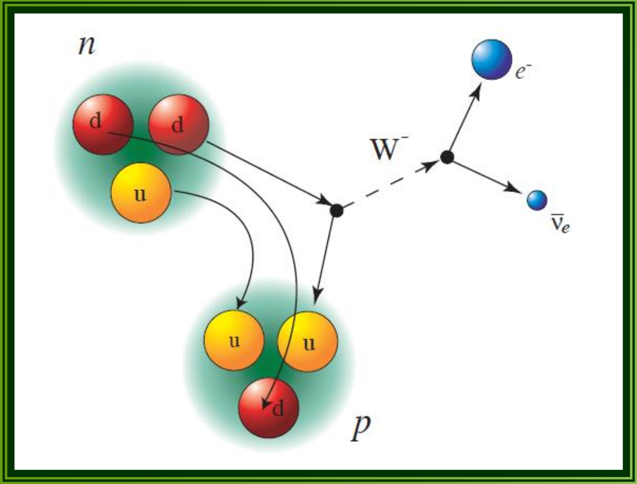
What experiments can we do?

- **Neutron lifetime**
- ***Free neutron β–decay***

Semi-Leptonic weak Interaction

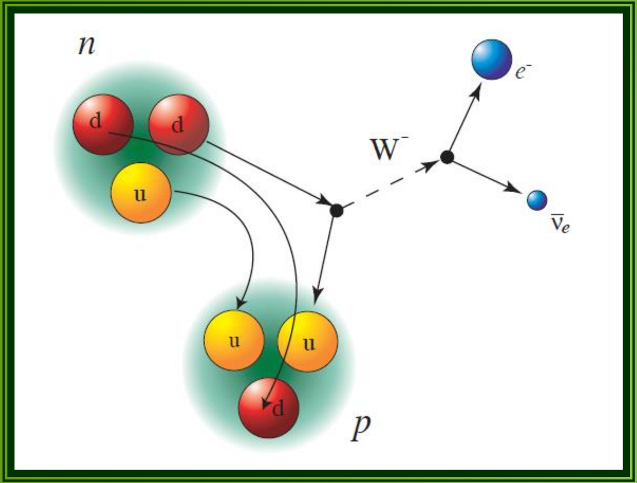
Observables in neutron β decay

$$dw \propto \rho(E_e)\cdot(1+2|\lambda|^2)\cdot\{1+a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu}+b\frac{m_e}{E_e}+\vec{\sigma}_n\cdot(A\frac{\vec{p}_e}{E_e}+B\frac{\vec{p}_\nu}{E_\nu}+D\frac{\vec{p}_e\times\vec{p}_\nu}{E_eE_\nu})\}$$



Observables in neutron β decay

$$dw \propto \rho(E_e)\cdot(1+2|\lambda|^2)\cdot\{1+a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu}+b\frac{m_e}{E_e}+\vec{\sigma}_n\cdot(A\frac{\vec{p}_e}{E_e}+B\frac{\vec{p}_\nu}{E_\nu}+D\frac{\vec{p}_e\times\vec{p}_\nu}{E_eE_\nu})\}$$



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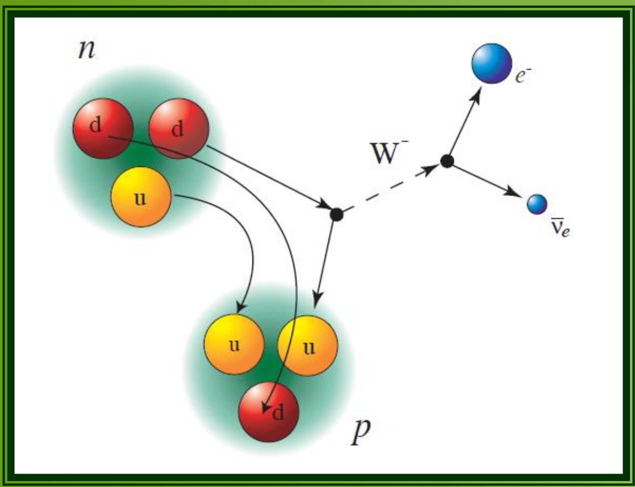


Fierz interference term (distortion in the electron spectrum)

$$A=-2\frac{|\lambda|^2+\mathrm{Re}\,\lambda}{1+3|\lambda|^2}$$

$$B=-2\frac{|\lambda|^2-\mathrm{Re}\,\lambda}{1+3|\lambda|^2}$$

Angular polarization coefficients

$$a=\frac{1-|\lambda|^2}{1+3|\lambda|^2}$$

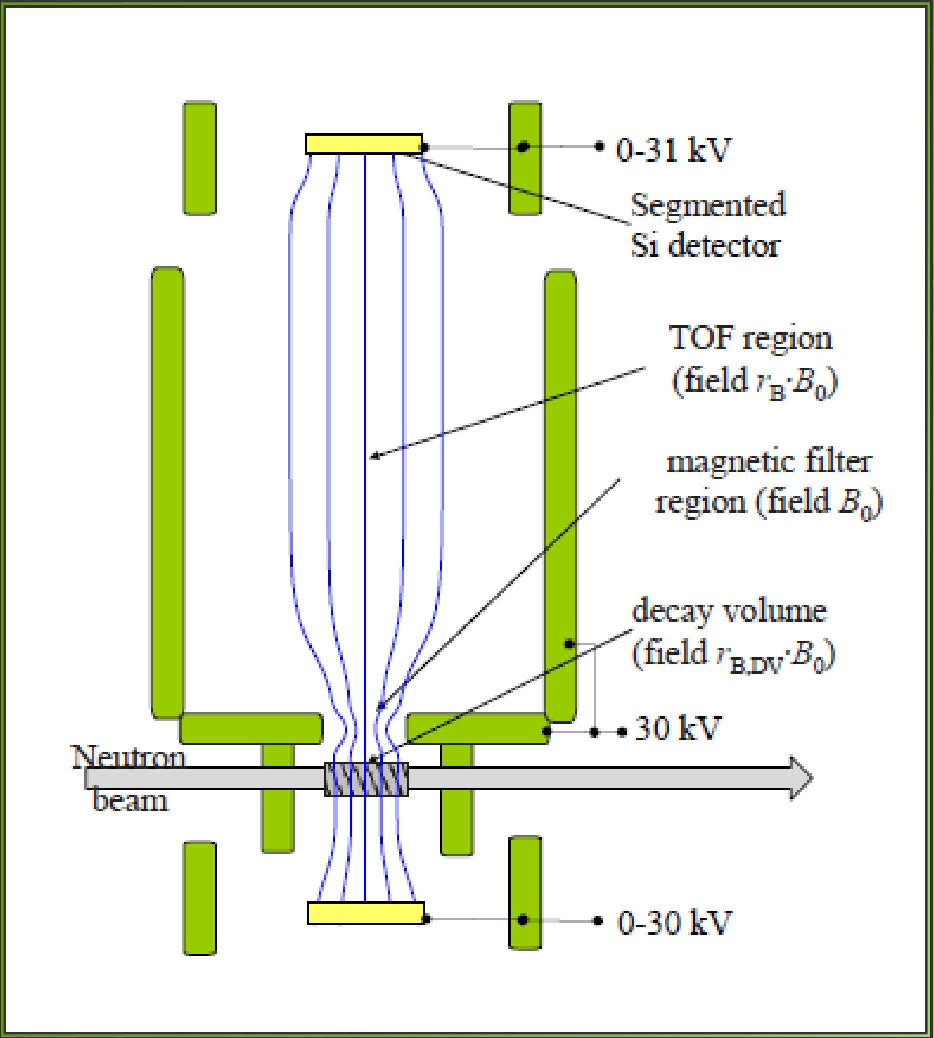
electron-neutron correlation (angular)

$$\tau_n^{-1}=\frac{2\pi}{\hbar}G_F{}^2V_{ud}{}^2(1+3|\lambda|^2)\int\rho(E_e)$$

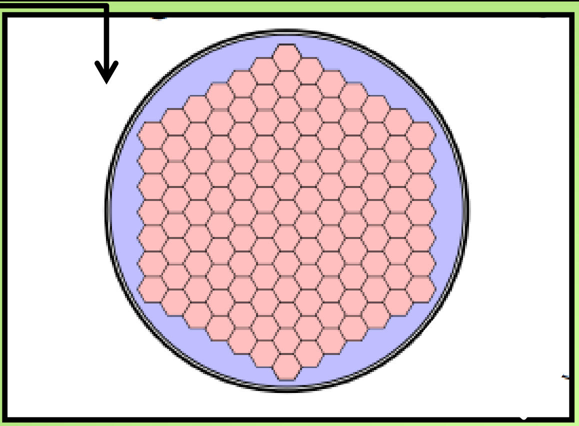
Need lifetime ***and*** λ for V_{ud}

$$\lambda=\frac{g_A}{g_V}$$

Example: Nab – first β-decay experiment at the SNS



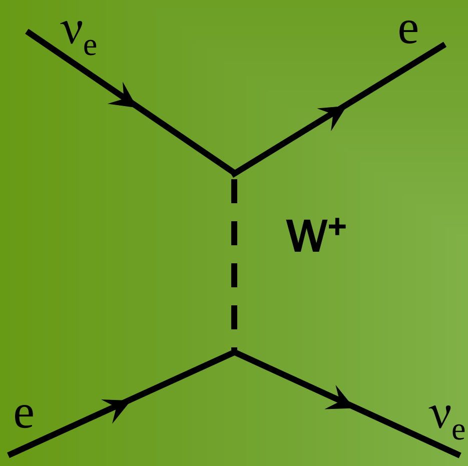
- Measure beta decay parameters ***a,b***:
  Δa/a ≈ 1e-3
  Δb ≈ 3e-3
- Detect electron and proton form neutron beta decay
- Measure electron energy spectrum and proton TOF → reconstruct decay kinematics
- Segmented Si detectors for decay particles



Spectrometer design lends itself to continued use by other β–decay experiments at the SNS

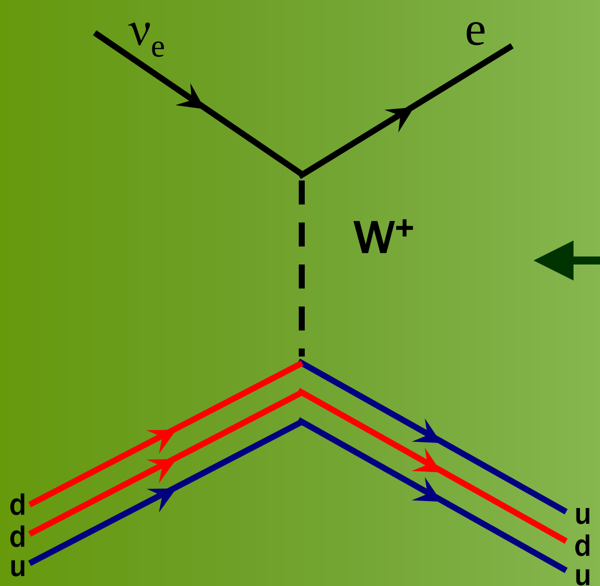
S. Baessler and D. Pocanic have a LOT more information

The Weak Force

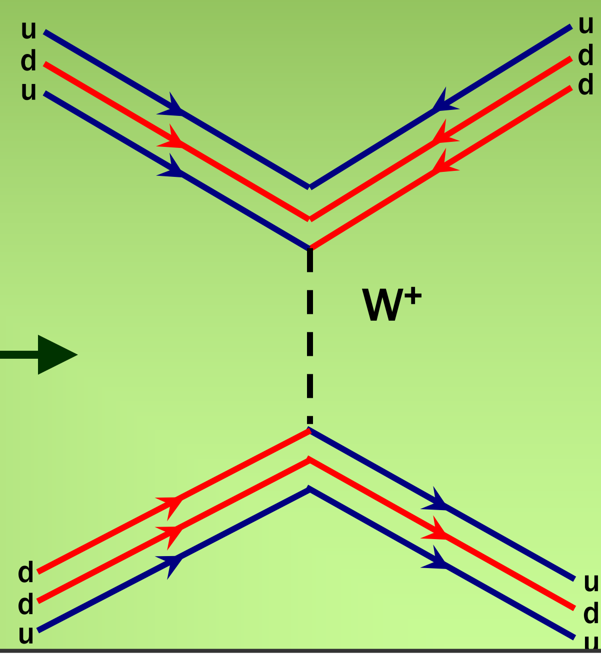


Leptonic weak Interaction

- Neutrons aren't helpful here



Enter: Neutrons

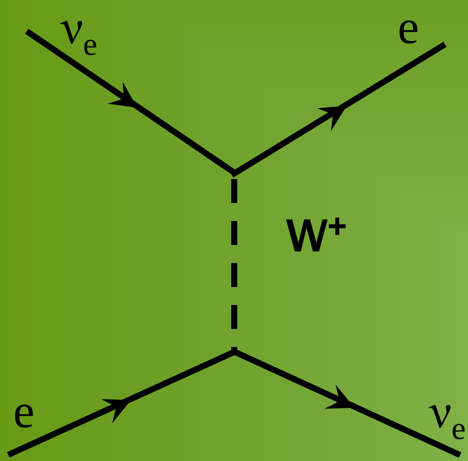


Semi-Leptonic weak Interaction

Hadronic weak Interaction

--strong force makes it tricky

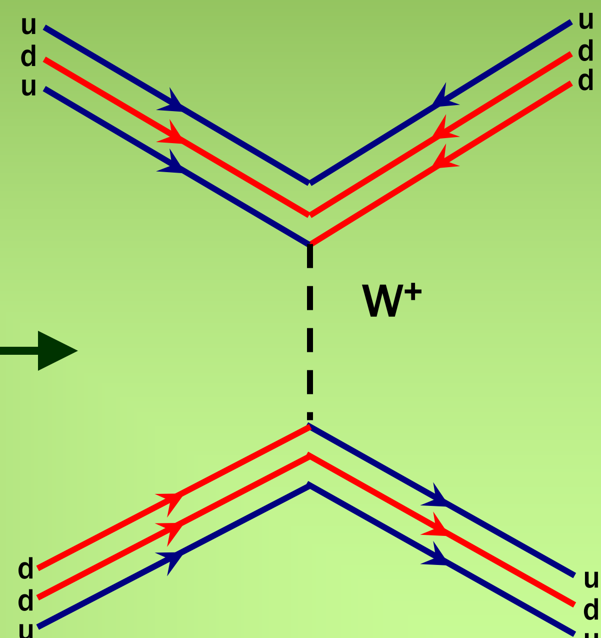
The Weak Force



Leptonic weak Interaction

- Neutrons aren't helpful here

- **Natural scale ~x10^{-7}, set by relative size of meson vs boson exchange amplitudes**
- Weak interaction at low momentum transfer between nucleons is accessible through measurements of small parity-odd amplitudes



Hadronic Weak Interaction (HWI)

--strong force makes it tricky

Hadronic Weak Interaction Models

1. **DDH model** – uses valence quarks to calculate effective PV meson-nucleon coupling directly from SM via 7 weak meson coupling constants

$$f_\pi^1, h_\rho^0, h_\rho^1, h_\rho^{1'}, h_\rho^2, h_\omega^0, h_\omega^1$$

- Observables can be written as their combinations

$$A = a_\pi^1 f_\pi^1 + a_\rho^0 h_\rho^0 + a_\rho^1 h_\rho^1 + a_\rho^2 h_\rho^2 + a_\omega^0 h_\omega^0 + a_\omega^1 h_\omega^1$$

	$n+p \to d+\gamma$ A_γ (ppm)	$n+d \to t+\gamma$ A_γ (ppm)	n-p φ_{PV} (μrad/m)	n-^{4}He φ_{PV} (μrad/m)	p-p $\Delta\sigma/\sigma$ (ppm)	p-^{4}He $\Delta\sigma/\sigma$ (ppm)
f_π	-0.107	-0.92	-3.12	-0.97		-0.340
h_ρ^0		-0.50	-0.23	-0.32	0.079	0.140
h_ρ^1	-0.001	0.103		0.11	0.079	0.047
h_ρ^2		0.053	-0.25		0.032	
h_ω^0		-0.160	-0.23	-0.22	-0.073	0.059
h_ω^1	0.003	0.002		0.22	0.073	0.059

$f_\pi \sim 4.5\text{x}10^{-7}$

Weak π−nucleon coupling (long range)

$$A_\gamma \approx -0.11 f_\pi^1$$

HWI Models - Continued

2. Effective Field Theory

– developed by Holstein, Ramsey-Musolf, van Kolck, Zhu and Maekawa

– model-independent

- NN potentials are expressed in terms of 12 parameters, whose linear combinations give us 5 low energy coupling constants
  - connect to 5 parity-odd S-P NN amplitudes

$\lambda_t, \lambda_s^{I=0,1,2}, \rho_t$ Corresponding to

$$^1S_0 \rightarrow {}^3P_0 \quad (\Delta I = 0,1,2)$$

$$^3S_1 \rightarrow {}^1P_1 \quad (\Delta I = 0)$$

$$^3S_1 \rightarrow {}^3P_1 \quad (\Delta I = 1)$$

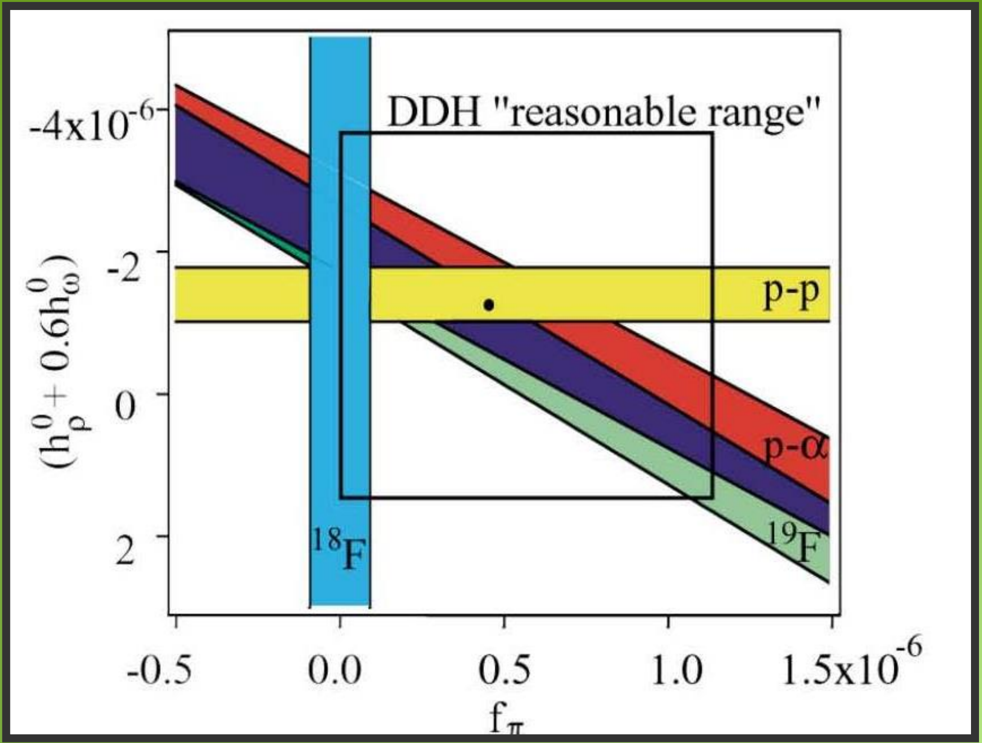
$$A_\gamma^{\vec{n}p} \approx -0.27\tilde{C}_6^\pi - 0.09 m_N \rho_t$$

3. Lattice QCD (NEW)

– J. Wasem, PRC C85 (2012)

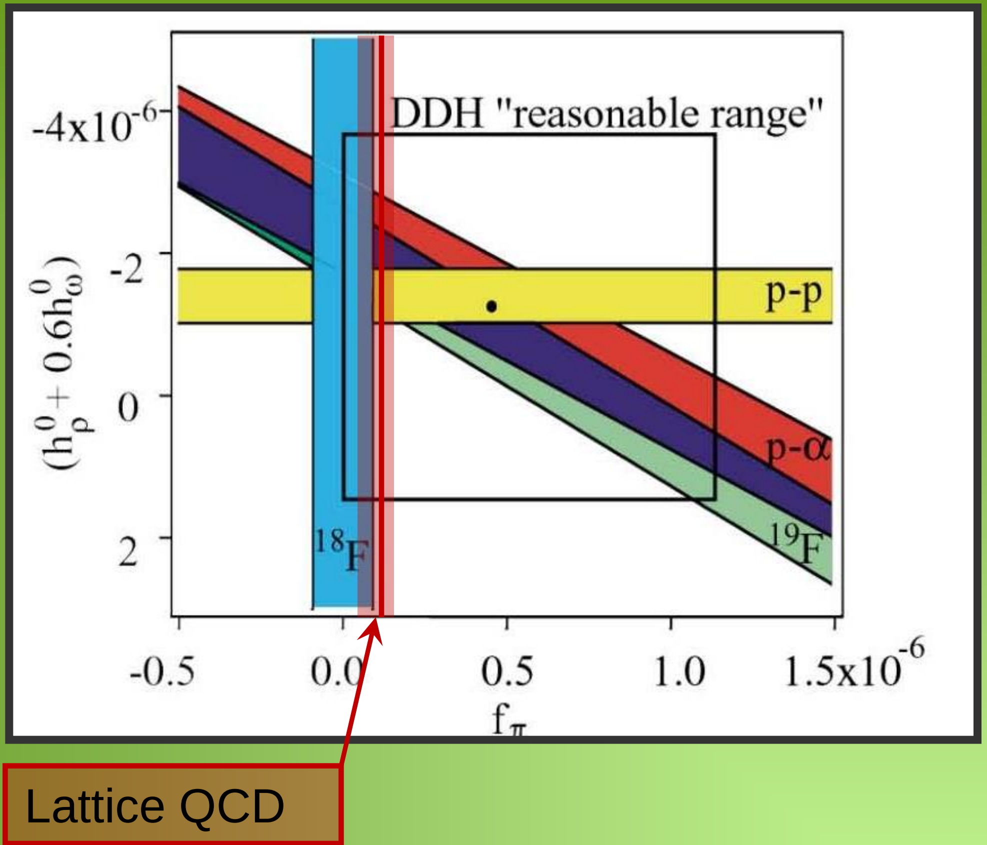
$$h^1_{\pi NN} = 1.099 \pm 0.505 {}^{+0.058}_{-0.064} \ [x10^{-7}]$$

f_π could be very small



- Experiments suggest a small f_π (nearly zero)
  - corresponds to ΔI=1 transition (should be large)
  - ΔI=0,2 do not contribute to A_γ
  - Observations are not well understood (ΔI=0 contribution appears to be large, and ΔI=1 appears to be small)

f_π could be very small



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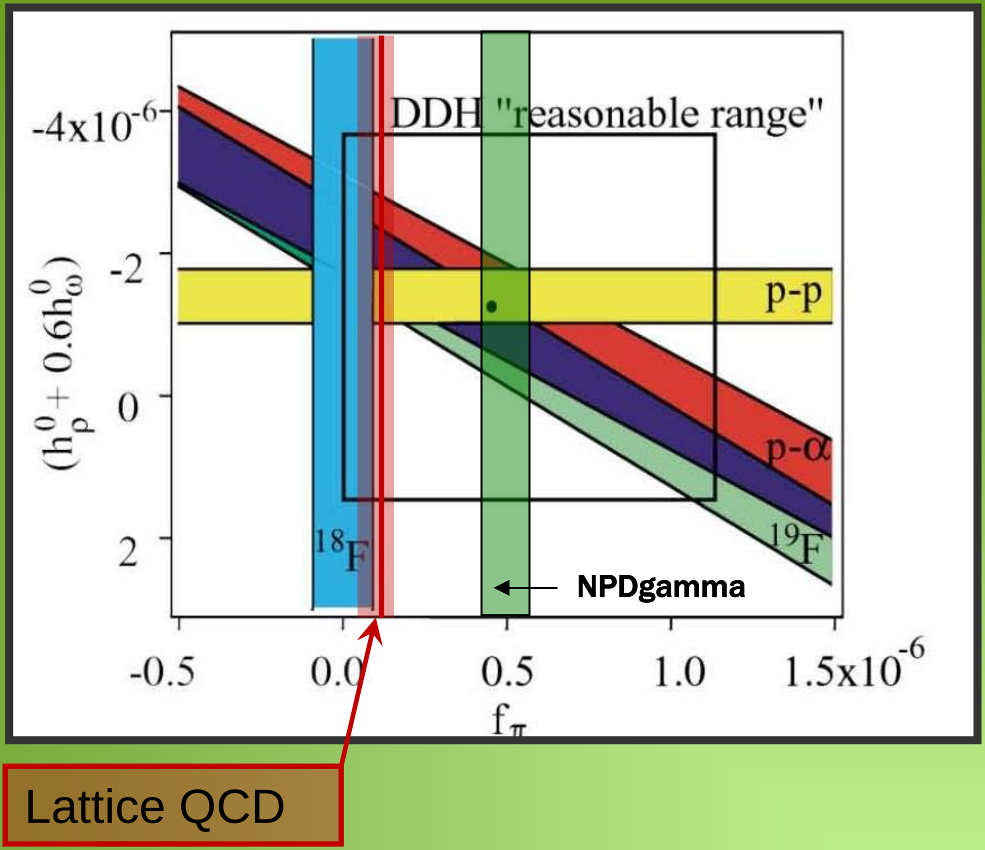

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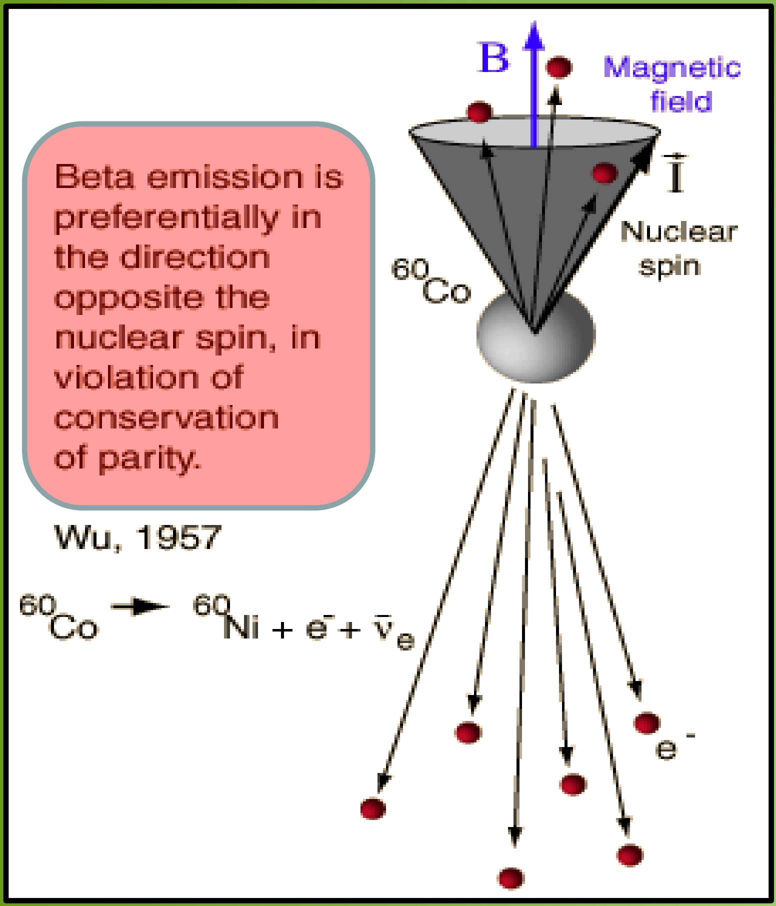
Parity Violation – a vital experimental tool

$$P : \begin{pmatrix} x \\ y \\ z \end{pmatrix} \mapsto \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix}.$$

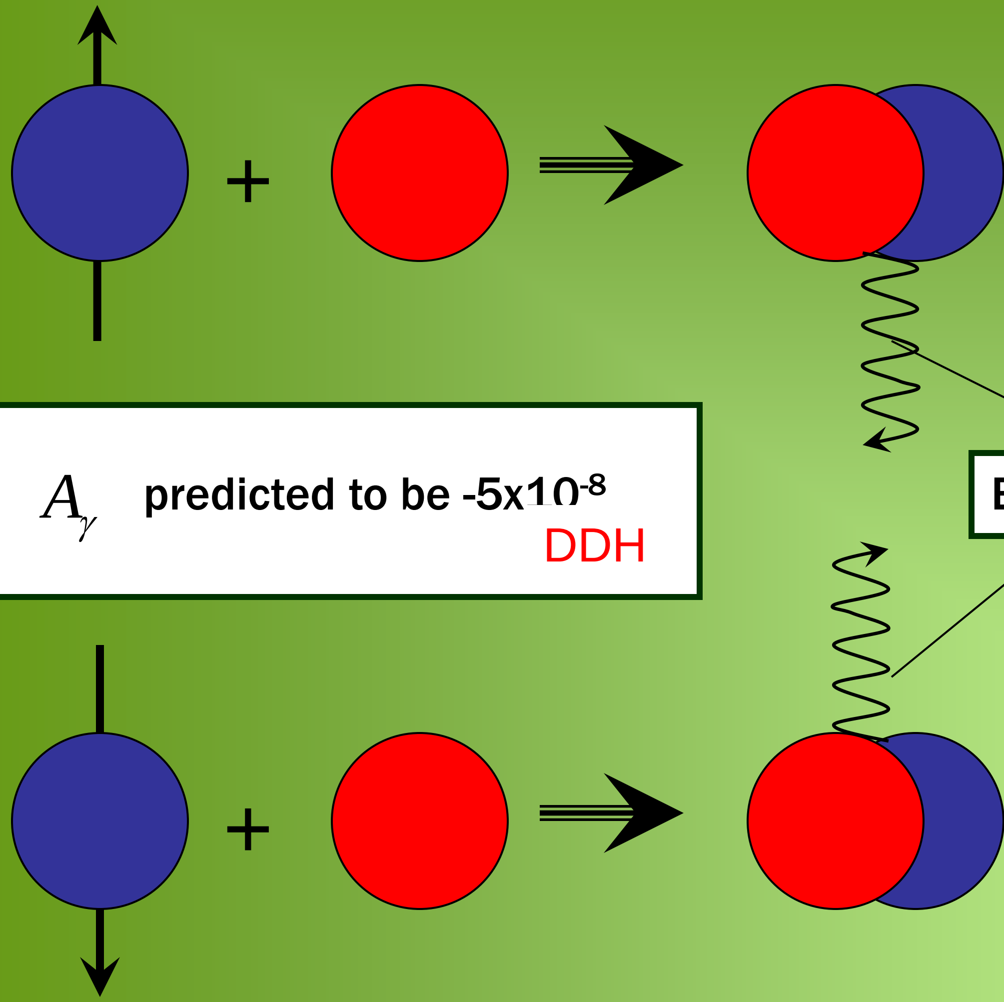
- *Does an object/process look like its mirror image under parity inversion?*
- *Not if it's weak!*



"Parity Violation"

Reaction of interest: $\vec{n} + p \Rightarrow d + \gamma$

isolates the ΔI=1 part of the weak interaction



$$\frac{d\sigma}{d\Omega} \propto \frac{1}{4\pi}\left(1 + A_\gamma \cos\theta\right)$$

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

E_γ=2.2MeV

A_γ predicted to be -5×10^{-8}
DDH

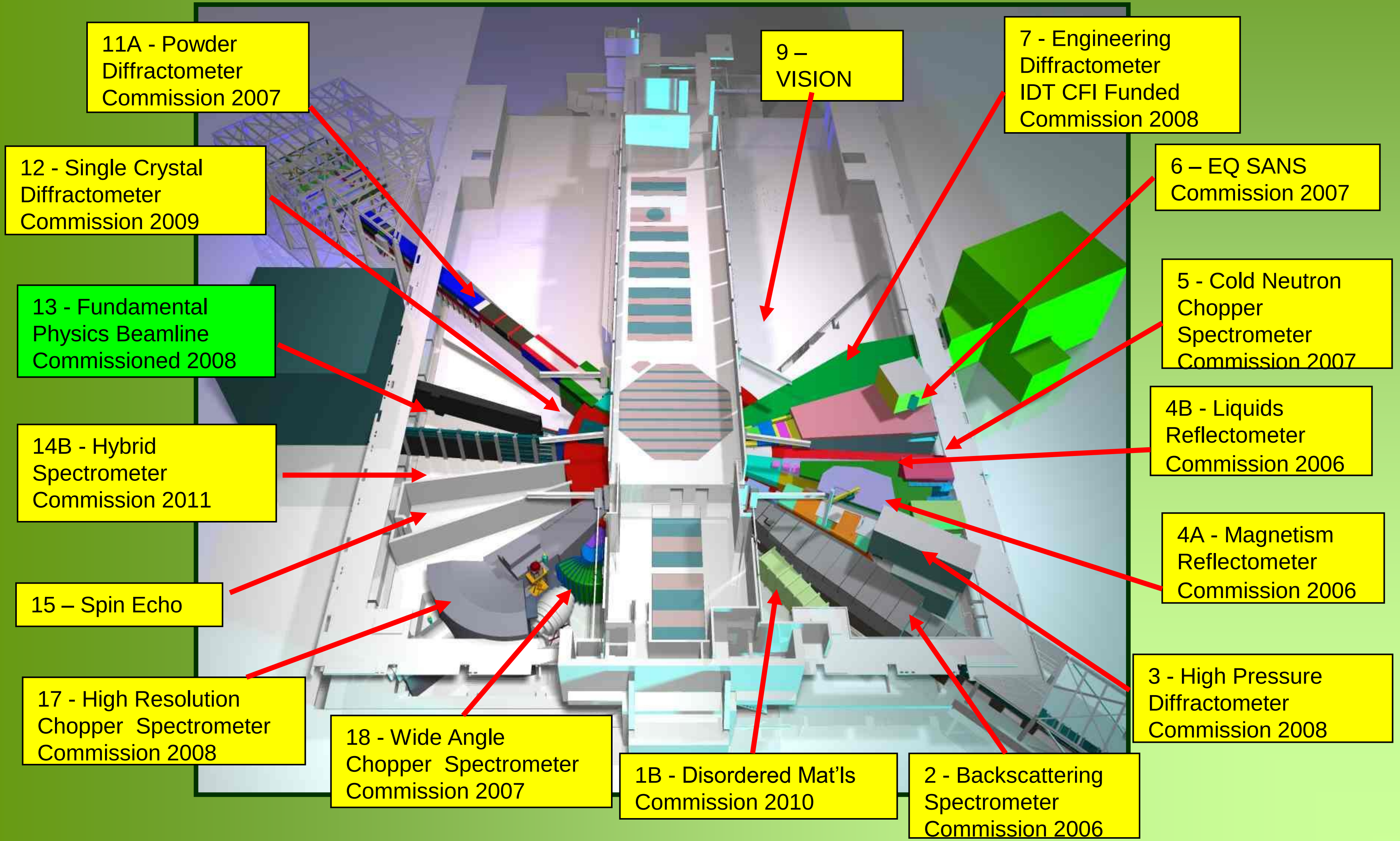
DDH

$$A_\gamma \approx -0.11 f_\pi^1$$

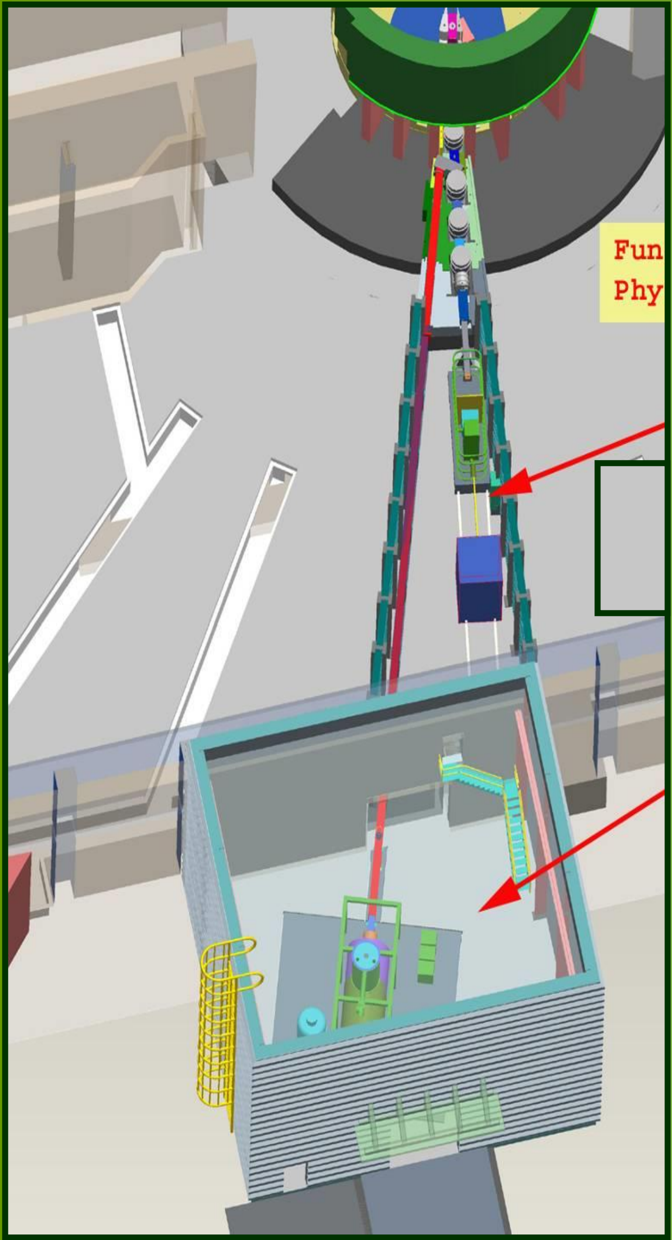
We measure A_γ, the PV asymmetry in the distribution of emitted gammas.

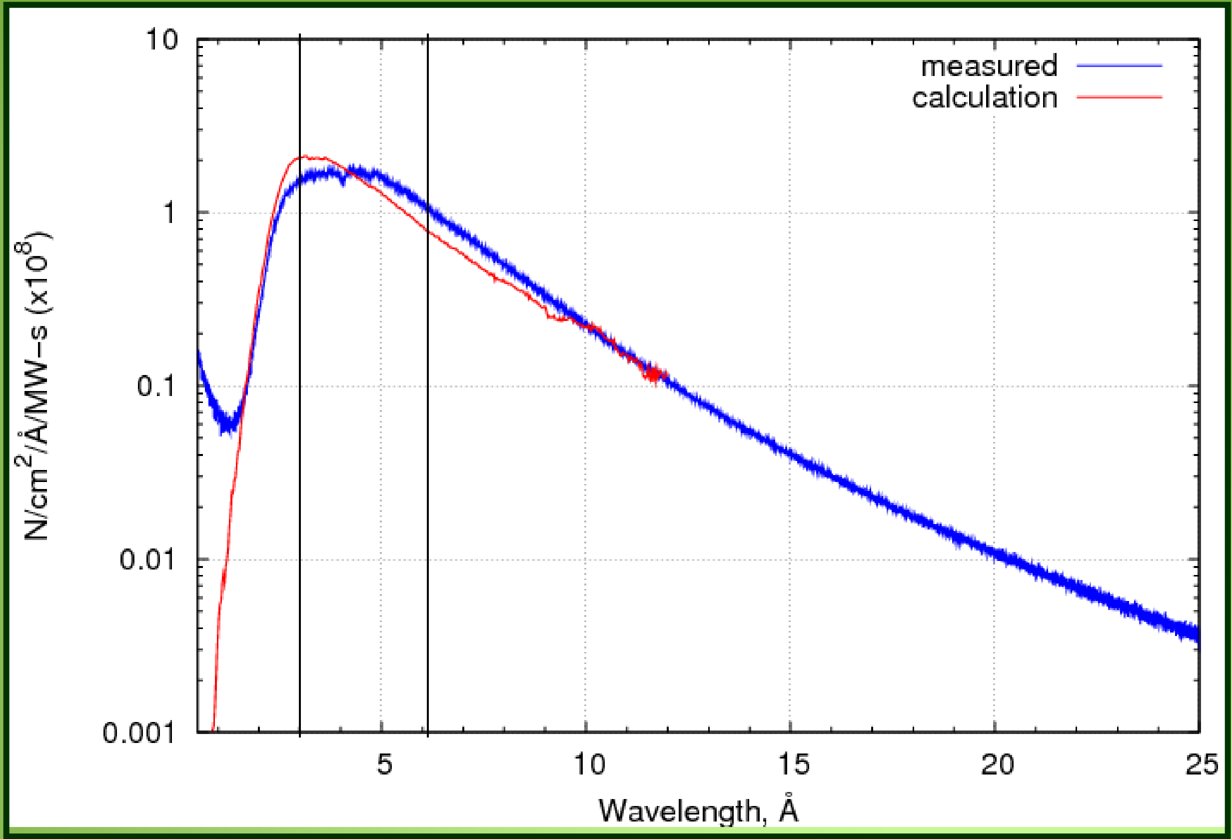
Spallation Neutron Source at ORNL

Reached 1MW of power – September, 2009

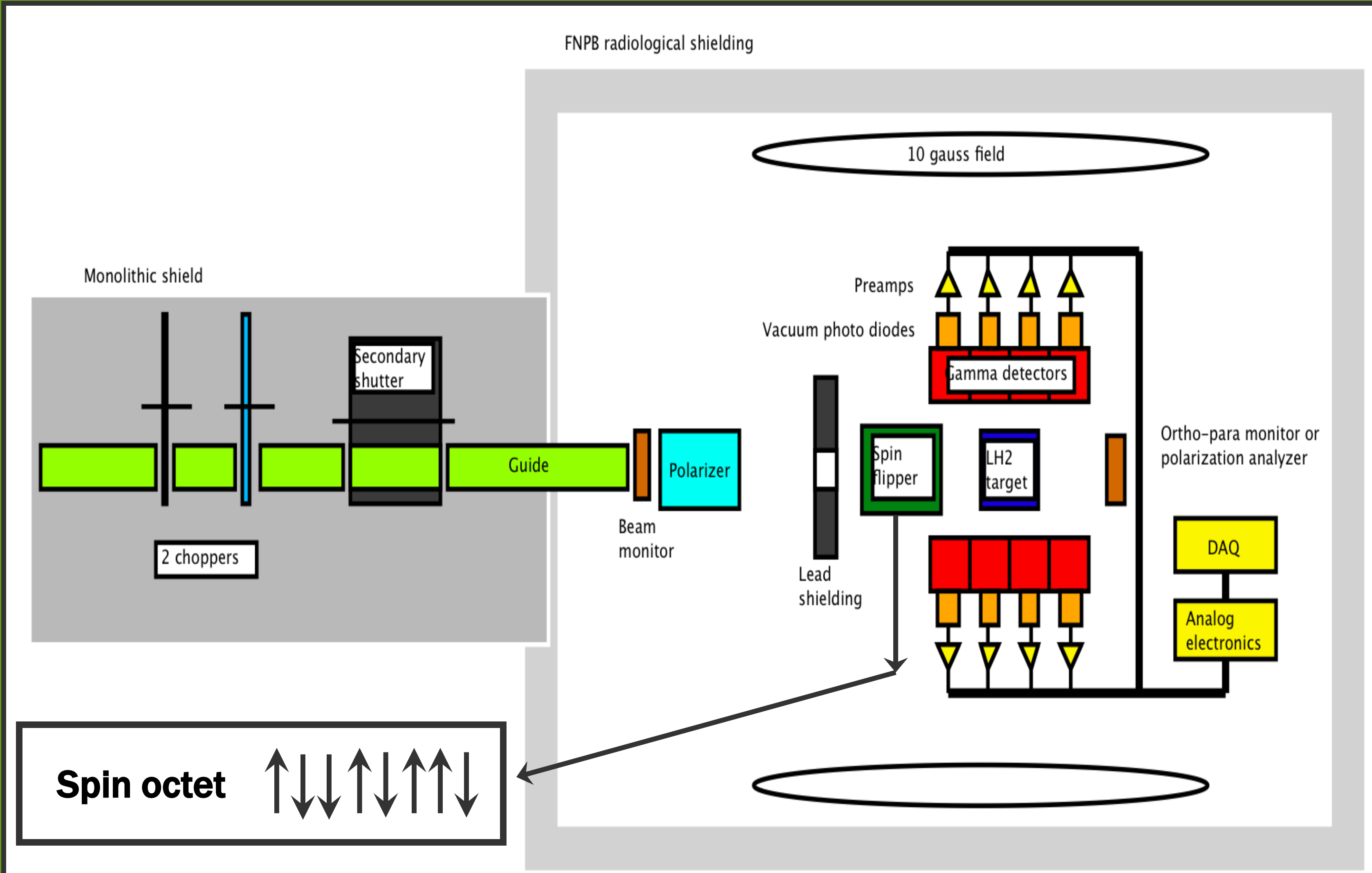


FnPB – cold beamline commissioned on Sep 12th, 2008





NPDGamma – Experimental Setup



Result from LANSCE run (2006) & Improvements for SNS

$A_{\gamma,UD}=(-1.2\pm2.0\pm0.2)\times10^{-7}$

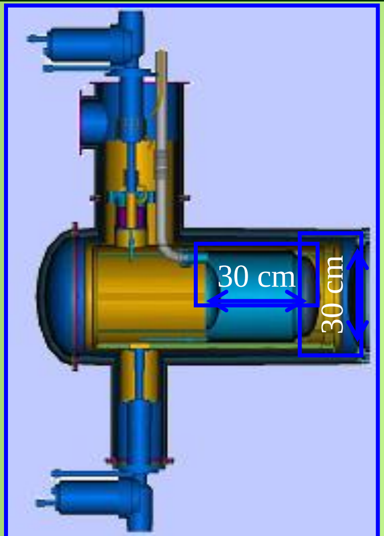
$A_{\gamma,LR}=(-1.8\pm2.1\pm0.2)\times10^{-7}$

	LANSCE	SNS
Sensitivity	2×10^{-7}	1×10^{-8}
Polarizer	^{3}He polarizer (average 55% NP)	SuperMirror Polarizer (95% NP)
FOM (NP^2)	8.9×10^7/s	X200 improvement
Target	16L, LH_2	New and improved, thinner windows

LH_2 target

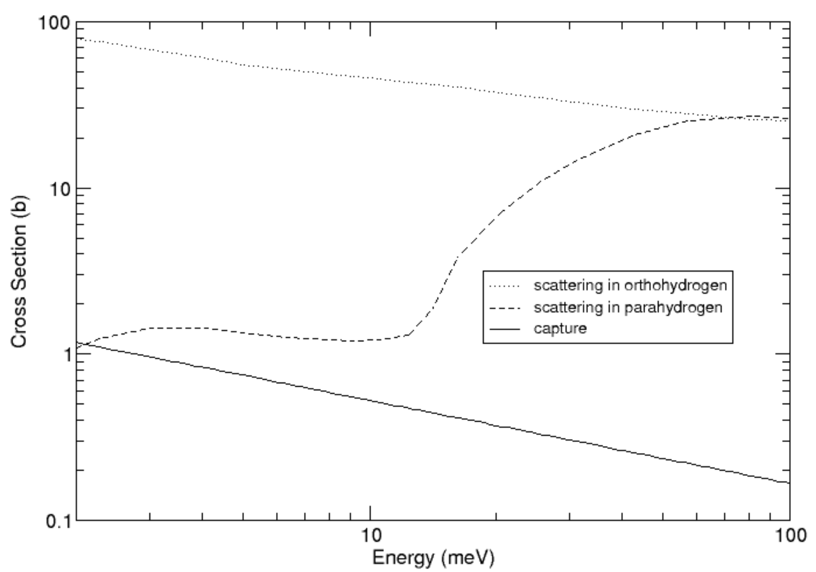
- 16L vessel of liquid parahydrogen
- Ortho-hydrogen scatters the neutrons and leads to beam depolarization

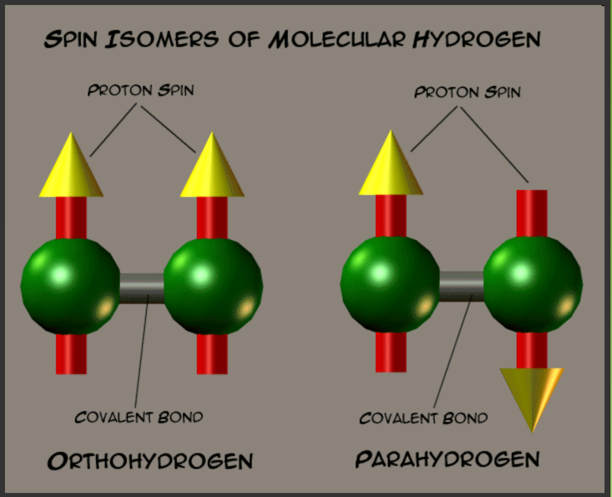
ASME code approved pressure vessel
See stamp!



LH_2 target - Parahydrogen

Orthohydrogen	*I=1 (aligned spins)*
Parahydrogen	*I=0 (anti-aligned spin)*





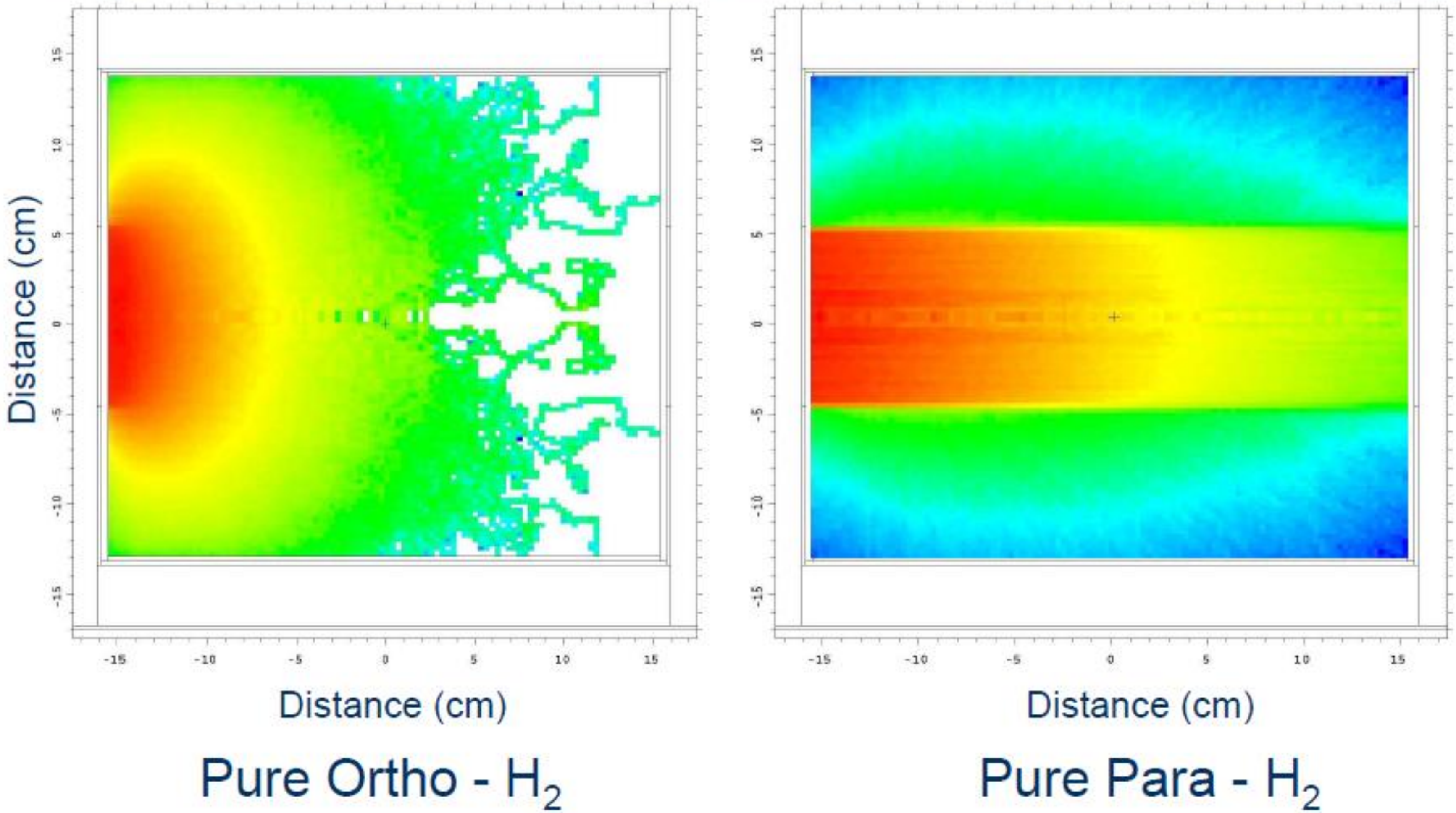
If E_n < *14.7meV*, cannot flip neutron spin

Para state dominates at low temperatures, helped by a catalyst (material with a solid paramagnetic surface)

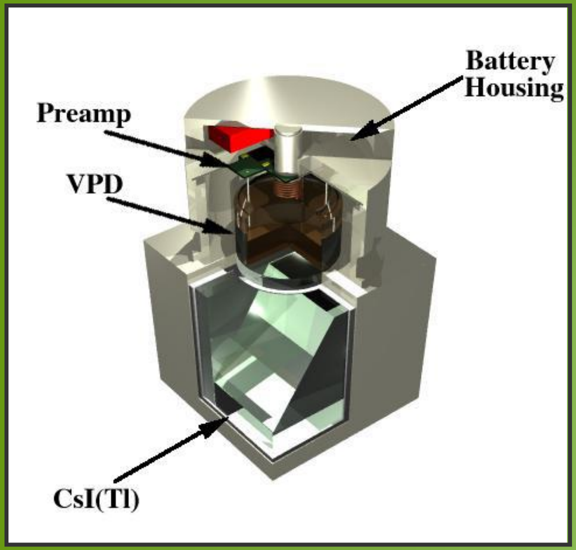
- No safety issues from sensors in the hydrogen system
- Energy dependence of the neutron transmission can be used

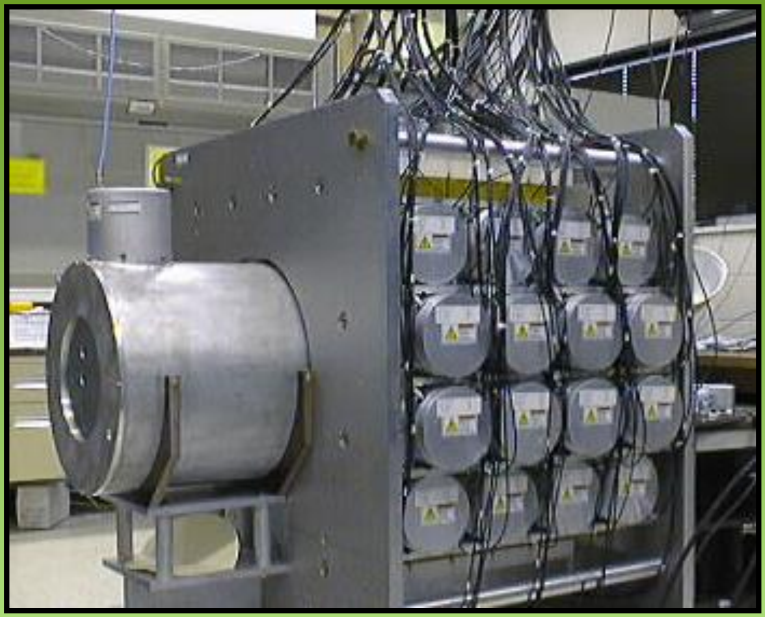
Parahydrogen Target

MCNP calculation of neutron beam intensity in liquid hydrogen target



Asymmetry Extraction





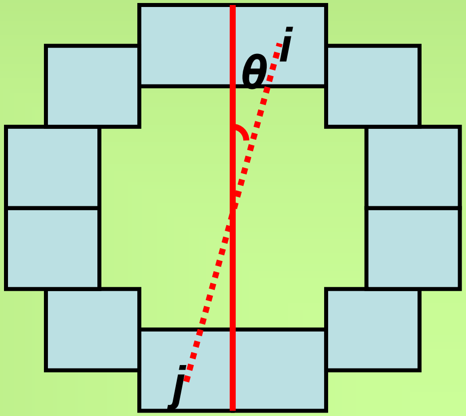
- In principle, experiment can be done with just one detector, reversing the neutron spin:

$$A_{raw} = \frac{Y^{\uparrow} - Y^{\downarrow}}{Y^{\uparrow} + Y^{\downarrow}}$$

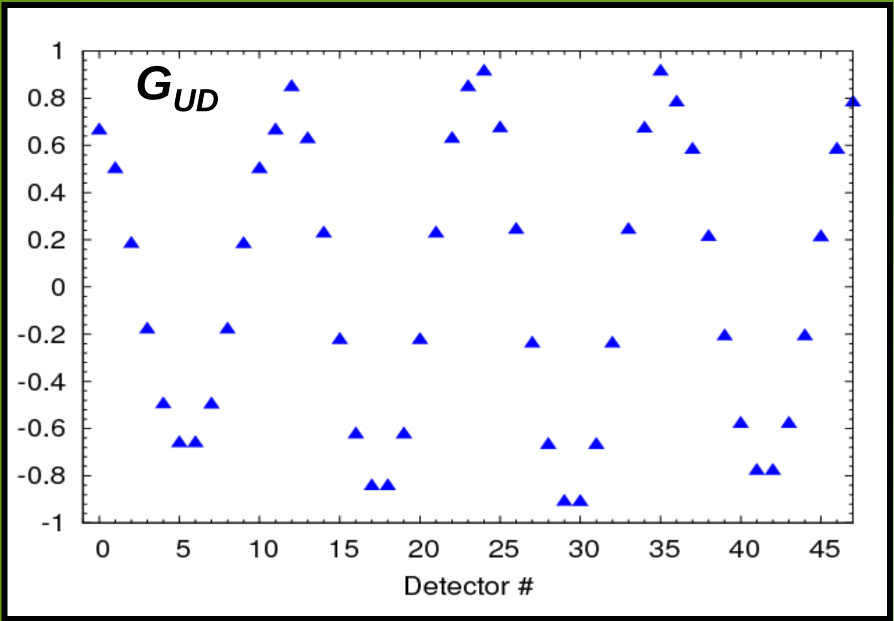
- Add opposite detector at same angle

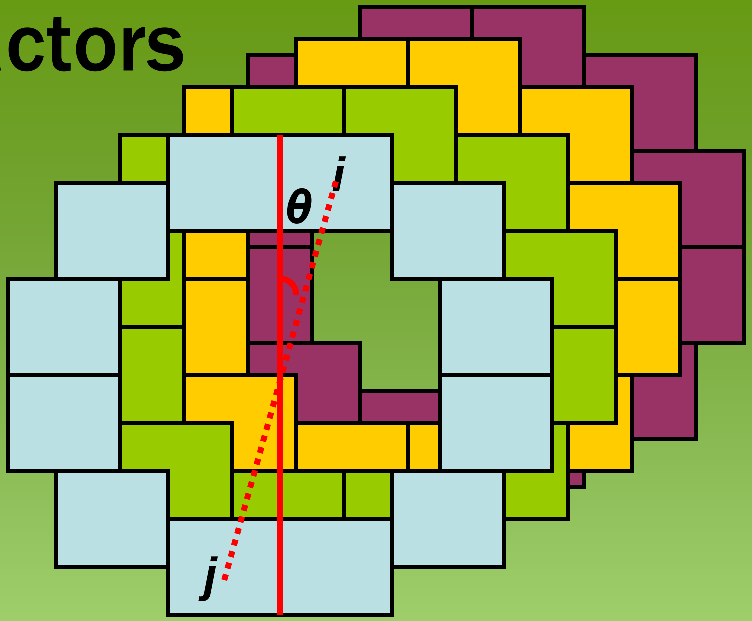
(eliminates some systematic errors):

$$A_{raw} = \frac{1}{2}\left(\frac{Y_i^{\uparrow} - Y_j^{\uparrow}}{Y_i^{\uparrow} + Y_j^{\uparrow}} + \frac{Y_j^{\downarrow} - Y_i^{\downarrow}}{Y_j^{\downarrow} + Y_i^{\downarrow}}\right)$$



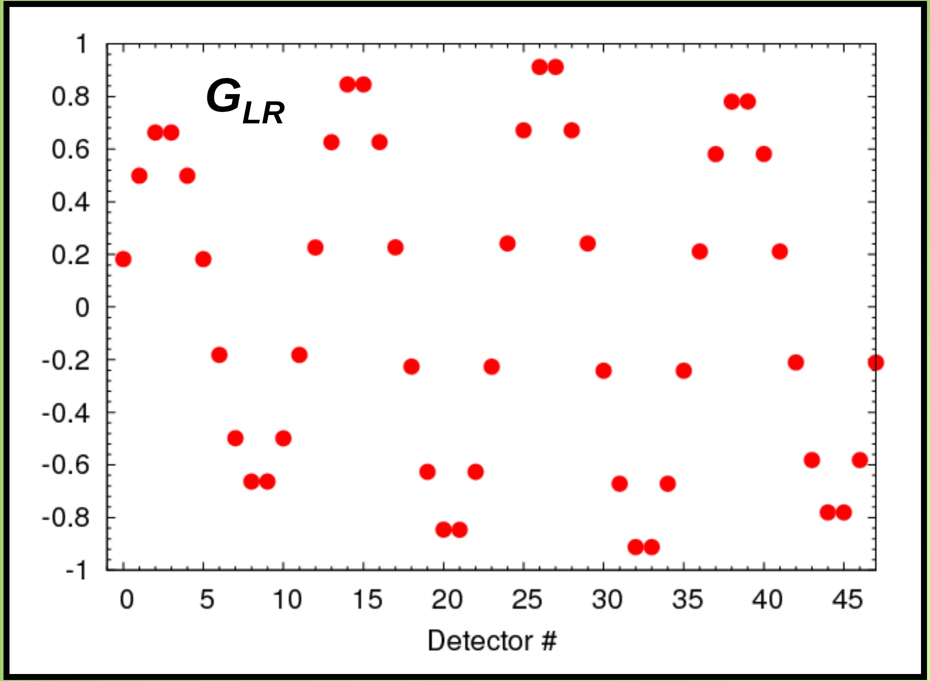
Geometrical Factors





$$G_{UD}(i) = <\hat{k}_\gamma \cdot \hat{\sigma}_n> = <\hat{k}_\gamma \cdot \hat{y}>$$

Generated via a combination of MCNPX and measurements with a gamma source



$$G_{LR}(i) = <\hat{k}_\gamma \cdot (\vec{\sigma}_n \times \hat{k}_n)> = <\hat{k}_\gamma \cdot \hat{x}>$$

Analysis Procedure

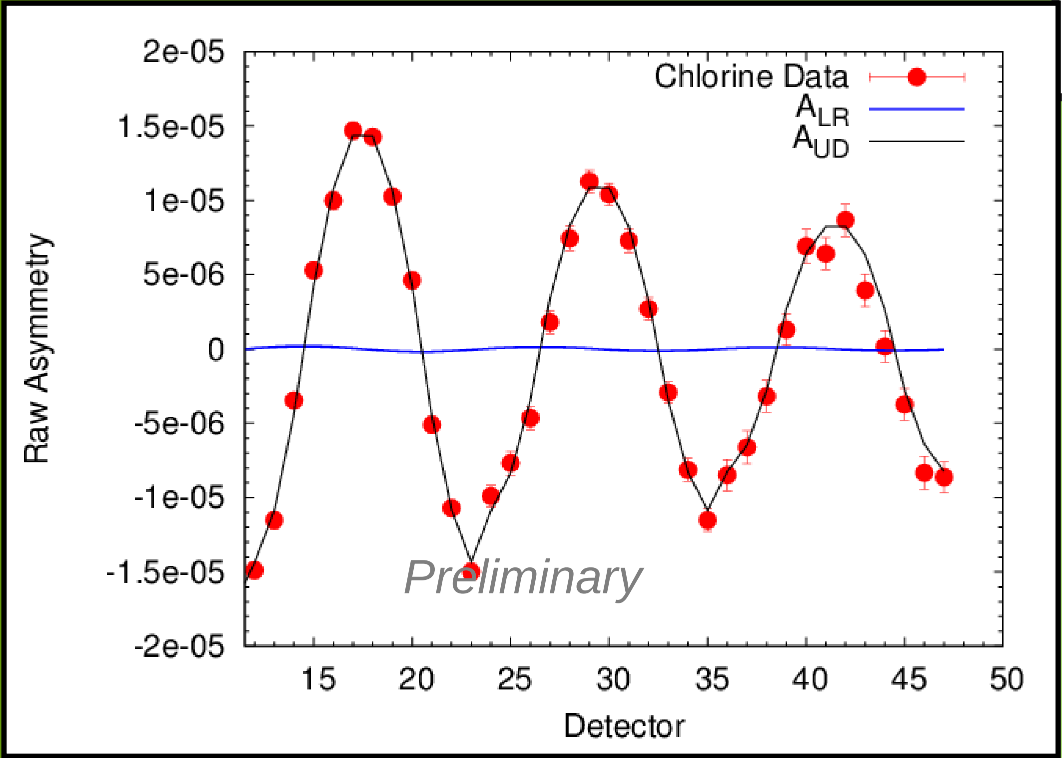
Calibration Target: ^{35}Cl

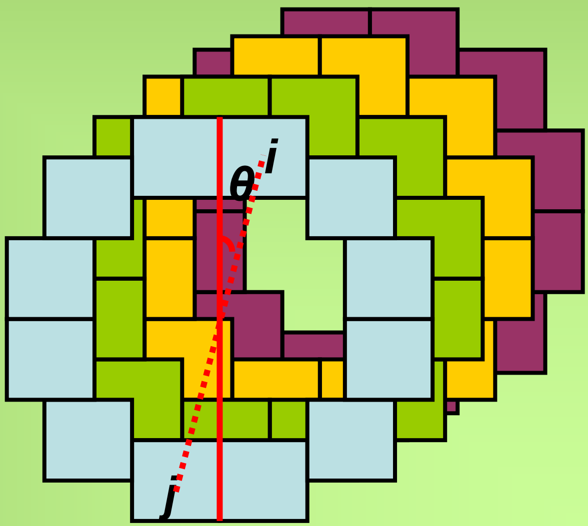
-target with a large and well-known γ-asymmetry

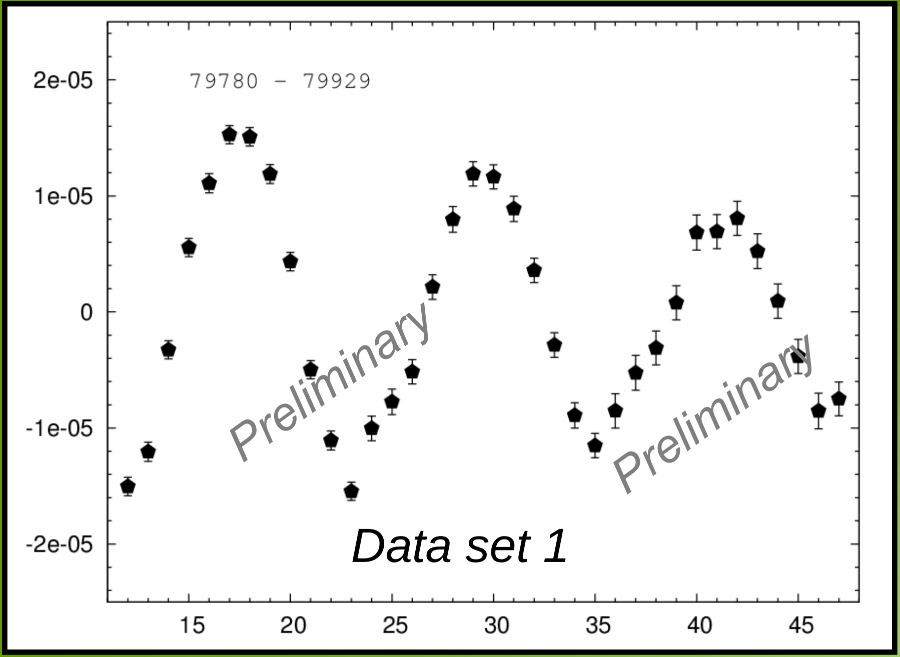
Asymmetry for a detector pair is then given by

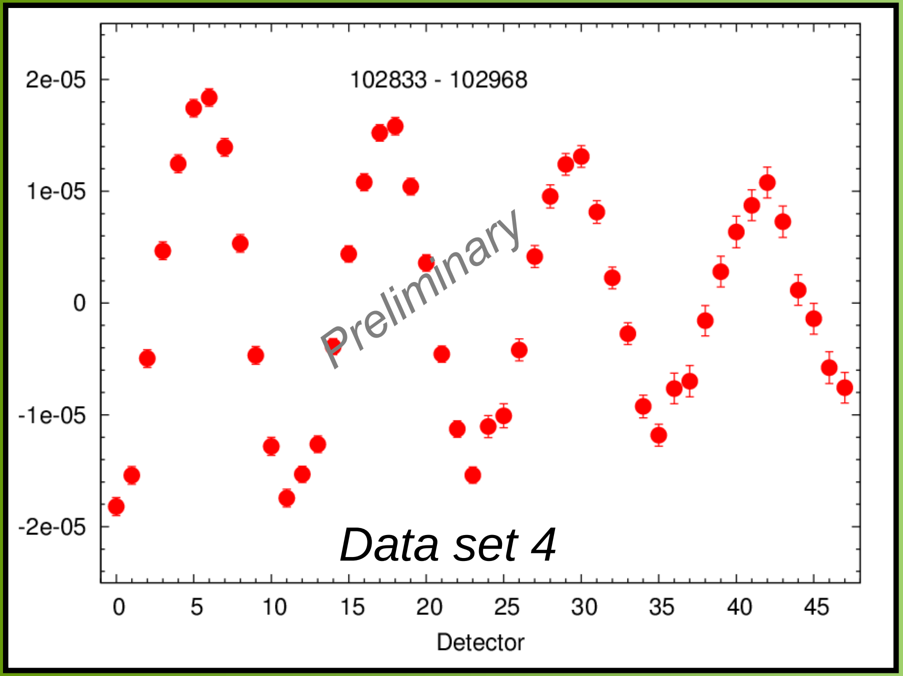
$$A_{raw} = A_{UD} \cdot G_{UD} + A_{LR} \cdot G_{LR}$$

•$\mathbf{A_{UD}}$ is extracted from a fit of $\mathbf{A_{raw}}$ to $\boldsymbol{\theta}$, the angle of detector pair









Chlorine Asymmetry Results

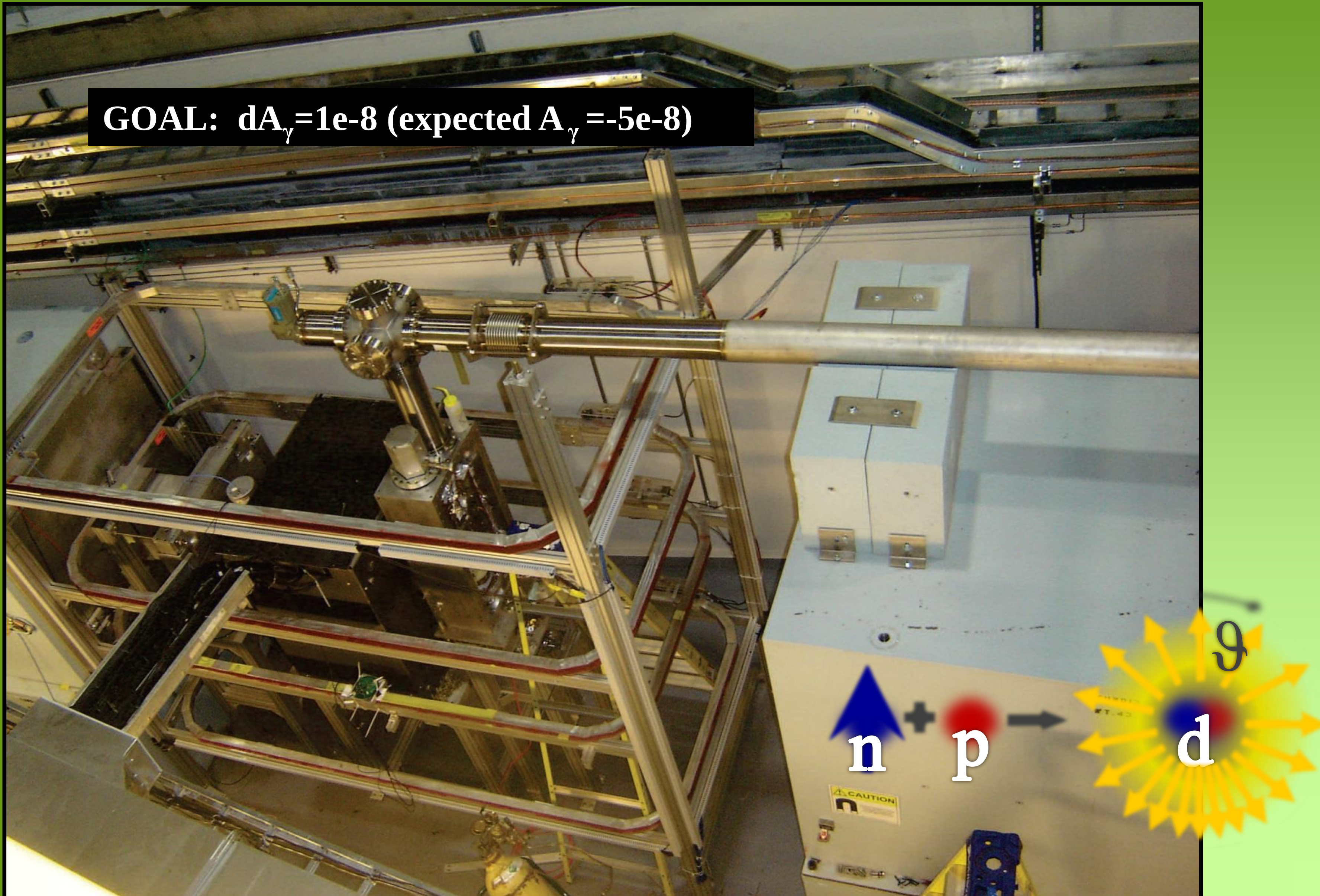
<u>Corrections:</u>

→ Background Subtraction
→ Beam Polarization
→ Beam Depolarization
→ RFSF Efficiency

1% Uncertainty from geometric factors

Measurement	A^{pv} (x10^{-6})
LANL	-29.1 ± 6.7
Leningrad	-27.8 ± 4.9
ILL	-21.2 ± 1.72
SNS (preliminary)	*-25.9 ± 0.6*

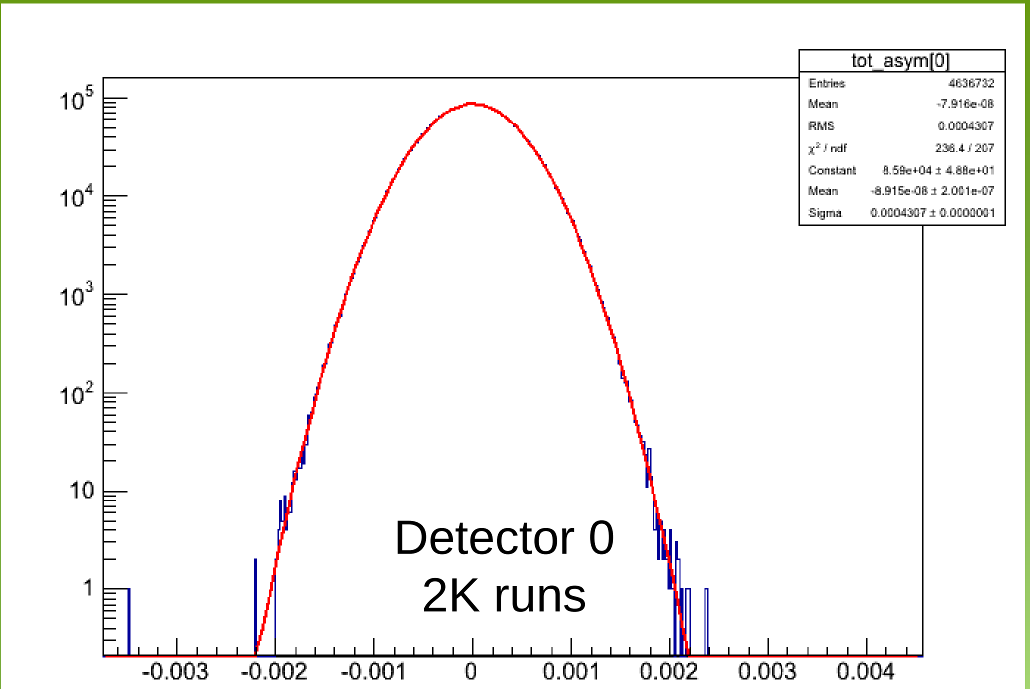
Production Hydrogen Running

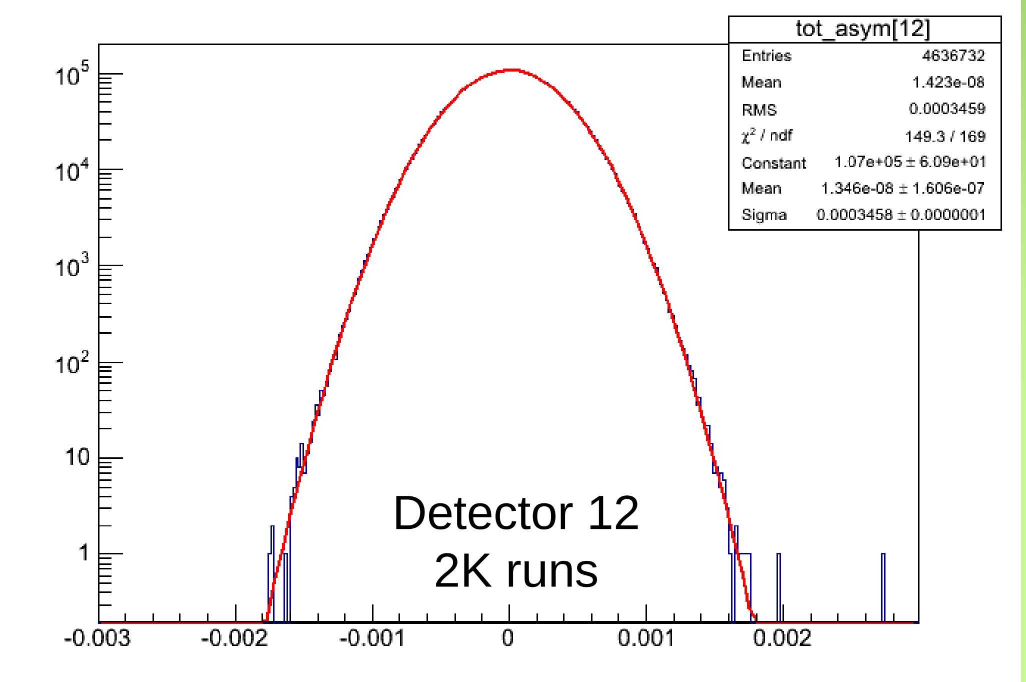


Early

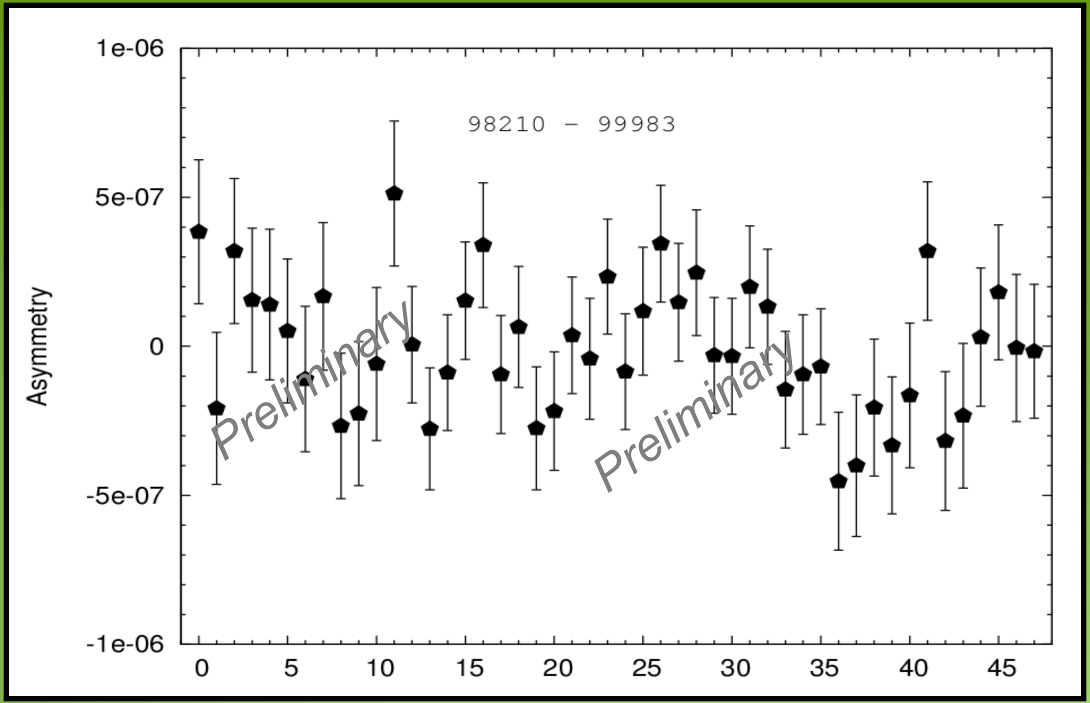
Hydrogen

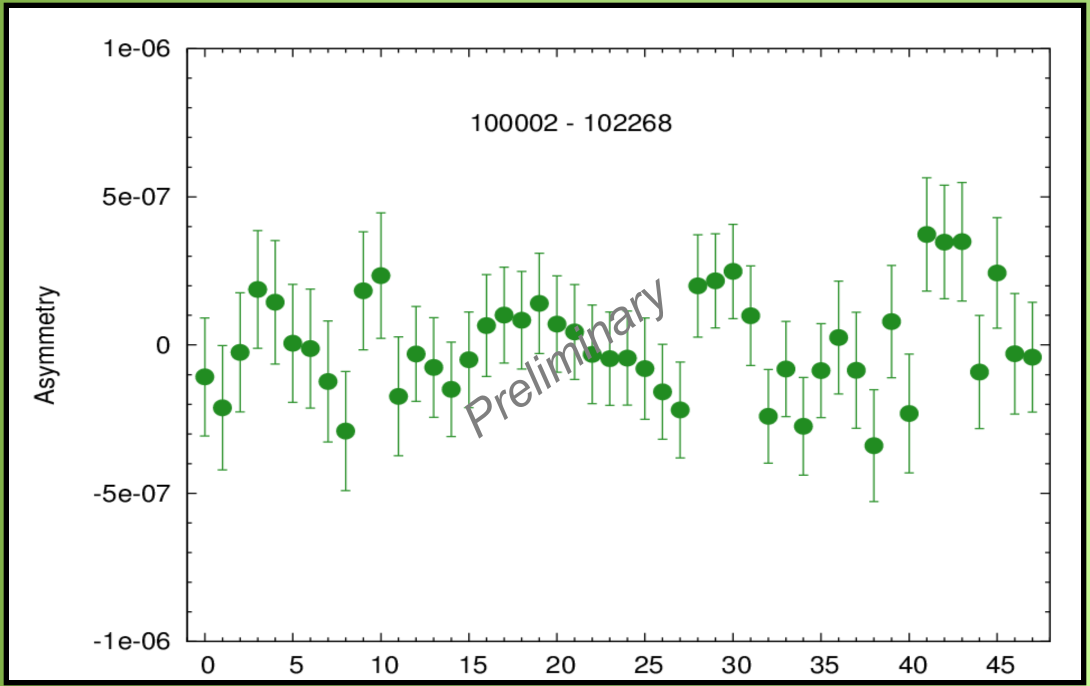
Data





Early Hydrogen Data





Systematic Effects which may cause false Asym	Size
Additive Asymmetry (instrumental)	$< 1 \times 10^{-9}$
Multiplicative Asymmetry (instrumental)	$< 1 \times 10^{-9}$
Stern-Gerlach (steering of the beam)	$< 1 \times 10^{-10}$
γ – ray circular polarization	$< 1 \times 10^{-12}$
β – decay in flight	$< 1 \times 10^{-11}$
Capture on ^{6}Li	$< 1 \times 10^{-11}$
Radiative β –decay	$< 1 \times 10^{-12}$
β - delayed Al gammas (internal + external)	$< 1 \times 10^{-9}$
Uncertainties in applied corrections	
Neutron beam polarization uncertainty	< 2%
RFSF efficiency uncertainty	~ 0.5%
Depolarization of the neutron beam	< 0.5% (target-dependent)
Uncertainty in geometric factors	1%
Polarization of overlap neutrons	0.1%
Target Position	0.03%
Statistical uncertainty in presented results	
Combined hydrogen and aluminum data	$\sim 4.4 \times 10^{-8}$

Preliminary Result

LANSCE 2006

$A_{\gamma,UD}=(-12\pm20\pm2)x10^{-8}$ $A_{\gamma,LR}=(-18\pm21\pm2)x10^{-8}$

SNS 2013

$A_{UD} = (-7.1 \pm 4.4)\ x10^{-8}$ $A_{LR} = (-0.91 \pm 4.3)x10^{-8}$

Data taking is still in progress towards a $dA=1x10^{-8}$ result

Summary

- Fundamental Neutron Physics is an exciting and challenging field with many vital measurements
  - State of the art beta-decay experiments
  - Ambitious nEDM search
  - HWI interaction measurements (NPDGamma and n+^{3}He)
- NPDGamma - Numerous improvements to the experiment will allow for the first measurement of A_γ that will test theoretical predictions
  - NPDGamma will make a $1\text{x}10^{-8}$ (goal) measurement – cleanest f_π measurement
  - Hydrogen production data taking as well as additional systematic effect studies are in progress

The NPDGamma collaboration

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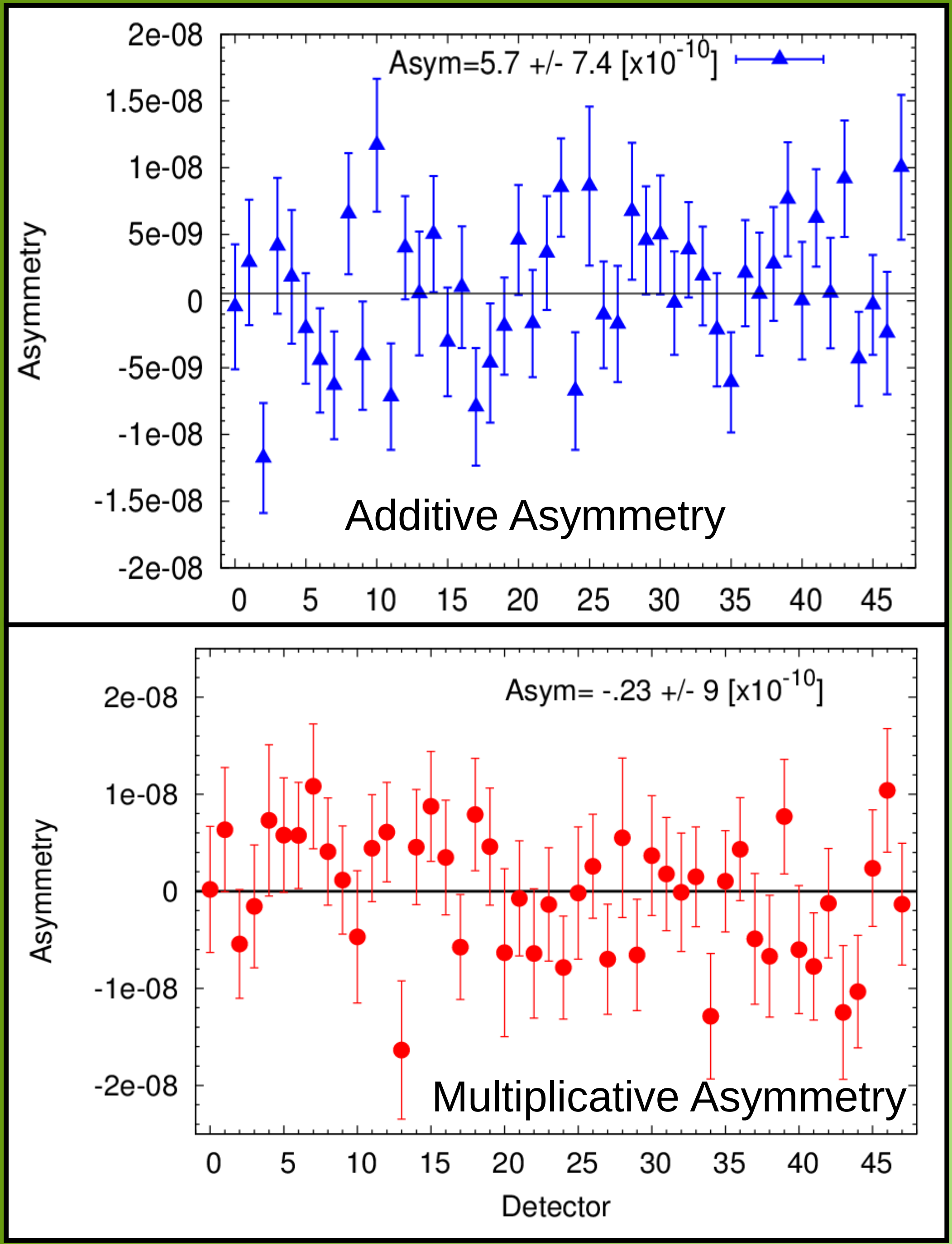
DOE and NSF (USA)
NSERC (CANADA)
CONACYT (MEXICO)
BARC (INDIA)

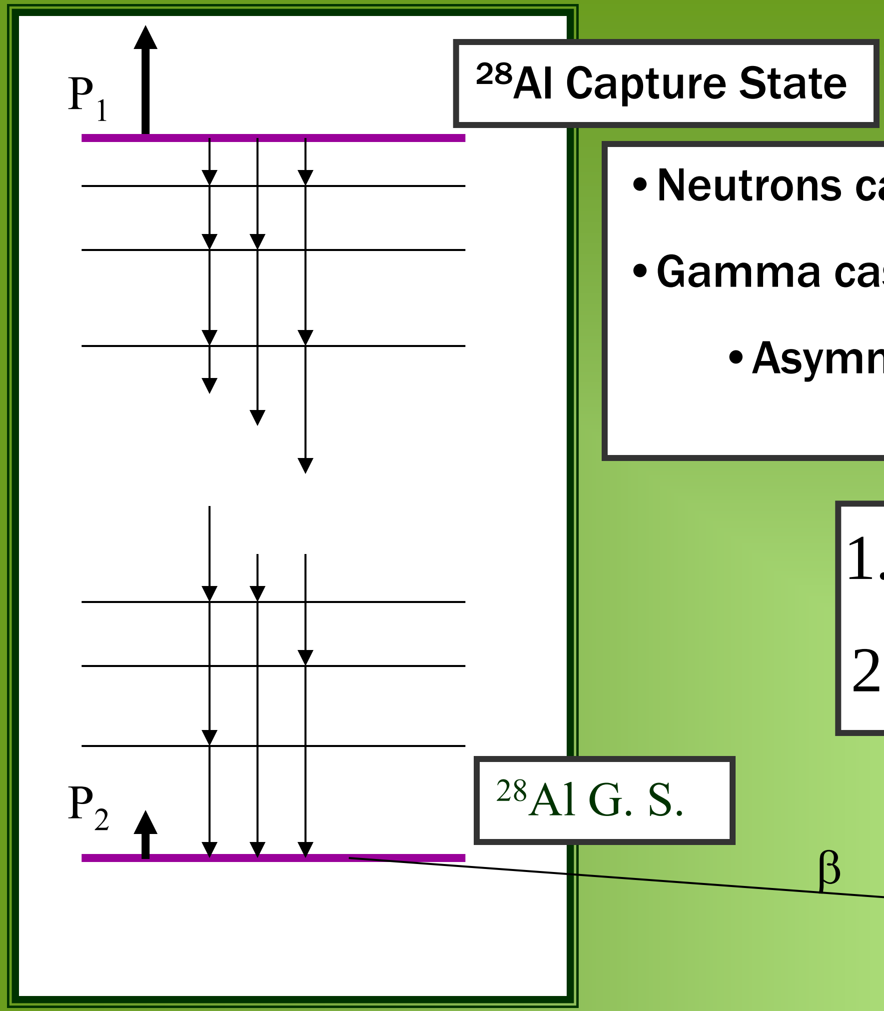
The End



Goal of the experiment: dA_γ = 1e-8

- Any instrumental asymmetries must be consistent with zero at 1e-9

Largest Background for Hydrogen → Aluminum



- Neutrons capture on $^{27}Al \rightarrow {}^{28}Al^*$
- Gamma cascade follows as $^{28}Al^* \rightarrow {}^{28}Al$ (g.s.)
  - Asymmetry correlated with σ_n

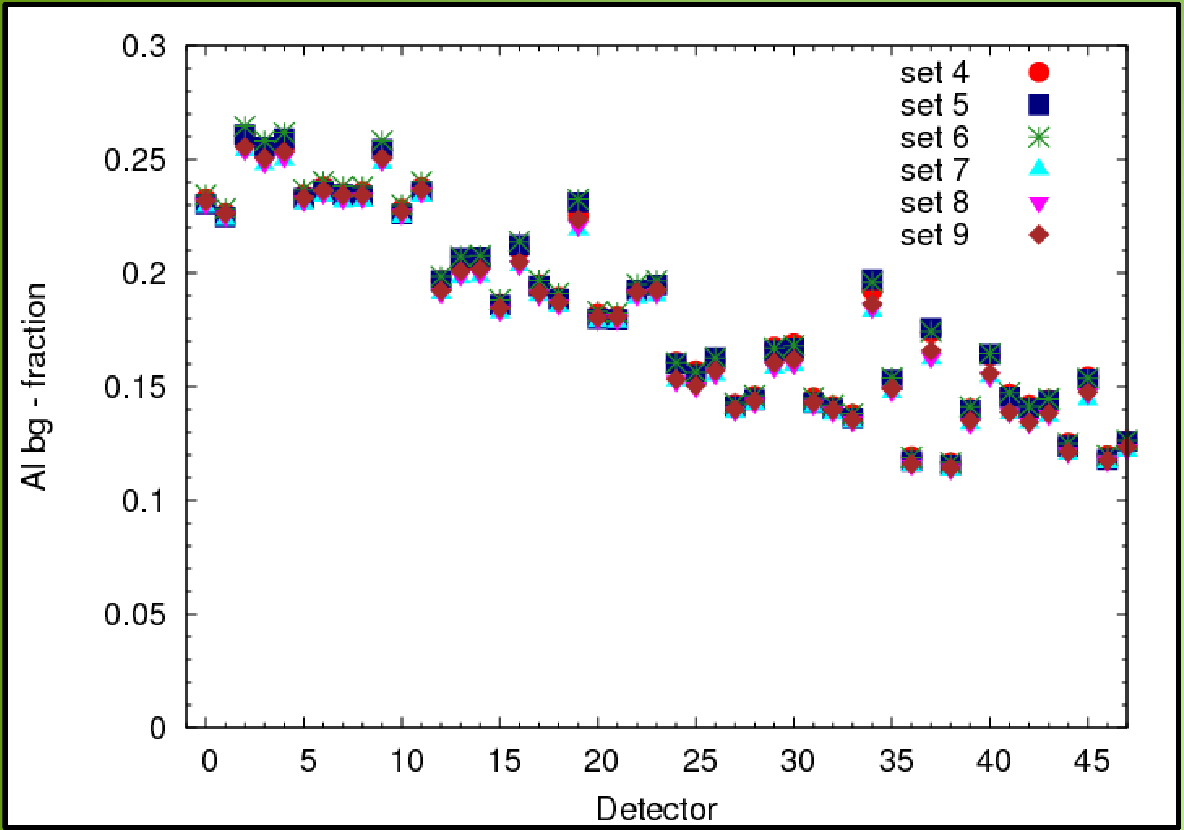
$$1.\quad P_1 \cdot k_\gamma \Rightarrow \sim 1\times10^{-8}$$

$$2.\quad P_2 \cdot k_\beta \Rightarrow \sim 1\times10^{-10}$$

- Fraction that capture in Aluminum – small
- Average over 8-step sequence is also small

Aluminum Target

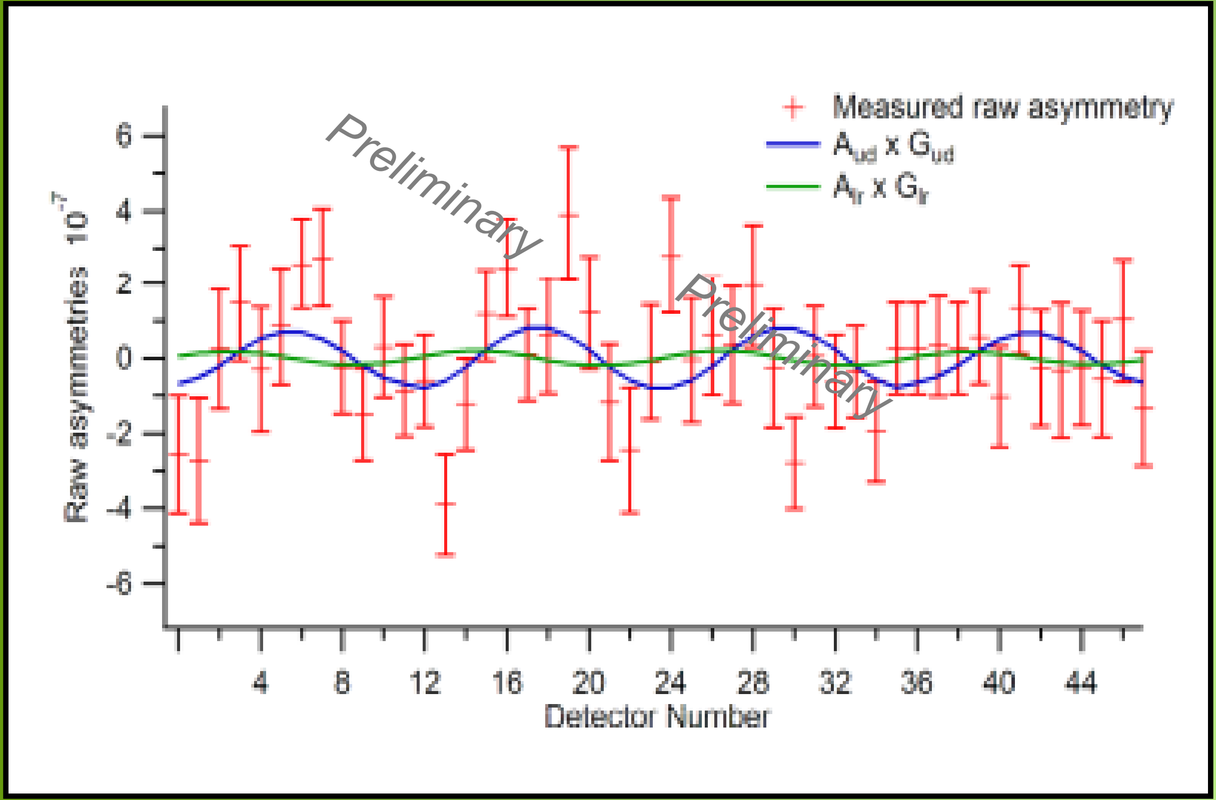
- Largest source of background in NPDGamma
- Need to measure asymmetry to ~3x10^{-8} (for final result)
- Subject of S. Balascuta's PhD thesis.



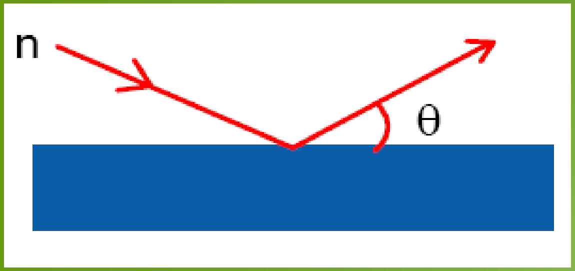
Aluminum contribution to total signal

Aluminum Target

- Largest source of background in NPDGamma
- Need to measure asymmetry to ~3x10^{-8} (for final result)
- Subject of S. Balascuta's PhD thesis.



SuperMirror Polarizer - spin-dependent scattering from a magnetic mirror

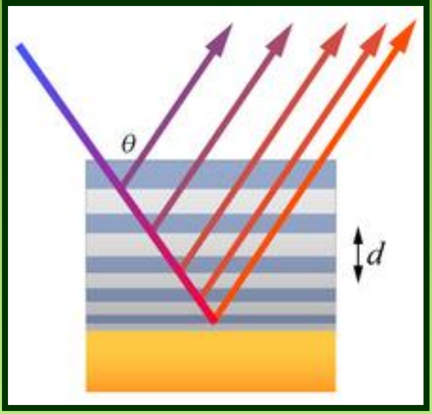


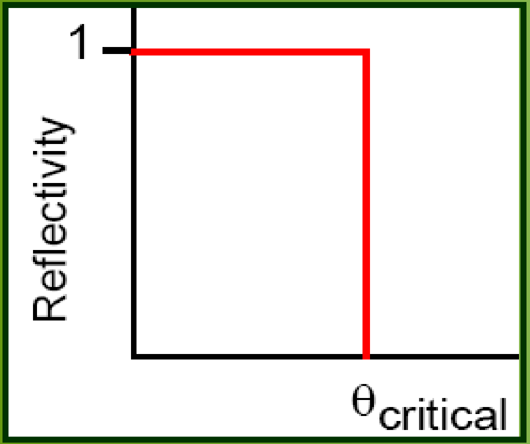
$$n = \sqrt{1 - \frac{V_{eff}}{E}}$$

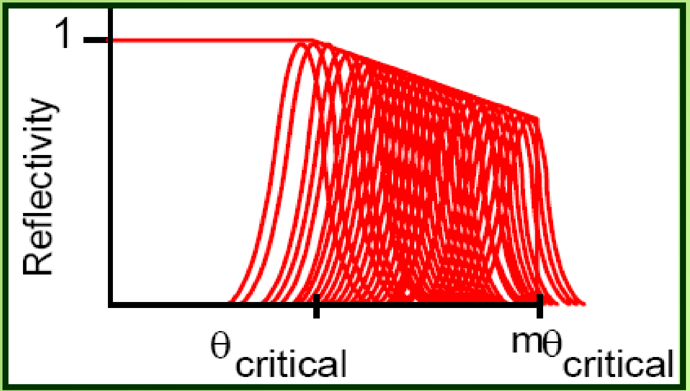
$$\cos\theta_c = n$$

$$V_{eff} = \frac{2\pi\hbar^2}{m} aN \pm \mu \cdot B$$

Multi-layers in a super-mirror act as a crystal; neutrons undergo Bragg diffraction. Varying layer spacing *d* allows multiple Bragg peaks, thus extending the critical angle.







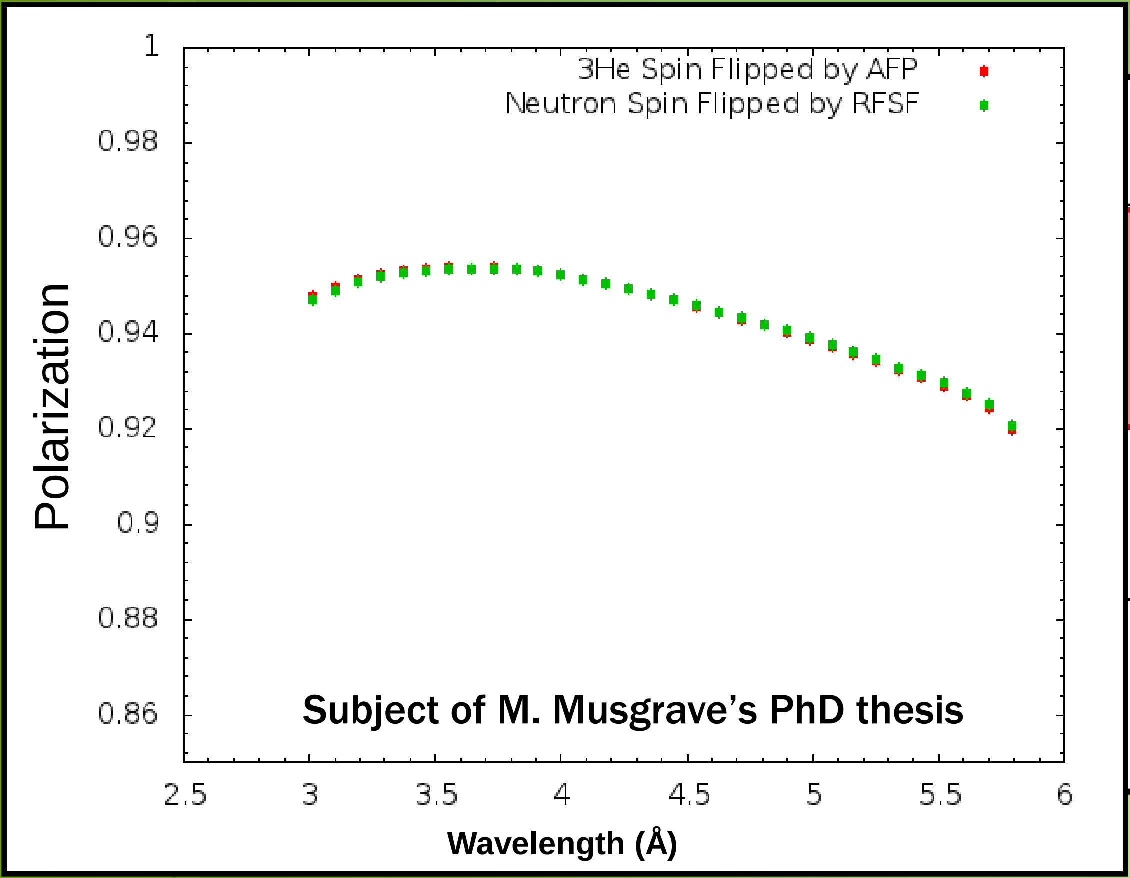
Result from LANSCE run (2006) & Improvements for SNS

$$R_{on} = \frac{T_{on}}{T_0} \qquad R_{off} = \frac{T_{off}}{T_0}$$

$$P_n(\lambda) = \frac{R_{on} - R_{off}}{\sqrt{\left[(2\varepsilon - 1)R_{on} + R_{off}\right]^2 - 4\varepsilon^2}}$$

$A_{\gamma,UD} = (-1.2 \pm 2.0 \pm 0.2) \times 10^{-7}$

$A_{\gamma,LR} = (-1.8 \pm 2.1 \pm 0.2) \times 10^{-7}$



SNS

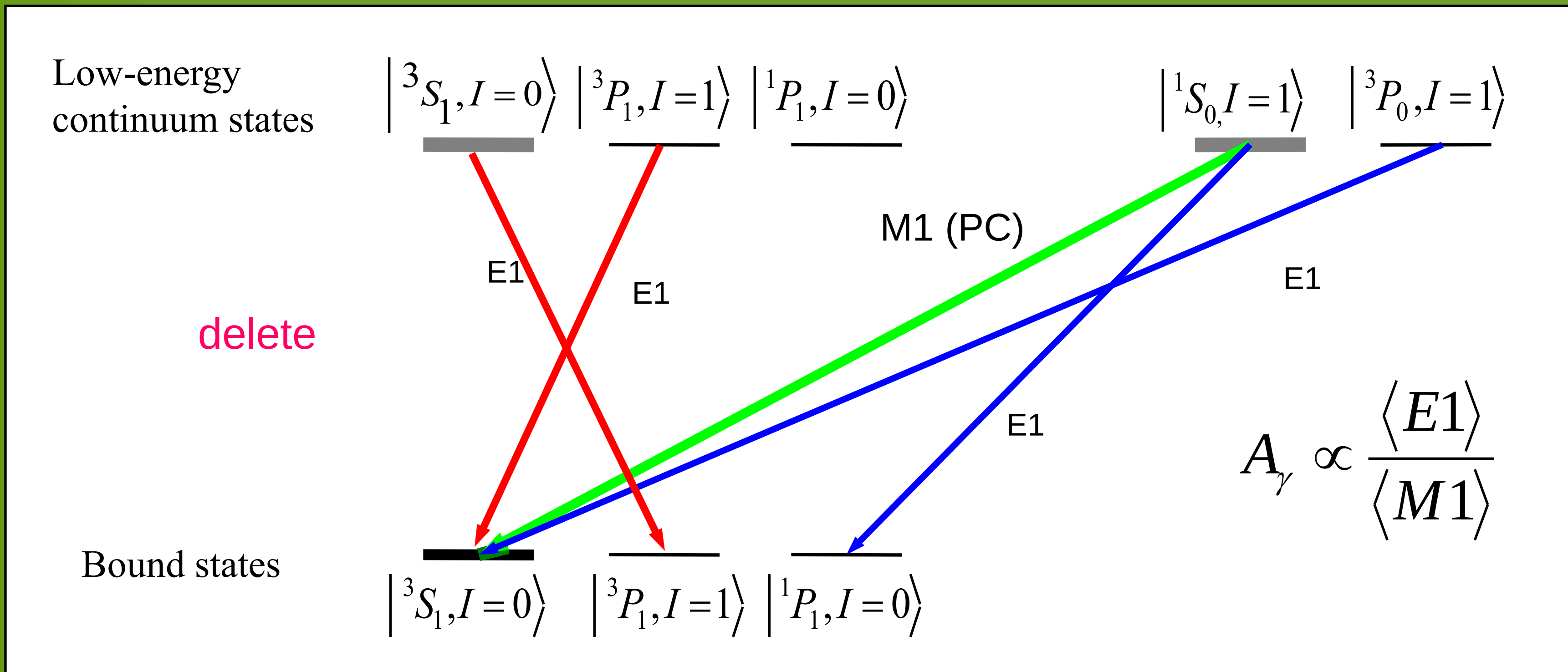
1×10^{-8}

SuperMirror Polarizer (95% NP)

X200 improvement

New and improved, thinner windows

What gives rise to parity violation in $\vec{n} + p \Rightarrow d + \gamma$?



$\vec{n} + p \rightarrow d + \gamma$ is primarily sensitive to the $\Delta I = 1$ component of the weak interaction

$$^1S_0 \rightarrow {}^3P_0 \quad (\Delta I = 0,1,2)$$

$$^3S_1 \rightarrow {}^1P_1 \quad (\Delta I = 0)$$

$$^3S_1 \rightarrow {}^3P_1 \quad (\Delta I = 1)$$

← π exchange