Ultracold neutron project

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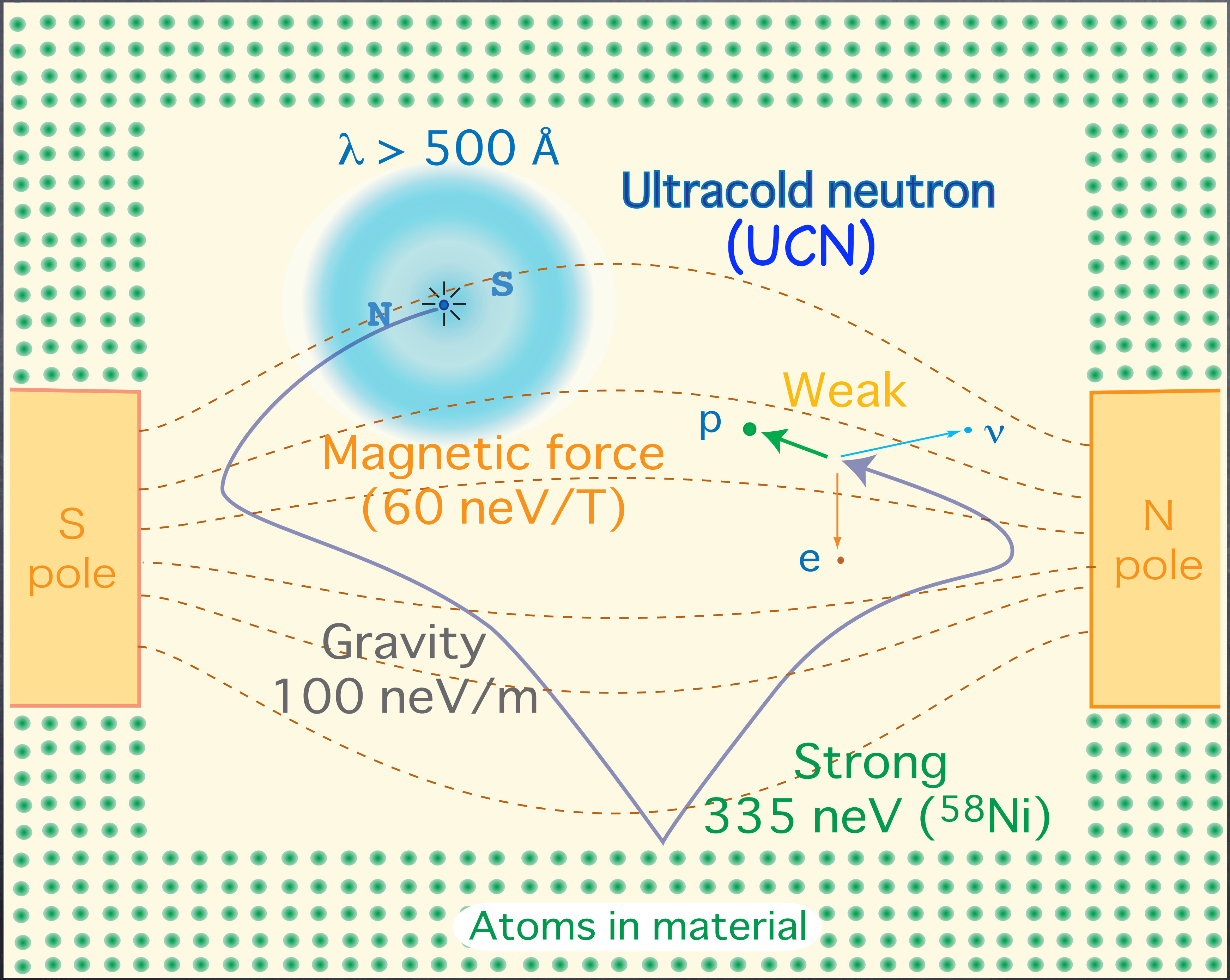
Neutron confinement



UCN physics

Neutron is a fundamental element in the universe

Creation of matter and nucleosynthesis
in the universe can be studied

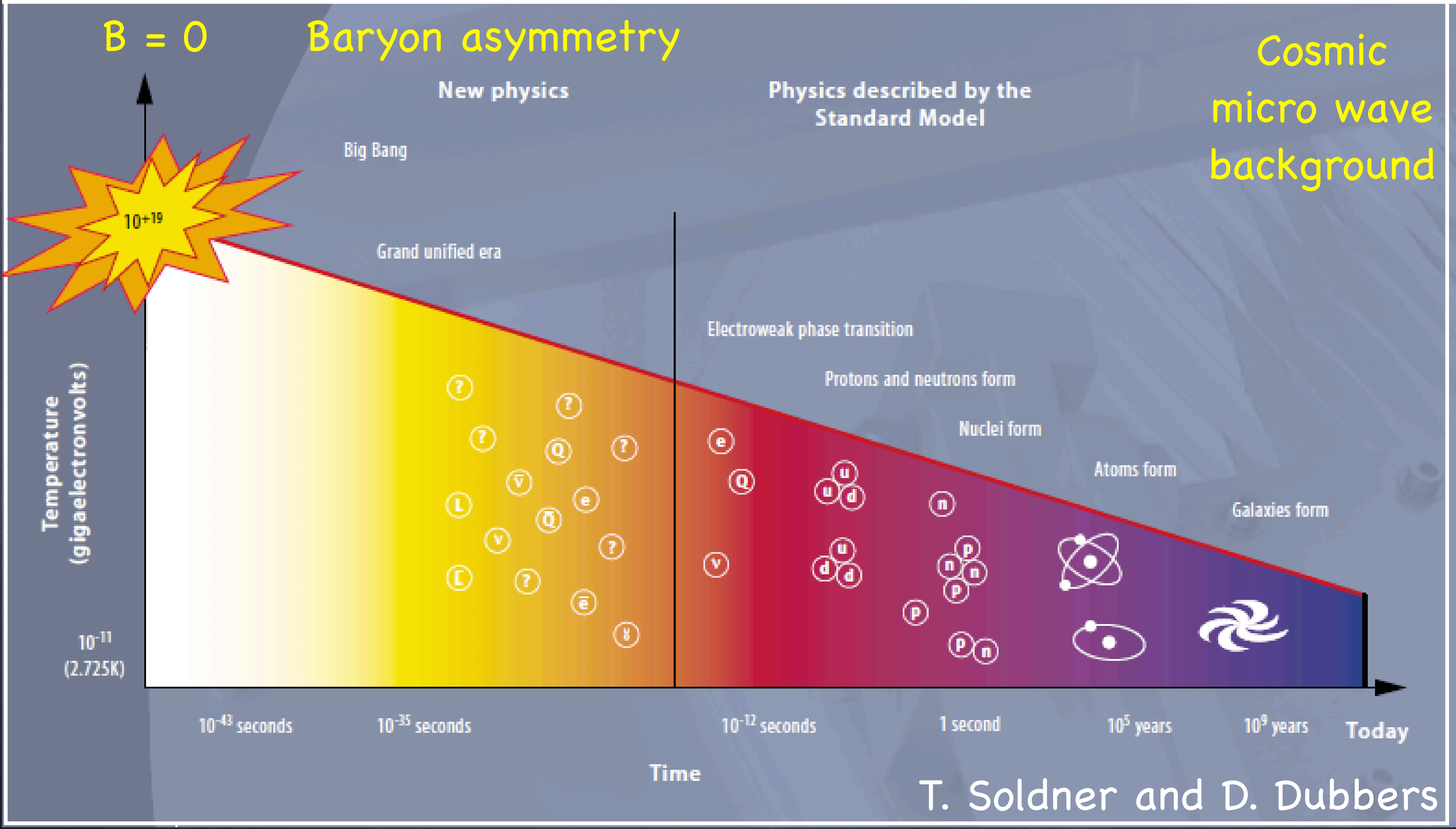
via experiments on

1. EDM: CP violation
2. N-Nbar oscillation
3. n beta decay: lifetime and asymmetry
4. gravity
5. neutron target

Big bang

10^{15} GeV ~ 100 GeV

Creation of matter



B = 0

Baryon asymmetry

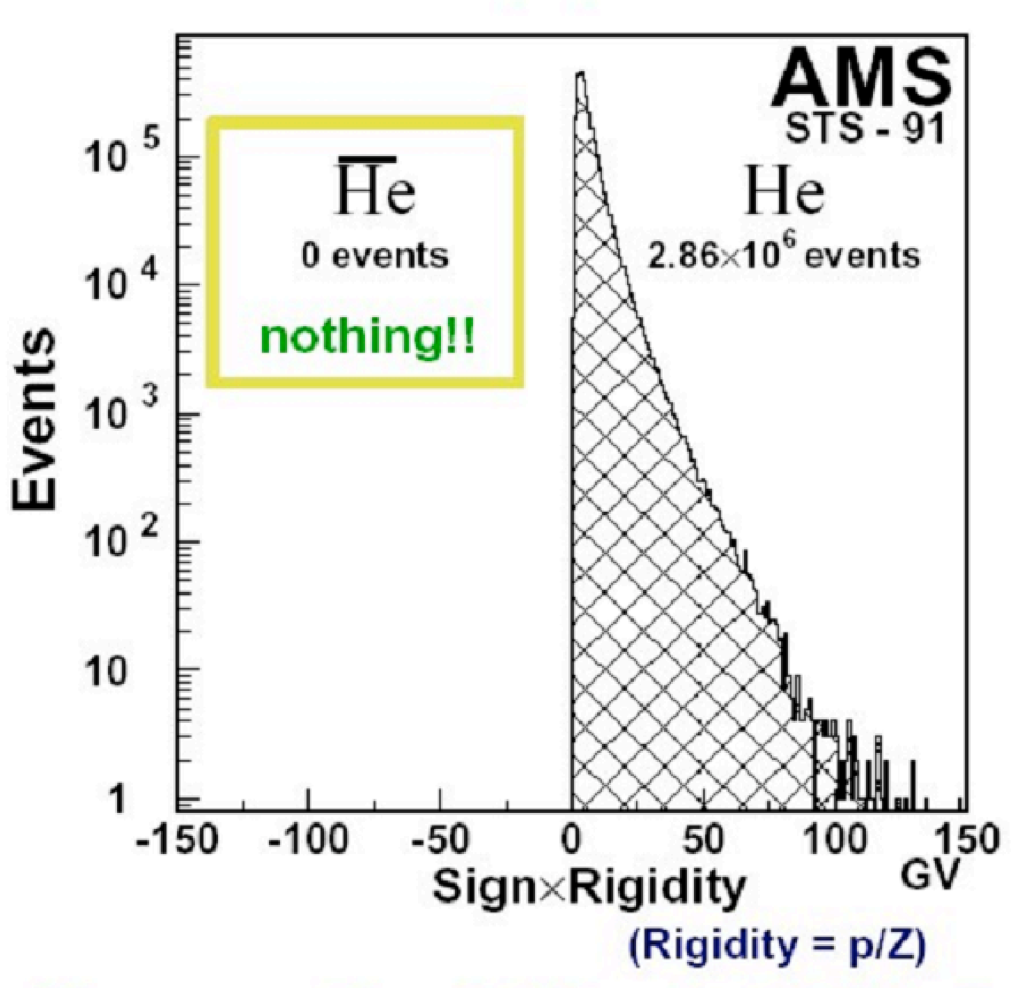
Cosmic micro wave background

T. Soldner and D. Dubbers

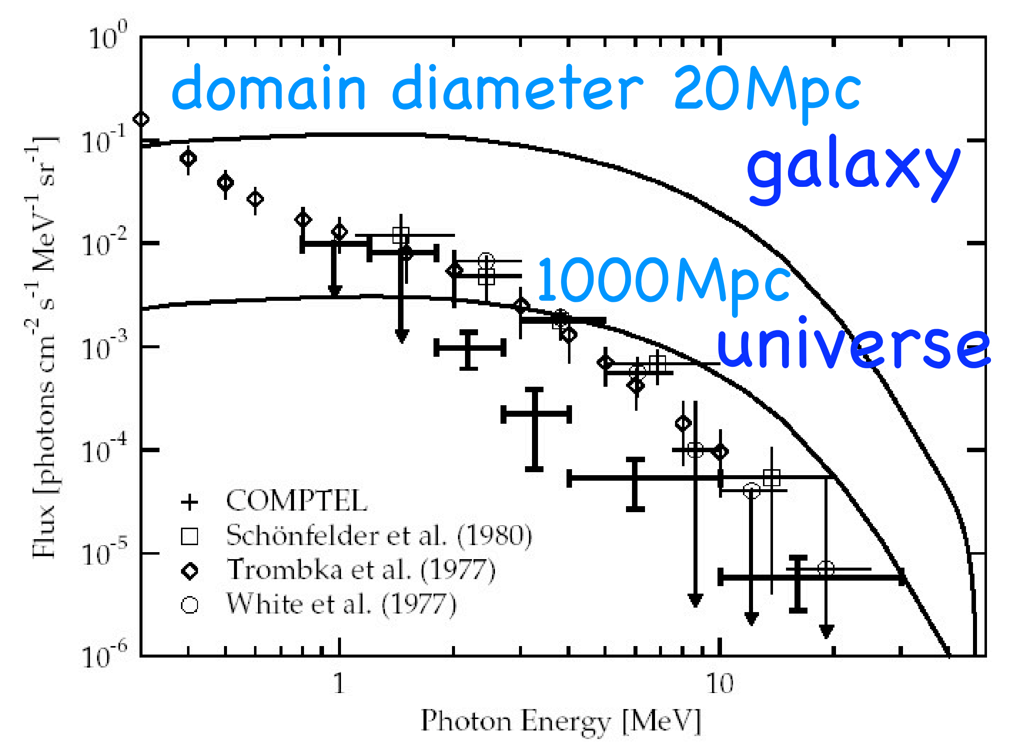
Sakharov’s condition

- Baryon number violation
- Departure from thermal equilibrium
- CP violation and C violation

No antimatter is observed



"Search for antihelium in cosmic rays"
Phys. Lett. B461 (1999) 387.



Diffuse γ flux from
annihilation at domain boundary
Astrophysical J. 495(1998)539

Extension of standard model

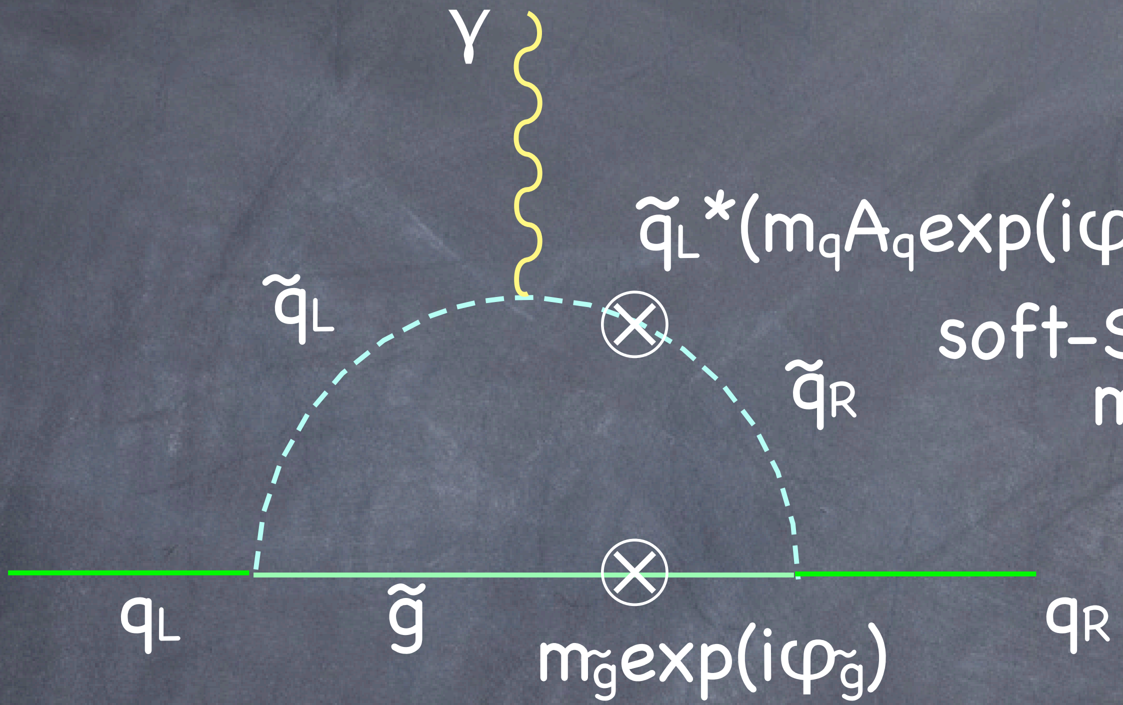
- Baryon asymmetry: $(N_B - N_{antiB})/N_\gamma \sim 10^{-10}$,

  but 10^{-25} in standard model

- SUSY

Explain the baryon asymmetry of 10^{-10}
Solve hierarchy problem
Include quantum gravity

EDM in SUSY



$\tilde{q}_L{}^*(m_q A_q \exp(i\varphi_{Aq}))\tilde{q}_R$ + h.c.

soft-SUSY-breaking
mass term

Barr 1993, Fortson, Sanders, Barr 2003

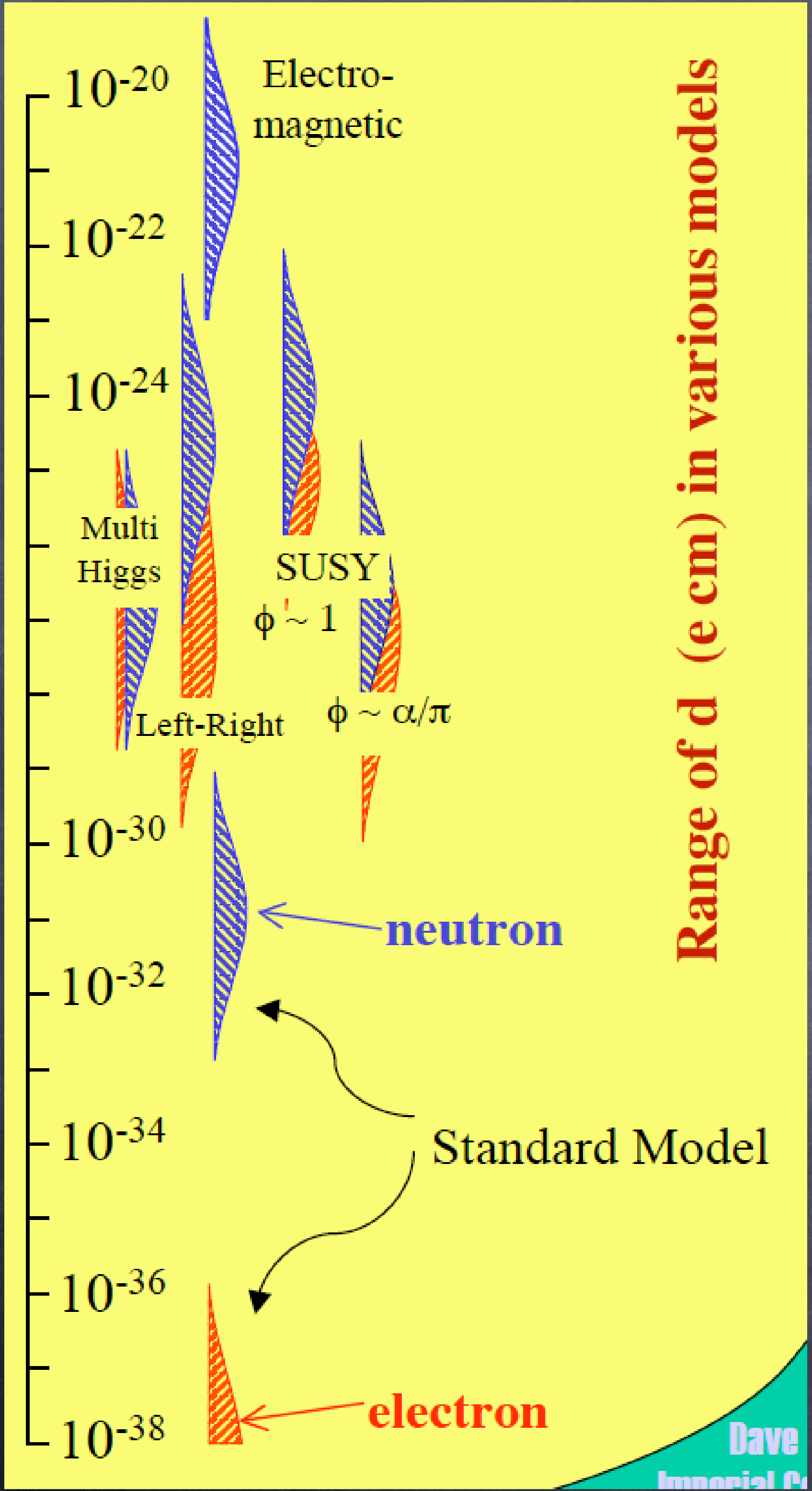
[Weinburg 1989: 1. EDM operator of $d_n\bar{\psi}\gamma_5\sigma_{\mu\nu}\psi F^{\mu\nu}$, 2. dimensional analysis (Manohar and Georgi 1984), 3. renormalization factor]

$$d_q = eQ(\alpha_s/18\pi)m_q\,|A_q/m_{\tilde{g}}{}^3|\,\sin(\varphi_{Aq}-\varphi_{\tilde{g}})\ f$$

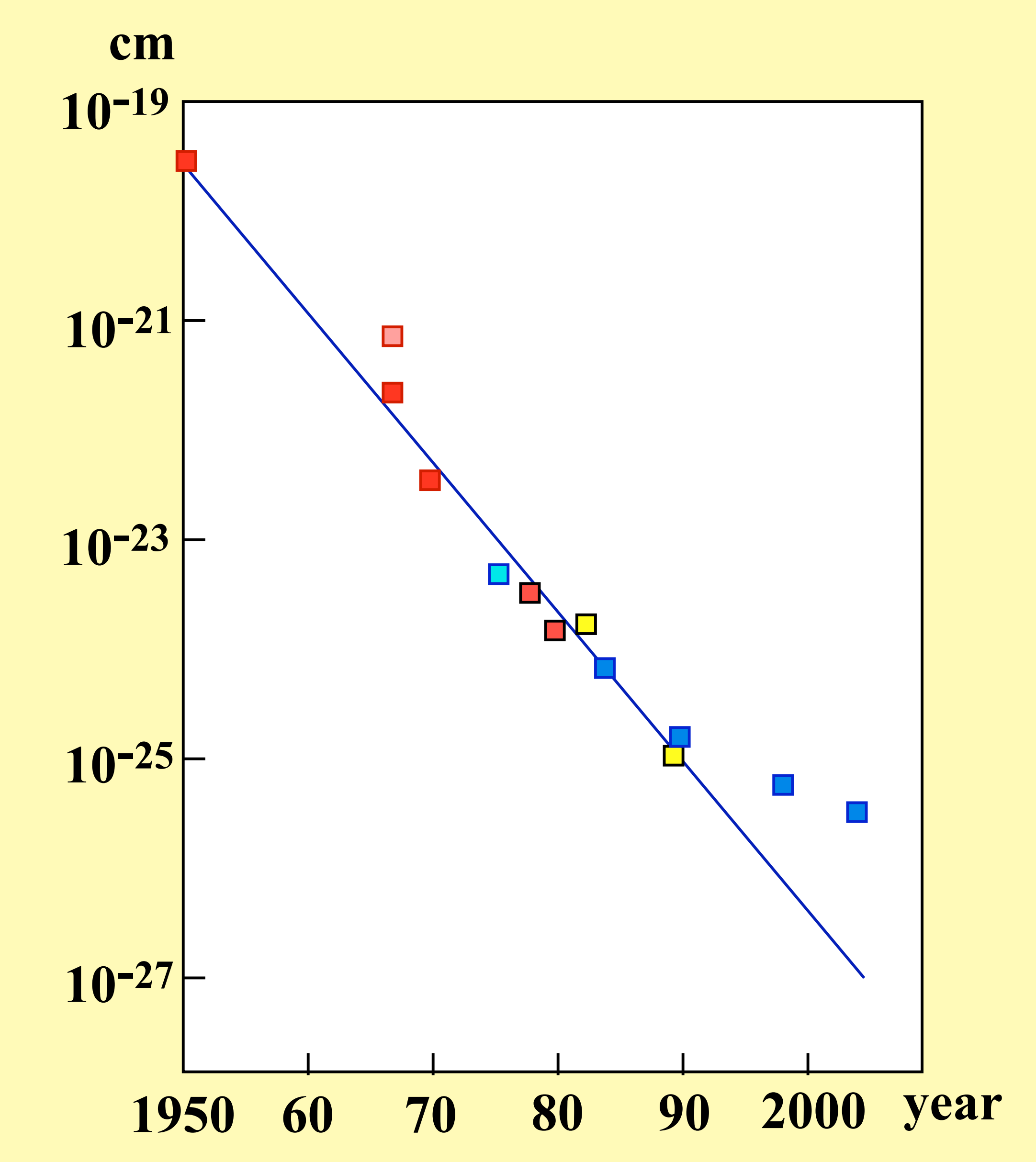
$$d_n \sim \epsilon_q\times(2.4\times10^{-24}\ e\cdot\mathrm{cm}),\ \epsilon_q\sim\sin(\varphi_{Aq}-\varphi_{\tilde{g}})$$

EDM

Theory



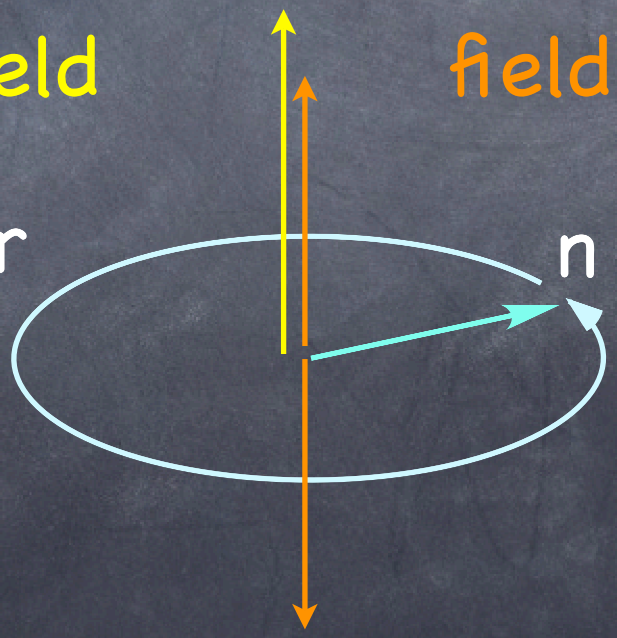
Experiment



EDM measurement

$$\mathcal{H} = -(\mu H + d_n E)$$

dynamical phase is measured
by means of a polarimetry



Magnetic
field

Electric
field

n spin

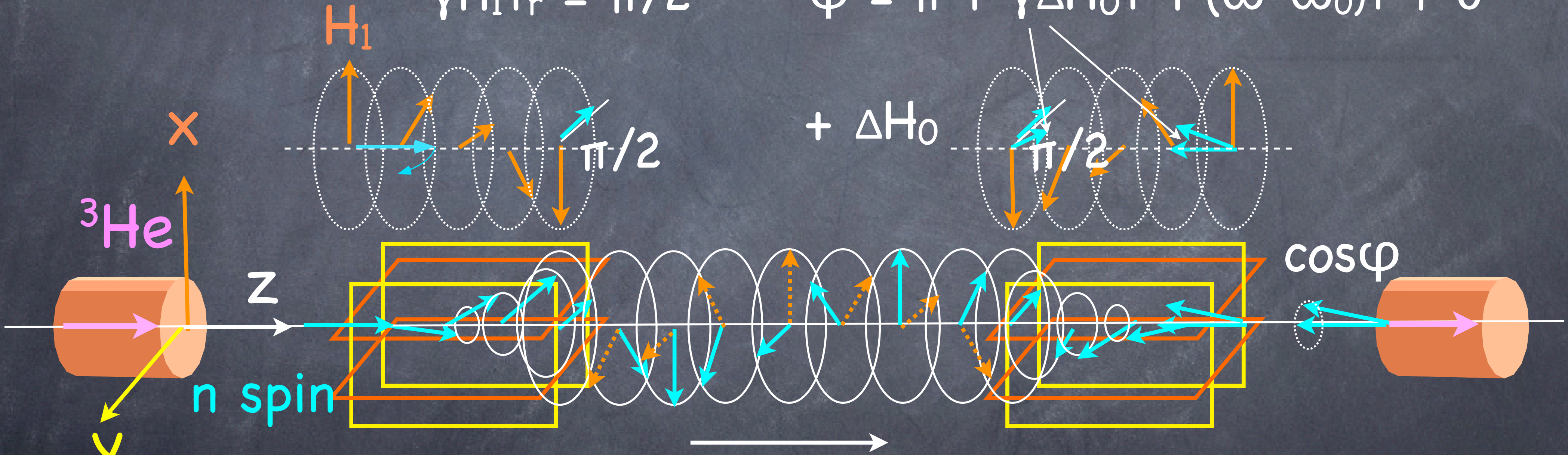
Comagnetometer
^{3}He spin
and SQUID

Ramsey resonance

Phys. Lett. A in press, available online 8 Dec. 2006

$\gamma H_1 t_r = \pi/2$

$\varphi = \pi + \gamma \Delta H_0 t + (\omega - \omega_0)t + \theta$

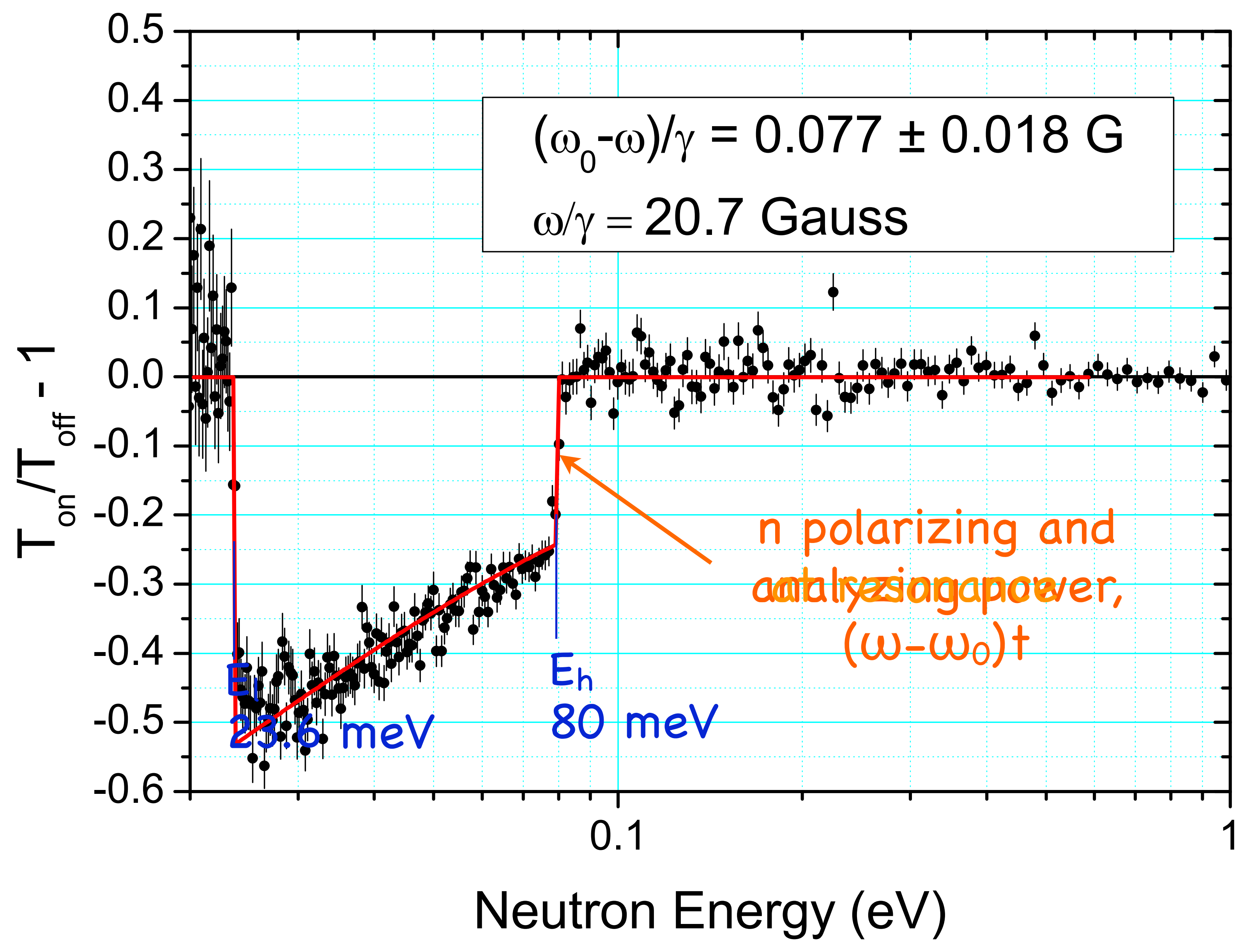


H_0 $(\omega_0 = \gamma H_0)$

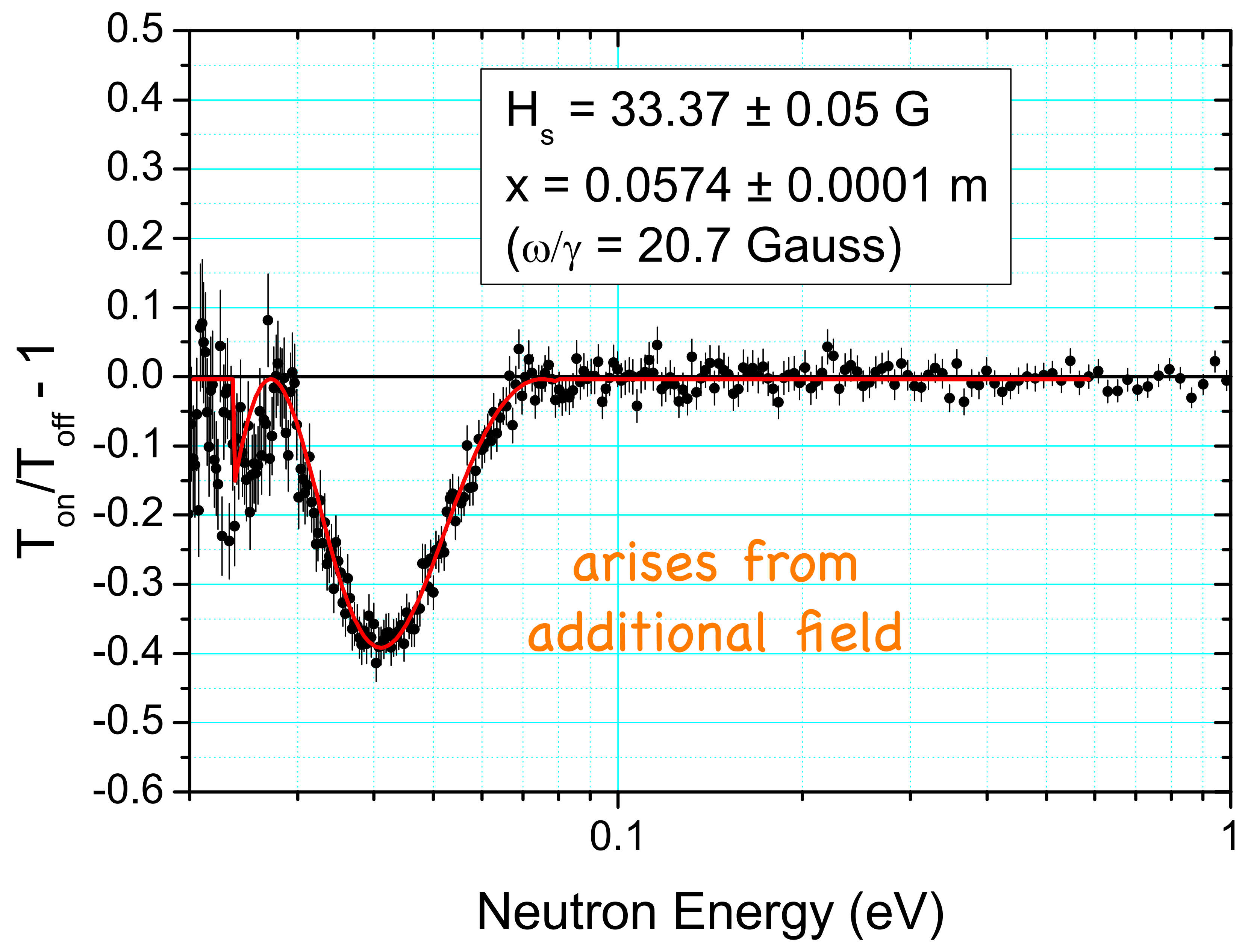
Rotating field
$H_1 \cdot x \cdot \cos\omega t_r + H_1 \cdot y \cdot \sin\omega t_r$
$\omega = \omega_0$

H_1 rotations and
Larmor precession
are coherent

Results for $\varphi = \pi + (\omega - \omega_0)t$



$\varphi = \pi + \gamma \Delta H_0 t$



arises from additional field

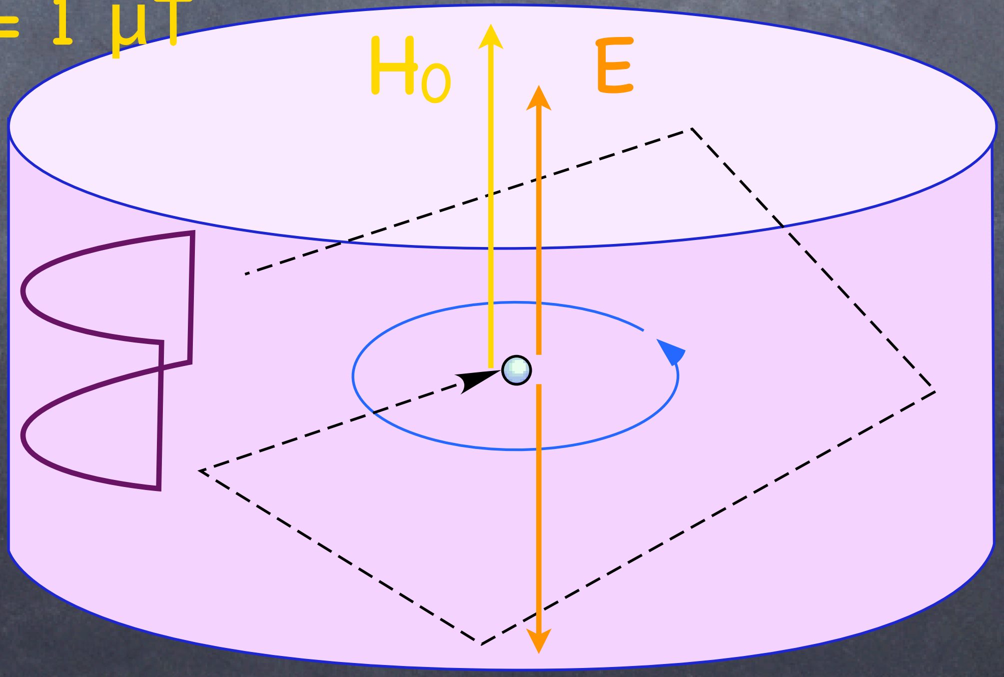
EDM with UCN

UCN can be confined in a bottle
long precession time in E

$\exp(-i\mu H_0/\hbar \cdot t)$

$\partial H_0/\partial z < 1$ nT/m
at $H_0 = 1$ μT

$\exp(-i d_n E/\hbar \cdot t)$



pick up of
^{3}He precession
with SQUID

magnetometer

Precision EDM measurement

Comagnetometer for leakage current effect

Homogeneous field

$\delta d_n = \hbar/\{2Et_c\surd mN\}$

t_c: coherent time, N: number of n in EDM cell

m: number of measurement

$\delta d_n \sim 10^{-28}$ cm: SUSY, Multi-Higgs, Left-Right

$E = 50$ kV/cm, $t_c = 130$ s,

$\rho = 300$ UCN/cm^3 in 8L

N-Nbar

- Baryon asymmetry

If EW phase transition is 2nd order,

$\Delta|B - L| \neq 0$ at grand unified scale,
Kuzmin, Phys.Lett. (1985)

N-Nbar: $\Delta B = 2$, $\Delta L = 0$

Nucleon decay: $\Delta B = 1$, $\Delta L = 1$, $\Delta|B - L| = 0$

Some Δ(B–L)≠0 nucleon decay modes (PDG'04)

(B–L)≠0 modes	Limit at 90% CL	S/B	Experiment'year
$p \to \nu\nu e^+$	$>1.7\times10^{31}$ yr	152/153.7	IMB'99
$p \to \nu\nu\mu^+$	$>2.1\times10^{31}$ yr	7/11.23	Fréjus'91
$n \to e^+e^-\nu$	$>2.57\times10^{32}$ yr	5/7.5	IMB'99
$n \to \mu^+\mu^-\nu$	$>7.9\times10^{31}$ yr	100/145	IMB'99
$n \to \nu\nu\bar{\nu}$	$>1.9\times10^{29}$ yr	686.8/656	SNO'04
$n \to \bar{n}$	$>7.2\times10^{31}$ yr	4/4.5	Soudan-II'02
$nn \to \nu\bar{\nu}$	$> 4.9\times10^{25}$ yr		Borexino'03

e.g. for $p \to \nu\nu e^+$ with a lifetime $>1.7\times10^{31}$ yr
Super-K should detect ~ 430 events/yr

$n \to e^+e^-\nu$ mode with highest limit

$n \to \nu\nu\bar{\nu}$ $\Delta B = -1$ mode with lowest limit

$nn \to \nu\bar{\nu}$ $\Delta B = -2$ mode with lowest limit

$n \to \bar{n}$ mode with highest future potential ?

Theories with $n \leftrightarrow \bar{n}$, no B-L=0 nucleon decay

$\tau_{N\text{-}Nbar}$ $10^9 \sim 10^{10}$ s

- Connection with neutrino mass physics via seesaw mechanism

K. Babu and R. Mohapatra, PLB 518 (2001) 269
B. Dutta, Y. Mimura, R. Mohapatra, PRL 96 (2006) 061801

- Connection to low quantum gravity scale ideas

G. Dvali and G. Gabadadze, PLB 460 (1999) 47
S. Nussinov and R. Shrock, PRL 88 (2002) 171601
C. Bambi et al., hep-ph/0606321

- Baryogenesis models at low-energy scale

A. Dolgov et al., hep-ph/0605263
K. Babu et al., hep-ph/0606144

Neutron-Antineutron Oscillations: Formalism

$(\alpha/\hbar)^2/[(\alpha/\hbar)^2 + \omega^2/4]\cdot\sin[(\alpha/\hbar)^2 + \omega^2/4]^{1/2}t$

α-mixing amplitude

$\Psi = \begin{pmatrix} n \\ \bar{n} \end{pmatrix}$ mixed n-nbar QM state

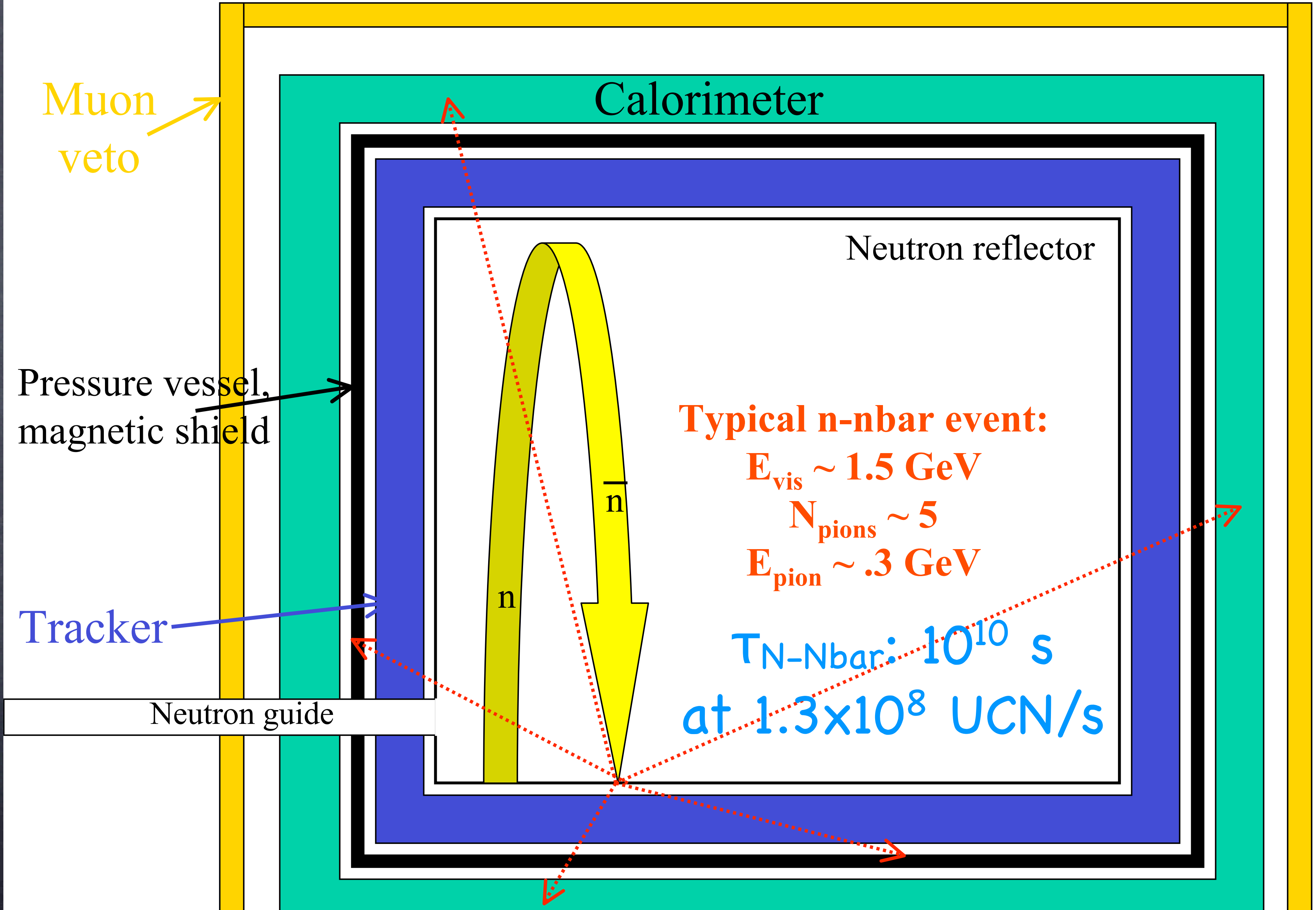
$H = \begin{pmatrix} E_n & \alpha \\ \alpha & E_{\bar{n}} \end{pmatrix}$ Hamiltonian of the system

$$E_n = m_n + \frac{p^2}{2m_n} + U_n \quad ; \quad E_{\bar{n}} = m_{\bar{n}} + \frac{p^2}{2m_{\bar{n}}} + U_{\bar{n}}$$

Important assumptions :

- $\alpha(n \to \bar{n}) = \alpha(\bar{n} \to n) = \alpha$ (i.e. T-invariance)
- $m_n = m_{\bar{n}}$ (CPT not violated)
- magnetic moment $\mu(\bar{n}) = -\mu(n)$ as follows from CPT

Possible apparatus for the "neutrons in the bottle" experiment



Typical n-nbar event:

$E_{vis} \sim 1.5$ GeV

$N_{pions} \sim 5$

$E_{pion} \sim .3$ GeV

$\tau_{N\text{-}Nbar}$: 10^{10} s

at 1.3×10^{8} UCN/s

Neutron β decay

- Lifetime

Nucleosynthesis at big bang: ^{4}He abundance etc.

p-p chain: $p + p \rightarrow D + e^+ + \nu_e$ ($n \rightarrow p + e^- + \nu_e$)

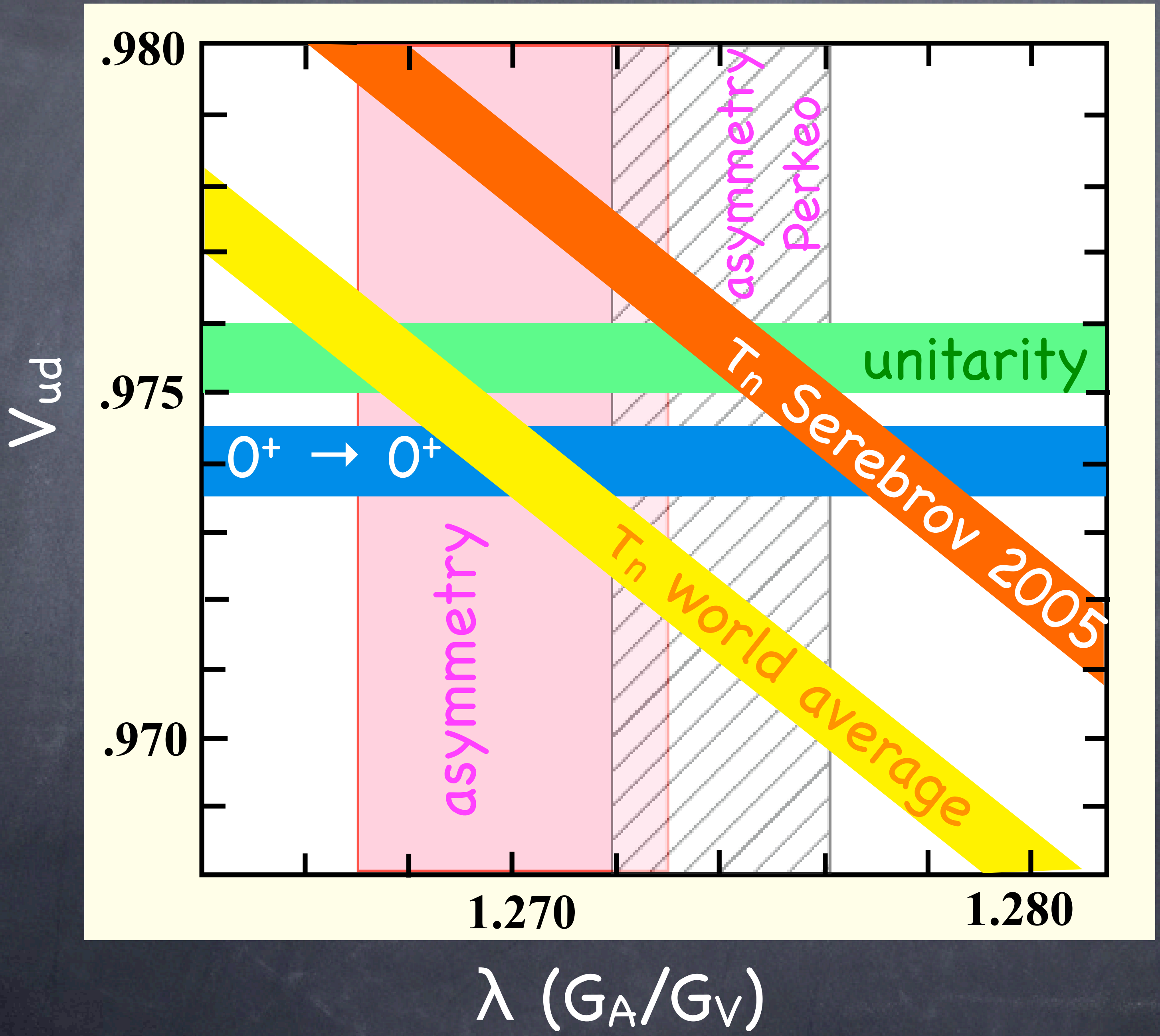
- Asymmetry + lifetime

G_V and G_A

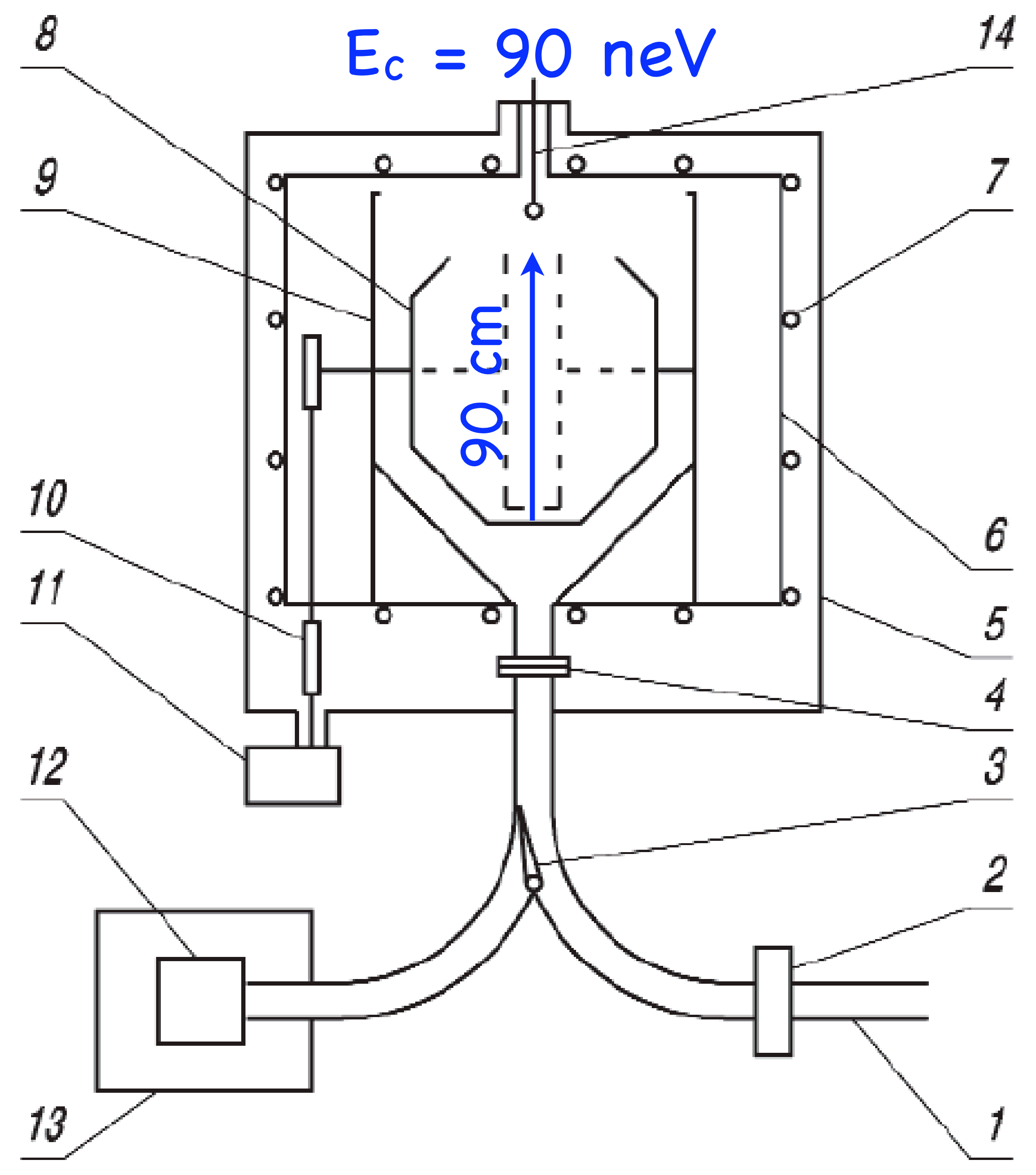
Unitarity: $G_V = G_F \cdot V_{ud}$

$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

G_V and G_A


.980
.975
.970
1.270
1.280
V_{ud}
λ (G_A/G_V)
unitarity
$0^+ \rightarrow 0^+$
τ_n Serebrov 2005
τ_n world average
asymmetry
asymmetry
Perkeo

n lifetime



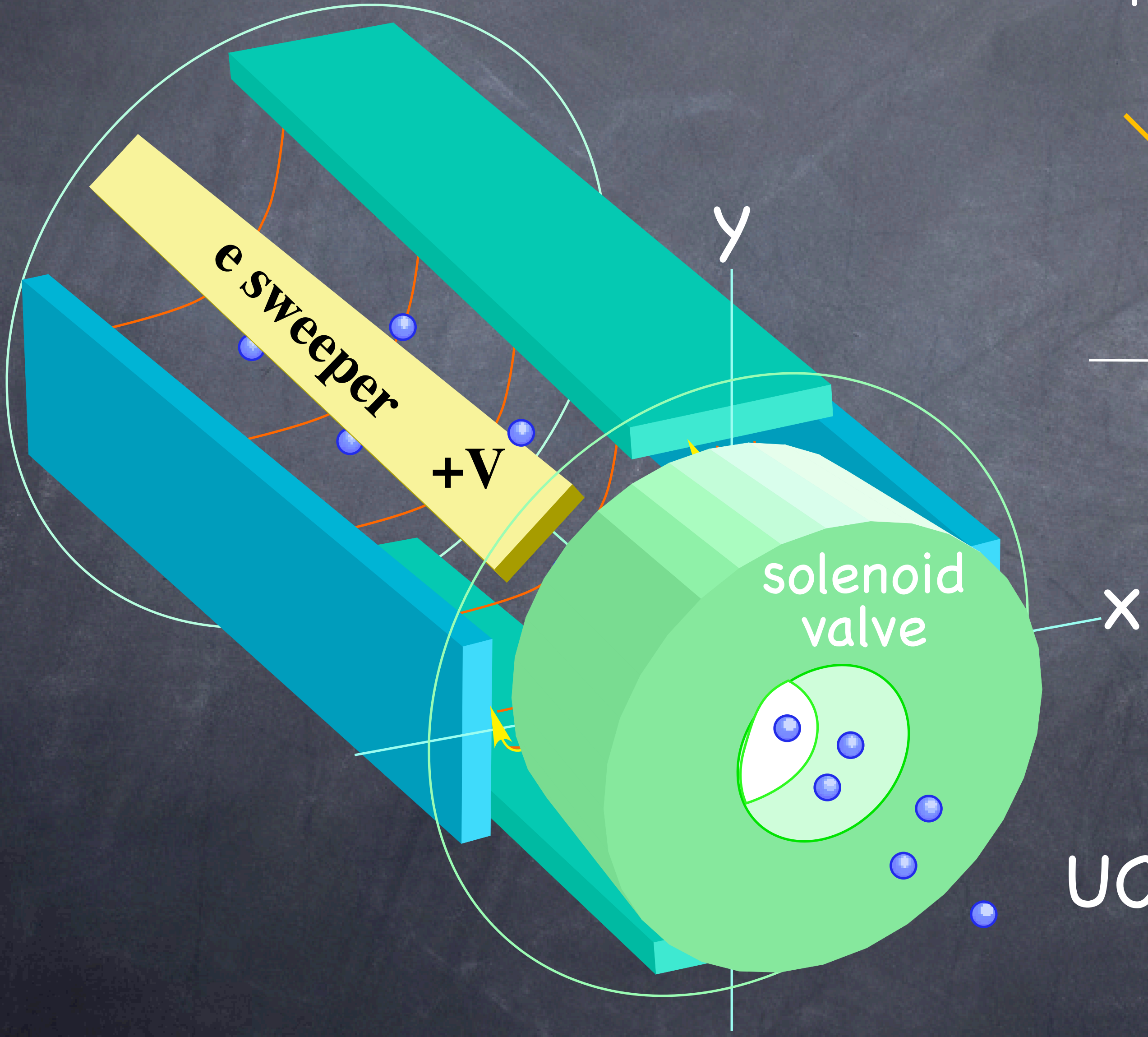
τ_n = 878.5 ± 0.8 s
Serebrov et. al,
Phys.Lett.B605(2005)72

7σ
difference

τ_n = 885.7 ± 0.8 s
PDG

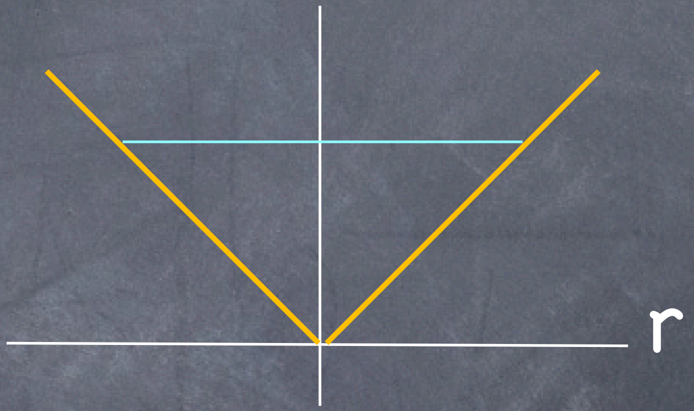
τ_n in a magnetic bottle

$\delta\tau_n/\tau_n \leq 10^{-4}$



UCN filling

magnetic potential

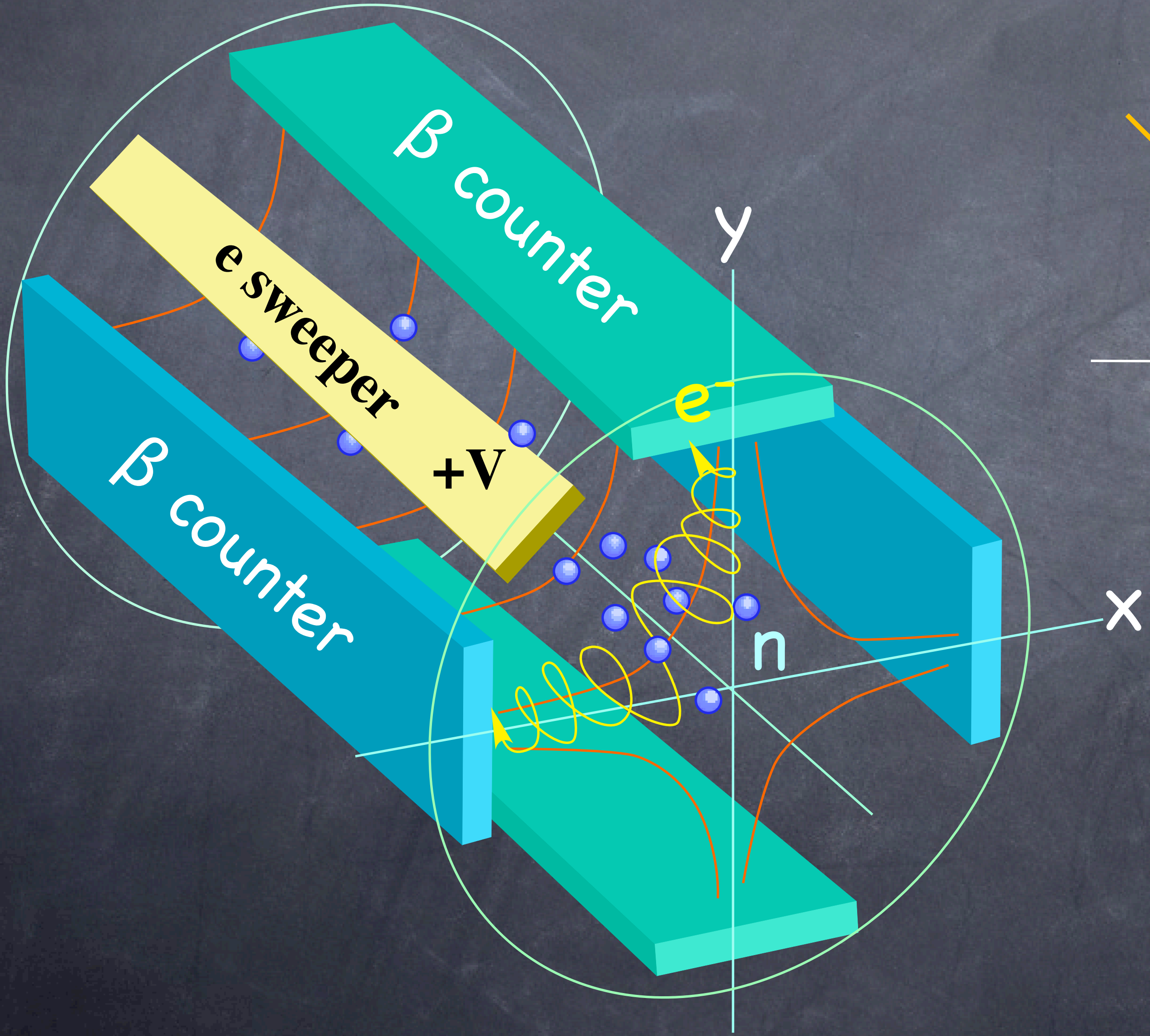


no wall loss

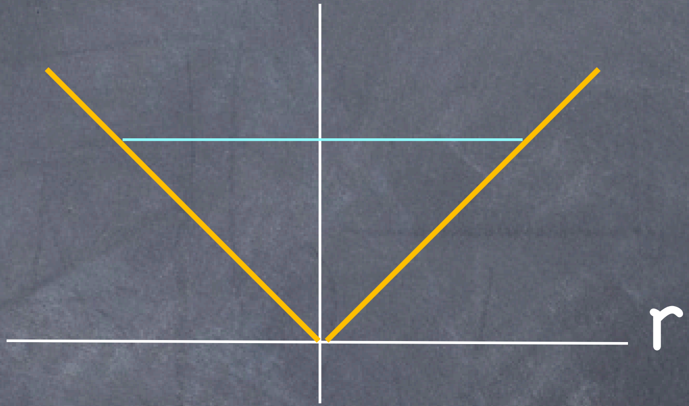
negligible Majorana transition

τ_n in a magnetic bottle

$\delta\tau_n/\tau_n \leq 10^{-4}$



magnetic potential



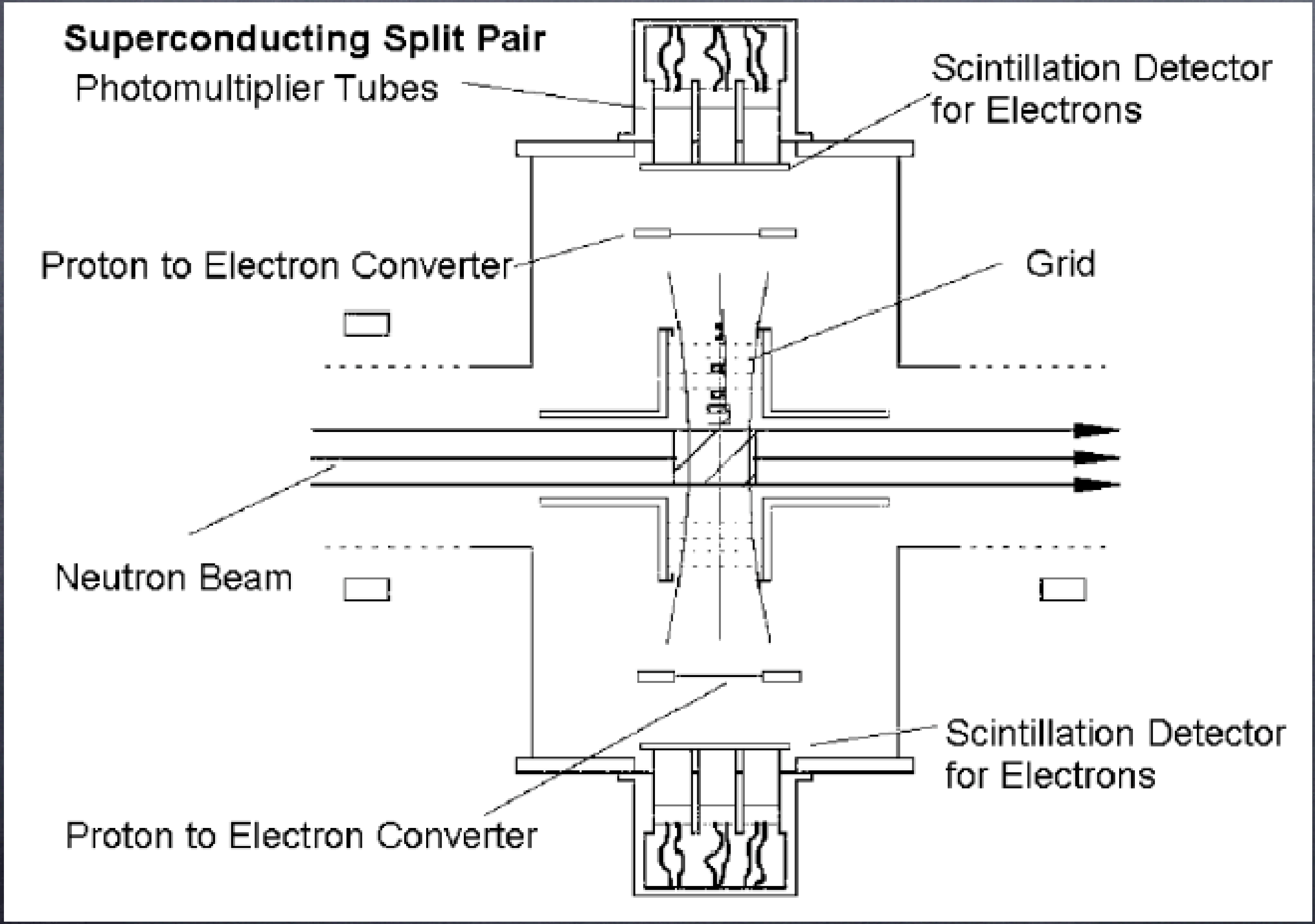
no wall loss

negligible Majorana transition

Measure
decay of β count

β asymmetry

PERKEO



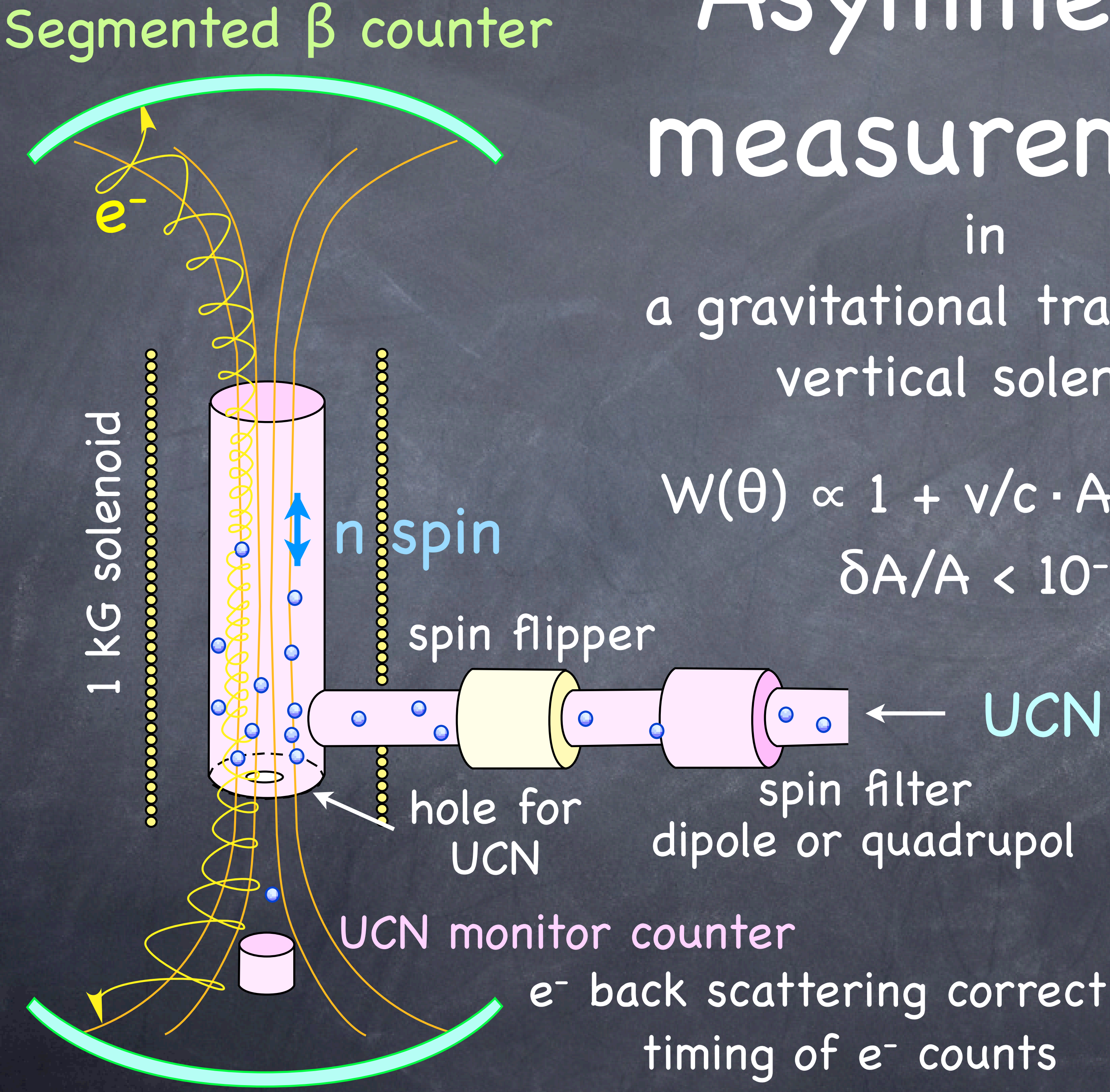
Asymmetry measurement

in

a gravitational trap with a vertical solenoid

$$W(\theta) \propto 1 + v/c \cdot A \cdot P_n \cdot \cos\theta$$

$$\delta A/A < 10^{-3}$$



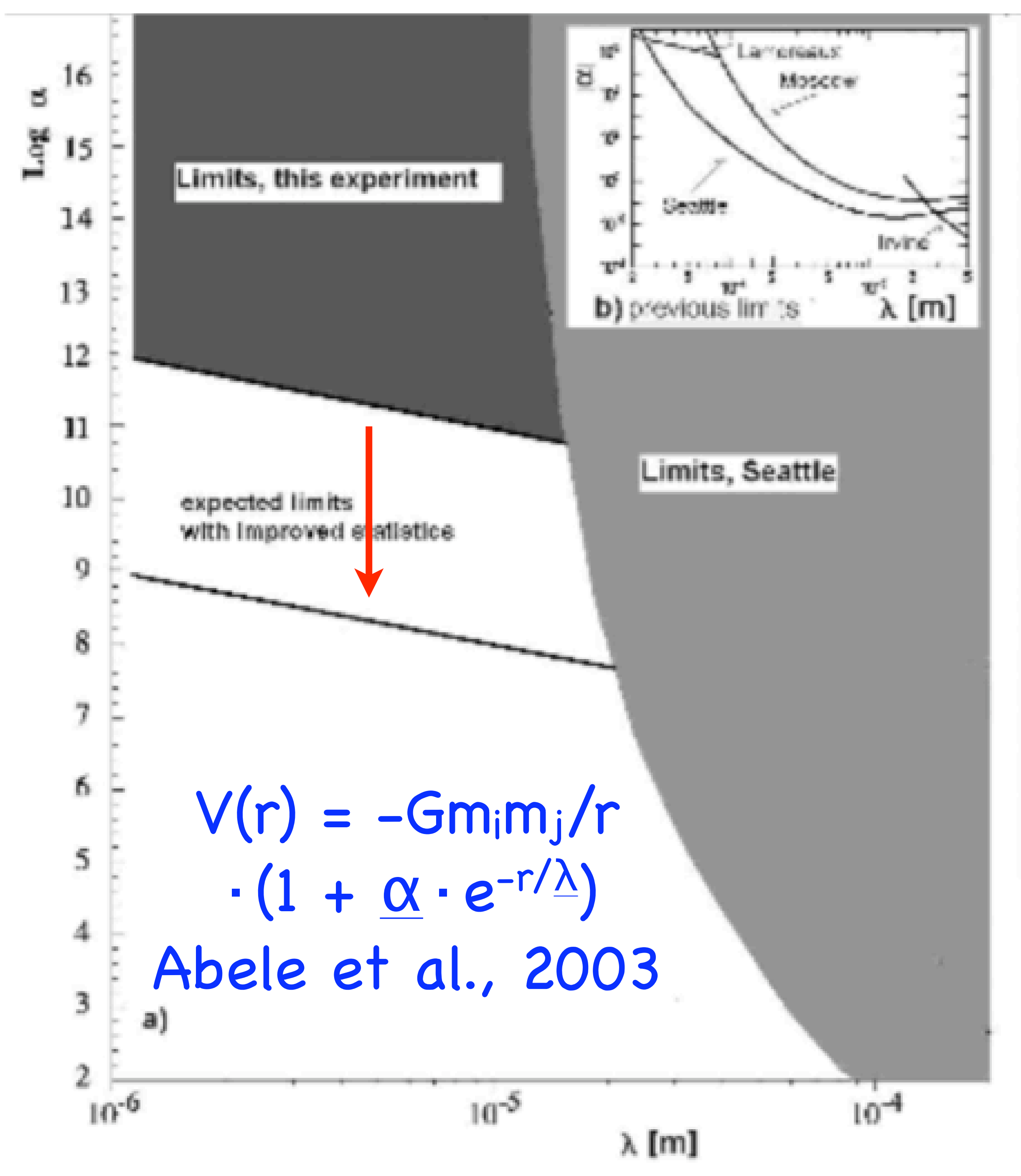
e^- back scattering correction

timing of e^- counts

Gravity

Newtonian gravity is valid at submillimater distance?

Gauge fields in extra dimension mediate repulsive force 10^6~10^8 times stronger than gravity at submillimater distance.
Arkani et al., 1999



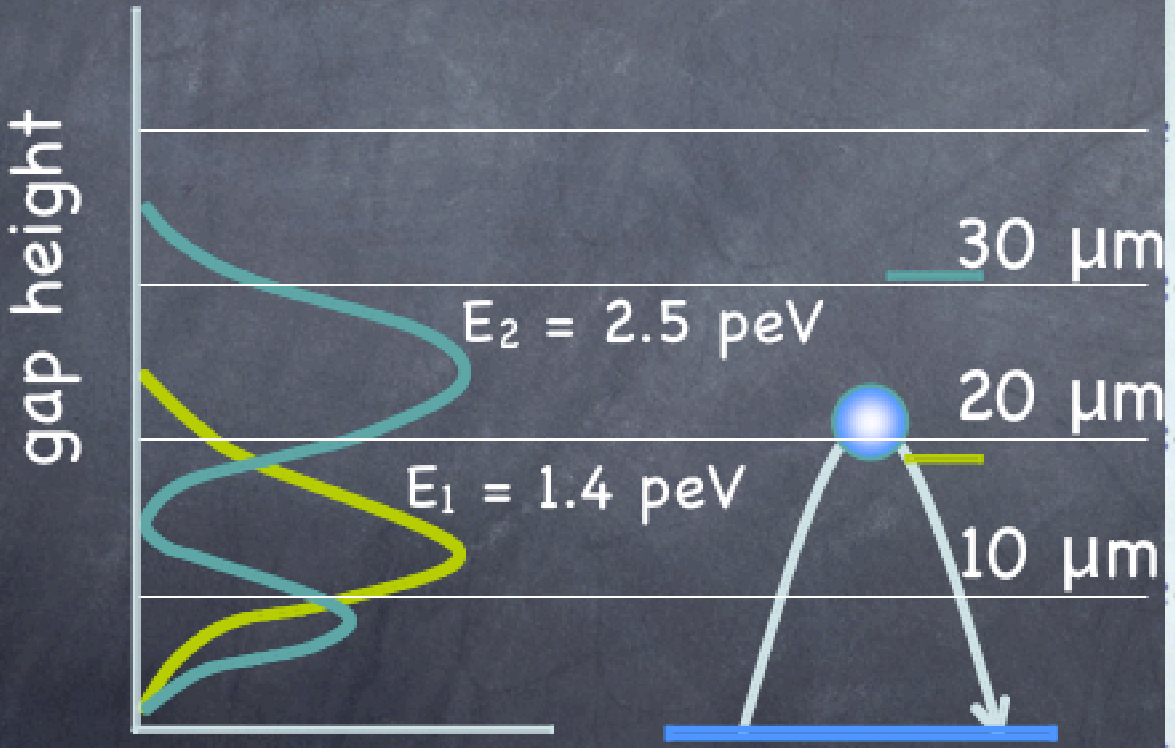
$$V(r) = -Gm_im_j/r \cdot (1 + \underline{\alpha} \cdot e^{-r/\underline{\lambda}})$$

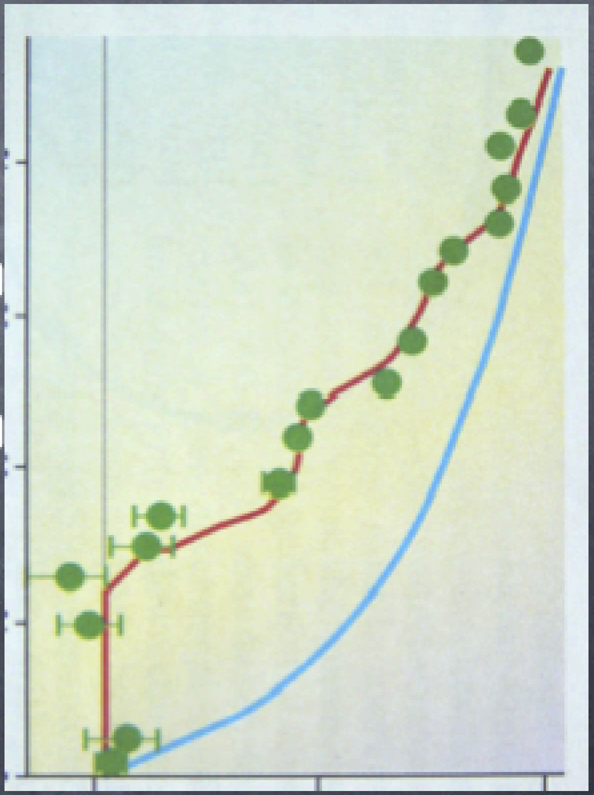
Abele et al., 2003

Quantization under Gravity

mgh: 1.02 peV/10μm

Nesvizhevsky et al.
Nature 415(2002)297





Required UCN density 1

- n lifetime

885.7±0.8 s (PDG) ↔ 878±0.7±0.3 s (Serebrov et al.)

For 10^{-4} measurement: 50 UCN/cm^3

- n β decay asymmetry

Test of CKM unitarity,

V_{ud} with 10^{-3}: 16 UCN/cm^3 at $\tau_s = 2.6$ s

continued

- n EDM

  $\delta d_n \sim 10^{-28}$ cm: SUSY, Multi-Higgs, Left-Right
  $E = 50$ kV/cm, $\tau_c = 130$ s, $\rho = 300$ UCN/cm^3

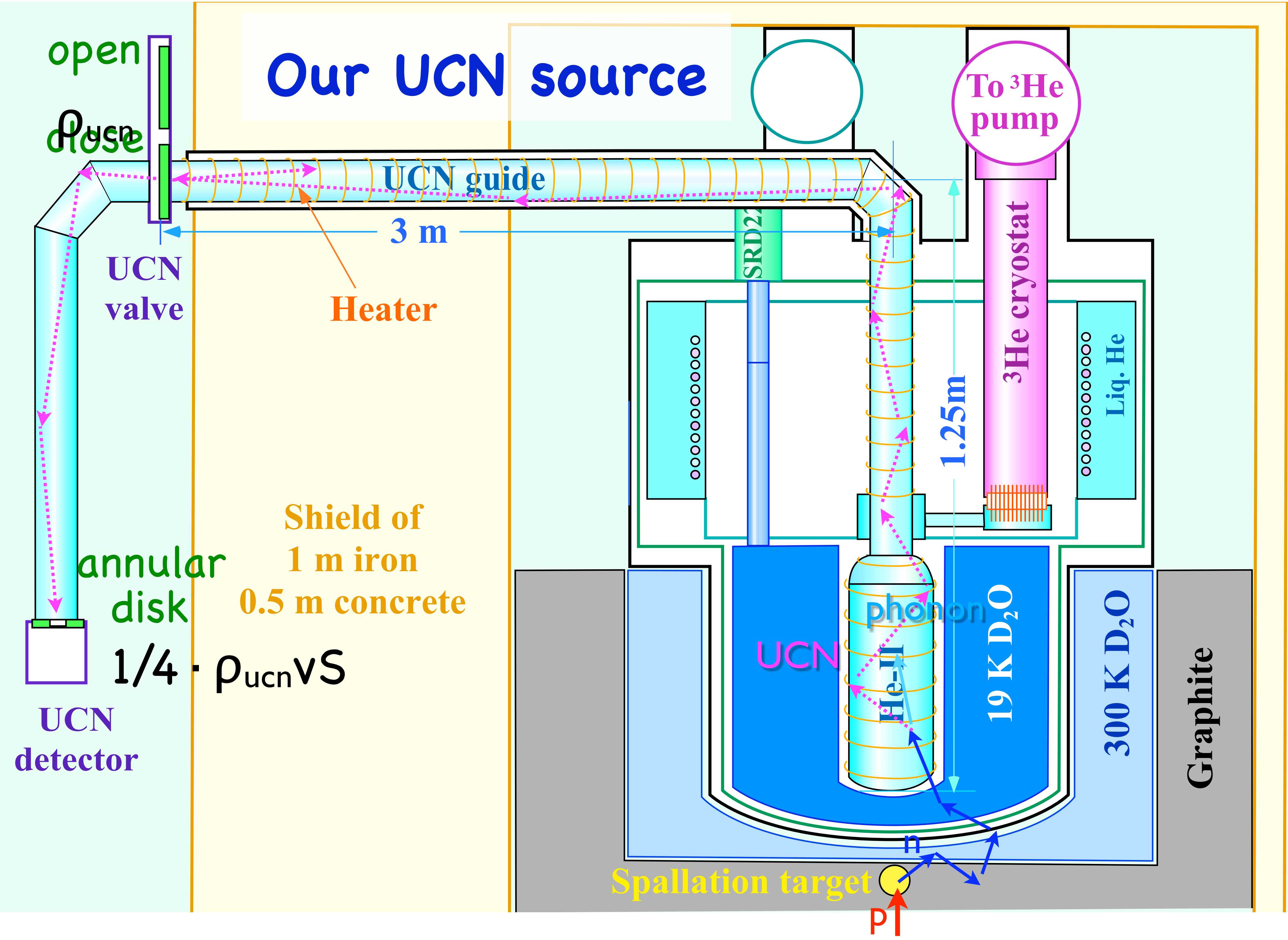
- n-nbar oscillation

  > 8.8×10^7 s cold n beam (1994), > 1.2×10^8 s Fréjus (1990), > 1.2×10^8 s Kamioka (1986)

  $10^9 \sim 10^{10}$ s SUSY with ν mass and See-Saw model

  1.3×10^8 UCN/s (5×10^5 UCN/cm^3 in 40 liter) → 10^{10} s

Our UCN source



World comparison

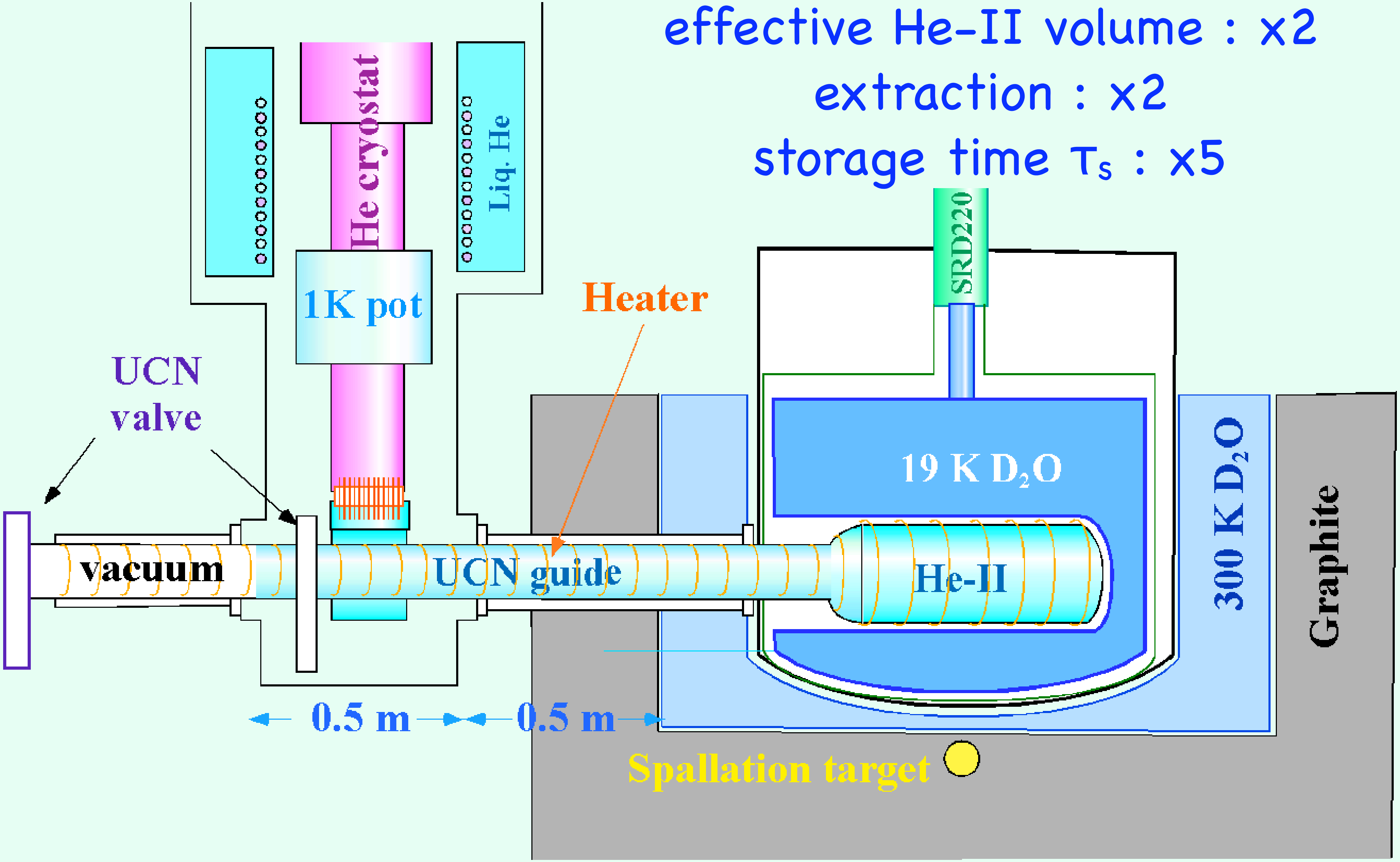
	Source type	E_c and τ_s	UCN density ρ_{UCN}(UCN/cm^3)
Ours vertical 100 W proton	0.96K He-II in D_2O	E_c = 90 neV τ_s = 30 s	10 in experiment
Grenoble 60MW reactor	Turbine	E_c = 335 neV	50 in source
Munich 20MW reactor	SD_2	E_c = 250 neV	10^4 in source
North Carolina 1 MW reactor	SD_2	E_c = 335 neV	1300 in source
PSI 12 kW proton	SD_2	E_c = 250 neV τ_s = 888 s	2000 in source
Los Alamos 2.4 kW proton	SD_2	E_c = 250 neV τ_s = 2.6 s	120 in source
SNS cold neutron beam	0.3K He-II	E_c = 134 neV τ_s = 500 s	430 in He-II

World comparison

	Source type	E_c and τ_s	UCN density ρ_{UCN}(UCN/cm^3)
Ours vertical 100 W proton	0.96K He-II in D_2O	E_c = 90 neV τ_s = 30 s	10 in experiment
Grenoble 60MW reactor	Turbine	E_c = 100 neV	2~3 in experiment
Munich 20MW reactor	SD_2	E_c = 250 neV	10^4 in source
North Carolina 1 MW reactor	SD_2	E_c = 335 neV	1300 in source
PSI 12 kW proton	SD_2	E_c = 250 neV τ_s = 888 s	2000 in source
Los Alamos 2.4 kW proton	SD_2	E_c = 250 neV τ_s = 2.6 s	120 in source
SNS cold neutron beam	0.3K He-II	E_c = 134 neV τ_s = 500 s	430 in He-II

Horizontal cryostat

p beam power $E_p x I_p$: x5
effective He-II volume : x2
extraction : x2
storage time τ_s : x5



World comparison

	Source type	E_c and τ_s	UCN density ρ_{UCN}(UCN/cm^3)
Ours horizontal 500 W proton	0.6K He-II in D_2O	E_c = 90 neV τ_s = 150 s	1000 in experiment
Grenoble 60MW reactor	0.5K He-II	E_c = 250 neV τ_s = 150 s	1000 in He-II
Munich 20MW reactor	SD_2	E_c = 250 neV	10^4 in source
North Carolina 1 MW reactor	SD_2	E_c = 335 neV	1300 in source
PSI 12 kW proton	SD_2	E_c = 250 neV τ_s = 888 s	2000 in source
Los Alamos 2.4 kW proton	SD_2	E_c = 250 neV τ_s = 2.6 s	120 in source
SNS cold neutron beam	0.3K He-II	E_c = 134 neV τ_s = 500 s	430 in He-II

World comparison

	Source type	E_c and τ_s	UCN density ρ_{UCN}(UCN/cm^3)
Ours horizontal 500 W proton	0.6K He-II in D_2O	E_c = 90 neV τ_s = 150 s	1000 in experiment
Grenoble 60MW reactor	0.5K He-II	E_c = 90 neV τ_s = 150 s	216 in He-II
Munich 20MW reactor	SD_2	E_c = 90 neV	2160 in source
North Carolina 1 MW reactor	SD_2	E_c = 90 neV	181 in source
PSI 12 kW proton	SD_2	E_c = 90 neV τ_s = 888 s	432 in source
Los Alamos 2.4 kW proton	SD_2	E_c = 90 neV τ_s = 2.6 s	26 in source
SNS cold neutron beam	0.3K He-II	E_c = 90 neV τ_s = 150 s	71 in He-II

World comparison

	Source type	E_c and τ_s	UCN density ρ_{UCN}(UCN/cm^3)
Our future 12.5 kW proton	0.6K He-II in D_2	E_c = 210 neV τ_s = 150 s	7×10^5 in experiment
Grenoble 60MW reactor	0.5K He-II	E_c = 250 neV τ_s = 150 s	1000 in He-II
Munich 20MW reactor	SD_2	E_c = 250 neV	10^4 in source
North Carolina 1 MW reactor	SD_2	E_c = 335 neV	1300 in source
PSI 12 kW proton	SD_2	E_c = 250 neV τ_s = 888 s	2000 in source
Los Alamos 2.4 kW proton	SD_2	E_c = 250 neV τ_s = 2.6 s	120 in source
SNS cold neutron beam	0.3K He-II	E_c = 134 neV τ_s = 500 s	430 in He-II

He-II or SD_2

	He-II	D_2
production rate	σ_{coh} = 0.76 b	σ_{coh} = 2.48 b
$\tau_a = 1/(\rho v \sigma_a)$	∞	0.2 s
operating temperature	< 1 K	5 K
mean free path	>> 1 m	several cm
structure	almost vacuum	dislocation, defect
heat conduction	excellent, no local heating	local heating
Fermi potential	negligibly small	109 neV