Particle Physics beyond the Energy Frontier via Nuclear Physics

通过核物理探索能量前沿之外的粒子物理学

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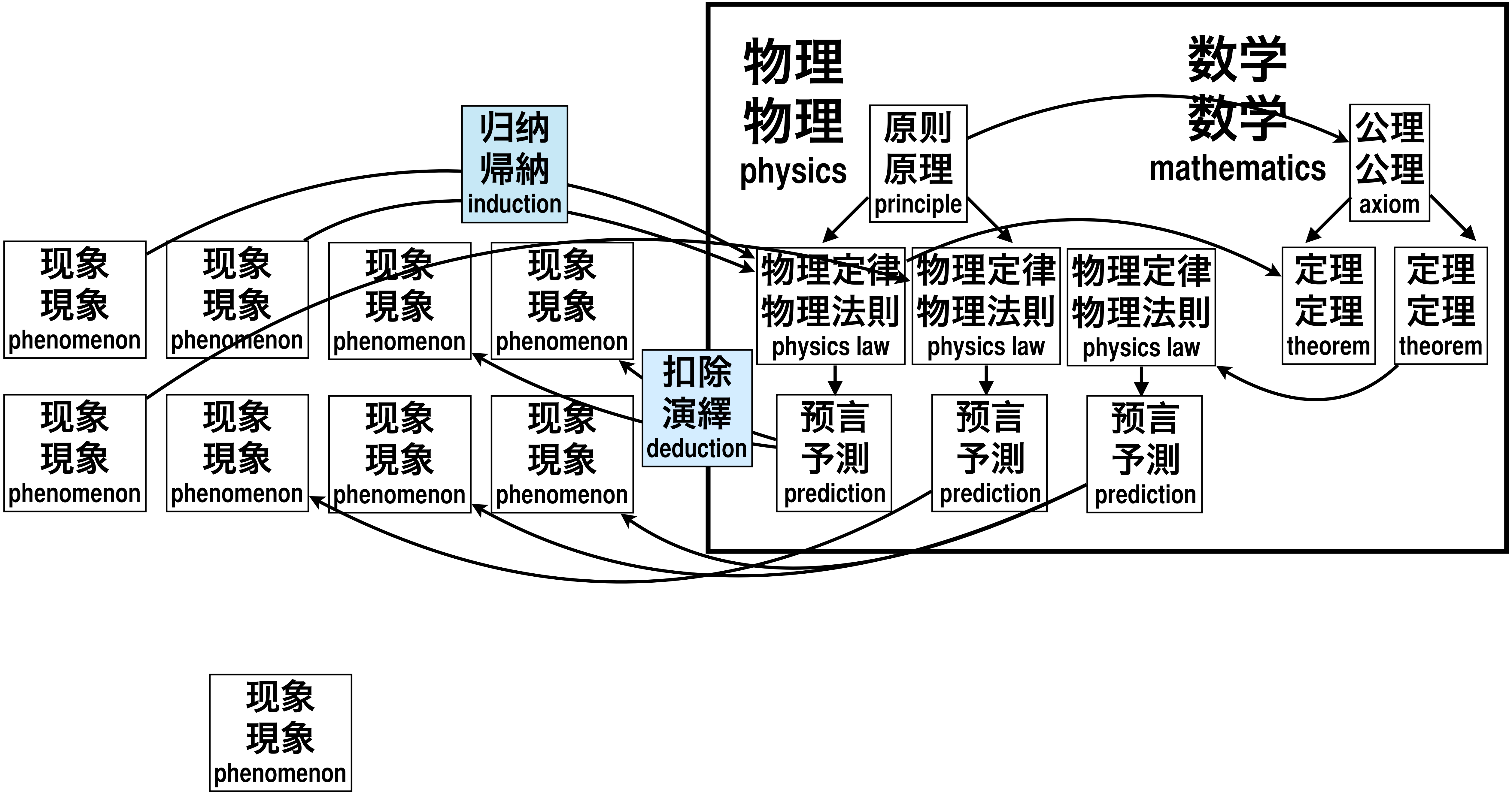

物理
物理
physics
数学
数学
mathematics
原则
原理
principle
公理
公理
axiom
归纳
帰納
induction
扣除
演繹
deduction
物理定律
物理法則
physics law
物理定律
物理法則
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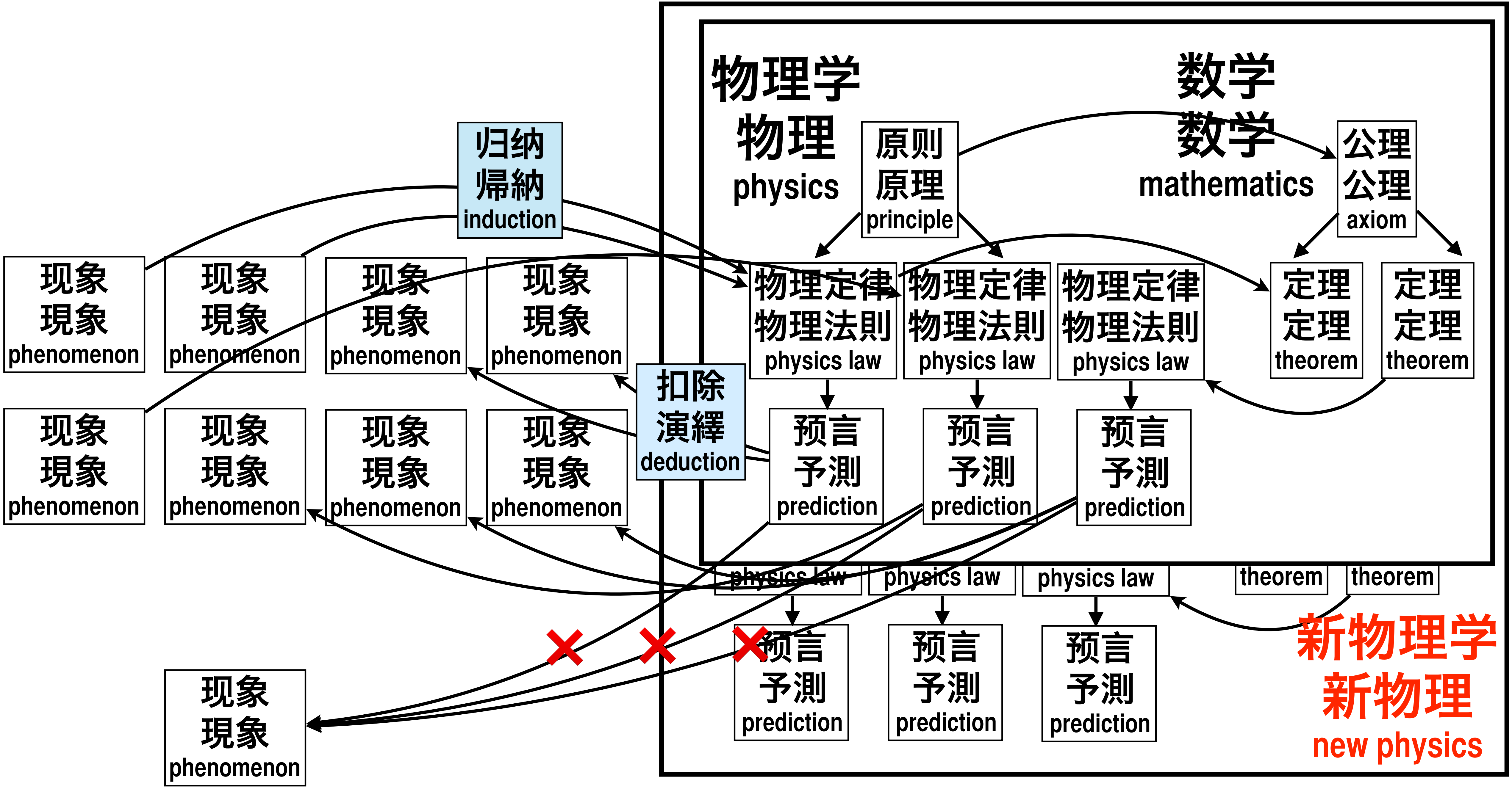
物理法則
physics law
定理
定理
theorem
定理
定理
theorem
预言
予測
prediction
预言
予測
prediction
预言
予測
prediction
现象
現象
phenomenon


物理学
物理
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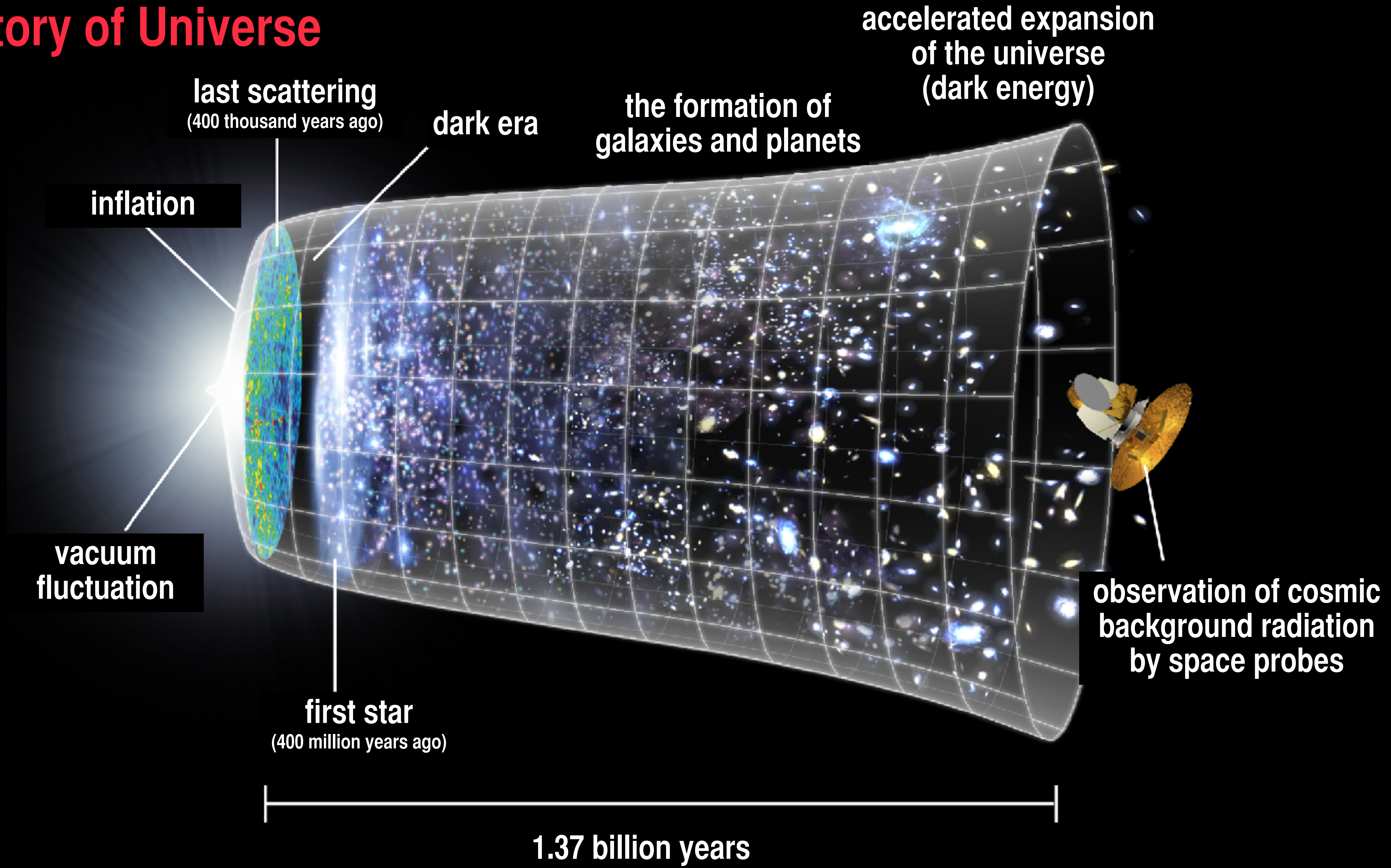
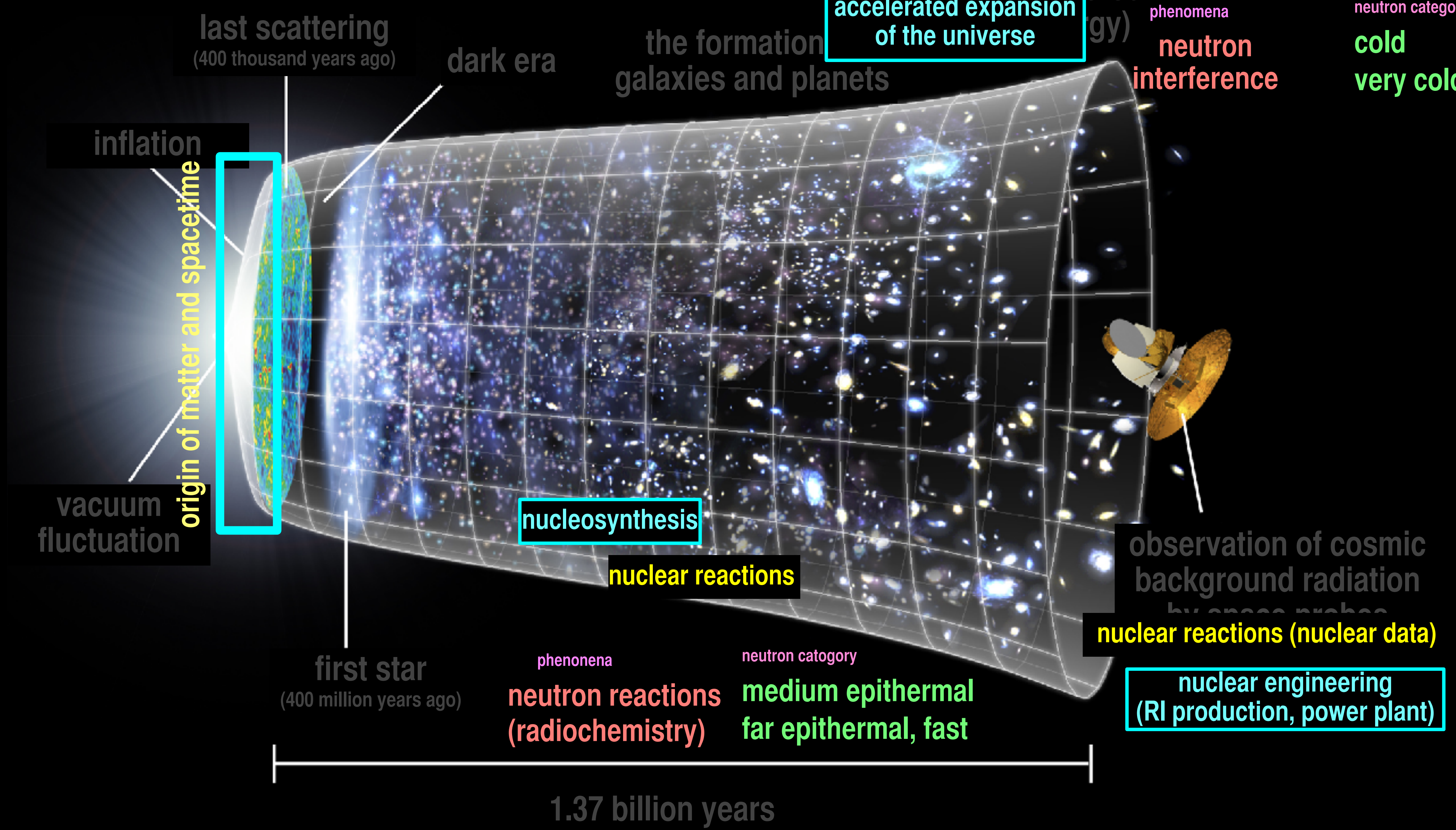
physics law
定理
定理
theorem
预言
予測
prediction
新物理学
新物理
new physics

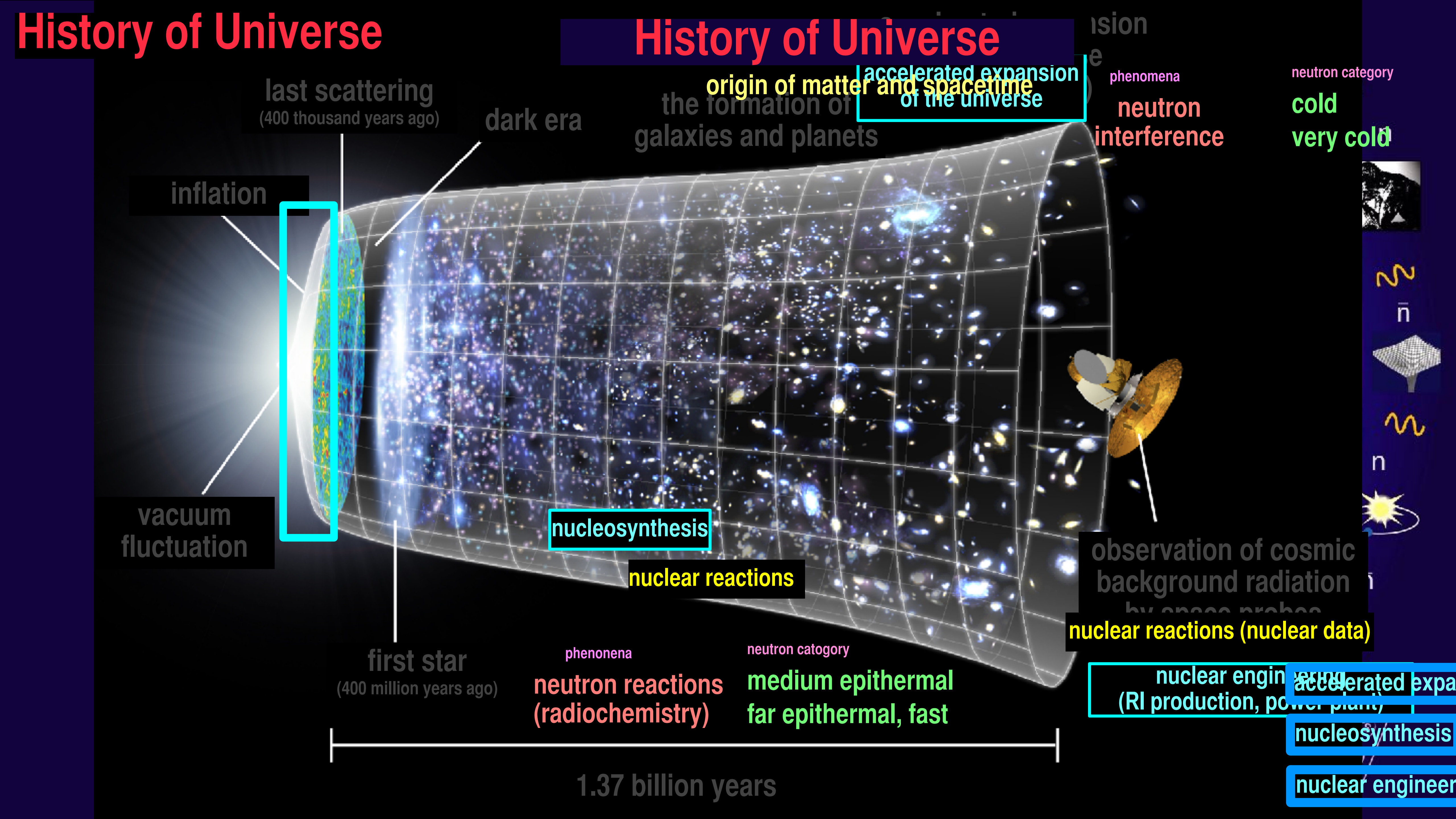
Introduction of Neutron Fundamental Physics in Japan

History of Universe



History of Universe




History of Universe
History of Universe
last scattering
(400 thousand years ago)
dark era
the formation of
galaxies and planets
origin of matter and spacetime
accelerated expansion
of the universe
phenomena
neutron
interference
neutron category
cold
very cold
inflation
vacuum
fluctuation
nucleosynthesis
nuclear reactions
observation of cosmic
background radiation
nuclear reactions (nuclear data)
nuclear engineering
(RI production, power plant)
accelerated expa
nucleosynthesis
nuclear engineer
first star
(400 million years ago)
phenonena
neutron reactions
(radiochemistry)
neutron catogory
medium epithermal
far epithermal, fast
n̄
n
1.37 billion years

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)

symmetry

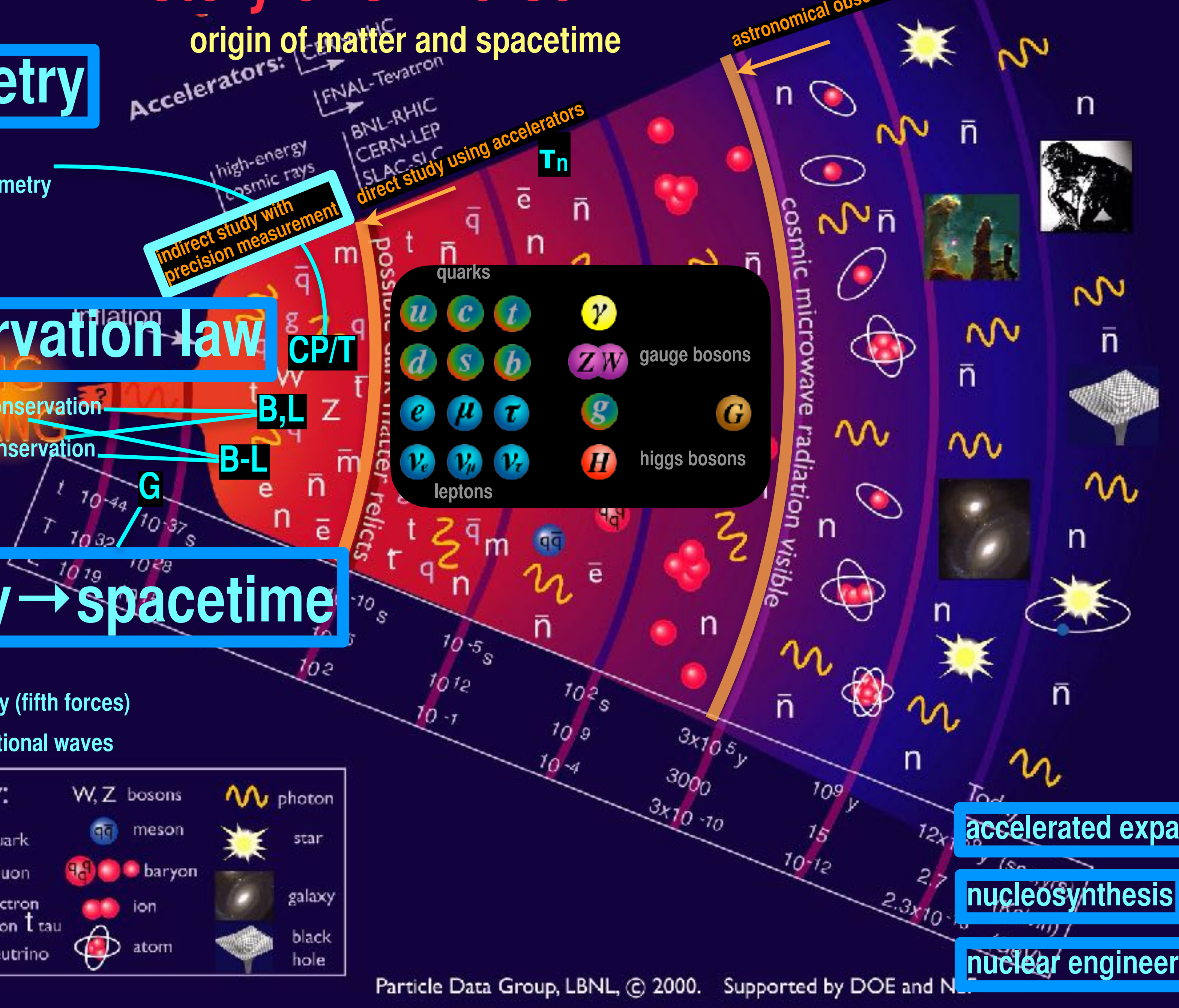
CP symmetry
time reversal symmetry

conservation law

baryon number conservation
lepton number conservation

gravity→spacetime

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



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

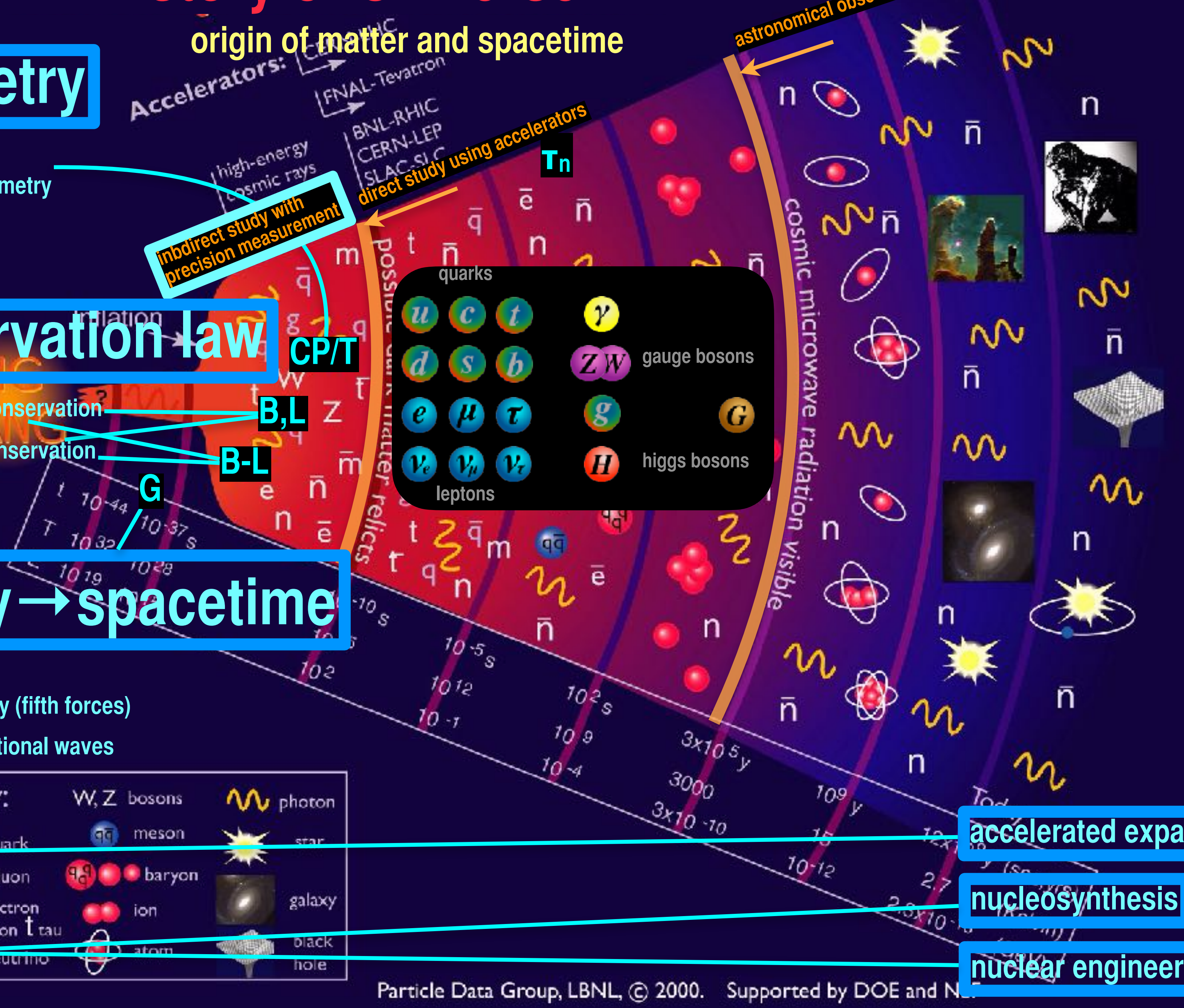
baryon number conservation
lepton number conservation

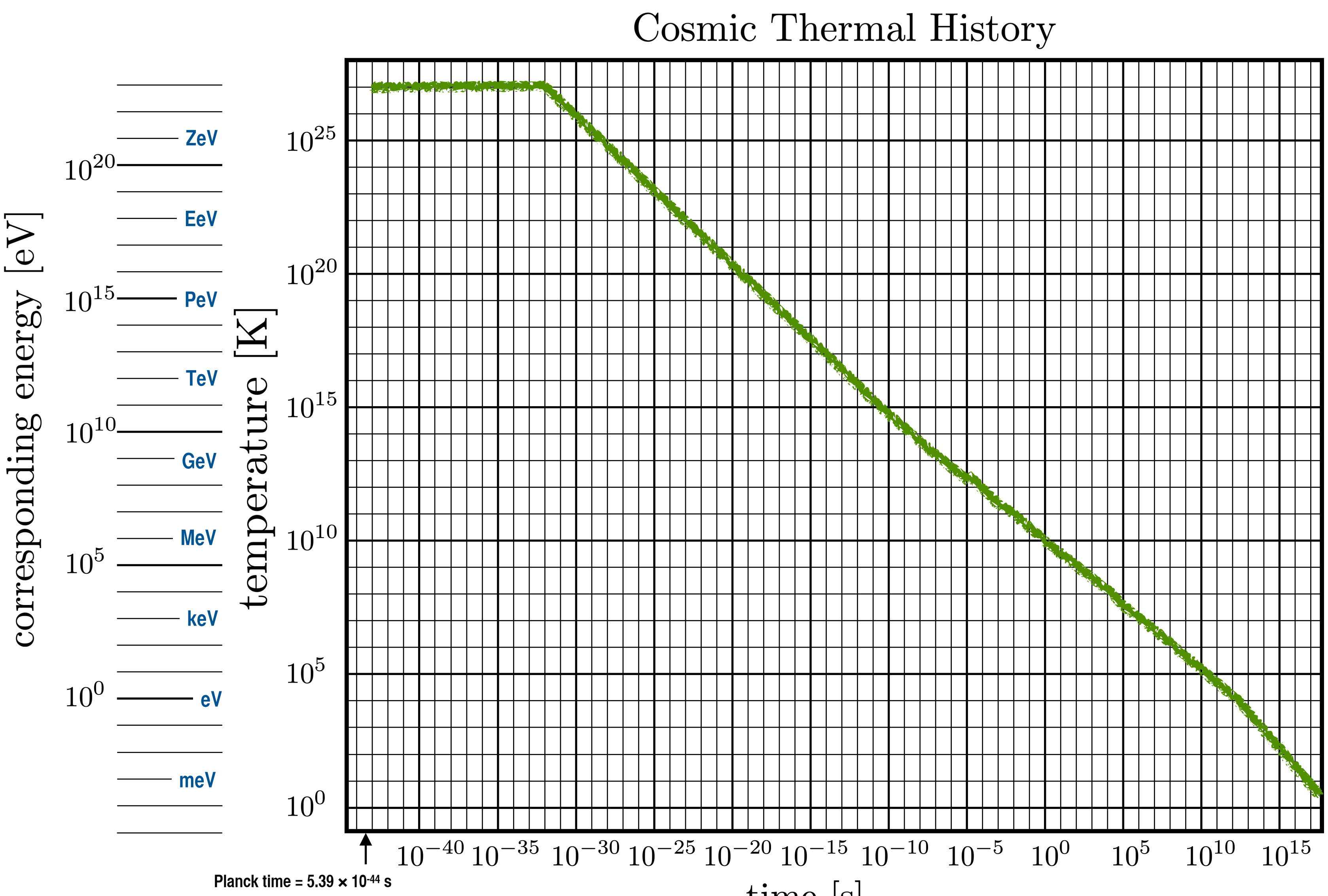
gravity → spacetime

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

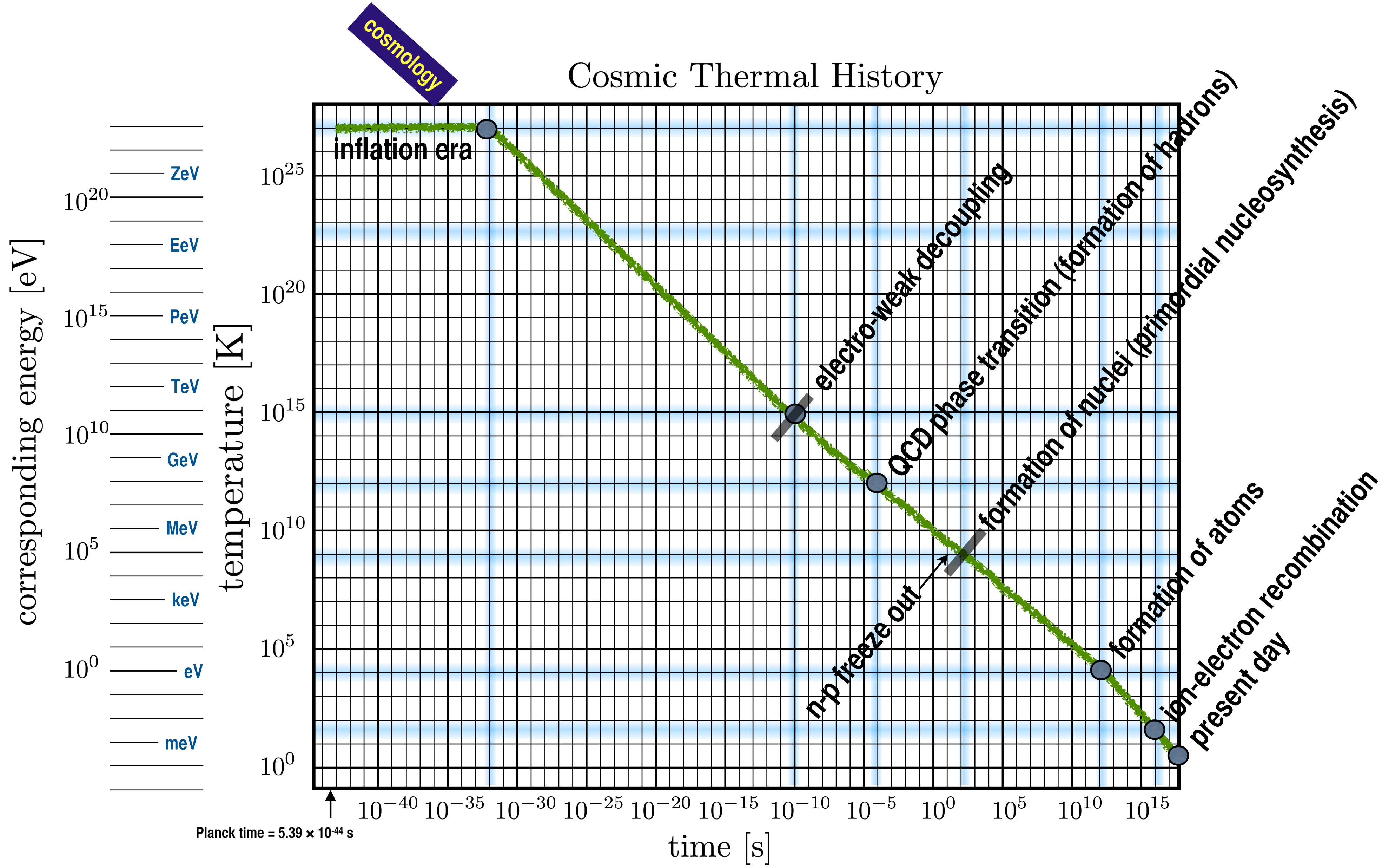
Dark Energy

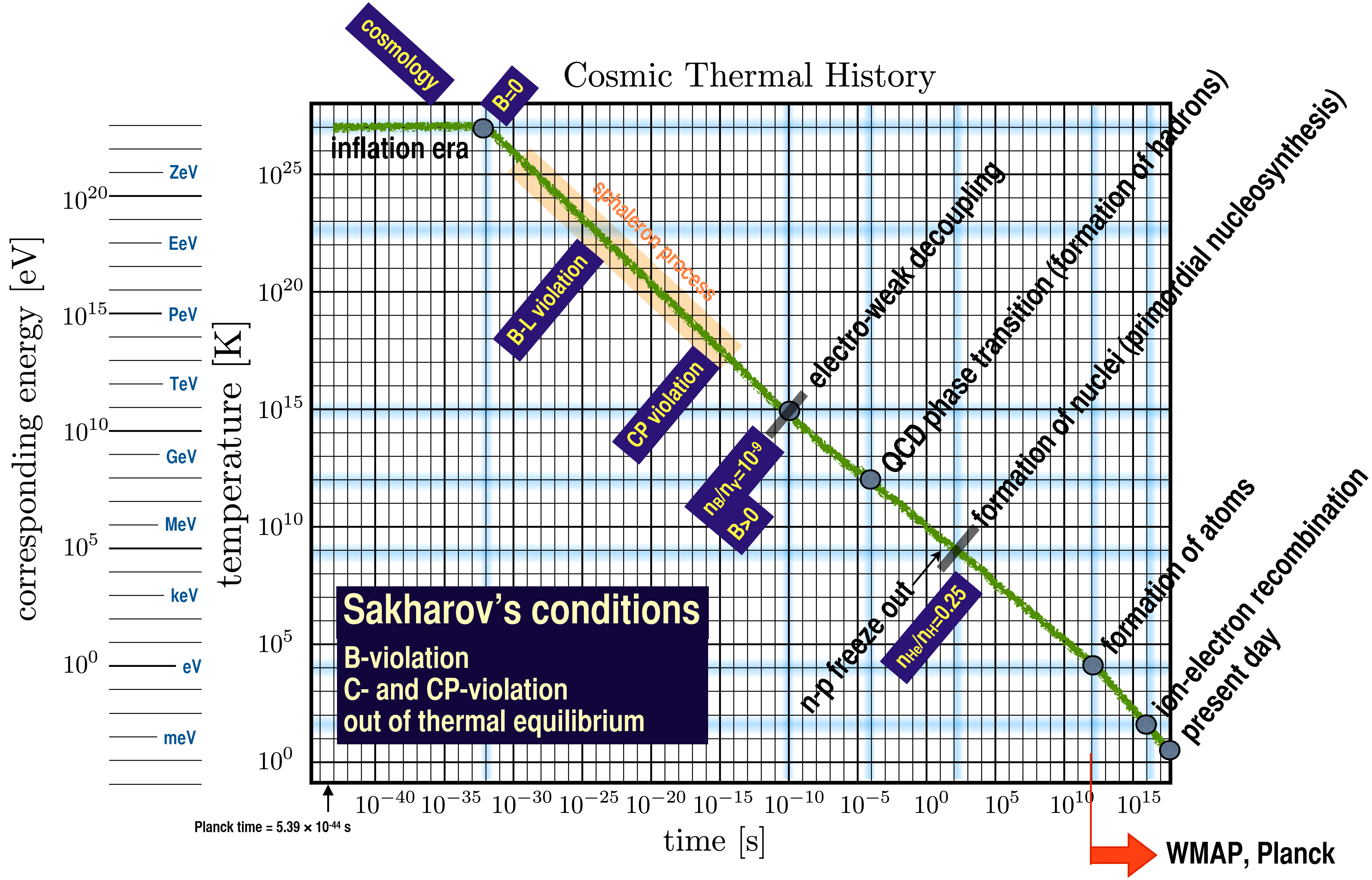
nuclear reaction





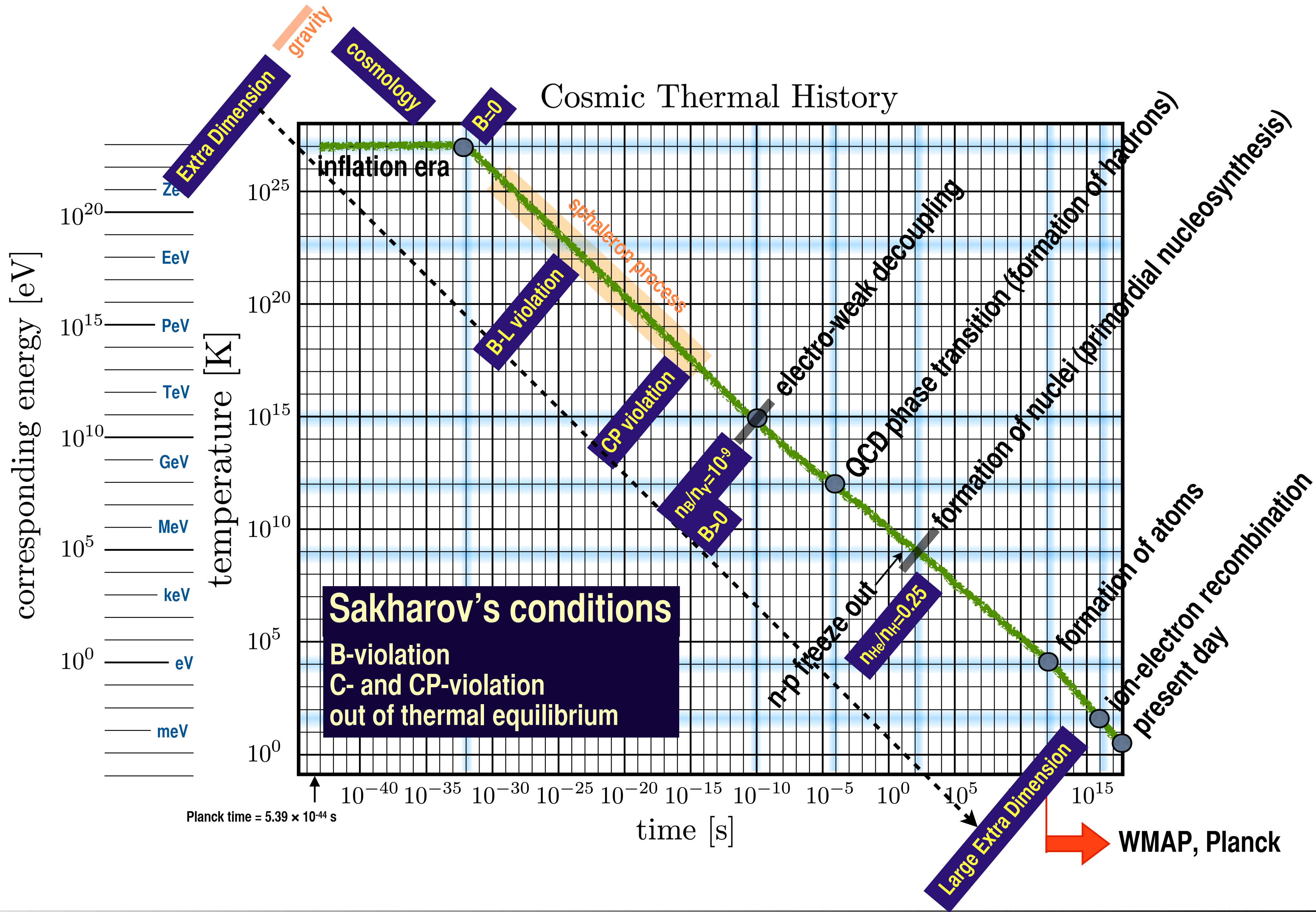
Cosmic Thermal History
corresponding energy [eV]
10^{20}
10^{15}
10^{10}
10^{5}
10^{0}
ZeV
EeV
PeV
TeV
GeV
MeV
keV
eV
meV
temperature [K]
10^{25}
10^{20}
10^{15}
10^{10}
10^{5}
10^{0}
10^{-40} 10^{-35} 10^{-30} 10^{-25} 10^{-20} 10^{-15} 10^{-10} 10^{-5} 10^{0} 10^{5} 10^{10} 10^{15}
time [s]
Planck time = 5.39×10^{-44} s


cosmology
Cosmic Thermal History
inflation era
electro-weak decoupling
QCD phase transition (formation of hadrons)
formation of nuclei (primordial nucleosynthesis)
n-p freeze out
formation of atoms
ion-electron recombination
present day
temperature [K]
corresponding energy [eV]
ZeV
EeV
PeV
TeV
GeV
MeV
keV
eV
meV
time [s]
Planck time = 5.39 × 10-44 s

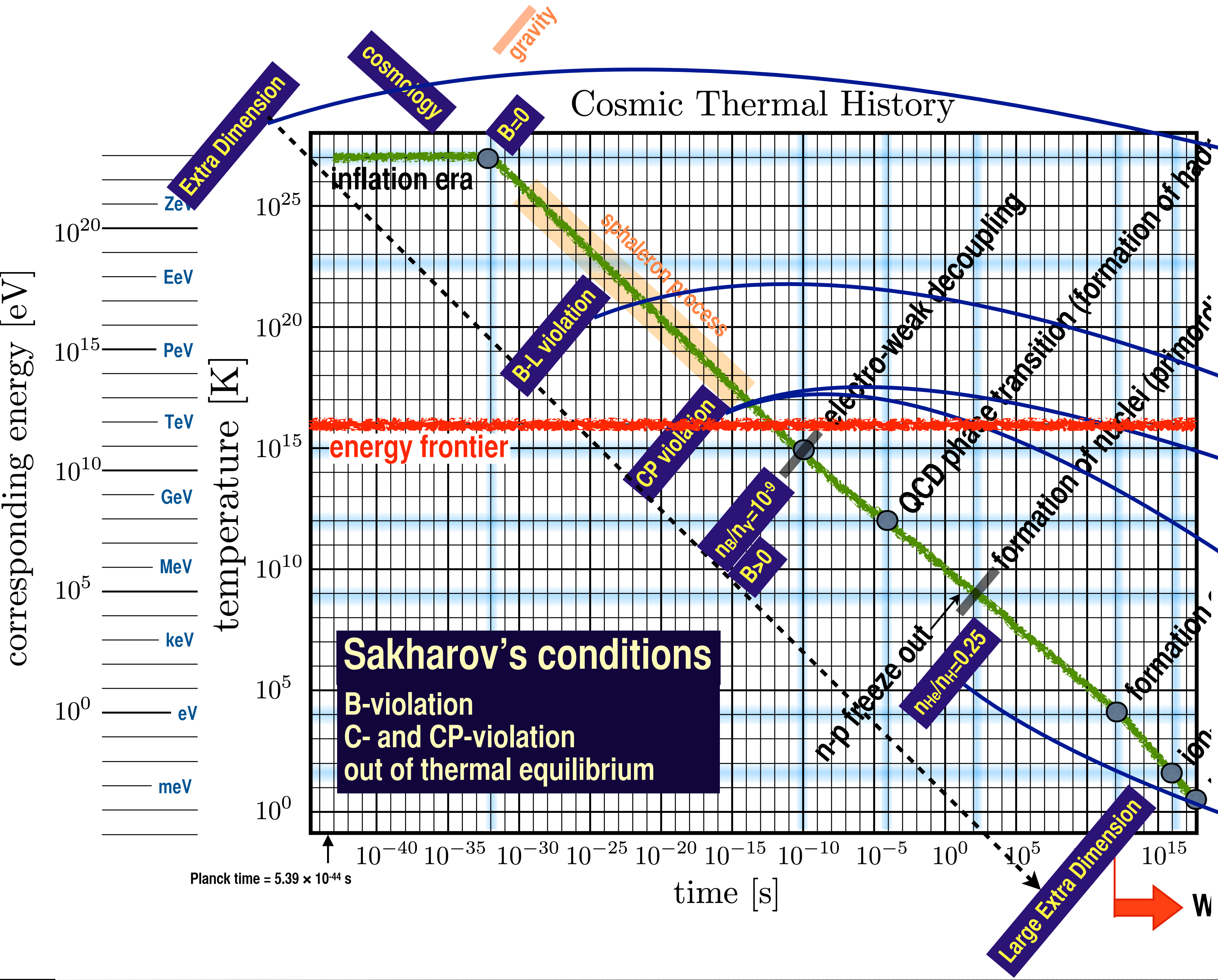


Sakharov's conditions

B-violation
C- and CP-violation
out of thermal equilibrium



Cosmic Thermal History
gravity
cosmology
Extra Dimension
B=0
inflation era
sphaleron process
B-L violation
CP violation
electro-weak decoupling
QCD phase transition (formation of hadrons)
formation of nuclei (primordial nucleosynthesis)
$n_B/n_\gamma=10^{-9}$
B>0
n-p freeze out
$n_{He}/n_H=0.25$
formation of atoms
ion-electron recombination
present day
Large Extra Dimension
WMAP, Planck
corresponding energy [eV]
temperature [K]
time [s]
Planck time = 5.39 × 10-44 s
ZeV
EeV
PeV
TeV
GeV
MeV
keV
eV
meV
Sakharov's conditions
B-violation
C- and CP-violation
out of thermal equilibrium



new-force search

(α, λ) $\qquad U(r) = \frac{U_0}{r} e^{-r/\lambda}$

neutron scattering
neutron interferometry
Pendellosung interference
GRANIT

Gravity $\quad U_g = \frac{GM}{r}\left(1 + \alpha e^{-r/\lambda}\right)$

Dark Matter, Dark Energy

spontaneous transition from neutron to antineutron

$\tau_{n\bar{n}}$

neutron antineutron oscillation

breaking of time reversal invariance

d_n

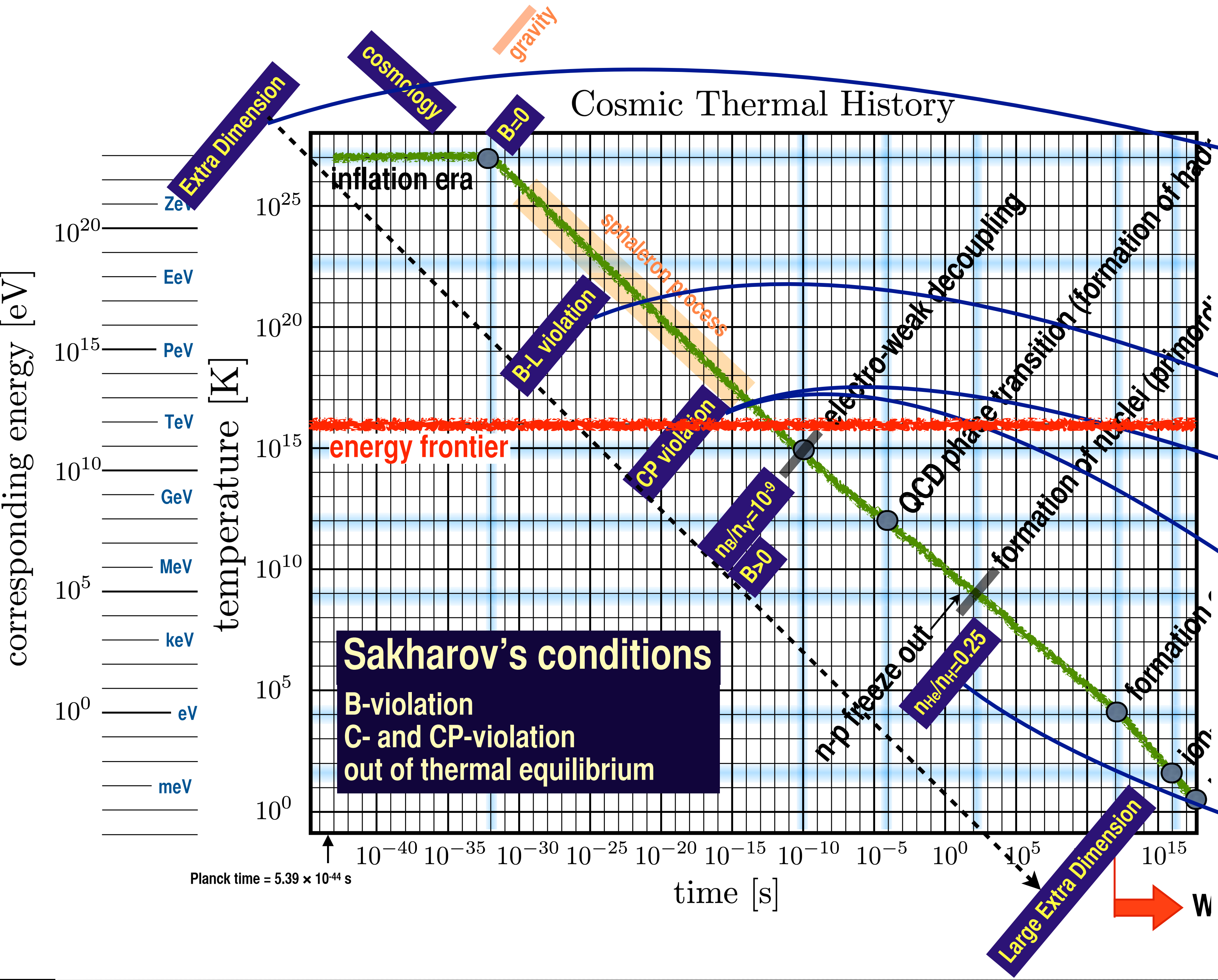
neutron EDM
TUCAN

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

epithermal neutron optics
NOPTREX

neutron β-decay

τ_n



new-force search

(α, λ) $U(r) = \frac{U_0}{r} e^{-r/\lambda}$

neutron scattering
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Pendellosung interference
GRANIT

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Dark Matter, Dark Energy

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neutron EDM
TUCAN

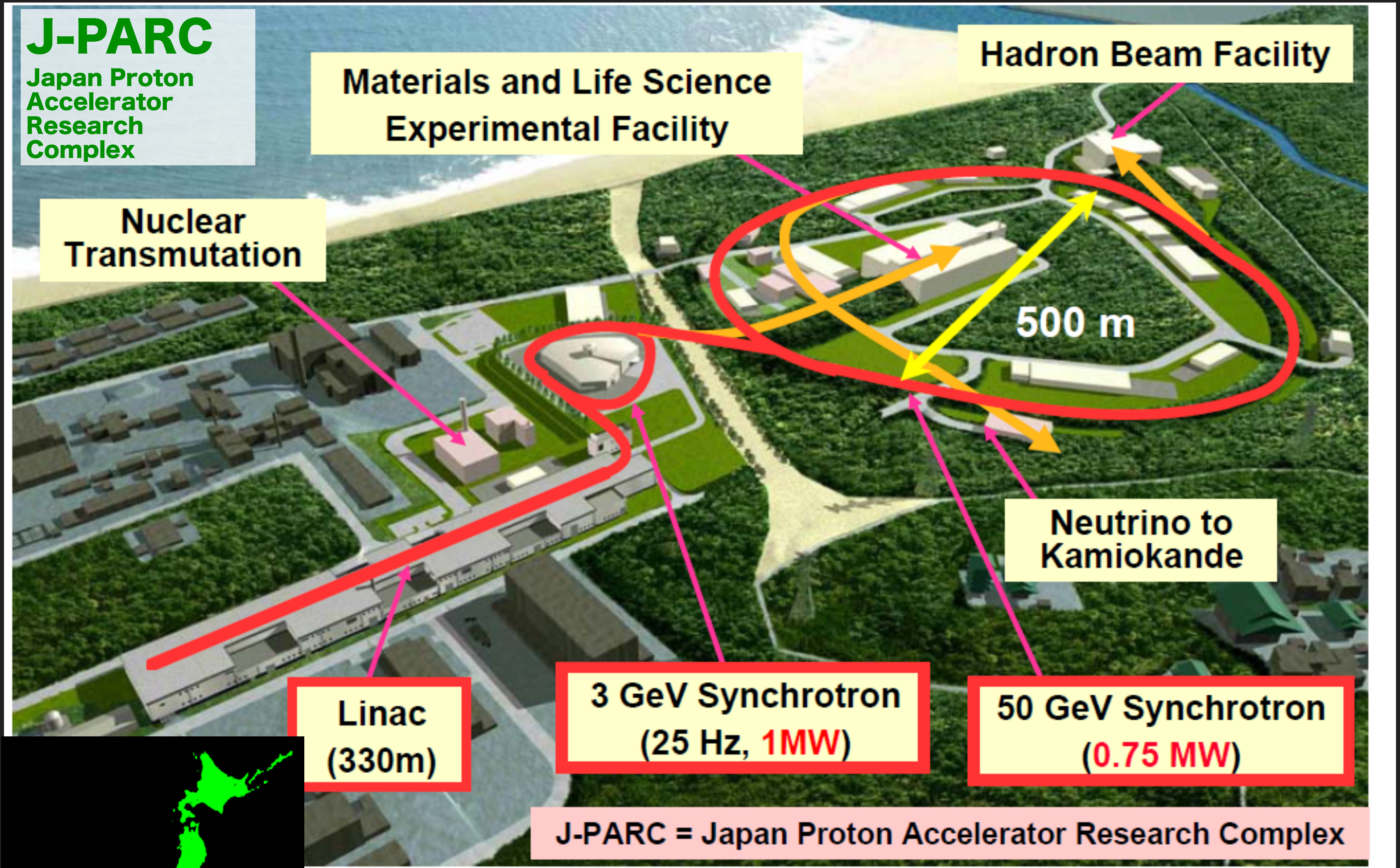
$\bar{g}_{\pi NN}$

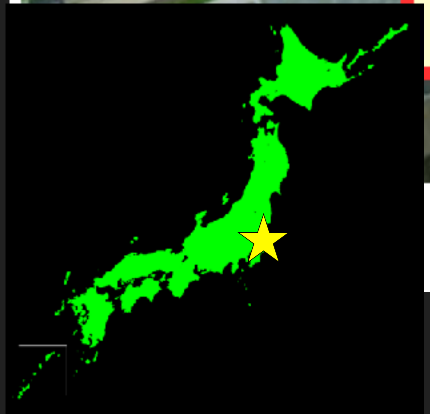
epithermal neutron optics

NOPTREX
Neutron Optical Parity and Time Reversal EXperiment

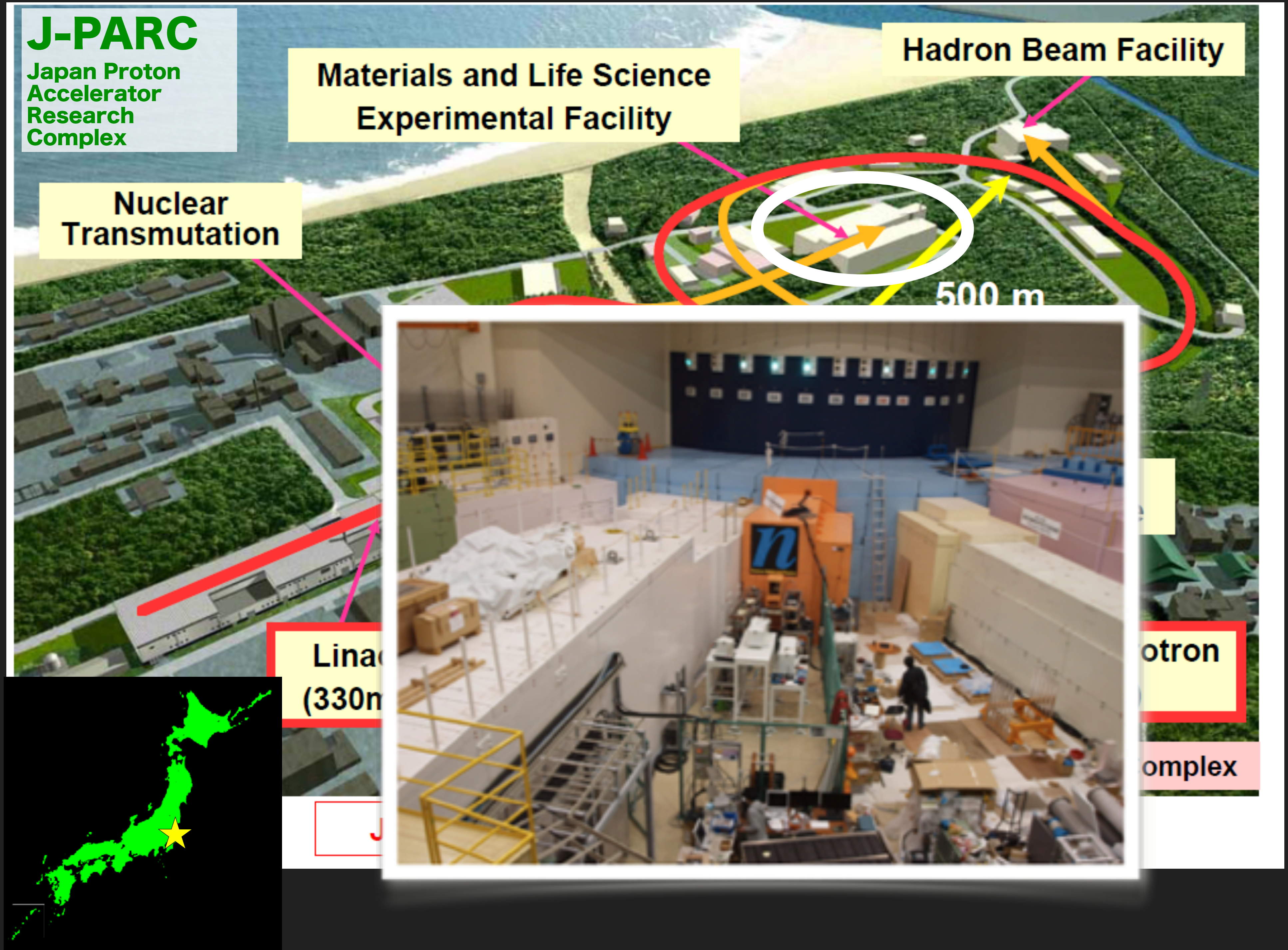
neutron β-decay

τ_n





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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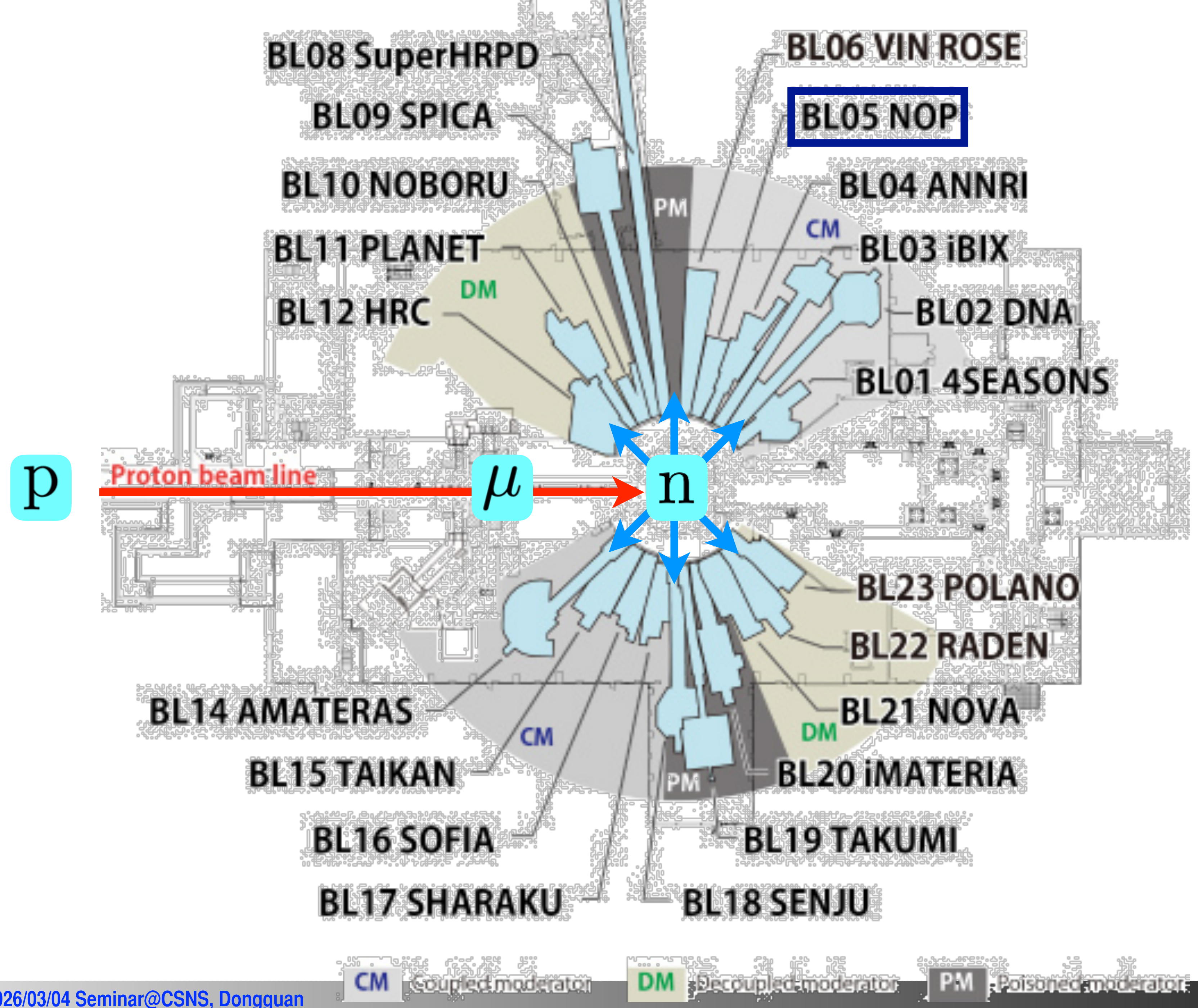
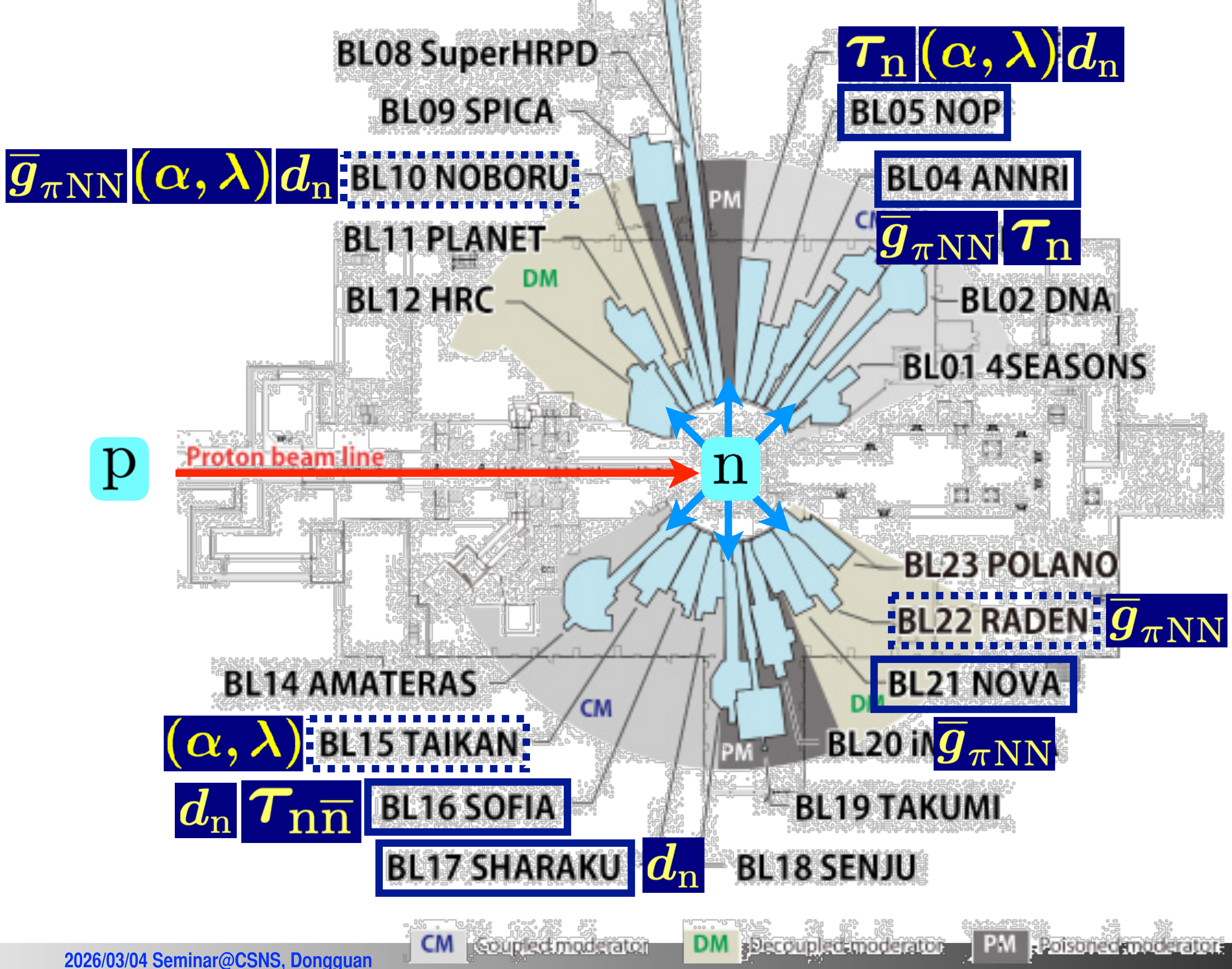
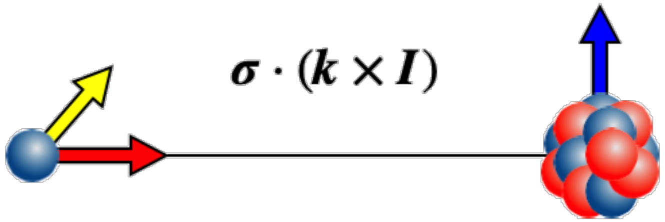

BL08 SuperHRPD
BL09 SPICA
BL10 NOBORU
BL11 PLANET
BL12 HRC
BL06 VIN ROSE
BL05 NOP
BL04 ANNRI
BL03 iBIX
BL02 DNA
BL01 4SEASONS
PM
CM
DM
p
Proton beam line
μ
n
BL23 POLANO
BL22 RADEN
BL21 NOVA
BL20 iMATERIA
BL19 TAKUMI
BL18 SENJU
BL17 SHARAKU
BL16 SOFIA
BL15 TAIKAN
BL14 AMATERAS
CM Coupled moderator
DM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


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

T-violation in compound nuclei

Enhanced symmetry violation appears
in neutron resonance capture reaction.

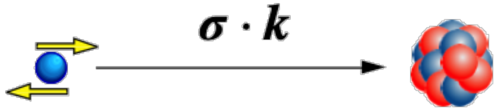
$\boldsymbol{\sigma} \cdot (\boldsymbol{k} \times \boldsymbol{I})$



Statistical nature of
compound states

P-violation

$\boldsymbol{\sigma} \cdot \boldsymbol{k}$



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

$$\Delta\sigma_T = \kappa(J)\frac{W_T}{W}\Delta\sigma_P$$

$$\kappa = 0.59 \pm 0.05$$

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)

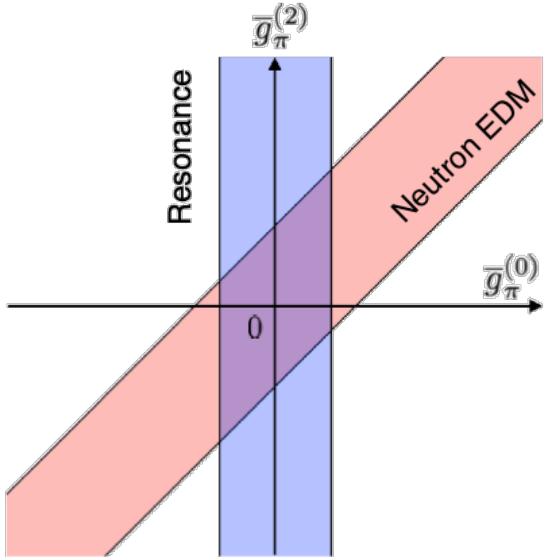
^{131}Xe
T. Okudaira et al. Phys. Rev. C 107, 054602 (2023)

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

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

⟷ complementary

Neutron EDM
10^{-26} e cm



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

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

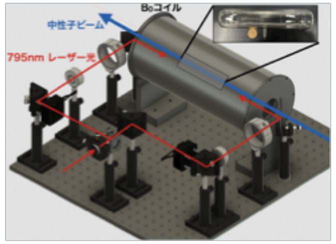
R&D for T-violation search

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

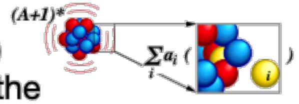
Neutron beam polarization

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

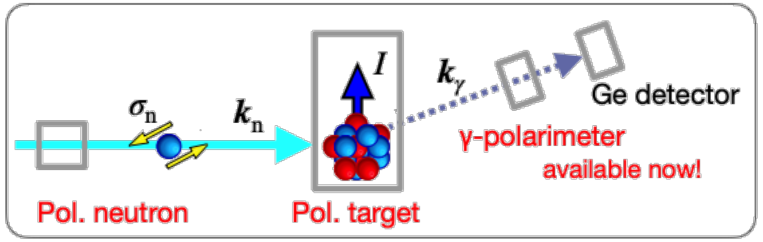
In-situ system is also available.



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



$$\frac{d\sigma}{d\Omega} = \frac{1}{2}\left\{ a_0 + a_1\, k_n \cdot k_\gamma + a_2\, \sigma_n \cdot (k_n \times k_\gamma) + a_3 \left((k_n \cdot k_\gamma)^2 - \frac{1}{3} \right) + \cdots \right\}$$

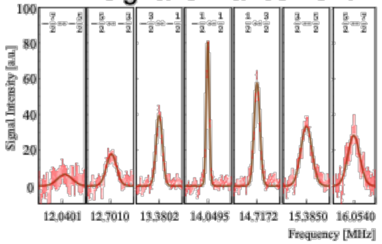


Target nuclei polarization

Dynamic nuclear polarization for ^{139}La with $LaAlO_3$ crystal

$P_{La} \rightarrow 31.9\%$

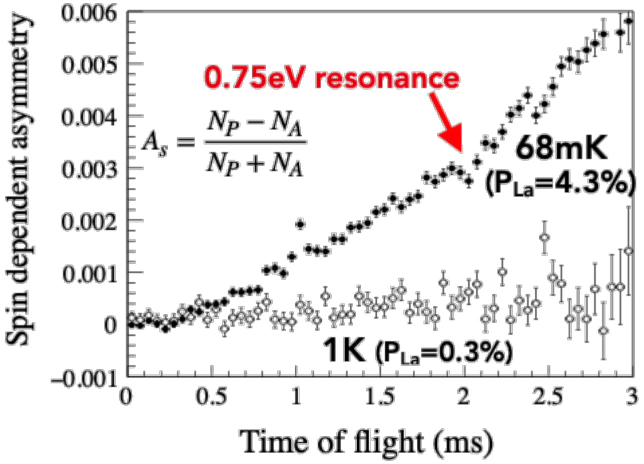
DNP signal enhancement



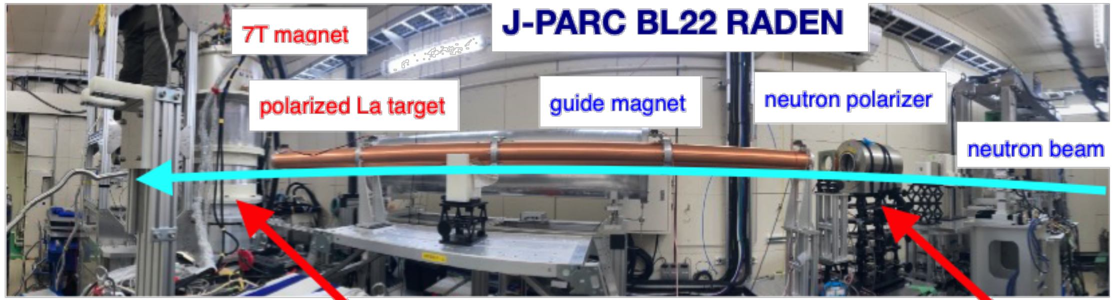
T. Yamamoto et. al., Phys. Rev. C101, 064624 (2020)
T. Okudaira et. al., Nucl. Instr. Meth. A977, 164301 (2020)
K. Ishizaki, et.al., Nucl. Instr. and Meth. A1020, 165845 (2021)
K. Ishizaki, et.al., Rev. Sci. Instrum. 95, 063301 (2024)
S. Endo et. al. Eur. Phys. J. A 60:166 (2024)

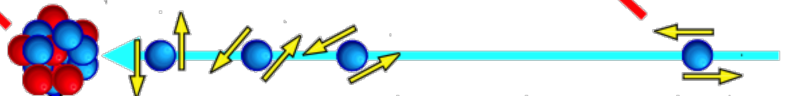
Demonstration of T-violation search

Asymmetry of absorption was observed.



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





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

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

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

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

R. Nakabe, PhD thesis (2024)

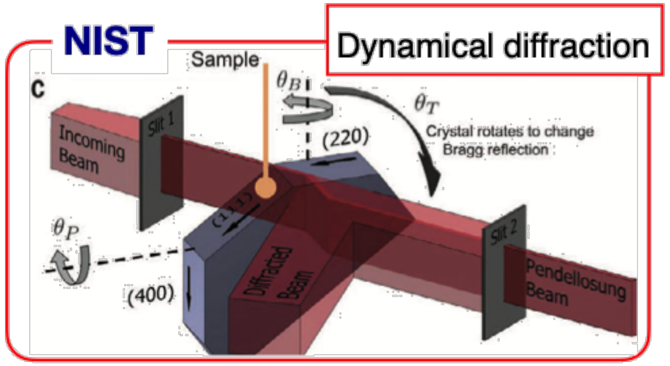
Unknown force search

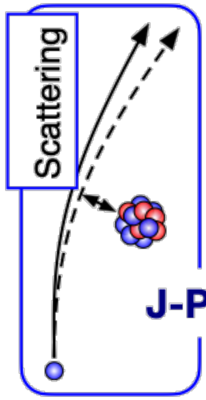
Extra-dimension, Dark energy

(α, λ)

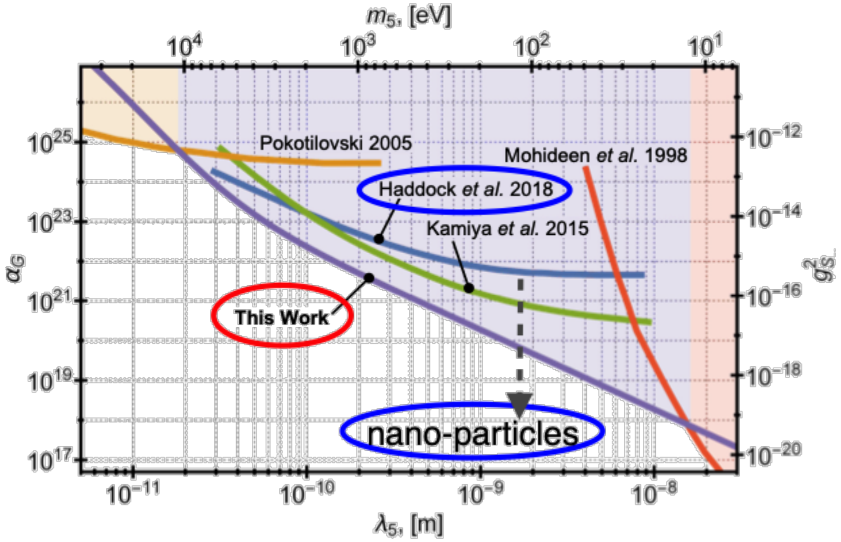
New limit for Yukawa-type intermediate force

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

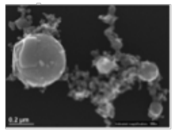




J-PARC BL05 NOP



nano-particles



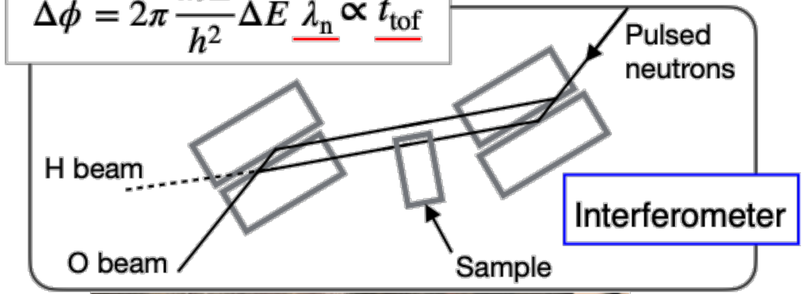
Hydrogen storage alloy

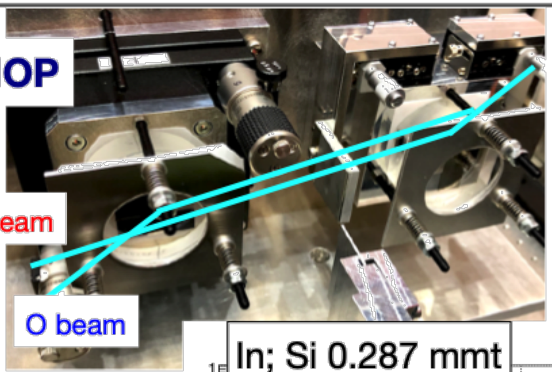
C. C. Haddock, et al., Phys. Rev. D97, 062002 (2018)

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

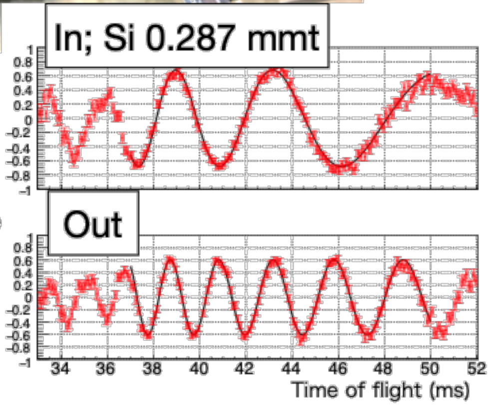
New interferometer with high precision

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





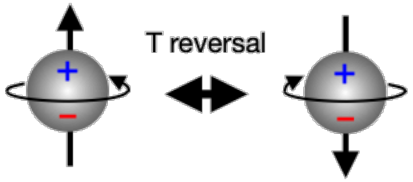
Phase-shift was observed due to refractive index of sample



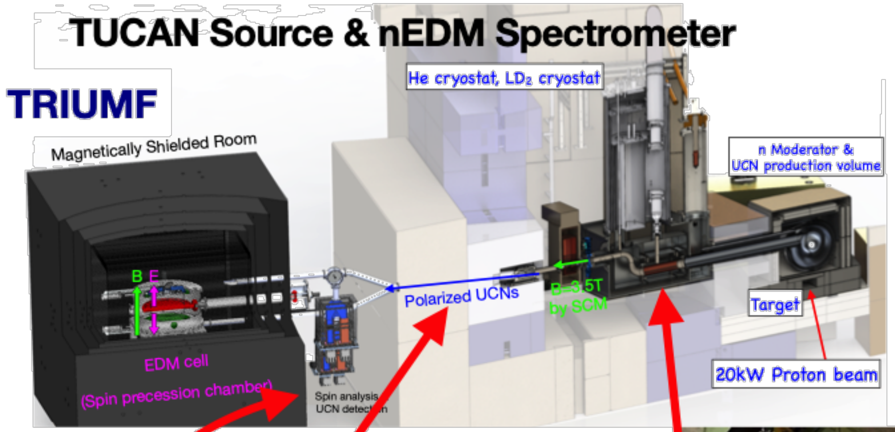
Precision measurements of neutron-nuclear scattering lengths were demonstrated.

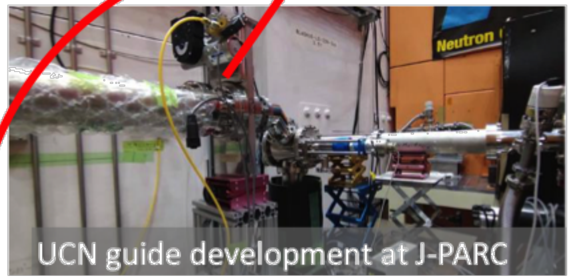
T. Fujiie, et al., PRL 132, 023402 (2024)

Neutron EDM using high-flux UCNs

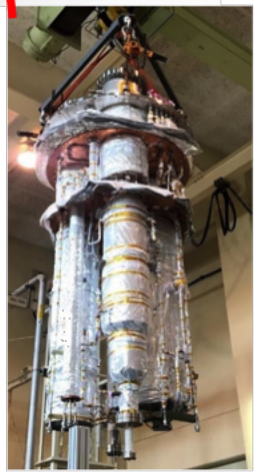


Permanent EDM signals
Time-reversal violation.



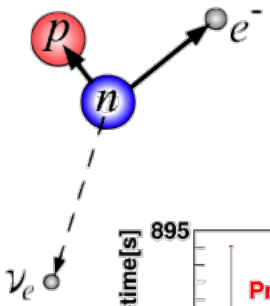


J-PARC BL05 NOP

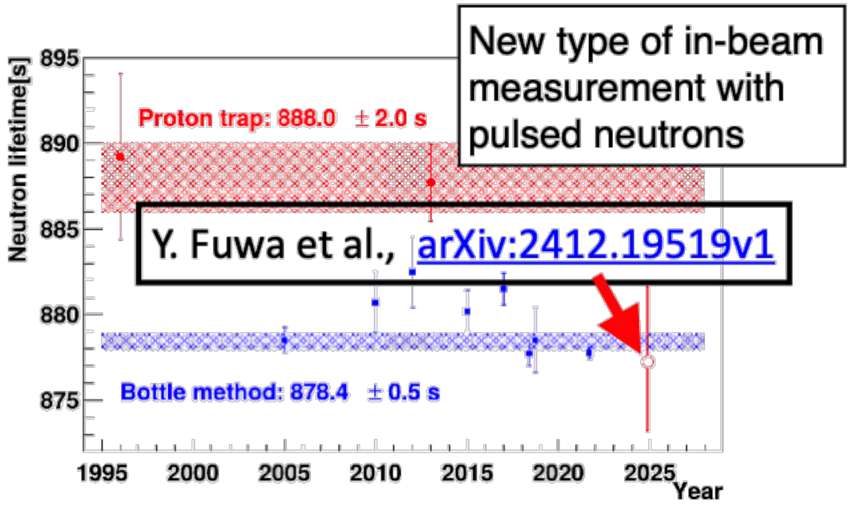


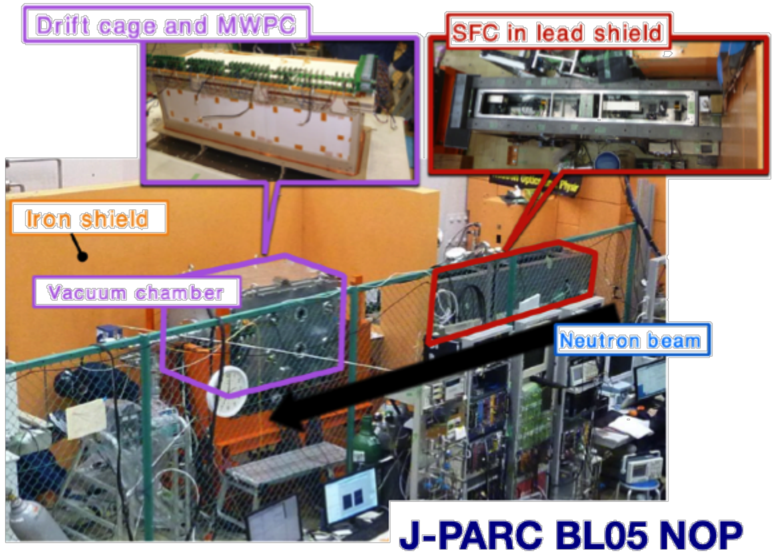
S. Ahmed, et.al., Phys. Rev. C 99, 025503 (2019)

Neutron Lifetime



CKM Unitarity check
Big Bang Nucleosynthesis
Decay to dark channel?

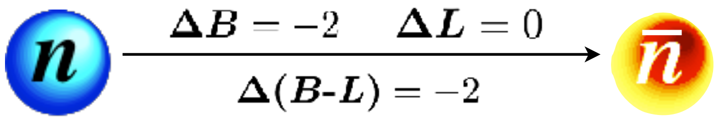




J-PARC BL05 NOP

B, B-L nonconservation

nnbar oscillation: spontaneous transition from neutron to antineutron



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

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

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

$$\tau_{\mathrm{n\bar{n},free}} > 0.86 \times 10^8 \, \mathrm{s} \, (\mathrm{CL90\%})$$

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

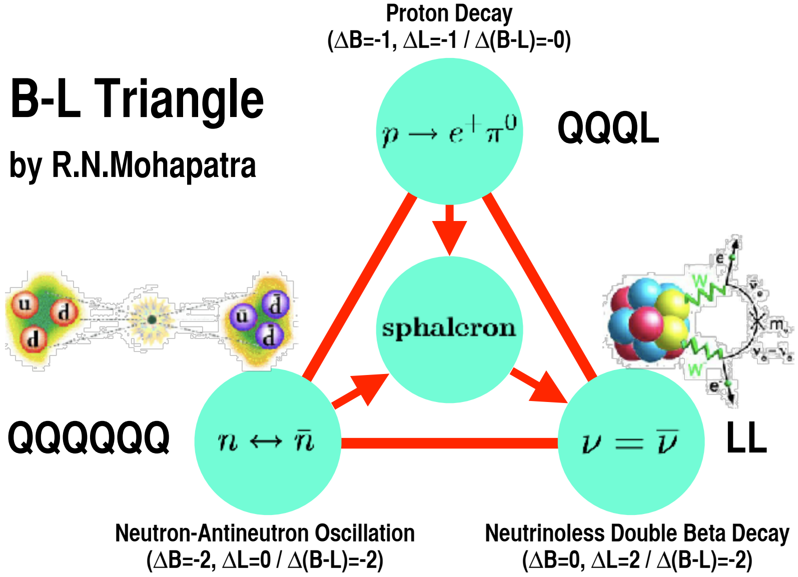
2-3 order improvement

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

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

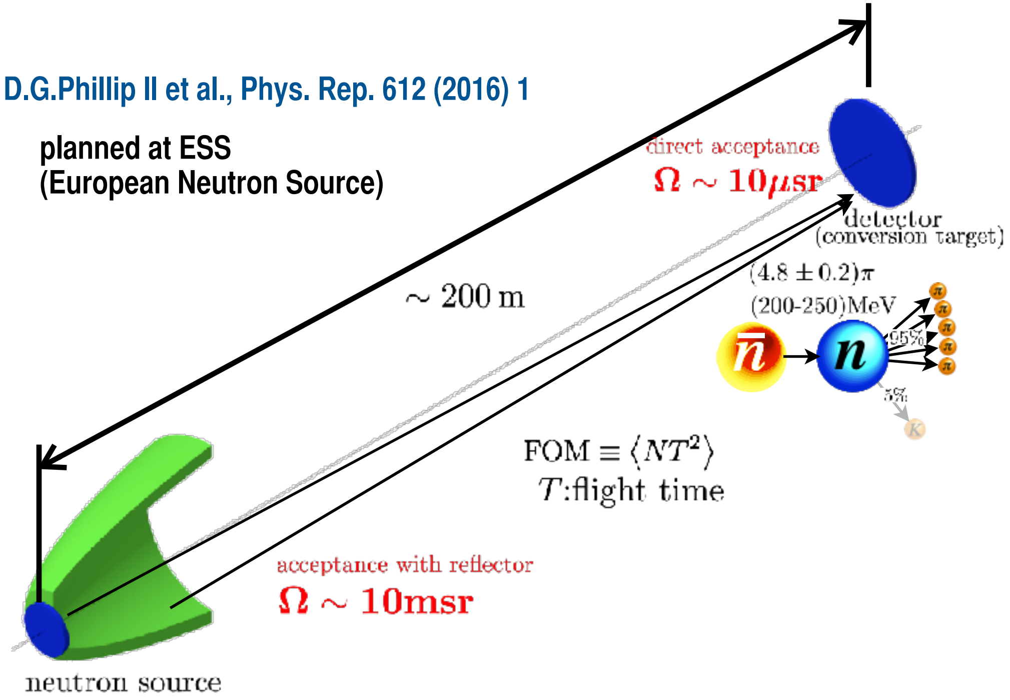
B-L Triangle

by R.N.Mohapatra



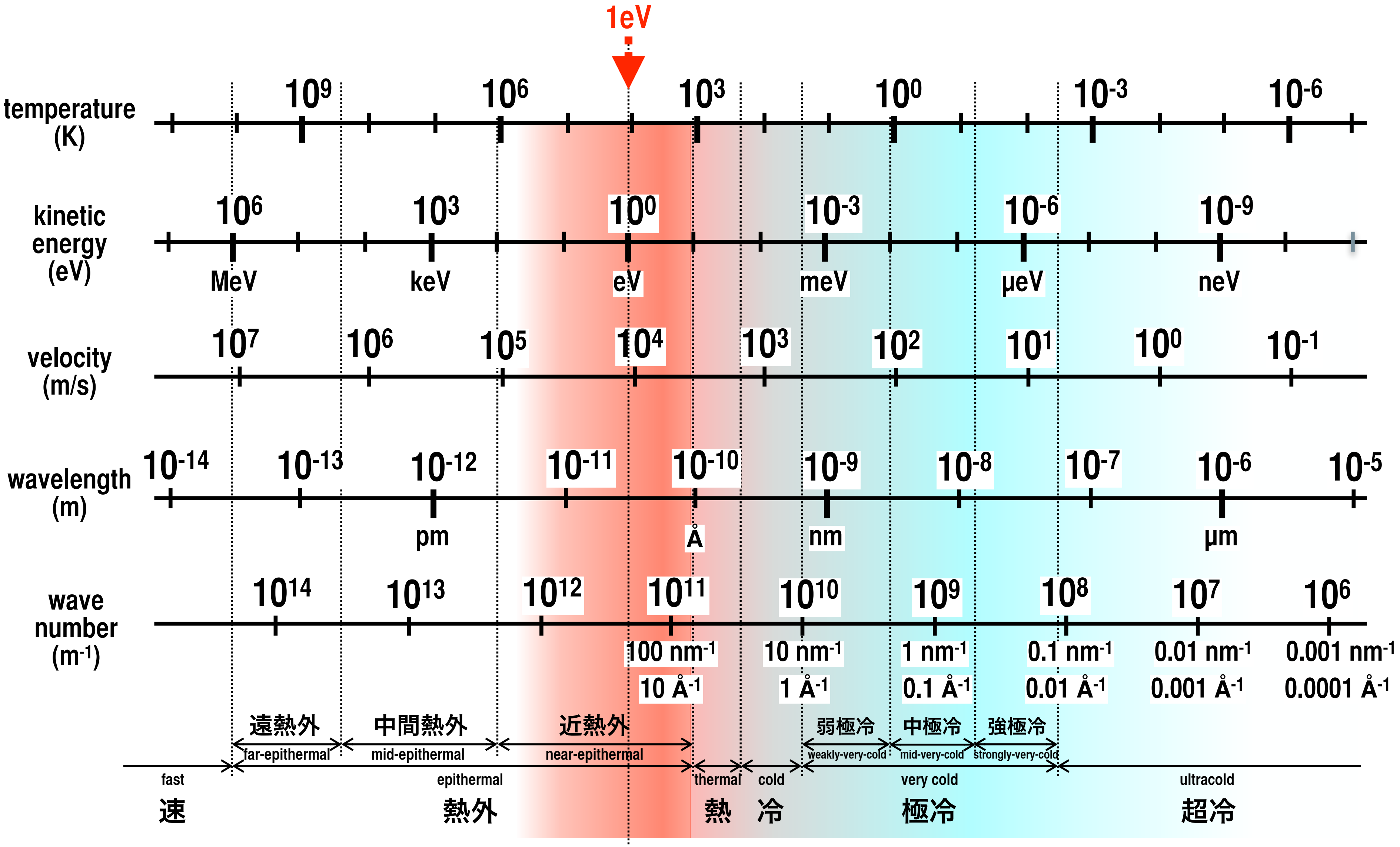
D.G.Phillip II et al., Phys. Rep. 612 (2016) 1

planned at ESS
(European Neutron Source)

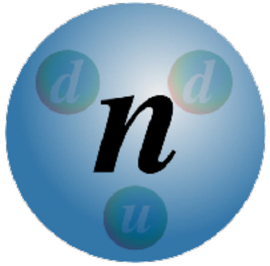


Neutron Optics

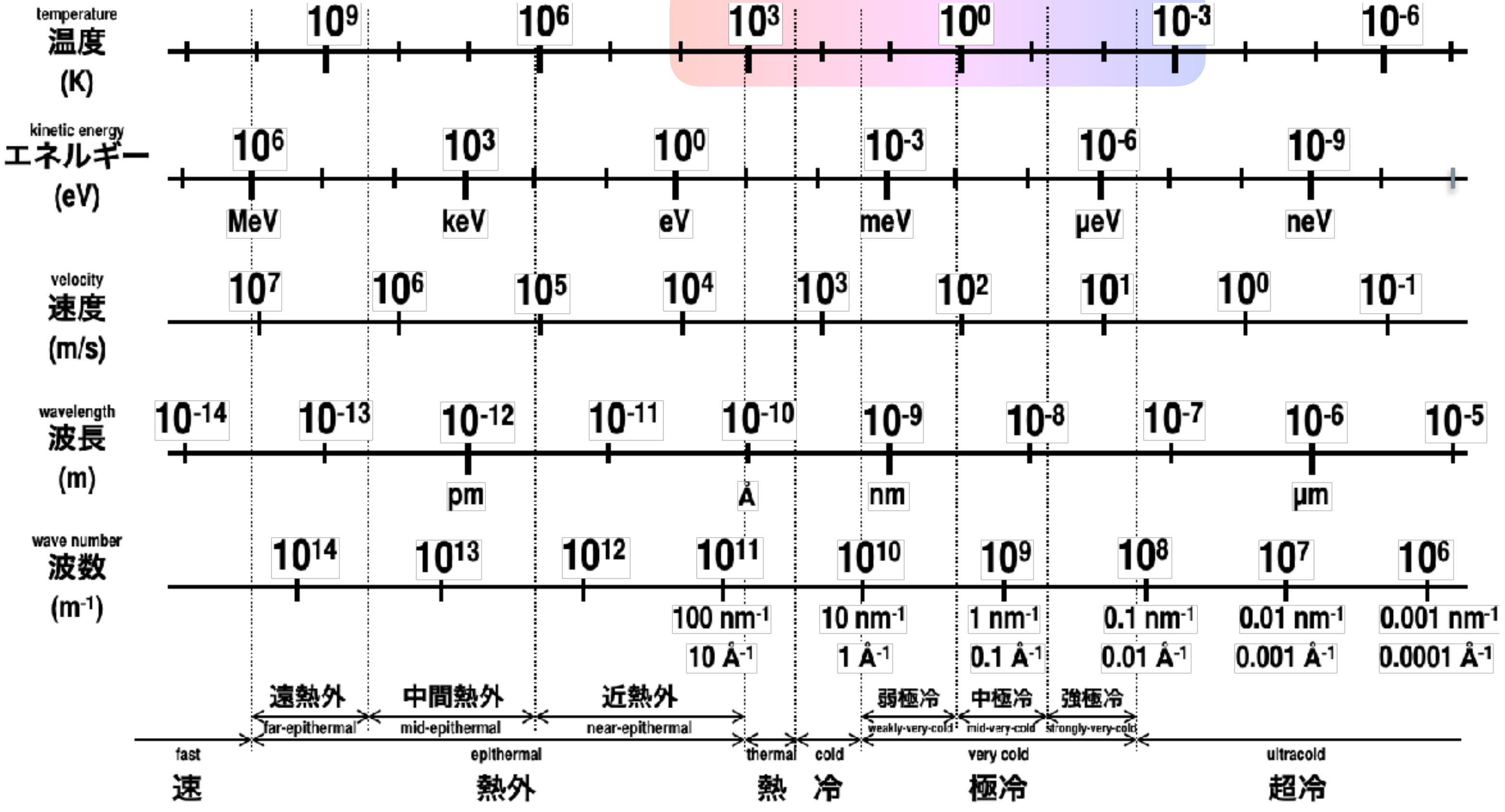
Neutrons conversions among kinematic variables and an example of energy range names



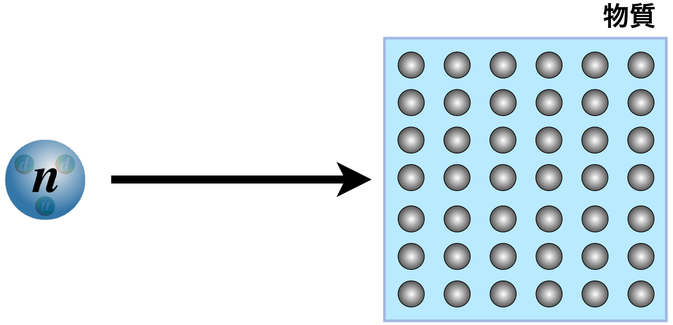
中性子波動



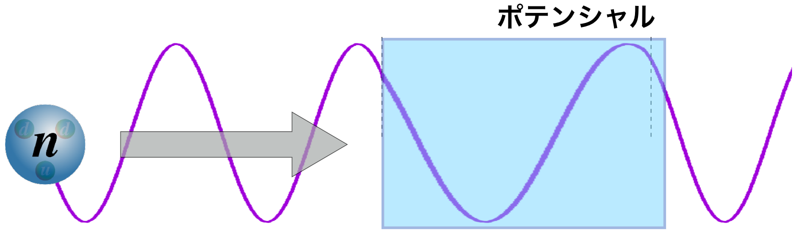
d
d
n
u



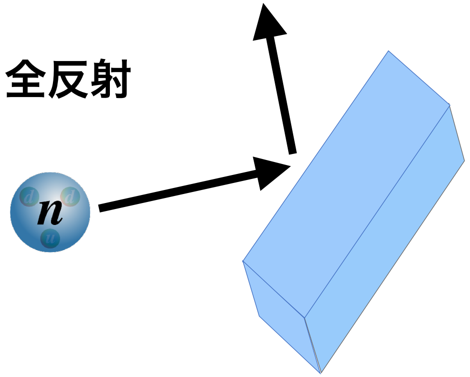
temperature
温度
(K)
10^9 10^6 10^3 10^0 10^{-3} 10^{-6}
kinetic energy
エネルギー
(eV)
10^6 10^3 10^0 10^{-3} 10^{-6} 10^{-9}
MeV keV eV meV μeV neV
velocity
速度
(m/s)
10^7 10^6 10^5 10^4 10^3 10^2 10^1 10^0 10^{-1}
wavelength
波長
(m)
10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5}
pm Å nm μm
wave number
波数
(m^{-1})
10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^9 10^8 10^7 10^6
100 nm^{-1} 10 nm^{-1} 1 nm^{-1} 0.1 nm^{-1} 0.01 nm^{-1} 0.001 nm^{-1}
10 $Å^{-1}$ 1 $Å^{-1}$ 0.1 $Å^{-1}$ 0.01 $Å^{-1}$ 0.001 $Å^{-1}$ 0.0001 $Å^{-1}$
遠熱外 far-epithermal
中間熱外 mid-epithermal
近熱外 near-epithermal
弱極冷 weakly-very-cold
中極冷 mid-very-cold
強極冷 strongly-very-cold
fast 速
epithermal 熱外
thermal 熱
cold 冷
very cold 極冷
ultracold 超冷



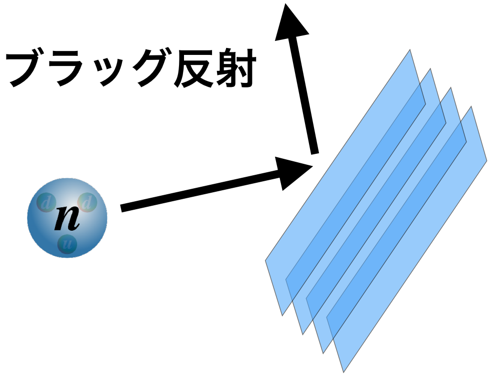
物質
n



ポテンシャル
n

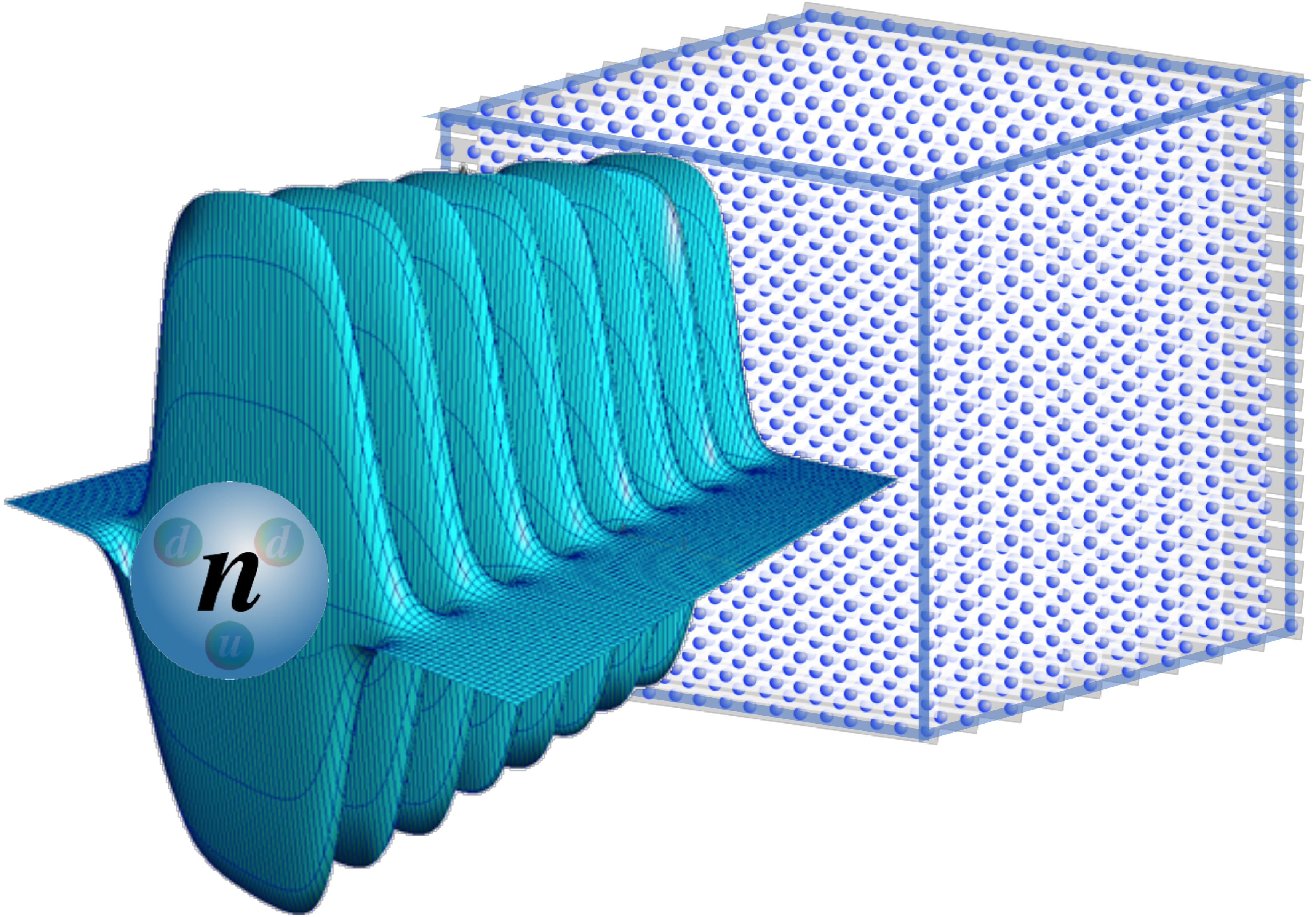


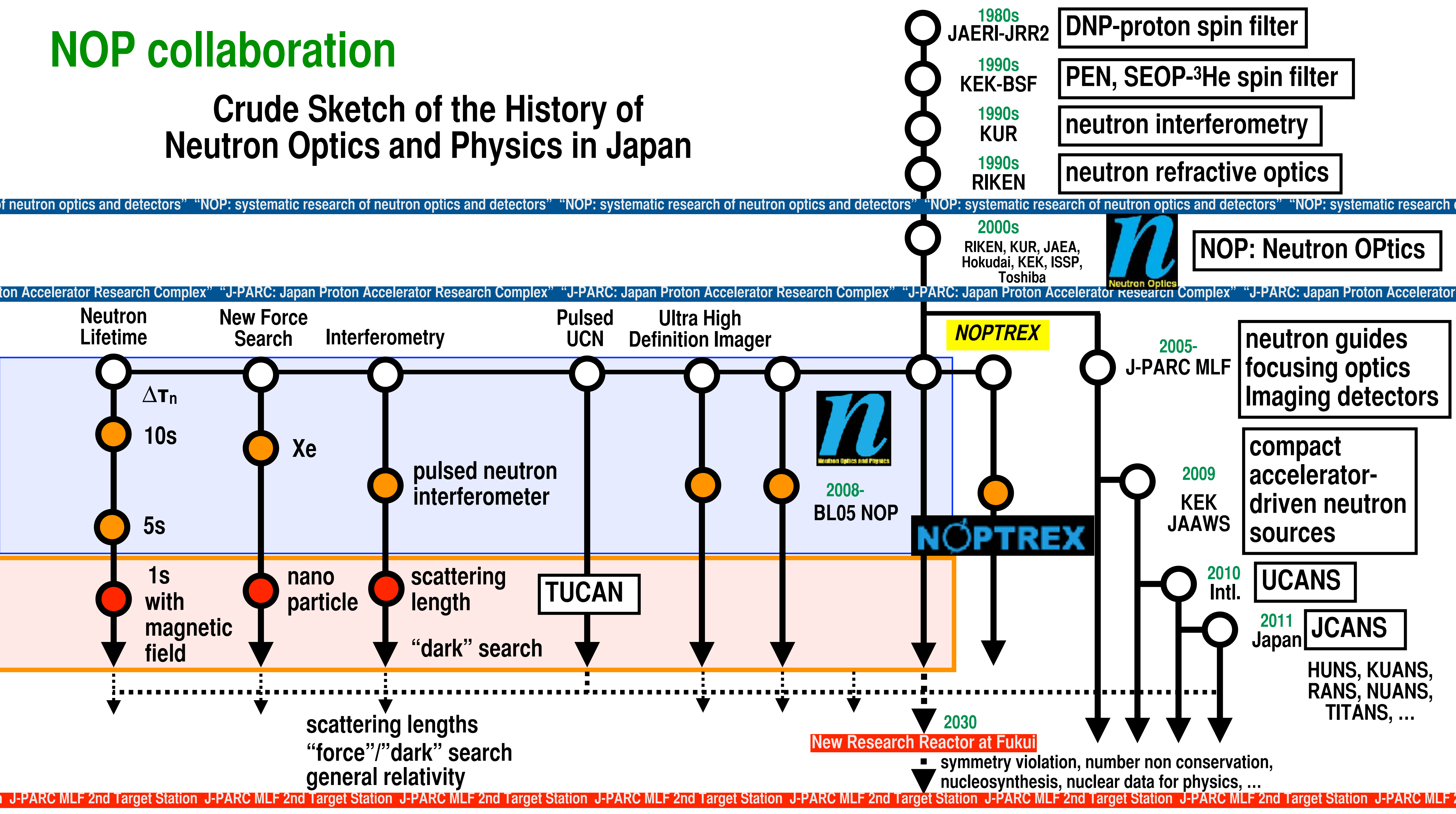
全反射
n



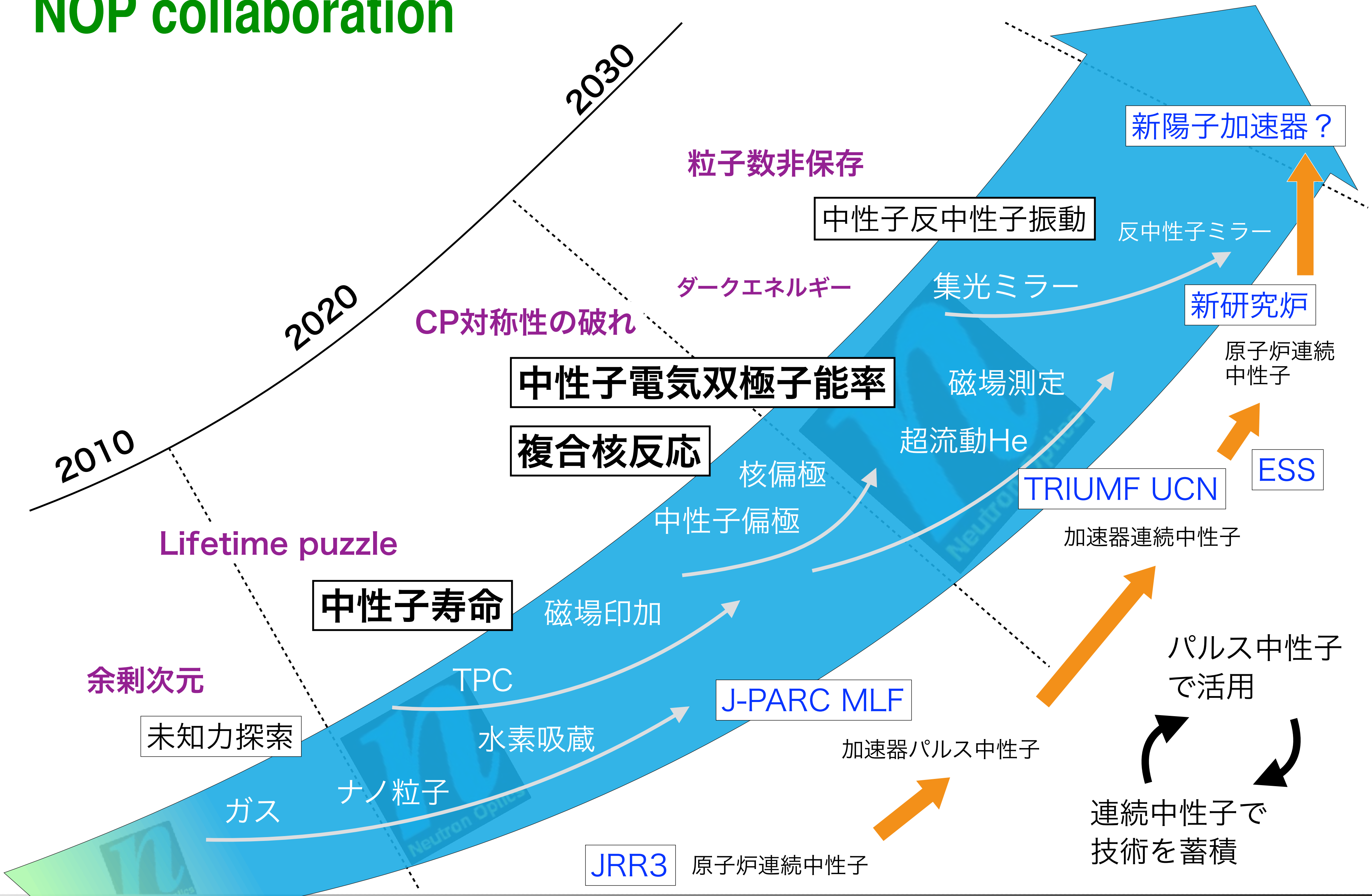
ブラッグ反射
n

中性子波動

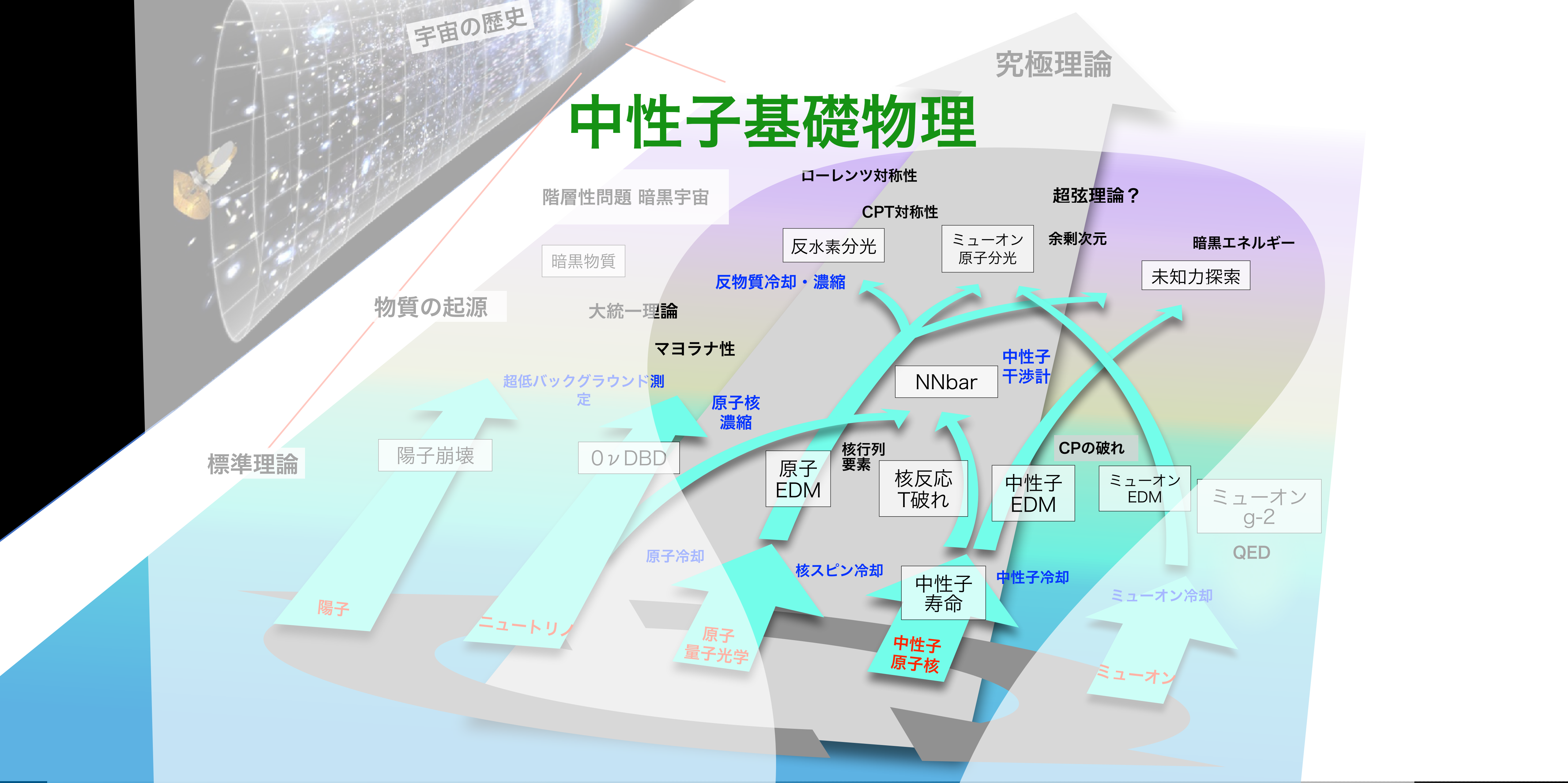



NOP collaboration
Crude Sketch of the History of
Neutron Optics and Physics in Japan
1980s
JAERI-JRR2
DNP-proton spin filter
1990s
KEK-BSF
PEN, SEOP-3He spin filter
1990s
KUR
neutron interferometry
1990s
RIKEN
neutron refractive optics
"NOP: systematic research of neutron optics and detectors"
2000s
RIKEN, KUR, JAEA,
Hokudai, KEK, ISSP,
Toshiba
Neutron Optics
NOP: Neutron OPtics
"J-PARC: Japan Proton Accelerator Research Complex"
Neutron
Lifetime
New Force
Search
Interferometry
Pulsed
UCN
Ultra High
Definition Imager
NOPTREX
2005-
J-PARC MLF
neutron guides
focusing optics
Imaging detectors
Δτn
10s
5s
1s
with
magnetic
field
Xe
nano
particle
pulsed neutron
interferometer
scattering
length
"dark" search
TUCAN
Neutron Optics and Physics
2008-
BL05 NOP
NOPTREX
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, ...
J-PARC MLF 2nd Target Station

NOP collaboration

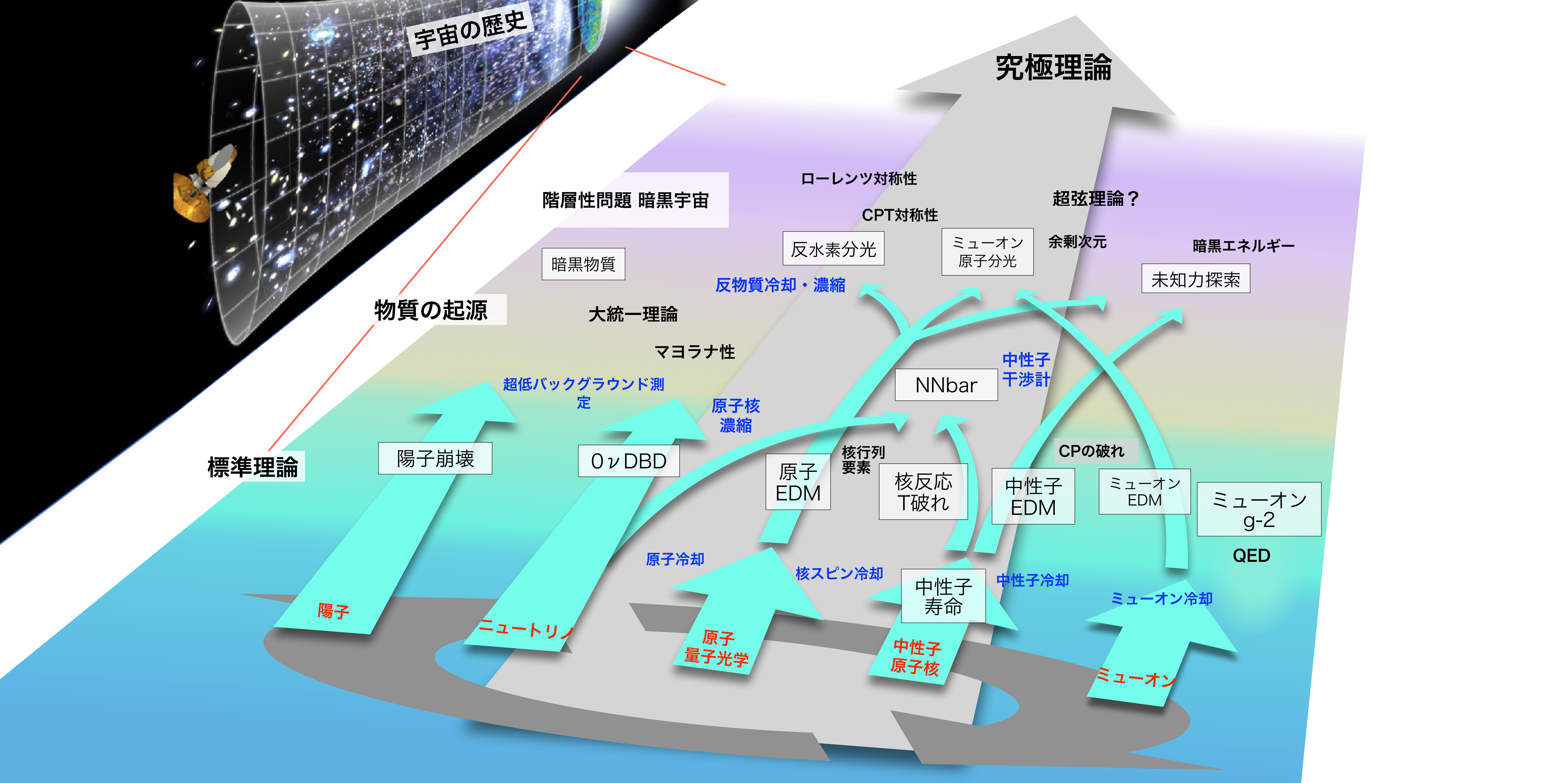


中性子基礎物理



宇宙の歴史
究極理論
中性子基礎物理
ローレンツ対称性
超弦理論？
階層性問題 暗黒宇宙
CPT対称性
反水素分光
ミューオン
原子分光
余剰次元
暗黒エネルギー
暗黒物質
未知力探索
反物質冷却・濃縮
物質の起源
大統一理論
マヨラナ性
中性子
干渉計
NNbar
超低バックグラウンド測定
原子核
濃縮
標準理論
陽子崩壊
0νDBD
核行列
要素
CPの破れ
原子
EDM
核反応
T破れ
中性子
EDM
ミューオン
EDM
ミューオン
g-2
QED
原子冷却
核スピン冷却
中性子
寿命
中性子冷却
ミューオン冷却
陽子
ニュートリノ
原子
量子光学
中性子
原子核
ミューオン

基礎物理



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原子核
濃縮
標準理論
陽子崩壊
0νDBD
核行列
要素
CPの破れ
原子
EDM
核反応
T破れ
中性子
EDM
ミューオン
EDM
ミューオン
g-2
QED
原子冷却
核スピン冷却
中性子
寿命
中性子冷却
ミューオン冷却
陽子
ニュートリノ
原子
量子光学
中性子
原子核
ミューオン

T-violation

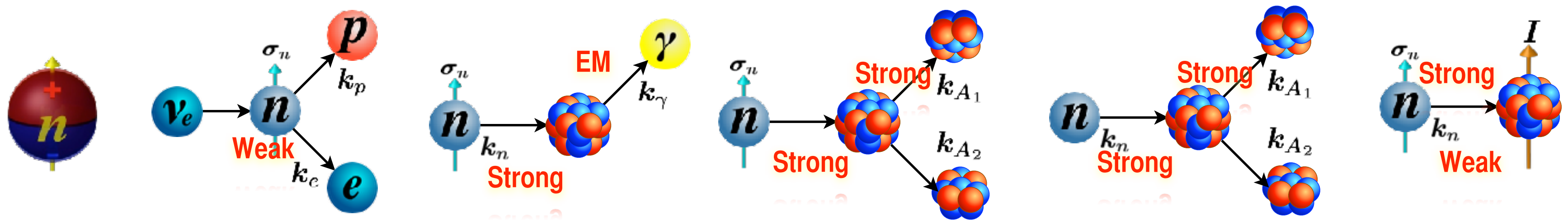
$$T : e^{i(\boldsymbol{k}\cdot\boldsymbol{r}-\omega t)}\chi \to e^{i(-\boldsymbol{k}\cdot\boldsymbol{r}+\omega t)}\chi^T$$

T-violation $\not\leftarrow$ / $\rightarrow$ **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)

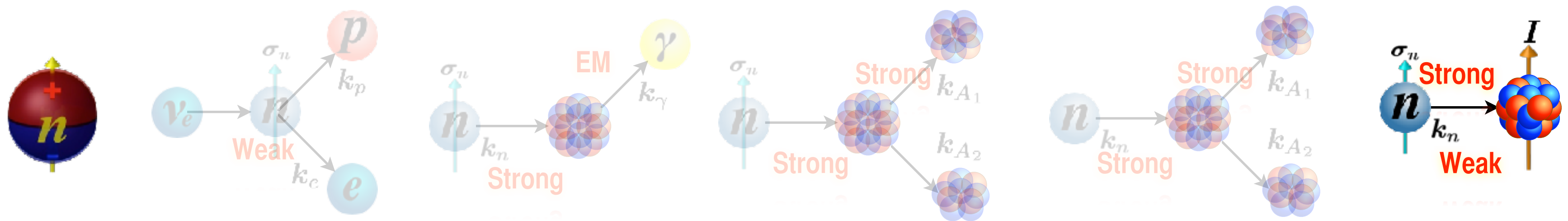
$$T : e^{i(\boldsymbol{k}\cdot\boldsymbol{r}-\omega t)}\chi \rightarrow e^{i(-\boldsymbol{k}\cdot\boldsymbol{r}+\omega t)}\chi^{T}$$

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



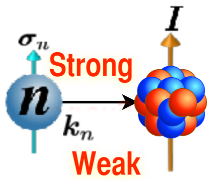
$\boldsymbol{d}_n$ | $\boldsymbol{\sigma}_n\cdot(\boldsymbol{k}_p\times\boldsymbol{k}_e)$ | $\boldsymbol{\sigma}_n\cdot(\boldsymbol{k}_n\times\boldsymbol{k}_\gamma)$ | $\boldsymbol{\sigma}_n\cdot(\boldsymbol{k}_{A_1}\times\boldsymbol{k}_{A_2})$ | $\boldsymbol{k}_n\cdot(\boldsymbol{k}_{A_1}\times\boldsymbol{k}_{A_2})$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

final state interaction (T-odd T-symmetric)

electric
dipole
moment

$\boldsymbol{d}_n$

forward scattering



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

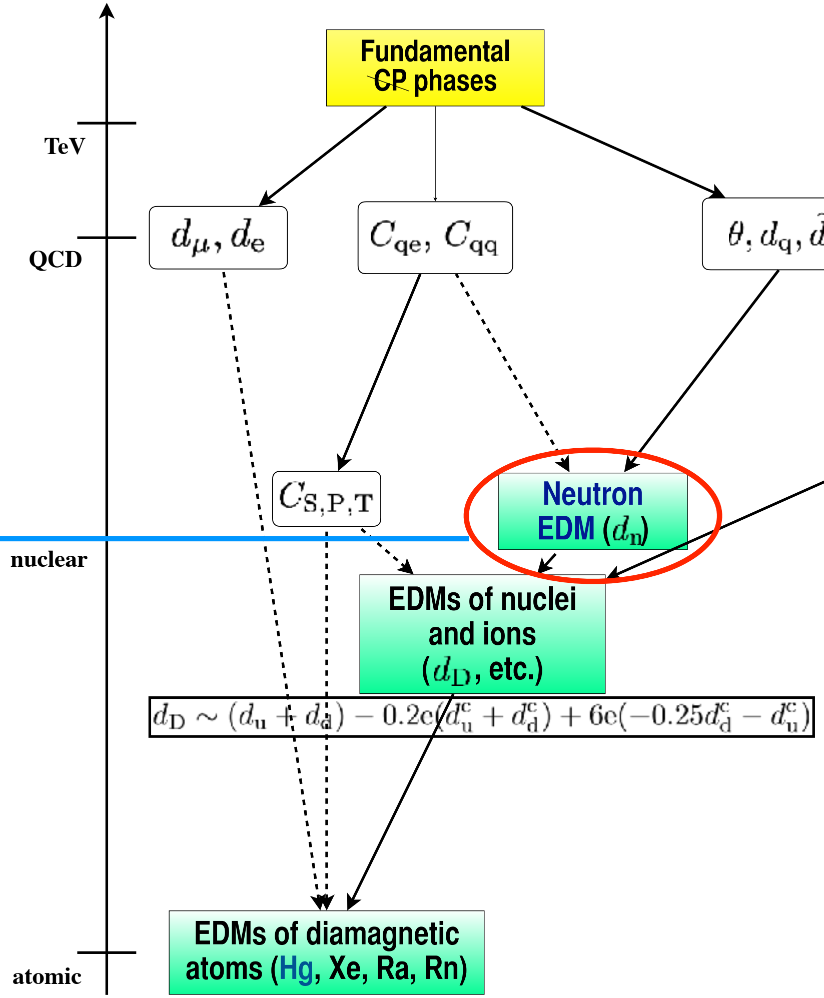
TUCAN

electric dipole moment

$$d_n$$

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

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

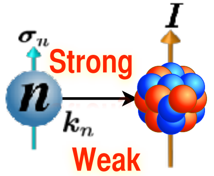


$$d_\mathrm{D} \sim (d_\mathrm{u} + d_\mathrm{d}) - 0.2e(d_\mathrm{u}^\mathrm{c} + d_\mathrm{d}^\mathrm{c}) + 6e(-0.25 d_\mathrm{d}^\mathrm{c} - d_\mathrm{u}^\mathrm{c})$$

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

NOPTREX (J-PARC P99)

forward scattering



$$D' \boldsymbol{\sigma}_\mathrm{n} \cdot (\hat{\boldsymbol{k}}_\mathrm{n} \times \hat{\boldsymbol{I}})$$

$$C' \boldsymbol{\sigma}_\mathrm{n} \cdot \hat{\boldsymbol{k}}_\mathrm{n}$$

$$\frac{D'}{C'} = \kappa(J) \frac{W_\mathrm{T}}{W}$$

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

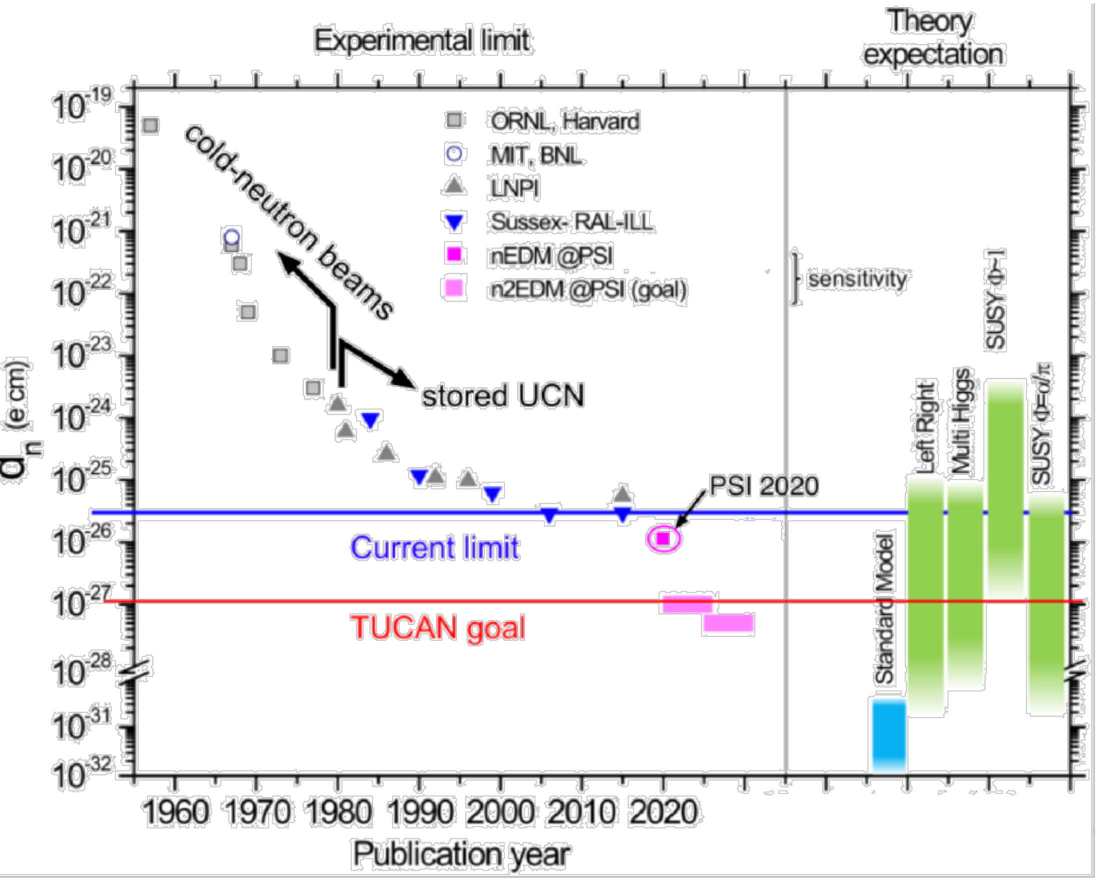
$$\frac{W_\mathrm{T}}{W} \sim \left| -1.0(\bar{d}_\mathrm{u} + \bar{d}_\mathrm{d}) + 24(\bar{d}_\mathrm{u} - \bar{d}_\mathrm{d}) \right| \times 10^{20}\ \mathrm{cm}^{-1}$$

TUCAN

electric dipole moment

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

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



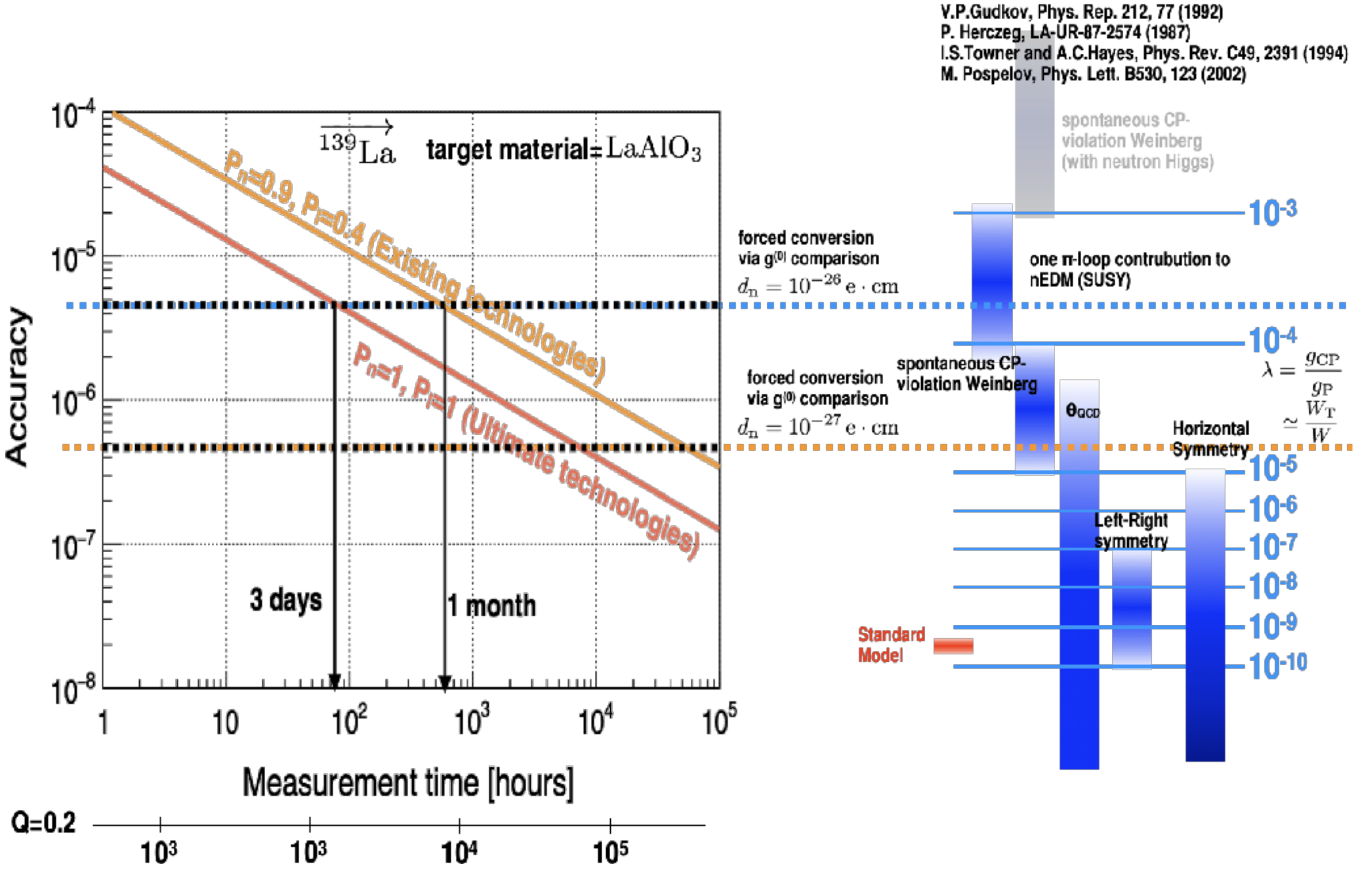
Slide courtesy: B. Lauss, nEDM workshop 2017, based on NIMA 440, 471 (2000), Phys. Rev. D 92, 092003 (2015) AIP Conf. Proc. 1753, 060002 (2016)

NOPTREX (J-PARC P99)

forward scattering

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

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



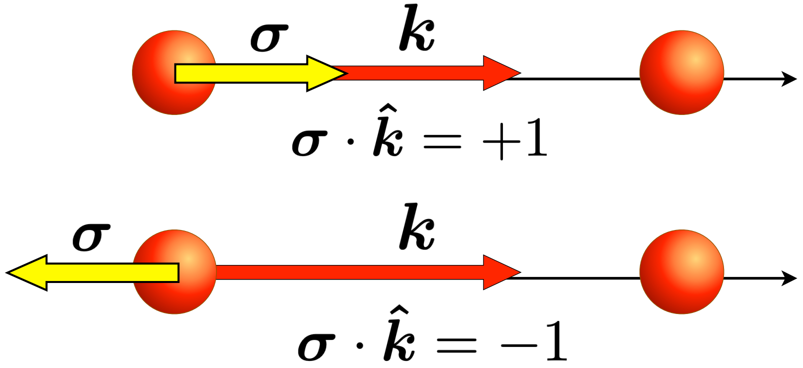
Parity Violation in Compound States

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

$$\sigma = \sigma_0 + \Delta\sigma(\boldsymbol{\sigma} \cdot \hat{\boldsymbol{k}})$$

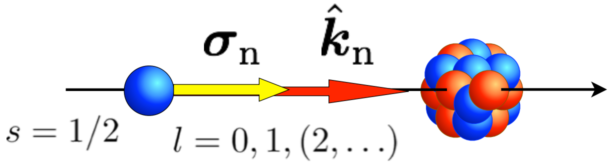


$$\sigma_0 + \Delta\sigma$$

$$\sigma_0 - \Delta\sigma$$

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

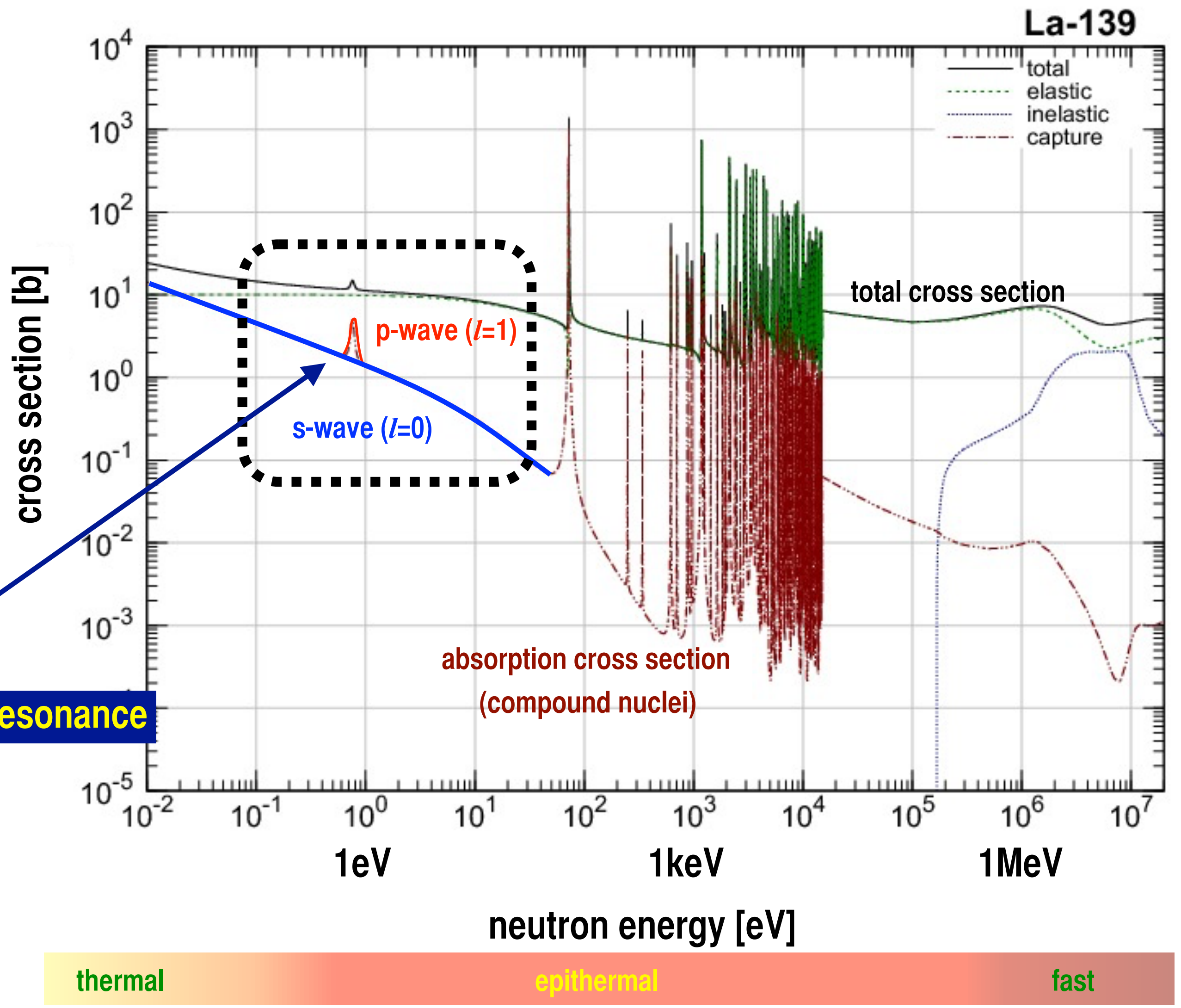
P-violation in Compound State



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

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

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

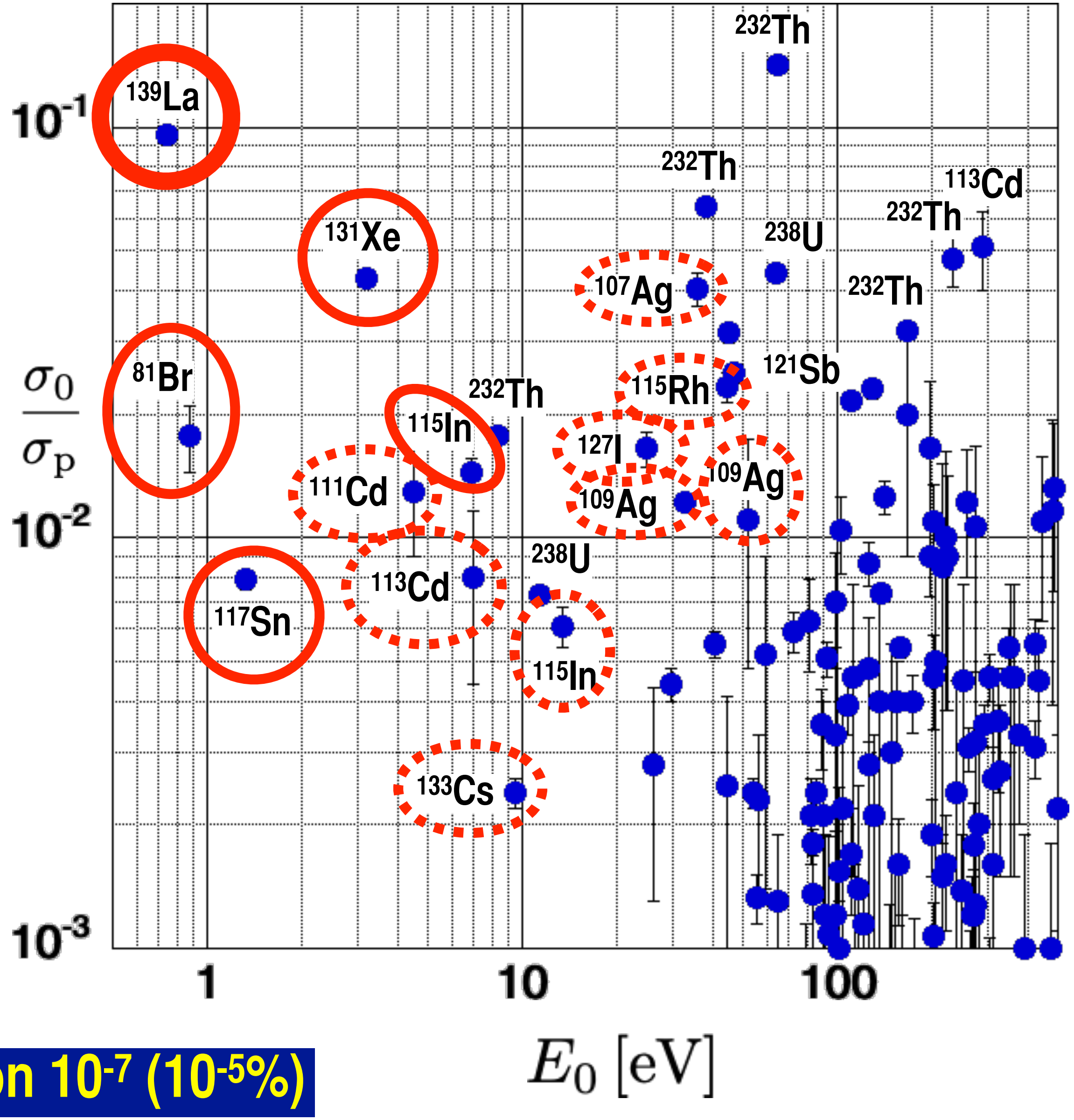


Enhancement of P-violation in Compound States

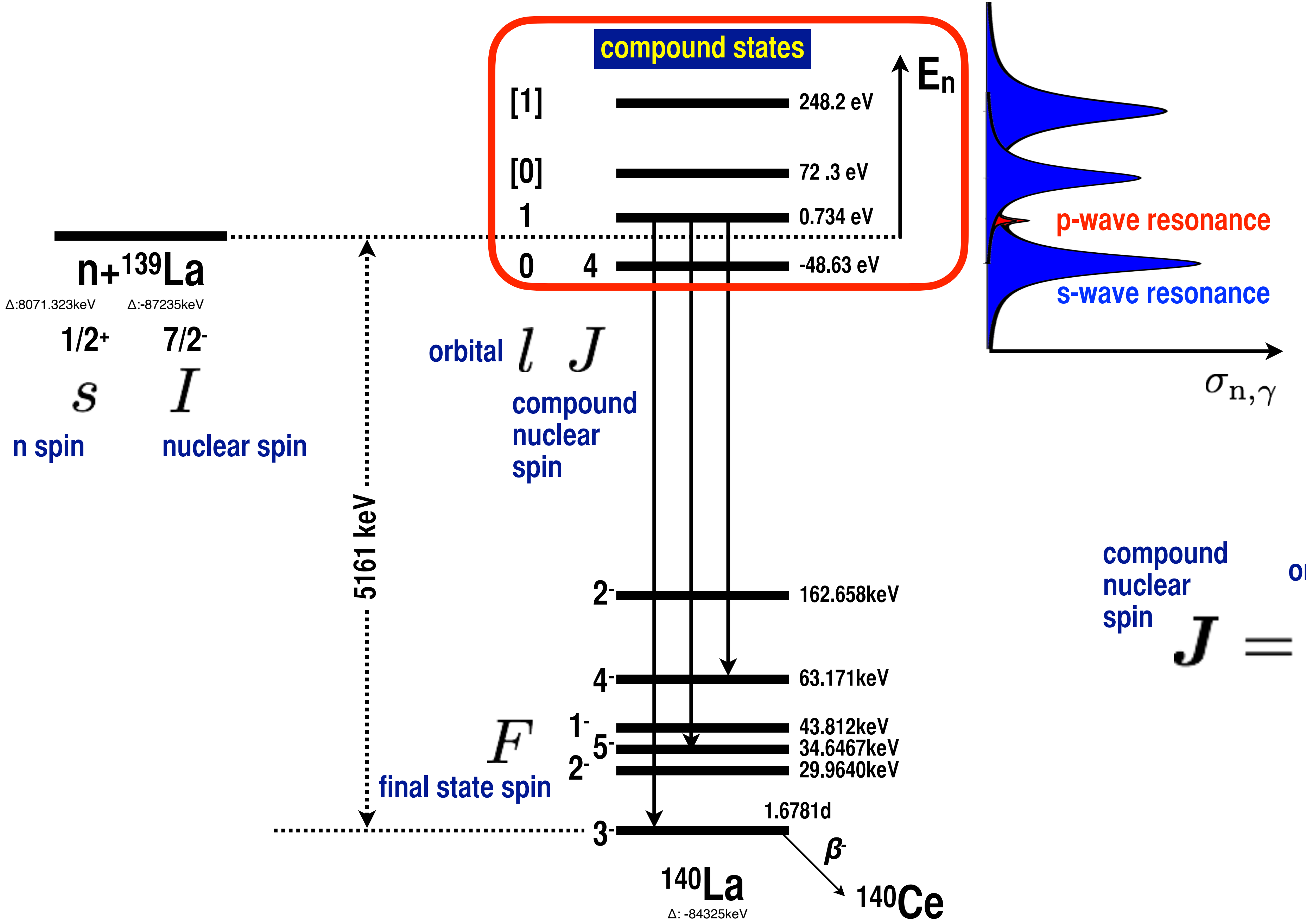
Mitchell, Phys. Rep. 354 (2001) 157
Shimizu, Nucl. Phys. A552 (1993) 293

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

10^{-7} for NN



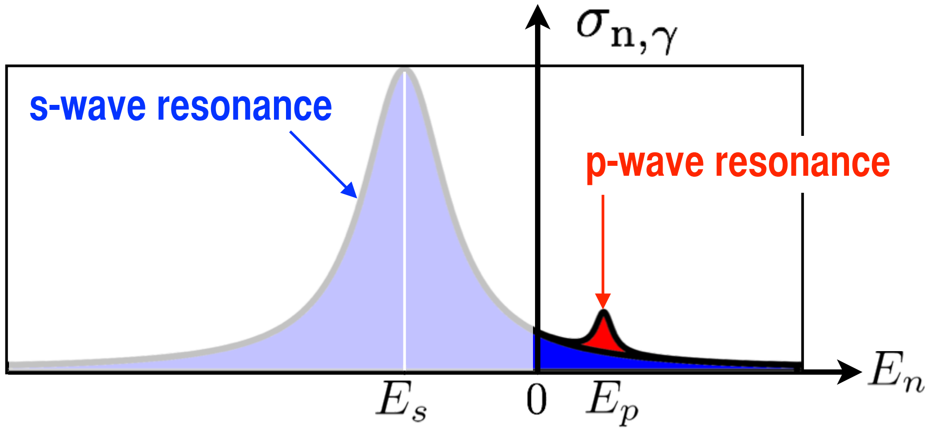
NN-interaction 10^{-7} (10^{-5}%)

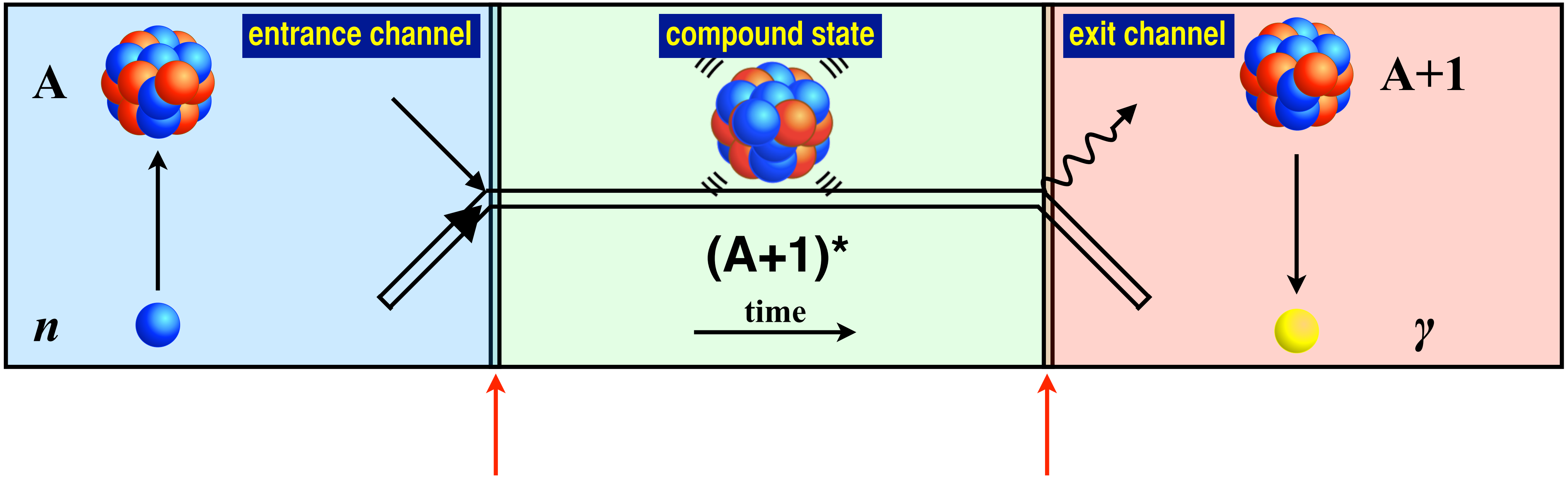


compound nuclear spin — orbital — n spin — target spin

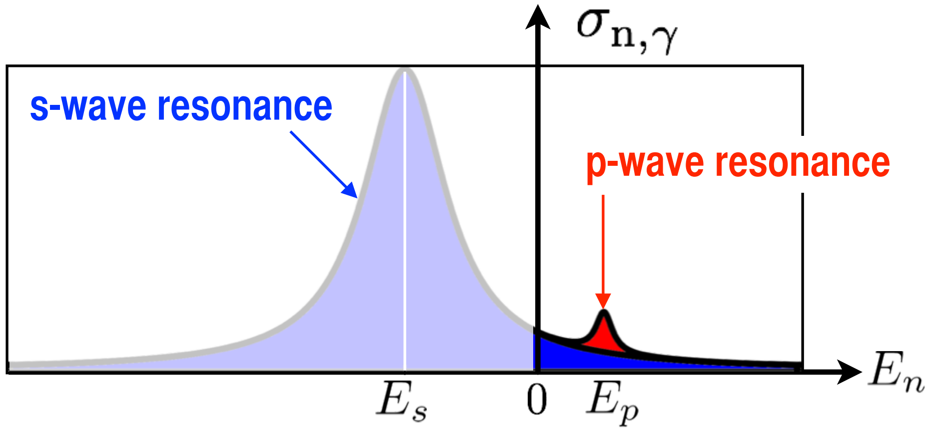
$$J = l + s + I$$

j n total spin ($j = l + s$)

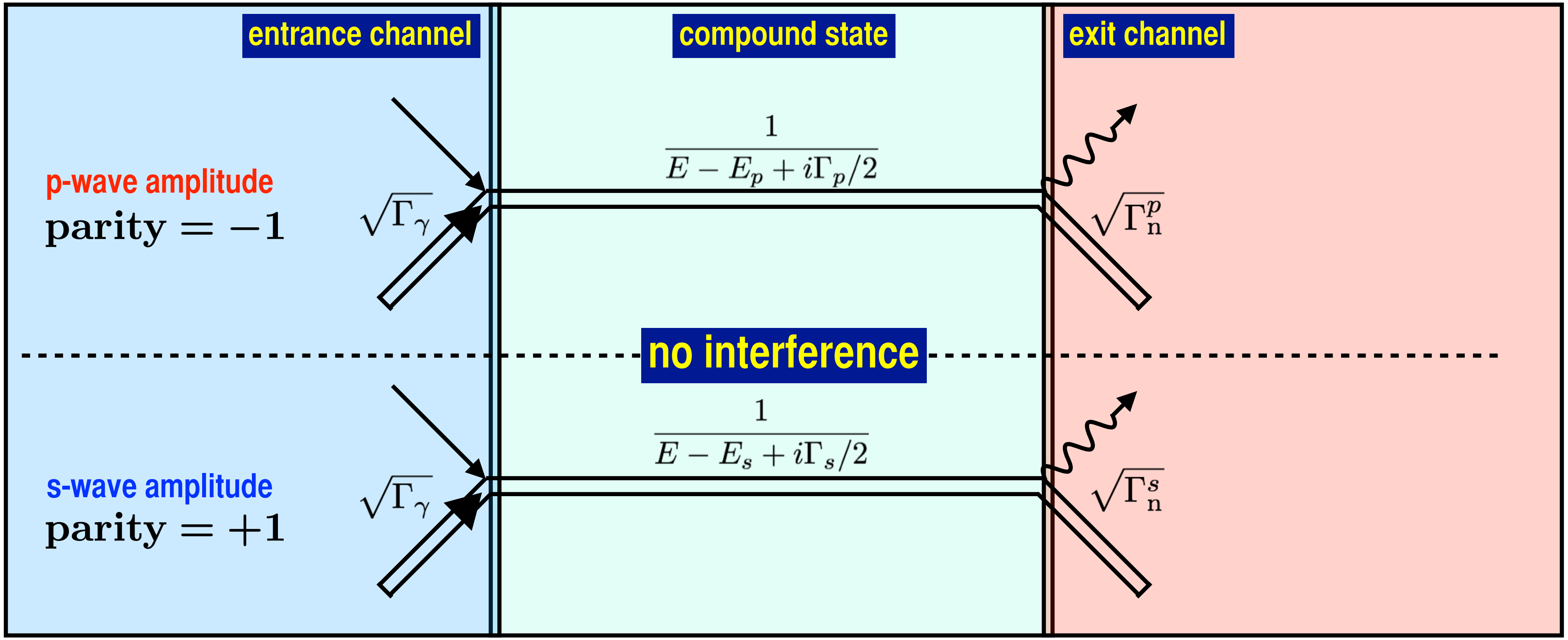




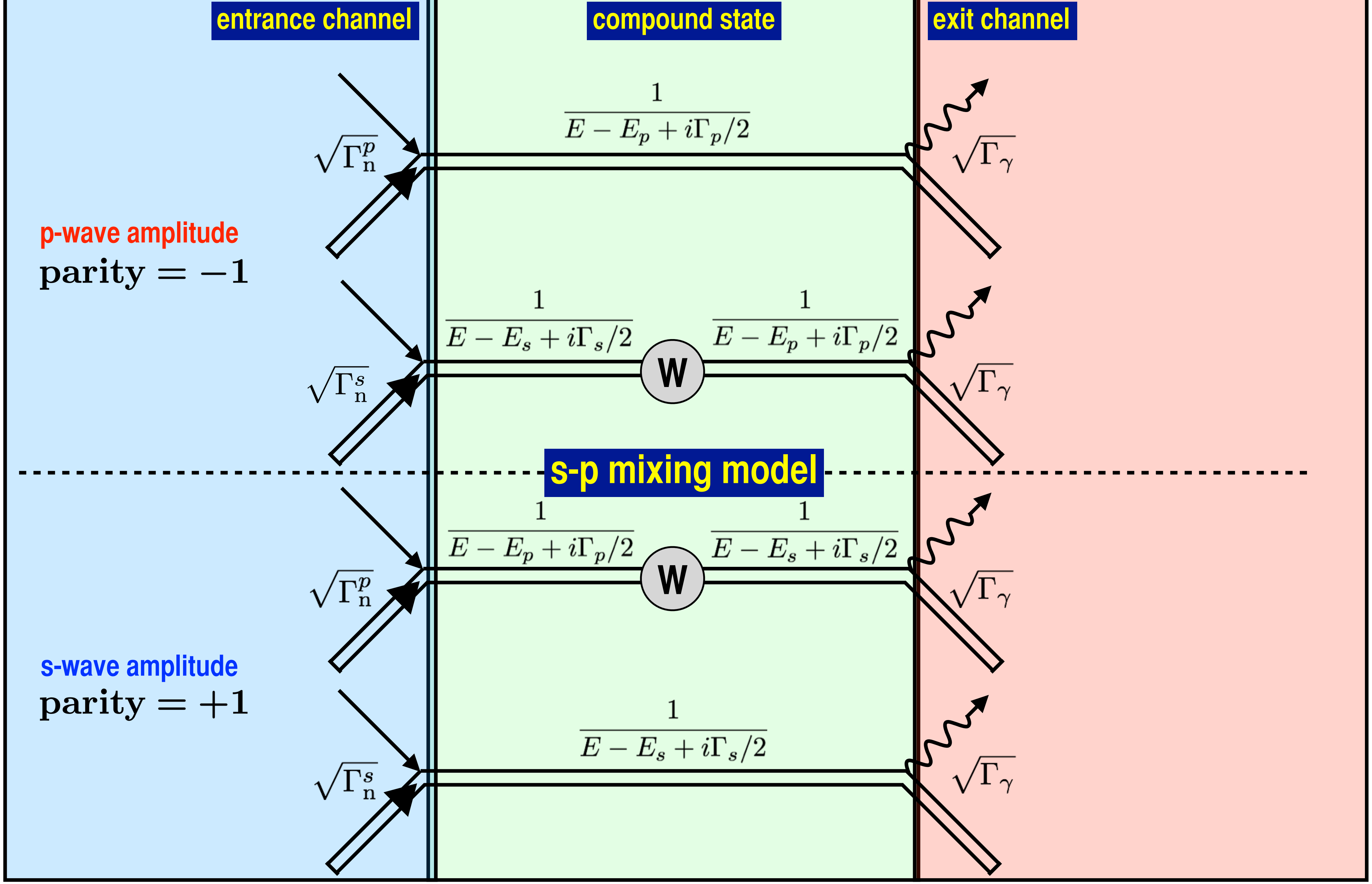
$$\sqrt{\Gamma_n}\frac{1}{E-E_0+i\Gamma/2}\sqrt{\Gamma_\gamma}$$



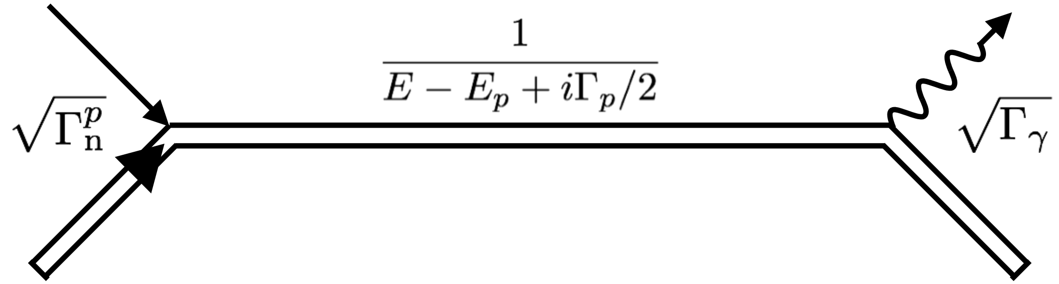
$\sigma_{n,\gamma}$
s-wave resonance
p-wave resonance
E_n
E_s
0
E_p



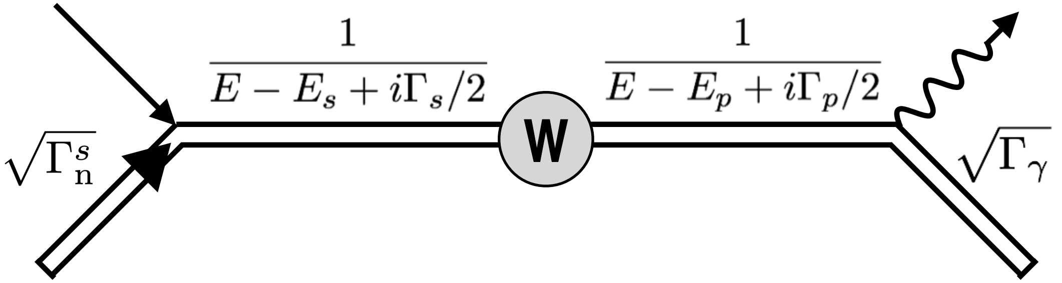
entrance channel
compound state
exit channel
p-wave amplitude
$\mathbf{parity} = -1$
$\sqrt{\Gamma_\gamma}$
$\frac{1}{E - E_p + i\Gamma_p/2}$
$\sqrt{\Gamma_n^p}$
no interference
s-wave amplitude
$\mathbf{parity} = +1$
$\sqrt{\Gamma_\gamma}$
$\frac{1}{E - E_s + i\Gamma_s/2}$
$\sqrt{\Gamma_n^s}$


entrance channel
compound state
exit channel
$\frac{1}{E-E_p+i\Gamma_p/2}$
$\sqrt{\Gamma_n^p}$
$\sqrt{\Gamma_\gamma}$
p-wave amplitude
$\mathrm{parity} = -1$
$\frac{1}{E-E_s+i\Gamma_s/2}$
W
$\frac{1}{E-E_p+i\Gamma_p/2}$
$\sqrt{\Gamma_n^s}$
$\sqrt{\Gamma_\gamma}$
s-p mixing model
$\frac{1}{E-E_p+i\Gamma_p/2}$
W
$\frac{1}{E-E_s+i\Gamma_s/2}$
$\sqrt{\Gamma_n^p}$
$\sqrt{\Gamma_\gamma}$
s-wave amplitude
$\mathrm{parity} = +1$
$\frac{1}{E-E_s+i\Gamma_s/2}$
$\sqrt{\Gamma_n^s}$
$\sqrt{\Gamma_\gamma}$

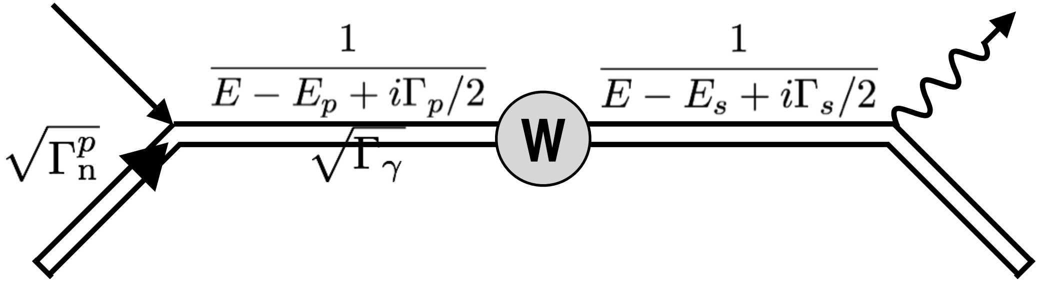
$$V_1 = \sqrt{\Gamma^{\rm n}_{\rm s}} \frac{1}{E - E_{\rm s} + i\Gamma_{\rm s}/2} \sqrt{\Gamma^{\gamma}_{\rm s}}$$



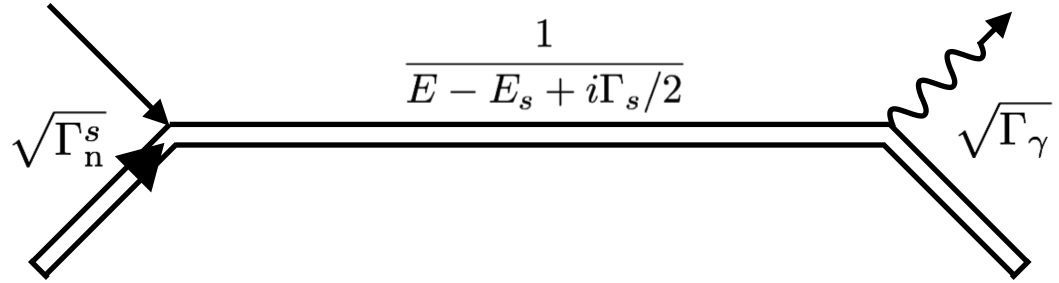
$$V_3 = \sqrt{\Gamma^{\rm n}_{\rm s}} \frac{1}{E - E_{\rm s} + i\Gamma_{\rm s}/2} W \frac{1}{E - E_{\rm p} + i\Gamma_{\rm p}/2} \sqrt{\Gamma^{\gamma}_{\rm p}}$$



$$V_4 = \sqrt{\Gamma^{\rm n}_{{\rm p}\frac{1}{2}}} \frac{1}{E - E_{\rm p} + i\Gamma_{\rm p}/2} W \frac{1}{E - E_{\rm s} + i\Gamma_{\rm s}/2} \sqrt{\Gamma^{\gamma}_{\rm s}}$$



$$V_2 = \sqrt{\Gamma^{\rm n}_{\rm p}} \frac{1}{E - E_{\rm p} + i\Gamma_{\rm p}/2} \sqrt{\Gamma^{\gamma}_{\rm p}}$$

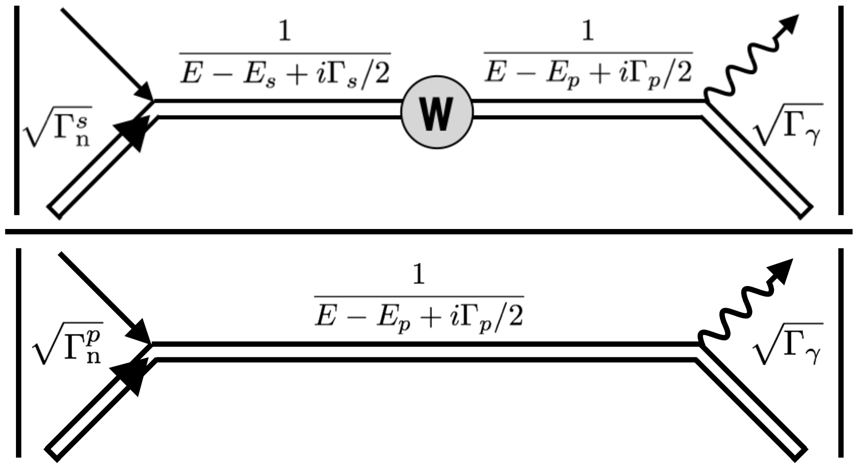


Crude Estimation of P-violation Enhancement

$$|f|^2 = |f_{\mathrm{PC}} + f_{\mathrm{PNC}}|^2 = |f_{\mathrm{PC}}|^2 + 2\mathrm{Re} f_{\mathrm{PC}} f_{\mathrm{PNC}}^* + |f_{\mathrm{PNC}}|^2$$

Parity-conserving   Parity-non-conserving

$$\alpha = \frac{2\mathrm{Re} f_{\mathrm{PC}} f_{\mathrm{PNC}}^*}{|f_{\mathrm{PC}}|^2} \sim 2\frac{|f_{\mathrm{PNC}}|}{|f_{\mathrm{PC}}|} \sim 2$$

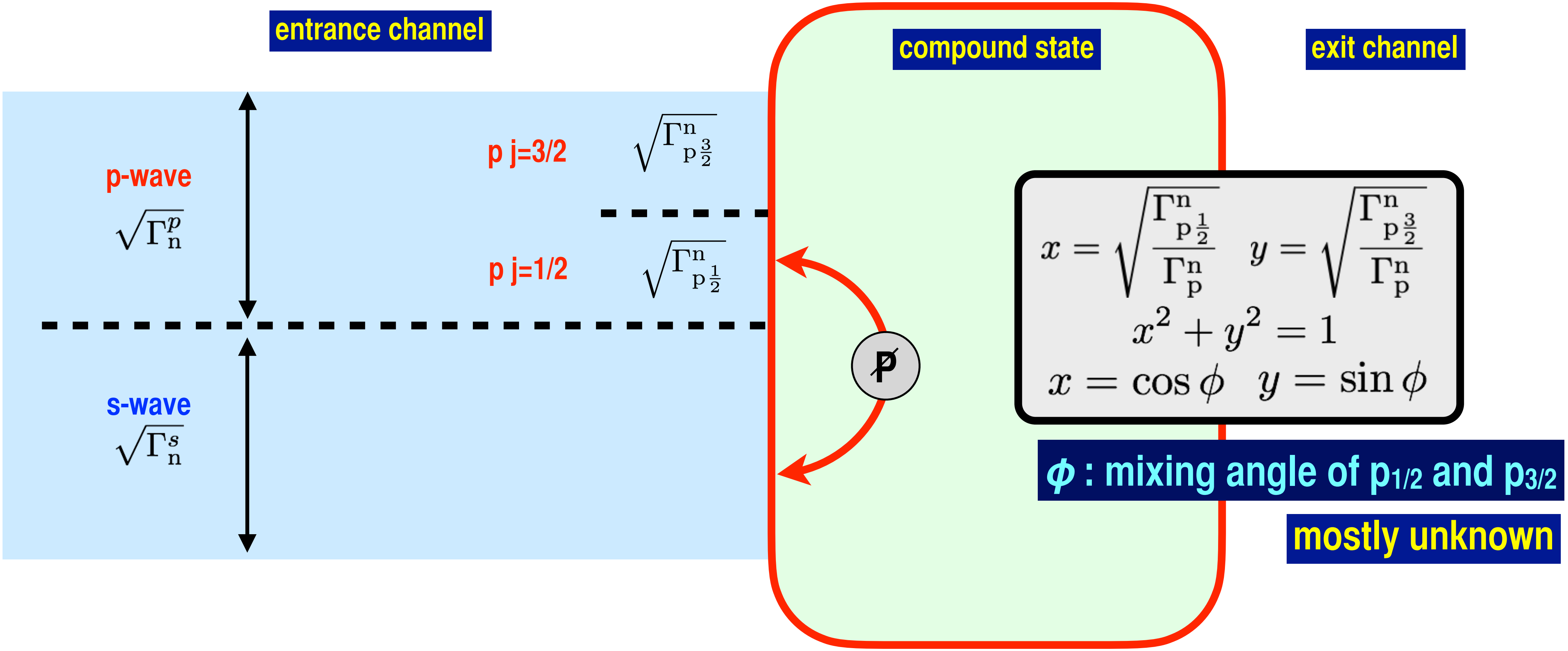


$$= 2\frac{\left|\sqrt{\Gamma_\gamma^p}\frac{1}{E - E_p + i\Gamma_p/2} W \frac{1}{E - E_s + i\Gamma_s/2}\sqrt{\Gamma_n^s}\right|}{\left|\sqrt{\Gamma_\gamma^p}\frac{1}{E - E_p + i\Gamma_p/2}\sqrt{\Gamma_n^p}\right|} \underset{E = E_p}{\sim} 2\frac{W}{|E_p - E_s|}\sqrt{\frac{\Gamma_n^s}{\Gamma_n^p}}$$

dynamical enhancement 10^2-10^3

kinematical enhancement 10^3

Details of Kinematical Enhancement and Entrance Channel Boundary



$$A_{\rm L} = -2\frac{W}{E_{\rm p} - E_{\rm s}}\sqrt{\frac{\Gamma^{\rm n}_{\rm s}}{\Gamma^{\rm n}_{\rm p}}}\cos\phi$$

Neutron-total-spin representation and Channel-spin representation

compound nuclear spin orbital n spin nuclear spin

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

n total spin $\boldsymbol{j}$ $\boldsymbol{S}$ channel spin

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

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

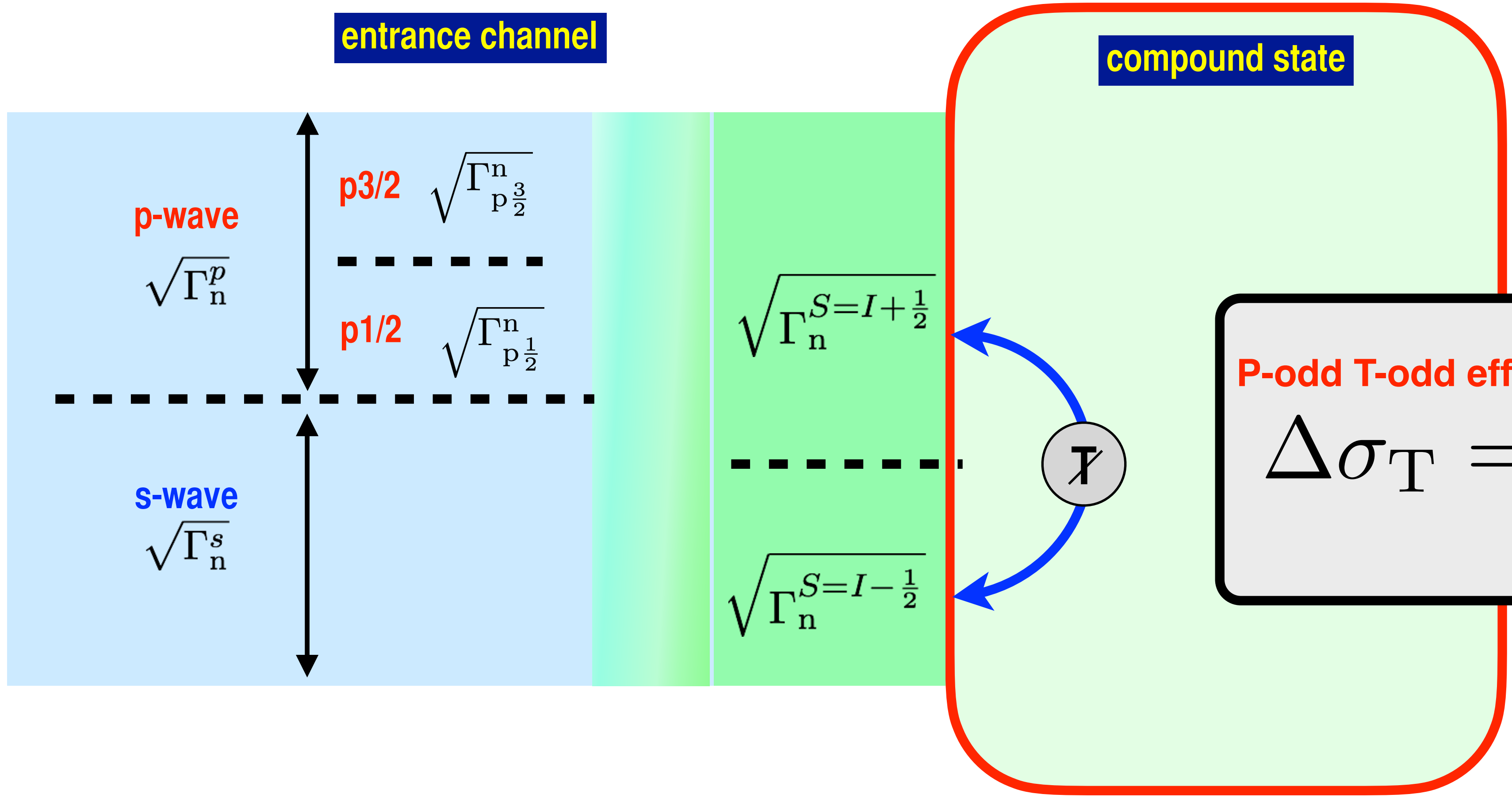
$$z_j = \begin{cases} x & (j=1/2) \\ y & (j=3/2) \end{cases}, \quad \tilde{z}_S = \begin{cases} x_S & (S=I-1/2) \\ y_S & (S=I+1/2) \end{cases} \quad \tilde{z}_S = \sum_j (-1)^{l+I+j+S}\sqrt{(2j+1)(2S+1)} \begin{Bmatrix} l & s & j \\ I & J & S \end{Bmatrix} z_j$$

s-p mixing ⇔ channel-spin mixing

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

$l = 0, 1$ **P-odd** $S = I \pm 1/2$ **T-odd**

Channel-spin mixing ➡ Kinematical Enhancement of T-violation



exit channel

V. P. Gudkov. *Phys. Rep.*, 212:77, 1992.

T-violating matrix element

P-odd T-odd effect

P-odd effect

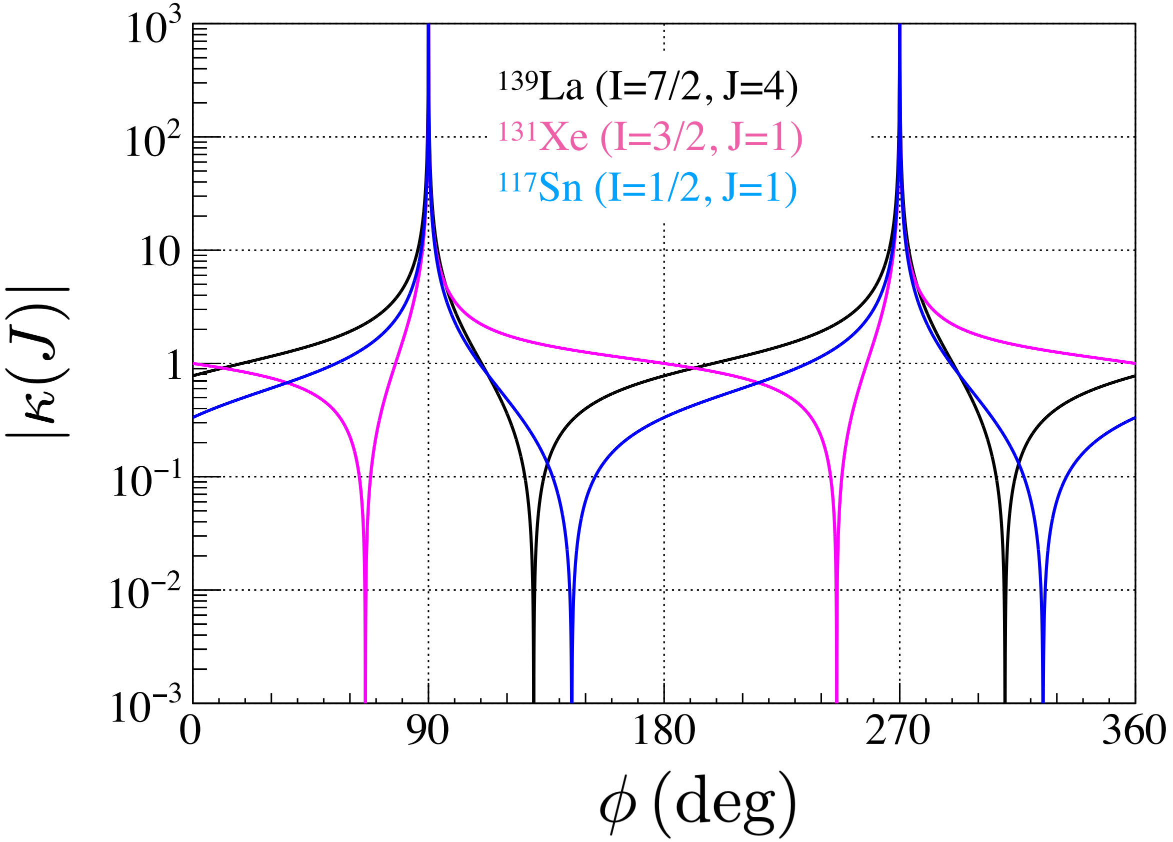
$$\Delta\sigma_{\rm T} = \kappa(J)\frac{W_{\rm T}}{W}\Delta\sigma_{\rm P}$$

P-violating matrix element

spin factor

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

Conversion factor of P-violation Enhancement and T-violation Enhancement



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

Measurement of (n,γ) Correlation Terms

for the determination of ϕ mixing angle of $p_{1/2}$ and $p_{3/2}$ partial amplitudes
which leads to the estimation of T-violation enhancement

for the refinement of resonance parameters including negative resonances

for the suggestion of J compound nuclear spin

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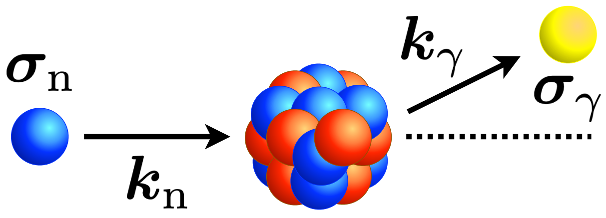
(n,γ) spin-angular correlation terms with s- and p-waves



$$
\begin{aligned}
\frac{\mathrm{d}\sigma_{\mathrm{n}\gamma_f}}{\mathrm{d}\Omega_\gamma} = \; & \frac{1}{2}\Bigg(a_0 + a_1 \hat{\boldsymbol{k}}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_\gamma + a_2 \boldsymbol{\sigma}_{\mathbf{n}} \cdot (\hat{\boldsymbol{k}}_{\mathbf{n}} \times \hat{\boldsymbol{k}}_\gamma) + a_3 \left((\hat{\boldsymbol{k}}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_\gamma)^2 - \frac{1}{3} \right) \\
& + a_4 (\hat{\boldsymbol{k}}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_{\mathbf{n}} \cdot (\hat{\boldsymbol{k}}_{\mathbf{n}} \times \hat{\boldsymbol{k}}_\gamma)) + a_5 (\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_\gamma) \\
& + a_6 (\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_{\mathbf{n}}) + a_7 (\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma) \left((\boldsymbol{\sigma}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_\gamma \cdot \hat{\boldsymbol{k}}_{\mathbf{n}}) - \frac{1}{3} \boldsymbol{\sigma}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_{\mathbf{n}} \right) \\
& + a_8 (\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma) \left((\boldsymbol{\sigma}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_{\mathbf{n}})(\hat{\boldsymbol{k}}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_\gamma) - \frac{1}{3} \boldsymbol{\sigma}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_\gamma \right) \\
& + a_9 \boldsymbol{\sigma}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_\gamma + a_{10} \boldsymbol{\sigma}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_{\mathbf{n}} + a_{11} \left((\boldsymbol{\sigma}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_\gamma \cdot \hat{\boldsymbol{k}}_{\mathbf{n}}) - \frac{1}{3} (\boldsymbol{\sigma}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_{\mathbf{n}}) \right) \\
& + a_{12} (\boldsymbol{\sigma}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_{\mathbf{n}}) \left((\hat{\boldsymbol{k}}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_\gamma) - \frac{1}{3} (\boldsymbol{\sigma}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_\gamma) \right) \\
& + a_{13} \boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma + a_{14} (\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_\gamma) \\
& + a_{15} (\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma) \boldsymbol{\sigma}_{\rm n} \cdot (\hat{\boldsymbol{k}}_{\mathbf{n}} \times \hat{\boldsymbol{k}}_\gamma) + a_{16} (\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma) \left((\hat{\boldsymbol{k}}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_\gamma)^2 - \frac{1}{3} \right) \\
& + a_{17} (\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_{\mathbf{n}} \cdot (\hat{\boldsymbol{k}}_{\mathbf{n}} \times \hat{\boldsymbol{k}}_\gamma)) \Bigg),
\end{aligned}
$$

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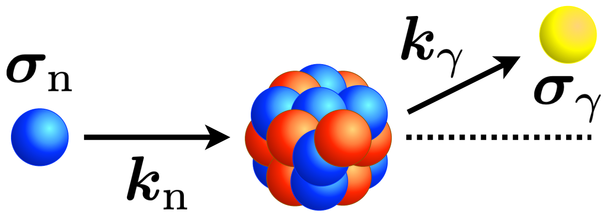
(n,γ) spin-angular correlation terms with s- and p-waves



$$
\begin{aligned}
\frac{d\sigma_{n\gamma_f}}{d\Omega_\gamma} = \; & \frac{1}{2}\Big(a_0 + a_1 \hat{\boldsymbol{k}}_{\mathrm{n}}\cdot\hat{\boldsymbol{k}}_\gamma + a_2 \boldsymbol{\sigma}_{\mathrm{n}}\cdot(\hat{\boldsymbol{k}}_{\mathrm{n}}\times\hat{\boldsymbol{k}}_\gamma) + a_3\left((\hat{\boldsymbol{k}}_{\mathrm{n}}\cdot\hat{\boldsymbol{k}}_\gamma)^2 - \frac{1}{3}\right)\\
&+ a_4(\hat{\boldsymbol{k}}_{\mathrm{n}}\cdot\hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_{\mathrm{n}}\cdot(\hat{\boldsymbol{k}}_{\mathrm{n}}\times\hat{\boldsymbol{k}}_\gamma)) + a_5(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_{\mathrm{n}}\cdot\hat{\boldsymbol{k}}_\gamma)\\
&+ a_6(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_{\mathrm{n}}\cdot\hat{\boldsymbol{k}}_{\mathrm{n}}) + a_7(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)\left((\boldsymbol{\sigma}_{\mathrm{n}}\cdot\hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_\gamma\cdot\hat{\boldsymbol{k}}_{\mathrm{n}}) - \frac{1}{3}\boldsymbol{\sigma}_{\mathrm{n}}\cdot\hat{\boldsymbol{k}}_{\mathrm{n}}\right)\\
&+ a_8(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)\left((\boldsymbol{\sigma}_{\mathrm{n}}\cdot\hat{\boldsymbol{k}}_{\mathrm{n}})(\hat{\boldsymbol{k}}_{\mathrm{n}}\cdot\hat{\boldsymbol{k}}_\gamma) - \frac{1}{3}\boldsymbol{\sigma}_{\mathrm{n}}\cdot\hat{\boldsymbol{k}}_\gamma\right)\\
&+ a_9\boldsymbol{\sigma}_{\mathrm{n}}\cdot\hat{\boldsymbol{k}}_\gamma + a_{10}\boldsymbol{\sigma}_{\mathrm{n}}\cdot\hat{\boldsymbol{k}}_{\mathrm{n}} + a_{11}\left((\boldsymbol{\sigma}_{\mathrm{n}}\cdot\hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_\gamma\cdot\hat{\boldsymbol{k}}_{\mathrm{n}}) - \frac{1}{3}(\boldsymbol{\sigma}_{\mathrm{n}}\cdot\hat{\boldsymbol{k}}_{\mathrm{n}})\right)\\
&+ a_{12}(\boldsymbol{\sigma}_{\mathrm{n}}\cdot\hat{\boldsymbol{k}}_{\mathrm{n}})\left((\hat{\boldsymbol{k}}_{\mathrm{n}}\cdot\hat{\boldsymbol{k}}_\gamma) - \frac{1}{3}(\boldsymbol{\sigma}_{\mathrm{n}}\cdot\hat{\boldsymbol{k}}_\gamma)\right)\\
&+ a_{13}\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma + a_{14}(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_{\mathrm{n}}\cdot\hat{\boldsymbol{k}}_\gamma)\\
&+ a_{15}(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)\boldsymbol{\sigma}_{\mathrm{n}}\cdot(\hat{\boldsymbol{k}}_{\mathrm{n}}\times\hat{\boldsymbol{k}}_\gamma) + a_{16}(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)\left((\hat{\boldsymbol{k}}_{\mathrm{n}}\cdot\hat{\boldsymbol{k}}_\gamma)^2 - \frac{1}{3}\right)\\
&+ a_{17}(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_{\mathrm{n}}\cdot\hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_{\mathrm{n}}\cdot(\hat{\boldsymbol{k}}_{\mathrm{n}}\times\hat{\boldsymbol{k}}_\gamma))\Big),
\end{aligned}
$$

$$
\begin{aligned}
a_0 &= \textstyle\sum_{J_{\mathrm{s}}}|V_1(J_{\mathrm{s}})|^2 + \sum_{J_{\mathrm{s}},j}|V_2(J_{\mathrm{p}}j)|^2\\
a_1 &= 2\mathrm{Re}\textstyle\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}}\tfrac{1}{2}j1IF)\\
a_2 &= -2\mathrm{Im}\textstyle\sum_{J_{\mathrm{s}},J_{\mathrm{p}},j} V_1(J_{\mathrm{s}})V_2^*(J_{\mathrm{p}}j)\beta_j P(J_{\mathrm{s}}J_{\mathrm{p}}\tfrac{1}{2}j1IF)\\
a_3 &= \mathrm{Re}\textstyle\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}\\
a_4 &= -\mathrm{Im}\textstyle\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)6\sqrt{5}\begin{Bmatrix}2 & 1 & 1\\ 1 & \frac{1}{2} & \frac{1}{2}\\ 2 & j & j'\end{Bmatrix}\\
a_5 &= -\mathrm{Re}\left[\textstyle\sum_{J_{\mathrm{s}},J'_{\mathrm{s}}} V_1(J_{\mathrm{s}}j)V_1^*(J'_{\mathrm{s}}j')P(J_{\mathrm{s}}J'_{\mathrm{s}}\tfrac{1}{2}\tfrac{1}{2}1IF) + \sum_{J_{\mathrm{p}},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'1IF)6\begin{Bmatrix}0 & 1 & 1\\ 1 & \frac{1}{2} & \frac{1}{2}\\ 1 & j & j'\end{Bmatrix}\right]\\
a_6 &= -2\mathrm{Re}\textstyle\sum_{J_{\mathrm{s}}} V_1(J_{\mathrm{s}}j)V_2^*(J_{\mathrm{p}}=J_{\mathrm{s}},\tfrac{1}{2})\\
a_7 &= \mathrm{Re}\textstyle\sum_{J_{\mathrm{s}},J_{\mathrm{p}}} V_1(J_{\mathrm{s}})V_2^*(J_{\mathrm{p}}\tfrac{3}{2})P(J_{\mathrm{s}}J_{\mathrm{p}}\tfrac{1}{2}\tfrac{3}{2}2IF)\\
a_8 &= -\mathrm{Re}\textstyle\sum_{J_{\mathrm{p}},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'1IF)18\begin{Bmatrix}2 & 1 & 1\\ 1 & \frac{1}{2} & \frac{1}{2}\\ 1 & j & j'\end{Bmatrix}\\
a_9 &= -2\mathrm{Re}\left[\textstyle\sum_{J_{\mathrm{s}},J'_{\mathrm{s}}} V_1(J_{\mathrm{s}}j)V_3^*(J'_{\mathrm{s}}j')P(J_{\mathrm{s}}J'_{\mathrm{s}}\tfrac{1}{2}\tfrac{1}{2}1IF) + \sum_{J_{\mathrm{p}},j,J'_{\mathrm{p}},j'} V_2(J_{\mathrm{p}}j)V_4^*(J'_{\mathrm{p}}j')P(J_{\mathrm{p}}J'_{\mathrm{p}}jj'1IF)6\begin{Bmatrix}0 & 1 & 1\\ 1 & \frac{1}{2} & \frac{1}{2}\\ 1 & j & j'\end{Bmatrix}\right]\\
a_{10} &= -2\mathrm{Re}\textstyle\sum_{J_{\mathrm{s}}}\left[V_2(J_{\mathrm{p}}=J_{\mathrm{s}},\tfrac{1}{2})V_3^*(J_{\mathrm{s}}) + V_1(J_{\mathrm{s}})V_4^*(J_{\mathrm{p}}=J_{\mathrm{s}},\tfrac{1}{2})\right]\\
a_{11} &= 2\mathrm{Re}\textstyle\sum_{J_{\mathrm{s}},J_{\mathrm{p}}}\left[V_2(J_{\mathrm{p}}\tfrac{3}{2})V_3^*(J_{\mathrm{s}}) + V_1(J_{\mathrm{s}})V_4^*(J_{\mathrm{p}}\tfrac{3}{2})\right]\sqrt{3}P(J_{\mathrm{s}}J_{\mathrm{p}}\tfrac{1}{2}\tfrac{1}{3}2IF)\\
a_{12} &= -\mathrm{Re}\textstyle\sum_{J_{\mathrm{s}},j,J'_{\mathrm{p}},j'} V_2(J_{\mathrm{p}}j)V_4^*(J'_{\mathrm{p}}j')P(J_{\mathrm{p}}J'_{\mathrm{p}}jj'1IF)18\begin{Bmatrix}2 & 1 & 1\\ 1 & \frac{1}{2} & \frac{1}{2}\\ 1 & j & j'\end{Bmatrix}\\
a_{13} &= 2\mathrm{Re}\left[\textstyle\sum_{J_{\mathrm{s}}} V_1(J_{\mathrm{s}})V_3^*(J_{\mathrm{s}}) + \sum_{J_{\mathrm{p}}j} V_2(J_{\mathrm{p}}j)V_4^*(J_{\mathrm{p}}j)\right]\\
a_{14} &= 2\mathrm{Re}\textstyle\sum_{J_{\mathrm{s}}J_{\mathrm{p}}j}\left[V_2(J_{\mathrm{p}}j)V_3^*(J_{\mathrm{s}}) + V_1(J_{\mathrm{s}})V_4^*(J_{\mathrm{p}}j)\right]P(J_{\mathrm{s}}J_{\mathrm{p}}\tfrac{1}{2}j1IF)\\
a_{15} &= 2\mathrm{Im}\textstyle\sum_{J_{\mathrm{s}}J_{\mathrm{p}}j}\left[V_2(J_{\mathrm{p}}j)V_3^*(J_{\mathrm{s}}) - V_1(J_{\mathrm{s}})V_4^*(J_{\mathrm{p}}j)\right]\beta_j P(J_{\mathrm{s}}J_{\mathrm{p}}\tfrac{1}{2}j1IF)\\
a_{16} &= 2\mathrm{Re}\textstyle\sum_{J_{\mathrm{p}},j,J'_{\mathrm{p}},j'} V_2(J_{\mathrm{p}}j)V_4^*(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}\\
a_{17} &= -2\mathrm{Im}\textstyle\sum_{J_{\mathrm{p}},j,J'_{\mathrm{p}},j'} V_2(J_{\mathrm{p}}j)V_4^*(J'_{\mathrm{p}}j')P(J_{\mathrm{p}}J'_{\mathrm{p}}jj'2IF)6\sqrt{5}\begin{Bmatrix}2 & 1 & 1\\ 1 & \frac{1}{2} & \frac{1}{2}\\ 2 & j & j'\end{Bmatrix}
\end{aligned}
$$

(n,γ) spin-angular correlation terms with s- and p-waves

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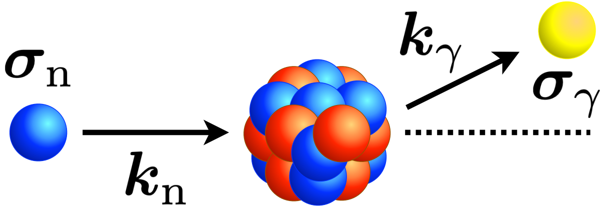


$$
\begin{aligned}
\frac{d\sigma_{n\gamma_f}}{d\Omega_\gamma} = & \frac{1}{2}\Big(a_0 + a_1\hat{\boldsymbol{k}}_{\rm n}\cdot\hat{\boldsymbol{k}}_\gamma + a_2\boldsymbol{\sigma}_{\rm n}\cdot(\hat{\boldsymbol{k}}_{\rm n}\times\hat{\boldsymbol{k}}_\gamma) + a_3\left((\hat{\boldsymbol{k}}_{\rm n}\cdot\hat{\boldsymbol{k}}_\gamma)^2 - \frac{1}{3}\right) \\
& + a_4(\hat{\boldsymbol{k}}_{\rm n}\cdot\hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_{\rm n}\cdot(\hat{\boldsymbol{k}}_{\rm n}\times\hat{\boldsymbol{k}}_\gamma)) + a_5(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_{\rm n}\cdot\hat{\boldsymbol{k}}_\gamma) \\
& + a_6(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_{\rm n}\cdot\hat{\boldsymbol{k}}_{\rm n}) + a_7(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)\left((\boldsymbol{\sigma}_{\rm n}\cdot\hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_\gamma\cdot\hat{\boldsymbol{k}}_{\rm n}) - \frac{1}{3}\boldsymbol{\sigma}_{\rm n}\cdot\hat{\boldsymbol{k}}_{\rm n}\right) \\
& + a_8(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)\left((\boldsymbol{\sigma}_{\rm n}\cdot\hat{\boldsymbol{k}}_{\rm n})(\hat{\boldsymbol{k}}_{\rm n}\cdot\hat{\boldsymbol{k}}_\gamma) - \frac{1}{3}\boldsymbol{\sigma}_{\rm n}\cdot\hat{\boldsymbol{k}}_\gamma\right) \\
& + a_9\boldsymbol{\sigma}_{\rm n}\cdot\hat{\boldsymbol{k}}_\gamma + a_{10}\boldsymbol{\sigma}_{\rm n}\cdot\hat{\boldsymbol{k}}_{\rm n} + a_{11}\left((\boldsymbol{\sigma}_{\rm n}\cdot\hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_\gamma\cdot\hat{\boldsymbol{k}}_{\rm n}) - \frac{1}{3}(\boldsymbol{\sigma}_{\rm n}\cdot\hat{\boldsymbol{k}}_{\rm n})\right) \\
& + a_{12}(\boldsymbol{\sigma}_{\rm n}\cdot\hat{\boldsymbol{k}}_{\rm n})\left((\hat{\boldsymbol{k}}_{\rm n}\cdot\hat{\boldsymbol{k}}_\gamma) - \frac{1}{3}(\boldsymbol{\sigma}_{\rm n}\cdot\hat{\boldsymbol{k}}_\gamma)\right) \\
& + a_{13}\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma + a_{14}(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_{\rm n}\cdot\hat{\boldsymbol{k}}_\gamma) \\
& + a_{15}(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)\boldsymbol{\sigma}_{\rm n}\cdot(\hat{\boldsymbol{k}}_{\rm n}\times\hat{\boldsymbol{k}}_\gamma) + a_{16}(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)\left((\hat{\boldsymbol{k}}_{\rm n}\cdot\hat{\boldsymbol{k}}_\gamma)^2 - \frac{1}{3}\right) \\
& + a_{17}(\boldsymbol{\sigma}_\gamma\cdot\hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_{\rm n}\cdot\hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_{\rm n}\cdot(\hat{\boldsymbol{k}}_{\rm n}\times\hat{\boldsymbol{k}}_\gamma))\Big),
\end{aligned}
$$

$$
\begin{aligned}
a_0 &= \textstyle\sum_{J_{\rm s}} |V_1(J_{\rm s})|^2 + \sum_{J_{\rm s},j} |V_2(J_{\rm p}j)|^2 \\
a_1 &= 2{\rm Re}\textstyle\sum_{J_{\rm s},J_{\rm p},j} V_1(J_{\rm s})V_2^*(J_{\rm p}j)P(J_{\rm s}J_{\rm p}\frac{1}{2}j1IF) \\
a_2 &= -2{\rm Im}\textstyle\sum_{J_{\rm s},J_{\rm p},j} V_1(J_{\rm s})V_2^*(J_{\rm p}j)\beta_j P(J_{\rm s}J_{\rm p}\frac{1}{2}j1IF \\
a_3 &= {\rm Re}\textstyle\sum_{J_{\rm s},j,J'_{\rm p},j'} V_2(J_{\rm p}j)V_2^*(J'_{\rm p}j')P(J_{\rm p}J'_{\rm p}jj'2IF) \\
a_4 &= -{\rm Im}\textstyle\sum_{J_{\rm s},j,J'_{\rm p},j'} V_2(J_{\rm p}j)V_2^*(J'_{\rm p}j')P(J_{\rm p}J'_{\rm p}jj'2I \\
a_5 &= -{\rm Re}\Big[\textstyle\sum_{J_{\rm s},J'_{\rm s}} V_1(J_{\rm s}j)V_1^*(J'_{\rm s}j')P(J_{\rm s}J'_{\rm s}\frac{1}{2}\frac{1}{2}1IF) + \\
a_6 &= -2{\rm Re}\textstyle\sum_{J_{\rm s}} V_1(J_{\rm s}j)V_2^*(J_{\rm p}=J_{\rm s},\frac{1}{2}) \\
a_7 &= {\rm Re}\textstyle\sum_{J_{\rm s},J_{\rm p}} V_1(J_{\rm s})V_2^*(J_{\rm p}\frac{3}{2})P(J_{\rm s}J_{\rm p}\frac{1}{2}\frac{3}{2}2IF) \\
a_8 &= -{\rm Re}\textstyle\sum_{J_{\rm p},j,J'_{\rm p},j'} V_2(J_{\rm p}j)V_2^*(J'_{\rm p}j')P(J_{\rm p}J'_{\rm p}jj'1I \\
a_9 &= -2{\rm Re}\Big[\textstyle\sum_{J_{\rm s},J'_{\rm s}} V_1(J_{\rm s}j)V_3^*(J'_{\rm s}j')P(J_{\rm s}J'_{\rm s}\frac{1}{2}\frac{1}{2}1IF) \\
a_{10} &= -2{\rm Re}\textstyle\sum_{J_{\rm s}} \left[V_2(J_{\rm p}=J_{\rm s},\frac{1}{2})V_3^*(J_{\rm s}) + V_1(J_{\rm s})V_4^*(\right. \\
a_{11} &= 2{\rm Re}\textstyle\sum_{J_{\rm s},J_{\rm p}} \left[V_2(J_{\rm p}\frac{3}{2})V_3^*(J_{\rm s}) + V_1(J_{\rm s})V_4^*(J_{\rm p}\frac{3}{2})\right] \\
a_{12} &= -{\rm Re}\textstyle\sum_{J_{\rm s},j,J'_{\rm p},j'} V_2(J_{\rm p}j)V_4^*(J'_{\rm p}j')P(J_{\rm p}J'_{\rm p}jj'1I \\
a_{13} &= 2{\rm Re}\Big[\textstyle\sum_{J_{\rm s}} V_1(J_{\rm s})V_3^*(J_{\rm s}) + \sum_{J_{\rm p}j} V_2(J_{\rm p}j)V_4^*(J_{\rm p} \\
a_{14} &= 2{\rm Re}\textstyle\sum_{J_{\rm s}J_{\rm p}j} \left[V_2(J_{\rm p}j)V_3^*(J_{\rm s}) + V_1(J_{\rm s})V_4^*(J_{\rm p}j)\right] \\
a_{15} &= 2{\rm Im}\textstyle\sum_{J_{\rm s}J_{\rm p}j} \left[V_2(J_{\rm p}j)V_3^*(J_{\rm s}) - V_1(J_{\rm s})V_4^*(J_{\rm p}j)\right] \\
a_{16} &= 2{\rm Re}\textstyle\sum_{J_{\rm p},j,J'_{\rm p},j'} V_2(J_{\rm p}j)V_4^*(J'_{\rm p}j')P(J_{\rm p}J'_{\rm p}jj'2IF \\
a_{17} &= -2{\rm Im}\textstyle\sum_{J_{\rm p},j,J'_{\rm p},j'} V_2(J_{\rm p}j)V_4^*(J'_{\rm p}j')P(J_{\rm p}J'_{\rm p}jj'2IF)6\sqrt{5}\begin{Bmatrix} 2 & 1 & 1 \\ 1 & \frac{1}{2} & \frac{1}{2} \\ 2 & j & j' \end{Bmatrix}
\end{aligned}
$$

	target spin	compound nuclear spin	resonance energy	resonance width	neutron width	gamma width	final state spin
$\lvert s\rangle$	I	J_s	E_s	Γ_s	Γ^n_s	Γ^γ_s	F
$\lvert p\rangle$		J_p	E_p	Γ_p	Γ^n_p	Γ^γ_p	

ϕ mixing angle of $p_{1/2}$ and $p_{3/2}$

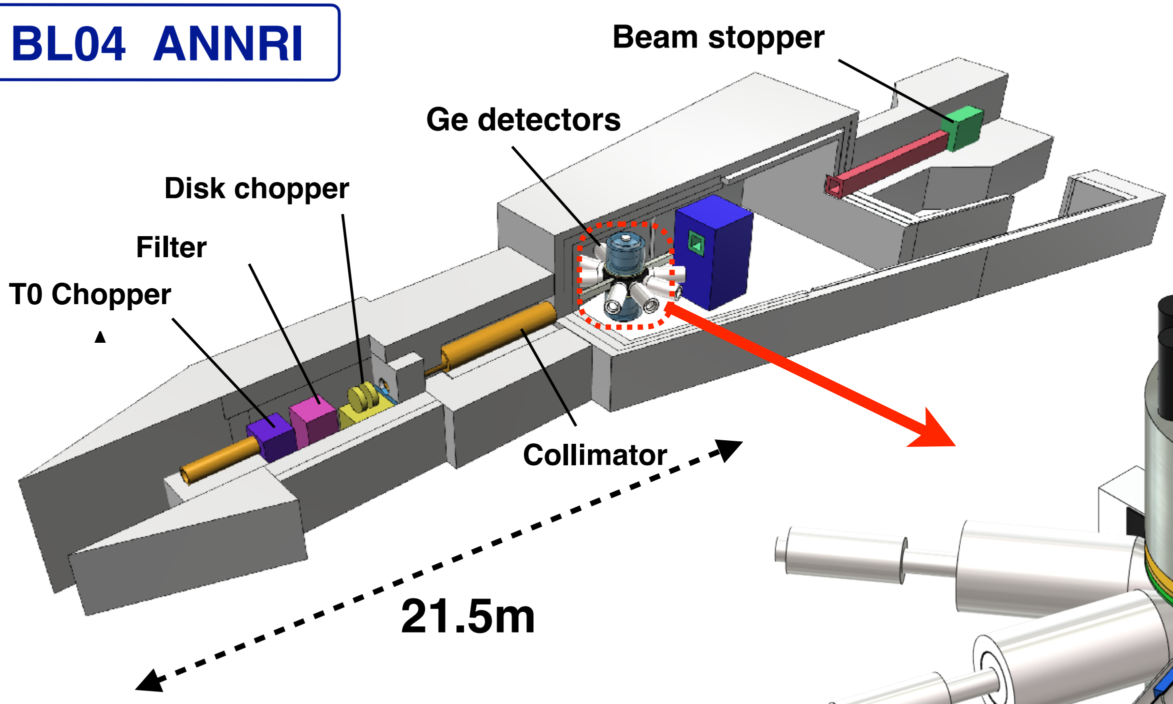
$\lvert p_{1/2}\rangle$ $\Gamma^n_{p,1/2}$ $\quad x^2 = \dfrac{\Gamma^n_{p,1/2}}{\Gamma^n_p}$ $\qquad$ $\lvert p_{3/2}\rangle$ $\Gamma^n_{p,3/2}$ $\quad y^2 = \dfrac{\Gamma^n_{p,3/2}}{\Gamma^n_p}$

$x = \cos\phi \qquad y = \sin\phi$

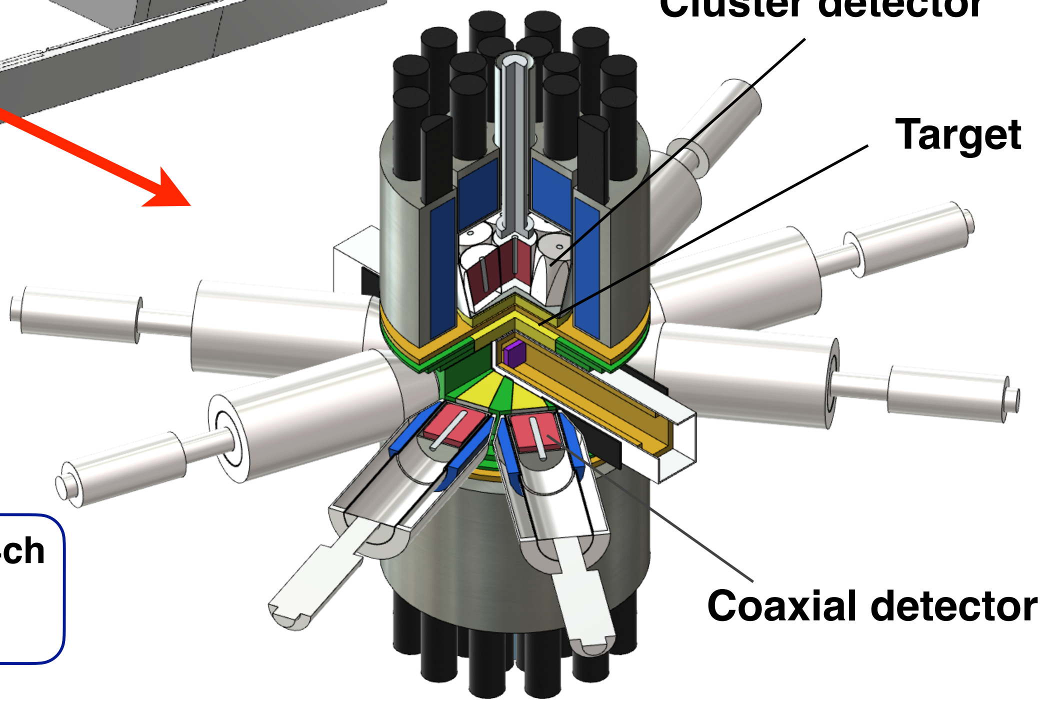
(n,γ) spin-angular correlation terms with s- and p-waves

The experiments to determine κ(J) is ongoing at ANNRI (Accurate Neutron-Nucleus Reaction measurement Instrument) beam line in J-PARC

BL04 ANNRI



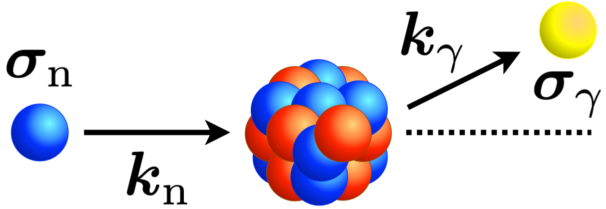
Ge Detectors @ ANNRI



2 Cluster Detector (up·down) 7ch ×2 : 14ch
8 Coaxial Detector (side) 8ch
Total 22ch

a_1: angular distribution without polarization

Flambaum, Nucl. Phys. A435 (1985) 352



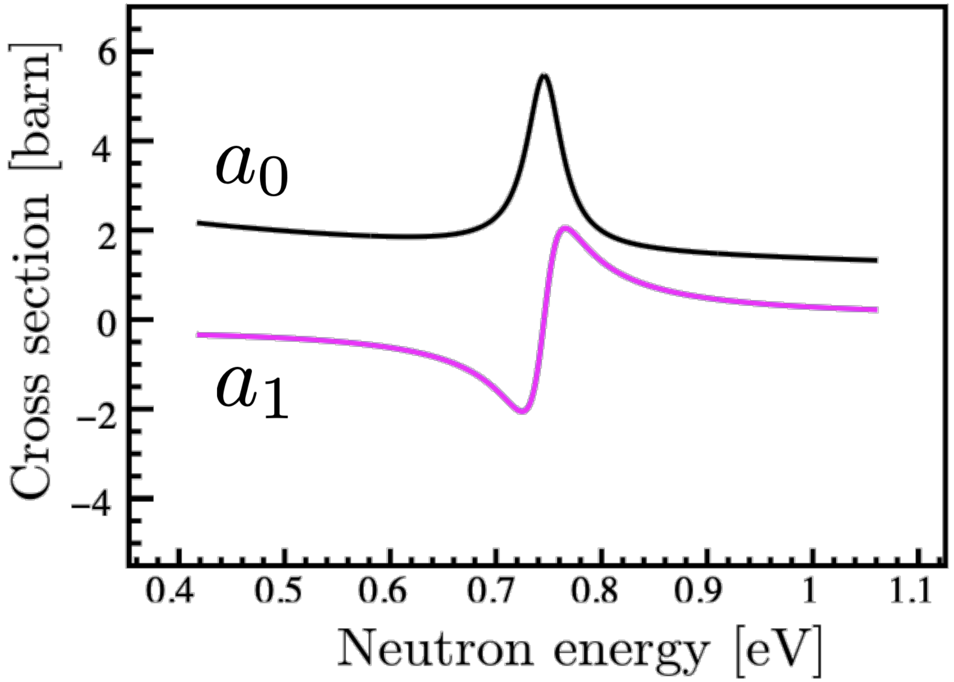
unpolarized case

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

$\boldsymbol{r}$

$$= \frac{1}{2}\left(a_0 + a_1 \cos\theta_\gamma + a_3 (\cos^2\theta_\gamma - \frac{1}{3})\right)$$

energy dependent angular distribution ⇔ angular-dependent distortion of resonance shape



courtesy of T.Okudaira

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

$$a_1 = 2\mathrm{Re} \sum_{J_\mathrm{s},J_\mathrm{p},j} V_1(J_\mathrm{s}) V_2^*(J_\mathrm{p} j) P(J_\mathrm{s} J_\mathrm{p} \tfrac{1}{2} j 1 I F)$$

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

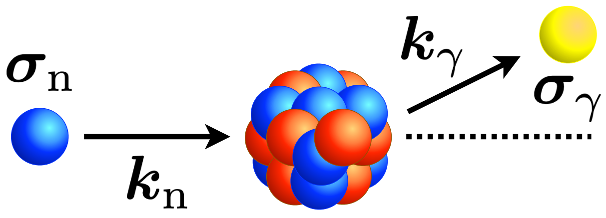
$$V_1 = \frac{1}{2k_s} \sqrt{\frac{E_s}{E}} \frac{\sqrt{g \Gamma_s^n \Gamma_\gamma}}{E - E_s + i\Gamma_s/2} \qquad V_2(j{=}\frac{1}{2}) = V_2 \cos\phi$$

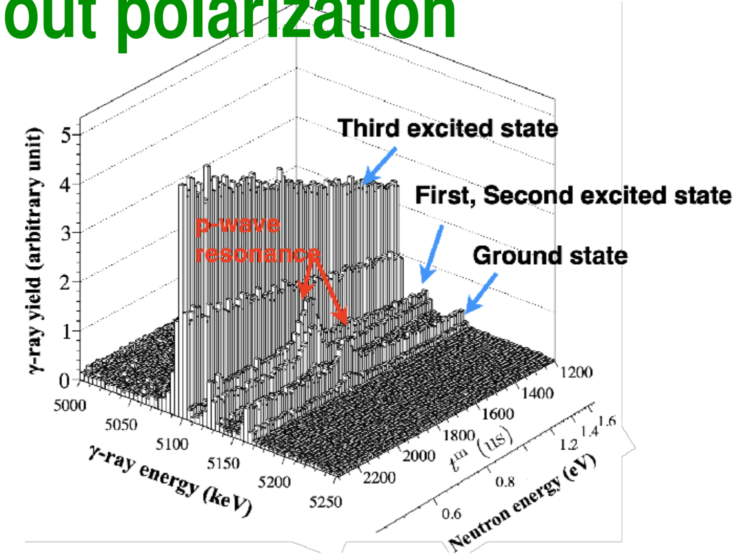
$$V_2(j) = \frac{1}{2k_p} \sqrt{\frac{E_p}{E}} \sqrt{\frac{\Gamma_{pj}^n}{\Gamma_p^n}} \frac{\sqrt{g \Gamma_p^n \Gamma_\gamma}}{E - E_p + i\Gamma_p/2} \qquad V_2(j{=}\frac{3}{2}) = V_2 \sin\phi$$

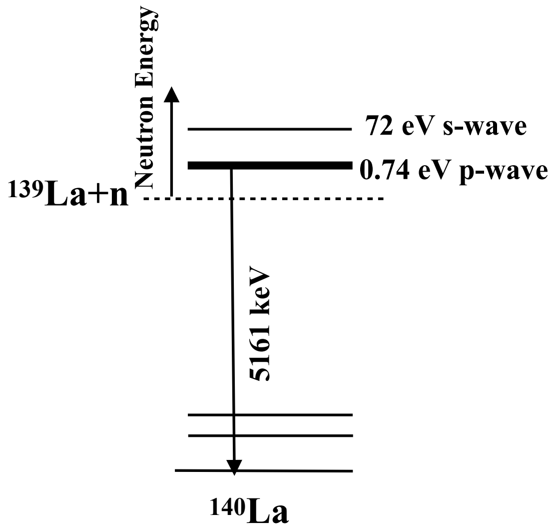
$$P(JJ'jj'kIF) = (-1)^{J+J'+j'+I+F} \frac{3}{2} \sqrt{(2J+1)(2J'+1)(2j+1)(2j'+1)} \begin{Bmatrix} j & j & j' \\ I & J' & J \end{Bmatrix} \begin{Bmatrix} k & 1 & 1 \\ F & J & J' \end{Bmatrix}$$

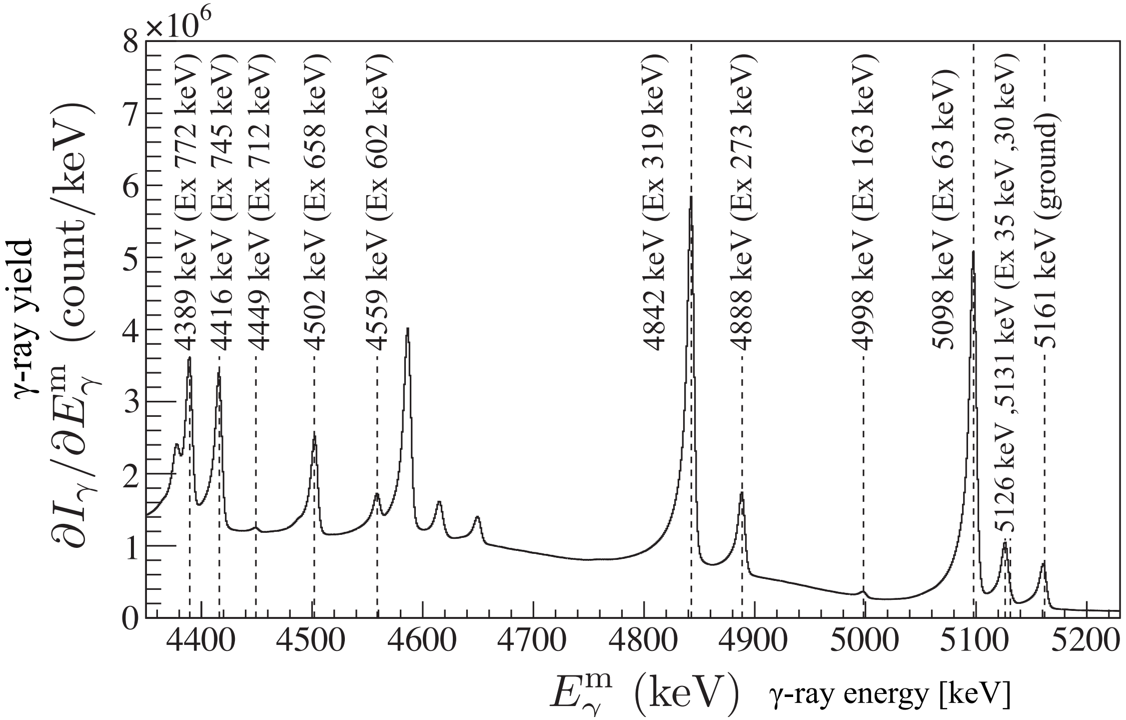
a_1: angular distribution without polarization

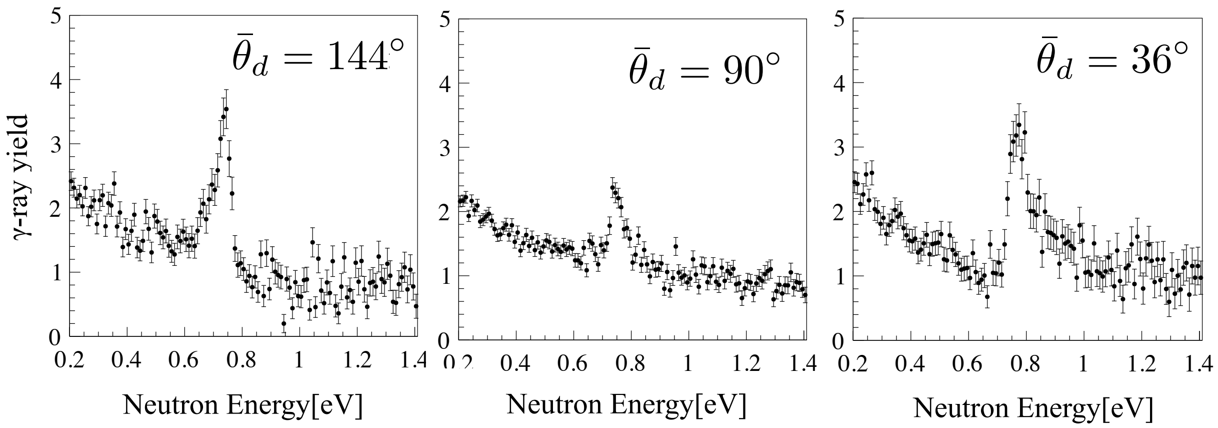
Okudaira, Phys. Rev. C93 (2018) 034622





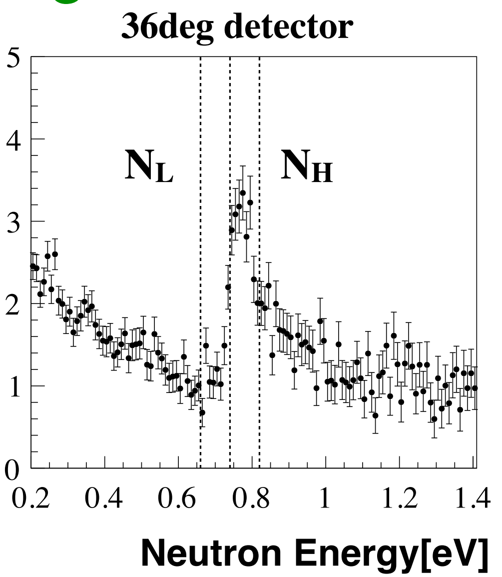






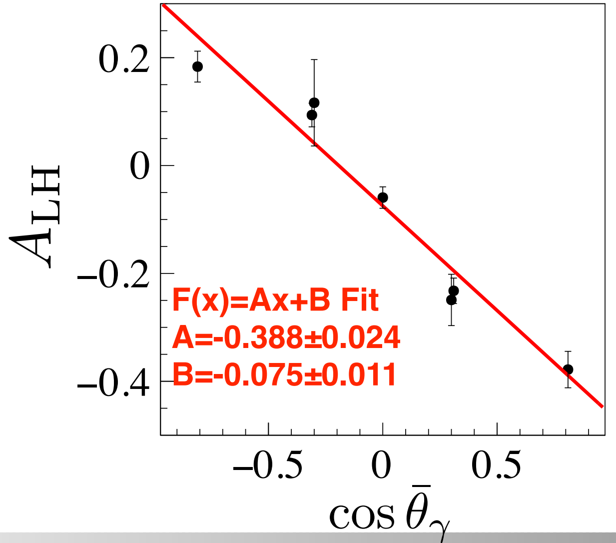
angular-dependent asymmetric resonance shape

a_1: angular distribution without polarization



$$A_{LH} = \frac{N_L - N_H}{N_L + N_H}.$$

angular-dependent asymmetric resonance shape
analyzed as
the angular distribution of low-high asymmetry

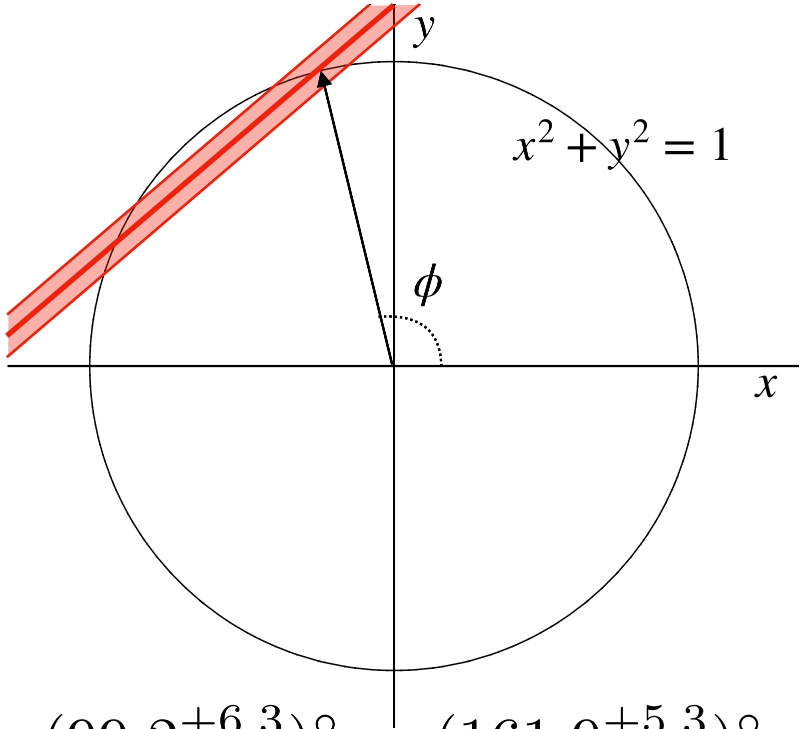


and compared with the s-p mixing model

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

Experimental result — Theoretical calculation

to restrict the allowed region of the mixing angle

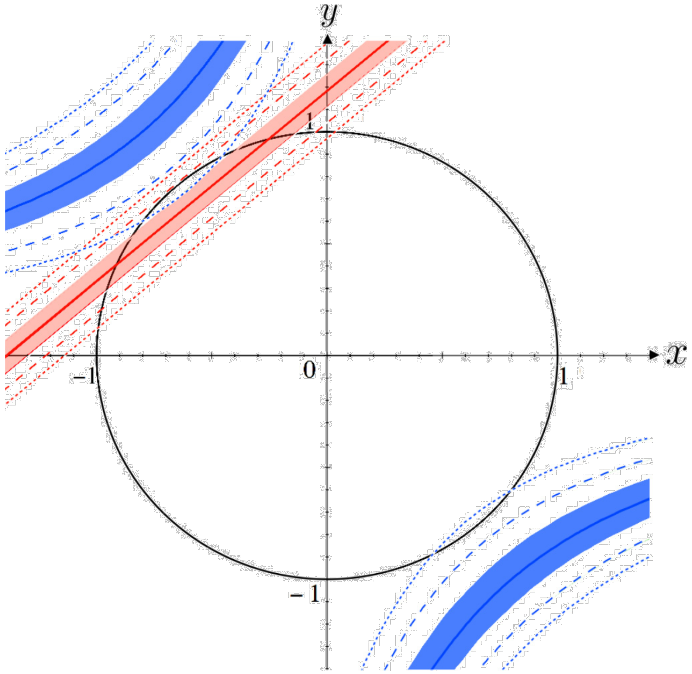


$$\phi \;= (99.2^{+6.3}_{-5.3})^\circ, \quad (161.9^{+5.3}_{-6.3})^\circ.$$

a_1: comparison of the cases for J=4 and J=3

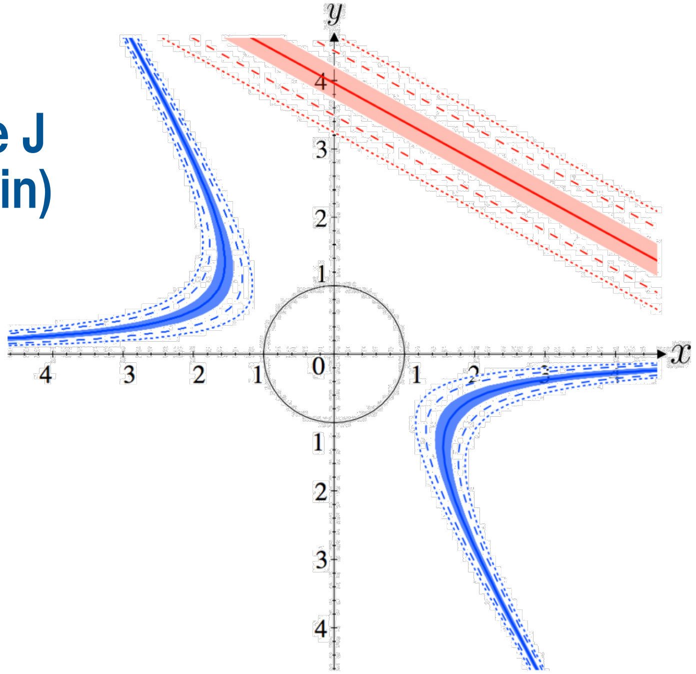
Okudaira, Phys. Rev. C93 (2018) 034622

$$J_{\mathrm{s}} = J_{\mathrm{p}} = 4$$



applicable to determine J
(compound nuclear spin)

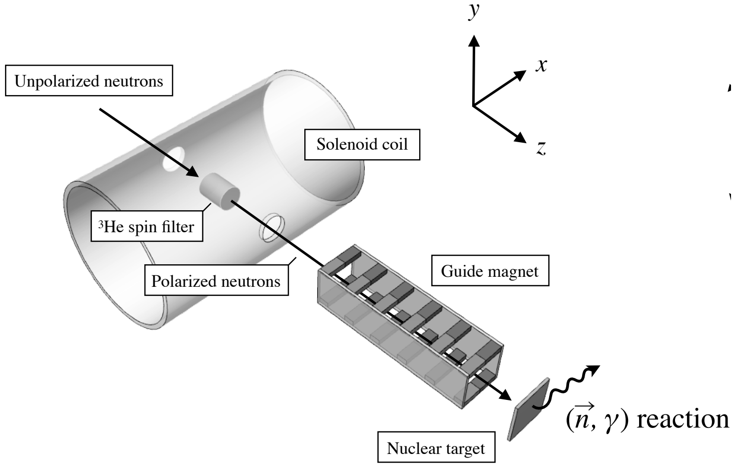
$$J_{\mathrm{s}} = J_{\mathrm{p}} = 3$$



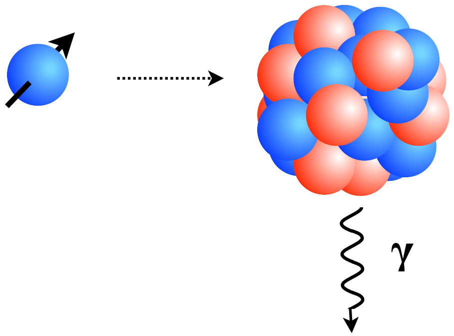
Another approach to detemrine compound nuclear spin

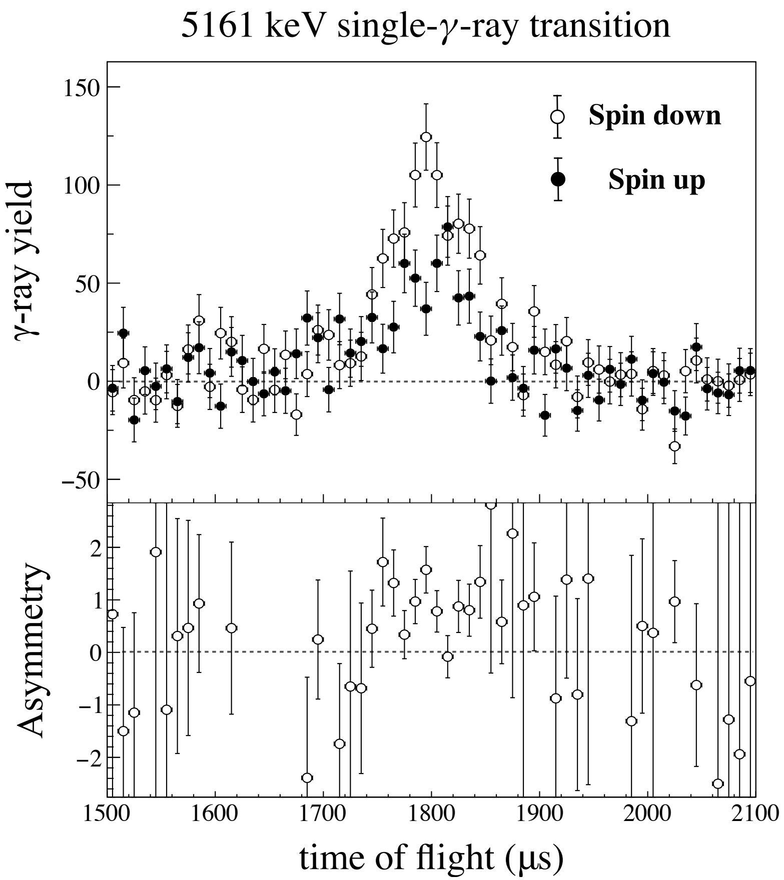
a_2: left-right asymmetry with transversely polarized neutron

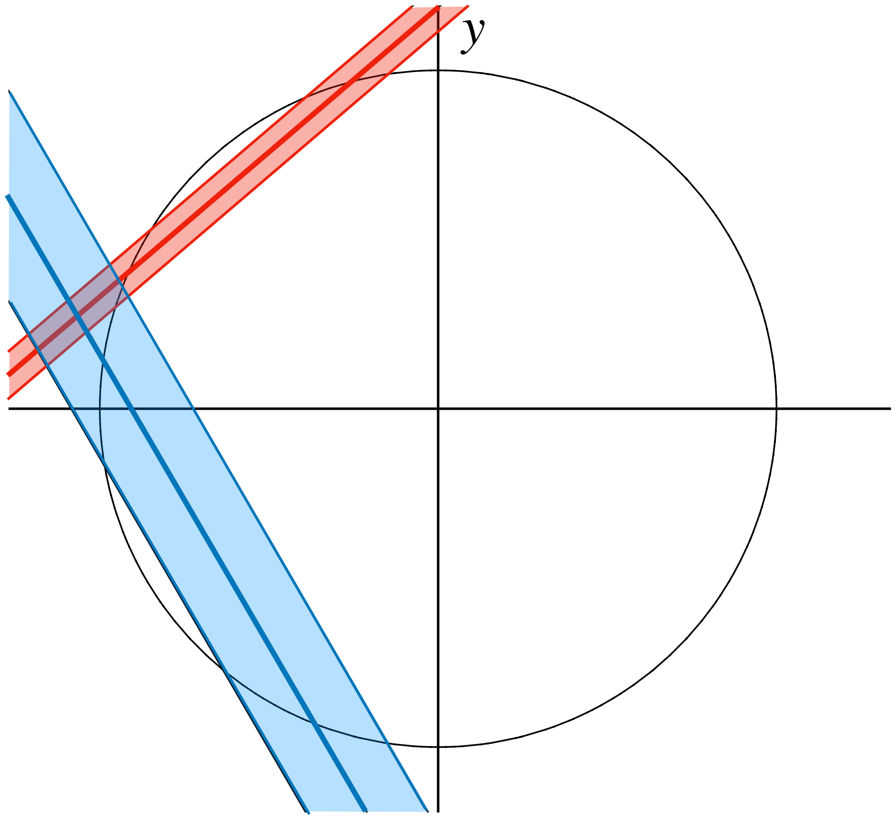
Yamamoto, Phys. Rev. C97 (2020) 064624



$$\sigma_n \cdot (\hat{k}_n \times \hat{k}_\gamma)$$







$$A_{\mathrm{LR}} = \frac{1}{P_n} \frac{N_{\mathrm{up}} - N_{\mathrm{down}}}{N_{\mathrm{up}} + N_{\mathrm{down}}}$$

$$-0.59 \pm 0.12 = 0.719 \cos\phi + 0.418 \sin\phi$$

Experimental result — Theoretical calculation with s-p mixing

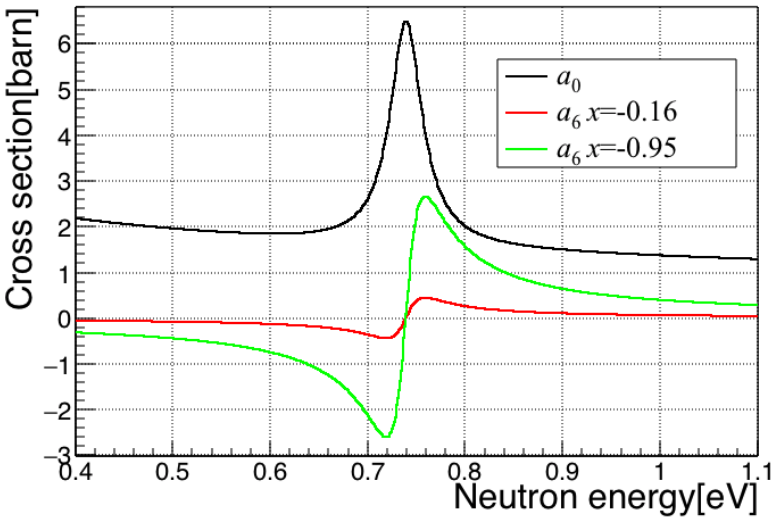
a_6,a_{13}: γ-ray polarization ($\lambda=\sigma_\gamma \cdot k_\gamma$)

courtesy of Endo

Neutron energy dependent γ-ray polarization polarization

γ-ray polarization with polarized neutrons

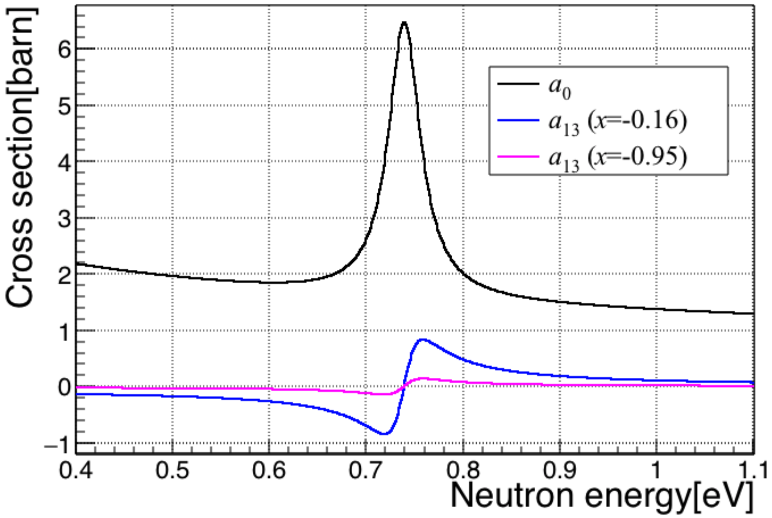
$$a_6\lambda(\sigma_\mathrm{n}\cdot k_\mathrm{n})$$



P-even

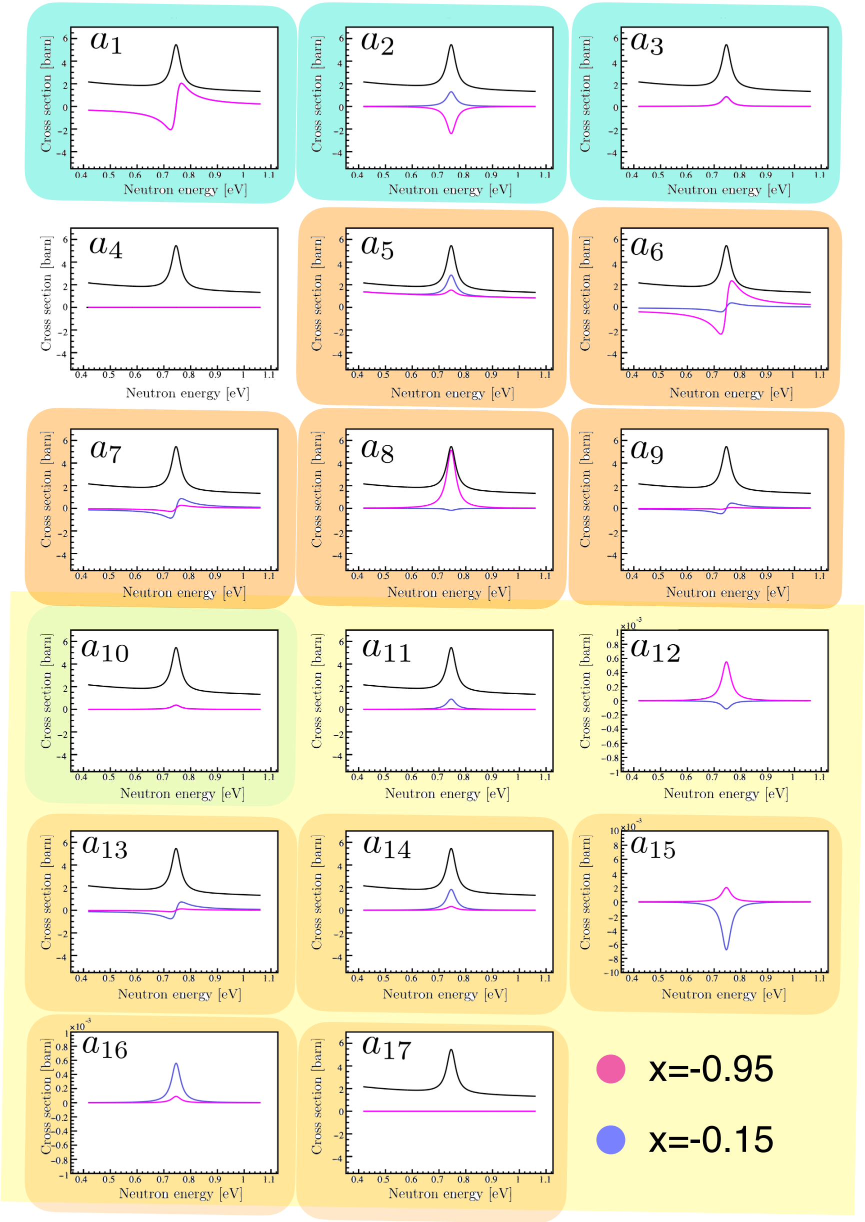
γ-ray polarization with unpolarized neutrons

$$a_{13}\lambda$$



P-odd

^{139}La+n spin-angular correlation terms for F=4



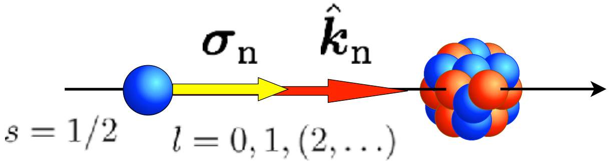
Measured

P-violating

γ-ray polarization

$$
\begin{aligned}
\frac{d\sigma_{n\gamma_f}}{d\Omega_\gamma} = \; & \frac{1}{2}\Big(a_0 + a_1 \hat{\boldsymbol{k}}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_\gamma + a_2 \boldsymbol{\sigma}_{\mathbf{n}} \cdot (\hat{\boldsymbol{k}}_{\mathbf{n}} \times \hat{\boldsymbol{k}}_\gamma) + a_3 \left((\hat{\boldsymbol{k}}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_\gamma)^2 - \frac{1}{3} \right) \\
& + a_4 (\hat{\boldsymbol{k}}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_{\mathbf{n}} \cdot (\hat{\boldsymbol{k}}_{\mathbf{n}} \times \hat{\boldsymbol{k}}_\gamma)) + a_5 (\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_\gamma) \\
& + a_6 (\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_{\mathbf{n}}) + a_7 (\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma) \left((\boldsymbol{\sigma}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_\gamma \cdot \hat{\boldsymbol{k}}_{\mathbf{n}}) - \frac{1}{3} \boldsymbol{\sigma}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_{\mathbf{n}} \right) \\
& + a_8 (\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma) \left((\boldsymbol{\sigma}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_{\mathbf{n}})(\hat{\boldsymbol{k}}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_\gamma) - \frac{1}{3} \boldsymbol{\sigma}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_\gamma \right) \\
& + a_9 \boldsymbol{\sigma}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_\gamma + a_{10} \boldsymbol{\sigma}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_{\mathbf{n}} + a_{11} \left((\boldsymbol{\sigma}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_\gamma \cdot \hat{\boldsymbol{k}}_{\mathbf{n}}) - \frac{1}{3} (\boldsymbol{\sigma}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_{\mathbf{n}}) \right) \\
& + a_{12} (\boldsymbol{\sigma}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_{\mathbf{n}}) \left((\hat{\boldsymbol{k}}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_\gamma) - \frac{1}{3} (\boldsymbol{\sigma}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_\gamma) \right) \\
& + a_{13} \boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma + a_{14} (\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_\gamma) \\
& + a_{15} (\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma) \sigma_{\mathrm{n}} \cdot (\hat{\boldsymbol{k}}_{\mathbf{n}} \times \hat{\boldsymbol{k}}_\gamma) + a_{16} (\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma) \left((\hat{\boldsymbol{k}}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_\gamma)^2 - \frac{1}{3} \right) \\
& + a_{17} (\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_{\mathbf{n}} \cdot \hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_{\mathbf{n}} \cdot (\hat{\boldsymbol{k}}_{\mathbf{n}} \times \hat{\boldsymbol{k}}_\gamma)) \Big),
\end{aligned}
$$

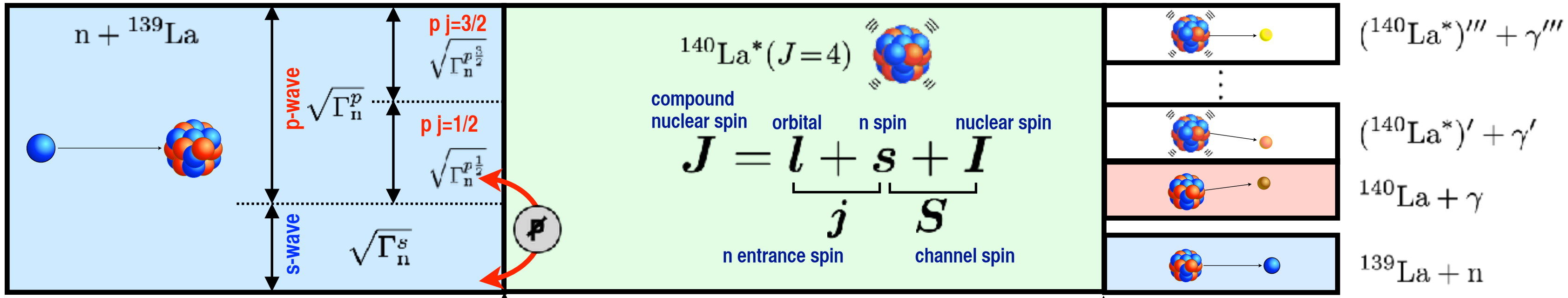
P-violation in Compound State



$$\sigma = \sigma_0 + \Delta\sigma(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_n)$$

10^{-7} for NN

initial state (entrance channel) | **compound state** | **final state** (exit channel)

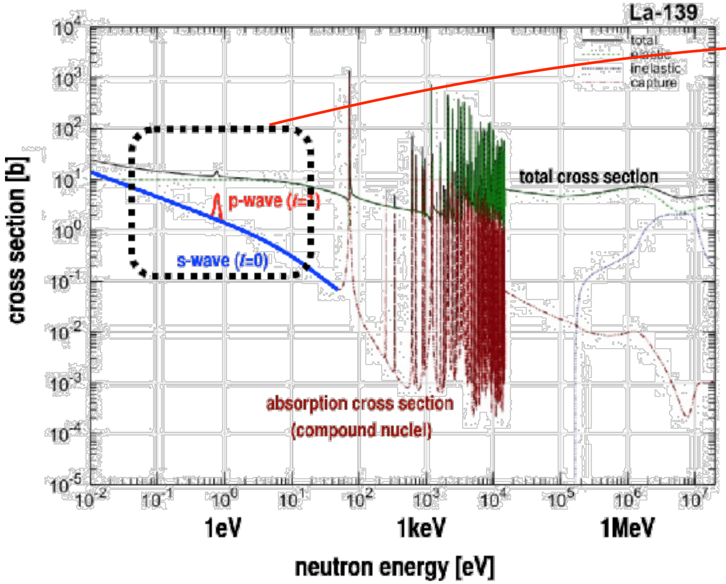


entrance channel boundary

$$\cos^2\phi = x^2 = \Gamma^n_{p\frac{1}{2}}/\Gamma^n_p \qquad \sin^2\phi = y^2 = \Gamma^n_{p\frac{3}{2}}/\Gamma^n_p$$

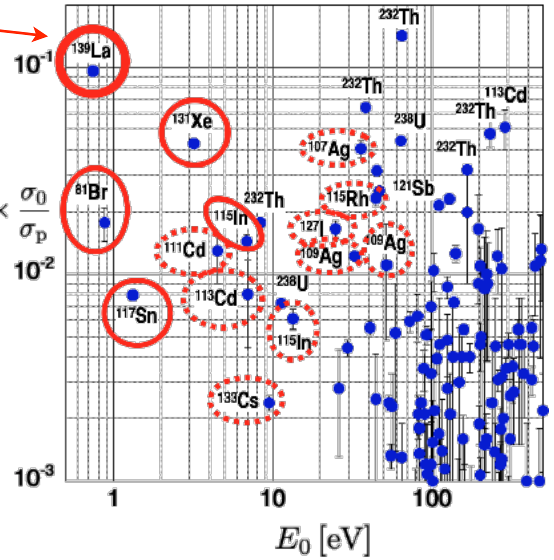
exit channel boundary

$$\Gamma_i^\gamma/\Gamma^\gamma$$

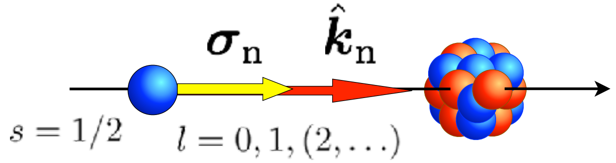


$$A_L = \frac{\Delta\sigma}{\sigma_0} \times \frac{\sigma_0}{\sigma_p}$$

10^{-7} for NN

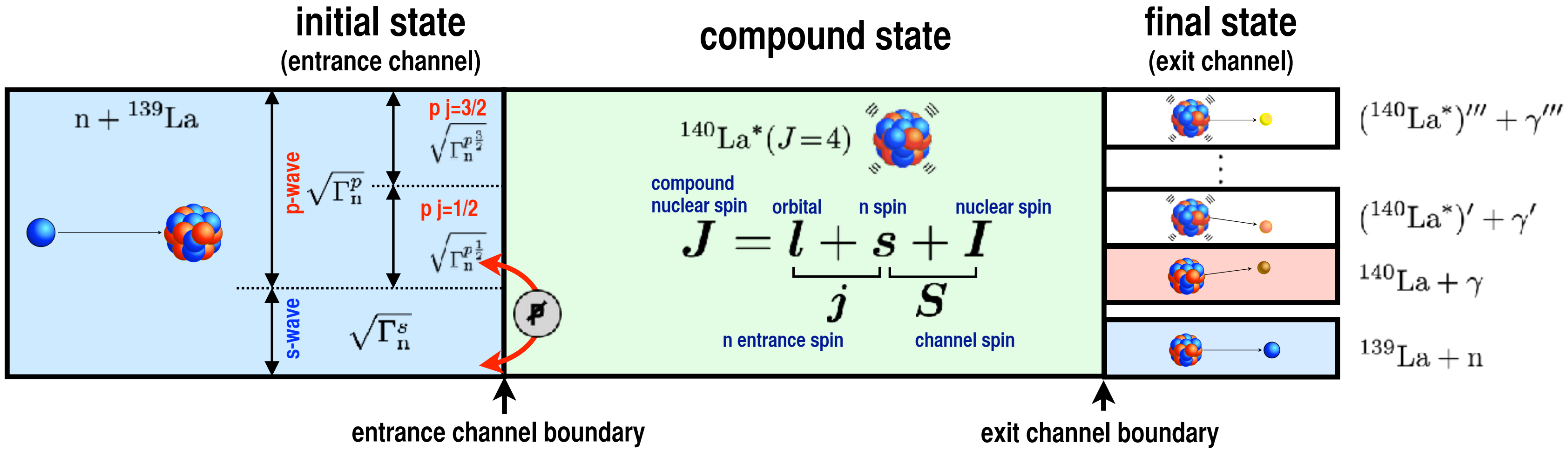


P-violation in Compound State



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

10^{-7} for NN



$\cos^2\phi = x^2 = \Gamma^{\rm n}_{\rm p\frac{1}{2}}/\Gamma^{\rm n}_{\rm p}$ $\quad \sin^2\phi = y^2 = \Gamma^{\rm n}_{\rm p\frac{3}{2}}/\Gamma^{\rm n}_{\rm p}$ $\quad \Gamma^{\gamma}_{i}/\Gamma^{\gamma}$

P-violating matrix element of the compound state

$$A_{\rm L} = -\frac{2W}{E_{\rm p} - E_{\rm s}}\sqrt{\frac{\Gamma^{\rm s}_{\rm n}}{\Gamma^{\rm p}_{\rm n}}}\cos\phi$$

P-violating asymmetry

~3200

level density of compound states

$$\frac{W}{E_{\rm p} - E_{\rm s}} \sim \sqrt{N}\frac{w_{\rm sp}}{d_{\rm sp}}$$

~400

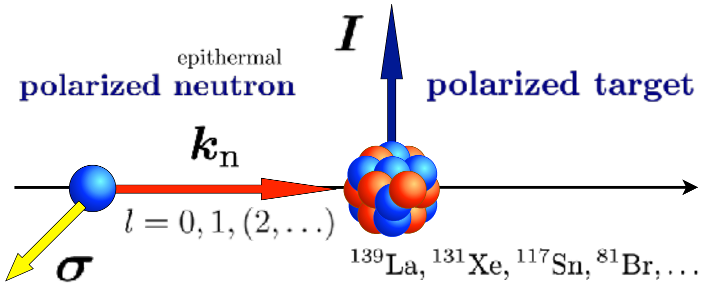
P-violating matrix element for single particle state

level spacing of single particle states

estimation assuming the symmetry-violating interaction is sufficiently small to be treated as a perturbation

Since T-violating effect can be naturally assumed to be sufficiently small, it can be enhanced by the same mechanism.

T-violation in Epithermal Neutron Optics



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

- 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

$$\frac{D'}{C'} = \kappa(J)\frac{W_{\rm T}}{W}$$

D': to be measured; C': measured; $\kappa(J)$: spin factor, being measured; $W_{\rm T}$: T-violating matrix element; W: P-violating matrix element, measured

$$\frac{W_{\rm T}}{W} = Q\frac{g_{\rm PT}}{g_{\rm P}}$$

$g_{\rm PT}$: T-violating nucleon coupling constant; $g_{\rm P}$: P-violating nucleon coupling constant

$$\frac{\langle s|W_{\rm T}|p\rangle}{\langle s|W|p\rangle} = Q\frac{\langle W_{\rm T}\rangle}{\langle W\rangle}$$

(nuclear; nuclear effect; nucleon)

Gudkov, Phys. Rep. 212 (1992) 77
(Koonin, Phys. Rev. Lett. 69 (1992)1163)

$Q \simeq 1 - 0.2$

Fadeev, Phys. Rev. C 100(2019)015504

$$\frac{\langle W_{\rm T}\rangle}{\langle W\rangle} \simeq -0.47\left(\frac{\bar{g}_\pi^{(0)}}{h_\pi^1} + 0.26\frac{\bar{g}_\pi^{(1)}}{h_\pi^1}\right)$$

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

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

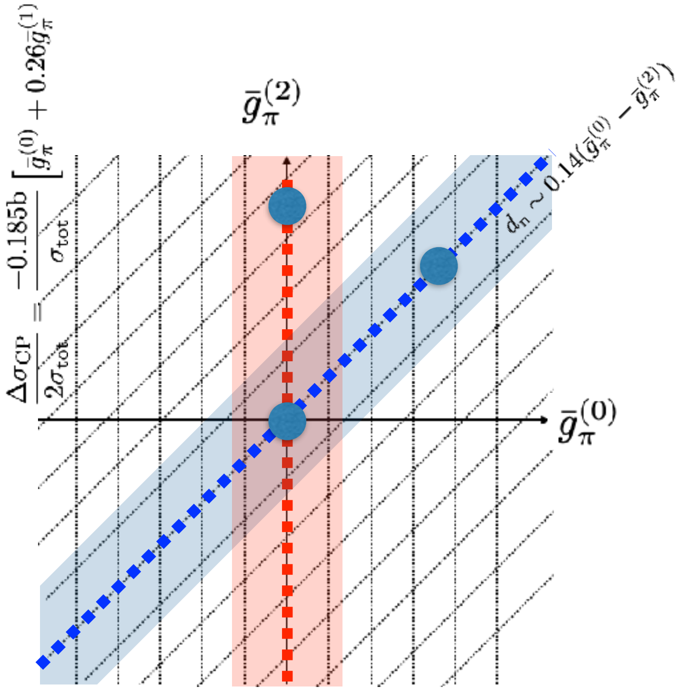
$h_\pi^1 \sim 3\times10^{-7}$ $\quad {\rm n + p \to d + \gamma}$

↓

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

↕

$\left|\frac{\langle W_{\rm T}\rangle}{\langle W\rangle}\right| < 3.9\times10^{-4}$ ←estimated discovery potential



NOPTREX

Neutron Optical Parity and Time Reversal EXperiment

1. Optical Test final-state interaction free

2. Enhancement dynamical and kinematical enhancement

3. New Type of New Physics Search chromo-EDM

Sketch of NOPTREX Steps

neutron polarizer

Step 1: find P-violation

γ-detector
or polarized target

Step 2: determine ϕ and W
in (n,γ), spin-spin correlation

neutron polarizer/analyzer
and polarized target

Step 3: measure D’ (T-odd)

Sketch of NOPTREX Steps

neutron polarizer

Step 1: find P-violation

$$A_L = -2\frac{W}{E_p - E_s}\sqrt{\frac{\Gamma^n_s}{\Gamma^n_p}}\cos\phi$$

$$W$$

$$\cos\phi = \sqrt{\frac{\Gamma^n_{p\frac{1}{2}}}{\Gamma^n_p}}$$

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

γ-detector
or polarized target

Step 2: determine ϕ and W in (n,γ), spin-spin correlation

$$a_1 = 2(-1)^{J_s+J_p+\frac{1}{2}+I+F}\sqrt{(2J_s+1)(2J_p+1)} \times \begin{Bmatrix} 1 & 1 & 1 \\ F & J_s & J_p \end{Bmatrix}\left(\begin{Bmatrix} 1 & \frac{1}{2} & \frac{1}{2} \\ I & J_p & J_s \end{Bmatrix}\cos\phi - \sqrt{2}\begin{Bmatrix} 1 & \frac{1}{2} & \frac{3}{2} \\ I & J_p & J_s \end{Bmatrix}\sin\phi\right) \times \frac{\sqrt{g_s g_p \Gamma^n_s(\Gamma^\gamma_s)_F \Gamma^n_p(\Gamma^\gamma_p)_F}}{4k^2}\frac{(E-E_s)(E-E_p)+\frac{\Gamma_s\Gamma_p}{4}}{\left((E-E_s)^2+\frac{\Gamma_s^2}{4}\right)\left((E-E_p)^2+\frac{\Gamma_p^2}{4}\right)}$$

$$C'$$

neutron polarizer/analyzer
and polarized target

Step 3: measure D' (T-odd)

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

T-violating matrix element

Reliable values of potential parameters, spin assignment, resonance parameters, are the basis of NOPTREX.

T-violation in Compound Nuclear States

A' — P-even T-even — $\frac{d\sigma_{n\gamma}}{d\Omega_\gamma}(E_n)$

C' $(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_n)$ — P-odd T-even — $(\vec{n},\gamma)\,(n,\vec{\gamma})\,(\vec{n},\vec{\gamma})$ $\frac{d\sigma_{\vec{n}\gamma}}{d\Omega_\gamma}(E_n)$

10^6 enhancement in compound nuclear state

B' $(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{I}})$ — P-even T-even

D' $\boldsymbol{\sigma}_n \cdot (\hat{\boldsymbol{k}}_n \times \hat{\boldsymbol{I}})$ — P-odd T-odd

10^6 enhancement in compound nuclear state

T-violation in Compound Nuclear States

$\underline{A'}$

P-even T-even

$$\frac{d\sigma_{n\gamma}}{d\Omega_\gamma}(E_n)$$

polarized neutron

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

P-odd T-even

$$(\vec{n}, \gamma)\,(n, \vec{\gamma})\,(\vec{n}, \vec{\gamma})$$

$$\frac{d\sigma_{\vec{n}\gamma}}{d\Omega_\gamma}(E_n)$$

10^6 enhancement in compound nuclear state

polarized target

$\underline{B'}$ $(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{I}})$

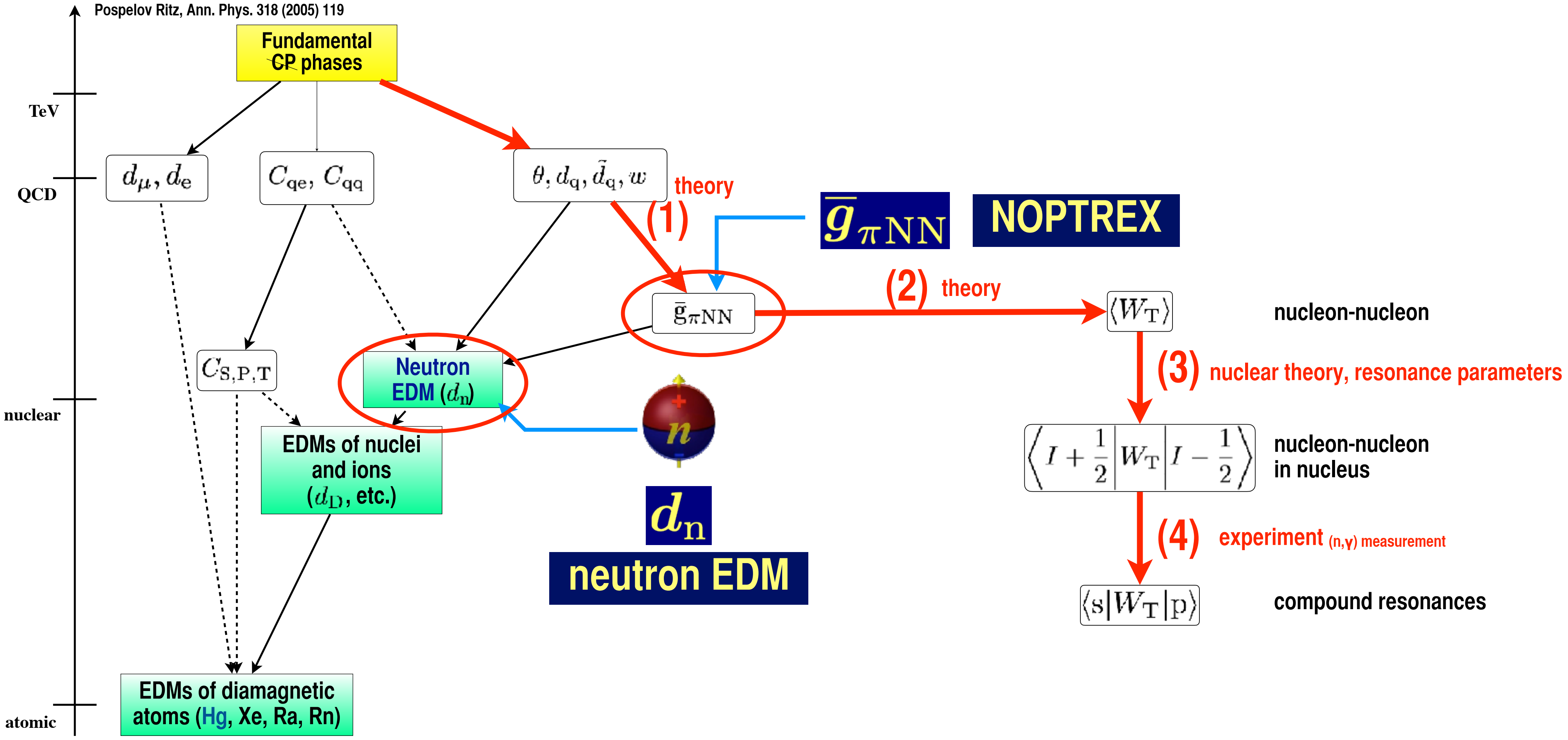
P-even T-even

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

P-odd T-odd

10^6 enhancement in compound nuclear state

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

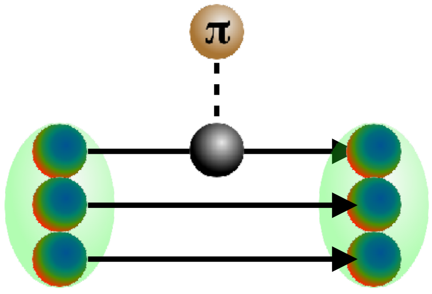


Present Sensitivity Estimation in Effective Field Theory

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

T-odd P-odd meson couplings

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



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

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

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

$$d_{\rm n} \sim 0.14(\bar{g}_\pi^{(0)} - \bar{g}_\pi^{(2)})$$

$$d_{\rm p} \sim -0.14(\bar{g}_\pi^{(0)} - \bar{g}_\pi^{(2)})$$

$$d_{^3{\rm He}} \sim (-0.0542 d_{\rm p} + 0.868 d_{\rm n}) + 0.0$$

$$d_{\rm d} \sim 0.19\bar{g}_\pi^{(1)} + 0.0035\bar{g}_\eta^{(1)} + 0.0017\bar{g}$$

$$d_{^3{\rm H}} \sim (0.868 d_{\rm p} - 0.0552 d_{\rm n}) - 0.072\left[\bar{g}_\pi^{(0}\right.$$

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

$$\frac{1}{N}\frac{{\rm d}\phi_{\rm CP}}{{\rm d}z} = (-65{\rm rad}\cdot{\rm fm}^2)\left[\bar{g}_\pi^{(0)} + 0.\right.$$

Present Sensitivity Estimation in Effective Field Theory

nuclear | nuclear effect | nucleon

$$\frac{\langle s|W_{\rm T}|p\rangle}{\langle s|W|p\rangle} = Q\frac{\langle W_{\rm T}\rangle}{\langle W\rangle}$$

Gudkov, Phys. Rep. 212 (1992) 77
(Koonin, Phys. Rev. Lett. 69 (1992)1163)

$$Q \simeq 1 - 0.2$$

Fadeev, Phys. Rev. C 100(2019)015504

$$\frac{\langle W_{\rm T}\rangle}{\langle W\rangle} \simeq -0.47\left(\frac{\bar{g}_\pi^{(0)}}{h_\pi^1} + 0.26\frac{\bar{g}_\pi^{(1)}}{h_\pi^1}\right)$$

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

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

$$h_\pi^1 \sim 3 \times 10^{-7}$$ $\mathrm{n} + \mathrm{p} \to \mathrm{d} + \gamma$

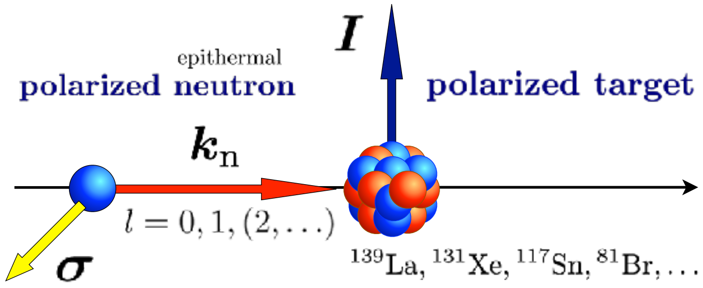
↓

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

↕

$$\left|\frac{\langle W_{\rm T}\rangle}{\langle W\rangle}\right| < 3.9 \times 10^{-4}$$ ←estimated discovery potential

T-violation in Epithermal Neutron Optics



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

- 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

T-violating matrix element

$$\frac{D'}{C'} = \kappa(J)\frac{W_\mathrm{T}}{W}$$

- D': to be measured
- C': measured
- $\kappa(J)$: spin factor, being measured
- W_T: T-violating matrix element
- W: P-violating matrix element, measured

$$\frac{W_\mathrm{T}}{W} = Q\frac{g_\mathrm{PT}}{g_\mathrm{P}}$$

- g_PT: T-violating nucleon coupling constant
- g_P: P-violating nucleon coupling constant

$$\frac{\langle s|W_\mathrm{T}|p\rangle}{\langle s|W|p\rangle} = Q\frac{\langle W_\mathrm{T}\rangle}{\langle W\rangle}$$

(nuclear; nuclear effect; nucleon)

$Q \simeq 1 - 0.2$

Gudkov, Phys. Rep. 212 (1992) 77
(Koonin, Phys. Rev. Lett. 69 (1992)1163)
Fadeev, Phys. Rev. C 100(2019)015504

$$\frac{\langle W_\mathrm{T}\rangle}{\langle W\rangle} \simeq -0.47\left(\frac{\bar{g}_\pi^{(0)}}{h_\pi^1} + 0.26\frac{\bar{g}_\pi^{(1)}}{h_\pi^1}\right)$$

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

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

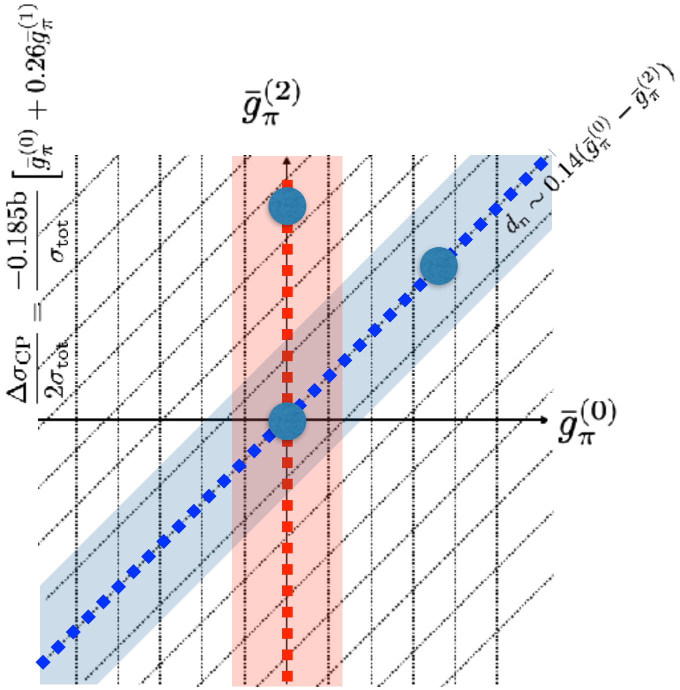
$h_\pi^1 \sim 3\times10^{-7}$ $\quad \mathrm{n}+\mathrm{p}\to\mathrm{d}+\gamma$

↓

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

↕

$\left|\frac{\langle W_\mathrm{T}\rangle}{\langle W\rangle}\right| < 3.9\times10^{-4}$ ←estimated discovery potential



T-violation in Compound Nuclear States

A'

P-even T-even

$\frac{d\sigma_{n\gamma}}{d\Omega_\gamma}(E_n)$

polarized neutron

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

P-odd T-even

$(\vec{n},\gamma)(n,\vec{\gamma})(\vec{n},\vec{\gamma})$

$\frac{d\sigma_{\vec{n}\gamma}}{d\Omega_\gamma}(E_n)$

$\bar{g}^{(0)}_{\pi NN}$ T-violating nucleon meson coupling

polarized target

B' $(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{I}})$

P-even T-even

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

P-odd T-odd

T-violating nuclear matrix element / T-violating nucleon matrix element

$$\frac{\langle s|W_T|p\rangle}{\langle s|W|p\rangle} = Q\frac{\langle W_T\rangle}{\langle W\rangle}$$

P-violating nuclear matrix element / nuclear factor / P-violating nucleon matrix element

nucleon

T-violating nuclear matrix element

$$\frac{D'}{C'} = \kappa(J)\frac{\langle s|W_T|p\rangle}{\langle s|W|p\rangle}$$

angular momentum factor / P-violating nuclear matrix element

nuclear

$$A_x = 4\mathrm{Re}A^*D + 4\mathrm{Im}B^*C \quad P_x = 4\mathrm{Re}A^*D - 4\mathrm{Im}B^*C \quad \cdots$$

epithermal neutron optics

$$\mathfrak{S} = e^{i\frac{2\pi\rho}{k_n}f} = A + B\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + C\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}}_n + D\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}}_n)$$

T-violation in Compound Nuclear States

$\underline{A'}$ P-even T-even

$\frac{d\sigma_{n\gamma}}{d\Omega_\gamma}(E_n)$

statistical nature of compound nuclear states

polarized neutron

$\bar{g}^{(0)}_{\pi NN}$

factorization of nuclear properties

$\underline{C'}$ $(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_n)$ P-odd T-even

$(\vec{n},\gamma)(n,\vec{\gamma})(\vec{n},\vec{\gamma})$

$\frac{d\sigma_{\vec{n}\gamma}}{d\Omega_\gamma}(E_n)$

polarized target

T-violating nuclear matrix element

T-violating nucleon matrix element

$$\frac{\langle s|W_T|p\rangle}{\langle s|W|p\rangle} = Q\frac{\langle W_T\rangle}{\langle W\rangle}$$

nuclear theory

nuclear factor

P-violating nuclear matrix element

P-violating nucleon matrix element

$\underline{B'}$ $(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{I}})$ P-even T-even

T-violating nuclear matrix element

$\underline{D'}$ $\boldsymbol{\sigma}_n \cdot (\hat{\boldsymbol{k}}_n \times \hat{\boldsymbol{I}})$ P-odd T-odd

$$\frac{D'}{C'} = \kappa(J)\frac{\langle s|W_T|p\rangle}{\langle s|W|p\rangle}$$

angular momentum factor

P-violating nuclear matrix element

$$A_x = 4\mathrm{Re}A^*D + 4\mathrm{Im}B^*C \quad P_x = 4\mathrm{Re}A^*D - 4\mathrm{Im}B^*C \quad \cdots$$

epithermal neutron optics

$$\mathfrak{S} = e^{i\frac{2\pi\rho}{k_n}f} = A + B\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + C\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}}_n + D\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}}_n)$$

T-violation in Compound Nuclear States

A' P-even T-even

polarized neutron

C' $(\boldsymbol{\sigma}_{\mathrm{n}} \cdot \hat{\boldsymbol{k}}_{\mathrm{n}})$ P-odd T-even

polarized target

B' $(\boldsymbol{\sigma}_{\mathrm{n}} \cdot \hat{\boldsymbol{I}})$ P-even T-even

D' $\boldsymbol{\sigma}_{\mathrm{n}} \cdot (\hat{\boldsymbol{k}}_{\mathrm{n}} \times \hat{\boldsymbol{I}})$ P-odd T-odd

$\frac{\mathrm{d}\sigma_{\mathrm{n}\gamma}}{\mathrm{d}\Omega_\gamma}(E_{\mathrm{n}})$

$(\vec{\mathrm{n}}, \gamma)\,(\mathrm{n}, \vec{\gamma})\,(\vec{\mathrm{n}}, \vec{\gamma})$

$\frac{\mathrm{d}\sigma_{\vec{\mathrm{n}}\gamma}}{\mathrm{d}\Omega_\gamma}(E_{\mathrm{n}})$

statistical nature of compound nuclear states

$\overline{g}^{(0)}_{\pi\mathrm{NN}}$

factorization of nuclear properties

T-violating nuclear matrix element

$\frac{\langle s|W_{\mathrm{T}}|p\rangle}{\langle s|W|p\rangle}$

P-violating nuclear matrix element

T-violating nucleon matrix element

$Q\,\frac{\langle W_{\mathrm{T}}\rangle}{\langle W\rangle}$

nuclear factor

P-violating nucleon matrix element

nuclear theory

T-violating nuclear matrix element

$$\frac{D'}{C'} = \kappa(J)\,\frac{\langle s|W_{\mathrm{T}}|p\rangle}{\langle s|W|p\rangle}$$

angular momentum factor

P-violating nuclear matrix element

$$A_x = 4\mathrm{Re}A^*D + 4\mathrm{Im}B^*C \quad P_x = 4\mathrm{Re}A^*D - 4\mathrm{Im}B^*C \quad \cdots$$

epithermal neutron optics

$$\mathfrak{S} = e^{i\frac{2\pi\rho}{k_{\mathrm{n}}}f} = A + B\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + C\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}}_{\mathrm{n}} + D\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}}_{\mathrm{n}})$$

New Physics Search via T-violation

new physics

↑

CP-violation

↑

CPT-theorem

$$\bar{g}^{(0)}_{\pi NN}$$ — $d_n \; d(^{199}\mathrm{Hg}) \; d(^{129}\mathrm{Xe}) \; d_p \cdots$

A' $\frac{d\sigma_{n\gamma}}{d\Omega_\gamma}(E_n)$

P-even T-even

polarized neutron

C' $(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_n)$ $(\vec{n},\gamma)(n,\vec{\gamma})(\vec{n},\vec{\gamma})$ $\frac{d\sigma_{\vec{n}\gamma}}{d\Omega_\gamma}(E_n)$

P-odd T-even

polarized target

B' $(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{I}})$

P-even T-even

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

P-odd T-odd

T-violating nuclear matrix element — T-violating nucleon matrix element

$$\frac{\langle s|W_T|p\rangle}{\langle s|W|p\rangle} = Q\frac{\langle W_T\rangle}{\langle W\rangle}$$

P-violating nuclear matrix element — nuclear factor — P-violating nucleon matrix element

nuclear theory

T-violating nuclear matrix element

$$\frac{D'}{C'} = \kappa(J)\frac{\langle s|W_T|p\rangle}{\langle s|W|p\rangle}$$

angular momentum factor — P-violating nuclear matrix element

$$A_x = 4\mathrm{Re}A^*D + 4\mathrm{Im}B^*C \quad P_x = 4\mathrm{Re}A^*D - 4\mathrm{Im}B^*C \quad \cdots$$

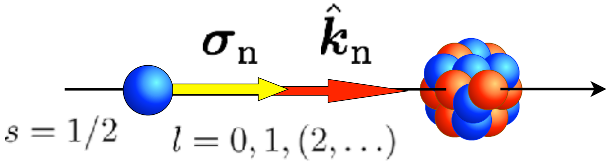
epithermal neutron optics

$$\mathfrak{S} = e^{i\frac{2\pi\rho}{k_n}f} = A + B\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + C\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}}_n + D\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}}_n)$$

APPENDIX

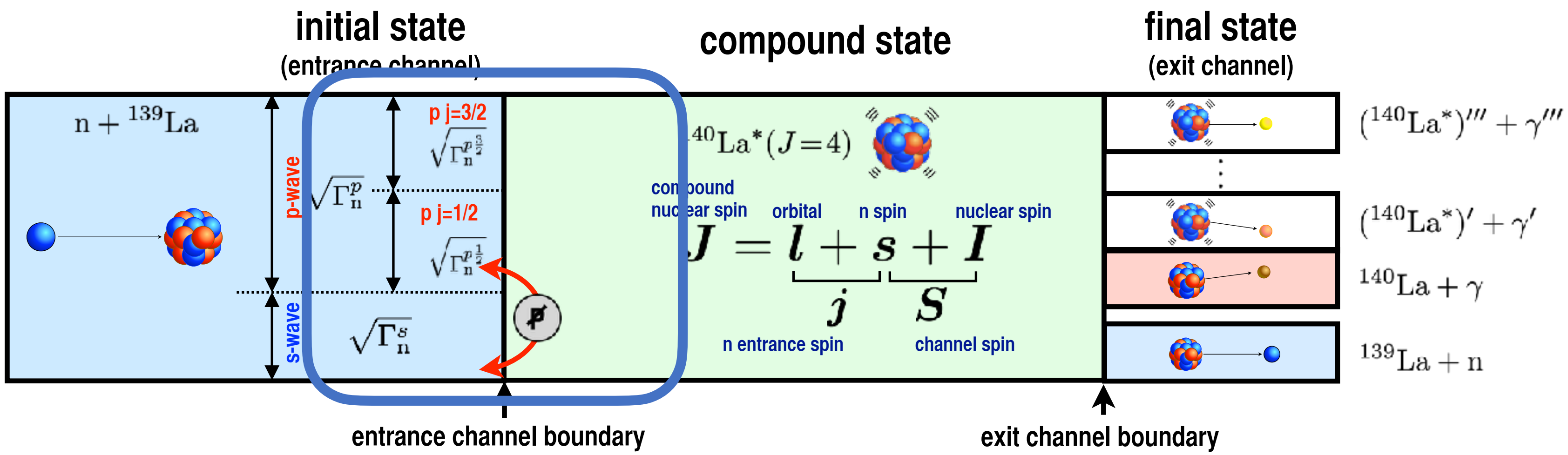
Enhancement Mechanism
(questions from us)

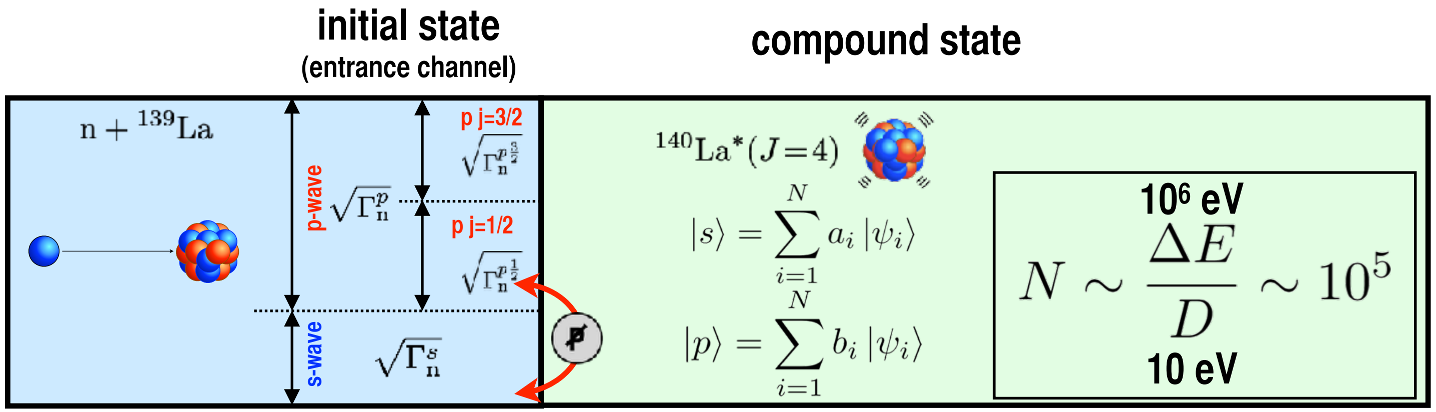
Enhancement Mechanism



$$\sigma = \sigma_0 + \Delta\sigma(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_n)$$

10^{-7} for NN



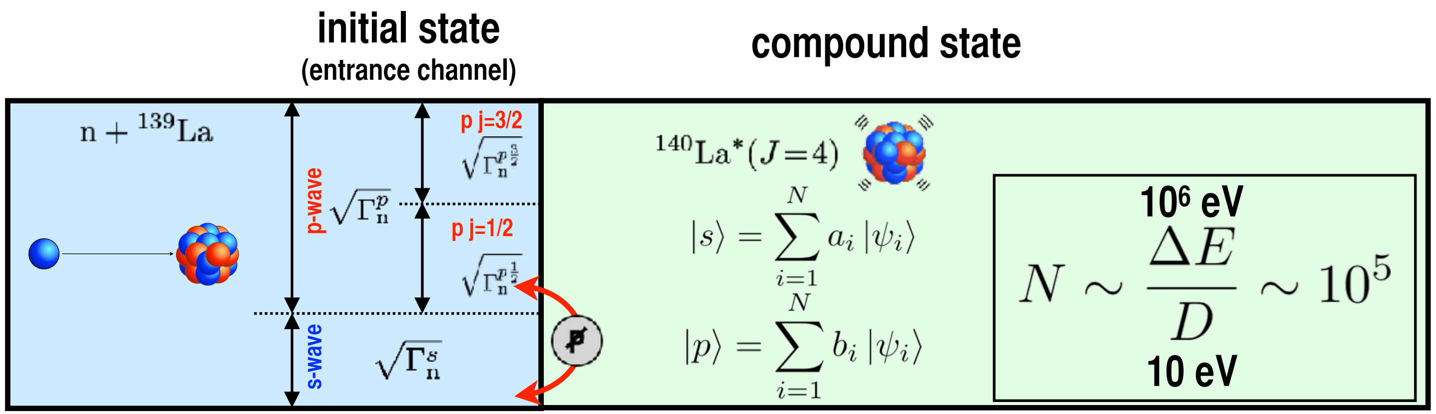


$$\langle s|W|p\rangle = \sum_{i,j}^{N} a_i^* b_j \langle\psi_i|W|\psi_j\rangle$$

$$\sim \frac{1}{\sqrt{N}} \frac{1}{\sqrt{N}} \langle W \rangle \sqrt{N}$$

randomness of expansion coefficients

Enhancement Mechanism



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

$$\sim \frac{1}{\sqrt{N}}\frac{1}{\sqrt{N}}\langle W\rangle\sqrt{N}$$

randomness of expansion coefficients

compound state = strongly correlated (isolated) quantum system

enhancement = deviation of perturbative symmetry-breaking of randomly distributed contributions in the densely correlated quantum system with huge number of freedom

direct connection between the entrance channel to the compound state

We are going to apply this statistical nature to search for new physics.
How reliably can we expect the enhancement of T-violation?

How does the system evolute from the entrance channel to the compound state?

- entrance channel : wave-like   compound state : particle-like (looks quantum mechanically uncorrelated accumulation)
- Friction? Where does it come from?

Intermediate channel(s) seems very thin (since the cross section and correlation terms are consistent with Breit-Wigner-type amplitudes).

- How precisely valid? <- The large enhancement may be built very quickly due to possible quantum mechanical random walk?

Microscopic assessment of the random matrix theory may be difficult.

- Accumulation of experimental results, which deny hypothetical possibilities out of random matrix theory, may be the possible approach.

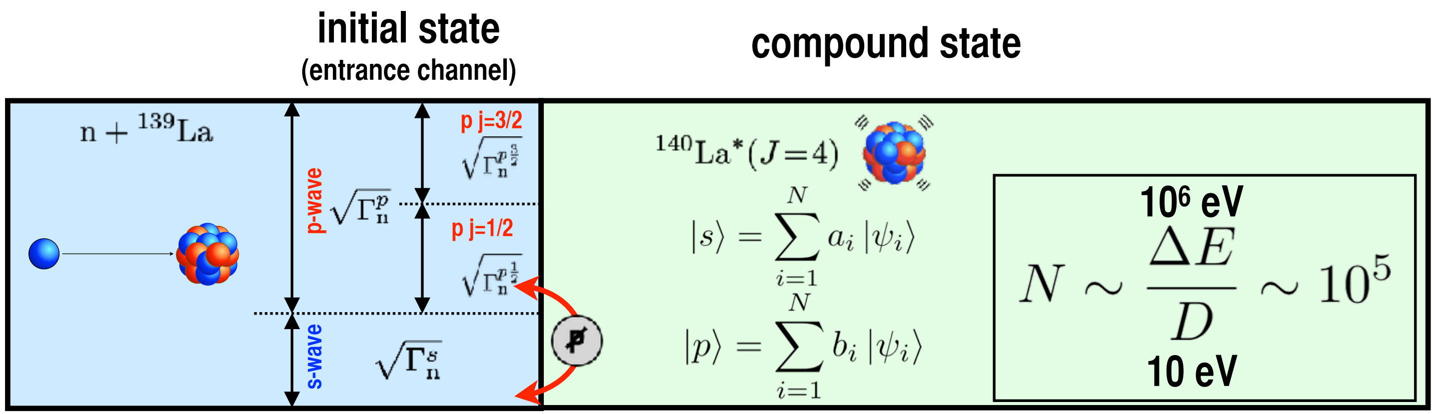
What kind of observables is appropriate to pick up deviations from the random matrix theory?

Enhancement Mechanism

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

$$\sim \frac{1}{\sqrt{N}}\frac{1}{\sqrt{N}}\langle W\rangle\sqrt{N}$$

randomness of expansion coefficients



compound state = strongly correlated (isolated) quantum system

enhancement = deviation of perturbative symmetry-breaking of randomly distributed contributions in the densely correlated quantum system with huge number of freedom

direct connection between the entrance channel to the compound state

We are going to apply this statistical nature to search for new physics.
How reliably can we expect the enhancement of T-violation?

What kind of observables is appropriate to pick up deviations from the random matrix theory?

deviation from the Porter-Thomas distribution

"Anomalous Fluctuations of s-Wave Reduced Neutron Widths of ${}^{192,194}Pt$ Resonances"
P.E.Koehler et al., Phys. Rev. Lett. 105 (2010) 072502

"Neutron Resonance Widths and the Porter-Thomas Distribution"
A.Volya, H.A.Weidenmuller, V.Zelevinsky, Phys. Rev. Lett. 115 (2015) 052501

What is the possible influence(s) to the enhanced sensitivity to T-violation?
(under the constraint of the experimentally observed P-violation enhancement)

B, B-L nonconservation

$$SO(10) \supset SU(5) \times U(1)_X$$

$$\downarrow$$

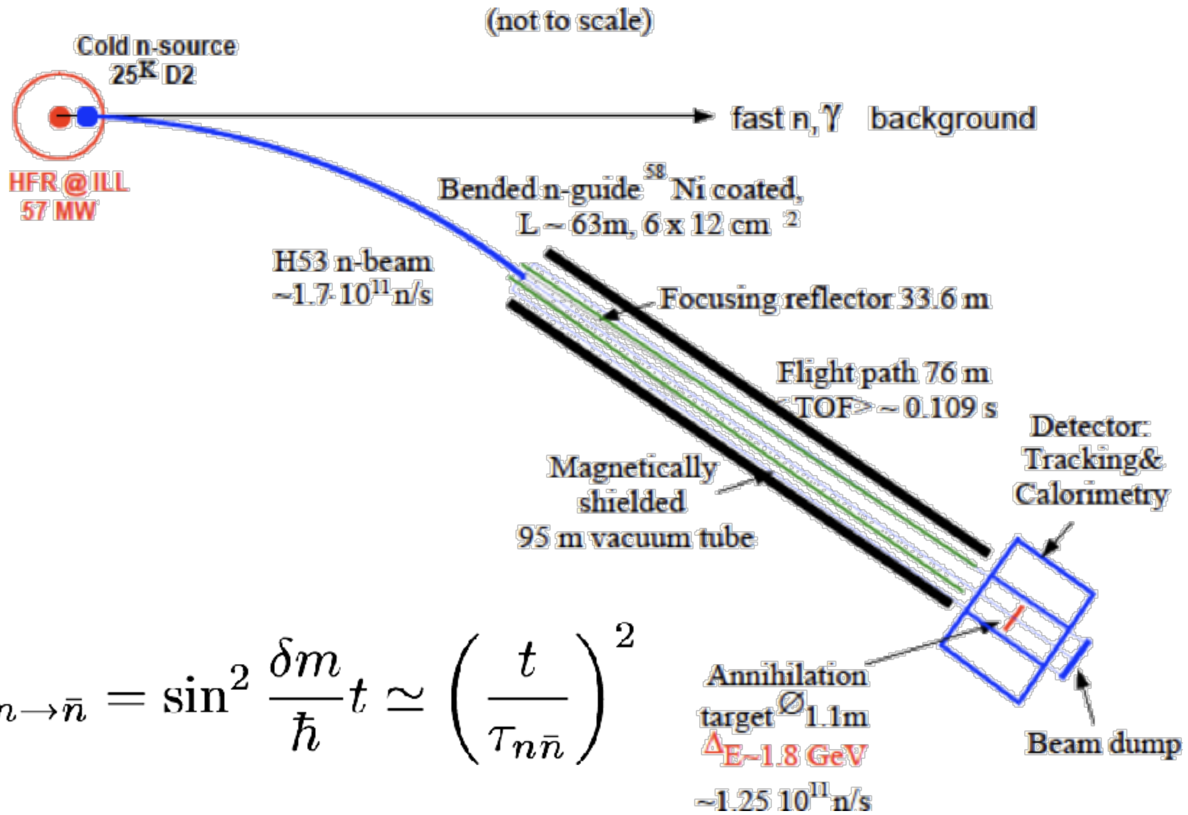
$$SU(5) \supset SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$SO(10) \supset SU(4) \times SU(2)_L \times SU(2)_R$$
$$\supset SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

中性子反中性子振動

中性子から反中性子への自発的遷移　　**磁場のない真空中に長時間滞在させる**

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



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

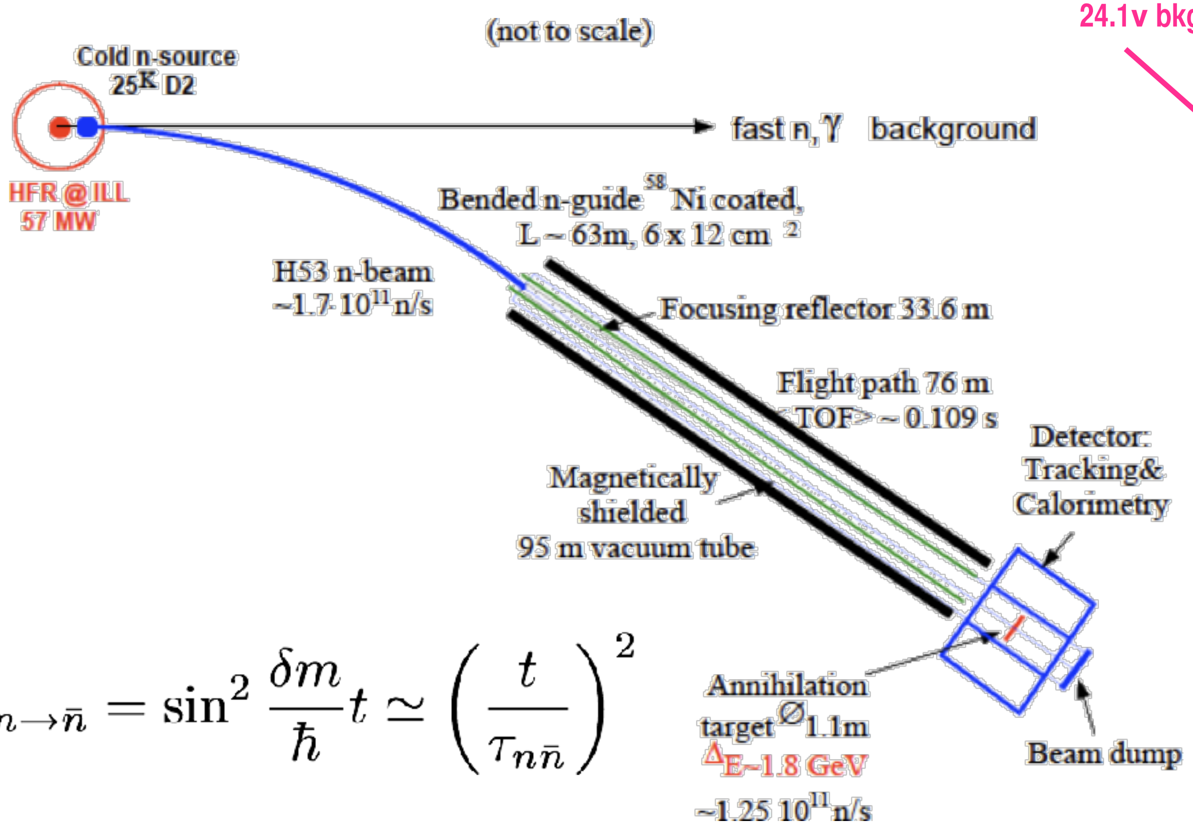
ILL cold neutron beam experiment
Z. Phys. C63 (1994) 409

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

nnbar oscillation causes nuclear instability

中性子から反中性子への自発的遷移

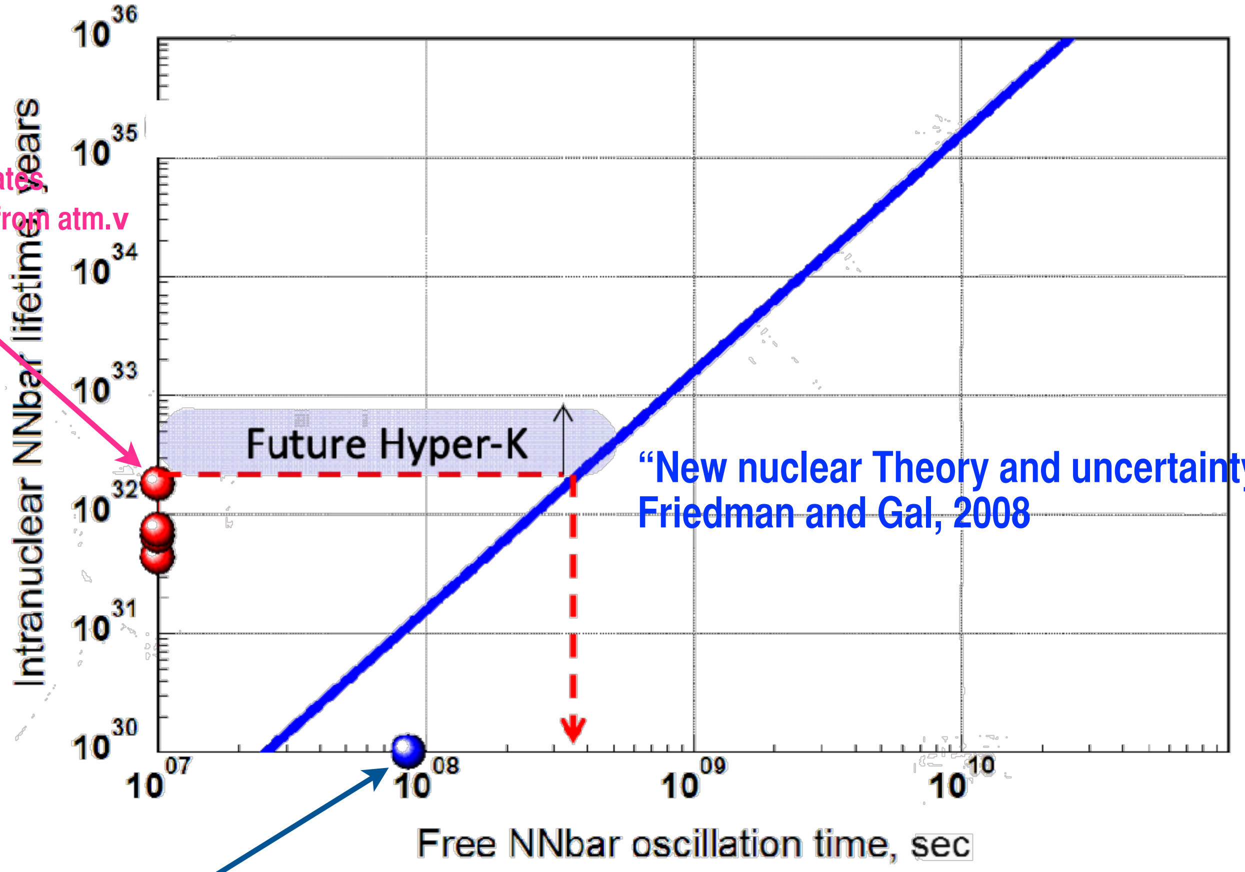
$\Delta B = -2 \quad \Delta(B - L) = -2$



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

$$P_{\rm decay} = N_n \left(1 - e^{-t_{\rm obs}/\tau_{\rm nucl}}\right) \qquad \tau_{\rm nucl} = R \times \tau_{n\bar{n}}^2$$

SK-limit
24ν candidates,
24.1ν bkgr from atm.ν



"New nuclear Theory and uncertainty"
Friedman and Gal, 2008

ILL cold neutron beam experiment
Z. Phys. C63 (1994) 409

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

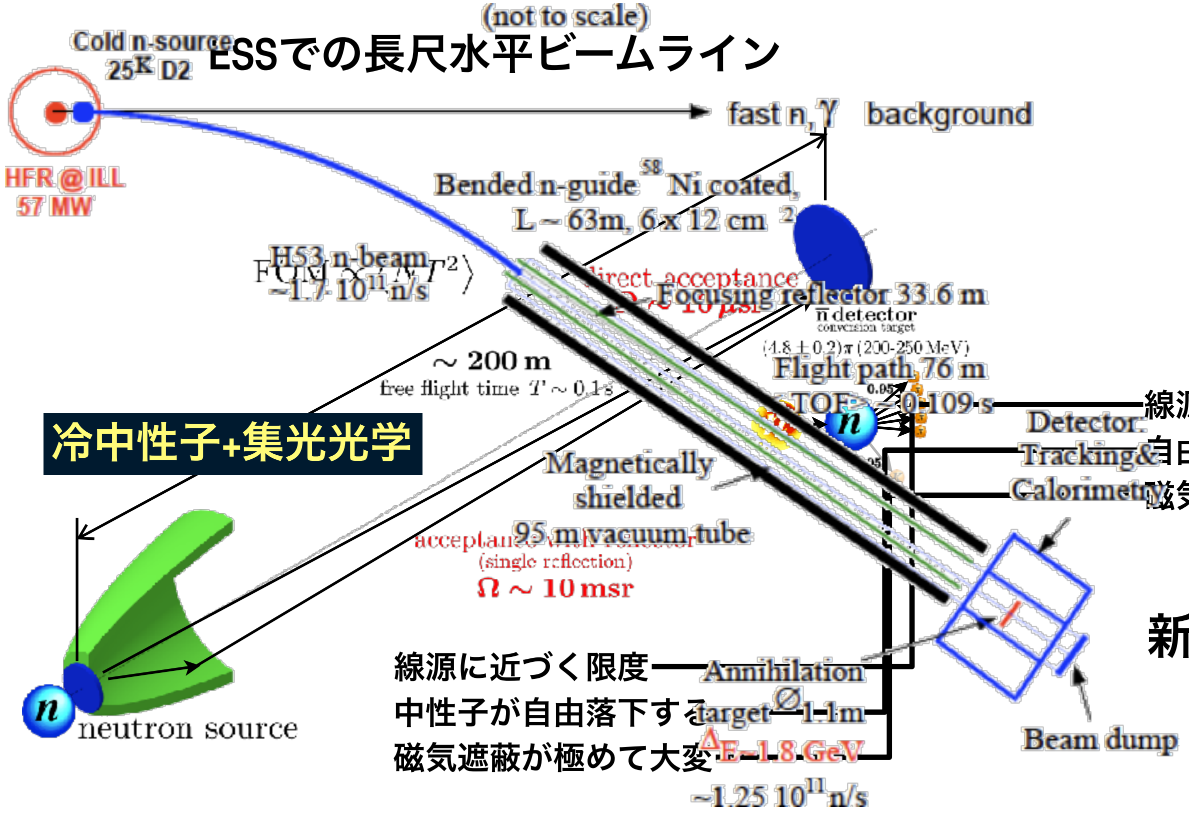
中性子反中性子振動

中性子から反中性子への自発的遷移　　磁場のない真空中に長時間滞在させる

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

ESSでの長尺水平ビームライン

冷中性子+集光光学



線源距離の制限緩和
自由落下は利点
磁気遮蔽が小規模

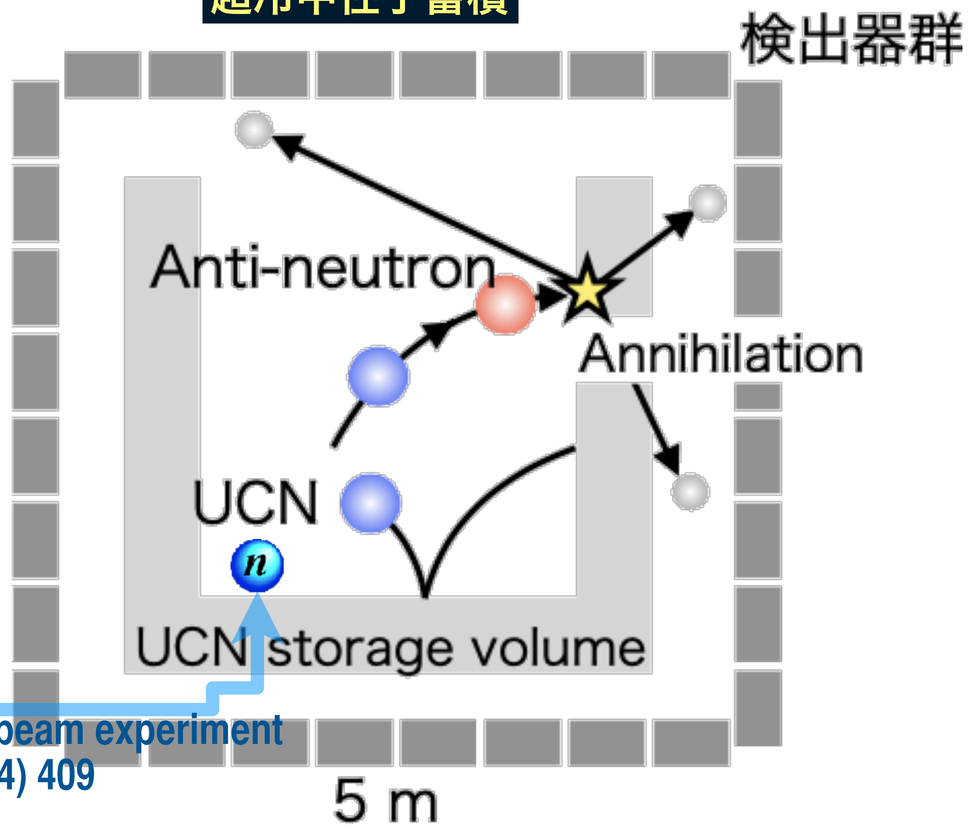
線源に近づく限度
中性子が自由落下する
磁気遮蔽が極めて大変

新試験研究炉

ILL cold neutron beam experiment
Z. Phys. C63 (1994) 409

新試験研究炉での

超冷中性子蓄積



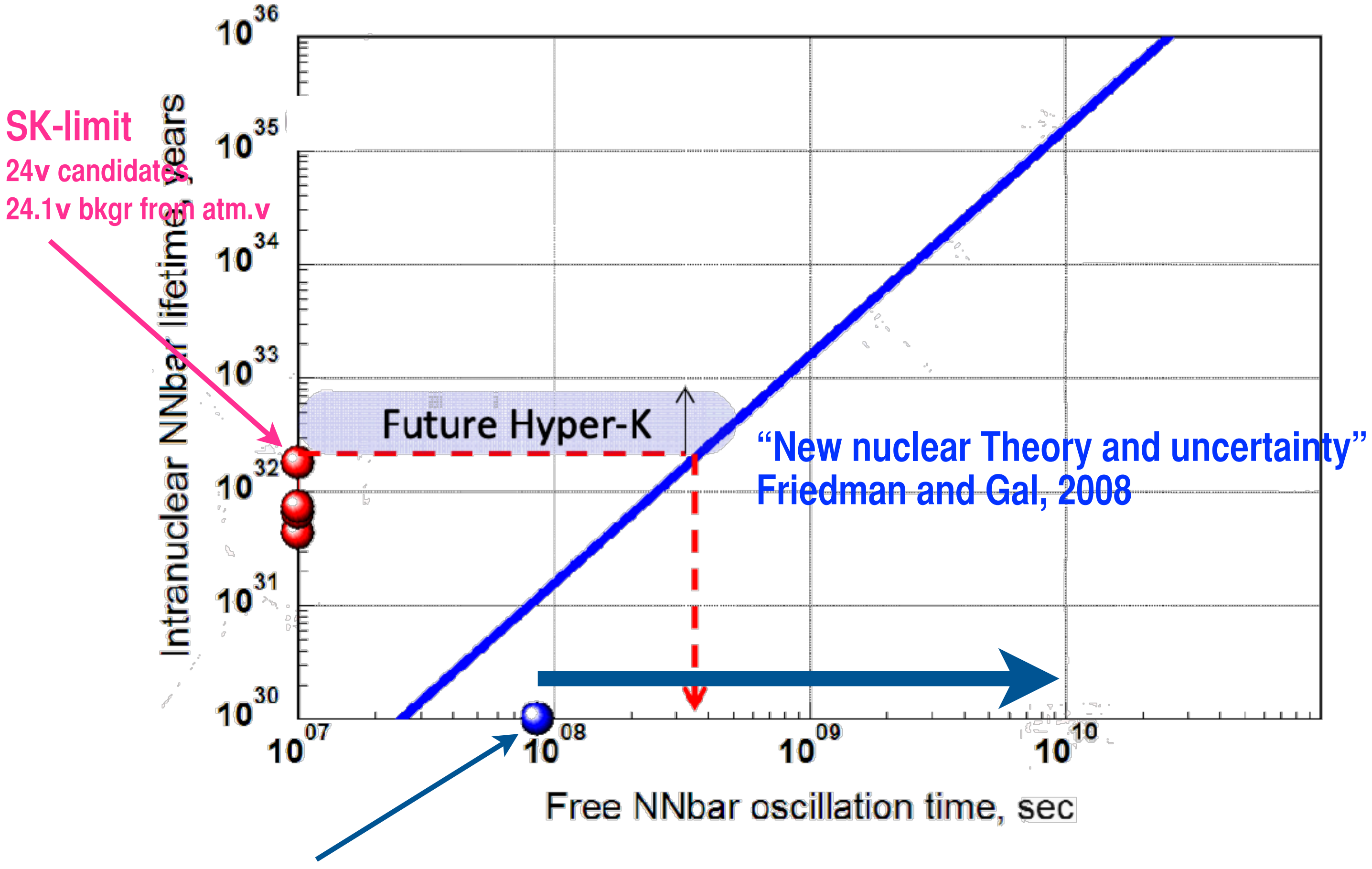
中性子反中性子振動

nnbar oscillation causes nuclear instability

$$P_{\rm decay} = N_n \left(1 - e^{-t_{\rm obs}/\tau_{\rm nucl}}\right) \qquad \tau_{\rm nucl} = R \times \tau_{n\bar{n}}^2$$

Type of GUT	Osc. period $\tau = 10^6 \sim 10^{10}$ sec ?
$SU(2)_L \times U(1)_Y$ (GWS)	forbidden
minimal SU(5)	forbidden
$SU(4)_C \times SU(2)_L \times SU(2)_R$	yes
SO(10)	no
SO(10) with low-energy $SU(4)_C$	yes
E_6	no
SUSY-SU(5)	too rapid
SUSY-E_6	yes

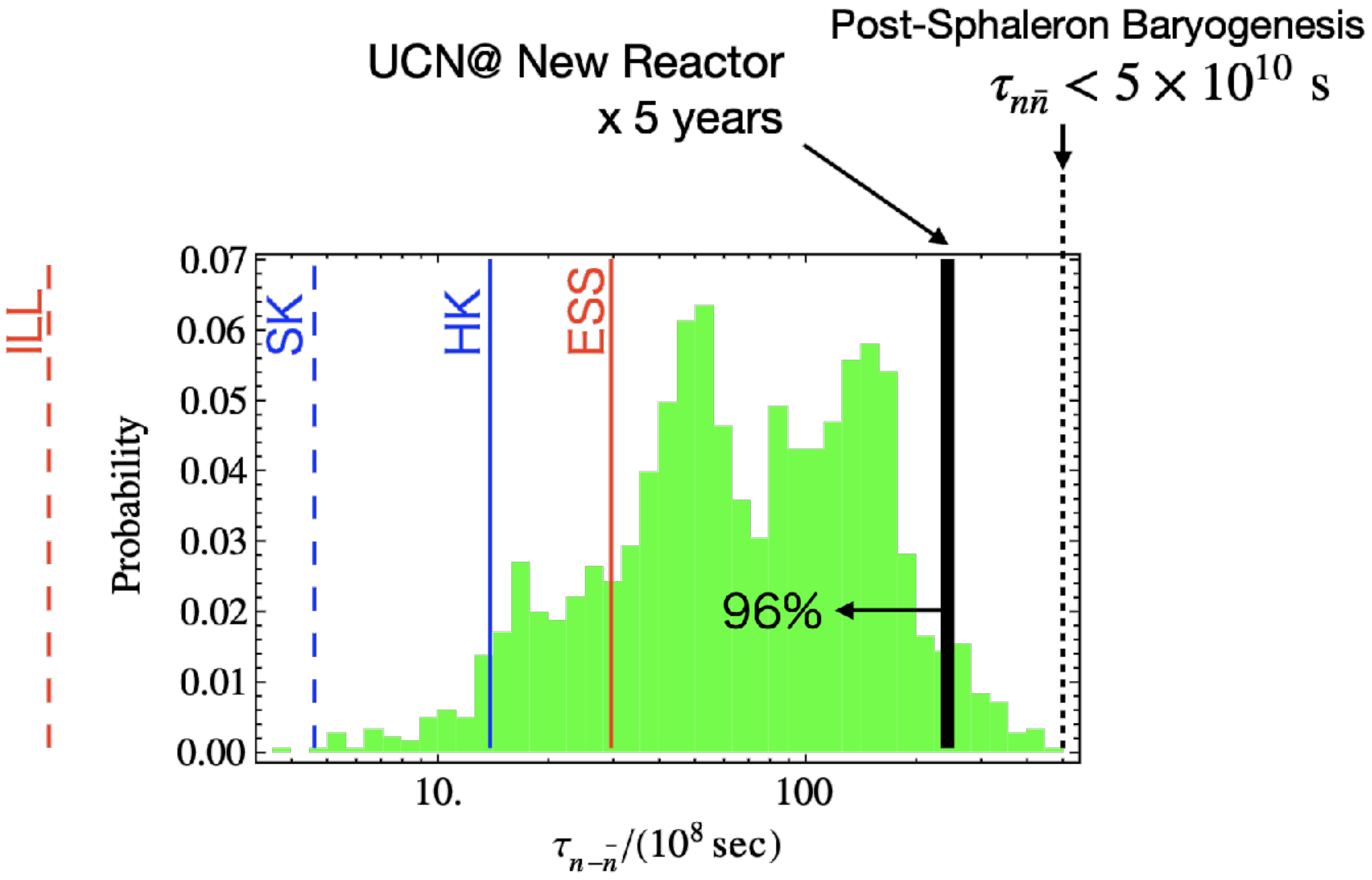
(R.N.Mohapatra, NIM A284 (1989) 1)



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

中性子反中性子振動

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

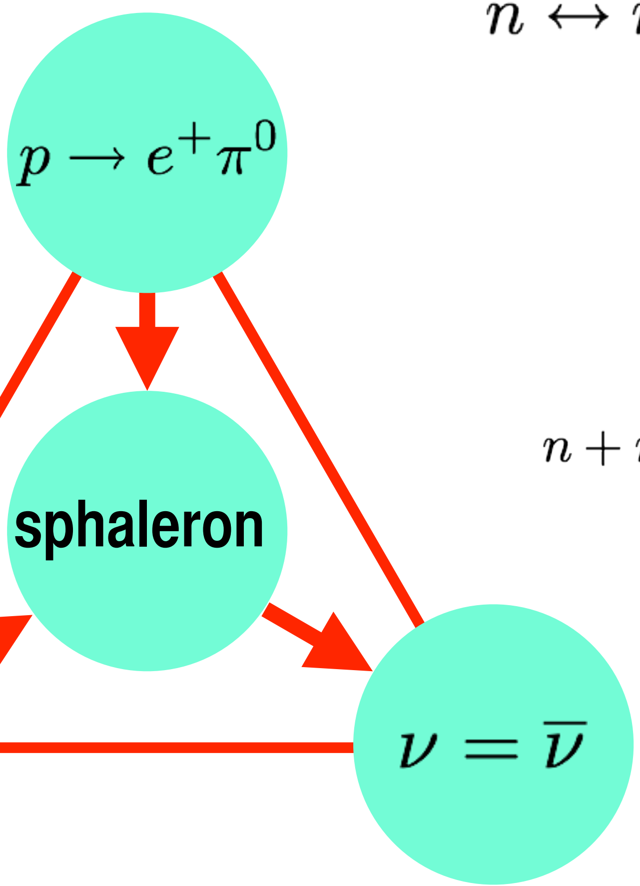


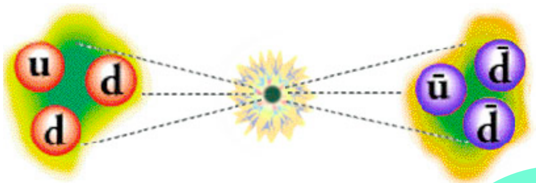
0νββ, 陽子崩壊, 中性子-反中性子振動

B-L Triangle by R.N.Mohapatra

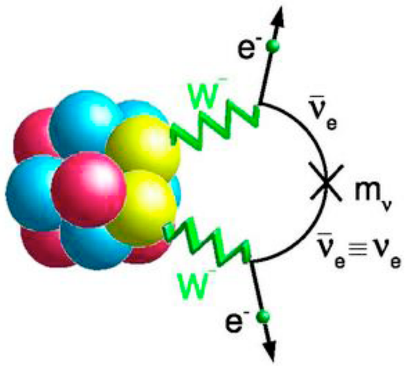
QQQQQQ	QQQL	LL
$n \leftrightarrow \bar{n}$	$p \to e^+\pi^0$	$\nu = \overline{\nu}$

Proton Decay
(ΔB=-1, ΔL=-1 / Δ(B-L)=0)





$n + n \to p + p + e^- + e^-$



Neutron-Antineutron Oscillation
(ΔB=-2, ΔL=0 / Δ(B-L)=-2)

Neutrinoless Double Beta Decay
(ΔB=0, ΔL=2 / Δ(B-L)=-2)

もんじゅサイトを利用した新試験研究炉

JAEA, 京都大学, 福井大学 (2030頃)

基礎物理

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