Precision Measurements with the Neutron at Low Energies and High Intensities

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Outline

- β-decay & Low Energy Neutrons
- Overview of Experiments utilizing CN and UCN.
- The UCNA Experiment at LANL.
- An Improved Search for NNBar Oscillations at FNAL.
- Summary

β-Decay Exp. Motivation

- *g_A is a fundamental parameter for the charged weak current of the nucleon.*

- g_A is required input to (high precision) solar fusion models and other astrophysical processes.
  E.G. Adelberger *et al*., Rev. Mod. Phys. **83**, 195 (2011).

- Lattice calculations of g_A are evolving into an interesting target for high precision calculations. T. Yamazaki *et al*., PRL **100**, 171602 (2008)

- g_A impacts antineutrino cross-sections in the reactor antineutrino anomaly. G. Mention *et al.*, PRD **83**, 073006 (2011)

Low Energy Neutrons

- CN ~ meV, UCN ~ 100’s neV.
- Large fraction of CN & UCN decay w/in detector.
- offers simplest "nuclear" system for weak decays without many body effects and extremely small coulomb effects.
- Use of UCN in a neutron β–decay experiment offers several advantages:
  - Higher polarization (> 99.48% at 68% CL)
  - Negligible neutron generated backgrounds.

CN & UCN Experiments

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto p_e E_e (E_0 - E_e)^2$$

$$a_0 = \frac{1-\lambda^2}{1+3\lambda^2}, \lambda = \frac{g_A}{g_V}$$

$$\times \left[1 + b\frac{m_e}{E_e} + a\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_e E_\nu} \right.$$

$$\left. + < \vec{\sigma_n} > \cdot \left(A\frac{\vec{p_e}}{E_e} + B\frac{\vec{p_\nu}}{E_\nu} + D\frac{\vec{p_e}\times\vec{p_\nu}}{E_e E_\nu} \right) \right]$$

N_{ab} Experiment:

$\Delta a/a \cong 10^{-3}$, $\Delta b \cong 10^{-3}$ D. Pocanic *et al.*, *NIM A* ***611****, 211 (2009)*

CN & UCN Experiments

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto p_e E_e (E_0 - E_e)^2$$

$$\times \left[1 + b\frac{m_e}{E_e} + a\frac{\vec{p_e} \cdot \vec{p_\nu}}{E_e E_\nu} \right.$$

$$\left. + < \vec{\sigma_n} > \cdot \left(A\frac{\vec{p_e}}{E_e} + B\frac{\vec{p_\nu}}{E_\nu} + D\frac{\vec{p_e} \times \vec{p_\nu}}{E_e E_\nu} \right) \right]$$

D = P-even, T-odd

emiT Experiment:

D = [-0.94 ± 1.89(stat) ± 0.97(sys)]10^{-4} *PRC* **86**, *035505 (2012)*

CN & UCN Experiments

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto p_e E_e (E_0 - E_e)^2$$

$$\times \left[1 + b\frac{m_e}{E_e} + a\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_e E_\nu} \right.$$

$$\left. + < \vec{\sigma_n} > \cdot \left(A\frac{\vec{p_e}}{E_e} + B\frac{\vec{p_\nu}}{E_\nu} + D\frac{\vec{p_e}\times\vec{p_\nu}}{E_e E_\nu} \right) \right]$$

PERKEO II:

$B_0 = 0.9802(34)_{stat}(36)_{sys}$, *PRL 99, 191803 (2007)*

$$B_0 = 2\frac{\lambda^2 - \lambda}{1 + 3\lambda^2}, \lambda = \frac{g_A}{g_V}$$

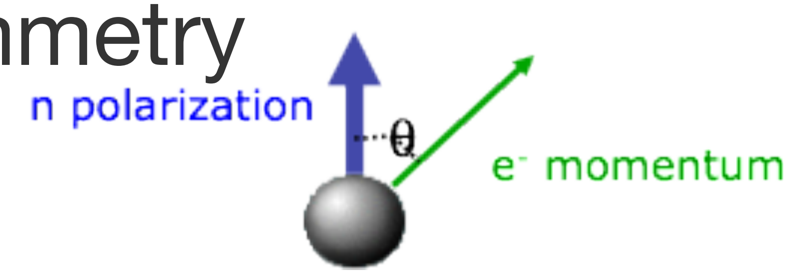
UCNA Experiment:

Next slides, *PRC 87, 032501(R) (2013)*

The UCNA Experiment at LANL

UCNA Exp. Motivation

- Experiment to measure the beta-asymmetry in neutron beta-decay:



$$R(E_e, \theta) = R_o(1 + \frac{v}{c} PA(E_e)\cos\theta)$$

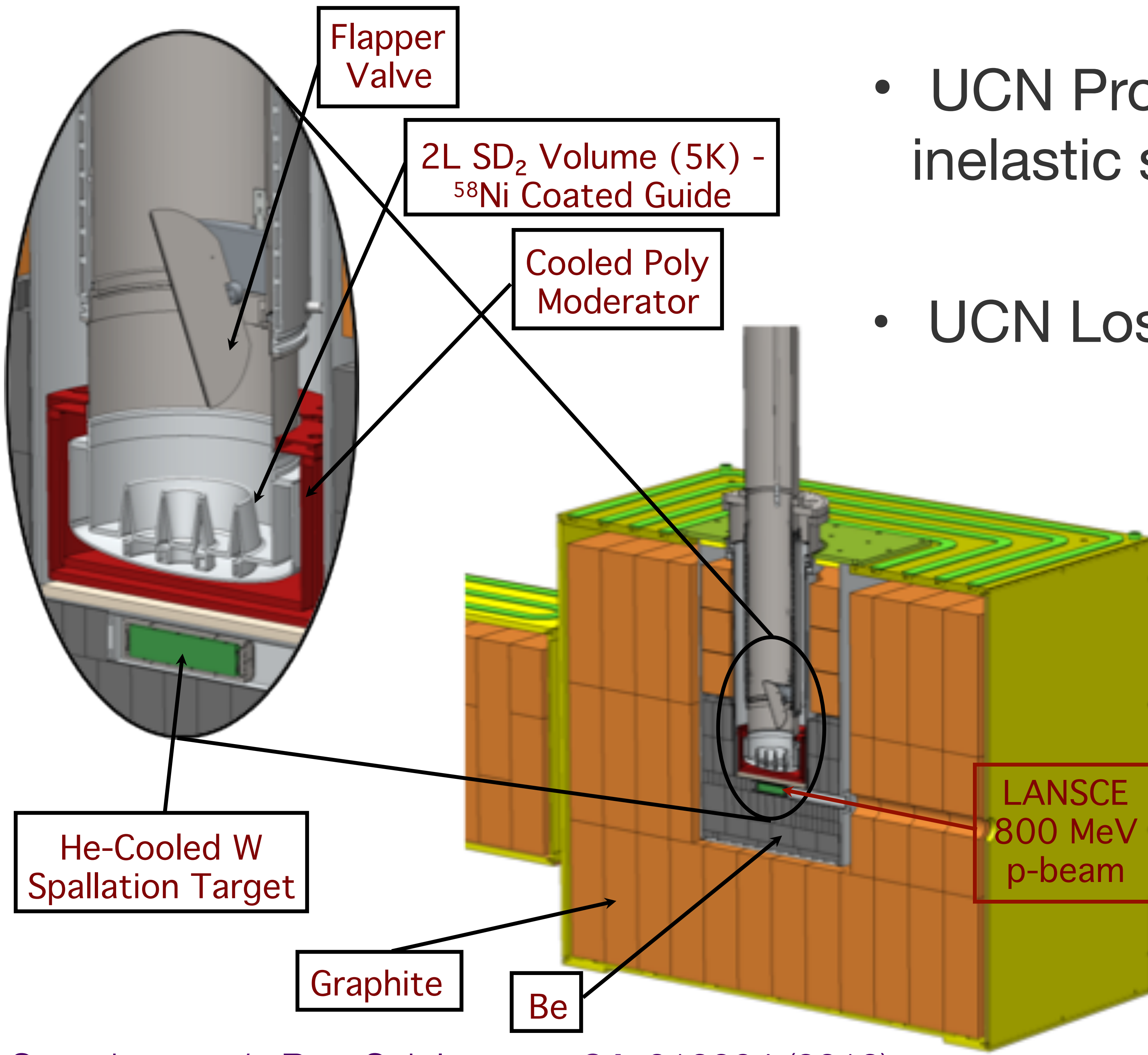
$$A(E_e) = A_o(1 + \Delta(E_e)), < \Delta >= \delta_{rec} + \delta_{rad}$$

- Beta-asymmetry = $A(E_e)$ in angular distribution of e^-'s.

$$\lambda = g_A/g_V, A_o = -2\frac{\lambda^2 + |\lambda|}{1 + 3\lambda^2}, \frac{1}{\tau_n} = \frac{G_F^2 |V_{ud}|^2}{2\pi^3} m_e^5 (1 + 3\lambda^2) f^R$$

$$220 < E_e(keV) < 670$$ (2010)

Solid D_2 UCN Source



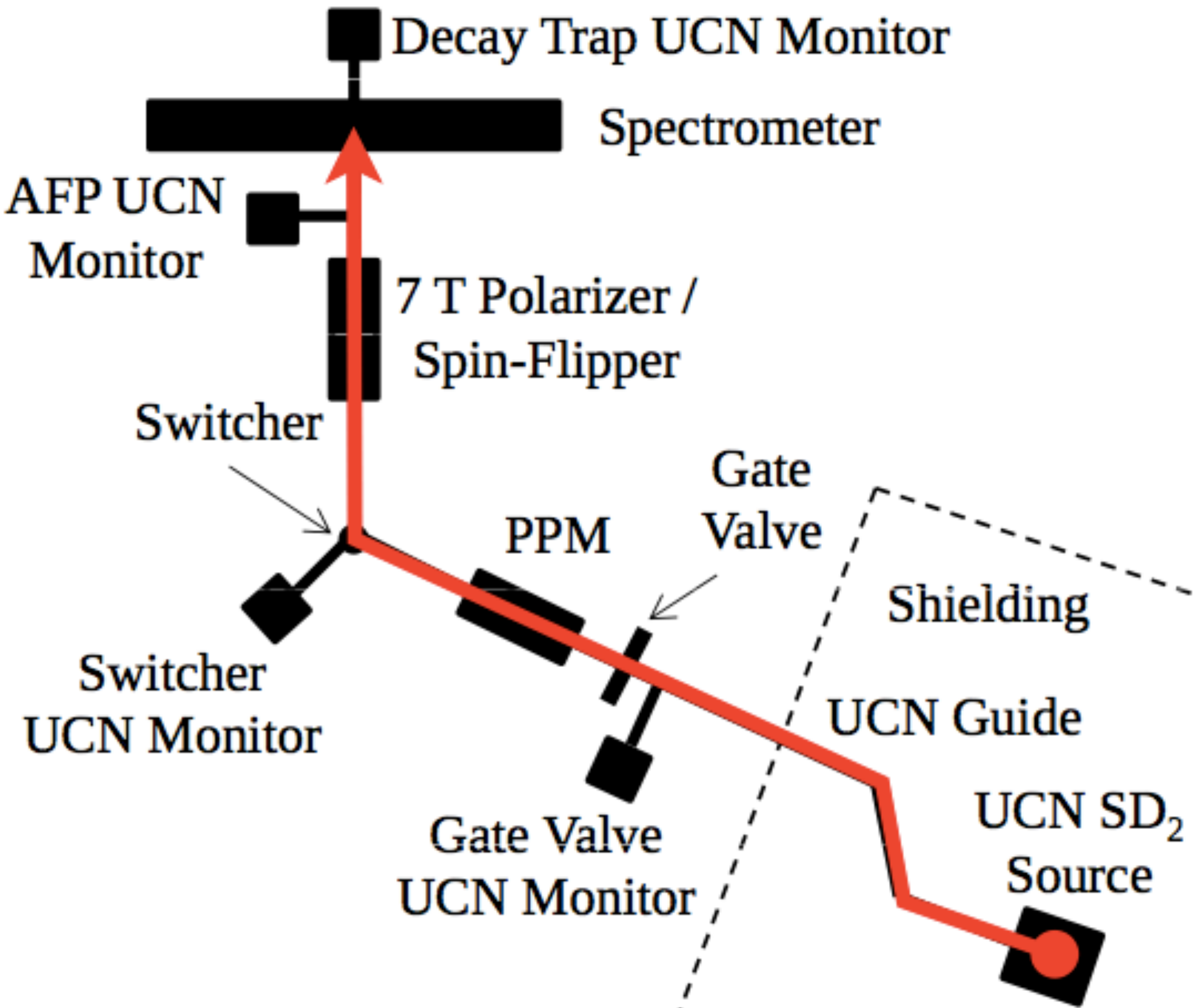
- UCN Production (*R*) - single inelastic scattering events.
- UCN Loss (*L*) via:
  - upscatter on D_2 (para-D_2, phonons)
  - absorption on D_2, H

Limiting UCN Density:

$$\rho = RL$$

A. Saunders *et al*., Rev. Sci. Instrum. **84**, 013304 (2013)

UCNA Guide & Transport

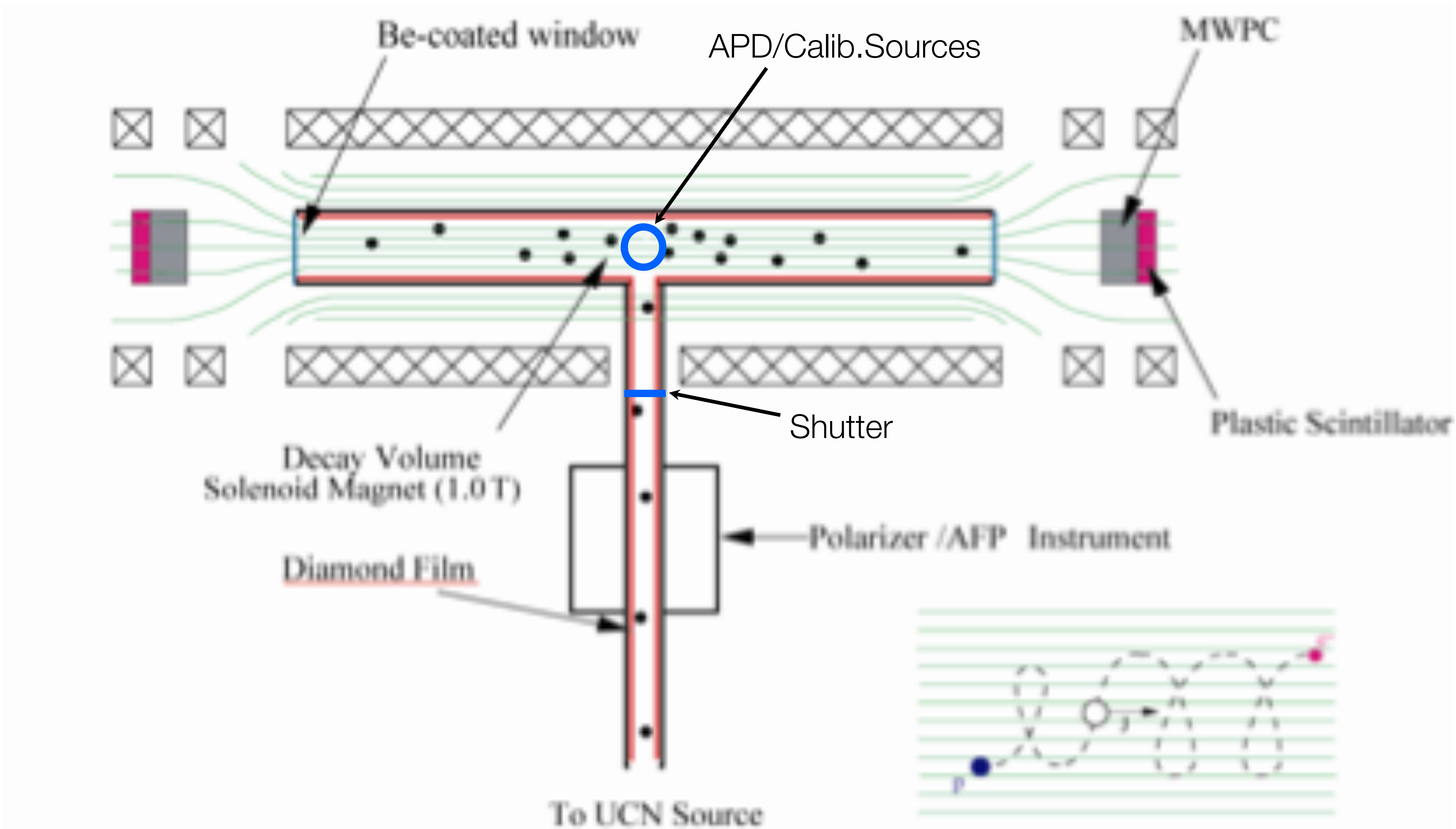


<u>2011-2013 Running</u>

- Running w/5 uA protons.
- $< \rho_{UCN} >$ (polarized) in spectrometer > 1 UCN/cm³
- $< \rho_{UCN} >$ at gate valve UCN mon. ~ 35 ± 6 UCN/cm³

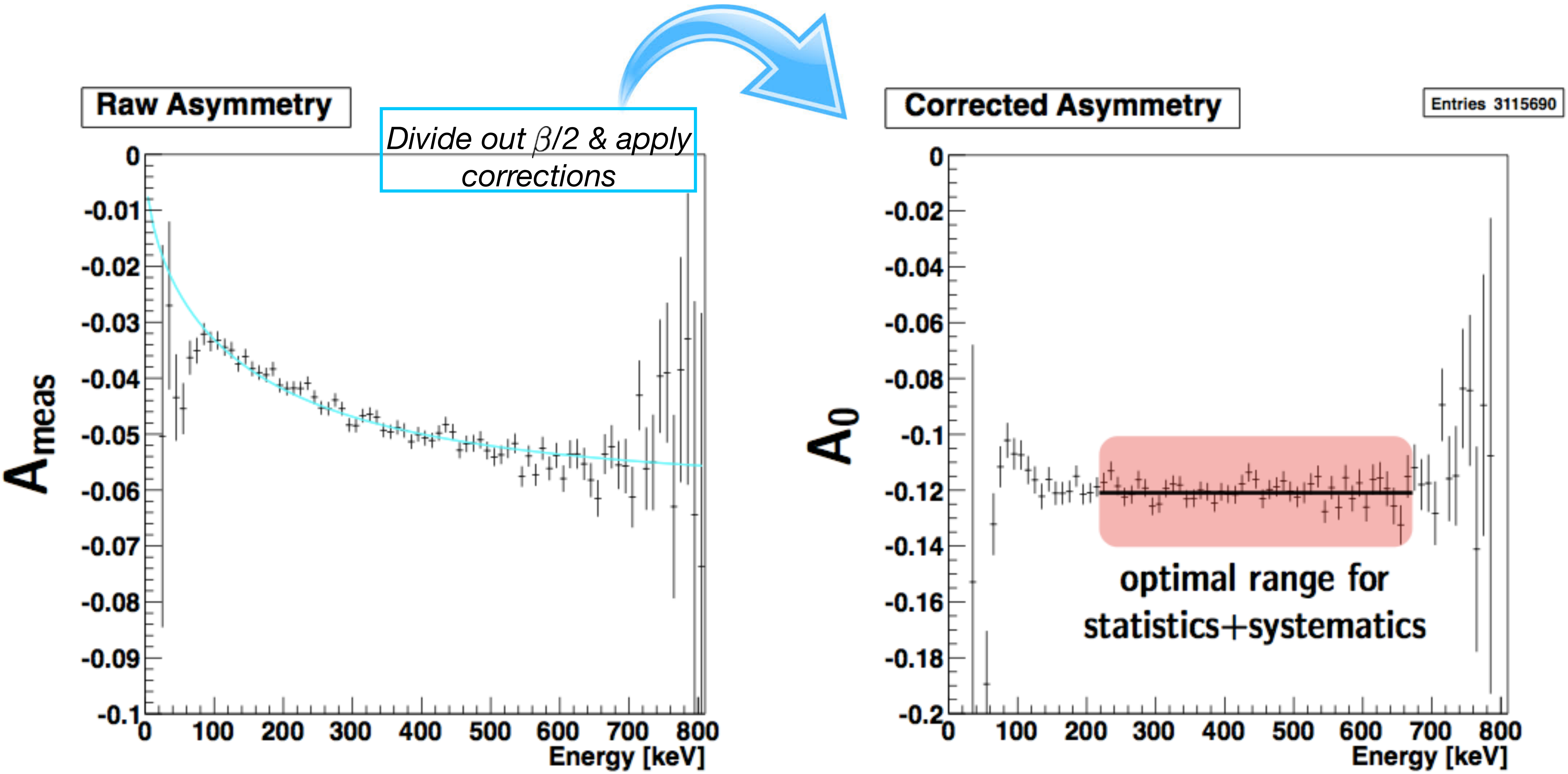
B. Plaster *et al*., PRC **86**, 055501 (2012)

UCNA Detectors



Calibration Sources: ^{207}Bi, ^{113}Sn, ^{139}Ce, ^{109}Cd, ^{137}Cs, ^{114}In, gaseous n-activated Xe

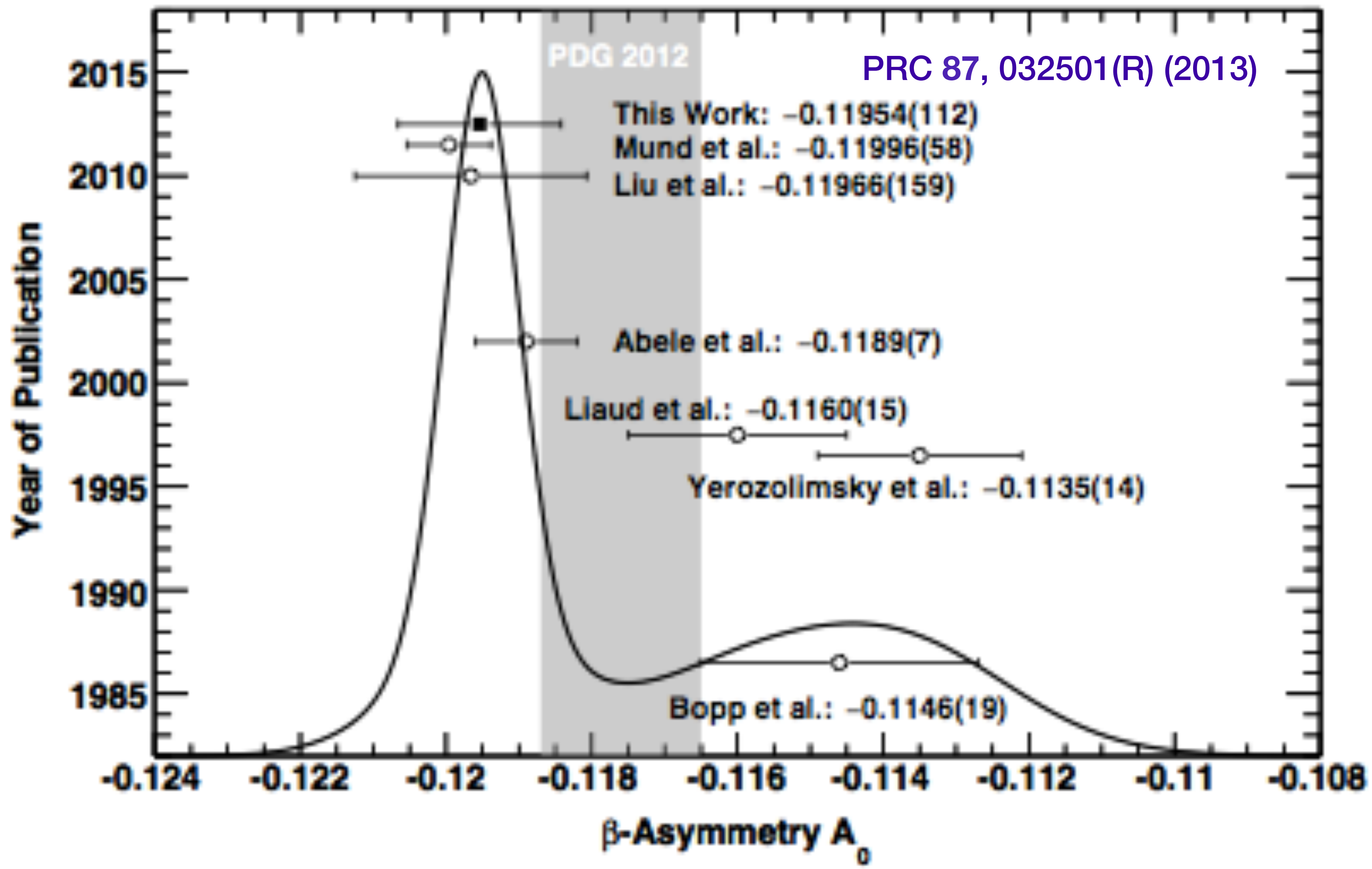
UCNA 2010 Analysis



M. P. Mendenhall et al., PRC 87, 032501(R) (2013)

UCNA 2010 Results

- 20.6 x 10^6 beta-decay events after all cuts applied.



$A_0 = -0.11954(55)_{stat}(98)_{sys}$

M. P. Mendenhall et al., PRC 87, 032501(R) (2013)

UCNA 2011-2013 Improvements

2010 Uncertainties

Systematic	Corr. (%)	Unc. (%)
Polarization	+0.67	± 0.56
$\Delta_{\text{backscattering}}$	+1.36	± 0.34
Δ_{angle}	−1.21	± 0.30
Energy reconstruction		± 0.31
Gain fluctuation		± 0.18
Field non-uniformity	+0.06	± 0.10
ϵ_{MWPC}	+0.12	± 0.08
Muon veto efficiency		± 0.03
UCN-induced background	+0.01	± 0.02
$\sigma_{\text{statistics}}$		± 0.46

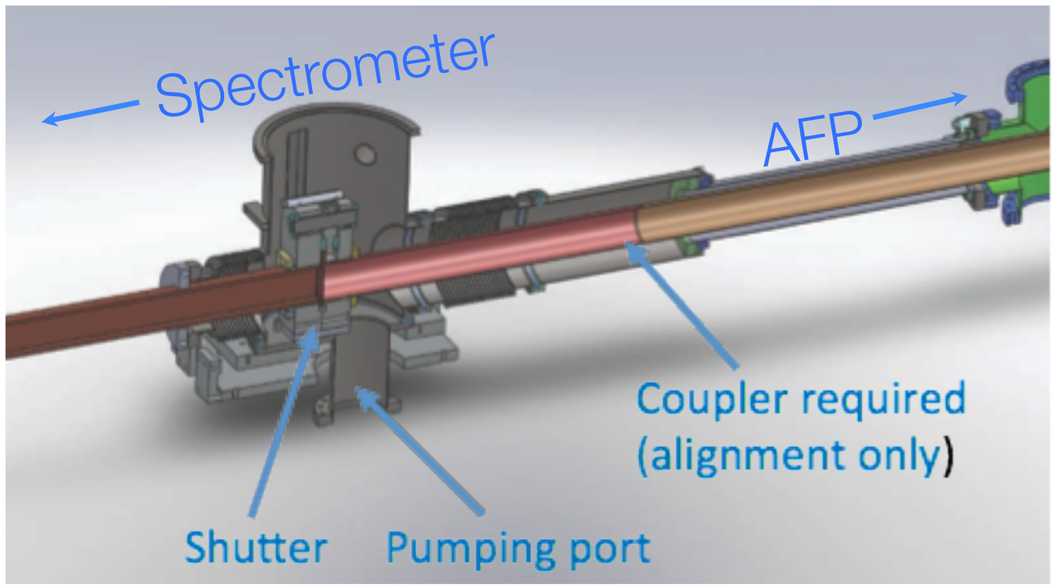
Shutter

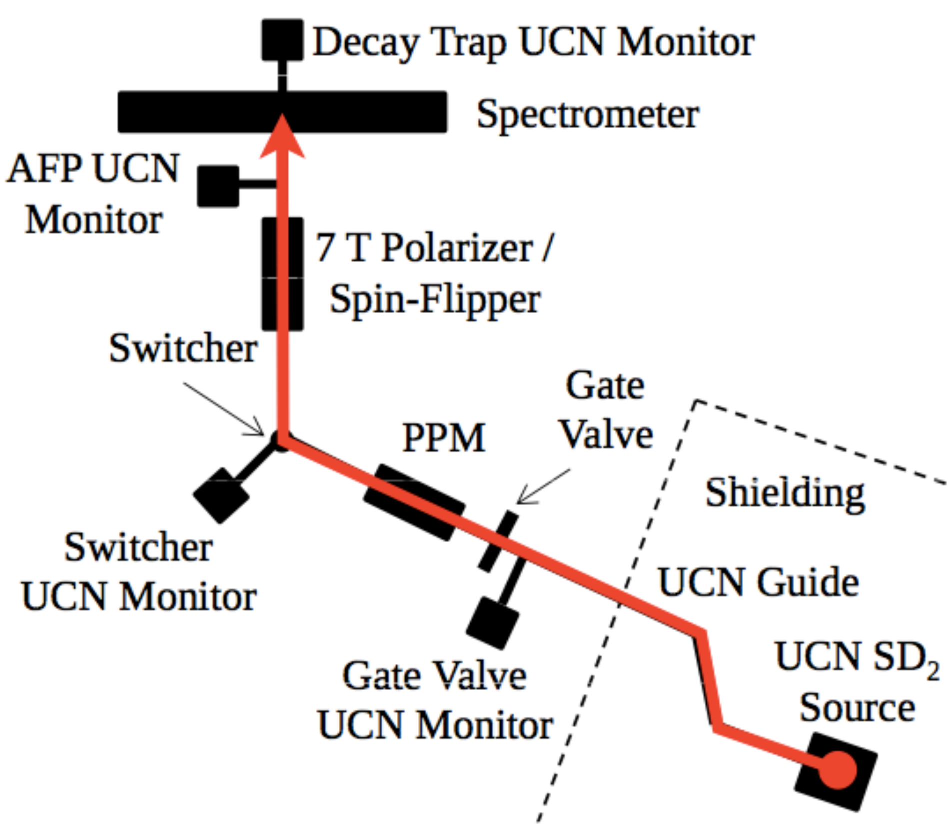
APD + ^{113}Sn, Thin Foils

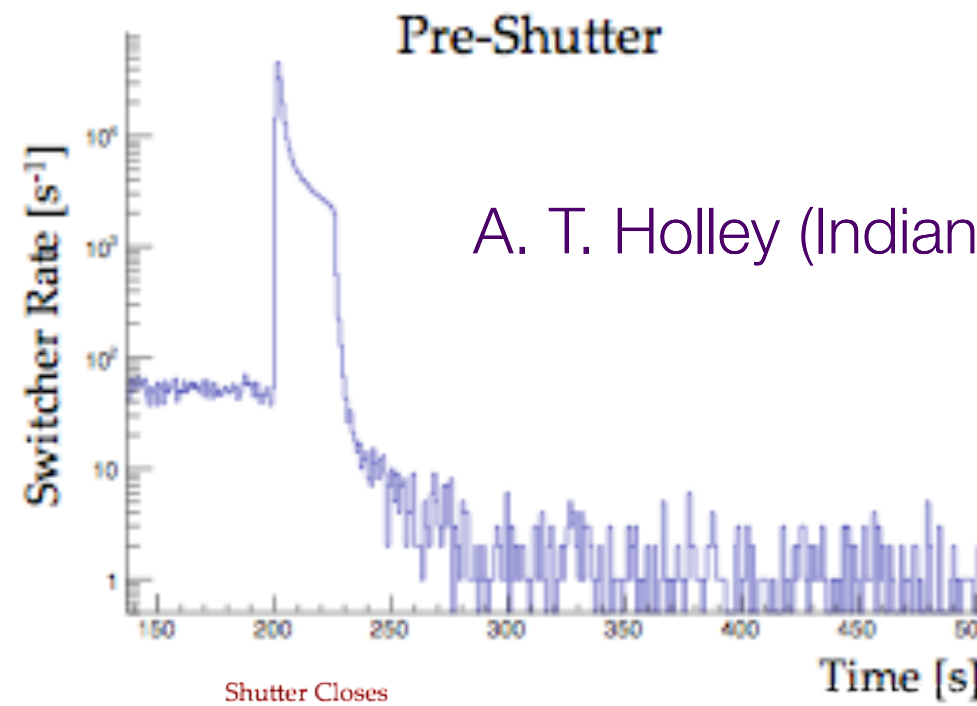
LED scanner, ^{207}Bi Pulsers, & Sources

M. P. Mendenhall et al., PRC 87, 032501(R) (2013)

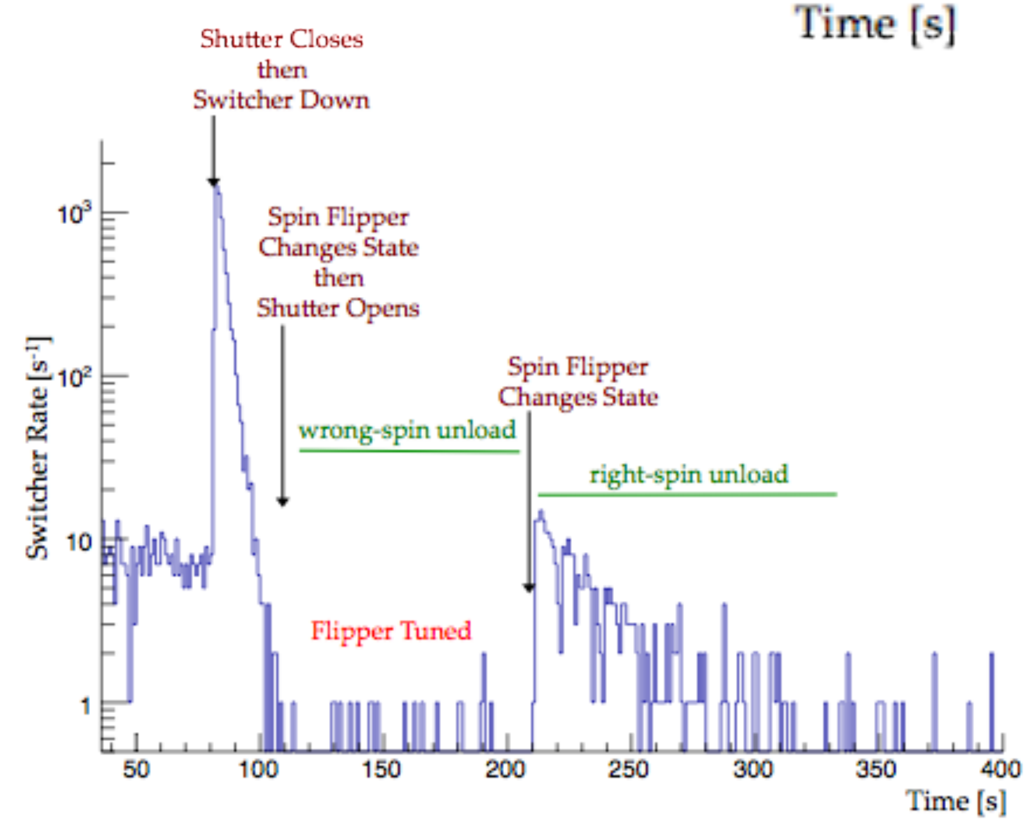
Improvements - Polarimetry







A. T. Holley (Indiana U.)



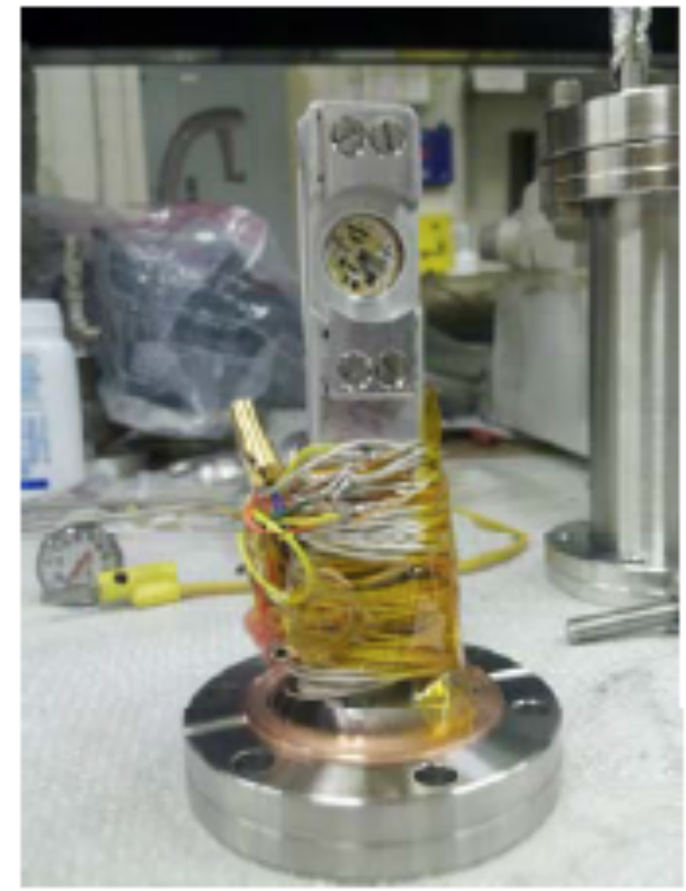
Improvements - Backscatter & Angle Effects

- Missed backscatters (from decay trap foils)
- Calib. sources isotropic -> different energy loss for *cos*θ & isotropic distributions.

Thin Decay Trap Foils

130/170 nm polyimide-like foils + 150 nm Be

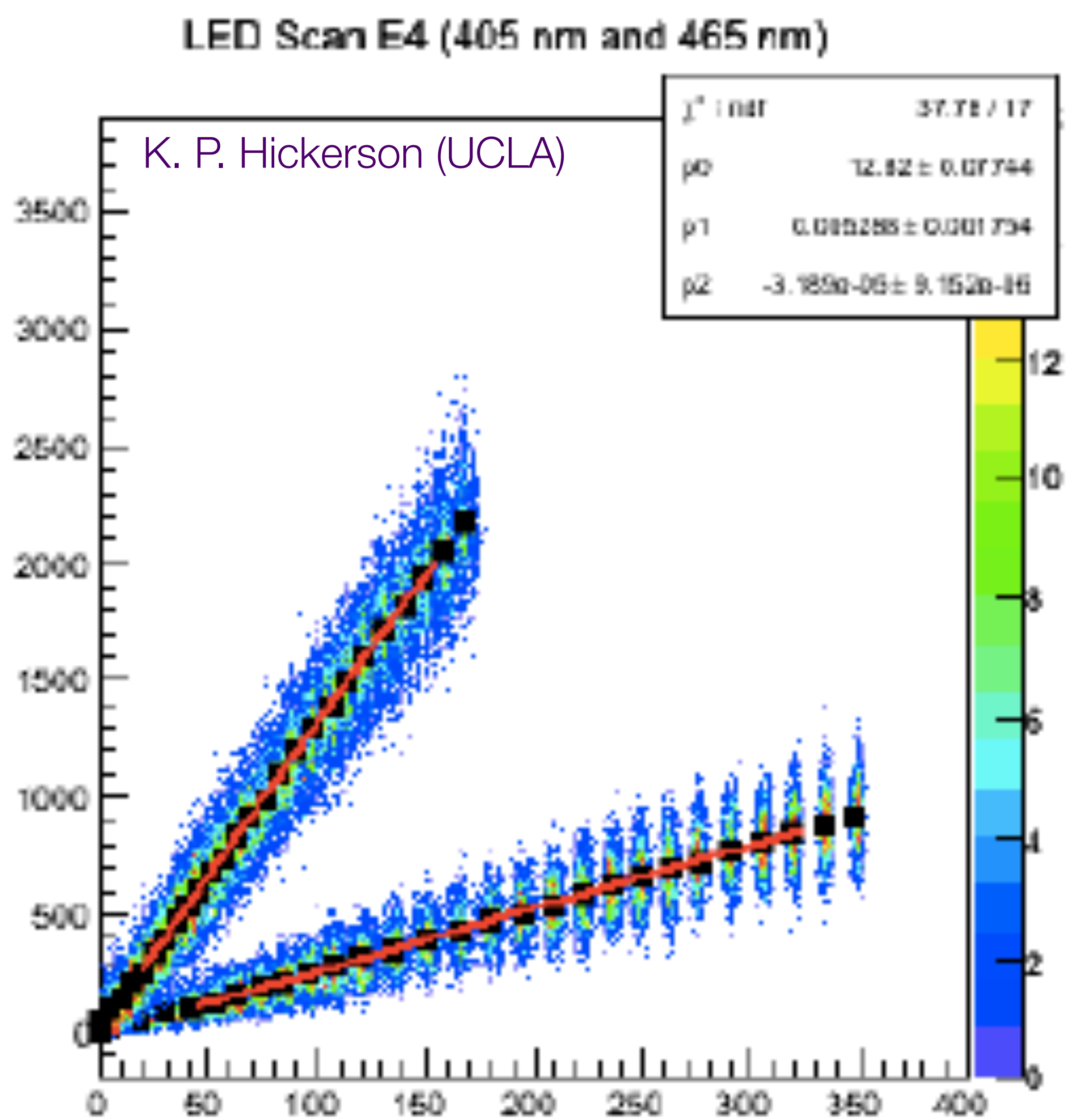
APD + ^{113}Sn source



for time-stamped + monoener. betas
(directly determine angle effects)

A. R. Young (NCSU)

Improvements - Gain Stab. & E_{recon}



- Thermal instabilities in PMT's.
- Use LED+PD pair (405 nm & 465 nm) and ^{207}Bi for energy linearity and gain stability.
- Analysis ongoing.

K. P. Hickerson (UCLA)

UCNA 2011-2013 Datasets

- 57.5×10^6 beta-decay events in combined 2011/2012, 2012/2013 datasets.
- Estimate stat. error on A_0 of < 0.4%.
- Hardware improvements & additions reduce backscatter, angle effects, polarimetry, gain and E_{recon} systematics.
- Expected total uncertainty in A_0 of 0.5% - 0.6%.

The Path Forward

- Data quality check of combined 2011-2013 datasets complete.
- Analysis of 2011-2013 calibration data underway.
- Refine MC approach (in particular for thin foils) and complete analysis of 2011-2013 data.
- Assess effectiveness of UCNA data taking during 2014 runcycle.

The UCNA Collaboration

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An Improved Search for NNBar Oscillations at FNAL

Why Look for NNBar Oscillations?

- Oscillations with neutral mesons (K^{0}' s, B^{0}' s) and neutral fermions (neutrinos) have already been observed.
- A number of reasons to believe that baryon number, *B*, is not conserved: Origin of matter, GUTs, SM sphalerons [2,3]...
- If *B* is violated, then there are a few scenarios to consider:

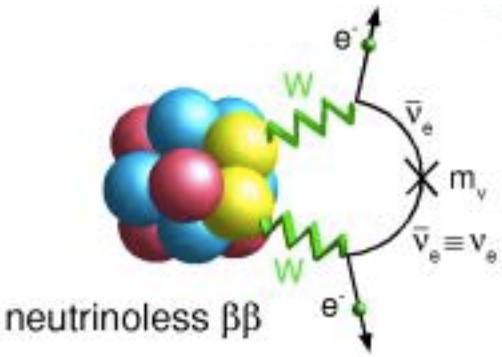
1) proton decay: $\Delta B = 1$ (GUT scale)

2) NNBar Oscillation: $\Delta B = 2$ (≥EW scale<<GUT scale)

$$\rightarrow \quad n \leftrightarrow \bar{n}$$

Why Look for NNBar Oscillations?

- Many experiments searching for neutrinoless double-beta decay (0vBB) [4,5,6]. For 0vBB, ΔL = 2.



Majorana Demonstrator: groups at UNC, NCSU, Duke U. (TUNL)

$$\nu \leftrightarrow \bar{\nu}$$

Global SM symmetry *B-L* broken by 2!

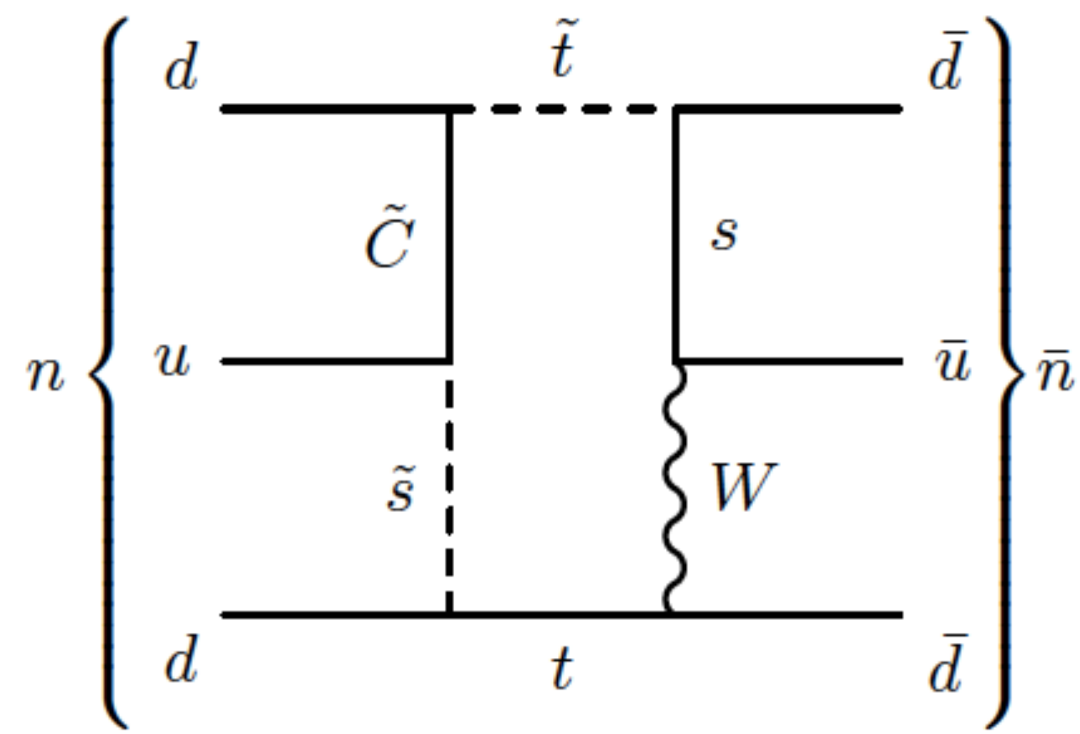
- If we couple quark-lepton unification with 0vBB, then ΔB = 2 processes such as NNBar oscillations are allowed.

What are NNBar Oscillations?

- Neutrons in vacuum and ultra-low magnetic field environment spontaneously convert to an anti-neutron.

- NNBar transition probability [1]:

$$P_{n\rightarrow\bar{n}}(t) = \frac{\alpha^2}{\alpha^2+\Delta E^2}\sin^2\left(\frac{\sqrt{\alpha^2+\Delta E^2}\cdot t}{\hbar}\right)$$



- Quasi-free condition (QFC):

$$\frac{\sqrt{\alpha^2+\Delta E^2}\cdot t}{\hbar} << 1$$

$$P_{n\rightarrow\bar{n}}(t) \underset{\text{QFC}}{\rightarrow} \left(\frac{\alpha t}{\hbar}\right)^2 = \left(\frac{t}{\tau_{n\bar{n}}}\right)^2$$

How to Look for NNBar Oscillations?

1) Neutron oscillates to anti-neutron within the nucleus and annihilates with other nucleons (intra-nuclear).

2) Free NNBar oscillations in a beam of cold neutrons.

• Large-scale underground nucleon decay experiments have an extremely large number of atoms available for study.

So, how are free neutrons competetive?

Previous NNBar Oscillation Experiments

- Best bound neutron NNBar search result from Super-K in ^{16}O [7]:

$$\tau(^{16}O) > 1.89 \times 10^{32}\text{yr} \ \text{(90\% CL)}$$

24 obs. candidates
24.1 exp. bkgd

- Challenge with intranuclear searches is the very short time that the QFC is satisfied for bound neutrons.

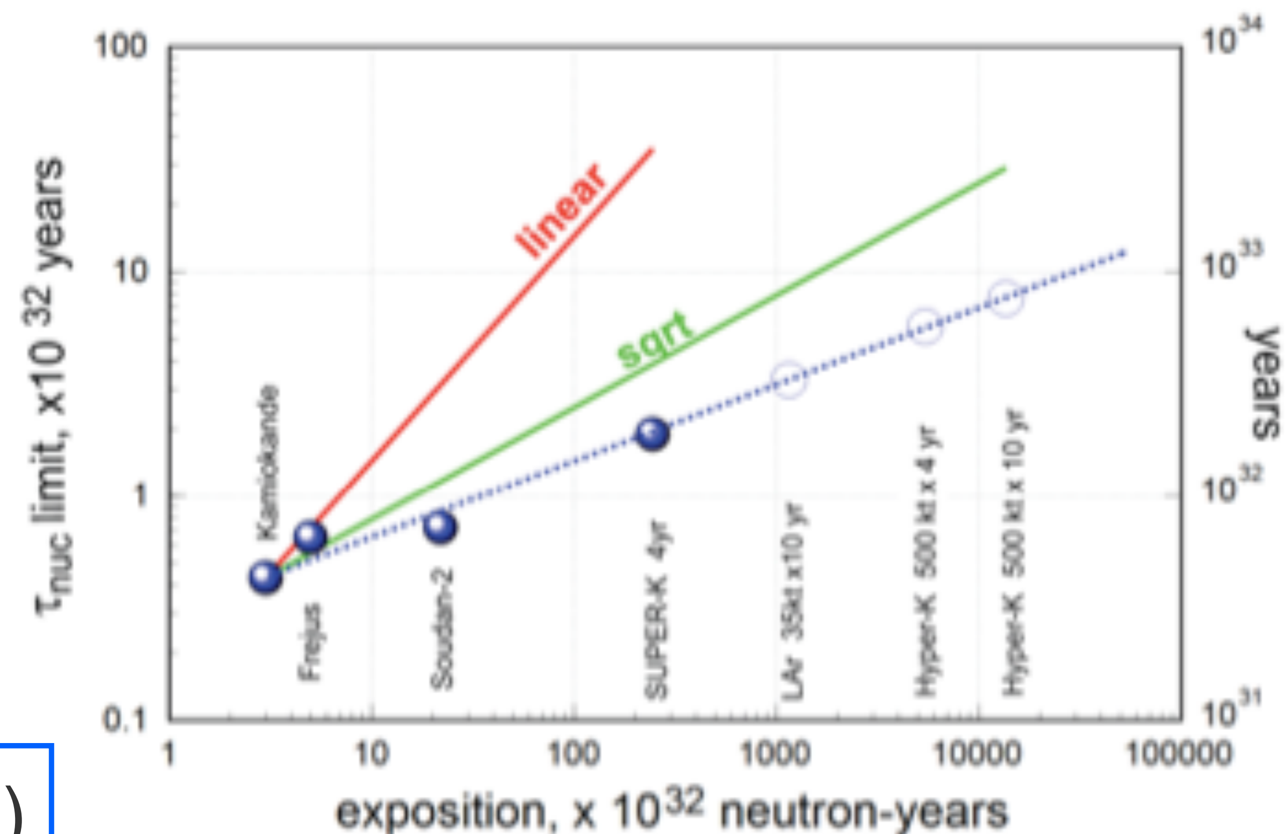
$$\tau_{nucl} = R \times \tau^2_{n\bar{n},free}$$

If $R(^{16}O) = 5 \times 10^{22} sec^{-1}$ [8],

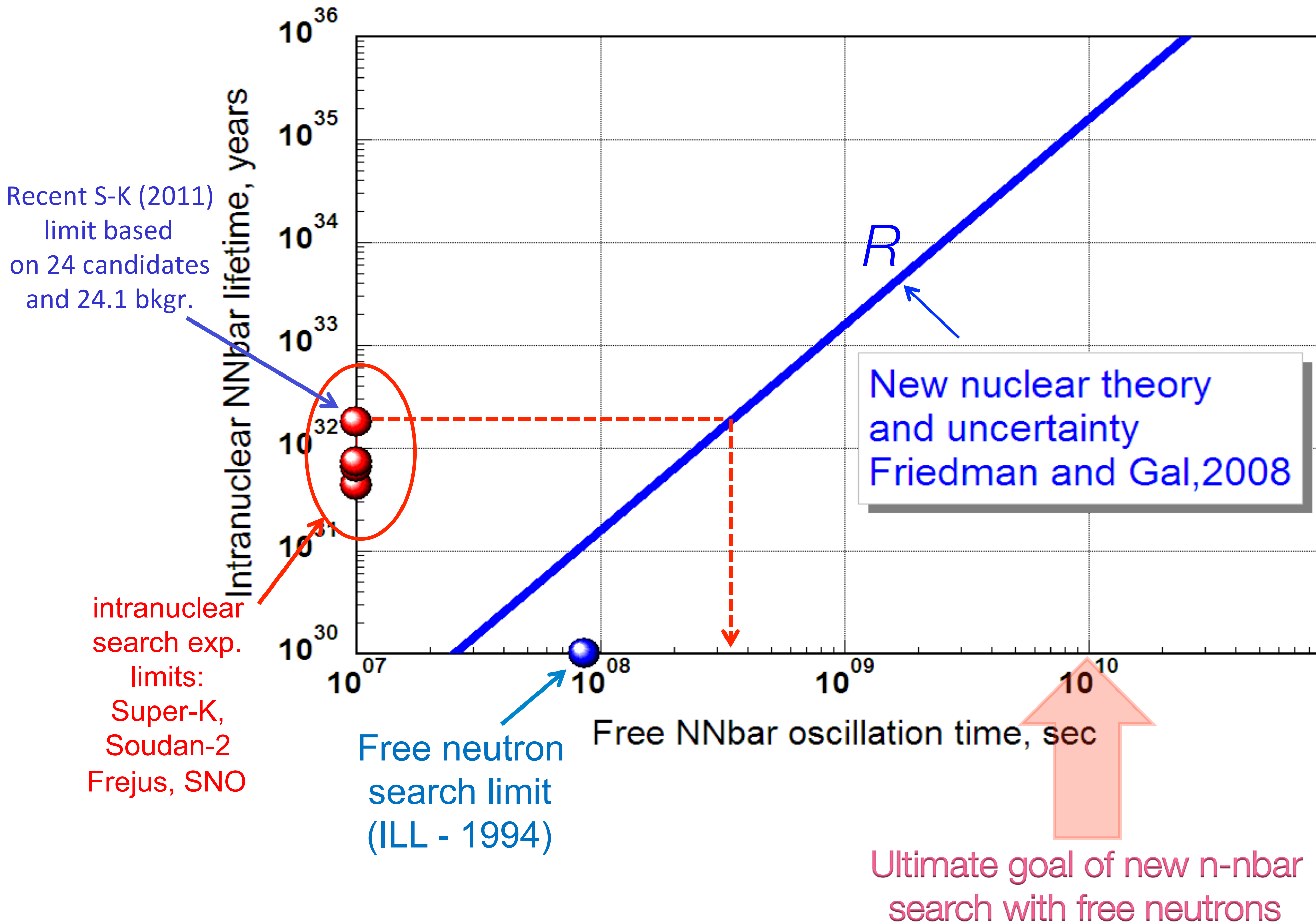
$$\tau_{n\bar{n},free}(^{16}O) > 3.5 \times 10^{8} sec$$

- ILL free neutron NNBar search [1]:

$$\tau_{n\bar{n},free} > 0.86 \times 10^{8} sec \ \text{(90\% CL)}$$

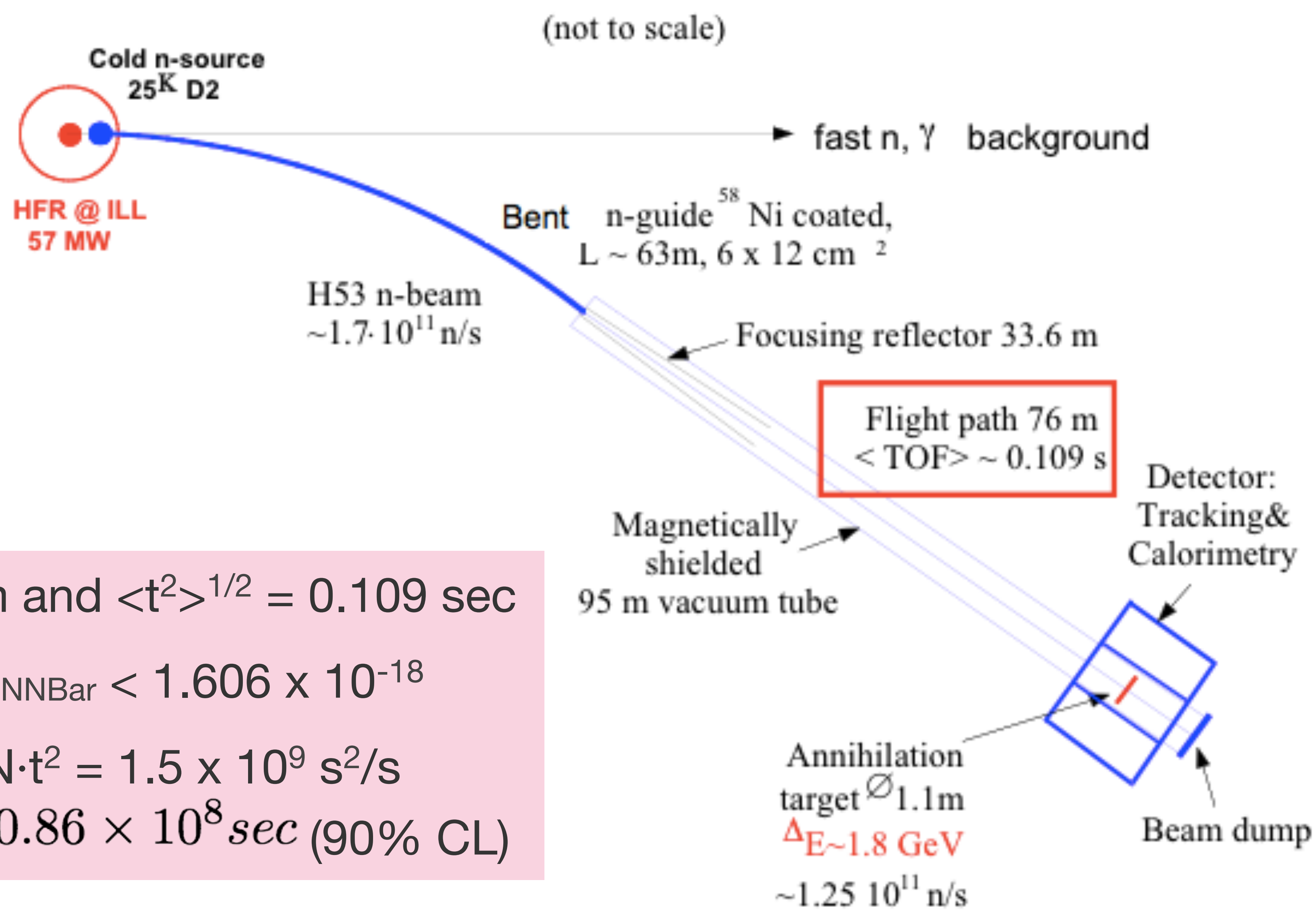


Previous NNBar Oscillation Experiments



Previous NNBar Oscillation Experiments

- Free neutron NNBar search experiment in 1989 - 1991 at ILL/Grenoble reactor by Heidelberg+ILL+Padova+Pavia collaboration [1]:



with L~90 m and $\langle t^2 \rangle^{1/2}$ = 0.109 sec

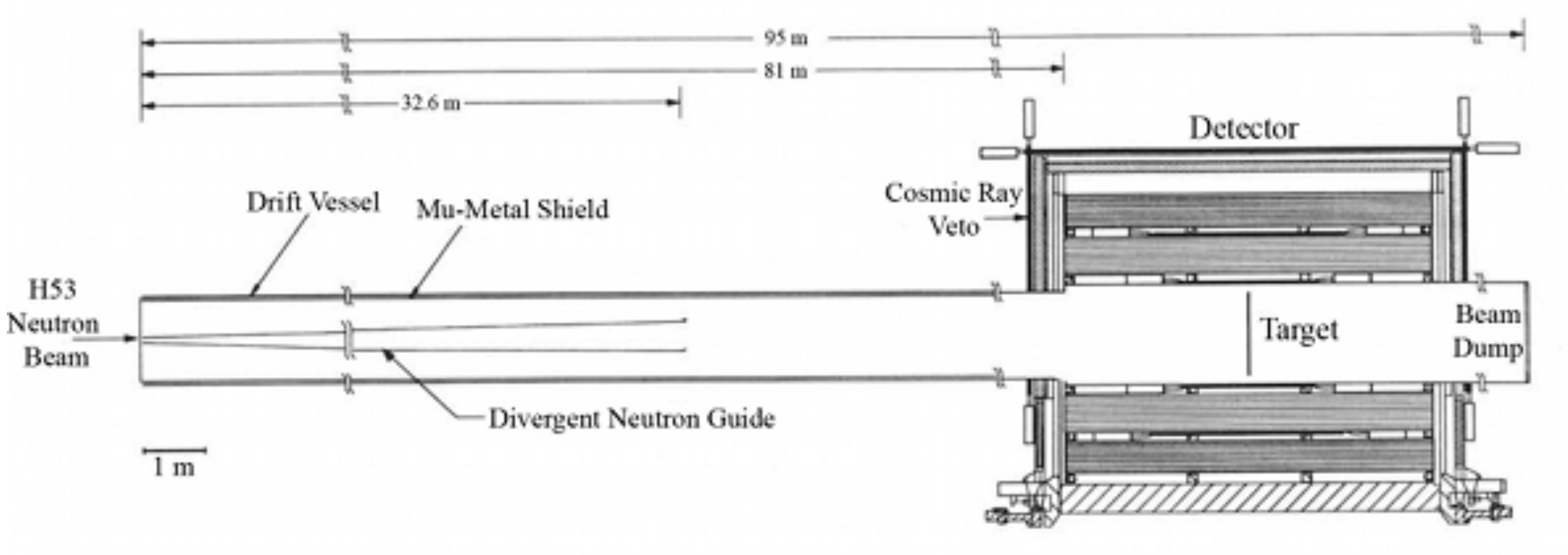
measured $P_{NNBar} < 1.606 \times 10^{-18}$

sensitivity: $N \cdot t^2 = 1.5 \times 10^9\ s^2/s$

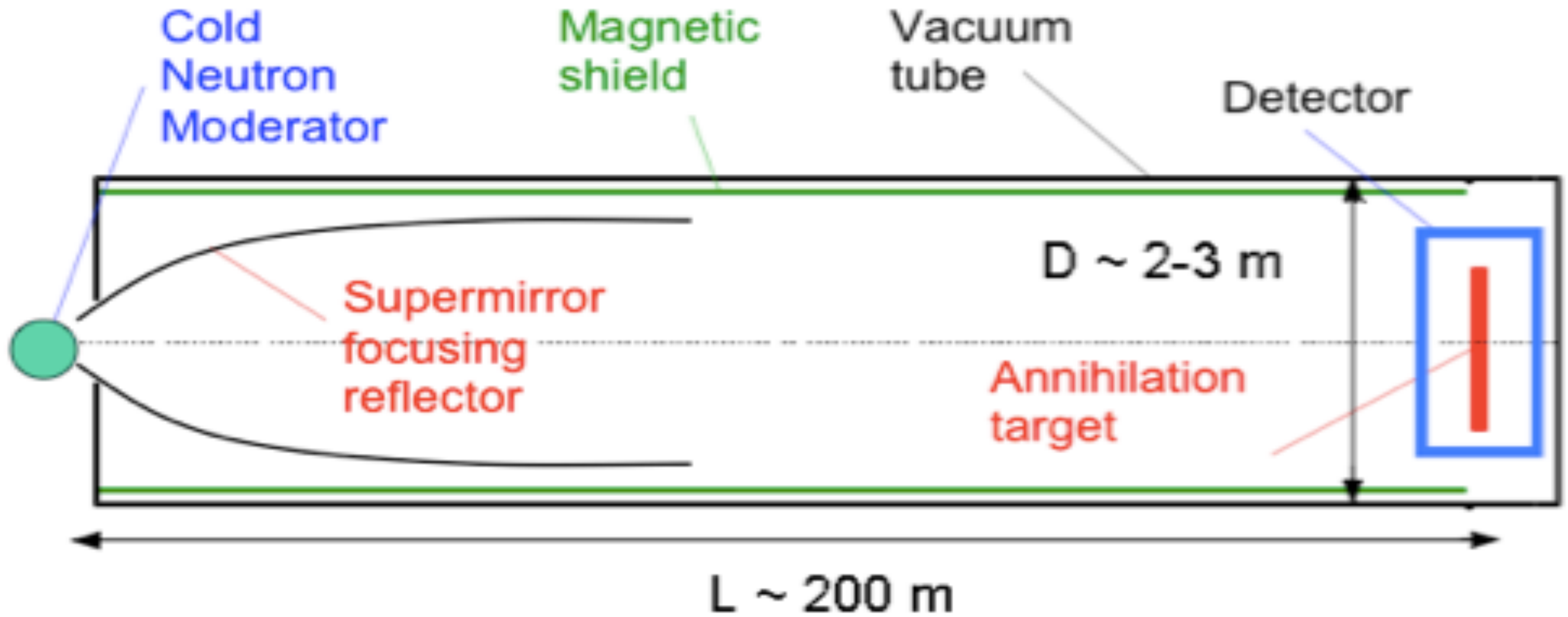
$\tau_{n\bar{n},free} > 0.86 \times 10^8 sec$ (90% CL)

Previous NNBar Oscillation Experiments

- Effective run time = $2.4\text{x}10^7$ s, $N_{events} = 6.8\text{x}10^7$.
- *n-nbar* detection efficiency ($\Delta\Omega/4\pi = 0.94$): 52% ± 2%.
- **No background** & no candidate events after analysis.



Conceptual Horiz. Configuration



Typical initial baseline parameters:	
Cold source configuration	C
Luminous source area, dia	30 cm
Annihilation target, dia	200 cm
Reflector starts at	2 m
Reflector ends at	50 m
Reflector semi-minor axis	2.4 m
Distance to target	200 m
Super-mirror	m=7
Vacuum	$< 10^{-5}$
Residual magnetic field	< 1 nT

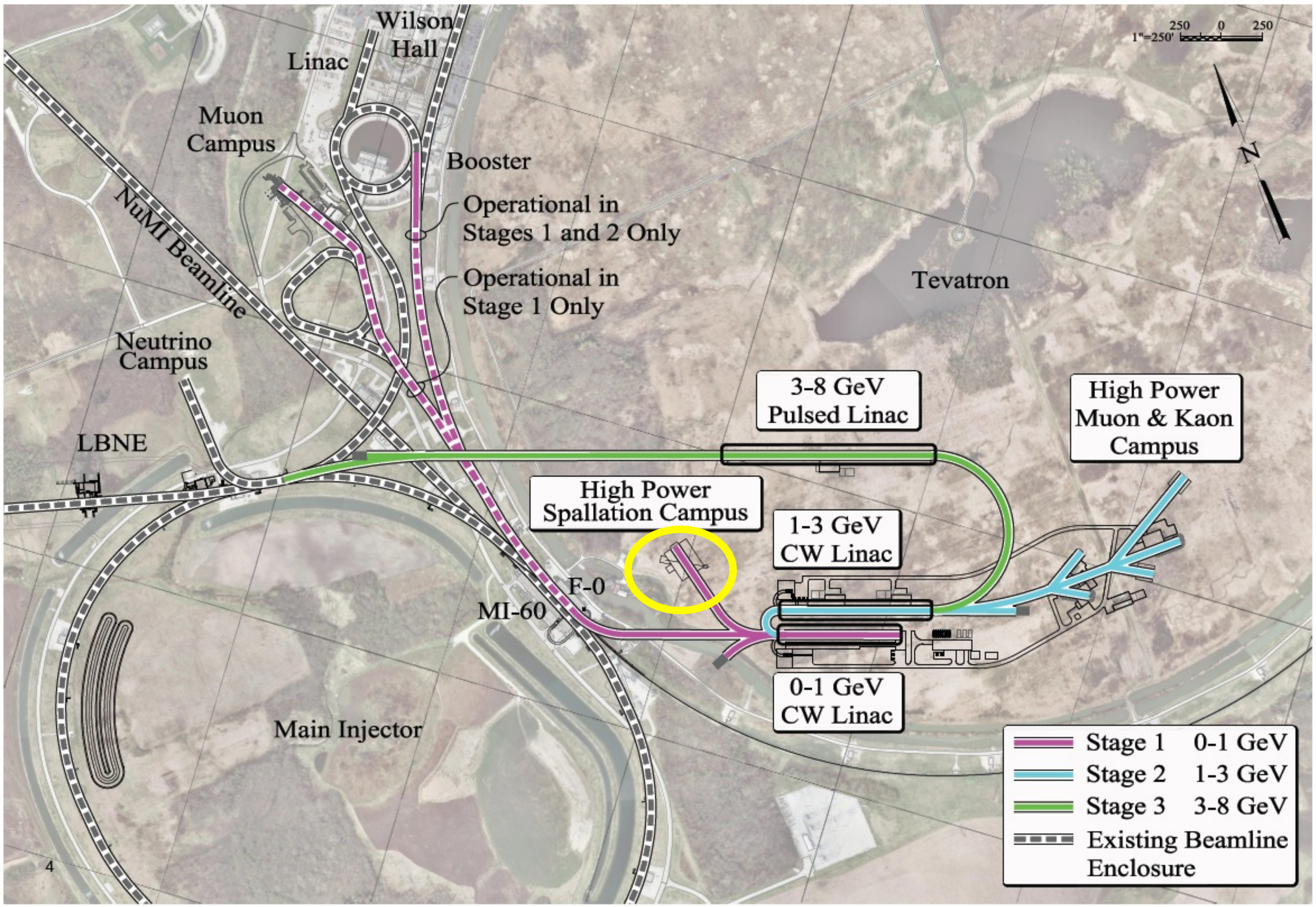
MC Simulated sensitivity Nt^2:

150 "ILL units" x years

Sensitivity and parameters are subject of optimization by Monte-Carlo including overall cost

N-nbar effect can be suppressed by weak magnetic field.

Project X at Fermilab



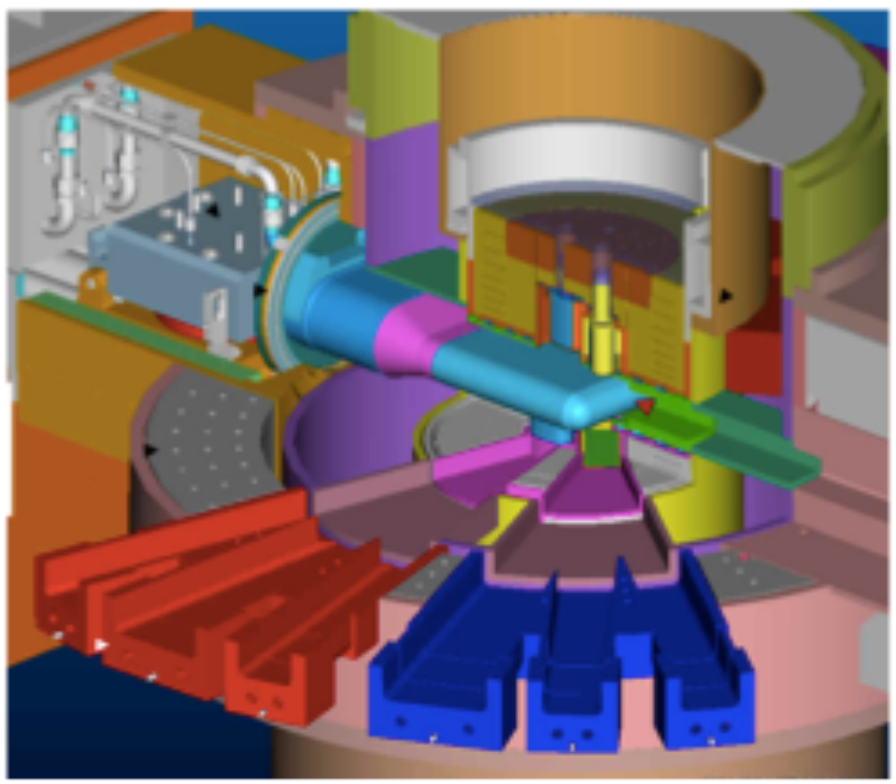
Searching for NNBar at Project X

- Need slow neutrons from high flux source plus access of neutron focusing reflector to cold source.
- Beam for Project X: quasi-CW 1 GeV, 1 MW spallation target
- free flight path of ~200m in horizontal beam line.
- Improvement in transition probability is possible with existing neutron optics technology.
- Cold neutron beam has mean velocity of ~600 m/s.
- Primary signal is 5π's from common vtx. (~200 MeV K.E. each).

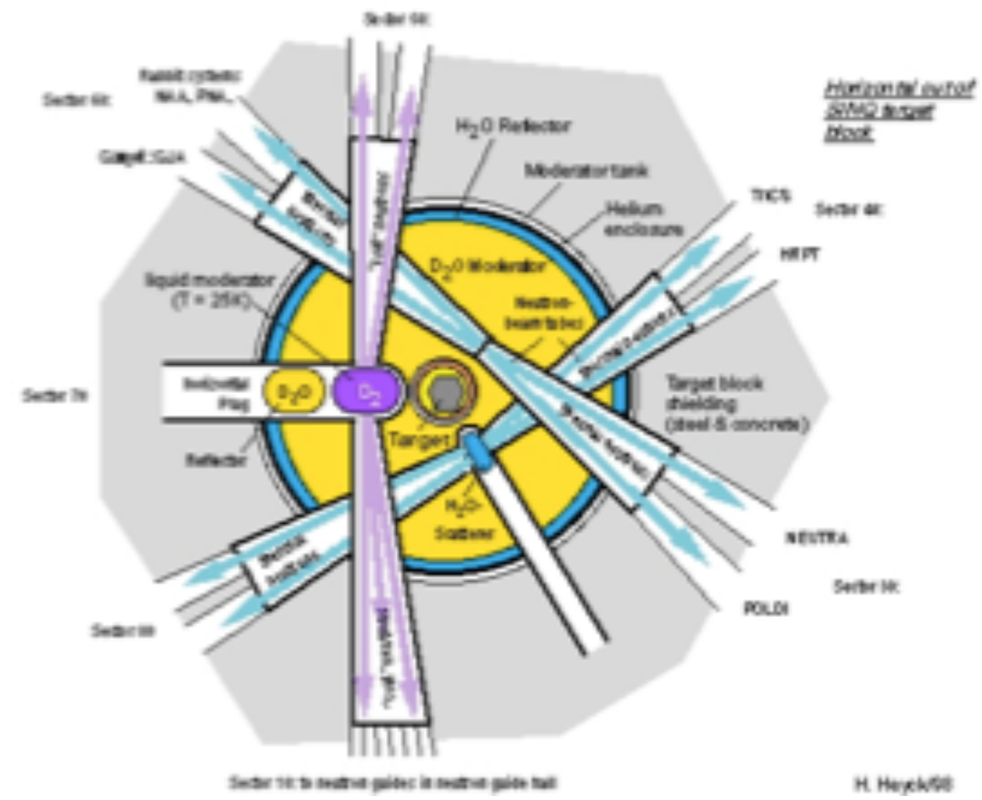
Searching for NNBar at Project X

- Spallation driven cold neutron source (1 MW at Project X).

SNS



PSI



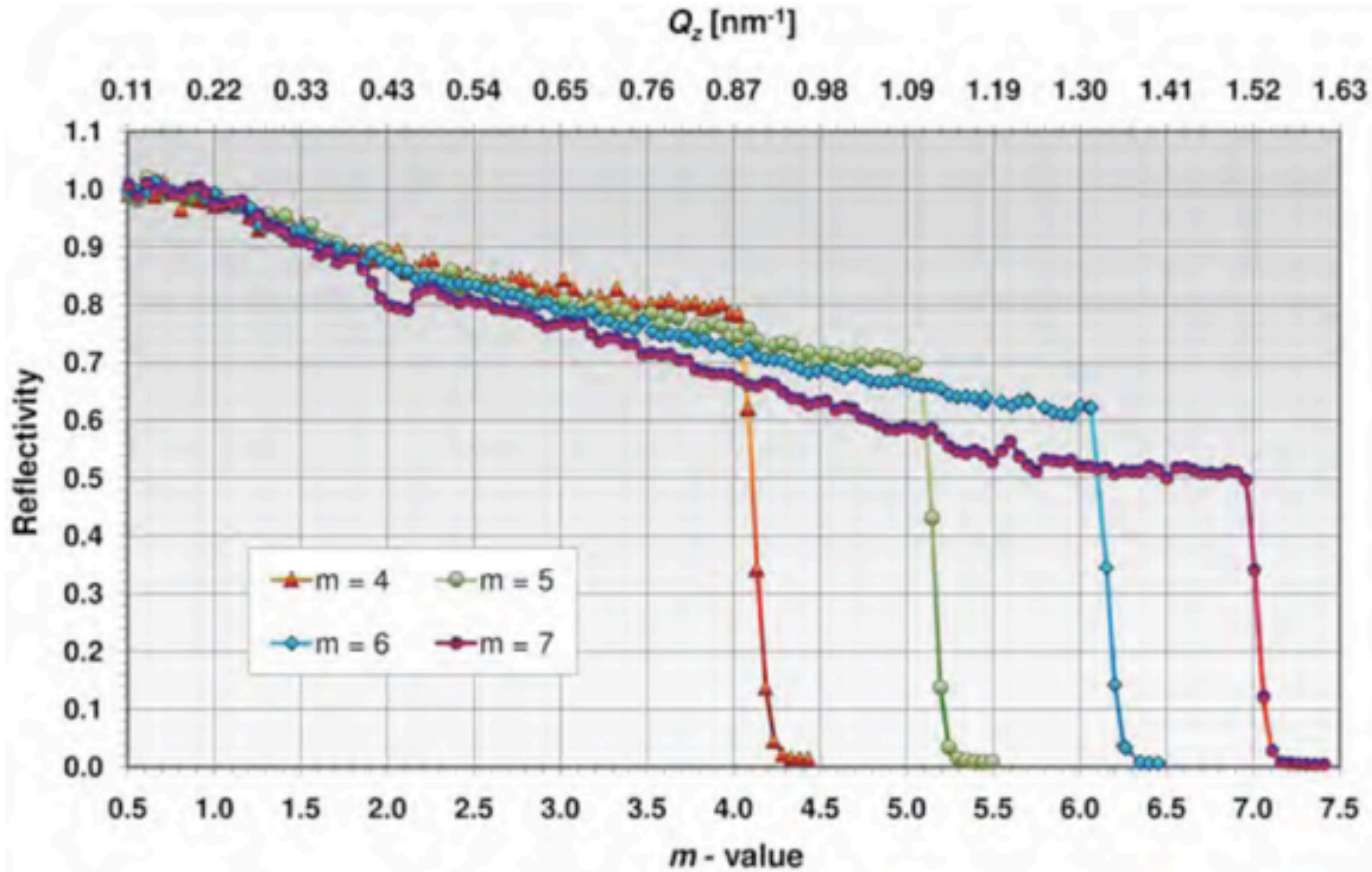
- Focusing neutron optics, high-m neutron guides.

Searching for NNBar at Project X

m=4-7 Supermirrors

http://www.swissneutronics.ch/

Supermirror: commercially available up to m=7 (v⊥=50m/s)



Date(2012/06/18) by(H.M.Shimizu)
Title(Supermirrors)
Conf(Project X Physics Meeting) At(Batavia, IL)

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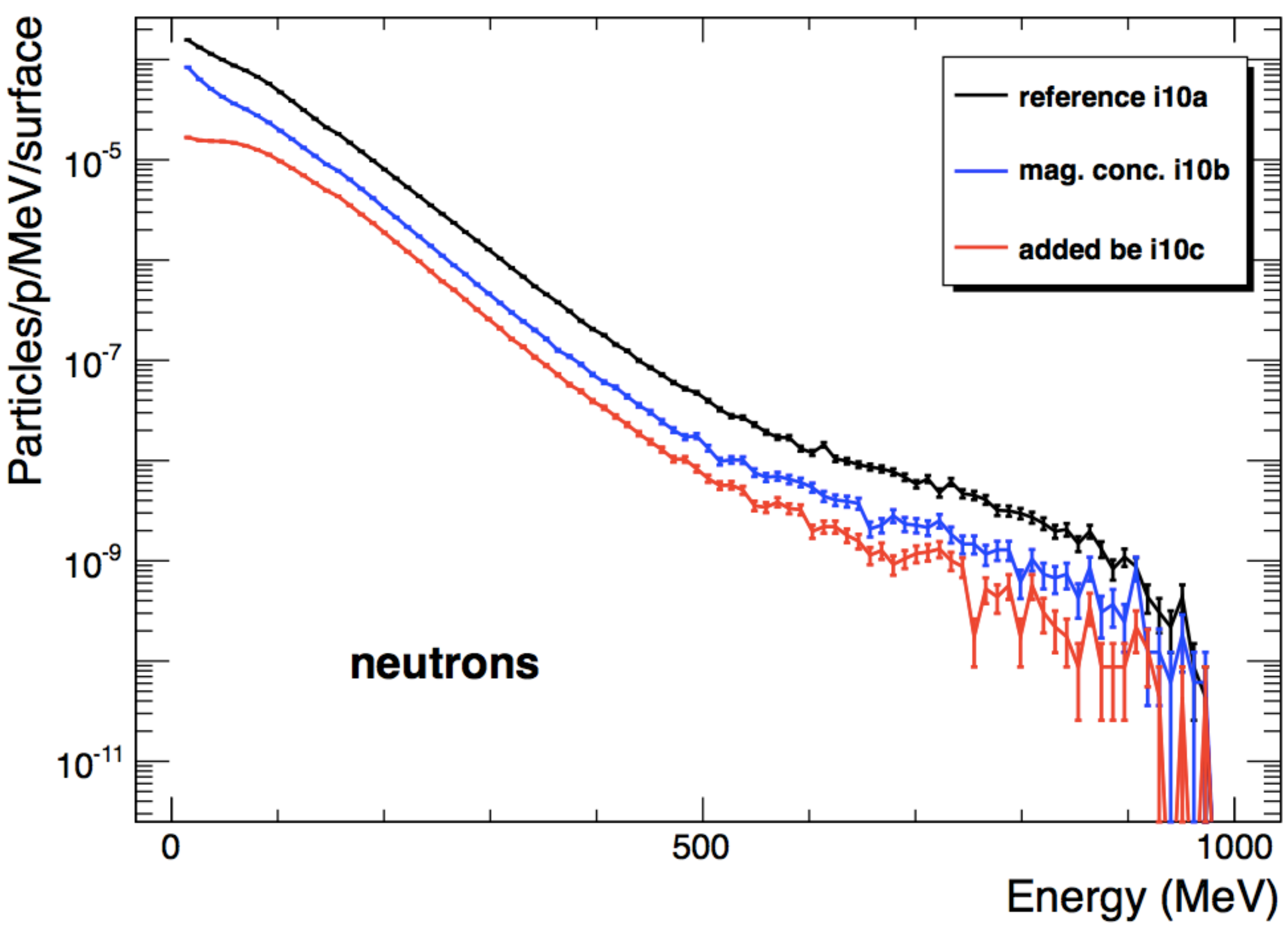
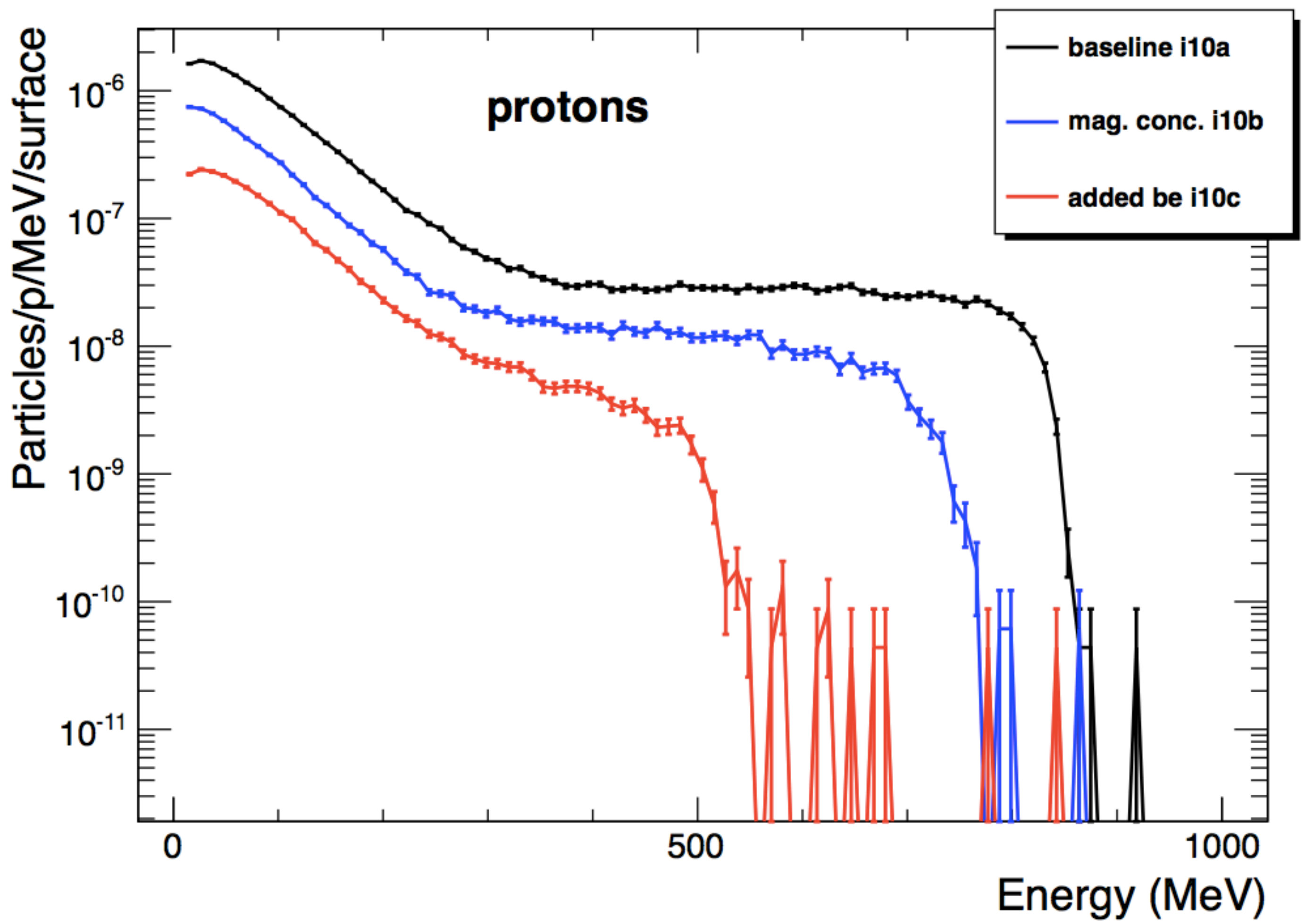
NNBarX Backgrounds

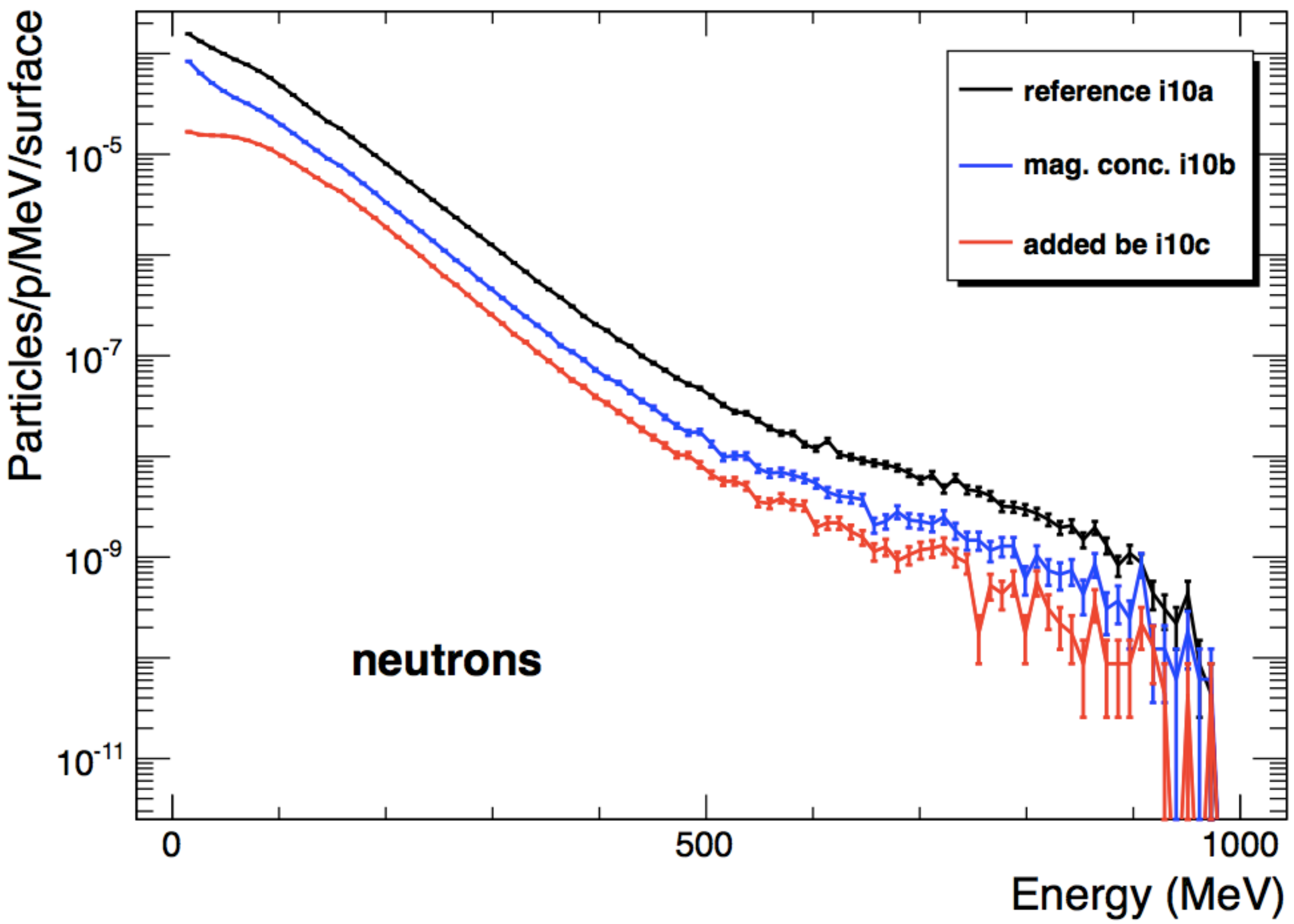
- Quasi-continuous production of fast n's, protons and γ's (MCNPX Simulation – M. Mocko, LANL).





NNBarX Backgrounds

- Quasi-continuous production of fast n's, protons and γ's.

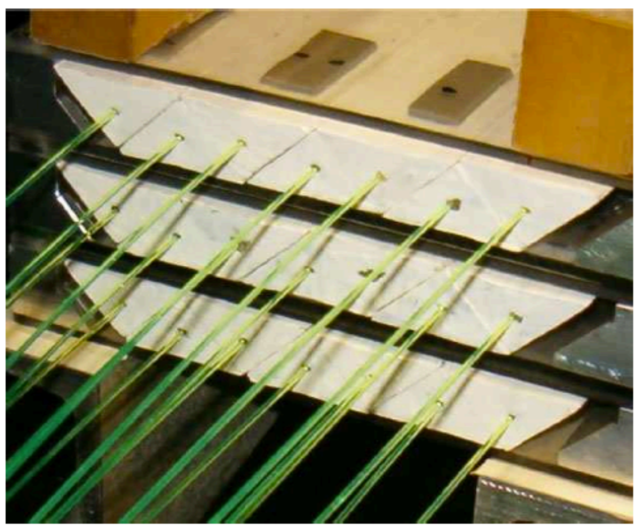


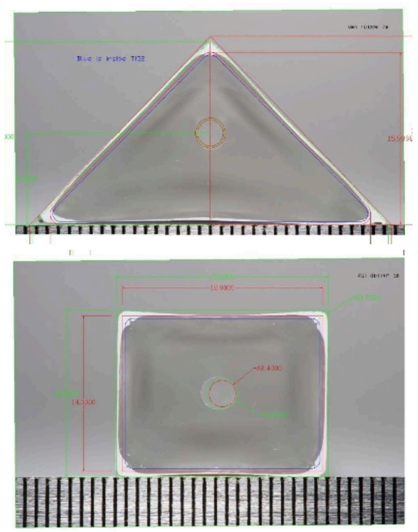
<u>Two scenarios:</u>

1. Beam on always
   - max. CN flux
   - max. fast backgrounds
2. Pulsed beam – e.g 1 ms on, 1 ms off
   - CN flux x 0.5
   - **No** fast backgrounds

NNBarX Scintillator Candidates

MINERVA Extruded Scintillator
(Affordable & Produced at FNAL)

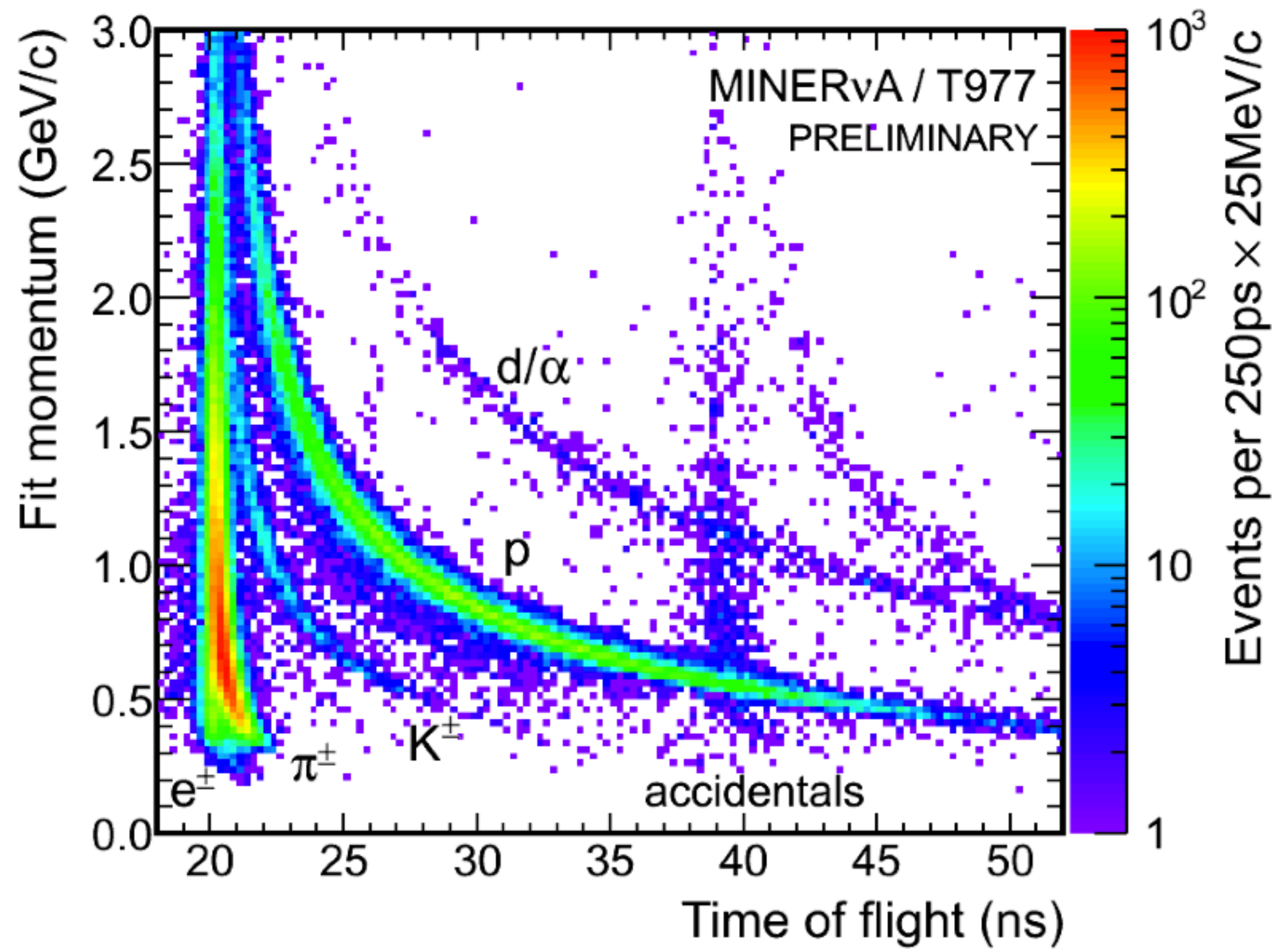




MINERvA images credit: E. Ramberg (FNAL)

PMT or SiPM

Content of Tertiary Beam from TOF System – MINERVA T977 Test Beam Experiment Data



Need to consider add'l alternatives.

NNBarX Tracker Candidates

- Prototype ATLAS TRT module from Indiana U.

- ATLAS TRT – hit precision: ~130 μm, ε ~ 94%, rad. L. = $0.264X_0$ (η = 0) & $0.219X_0$ (η = ±1.8) [18].

- Straw tube fill gas options need to be identified and tested.

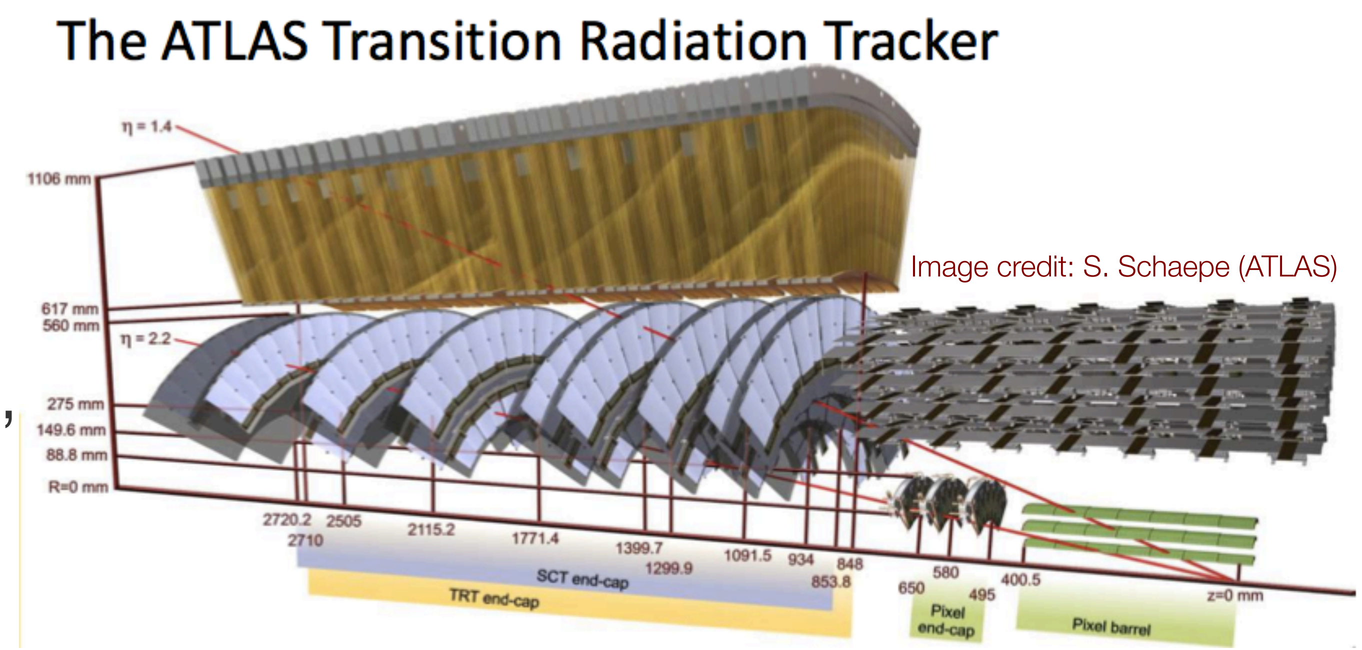
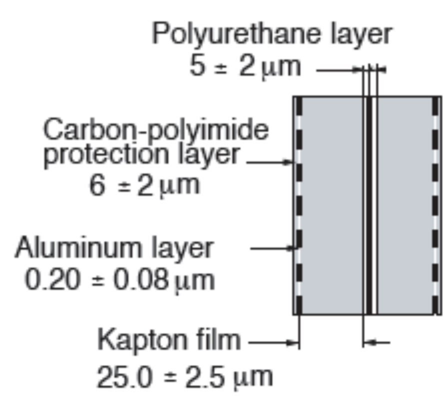


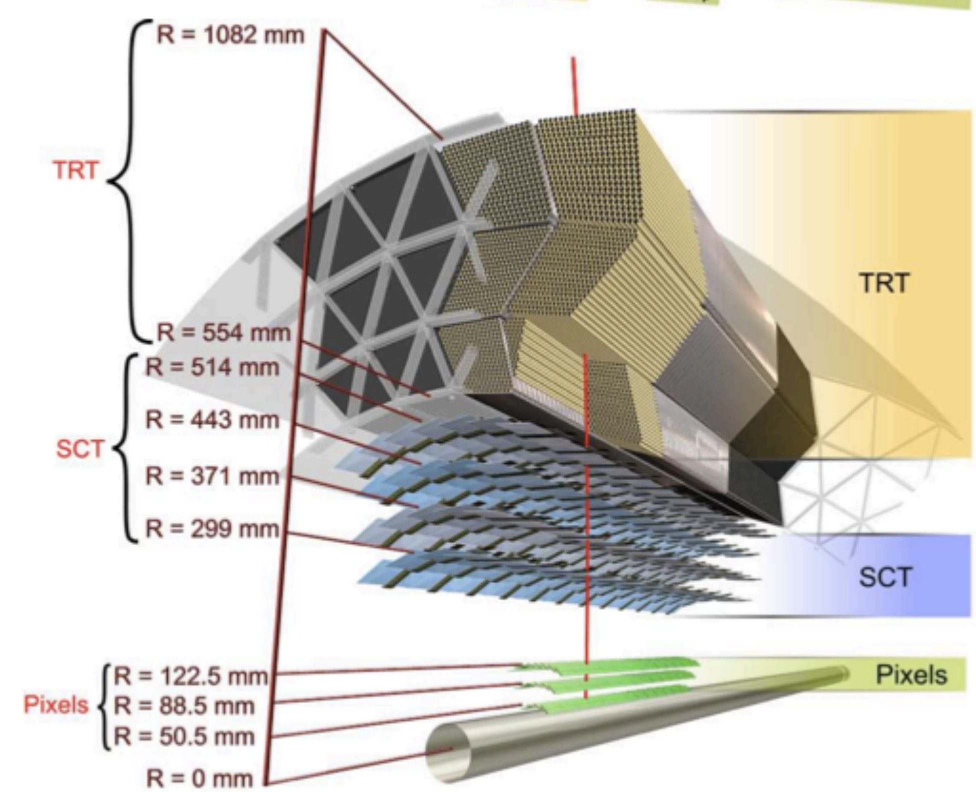
Image credit: S. Schaepe (ATLAS)

Other Options

- Range stack MWPC's.

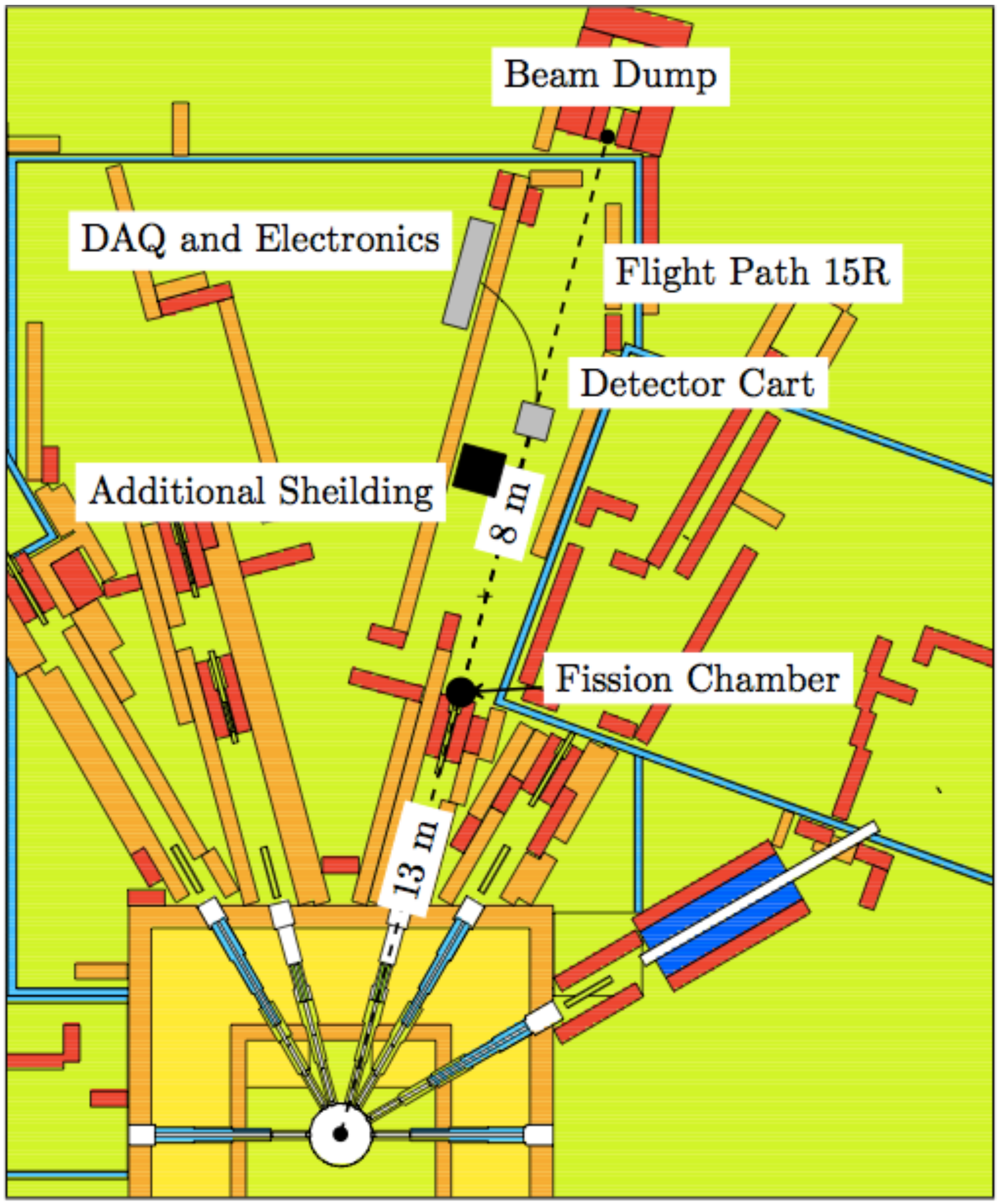
Straw Tube Schematic





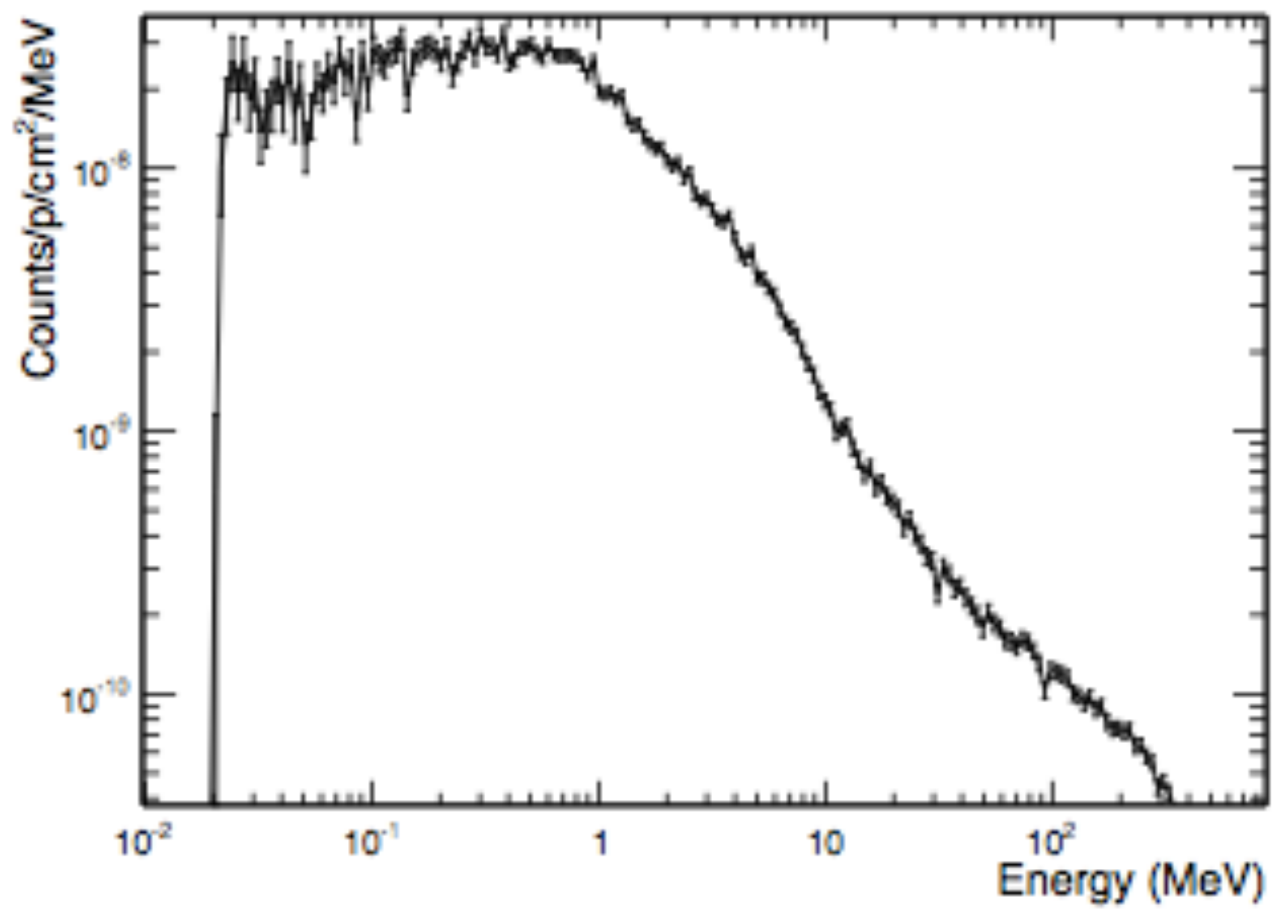
LANL WNR Tests

LANL WNR-15R Beamline



M. Mocko (LANL)

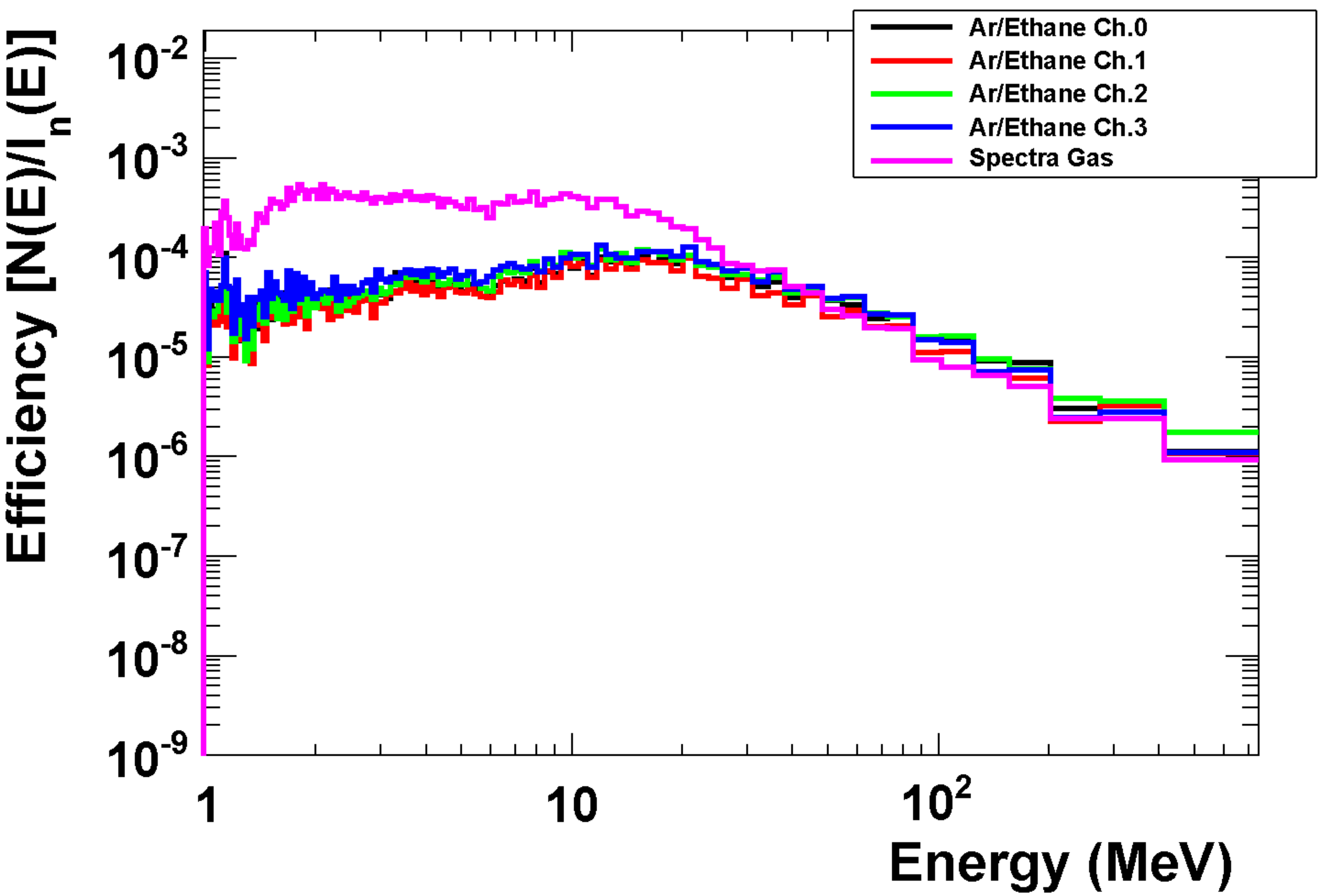
Predicted *n*-flux 20m from target (MCNPX)



Similar to energies that we'll encounter at Project X

LANL WNR Tests

[LANL Proportional Tubes](#)



R. W. Pattie Jr. (NCSU) et al.

- 50/50 Ar/Ethane.
- 50/44/6 Ar/CF_4/Ethane.
- $\varepsilon < 10^{-5}$ (E > 100 MeV)
- Nov. 2013 run:
  - ATLAS TRT
  - MINERvA Extr. Scint.

Searching for NNBar at Project X

Simulation of Antineutron Detector (GEANT4):

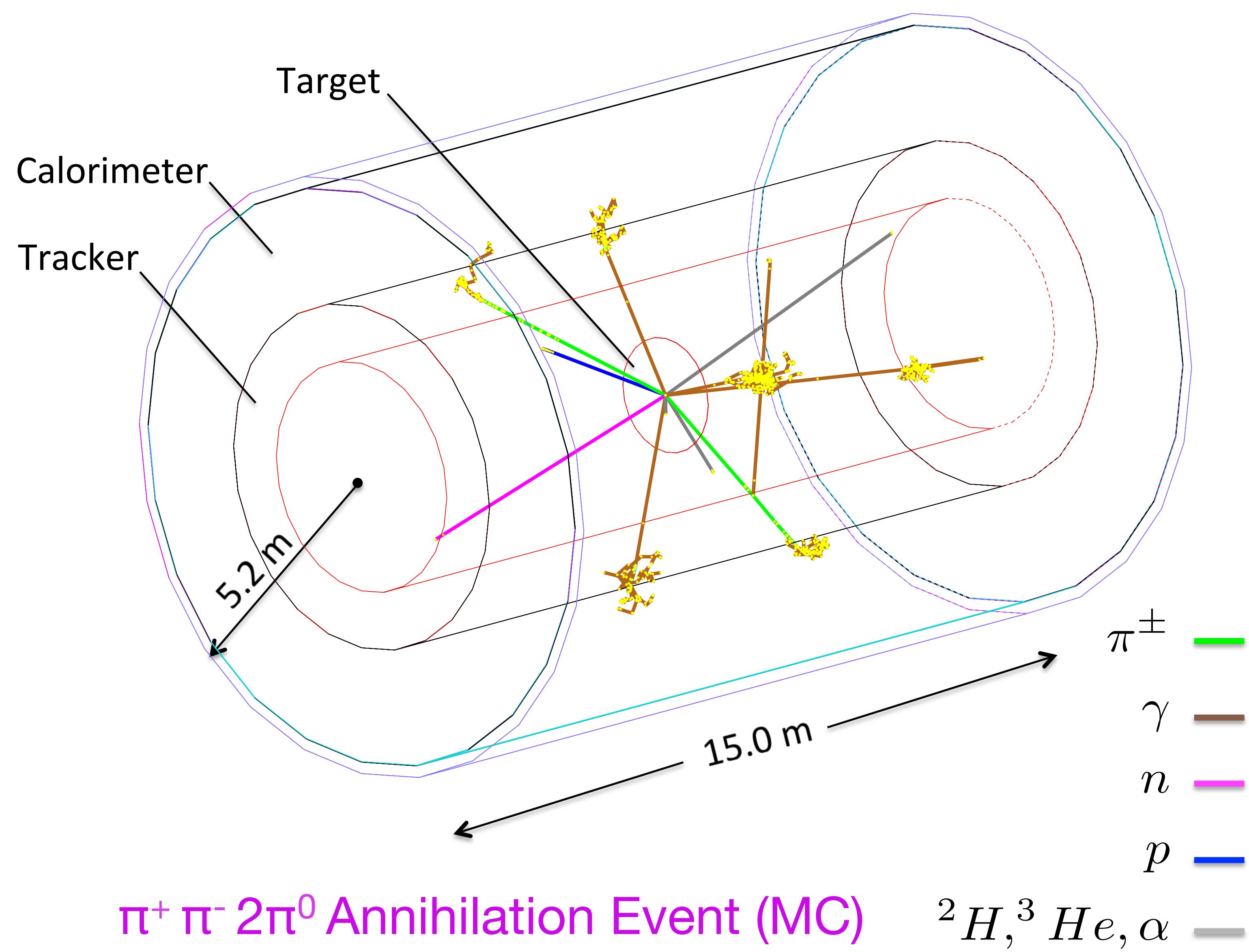
- ~100um thick carbon target.
- Straw-tube tracker.
- Polystyrene calorimeter.

$$\sigma_{annihilation} \sim 4\text{Kb}$$

$$\sigma_{nC,capture} \sim 4\text{mb}$$

$$\bar{n} + A \rightarrow <5> \pi$$

(1.8 GeV)



$\pi^+ \pi^- 2\pi^0$ Annihilation Event (MC)

NNBar Summary

- Large gain in sensitivity over previous free neutron NNBar experiments is possible by upgrading to modern technology.
- If discovered, NNBar observation would violate *B*-*L* by 2, signal new beyond SM physics, and might shed some light on matter-antimatter asymmetry of the universe.
- If not discovered, will set a new limit on stability of "normal" matter via antimatter transformation channel. Will set constraints on *B*-*L* violation.

NNBarX Collaboration

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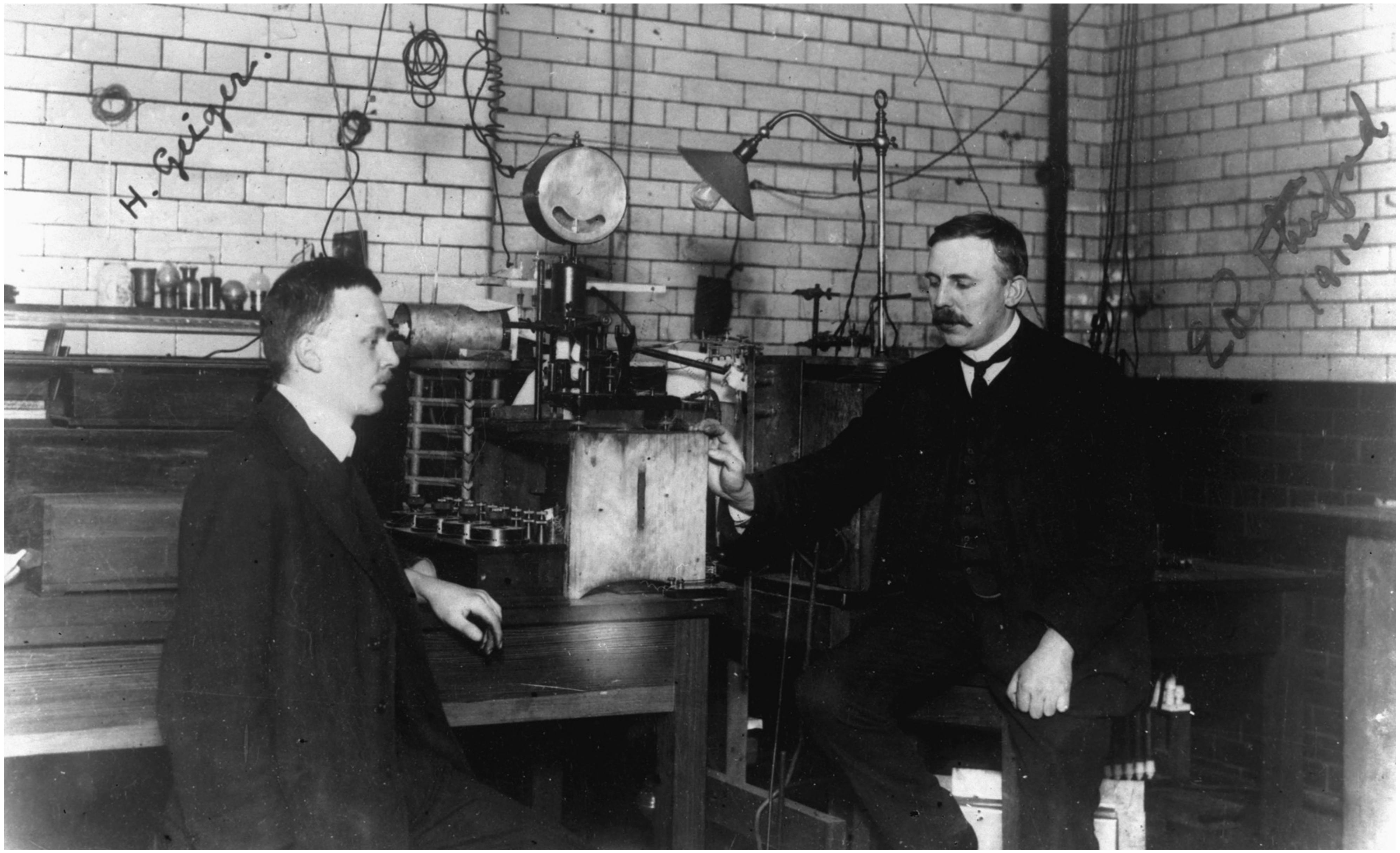
Thank You



"Gentlemen, we've run out of money. It's time to start thinking."

- Ernest Rutherford

References

[1] M. Baldo-Ceolin *et al.*, Z. Phys. C **63**, 409 - 416 (1994).

[2] A. D. Dolgov and F. R. Urban, Nucl. Phys. B **752**, 297 - 315 (2006).

[3] K. Babu *et al.*, PRL **97**, 131301 (2006).

[4] D. G. Phillips II *et al.*, J. Phys.: Conf. Ser. **381** (2012) 012044.

[5] S. R. Elliott, Mod. Phys. Lett. A **27** (2012) 1230009.

[6] E. Cartlidge, Nature **487**, 160 - 162 (2012).

[7] K. Abe *et al.*, arXiv:1109.4227v1.

[8] E. Friedman and A. Gal, PRD **78**, 016002 (2008).

Extra Slides

emiT Experiment

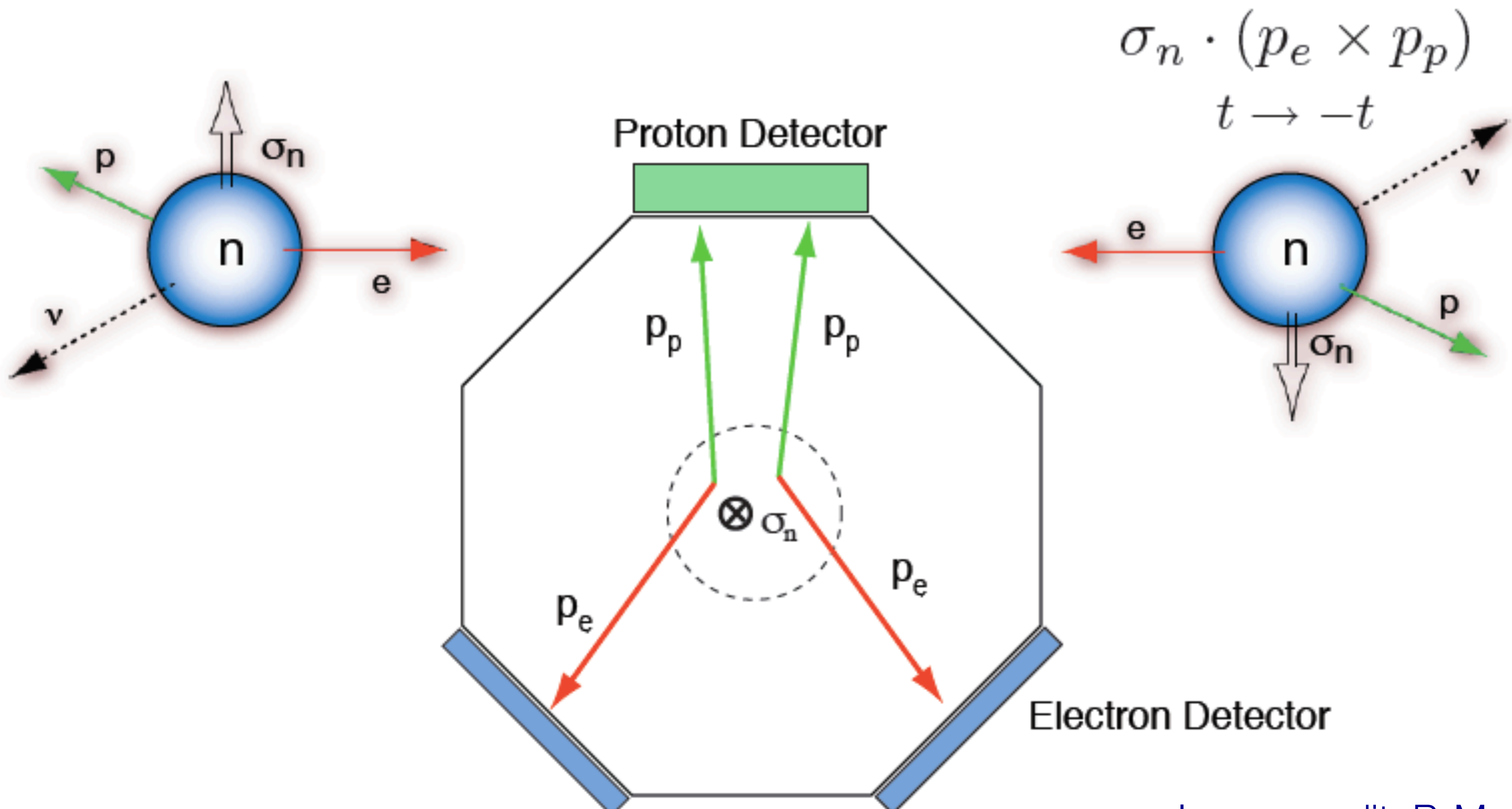
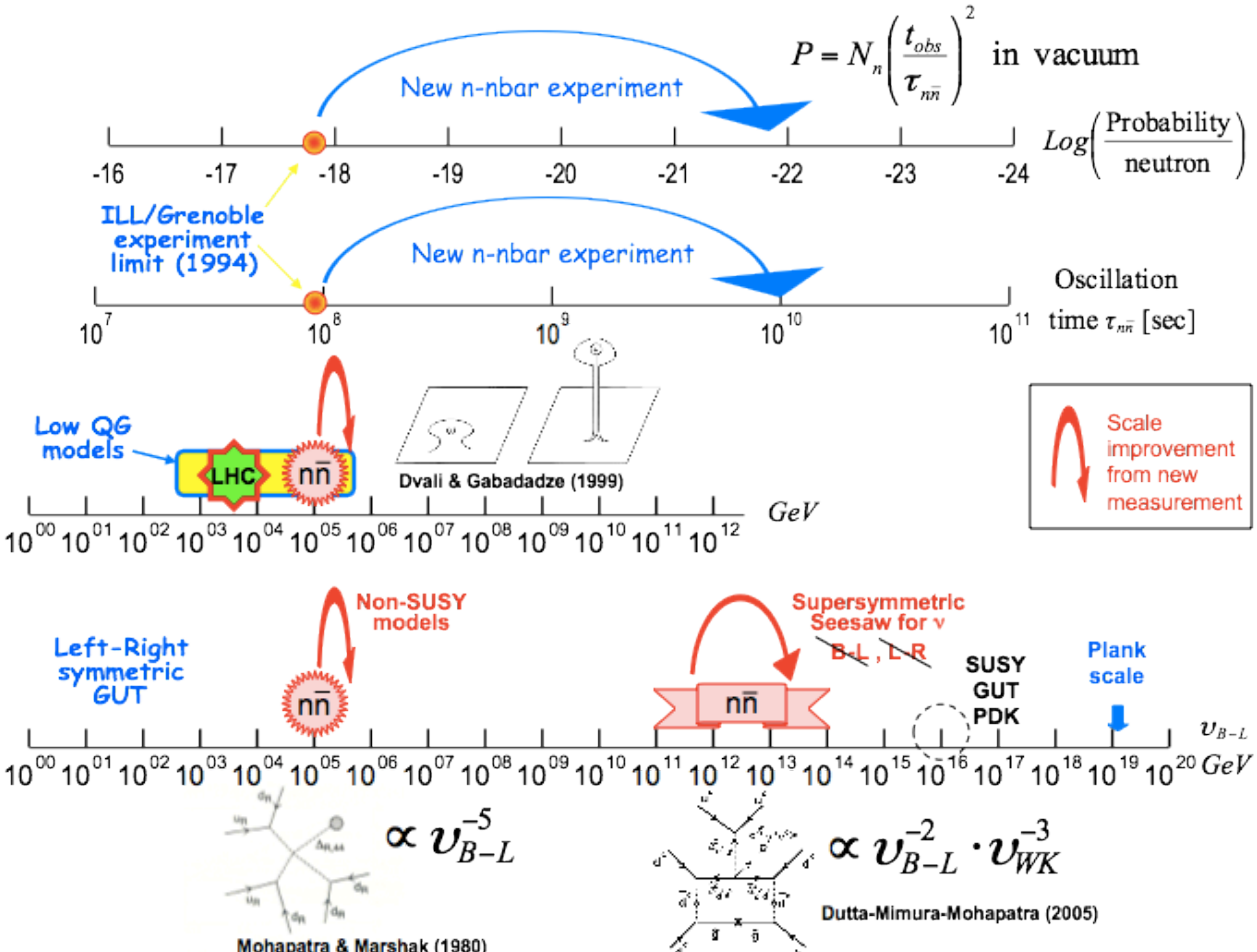


Image credit: P. Mumm (NIST)

emiT Results:

D = [-0.94 ± 1.89(stat) ± 0.97(sys)]10^{-4} *PRC 86, 035505 (2012)*

Scales of NNBar



ILL Triggers, Cuts, Acceptance

Trigger Requirement	Trigger Rate (Hz)
1) Coinc. Of Inner & Outer SC (same det. quad.) in anticoinc. w/CRV.	2000
2) Cond. 1) + 1 track in same vtx. det. quad. as SC coinc.	800
3) Cond. 2) + 1 SC hit (diff. quad.) + 2^{nd} track (in vtx. det. or calor.)	6
4) Cond. 3) + ≥ 120 hits in LST det.	4
Spurious triggers from high beam radiation	2.7
Cosmics w/out CRV trigger	0.3

ε_{trig} = 77%

SW Filter Requirement	Data Acceptance	MC Acceptance
2.0 GeV > E_{vis} > (0.87 ± 0.17) GeV, R_{orig} ≤ 80 cm	10.0%	85.0%
TOF: $T_{SC,OUT} - T_{SC,IN}$ < 5 ns	16.4%	96.0%
Vertex: R_{orig} ≤ 60 cm, |z| < 32 cm, θ_{track} > 170°	1.2%	89.0%
Total	0.018%	72.0%

ε_{filter}

ILL Triggers, Cuts, Acceptance

N_{events} surviving SW Filter: 1.2×10^4

Analysis Requirement	Remaining Events
Incorrectly reconstructed vtx. (visual inspection)	403
Charged CR	335
$R_{orig} \leq 55$ cm, $\lvert z \rvert \leq 15$ cm	5
$E_{vis} > 800$ MeV	2
$y_{vb} > -60$ cm	0

$\varepsilon_{analysis} = 95\%$

$\varepsilon_{trig} \bullet \varepsilon_{filter} \bullet \varepsilon_{analysis} = (52 \pm 2)\%$ [1]