Fundamental Neutron Physics with Long-Pulsed Spallation Sources

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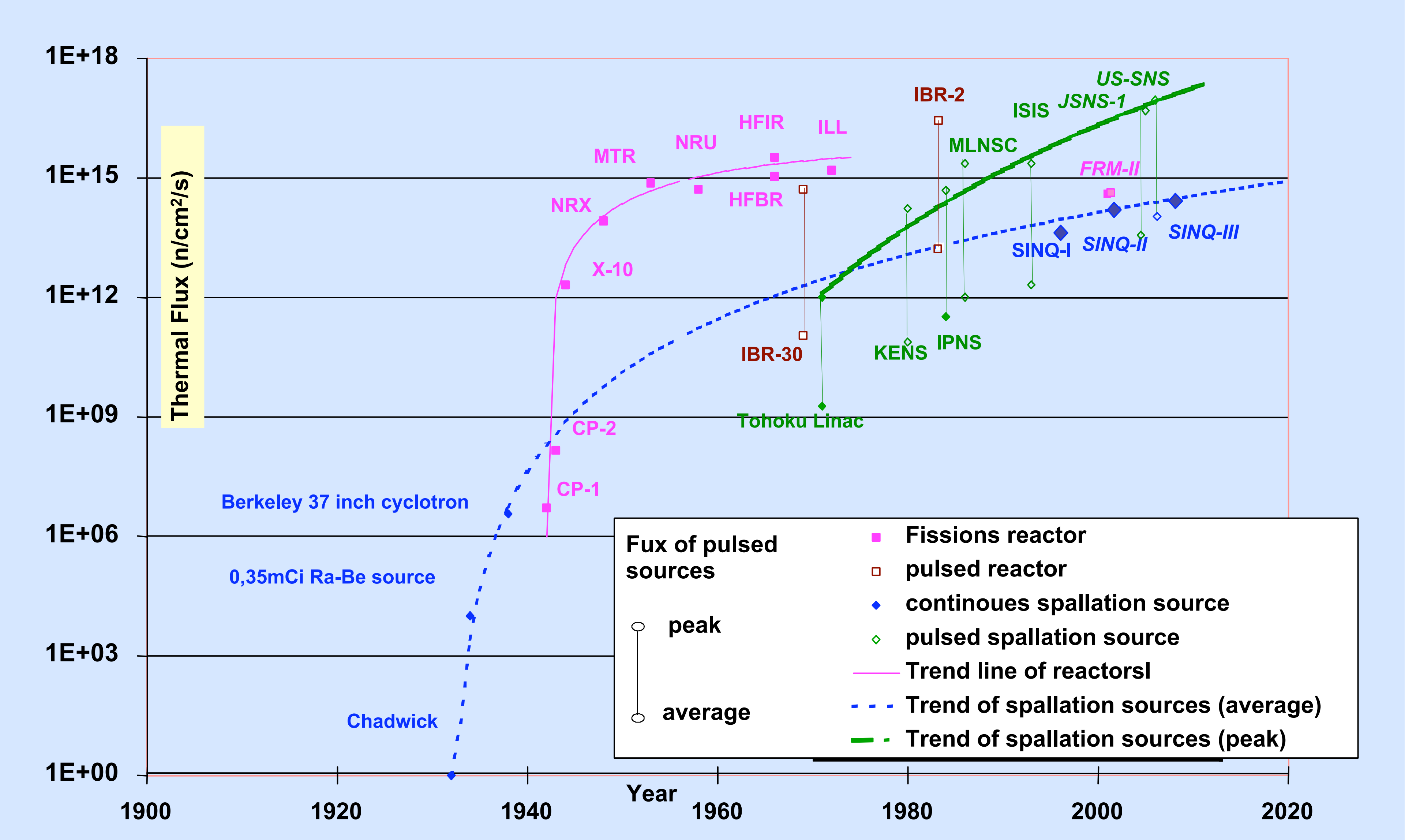
1. What is a long-pulsed spallation source and why do it?
2. Advantages of a LPSS for fundamental neutron physics
3. Examples of slow neutron experiments that can benefit from LPSS
4. Ultracold neutrons

Thanks for slides from: R. Eichler, F. Mezei, K. Andersen, D. Dubbers, T. Yamada, B. Maerkisch, S. Baessler, G. Greene, T. Jenke,…

Neutron flux is increasing only slowly with time. What is the best next step to take?



R. Eichler, PSI

ILL Reactor Neutron Source

- Highly-enriched uranium
- Compact design for high brightness
- Heavy-water cooling
- Single control rod
- 57MW thermal power

K. Andersen

Further brightness increases are difficult: the core starts to melt

Energy efficiency is key for high intensity neutron beam production

Fast neutrons produced / joule heat deposited in target station

Fission reactors:	$\sim 10^{9}$	(in ~ 50 liter volume)
Spallation:	$\sim 10^{10}$	(in ~ 2 liter volume)
Fusion:	$\sim 1.5\times10^{10}$	(in ~ 2 liter volume) (but neutron slowing down efficiency reduced by ~20 times)
Photo neutrons:	$\sim 10^{9}$	(in ~ 0.01 liter volume)
Nuclear reaction (p, Be):	$\sim 10^{8}$	(in ~ 0.001 liter volume)
Laser induced fusion:	$\sim 10^{4}$	(in ~ 10^{-9} liter volume)

Spallation: most favourable for the foreseeable future

Neutron Production in Spallation

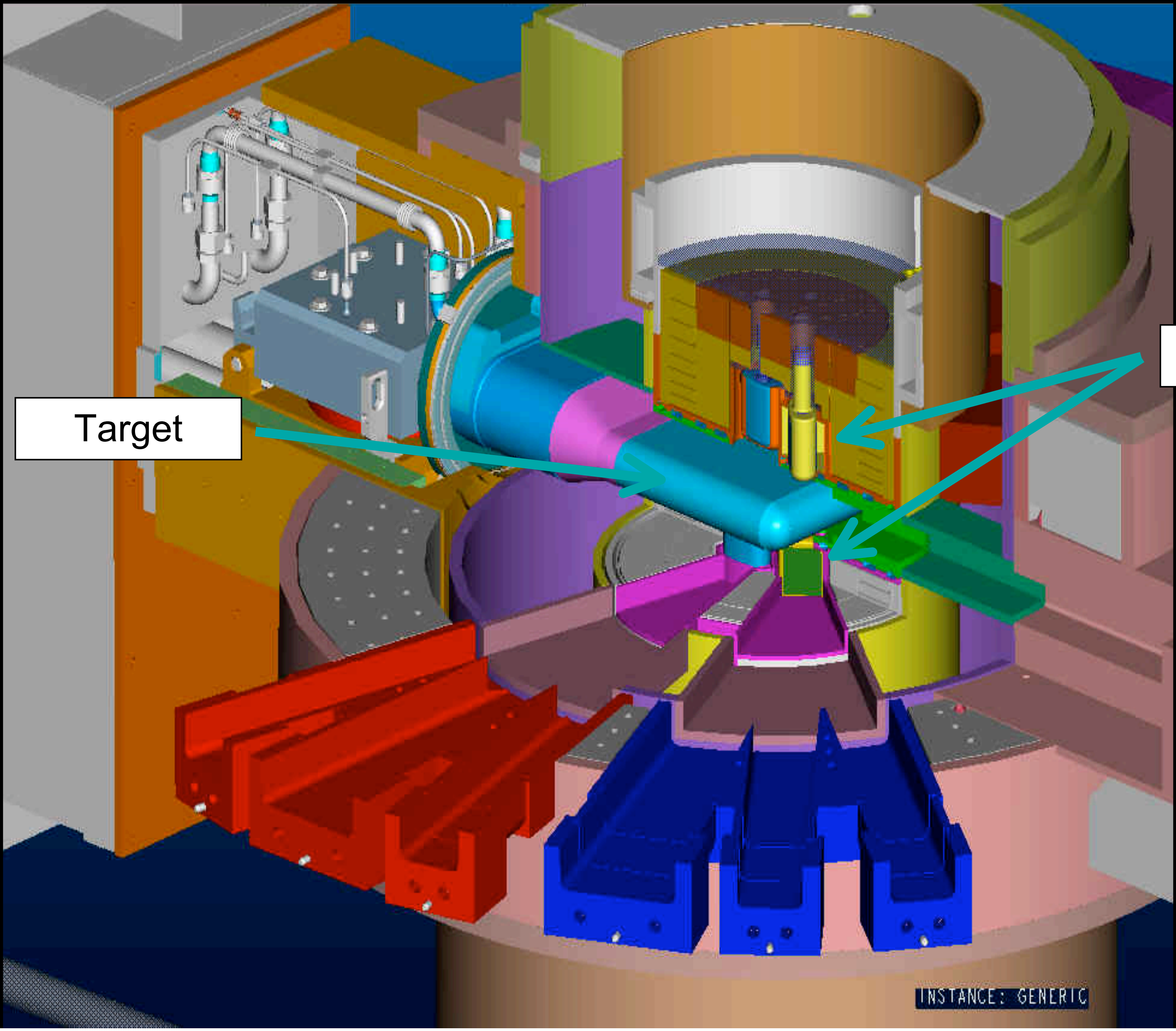
Complicated nuclear reaction process involving high energy (~1 GeV) proton reactions on heavy nuclei.

Highly excited nuclei "evaporate" by emitting neutrons, again with about ~ 2 MeV energies as in fission, but there is also a high energy component

~20 neutrons/ 1 GeV proton

~60% of proton beam energy appears as heat in the target

->spallation dissipates ~30 MeV heat per useful neutron, better than fission by almost an order of magnitude



Target

Moderator

Energy and Angular Distributions in Spallation

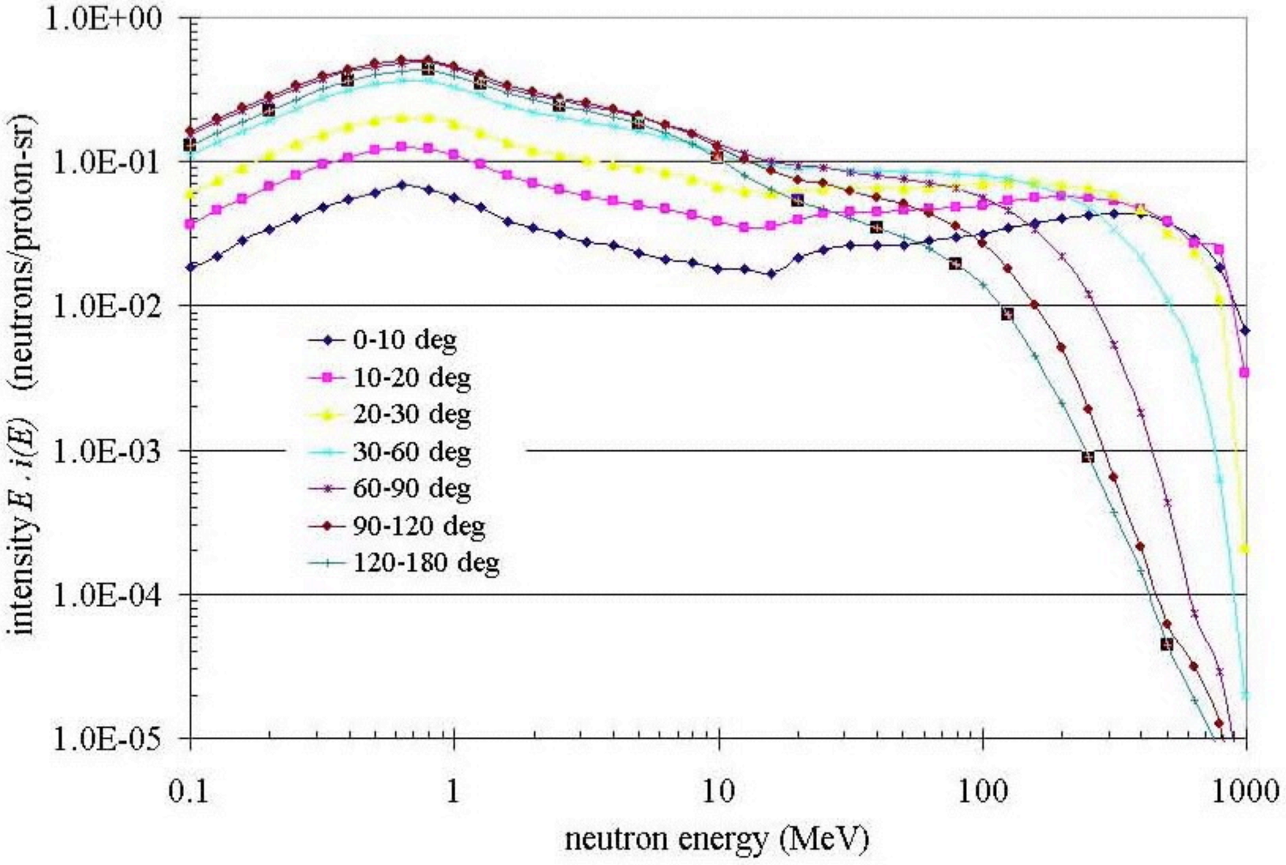
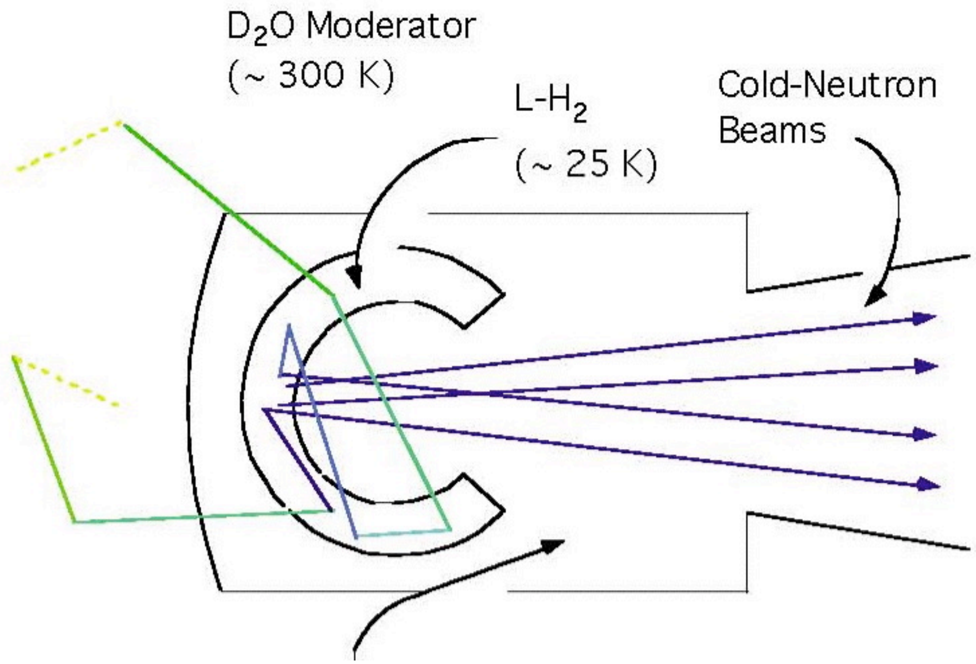


Figure 4. The energy and angular distribution of neutrons emerging from a tantalum target irradiated by 1-GeV protons. The target is 31 cm long, 7 cm wide and 20 cm high. Courtesy B. J. Micklich.

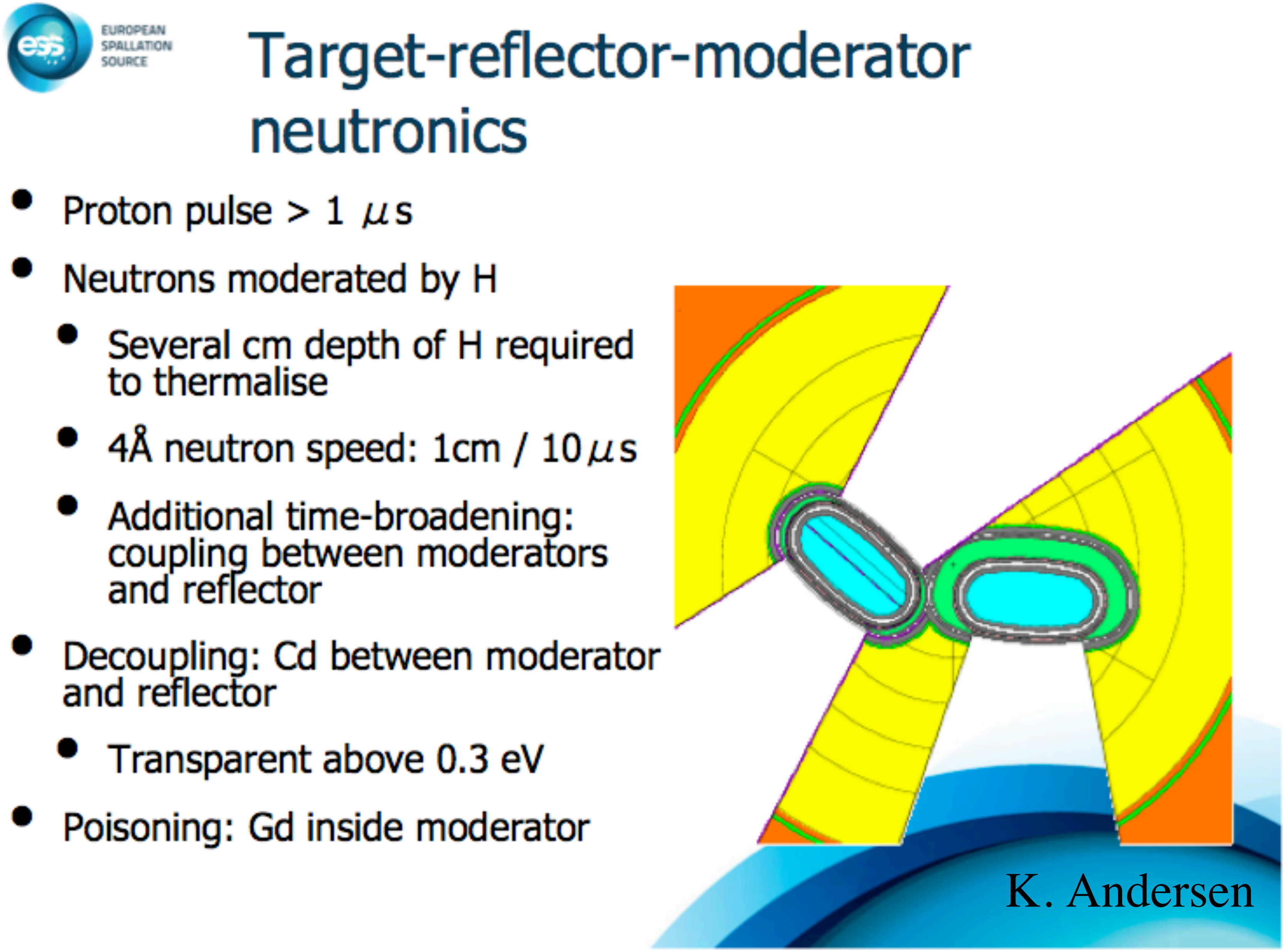
Spallation Target and Neutron Moderator

Serious
Spallation
target



A spallation neutron source does not possess the requirement to maintain the nuclear chain reaction -> greater degree of freedom in design of targets, neutron moderators, and neutron reflectors

Present pulsed spallation sources strive to produce narrow neutron pulse widths for high energy resolution using neutron time-of-flight



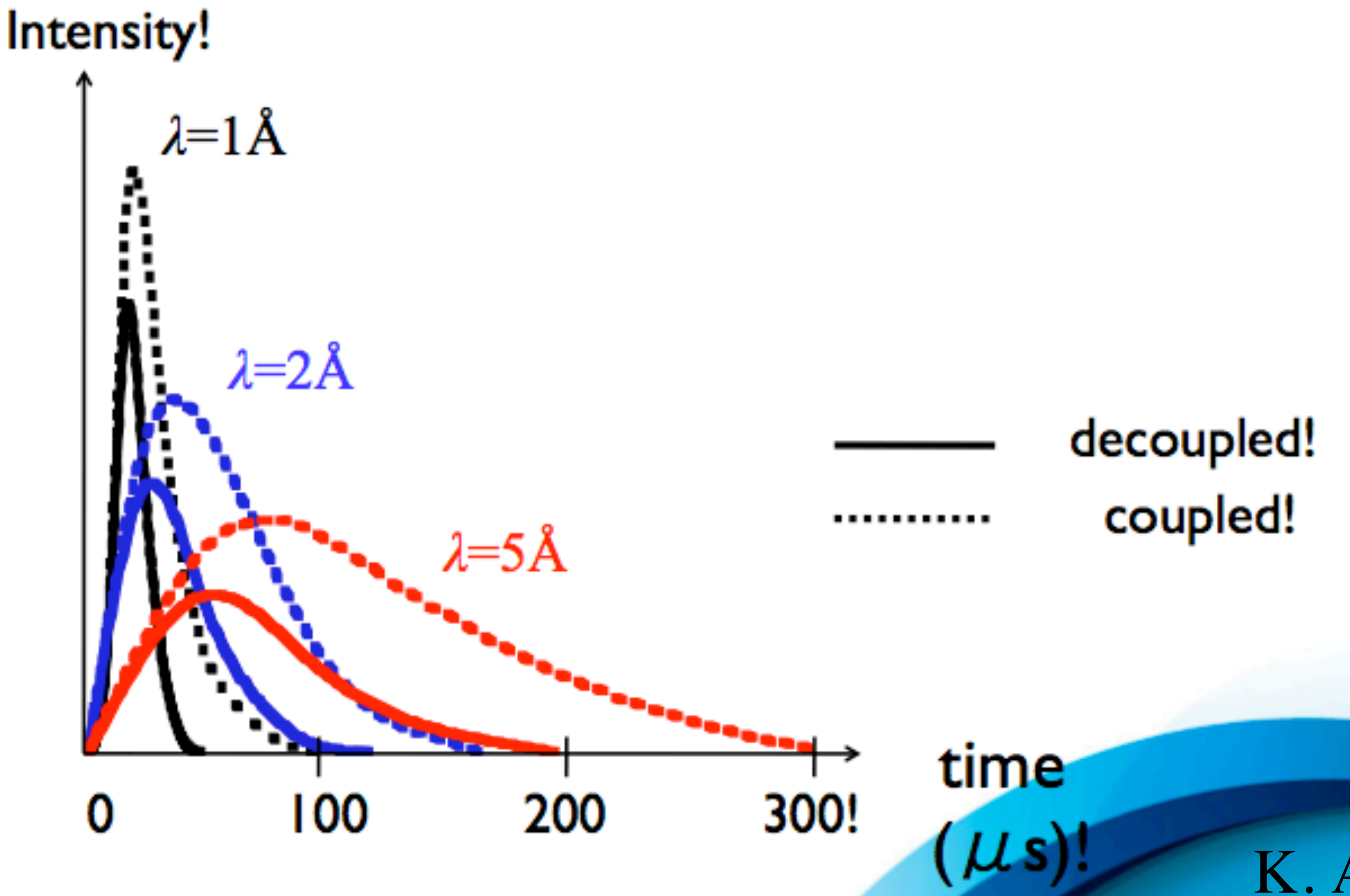
Target-reflector-moderator neutronics

- Proton pulse > 1 μs
- Neutrons moderated by H
  - Several cm depth of H required to thermalise
  - 4Å neutron speed: 1cm / 10μs
  - Additional time-broadening: coupling between moderators and reflector
- Decoupling: Cd between moderator and reflector
  - Transparent above 0.3 eV
- Poisoning: Gd inside moderator

K. Andersen

Neutron absorbers in the moderator! “killing the neutrons at birth”

Pulsed-Source Moderators



K. Andersen

Neutron absorption needed to sharpen pulses lowers intensity

Highest flux short pulse sources

SNS (Oak Ridge, USA)

J-PARC (Tokai Japan)

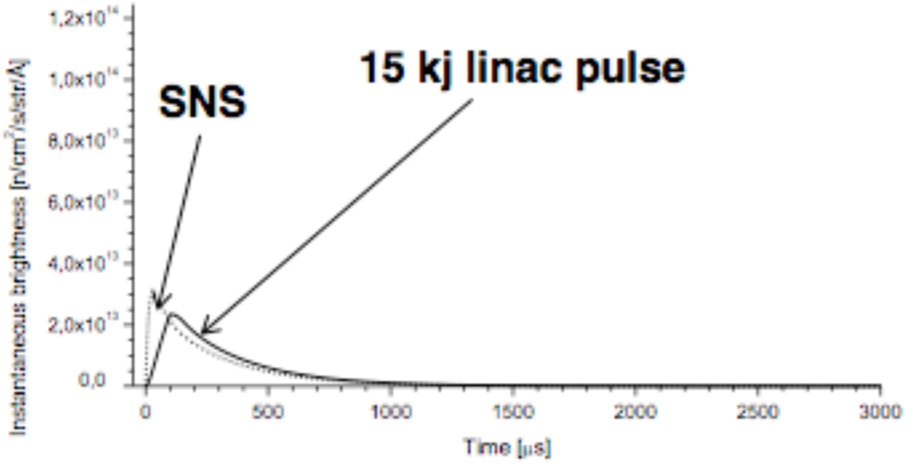
Instantaneous power on target (e.g. 1 MW at 60 Hz, i.e. 17 kj in ~1 μs pulses on target): **17 x**

→ **Pressure wave: 300 bar**

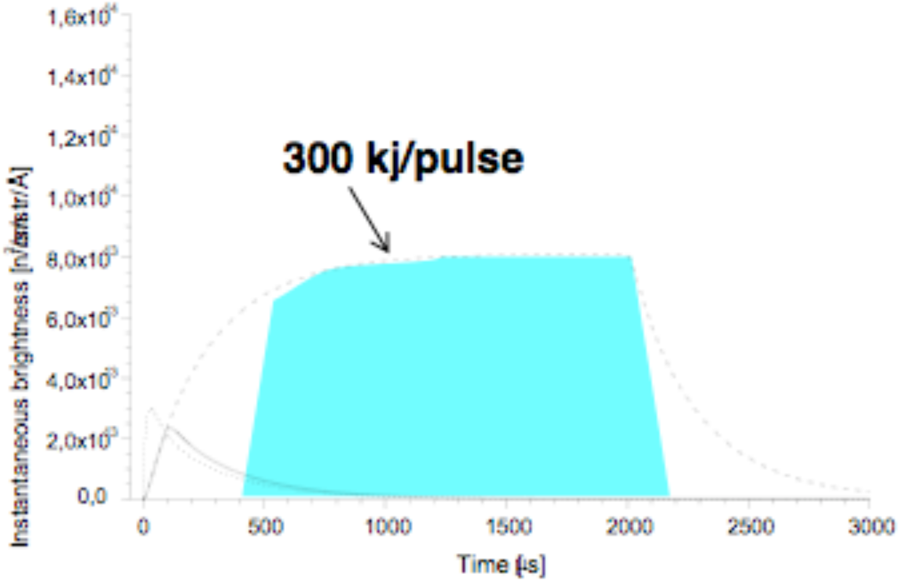
Reaches limits of technology

Highest flux short pulse sources

But:
Cost equivalent linear accelerator alone can produce the same **cold neutron pulses by ~100 μs proton pulses at ~ 0.15 GW instantaneous power: 2 x ILL**



Next generation: long pulses



Cost equivalent linear accelerator alone can produce the same cold neutron pulses **by ~100 μs proton pulses at ~ 0.15 GW instantaneous power** → Leave the linac on for **more neutrons per pulse and higher peak brightness…** and use mechanical pulse shaping

→ **Long Pulse source**

ESS: 5 MW accelerator power
→ **more neutrons for the same costs and reduced complexity**

F. Mezei

Long-Pulse Spallation Source: match proton linac pulse to n moderation time

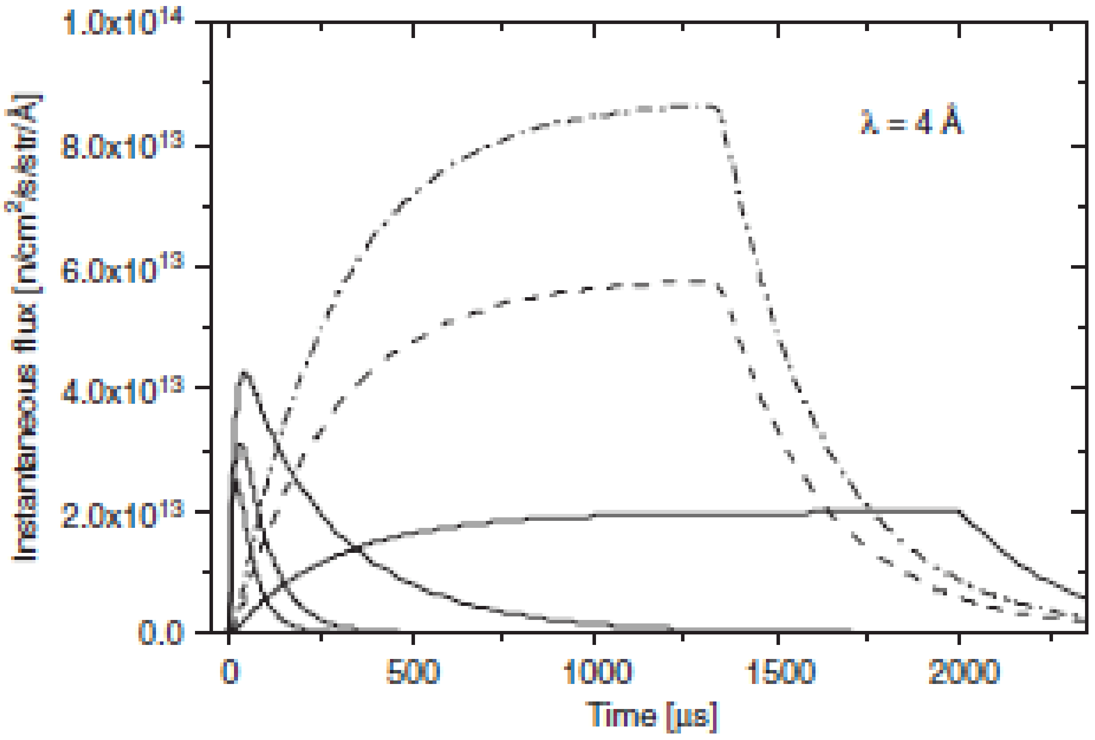


Fig. 1. Estimated cold neutron pulse shapes for the various moderator and pulse length options for ESS (continuous lines) and for an optimized long pulse source (dashed line). The dot-dashed line is explained in the text.

Matches the timescale for slow neutron thermalization/emission from 20K LH2 (<~1 msec) with the macropulse from the Gev proton linac (also~1 msec) to maximize neutron brightness

F. Mezei, NIM A562, 553 (2006).

Long-Pulsed Spallation Source: Increased Brightness for Cold Neutrons

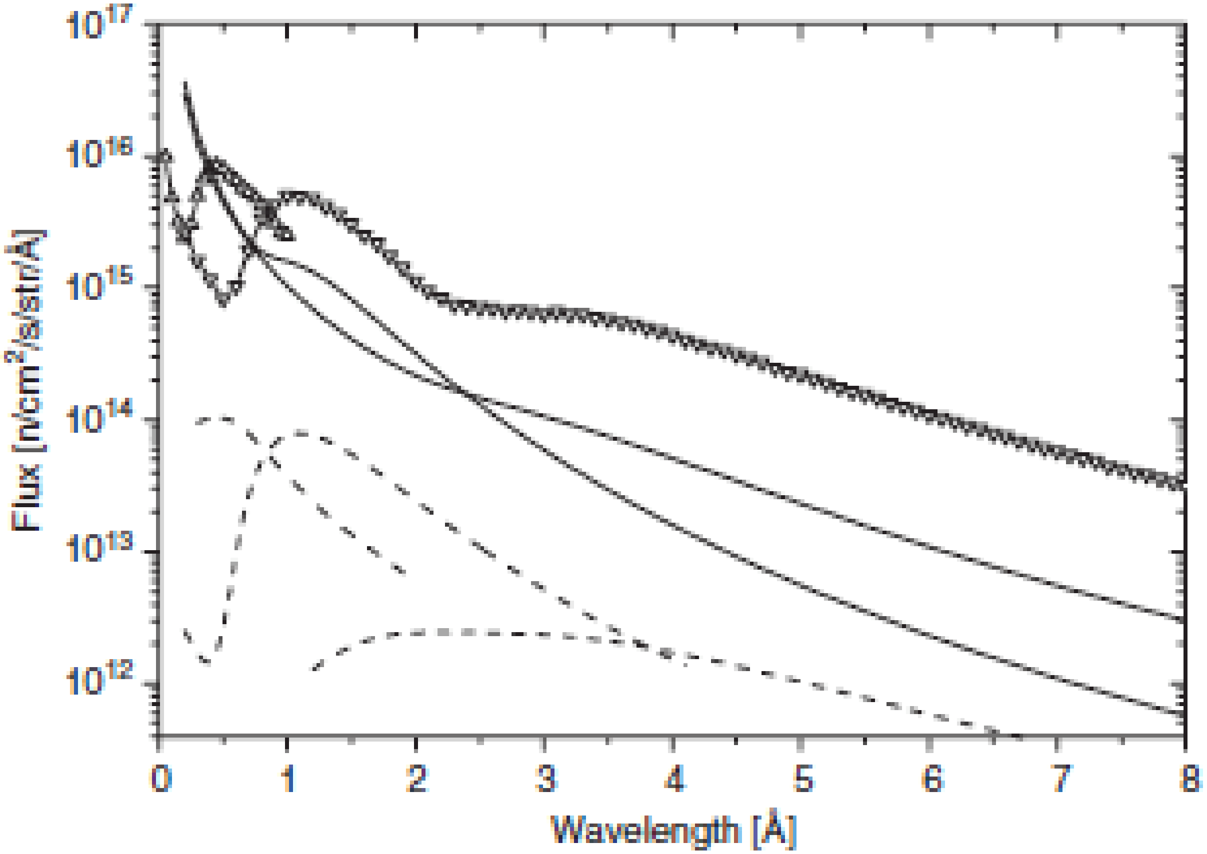
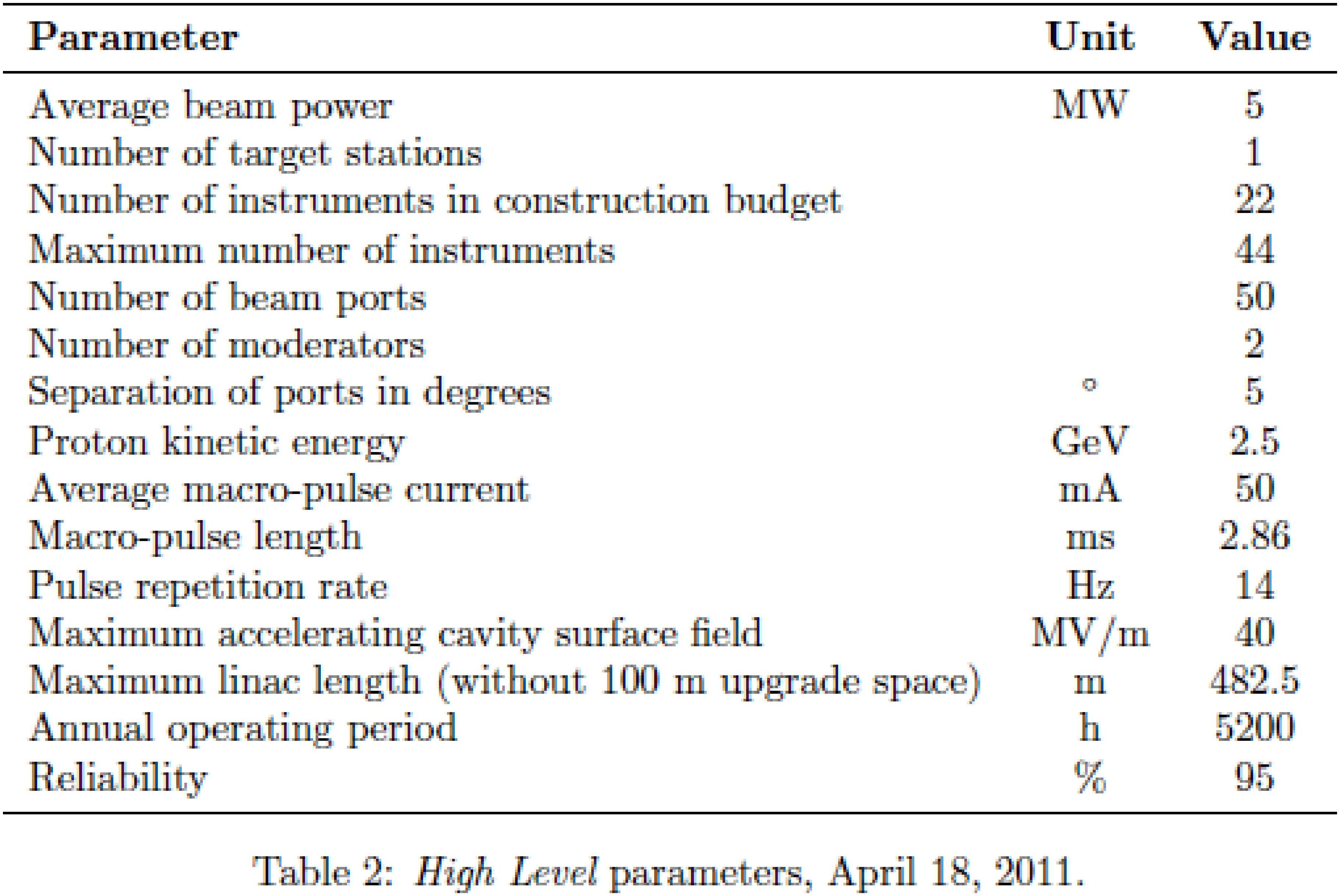


Fig. 2. Estimated peak neutron brightness as a function of wavelength for an optimized long pulse source (triangles) compared with moderator options at SNS (continuous lines) and ILL (dashed lines, steady state brightness).

F. Mezei, NIM A562, 553 (2006).

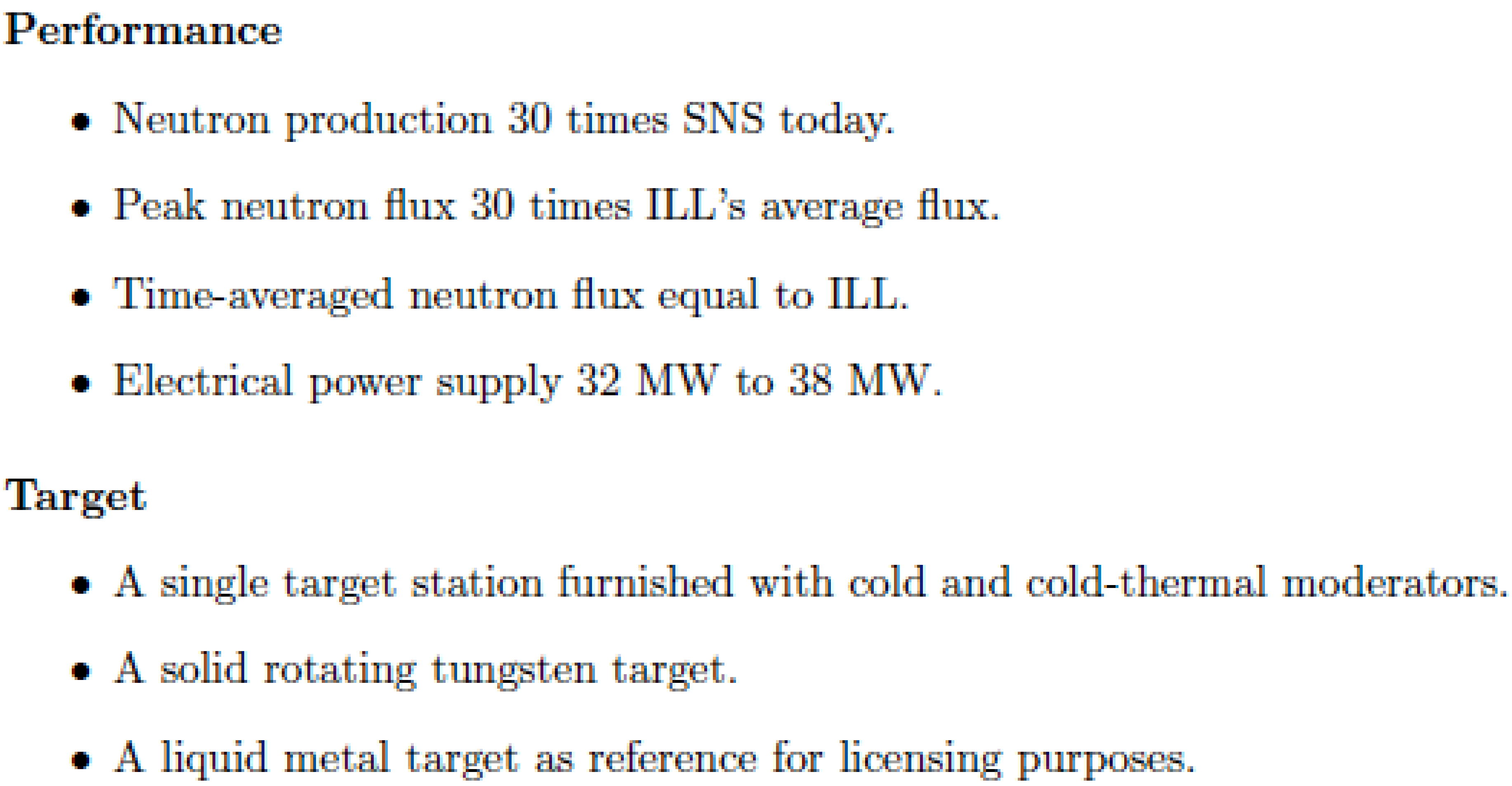
ESS Design Parameters (4/18/2011)



Parameter	Unit	Value
Average beam power	MW	5
Number of target stations		1
Number of instruments in construction budget		22
Maximum number of instruments		44
Number of beam ports		50
Number of moderators		2
Separation of ports in degrees	°	5
Proton kinetic energy	GeV	2.5
Average macro-pulse current	mA	50
Macro-pulse length	ms	2.86
Pulse repetition rate	Hz	14
Maximum accelerating cavity surface field	MV/m	40
Maximum linac length (without 100 m upgrade space)	m	482.5
Annual operating period	h	5200
Reliability	%	95

Table 2: *High Level* parameters, April 18, 2011.

ESS Design Parameters (4/18/2011)



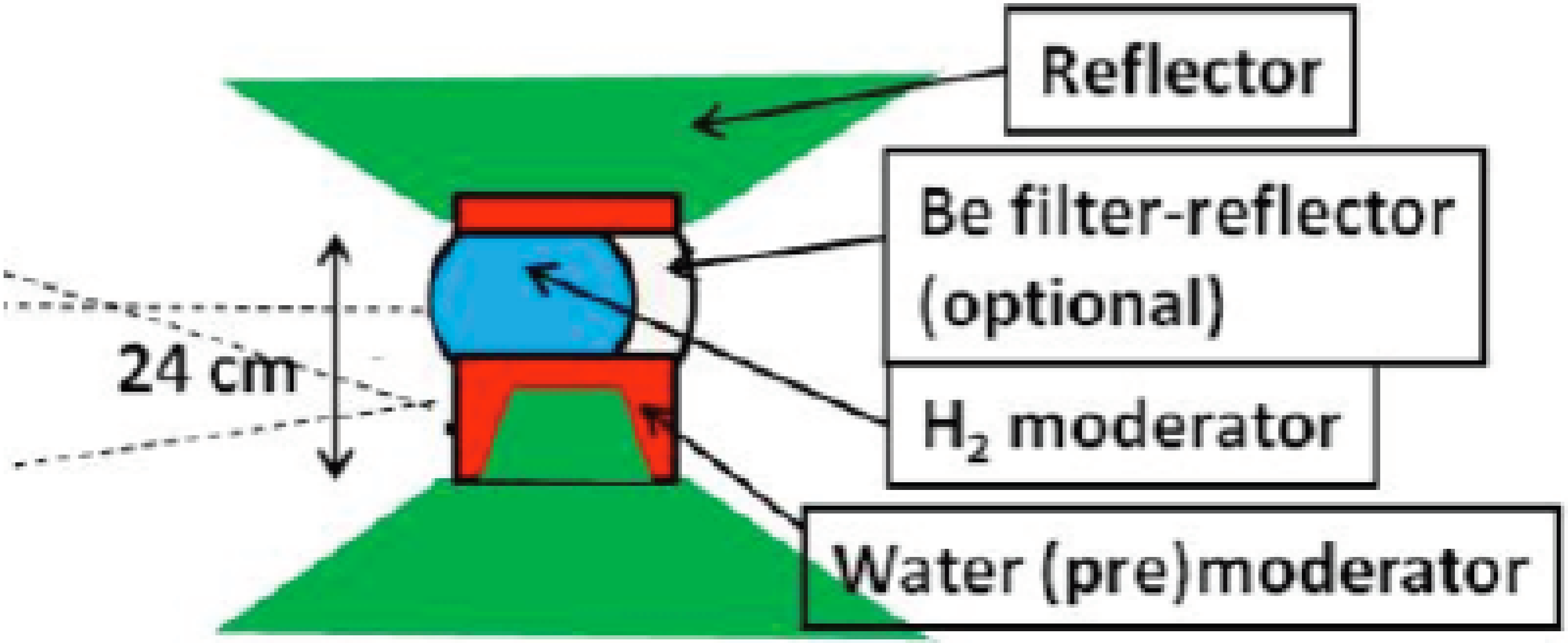
Performance

- Neutron production 30 times SNS today.
- Peak neutron flux 30 times ILL's average flux.
- Time-averaged neutron flux equal to ILL.
- Electrical power supply 32 MW to 38 MW.

Target

- A single target station furnished with cold and cold-thermal moderators.
- A solid rotating tungsten target.
- A liquid metal target as reference for licensing purposes.

ESS Cold Neutron Moderators (4/18/2011 conceptual design report)



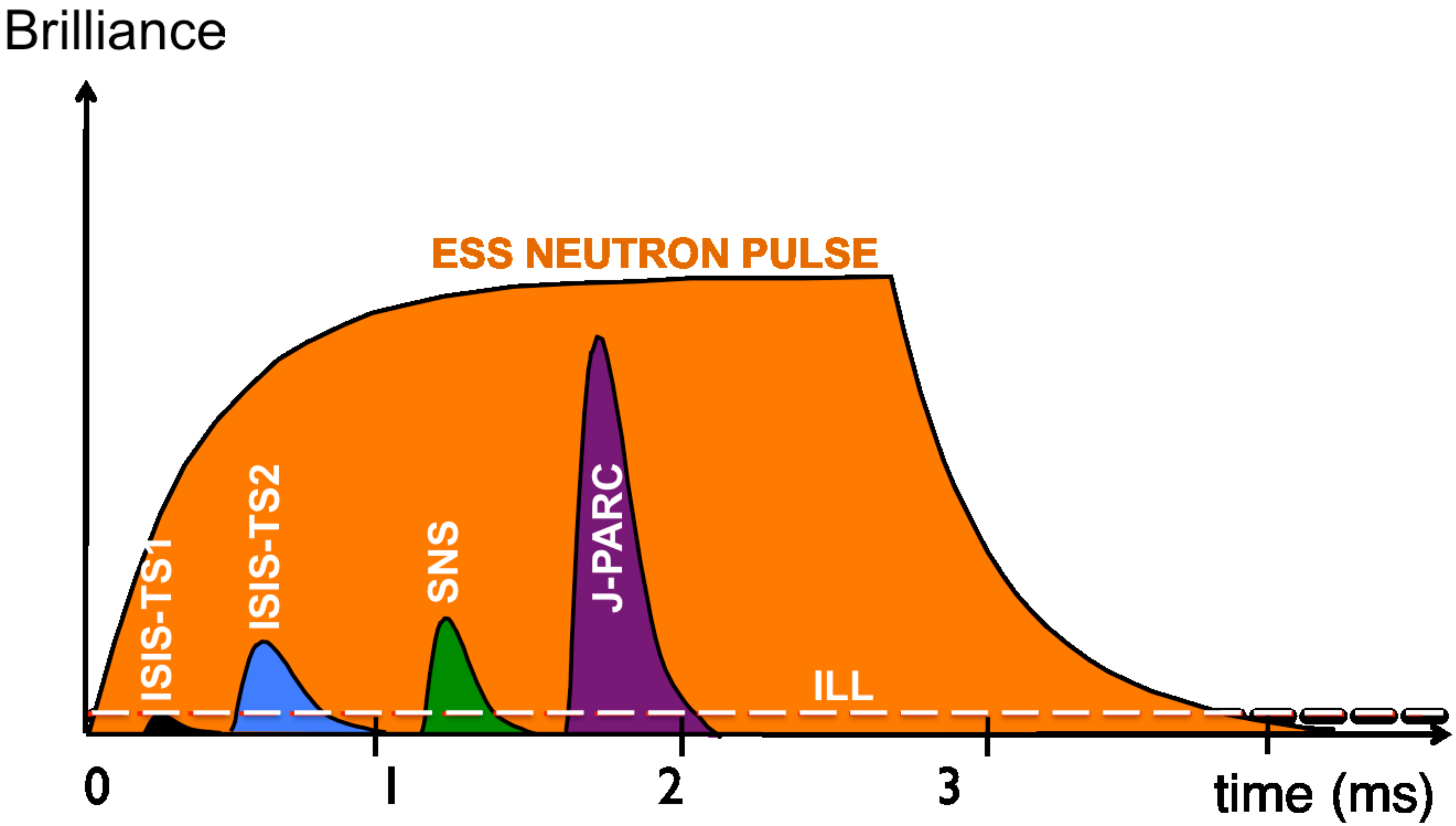
Reflector

Be filter-reflector (optional)

H_2 moderator

Water (pre)moderator

ESS Peak Brilliance (from website) relative to other sources



Is the ESS, crudely speaking a ~16 Hz “pulsed ILL”, of interest for nuclear/particle/astrophysics with neutrons?

YES! YES!
HELL YES!

Nuclear/Particle/Astrophysics with Slow Neutrons: What physics can be done?

1. Neutron decay (Big Bang 4He abundance, weak interaction tests, time reversal violation searches,…)
2. Search for neutron electric dipole moment: time reversal violation
3. Tests of quantum mechanics/entanglement/information
4. Neutrons and gravity (gravitational bound states, transitions, etc.)
5. NN weak interactions
6. Search for weakly coupled new forces with mm-Angstrom ranges
7. Search for neutron-antineutron oscillations: baryon number violation
8. Others…

J. Nico and W. M. Snow, Annual Reviews of Nuclear and Particle Science **55**, 27-69 (2005).

H. Abele, Progress in Particle and Nuclear Physics **60**, 1-81 (2008).

D. Dubbers and M. Schmidt, Reviews of Modern Physics (2011).

Why nuclear/particle/astrophysics with neutrons @ESS?

1. Combination of <u>both</u> time-averaged neutron intensity <u>and</u> neutron energy information enables high-precision measurements with control of systematic errors for cold neutron experiments

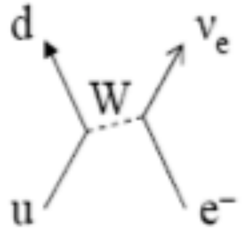
<u>Cold neutron experiment examples:</u>

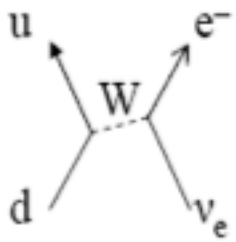
Neutron decay
NN weak interactions
Weak force searches

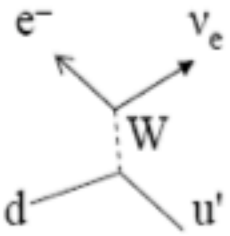
2. Pulsed nature of the source enables the possibility of constructing a more intense ultracold neutron source

(see later talks of Mike Pendlebury and Geoff Greene etc.)

Primordial element formation	$n + e+ \rightarrow p + \nu'_e$
(^{2}H, ^{3}He, ^{4}He, ^{7}Li, …)	$p + e^- \rightarrow n + \nu_e$
	$n \rightarrow p + e^- + \nu'_e$
Solar cycle	$p + p \rightarrow {}^2H + e^+ + \nu_e$
	$p + p + e^- \rightarrow {}^2H + \nu_e$ etc.
Neutron star formation	$p + e^- \rightarrow n + \nu_e$
Pion decay	$\pi^- \rightarrow \pi^0 + e^- + \nu'_e$
Neutrino detectors	$\nu'_e + p \rightarrow e^+ + n$
Neutrino forward scattering	$\nu_e + n \rightarrow e^- + p$ etc.
W and Z production	$u' + d \rightarrow W^- \rightarrow e^- + \nu'_e$ etc.



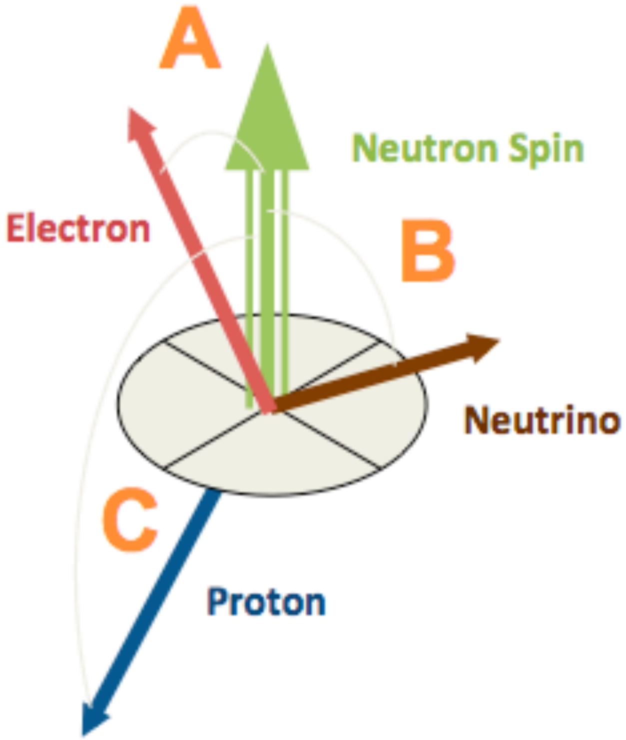




B. Markisch

SLOW NEUTRONS
DFG SPP 1491

Correlations Coefficients



Unmeasured:
Fierz interference term
Weak magnetism
Electron helicity

Some recent measurements

P-odd

UCNA, arXiv:1210.7048
Perkeo II, arXiv:1204.0013

Perkeo III, dissertation Mest (2011)

P-odd

Perkeo II, PRL 99 (2007)

P-odd

Perkeo II, PRL 100 (2008)

Byrne et al., J. Phys. G 28 (2002)
*a*Spect – running @ ILL
aCORN – running @ NIST

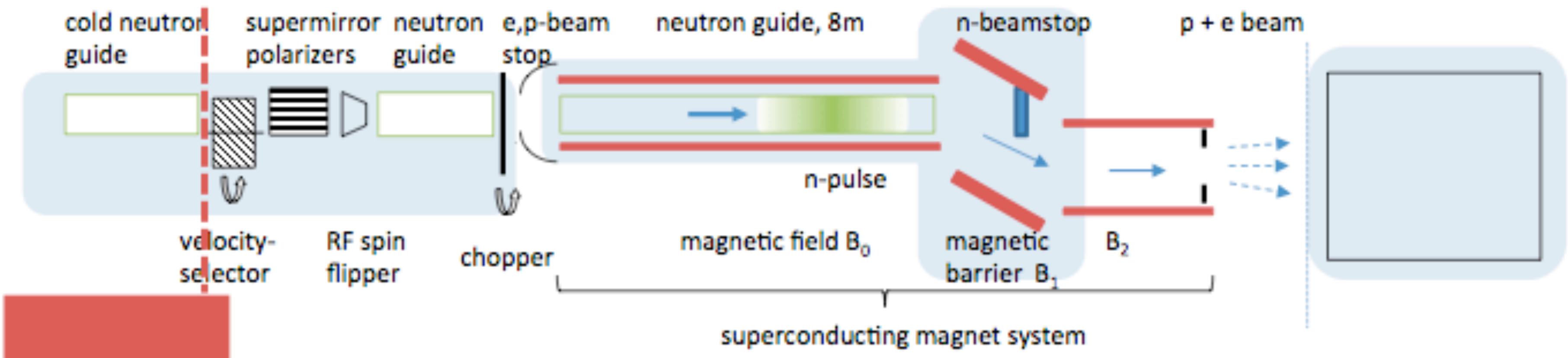
T-odd **Triple Coefficient**

TRINE, PLB 581 (2004)
emiT, PRL 107 (2011)
Kozela et al., PRL 102 (2009)

T-odd

B. Markisch

The PERC instrument



- ▪! Clean
- ▪! Decay volume defined by (8m)

  Maximum neutron phase space density
- ▪! $B_0 = 1.5$ T

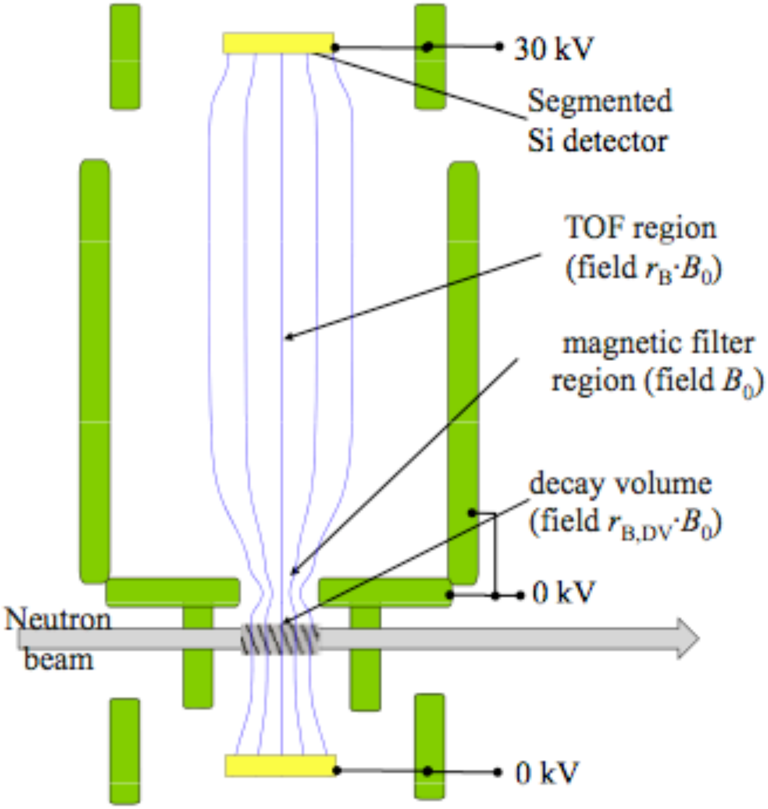
  Small detector area – improved S/B
- ▪! $B_1 = 6$ T

  Define phase space of decay products in detector
- ▪!

  User experiments, open to others!

See C. Klauser talk

The asymmetric version of Nab @ SNS



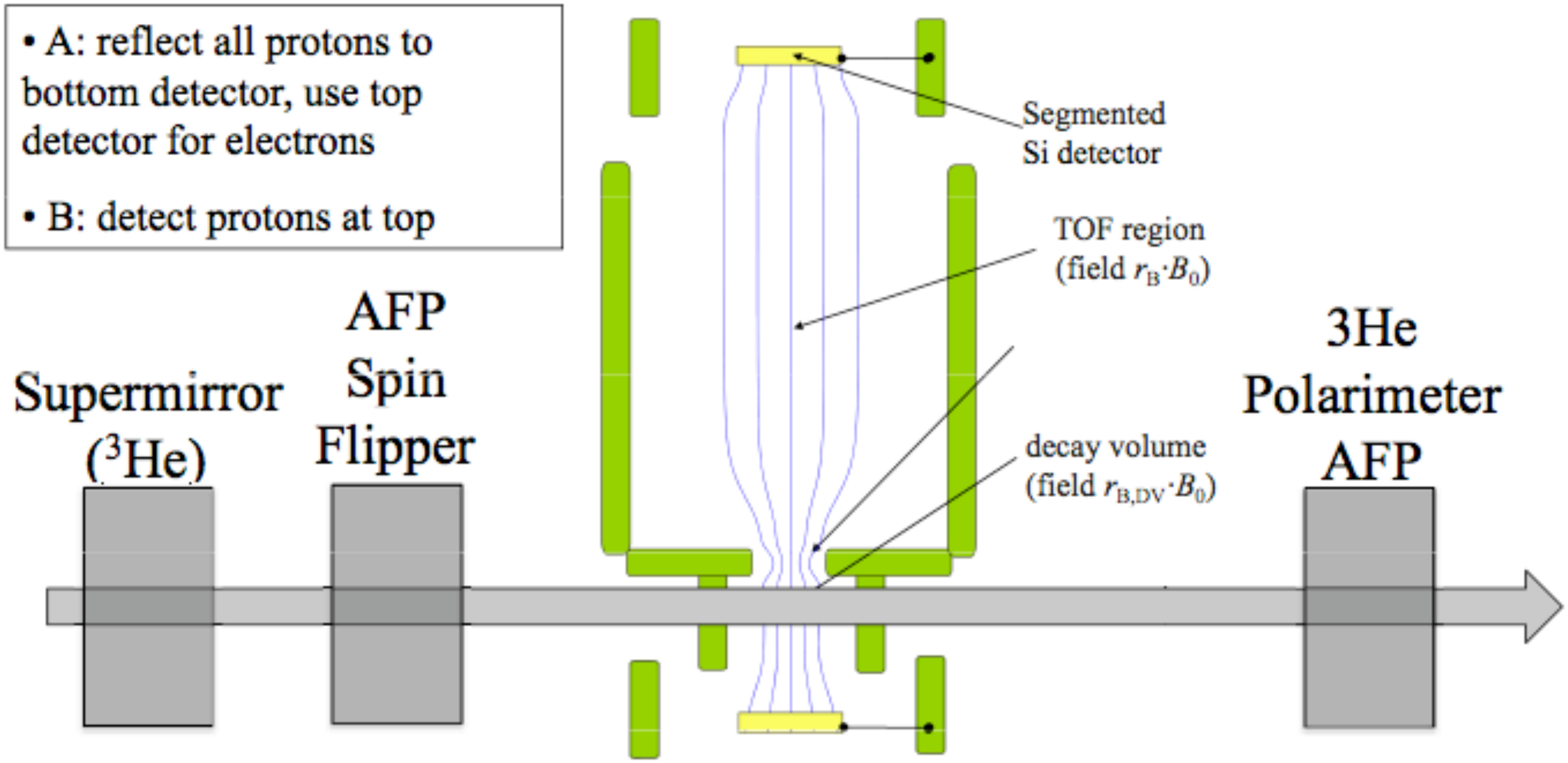
Advantages of asymmetric configuration:

- Detection function: Improved flight path length
- Reduced sensitivity to electrostatic and magnetic potential inhomogeneities
- Avoid deep Penning trap
- Statistical uncertainty: Bigger decay volume vs. angular acceptance
- Polarized experiment (abBA, PANDA) still possible

S. Baeßler

A/B at SNS or NIST: abBA / Nab / PANDA

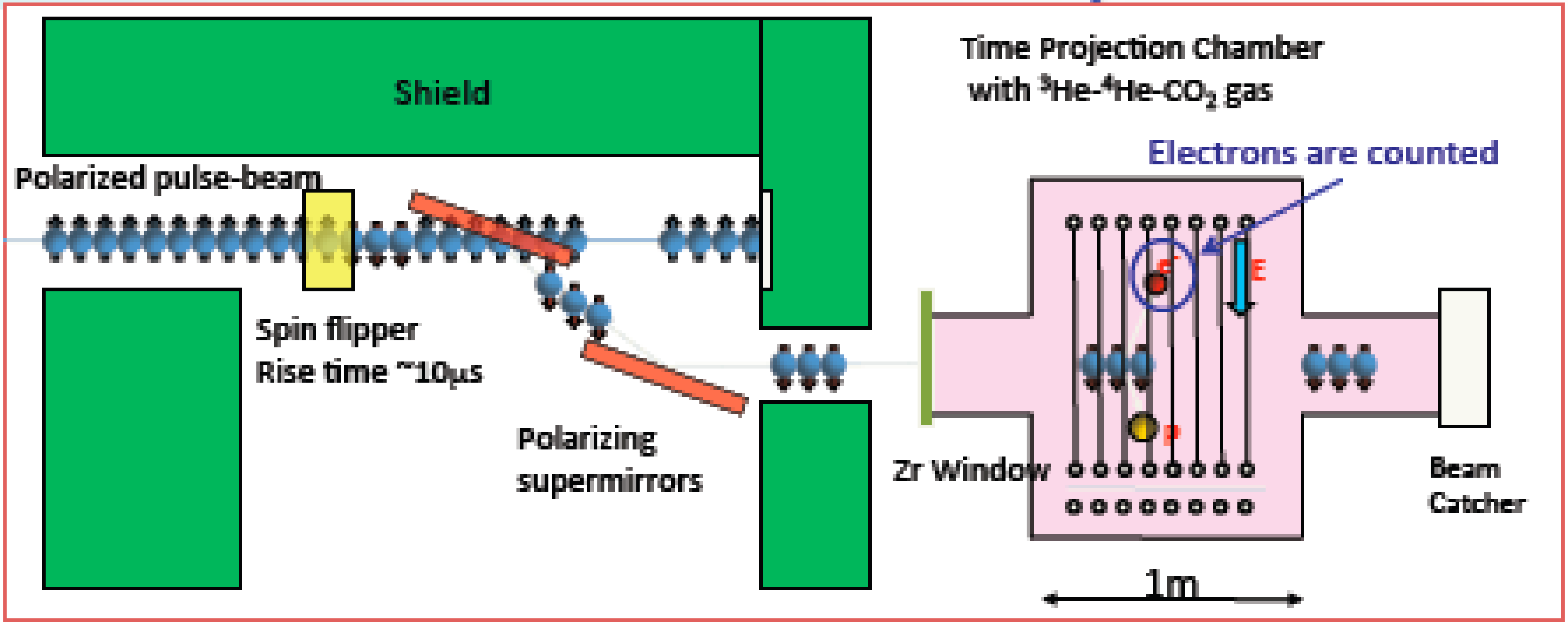
- A: reflect all protons to bottom detector, use top detector for electrons
- B: detect protons at top



- Main uncertainties in PERKEO II: statistics, detector, polarization, background
- Superior detector energy resolution, good enough time resolution
- Keep coincidences to improve background
- Asymmetric detector: Filter improves on systematics; statistics @ SNS is an issue for A
- Polarization measurement seems manageable (XSM or He-3)

S. Baeßler

Schematic view of this experiment



- Electrons by beta decay are measured by a gas detector of 1m length.
- Neutrons are transported into the detector with a bunch length of 40 cm.

Good efficiency: All neutrons are inside of detector in a certain time region.

Low background : Background from windows, beam catcher, and chopper can be separated by TOF.

T. Yamada

Neutron decay: What could be learned/done at ESS?

Huge number of observables in neutron decay of broad importance in nuclear and particle physics. Many have never been measured.

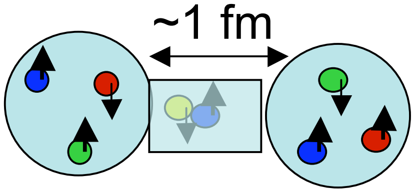
Present sensitivity to new physics of different types in charged weak processes is comparable to or better than constraints from LHC

Hard to believe that these measurements will become uninteresting a decade later

Apparatus are now in preparation for experiments at SNS, JPARC, FRM,… which will or can make essential use of the pulsed structure of the neutron beam

Pulsed ESS source helps increase signal/background in neutron decay experiments and also helps control systematic errors for absolute neutron polarization measurement

N-N Weak Interaction: Size and Mechanism

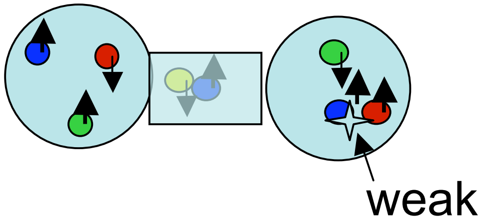


NN repulsive core → 1 fm range for NN strong force

$|N\rangle = |qqq\rangle + |qqqq\bar{q}\rangle + \cdots$ = valence + sea quarks + gluons + …

NN strong force at low energy mediated by mesons $|m\rangle = |q\bar{q}\rangle + |q\bar{q}q\bar{q}\rangle + \cdots$

QCD possesses only vector quark-gluon couplings → conserves parity



Both W and Z exchange possess much smaller range [~1/100 fm]

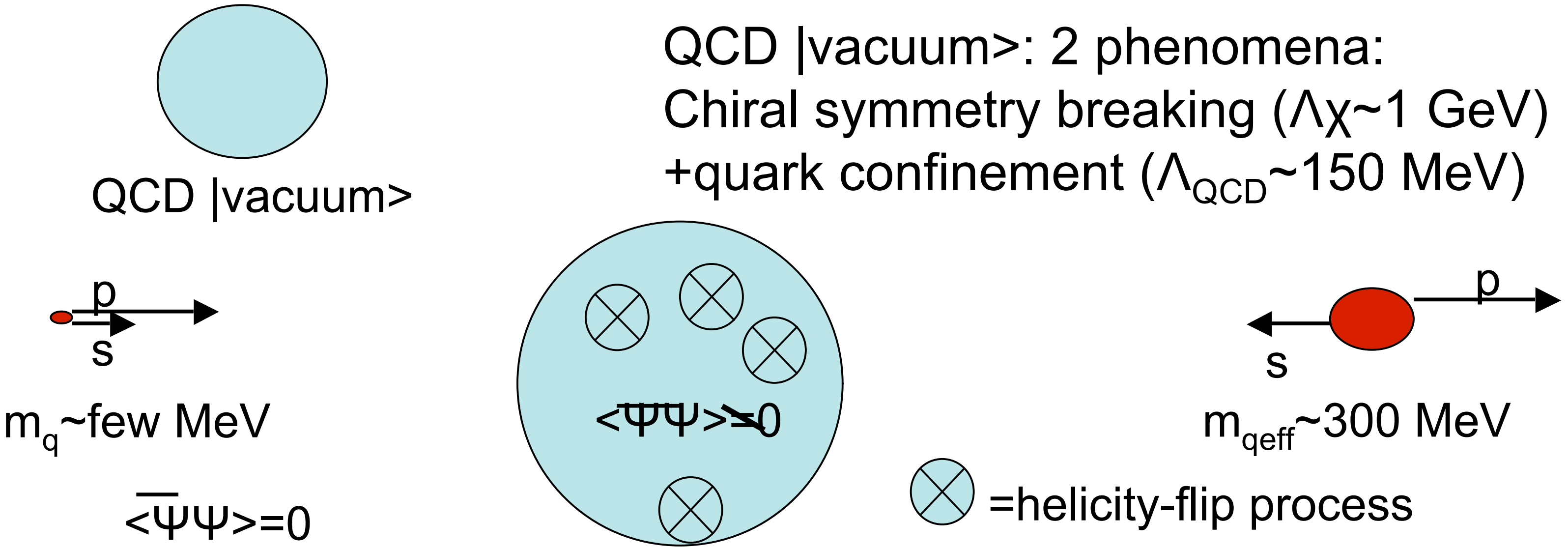
Relative strength of weak / strong amplitudes: $\left(\frac{e^2}{m_W{}^2}\right)/\left(\frac{g^2}{m_\pi{}^2}\right) \approx 10^{-6}$

NN weak amplitudes first-order sensitive to qq correlations

Weak interaction violates parity. Use parity violation to isolate the weak contribution to the NN interaction.

How can the Weak NN Interaction help us with QCD?

QCD |vacuum>: 2 phenomena:
Chiral symmetry breaking ($\Lambda\chi$~1 GeV)
+quark confinement (Λ_{QCD}~150 MeV)



- Physical nature of the ground state of QCD is not fully understood
- Single-particle models (quark model, bag model) are wrong ($\mu_p/\ \mu_n$~-2/3 seems to be an accident: ~1/3 of proton's J=1/2 comes from quark spin).
- Chiral symmetry breaking seems to dominate dynamics of light hadrons such as protons and neutrons
- Strong QCD is "really" many body physics.
- Lesson from condensed matter physics: understand the correlations!
- weak qq interaction range~1/100 size of nucleon-> sensitive to short-range q-q correlations+vacuum modifications, an "inside-out" probe of QCD

NN Weak Interaction:
5 Independent Elastic Scattering Amplitudes at Low Energy

Using isospin symmetry applied to NN elastic scattering we get the usual Pauli-allowed L,S,J combinations:

I_{tot} = 1 *(isospin-S)*:

Space-S (even L) ✖ spin-A (S_{tot} = 0) -> $^1S_0$, $^1D_2$, $^1G_4$, …

or Space-A (odd L) ✖ spin-S (S_{tot} = 1) -> $^3P_{0,1,2}$, $^3F_{2,3,4}$, …

I_{tot} = 0 *(isospin-A)*:

Space-A (odd L) ✖ spin-A (S_{tot} = 0) -> $^1P_1$, $^1F_3$, …

Space-S (even L) ✖ spin-S (S_{tot} = 1) -> $^3S_1$, $^3D_{1,2,3}$, $^3G_{3,4,5}$, …

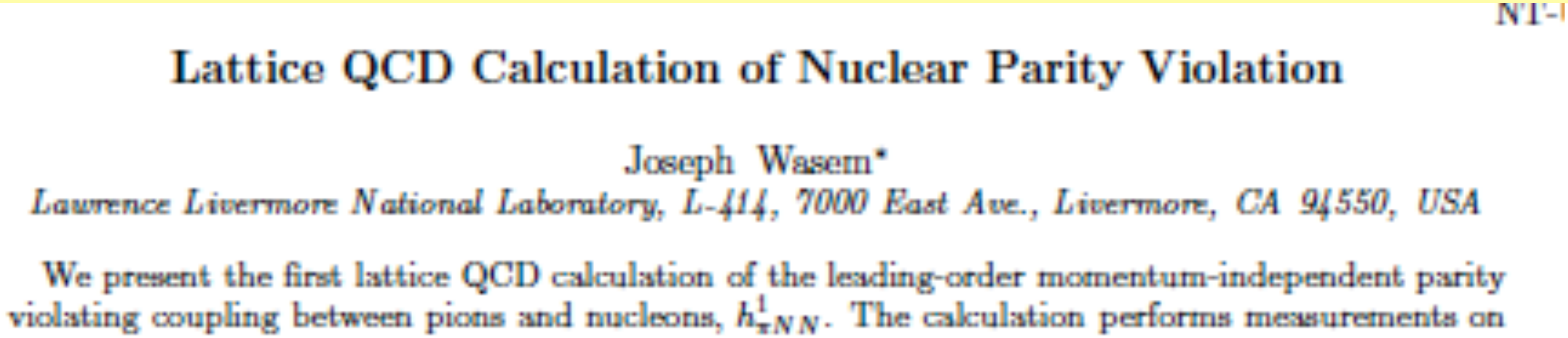
$^{(2S+1)}L_J$ notation, with L=0,1,2,3,4,… denoted as S,P,D, F,G,…

If we use energies low enough that **only *S*-waves are important for strong interaction,** parity violation is dominated by ***S- P interference***,

Then we have 5 independent NN parity-violating transition amplitudes:

$^3S_1$-> $^1P_1$(ΔI=0, np); $^3S_1$-> $^3P_1$(ΔI=1, np); $^1S_0$-> $^3P_0$(ΔI=0,1,2; nn,pp,np)

Calculations of NN Weak Amplitudes from Standard Model Now Becoming Possible!



NT-

Lattice QCD Calculation of Nuclear Parity Violation

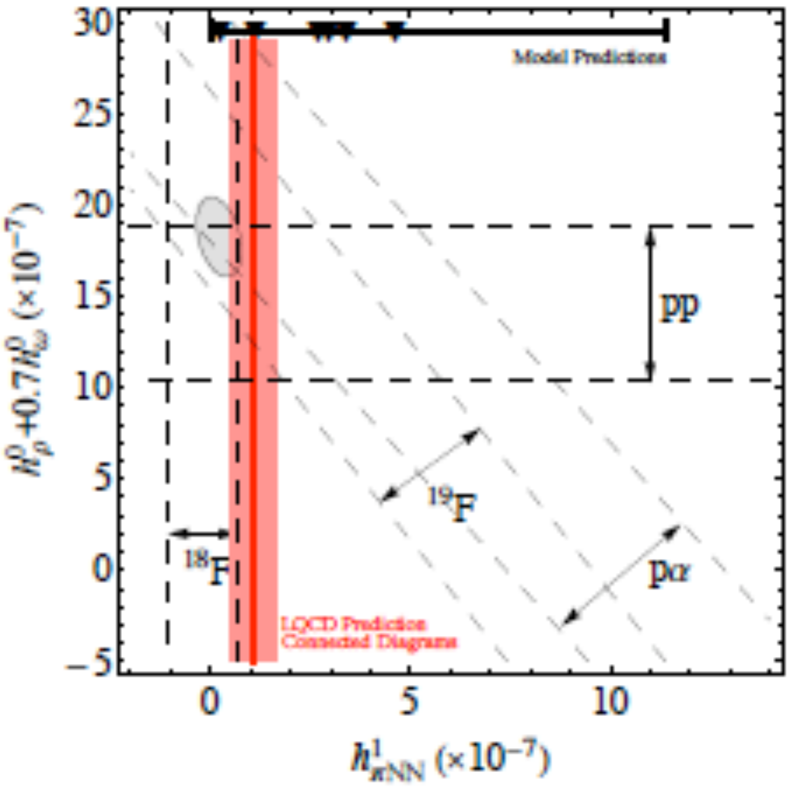
Joseph Wasem*

Lawrence Livermore National Laboratory, L-414, 7000 East Ave., Livermore, CA 94550, USA

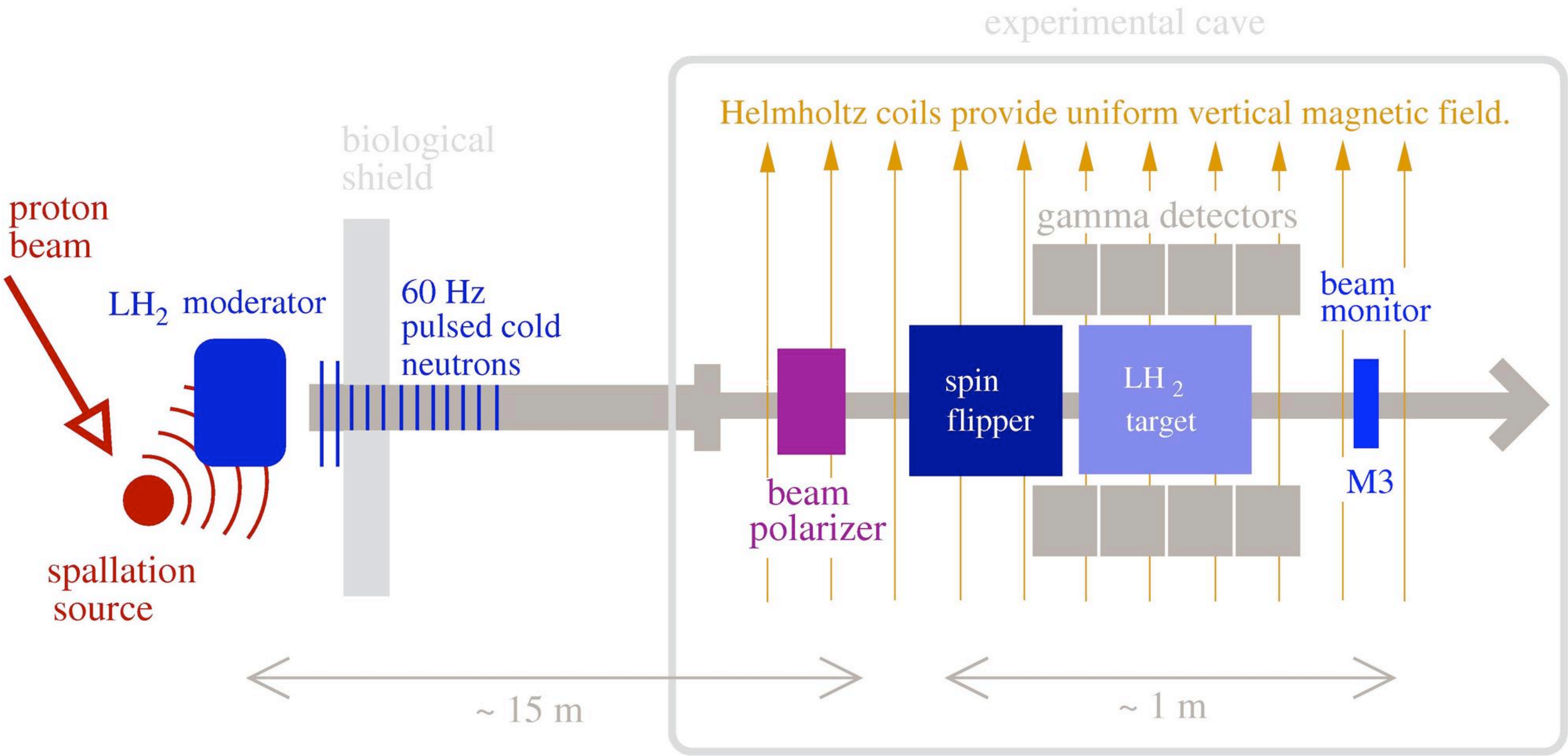
We present the first lattice QCD calculation of the leading-order momentum-independent parity violating coupling between pions and nucleons, $h^1_{\pi NN}$. The calculation performs measurements on

arXiv: 1108.1151, 14 March 2012

- Calculation of NN weak amplitudes is just now becoming possible using lattice gauge theory
- On timescale of ESS, we can expect real predictions for the 5 S→P weak NN transition amplitudes from the Standard Model
- New opportunity to get information on nontrivial QCD ground state dynamics

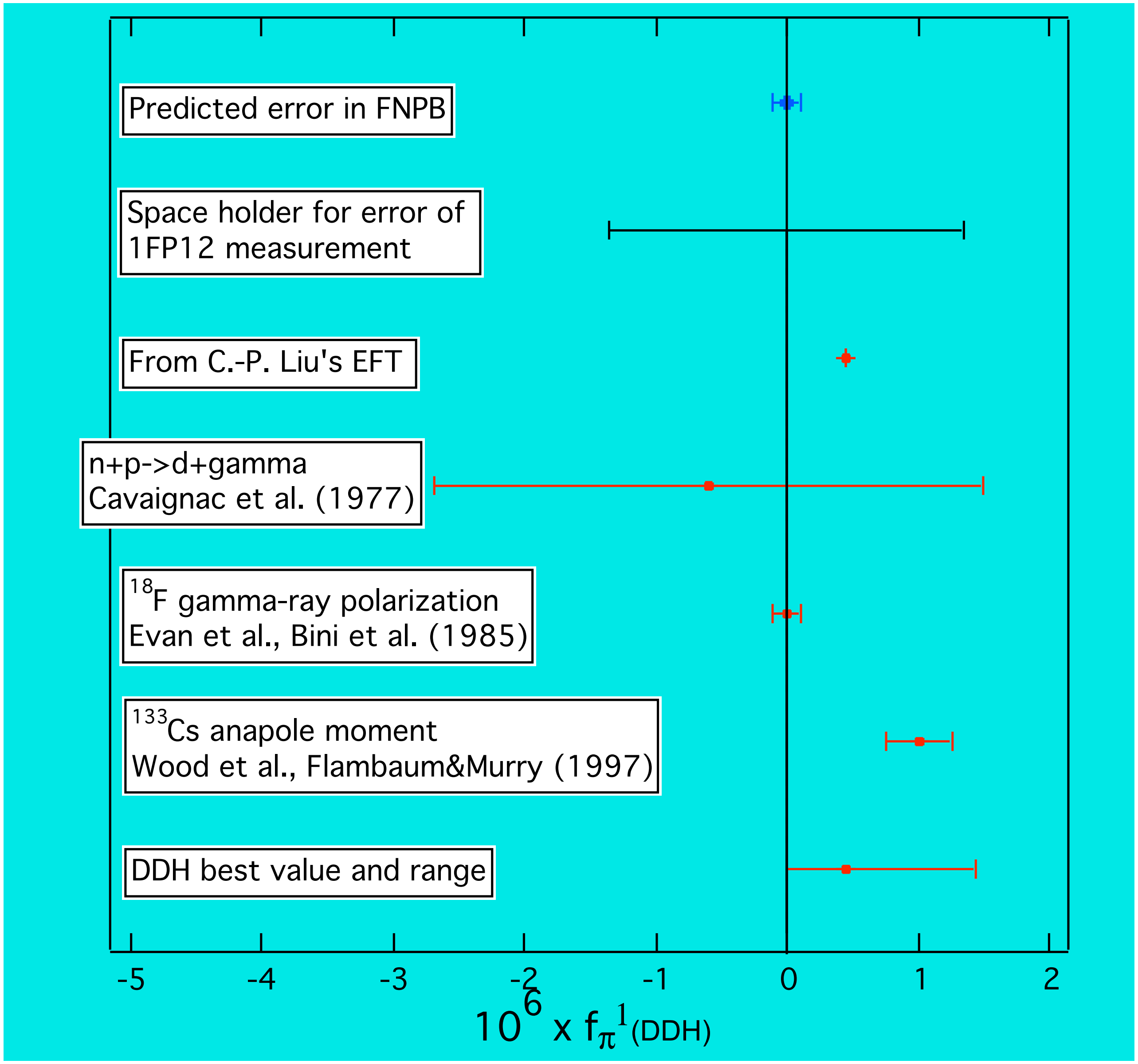


PV Gamma Asymmetry in Polarized Neutron Capture



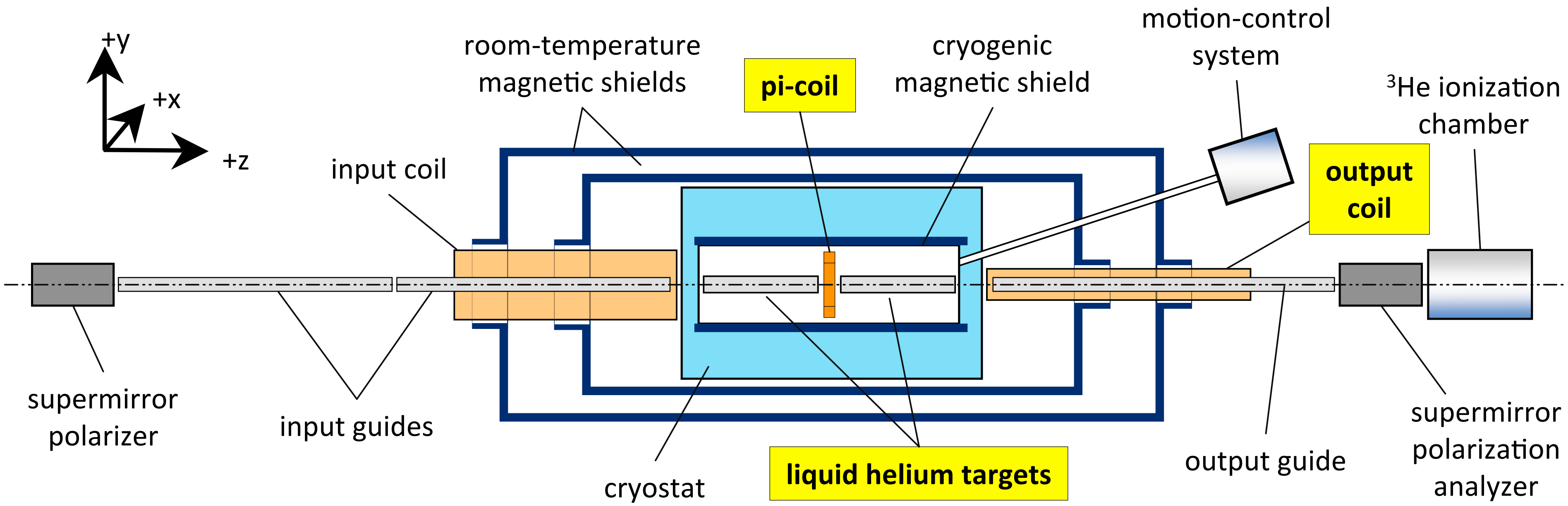
- Pulsed neutron source important for control of systematic errors
- Needs serious liquid parahydrogen target (16 liters)
- Apparatus for a future n+D asymmetry experiment is similar.
- Goal at SNS: 1×10^{-7} for A_Υ in n+p->D+ϒ
- STATUS: now taking data at SNS (see S. Wilburn talk)

Anticipated sensitivity of n+p→d+ γ at FNPB



Parity Violation in Neutron Spin Rotation

Apparatus measures the horizontal component of neutron spin generated in the liquid target starting from a vertically-polarized beam



$$|\uparrow>= \frac{1}{\sqrt{2}}(|+>+|->) \rightarrow \frac{1}{\sqrt{2}}(e^{i\phi_+}|+>+e^{i\phi_-}|->)$$

Weak NN: What could be learned at ESS?

-> 2 classes of experiments: PV spin rotation [~Re(f)] and reactions with inelastic channels [gamma capture]

Possible experiments: PV spin rotation in n-p, n-D, and n-4He, PV gamma asymmetry in n-p and n-D

Two experiments are in progress now at SNS/NIST, these apparatus could be taken to ESS and others could be developed

One could imagine measuring weak NN couplings at ESS to ~10-20% accuracy. This would match expected calculations from the Standard Model using lattice gauge theory

Neutron energy information from pulsed ESS source essential for control of systematic errors for measurement of 10-100 ppb asymmetries to ~10% accuracy

New interactions with ranges from millimeters to microns… "Who ordered that?"

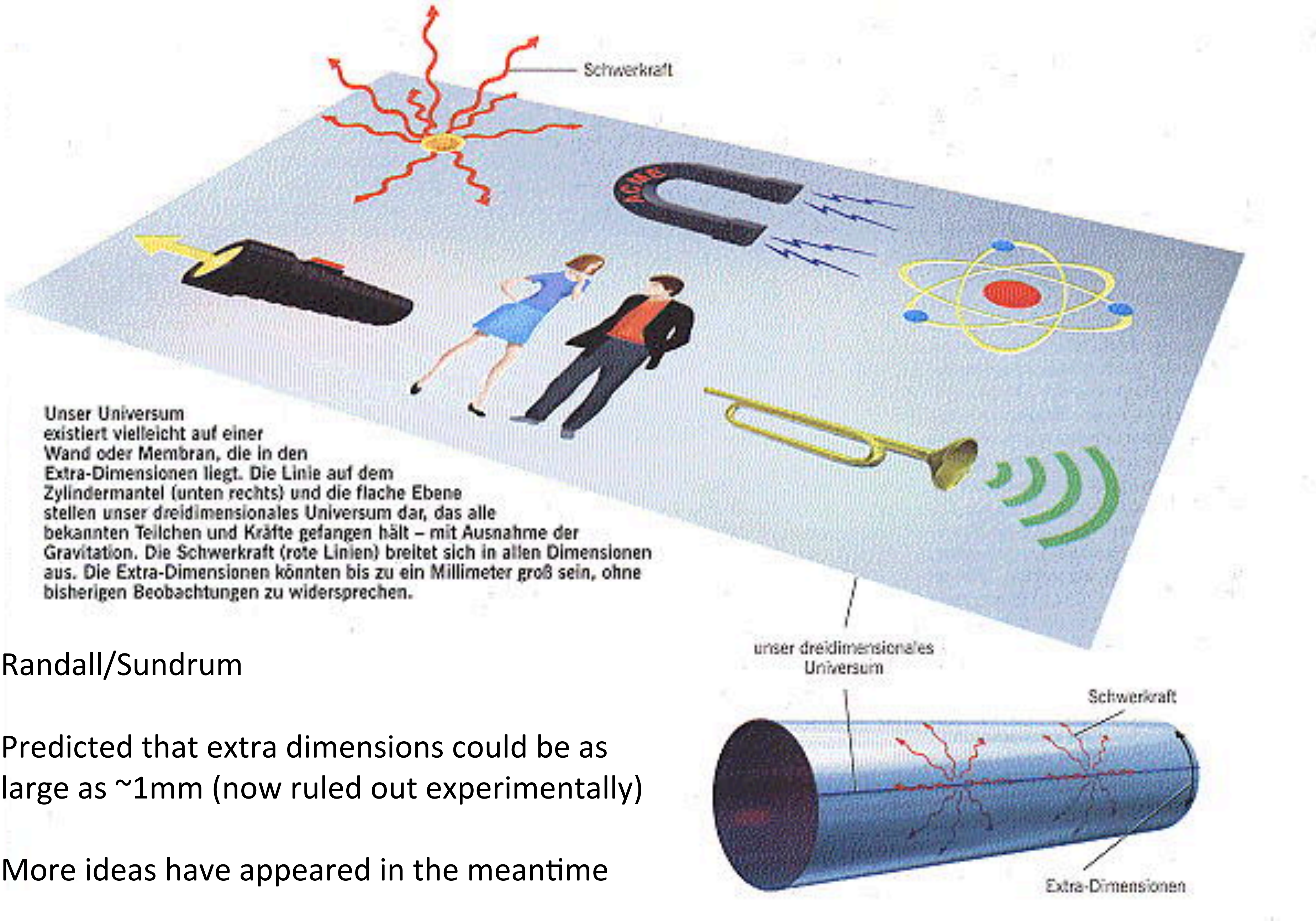
1. Weakly-coupled, long-range interactions are a generic consequence of spontaneously broken continuous symmetries (Goldstone theorem)
2. Specific theoretical ideas (axions, extra dimensions for gravity) imply new interactions at ~mm-μm scales
3. Dimensional analysis: dark energy->100 microns

Not so many precision experiments have been conducted to search for new interactions over "mesoscopic" ranges

Comptes Rendus Physique 12, 755-778 (2011)

J. Jaeckel and A. Ringwald, Ann. Rev. Nucl. Part. Sci. **60, 405 (2010).**

Example: Extra Compact Dimensions of Spacetime



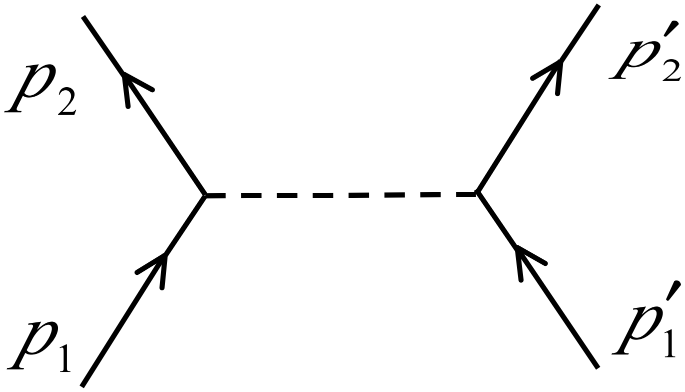
Unser Universum existiert vielleicht auf einer Wand oder Membran, die in den Extra-Dimensionen liegt. Die Linie auf dem Zylindermantel (unten rechts) und die flache Ebene stellen unser dreidimensionales Universum dar, das alle bekannten Teilchen und Kräfte gefangen hält – mit Ausnahme der Gravitation. Die Schwerkraft (rote Linien) breitet sich in allen Dimensionen aus. Die Extra-Dimensionen könnten bis zu ein Millimeter groß sein, ohne bisherigen Beobachtungen zu widersprechen.

Randall/Sundrum

Predicted that extra dimensions could be as large as ~1mm (now ruled out experimentally)

More ideas have appeared in the meantime

Spin-dependent macroscopic interactions meditated by light bosons: general classification



$$\vec{q} \equiv \vec{p}_2 - \vec{p}_1$$

$$\vec{P} \equiv \frac{1}{2}(\vec{p}_1 + \vec{p}_2) \ .$$

- Assume elastic fermion-fermion interactions, rotational invariance
- Fourier transform to get potentials
- Assume particles are spin-1/2

B. Dobrescu and I. Mocioiu, J. High Energy Phys. 11,005 (2006)

Spin-dependent macroscopic interactions meditated by light bosons: general classification

$$\mathcal{O}_1 = 1 \ ,$$

$$\mathcal{O}_2 = \vec{\sigma}\cdot\vec{\sigma}\,' \ ,$$

$$\mathcal{O}_3 = \frac{1}{m^2}\,(\vec{\sigma}\cdot\vec{q})\ (\vec{\sigma}\,'\cdot\vec{q}) \ ,$$

$$\mathcal{O}_{4,5} = \frac{i}{2m^2}\,(\vec{\sigma}\pm\vec{\sigma}\,')\cdot\left(\vec{P}\times\vec{q}\right) \ ,$$

$$\mathcal{O}_{6,7} = \frac{i}{2m^2}\left[\left(\vec{\sigma}\cdot\vec{P}\right)\ (\vec{\sigma}\,'\cdot\vec{q})\pm(\vec{\sigma}\cdot\vec{q})\ \left(\vec{\sigma}\,'\cdot\vec{P}\right)\right] \ ,$$

$$\mathcal{O}_8 = \frac{1}{m^2}\left(\vec{\sigma}\cdot\vec{P}\right)\ \left(\vec{\sigma}\,'\cdot\vec{P}\right) \ .$$

$$\mathcal{O}_{9,10} = \frac{i}{2m}\,(\vec{\sigma}\pm\vec{\sigma}\,')\cdot\vec{q} \ ,$$

$$\mathcal{O}_{11} = \frac{i}{m}\,(\vec{\sigma}\times\vec{\sigma}\,')\cdot\vec{q} \ ,$$

$$\mathcal{O}_{12,13} = \frac{1}{2m}\,(\vec{\sigma}\pm\vec{\sigma}\,')\cdot\vec{P} \ ,$$

$$\mathcal{O}_{14} = \frac{1}{m}\,(\vec{\sigma}\times\vec{\sigma}\,')\cdot\vec{P} \ ,$$

$$\mathcal{O}_{15} = \frac{1}{2m^3}\left\{\left[\vec{\sigma}\cdot\left(\vec{P}\times\vec{q}\right)\right](\vec{\sigma}\,'\cdot\vec{q})+(\vec{\sigma}\cdot\vec{q})\left[\vec{\sigma}\,'\cdot\left(\vec{P}\times\vec{q}\right)\right]\right\}$$

$$\mathcal{O}_{16} = \frac{i}{2m^3}\left\{\left[\vec{\sigma}\cdot\left(\vec{P}\times\vec{q}\right)\right]\left(\vec{\sigma}\,'\cdot\vec{P}\right)+\left(\vec{\sigma}\cdot\vec{P}\right)\left[\vec{\sigma}\,'\cdot\left(\vec{P}\times\vec{q}\right)\right]\right\} \ .$$

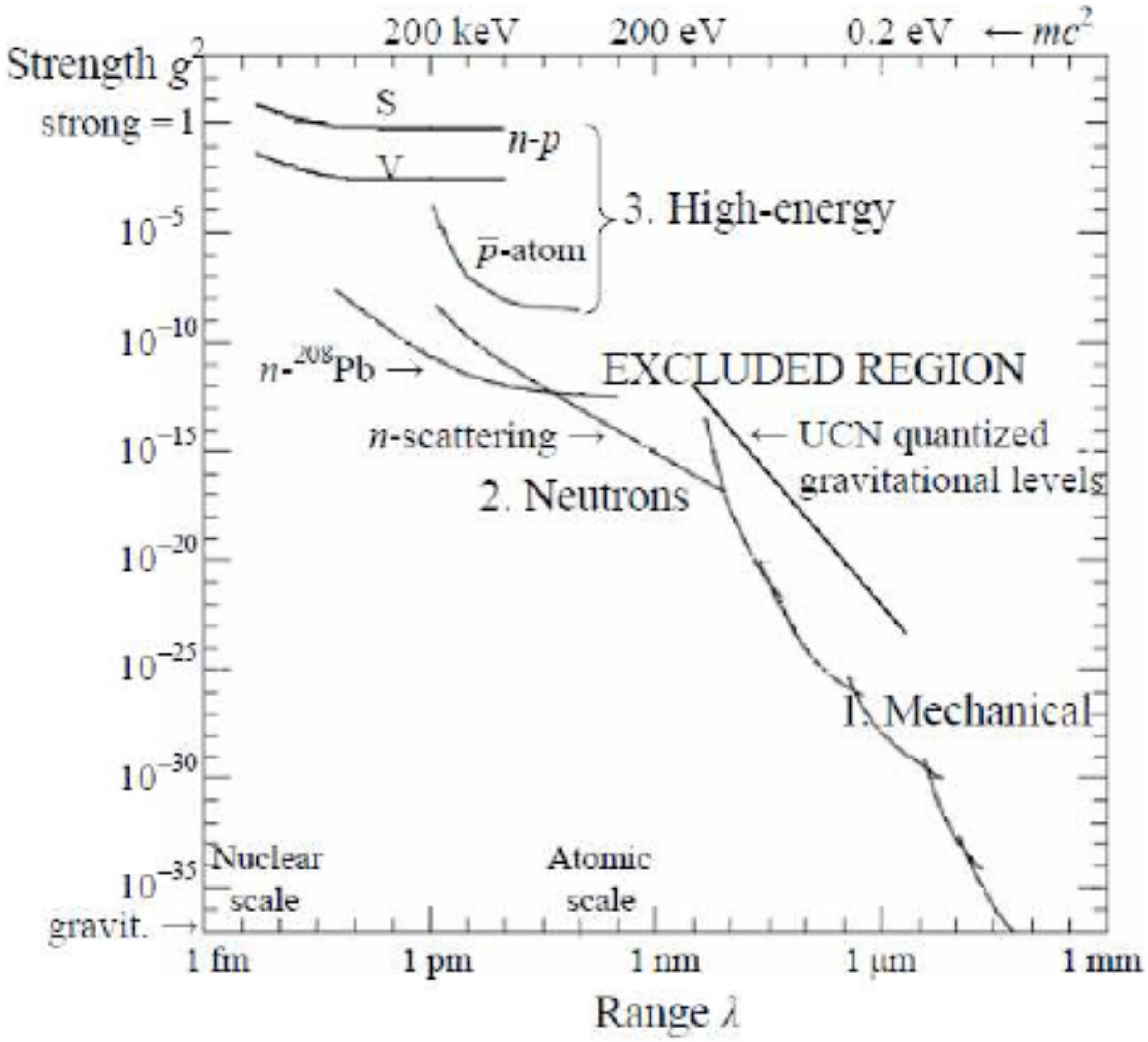
- 16 independent scalars can be formed: 8 P-even, 8 P-odd
- 15/16 depend on spin
- Traditional “fifth force” searches constrain O_1

B. Dobrescu and I. Mocioiu, J. High Energy Phys. 11,005 (2006)

Why use neutrons?

1. Zero electric charge, small magnetic moment, very small electric polarizability->low ”background” from Standard Model interactions
2. Deep penetration distance into macroscopic matter, so neutrons can interact with a lot of matter
3. Coherent interactions with matter->phase sensitive measurements possible
4. High neutron polarization (~99%) routine for slow neutron beams->useful in searching for spin-dependent interactions

Constraints on Yukawa interactions



Neutron measurements give the best constraints on new Yukawa interactions
over 5 orders of magnitude
of distance scales

Dubbers/Schmidt, Rev. Mod. Phys (2011).

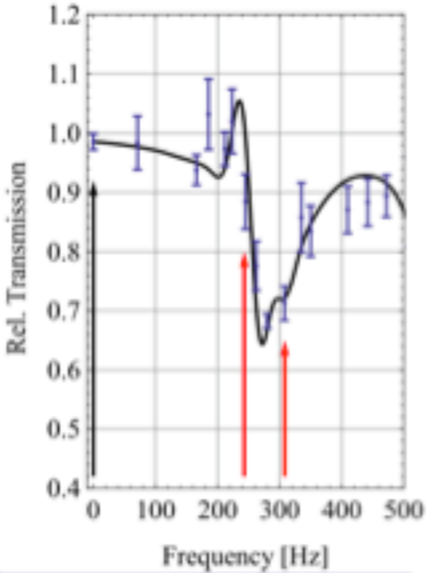
Applications II: Spin-dependant short-ranged interactions

[data 2011 + 2011]

in collaboration with U. Schmidt (Heidelberg) and T. Lauer (Garching)

$$V_{\text{axion}} = \frac{g_s g_p \hbar}{8\pi m_n c} \vec{\sigma}\vec{n} \left(\frac{1}{\lambda r} + \frac{1}{r^2} \right)$$

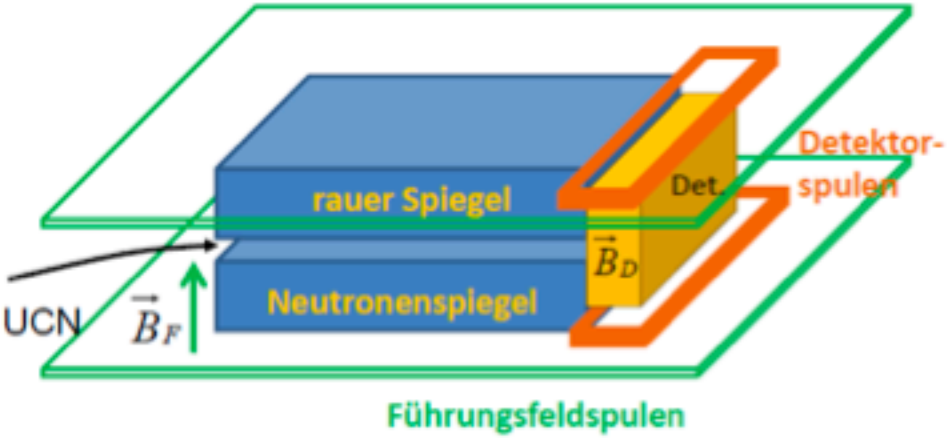
J.E. Moody, F. Wilczek, Phys. Rev. **D30**, 131-138 (1984)



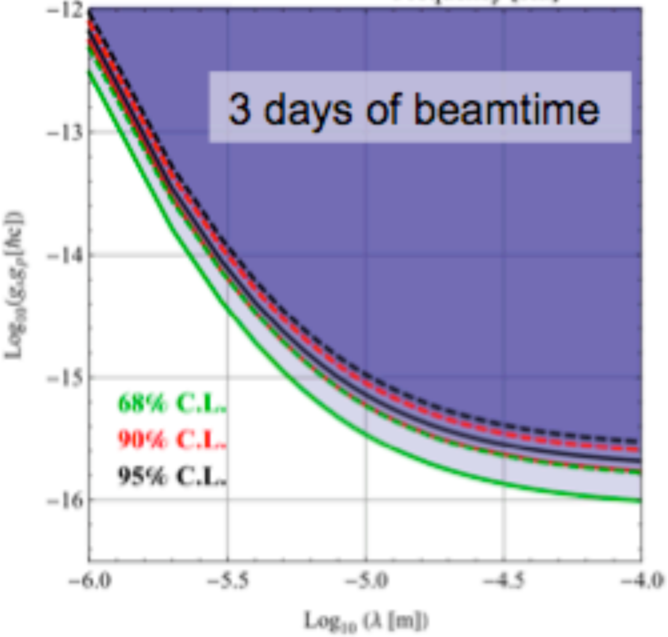
discovery potential [Setup 2010]:

$$g_s g_p / \hbar c \geq \frac{3 \cdot 10^{-16}}{\sqrt{days}}$$

$$(\lambda = 10\mu\text{m}, 68\%\text{C.L.})$$



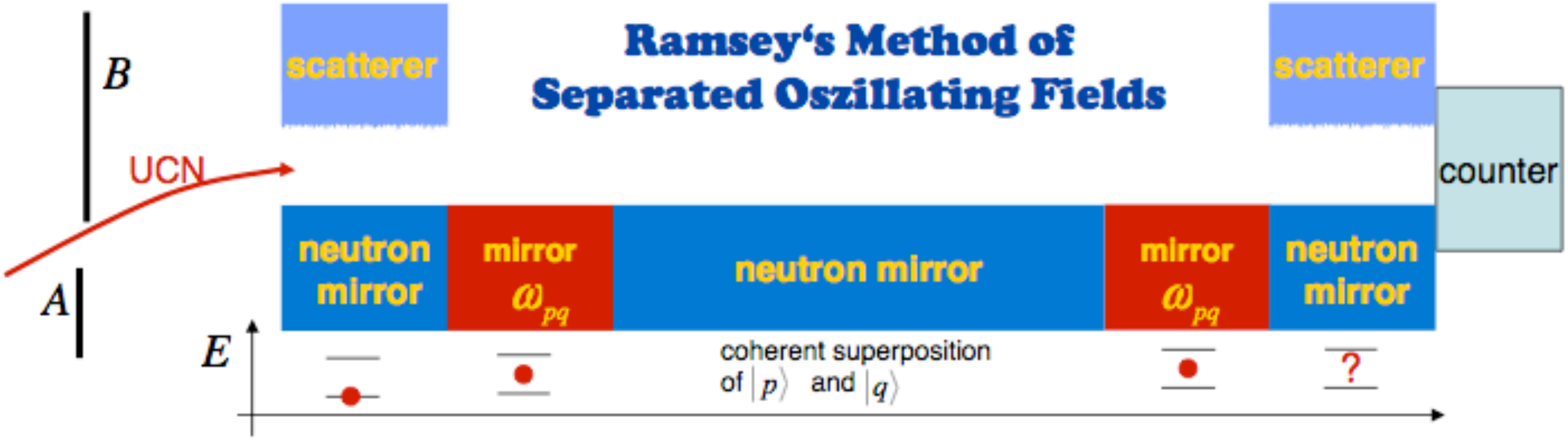
T. Jenke et.al., arXiv:1208.3875 (2012)



Summary & Outlook

- Measurement of the Time Evolution of Gravitational States -> Poster
- Realization of Gravity Resonance Spectroscopy Technique
  - |1> -> |2>
  - |1> -> |3>
  - |2> -> |3>
- qBounce measurements as tool for
  - Search for Non-Newtonian Gravity
  - hypothetical spin-mass couplings (axion-like particles)

see: H. Abele et. al., Phys. Rev. D 81, 065019 (2010)

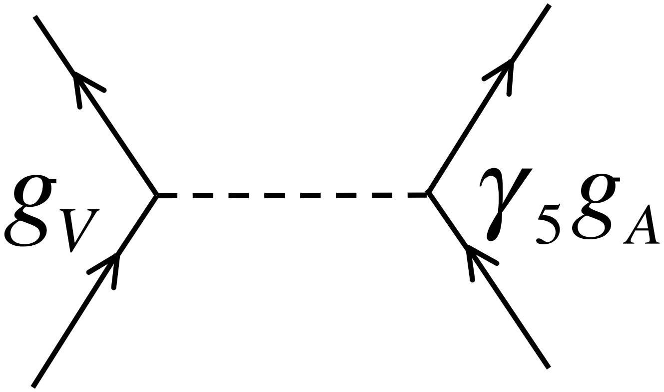


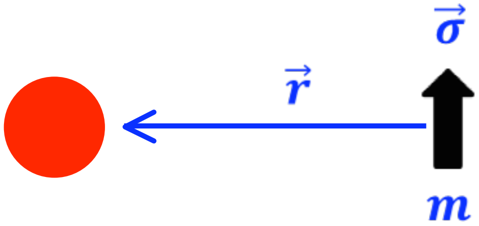
Ramsey's Method of Separated Oszillating Fields

See T. Jencke and P. Brax talks

Example of a nonstandard spin dependent interaction from spin 1 boson exchange:

[Dobrescu/Mocioiu 06, general construction of interaction between nonrelativistic fermions]

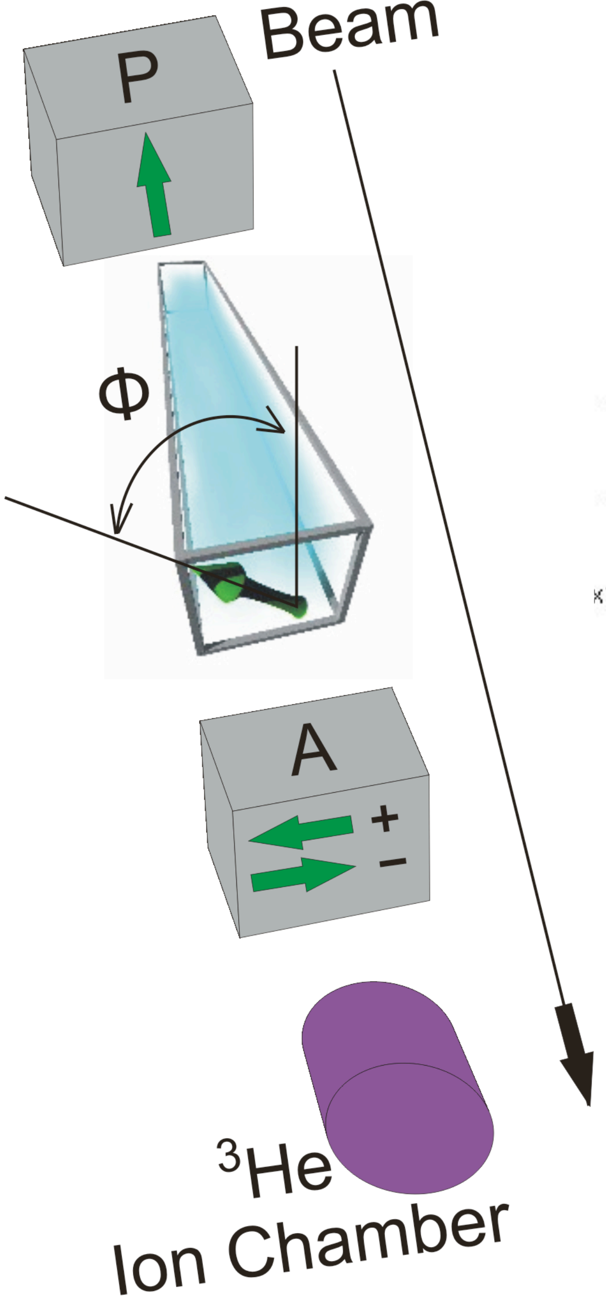


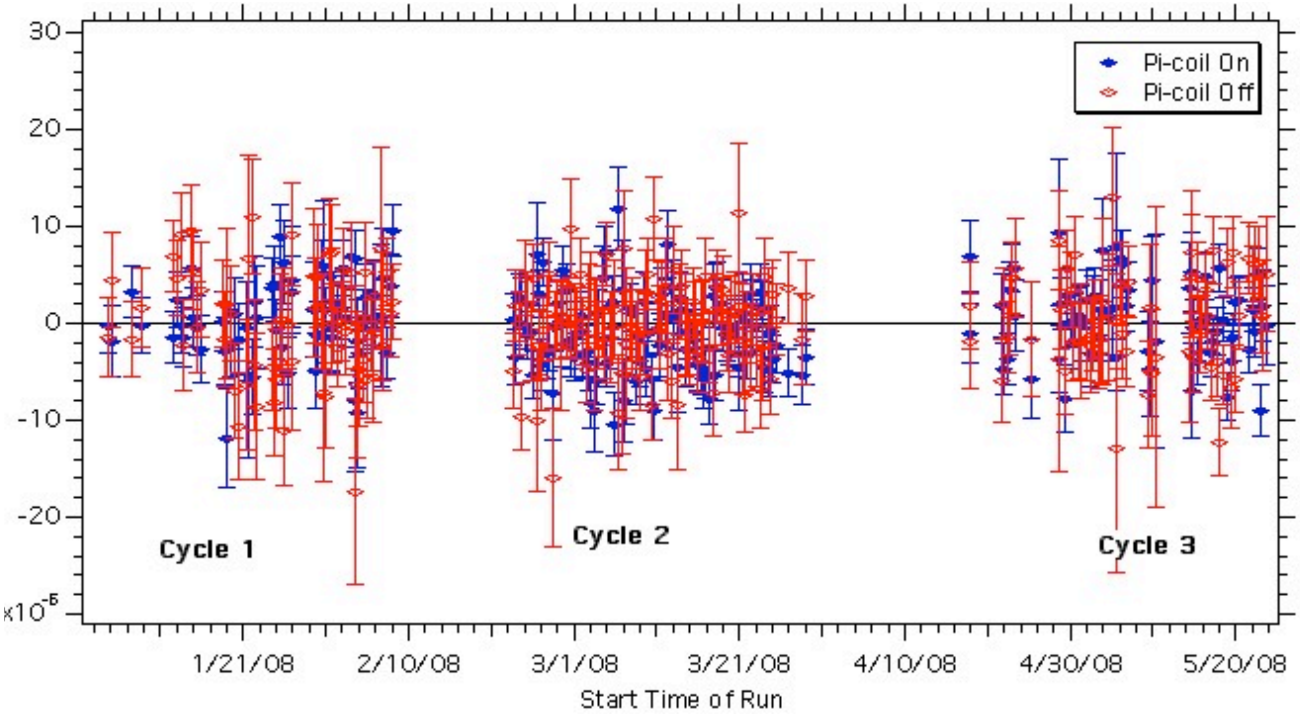


$$V(\vec{\sigma},\vec{r},\vec{v})=\frac{\hbar}{8\pi mc^2}g_A g_V\vec{\sigma}\bullet\vec{v}\,\frac{1}{r}e^{-\frac{r}{\lambda}}$$

- Induces an interaction between polarized and unpolarized matter
- Violates P symmetry
- Not very well constrained over “mesoscopic” ranges(millimeters to microns)
- Best investigated using a beam of polarized particles

Neutron Spin Rotation in n+4He





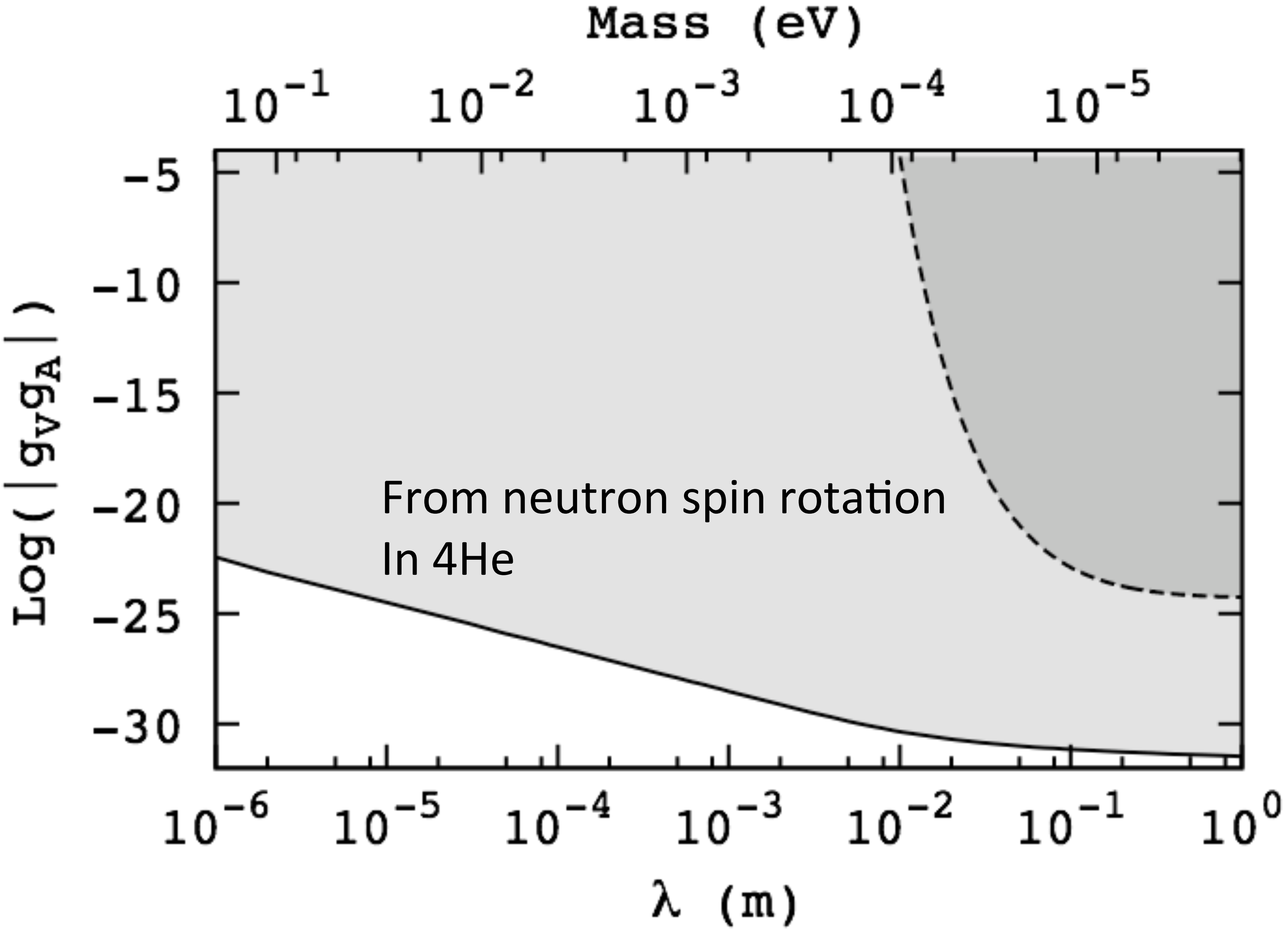
Transversely polarized neutrons corkscrew due to parity violation

ϕ_{PNC}= [+1.7 ± 9.1 (stat) ±1.4 (sys)] x 10^{-7} rad/m

W. M. Snow et al., Phys. Rev. C83, 022501(R) (2011).

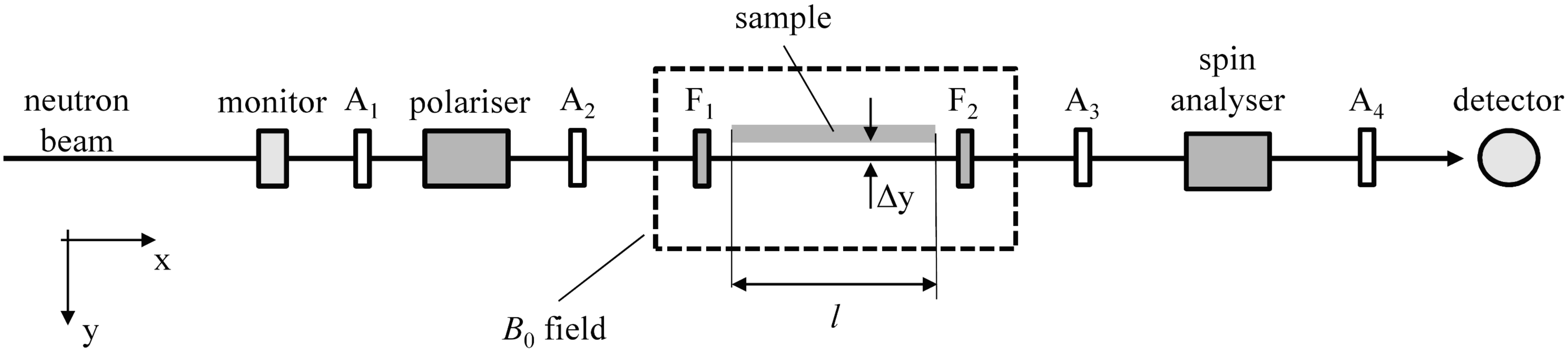
Sets upper bound on any P-odd neutron coupling to protons, neutrons, electrons in 4He

Constraints on V-A interactions



H. Yan, and W. M. Snow, arXiv:1211.6523 (2012), PRL 110, 082003 (2013)

Also Constraints on A-A interactions using Polarized Neutrons



Neutrons polarized along +z and –z feel different potentials from the mass. Put the spin state of the neutrons in a coherent superposition of +z and –z and look for a relative phase shift using the Ramsey technique (see Piegsa talk). Relation between the phase shift and the parameters of the potential is:

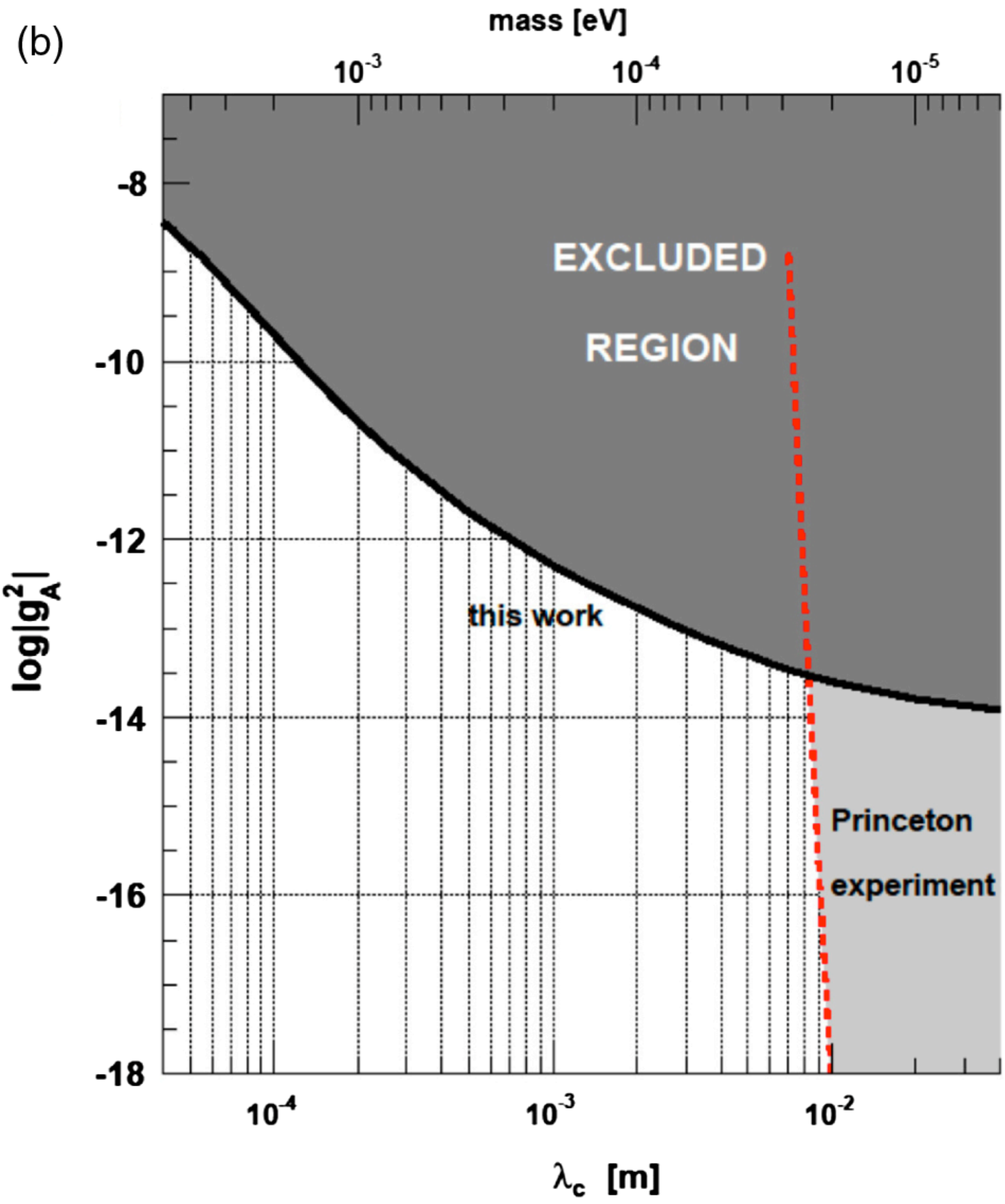
$$\phi = l \frac{g_A^2}{4} N \frac{\hbar}{mc} \lambda_c e^{-\frac{\Delta y}{\lambda_c}}$$

Constraints on A-A interactions

F. Piegsa and G. Pignol, PRL 108, 181801 (2012).

There is much room for further improvement in sensitivity

See F. Piegsa, A. Frank, and K. Taketani talks

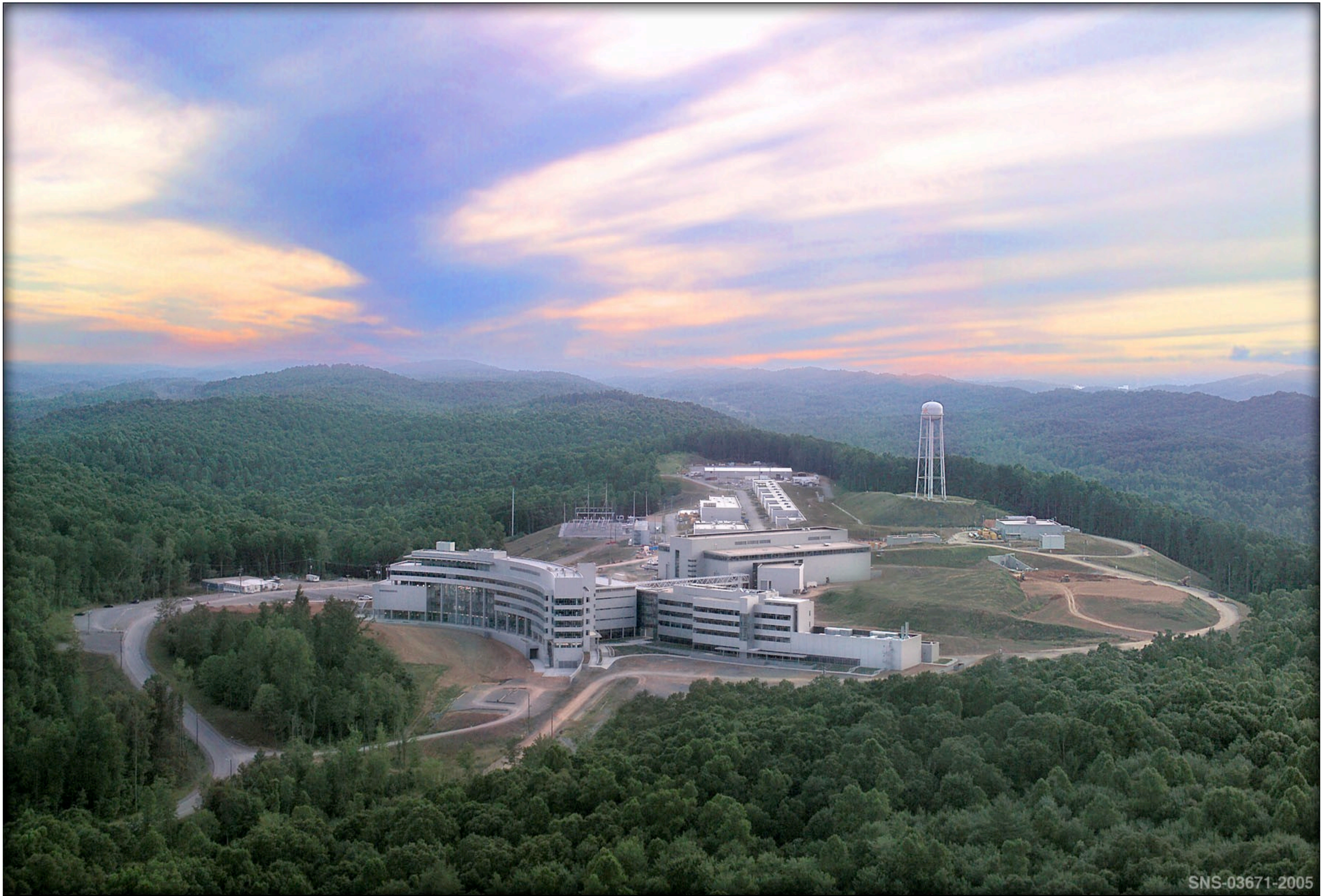


New forces: What could be learned at ESS?

a model-independent analysis shows that there are several different types of exotic interaction which can be sought, and general arguments show that weakly-coupled interactions with ranges accessible to slow neutron measurement can always be just around the corner

Not easy to predict ahead of time what specific ideas will appear, but it is hard to believe that theorists will be uncreative in attempting to understand dark matter and dark energy

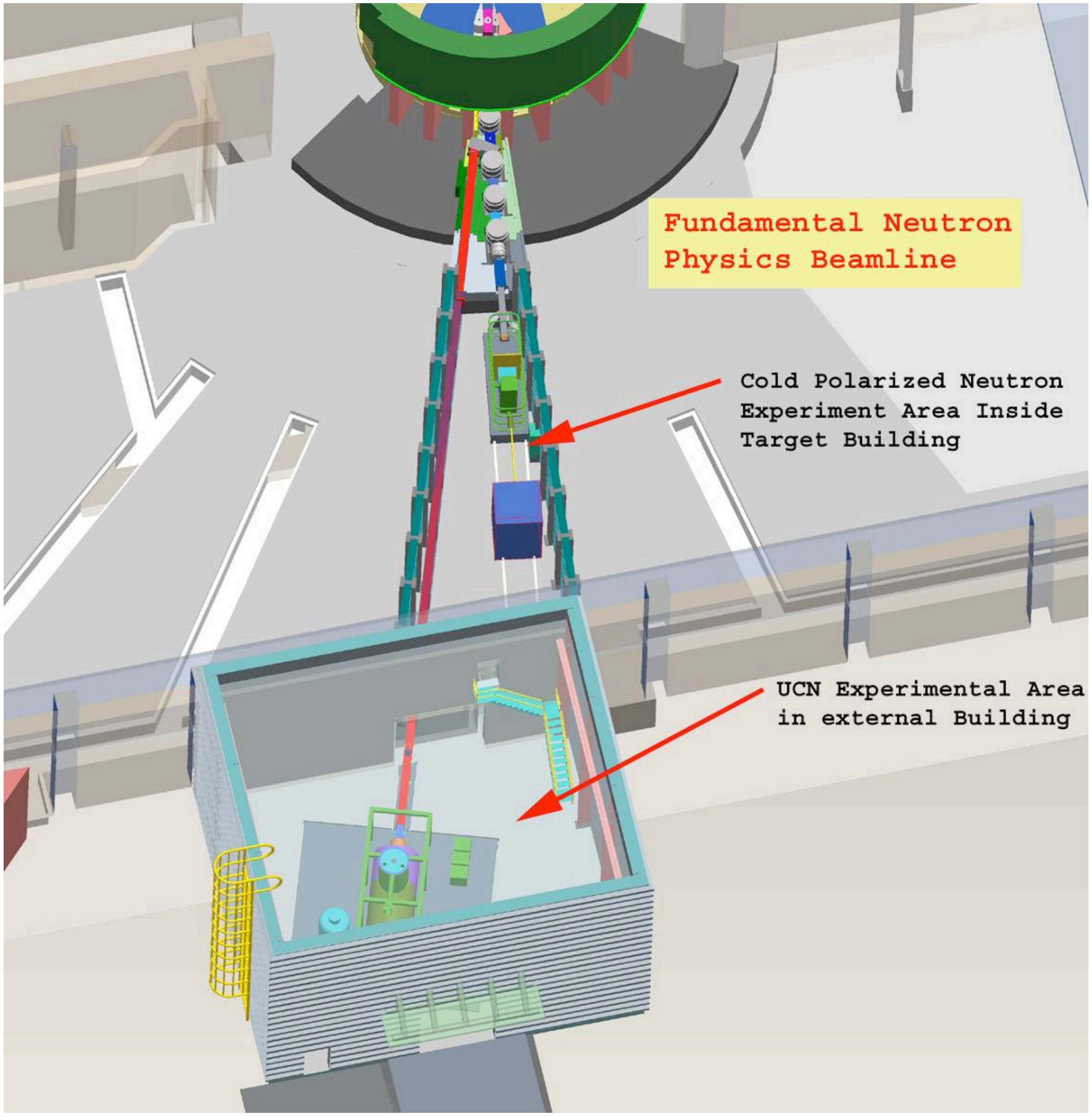
Neutron energy/momentum transfer information from measurements with a cold beam at a pulsed ESS source can be used to scan a wide dynamic range of interaction ranges and seek for the predicted momentum transfer dependence for an interaction of known form



The Spallation Neutron Source at ORNL

www.sns.gov

Flight Path 13 (Cold Moderator) is Allocated for Nuclear Physics



Fundamental Neutron Physics Beamline

Cold Polarized Neutron Experiment Area Inside Target Building

UCN Experimental Area in external Building

Why the SNS for fundamental neutron physics? (our list at the time)

1. Accurate TOF and the use of spin polarized ^{3}He as a neutron spin filter allows very accurate measurement of neutron polarization.

2. TOF will allow substantial reduction in systematic effects in very sensitive experiments (For example the effects of stray magnetic fields in “spin rotation” experiments).

3. A low-background, low “stray field,” low vibration external facility will allow sensitive Ultra-Cold Neutron Experiments (neutron lifetime and neutron edm)

4. The SNS will have a higher time averaged neutron **fluence** than any other facility in the US.

5. …

Why ESS for fundamental neutron physics?

<u>Neutron decay</u>: pulsed source can reduce background in detectors of neutron decay products and provide energy information useful for absolute neutron polarization systematics

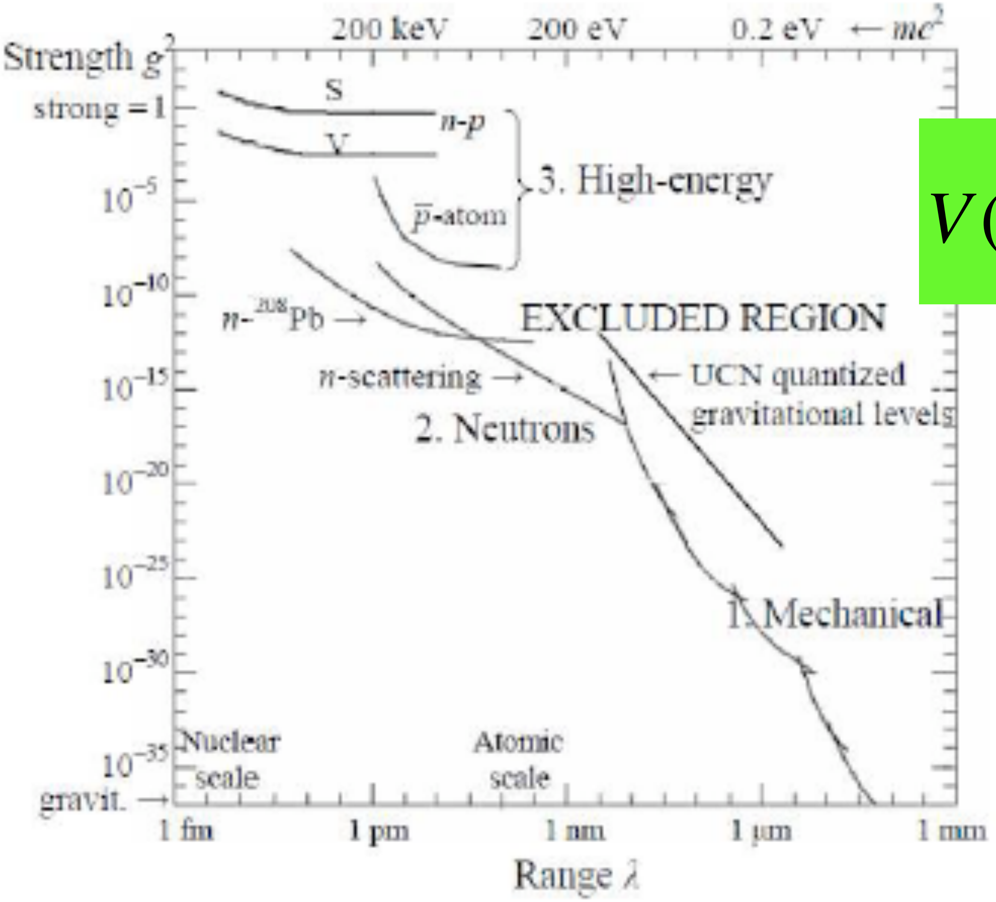
<u>NN weak interactions</u>: neutron energy from time-of flight needed for control of systematic errors (P-odd asymmetries of ~1E-7 typical for these measurements)

<u>New force searches</u>: neutron energy info needed to identify range of interaction through momentum dependence

<u>Ultracold neutrons</u>: opportunity to build on experience at many facilities and use pulsed nature of source to construct very intense source

AND all of the other opportunities we will discuss at this meeting!

Constraints on Yukawa interactions



$$V(\vec{r}) = \frac{\hbar}{8\pi mc} g^2{}_s \frac{1}{r} e^{-\frac{r}{\lambda}}$$

Neutron measurements give the best constraints on new Yukawa interactions over 5 orders of magnitude of distance scales

FIG. 16. Exclusion plot on new short-range interactions. Shown are the strength g^2 of the interaction versus its range λ. The upper scale gives the corresponding mass $m = h/\lambda c$ of the exchanged boson. Values above the curves shown are excluded by experiment. The constraints from neutron scattering in the subatomic range are combined from several different neutron measurements, see Nesvizhevsky *et al*. (2004, 2008). Most curves are adapted from Kamyshkov *et al*. (2008)

Dubbers/Schmidt, Rev. Mod. Phys (2011).

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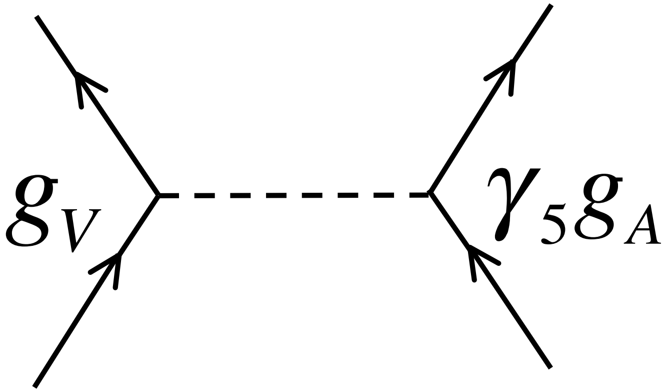
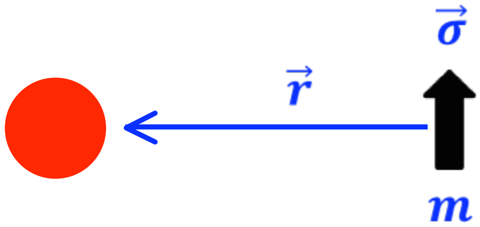
[Dobrescu/Mocioiu 06, general construction of interaction between nonrelativistic fermions]





$$V(\vec{\sigma},\vec{r},\vec{v}) = \frac{\hbar}{8\pi mc^2} g_A g_V \vec{\sigma} \bullet \vec{v} \frac{1}{r} e^{-\frac{r}{\lambda}}$$

- Induces an interaction between polarized and unpolarized matter
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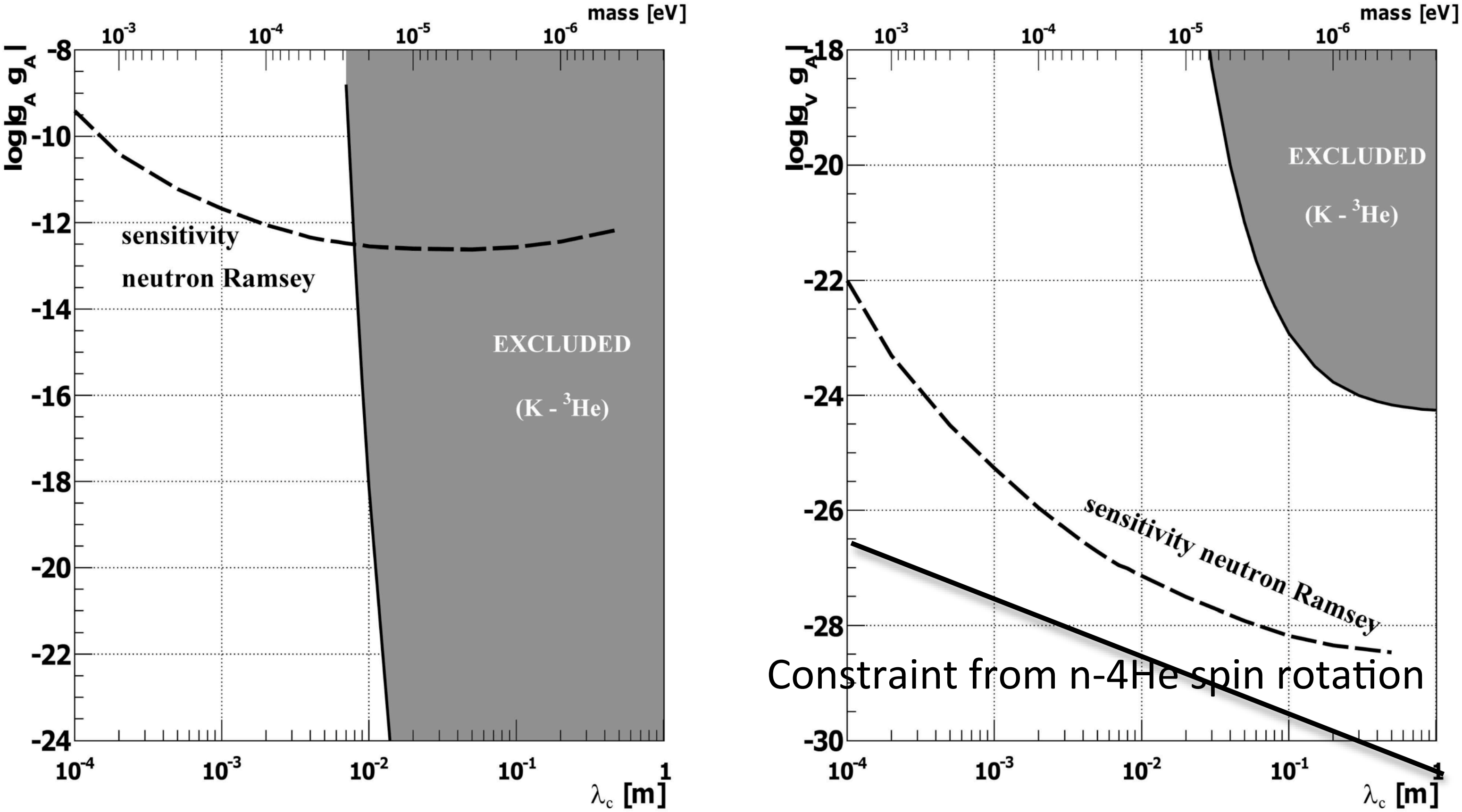
Present/Proposed Constraints on Possible V-V and V-A interactions



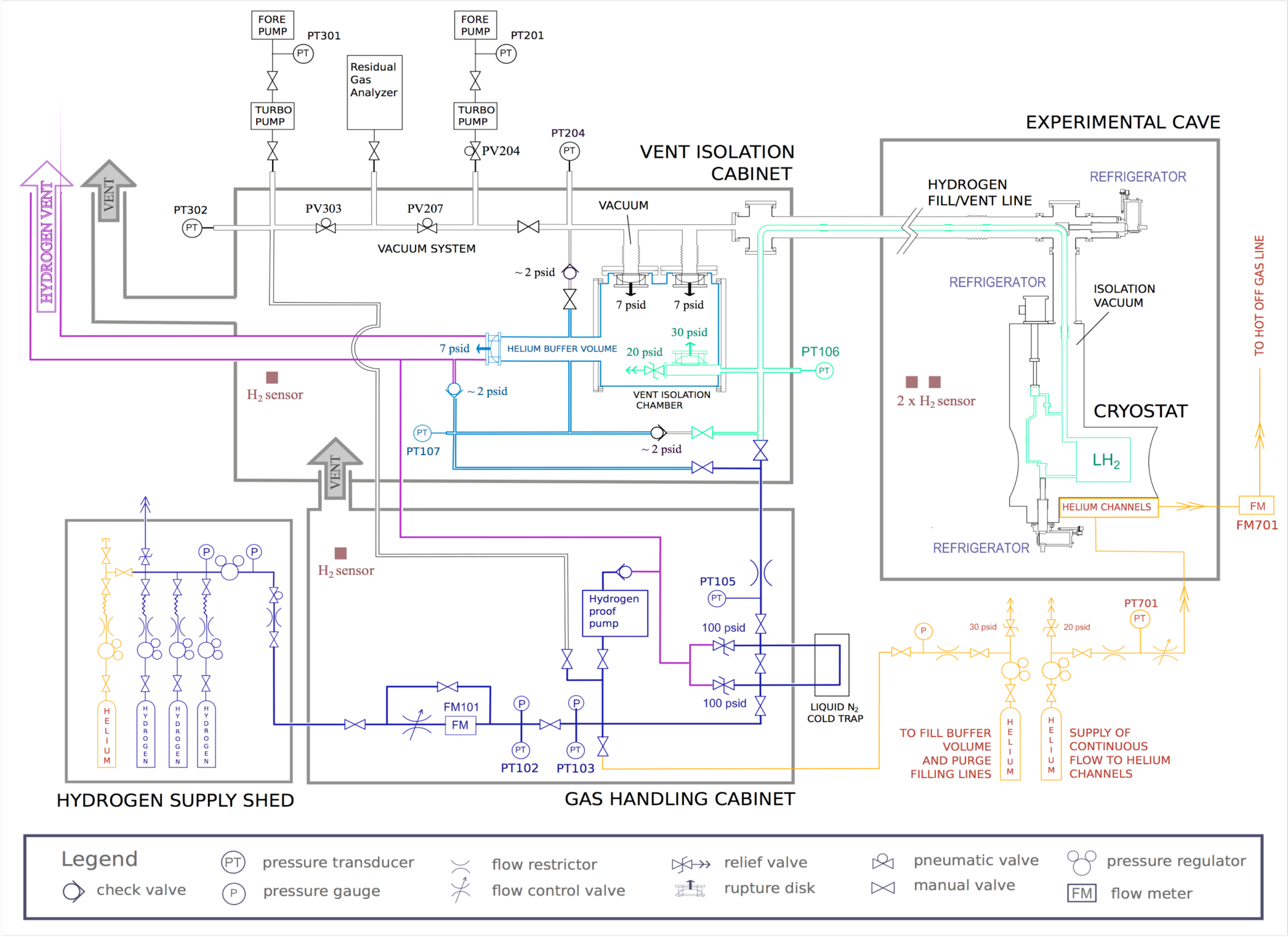
Constraint from n-4He spin rotation

Figure 2. Expected sensitivity of the neutron Ramsey setup (dashed lines) for the axial-axial interaction (left) and the vector-axial interaction (right) as a function of the Compton wavelength λ_c. The grey shaded areas represent the exclusion by the Princeton experiment [12].

Image/Proposed Future Constraints from F. M. Piegsa, G. Pignol, arXiv:1111.1944 [nucl-ex] (2011

NPDGamma Apparatus at SNS

Hydrogen Safety: Nontrivial Requirement!

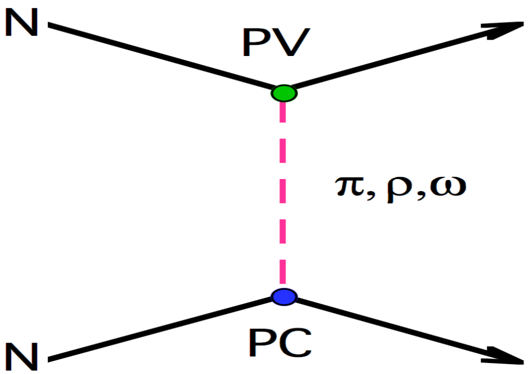


q-q Weak Interaction: Isospin Dependence

At energies below the W± and Zo mass, the q-q weak interaction can be written in a current-current form, with contributions from charged currents and neutral currents.

$$M_{CC} = \frac{g^2}{2M_W^2} J^{\dagger}_{\mu,CC} J^{\mu}_{CC} ; M_{NC} = \frac{g^2}{\cos^2\theta_W M_Z^2} J^{\dagger}_{\mu,NC} J^{\mu}_{NC}$$

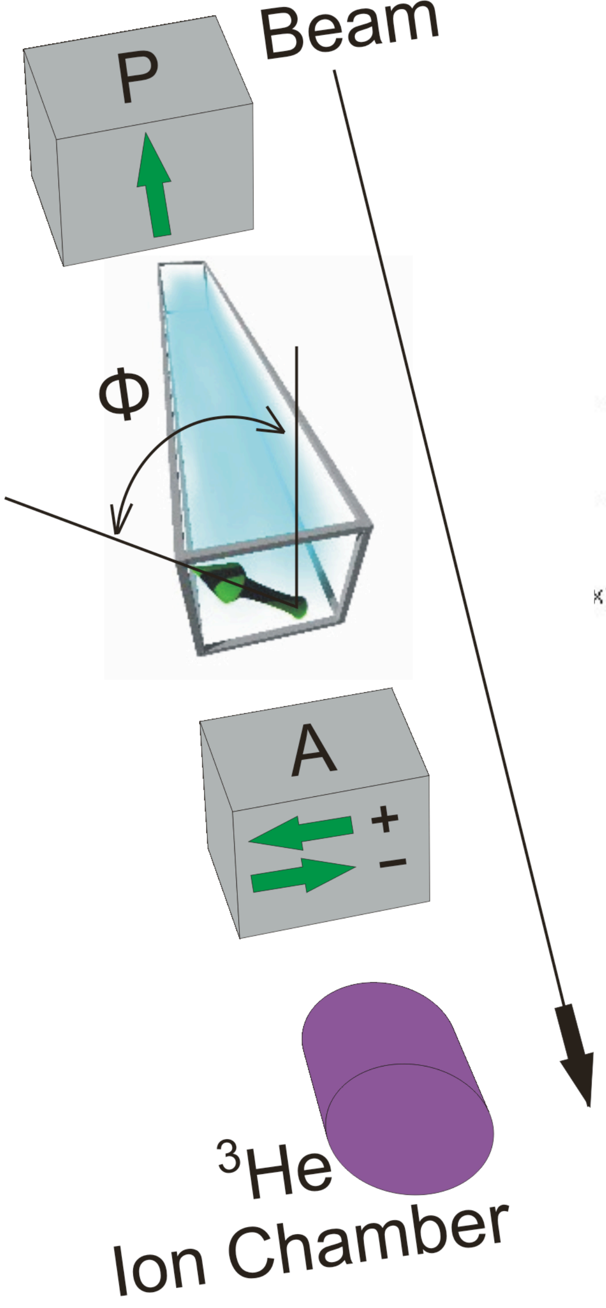
$$J^{\mu}_{CC} = u\frac{-1}{2}\gamma^{\mu}(1-\gamma^5)\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} d \\ s \end{pmatrix} ; J^{\mu}_{NC} = \sum_{q=u,d} q\frac{-1}{2}\gamma^{\mu}(c^q_V - c^q_A\gamma^5)q$$

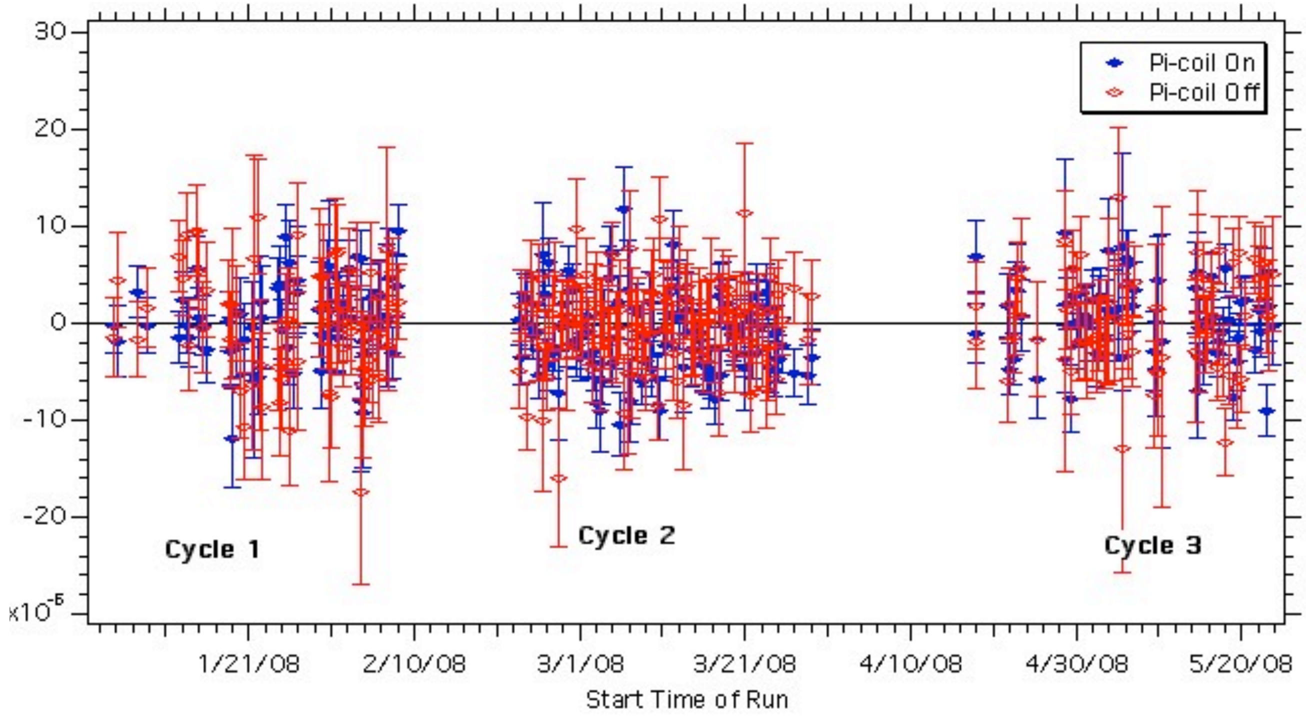


possible isospin changes from q-q weak interactions	
	Δ I
charged current	0, 2 : (~V^2_{ud}) 1 : (~V^2_{us})
neutral current	0, 1, 2

Charged currents in ΔI=1 NN weak processes are Cabbibo-suppressed at tree level

Neutron Spin Rotation in n+4He





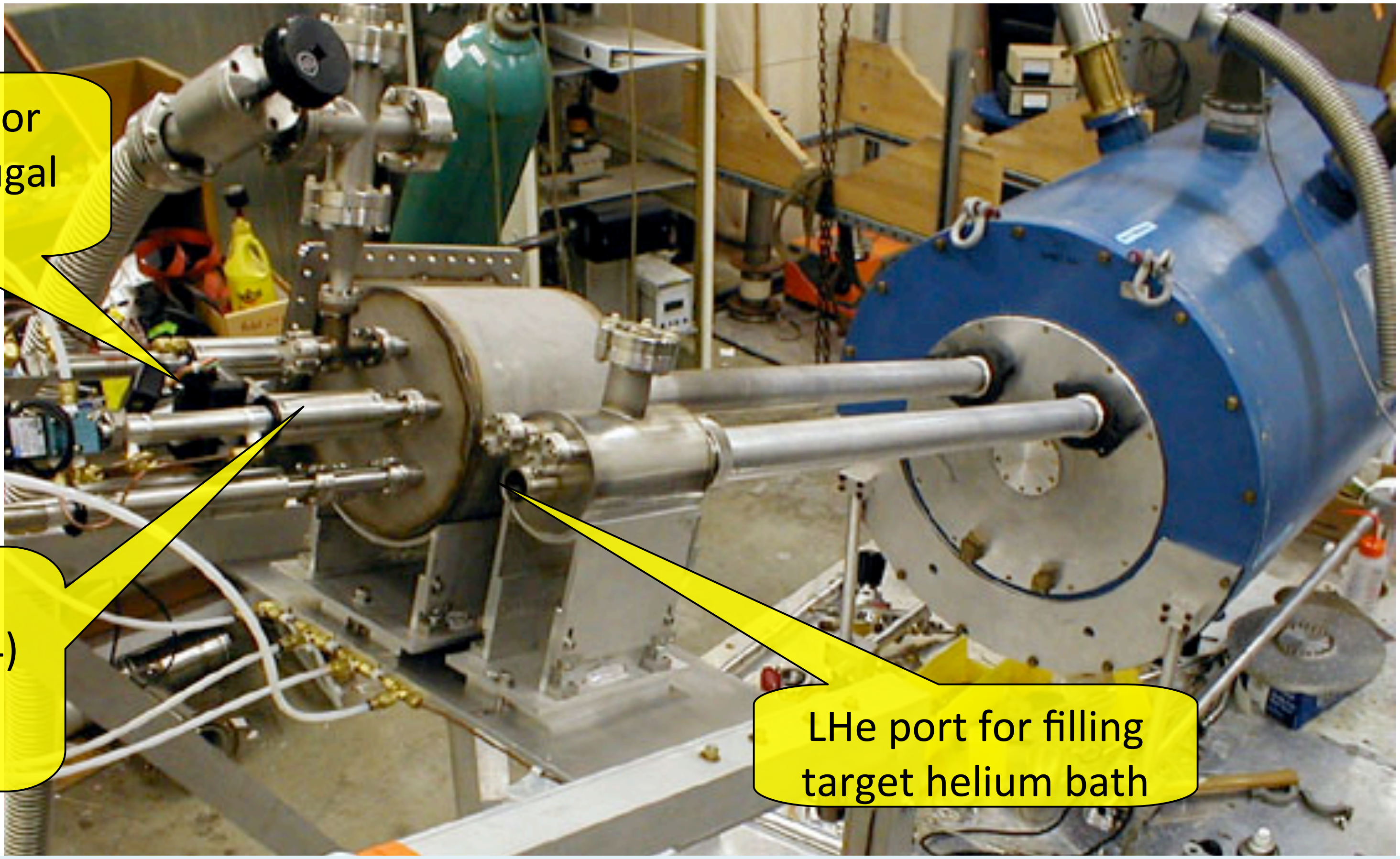
Transversely polarized neutrons corkscrew due to weak interaction

ϕ_{PNC}= [+1.7 ± 9.1 (stat) ±1.4 (sys)] x 10^{-7} rad/m

W. M. Snow et al., Phys. Rev. C83, 022501(R) (2011).

PLAN: experiment to be repeated at NIST, ~1 x 10^{-7} rad/m goal

Liquid Helium Cryostat and Motion Control



Stepper motor turns centrifugal pump

Pneumatic actuators (x4) raise/lower drainpipes

LHe port for filling target helium bath

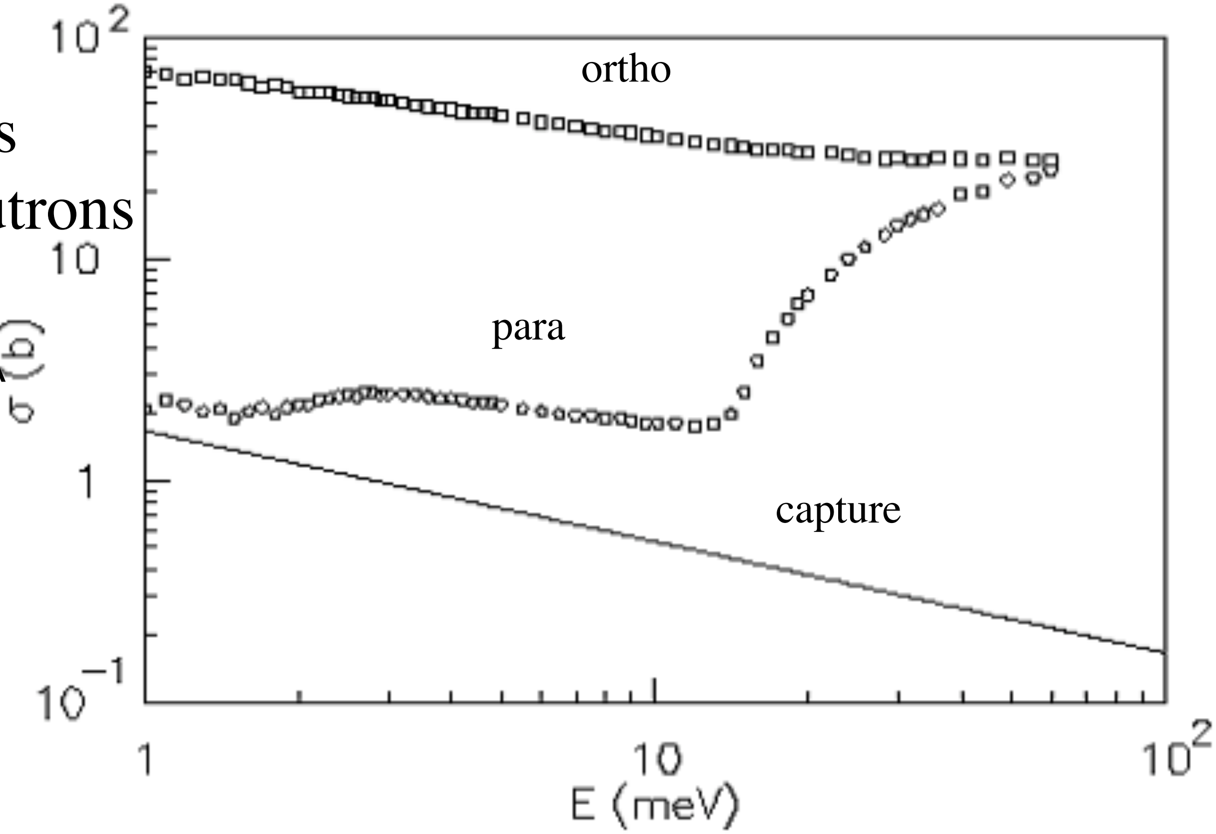
- Nonmagnetic movement of liquid helium.

•Cryogenic target of 4K helium, volume~10 liters

C. D. Bass et al, Nucl. Inst. Meth. A612, 69-82 (2009).

Why is liquid parahydrogen a good choice?

Parahydrogen becomes transparent to cold neutrons -> can extract more neutrons from deeper \ in the moderator



For similar reason can place Be reflector in FRONT of exit of cold source to increase brightness, it is transparent below Bragg cutoff but reflects higher E neutrons back inside for more moderation

Cold Moderators: Kiyanagi: p-H$_2$ is the best! (certainly at high power)

M. Harada, M. Teshigawara, N. Watanabe,T. Kai and Y. Ikeda , ICANS XVI

Pulse characteristics with ortho-para hydrogen ratio

- **o-p H$_2$ ratio plays an important role in pulse characteristics.**
- **100% p-H$_2$ gives the best performance, the highest I$_{peak}$ with the narrowest pulse width & the fastest pulse-tail decay in E$_n$ < 50 meV.**