Fundamental Physics with Slow Neutrons

Center for Experimental Studies, KMI
Laboratory for Particle Properties (Φ-Lab)
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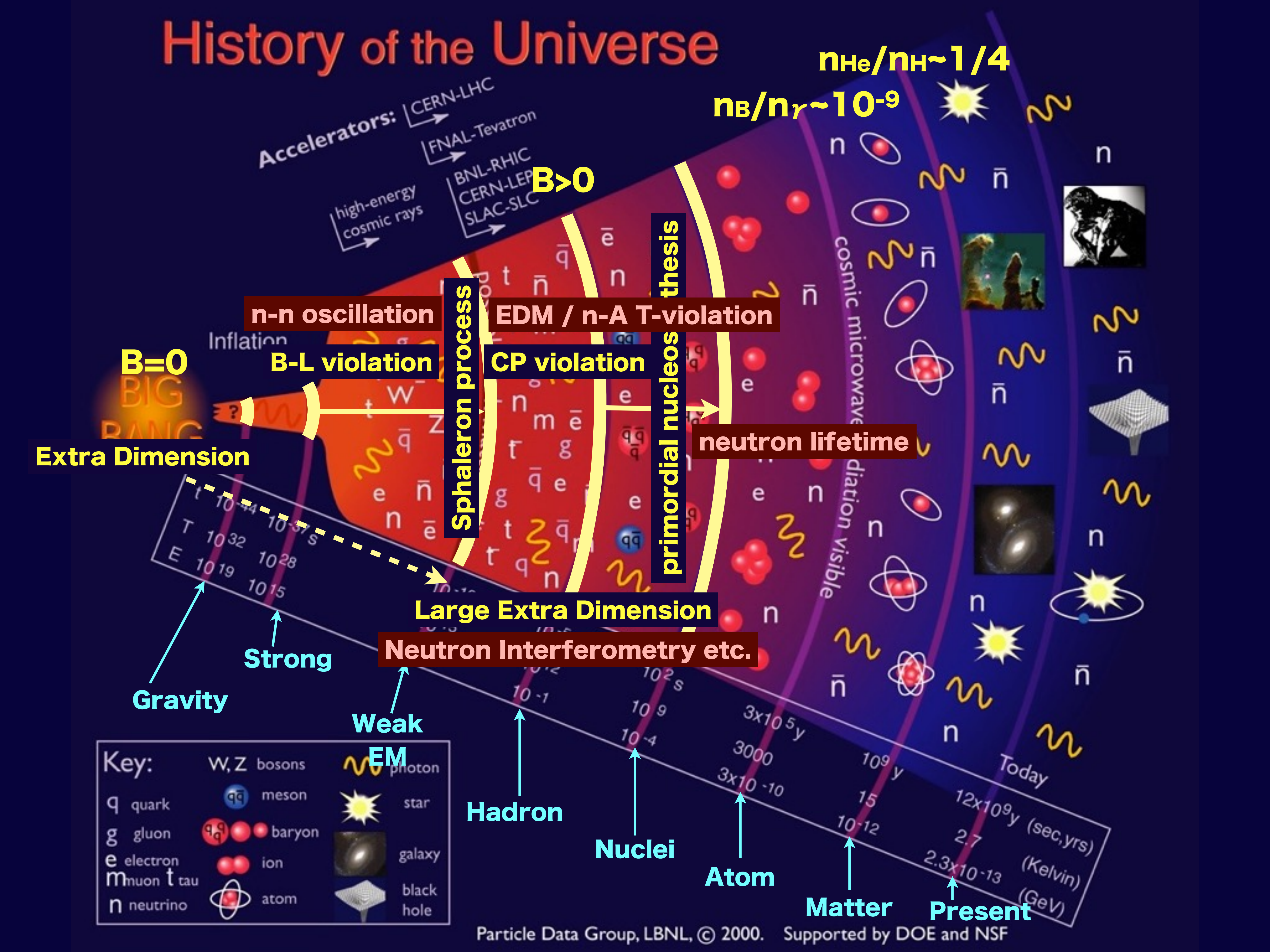
Abstract

Neutron is suitable for the precision measurement of the small influence of new physics beyond the standard model of elementary particles.

Combination of the instantaneousely luminous cold neutrons at J-PARC and the advanced neutron optical devices enables us to perform new types of high precision measurements.

- Lifetime → big-bang nucleosynthesis
- EDM → T violation
- compound nuclei → T violation
- n-nbar → B-L violation
- short range force → gravity


History of the Universe
n_{He}/n_H~1/4
n_B/n_γ~10^{-9}
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
B>0
B=0
BIG BANG
Inflation
n-n oscillation
B-L violation
Sphaleron process
EDM / n-A T-violation
CP violation
primordial nucleosynthesis
neutron lifetime
cosmic microwave radiation visible
Extra Dimension
Large Extra Dimension
Neutron Interferometry etc.
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Gravity
Strong
Weak
EM
Hadron
Nuclei
Atom
Matter
Present
Key:
W,Z bosons
photon
q quark
meson
star
g gluon
baryon
galaxy
e electron
ion
m muon t tau
black hole
n neutrino
atom
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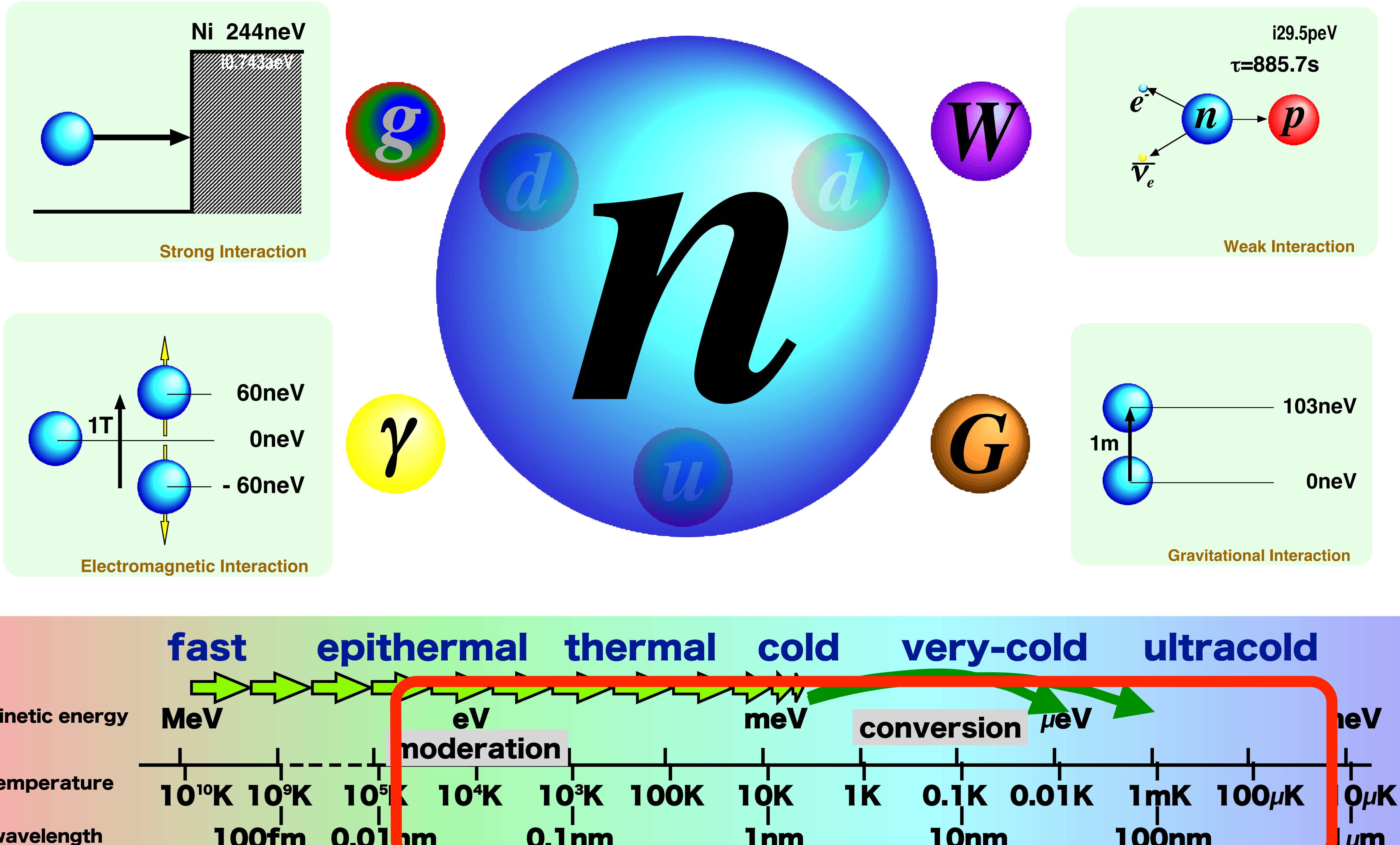
Neutron



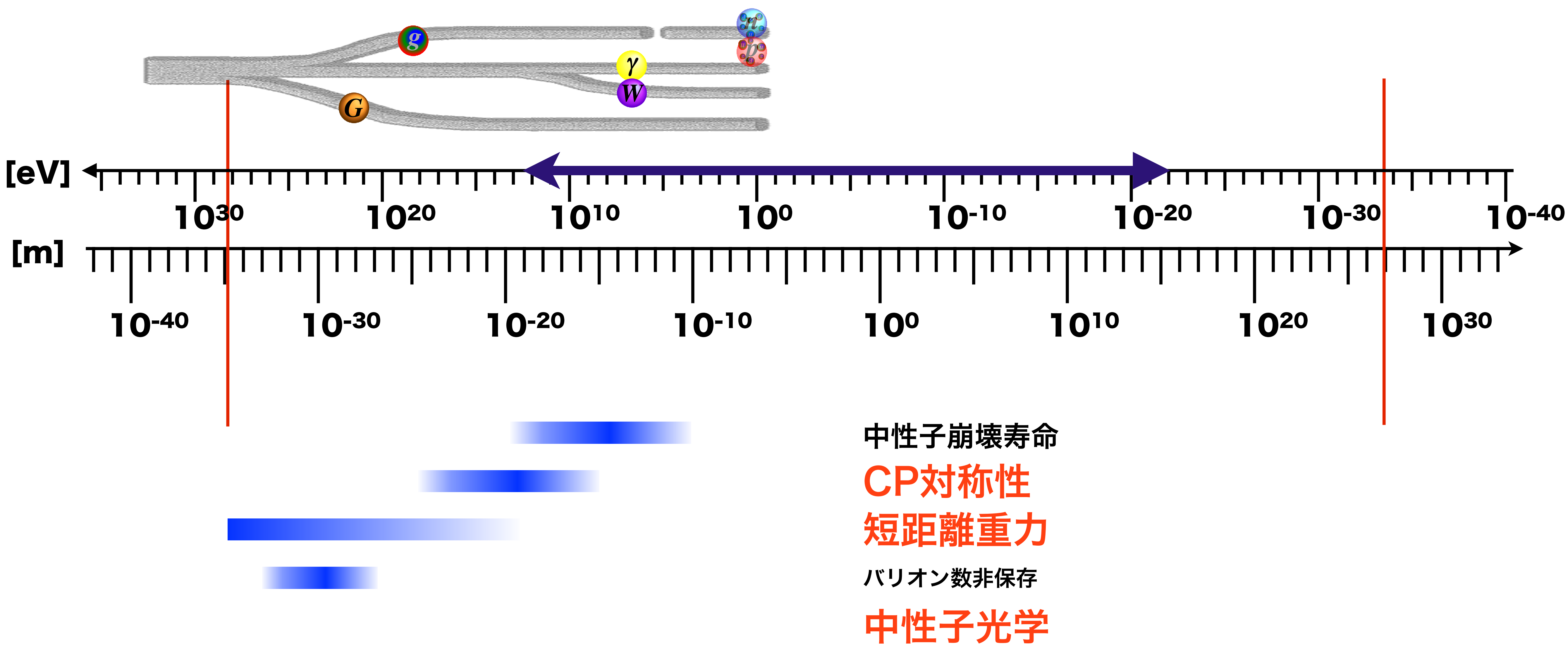
Ni 244neV
Strong Interaction
n
d
d
u
g
W
γ
G
τ=885.7s
e
n
p
ν
Weak Interaction
1T
60neV
0neV
- 60neV
Electromagnetic Interaction
1m
103neV
0neV
Gravitational Interaction
fast
epithermal
thermal
cold
very-cold
ultracold
kinetic energy
MeV
eV
meV
μeV
neV
moderation
conversion
temperature
10¹⁰K
10⁹K
10⁵K
10⁴K
10³K
100K
10K
1K
0.1K
0.01K
1mK
100μK
0μK
wavelength
100fm
0.01nm
0.1nm
1nm
10nm
100nm
μm

Neutron Physics

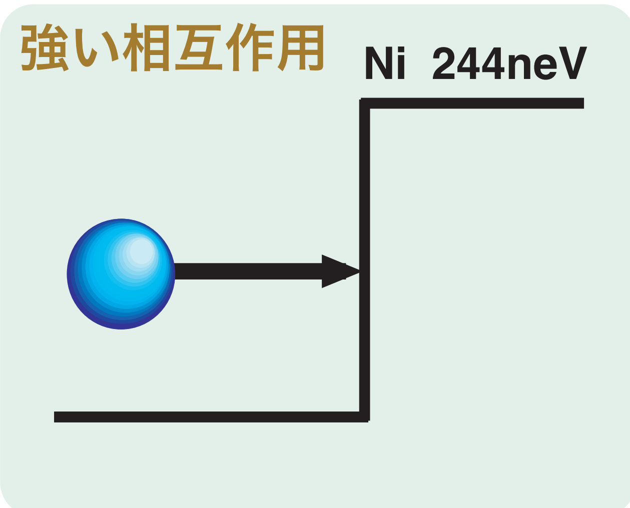
電荷を持たない　　光学的制御

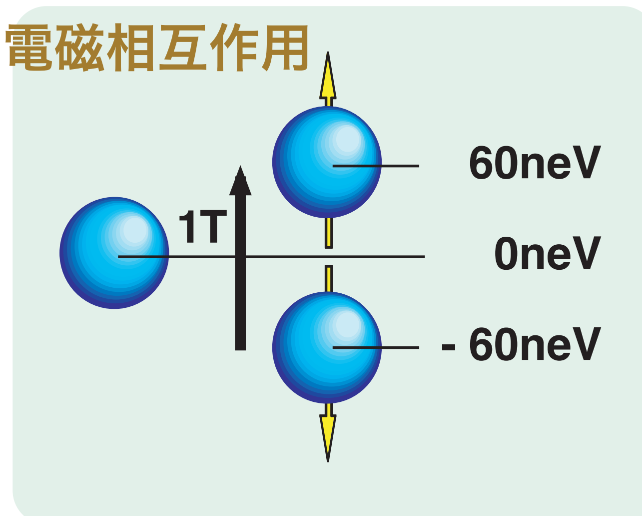
量子放射補正項の精密測定

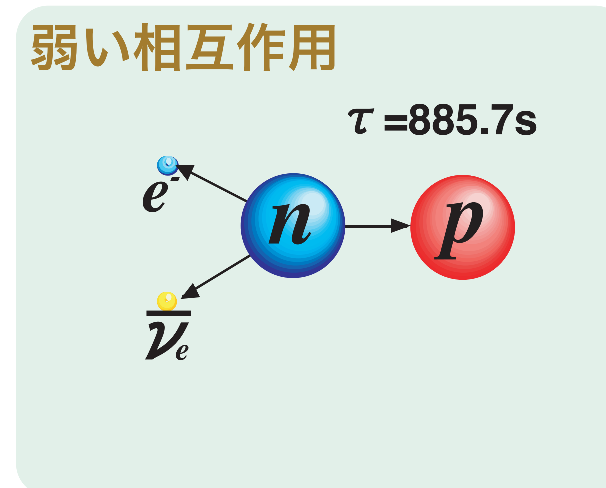
標準模型を超える新物理探索

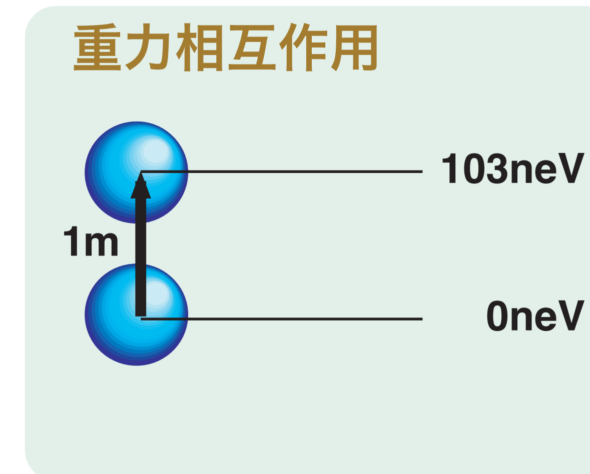


Control neutrons



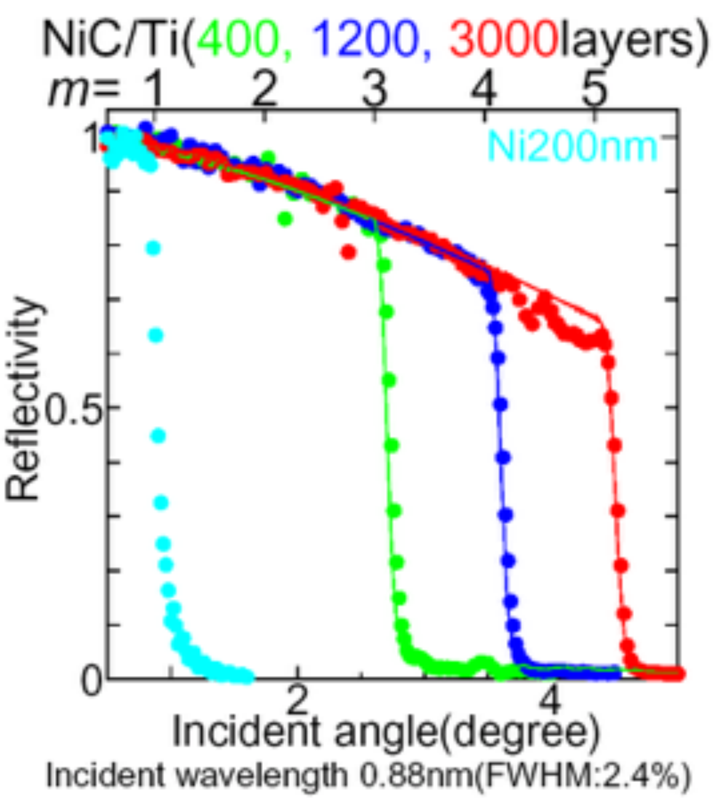




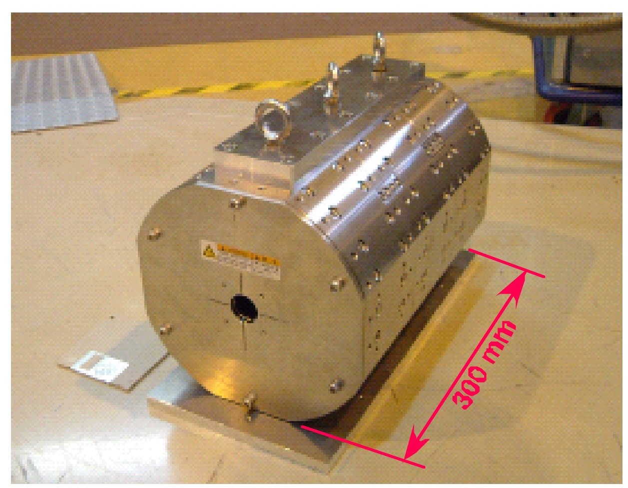


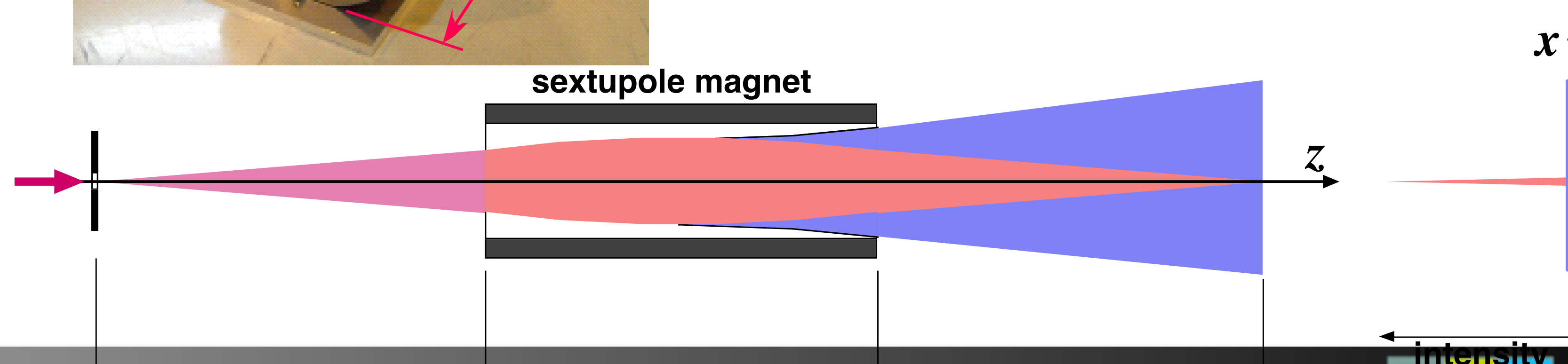
Optical control

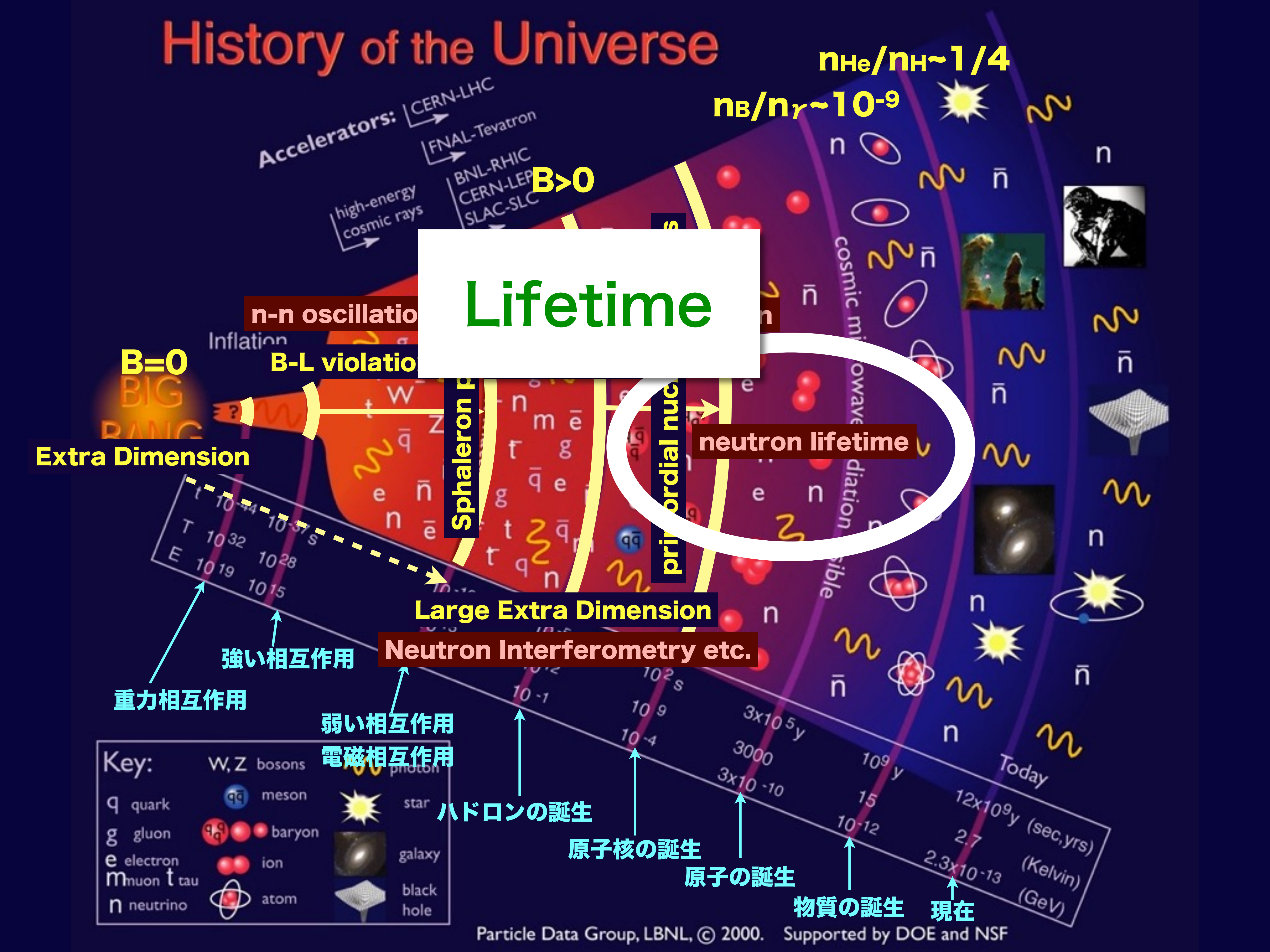
neutron mirror



magnetic lens, polarizer



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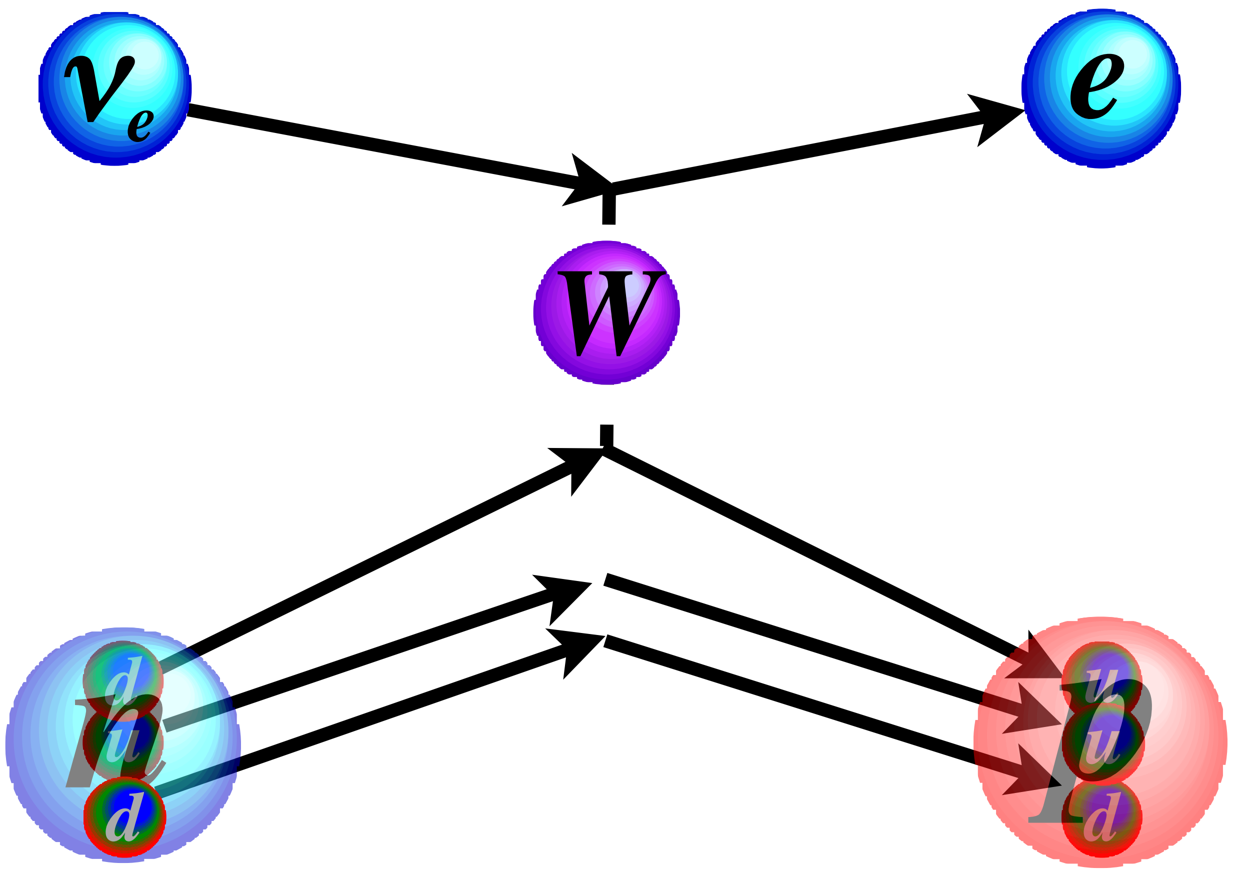
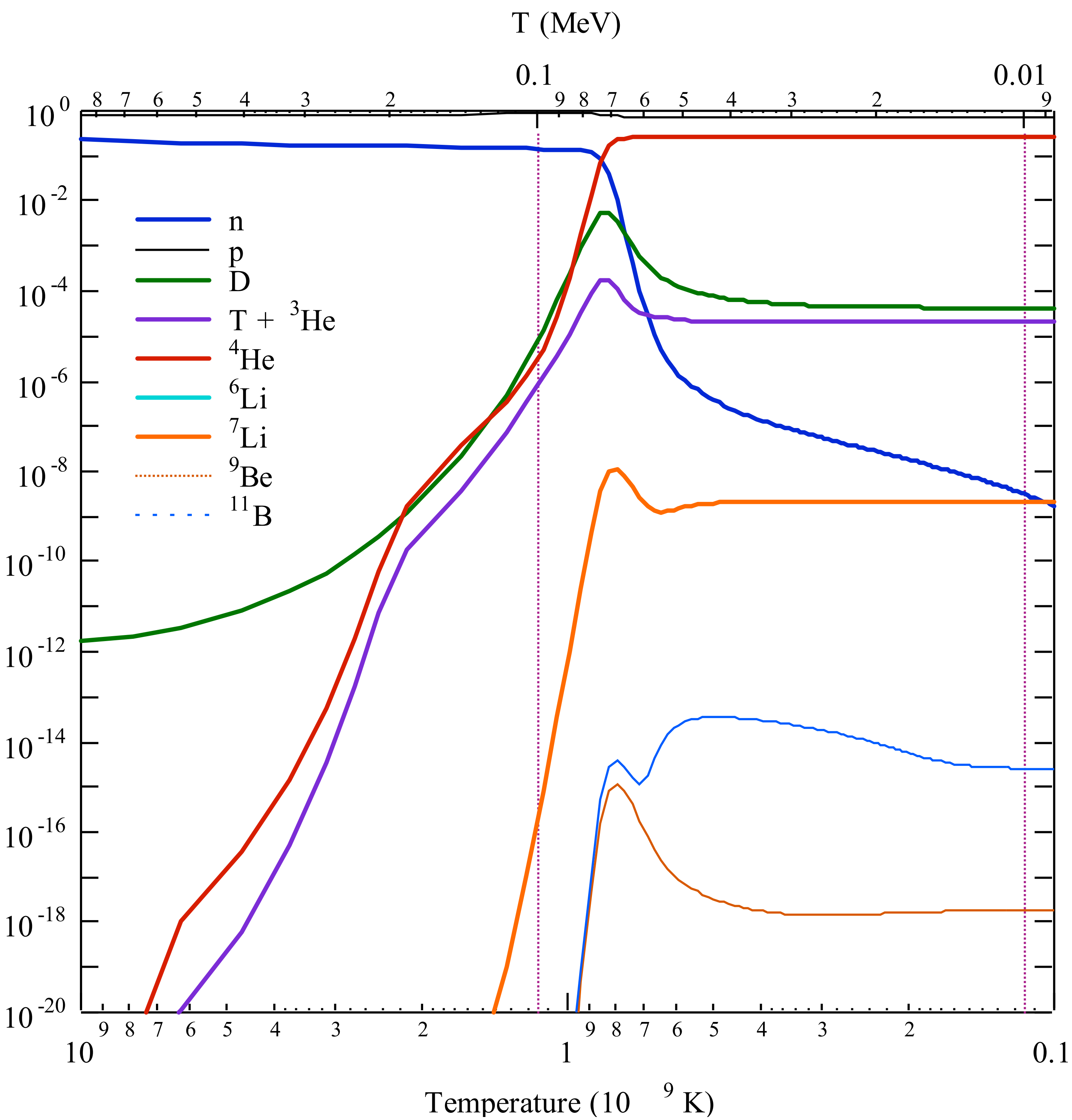
B>0
B=0
Lifetime
n-n oscillatio
Inflation
B-L violatio
Extra Dimension
Sphaleron
primordial nuc
neutron lifetime
cosmic microwave radiation
Large Extra Dimension
Neutron Interferometry etc.
強い相互作用
重力相互作用
弱い相互作用
電磁相互作用
ハドロンの誕生
原子核の誕生
原子の誕生
物質の誕生
現在
Today
Key:
q quark
g gluon
e electron
muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
(sec,yrs)
(Kelvin)
(GeV)
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

中性子β崩壊

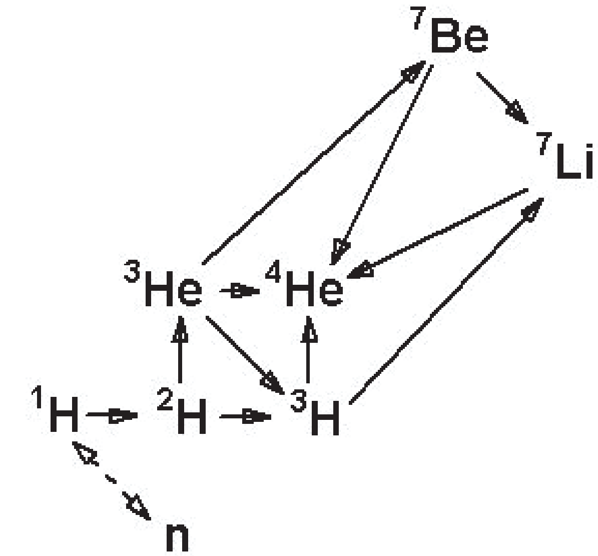
$$n \longrightarrow p + e + \bar{\nu}_e$$



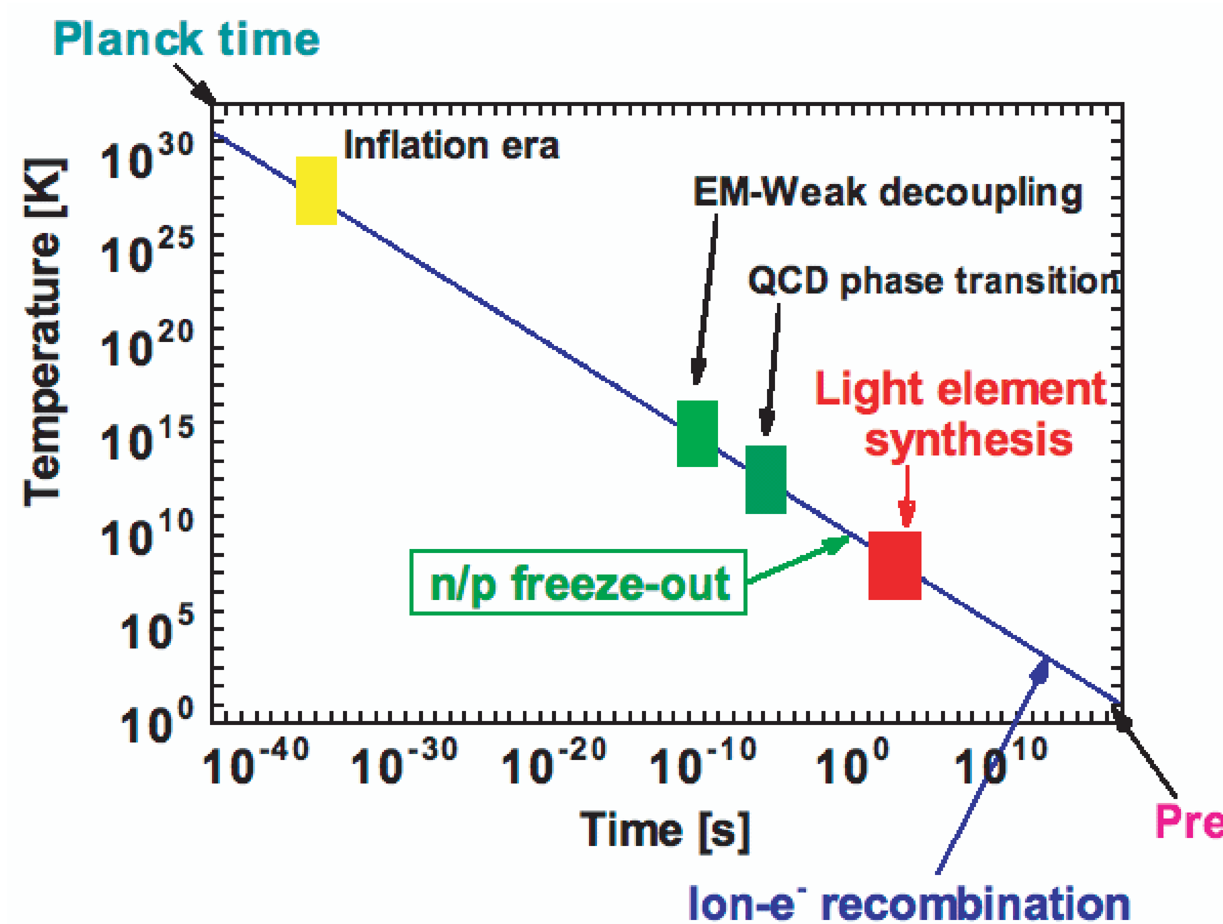
中性子寿命



T (MeV)
0.1
0.01
Temperature (10 ^{9} K)
10
1
0.1
n
p
D
T + ^{3}He
^{4}He
^{6}Li
^{7}Li
^{9}Be
^{11}B



^{7}Be
^{7}Li
^{3}He
^{4}He
^{1}H
^{2}H
^{3}H
n



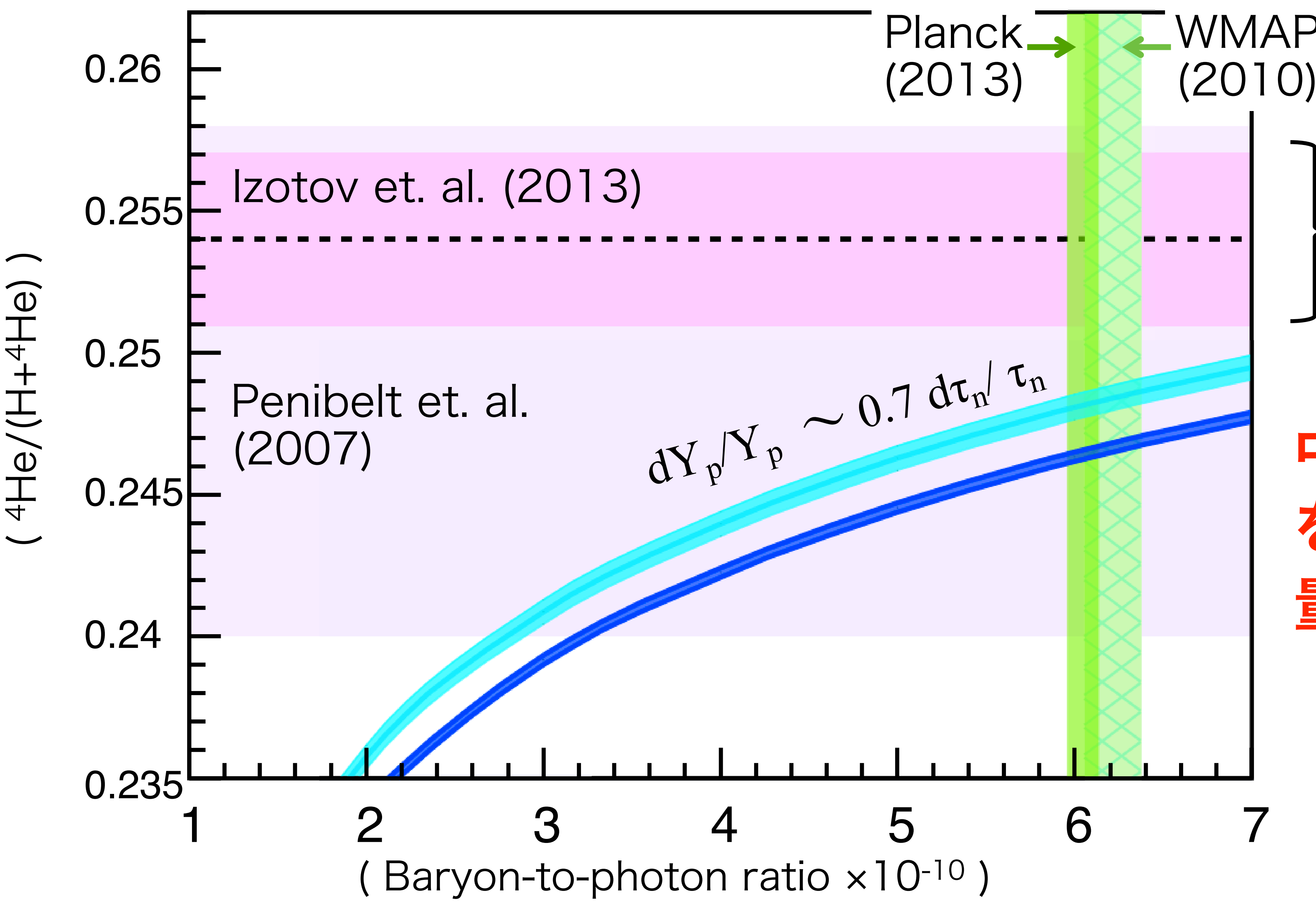
Planck time
Inflation era
EM-Weak decoupling
QCD phase transition
Light element synthesis
n/p freeze-out
Temperature [K]
Time [s]
Ion-e$^-$ recombination
Pre

Big Bang 元素合成と中性子寿命測定

中性子・陽子平衡が破れ核合成が始まるまでに中性子が崩壊
軽元素の合成量は材料である中性子の量に依存
→**中性子寿命が宇宙の元素合成量に影響**

τ_n = 887.7±1.2(stat)±1.9(sys) s (NIST, 2013)
τ_n = 878.5±0.7(stat)±0.3(sys) s (PNPI, 2005)

様々な中性子寿命の実験で
値が有意にばらついている



初期天体の観測値
（中性He原子の発光の
モデル依存性がある）

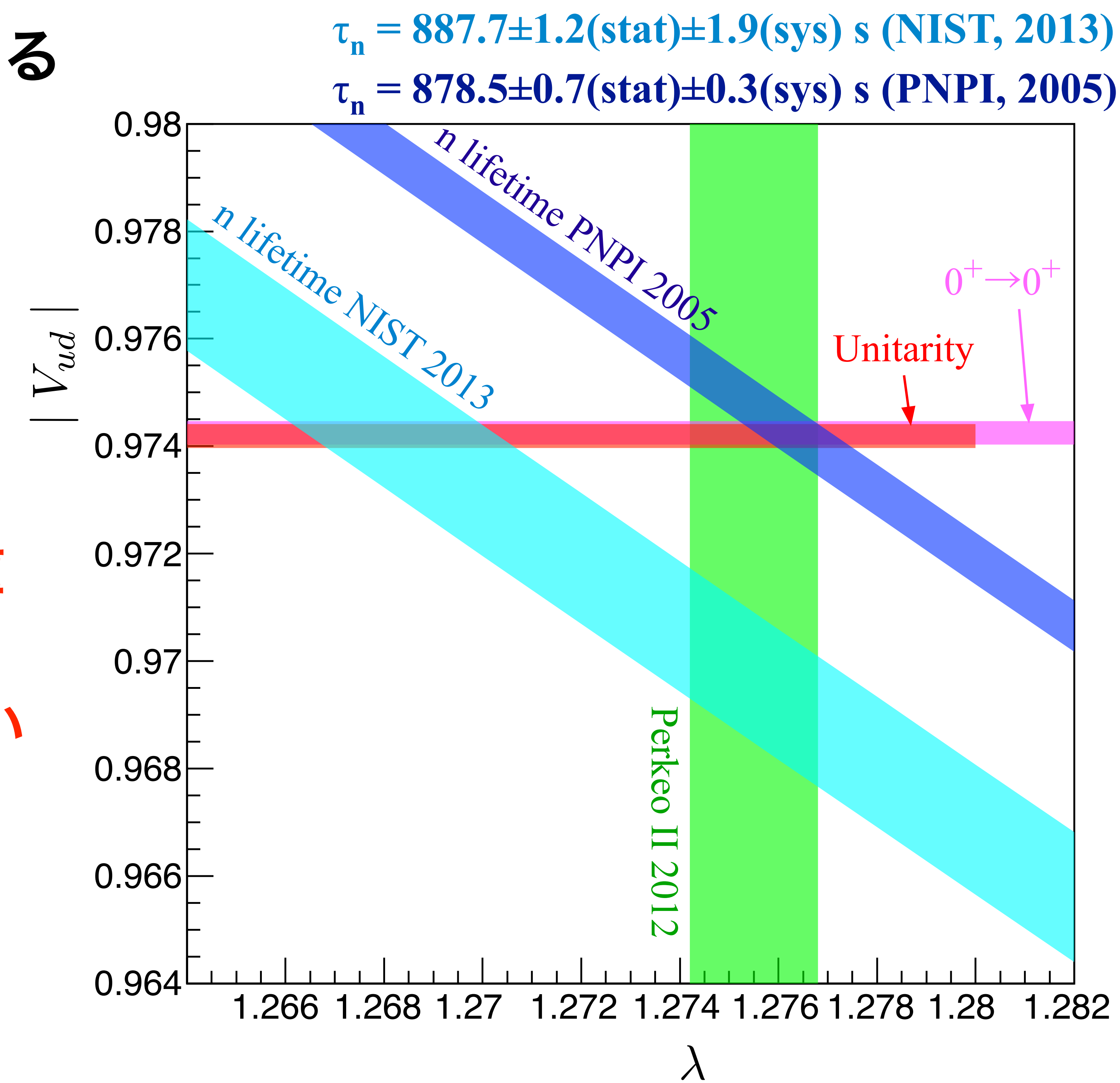
中性子寿命の精度向上を通じて始原的軽元素量の観測値および標準ビッグバン元素合成理論を検証できる

CKM行列要素 V_{ud}と中性子寿命測定

中性子β崩壊の角相関項からλが求まる
＋中性子寿命から、
→小林益川行列の V_{ud} が求まる

$$|V_{ud}|^2 = \frac{1}{\tau_n}\frac{(4908.7 \pm 1.9)\ \mathrm{s}}{(1+3\lambda^2)};$$

$$\text{with} \quad \lambda = \frac{G_A}{G_V} = \frac{g_A}{g_V}.$$



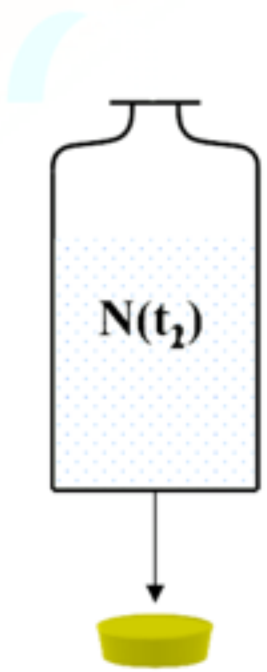
個々の実験での中性子寿命の値から求めた V_{ud}の値ではCMK行列がunitaryにならない

様々な中性子寿命の実験で
値が有意にばらついている

Neutron Lifetime

Stored UCN

"counting the surviving neutrons"



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

$$\frac{1}{\tau_n} = \frac{1}{\tau_\beta} + \frac{1}{\tau_{wall}} + \frac{1}{\tau_{leak}} + \frac{1}{\tau_{vacuum}} + \ldots$$

→ 0 (experiment)

$$\frac{1}{\tau_{wall}} = M \cdot V_{eff}$$ → 0 (extrapolation)

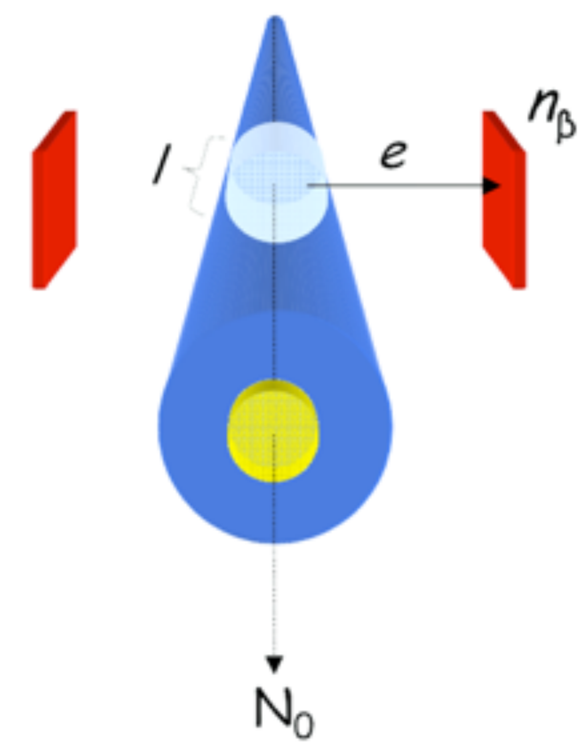
⇒ $$\frac{1}{\tau_n} = \frac{1}{\tau_\beta}$$

Two relative measurements

Imperfect storage bottle

Cold neutron beam

"counting the dead neutrons"



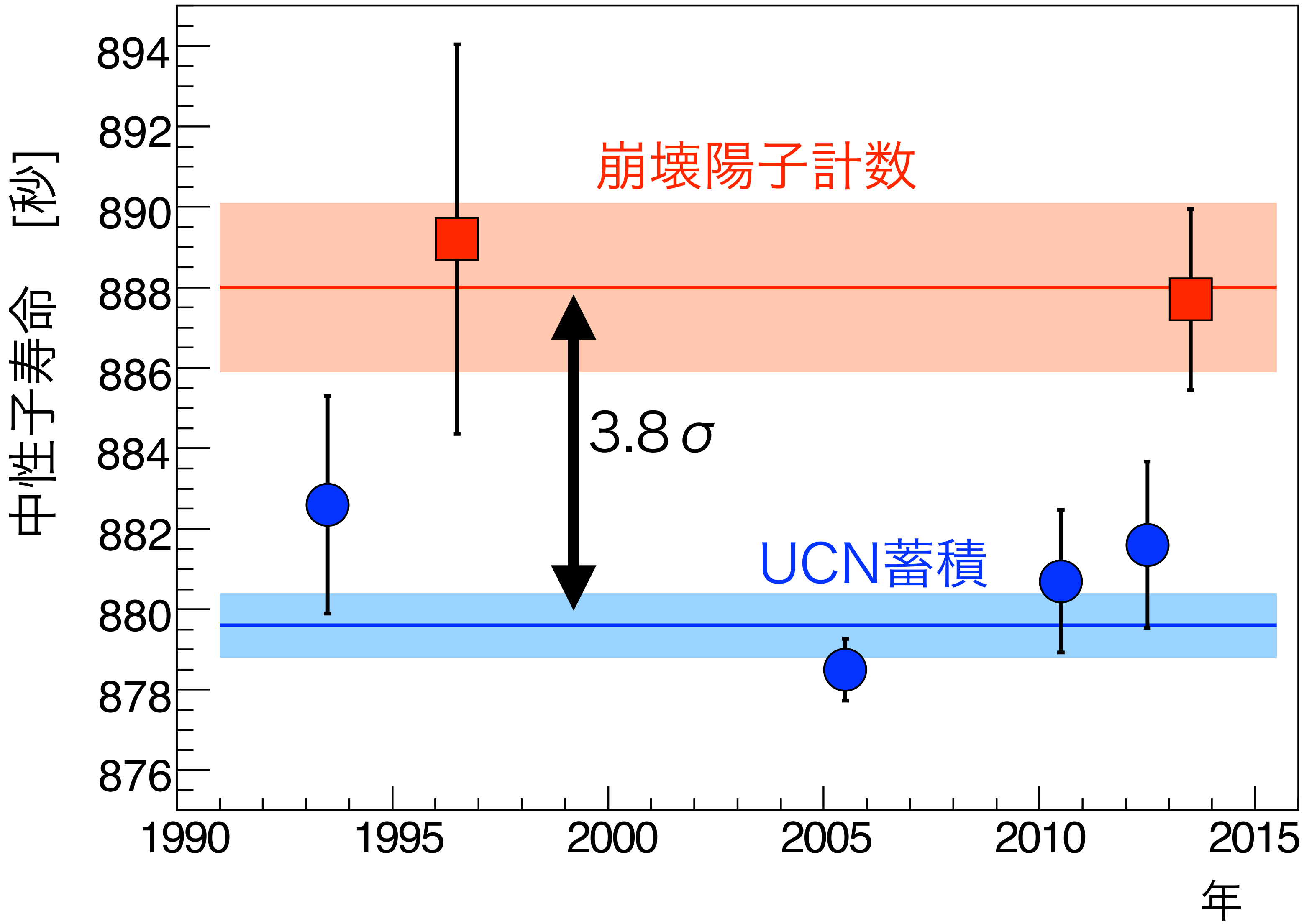
$$n_\beta = \frac{dN}{dt} = -\frac{N_0}{\tau_n} e^{-\frac{l}{v \cdot \tau_n}}$$

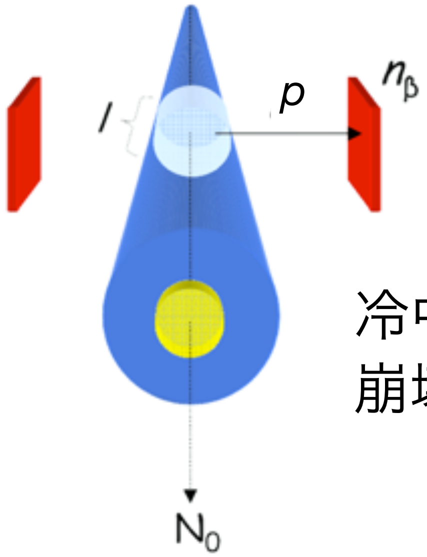
Two absolute measurements

Efficiency of measurement of incident neutrons

中性子寿命測定

様々な中性子寿命の実験があるが、値が有意にばらついている



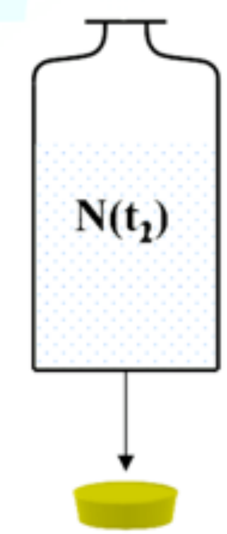


崩壊陽子計数
(penning trap)

冷中性子ビームから
崩壊で出てくる陽子を計数

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

入射フラックスの不確かさ



UCN蓄積

超冷中性子の
生き残りを計数

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

壁でのロスの不確かさ

新しい手法での
O(0.1%) の高精度測定が必要

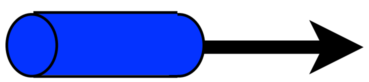
J-PARC パルス中性子を用いた高精度測定

冷中性子がTPC内で飛行中に崩壊して発生する

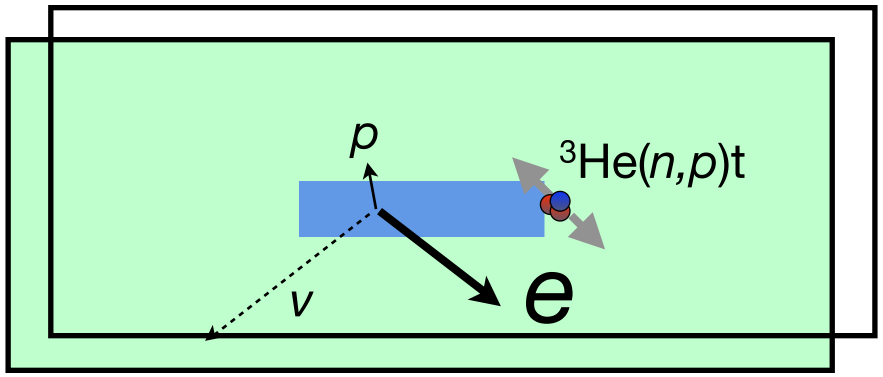
電子（0〜782keV）を直接計数

測定原理　（Kossakowski,1989）

TPCより短く、速度のそろった
中性子バンチ



バンチがTPC内にある
時間だけ計測



入射中性子fluxは
^{3}He 吸収反応で
同時測定

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

β崩壊数　$S_\beta = \epsilon_e N \dfrac{L}{\tau_n v}$

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

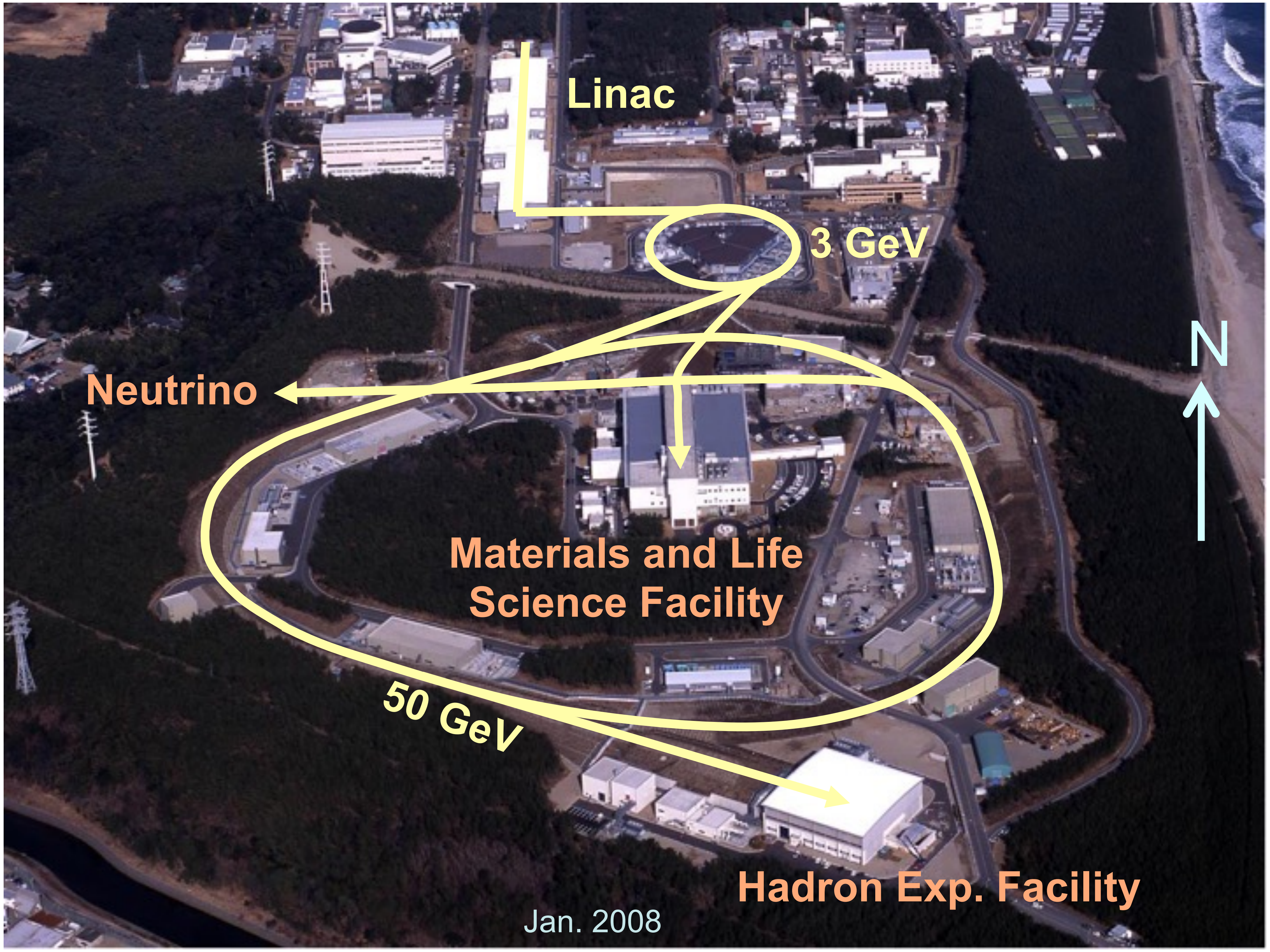
- τ_n：中性子寿命
- v：中性子の速度
- ε_e：電子の検出効率
- ε_n：^{3}He吸収反応の検出効率
- ρ：^{3}Heの密度
- σ：^{3}Heの中性子吸収断面積

$\sigma v = \sigma_0 v_0$　2200m/sの中性子に対する吸収断面積

Flux monitor、wall loss は原理的に起こらない

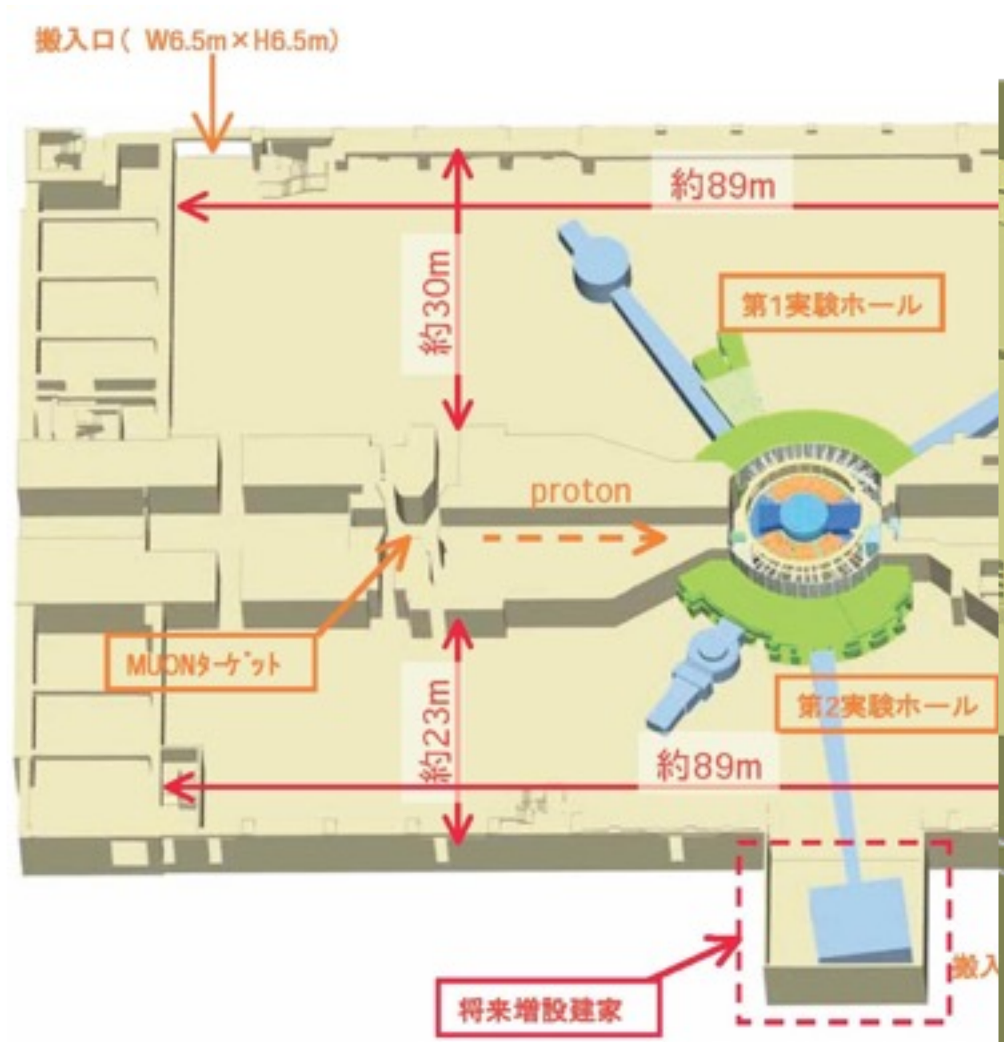
Neutron Lifetime

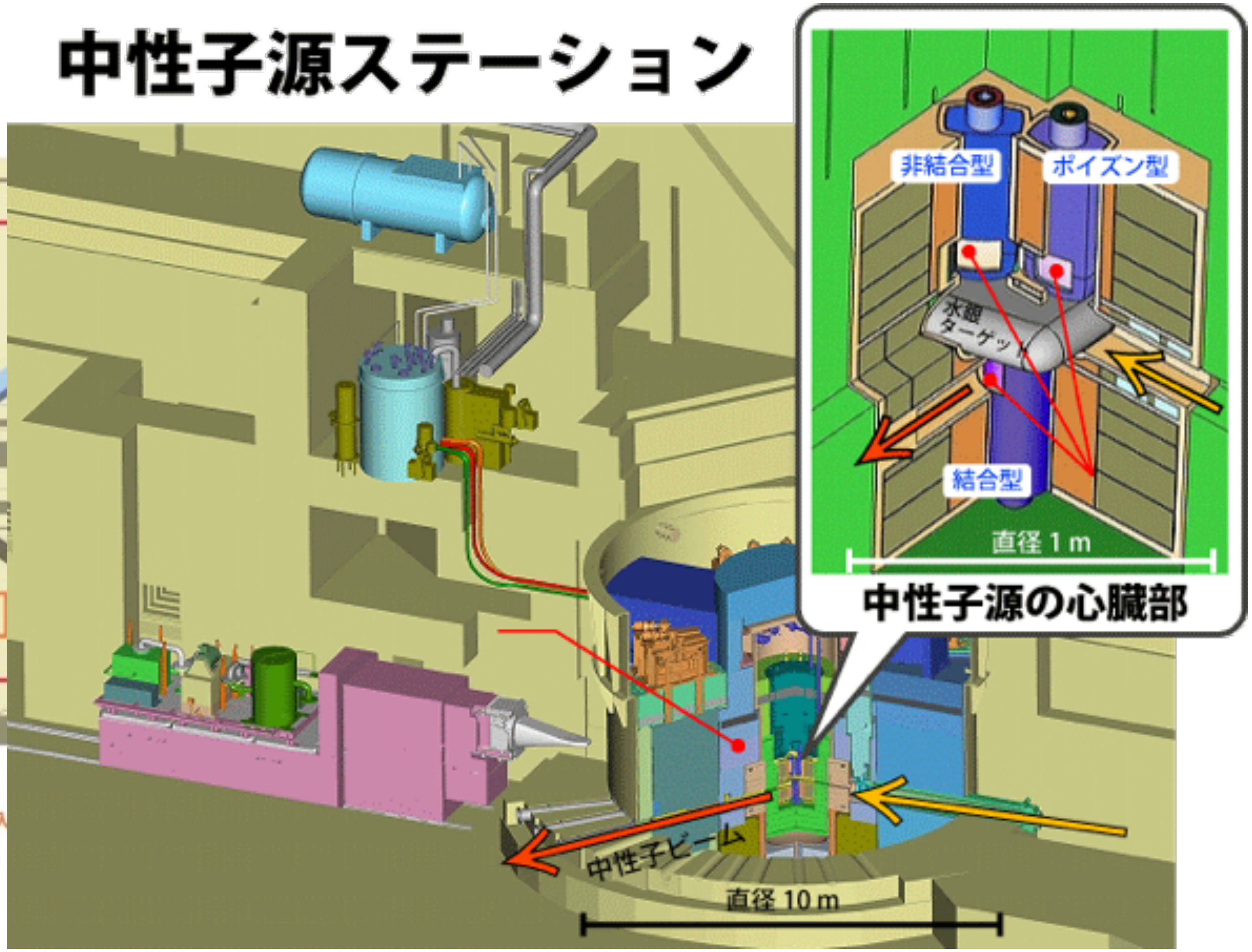
J-PARC MLF



Neutron Lifetime

J-PARC MLF

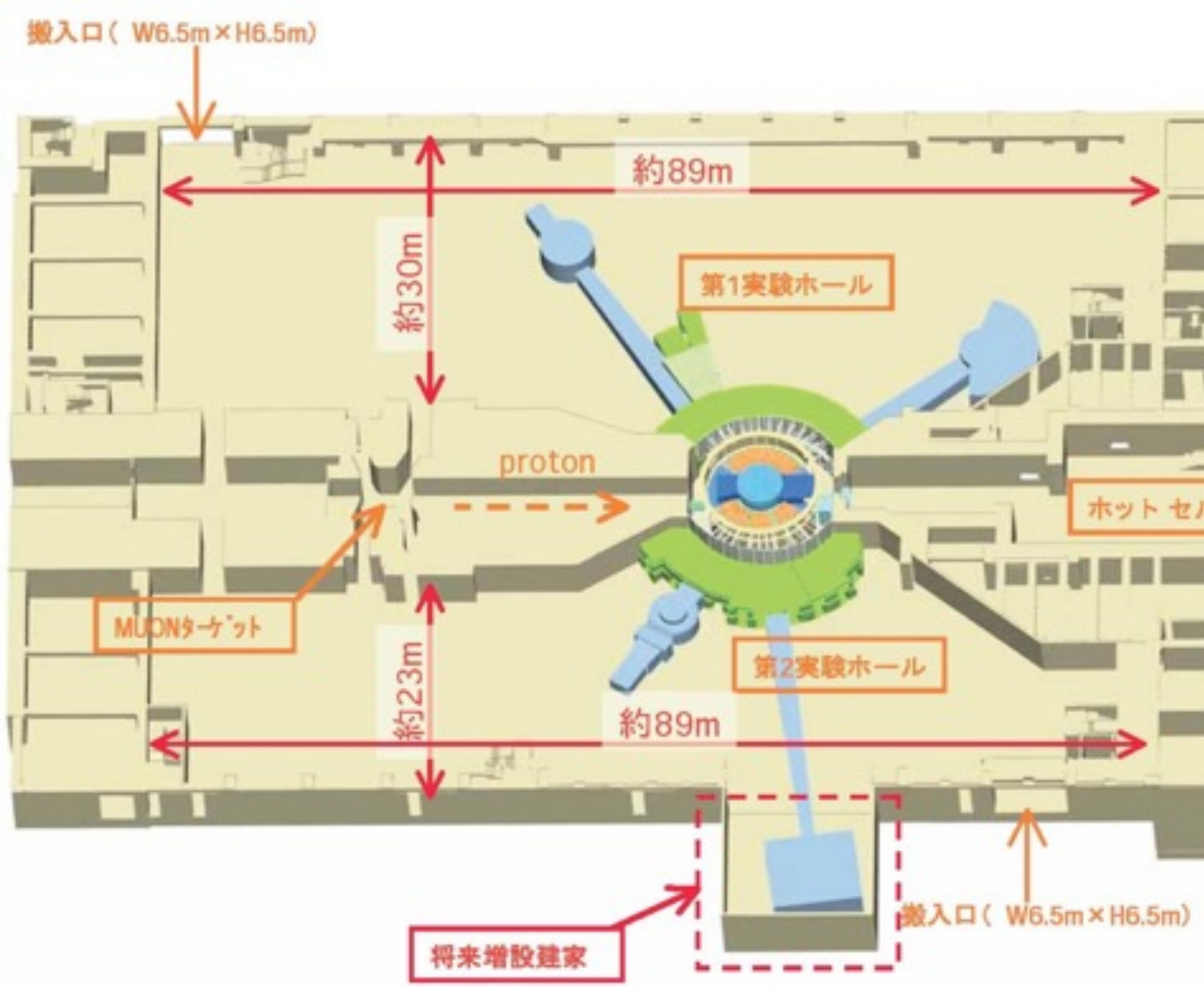


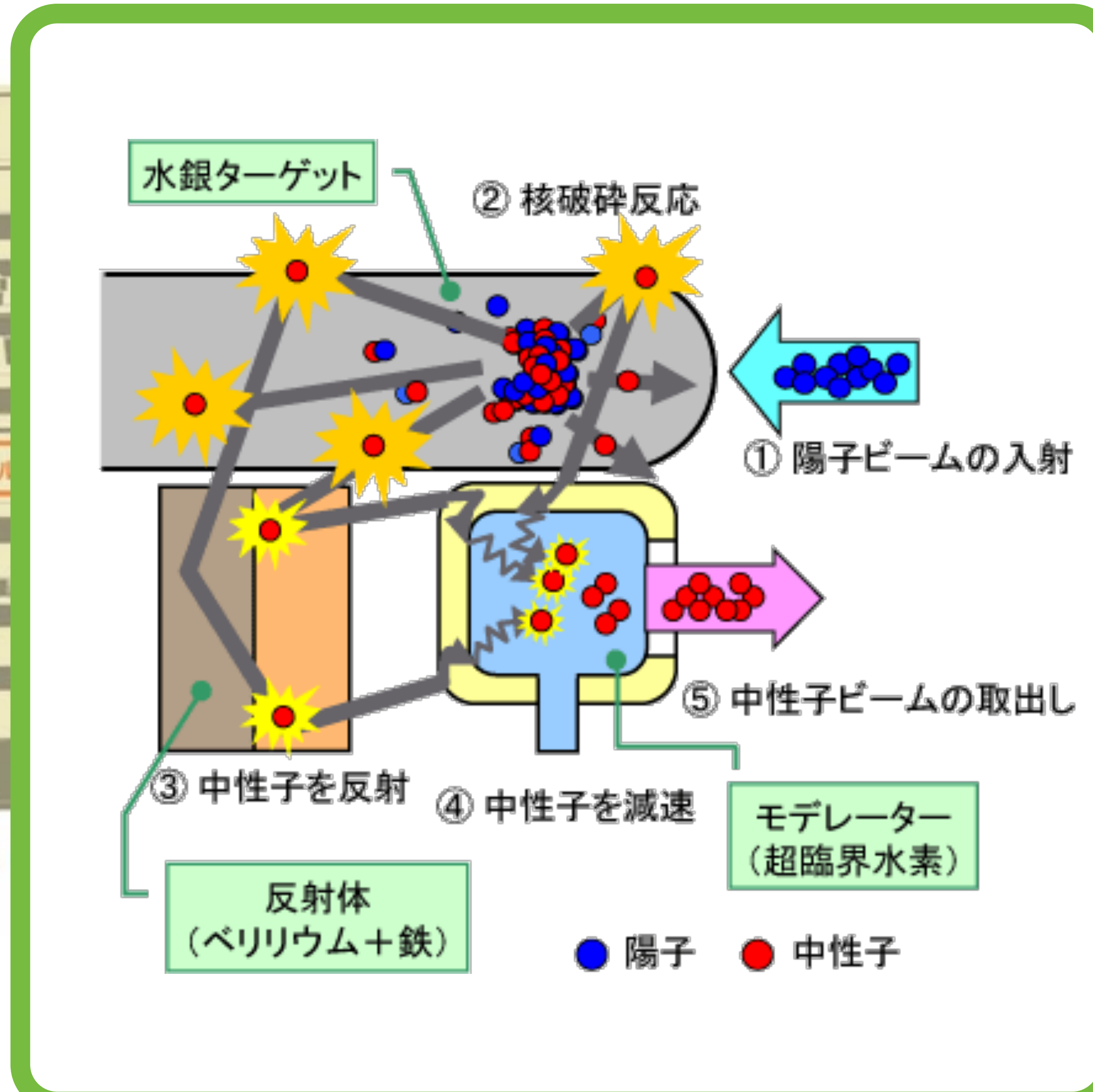


Jan. 2008

Neutron Lifetime

J-PARC MLF





Jan. 2008

Neutron Lifetime

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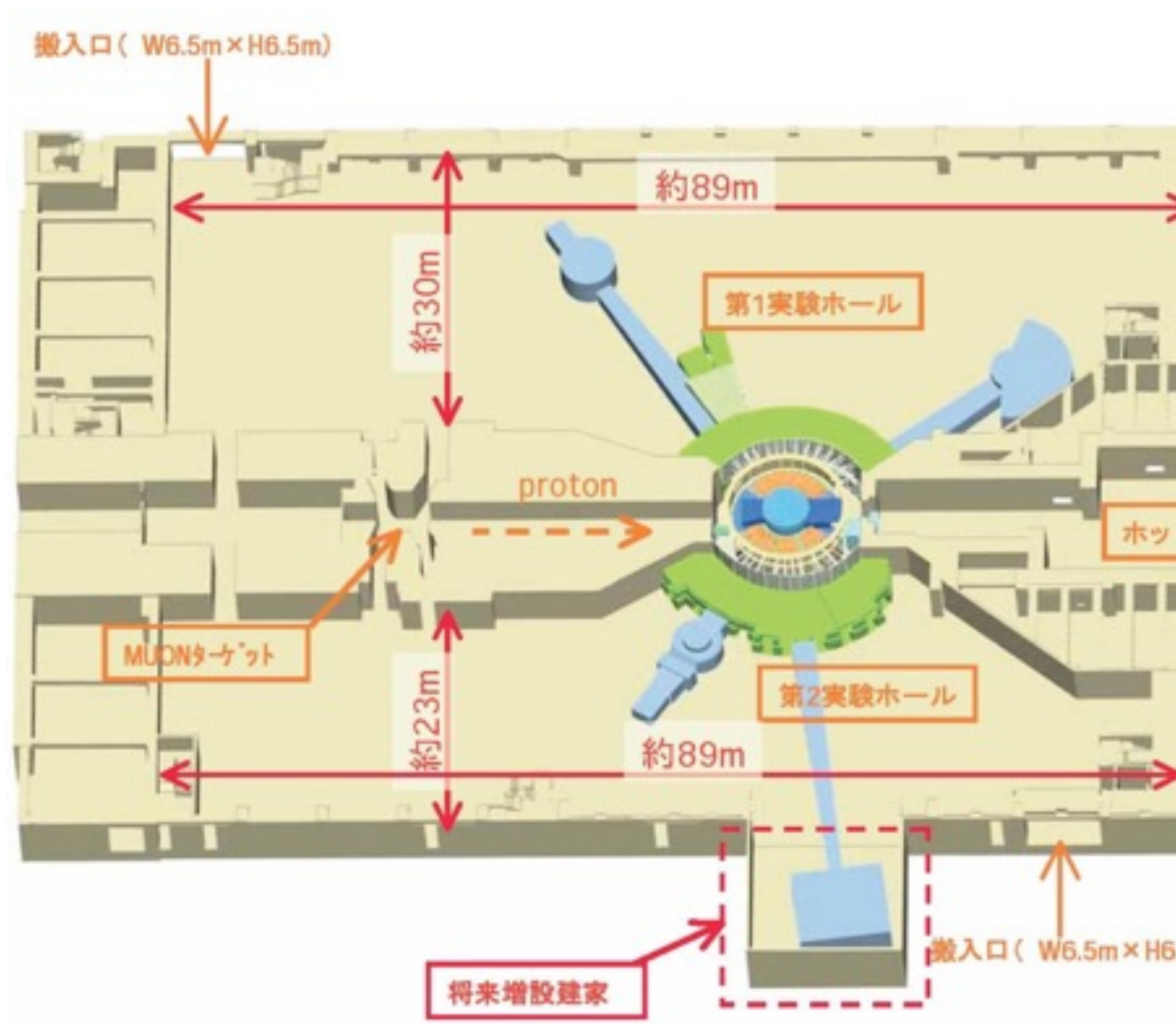
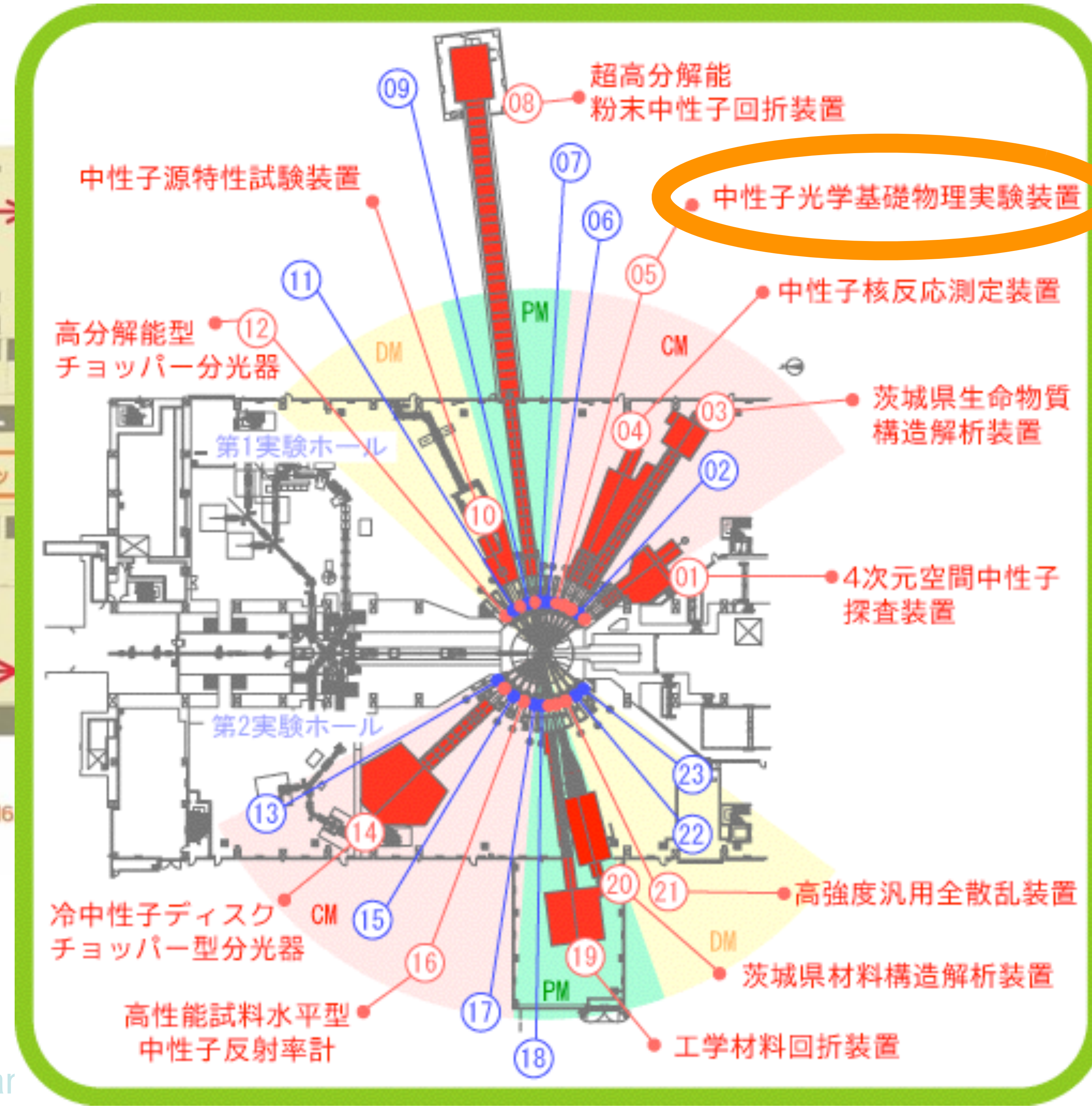
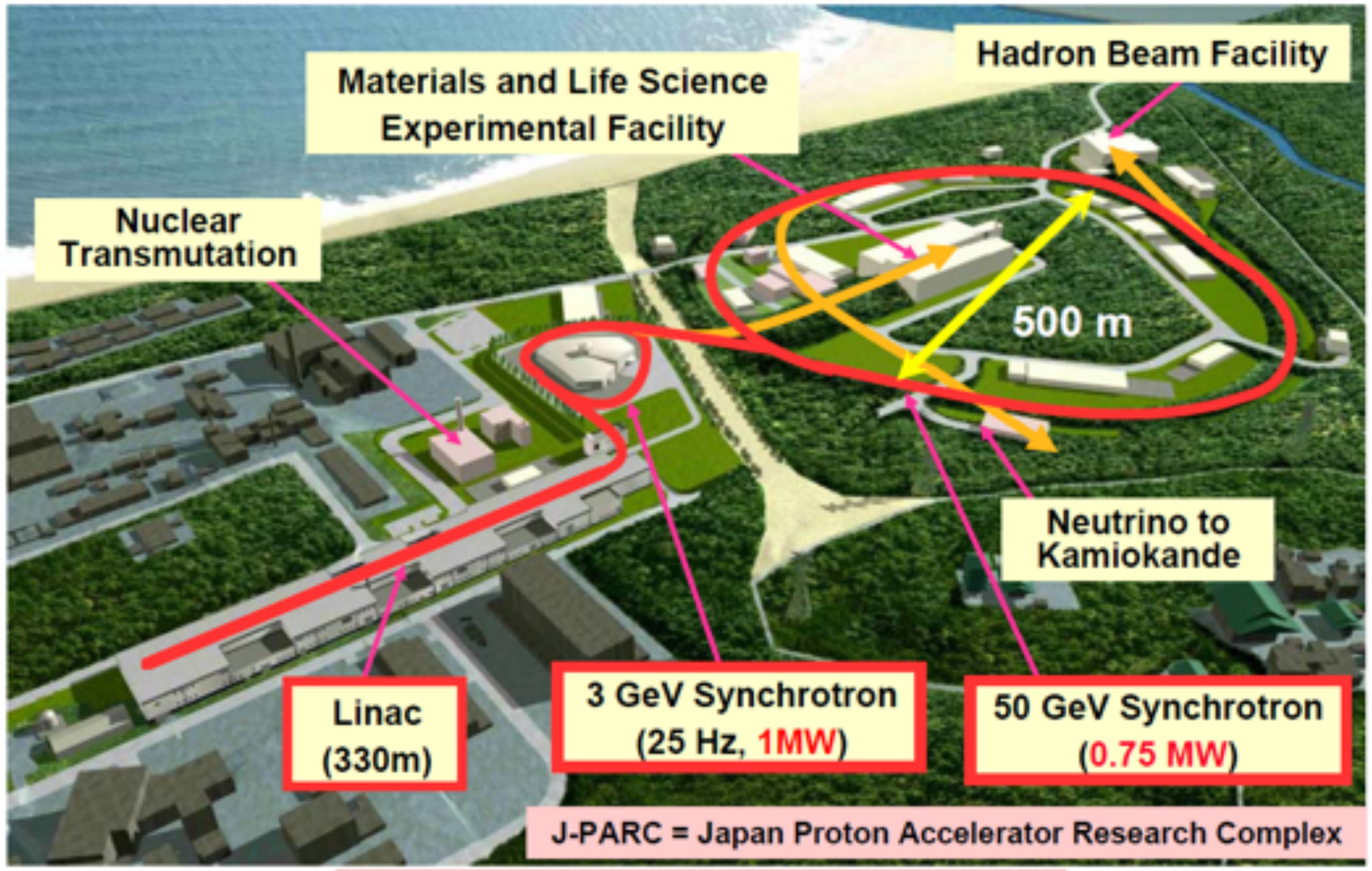




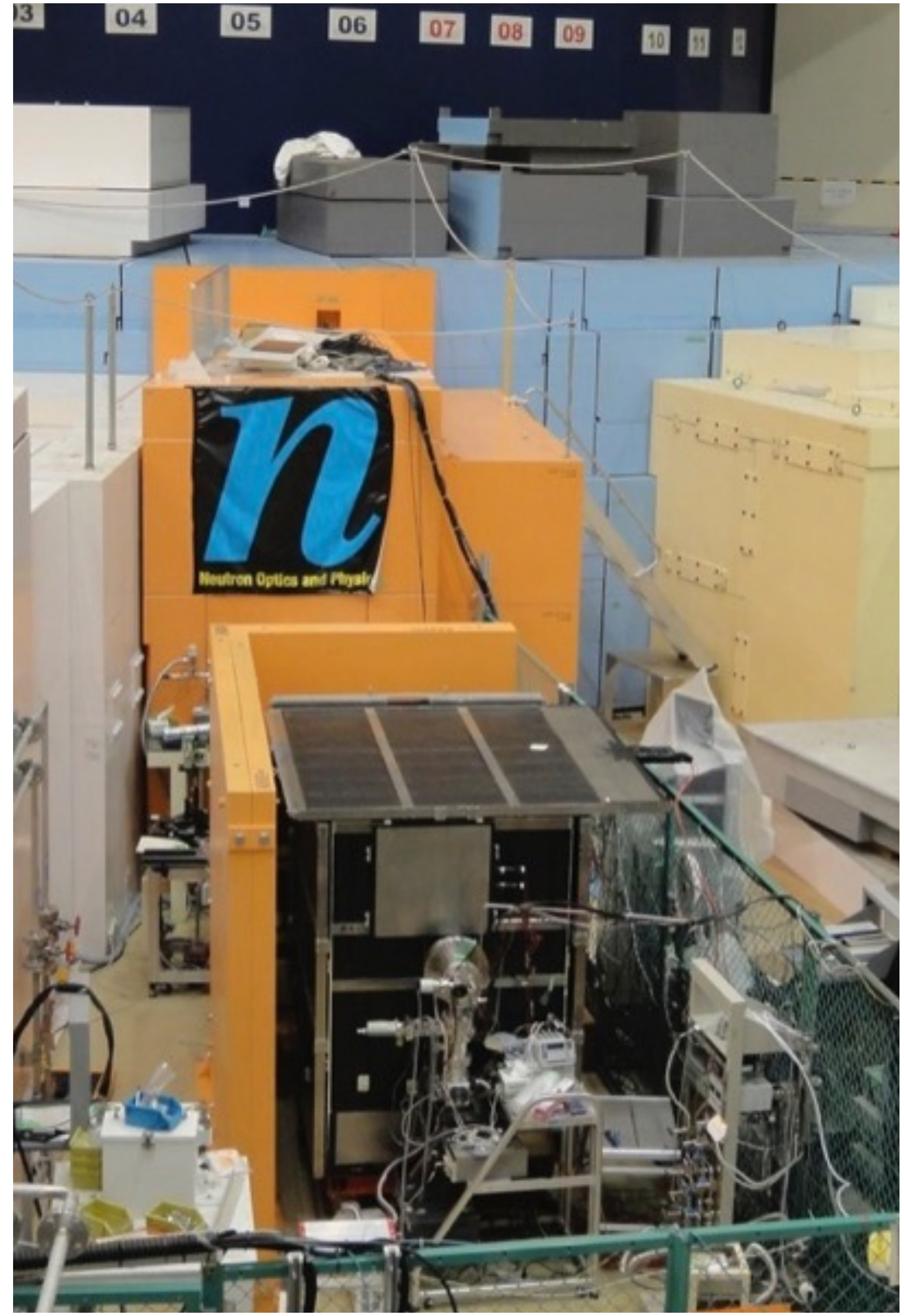
J-PARC パルス中性子を用いた高精度測定



Joint Project between KEK and JAEA

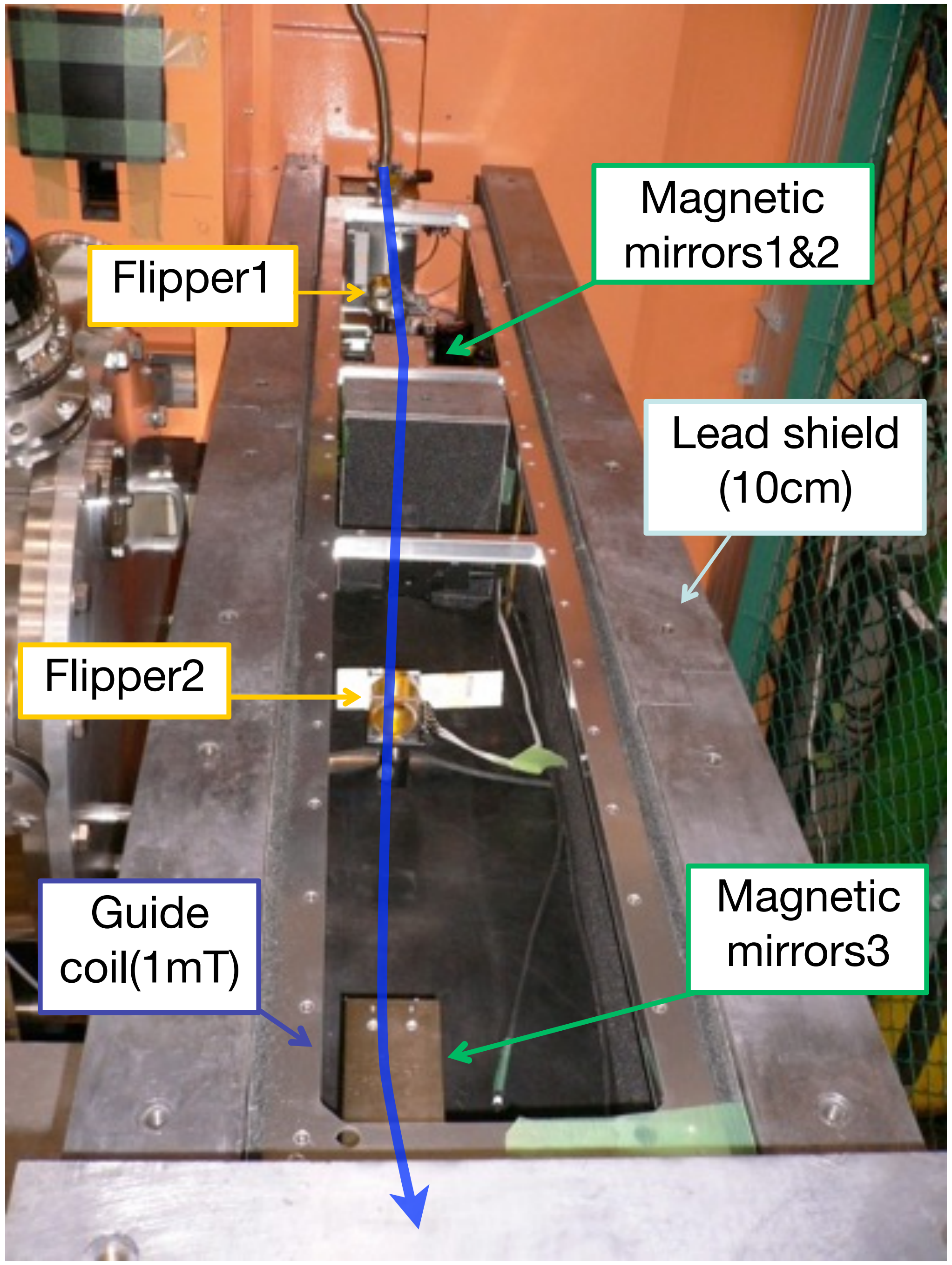
J-PARC
物質生命科学実験施設（MLF）
　ビームライン BL05
中性子基礎物理ビームライン（NOP）

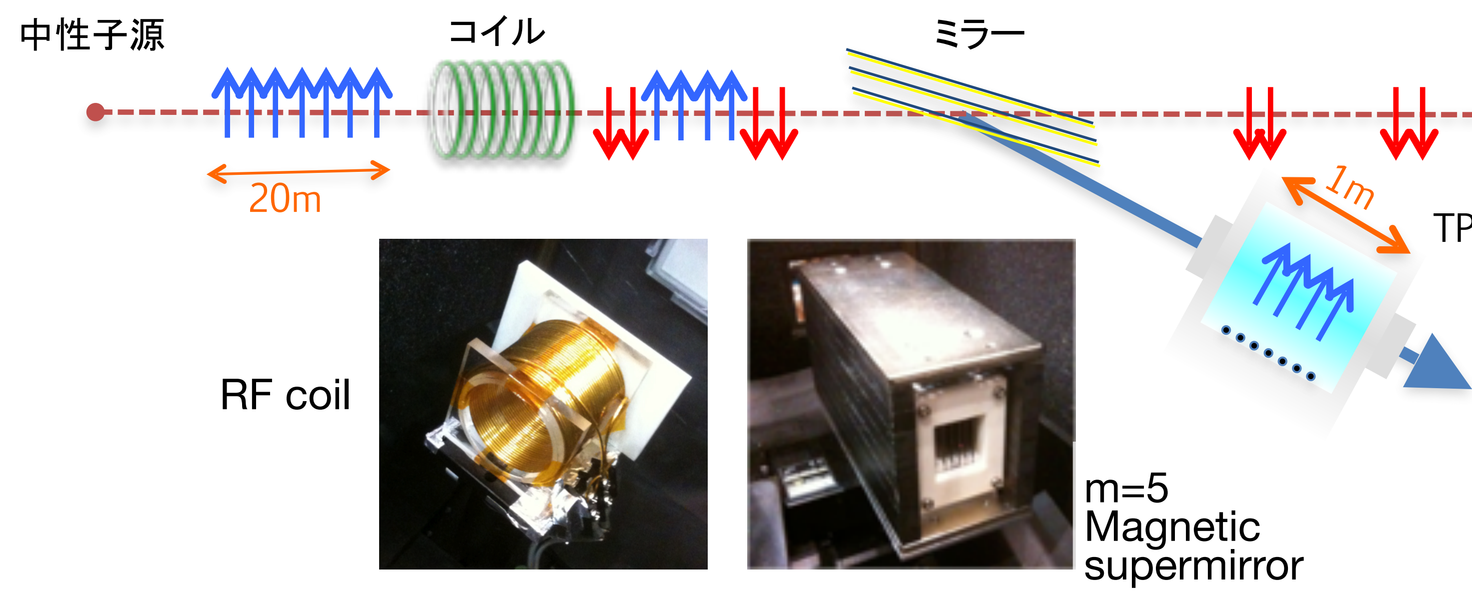
高偏極ビームブランチに
　寿命測定のための機器を配置

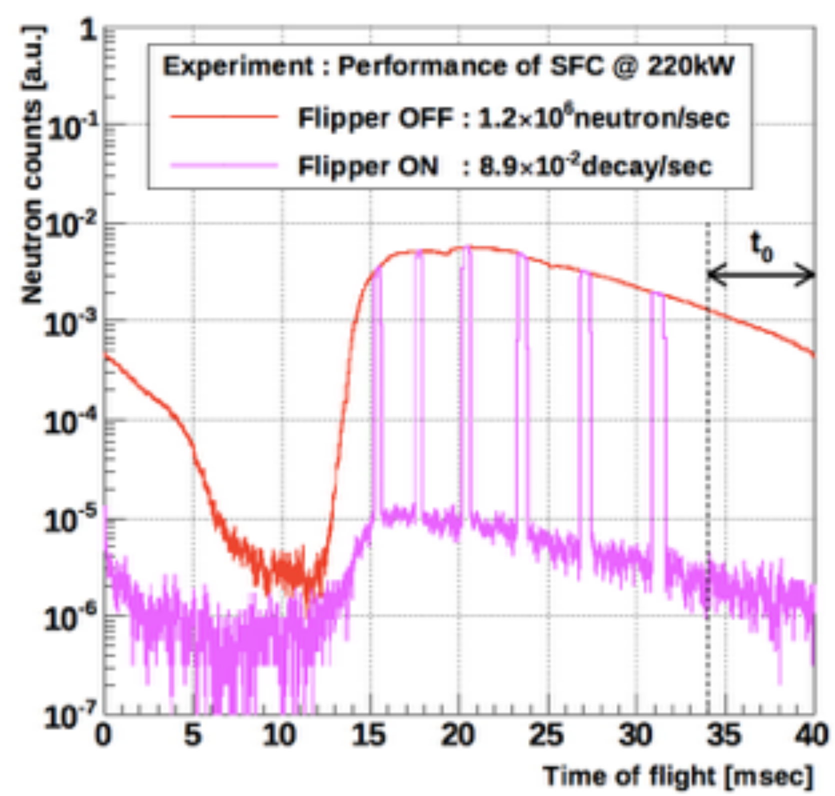


J-PARC パルス中性子を用いた高精度測定

スピンフリップチョッパー（SFC）　短く、速度のそろった中性子バンチを作る





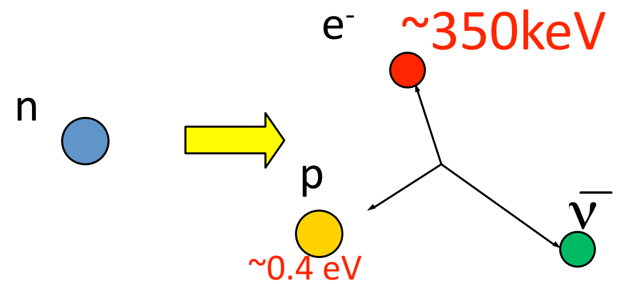


ON/OFF コントラスト > 400:1 を達成

Neutron Lifetime

Time projection chamber

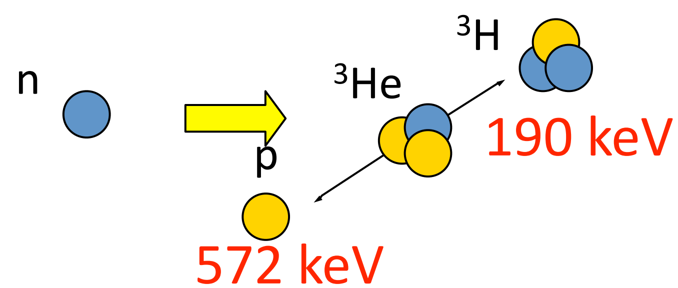
Beta decay



$$N_e = \frac{\varepsilon_e t \rho_n}{\tau_n}$$

~10^{-6} decay in 1m for cold neutron (1100m/s)

$^3He(n,p)^3H$



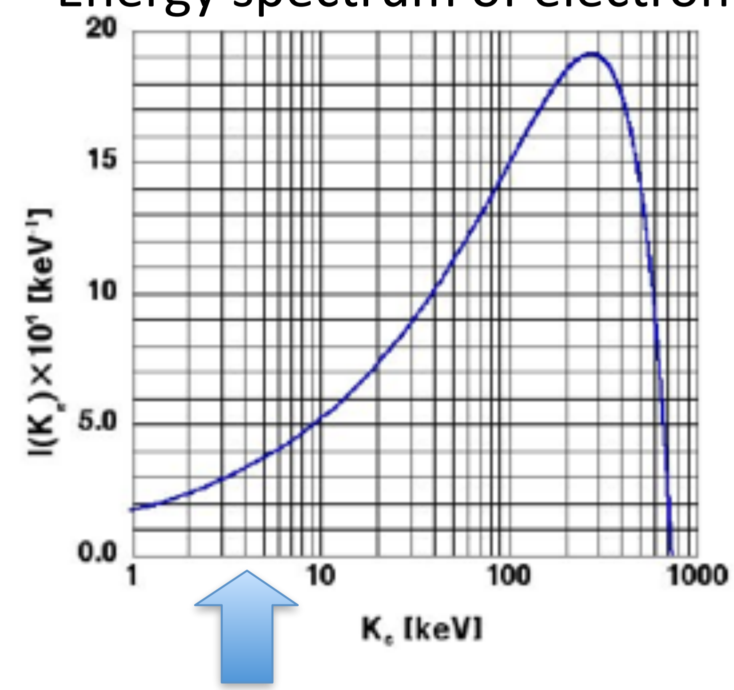
$$N_p = \varepsilon_p t \rho_n \rho_{^3He} \sigma_{^3He}(v_n)$$

$$\sigma_{3He}(v_n)\, v_n = \sigma_{3He}(v_0)\, v_0$$

Reaction rate is proportional to $1/v$

β *decay ~3.6mPa* ^{3}He

Energy spectrum of electron



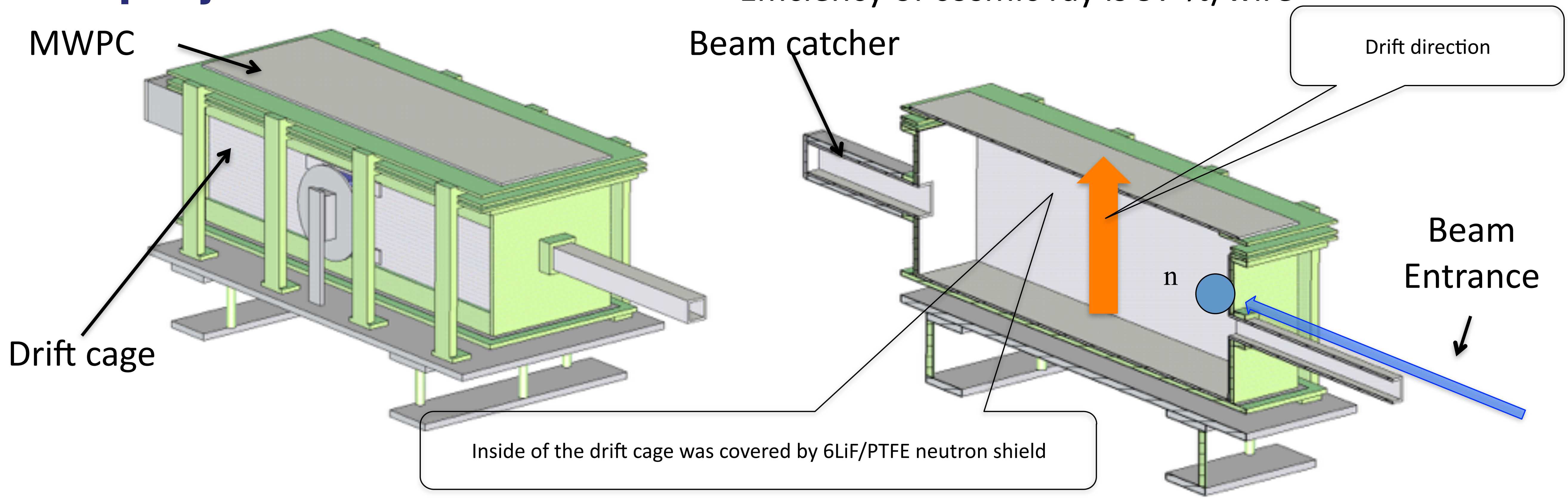
Both of β-decay events and He capture events are detected with high efficiency in a same detector.

Efficiency 99.9%   electron >4 keV

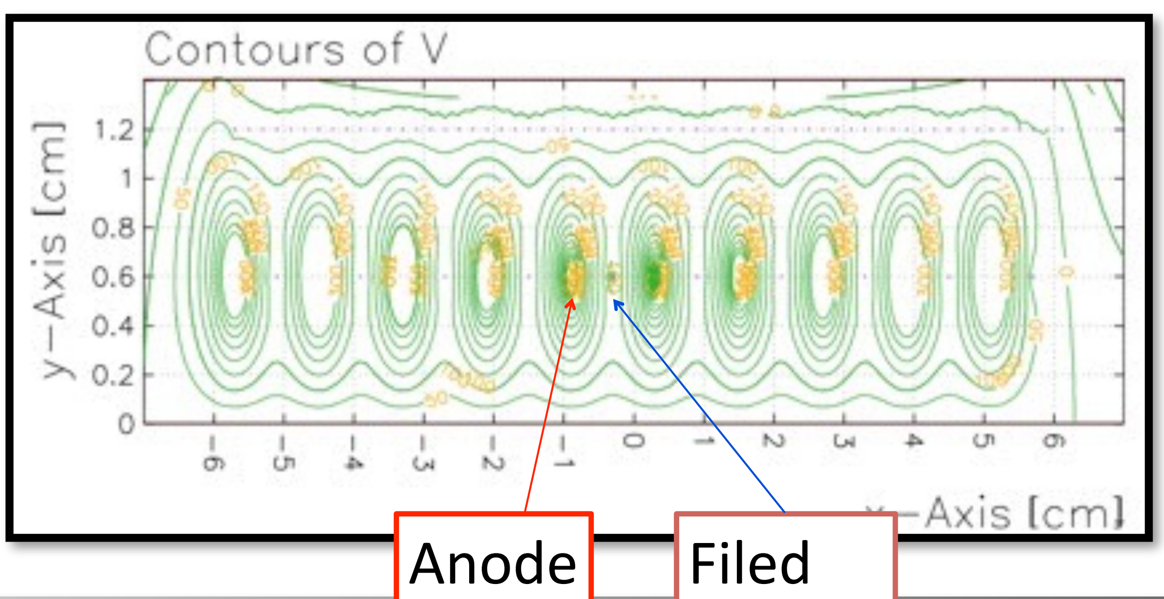
Neutron Lifetime

Time projection chamber

Efficiency of cosmic ray is 97 %/wire



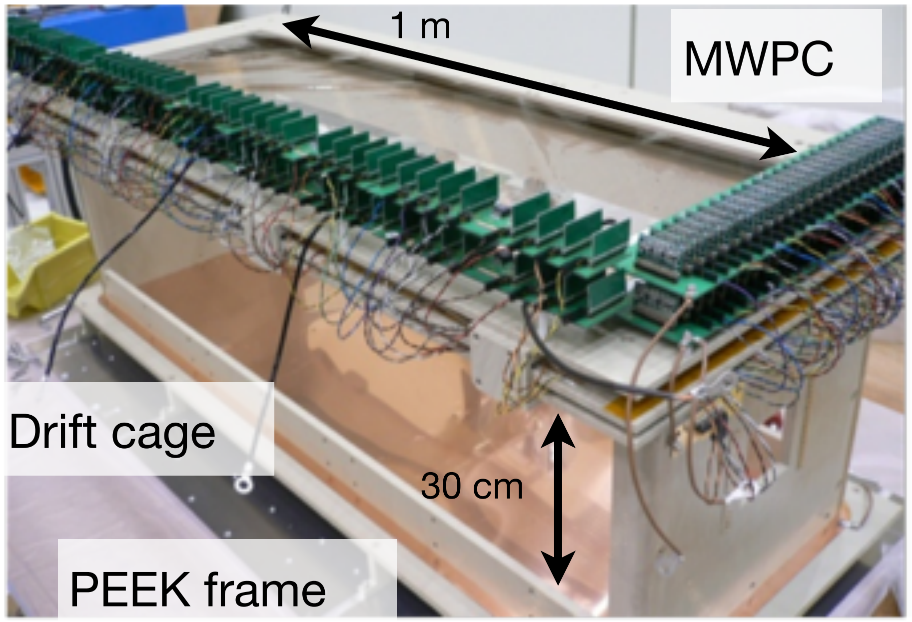
Voltage of MWPC (12 mm pitch)



Anode wire	29 of W-Au wires(+1780V)
Field wire	28 of Be-Cu (0V)
Cathode wire	120 of Be-Cu (0V)
Drift length	30 cm (-9000V)
Gas mixture	He:CO2=85kPa:15kPa
TPC size(mm)	300,300,970

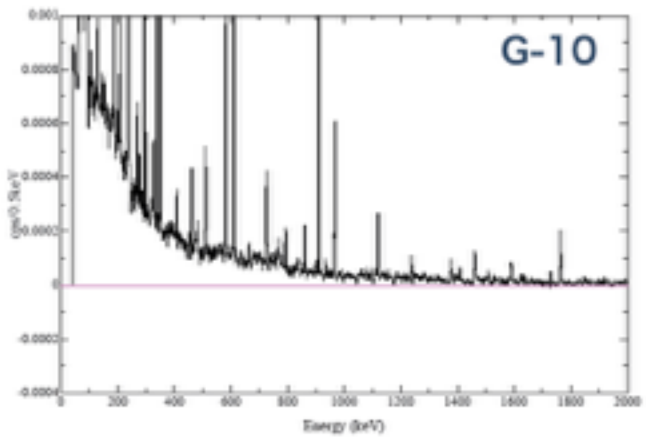
J-PARC パルス中性子を用いた高精度測定

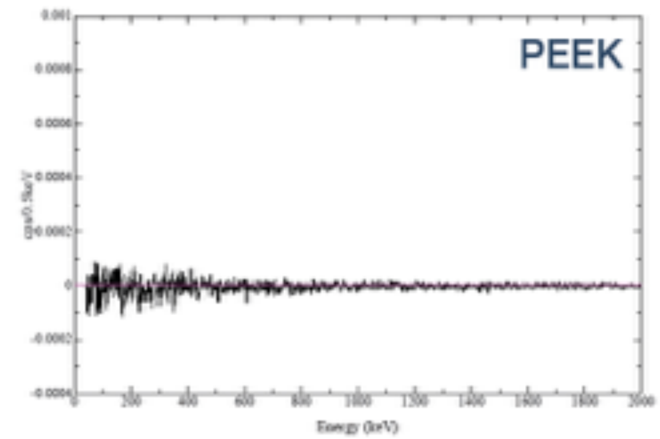
タイムプロジェクションチェンバー（TPC）



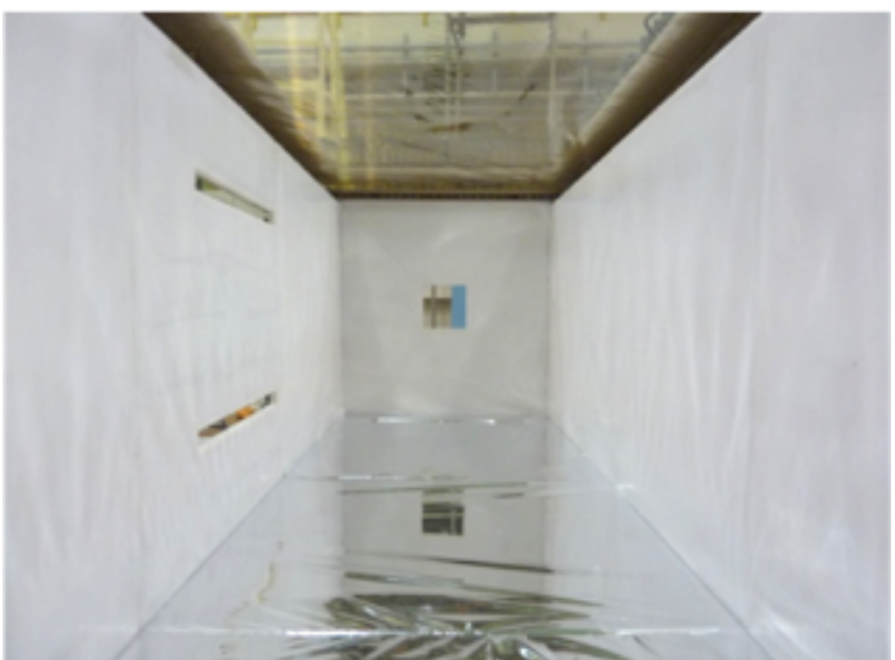
崩壊β線、^{3}He吸収反応を高効率で同時計数
24本24chのAnode/Field Wireを
120本40chのCathode Wire2層でサンド

PEEK使用　→放射性物質からのBG大幅低減





^{6}Liで内部100%覆う
→ビーム起因即発γ線BGを低減



Veto

S/N ~ 1:1 を達成

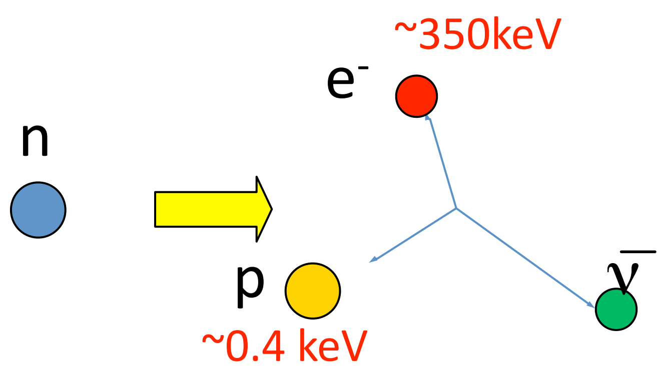
ドリフト速度ばらつき1%以下

高精度測定のための解析手法の開発

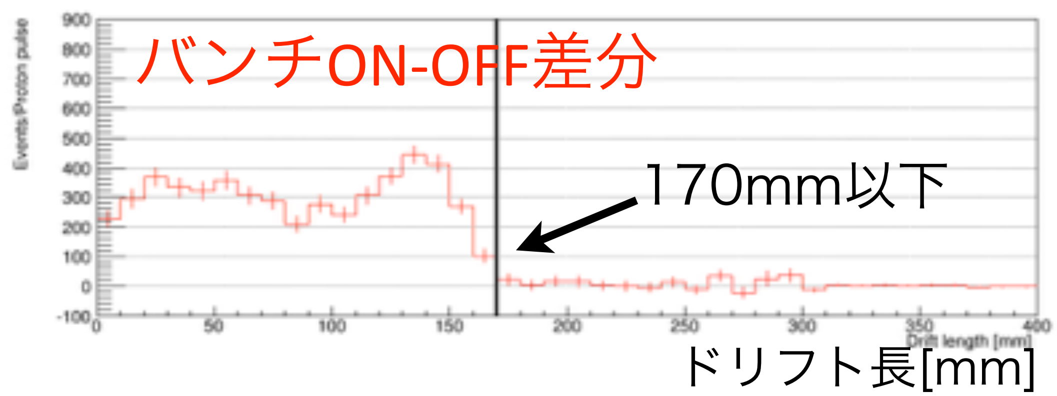
TPCコミッショニングを行い、イベントを確認した

中性子β崩壊

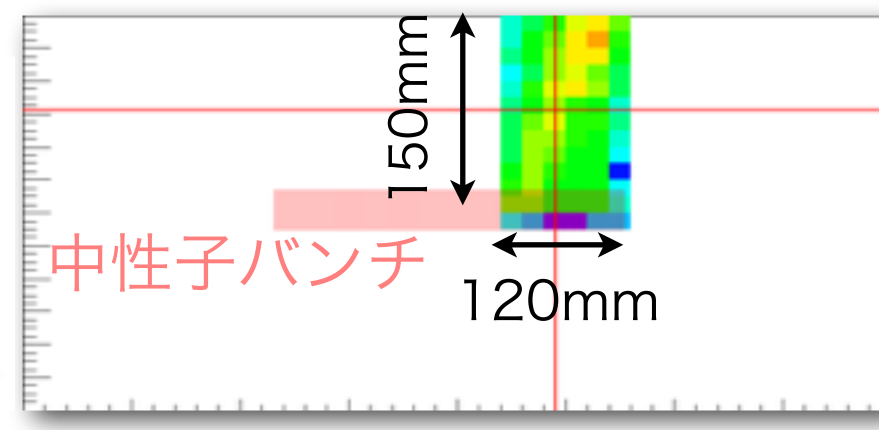
Q valueは 0-782keVの連続分布。Energy depositは10keV程度。



トラック端点の位置など
中性子バンチから発生していることを要請



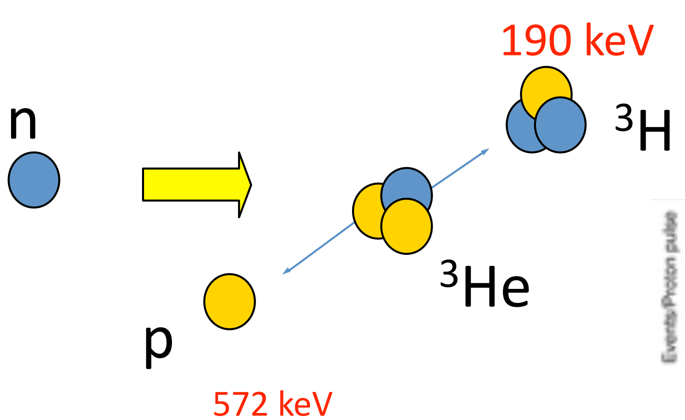
MWPC上側から見た
イベントディスプレイ



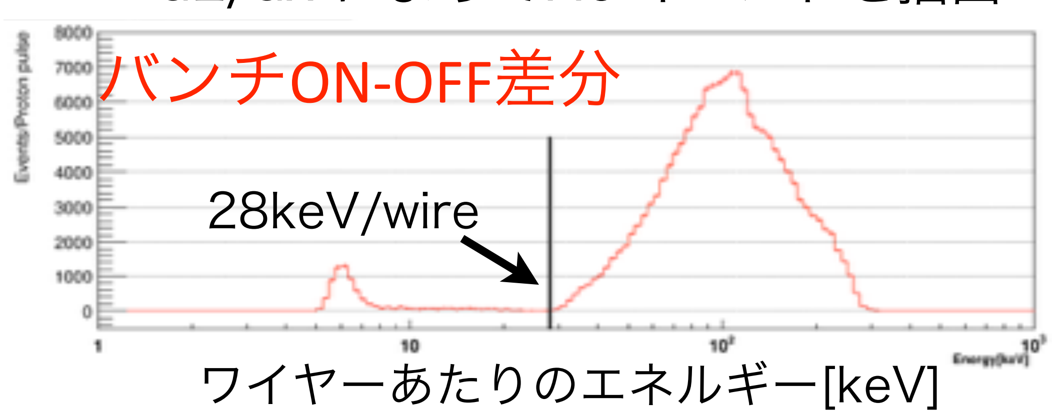
ビーム進行方向→

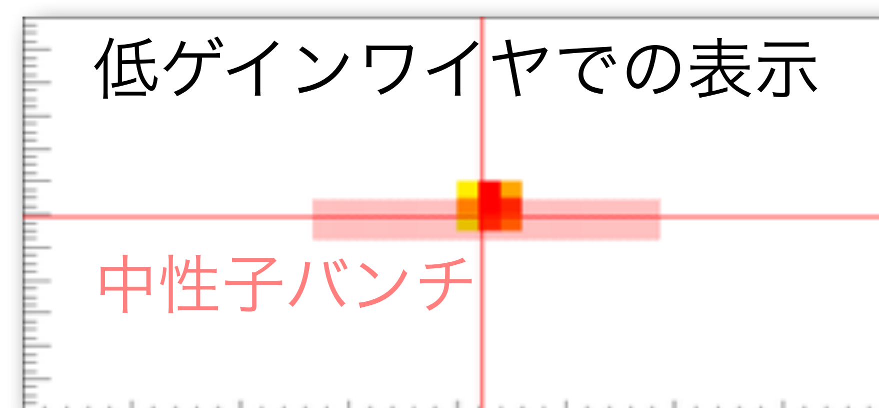
^{3}He(n,p)^{3}H

Q valueは762keV(単色)を全てTPCに落とす。100kPaでは飛程 5cm。



dE/dx によってHe イベントを抽出





高精度測定のための解析手法の開発

TPCコミッショニングを行い、イベントを確認した

シミュレーションでバックグラウンドを含んだイベントを作成

イベント形状、スペクトルなどを評価し、（ビーム起因）バックグラウンドの含有率を推定。β崩壊イベントの量を見積もる
→測定の妥当性の評価に用いることができる、系統誤差はO(1%)まで

Data driven のイベント抽出による解析で、精度O(0.1%)へ

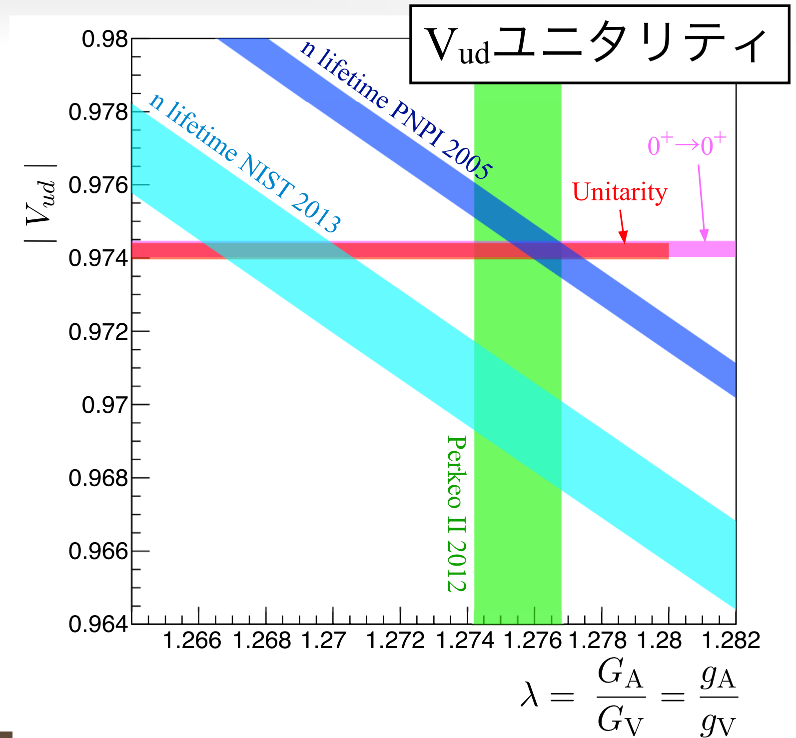
ガス圧の違うランなど複数の測定を組み合わせてバックグラウンドを除去しイベントを抽出。
→バックグラウンドを（シミュレーションに依らずに）引き算できる
　系統誤差はO(0.1%)まで下げることを目指している

有効相互作用理論の精査（中性子β崩壊角相関項）

名大・理研・KEK

$$w\ dE_e\,d\Omega_e\,d\Omega_{\bar{\nu}_e} = \frac{1}{(2\pi)^5}\,p_eE_e\,(E_0-E_e)^2\,dE_e\,d\Omega_e\,d\Omega_{\bar{\nu}_e}\,\xi \times\left[1+a\frac{\mathbf{p}_e\cdot\mathbf{p}_{\bar{\nu}_e}}{E_e\,E_{\bar{\nu}_e}}+b\frac{m_e}{E_e}+\frac{\mathbf{J}}{J}\cdot\left(A\frac{\mathbf{p}_e}{E_e}+B\frac{\mathbf{p}_{\bar{\nu}_e}}{E_{\bar{\nu}_e}}+D\frac{\mathbf{p}_e\times\mathbf{p}_{\bar{\nu}_e}}{E_eE_{\bar{\nu}_e}}\right)\right]$$

$$a=\frac{1-|\lambda|^2}{1+3|\lambda|^2},\ b=0,\ A=-2\frac{|\lambda|\cos\phi+|\lambda|^2}{1+3|\lambda|^2},\ B=-2\frac{|\lambda|\cos\phi-|\lambda|^2}{1+3|\lambda|^2},\ D=2\frac{|\lambda|\sin\phi}{1+3|\lambda|^2}$$



$$\lambda=\frac{G_A}{G_V}=\frac{g_A}{g_V}$$

標準理論の高精度検証

寿命と合わせて CKM行列のUnitarityを検証　$|V_{ud}|^2=\frac{1}{\tau_n}\frac{(4908.7\pm1.9)\ \mathrm{s}}{(1+3\lambda^2)}$

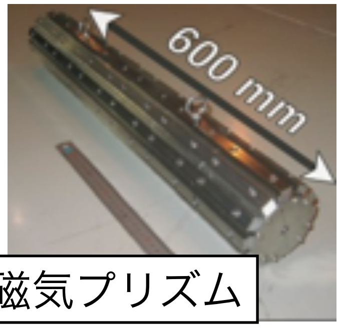
➡ **A項：中性子スピンと電子の運動量**

入射中性子の **偏極を10^{-4}の精度 ＋ 大強度化**

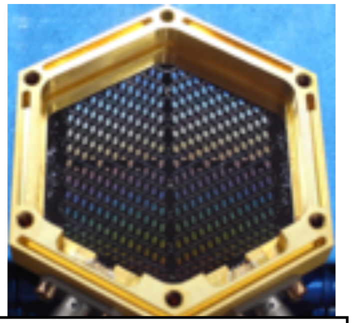
Next Leading Order項の測定

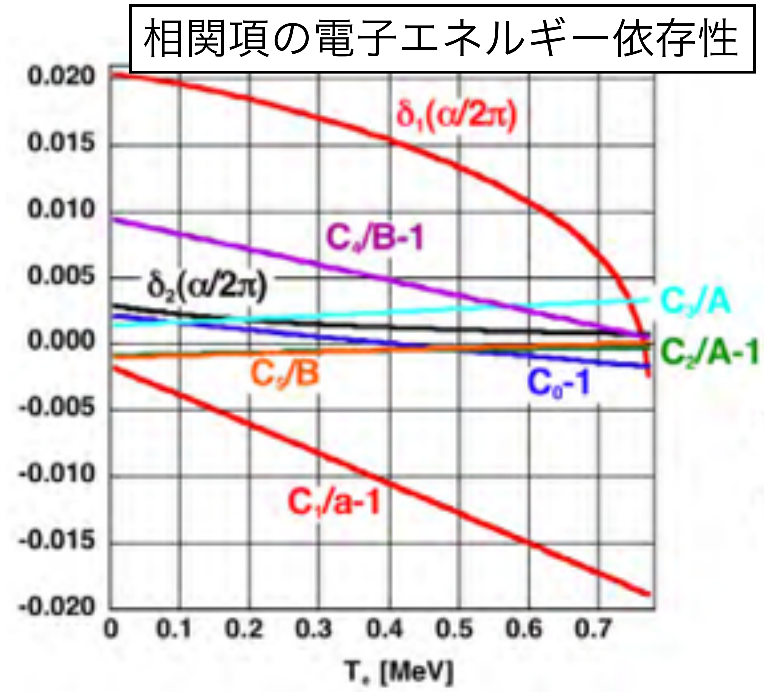
➡ **a項：陽子のエネルギースペクトル**

陽子エネルギー測定のための **超電導検出器**



磁気プリズム


超電導検出器 KID



標準理論を超える物理の探索

新物理は、標準理論と異なる依存性がNLOに現れる

➡ **B項：ニュートリノ非対称度**

D項は標準理論ではゼロ、時間反転対称性を破る

➡ **D項：ベクトル三重積**

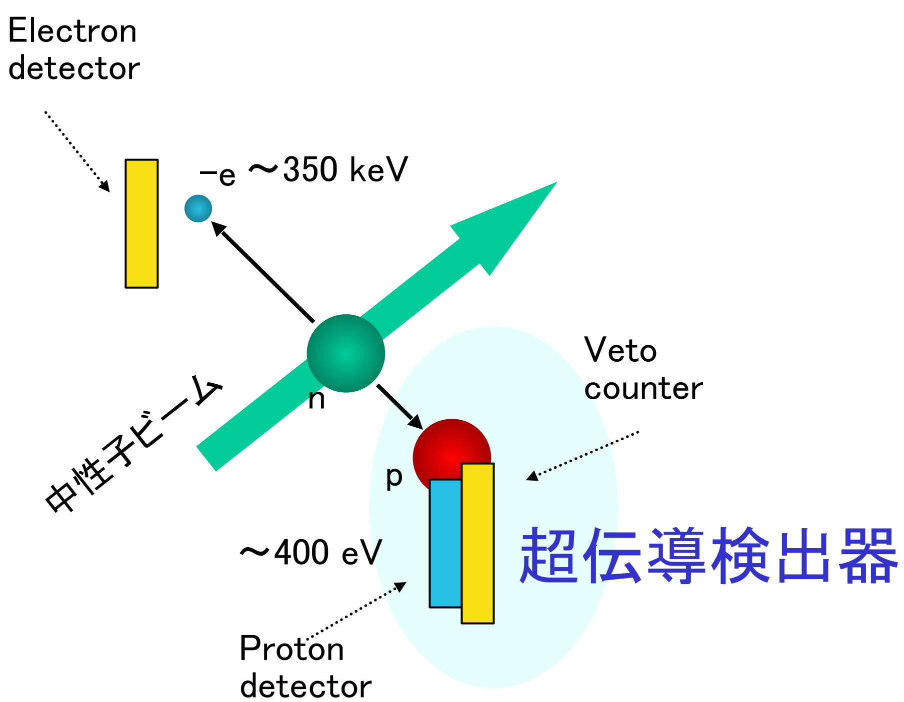
電子・陽子の運動量測定と中性子バンチによる

崩壊点決定で三体崩壊を完全に決定できる

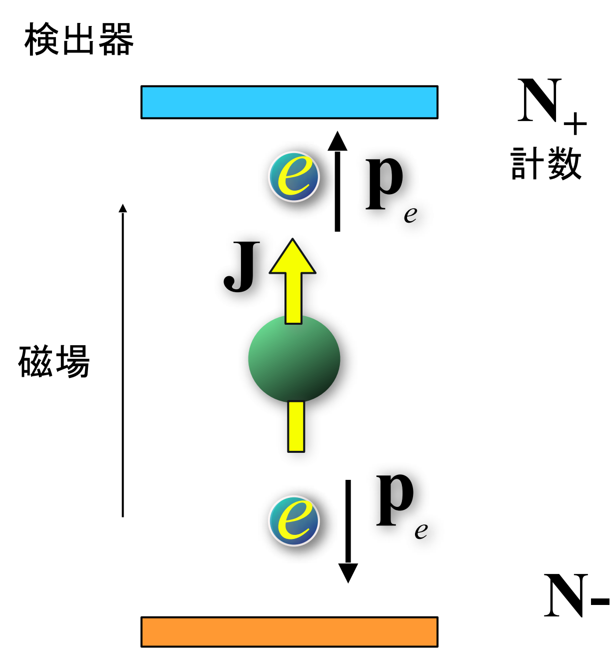
$$dN \propto \left[1 + a\frac{\boldsymbol{p}_e \cdot \boldsymbol{p}_{\overline{\nu}}}{E_e \cdot E_{\overline{\nu}}} + \frac{\mathbf{J}}{J} \cdot \left(A\frac{\boldsymbol{p}_e}{E_e} + B\frac{\boldsymbol{p}_{\overline{\nu}}}{E_{\overline{\nu}}} + D\frac{\boldsymbol{p}_e \times \boldsymbol{p}_{\overline{\nu}}}{E_e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

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

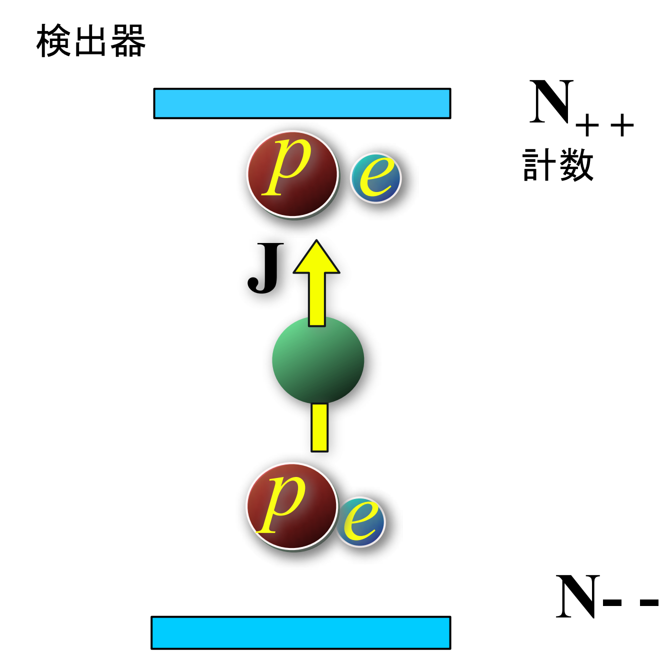
$$\tau = \frac{K/\ln 2}{V_{\mathrm{ud}}^2 G_{\mathrm{F}}^2 (1 + \lambda^2) f}$$



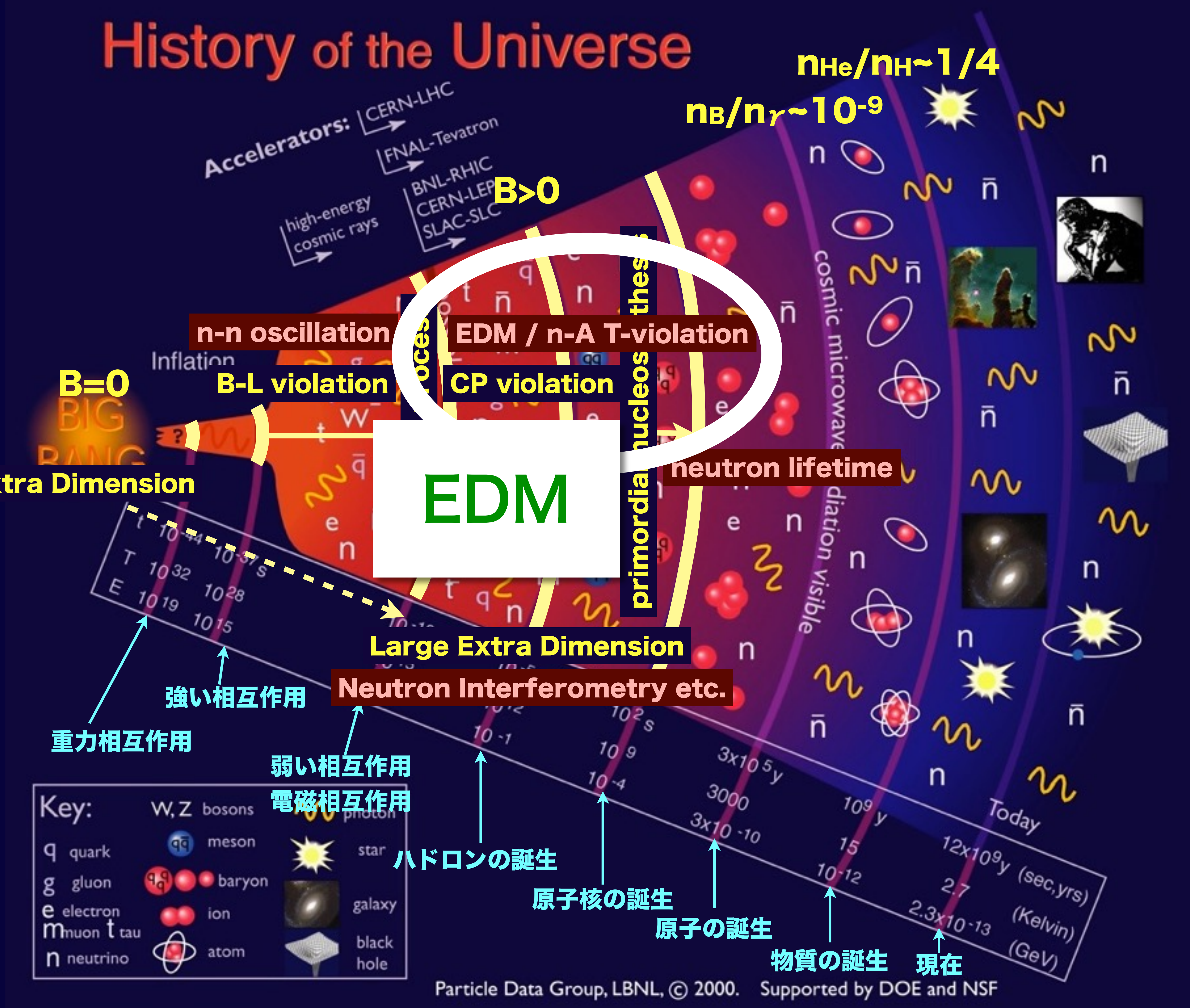
a=－0.103±0.004



A=−0.1176 ±0.0011

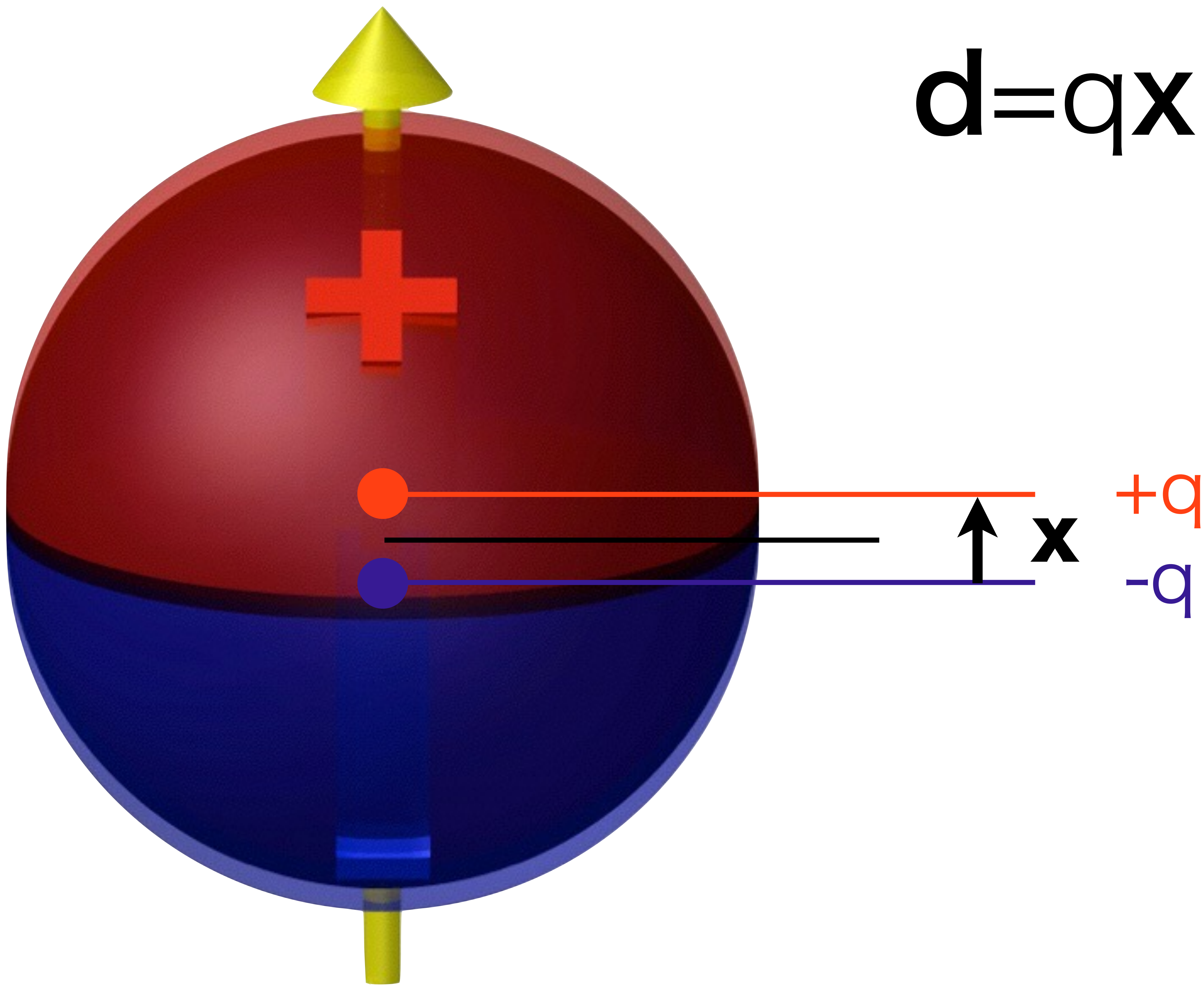


B=0.9807 ±0.0030

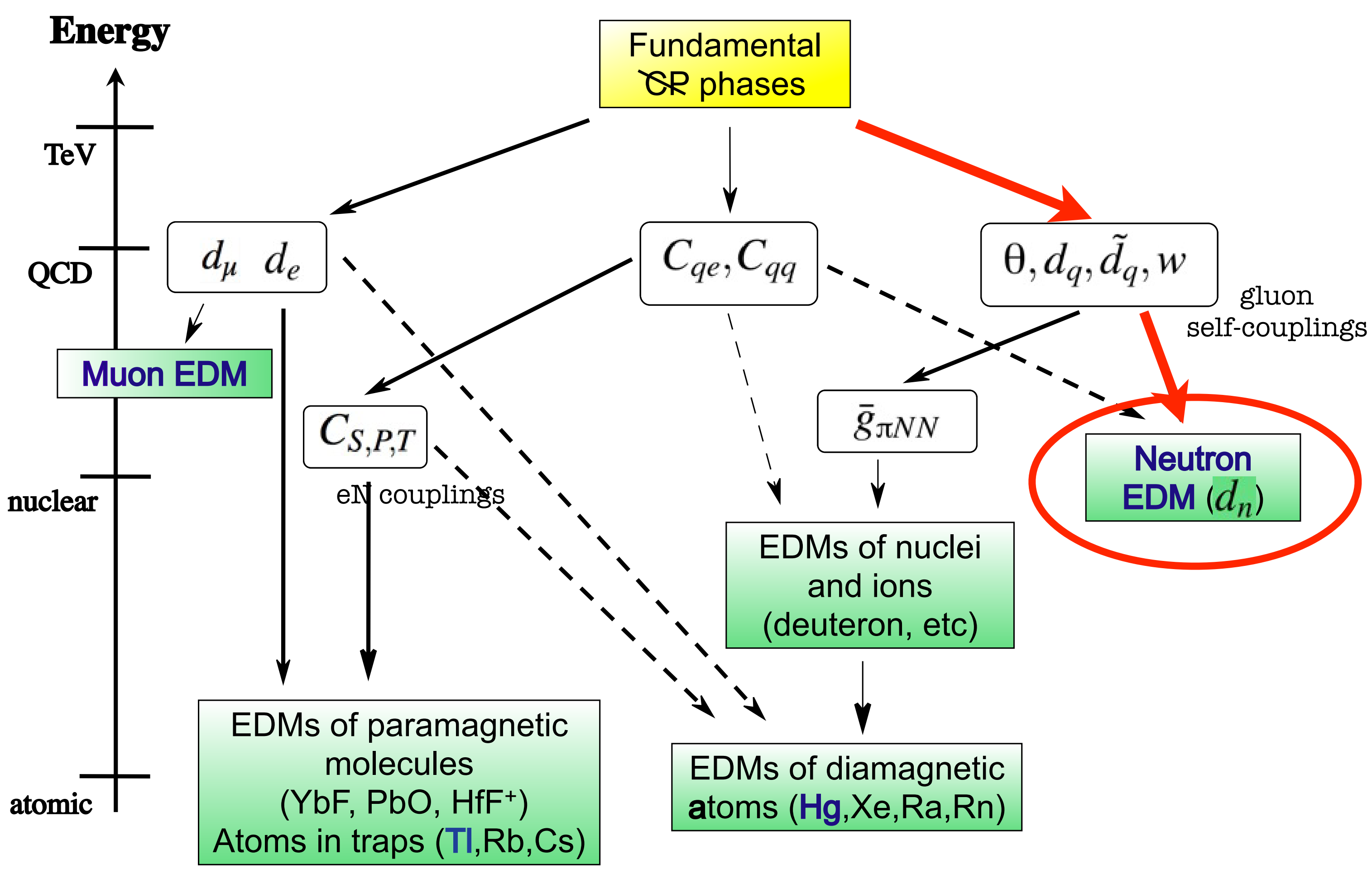


History of the Universe
$n_{He}/n_H \sim 1/4$
$n_B/n_\gamma \sim 10^{-9}$
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
B>0
B=0
Inflation
n-n oscillation
B-L violation
EDM / n-A T-violation
CP violation
primordial nucleosynthesis
cosmic microwave radiation visible
neutron lifetime
EDM
Extra Dimension
Large Extra Dimension
Neutron Interferometry etc.
強い相互作用
重力相互作用
弱い相互作用
電磁相互作用
ハドロンの誕生
原子核の誕生
原子の誕生
物質の誕生
現在
Today
(sec,yrs)
(Kelvin)
(GeV)
Key:
q quark
g gluon
e electron
m muon
t tau
n neutrino
W,Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

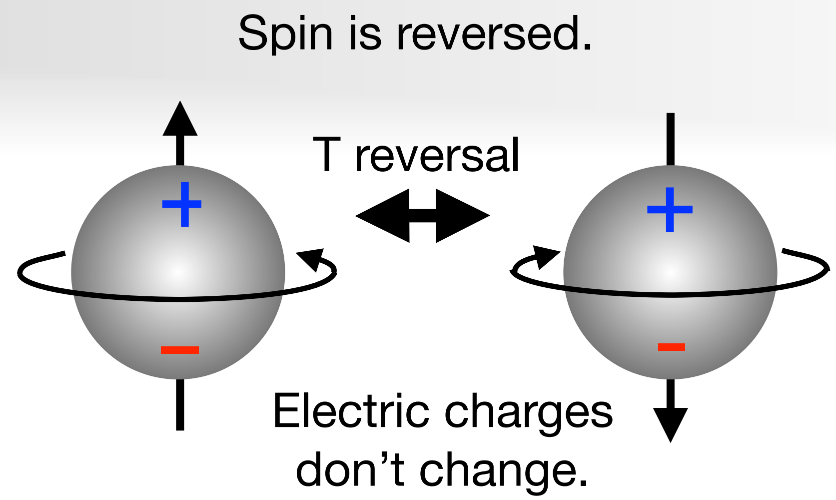
Neutron EDM

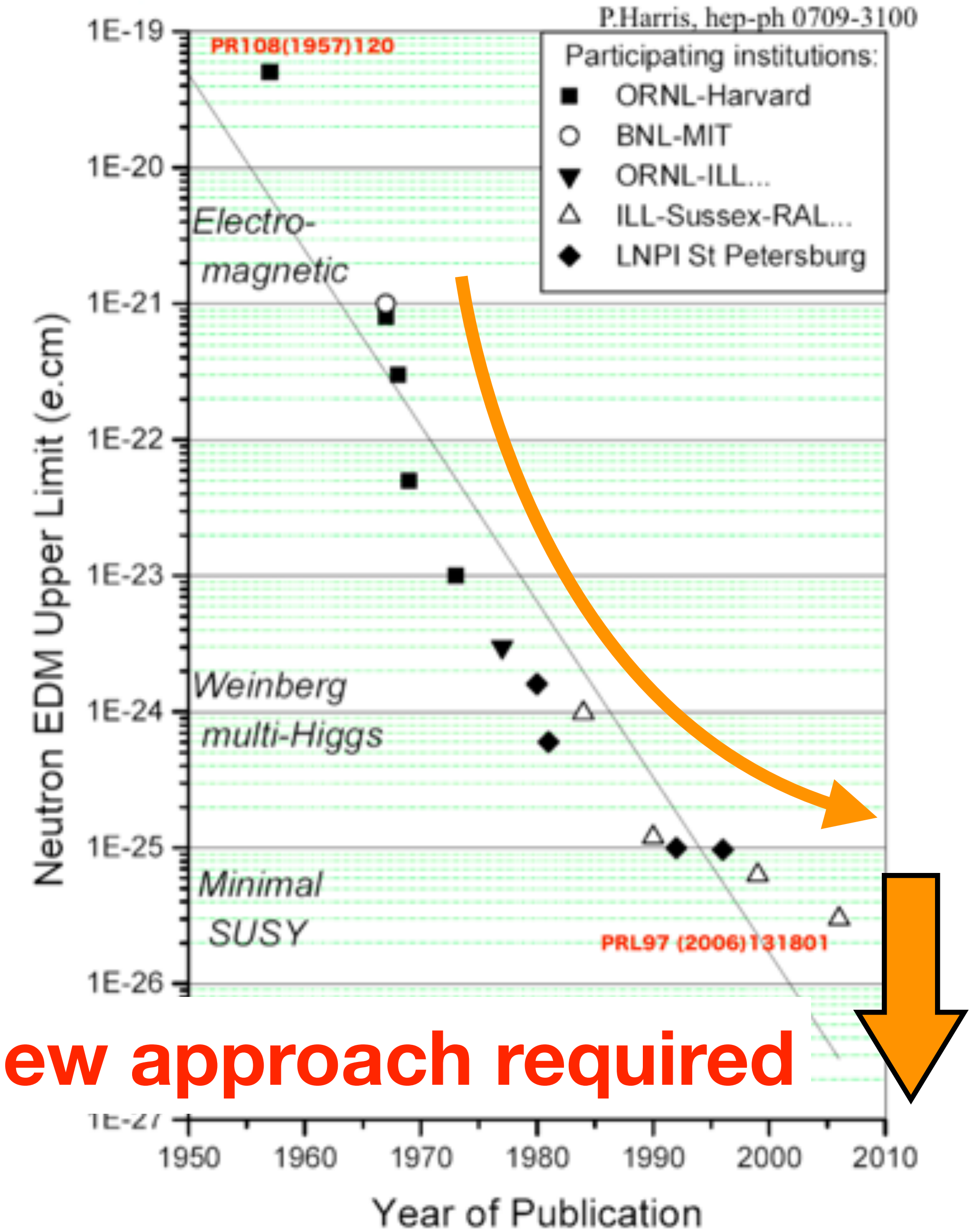


Neutron EDM



Pospelov Ritz, Ann Phys 318 (05) 119





Present upper limit $|d_n| < 2.9 \times 10^{-26}\ e$ cm

is approaching to the predictions of some physics beyond the standard model of particle physics.

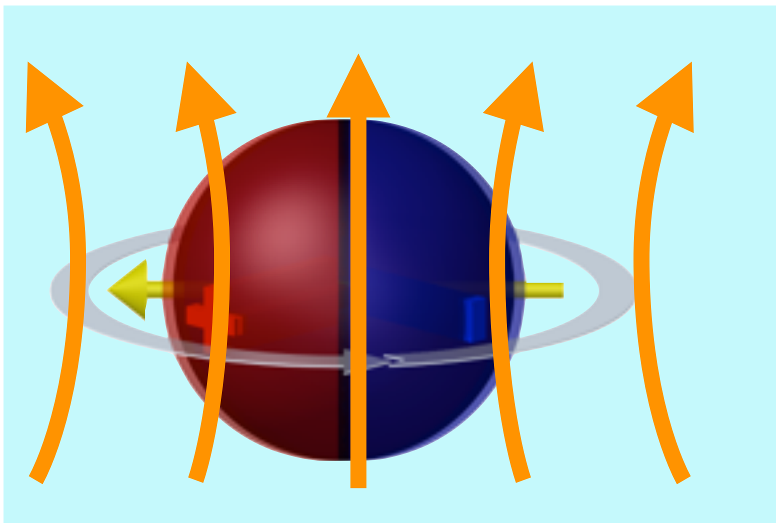
Standerd Model : $|d_n| \sim 10^{-32}\ e$ cm

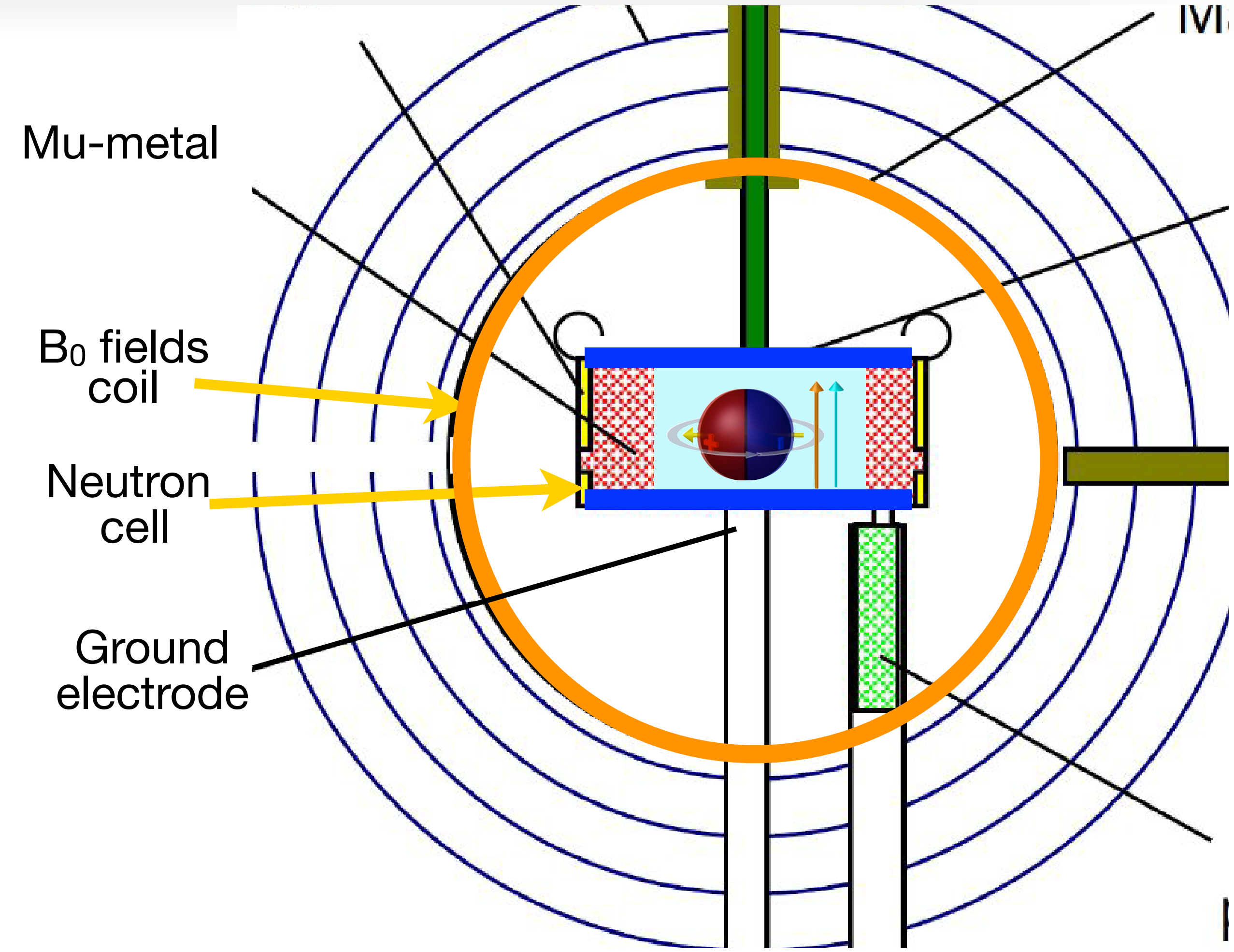
New Physics (SUSY ...) : $|d_n| \sim 10^{-27 \sim -28}\ e$ cm

New approach required

How to measure EDM

Precessions of stored UCNs are measured in magnetic and electric field.



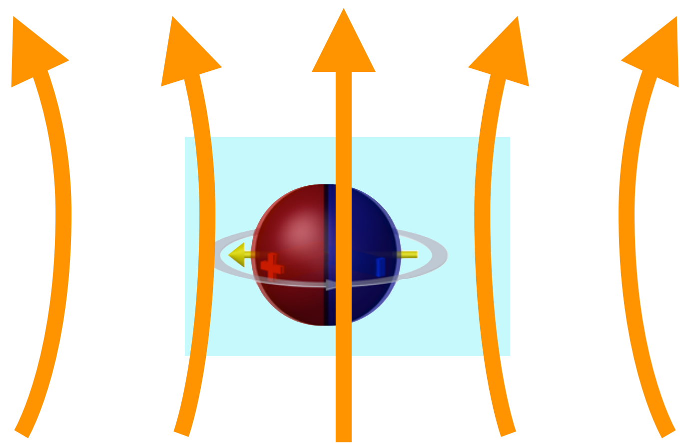


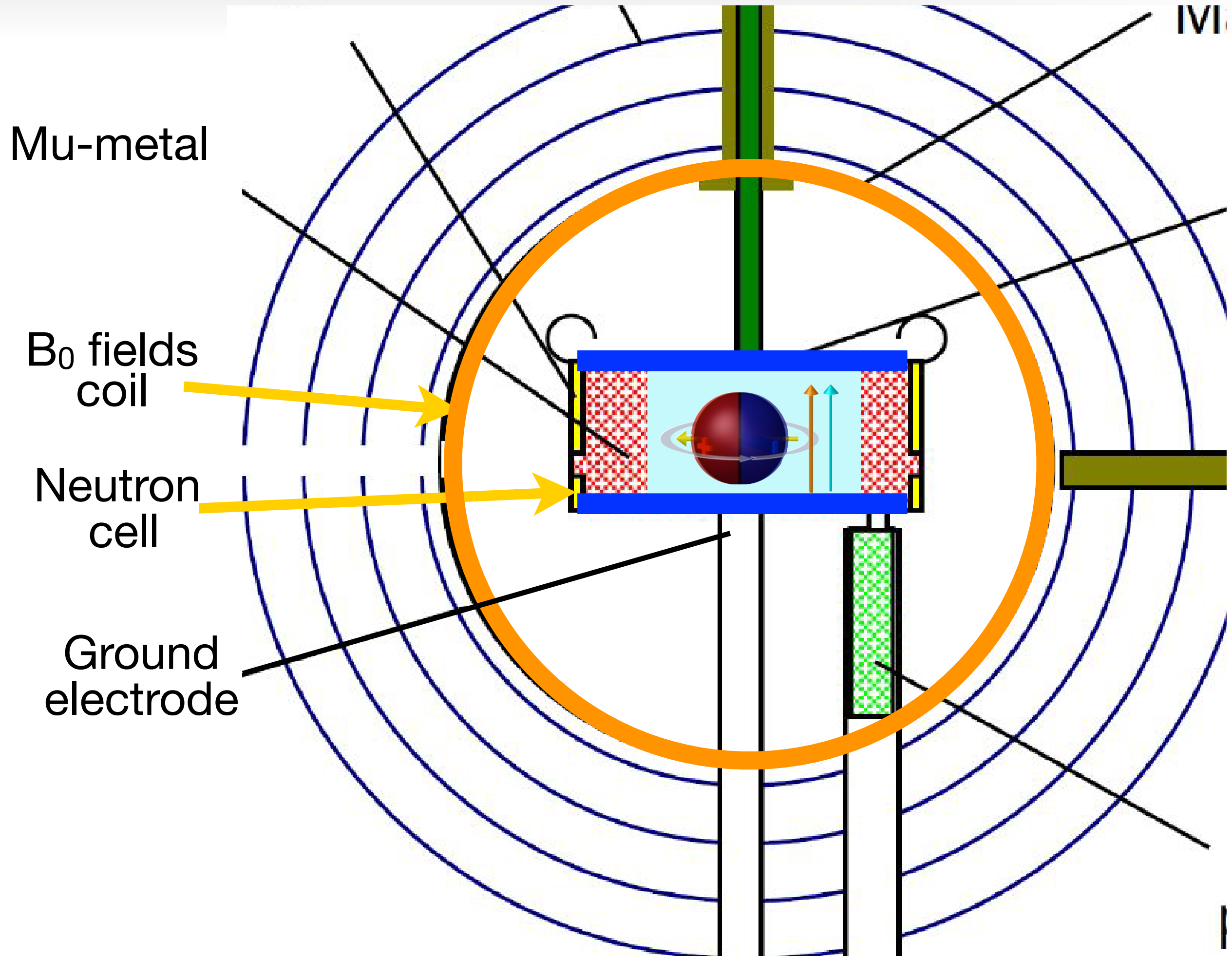
Small storage area is better.

Stable and uniform magnetic field are required.
Precision measurement of the magnetic field is also required.

How to measure EDM

Precessions of stored UCNs are measured in magnetic and electric field.





Small storage area is better.

Dense UCNs & understanding of systematic uncertainties

Our new approach is **UCN precision optics**

Stable and uniform magnetic field are required.
Precision measurement of the magnetic field is also required.

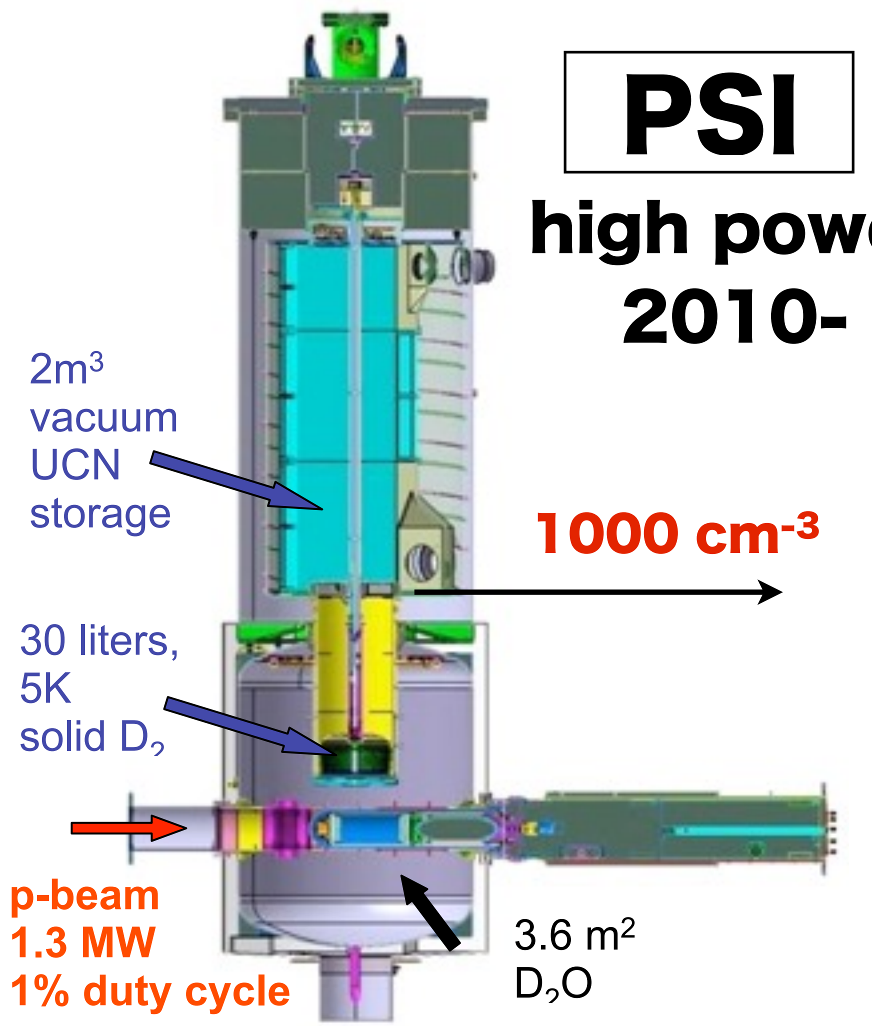
How to increase UCN density

Use intense source

High power proton beam (by accelerator)
and large volume neutron target can make intense UCNs.

PSI

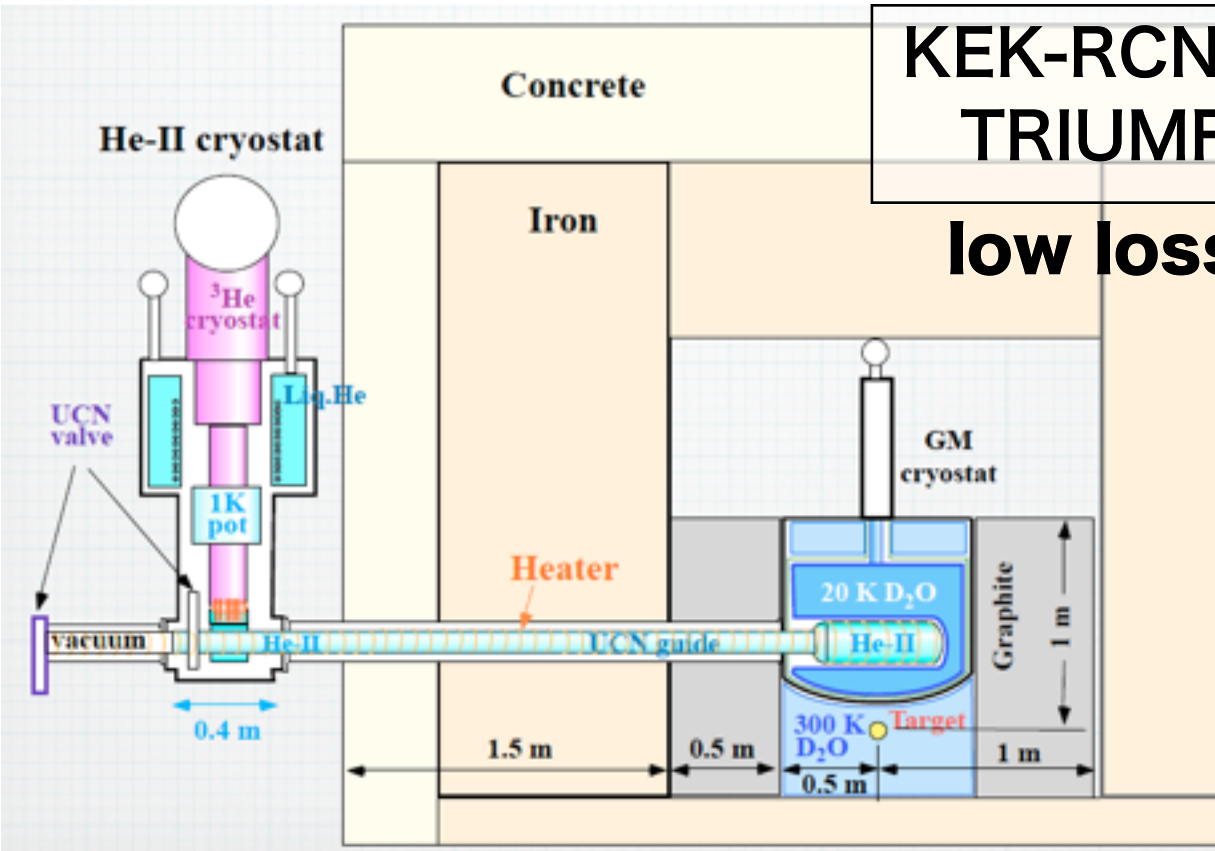
high power 2010-



average = 13kW
max. peak power = 1.3MW

KEK-RCNP-TRIUMF

low loss



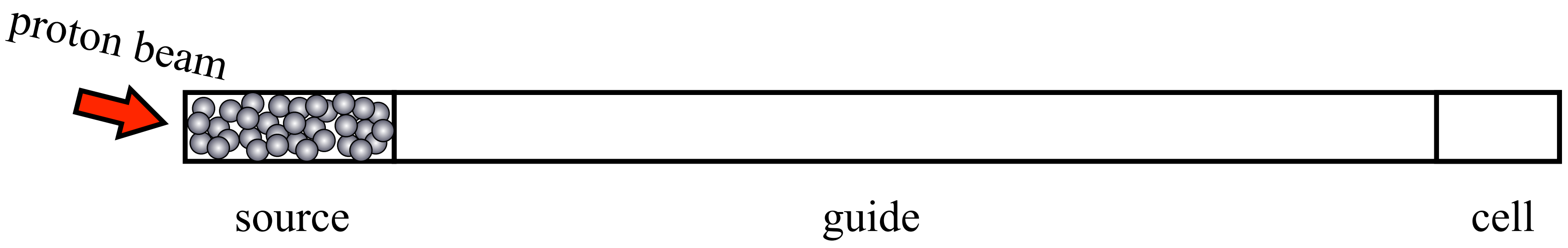
average=20kW
max. peak power = 200kW

How to increase UCN density

Use intense source

High power proton beam (by accelerator)
and large volume neutron target can make intense UCNs.

High power proton beam also makes heavy heat load at the source.
It is difficult to increase the UCNs anymore.



How to increase UCN density

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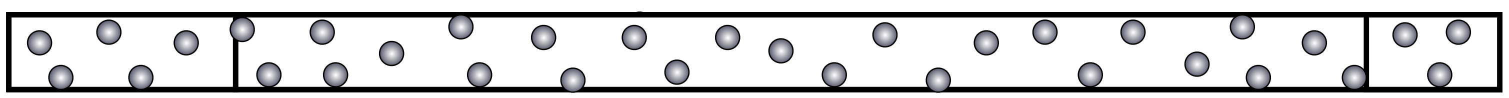


UCNs are spread spatially while transport, however,
intense source makes enough UCNs at the cell.

Most of UCNs are not used for measurement.

More efficient way ? → **UCN precision optics**

How to increase UCN density

Use efficient transport

If UCN pulse can be delivered, we can get dense UCNs at the cell.

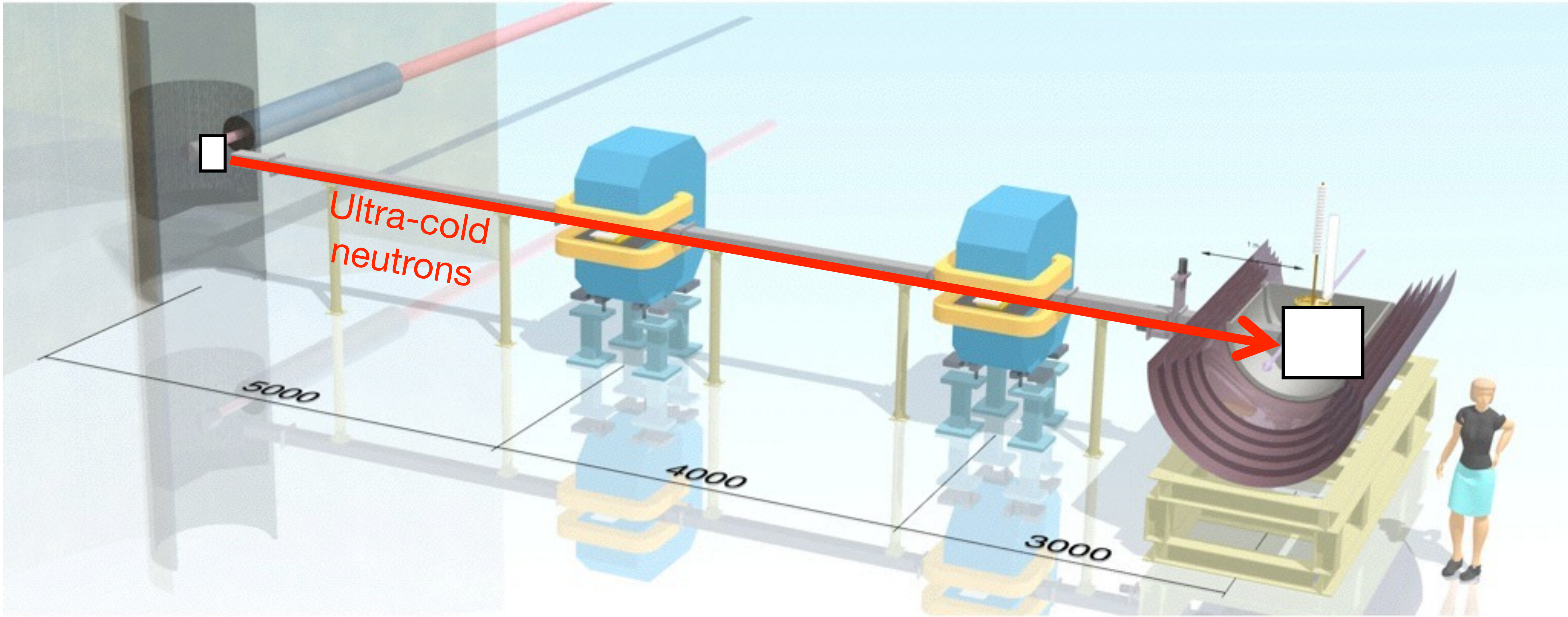
How can we realize such kind of transport ?

?

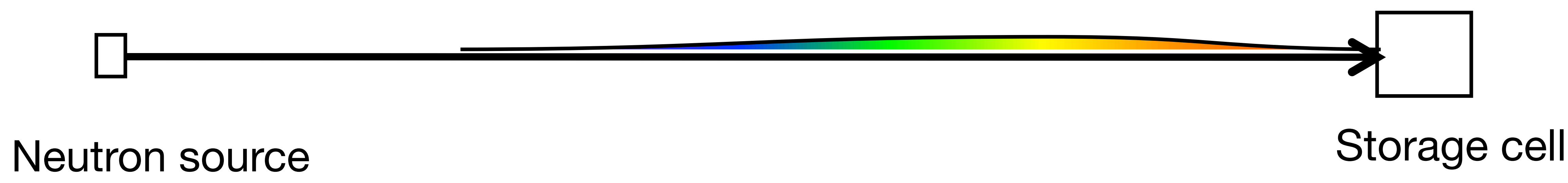
UCN Rebuncher, a UCN optical device

requires controlling the UCN velocity properly
and keeping velocity before and after the device.

Pulsed UCN transport



Pulsed UCN transport

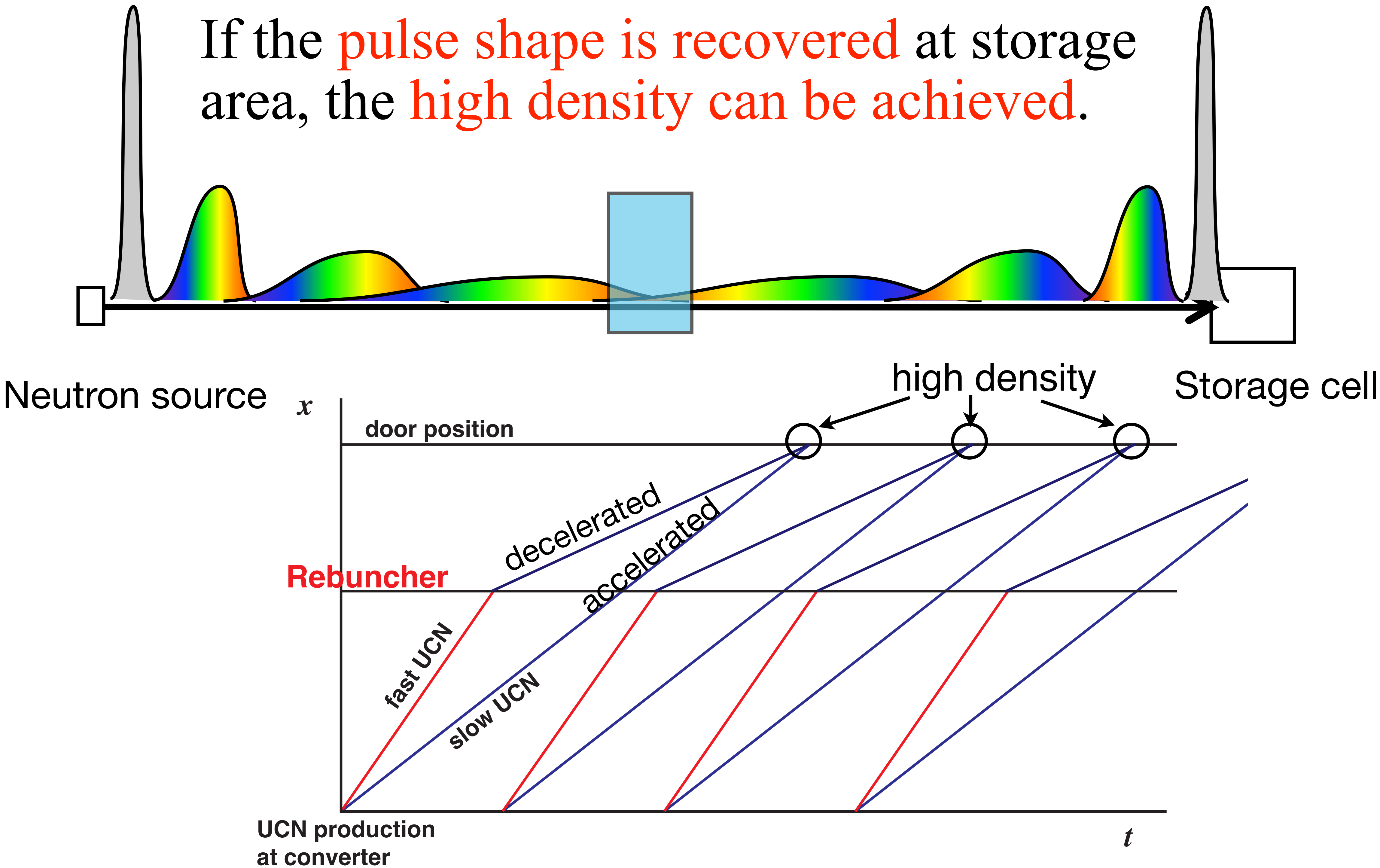


Pulsed UCNs spread spatially,
Density decreases quickly
without any treatment.

Pulsed UCN transport

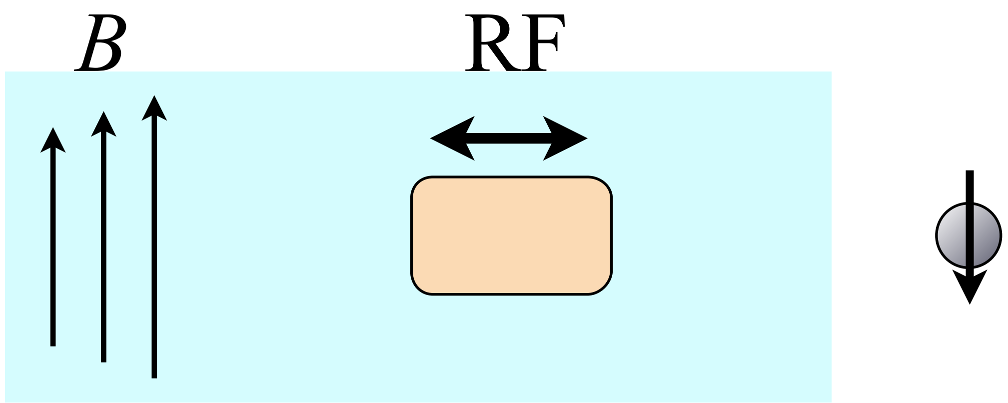
UCN Rebuncher = Neutron Accelerator

If the pulse shape is recovered at storage area, the high density can be achieved.



Rebuncher

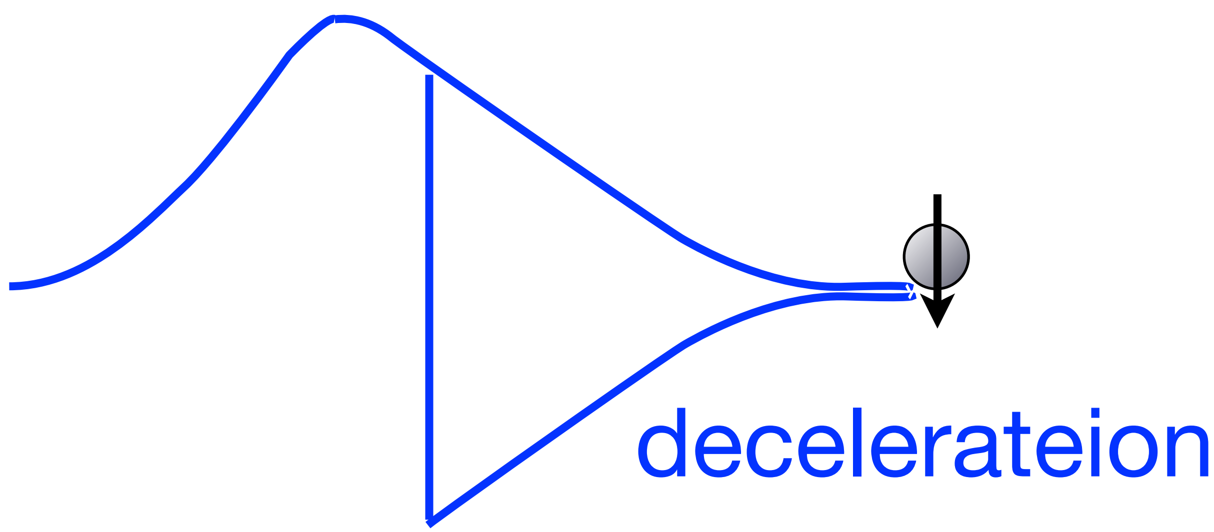
Adiabatic Fast Passage (AFP) spin flipper is used for control of the neutron energy.



RF magnetic field in gradient field gives/removes the energy with spin flip.

$$2\mu B = \hbar\omega$$

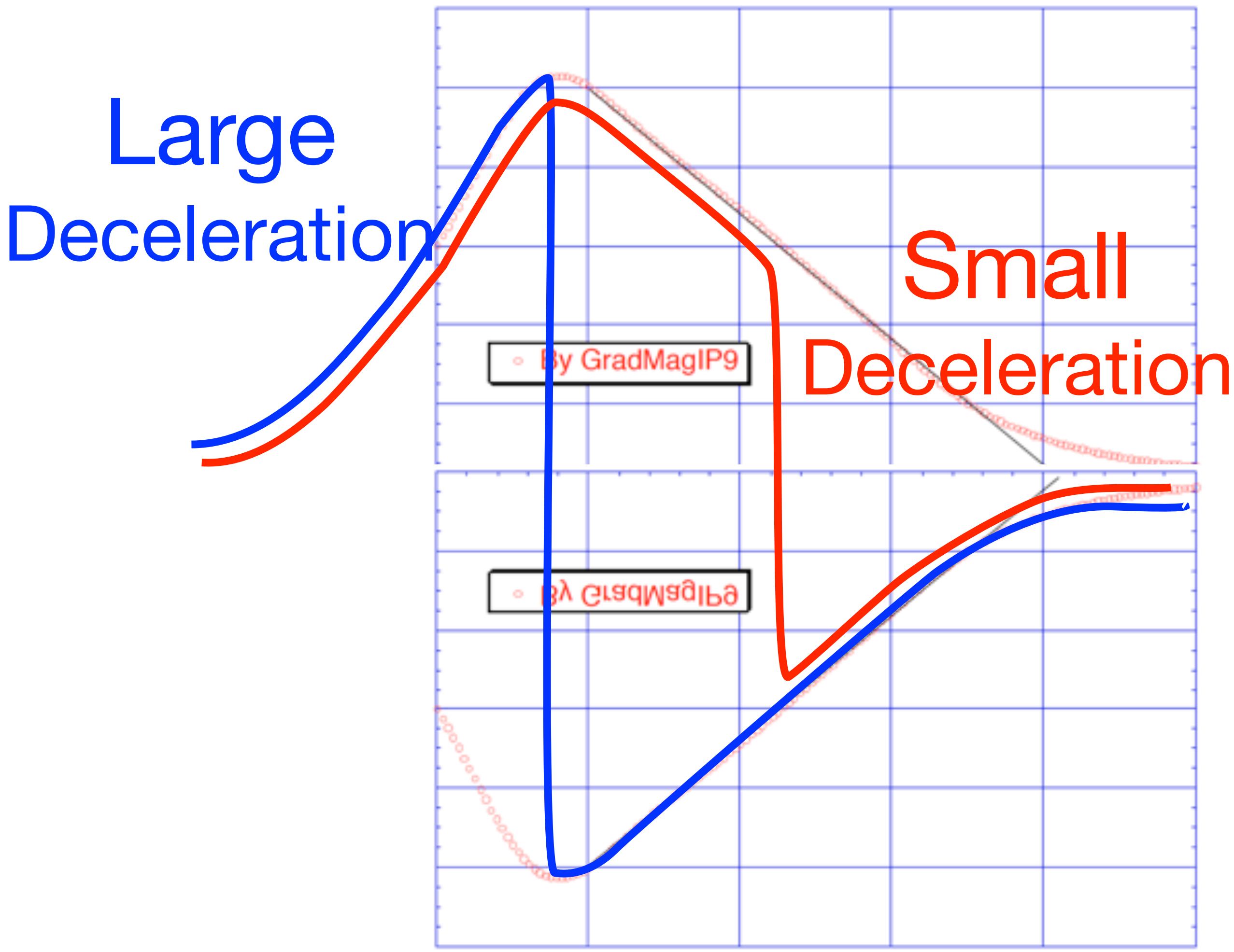
30 MHz = 1T = 120 neV



Opposite-spin neutrons are accelerated.

Rebuncher

Adiabatic Fast Passage (AFP) spin flipper is used for control of the neutron energy.



Energy exchange is proportional to the RF frequency.

RF magnetic field in gradient field gives/removes the energy with spin flip.

$$2\mu B = \hbar\omega$$

30 MHz = 1T = 120 neV

Faster neutrons arrive early.

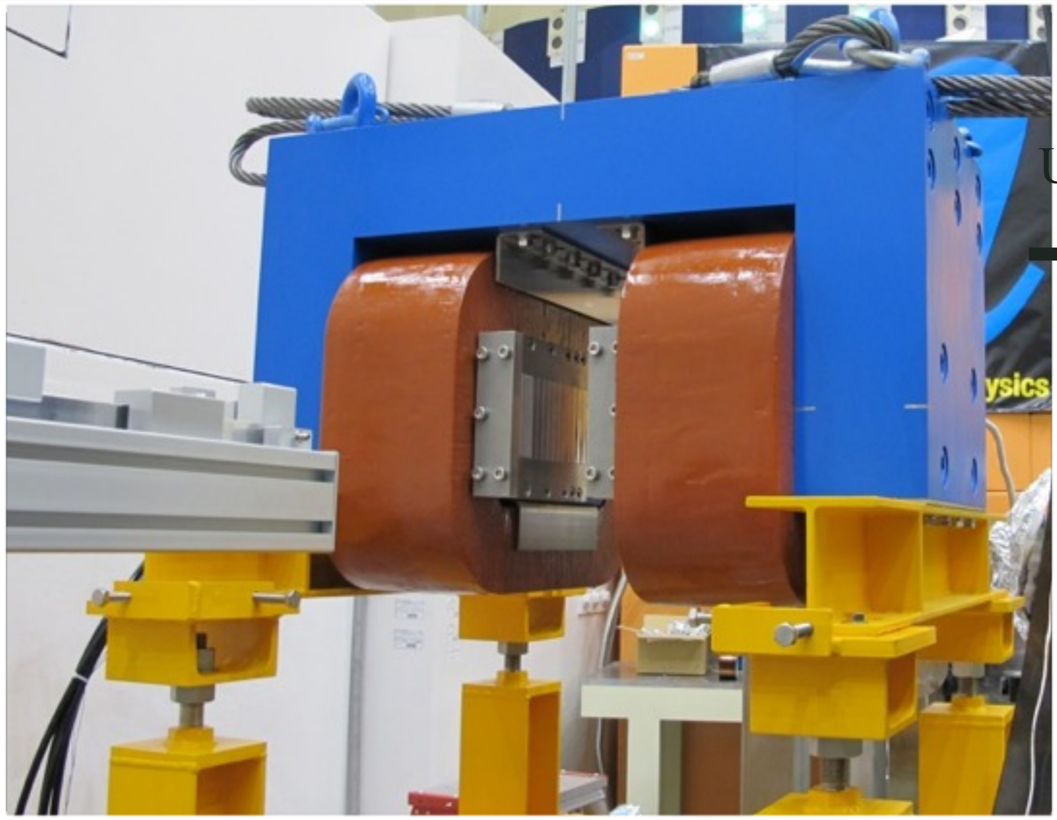
Large deceleration = High Freq. RF

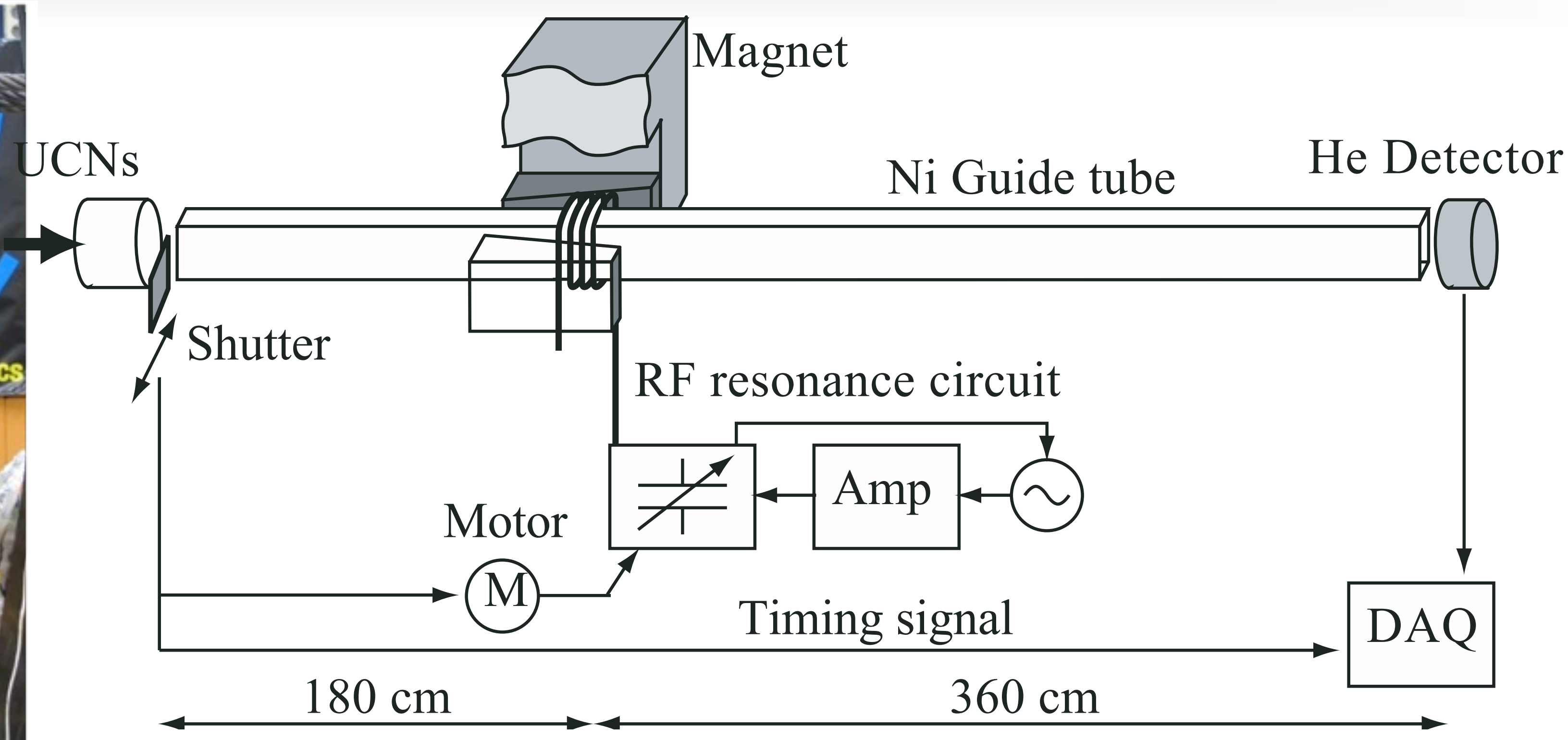
Slower neutrons arrive late.

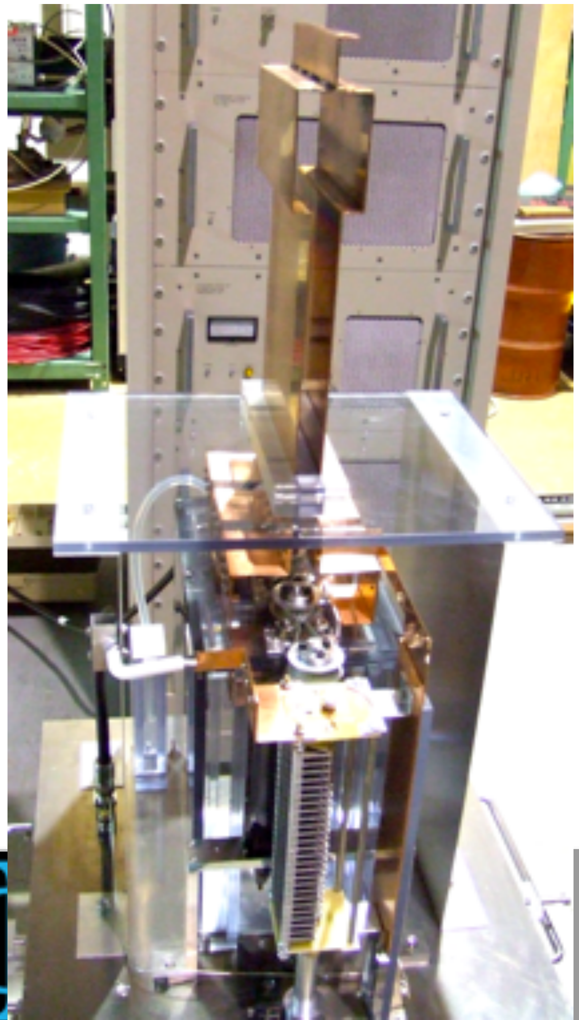
Small deceleration = Low Freq. RF

Sweeping frequency according to time

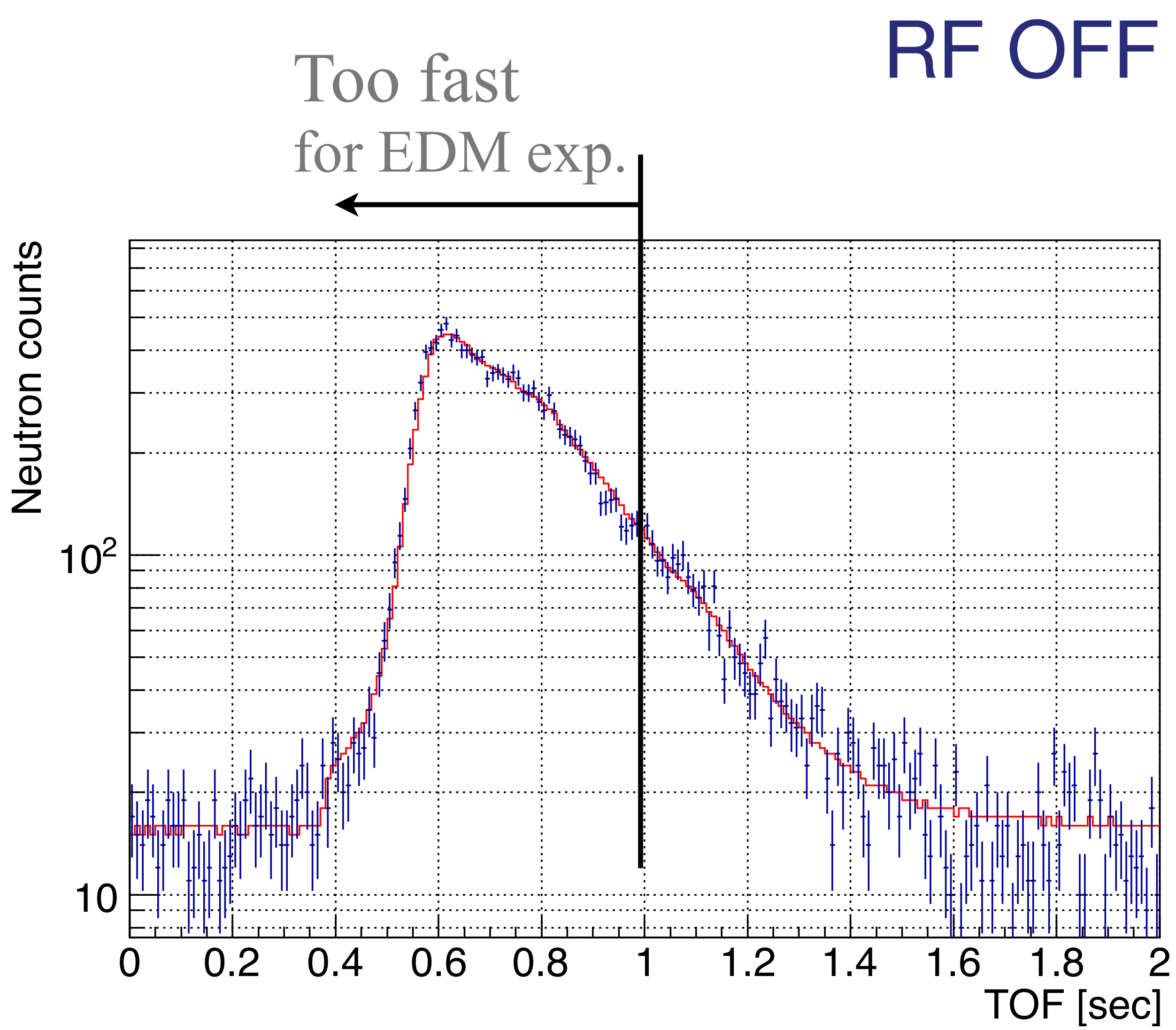
Rebuncher

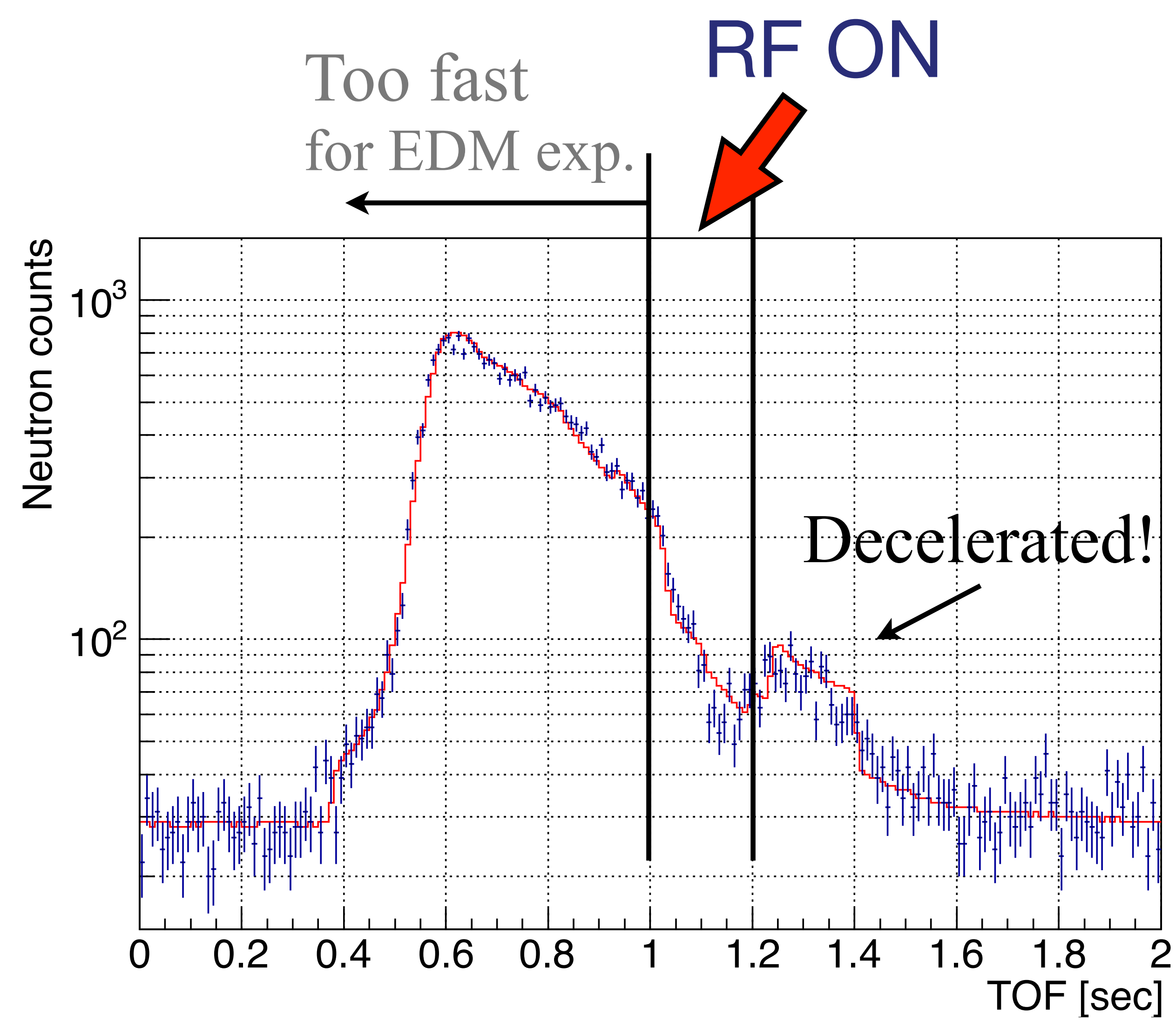



Magnet
UCNs
Ni Guide tube
He Detector
Shutter
RF resonance circuit
Amp
Motor
M
Timing signal
DAQ
180 cm
360 cm



Demonstration in HFR at ILL

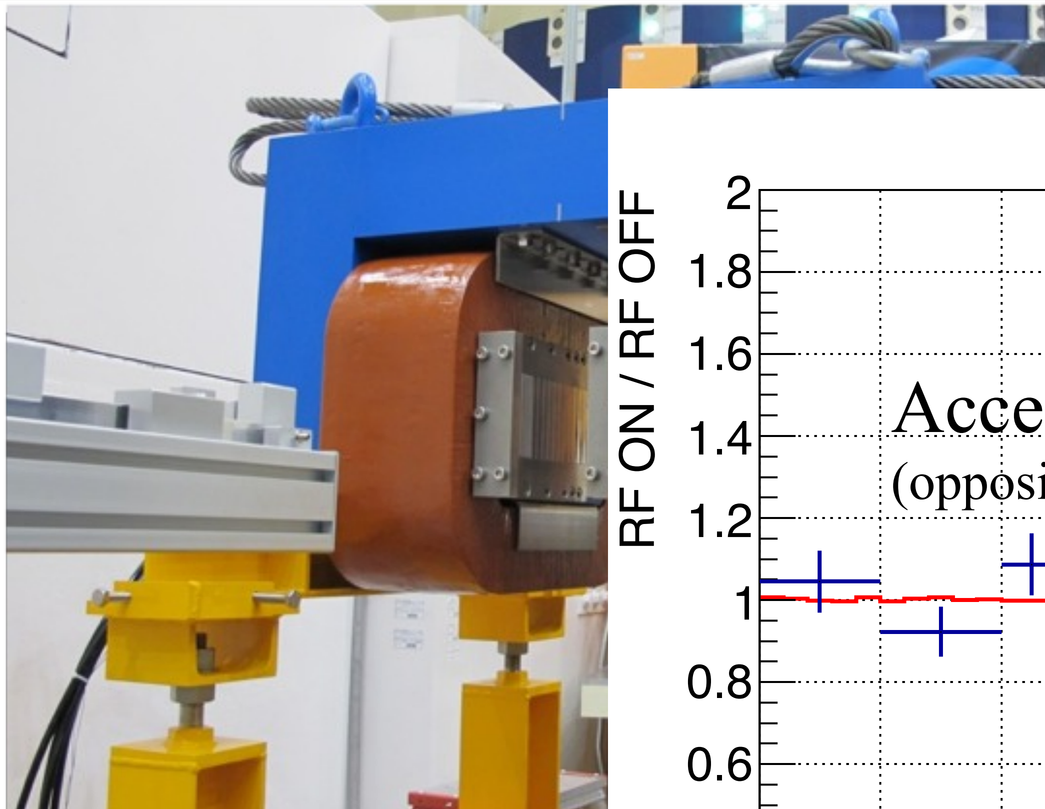


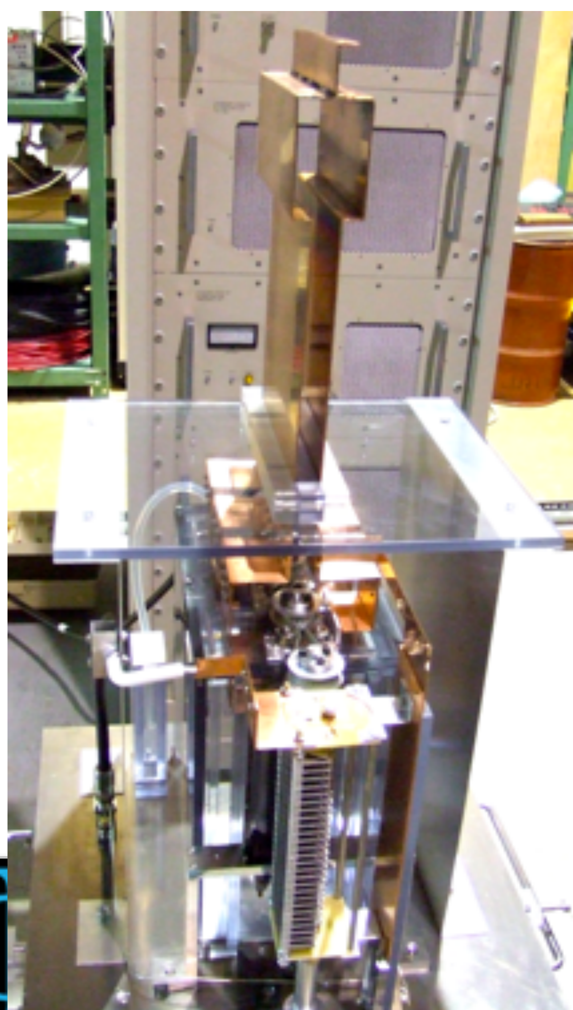


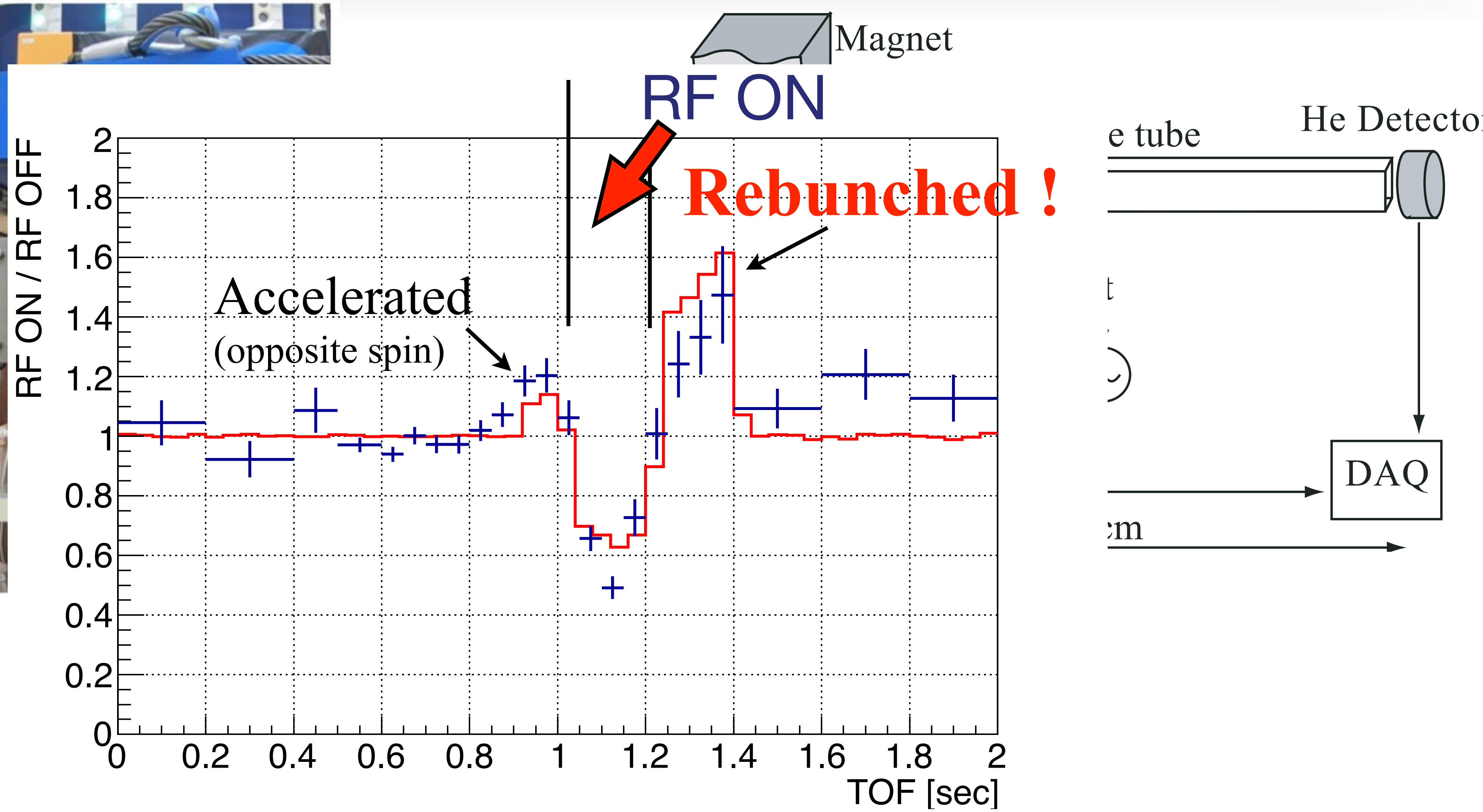
Blue : Exp. Data
Red : Simulation

Y. Arimoto, et., al.,
Phys. Rev. A 86, 023843 (2012).

Rebuncher







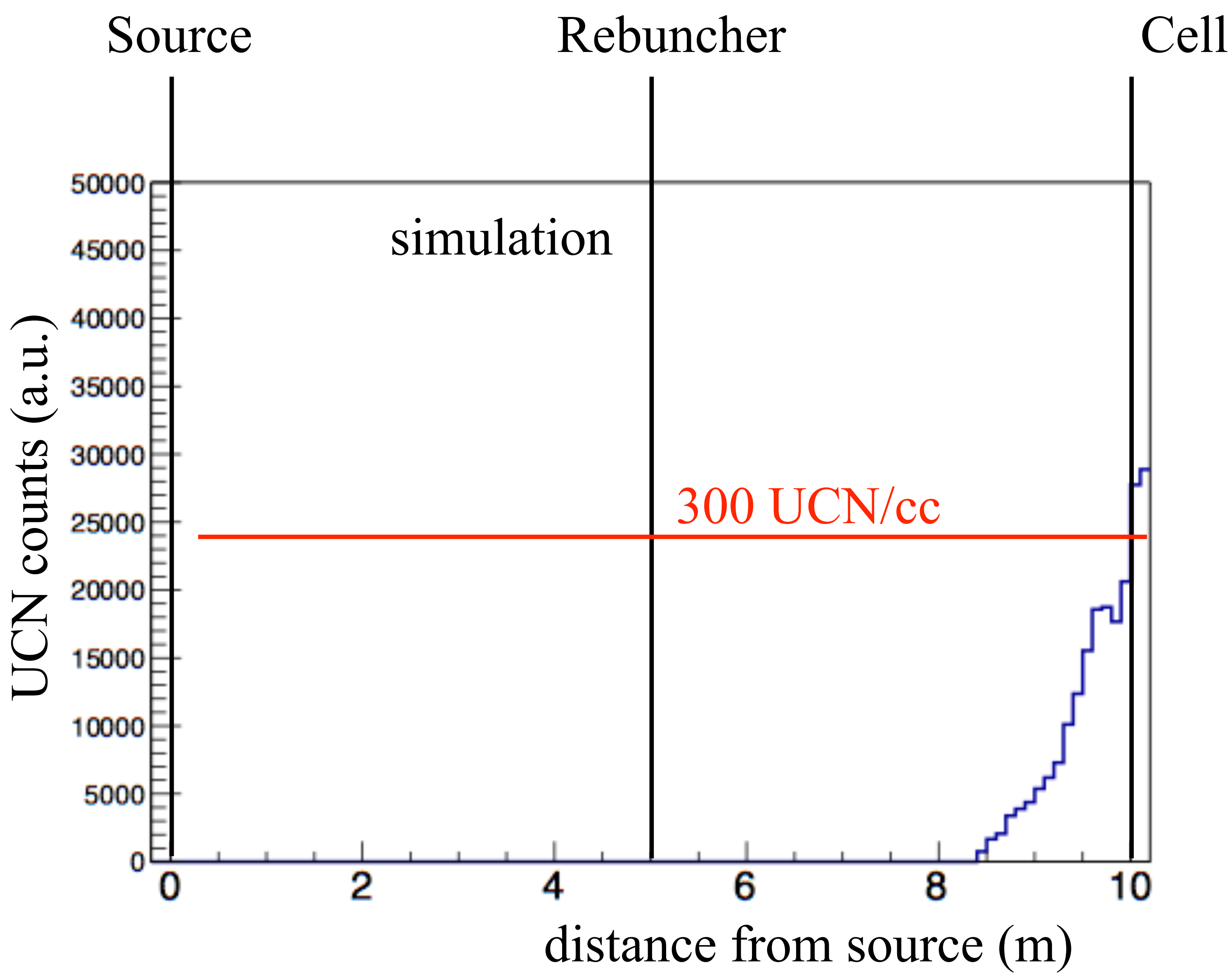
Blue : Exp. Data
Red : Simulation

Y. Arimoto, et., al.,
Phys. Rev. A 86, 023843 (2012).

Rebunching of UCNs was demonstrated !

Pulsed UCN transport

J-PARC LINAC



This shows only polarized UCNs which can be used for measurement.

Small converter is enough.

Statistical error

$$(\Delta d_n)_{\rm stat} = \frac{\hbar/2}{\alpha E T \sqrt{N}},$$

physics run 5000 h in one year,
100 s for one measurement,
E = 10 kV/cm, α = 0.75,

$$(\Delta d_n)_{\rm stat} \times \sqrt{\frac{100}{5000 \times 3600}} = 10^{-27} \text{ e cm}$$

$$N = 1.1 \times 10^6$$

For example, cylindrical cell with 20cm diameter, 20cm high,

density = 175 UCN/cc

Understanding of systematic uncertainties

Simulation of UCN movement

When the randomization of UCN movement in the storage cell is not perfect, false EDM appears.

We must understand how much the injected UCNs are randomized in a finite storage time with real surface of the cell.

➔ **UCN precision optics**

We have developed the simulation tools based on GEANT4.

. Add the reflection law
. Incorporate relativistic spin precession
. Adopt high precision variable to avoid rounding error

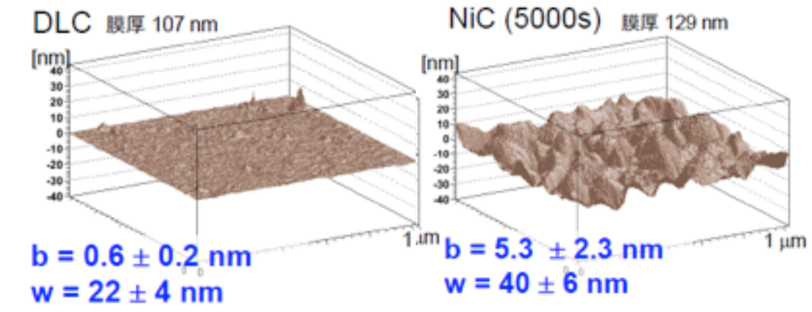
Now we can estimate the false EDM by movement of UCNs in the cell with actual surface.

Other development items

DLC mirror

Neutron mirror with high reflectivity on complex shape can be fabricated using diamond-like carbon by CVD.

potential 240 neV
off-specular reflection < 1%



Hg Co-magnetometer

Hg laser with power of 1mW/cm^2 and frequency accuracy better than 1MHz can measure the magnetic field of the order of 0.1 fT by Faraday rotation method.

Hg laser

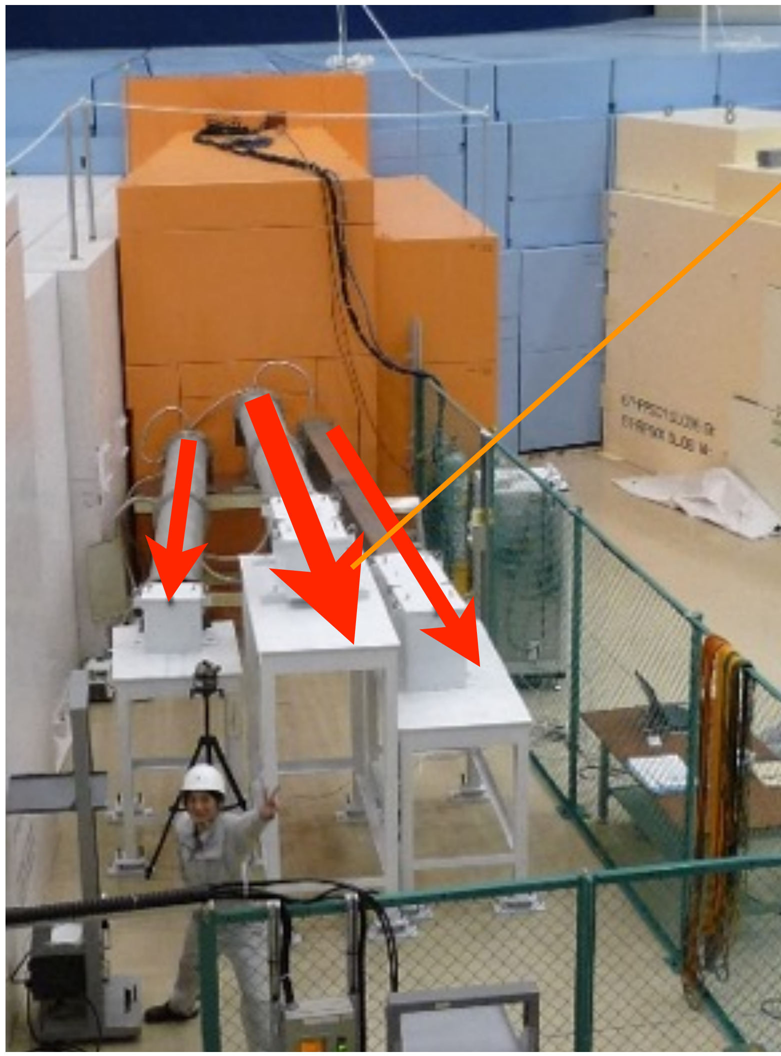
Kyoto Univ.

VCN moderator and UCN converter

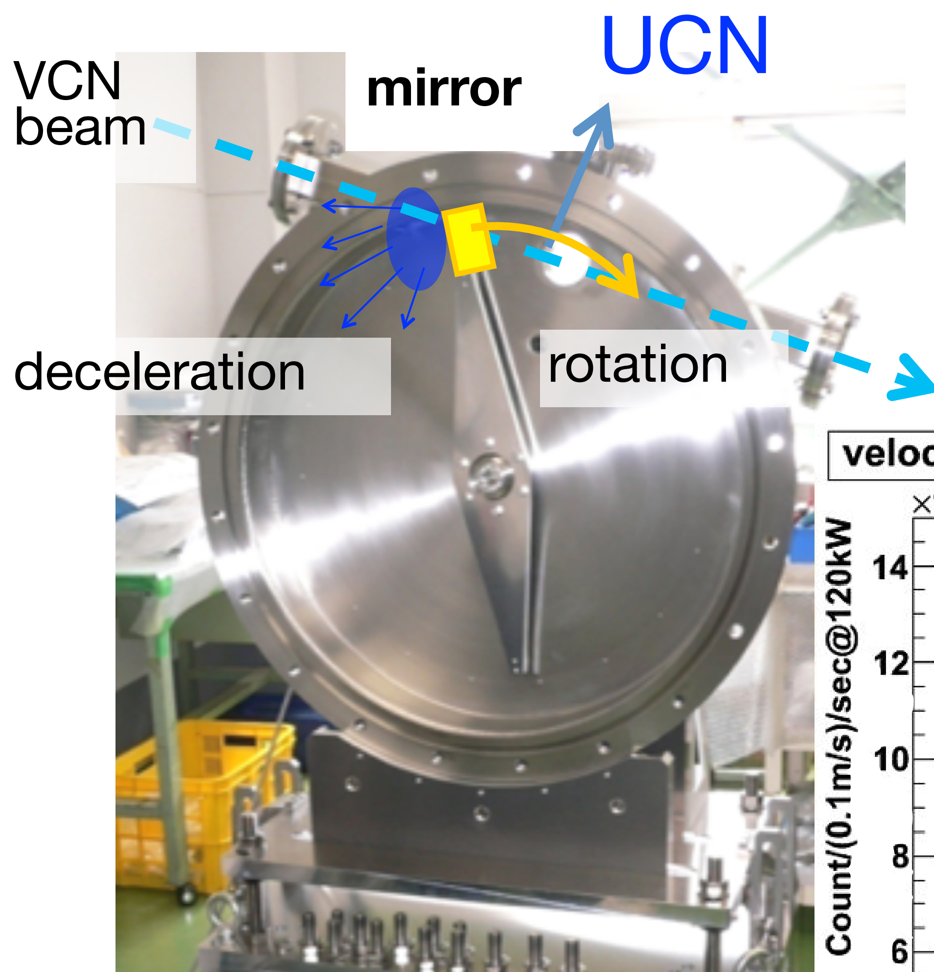
Injecting Very-Cold Neutrons should be increased before the UCN converter. Optimization of the shape of moderator is required.
For pulsed UCN, high production rate and fast extraction are better.

Development of UCN optical devices

To develop UCN optical devices, our own UCN generator was constructed at J-PARC MLF BL05 (NOP beam line).

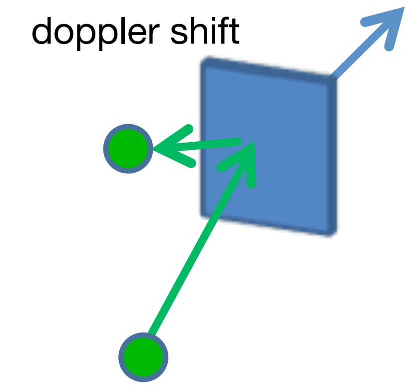


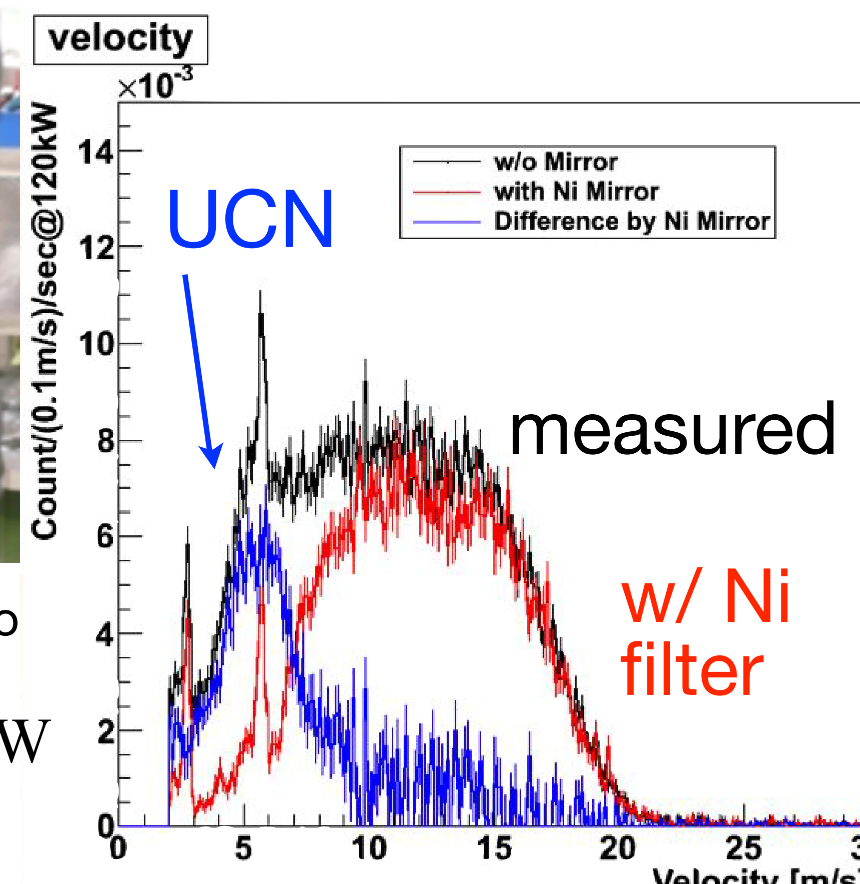
Three branches of cold neutrons are extracted through the supermirror bender.



high Qc mirror for direct reflectio
m=10, R=0.4

~1 cps @ 120kW





Summary

Neutron is suitable for the precision measurement of the small influence of new physics beyond the standard model of elementary particles.

Precision measurement of neutron lifetime has started at J-PARC BL05 NOP.

Spin Flip Chopper and Time Projection Chamber enables us to perform extremely-low back ground experiment.

We are now planning the new nEDM experiment using UCN precision optics at high intensity pulsed beam facility, J-PARC.

In order to increase the sensitivity of the experiment using UCNs, UCN optical devices has been developed.

Various experiments are planning and now under developing.

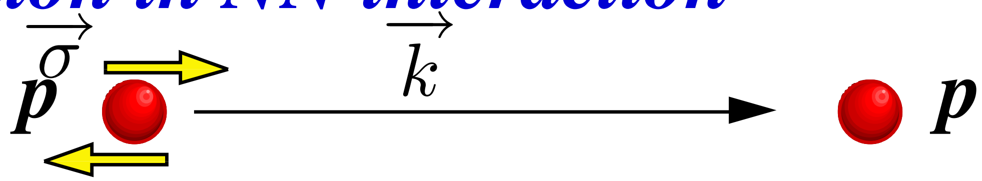
複合核共鳴吸収反応

P対称性

Helicity Dependence of Cross Section

非対称度～10^{-7}

P-violation in NN interaction



15MeV	$-(1.7\pm0.8)\times10^{-7}$
45MeV	$-(2.3\pm0.8)\times10^{-7}$
45MeV	$-(1.3\pm0.8)\times10^{-7}$
800MeV	$-(2.4\pm1.1\pm0.1)\times10^{-7}$

Epithermal Neutron Capture Reactions

P-violation 増幅率～10^6

$$\Delta\sigma_{\mathrm{P}}^{nA} \leq \Delta\sigma_{\mathrm{P}}^{NN} \times 10^6$$

複合核共鳴～10^{-1}

$^{139}La(E_n=0.734eV)$	0.097 ± 0.003 of p-wave resonance cross section
$^{81}Br(E_n=0.88eV)$	0.021 ± 0.001
$^{111}Cd(E_n=4.53eV)$	$-(0.013^{+0.007}_{-0.004})$

~ 2% of total cross section

複合核共鳴吸収反応

T対称性 でも同様の増幅効果がある可能性がある

meson交換によるEDM（chromo-EDM）のみ着目

$$\left|\Delta\sigma_{\mathrm{T}}^{nA}\right| \le 10^6 \times \kappa(J)\left[\bar{g}_\pi^{(0)} + 0.26\bar{g}_\pi^{(1)} - 0.0012\bar{g}_\eta^{(0)} + 0.0034\bar{g}_\eta^{(1)} - 0.0071\bar{g}_\rho^{(0)} + 0.0035\bar{g}_\rho^{(1)} + 0.0019\bar{g}_\omega^{(0)} - 0.00063\bar{g}_\omega^{(1)}\right]$$

$$\simeq 10^5[\mathrm{b}] \times \boxed{\kappa(J)} \times \boxed{\bar{g}_\pi^{(0)}}$$

nEDMの上限値 $|d_n| < 2.9 \times 10^{-26}[\mathrm{e\ cm}]$ は $\bar{g}_\pi^{(0)} < 2.5 \times 10^{-10}$ に対応

$$\Rightarrow \quad \left|\Delta\sigma_{\mathrm{T}}^{nA}\right| < 2.5 \times 10^{-4}[\mathrm{b}] \times \boxed{\kappa(J)}$$

$0.25[\mathrm{mb}] \times \kappa(J)$ **より高い精度で測定すると、**

nEDMより高感度で新物理探索

複合核共鳴吸収反応

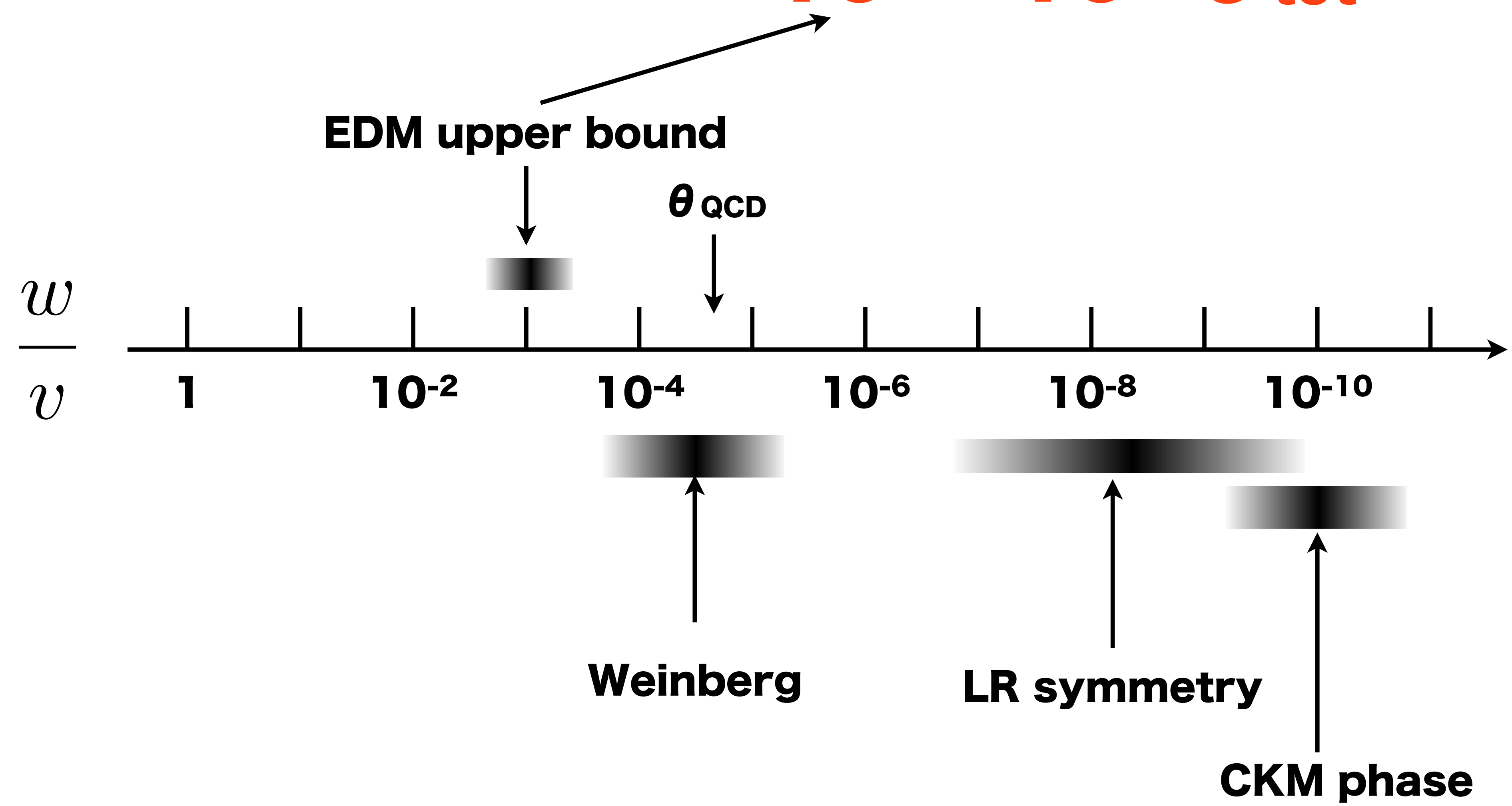
Gudkov, Phys. Rep. 212 (1992) 77

T対称性

$$\Delta\sigma_{\mathrm{CP}} = \kappa(J)\frac{w}{v}\Delta\sigma_{\mathrm{P}}$$

T-violation　　g_{CP}/g_P　　P-violation

測定すべき非対称度　　10^{-3}　　$10^{-2}\sigma_{tot}$



複合核共鳴吸収反応

Gudkov, Phys. Rep. 212 (1992) 77

T対称性

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T-violation　　g_{CP}/g_P　　P-violation

測定すべき非対称度　　10^{-3}　　$10^{-2}\sigma_{\mathrm{tot}}$

$$\kappa(J = I + \frac{1}{2}) = \frac{3}{2\sqrt{2}}\left(\frac{2I+1}{2I+3}\right)\frac{\sqrt{2I+1}(2\sqrt{I}x - \sqrt{2I+3}y)}{(2I-3)\sqrt{2I+3}x - (2I+9)\sqrt{I}y}$$

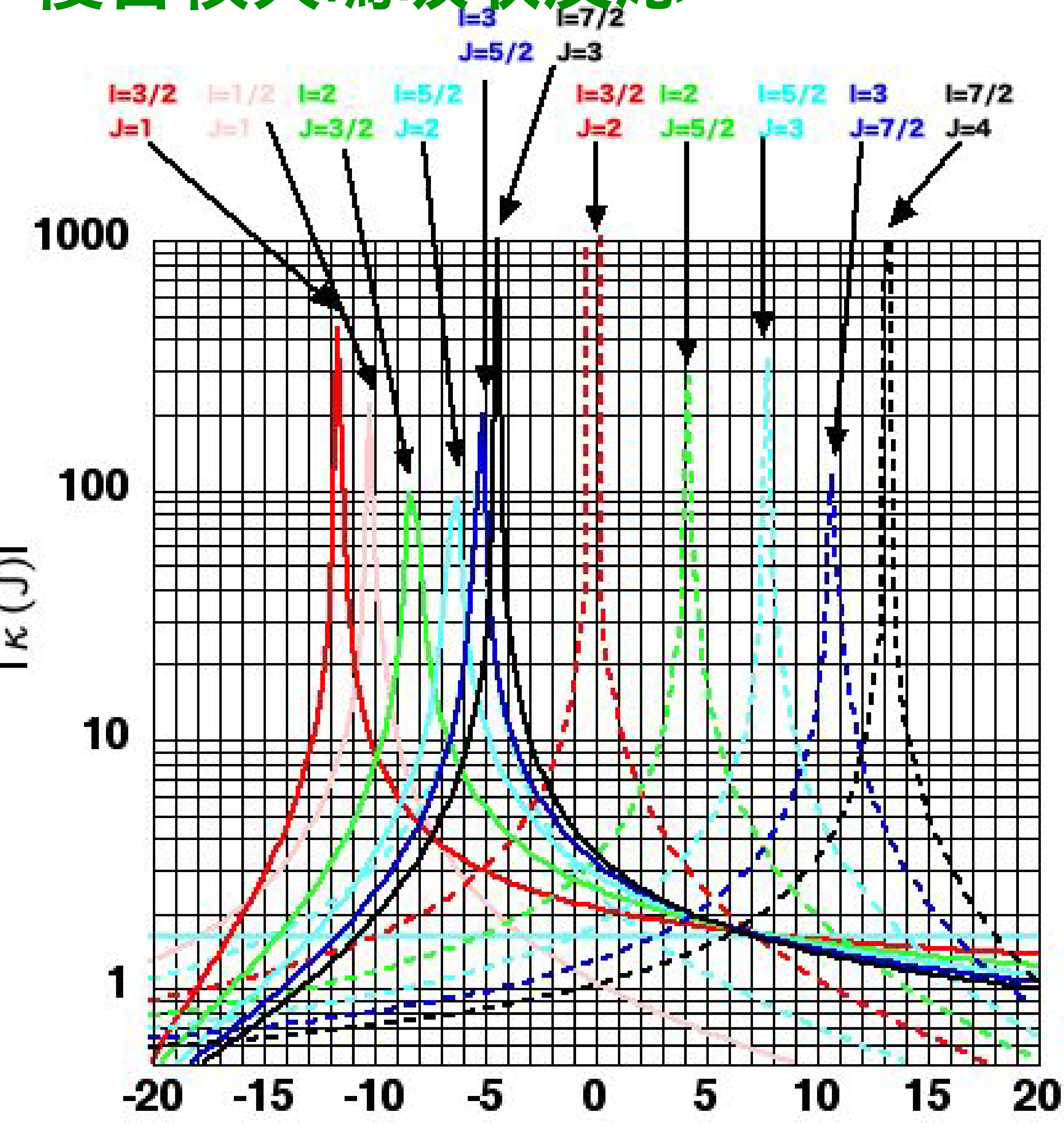
$$\kappa(J = I - \frac{1}{2}) = -\frac{3}{2\sqrt{2}}\left(\frac{(2I+1)\sqrt{I}}{\sqrt{(I+1)(2I-1)}}\right)\frac{2\sqrt{I+1}x + \sqrt{2I-1}y}{(I+3)\sqrt{2I-1}x + (4I-3)\sqrt{I+1}y}$$

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

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

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

複合核共鳴吸収反応



ov, Phys. Rep. 212 (1992) 77

$$\frac{w}{v}\Delta\sigma_{\mathrm{P}}$$

cP/gP P-violation

0^{-3} $10^{-2}\sigma_{tot}$

$$x = \cos\phi$$

$$y = \sin\phi$$

複合核共鳴吸収反応

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

$$a_0 = \sum_{J_s} |V_1(J_s)|^2 + \sum_{J_s, j} |V_2(J_p j)|^2$$

Flambaum, Nucl. Phys. A435 (1985) 352

$$a_1 = 2\mathrm{Re} \sum_{J_s, J_p, j} V_1(J_s) V_2^*(J_p j) P(J_s J_p \frac{1}{2} j 1 I F)$$

$$a_3 = \mathrm{Re} \sum_{J_s, j, J'_p, j'} V_2(J_p j) V_2^*(J'_p j') P(J_p J'_p j j' 2 I F) 3\sqrt{10} \left\{\begin{array}{ccc} 2 & 1 & 1 \\ 0 & \frac{1}{2} & \frac{1}{2} \\ 2 & j & j' \end{array}\right\}$$

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

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

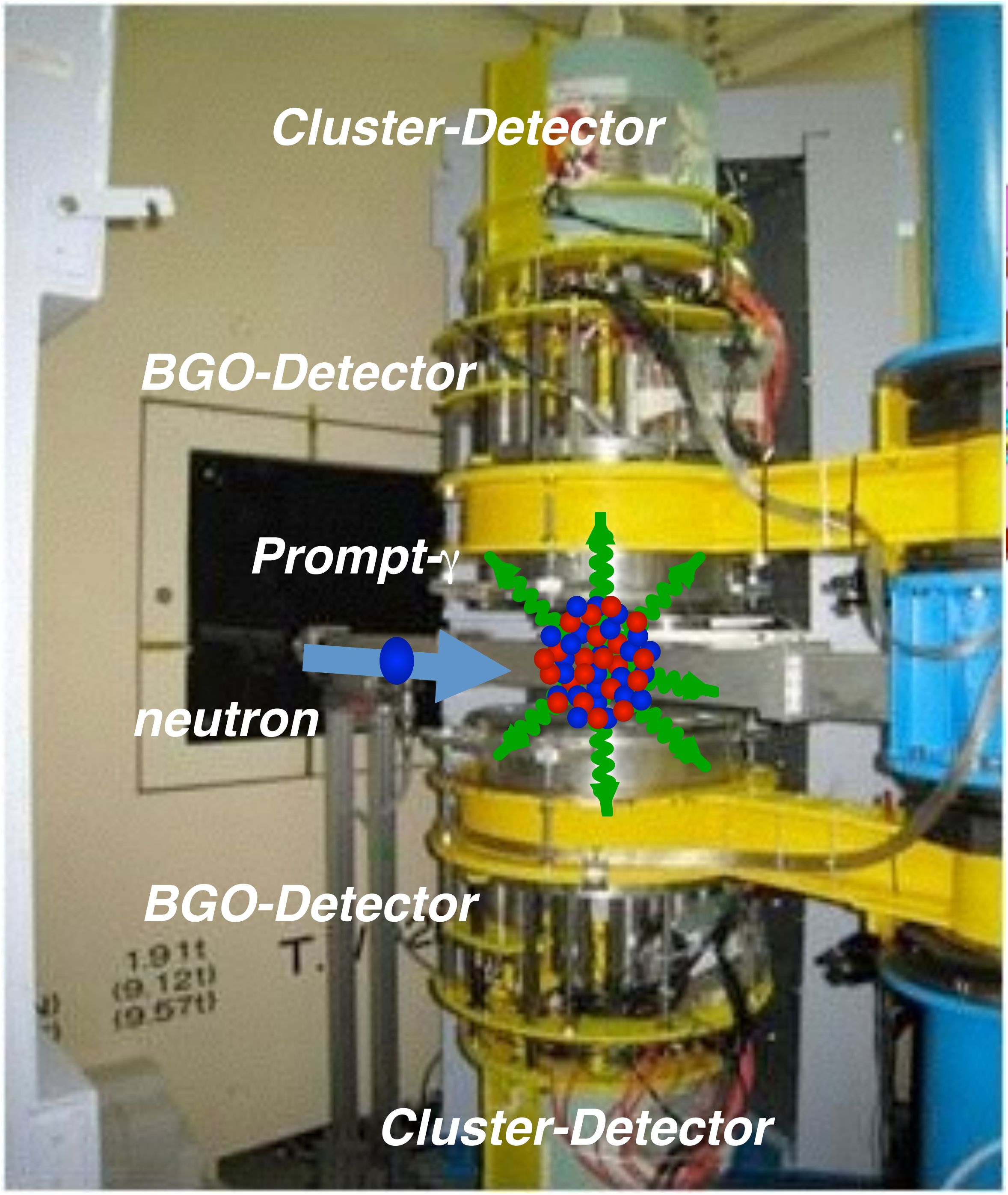
n, γ の角相関から φ が求まる

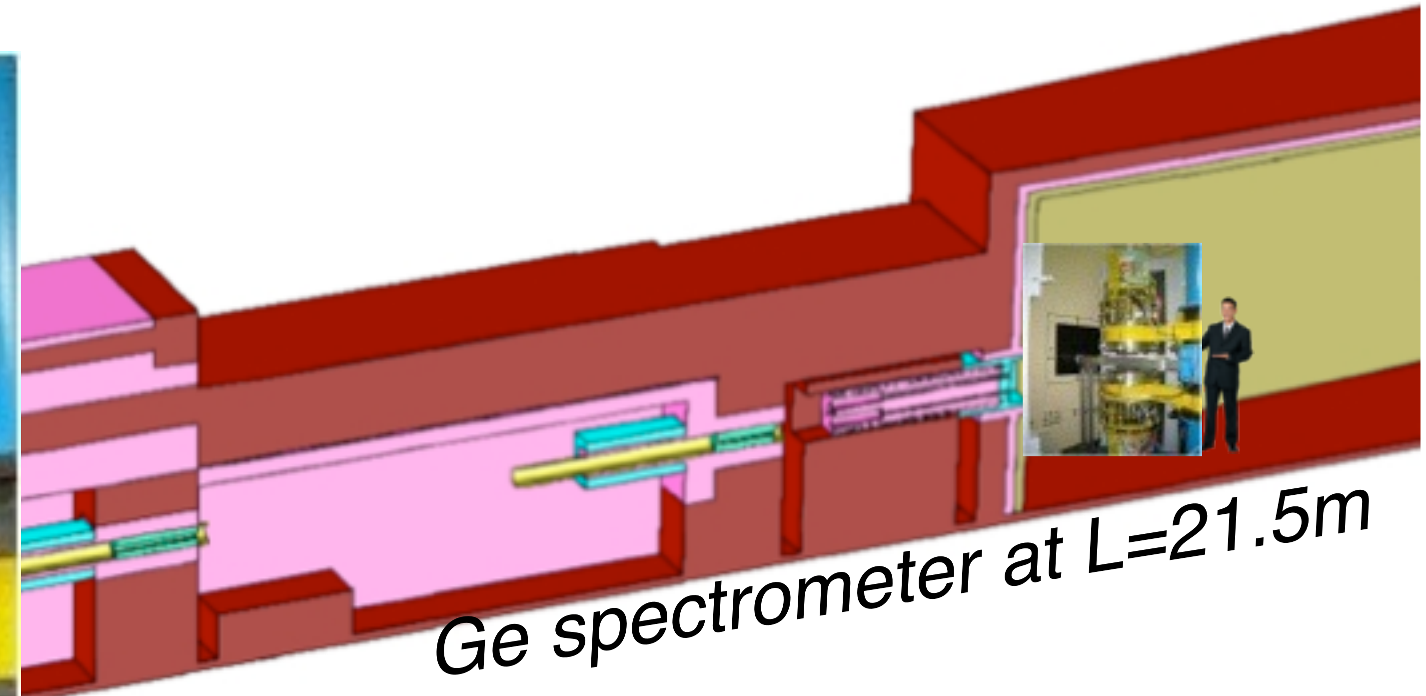
$V_2(j=1/2)=xV_2$
$V_2(j=3/2)=yV_2$

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

複合核共鳴吸収反応

MEASUREMENT OF NEUTRON-CAPTURE CROSS SECTION with 4πGe at ANNRI





The 4πGe spectrometer

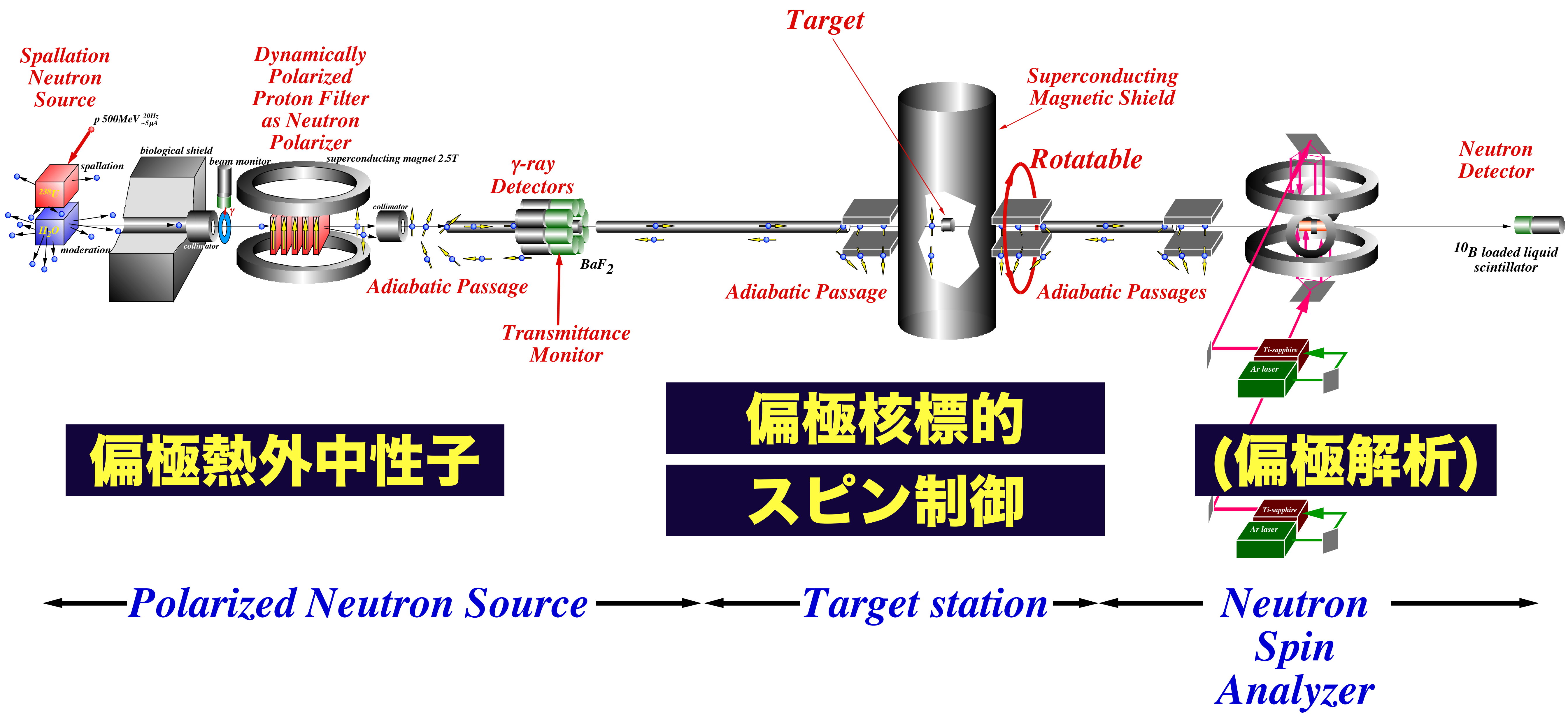
- ***Two Cluster Ge detectors with BGO anti-coincidence shields were used.***
- ***One to Eight coaxial Ge detectors can be installed.***

The beam condition

- ***120 kW, 25 Hz, Double-Bunch***
- ***Notch filters: Mn, Co, In, Ag, Cd***

複合核共鳴吸収反応

実験の概念図



偏極熱外中性子

偏極核標的
スピン制御

(偏極解析)

複合核共鳴吸収反応

増幅効果が大きければ
新物理の探索感度が急激に向上しうる

κ (J)の大きな原子核の探索

J-PARC MLF BL04 での (n, γ)測定　⇒　進行中

$$\Delta\sigma_{\rm CP} = \kappa(J)\frac{w}{v}\Delta\sigma_{\rm P}$$

P非対称度 $$A_{\rm L} = -\frac{2xv}{E_{\rm p}-E_{\rm s}}\sqrt{\frac{\Gamma^n_{\rm s}}{\Gamma^n_{\rm p}}}$$

xは(n, γ)測定で分かる $$x^2 = \frac{\Gamma^n_{{\rm p},1/2}}{\Gamma^n_{\rm p}}$$

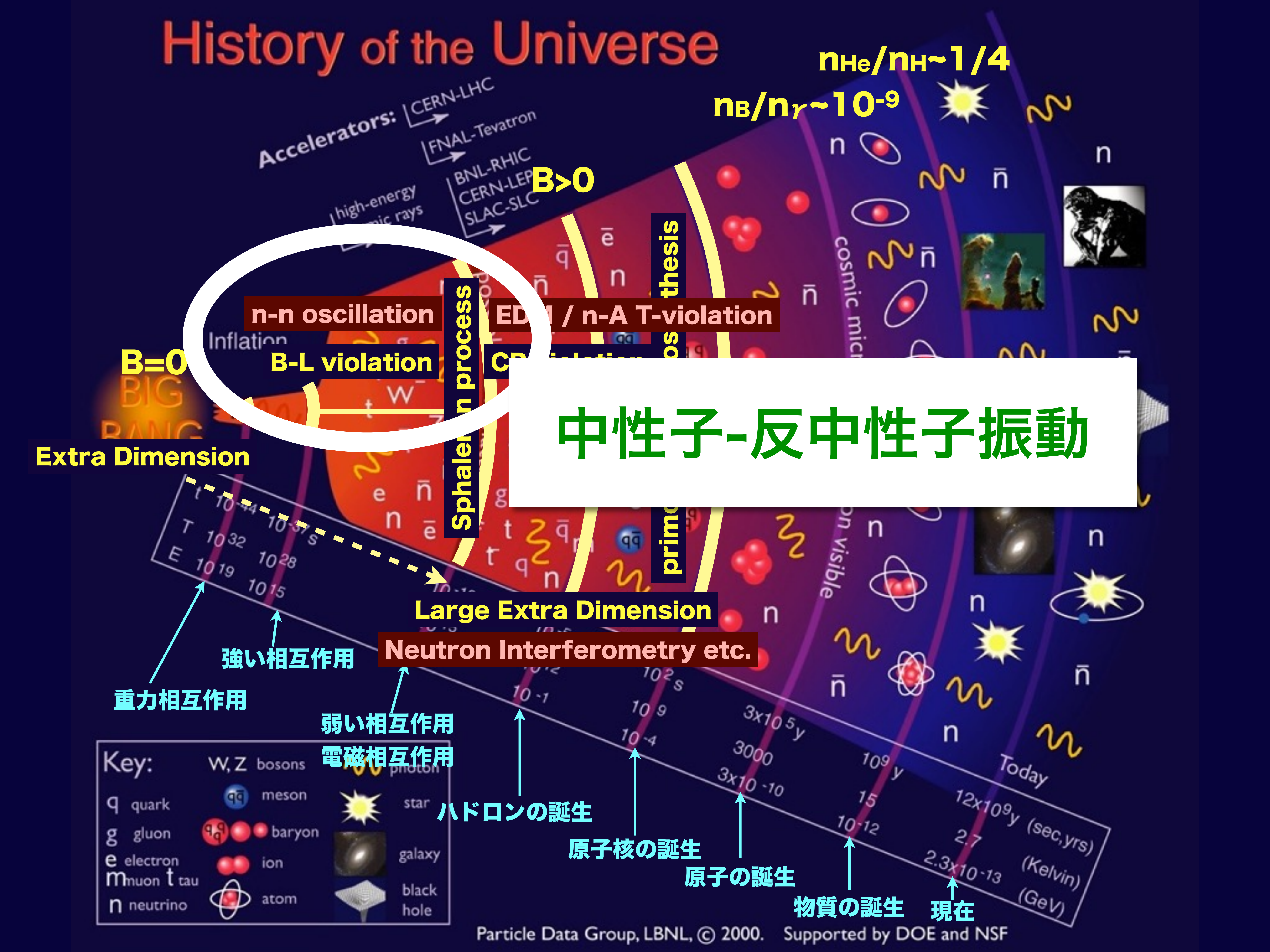
⇒　CPを破る行列要素 w

κ はxの関数 $$y^2 = \Gamma^n_{{\rm p},3/2}/\Gamma^n_{\rm p} = 1 - x^2$$

$$\kappa(J=I+\tfrac{1}{2}) = \frac{3}{2\sqrt{2}}\left(\frac{2I+1}{2I+3}\right) \times \frac{\sqrt{2I+1}(2\sqrt{I}x-\sqrt{2I+3}y)}{(2I-3)\sqrt{2I+3}x-(2I+9)\sqrt{I}y}$$

$$\kappa(J=I-\tfrac{1}{2}) = -\frac{3}{2\sqrt{2}}\left(\frac{(2I+1)\sqrt{I}}{\sqrt{(I+1)(2I-1)}}\right) \times \frac{2\sqrt{I+1}x+\sqrt{2I-1}y}{(I+3)\sqrt{2I-1}x+(4I-3)\sqrt{I+1}y}$$

新物理が核子間相互作用に与える効果のモデル計算


History of the Universe
n_{He}/n_H~1/4
n_B/n_γ~10^{-9}
Accelerators: CERN-LHC FNAL-Tevatron BNL-RHIC CERN-LEP SLAC-SLC
high-energy cosmic rays
B>0
B=0
n-n oscillation
B-L violation
Inflation
Sphaleron process
EDM / n-A T-violation
CP violation
primordial nucleosynthesis
cosmic microwave
visible
中性子-反中性子振動
Extra Dimension
Large Extra Dimension
Neutron Interferometry etc.
強い相互作用
重力相互作用
弱い相互作用
電磁相互作用
ハドロンの誕生
原子核の誕生
原子の誕生
物質の誕生
現在
Today
(sec,yrs)
(Kelvin)
(GeV)
Key: W,Z bosons; q quark; g gluon; e electron; muon; tau; neutrino; meson; baryon; ion; atom; photon; star; galaxy; black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

中性子反中性子振動

Sakharovの3条件

1. B非保存
2. C, CP非保存
3. 熱平衡からのズレ

$$B_f = \frac{8N_g + 4}{22N_g + 13}(B-L)_i \simeq 0.35(B-L)_i$$ for SM and MSSM

$$B_i \neq 0,\ (B-L)_i = 0 \rightarrow B_f = 0$$ ~~SU(5) GUT Baryogenesis~~

$$B_i = 0,\ L_i \neq 0, (B-L)_i \neq 0 \rightarrow B_f \neq 0$$ Leptogenesis

ニュートリノ質量は極めて小さい

Seesaw Mechanism

重い右巻きマヨラナニュートリノ

崩壊 $N \rightarrow l + H\ (\Delta L = +1)$
$\rightarrow \bar{l} + \bar{H}\ (\Delta L = -1)$

両反応のレートが異なるとレプトン数が保たれない

→ Sphaleron → バリオン数

$$(B-L)_i = 0,\ (B+L)_i \neq 0 \rightarrow B_f \neq 0$$ Electroweak Baryogensis

KM行列だけではCPの破れが小さすぎる　etc.

中性子反中性子振動

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

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

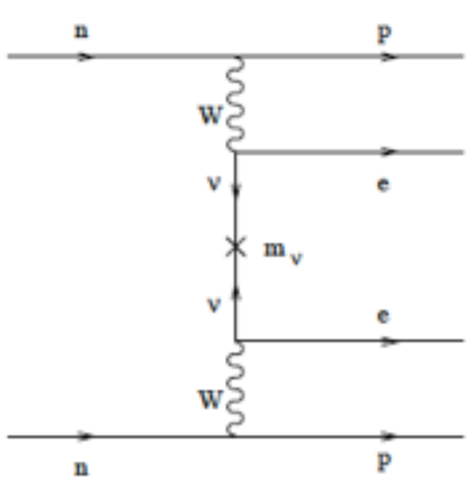
$$\psi = \begin{pmatrix} n \\ \bar{n} \end{pmatrix} \qquad M = \begin{pmatrix} E_0 & c^2\delta m \\ c^2\delta m & E_0 \end{pmatrix}$$

$$|n_{1,2}\rangle = \frac{1}{\sqrt{2}}\left(|n\rangle \pm |\bar{n}\rangle\right) \qquad m_{1,2} = m_n \pm \delta m$$

$$I(t) = I(0)\sin^2 \frac{c^2\delta m}{\hbar} t$$

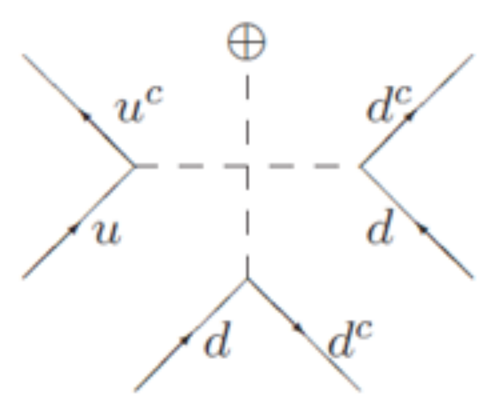
$$\delta m \propto \frac{1}{m_\nu}$$

Neutrinoless Double Beta Decay: $n + n \rightarrow p + p + e^- + e^-$ B=2; L=0; Neutron-Antineutron Oscillation: $n \leftrightarrow \bar{n}$

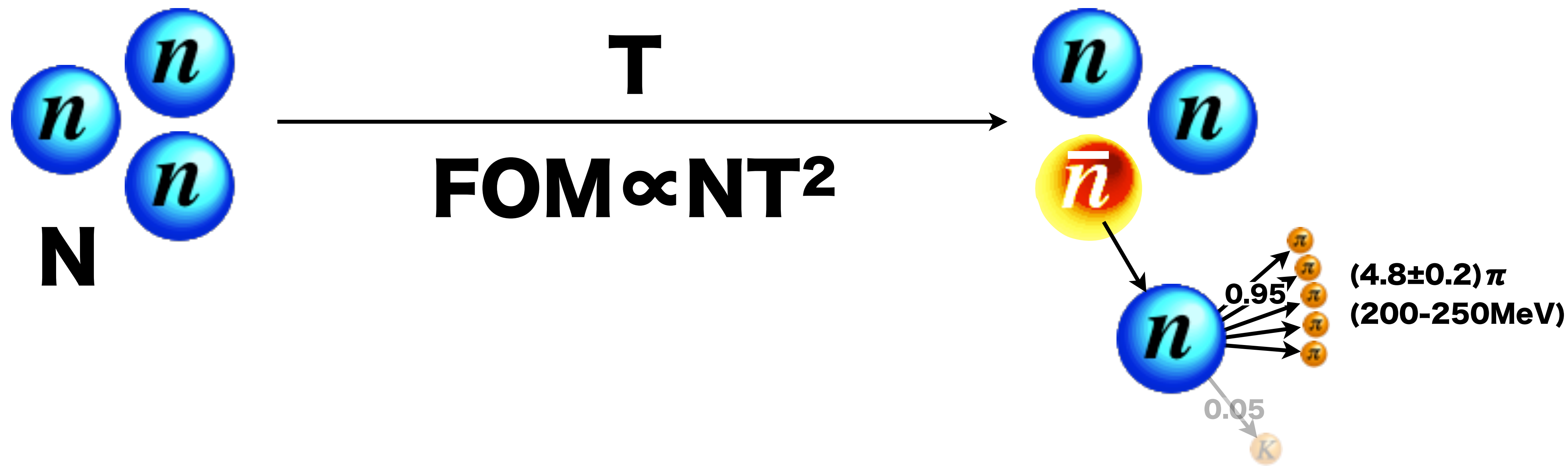


[W Fury]

[Marshak and Mohapatra]



中性子反中性子振動



free neutron $\tau_{n\bar{n},\mathrm{free}} > 8.6 \times 10^{7}\,\mathrm{s}\ (\mathrm{CL} = 90\%)$

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

$$\psi = \begin{pmatrix} n \\ \bar{n} \end{pmatrix} \qquad M = \begin{pmatrix} E_0 & c^2 \delta m \\ c^2 \delta m & E_0 \end{pmatrix}$$

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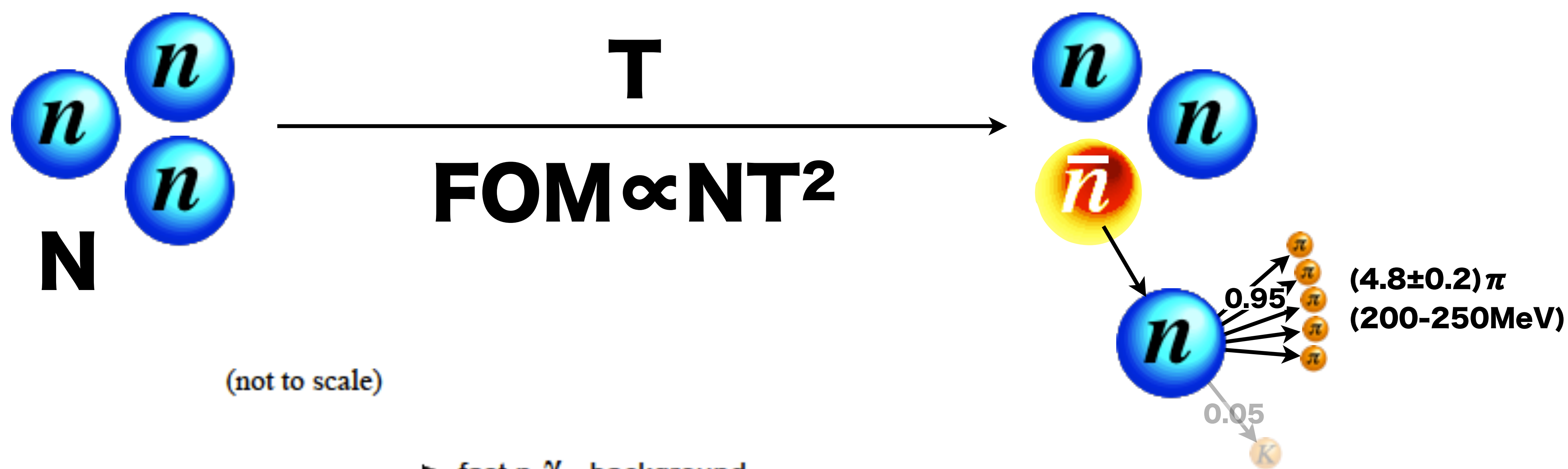
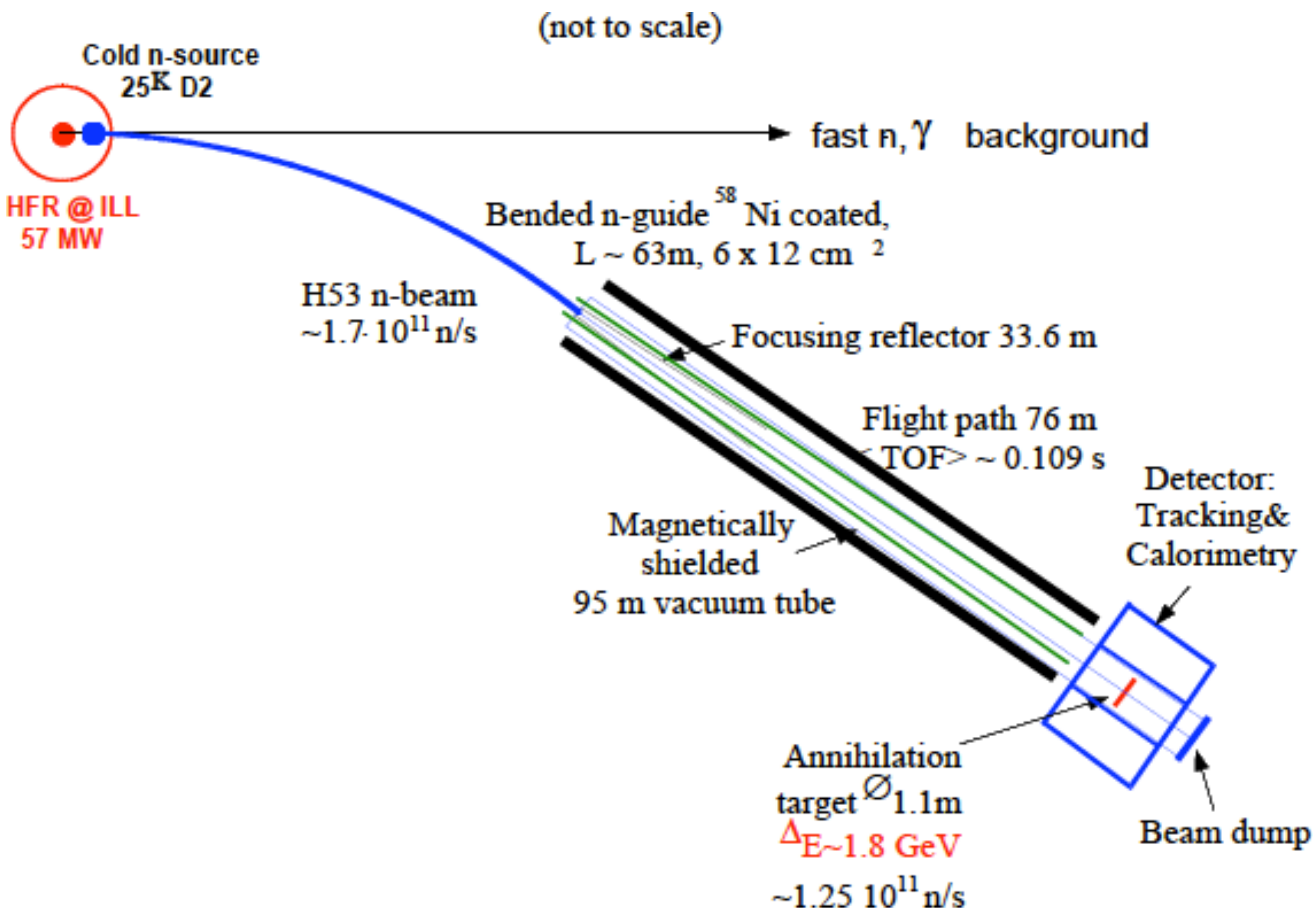
中性子反中性子振動



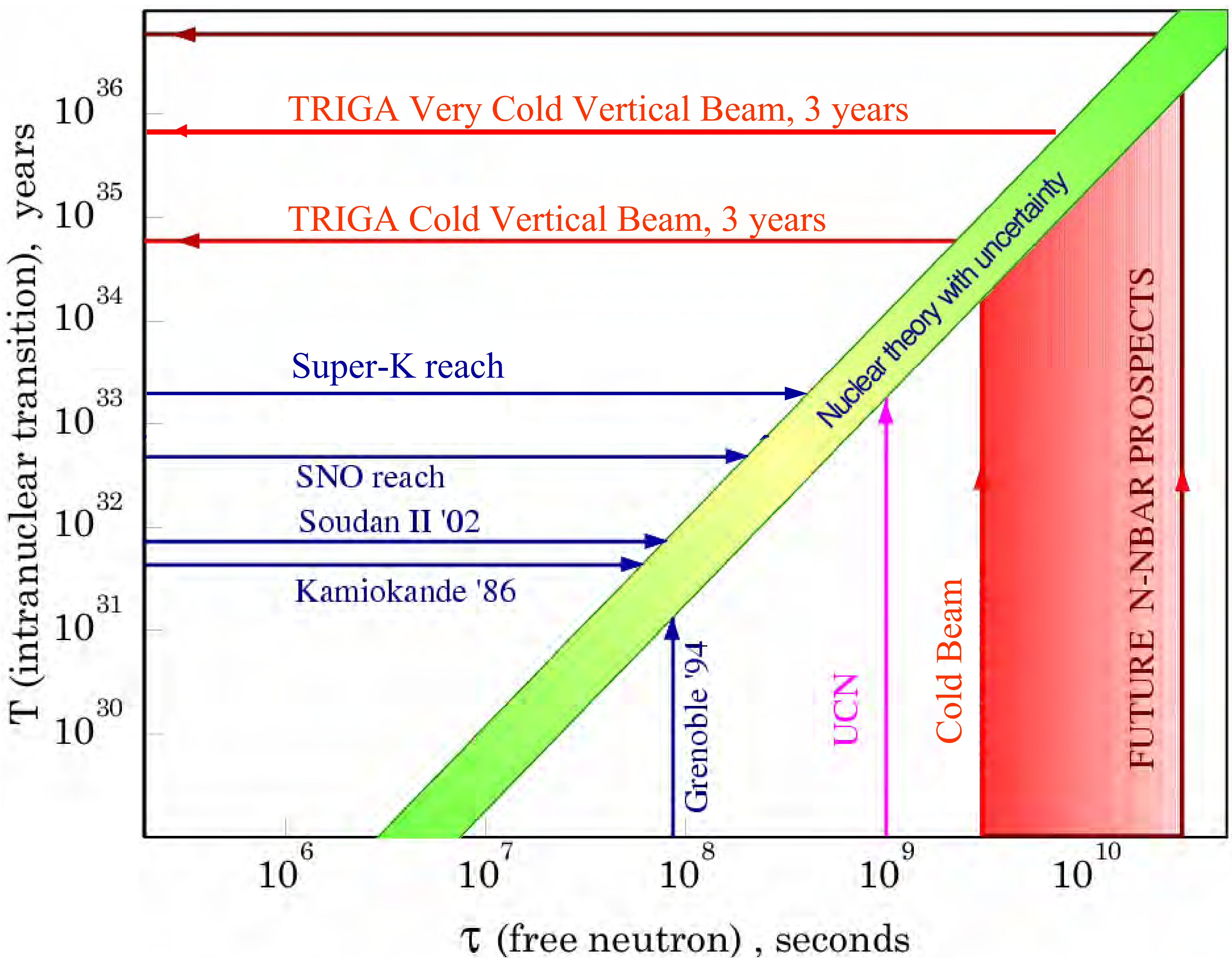


$$\tau_{n\bar{n},\mathrm{free}} > 8.6 \times 10^{7}\,\mathrm{s}\ (\mathrm{CL} = 90\%)$$

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

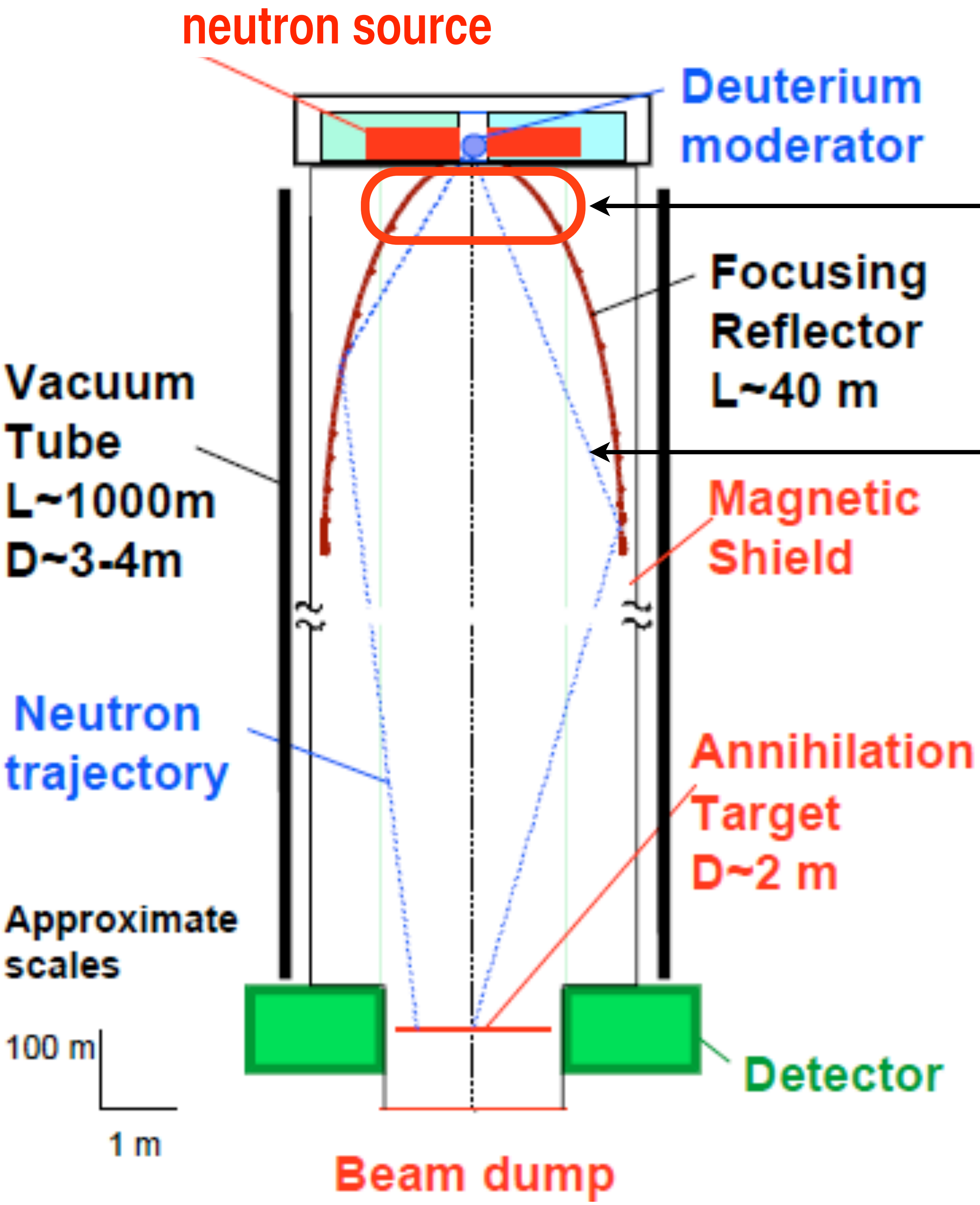
$\Omega \sim 2\pi \times 60\ \mu\mathrm{sr}$

中性子反中性子振動


TRIGA Very Cold Vertical Beam, 3 years
TRIGA Cold Vertical Beam, 3 years
Super-K reach
SNO reach
Soudan II '02
Kamiokande '86
Nuclear theory with uncertainty
Grenoble '94
UCN
Cold Beam
FUTURE N-NBAR PROSPECTS
T (intranuclear transition), years
τ (free neutron) , seconds

中性子反中性子振動

Fermilab ProjectX
NNbarX



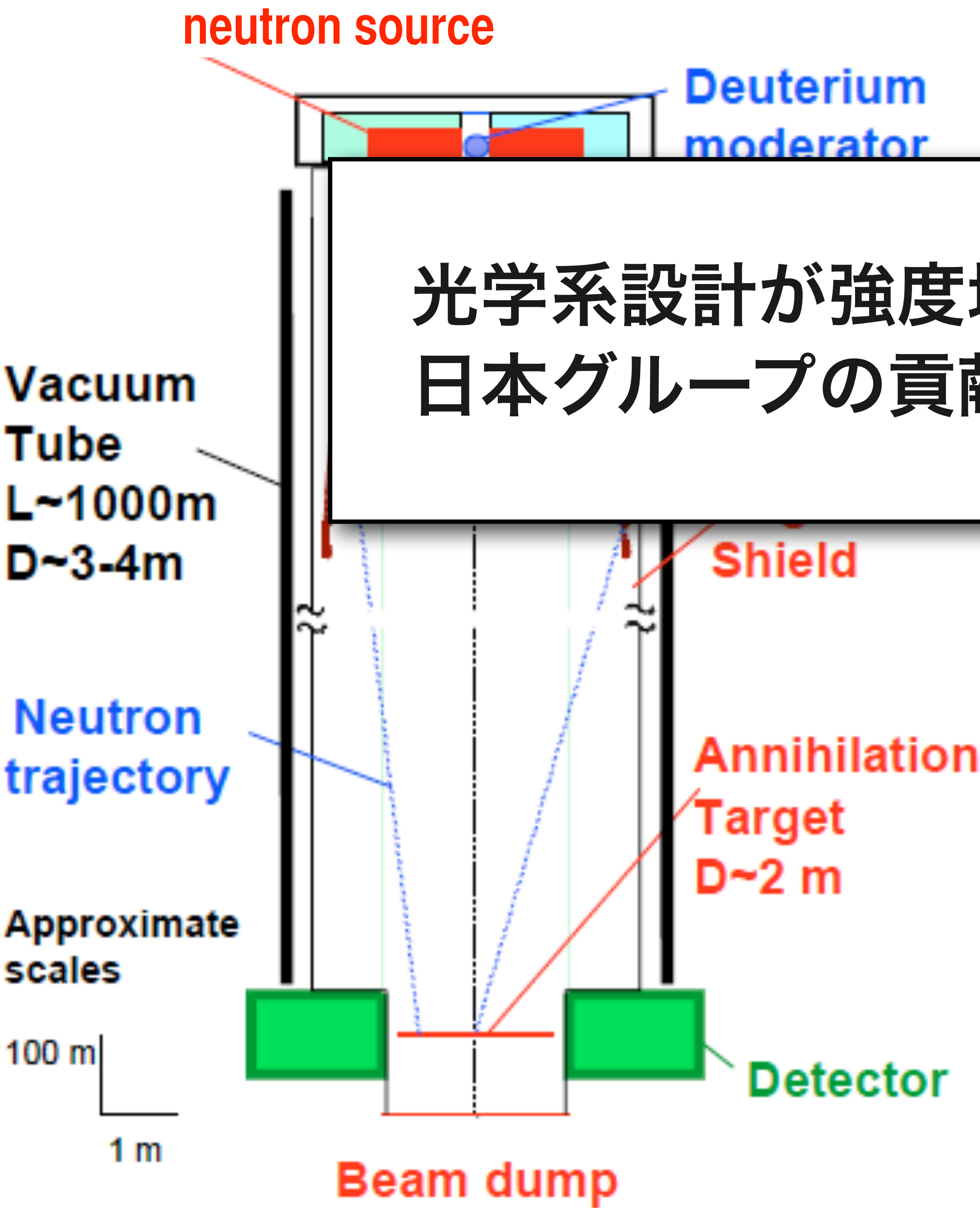
acceptance is dominated here

reflection angle is well-defined

band reflector is applicable

中性子反中性子振動

Fermilab ProjectX NNbarX

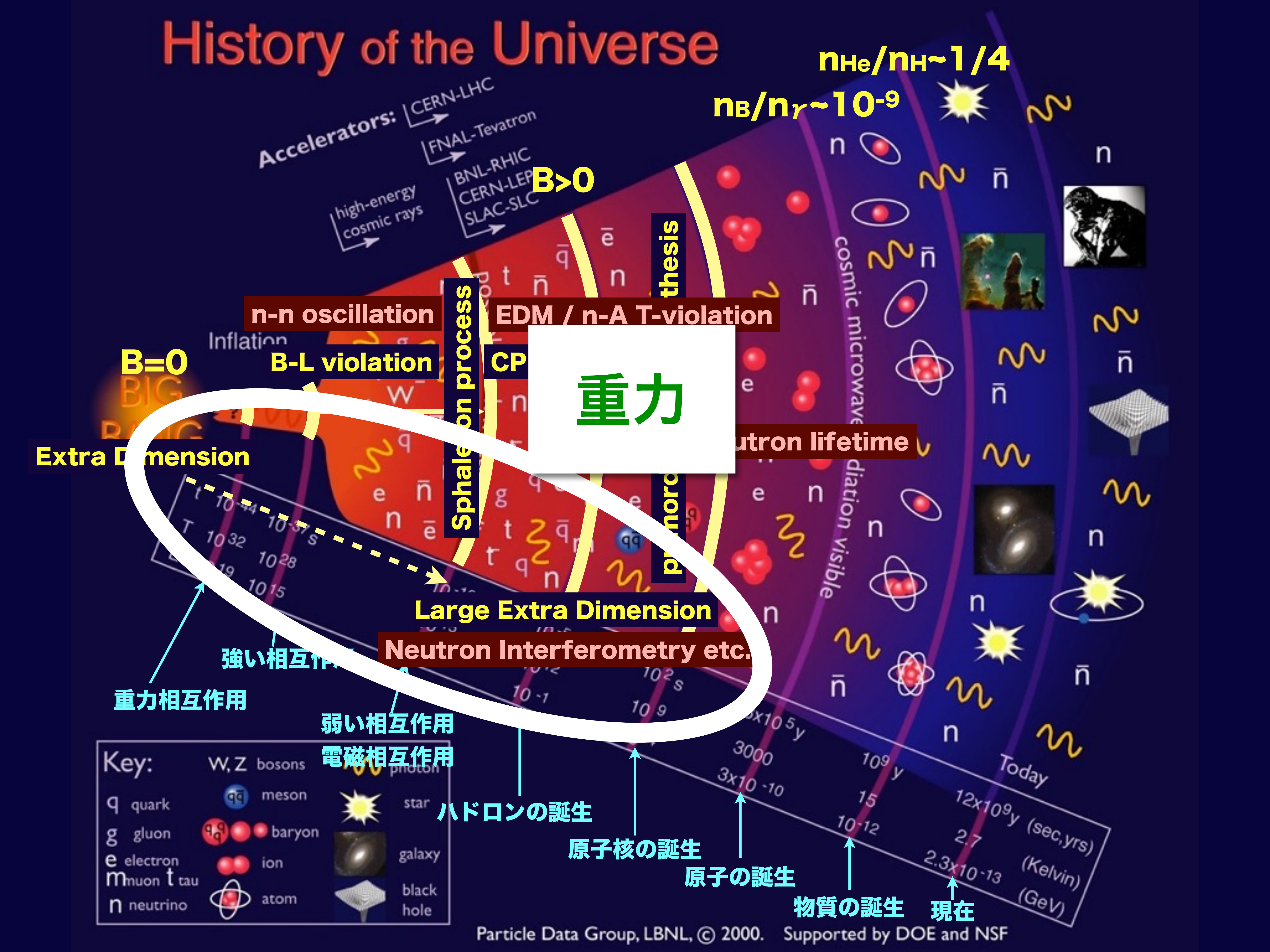


光学系設計が強度増加の鍵
日本グループの貢献が期待されている

…ated here

…ell-defined

band reflector is applicable



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B>0
B=0
Inflation
n-n oscillation
B-L violation
EDM / n-A T-violation
CP
重力
Sphaleron process
Neutron lifetime
Extra Dimension
Large Extra Dimension
Neutron Interferometry etc.
cosmic microwave radiation visible
強い相互作用
重力相互作用
弱い相互作用
電磁相互作用
ハドロンの誕生
原子核の誕生
原子の誕生
物質の誕生
現在
Today
(sec,yrs)
(Kelvin)
(GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

末知短距離力・重力

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	重力 (Gravitational)	弱い力 (Electroweak)	電磁力 (Electromagnetic)	強い力 Fundamental	強い力 Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for 二つの陽子	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

何故重力だけが極端に弱い？

Gravity is not renormalizable.

Gravity is the nature of space time.

Gravity is essential at the Planck scale.

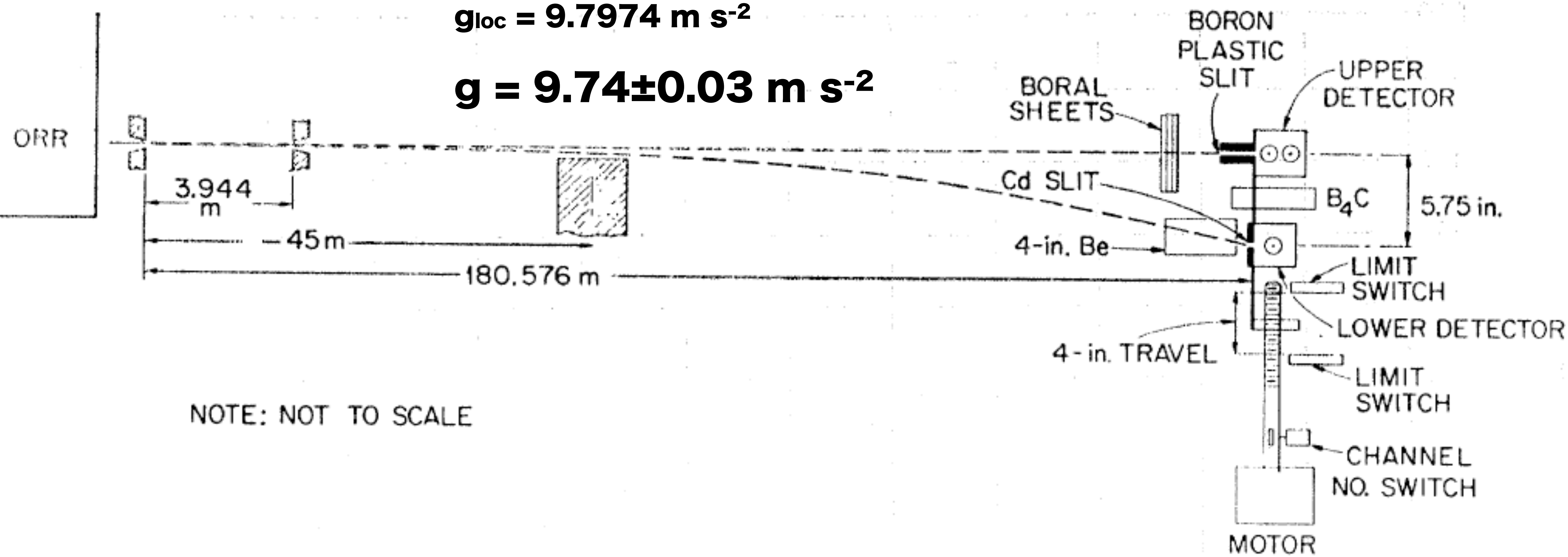
未知短距離力・重力

中性子は重力を感じる

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

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

g = 9.74±0.03 m s^{-2}



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

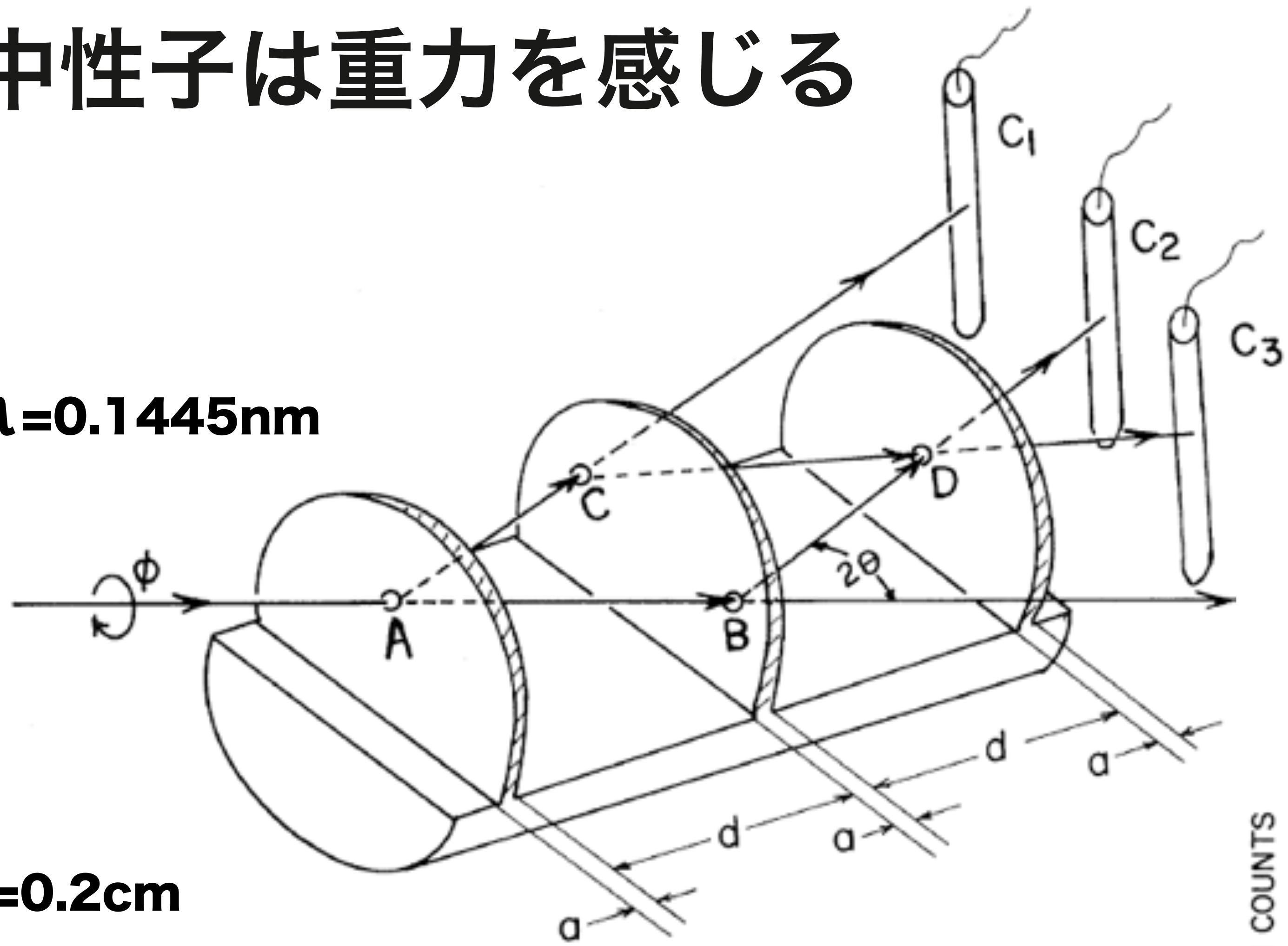
g = 9.801±0.013 m s^{-2}

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

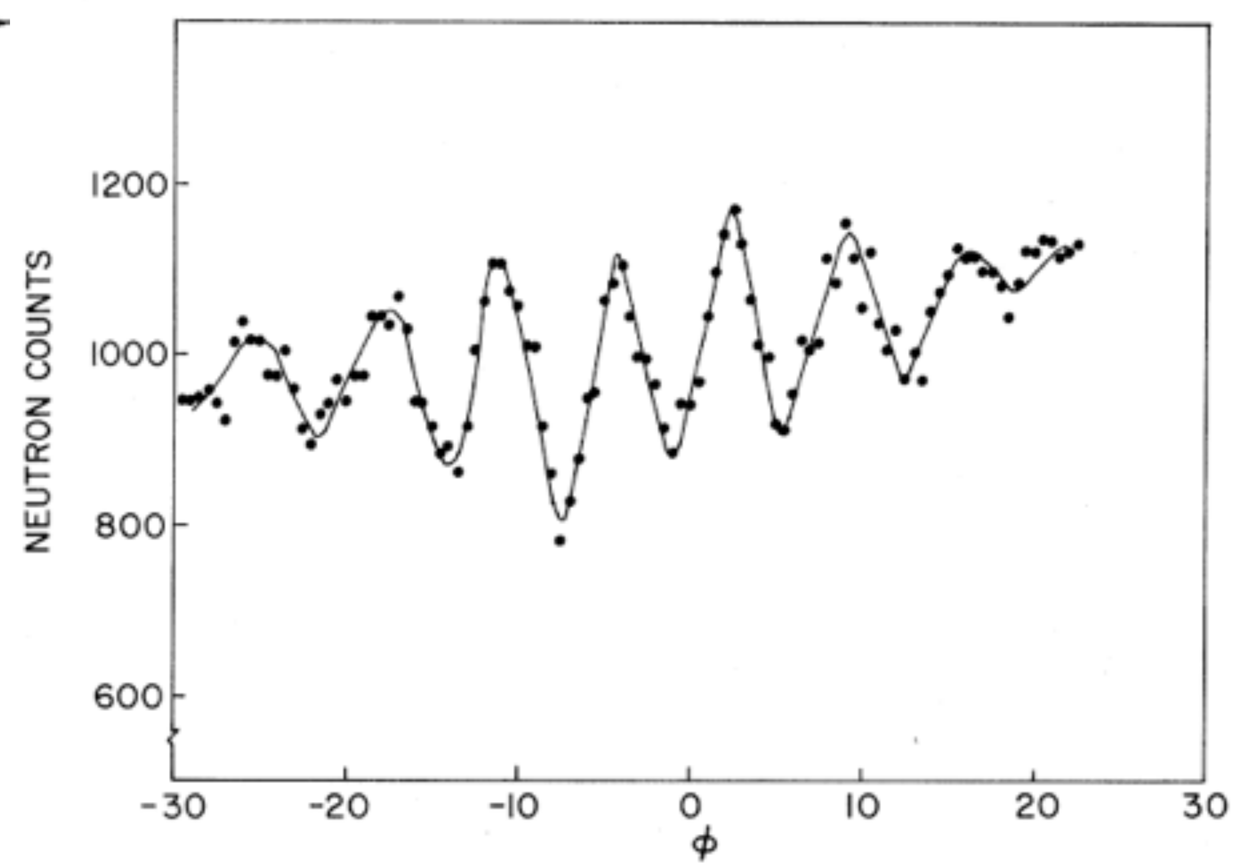
末知短距離力・重力

中性子は重力を感じる

λ=0.1445nm



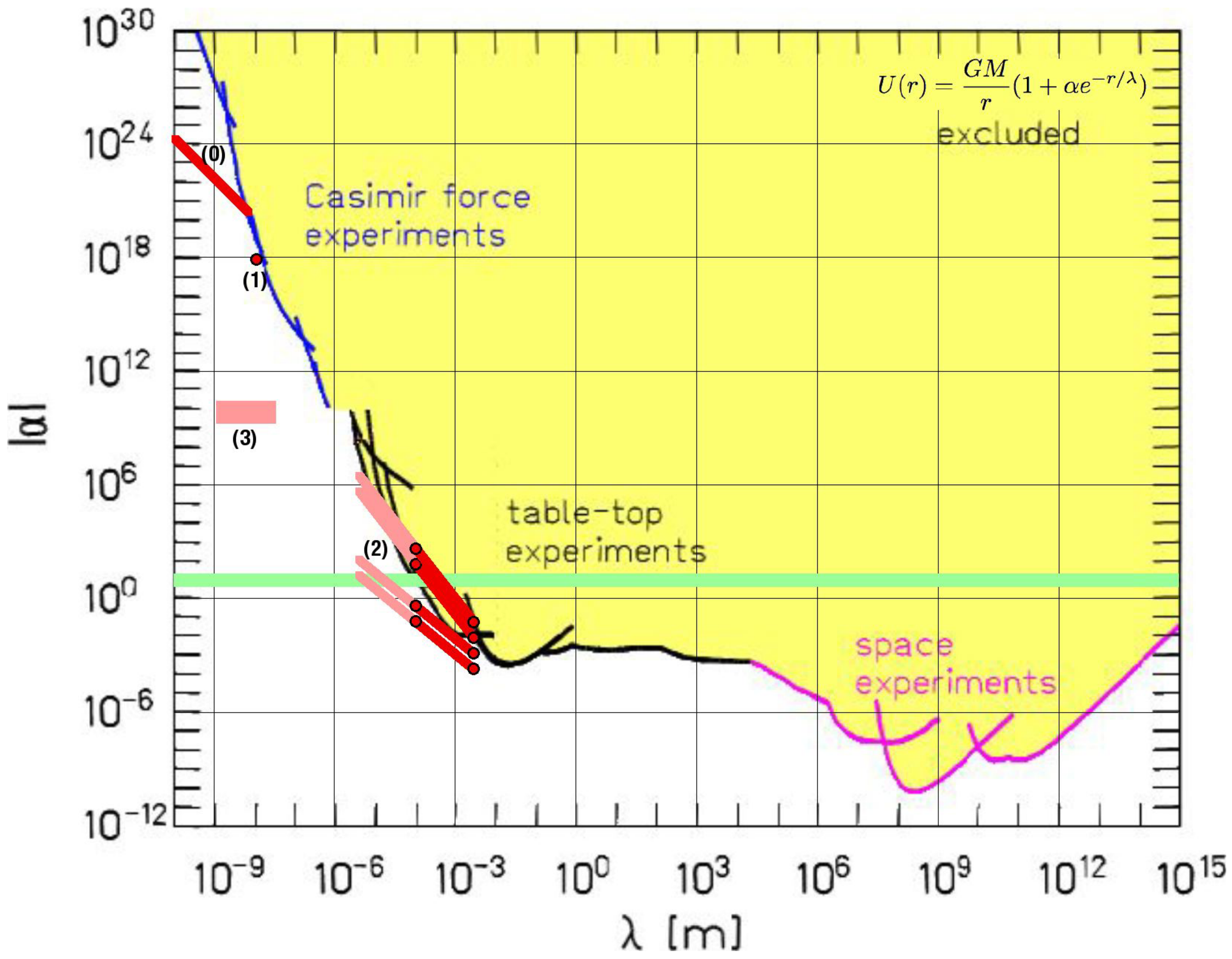
a=0.2cm
d=3.5cm
θ=22.1°



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

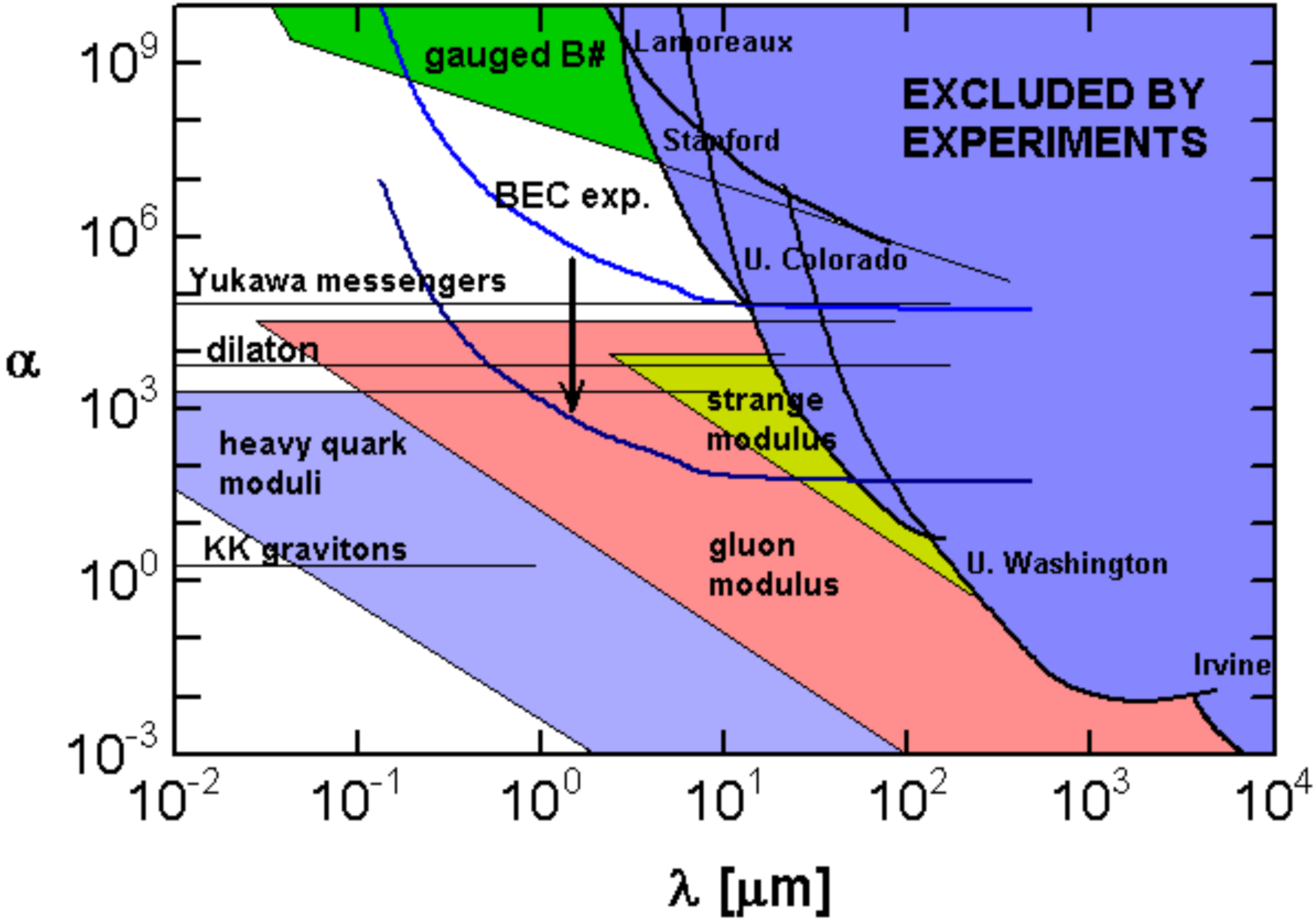
未知短距離力・重力

V(r)=-(GM/r)(1+αe^-r/λ)



未知短距離力・重力

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



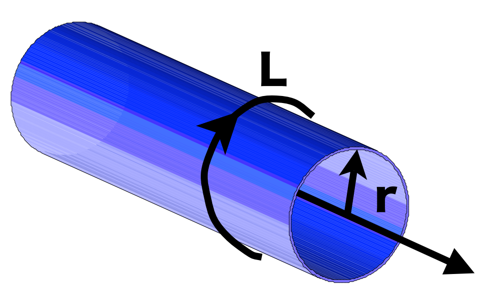
未知短距離力・重力

Newtonian　　exotic interaction (Yukawa-type)

$$V_G(r) = V_g(r)\cdot(1+\alpha\exp(-r/\lambda))\qquad \left(V_g(r) = -G\frac{M\cdot m}{r}\right)$$

Newton重力からのズレを探索する

大きな余剰次元モデル



N次元のうち3次元以外は
コンパクト化されている

3次元空間における重力

$$F_3(r) = G_3\frac{m_1 m_2}{r^2}$$

N次元空間における重力

$$F_N(r) = G_N\frac{m_1 m_2}{r^{N-1}}$$

r=R*において接続

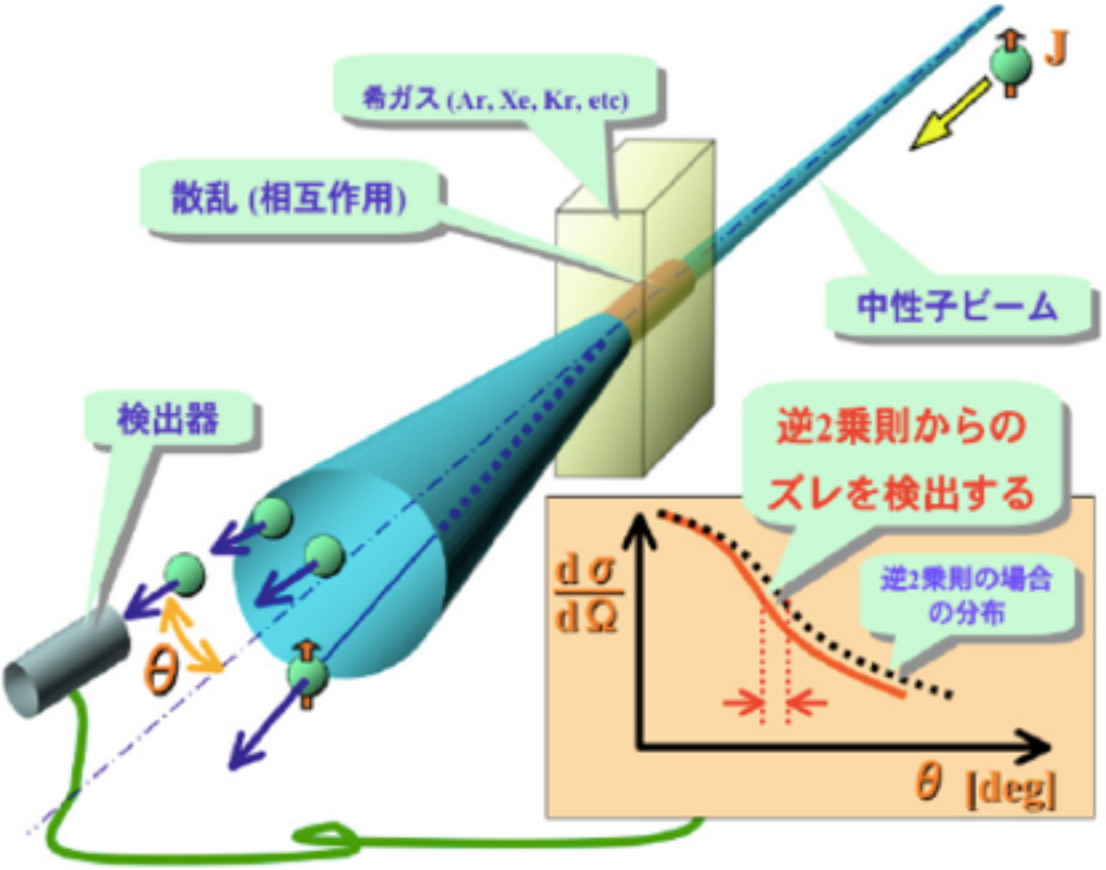
$$\frac{G_3}{R*^2} = \frac{G_N}{R*^{N-1}} \Rightarrow G_3 = \frac{G_N}{R*^{N-3}}$$

$$\frac{V(r)}{m_1 m_2} = G_3\sum_{(k_1,\ldots k_n)}\frac{e^{-(2\pi|k|/L)r}}{r}$$

$$\xrightarrow[r<<L]{} G_3\frac{1}{r}\left(\frac{L}{2\pi r}\right)^n\int d^n u e^{-|u|}$$

未知短距離力・重力

希ガスによる小角散乱



λ~10nmのオーダーの測定が可能

重力を含めた断面積

$$\frac{d\sigma(\theta)}{d\Omega} = \left[a_N + a_{ne} Z F_e(\theta) + a_G F_G(\theta)\right]^2$$

$$\cong a_N{}^2 + 2a_N a_{ne} Z F_e(\theta) + a_{ne}{}^2 Z^2 F_e(\theta)^2 + 2a_N a_G F_G(\theta)$$

$a_G \propto \alpha$

$$\frac{d\sigma_G(\theta)}{d\Omega} = 2\cdot\sigma_N^{1/2}\cdot\alpha\cdot\left(\frac{G\cdot m_n\cdot M}{4}\right)\cdot\left(\frac{1}{\frac{1}{m_n c^2}\left(\frac{\hbar c}{\lambda}\right)^2 + 8E_n \sin^2\frac{\theta}{2}}\right)$$

未知短距離力探索（短距離重力）

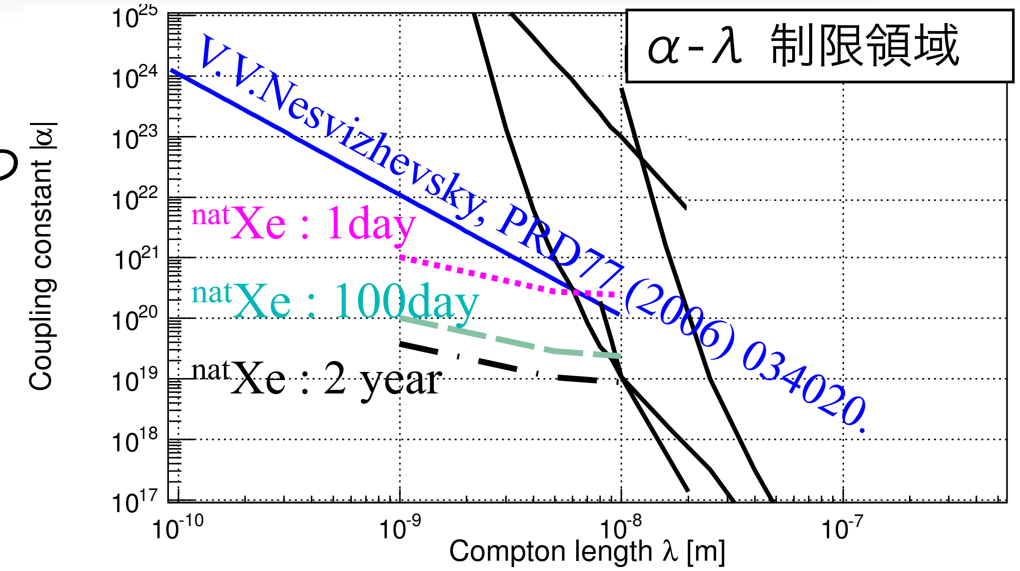
九大・名大・KEK・Indiana Univ.

中性子散乱の角分布を精密測定

短距離離力を含んだポテンシャルによる散乱は前方ピークを持つ

$$V(r) = G\frac{m_1 m_2}{r}(1+\alpha e^{-r/\lambda})$$

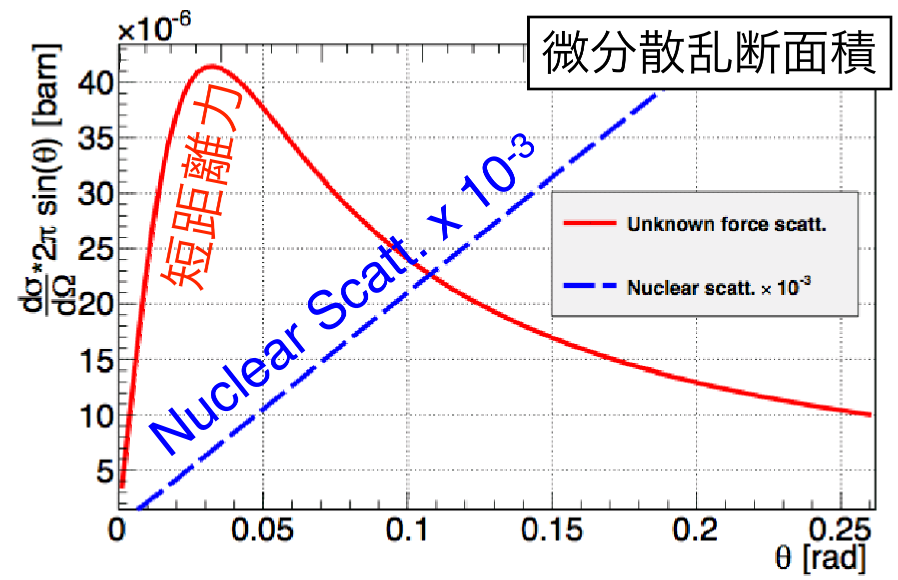
$$\frac{d\sigma_G(\theta)}{d\Omega} = 2\cdot\sigma_N^{1/2}\cdot\alpha\cdot\left(\frac{G\cdot m_n\cdot M}{4}\right)\left(\frac{1}{\frac{1}{m_n c^2}\left(\frac{\hbar c}{\lambda}\right)^2 + 8E_n\sin^2\frac{\theta}{2}}\right)$$



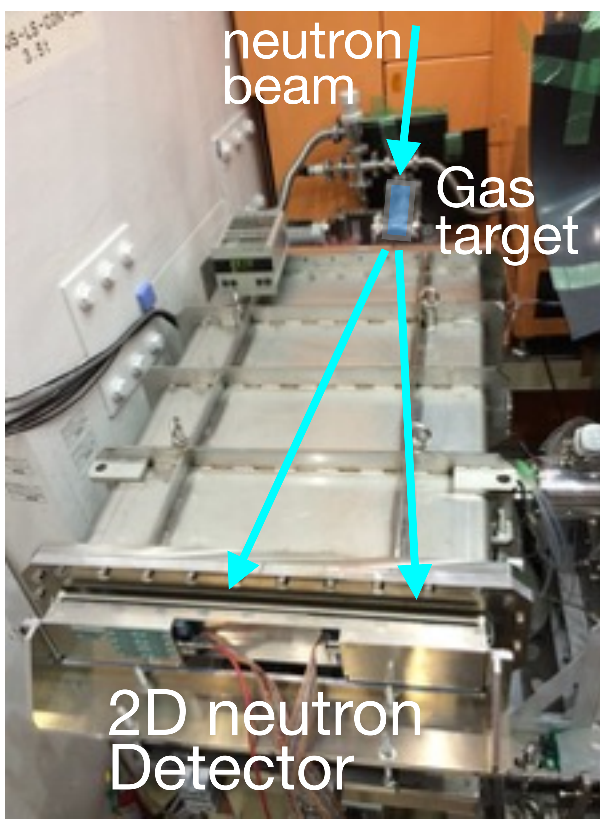
➜ 希ガス原子の中性子散乱を測定

NOPの大強度ビーム＋Xeターゲット

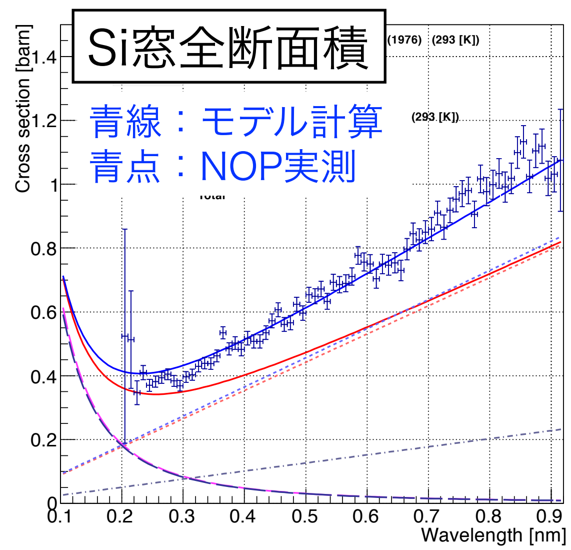
→ 100日で$\alpha=10^{20}$に到達



$\alpha=10^{23}$　$\lambda=0.5$ nm　$E_n=20$ meV



NOP低発散ビームで phase 1 開始



バックグラウンドになるSi窓の散乱を確認

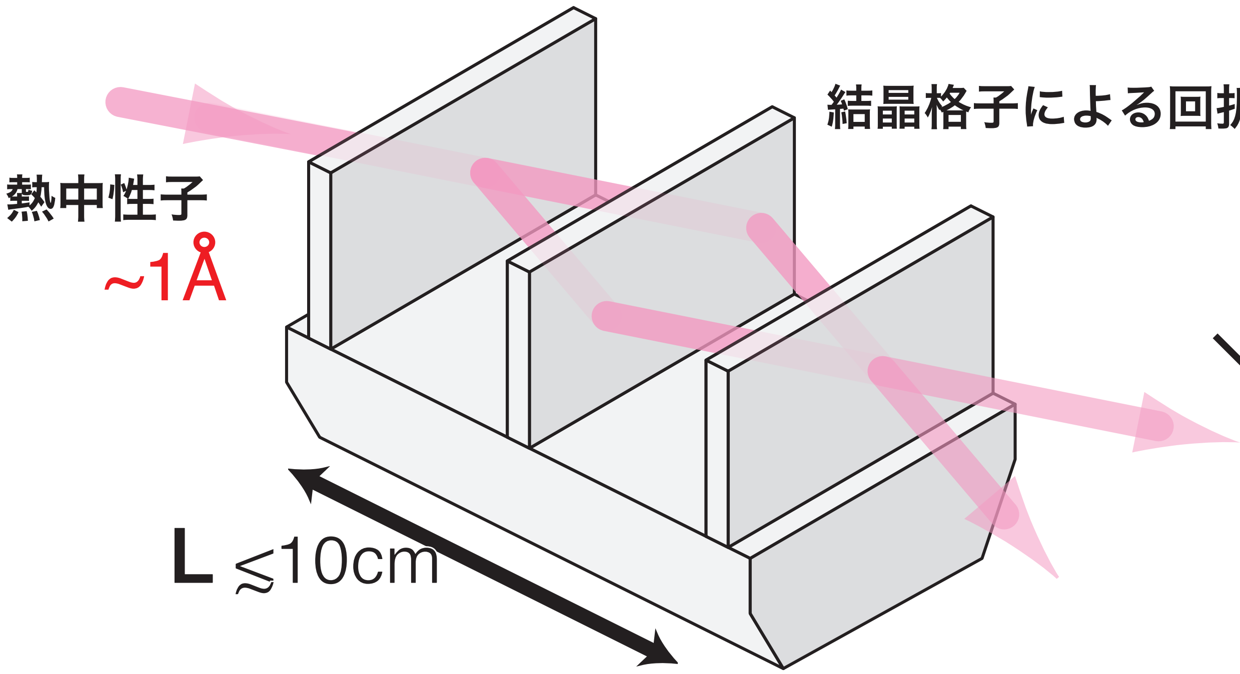
➜ 大強度ビームでの実験で下限値を下げていく

非偏極ブランチに移設、**ビーム輸送系更新＋大型散乱槽**

未知短距離力・重力

干渉計による重力

Si 単結晶による干渉計



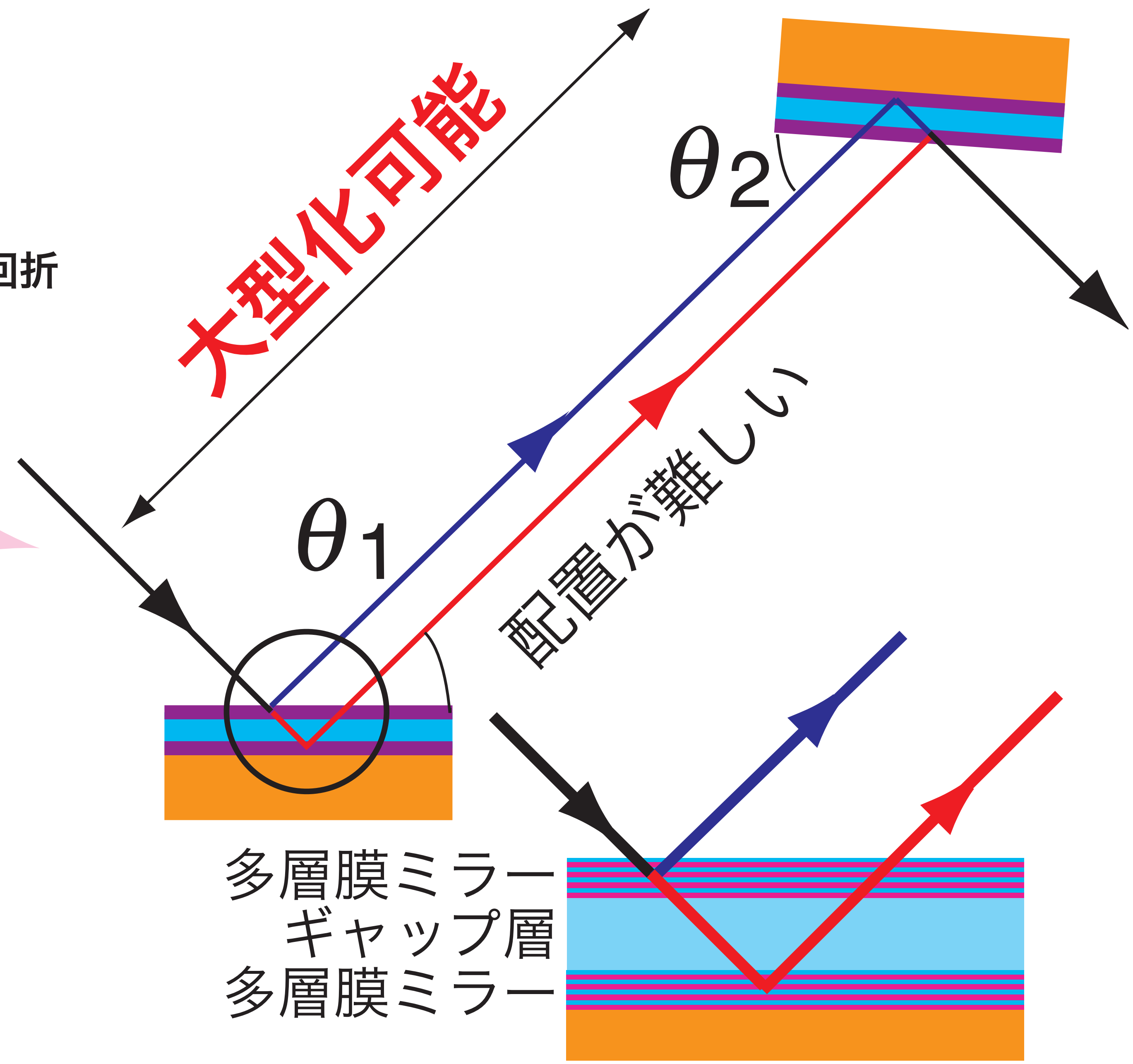
４枚のミラーが原理的に並んでいる

決まった波長しか使えない

結晶の大きさに限界がある

動的回折で経路が決まらない

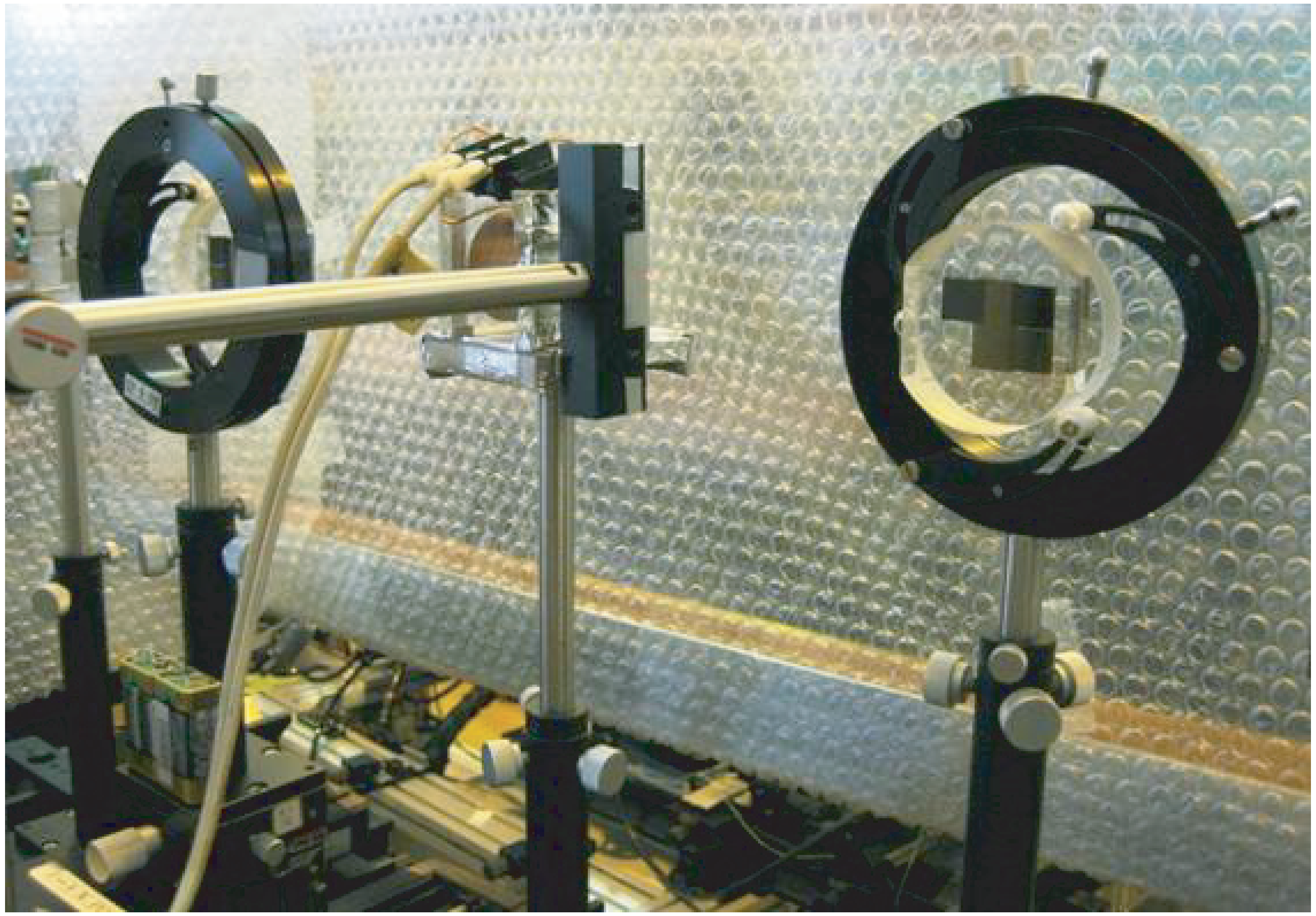
多層膜干渉計

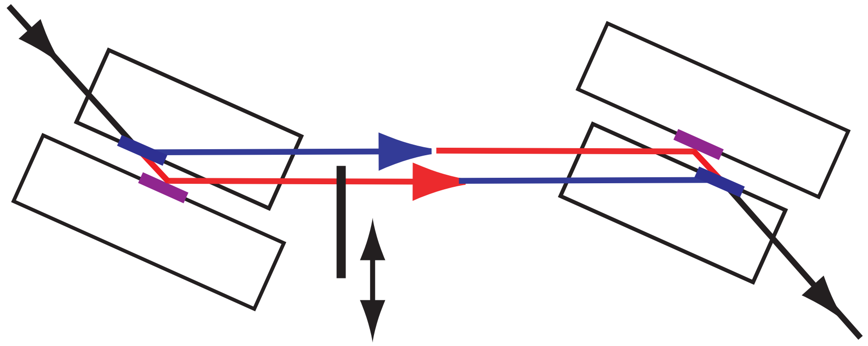


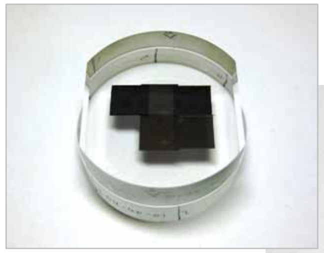
H. Funahashi *et al*,
Phys. Rev. **A54**(1996) 649

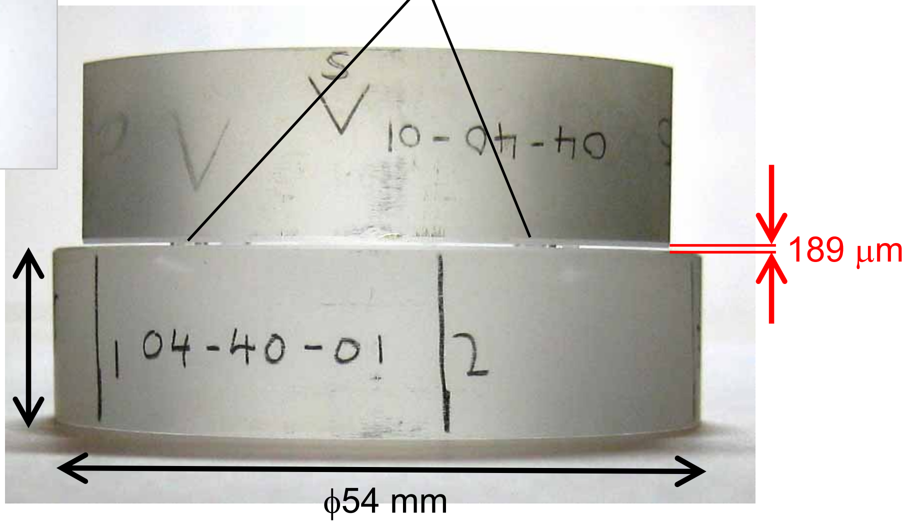
未知短距離力・重力

干渉計による重力





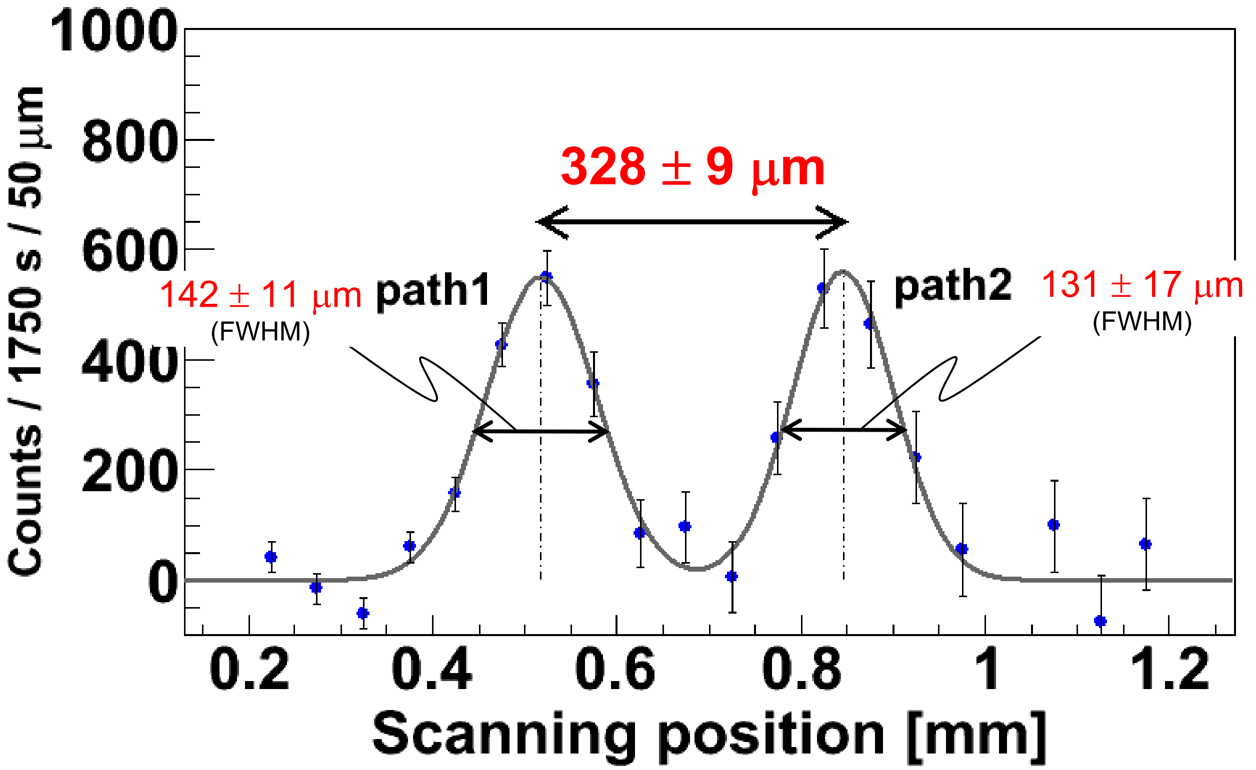




平面度 $\lambda_{He\text{-}Ne}/100$

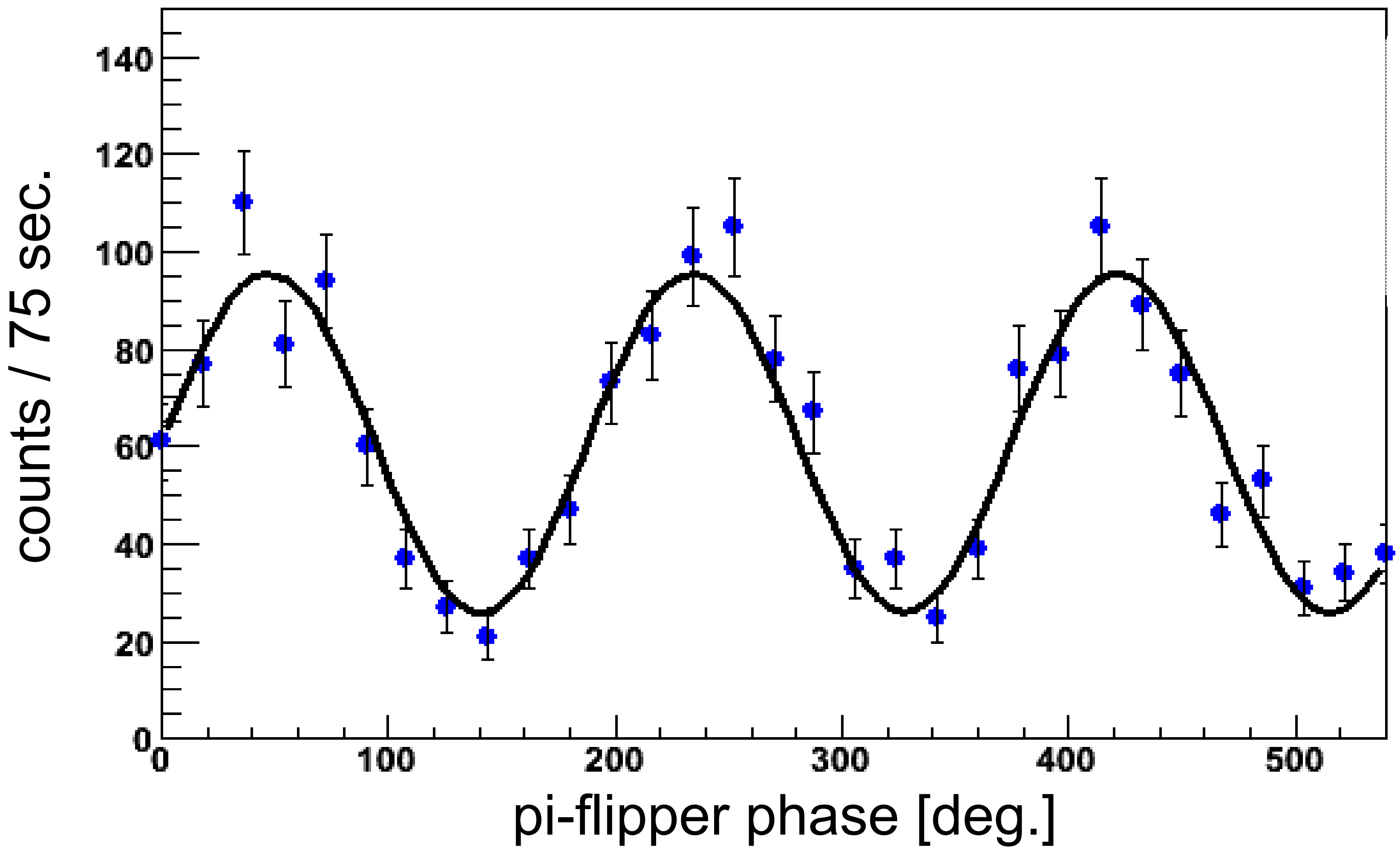
平行度 $\lambda_{He\text{-}Ne}/100$

8



未知短距離力・重力

干渉計による重力



Y. Seki *et al.*
J. Phys. Soc. Jpn. **79** (2010)124201.

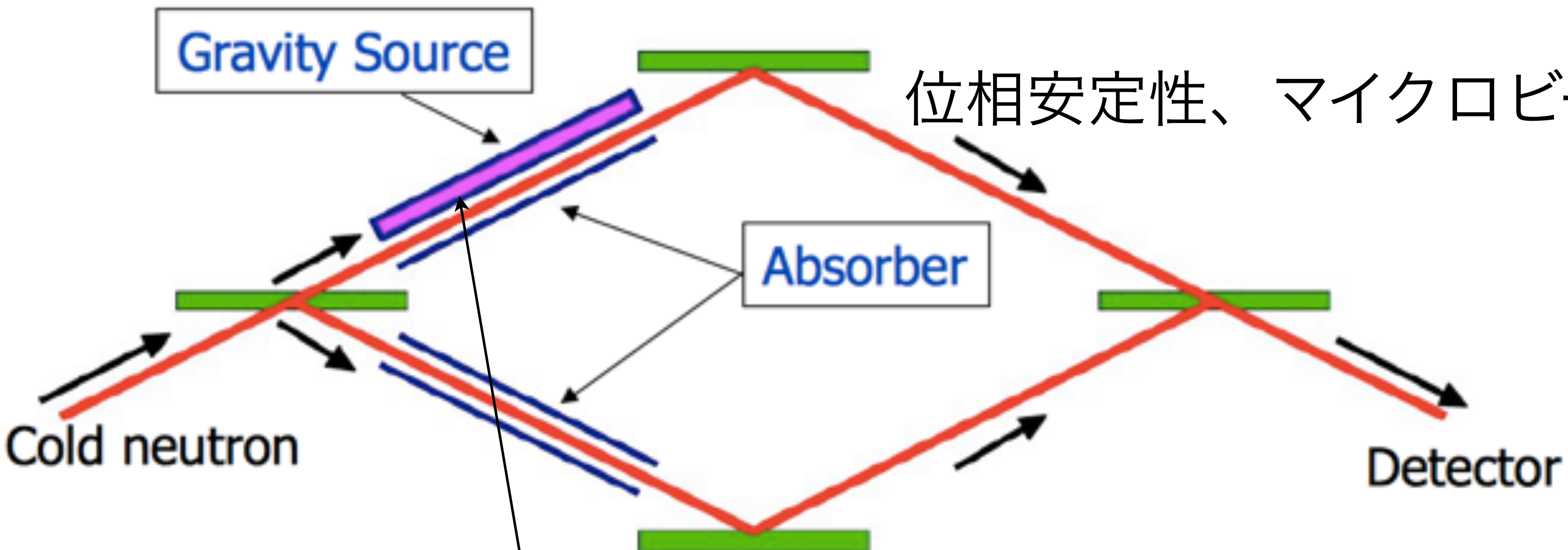
→2経路を完全分離する多層膜中性子干渉計

未知短距離力・重力

干渉計による重力

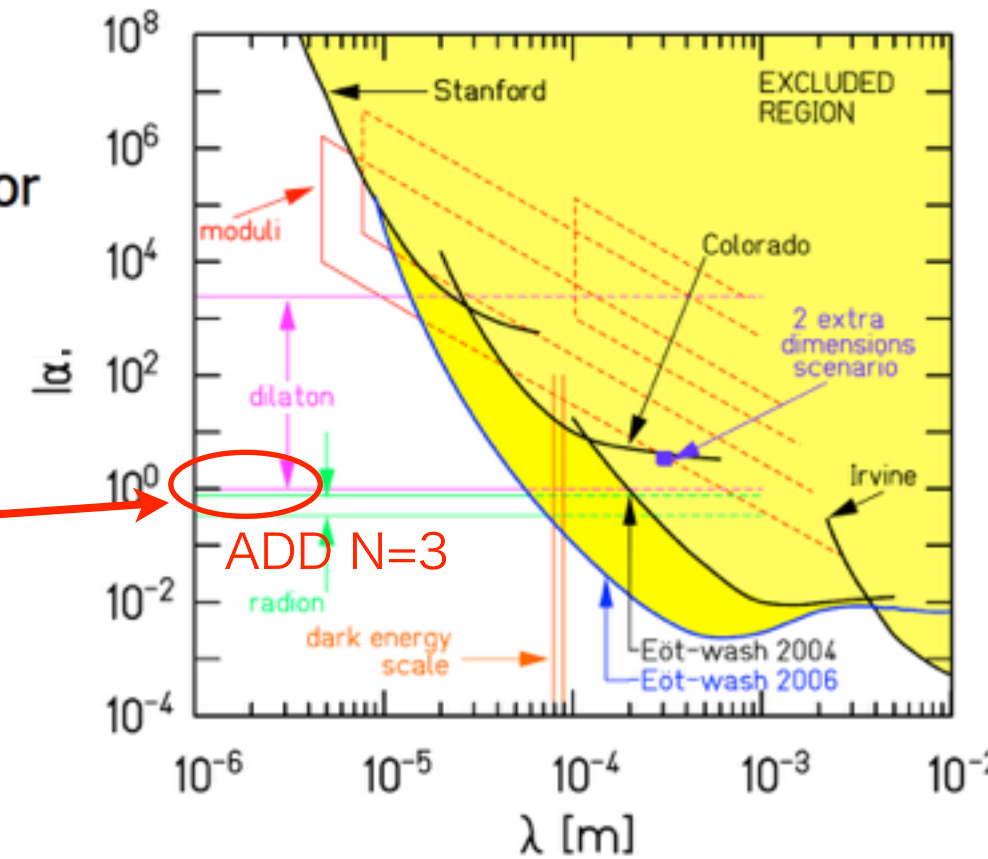
λ~10μm のオーダーの測定が可能

干渉計の片経路の重力ポテンシャルを位相シフトから検出



位相安定性、マイクロビームの強度

ビームとのギャップを1μm
まで近づけられれば（ビー
ム断面も同程度）ADD
N=3 の検証の可能性がある



未知短距離力・重力

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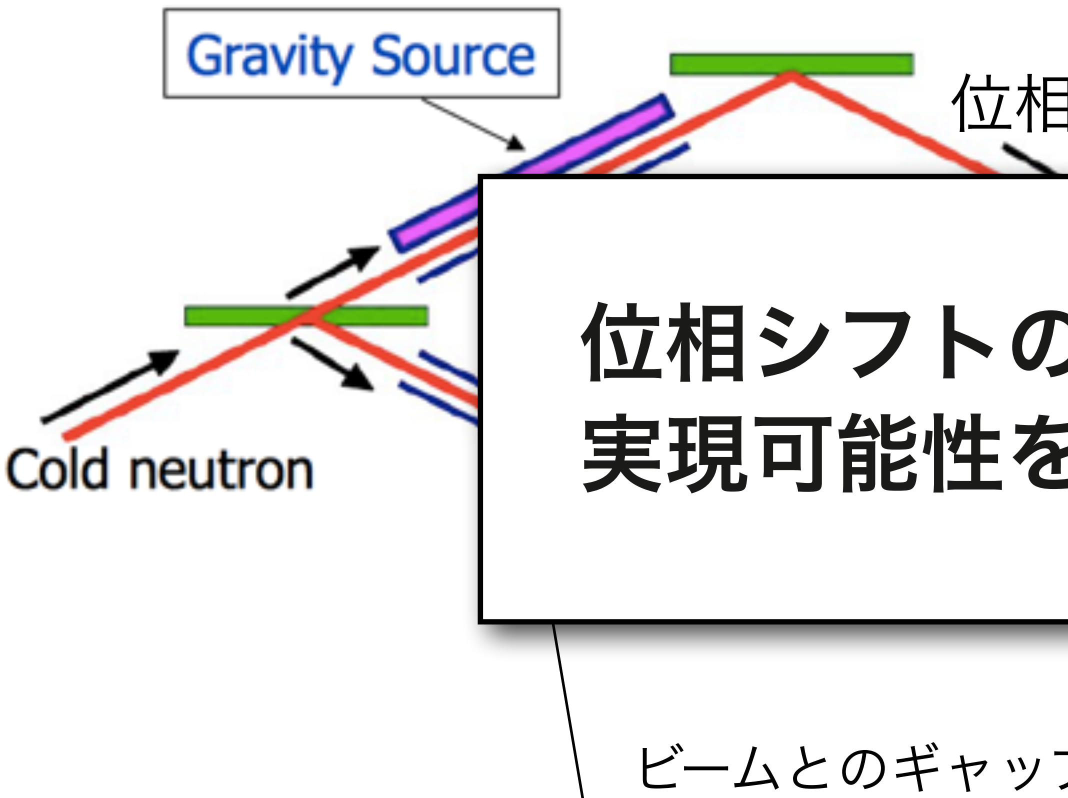
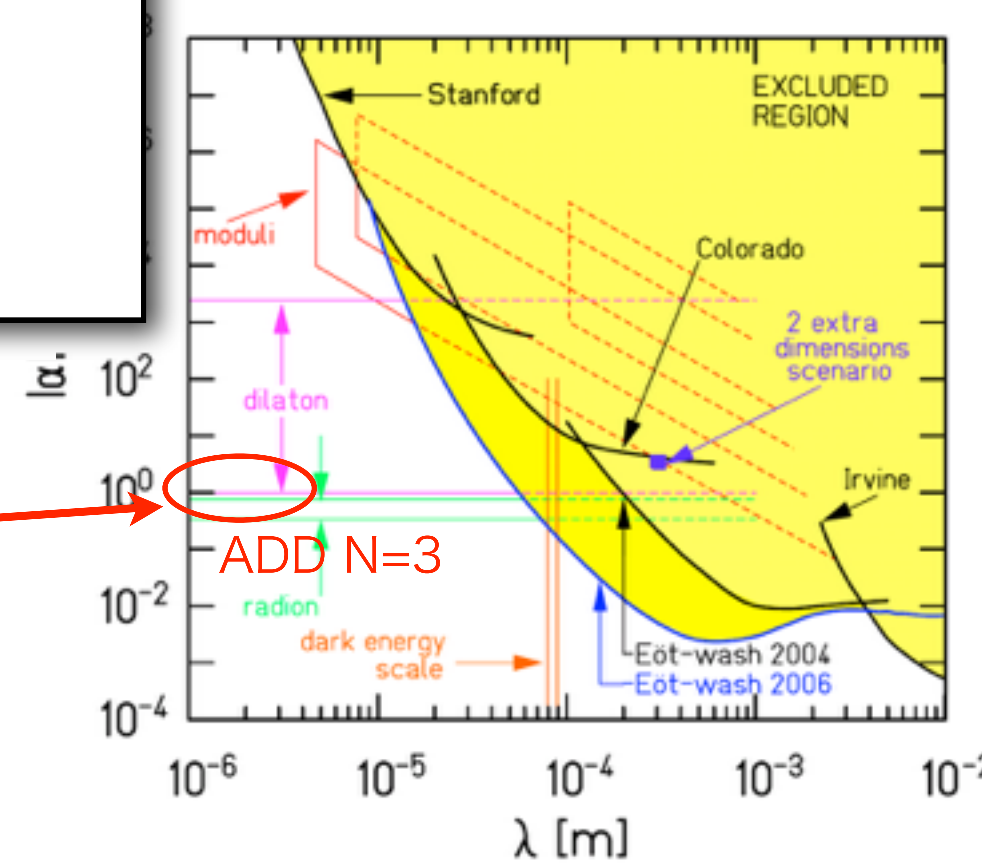


位相安定性、マイクロビームの強度

位相シフトの見積もり
実現可能性を議論中

ビームとのギャップを1μm まで近づけられれば（ビーム断面も同程度）ADD N=3 の検証の可能性がある



まとめ

中性子を用いた基礎物理実験は
様々な実験と互いに制限をつけ合う　波及効果は大きい