Neutron Experiments at J-PARC

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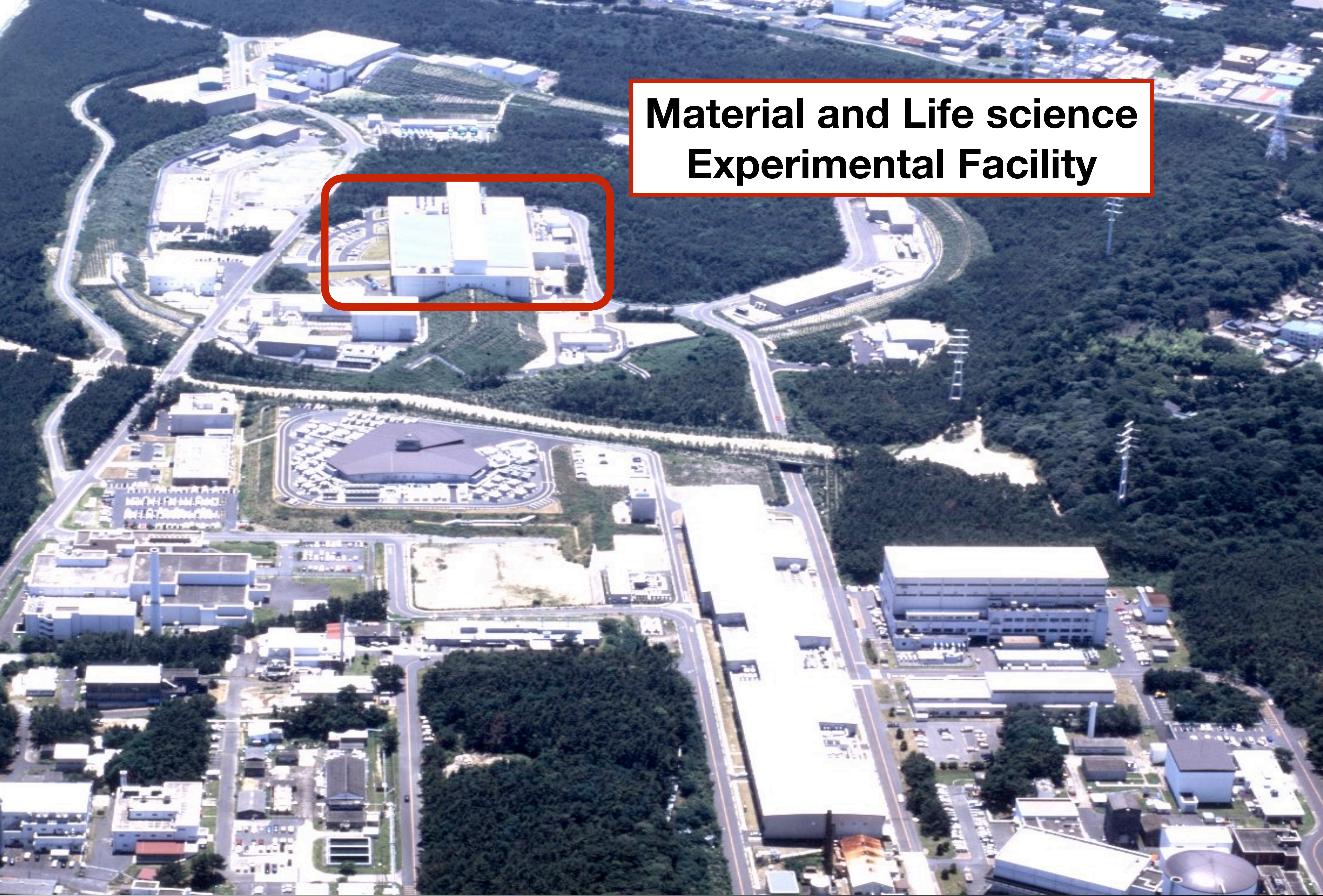
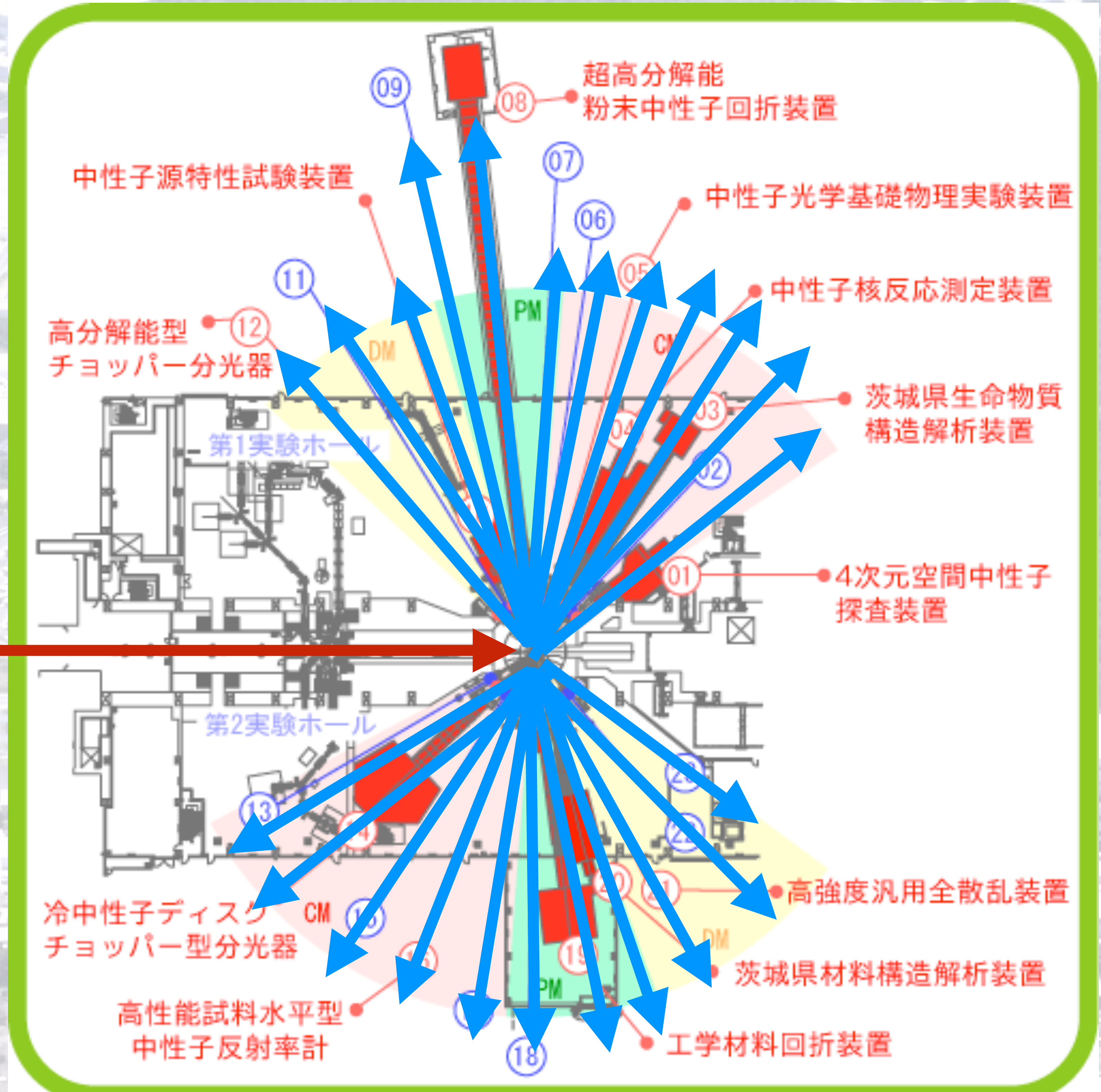

Material and Life science
Experimental Facility

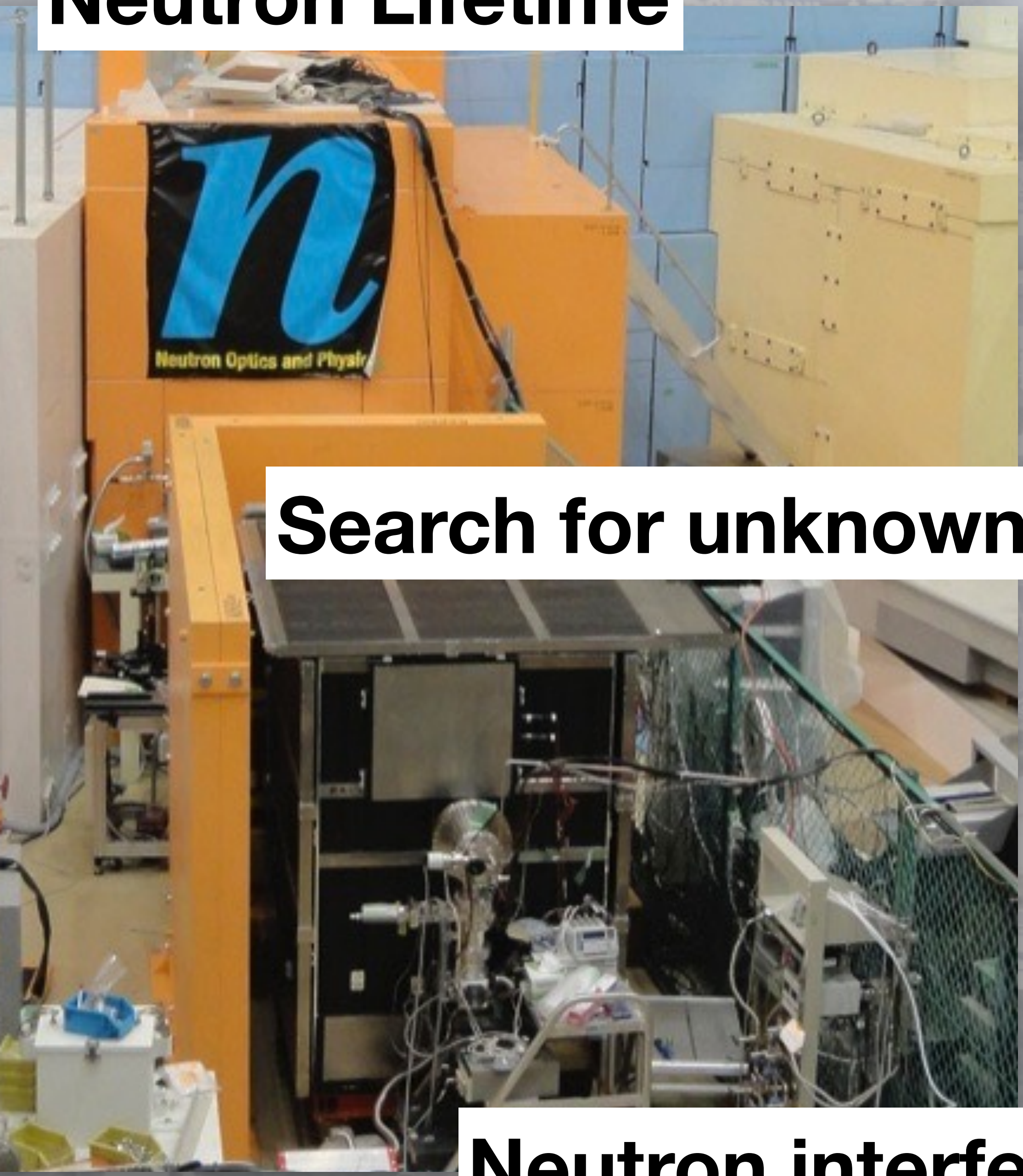


超高分解能
粉末中性子回折装置
中性子源特性試験装置
中性子光学基礎物理実験装置
中性子核反応測定装置
高分解能型
チョッパー分光器
茨城県生命物質
構造解析装置
第1実験ホール
4次元空間中性子
探査装置
第2実験ホール
高強度汎用全散乱装置
冷中性子ディスク
チョッパー型分光器
茨城県材料構造解析装置
高性能試料水平型
中性子反射率計
工学材料回折装置
PM
DM
CM
01
02
06
07
08
09
11
12
13
18

Neutron Lifetime

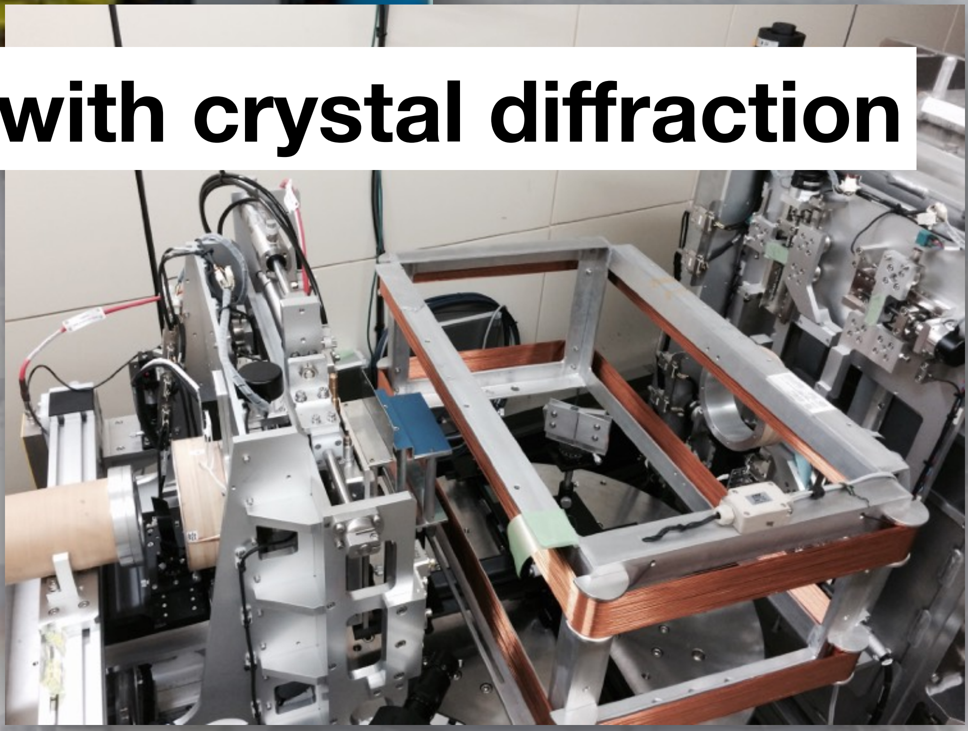
Search for unknown force

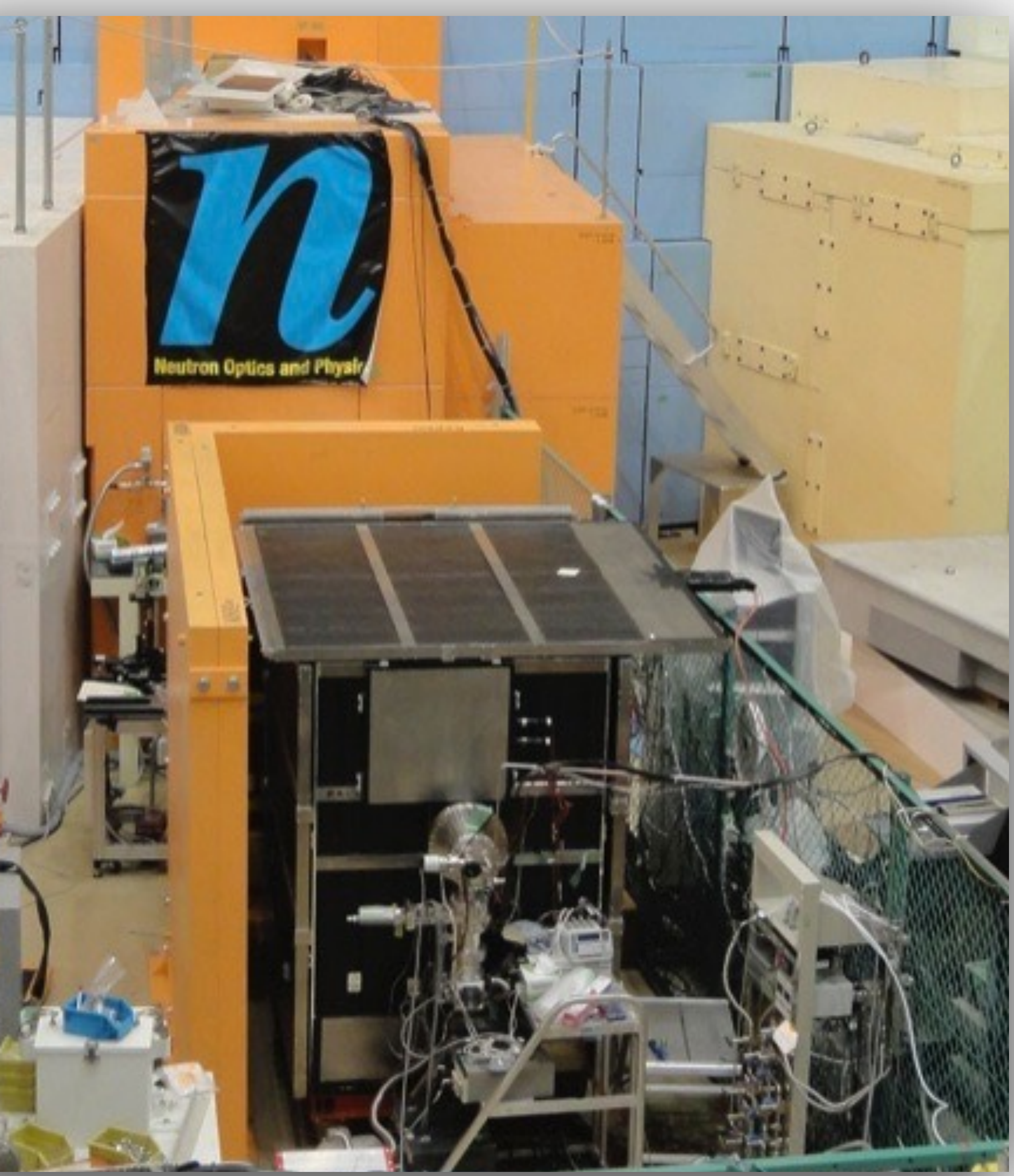
Neutron interferometer



T-violation in compound nuclei

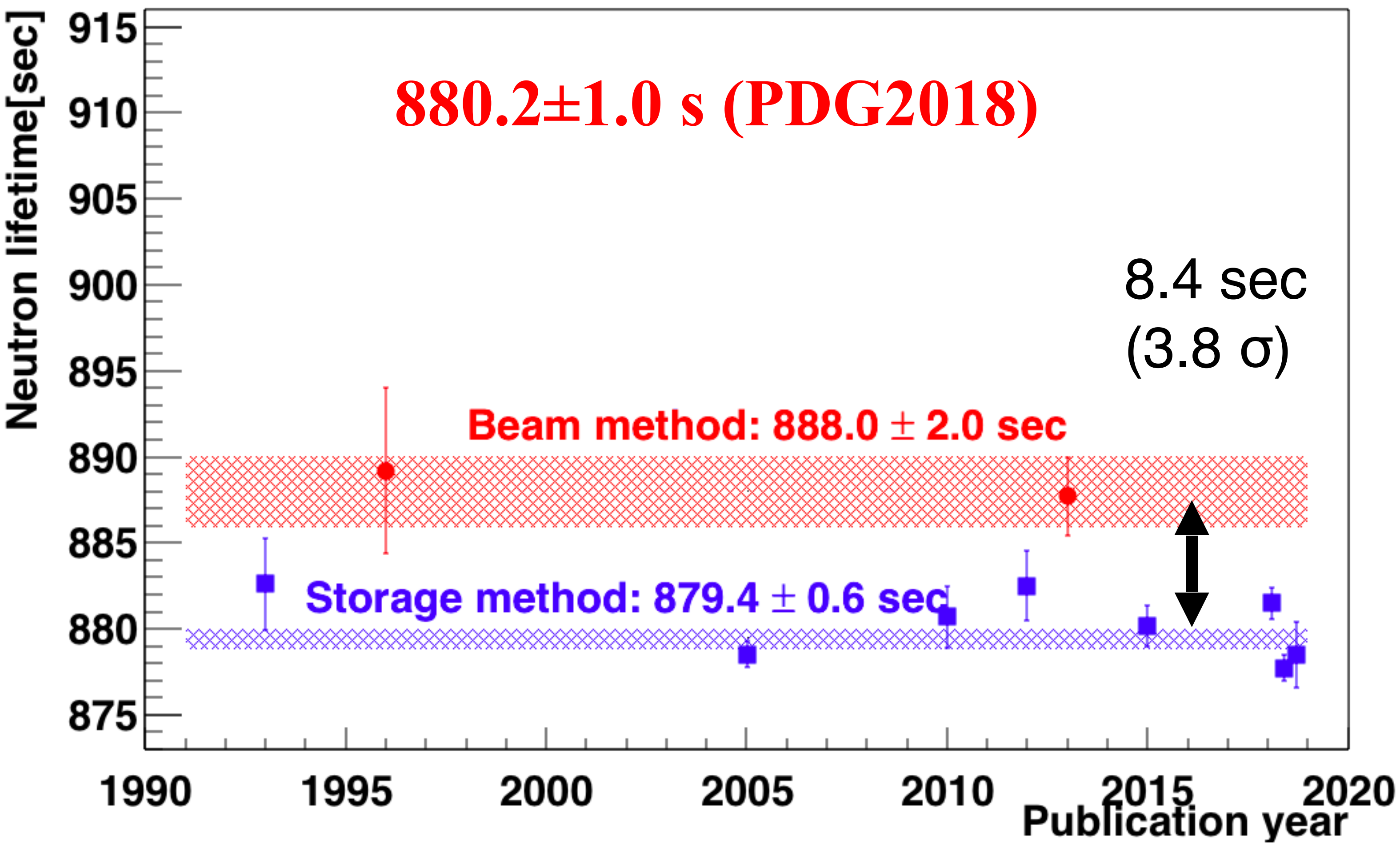
EDM with crystal diffraction

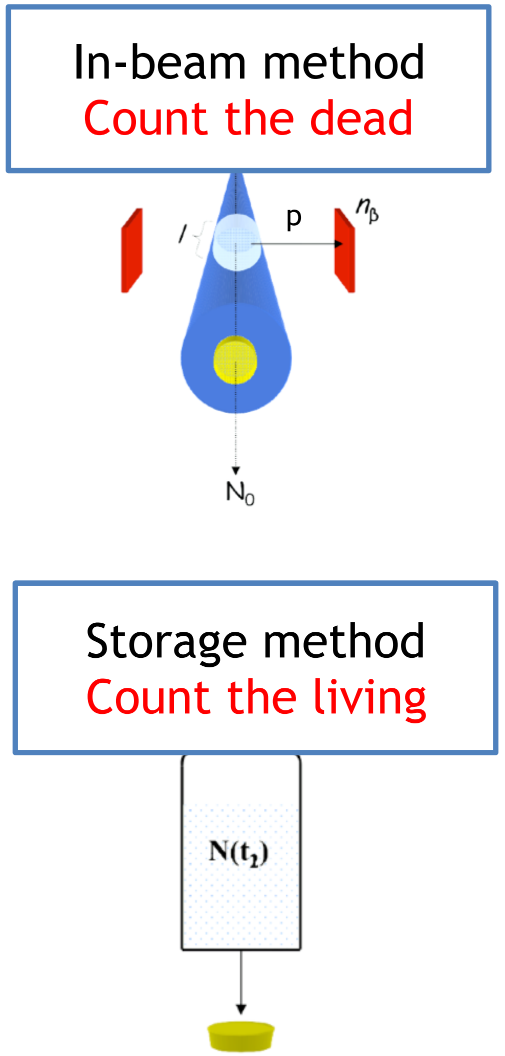




Neutron lifetime

Neutron lifetime





Neutron lifetime is an key parameter for

CKM unitarity check

Big Bang Nucleosynthesis

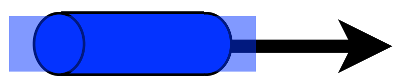
Discrepancy between methods may suggest new physics?

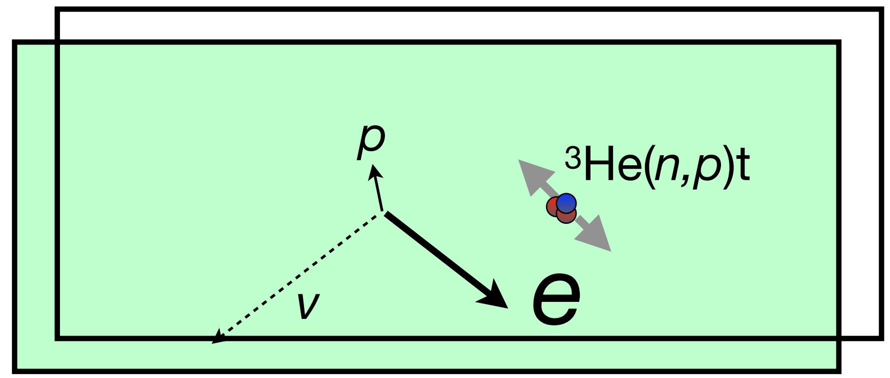
Principle of measurement in J-PARC

In-beam measurement with pulsed neutrons

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

Well-defined neutron bunch





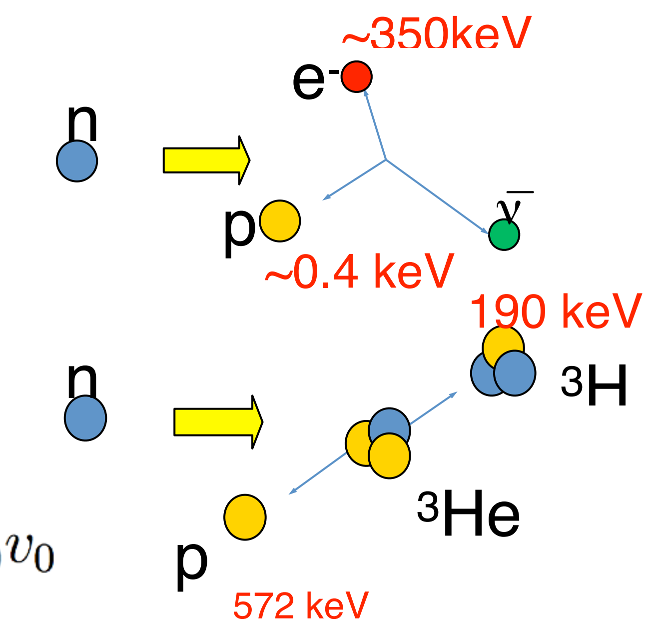
Count up only when the bunch is in TPC

incident flux is also measured in TPC with ³He capture

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

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

³He reaction $\quad S_n = \epsilon_n N \rho\sigma L$

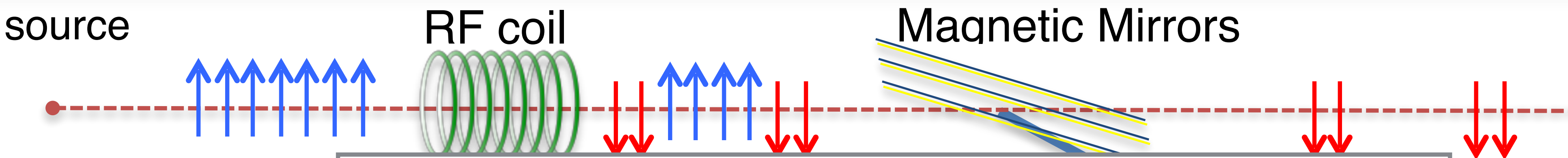


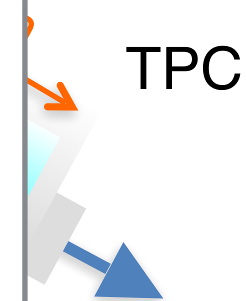
τ_n	: lifetime	ε_n	: efficiency for ³He reaction
v	: velocity	ρ	: density of ³He
ε_e	: efficiency for electrons	σ	: absorption cross section of ³He $\quad \sigma v = \sigma_0 v_0$

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

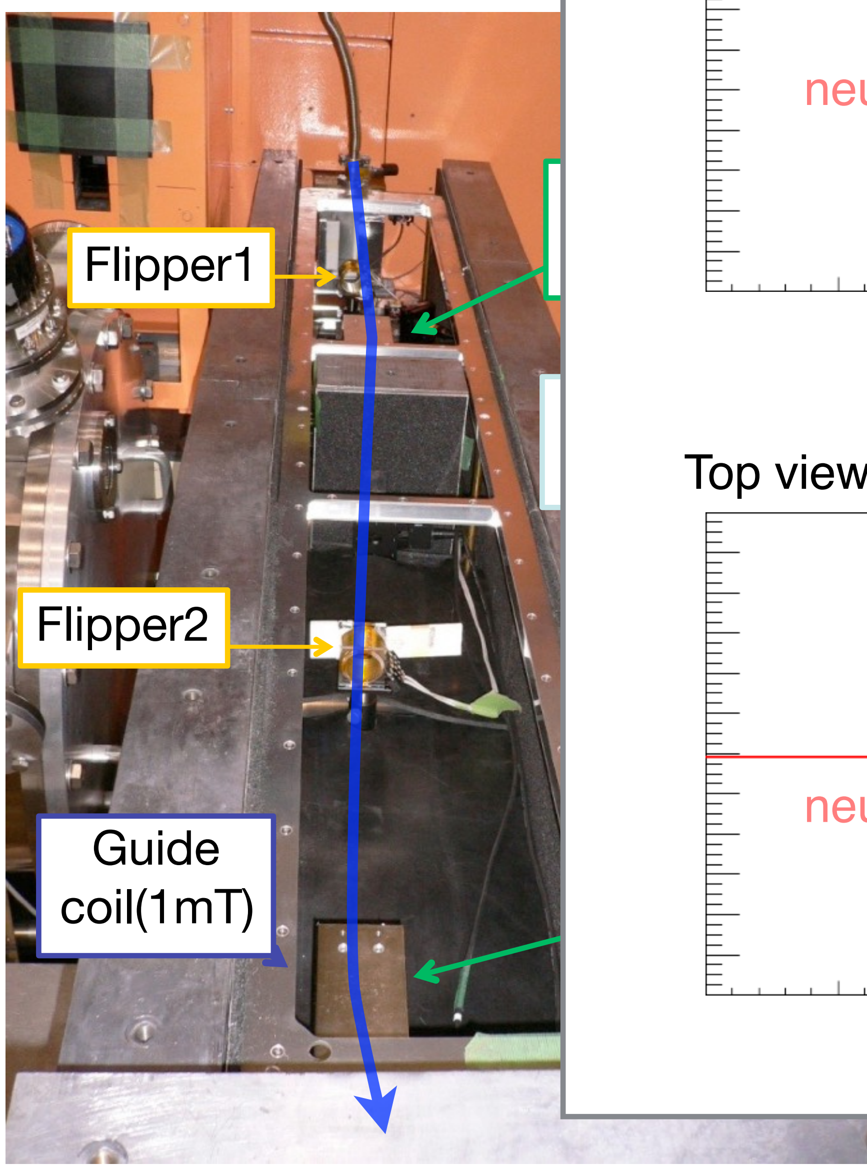
No External Flux monitor, No wall loss

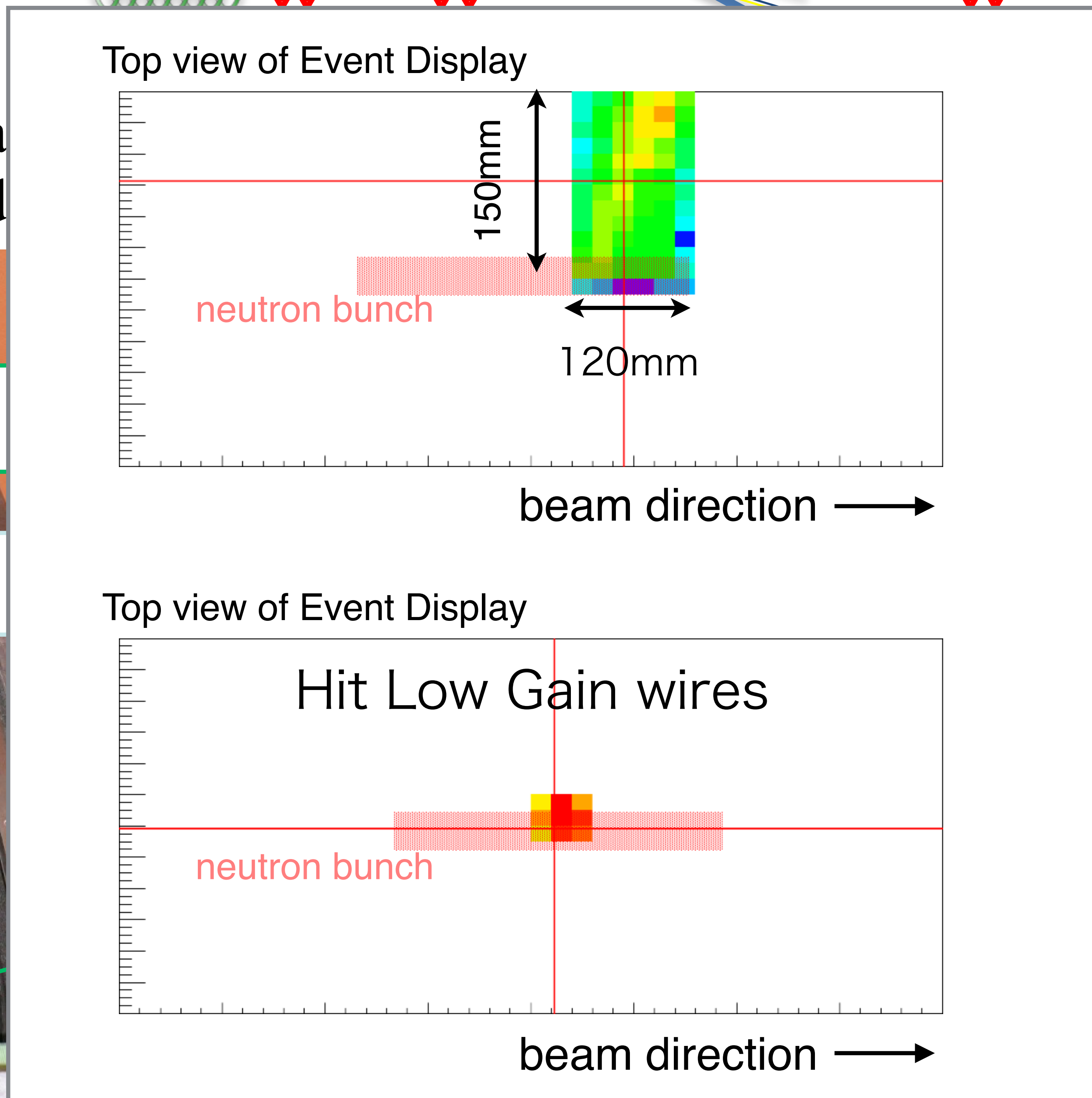
Spin Flip Chopper and Time Projection Chamber

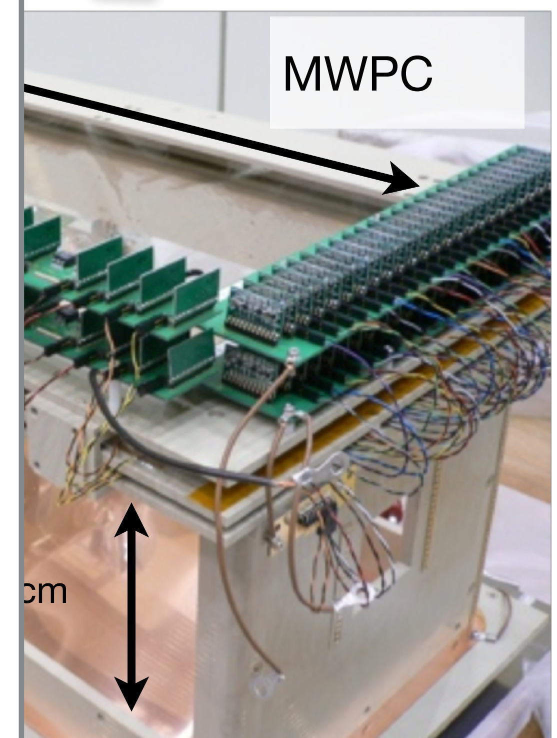




Neutron bunches a
spin flipper accord



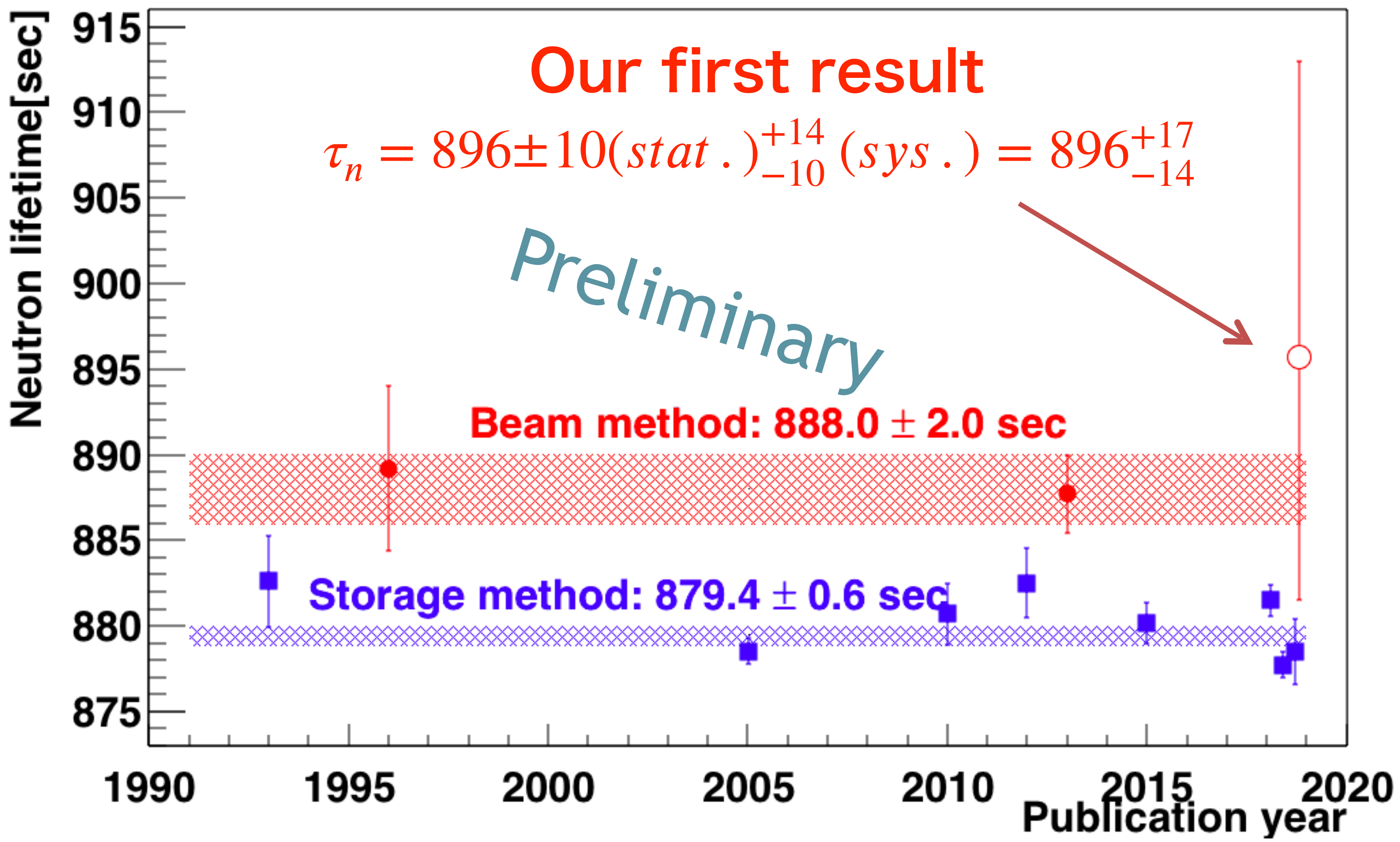




etection for
nd ^{3}He reaction
ner ^{6}Li wall
suppress BG.

S/N ~ 1:1

Neutron lifetime



K. Mishima,
Particle Physics with Neutrons at the ESS,
Stockholm, December 2018.

We have already taken data corresponding to 0.5% statistics.
Analysis is ongoing.

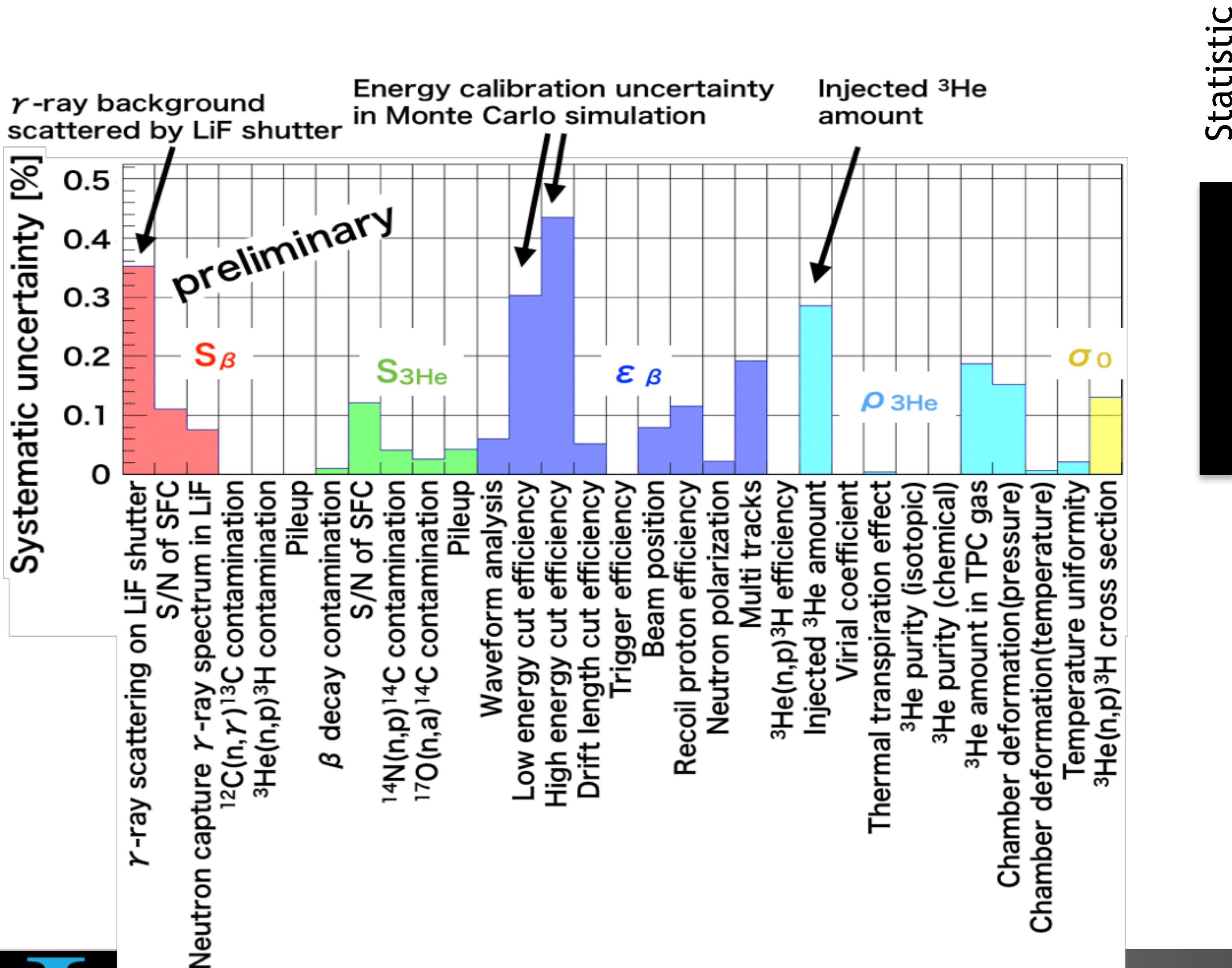
Neutron lifetime upgrade plan

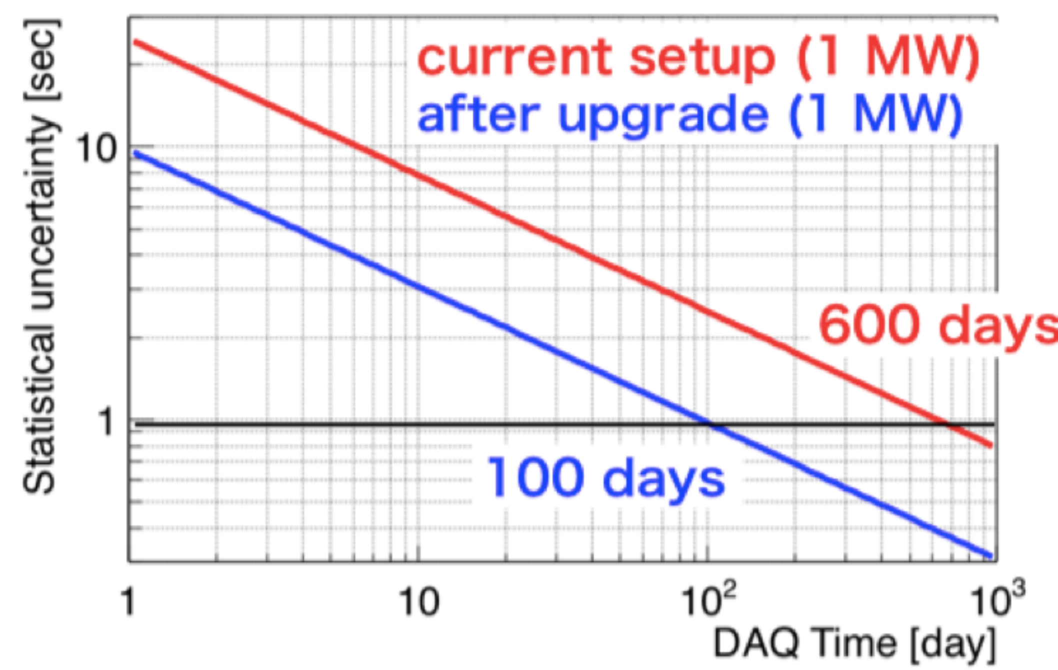
Upgrades are ongoing.

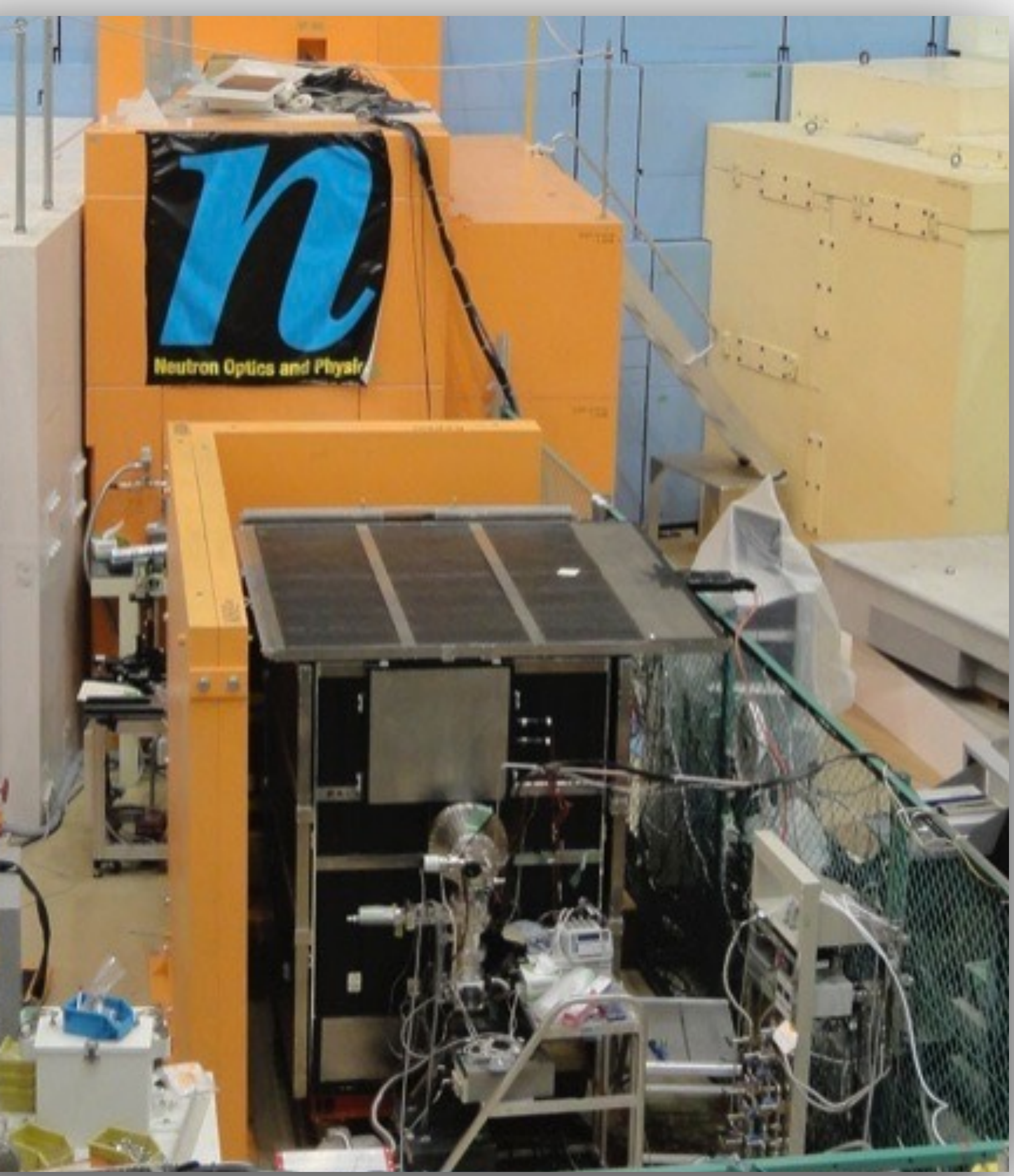
Systematic uncertainty will be smaller with more intelligent cuts.

^{3}He injection will be 0.11%.

Beam optics upgrade (enlarging SFC mirror) makes beam intensity by 5 times.







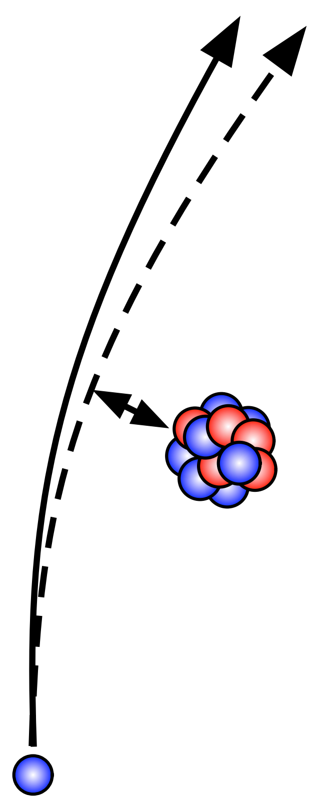
Search for unknown force

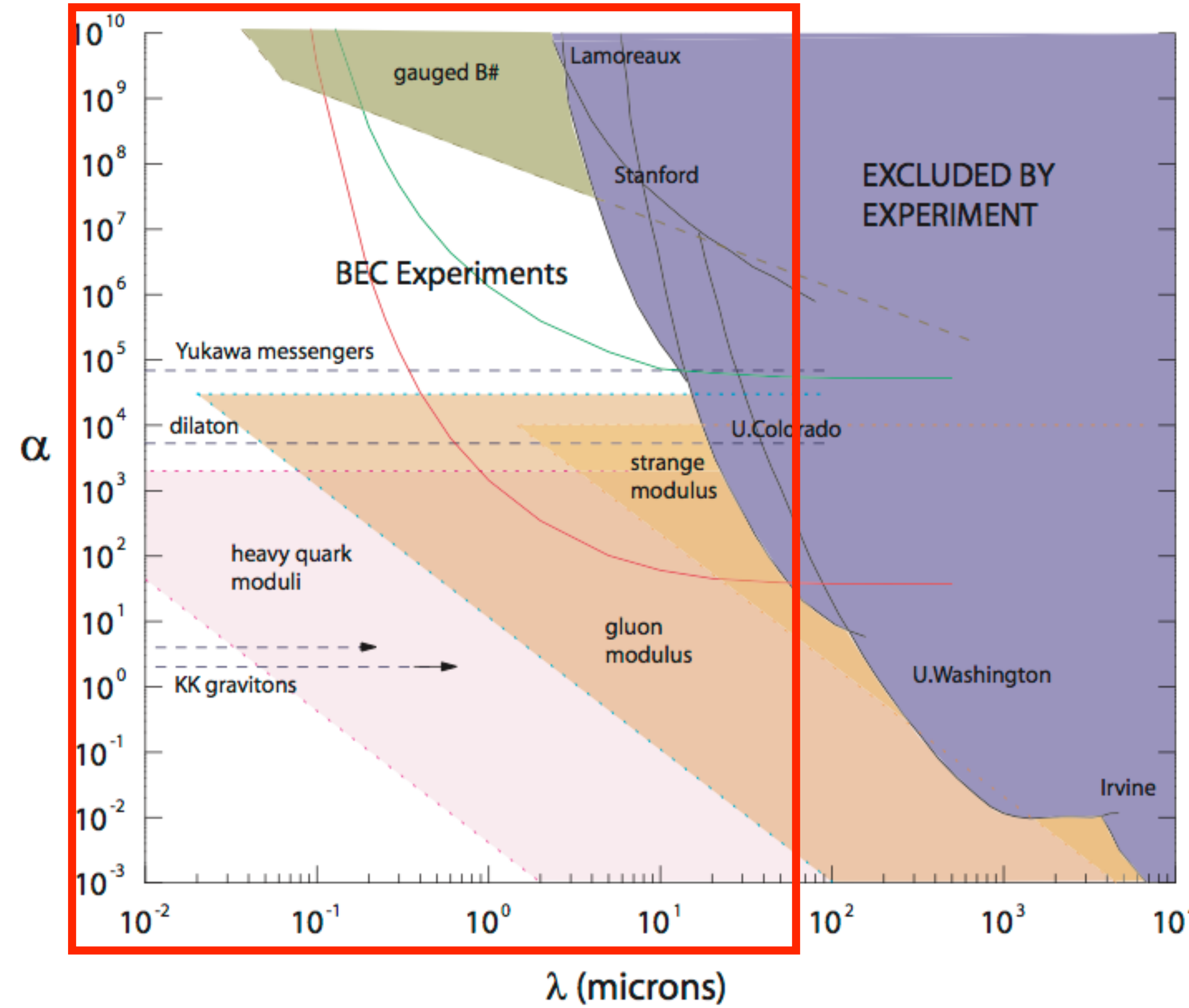
Intermediate force search by neutron scattering

non-Newtonian gravity

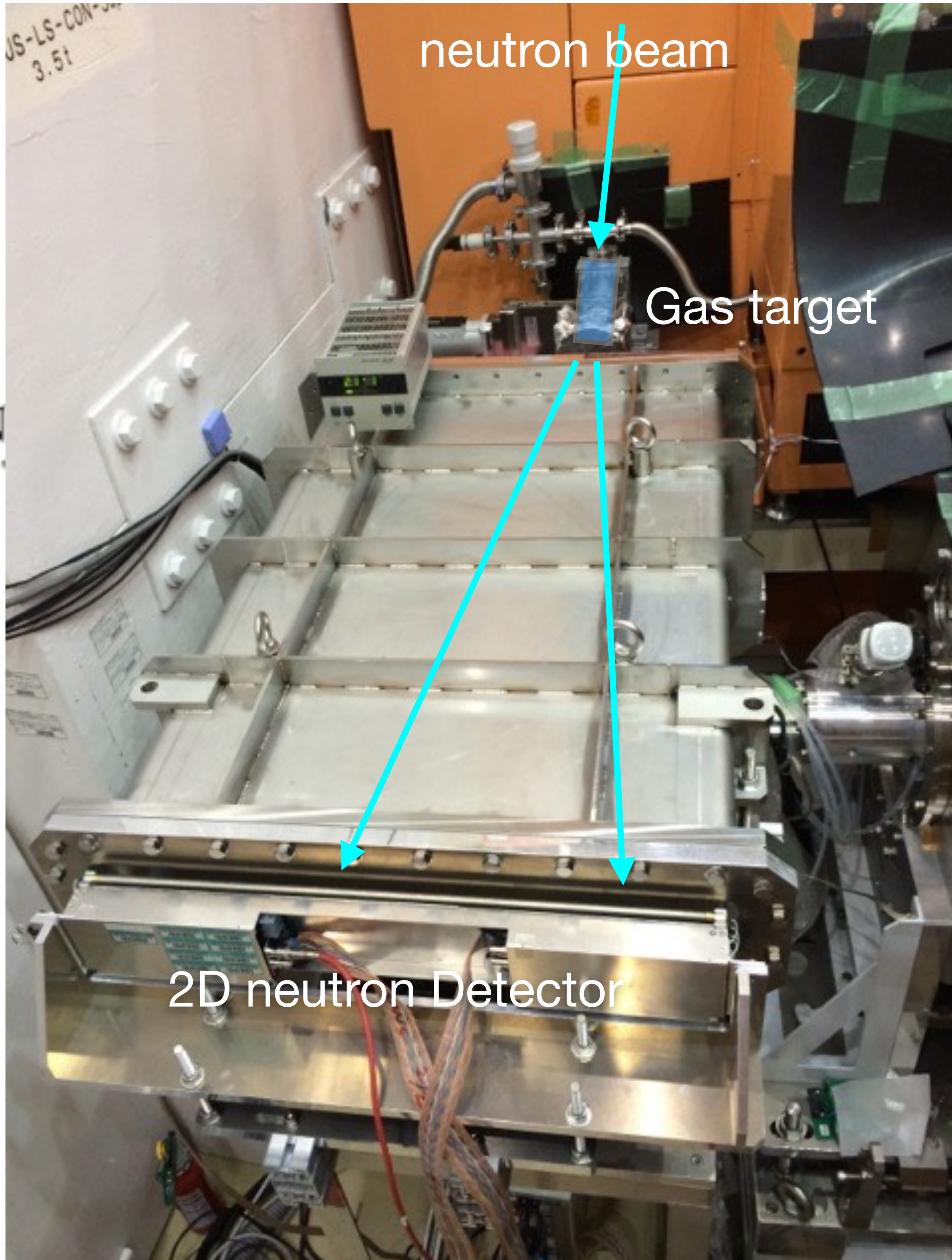
$$V(r) = -G_N \frac{m_1 m_2}{r}\left(1+\alpha \cdot e^{-\frac{r}{\lambda}}\right)$$

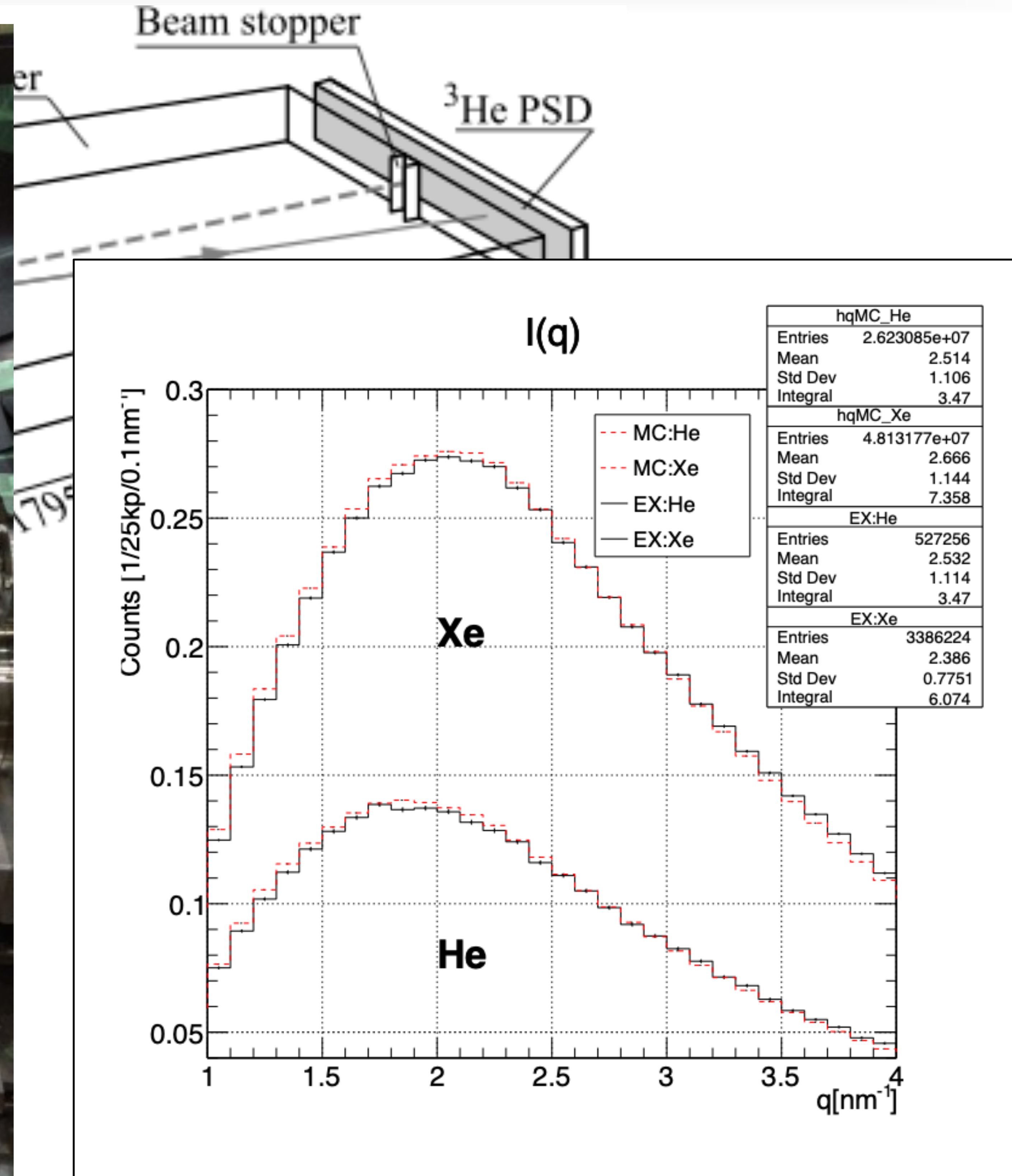
Newtonian + α in **nm** range can be searched by neutron scattering.



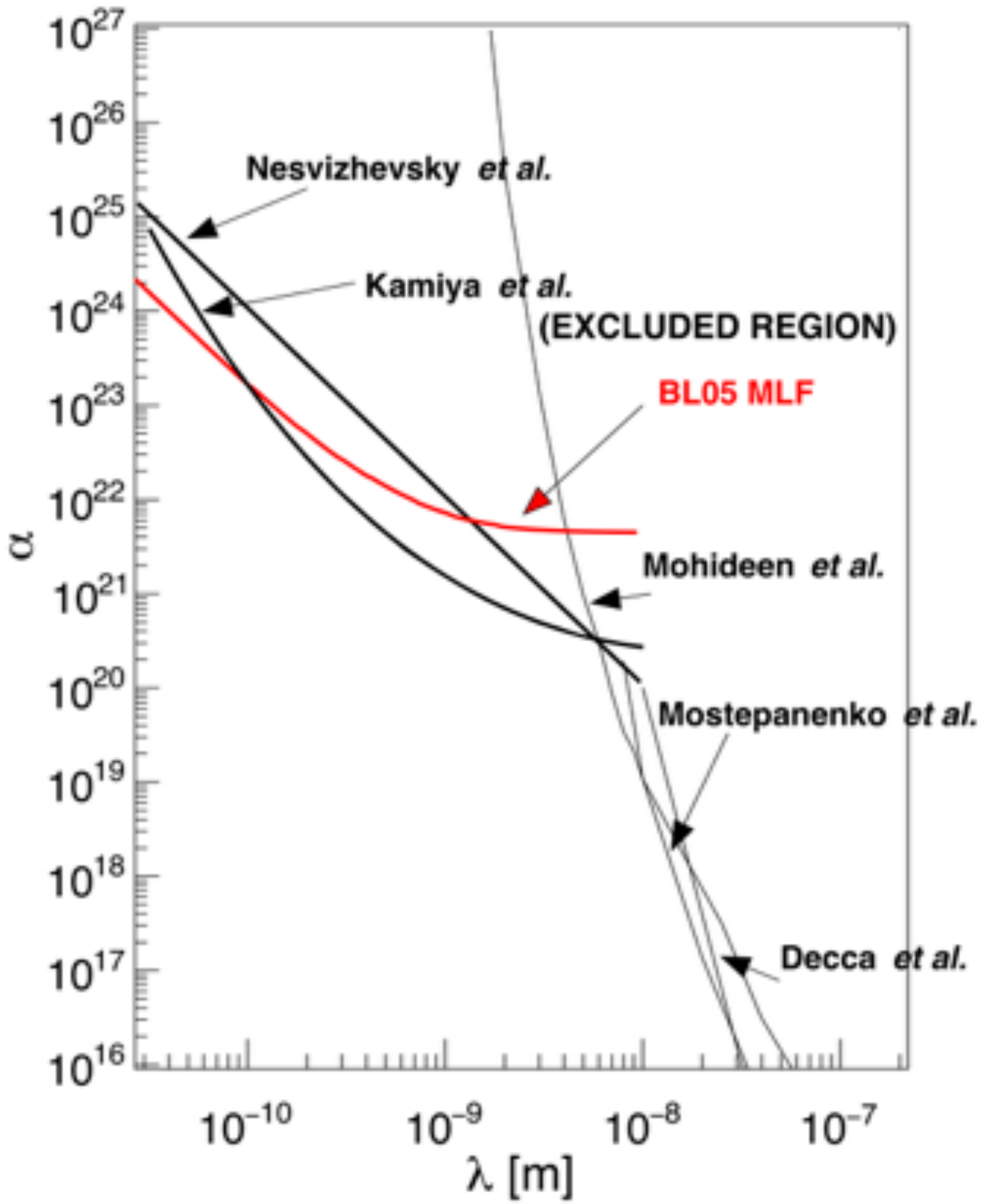


Neutron scattering apparatus





Neutron scattering result and plan



Upgrades are ongoing.

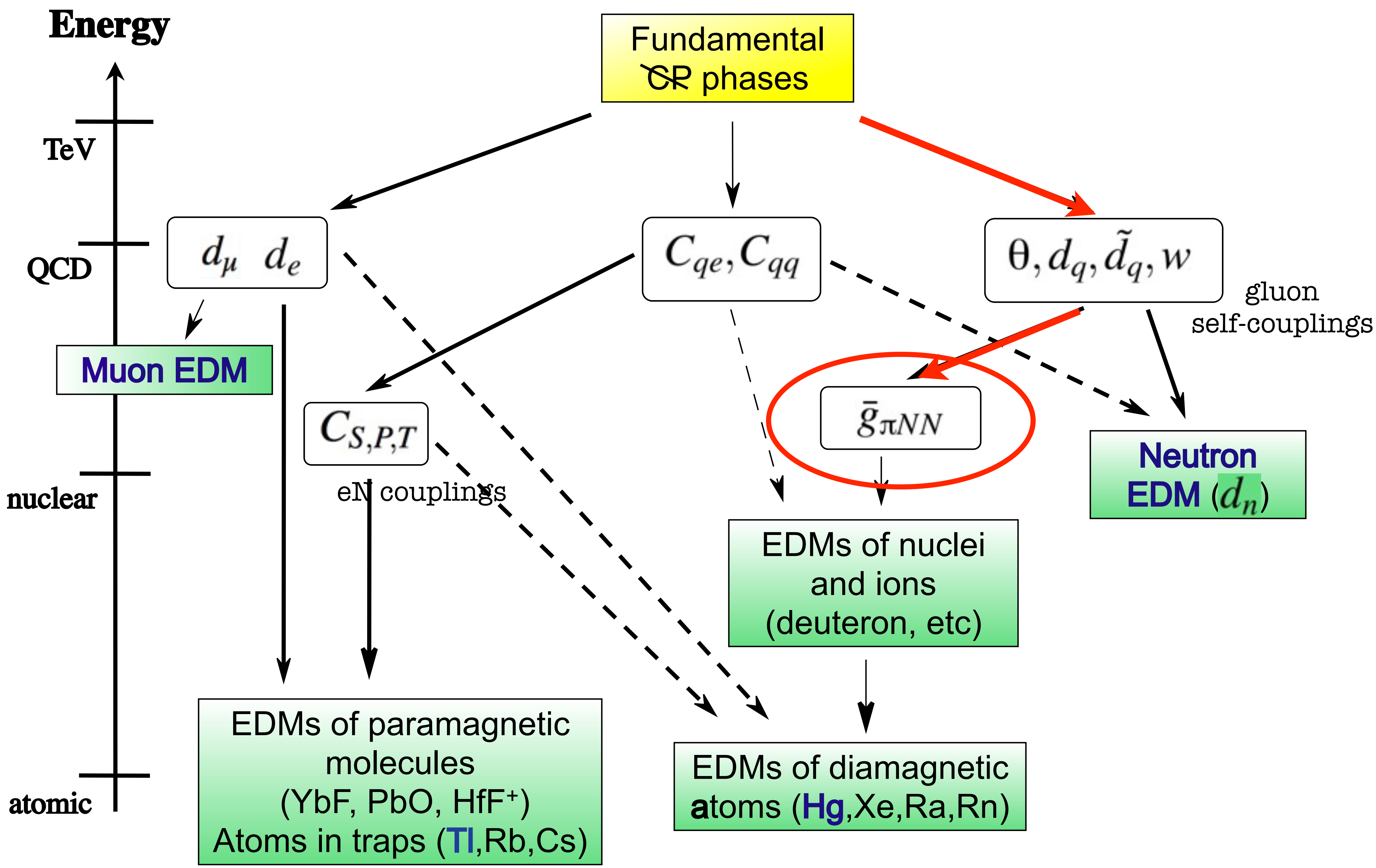
New type of target (nano particle?) will be used for more sensitivity. Other beamline with large area detector will help us for more neutrons.

Highlighted in APS

C. C. Haddock, *et al.*, Phys. Rev. D97, 062002 (2018).

T-violation in compound nuclei

Symmetry violation in compound nuclei

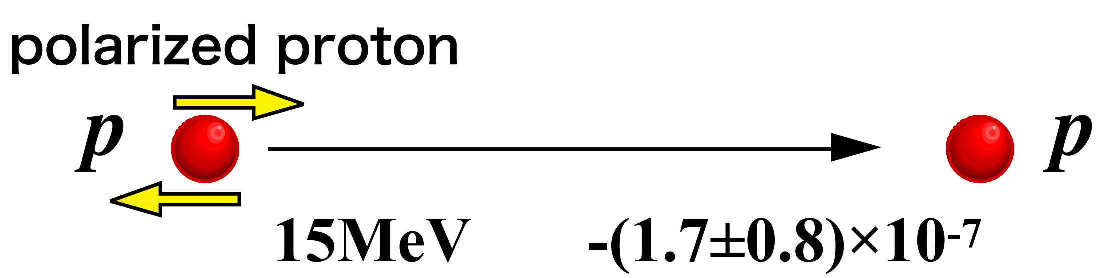


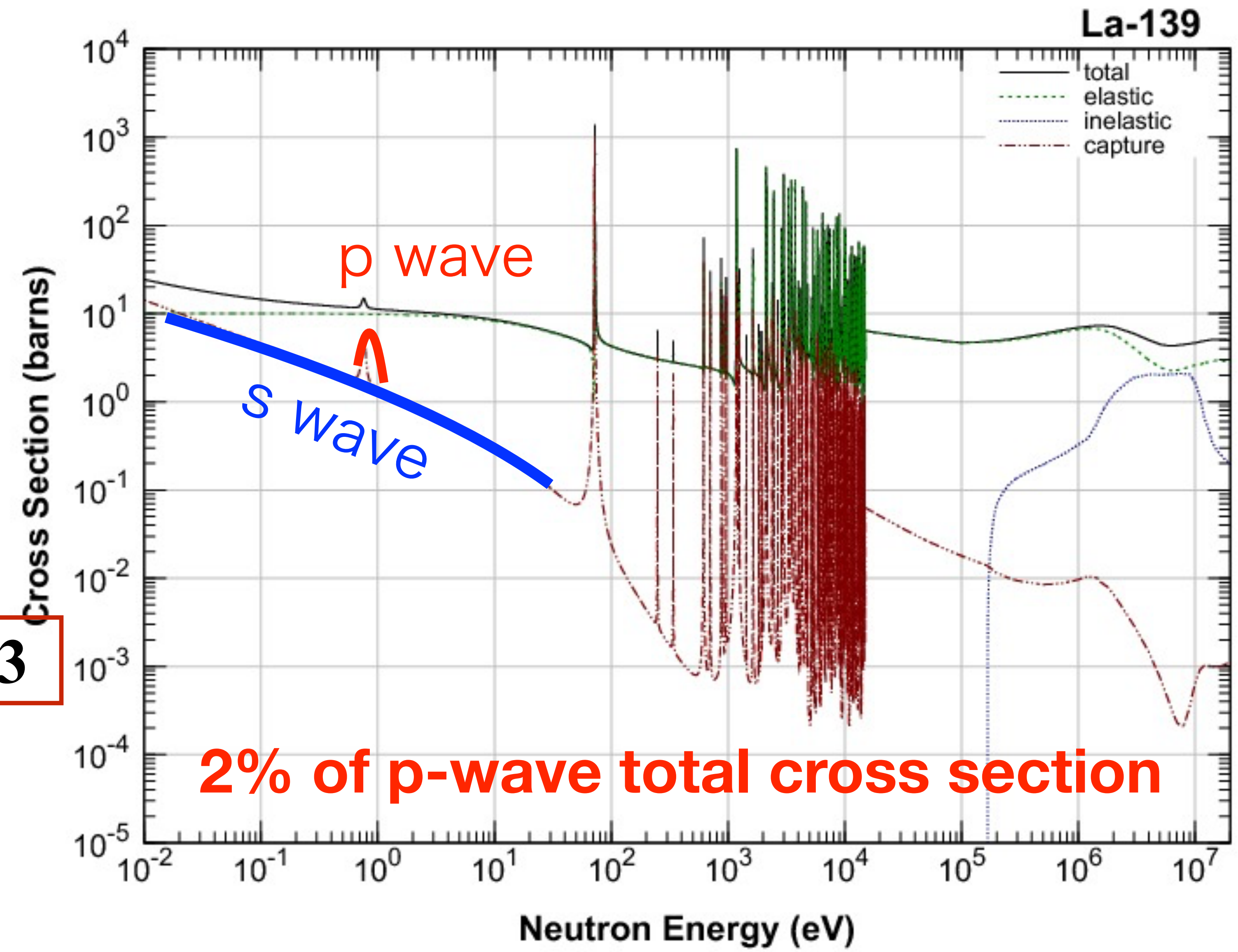
Pospelov Ritz, Ann Phys 318 (05) 119

Symmetry violation in compound nuclei

neutron capture
around p-wave resonance

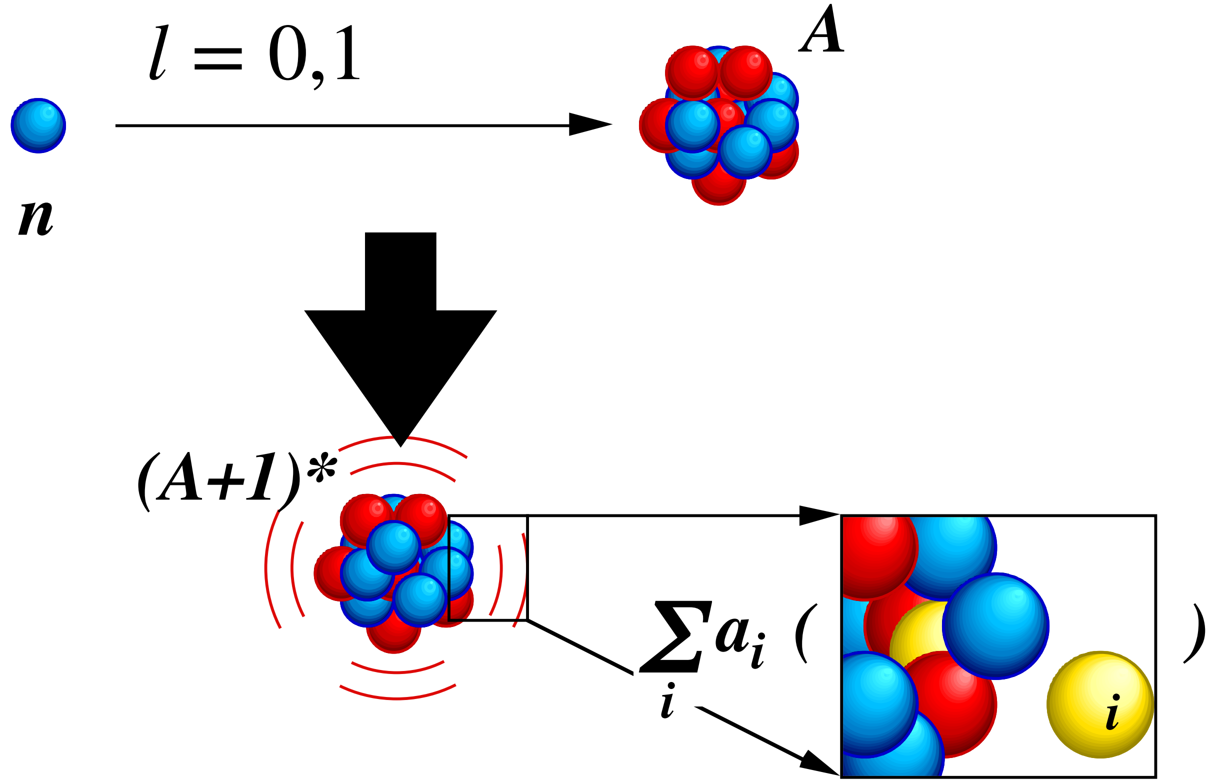
^{139}La	$E_n = 0.734$ eV	0.097±0.003





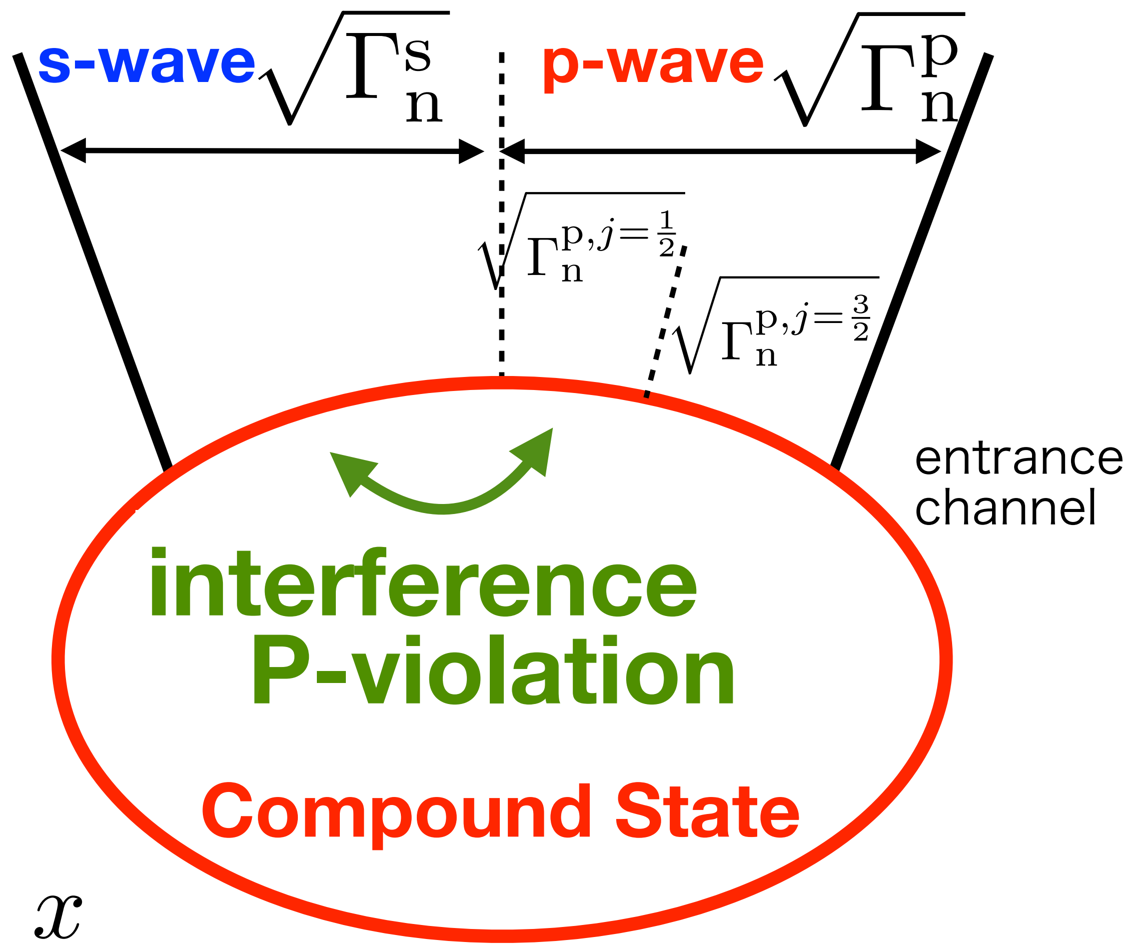
P-violation is enhanced in the interference between s-wave and p-wave of compound nuclei.

Symmetry violation in Compound nuclei



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

Resonance spin — target spin — neutron total angular momentum



$$A_L = -\frac{2W}{E_p - E_s}\sqrt{\frac{\Gamma_n^s}{\Gamma_n^p}}\underbrace{\sqrt{\frac{\Gamma_n^{p,j=\frac{1}{2}}}{\Gamma_n^p}}}_{=x}$$

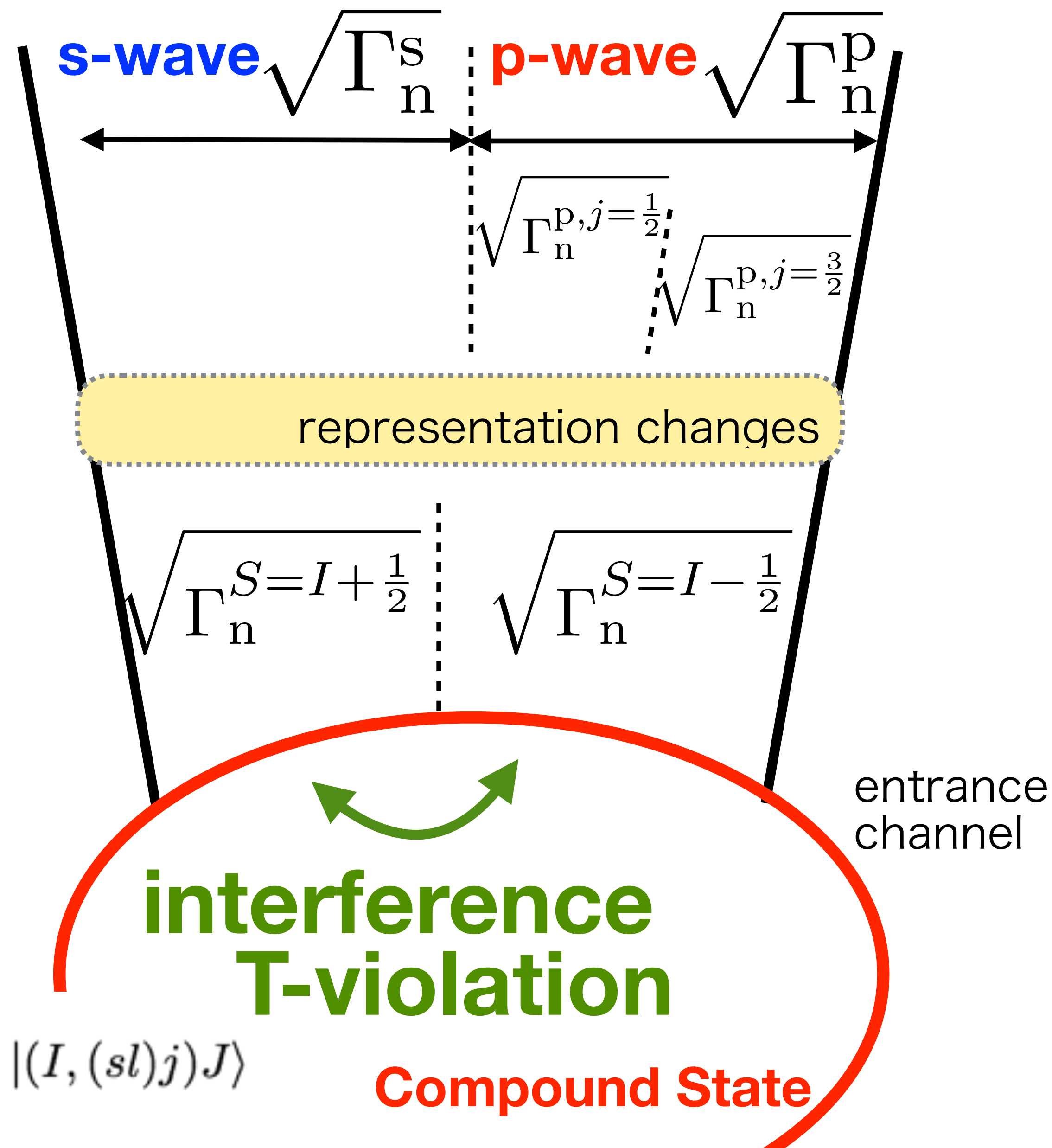
$$\left(x = \sqrt{\frac{\Gamma_n^{p,j=\frac{1}{2}}}{\Gamma_n^p}} \quad y = \sqrt{\frac{\Gamma_n^{p,j=\frac{3}{2}}}{\Gamma_n^p}} \quad x^2 + y^2 = 1 \quad \begin{array}{l} x = \cos\phi \\ y = \sin\phi \end{array} \right)$$

Unknown parameter

Symmetry violation in Compound nuclei

The interference between s-wave and p-wave results in the interference between partial waves with different channel spin.

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



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

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

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

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

Enhancement of symmetry violation

The interference between s-wave and p-wave results in the interference between partial waves with different channel spin.

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

T-violating matrix element

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

T-violation

P-violation

P-violating matrix element

Angular momentum factor

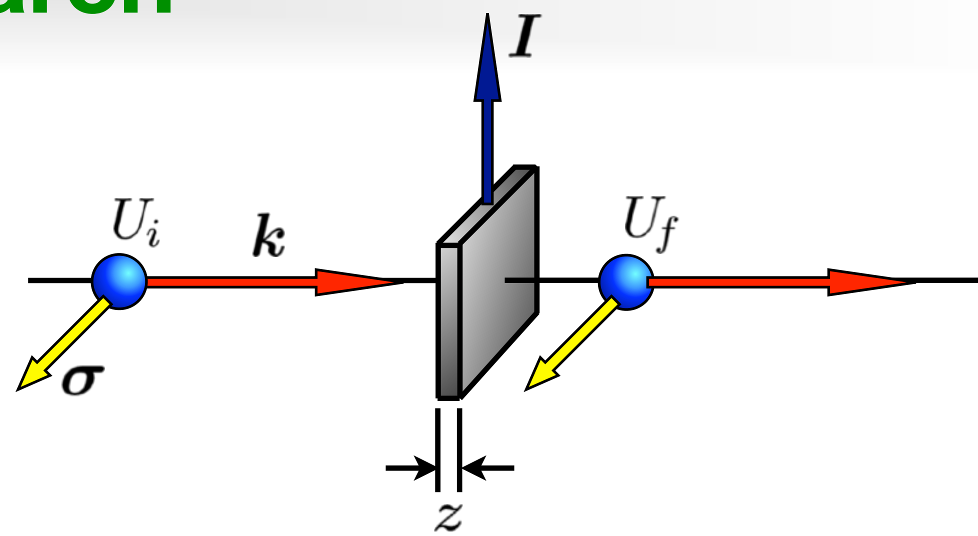
$$\kappa(J) = \begin{cases} (-1)^{2I}\left(1+\frac{1}{2}\sqrt{\frac{2I-1}{I+1}}\frac{y}{x}\right) & (J = I - \frac{1}{2}) \\ (-1)^{2I+1}\frac{I}{I+1}\left(1-\frac{1}{2}\sqrt{\frac{2I+3}{I}}\frac{y}{x}\right) & (J = I + \frac{1}{2}) \end{cases}$$

$$x = \sqrt{\frac{\Gamma_{\mathrm{n}}^{\mathrm{p},j=\frac{1}{2}}}{\Gamma_{\mathrm{n}}^{\mathrm{p}}}} \qquad y = \sqrt{\frac{\Gamma_{\mathrm{n}}^{\mathrm{p},j=\frac{3}{2}}}{\Gamma_{\mathrm{n}}^{\mathrm{p}}}} \qquad x^2 + y^2 = 1 \qquad \begin{aligned} x &= \cos\phi \\ y &= \sin\phi \end{aligned}$$

Unknown parameter

Experimental setup for T-violation search

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



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

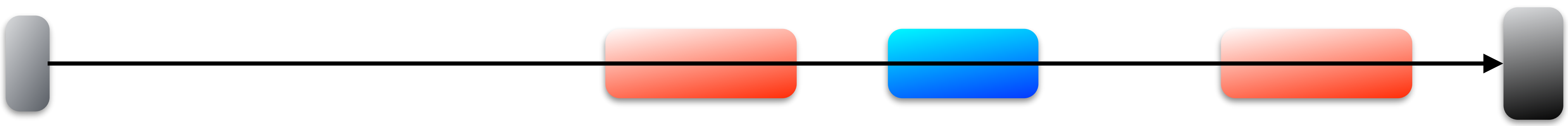
- A: Spin Independent, P-even T-even
- B: Spin Dependent, P-even T-even
- C: P-violation, P-odd T-even
- D: T-violation, P-odd T-odd

Pulsed Neutron Source

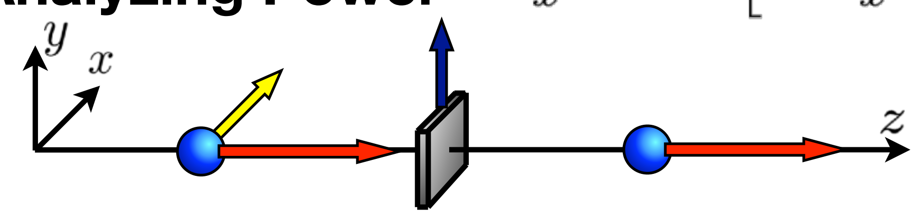
Neutron Polarizer

Polarized Target

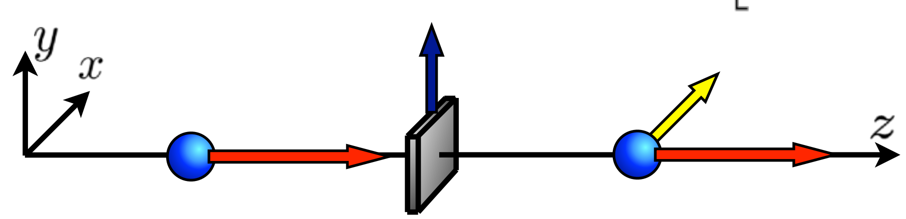
Epi-thermal neutron detector



Analyzing Power $A_x \equiv \mathrm{Tr}\left[\delta^\dagger \sigma_x \delta\right]$



Polarization $P_x \equiv \mathrm{Tr}\left[\sigma_x \delta^\dagger \delta\right]$



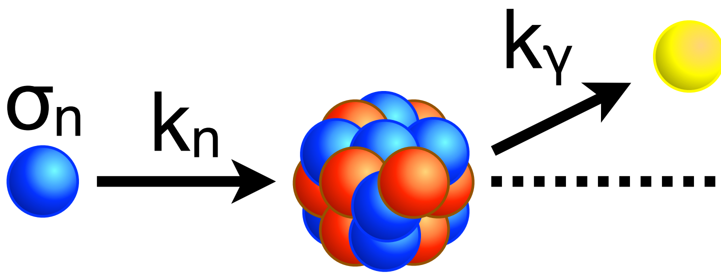
$$A_x + P_x = 8\mathrm{Re}\, A^* D$$

Measurement of enhancement factor

(n, γ) reaction (for unpolarized case)

Flambaum, Nucl. Phys. A435 (1985) 352

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



$$a_0 = \sum_{J_\mathrm{s}} |V_1(J_\mathrm{s})|^2 + \sum_{J_\mathrm{s},j} |V_2(J_\mathrm{p}j)|^2$$

$$\boxed{a_1} = 2\mathrm{Re}\sum_{J_\mathrm{s},J_\mathrm{p},j} V_1(J_\mathrm{s})V_2^*(J_\mathrm{p}j)P(J_\mathrm{s}J_\mathrm{p}\frac{1}{2}j1IF)$$

$$\boxed{a_3} = \mathrm{Re}\sum_{J_\mathrm{s},j,J'_\mathrm{p},j'} V_2(J_\mathrm{p}j)V_2^*(J'_\mathrm{p}j')P(J_\mathrm{p}J'_\mathrm{p}jj'2IF)3\sqrt{10}\begin{Bmatrix} 2 & 1 & 1 \\ 0 & \frac{1}{2} & \frac{1}{2} \\ 2 & j & j' \end{Bmatrix}$$

$$V_1 = \frac{1}{2k_s}\sqrt{\frac{E_s}{E}}\frac{\sqrt{g\Gamma_s^n\Gamma_\gamma}}{E - E_s + i\Gamma_s/2}$$

$$V_2(j) = \frac{1}{2k_p}\sqrt{\frac{E_p}{E}}\sqrt{\frac{\Gamma_{pj}^n}{\Gamma_p^n}}\frac{\sqrt{g\Gamma_p^n\Gamma_\gamma}}{E - E_p + i\Gamma_p/2}$$

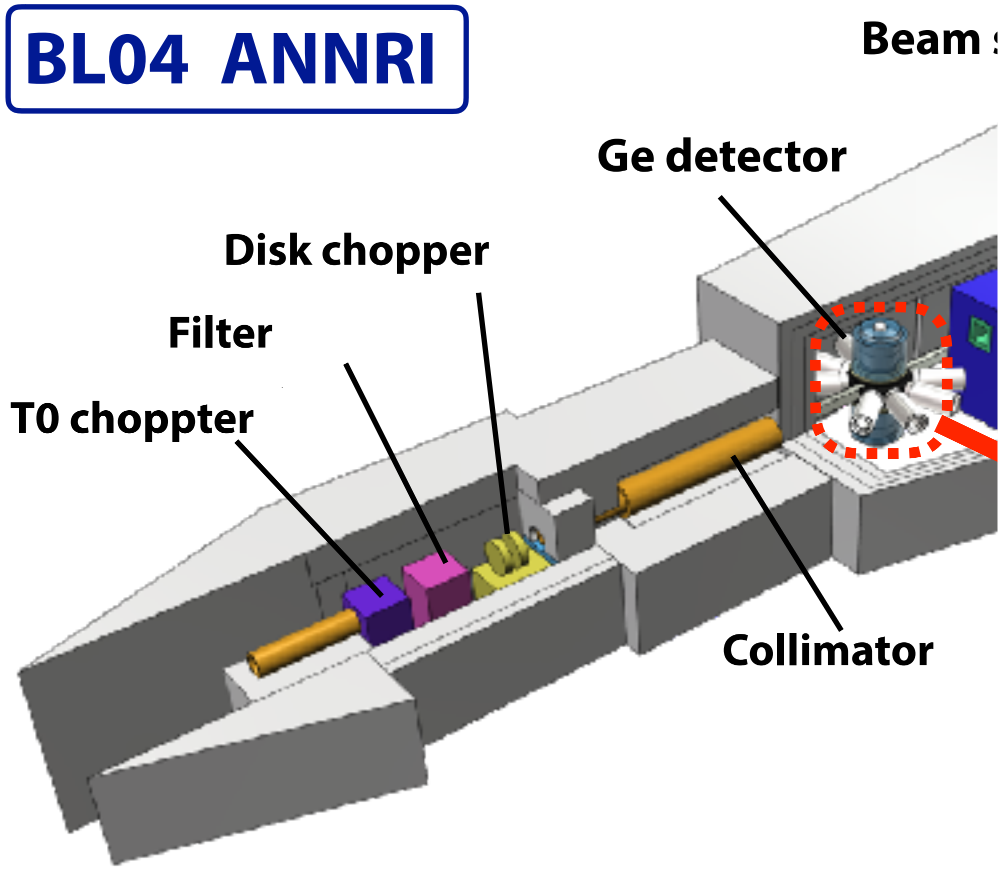
$V_2(j=1/2) = xV_2 = V_2\cos\boxed{\phi}$

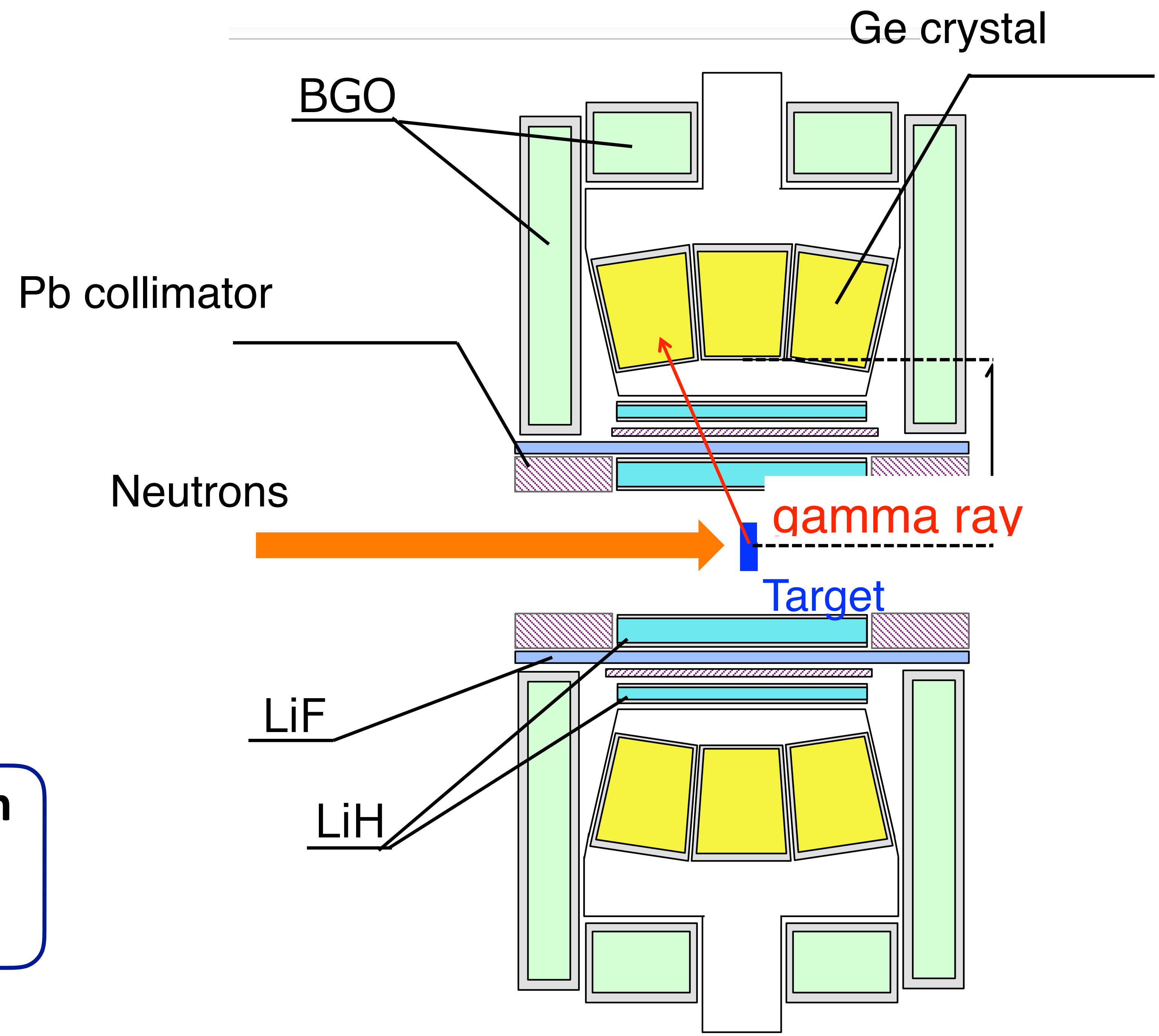
$V_2(j=3/2) = yV_2 = V_2\sin\boxed{\phi}$

$$P(JJ'jj'kIF) = (-1)^{J+J'+j'+I+F}\frac{3}{2}\sqrt{(2J+1)(2J'+1)(2j+1)(2j'+1)}\begin{Bmatrix} j & j & j' \\ I & J' & J \end{Bmatrix}\begin{Bmatrix} k & 1 & 1 \\ F & J & J' \end{Bmatrix}$$

Measurement of enhancement factor

BL04 ANNRI





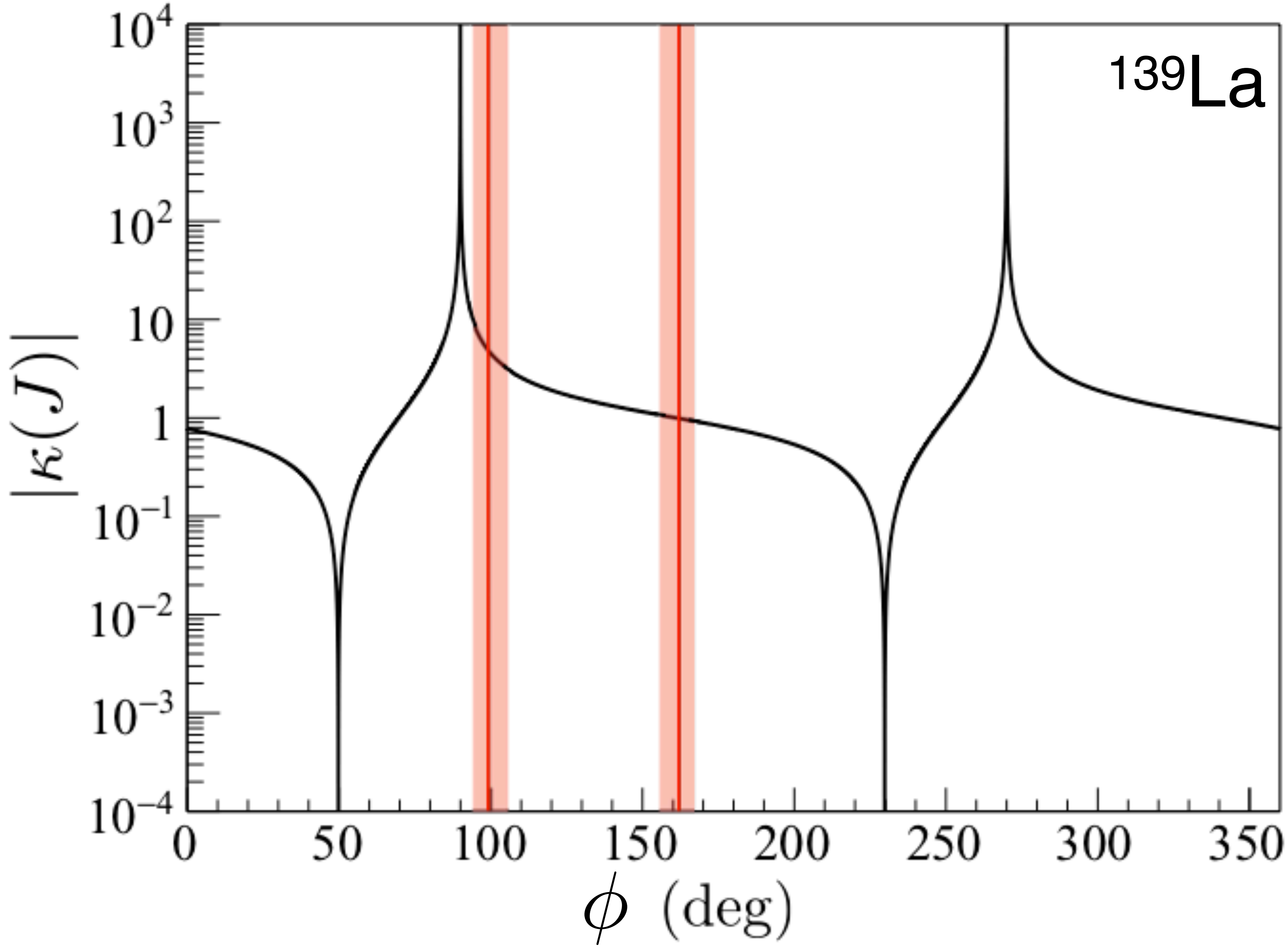
2 Cluster Ge Detector 7ch ×2 : 14ch
8 Coaxial Ge Detector 8ch
22ch → 7 angles

Targets : ^{nat}La 40mm x 40mm x 1mm

T. Okudaira et. al. , Phys. Rev. C97 (2018) 034622.

Measurement of enhancement factor

$$\kappa(J) = 0.99^{+0.88}_{-0.07}, 4.84^{+5.58}_{1.69}$$



T. Okudaira et. al. , Phys. Rev. C97 (2018) 034622.

Feasibility of T-violation experiment

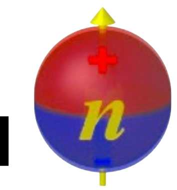
T-violation is also enhanced!

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

T-violation

g_{CP}/g_P P-violation

compare with EDM



from upper limit of nEDM

$$|d_n| < 2.9 \times 10^{-26}\,\mathrm{e\,cm}$$

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

from upper limit of Hg EDM

$$|d_{\mathrm{Hg}}| < 3.1 \times 10^{-29}\mathrm{e\cdot cm}$$

$$\bar{g}_\pi^{(1)} < 0.5 \times 10^{-11}$$

from NPDGamma

$$h_\pi^1 \sim 3 \times 10^{-7}$$

Estimation in effective field theory

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

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

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

Discovery potential

$$|\Delta\sigma_{\mathrm{T}}| < 1.0 \times 10^{-4}\ \mathrm{barn}$$

Feasibility of T-violation experiment

Pulsed Neutron Source

J-PARC

Neutron Polarizer

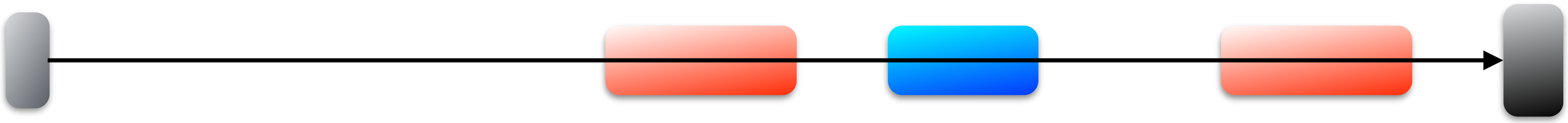
^{3}He spin filter
100 atm cm
Polarization 0.7
Transmission 0.4

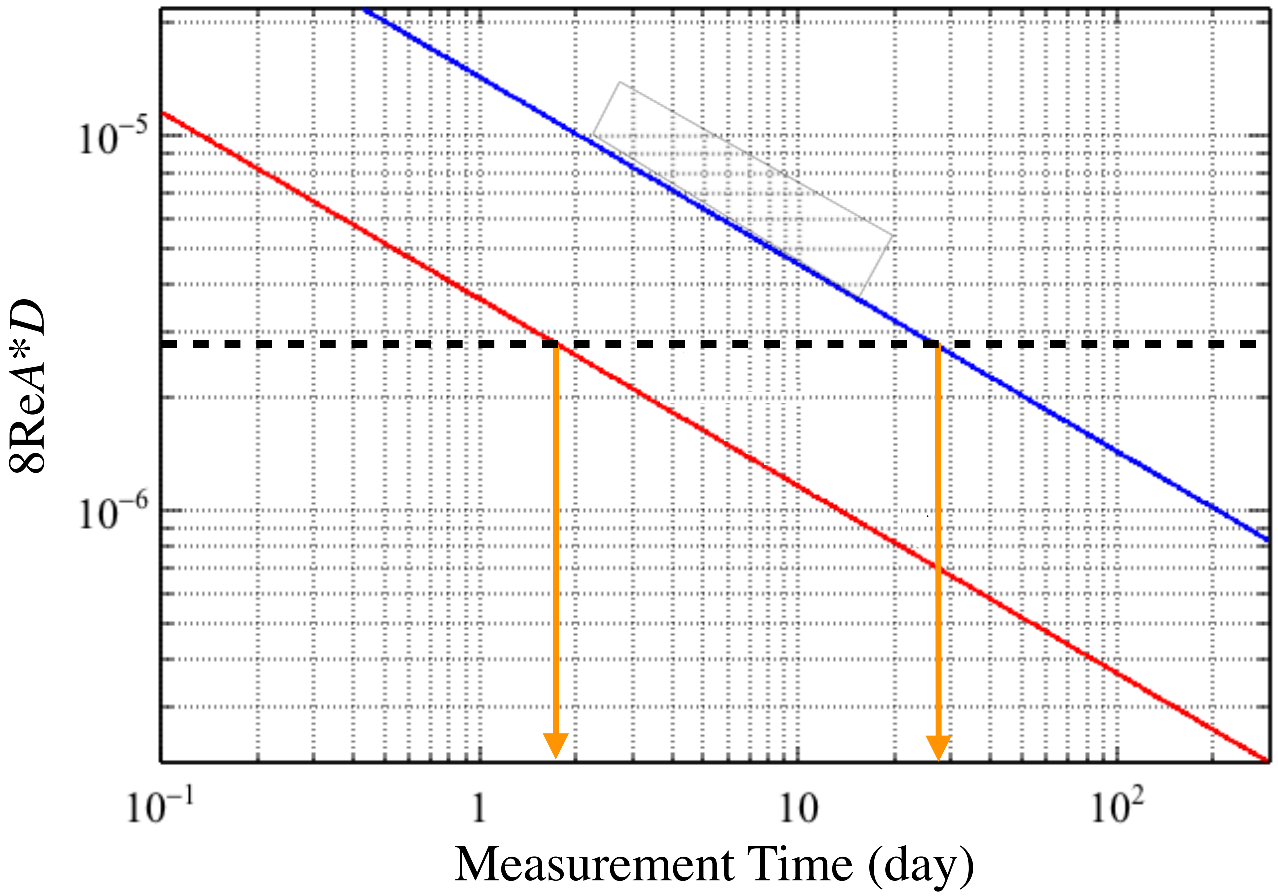
Polarized Target

$LaAlO_3$
4 cm x 4cm x 6 cm

Polarization 0.4

Epi-thermal neutron detector





d_n =3.0×10-26 e cm equiv.

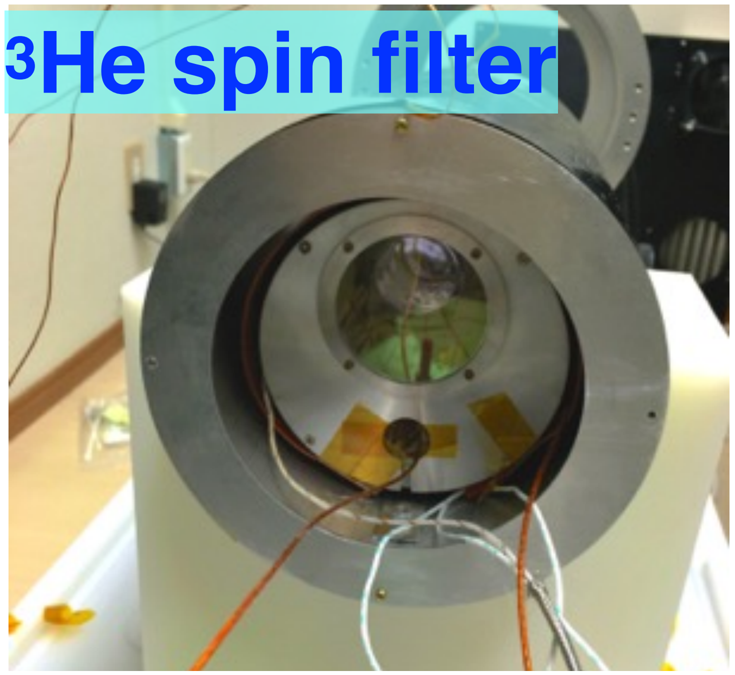
Neutron Pol. = 0.7, ^{139}La Pol. = 0.4

Neutron Pol. = 1.0, ^{139}La Pol. = 1.0

R&D

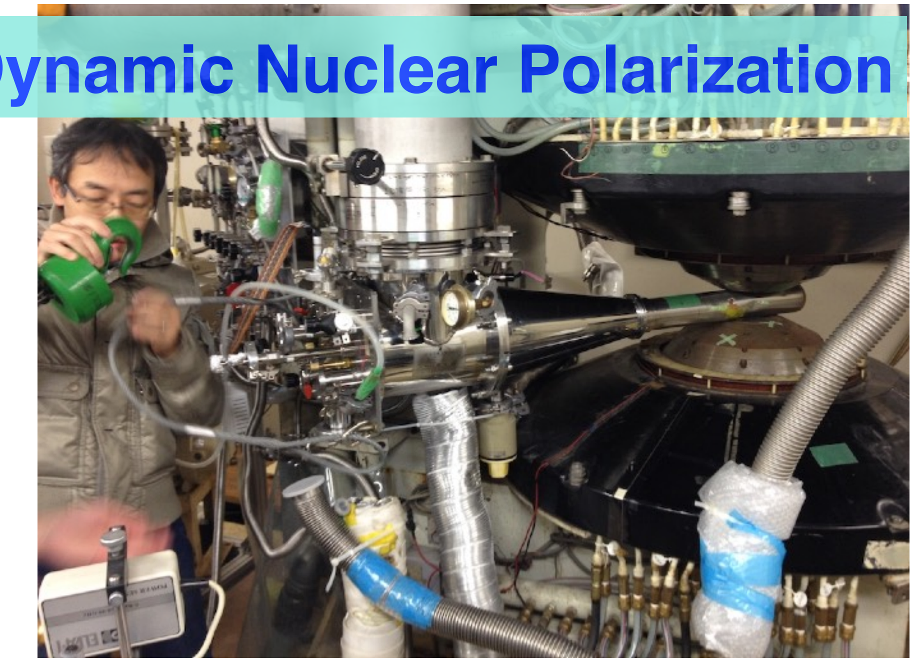
Neutron Polarizer

^{3}He spin filter

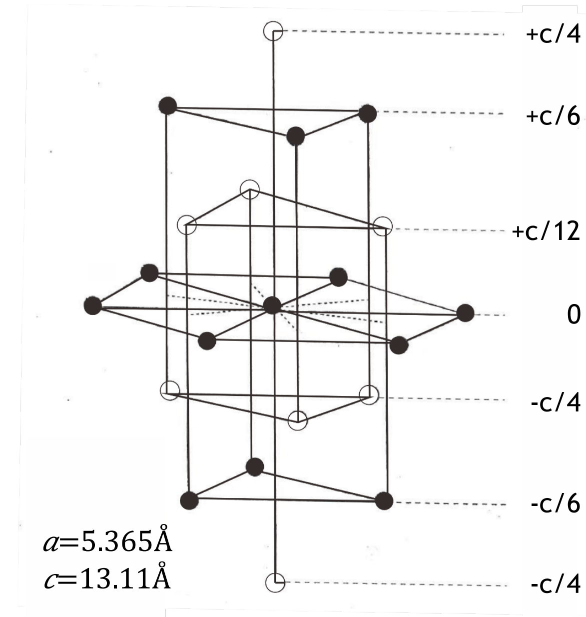


Target Polarizer

Dynamic Nuclear Polarization



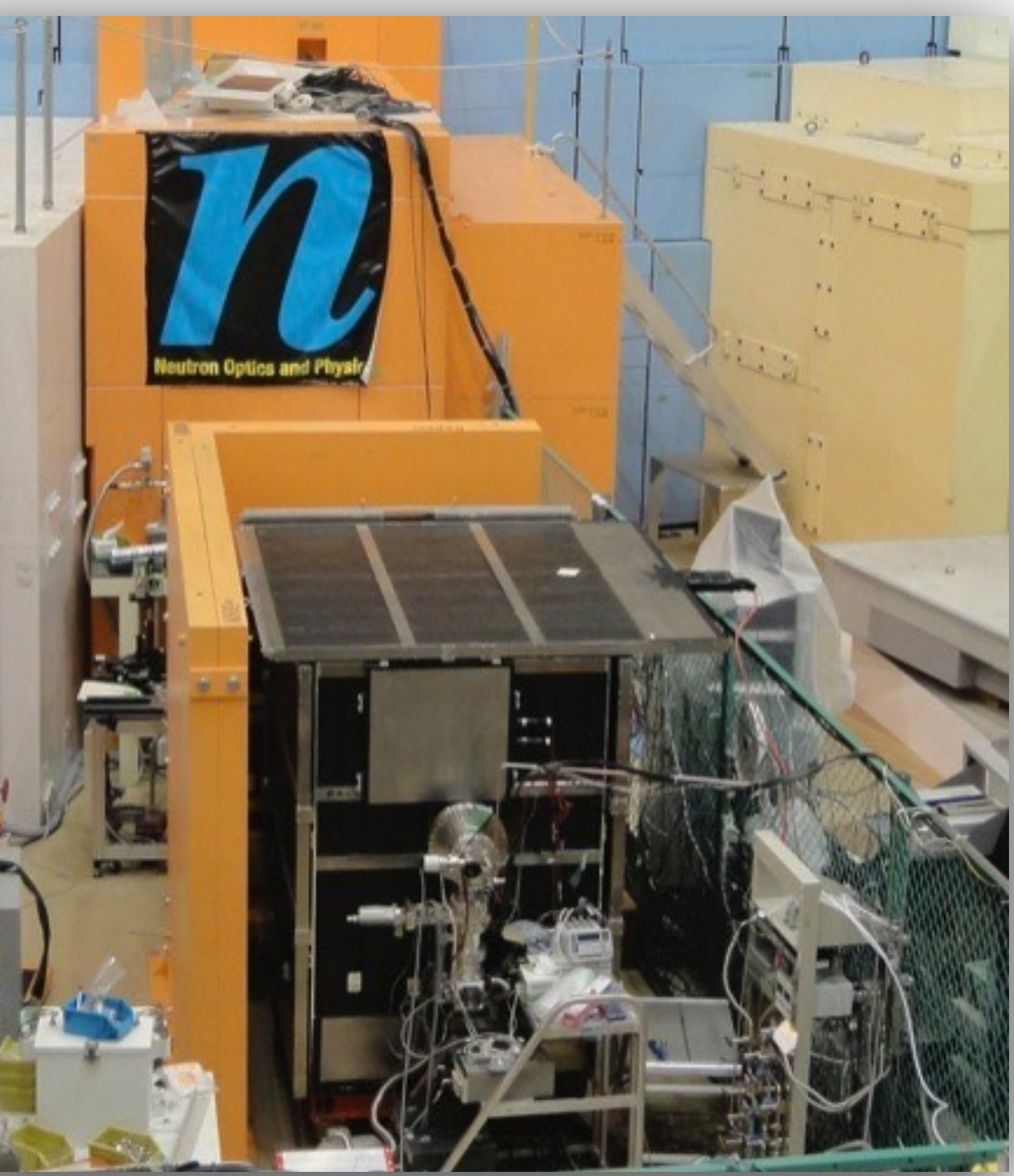
$Nd^{3+}LaAlO_3$



Other target candidates

	large $\Delta\sigma_P$	low E_p	small spin	method of pol.
^{81}Br	😍	😍	😀	Triplet DNP?
^{117}Sn	😀	😀	😍	?
^{131}Xe	😍	😀	😀	Optical Pump?

eV neutron detector



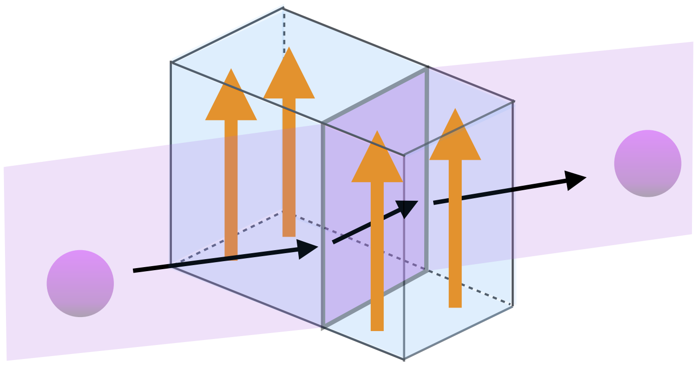
Other topics

Others, R&D

Pendellösung interference fringes
with pulsed neutrons was observed clearly
to be basis of **crystal-EDM technique**.

S. Itoh *et. al.* ,
Nucl. Instr. Meth A908, 78-81 (2018).

Dynamical diffraction inside crystal



Nuclear emulsion detector with ^{10}B thin layer
can detect neutrons with position resolution
less than **100 nm**.

N. Naganawa *et. al.* ,
Eur. Phys. J. C (2018) 78:959

Neutron resonance in gravitational potential

Neutron interferometer for pulsed neutrons
is developing for **dark energy search** or gravity experiments.

Summary

Neutron lifetime measurement with new in-beam method are continuing on BL05.
It will be upgraded to 0.1% precision.

Neutron scattering made a new limit of Yukawa-type unknown force, non-Newtonian gravity.

Discrete symmetry violation is enhanced in Compound States induced by Epithermal Neutron.
T-violation in compound nuclei has a discovery potential of new physics beyond the standard model.

Many kind of neutron devices are developed for various experiments.