Ultracold Neutrons in Canada and Japan

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NSERC
CRSNG

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TRIUMF

International Spallation Ultracold Neutron Source

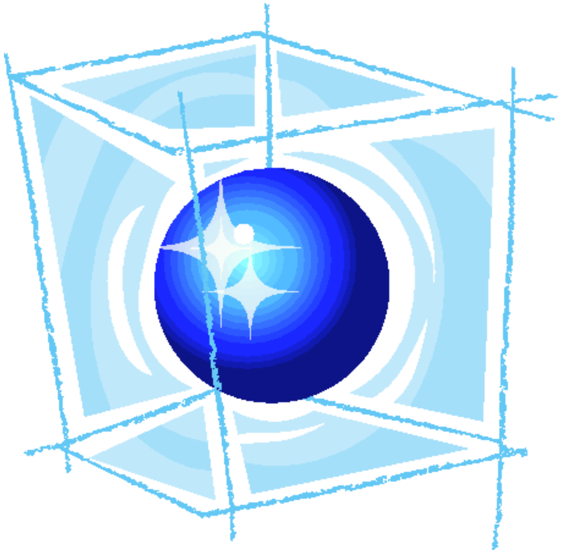
Spokespeople: J.W. Martin (Winnipeg), Y. Masuda (KEK)

Collaborators: J. Birchall, J.D. Bowman, L. Buchmann, L. Clarke, C. Davis, B.W. Filippone, M. Gericke, R. Golub, K. Hatanaka, M. Hayden, T.M. Ito, S. Jeong, I. Kato, S. Komamiya, E. Korobkina, E. Korkmaz, L. Lee, K. Matsuta, A. Micherdzinska, W.D. Ramsay, S.A. Page, B. Plaster, I. Tanihata, W.T.H. van Oers, Y. Watanabe, S. Yamashita, T. Yoshioka

(KEK, Winnipeg, Manitoba, ORNL, TRIUMF, NCSU, Caltech, RCNP, SFU, LANL, Tokyo, UNBC, Osaka, Kentucky)

We propose to construct the world's highest density source of ultracold neutrons and use it to conduct fundamental and applied physics research using neutrons.

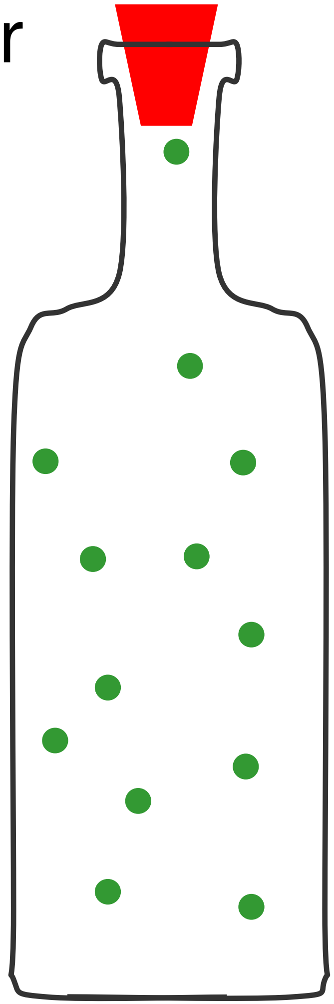
Ultracold Neutrons (UCN)



- What are UCN?
- Interactions of UCN.
- How to make UCN.
- Plans for the International Spallation Ultracold Neutron Source (i-SUN).
- Experiments that we would do there.

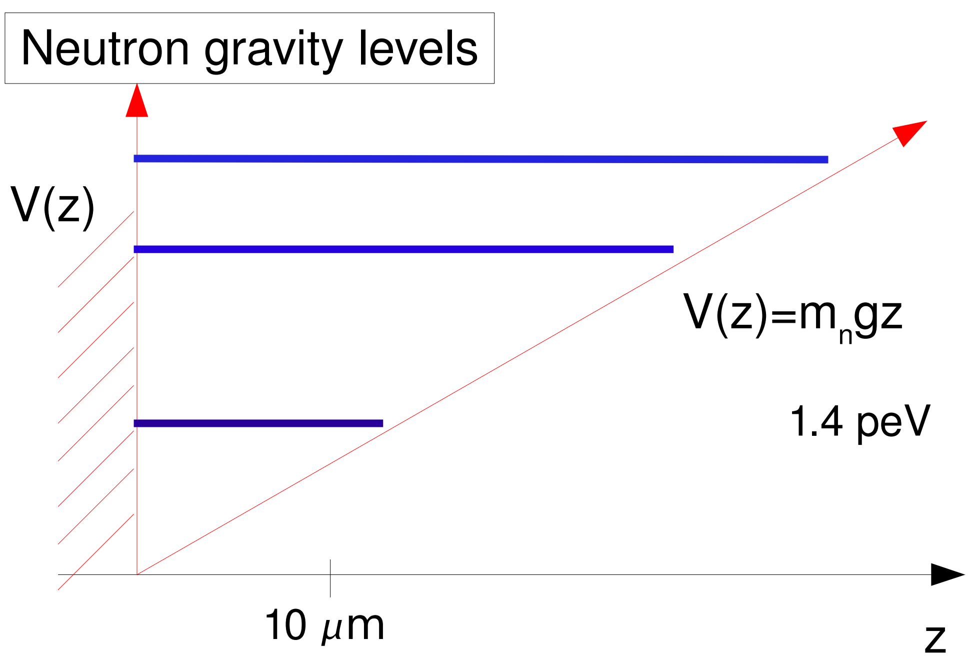
Ultracold Neutrons (UCN)

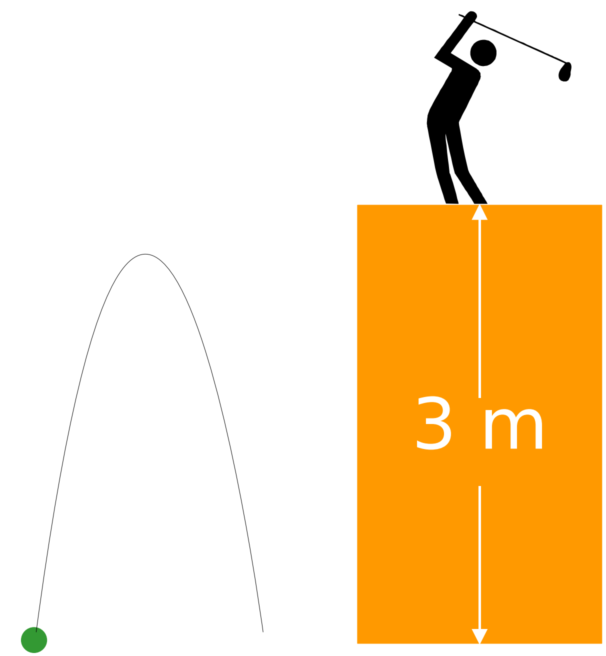
- UCN are neutrons that are moving so slowly that they are totally reflected from a variety of materials.
- So, they can be confined in material bottles for long periods of time.
- Typical parameters:
  - velocity < 8 m/s = 30 km/h
  - temperature < 4 mK
  - kinetic energy < 300 neV
- Interactions:
  - gravity: $V=mgh$
  - weak interaction (allows UCN to decay)
  - magnetic fields: $V=-\mu \bullet B$
  - strong interaction



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 metres

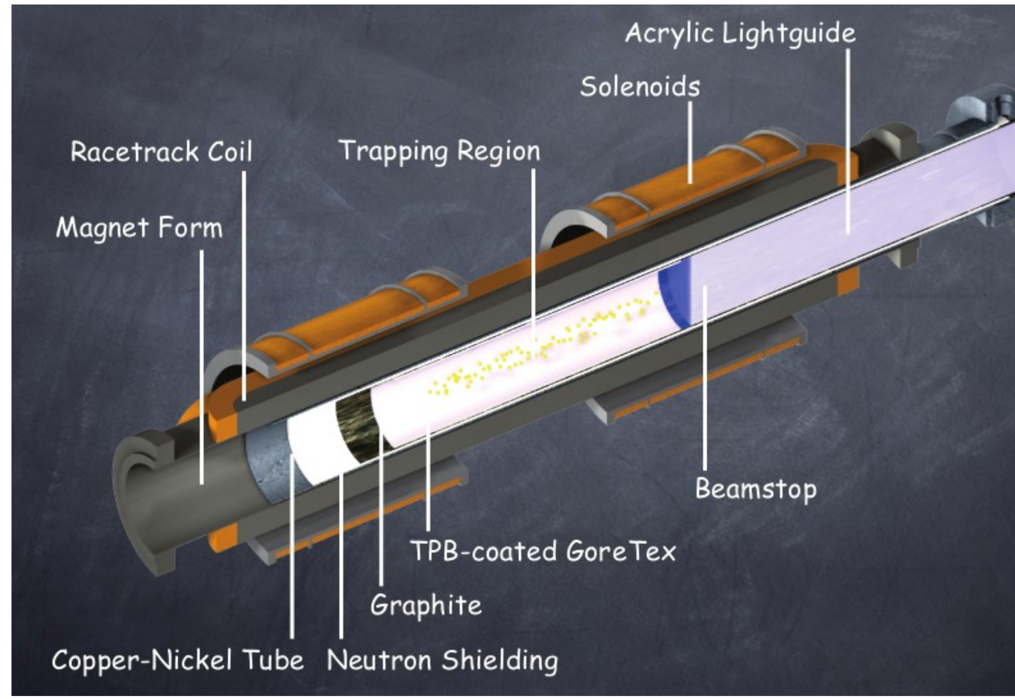




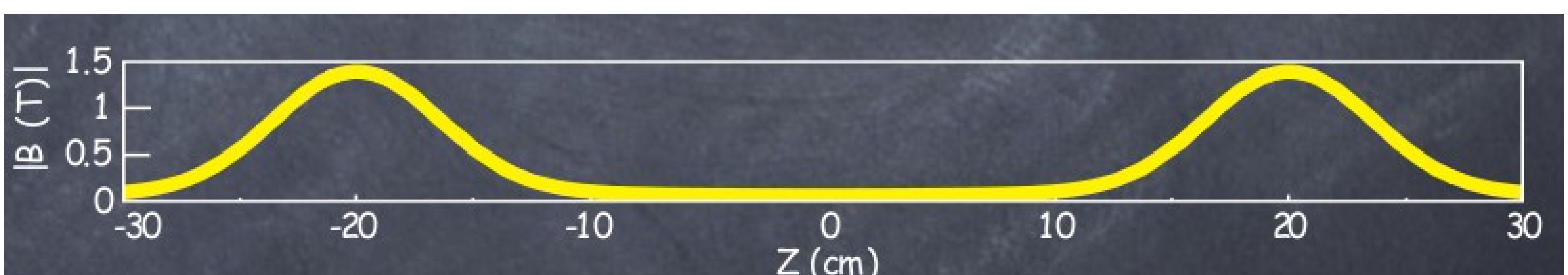
Magnetic Fields

- Neutrons magnetic moment is 60 neV/T
- UCN 100% polarization achieved by passage through 7 T field.
- You can trap ultracold neutrons in a magnetic bottle!

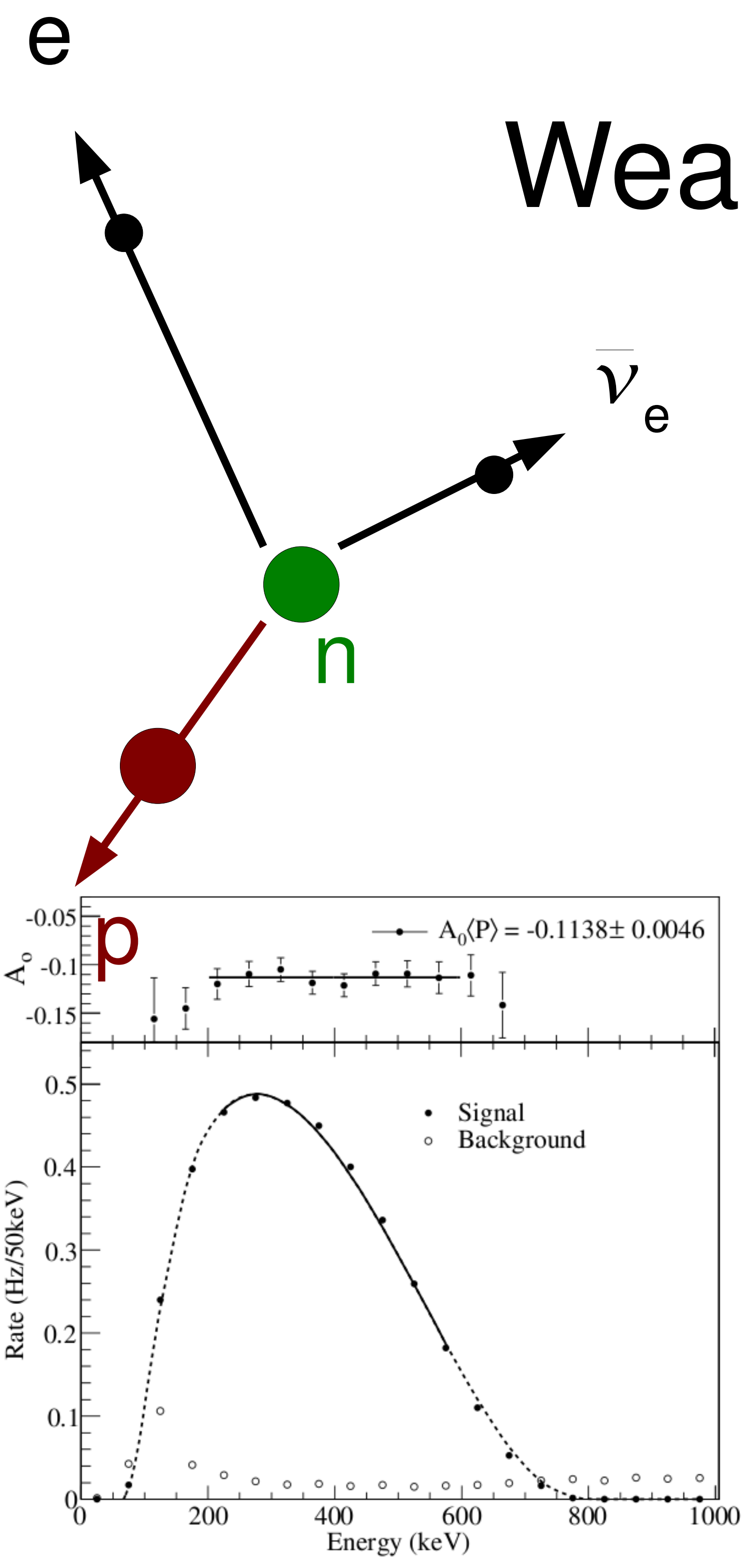
$$V = -\mu \cdot B$$



www.nist.gov



Weak Nuclear Force

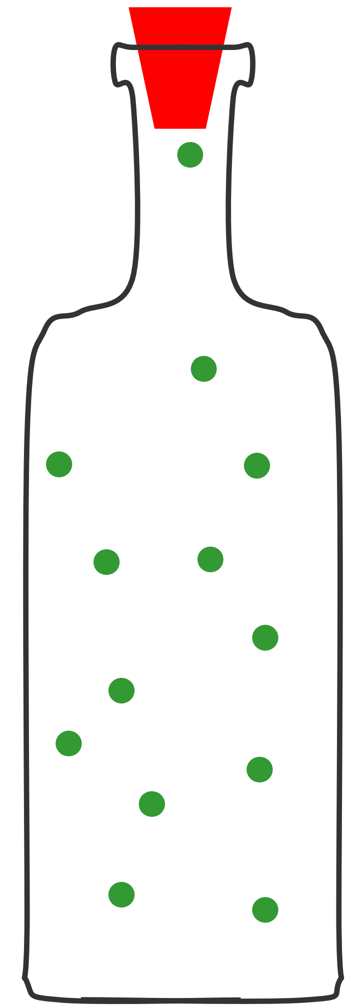


- Causes free neutrons to decay
- Neutrons live for about 15 minutes
- An interesting experiment:
  - Put ultracold neutrons in a bottle
  - Wait a while (about 15 minutes)
  - Open the bottle and see how many neutrons come out
- Also interesting experiment:
  - Measure the beta spectrum

D. Harrison, MSc project

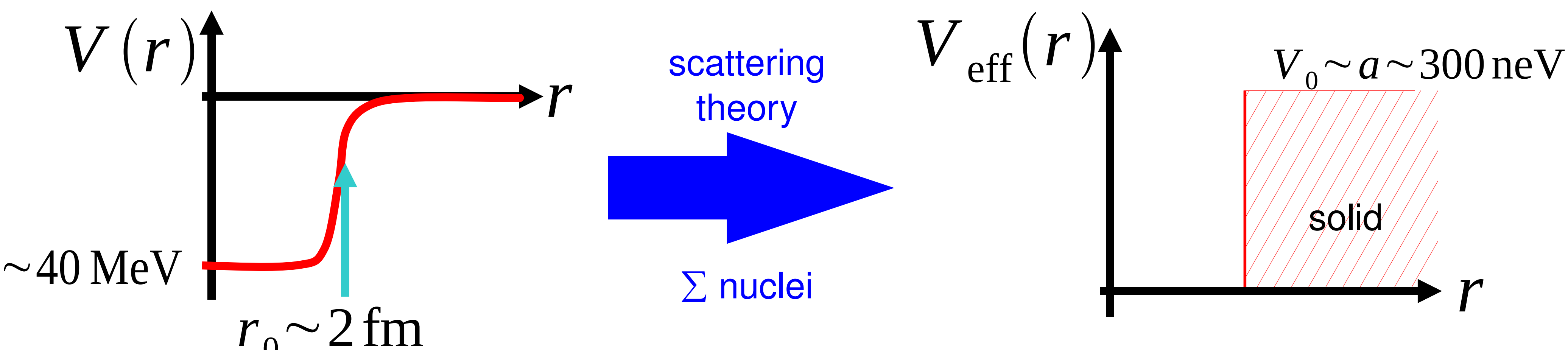
Strong Nuclear Force

- Ultracold neutrons are moving so absurdly slowly that they undergo total reflection from surfaces.
- This arises because of the strong nuclear force
- You can store UCN in a material bottle!



n-Nucleus interaction

n-solid interaction

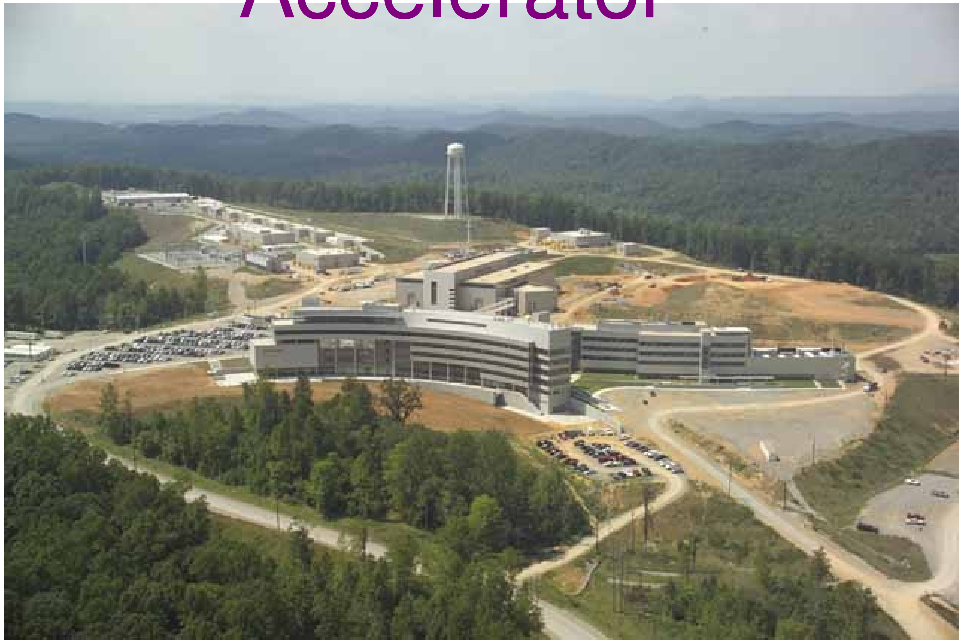


How to make lots of neutrons: Liberate them from nuclei!

1) In a nuclear reactor (fission).

2) At an accelerator (spallation).

Accelerator



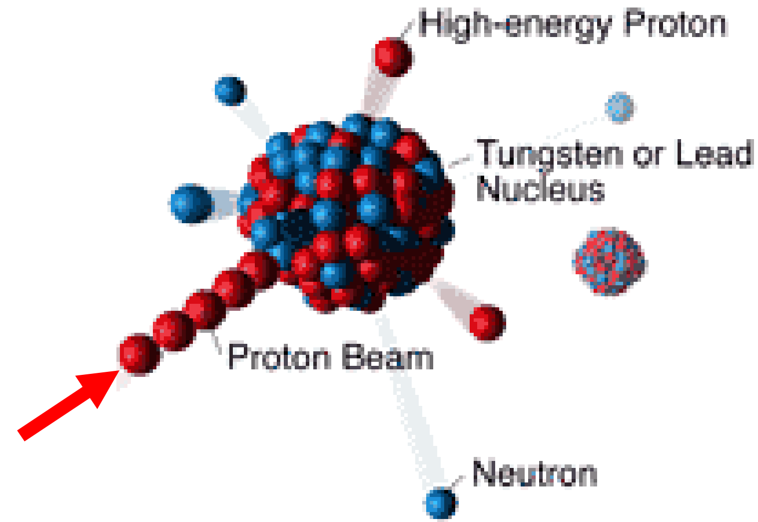
Spallation Neutron Source,
Oak Ridge, Tennessee, www.sns.gov

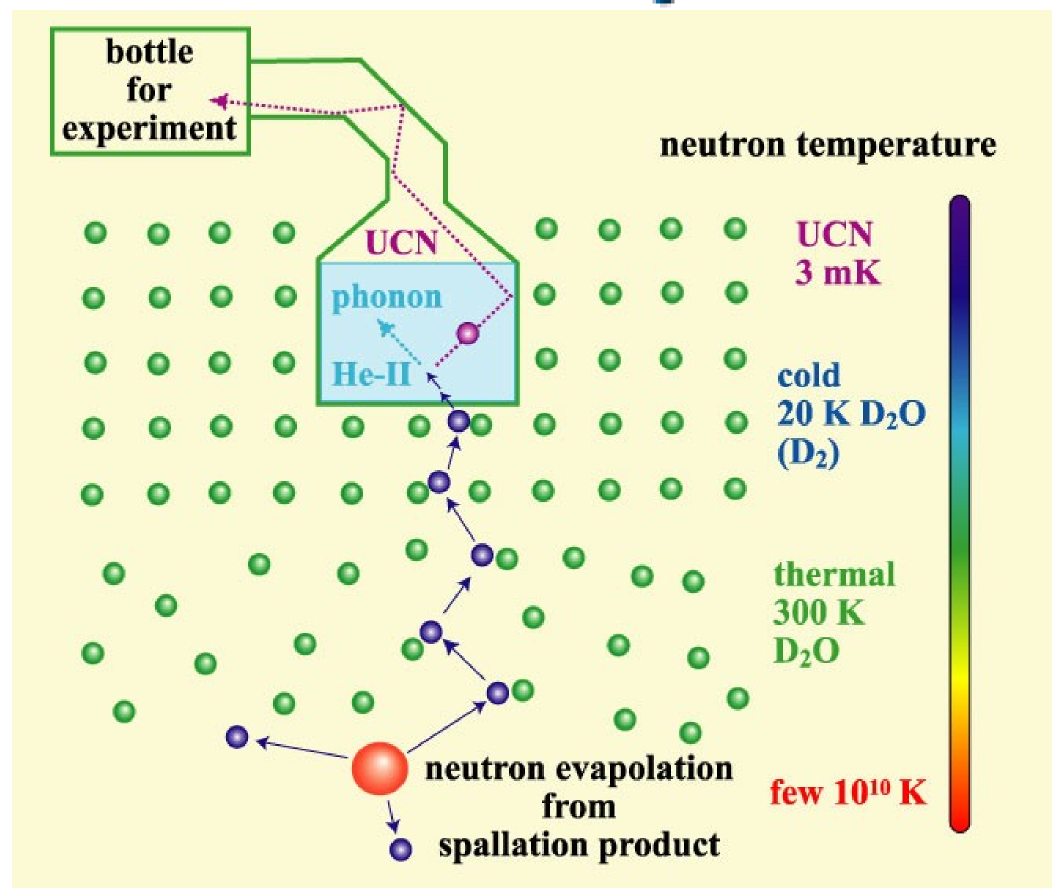
Reactor

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

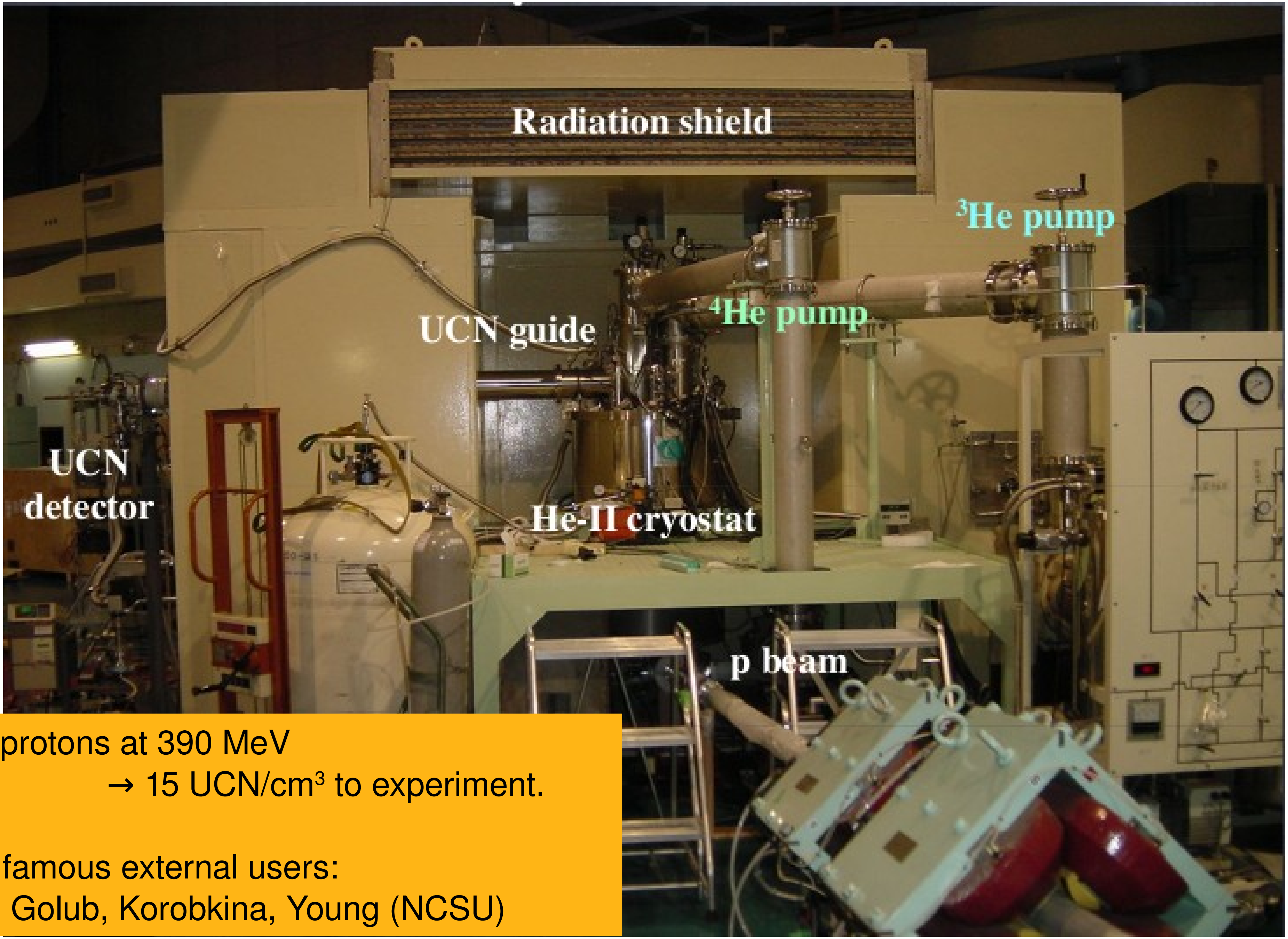
How to make UCN

- Liberate neutrons by proton-induced spallation.
- Moderate (thermalize) in cold (20 K) D_2O.
- Cold neutrons then “downscatter” to near zero energy (4 mK) in superfluid helium through phonon production.





Japan UCN Source (Masuda, et al)



1 μa protons at 390 MeV
→ 15 UCN/cm^3 to experiment.

Very famous external users:
- e.g. Golub, Korobkina, Young (NCSU)

- Proposed beam parameters for TRIUMF UCN source:
  - 500 MeV protons at 40 uA
- Recall RCNP, Osaka:
  - 390 MeV protons at 1 μA
- A fifty-fold increase in beam power.
- Cyclotron operates ~ 8 months/yr.

Japanese Section: UCN cryostat

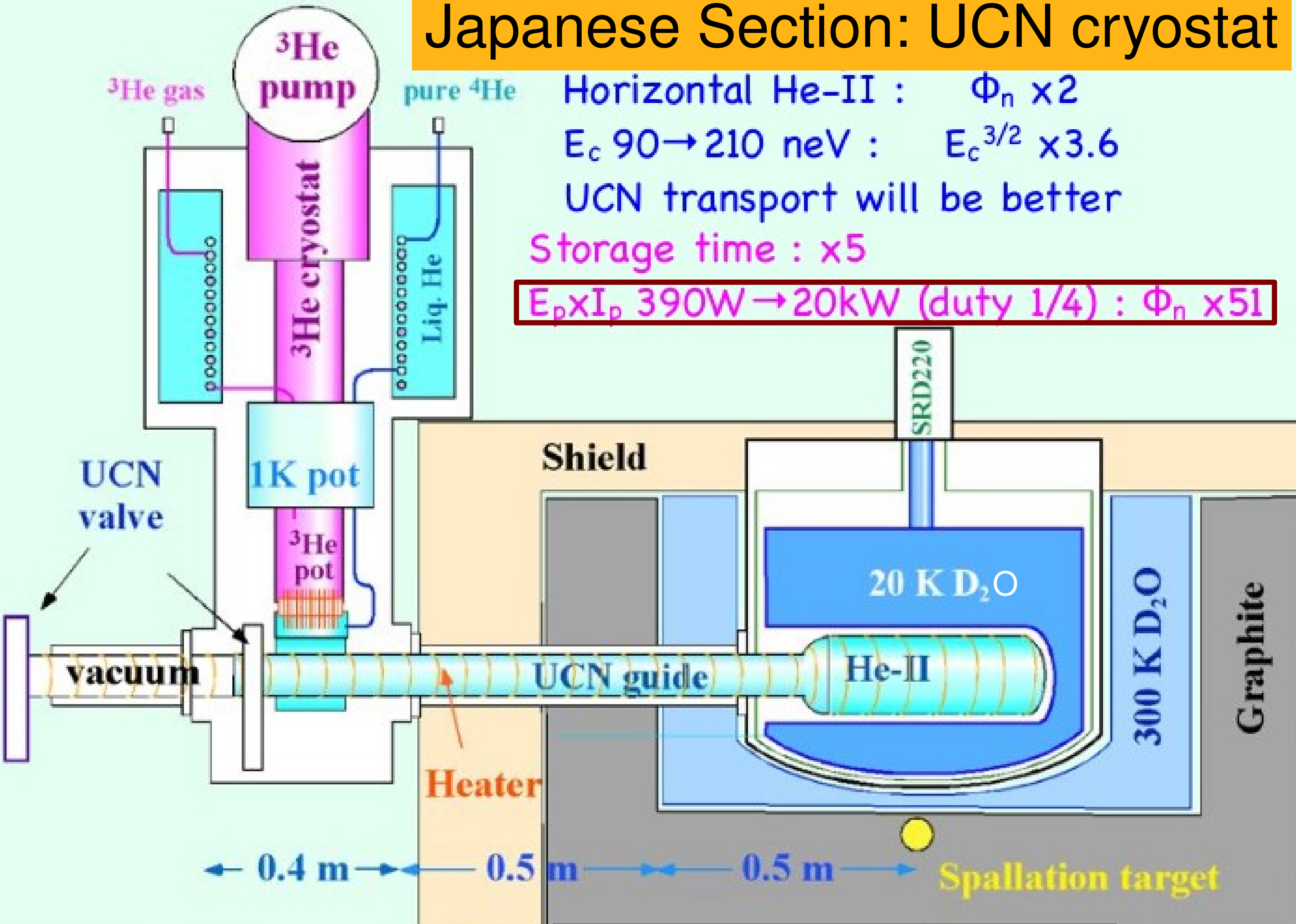
Horizontal He-II : Φ_n x2

E_c 90→210 neV : $E_c^{3/2}$ x3.6

UCN transport will be better

Storage time : x5

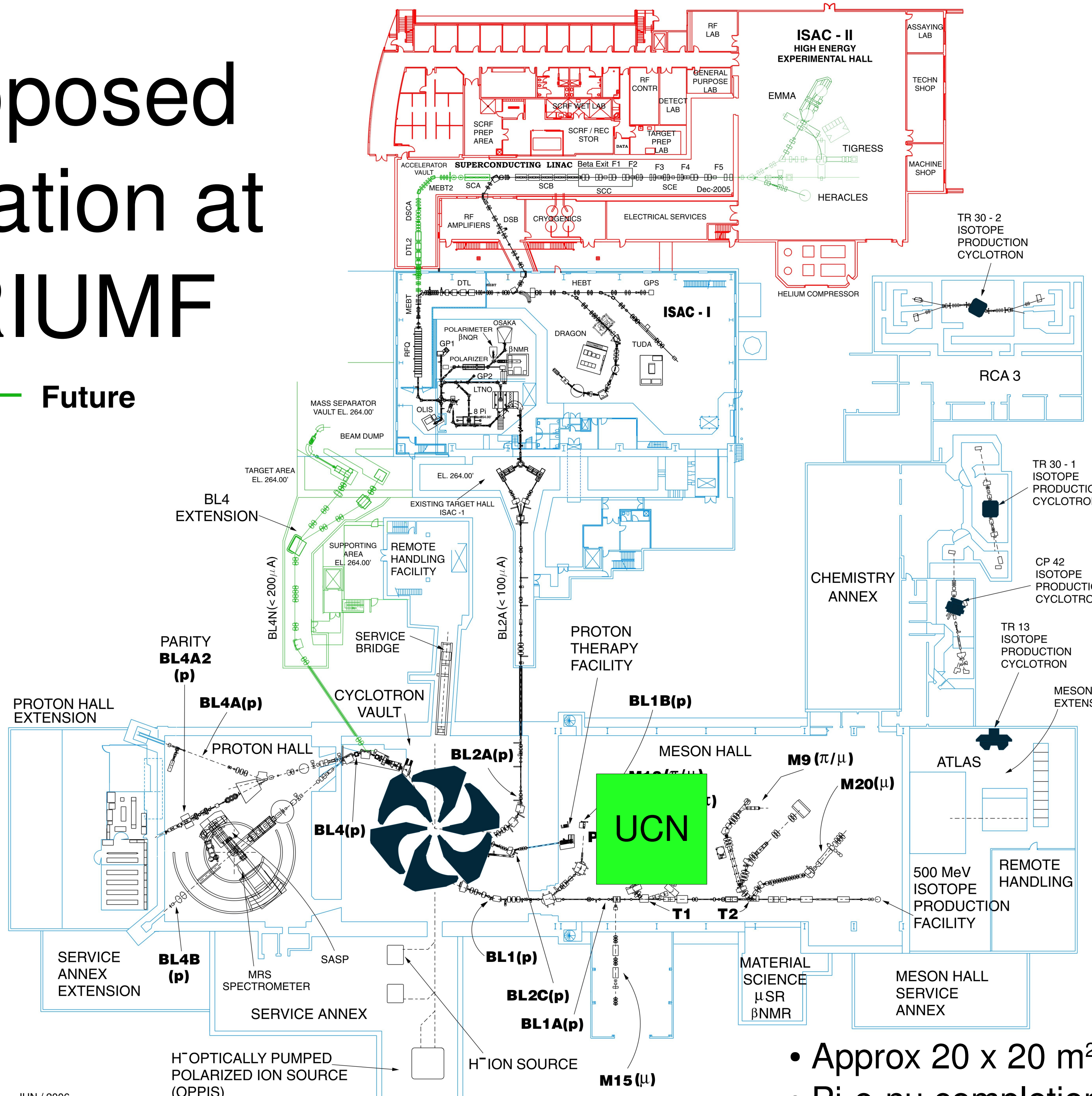
E_pxI_p 390W→20kW (duty 1/4) : Φ_n x51



Future Upgrade: D_2O ice → LD_2 : x5

Proposed Location at TRIUMF

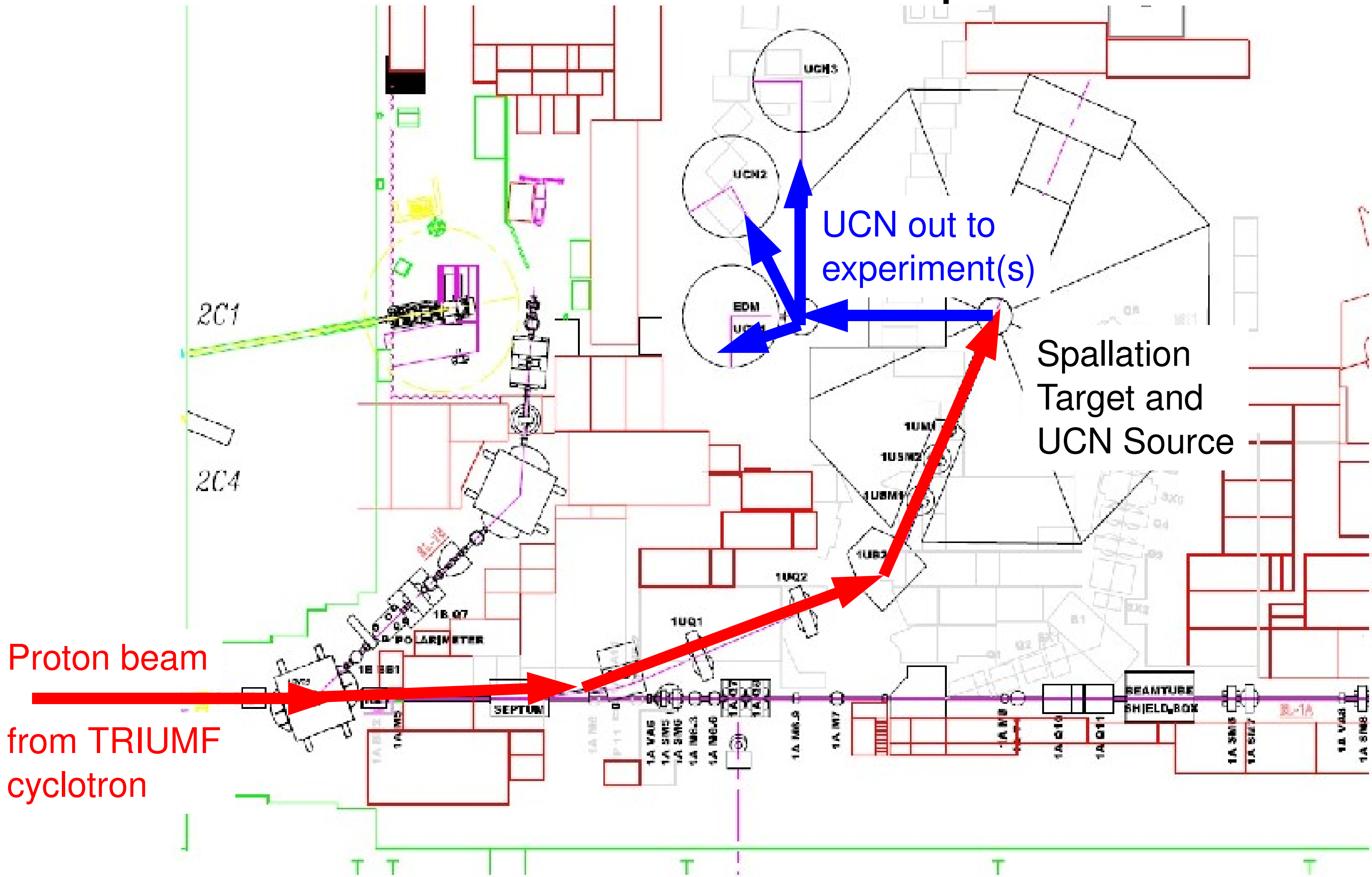
Future



- Approx 20 x 20 m^2 box
- Pi-e-nu completion 2011

i-SUN Implementation at TRIUMF

Meson Hall concept



Challenges in Implementation

- For counting-mode physics experiments, it can be highly advantageous to switch the beam off.
- E.g. At RCNP:
  - 1 min beam on, 3 mins beam off.
- At TRIUMF, we will use a fast kicker to achieve this pulsing.
- Constraints of beam structure from cyclotron.
- We must also be careful to not affect downstream users (muSR CMMS facility)

Technical Progress

- Beamline design (J. Doornbos, G. Clark)
- Kicker feasibility, design (M. Barnes)
- Shielding estimates (A. Trudel)
- Layout (S. Austen, C. Davis)
- Cost/Sched/Manpower (V. Verma, W.D. Ramsay, C. Davis)
- ...and many useful discussions with E. Blackmore, R. Baartman, P. Schmor ...

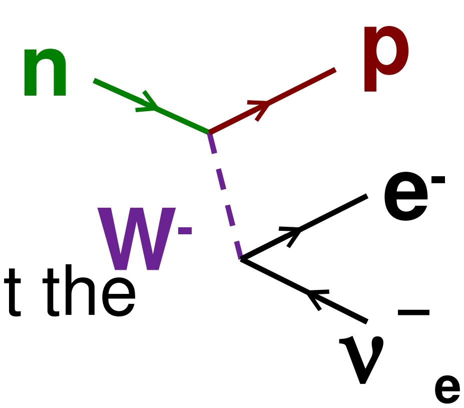
World's UCN projects

	source type	E_c neV	P_{UCN} /cm^3/s	τ_s s	ε_{ext}	ρ_{UCN} /cm^3 source/exp.
TRIUMF	spallation He-II	210	0.4×10^4 (10L)	150	~1	3×10^5 (20L) 1-5 x 10^4
ILL	n beam He-II	250	10	150	~1	**/1000
SNS	n beam He-II	134	0.3 (7L)	500	1	**/150
LANL *	spallation SD2	250	4.4×10^4 (240cm^3)	1.6	1.3×10^3/ 4.4×10^4	**/120
PSI	spallation SD2	250	2.9×10^5 (27L*)	6	0.1	2000 (2m^3) /1000
NCSU	reactor SD2	335	2.7×10^4 (1L)	**	**	1300/**
Munich	reactor SD2	250	**	**	**	1×10^4/**

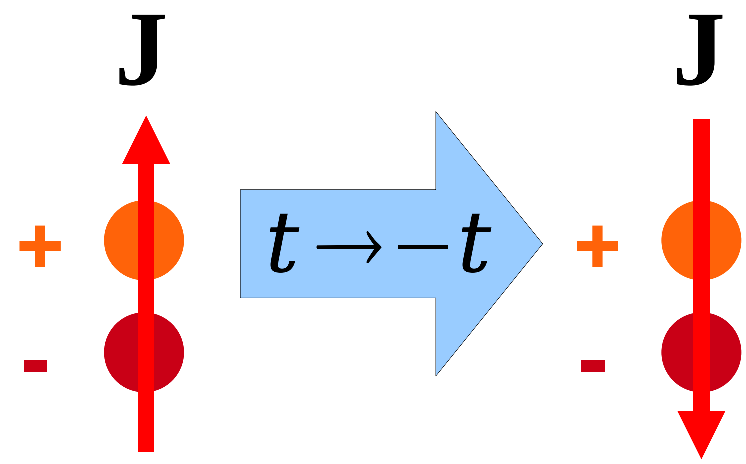
Physics Experiments with UCN

Fundamental Physics and Neutrons

- Neutrons and their interactions are a hot topic in particle physics.
  - How fast do neutrons decay? BBN.
  - Details about how neutrons decay tell us about the weak nuclear force. (V_{ud})



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



  - Interactions of neutrons with gravity and are there extra dimensions?

Physics Experiments for i-SUN

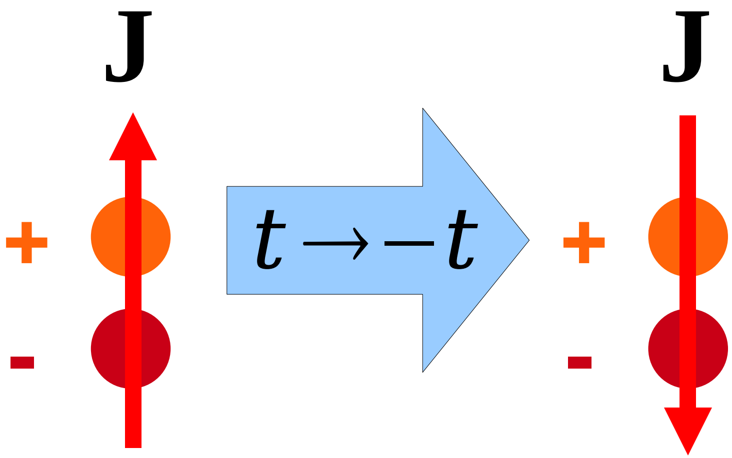
- neutron lifetime
- gravity levels
- n-EDM

near term

- n$\bar{n}$-oscillations
- Free n target

longer term

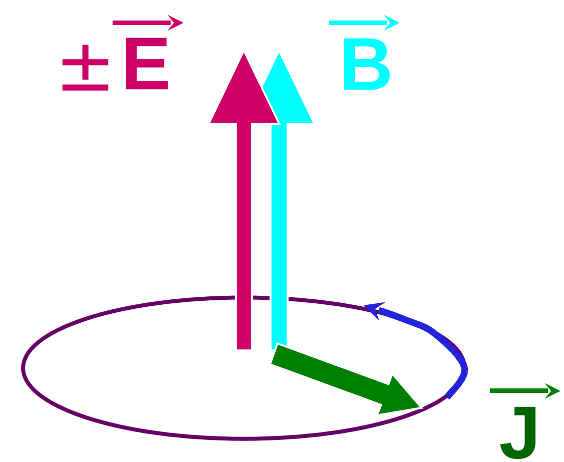
Neutron Electric Dipole Moment
(n-EDM, d_n)



$$d_n \Rightarrow \not{T} \Rightarrow \not{CP}$$

New sources of CP violation are required to explain the baryon asymmetry of the universe.

Experimental technique:
- put UCN in a bottle with *E*-, *B*-fields
- search for a change in spin precession frequency upon *E* reversal.

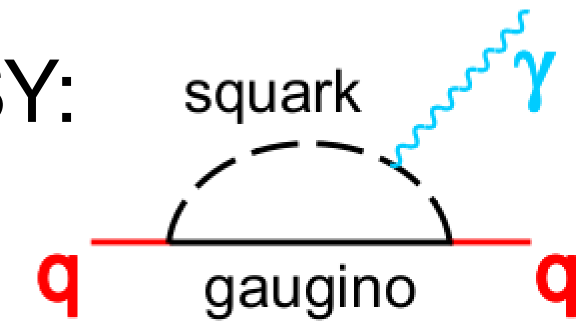


$$h\nu = 2\mu_n B \pm 2 \mathrm{d}_e E$$

EDM's and SUSY

- Scale of EDM's for quarks in SUSY:

$$d_q \sim \frac{\alpha}{\pi} \times \frac{m_q}{\Lambda^2_{SUSY}} \times \sin\theta_{CP}$$



from P. Harris, Sussex

- For “reasonable” values of new parameters:

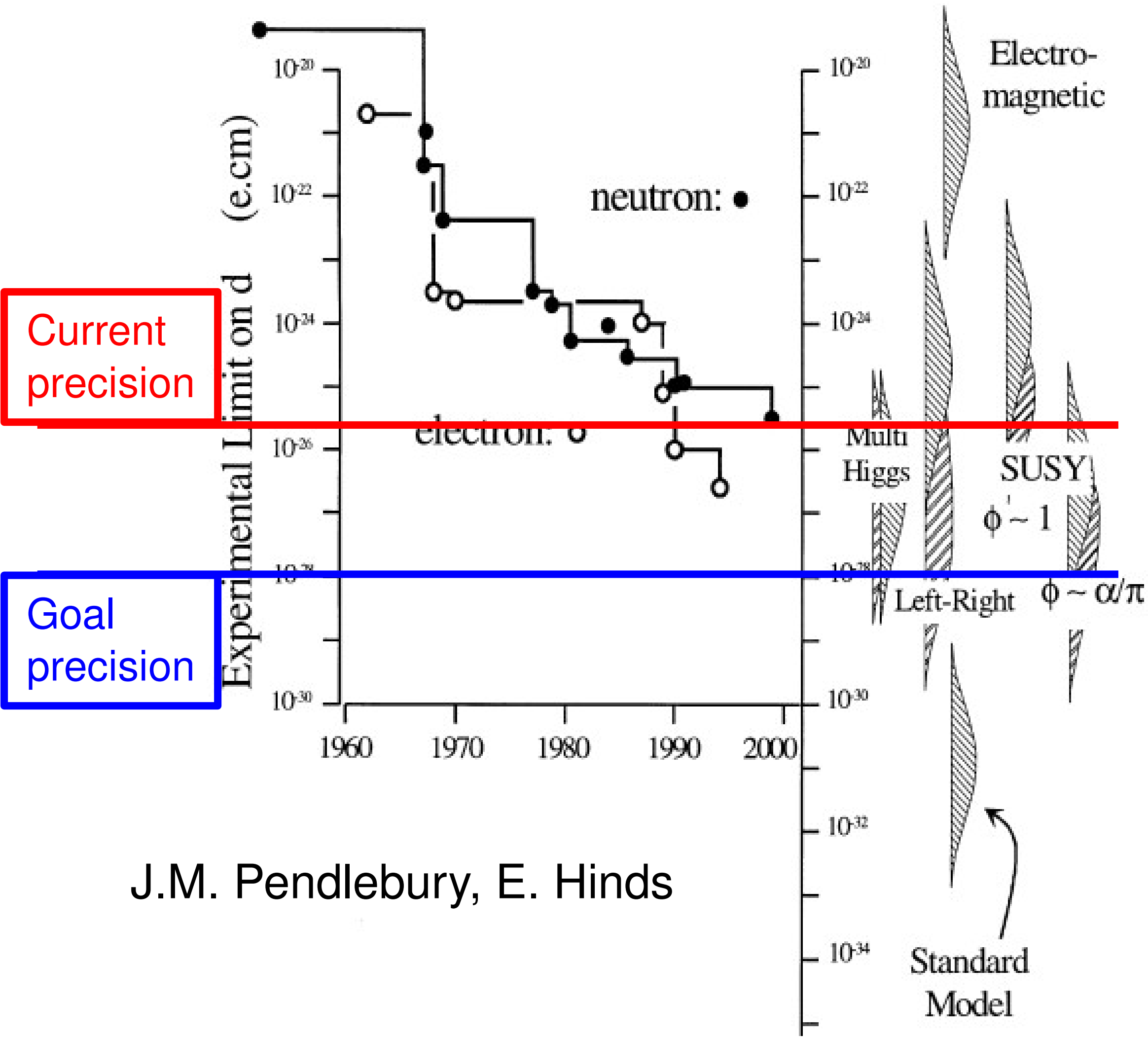
$$d_q \sim 3 \times 10^{-24}\, e \cdot cm$$

- According to neutron EDM measurements:

$$d_u < 2 \times 10^{-25}\, e \cdot cm \qquad d_d < 5 \times 10^{-26}\, e \cdot cm$$

- Unattractive solution:
  - Λ_{SUSY} > 2 TeV and/or θ_{CP} < 0.01
  - “SUSY CP problem”

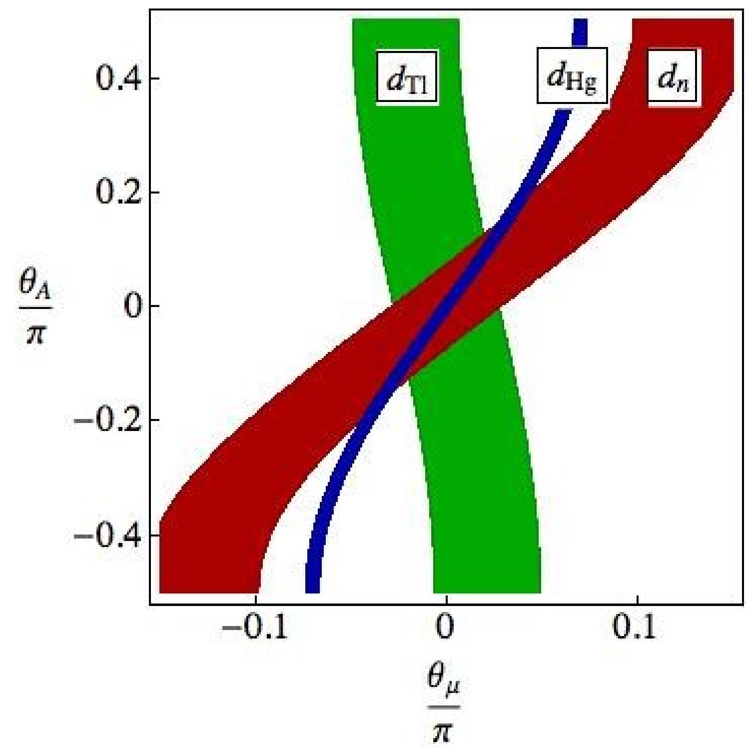
EDMs, the SM, and beyond



J.M. Pendlebury, E. Hinds

M. Romalis, MO-A4-2
A. Ritz, M. Pospelov, et al

SUSY M = 1 TeV, tanβ = 3

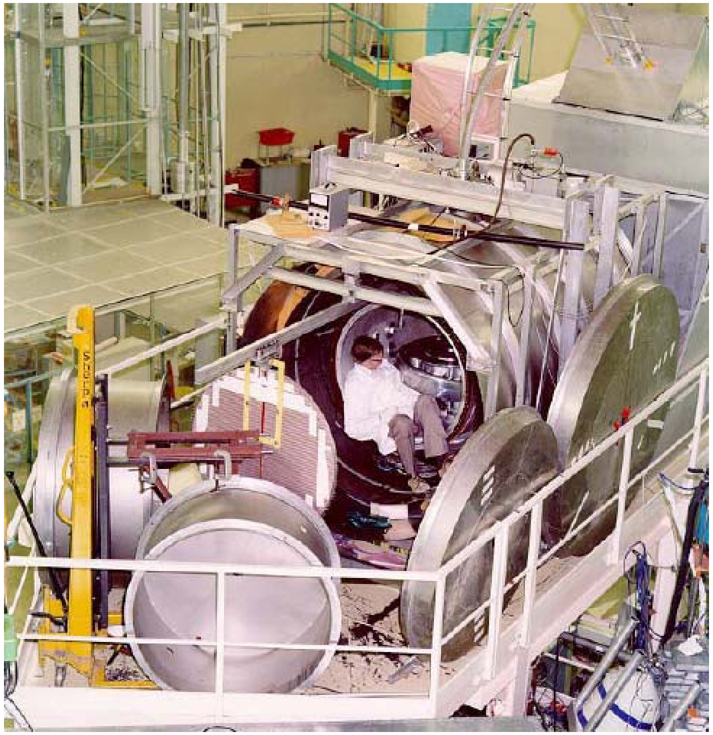


Note: universality assumptions are now even being tested
M. Ramsey-Musolf, TU-A10-3
A. Ritz, ...

- Ultimate goal: reach the SM limit

Past and Future n-EDM efforts

- Sussex-RAL-ILL expt. ($d_n < 3\times10^{-26}$ e-cm)
  - 0.7 UCN/cc, room temp, in vacuo
- CryoEDM (Sussex-RAL-ILL)
  - 1000 UCN/cc, in superfluid 4He
- SNS
  - 430 UCN/cc, in superfluid 4He
- PSI
  - 1000 UCN/cc, in vacuo
- TRIUMF: 1-5 x 10^4 UCN/cc

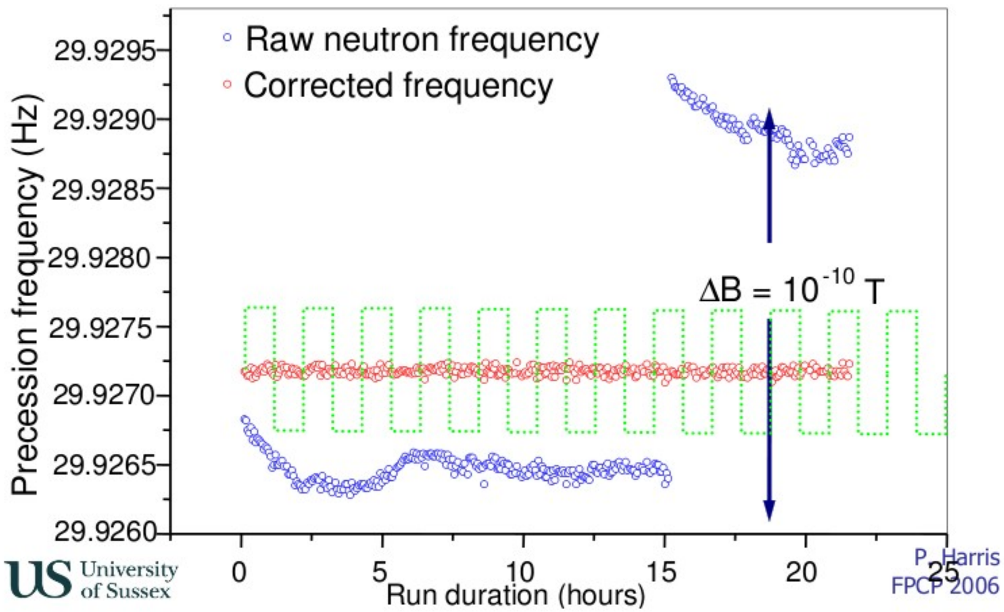


Sussex-RAL-ILL experiment

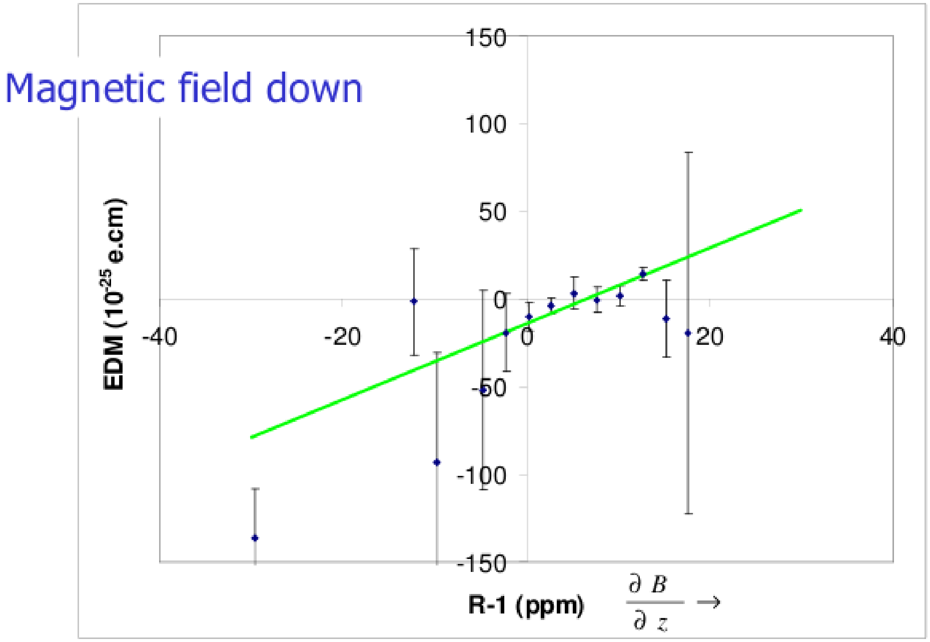
n-EDM Systematics

- magnetic field variations
- leakage currents
- geometric phase effect
  - false EDM arising from field inhomogeneity and E x v.

(co)magnetometry

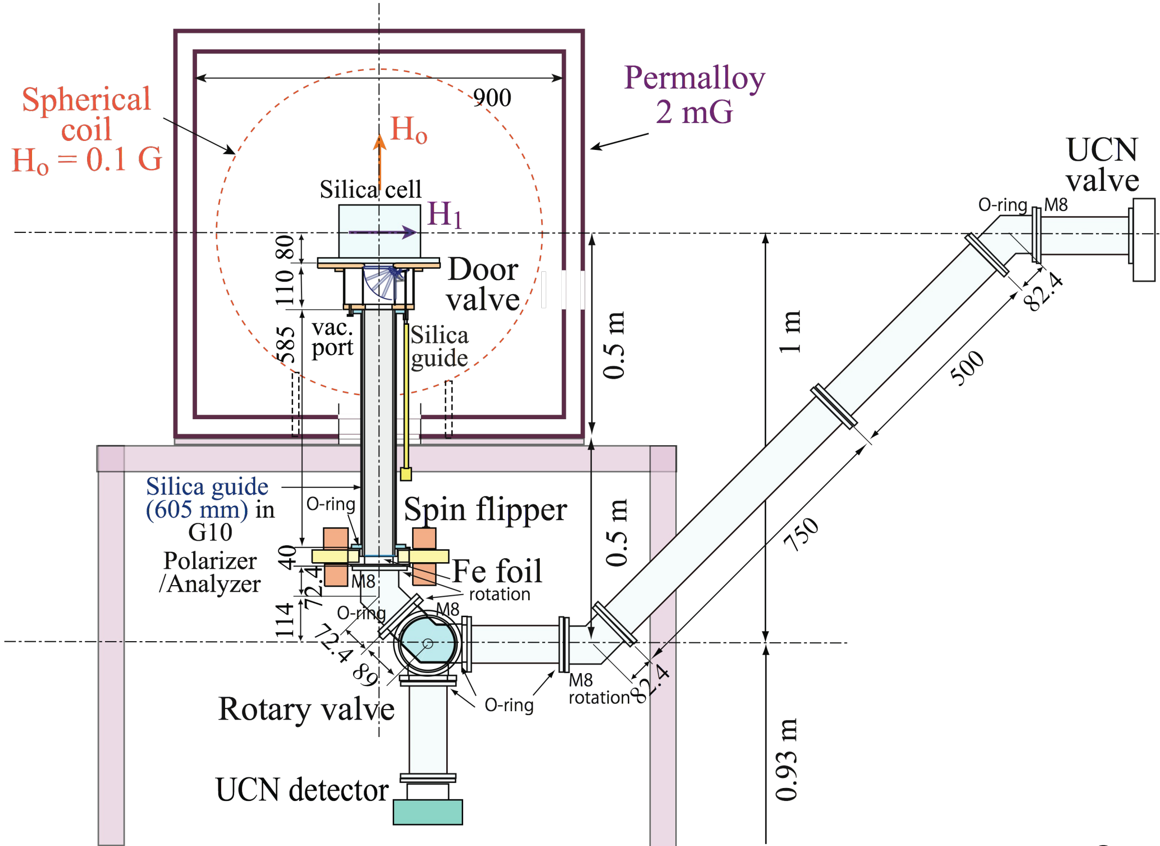


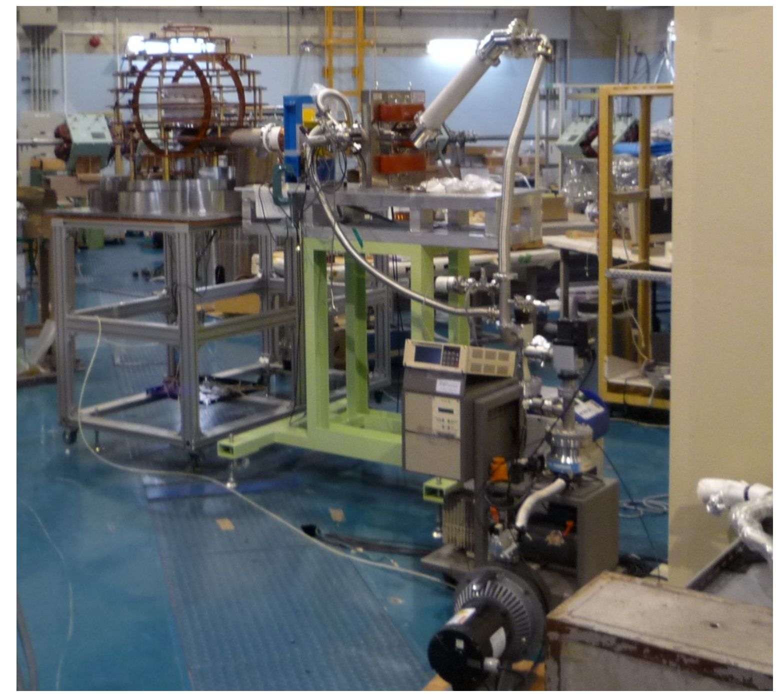
comagnetometry



false EDM (GP) effect

n-EDM development in Japan





- Masuda, et al. First experiments July 7-16 at RCNP, Osaka.

- Development of:
  - Comagnetometers
  - Ramsey resonance
  - New B-field geometry

Plans for TRIUMF

- Complete experiments in Japan, 2009-2011.
- Develop proposal for TRIUMF ~ 2011.
  - higher UCN density allows smaller cell size
    - smaller GP effect
- Expect number of EDM-experienced collaborators to grow if UCN source is approved:
  - e.g. B. Filippone, R. Golub, T. Ito, E. Korobkina, M. Hayden, B. Plaster (all work on SNS EDM project)

Involvement from more Canadian collaborators in this exciting experiment is very welcome!

i-SUN timeline

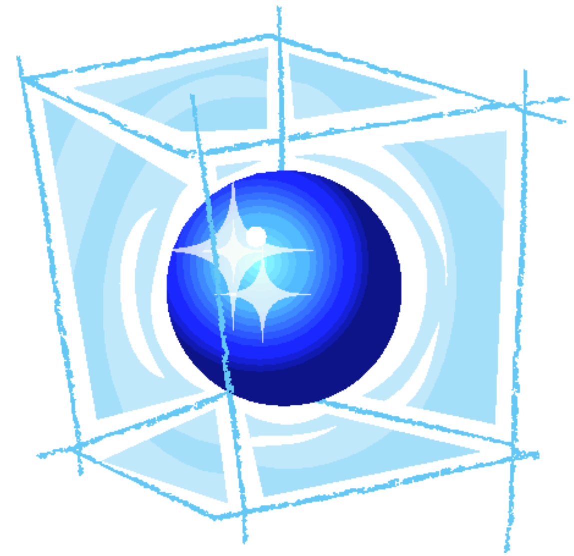
- 2007-8: UCN source supported by TRIUMF committees, included in plan for TRIUMF
- 2008: CFI NIF proposal submitted
  - In-kind contributions from Japan, TRIUMF

We are fully funded in Japan!

- 2009-12:
  - develop UCN source in Japan, EDM experiments
  - preparations and design in Canada
  - develop collaborations and proposals for experiments
- 2012-13: Install, commission at TRIUMF
- 2012-15: First experiments

Summary

- Ultracold neutrons are very interesting objects.



- We can use them for a variety of fundamental physics experiments with a long-term future.
- We want to build the world's most intense source of ultracold neutrons.

References

- My research group:
  - http://nuclear.uwinnipeg.ca
- International Spallation Ultracold Neutron Source:
  - http://nuclear.uwinnipeg.ca/ucn/triumf

jmartin@nuclear.uwinnipeg.ca

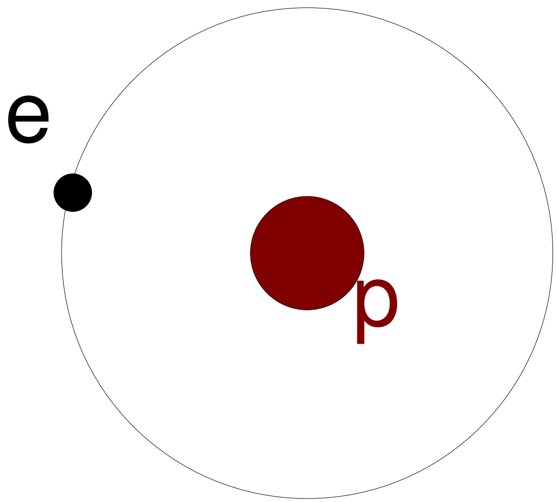
Summary of CFI request

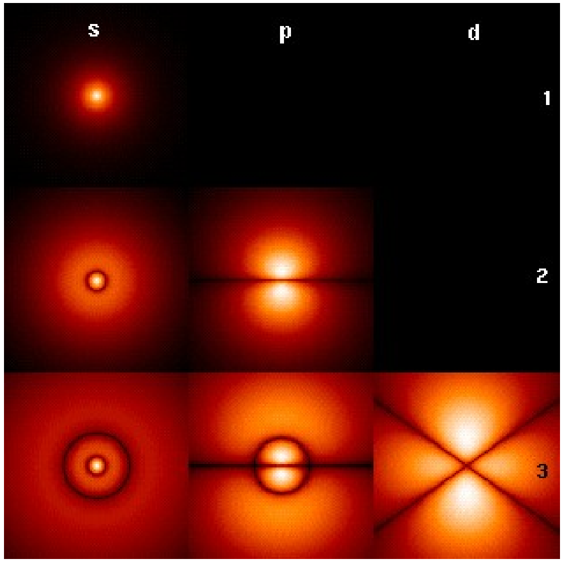
Item	Cost	Funding Source
UCN cryostat system	$4M	Japanese collaborators
Beamline	$2M	TRIUMF
Kickers, shielding, spallation target	$4.225M	CFI NIF
Moderator design	$0.675M	Manitoba + Acsion Industries
Total	$10.9M	

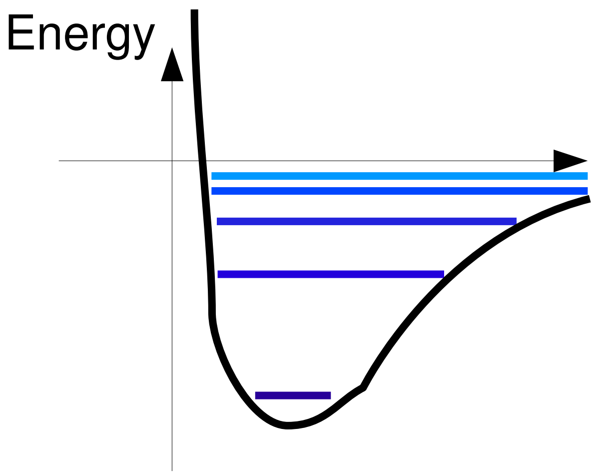
- UCN cryostat system includes:
  - Existing UCN source ($2M)
  - Modifications to source for TRIUMF ($2M)
    - Horizontal extraction, improved guide technology, etc.
- Canadian money for physics experiments:
  - separate budget from NSERC.

Quantum Physics

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

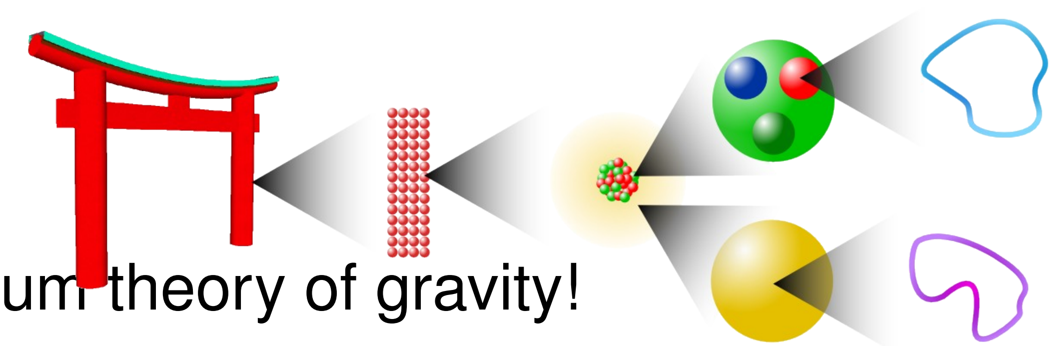






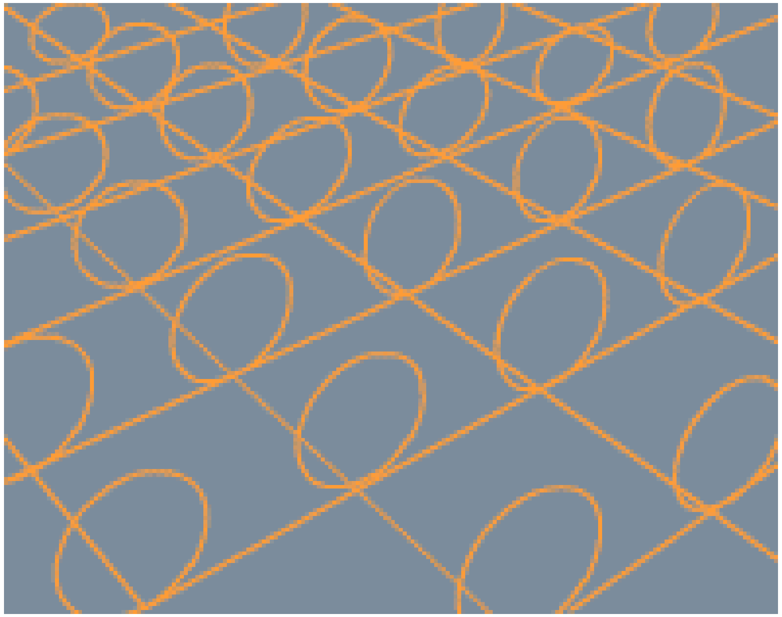
Quantum Physics and Gravity: They Don't Work Well Together

- So far, no one has figured out how to make gravity work with quantum physics.
- But people are trying:



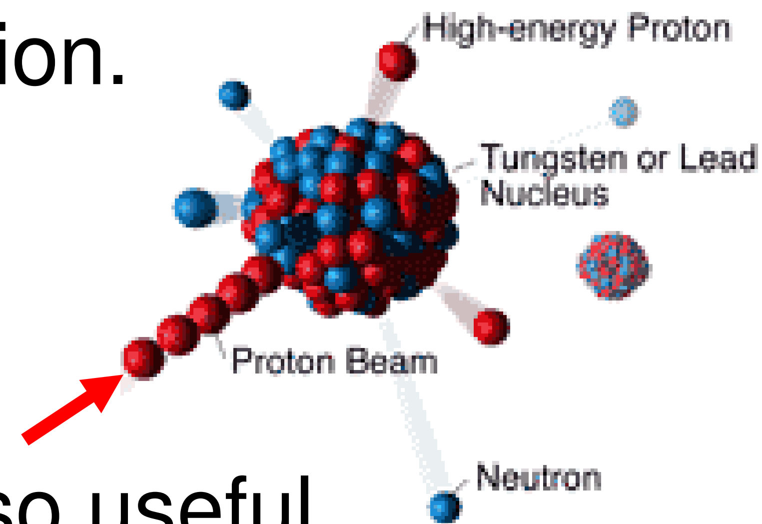
  - string theory
    - might be the real quantum theory of gravity!
  - models of quantum behavior in black holes
    - J. Ziprick, G. Kunstatter, and R. Kobes, U. Winnipeg

Extra Dimensions?



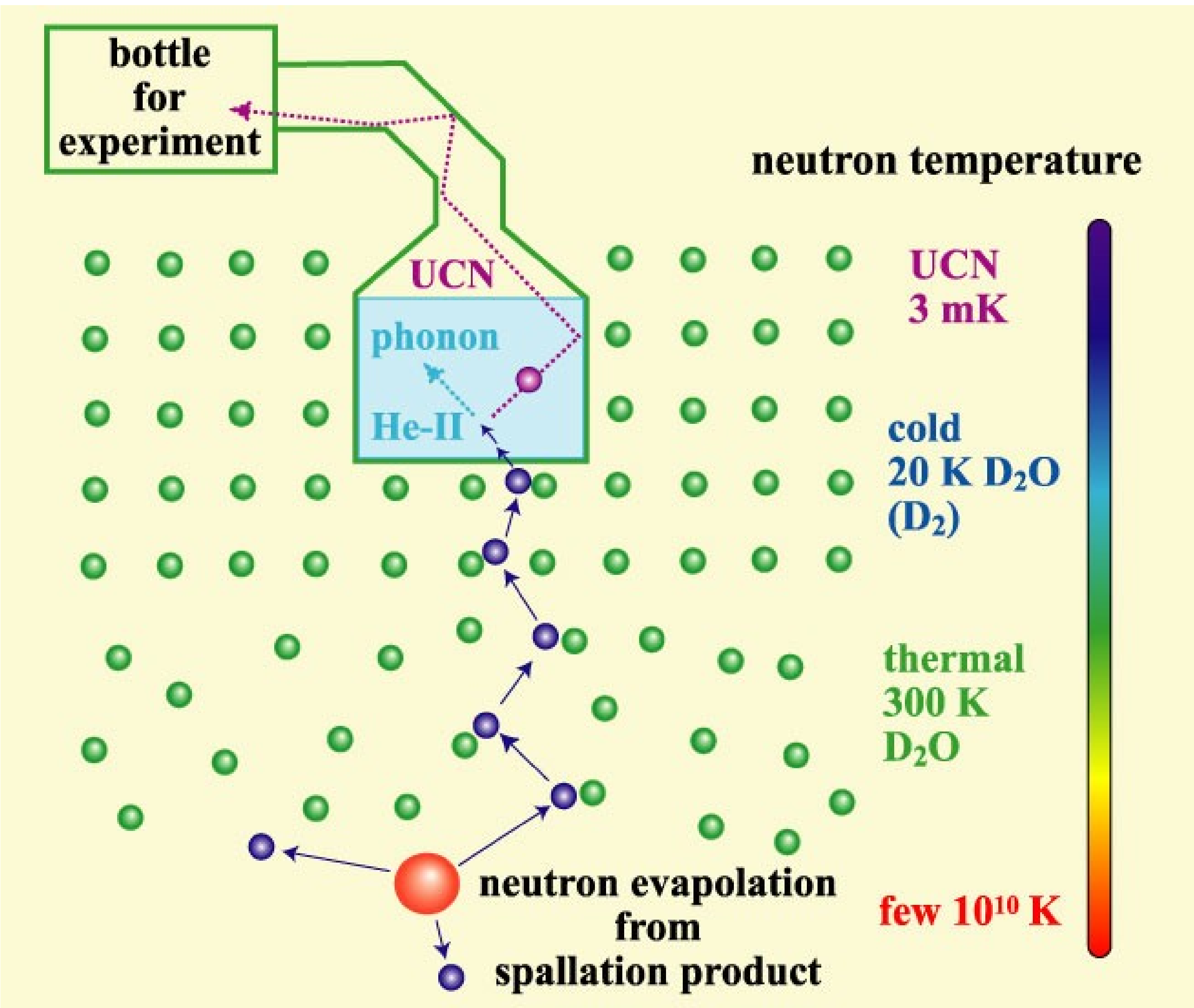
- One “prediction” of string theory is extra dimensions.
- If they exist, where are they?
- Clever theorists have suggested that maybe they are “curled up” or “compactified”.
- These curled up dimensions would modify gravity at scales below the size of the curling.
- If gravity is modified at these scales, neutron gravity experiments should see it.

How we will make neutrons.



- Using proton-induced spallation.
- This makes very fast-moving neutrons (T = 1 billion K)
- Such “hot” neutrons are not so useful.
- We need to cool them down to make them useful (I'll show you why in a moment).

How we cool neutrons
Step One: Cold Neutrons



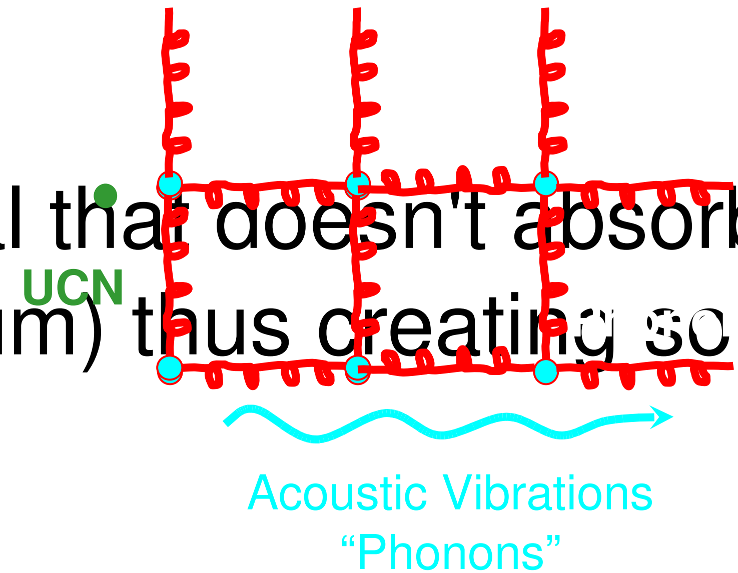
- Bring them into contact with a material at some temperature T.
- The neutrons bounce around for a while and eventually come into equilibrium with the material
- T = 20 K. (20 degrees above absolute zero.)
- But we desire ultracold neutrons

How we cool neutrons
Step Two: Ultracold Neutrons

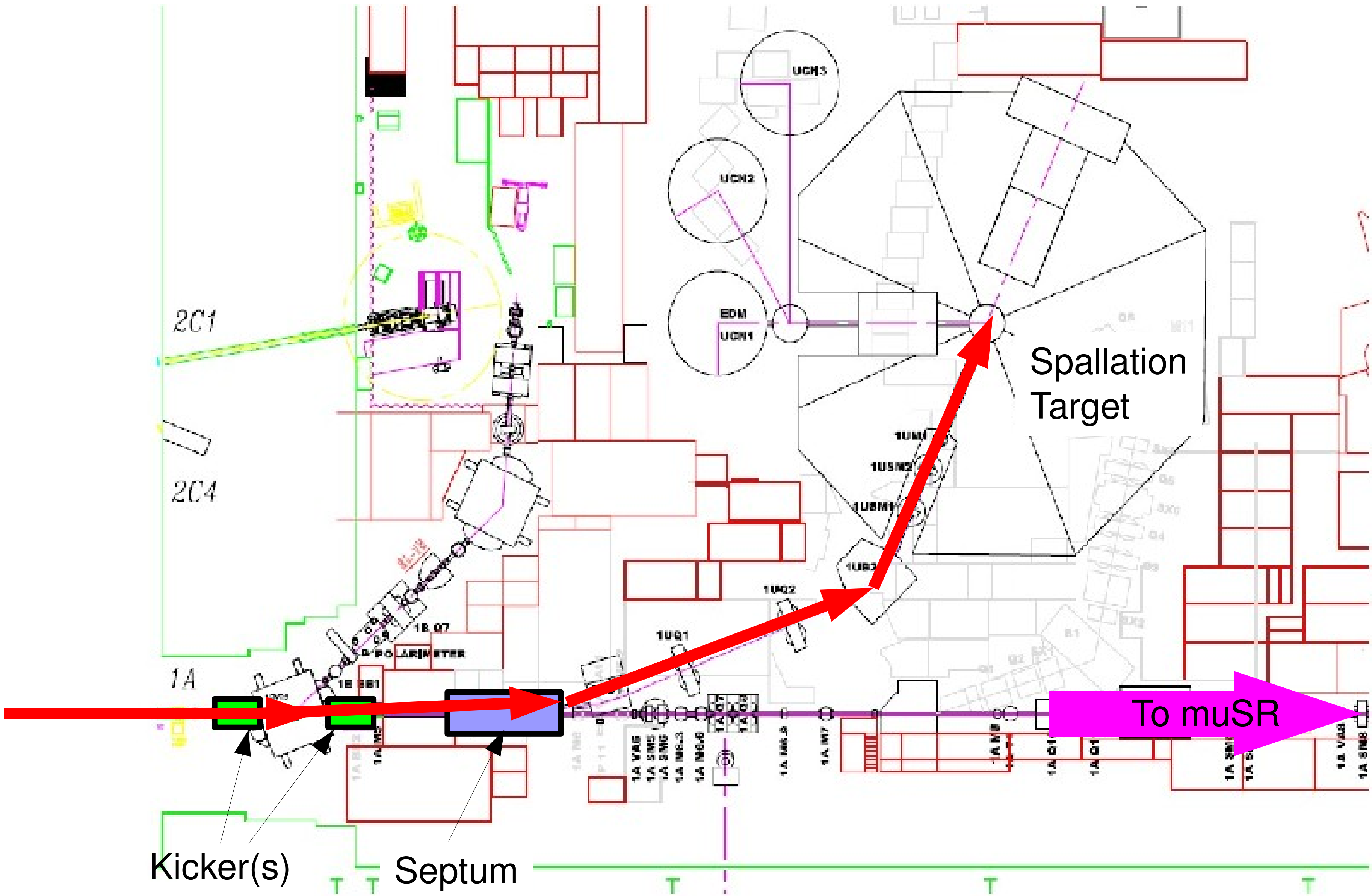
- Scatter them off a material that doesn't absorb them (e.g. superfluid helium)

How we cool neutrons
Step Two: Ultracold Neutrons

- Scatter them off a material that doesn't absorb them (e.g. superfluid helium) thus creating sound waves (“phonons”).



Kicker Concept



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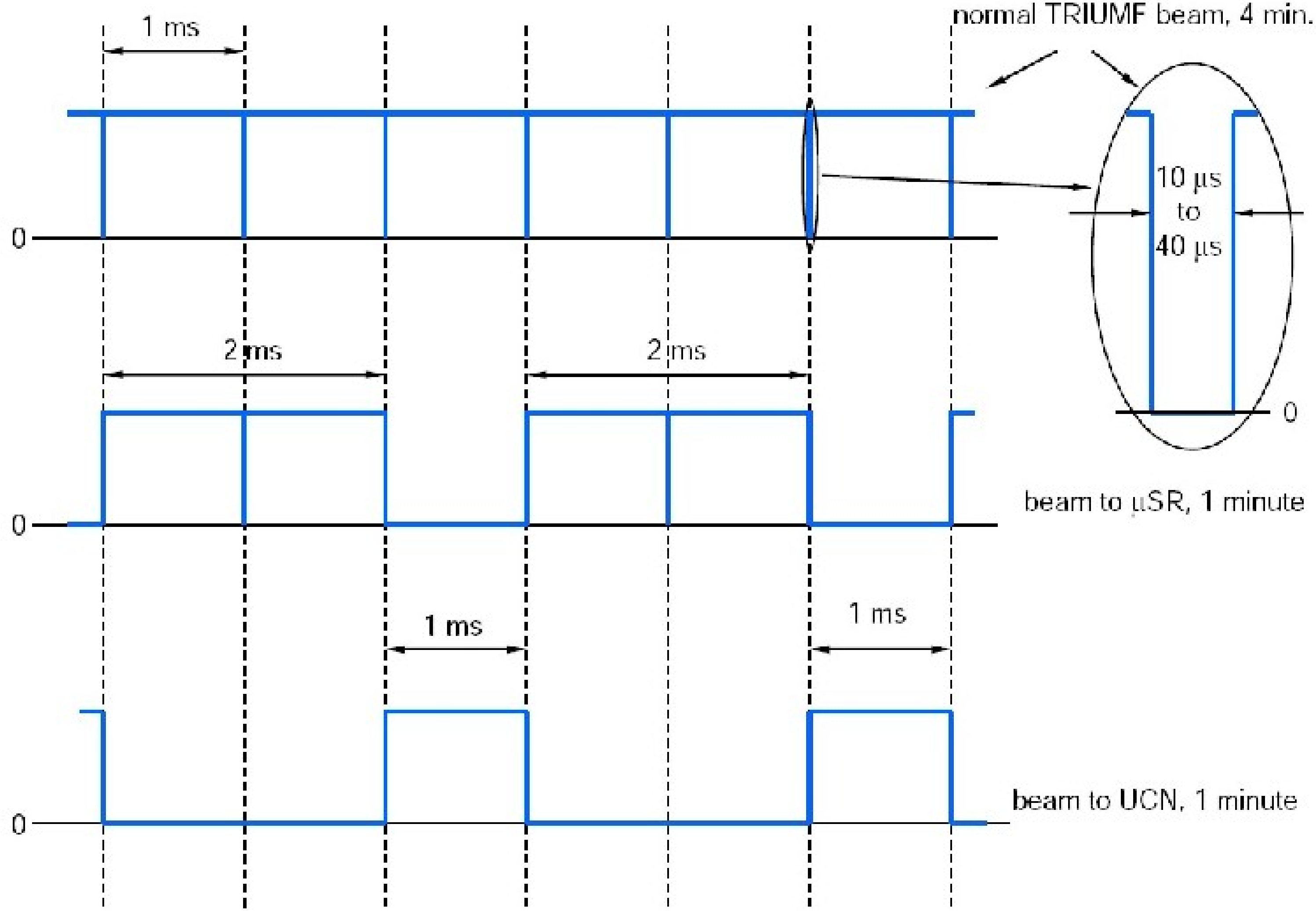

- Downstream users affected only at 7% level.
- UCN data when cyclotron is on (8 months/yr.)