中性子基礎物理

北口雅暁

名古屋大学　素粒子宇宙起源研究所／素粒子物性研究室（Φ研）

Masaaki KITAGUCHI
Kobayashi-Maskawa Institute
Laboratory for Particle Properties (Φ-Lab.), Department of Physics
Nagoya University

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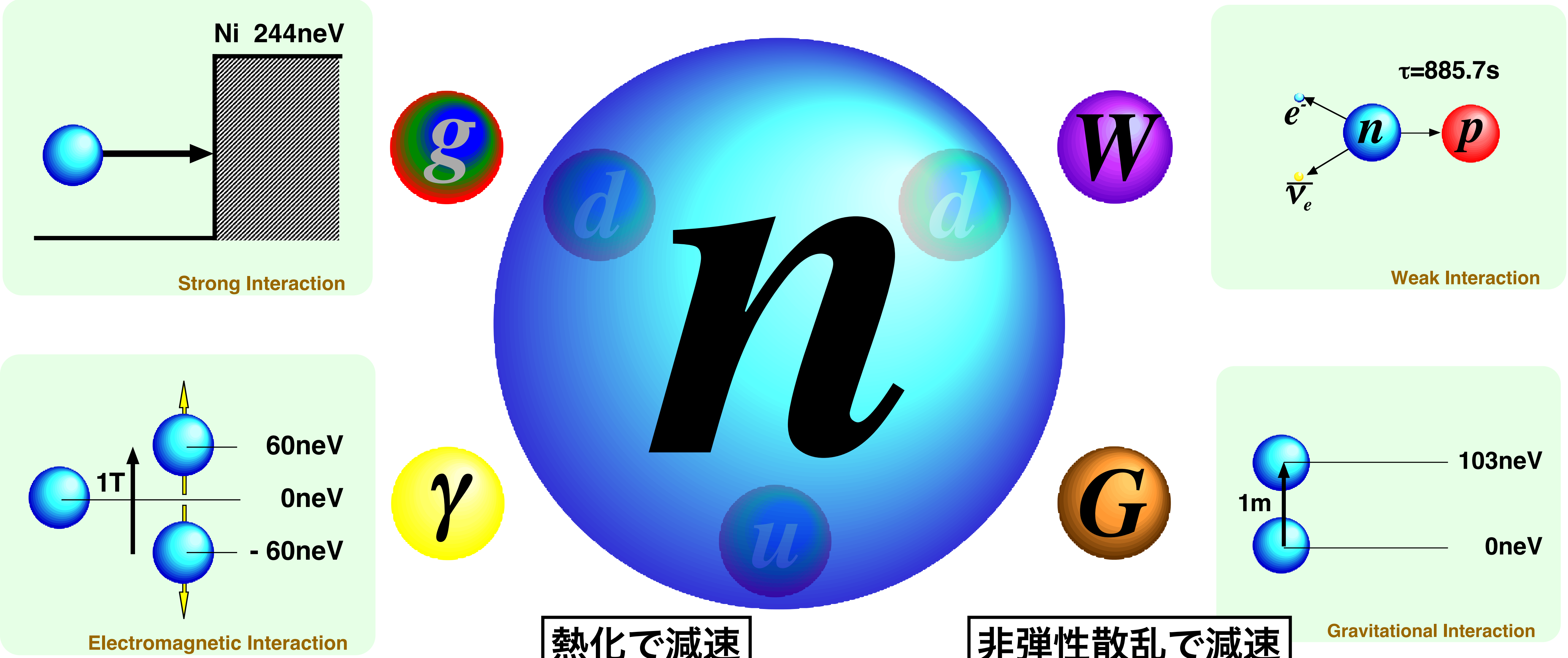
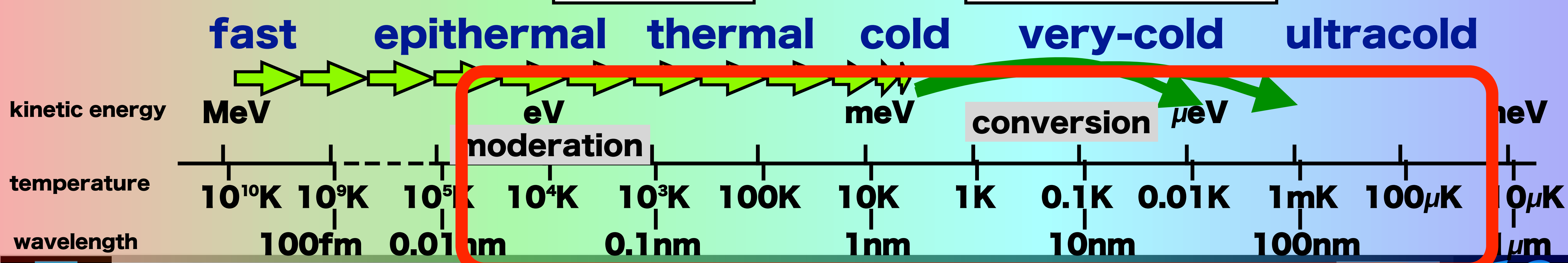
Fundamental Physics with Neutrons

低エネルギー中性子は４つの相互作用が同じオーダーで働く



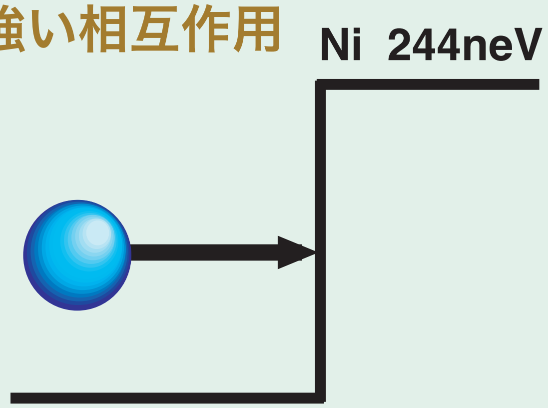
熱化で減速

非弾性散乱で減速

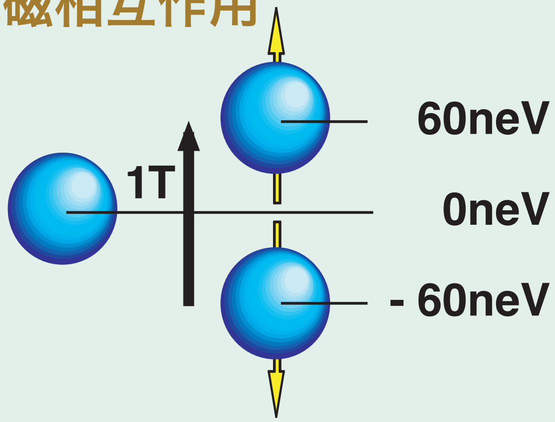


Fundamental Physics with Neutrons

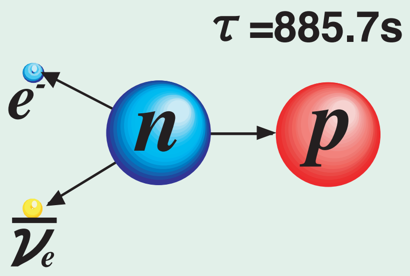
強い相互作用



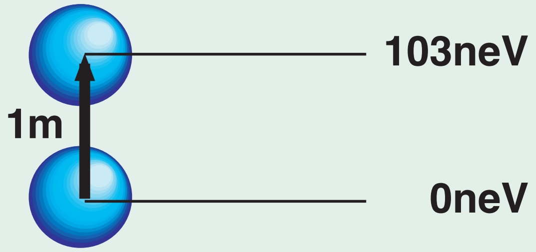
電磁相互作用



弱い相互作用

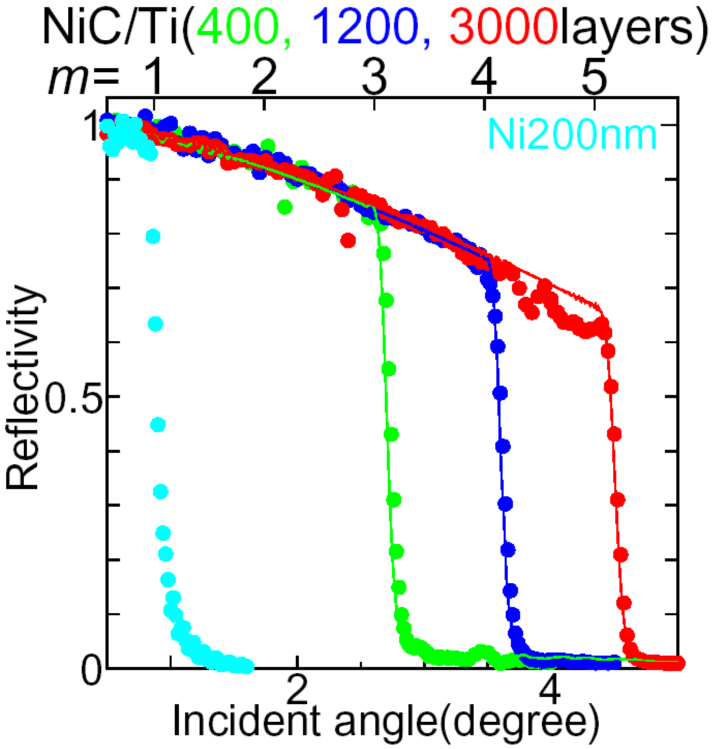


重力相互作用



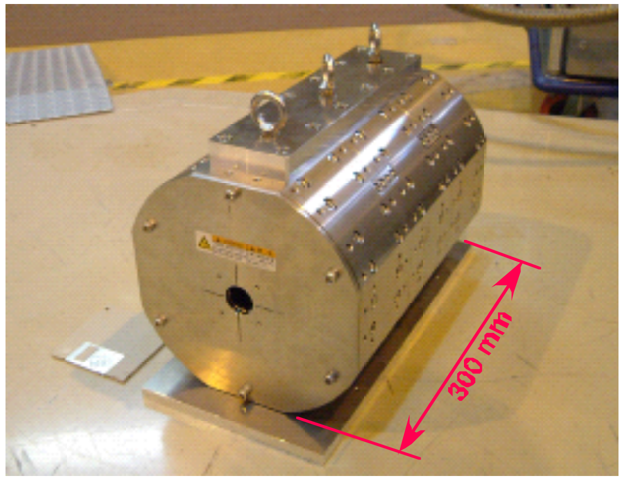
これらの相互作用を使って光学的に制御できる

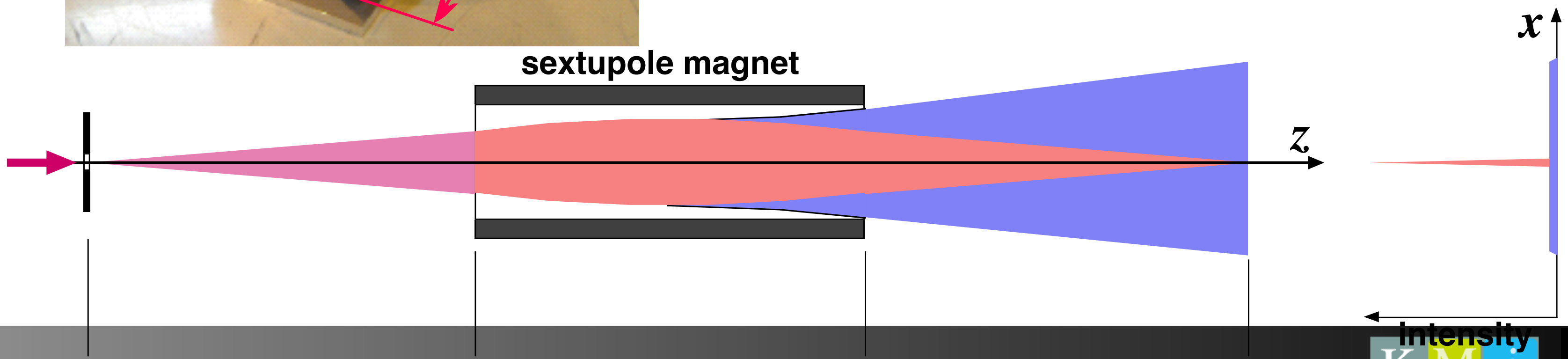
中性子スーパーミラー



Incident wavelength 0.88nm(FWHM:2.4%)

磁気レンズ、偏極子

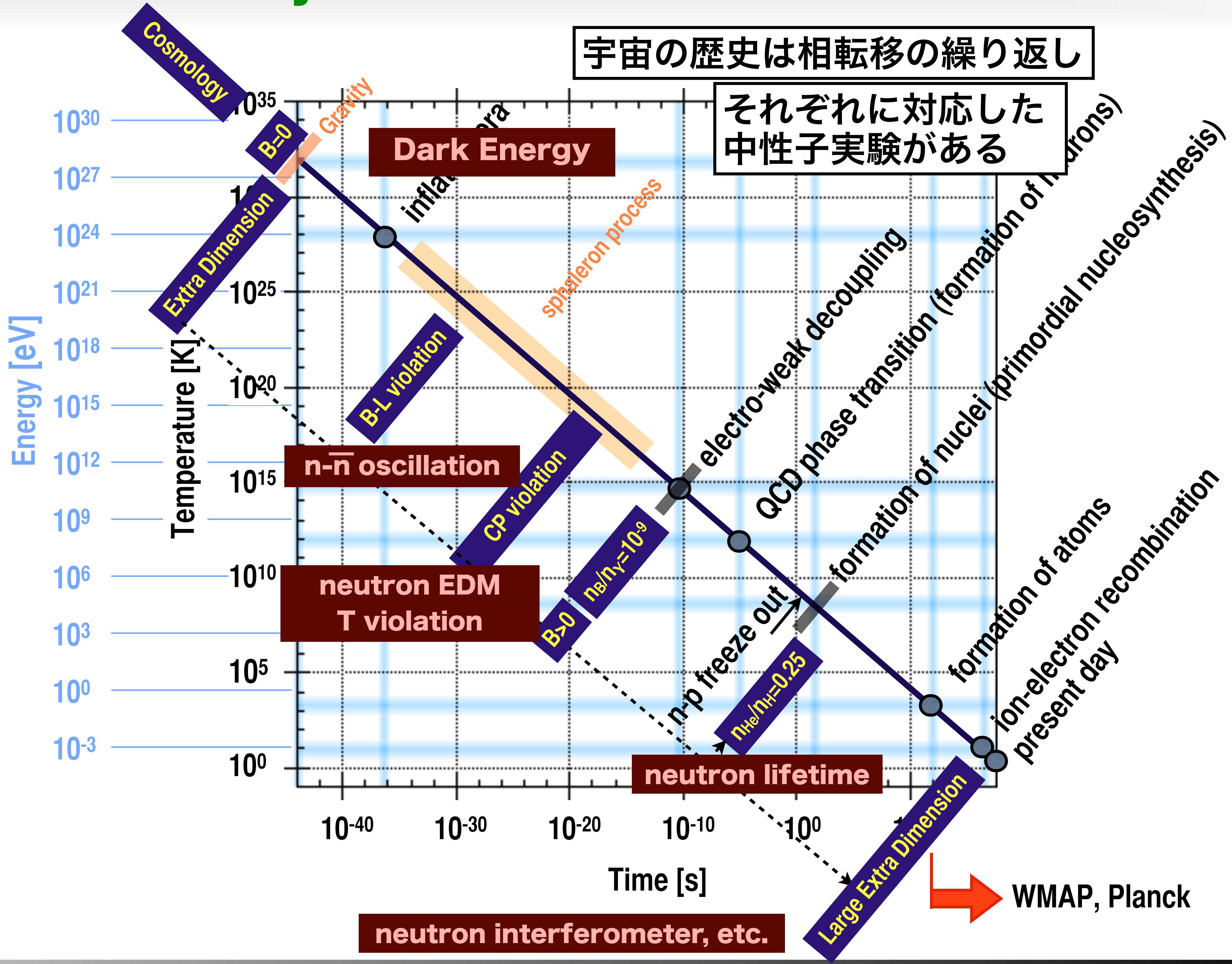




Fundamental Physics with Neutrons

宇宙の歴史は相転移の繰り返し

それぞれに対応した
中性子実験がある

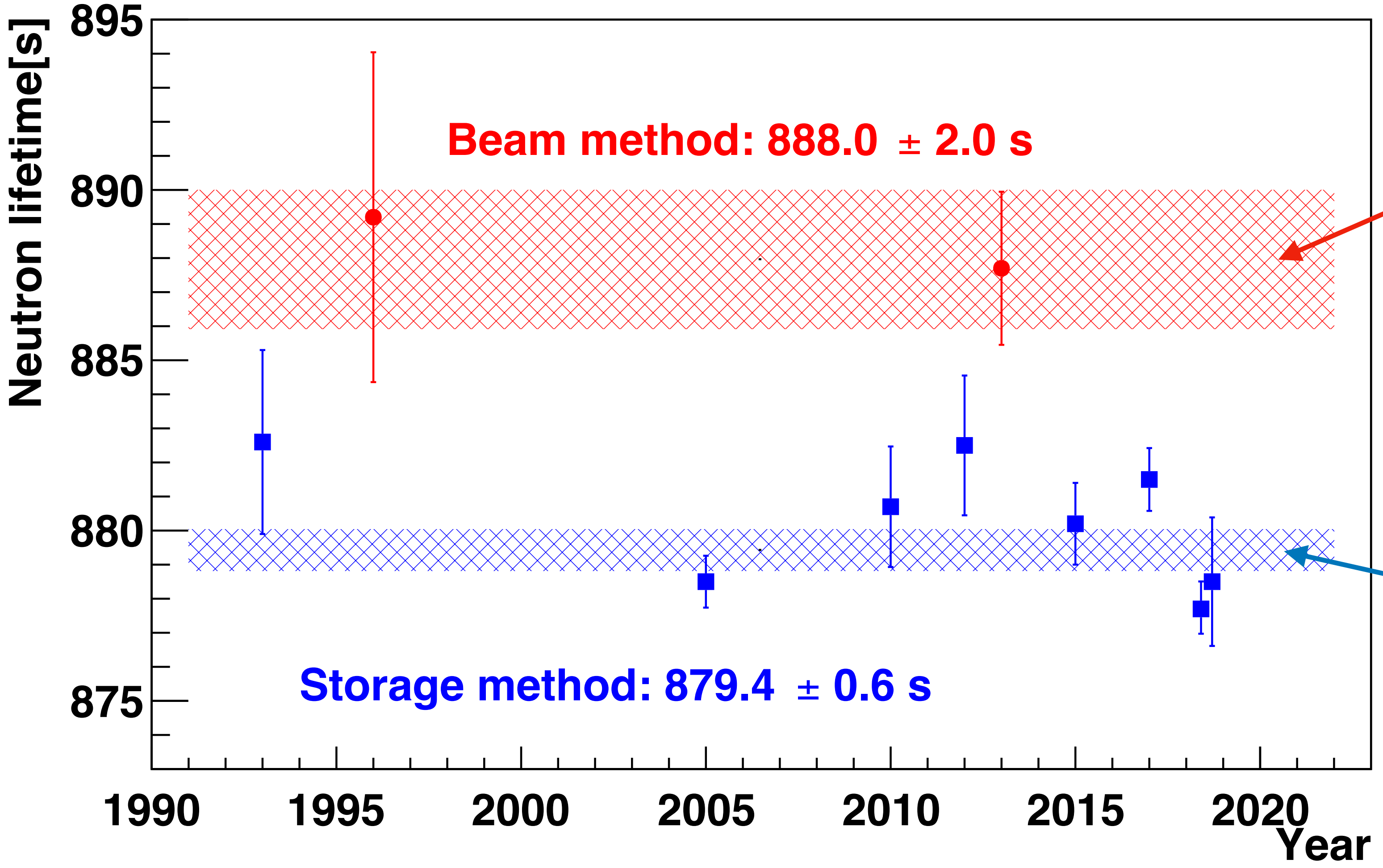


Neutrons Lifetime

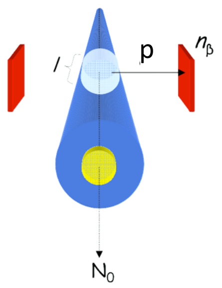
中性子寿命

$n \rightarrow p + e^{-} + \bar{\nu}_e$　　寿命　879.4 ± 0.6 s　(PDG2019)

実験手法によって測定値が異なっている。

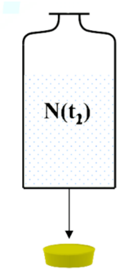


beam法: 崩壊生成物を数える



$$-\frac{\mathrm{d}N}{\mathrm{d}t} = \frac{N}{\tau}$$

storage法: 生き残りを数える (bottle法、UCN法)



$$\frac{N_1}{N_2} = e^{-(t_1 - t_2)/\tau}$$

Neutron Lifetime - Big Bang Nucleosynthesis

Thermal Equilibrium (T > 1 MeV)

$$p + \bar{\nu}_e \leftrightarrow n + e^+$$
$$n + \nu_e \leftrightarrow p + e^-$$

$n/p \sim e^{-Q/T}$

Neutron lifetime

After Freezeout

$n/p \sim 1/6$

n/p decreases due to neutron decay

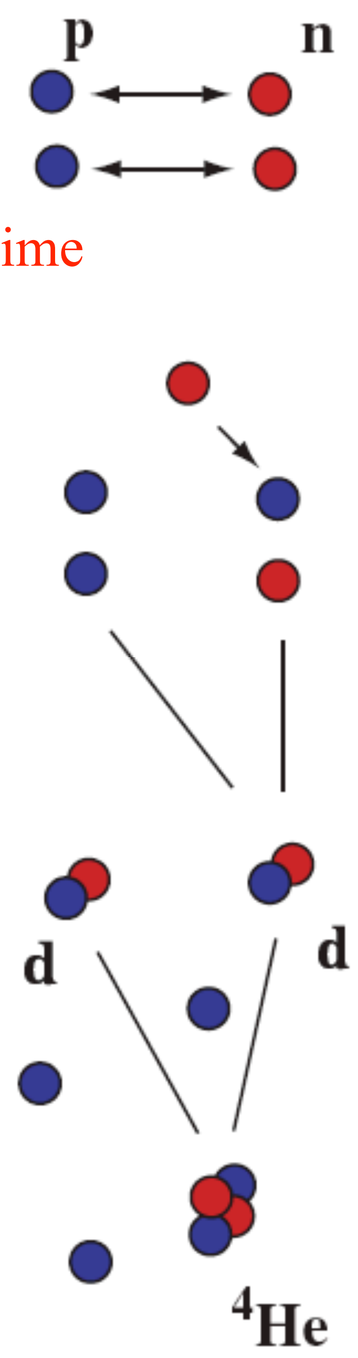
$$n \rightarrow p + e^- + \bar{\nu}_e$$

Nucleosynthesis (T~0.1 MeV)

Light elements are formed.

$$p + n \rightarrow d + \gamma$$
$$d + d \rightarrow {}^4He + \gamma$$

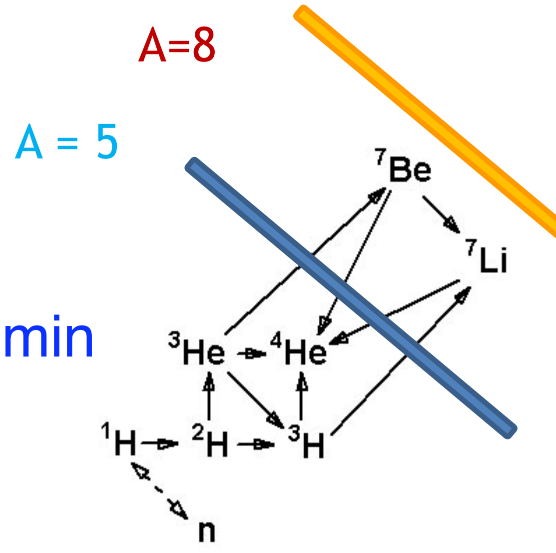
almost all neutrons present → ^4He



1μs

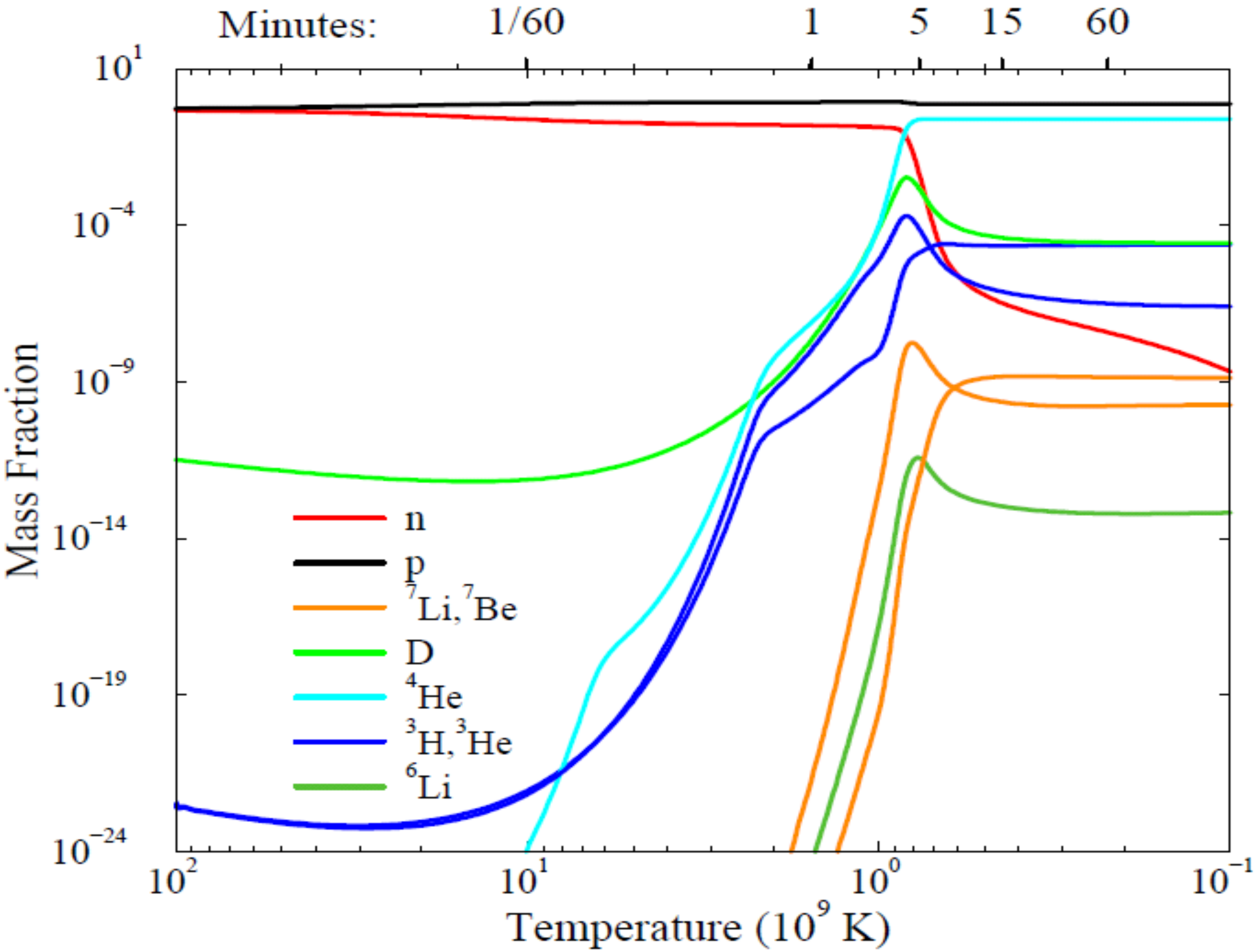
1 s

10 min

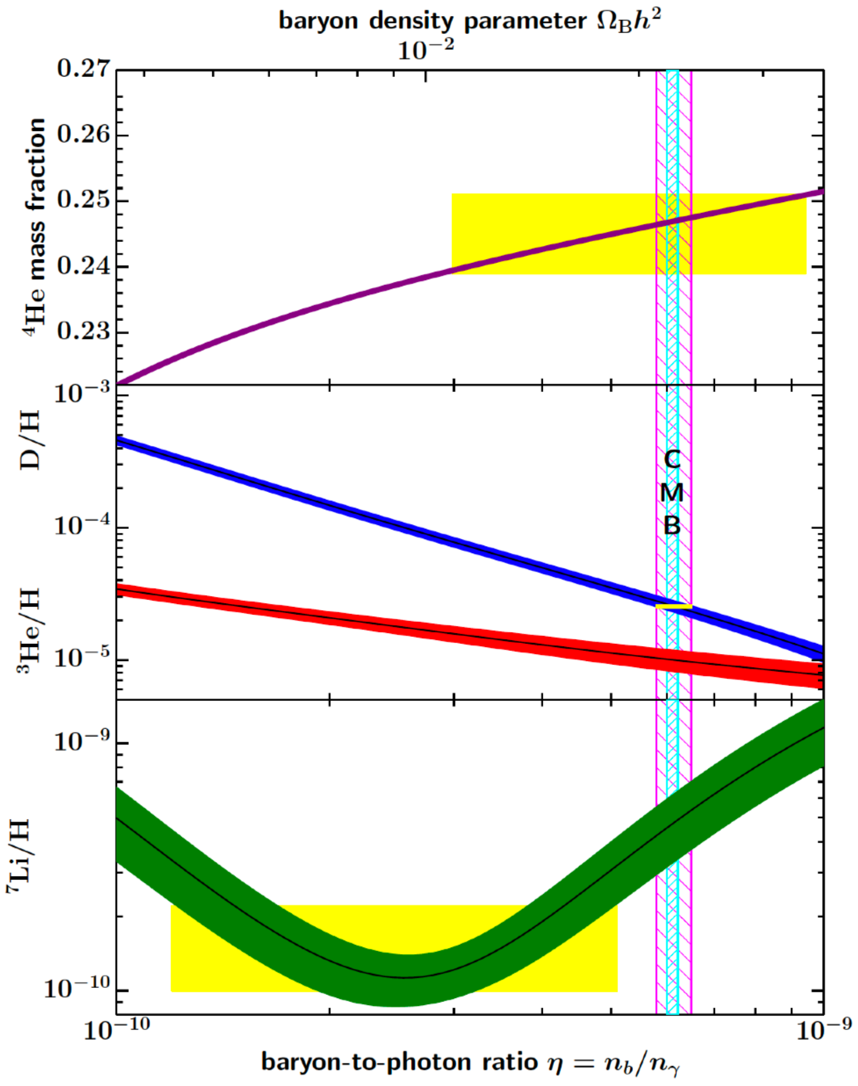


Neutron lifetime dominates theoretical uncertainty in ^4He abundance.

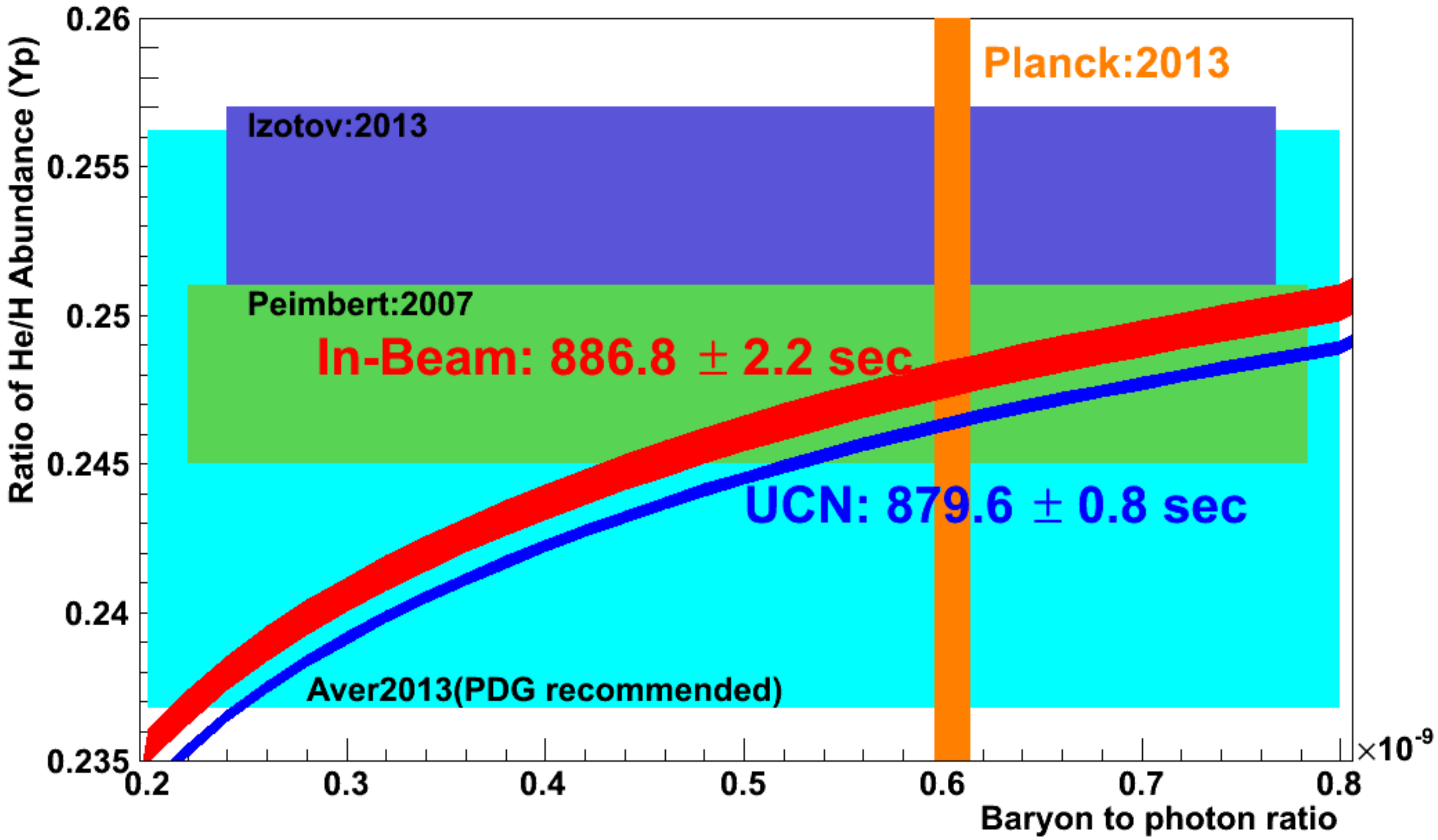
Neutron Lifetime - Big Bang Nucleosynthesis



Neutron Lifetime - Big Bang Nucleosynthesis



[PDG ('20)]

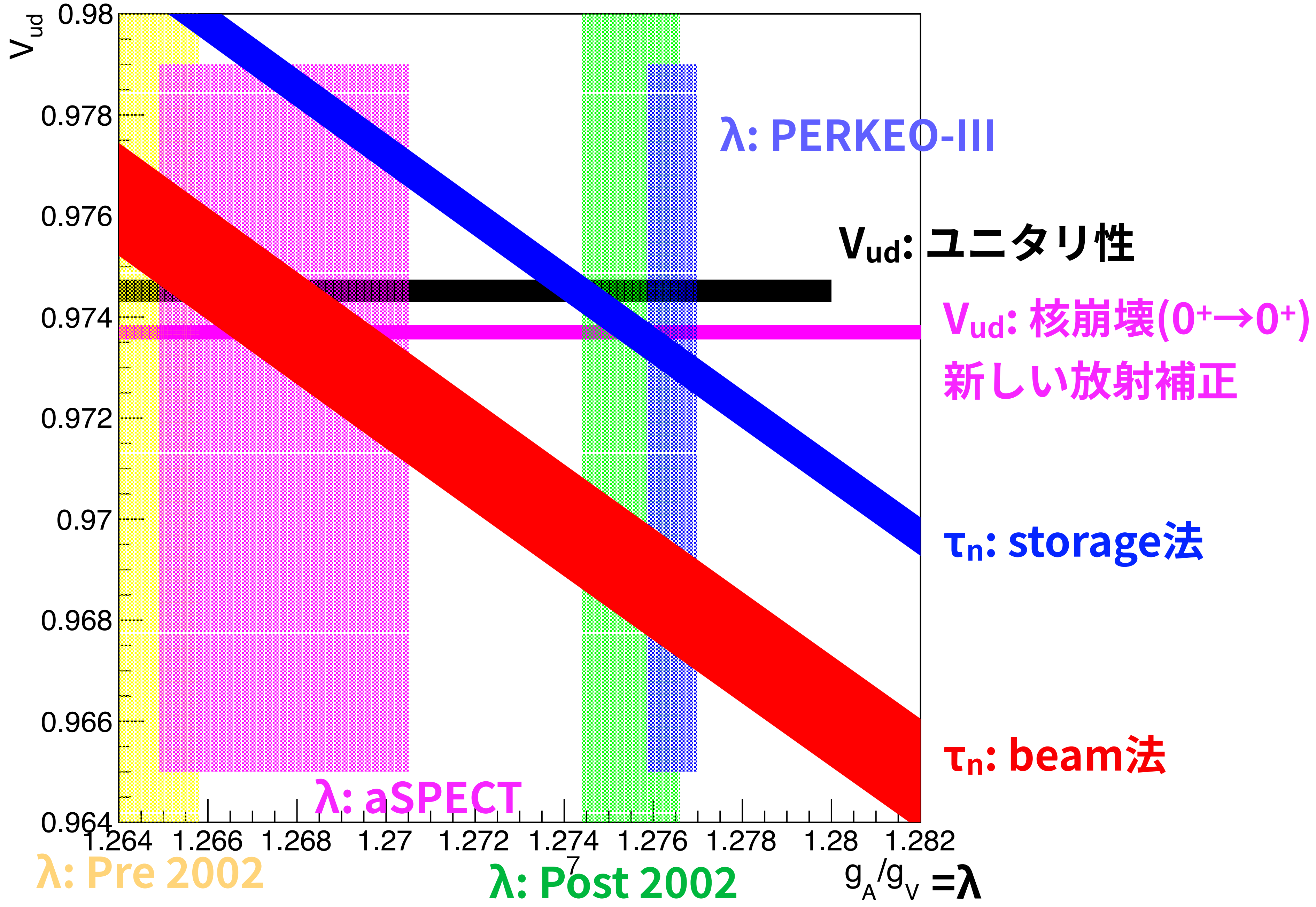


Neutron Lifetime - CKM Unitarity

$$|V_{\mathrm{ud}}|^2 = \frac{2\pi^3}{\tau_{\mathrm{n}}(1+3\lambda^2)G_F{}^2 m_{\mathrm{e}}^2 f(1+\mathrm{RC})} = \frac{(4908.7 \pm 1.9)\mathrm{s}}{\tau_{\mathrm{n}}(1+3\lambda^2)}$$

τ_{n} 中性子寿命

$\lambda = g_A/g_V$



Neutron Lifetime - CKM Unitarity

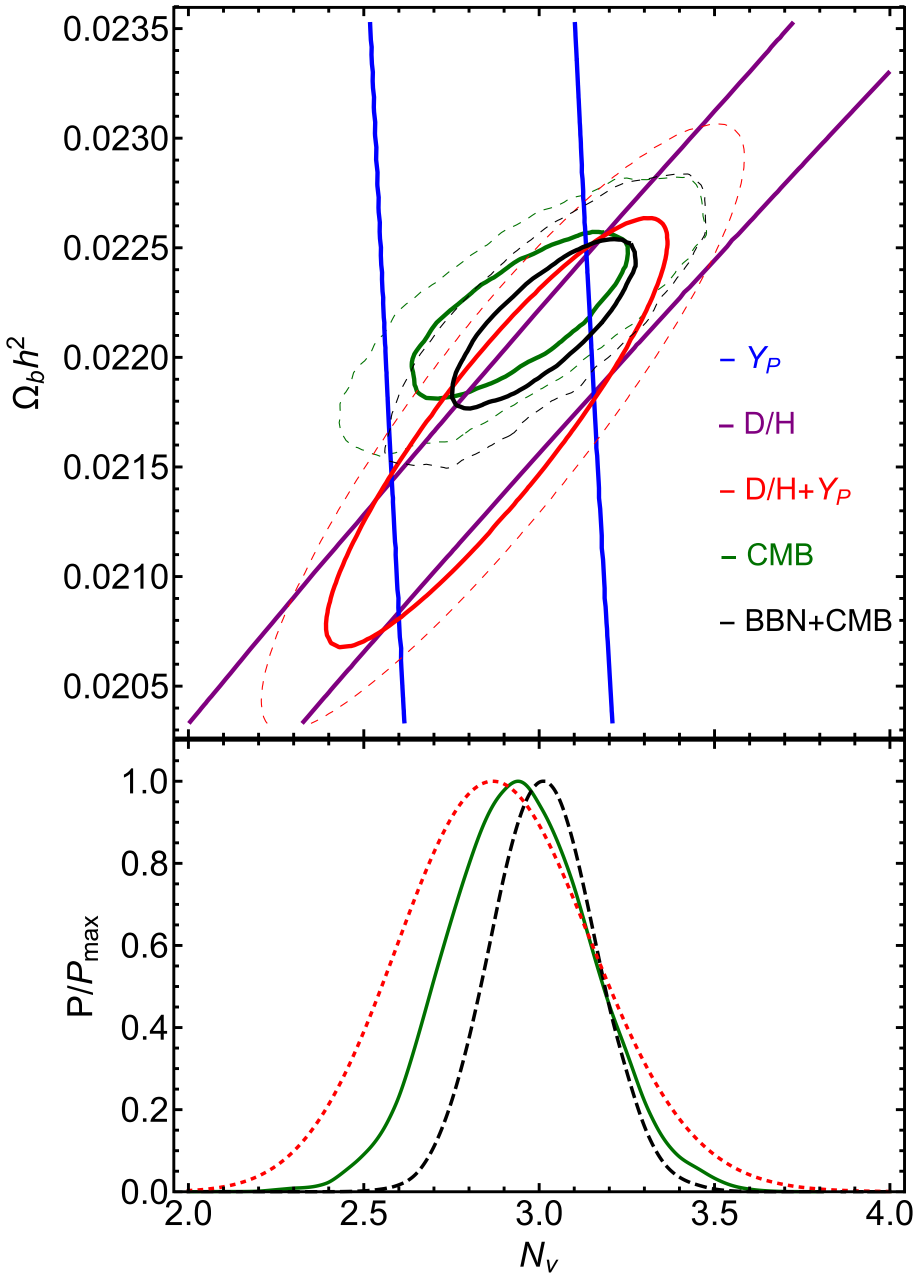


Fig. 29. Top: $P(\Omega_b h^2, N_\nu)$ with 68.27% and 95.45% contours for different combinations of data. Bottom : $P(N_\nu)$ from marginalization. Continuous green is from CMB only, dotted red from BBN only, and dashed black is the combination of BBN and CMB. Note that the average value of N_ν for the combination of BBN and CMB is not between the corresponding averages obtained from CMB and BBN considered separately. There is no contradiction since the nearly elliptic preferred regions in the $(\Omega_b h^2, N_\nu)$ space for BBN and CMB taken separately overlap away from the line defined by their respective average points.

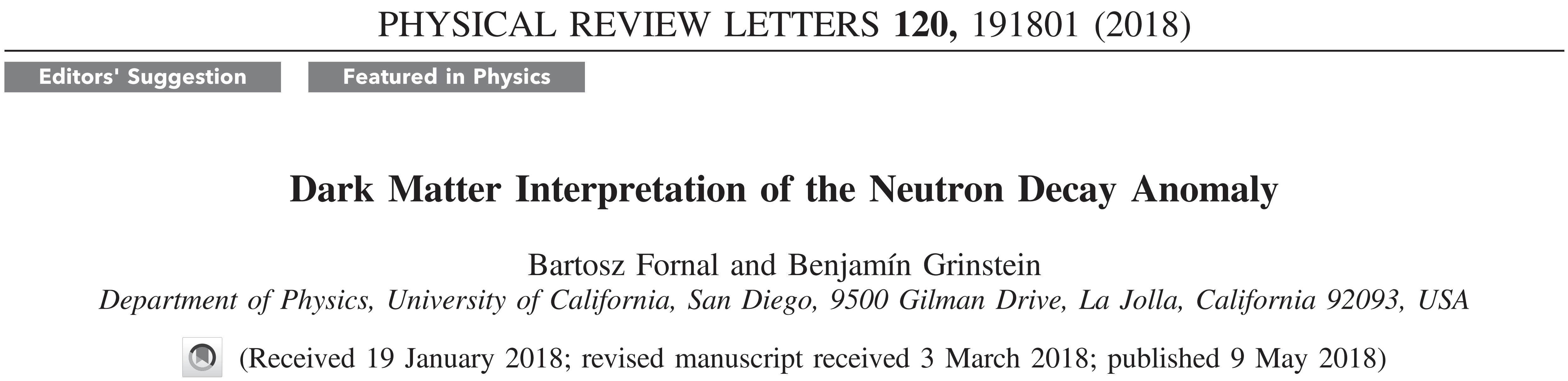
宇宙背景放射+BBN

$N_\nu = 3.01 \pm 0.15$

$\tau_n = 879.5$ s

C. Pitrou et al., Physics Reports 754 (2018) 1–66

Neutron Lifetime - Dark decay



PHYSICAL REVIEW LETTERS **120,** 191801 (2018)

Editors' Suggestion **Featured in Physics**

Dark Matter Interpretation of the Neutron Decay Anomaly

Bartosz Fornal and Benjamín Grinstein

Department of Physics, University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093, USA

(Received 19 January 2018; revised manuscript received 3 March 2018; published 9 May 2018)

既知の崩壊モード以外が１％あれば、ビーム法と蓄積法のズレを説明できる

一部がダークセクターに崩壊すると仮定して計算してみた。

1. $n\to\chi\gamma$
2. $n\to\chi\phi$
3. $n\to\chi e+e-$

Neutron Lifetime - Dark decay

$$n \to \chi\gamma$$

中性子崩壊の1%がのγ線放出を予想

中性子と^{9}BeのQ値から0.782 MeV < Eγ < 1.664 MeV

⇩

Search for the Neutron Decay n→X+γ, where X is a dark matter particle.

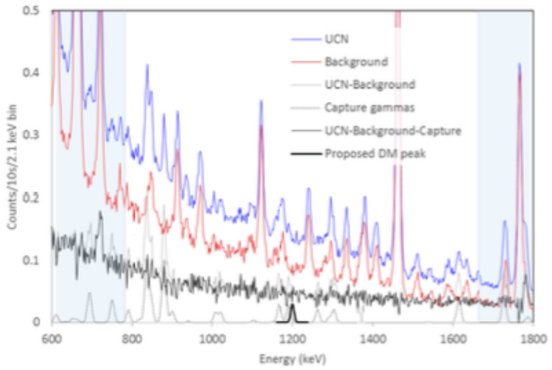
検出されず

https://arxiv.org/abs/1802.01595

Quantamagazine

NUCLEAR PHYSICS

Neutron Lifetime Puzzle Deepens, but No Dark Matter Seen



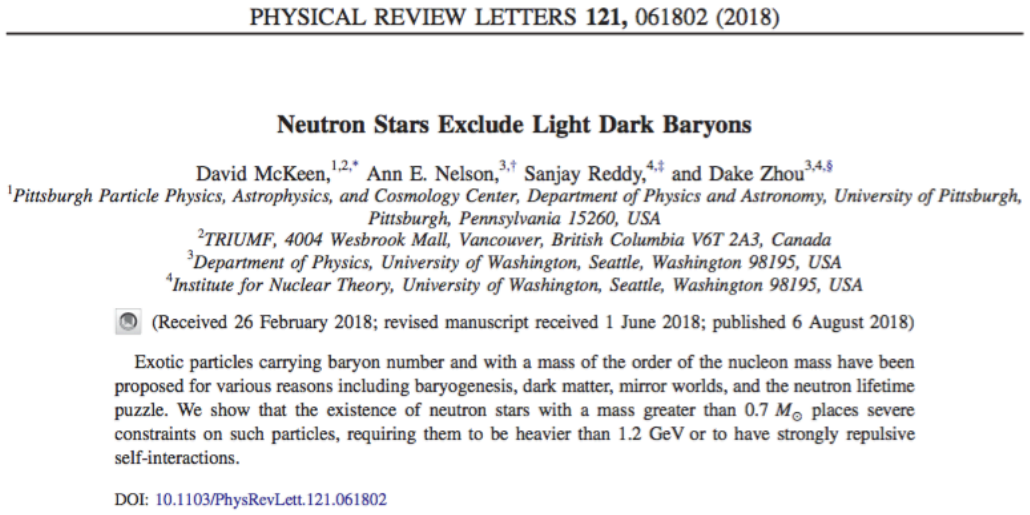
https://www.quantamagazine.org/neutron-lifetime-puzzle-deepens-but-no-dark-matter-seen-20180213/

The UCNtau experiment at Los Alamos National Laboratory, which uses the "bottle method" to measure the neutron lifetime.

Neutron Lifetime - Dark decay

$$n \to \chi \phi$$

中性子星質量からの制限



PHYSICAL REVIEW LETTERS **121,** 061802 (2018)

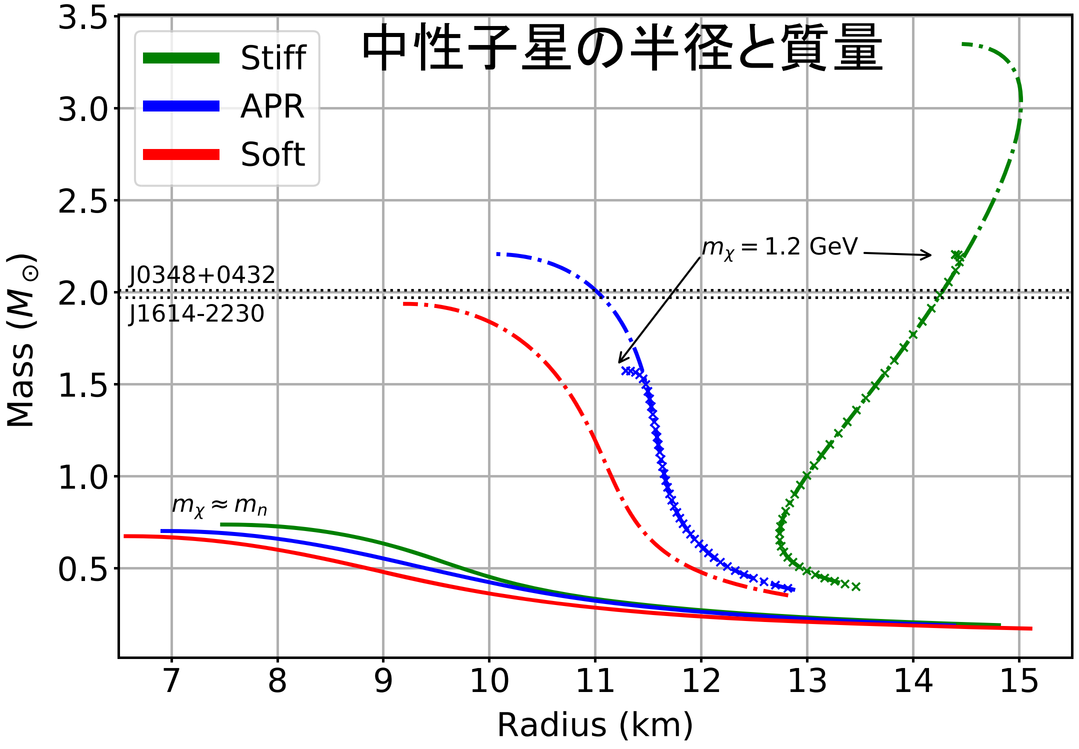
Neutron Stars Exclude Light Dark Baryons

David McKeen,[1,2,*] Ann E. Nelson,[3,†] Sanjay Reddy,[4,‡] and Dake Zhou[3,4,§]
[1] *Pittsburgh Particle Physics, Astrophysics, and Cosmology Center, Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA*
[2] *TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada*
[3] *Department of Physics, University of Washington, Seattle, Washington 98195, USA*
[4] *Institute for Nuclear Theory, University of Washington, Seattle, Washington 98195, USA*

(Received 26 February 2018; revised manuscript received 1 June 2018; published 6 August 2018)

Exotic particles carrying baryon number and with a mass of the order of the nucleon mass have been proposed for various reasons including baryogenesis, dark matter, mirror worlds, and the neutron lifetime puzzle. We show that the existence of neutron stars with a mass greater than 0.7 $M_\odot$ places severe constraints on such particles, requiring them to be heavier than 1.2 GeV or to have strongly repulsive self-interactions.

DOI: 10.1103/PhysRevLett.121.061802



中性子からダークセクターへの
崩壊モードがあるとすると、存在できる
中性子星の質量が変化する。

$m_\chi = m_n$とすると0.7 $M_\odot$以上の中性子星は存在できなくなる。

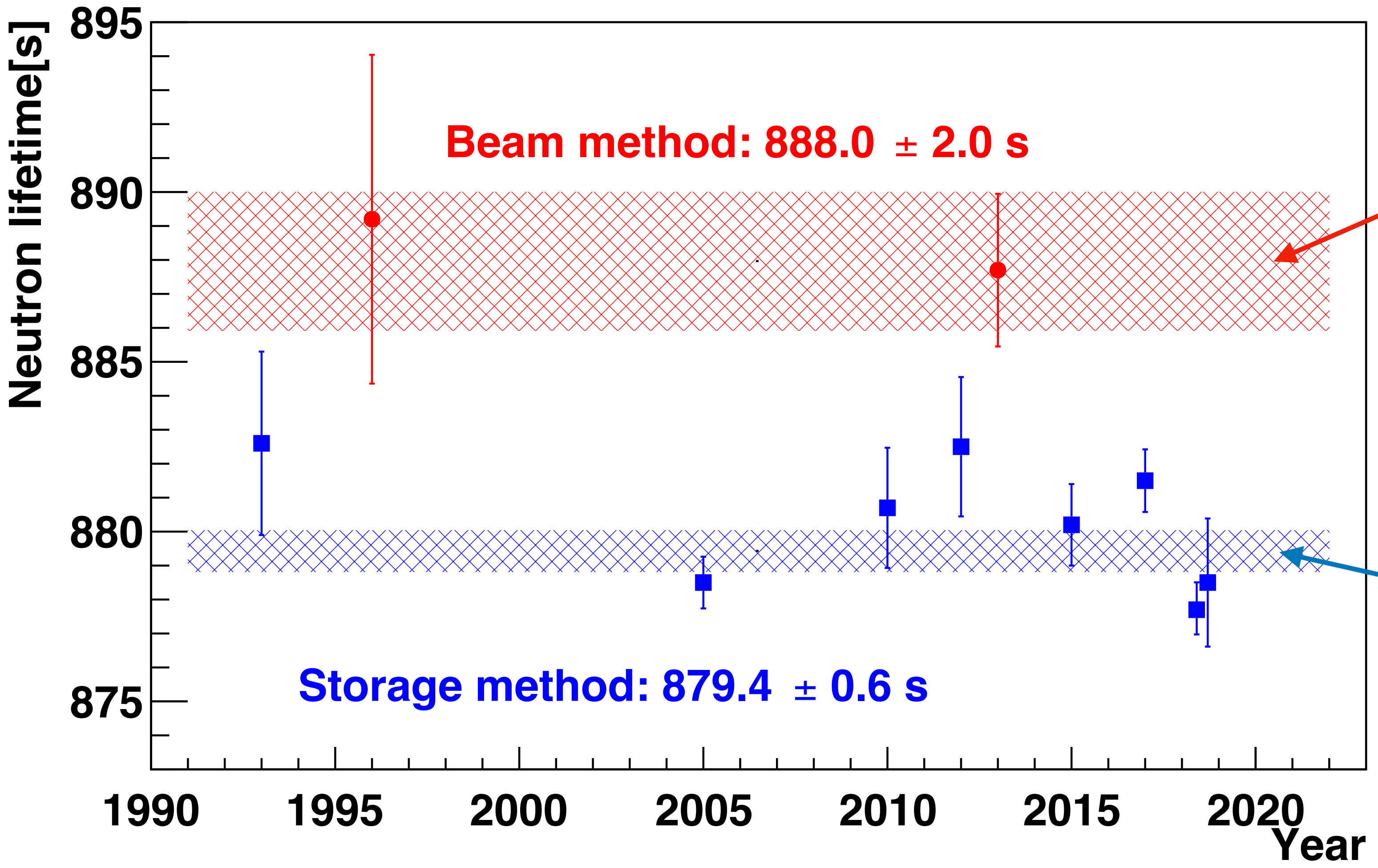
実際には2 $M_\odot$まで存在している。χがrepulsiveな性質を持っているなどの仮定を考えないと実測と合わなくなる。

中性子寿命

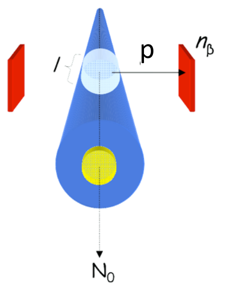
$$n \rightarrow p + e^{-} + \bar{\nu}_e$$

寿命 $879.4 \pm 0.6\,\mathrm{s}$ (PDG2019)

実験手法によって測定値が異なっている。

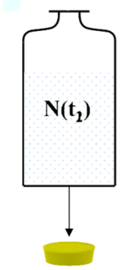


beam法: 崩壊生成物を数える



$$-\frac{\mathrm{d}N}{\mathrm{d}t} = \frac{N}{\tau}$$

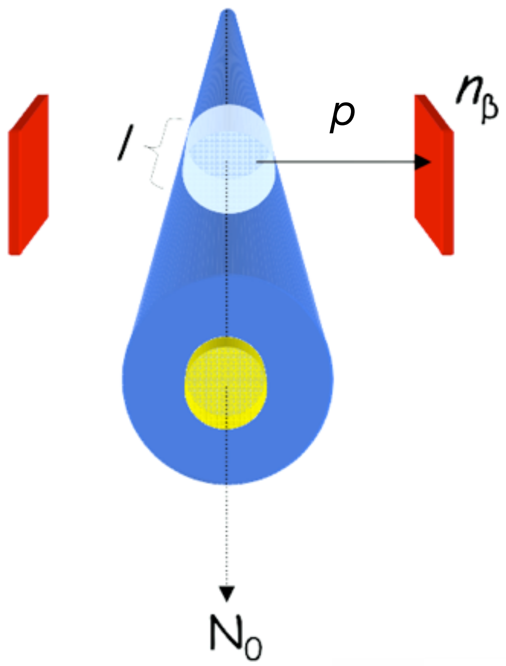
storage法: 生き残りを数える (bottle法、UCN法)



$$\frac{N_1}{N_2} = e^{-(t_1 - t_2)/\tau}$$

Neutron Lifetime - In-beam method

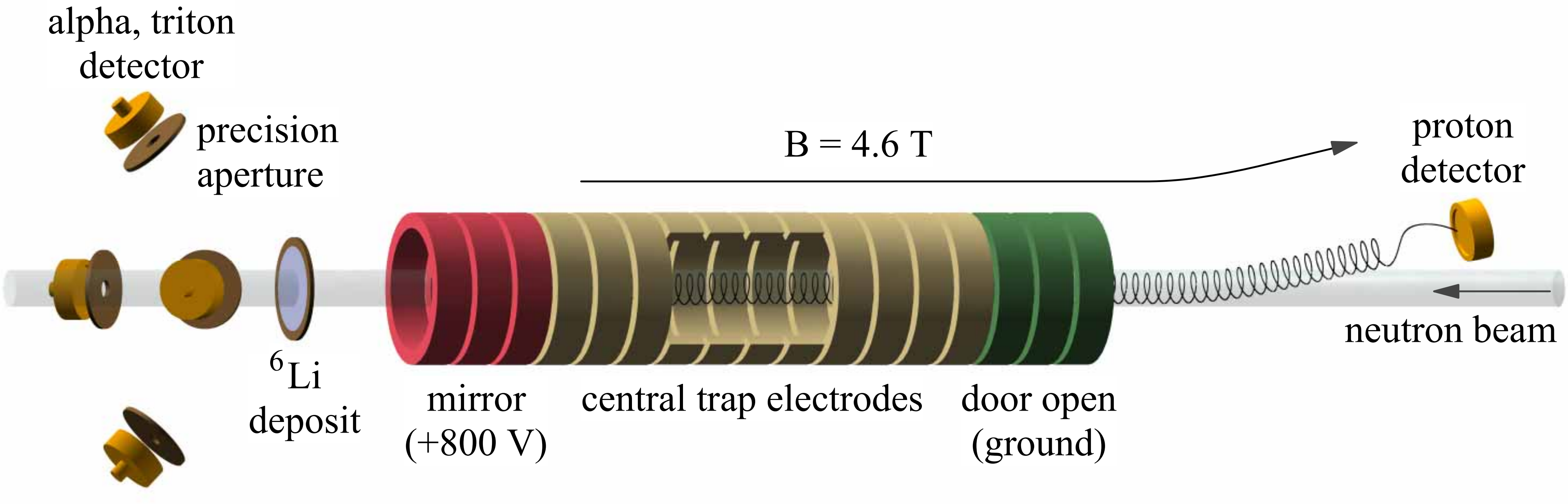
proton trapping
(penning trap)



Count decay-protons

$$n_B = \frac{dN}{dt} = -\frac{N_0}{\phi_n} e^{-\frac{l}{v \cdot \phi_n}}$$

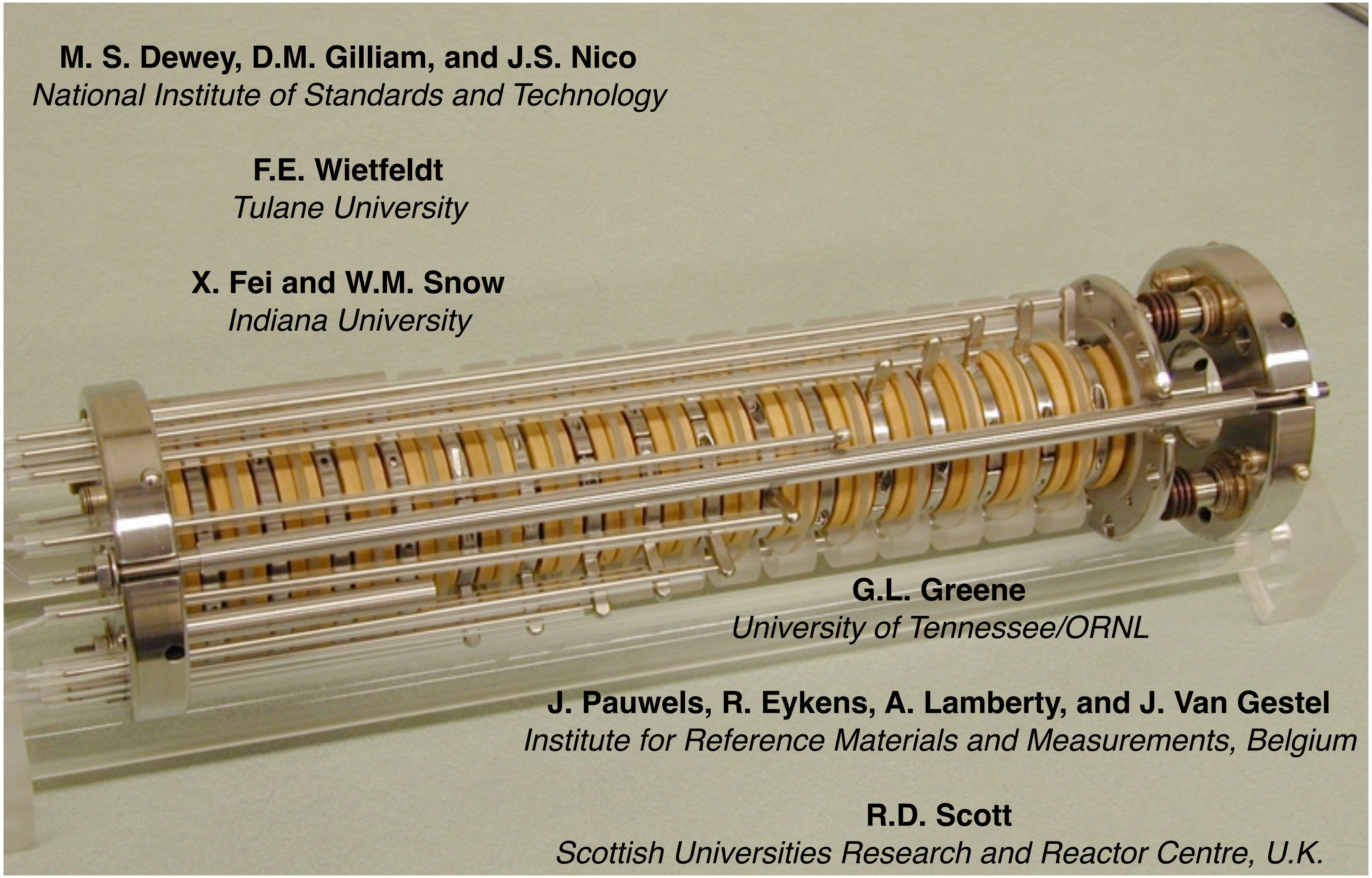
Uncertainty from
Flux Measurement



J.S.Nico, et. al., Phys. Rev. C71, 055502 (2005)

Neutron Lifetime

proton trapping
(penning trap)



M. S. Dewey, D.M. Gilliam, and J.S. Nico
National Institute of Standards and Technology

F.E. Wietfeldt
Tulane University

X. Fei and W.M. Snow
Indiana University

G.L. Greene
University of Tennessee/ORNL

J. Pauwels, R. Eykens, A. Lamberty, and J. Van Gestel
Institute for Reference Materials and Measurements, Belgium

R.D. Scott
Scottish Universities Research and Reactor Centre, U.K.

Neutron Lifetime

Result

$$\tau = 886.3 \pm 1.2 \pm 3.2\ \mathrm{s}$$

[stat] [sys]

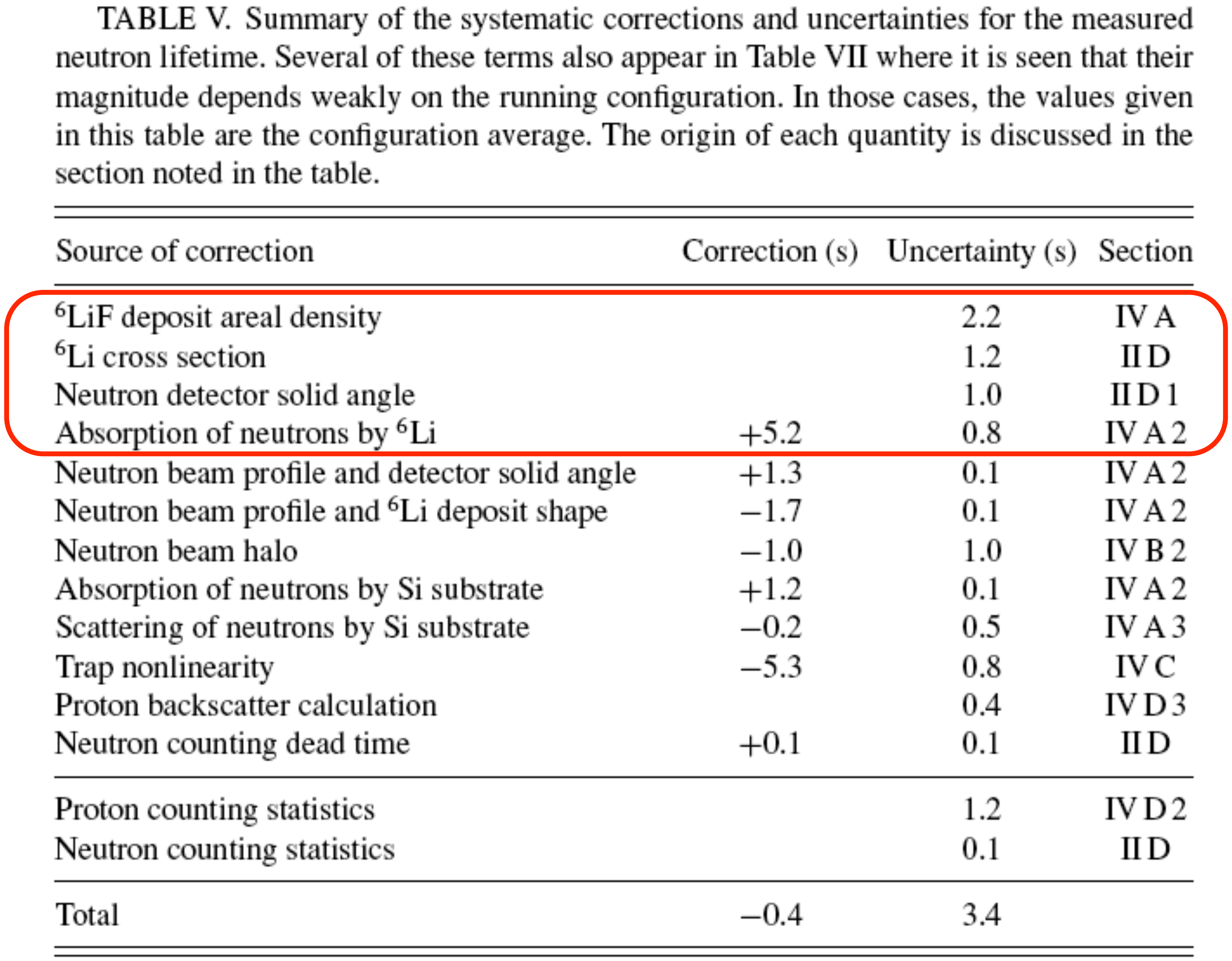


TABLE V. Summary of the systematic corrections and uncertainties for the measured neutron lifetime. Several of these terms also appear in Table VII where it is seen that their magnitude depends weakly on the running configuration. In those cases, the values given in this table are the configuration average. The origin of each quantity is discussed in the section noted in the table.

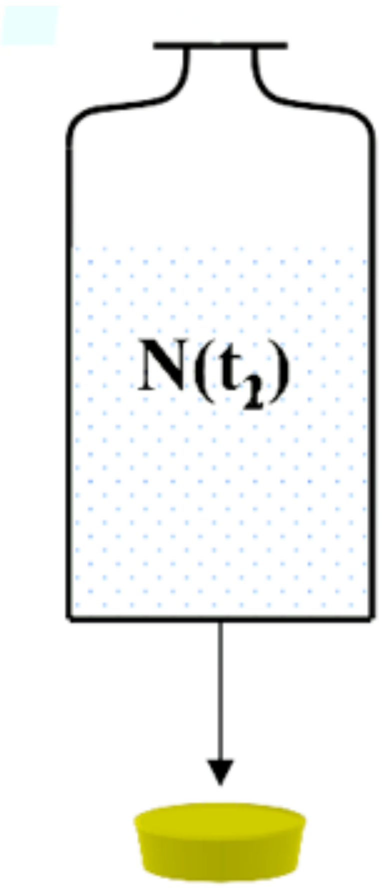
Source of correction	Correction (s)	Uncertainty (s)	Section
^{6}LiF deposit areal density		2.2	IV A
^{6}Li cross section		1.2	II D
Neutron detector solid angle		1.0	II D 1
Absorption of neutrons by ^{6}Li	+5.2	0.8	IV A 2
Neutron beam profile and detector solid angle	+1.3	0.1	IV A 2
Neutron beam profile and ^{6}Li deposit shape	−1.7	0.1	IV A 2
Neutron beam halo	−1.0	1.0	IV B 2
Absorption of neutrons by Si substrate	+1.2	0.1	IV A 2
Scattering of neutrons by Si substrate	−0.2	0.5	IV A 3
Trap nonlinearity	−5.3	0.8	IV C
Proton backscatter calculation		0.4	IV D 3
Neutron counting dead time	+0.1	0.1	II D
Proton counting statistics		1.2	IV D 2
Neutron counting statistics		0.1	II D
Total	−0.4	3.4	

J.S.Nico, et. al., Phys. Rev. C71, 055502 (2005)

Neutron Lifetime

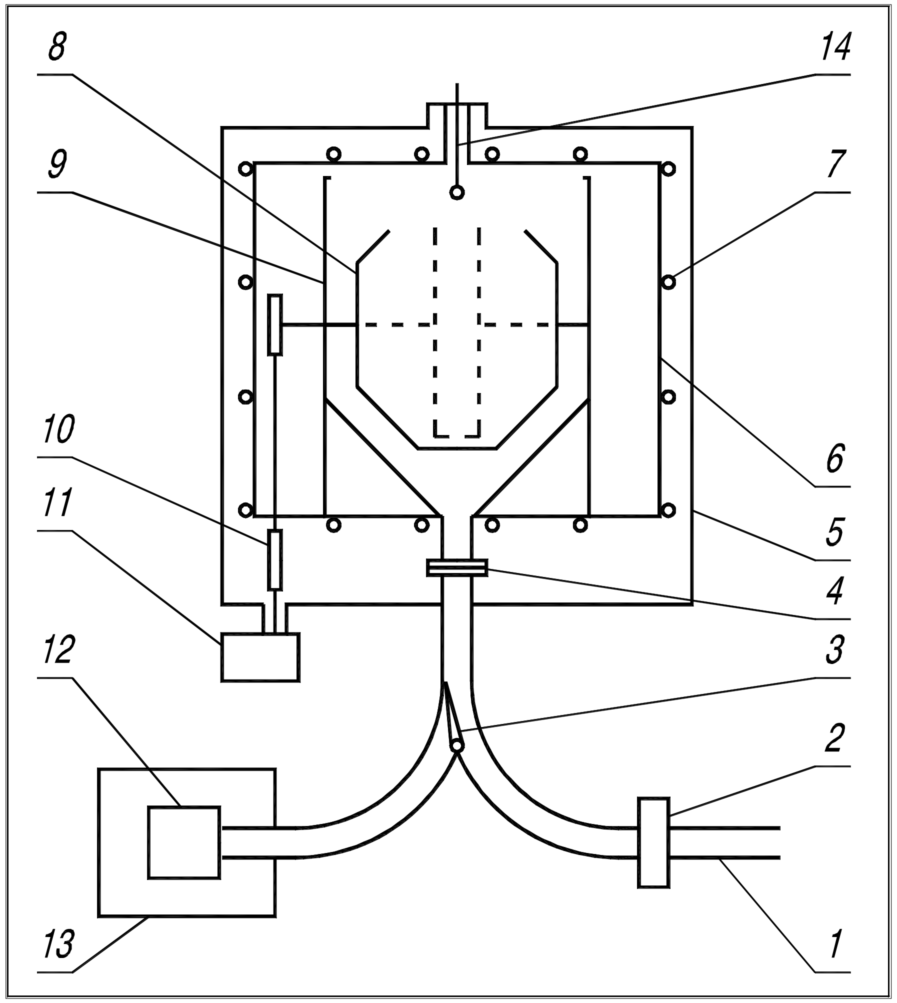
UCN storage

Count survived UCNs



$$\frac{1}{\phi_m} = \frac{1}{t_2 - t_1} \cdot \ln \frac{N(t_1)}{N(t_2)}$$

Uncertainty from
Wall Loss



1 – neutron guide from UCN Turbine;
2 – UCN inlet valve;
3 – beam distribution flap valve;
4 – aluminium foil (now removed);
5 – “dirty” vacuum volume;
6 – “clean” (UHV) vacuum volume;
7 – cooling coils;
8 – UCN storage trap;
9 – cryostat;
10 – mechanics for trap rotation;
11 – stepping motor;
12 – UCN detector;
13 – detector shielding;
14 – evaporator

Neutron Lifetime

Gravitational trap
at ILL High Flux Reactor

Neutron Lifetime

Gravitational trap storage experiments

Size extrapolation	Value,s	Uncertainty, s
n-lifetime	878.07	0.73
Systematic effect	Value,s	Uncertainty, s
Method of γ values calculation	0	0.236
Influence of mu-function shape	0	0.144
Spectrum uncertaities	0	0.104
Uncertaities of traps sizes(1mm)	0	0.058
Influence of the residual gas	0.40	0.024
Uncertaity of LTF critical energy (20 neV)	0	0.004
Total systematic effect	0.40	0.30

$$\tau = 878.0 \pm 1.2 \pm 3.2 \text{ s}$$

[stat] [sys]

Neutron Lifetime

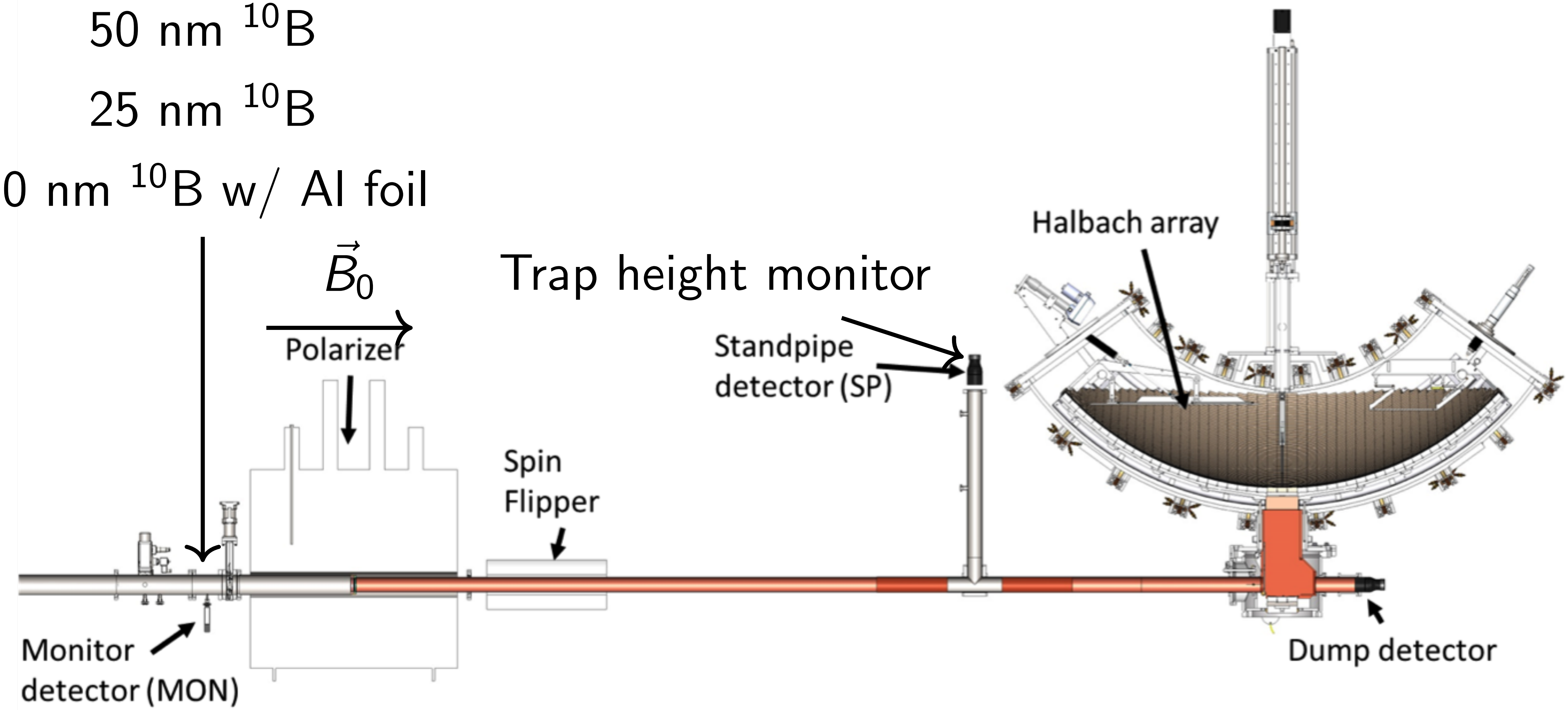
Magnet-Gravi trap storage experiments　Los Alamos National Laboratory

UCN Monitors:

50 nm ^{10}B

25 nm ^{10}B

50 nm ^{10}B w/ Al foil



$\vec{B}_0$

Trap height monitor

n　n　n

Low Field Seekers

High Field Seekers

Neutron Lifetime

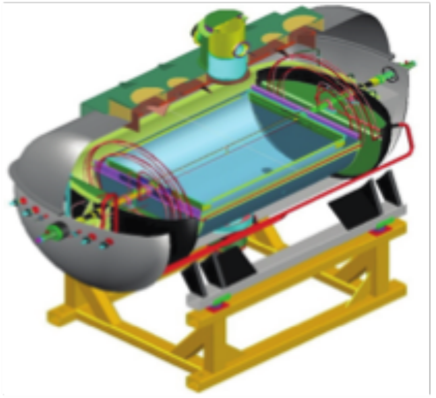
Effect	$\delta\tau_n$ [s]	Evaluation
Depolarization	$+0.07$	Varied Holding Field
Microphonic heating	$+0.24$	Detected Heated UCN
Cleaning	$+0.07$	Detected Uncleaned UCN
Deadtime / pileup	± 0.04	Known Hardware deadtime
Phase space evolution	± 0.10	Measured shift of arrival time
Vacuum	± 0.03	Measured XS and RGA
Background Shifts	$< \pm 0.01$	Measured Bkgd vs. Height
Total	+0.28 / - 0.1	

Statistics limited! Should improve with more data.

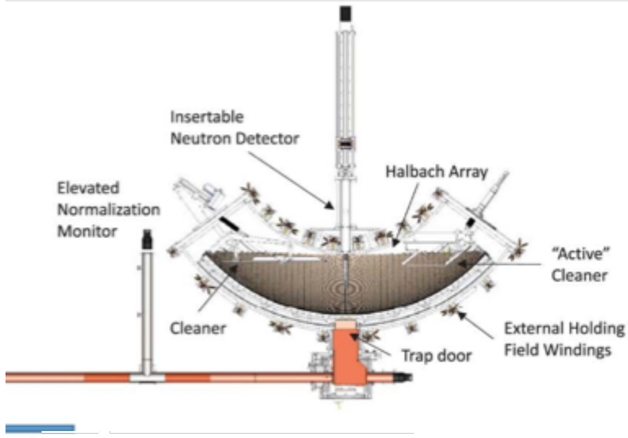
$$\tau_n = 877.7 \text{ s } (0.7 \text{ s})_{stat} \ ({}^{+0.4}_{-0.2} s)_{sys}$$

Neutron Lifetime

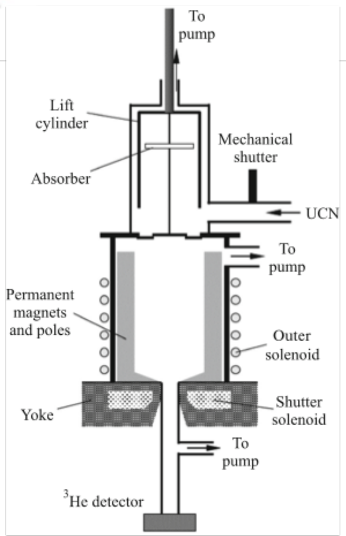
1. PNPI/ILL Large storage bottle
   - New neutron lifetime measurements with the big gravitational trap and review of neutron lifetime data.
   - Serebrov, A. P. et al., *KnE Energy & Physics*, *3*(1) (2018) 121-128.
   - $\tau_n = (881.5 \pm 0.7 \text{ (stat)} \pm 0.6 \text{ (sys)})$ sec



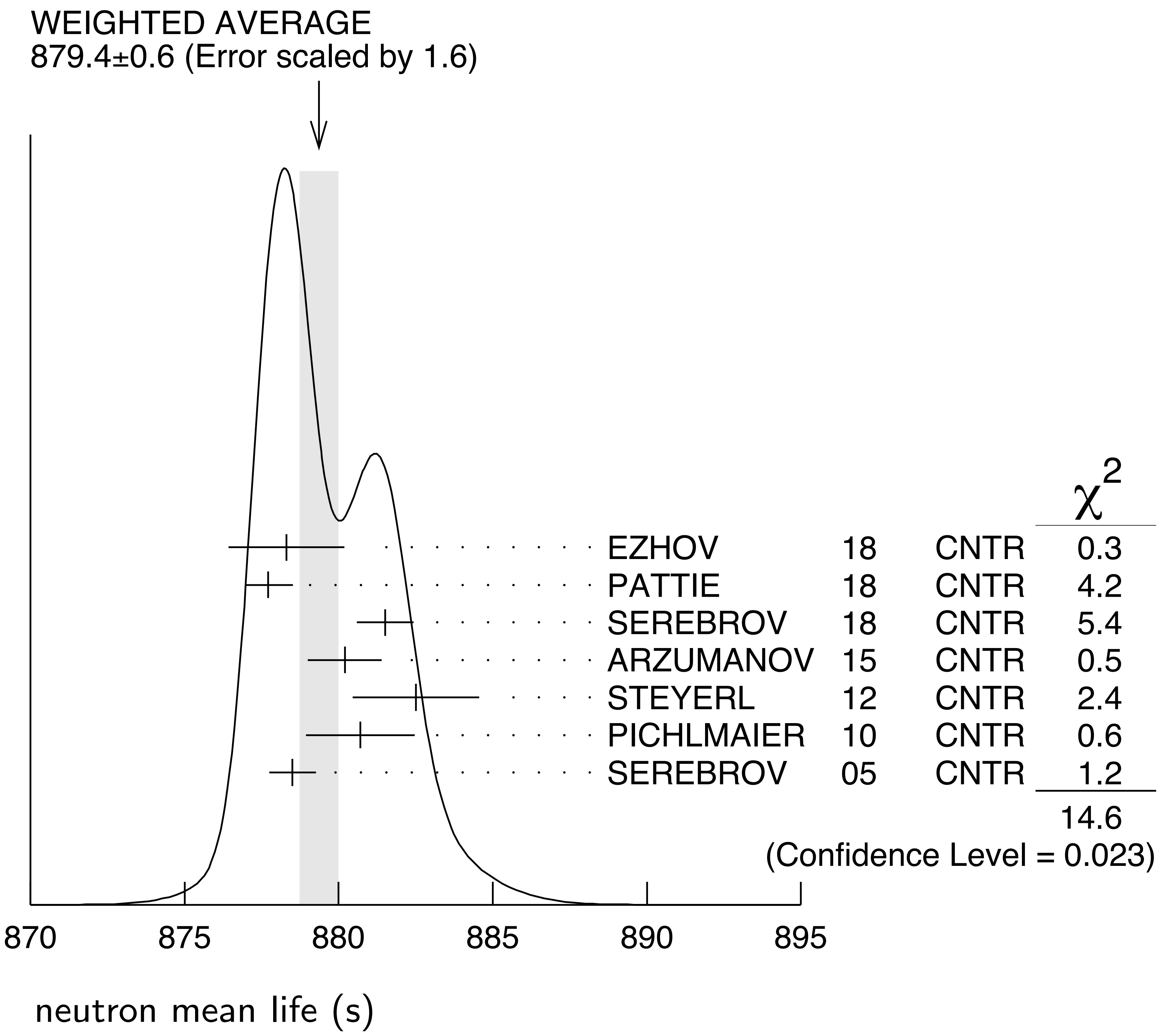
2. LANL Magnetic Trap
   - Measurement of the neutron lifetime using an asymmetric magneto-gravitational trap and in situ detection.
   - R. W. Pattie Jr. et al ., Science 10.1126/science.aan8895 (2018).
   - $\tau_n = (877.7 \pm 0.7 \text{ (stat)} {}^{+0.4}/_{-0.2} \text{ (sys)})$ sec



3. PNPI/ILL Magnetic bottle
   - Ezhov, V. F. et al., JETP Letters (2018) 1-6.
   - Measurement of the neutron lifetime with ultra-cold neutrons stored in a magneto-gravitational trap.
   - $\tau_n = (878.3 \pm 1.6\text{stat} \pm 1.0\text{syst})$ sec

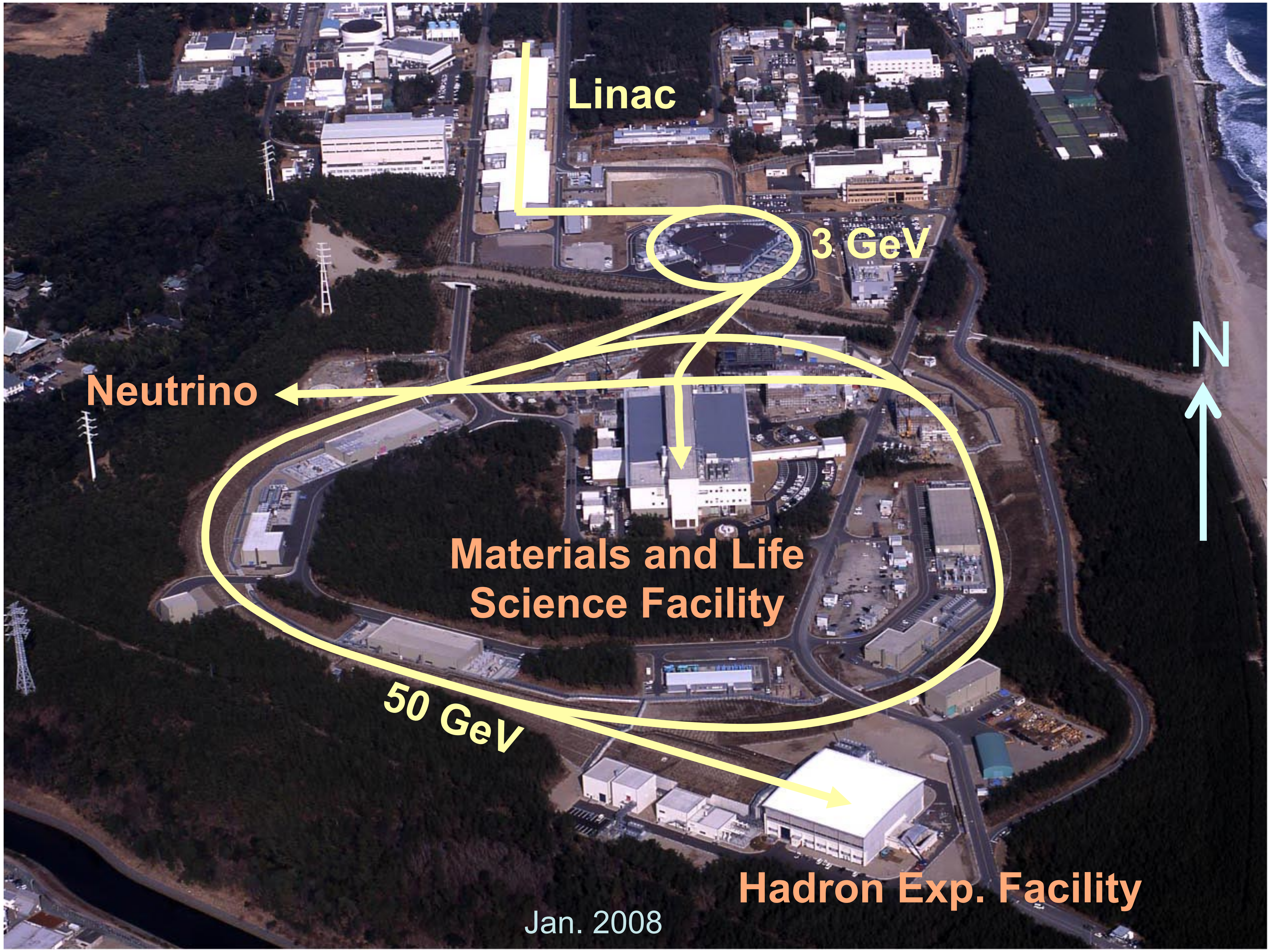


Neutron Lifetime



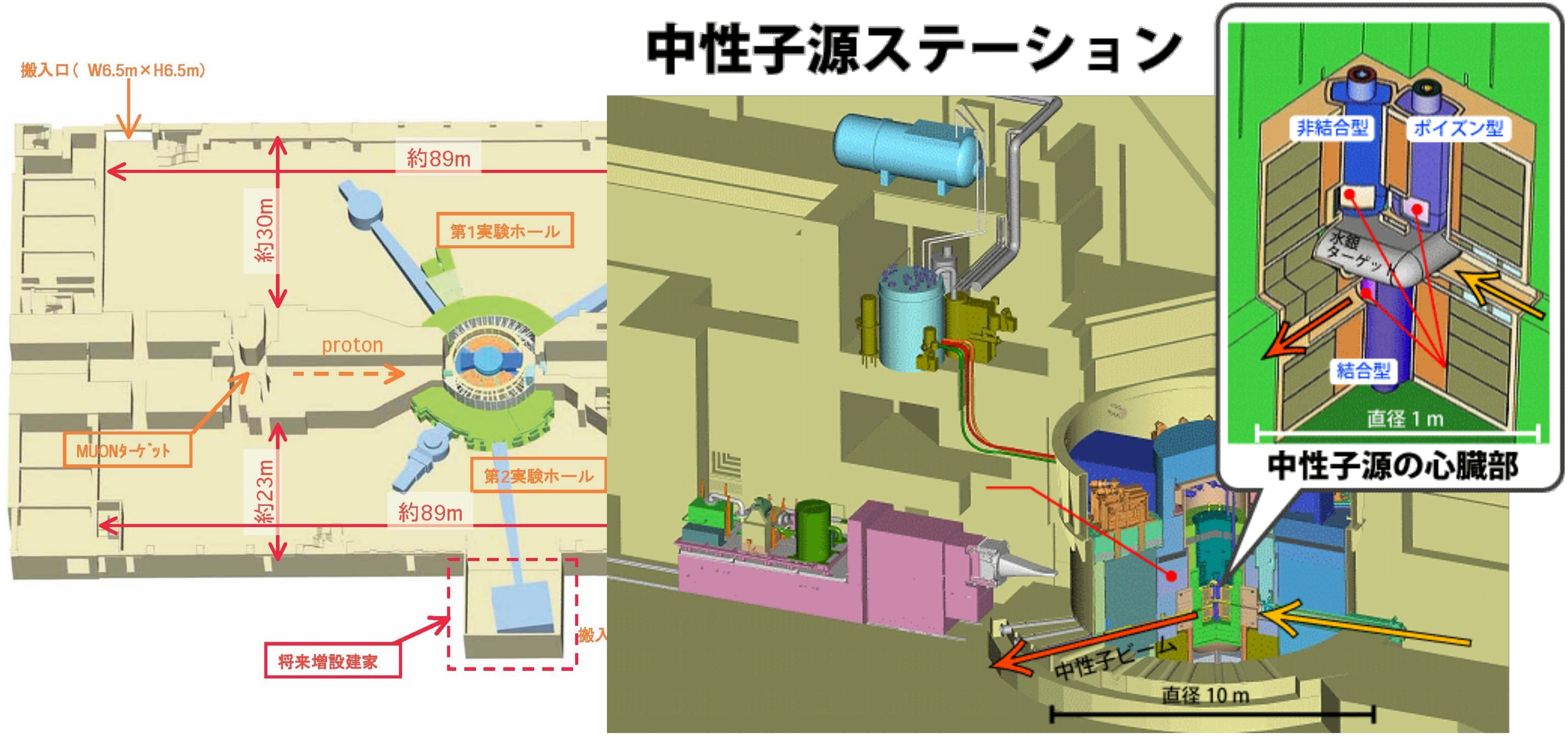
Neutron at J-PARC

J-PARC MLF



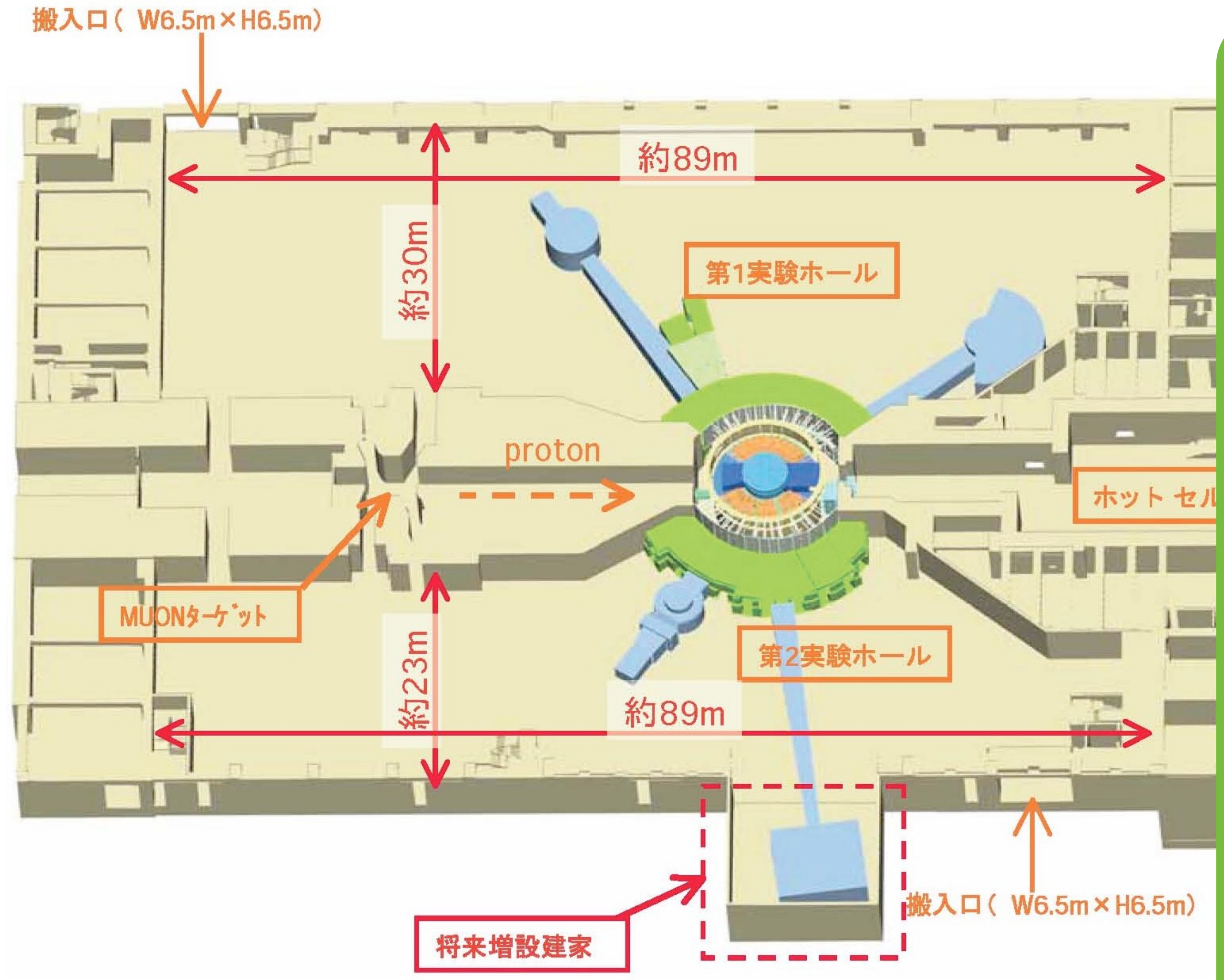
Neutron at J-PARC

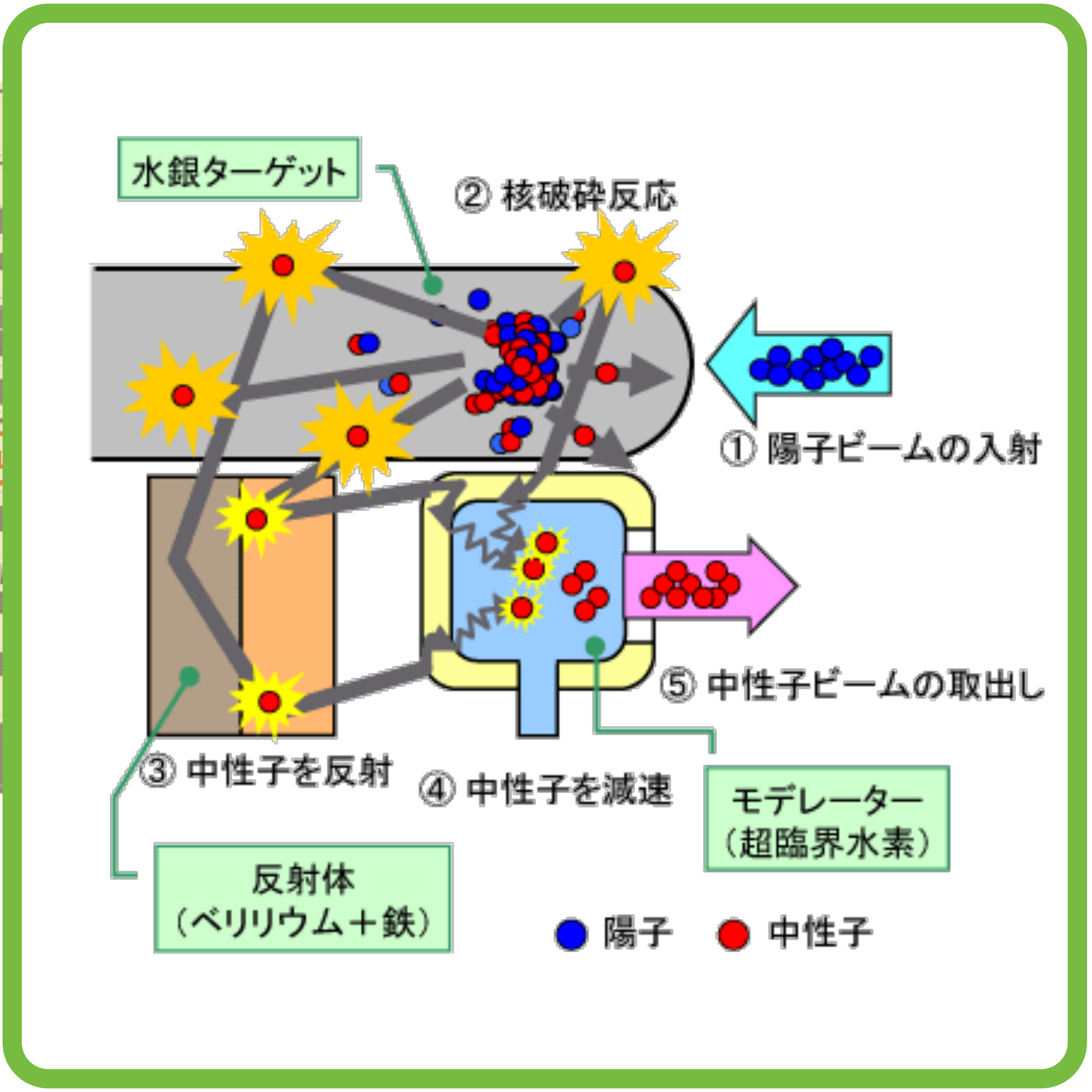
J-PARC MLF



Neutron at J-PARC

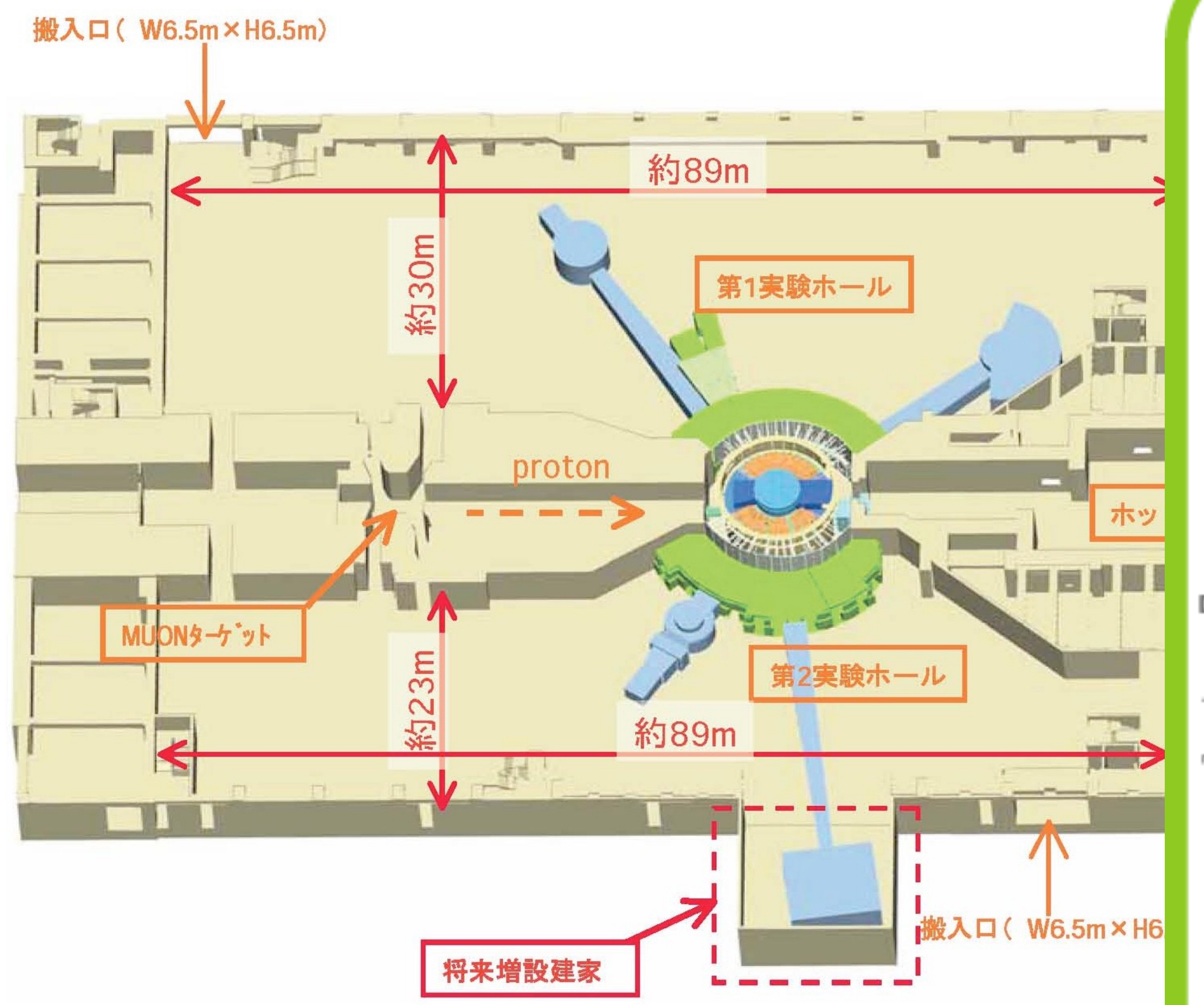
J-PARC MLF

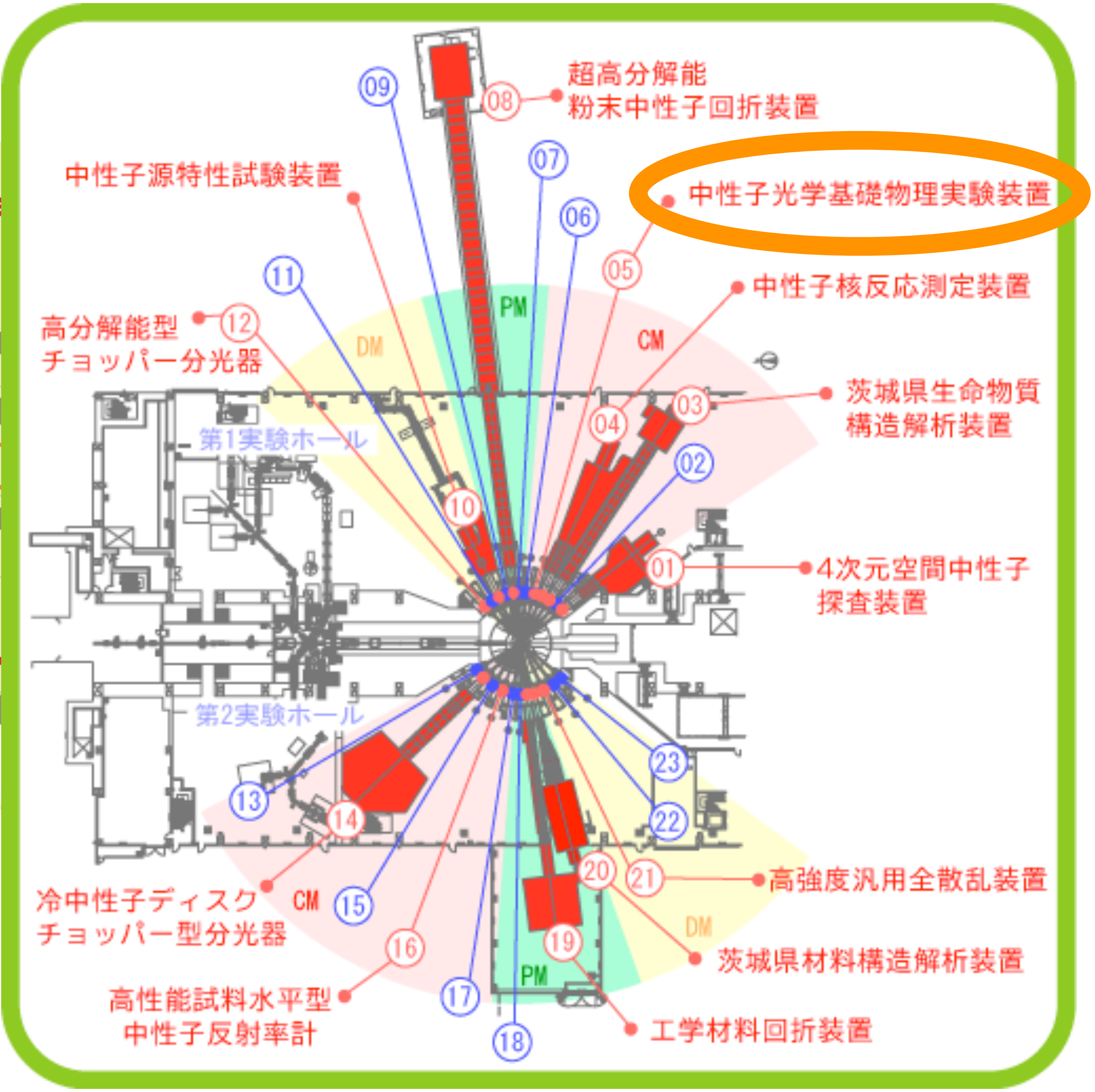




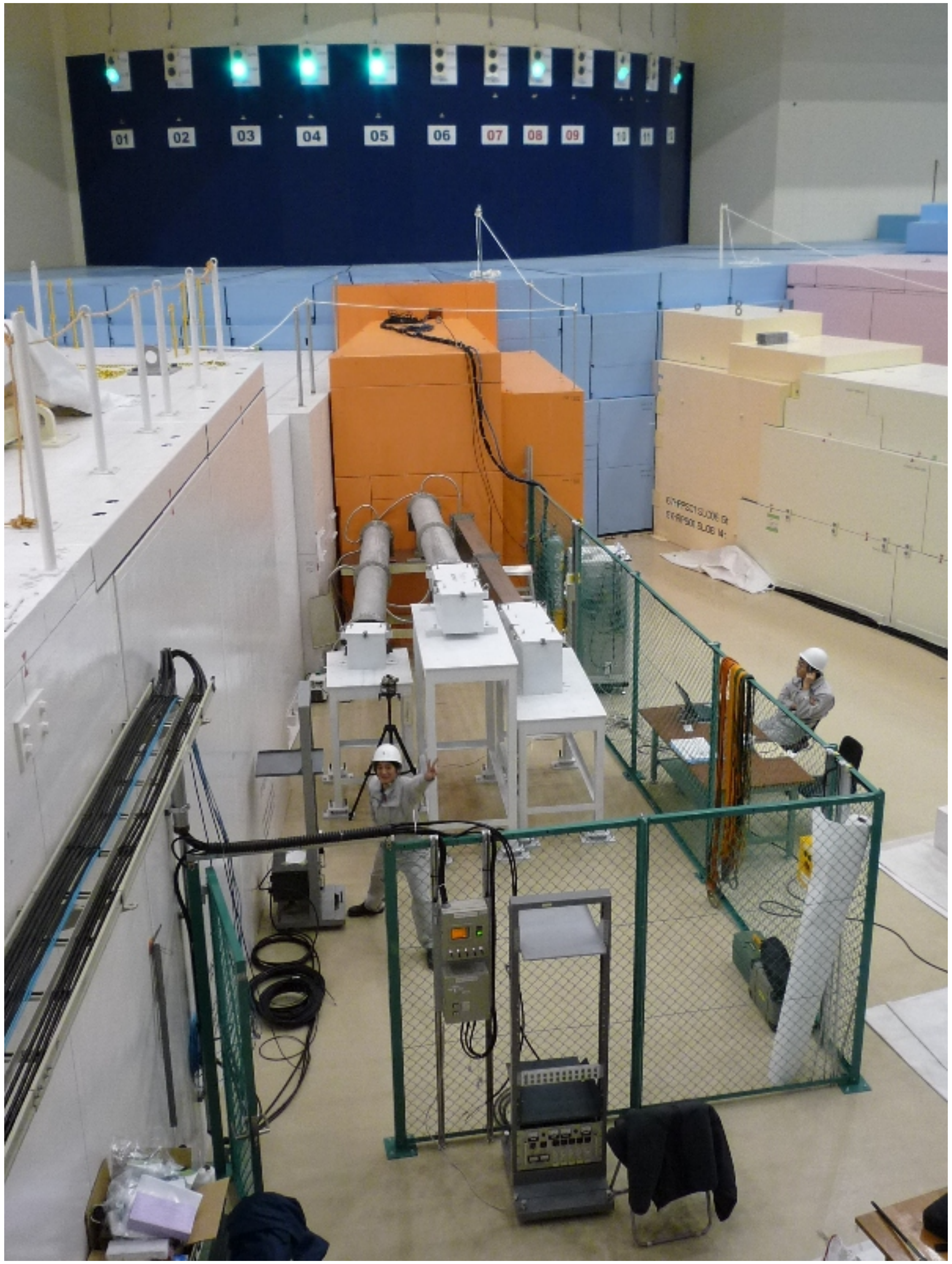
Neutron at J-PARC

J-PARC MLF





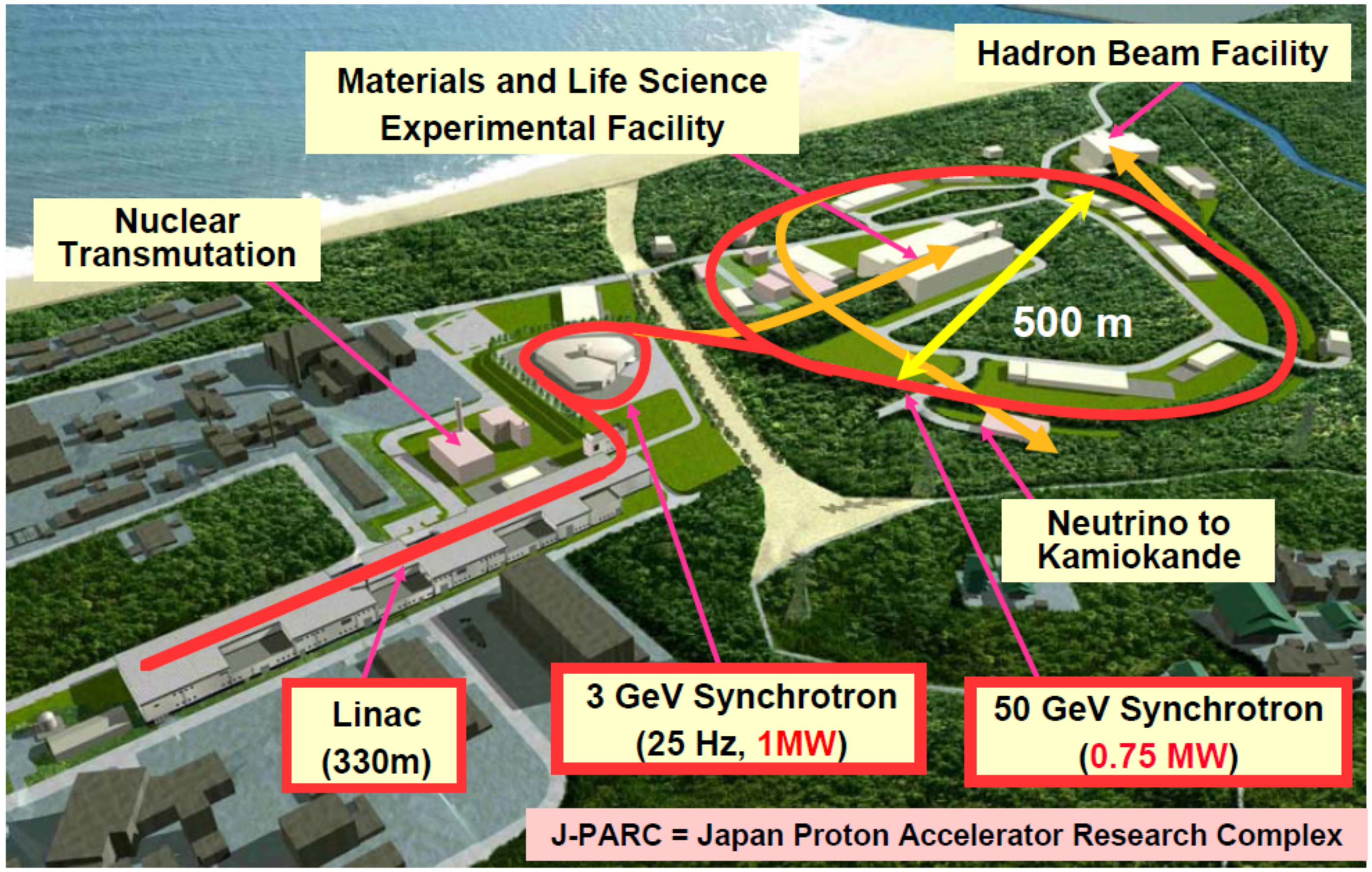
Neutron at J-PARC



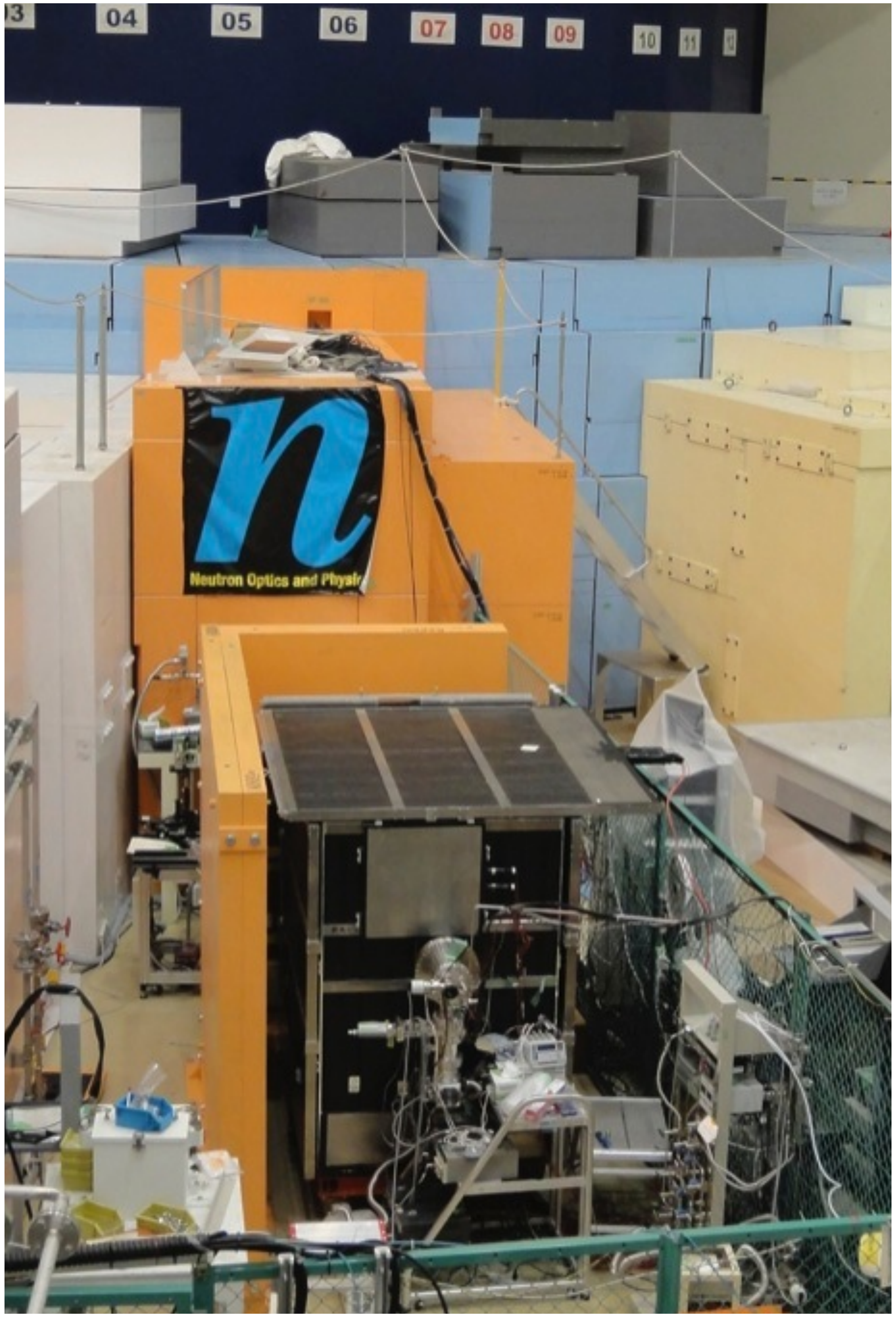
J-PARC MLF BL05 NOP

First beam 22:15
9 Dec. 2008

Neutron at J-PARC



Joint Project between KEK and JAEA



We constructed the cold neutron beamline “**NOP**” for fundamental physics in Material and Life science Facility.

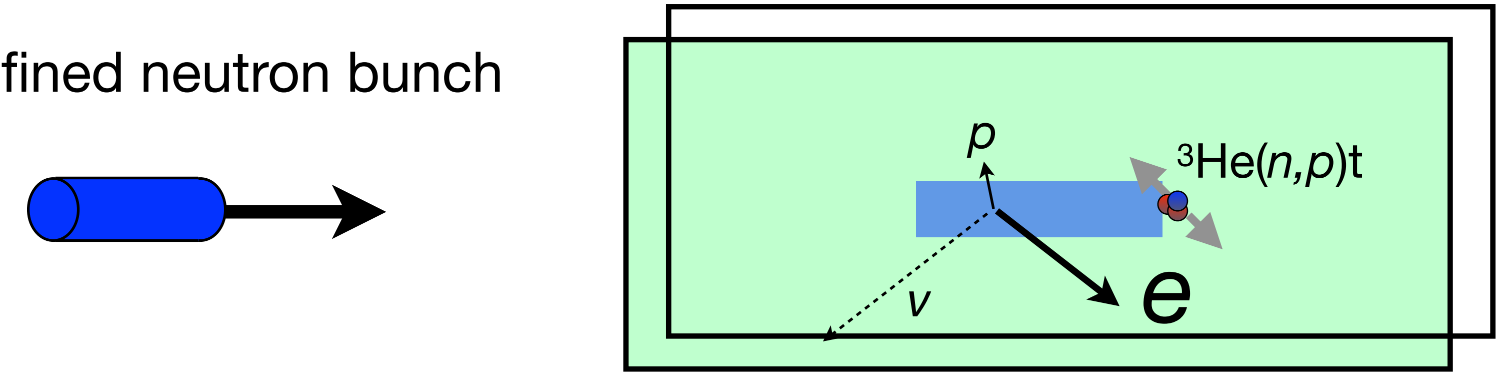
Tree branches are available.

- Polarized beam
- Unpolarized beam
- Low-divergence beam

Neutron Lifetime Measurement at J-PARC

In-beam measurement with pulsed neutrons

Direct measurement of decay-electrons（0〜782keV） (Kossakowski,1989)



Well-defined neutron bunch

Count up only when the bunch is in TPC

incident flux is also measured in TPC with ^{3}He capture

$$\tau_n = \frac{1}{\rho\sigma_0 v_0}\left(\frac{S_n/\epsilon_n}{S_\beta/\epsilon_\beta}\right)$$

β decay $$S_\beta = \epsilon_e N \frac{L}{\tau_n v}$$

^{3}He reaction $$S_n = \epsilon_n N \rho \sigma L$$

τ_n : lifetime

v : velocity

ε_e : efficiency for electrons

ε_n : efficiency for ^{3}He reaction

ρ : density of ^{3}He

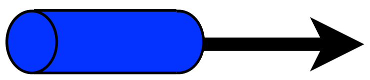
σ : absorption cross section of ^{3}H

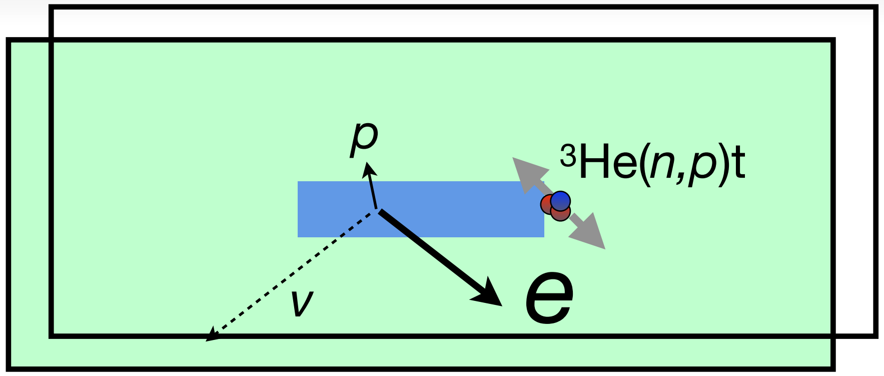
$$\sigma v = \sigma_0 v_0$$ absorption cross section for neutrons with 2200m/s

No External Flux monitor、No wall loss

Neutron Lifetime Measurement at J-PARC

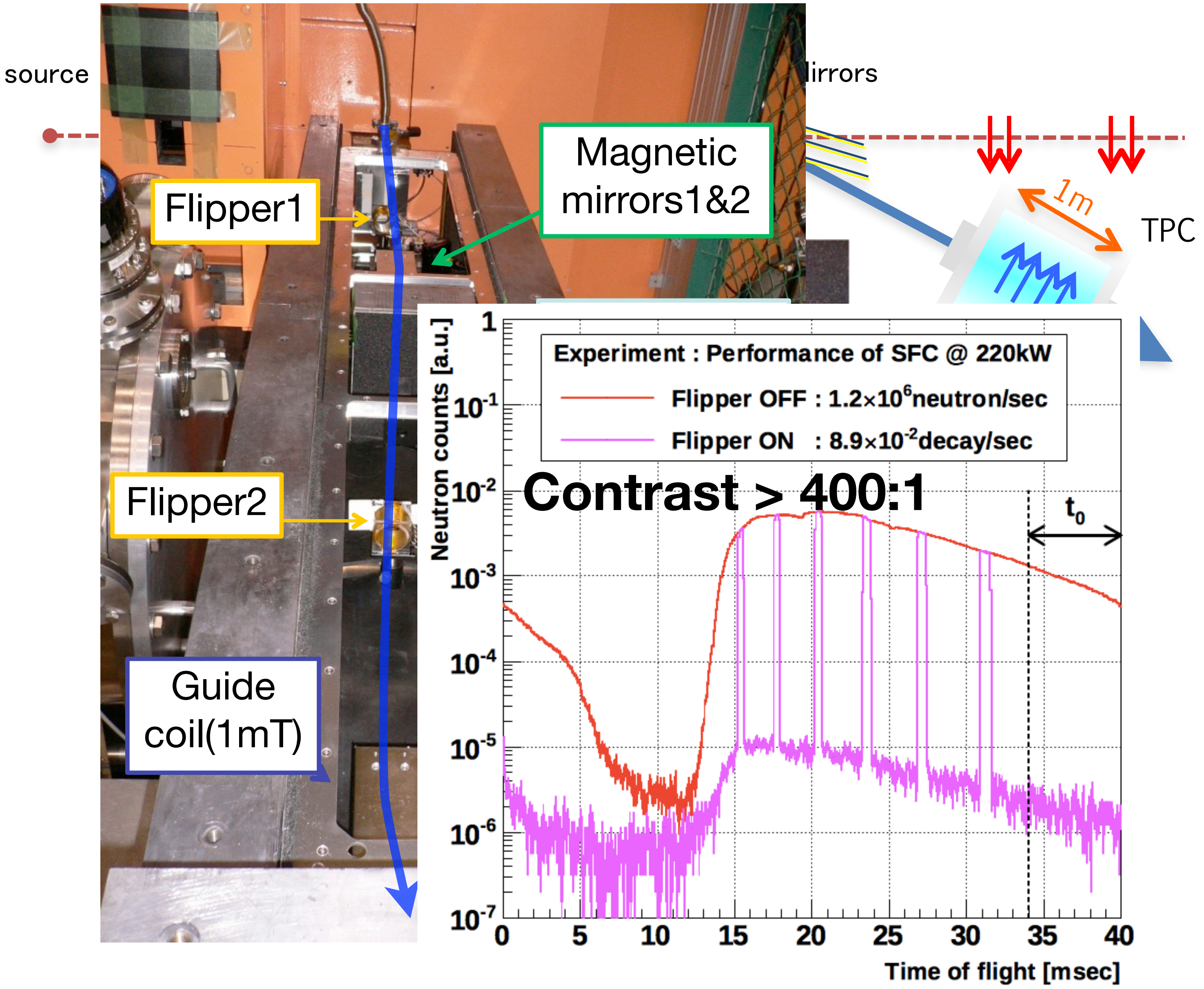
Well-defined neutron bunch



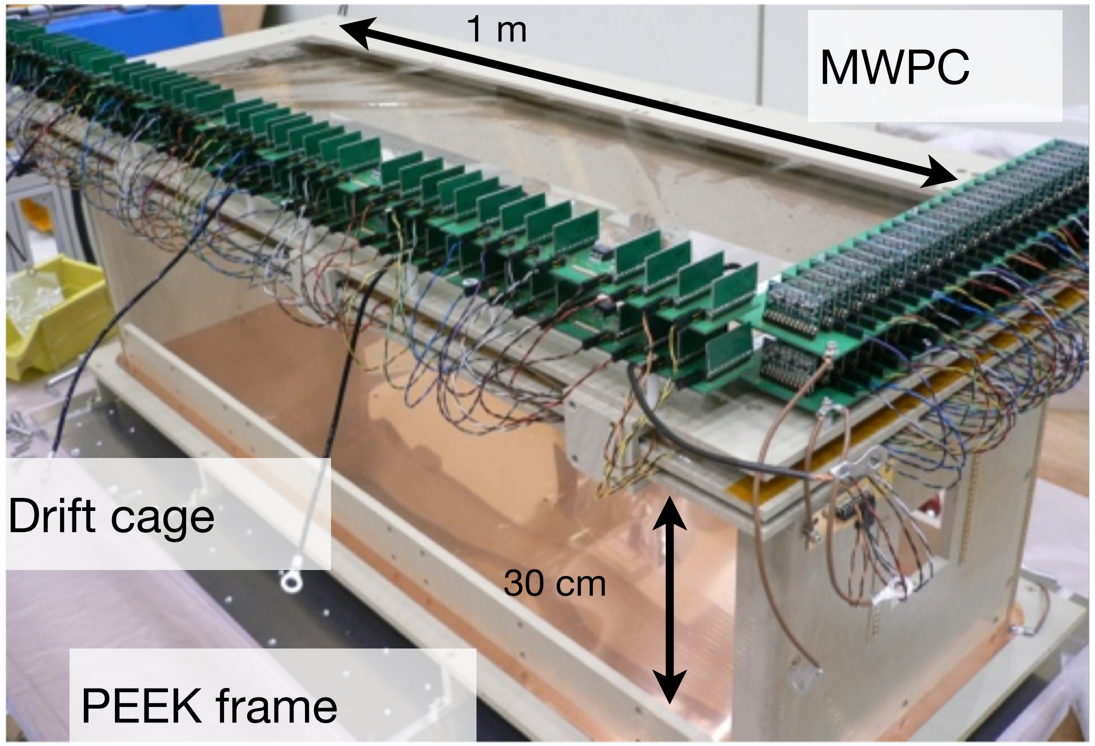


incident flux is also measured in TPC with ^{3}He capture

Spin Flip Chopper



Time Projection Chamber



High efficiency detection for
both of β-decay and ^{3}He reaction

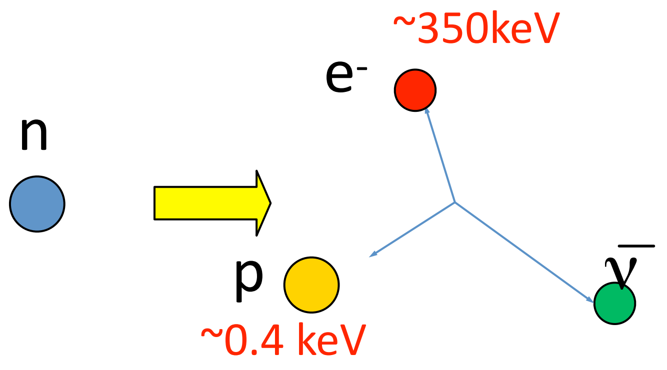
PEEK frame & inner ^{6}Li wall suppress BG.

S/N ~ 1:1

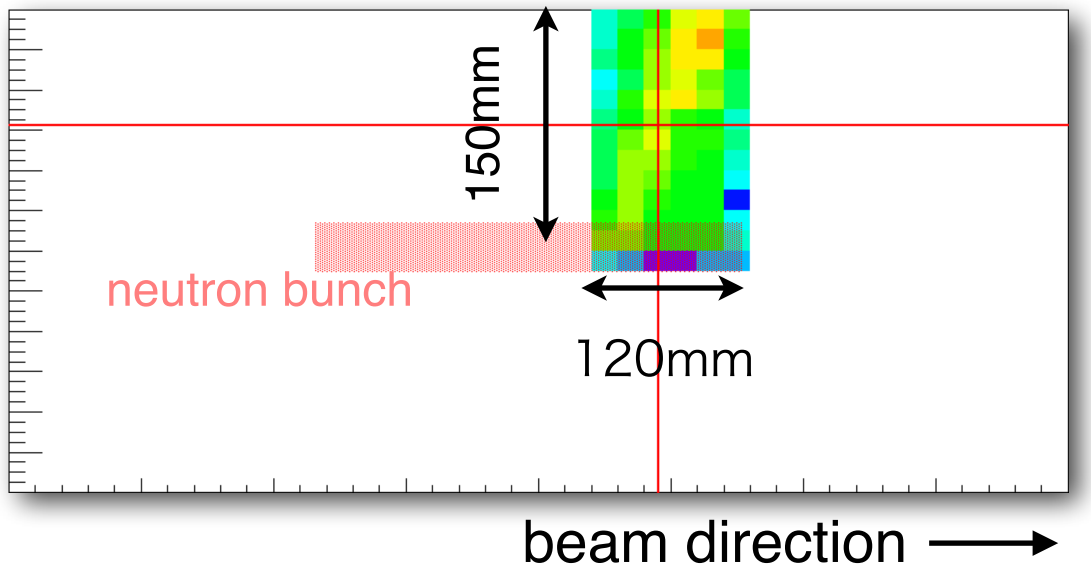
Neutron Lifetime Measurement at J-PARC

TPC commissioning has been performed.

β-decay



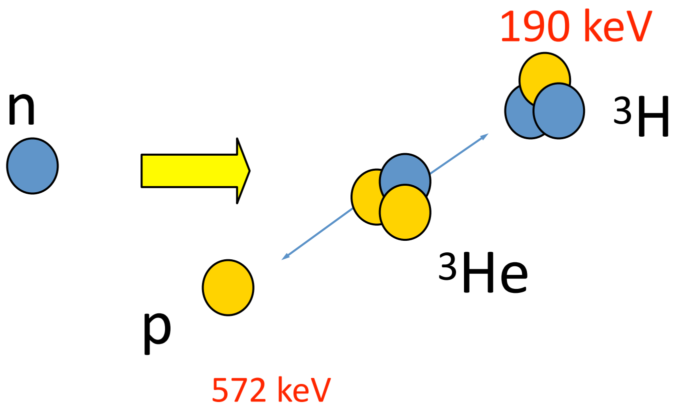
Top view of Event Display



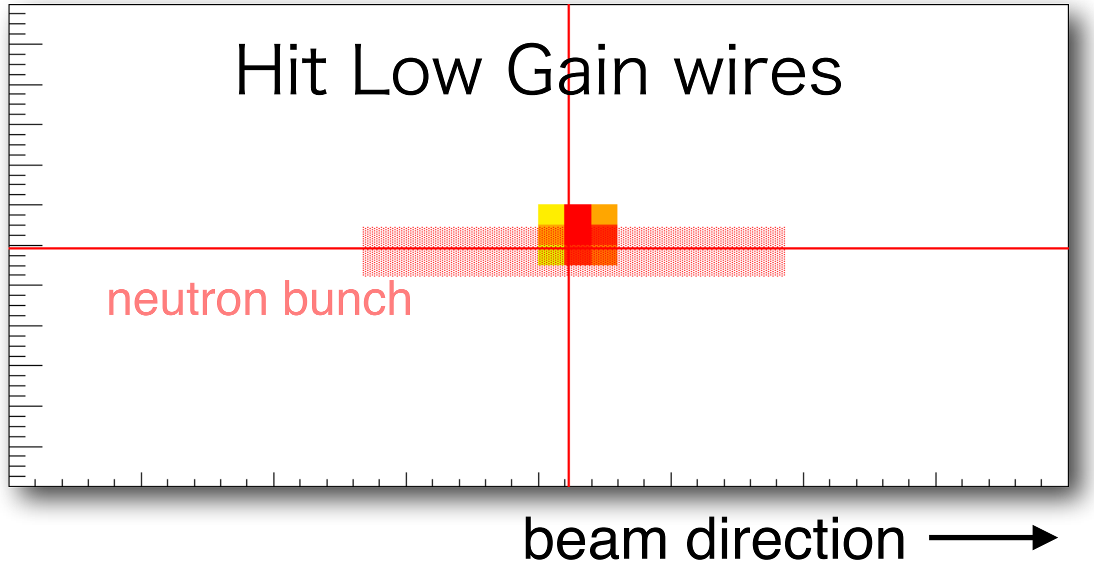
Energy is distributed 0 - 782 keV continuously.
Energy deposit ~ 10 keV / wire

Event ID by
energy deposit,
track topology, and so on.

^{3}He(n,p)^{3}H



Top view of Event Display



Full of Energy of 762 keV is deposited in TPC.
Range ~ 5 cm in TPC gas with 100 kPa.

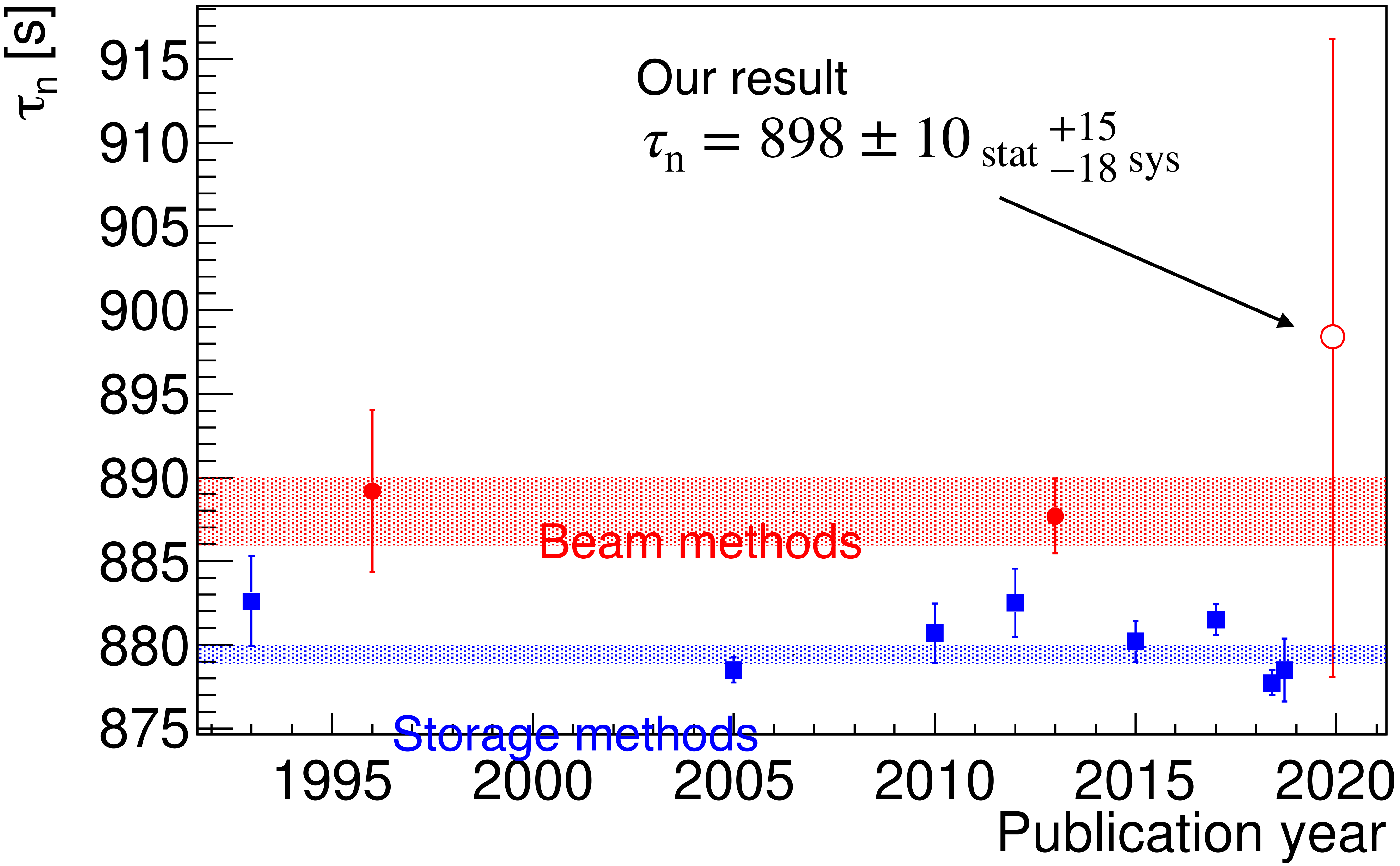
Neutron Lifetime Measurement at J-PARC

Year	Gas set number	MLF power [kW]	Total incident neutrons [×10^{11}]
2014A	1	300	0.2
2015A	1	500	0.2
2016A	4	200	1.2
2017A	8	150	0.8
2017B	9	300, 400	3.7
2018A	6	400, 500	~4
2019A	3	500	~2

最初の論文に
用いたデータ

全部使うと
4s の統計精度

Neutron Lifetime Measurement at J-PARC



K. Hirota, et. al., PTEP, to be published.

Neutron Lifetime Measurement at J-PARC

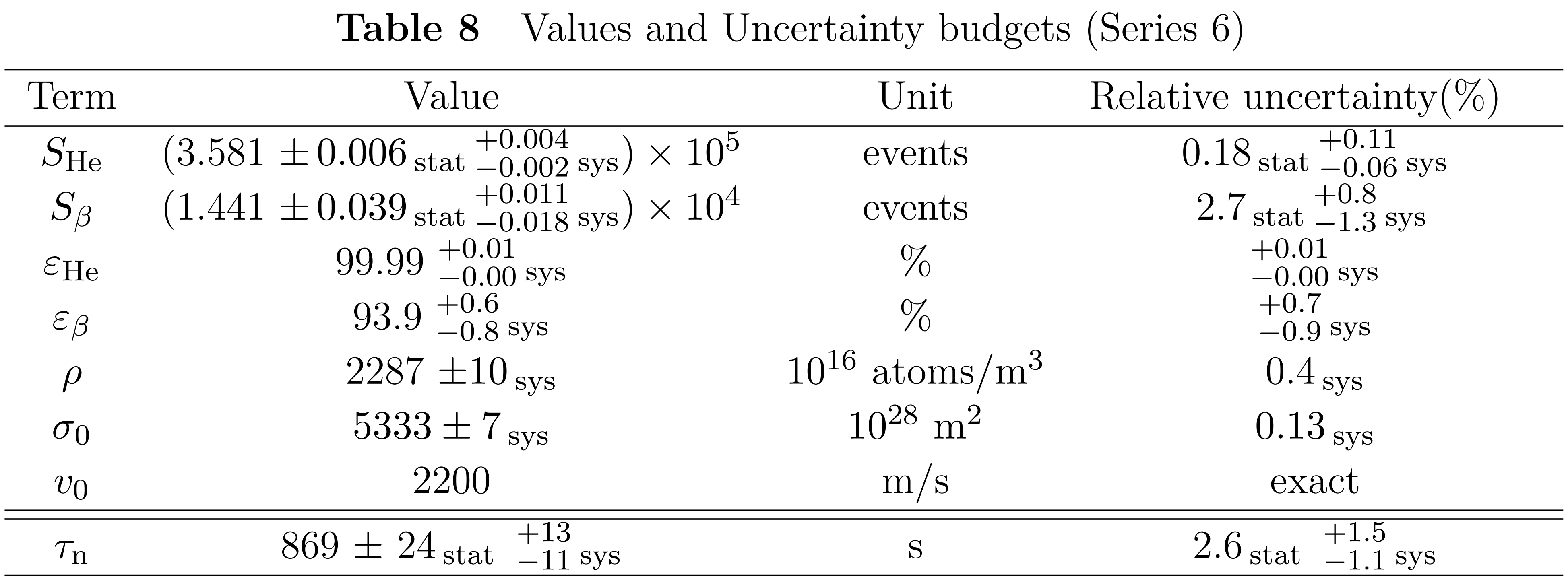


Table 8 Values and Uncertainty budgets (Series 6)

Term	Value	Unit	Relative uncertainty(%)
S_{He}	$(3.581 \pm 0.006_{\mathrm{stat}}\ {}^{+0.004}_{-0.002}{}_{\mathrm{sys}}) \times 10^5$	events	$0.18_{\mathrm{stat}}\ {}^{+0.11}_{-0.06}{}_{\mathrm{sys}}$
S_β	$(1.441 \pm 0.039_{\mathrm{stat}}\ {}^{+0.011}_{-0.018}{}_{\mathrm{sys}}) \times 10^4$	events	$2.7_{\mathrm{stat}}\ {}^{+0.8}_{-1.3}{}_{\mathrm{sys}}$
$\varepsilon_{\mathrm{He}}$	$99.99\ {}^{+0.01}_{-0.00}{}_{\mathrm{sys}}$	%	${}^{+0.01}_{-0.00}{}_{\mathrm{sys}}$
ε_β	$93.9\ {}^{+0.6}_{-0.8}{}_{\mathrm{sys}}$	%	${}^{+0.7}_{-0.9}{}_{\mathrm{sys}}$
ρ	$2287 \pm 10_{\mathrm{sys}}$	10^{16} atoms/m^3	0.4_{sys}
σ_0	$5333 \pm 7_{\mathrm{sys}}$	10^{28} m^2	0.13_{sys}
v_0	2200	m/s	exact
τ_{n}	$869 \pm 24_{\mathrm{stat}}\ {}^{+13}_{-11}{}_{\mathrm{sys}}$	s	$2.6_{\mathrm{stat}}\ {}^{+1.5}_{-1.1}{}_{\mathrm{sys}}$

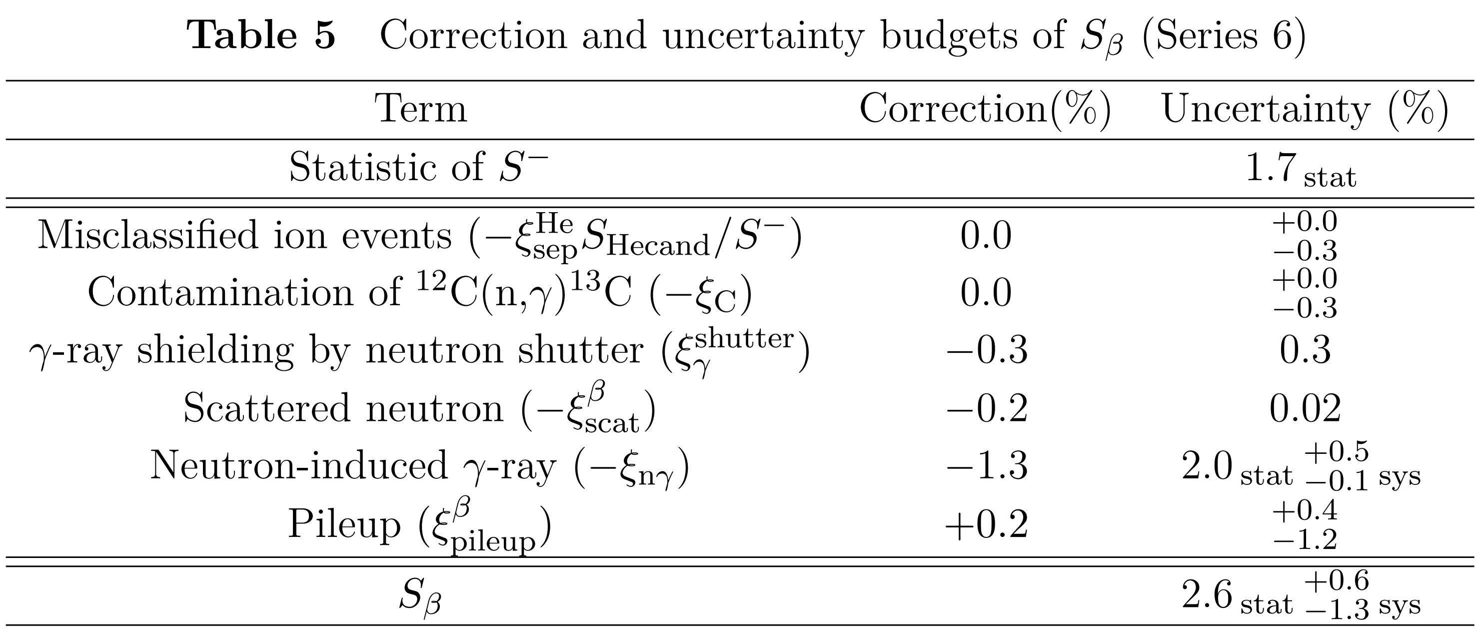


Table 5 Correction and uncertainty budgets of S_β (Series 6)

Term	Correction(%)	Uncertainty (%)
Statistic of S^-		1.7_{stat}
Misclassified ion events $(-\xi^{\mathrm{He}}_{\mathrm{sep}} S_{\mathrm{Hecand}}/S^-)$	0.0	${}^{+0.0}_{-0.3}$
Contamination of $^{12}\mathrm{C}(\mathrm{n},\gamma)^{13}\mathrm{C}$ $(-\xi_{\mathrm{C}})$	0.0	${}^{+0.0}_{-0.3}$
γ-ray shielding by neutron shutter $(\xi^{\mathrm{shutter}}_\gamma)$	−0.3	0.3
Scattered neutron $(-\xi^\beta_{\mathrm{scat}})$	−0.2	0.02
Neutron-induced γ-ray $(-\xi_{\mathrm{n}\gamma})$	−1.3	$2.0_{\mathrm{stat}}\ {}^{+0.5}_{-0.1}{}_{\mathrm{sys}}$
Pileup $(\xi^\beta_{\mathrm{pileup}})$	+0.2	${}^{+0.4}_{-1.2}$
S_β		$2.6_{\mathrm{stat}}\ {}^{+0.6}_{-1.3}{}_{\mathrm{sys}}$

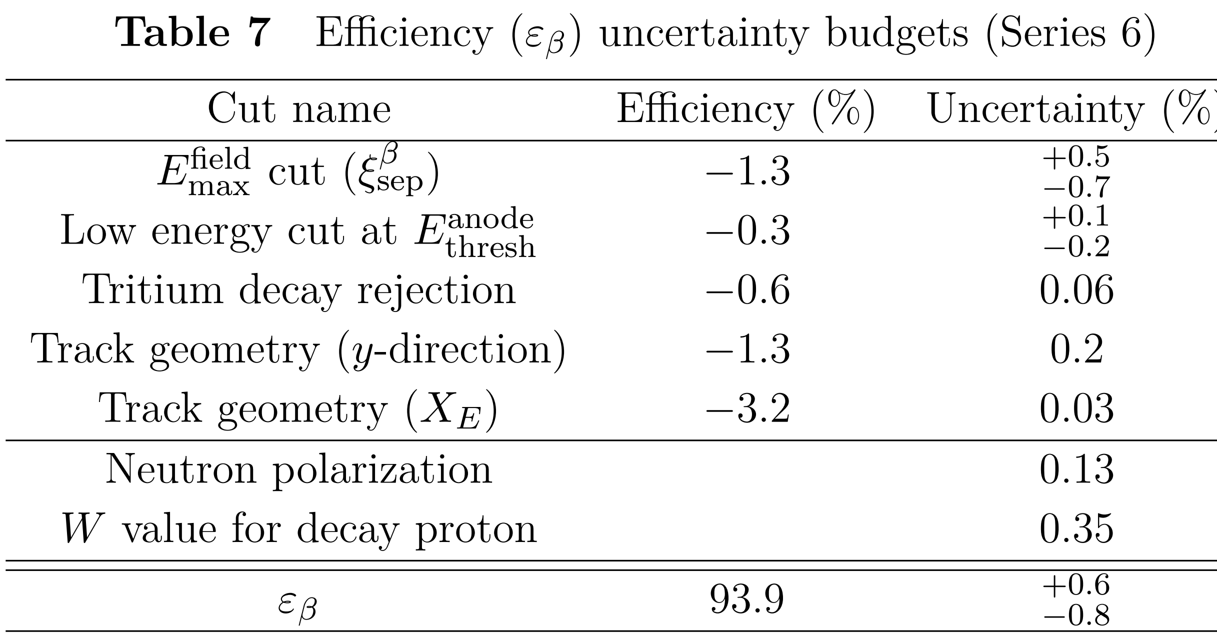


Table 7 Efficiency (ε_β) uncertainty budgets (Series 6)

Cut name	Efficiency (%)	Uncertainty (%
$E^{\mathrm{field}}_{\mathrm{max}}$ cut $(\xi^\beta_{\mathrm{sep}})$	−1.3	${}^{+0.5}_{-0.7}$
Low energy cut at $E^{\mathrm{anode}}_{\mathrm{thresh}}$	−0.3	${}^{+0.1}_{-0.2}$
Tritium decay rejection	−0.6	0.06
Track geometry (y-direction)	−1.3	0.2
Track geometry (X_E)	−3.2	0.03
Neutron polarization		0.13
W value for decay proton		0.35
ε_β	93.9	${}^{+0.6}_{-0.8}$

K. Hirota, et. al., PTEP, to be published.

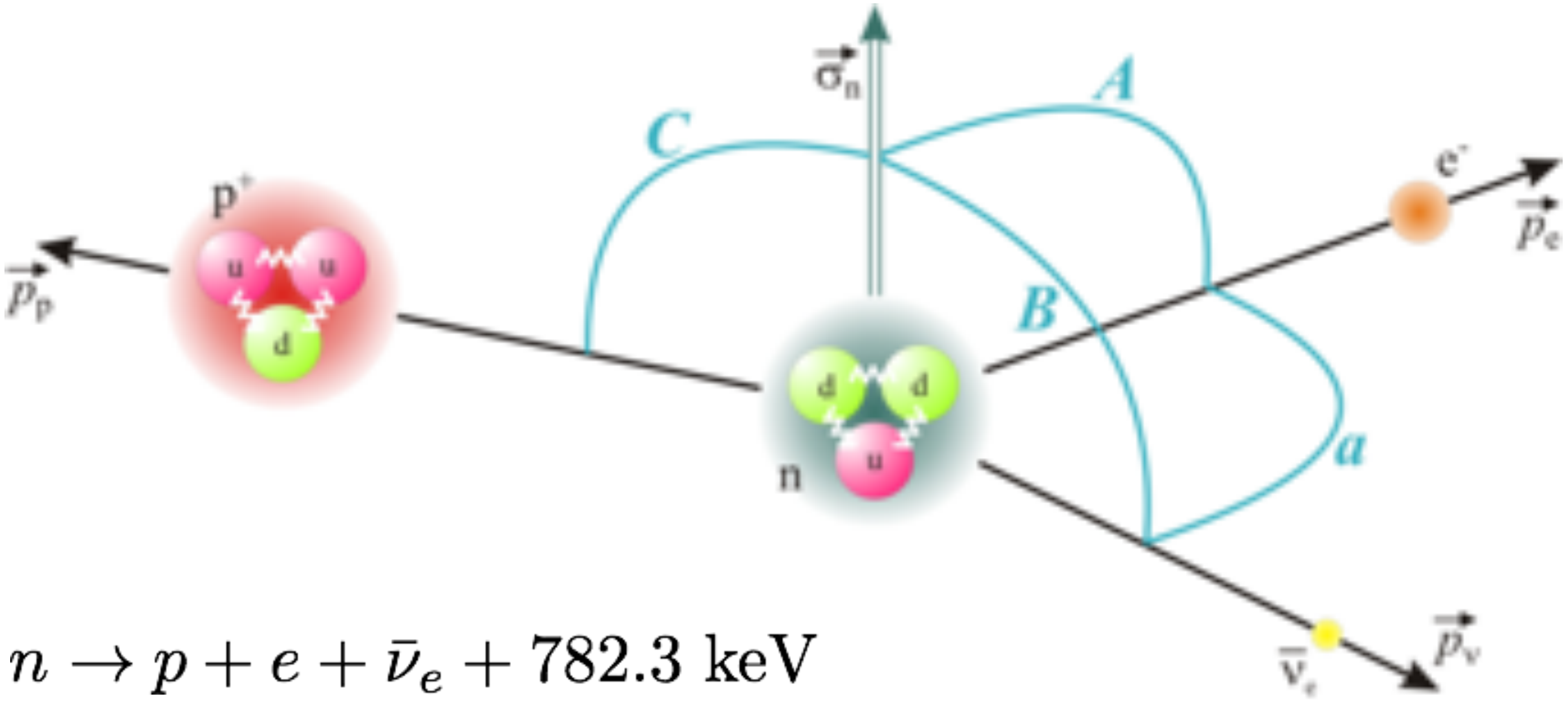
中性子β崩壊　角相関項

中性子β崩壊　角相関項

$$dN \propto \left[1 + a\frac{\boldsymbol{p}_e \cdot \boldsymbol{p}_{\overline{\nu}}}{E_e \cdot E_{\overline{\nu}}} + \frac{\mathbf{J}}{J}\cdot\left(A\frac{\boldsymbol{p}_e}{E_e} + B\frac{\boldsymbol{p}_{\overline{\nu}}}{E_{\overline{\nu}}} + D\frac{\boldsymbol{p}_e \times \boldsymbol{p}_{\overline{\nu}}}{E_e E_{\overline{\nu}}}\right) + \ldots\right]$$

$$a = \frac{1-|\lambda|^2}{1+3|\lambda|^2} \quad A = -2\frac{|\lambda|\cos\phi + |\lambda|^2}{1+3|\lambda|^2} \quad B = -2\frac{|\lambda|\cos\phi - |\lambda|^2}{1+3|\lambda|^2} \quad D = 2\frac{|\lambda|\sin\phi}{1+3|\lambda|^2}$$

$$\tau = \frac{K/\ln 2}{V_{\mathrm{ud}}^2 G_{\mathrm{F}}^2 (1+\lambda^2) f}$$



$$n \rightarrow p + e + \bar{\nu}_e + 782.3\ \mathrm{keV}$$

中性子β崩壊　角相関項

$$dN \propto \left[1 + a\frac{\boldsymbol{p}_e \cdot \boldsymbol{p}_{\overline{\nu}}}{E_e \cdot E_{\overline{\nu}}} + \frac{\mathbf{J}}{J}\cdot\left(A\frac{\boldsymbol{p}_e}{E_e} + B\frac{\boldsymbol{p}_{\overline{\nu}}}{E_{\overline{\nu}}} + D\frac{\boldsymbol{p}_e \times \boldsymbol{p}_{\overline{\nu}}}{E_e E_{\overline{\nu}}}\right) + \ldots\right]$$

$$a = \frac{1-|\lambda|^2}{1+3|\lambda|^2} \quad A = -2\frac{|\lambda|\cos\phi + |\lambda|^2}{1+3|\lambda|^2} \quad B = -2\frac{|\lambda|\cos\phi - |\lambda|^2}{1+3|\lambda|^2} \quad D = 2\frac{|\lambda|\sin\phi}{1+3|\lambda|^2}$$

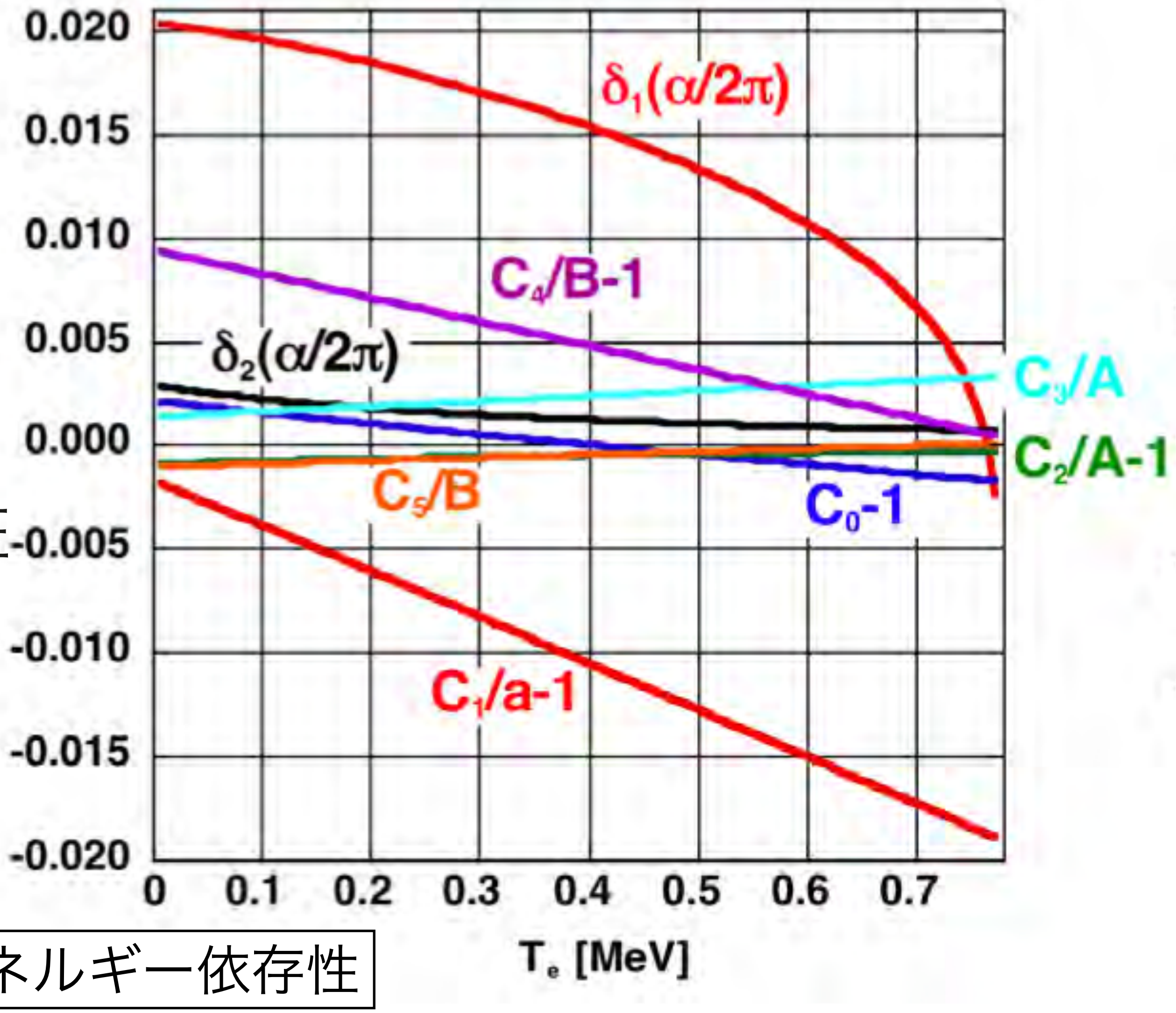
$$\tau = \frac{K/\ln 2}{V_{\rm ud}^2 G_{\rm F}^2 (1+\lambda^2) f}$$

***A*項** 寿命と組み合わせてCKM行列 V_{ud}

***a*項** 陽子エネルギーから終状態相互作用を検証

***B*項** 超対称性模型に感度

***D*項** 時間反転対称性の破れ

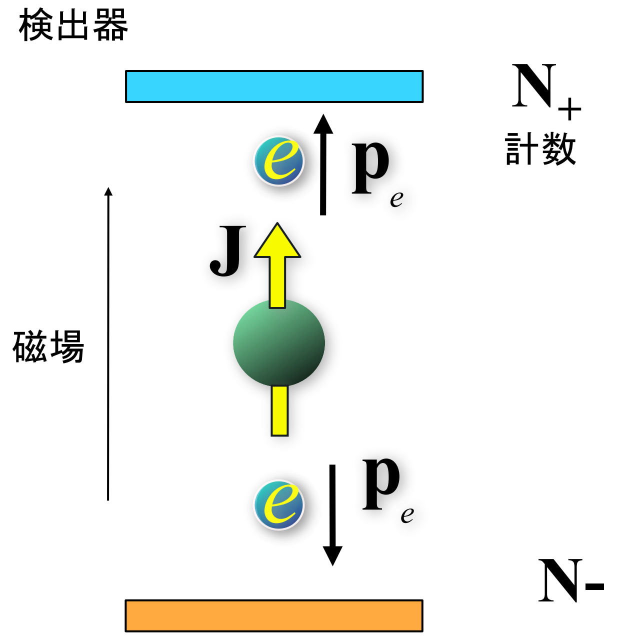


相関項の電子エネルギー依存性

中性子β崩壊　角相関項

角相関　A項

中性子スピン偏極方向と電子の運動量の内積



$$\boxed{\frac{N_+ - N_-}{N_+ + N_-} = \frac{1}{2} A\, P \frac{P_e}{E_e}}$$

PDGの最高値（PERKEOIII)
A=–0.11985±0.00021

主なAの誤差の原因

- 偏極度　　~ **ΔA/A= 0.064%**
- magnetic mirror effect　~ **ΔA/A= 0.045%**
- 統計　　　~ **ΔA/A= 0.14%**

偏極度Pが大きいほど、非対称度も大きくなる

偏極度Pの誤差が、測定値の誤差に影響する

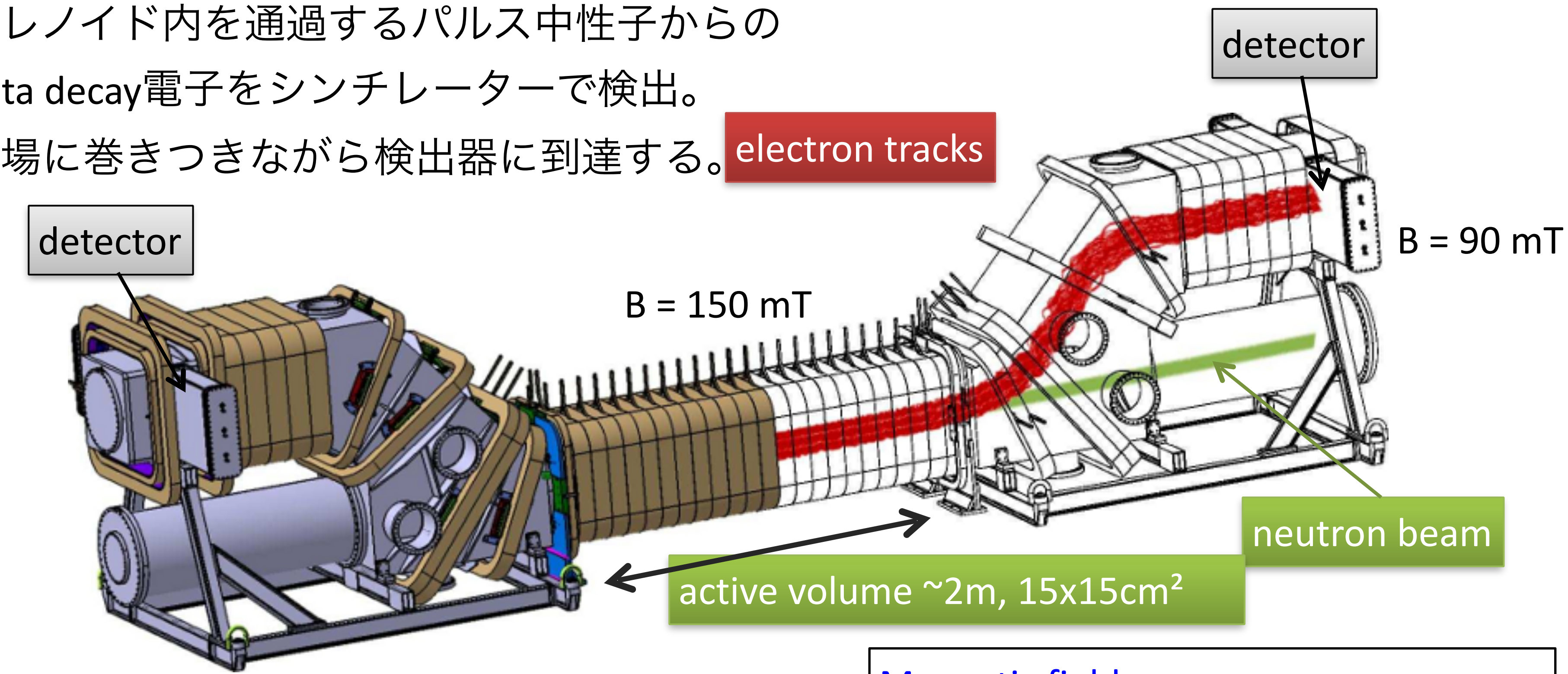
実験の鍵は統計、偏極度測定、磁場

中性子β崩壊　角相関項

角相関　A項

Perkeo III実験

ソレノイド内を通過するパルス中性子からの
Beta decay電子をシンチレーターで検出。
磁場に巻きつきながら検出器に到達する。



54 water-cooled copper coils
Total Weight: 8 t
Total Length: 8 m
Electric: 300 kW, 540 A

10.9.2013　PSI2013
Bastian Märkisch

Magnetic field :

- alignment of n–spin
- guide e⁻, p onto detectors
  ⇒ 2 x 2 π detector
- separation into hemispheres

中性子β崩壊　角相関項

角相関　A項

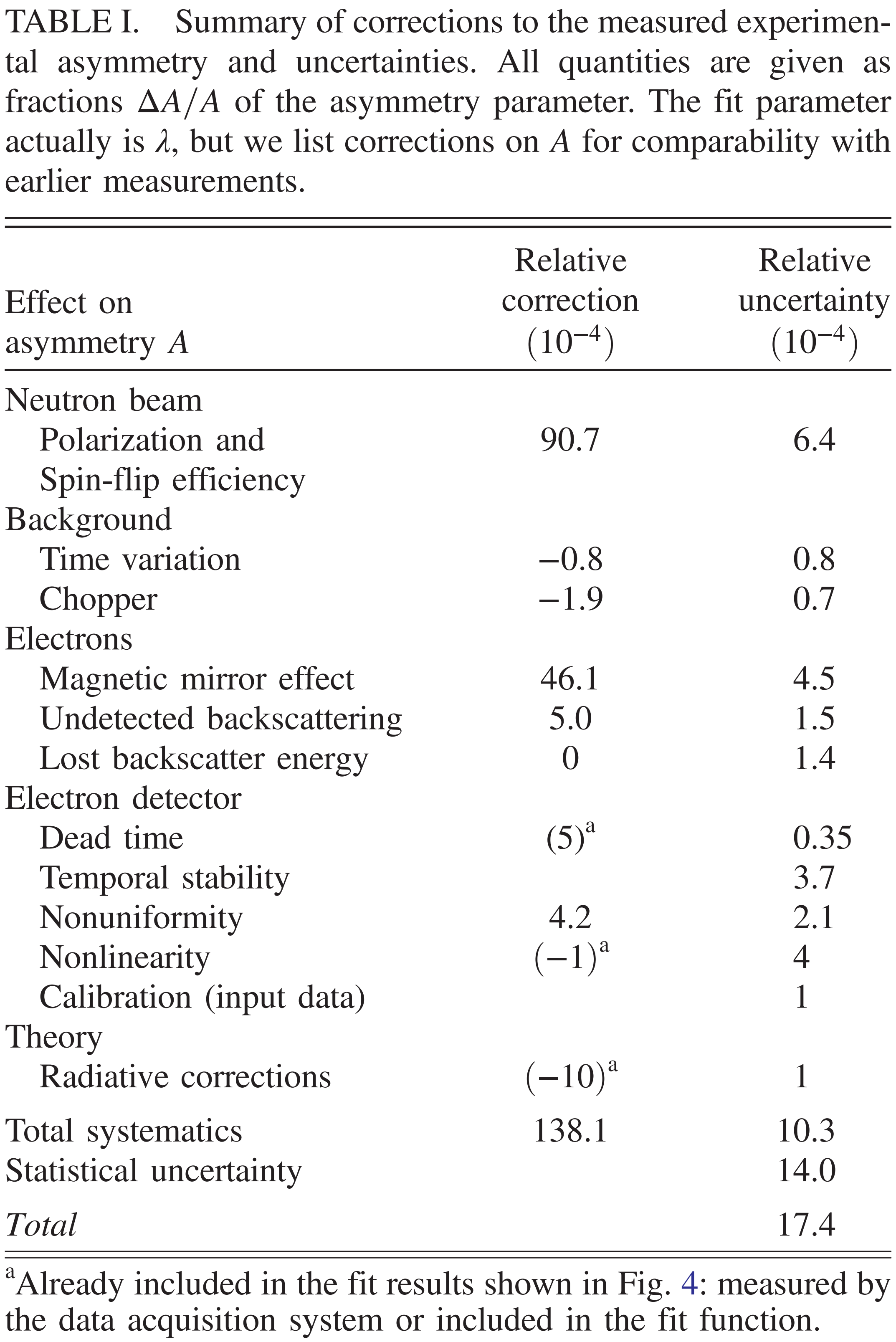


TABLE I. Summary of corrections to the measured experimental asymmetry and uncertainties. All quantities are given as fractions $\Delta A/A$ of the asymmetry parameter. The fit parameter actually is λ, but we list corrections on A for comparability with earlier measurements.

Effect on asymmetry A	Relative correction (10^{-4})	Relative uncertainty (10^{-4})
Neutron beam		
Polarization and Spin-flip efficiency	90.7	6.4
Background		
Time variation	−0.8	0.8
Chopper	−1.9	0.7
Electrons		
Magnetic mirror effect	46.1	4.5
Undetected backscattering	5.0	1.5
Lost backscatter energy	0	1.4
Electron detector		
Dead time	(5)[a]	0.35
Temporal stability		3.7
Nonuniformity	4.2	2.1
Nonlinearity	(−1)[a]	4
Calibration (input data)		1
Theory		
Radiative corrections	(−10)[a]	1
Total systematics	138.1	10.3
Statistical uncertainty		14.0
Total		17.4

[a] Already included in the fit results shown in Fig. 4: measured by the data acquisition system or included in the fit function.

中性子β崩壊　角相関項

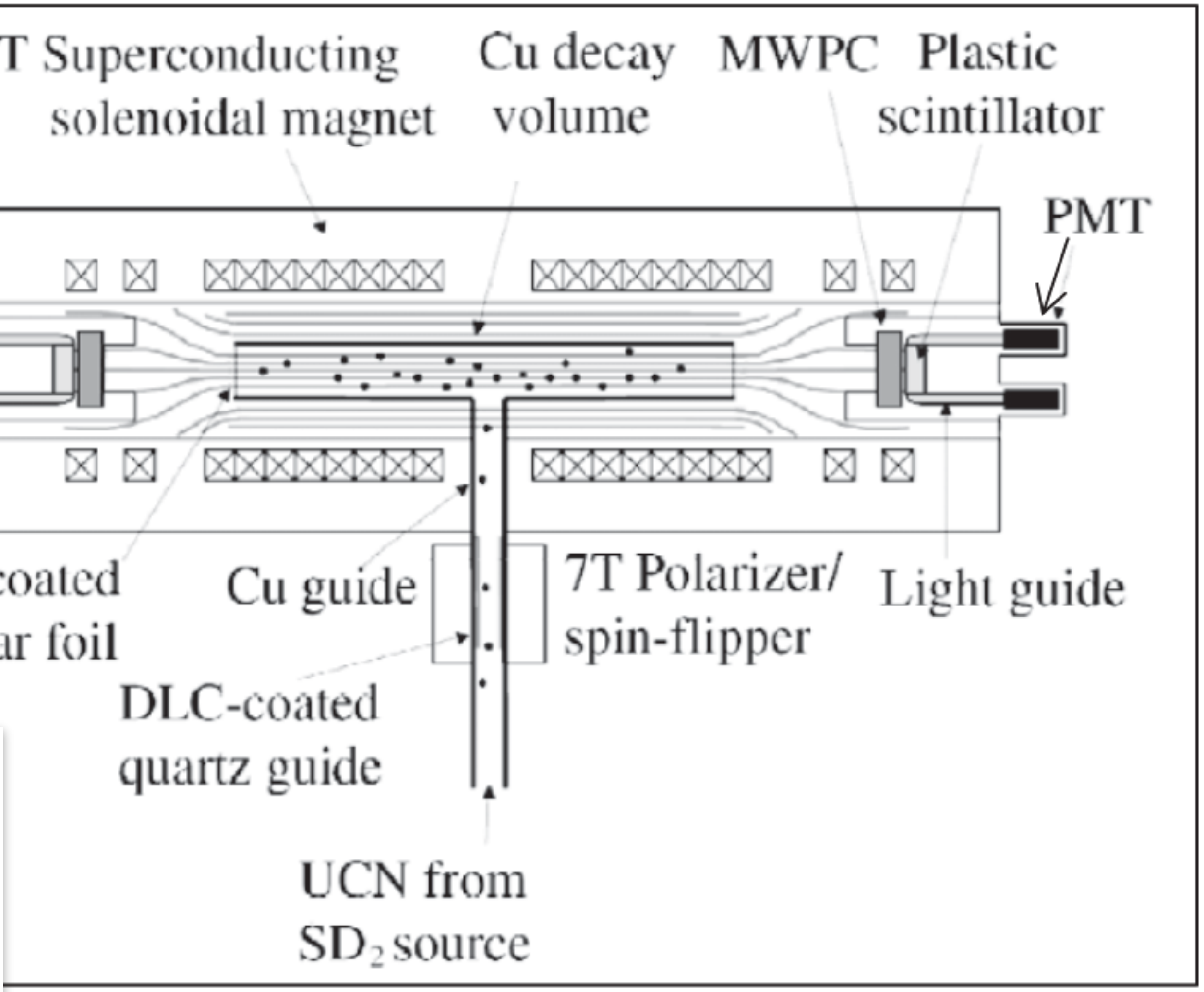
角相関　A項

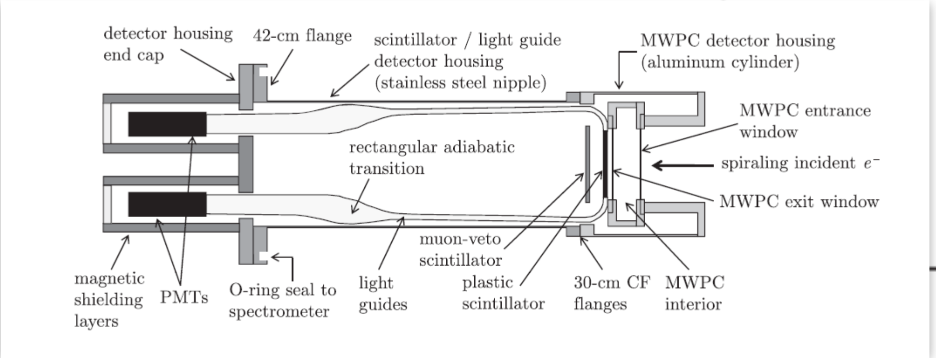
UCNA実験

UCNを7Tの磁場で完全に偏極させ容器に閉じ込める。1Tのソレノイド磁場で

両端の検出器で測定する。

検出器は低圧ガス検出器とシンチレーター。



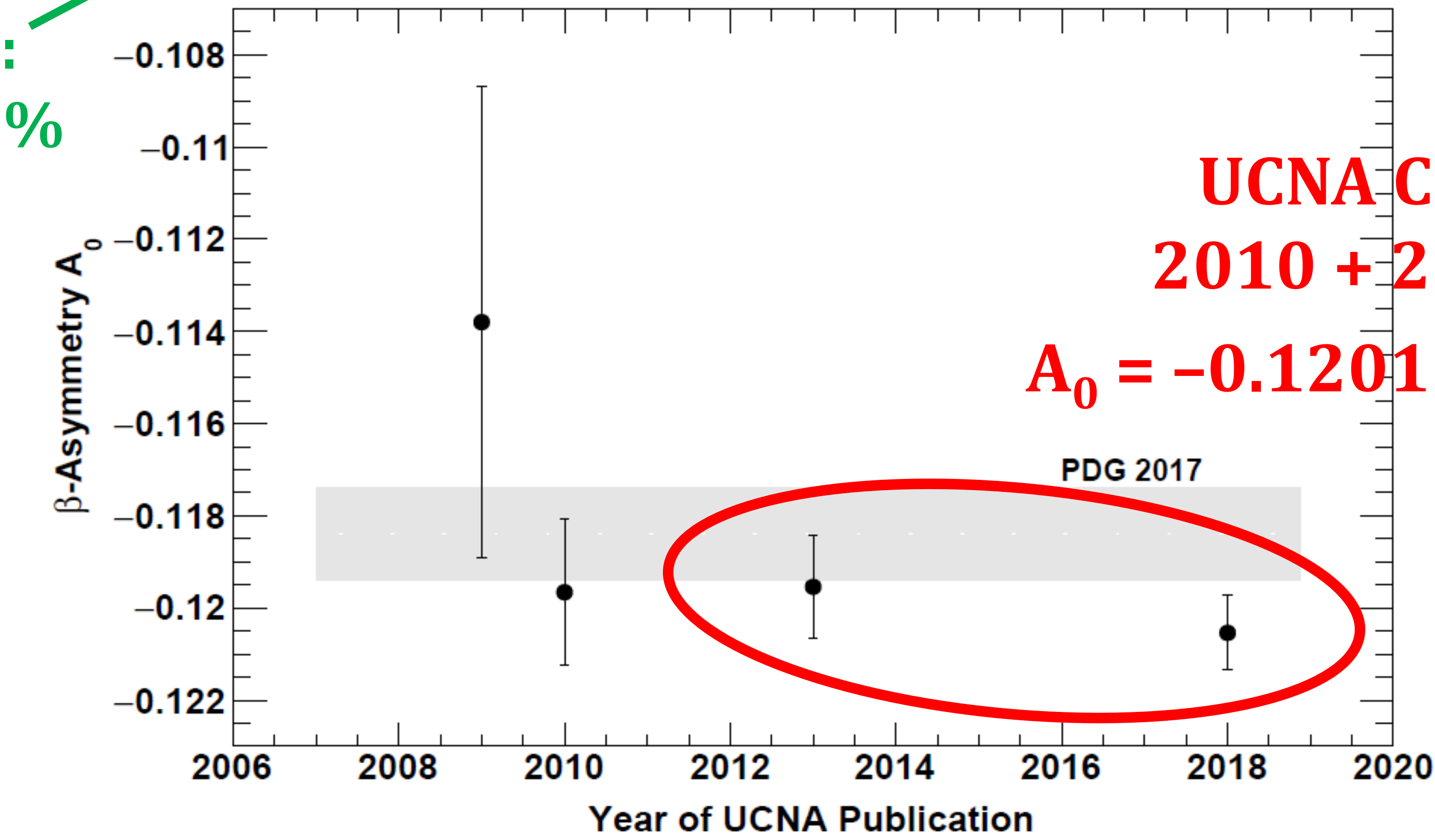


B. Plaster et al., PHYSICAL REVIEW C **86**, 055501 (2012)

中性子β崩壊　角相関項

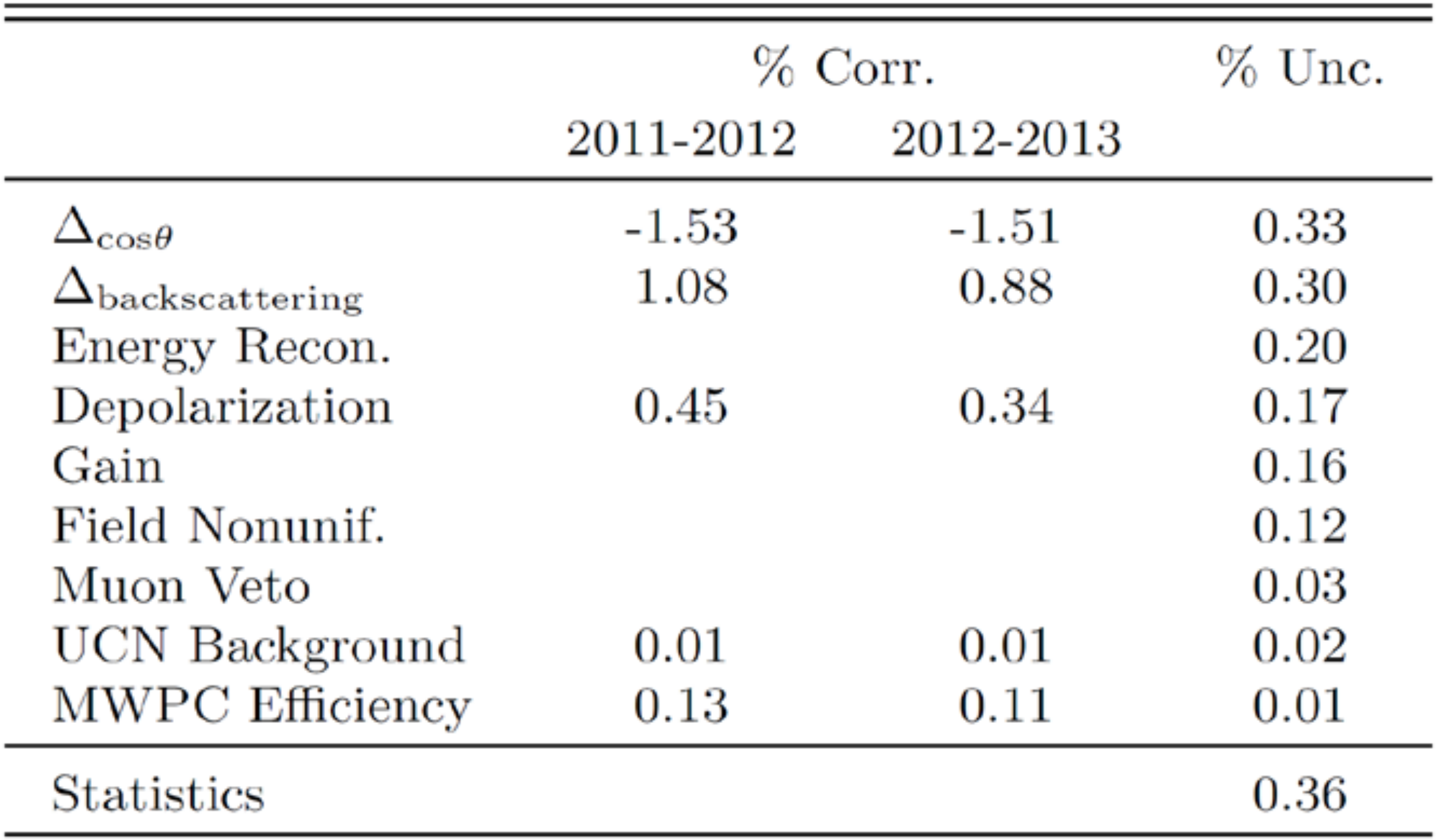
	δA/A Stat [%]	δA/A Syst [%]	‘*A*’ Result
2007	4.0	1.8	PRL 102, 012301 (2009)
2008-9	0.74	1.1	PRL 105, 181803 (2010), PRC 86, 055501 (2012)
2010	0.46	0.82	PRC 87, 032501(R) (2013)
2011-13	0.37	0.56	PRC 97, 035505 (2018)

Polarization:
0.56% → 0.17%



UCNA Combined
2010 + 2011-2013:
$A_0 = -0.12015(34)_{stat}(63)_{syst}$

中性子β崩壊　角相関項



	% Corr.		% Unc.
	2011-2012	2012-2013	
$\Delta_{\cos\theta}$	-1.53	-1.51	0.33
$\Delta_{\text{backscattering}}$	1.08	0.88	0.30
Energy Recon.			0.20
Depolarization	0.45	0.34	0.17
Gain			0.16
Field Nonunif.			0.12
Muon Veto			0.03
UCN Background	0.01	0.01	0.02
MWPC Efficiency	0.13	0.11	0.01
Statistics			0.36

中性子β崩壊　角相関項

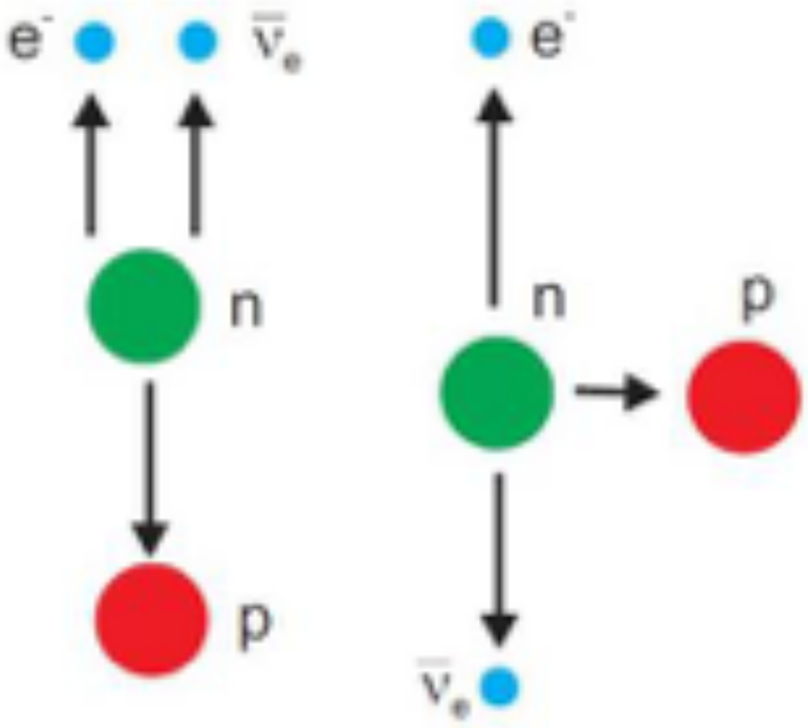
角相関　a項

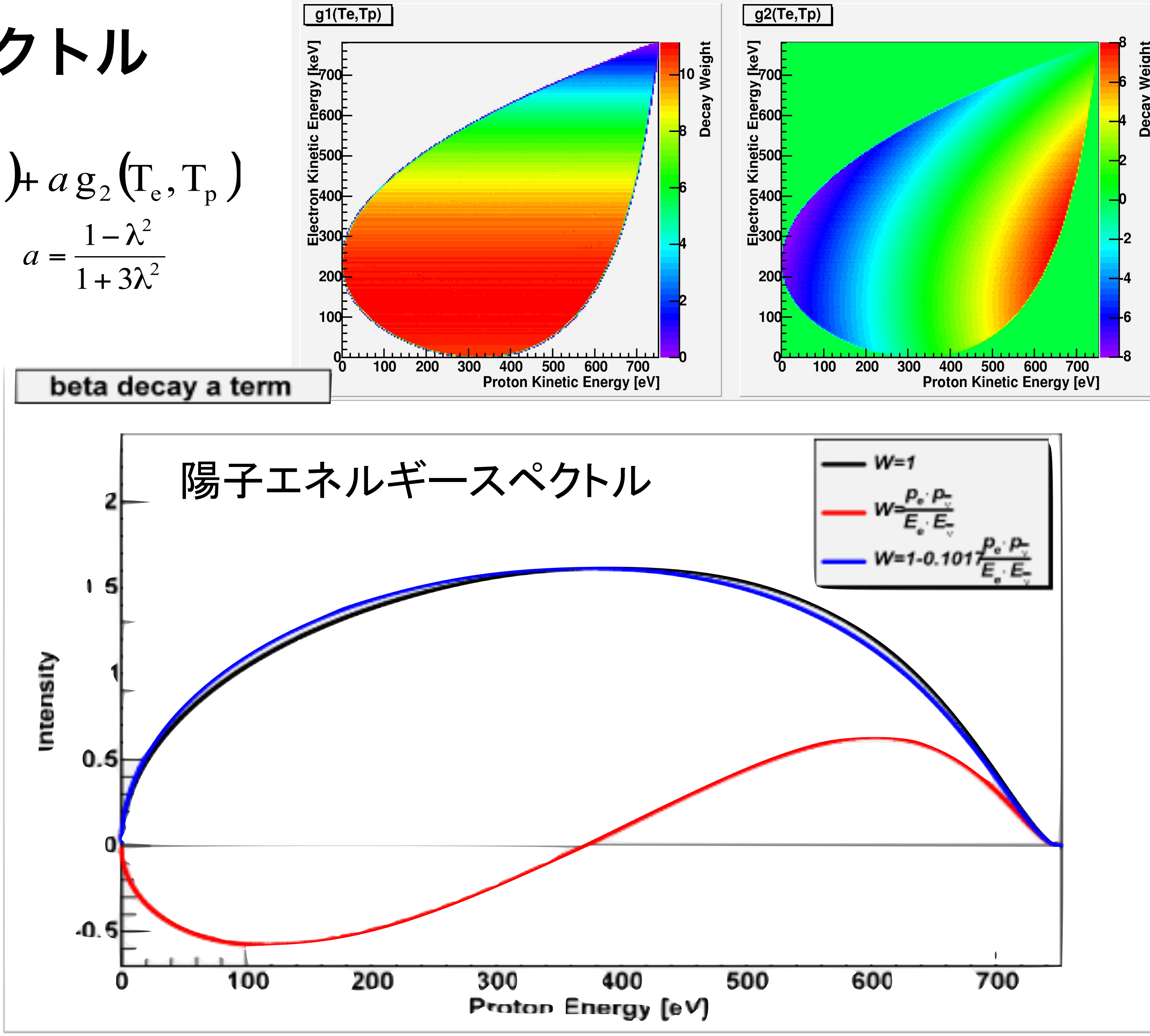
Next Leading Order項の測定

陽子のエネルギースペクトル

$$P(T_e, T_p) = g_1(T_e, T_p) + a\, g_2(T_e, T_p)$$

where $a = \dfrac{1-\lambda^2}{1+3\lambda^2}$

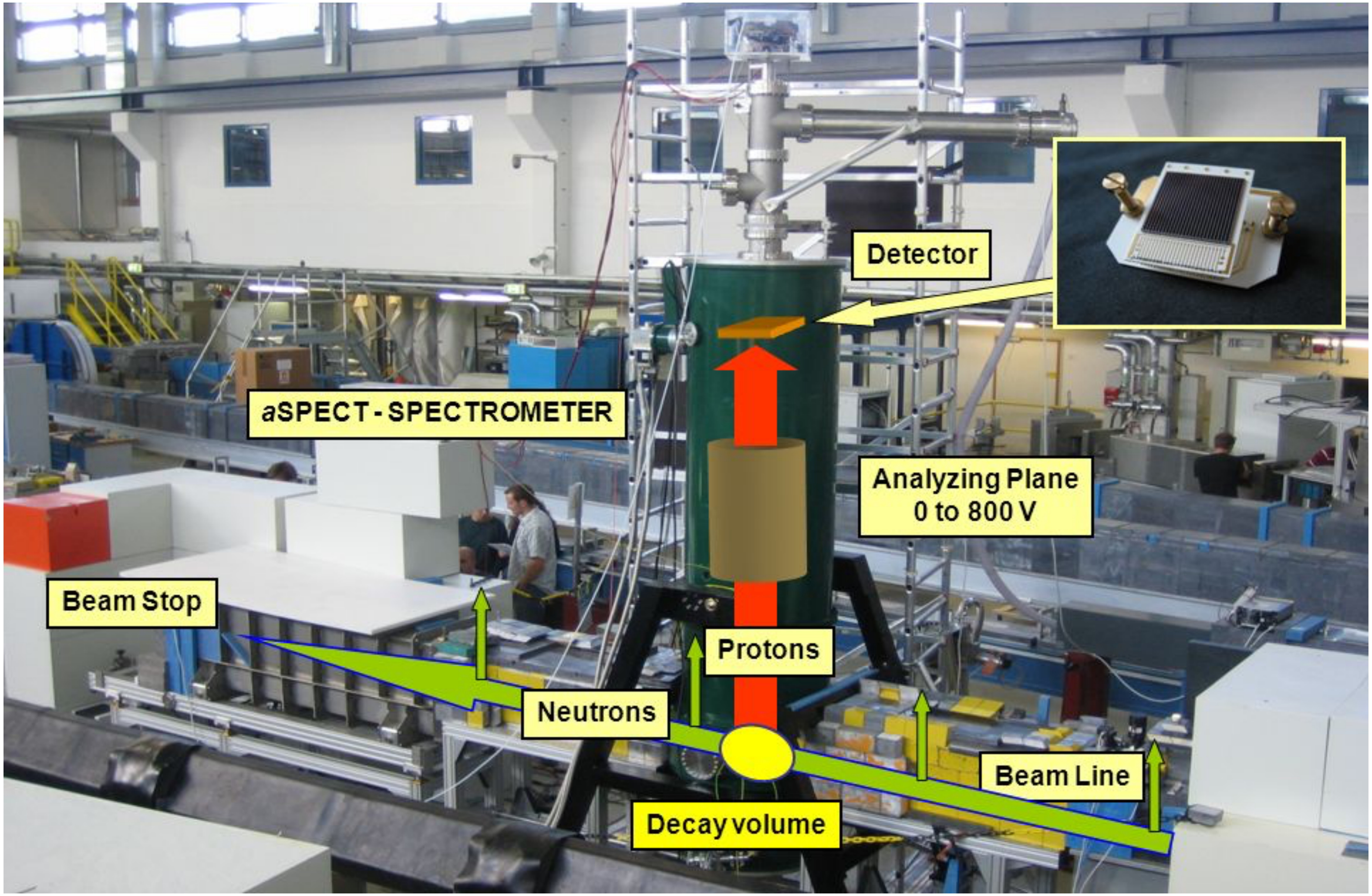




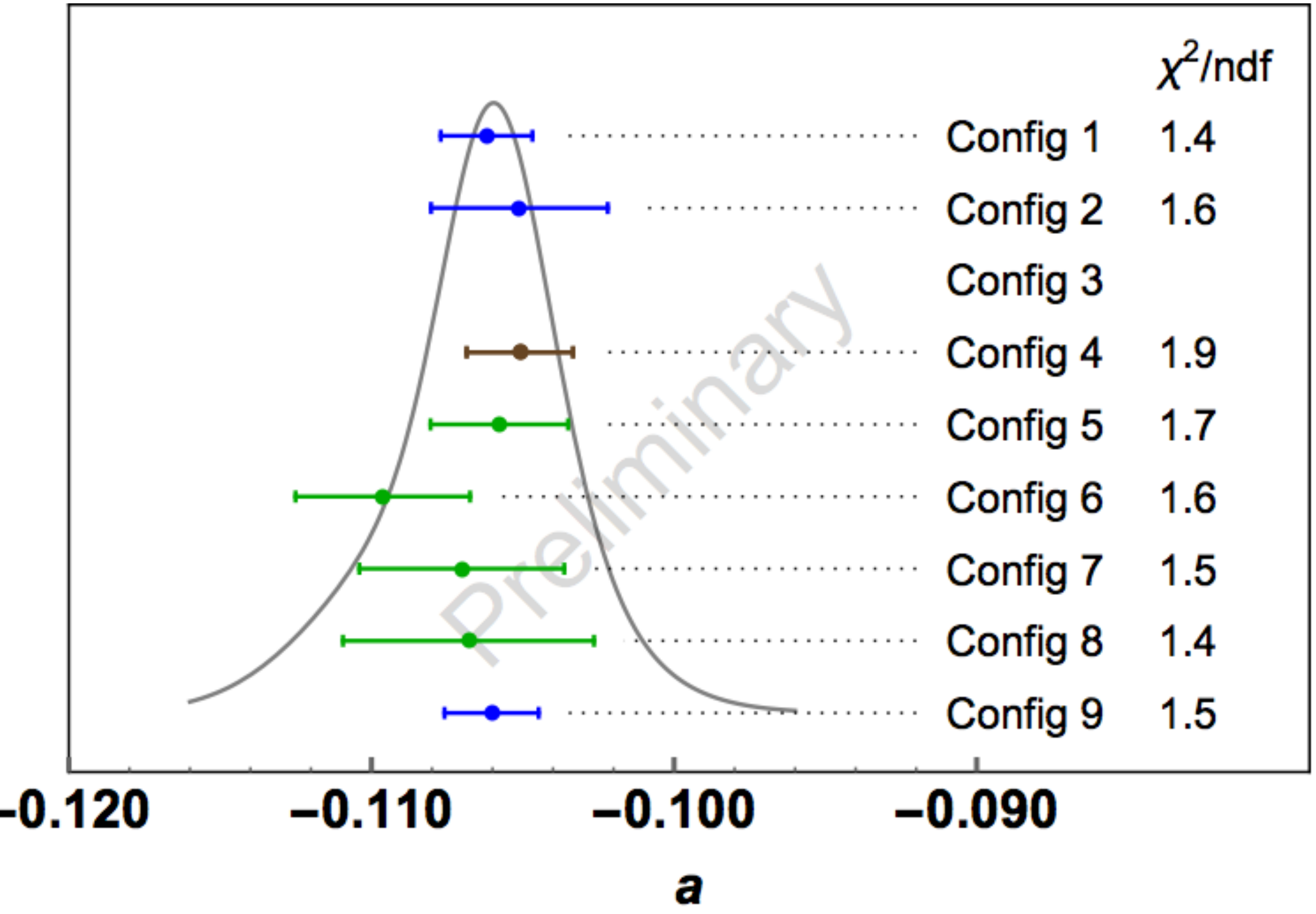
第6回勉強会
「中性子基礎物理」2020年12月7日
北口雅暁（名古屋大学KMI）

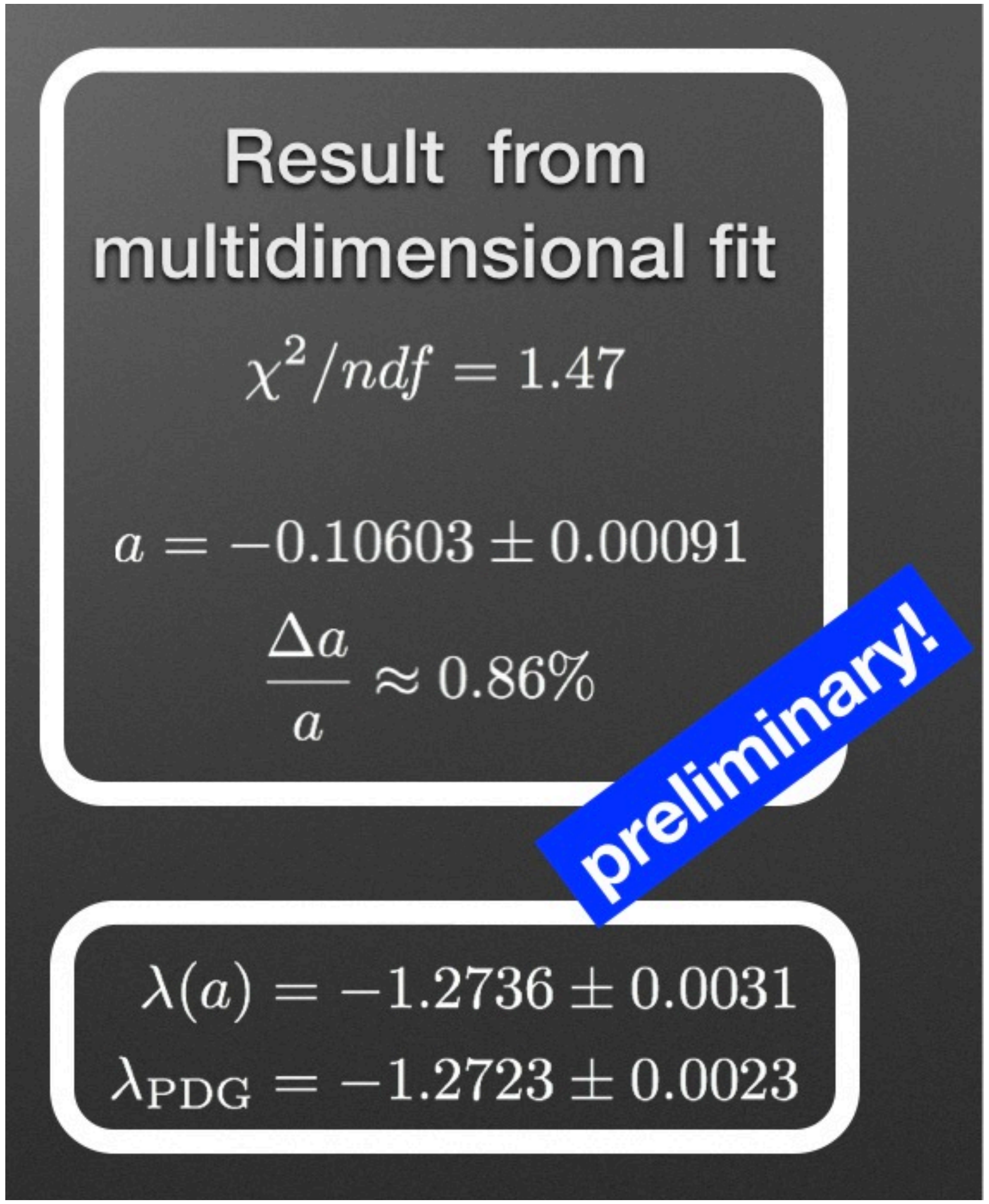
中性子β崩壊　角相関項

aSPECT at ILL



中性子β崩壊　角相関項




Result from multidimensional fit

$\chi^2/ndf = 1.47$

$a = -0.10603 \pm 0.00091$

$\frac{\Delta a}{a} \approx 0.86\%$

$\lambda(a) = -1.2736 \pm 0.0031$

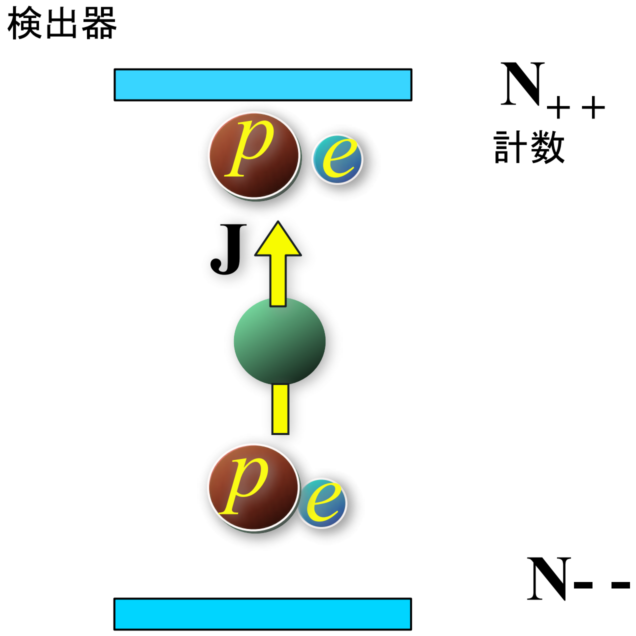
$\lambda_{\mathrm{PDG}} = -1.2723 \pm 0.0023$

中性子β崩壊　角相関項

角相関　B項

新物理は、標準理論と異なる依存性がNLOに現れる

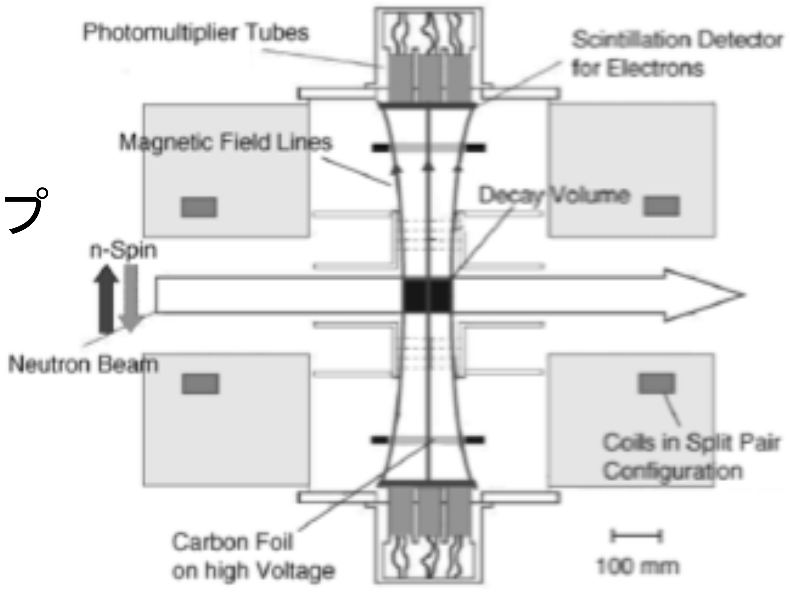
中性子スピン偏極方向とニュートリノ電子の運動量の内積



$$\frac{N_{--}(E)-N_{++}(E)}{N_{--}(E)+N_{++}(E)} = \mathbf{B}\ \mathbf{P}$$

Right-handed gauge boson探索

測定セットアップ



$B = 0.9802 \pm 0.0050$

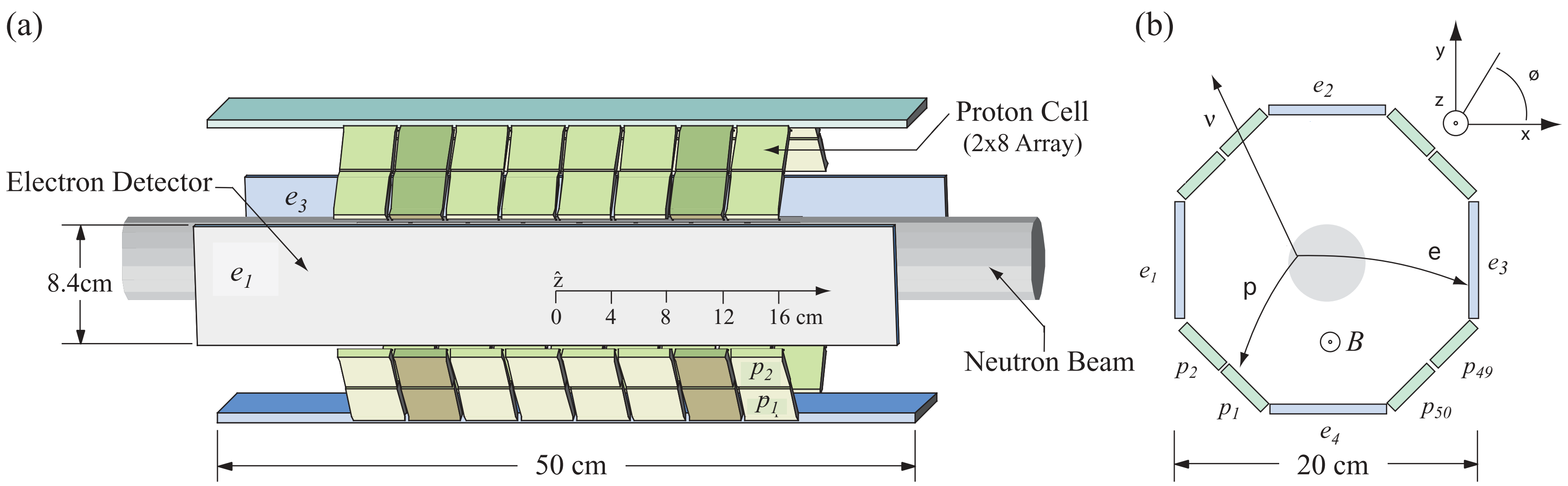
M. Schumann et al.,PRL **99,** 191803 (2007)

中性子β崩壊　角相関項

角相関　D項

D項は標準理論ではゼロ、時間反転対称性を破る

Source	Limit on D_T
CKM phase	10^{-12}
θ_{QCD}	2×10^{-15}
Left-right symmetry	10^{-7}–10^{-5}
Non-SM fermions	10^{-7}–10^{-5}
Charged Higgs SUSY	10^{-7}–10^{-6}
Leptoquark	10^{-5}–10^{-4}



T. E. Chupp, *et al.*

PHYSICAL REVIEW C **86** 035505 (2012)

$$D = [-0.94 \pm 1.89(\text{stat}) \pm 0.97(\text{sys})] \times 10^{-4}$$

$$C_A/C_V = |\lambda| e^{i\phi_{AV}}$$

$$\phi_{AV} = 180.012^\circ \pm 0.028^\circ \; (68\% \text{ confidence level})$$

CP violation

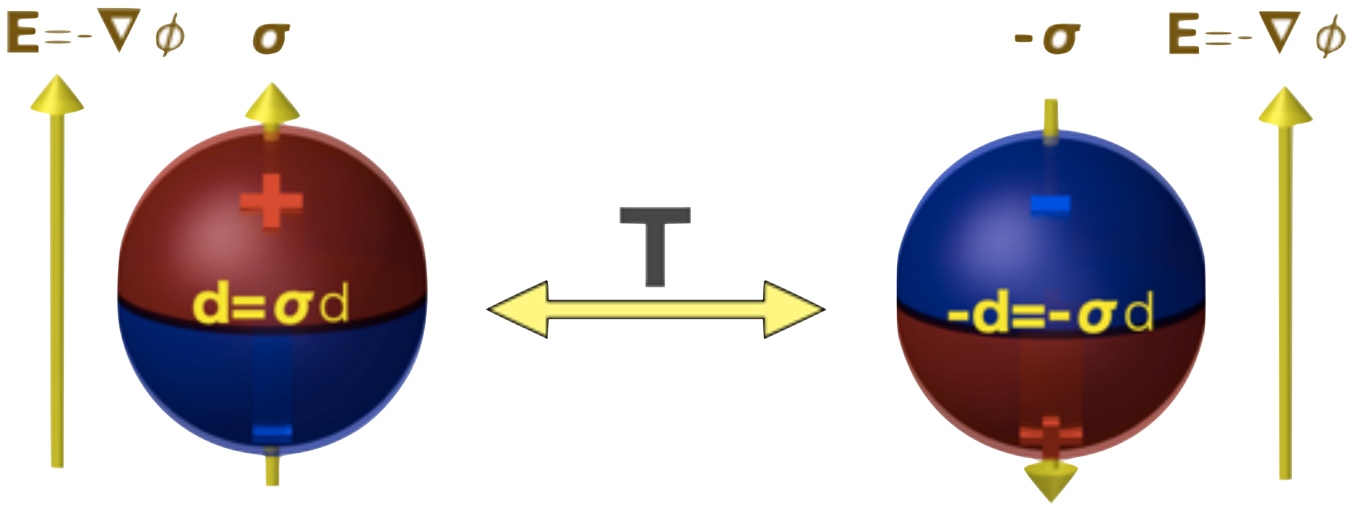
CP violation

$$CPT=1 \qquad CP\neq 1 \Leftrightarrow T\neq 1$$

CP-violation

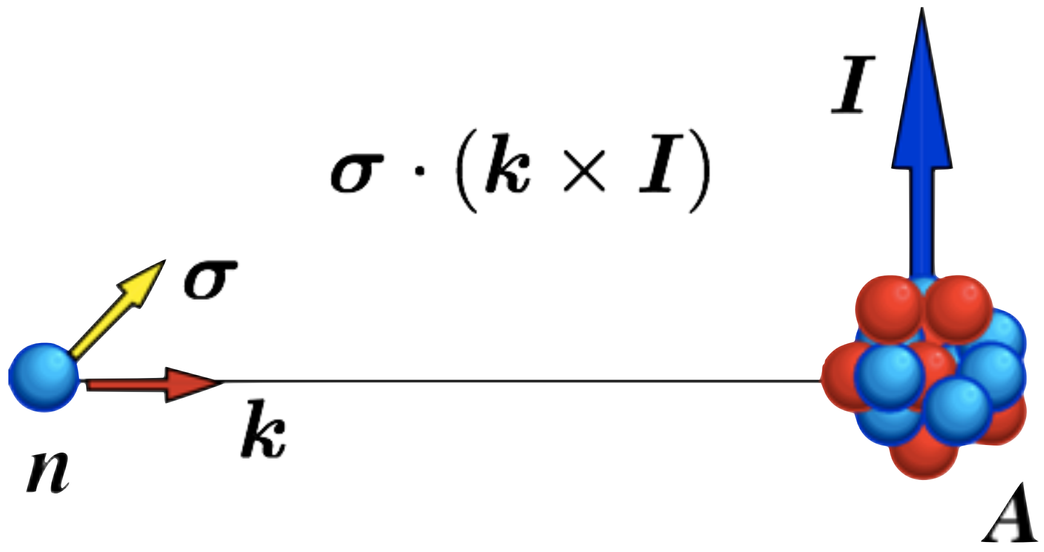
T-violation

Electric Dipole Moment

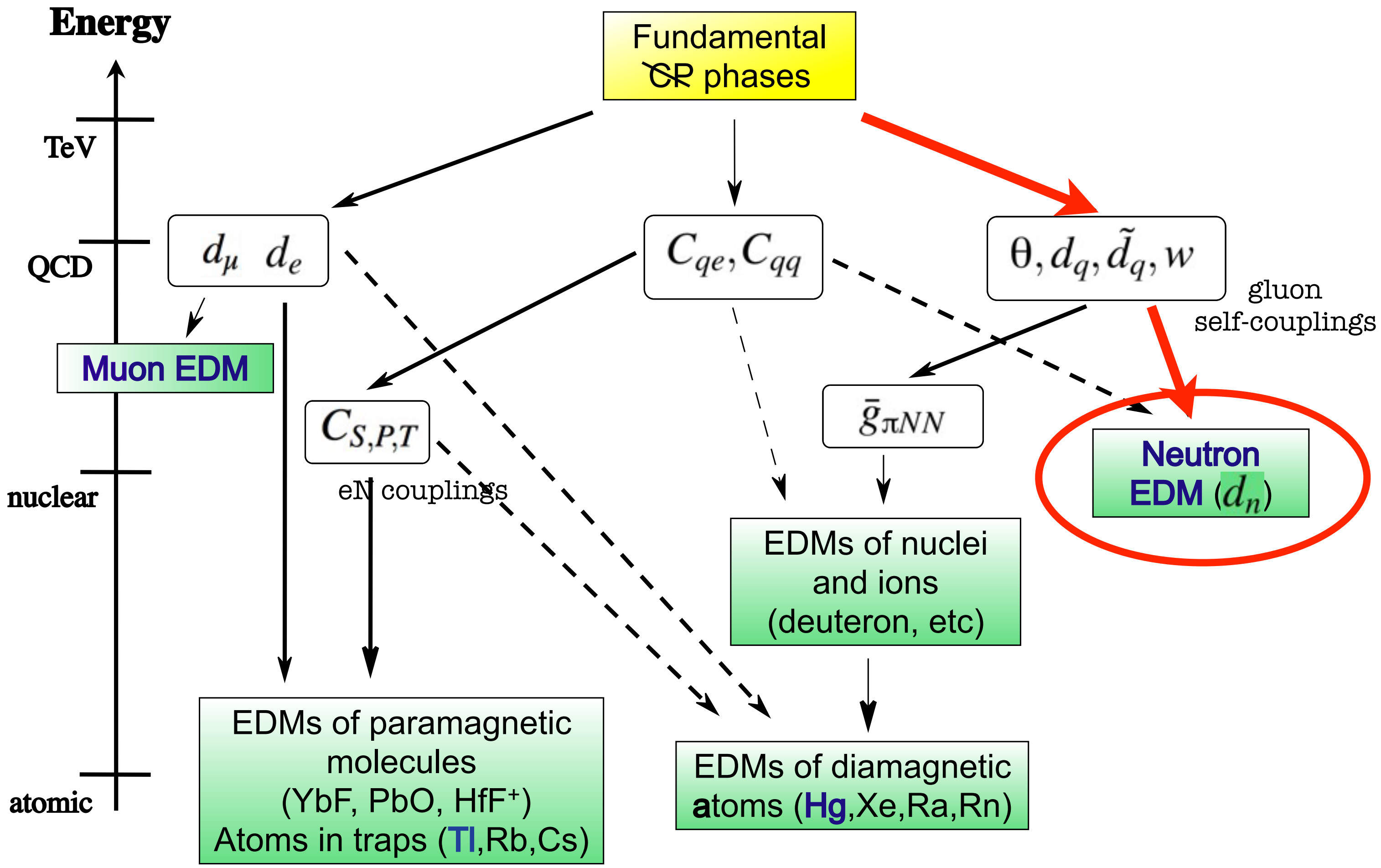


T-odd Correlation Terms

$$\boldsymbol{\sigma}\cdot(\boldsymbol{k}\times\boldsymbol{I})$$



Neutron EDM



Energy

TeV

QCD

nuclear

atomic

Fundamental $\not{C}\not{P}$ phases

$d_\mu \quad d_e$

C_{qe}, C_{qq}

$\theta, d_q, \tilde{d}_q, w$

gluon self-couplings

Muon EDM

$C_{S,P,T}$

eN couplings

$\bar{g}_{\pi NN}$

Neutron EDM (d_n)

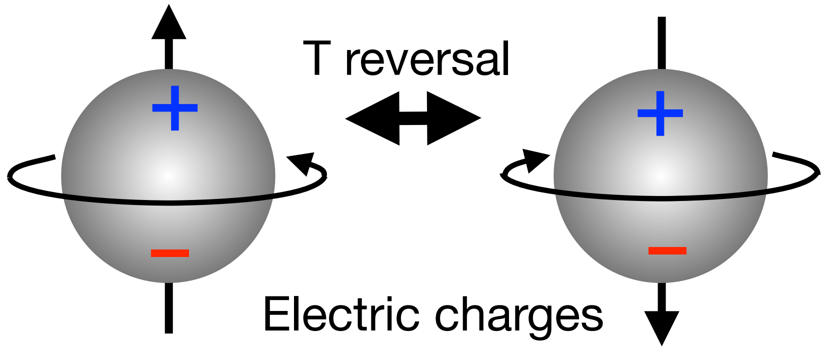
EDMs of nuclei and ions (deuteron, etc)

EDMs of paramagnetic molecules (YbF, PbO, HfF$^+$) Atoms in traps (**Tl**,Rb,Cs)

EDMs of diamagnetic atoms (**Hg**,Xe,Ra,Rn)

Pospelov Ritz, Ann Phys 318 (05) 119

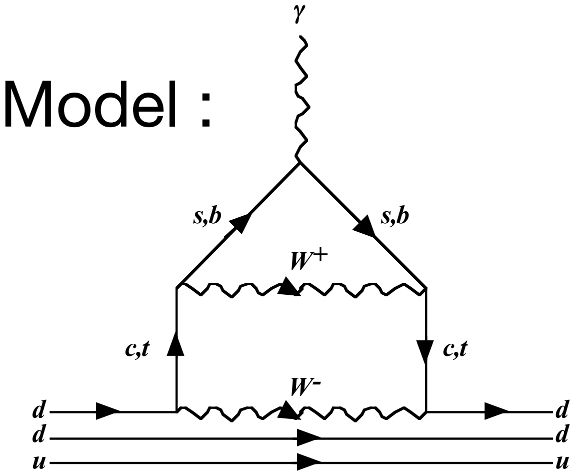
Spin is reversed.



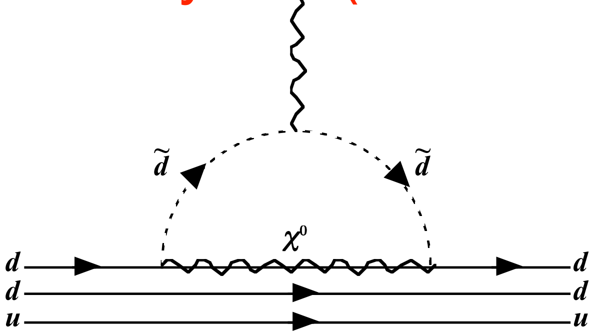
T reversal

Electric charges don't change.

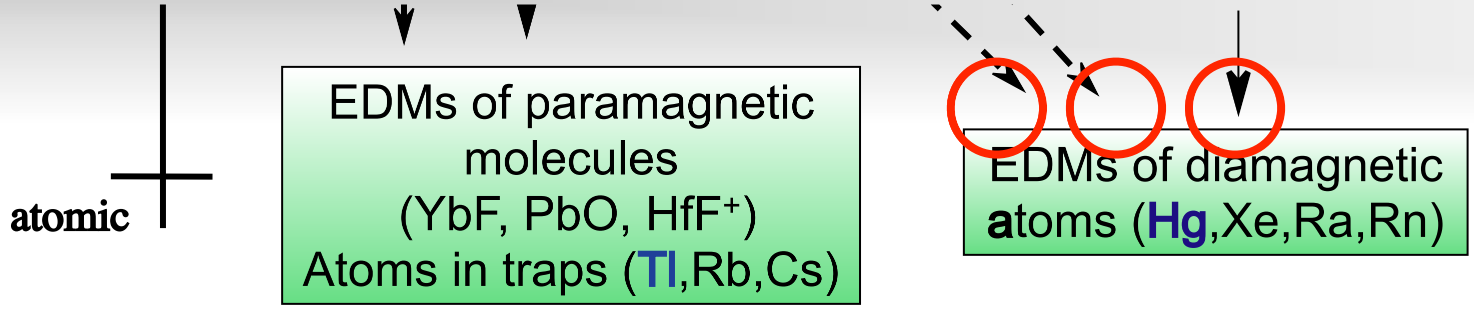
Standerd Model :



New Physics (SUSY ...) :



原子核EDM



EDMs of paramagnetic molecules (YbF, PbO, HfF⁺)
Atoms in traps (**Tl**,Rb,Cs)

EDMs of diamagnetic atoms (**Hg**,Xe,Ra,Rn)

nucleon EDMs

Nucleon-electron int.

$$d_{\mathrm{dia}} = \boxed{\alpha_{\mathrm{Sch}} S_{\mathrm{Sch}}} + \alpha_{d_{\mathrm{p}}} d_{\mathrm{p}} + \alpha_{d_{\mathrm{n}}} d_{\mathrm{n}} + \alpha_{C_{\mathrm{T}}^{(0)}} C_{\mathrm{T}}^{(0)} + \boxed{\alpha_{C_{\mathrm{T}}^{(1)}} C_{\mathrm{T}}^{(1)}}$$

d_{Hg} : Vanishingly small contribution from $\bar{g}_{\pi NN}^{(1)}$

Coefficient values, from the compilation of:
[J. Engel *et al.*, *Prog. Part. Nucl. Phys.* **71** (2013) 21]

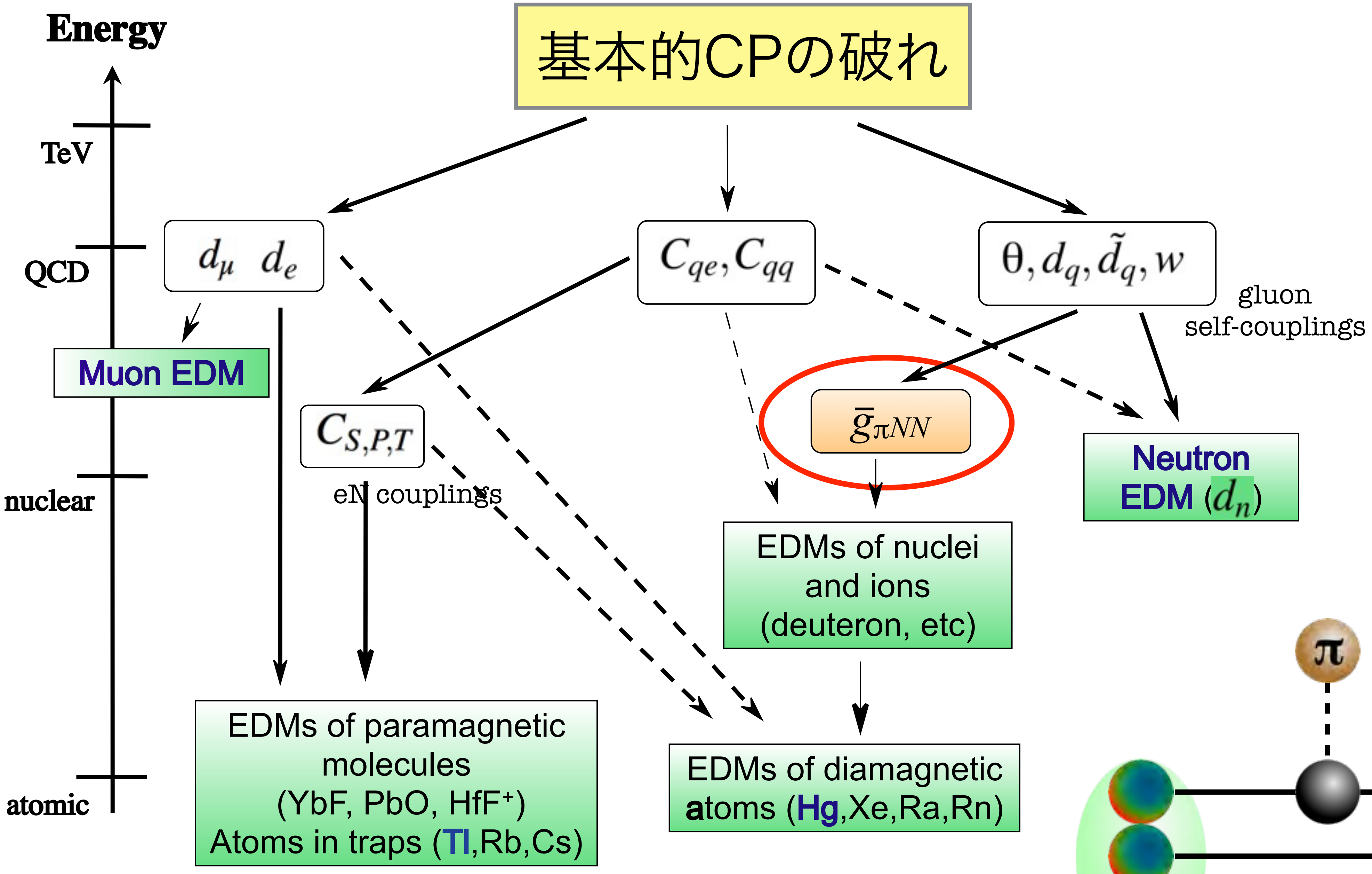
$$d_{\mathrm{Hg}} = -\left(0.38^{+2.3}_{-0.19} \times 10^{-17}\right) \cdot \bar{g}_{\pi NN}^{(0)} + \left(0^{+1.6}_{-4.9} \times 10^{-17}\right) \cdot \bar{g}_{\pi NN}^{(1)} - \left(2.0^{+3.9}_{-0.0} \times 10^{-20}\right) \cdot C_{\mathrm{T}}$$

$$d_{\mathrm{Xe}} = -\left(0.29^{+2.3}_{-0.11} \times 10^{-18}\right) \cdot \bar{g}_{\pi NN}^{(0)} - \left(0.22^{+1.7}_{-0.11} \times 10^{-18}\right) \cdot \bar{g}_{\pi NN}^{(1)} + \left(4^{+2}_{-0} \times 10^{-21}\right) \cdot C_{\mathrm{T}}$$

$$d_{\mathrm{n}} = -\left(1.5 \times 10^{-14}\right) \cdot \bar{g}_{\pi NN}^{(0)} + \left(1.4 \times 10^{-16}\right) \cdot \bar{g}_{\pi NN}^{(1)}$$

d_{n} : No contribution from C_{T}

複合核共鳴における対称性の破れ



Energy

TeV

QCD

nuclear

atomic

基本的CPの破れ

$d_\mu \quad d_e$

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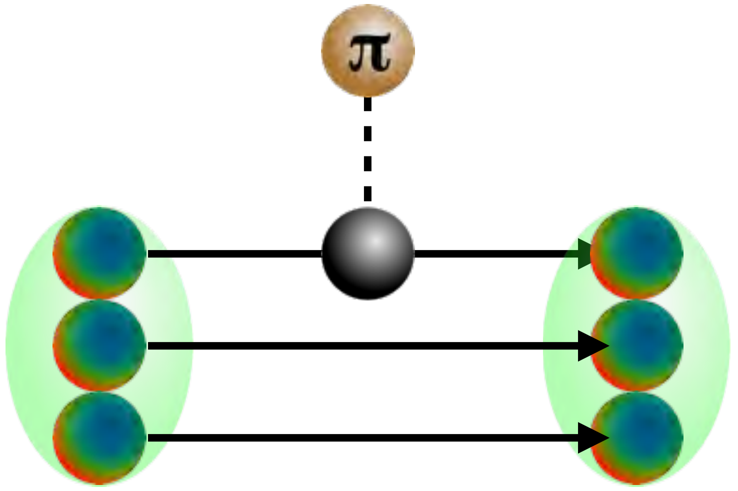
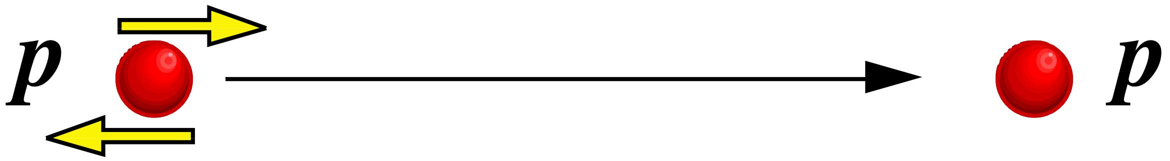
Pospelov Ritz, Ann Phys 318 (05) 119



T-odd P-odd pion-nucleon coupling

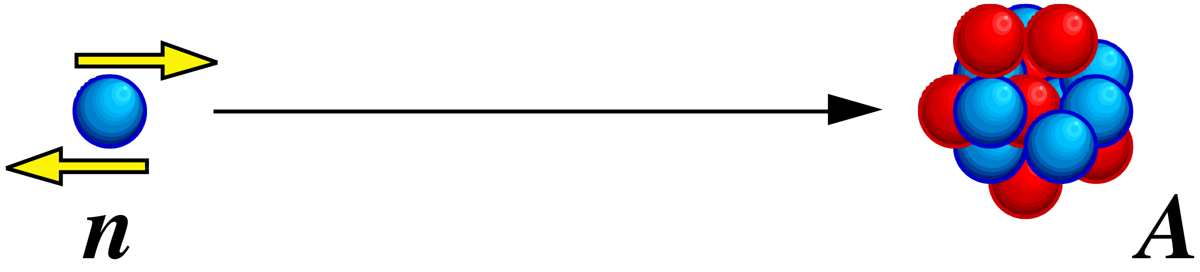
対称性の破れの増幅

核子-核子　反応での P非対称度

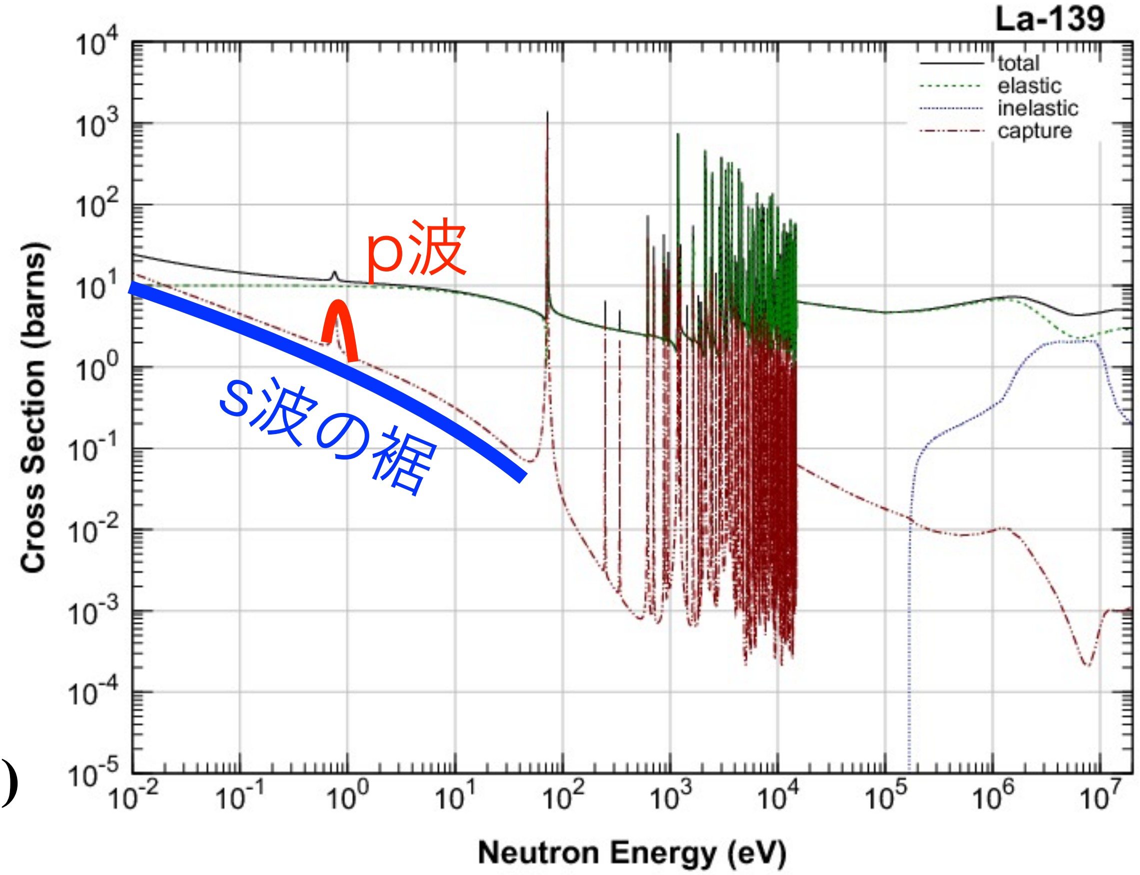


15MeV	$-(1.7\pm0.8)\times10^{-7}$
45MeV	$-(2.3\pm0.8)\times10^{-7}$
800MeV	$-(2.4\pm1.1\pm0.1)\times10^{-7}$

中性子-原子核　反応での P非対称度



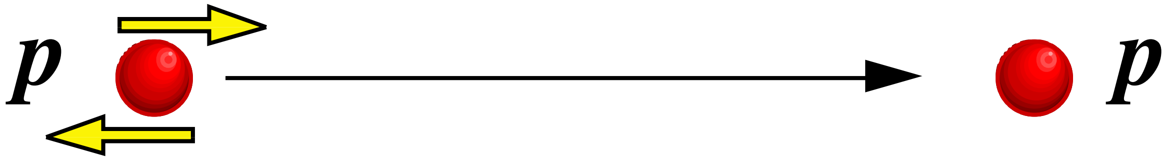
^{139}La	$E_n = 0.734$ eV	0.097 ± 0.003
^{81}Br	$E_n = 0.734$ eV	0.021 ± 0.001
^{111}Cd	$E_n = 4.53$ eV	$-(0.013^{+0.007}_{-0.004})$



隣接するs波とp波の干渉によって、非対称度が 10^6 増幅する

対称性の破れの増幅

核子-核子　反応での P非対称度



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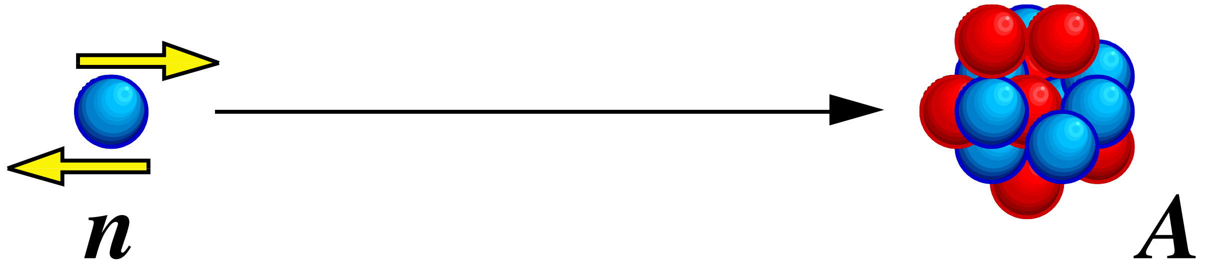

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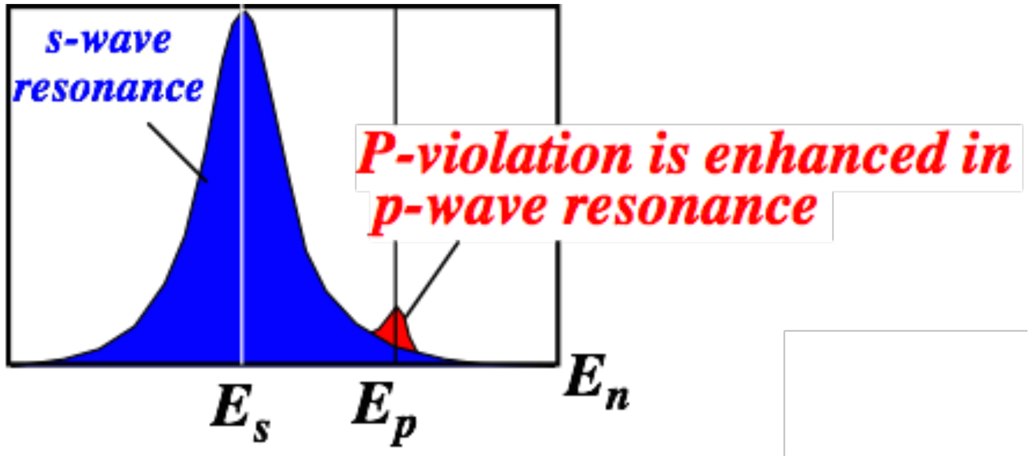
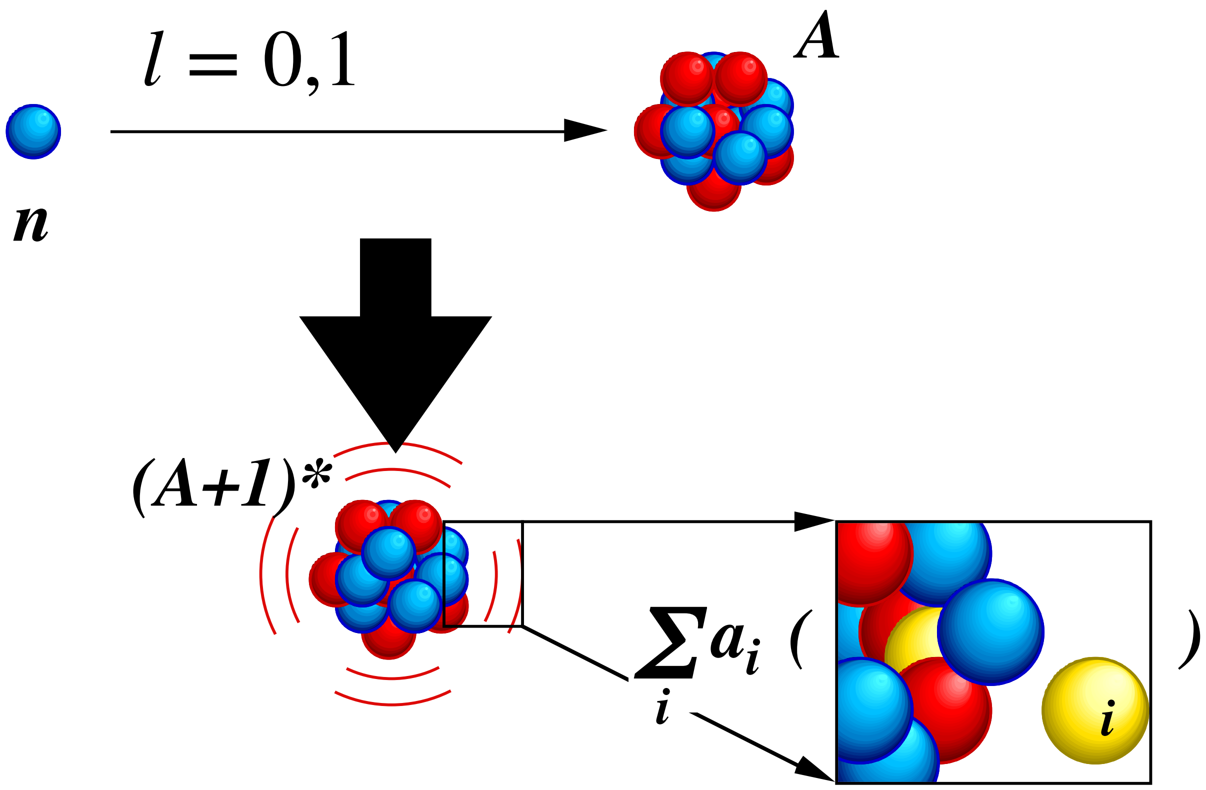


p波共鳴の断面積に対して

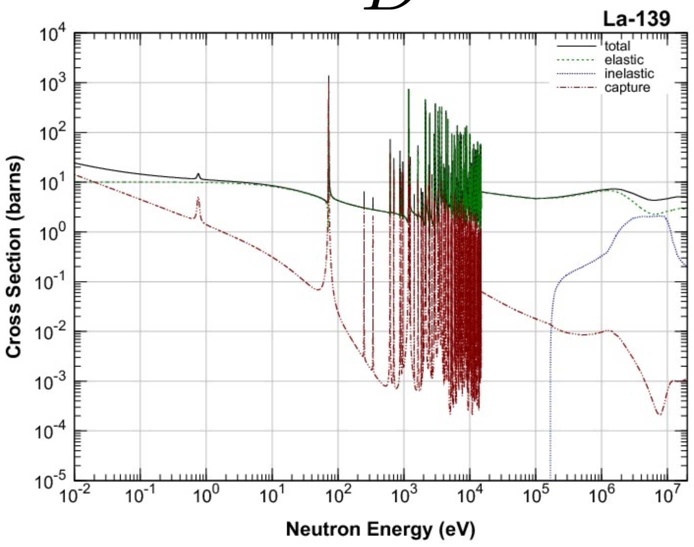
全断面積のおよそ２％

隣接するs波とp波の干渉によって、非対称度が 10^6 増幅する

P対称性の破れの増幅



$$N \sim \frac{\Delta E}{D} \sim 10^5$$

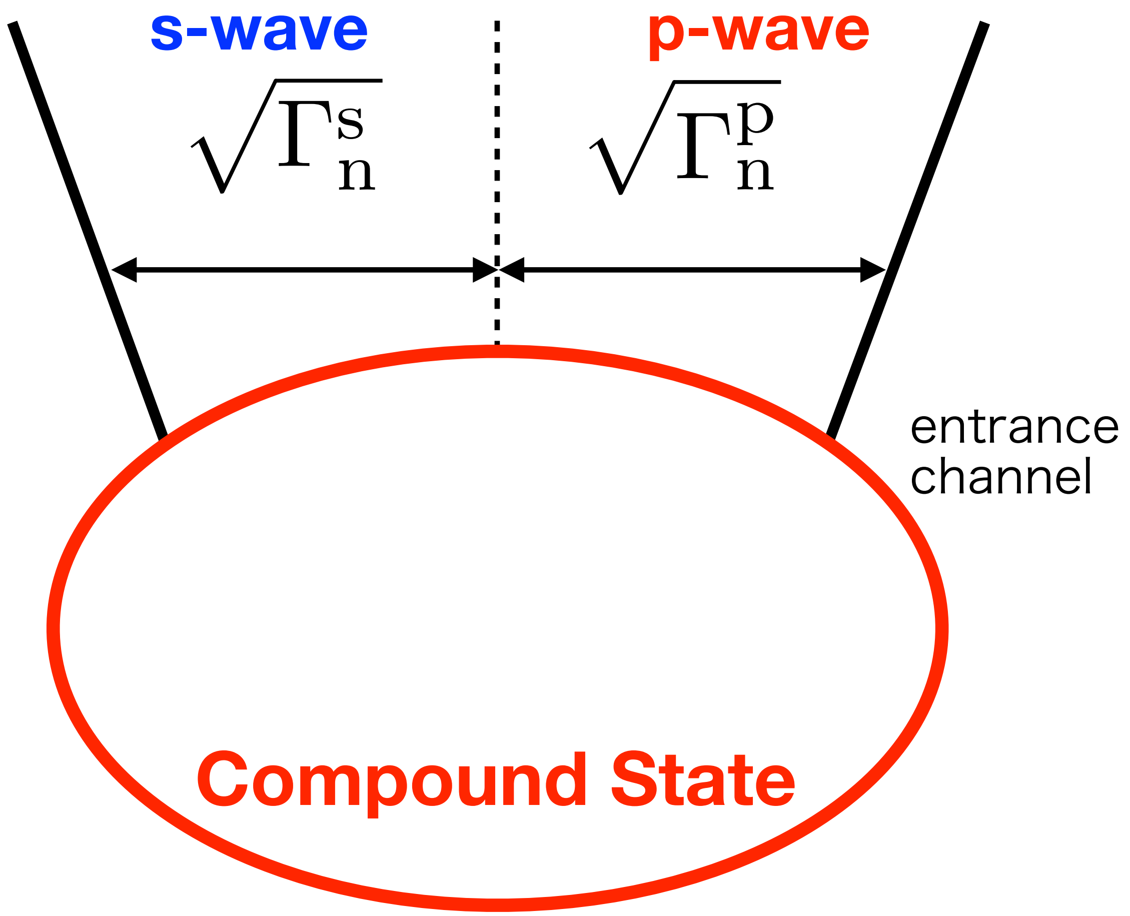


$$\boldsymbol{J} = \boldsymbol{I} + \boldsymbol{j} \qquad \boldsymbol{j} = \boldsymbol{l} + \boldsymbol{s}$$

Resonance spin

target spin

neutron total angular momentum

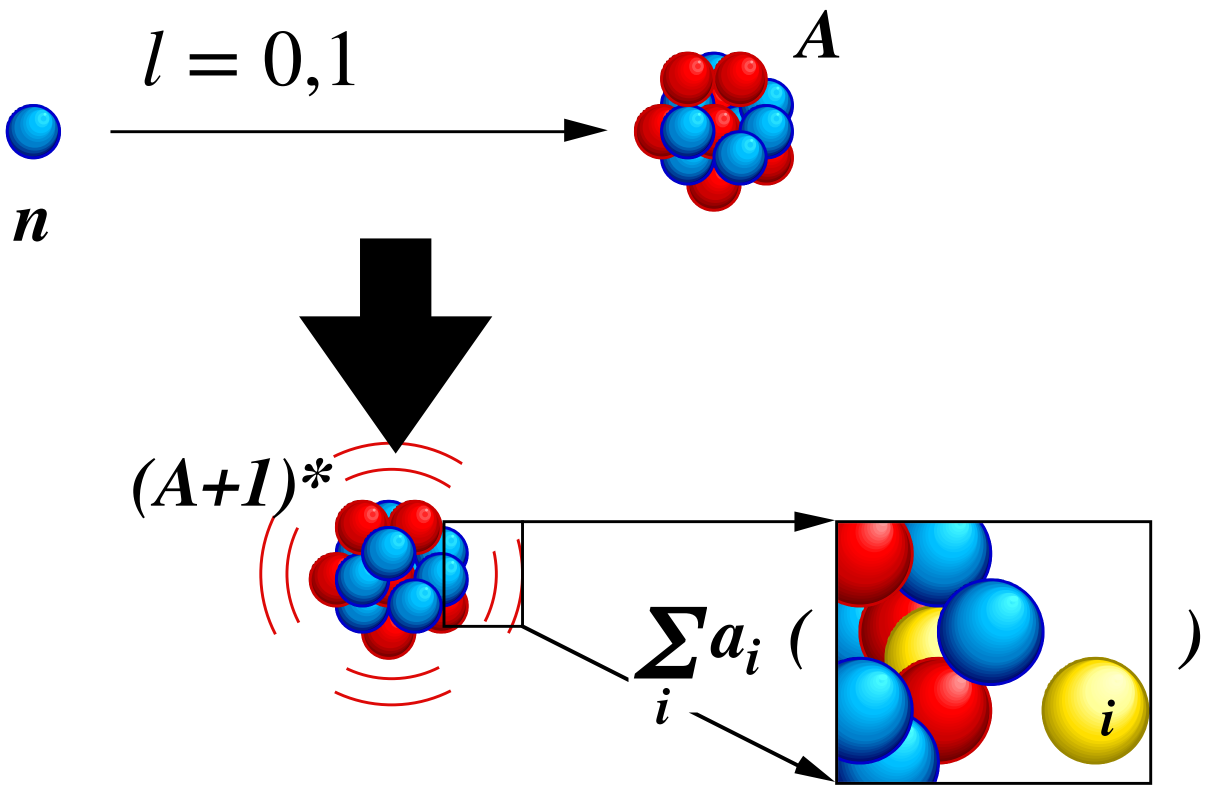


$$|\mathrm{p}\rangle = \sum_{i=1}^{N} b_i \, |\psi_i\rangle$$

$$|\mathrm{s}\rangle = \sum_{i=1}^{N} a_i \, |\psi_i\rangle$$

$$\langle \mathrm{s}|W|\mathrm{p}\rangle = \sum_{i,j}^{N} a_i^* b_j \, \langle \psi_i|W|\psi_j\rangle \sim \frac{1}{\sqrt{N}} \frac{1}{\sqrt{N}} \langle W \rangle \sqrt{N}$$

P対称性の破れの増幅

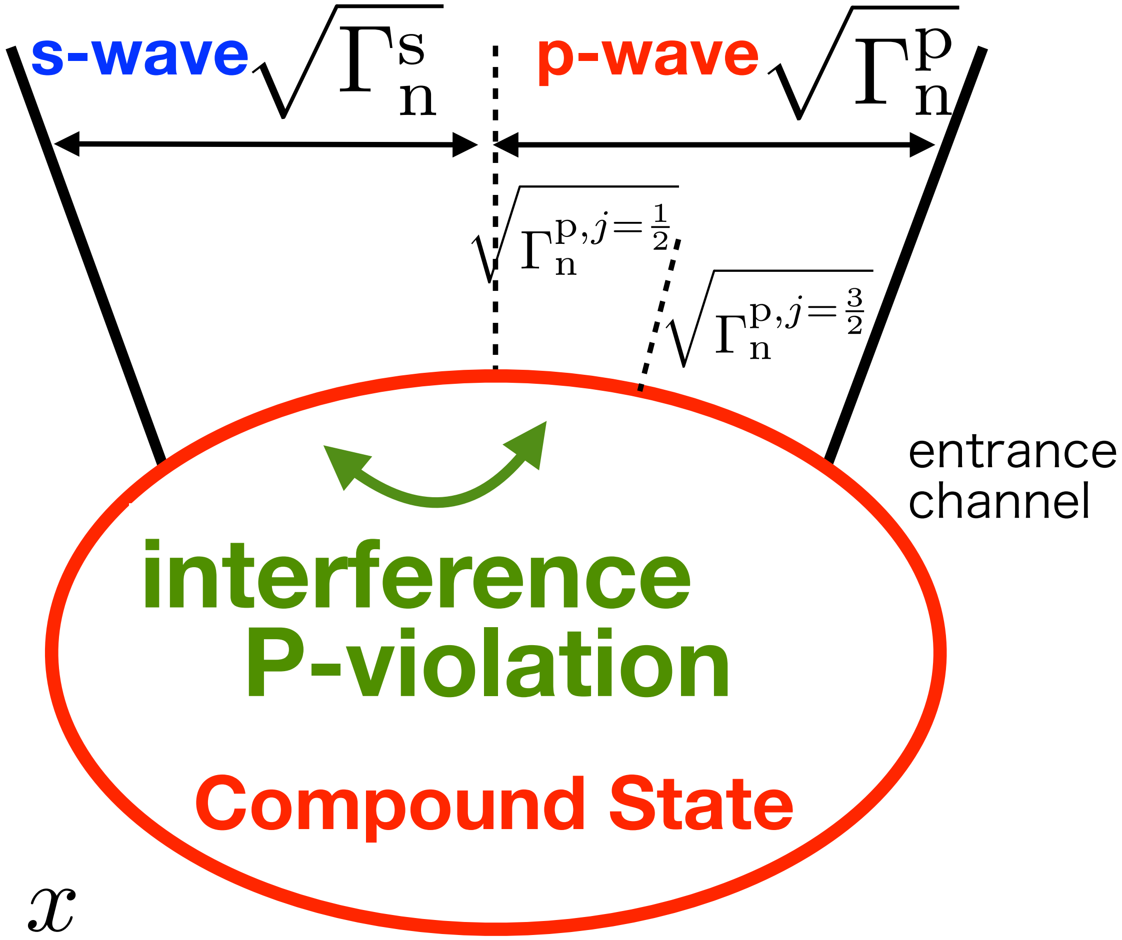


$$J = I + j \qquad j = l + s$$


Resonance spin

target spin

neutron total angular momentum


s-wave $\sqrt{\Gamma_n^s}$

p-wave $\sqrt{\Gamma_n^p}$

$\sqrt{\Gamma_n^{p,j=\frac{1}{2}}}$

$\sqrt{\Gamma_n^{p,j=\frac{3}{2}}}$

interference

P-violation

Compound State

entrance channel

$$A_{\rm L} = -\frac{2W}{E_{\rm p} - E_{\rm s}}\sqrt{\frac{\Gamma_{\rm n}^{\rm s}}{\Gamma_{\rm n}^{\rm p}}}\,\underline{\sqrt{\frac{\Gamma_{\rm n}^{{\rm p},j=\frac{1}{2}}}{\Gamma_{\rm n}^{\rm p}}}} = x$$

$$\left(x = \sqrt{\frac{\Gamma_{\rm n}^{{\rm p},j=\frac{1}{2}}}{\Gamma_{\rm n}^{\rm p}}} \quad y = \sqrt{\frac{\Gamma_{\rm n}^{{\rm p},j=\frac{3}{2}}}{\Gamma_{\rm n}^{\rm p}}} \quad x^2 + y^2 = 1 \quad \begin{array}{l} x = \cos\phi \\ y = \sin\phi \end{array} \quad \text{Unknown parameter} \right)$$

時間反転対称性の破れの増幅

異なるチャンネルスピンの部分波間の干渉によって

時間反転対称性の破れでも、
同様の増幅効果がある

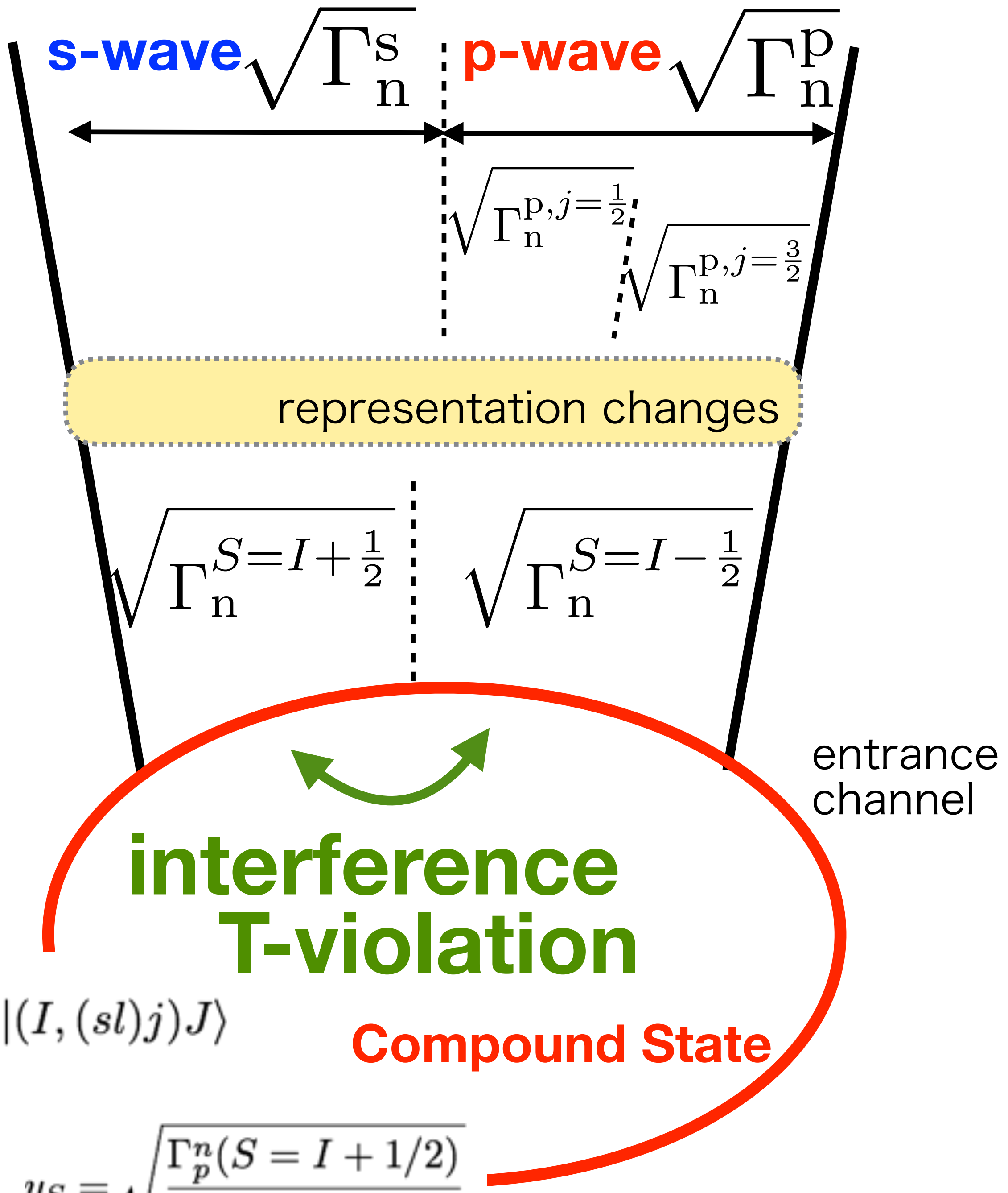
Gudkov, Phys. Rep. 212 (1992) 77.

$$P : |lsI\rangle \rightarrow (-1)^{l}\,|lsI\rangle$$
$$T : |lsI\rangle \rightarrow (-1)^{i\pi S_y} K\,|lsI\rangle$$

$$|((Is)S,l)J\rangle = \sum_j \langle (I,(sl)j)J|((Is)S,l)J\rangle\,|(I,(sl)j)J\rangle$$
$$= \sum_j (-1)^{l+s+I+J}\sqrt{(2j+1)(2S+1)}\left\{\begin{array}{ccc} I & s & l \\ J & S & j \end{array}\right\}|(I,(sl)j)J\rangle$$

$$x = \sqrt{\frac{\Gamma_p^n(j=1/2)}{\Gamma_p^n}} \qquad y = \sqrt{\frac{\Gamma_p^n(j=3/2)}{\Gamma_p^n}} \qquad x_S = \sqrt{\frac{\Gamma_p^n(S=I-1/2)}{\Gamma_p^n}} \qquad y_S = \sqrt{\frac{\Gamma_p^n(S=I+1/2)}{\Gamma_p^n}}$$

$$z_j = \left\{\begin{array}{ll} x & (j=1/2) \\ y & (j=3/2) \end{array}\right. , \qquad \tilde{z}_S = \left\{\begin{array}{ll} x_S & (S=I-1/2) \\ y_S & (S=I+1/2) \end{array}\right. \qquad \tilde{z}_S = \sum_j (-1)^{l+I+j+S}\sqrt{(2j+1)(2S+1)}\left\{\begin{array}{ccc} l & s & j \\ I & J & S \end{array}\right\} z_j$$



時間反転対称性の破れに対する感度

異なるチャンネルスピンの部分波間の干渉によって

時間反転対称性の破れでも、同様の増幅効果がある

$$\Delta\sigma_{\rm CP} = \kappa(J)\frac{W_{\rm T}}{W}\Delta\sigma_{\rm P}$$

T-violation

gCP/gP　P-violation

compare with EDM

from upper limit of nEDM

$$|d_n| < 2.9\times10^{-26}\,\mathrm{e\,cm}$$

$$\boxed{\bar{g}_\pi^{(0)} < 2.5\times10^{-10}}$$

from upper limit of Hg EDM

$$|d_{\rm Hg}| < 3.1\times10^{-29}\mathrm{e\cdot cm}$$

$$\boxed{\bar{g}_\pi^{(1)} < 0.5\times10^{-11}}$$

from NPDGamma

$$\boxed{h_\pi^1 \sim 3\times10^{-7}}$$

Estimation in effective field theory

Y.-H.Song et al., Phys. Rev. C83 (2011) 065503

$$\frac{W_{\rm T}}{W} = \frac{\Delta\sigma^{\not T\not P}}{\Delta\sigma^{\not P}} \simeq (-0.47)\left(\frac{\bar{g}_\pi^{(0)}}{h_\pi^1} + (0.26)\frac{\bar{g}_\pi^{(1)}}{h_\pi^1}\right)$$

$$\kappa(J)\ \sim 1$$

Discovery potential

$$\boxed{|\Delta\sigma_{\rm T}| <\ \ 1.0\times10^{-4}\ \ \mathrm{barn}}$$

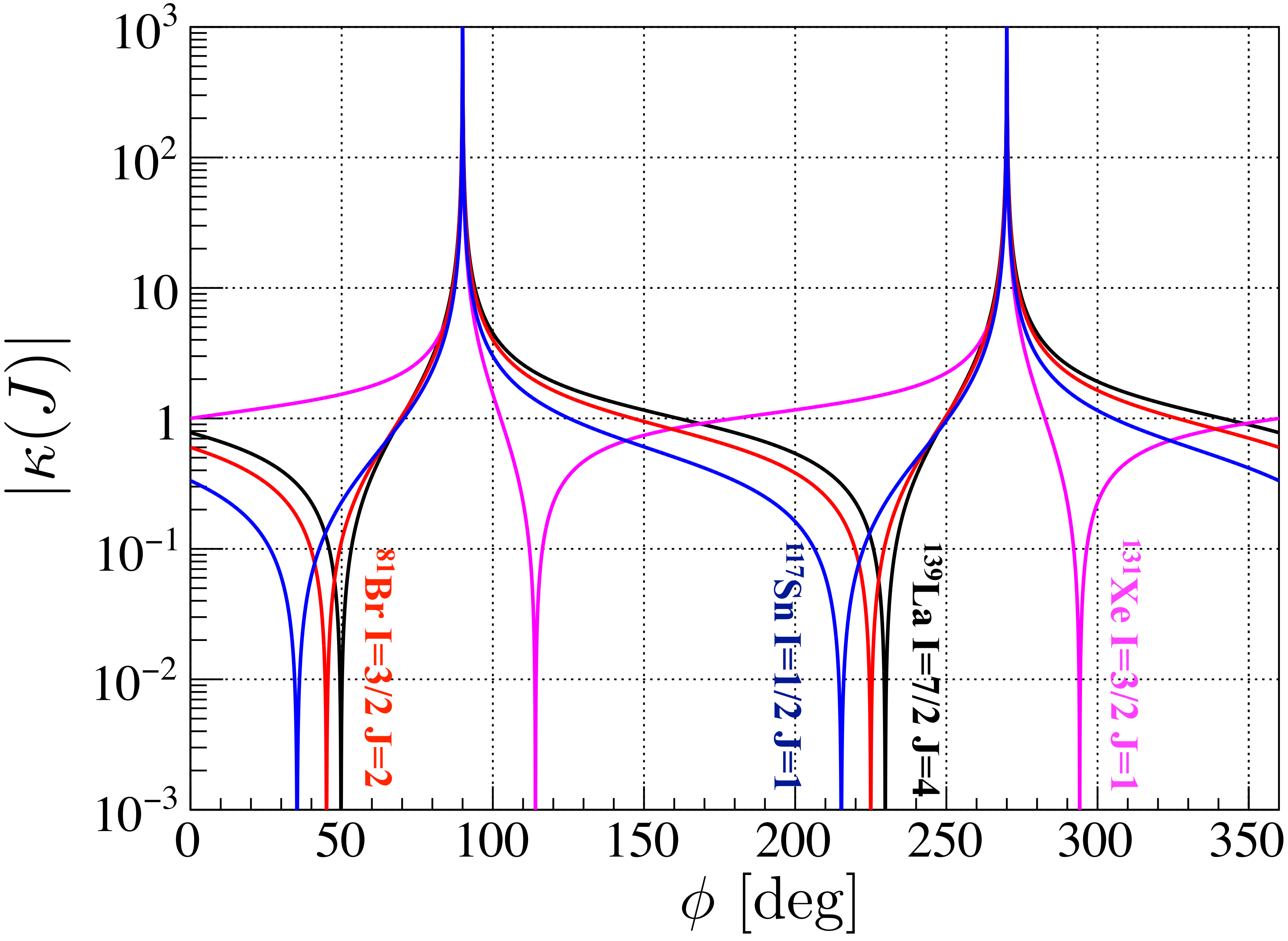
時間反転対称性の破れに対する感度

$$\kappa(J) = \begin{cases} (-1)^{2I}\left(1+\frac{1}{2}\sqrt{\frac{2I-1}{I+1}}\,\frac{y}{x}\right) & (J = I - \frac{1}{2}) \\ (-1)^{2I+1}\frac{I}{I+1}\left(1-\frac{1}{2}\sqrt{\frac{2I+3}{I}}\,\frac{y}{x}\right) & (J = I + \frac{1}{2}) \end{cases}$$

$$x^2 = \frac{\Gamma^{\rm n}_{{\rm p},j=\frac{1}{2}}}{\Gamma^{\rm n}_{\rm p}}, \quad y^2 = \frac{\Gamma^{\rm n}_{{\rm p},j=\frac{3}{2}}}{\Gamma^{\rm n}_{\rm p}}.$$

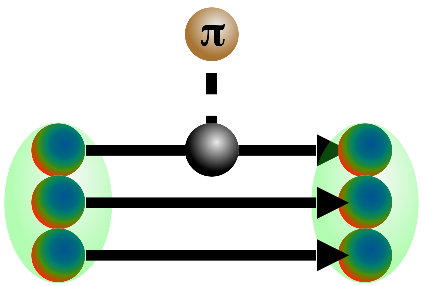
$$x^2 + y^2 = 1$$

$$x = \cos\phi, \quad y = \sin\phi$$



非対称増幅効果の理論的研究

$$\begin{aligned}V_{\mathrm{CP}}=&\left[-\frac{\bar{g}_\eta^{(0)}g_\eta}{2m_N}\frac{m_\eta^2}{4\pi}Y_1(x_\eta)+\frac{\bar{g}_\omega^{(0)}g_\omega}{2m_N}\frac{m_\omega^2}{4\pi}Y_1(x_\omega)\right]\boldsymbol{\sigma}_-\cdot\hat{\boldsymbol{r}}\\
&+\left[-\frac{\bar{g}_\pi^{(0)}g_\pi}{2m_N}\frac{m_\pi^2}{4\pi}Y_1(x_\pi)+\frac{\bar{g}_\rho^{(0)}g_\rho}{2m_N}\frac{m_\rho^2}{4\pi}Y_1(x_\rho)\right]\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2\boldsymbol{\sigma}_-\cdot\hat{\boldsymbol{r}}\\
&+\left[-\frac{\bar{g}_\pi^{(2)}g_\pi}{2m_N}\frac{m_\pi^2}{4\pi}Y_1(x_\pi)+\frac{\bar{g}_\rho^{(2)}g_\rho}{2m_N}\frac{m_\rho^2}{4\pi}Y_1(x_\rho)\right]T_{12}^z\boldsymbol{\sigma}_-\cdot\hat{\boldsymbol{r}}\\
&+\left[-\frac{\bar{g}_\pi^{(1)}g_\pi}{2m_N}\frac{m_\pi^2}{4\pi}Y_1(x_\pi)+\frac{\bar{g}_\eta^{(1)}g_\eta}{2m_N}\frac{m_\eta^2}{4\pi}Y_1(x_\eta)+\frac{\bar{g}_\rho^{(1)}g_\rho}{2m_N}\frac{m_\rho^2}{4\pi}Y_1(x_\rho)+\frac{\bar{g}_\omega^{(1)}g_\omega}{2m_N}\frac{m_\omega^2}{4\pi}Y_1(x_\omega)\right]\tau_+\boldsymbol{\sigma}_-\cdot\hat{\boldsymbol{r}}\\
&+\left[-\frac{\bar{g}_\pi^{(1)}g_\pi}{2m_N}\frac{m_\pi^2}{4\pi}Y_1(x_\pi)-\frac{\bar{g}_\eta^{(1)}g_\eta}{2m_N}\frac{m_\eta^2}{4\pi}Y_1(x_\eta)-\frac{\bar{g}_\rho^{(1)}g_\rho}{2m_N}\frac{m_\rho^2}{4\pi}Y_1(x_\rho)+\frac{\bar{g}_\omega^{(1)}g_\omega}{2m_N}\frac{m_\omega^2}{4\pi}Y_1(x_\omega)\right]\tau_+\boldsymbol{\sigma}_+\cdot\hat{\boldsymbol{r}}\end{aligned}$$



$$\boldsymbol{\sigma}_\pm=\boldsymbol{\sigma}_1\pm\boldsymbol{\sigma}_2 \qquad \boldsymbol{r}=\boldsymbol{r}_1-\boldsymbol{r}_2 \qquad x_a=m_a r$$

$$T_{12}^z=3\tau_1^z\tau_2^z-\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2 \qquad Y_1(x)=\left(1+\frac{1}{x}\right)\frac{e^{-x}}{x}$$

$$g_\pi=13.07,\quad g_\eta=2.24,\quad g_\rho=2.75,\quad g_\omega=8.25$$

Y.-H.Song et al.,
Phys. Rev. C83 (2011) 065503,
Phys. Rev. C84 (2011) 025501

電気双極子能率 ➡

$$d_n\simeq 0.14\left(\bar{g}_\pi^{(0)}-\bar{g}_\pi^{(2)}\right)$$

$$d_p\simeq 0.14\bar{g}_\pi^{(2)}$$

$$d_d\simeq 0.22\bar{g}_\pi^{(1)}$$

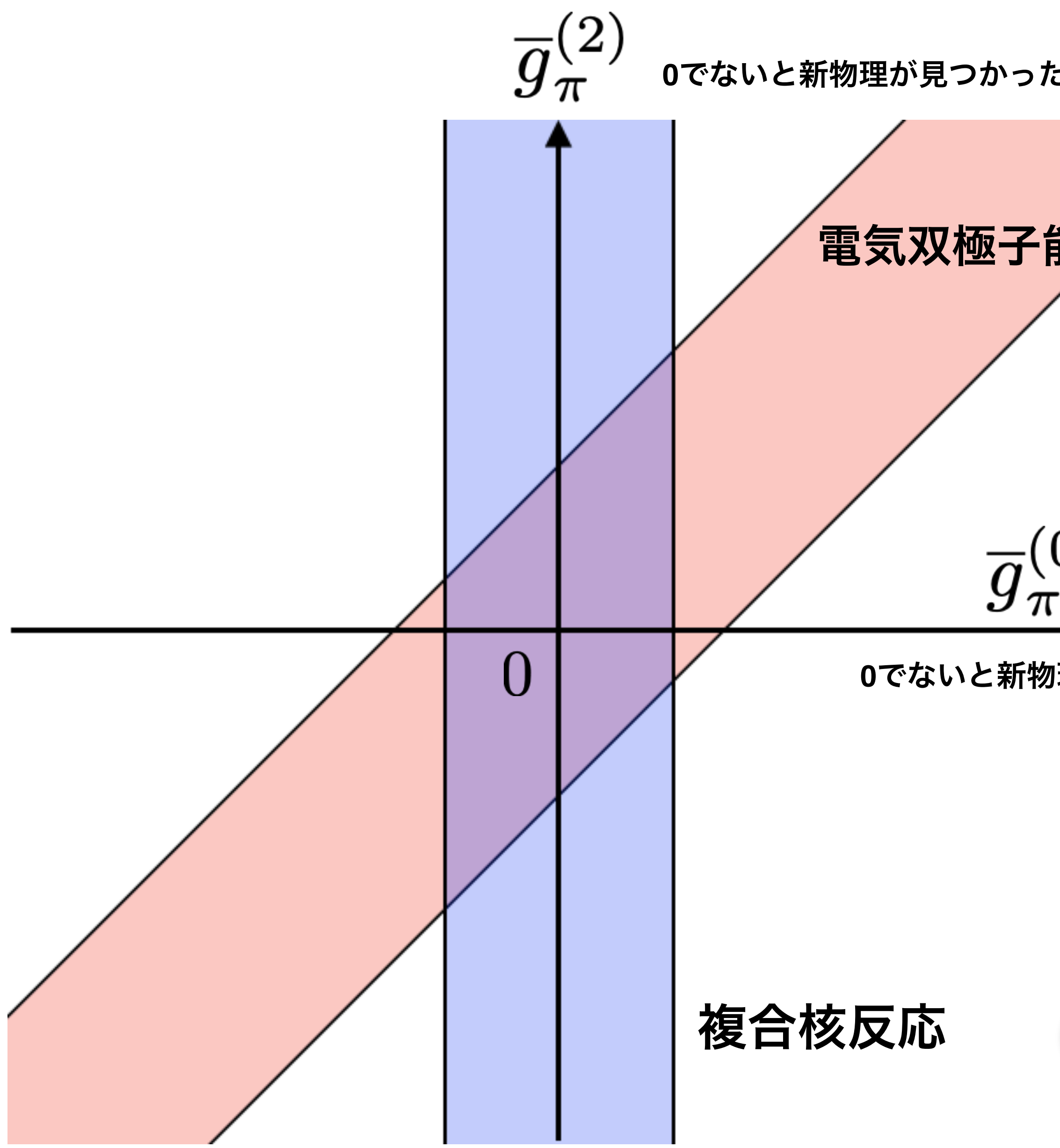
$$d_{^3\mathrm{He}}\simeq 0.2\bar{g}_\pi^{(0)}+0.14\bar{g}_\pi^{(1)}$$

$$d_{^3\mathrm{H}}\simeq 0.22\bar{g}_\pi^{(0)}-0.14\bar{g}_\pi^{(1)}$$

今回の測定 ➡

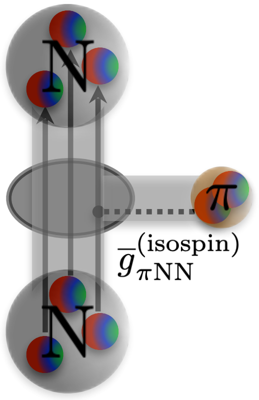
$$\frac{\Delta\sigma_{\mathrm{CP}}}{2\sigma_{\mathrm{tot}}}=\frac{-0.185[\mathrm{b}]}{2\sigma_{\mathrm{tot}}}\left(\bar{g}_\pi^{(0)}+0.26\bar{g}_\pi^{(1)}\right)$$

EDMとの関連



電機双極子能率と相補的に
パラメータ空間を探索

電機双極子能率とは
異なる系統誤差で探索



時間反転非対称パラメータ (leading terms)

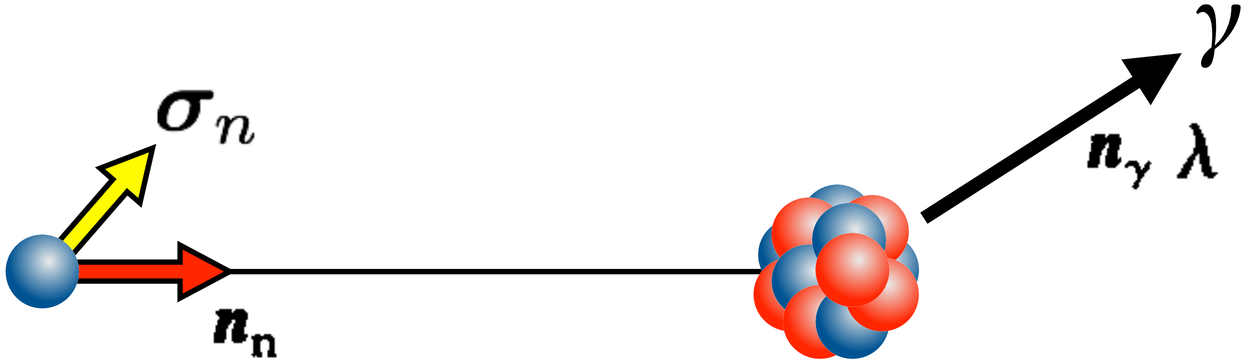
$\overline{g}_{\pi}^{(0)}$	時間反転対称性を破るアイソスカラー結合定数
$\overline{g}_{\pi}^{(1)}$	時間反転対称性を破るアイソベクトル結合定数 原子電子双極子能率の測定で小さいことが分かっている
$\overline{g}_{\pi}^{(2)}$	時間反転対称性を破るアイソテンソル結合定数

時間反転対称性の破れに対する感度

時間反転対称性の破れの増幅は、異なるチャンネルスピンの部分波間の干渉

成り立っているか実験的に確認する必要

(n, γ)測定の角相関項を
逐一測定していく



$$\frac{d\sigma(\boldsymbol{n}_\gamma, \lambda)}{d\Omega} = \tfrac{1}{2}\{a_0 + \boxed{a_1(\boldsymbol{n}_\mathrm{n} \cdot \boldsymbol{n}_\gamma)} + \boxed{\tilde{a}_2 \boldsymbol{\sigma} \cdot [\boldsymbol{n}_\mathrm{n} \times \boldsymbol{n}_\gamma]} + \boxed{a_3[(\boldsymbol{n}_\mathrm{n} \cdot \boldsymbol{n}_\gamma)^2 - \tfrac{1}{3}]}$$

Unpol. neutrons

$$+ \boxed{\tilde{a}_4(\boldsymbol{n}_\mathrm{n} \cdot \boldsymbol{n}_\gamma)\boldsymbol{\sigma} \cdot [\boldsymbol{n}_\mathrm{n} \times \boldsymbol{n}_\gamma]} + a_5\lambda(\boldsymbol{\sigma} \cdot \boldsymbol{n}_\gamma) + a_6\lambda(\boldsymbol{\sigma} \cdot \boldsymbol{n}_\mathrm{n}) + a_7\lambda$$

$$\times[(\boldsymbol{\sigma} \cdot \boldsymbol{n}_\gamma)(\boldsymbol{n}_\gamma \cdot \boldsymbol{n}_\mathrm{n}) - \tfrac{1}{3}(\boldsymbol{\sigma} \cdot \boldsymbol{n}_\mathrm{n})] + a_8\lambda[(\boldsymbol{\sigma} \cdot \boldsymbol{n}_\mathrm{n})(\boldsymbol{n}_\mathrm{n} \cdot \boldsymbol{n}_\gamma) - \tfrac{1}{3}(\boldsymbol{\sigma} \cdot \boldsymbol{n}_\gamma)]$$

Pol. neutrons

^{3}Heフィルタによって
可能になった

$$+ \boxed{a_9(\boldsymbol{\sigma} \cdot \boldsymbol{n}_\gamma)} + \boxed{a_{10}(\boldsymbol{\sigma} \cdot \boldsymbol{n}_\mathrm{n})} + \boxed{a_{11}[(\boldsymbol{\sigma} \cdot \boldsymbol{n}_\gamma)(\boldsymbol{n}_\gamma \cdot \boldsymbol{n}_\mathrm{n}) - \tfrac{1}{3}(\boldsymbol{\sigma} \cdot \boldsymbol{n}_\mathrm{n})]}$$

$$+ \boxed{a_{12}[(\boldsymbol{\sigma} \cdot \boldsymbol{n}_\mathrm{n})(\boldsymbol{n}_\mathrm{n} \cdot \boldsymbol{n}_\gamma) - \tfrac{1}{3}(\boldsymbol{\sigma} \cdot \boldsymbol{n}_\gamma)]} + a_{13}\lambda + a_{14}\lambda(\boldsymbol{n}_\mathrm{n} \cdot \boldsymbol{n}_\gamma)$$

$$+ \tilde{a}_{15}\lambda\boldsymbol{\sigma} \cdot [\boldsymbol{n}_\mathrm{n} \times \boldsymbol{n}_\gamma] + a_{16}\lambda[(\boldsymbol{n}_\mathrm{n} \cdot \boldsymbol{n}_\gamma)^2 - \tfrac{1}{3}]$$

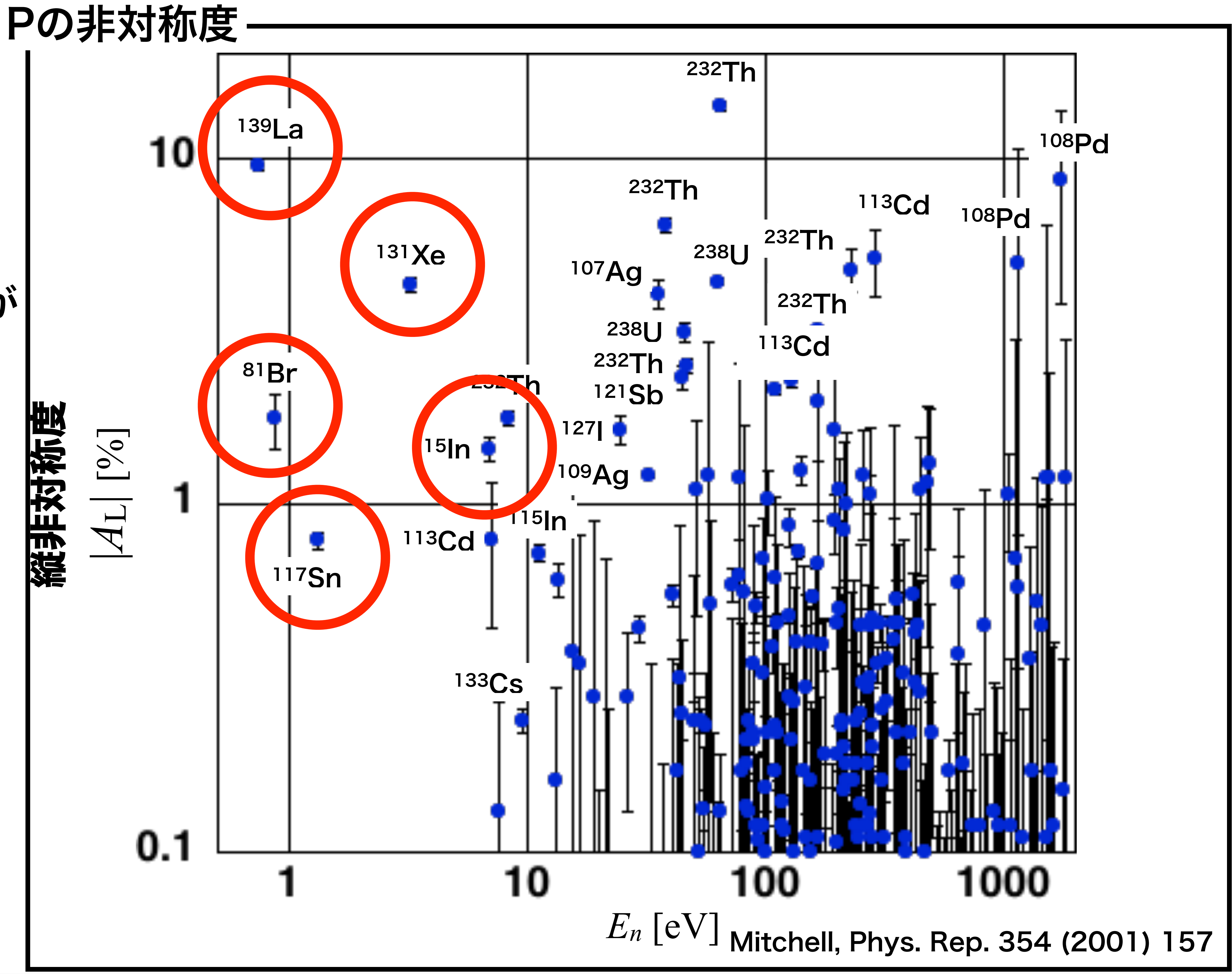
$$+ \tilde{a}_{17}\lambda(\boldsymbol{n}_\mathrm{n} \cdot \boldsymbol{n}_\gamma)\boldsymbol{\sigma} \cdot [\boldsymbol{n}_\mathrm{n} \times \boldsymbol{n}_\gamma]\} .$$

Flambaum, Nucl. Phys. A435 (1985) 352

時間反転対称性の破れに対する感度

Pの非対称度が大きく
中性子のエネルギーが
小さいものが候補

だが、他ももちろん
ありうる



Mitchell, Phys. Rep. 354 (2001) 157

時間反転対称性の破れに対する感度

候補原子核

	^{139}La	^{81}Br	^{117}Sn	^{131}Xe
P-violationが大きい	◎	○	◎	◎
共鳴エネルギーが小さい	◎	◎	○	○
原子核スピンが小さい	7/2 △	3/2 ○	1/2 ◎	3/2 ○
自然同位体比が大きい	◎	○	×	△
|κ(J)|が大きい	?	?	?	?
核偏極技術	DNP	—	—	OP

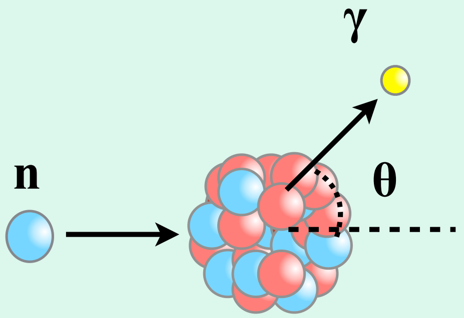
（n, γ）反応による物理の確認、増幅の見積もり

（n, γ）反応断面積

無偏極中性子を入射させ、かつγ線の偏極を測定しない場合

（n,γ） Cross section (non-polarized neutron)

$$\frac{d\sigma}{d\Omega}=\frac{1}{2}\left(\underline{a_0}+\underline{a_1}\cos\theta+\underline{a_3}\left(\cos^2\theta-\frac{1}{3}\right)\right)$$



Breit-Wigner

ϕ及び終状態の角運動量の関数

→ p波共鳴の形が角度ごとで変わる

→ a_1,a_3を抽出

→ ϕを求める

（n, γ）反応による物理の確認、増幅の見積もり

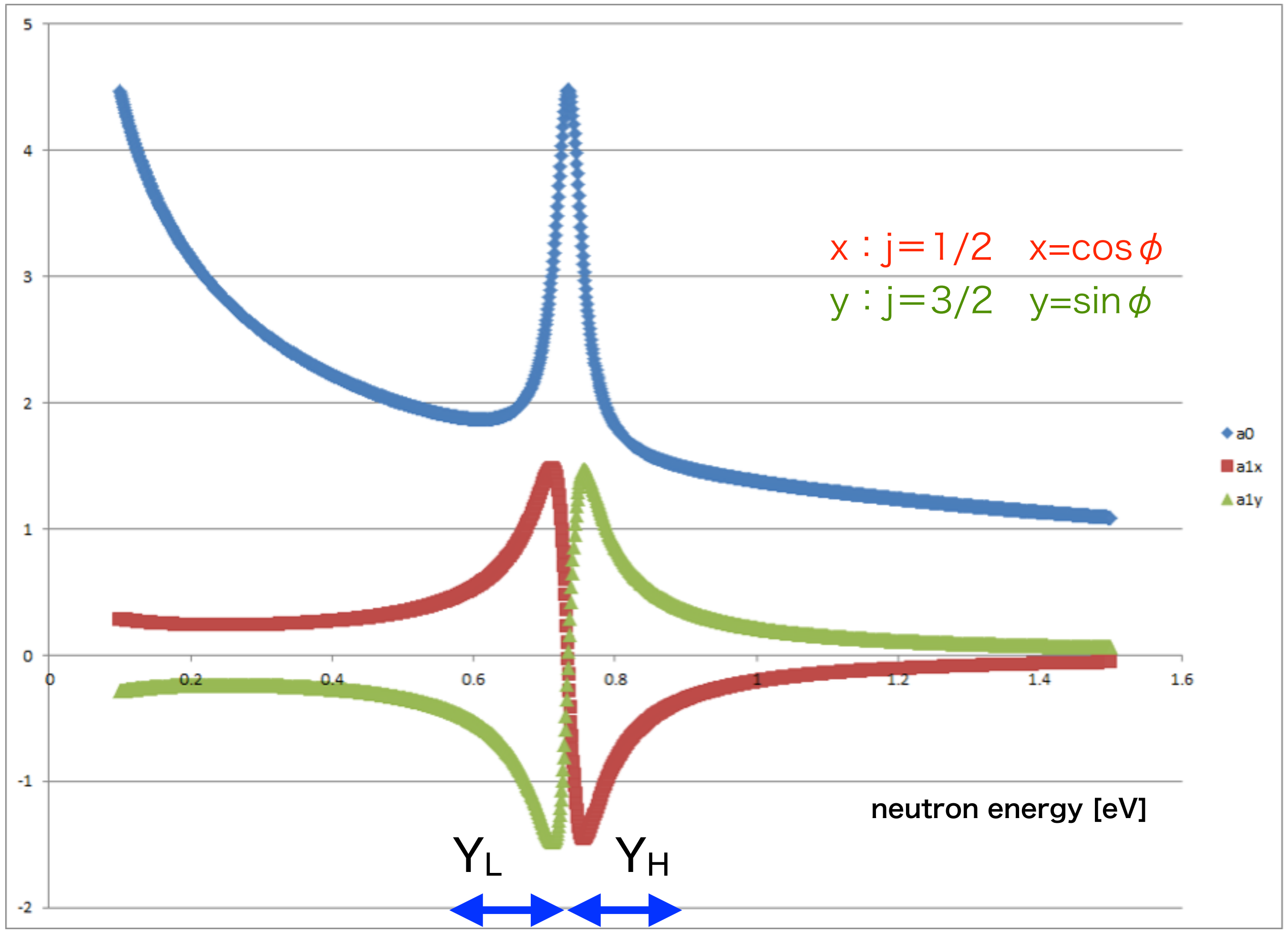
（n, γ）反応断面積

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{1}{2}\left(a_0 + a_1 \boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma + a_3\left((\boldsymbol{k}_n \cdot \boldsymbol{k})^2 - \frac{1}{3}\right)\right)$$

$$a_1 \equiv a_{1x}\cos\phi + a_{1y}\sin\phi$$

$$a_3 \equiv a_{3xy}\cos\phi\sin\phi + a_{3yy}\sin^2\phi$$

^{139}La(n,γ) P-wave resonance 0.73 eV



a_{1x} と a_{1y} は理論的に計算できる

ϕ の値で a_1 内での大きさが変化

$$\frac{Y_\mathrm{L} - Y_\mathrm{H}}{Y_\mathrm{L} + Y_\mathrm{H}}$$

p波のピークの形を実測と比較して

ϕ を求めることができる

（n, γ）反応による物理の確認、増幅の見積もり

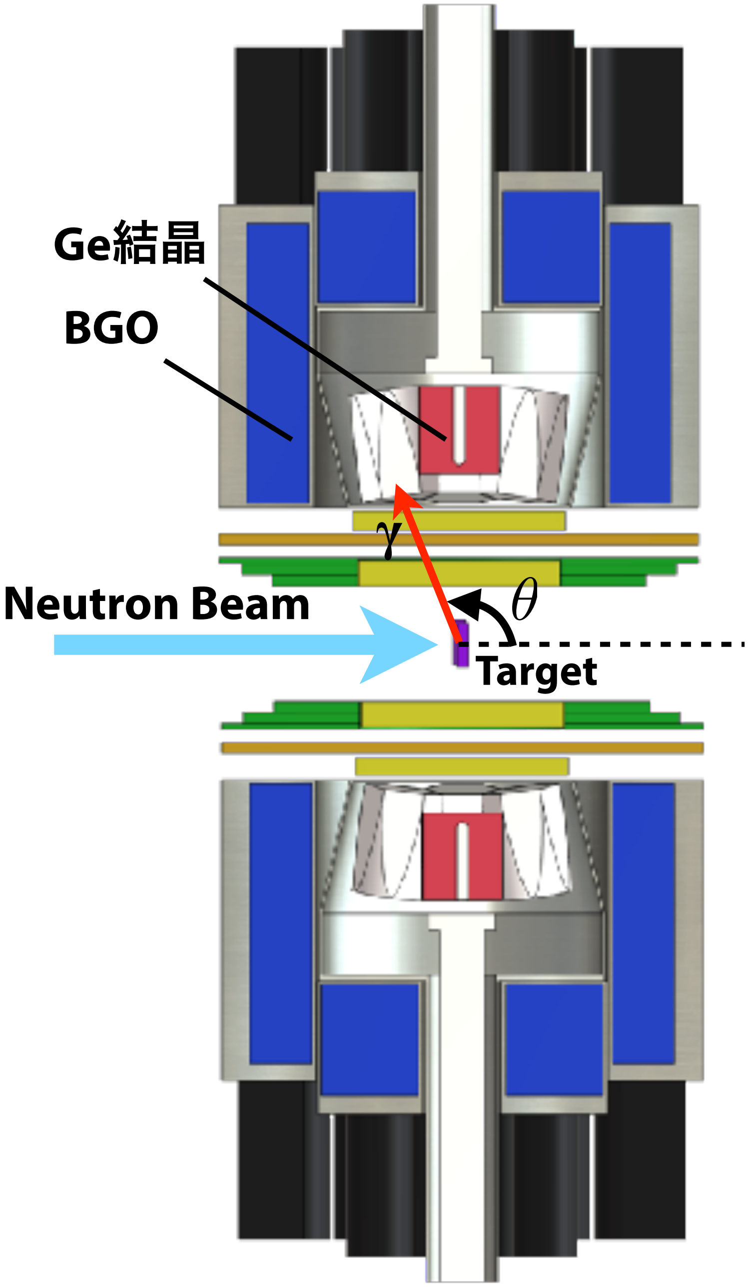
J-PARC MLF BL04 ANNRI

Intensity : ～3 x 10^5 n/cm²/s : 0.9 eV < En < 1.1eV @300kW

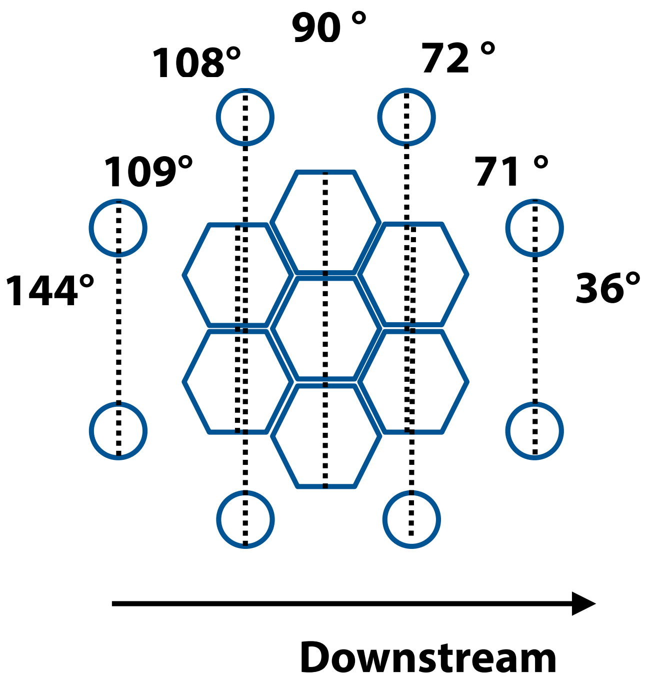
14 Ge（+BGO）Detectors, θ＝70,90,110 deg.

(n, γ) 反応による物理の確認、増幅の見積もり

J-PARC MLF BL04 ANNRI



エネルギー分解能 : 2.4keV @ 1.33MeV
検出効率 : 3.64±0.11% @ 1.33MeV
DAQレート : ~200kHz



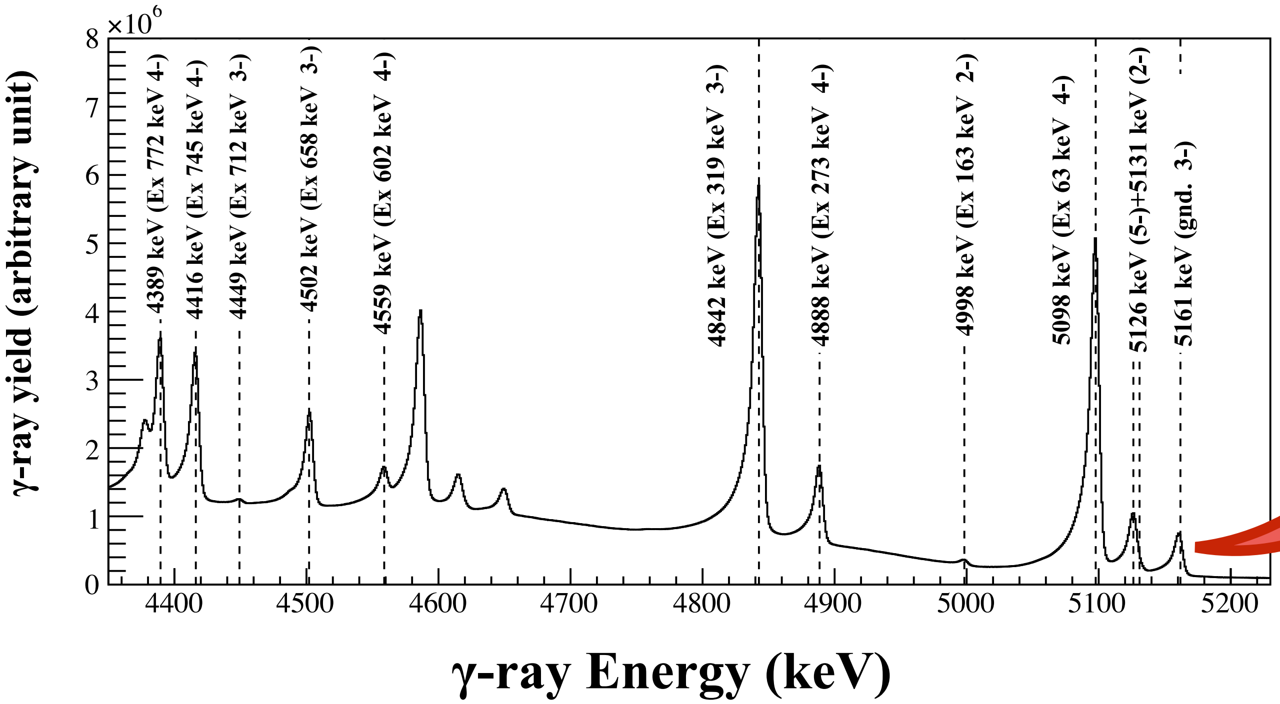
陽子ビームの入射時間と
中性子吸収によるガンマ線の検出時間から

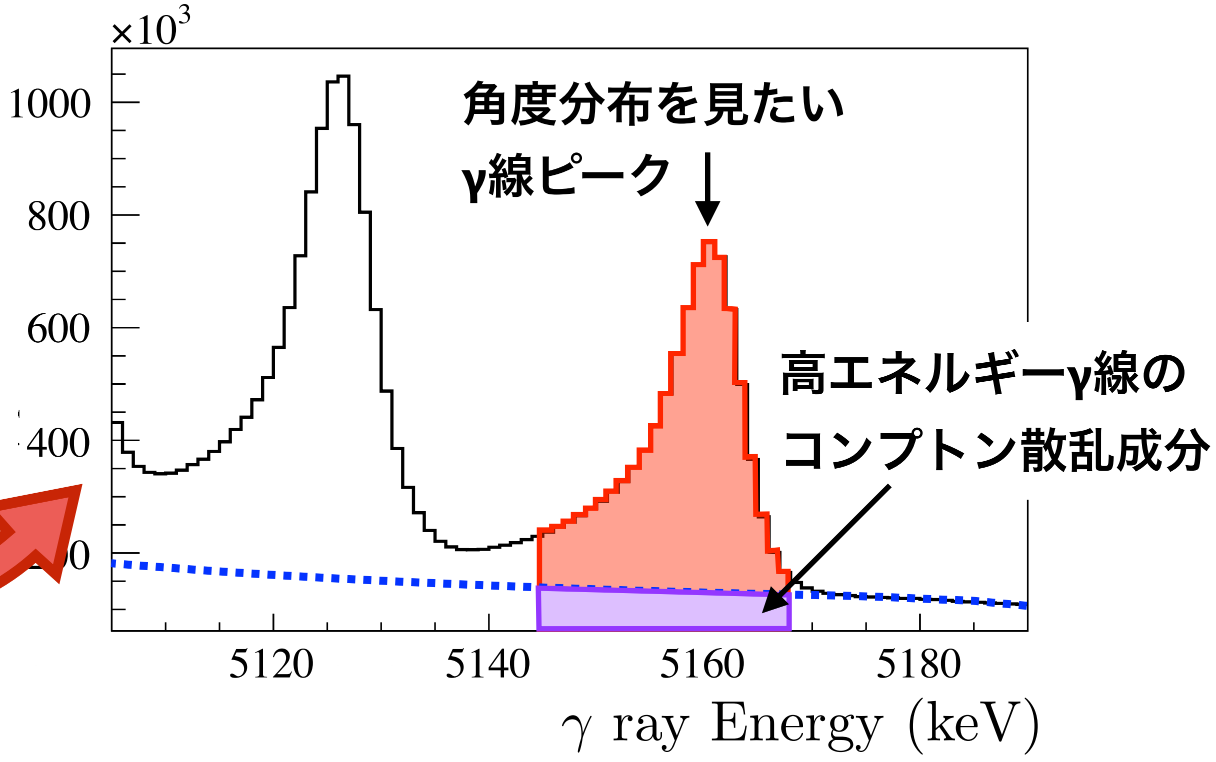
Time of Flight法 で中性子エネルギーを決定
ゲルマニウム検出器でガンマ線のエネルギーを決定

22個のGe検出器でγ線の角度分布を測定

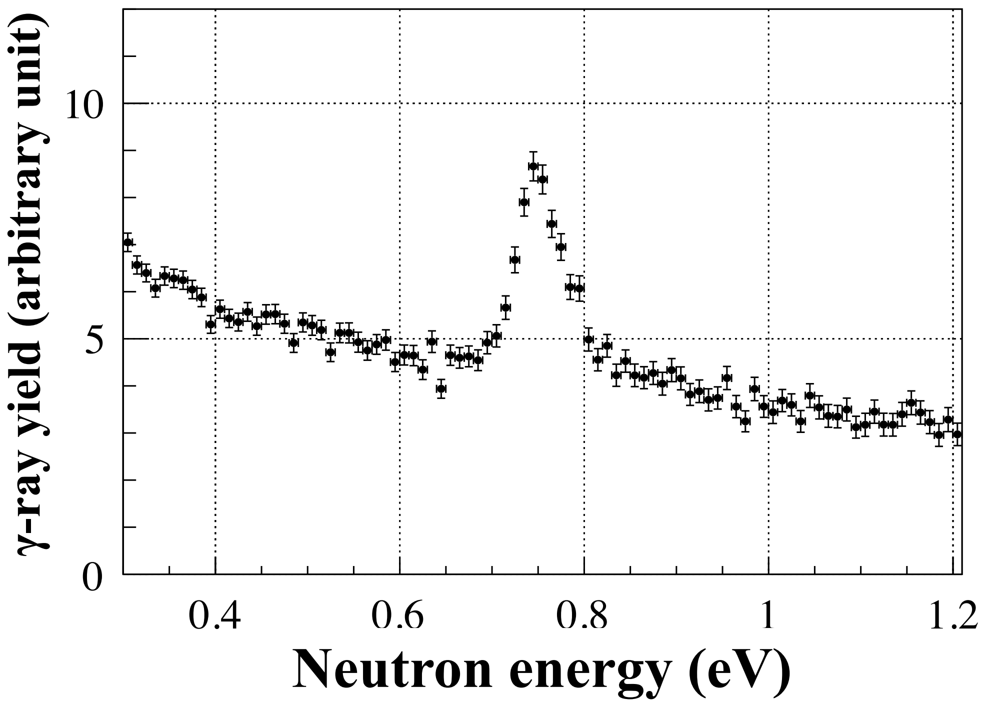
（n, γ）反応による物理の確認、増幅の見積もり

γ線スペクトル

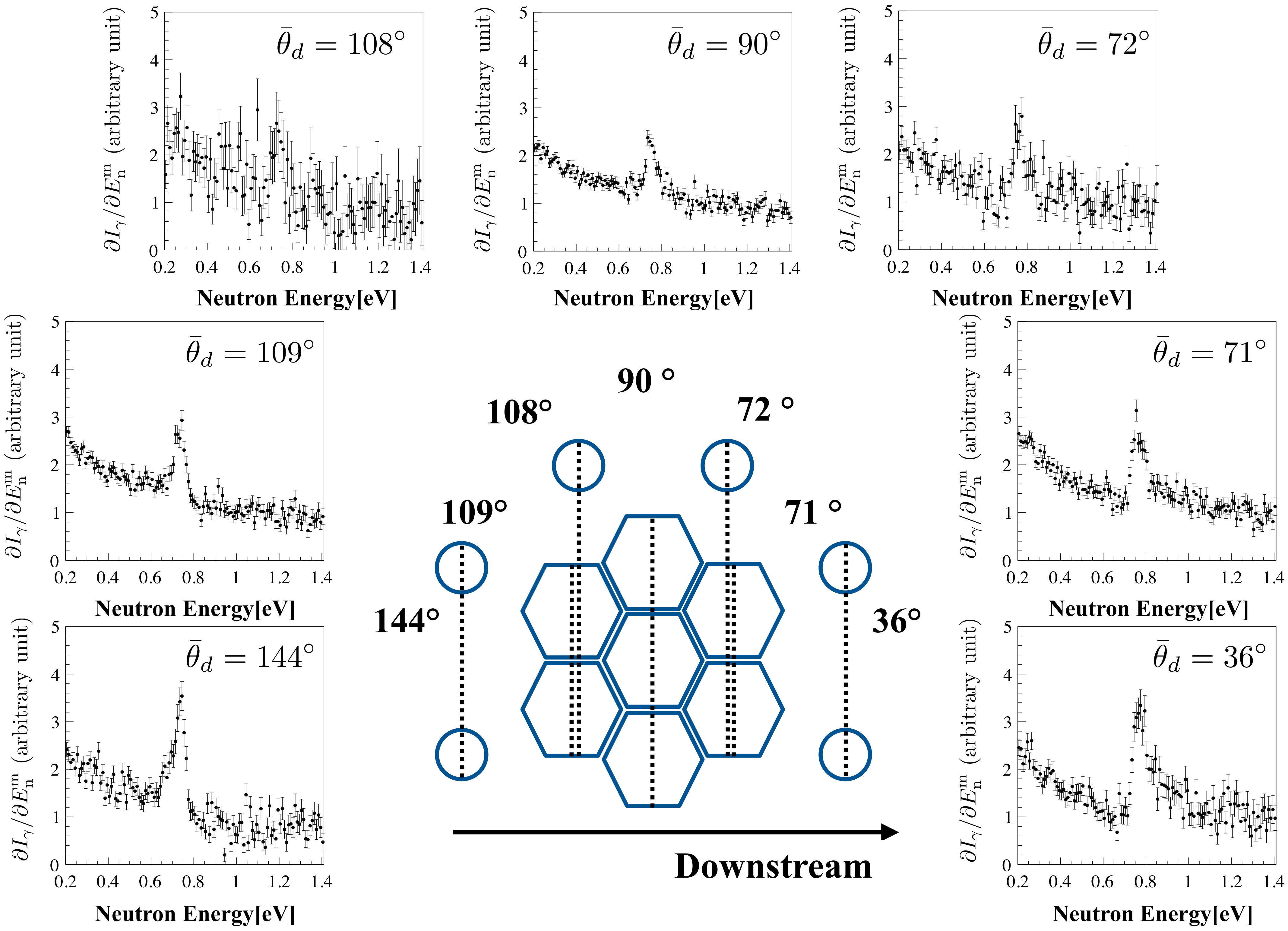




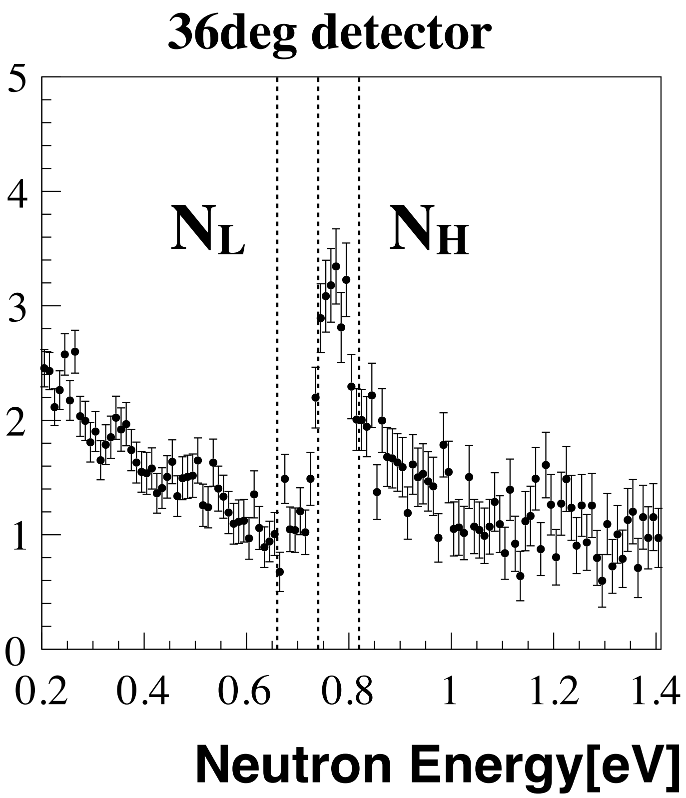
5161keVγ線でゲートをかけた中性子スペクトル



（n, γ）反応による物理の確認、増幅の見積もり

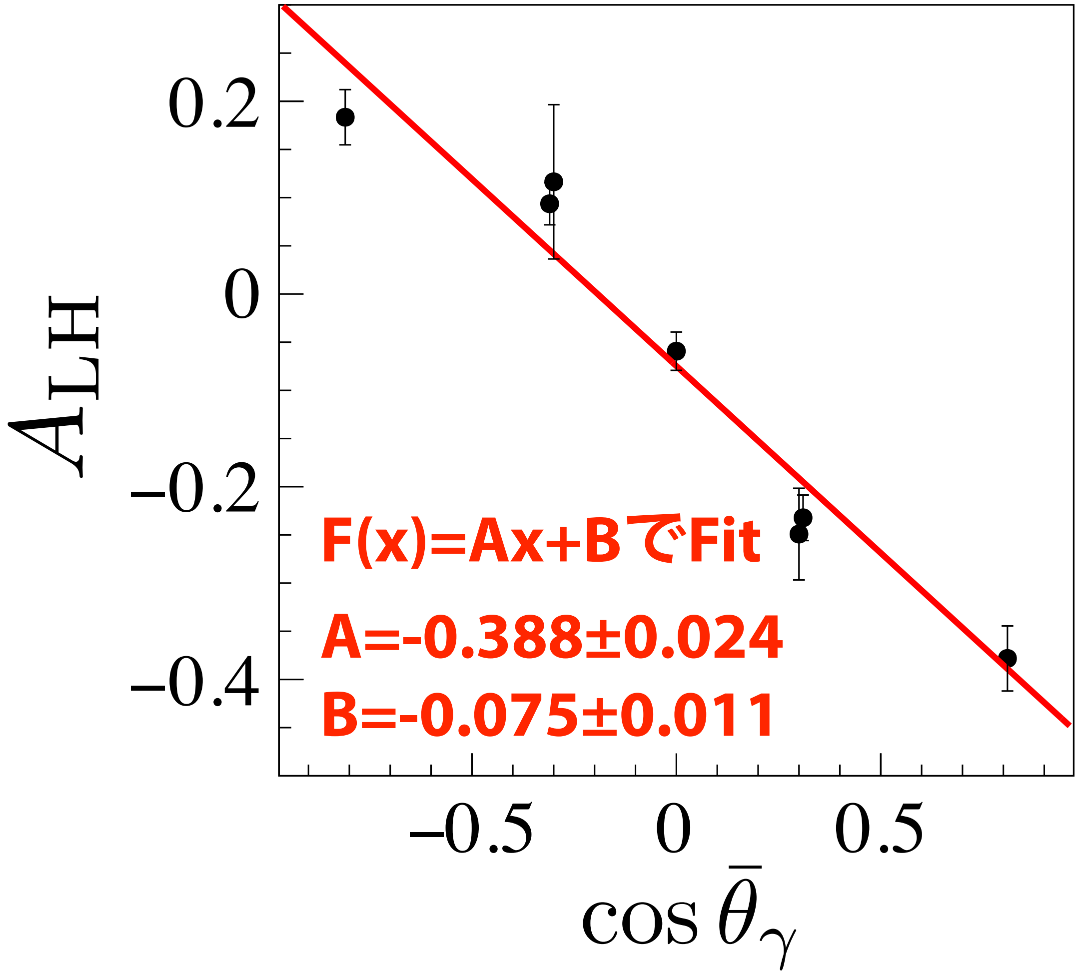


(n, γ）反応による物理の確認、増幅の見積もり



$$A_{\mathrm{LH}} = \frac{N_{\mathrm{L}} - N_{\mathrm{H}}}{N_{\mathrm{L}} + N_{\mathrm{H}}}.$$

A_{LH}を角度ごとにプロット



F(x)=Ax+BでFit

A=-0.388±0.024

B=-0.075±0.011

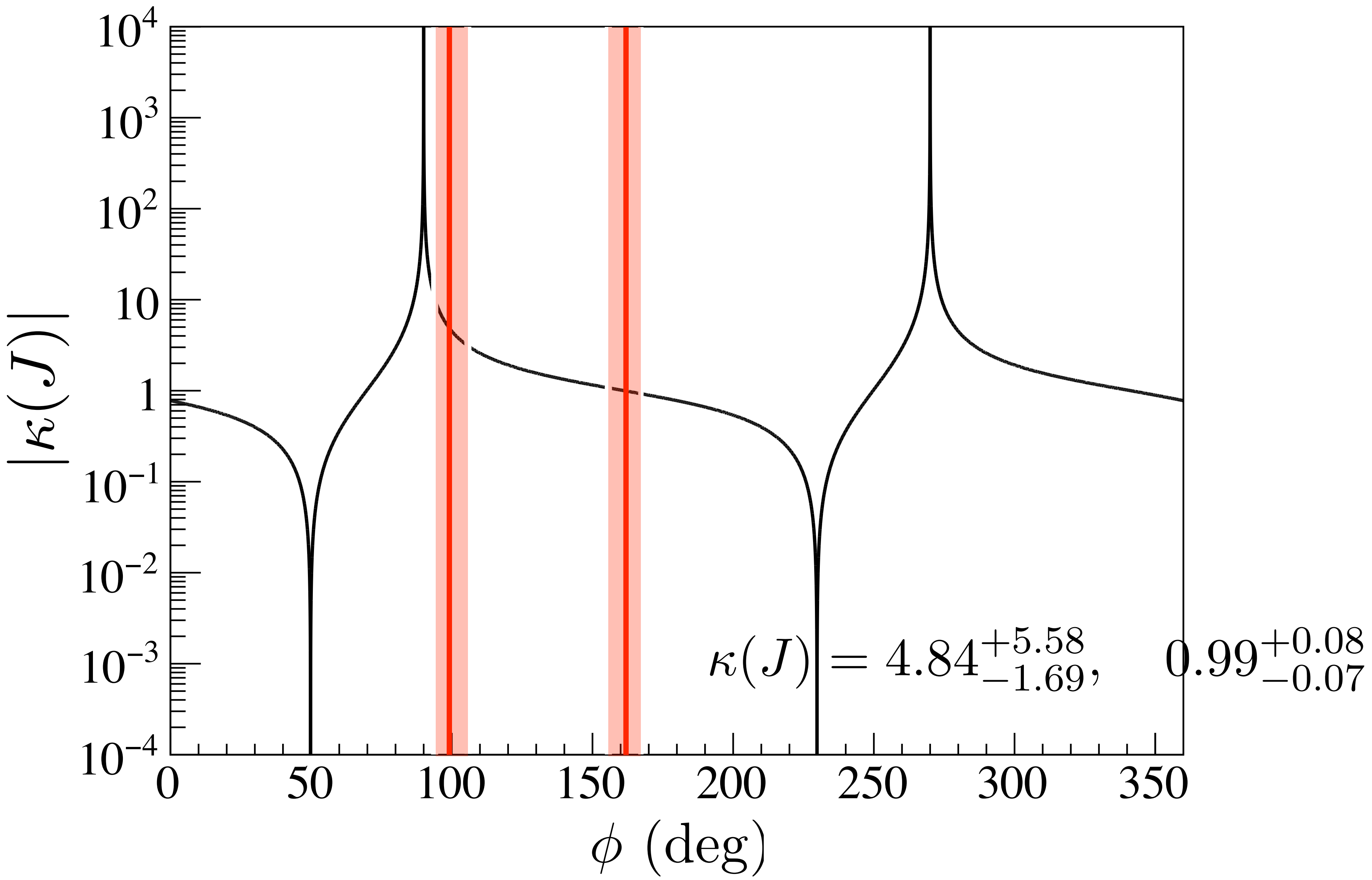
角度依存性をFlambaum Formalismの理論計算と比較する

$$\boxed{-0.388 \pm 0.024} = \boxed{0.295\cos\phi \quad - 0.345\sin\phi}$$

実験値　　理論値

この方程式を解きϕを求める

（n, γ）反応による物理の確認、増幅の見積もり



T-violationもP-violationと同様に10^6倍程度増幅していることを示唆

T.Okudaira, et. al., Phys. Rev. C **97**, 034622

（n, γ）反応による物理の確認、増幅の見積もり

複合核内の核子同士のT-violationの大きさとP-violationの大きさの比: W_T/Wを見積もる

pion exchangeの際のT-violatingなCoupling Constant

$$\frac{W_\mathrm{T}}{W} = \frac{\Delta\sigma^\mathrm{TP}}{\Delta\sigma^\mathrm{P}} \simeq (-0.47)\left(\frac{\bar{g}_\pi^{(0)}}{h_\pi^1} + (0.26)\frac{\bar{g}_\pi^{(1)}}{h_\pi^1}\right)$$

pion exchangeの際のP-violatingなCoupling Constant

n+p→d+γ実験によって $h_\pi^1 = (3.04 \pm 1.23) \times 10^{-7}$

$$d_n = \frac{e}{m_N}\frac{g_\pi(\bar{g}_\pi^{(0)} - \bar{g}_\pi^{(2)})}{4\pi^2}\ln\frac{m_N}{m_\pi} \simeq 0.14(\bar{g}_\pi^{(0)} - \bar{g}_\pi^{(2)})$$

nEDM searchによって $\bar{g}_\pi^{(0)} < 2.5 \times 10^{-10}$

^{199}Hg EDM searchによって $\bar{g}_\pi^{(1)} < 0.5 \times 10^{-11}$

→ $\left|\frac{W_\mathrm{T}}{W}\right| < 3.9 \times 10^{-4}$

$\kappa(J) = 0.99^{+0.08}_{-0.07}$ を使うと $\Delta\sigma_\mathrm{T} = \kappa(J)\frac{W_\mathrm{T}}{W}\Delta\sigma_\mathrm{P}$ より $|\Delta\sigma_\mathrm{T}| < 1.0 \times 10^{-4}$ barn

J-PARCでの実験の可能性

振幅

$$f = \underbrace{A'}_{} + \underbrace{B'}_{}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + \underbrace{C'}_{}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + \underbrace{D'}_{}\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}})$$

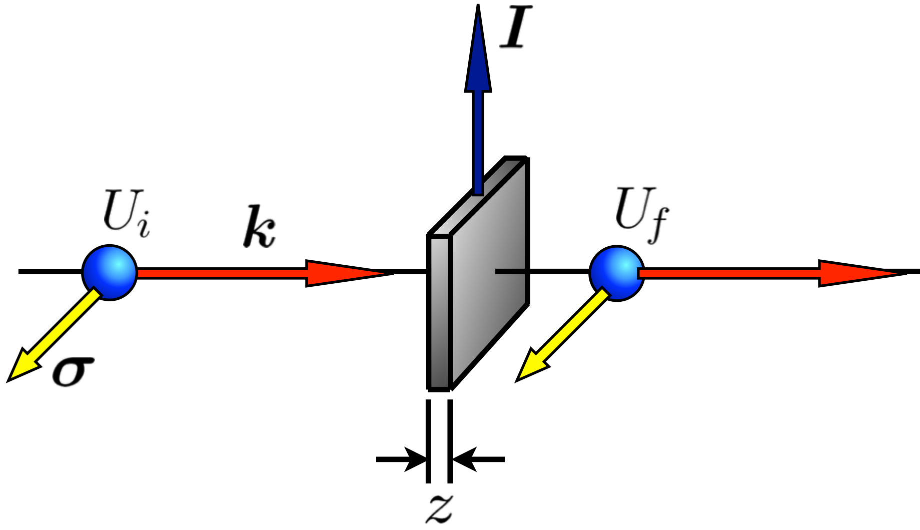
Spin Independent
P-even T-even

Spin Dependent
P-even T-even

P-violation
P-odd T-even

T-violation
P-odd T-odd

有限厚さの試料の「振幅」



$$U_f = \delta U_i \qquad \delta = e^{i(n-1)kz} \qquad n = 1 + \frac{2\pi\rho}{k^2}f$$

$$\delta = \underbrace{A}_{} + \underbrace{B}_{}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + \underbrace{C}_{}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + \underbrace{D}_{}\boldsymbol{\sigma}\cdot\left(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}}\right)$$

Spin Independent
P-even T-even

Spin Dependent
P-even T-even

P-violation
P-odd T-even

T-violation
P-odd T-odd

$$A = e^{iZA'}\cos b \qquad B = ie^{iZA'}\frac{\sin b}{b}ZB'$$

$$Z = \frac{2\pi\rho}{k}z \qquad C = ie^{iZA'}\frac{\sin b}{b}ZC'$$

$$b = Z(B'^2 + C'^2 + D'^2)^{1/2} \qquad D = ie^{iZA'}\frac{\sin b}{b}ZD'$$

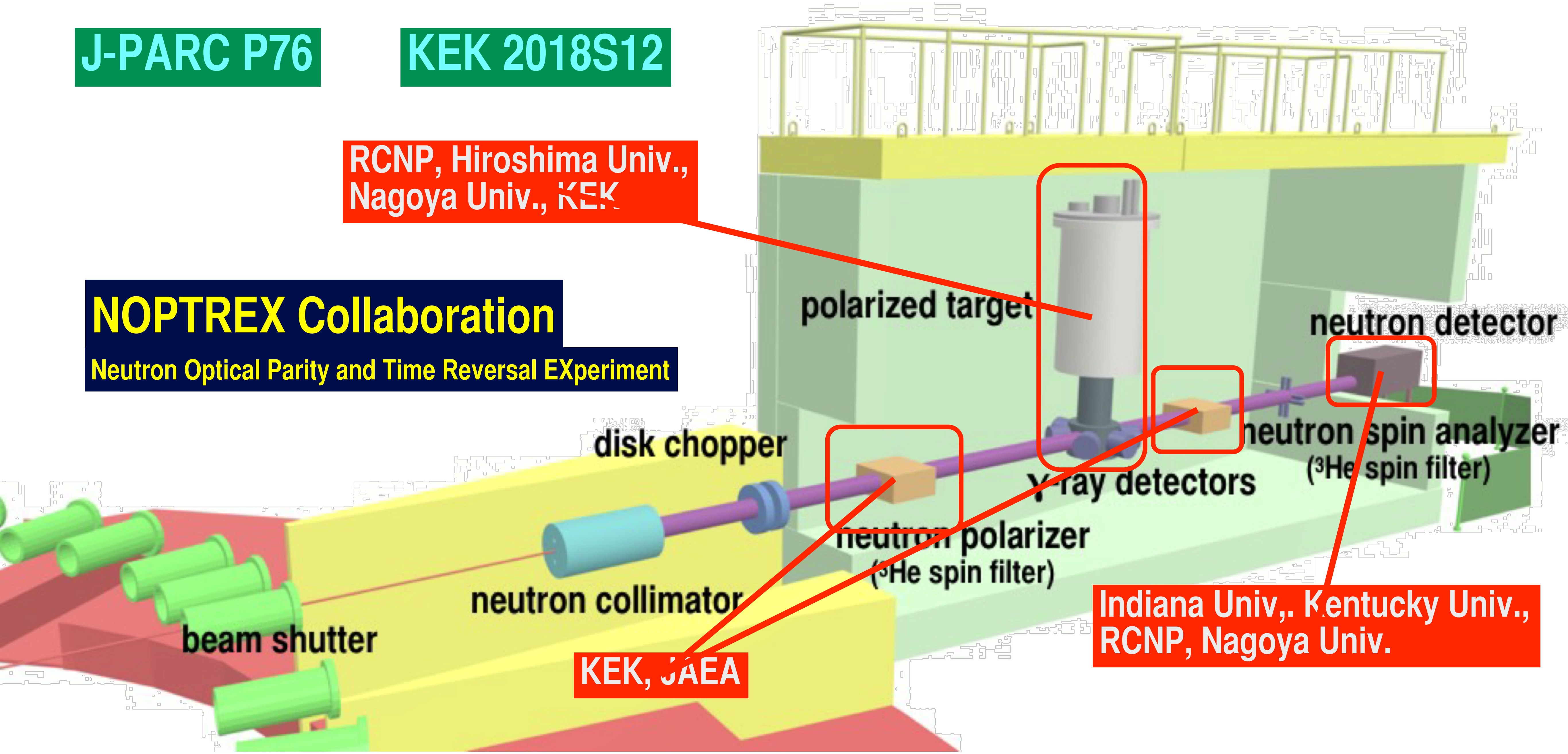
J-PARCでの実験の可能性

J-PARC P76

KEK 2018S12

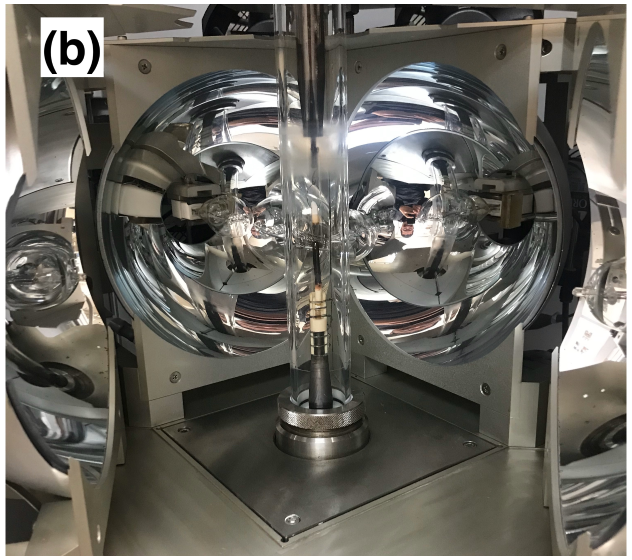
NOPTREX Collaboration

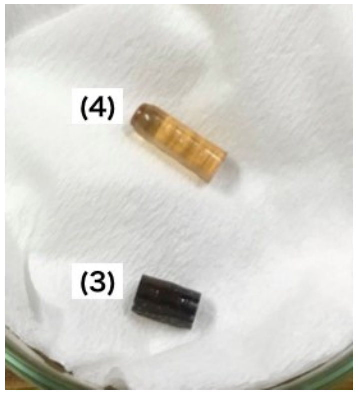
Neutron Optical Parity and Time Reversal EXperiment



偏極各標的の開発

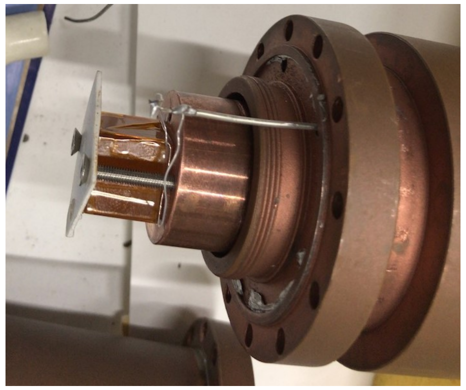
結晶育成　東北大金属材料研





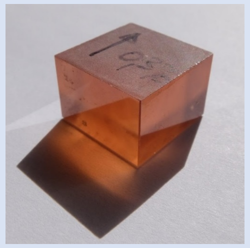
東北大金研
広島大
名古屋大

核偏極基礎研究　阪大核物理研究センター



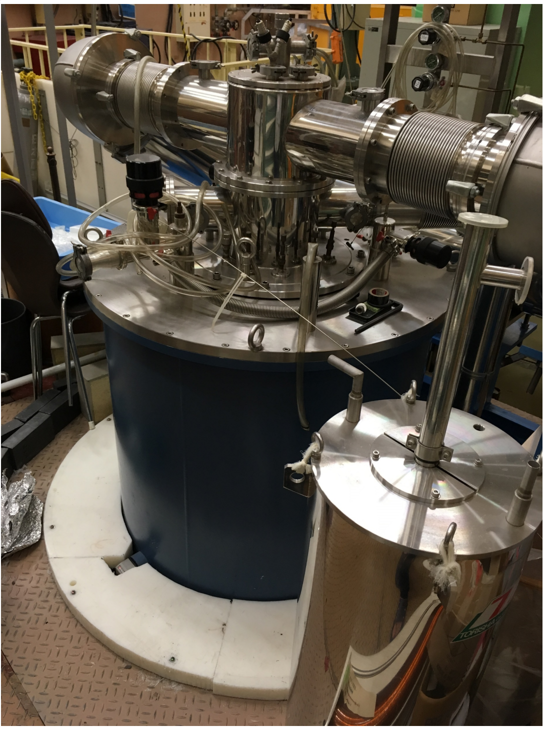
阪大核物理センター
広島大、名古屋大
山形大

偏極La核標的



LaAlO$_3$単結晶
Ndドープ結晶
純粋結晶

低温技術



名古屋大学
理化学研究所
日本女子大
足利大
広島大

極低温・高冷却能力
冷凍機開発

緩和時間制御

広大自然開発センター

広島大
名古屋大

芳香族有機分子による
緩和時間制御

J-PARCでの実験の可能性

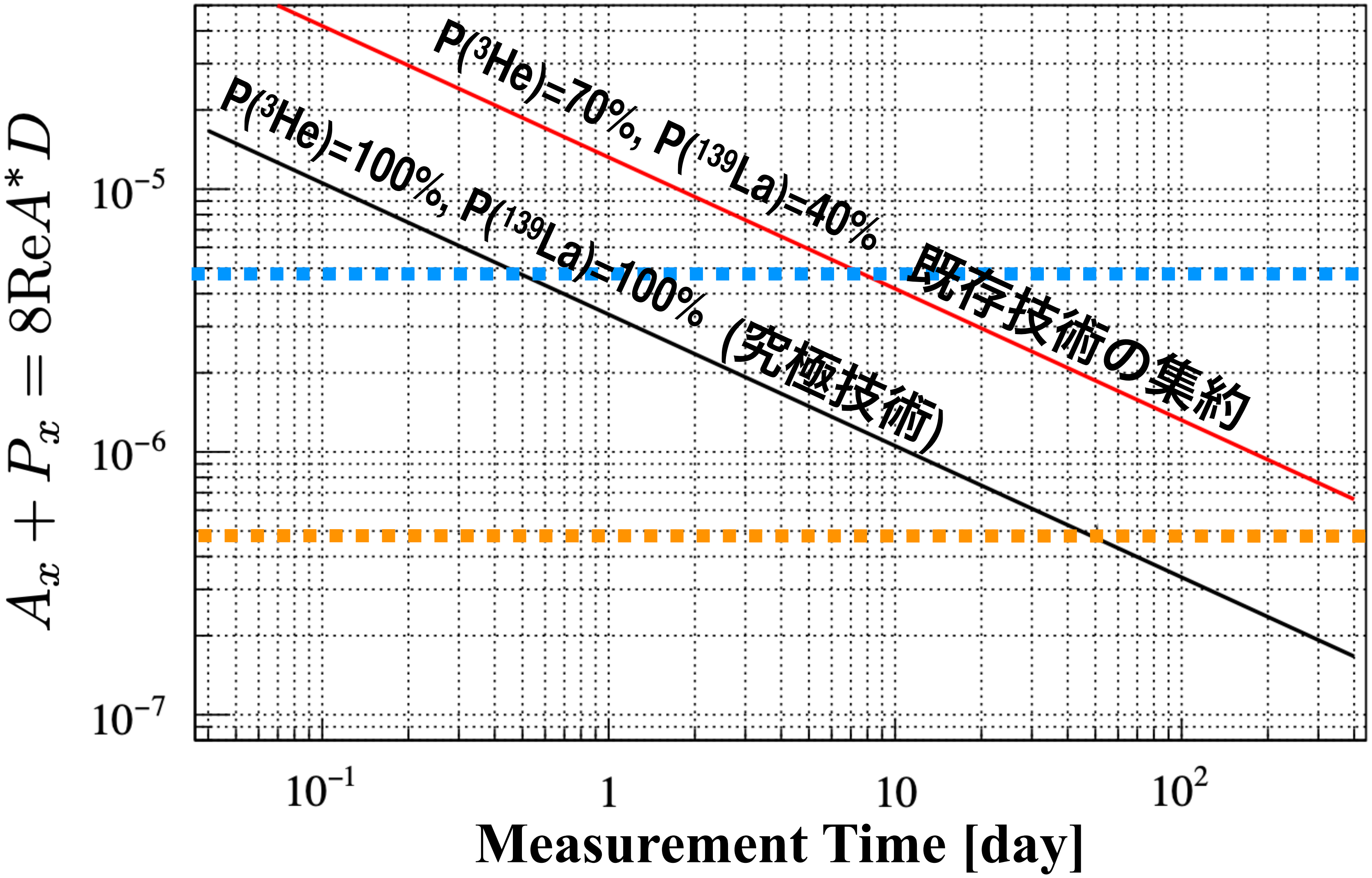
$\overrightarrow{^{139}\mathrm{La}}$　　$\mathrm{LaAlO_3}$

$P(^{139}\mathrm{La})\geq 0.4$, $V\geq 4\,\mathrm{cm}\times 4\,\mathrm{cm}\times 2.8\,\mathrm{cm}$
$B_0\leq 0.1\,\mathrm{T}$

$$\left|\frac{\langle W_{\mathrm{T}}\rangle}{\langle W\rangle}\right| < 3.9\times 10^{-4}$$

↕

$$8\mathrm{Re}A^*D = 5.3\times 10^{-5}$$



discovery potential corresponding to $d_n = 3.0\times10^{-26}$ e cm

discovery potential corresponding to $d_n = 3.0\times10^{-27}$ e cm

n-$\bar{n}$ oscillation

Neutron-Antineutron oscillation

D. G. Phillips II et al., arXiv: hep-ex/1410.1101

NNbar oscillation

$n \longrightarrow \bar{n}$ $\Delta B = 2 \longrightarrow$ **Baryogenesis**

quark-lepton unified seesaw mechanism

$SU(2)_L \times SU(2)_R \times SU(4)_c$ realized in the multi-TeV scale

post-sphaleron baryogenesis $\longrightarrow$ $\tau_{n\bar{n}} \leq 5 \times 10^{10}$ s

K.S.Babu et al., Phys. Rev. D 87, 115019 (2013)

There are several theories predict nnbar osc. in that scale. $\tau_{n\bar{n}} \sim 10^{10}$ s

Current limit by direct searches $\tau_{n\bar{n}} > 0.86 \times 10^8$ s

10^2-10^3 improvement is necessary

Neutron-Antineutron oscillation

$$\psi = \begin{pmatrix} n \\ \bar{n} \end{pmatrix} \qquad \mathscr{M} = \begin{pmatrix} m_n - i\lambda/2 & \delta m \\ \delta m & m_n - i\lambda/2 \end{pmatrix}$$

$$|n_\pm\rangle = \frac{1}{\sqrt{2}}(|n\rangle \pm |\bar{n}\rangle) \qquad m_\pm = (m_n \pm \delta m) - i\lambda/2$$

$$P(n(t) = \bar{n}) = |\langle \bar{n} | n(t) \rangle|^2 = [\sin^2(t/\tau_{n\bar{n}})]\mathrm{e}^{-\lambda \mathrm{t}} \simeq (\mathrm{t}/\tau_{\mathrm{n\bar{n}}})^2$$

$$\tau_{n\bar{n}} = 1/|\delta m|$$

$$\text{Sensitivity (Figure of Merit)} \propto \underset{\text{Number of neutrons}}{N} \; \underset{\text{(Average square of) free flight time}}{T^2}$$

Neutron-Antineutron oscillation

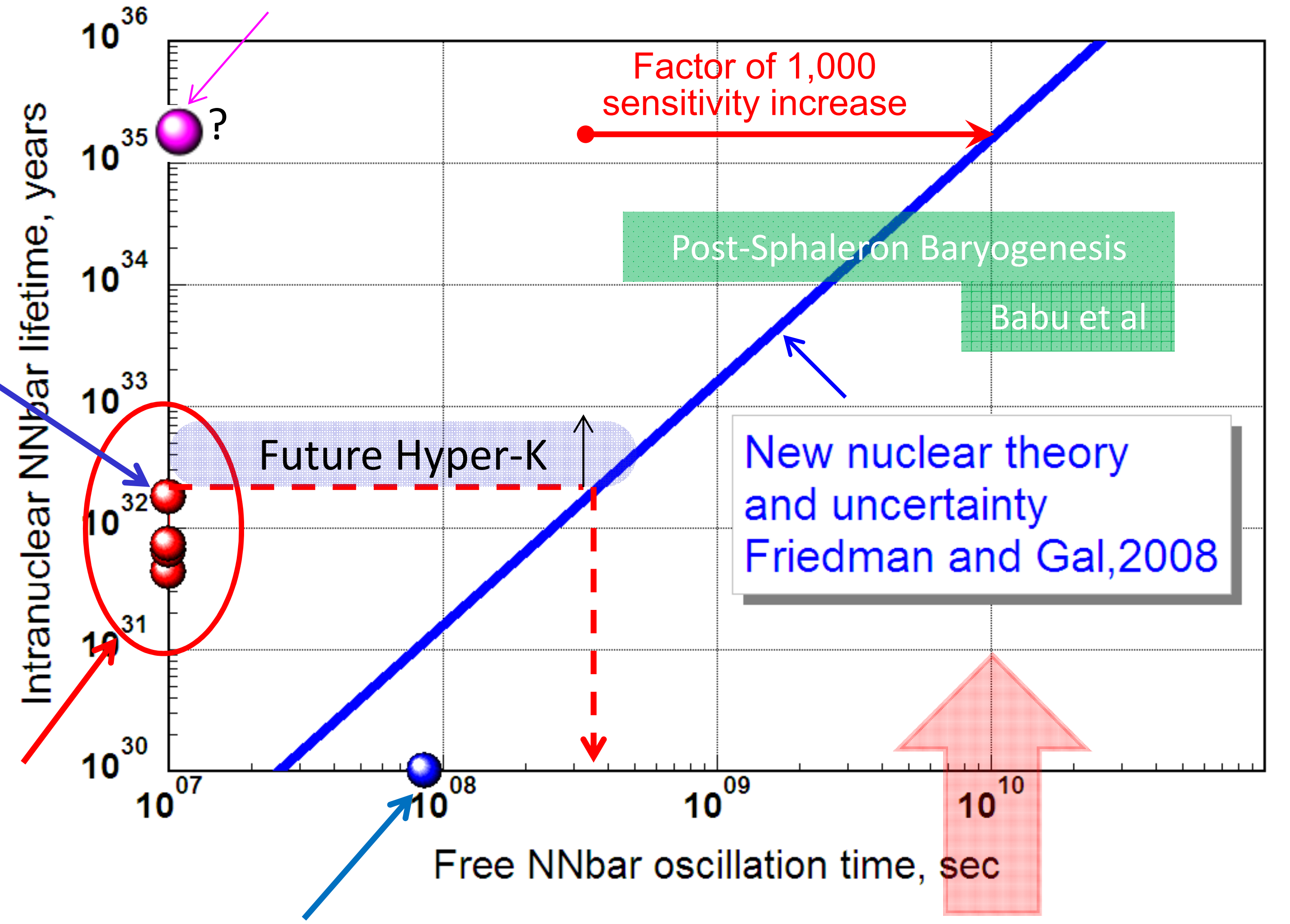
$$\tau_{bound} = R \times \tau^2_{free}$$

Free Neutron vs Bound Neutrons
NNbar Search Sensitivity Comparison

(see backup slides on complementarity of free and bound neutron search)

LBNE 35 kt, 10 years, if zero atm. ν background ? (R&D issue)

Recent S-K (2011) limit based on 24 candidates and 24.1 bkgr. from atm. ν



intranuclear search exp. limits:
Super-K,
Soudan-2
Frejus

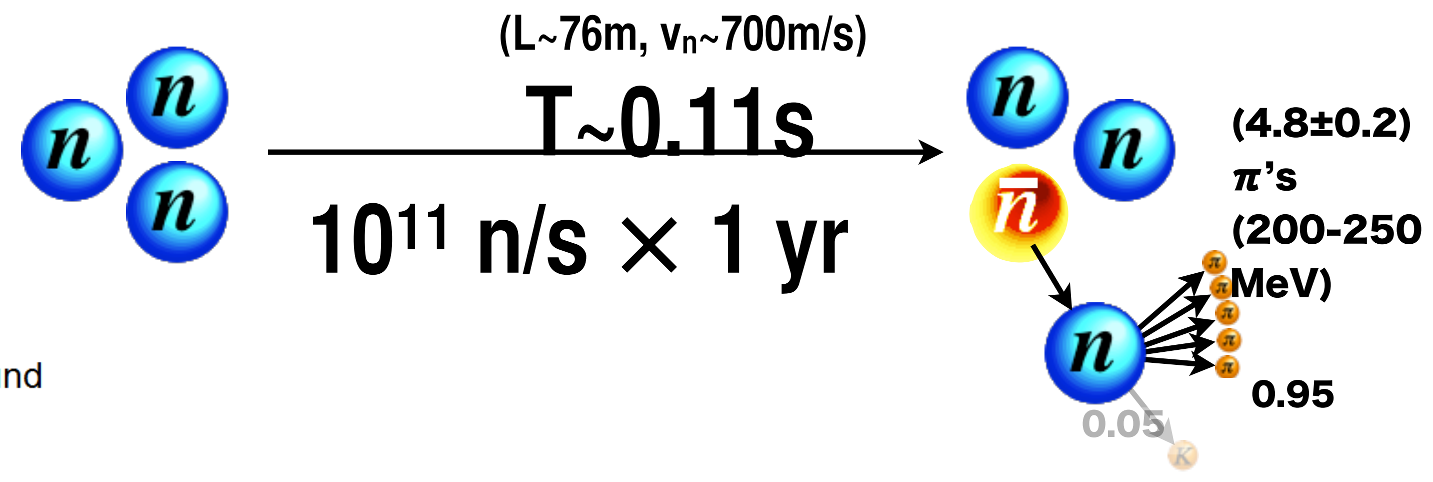
Free neutron search limit (ILL - 1994)

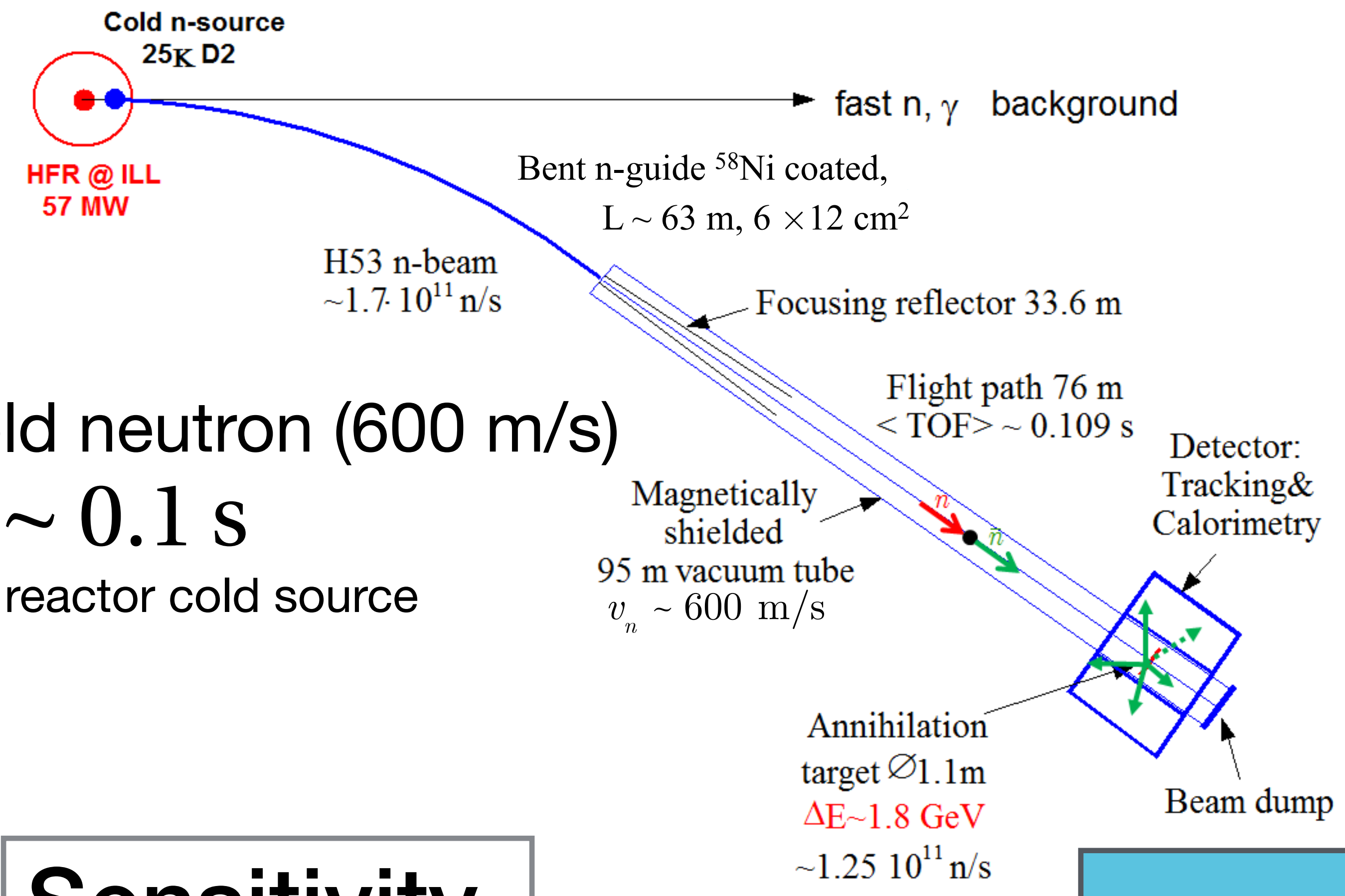
Goal of new n-nbar search with free neutrons

Neutron-Antineutron oscillation

Free Neutron Search

M. Baldo-Ceolin et al., Z Phys. C 63 (1994) 409





Cold neutron (600 m/s)

$T \sim 0.1$ s

ILL reactor cold source

$$\tau_{n\bar{n}} > 0.86 \times 10^8 \text{ s}$$

$$O(10^{10}) \text{ s}$$

Physics motivation

Sensitivity

$$\propto NT^2$$

Can be improved by 10^2-10^3

by improved n source and optics

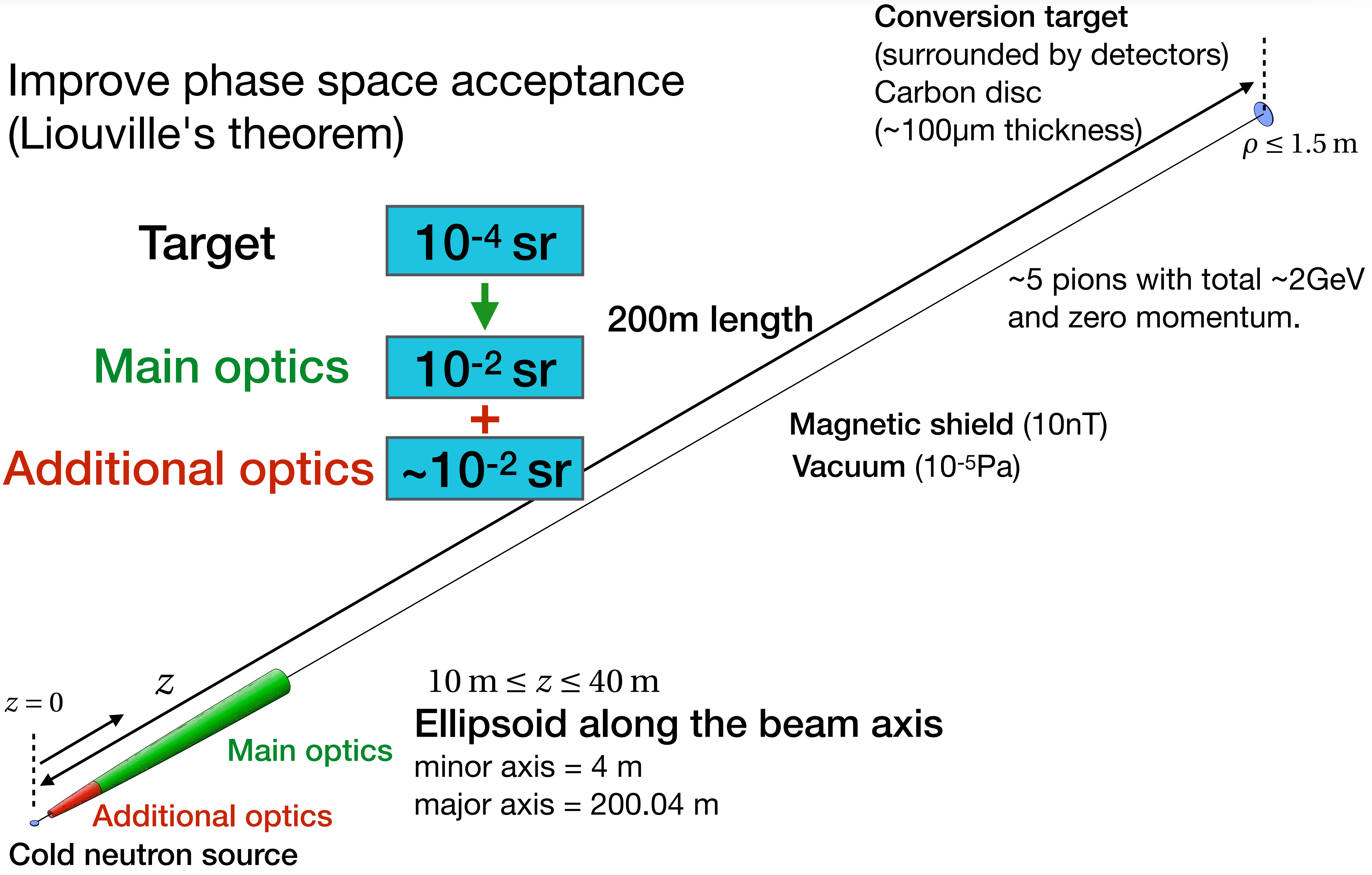
Neutron-Antineutron oscillation

The European Spallation Source (ESS)

2GeV 14Hz 5MW
cold neutron production ~ 12×ILL
2014: ESS Construction start
2019: ESS first neutrons NNbar commissioning start

Neutron Optics for nnbar

Improve phase space acceptance
(Liouville's theorem)



Target 10^{-4} sr

Main optics 10^{-2} sr

\+

Additional optics $\sim 10^{-2}$ sr

Conversion target
(surrounded by detectors)
Carbon disc
(~100μm thickness)

$\rho \leq 1.5\,\mathrm{m}$

200m length

~5 pions with total ~2GeV
and zero momentum.

Magnetic shield (10nT)
Vacuum (10^{-5}Pa)

z

$z = 0$

$10\,\mathrm{m} \leq z \leq 40\,\mathrm{m}$

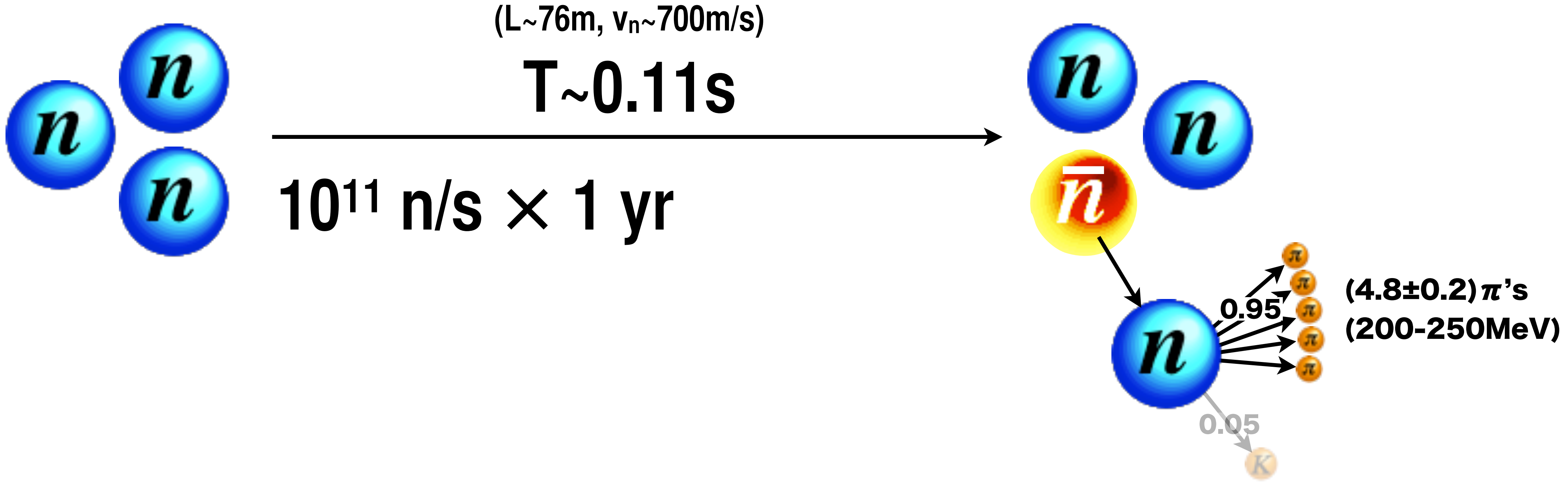
Ellipsoid along the beam axis
minor axis = 4 m
major axis = 200.04 m

Main optics

Additional optics

Cold neutron source

Neutron Optics for nnbar



(L~76m, v_n~700m/s)

T~0.11s

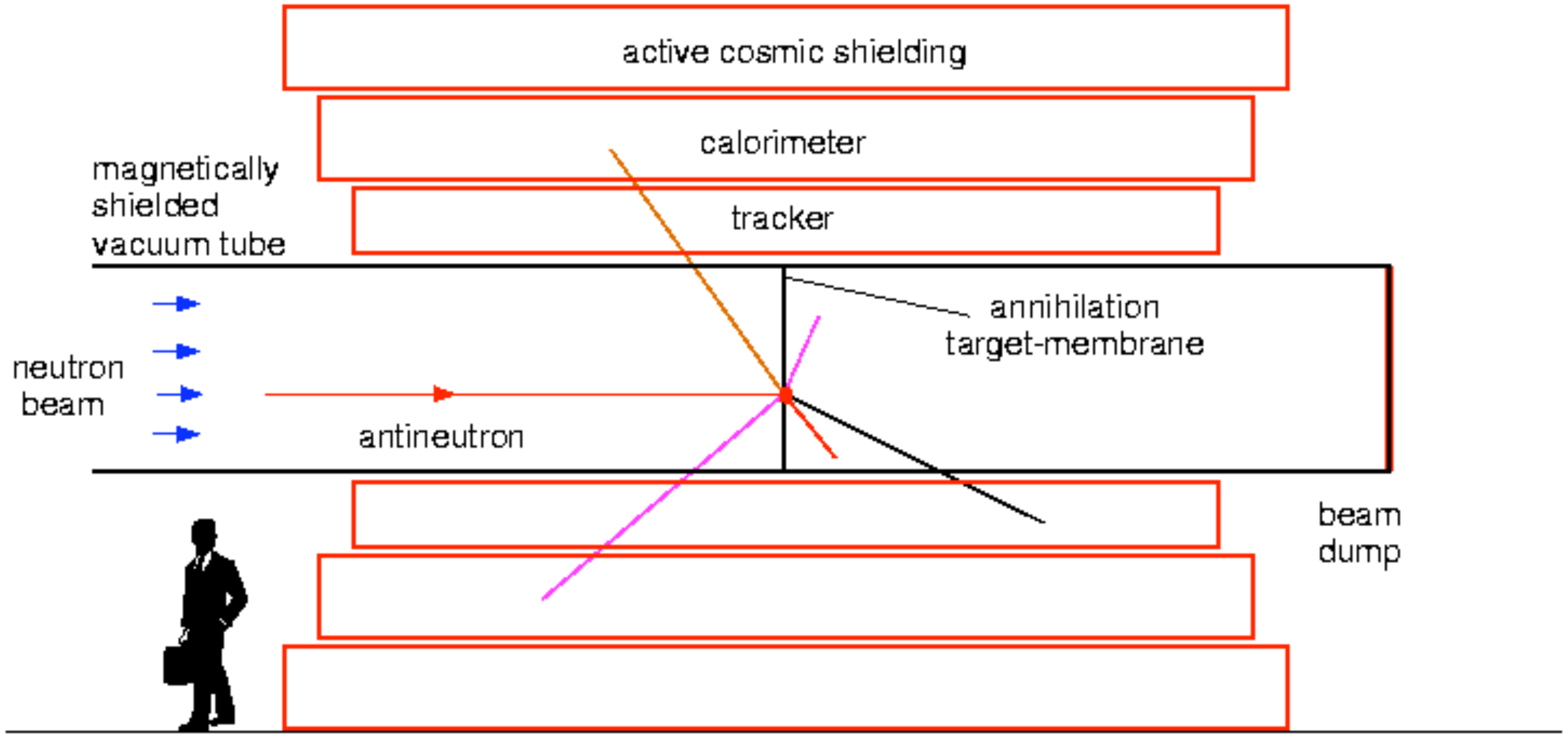
10^{11} n/s × 1 yr

(4.8±0.2)π's

(200-250MeV)

Neutron Optics for nnbar

The conceptual scheme of antineutron detector



$$\boxed{\bar{n} + A \rightarrow \langle 5 \rangle \; pions \quad (1.8 \text{ GeV})}$$

Annihilation target: ~100μ thick Carbon film

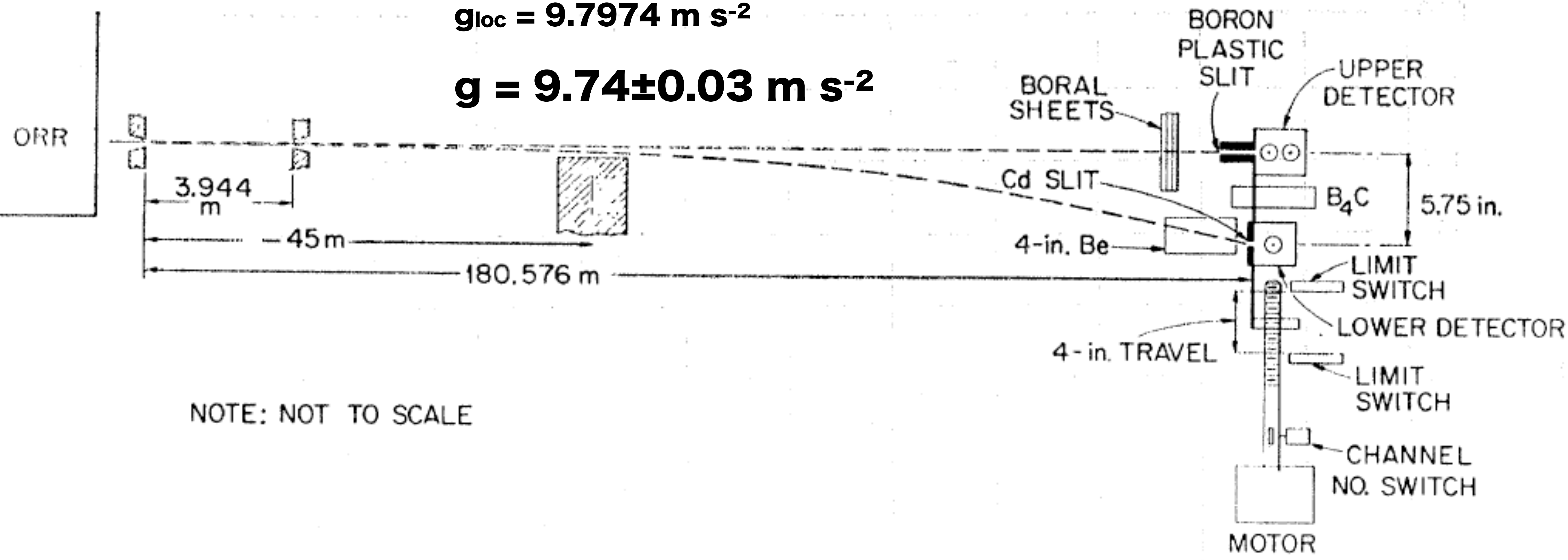
$\sigma_{\text{annihilation}} \sim 4$ Kb $\quad \sigma_{\text{nC capture}} \sim 4$ mb

Scattering Experiment to study Intermediate-range Force

中性子は重力を感じる

中性子の自由落下

Dabbs et al., Phys. Rev. 139 (1965) B756



g_{loc} = 9.7974 m s^{-2}

g = 9.74±0.03 m s^{-2}

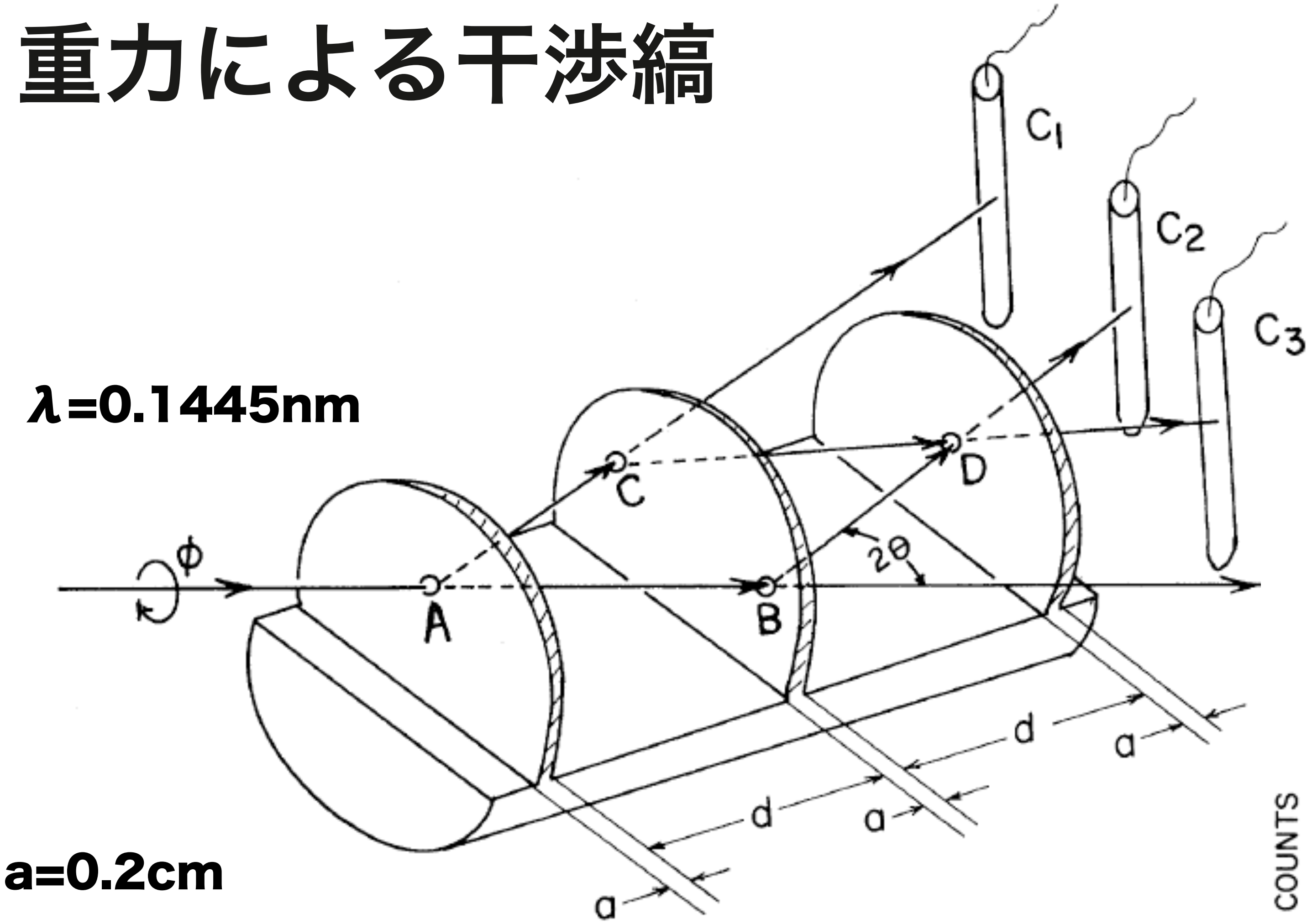
Gregoriev et al., Proc. 1st Int. Conf. Neutr. Phys., Kiev, 1 (1988) 60

g = 9.801±0.013 m s^{-2}

g_{loc} = 9.814 m s^{-2}

中性子は重力を感じる

重力による干渉縞

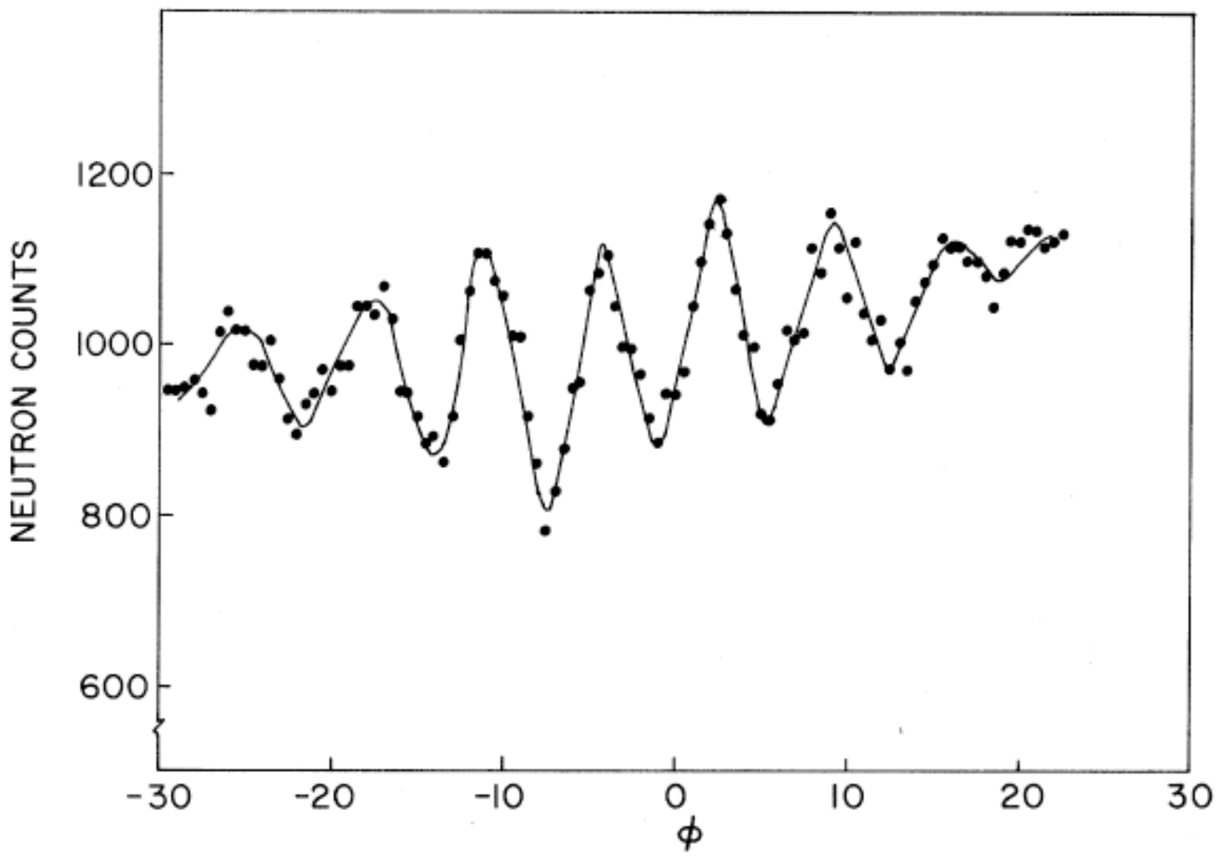


λ=0.1445nm

a=0.2cm

d=3.5cm

θ=22.1°



Collela, Overhauser, Werner, Phys. Rev. Lett. 34 (1975) 1472

Scattering Experiment to study Intermediate-range Force

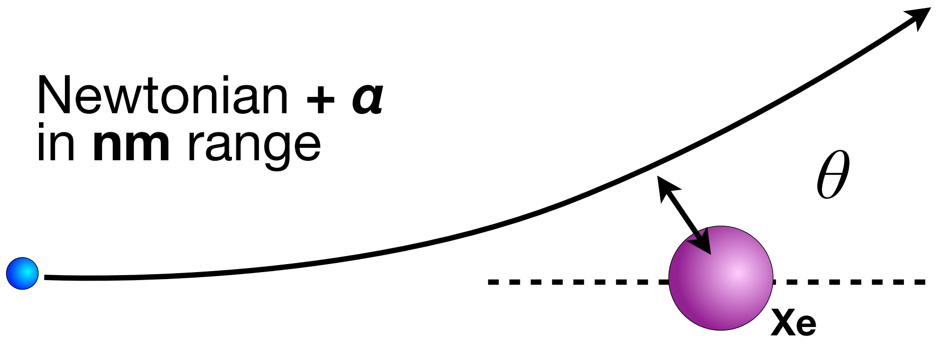
Gravity in short range

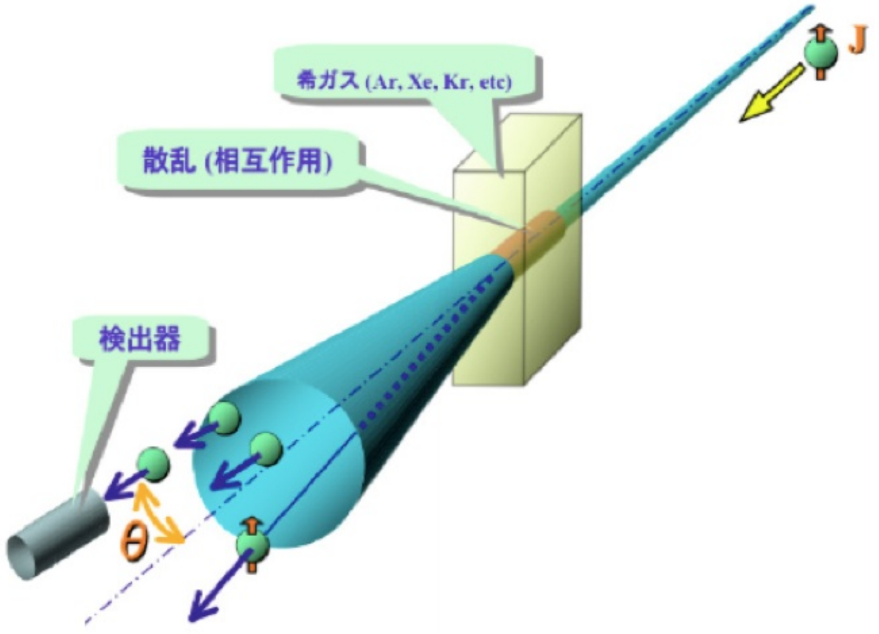
non-Newtonian gravity

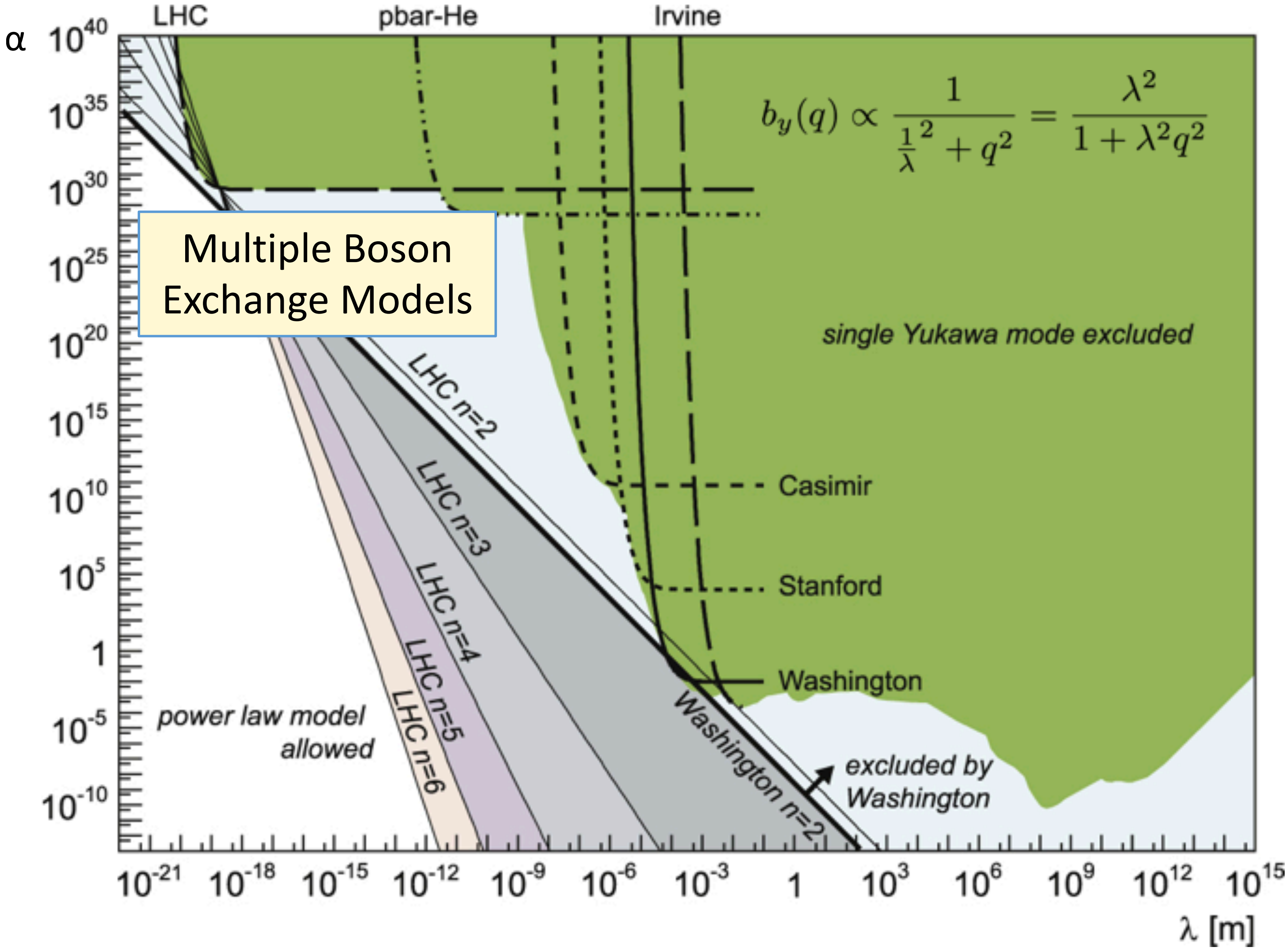
$$V(r) = -G_N \frac{m_1 m_2}{r}\left(1+\alpha\cdot e^{-\frac{r}{\lambda}}\right)$$

ガス散乱

Newtonian + ***α***
in **nm** range







Multiple Boson Exchange Models

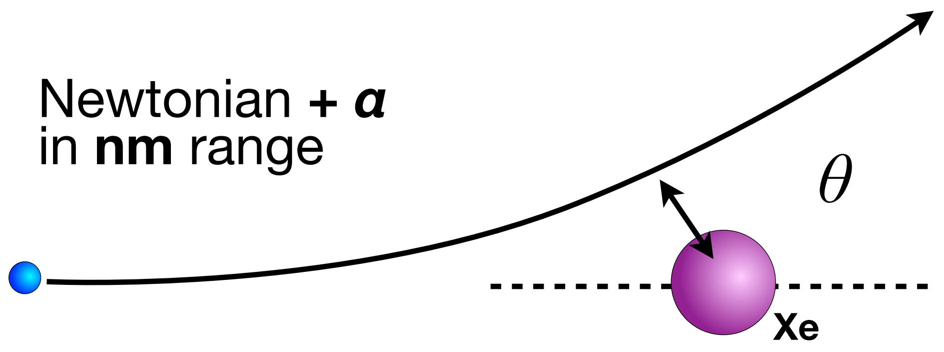
Scattering Experiment to study Intermediate-range Force

Gravity in short range

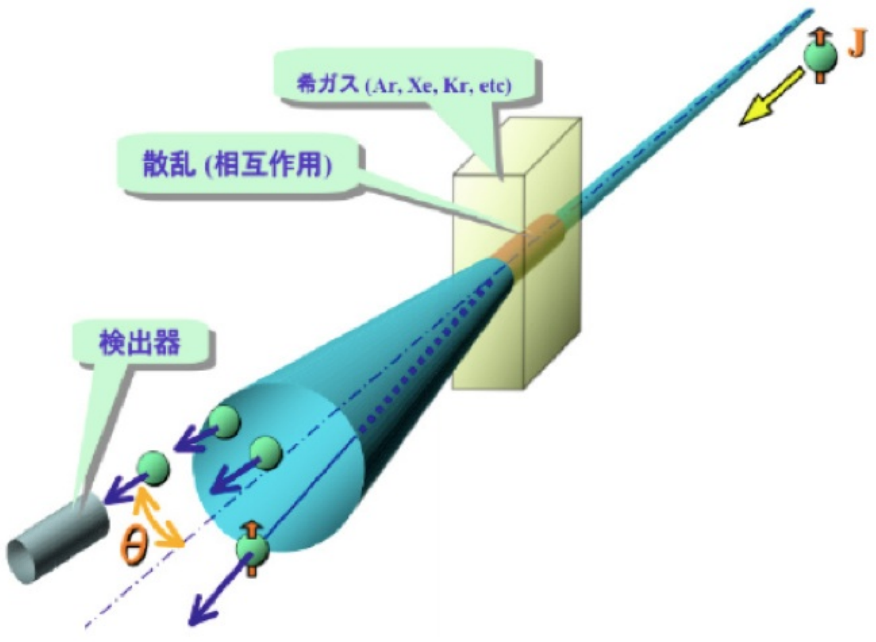
non-Newtonian gravity

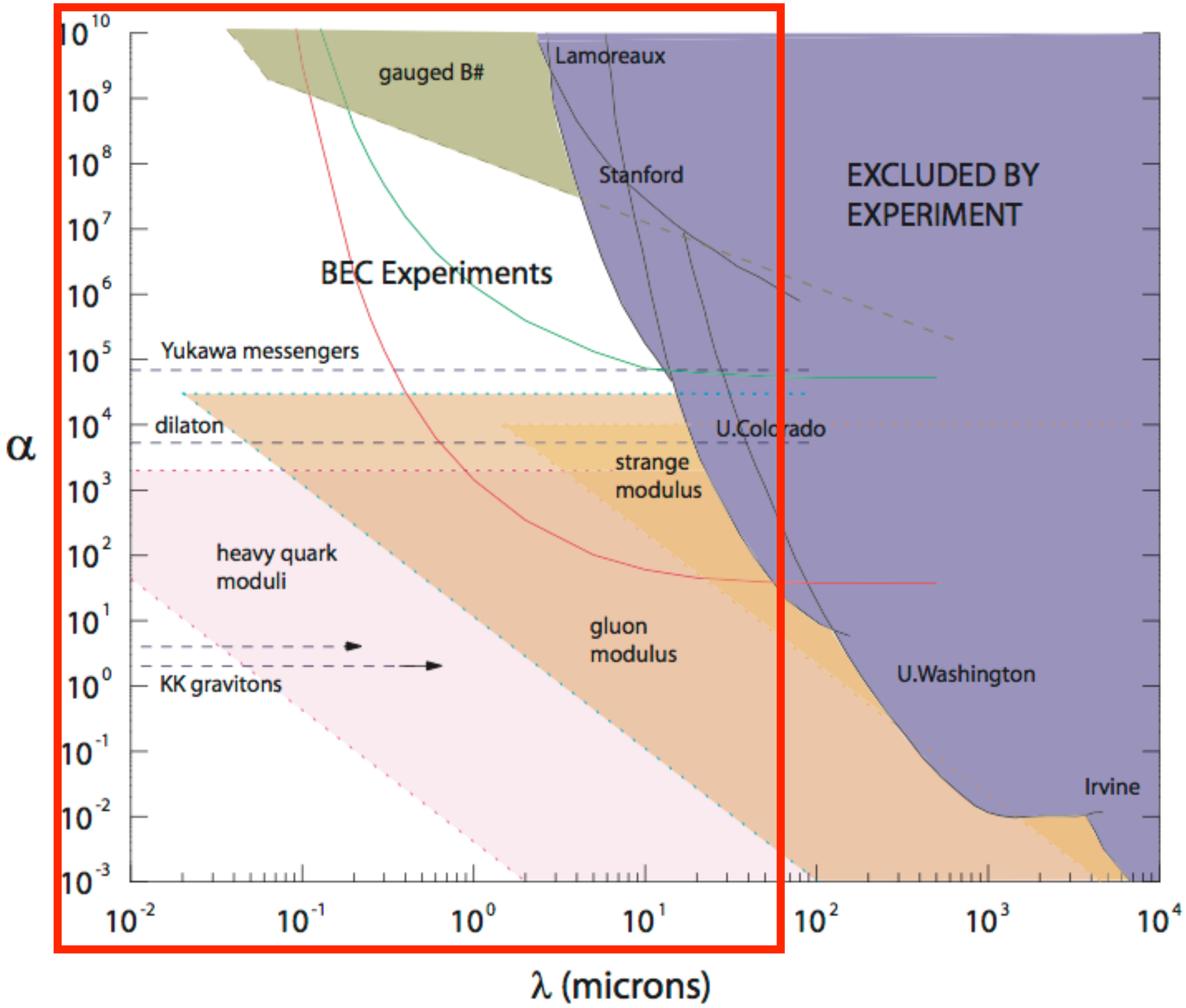
$$V(r) = -G_N \frac{m_1 m_2}{r}\left(1+\alpha\cdot e^{-\frac{r}{\lambda}}\right)$$

ガス散乱

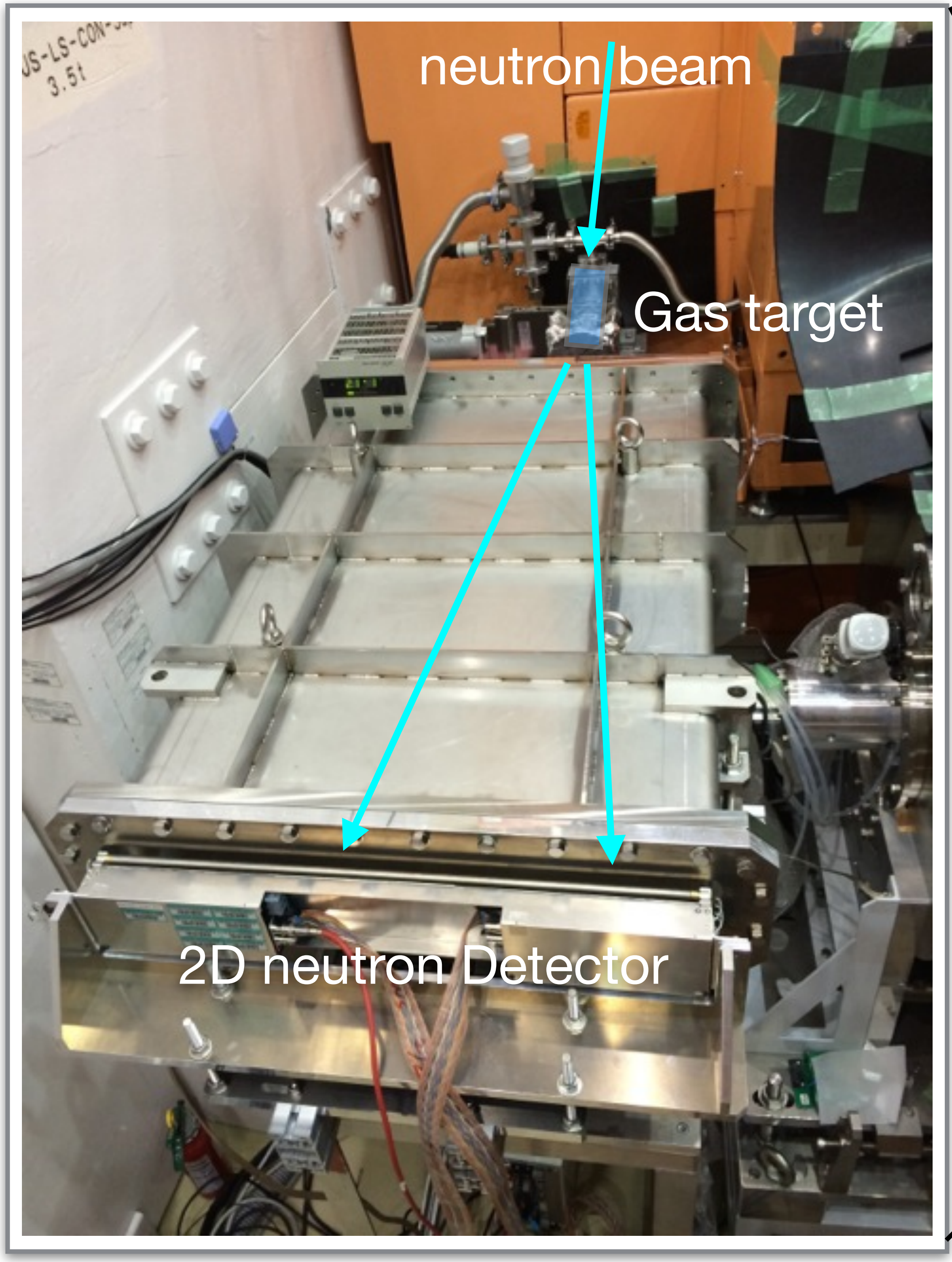


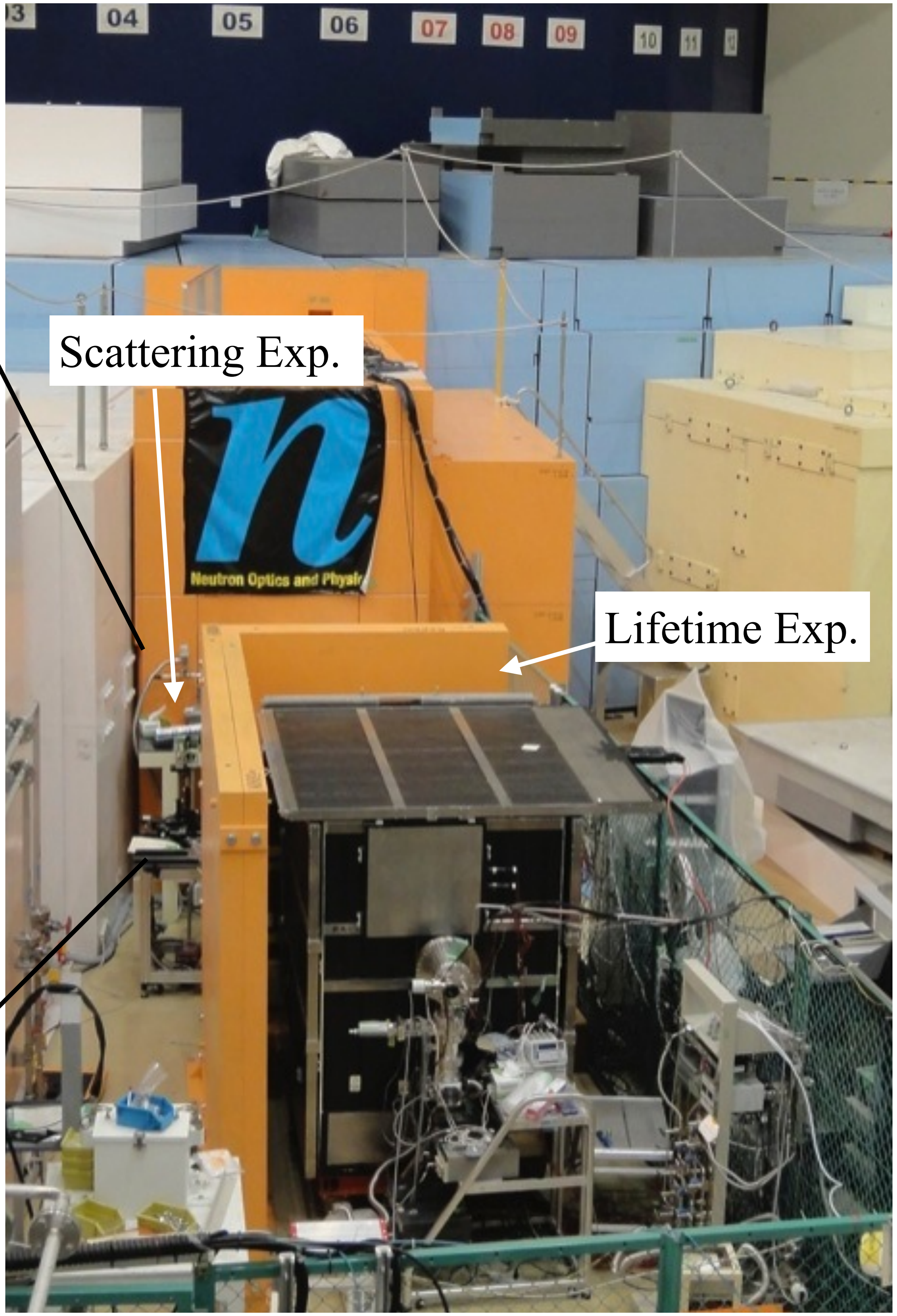
Newtonian + ***α***
in **nm** range



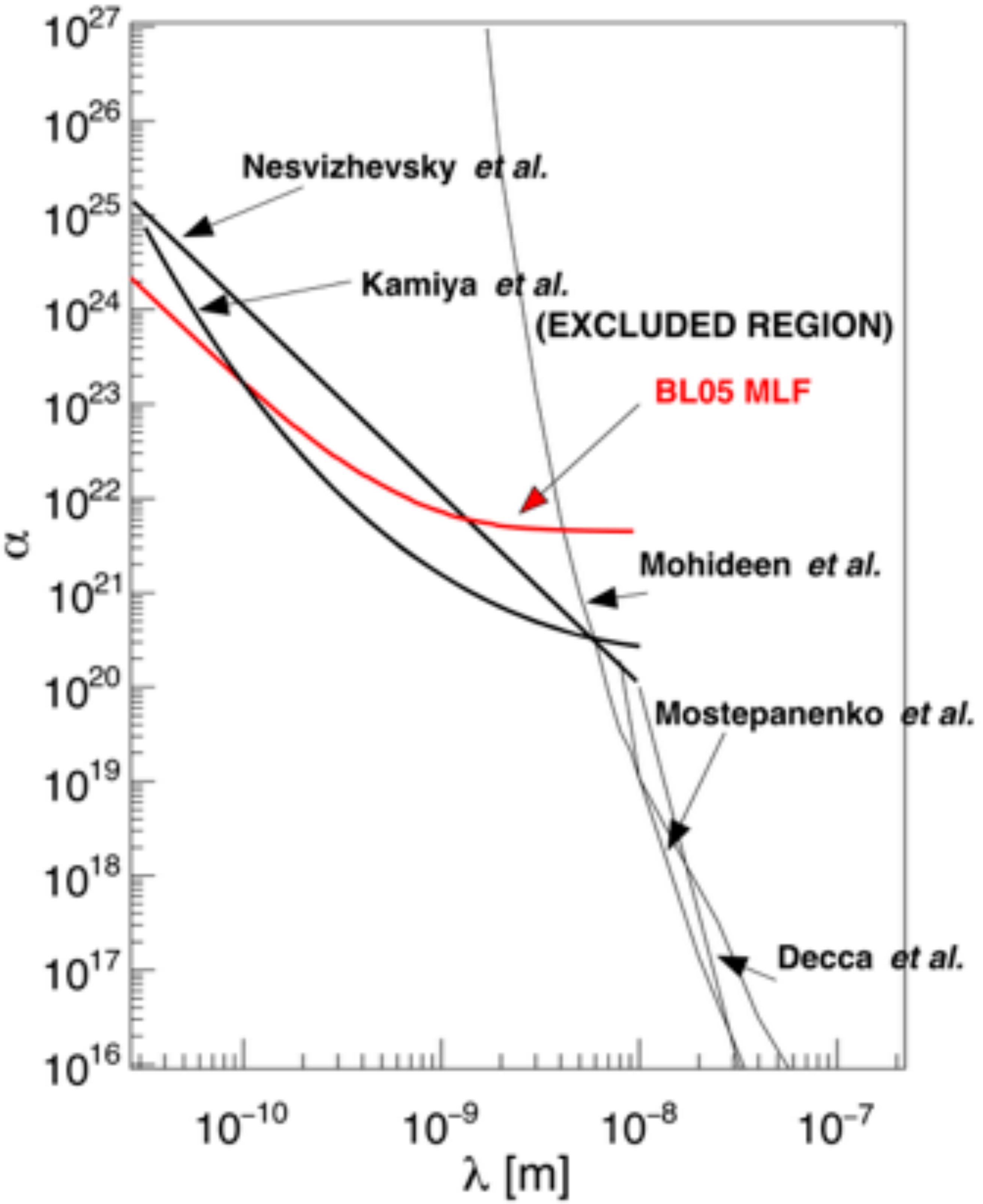


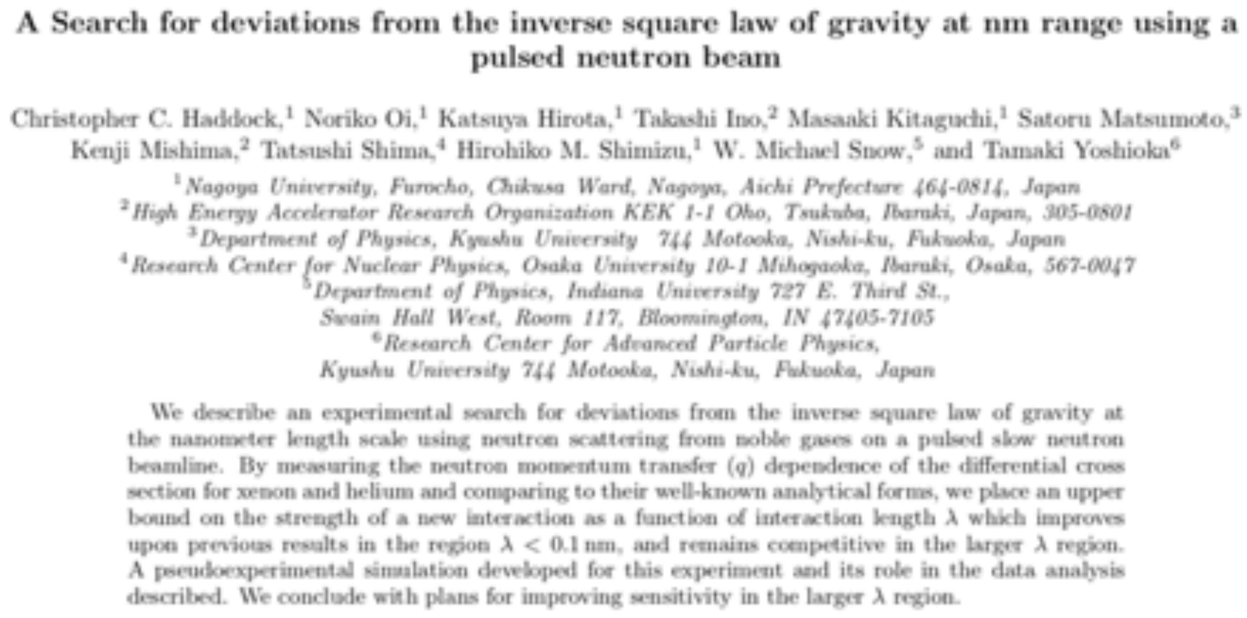
Scattering Experiment to study Intermediate-range Force





Scattering Experiment to study Intermediate-range Force





A Search for deviations from the inverse square law of gravity at nm range using a pulsed neutron beam

Christopher C. Haddock,[1] Noriko Oi,[1] Katsuya Hirota,[1] Takashi Ino,[2] Masaaki Kitaguchi,[1] Satoru Matsumoto,[3]
Kenji Mishima,[2] Tatsushi Shima,[4] Hirohiko M. Shimizu,[1] W. Michael Snow,[5] and Tamaki Yoshioka[6]

[1]*Nagoya University, Furocho, Chikusa Ward, Nagoya, Aichi Prefecture 464-0814, Japan*
[2]*High Energy Accelerator Research Organization KEK 1-1 Oho, Tsukuba, Ibaraki, Japan, 305-0801*
[3]*Department of Physics, Kyushu University 744 Motooka, Nishi-ku, Fukuoka, Japan*
[4]*Research Center for Nuclear Physics, Osaka University 10-1 Mihogaoka, Ibaraki, Osaka, 567-0047*
[5]*Department of Physics, Indiana University 727 E. Third St.,*
Swain Hall West, Room 117, Bloomington, IN 47405-7105
[6]*Research Center for Advanced Particle Physics,*
Kyushu University 744 Motooka, Nishi-ku, Fukuoka, Japan

We describe an experimental search for deviations from the inverse square law of gravity at the nanometer length scale using neutron scattering from noble gases on a pulsed slow neutron beamline. By measuring the neutron momentum transfer (q) dependence of the differential cross section for xenon and helium and comparing to their well-known analytical forms, we place an upper bound on the strength of a new interaction as a function of interaction length λ which improves upon previous results in the region $\lambda < 0.1$ nm, and remains competitive in the larger λ region. A pseudoexperimental simulation developed for this experiment and its role in the data analysis described. We conclude with plans for improving sensitivity in the larger λ region.

C. C. Haddock, et. al.,
Phys. Rev. D 97, 062002 (2018).

Neutrons for Dark Universe

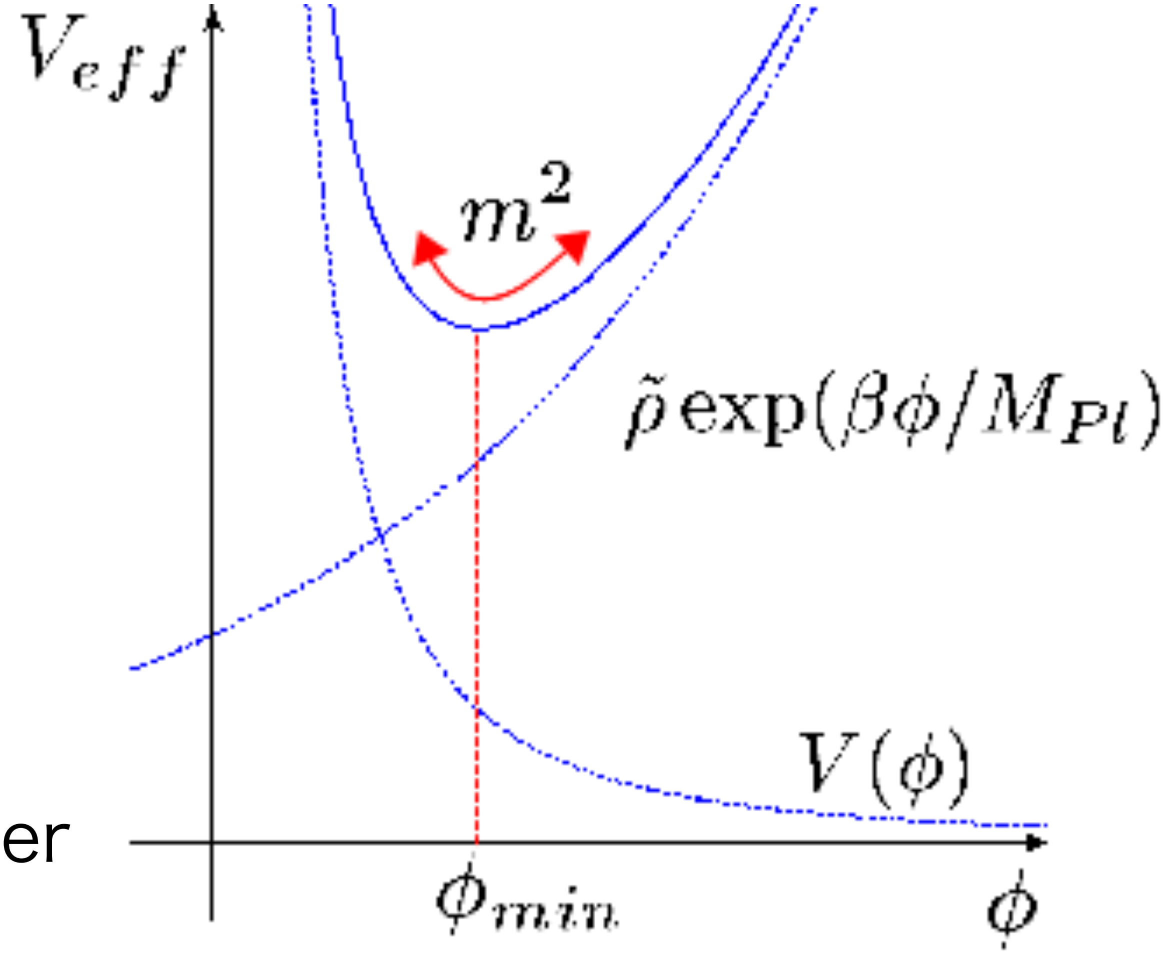
Neutrons for Dark Energy

ダークエネルギーとカメレオン機構

インフレーションするために負の圧力が必要　→**スカラー場**

←太陽系・地上実験で「第５の力」が
見つからない

→**カメレオン機構**



物質場と結合するスカラー場を導入

$$\bar{\Box}\phi = V'(\phi) + \frac{\beta}{M_{\rm Pl}}\tilde{\rho}e^{\beta\phi/M_{\rm Pl}}$$

$$V_{\rm eff}(\phi) \equiv V(\phi) + \tilde{\rho}e^{\beta\phi/M_{\rm Pl}}$$

runaway　　couple to matter

$$V'(\phi) < 0, \quad V''(\phi) > 0, \quad V'''(\phi) < 0$$

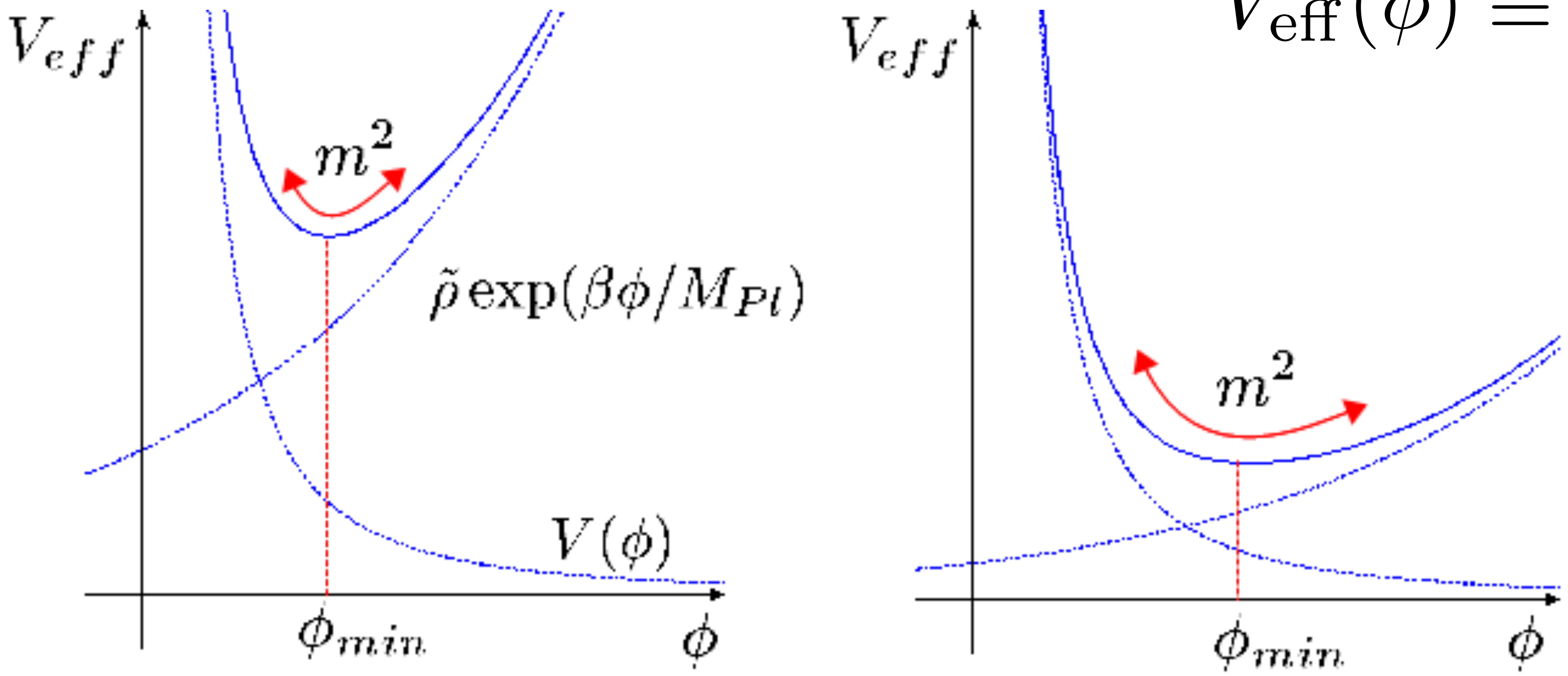
Neutrons for Dark Energy

ダークエネルギーとカメレオン機構

物質場と結合するスカラー場を導入

→物質密度によって有効ポテンシャルが変形する

$$V_{\mathrm{eff}}(\phi) \equiv V(\phi) + \tilde{\rho} e^{\beta\phi/M_{\mathrm{Pl}}}$$



高密度　低密度

→高密度では場の質量が大きくなる

→到達距離が短くなる　→スカラー場の影響が小さくなる

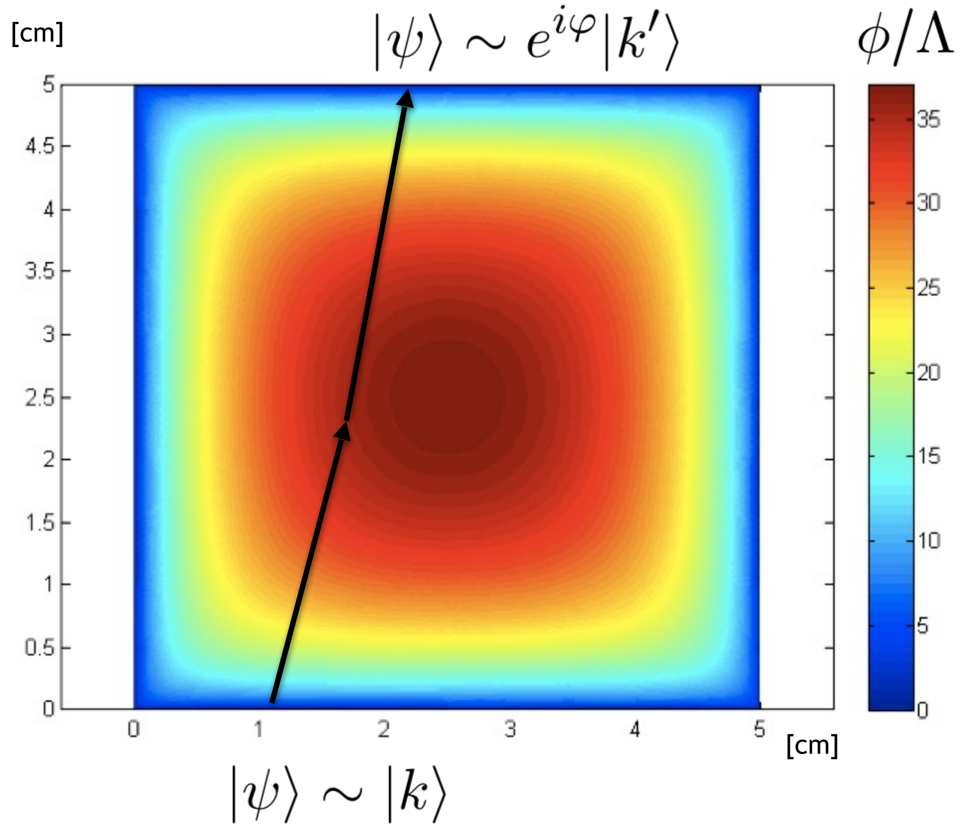
Neutrons for Dark Energy

カメレオン場の探索

Ratra-Peeblesポテンシャル

$$A(\phi) \rightarrow \frac{\beta}{M_{\mathrm{Pl}}}\phi$$

$$V(\phi) \rightarrow \frac{\Lambda^{4+n}}{\phi^n}$$



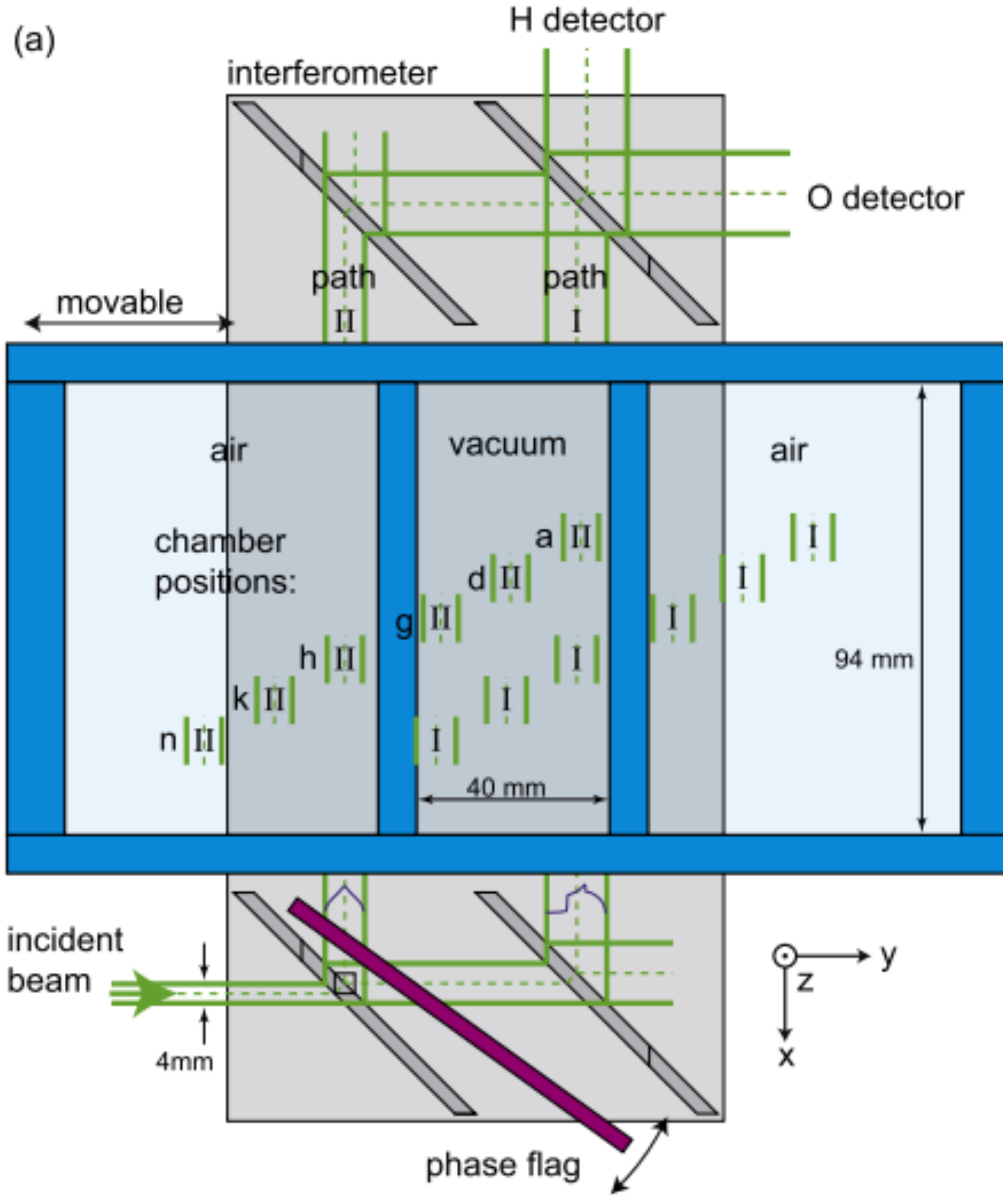
β - Coupling to matter. How well is the chameleon screened?
Λ - 2.4 meV - Measured dark energy scale
n - Ratra-Peebles Index. Shape of the field.

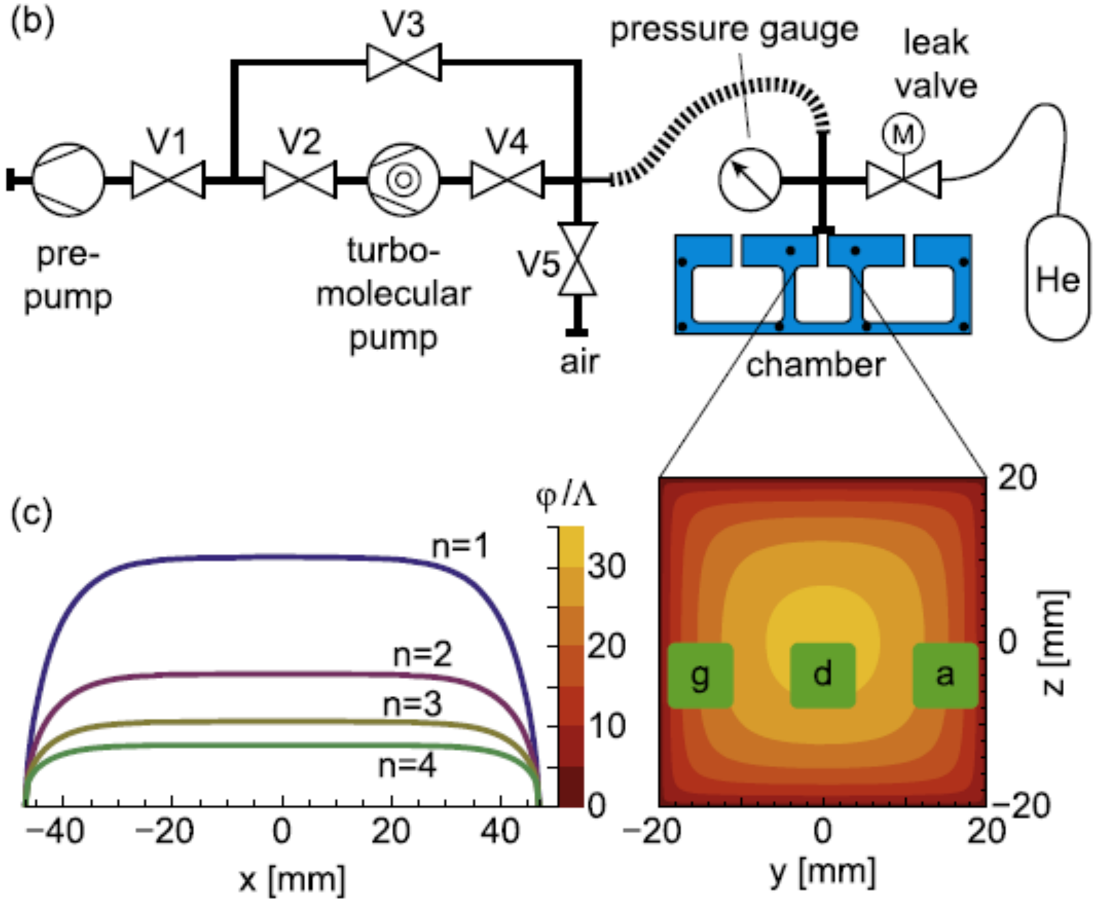
→キャビティを通過する際にポテンシャルの影響をうける

Neutrons for Dark Energy

中性子干渉計を用いたカメレオン場の探索

ILL実験

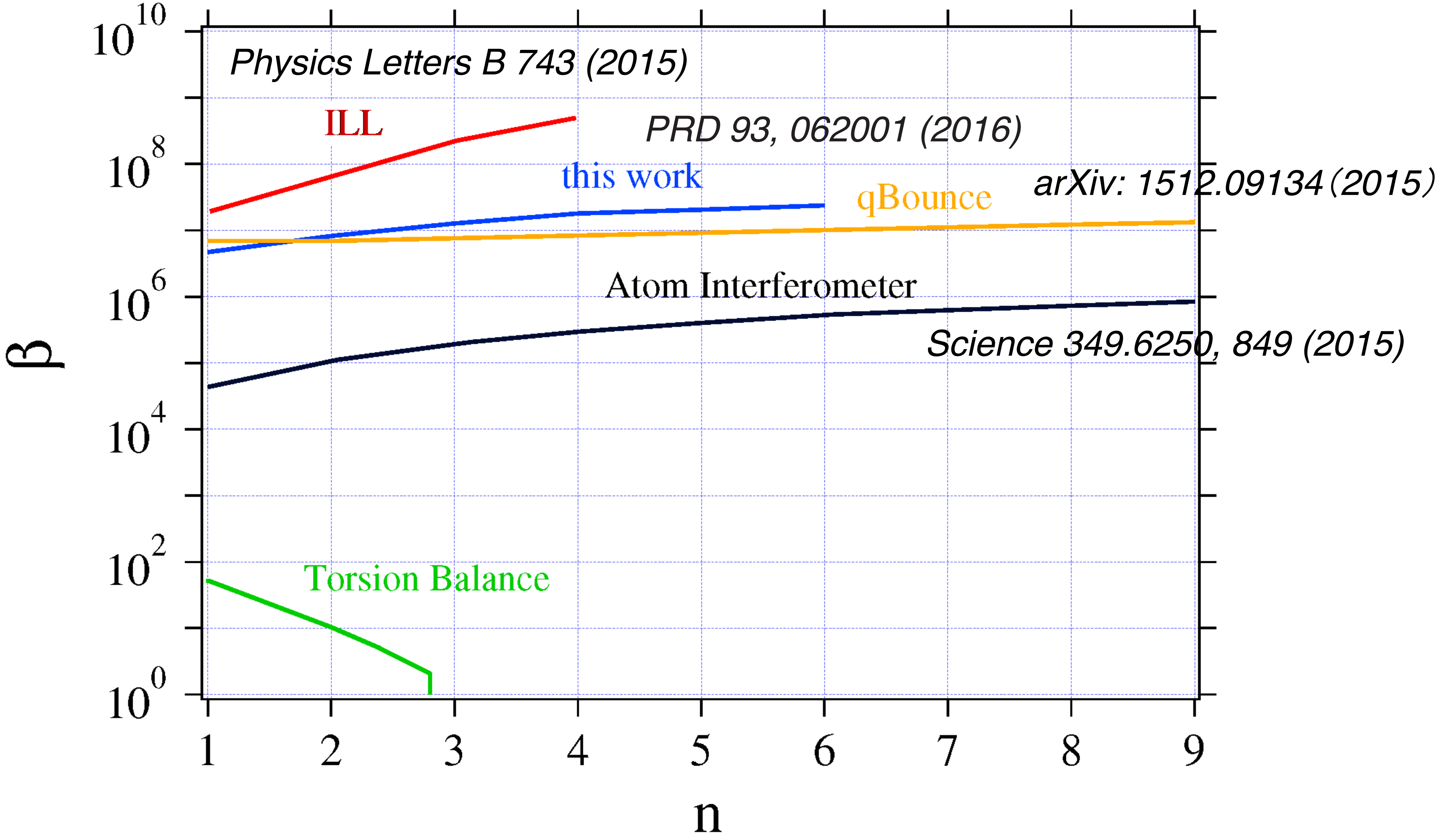




Physics Letters B 743 (2015)
See poster by T. Jenke

Neutrons for Dark Energy

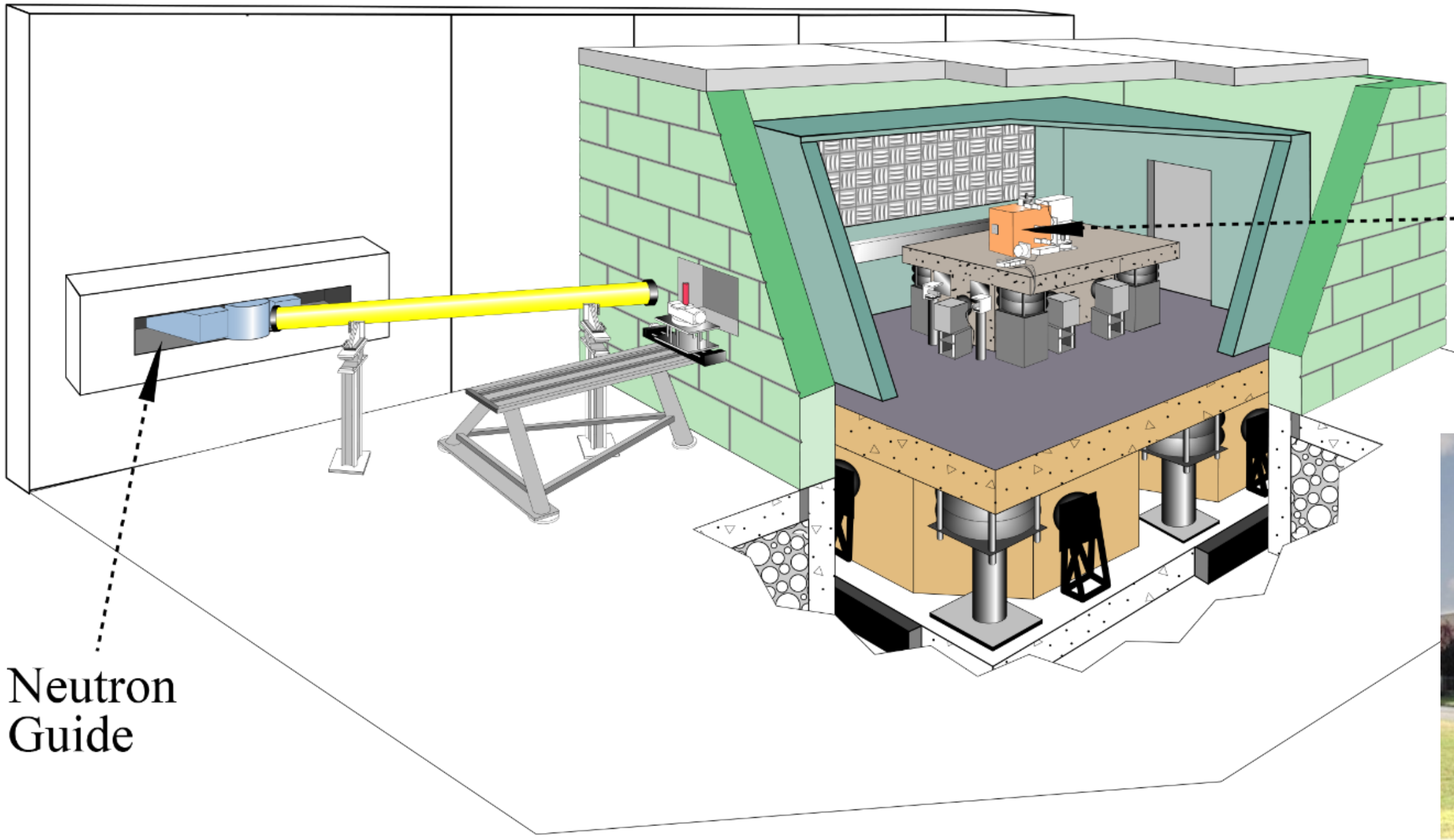
カメレオン場の探索

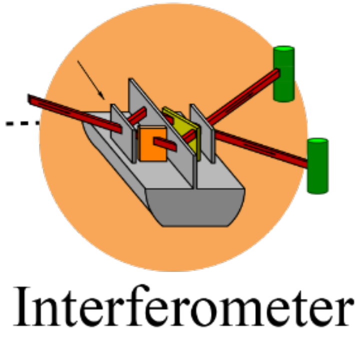


Neutrons for Dark Energy

中性子干渉計を用いたカメレオン場の探索　@NIST

Neutron Optics and Interferometry Facility (NIOF)

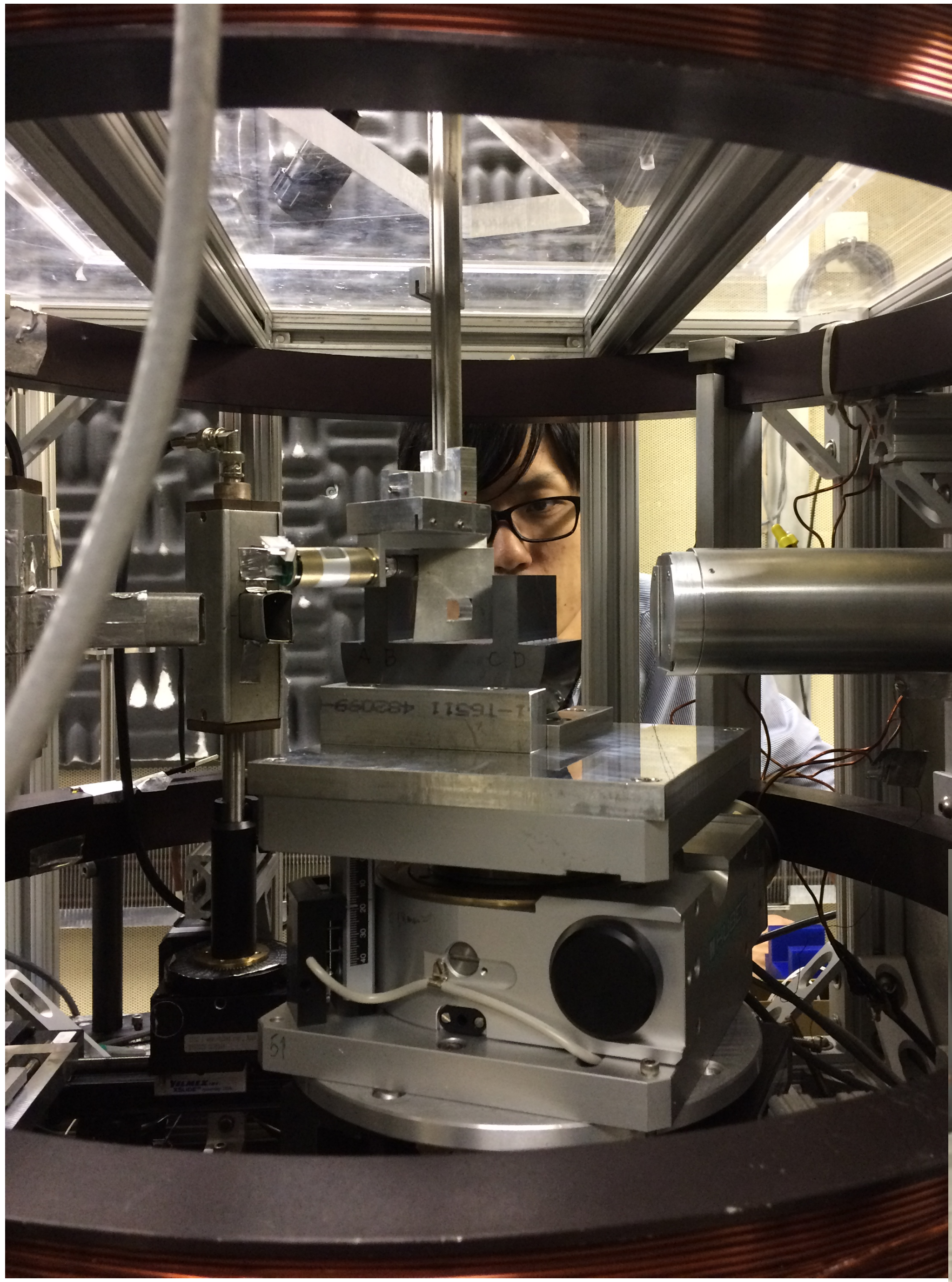




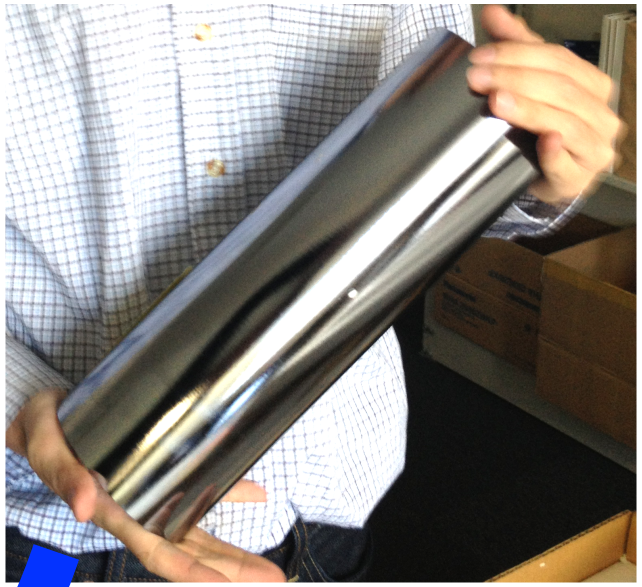
Isolated 40,000 Kg room is supported by six airsprings
Active Vibration Control eliminates vibrations less than 10Hz
Temperature Controlled to +/- 5 mK

Neutrons for Dark Energy

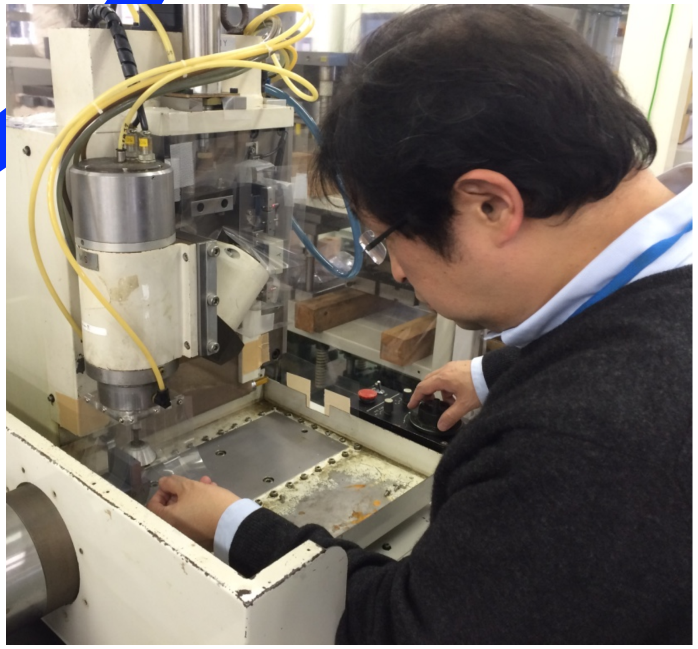
中性子干渉計を用いたカメレオン場の探索　@NIST



テストピースを作成
理研精密加工



NISTで評価実験
干渉縞を観測



動力学的回折を用いた探索

結晶構造因子は以下の式で書き下せる

$$F_H = \underline{e^{W(H)}}\ \underline{\left[b_N + Z(1-f(H))b_{\rm ne} + b_5(H)\right]}$$

H; 運動量移行

核散乱　形状因子　**未知相互作用項**

温度因子

$$W(H) = \frac{B}{16\pi^2}H^2,$$

$$B = -0.57 \pm 0.01\ \ [\text{Å}]$$

for Germanium at 293 K
by Butt et. al., 1988

中性子電子散乱

$$b_{\rm ne} = (-1.345 \pm 0.025) \times 10^{-3}\ \ [\rm fm]$$

(Unc. 2%) by PDG 2018

過去の実験では未知相互作用の存在が考慮されていない

→ **未知相互作用の存在を仮定 & 温度因子と中性子電子散乱長を決定**

することで現在の未知相互作用の存在上限を超える

動力学的回折を用いた探索

結晶の周期性を用いて展開可能

$$v_H = 2m\tilde{V} = \sum_n V_n \exp\left(i\vec{H}\cdot\vec{x}_n\right)$$

$$v_H = A\frac{4\pi}{V_{\text{cell}}}\underbrace{e^{W(H)}}_{\text{温度因子}}\overbrace{\left[\underbrace{b_N}_{\text{核散乱}} + Z(1-\underbrace{f(H)}_{\text{形状因子}})\underbrace{b_{\text{ne}}}_{\text{中性子電子散乱}} + \underbrace{b_5(H)}_{\textbf{未知相互作用項}}\right]}^{\text{Structure Form Factor } F_{\text{H}}}$$

H; 運動量移行

Yukawa型のポテンシャルを想定する

$$V = -G\frac{m_1 m_2}{r}\left[1 + \alpha\exp(-r/\lambda)\right]$$

$$b_5(H) = -\alpha\left(\frac{2m_n^2 MG}{\hbar^2}\right)\frac{\lambda_5^2}{1+(H\lambda_5)^2}$$

H; Reciprocal lattice vector
Z; Atomic Number
α; coupling constant
m_n; neutron mass
M; atomic mass
G; gravity constant
λ; effective range

V. V. Nesvizhevsky et. al., 2008

動力学的回折を用いた探索

$$v_H = A\frac{4\pi}{V_{\text{cell}}}\overbrace{\underbrace{e^{W(H)}}_{\text{温度因子}}\left[\underbrace{b_N}_{\text{核散乱}} + Z(1-\underbrace{f(H)}_{\text{形状因子}})\underbrace{b_{\text{ne}}}_{\text{中性子電子散乱}} + \underbrace{b_5(H)}_{\text{未知相互作用項}}\right]}^{\text{Structure Form Factor } F_{\mathrm{H}}}$$

H; 運動量移行

中性子電子散乱長の実験値

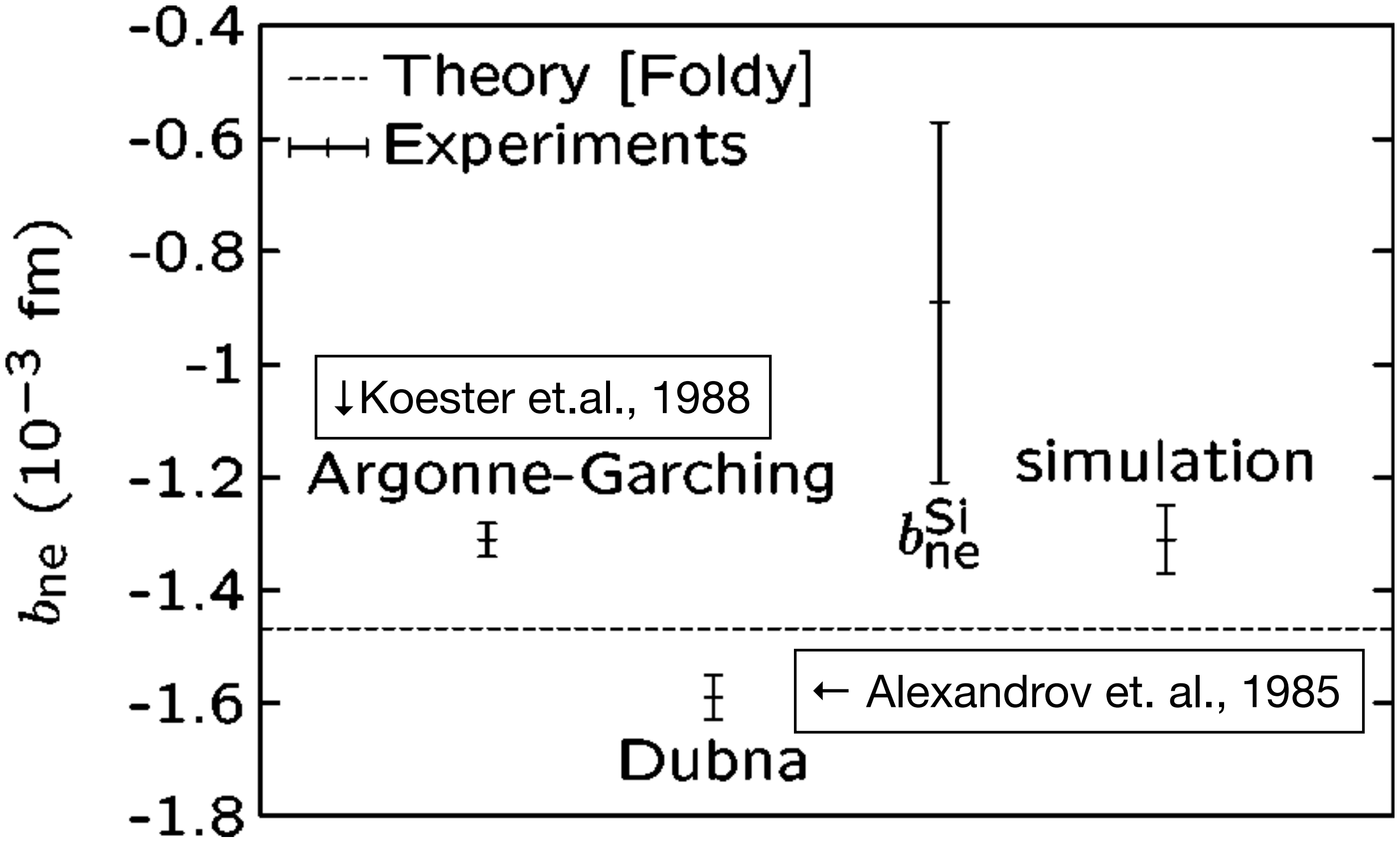
→ Argonne-Garching実験と

Dubna実験間で3σの乖離

これまでの実験手法と異なる

結晶回折を用いてこの乖離問題

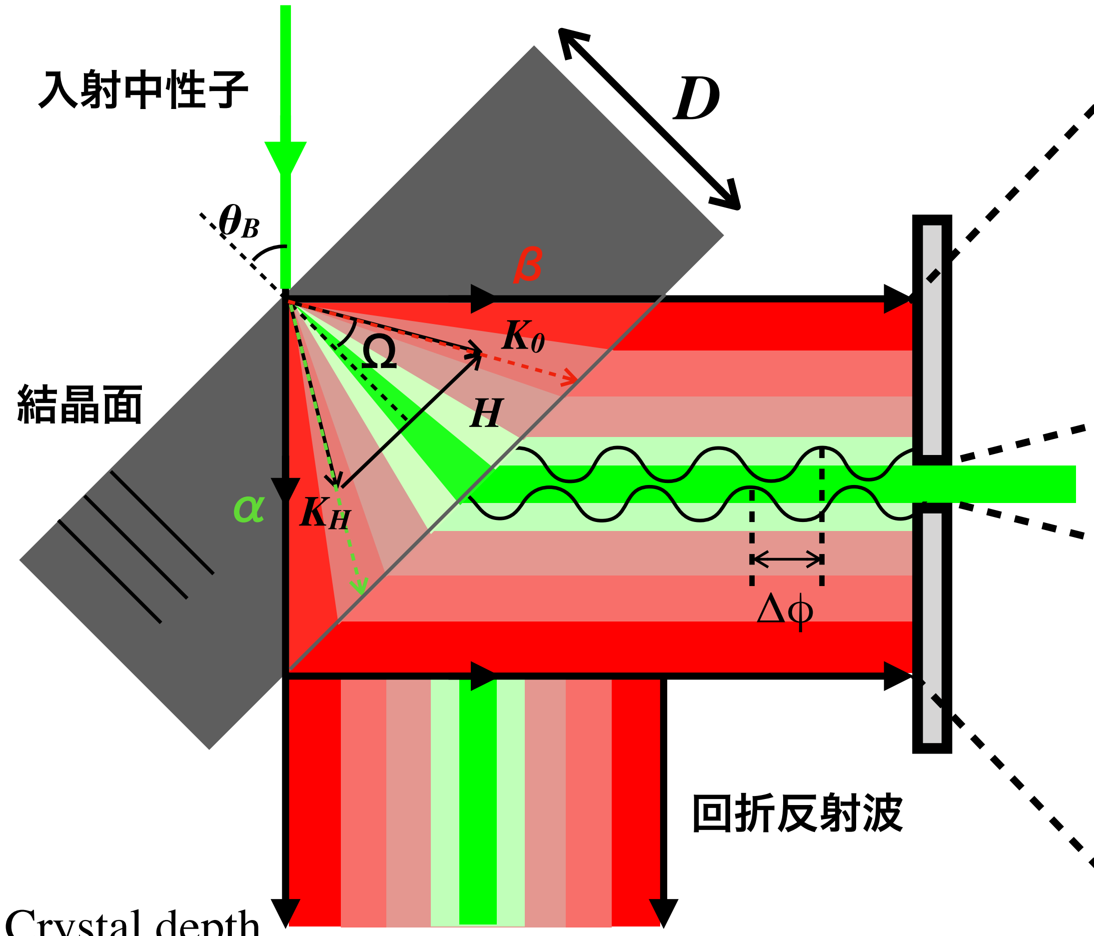
へアプローチが可能

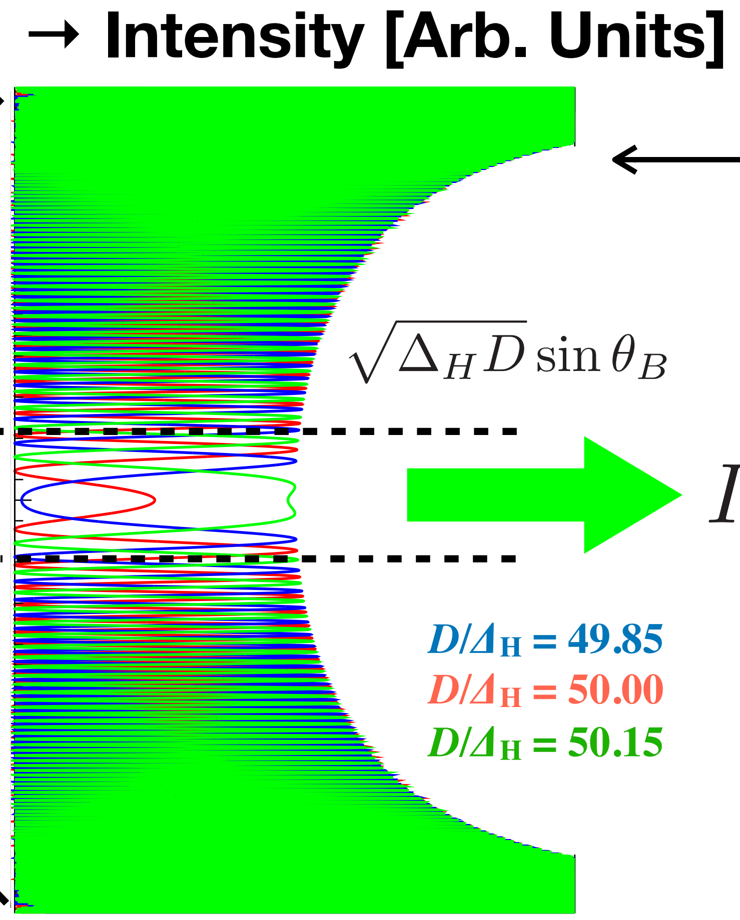


by Sparenberg et. al., 2002

動力学的回折を用いた探索

回折波の強度分布はその結晶厚さ(D), **結晶内ポテンシャル(v_H)**に依存





← ペンデル干渉縞

$$I \propto \cos\left(\frac{v_H D}{H\tan\theta_B}\right)$$

結晶内ポテンシャル

$$v_H = \frac{4\pi}{V_{\text{cell}}} F_H$$

$$F_H = e^{W(H)}\left[b_N + Z(1 - f(H))b_{\text{ne}} + b_5(H)\right]$$

温度因子

核散乱

形状因子

中性子電子散乱

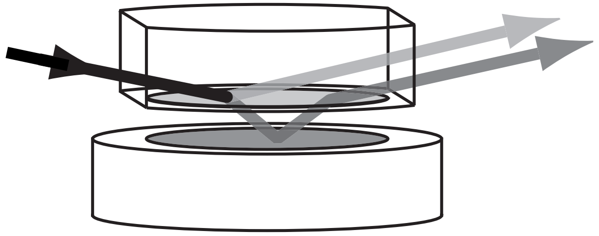
未知相互作用項

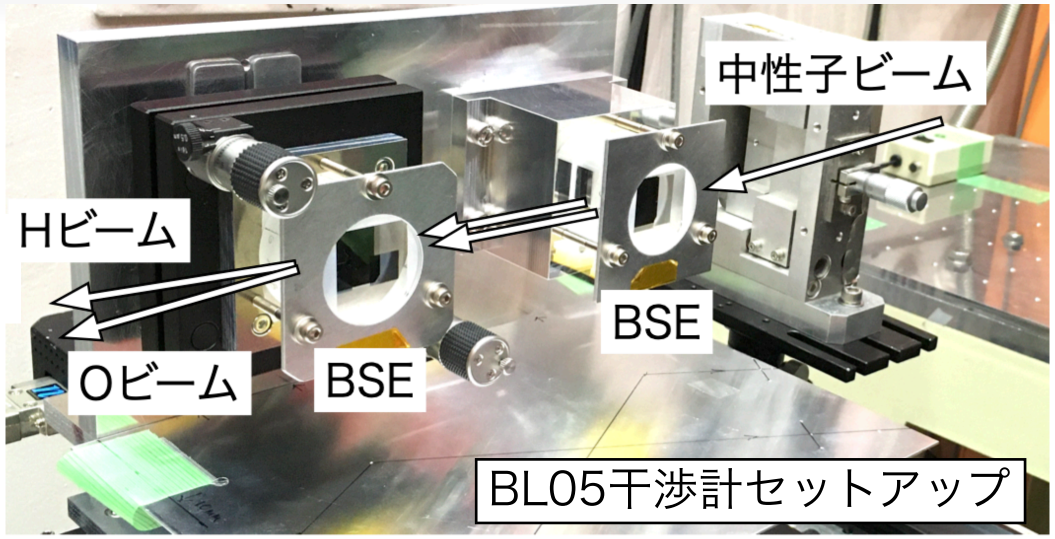
D; Crystal depth
θ_B; Bragg angle
k_0; Wave vector
H; Reciprocal lattice vector
Z; Atomic Number
a; unit cell volume
A; Constant value of crystal

$$\Delta\phi = 2\pi\frac{D}{\Delta_H} \qquad \vec{H} = \frac{2\pi}{a}\vec{\ell}, \quad \ell_i \in \mathbb{Z}$$

多層膜パルス中性子干渉計

ビームスプリッティングエタロン
で経路を分割・重ね合わせ





Time of flight 方向に干渉縞

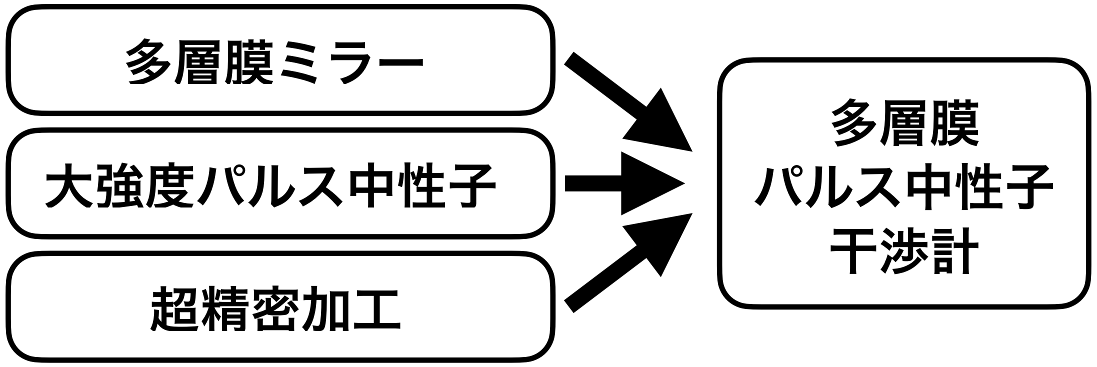
$$\Delta\phi = \frac{2\pi m_{\rm n}\lambda_{\rm n}L}{h^2}\Delta V$$

例えば **物質の中性子散乱長** を測定する場合

位相変化 $\Delta\phi = (n-1)k_{\rm n}d = Nbd\lambda_{\rm n}$

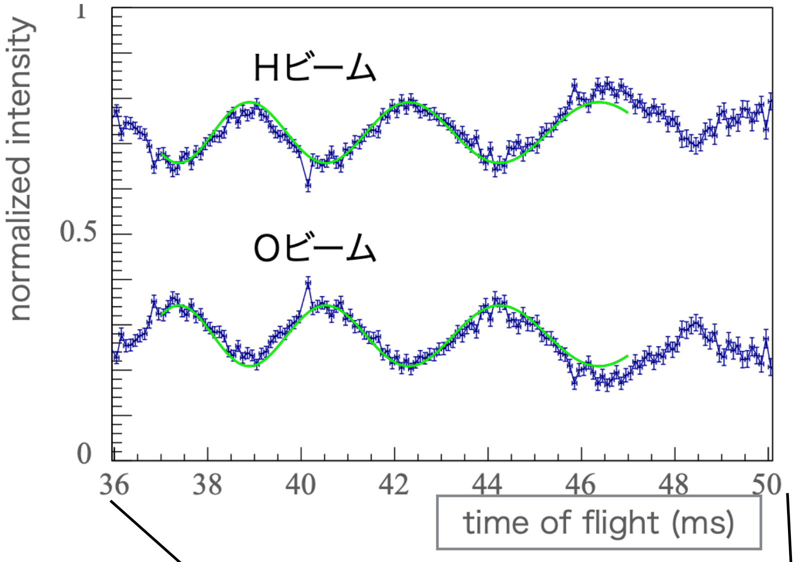
縞の周期 $T = \dfrac{2\pi}{Nbd}$

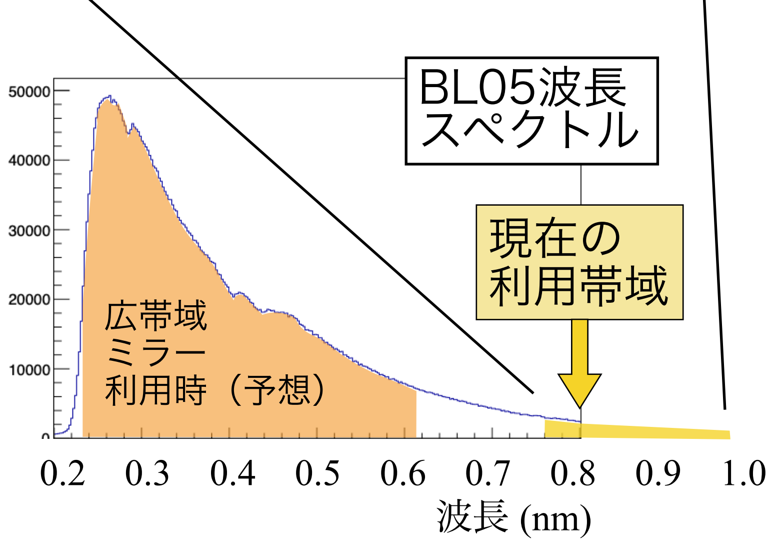
周期の変化を見れば
散乱長が求まる



多層膜ミラー
大強度パルス中性子
超精密加工

多層膜
パルス中性子
干渉計





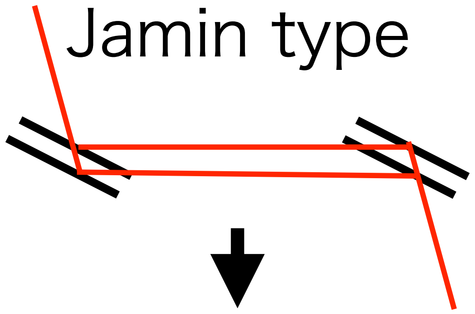
Neutrons for General Relativity

$$\begin{aligned}\mathcal{H} &= \frac{\boldsymbol{p}}{2m_n} + \underline{m\phi} + \boldsymbol{\Omega}\cdot(\boldsymbol{L}+\boldsymbol{S}) \\ &+ \frac{1}{c^2}\left(\underline{\frac{4GMR^2}{5r^3}\boldsymbol{\Omega}\cdot(\boldsymbol{L}+\boldsymbol{S})} - \frac{\boldsymbol{p}^4}{8m^3} + \frac{m\phi^2}{2} + \frac{3\boldsymbol{p}\cdot\phi\boldsymbol{p}}{2m}\right. \\ &+ \left.\frac{3GM}{2mr^3}\boldsymbol{L}\cdot\boldsymbol{S} + \frac{6GMR^3}{5r^5}\boldsymbol{S}\cdot[r\times(r\times\Omega)]\right)\end{aligned}$$

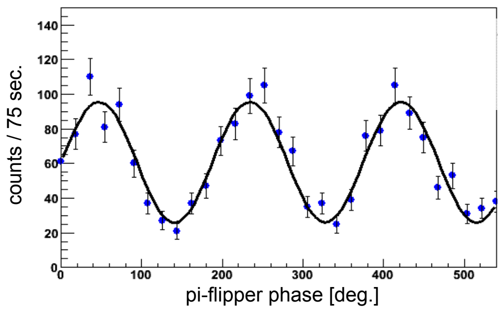
	COW	Lense-Thiring
	$m\phi$	$4GMR^2\boldsymbol{\Omega}\cdot(\boldsymbol{L}+\boldsymbol{S})/5r^3c^2$
$\lambda\sim 0.1\mathrm{nm},\ A\sim 1\mathrm{cm}\times 1\mathrm{cm}$	5	10^{-10}
$\lambda\sim 1.0\mathrm{nm},\ A\sim 1\mathrm{m}\times 1\mathrm{m}$	10^5	10^{-6}

1m², long-wavelength interferometer can search the effect of General Relativity.

Continuous development is important.



Jamin type

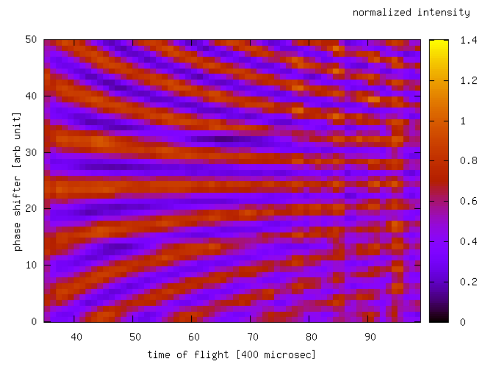


↓

pulsed neutron

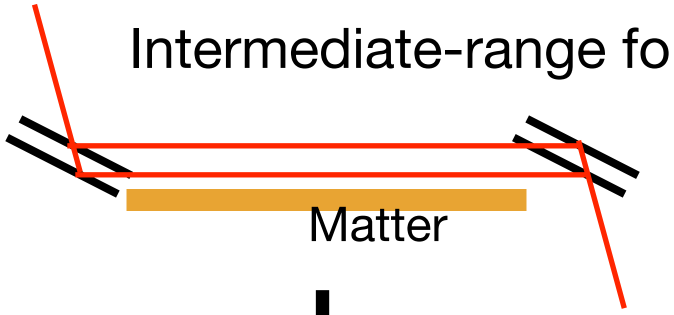
COW exp.

↓



Long

Intermediate-range force

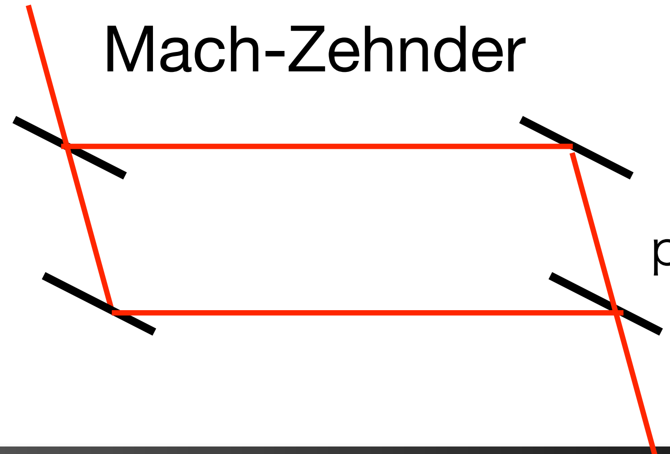


λ~100μm

↓

Large area

Mach-Zehnder



post-Newtonian

まとめ

中性子崩壊寿命はビッグバン元素合成、CKM行列ユニタリティの検証、dark decay 探索に感度がある。

UCN貯蔵法、ビーム法など方法で値が異なっており、相互検証が必要。

J-PARCでも最初の結果。アップグレード進行中。

崩壊角相関項も新物理に感度。

複合核反応ではCP対称性の破れが増幅されて観測される可能性がある。
複合核の取り扱いを実験的・理論的に確かめる研究が進行中。

中性子反中性子振動は、バリオン数の破れ探索に感度がある。

中性子は**重力の研究や、ダークエネルギーなど未知の相互作用の探索**にも利用できる。