Beta decay of neutrons

András Sveiczer
ELTE TTK
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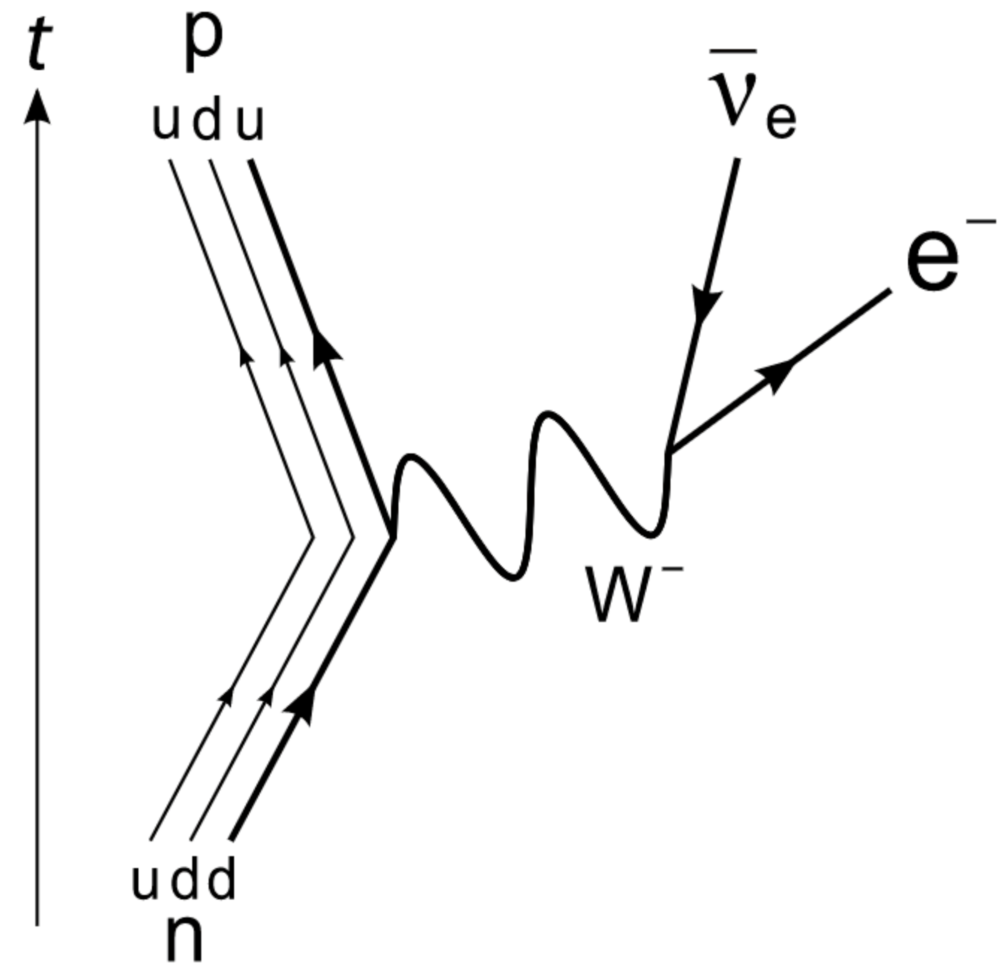
Neutrons

- Discovered in 1932
- "Made of three quarks: u,d,d"
- Spin: 1/2
- Mass:
  939.5 654 133(58) MeV/c^2
- Magnetic moment:
  −1.91 304 273(45) μ_N
- Half-life: 881.5(15) s

Decay of neutrons

- Second lightest baryon, proton is the lightest
- According to the Standard Model of particle physics, it can decay into a proton exclusively (conservation of baryon number and energy)
- On the quark-level, a down quark decays into an up quark and a W^- boson
- The W^- boson decays further into an electron, and an electron-type antineutrino



Lifetime of neutrons

- Its value is inaccurate!
- Determines the $|V_{ud}|$ element of the CKM-matrix, since it's a down quark to up quark conversion.

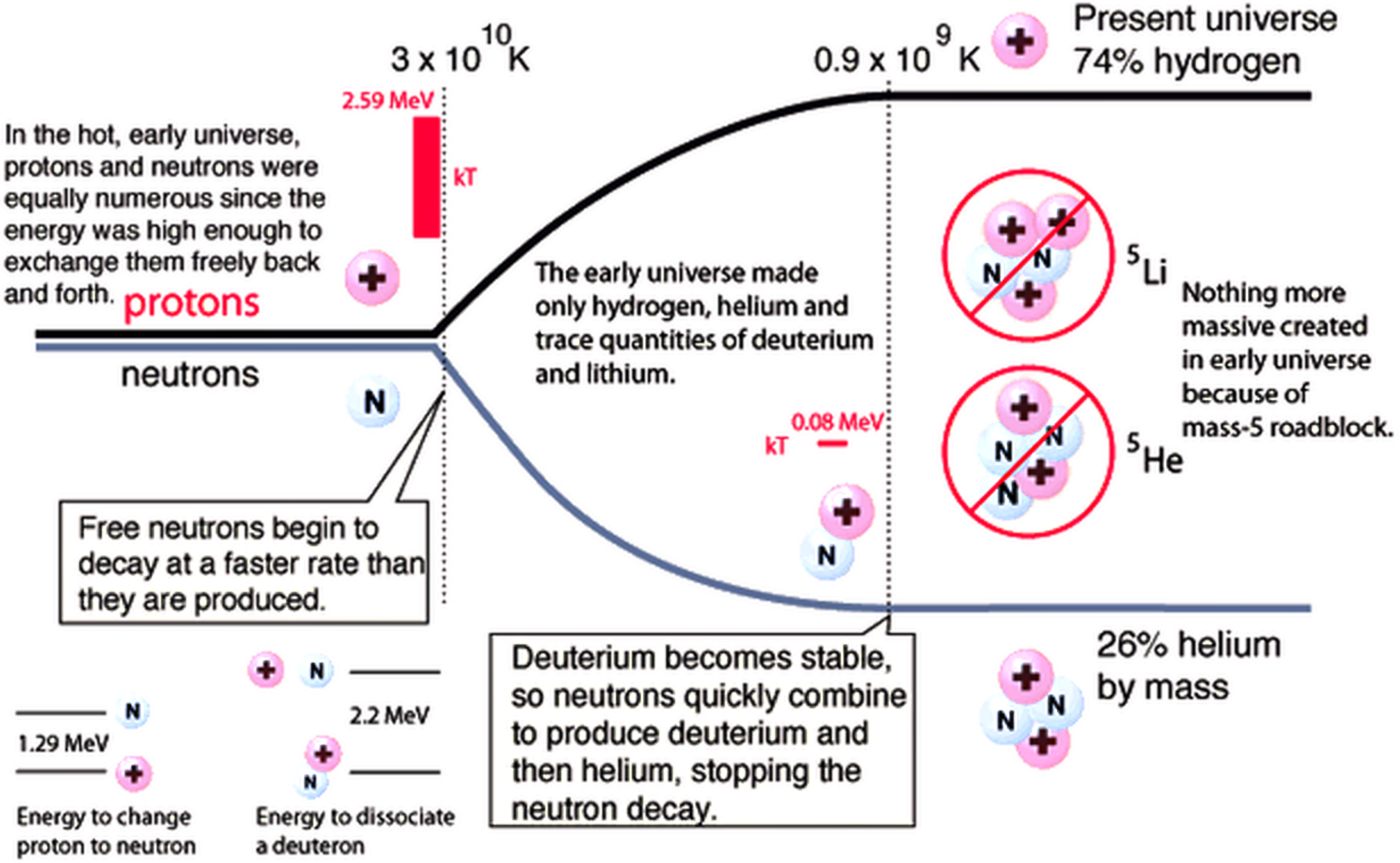
$$|V_{ud}|^2 = \frac{4908.7 \pm 1.9\ \mathrm{s}}{\boxed{\tau_n}(1 + 3\lambda^2)},$$

$\lambda = G_A / G_V$ is the ratio of the axial-vector weak coupling constant to the vector weak coupling constant

- Determines the H:He ratio of the universe!

881.5(15) s

H:He ratio



In the hot, early universe, protons and neutrons were equally numerous since the energy was high enough to exchange them freely back and forth.

The early universe made only hydrogen, helium and trace quantities of deuterium and lithium.

Free neutrons begin to decay at a faster rate than they are produced.

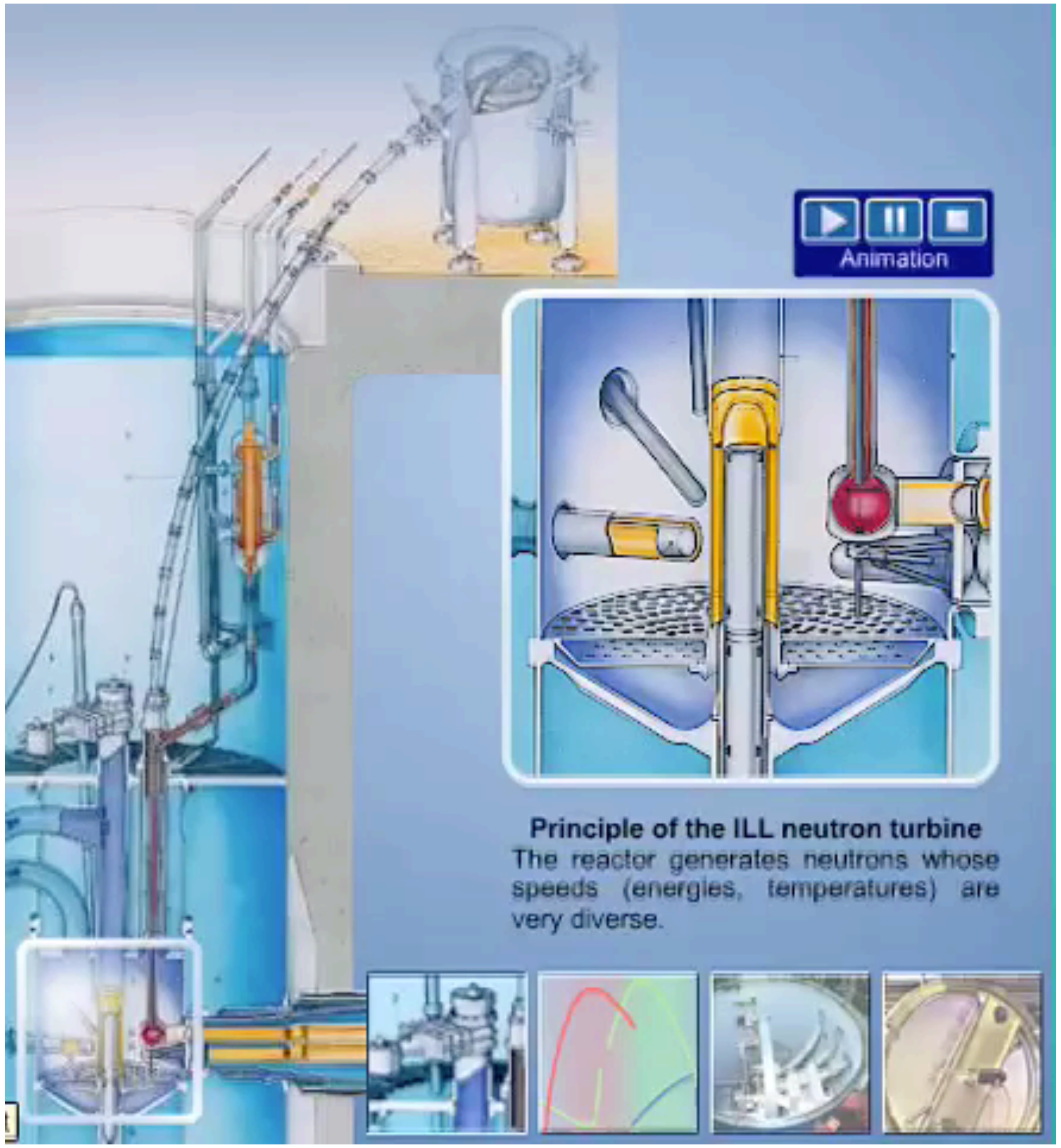
Deuterium becomes stable, so neutrons quickly combine to produce deuterium and then helium, stopping the neutron decay.

Nothing more massive created in early universe because of mass-5 roadblock.

Present universe 74% hydrogen

26% helium by mass

Measuring the life time:
Cold and ultra cold neutrons



Principle of the ILL neutron turbine

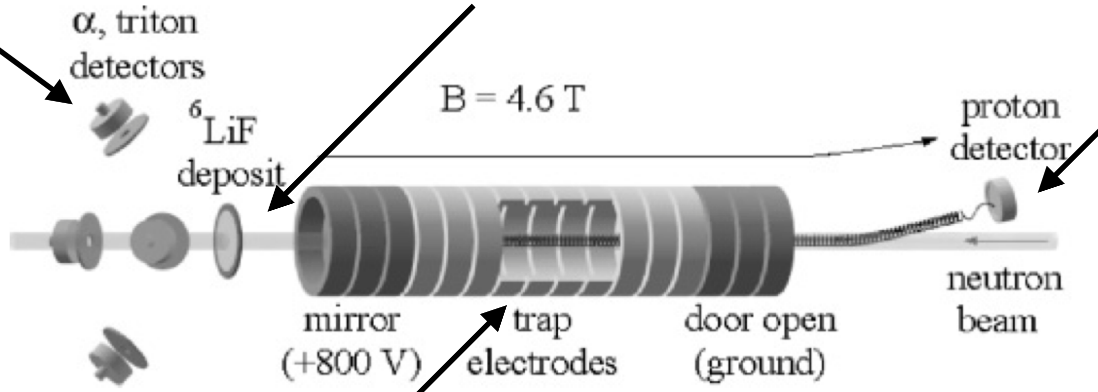
The reactor generates neutrons whose speeds (energies, temperatures) are very diverse.

Measuring the lifetime: Beam experiments

$$\dot{N}_{\alpha+t} = \epsilon_o v_o \int_A \int da I(v) \frac{1}{v} dv$$

$^6\mathrm{Li}(n,t)^4\mathrm{He}$

$$\dot{N}_p = \tau^{-1} \epsilon_p L \int_A \int da I(v) \frac{1}{v} dv$$



$$N_n = L \underbrace{\int_A \int da I(v) \frac{1}{v} dv}_{\text{number of particles per unit of length}}$$

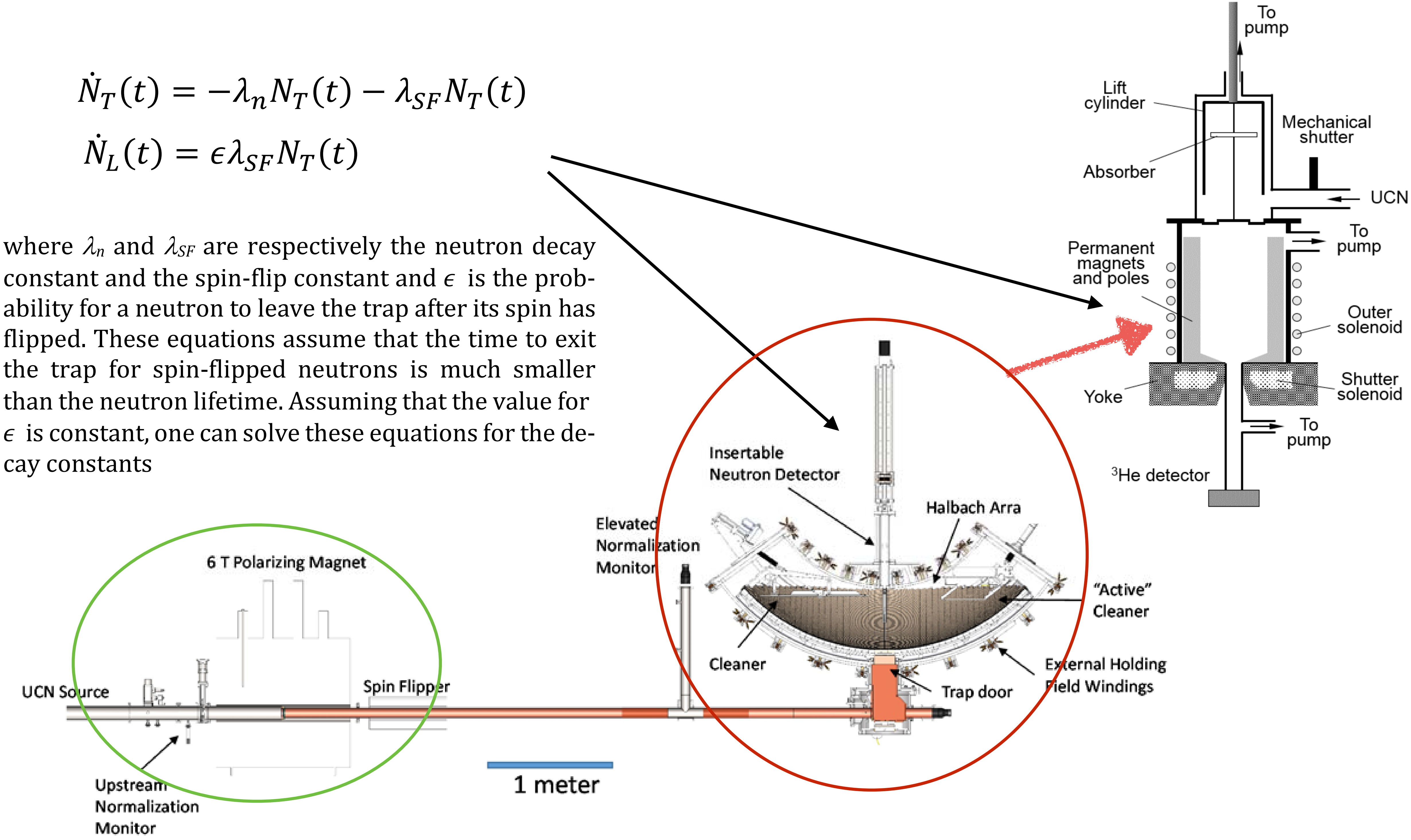
$$\boxed{\tau_n = \frac{L}{\dot{N}_p} \frac{\dot{N}_{\alpha+t}}{\epsilon_o} \frac{\epsilon_p}{v_o}}$$

Measuring the lifetime: Bottle experiments

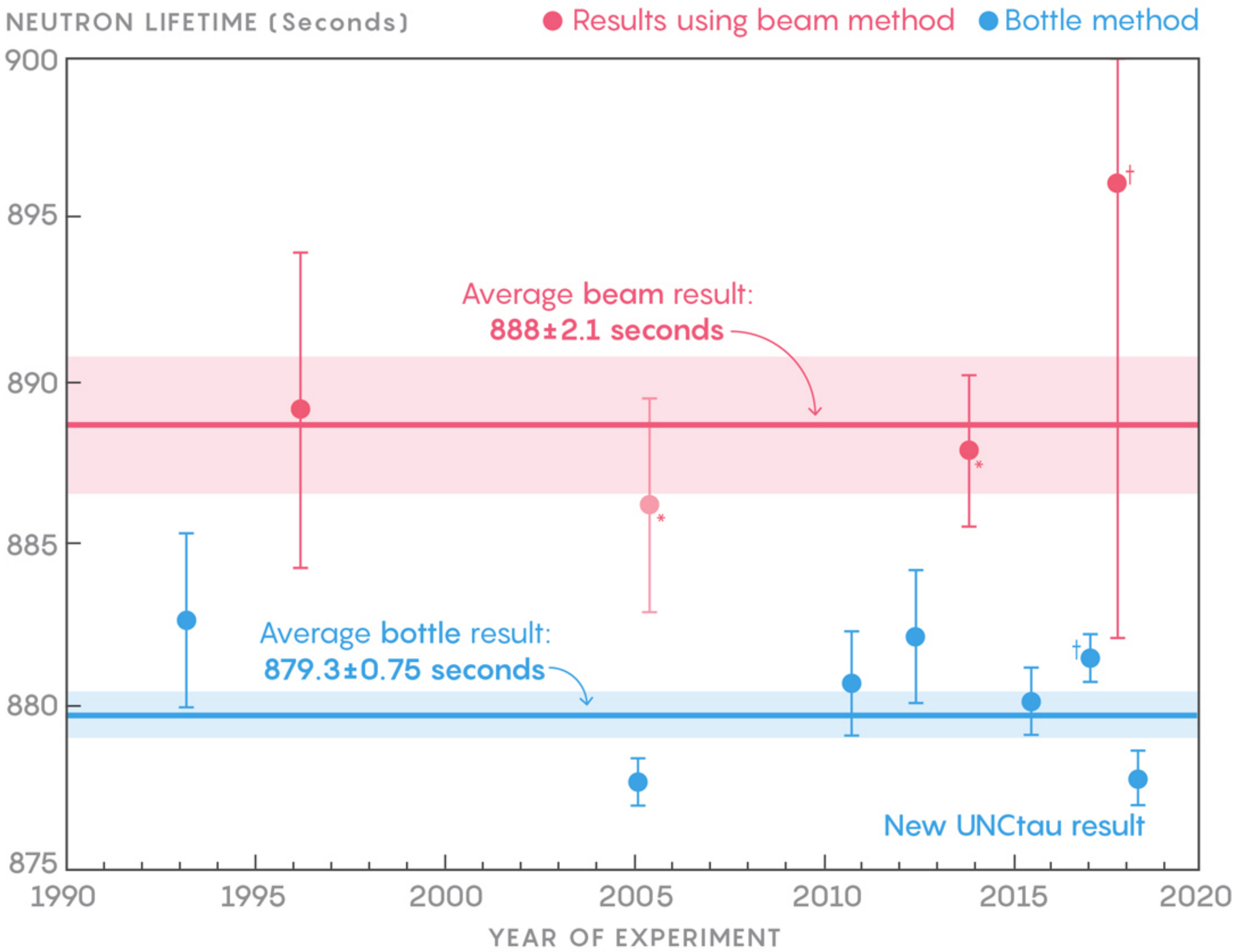
$$\dot{N}_T(t) = -\lambda_n N_T(t) - \lambda_{SF} N_T(t)$$

$$\dot{N}_L(t) = \epsilon \lambda_{SF} N_T(t)$$

where λ_n and λ_{SF} are respectively the neutron decay constant and the spin-flip constant and ϵ is the probability for a neutron to leave the trap after its spin has flipped. These equations assume that the time to exit the trap for spin-flipped neutrons is much smaller than the neutron lifetime. Assuming that the value for ϵ is constant, one can solve these equations for the decay constants



Results



*Nico result (2005) was superseded by an updated and improved result, Yue (2013);

†Preliminary results

What can cause the difference?

- About 4 sigma difference, that's huge
- Beam experiment: we measure the # of protons, which should be exactly the same as the neutrons
- Bottle experiment: we measure the # of neutrons, and we measure more decays than protons
- Does the neutron have another way of decay?

Explanations

- Maybe some unrecognised systematic errors
- The only other possibility is some new physics
    - Baryon number not conserved?
    - Dark matter? We don't know of any possible outcomes in the SM
    - Mirror particles?

Dark matter

What's dark matter? We don't know. It interacts with ordinary matter gravitationally, and does not interact with electromagnetic waves. "Invisible".

From astronomical obervations we know it for sure, that some form of dark matter is present in our universe.

Most likely it's made of some yet unknown particles.

Possible decays

1) $n \rightarrow \text{invisible} + \text{visible}\,,$

2) $n \rightarrow \text{invisible}\,.$

Sum of the invariant masses in the final state

$$\boxed{M_f < m_n}$$

Violates the conservation of baryon number! The proton could also decay?

$$\boxed{p \rightarrow n^* + e^+ + \nu_e}$$

$$\boxed{m_p - m_e < M_f}$$

But its lifetime > 2.1 x 10^{29} years,
we have never seen it!

There could be some nuclear (Z,A) -> (Z,A-1) decays?

Never seen those either!

Largest mass difference at ^{9}Be -> ^{8}Be: $\boxed{937.900\ \text{MeV} < \min\{M_{f'}\} \leq M_f}$

The mass of the DM particle:

$$\boxed{937.900\ \text{MeV} < \min\{M_{f'}\} \leq M_f < 939.565\ \text{MeV}}$$

The case of n $\longrightarrow$ X + γ

We assume that the $\chi \rightarrow p + e^{-} + \bar{\nu}_e$ process is forbidden, since X is a DM particle.

$$\boxed{m_\chi < m_p + m_e = 938.783 \text{ MeV}}$$

$$\boxed{937.900 \text{ MeV} < m_\chi < 938.783 \text{ MeV}}$$

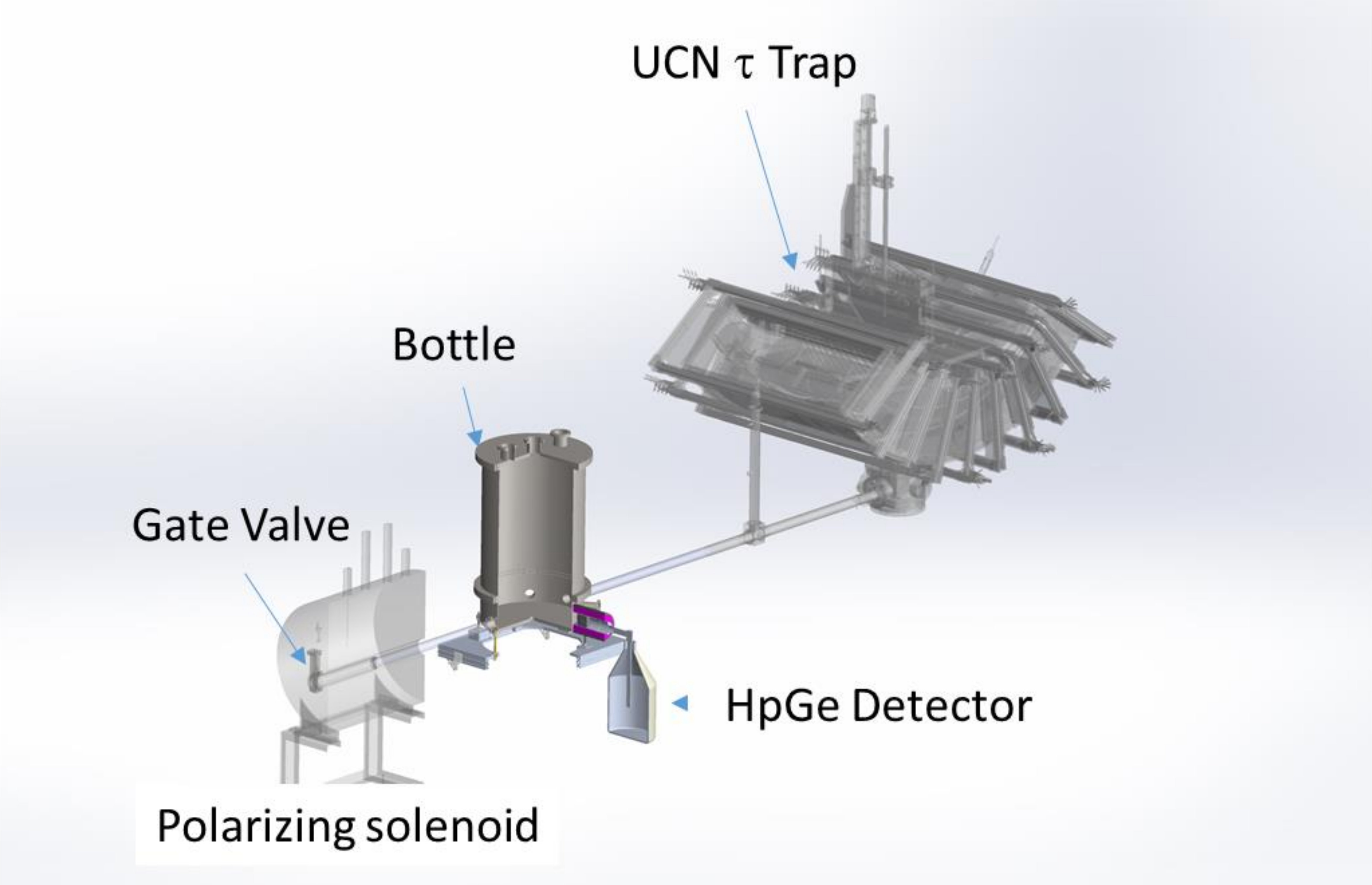
$$\boxed{0.782 \text{ MeV} < E_\gamma < 1.664 \text{ MeV}}$$

(we neglect the kinetic energy of X)

The energy of the photon is also discrete (two body decay)!
This kind of decay would make up about 1% of all the decays, which is consistant with the experimental data (can be estimated)!

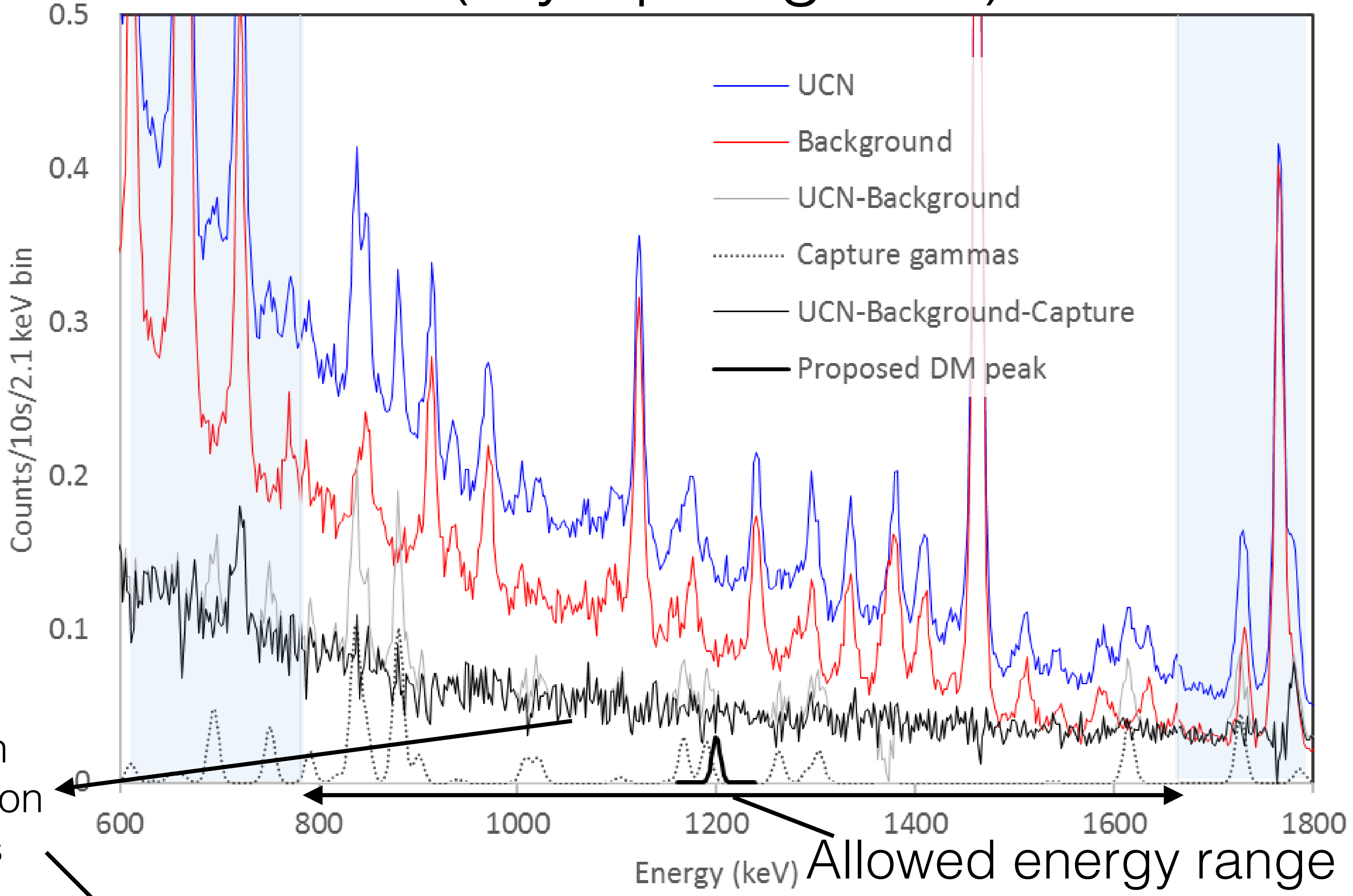
We should be able to see it with gamma detectors!!!

Bottle experiment with gamma detectors



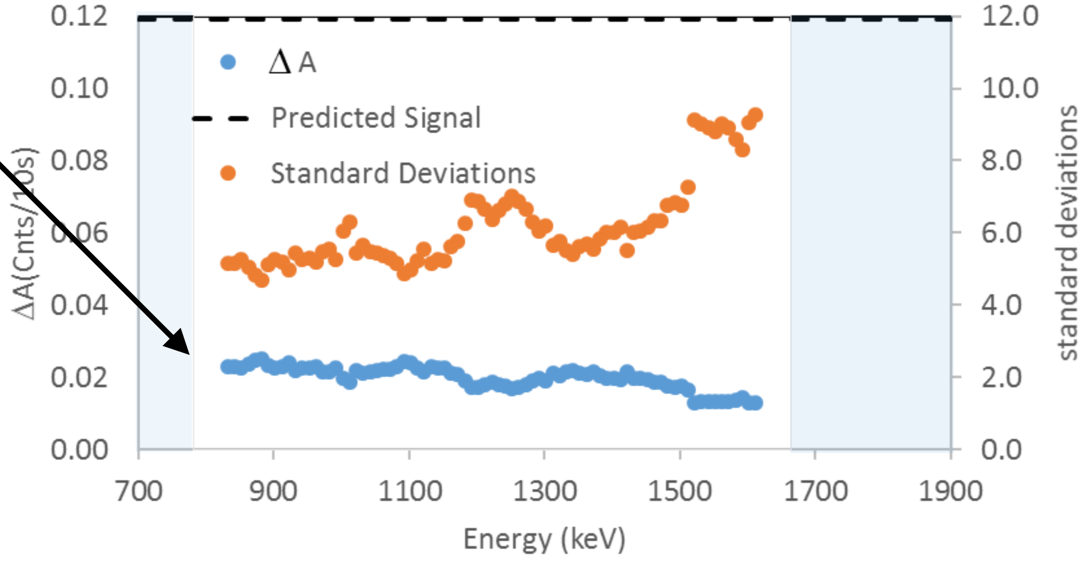
Results

(my apologies...)



Gaussian fits with linear background on 100 keV intervals

Allowed energy range of the photon



???

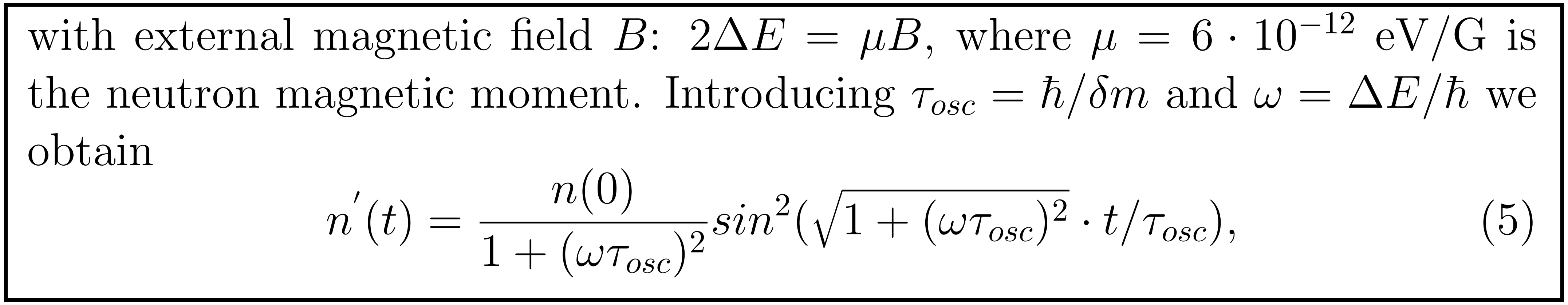
$$\Delta A = \sqrt{3\sigma_{peak} RMS}$$

Even the dimension is incorrect...
It should be (keV)$^{-3/2}$(s)$^{-2}$

Nevertheless, no sign of such photons

Mirror neutrons

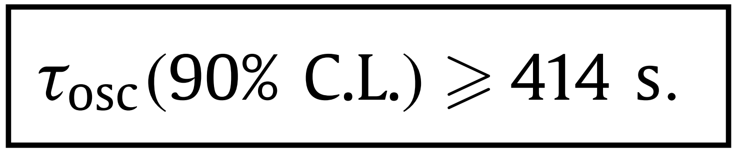
According to the theory of mirror particles, every particle would have its mirrored pair. There would be a very small mass diference, and the two particles would be mixed in reality.



with external magnetic field B: $2\Delta E = \mu B$, where $\mu = 6 \cdot 10^{-12}$ eV/G is the neutron magnetic moment. Introducing $\tau_{osc} = \hbar/\delta m$ and $\omega = \Delta E/\hbar$ we obtain

$$n^{'}(t) = \frac{n(0)}{1+(\omega\tau_{osc})^2} sin^2(\sqrt{1+(\omega\tau_{osc})^2} \cdot t/\tau_{osc}), \tag{5}$$

This has to be examined experimentally. No observation to date. Lower limit of n -> n' lifetime:



$\tau_{\mathrm{osc}}(90\%\ \mathrm{C.L.}) \geqslant 414$ s.

Conclusion

- There is a 4 sigma difference in the lifetime of neutrons depending on the experiment
- No valid explanation supported by experimental data is available
- Not just the explanation, but the value itself is important, we must get to the bottom of this problem!

Thanks for your attention!