Fundamental Physics with Optically Controlled Neutrons

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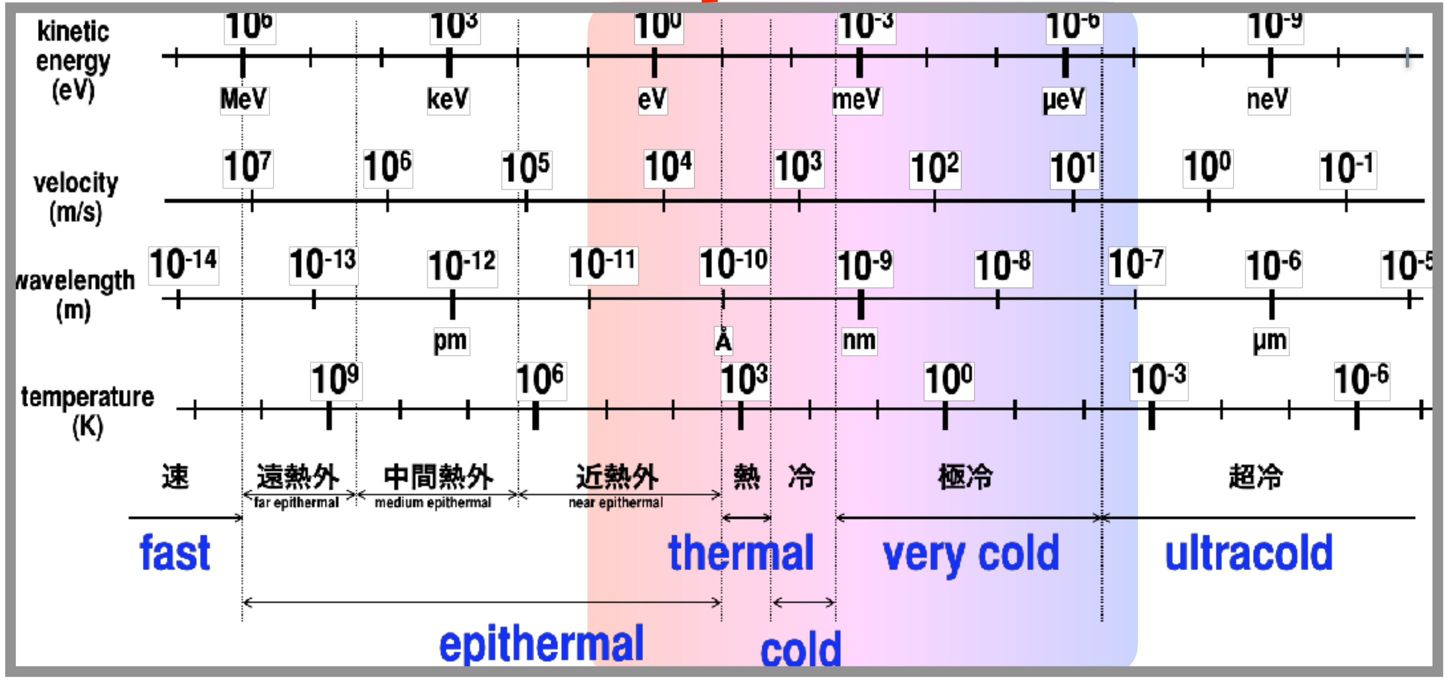
Experimental activities on fundamental physics using neutrons are in progress in Japan at the J-PARC pulsed spallation source and the research reactor JRR3. Research items are the measurement of neutron lifetime with the electron detection, differential scattering cross section for the search for new Yukawa interaction terms possibly connected to the anomalous short-range gravity, neutron interferometry for the determination of neutron scattering length and the study of neutron-induced compound nuclear states which exhibit largely enhanced parity-violation for possible new search for the breaking of time-reversal-invariance. These activities have been developed on the basis of neutron optics which can be most efficiently in the energy range of VCN and UCN. Possible improvement of fundamental physics in combination of advanced optics and VCN/UCN source at the INP will be discussed together with the on-going planning of new reactor source scheduled around 2030 in Japan.

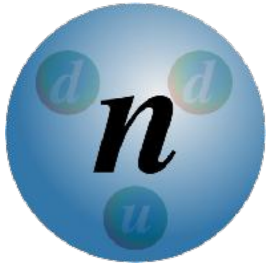
Fundamental Physics with Optically Controlled Neutrons

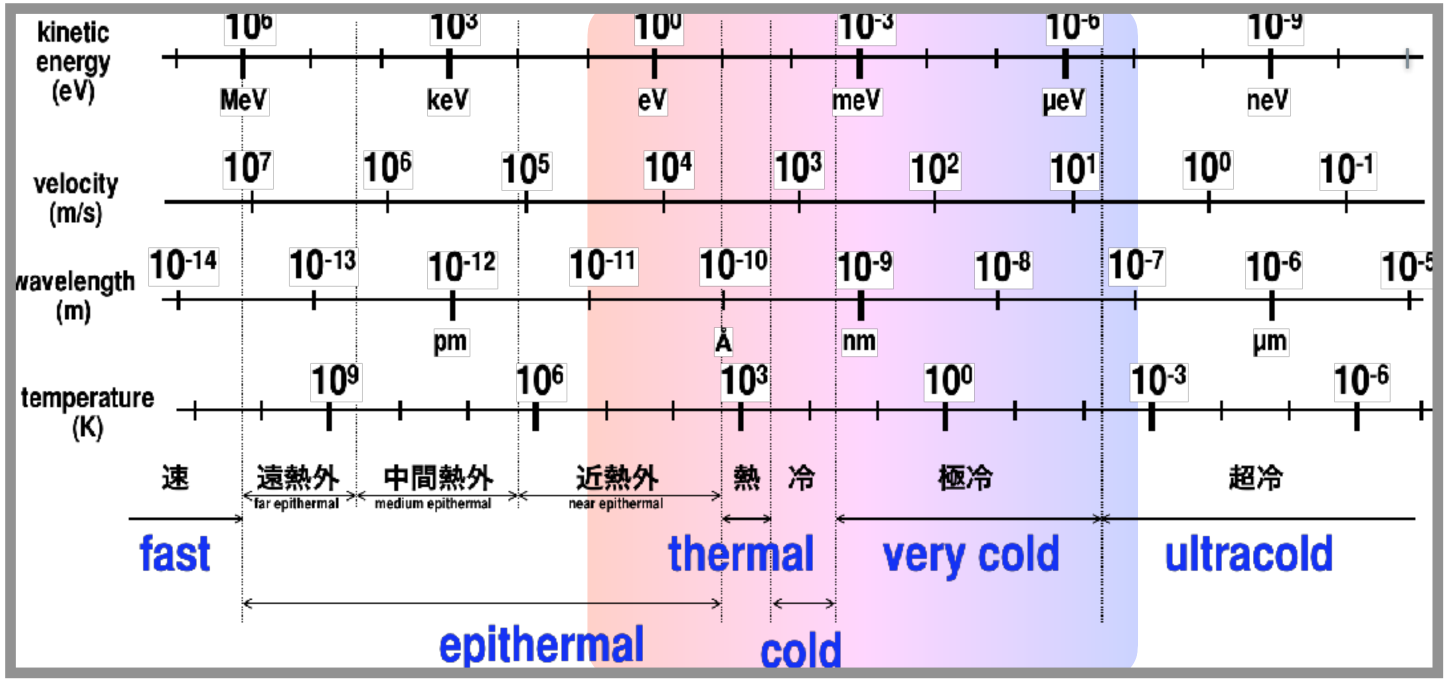
Space-Time **Symmetry**
Number Conservation

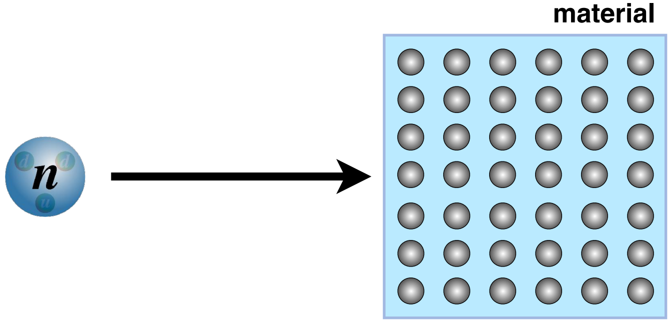
β-decay
Fermion Interference
New Force Search
Gravity
...

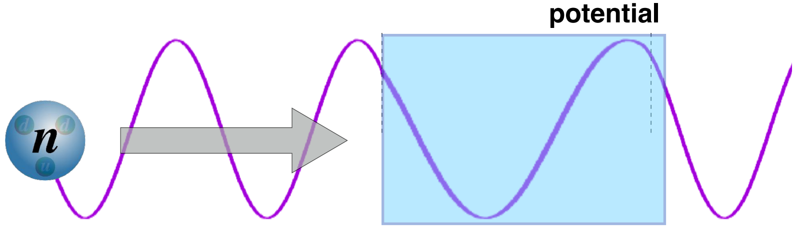


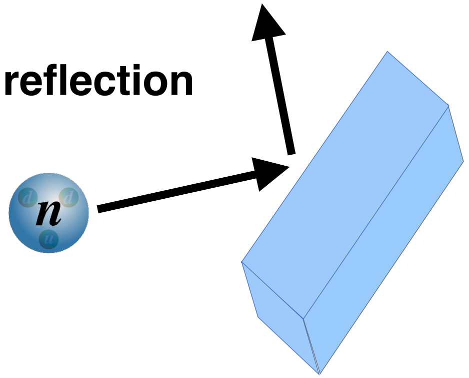
NOP collaboration

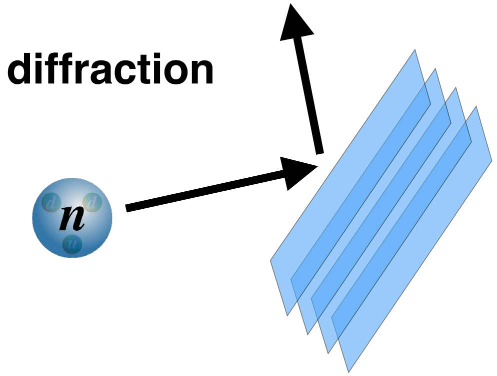






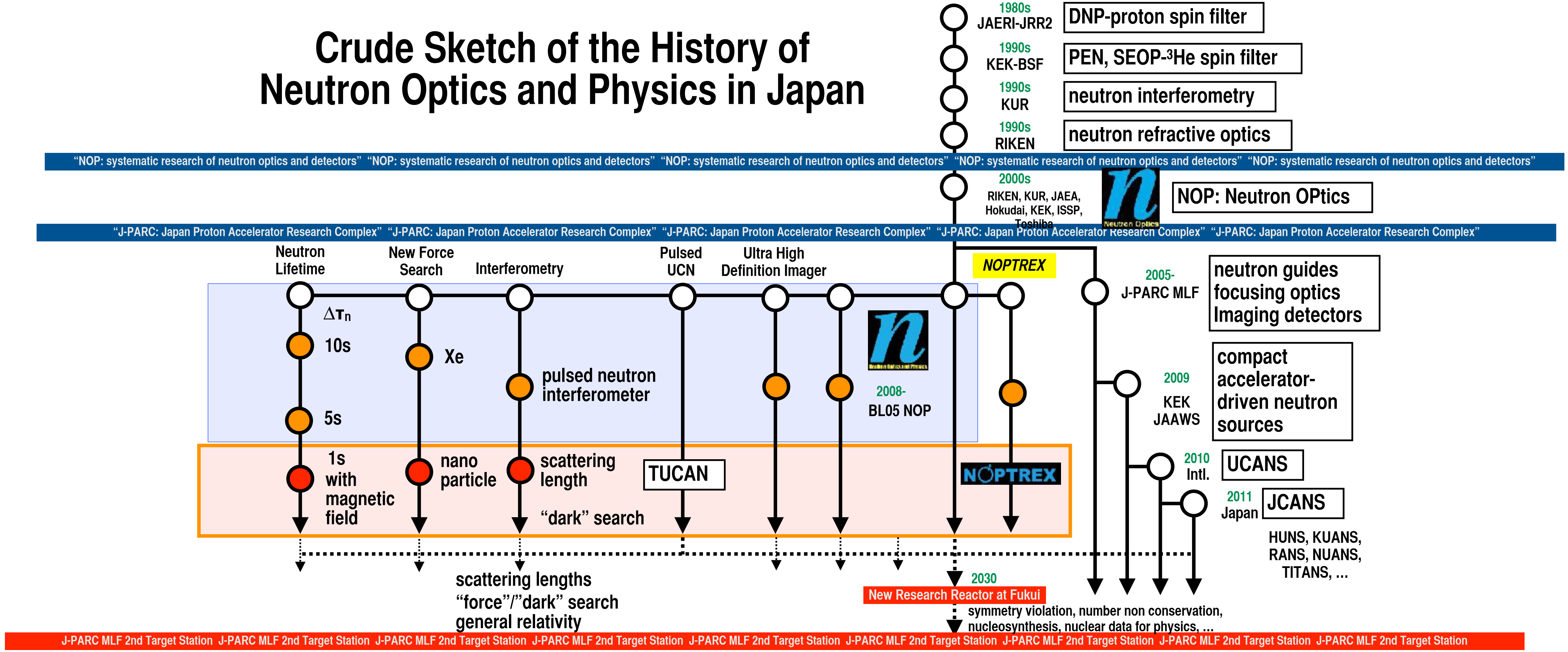






NOP collaboration

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



T-violation

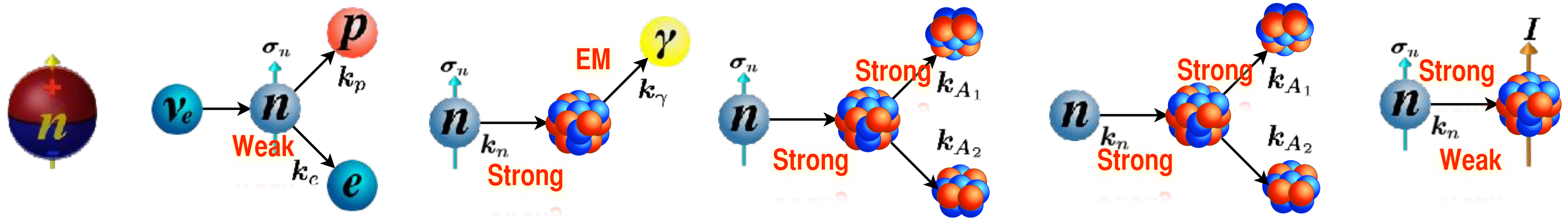
$$T : e^{i\boldsymbol{k}\cdot\boldsymbol{r}-\omega t}\chi \rightarrow e^{-i\boldsymbol{k}\cdot\boldsymbol{r}+\omega t}\chi^{T}$$

T-violation ⇄ (✕ ←) **T-odd** observables

CP-violation via CPT-theorem

changing sign under T

electric dipole moment	D-coefficient in neutron β-decay	γ-ray angular distribution	ternary fission	ternary fission	forward scattering



$\boldsymbol{d}_n$	$\boldsymbol{\sigma}_n \cdot (\boldsymbol{k}_p \times \boldsymbol{k}_e)$	$\boldsymbol{\sigma}_n \cdot (\boldsymbol{k}_n \times \boldsymbol{k}_\gamma)$	$\boldsymbol{\sigma}_n \cdot (\boldsymbol{k}_{A_1} \times \boldsymbol{k}_{A_2})$	$\boldsymbol{k}_n \cdot (\boldsymbol{k}_{A_1} \times \boldsymbol{k}_{A_2})$	$\boldsymbol{\sigma}_n \cdot (\boldsymbol{k}_n \times \boldsymbol{I})$

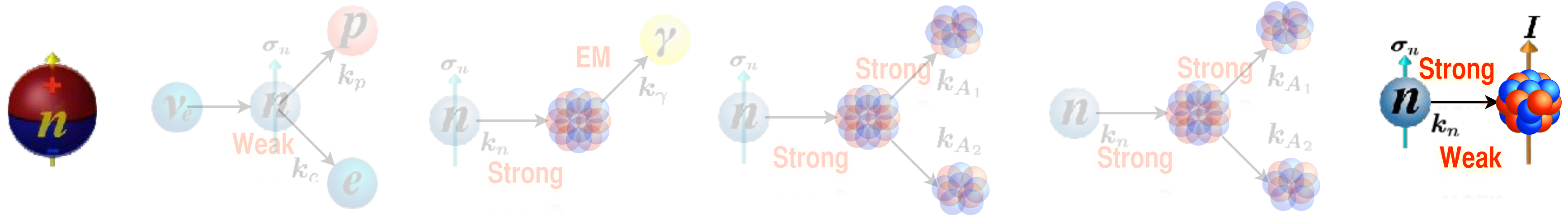
final state interaction (T-odd T-symmetric)

$$T : e^{i\boldsymbol{k}\cdot\boldsymbol{r}-\omega t}\chi \rightarrow e^{-i\boldsymbol{k}\cdot\boldsymbol{r}+\omega t}\chi^{T}$$

T-violation ⇄ T-odd observables

CP-violation via CPT-theorem — changing sign under T

electric dipole moment	D-coefficient in neutron β-decay	γ-ray angular distribution	ternary fission	ternary fission	forward scattering



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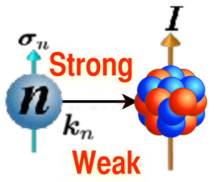
final state interaction (T-odd T-symmetric)

electric
dipole
moment

$\boldsymbol{d}_n$

forward scattering



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

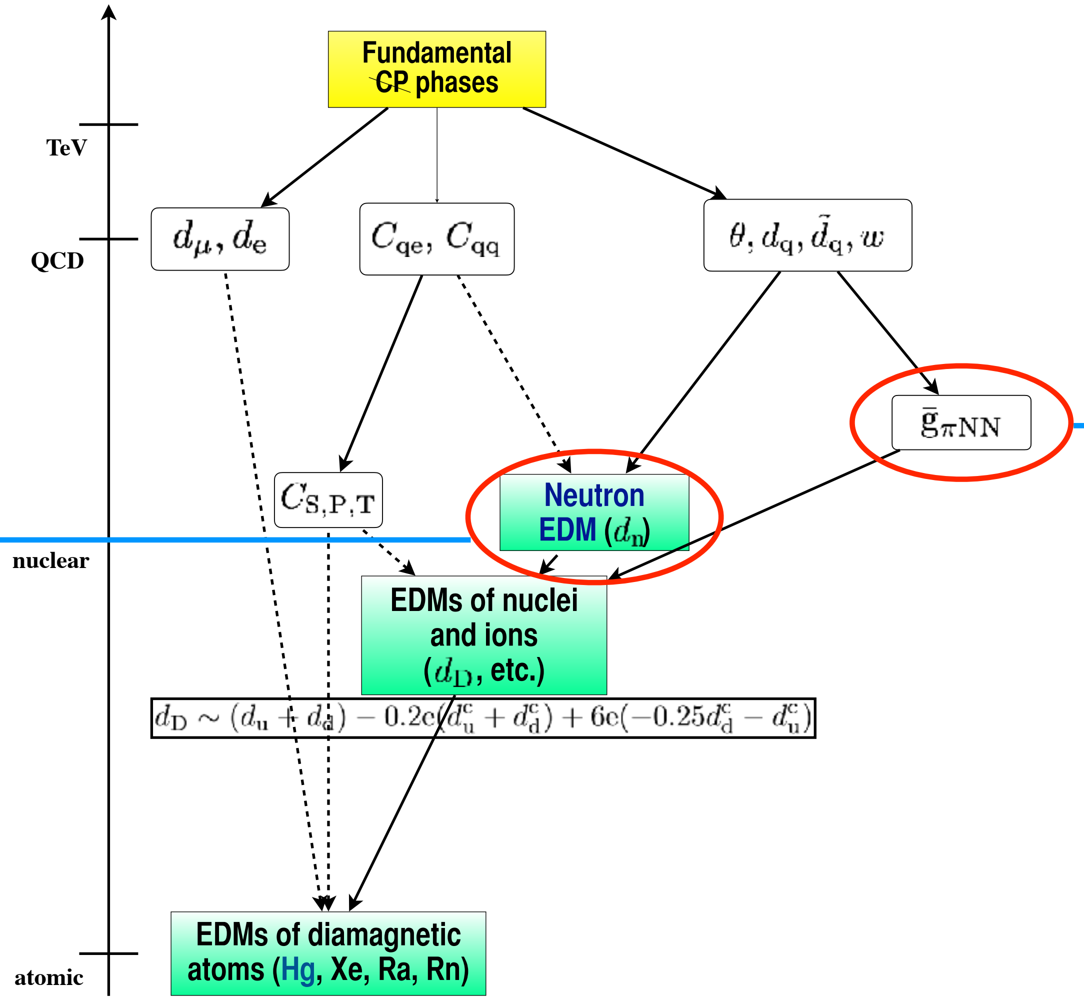
TUCAN

electric
dipole
moment

$\boldsymbol{d}_n$

$$d_n = -(1.5 \pm 0.7) \times 10^{-16} \theta_{QCD}$$

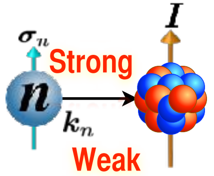
$$d_n \sim 1.1e(0.5 d_u^c + d_d^c) + 1.4 \times (-0.25 d_u + d_d)$$



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

NOPTREX (J-PARC P99)

forward scattering



$$D' \boldsymbol{\sigma}_n \cdot (\hat{\boldsymbol{k}}_n \times \hat{\boldsymbol{I}})$$

$$C' \boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_n$$

$$\frac{D'}{C'} = \kappa(J) \frac{W_T}{W}$$

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

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

TUCAN

electric dipole moment

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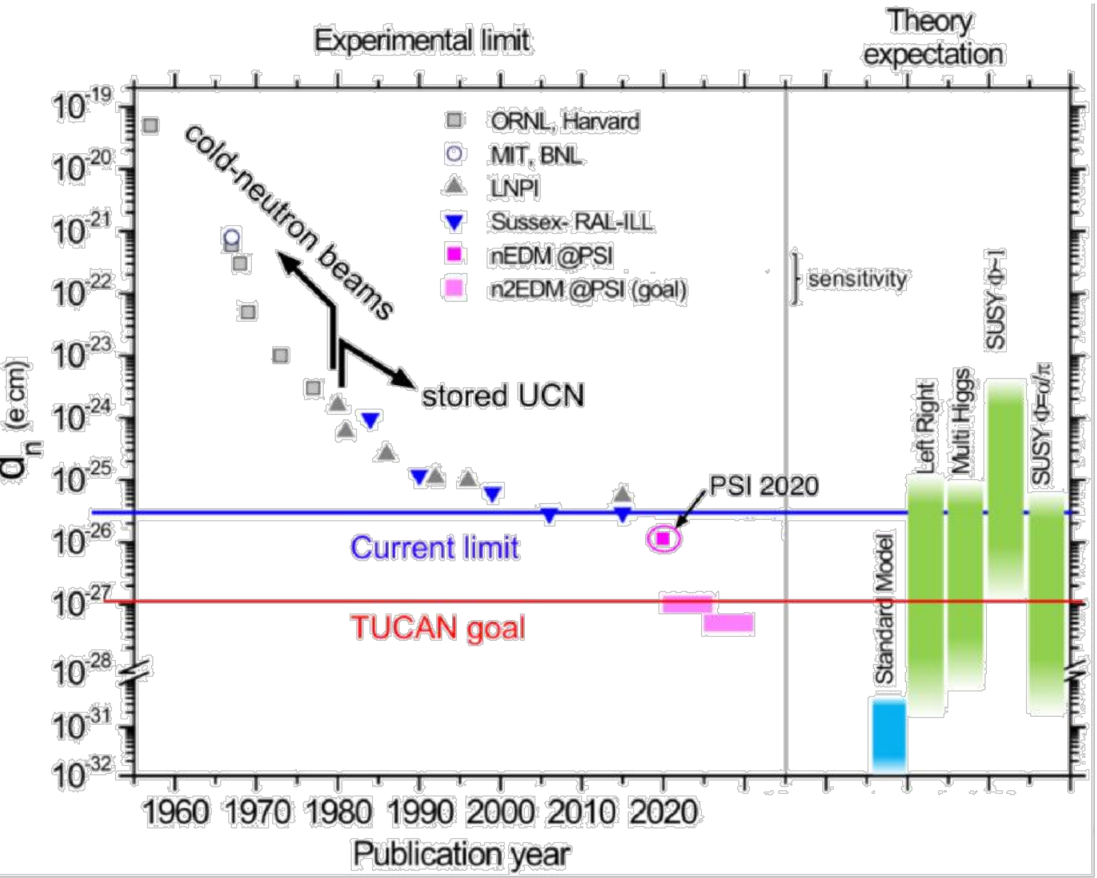

Slide courtesy: B. Lauss, nEDM workshop 2017, based on NIMA 440, 471 (2000), Phys. Rev. D 92, 092003 (2015) AIP Conf. Proc. 1753, 060002 (2016)

NOPTREX (J-PARC P99)

forward scattering

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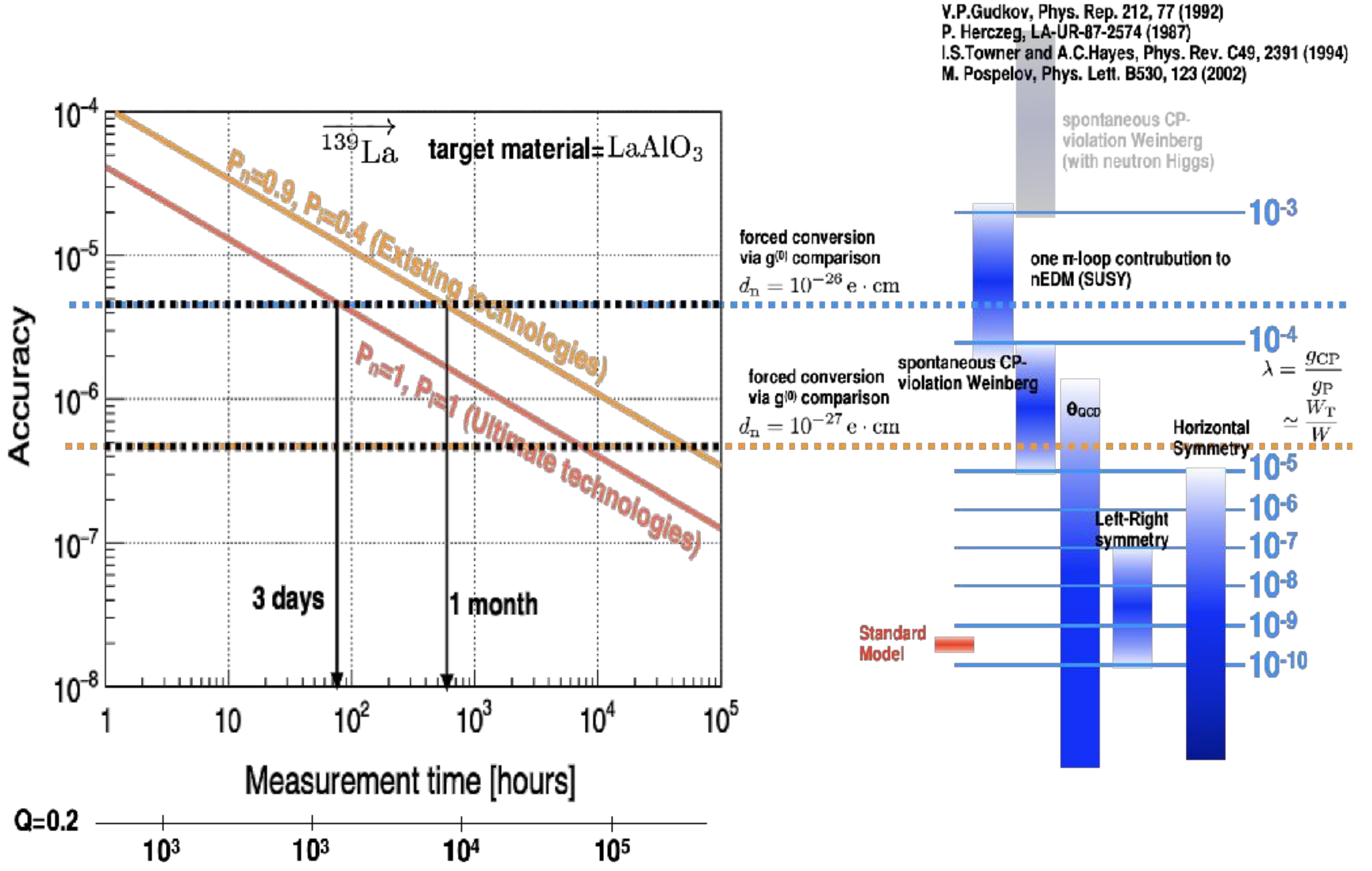
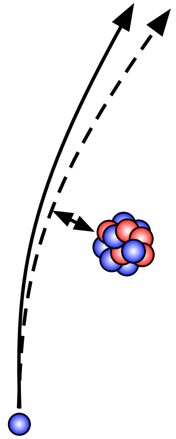


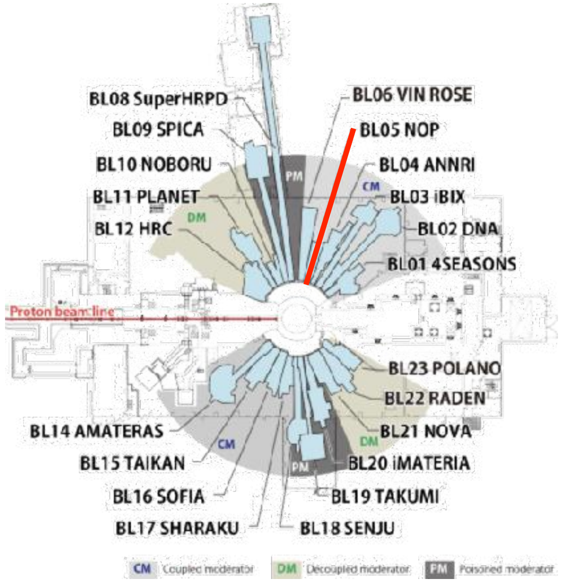
Gravity, New Force Search

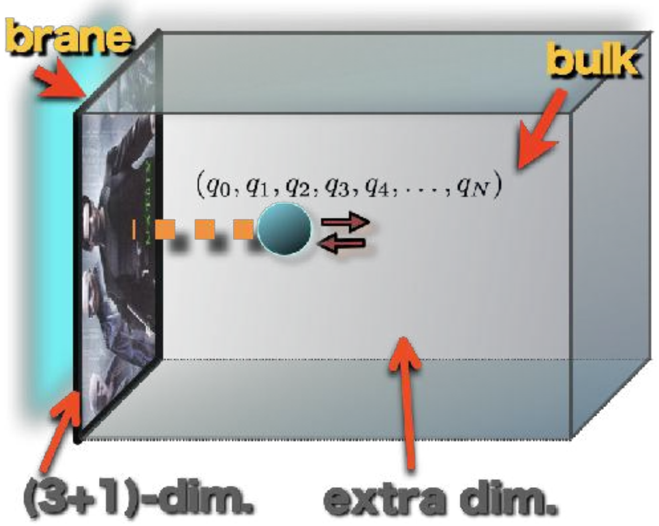
Neutron Scattering

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



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



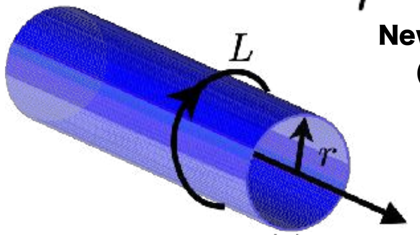


$$q_0^2 - q_1^2 - q_2^2 - q_3^2 - q_4^2 - \cdots - q_N^2 = 0 \quad \Longleftrightarrow \quad q_0^2 - q_1^2 - q_2^2 - q_3^2 = q_4^2 + \cdots + q_N^2$$

$$q_4^2 + \cdots + q_N^2 = \mu^2 > 0$$

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

Newtonian (μ=0) **Extra-dimension (μ>0)**

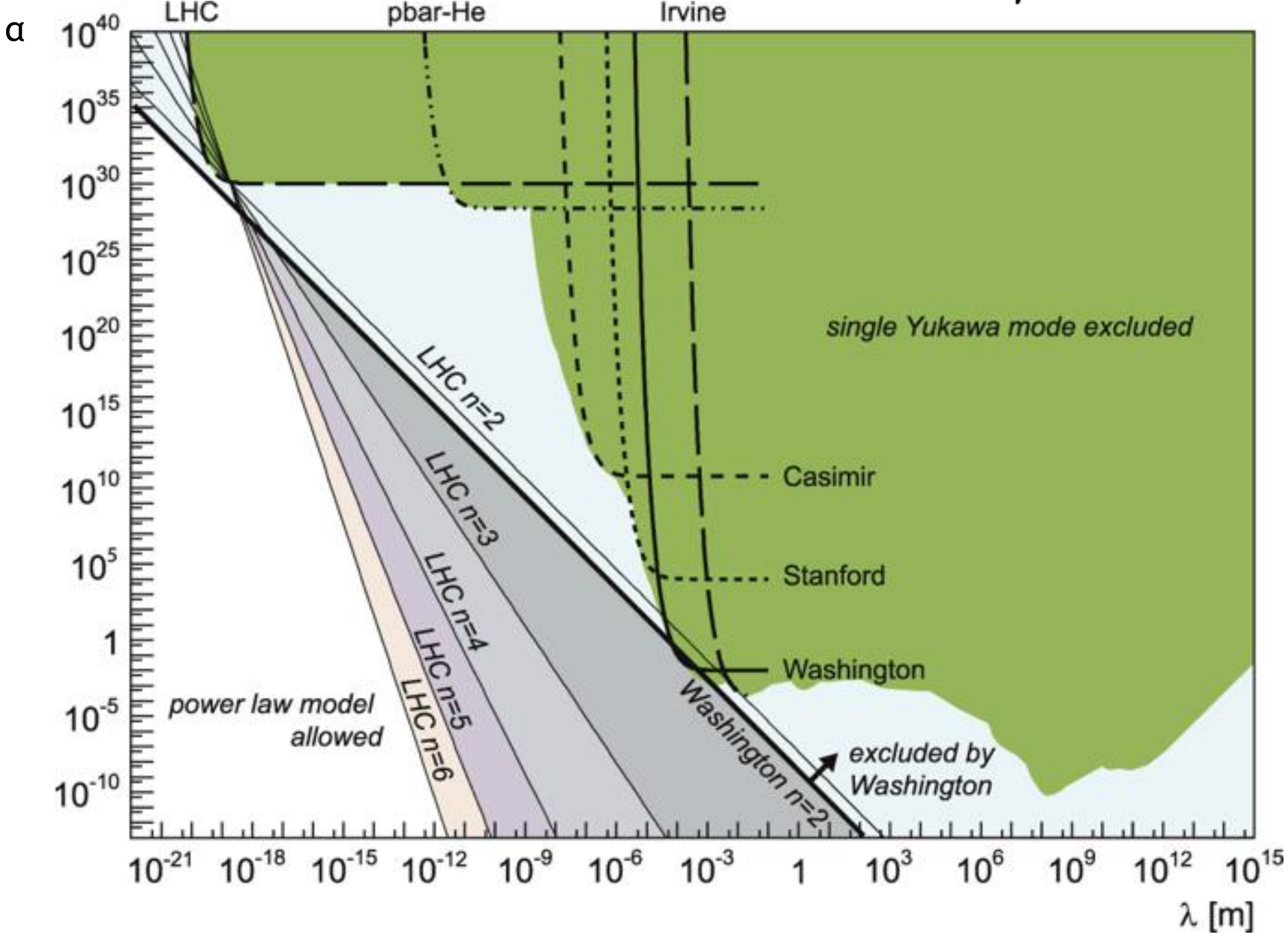


momentum is quantized in the unit of $2\pi/L$
in the extra-dimension

$$\frac{V(r)}{m_1 m_2} = G_3 \sum_{(k_1,\ldots,k_n)} \frac{e^{-(2\pi|k|/L)r}}{r} \xrightarrow[r \ll L]{} G_3 \frac{1}{r}\left(\frac{L}{2\pi r}\right)^n \int d^n u e^{-|u|}$$

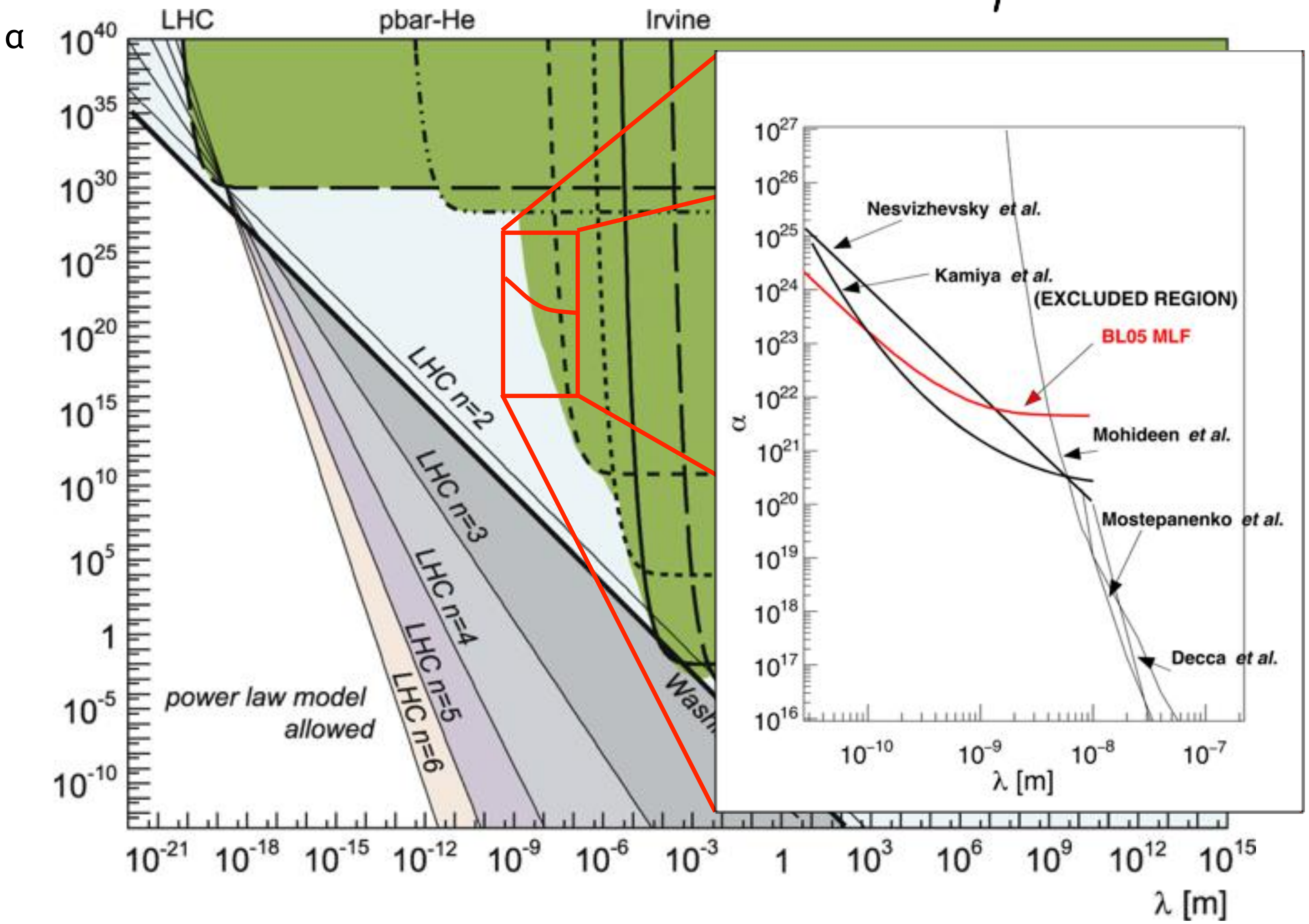
Neutron Scattering

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



Neutron Scattering

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



Pilot experiment on gravitation and short-range force using quantized ultracold neutrons

Setup of the experiment
(V. V. Nesvizhevsky et al., Nuclear Instruments and Methods in Physics Research A 440 (2000) 754-759.)

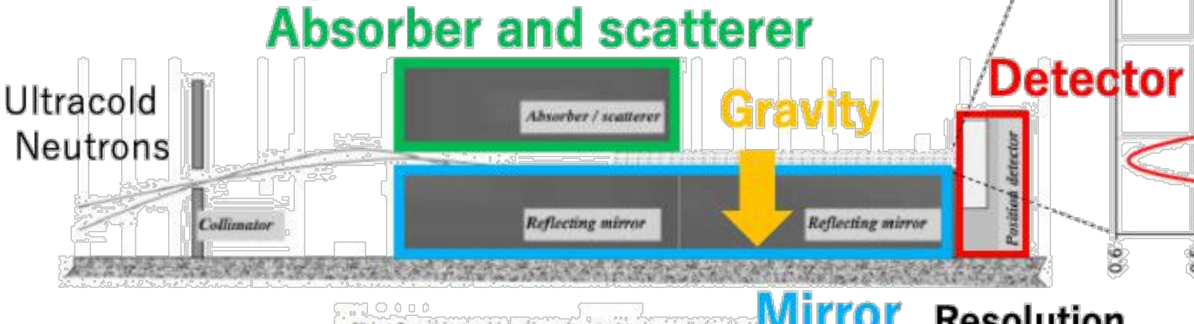
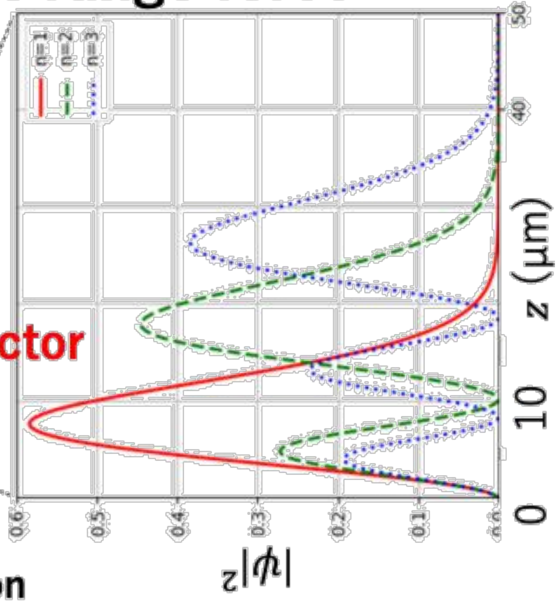


Fig. 3. General scheme of the experiment.



Resolution ~ 2 μm

$$E\psi(z) = \left(-\frac{\hbar^2}{2m}\cdot\frac{\partial^2}{\partial z^2} + mgz\right)\psi(z)$$

In the case of effect of Yukawa potential

$$mgz - 2\pi G m\rho\alpha\lambda^2 e^{-\frac{z}{\lambda}}$$

ρ: Density of mirror, λ : Range
G: Gravitational constant,
α: Coupling constant

Boundary conditions
$\psi(z=0)=0,$
$\lim_{a\to\infty}\psi(z=a)=0$

$$Z_n(z) = \frac{z}{z_0} - \frac{E_n}{E_0},$$
$$z_0 = \left(\frac{\hbar^2}{2m^2 g}\right)^{\frac{1}{3}},$$
$$E_0 = mgz_0$$

$$\boldsymbol{\psi_n(z) = C_n \mathrm{Ai}(Z_n(z))}$$
Ai(x): The Airy function

2

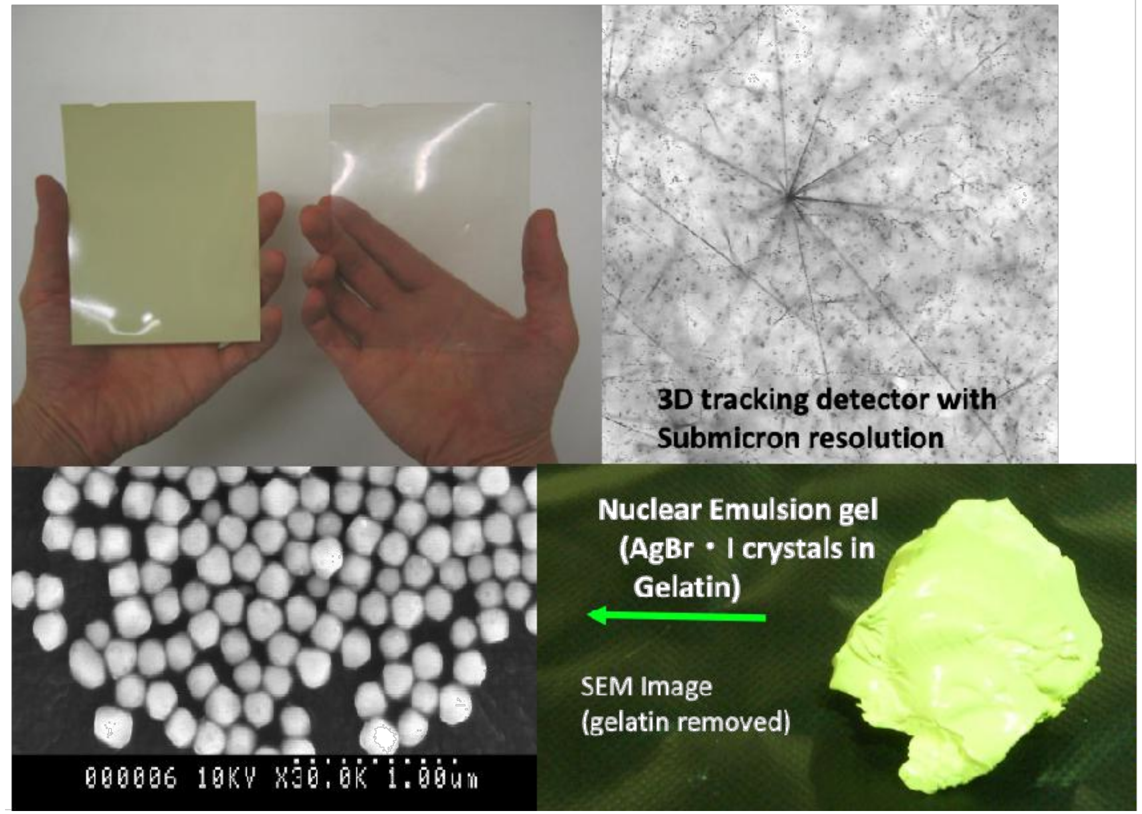
Purpose of the experiment
- **Search for short-range force**

Experimental method
Measurement of the position distribution

Analysis method
Comparison with the known position distribution

High spatial resolution is required.

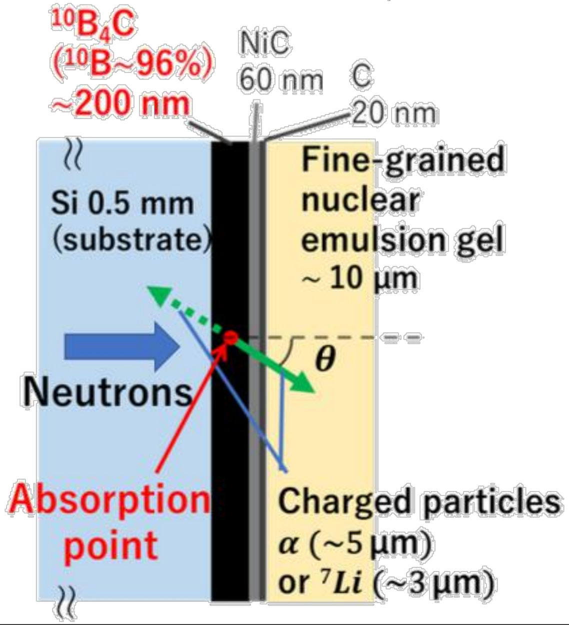
Nuclear emulsion



Emulsion detector for ultracold neutrons

・Detection principle $n + {}^{10}B \rightarrow \alpha + {}^{7}Li$

・Structure
(Cross sectional view)

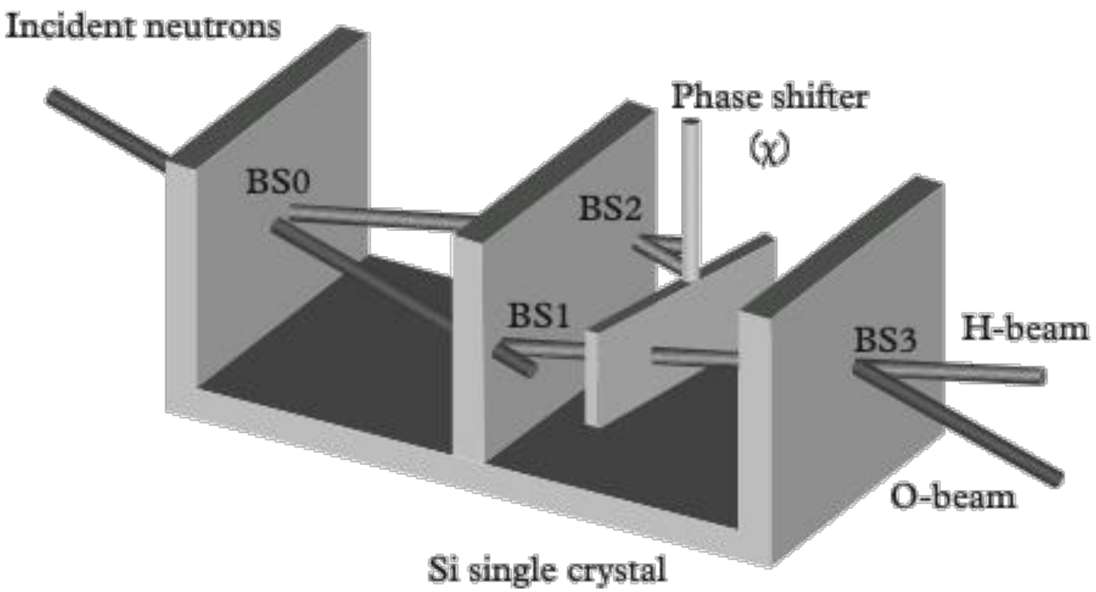


Resolution < 100 nm ($\theta \leq 0.9$)
(Estimation of fitting track and Extrapolating to $^{10}B_4C$)

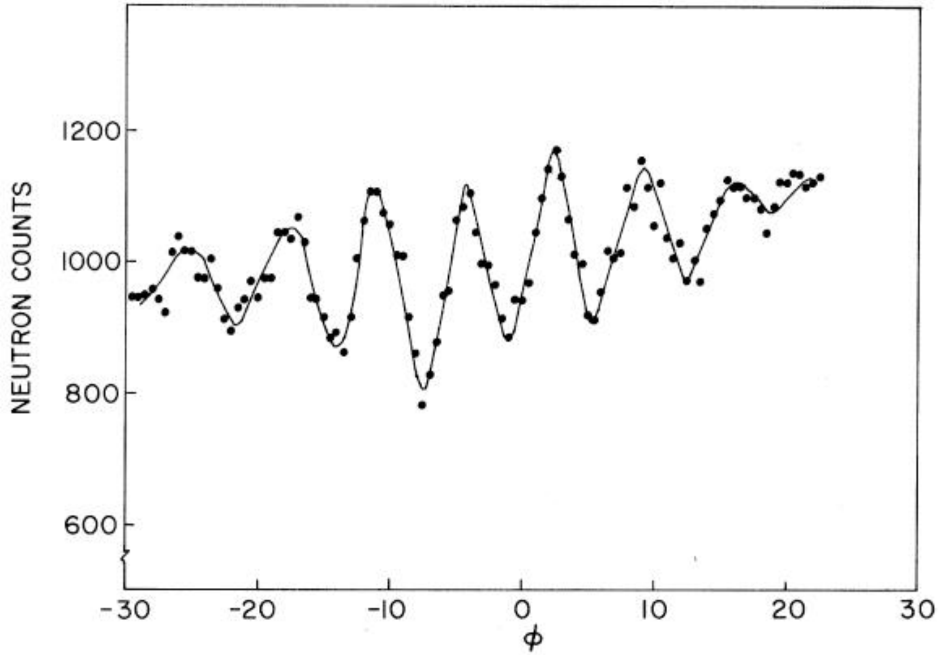
→1~2 order higher than existing detectors

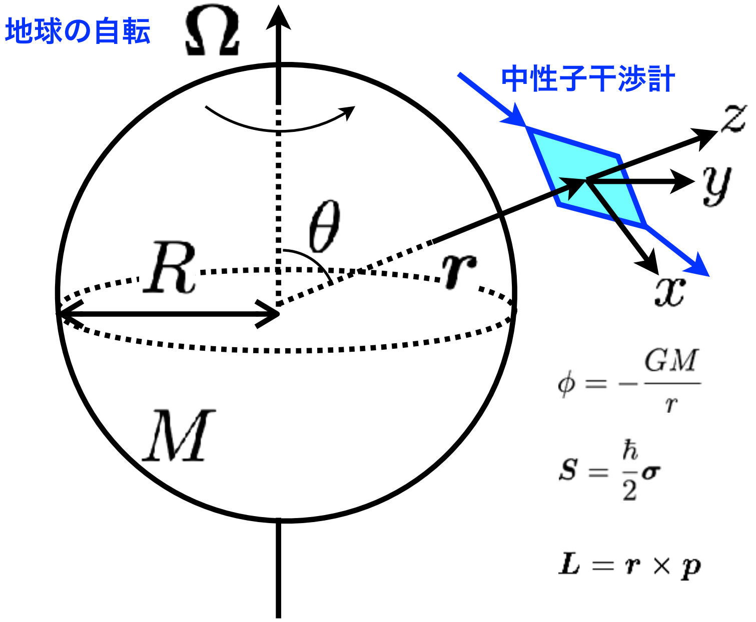
Absorption efficiency ~41%
(velocity of neutrons ~10 m/s)

Neutron Interferometry



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





$\phi = -\frac{GM}{r}$

$S = \frac{\hbar}{2}\sigma$

$L = r \times p$

T.Morishima Nucl. Instrum. Methods A529 (2024)

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

accessible with J-PARC

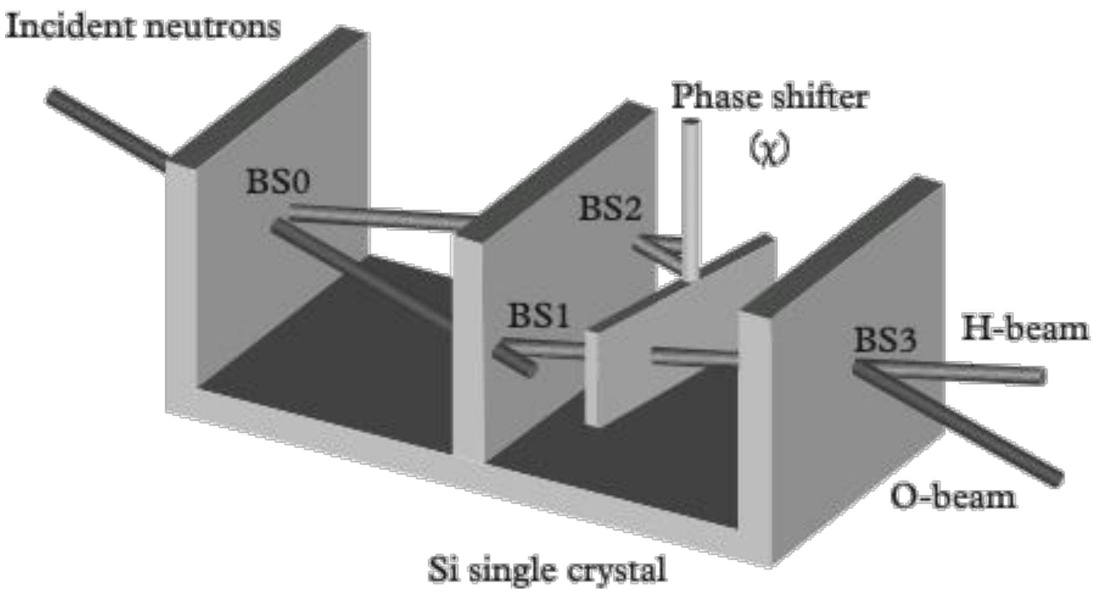
COW

$$\mathcal{H} = \frac{p^2}{2m} + m\phi - \Omega\cdot(L+S)$$
$$+\frac{1}{c^2}\left(-\frac{p^4}{8m^3} + \frac{m}{2}\phi^2 + \frac{3}{2m}p\cdot(\phi p) + \frac{3GM}{2mr^3}L\cdot S + \frac{4GMR^2}{5r^3}\Omega\cdot(L+S) + \frac{6GMR^2}{5r^5}S\cdot(r\times(r\times\Omega))\right)$$

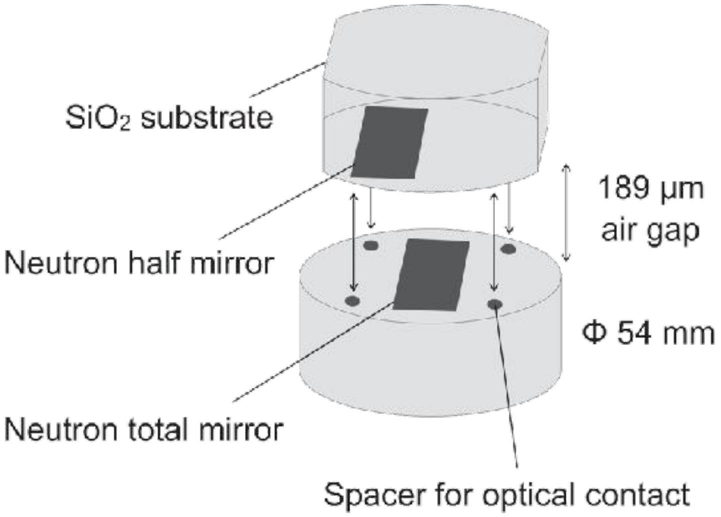
Lense-Thirring

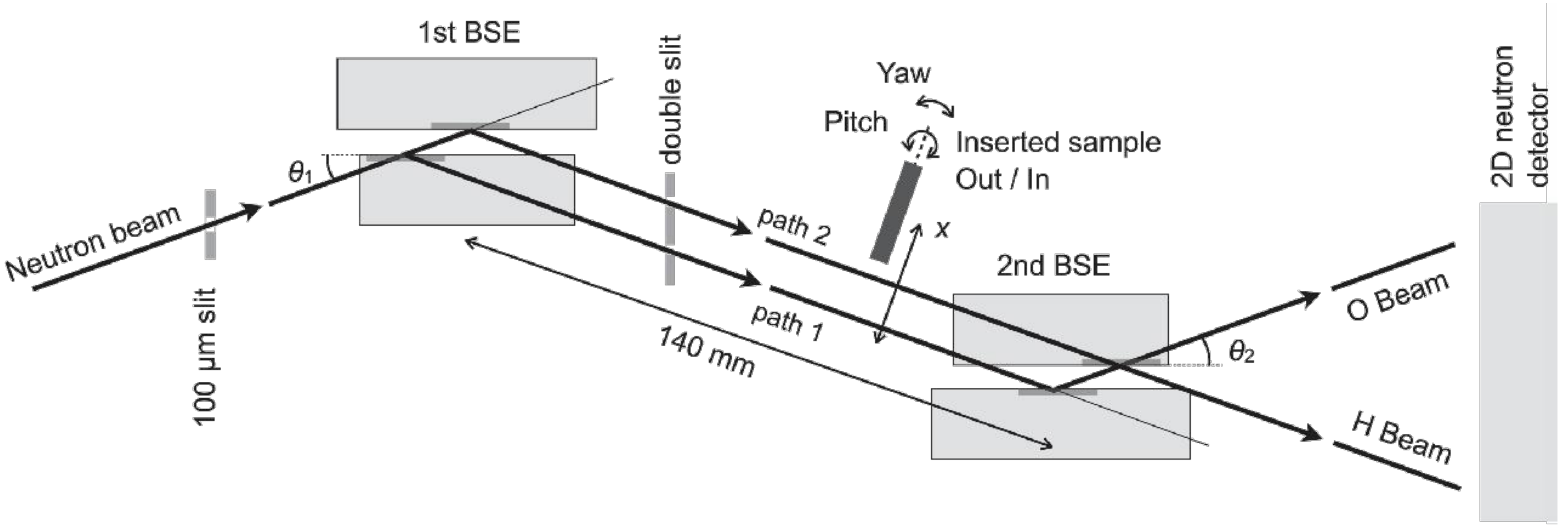
Neutron Interferometry

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



T.Fujiie et al., Phys. Rev. Lett. 132 (2024) 023402





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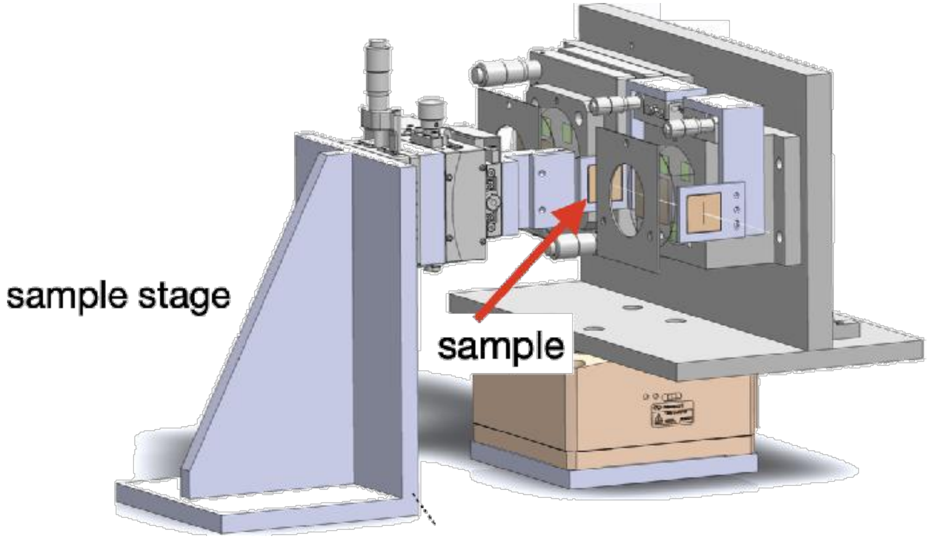
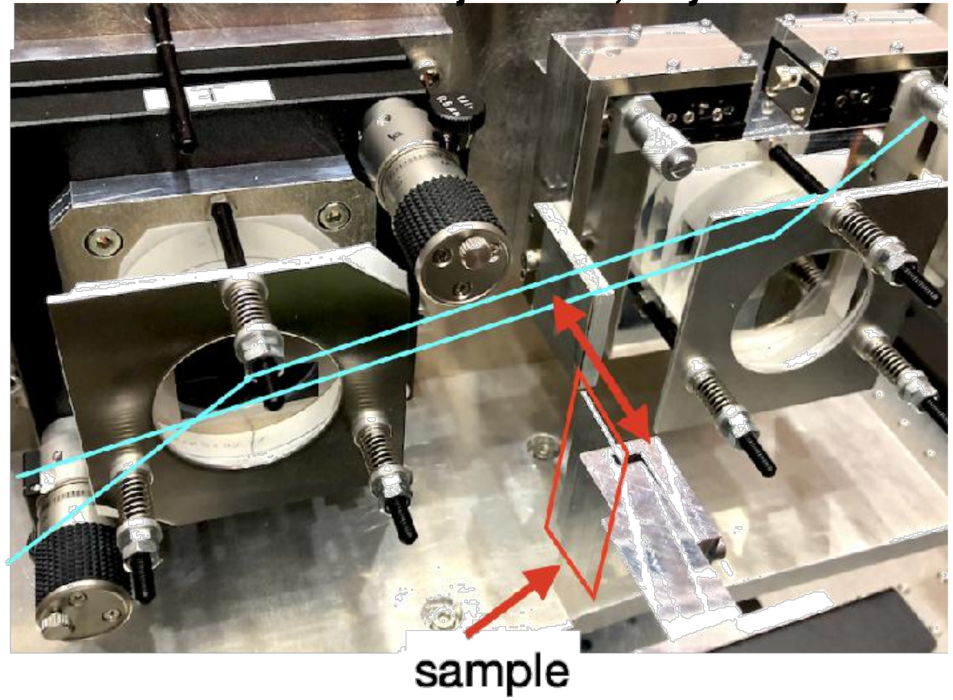
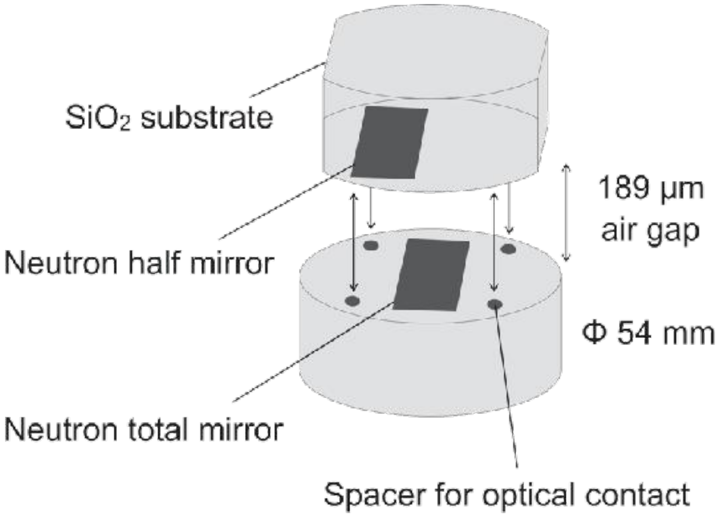
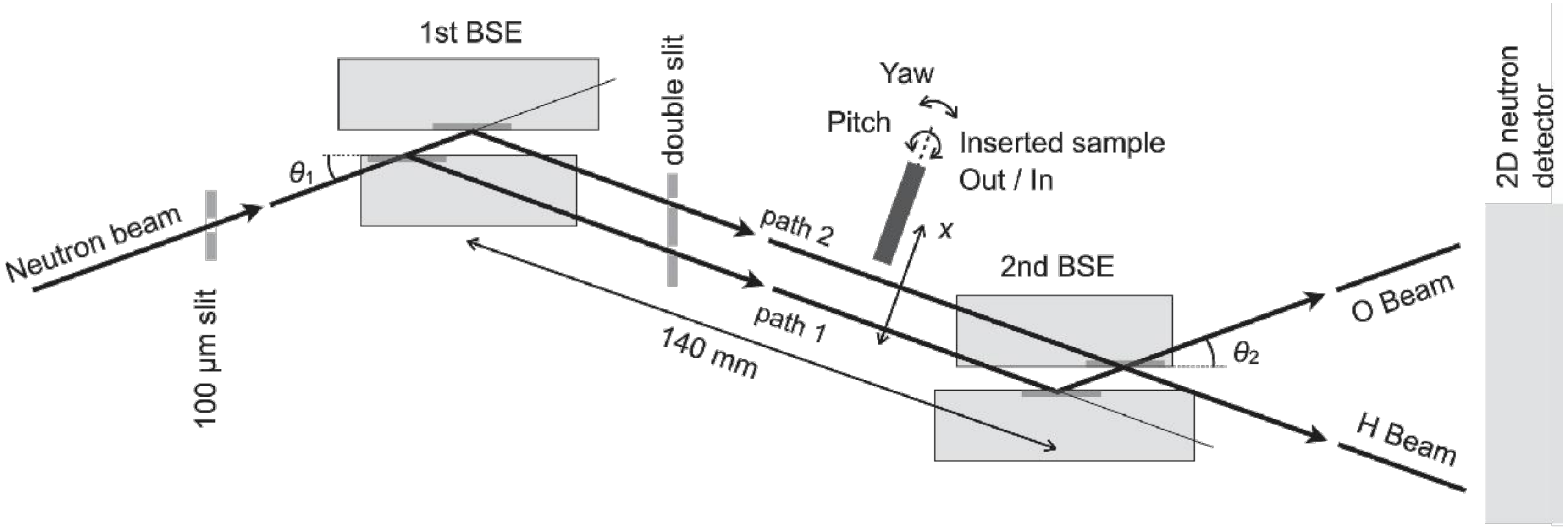








 T.Fujiie et al., Phys. Rev. Lett. 132 (2024) 023402

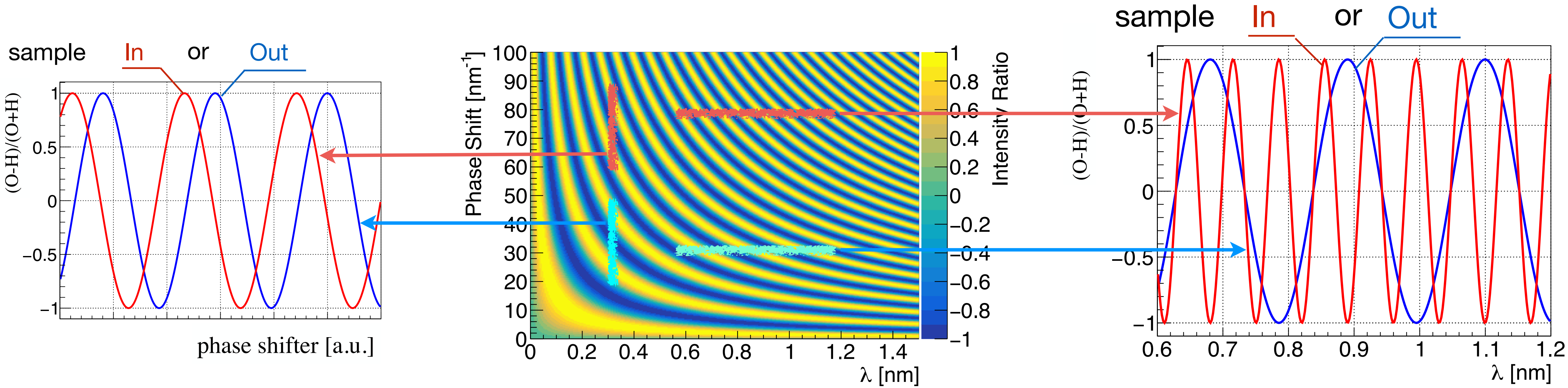
Interference fringe is recorded for every neutron pulse as a function of neutron TOF.

$$\Delta\phi = 2\pi \frac{m_{\mathrm{n}}\lambda_{\mathrm{n}}L}{\hbar^2}\Delta E \propto \mathrm{TOF}$$

Stable operation has been enabled since the fluctuation of optical paths can be corrected at the pulse repetition frequency or lower frequencies,

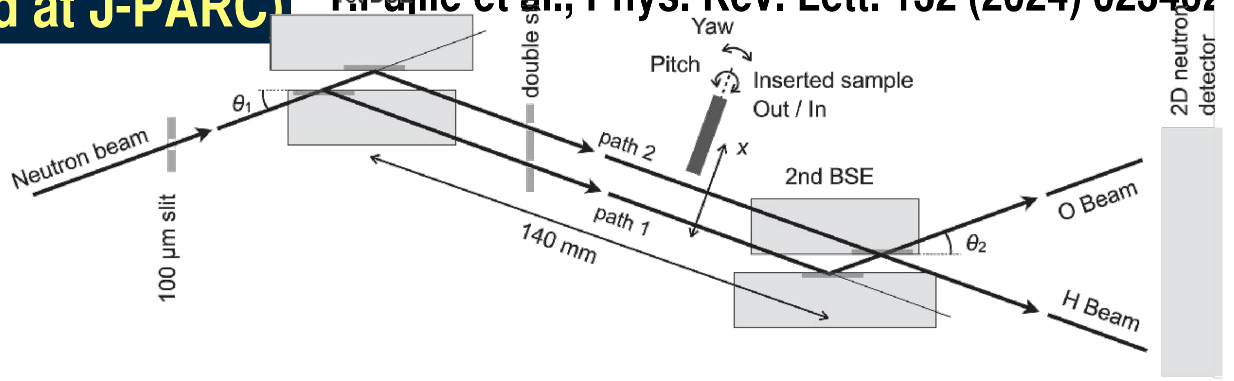
Conventional interferometer

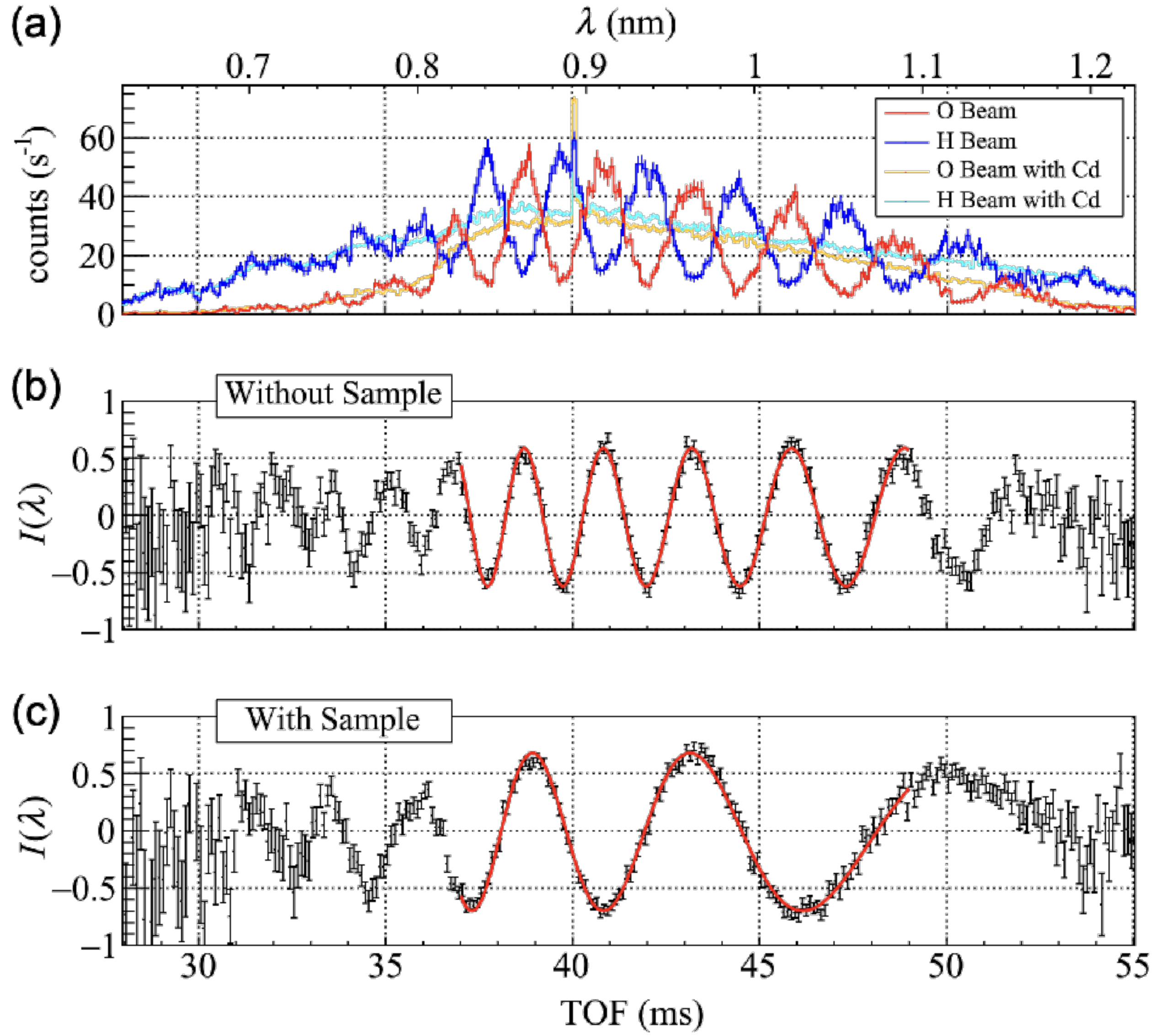
Novel interferometer



Neutron Interferometry (TOF-dependent Fringes obtained at J-PARC)

T.Fujiie et al., Phys. Rev. Lett. 132 (2024) 023402

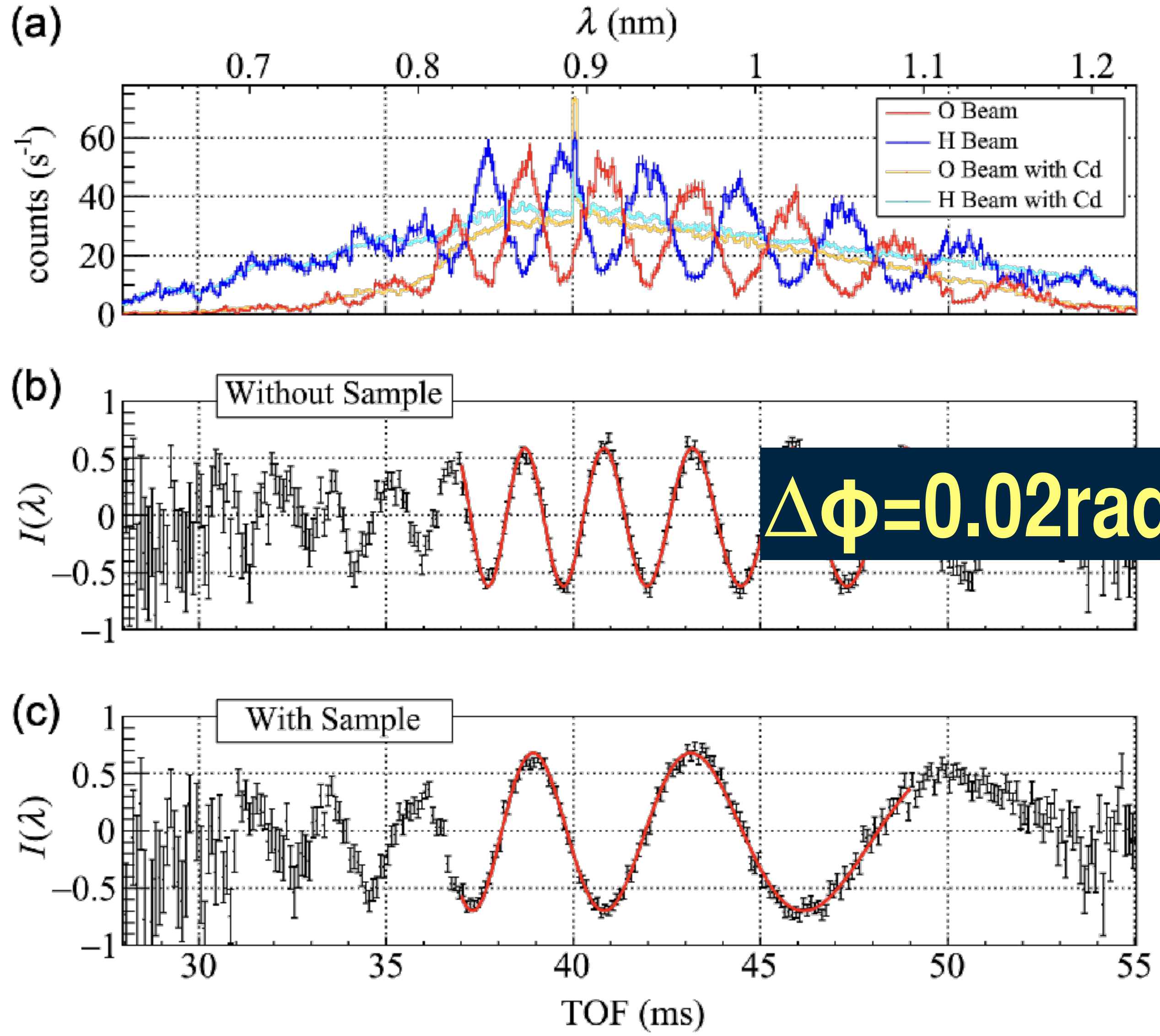


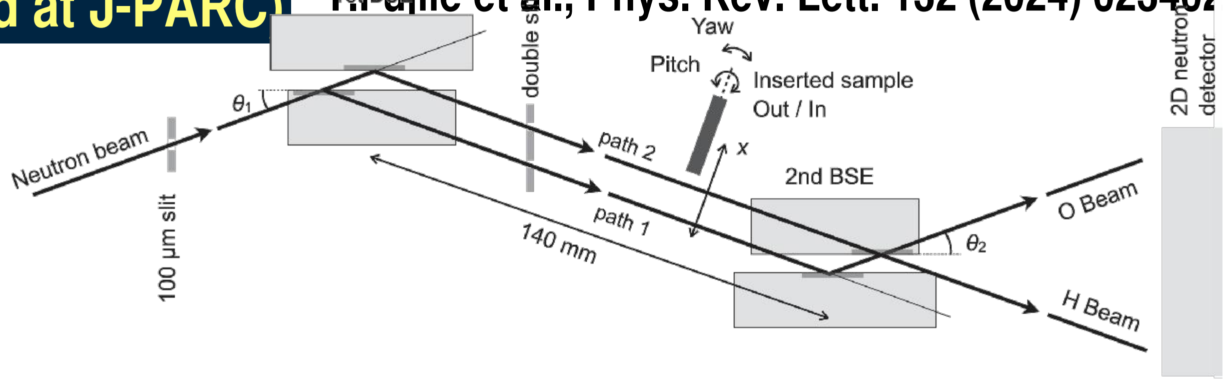


Sample	b_c (fm)	b_c/b_c^{ref}
Si[a]	4.060 ± 0.027	0.978 ± 0.007
Ti	-3.477 ± 0.062	1.011 ± 0.018
	-3.386 ± 0.064	0.985 ± 0.019
Al	3.408 ± 0.050	0.988 ± 0.015
	3.423 ± 0.027	0.992 ± 0.008
	3.466 ± 0.020	1.005 ± 0.006
V	-0.522 ± 0.004	1.364 ± 0.010
	-0.520 ± 0.004	1.361 ± 0.011
V averaged	-0.521 ± 0.003	1.363 ± 0.008
V-Ni alloy[c]	-0.062 ± 0.001	-0.528 ± 0.010

Neutron Interferometry (TOF-dependent Fringes obtained at J-PARC)

T.Fujiie et al., Phys. Rev. Lett. 132 (2024) 023402





Δφ=0.02rad in 20 min.

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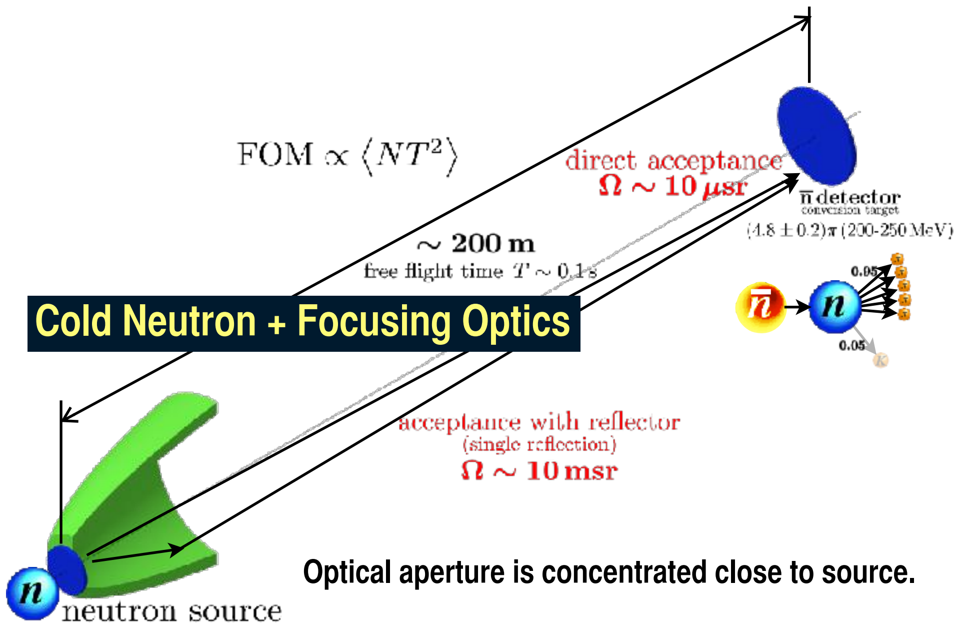
Understanding the scattering lengths would enable anti-neutron scattering lengths and leads to improved sensitivity to search for neutron anti-neutron oscillation and B, B-L violation.

→ FPUR (http://fpur.org)

Neutron Anti-neutron Oscillation

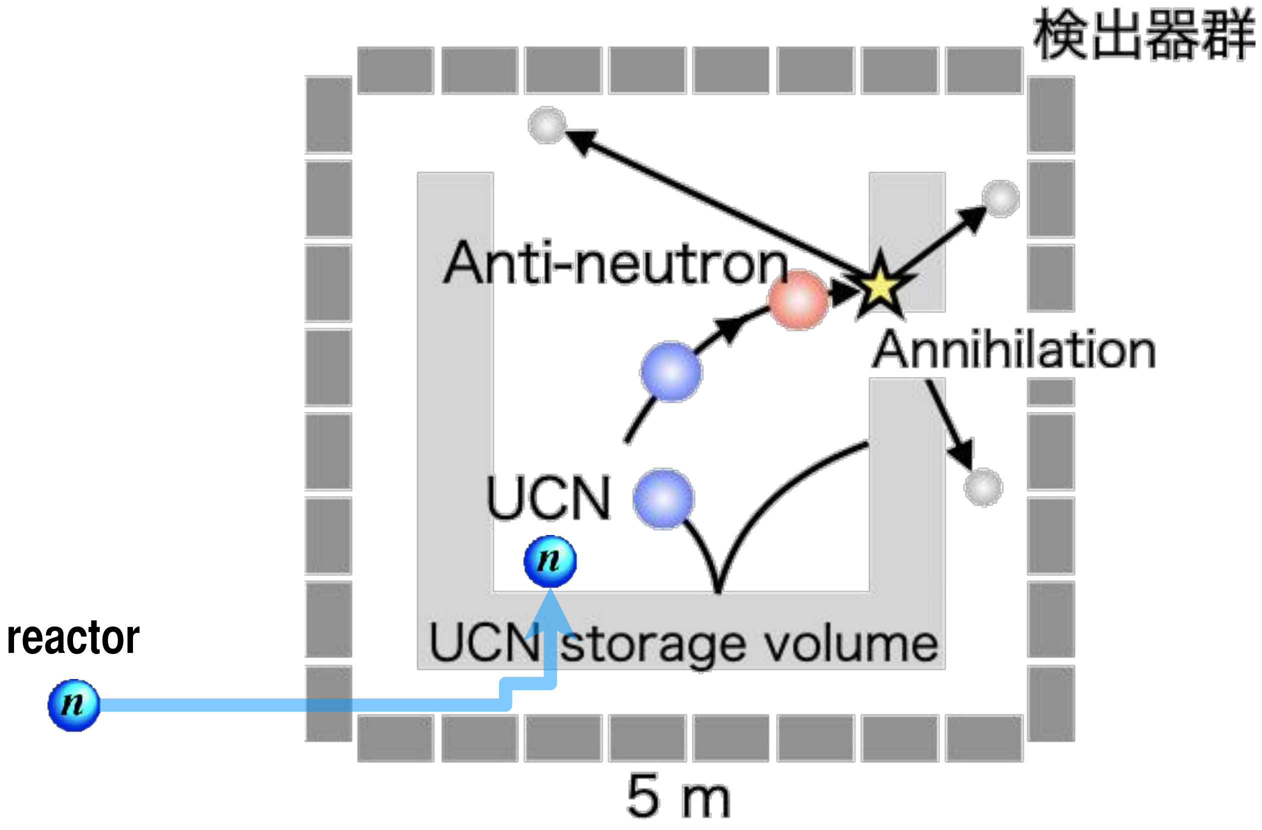
$$\Delta B = -2 \qquad \Delta(B - L) = -2$$

NNBAR@ESS (Horizontal Long Flight Path)



Optical aperture is concentrated close to source.

NNBAR with a confined UCN



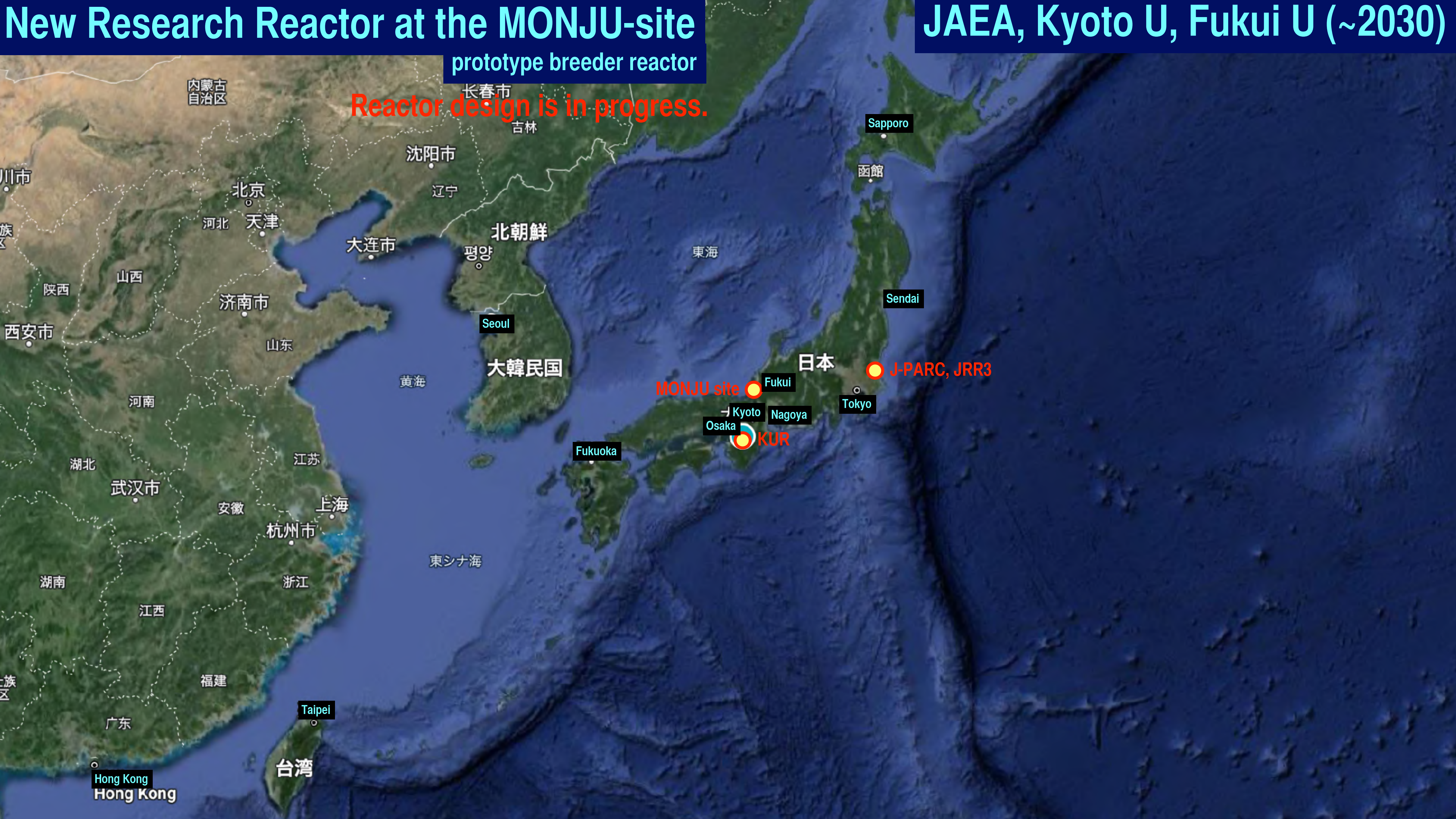
A certain accuracy in the estimation of anti-neutron optical properties is necessary.

New Research Reactor at the MONJU-site

JAEA, Kyoto U, Fukui U (~2030)

prototype breeder reactor

Reactor design is in progress.

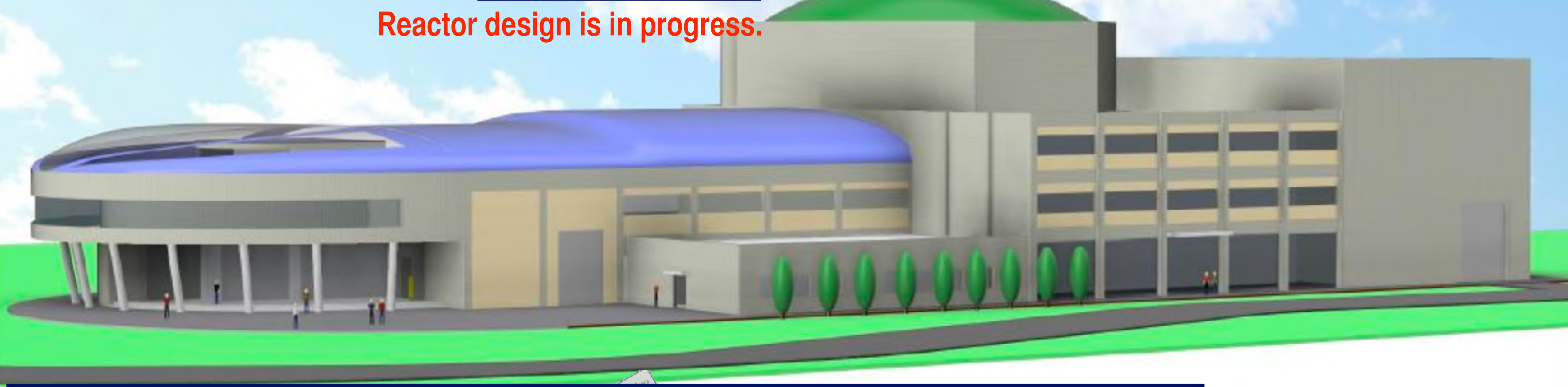


New Research Reactor at the MONJU-site

prototype breeder reactor

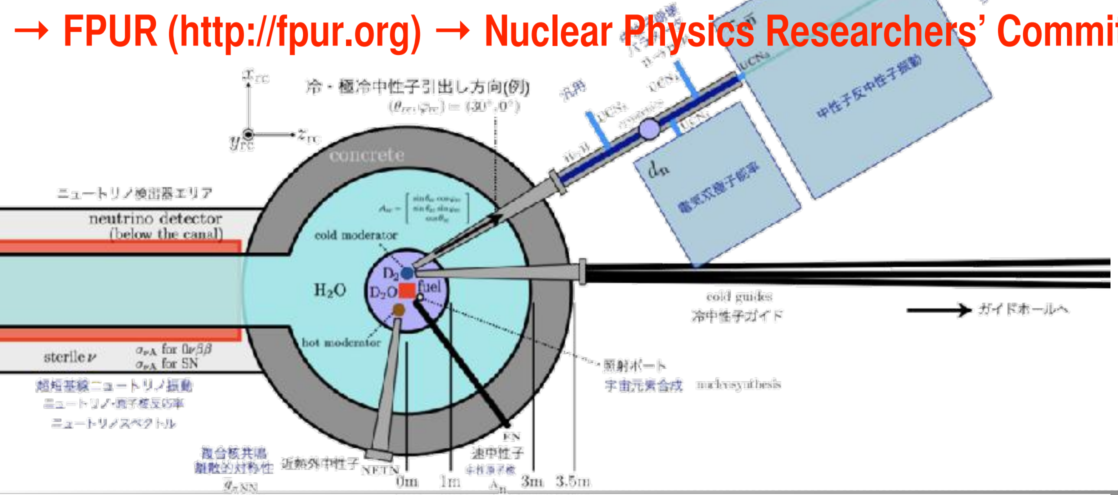
JAEA, Kyoto U, Fukui U (~2030)

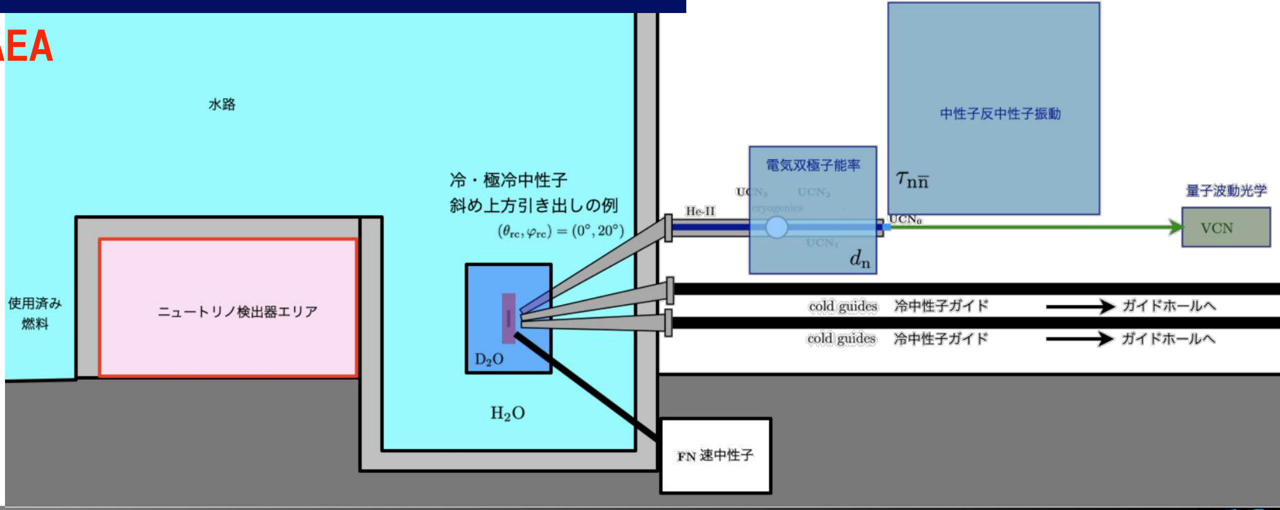
Reactor design is in progress.



proposal by FPUR (A researchers' team to discuss Fundamental Physics Using Reactors)

→ FPUR (http://fpur.org) → Nuclear Physics Researchers' Committee → JAEA



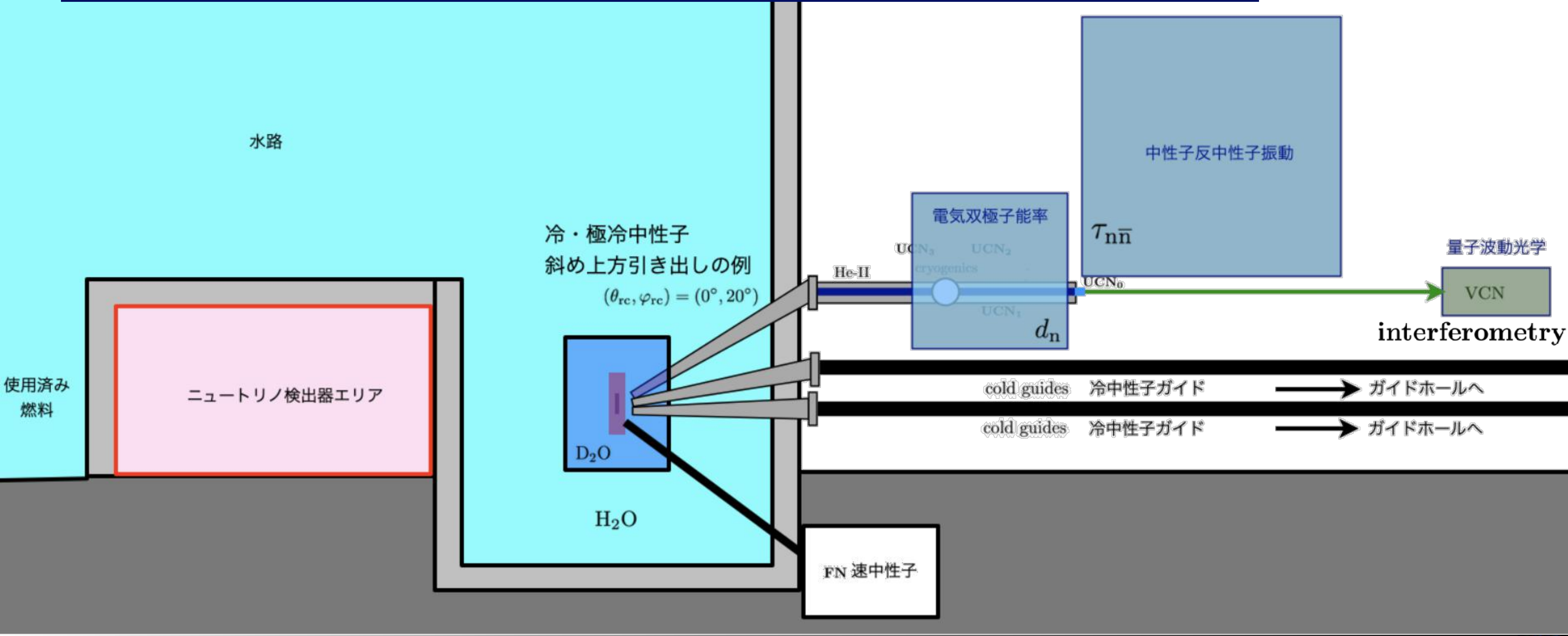


New Research Reactor at the MONJU-site

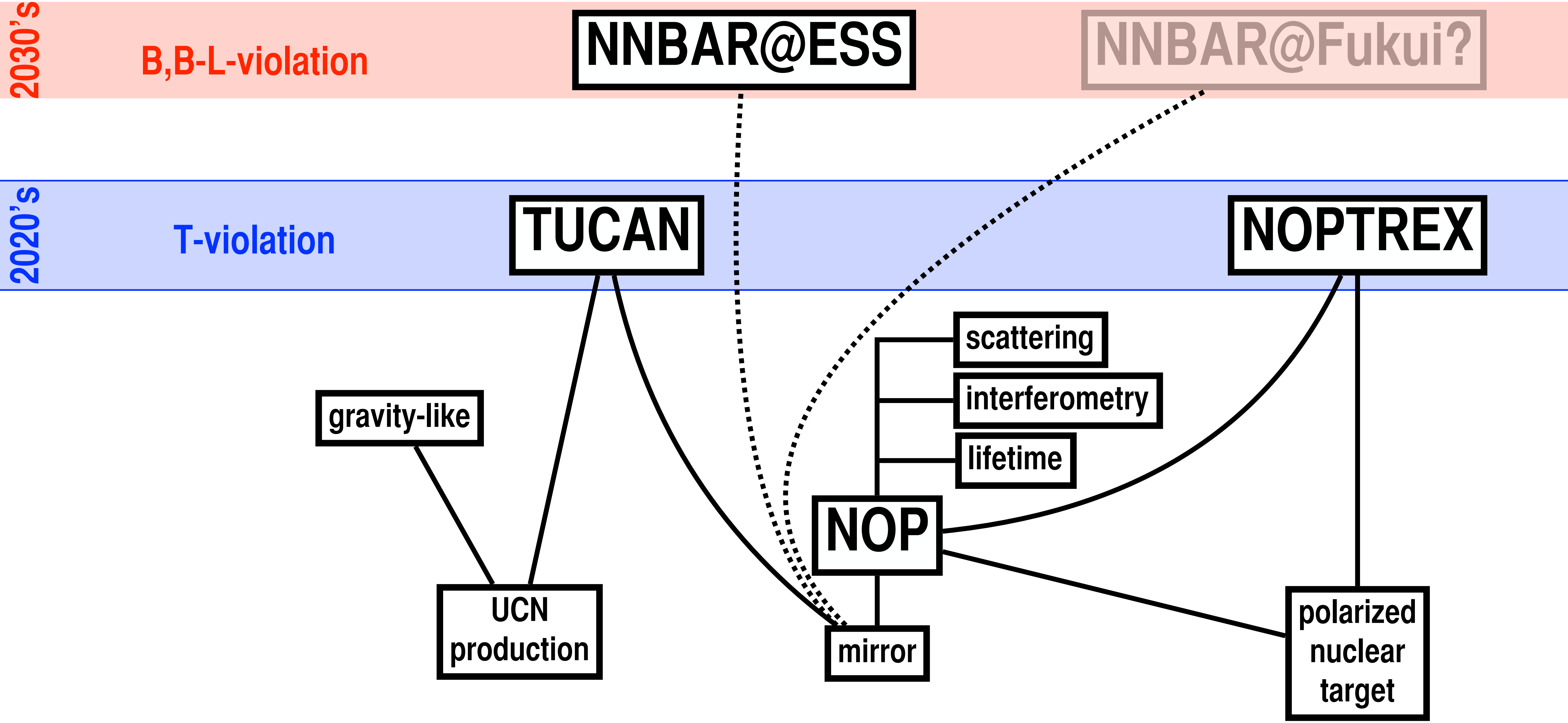
prototype breeder reactor

Reactor design is in progress.

proposal by FPUR (A researchers' team to discuss Fundamental Physics Using Reactors)



Optically Controlled Neutrons (2020's to 2030's)



ご清聴ありがとうございました。

Назар аударғаныңызға рақмет.

Спасибо за внимание.

Thank you for your attention.