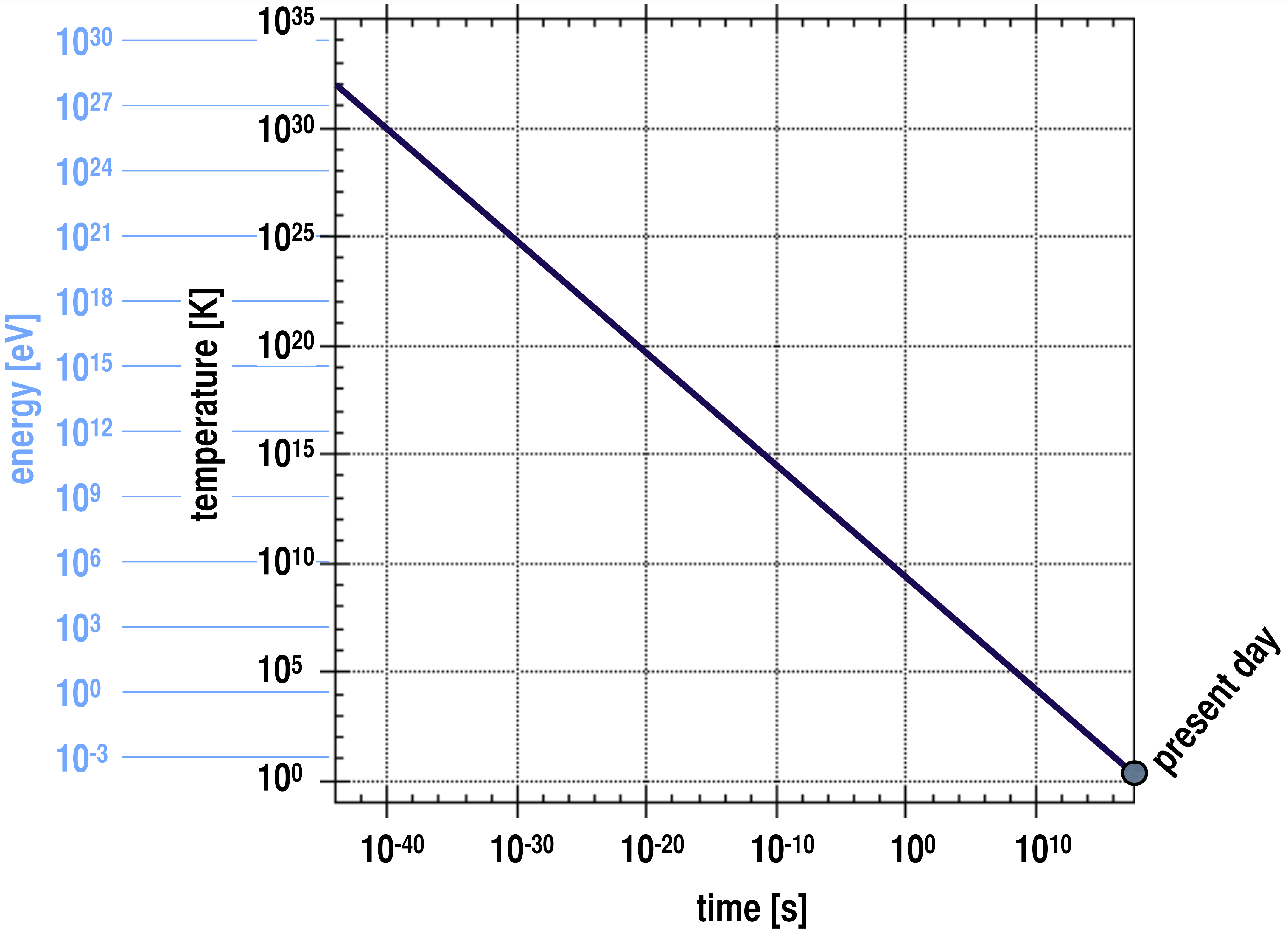
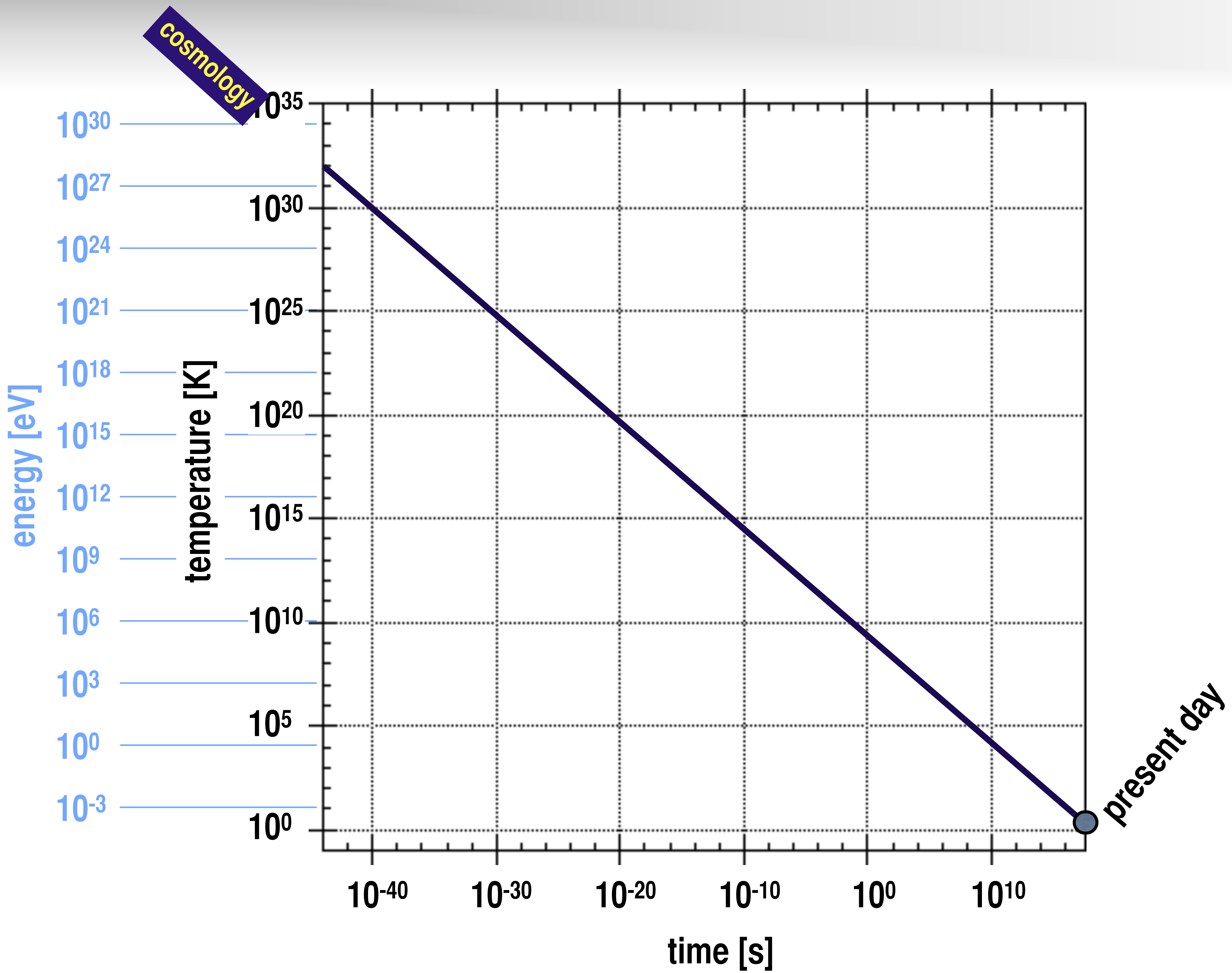
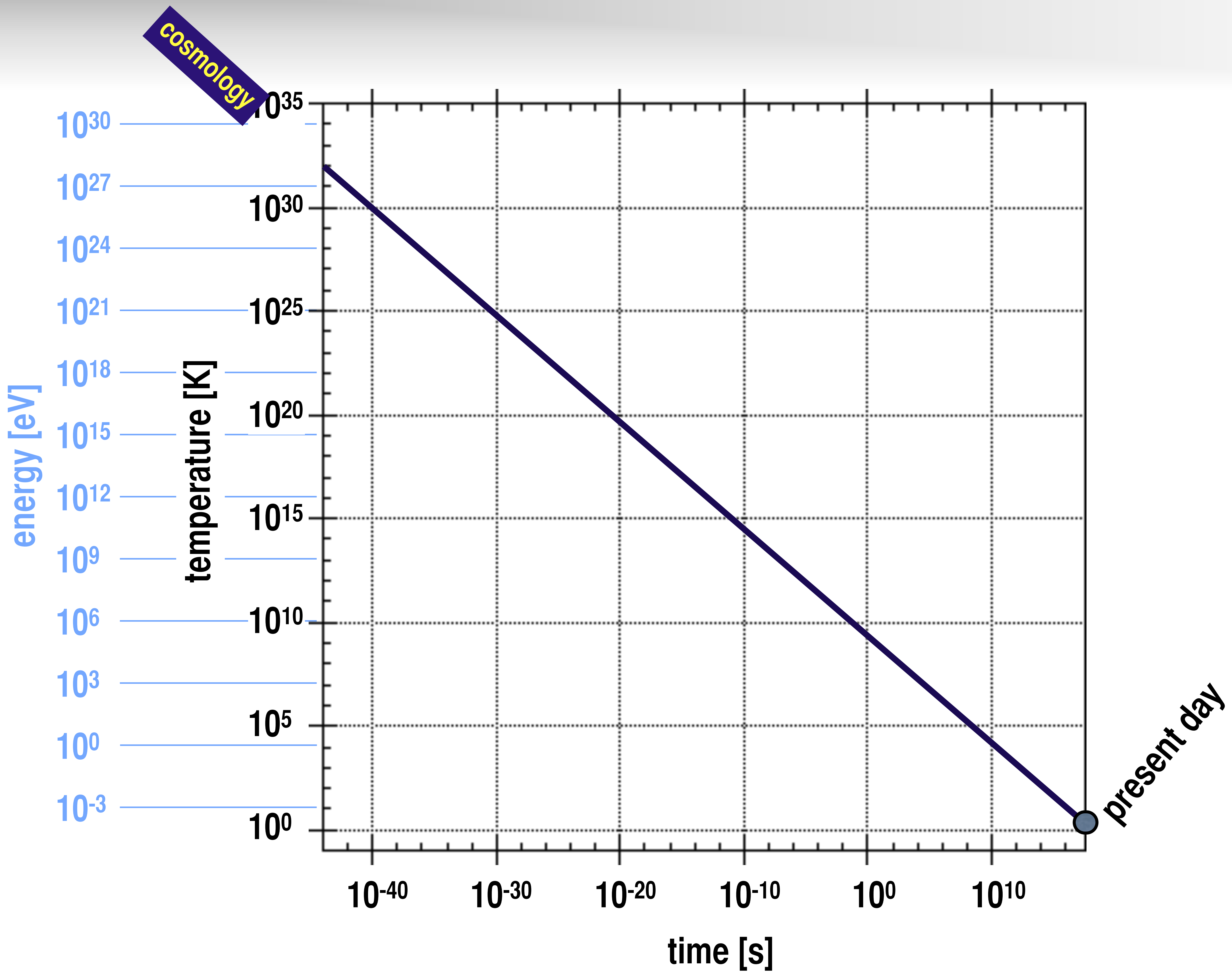
Fundamental Physics with Slow Neutrons

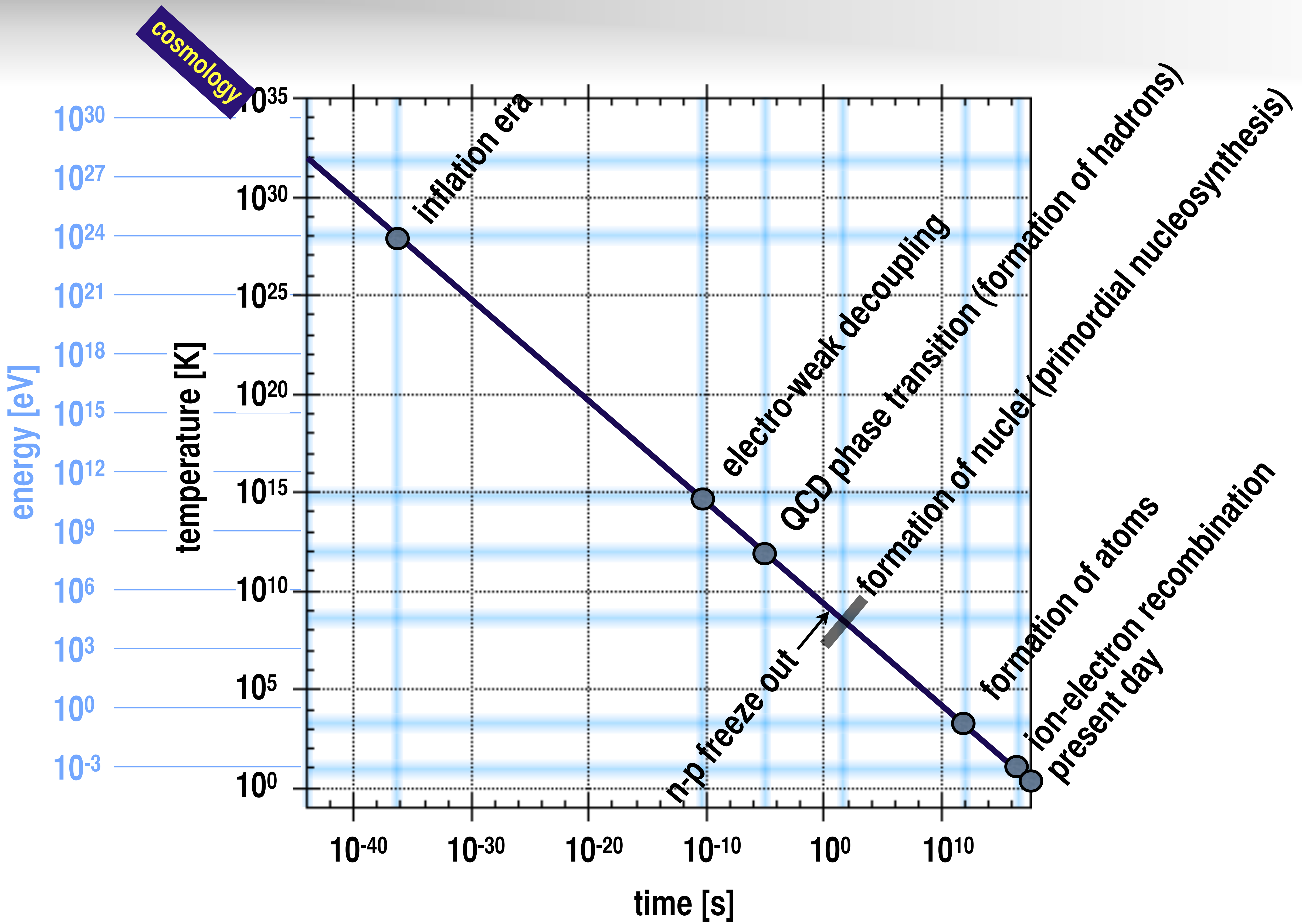
H.M.Shimizu

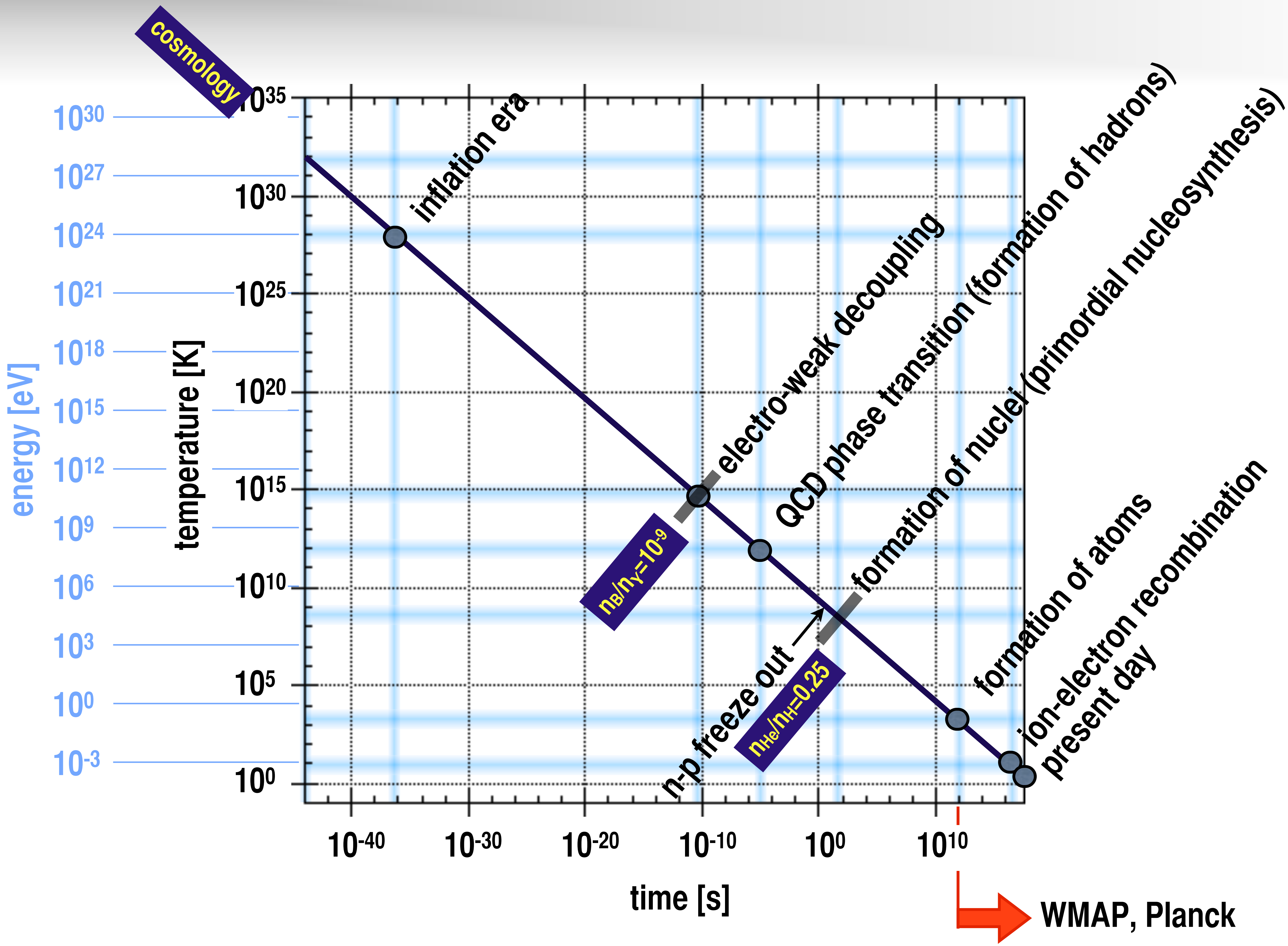
Department of Physics, Nagoya University
hirohiko.shimizu@nagoya-u.jp


energy [eV]
10^{30}
10^{27}
10^{24}
10^{21}
10^{18}
10^{15}
10^{12}
10^{9}
10^{6}
10^{3}
10^{0}
10^{-3}
temperature [K]
10^{35}
10^{30}
10^{25}
10^{20}
10^{15}
10^{10}
10^{5}
10^{0}
10^{-40}
10^{-30}
10^{-20}
10^{-10}
10^{0}
10^{10}
time [s]
present day

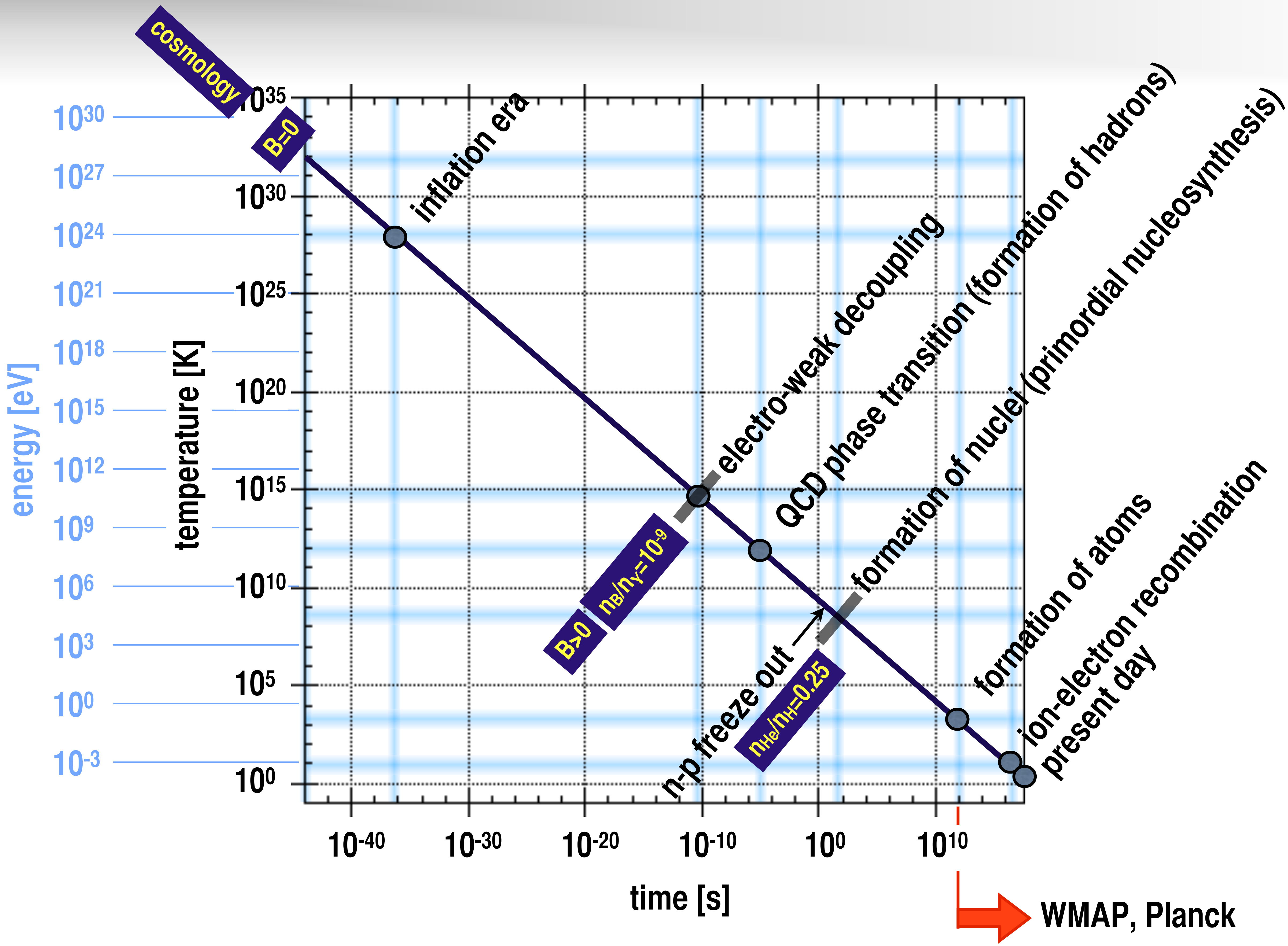

cosmology
energy [eV]
10^30
10^27
10^24
10^21
10^18
10^15
10^12
10^9
10^6
10^3
10^0
10^-3
temperature [K]
10^35
10^30
10^25
10^20
10^15
10^10
10^5
10^0
10^-40
10^-30
10^-20
10^-10
10^0
10^10
time [s]
present day

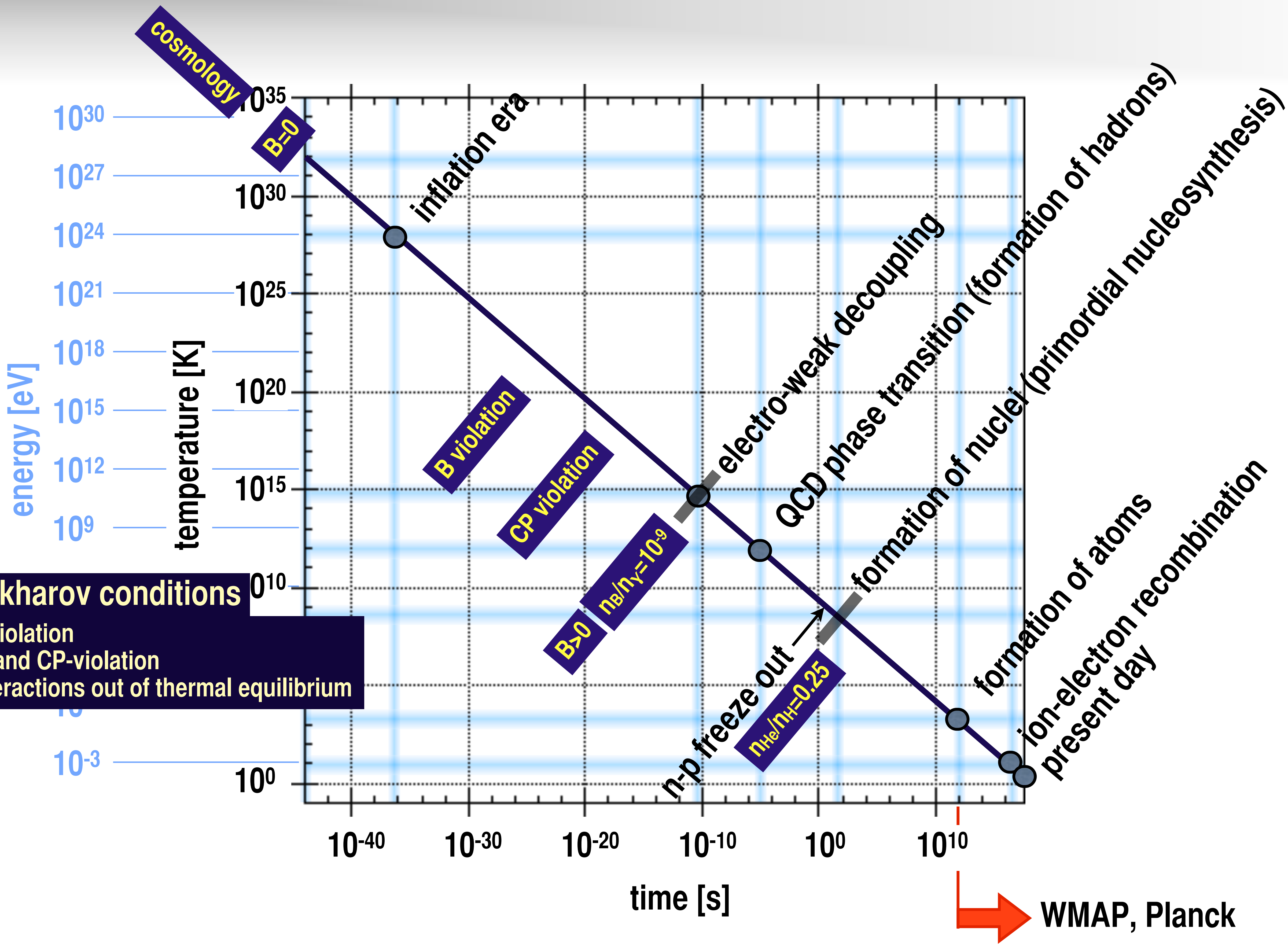

cosmology
energy [eV]
10^30
10^27
10^24
10^21
10^18
10^15
10^12
10^9
10^6
10^3
10^0
10^-3
temperature [K]
10^35
10^30
10^25
10^20
10^15
10^10
10^5
10^0
10^-40
10^-30
10^-20
10^-10
10^0
10^10
time [s]
present day


cosmology
energy [eV]
temperature [K]
time [s]
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
10^{30}
10^{27}
10^{24}
10^{21}
10^{18}
10^{15}
10^{12}
10^{9}
10^{6}
10^{3}
10^{0}
10^{-3}
10^{35}
10^{30}
10^{25}
10^{20}
10^{15}
10^{10}
10^{5}
10^{0}
10^{-40}
10^{-30}
10^{-20}
10^{-10}
10^{0}
10^{10}



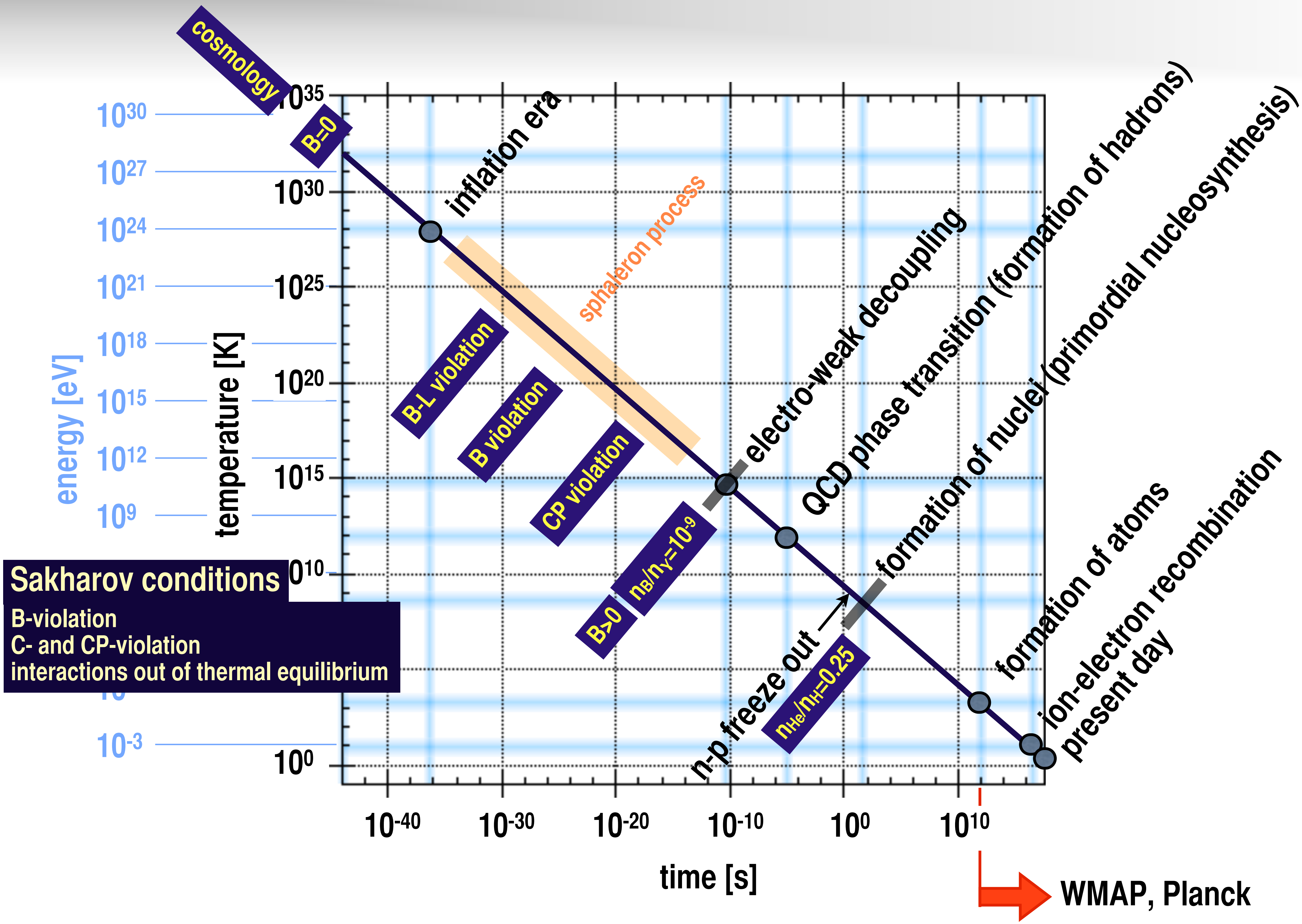
cosmology
energy [eV]
temperature [K]
time [s]
inflation era
electro-weak decoupling
QCD phase transition (formation of hadrons)
formation of nuclei (primordial nucleosynthesis)
formation of atoms
ion-electron recombination
present day
n-p freeze out
n_B/n_γ~10^{-9}
n_{He}/n_H=0.25
WMAP, Planck

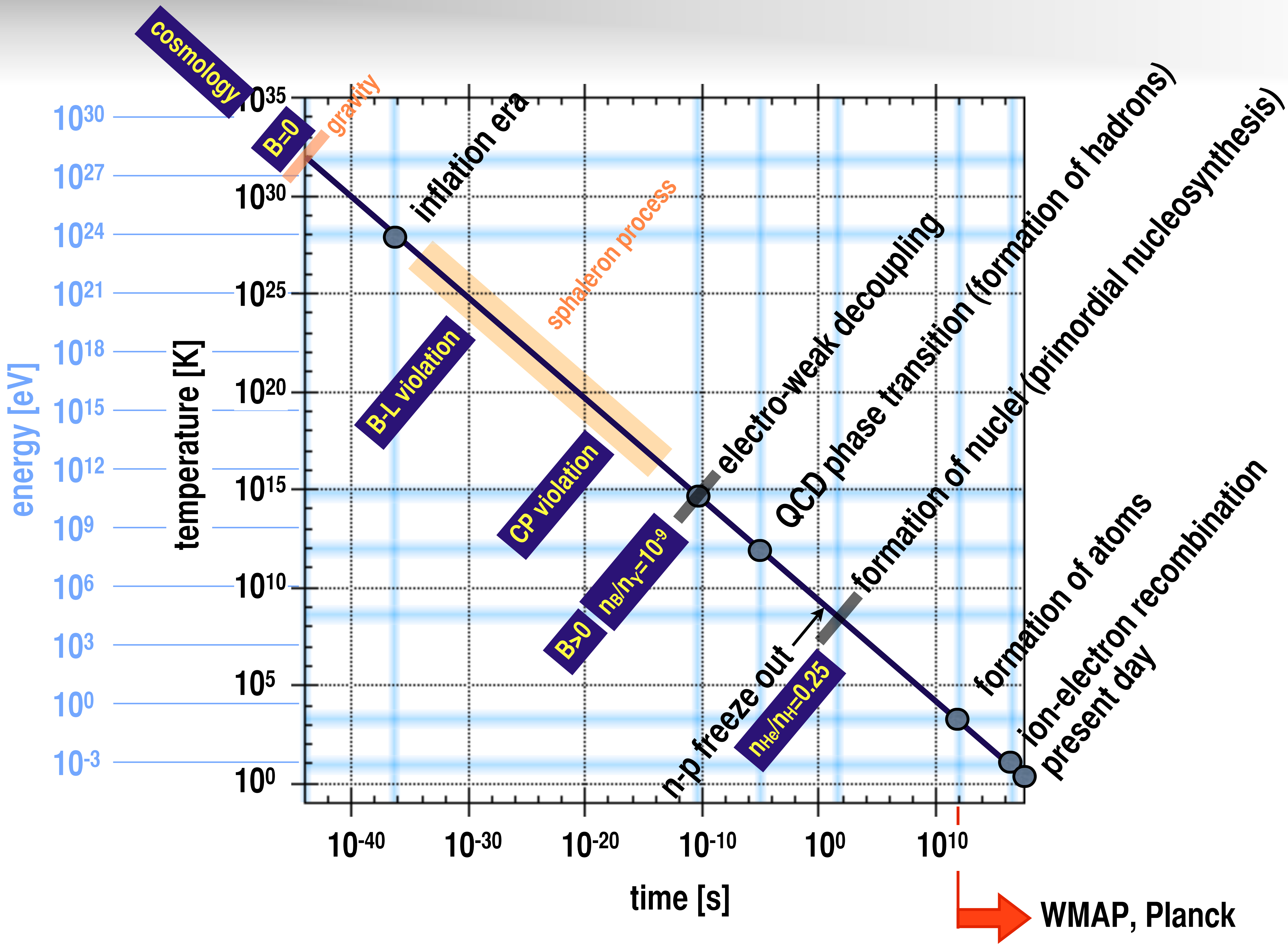

cosmology
B=0
inflation era
electro-weak decoupling
QCD phase transition (formation of hadrons)
formation of nuclei (primordial nucleosynthesis)
formation of atoms
ion-electron recombination
present day
n-p freeze out
n_B/n_γ~10^{-9}
B>0
n_{He}/n_H=0.25
energy [eV]
temperature [K]
time [s]
WMAP, Planck

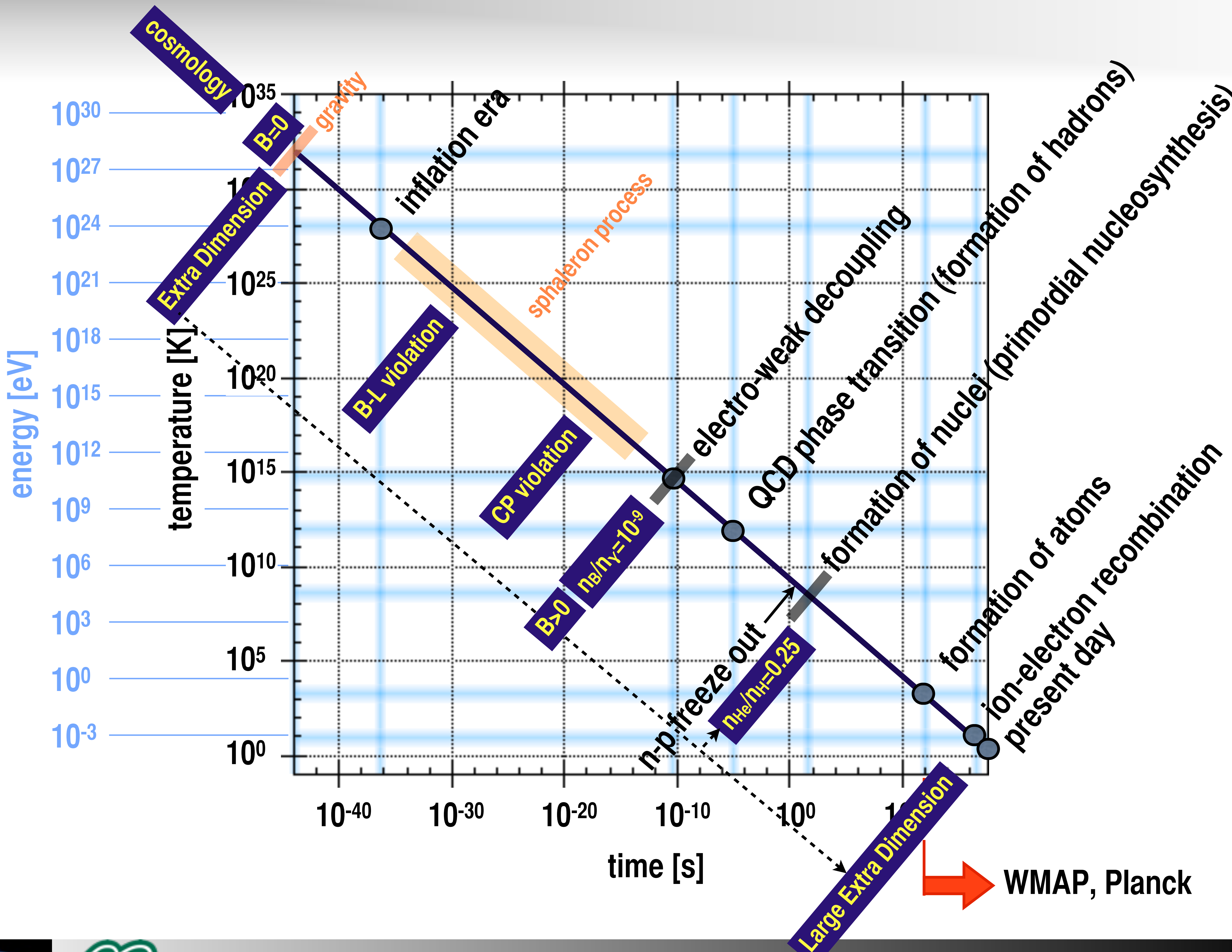


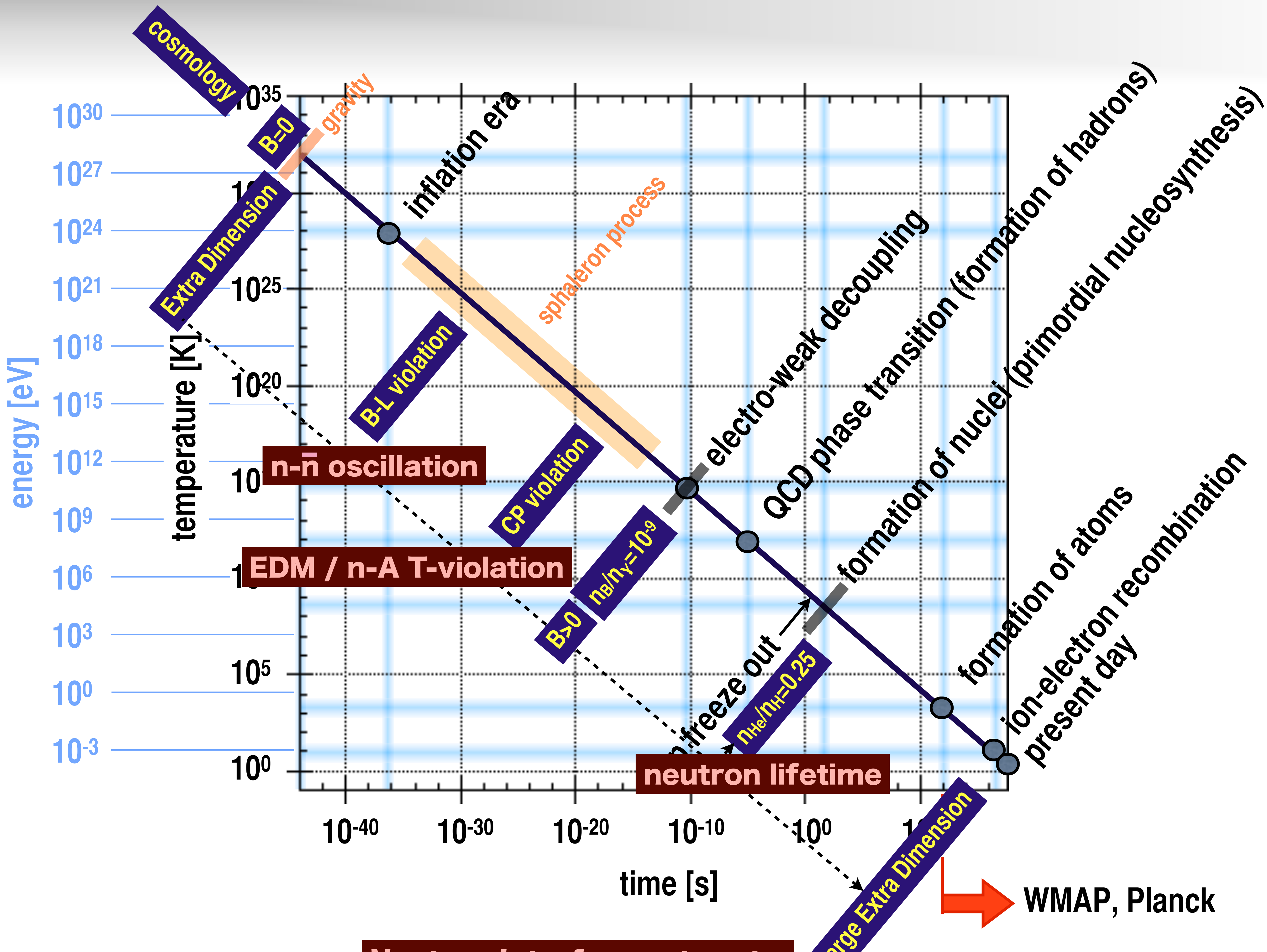
Sakharov conditions

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


cosmology
B=0
inflation era
sphaleron process
electro-weak decoupling
QCD phase transition (formation of hadrons)
formation of nuclei (primordial nucleosynthesis)
formation of atoms
ion-electron recombination
present day
B-L violation
B violation
CP violation
n_B/n_γ~10^{-9}
B>0
n-p freeze out
n_{He}/n_H=0.25
energy [eV]
10^{30}
10^{27}
10^{24}
10^{21}
10^{18}
10^{15}
10^{12}
10^{9}
10^{-3}
temperature [K]
10^{35}
10^{30}
10^{25}
10^{20}
10^{15}
10^{10}
10^{0}
10^{-40}
10^{-30}
10^{-20}
10^{-10}
10^{0}
10^{10}
time [s]
WMAP, Planck
Sakharov conditions
B-violation
C- and CP-violation
interactions out of thermal equilibrium


cosmology
gravity
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)
$n_B/n_\gamma \sim 10^{-9}$
B>0
n-p freeze out
$n_{He}/n_H = 0.25$
formation of atoms
ion-electron recombination
present day
energy [eV]
temperature [K]
time [s]
10^{30}
10^{27}
10^{24}
10^{21}
10^{18}
10^{15}
10^{12}
10^{9}
10^{6}
10^{3}
10^{0}
10^{-3}
10^{35}
10^{30}
10^{25}
10^{20}
10^{15}
10^{10}
10^{5}
10^{0}
10^{-40}
10^{-30}
10^{-20}
10^{-10}
10^{0}
10^{10}
WMAP, Planck


cosmology
gravity
B=0
Extra Dimension
inflation era
sphaleron process
B-L violation
CP violation
n_B/n_γ~10^{-9}
B>0
electro-weak decoupling
QCD phase transition (formation of hadrons)
formation of nuclei (primordial nucleosynthesis)
n-p freeze out
n_{He}/n_H=0.25
formation of atoms
ion-electron recombination
present day
Large Extra Dimension
WMAP, Planck
energy [eV]
10^{30}
10^{27}
10^{24}
10^{21}
10^{18}
10^{15}
10^{12}
10^{9}
10^{6}
10^{3}
10^{0}
10^{-3}
temperature [K]
10^{35}
10^{25}
10^{20}
10^{15}
10^{10}
10^{5}
10^{0}
time [s]
10^{-40}
10^{-30}
10^{-20}
10^{-10}
10^{0}


cosmology
gravity
B=0
inflation era
Extra Dimension
sphaleron process
B-L violation
electro-weak decoupling
QCD phase transition (formation of hadrons)
formation of nuclei (primordial nucleosynthesis)
n-n̄ oscillation
CP violation
n_B/n_γ~10^{-9}
EDM / n-A T-violation
B>0
freeze out
n_{He}/n_H=0.25
formation of atoms
ion-electron recombination
present day
neutron lifetime
energy [eV]
temperature [K]
time [s]
10^{30}
10^{27}
10^{24}
10^{21}
10^{18}
10^{15}
10^{12}
10^{9}
10^{6}
10^{3}
10^{0}
10^{-3}
10^{35}
10^{25}
10^{20}
10^{5}
10^{0}
10^{-40}
10^{-30}
10^{-20}
10^{-10}
10^{0}
Large Extra Dimension
WMAP, Planck
Neutron Interferometry etc.

n-$\bar{n}$ oscillation

EDM / n-A T-violation

neutron lifetime

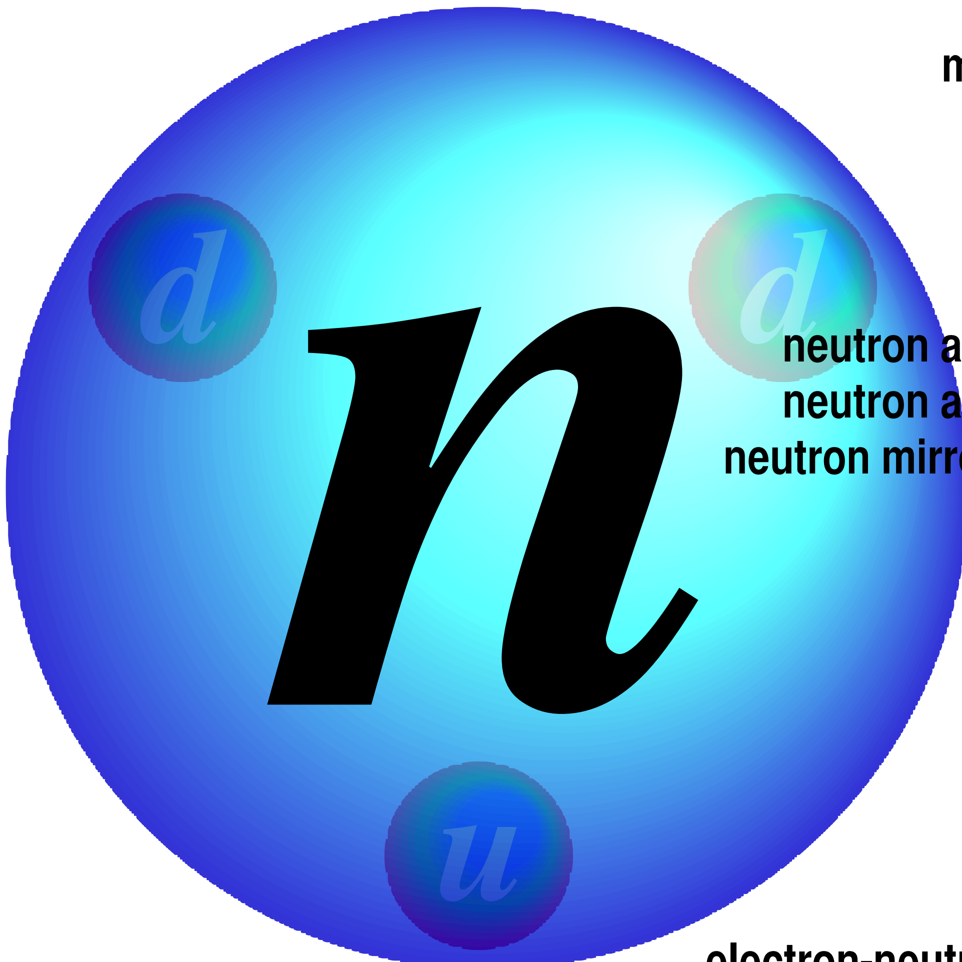
Neutron Interferometry etc.

1. Overview
2. neutron lifetime
3. EDM / n-A T-violation (CP-violation)
4. Neutron Interferometry etc. orce (Gravity)
5. etc (B, B $n\text{-}\bar{n}$ oscillation ion)

1. Overview
2. Lifetime
3. T-violation (CP-violation)
4. Medium-range Force (Gravity)
5. etc (B, B-L violation)

1. Overview

neutron

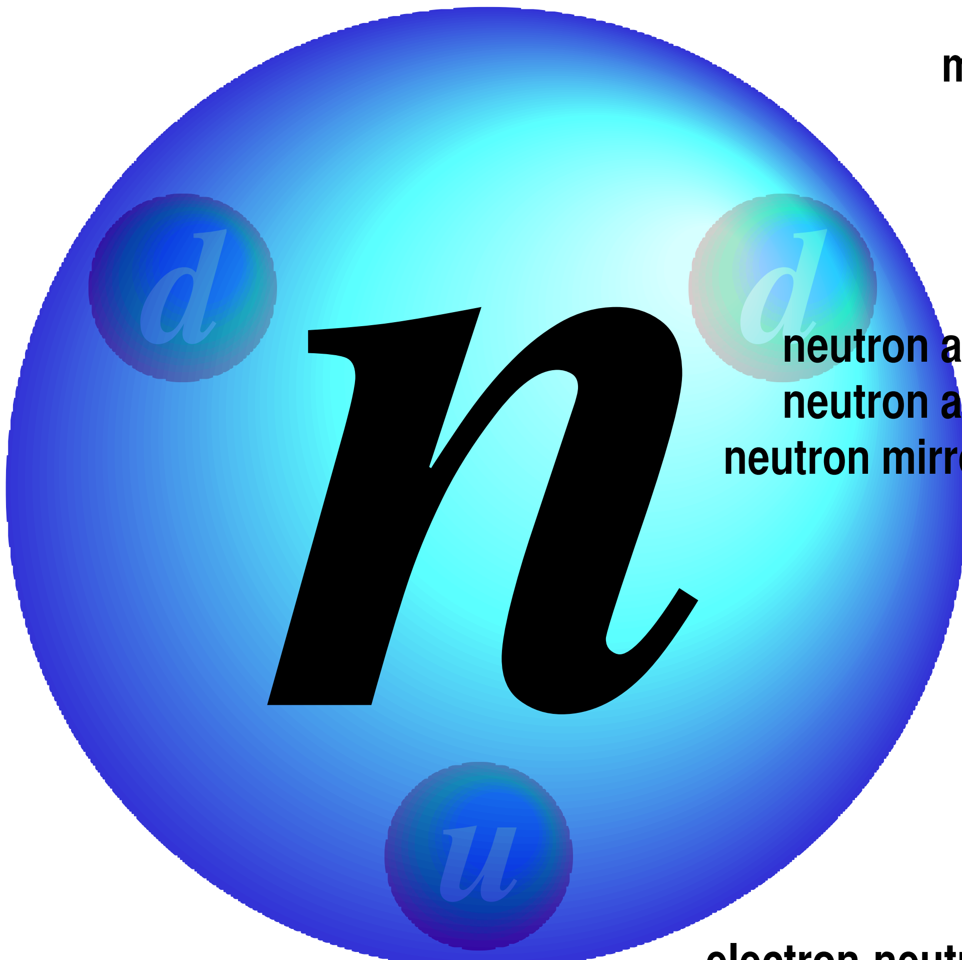


mass	m_n	$(939.565379 \pm 0.000021)$[MeV]
mass	$m_{\bar{n}}$	(939.485 ± 0.051)[MeV]
lifetime	τ_n	(880.0 ± 0.9)[s]
magnetic dipole moment	μ_n	$(-1.91304272 \pm 0.00000045)\mu_N$
electric dipole moment	d_n	$< 0.29 \times 10^{-25} e\,\mathrm{cm}$ (90%CL)
mean square charge radius	$\langle r_n^2 \rangle$	$(-0.1161 \pm 0.0022)[\mathrm{fm}^2]$
magnetic radius	$\sqrt{\langle r_M^2 \rangle}$	$(0.862^{+0.009}_{-0.008})$[fm]
electric polarizability	α_m	$(11.6 \pm 1.5) \times 10^{-4}[\mathrm{fm}^3]$
magnetic polarizability	β_m	$(3.7 \pm 2.0) \times 10^{-4}[\mathrm{fm}^3]$
charge	q_n	$(-0.2 \pm 0.8) \times 10^{-21} e$
neutron antineutron oscillation time	$\tau_{n\bar{n},\mathrm{bound}}$	$> 1.3 \times 10^8$[s] (90%CL)
neutron antineutron oscillation time	$\tau_{n\bar{n},\mathrm{free}}$	$> 8.6 \times 10^7$[s] (90%CL)
neutron mirror-neutron oscillation time	$\tau_{nn'}$	> 414[s] (90%CL)
decay mode	$\Gamma(pe^-\bar{\nu}_e)$	100%
branching ratio	$\Gamma(pe^-\bar{\nu}_e\gamma)/\Gamma_{\mathrm{total}}$	$(3.09 \pm 0.11 \pm 0.30) \times 10^{-3}$
branching ratio	$\Gamma(\mathrm{H}\,\bar{\nu}_e)/\Gamma_{\mathrm{total}}$	$< 3 \times 10^{-2}$ (95%CL)
branching ratio	$\Gamma(p\nu_e\bar{\nu}_e)/\Gamma_{\mathrm{total}}$	$< 8 \times 10^{-27}$ (68%CL)
axial vector coupling	$\lambda = g_A/g_V$	-1.2701 ± 0.0025
electron asymmetry	A	-0.1176 ± 0.0011
neutrino asymmetry	B	0.9807 ± 0.0030
proton asymmetry	C	$-0.2377 \pm 0.0010 \pm 0.0024$
electron-neutrino correlation coefficient	a	-0.103 ± 0.004
phase of g_A relative to g_V	ϕ_{AV}	$(180.017 \pm 0.026)^\circ$
triple correlation coefficient	D	$(-1.2 \pm 2.0) \times 10^{-4}$
triple correlation coefficient	R	$+0.004 \pm 0.012 \pm 0.005$

J.Beringer et al., PRD86(2012)010001 2013 partial update

1. Overview

neutron



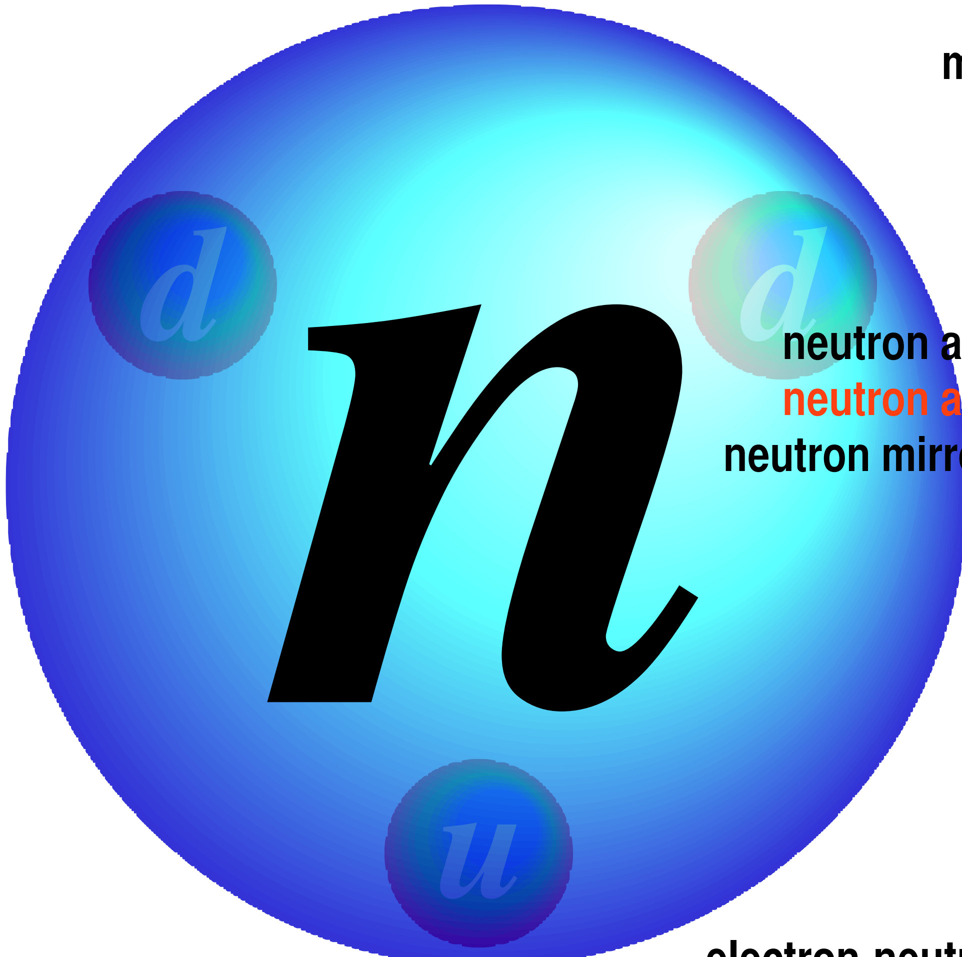
chargeless
massive
very long lifetime

mass	m_n	$(939.565379 \pm 0.000021)[\mathrm{MeV}]$
mass	$m_{\bar{n}}$	$(939.485 \pm 0.051)[\mathrm{MeV}]$
lifetime	τ_n	$(880.0 \pm 0.9)[\mathrm{s}]$
magnetic dipole moment	μ_n	$(-1.91304272 \pm 0.00000045)\mu_N$
electric dipole moment	d_n	$< 0.29 \times 10^{-25} e\,\mathrm{cm}$ (90%CL)
mean square charge radius	$\langle r_n^2 \rangle$	$(-0.1161 \pm 0.0022)[\mathrm{fm}^2]$
magnetic radius	$\sqrt{\langle r_M^2 \rangle}$	$(0.862^{+0.009}_{-0.008})[\mathrm{fm}]$
electric polarizability	α_m	$(11.6 \pm 1.5) \times 10^{-4}[\mathrm{fm}^3]$
magnetic polarizability	β_m	$(3.7 \pm 2.0) \times 10^{-4}[\mathrm{fm}^3]$
charge	q_n	$(-0.2 \pm 0.8) \times 10^{-21} e$
neutron antineutron oscillation time	$\tau_{n\bar{n},\mathrm{bound}}$	$> 1.3 \times 10^8[\mathrm{s}]$ (90%CL)
neutron antineutron oscillation time	$\tau_{n\bar{n},\mathrm{free}}$	$> 8.6 \times 10^7[\mathrm{s}]$ (90%CL)
neutron mirror-neutron oscillation time	$\tau_{nn'}$	$> 414[\mathrm{s}]$ $(90\%CL)$
decay mode	$\Gamma(pe^-\bar{\nu}_e)$	100%
branching ratio	$\Gamma(pe^-\bar{\nu}_e\gamma)/\Gamma_{\mathrm{total}}$	$(3.09 \pm 0.11 \pm 0.30) \times 10^{-3}$
branching ratio	$\Gamma(\mathrm{H}\,\bar{\nu}_e)/\Gamma_{\mathrm{total}}$	$< 3 \times 10^{-2}$ (95%CL)
branching ratio	$\Gamma(p\nu_e\bar{\nu}_e)/\Gamma_{\mathrm{total}}$	$< 8 \times 10^{-27}$ (68%CL)
axial vector coupling	$\lambda = g_A/g_V$	-1.2701 ± 0.0025
electron asymmetry	A	-0.1176 ± 0.0011
neutrino asymmetry	B	0.9807 ± 0.0030
proton asymmetry	C	$-0.2377 \pm 0.0010 \pm 0.0024$
electron-neutrino correlation coefficient	a	-0.103 ± 0.004
phase of g_A relative to g_V	ϕ_{AV}	$(180.017 \pm 0.026)^\circ$
triple correlation coefficient	D	$(-1.2 \pm 2.0) \times 10^{-4}$
triple correlation coefficient	R	$+0.004 \pm 0.012 \pm 0.005$

J.Beringer et al., PRD86(2012)010001 2013 partial update

1. Overview

neutron



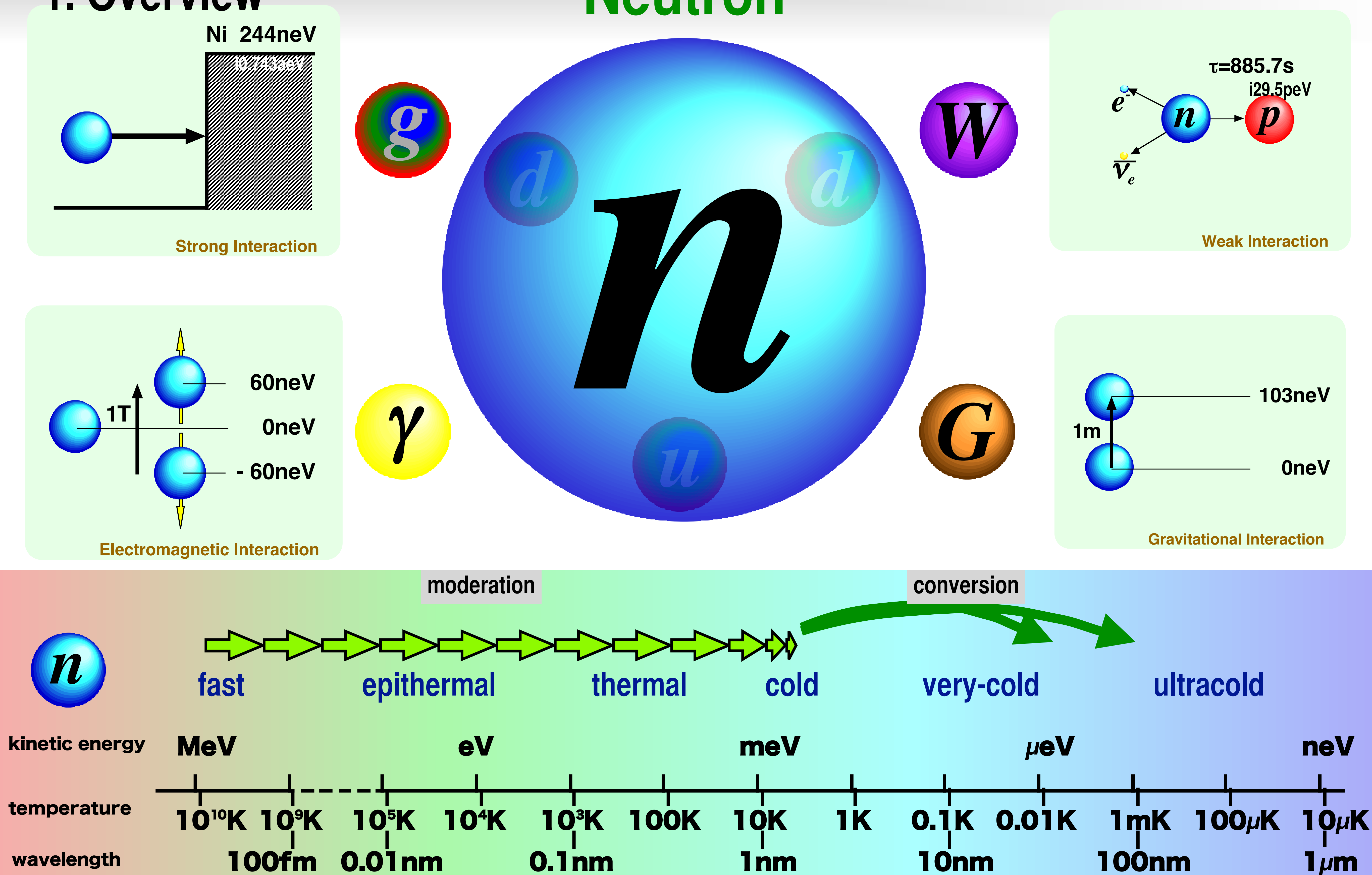
chargeless
massive
very long lifetime

mass	m_n	$(939.565379 \pm 0.000021)[\mathrm{MeV}]$
mass	$m_{\overline{n}}$	$(939.485 \pm 0.051)[\mathrm{MeV}]$
lifetime	τ_n	$(880.0 \pm 0.9)[\mathrm{s}]$
magnetic dipole moment	μ_n	$(-1.91304272 \pm 0.00000045)\mu_{\mathrm{N}}$
electric dipole moment	d_n	$< 0.29 \times 10^{-25} e\,\mathrm{cm}$ (90%CL)
mean square charge radius	$\langle r_n^2 \rangle$	$(-0.1161 \pm 0.0022)[\mathrm{fm}^2]$
magnetic radius	$\sqrt{\langle r_M^2 \rangle}$	$(0.862^{+0.009}_{-0.008})[\mathrm{fm}]$
electric polarizability	α_m	$(11.6 \pm 1.5) \times 10^{-4}[\mathrm{fm}^3]$
magnetic polarizability	β_m	$(3.7 \pm 2.0) \times 10^{-4}[\mathrm{fm}^3]$
charge	q_n	$(-0.2 \pm 0.8) \times 10^{-21} e$
neutron antineutron oscillation time	$\tau_{n\overline{n},\mathrm{bound}}$	$> 1.3 \times 10^8[\mathrm{s}]$ (90%CL)
neutron antineutron oscillation time	$\tau_{n\overline{n},\mathrm{free}}$	$> 8.6 \times 10^7[\mathrm{s}]$ (90%CL)
neutron mirror-neutron oscillation time	$\tau_{nn'}$	$> 414[\mathrm{s}]$ $(90\%CL)$
decay mode	$\Gamma(pe^-\overline{\nu}_e)$	100%
branching ratio	$\Gamma(pe^-\overline{\nu}_e\gamma)/\Gamma_{\mathrm{total}}$	$(3.09 \pm 0.11 \pm 0.30) \times 10^{-3}$
branching ratio	$\Gamma(\mathrm{H}\,\overline{\nu}_e)/\Gamma_{\mathrm{total}}$	$< 3 \times 10^{-2}$ (95%CL)
branching ratio	$\Gamma(p\nu_e\overline{\nu}_e)/\Gamma_{\mathrm{total}}$	$< 8 \times 10^{-27}$ (68%CL)
axial vector coupling	$\lambda = g_A/g_V$	-1.2701 ± 0.0025
electron asymmetry	A	-0.1176 ± 0.0011
neutrino asymmetry	B	0.9807 ± 0.0030
proton asymmetry	C	$-0.2377 \pm 0.0010 \pm 0.0024$
electron-neutrino correlation coefficient	a	-0.103 ± 0.004
phase of g_A relative to g_V	ϕ_{AV}	$(180.017 \pm 0.026)°$
triple correlation coefficient	D	$(-1.2 \pm 2.0) \times 10^{-4}$
triple correlation coefficient	R	$+0.004 \pm 0.012 \pm 0.005$

J.Beringer et al., PRD86(2012)010001 2013 partial update

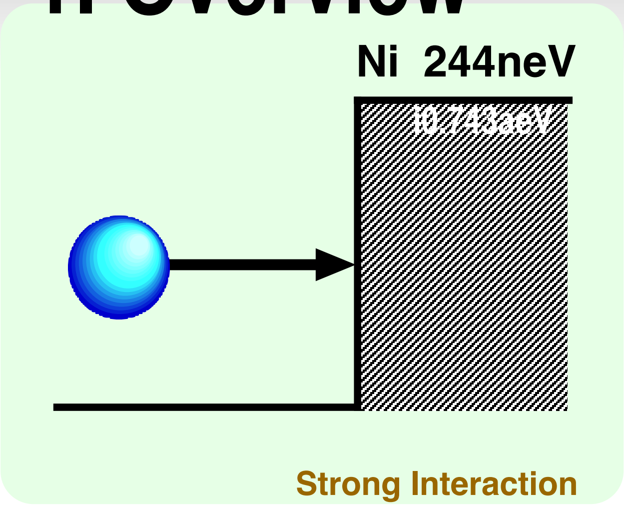
1. Overview

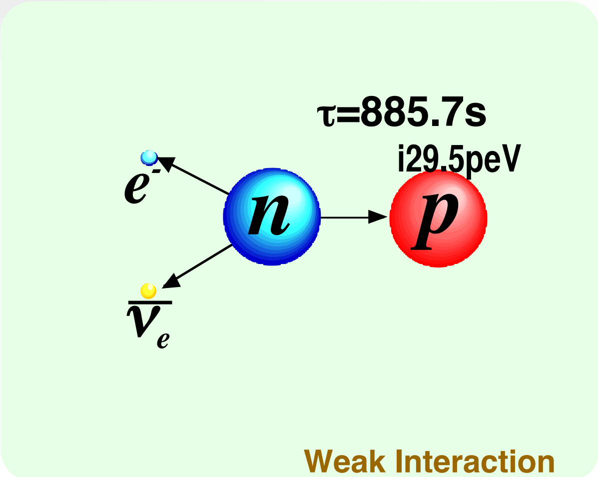
Neutron

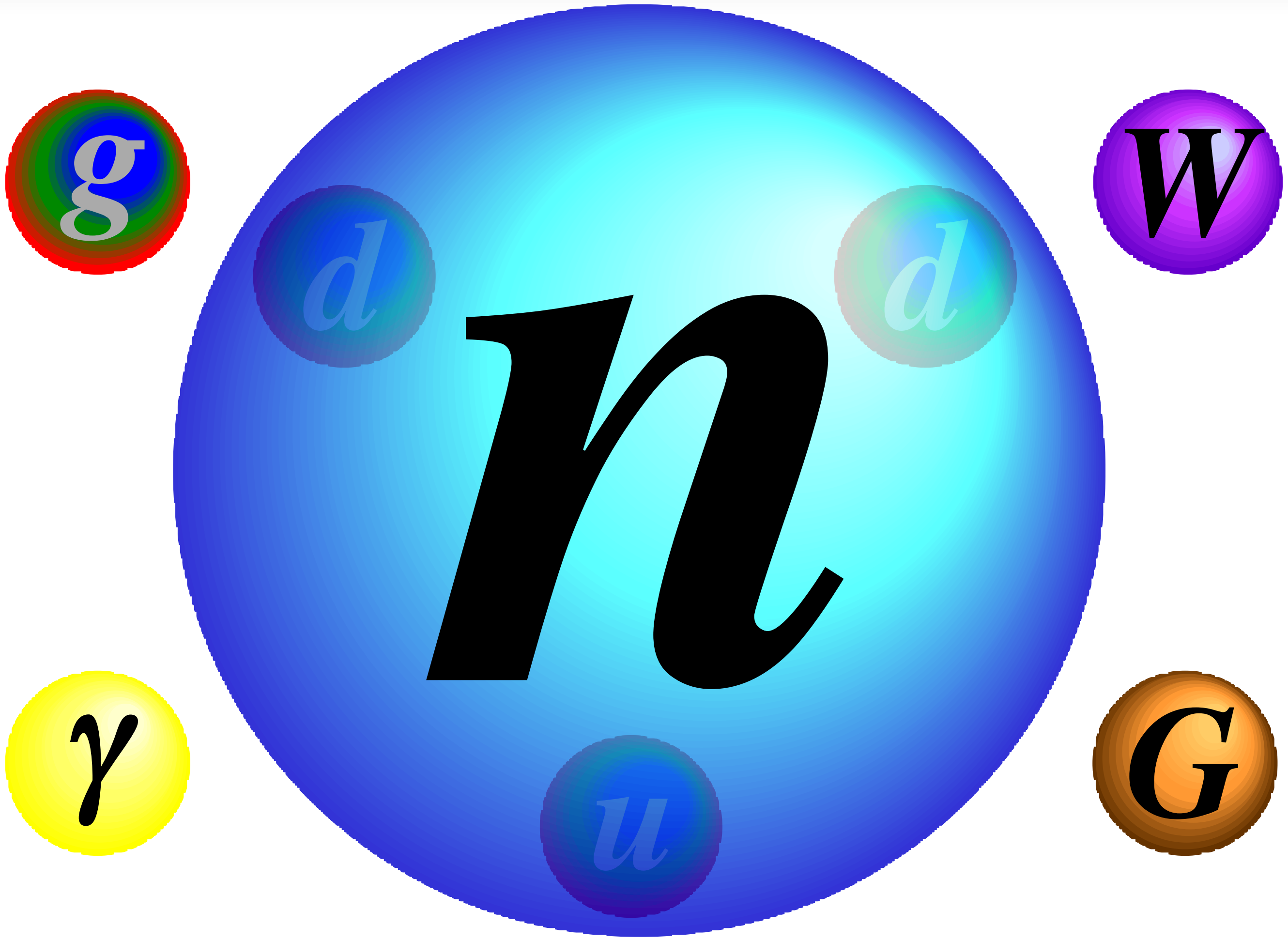


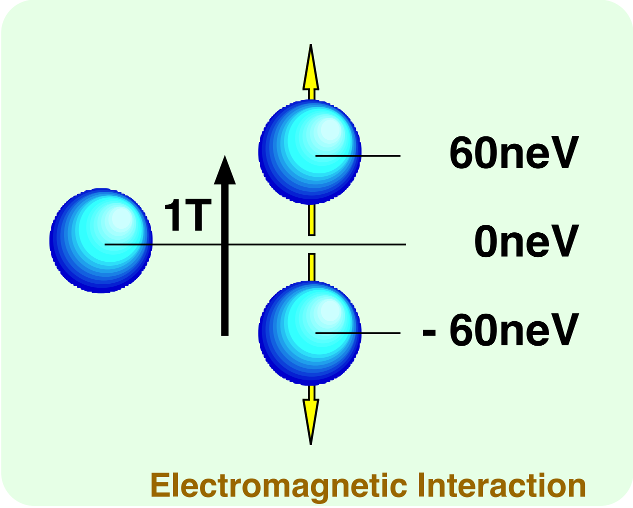
1. Overview

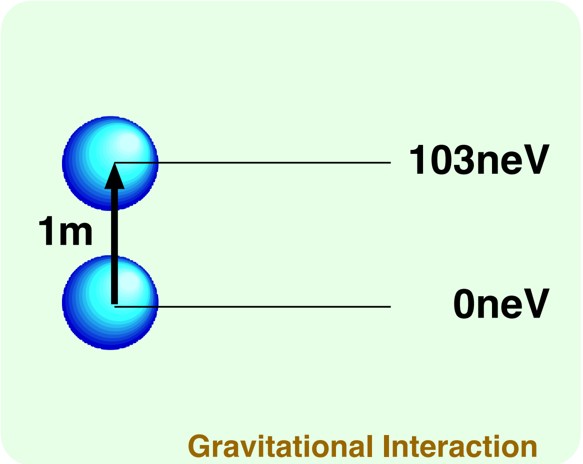
Neutron

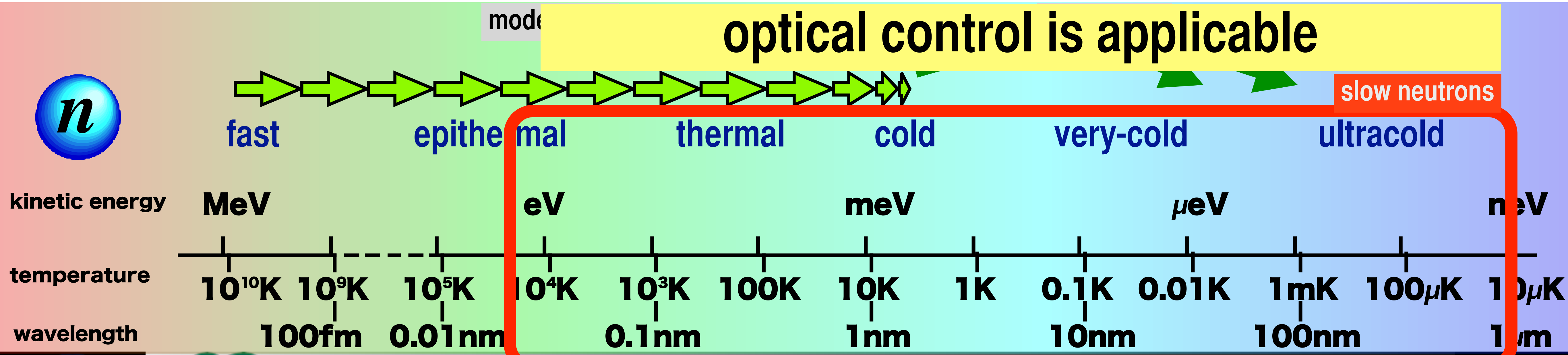










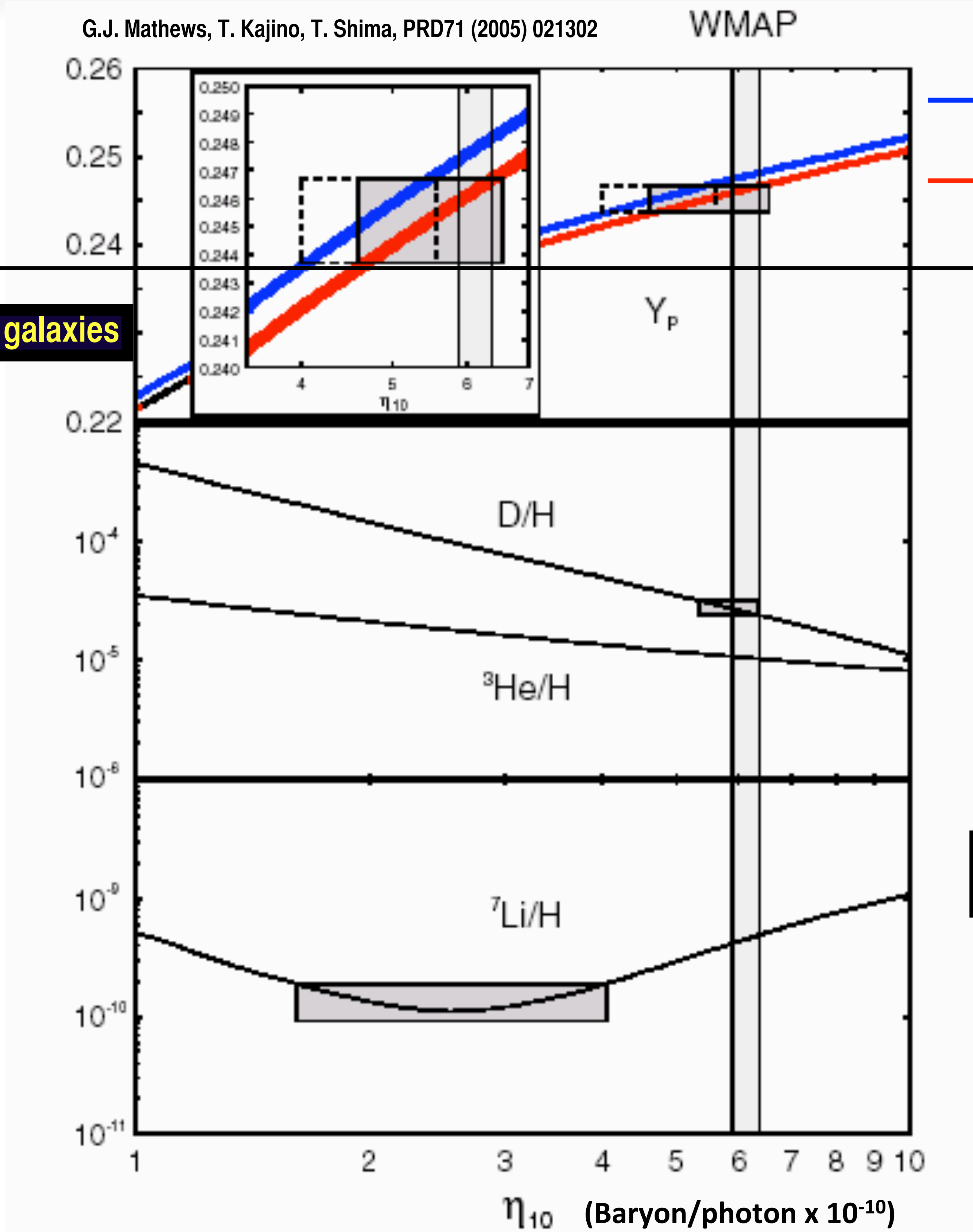


2. Neutron Lifetime

coupling constant of weak interaction in quark sector

primordial nucleosynthesis

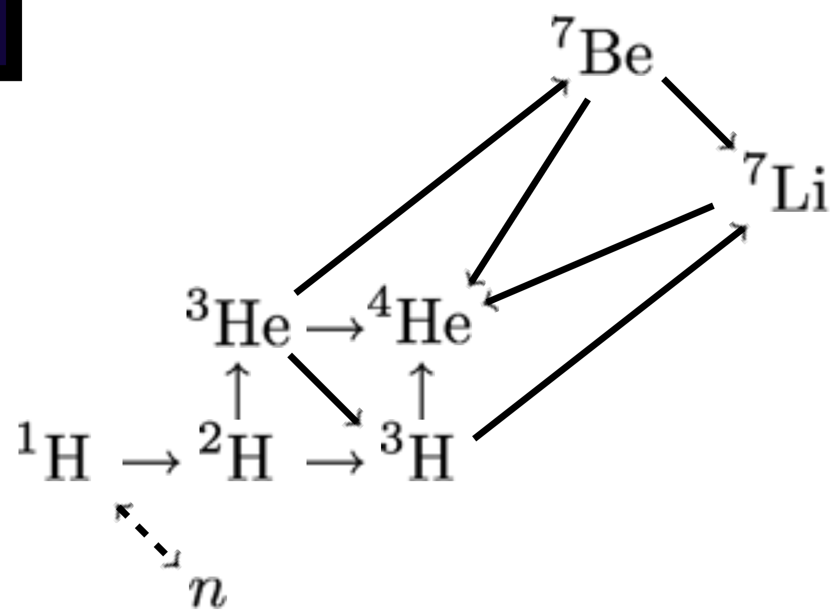
2. Neutron Lifetime



τ_n = 885.7±0.8 s (PDG2010)

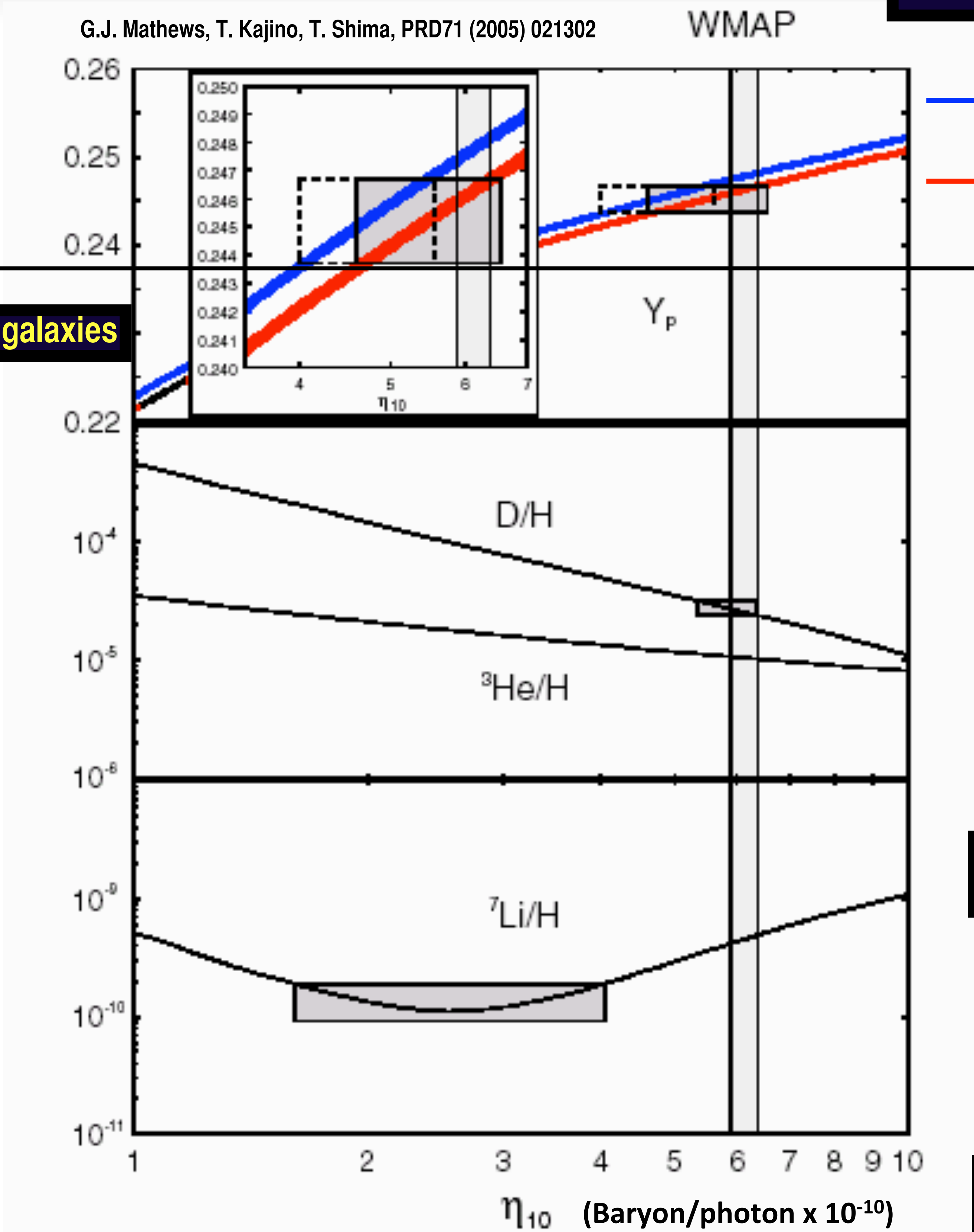
τ_n = 878.5±0.7±0.3 s (PNPI-ILL)

^{4}He/H of low-metalicity galaxies ↔ τ_n ← p and n density ← n_{baryon}/n_{photon}



2. Neutron Lifetime

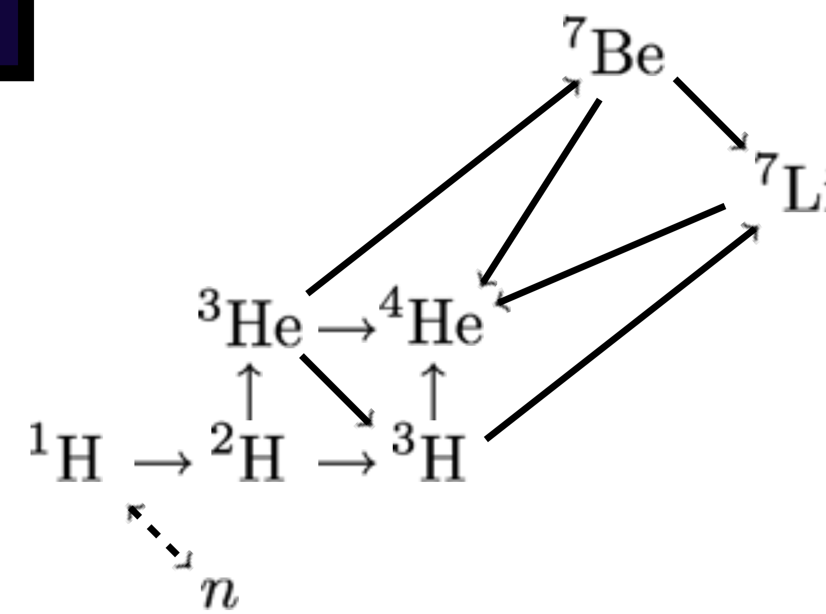
$\Delta\tau_n < 1s$



τ_n = 885.7±0.8 s (PDG2010)

τ_n = 878.5±0.7±0.3 s (PNPI-ILL)

$^4He/H$ of low-metalicity galaxies ⟷ τ_n

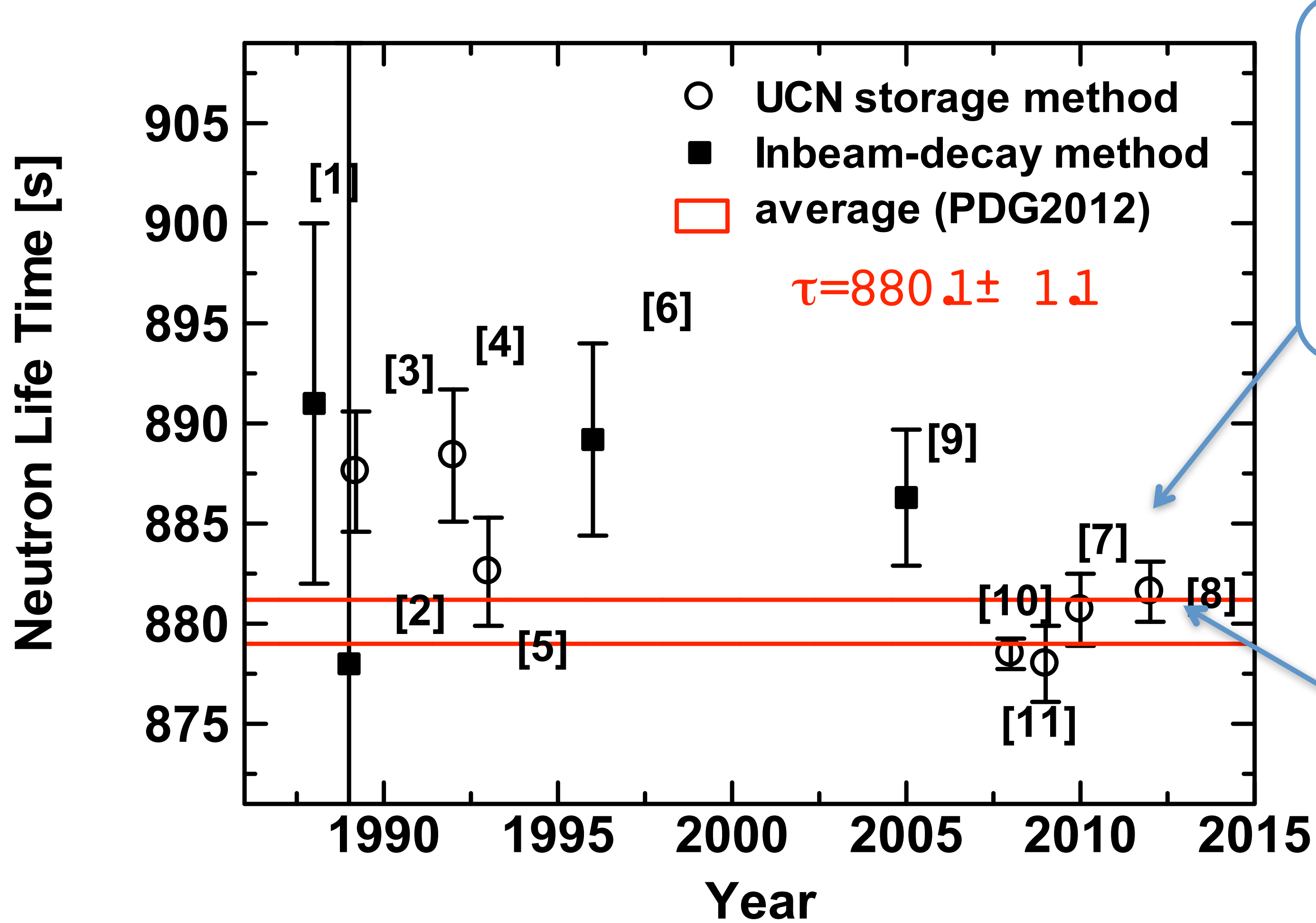


p and n density

n_{baryon}/n_{photon}

2. Neutron Lifetime

τ_n = 880.1 ± 1.1 sec (PDG2012)



A .Pichlmaier et al., Physics Letters B693 (2010) 221.

880.7 ±1.3 ± 1.2

UCN Material trap

S. Arzumanov et al., JETPL 95 (2012)224.

881.6 ±0.8 ± 1.9

UCN Material trap

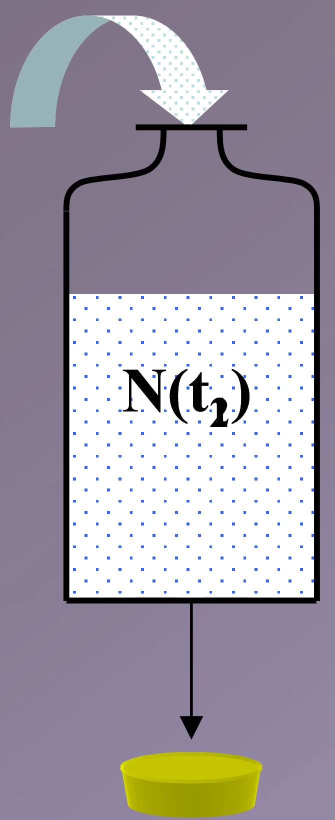
Gravitrap has been taken account in the average.
Two data (UCN material trap) have been revised.
Measured τ_n decreased by 5.6 sec(~6σ) from 2010.

2. Neutron Lifetime

Storage experiments with UCN

"counting the surviving neutrons"

"UCN bottle"



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

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

$\rightarrow 0$ (experiment)

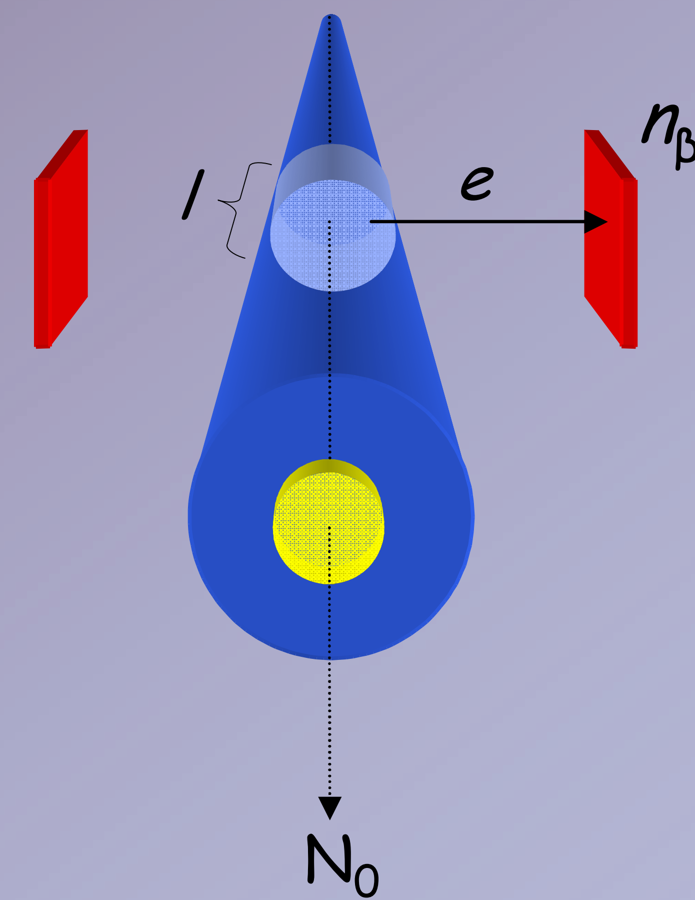
$$\frac{1}{\tau_{wall}} = M \cdot V_{eff} \rightarrow 0 \text{ (extrapolation)}$$

$$\Rightarrow \frac{1}{\tau_m} = \frac{1}{\tau_\beta}$$

Two relative measurements

Beam experiments with cold neutrons

"counting the dead neutrons"



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

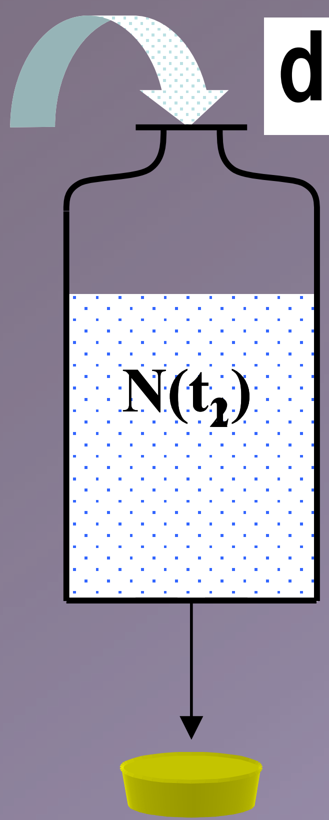
Two absolute measurements

2. Neutron Lifetime

Storage experiments with UCN

"counting the surviving neutrons"

"UCN bottle"



decrease of confined neutrons

τ_m $t_2 - t_1$ $N(t_2)$

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

→ 0 (experiment)

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

leakage correction

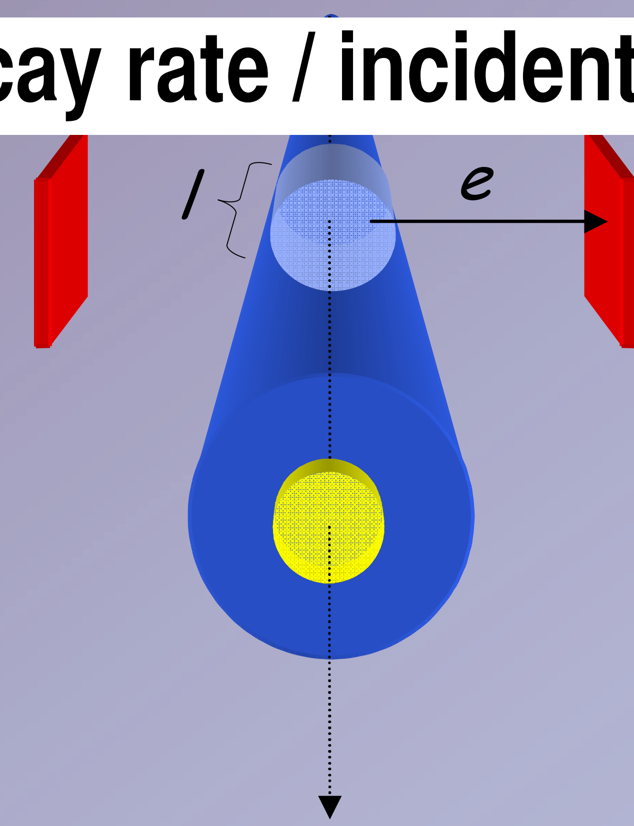
τ_m τ_β

Two relative measurements

Beam experiments with cold neutrons

"counting the dead neutrons"

decay rate / incident rate



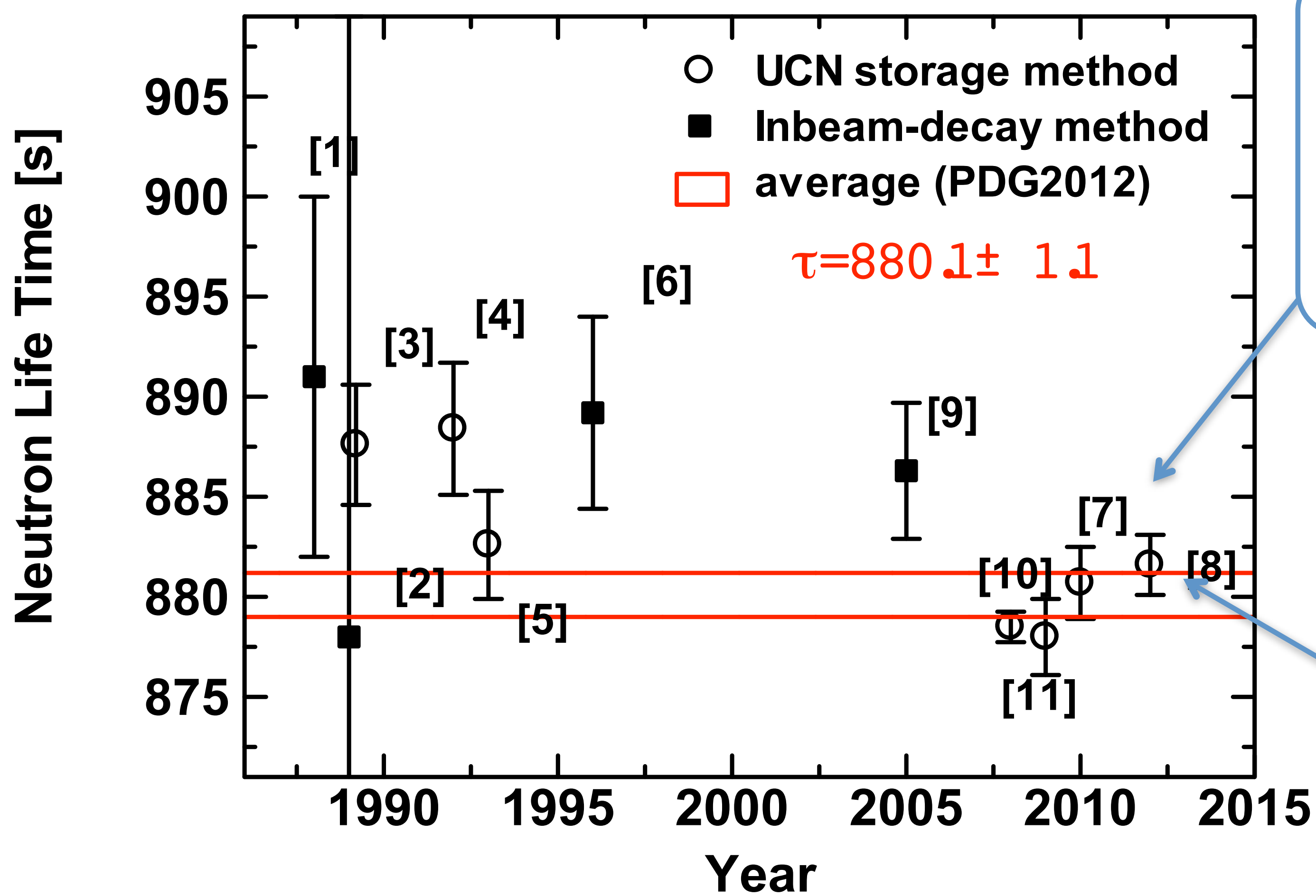
calibration of detection efficiencies

dt τ_n

Two absolute measurements

2. Neutron Lifetime

$\tau_n = 880.1 \pm 1.1$ sec (PDG2012)



A .Pichlmaier et al., Physics Letters B693 (2010) 221.

880.7 ±1.3 ± 1.2

UCN Material trap

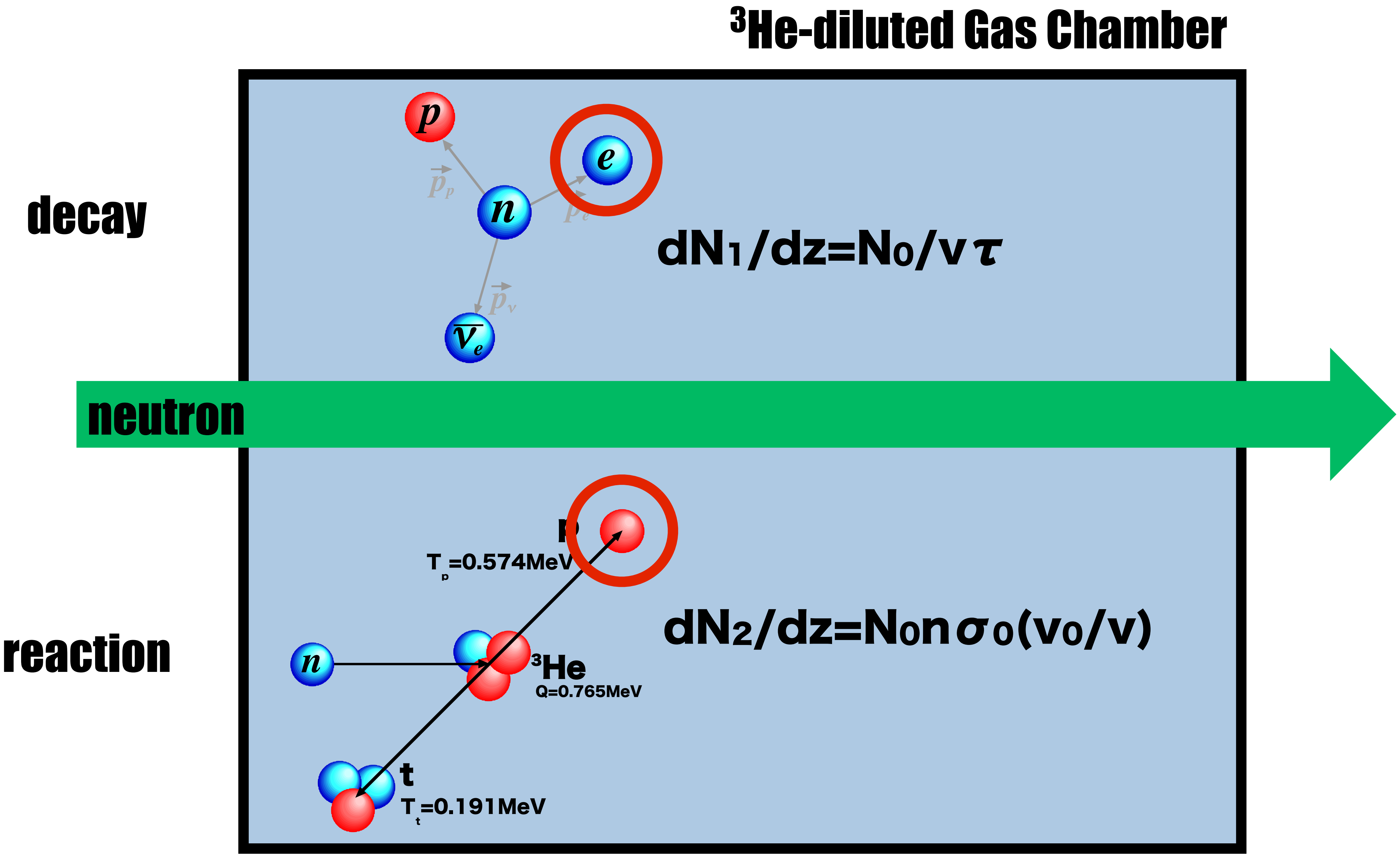
S. Arzumanov et al., JETPL 95 (2012)224.

881.6 ±0.8 ± 1.9

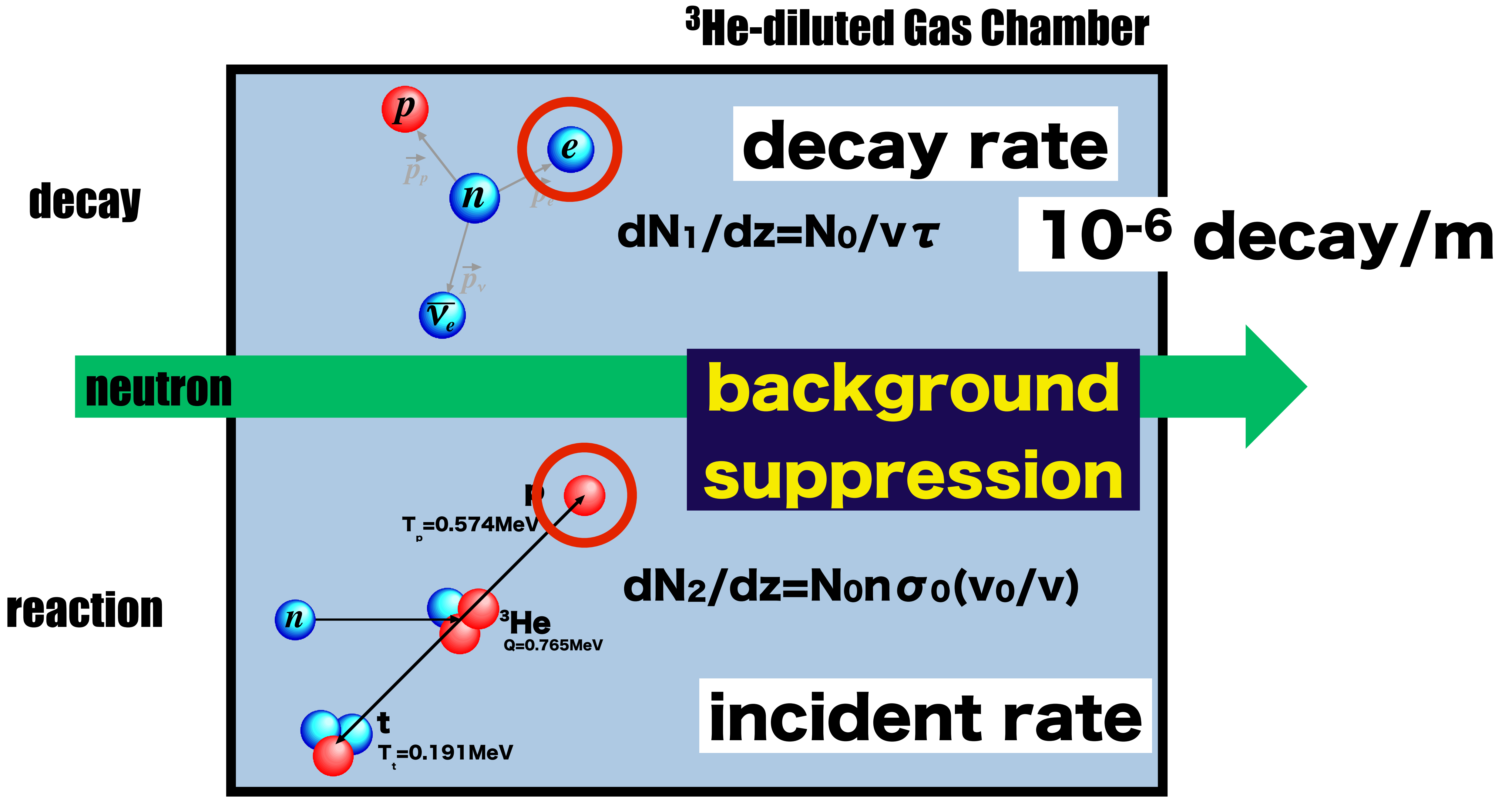
UCN Material trap

Gravitrap has been taken account in the average.
Two data (UCN material trap) have been revised.
Measured τ_n decreased by 5.6 sec(~6σ) from 2010.

2. Neutron Lifetime



single detector

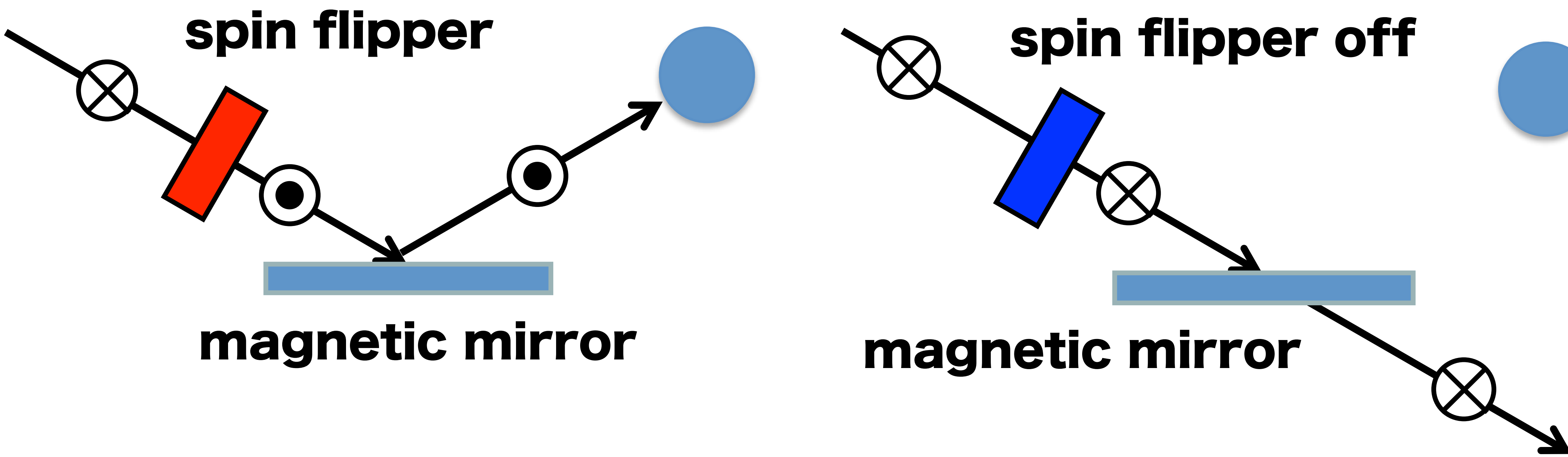


$$N_1/N_2=1/(\tau n\sigma_0 v_0)$$

2. Neutron Lifetime

spin-flip chopper: electromagnetic neutron beam steering device

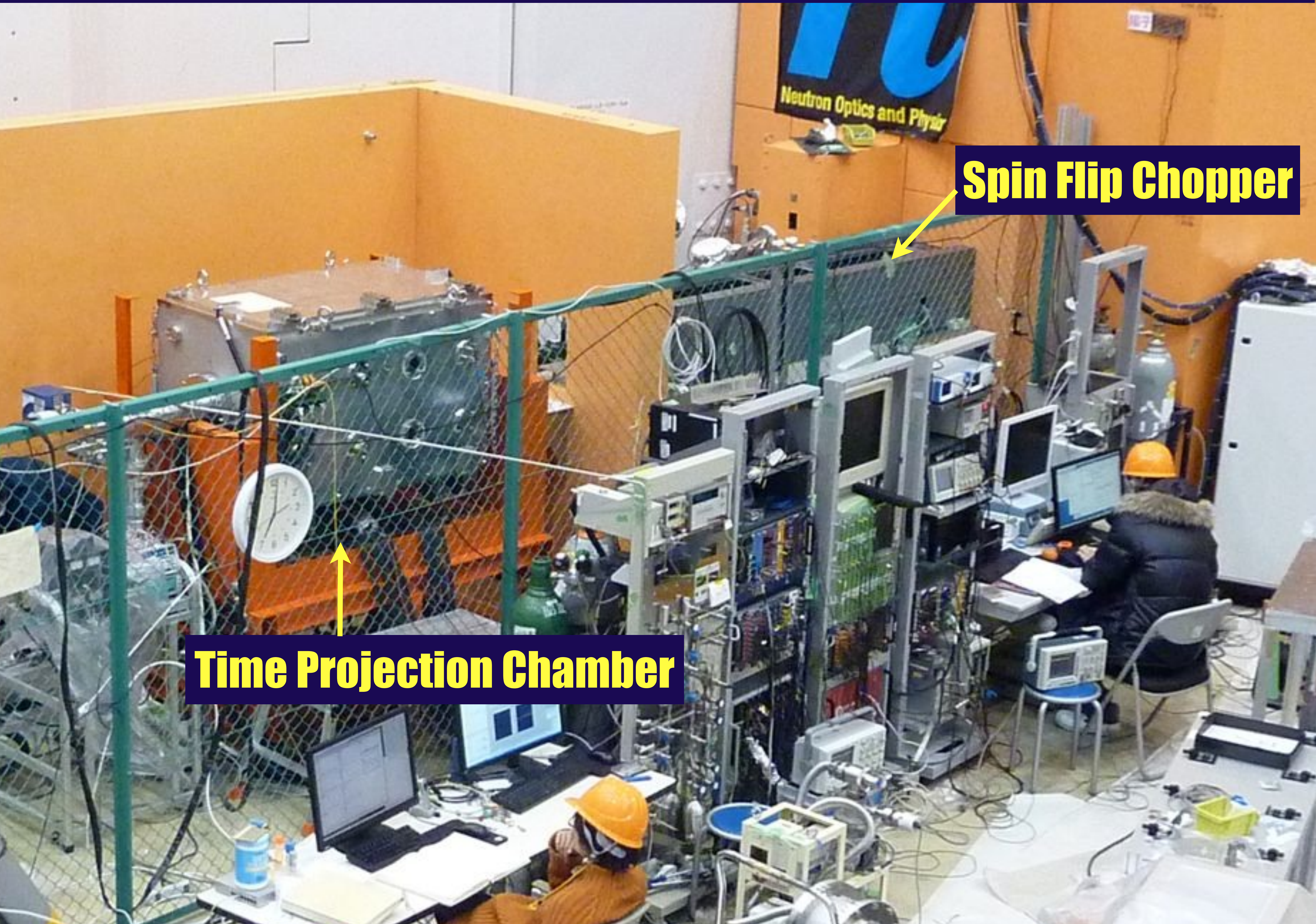
fast steering of cold neutron beam by controling the neutron spin with radio-frequency



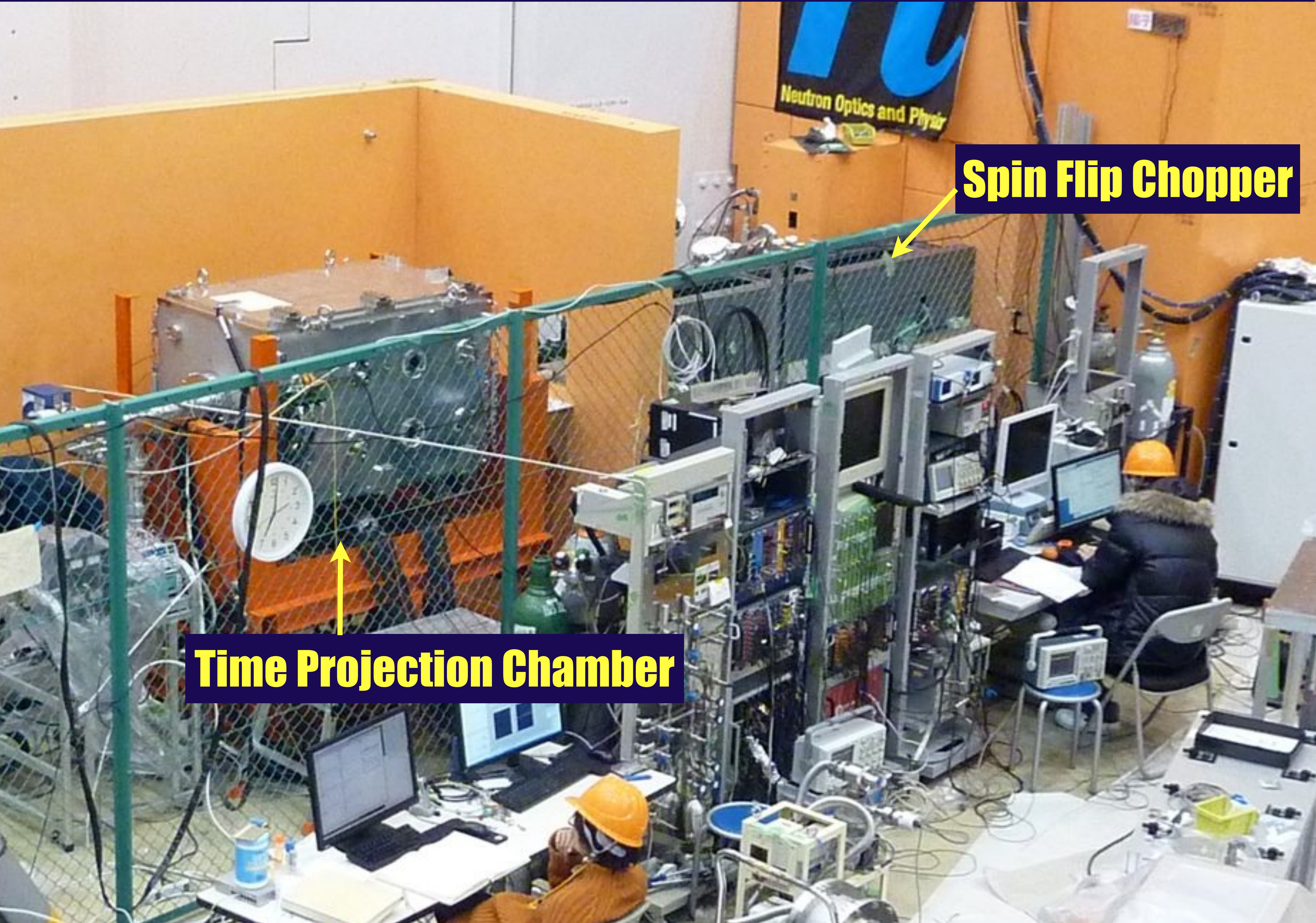
deriving monochromatic neutron beam bunch into the fiducial volume of the detector

suppression of neutron-induced background

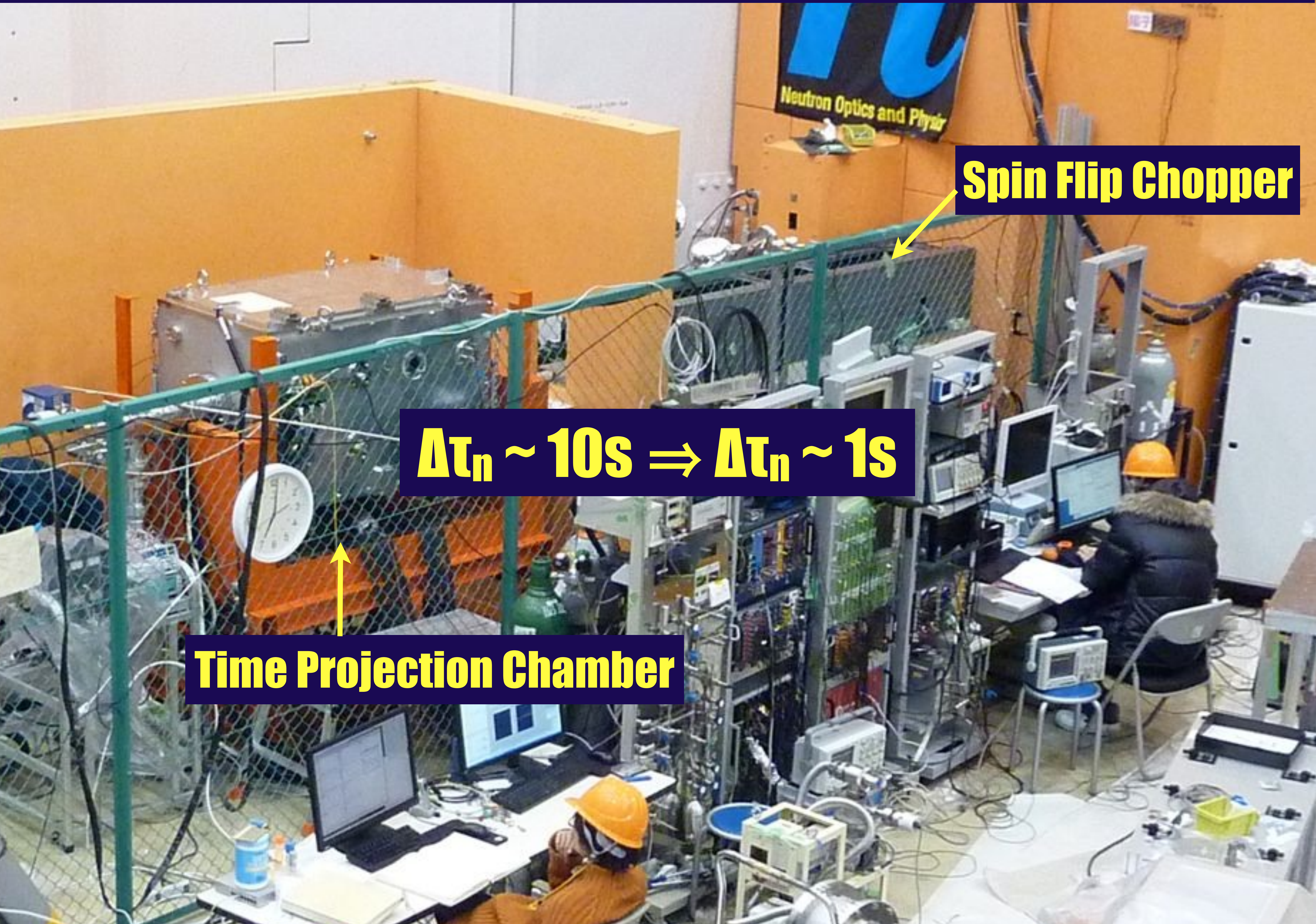
J-PARC/MLF BL05 (NOP: Neutron Optics and Physics)



J-PARC/MLF BL05 (NOP: Neutron Optics and Physics)



J-PARC/MLF BL05 (NOP: Neutron Optics and Physics)

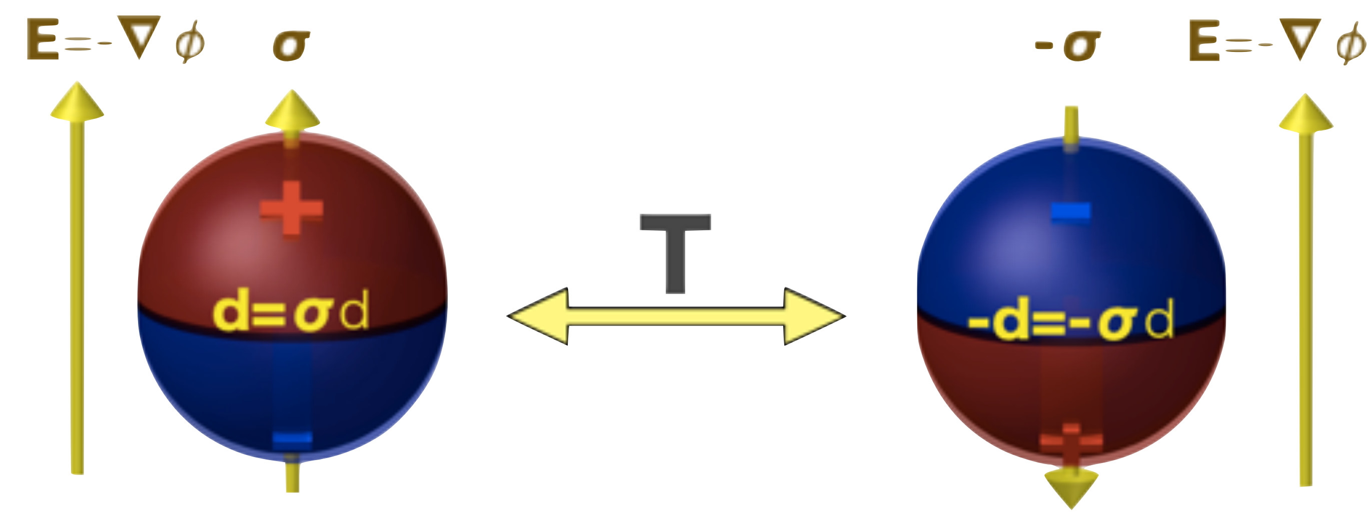


3. T-violation

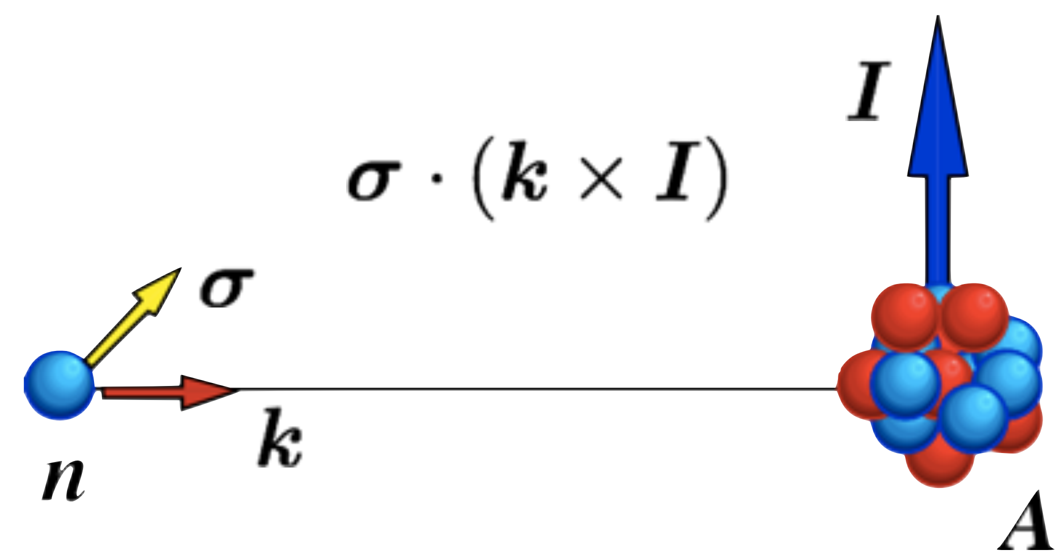
CPT=1 **CP≠1 ⇔ T≠1**

CP-violation **T-violation**

Electric Dipole Moment



T-odd Correlation Terms



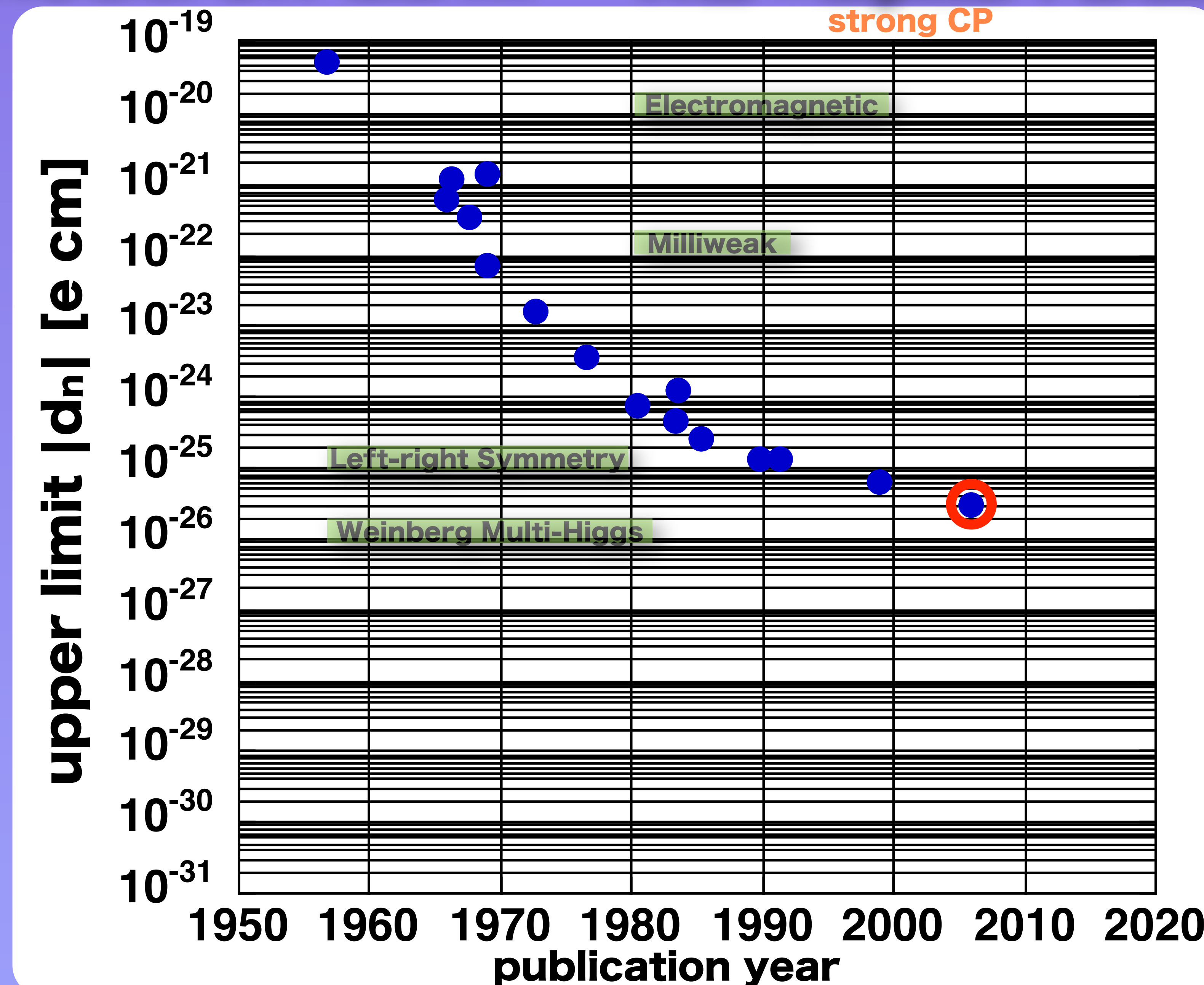
Neutron Electric Dipole Moment

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

(90%C.L.)

Baker et al., PRL97 (2006)131801

neutron EDM $\hbar\omega = 2\mu_n B + 2 d_n E$



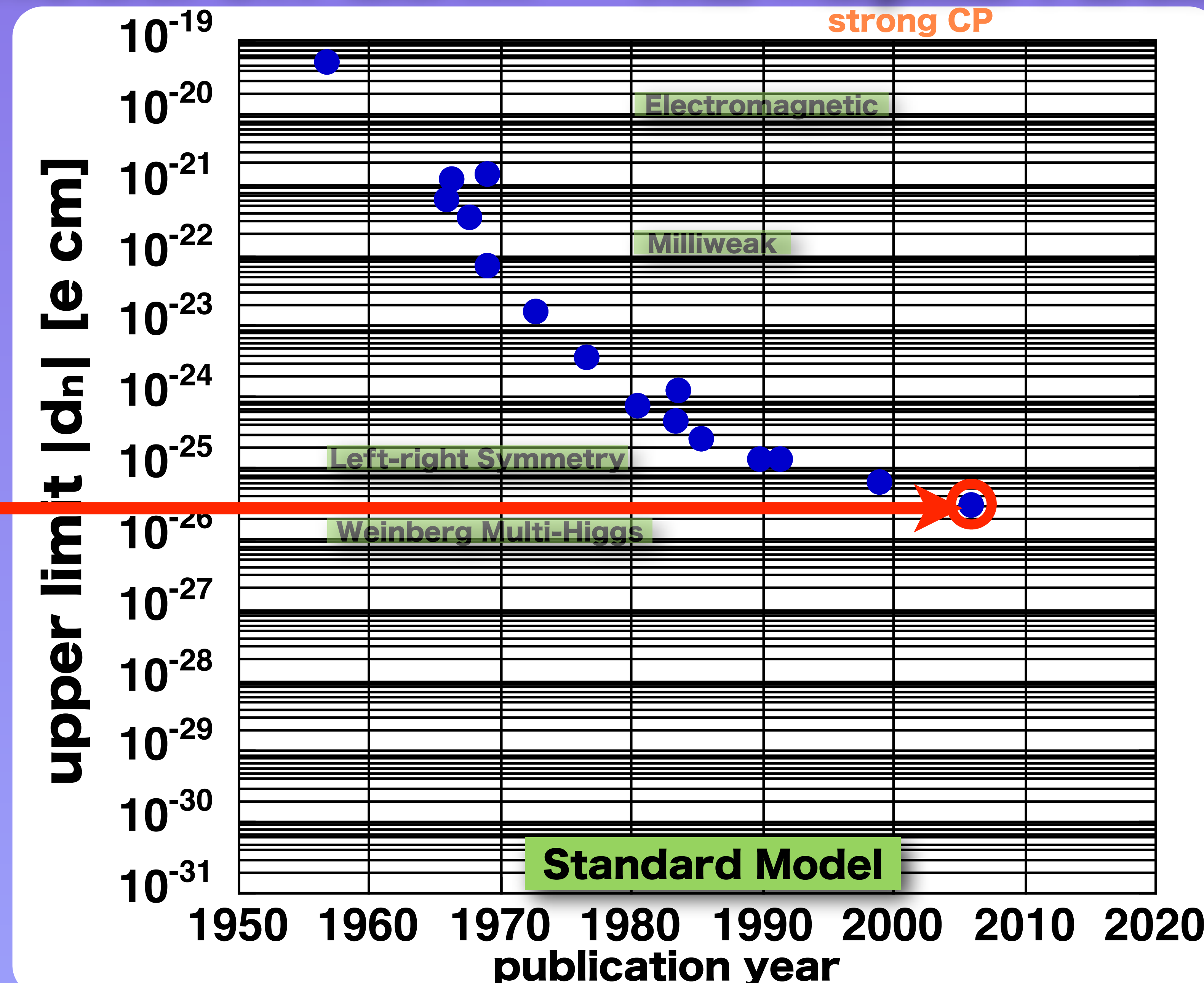
Neutron Electric Dipole Moment

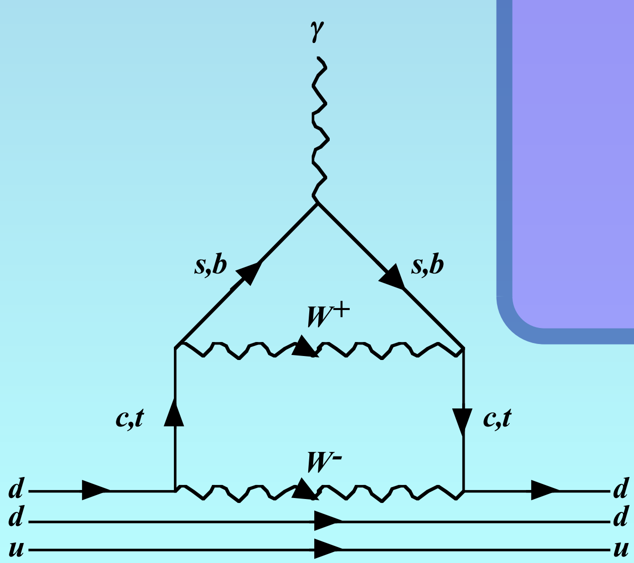
$|d_n| < 2.9\times10^{-26}$ e cm

(90%C.L.)

Baker et al., PRL97 (2006)131801

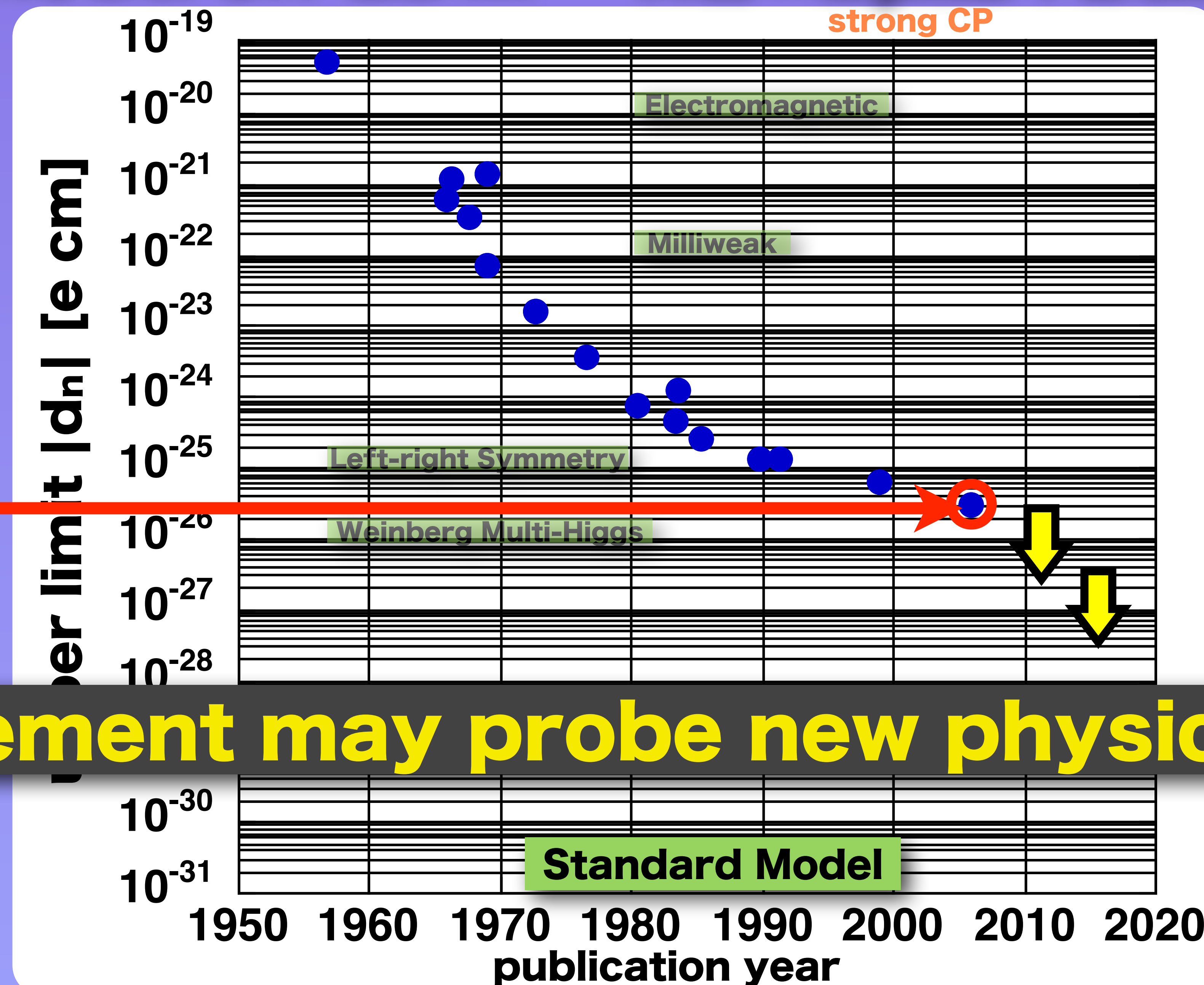
neutron EDM $\hbar\omega = 2\mu_n B + 2d_n E$





Neutron Electric Dipole Moment

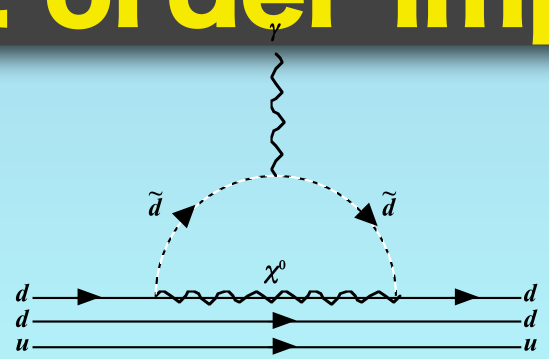
neutron EDM $\hbar\omega = 2\mu_n B + 2d_n E$



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

Baker et al., PRL97 (2006)131801

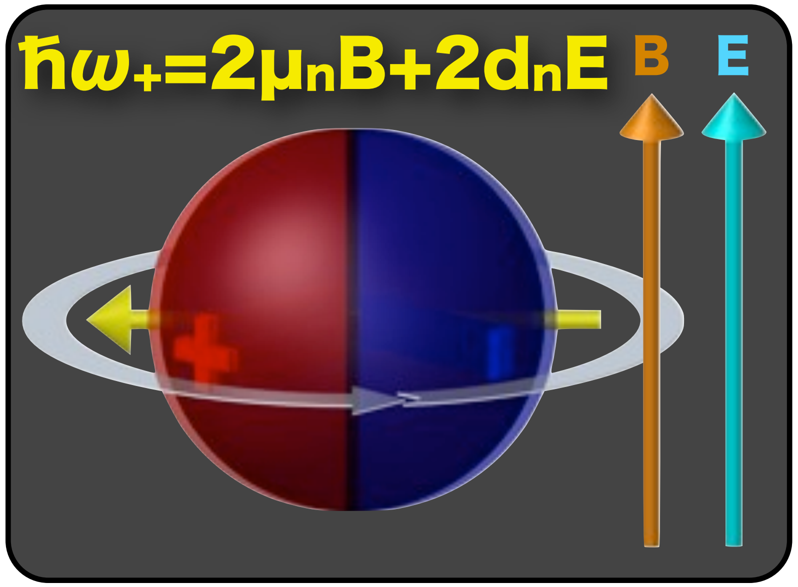
1-2 order improvement may probe new physics



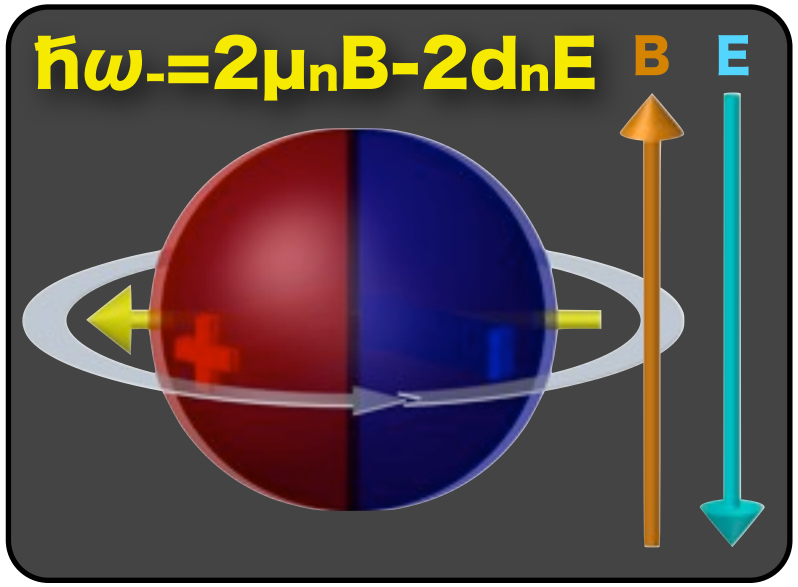
Measurement of Neutron Electric Dipole Moment

search for the phase change when the electric field is reversed

$$\hbar\omega_+ = 2d_nE + 2\mu_nB$$



$$\hbar\omega_- = 2d_nE - 2\mu_nB$$



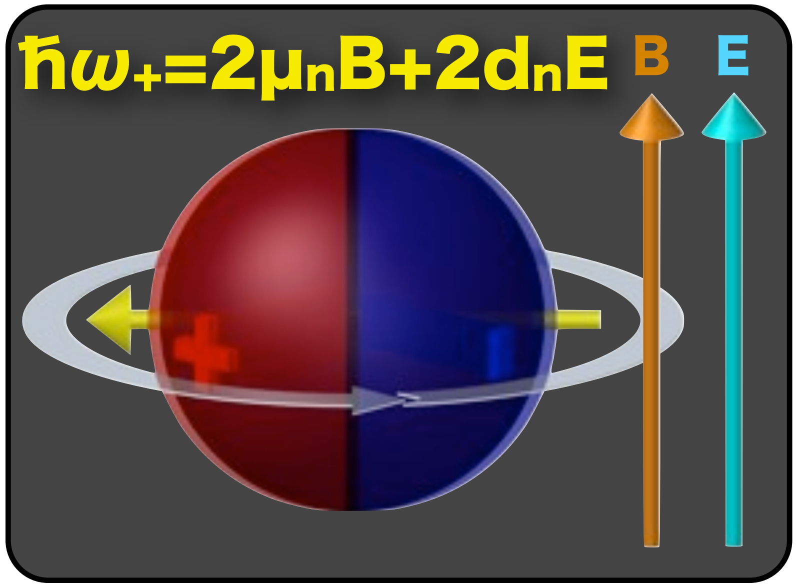
$$\Delta\phi = \int(\omega_+ - \omega_-)\mathrm{d}t = \frac{2d_nET}{\hbar}$$

$$\Delta d_n = \frac{\hbar/2}{ET\sqrt{N}}$$

Measurement of Neutron Electric Dipole Moment

search for the phase change when the electric field is reversed

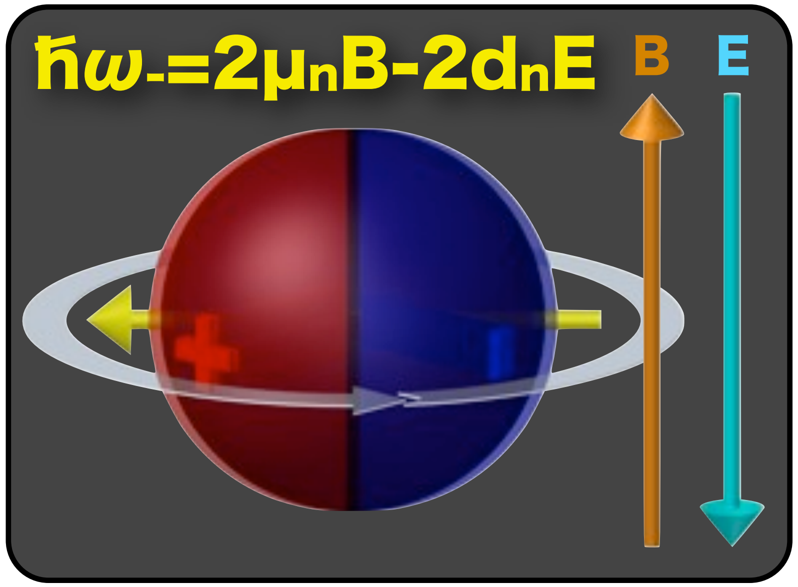
$$\hbar\omega_+ = 2d_n E + 2\mu_n B$$



$$\Delta\phi = \int (\omega_+ - \omega_-)\mathrm{d}t = \frac{2d_n ET}{\hbar}$$

$$\Delta d_n = \frac{\hbar/2}{ET\sqrt{N}}$$

$$\hbar\omega_- = 2d_n E - 2\mu_n B$$



Confined Ultracold Neutron Spin Precession Frequency

$E=10^4$ V/cm, T=100s

long precession time

Cold Neutron Diffraction in Single Crystal

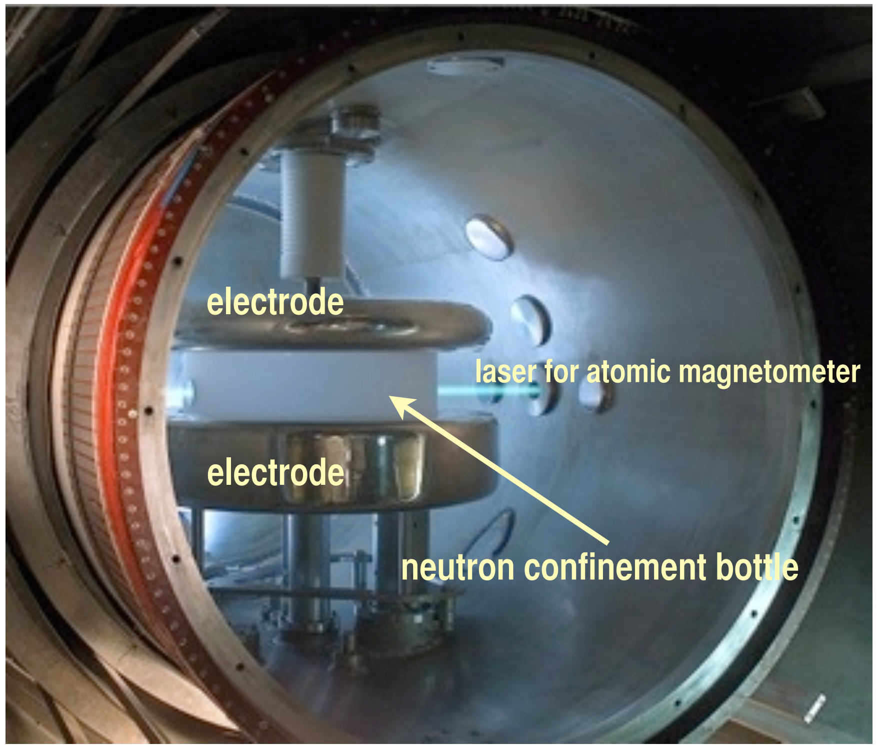
$E=10^9$ V/cm, T=1ms

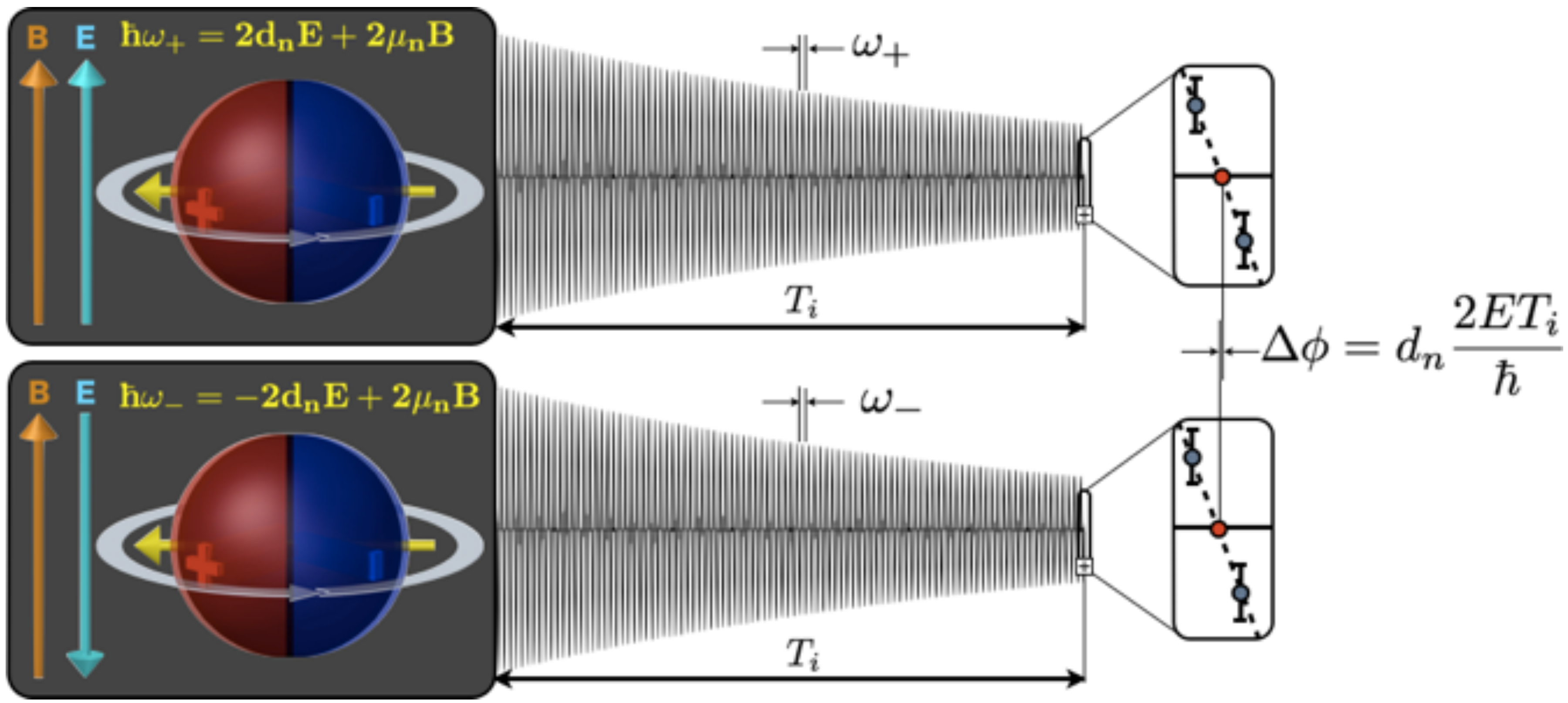
strong electric field

$$ET = 10^6 \text{ [s kV/cm]}$$

Measurement of Neutron Electric Dipole Moment

Confined Ultracold Neutron Spin Precession Frequency





$$\frac{\omega_\pm}{2\pi} = 30[\mathrm{Hz}]\frac{B}{1\,[\mu\mathrm{T}]} \pm 5\times10^{-8}[\mathrm{Hz}]\frac{d_n}{10^{-26}\,[\mathrm{e}\cdot\mathrm{cm}]}\frac{E}{10\,[\mathrm{kV/cm}]}$$

magnetic field **1μT**

electric field **1fT equiv.**

Measurement of Neutron Electric Dipole Moment

Confined Ultracold Neutron Spin Precession Frequency

$$\frac{\omega_\pm}{2\pi} = 30\,[\mathrm{Hz}]\,\frac{B}{1\,[\mu\mathrm{T}]} \pm 5\times 10^{-8}\,[\mathrm{Hz}]\,\frac{d_n}{10^{-26}\,[\mathrm{e}\cdot\mathrm{cm}]}\,\frac{E}{10\,[\mathrm{kV/cm}]}$$

magnetic field **1μT** electric field **1fT equiv.**

precision control of magnetic field

density of confined neutrons

- superthermal production of ultracold neutron
- transport optics with minimum density decrease

control of the motion of confined neutrons

- optical properties of neutron reflectors

accuracy of the magnetic field measurement

- atomic magnetometry

Measurement of Neutron Electric Dipole Moment

Confined Ultracold Neutron Spin Precession Frequency

$$\frac{\omega_\pm}{2\pi} = 30[\mathrm{Hz}]\frac{B}{1\,[\mu\mathrm{T}]} \pm 5\times 10^{8}[\mathrm{Hz}]\frac{d_n}{10^{-26}\,[\mathrm{e}\cdot\mathrm{cm}]}\frac{E}{10\,[\mathrm{kV/cm}]}$$

magnetic field **1μT** electric field **1fT equiv.**

precision control of magnetic field

- **density of confined neutrons**
  - **superthermal production of ultracold neutron**
  - **transport optics with minimum density decrease**
- **control of the motion of confined neutrons**
  - **optical properties of neutron reflectors**
- **accuracy of the magnetic field measurement**
  - **atomic magnetometry**

Measurement of Neutron Electric Dipole Moment

Cold Neutron Diffraction in Single Crystal

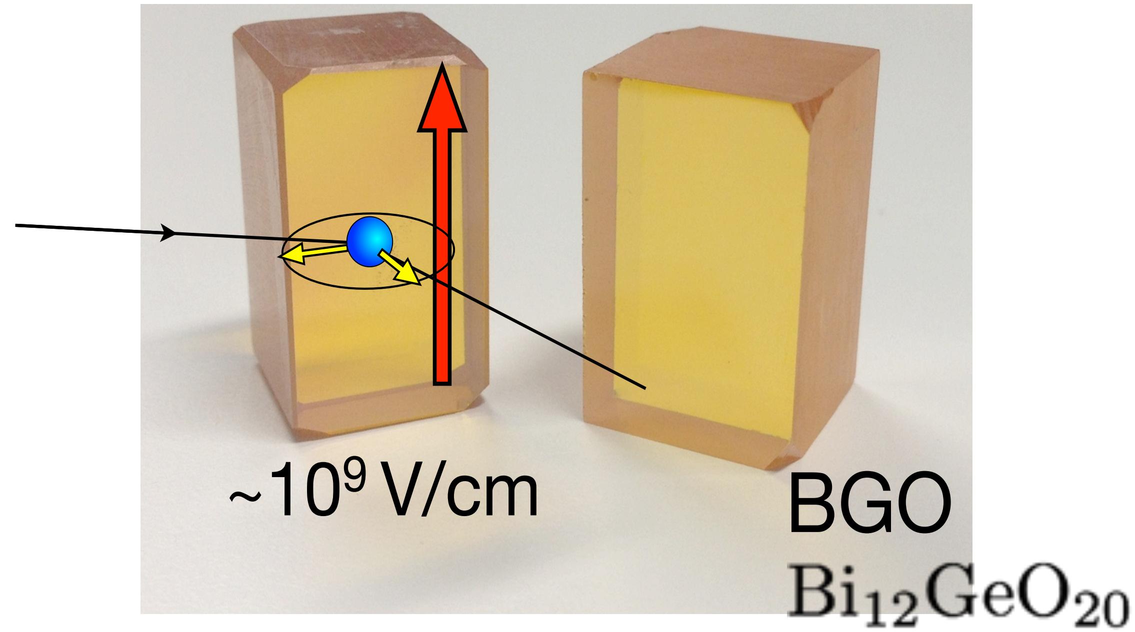
$$f(\boldsymbol{q}) = \underline{f_0} + \underline{f_{\mathrm{Schw}}(\boldsymbol{q})} + \underline{f_{\mathrm{EDM}}(\boldsymbol{q})}$$

$$a \qquad i\frac{2e\mu_n}{\hbar c}(Z - F(q))\frac{\boldsymbol{\sigma}\cdot(\boldsymbol{k}\times\boldsymbol{q})}{q^2} \qquad i\frac{2med_n}{\hbar^2}(Z - F(q))\frac{\boldsymbol{\sigma}\cdot\boldsymbol{q}}{q}$$

$$F(\boldsymbol{q}) = \int \rho(\boldsymbol{q})e^{i\boldsymbol{q}\cdot\boldsymbol{r}}\mathrm{d}\boldsymbol{r}$$ atomic form factor

incompleteness of crystal
size of crystal

$\Delta d_n \sim 10^{-24}$ e cm → $\Delta d_n \sim 10^{-26}$ e cm



T-odd Correlation in Compound Nuclei

Parity-violating effect is enhanced in p-wave compound resonances due to the interference between partial waves with different parities (orbital angular momenta).

enhancement factor ~ 10^6

The mechanism enhances T-violating effects in effective nucleon-nucleon interaction if the mixing angle of partial-waves with different T-parity (channel spin momenta).

sensitivity estimation

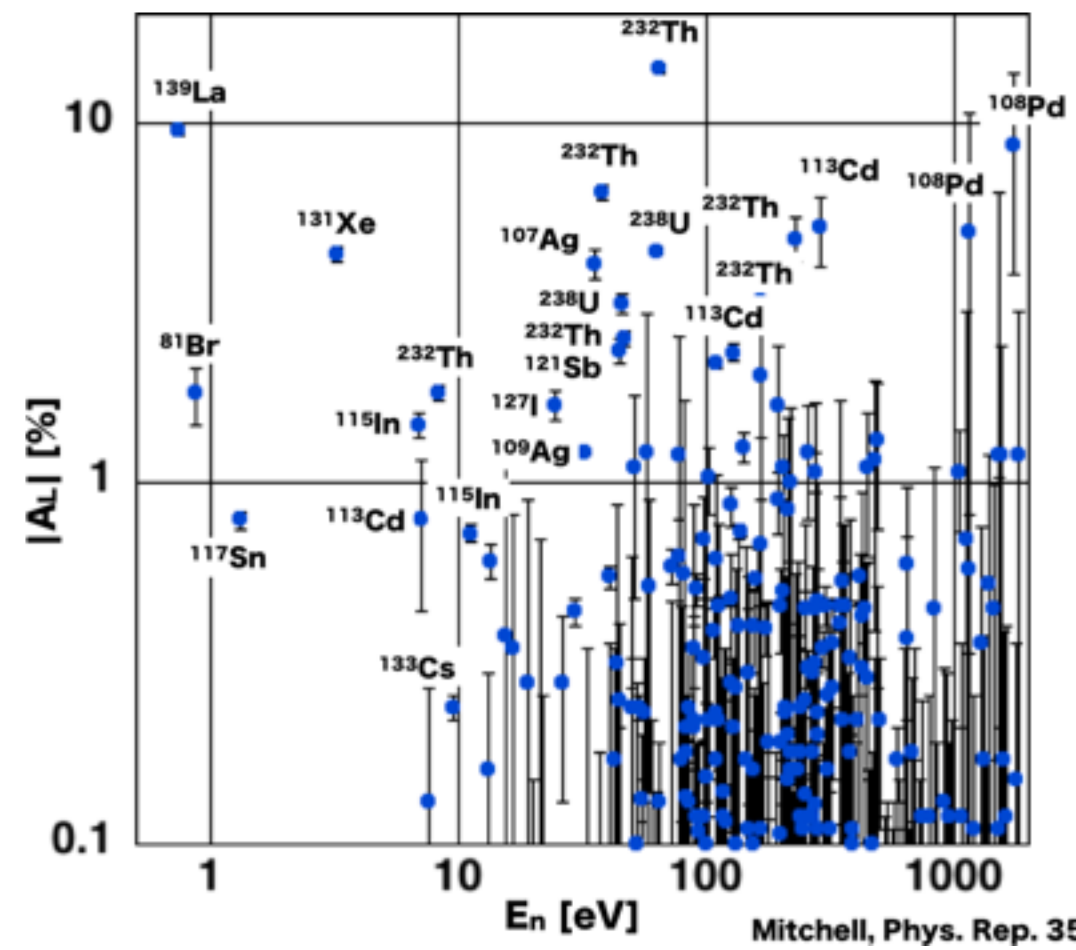
$$\left|\Delta\sigma_{\mathrm{T}}^{nA}\right| < 2.5 \times 10^{-4}[\mathrm{b}] \times \kappa(J)$$

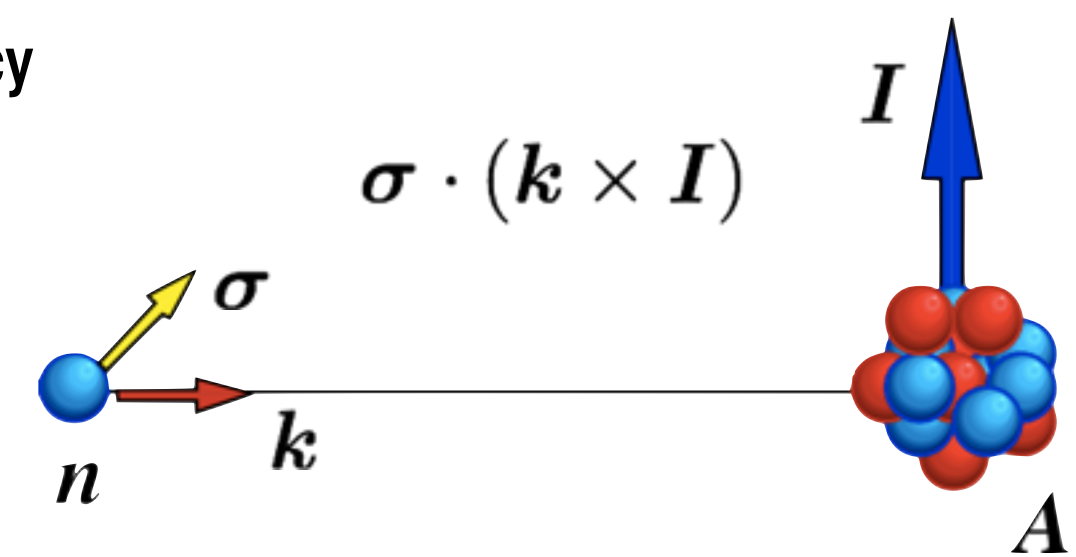
T-odd term

equivalent to EDM search assuming enh.fac.~10^6

mixing efficiency

J-PARC can achieve the statistics corresponding to $|d_n|<10^{-27}$ e cm in 1-year in case κ=1.





4. Medium-range Force (Gravity)

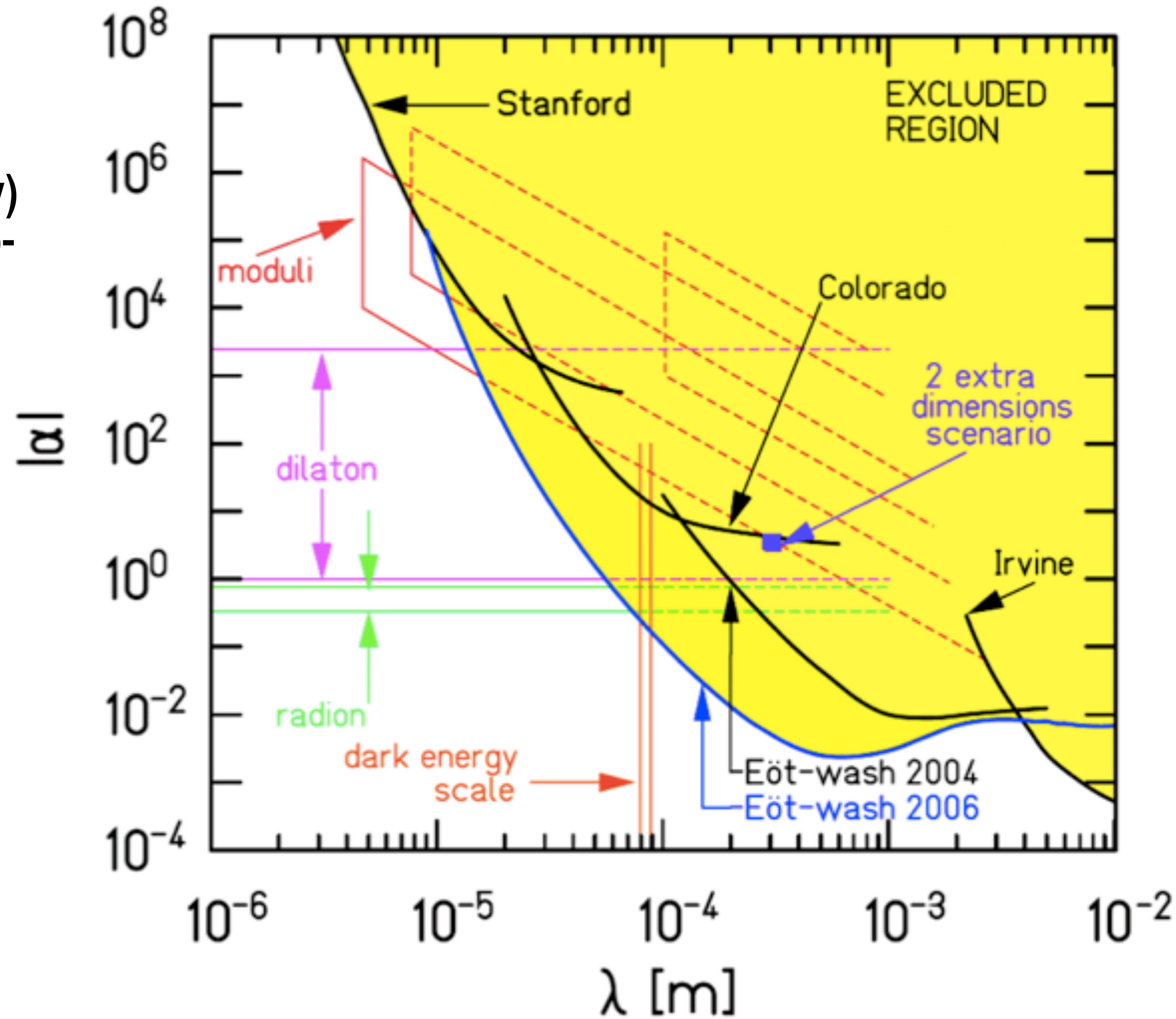
$$U(r) = \frac{GMm}{r^2}\left(1 + \alpha e^{-r/\lambda}\right)$$

Newtonian   exotic interaction

van der Waals force
(proportional to electric polarizability)
is the dominant background in micro-
and nanometer-range

$$\alpha_{\rm atom} \sim 10^{-24}[{\rm cm}^3]$$

$$\alpha_n \sim 10^{-42}[{\rm cm}^3]$$



4. Medium-range Force (Gravity)

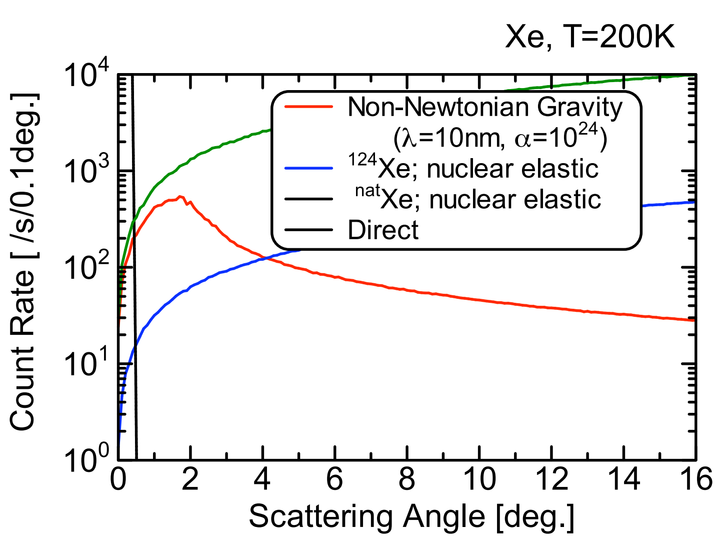
$$U(r) = \frac{GMm}{r^2}\left(1 + \alpha e^{-r/\lambda}\right)$$

Newtonian — exotic interaction

The exotic interaction can be searched in the angular distribution of neutron scattering by atoms

$$\frac{d\sigma}{d\Omega} = |a_{\mathrm{N}} + a_{ne}ZF_e(\theta) + a_G F_G(\theta)|^2$$

$$\simeq a_{\mathrm{N}}^2 + 2a_{\mathrm{N}}a_{ne}ZF_e(\theta) + a_{ne}^2Z^2F_e(\theta)^2 + 2a_{\mathrm{N}}a_G F_G(\theta)$$

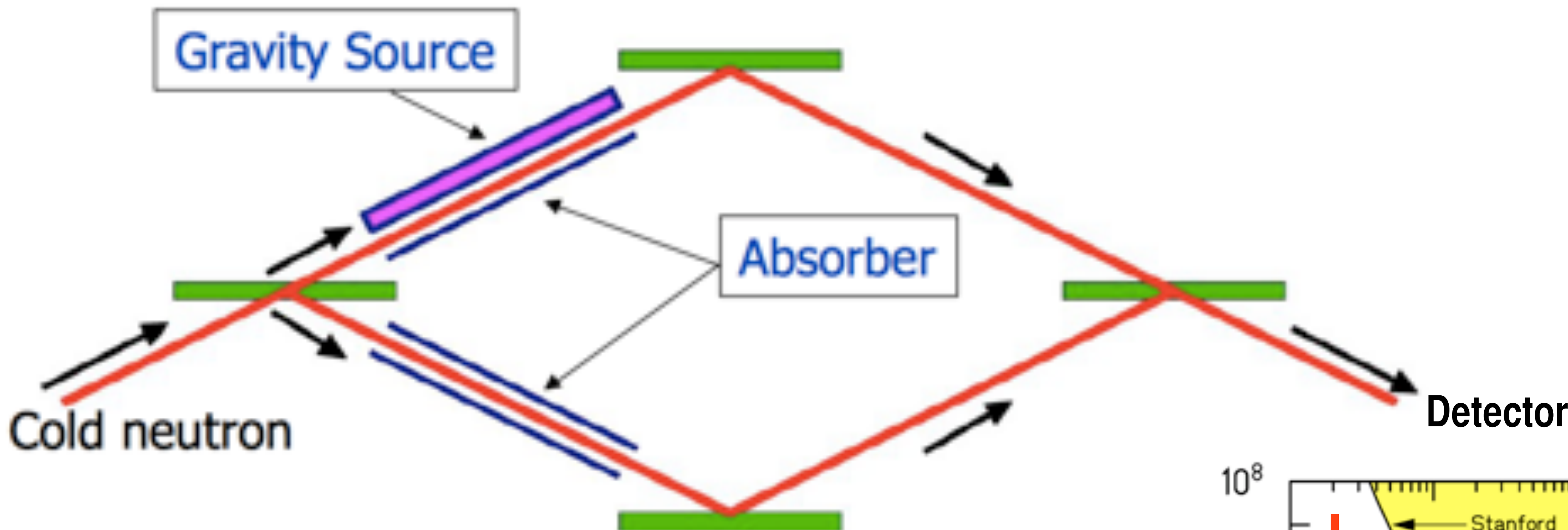


$$\frac{d\sigma_G}{d\Omega} = \alpha^2\left(\frac{GMm_n}{4}\right)^2\left(\frac{1}{\frac{1}{m_nc^2}\left(\frac{\hbar c}{\lambda}\right)^2 + 8E_n\sin^2\frac{\theta}{2}}\right)^2$$

4. Medium-range Force (Gravity)

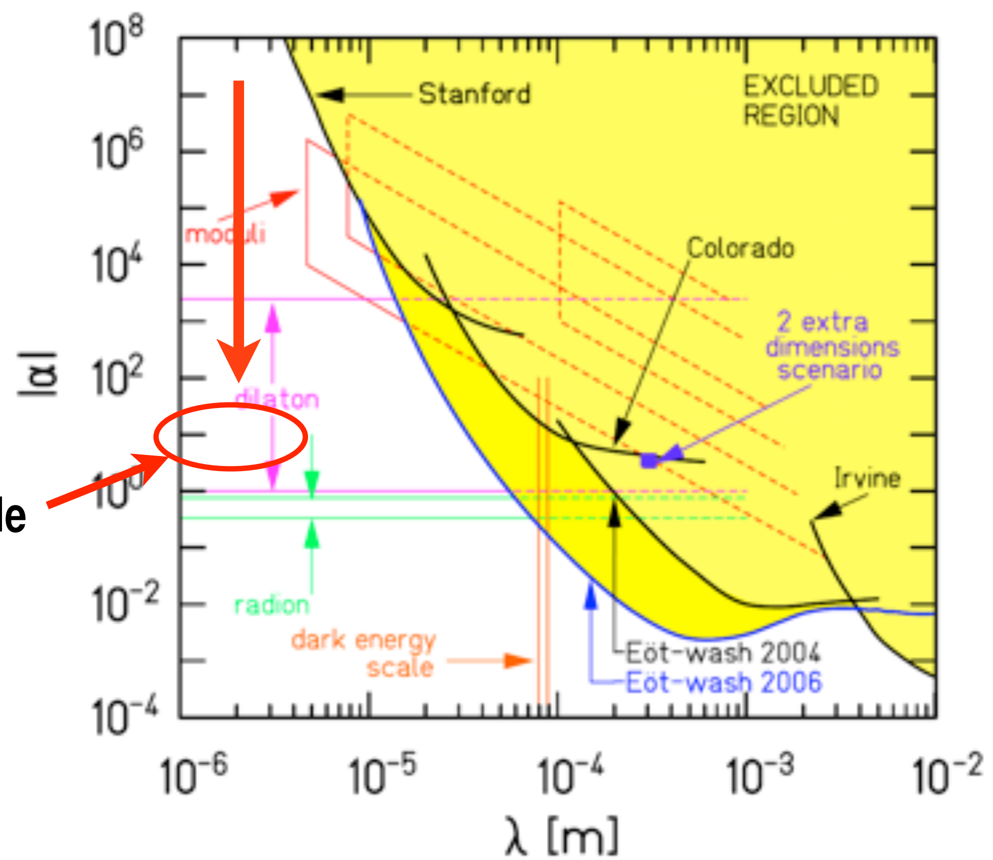
Neutron Interferometry

detecting exotic potential by measuring the phase shift between two paths



technical challenges :
phase stability and microbeam delivery

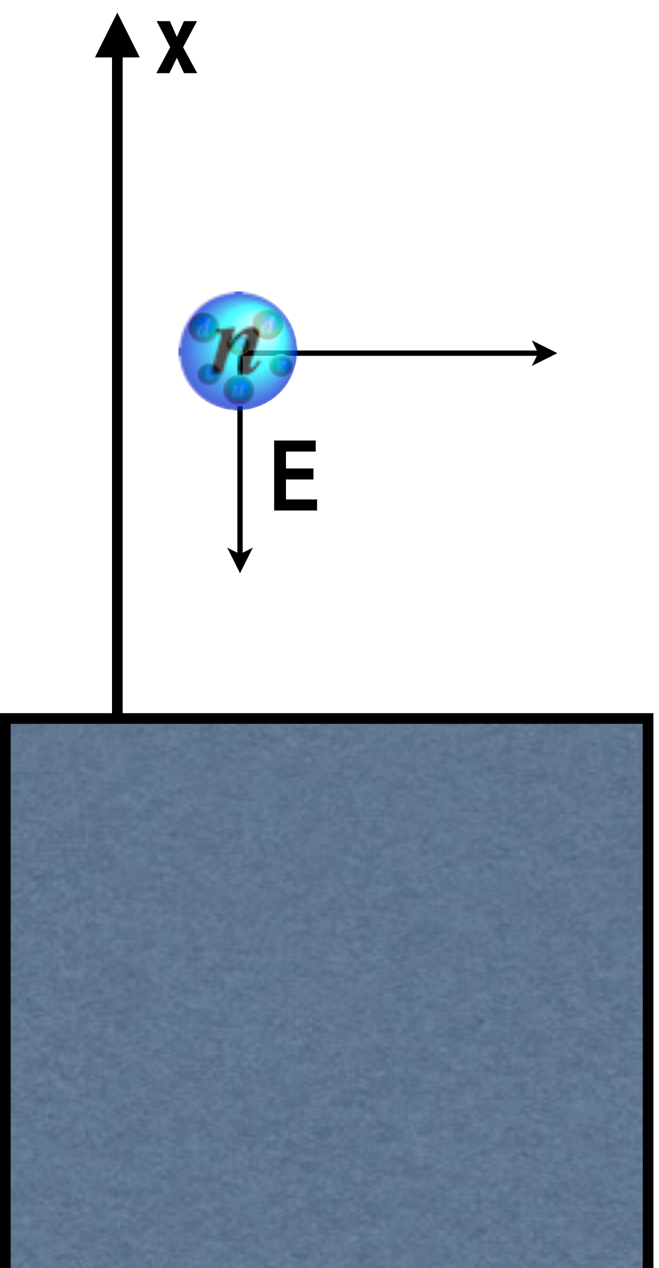
ADD-model N=3 is reachable

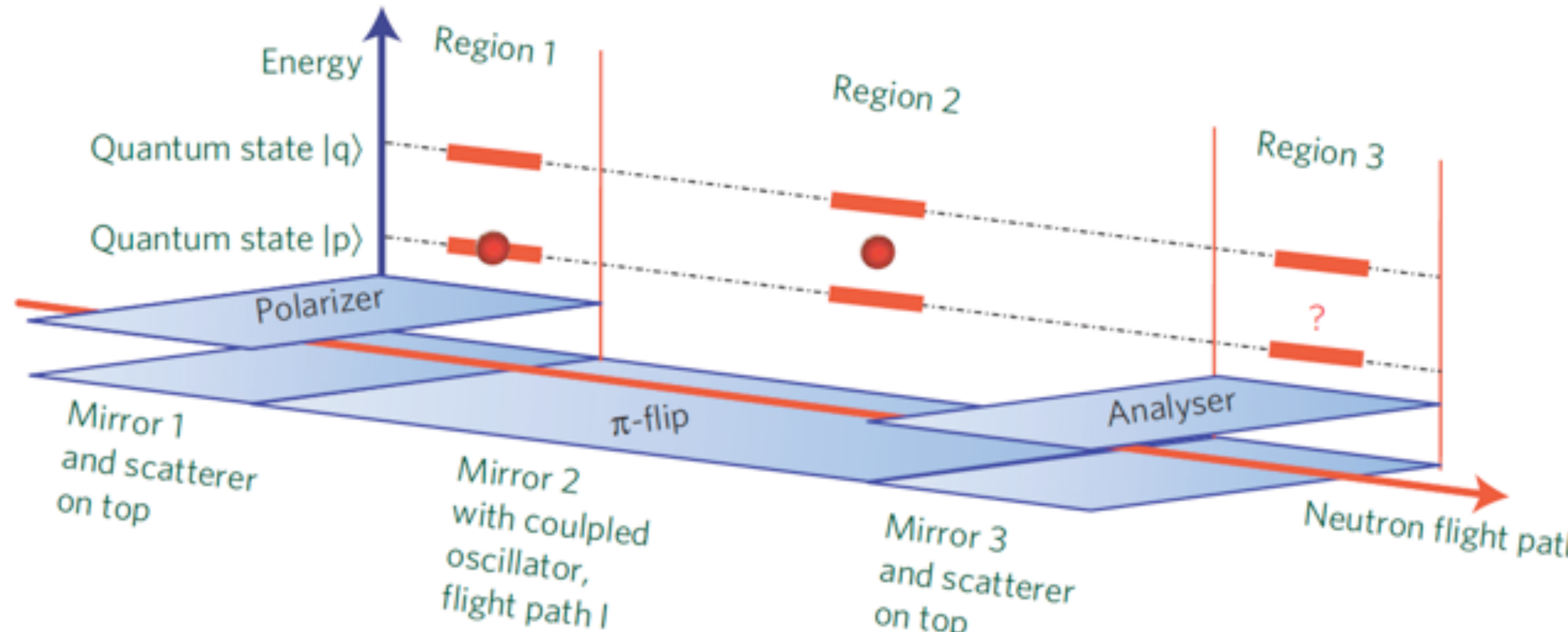


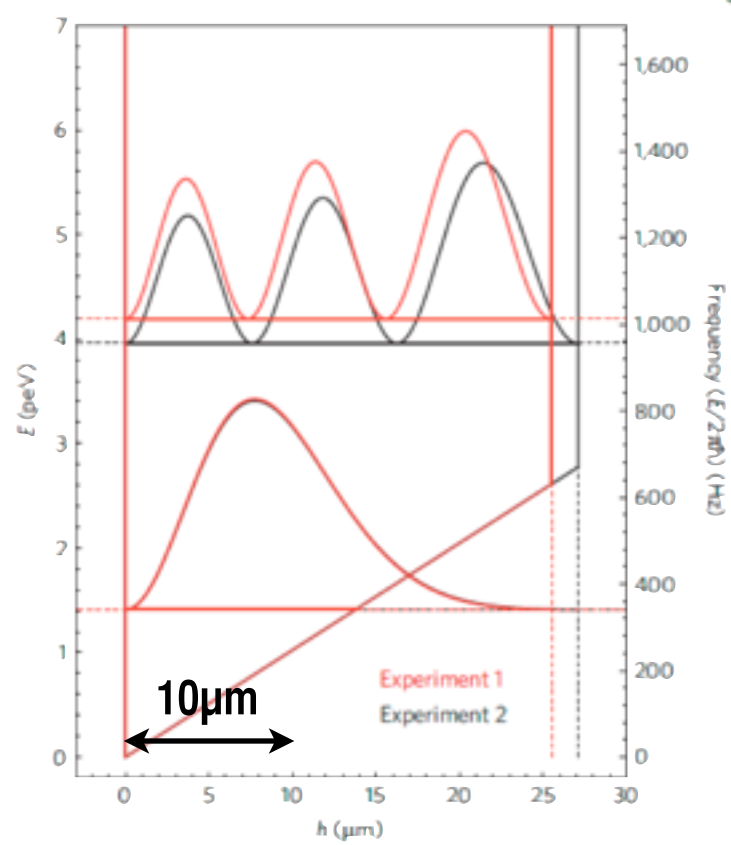
4. Medium-range Force (Gravity)

Gravitationally Quantized States

$$\left(-\frac{\hbar^2}{2m}\frac{\mathrm{d}^2}{\mathrm{d}x^2}+mgx\right)\psi=E\psi$$





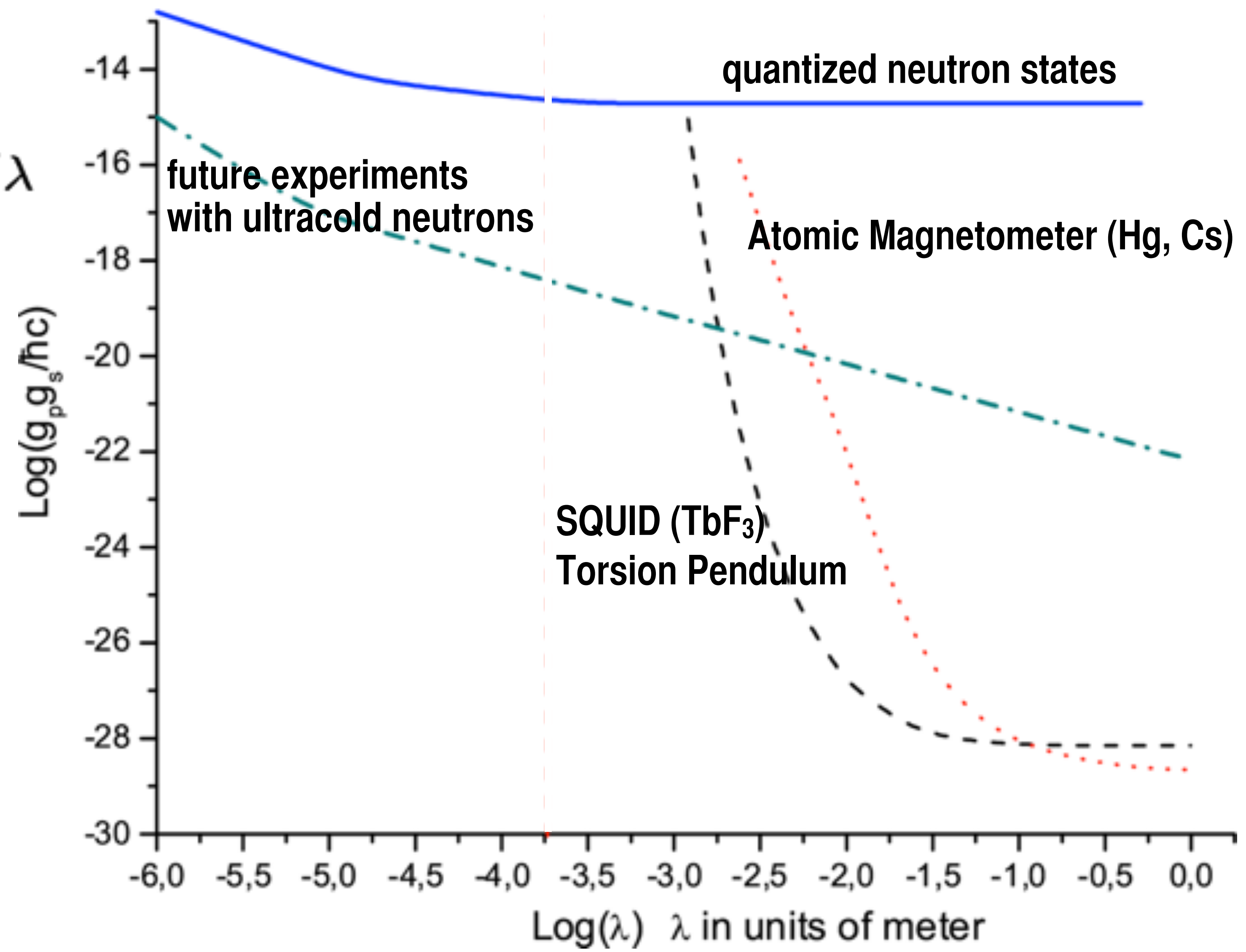


μm resolution efficient detector

4. Medium-range Force (not only gravity)

axion search

$$U(r) = \frac{\hbar g_p g_s}{8\pi mc}\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right) e^{-r/\lambda}$$



5. B, B-L violation

B, L are probably not conserved.

No evidence that either B or L is locally conserved like Q: where is the macroscopic B/L force? (not seen in equivalence principle tests).

Baryon Asymmetry of Universe (BAU) is not zero. If B(t=after inflation)<<BAU (otherwise inflation is destroyed, Dolgov/Zeldovich), we need B violation.

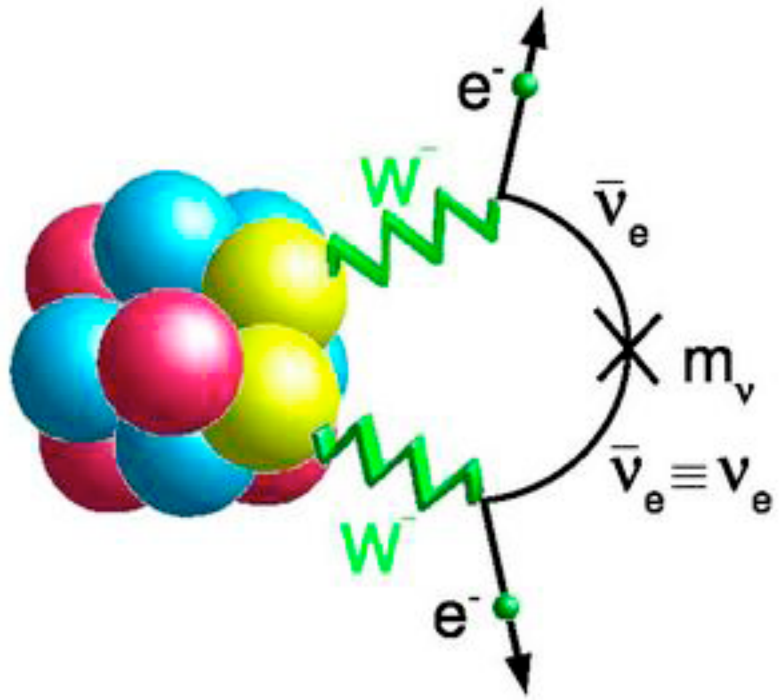
Both B and L conservation are “accidental” global symmetries: given SU(3)⊗SU(2)⊗U(1) gauge theory and matter content, no dimension-4 term in Standard Model Lagrangian violates B or L in perturbation theory.

Nonperturbative EW gauge field fluctuations (sphalerons) present in SM, VIOLATE B, L, B+L, but conserve B-L. Very important process for trying to understand the physics of the baryon asymmetry in the early universe

	nucleon decay	nnbar oscillation
B, L	$\Delta B=1, \Delta L=1$ $\Delta(B-L)=0$	$\Delta B=-2, \Delta L=0$ $\Delta(B-L)=-2$
effective operator	$L = \frac{g}{M^2} QQQL$	$L = \frac{g}{M^5} QQQ\overline{QQQ}$
mass-scale probed	GUT scale	> EW scale (<<GUT)

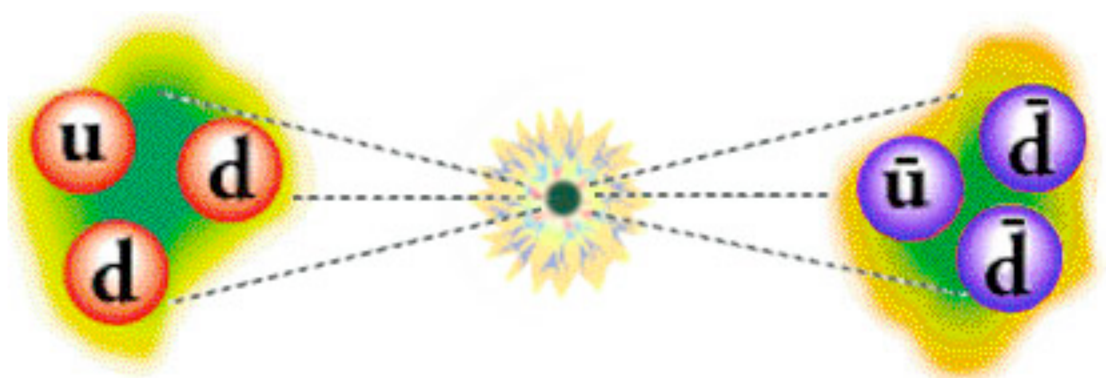
Neutrinoless Double Beta Decay (ΔB=0, ΔL=2 / Δ(B-L)=-2)

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

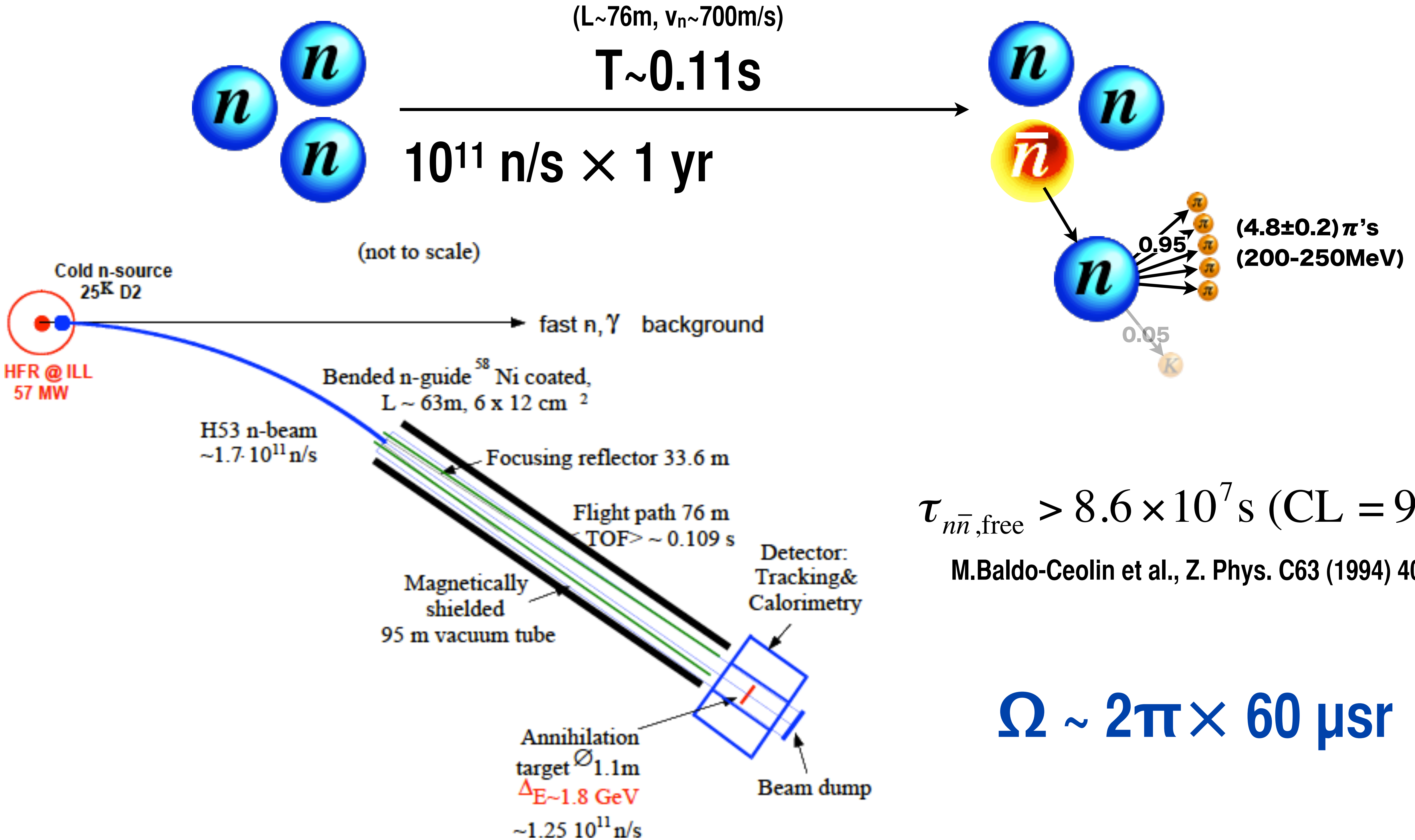


Neutron-Antineutron Oscillation (ΔB=-2, ΔL=0 / Δ(B-L)=-2)

$$n \leftrightarrow \bar{n}$$



Experimental Setup of ILL $n\bar{n}$ Experiment



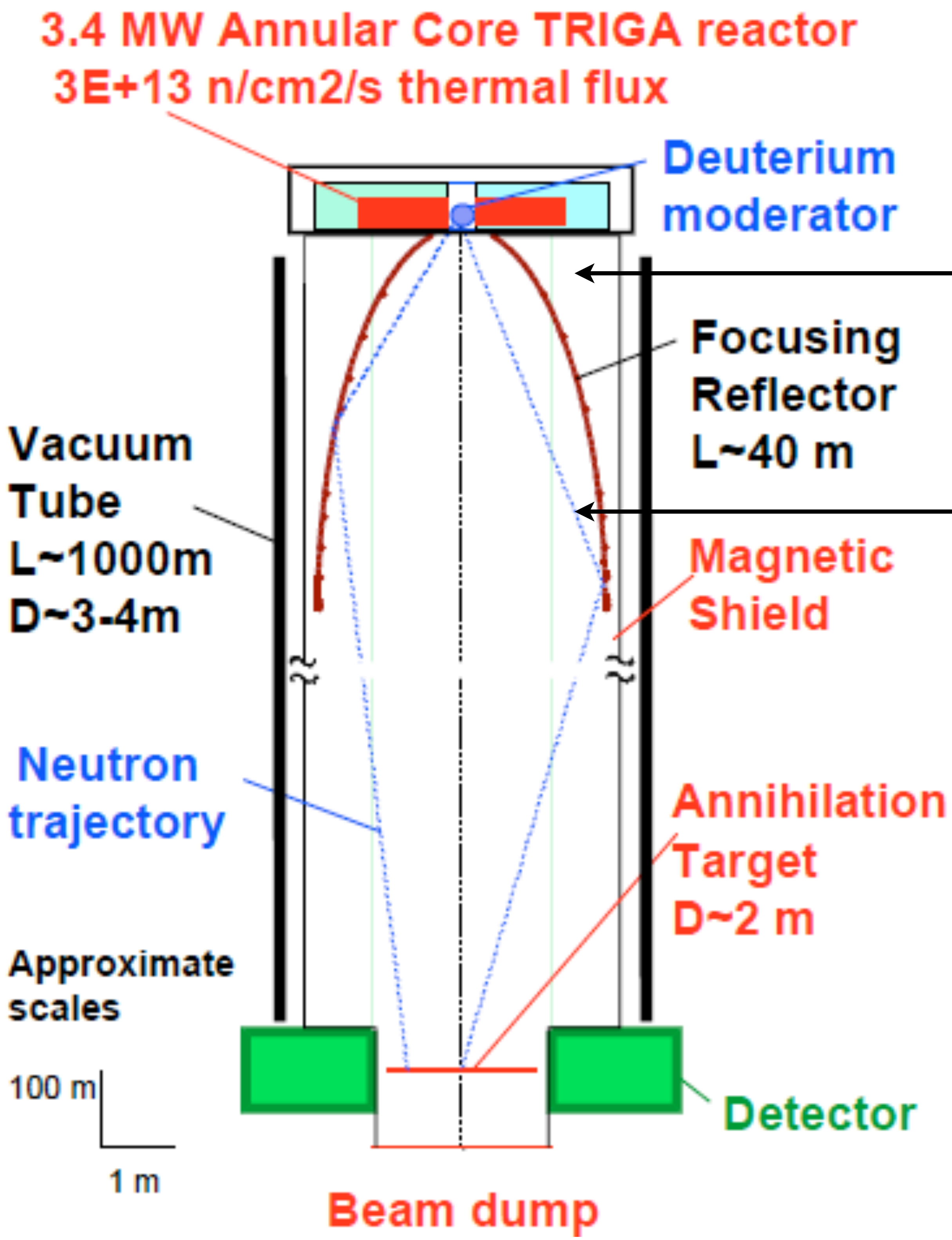
$$\tau_{n\bar{n},\mathrm{free}} > 8.6\times10^{7}\,\mathrm{s}\ (\mathrm{CL}=90\%)$$

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

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

5. B, B-L violation

Conceptual Scheme of Vertical Slow Neutron N-Nbar Experiment



acceptance is dominated here

reflection angle is well-defined
band reflector is applicable

T~1s

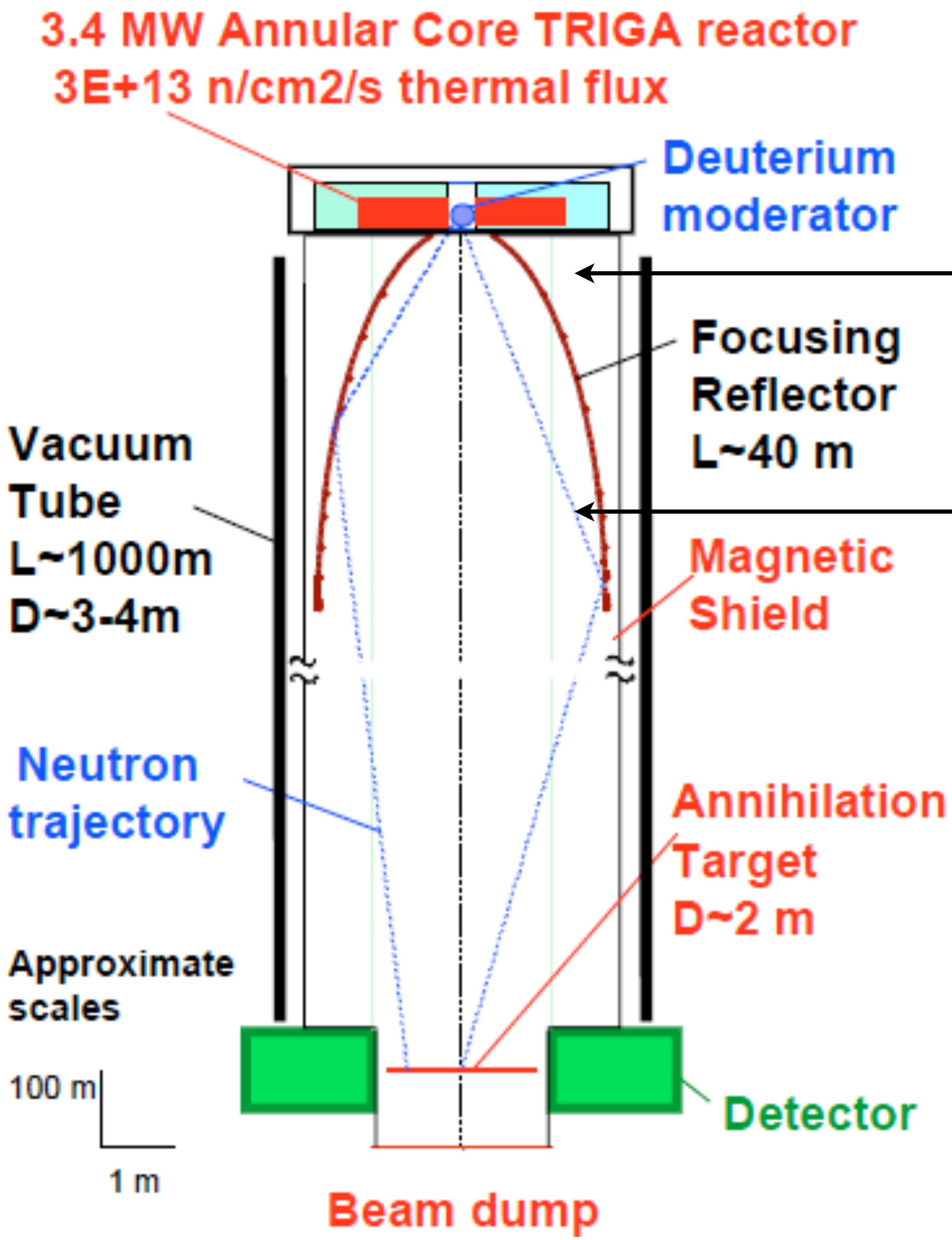
$\Omega \sim 2\pi \times 10$ msr

10^3-10^4 improvement is possible
by scale-up of existing technologies

$\tau_{nn} \sim 10^{10}$ s

5. B, B-L violation

Conceptual Scheme of Vertical Slow Neutron N-Nbar Experiment



acceptance is dominated here

reflection angle is well-defined
band reflector is applicable

$T \sim 1s$

$\Omega \sim 2\pi \times 10$ msr

10^3-10^4 improvement is possible
by scale-up of existing technologies

$\tau_{nn} \sim 10^{10}$ s

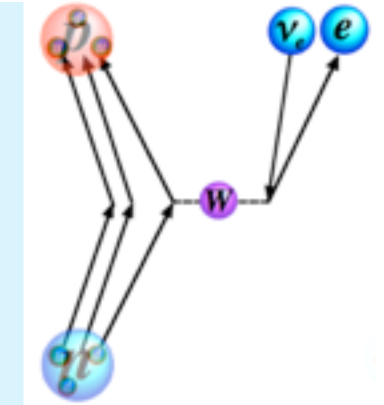
1. Overview
2. Lifetime
3. T-violation (CP-violation)
4. Medium-range Force (Gravity)
5. etc (B,B-L violation)

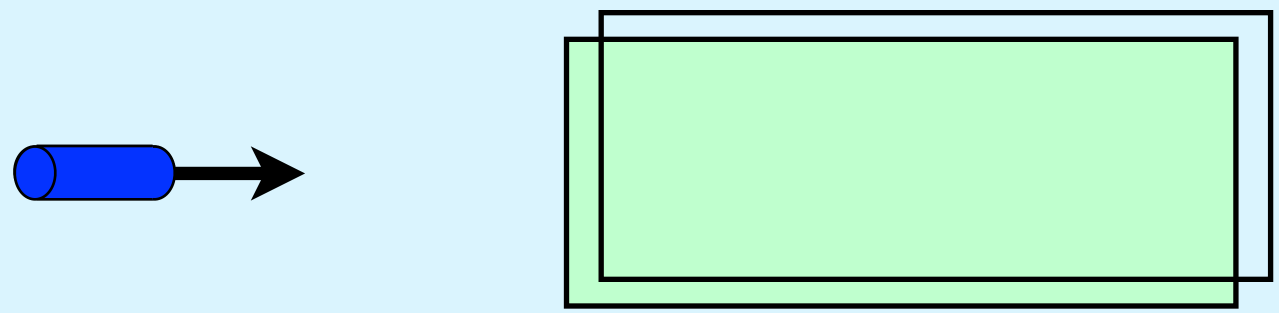
BL05 Neutron for Optics and Physics

Neutron Lifetime

In-beam measurement with pulsed neutrons

Well-defined bunch + Time Projection Chamber





pulse shape can be defined by **Spin Flip Chopper**

measure only when the bunch is in **TPC**

incident flux is also measured in TPC with ^{3}He capture

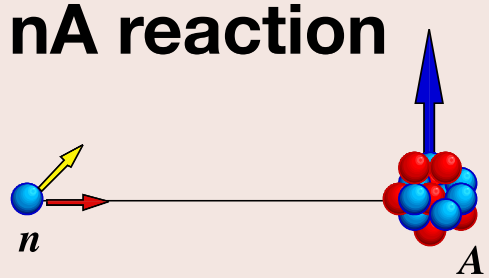
2013 Advanced Analysis -> Δτ~10s

SFC, TPC, DAQ upgrade for high flux

2014 Physics run for Δτ~1s

CP Violation

Enhancement in nA reaction



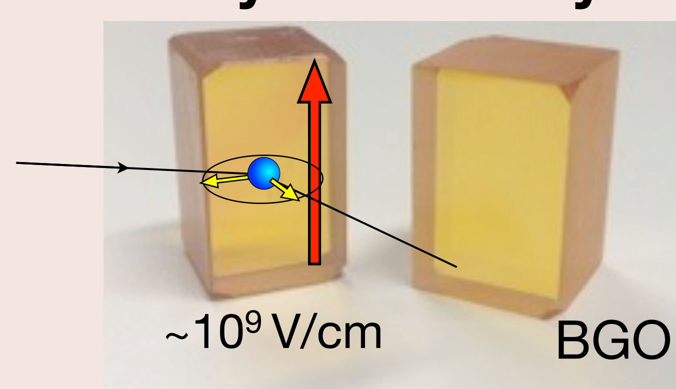
asymmetry <-> nEDM

$$|\Delta\sigma_T^{nA}| < 2.5\times10^{-4}[\mathrm{b}]\times\kappa(J)$$

10^{-27}ecm equiv. / yr (*κ*=1)

n, target polarization required

EDM measurement with noncentrosymmetric crystal

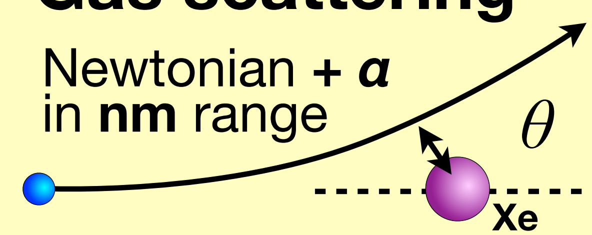


measure spin precession in high voltage

Gravity

Gas scattering

Newtonian + ***α*** in **nm** range



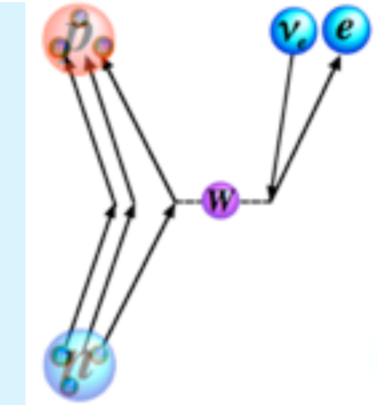
Interference

Newtonian + ***α*** in **μm** range

Neutron Beam Splitter

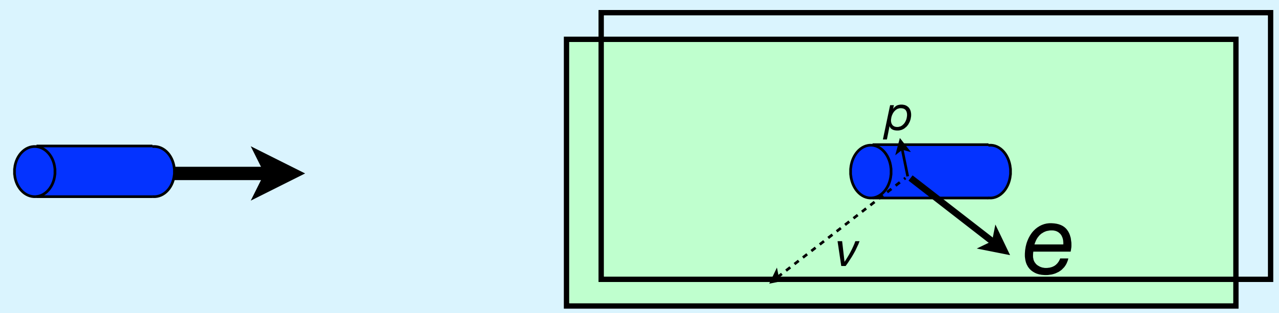
BL05 Neutron for Optics and Physics

Neutron Lifetime



In-beam measurement with pulsed neutrons

Well-defined bunch + Time Projection Chamber



pulse shape can be defined by **Spin Flip Chopper**

measure only when the bunch is in **TPC**

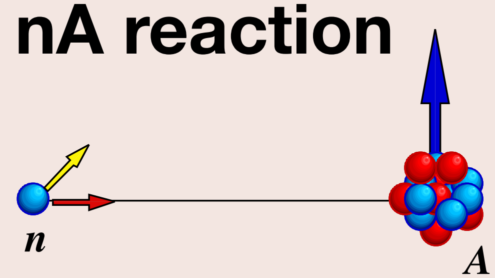
incident flux is also measured in TPC with ^{3}He capture

2013 Advanced Analysis -> Δτ~10s
SFC, TPC, DAQ upgrade for high flux

2014 Physics run for Δτ~1s

CP Violation

Enhancement in nA reaction



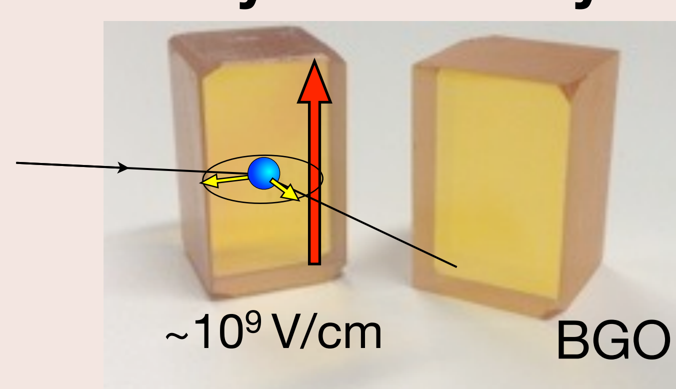
asymmetry <-> nEDM

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

10^{-27}ecm equiv. / yr (*κ*=1)

n, target polarization required

EDM measurement with noncentrosymmetric crystal

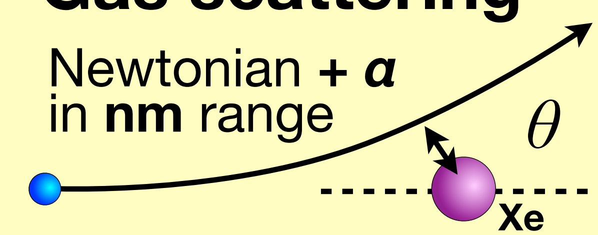


measure spin precession in high voltage

Gravity

Gas scattering

Newtonian + ***α*** in **nm** range



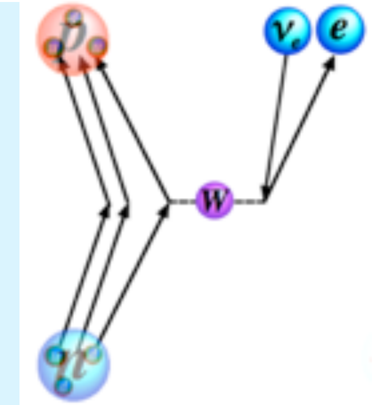
Interference

Newtonian + ***α*** in **μm** range

Neutron Beam Splitter

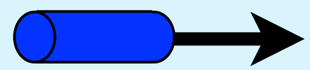
BL05 Neutron for Optics and Physics

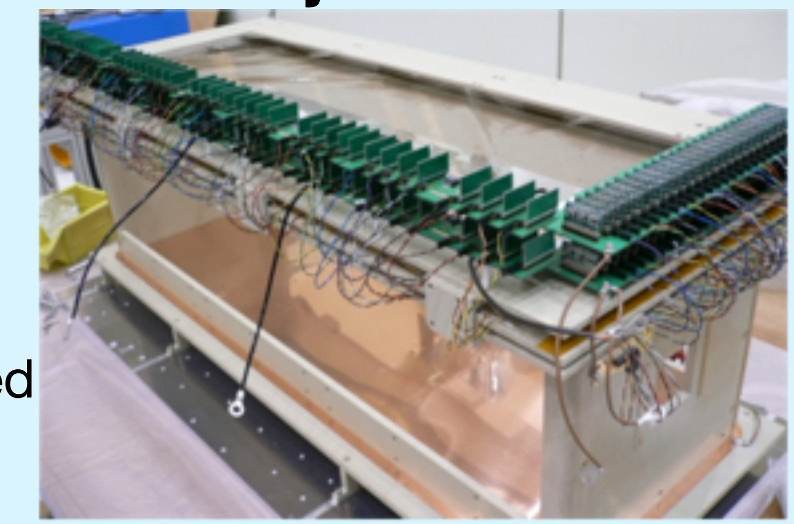
Neutron Lifetime



In-beam measurement with pulsed neutrons

Well-defined bunch + Time Projection Chamber





pulse shape can be defined by **Spin Flip Chopper**

incident flux is also measured in TPC with ^{3}He capture

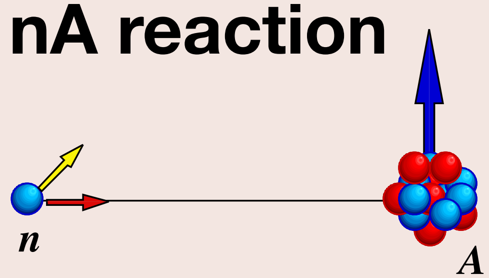
2013 Advanced Analysis -> Δτ~10s

SFC, TPC, DAQ upgrade for high flux

2014 Physics run for Δτ~1s

CP Violation

Enhancement in nA reaction



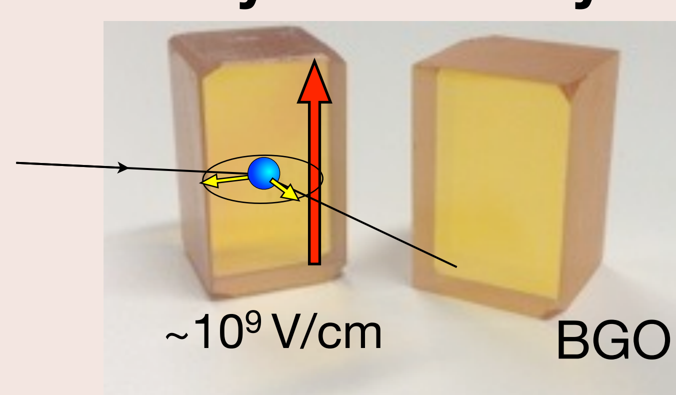
asymmetry <-> nEDM

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

10^{-27}ecm equiv. / yr (*κ*=1)

n, target polarization required

EDM measurement with noncentrosymmetric crystal

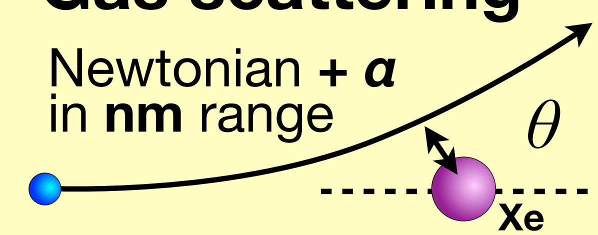


measure spin precession in high voltage

Gravity

Gas scattering

Newtonian + ***α*** in **nm** range



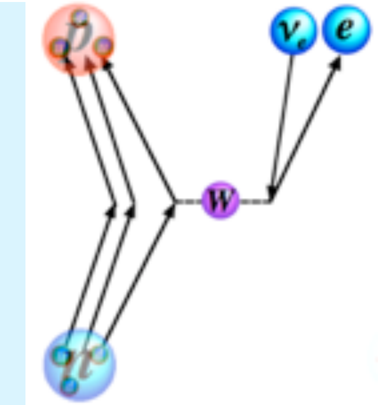
Interference

Newtonian + ***α*** in **μm** range

Neutron Beam Splitter

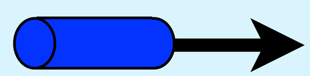
BL05 Neutron for Optics and Physics

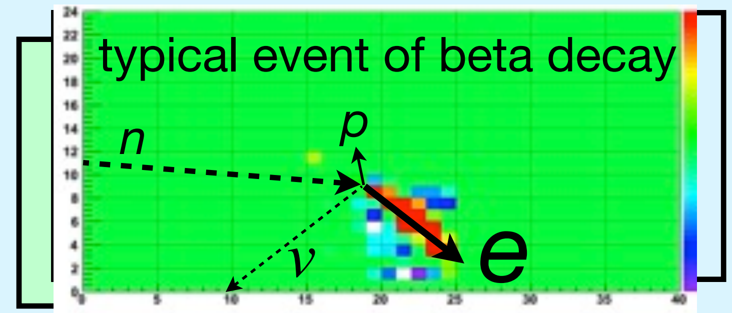
Neutron Lifetime



In-beam measurement with pulsed neutrons

Well-defined bunch + Time Projection Chamber





pulse shape can be defined by **Spin Flip Chopper**

measure only when the bunch is in **TPC**

incident flux is also measured in TPC with ^{3}He capture

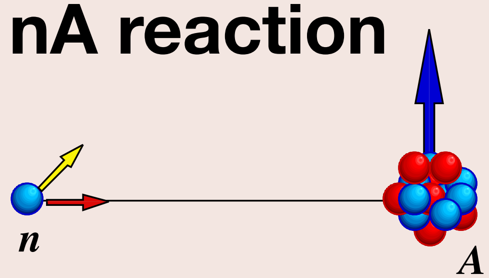
2013 Advanced Analysis -> Δτ~10s

SFC, TPC, DAQ upgrade for high flux

2014 Physics run for Δτ~1s

CP Violation

Enhancement in nA reaction



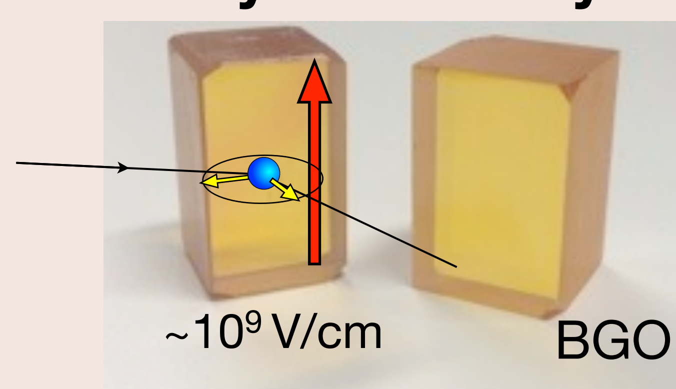
asymmetry <-> nEDM

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

10^{-27}ecm equiv. / yr (κ=1)

n, target polarization required

EDM measurement with noncentrosymmetric crystal

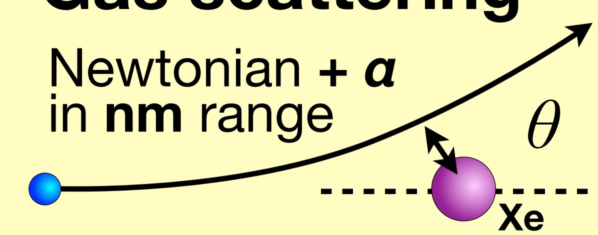


measure spin precession in high voltage

Gravity

Gas scattering

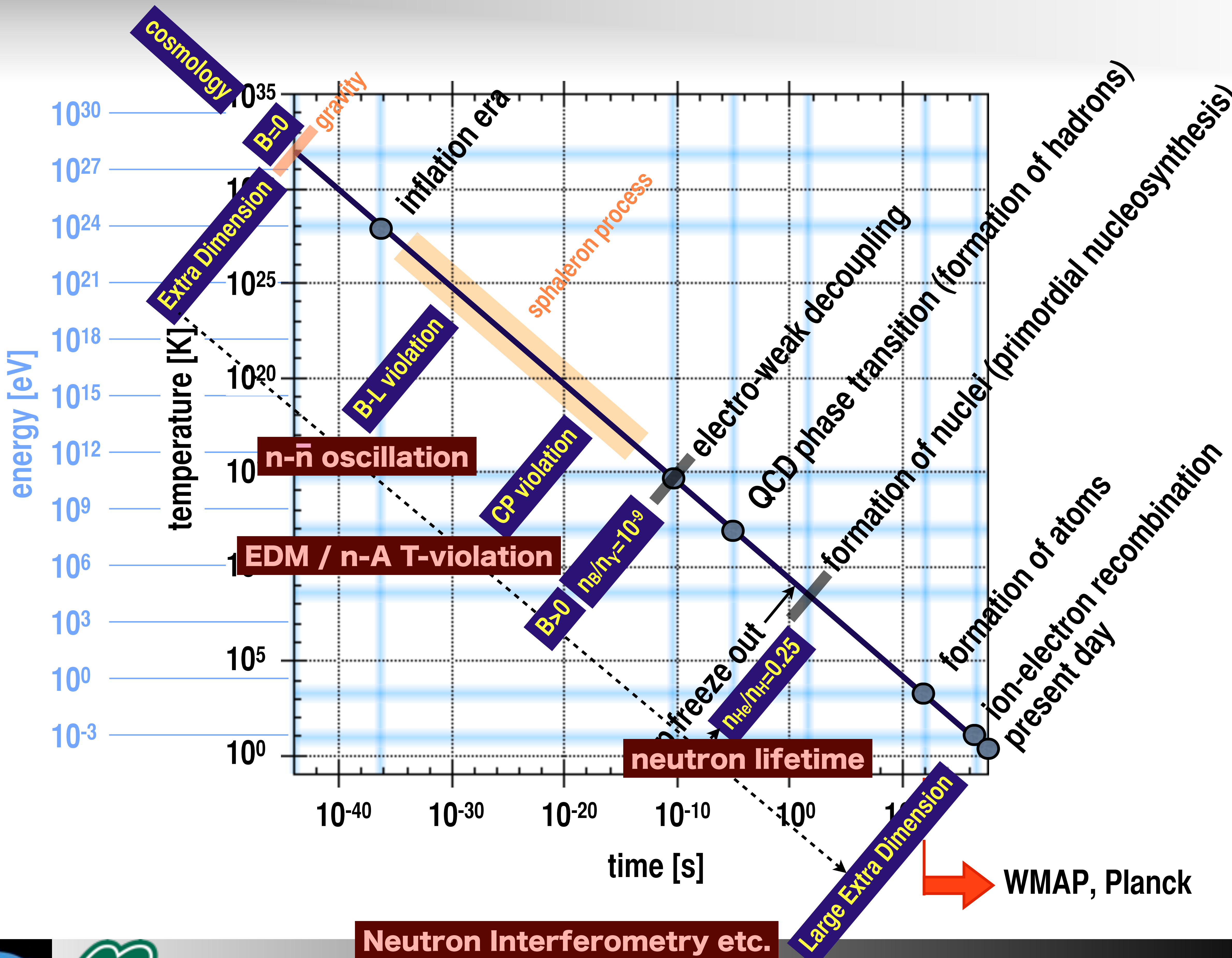
Newtonian + ***α*** in **nm** range



Interference

Newtonian + ***α*** in **μm** range

Neutron Beam Splitter


cosmology
gravity
B=0
inflation era
Extra Dimension
sphaleron process
B-L violation
electro-weak decoupling
QCD phase transition (formation of hadrons)
formation of nuclei (primordial nucleosynthesis)
n-n̄ oscillation
CP violation
EDM / n-A T-violation
n_B/n_γ~10^{-9}
B>0
n freeze out
n_{He}/n_H=0.25
formation of atoms
ion-electron recombination
present day
neutron lifetime
Large Extra Dimension
WMAP, Planck
energy [eV]
temperature [K]
time [s]
10^{30}
10^{27}
10^{24}
10^{21}
10^{18}
10^{15}
10^{12}
10^{9}
10^{6}
10^{3}
10^{0}
10^{-3}
10^{35}
10^{25}
10^{20}
10^{5}
10^{0}
10^{-40}
10^{-30}
10^{-20}
10^{-10}
10^{0}
Neutron Interferometry etc.