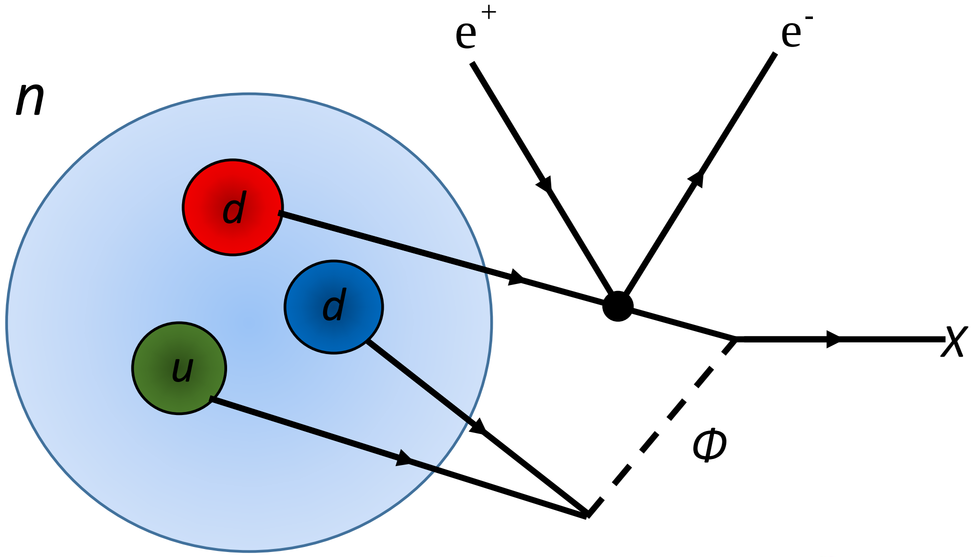
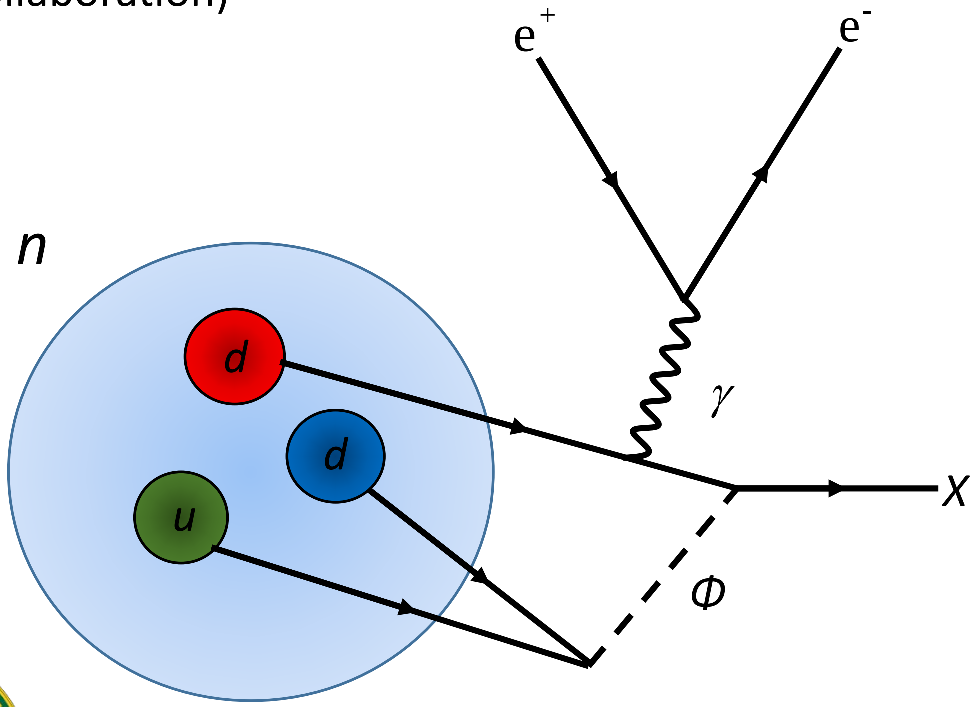
Search for a Dark Matter Decay of the Free Neutron from the UCNA Experiment: $n \rightarrow X + e^{+}e^{-}$

Dr. Christopher Swank
(On behalf of the UCNA Collaboration)





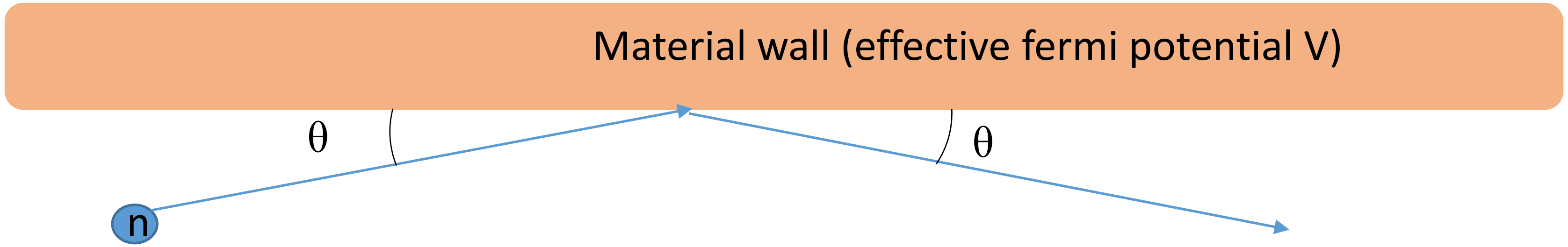
Caltech

Outline

- Ultracold Neutrons
  - Storing neutrons in a box
- Neutron lifetime anomaly
  - Dark decay?
- Search for a dark decay of UCN with the UCNA apparatus.

Ultracold neutrons

- Fermi realized that coherent scattering of slow neutrons (neutrons from a cold source) results in an index of refraction.



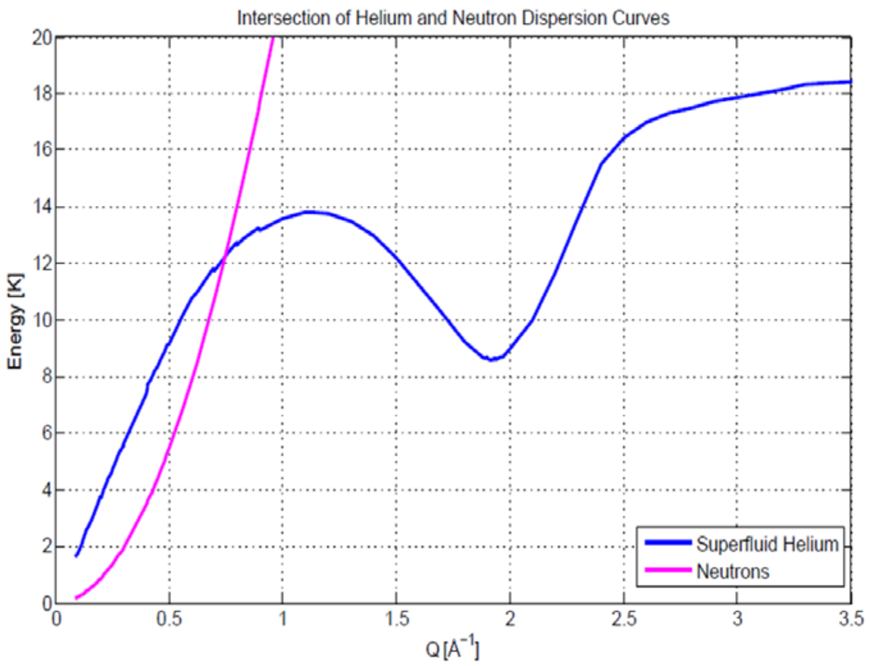
- Total internal reflection when $\theta<\theta_c$ found from

$$E \sin\theta \leq V, \qquad \sin\theta_c = \left(\frac{V}{E}\right)^{\frac{1}{2}}$$

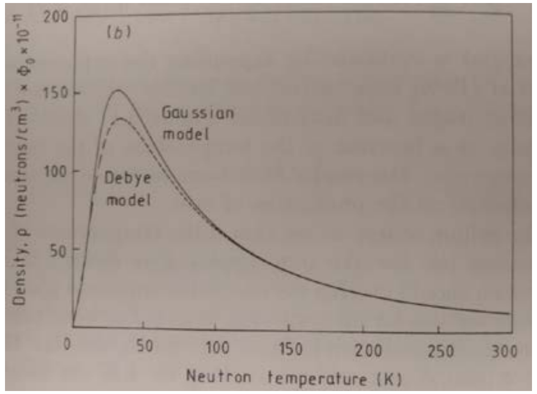
- If $E \leq V$ all angles reflect and neutrons can be trapped in a material bottle. $E \leq V$ is the definition of Ultracold Neutrons (UCN).

UCN production

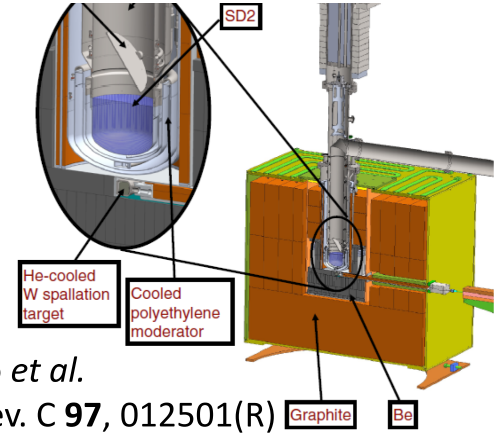
- 3 types of sources of UCN have been implemented.
  - Superfluid Helium, Solid Deuterium, and turbines.



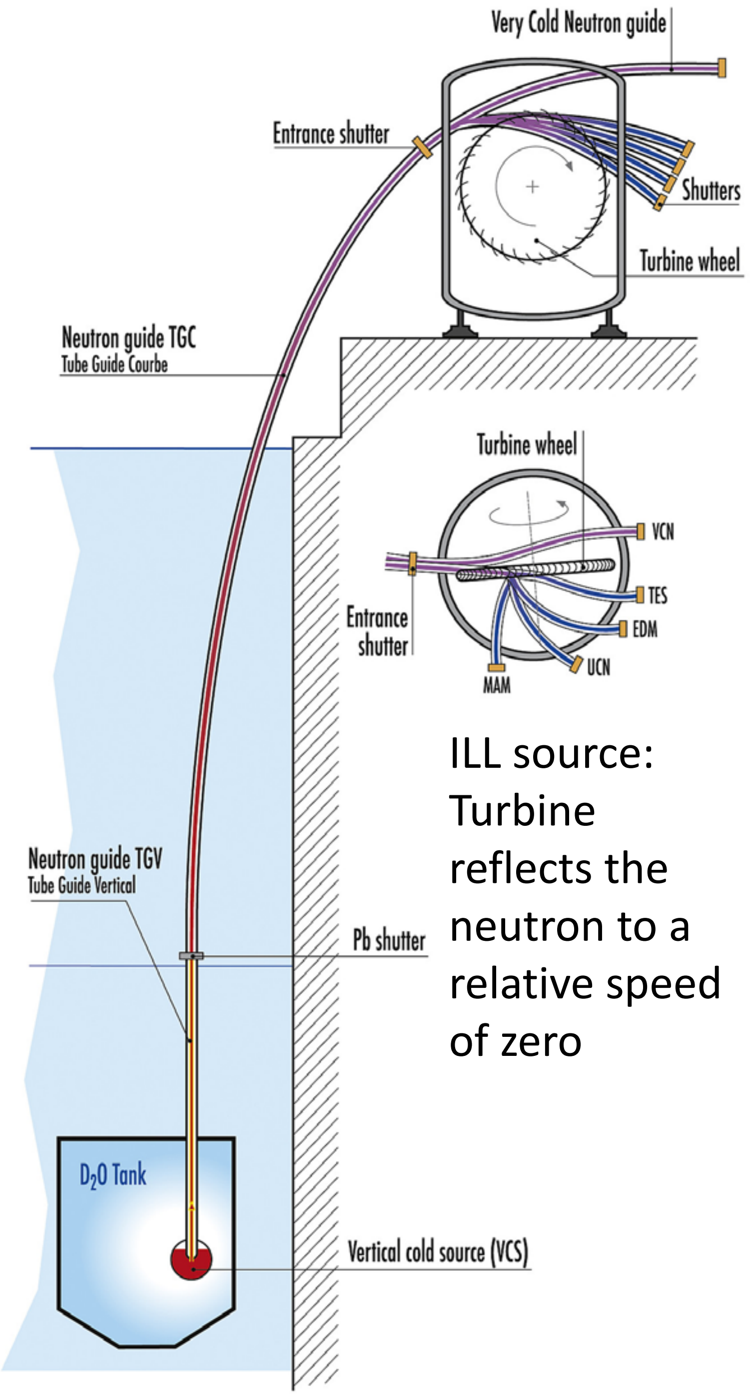
Helium
Monochromatic production around 8.9 Angstrom neutrons.



Solid Deuterium
Distribution of production maximum for neutron temperature of 28 K

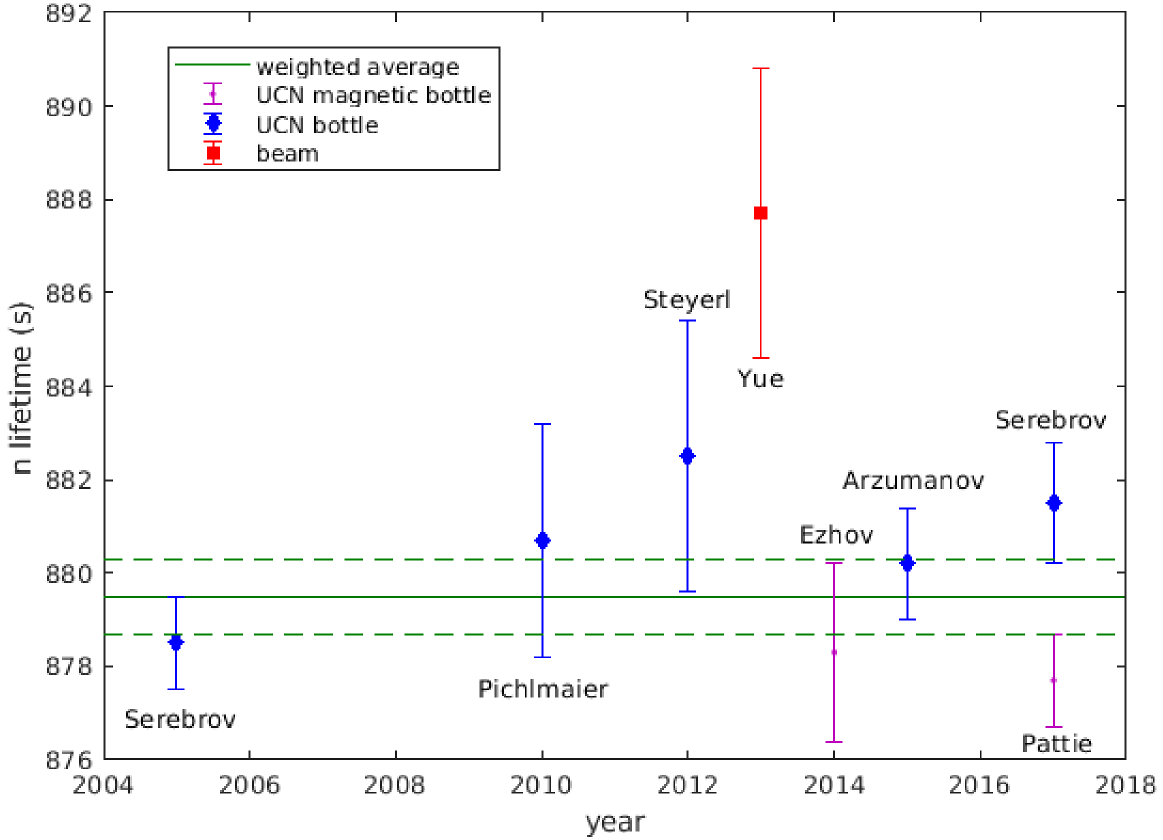


T. M. Ito *et al.*
Phys. Rev. C **97**, 012501(R)



ILL source: Turbine reflects the neutron to a relative speed of zero

n lifetime



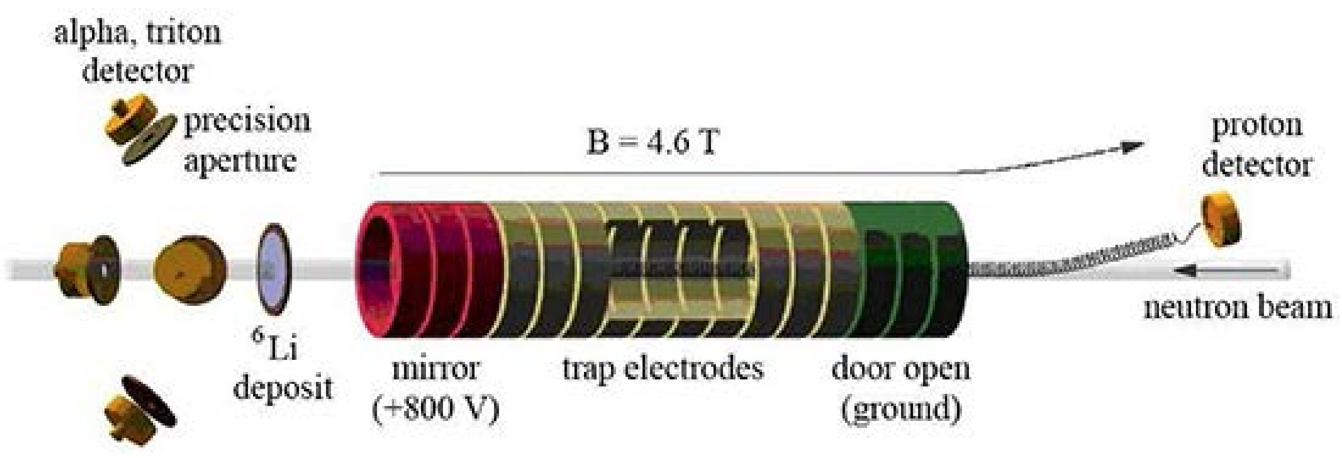
- Measurement method leads to disagreement of 8 s, 1%, or 4.0 σ
- Beam Systematics
  - Beam fluency
    - five fold improvement from last measurement!
- Bottle Systematics
  - Losses on surfaces
  - Marginal trapping

n lifetime

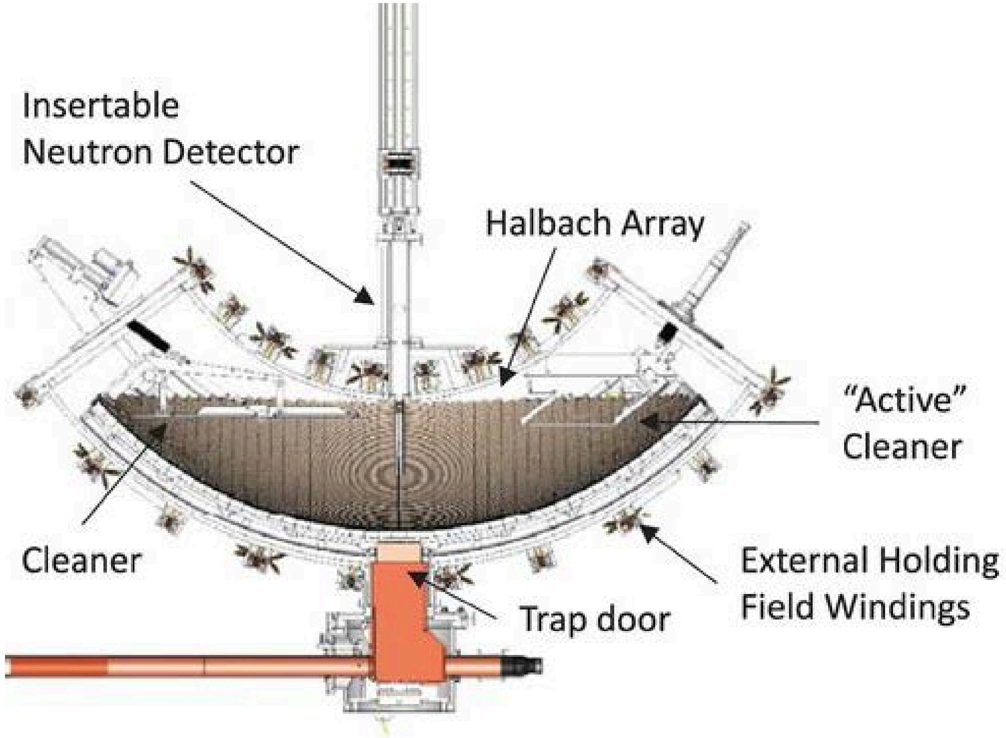
- Fundamental Measurement difference, Beam vs Bottle

Beam measures protons

Bottle measures surviving neutrons



A. T. Yue, et al. [DOI: 10.1103/PhysRevLett.111.222501](https://doi.org/10.1103/PhysRevLett.111.222501)

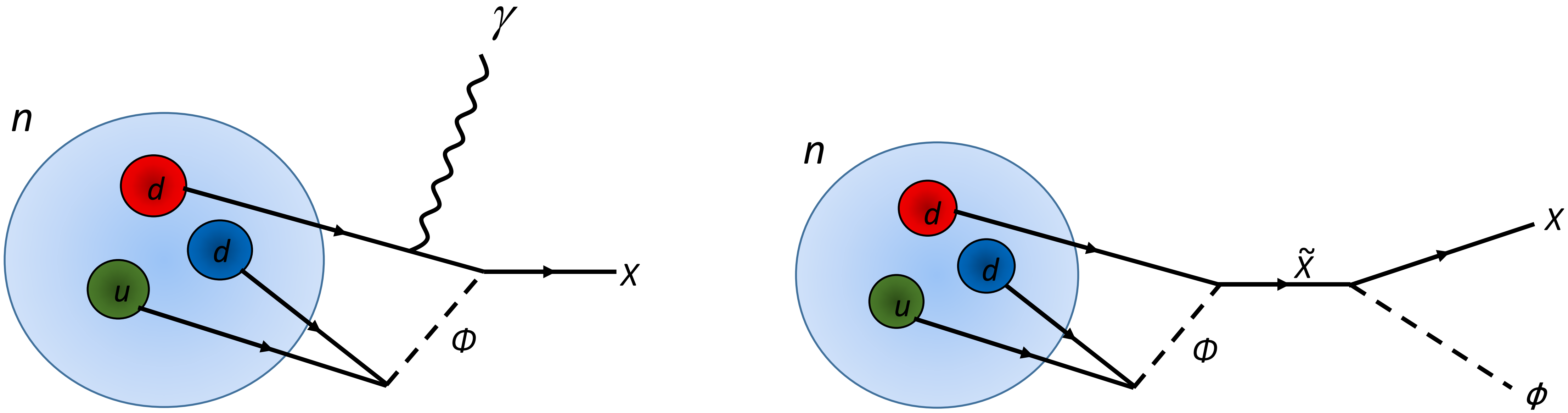


R.W. Pattie, et al. DOI: 10.1126/science.aan8895

Talk by Nathan Callahan 16:10 Wednesday

n lifetime

Discrepancy explained if 1% of neutrons decay to the dark sector



Dark Matter Interpretation of the Neutron Decay Anomaly

Bartosz Fornal and Benjamín Grinstein

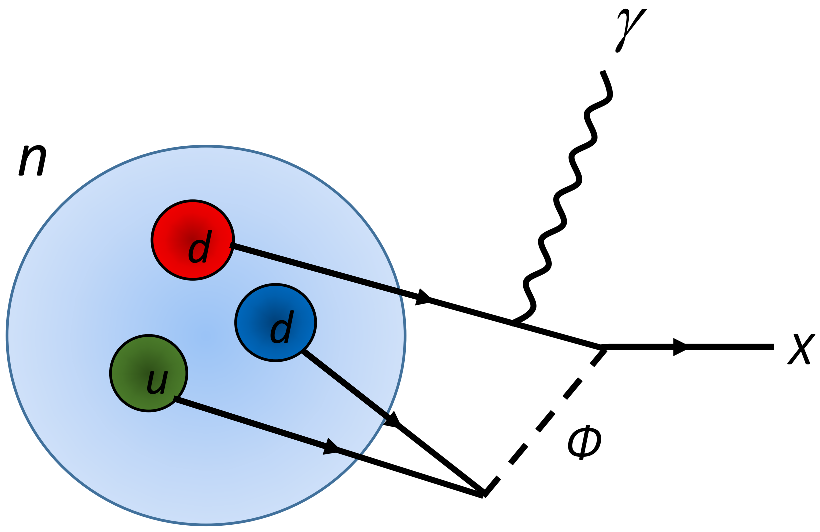
(previous speaker)

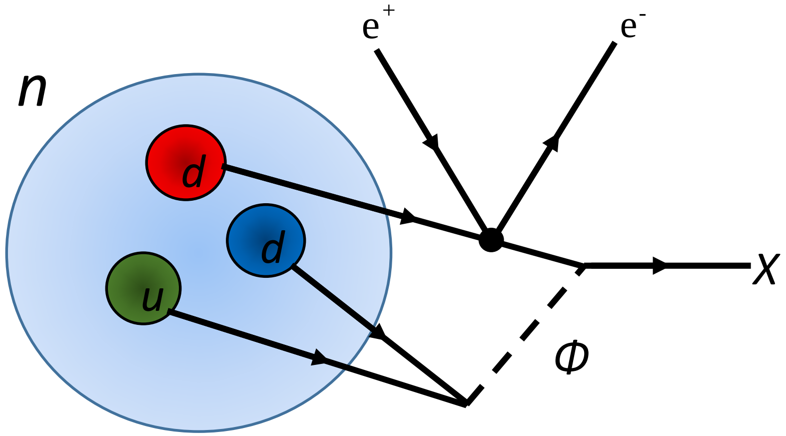
Phys. Rev. Lett. **120**, 191801 (2018)

n dark matter decay

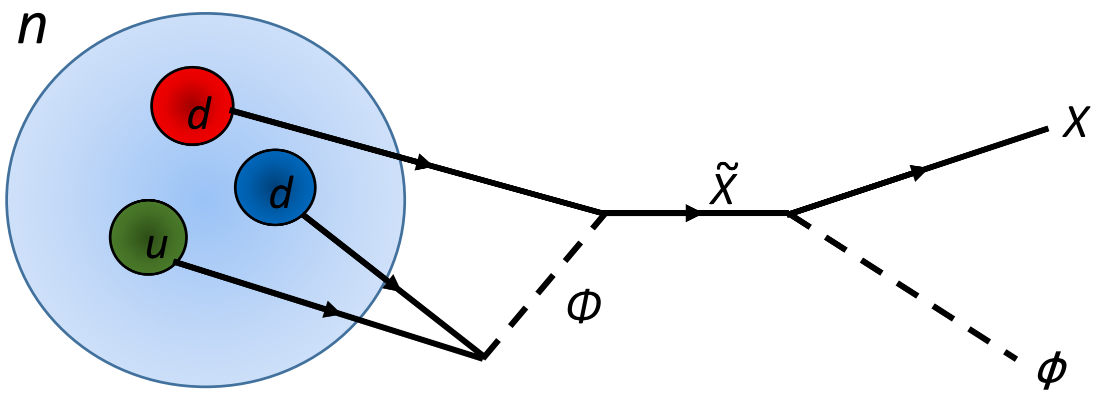
3 decays proposed by Fornal and Grinstein

2 are detectable (with modern technology)





1 is a purely dark decay



n dark decay

3 decays proposed by Fornal and Grinstein

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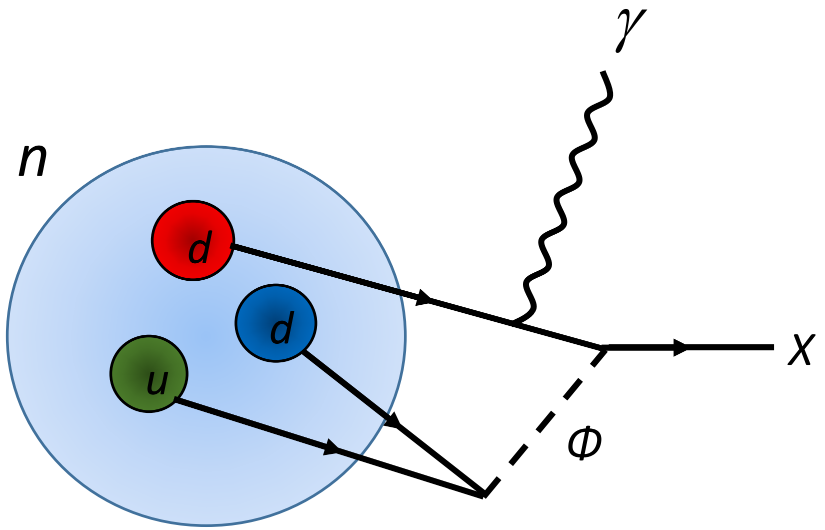
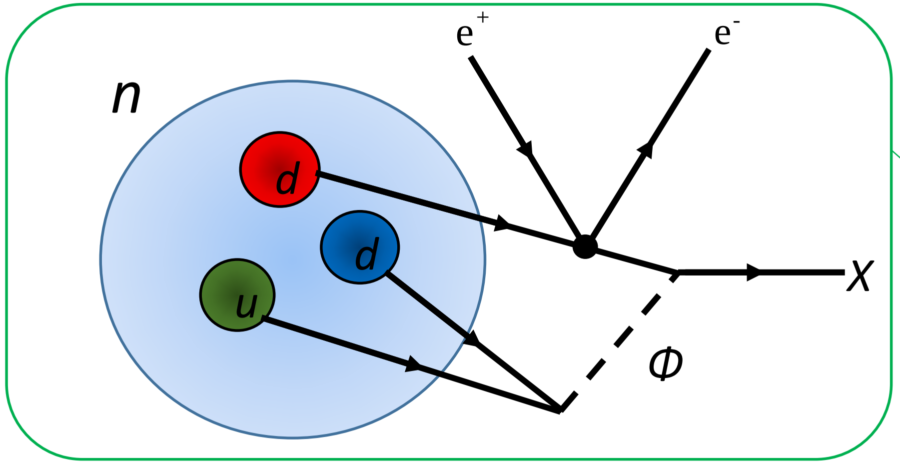
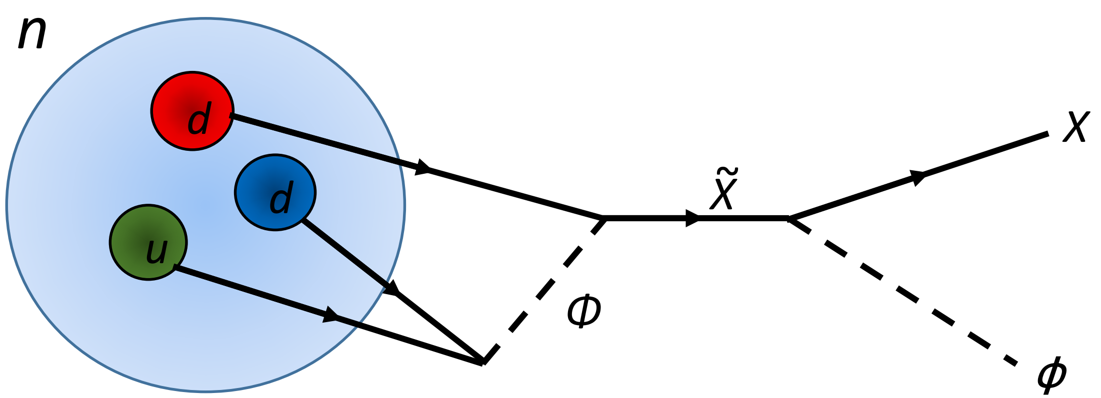




1 is a purely dark decay

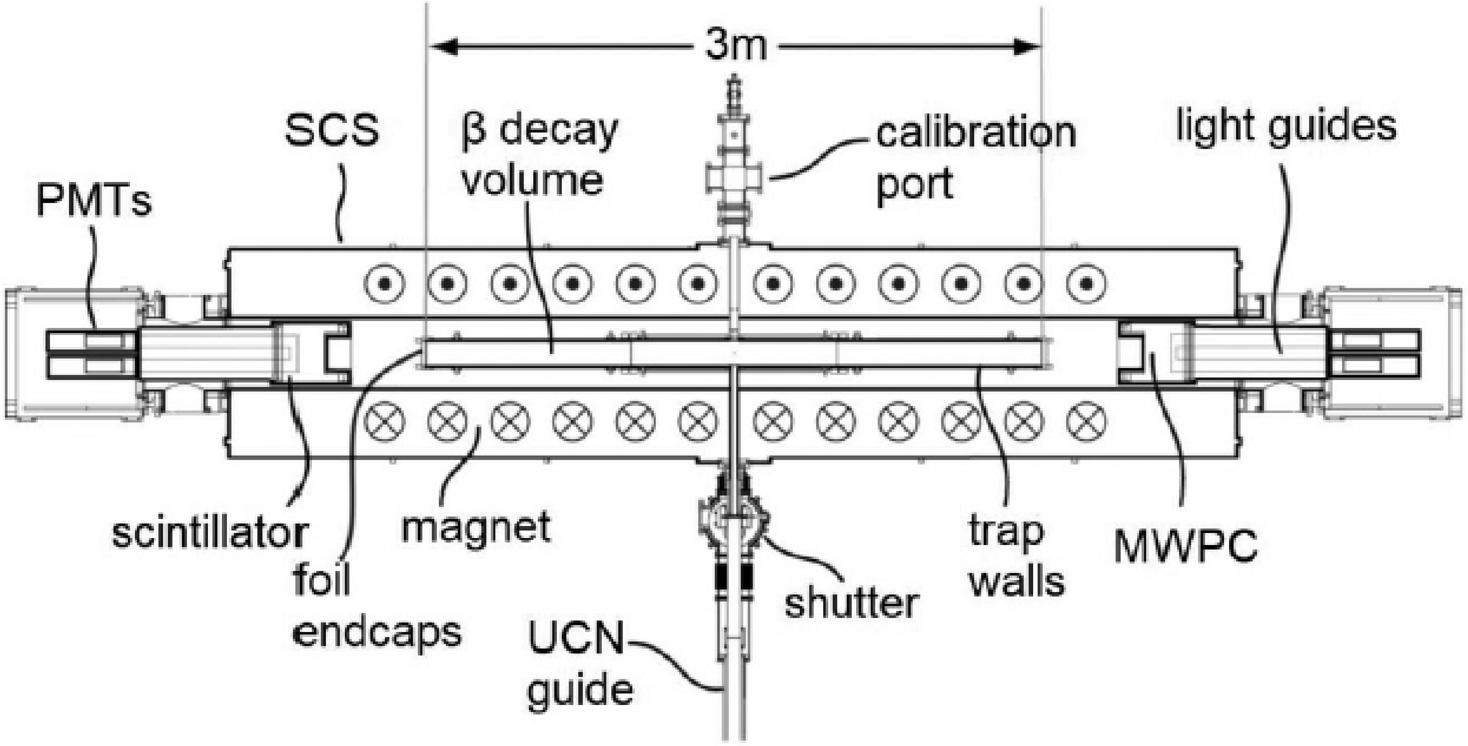


UCNA apparatus has sensitivity to this proposed decay.

UCNA Experiment

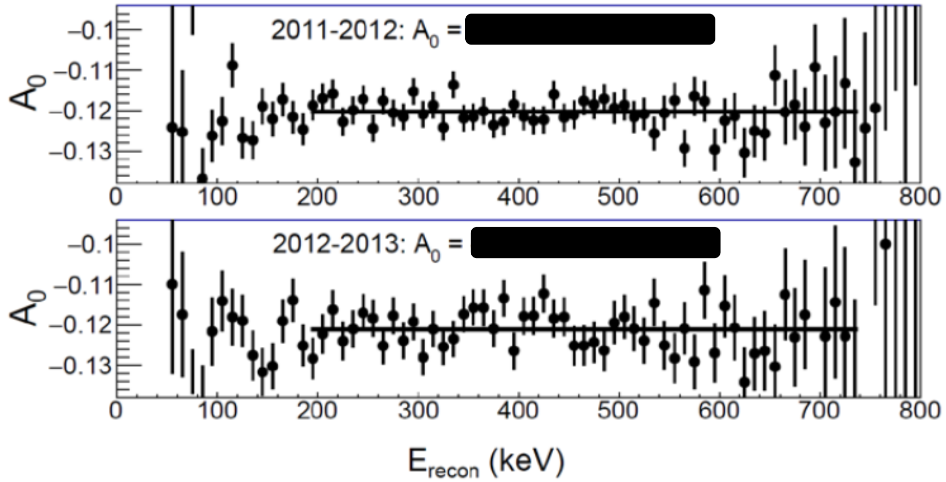
Polarized UCN bottle/detector to measure P violation in free neutron beta decay

- Measurement of A coefficient; correlating the neutron spin and beta momentum



1 T magnetic field on the axis gives 4 π detection of electrons (positrons)

	% Corr. 2011-2012	% Corr. 2012-2013	% Unc.
$\Delta_{\cos\theta}$	-1.53	-1.51	0.33
$\Delta_{\text{backscattering}}$	1.08	0.88	0.30
Energy Recon.			0.20
Depolarization	0.45	0.34	0.17
Gain			0.16
Field Nonunif.			0.12
Muon Veto			0.03
UCN Background	0.01	0.01	0.02
MWPC Efficiency	0.13	0.11	0.01
Statistics			0.36

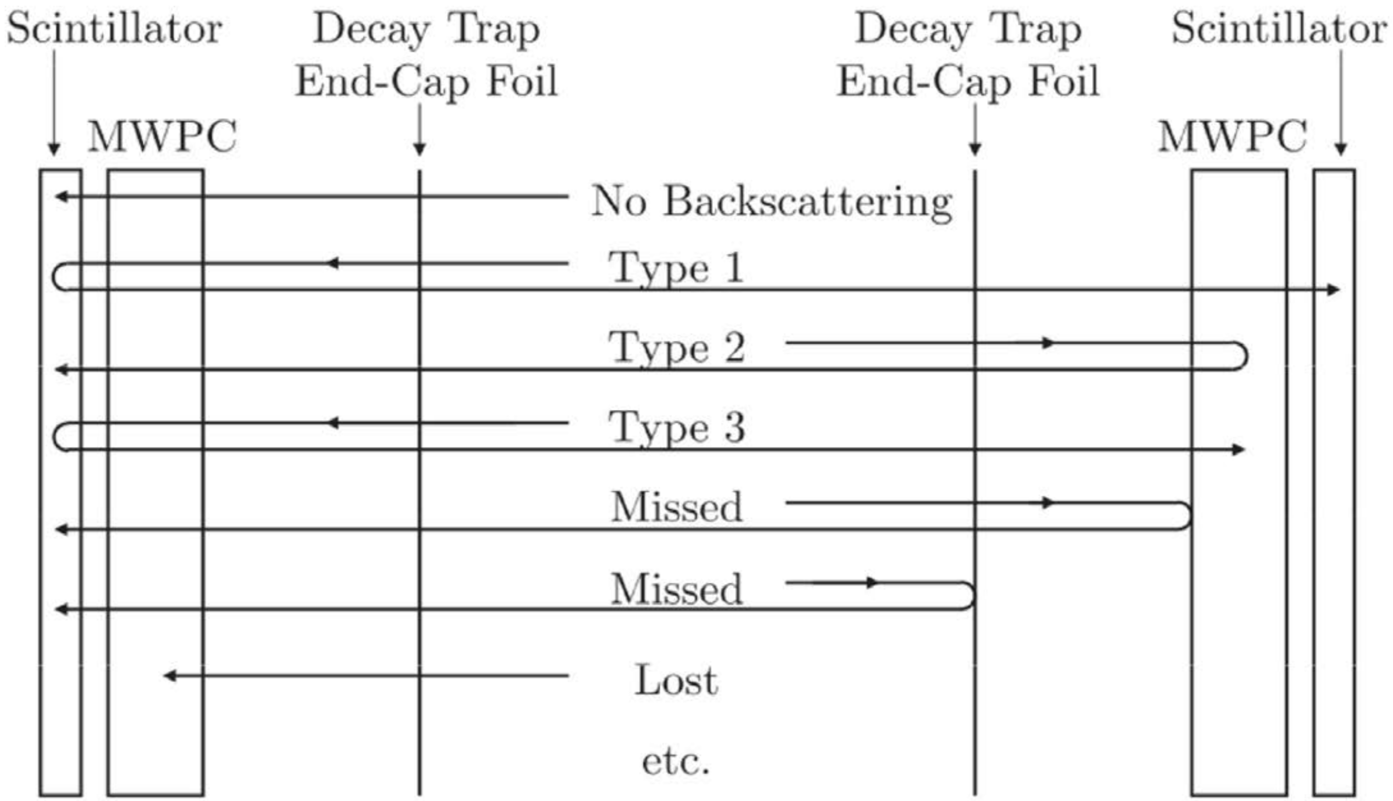


M. A.-P. Brown *et al.* (UCNA Collaboration)
Phys. Rev. C 97, 035505

Talk by Eric Dees, Wed 16:50

UCNA Backscatter systematic

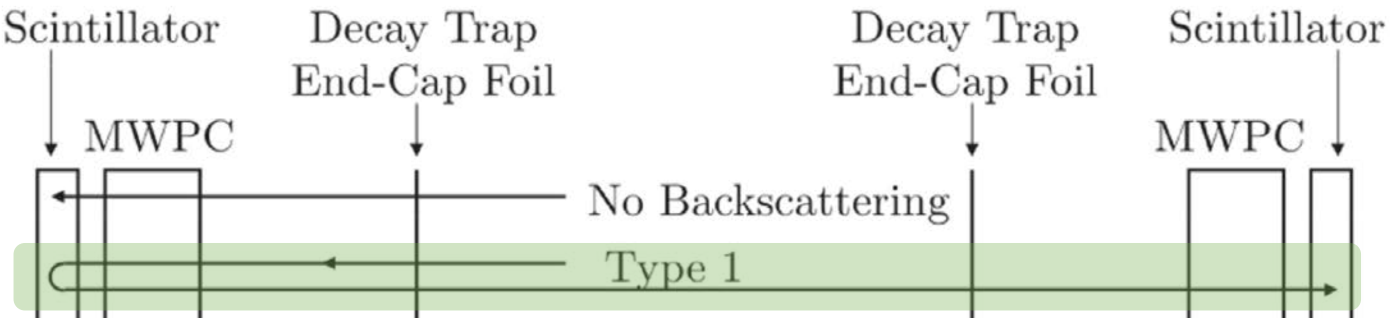
- Detailed analysis of backscatter systematics required for the UCNA experiment.

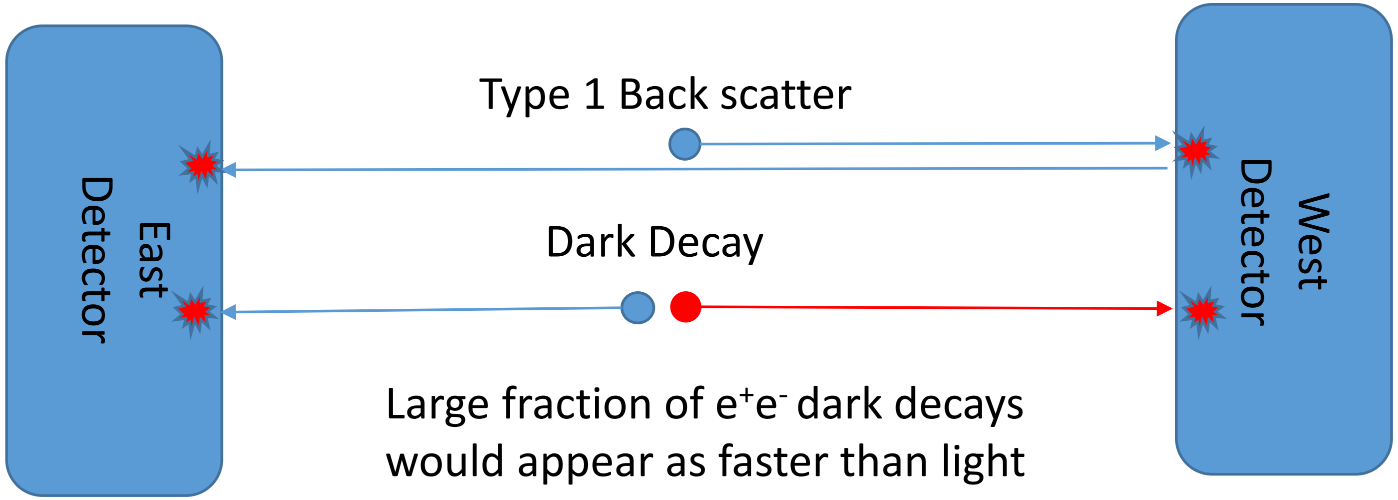


UCNA systematic could be a dark decay signal

- Look for Type 1 backscatter that travel faster than light! (17 ns)

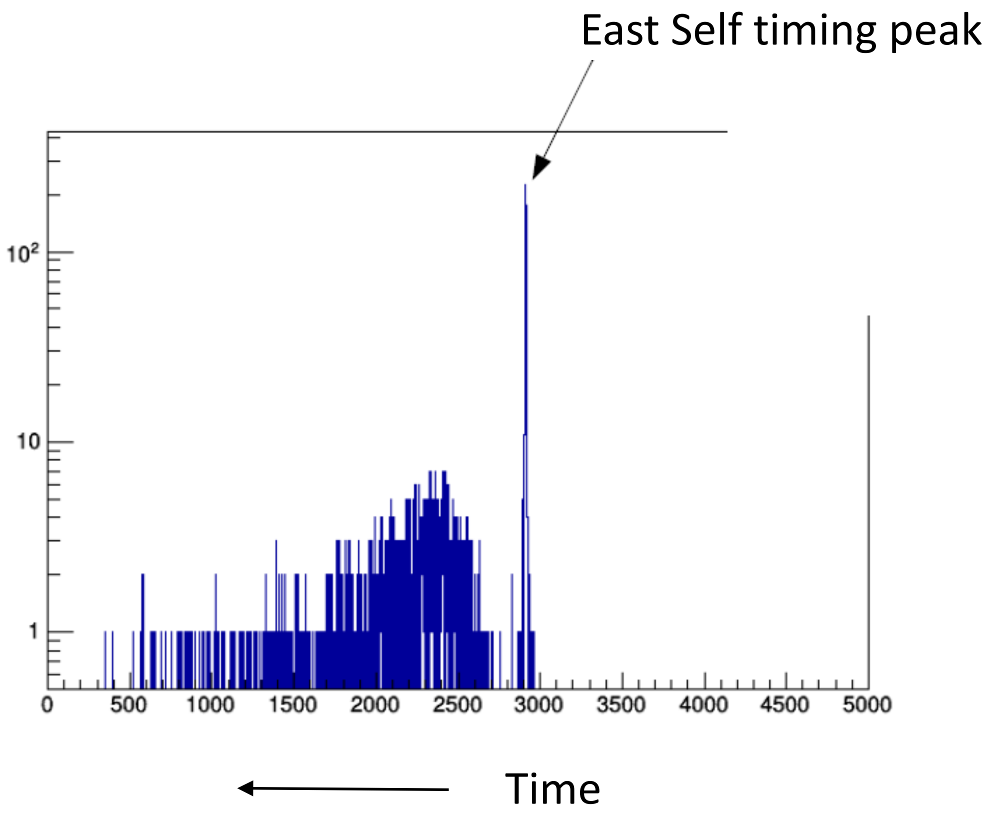
Dark Decay would present as a Type 1 Backscatter

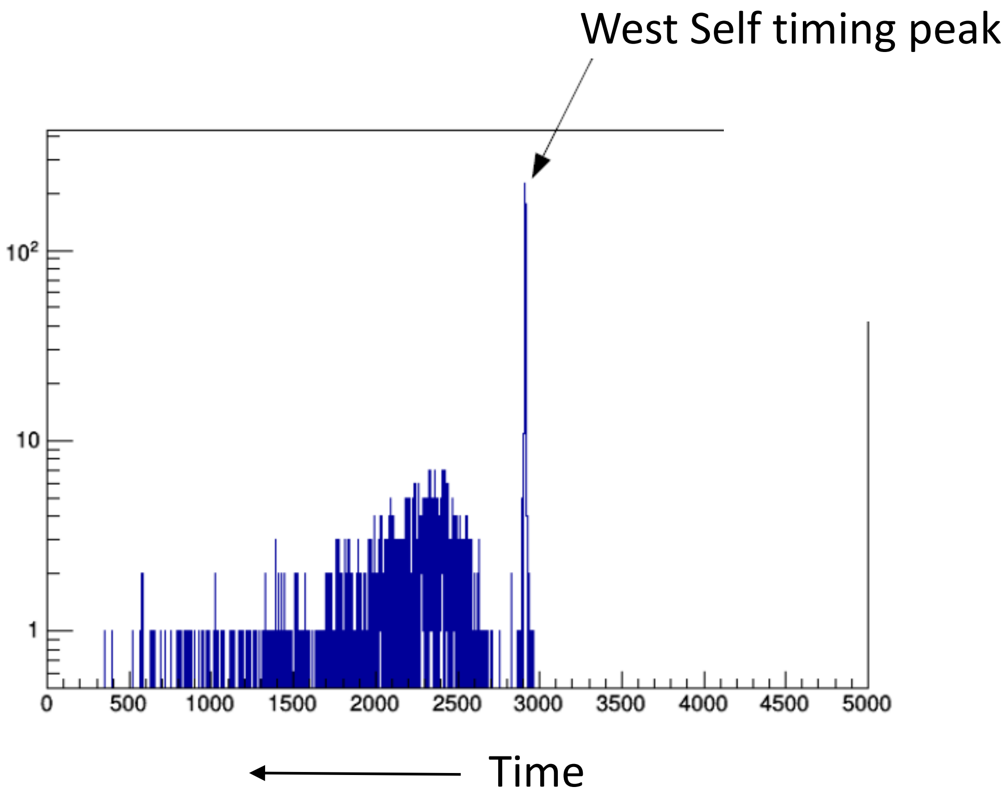




Large fraction of e^+e^- dark decays would appear as faster than light (17 ns) backscatters

Signal observed from detectors (scintillators)

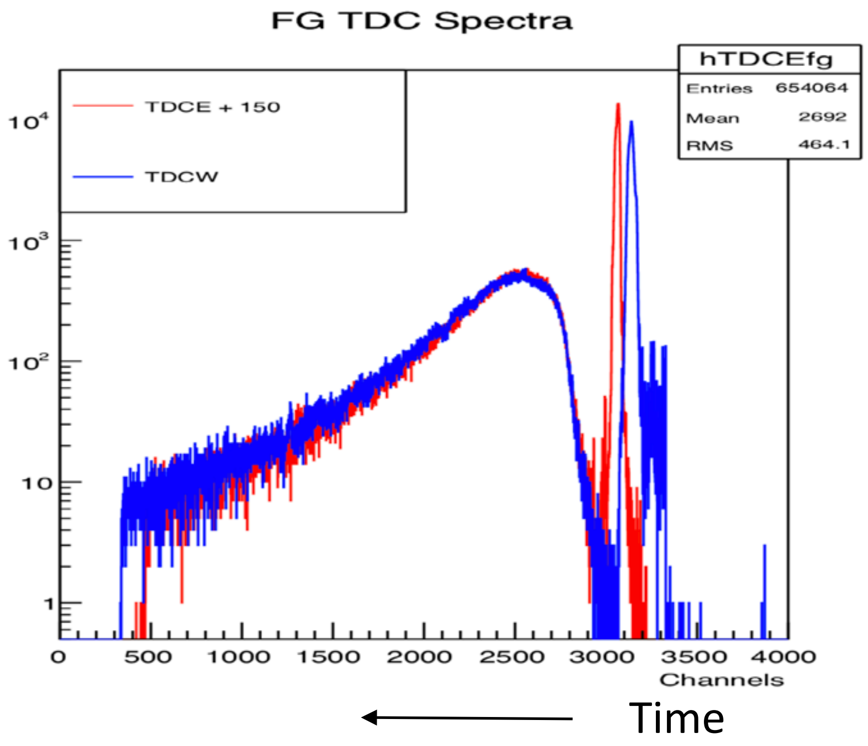




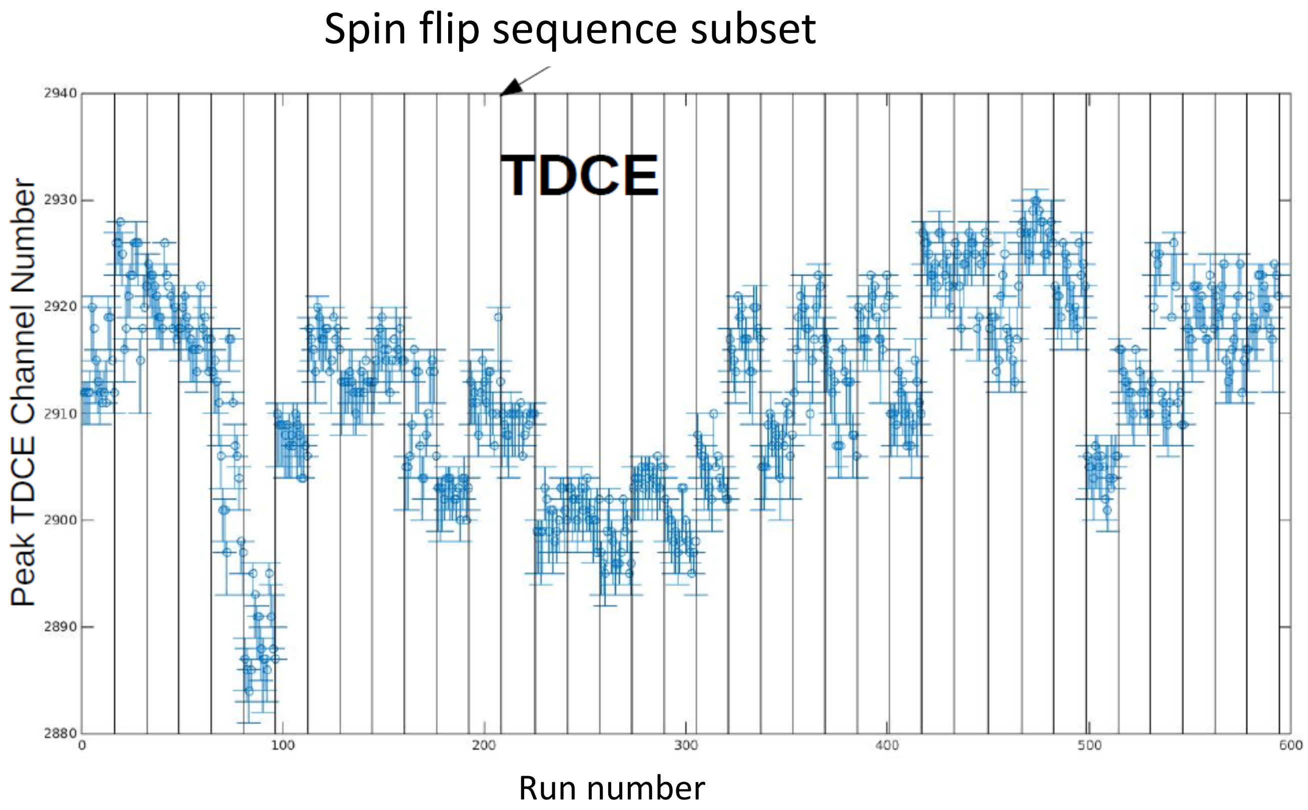
- We are looking for coincidences between East and West detector
- One or both self timing peak simultaneous in East and West,
  - if only one (in East or West) another shortly after (in West or East, up to several nanoseconds lag)

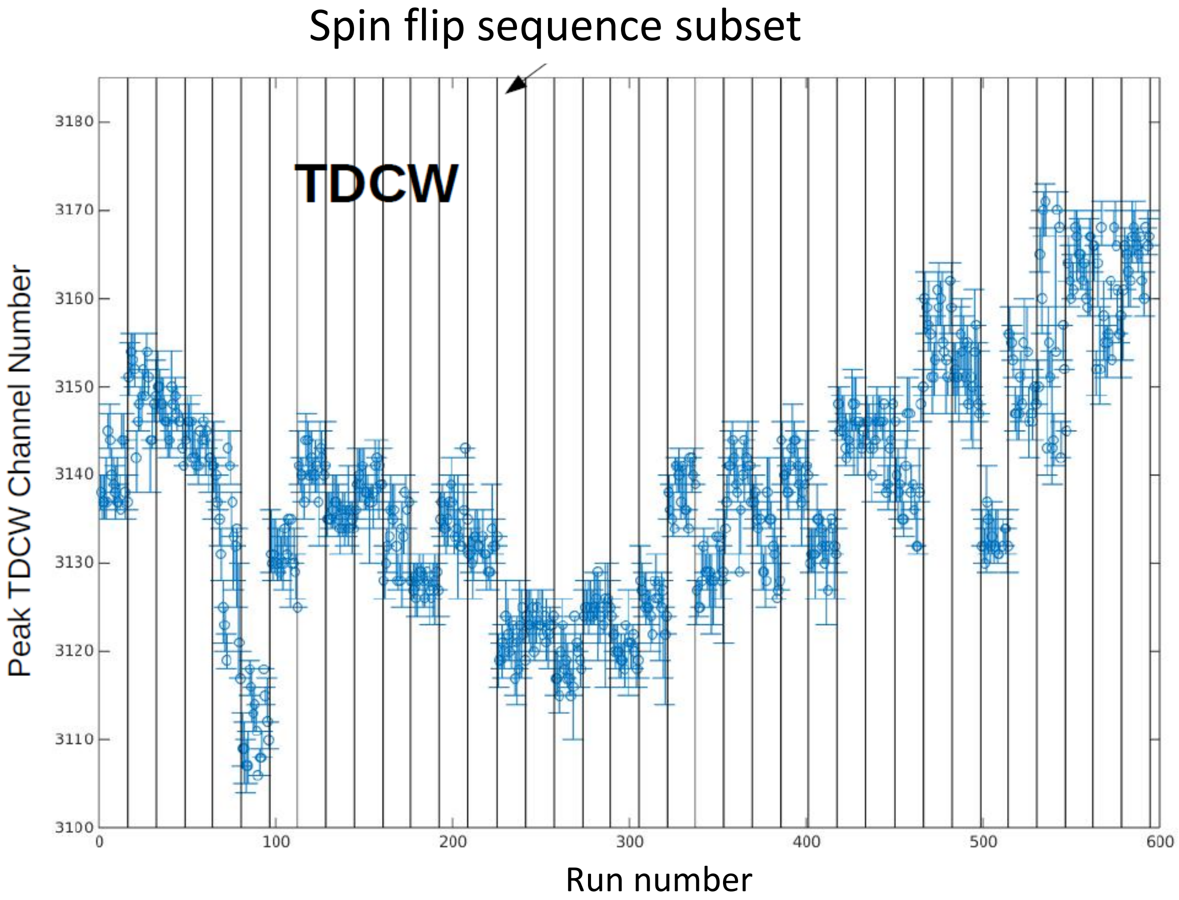
Systematic effects

- Roughly half of the 2011-2013 UCNA Data is useful
  - Hardware timing jumps washed out resolution
  - This was determined and fixed with about ½ way through the scheduled data run cycle
  - Not a large systematic effect for A measurement
- Jitter of the electronics is around 4 ns
  - Reducing our window and thus statistics
- Cable length/time to propagate (Shifts timing of trigger logic)
  - This effect was corrected for by calibration of full backscatter curve
  - TDC West window starts ~1.7 ns later than TDC East
  - 1.7 ns electronic dead time where no signal can exist. Must be cut
- Electronic variation due to Temperature/Environment



Timing is everything



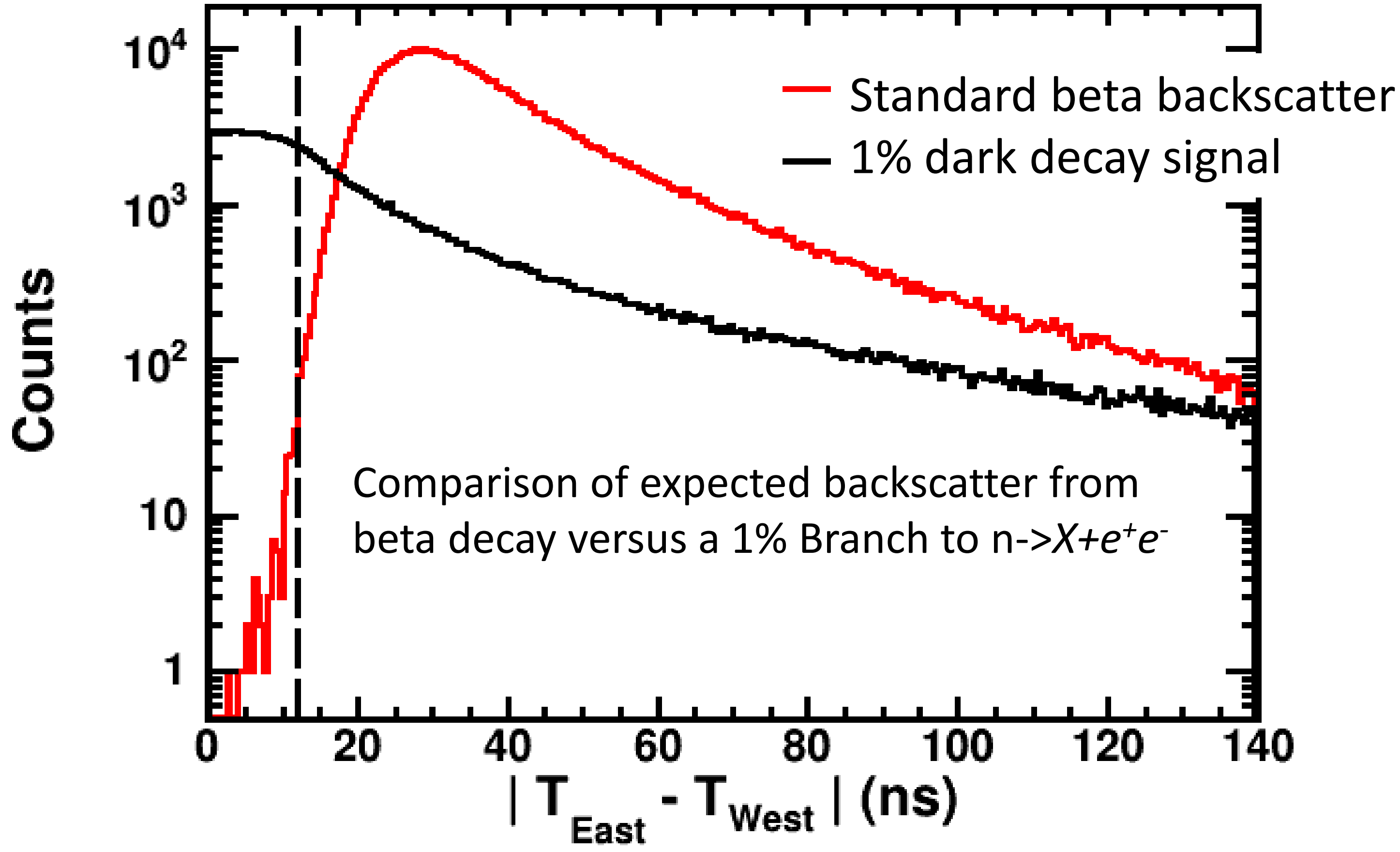


- Calibration of self timing peak reduces systematic error
- Large counts per run allowed run by run calibration of timing peaks.

Simulated Counts for e+e-

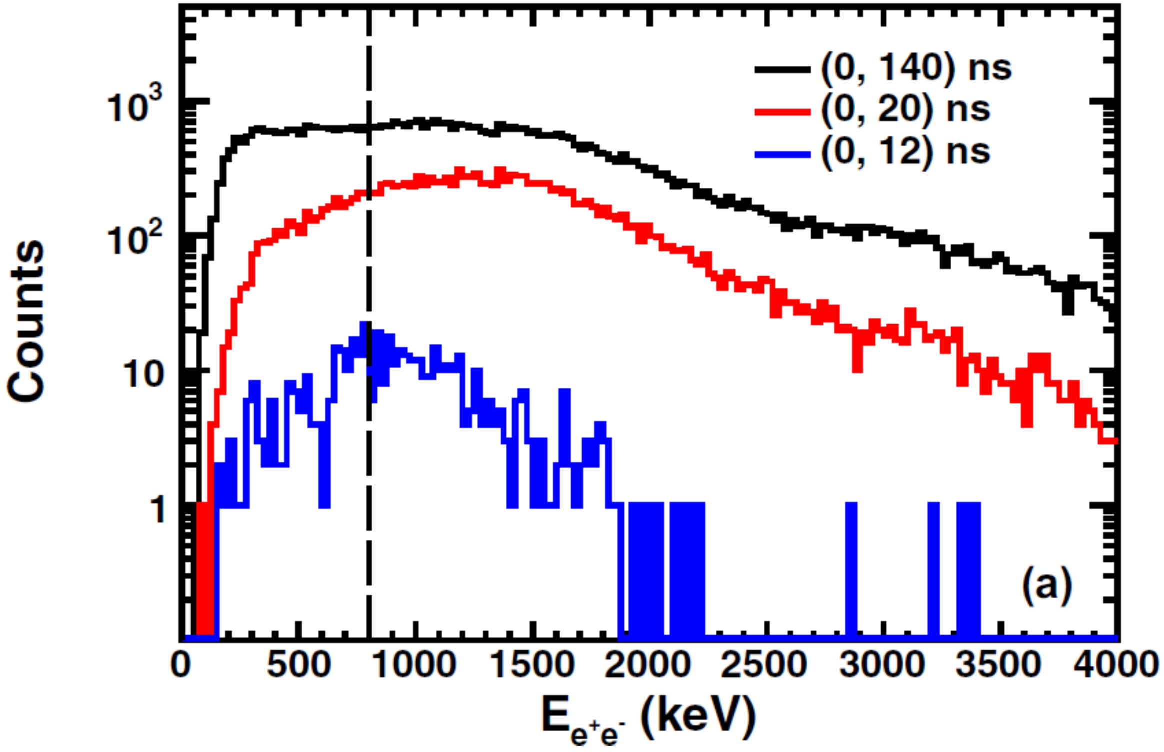
Kinematics and phase space of the decay simulated in Monte Carlo

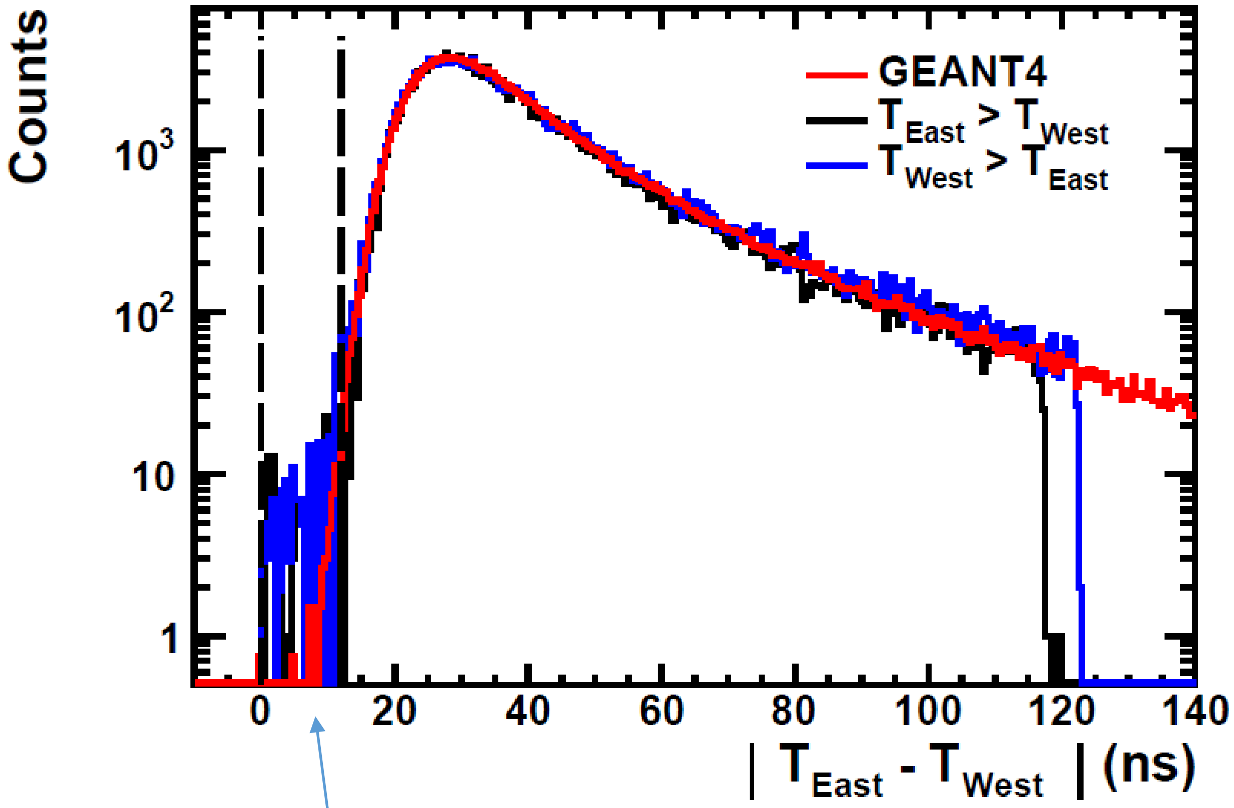
Detection efficiency simulated in GEANT4; e^+ detection is 80% compared to e^-



Timing is everything

- As the timing window is shortened dark decay signal is enhanced over backscatter events





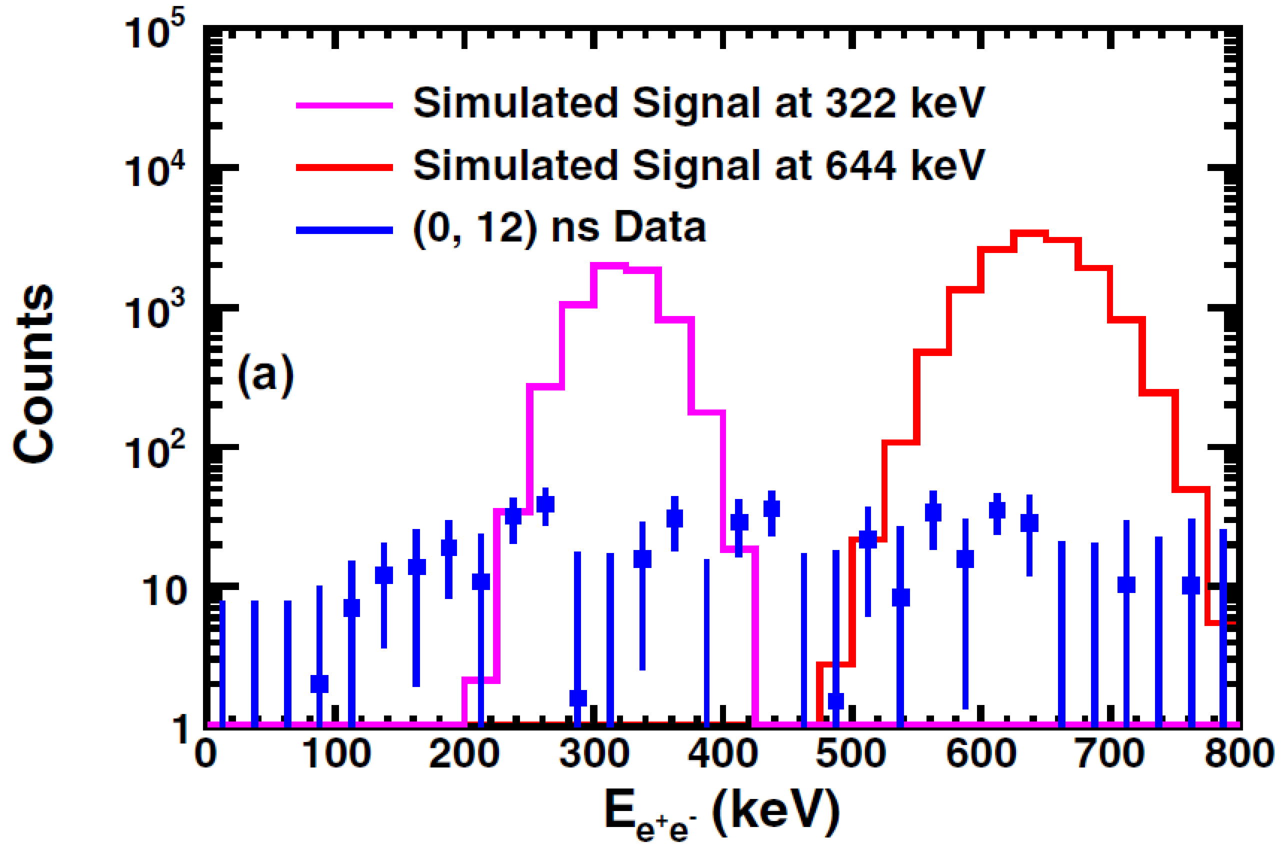
Excess determines the limit of our dark decay.

X. Sun *et al.* (UCNA Collaboration)
Phys. Rev. C 97, 052501(R)

Poster by Xuan Sun

Probe for signal versus decay energy.

- Decay signal as a function of *X* mass simulated to interpret data.
  - Peak height as a function of energy.
- Data is binned in 100 keV bins every 50 keV, looking for an excess.



Confidence contour including 'look elsewhere' effect.

Data is binned
Each bin is a trial

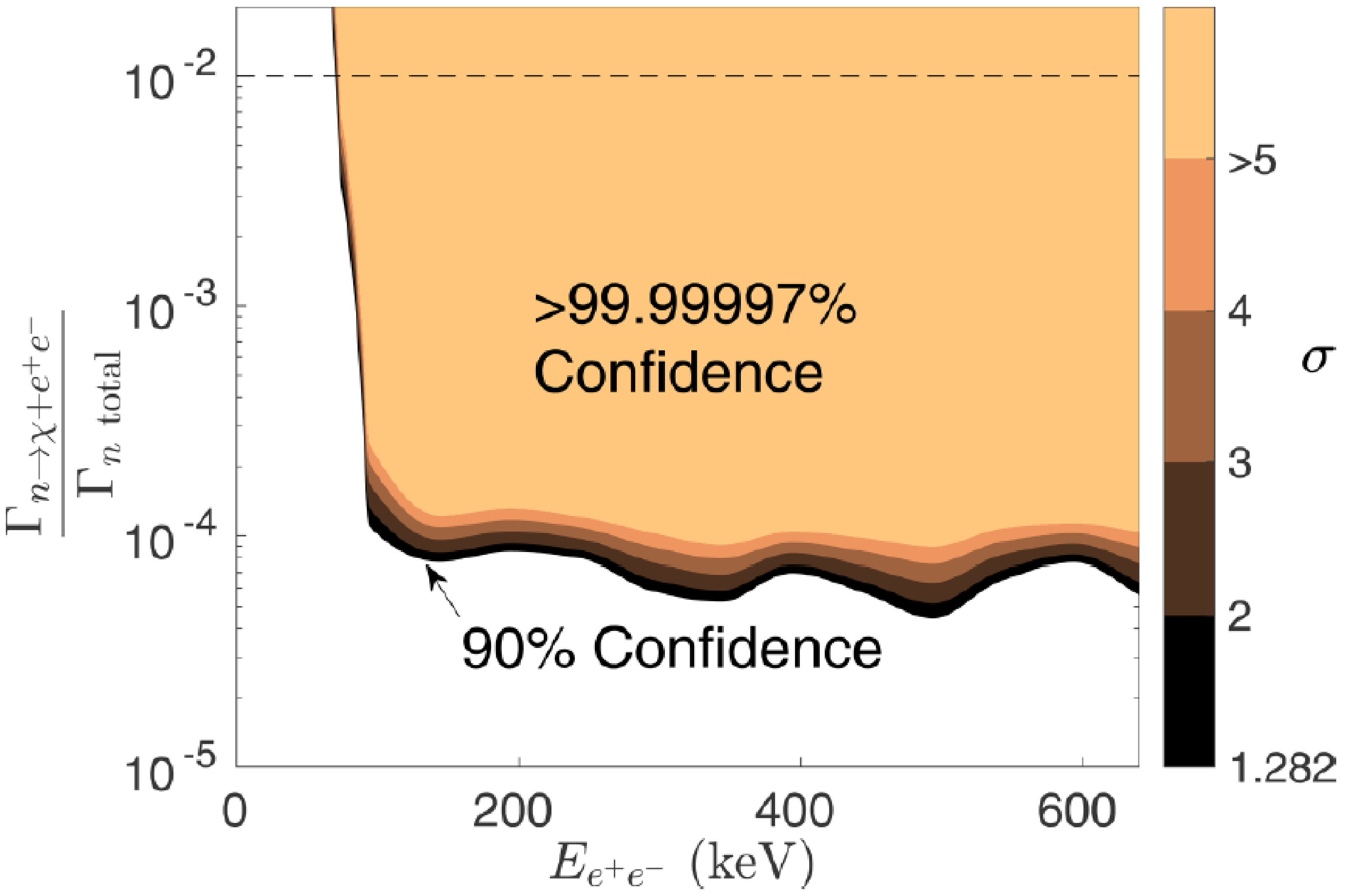
Trial factor must be accounted for.

100M experiments simulated produce a probability distribution function from a statistical measure ξ

$$\xi = \sum_i \frac{N_i - \mu_i}{\sigma_i} \quad \text{for } N_i > \mu_i$$

Contours solved for with ξ's pdf.

2σ→1σ
5.3σ→5σ



Summary

- Neutron lifetime anomaly can be accounted for with a 1% decay to a dark sector
- UCNA has sensitivity to the proposed n→*X*+e^+e^- decay
- UCNA has sensitivity for n→*X*+e^+e^- down to a branching ratio of 0.01% for kinetic energies of e^+e^- above 100 keV. It did not detect this decay.

PHYSICAL REVIEW C **97**, 052501(R) (2018)

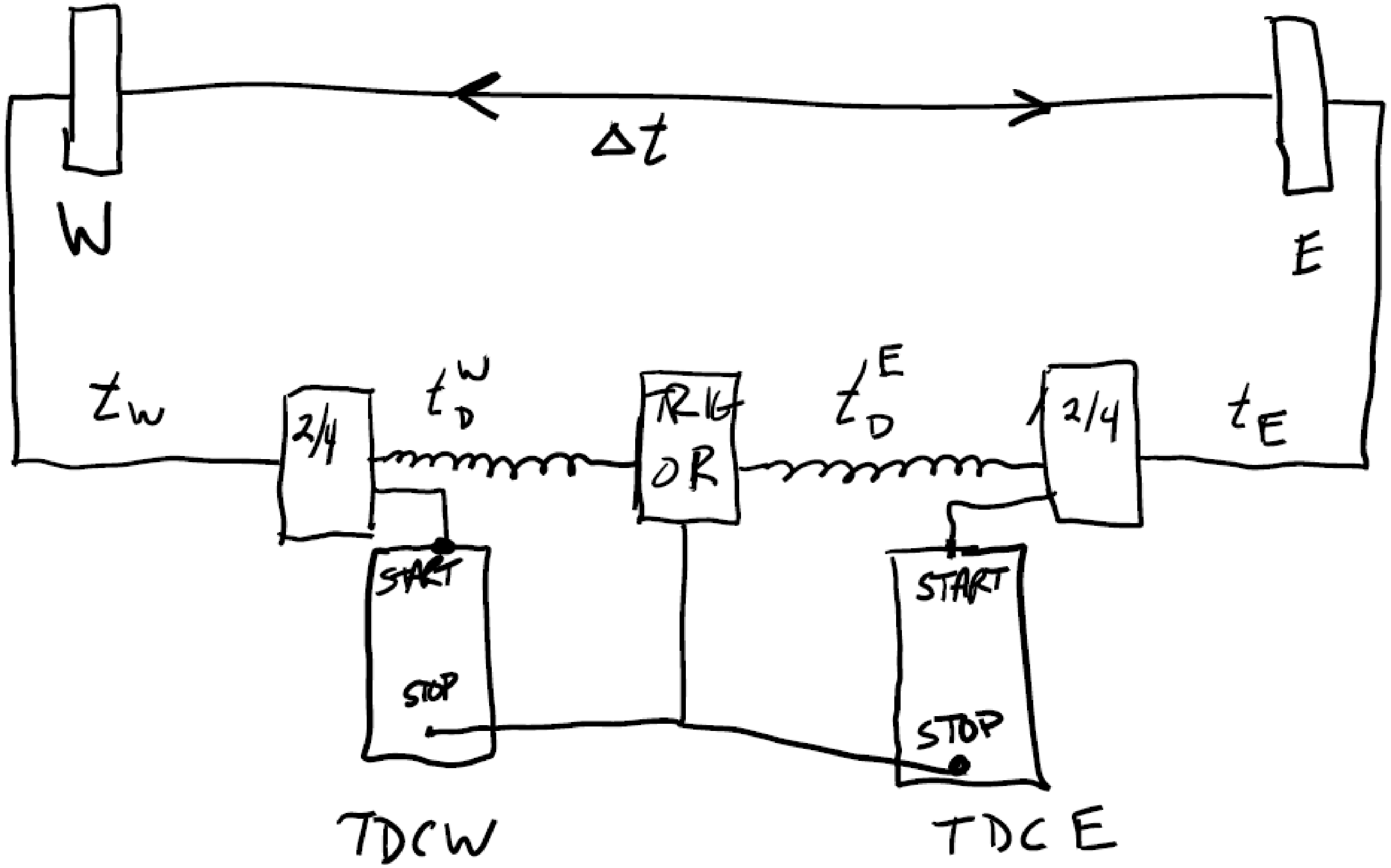
Rapid Communications

Search for dark matter decay of the free neutron from the UCNA experiment: $n \rightarrow \chi + e^+e^-$

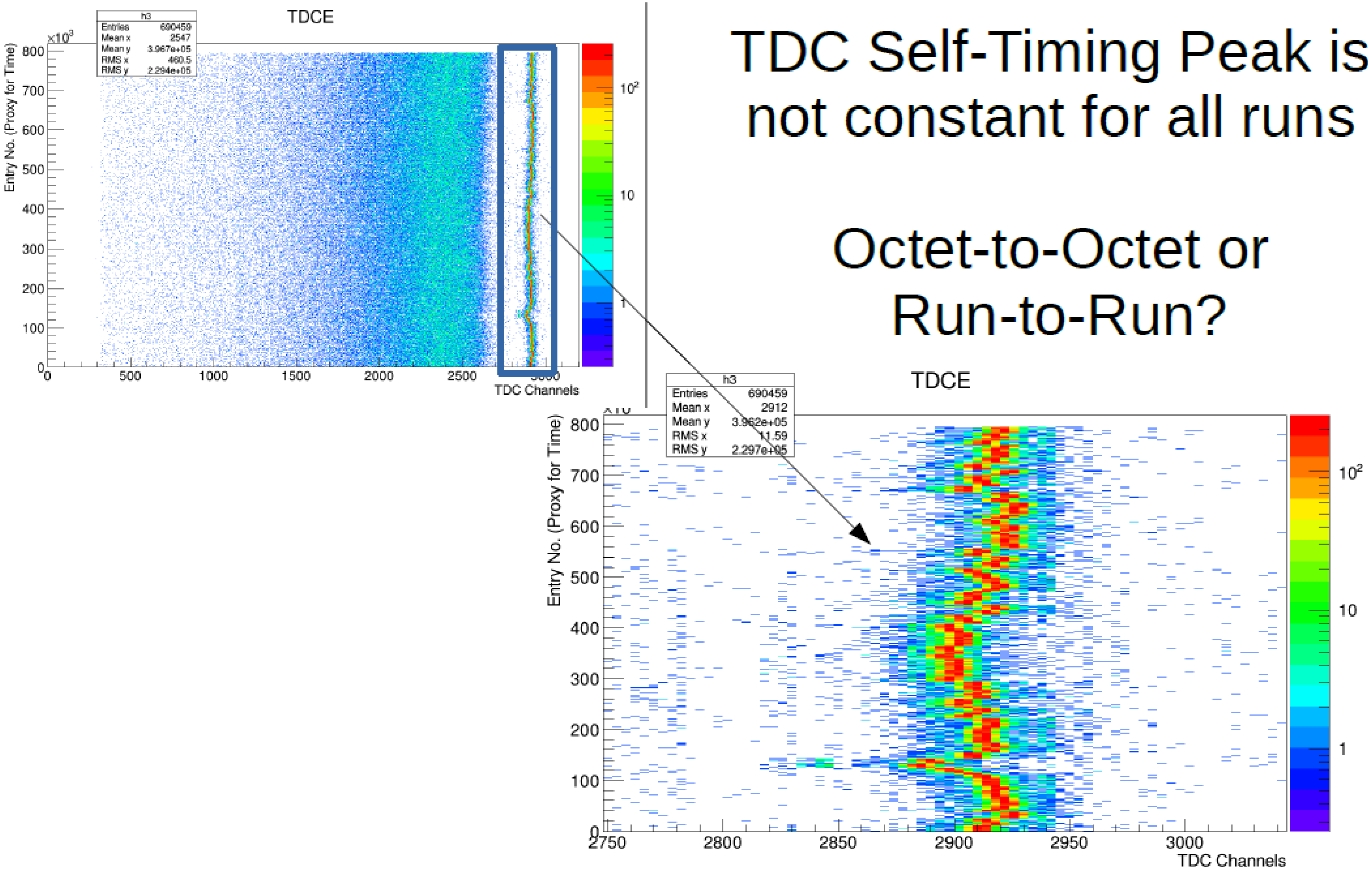
X. Sun,[1] E. Adamek,[2] B. Allgeier,[3] M. Blatnik,[1] T. J. Bowles,[4] L. J. Broussard,[4,*] M. A.-P. Brown,[3,†] R. Carr,[1] S. Clayton,[4] C. Cude-Woods,[5] S. Currie,[4] E. B. Dees,[5,6] X. Ding,[7] B. W. Filippone,[1] A. García,[8] P. Geltenbort,[9] S. Hasan,[3] K. P. Hickerson,[1] J. Hoagland,[5] R. Hong,[8] G. E. Hogan,[4] A. T. Holley,[5,2,‡] T. M. Ito,[4] A. Knecht,[8,§] C.-Y. Liu,[2] J. Liu,[10] M. Makela,[4] R. Mammei,[11] J. W. Martin,[1,11] D. Melconian,[12] M. P. Mendenhall,[1,‖] S. D. Moore,[5] C. L. Morris,[4] S. Nepal,[3] N. Nouri,[3,¶] R. W. Pattie, Jr.,[5,6,#] A. Pérez Galván,[1,**] D. G. Phillips II,[5] R. Picker,[1,††] M. L. Pitt,[7] B. Plaster,[3] J. C. Ramsey,[4] R. Rios,[4,13] D. J. Salvat,[8] A. Saunders,[4] W. Sondheim,[4] S. Sjue,[4] S. Slutsky,[1] C. Swank,[1] G. Swift,[6] E. Tatar,[13] R. B. Vogelaar,[7] B. VornDick,[5] Z. Wang,[4] W. Wei,[1] J. Wexler,[5] T. Womack,[4] C. Wrede,[8,14] A. R. Young,[5,6] and B. A. Zeck[5]
(UCNA Collaboration)

Backup slides.

Timing electronics sketch (Brad Filippone)



TDC Self-Timing Peak Variations



TDC Self-Timing Peak is not constant for all runs

Octet-to-Octet or Run-to-Run?