Cryogenics for Neutron Fundamental Physics

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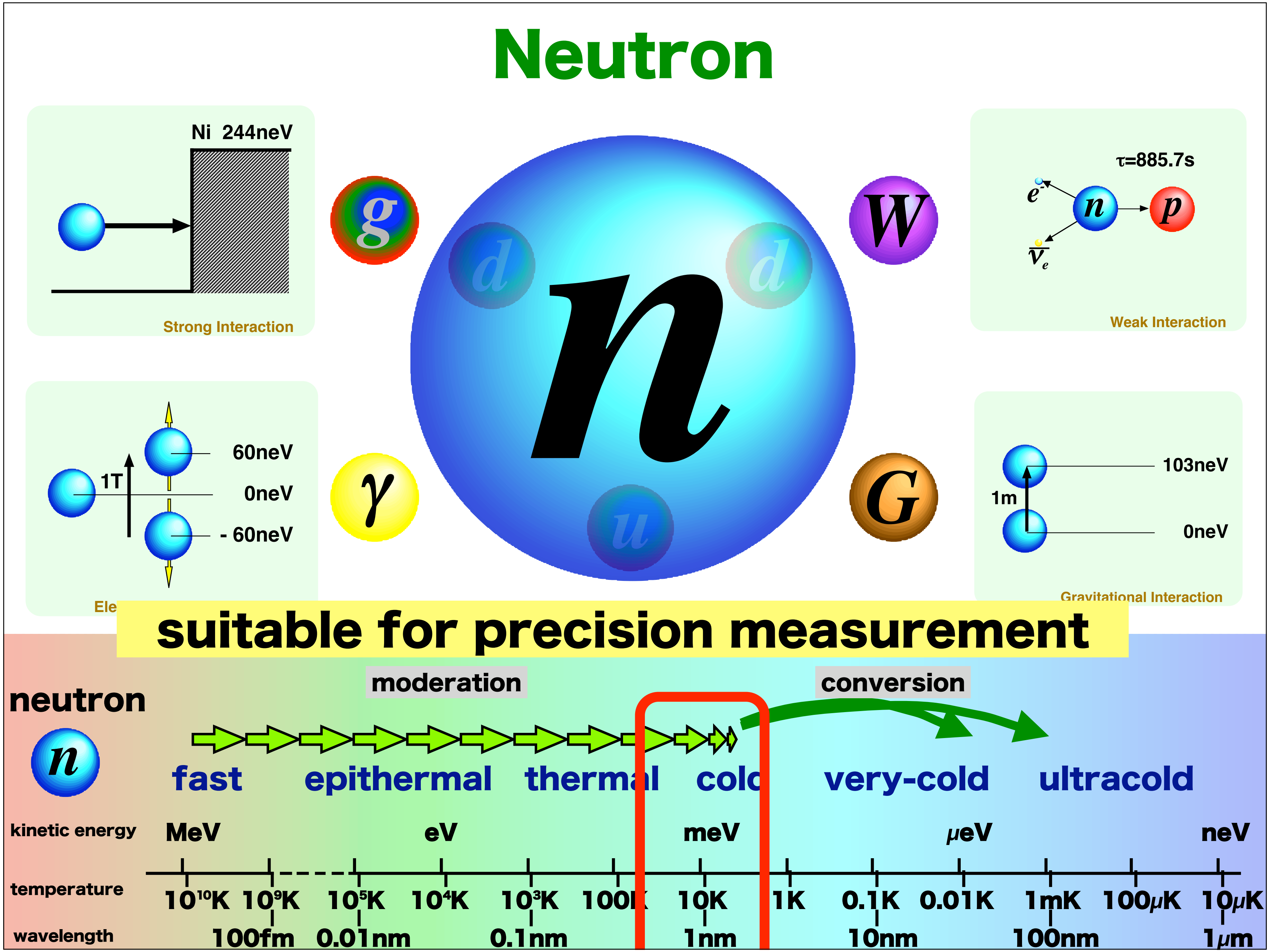
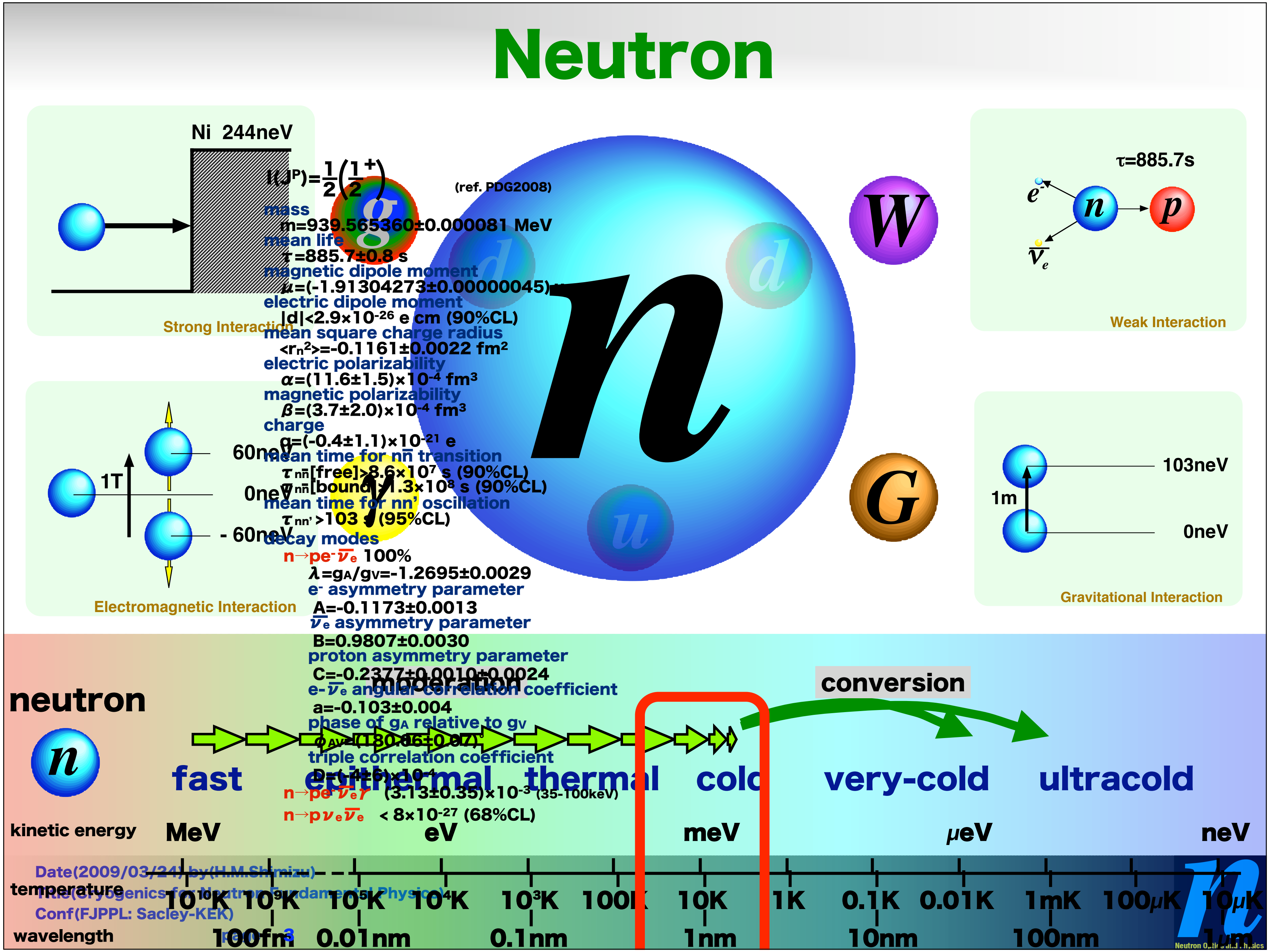


Neutron
Ni 244neV
Strong Interaction
τ=885.7s
e
n
p
Weak Interaction
g
W
d
d
n
u
γ
G
1T
60neV
0neV
- 60neV
103neV
1m
0neV
Gravitational Interaction
suitable for precision measurement
moderation
conversion
neutron
n
fast
epithermal
thermal
cold
very-cold
ultracold
kinetic energy
MeV
eV
meV
μeV
neV
temperature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


Neutron
Ni 244neV
Strong Interaction
$I(J^P)=\frac{1}{2}(\frac{1}{2}^+)$
(ref. PDG2008)
mass
m=939.565360±0.000081 MeV
mean life
τ=885.7±0.8 s
magnetic dipole moment
μ=(-1.91304273±0.00000045)
electric dipole moment
|d|<2.9×10^-26 e cm (90%CL)
mean square charge radius
<r_n^2>=-0.1161±0.0022 fm^2
electric polarizability
α=(11.6±1.5)×10^-4 fm^3
magnetic polarizability
β=(3.7±2.0)×10^-4 fm^3
charge
q=(-0.4±1.1)×10^-21 e
mean time for nn̄ transition
τ_nn̄[free]>8.6×10^7 s (90%CL)
τ_nn̄[bound]>1.3×10^8 s (90%CL)
mean time for nn' oscillation
τ_nn' >103 s (95%CL)
decay modes
n→pe^- ν̄_e 100%
λ=g_A/g_V=-1.2695±0.0029
e^- asymmetry parameter
A=-0.1173±0.0013
ν̄_e asymmetry parameter
B=0.9807±0.0030
proton asymmetry parameter
C=-0.2377±0.0010±0.0024
e-ν̄_e angular correlation coefficient
a=-0.103±0.004
phase of g_A relative to g_V
φ_AV=(180.06±0.07)°
triple correlation coefficient
D=(-4±6)×10^-4
n→pe^- ν̄_e γ (3.13±0.35)×10^-3 (35-100keV)
n→pν_e ν̄_e <8×10^-27 (68%CL)
60neV
0neV
- 60neV
1T
Electromagnetic Interaction
g
d
d
u
n
γ
W
G
τ=885.7s
e^-
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Weak Interaction
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wavelength
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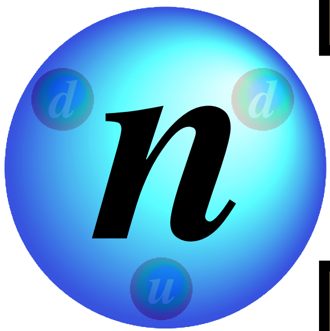
Date(2009/03/24) by(H.M.Shimizu)
Title(Cryogenics for Neutron Fundamental Physics)
Conf(FJPPL: Saclay-KEK)
page 3

Neutron

$I(J^P)=\frac{1}{2}(\frac{1}{2}^+)$ (ref. PDG2008)



mass
$m=939.565360\pm0.000081$ MeV

mean life
$\tau=885.7\pm0.8$ s

magnetic dipole moment
$\mu=(-1.91304273\pm0.00000045)\mu_N$

electric dipole moment
$|d|<2.9\times10^{-26}$ e cm (90%CL)

mean square charge radius
$\langle r_n^2\rangle=-0.1161\pm0.0022$ fm^2

electric polarizability
$\alpha=(11.6\pm1.5)\times10^{-4}$ fm^3

magnetic polarizability
$\beta=(3.7\pm2.0)\times10^{-4}$ fm^3

charge
$q=(-0.4\pm1.1)\times10^{-21}$ e

mean time for $n\bar{n}$ transition
$\tau_{n\bar{n}}$[free]>8.6×10^7 s (90%CL)
$\tau_{n\bar{n}}$[bound]>1.3×10^8 s (90%CL)

mean time for nn' oscillation
$\tau_{nn'}$>103 s (95%CL)

decay modes
$n\to pe^-\bar{\nu}_e$ 100%
$\lambda=g_A/g_V=-1.2695\pm0.0029$
e^- asymmetry parameter
$A=-0.1173\pm0.0013$
$\bar{\nu}_e$ asymmetry parameter
$B=0.9807\pm0.0030$
proton asymmetry parameter
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e-$\bar{\nu}_e$ angular correlation coefficient
$a=-0.103\pm0.004$
phase of g_A relative to g_V
$\phi_{AV}=(180.06\pm0.07)^\circ$
triple correlation coefficient
$D=(-4\pm6)\times10^{-4}$
$n\to pe^-\bar{\nu}_e\gamma$ $(3.13\pm0.35)\times10^{-3}$ (35-100keV)
$n\to p\nu_e\bar{\nu}_e$ $<8\times10^{-27}$ (68%CL)

CKM matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$\lambda=g_A/g_V$

T-violation in a static system

medium range force search

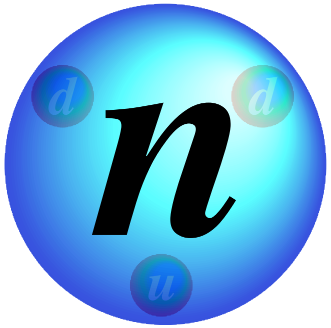
Neutron

CKM matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

search for footprints of higher energy phenomena in quantum loops

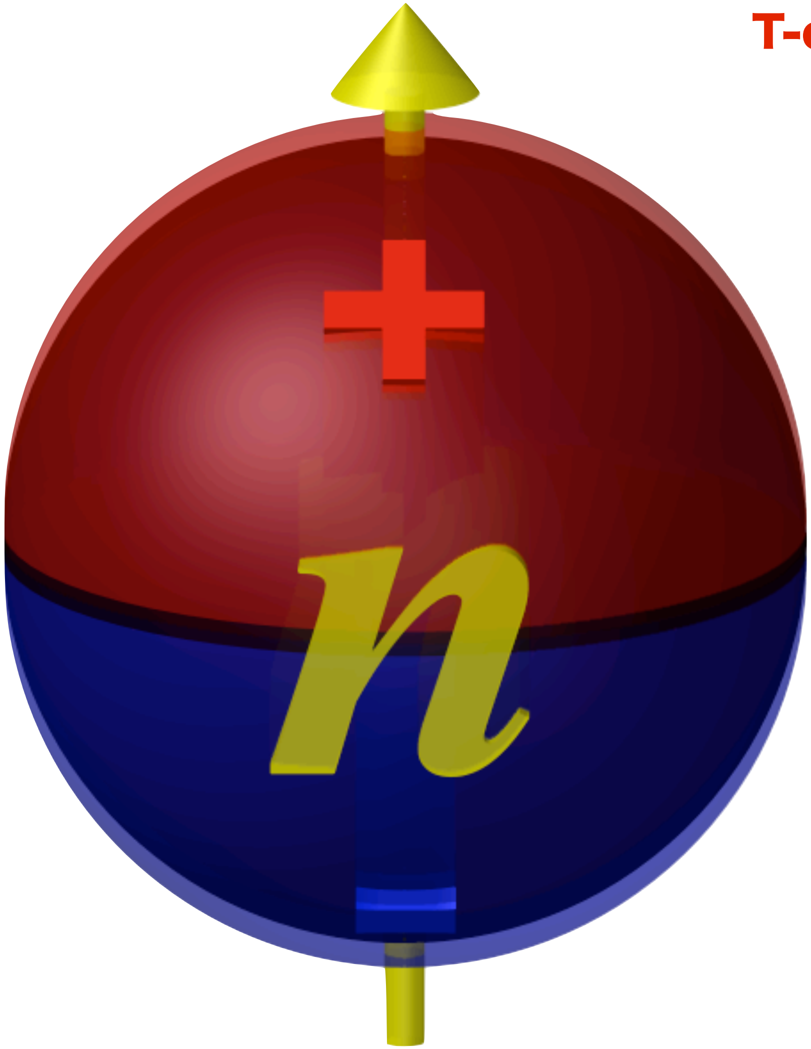
$\lambda = g_A / g_V$



T-violation in a static system

medium range force search

Neutron Electric Dipole Moment



T-odd observable in a static system
→ T-violation

$$\hbar\omega = -2\vec{\mu}_n \cdot \vec{B} - 2\vec{d}_n \cdot \vec{E}$$

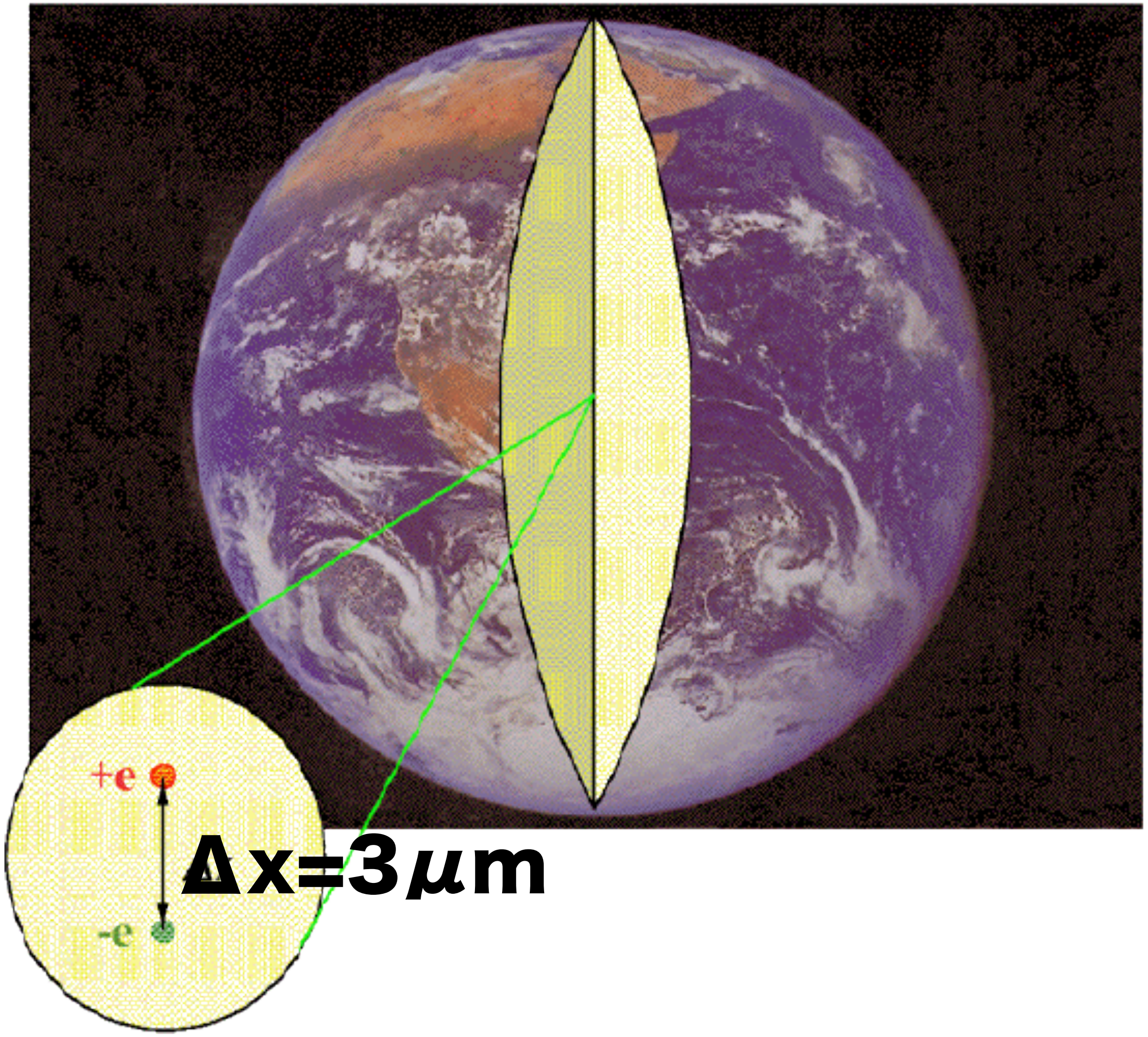
P-odd T-odd

$|d_n| < 2.9\times10^{-26}$ e cm (90%CL)

Baker et al., PRL97 (2006)131801

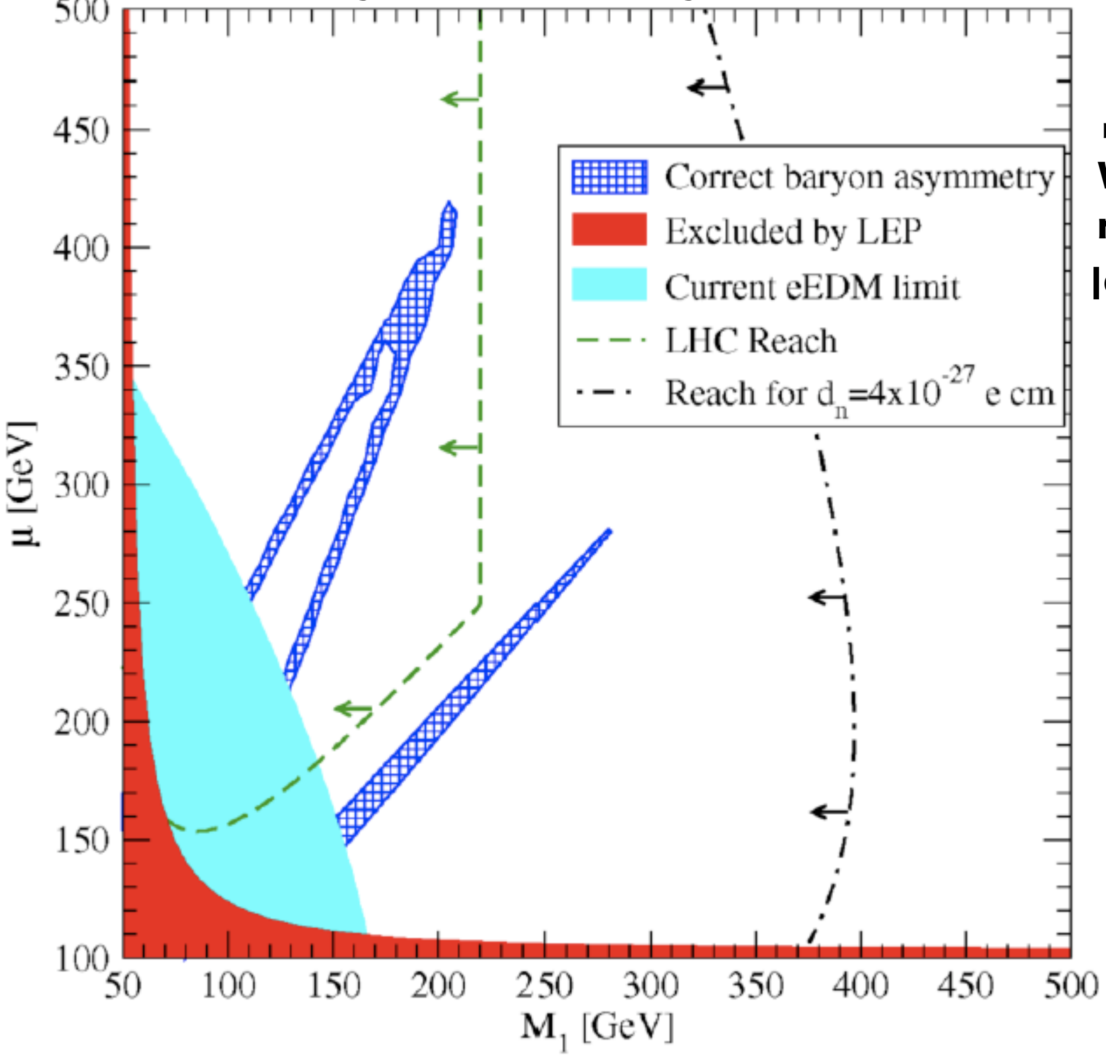
$|d_n| < 2.9\times10^{-26}$ e cm (90%CL)

The moment corresponds to 3μm difference of charge centers in the earth.



Neutron Electric Dipole Moment

Ramsey-Musolf, Nucl.Phys.A805(2008)137c



$M_2=2M_1$, $M_A=1$TeV, $|\sin\phi_\mu|=0.5$

WMAP BAU

$m_{\chi^+}<103.5$GeV

$|d_e|<1.9\times10^{-27}$ e cm

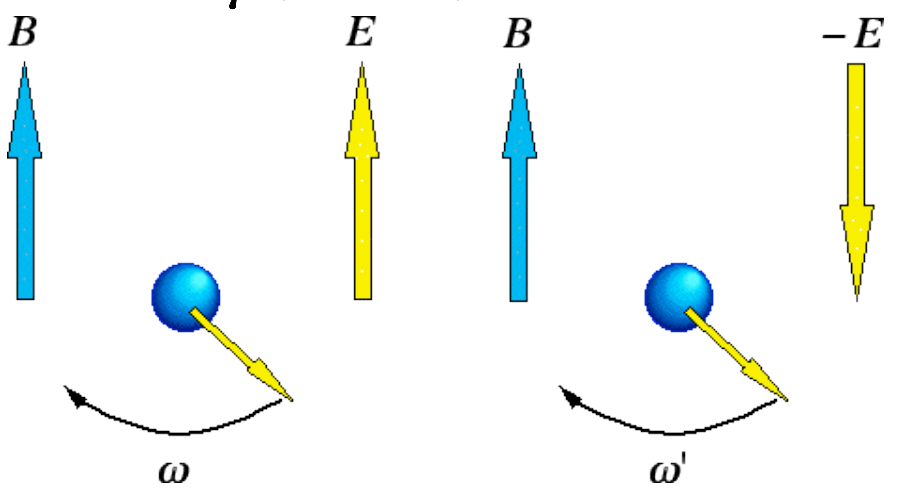
stringent restriction

Neutron Electric Dipole Moment

$|d_n| < 2.9\times10^{-26}$ e cm (90%CL)

$$\hbar\omega = -2\mu_n \bullet B - 2d_n \bullet E$$

P-odd T-odd



$$\omega \neq \omega' \Leftrightarrow d_n \neq 0$$

$$\phi = 2(E \cdot d_n)t/\hbar$$

sensitivity

$$\sigma_D = \frac{(\hbar/2)}{\alpha E t N^{1/2}}$$

UCN can be stored in material bottle→remarkable increase of interaction time t

UCN

ultracold neutron

$E \sim 10^4$ V cm^{-1}

$t \sim 10^3$ s

$Et \sim 10^7$ V s cm^{-1}

$Et \sim 10^6$ V s cm^{-1}

energy sensitivity

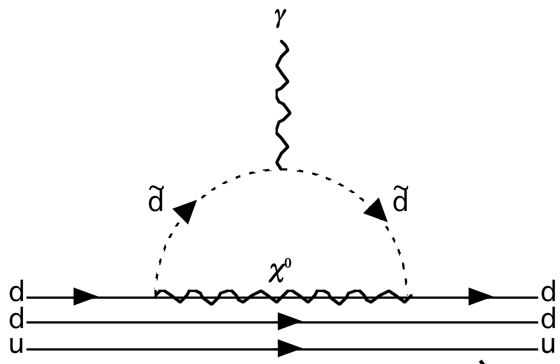
$$2d_nE = 6\times10^{-22}\ \text{eV}$$

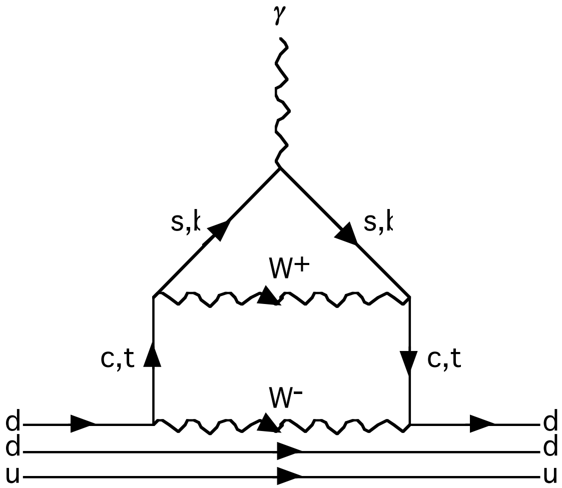
discovery potential

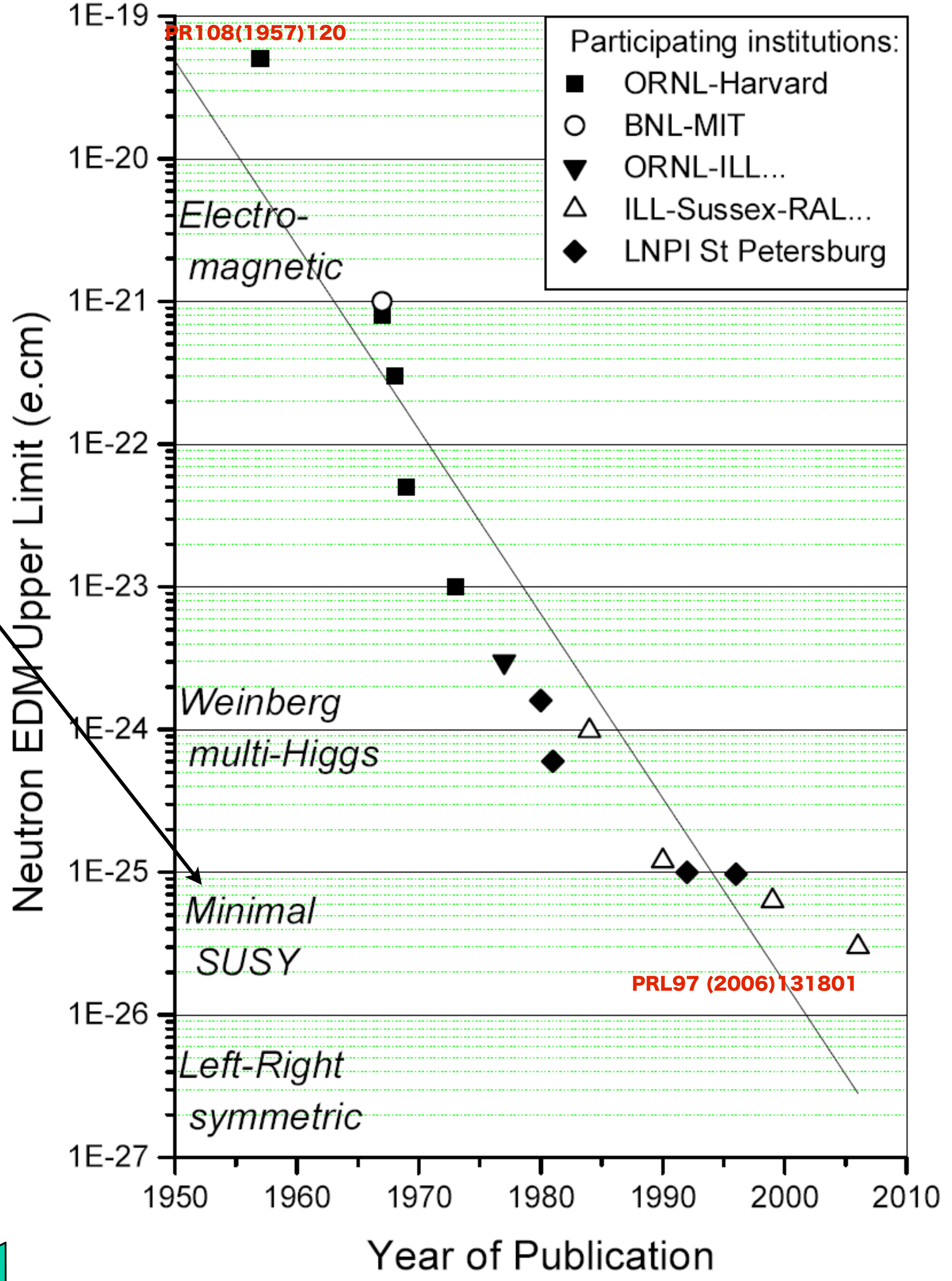
Electric Dipole Moment

$$d_n \sim 10^{-27}\ \mathrm{e\ cm} \quad \Leftarrow \quad (10^{-26}\ \mathrm{e\ cm})$$

P.Harris, hep-ph 0709-3100



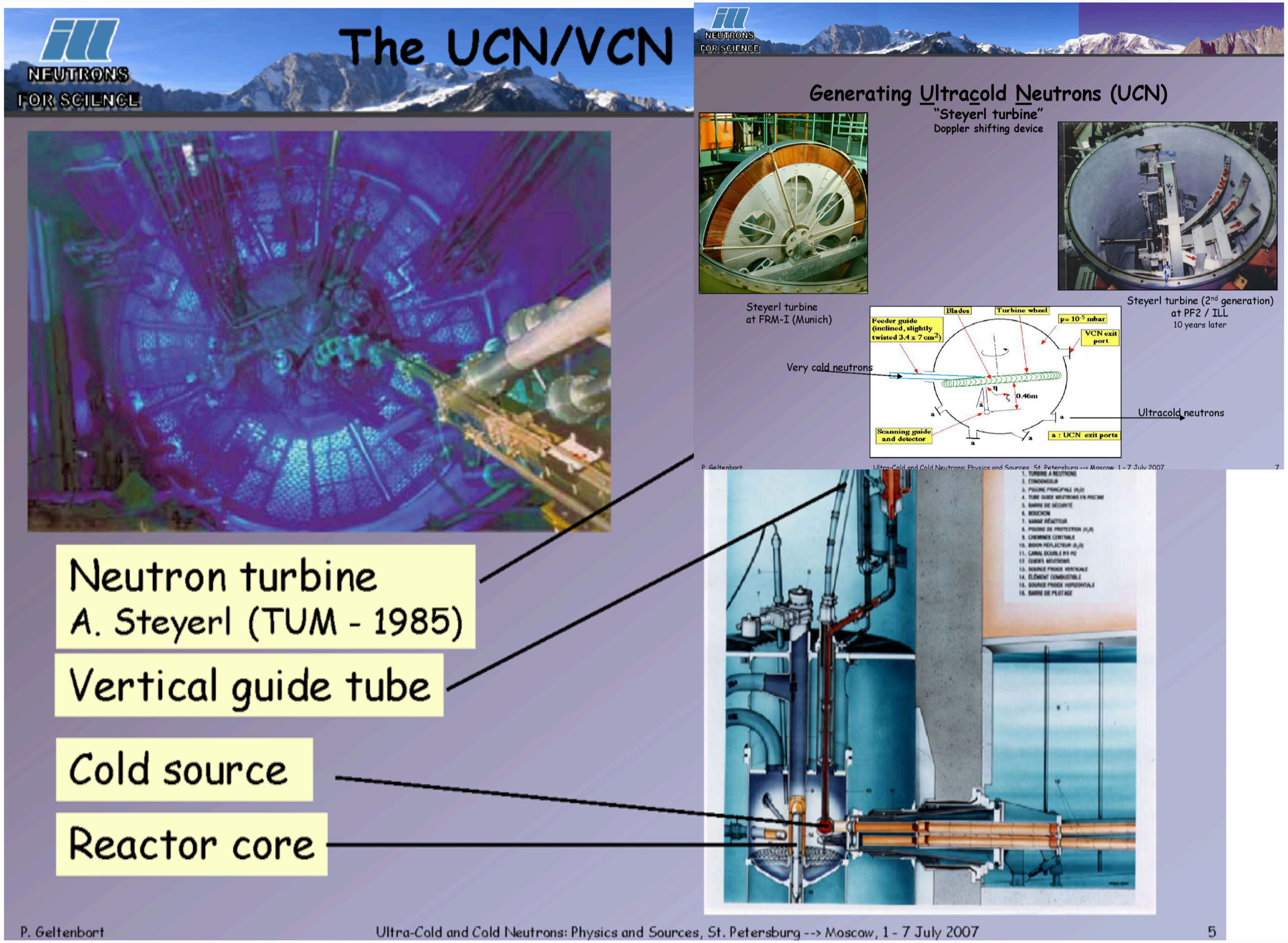




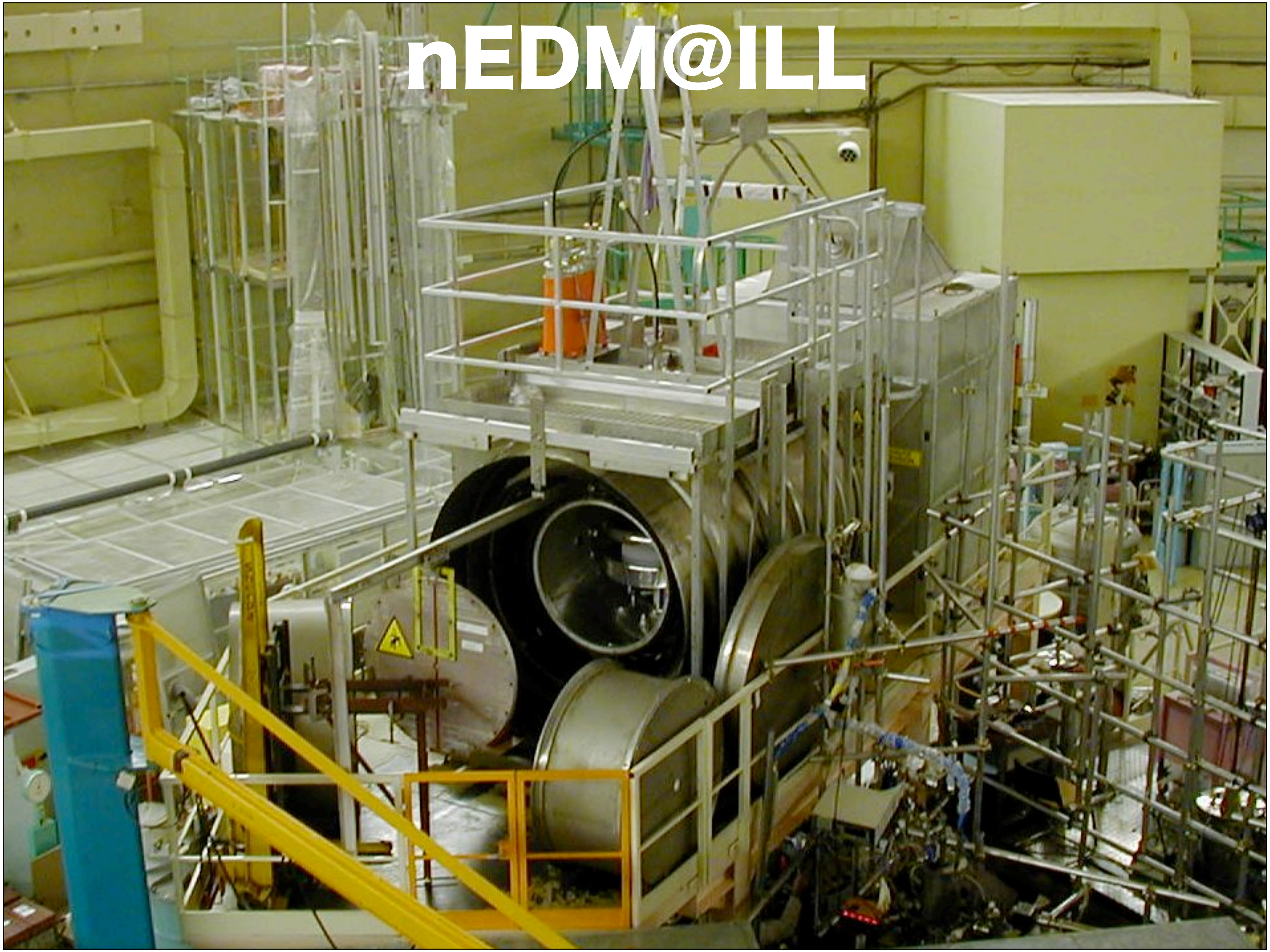
Standard Model ~ 10^{-32}

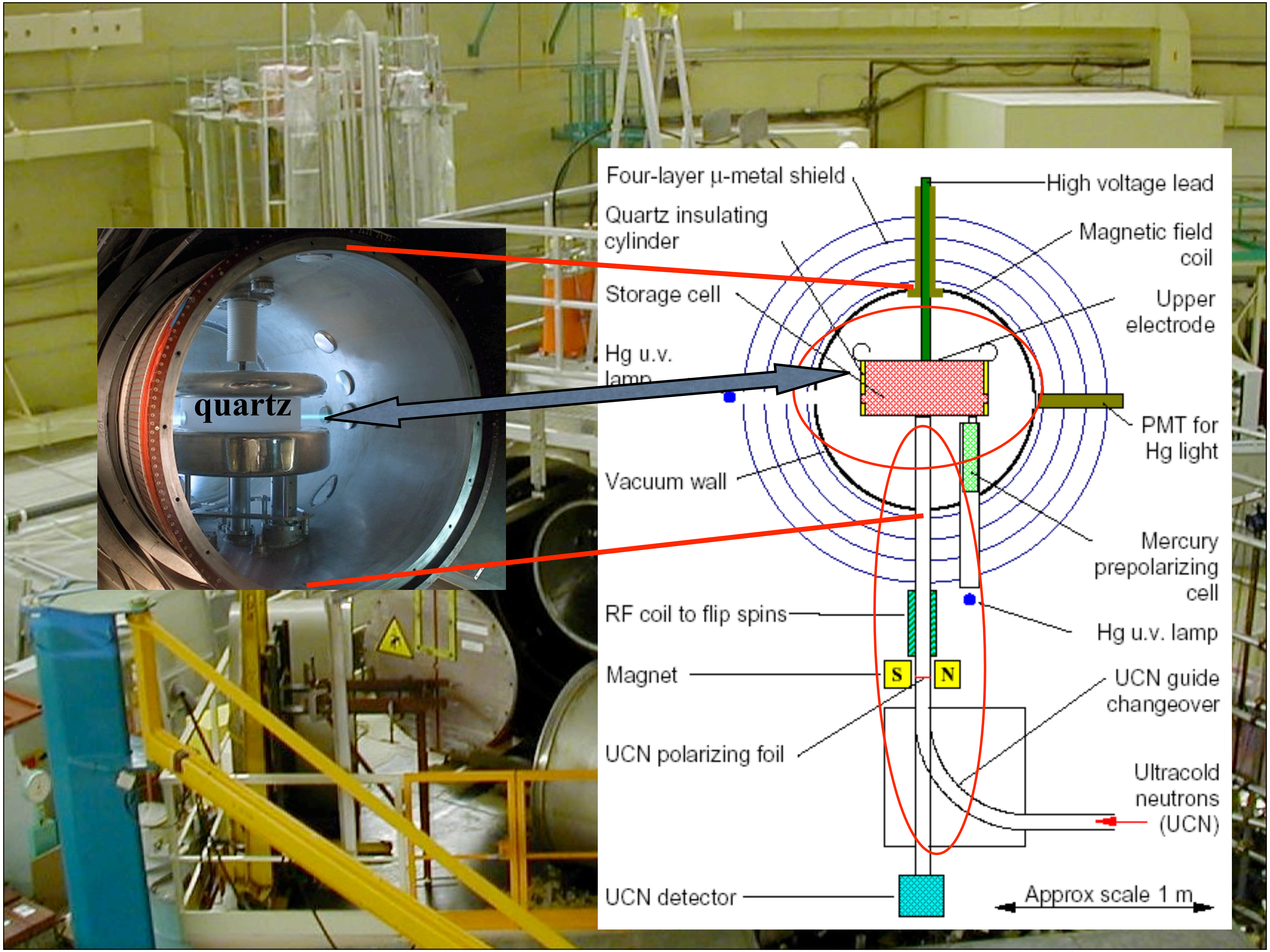
ILL-UCN

gravitational+tubine deceleratrion

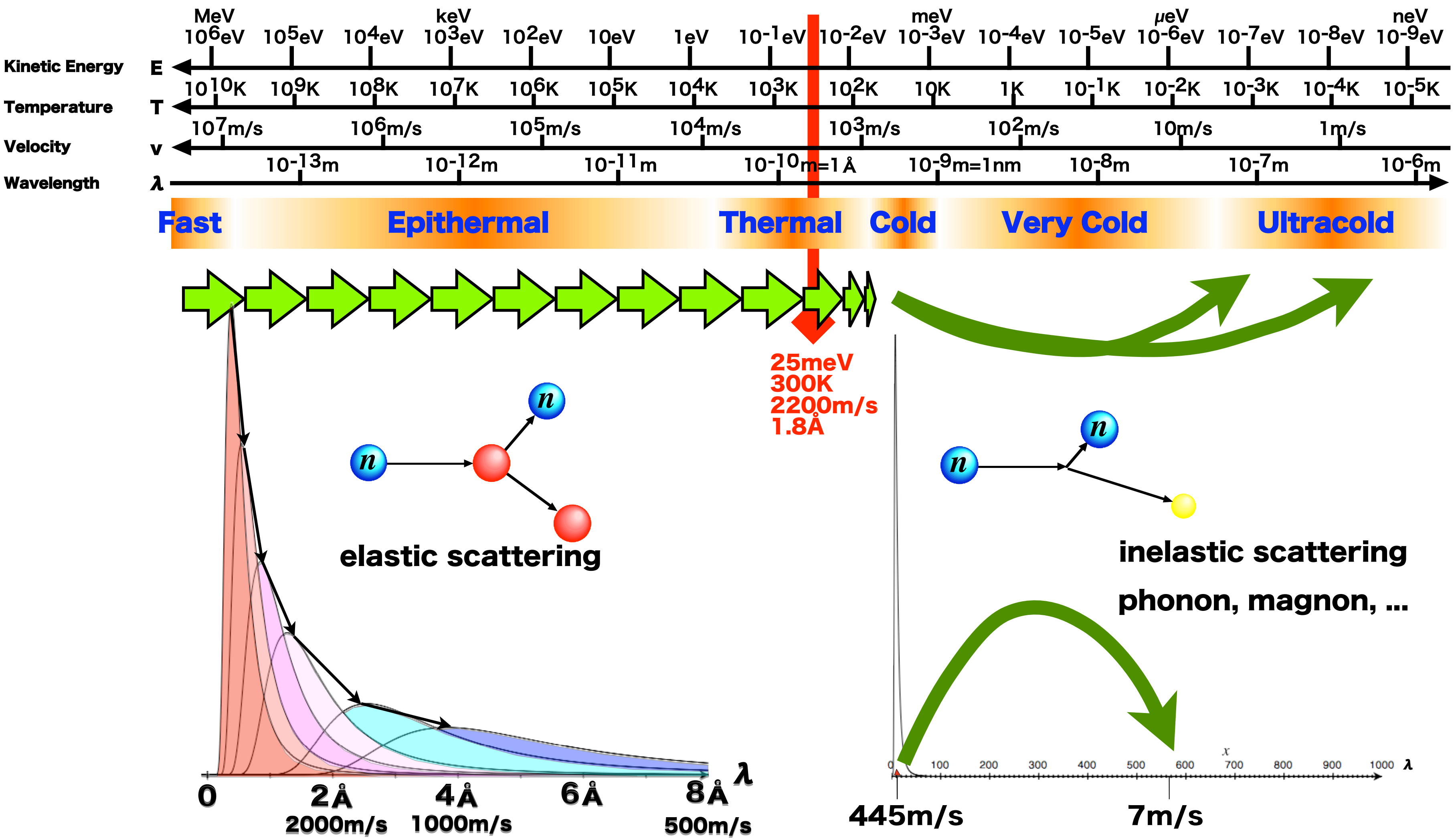


nEDM@ILL




quartz
Four-layer μ-metal shield
Quartz insulating cylinder
Storage cell
Hg u.v. lamp
Vacuum wall
RF coil to flip spins
Magnet
S
N
UCN polarizing foil
UCN detector
High voltage lead
Magnetic field coil
Upper electrode
PMT for Hg light
Mercury prepolarizing cell
Hg u.v. lamp
UCN guide changeover
Ultracold neutrons (UCN)
Approx scale 1 m

Superthermal Production



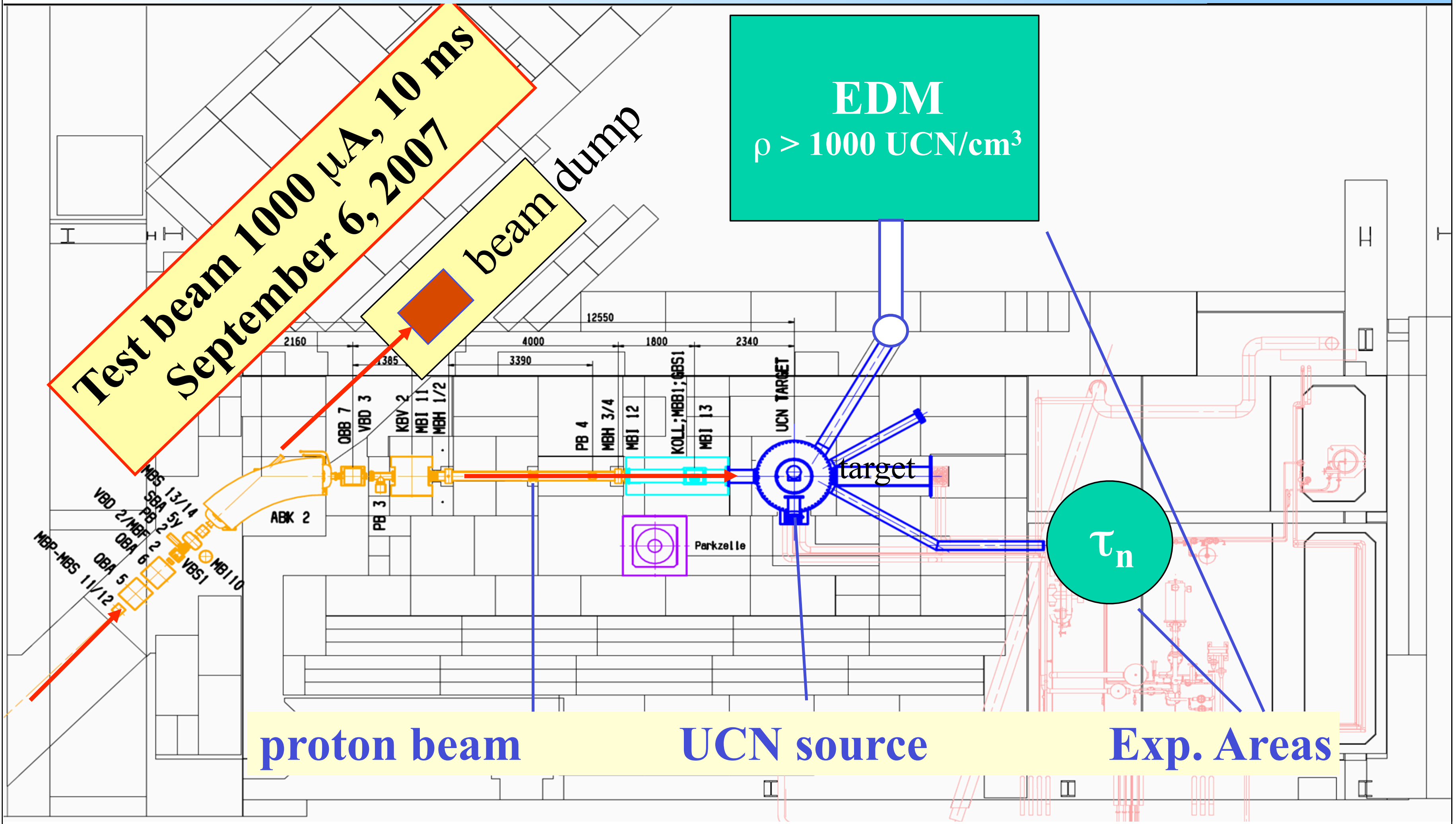
PSI-UCN

Proton accelerator @ PSI

Ring cyclotron: 590MeV,
2mA → total: 1.2 MW

UCN experiments

Experimental areas



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PSI

UCN

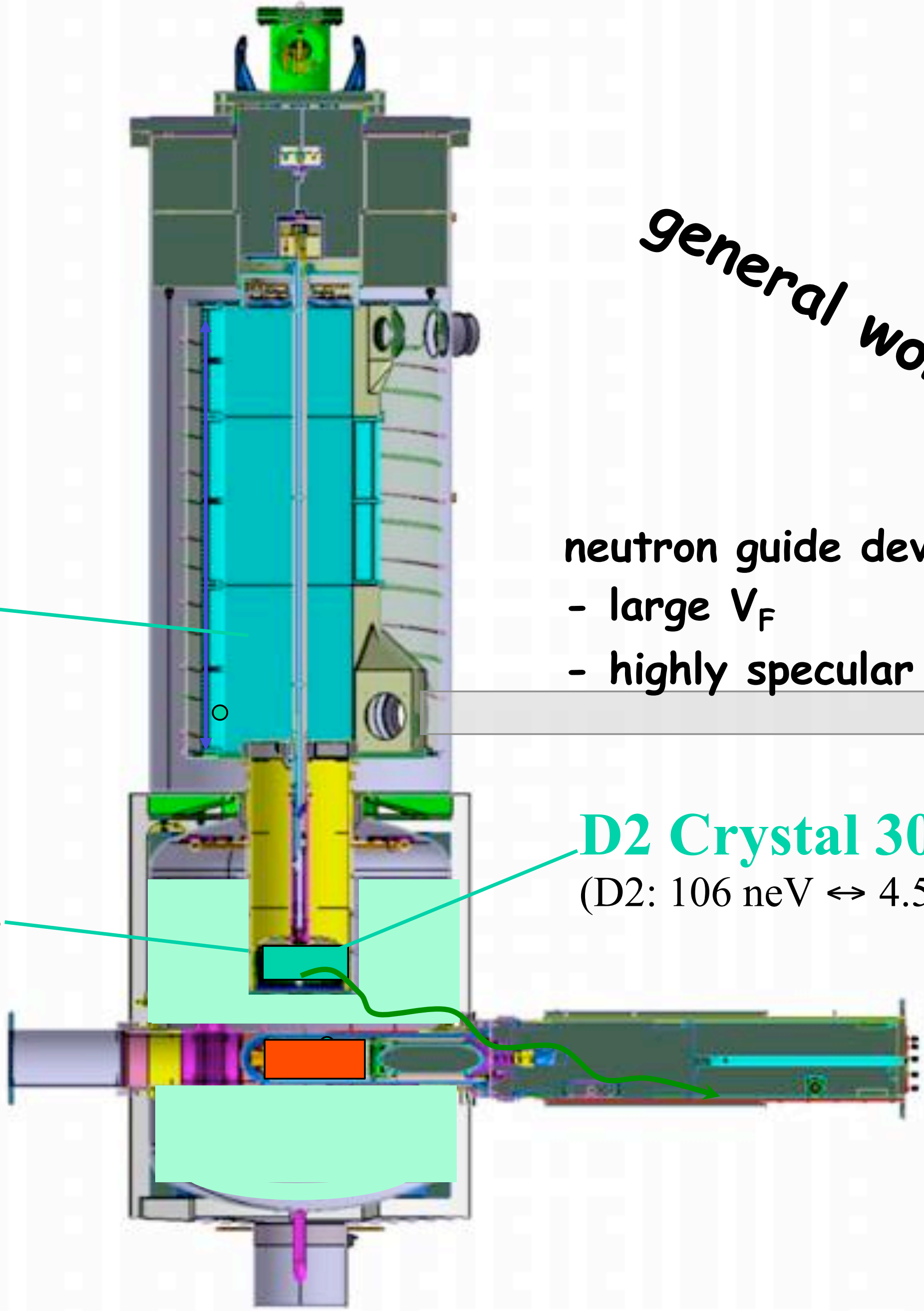
Ultra Cold Neutron Source

general working principle

Storage Volume
height = 2.5 m
volume » 1.8 m³
DLC coating

$\rho_n \sim 2000\ cm^{-3}$

$v_n = 0 - 7$ m/s



neutron guide development

- large V_F
- highly specular

$\rho_n \sim 1000\ cm^{-3}$

D2 Crystal 30 dm³ at 5K

(D2: 106 neV ↔ 4.5 m/s)

$v_n = 5 - 9$ m/s

$\rho_n \sim 5000\ cm^{-3}$

UCN production at PSI

PSI experiment: F.Atchison et al., PRC **71,** 054601 (2005).

$R_{solid,8K}$ = (1.11 ± 0.23) x 10^{-8} cm^{-1} (UCN production x-section @ 5K)

in agreement with Z.-Ch. Yu et al., ZPB62(1986)137

Estimate for PSI UCN source:

– $\Phi_{CN} \sim 2 \times 10^{13}\ cm^{-2}\ s^{-1}\ mA^{-1}$

– $\tau_{UCN} \sim 30$ ms

- 50% of equilibrium density after 4s proton pulse

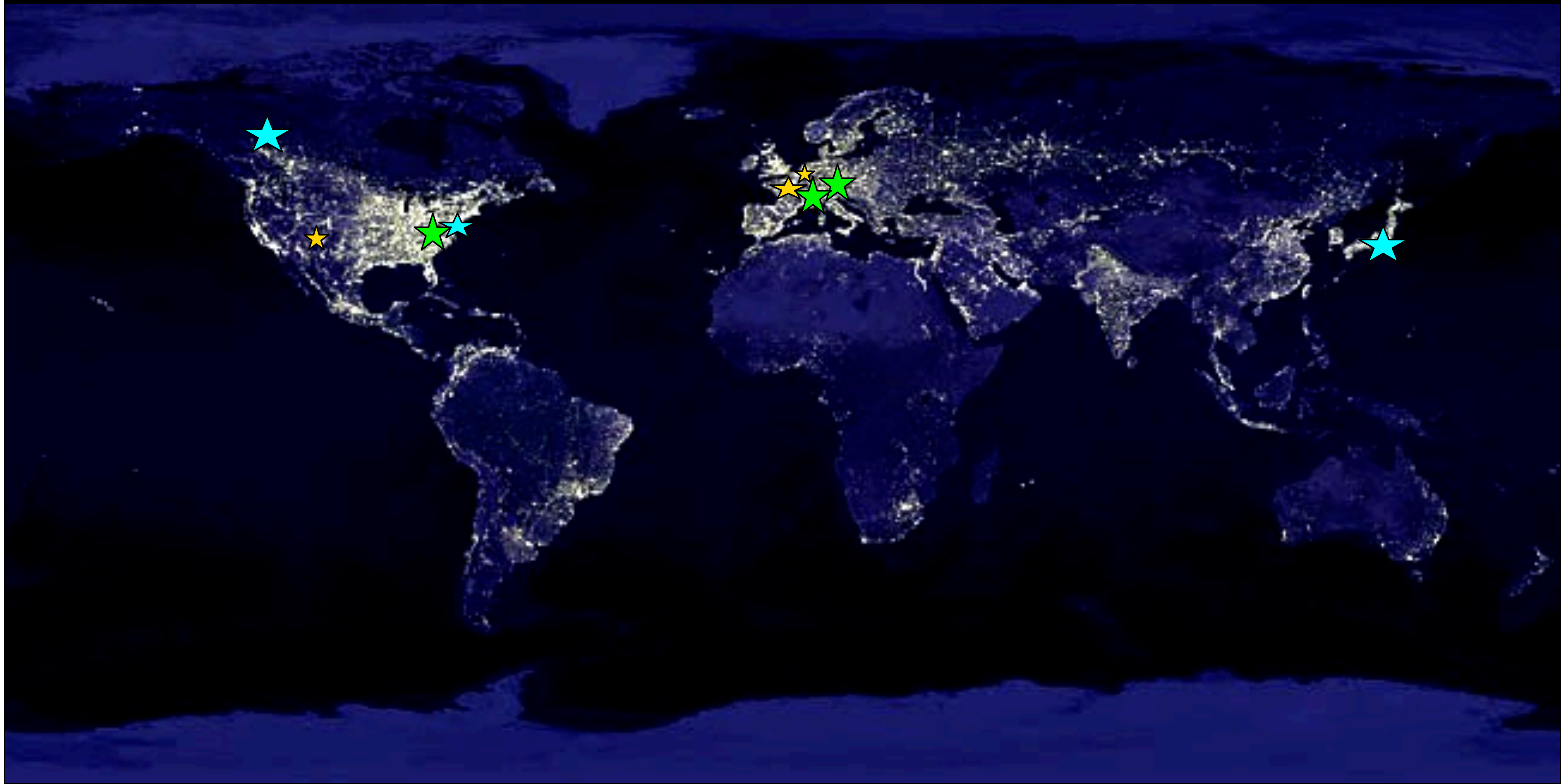
$\rho_{UCN} = R_{solid,8K} \times \Phi_{CN} \times \tau_{UCN} \times 0.5 \approx 5000\ cm^{-3}$

2000 cm^{-3} in storage,

1000cm^{-3} in experiments

ILL: $\rho(UCN) = 10\ UCN\ cm^{-3}$

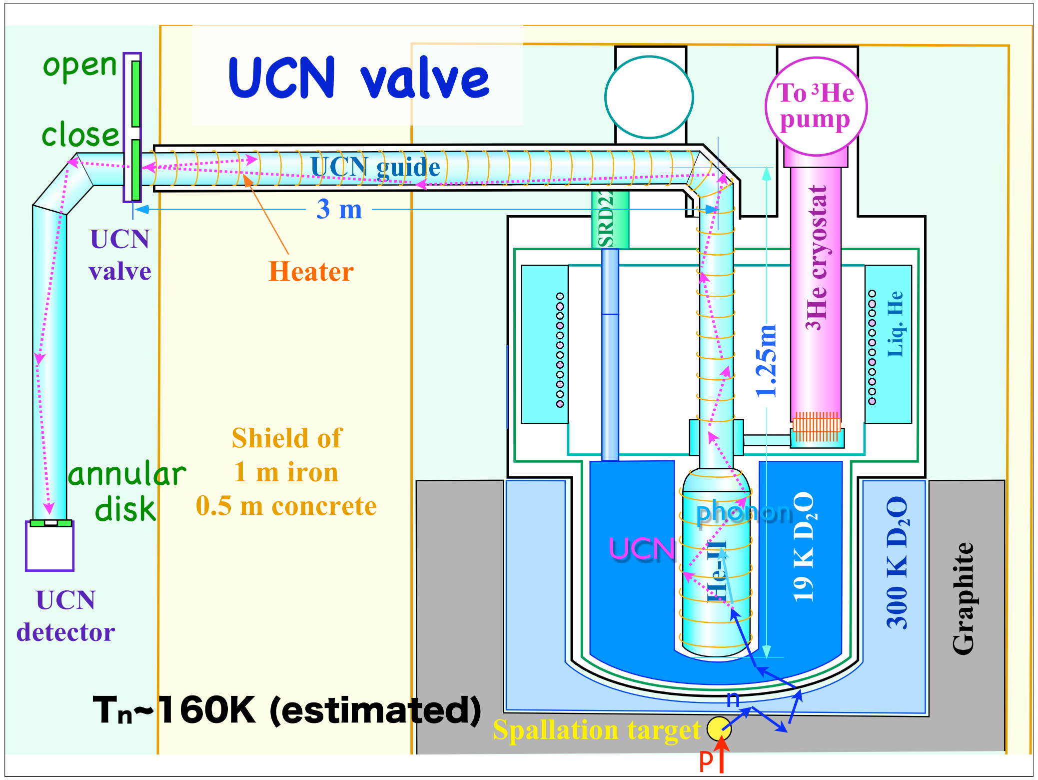
UCN Facilities



- existing UCN facilities - ILL / LANL / Mainz I ~ 10^1
- UCN facilities in construction - PSI / SNS / TUM I ~ >10^3
- UCN facilities planned - J-PARC / TRIUMF / NCSU

RCNP-UCN

400W (400MeV×1μA、3.4×10^{13} n s^{-1})　　Y.Masuda



K.Mishima et al., Proc. ICANS-XV (2000)

UCN Production (T_n=30K)	14 cm^{-3} s^{-1}
Neutron Flux at He-II Bottle	1.5×10^{10} cm^{-2} s^{-1}
He-II Volume	1.1×10^{4} cm^{3}
Heat Deposit at He-II Bottle	75mW

storage time = 20 s
ρ_{UCN} = 10 cm^{-3} s^{-1} → production rate : P = 0.5 cm^{-3} s^{-1}

Superthermal Converters

$\rho_{UCN} = P\tau(1 - e^{-t/\tau})$

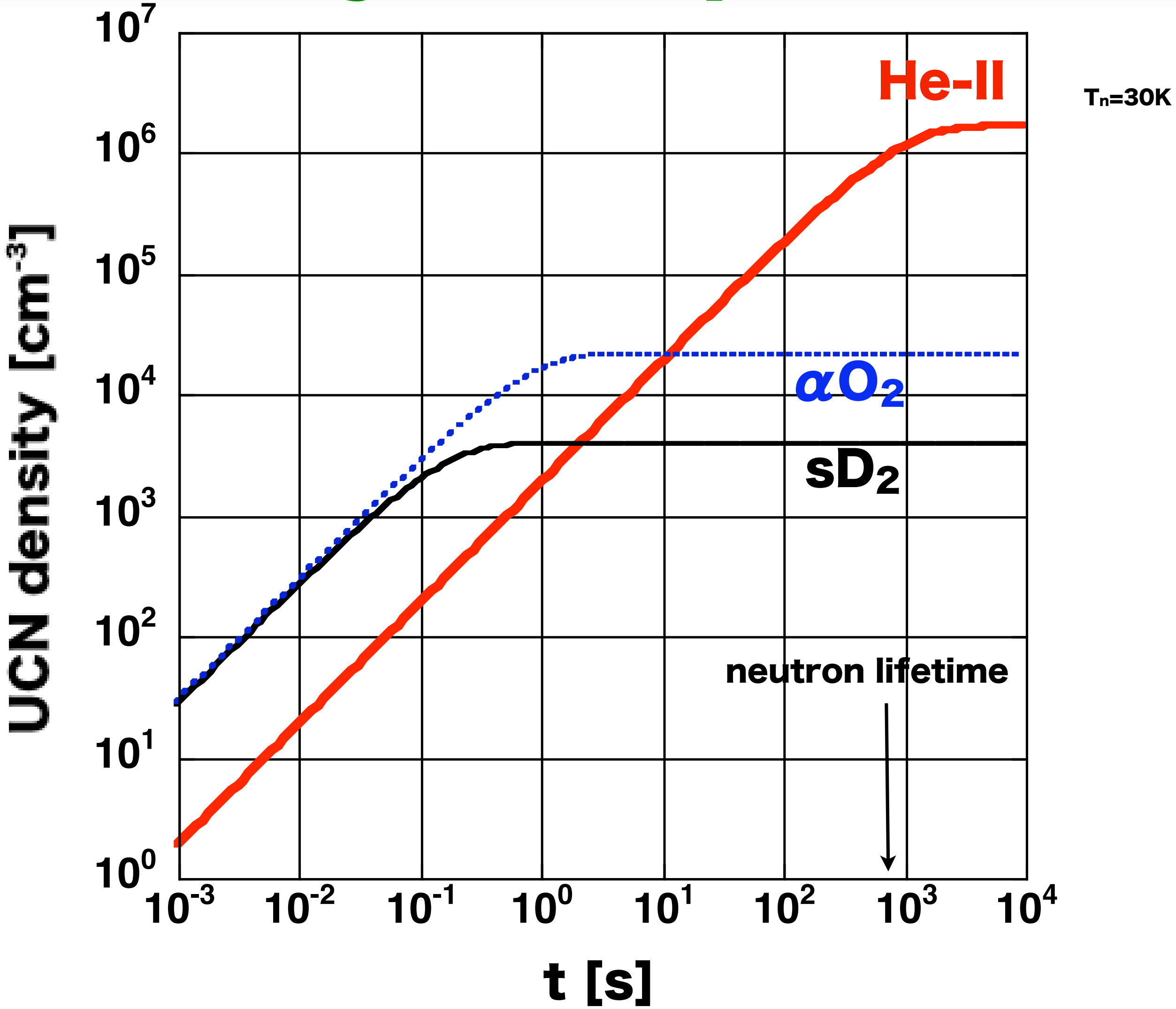
C.-Y.Liu, Dissertation, Princeton Univ. (2002)

converter	He-II	Solid ortho-D_2	α-O_2
interaction	phonon	phonon	magnon
converter temperature	0.7K	5K	2K
optimal neutron temperature	9K	29K	12K
production rate (30K neutrons)	$9.3\times10^{-10}\Phi_0$ cm^{-3} s^{-1}	$1.3\times10^{-8}\Phi_0$ cm^{-3} s^{-1}	$1.4\times10^{-8}\Phi_0$ cm^{-3} s^{-1}
ideal lifetime (no wall loss, no upscattering)	886 s	146 ms	750 ms
UCN density with 30K neutrons	$8.2\times10^{-7}\Phi_0$ cm^{-3}	$1.9\times10^{-9}\Phi_0$ cm^{-3}	$9.1\times10^{-8}\Phi_0$ cm^{-3}

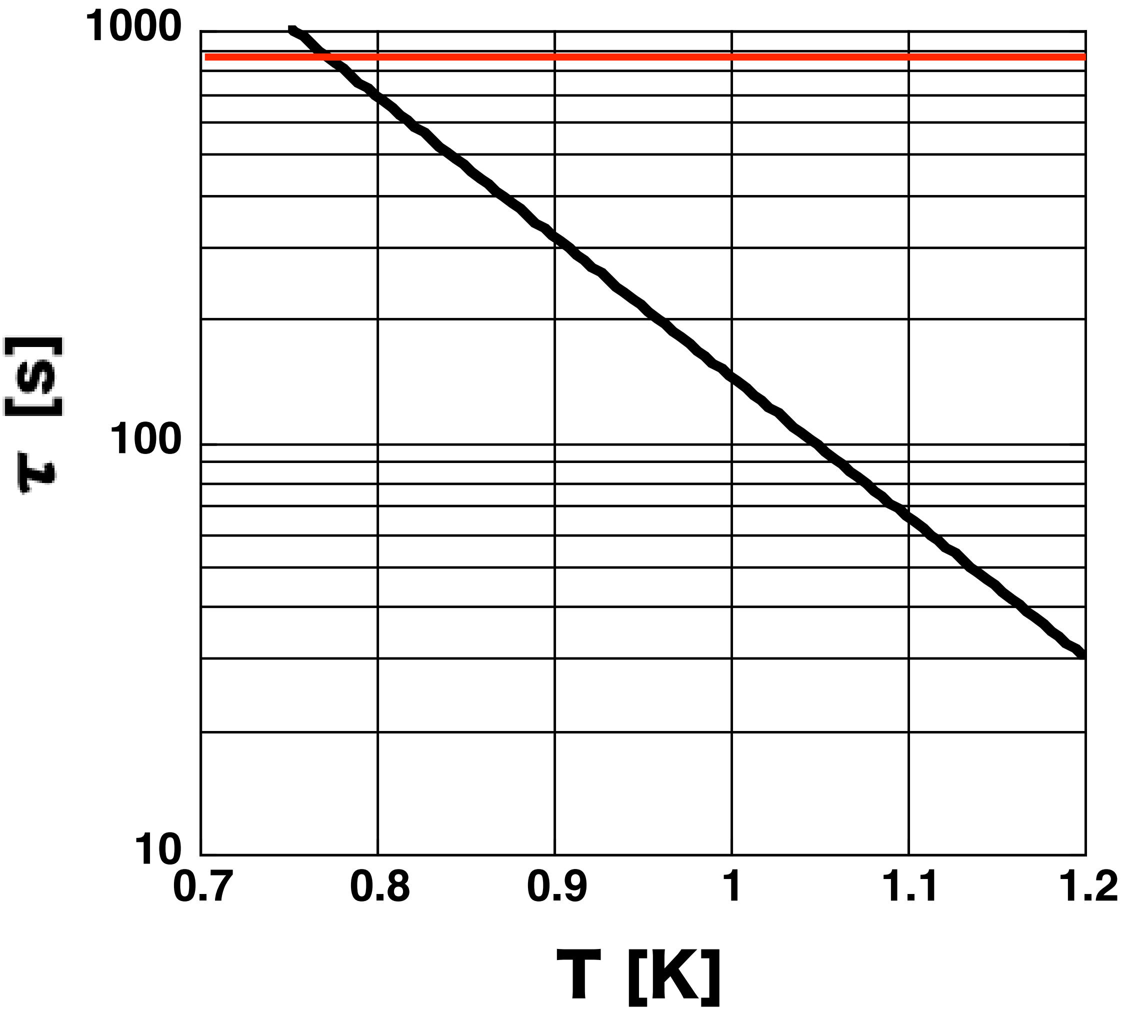
$\rho_{UCN} = 10^{-11}\Phi_0$

(thermal moderator)

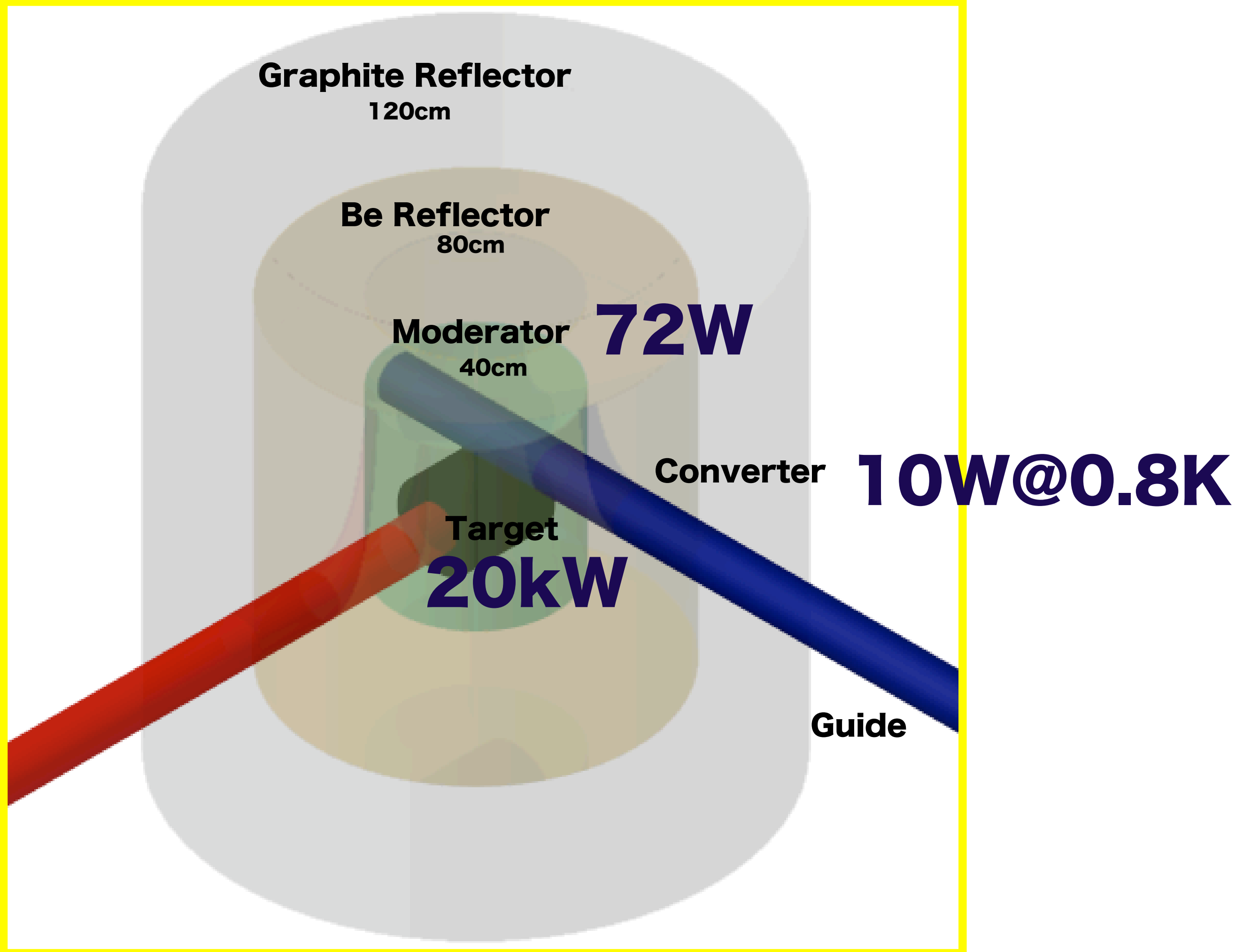
UCN density buildup



UCN loss due to upscattering



Superthermal UCN Source



UCN production @ J-PARC under discussion