What’s Cooler Than Being Cool?
UltraCold Neutrons

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UltraCold Neutrons (UCN)

Main points to *"take away"* :

What are UltraCold Neutrons (UCN)?
Neutrons cooled to near absolute zero
(-273° C, or 0 K) and therefore are very **SLOW**

Why are UCN interesting?
Because they are so **slow**, UCN have unique properties.

These unique properties allow us to use UCN:

⇨ *For fundamental research*
⇨ *For applied research ("high-tech" tool to probe the structure of advanced materials)*

UltraCold Neutrons (UCN)

<u>Briefly review:</u>

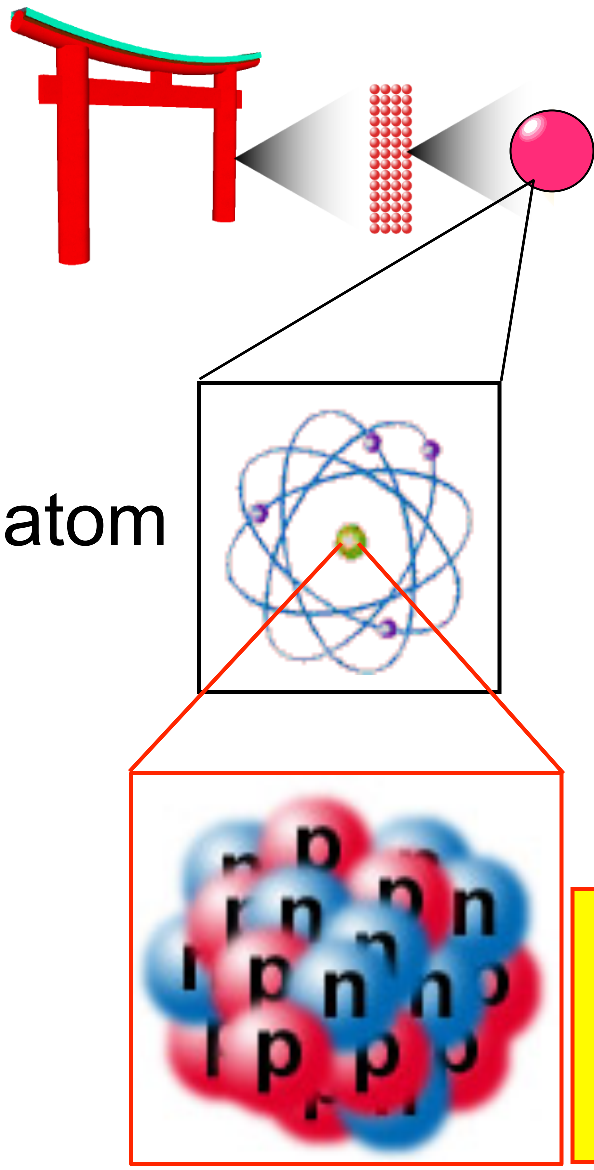
- What are neutrons?
- Why are they important?
- How to make lots of neutrons

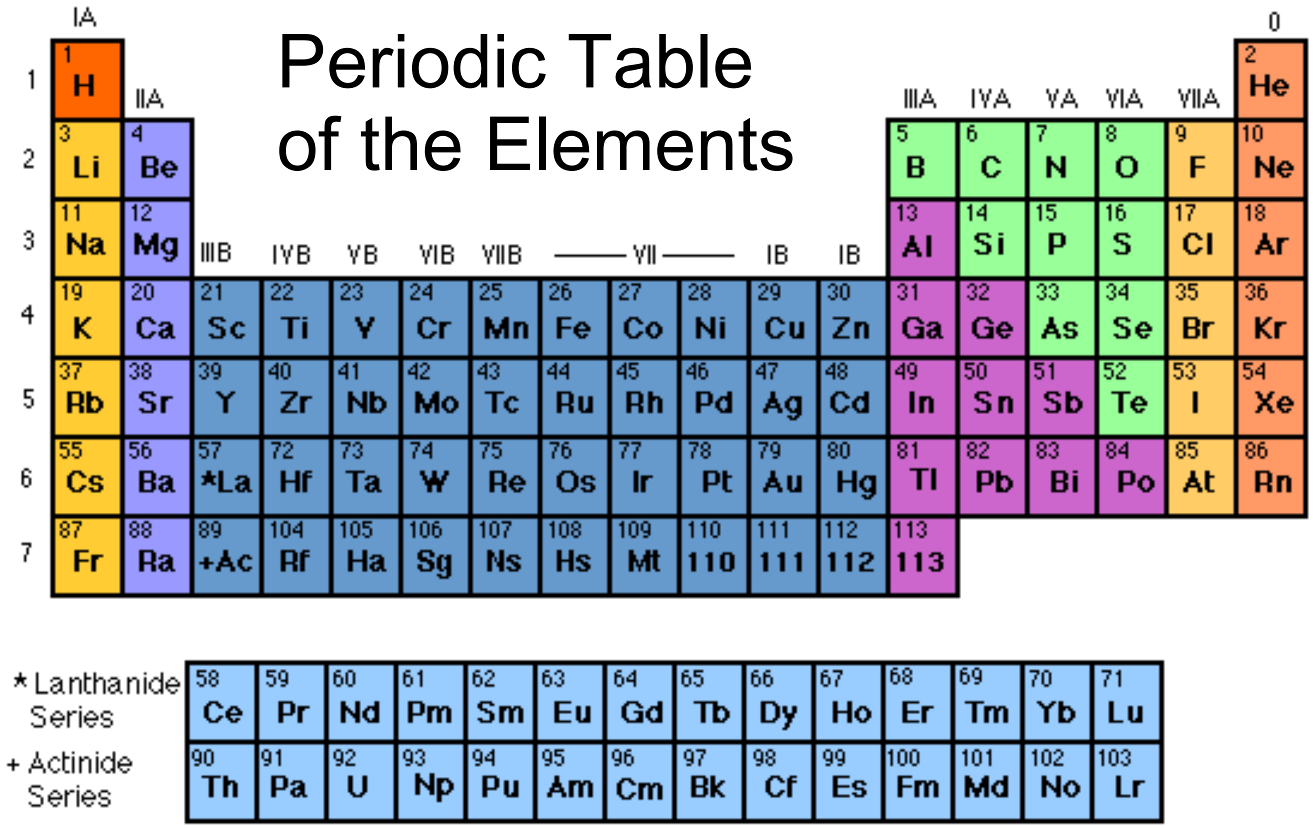
<u>Jump over to UCN:</u>

- How to make ultracold neutrons
- Interesting properties of ultracold neutrons
- Ultra-cool experiments and uses for UCN
- The world’s most intense source of UCN (at TRIUMF)
- The Electric Dipole Moment of the Neutron

What are Neutrons?

⇨ Neutrons are a basic constituent of matter

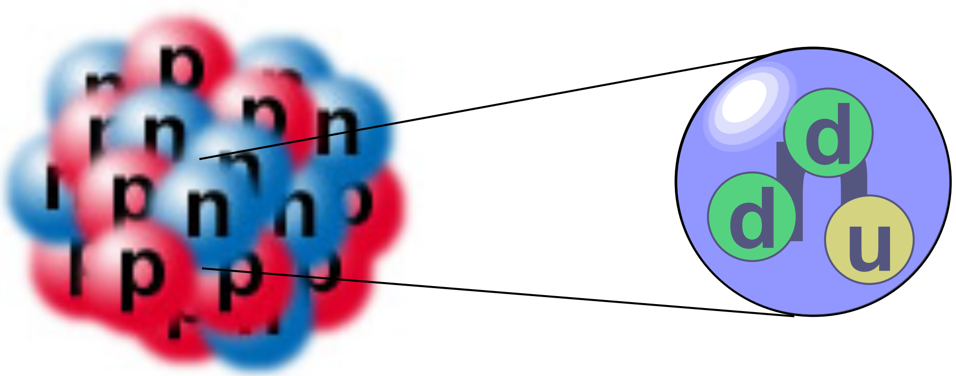




The atomic nucleus
is made of
protons and neutrons

What are Neutrons?

The atomic nucleus is made of protons & neutrons

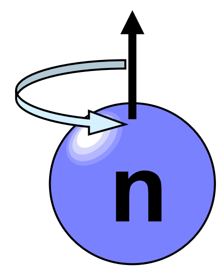


The neutron has no charge

A neutron walks into a bar,
sits down, and orders a drink.
Finishing, he asks, “How much?”
The bartender replies,
“For you, no charge.”

⇨ The neutron contains quarks

⇨ The neutron carries “spin” and has a Magnetic Moment



Think of a spinning top

Think of a bar magnet

⇨ When freed from a nucleus, neutrons decay

⇨ Discovered by J.Chadwick in 1932 (Nobel Prize,1935)

Why are Neutrons Important?

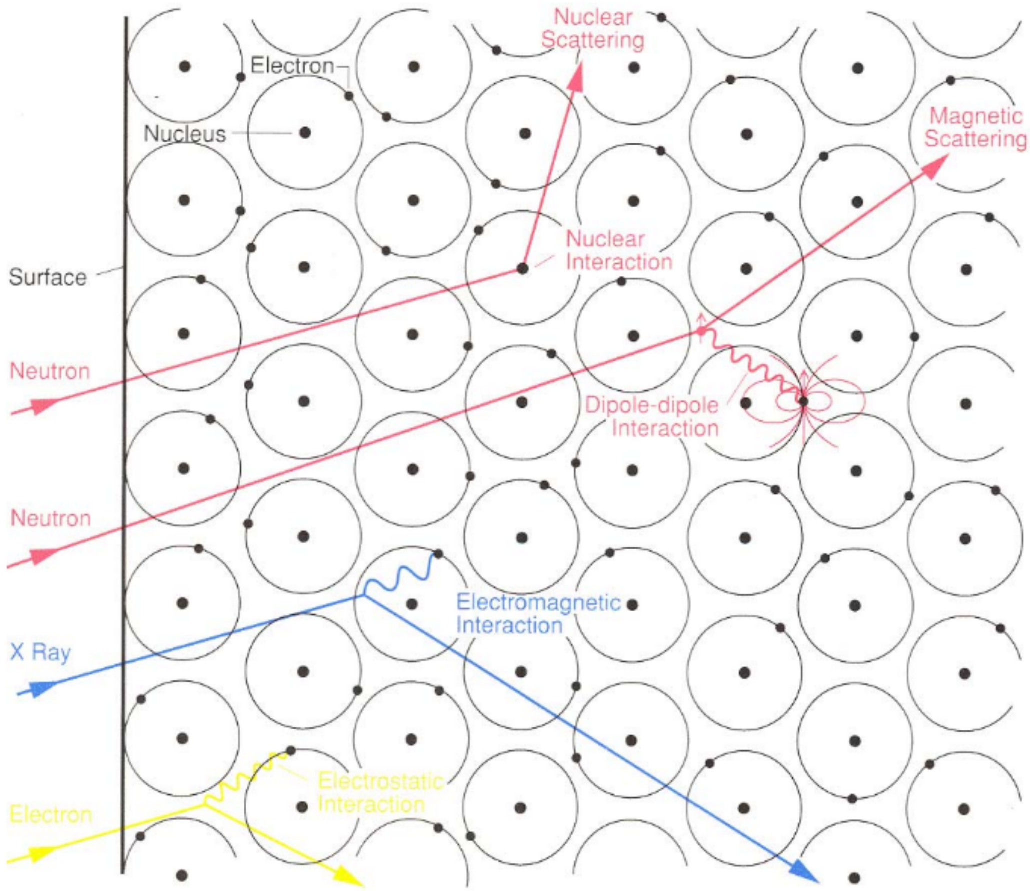
- They keep the nucleus together (without them, only H)
- Free neutrons were one of the first things present in the early universe. *Their decay half-life is intimately related to the amount of (D, He, Li) in the universe.*
- Important in many reactions going on in our sun (nuclear fusion), and in nuclear reactors (nuclear fission).
- **We're made of them**

Neutrons are used to:

- Study many Fundamental Physics questions
- Probe the structure of materials

Materials Science and Neutrons

Neutron scattering: A valuable tool for studying the structure of materials



X-rays:
Sensitive to the electron clouds (charge) in the atoms

Neutrons:
Sensitive to the atomic nucleus
(Interact mainly thru strong force)

They are "Complementary" probes, sensitive to different aspects of the sample material.

How to make a lot of Neutrons?
Liberate them from nuclei

- ⇨ In a nuclear reactor
- ⇨ In an atom smasher (accelerator)

Reactor

Insititut Laue-Langevin,
Grenoble, France, www.ill.fr

Accelerator

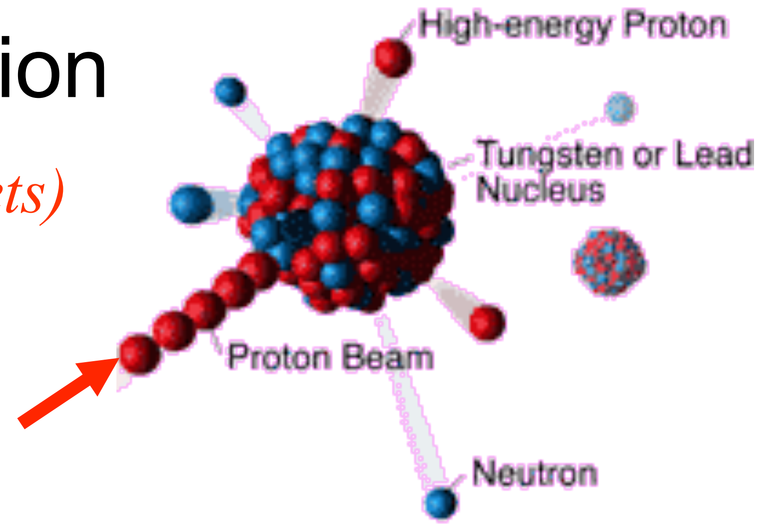
Spallation Neutron Source,
Oak Ridge, Tennessee, www.sns.gov

How to make Neutrons?

Accelerator-driven:

- Using proton-induced spallation

("Shoot" protons at tungsten or lead targets)



- Creates very fast-moving neutrons (T ~ 1 billion °C)

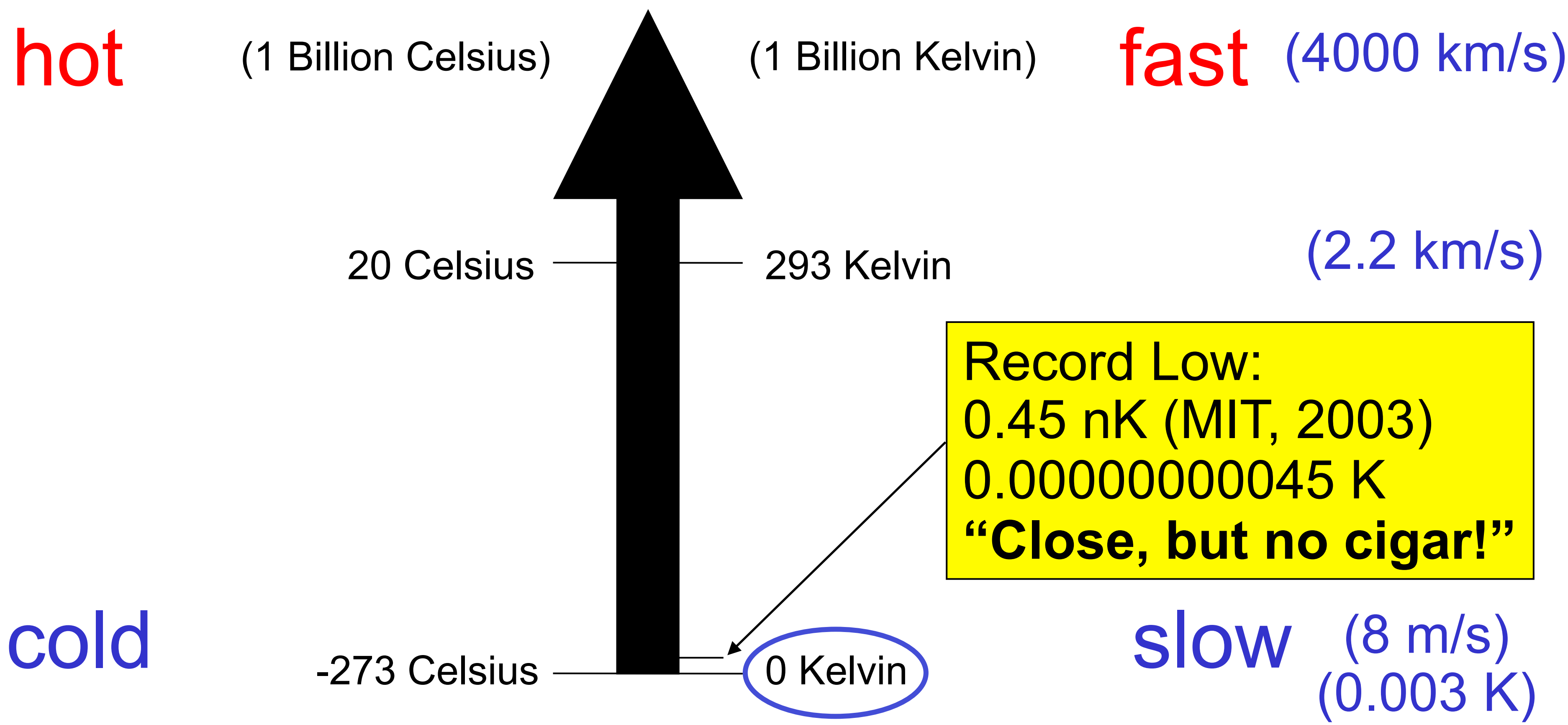
- Such "hot" neutrons are not so useful.

fast

- Need to cool them down to make them useful.

slow

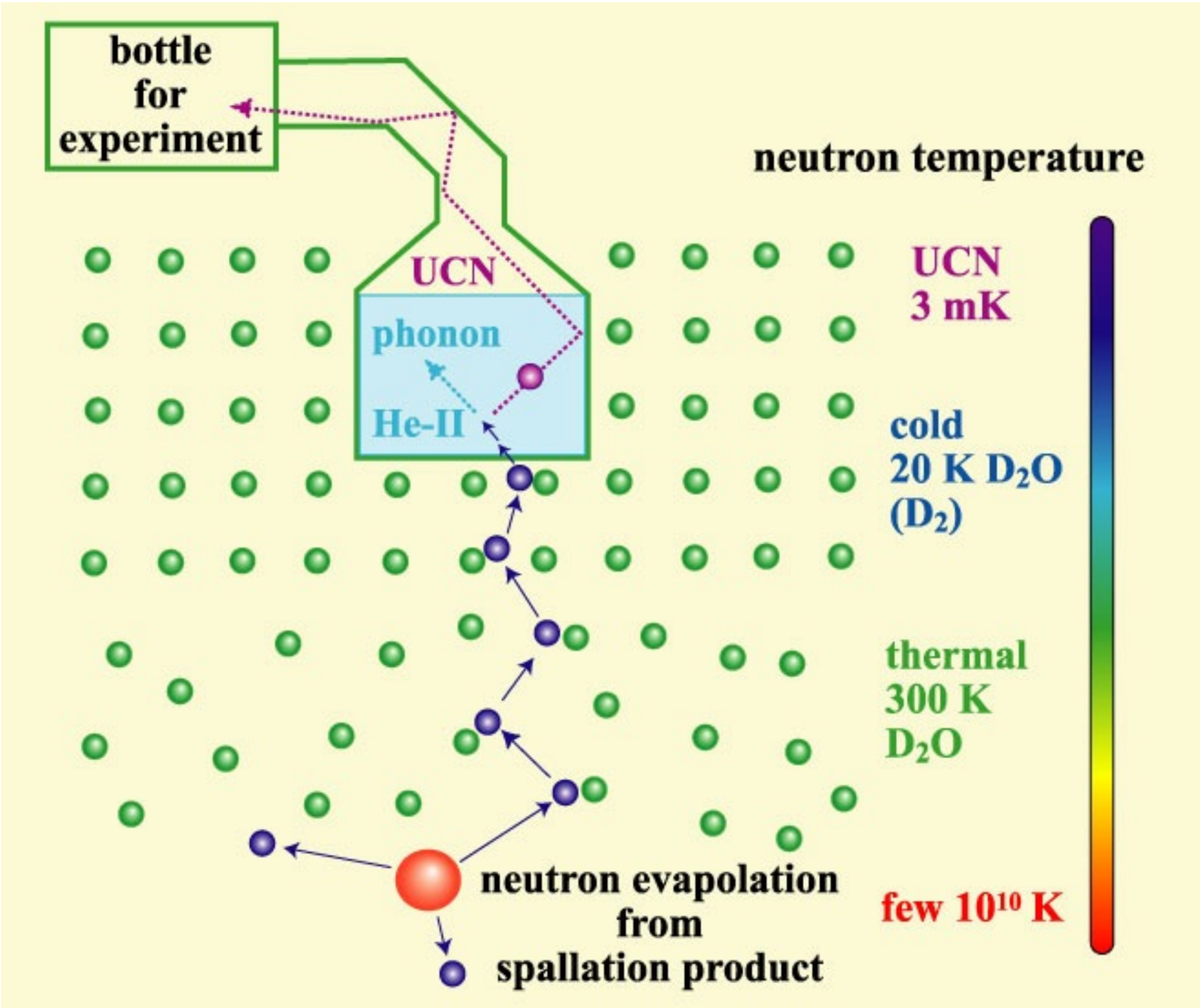
Temperature & Kinetic Energy



What is absolute zero (0 K)?

At Absolute Zero, no more heat can be removed from a system

How do we cool “hot” neutrons?
Step 1: Cold Neutrons



Cool in stages. (Neutrons start off at 1-30 B °C)

Bring them into contact with a material at room temperature (300 K, 25°C)

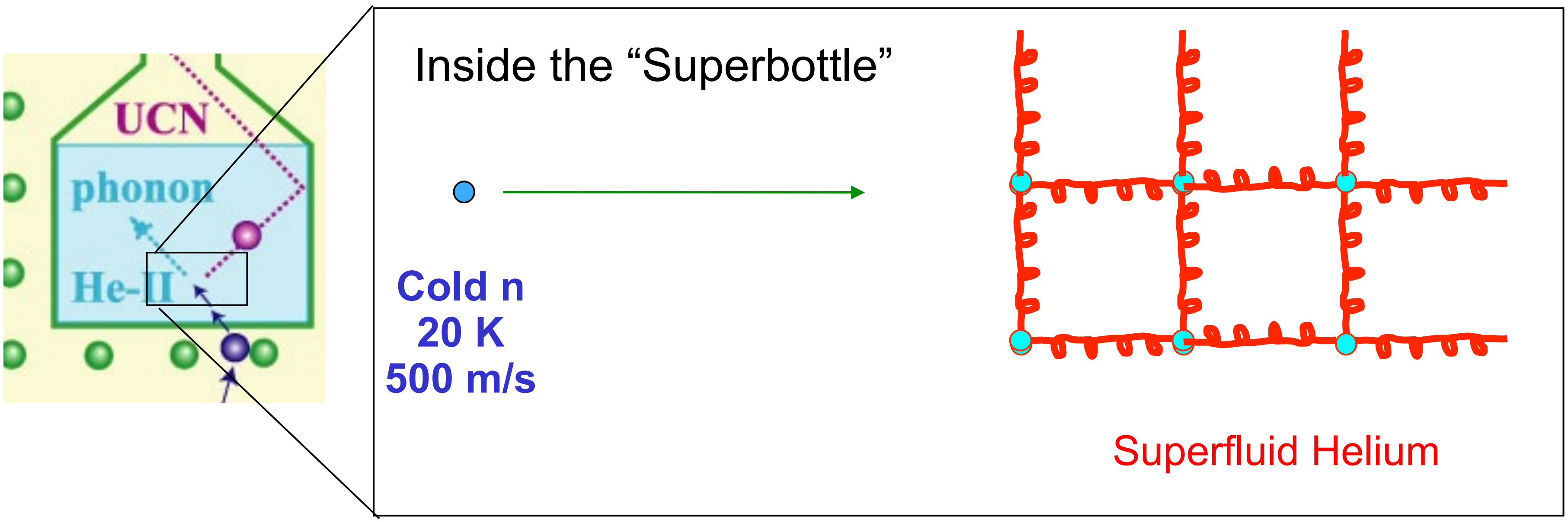
They bounce around and eventually come into equilibrium with material

Next, into cold “heavy” ice (20 K or -253 C)

At ~ 20 K, bring them in to the “Superbottle”!

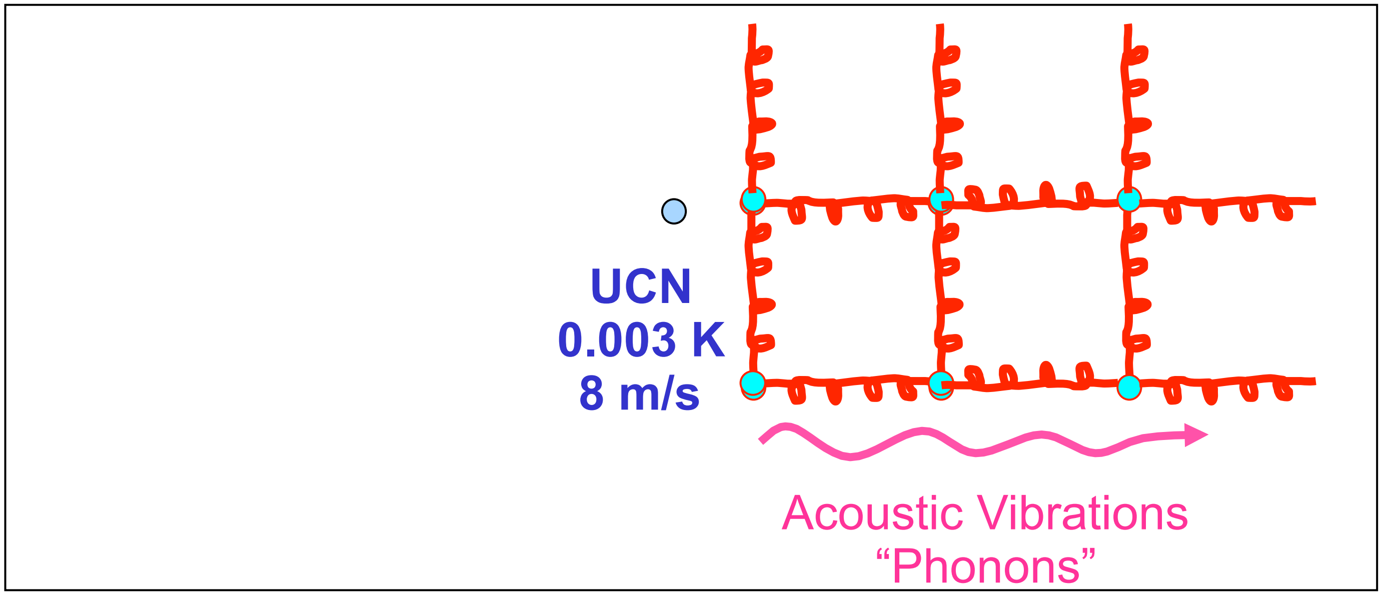
Superfluid Helium ! (He-II)

How we cool neutrons
Step 2: UltraCold Neutrons



Bounce neutron off superfluid helium because it won't gobble or heat them up (as many other materials can)

How we cool neutrons
Step 2: UltraCold Neutrons



The superfluid helium can absorb most of the neutron’s remaining energy, converting it to “sound waves” (called “phonons”).

Properties of UltraCold Neutrons

Once the neutrons are ultracold they have some very interesting properties.

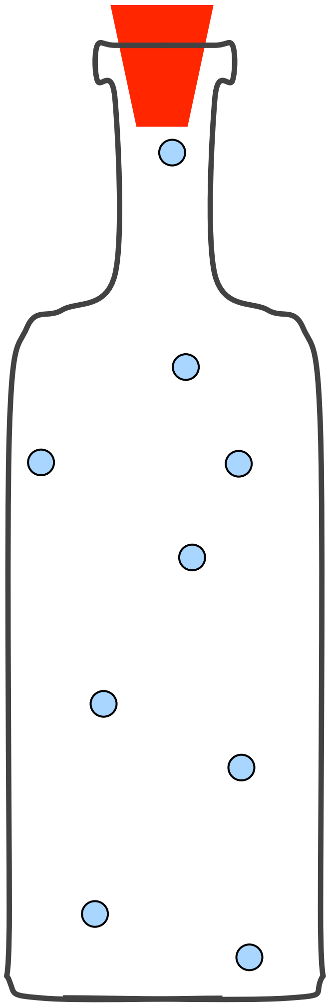
- Temperature < 0.004 K (degrees above absolute zero).
- speed < 30 km/h (8 m/s)

Neutrons interact with all the fundamental forces.

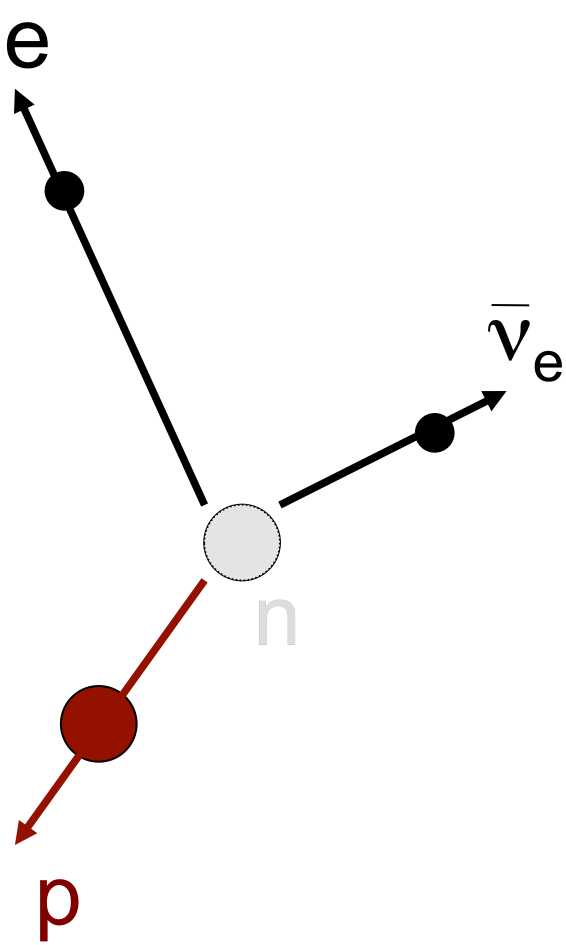
1. Strong nuclear force (keeps the nucleus together)
2. Weak nuclear force (responsible for radioactive decay)
3. Magnetic force (EM) (electricity & magnetism)
4. Gravity (keeps us on earth; planets)

1. Strong Nuclear Force

- Ultracold neutrons are moving so absurdly slow that they undergo total reflection from surfaces.
- This arises because of the strong nuclear force (the neutrons bumping into atomic nuclei)
- Because of this, you can "trap" them in a material bottle!



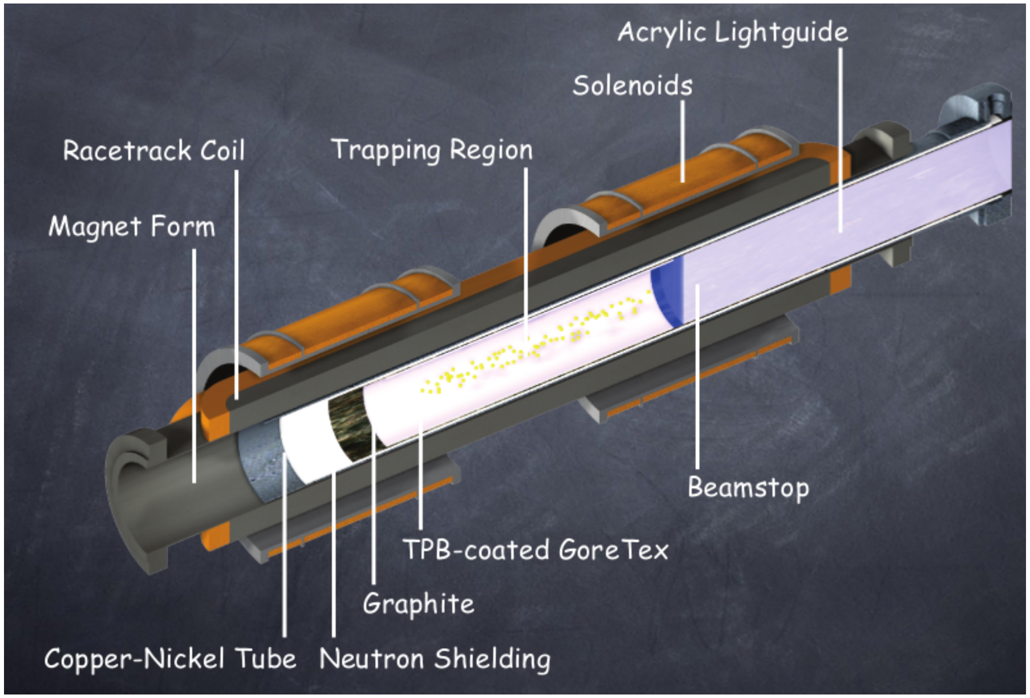
2. Weak Nuclear Force



- Causes free neutrons to decay
- Neutrons live for about 15 minutes
- An interesting experiment:
  - Put ultracold neutrons in a bottle
  - Wait a while (about 15 minutes)
  - Open the bottle and see how many neutrons come out

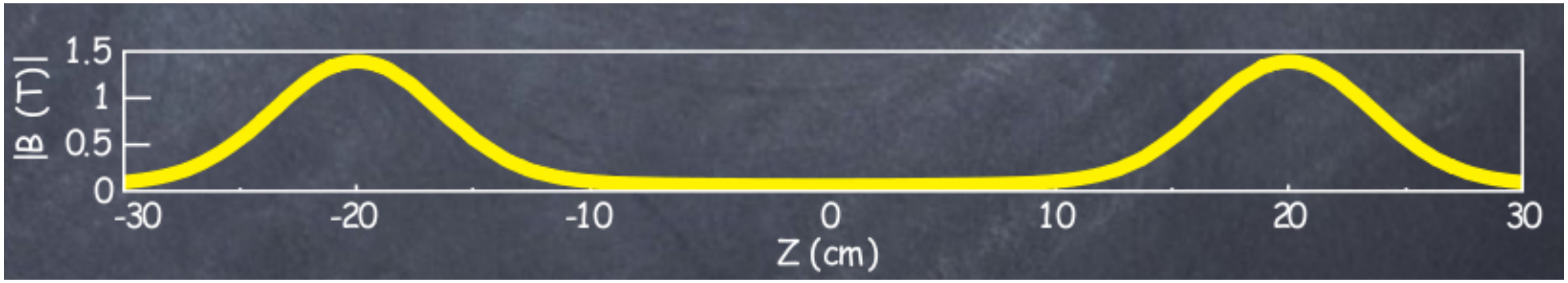
3. Magnetic Force *(Magnetism)*

- Neutrons have a "magnetic moment"
  - They behave like little bar magnets.
- Ultracold neutrons can be "trapped" in a "magnetic bottle"!



www.nist.gov

$V = -\mu \cdot \mathbf{B}$

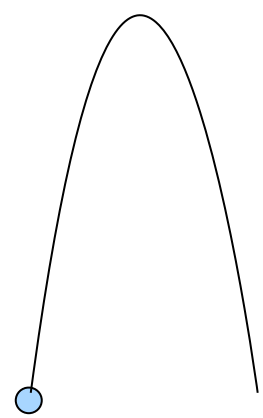


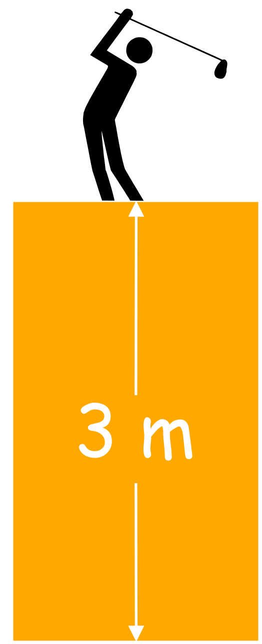
4. Gravity

- Question: If I threw something straight up at an initial speed of 30 km/h, how high would it go?

- Answer (from high-school physics):
  - about 3 meters (10 feet).

- Ultracold neutrons are vertically “trapped” by gravity (< ~3m)





UCN Recap

You can: Trap and hold them in a material bottle
Trap and hold them in a magnetic bottle
Trap and hold them in a gravity well

UCN don't overstay their welcome (stay ~15 min.)

Neutrons & their interactions are a hot topic in particle physics. *Some studies will benefit from using UCN.*

Normally, free (hot or thermal) neutrons → "gone" in ns or μs

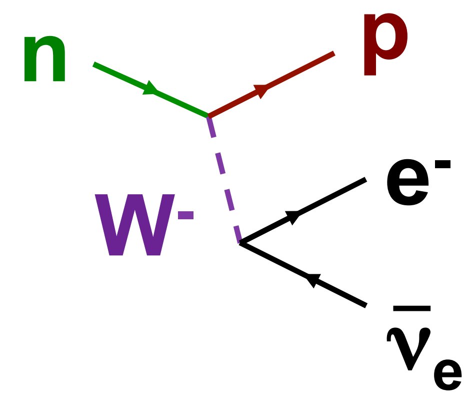
UCN hang around → greatly increased observation time
→ you can "play with" (manipulate) them

A convenient circumstance for UCN: "300"

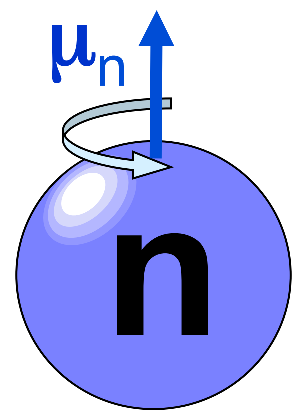
→ UCN Kinetic Energy ~ 300 neV
→ comparable to nuclear, magnetic, gravitational potentials

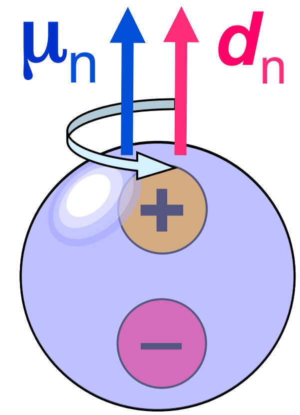
Fundamental Physics and UCN

- **Precision Decay Experiments**
  How fast do neutrons decay? What are the angular distributions of the decay products?



- Does the neutron possess an **electric dipole moment**? The predominance of matter over antimatter in the universe.

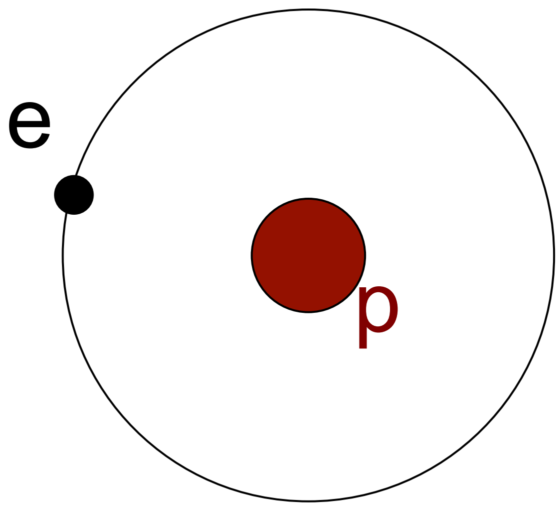




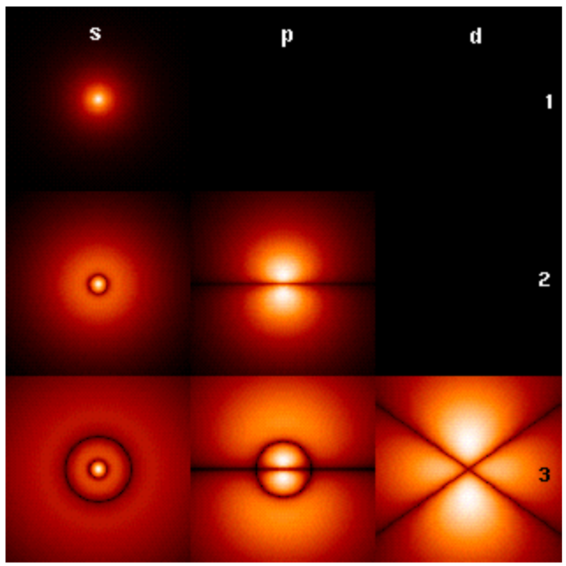
- Interactions of neutrons w/ gravity (quantum physics and gravity).

Quantum Physics

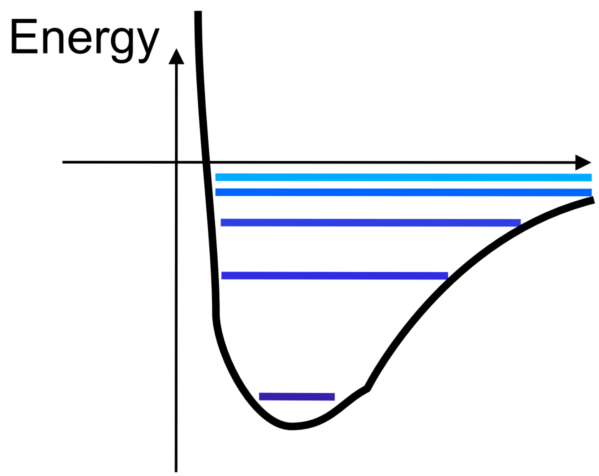
- We think the universe is governed by the laws of quantum physics.
- Quantum physics effects are usually only seen, in really small things. (e.g. atoms ~ 0.1 nm = one-billionth of ten centimeters)
- One successful prediction of quantum mechanics: "Quantization" of energy levels for particles bound in potential wells. (e.g. H-atoms)



Hydrogen Atom



Quantized "orbits"



Quantized energy levels

Quantum Physics and Gravity:
They don't work well together

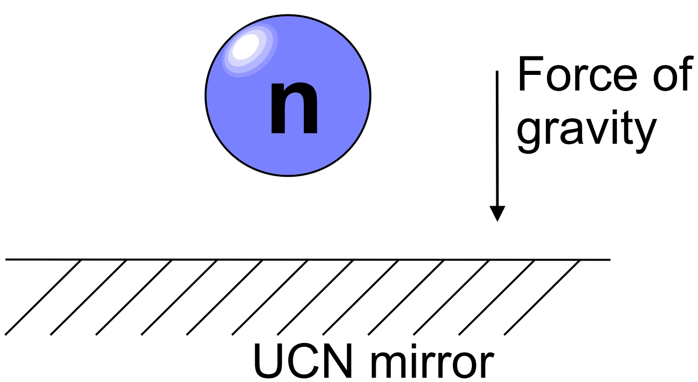
- 3 of the 4 fundamental forces (strong nuclear, weak nuclear, electromagnetism) "work well" with quantum physics.

- So far, no one has figured out how to make gravity work with quantum physics.

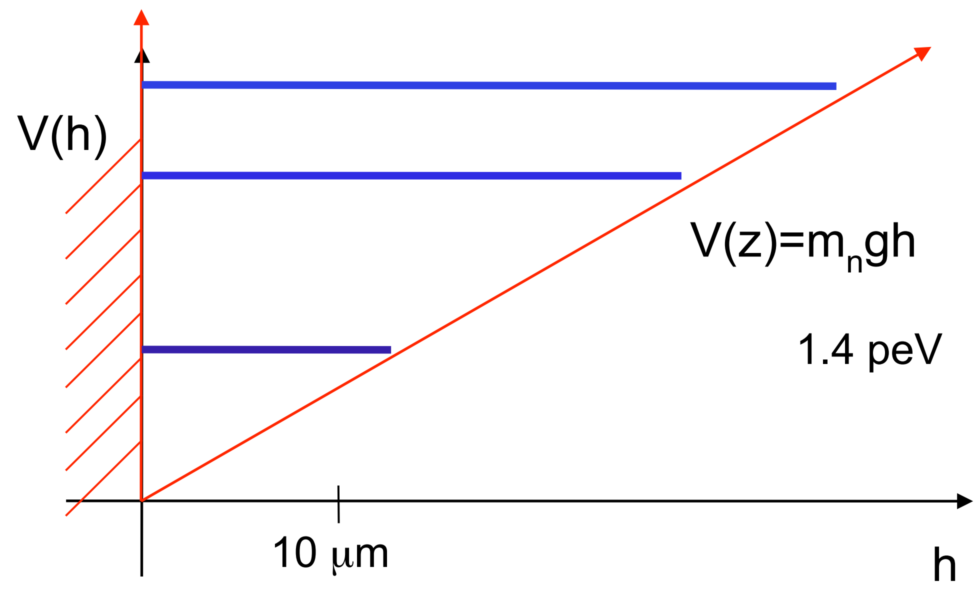
- Can ultracold neutrons be used to shed any light on this problem?

Quantum Physics, Gravity and UltraCold Neutrons

- Ultracold neutrons are “small” (quantum regime)
- Ultracold neutrons can be confined in the Earth's gravity field. *(< 3m above where they are made)*



Quantum mechanically,
only particular energies are allowed

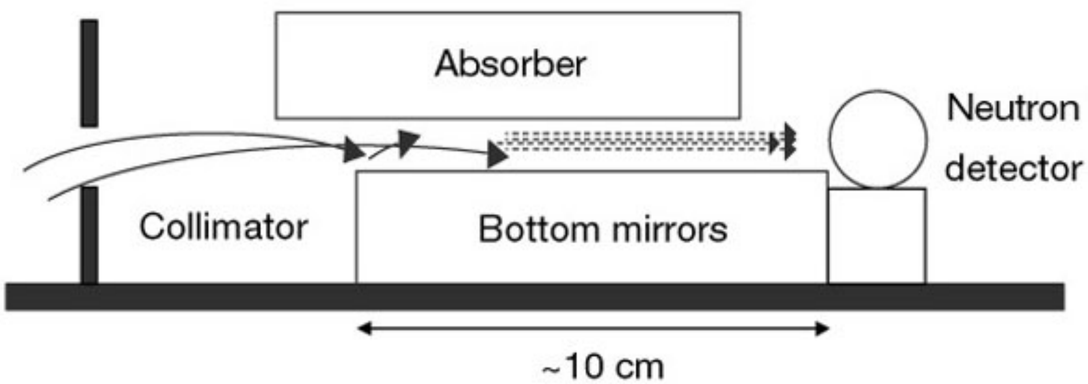


“Gravitational Potential well”

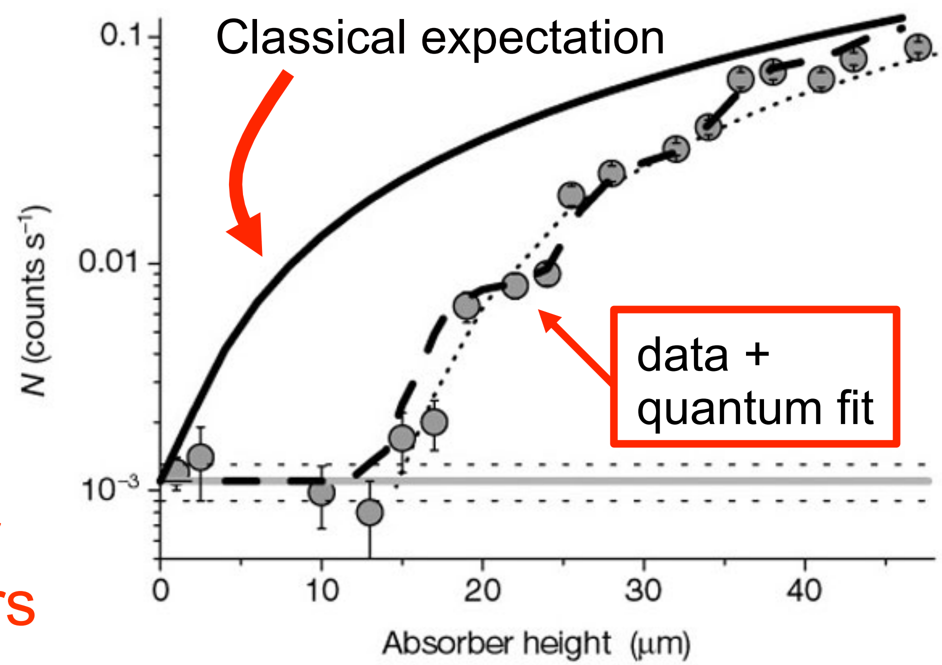
Experiment on Quantum Mechanics and Gravity using UCN

- Recently, the "first" observation of quantized energy-levels in the Earth's gravity field was made.

Conducted in Grenoble, France.



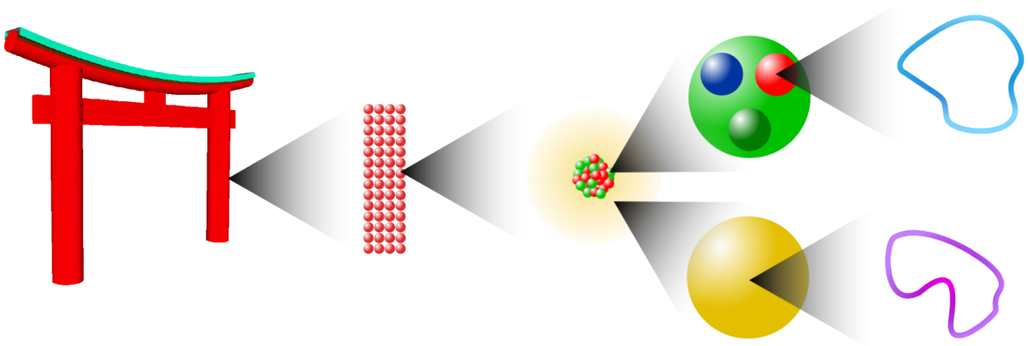
No UCN "made it thru" until Absorber was raised 15μm above Bottom Mirrors



Do these results really show quantum effects with gravity?

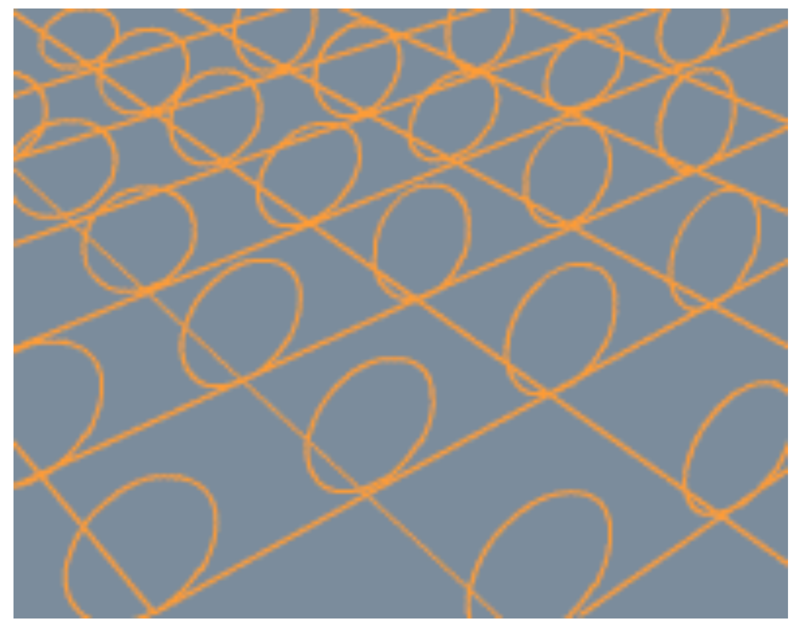
Quantum Physics and Gravity

- What is the real quantum theory of gravity? String theory?



One "prediction" of string theory is extra dimensions. ***Where are they?***

- String theory suggests that they are "curled up" (compactified).
- The curled up dimensions would modify gravity at small scales.
- *If gravity is modified at these scales, ultracold neutron gravity experiments might see it.*



Materials Science and UCN

UCN's properties (low energy, long wavelength)

- sensitive to slow motions and low energy excitations (in the materials to which in comes in contact)
- interest in using UCN to study large biological molecules

Many techniques for using UCN to probe materials

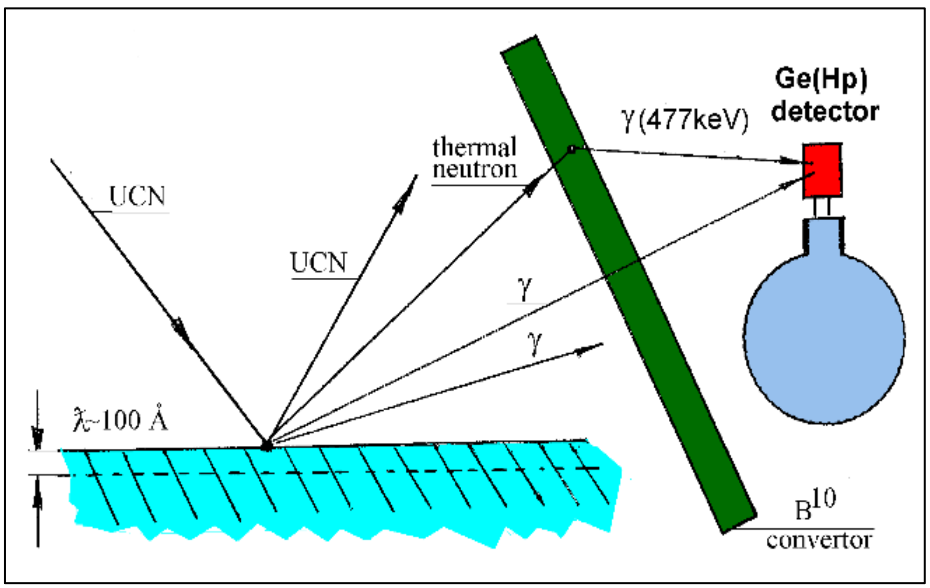
(*Reflection, tunneling, Elastic scattering, Quasielastic and Inelastic scattering, Upscattering)*

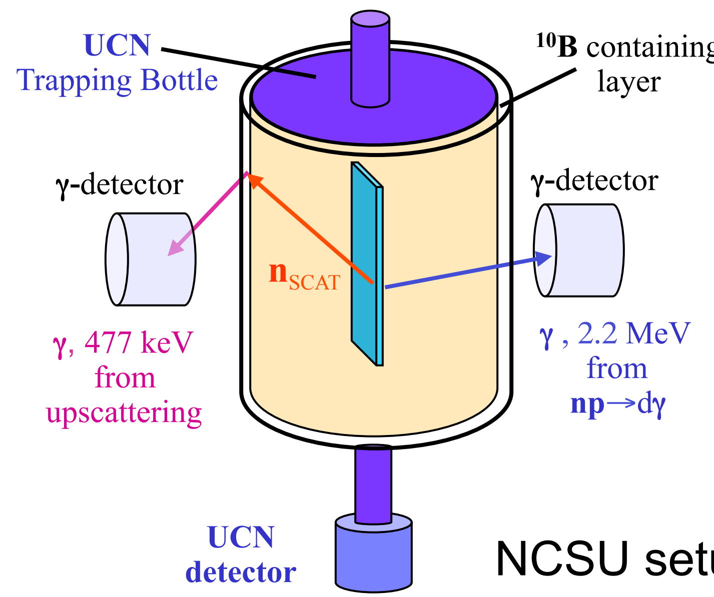
Presently, much interest in UCN Inelastic Scattering

Materials Science and UCN

UCN Inelastic Scattering Reflectometry (ISR)

- particularly sensitive to materials containing hydrogen
- can be used to study thin (10 nm) surface films
- *Measure UCN loss rate and/or Upscattering*





NCSU setup

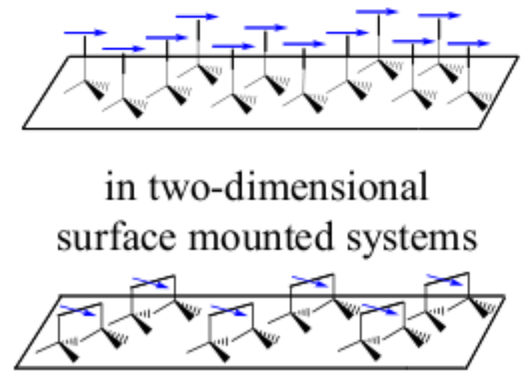
Use to study: "Smart" surfaces, surface-mounted molecular rotors

Materials Science and UCN

UCN ISR as a Probe

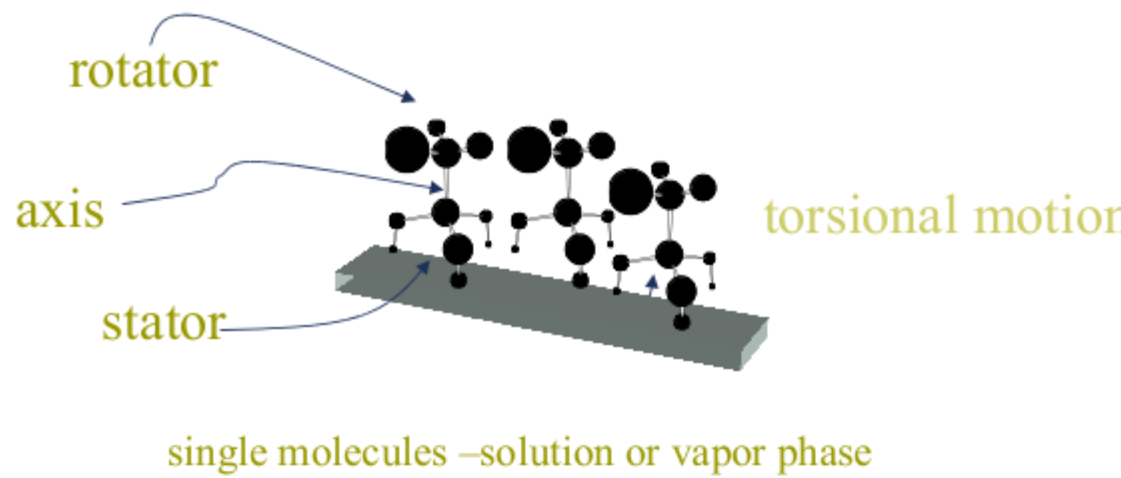
<u>*“Smart surfaces”*</u>

Surfaces that change their properties when subjected to external stimuli *(e.g. for drug delivery applications)*



<u>*Molecular Rotors*</u>

Molecules designed to have rotational functionality *(e.g. nanomachines, reduce friction, information storage)*



A high-intensity UCN source is needed to make more rapid progress in this field

TRIUMF & UltraCold Neutrons

- We are planning to construct the world's most intense source of UltraCold Neutrons at **TRIUMF** (Canada's National Nuclear and Particle Physics Lab, Vancouver).
- Joint project between Japan and Canada, involving 3 Labs (KEK, RCNP, TRIUMF).
- We hope to use these neutrons to:
  - perform precision tests of Fundamental Symmetries in Physics, ***starting with a measurement of the neutron Electric Dipole Moment***
  - carry out precision tests of quantum mechanics as applied to gravity and extra dimensions
  - provide a new window into materials science

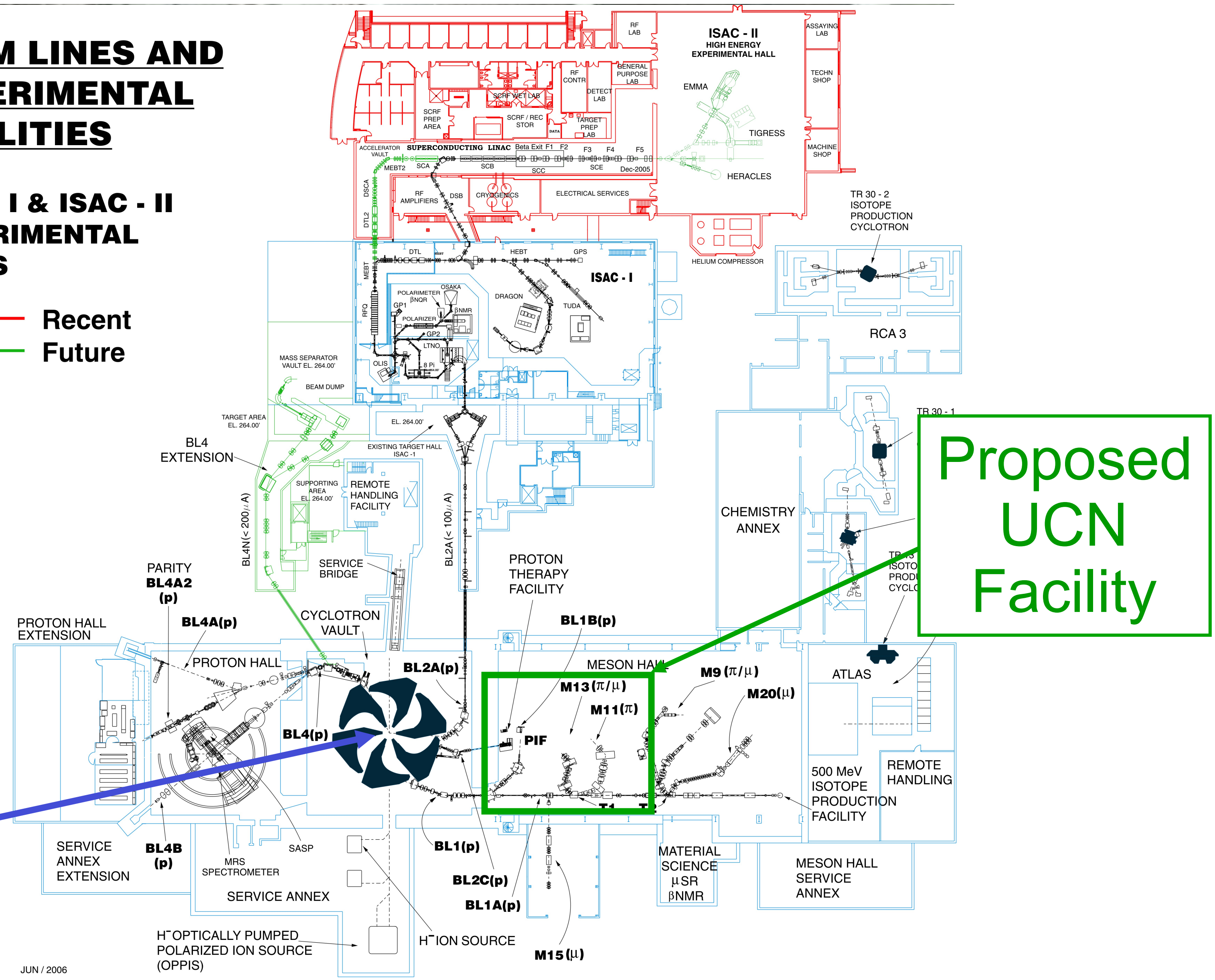
TRIUMF

BEAM LINES AND EXPERIMENTAL FACILITIES

ISAC - I & ISAC - II EXPERIMENTAL HALLS

Recent

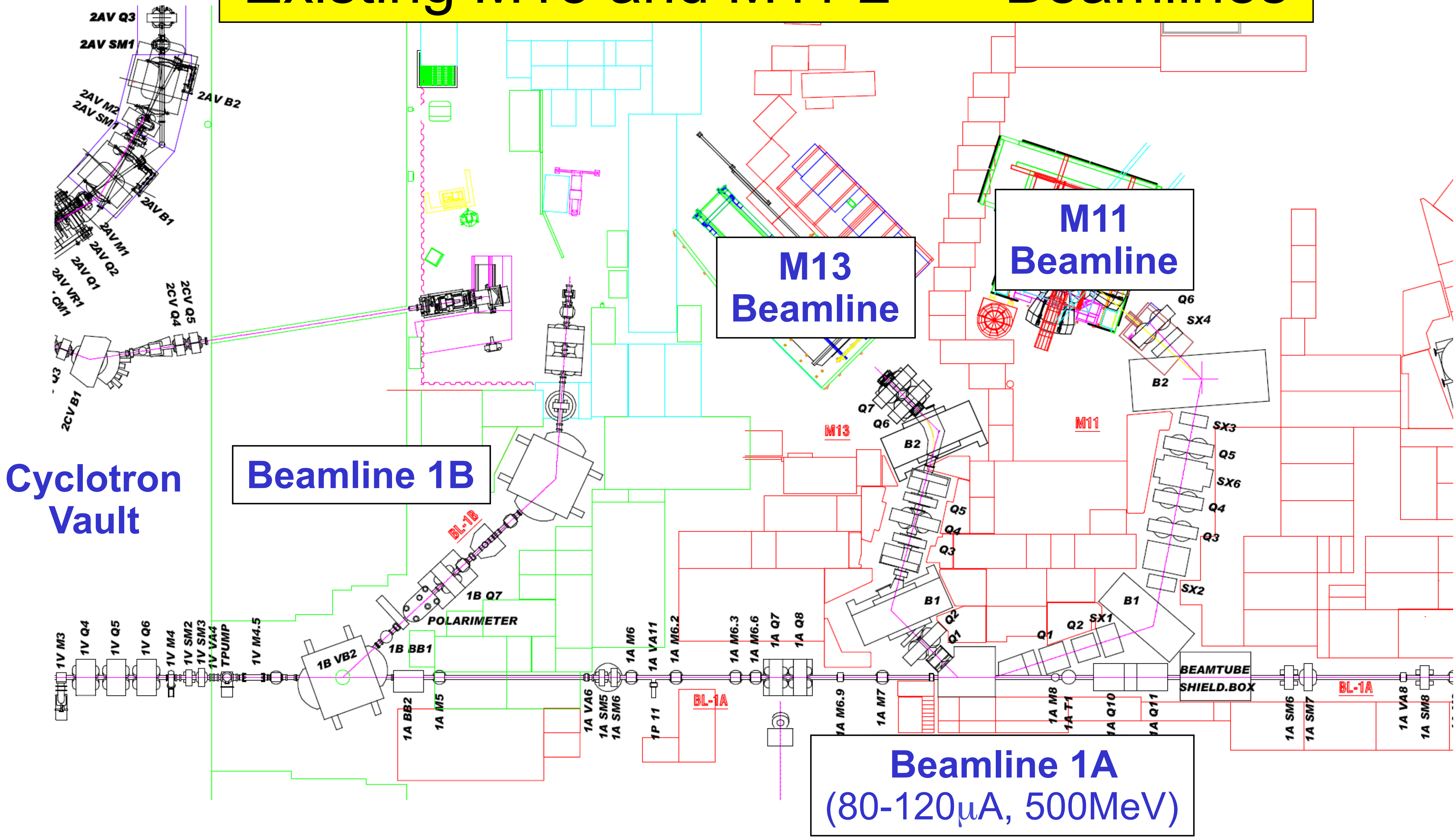
Future



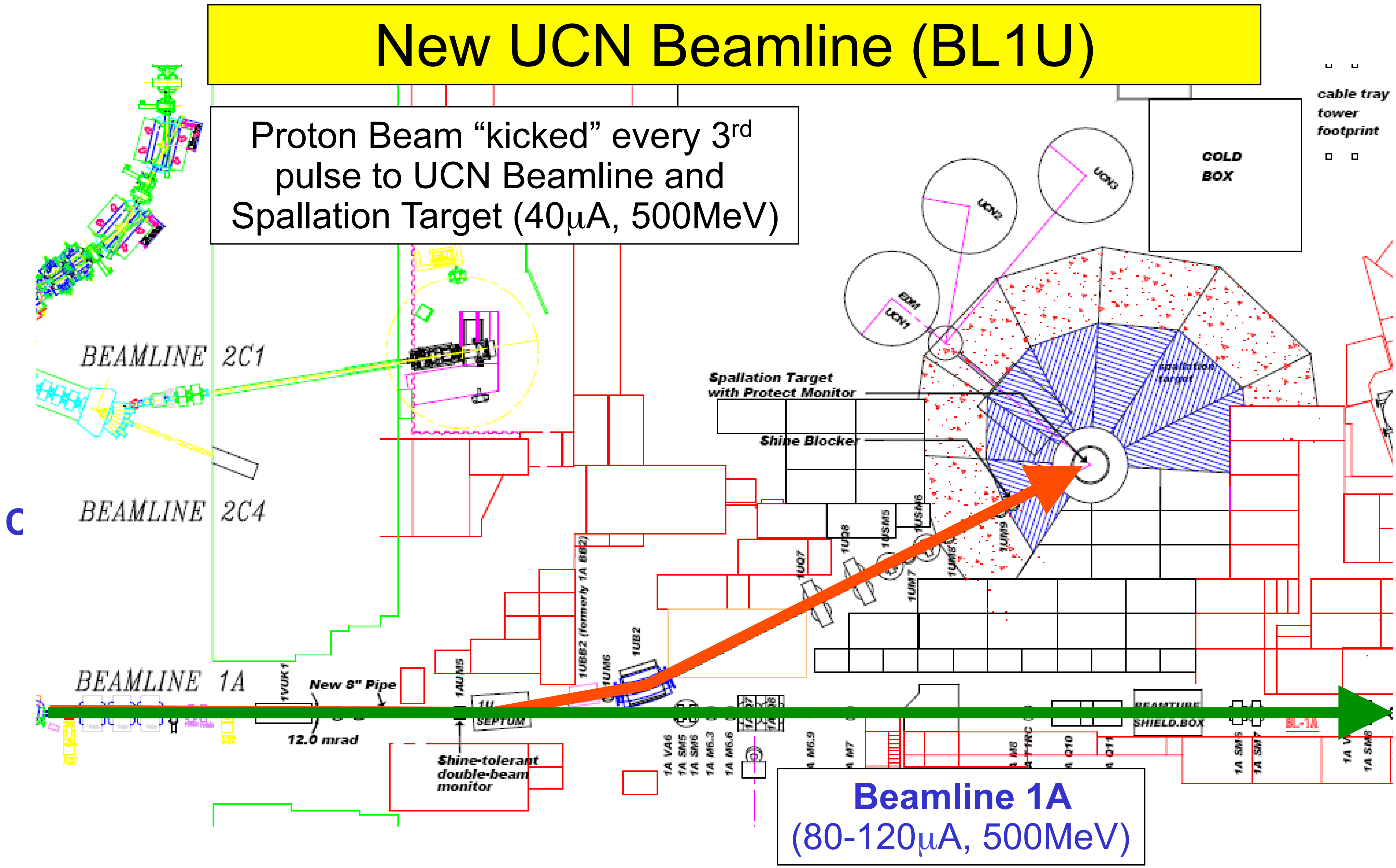
Main Cyclotron

TRIUMF Meson Hall

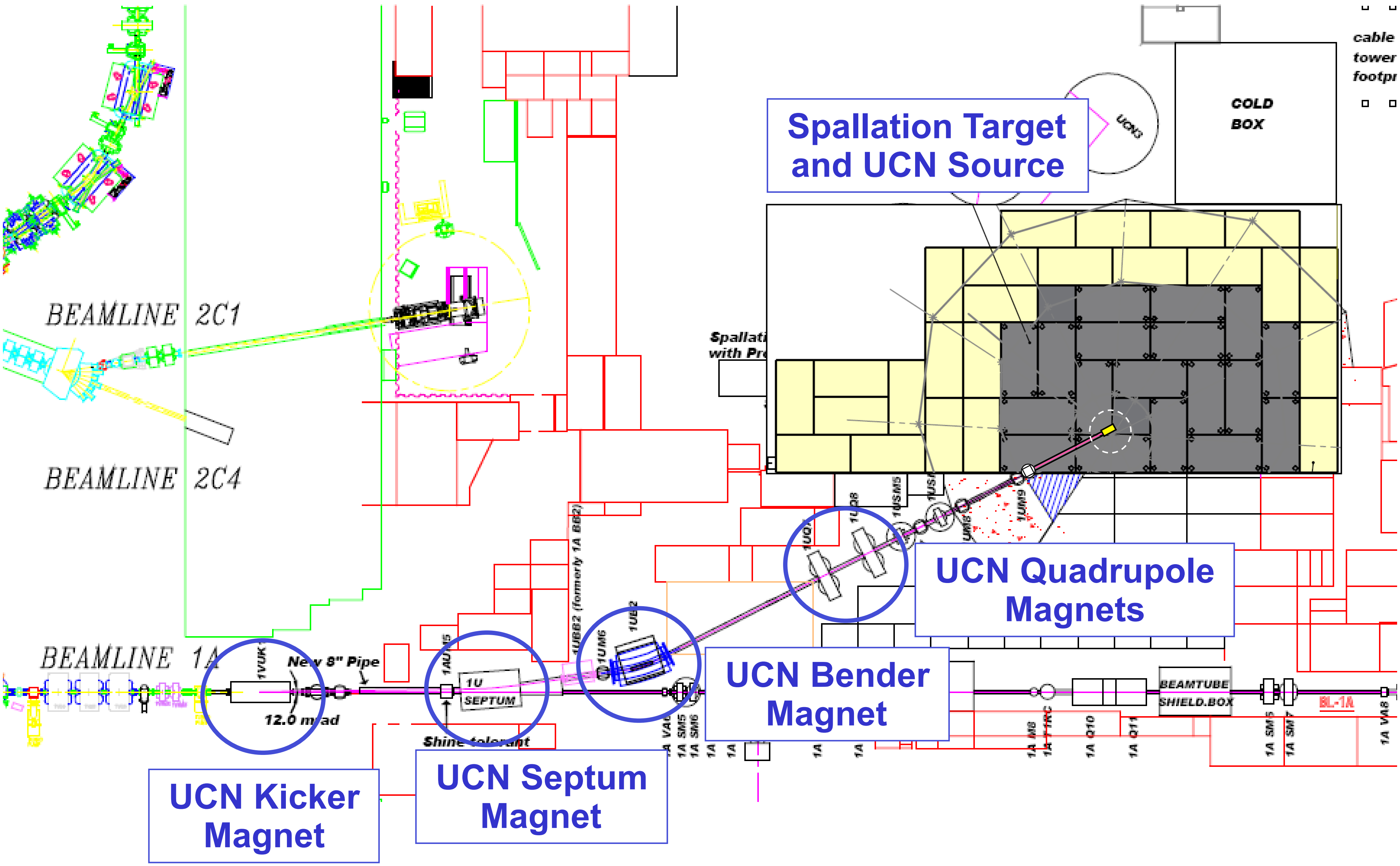
Existing M13 and M11 2ndary Beamlines



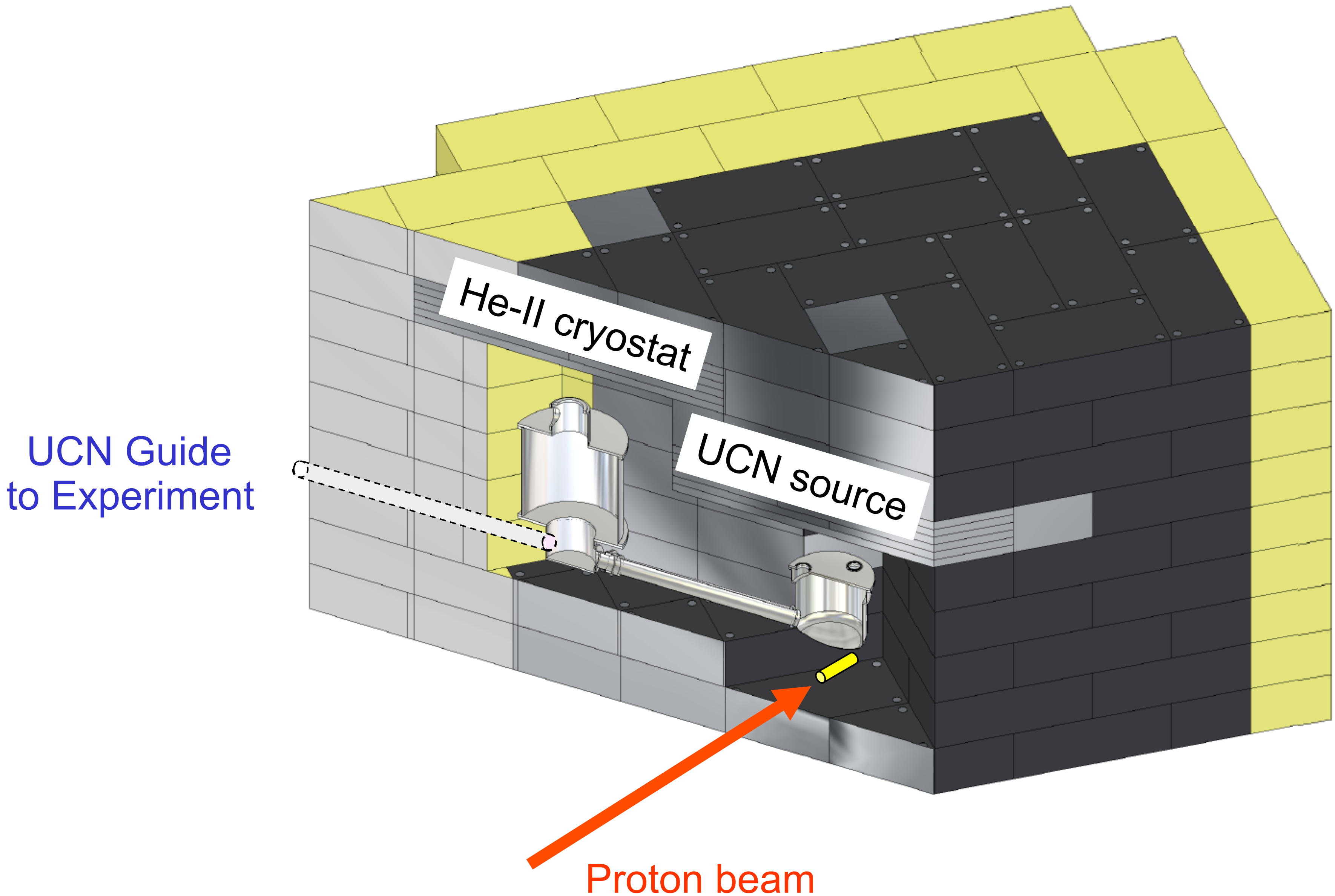
TRIUMF Meson Hall



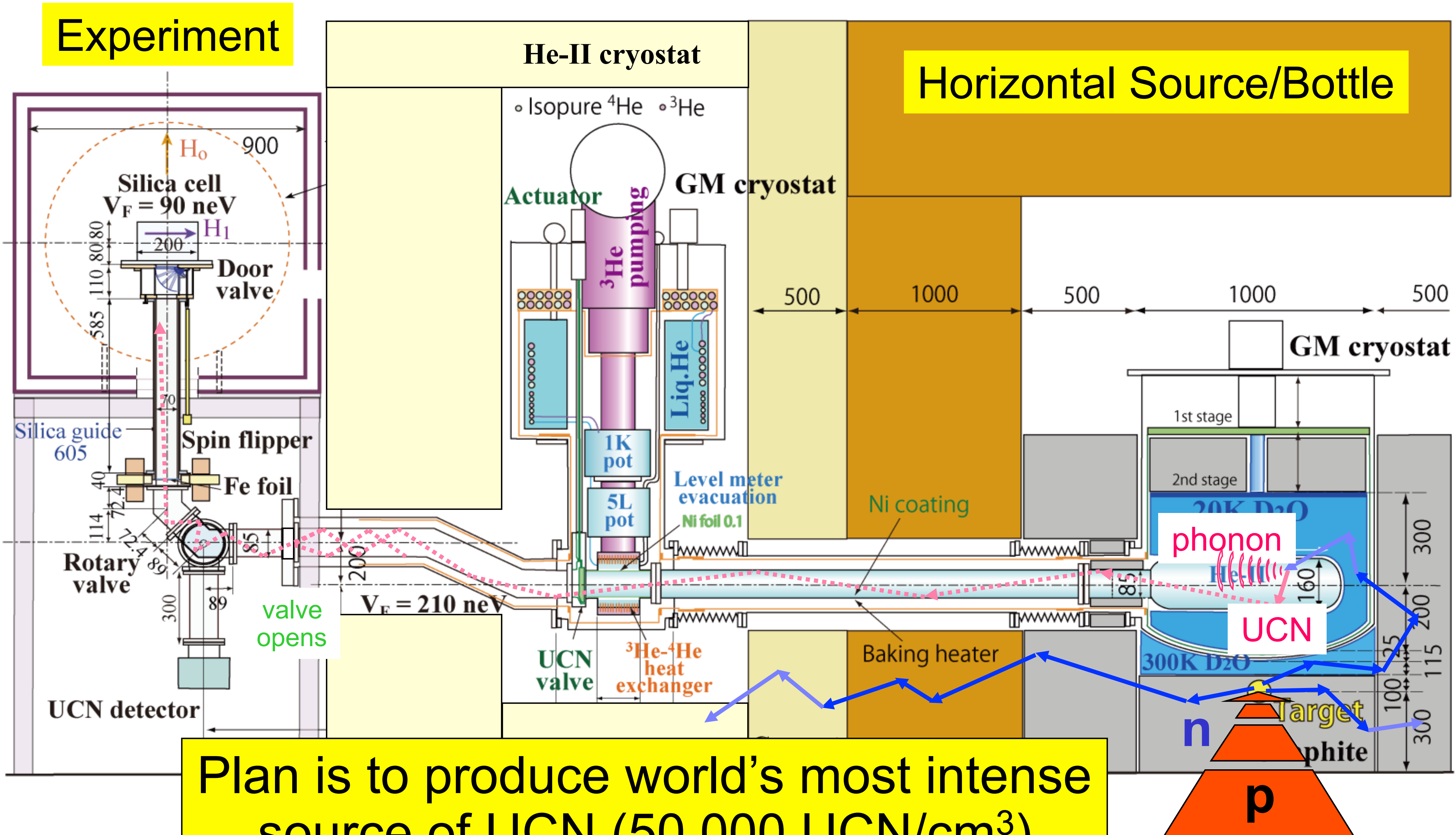
UCN Facility at TRIUMF



Spallation Target & UCN Source



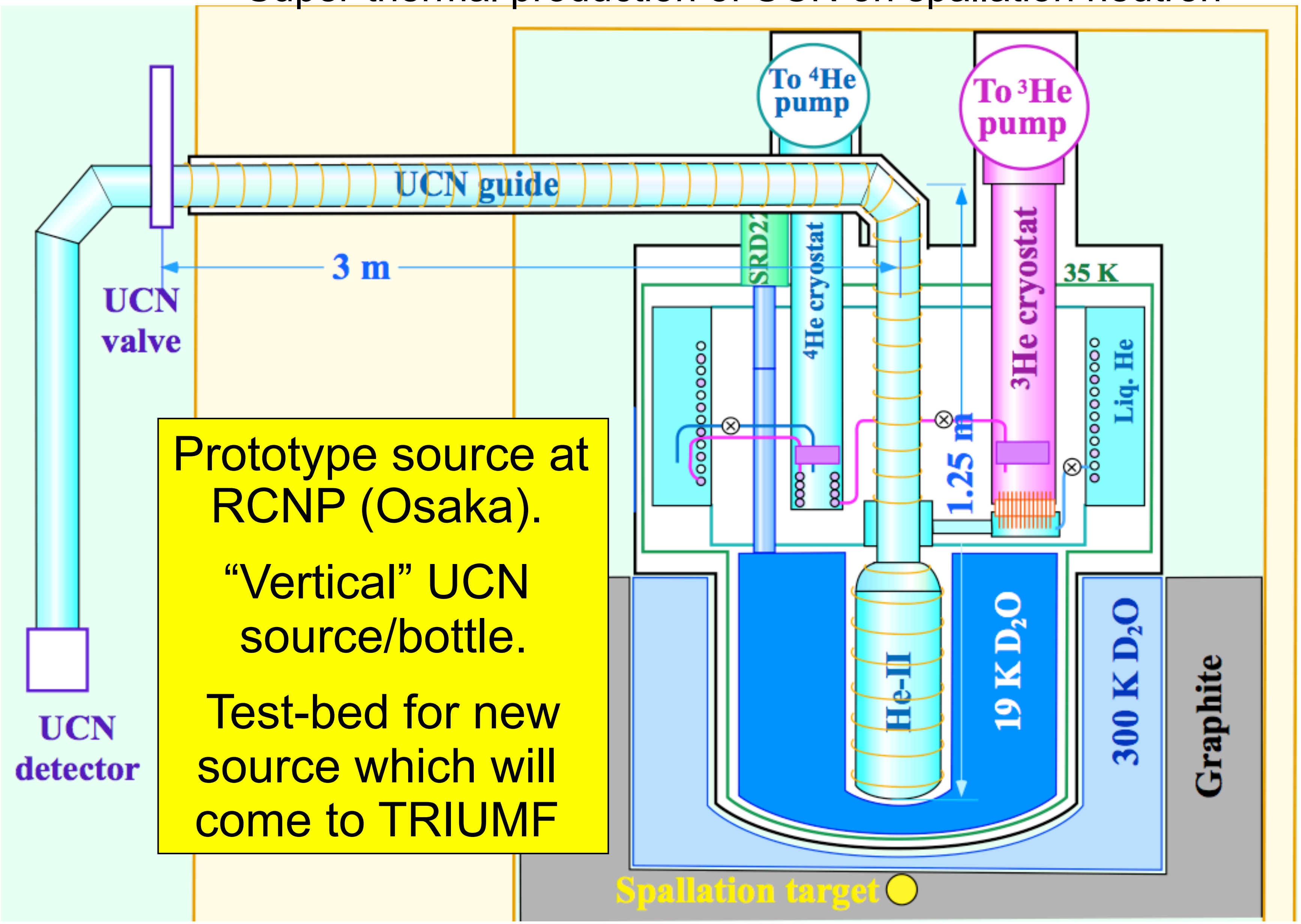
UCN Source at TRIUMF



Plan is to produce world's most intense source of UCN (50,000 UCN/cm^3)

Prototype UCN Source (Japan)

Super-thermal production of UCN on spallation neutron



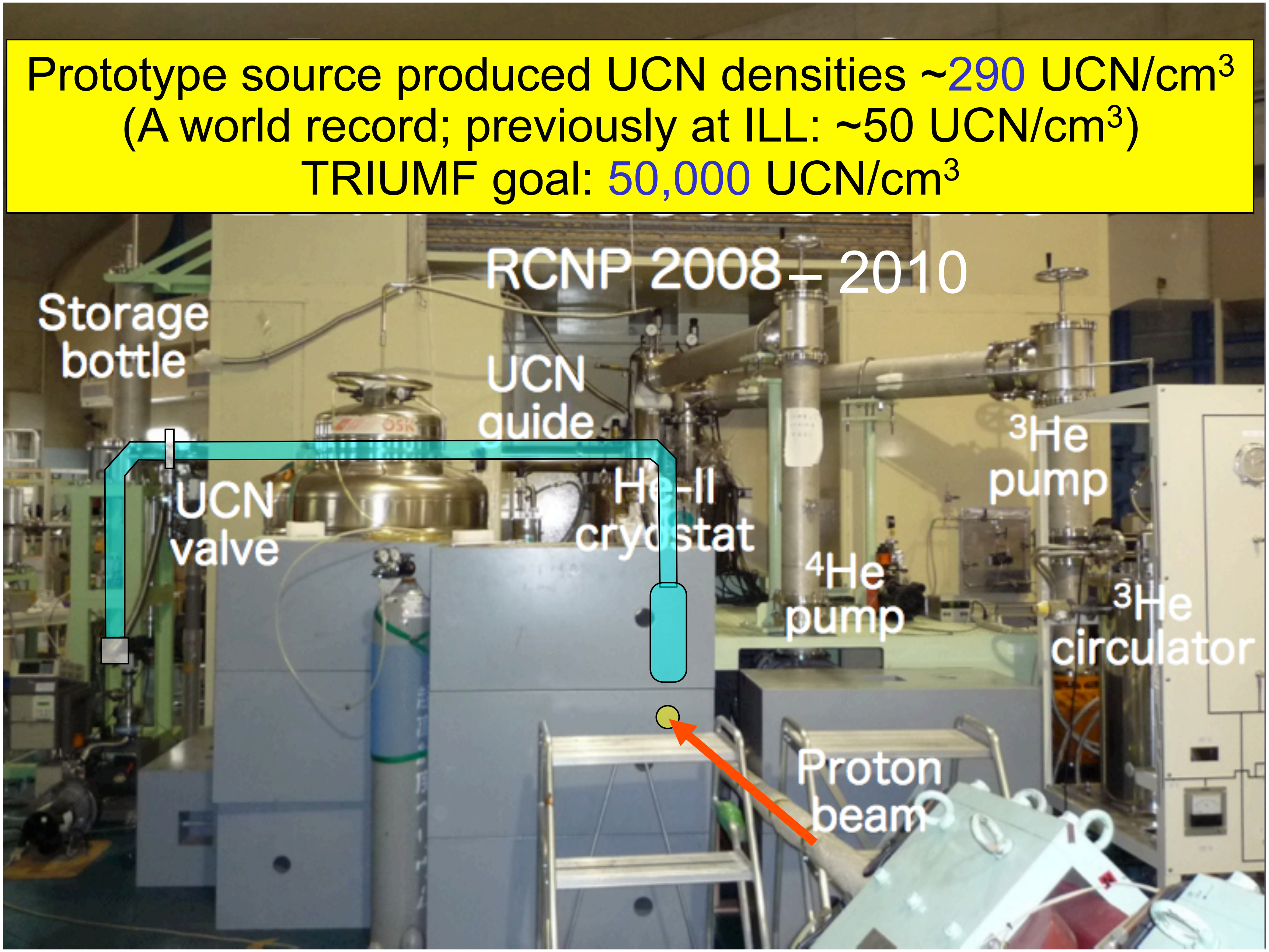
Prototype source at RCNP (Osaka).

"Vertical" UCN source/bottle.

Test-bed for new source which will come to TRIUMF

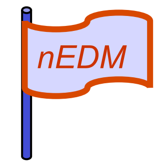
Prototype UCN Source in Japan

Prototype source produced UCN densities ~290 UCN/cm^3
(A world record; previously at ILL: ~50 UCN/cm^3)
TRIUMF goal: 50,000 UCN/cm^3

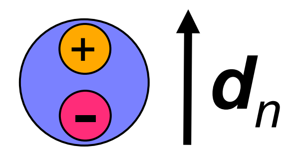


Neutron Electric Dipole Moment
(nEDM)

"Flagship" Experiment of TRIUMF UCN Facility



Measurement of the Neutron Electric Dipole Moment (EDM)



Q1: Why do we want to measure this?

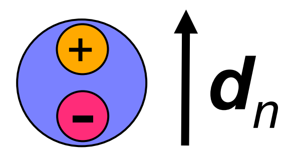
See next slide

Q2: Why are UCN important for this experiment?

Our measurement requires the neutrons to be held inside a "bottle", and their spin manipulated under a combination of electric and magnetic fields. ***This can be done only with UCN.***

Neutron Electric Dipole Moment
(nEDM)

Measurement of the Neutron Electric Dipole Moment (EDM)



Q1: Why do we want to measure this?

*1) Because it's **NOT** there (or not supposed to be)*

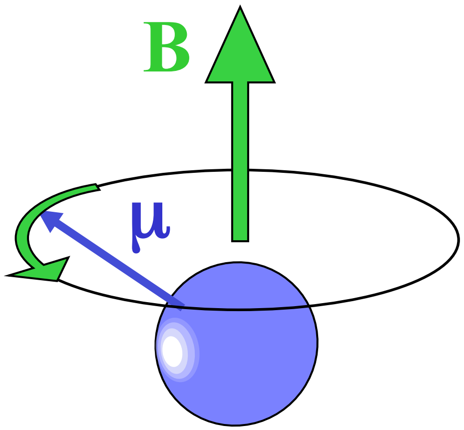
- Its existence is "supposedly" forbidden because it would violate CP and "Time-reversal" (T) symmetry; symmetries which are regarded as "fundamental".

*2) Because I can't find my **antimatter "twin"***

- A non-zero EDM means CP symmetry is violated

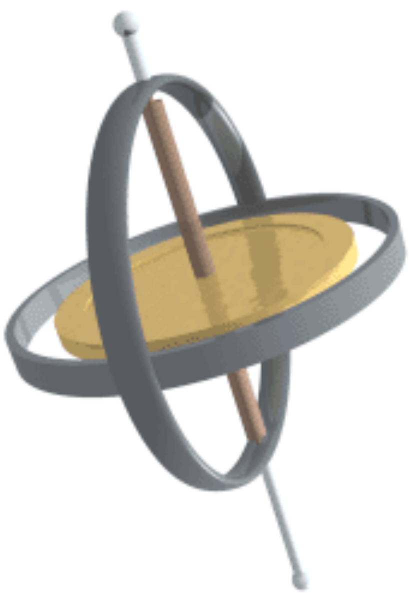
- The same CP-violating mechanism responsible for the EDM may simultaneously also explain why there is more Matter than Antimatter in the universe today (a.k.a. Baryogenesis).

How to measure the Neutron EDM?
Precession Speed



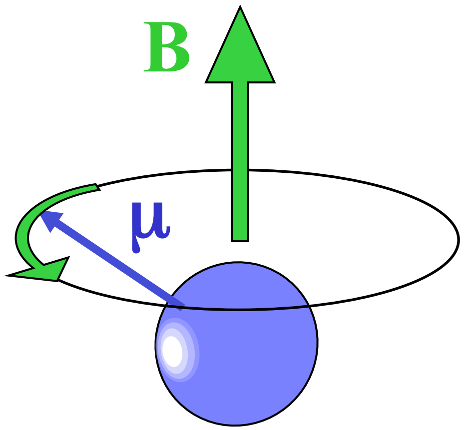
Precesses

When placed in an external magnetic field (**B**), particle's magnetic moment (μ) precesses about the magnetic field.



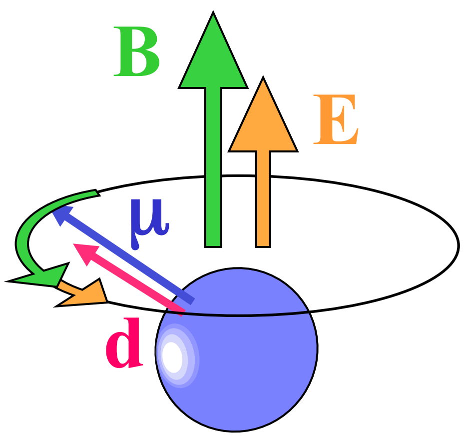
How to measure the Neutron EDM?

Precession Speed



Precesses

When placed in an external magnetic field (**B**), particle's magnetic moment (**μ**) precesses about the magnetic field.



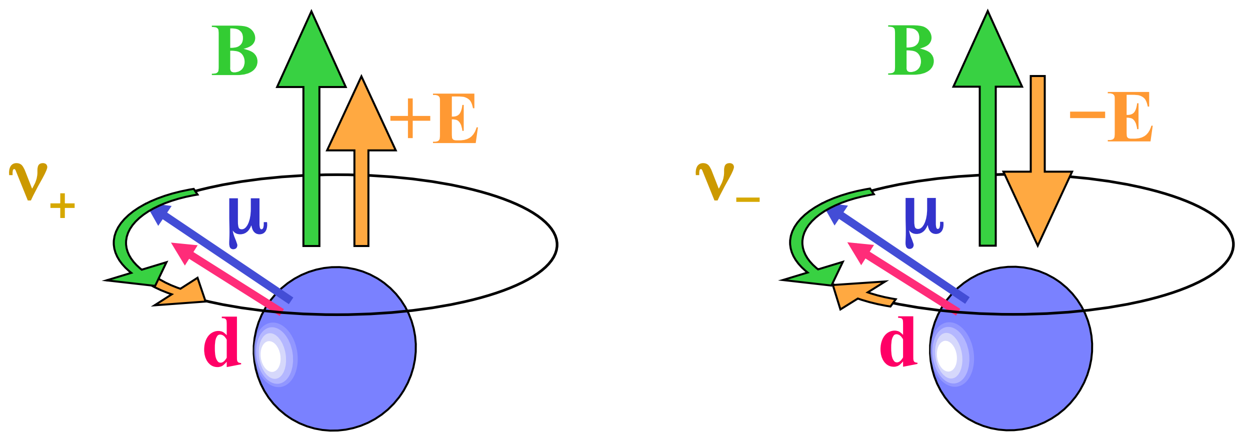
Precesses Faster

If the particle also has a non-zero EDM (**d**), adding an electric field (**E**), changes the precession frequency (increases or decreases depending on the direction of the electric field).

How to measure the Neutron EDM?

General Principle

n-EDM Experiment: Measure precession frequencies (ν_+ ,ν_-) with electric fields pointed up (+E) vs down (-E).



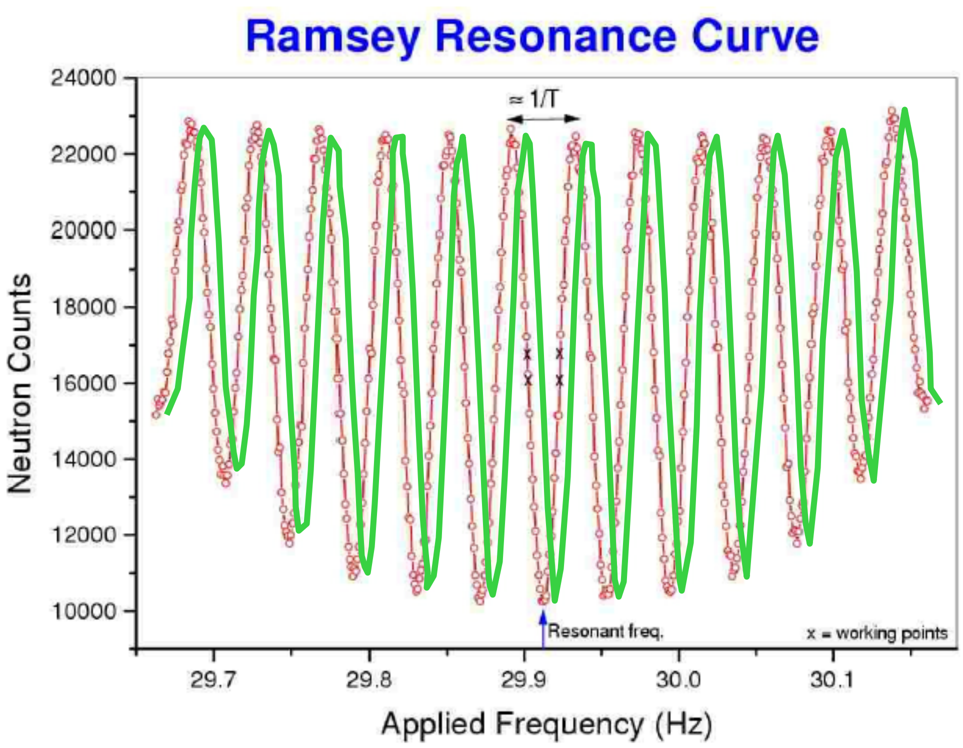
Precesses Faster *Precesses Slower*

Electric Dipole Moment: $d_n = (h/2E)(\nu_+ - \nu_-)$

How to measure the Neutron EDM?

Measurement Technique

Use low-field NMR ("Ramsey Resonance") technique:

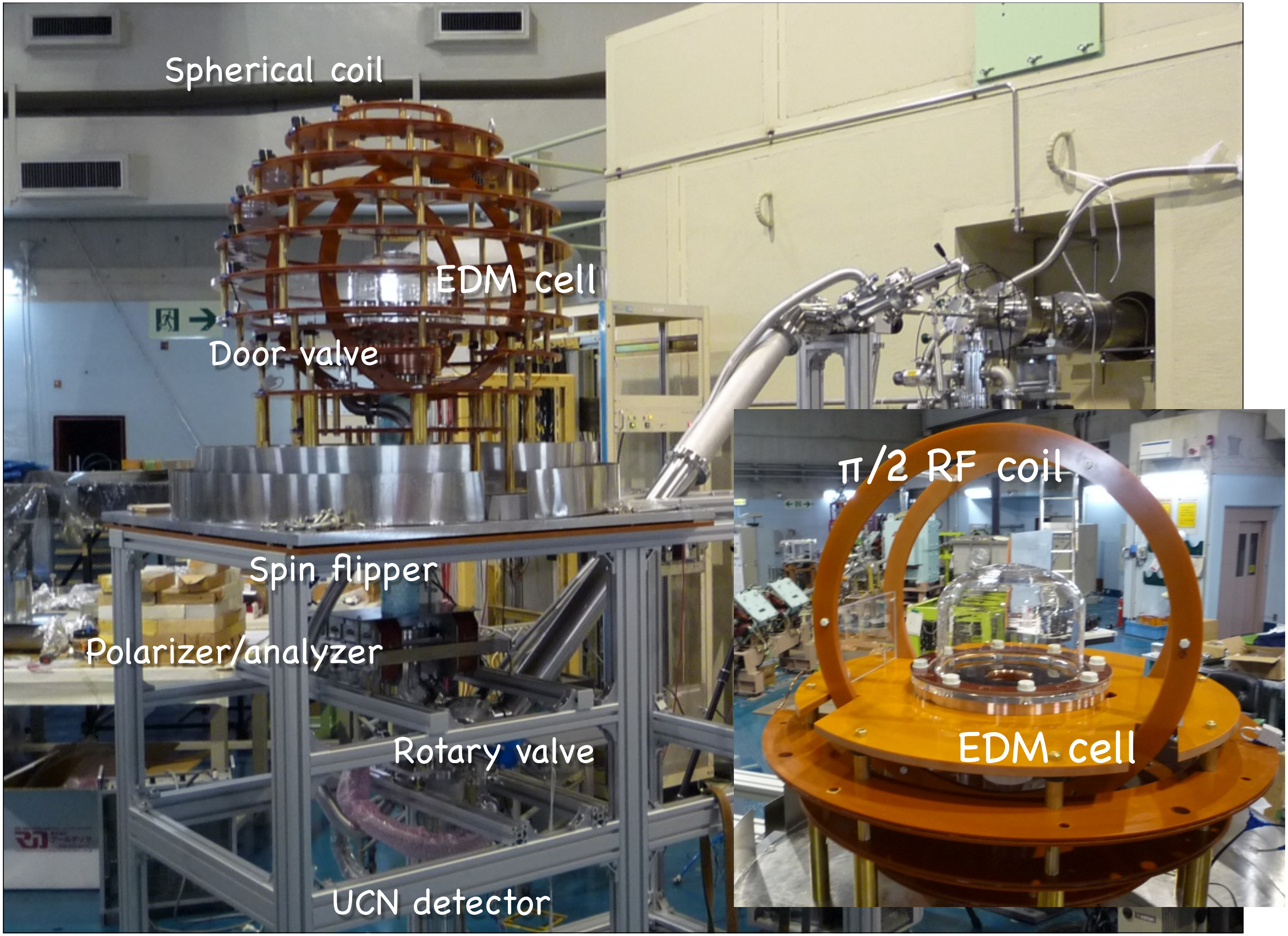


Put UCN in bottle with **B**,**E** field

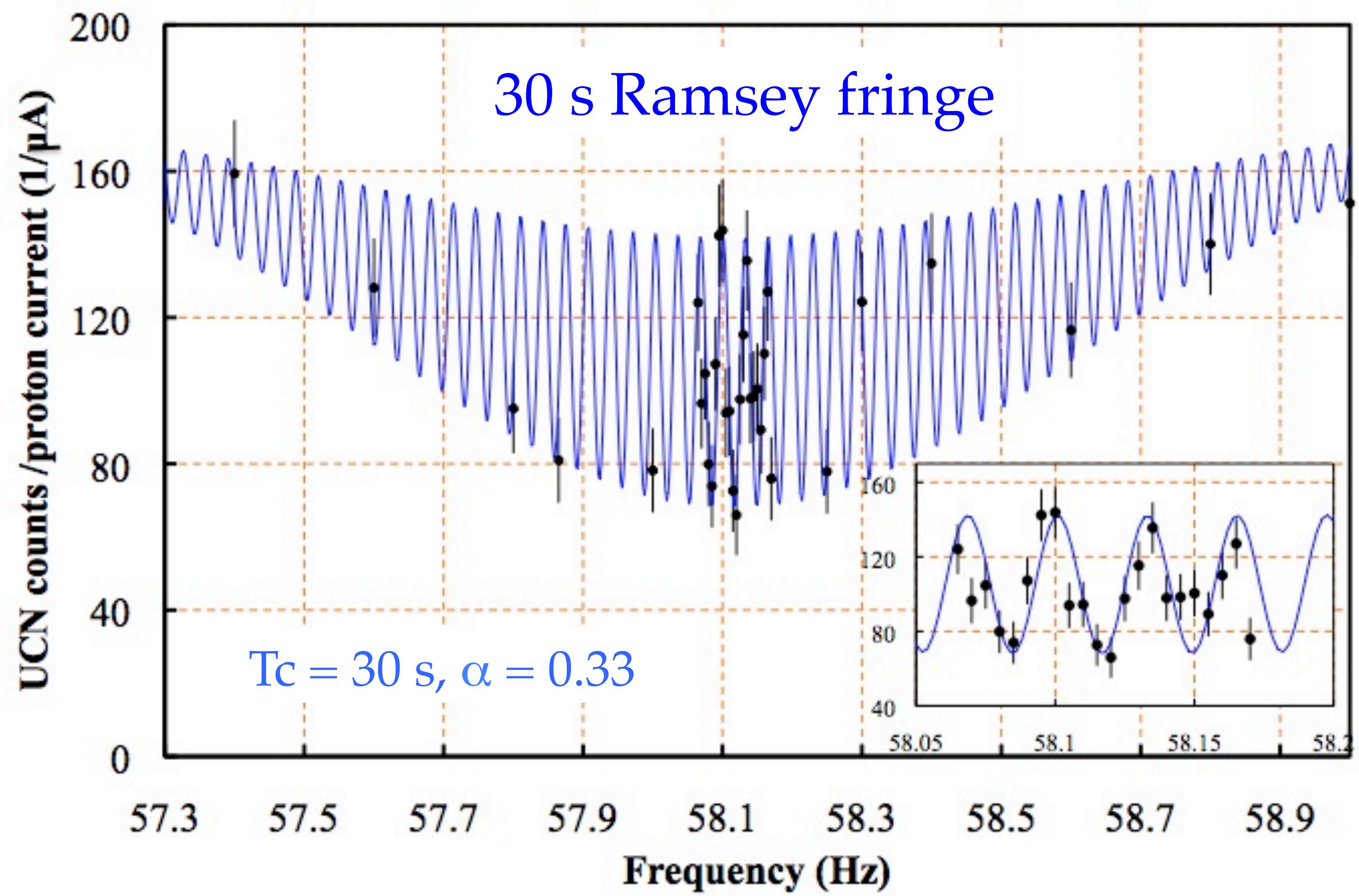
Manipulate spin, get fringe pattern

Reverse the **E**-field direction and measure frequency shift of fringes

Prototype n-EDM Cell at RCNP



Results: Prototype Ramsey Cell



Prototype EDM cell → We have conducted tests at RCNP (Japan)
→ Observed Ramsey Resonance fringe patterns

Next Step → Install Electrode Plates & Turn-On Electric Field

Timeframe for TRIUMF UCN Facility

Present – 2012:
Design stage for TRIUMF UCN Beamline
Build and test Prototype Equipment in Japan

2013 – 2014:
Begin building UCN Beamline at TRIUMF
Run phase-1 (lower precision) nEDM experiment in Japan

2015:
Complete & Commission UCN Beamline at TRIUMF

2016 and beyond:
Run 2nd phase (high precision, high intensity) UCN-nEDM program at TRIUMF

UCN Collaboration

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Summary

- Ultracold neutrons are super cool.
- We can use them for a variety of purposes, for example to test quantum gravity, or search for EDM's.
- We plan to build the world's most intense source of ultracold neutrons, and locate it in Canada.

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