NOPTREX

Neutron Optical Parity and Time Reversal EXperiment

Experimental Study of Parity and Time-Reversal Symmetries in Polarized Epithermal Neutron Optics

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(NOPTREX Collaboration)

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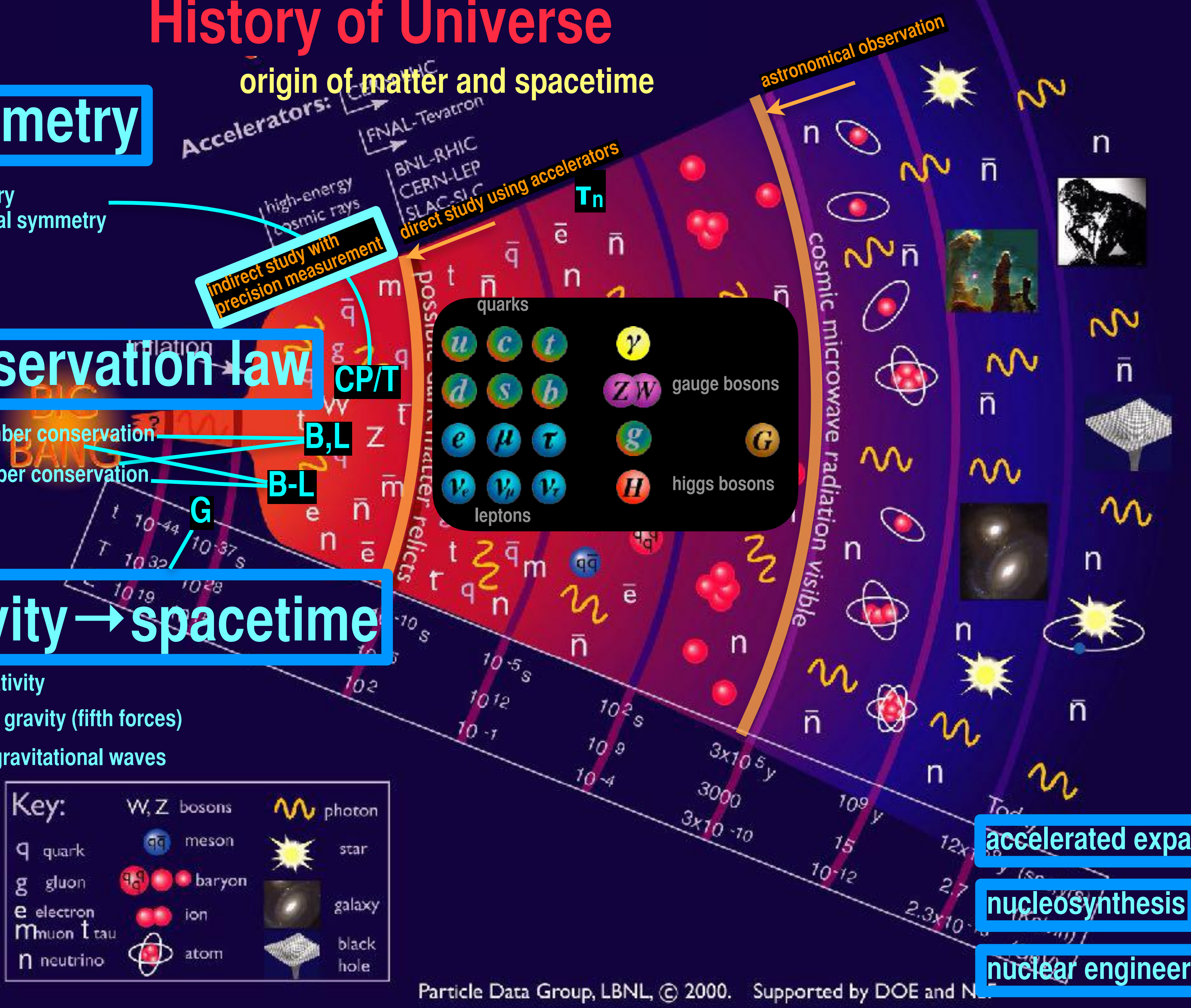
The parity violating effects in nuclear interactions is extremely enhanced in resonant neutron absorption processes via compound nuclear states for some of medium-heavy nuclei. The enhancement is explained as a result of the interference between parity-unfavored partial amplitudes of the compound nuclear process, which is referred to as "s-p mixing". The "s-p mixing" is expected to enhance the visibility of the effect of the breaking of both parity and time-reversal symmetry (P-odd T-odd). Based on these considerations, an experimental approach to search for the P-odd T-odd effects to activate a novel type of new physics search beyond the standard model is in progress using the pulsed neutron beam from the pulsed spallation neutron source of Japan Proton Accelerator Research Complex (J-PARC) under the collaboration "Neutron Optical Parity and Time-Reversal Experiment (NOPTREX)" as the program number J-PARC E99. P-odd T-odd effects will be studied in neutron optics in which fake T-violating effects can be controlled, with the enhanced sensitivity biased to chromo-EDM. We discuss the studies of the "s-p mixing" in ^{139}La(n,γ)^{140}La and the plan of T-violation search with polarized lanthanum target

Introduction of Neutron Fundamental Physics in Japan

History of Universe

origin of matter and spacetime

neutron catogory	phenomena
ultracold	electric dipole moment
near epithermal	T-violating correlations
ultracold	neutron antineutron oscillation
neutrino	neutrino physics double beta-decay neutrino oscillation
cold	neutron interference neutron scattering
very cold	neutron diffraction (neutron gravitational antenna)



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symmetry

CP symmetry
time reversal symmetry

indirect study with precision measurement

direct study using accelerators

astronomical observation

Tn

CP/T

conservation law

baryon number conservation
lepton number conservation

B,L

B-L

G

gravity→spacetime

general relativity
short-range gravity (fifth forces)
primordial gravitational waves

accelerated expa

nucleosynthesis

nuclear engineer

History of Universe

origin of matter and spacetime

neutron catogory	phenomena
ultracold	electric dipole moment
near epithermal	T-violating correlations
ultracold	neutron antineutron oscillation
neutrino	neutrino physics
	double beta-decay
	neutrino oscillation
cold	neutron interference
	neutron scattering
very cold	neutron diffraction
	(neutron gravitational antenna)
cold, very cold	neutron interference
medium epithermal	
far epithermal, fast	nuclear reactions

symmetry

CP symmetry
time reversal symmetry

conservation law

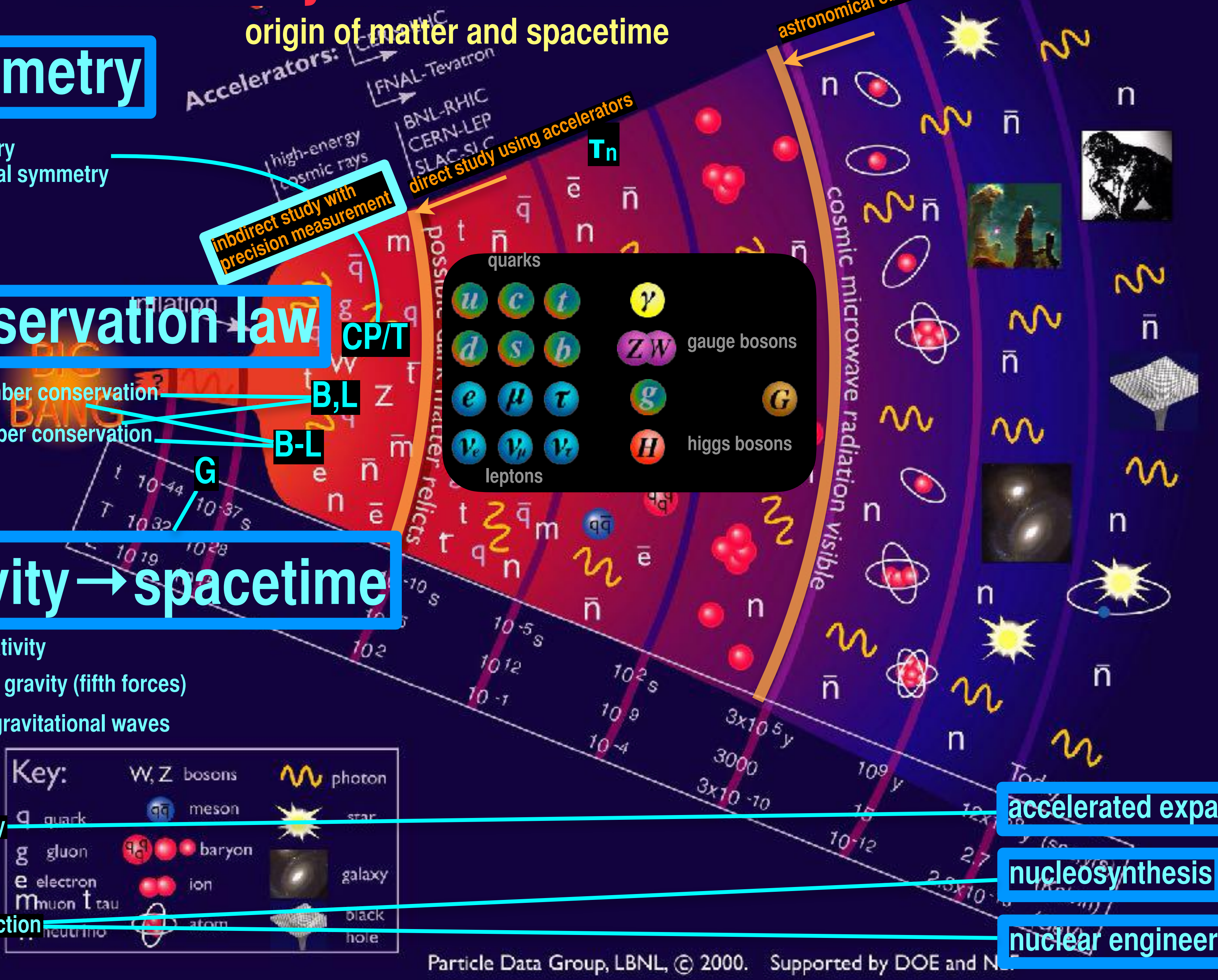
baryon number conservation
lepton number conservation

gravity→spacetime

general relativity
short-range gravity (fifth forces)
primordial gravitational waves

Dark Energy

nuclear reaction



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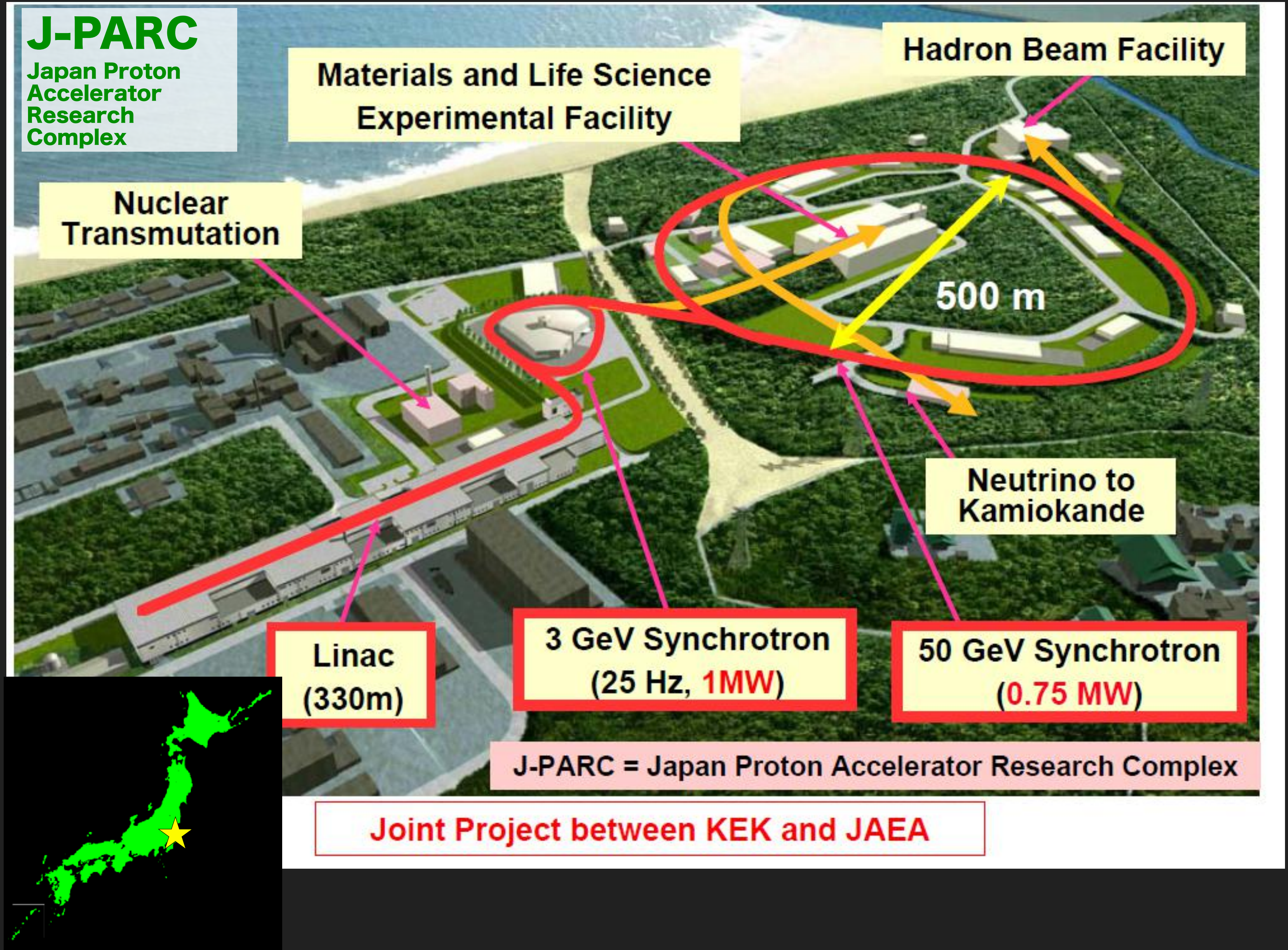
accelerated expa

nucleosynthesis

nuclear engineer

J-PARC

Japan Proton Accelerator Research Complex



Materials and Life Science Experimental Facility

Hadron Beam Facility

Nuclear Transmutation

500 m

Neutrino to Kamiokande

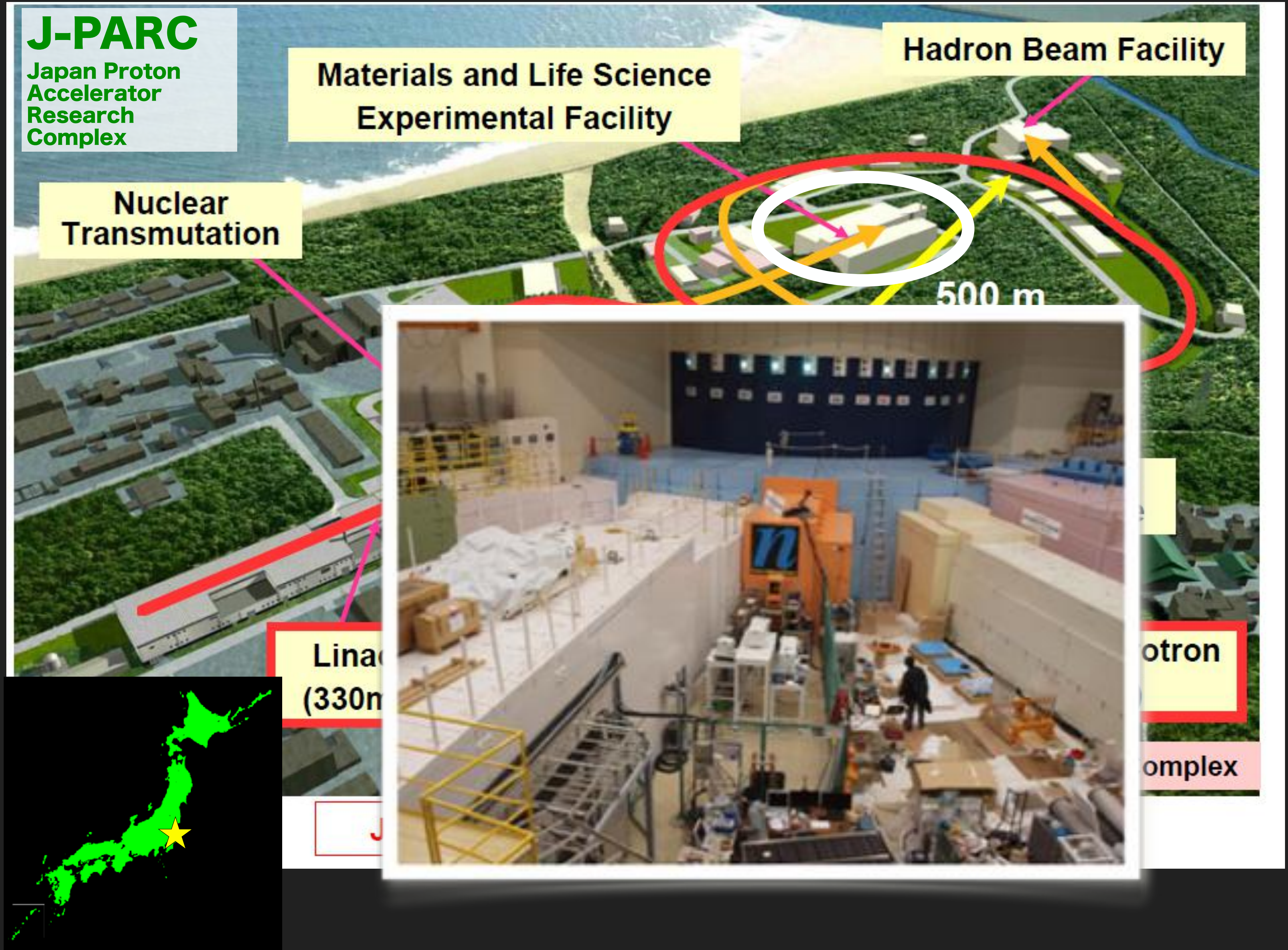
Linac (330m)

3 GeV Synchrotron (25 Hz, 1MW)

50 GeV Synchrotron (0.75 MW)

J-PARC = Japan Proton Accelerator Research Complex

Joint Project between KEK and JAEA


J-PARC
Japan Proton Accelerator Research Complex
Materials and Life Science Experimental Facility
Hadron Beam Facility
Nuclear Transmutation
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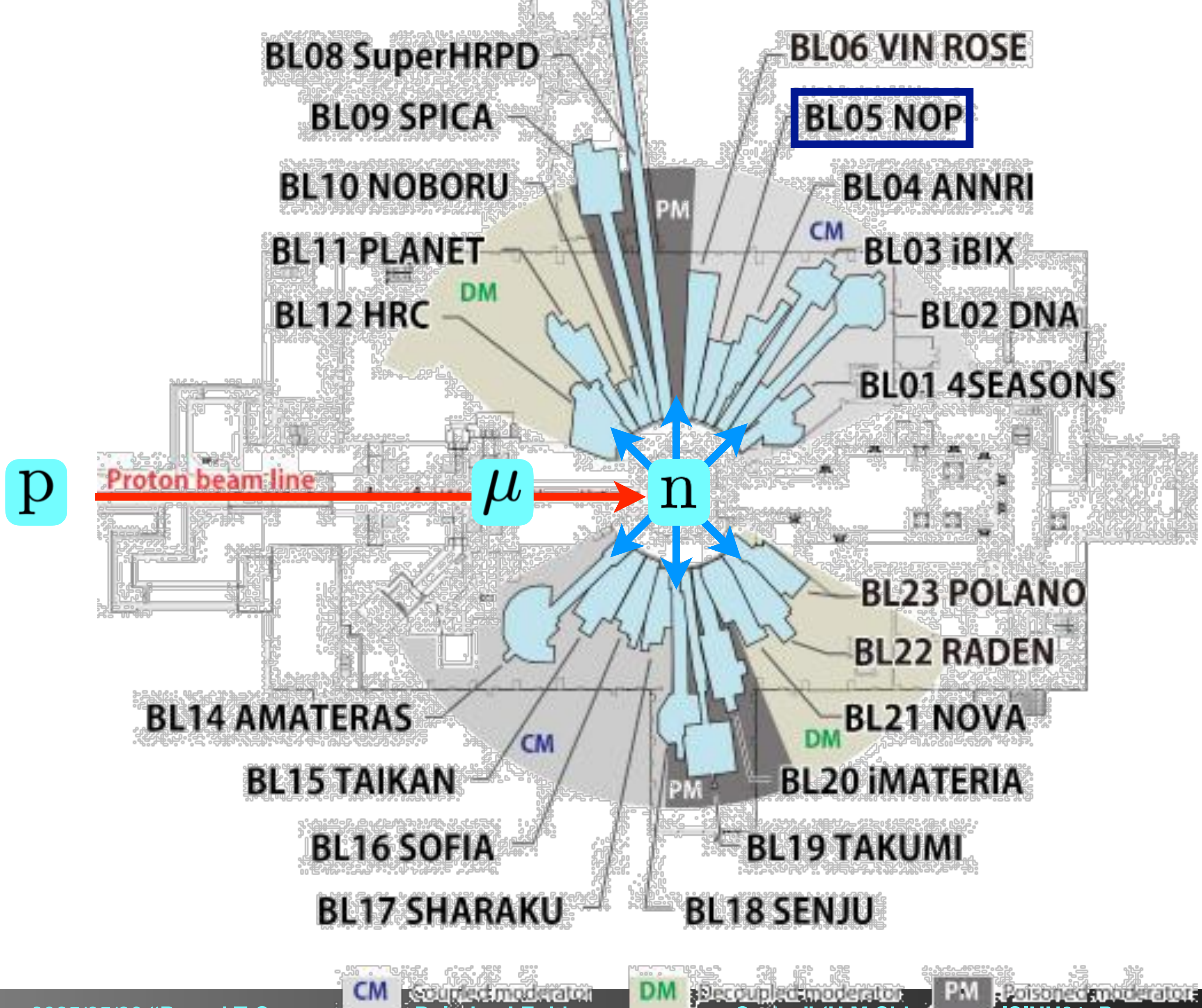
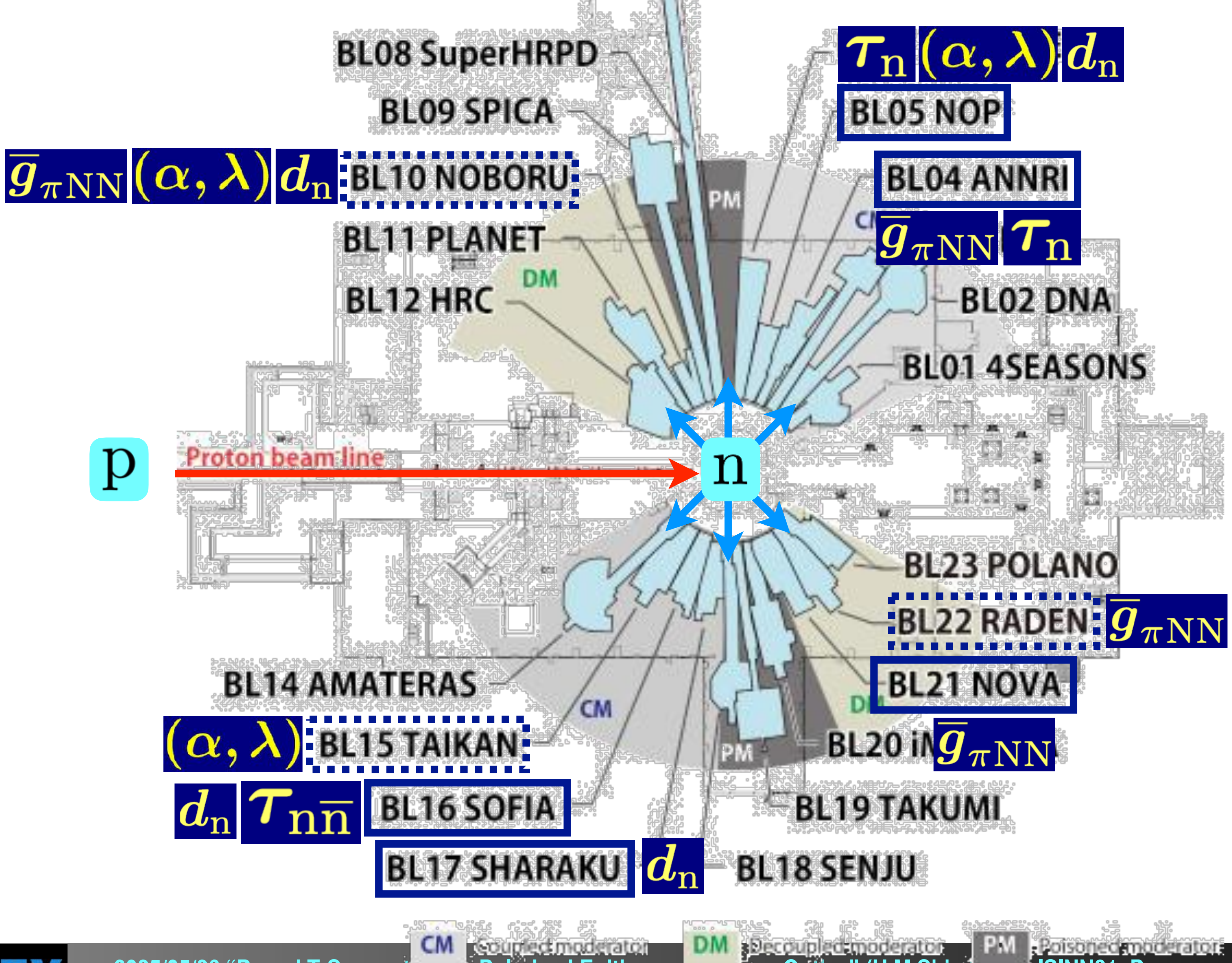

BL08 SuperHRPD
BL09 SPICA
BL10 NOBORU
BL11 PLANET
BL12 HRC
BL06 VIN ROSE
BL05 NOP
BL04 ANNRI
BL03 iBIX
BL02 DNA
BL01 4SEASONS
PM
CM
DM
p
Proton beam line
μ
n
BL23 POLANO
BL22 RADEN
BL21 NOVA
DM
BL20 iMATERIA
PM
BL19 TAKUMI
BL18 SENJU
BL17 SHARAKU
BL16 SOFIA
BL15 TAIKAN
CM
BL14 AMATERAS
CM Coupled moderator
DM Decoupled moderator
PM Poisoned moderator


BL08 SuperHRPD
τ_{n} (α, λ) d_{n}
BL05 NOP
BL09 SPICA
$\bar{g}_{\pi\mathrm{NN}}$ (α, λ) d_{n} BL10 NOBORU
BL04 ANNRI
$\bar{g}_{\pi\mathrm{NN}}$ τ_{n}
PM
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BL11 PLANET
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BL12 HRC
BL02 DNA
BL01 4SEASONS
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BL22 RADEN $\bar{g}_{\pi\mathrm{NN}}$
BL14 AMATERAS
BL21 NOVA
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(α, λ) BL15 TAIKAN
PM
BL20 iM $\bar{g}_{\pi\mathrm{NN}}$
d_{n} $\tau_{\mathrm{n\bar{n}}}$ BL16 SOFIA
BL19 TAKUMI
BL17 SHARAKU d_{n}
BL18 SENJU
CM Coupled moderator
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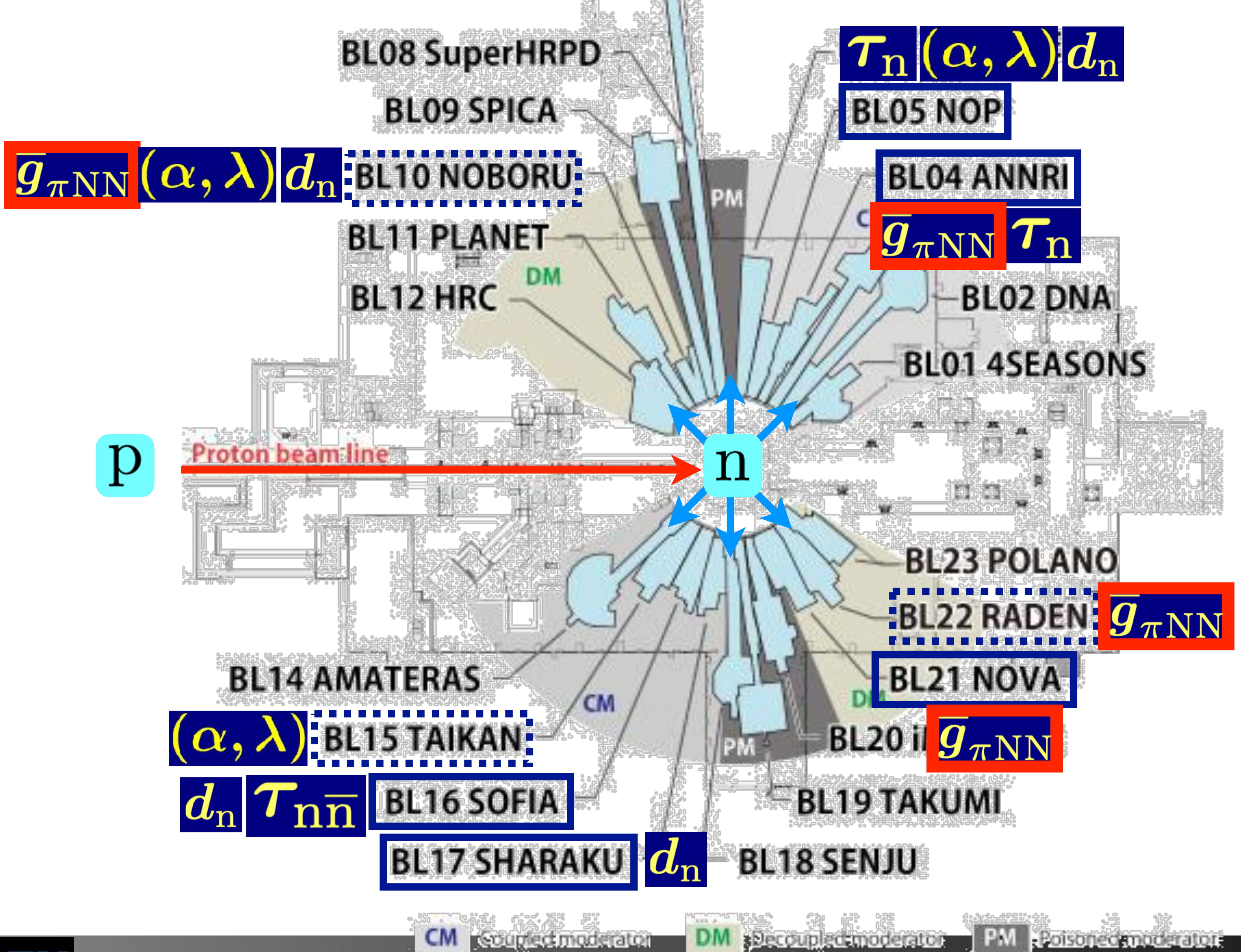
BL08 SuperHRPD
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$\bar{g}_{\pi NN}$ (α, λ) d_n BL10 NOBORU
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τ_n (α, λ) d_n
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BL04 ANNRI
$\bar{g}_{\pi NN}$ τ_n
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Proton beam line
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BL23 POLANO
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d_n $\tau_{n\bar{n}}$ BL16 SOFIA
BL17 SHARAKU d_n
BL18 SENJU
BL19 TAKUMI
CM Coupled moderator
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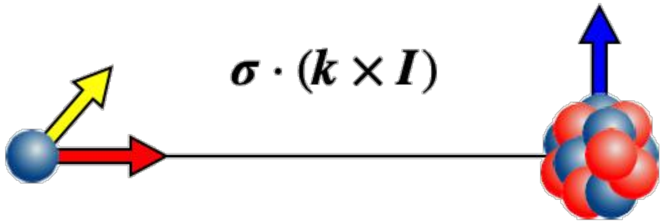
T-violation in compound nuclei

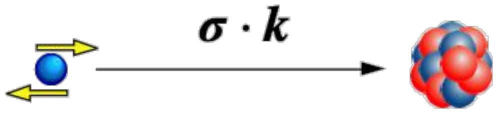
$\overline{g}_{\pi\mathrm{NN}}$

Enhanced symmetry violation appears
in neutron resonance capture reaction.



Statistical nature of
compound states

P-violation



In the case of ^{139}La,
P-violation is **10^6** times enhanced.

Determine enhancement factor **~10^6**
also for T-violation in ^{139}La

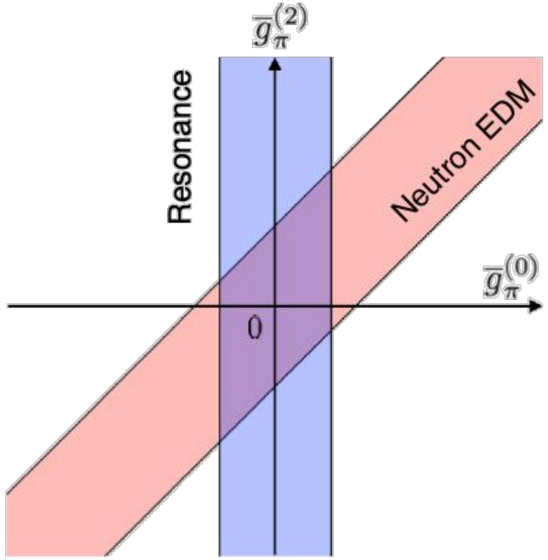
$$\Delta\sigma_{\mathrm{T}} = \kappa(J)\frac{W_{\mathrm{T}}}{W}\Delta\sigma_{\mathrm{P}}$$

$$\kappa = \underline{0.59 \pm 0.05}$$

Suggest discovery potential for T-violation
search competitive with neutron EDM

Target candidate search

^{139}La	T. Okudaira *et. al.* , Phys. Rev. C. 97 034622 (2018) T. Yamamoto *et al.* Phys. Rev. C. 101, 064624 (2020) T. Okudaira *et. al.* , Phys. Rev. C. 104, 014601(2021) M. Okuizumi *et al.* Phys. Rev. C. accepted (2025)
^{117}Sn	J. Koga *et. al.*, Phys. Rev. C. 105, 05461 (2022) S. Endo *et al.*, Phys. Rev. C.106 064601 (2022)
^{131}Xe	T. Okudaira et al. Phys. Rev. C 107, 054602 (2023)



^{139}La resonance
30 days
at J-PARC

complementary

Neutron EDM
10^{-26} e cm

$$\frac{\Delta\sigma_{\mathrm{CP}}}{2\sigma_{\mathrm{tot}}} = \frac{-0.185[\mathrm{b}]}{2\sigma_{\mathrm{tot}}}\left(\overline{g}_\pi^{(0)} + 0.26\overline{g}_\pi^{(1)}\right) \qquad d_n \simeq 0.14\left(\overline{g}_\pi^{(0)} - \overline{g}_\pi^{(2)}\right)$$

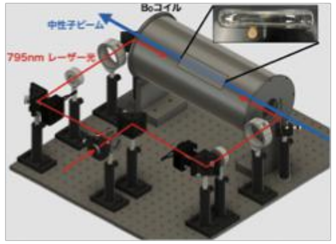
R&D for T-violation search

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

Neutron beam polarization

^{3}He spin filter for eV neutrons is available now! P~80% at 0.75eV

In-situ system is also available.

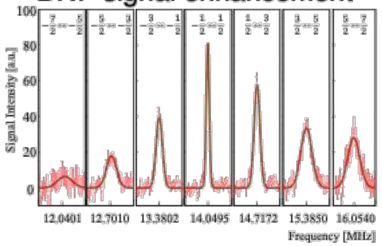


Target nuclei polarization

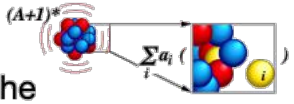
Dynamic nuclear polarization for ^{139}La with LaAlO$_3$ crystal

$P_{La} \rightarrow 31.9\%$

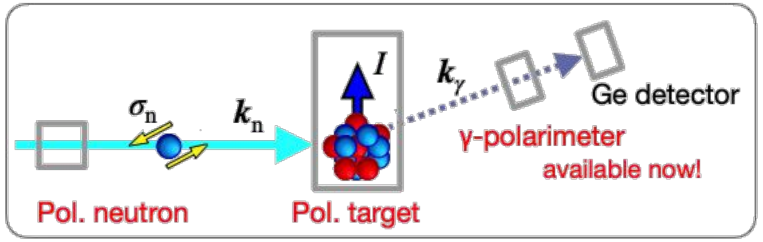
DNP signal enhancement



Many correlation terms of (n, γ) reaction can be used to study the statistical nature of compound states.



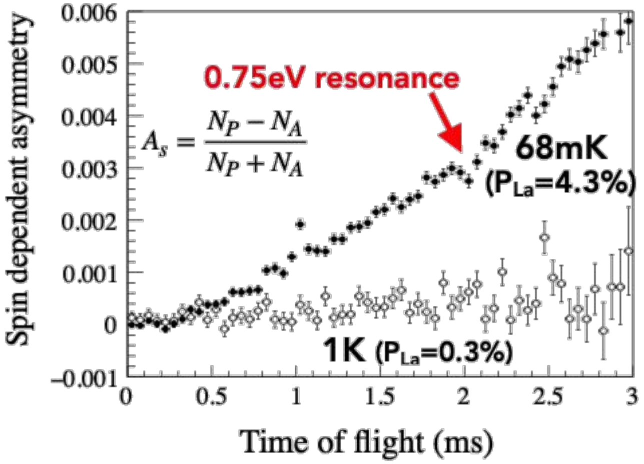
$$\frac{d\sigma}{d\Omega} = \frac{1}{2}\left\{\underline{a_0} + \underline{a_1}\, \boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma + \underline{a_2}\, \boldsymbol{\sigma}_n \cdot (\boldsymbol{k}_n \times \boldsymbol{k}_\gamma) + \underline{a_3} \left((\boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma)^2 - \frac{1}{3}\right) + \cdots\right\}$$



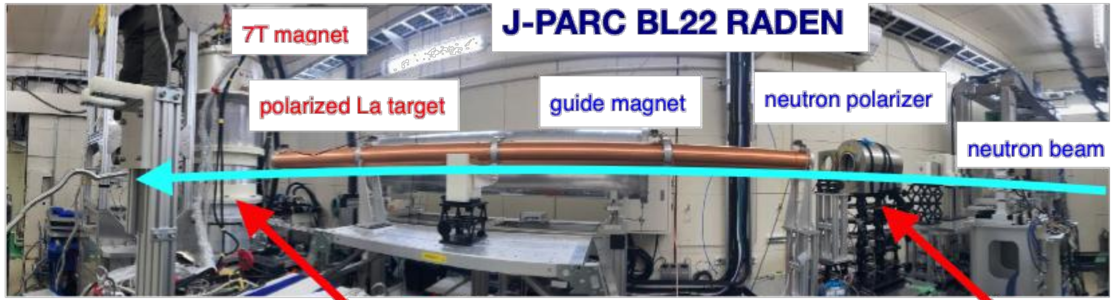
T. Yamamoto et. al., Phys. Rev. C101, 064624 (2020)
T. Okudaira et. al., Nucl. Instr. Meth. A977, 164301 (2020)
K. Ishizaki, et.al., Nucl. Instr. and Meth. A1020, 165845 (2021)
K. Ishizaki, et.al., Rev. Sci. Instrum. 95, 063301 (2024)
S. Endo et. al. Eur. Phys. J. A 60:166 (2024)

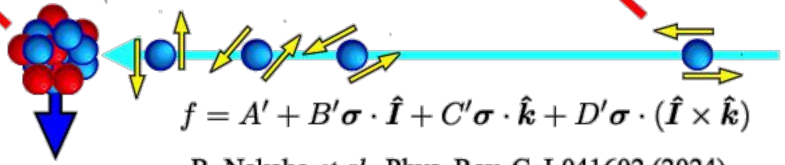
Demonstration of T-violation search

Asymmetry of absorption was observed.



T. Okudaira *et al.*, Phys. Rev. C., 109, 044606 (2024)





This asymmetry can be translated into an upper limit on CP violation.

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

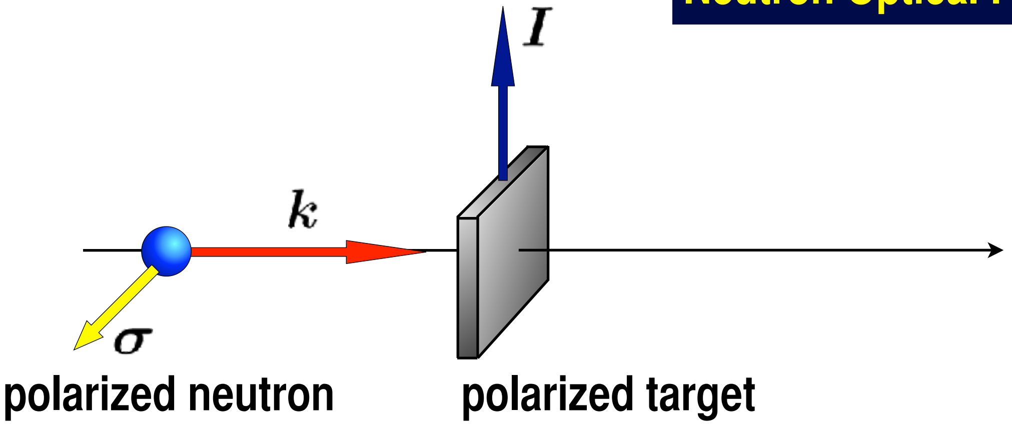
R. Nakabe *et al.*, Phys. Rev. C. L041602 (2024)

Same order of nEDM with 10^{-19} e cm (~ first nEDM limit)

R. Nakabe, PhD thesis (2024)

NOPTREX

Neutron Optical Parity and Time Reversal EXperiment



$$f = \underbrace{A'}_{\text{Spin Independent P-even T-even}} + \underbrace{B'}_{\text{Spin Dependent P-even T-even}}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + \underbrace{C'}_{\text{P-violation P-odd T-even}}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + \boxed{\underbrace{D'}_{\text{T-violation P-odd T-odd}}\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}})}$$

$$P : \boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} \rightarrow \boldsymbol{\sigma}\cdot(-\hat{\boldsymbol{k}})$$

P-odd

$$P : \boldsymbol{\sigma}\cdot(\hat{\boldsymbol{k}}\times\hat{\boldsymbol{I}}) \rightarrow \boldsymbol{\sigma}\cdot((-\hat{\boldsymbol{k}})\times\hat{\boldsymbol{I}})$$

$$T : \boldsymbol{\sigma}\cdot(\hat{\boldsymbol{k}}\times\hat{\boldsymbol{I}}) \rightarrow (-\boldsymbol{\sigma})\cdot((-\hat{\boldsymbol{k}})\times(-\hat{\boldsymbol{I}}))$$

P-odd T-odd

1. Optical Test final-state interaction controllable

2. Enhancement dynamical and kinematical enhancement

3. New Type of New Physics Search biased sensitivity to chromo-EDM

NOPTREX

Neutron Optical Parity and Time Reversal EXperiment

2024/08/20

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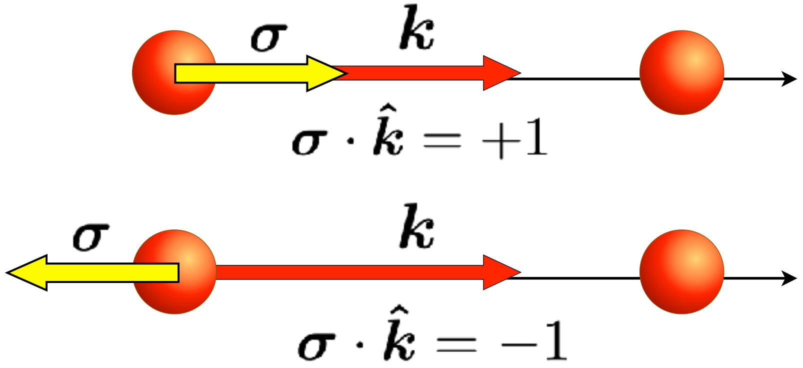
P-violation in Nuclear Interaction

	ST	**WK**
	strong interaction	weak interaction
P $\boldsymbol{\sigma} \to \boldsymbol{\sigma} \quad \boldsymbol{k} \to -\boldsymbol{k}$ $\boldsymbol{\sigma} \cdot \boldsymbol{k} \to -\boldsymbol{\sigma} \cdot \boldsymbol{k}$	**even**	**odd**

nucleon-nucleon cross section $\sigma = \sigma_0 + \Delta\sigma(\boldsymbol{\sigma} \cdot \hat{\boldsymbol{k}})$

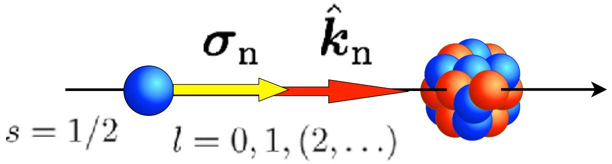


$\sigma_0 + \Delta\sigma$

$\sigma_0 - \Delta\sigma$

$$\frac{\Delta\sigma}{\sigma_0} \sim 10^{-7}$$

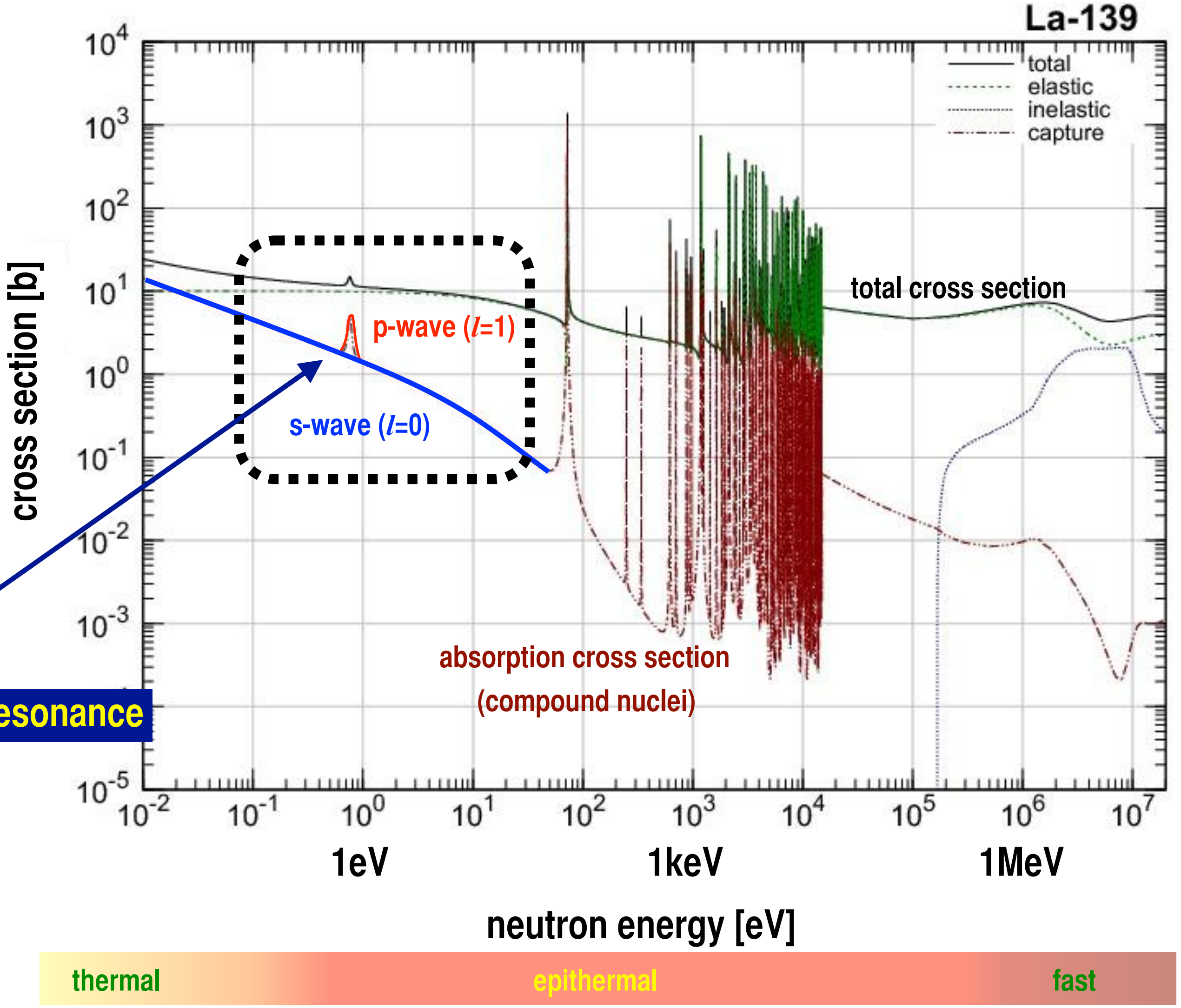
P-violation in Compound State



$$\sigma = \sigma_0 + \boxed{\Delta\sigma}(\boldsymbol{\sigma}_\mathrm{n} \cdot \hat{\boldsymbol{k}}_\mathrm{n})$$

$$A_\mathrm{L} = \frac{\Delta\sigma}{\sigma_0} \times \frac{\sigma_0}{\sigma_\mathrm{p}}$$

P-violation reaches 10^{-1} in this p-wave resonance

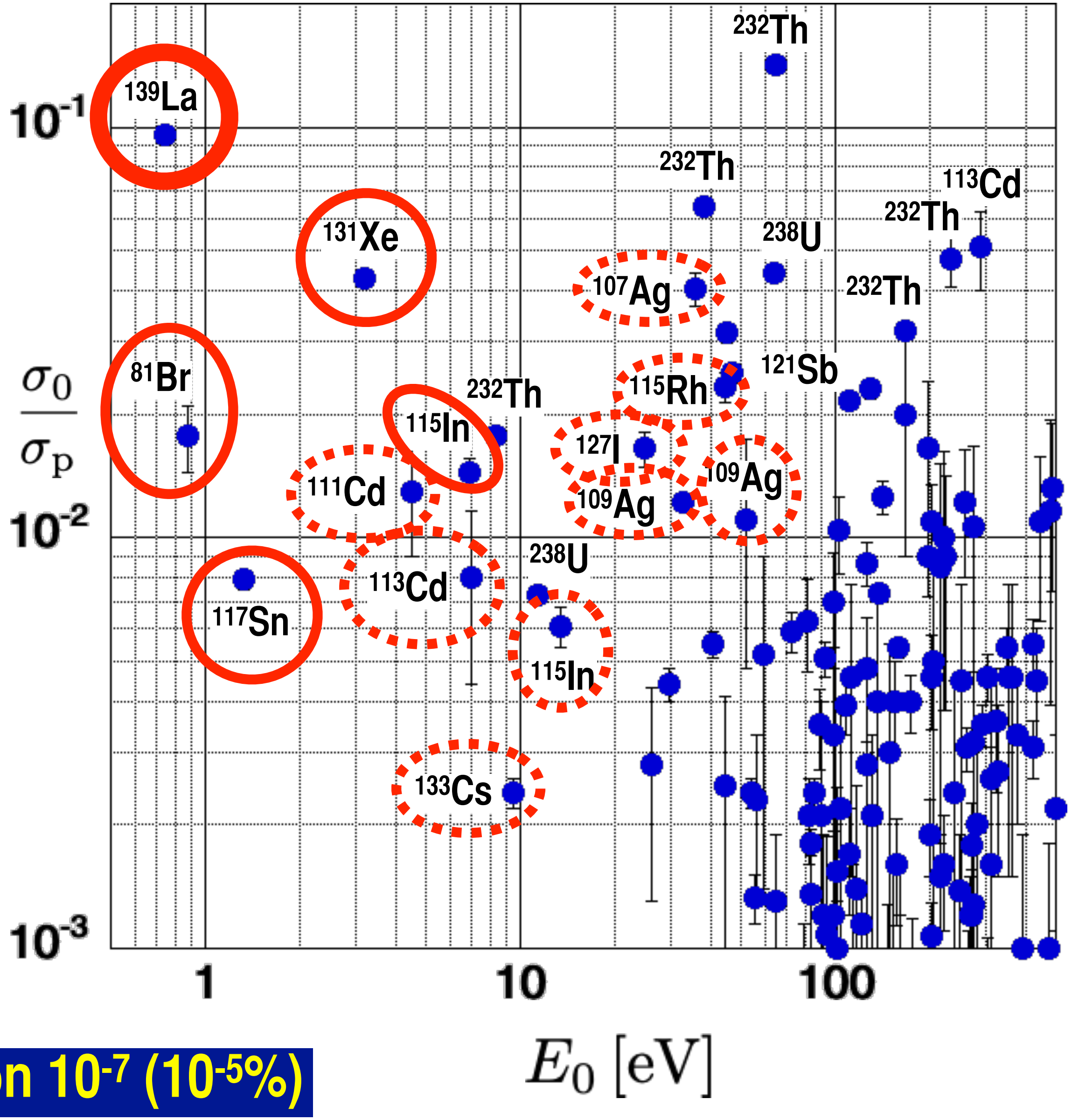


Enhancement of P-violation in Compound States

Mitchell, Phys. Rep. 354 (2001) 157
Shimizu, Nucl. Phys. A552 (1993) 293

$$A_L = \frac{\Delta\sigma}{\sigma_0} \times \frac{\sigma_0}{\sigma_p}$$

10^{-7} for NN

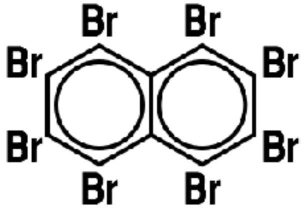


NN-interaction 10^{-7} (10^{-5}%)

Choice of Target Nuclei

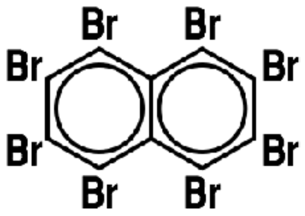
	^{139}La	^{81}Br	^{117}Sn	^{131}Xe	^{115}In
large $\Delta\sigma_P$	◎	○	◎	◎	◎
low E_p [eV]	◎	◎	○	○	△
small nonzero I	7/2 △	3/2 ○	1/2 ◎	3/2 ○	9/2 △
isotopic abn	◎	○	×	△	◎
large $\lvert\kappa(J)\rvert$	○	?	?	○ ?	?
method of pol.	DNP	Triplet -DNP?	—	OP	—

La(Nd)AlO$_3$



Key-technique: Polarized Target

Choice of Target Nuclei

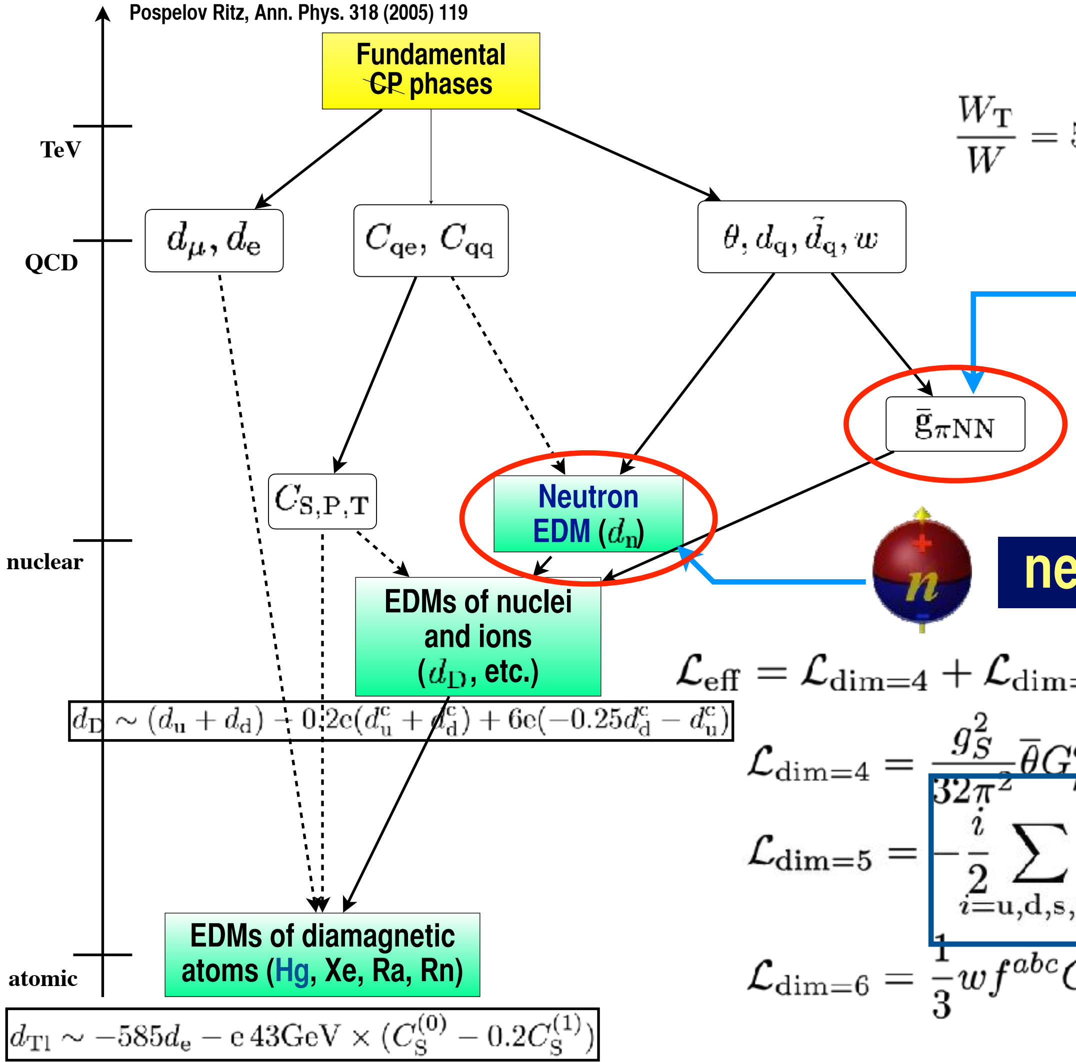
	^{139}La	^{81}Br	^{117}Sn	^{131}Xe	^{115}In
large $\Delta\sigma_P$	◎	○	◎	◎	◎
low E_p [eV]	◎	◎	○	○	△
small nonzero I	7/2 △	3/2 ○	1/2 ◎	3/2 ○	9/2 △
isotopic abn	◎	○	×	△	◎
large $\lvert\kappa(J)\rvert$	○	?	?	○ ?	?
method of pol.	DNP	Triplet-DNP?	—	OP	—
	La(Nd)AlO$_3$				

Key-technique: Polarized Target

New Type of New Physics Search

biased sensitivity to chromo-EDM

Propagation of CP-violation beyond the Standard Model into Low Energy Observables



$$d_D \sim (d_u + d_d) - 0.2e(d_u^c + d_d^c) + 6e(-0.25d_d^c - d_u^c)$$

$$d_{Tl} \sim -585d_e - e\,43\mathrm{GeV} \times (C_S^{(0)} - 0.2C_S^{(1)})$$

$$\frac{W_T}{W} = 5.3 \times 10^4 \,|\theta_{QCD}|$$

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

NOPTREX

chromo-EDM

$$\frac{W_T}{W} \sim \left|-1.0(\bar{d}_u + \bar{d}_d) + 24(\bar{d}_u - \bar{d}_d)\right| \times 10^{20}\,\mathrm{cm}^{-1}$$

J.de Vries, PRC92(2015)045201
V.V.Flambaum, PRC104(2022)015501

d_n

neutron EDM

chromo-EDM **quark-EDM**

$$d_n \sim 1.1e(0.5d_u^c + d_d^c) + 1.4 \times (-0.25d_u + d_d)$$

M.Pospelov, PLB530(2002)123

$$\mathcal{L}_{eff} = \mathcal{L}_{dim=4} + \mathcal{L}_{dim=5} + \mathcal{L}_{dim=6}$$

$$\mathcal{L}_{dim=4} = \frac{g_S^2}{32\pi^2}\bar{\theta}G^a_{\mu\nu}\tilde{G}^{\mu\nu,a}$$

$$\mathcal{L}_{dim=5} = \boxed{-\frac{i}{2}\sum_{i=u,d,s,e,\mu} d_i\bar{\psi}_i(F\sigma)\gamma_5\psi_i - \boxed{\frac{i}{2}\sum_{i=u,d,s}\tilde{d}_i\bar{\psi}_i g_s(G\sigma)\gamma_5\psi_i}}$$

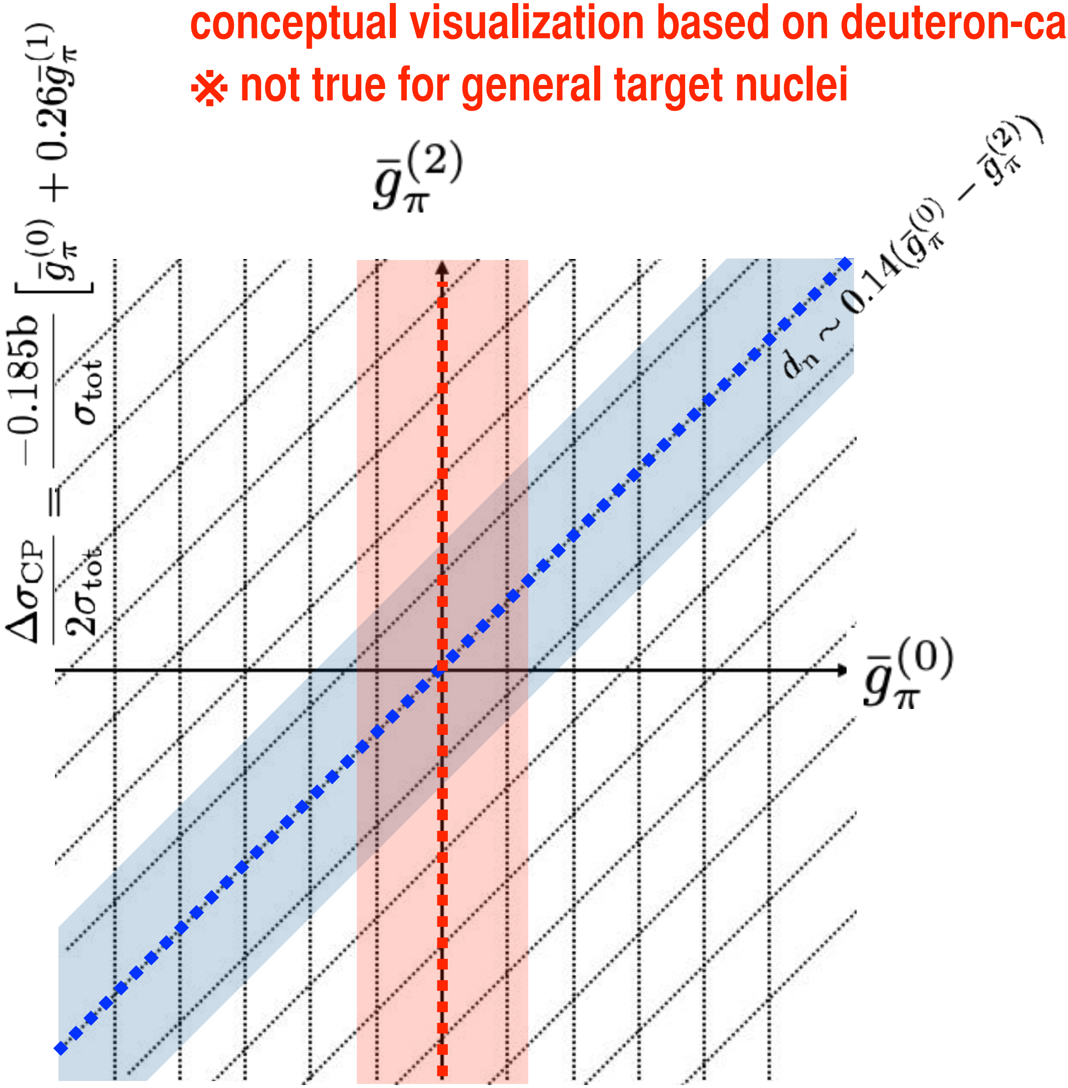
$$\mathcal{L}_{dim=6} = \frac{1}{3}wf^{abc}G^a_{\mu\nu}\tilde{G}^{\nu\beta,b}G^{\mu,c}_{\beta} + \sum_{i,j}C_{ij}(\bar{\psi}_i\psi_i)(\bar{\psi}_j i\gamma_5\psi_j) + \cdots$$

New Type of New Physics Search

biased sensitivity to chromo-EDM

conceptual visualization based on deuteron-case

※ not true for general target nuclei



$$\frac{W_{\rm T}}{W} = 5.3 \times 10^4 \, |\theta_{\rm QCD}|$$

J.de Vries, PRC92(2015)045201
V.V.Flambaum, PRC105(2022)015501

NOPTREX

$$\boxed{\frac{W_{\rm T}}{W} \sim \left|-1.0(\bar{d}_{\rm u} + \bar{d}_{\rm d}) + 24(\bar{d}_{\rm u} - \bar{d}_{\rm d})\right| \times 10^{20}\,{\rm cm}^{-1}}$$

neutron EDM

$$\boxed{d_{\rm n} \sim 1.1{\rm e}(0.5d_{\rm u}^{\rm c} + d_{\rm d}^{\rm c}) + 1.4 \times (-0.25d_{\rm u} + d_{\rm d})}$$

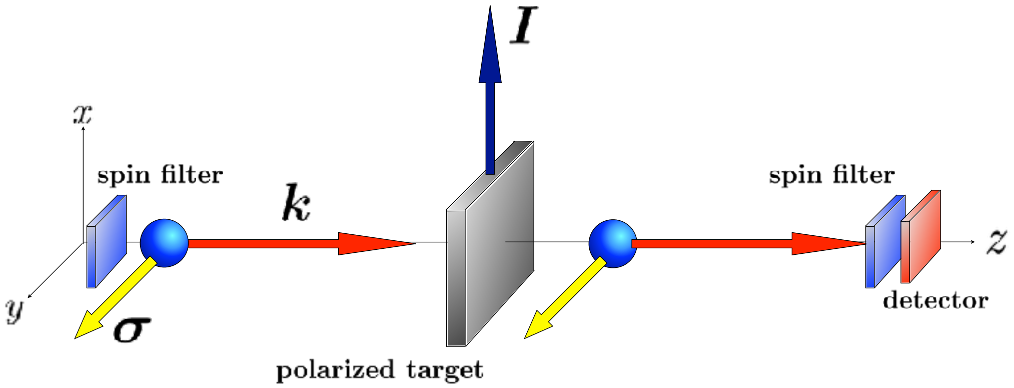
$$\boxed{d_{\rm Hg} \sim 7 \times 10^{-3}{\rm e}(0.5d_{\rm u}^{\rm c} + d_{\rm d}^{\rm c})}$$

$$\boxed{d_{\rm D} \sim (d_{\rm u} + d_{\rm d}) - 0.2{\rm e}(d_{\rm u}^{\rm c} + d_{\rm d}^{\rm c}) + 6{\rm e}(-0.25d_{\rm d}^{\rm c} - d_{\rm u}^{\rm c})}$$

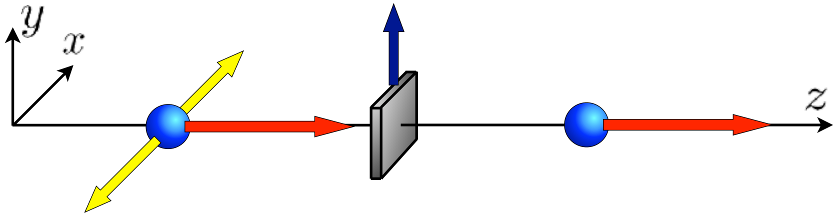
$$\boxed{d_{\rm Tl} \sim -585d_{\rm e} - {\rm e}\,43{\rm GeV} \times (C_{\rm S}^{(0)} - 0.2C_{\rm S}^{(1)})}$$

New Type of New Physics Search

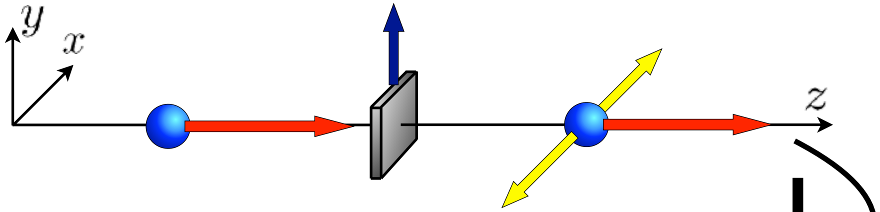
visualization of measurements



We consider the case that neutrons polarized along y-axis transmit through the lanthanum target polarized along x-axis.
One spin filter will be set upstream of the polarized target and another spin filter downstream. Neutron transmission will be measured by the detector put downstream of the second spin filter.



$$A_y \equiv \mathrm{Tr}\left[\mathfrak{S}^\dagger \sigma_y \mathfrak{S}\right] = 4(\mathrm{Re}\underbrace{A^*}_{\substack{\text{Spin Independent}\\ \text{P-even T-even}}}\underbrace{D}_{\substack{\text{T-violation}\\ \text{P-odd T-odd}}} + \mathrm{Im}\underbrace{B^*}_{\substack{\text{Spin Dependent}\\ \text{P-even T-even}}}\underbrace{C}_{\substack{\text{P-violation}\\ \text{P-odd T-even}}})$$



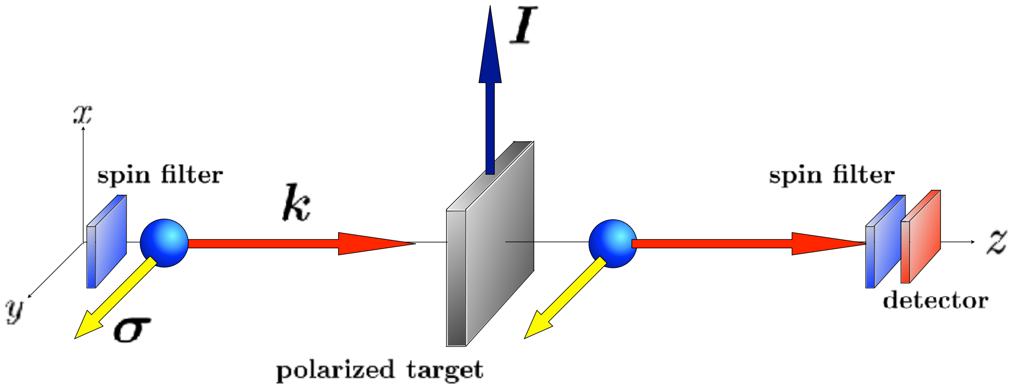
$$P_y \equiv \mathrm{Tr}\left[\sigma_y \mathfrak{S}^\dagger \mathfrak{S}\right] = 4(\mathrm{Re}\underbrace{A^*}_{\substack{\text{Spin Independent}\\ \text{P-even T-even}}}\underbrace{D}_{\substack{\text{T-violation}\\ \text{P-odd T-odd}}} - \mathrm{Im}\underbrace{B^*}_{\substack{\text{Spin Dependent}\\ \text{P-even T-even}}}\underbrace{C}_{\substack{\text{P-violation}\\ \text{P-odd T-even}}})$$

$$+$$

$$A_y + P_y = 8\mathrm{Re}A^* D$$

New Type of New Physics Search

visualization of measurements



We consider the case that neutrons polarized along y-axis transmit through the lanthanum target polarized along x-axis.
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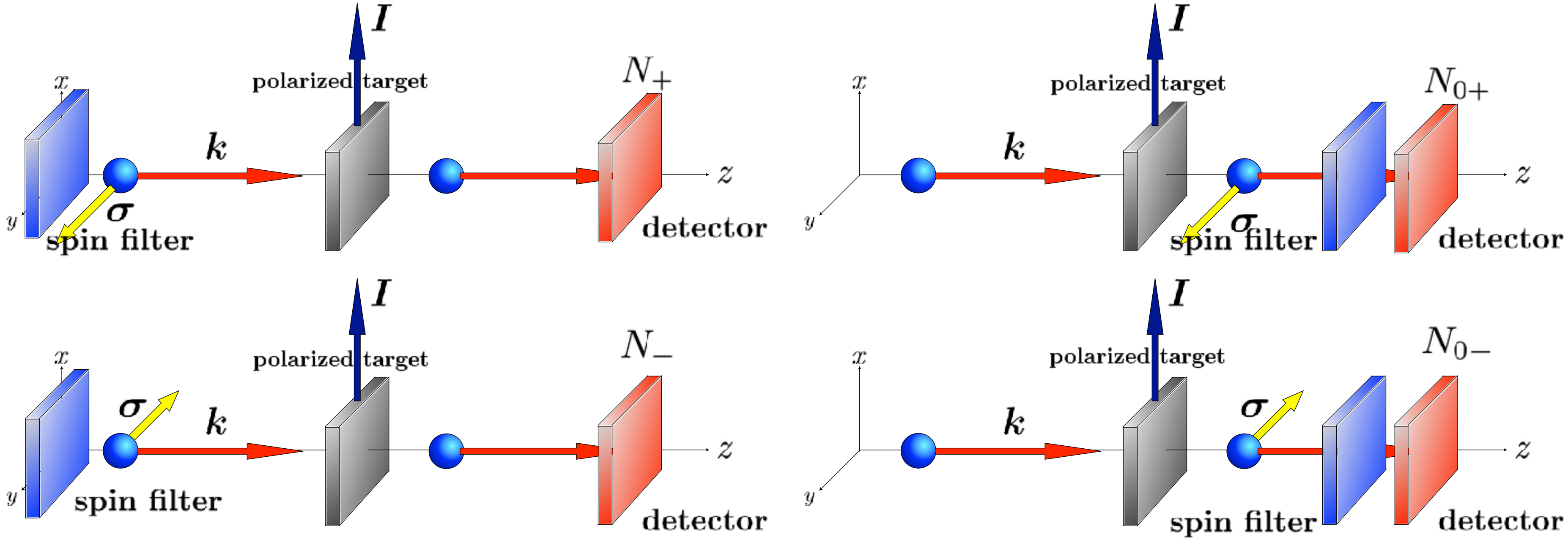
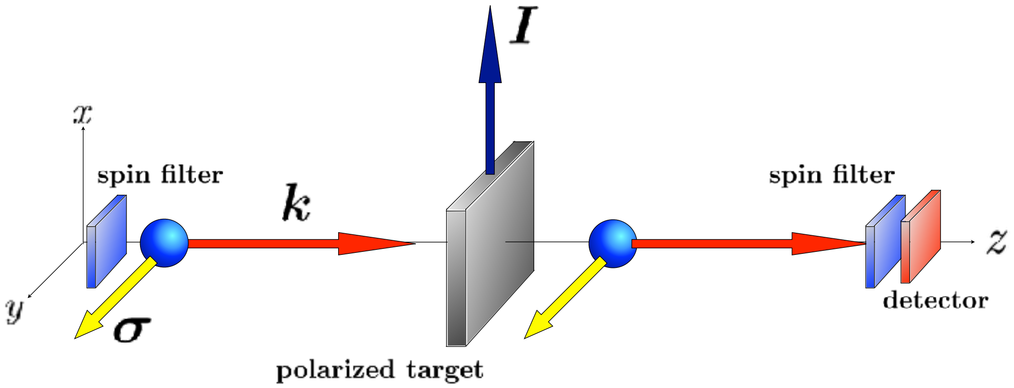


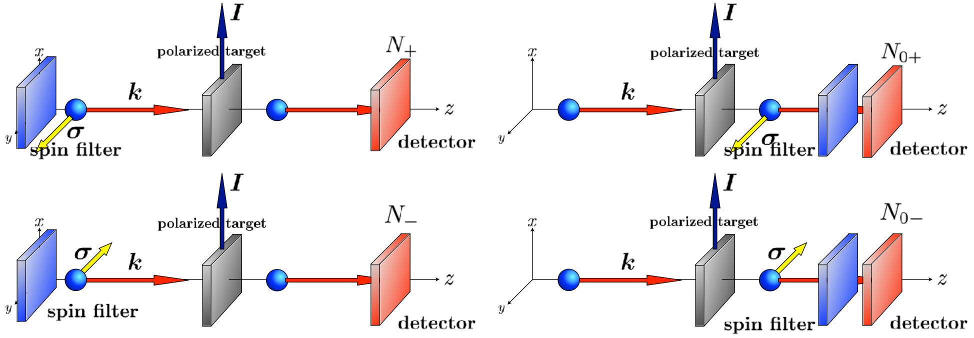
$$A_y = \frac{N_+ - N_-}{N_+ + N_-}$$

$$P_y = \frac{N_{0+} - N_{0-}}{N_{0+} + N_{0-}}$$

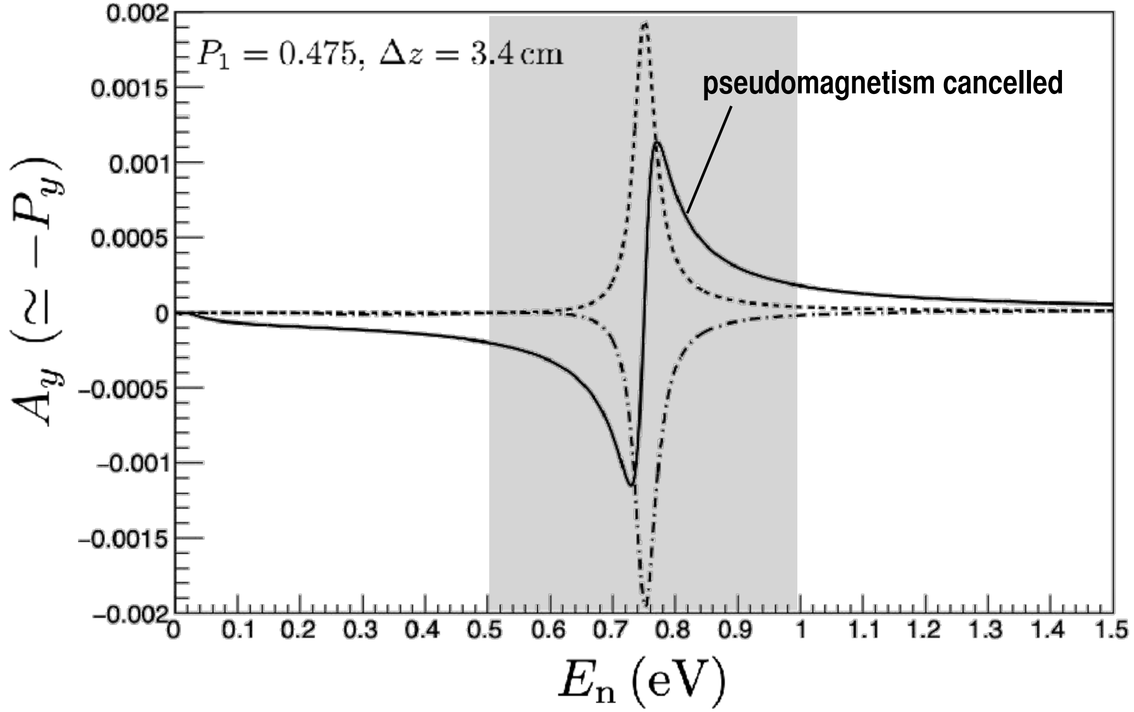
New Type of New Physics Search

visualization of measurements

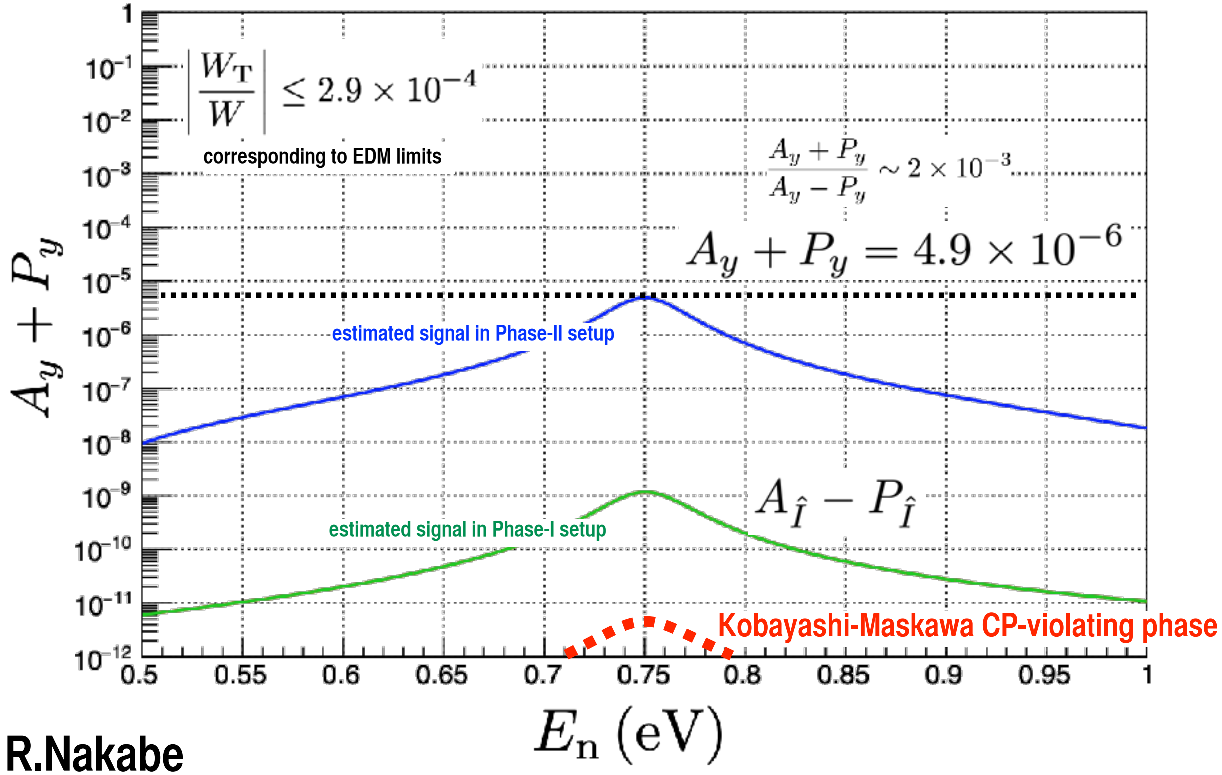




$$A_y = \frac{N_+ - N_-}{N_+ + N_-} \qquad P_y = \frac{N_{0+} - N_{0-}}{N_{0+} + N_{0-}}$$



pseudomagnetism cancelled



$$\left|\frac{W_\mathrm{T}}{W}\right| \leq 2.9 \times 10^{-4}$$

corresponding to EDM limits

$$\frac{A_y + P_y}{A_y - P_y} \sim 2 \times 10^{-3}$$

$$A_y + P_y = 4.9 \times 10^{-6}$$

estimated signal in Phase-II setup

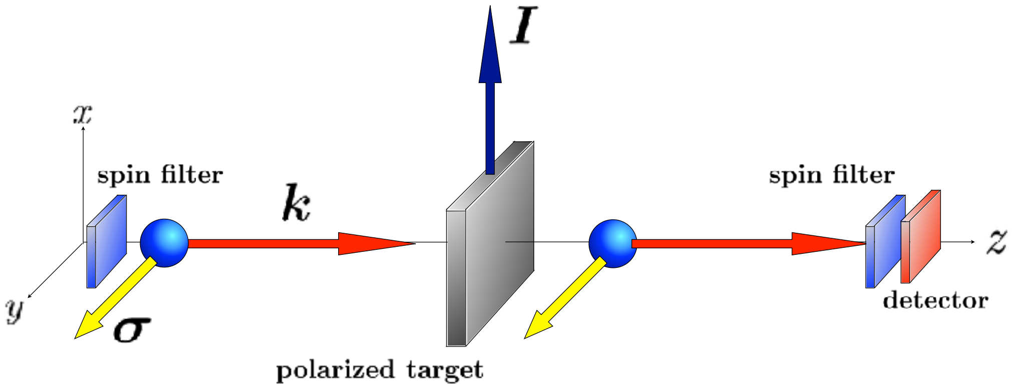
estimated signal in Phase-I setup

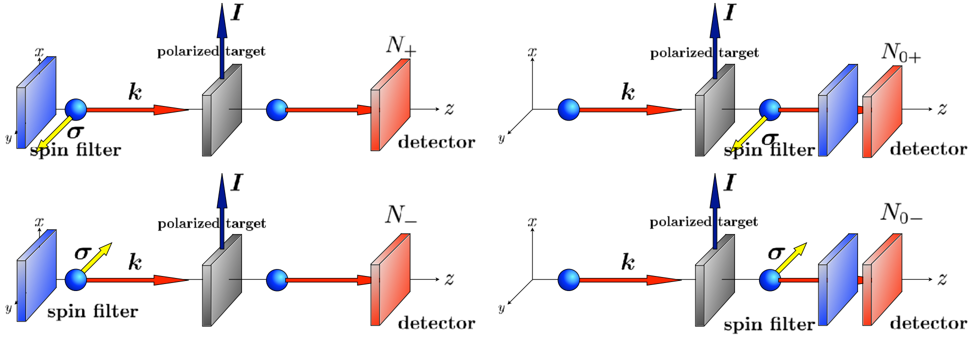
Kobayashi-Maskawa CP-violating phase

dissertation R.Nakabe

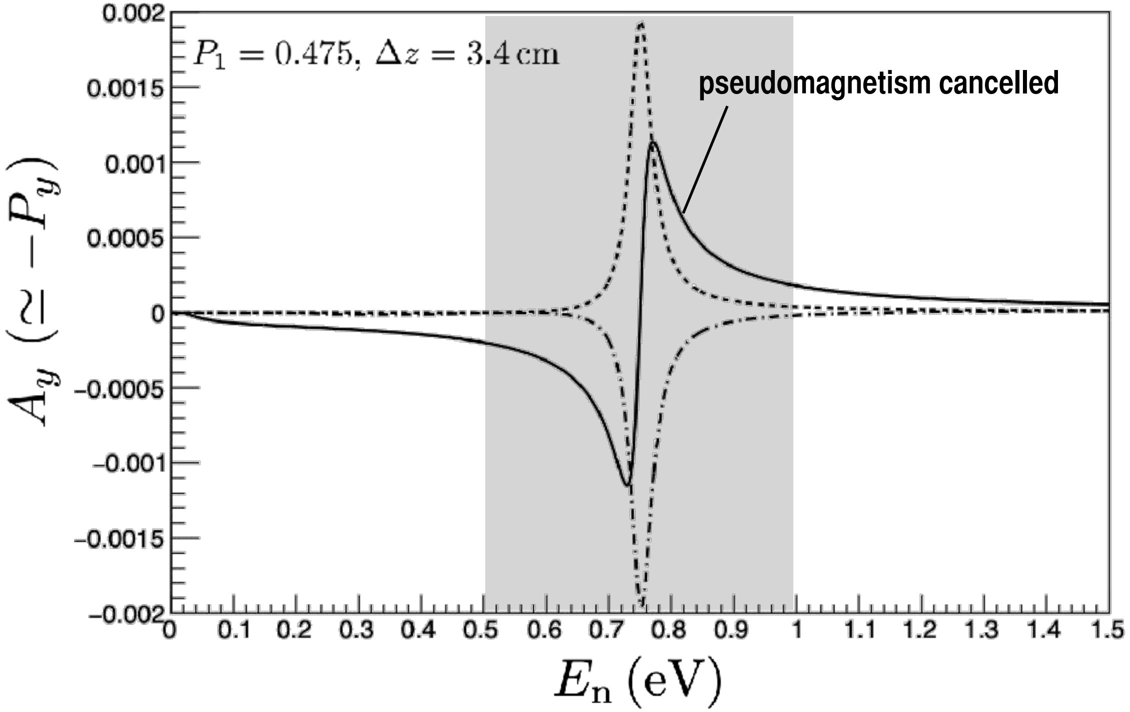
New Type of New Physics Search

visualization of measurements

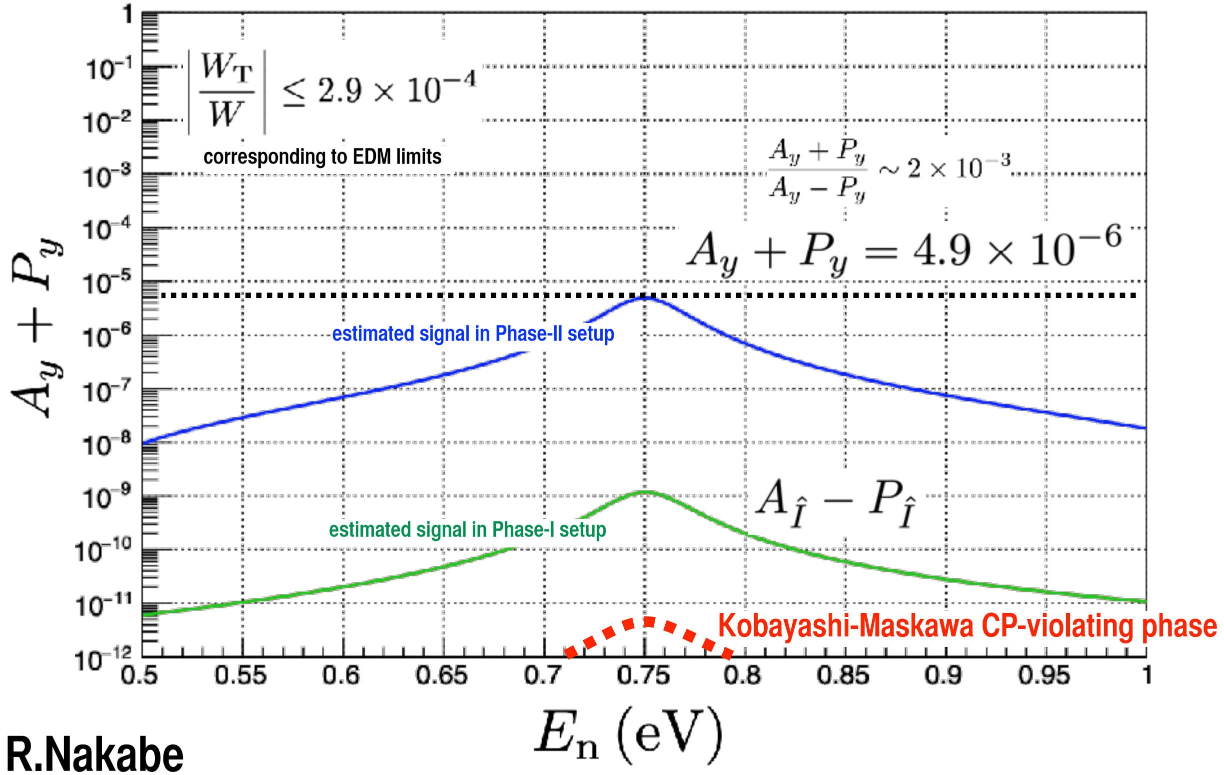




Comparison with EDM is estimated under the assumption of isotensor contribution is zero and only pion can contribute to our approach.



pseudomagnetism cancelled



$\left|\frac{W_\mathrm{T}}{W}\right| \leq 2.9 \times 10^{-4}$

corresponding to EDM limits

$\frac{A_y + P_y}{A_y - P_y} \sim 2 \times 10^{-3}$

$A_y + P_y = 4.9 \times 10^{-6}$

estimated signal in Phase-II setup

$A_{\hat{I}} - P_{\hat{I}}$

estimated signal in Phase-I setup

Kobayashi-Maskawa CP-violating phase

dissertation R.Nakabe

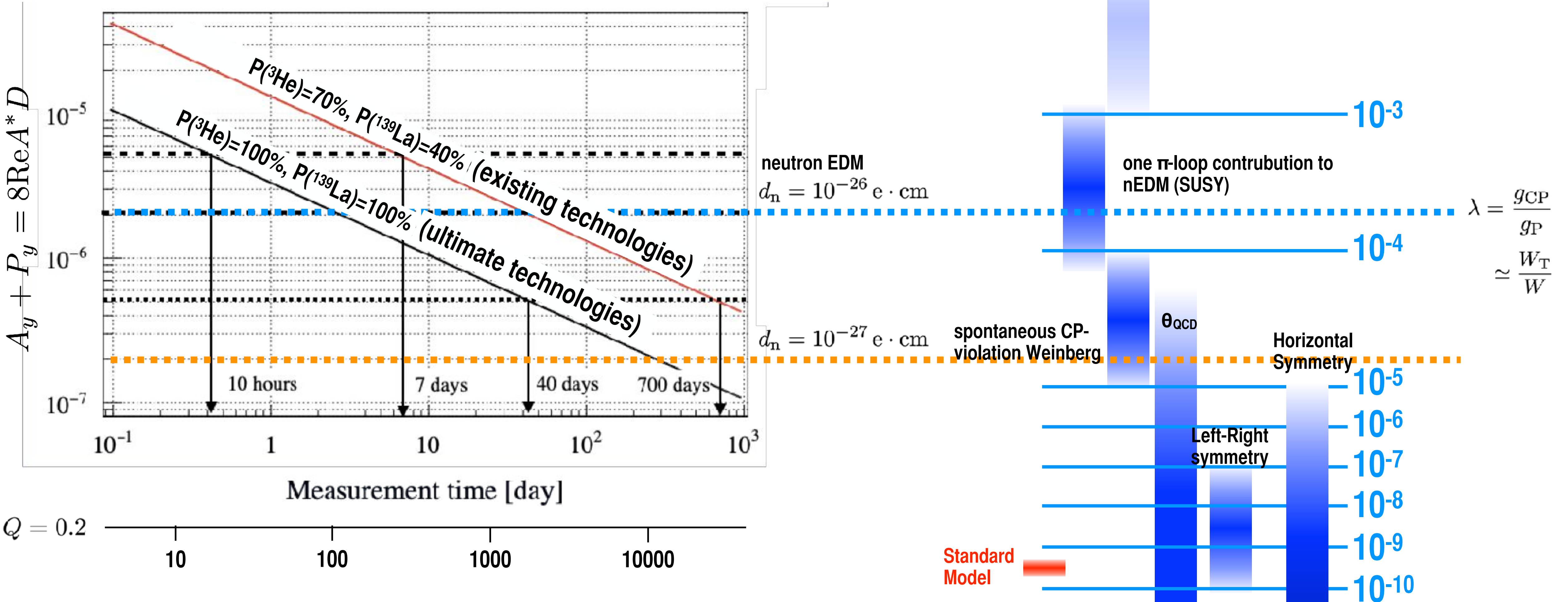
New Type of New Physics Search

Any upper limit delivers a new restriction.

Comparison with EDM is shown under the assumption of isotensor contribution is zero and only pion can contribute to our approach.

V.P.Gudkov, Phys. Rep. 212, 77 (1992)
P. Herczeg, LA-UR-87-2574 (1987)
I.S.Towner and A.C.Hayes, Phys. Rev. C49, 2391 (1994)
M. Pospelov, Phys. Lett. B530, 123 (2002)

$\overrightarrow{{}^{139}\mathrm{La}}$ target material=$\mathrm{LaAlO_3}$



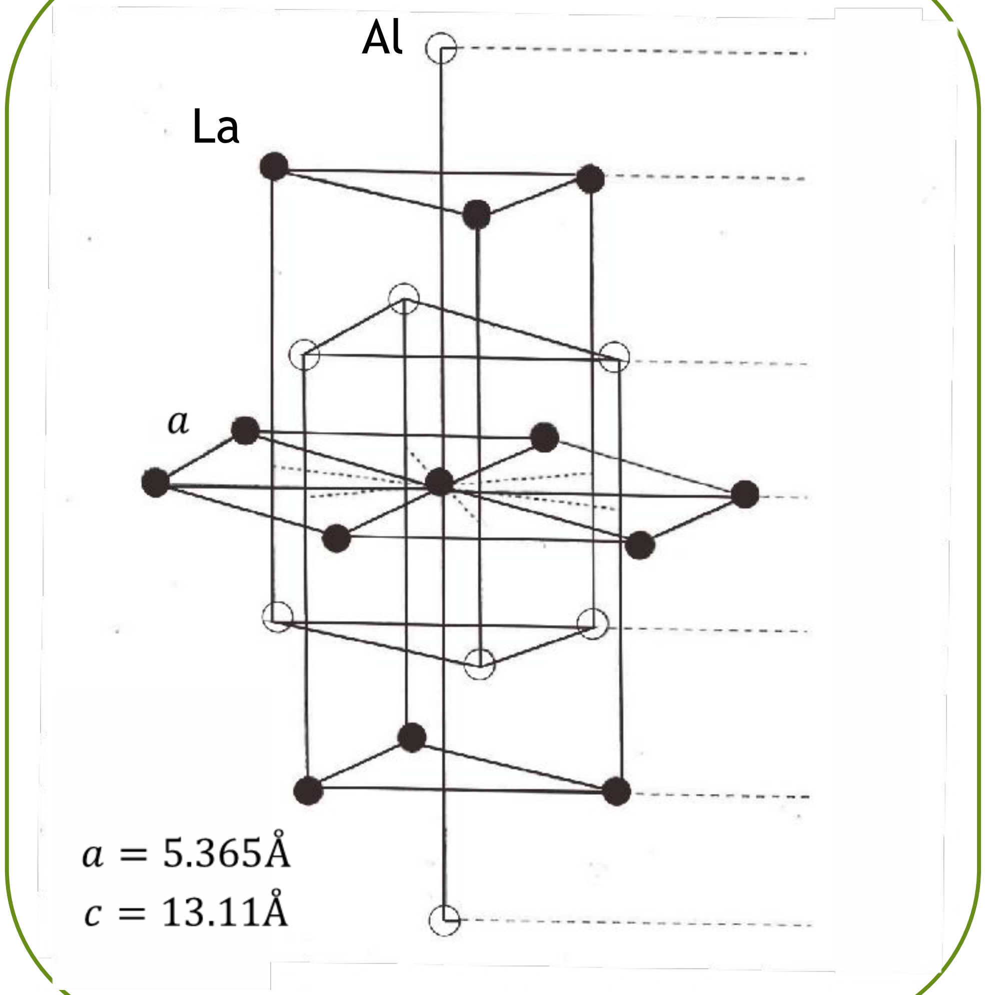
Polarized Lanthanum Target

Lanthanum Aluminate diluted with Neodymium as the Polarized Lanthanum Target Material

Advantage

- Narrow ESR linewidth : ~ 5G (~40G in LaF_3)
- C_{3v} symmetry in La ions
- Diagonalization of quadratic coupling in the crystal C_3 axis

$$g\text{-factor of } \mathrm{Nd}^{3+} : g_{//} = 2.12, g_{\perp} = 2.68$$



Spin Hamiltonian

$$\mathcal{H} = -\hbar\gamma_N \boldsymbol{I} \cdot \boldsymbol{H} + \hbar D_{zz}(I_z^2 - \frac{I(I+1)}{3})$$

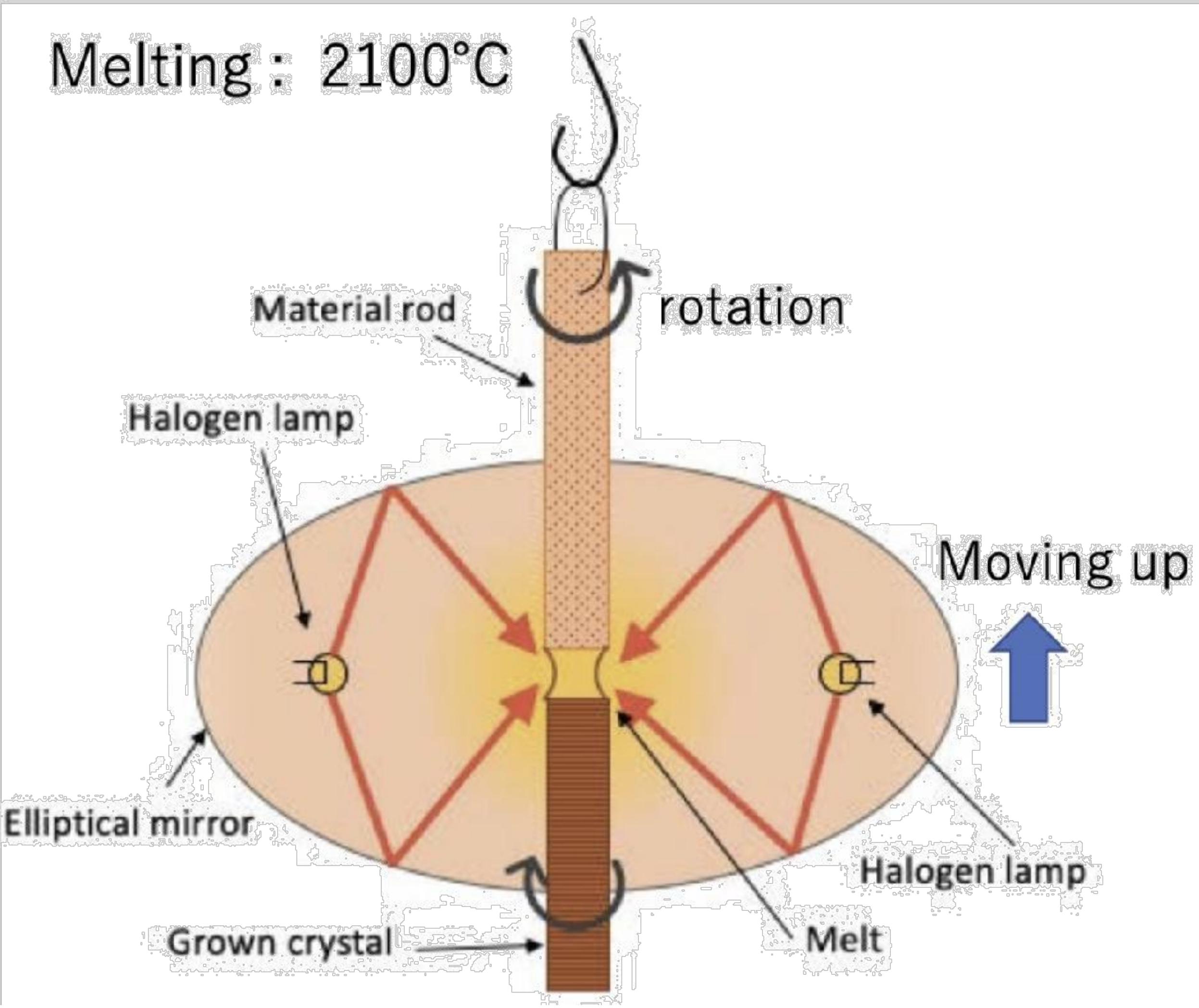
γ_N : gyromagnetic ratio ($\gamma_N/2\pi = 0.6\,\mathrm{kHz/G}$)

I : nuclear spin of La ($I = 7/2$)

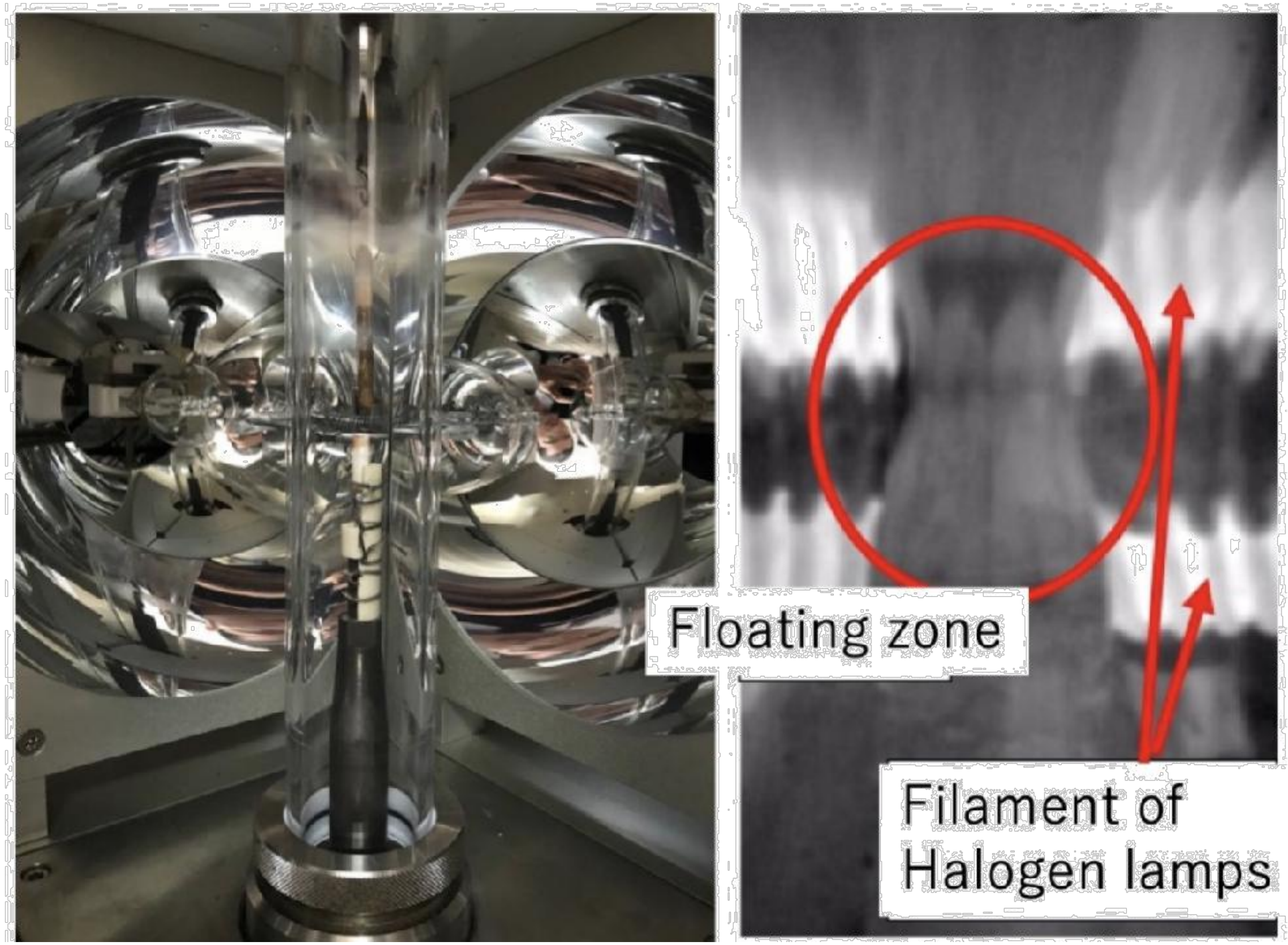
D_{zz} : quadratic coupling constant ($D_{zz}/2\pi = 0.36\,\mathrm{MHz}$)

Crystal Growth at the Institute for Material Research, Tohoku Univ.

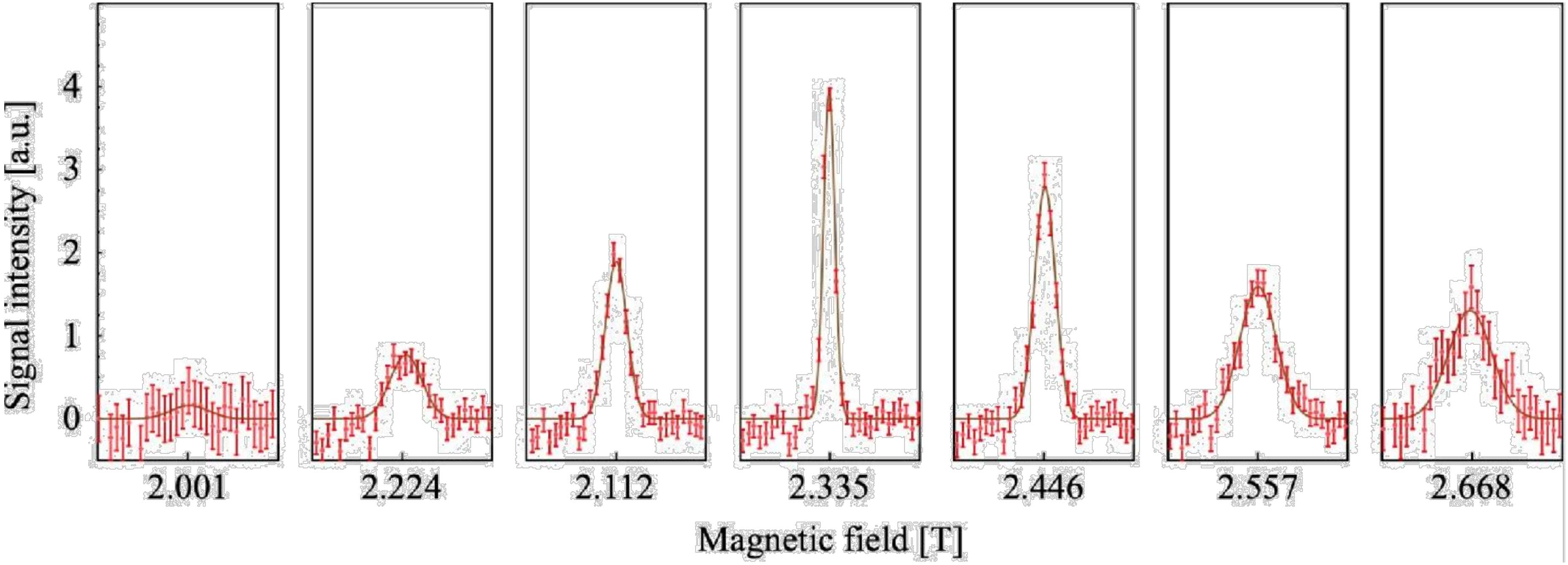
Melting : 2100°C

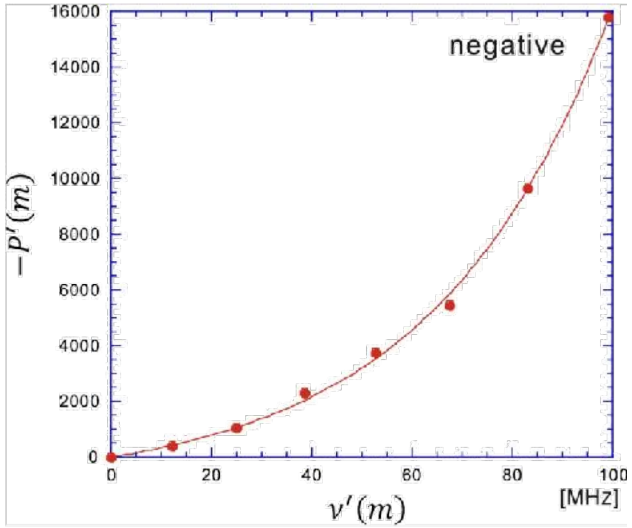


Mixed sample : powder of $La(OH)_3 + Al_2O_3$



Complete Determination of Occupancy Distribution (consistent with single spin temperature)



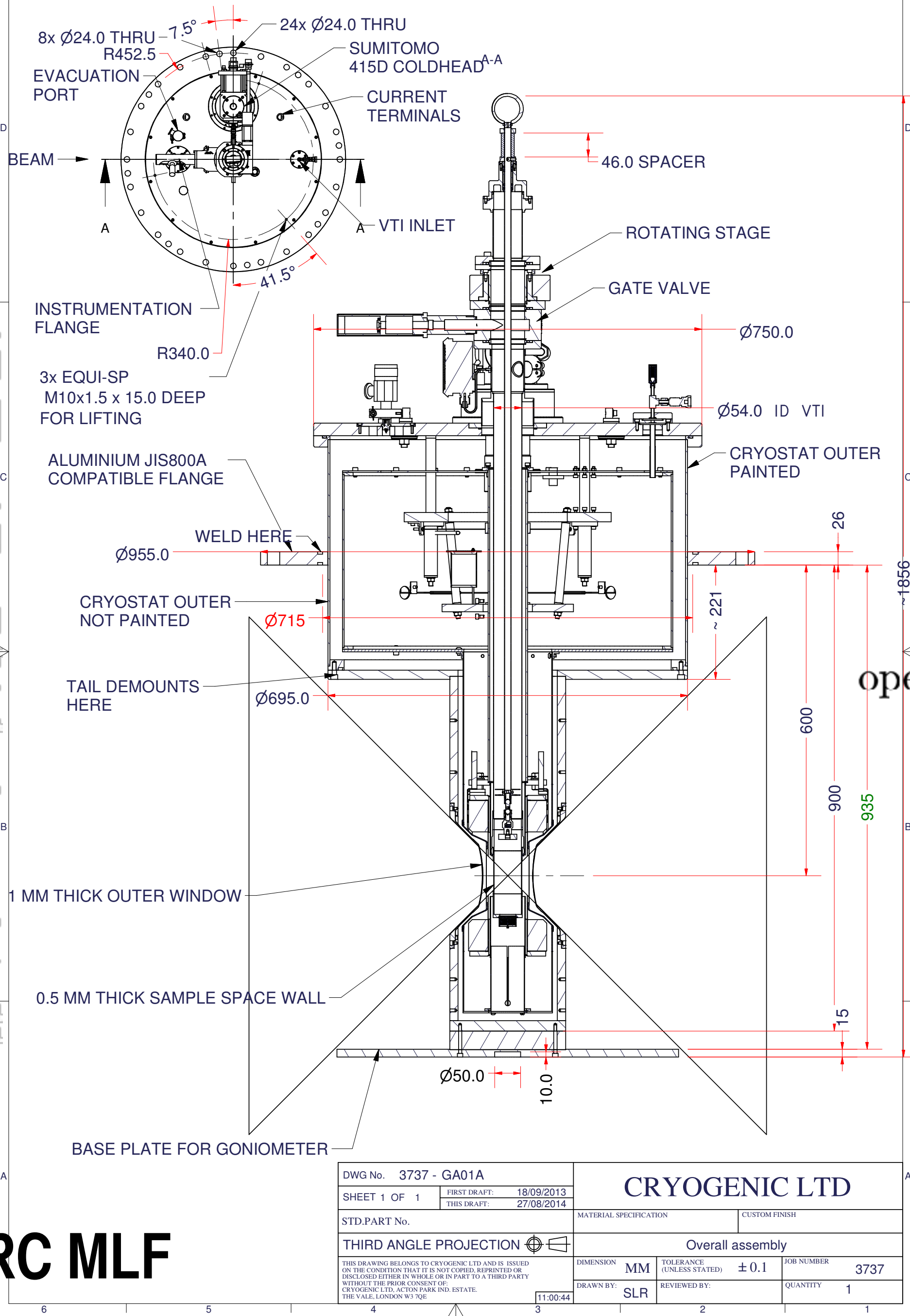


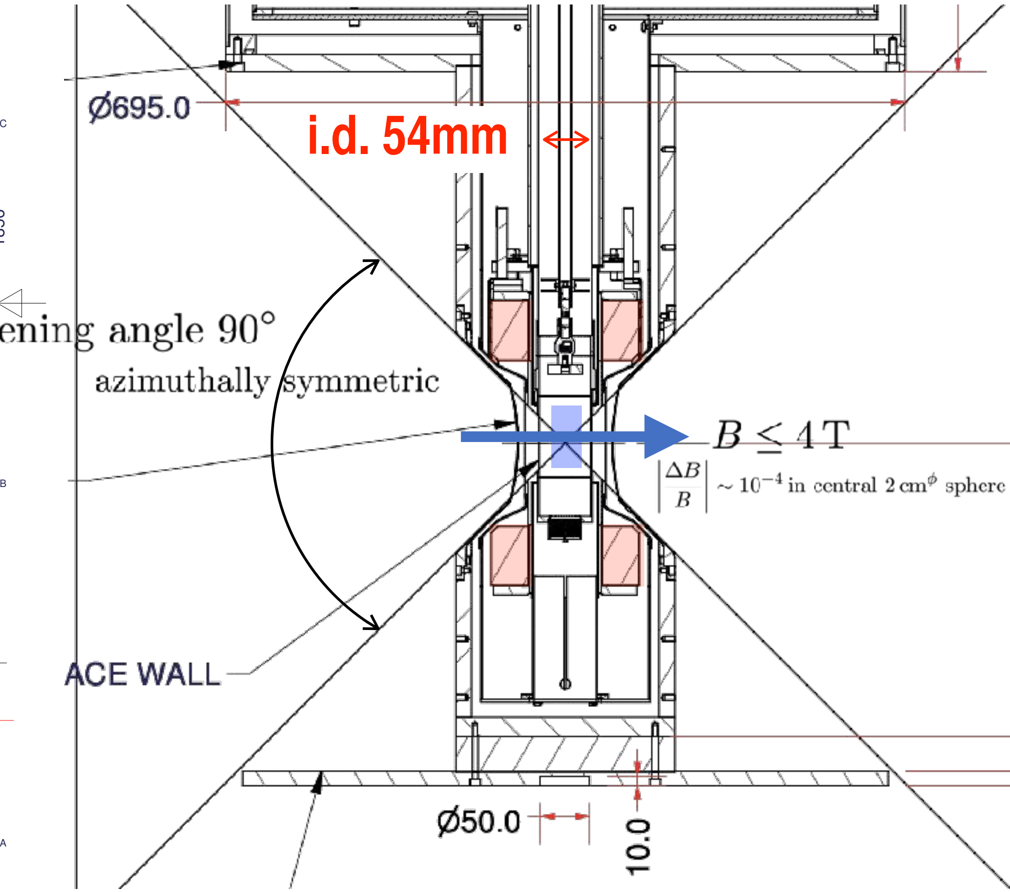
Optimization/Control of the Doping Rate of Paramagnetic Centers

Nd (mol%)		P(La)		T_1	
		2.3T,1.3K	2.3T,0.3K	2.3T,1.3K	0.1T,0.1K
0.3	comm.	small			
0.05	IMR	0.2%		15 min.	
0.03	comm.	20%	49.8%	85 min.	>60 min.
0.01	IMR	>20%	(>81%)	>120 min.	(>180 min.)
0.003	IMR	crystal growth scheduled in May and June, 2024			
0.001	IMR	enhancement was below our sensitivity			

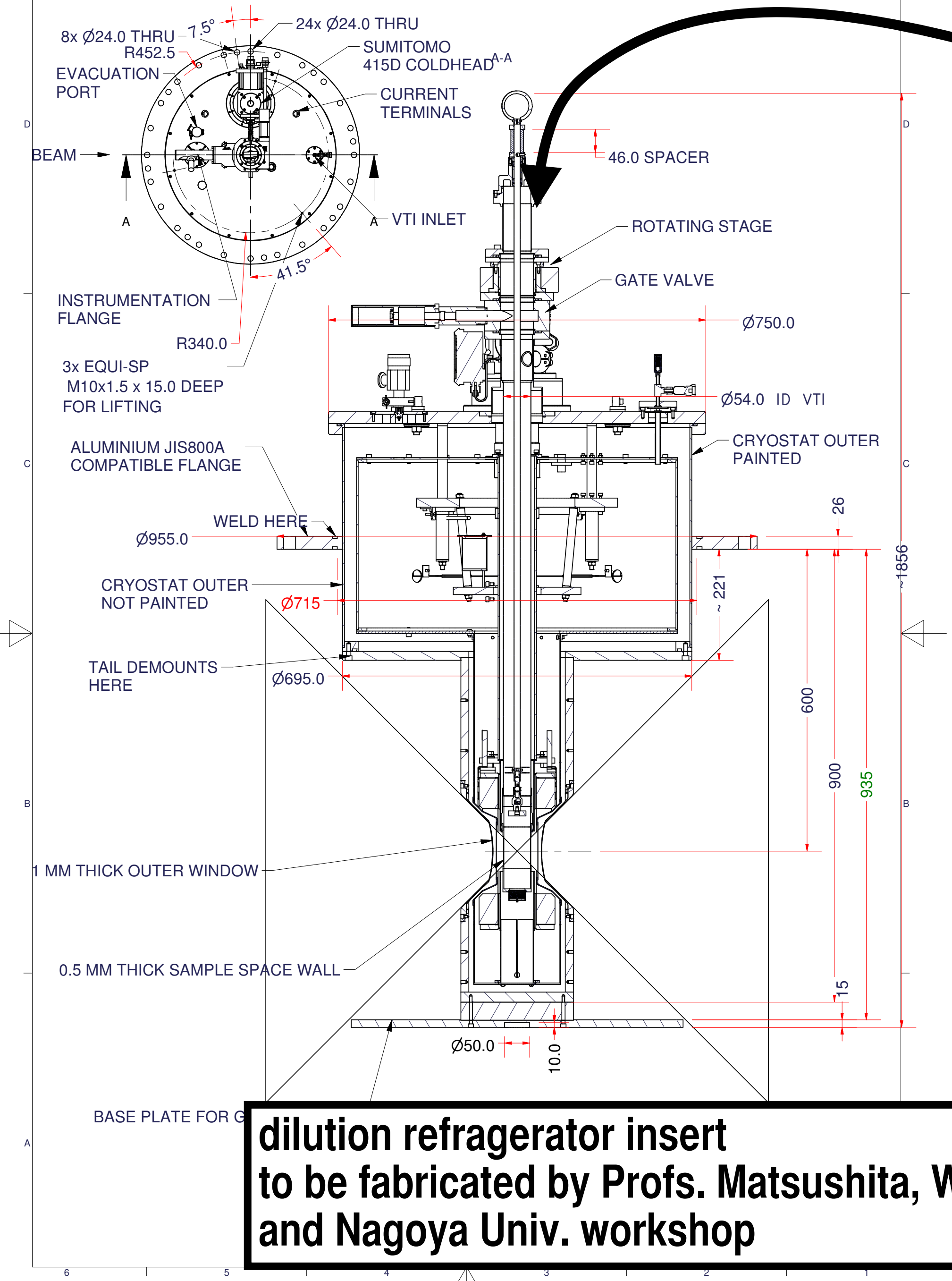
Dependence of the spin relaxation time (T_1) on the magnetic field is being measured.

for Phase-I

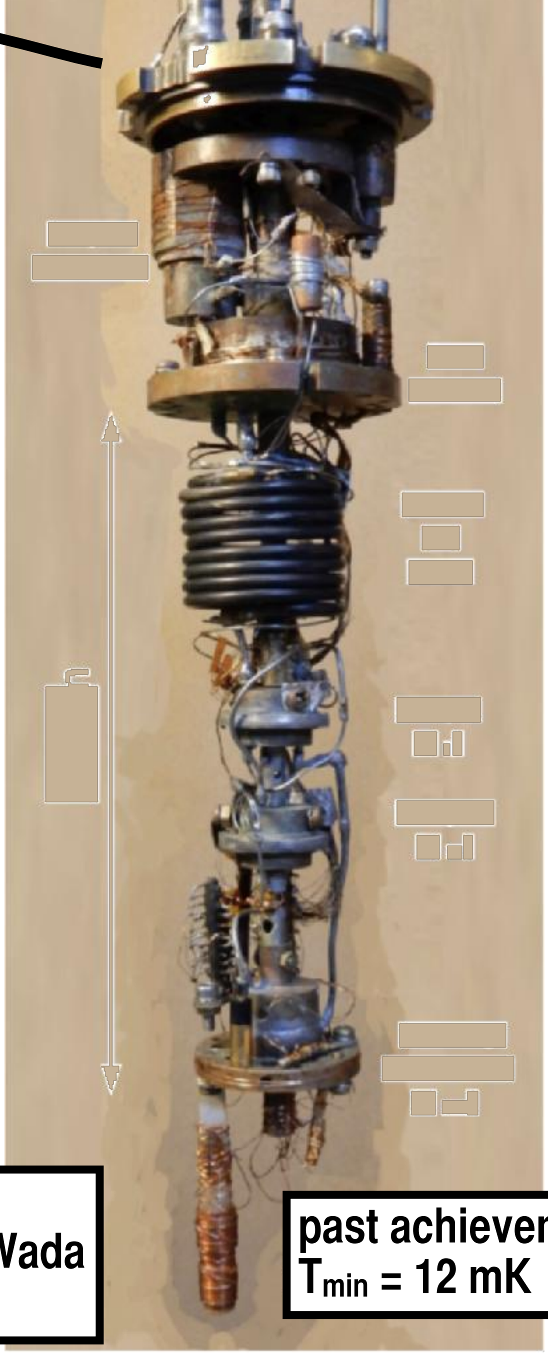




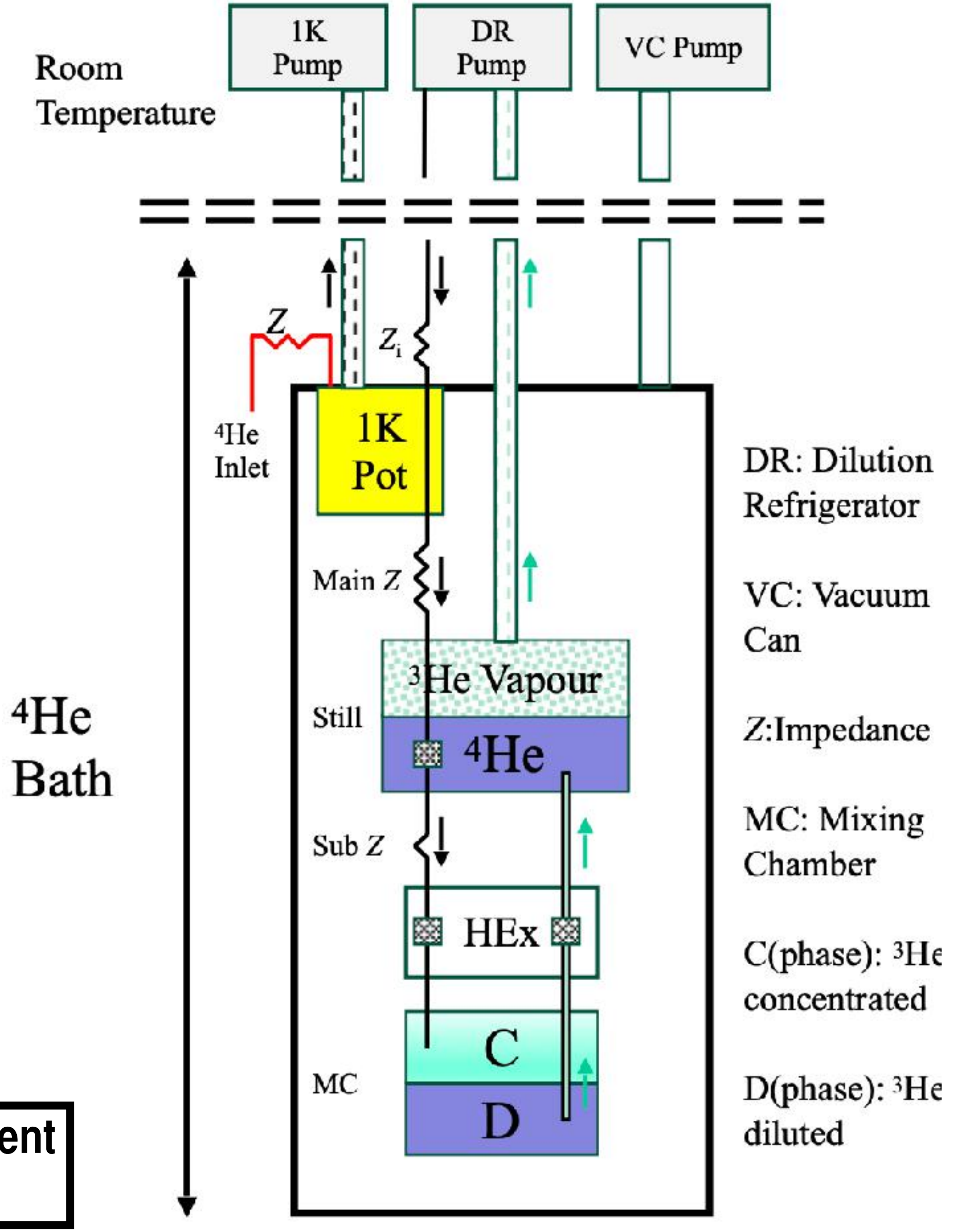
ready for use at J-PARC MLF



dilution refragerator insert
to be fabricated by Profs. Matsushita, Wada
and Nagoya Univ. workshop



past achievement
T_{min} = 12 mK



DR: Dilution Refrigerator

VC: Vacuum Can

Z:Impedance

MC: Mixing Chamber

C(phase): ^{3}He concentrated

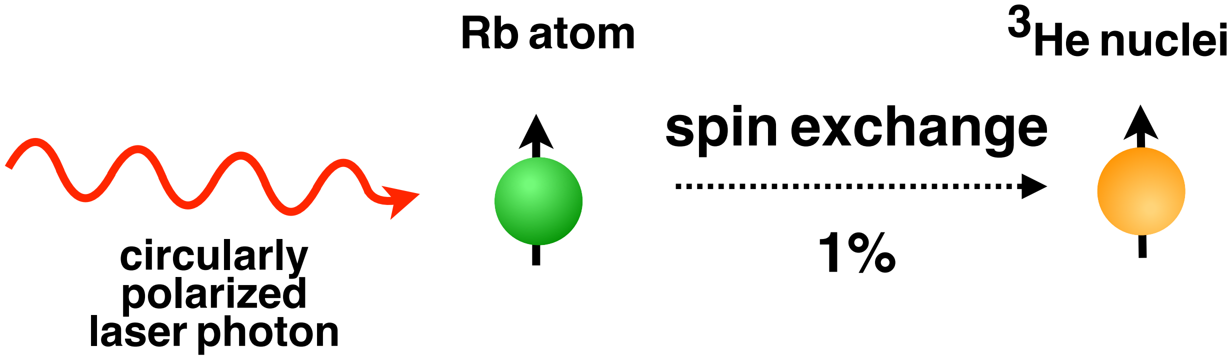
D(phase): ^{3}He diluted

^{3}He Spin Filter

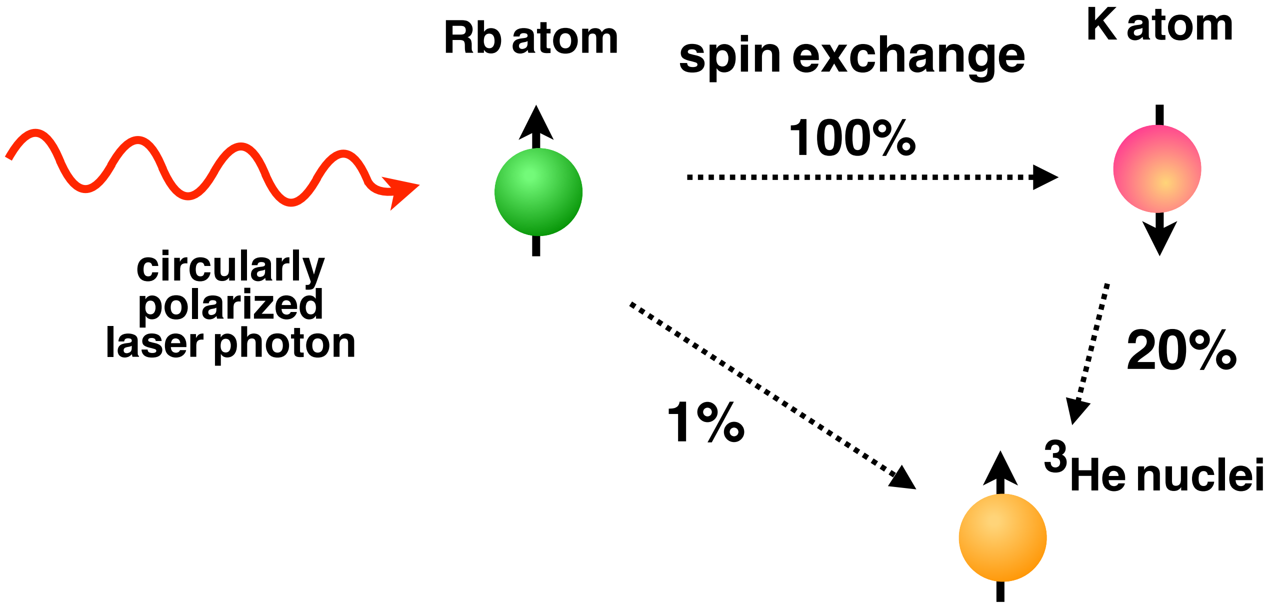
Application of Rb-K Hybrid Spin Exchange Optical Pumping (SEOP)

Hybrid SEOP $\quad {}^3$He polarization > 0.7 $\quad$ (up to ~ 0.8)

conventional SEOP



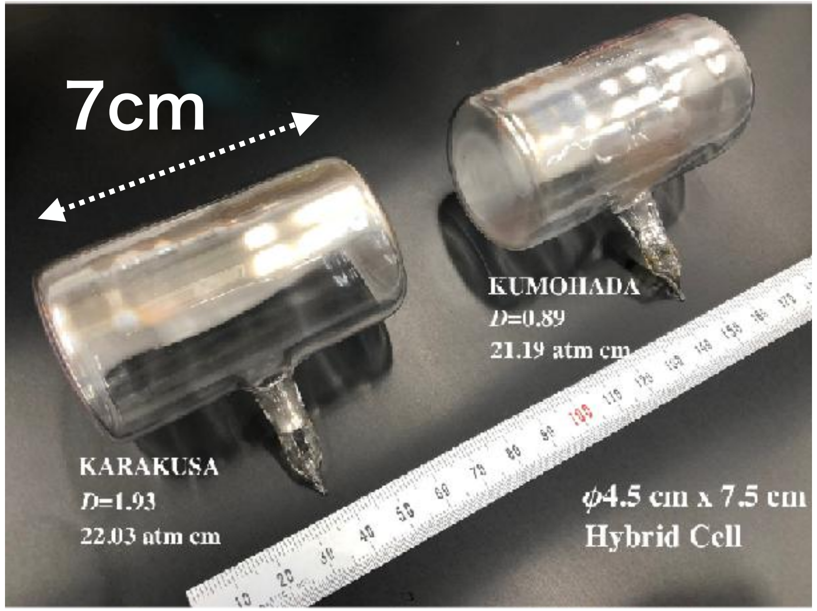
hybrid SEOP

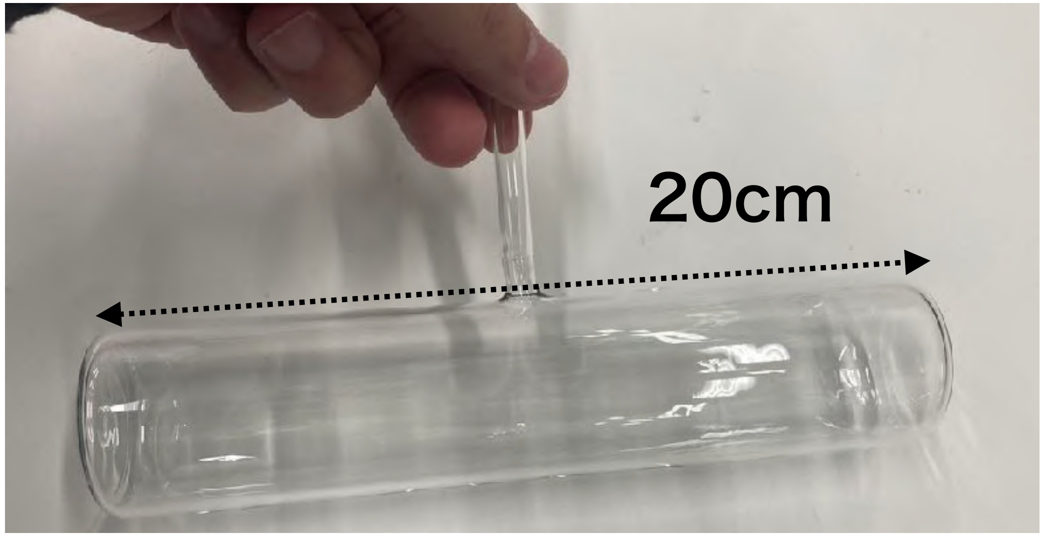


Development of Larger Cells

^{3}He gas thickness > 3 atm. × 15 cm (up to 3 atm. × 20 cm)

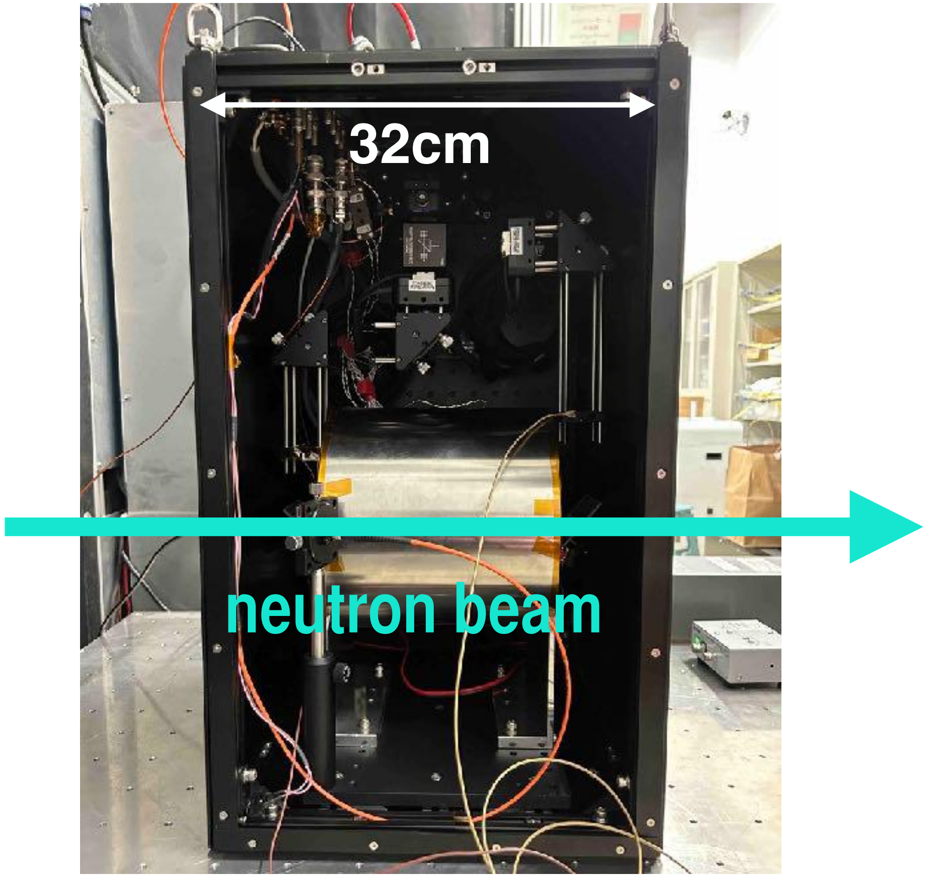
cell fiducial cross section ≥ 5 cm × 5 cm

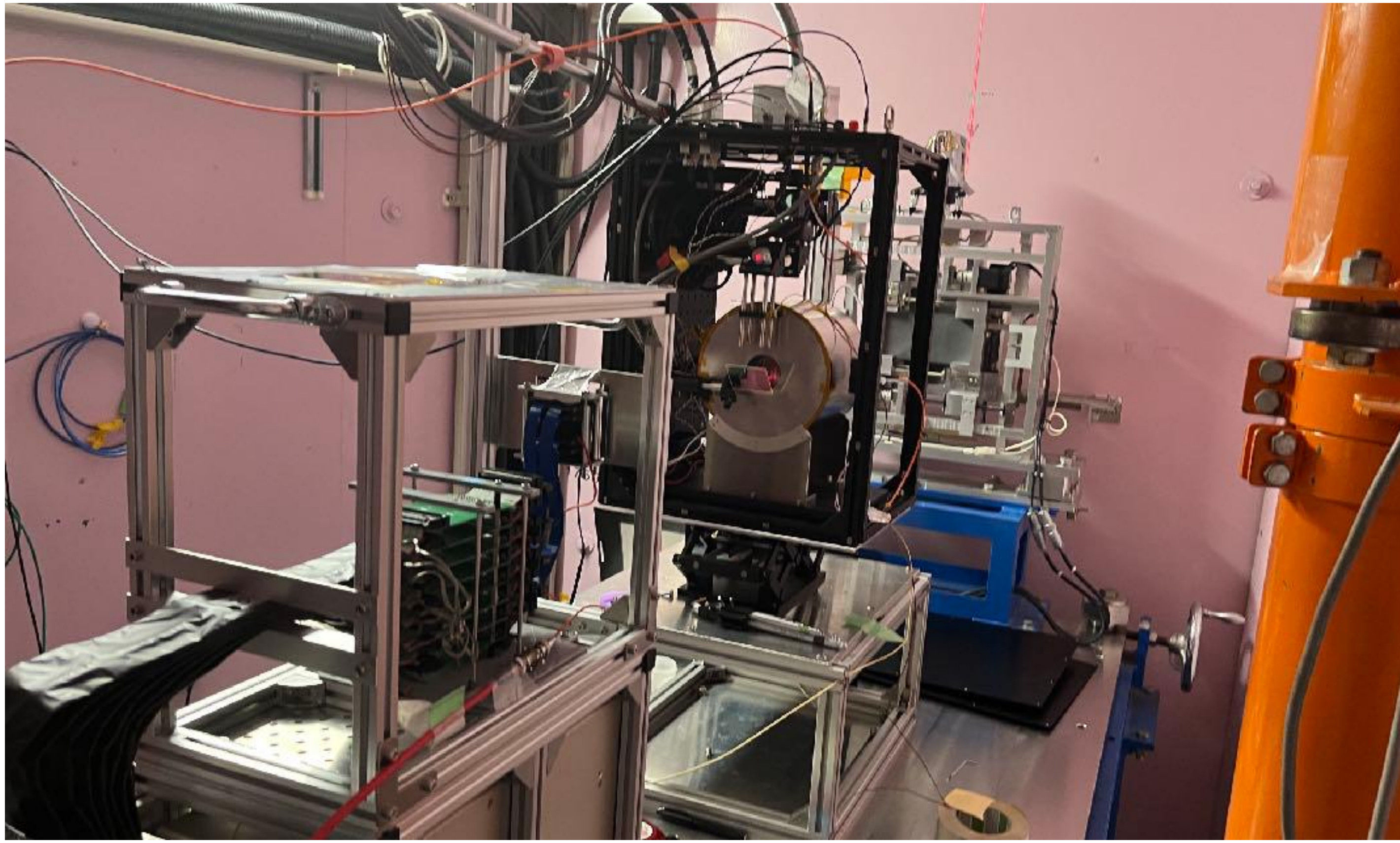




In-situ SEOP

a compact in-situ SEOP



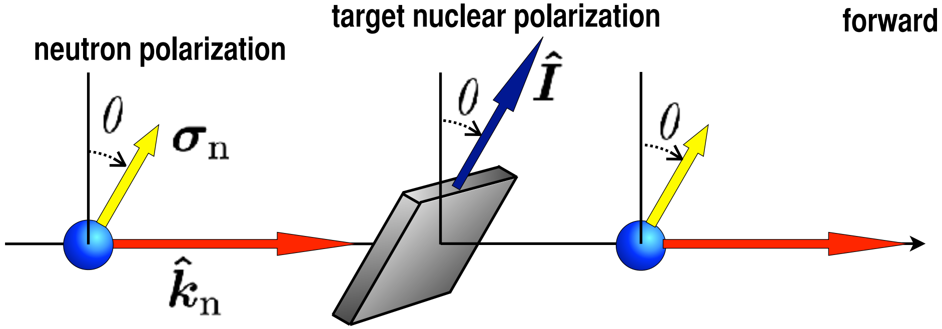


J-PARC : engineering test done in May for 4 day continuous operation

LANL : successfully operated for one beam cycle

Phase-I

NOPTREX (Phase-I) Transverse spin control is not necessary.



forward scattering amplitude $f = \alpha + \boldsymbol{\beta}\cdot\boldsymbol{\sigma}_{\rm n}$

$$\alpha = \underbrace{A'}_{\text{P-even T-even}} + P_1\underbrace{H'}_{\text{P-odd T-even}}(\hat{\boldsymbol{k}}_{\rm n}\cdot\hat{\boldsymbol{I}})$$

$$\boldsymbol{\beta} = P_1\underbrace{B'}_{\text{P-even T-even}}\hat{\boldsymbol{I}} + \left\{\underbrace{C'}_{\text{P-odd T-even}} + P_1\underbrace{K'}_{\text{P-even T-even}}(\hat{\boldsymbol{k}}_{\rm n}\cdot\hat{\boldsymbol{I}})\right\}\hat{\boldsymbol{k}}_{\rm n} + P_1\underbrace{D'}_{\text{P-odd T-odd}}(\hat{\boldsymbol{k}}_{\rm n}\times\hat{\boldsymbol{I}})$$

$$\beta = (\boldsymbol{\beta}\cdot\boldsymbol{\beta})^{1/2} \quad Z = \frac{2\pi\rho}{k_{\rm n}}z$$

$$\mathcal{A} = \mathcal{X} + \boxed{\mathcal{Y}}$$

T-violation
P-odd T-odd

$$\mathcal{X} = 4e^{-2\mathrm{Im}\alpha}Z\,\mathrm{Im}\left[\frac{\sin\beta}{\beta}\cos\beta^*\left\{P_1\underbrace{B'}_{\text{P-even T-even}} - \mu_{\rm eff}\underbrace{B_{\rm ext}}_{\text{印加磁場}} + \underbrace{C'}_{\text{P-odd T-even}}\cos\theta + P_1\underbrace{K'}_{\text{P-even T-even}}\cos^2\theta\right\}\right]$$

$$\mathcal{P} = \mathcal{X} - \boxed{\mathcal{Y}}$$

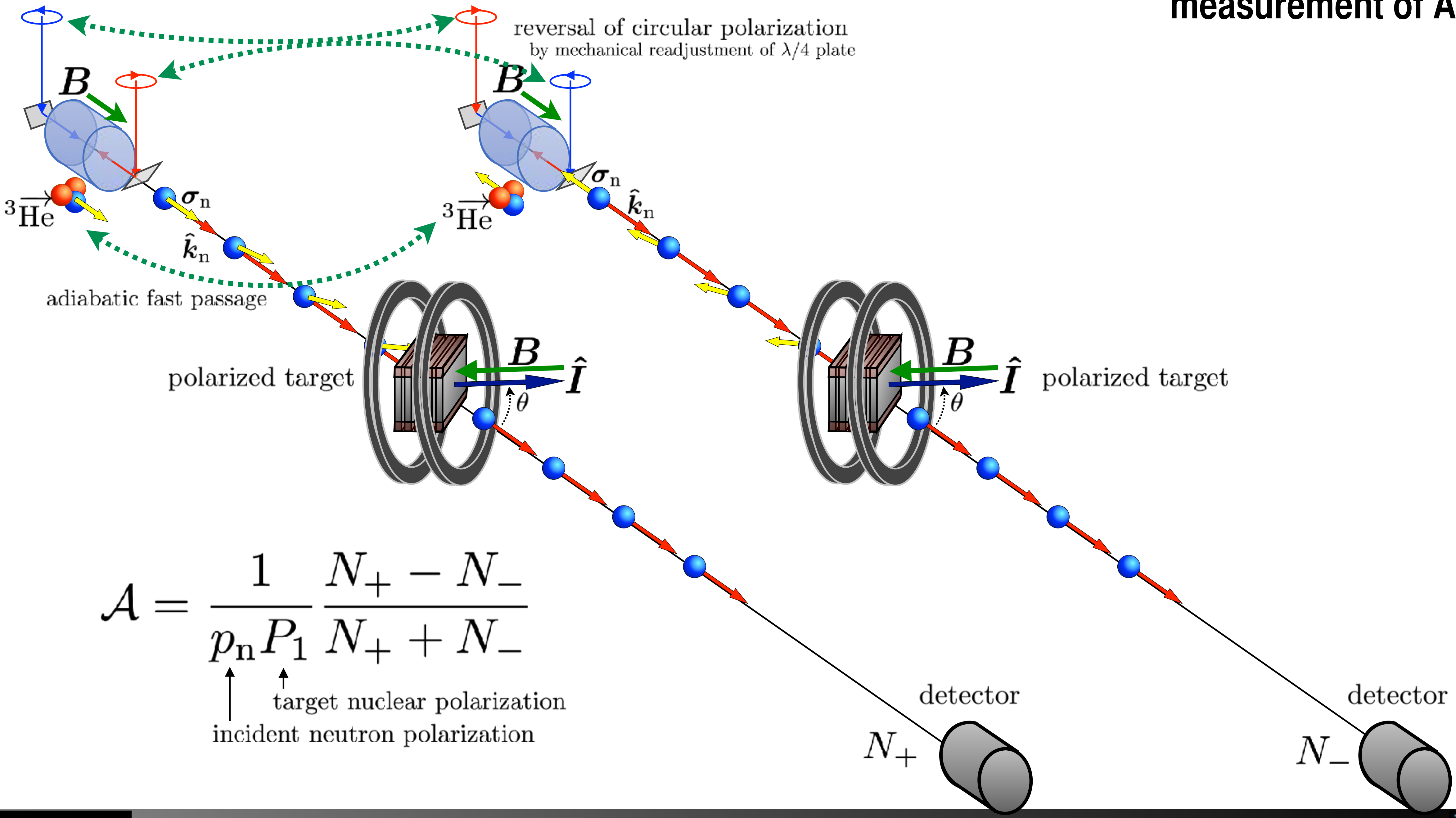
$$\mathcal{Y} = 4e^{-2\mathrm{Im}\alpha}\boxed{\left|\frac{\sin\beta}{\beta}\right|^2}Z^2P_1\cos\theta\sin^2\theta\,\mathrm{Im}\underbrace{D'^2}_{\text{P-odd T-odd}}\underbrace{K'}_{\text{P-even T-even}}$$

Sensitivity deterioration due to magnetic and pseudomagnetic spin rotation cancellation remains also in this case.

Step-1: Dynamic Nuclear Polarization at $B_{\rm ext}$ ~ 2.3 T and T ~ 1 K

Step-2: Spin Freezing at $B_{\rm ext}$ ~ 0.1 T and T ≤ 0.1 K

measurement of A

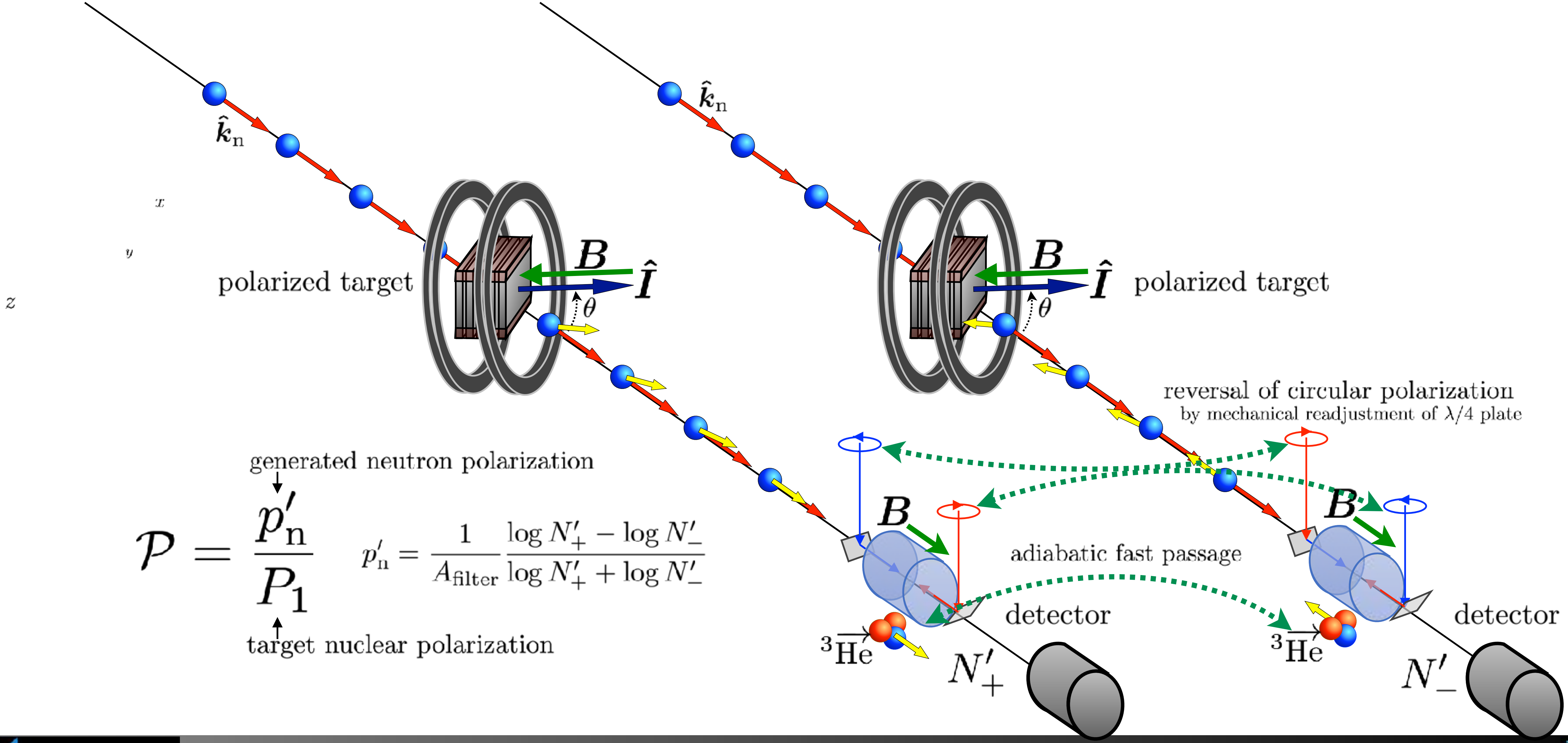


$$\mathcal{A} = \frac{1}{p_\mathrm{n} P_1} \frac{N_+ - N_-}{N_+ + N_-}$$

target nuclear polarization

incident neutron polarization

measurement of P



generated neutron polarization

$$\mathcal{P} = \frac{p'_\mathrm{n}}{P_1} \qquad p'_\mathrm{n} = \frac{1}{A_\mathrm{filter}} \frac{\log N'_+ - \log N'_-}{\log N'_+ + \log N'_-}$$

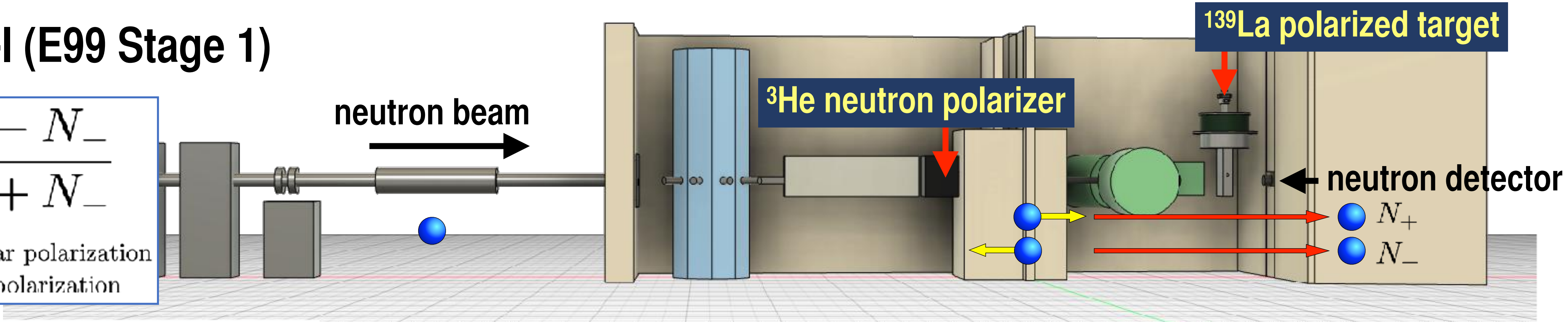
target nuclear polarization

NOPTREX Phase-I (E99 Stage 1)

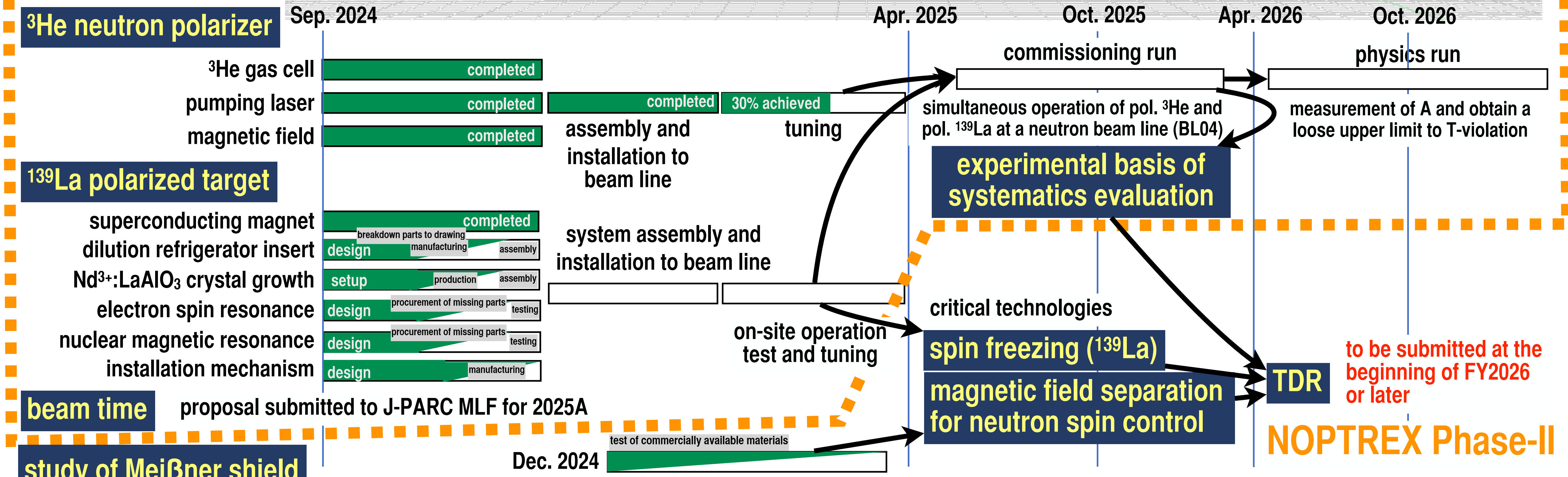
$$A_{\hat{I}} = \frac{1}{p_n P_1} \frac{N_+ - N_-}{N_+ + N_-}$$

target nuclear polarization

incident neutron polarization



NOPTREX Phase-I @ MLF BL04



^{3}He neutron polarizer

- ^{3}He gas cell
- pumping laser
- magnetic field

assembly and installation to beam line

tuning

^{139}La polarized target

- superconducting magnet
- dilution refrigerator insert
- Nd^{3+}:LaAlO$_3$ crystal growth
- electron spin resonance
- nuclear magnetic resonance
- installation mechanism

system assembly and installation to beam line

on-site operation test and tuning

beam time

proposal submitted to J-PARC MLF for 2025A

study of Meißner shield

Dec. 2024

commissioning run

simultaneous operation of pol. ^{3}He and pol. ^{139}La at a neutron beam line (BL04)

experimental basis of systematics evaluation

physics run

measurement of A and obtain a loose upper limit to T-violation

critical technologies

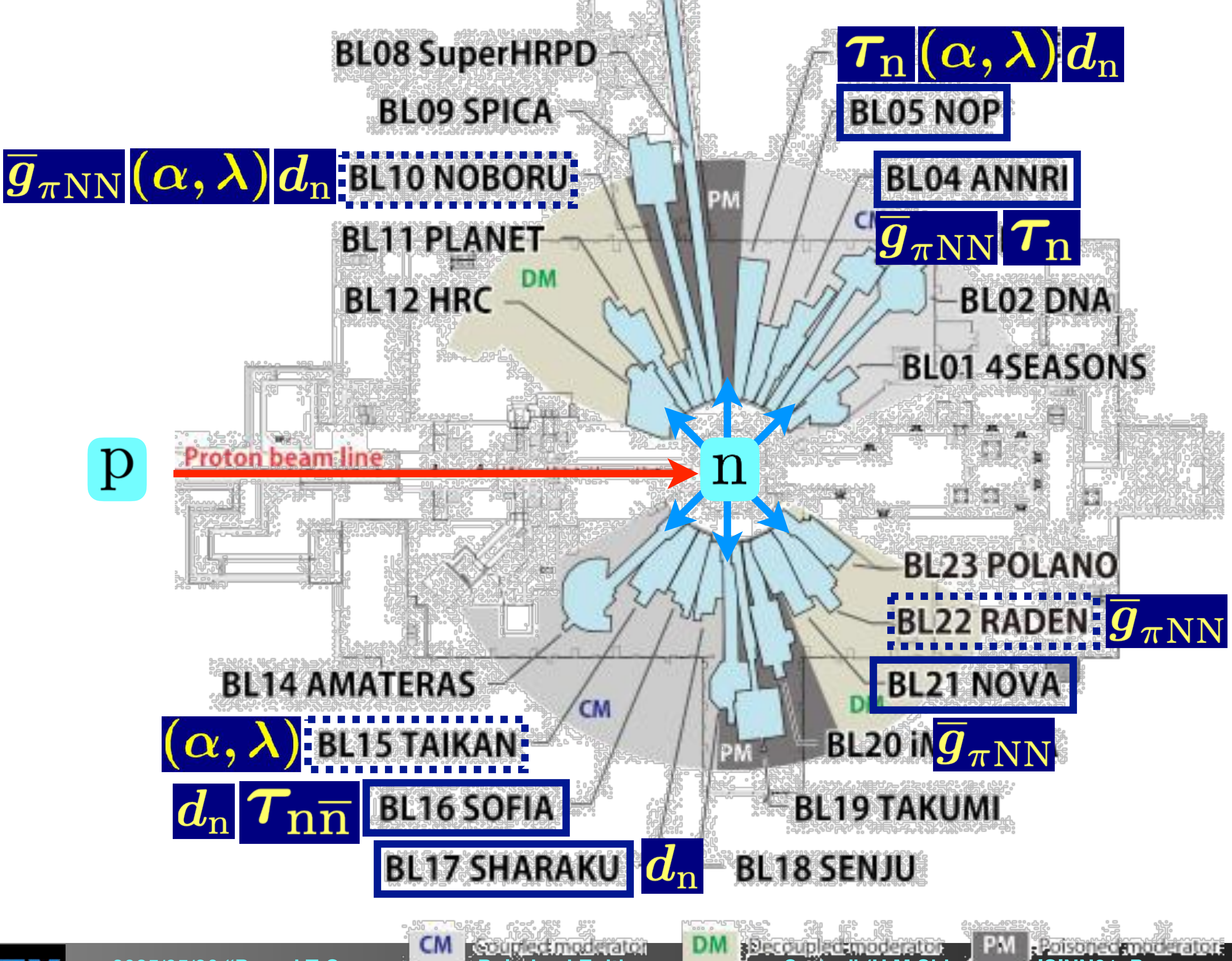
spin freezing (^{139}La)

magnetic field separation for neutron spin control

TDR

to be submitted at the beginning of FY2026 or later

NOPTREX Phase-II



BL08 SuperHRPD

BL09 SPICA

$\bar{g}_{\pi \mathrm{NN}}$ (α, λ) d_n BL10 NOBORU

BL11 PLANET

BL12 HRC

DM

PM

τ_n (α, λ) d_n

BL05 NOP

BL04 ANNRI

CM

$\bar{g}_{\pi \mathrm{NN}}$ τ_n

BL02 DNA

BL01 4SEASONS

p

Proton beam line

n

BL23 POLANO

BL22 RADEN $\bar{g}_{\pi \mathrm{NN}}$

BL21 NOVA

DM

BL20 i$\bar{g}_{\pi \mathrm{NN}}$

BL19 TAKUMI

BL14 AMATERAS

CM

(α, λ) BL15 TAIKAN

PM

d_n $\tau_{\mathrm{n}\bar{\mathrm{n}}}$ BL16 SOFIA

BL17 SHARAKU d_n

BL18 SENJU

CM Coupled moderator

DM Decoupled moderator

PM Poisoned moderator

Unknown force search

Extra-dimension, Dark energy

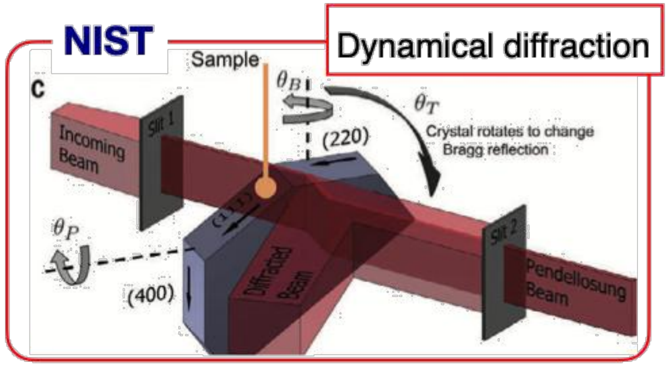
(α, λ)

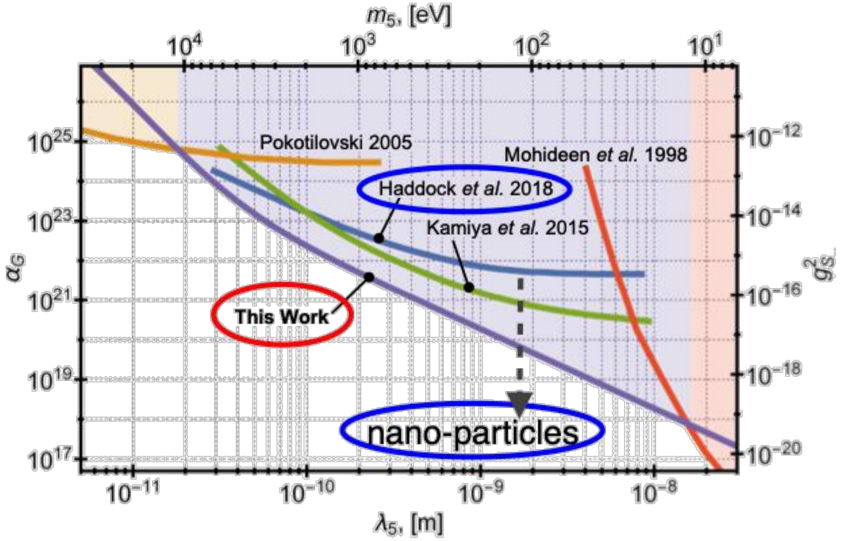
New limit for Yukawa-type intermediate force

$$V(r) = -G_N \frac{mM}{r}(1 + \alpha\, e^{-r/\lambda})$$

NIST

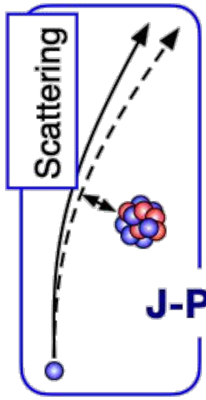
Dynamical diffraction





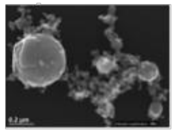
C. C. Haddock, et al., Phys. Rev. D97, 062002 (2018)

B. Heacock et. al., Science 373 6560 (2021)



J-PARC BL05 NOP

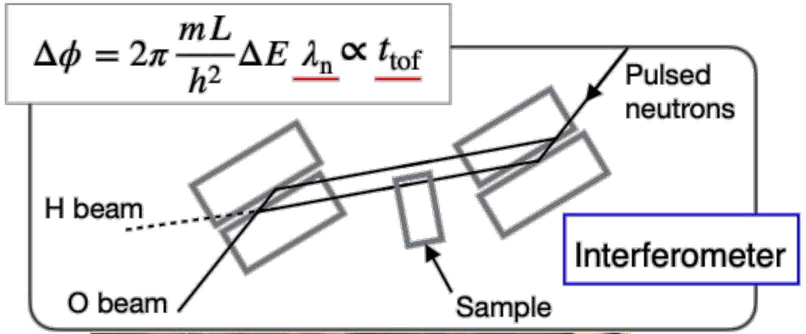
nano-particles

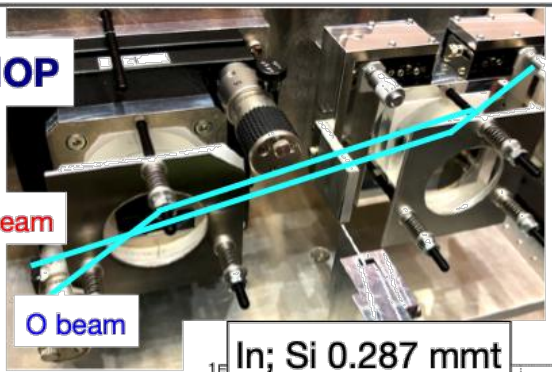


Hydrogen storage alloy

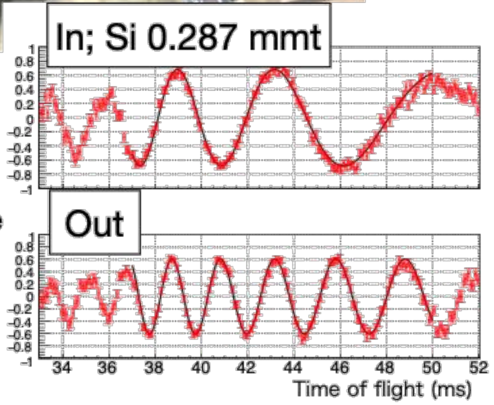
New interferometer with high precision

$$\Delta\phi = 2\pi \frac{mL}{h^2}\Delta E\ \underline{\lambda_n} \propto \underline{t_{\mathrm{tof}}}$$





Phase-shift was observed due to refractive index of sample

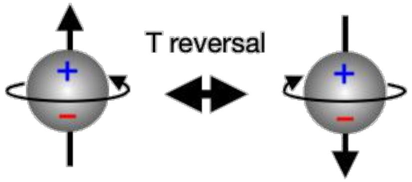


Precision measurements of neutron-nuclear scattering lengths were demonstrated.

T. Fujiie, et al., PRL 132, 023402 (2024)

d_n

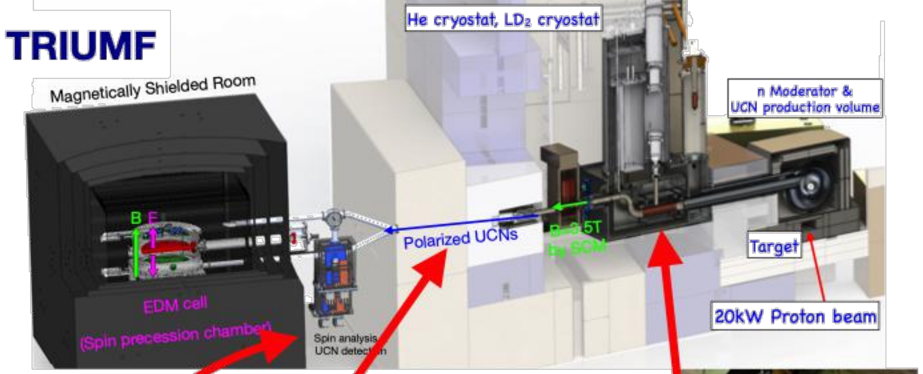
Neutron EDM using high-flux UCNs

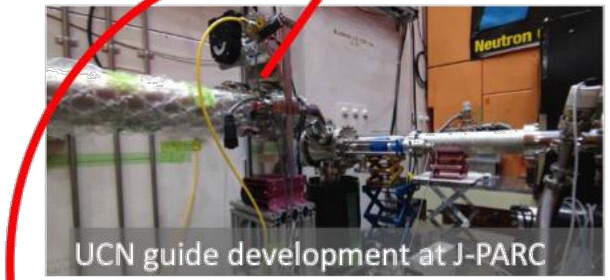


Permanent EDM signals
Time-reversal violation.

TUCAN Source & nEDM Spectrometer

TRIUMF




UCN guide development at J-PARC

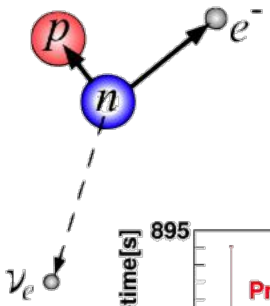

Spin Analyzer Development at J-PARC

S. Ahmed, et.al.,
Phys. Rev. C 99, 025503 (2019)

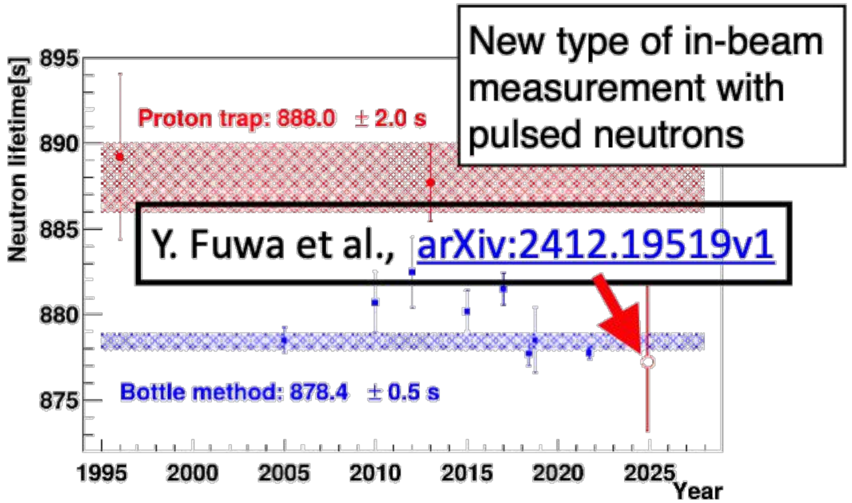
J-PARC BL05 NOP

τ_n

Neutron Lifetime

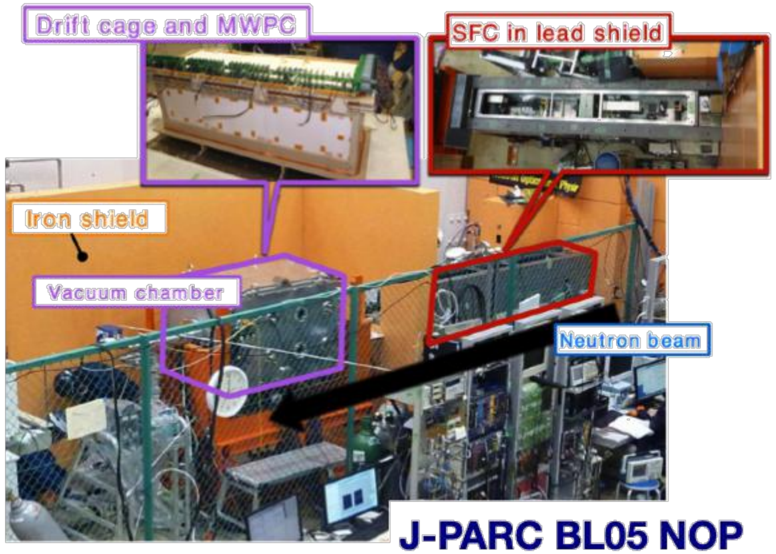


CKM Unitarity check
Big Bang Nucleosynthesis
Decay to dark channel?



New type of in-beam measurement with pulsed neutrons

Y. Fuwa et al., arXiv:2412.19519v1



J-PARC BL05 NOP

B, B-L nonconservation

nnbar oscillation: spontaneous transition from neutron to antineutron

$$n \xrightarrow[\Delta(B\text{-}L)=-2]{\Delta B=-2 \quad \Delta L=0} \bar{n}$$

$$\mathcal{L} = \overline{\psi} M \psi$$

$$\psi = \begin{bmatrix} n \\ n \end{bmatrix} \quad M = \begin{bmatrix} m_n & \delta m \\ \delta m & m_n \end{bmatrix} \qquad |n_{1,2}\rangle = \frac{1}{\sqrt{2}}(|n\rangle \pm |\bar{n}\rangle)$$

$$m_{1,2} = m_n \pm \delta m$$

$$P_{n\to\bar{n}} = \sin^2 \frac{\delta m}{\hbar} t \simeq \left(\frac{t}{\tau_{n\bar{n}}}\right)^2 \qquad \tau_{n\bar{n}} = \frac{\hbar}{\delta m}$$

$$\tau_{\mathrm{n\bar{n}},\mathrm{free}} > 0.86 \times 10^8\ \mathrm{s}\ (\mathrm{CL}90\%)$$

M.Baldo-Ceolin et al., Z. Phys. C63 (1994) 409

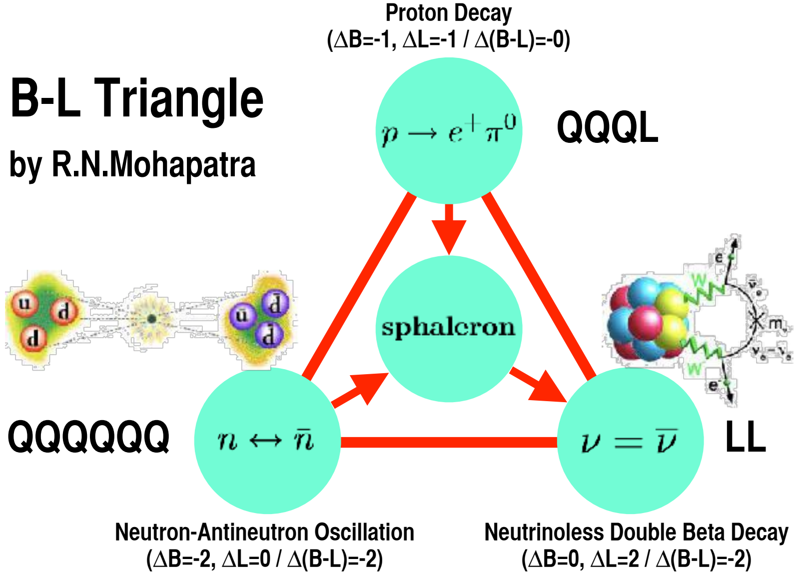
2-3 order improvement

$$\tau_{\mathrm{n\bar{n}}} = \mathcal{O}(10^{10}\mathrm{s})$$

K.S.Babu et al., Phys. Rev. D87(2013)115019

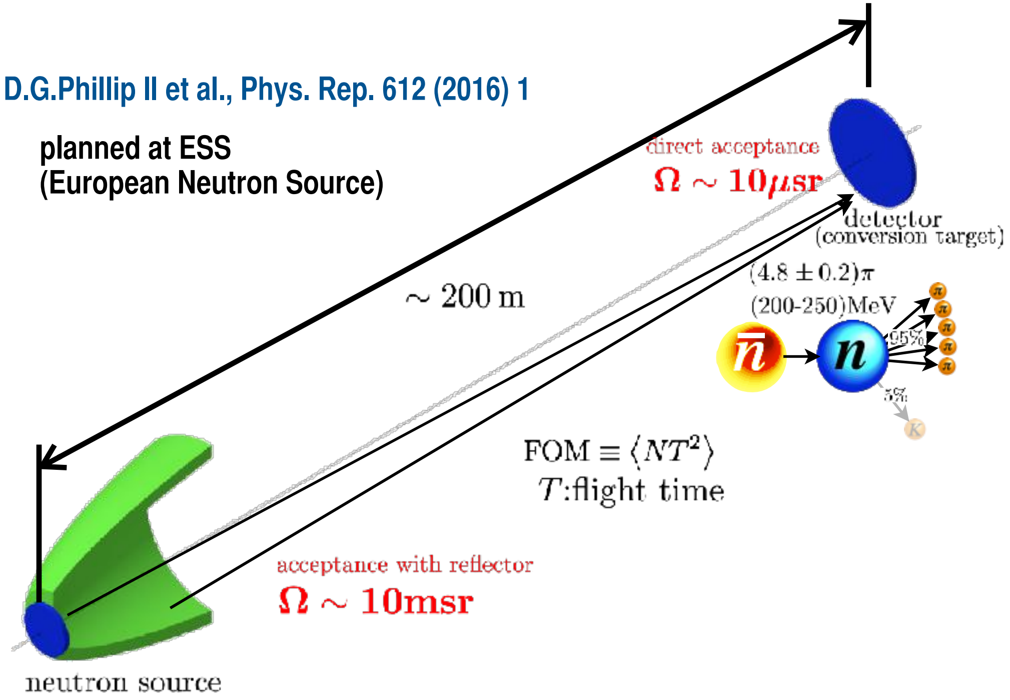
B-L Triangle

by R.N.Mohapatra



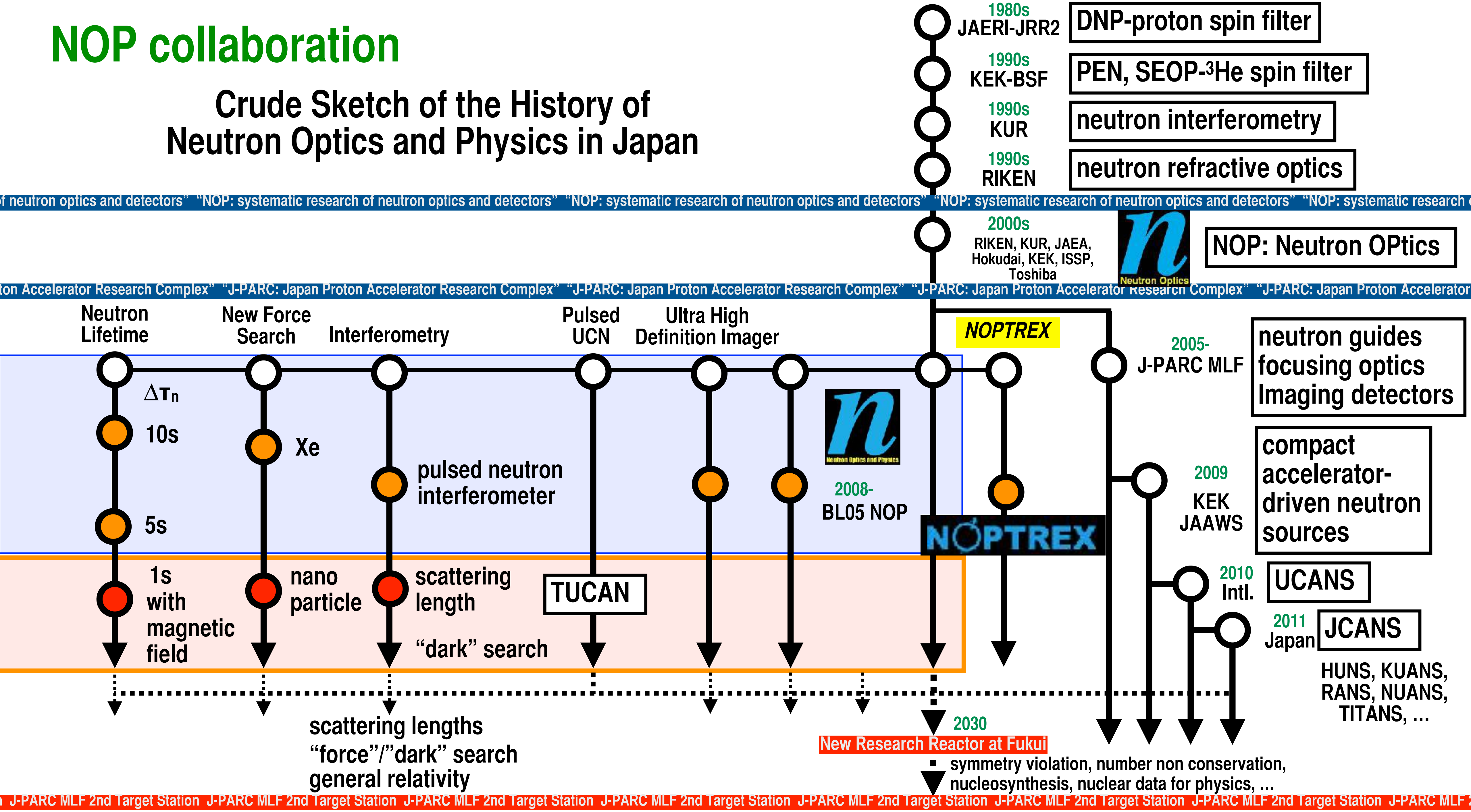
D.G.Phillip II et al., Phys. Rep. 612 (2016) 1

planned at ESS
(European Neutron Source)



NOP collaboration

Crude Sketch of the History of Neutron Optics and Physics in Japan



1980s JAERI-JRR2 — DNP-proton spin filter

1990s KEK-BSF — PEN, SEOP-^{3}He spin filter

1990s KUR — neutron interferometry

1990s RIKEN — neutron refractive optics

f neutron optics and detectors” “NOP: systematic research of neutron optics and detectors” “NOP: systematic research of neutron optics and detectors” “NOP: systematic research of neutron optics and detectors” “NOP: systematic research o

2000s
RIKEN, KUR, JAEA, Hokudai, KEK, ISSP, Toshiba — NOP: Neutron OPtics

ton Accelerator Research Complex” “J-PARC: Japan Proton Accelerator Research Complex” “J-PARC: Japan Proton Accelerator Research Complex” “J-PARC: Japan Proton Accelerator Research Complex” “J-PARC: Japan Proton Accelerator

Neutron Lifetime
$\Delta\tau_n$
10s
5s
1s with magnetic field

New Force Search
Xe
nano particle

Interferometry
pulsed neutron interferometer
scattering length
“dark” search

Pulsed UCN
TUCAN

Ultra High Definition Imager

2008-
BL05 NOP

NOPTREX

2005-
J-PARC MLF — neutron guides focusing optics Imaging detectors

2009
KEK JAAWS — compact accelerator-driven neutron sources

2010
Intl. — UCANS

2011
Japan — JCANS

HUNS, KUANS, RANS, NUANS, TITANS, ...

scattering lengths
“force”/”dark” search
general relativity

2030
New Research Reactor at Fukui
symmetry violation, number non conservation, nucleosynthesis, nuclear data for physics, ...

n J-PARC MLF 2nd Target Station J-PARC MLF 2nd Target Station J-PARC MLF 2nd Target Station J-PARC MLF 2nd Target Station J-PARC MLF 2nd Target Station J-PARC MLF 2nd Target Station J-PARC MLF 2nd Target Station J-PARC MLF 2

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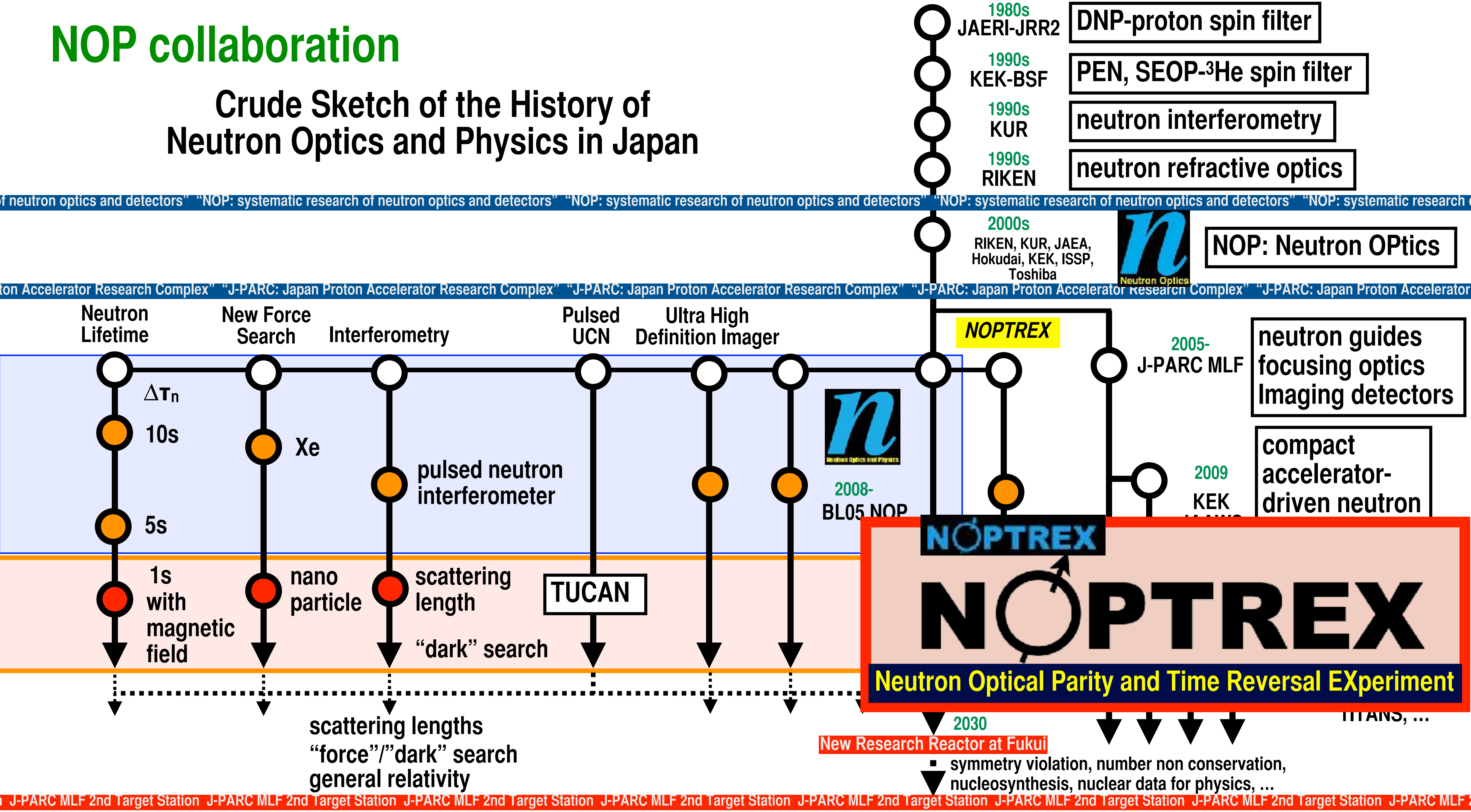

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Neutron Lifetime

New Force Search

Interferometry

Pulsed UCN

Ultra High Definition Imager

NOPTREX

2005- J-PARC MLF — neutron guides focusing optics Imaging detectors

$\Delta\tau_n$

10s

5s

1s with magnetic field

Xe

nano particle

pulsed neutron interferometer

scattering length

"dark" search

TUCAN

Neutron Optics and Physics

2008- BL05 NOP

2009 KEK — compact accelerator-driven neutron

TITANS, ...

NOPTREX

Neutron Optical Parity and Time Reversal EXperiment

scattering lengths
"force"/"dark" search
general relativity

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J-PARC MLF 2nd Target Station J-PARC MLF 2nd Target Station J-PARC MLF 2nd Target Station J-PARC MLF 2nd Target Station J-PARC MLF 2nd Target Station J-PARC MLF 2nd Target Station J-PARC MLF 2nd Target Station J-PARC MLF