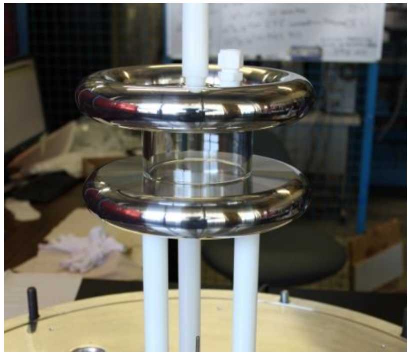
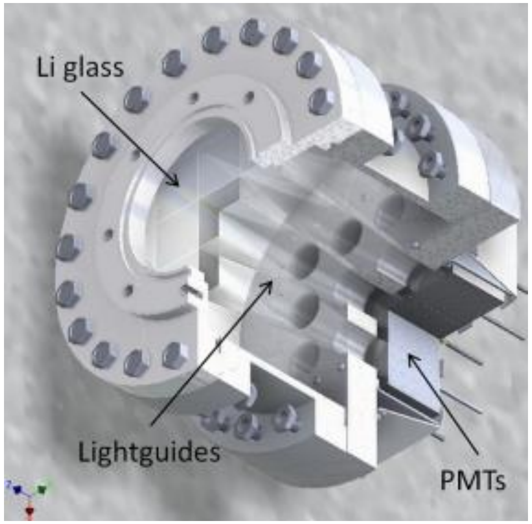
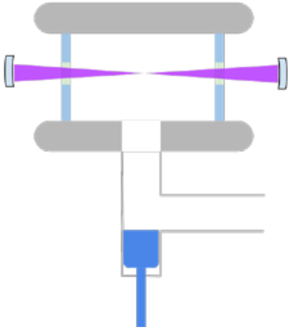
# Testing Fundamental Symmetries with the Next Generation Ultracold Neutron Source at TRIUMF

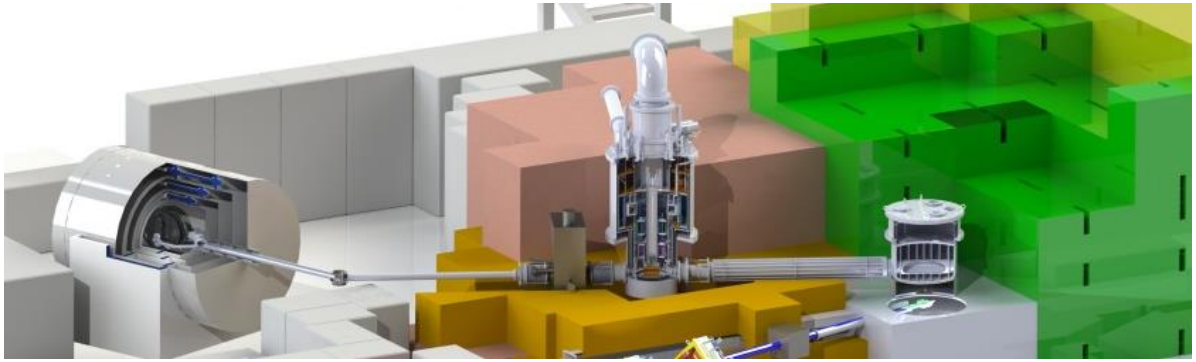


**Russell Mammei**

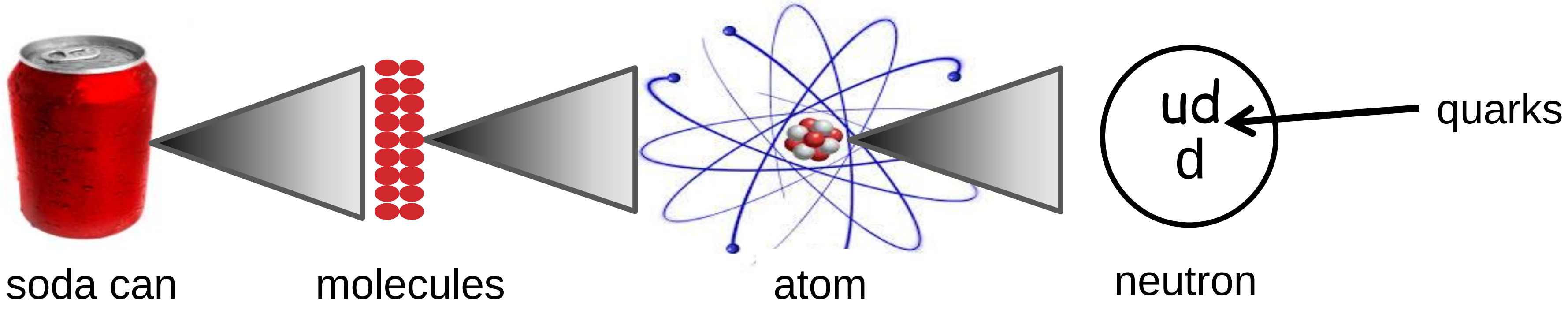
**The University of Winnipeg**

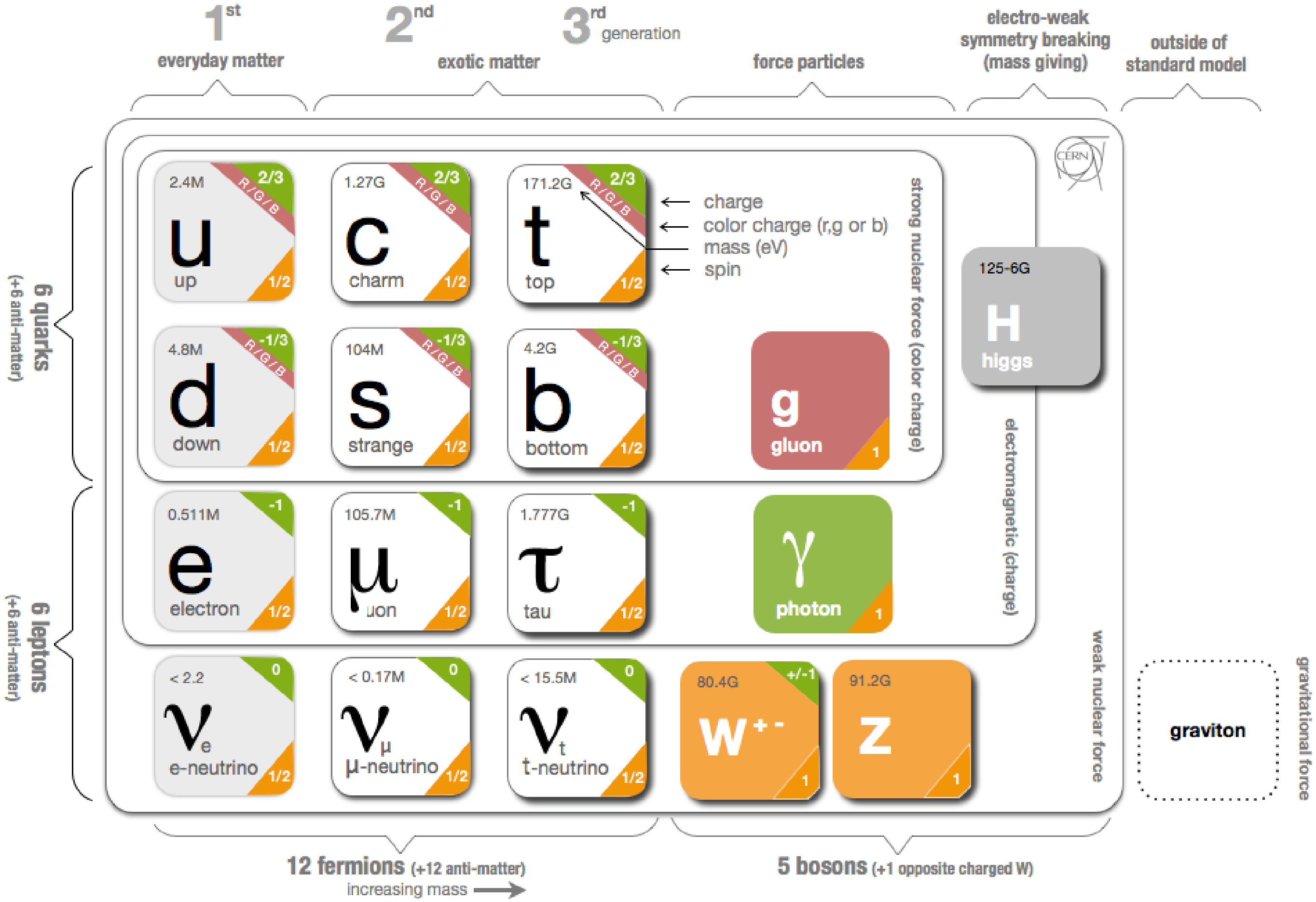






# THE STANDARD MODEL (SM)





Infographic from CERN's 2012 WEBFEST
http://cds.cern.ch/journal/CERNBulletin/2012/35/News%20Articles/1473657

# DISCRETE SYMMETRIES

Continuous Symmetries:

- Translation in space → momentum conservation
- Translation in time → energy conservation
- Rotation → angular momentum conservation

Discrete Symmetries:

- Spatial Inversion (P) → P-invariance (parity)
- Charge Conjugation (C) → C-invariance
- Time reversal (T) → T-invariance

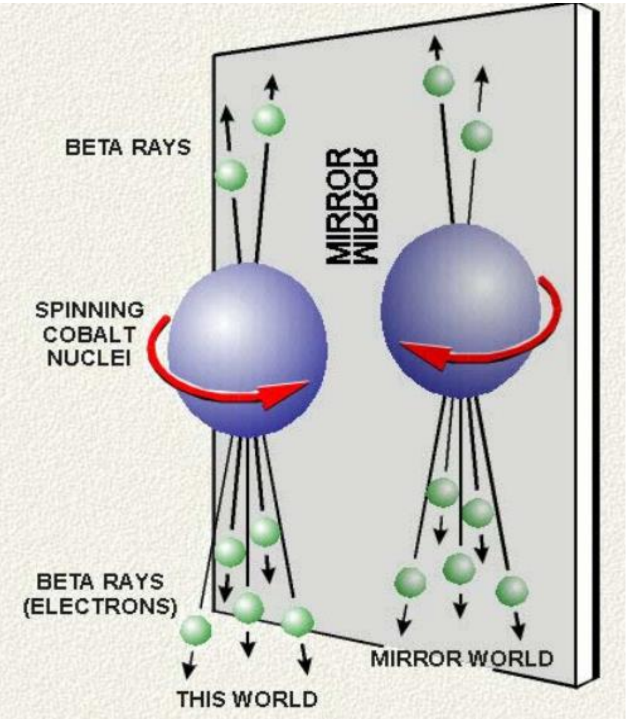
But Wait…

- Parity violation discovered in 1950s
- Charge parity (CP) violation discovered in 1960s
  - kaon sector (1964, 1990s)
  - B meson sector  (2000's)

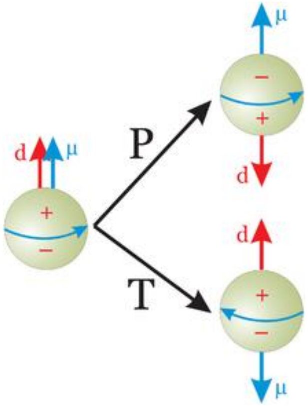
    See. D. London's talk Thursday

A neutron electric dipole moment would be a violation of both parity and time reversal invariance

CPT still thought to be not violated ("good symmetry")

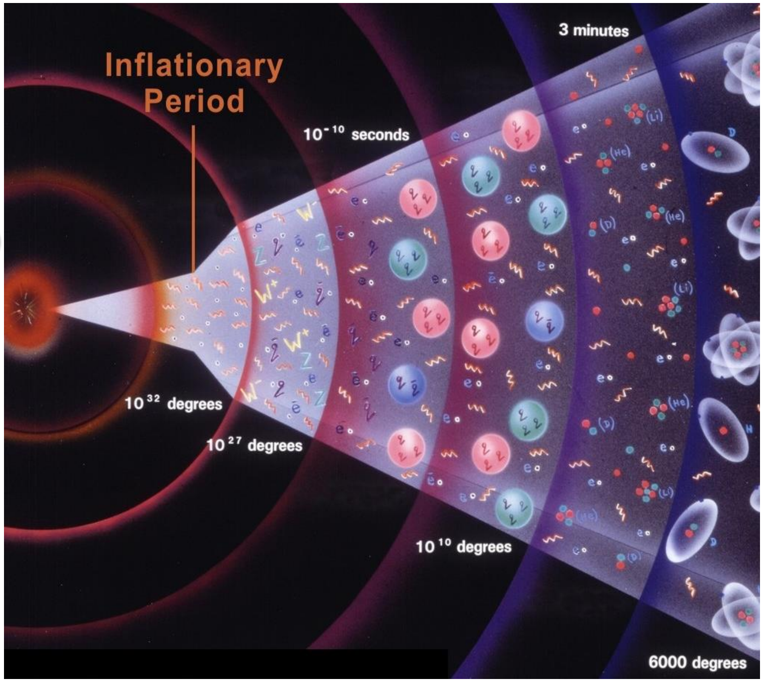


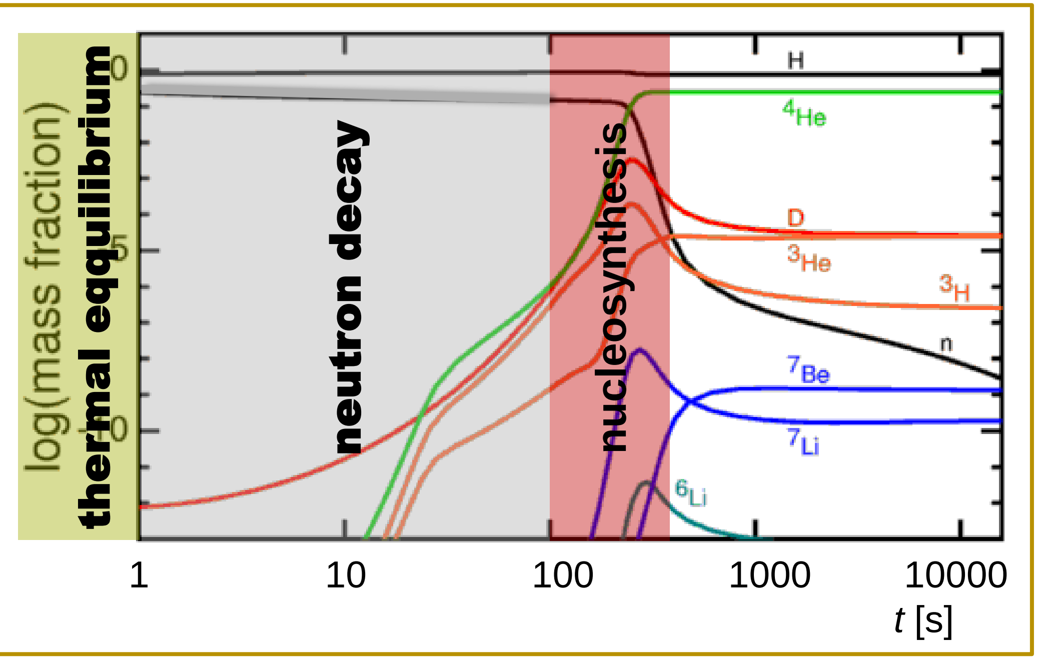
parity (P) violation in $\beta$-decay (Madam Wu, 1957)



# THE BIG QUESTIONS

1. **Baryon asymmetry of the universe**
   Sakarov Criteria
   EW Baryogenesis (Sphalerons) ✓
   Departure from thermal equilibrium ✓
   CP violation –need more **nEDM would help**
2. **Number of quark flavors/generations**
   (CKM unitarity) **Neutron Decay**
3. **Predictions of elemental abundances in the universe**
4. **Testing Short-range Gravitation Interactions**





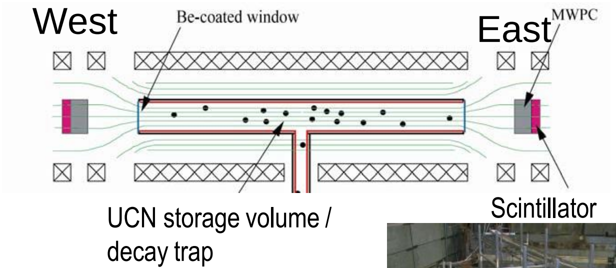
CKM Matrix

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

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

# UCN EXPERIMENTS

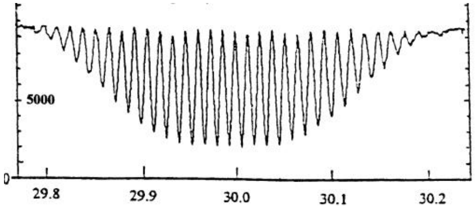
## Neutron decay correlations



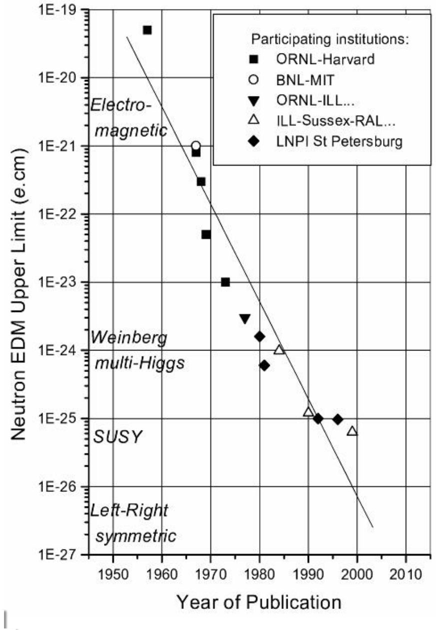
$$A = -2\frac{|\lambda|^2 + \Re(\lambda)}{1+3|\lambda|^2}$$

UCNA @ LANL

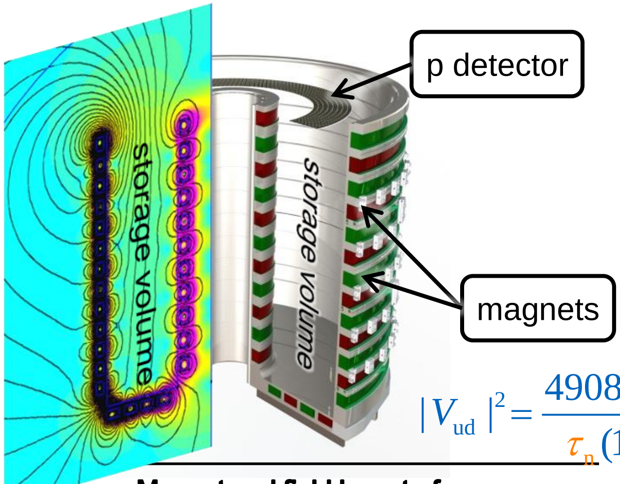
## Electric dipole moment



RAL Sussex EDM @ ILL



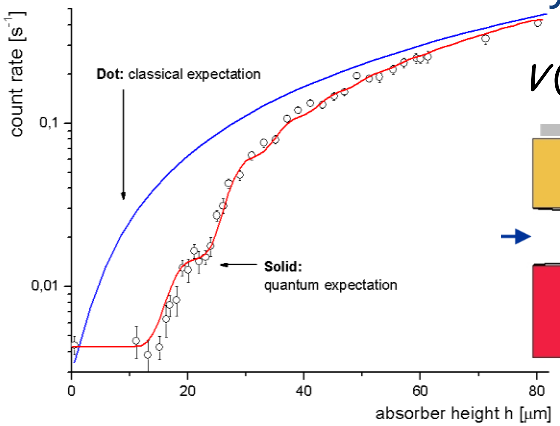
## Neutron lifetime



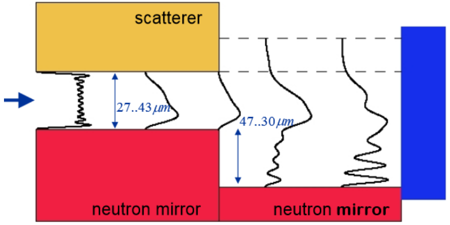
$$|V_{ud}|^2 = \frac{4908.7(1.9)\ \mathrm{s}}{\tau_n(1+3\lambda^2)}$$

**Magnet and field layout of PENeLOPE**

## Gravity



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



# ULTRACOLD NEUTRONS (UCN)

Neutrons moving so slowly that they bounce off surfaces and can be bottled.

$$v < 8\ m/s = 30\,km/hr$$
$$KE < 300\,neV$$
$$\lambda > 50\,nm$$

## Interactions

- **Strong interaction**

  long wavelength samples over many atoms in materials

  $\Rightarrow$ average Fermi potential, total reflection

- **Electromagnetic Interaction** $V_m = -\mu \cdot B = \pm 60\,neV\ per\ Tesla$

  We can make beam beam of 100% polarized UCN !!!

- **Gravity** $V_g = mgh \approx 100\,neV\ per\ meter$

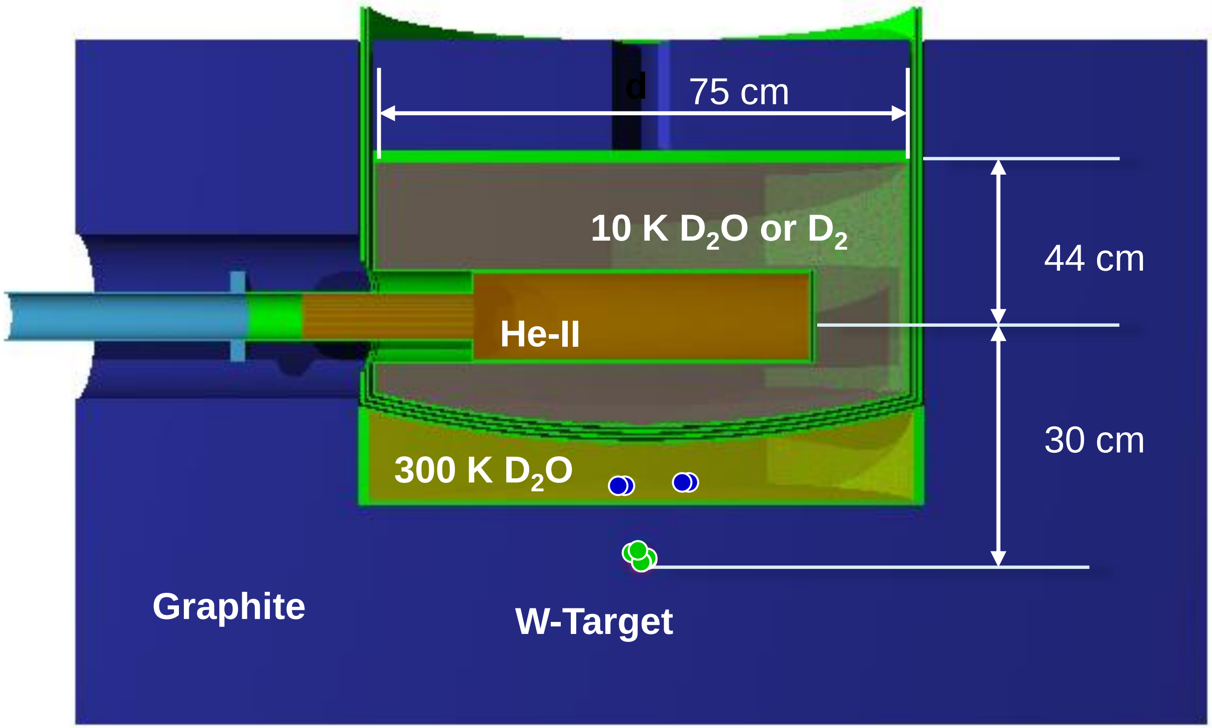
- **Weak Interaction**

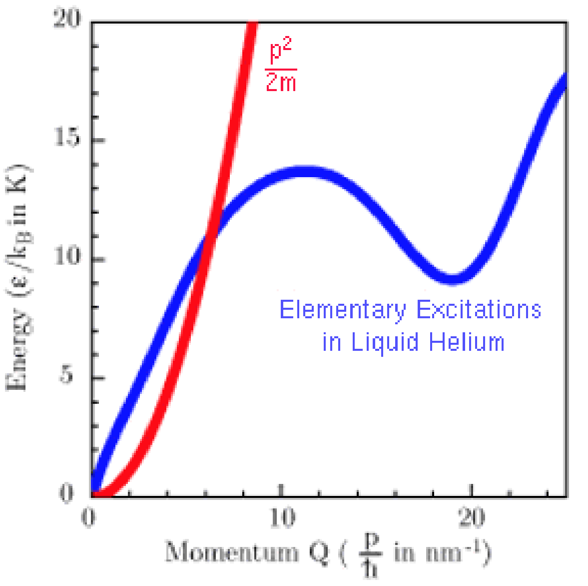
  $\beta$-decay $n \rightarrow p + e + \bar{\nu}_e, 728\,keV\ \ liftime\ \sim 15min$

**Can store/transport UCN on times comparable to lifetime**

# HOW DO WE MAKE UCN AT TRIUMF?

- Spallation –Free the neutrons from W target
- Moderation –Cool the neutrons in $D_2$/$D_2$0
- Conversion –Really cool the neutrons in He-II





**MeV neutrons**

**(ultra-)cold neutrons**

**Spallation target, thermal and cold moderator and He-II converter**

Technology developed at RCNP Osaka

**480 MeV protons**

# TRIUMF UCN HISTORY SO FAR

2006: UCN project was first introduced into the TRIUMF 5Y planning

2007: International Workshop UCN sources and Experiments at TRIUMF

2008: Positive review by TRIUMF's Experiments Evaluation Committee (EEC)

2009: **CFI-NIF Award for UCN Source**

2010: International Review endorses UCN program strongly

2011: MoU between Uwpg, KEK, RCNP and TRIUMF was signed…

- to build a He-II spallation source at KEK/RCNP and move it to TRIUMF
- to develop and conduct a neutron EDM experiment
- to build a dedicated beam line and target at TRIUMF

2011-2013: development of beam line in Meson hall

- Kicker, septum, bender, focusing elements, diagnostics, target
- Shielding upgrade
- clean-up of Meson hall

2012 Two new hires in Winnipeg that work on UCN

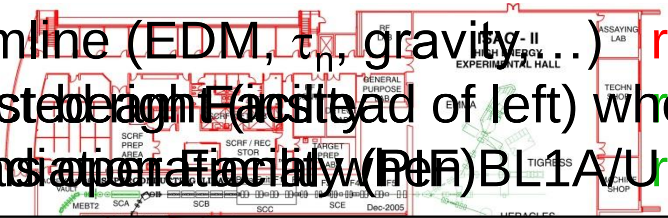
2013: TRIUMF hires are research scientist for UCN

2014: First substantial installations occurred this spring

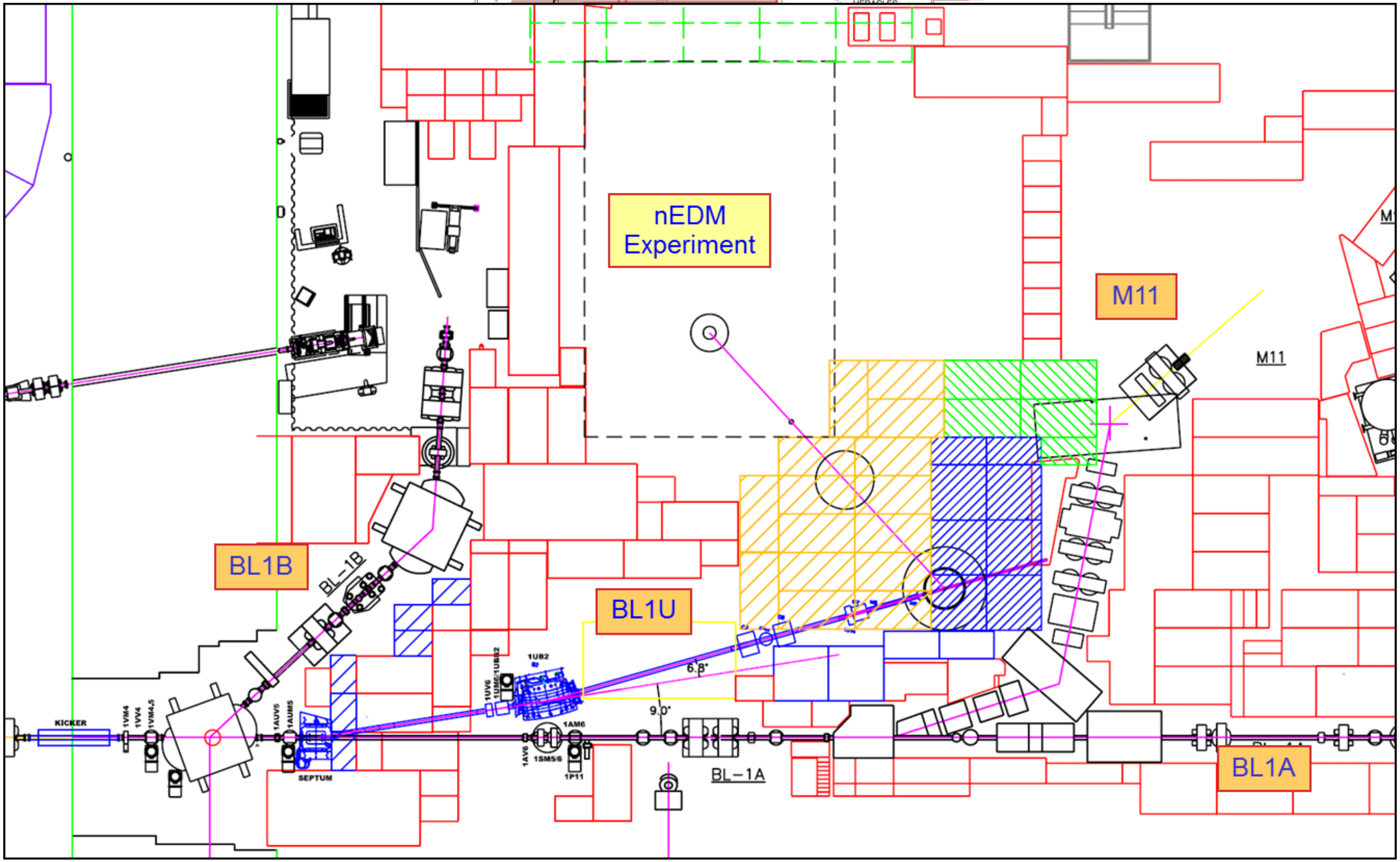
**Seeking CFI-IF for nEDM experiment, 2$^{nd}$ experiment port, & my coating facility**

# UCN FACILITY AT TRIUMF: MESON HALL

**BEAM LINES AND EXPERIMENTAL FACILITIES**



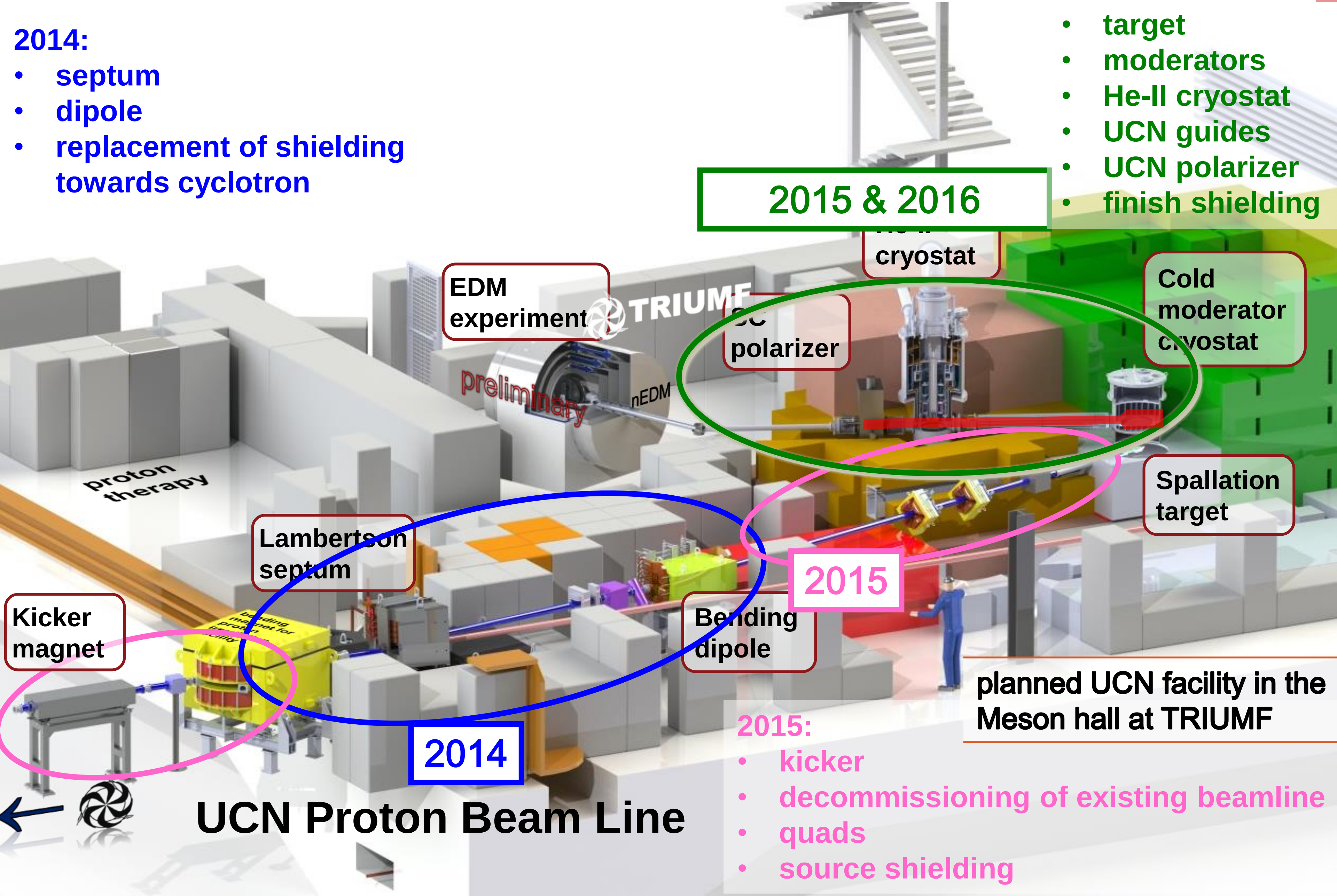
- ♦ BL1U: UCN Beamline (EDM, $\tau_n$, gravity…)
- ♦ M13 removed
- ♦ M11: Detector Test Beam Facility
- ♦ M11: Beam deflected right (instead of left) when space needed reconfigured
- ♦ BL1B: Proton Irradiation Facility (PIF)
- ♦ BL1B/PIF: remain operational when BL1A/U off (Cyc. cooldown) remains



# INSTALLATION SCHEDULE

**2014:**
- septum
- dipole
- replacement of shielding towards cyclotron

**2015/16:**
- target
- moderators
- He-II cryostat
- UCN guides
- UCN polarizer
- finish shielding

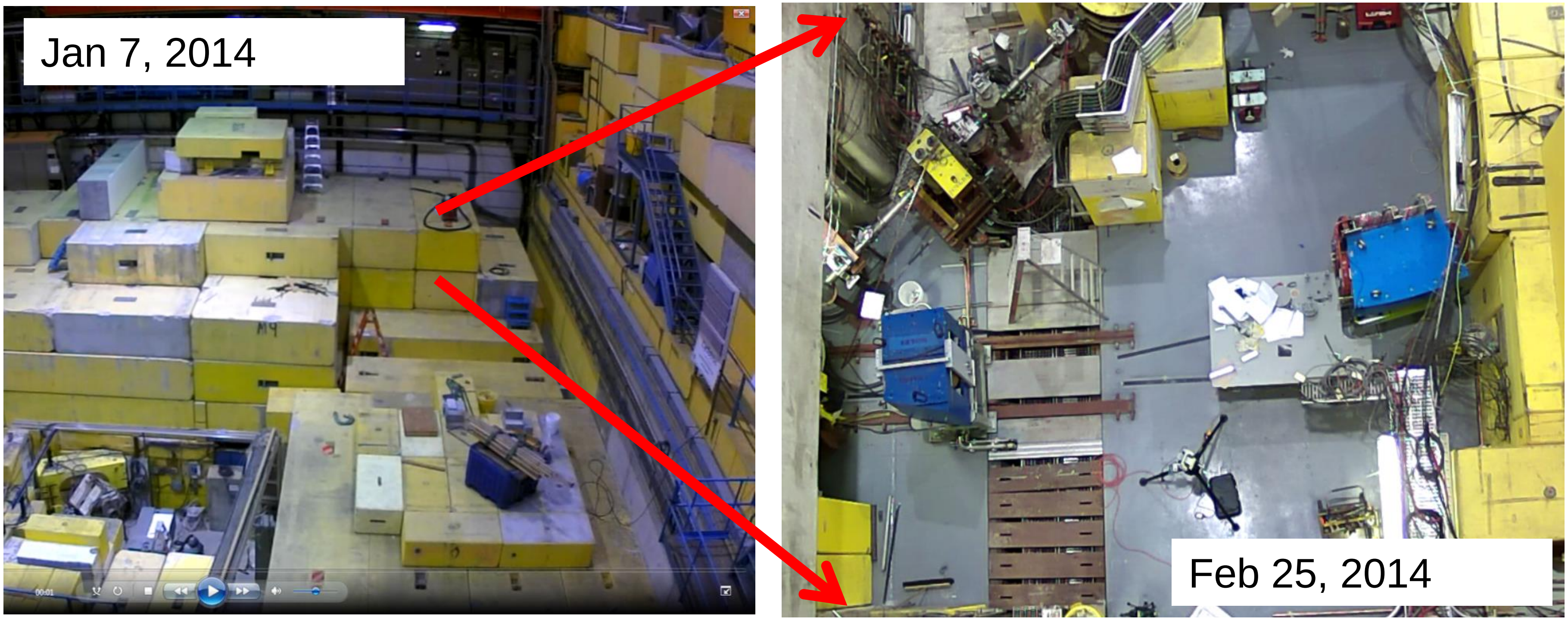


planned UCN facility in the Meson hall at TRIUMF

**2015:**
- kicker
- decommissioning of existing beamline
- quads
- source shielding

UCN Proton Beam Line

# 2014 INSTALLATION



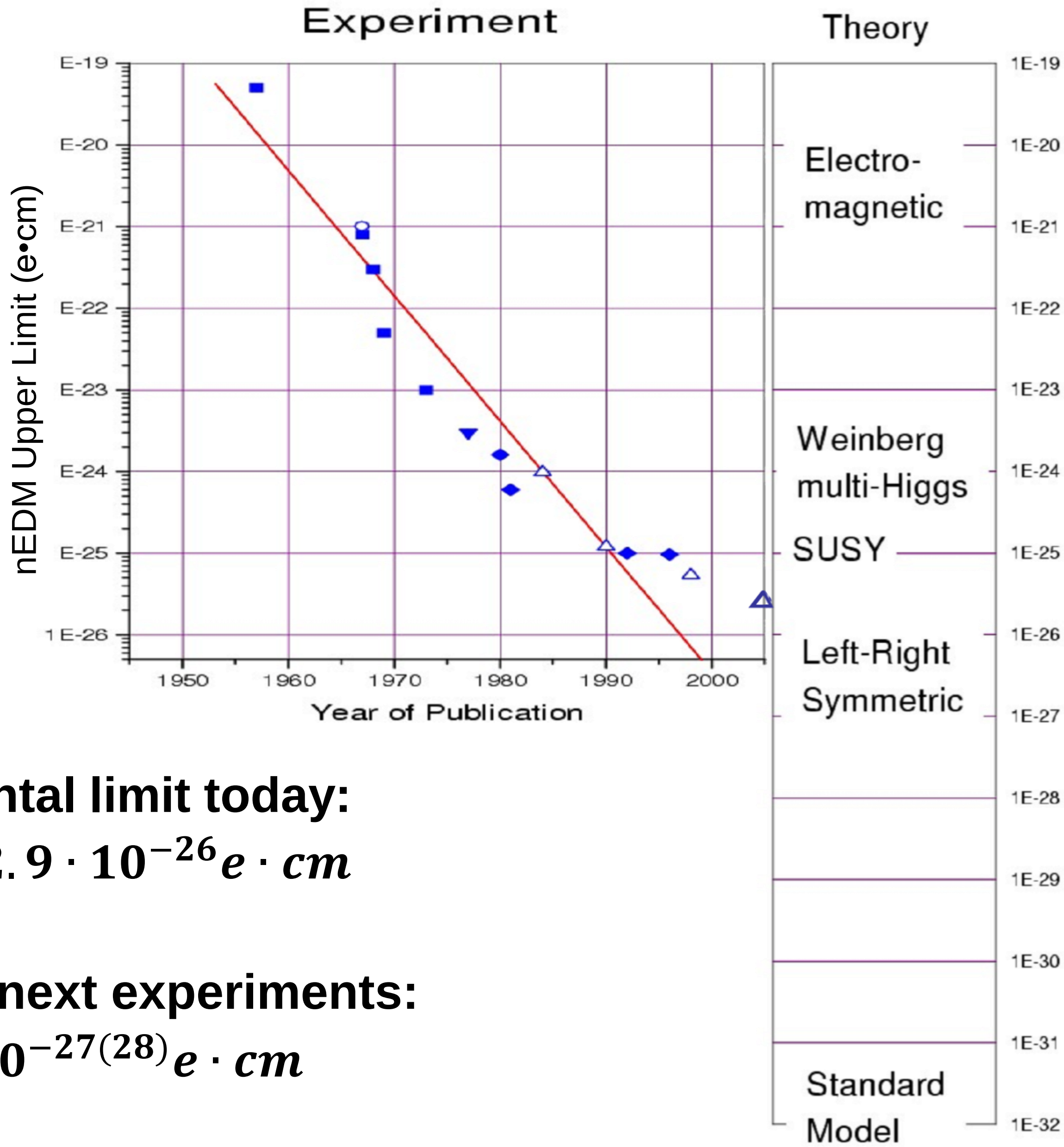
**Primary goals for 2014 installation met**

- ✓ Reconfigure Cyclotron shielding (Shield-Plug)
- ✓ Septum subsystem (1AM5: vacuum vessel only)
- ✓ Rough-in (trench) services
- ✓ BL1U → UCN-Dipole, girder, reconfiguration of BL1A

**"Best Efforts" goals 90-95 %**

- ✓ Rough-in (non-trench) services
- Complete services
- BL1U girder components

# SEARCH FOR THE NEUTRON ELECTRIC DIPOLE MOMENT



**Experimental limit today:**

$$d_n < 2.9 \cdot 10^{-26} e \cdot cm$$

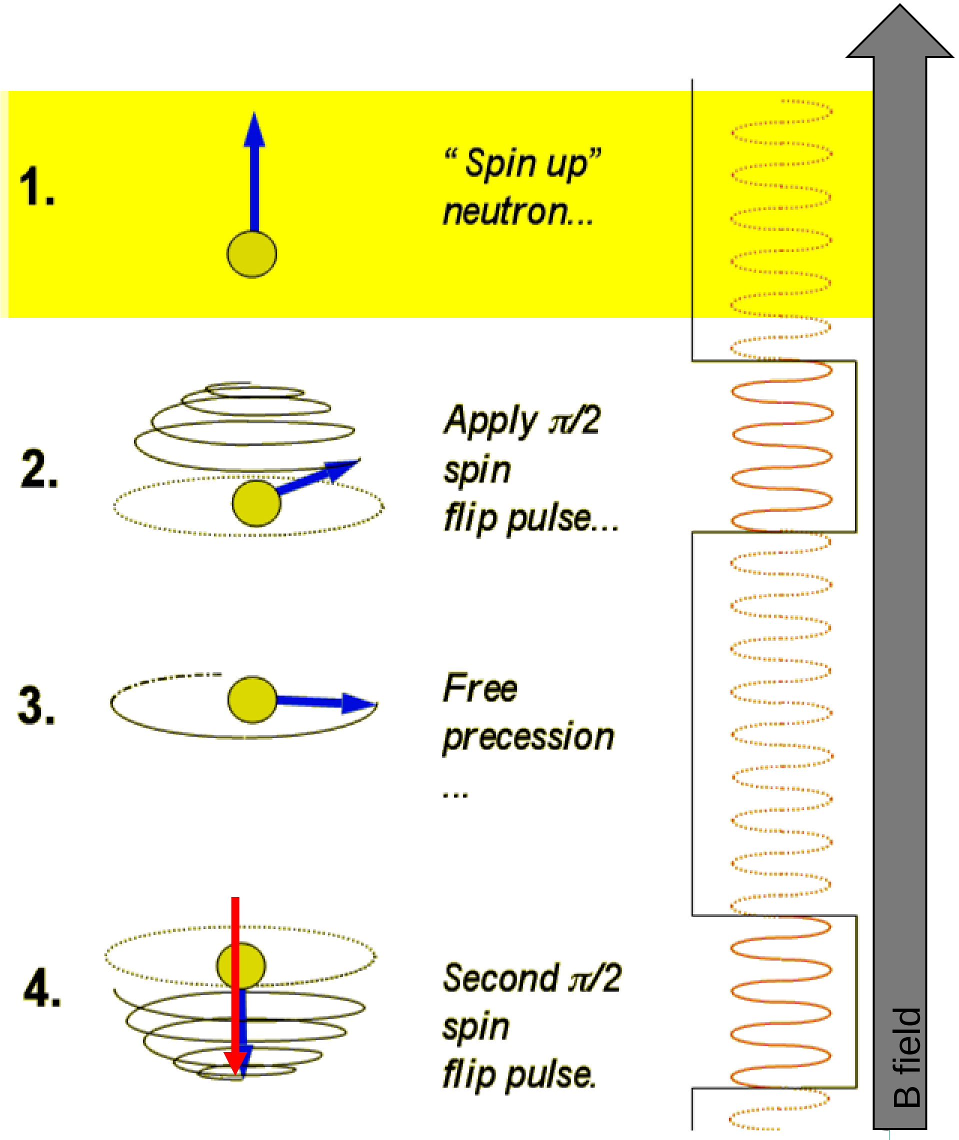
**Goals for next experiments:**

$$d_n < 10^{-27(28)} e \cdot cm$$

# nEDM EXPERIMENTAL SITES

# RAMSEY'S METHOD

1. prepare a sample of polarized neutrons
2. make a $\pi/2$ spin flip ("start clock")
3. allow free spin precession in (anti-)parallel ***B*** and ***E*** static fields
4. make a $\pi/2$ spin flip ("stop clock")
5. analyze direction of neutron spin

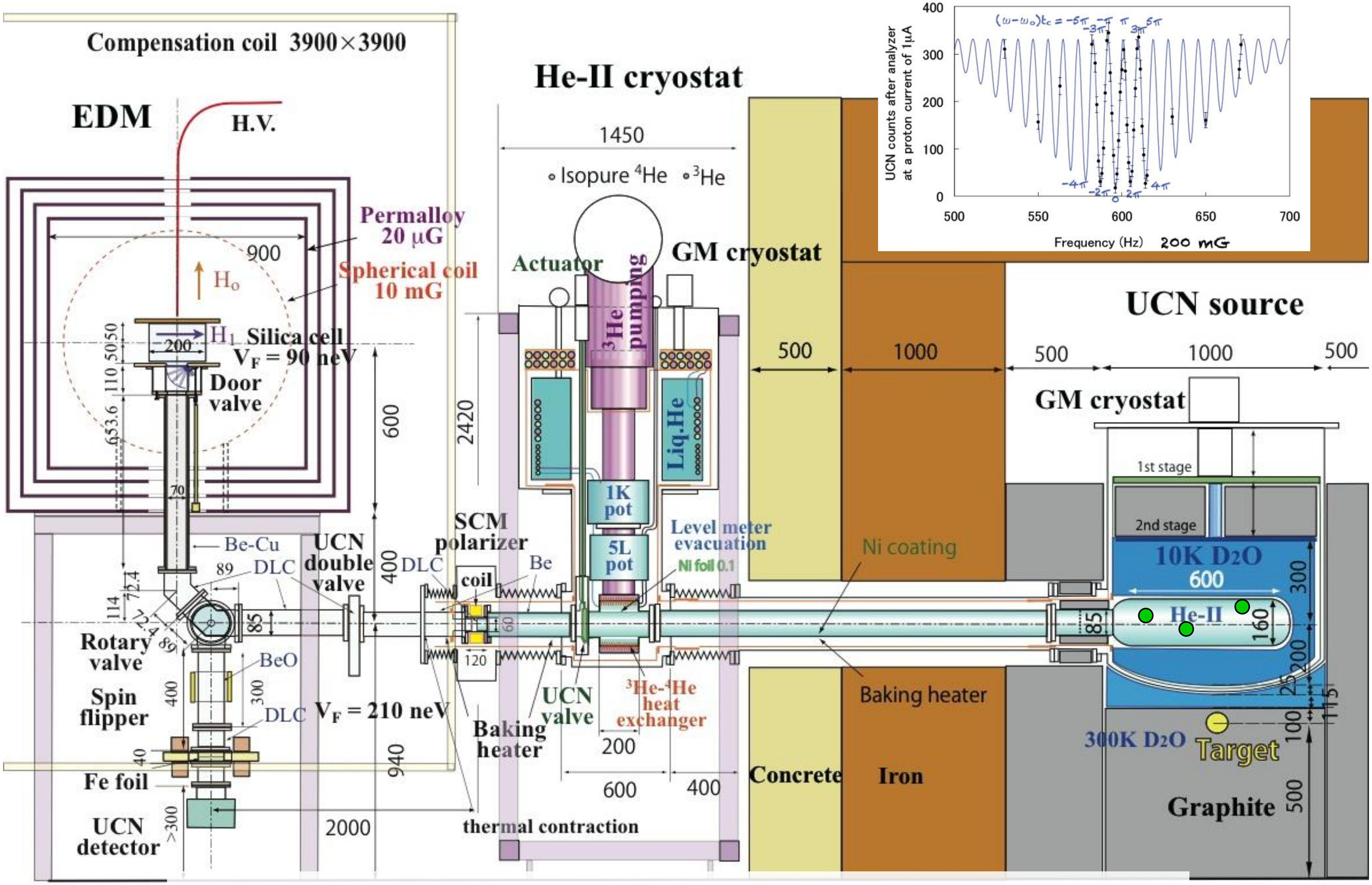


look at energy (frequency) shift under Electric field inversion:

$$\Delta\varepsilon = h\,|\Delta\nu| = 4Ed_n$$

N. F. Ramsey, Phys.Rev.**76** 996 (1949)

# THE EXPERIMENT



Look at energy (frequency) shift under E field inversion:

$\Delta\varepsilon = h\,|\Delta\nu| = 4Ed_n$

# ERROR BUDGET

Best nEDM limit so far is 2.9 ·$10^{-26}$ e·cm (ILL/RAL/SUSSEX)

## EDM statistical sensitivity:

$$\sigma_\mathrm{d} = \frac{\hbar}{2\alpha E T\sqrt{N}}$$

$\alpha$: visibility
E: electric field
T: observation time
N: # of neutrons

ultra-cold neutrons are:
…totally reflected*
$\Rightarrow$ long observation time *T*
…enough from our new source
$\Rightarrow$ sufficient statistics $\sqrt{N}$
…polarizable to 100%
$\Rightarrow$ good visibility $\alpha$

Expect in one year

$$\sigma_\mathrm{d} \sim 10^{-27}\ e \cdot cm$$

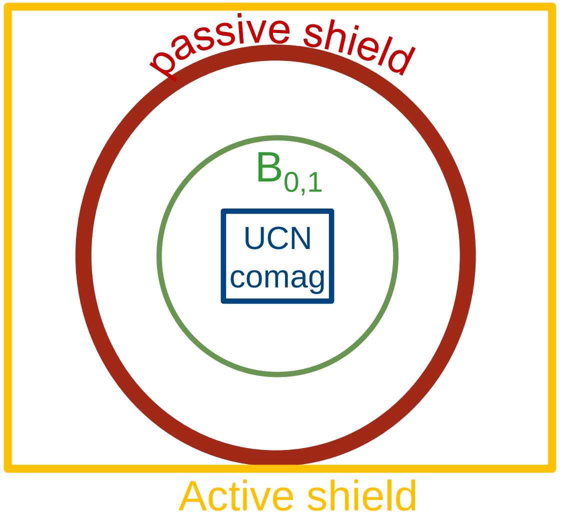
*by suitable materials under all angles of incidence

## Systematics Errors are Key

Biggest Error due in-homogeneities in the magnetic field (GPE effect)

Requirements for $10^{-27}$ e•cm

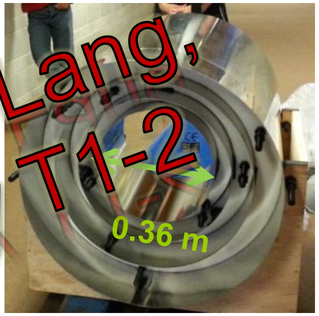
- $B_0 \sim 1\ \mu T$
- Homogeneity < nT/m
  $\Rightarrow$ < 100 pT across the cell
- Stability controlled to < pT



# CANADIAN EDM R&D

## Magnetic environment

- active shielding
- passive shielding
- creation of stable and homogeneous B fields
- magnetometry



**Cylindrical shells of the 4 layer passive shield**

talk by M. Lang, Tuesday T1-2

**Univ. Winnipeg**

## UCN detection

n+$^6$Li → $^3$H (2.74 MeV) +$^4$He (2.05 MeV)

- conventional $^3$He detectors too slow
- high rate capability
- Li glass scintillators + lightguide + PMTs

talk by L. Rebenitsch Tuesday T1-2

**Univ. Winnipeg, Univ. Manitoba, TRIUMF**

## Dual Co-magnetometer

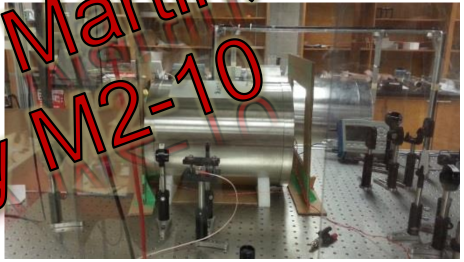
| | $^{199}$Hg | **$^{129}$Xe** | *n* |
|---|---|---|---|
| Spin | ½ | **½** | ½ |
| $\gamma$(MHz/T) | 7.65 | **-11.77** | -29.16 |
| UCN capt. σ (barns) | 2150 | **21.0** | |
| transition (nm) | 253.7 nm | **252.4 nm** | |
| transition process | one-photon | **two-phot'n** | |

Talk by K. Katsika, This session

**Univ. Brit. Col., Simon Fraser Univ.**

## Optical Magnetometry

- Conventional Sensors ~ 1-10 pT sensitivity
- NMOR Rb 85/87 Sensor
  - All Optical
  - ~ fT Sensitivity



talk by J. Martin, Monday M2-10

**Univ. Winnipeg**

# CONCLUSIONS

- Good physics can be done with neutrons
  - Search for new sector of CP violation (nEDM)
  - Search for beyond standard model interactions (via neutron decay)
- TRIUMF will have the best UCN source in the world
  - Proton beamline installation started this year
  - On track to do commissioning in 2016
  - first measurements in 2017
- nEDM at TRIUMF
  - Subsystem R&D well underway
  - Seeking CFI-IF
  - High discovery potential of a nEDM

# UCN CANADIAN COLLABORATION

T. Adachi[1], E. Altiere[2], T. Andalib[3,4], C. Bidinosti[3], J. Birchall[4], C. Davis[5], F. Doresty[4], W. Falk[4], M. Gericke[4], K. Hatanaka[6], B. Jamieson[3], S.C. Jeong[1], D. Jones[2], K. Katsika[5], S. Kawasaki[1], A. Konaka[5], E. Korkmaz[7], M. Lang[3,4], L. Lee[4,5], K. Madison[2], J. Mammei[4], R. Mammei[3], J.W. Martin[3], Y. Masuda[1], R. Matsumiya[6], K. Matsuta[8], M. Mihara[8], C.A. Miller[5], E. Miller[2], K. Mishima[10], T. Momose[2], W.D. Ramsay[5], S.A. Page[4], R. Picker[5], E. Pierre[8,5], L. Rebenitsch[3,4], J. Sonier[9], I. Tanihata[6,10], W.T.H. van Oers[4,5], Y. Watanabe[1], and J. Weinands[2]

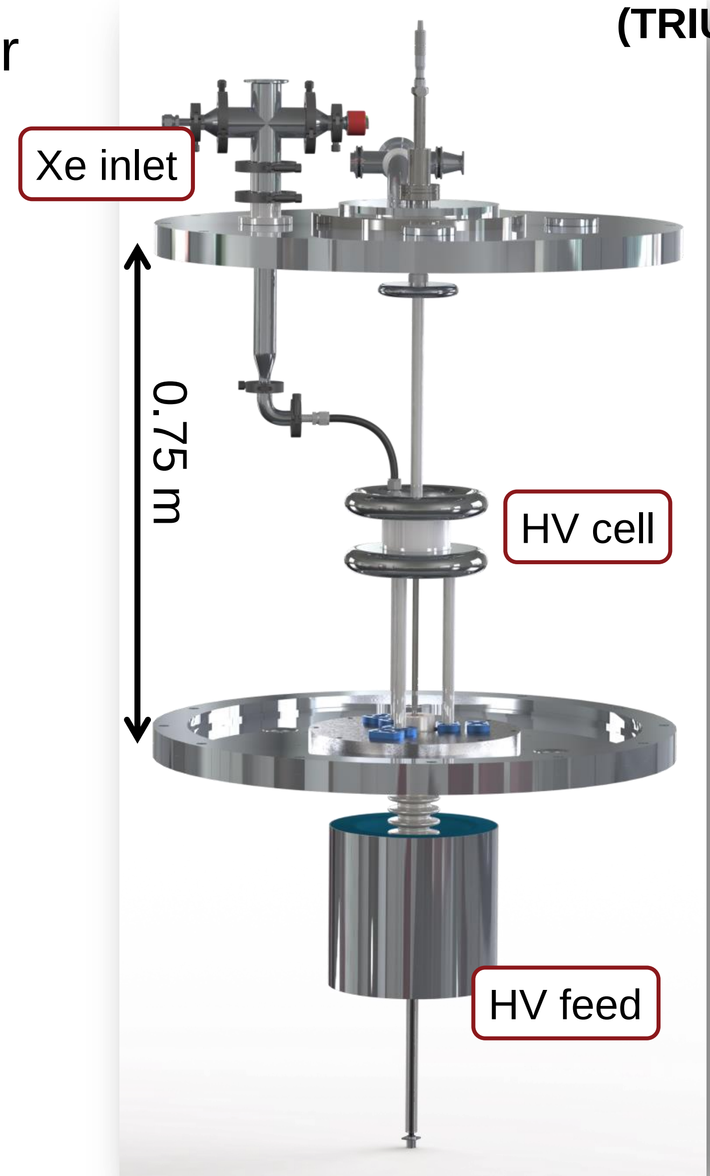
*[1]KEK, [2]UBC, [3]Winnipeg, [4]Manitoba, [5]TRIUMF,*
*[6]RCNP Osaka, [7]UNBC, [8]Osaka, [9]SFU, [10]Beihan*

# BACKUP SLIDES

# EDM CELL AND ELECTRIC FIELD

- dielectric strength of Xe at $10^{-3}$ mbar unknown
- HV test setup at TRIUMF
- 50x100 mm cylindrical test cell
- field strength goal > 10 kV/cm
- test of different cell materials
- **commissioned 8/2013**

**HV/EDM cell mock-up at TRIUMF**



(TRIUMF)

**HV setup at TRIUMF**

# Parameter s of Big Bang Nucleosynthesis

$$Y_P = 0.228 + 0.023\, log\eta_{10} + 0.012N_\nu + 0.018(\tau_n - 10.28)$$

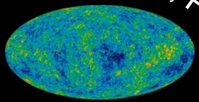
cosmic helium abundance He/p

from old stars

cosmic baryon density

$(n_\gamma/n_B)\cdot 10^{-10}$

WMAP, Planck

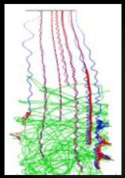


# of neutrino flavors

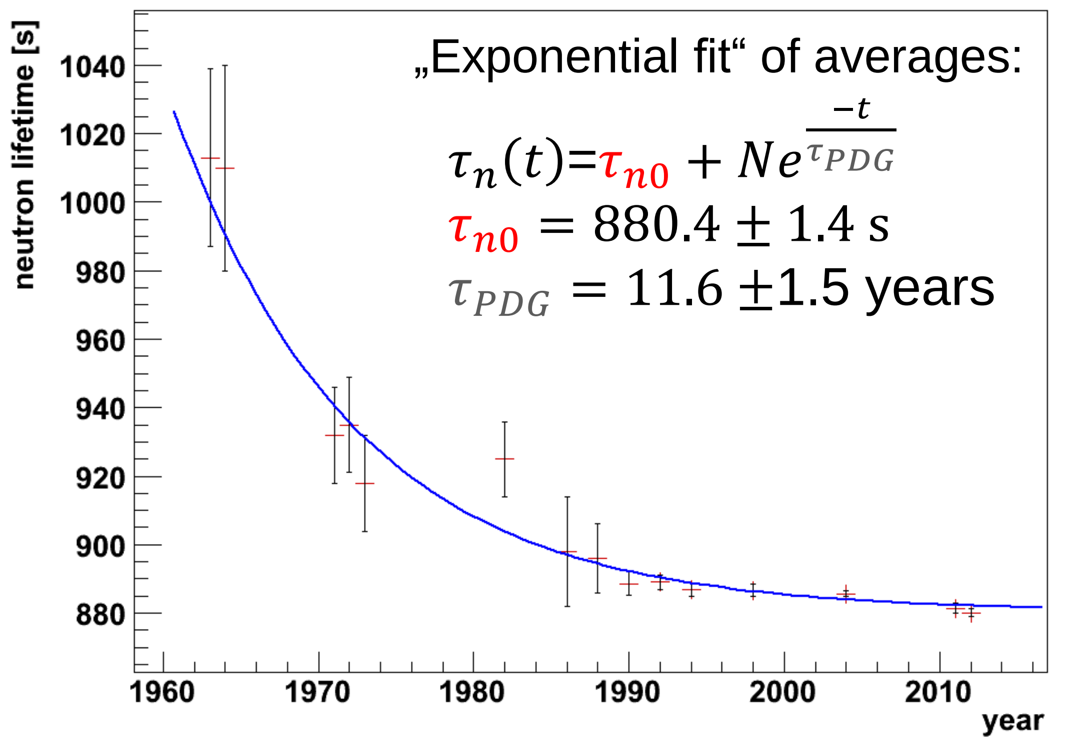
3

neutron lifetime

PENeLOPE



- the particle data group (PDG) reviews all major particle properties annually *http://pdg.lbl.gov/*
- PDG „world“ averages of the neutron lifetime for the last 50 years



„Exponential fit“ of averages:

$$\tau_n(t) = \tau_{n0} + N e^{\frac{-t}{\tau_{PDG}}}$$

$$\tau_{n0} = 880.4 \pm 1.4\ s$$

$$\tau_{PDG} = 11.6 \pm 1.5 \text{ years}$$

⇒ **PENeLOPE**

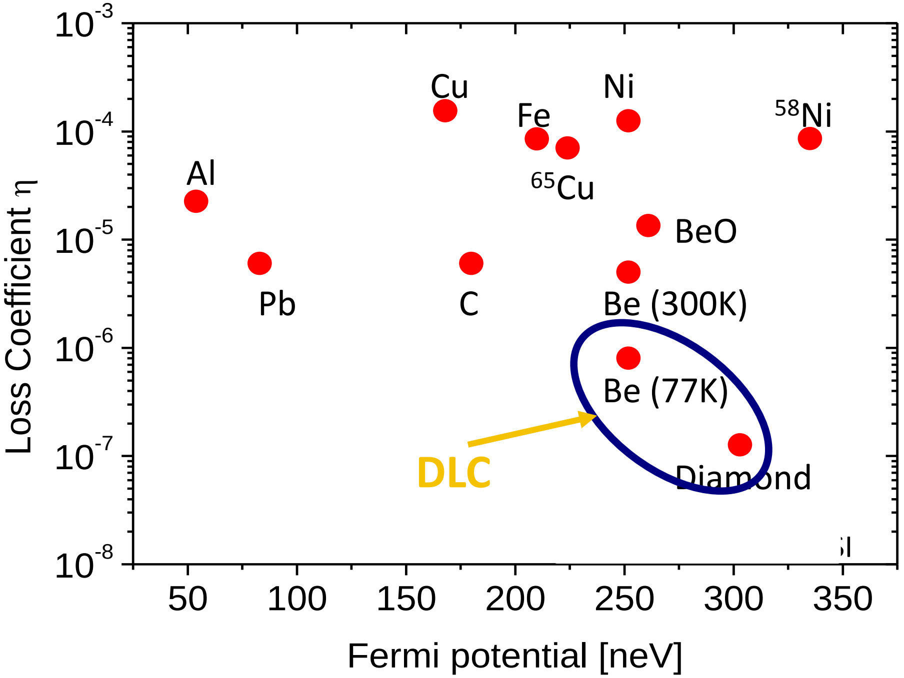
(**P**recision **E**xperiment on the **N**eutron **L**ifetime **O**perating with **P**roton **E**xtraction)

- Combination of **magnetic storage of ultra-cold neutrons** and in-situ **proton detection**
- Large volume
- Blind analysis
- Many knobs to turn to investigate systematic effects

# Transport and Storage of UCN

## Fermi (Material) Potential

$$V = \frac{2\pi\hbar^2}{m} Nb \qquad \text{UCN flux} \propto (V)^{3/2}$$



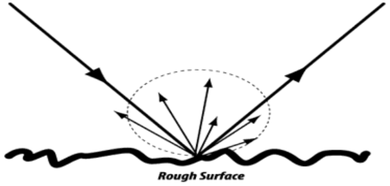
## UCN Loss Probability

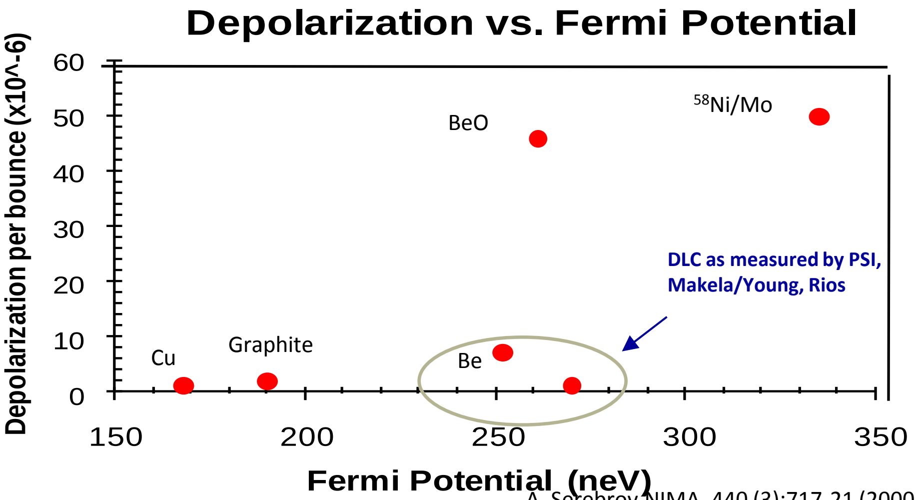
--Neutron absorption

--Inelastic upscattering

## Depolarization Probability

## Roughness/Specular Reflection





A. Serebrov NIMA, 440 (3):717-21 (2000)
A. Serebrov PLA, 313 (5-6):373-79 (2003)

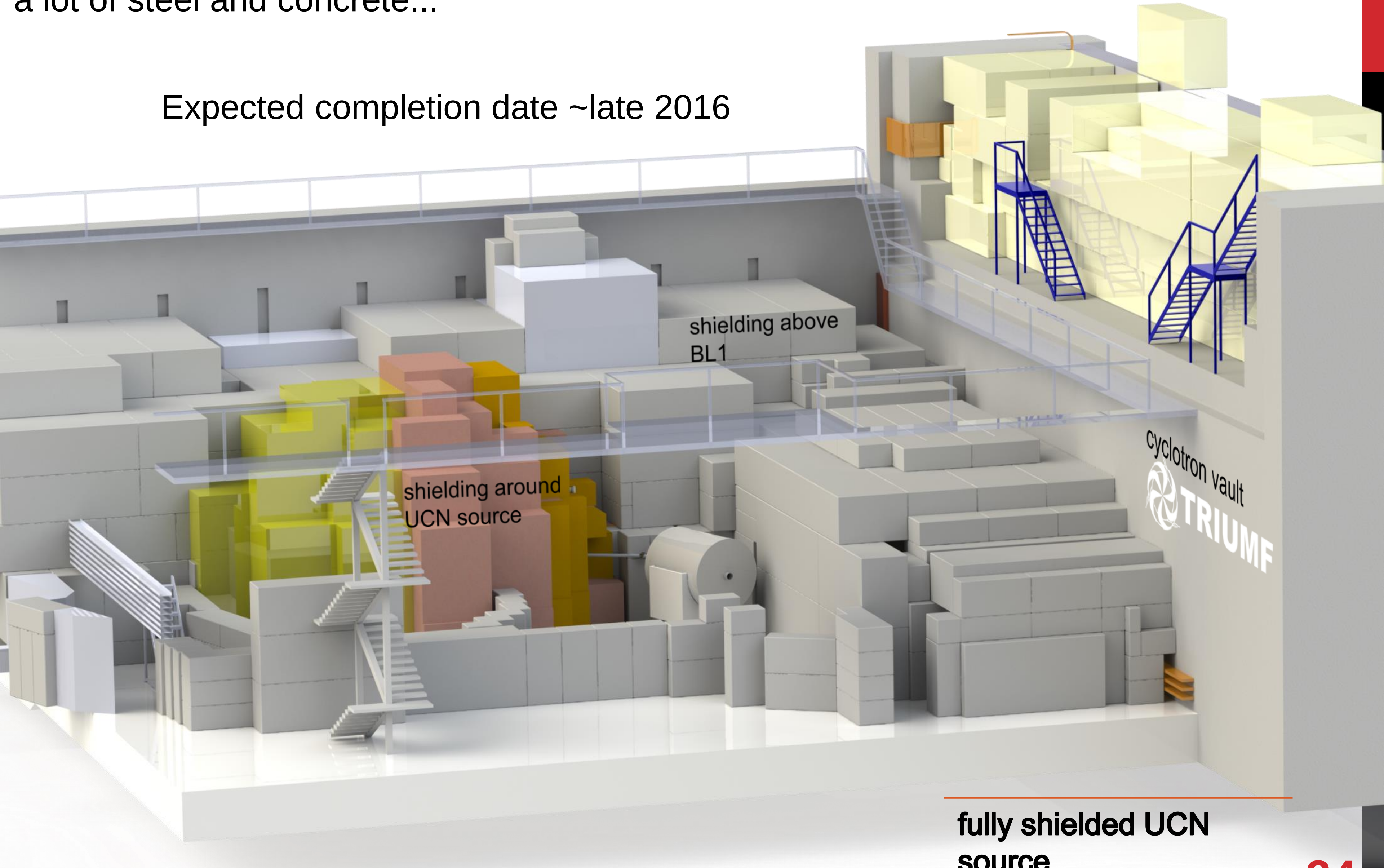
Usually means applying a coating on industrial, machined components

Need dedicated facility

# UCN SOURCE FULLY SHIELDED

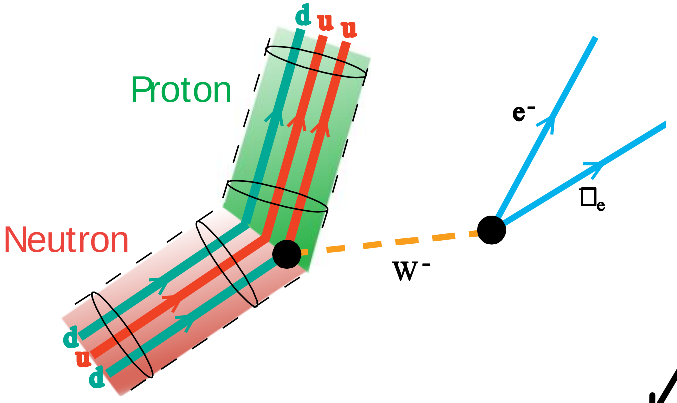
a lot of steel and concrete...

Expected completion date ~late 2016



fully shielded UCN source

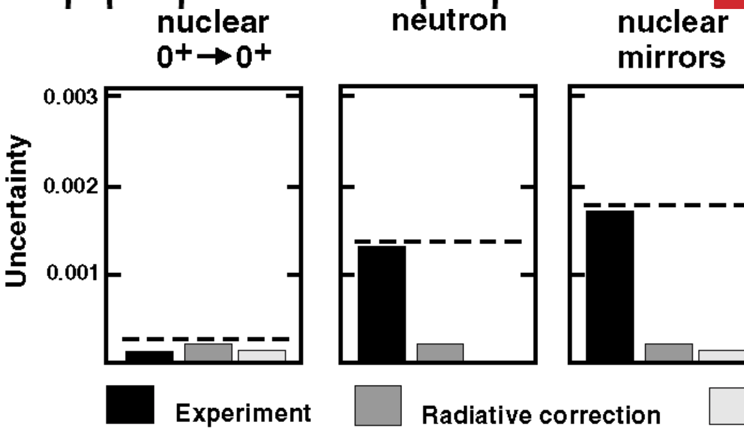
# Neutron Decay



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

$|V_{ud}|^2$

$$\begin{tikzcd} & A \arrow[dl, leftrightarrow] \arrow[dr, leftrightarrow] & \\ V_{ud} \arrow[rr, leftrightarrow] & & \tau_n \end{tikzcd}$$



## "Master Formula"

$$\frac{1}{\tau_n} = W = (G_V V_{ud})^2 g_V{}^2 \left(1+3\left(\frac{g_A}{g_V}\right)^2\right)(1+\Delta_R) f_n p_e E_e (E_0 - E_e)^2 \left[1 + m_e b \frac{I_b}{f_n}\right]$$

## Angular Correlations (directional distribution shown)

$$\frac{dW}{d\Omega_e d\Omega_\nu dE_e} \propto p_e E_e (E_0 - E_e)^2 \left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \left\langle \frac{\vec{J}_n}{J_n} \right\rangle \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\right)\right]$$

## Big Bang Nucleosythtniss –neutron lifetime matters

**Parameter s of Big Bang Nucleosynthesis**

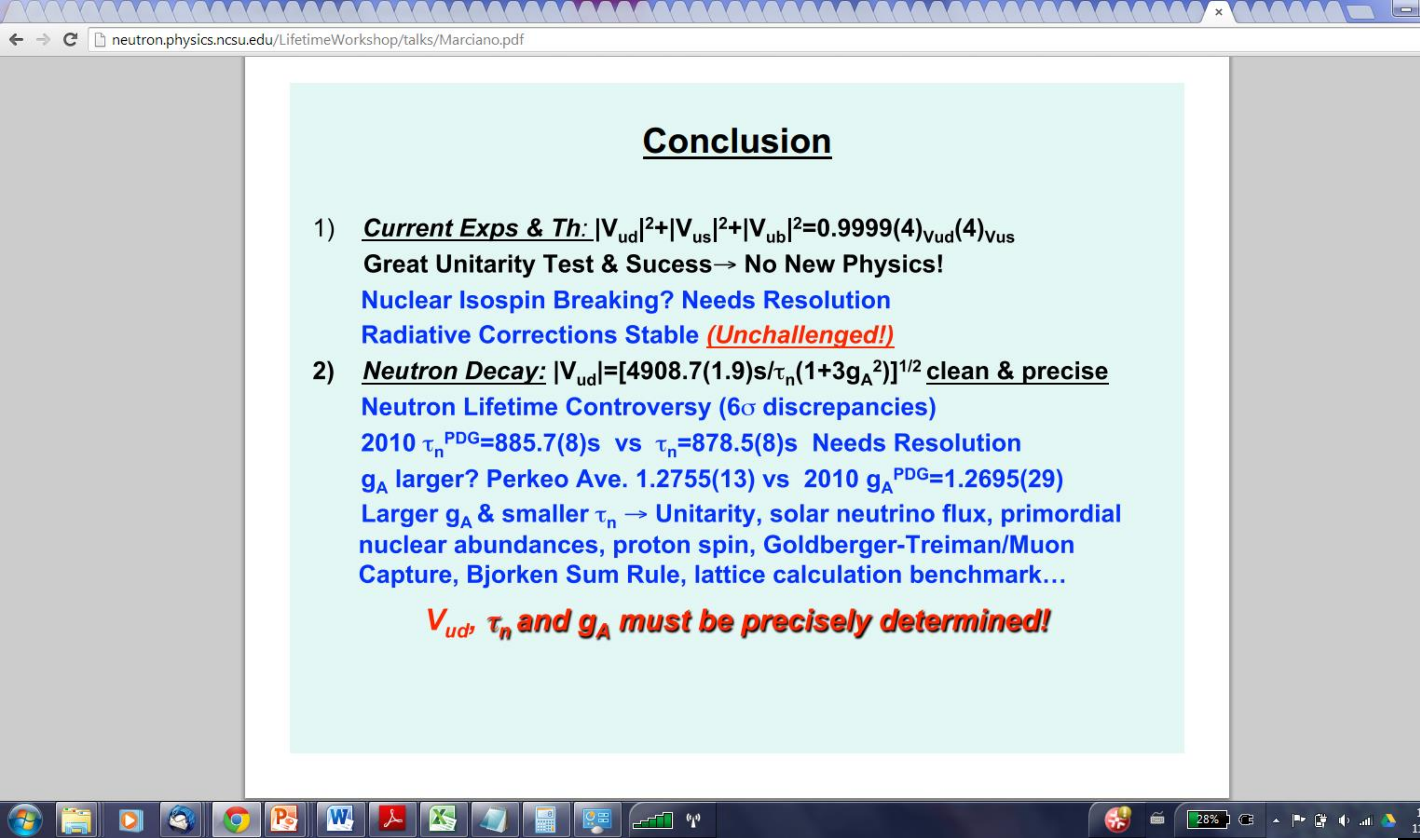
$$Y_P = 0.228 + 0.023\, log\, \eta_{10} + 0.012 N_\nu + 0.018(\tau_n - 10.28)$$

cosmic helium
abundanc
from ol

cosmic baryon d
$(n_\gamma/n_B)\cdot 10^{-10}$
WMAP, Pl

# of neutrino fl
3

neutron lifetim
PENeLOPE



## Conclusion

1) ***Current Exps & Th:*** $|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=0.9999(4)_{Vud}(4)_{Vus}$

**Great Unitarity Test & Sucess→ No New Physics!**

**Nuclear Isospin Breaking? Needs Resolution**

**Radiative Corrections Stable *(Unchallenged!)***

2) ***Neutron Decay:*** $|V_{ud}|=[4908.7(1.9)s/\tau_n(1+3g_A^2)]^{1/2}$ **clean & precise**

**Neutron Lifetime Controversy (6σ discrepancies)**

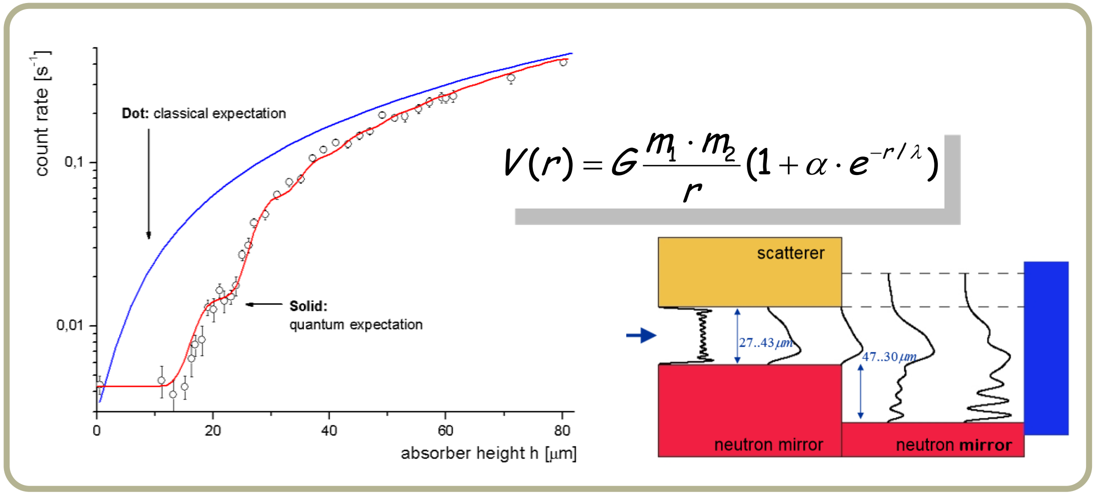
**2010 $\tau_n^{PDG}=885.7(8)s$ vs $\tau_n=878.5(8)s$ Needs Resolution**

**$g_A$ larger? Perkeo Ave. 1.2755(13) vs 2010 $g_A^{PDG}=1.2695(29)$**

**Larger $g_A$ & smaller $\tau_n$ → Unitarity, solar neutrino flux, primordial nuclear abundances, proton spin, Goldberger-Treiman/Muon Capture, Bjorken Sum Rule, lattice calculation benchmark…**

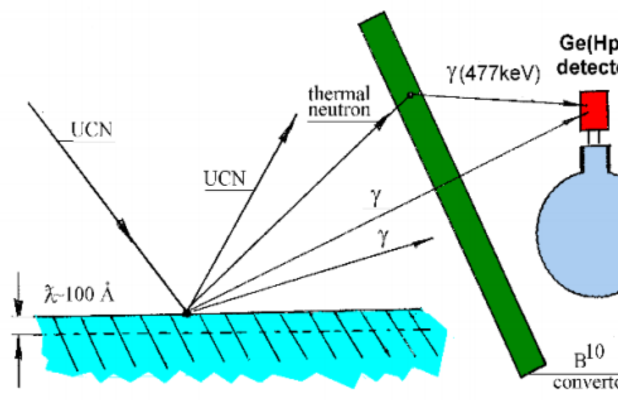
***$V_{ud}$, $\tau_n$ and $g_A$ must be precisely determined!***

# Gravity



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

Material science



Molecular rotor UCN inelastic scattering reflectormeter get pictures

# Neutron Decay ($n \rightarrow pe\nu$) & $V_{ud}$

$$|V_{ud}|^2 = \frac{\underline{4908.7(1.9)\text{sec}}}{\tau_n(1+3g_A^2)}$$ **Master Relation**

Measure $\tau_n$ and $g_A \equiv G_A/G_V$ (decay asymmetries)

2008 PDG $\tau_n^{ave}$=**885.7(8)**sec, $g_A^{ave}$=1.2695(29)

$\rightarrow |V_{ud}|^{ave} = \mathbf{0.9746(4)_{\tau n}(18)_{gA}(2)_{RC}}$ **reasonable but …**

2012 $\tau_n^{PDG} \approx$ **880.1(1.1)**sec? & $g_A \approx$ **1.2755(13)** **Perkeo II**

$\rightarrow |V_{ud}| = \mathbf{\underline{0.9739}(6)_{\tau n}(8)_{gA}(2)_{RC}}$

**Agrees with superallowed!** $0^+ \rightarrow 0^+$ Nuclear Beta $V_{ud}$=0.97425(22)

(Are $\tau_n$ & $g_A$ both shifting?)

**History $g_A$=1.18→1.23→1.25→1.26→1.27→1.275?**

***Many New $\tau_n$ & $g_A$ Experiments Planned***

# Neutron Electric Dipole Moment (nEDM)

Get picture here…

**Non-zero nEDM implies violation of time-reversal symmetry (T).**

**In QFT, this is equivalent to CP violation. (CPT=1)**

**The nEDM is sensitive to sources of CP violation:**

- within the Standard Model, via $\theta_{QCD}$ nEDM $\approx 10^{-32}$ ecm
- beyond the Standard Model, e.g. as required by Electroweak Baryogenesis in order to generate the baryon asymmetry of the universe

Where is all the antimatter

**Sakharov Conditions:** **(A.D. Sakharov, JETP Lett. 5, 24-27, 1967)**

**(1)Baryon number violation (may imply proton decay)**

- **Baryon: particle made out of 3 quarks (proton, neutron, lambda…)**
- **proton is lightest baryon (uud), could only decay to leptons or mesons (2 quarks)**

**(2)Departure from thermal equilibrium**

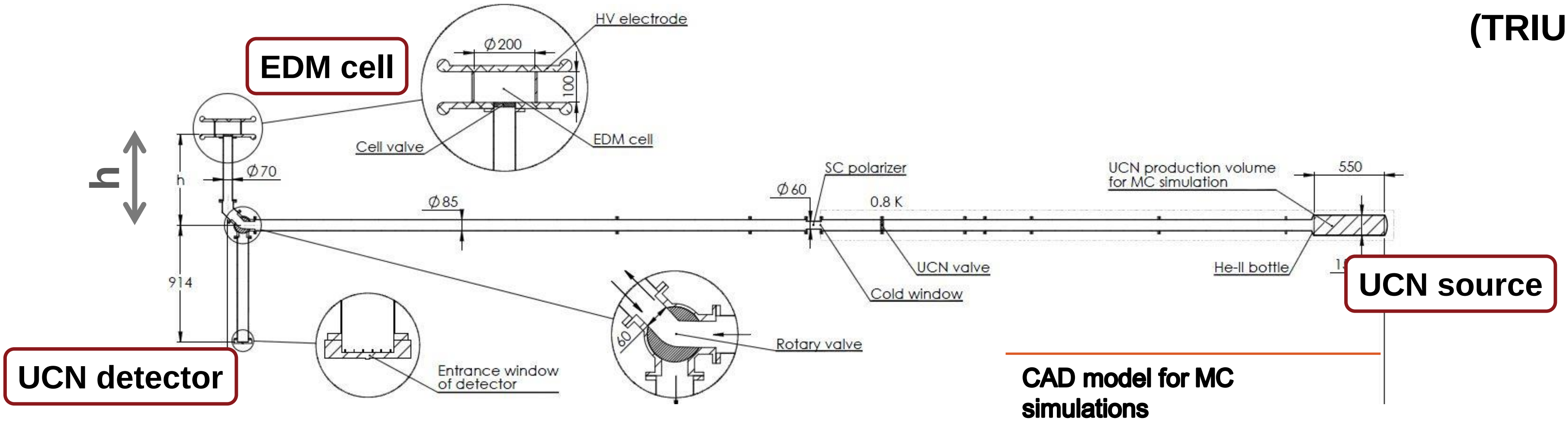
- **Phase transitions**
- **Expansion of the Universe (Inflation)**

**(3)Time reversal violation (⇒ CP violation)**

- **not enough in Standard Model ⇒ electric dipole moment would help**

# MONTE CARLO SIMULATION: ONE EXAMPLE

**(TRIUMF)**



**CAD model for MC simulations**

Which **height of EDM cell** is best at what **storage time**?

$$\sigma_{d_n} = \frac{\hbar}{2\alpha E T \sqrt{N}}$$ → figure of merrit→

$$\sqrt{N(T,h)} \cdot T = \sqrt{\sum_{\mathrm{bin}=0}^{\mathrm{n}} N_{0,\mathrm{bin}}(h)\, \exp\left(-\frac{T}{\tau_{s,\mathrm{bin}}}\right)} \cdot T$$

Plans to simulate:

⇒ depolarization

⇒ spin evolution

⇒ various GPEs

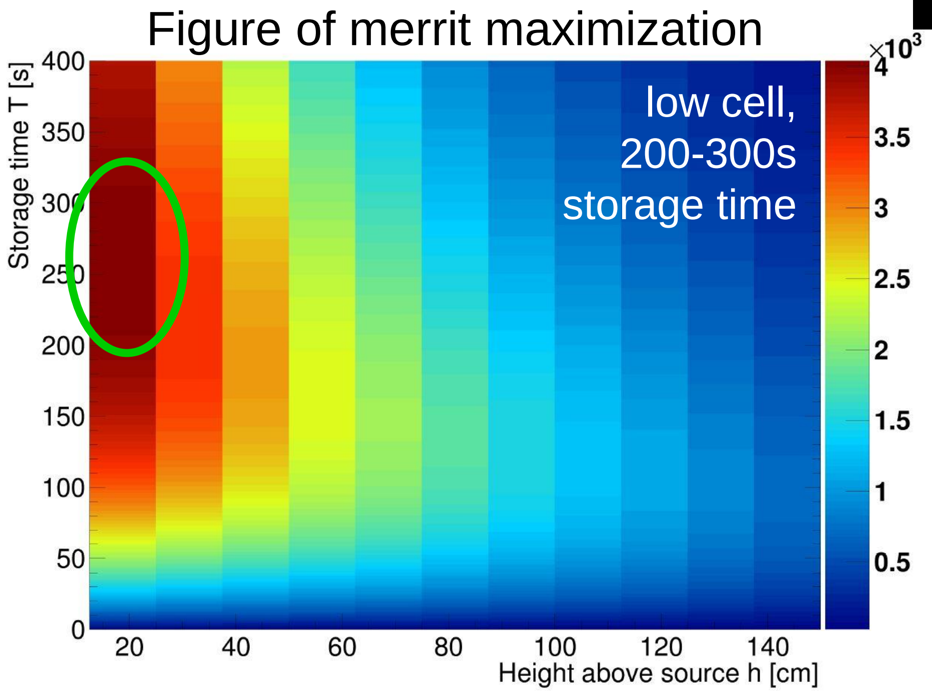
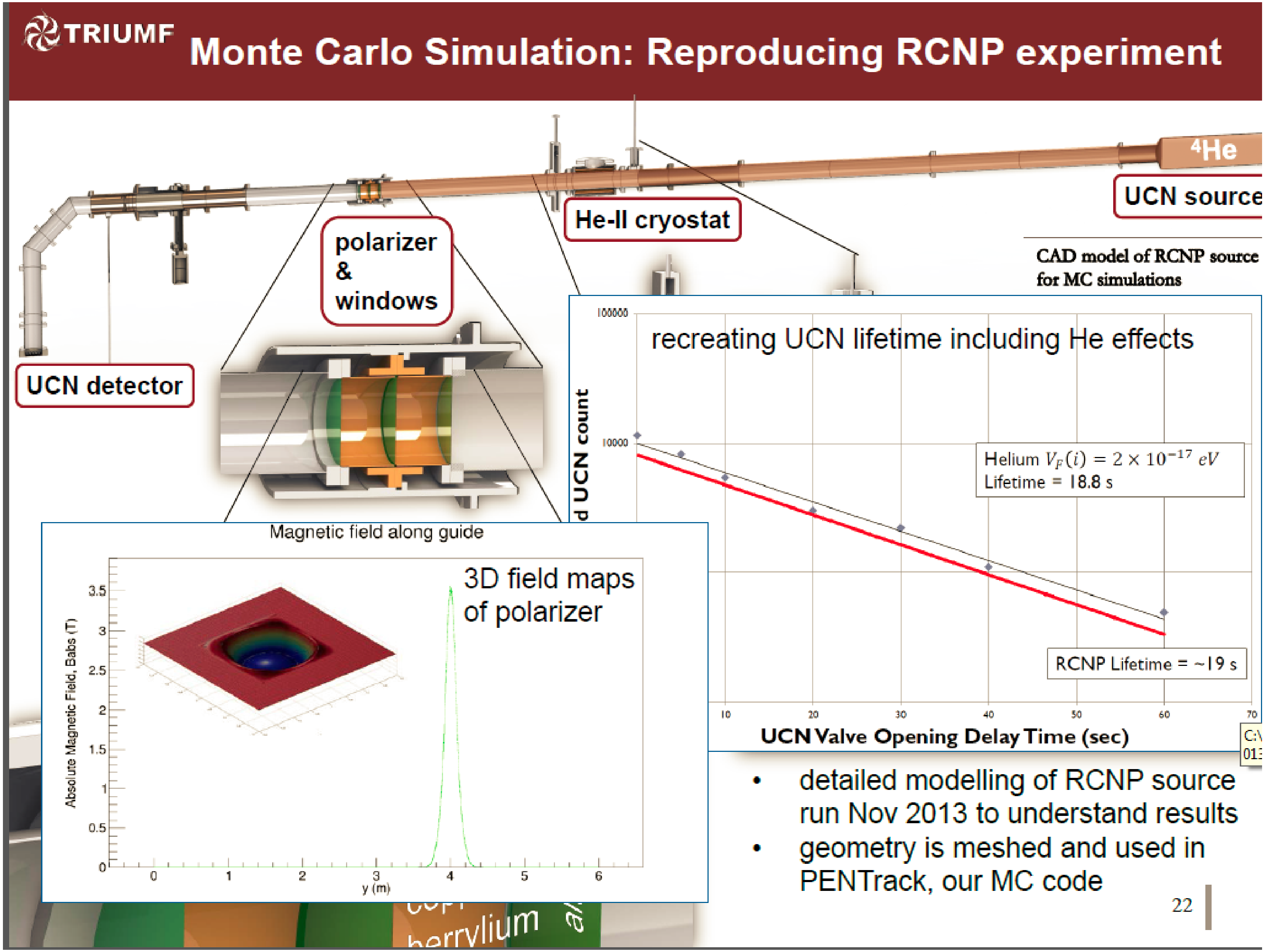


Figure of merrit maximization

low cell, 200-300s storage time

© M. Losekamm, BSC thesis, W. Schreyer, Diploma thesis, R.P. PhD thesis



TRIUMF

# Monte Carlo Simulation: Reproducing RCNP experiment

CAD model of RCNP source for MC simulations

recreating UCN lifetime including He effects

Helium $V_F(i) = 2 \times 10^{-17}\ eV$
Lifetime = 18.8 s

RCNP Lifetime = ~19 s

UCN Valve Opening Delay Time (sec)

Magnetic field along guide

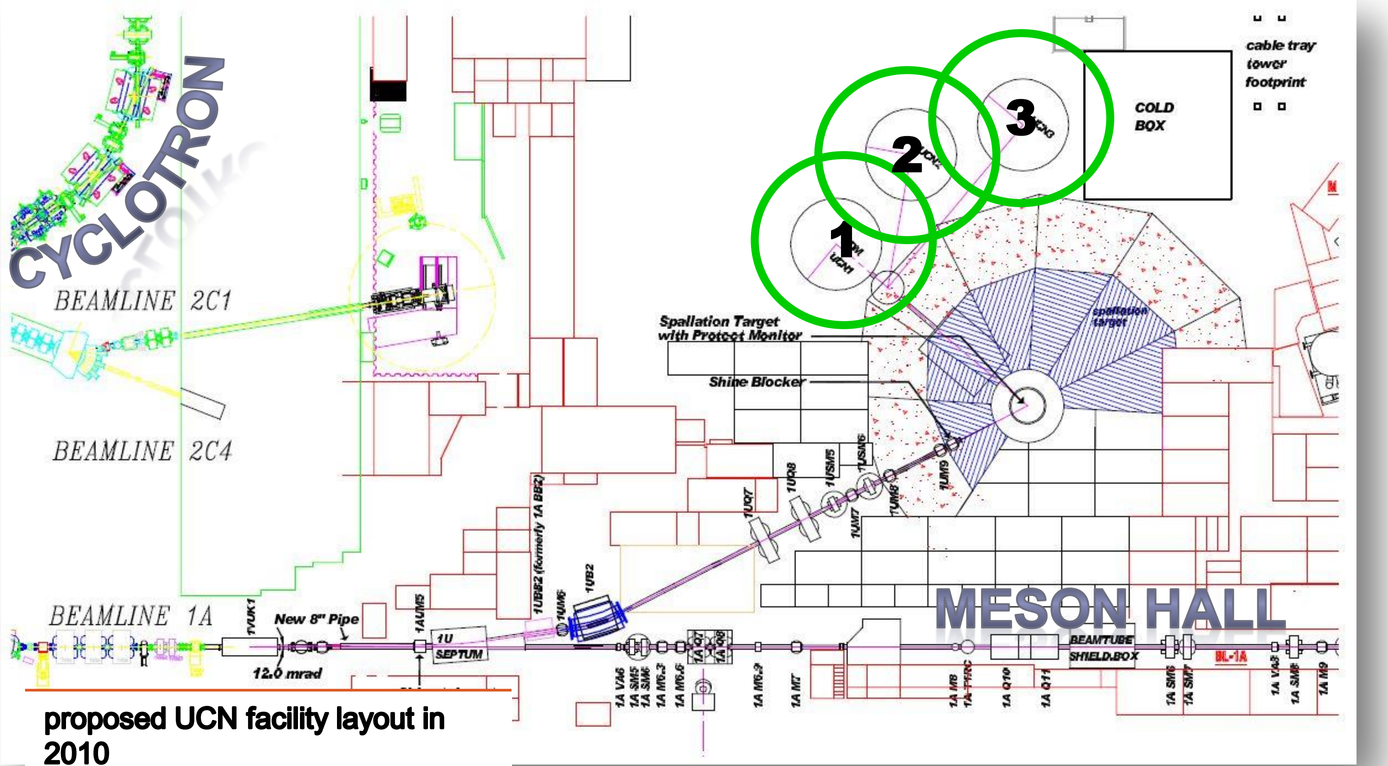
3D field maps of polarizer

- detailed modelling of RCNP source run Nov 2013 to understand results
- geometry is meshed and used in PENTrack, our MC code

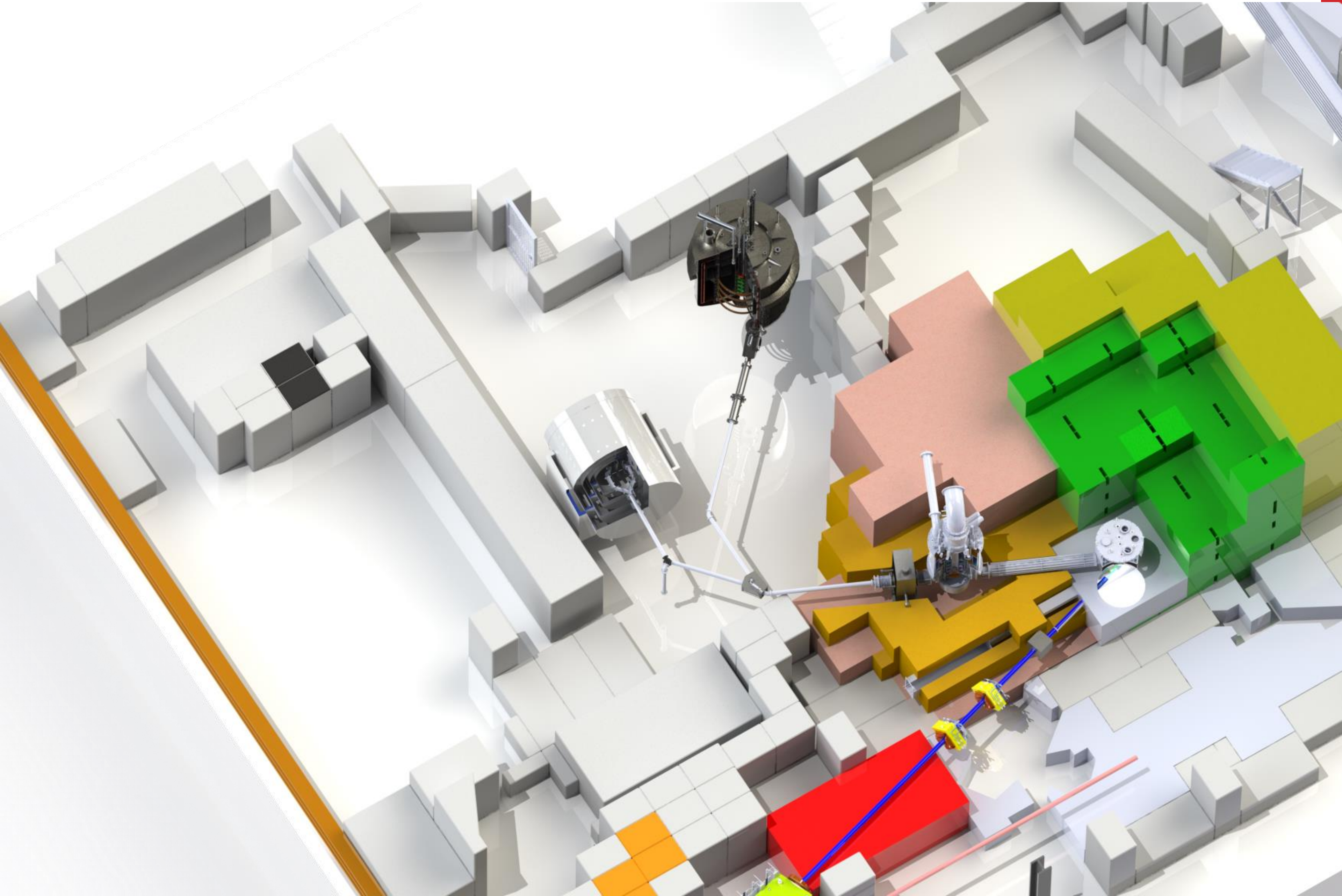
22

# UCN FACILITY AT TRIUMF

- **second UCN experiment port** very valuable
  - short term: for beam development, detector and guide **tests**
  - long term: for experiments besides EDM: **lifetime, neutron decay, charge, gravity**
- included in our upcoming CFI request
- big **step towards** a real **user facility**
- **will attract UCN physicists from around the world**

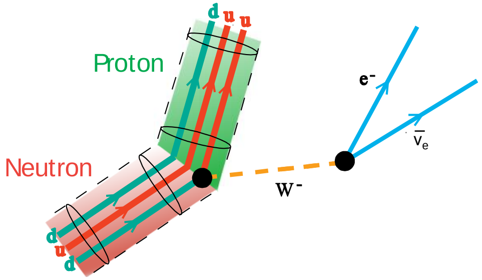


**proposed UCN facility layout in 2010**



# PHYSICS WITH SLOW NEUTRONS

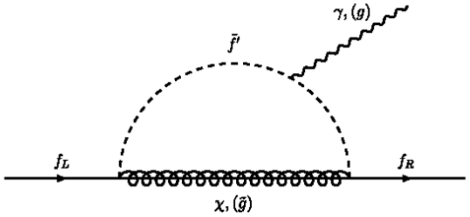
## $\beta$-decay



Charged Current parameters

BSM (S,V,A,T)
≥ 7 TeV
**best limits/values are possible**

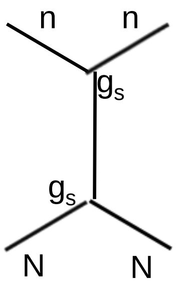
## Charge and Moments



nEDM**: best constraints**
CP, T violation

Charge: GUT-level effects

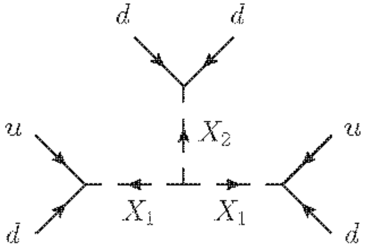
## Short range Forces



**best limits**
~nm scale

Grav. states:
~µm scale

## n→n̄ Oscillation



Probes ΔB=2
>100 TeV
M.I. scale

**Best limits are possible**