Neutron Lifetime Anomaly and Laboratory Tests of n-n’ Oscillations

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Update: http://sites.nd.edu/wtan/smm

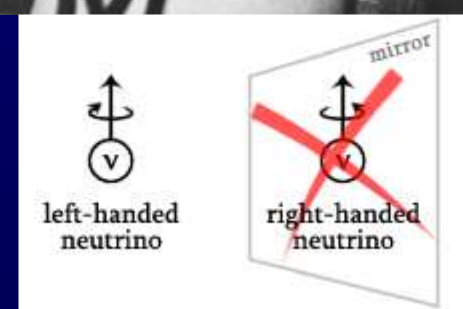
LANL UCN Collaboration Meeting • 2020

Parity Violation

T. D. Lee and C. N. Yang,
Phys. Rev. **104**, 254 (1956)

right and the left. If such asymmetry is indeed found, the question could still be raised whether there could not exist corresponding elementary particles exhibiting opposite asymmetry such that in the broader sense there will still be over-all right-left symmetry. If this is the case, it should be pointed out, there must exist two kinds of protons p_R and p_L, the right-handed one and the left-handed one. Furthermore, at the present

C. S. Wu et al., Phys. Rev. **105**, 1413 (1957)



Mirror Matter Theory

Origin: T. D. Lee and C. N. Yang, Phys. Rev. 104, 254 (1956)

- Does the Universe have a mirror sector?

- I. Y. Kobzarev, L. B. Okun, and I. Y. Pomeranchuk, Sov. J. Nucl. Phys. 3, 837 (1966)
- S. I. Blinnikov & M. Y. Khlopov, Soviet Astronomy 27, 371 (1983).
- E. W. Kolb, D. Seckel, & M. S. Turner, Nature 314, 415 (1985)
- H. M. Hodges, Phys. Rev. D 47, 456 (1993)
- L. B. Okun, Phys.-Usp. 50, 380 (2007)

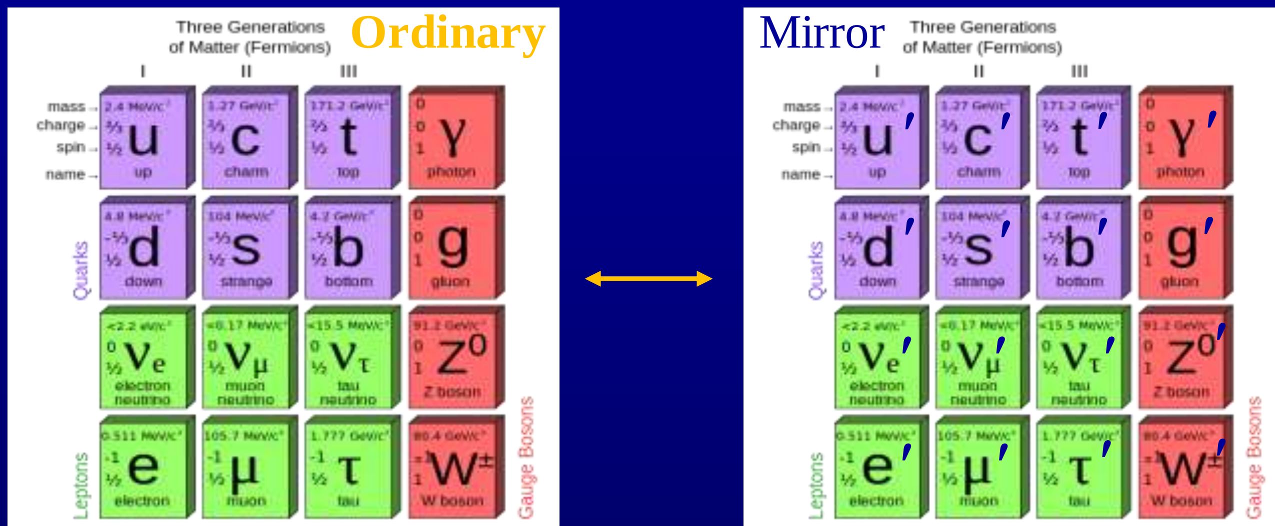
- R. Foot, Int. J. Mod. Phys. D 13, 2161 (2004)
- Z. Berezhiani, Int. J. Mod. Phys. A 19, 3775 (2004)
- Z. Berezhiani & L. Bento, Phys. Rev. Lett. **96**, 081801 (2006)
- Jian-Wei Cui, Hong-Jian He, Lan-Chun Lü, and Fu-Rong Yin, Phys. Rev. D 85, 096003 (2012)

- Other Imcomplete/Variant Models: Twin Higgs, mQCD, Braneworlds …

Ordinary – Mirror Worlds

- Ordinary and mirror sectors share the same gravity only.

Two worlds In the Same Universe



- Each sector has its own interactions (electromagnetic, strong, and weak forces) and vacuum.
- New model: no explicit gauge interactions between the two sectors

Standard Model with Mirror Matter (SM^3)

arXiv:1908.11838

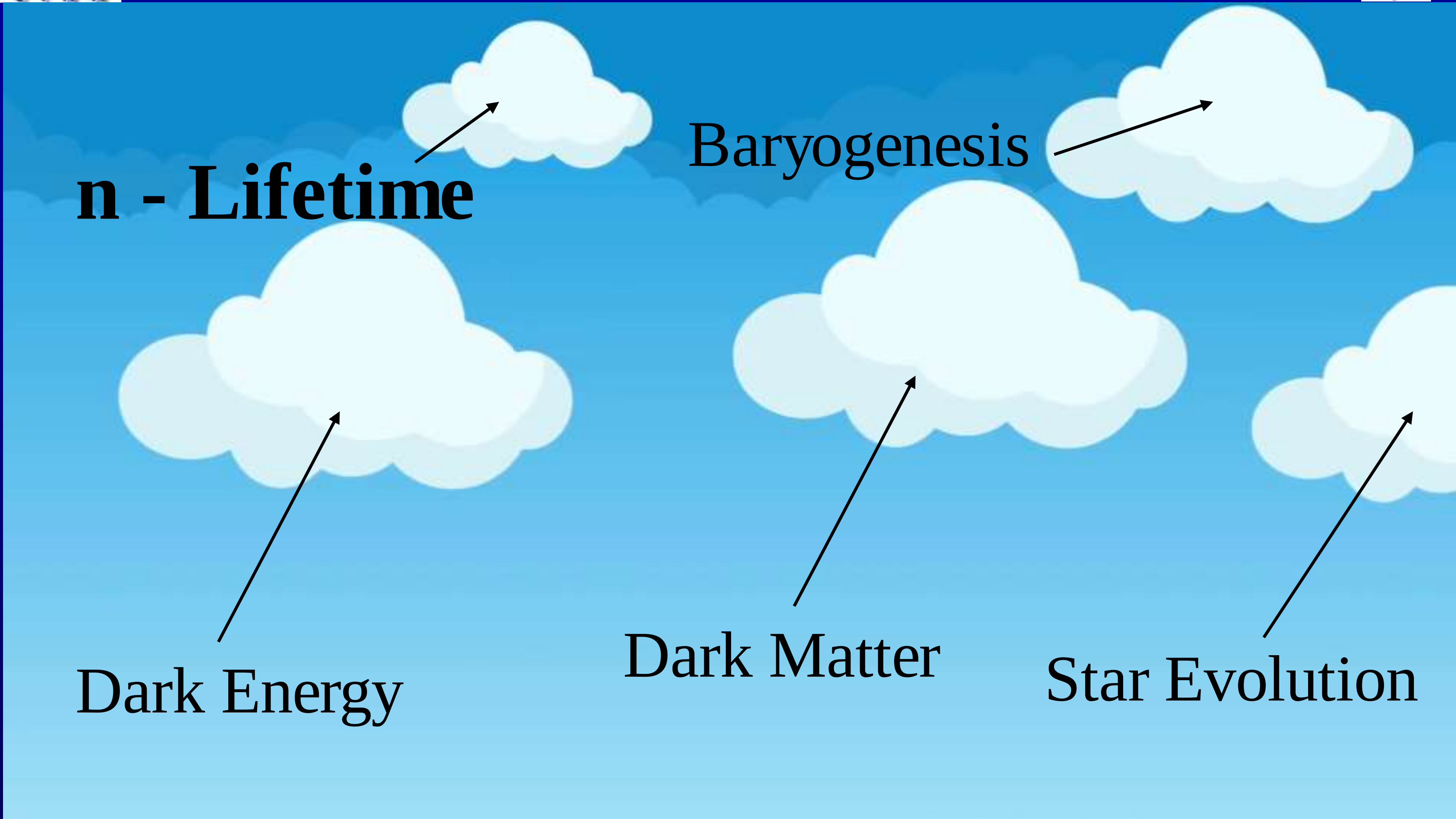
- Mirror symmetry is chiral → Higgs is mirror odd

$$\mathcal{M}: \; \psi_L \to -\psi'_L, \; \psi_R \to \psi'_R, \; \phi \to -\phi'$$

$$\mathcal{L} = \mathcal{L}_{\rm SM}(G, W, B, \psi_L, \psi_R, \phi) + \mathcal{L}'_{\rm SM}(G', W', B', -\psi'_L, \psi'_R, -\phi')$$

- Spontaneous SB → $SU_L(2)$ and $SU'_R(2)$
  - Very small breaking scale $\delta m/m \sim 10^{-15}$–10^{-14}
- Neutrino degeneracy
  - All left-handed neutrinos in our sector
  - All right-handed neutrinos in mirror sector
- Strong and EM interactions do not cause particle mixing
- Weak interaction does, affected by SSB
- SSB: staged quark condensation
- O-M neutrinos do not mix → neither do charged leptons
- Only possibility: neutral hadron-mirror hadron oscillations
  - CKM is not unitary

What puzzles SMM can solve?



- and many more: time arrow, unitarity of CKM, 7Li problem, nature & tiny masses of neutrinos, UHE cosmic rays …

Oscillations of neutral particles

- Probability of n-n' oscillations in free space:

Two model parameters

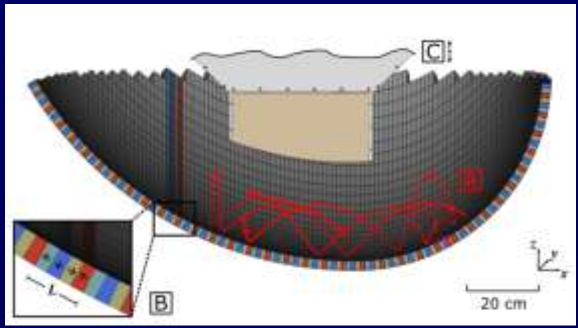
$$P_{nn'}(t) = \sin^2(2\theta)\sin^2(\frac{1}{2}\Delta_{nn'}t)$$

- Transition rate in trap or medium

$$\lambda_{nn'} = \frac{1}{\tau_f}\sin^2(2\theta) < \sin^2(\frac{1}{2}\Delta_{nn'}\tau_f) >$$

- If the mass difference of n-n' is large enough,

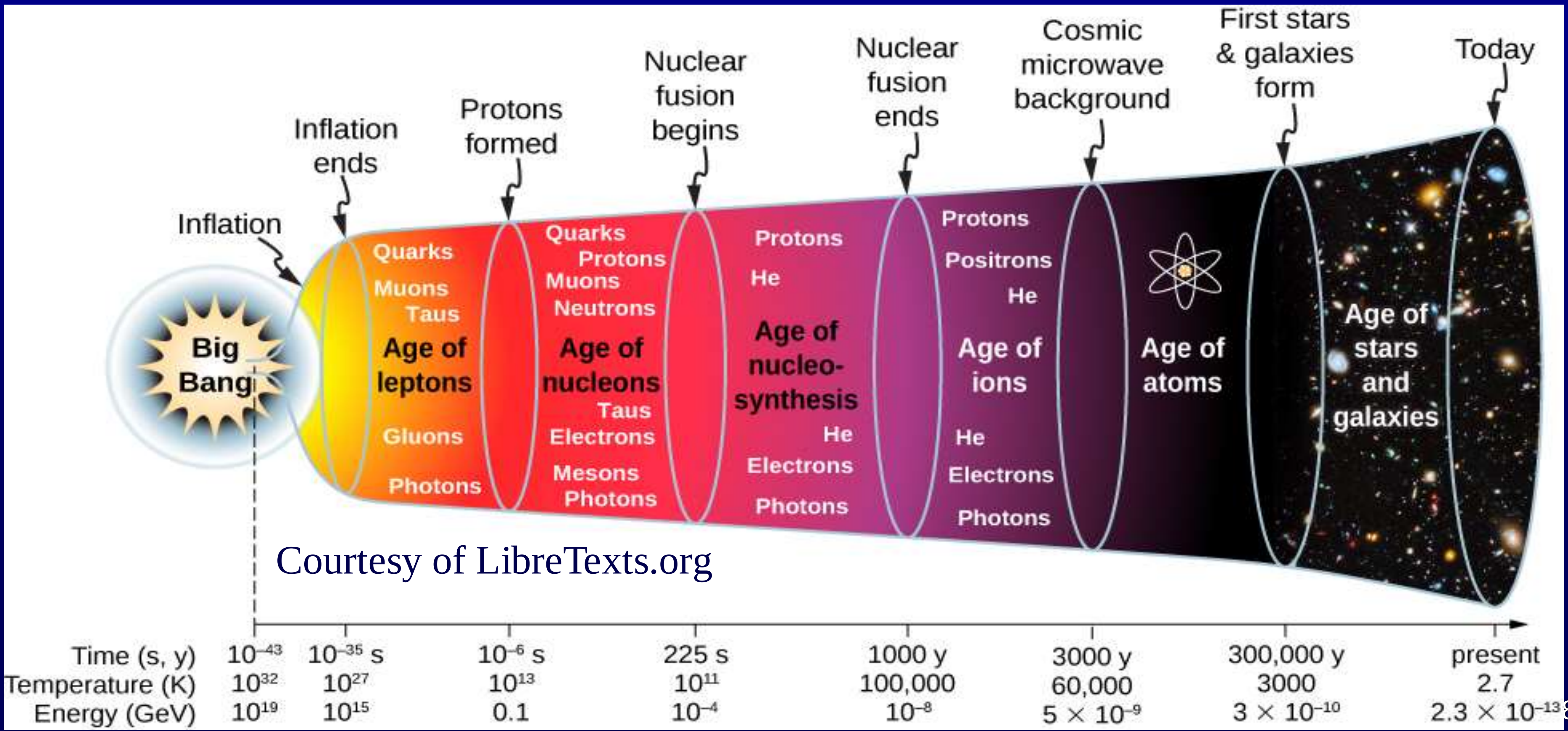
$$\lambda_{nn'}(\text{bottle}) = \frac{1}{2\tau_f}\sin^2(2\theta)$$



Dark Matter and Baryon Asymmetry

PLB 797, 134921 (2019); **PRD** 100, 063537 (2019)

- **n-lifetime: $8\times10^{-6} < \sin^2(2\theta) < 4\times10^{-5}$, what about $\Delta_{nn'}$?**
- **nn' oscillations: $\sin^2(2\theta)(nn') = 2\times10^{-5}$, $\Delta_{nn'} = 2\times10^{-6}$ eV**
- **$K^0K^{0'}$ oscillations: $\sin^2(2\theta)(K^0K^{0'}) \sim 10^{-4}$, $\Delta_{K^0K^{0'}} \sim 10^{-6}$ eV**
- T '/T < 1/2



Consistent origin of BAU & DM

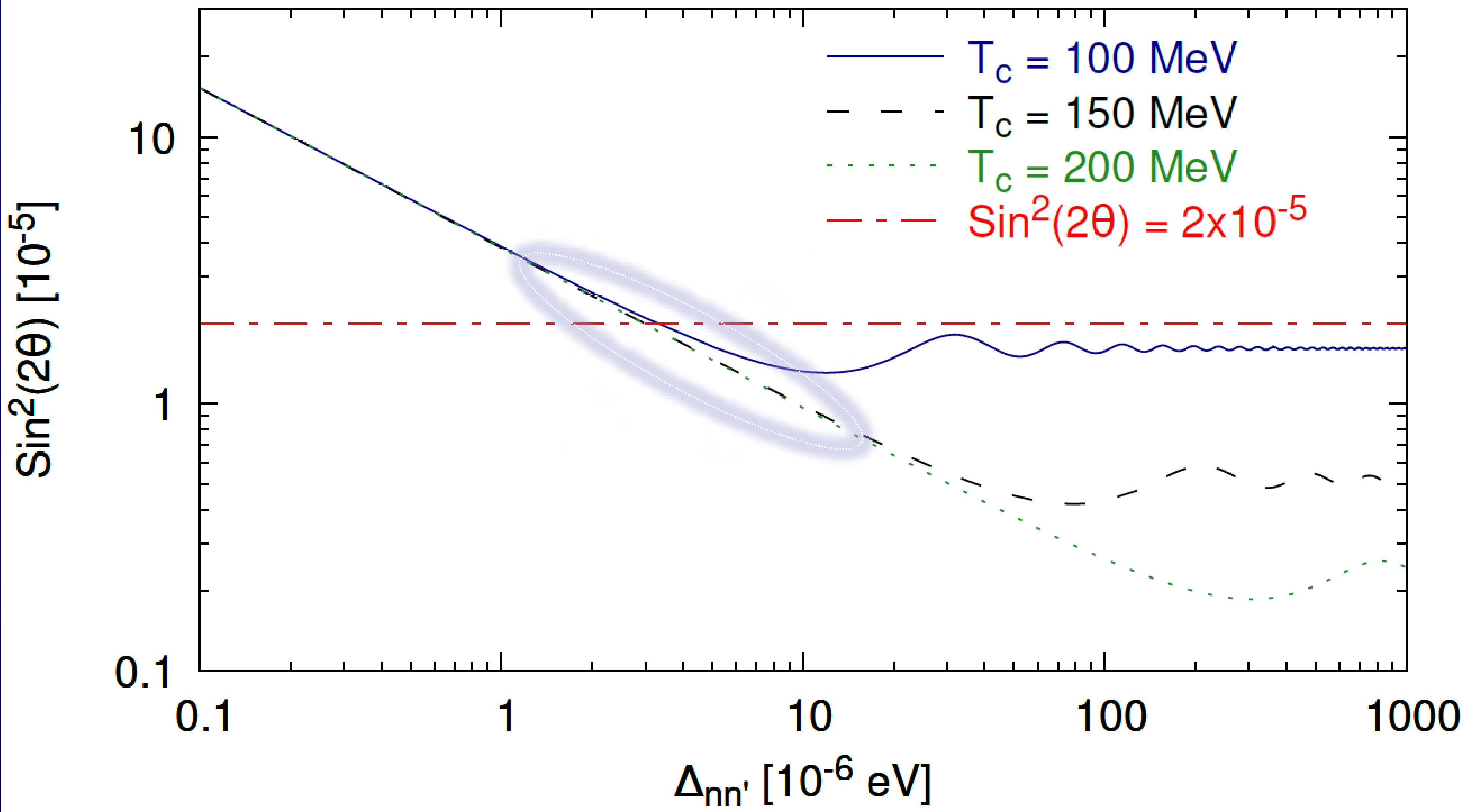
Temperature Going down → | Age of the Universe →

Temperature		Age of the Universe
10^{15} K	10^2 GeV: top quark condensation / EWPT	10^{-11} s
	b- /c- quark condensation	
10^{12} K	10^2 MeV: Strange quark condensation	2×10^{-5} s
	100-200 MeV: K0-K0′ oscillations → BAU	
8×10^{11} K	10^2 MeV: u-/d- quark condensation QCD phase transition	10^{-5} s
	70 MeV: n-n′ oscillations → dark/mirror matter	
10^9 K	0.1 MeV: BBN	10^2 s
2.7 K	Today’s Universe	1.4×10^{10} years

PLB 797, 134921 (2019); **PRD** 100, 063537 (2019)

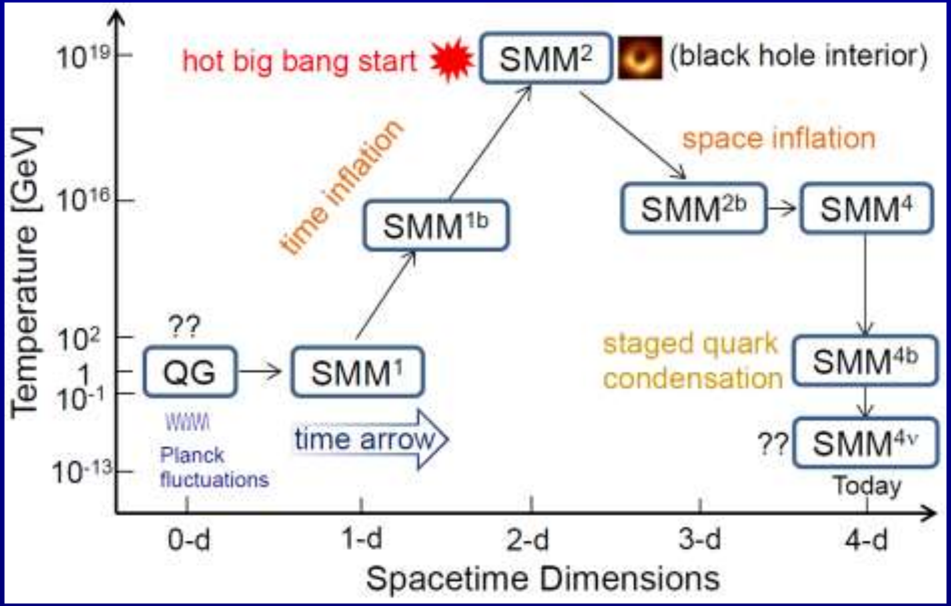
Correlation of parameters

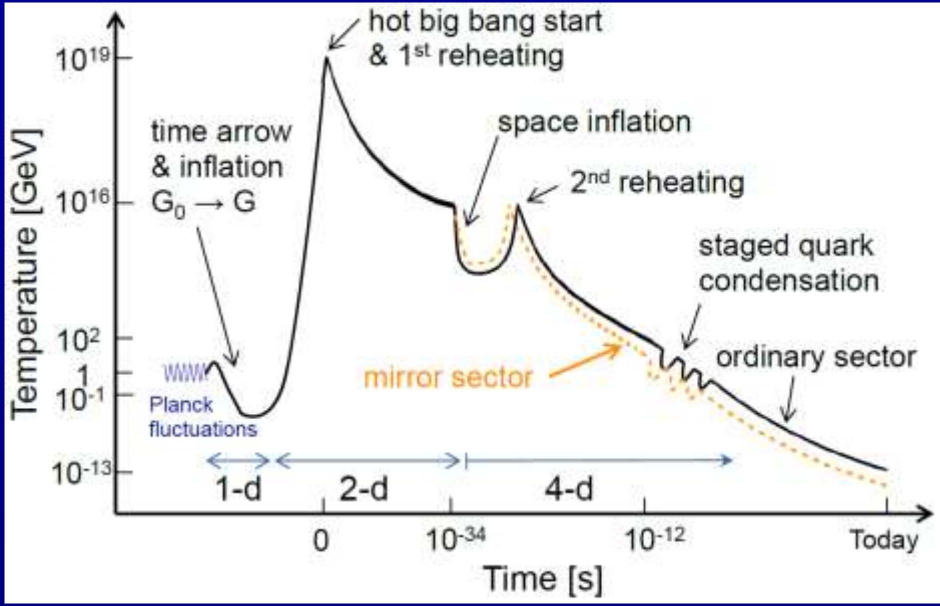
- Mirror/baryon ratio of 5.4 is assumed



Supersymmtric Mirror Models

https://doi.org/10.31219/osf.io/8qawc





- Dynamical / dimensional phase transition – spontaneous symmetry breaking
- 1-d time: time inflation and birth of time arrow
- 2-d spacetime: SMM² -- N=1 SUSY (Majorana / U(1) gauge)
  - Φ and Φ' (Majorana condensation) → double space inflation → emergence of two sectors
- 4-d spacetime: SMM⁴ -- Dirac / U(6)xSU(3)xSU(2)xU(1) gauge
  - Staged quark condensation → N=4 pseudo-SUSY (SMM4b)

Neutron lifetime puzzle

- Neutron (udd): 15-min lifetime
- The only known decay mode of neutrons:

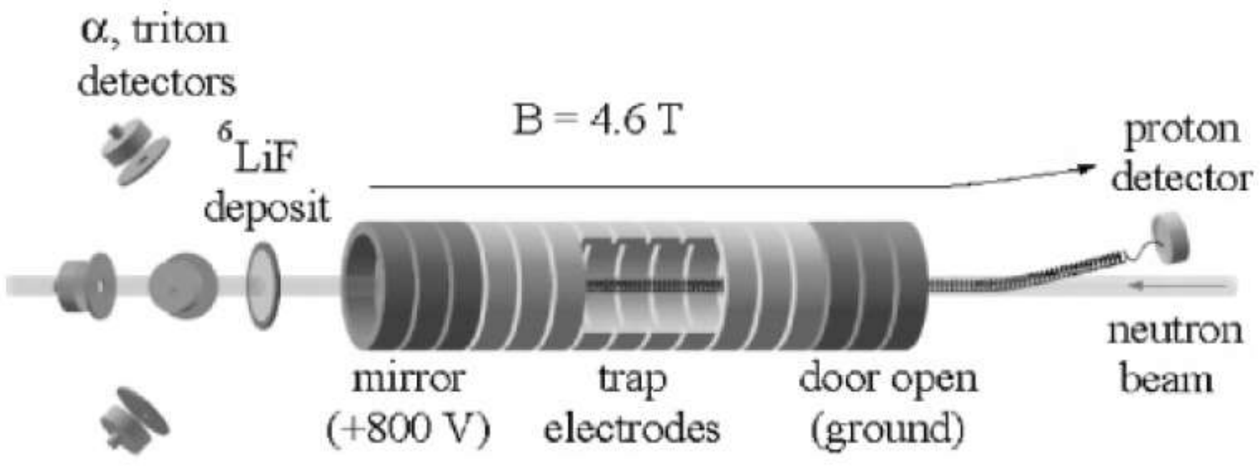
$$n \rightarrow p + e^{-} + \bar{\nu}_e$$

- Two ways to measure its lifetime
  - Directly measure the decay products: protons or electrons
    → Beta decay lifetime ("Beam" approach)
  - Count neutrons before and after certain period of time
    → Neutron disappearing lifetime ("Bottle" approach)
- If a hidden process exists,
  - the two measured lifetimes will differ from each other.
  - 1% discrepancy observed

High precision measurement (I)

- "Beam" approach at NIST

Yue et al., Phys. Rev. Lett. 111, 222501 (2013)
Nico et al., Phys. Rev. C 71, 055502 (2005)



- Cold neutrons at 40K

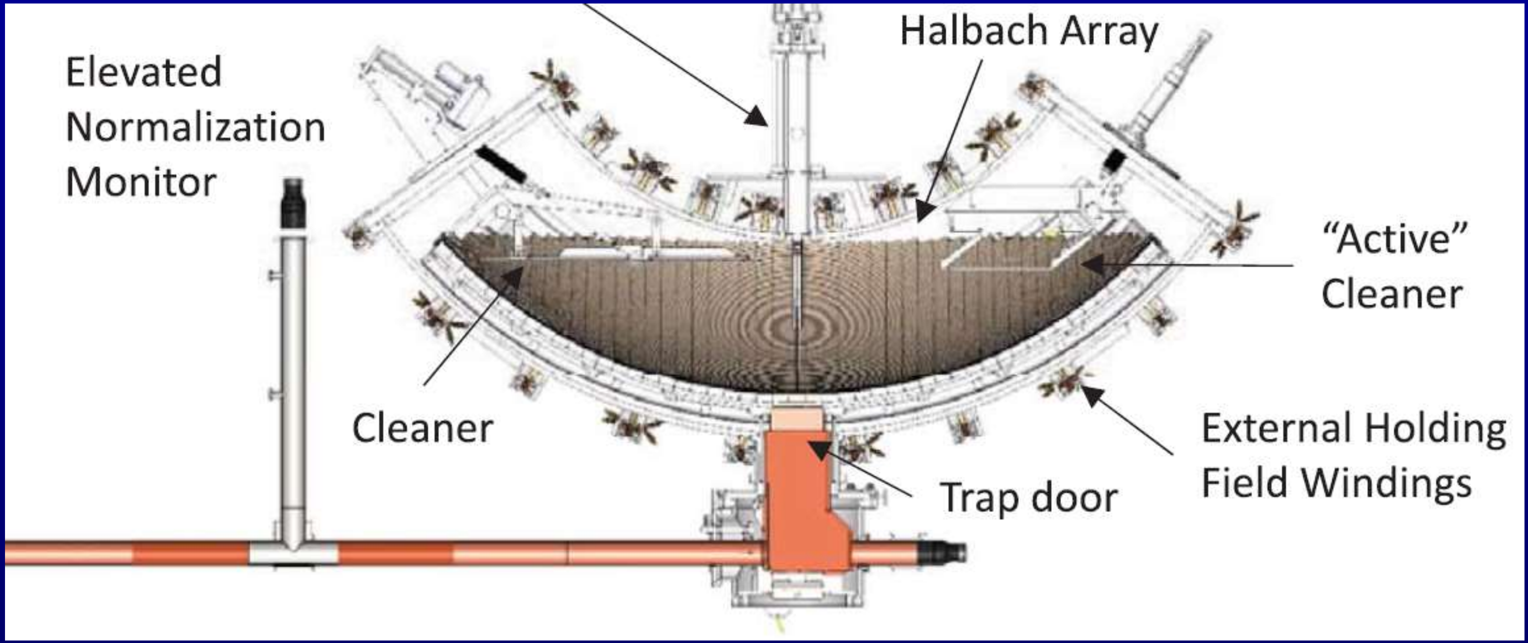
- Beta decay lifetime

$$887.7 \pm 1.2(stat) \pm 1.9(sys)\ \mathrm{s}$$

High precision measurement (II)

- “Bottle” approach by UCNτ at LANL

Pattie et al., Science 360, 627 (2018)



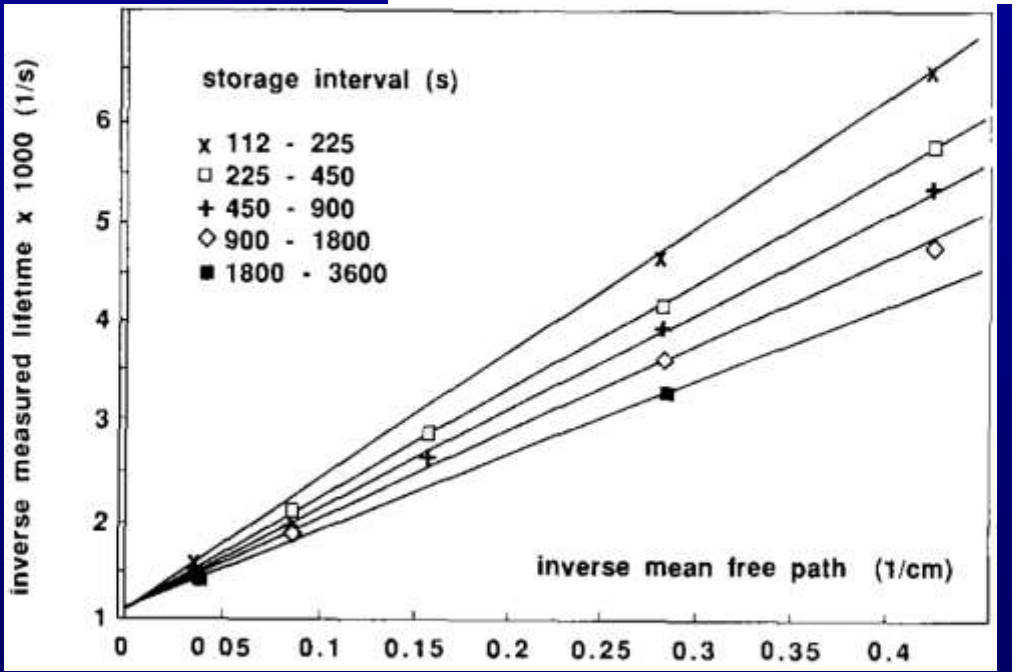
- UCN (<10^{-7} eV) confined by gravity and magnetic field
- n-disappearing lifetime

$$877.7 \pm 0.7(stat) + 0.4/-0.2(sys)\ \mathrm{s}$$

A beautiful experiment

- An early "bottle" experiment, Mampe et al., PRL 63, 593, 1989

$$\theta_m[s^{-1}] = \theta_\beta + \theta_W = \theta_\beta + \mu(v)\frac{v}{\lambda} = \frac{\ln(N(t_1) - N(t_2))}{t_2 - t_1}$$



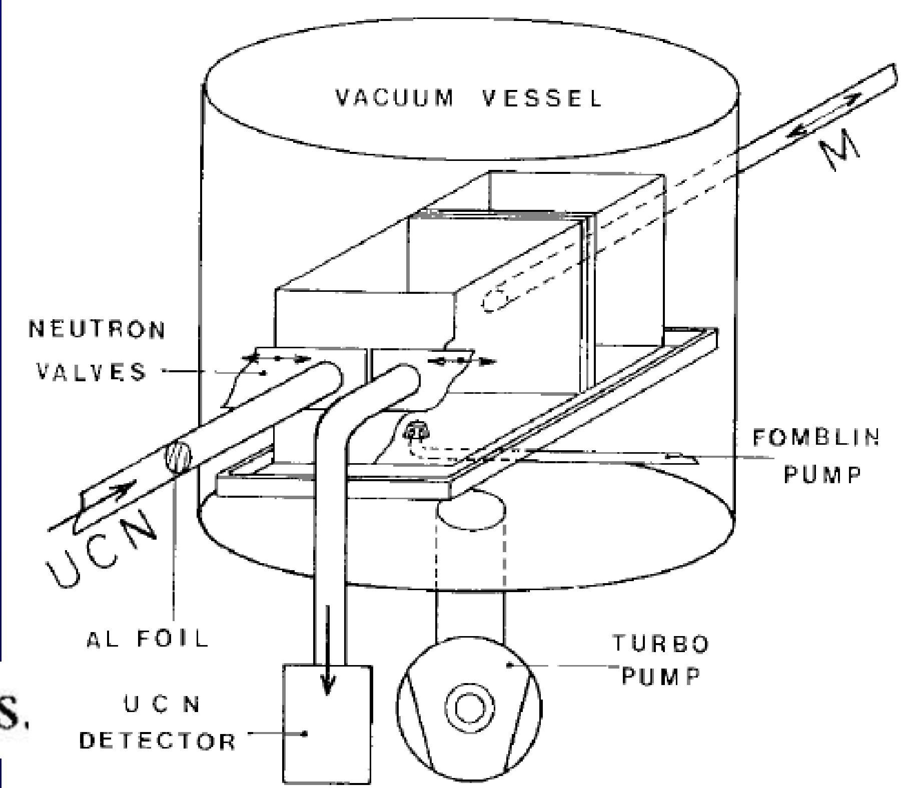


Fig. 1 Sketch of the apparatus.

$\tau_\beta = (887.6 \pm 1.1)$ (887.6 ± 3) s.

→ $\mathbf{Sin^2(2\theta) = 2x10^{-5}}$

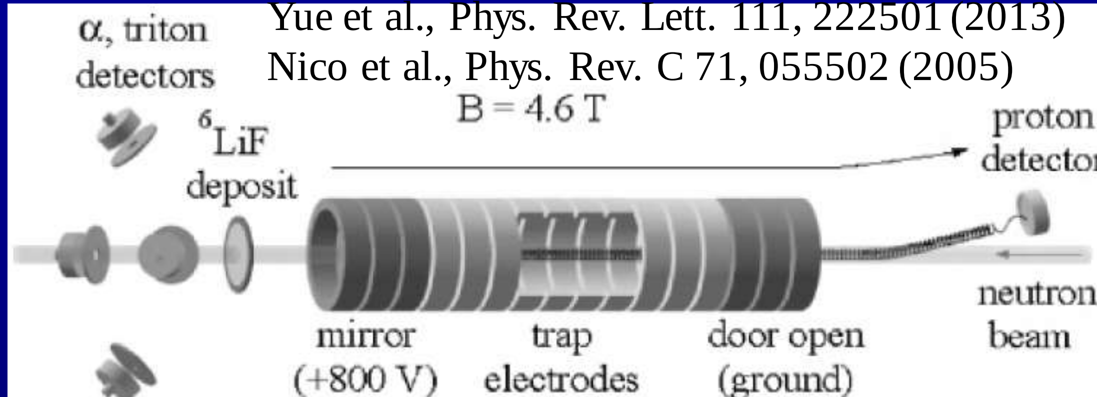
The 1% difference

- "Beam" experiment

$$P_{nn'}(\text{beam}) = \frac{1}{2}\sin^2(2\theta) \sim 10^{-5}$$

$$\tau_n = \frac{L}{\dot{N}_p}\frac{\dot{N}_{\alpha+t}}{\epsilon_o}\frac{\epsilon_p}{v_o}$$

Yue et al., Phys. Rev. Lett. 111, 222501 (2013)
Nico et al., Phys. Rev. C 71, 055502 (2005)

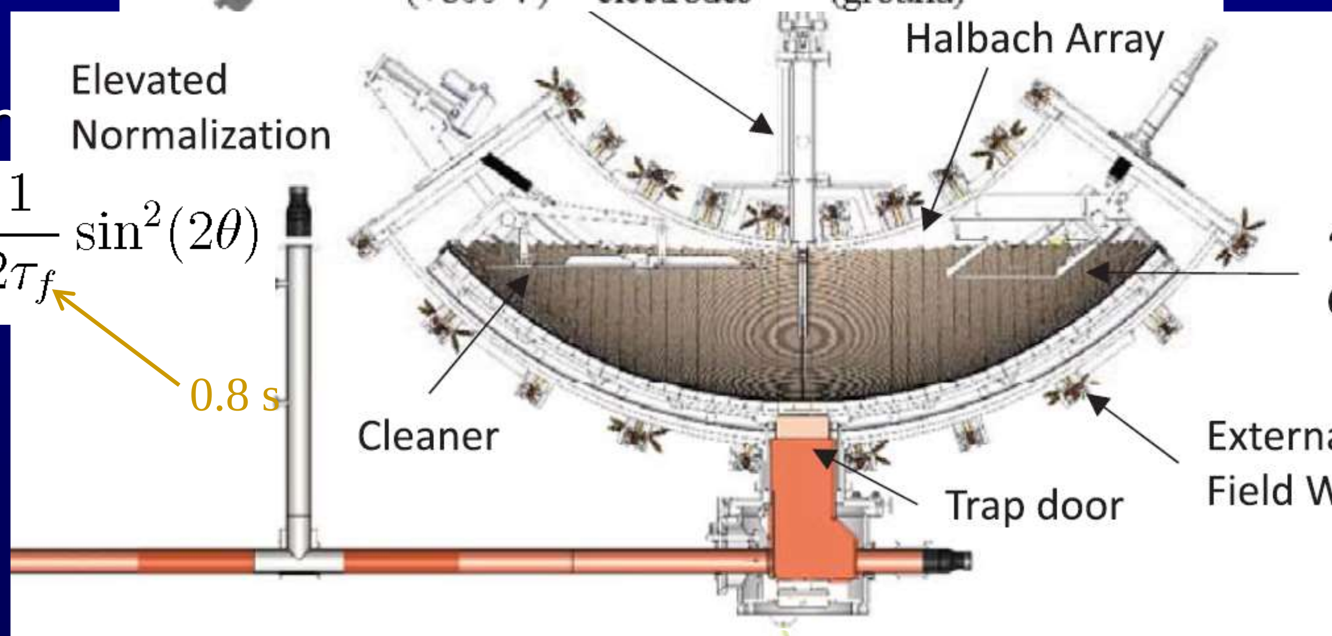


- "Bottle" experimen

$$\lambda_{nn'}(\text{bottle}) = \frac{1}{2\tau_f}\sin^2(2\theta)$$

0.8 s

$$\frac{1}{\tau_n} = \frac{1}{\tau_\beta} +$$



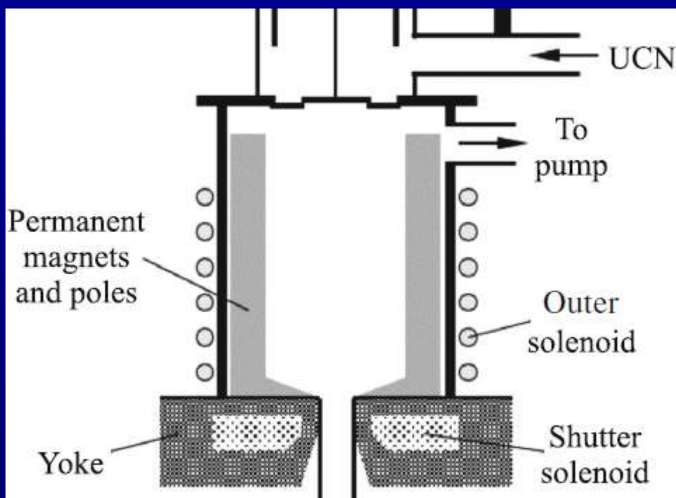
Pattie et al., Science 360, 627 (2018)

Other Experiments with Magnetic Traps

- Two experiments at ILL, Grenoble, France

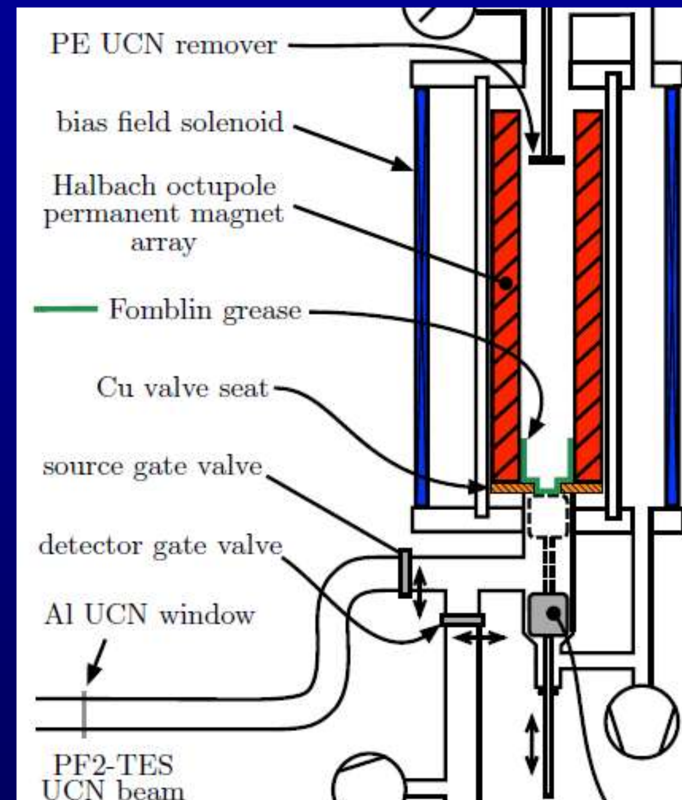
Leung et al., Phys. Rev. C 94, 045502 (2016)

Ezhov et al., JETP Lett 107, 671 (2018)



$$\tau_S = 1/\lambda_S = (874.6 \pm 1.7)\ \text{s}$$

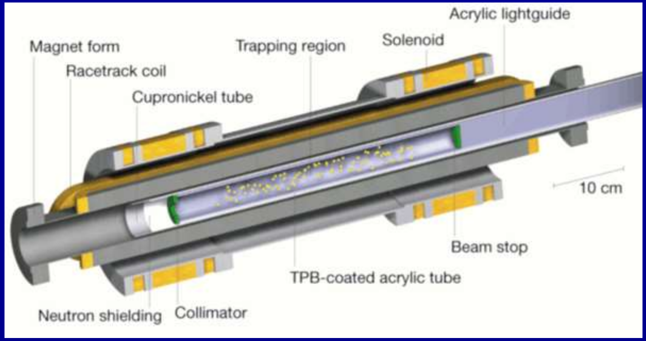
$$\lambda_{nn'}(\text{bottle}) = \frac{1}{2\tau_f}\sin^2(2\theta)$$



(835 ± 36) s	65-cm
(824 ± 32) s	80-cm

NIST magnetic trap

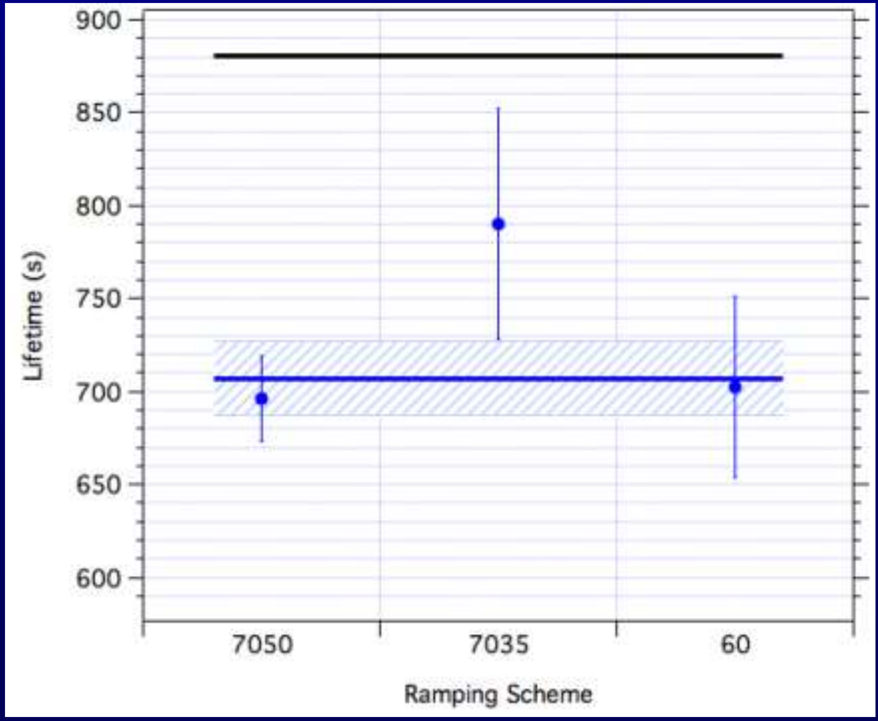
- Huffman et al., Nature 403, 62 (2000) $\tau = 750^{+330}_{-200}$ s



- Dzhosyuk et al., J. Res. NIST. **110**, 339 (2005) $\tau = (833^{+74}_{-63})$ s

- Craig Huffer, Ph.D dissertation at NCSU, 2017

lifetime of 707 ± 20 s



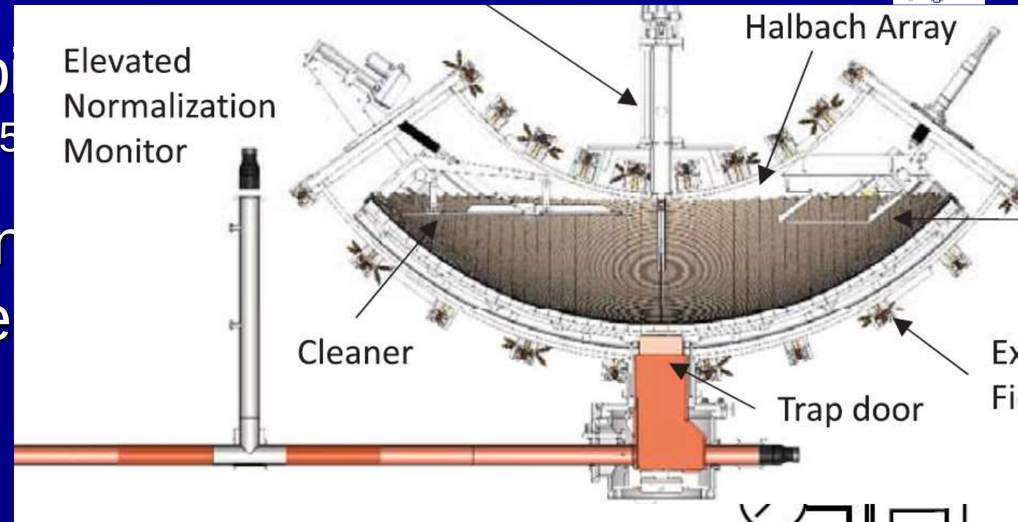
Laboratory Tests

- Further experiments to verify or better measure the parameters of the theory
  - W. Tan, **arXiv: 1906.10262** – extension of CKM and laboratory tests
- **Magnetic UCN traps of different sizes**
- n-n’ oscillations in scintillators of abs-free dense materials (4He, D2O)
- **Branching fraction of K^0 → Invisible, Λ^0 → Invisible**

  10^{-6} for K_S^0 and 10^{-4} for K_L^0 $\quad$ $B_{\rm inv}(\Lambda^0) \simeq 4.4\times10^{-7}$, $B_{\rm inv}(\Xi^0) \simeq 3.6\times10^{-8}$
- βp/β’p’ decays of one-neutron halo nuclei like 11Be
- **Resonant n-n’ oscillations in strong magnetic fields (B ~ 50 T)**
- better measurements of K_{l3}, $K_{\mu2}$, $\pi_{\mu2}$, and π beta decays combined with better lattice QCD calculations

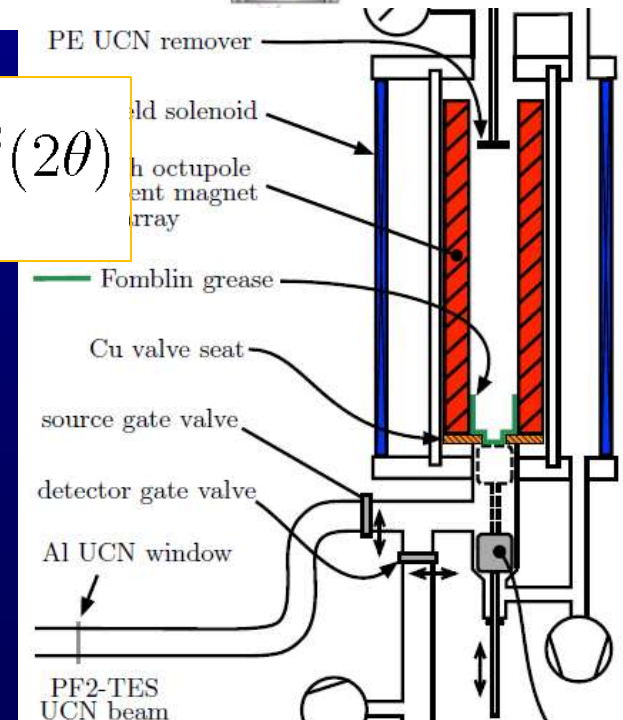
UCN traps of different geometry

- Average neutron loss probabi
bounce is ~ ½*sin²(2θ) ~ 10⁻⁵
- Apparent lifetime depends or
geometry of the trap, i.e., the
flight time of UCNs
- Magnetic traps are ideal



- $$\frac{1}{\tau_n} = \frac{1}{\tau_\beta} + \lambda_{nn'}$$

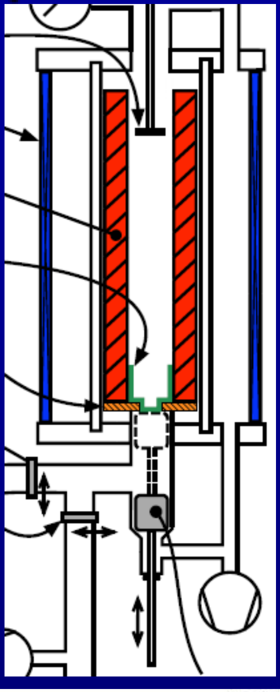
$$\lambda_{nn'}(\text{bottle}) = \frac{1}{2\tau_f}\sin^2(2\theta)$$

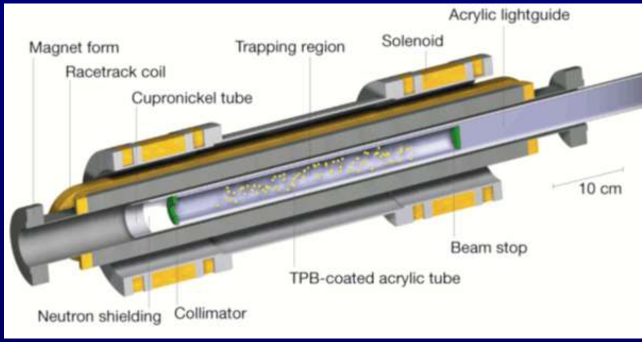


- Systematic variation of the trap sizes
- Narrow cylindrical traps like “HOPE” at ILL, Ioffe at NIST, tauSPECT at Mainz
- HOPE: vary the height of the volume

Narrow cylindrical magnetic traps

- HOPE design
  - Octupole Perm. Magnets + Gravity
  - Can vary the height – lifetime dependent
- NIST design
  - Solenoids + Quad magnet
  - LHe4 for both UCN creation and detection
  - Large mean UCN velocity (i.e., large anomaly)
- Or mixed
  - Solenoids + Oct. Perm. Magnets
  - LHe4 or vacuum
- Improvements:
  - TPC or PSD in LHe for separation of n beta decay from n-capture on 3He
  - Controllable UCN energy distribution





Summary and Outlook

- A perfectly imperfect mirror symmetry is the key to unlock the beauty and elegance of our universe

$$\delta v/v \sim 10^{-14}$$

- Neutron lifetime anomaly under the new n-n' model:
  - CKM matrix is NOT unitary
  - "Beam" approach gives true τ_β (and V_{ud})
  - However, "bottle" approach reveals new physics. In particular, narrow magnetic traps could provide immediate tests on the new model
- Update: http://sites.nd.edu/wtan/smm/
  - **arXiv: 1902.01837, PLB 797, 134921 (2019), dark matter & n-lifetime**
  - arXiv: 1902.03685, evolution of stars
  - arXiv: 1903.07474, ultrahigh energy cosmic rays
  - arXiv: 1904.03835, **PRD** 100, 063537 (2019), K^0-K^{0}' & baryon asymmetry
  - **arXiv: 1906.10262, unitarity of CKM and laboratory tests**
  - arXiv: 1908.11838, dark energy and nature of neutrinos
  - https://doi.org/10.31219/osf.io/8qawc: Supersymmetric Mirror Models
  - https://doi.org/10.31219/osf.io/2jywx: Gravity and 2-d Black Holes
  - arXiv: 2006.10746, CP and Mirror symmetries; invisible decays; better model parameters