# An Ultracold Neutron Source for TRIUMF

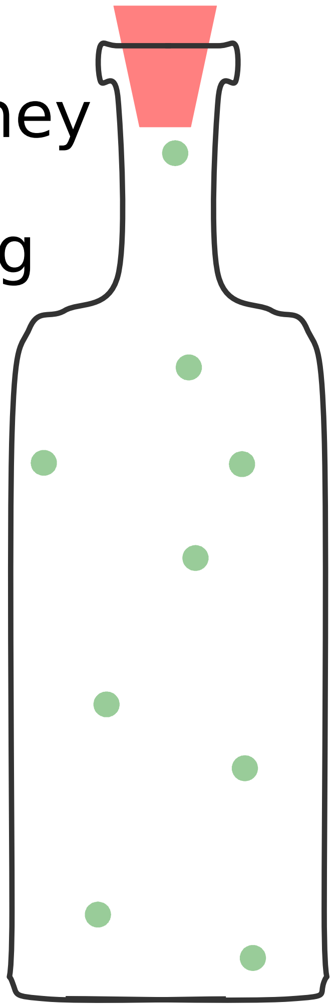
Jeff Martin (U. Winnipeg)

for Lothar Buchmann, Chuck Davis, Michael Gericke, Bob Golub, Akira Konaka, Larry Lee, Yasuhiro Masuda, Ania Micherdzinska, Shelley Page, Des Ramsay, Wim van Oers

(KEK, TRIUMF, NCSU, U. Manitoba, U. Winnipeg)

1. Introduction to Ultracold Neutrons (UCN)
2. UCN physics experiments
3. Source work at RCNP for TRIUMF
4. TRIUMF facility
5. CFI, relationship, collaboration, KEK

# Ultracold Neutrons



- UCN are neutrons that are moving so slowly that they are totally reflected from surfaces of materials.
- So, they can be confined in material bottles for long periods of time.
- Typical parameters:
  - velocity < 8 m/s
  - temperature < 4 mK
  - kinetic energy < 300 neV
- Interactions:
  - gravity: V=mgh (h < 3 m)
  - weak interaction (allows UCN to decay)
  - magnetic fields: $V=-\mu \bullet B$ (100% polarization)
  - strong interaction
- Experiments at UCN sources are chronically limited by UCN density. TRIUMF has the potential to be a world leader in this regard.

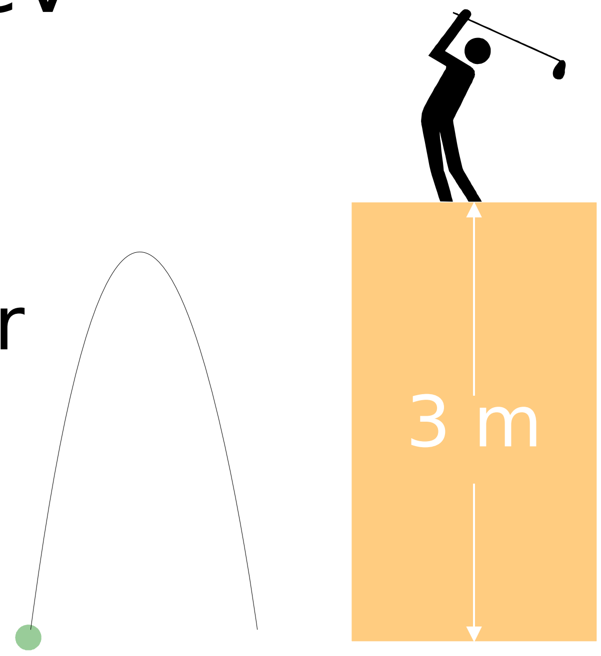
# Gravity

- $V = mgh$
- For a neutron on the planet Earth:

  $m = 1\ \text{GeV}/c^2$, $g = 10\ \text{m/s}^2$, $h = 3\ \text{m}$

  $$\Rightarrow V = 300\ \text{neV}$$

- Recall, $T_{UCN} < 300$ neV
- Uses:
  - UCN gravity spectrometer
  - gravitational levels expt



# Weak Interaction

$n \rightarrow p + e^- + \nu + 782$ keV

$\tau = 885.7 +/- 0.8$ s

(needed for BBN)

a, B, A

(+ tau needed to extract Vud)

b, D, R

(are zero in SM)

# Magnetic Interaction

- The neutron has a magnetic moment:

$$\mu = -1.9\ \mu_N = -\ 60\ \text{neV/T}$$

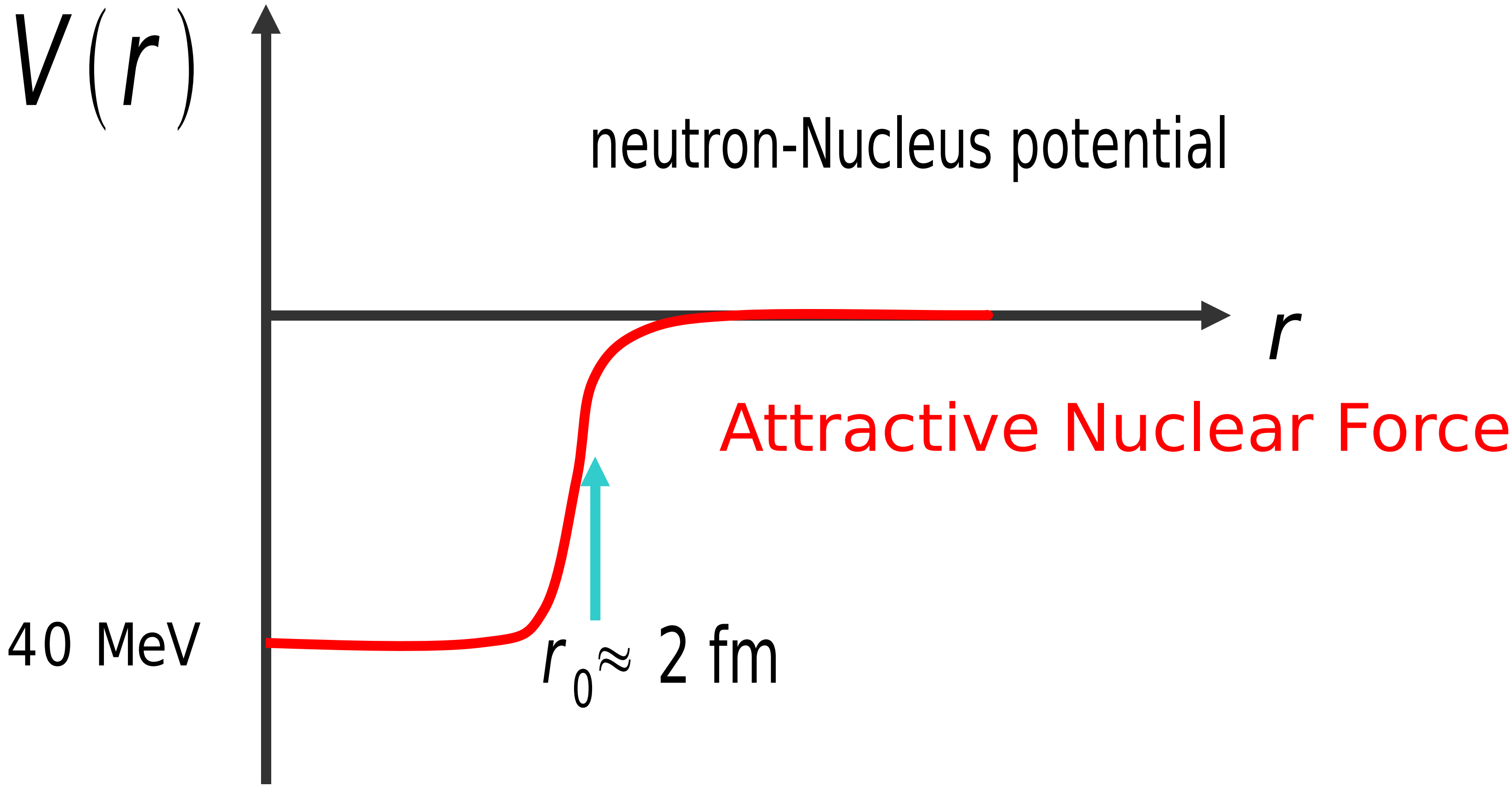
- The potential energy of a magnetic moment in a magnetic field is:

$$V = -\ \mu \bullet B$$

B = 7 T rejects one spin state of UCN (if adiabaticity obeyed)

=> UCN can be 100% polarized.

# Strong Interaction




For $T_n \leq 1$ MeV, $l \sim pr_0 \sim 0$, $s-wave$ scattering (isotropic)

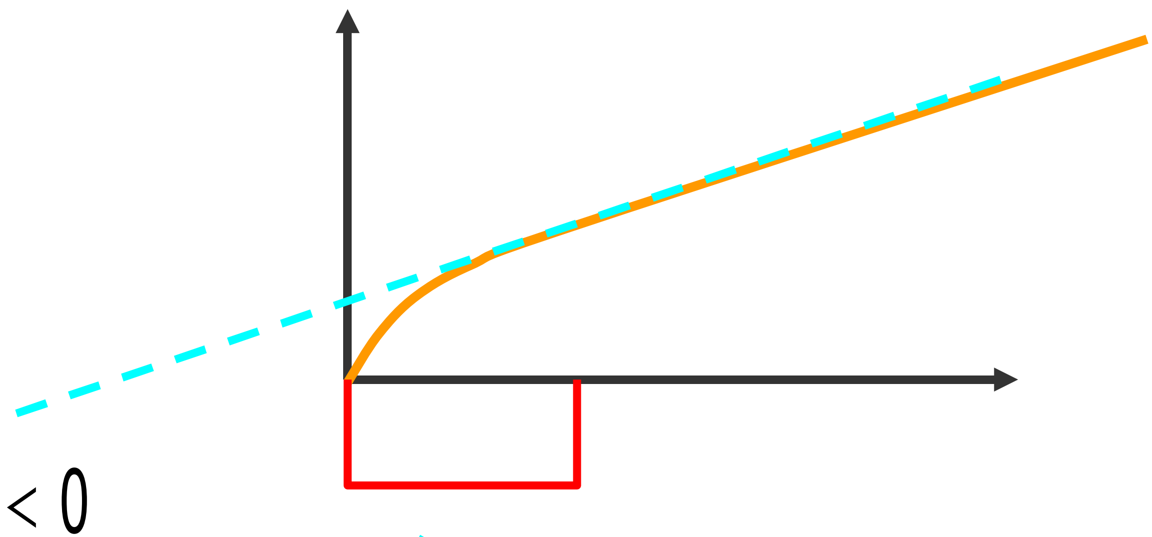
For $T_n << 1$ MeV,

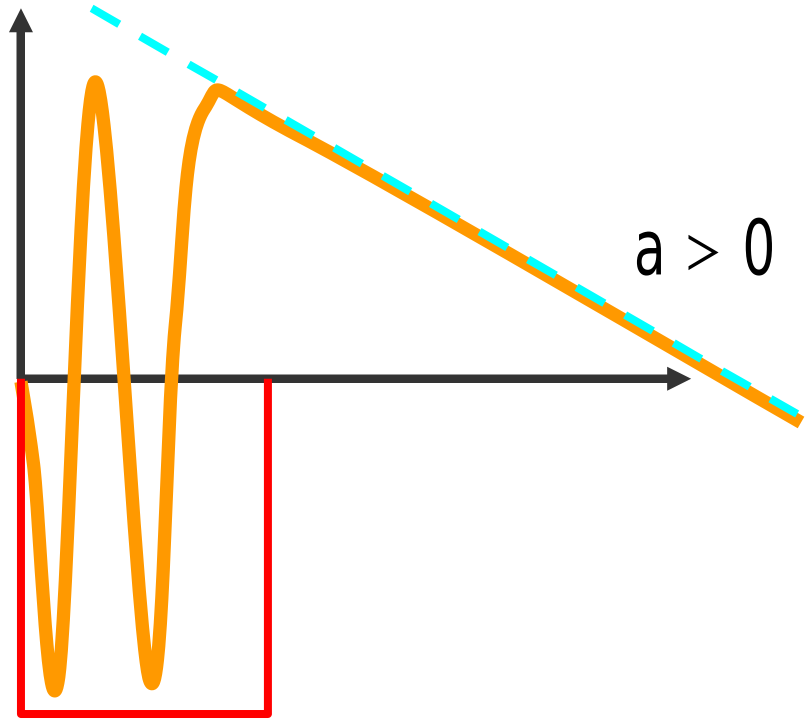
$$\sigma_{tot} = 4\pi \, a^2$$

a≡ scattering length

# Scattering Length

Weak potential




Strong potential

Many different potentials can give rise to the same value for "a"

Odds are, a > 0

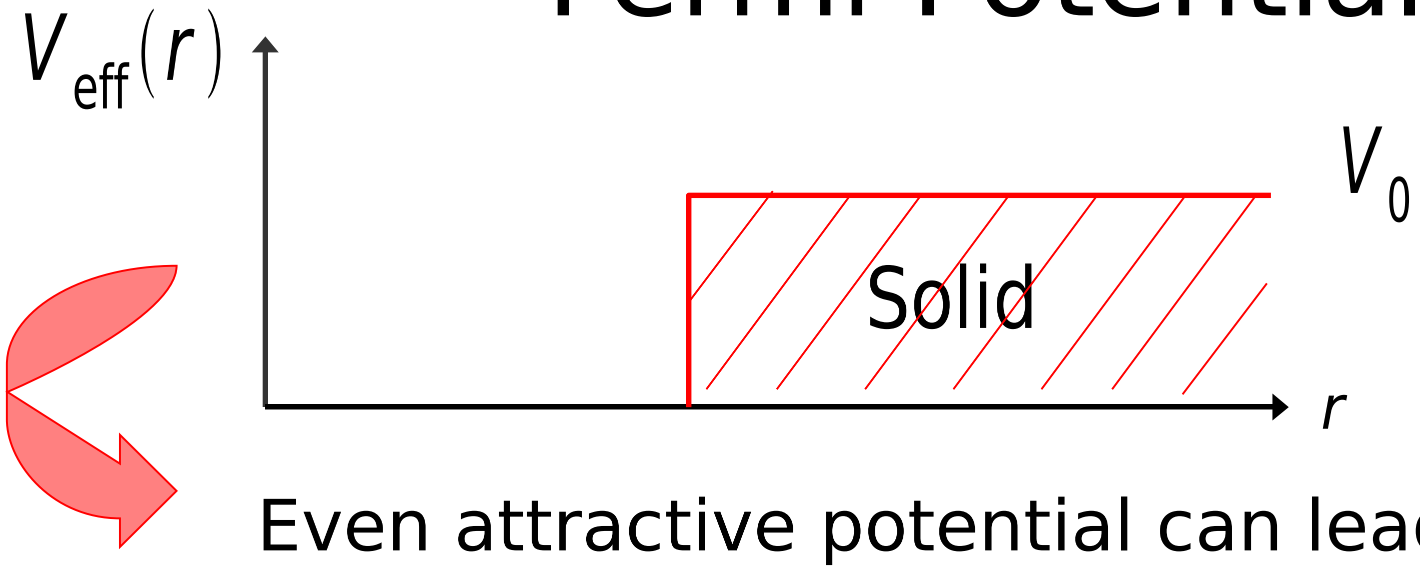
# Fermi Potential

$$V_{eff}(r) = \frac{2\pi\hbar^2 a}{m}\delta(r)$$

$$V_{eff}(r) = \frac{2\pi\hbar^2}{m}\sum_i a_i \delta(r - r_i)$$

$$V_{eff}(r) = \frac{4\pi a\hbar^2}{2m} N_0 \int \frac{d^3 r'}{V}\delta(r - r') = \frac{2\pi a\hbar^2 n_0}{m}\theta(r \notin V) \equiv V_0\,\theta(r \notin V)$$

# Fermi Potential




Even attractive potential can lead to repulsive effective potential!
(the "Fermi Potential")
Just as long as a > 0

Largest Fermi potential is for Nickel-58 ($^{58}$Ni)
$V_0$ = 335 neV

# Physics Experiments Using UCN

- All previous experiments using UCN were chronically limited by UCN density.

# UCN Source at TRIUMF would be a world-class facility

| | Source type | $E_c$ and $\tau_s$ | UCN density $\rho_{UCN}$(UCN/cm$^3$) |
|---|---|---|---|
| TRIUMF 5 kW$_{av}$ proton | 0.8K He-II | $E_c$ = 210 neV $\tau_s$ = 150 s | 1.8 x $10^4$ at experimental port |
| Grenoble 60MW reactor | 0.5K He-II | $E_c$ = 250 neV $\tau_s$ = 150 s | 1000 in He-II |
| SNS cold neutron beam | 0.3K He-II | $E_c$ = 134 neV $\tau_s$ = 500 s | 430 in He-II |
| Munich 20MW reactor | $SD_2$ | $E_c$ = 250 neV | $10^4$ in source |
| North Carolina 1 MW reactor | $SD_2$ | $E_c$ = 335 neV | 1300 in source |
| PSI 12 kW$_{av}$ proton | $SD_2$ | $E_c$ = 250 neV $\tau_s$ = 888 s | 2000 in source |
| Los Alamos 2.4 kW$_{av}$ proton | $SD_2$ | $E_c$ = 250 neV $\tau_s$ = 2.6 s | 120 in source |

# The Most Successful UCN Experiments to Date

- EDM
- Lifetime
- Gravity Levels
- Mirror Neutrons

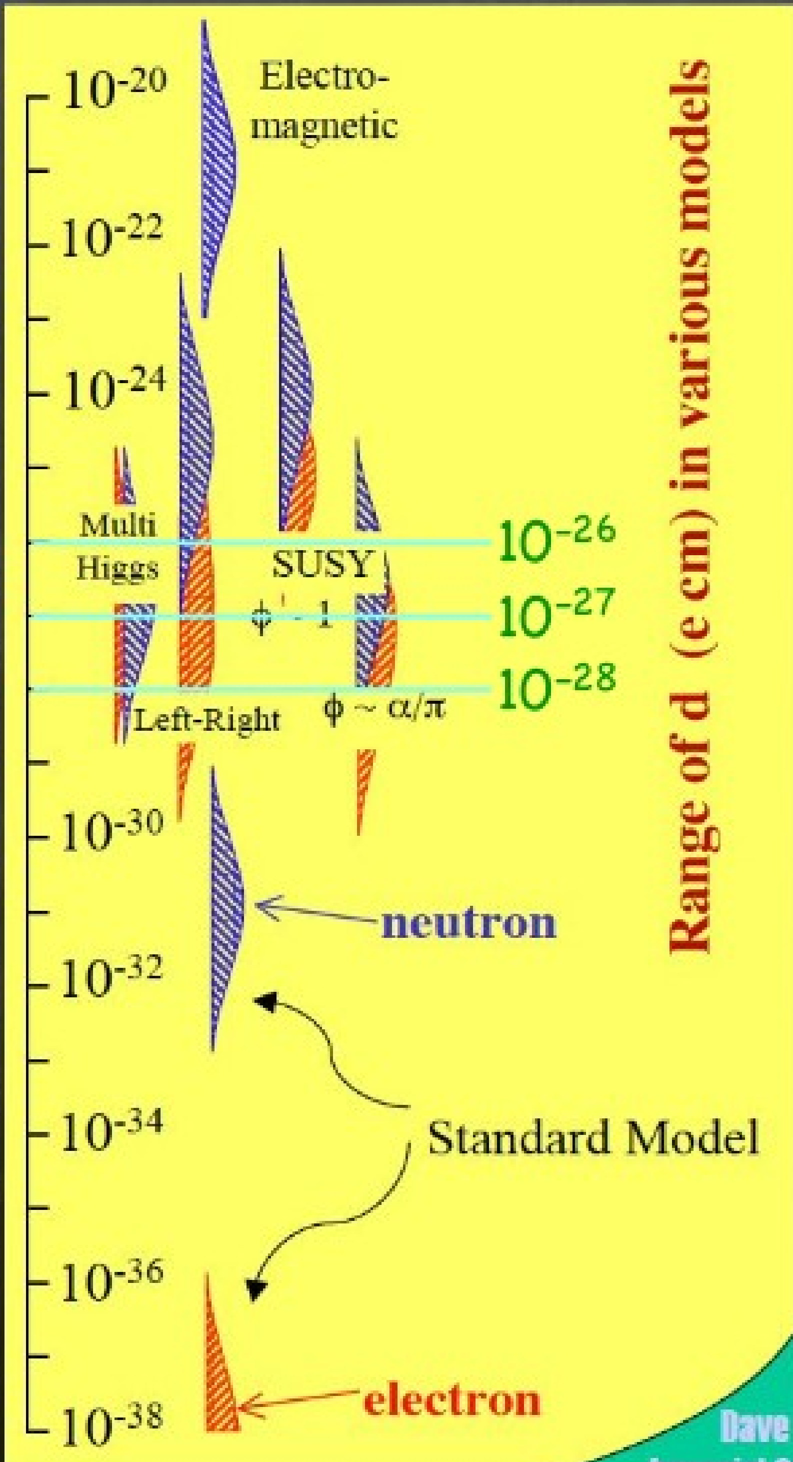
all of them were done at ILL, Grenoble

# Future UCN Experiments

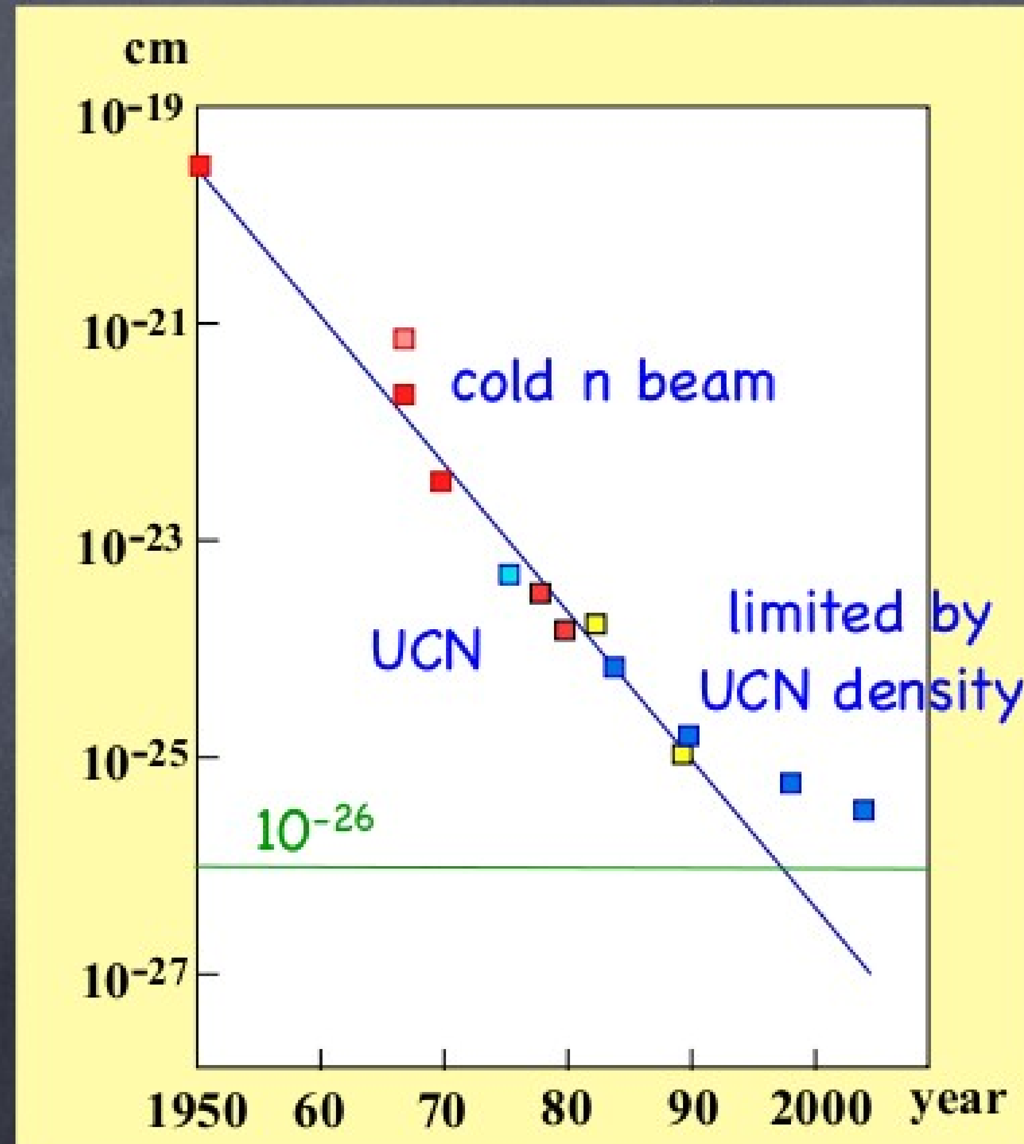
- EDM
  - in vacuo (PSI)
  - in 4He/3He (SNS)
  - ILL
  - KEK
- Lifetime
  - gravito-magnetic bottle (LANL)
  - magnetic bottle in 4He (SNS)
- Gravity Levels
  - ILL with new 4He source
- $\beta$-Decay Correlations (A)
  - UCNA (LANL)
- r-process, free neutron target
- nnbar oscillations
- mirror neutrons
- surface physics
- physics of UCN production
  - e.g. O2

# EDM history

Theory

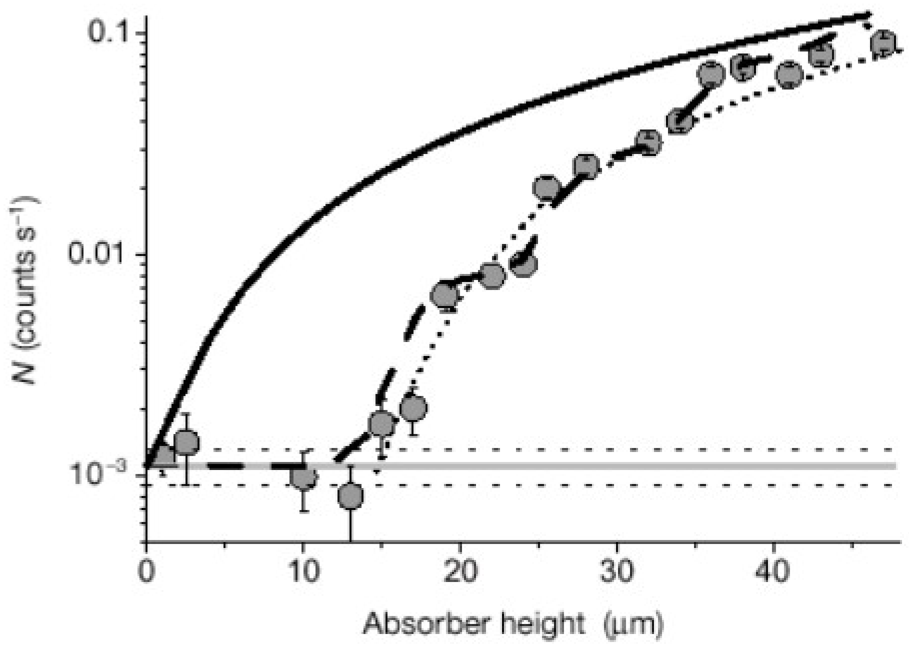


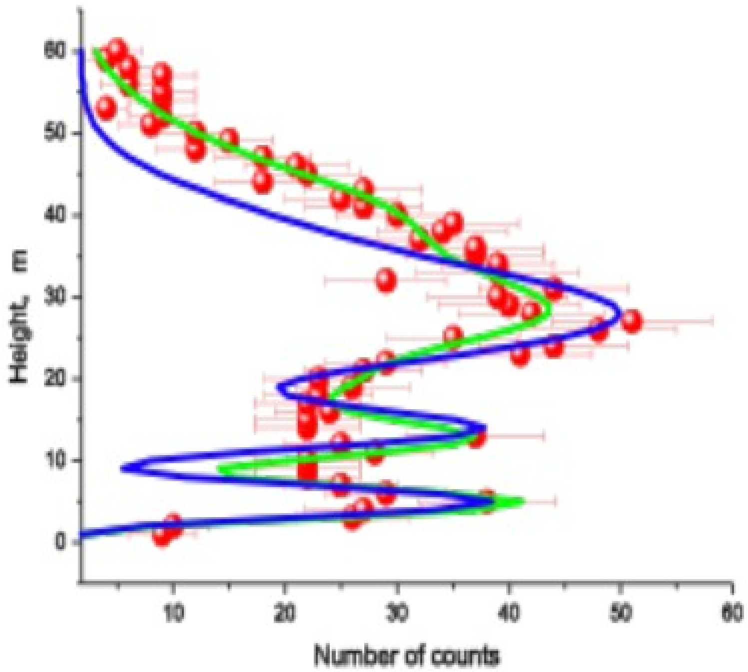

Experiment

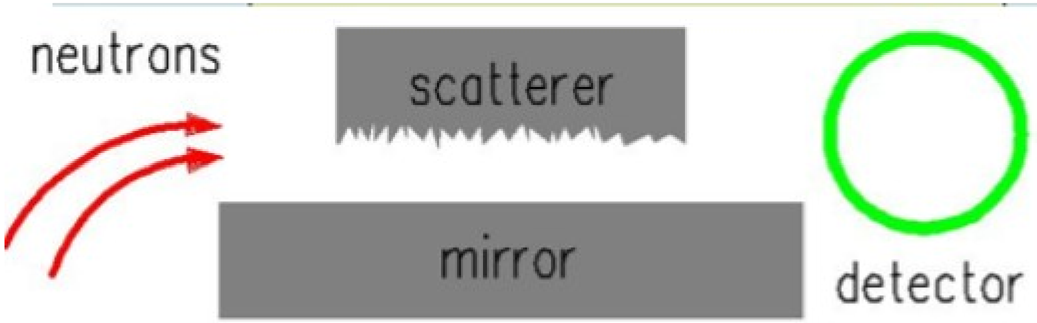


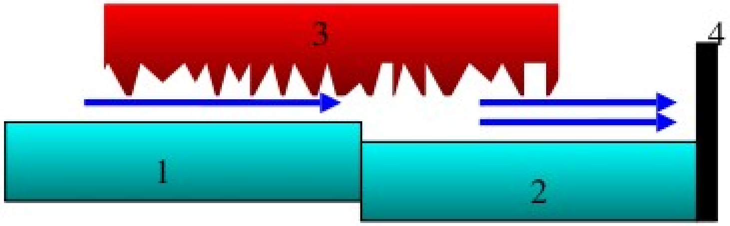
# UCN quantum states in gravity

- test of gravity at 10 um scale



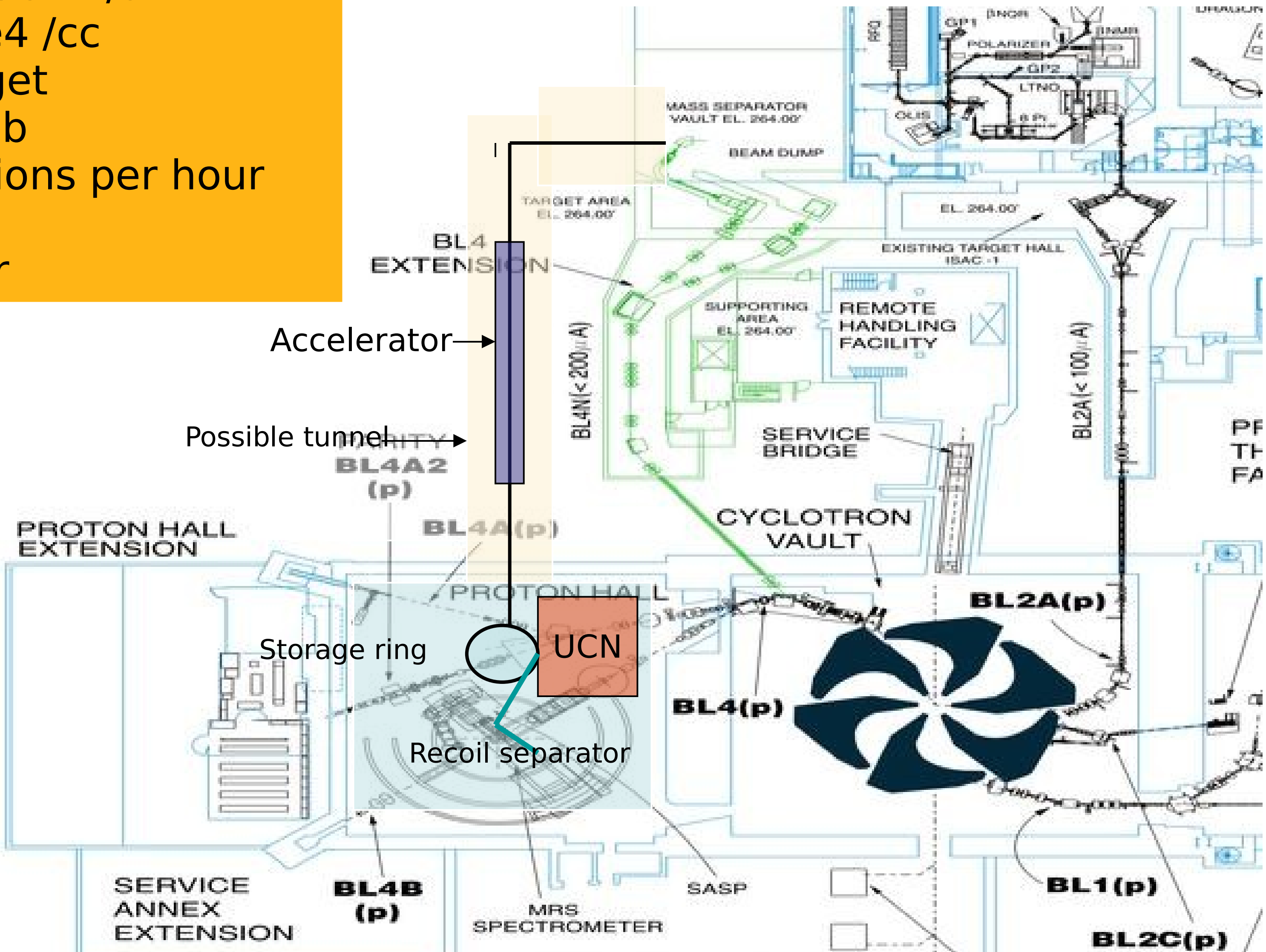



# Measuring (n,ɣ) cross sections of the r-process (Buchmann)

132Sn stored in ring interacts with free neutron (UCN) target.

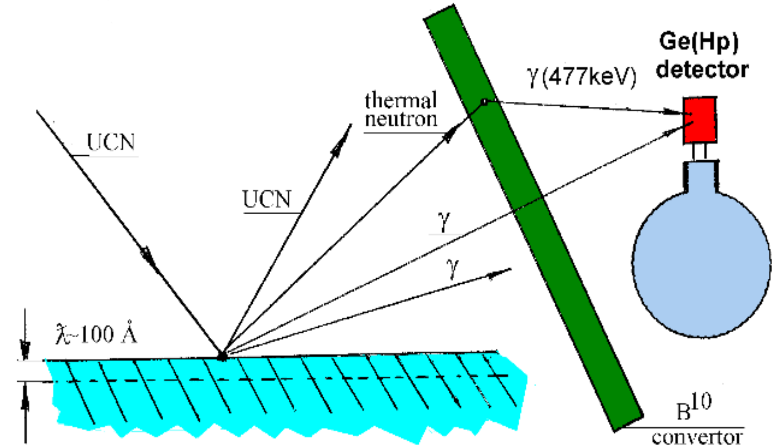
132Sn current 5e17 /s
UCN density 2e4 /cc
meter-long target
sigma ~ 100 mb
=> 50 interactions per hour

recoil separator



# Surface Physics

- Many ideas to use UCN to study 10 nm thin surface films
  - (n,gamma)
  - UCN loss measurements
  - n scattering
  - reflectometry
    - polarization for magnetic films




Korobkina, NCSU

- shown to be sensitive to low-frequency excitations (interesting for surface physics)
- In all cases, lack of UCN worldwide is the problem

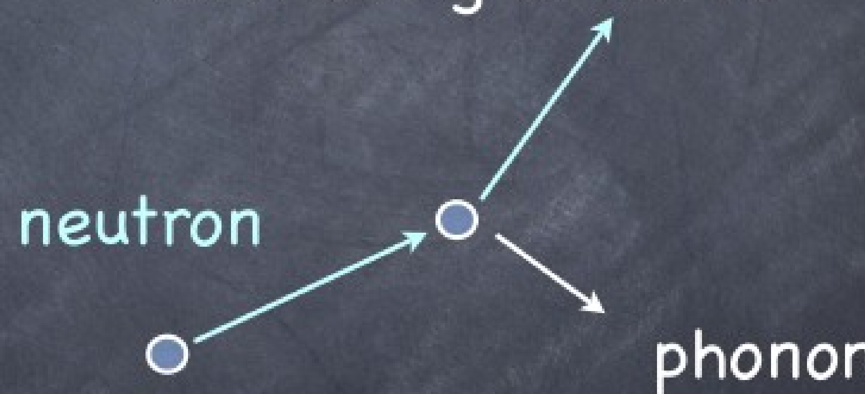
# UCN Source Design and How We Would Achieve the World's Highest UCN Density

- Most other proposed sources use solid deuterium (ortho) at ~4K
  - ice quality
  - material potential
  - para fraction, H-contamination
- We would use superfluid He-II (Masuda et al PRL)
  - lower specific production
  - NO loss mechanisms.

# Superthermal UCN production in He-II


M.R. Gibbs et al. (1999)

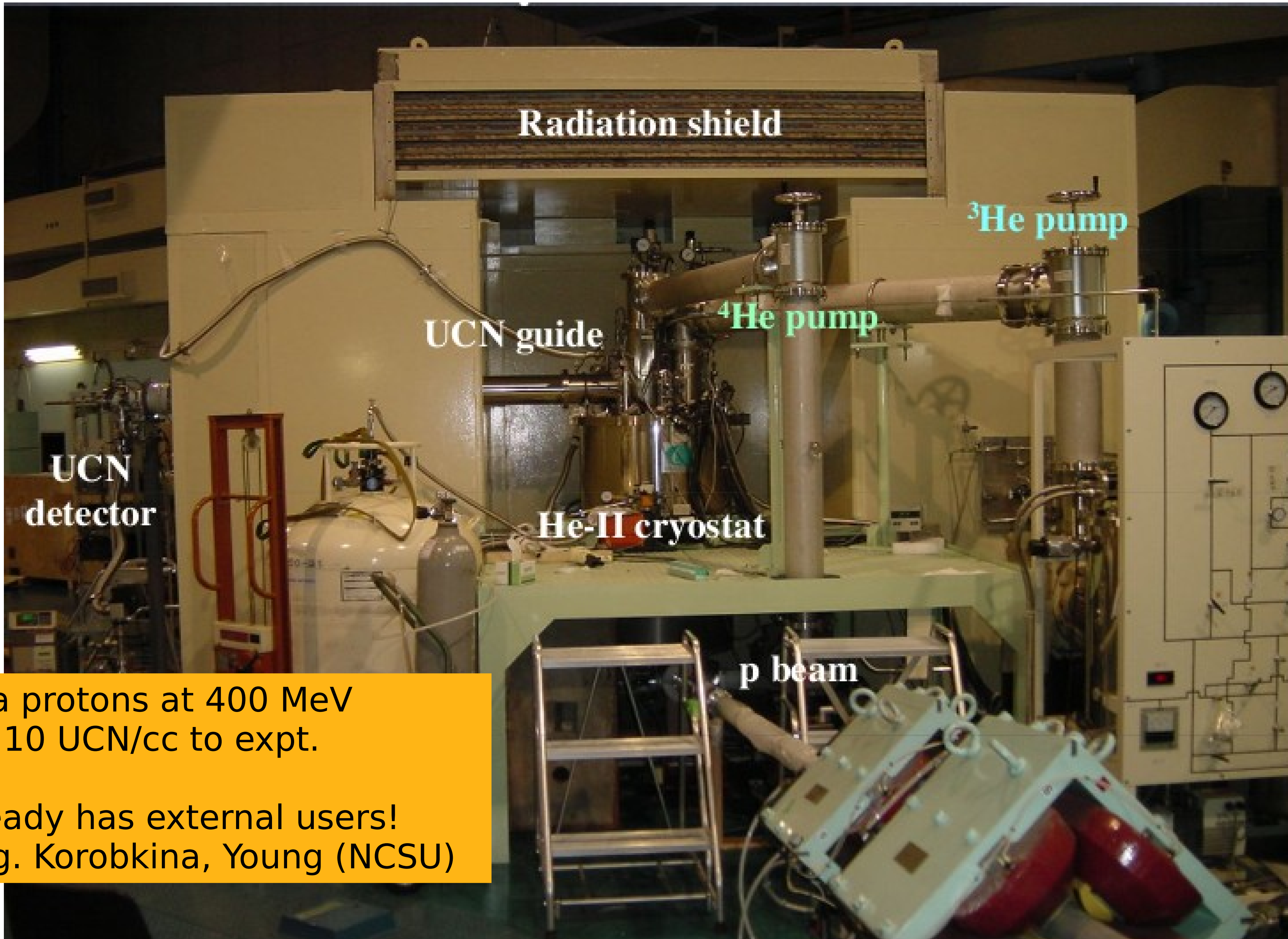
Coherent inelastic neutron scattering in He-II




Born approximation

$$d^2\sigma/dQd\omega$$
$$= k_f/k_i\, a^2\, S(Q,\omega)$$
$$= \sigma_{coh}/4\pi \cdot k_f/k_i \cdot S(Q,\omega)$$

# RCNP UCN Source (Masuda, et al)




1 ua protons at 400 MeV
=> 10 UCN/cc to expt.

Already has external users!
- e.g. Korobkina, Young (NCSU)

# Gain Factors for TRIUMF

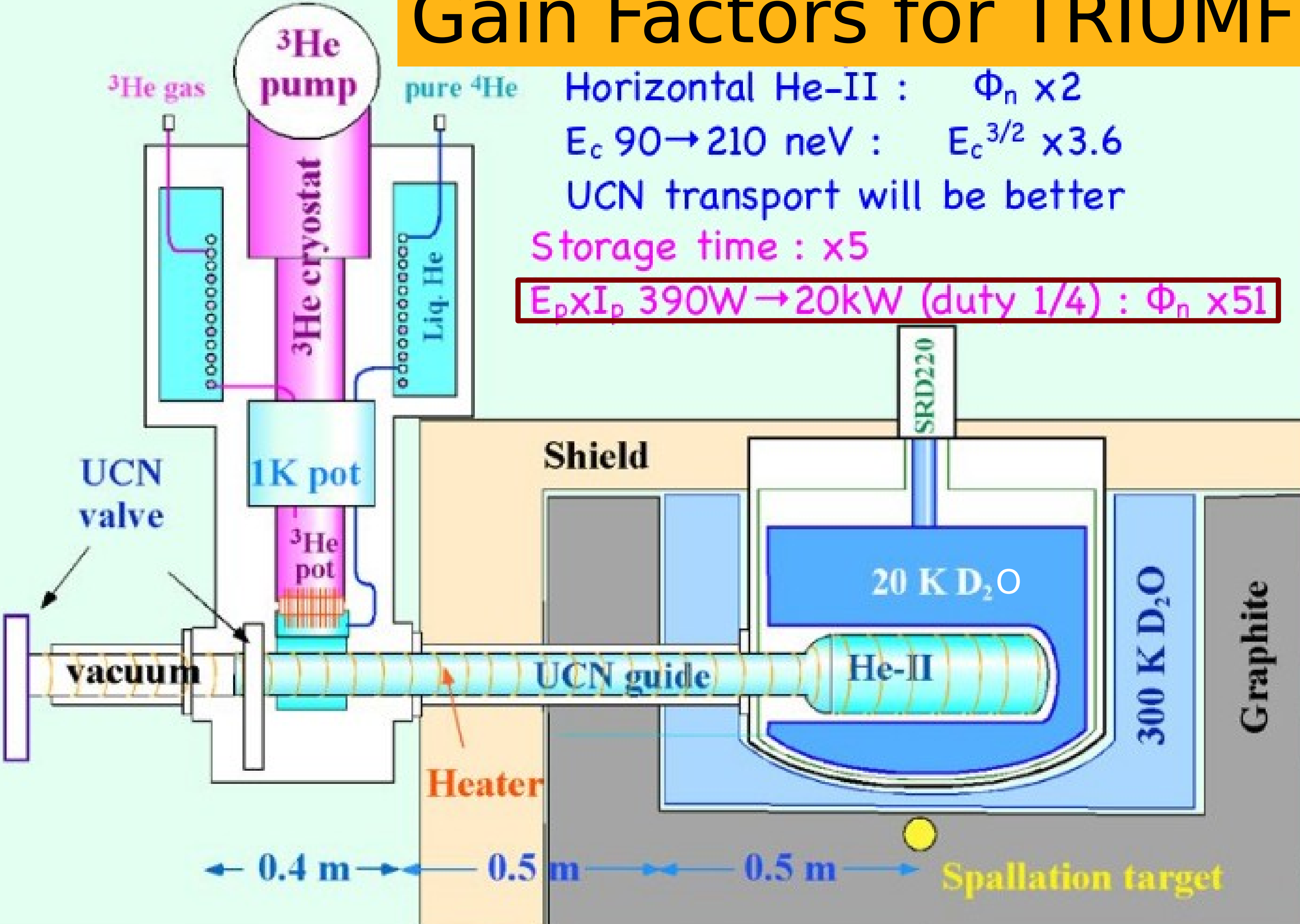
Horizontal He-II : $\Phi_n$ x2

$E_c$ 90→210 neV : $E_c^{3/2}$ x3.6

UCN transport will be better

Storage time : x5

$E_p x I_p$ 390W→20kW (duty 1/4) : $\Phi_n$ x51



# Recent Progress on UCN at TRIUMF

- Aug. 2007 TUG working group (Canadians + Masuda), draft of white paper.
- Sept. 2007 International UCN Workshop (+ world experts).
- Sept. 2007 Presentation to Agency Committee on TRIUMF (ACT)
- Oct.-Nov. 2007 phone meetings relating to conceptual design
- Nov. 2007 ACOT

My old advertisement slide...

# International Workshop: UCN Sources and Experiments

September 13-14, 2007
TRIUMF, Vancouver, Canada
http://www.triumf.info/hosted/UCN

~25 speakers from all over the world
ILL, FRM-II, NCSU, LANL, PSI, KEK, Mainz, ...

Supported by TRIUMF and TUNL

# Speakers at TRIUMF UCN Workshop Sept. 13-14, 2007

H. Abele, Heidelberg

S. Baessler, Mainz/UVa

L. Buchmann, TRIUMF

M. Daum, PSI

S. Gardner, U. Kentucky

P. Geltenbort, ILL

E. Gutsmiedl, Munich FRM-II

R. Golub, NCSU

B. Filippone, Caltech

P. Huffman, NCSU

T. Ito, LANL

E. Korobkina, NCSU

C.-Y. Liu, Indiana U.

M. Makela, LANL

J.W. Martin, U. Winnipeg

Y. Masuda, KEK

P. Mumm, NIST

J. Nico, NIST

J. Ng, TRIUMF

M. Pospelov, U. Victoria/Perimeter Inst.

J.-M. Poutissou, TRIUMF

W.M. Snow, Indiana U.

F. Wietfeldt, Tulane U.

A. Young, NCSU

G. Hampel, Mainz

K. Hickerson, Caltech

# Results of Workshop

- Very strong statement from the international UCN community (particularly R. Golub) that a He-II source should be pursued.  Masuda clearly regarded as a leader in this field.
- TRIUMF would be an ideal venue for such a source.
- Many interesting physics experiments would be possible with the higher UCN densities achievable at this source.

# Schedule

- Prior to 2010, pursue development of new UCN cryostat for TRIUMF at RCNP, Osaka.
  - This would allow us to demonstrate all the gain factors from horizontal extraction, better UCN guides. (aside from beam power)
- After 2010, begin construction of UCN source at TRIUMF (2010 = coincident with major reconstruction for ISAC 3).

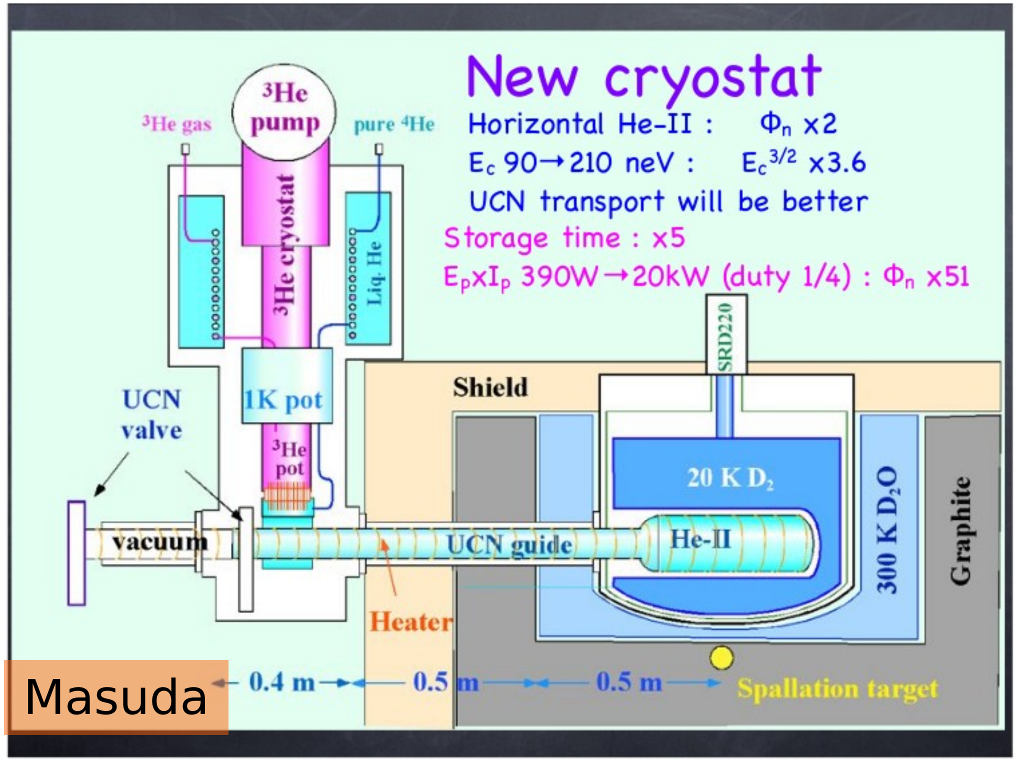
# Experimental Plan

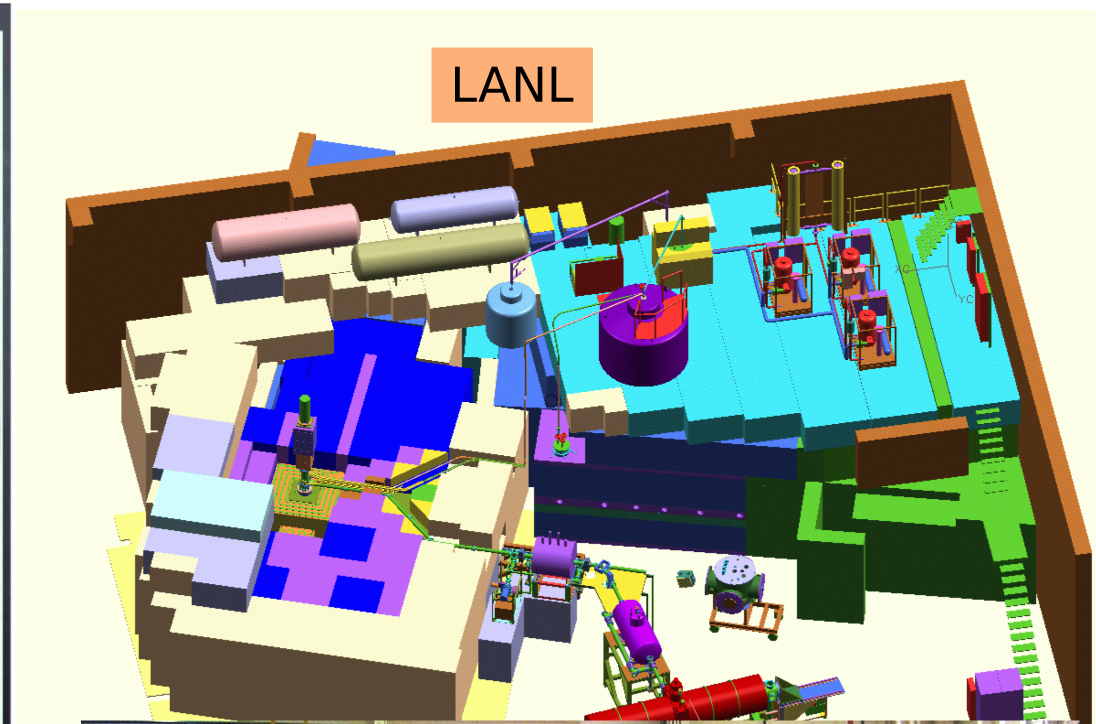
- Conduct one initial high-profile, world's best, fundamental physics experiment (likely either n-lifetime or gravity)
- Simultaneous development of surface physics apparatus
- Developments towards future n-EDM experiments
- Other large-scale experiments and transition to JPARC.

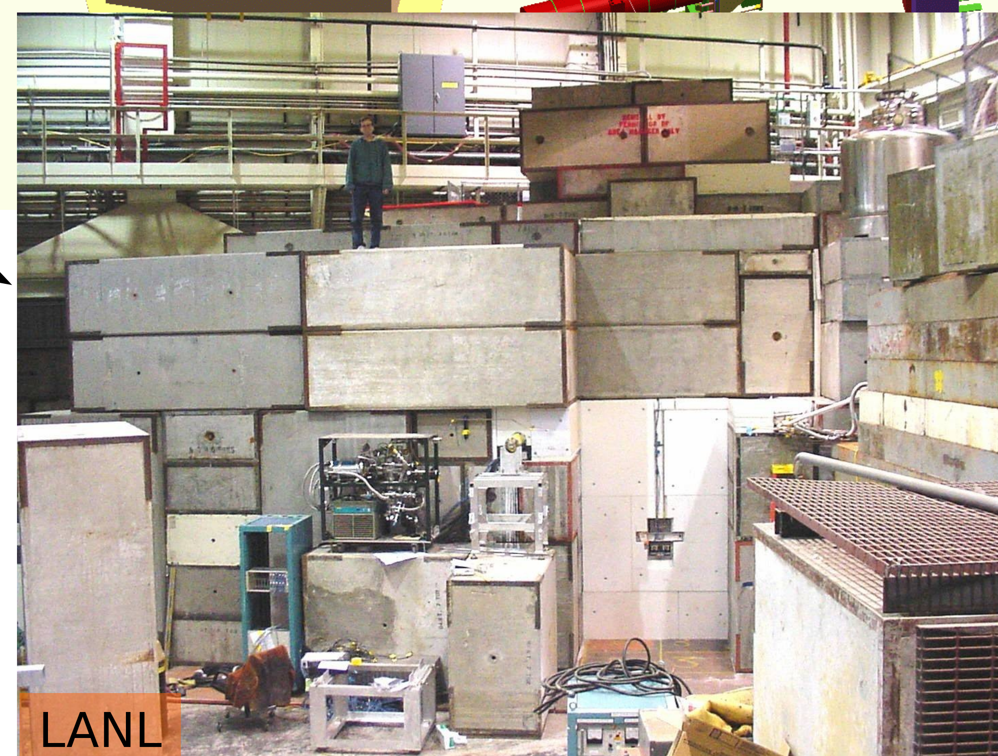
# Technical Issues for UCN

- Location.
- Beam sharing.
- Space (12m x 12m source + 12m x 6m expts)
- To carry out precision experiments, it is highly advantageous to pulse the UCN source. E.g. RCNP uses 1 min beam on, 3 mins beam off. During beam off, UCN can be counted (or their decays, etc.)
  - pulsing at ion source incompatible with other users.
  - achieve pulsing by diverting beam to well-shielded dump using kicker.

# Conceptual to technical design for the UCN source and experiment

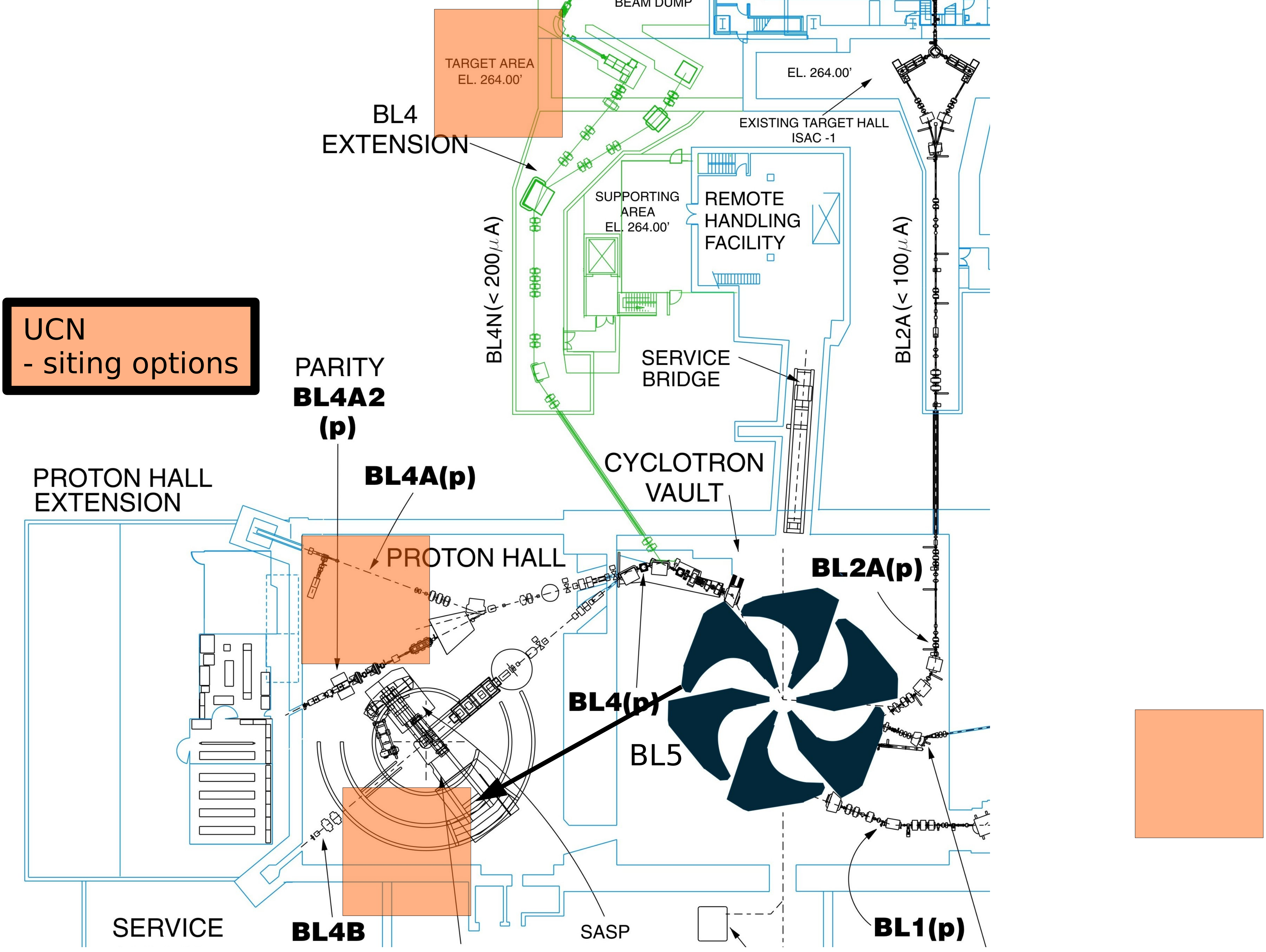



Other Issues:

- radiation, remote handling
- cryogenics
- neutronics
- division of tasks
    - Masuda, Golub, others? very interested in cryogenics and neutronics
    - need TRIUMF support to bring to fruition


UCN
- siting options
BEAM DUMP
TARGET AREA
EL. 264.00'
BL4
EXTENSION
EL. 264.00'
EXISTING TARGET HALL
ISAC -1
SUPPORTING
AREA
EL. 264.00'
REMOTE
HANDLING
FACILITY
BL4N(< 200$\mu$A)
BL2A(< 100$\mu$A)
SERVICE
BRIDGE
PARITY
BL4A2
(p)
CYCLOTRON
VAULT
PROTON HALL
EXTENSION
BL4A(p)
PROTON HALL
BL2A(p)
BL4(p)
BL5
SERVICE
BL4B
SASP
BL1(p)

# Cost

- Cryostat, LHe cooling costs very well-understood (1.4 M$ CAD)
- Masuda request to Japanese funding sources for 2.4 M$ CAD over the next four years (the above plus EDM development) explicitly mentions TRIUMF. (submitted Nov. 2007)
- Interest in submitting a CFI proposal from the Canadian groups in 2008 for the remaining infrastructure.

# Summary

- An opportunity exists to create the world's highest density UCN source at TRIUMF
- A flagship physics experiment done this facility would be world's best
- The UCN facility would be tied to the ISAC-3 program in terms of both physics and facility
- We would like to pursue this unique and timely opportunity

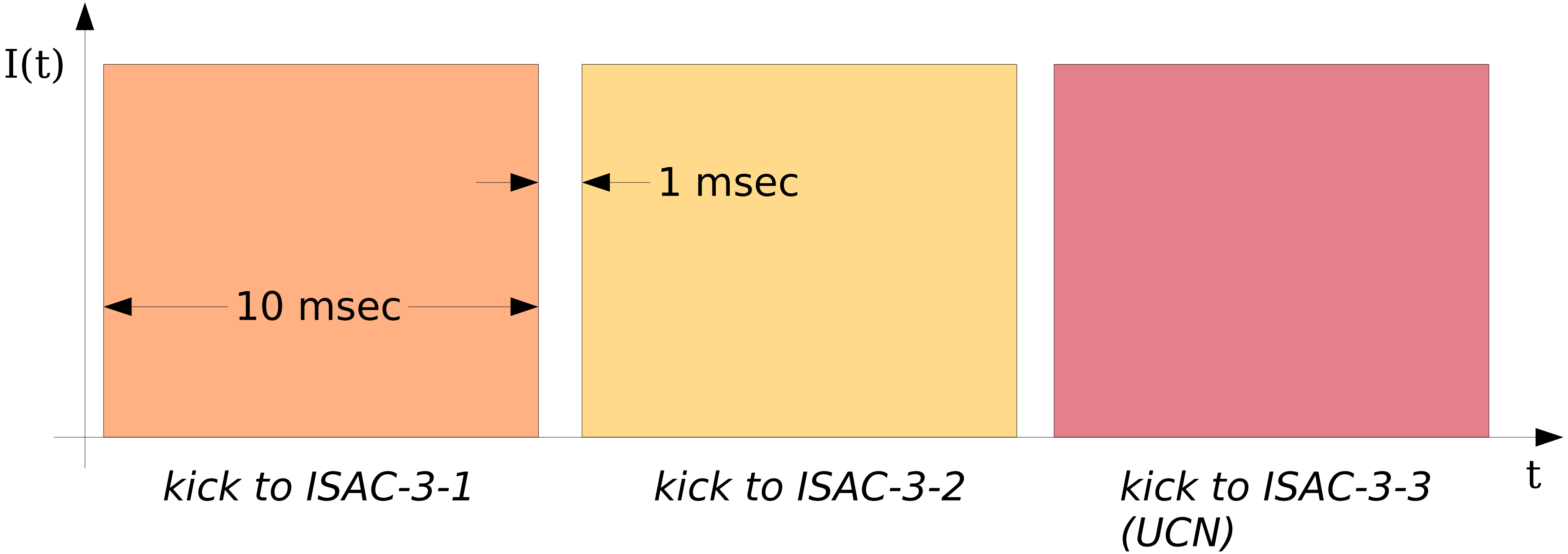
# Back-ups

# Cryogenics/Shielding Numbers from Masuda

- According to MC + estimates, for time-avg p-beam power of 12 kW in W target:
  - 0.45e12 n/cm2/s in He-II
  - 2.3 W in He-II
  - 30-60 W in 20 K D2O
  - 1.7 kW in 300 K D2O
- Masuda's current 3He pump can take 8 W.
- Clever arrangement of 208Pb can reduce gamma-heating of He-II even lower.
- Radiation #'s consistent/lower cf. LANL.

simultaneous operation with ISAC-3 by decoupling on kHz scale with kicker/ion source manipulation. Advantageous for ISAC-3: run all three targets simultaneously.

# ion source current vs. time



# Solutions Discussed for Technical Issues

- Location:
  - BL5 area
    - Advantages:
      - decoupled from ISAC 3.
    - Disadvantages:
      - new beam port must be constructed
      - beam line must not conflict with cyclotron probe extraction point
      - high-power dump required to achieve pulsing with kicker.
      - space in Proton Hall tighter – likely requires excavation for dump.

Shameless advertising

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Aug. 1

morning - plenary session, charge, and introduction of working groups

12:00 lunch

13:00 Welcome + Charge (Martin) (10+5)
13:15 UCN Sources Worldwide and for TRIUMF (Masuda) (45+10)
14:10 Photofission, (gamma,n) Sources and UCN (Behr) (10+10)
14:30 coffee (30)
15:00 SCRF joint session: Electron Linac Design (Koscielniak) (20+10)
15:30 UCN Infrastructure and Proton Hall Floorplan (Davis) (10+10)
15:50 Proton Hall Radiation Limits (Trudel) (10)
16:00 Discussion (Chair: Davis) (30)
16:30 tour of proton hall? (if desired) (Davis) (30)

# Agenda
from townhall meeting (Aug. 07)

Aug. 2

09:00 Continued infrastructure Discussion (60)
10:00 UCN Physics Intro (Martin) (10+5)
10:15 UCN Beta Decay (Melconian) (20+10)
10:45 coffee (30)
11:15 n-EDM (Masuda and/or Hayden?) (20+10)
11:45 radioactive beams (Buchmann) (10+10)

12:05 lunch

13:15 gravity levels (Konaka) (5+10)
13:30 other physics (Martin) (15+10)
13:55 discussion of physics priorities and strategy (chair: Martin) (35)
14:30 begin writing
- more joint sessions
- draft Aug. 3 morning presentation

Aug. 3

morning - presentations of results from the working groups.

# Outline of White Paper

- Physics
  - prioritized and realistic, as much as possible
- UCN Source
  - proposed intensity at TRIUMF
  - world context and relevance
- Required Infrastructure
  - floorspace, shielding
  - duty cycle
  - He liquefier
- Required funding
  - CFI and collaboration, and international