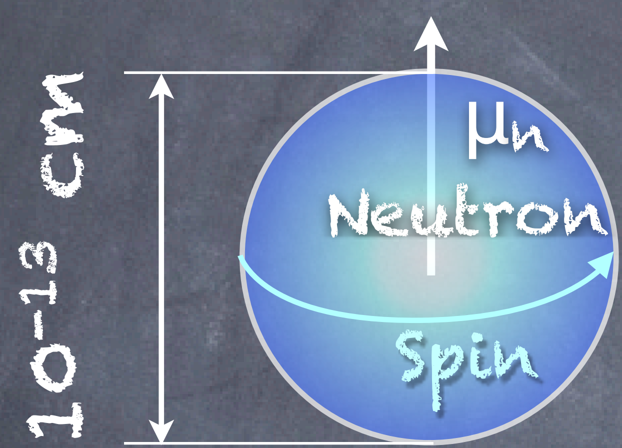
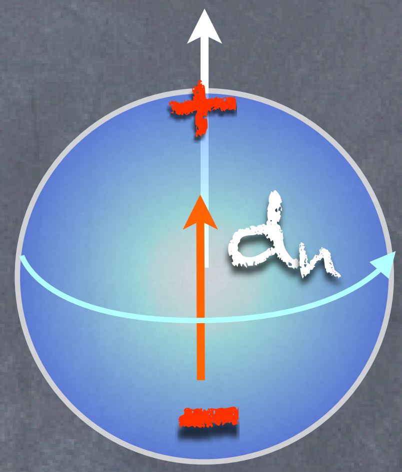
UCN実験の現状と将来

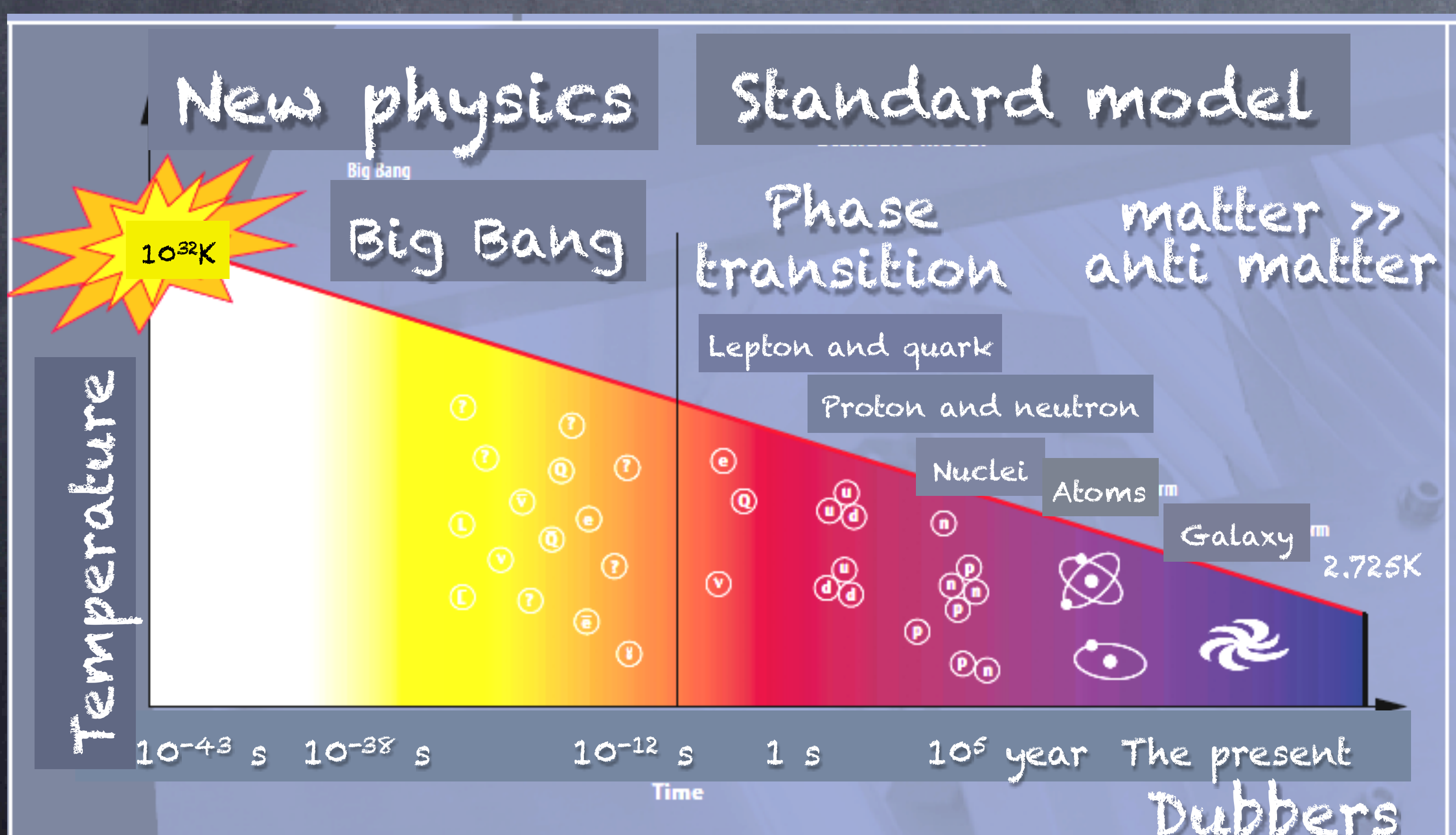
EDM:旗艦研究

増田康博 (KEK)　2012年9月28日 RCNP



CP violation
電荷分布のシフト





Baryogenesisの謎

CP violationが物質を作った

しかし標準理論は

baryon asymmetry

を説明できない

EDM 測定計画

新物理による
EDM予言値

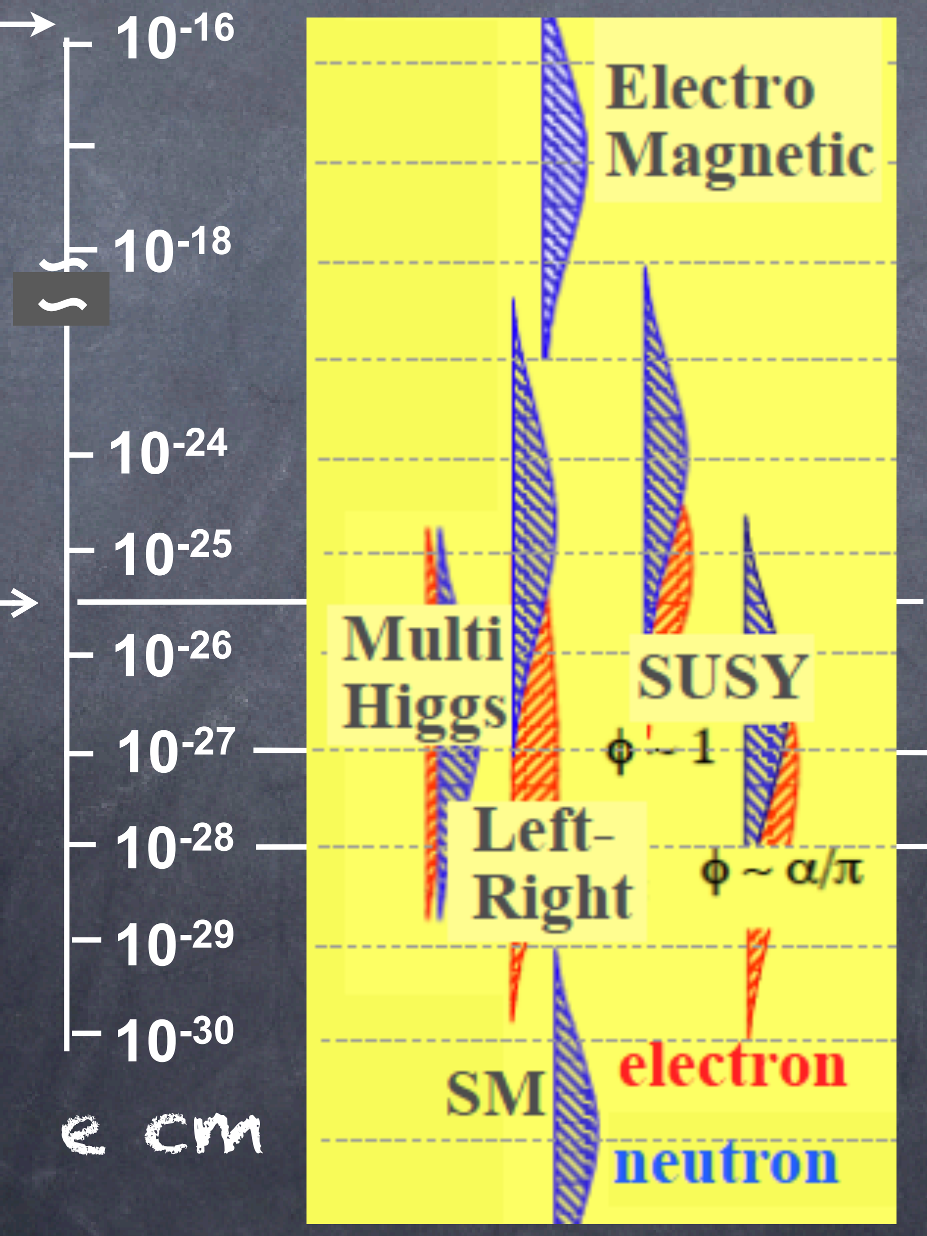
地磁気
($\mu_n H_0/E$)

ILLによるEDM上限値

統計誤差 1.5×10^{-26}

系統誤差 0.7×10^{-26}

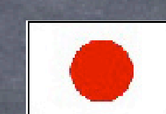
磁場に起因



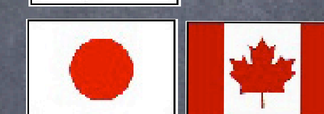
本研究

統計誤差に対して

高密度超冷中性子



10^{-27} e·cm



10^{-28} e·cm

系統誤差に対して

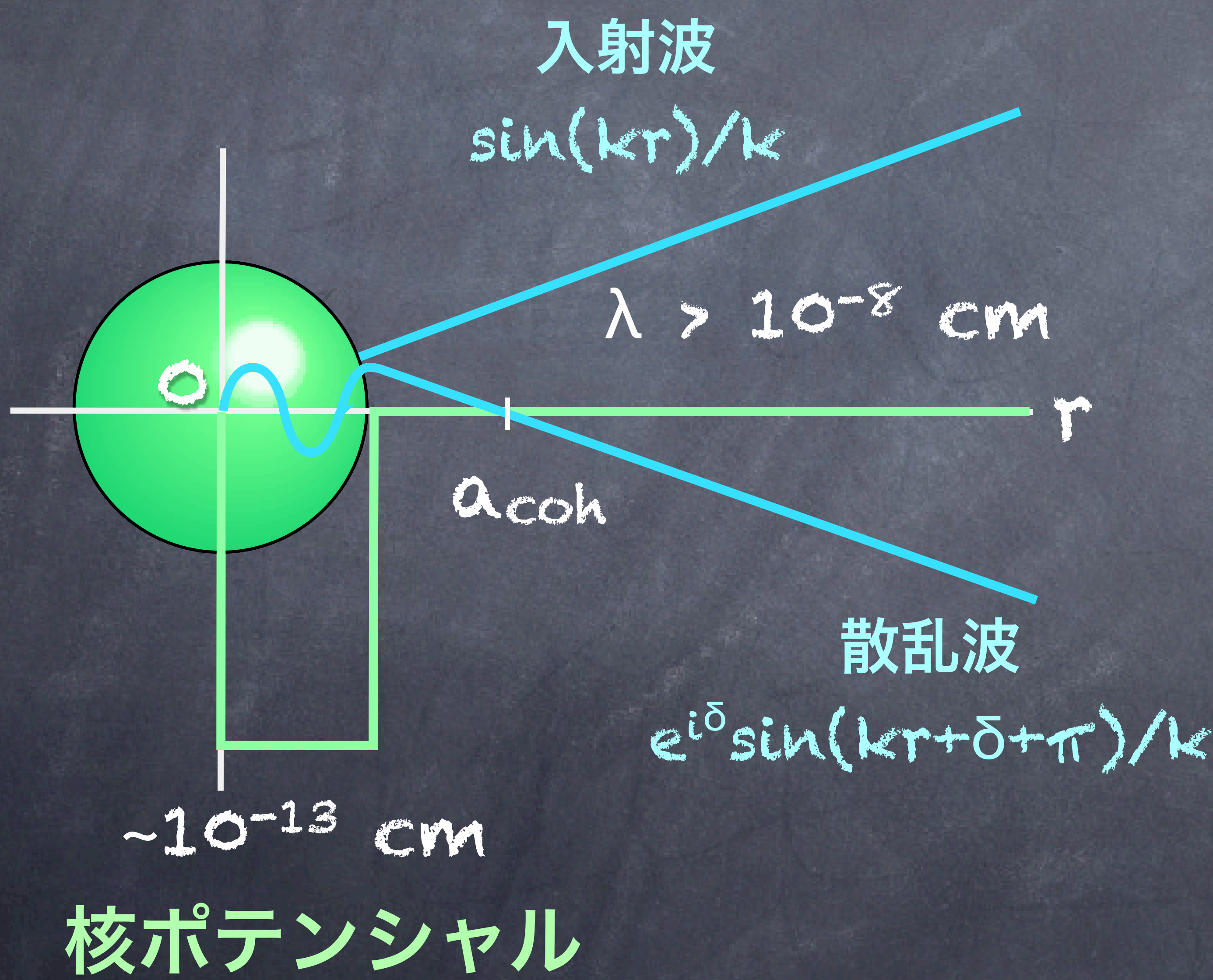
バッファガス磁力計

10^{-28} e·cm

UCNとは

エネルギーが非常に低い中性子

中性子波に対する核力の影響



Fermi ポテンシャル

$V_F = (2\pi\hbar^2/m)\, a_{coh}\, \delta(r)$

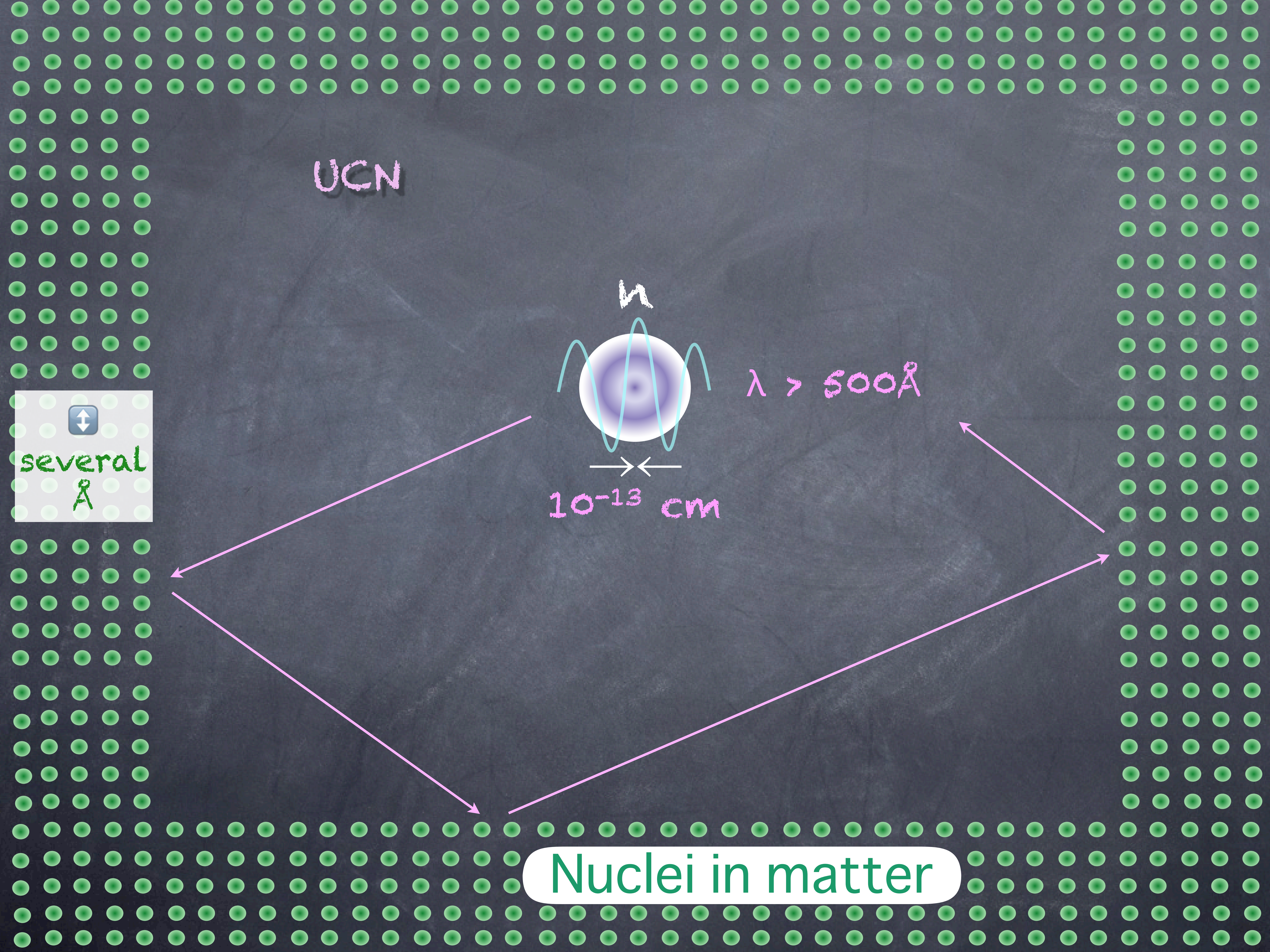
a_{coh} が正の時、斥力

UCN とは

E_n < coherent sum of V_F

335 neV for ^{58}Ni

210 neV for iron


UCN
n
λ > 500Å
10-13 cm
several Å
Nuclei in matter

中性子の閉じ込め

UCN 実験

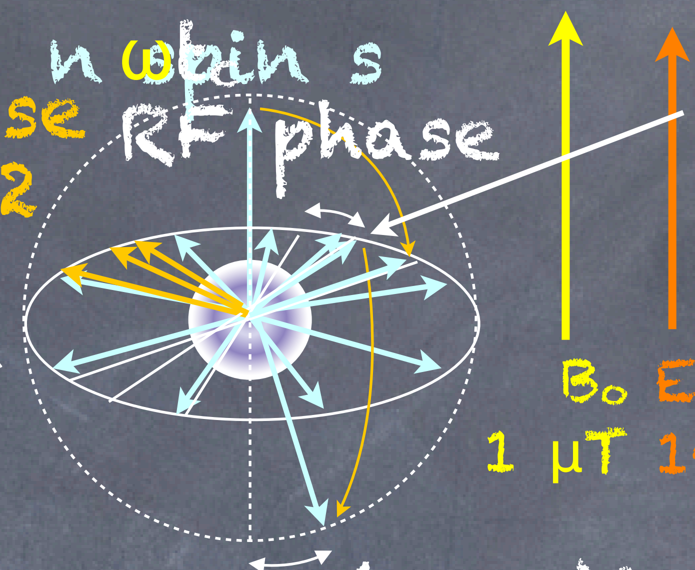
EDM, beta decay
gravity, NNbar

運動量空間と実空間の
体積は制限されている

位相空間密度が重要

EDM 測定

for neutron polarimetry



ω_0: $2\mu_n B_0 \pm 2d_n E$

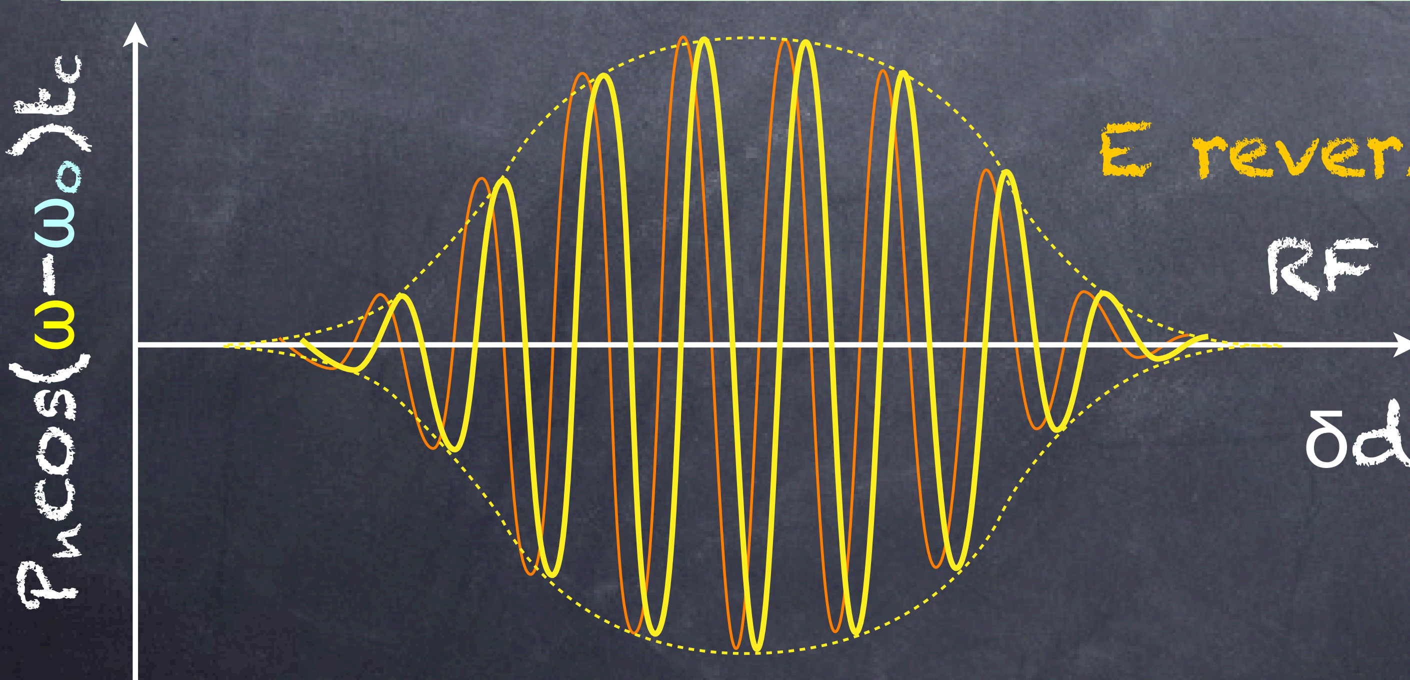
t_c: precession time

Neutron precession

$$S = \exp\{i(\mu \cdot B_0 + d_n \cdot E)/\hbar \cdot t\}$$

μ, $d_n \propto s$

UCN bottle



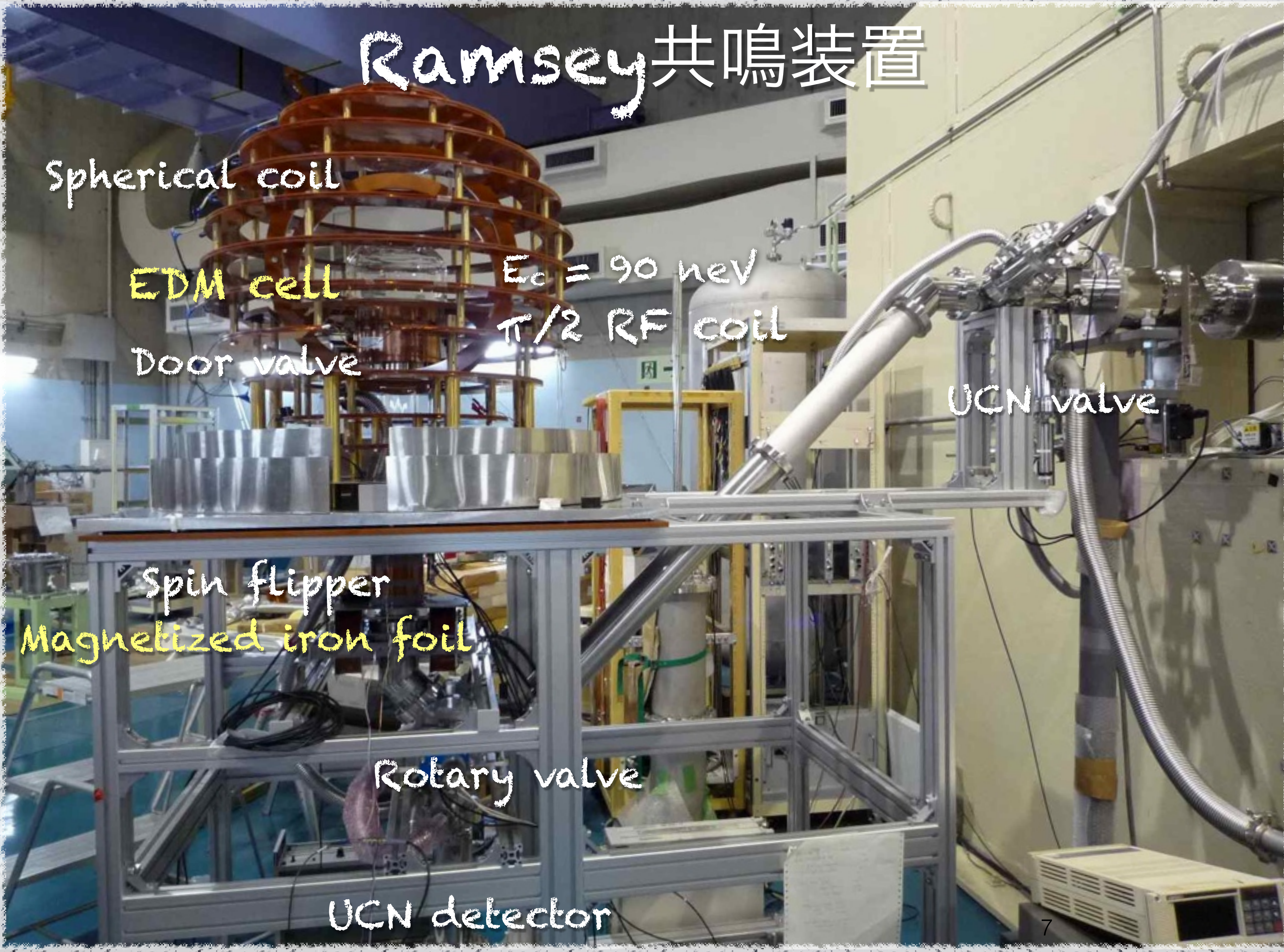
E reversal for extraction of d_n

$$\delta d_{sta} = \hbar/\{2P_n E t_c \sqrt{N}\}$$

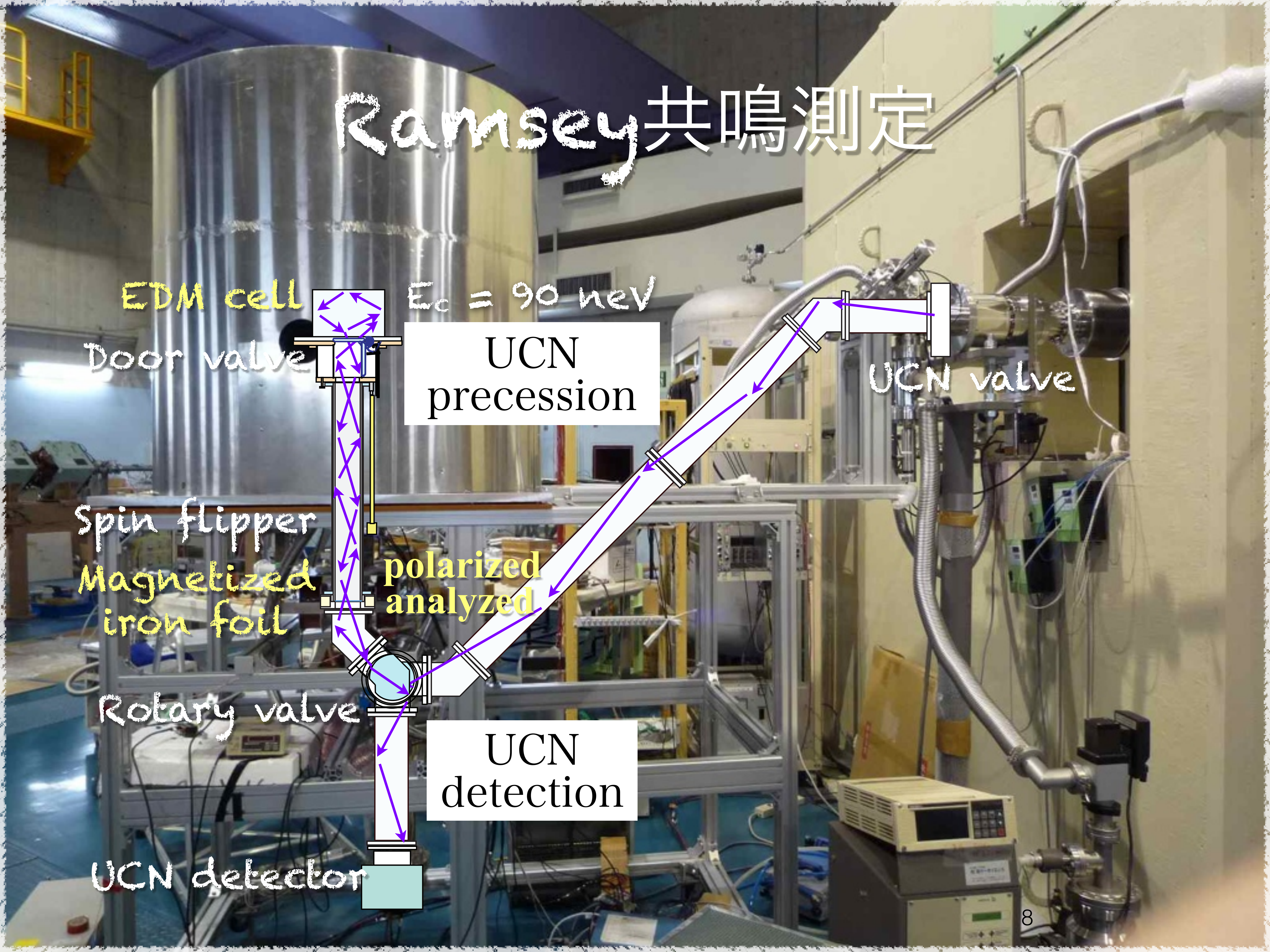
P_n : UCN polarization

N : number of UCN

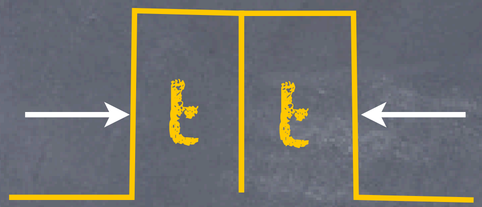
Ramsey共鳴装置


Spherical coil
EDM cell
E_c = 90 neV
π/2 RF coil
Door valve
UCN valve
Spin flipper
Magnetized iron foil
Rotary valve
UCN detector

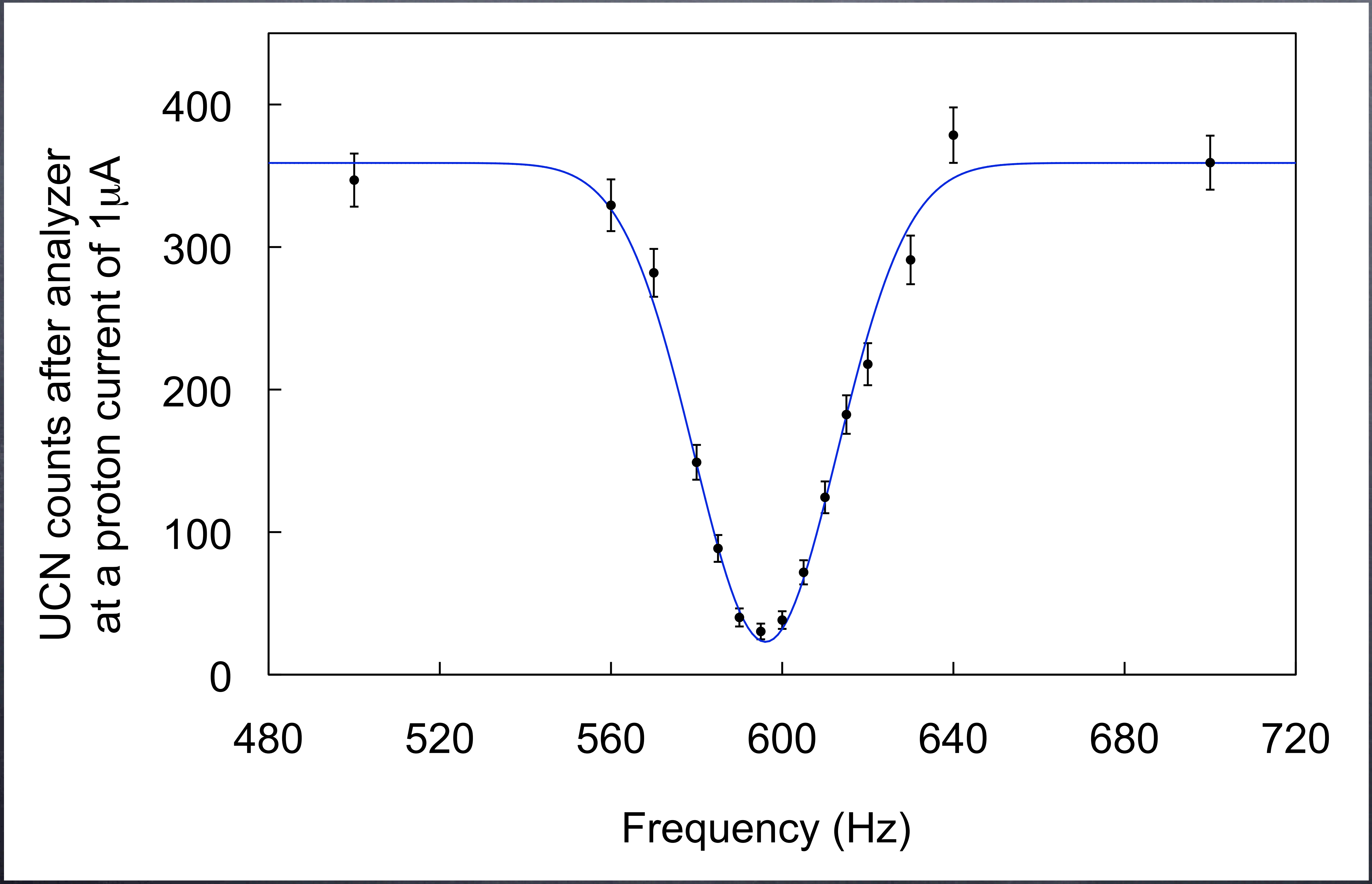
Ramsey共鳴測定


EDM cell
E_c = 90 neV
Door valve
UCN precession
UCN valve
Spin flipper
Magnetized iron foil
polarized
analyzed
Rotary valve
UCN detection
UCN detector

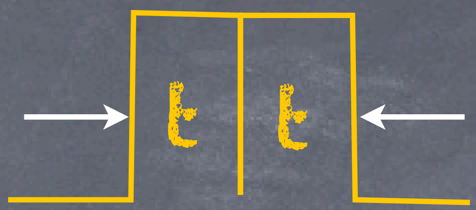
UCN NMR

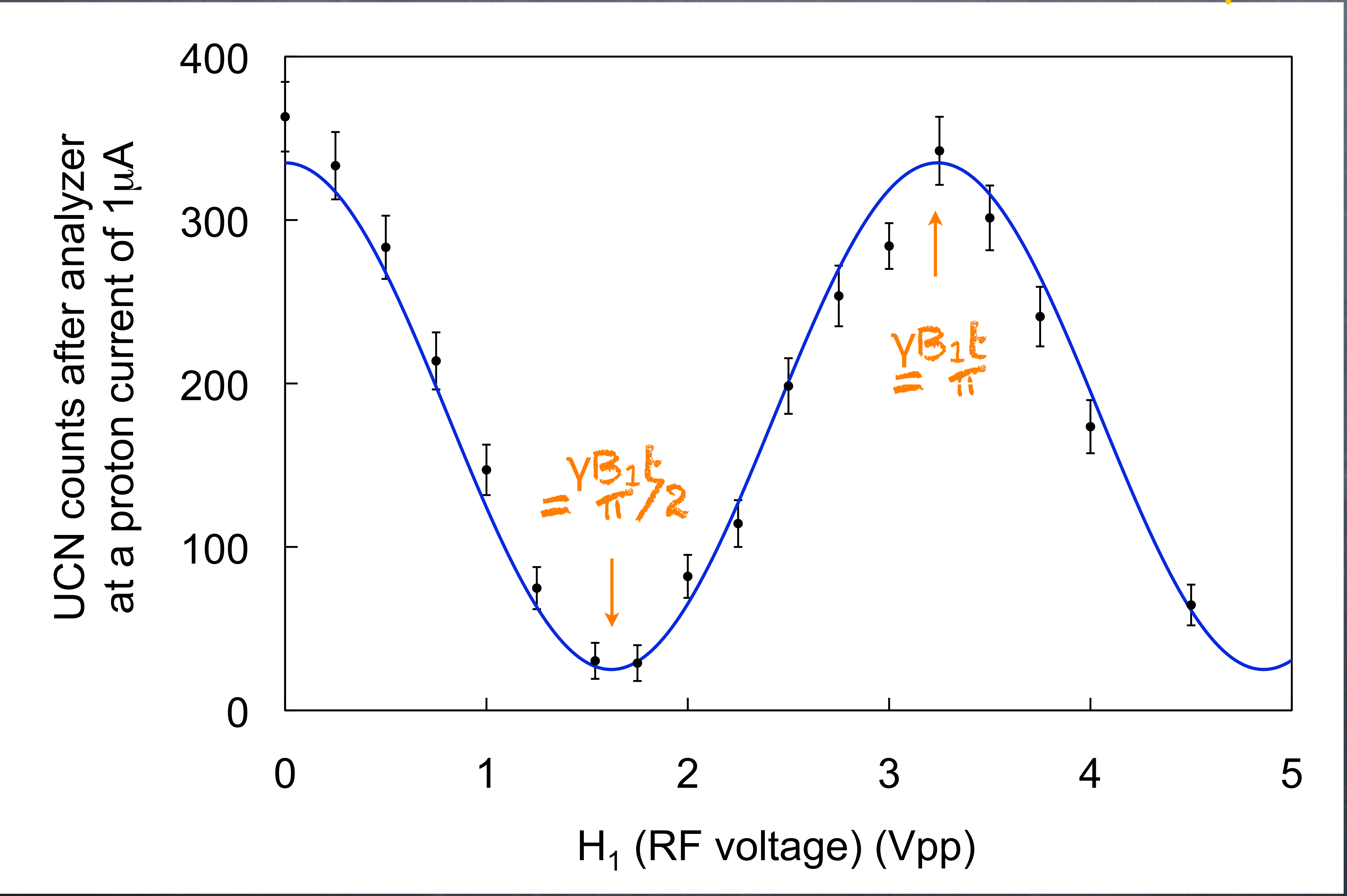


two coherent $\pi/2$ RF pulses



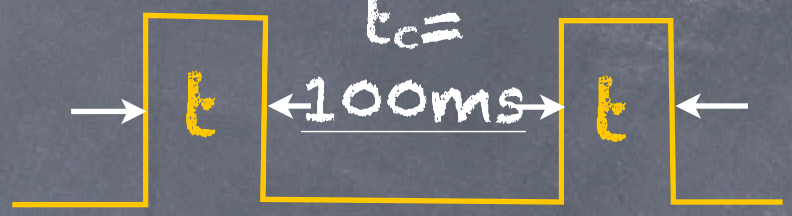
γB₁tによるUCNスピン回転



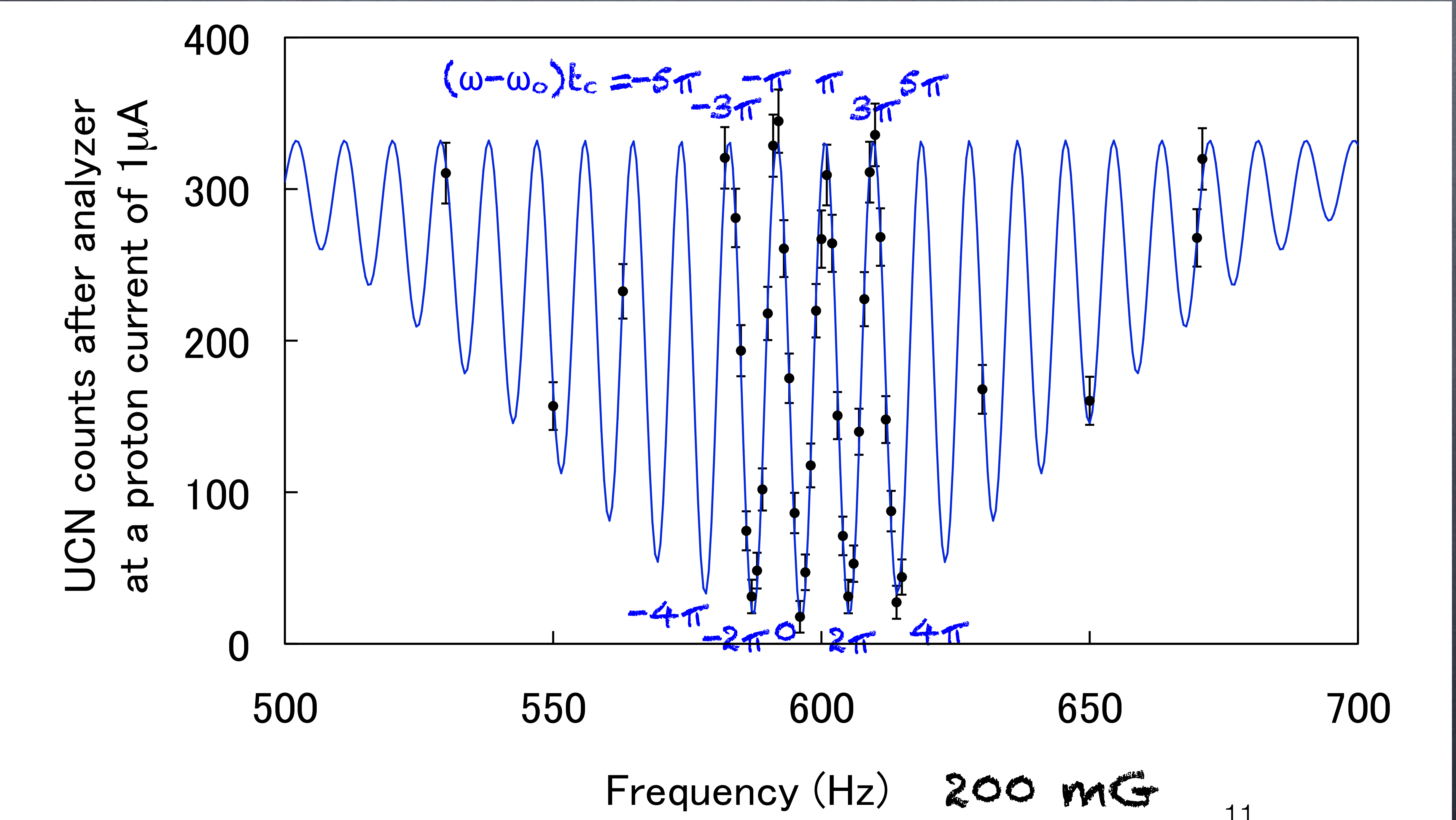


Ramsey 共鳴

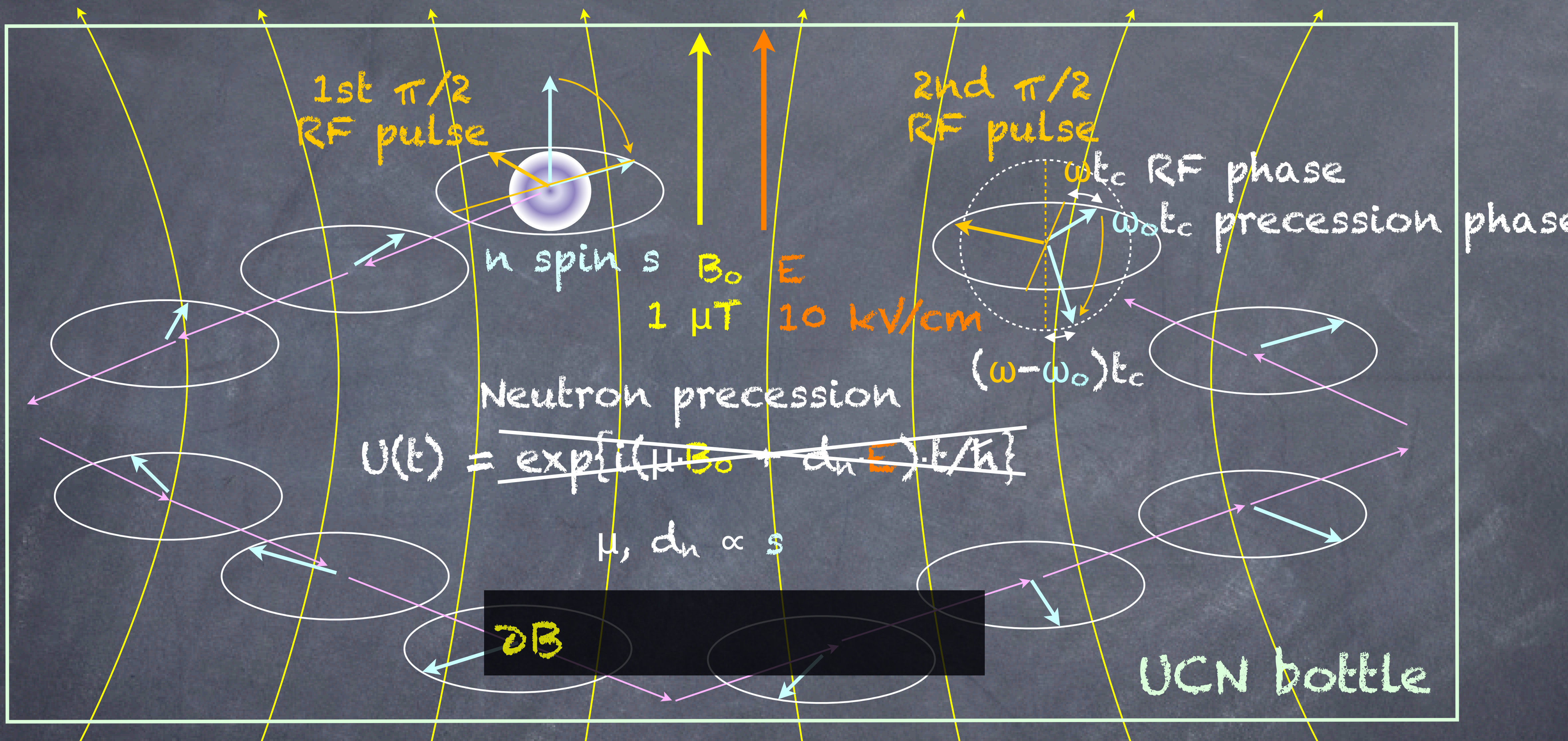
visibility α =
(Nmax − Nmin)/(Nmax + Nmin) = 0.9



two coherent π/2 RF pulses



幾何学的位相効果（GPE）



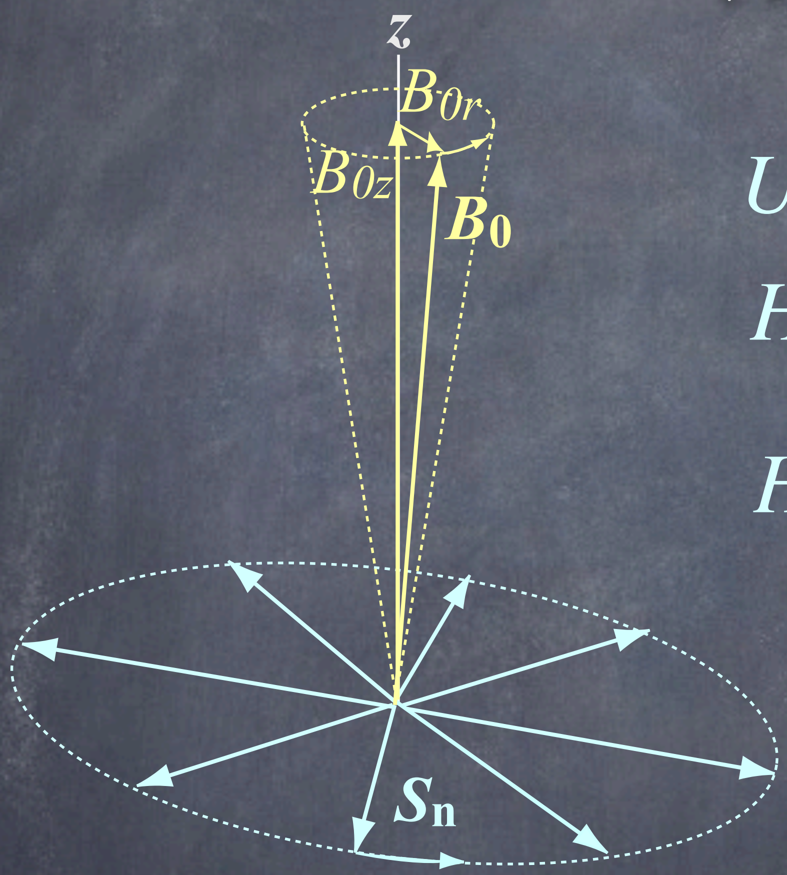
横磁場回転による幾何学的位相シフト

$$\propto \{(\partial B_0/\partial z)r/2 + Exv/c^2\}^2$$

Pendlebury, Phys. Rev. A70(2004)032102.
Lamoreaux, Phys. Rev. A71(2005)052115.

時間に依存する相互作用の影響

Phys.Lett. A376(2012)1347



$$U(t) = \exp(-iH_0 t/\hbar)$$

$$H_0 = -\boldsymbol{\mu}\cdot\boldsymbol{B}_0 - \boldsymbol{d}_n\cdot\boldsymbol{E}$$

$$H = H_0 + V(t)$$

$$V(t) = -\boldsymbol{\mu}\cdot\boldsymbol{B}_{xy}(t) = -\gamma\boldsymbol{s}\cdot(\boldsymbol{B}_v(t) + \boldsymbol{B}_{0r}(t))$$

$$\boldsymbol{B}_v = \boldsymbol{E}\times\boldsymbol{v}/c^2 \quad \boldsymbol{B}_{0r} = -(\partial B_{0z}/\partial z)\boldsymbol{r}/2$$

$$U_I(t) = 1 + \frac{is_z}{\hbar}\frac{1}{4}\gamma^2\frac{E}{c^2}\frac{\partial B_{0z}}{\partial z}\int_0^t dt'\int_0^{t'} d\tau\cos(\omega_0\tau)$$

$$\{x(t')v_x(t'-\tau) - x(t'-\tau)v_x(t') + y(t')v_y(t'-\tau) - y(t'-\tau)v_y(t')\}$$

GPE問題に対する解答

Phys.Lett. A376(2012)1347

$$\int_0^t d\tau \cos(\omega_0 \tau)\{x(t')v_x(t'-\tau) - x(t'-\tau)v_x(t') + y(t')v_y(t'-\tau) - y(t'-\tau)v_y(t')\}$$

$d_{afHgn} =$
$\hbar/8 \cdot \gamma_n \gamma_{Hg} (\partial B_{0z}/\partial z) \underline{R}^2/c^2$

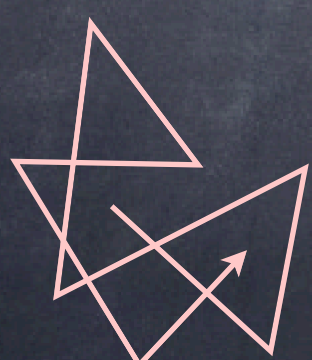
5x10^{-26} e cm at R = 25 cm

$d_{afn} =$
$-\hbar/4 \cdot (\partial B_{0z}/\partial z)/B_{0z}^2 \cdot v_{xy}^2/c^2$

1x10^{-27} e·cm at 1nT/m, 1μT

^{129}Xe 平均自由行程

$n = 1.8 \times 10^{14}$/cc
$\sigma_{Xe-Xe} >> 838 \text{Å}^2$
$\lambda = 1/n\sigma$ 0.7~5 mm



r(t) あまり変化しない
$v(t-\tau)$ 急速に変化
$\langle r(t)v(t-\tau)\rangle \to \ll 1$

$d_{afXen} \to 1\times10^{-28}$ e·cm

$(\partial B_{0z}/\partial z)/B_{0z}^2$ 、例えば
$\partial B_{0z}/\partial z$ 1→0.1 nT/m

$d_{afn} \to 1\times10^{-28}$ e·cm

ILLのUCN源

Turbine

Vertical guide

Cold source

60 MW Reactor

重力と

Doppler効果で減速

36 UCN/cm^3 E_c = 190 neV
in the source

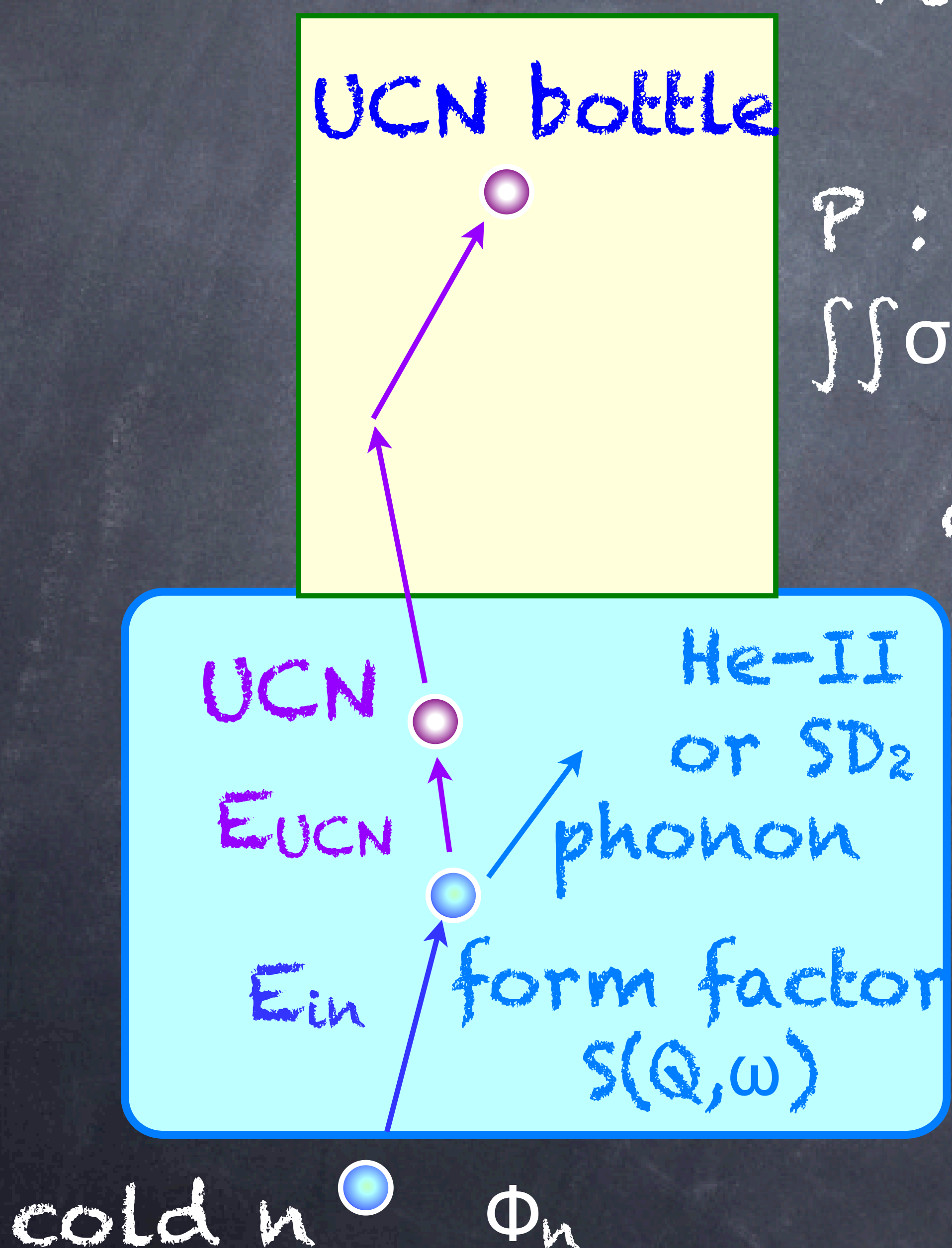
2 to 3 UCN/cm^3
in an experimental
bottle of E_c = 100 neV
0.7 UCN/cm^3
in a EDM cell

UCN density is limited
by Liouville's theorem

新しい UCN 源

フォノンで中性子を冷却する

ILL, KEK-RCNP, LANL, Mainz, PSI, TUM, SNS, NCSU, Indiana, PNPI, J-PARC



P : production rate

$$\iint \sigma(E_{in} \to E_{UCN}) d\Phi_n(E_{in})/dE_{in} N dE_{in} dE_{UCN}$$

$$d^2\sigma/dQd\omega = k_f/k_i \; \sigma_{coh}/4\pi \; S(Q,\omega)$$

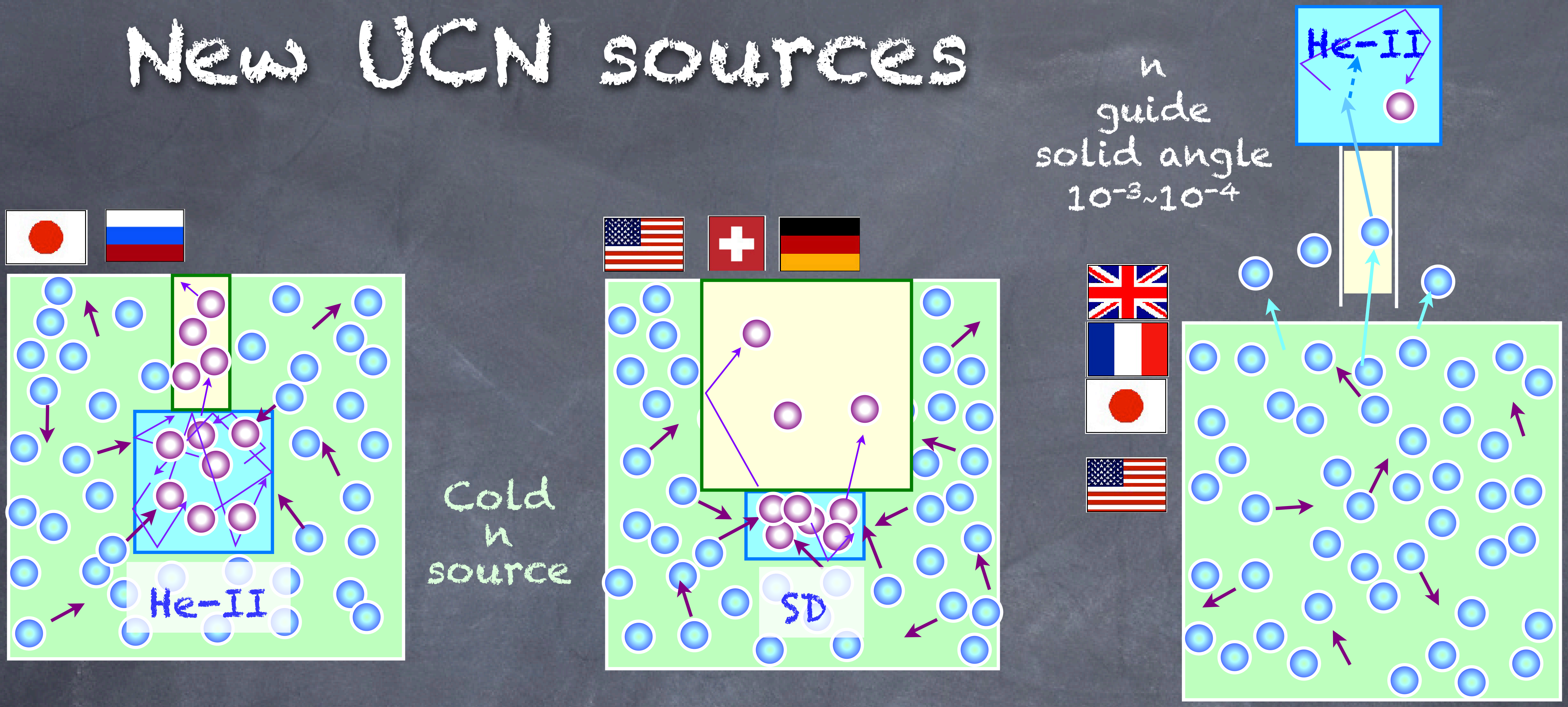
$$\rho_{UCN} = P \tau_s\{1-\exp(-t/\tau_s)\}$$

$\to P\,t \quad t \ll \tau_s$

$\to P\,\tau_s \quad t \gg \tau_s$

τ_s : storage lifetime

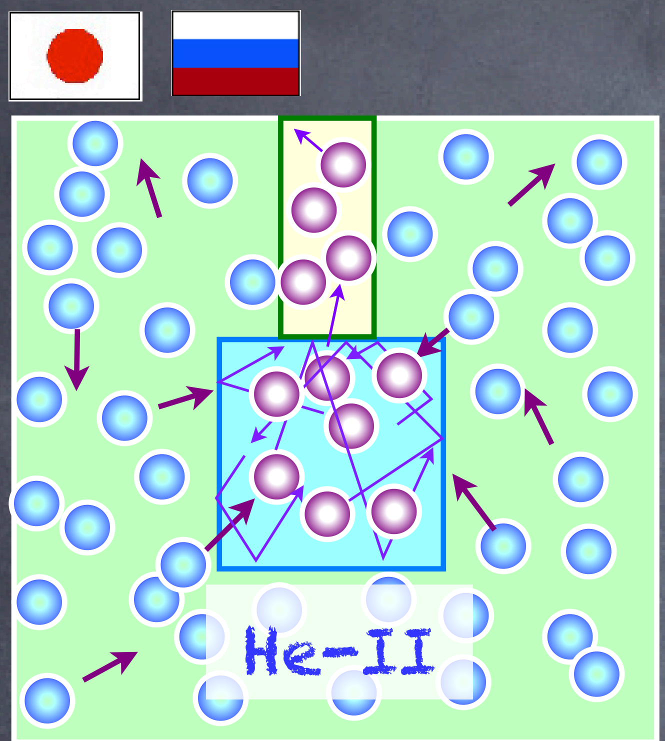
New UCN sources

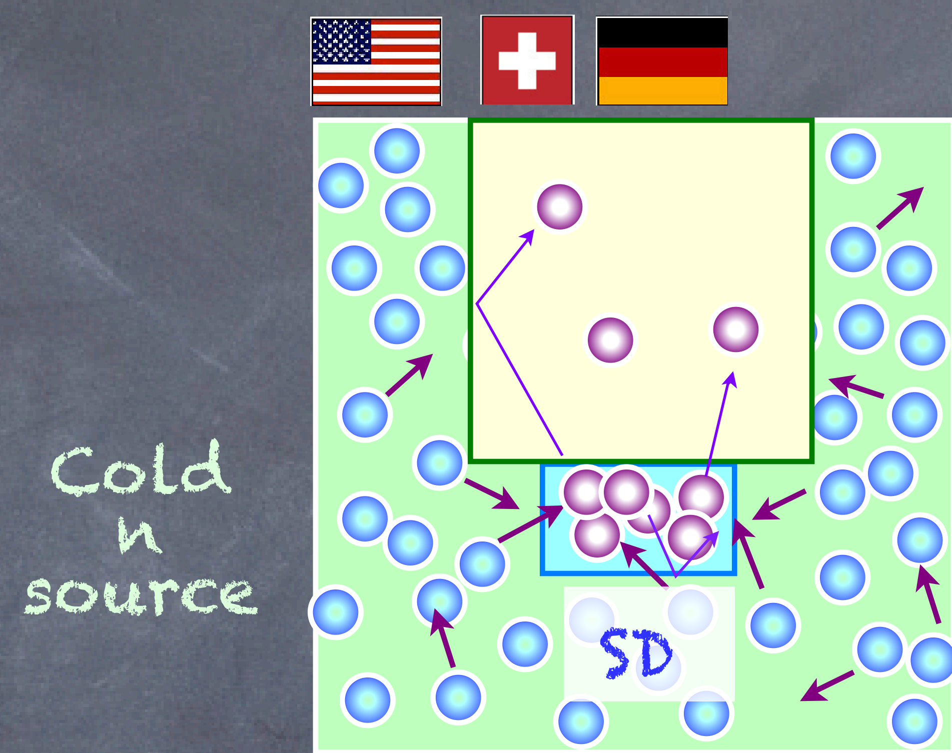


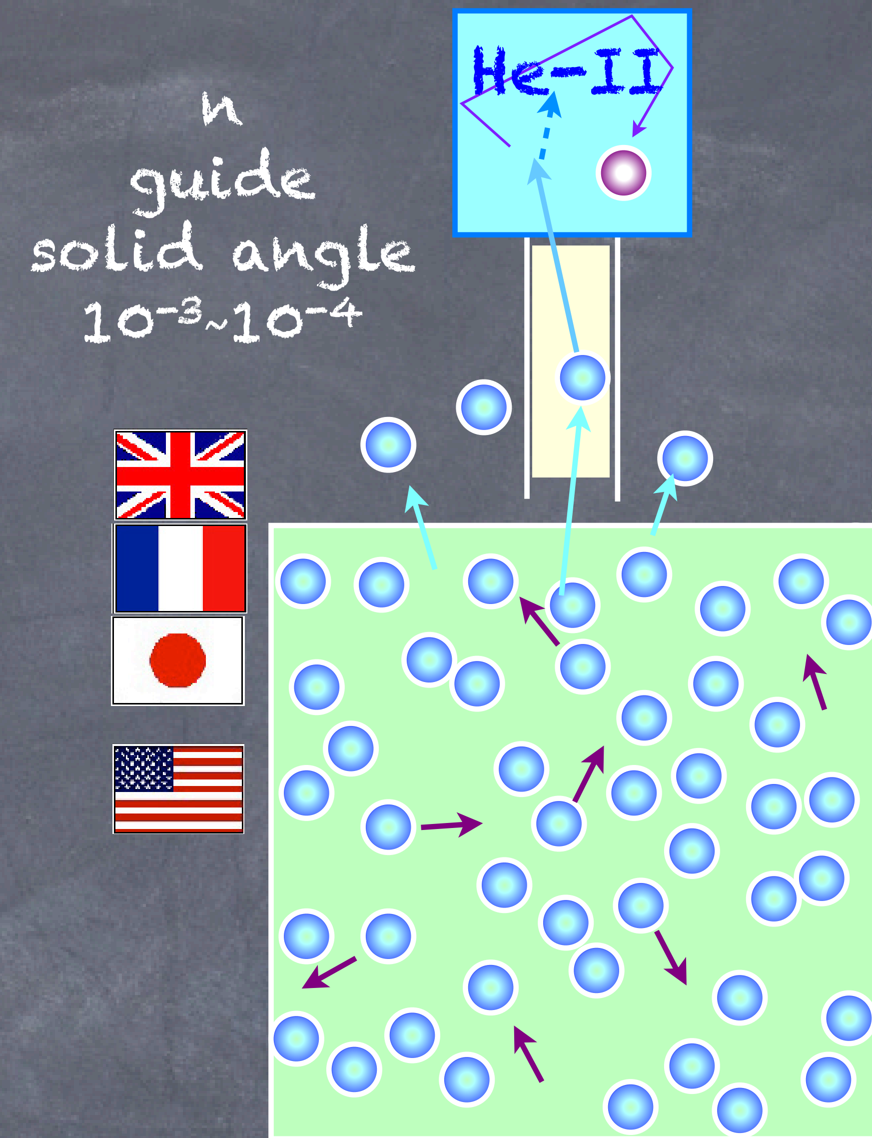
$$\rho_{UCN} = P(\text{production}) \times \tau_s(\text{life}) \times \varepsilon_{ext}(\text{extraction}) \times \varepsilon_d(\text{dilution})$$

P	midium	large	small
τ_s	long	short	long
ε_{ext}	large	small	large
ε_d	large	small	large

New UCN sources





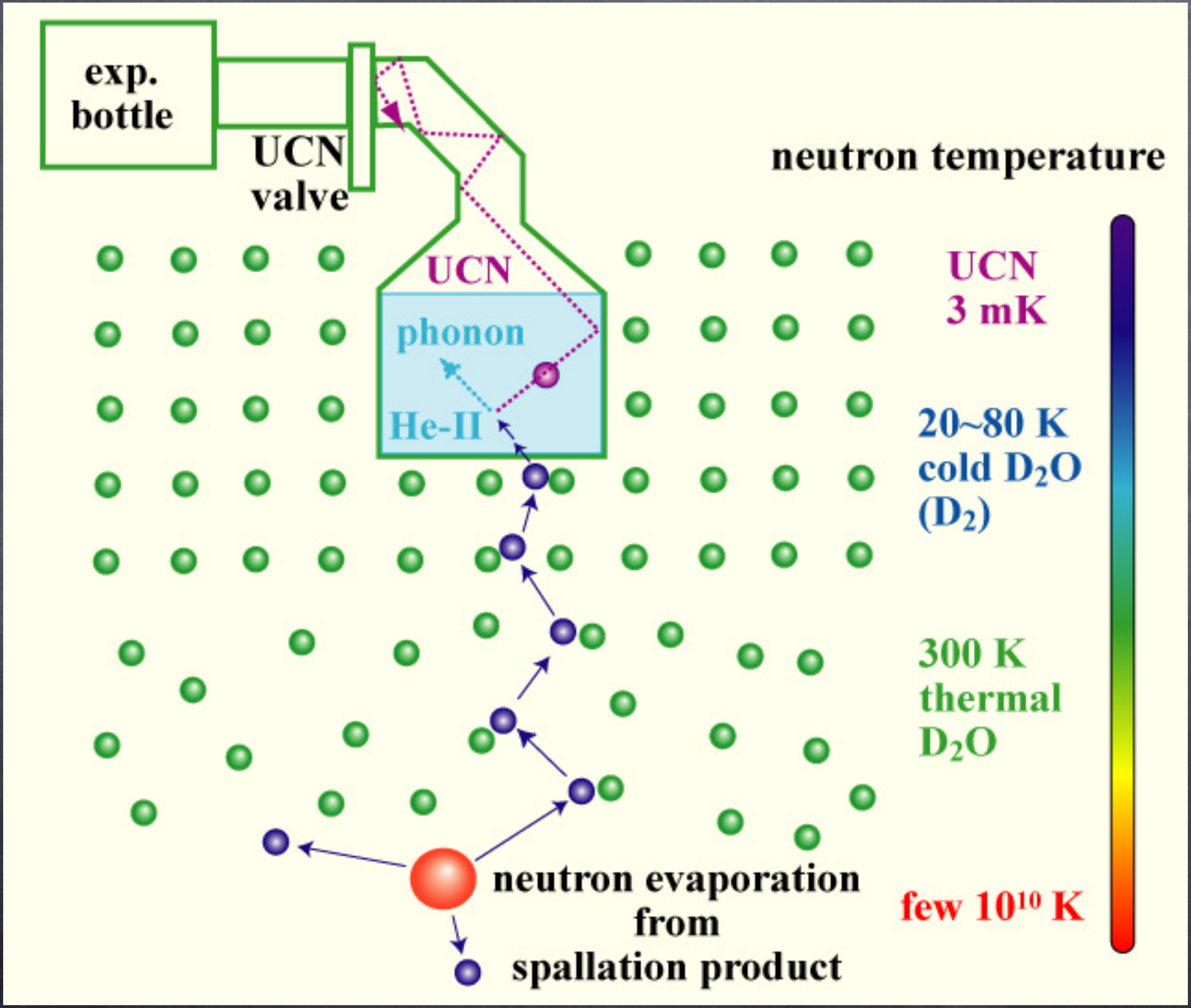


$\rho_{UCN} = P(\text{production}) \times \tau_s(\text{life}) \times \varepsilon_{ext}(\text{extraction}) \times \varepsilon_d(\text{dilution})$

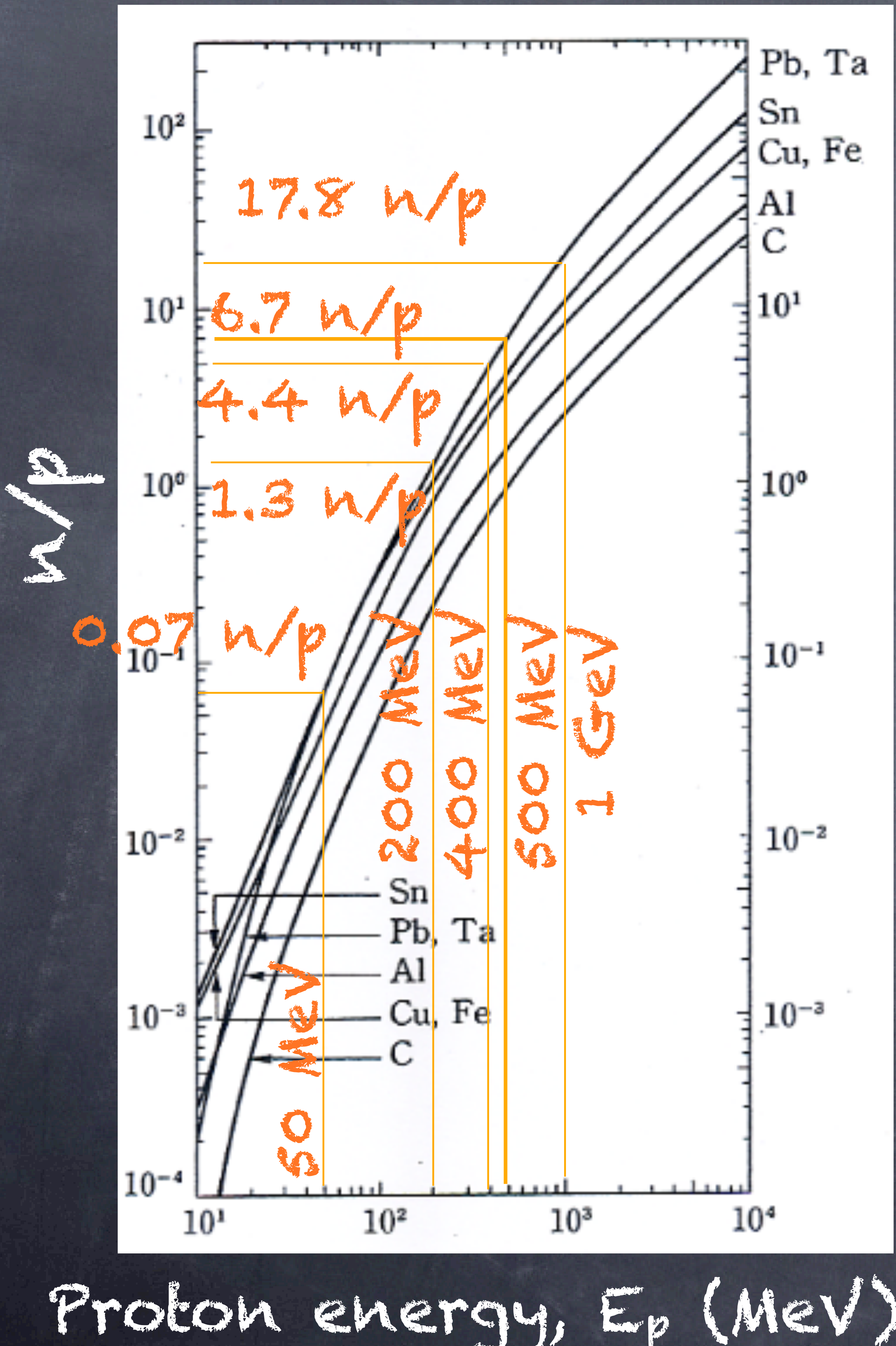
	He-II KEK-RCNP	SD_2 Los Alamos	SD_2 PSI
P_{UCN}($UCN/cm^3/s$)	2×10^3/20kW D_2	4.4×10^4/76kW	2.9×10^5/1.2MW
τ_s (s)	150 (81)	$24\times10^{-3} \rightarrow 1.6$	$24\times10^{-3} \rightarrow 6$
ε_{ext}	1	0.03*	0.1
ε_d	12L → 30L	0.24L → 9.6L	27L → 2000L*

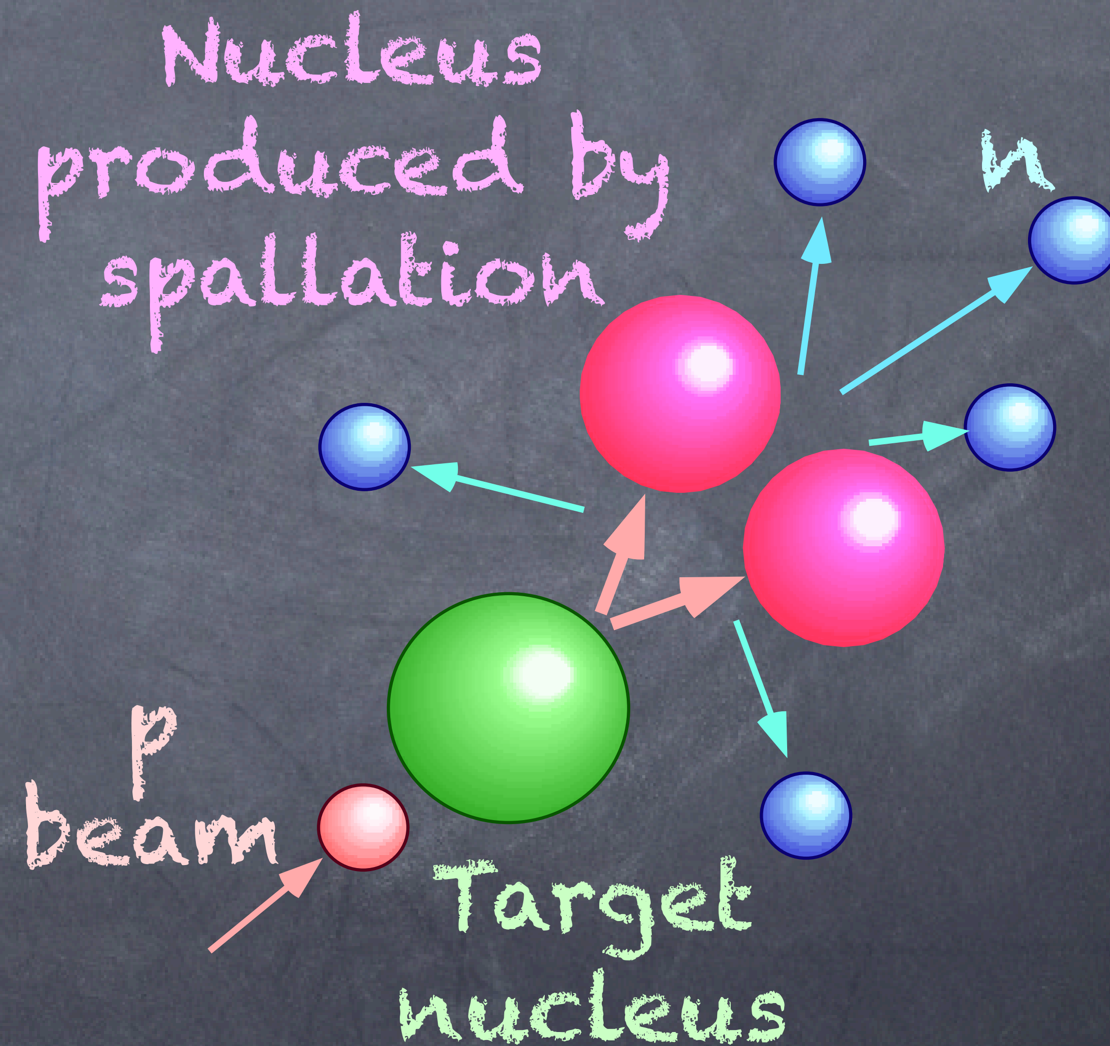
Phys.Lett.A301(2002)462 Phys.Lett.B593(2004)55 Phys.Rev.C71(2005)054601
PhysRevLett 89(2002)

我々のUCN生成法


exp.
bottle
UCN
valve
neutron temperature
UCN
phonon
He-II
UCN
3 mK
20~80 K
cold D2O
(D2)
300 K
thermal
D2O
neutron evaporation
from
spallation product
few 10^10 K

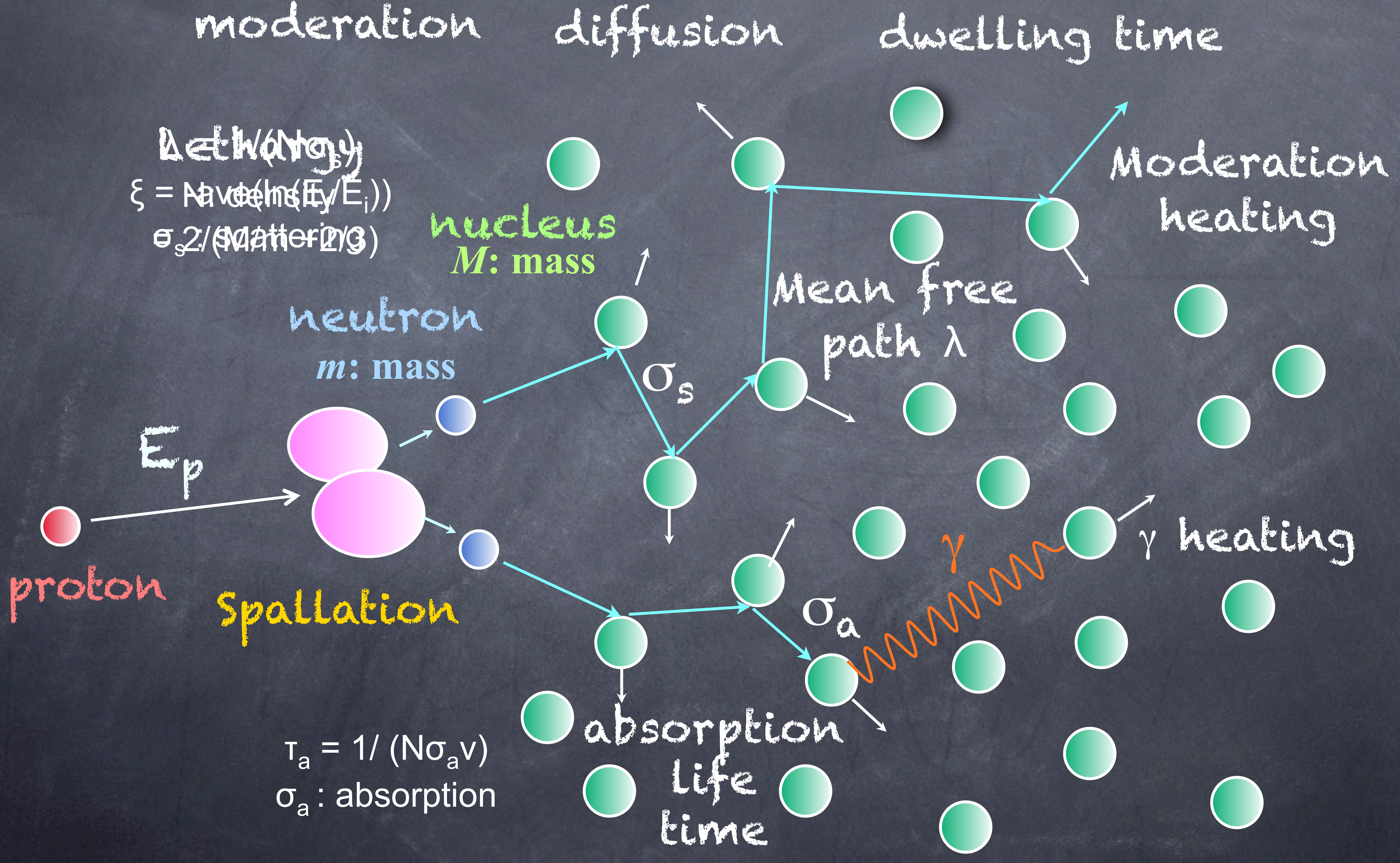
中性子の発生





K. Tesch (1985)

中性子源の基本パラメータ



モデレータの材料

High Φ_n(1 meV): high lethargy and
short mean free path, low absorption (= low γ heating)

	H_2O	D_2O	D_2	Be	C	Pb
Lethargy	0.95	0.57	0.75	0.21	0.16	0.01
Mean free path (cm) $\lambda = 1/(N\sigma_s)$	0.29	2.2	6.0	1.2	2.6	2.7
Density N ($10^{23}/cm^3$)	0.34	0.33	0.25	1.24	0.80	0.33
Scattering σ_s (b)	103	13.6	6.8	7.0	4.8	11.3
Life time (ms) $\tau_a = 1/(N\sigma_a v)$	0.21	100	177	3.46	13	0.81
Absorption σ_a (mb)	665	1.23	1.04	7.6	3.53	171

UCNの取出し

Superfluid He, ε_{ext}~100%

SD$_2$, ε_{ext}~10% [Phys.Rev.C71(2005)054601]

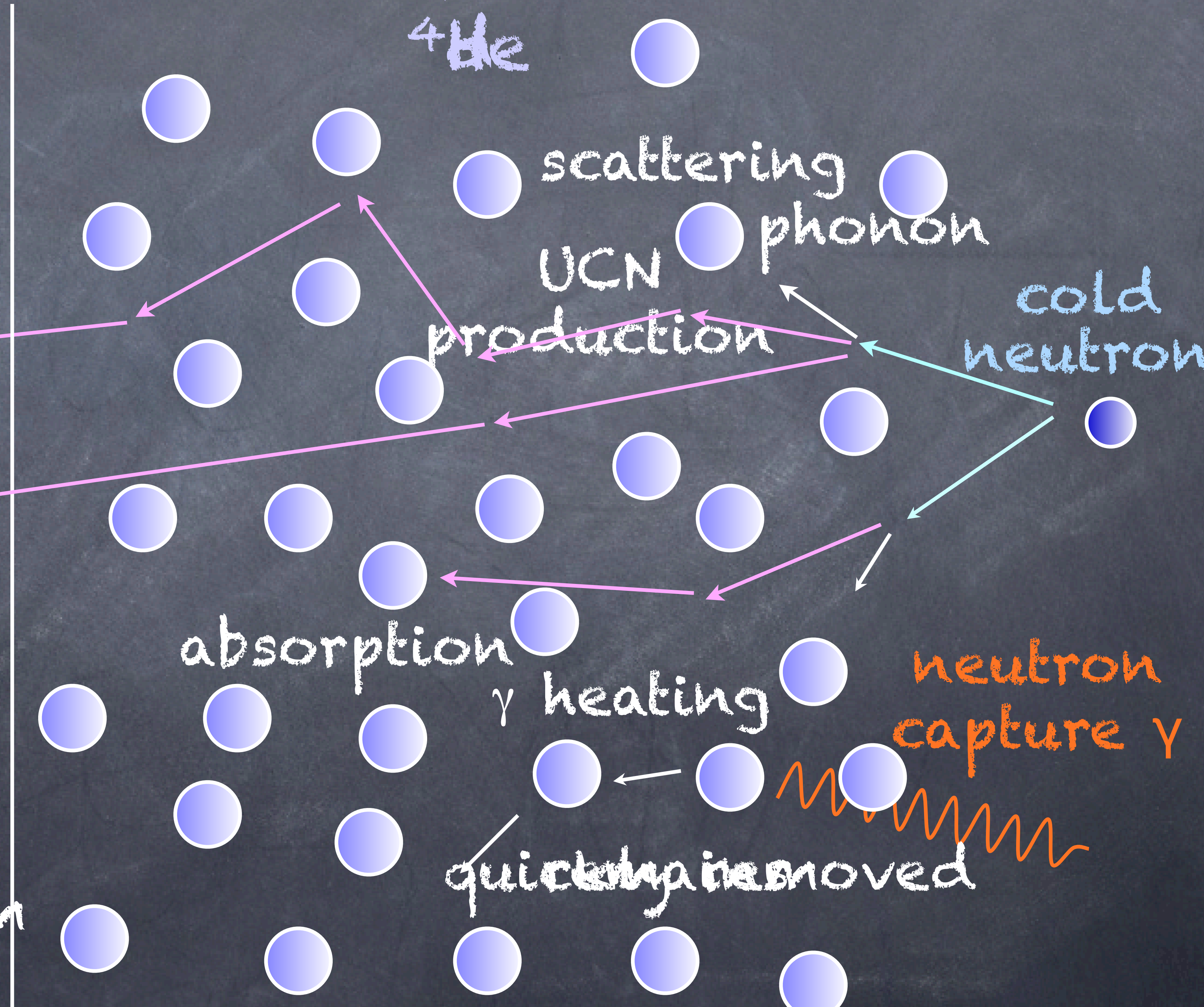
Vacuum

diffuse to
UCN guide /
storage volume

acceleration

UCN
average velocity
v_{av} = 5m/s

$(v_{av}/4)\cdot 24ms$ = 3 cm



大強度UCN生成には

UCN実験の時定数は数100秒なので、

長時間生成が重要。

取り出し効率も重要。

実験容器充填時の希釈を考え、

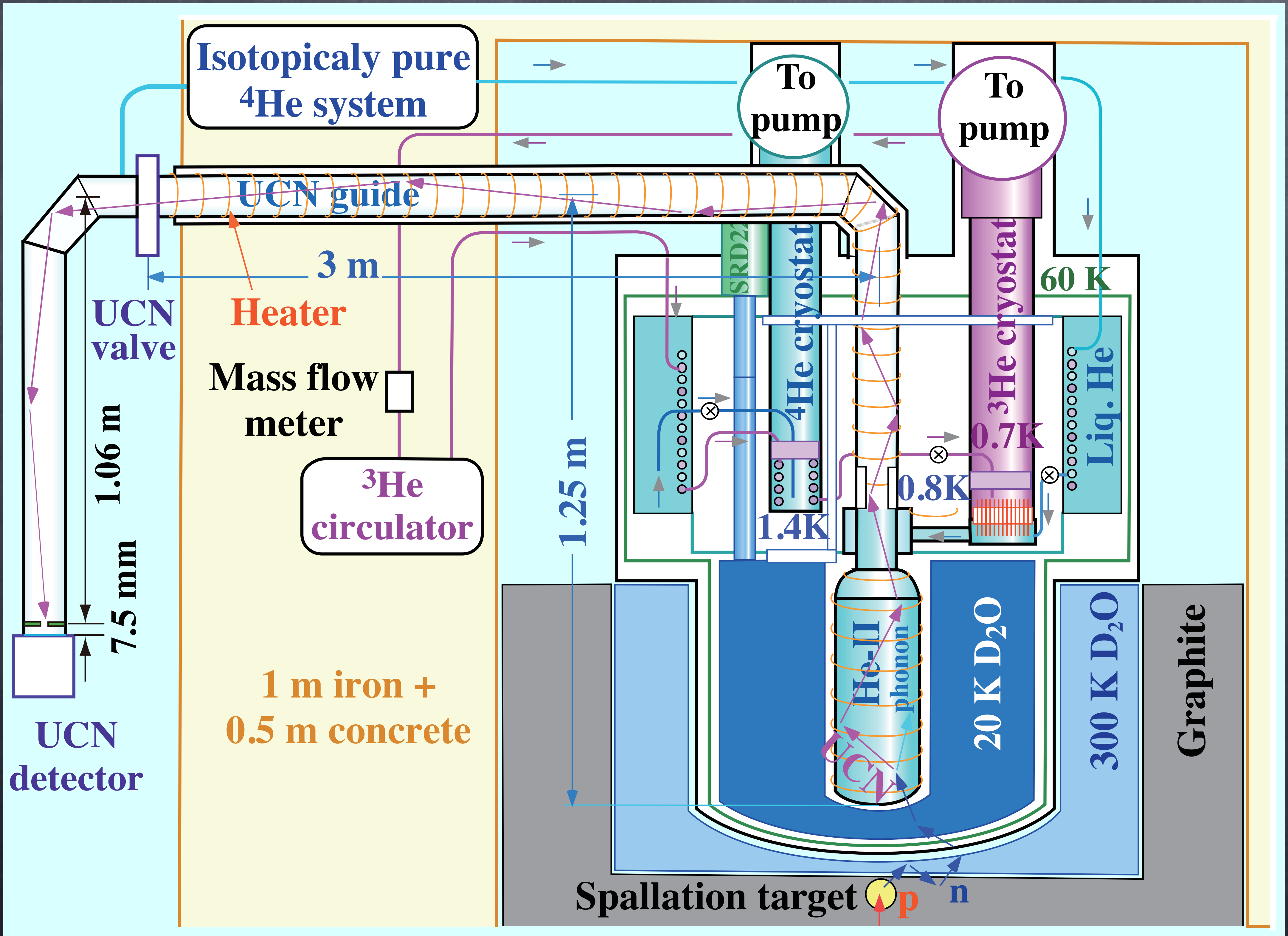
大きな生成体積も重要。

実験時、バックグランドを考えると、

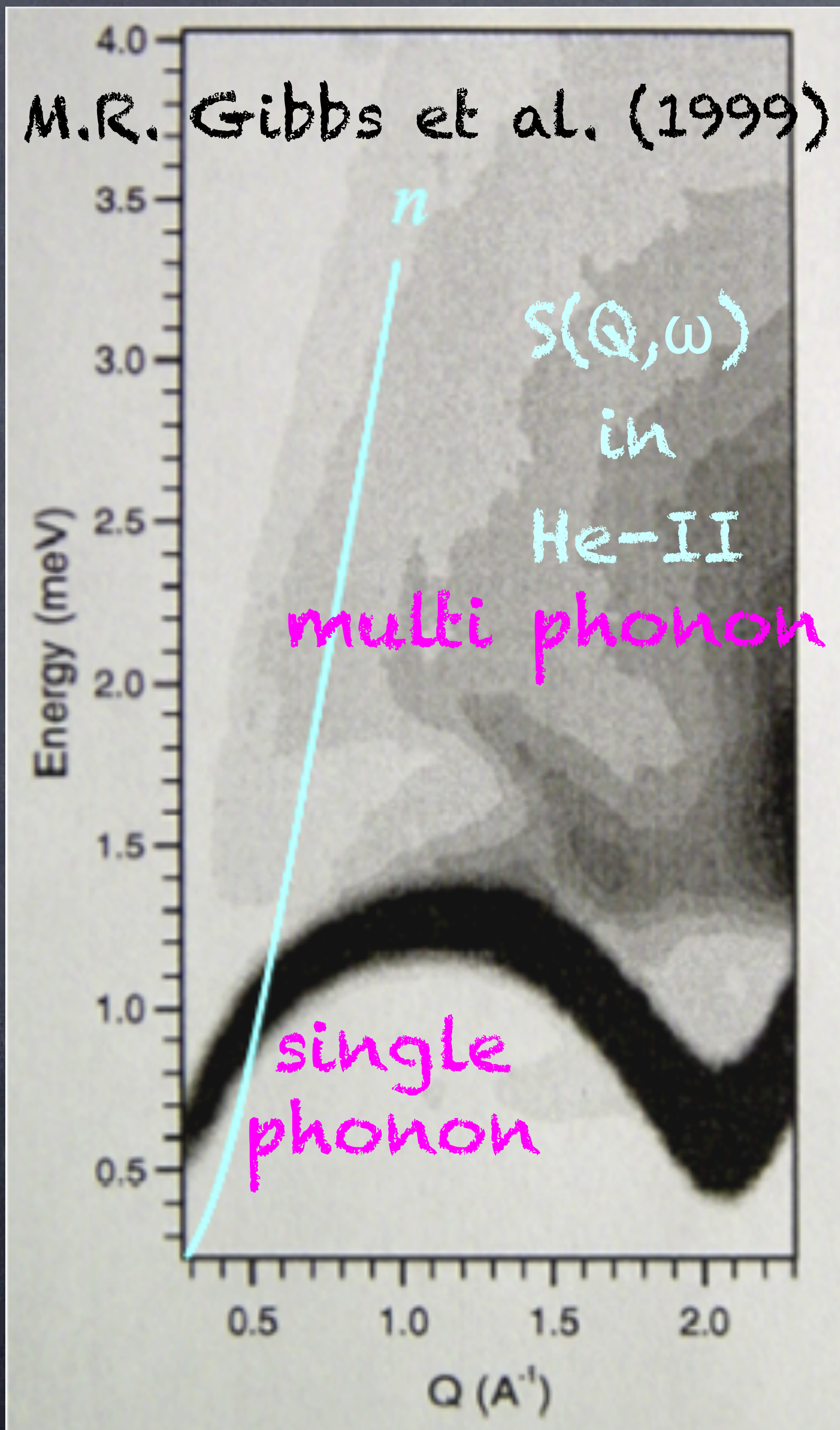
中性子の発生を止めれるのが良い。

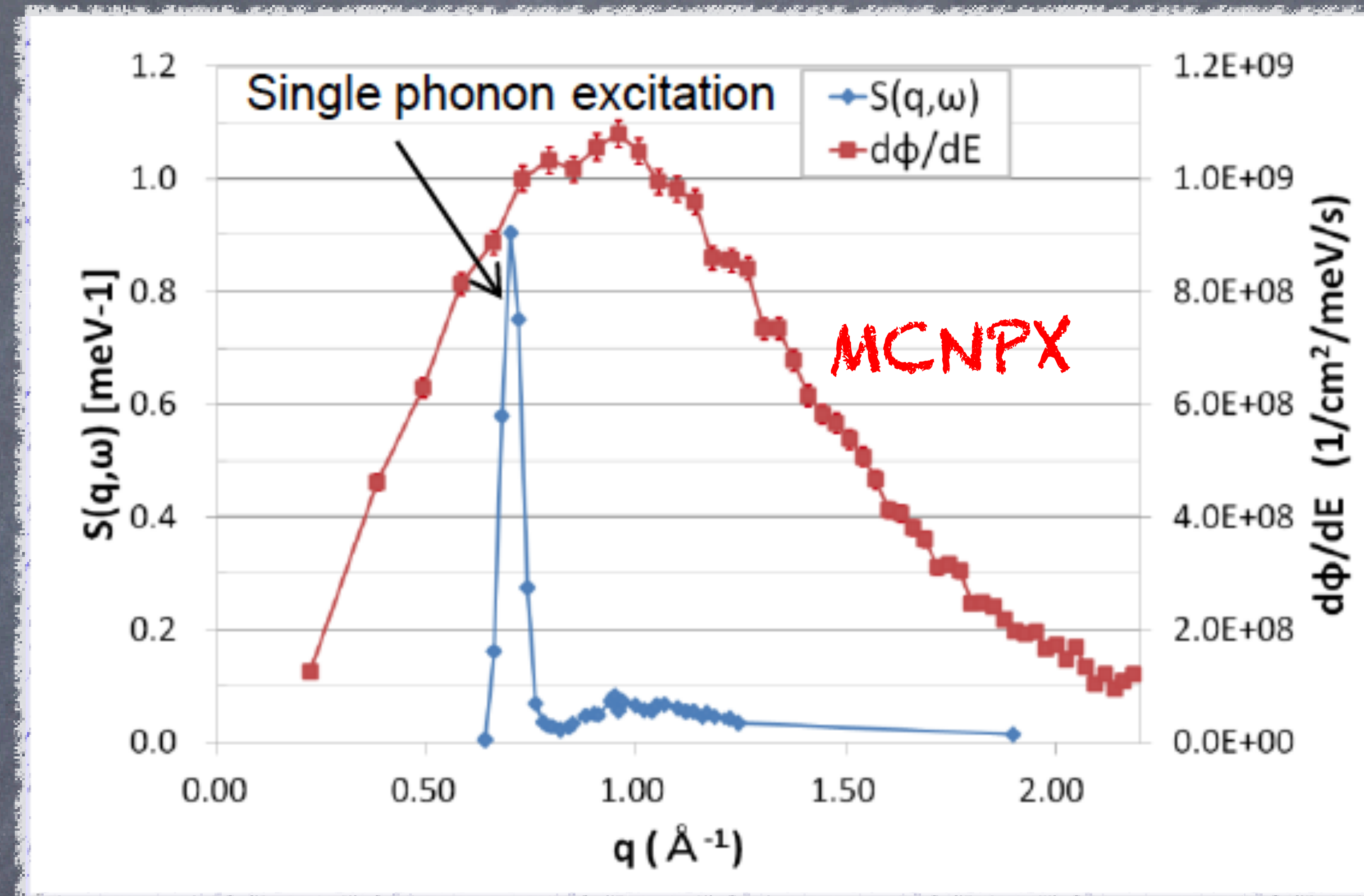
サイクロトロンとHe-IIを用いるのが良い

プロトタイプUCN源 垂直型



He-II内でのUCN生成

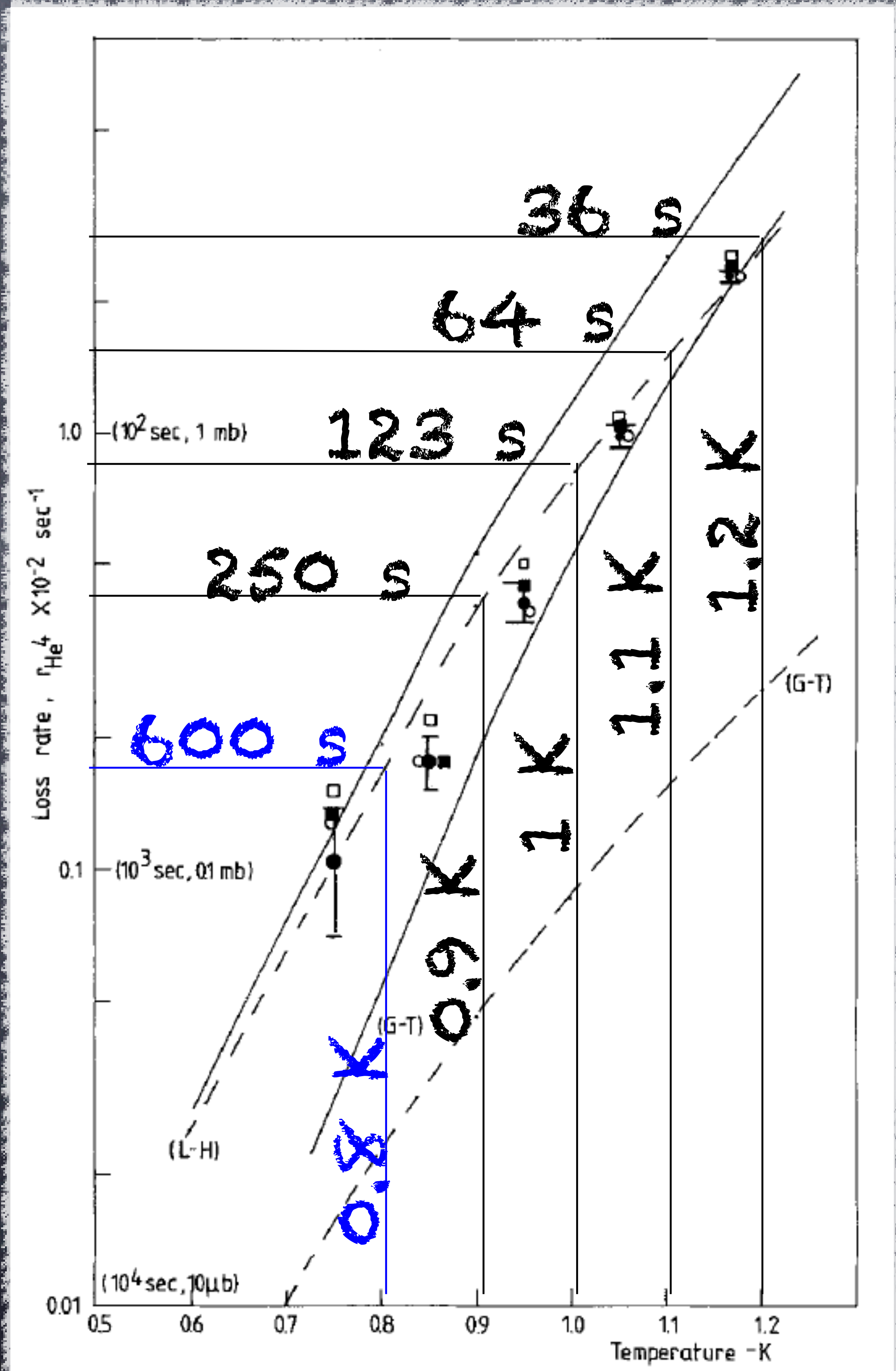




$$P=\int p(E_u)dE_u = N_{He}4\pi b^2\left(\frac{\hbar}{m_n}\right)^2\frac{k_c^3}{3}\left[\int\frac{d\Phi(q)}{dE}S\left(q,\hbar\omega=\frac{\hbar^2q^2}{2m_n}\right)dq\right]$$

P = 14 UCN/cm3/s at 20K
= 6 at 50K
= 4 at 80K

UCN寿命 τ_s



He-II [Golub et al. (1983)]

phonon up-scattering, $1/\tau_{ph} \propto T^7$

τ_{ph}= 600 s at 0.8 K

τ_β = 886 s (β decay)

τ_w = 246 s (wall loss)

Z. Phys. B59(1985)261

$\tau_s = 1/\{1/\tau_{ph} + 1/\tau_\beta + 1/\tau_w\}$

= 150 s

SD_2 [Phys.Rev.C71(2005)054601]

τ_{ph} = 40 ms at 8 K

$\tau_{ortho\text{-}para}$ = 100 ms

τ_a = 150 ms

τ_s = 24 ms

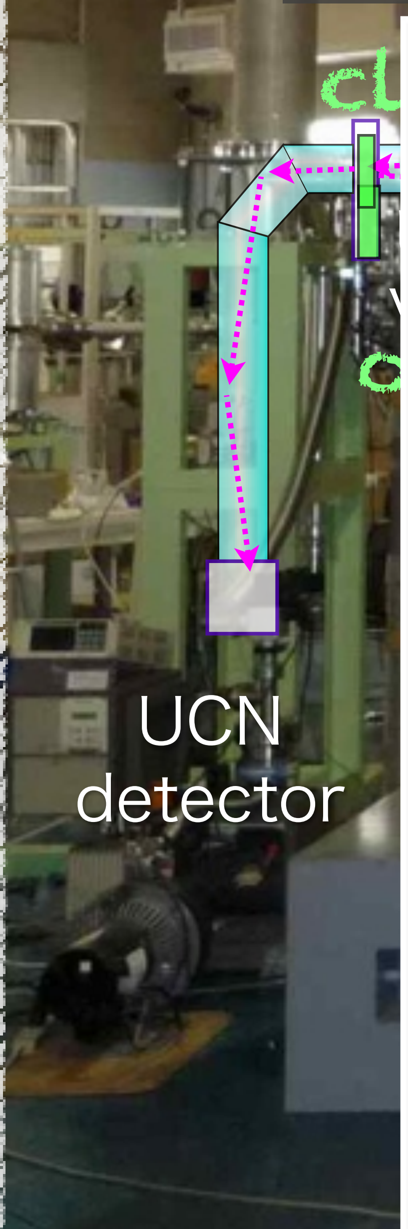
diluted with vacuum

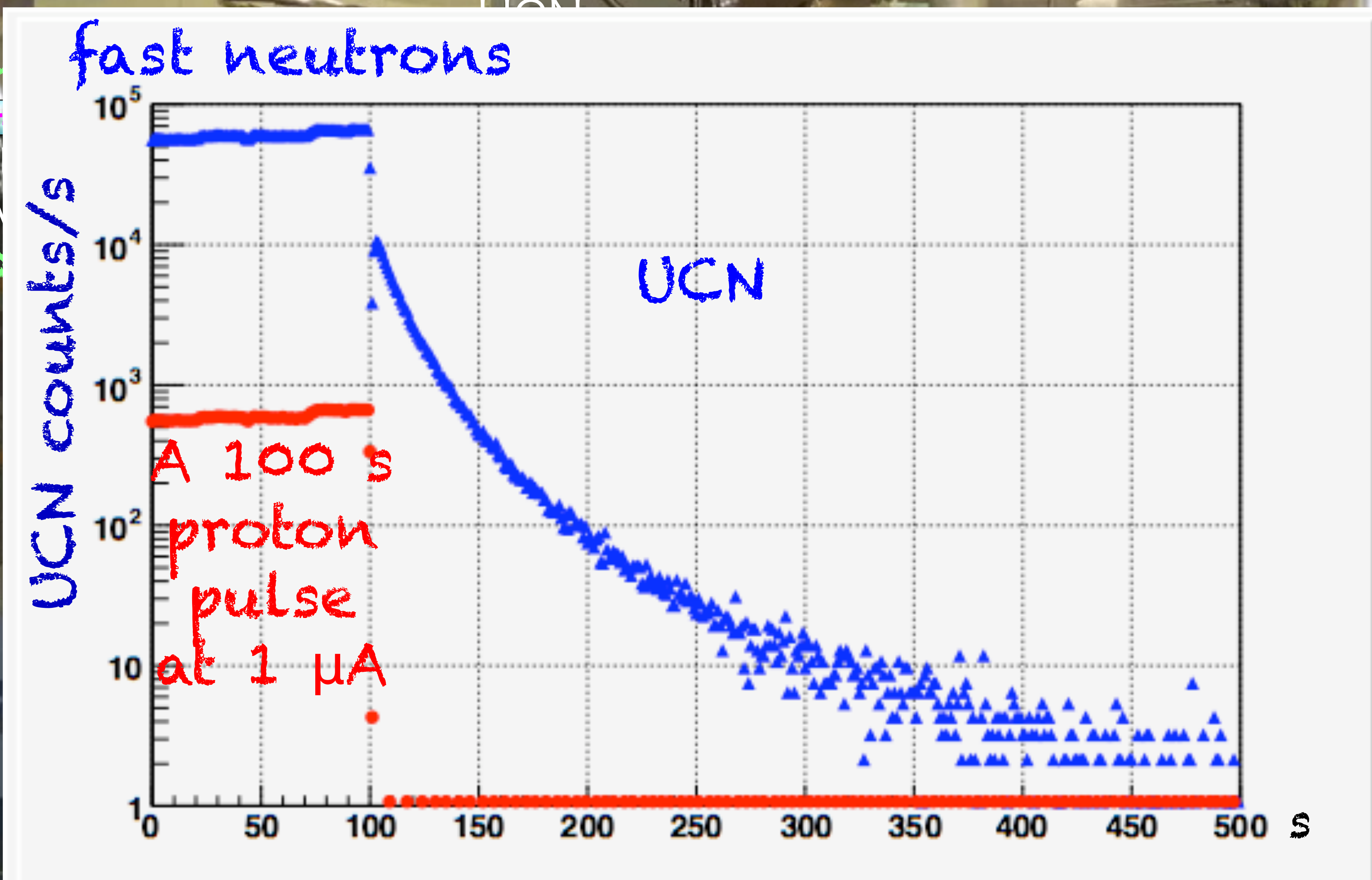
→ τ_s = 1.6 s, Los Alamos

→ τ_s = 6 s, PSI

RCNPでのUCN生成

26 UCN/cm		
75 (		
36	180	4 kW D2 Los Alamos (2010)
18	250	1 MW D2 PSI (2012)
55 (in source)	230	60 MW He-II ILL (





本番のUCN源

$$\rho_{UCN} = P\ \tau_s\ \varepsilon_d$$

Vertical UCN source: P = 4 UCN/cm^3/s

UCN density in 8L He-II 320 UCN/cm^3

Phys. Rev. Lett. 108(2012)134801

Horizontal:

improving geometry	×1.2
increasing RCNP p beam 10μA×400MeV	×10
using TRIUMF p beam 40μA×500MeV	×5
storage lifetime τ_s = 81 s → 150 s	×2

$P\ \tau_s$ = 36000 UCN/cm^3

in 11L He-II

$P\ \tau_s\ \varepsilon_d$ = 12000 UCN/cm^3

at UCN valve in He-II

ε_d : dilution factor

世界の nEDM 計画

	Magnetic field	Magnetometer	EDM cell	UCN source	UCN density
KEK-RCNP	Spherical coil Finemet	^{129}Xe comagnetometer no GPE	T = 300 K	He-II @n-source	12000* 210neV
Sussex	Solenoid μ metal supercon.	external n magnetometer no GPE	T ~ 0.5 K	He-II @n-beam	1000 250neV
SNS	truncate cosθ Metglass	^{3}He comagnetometer GPE	T ~ 0.5 K	He-II @n-beam	150 134neV
PSI	truncate cosθ μ metal	external Cs magnetometer no GPE	T = 300 K	D_2 @n-source	1000* 250neV
TUM	truncate cosθ μ metal	external 199Hg magnetometer no GPE	T = 300 K	D_2 @n-source	**
PNPI	*	external magnetometer no GPE	T = 300 K	He-II @n-source	7500* 250neV

* At EDM experiment port

Thanks