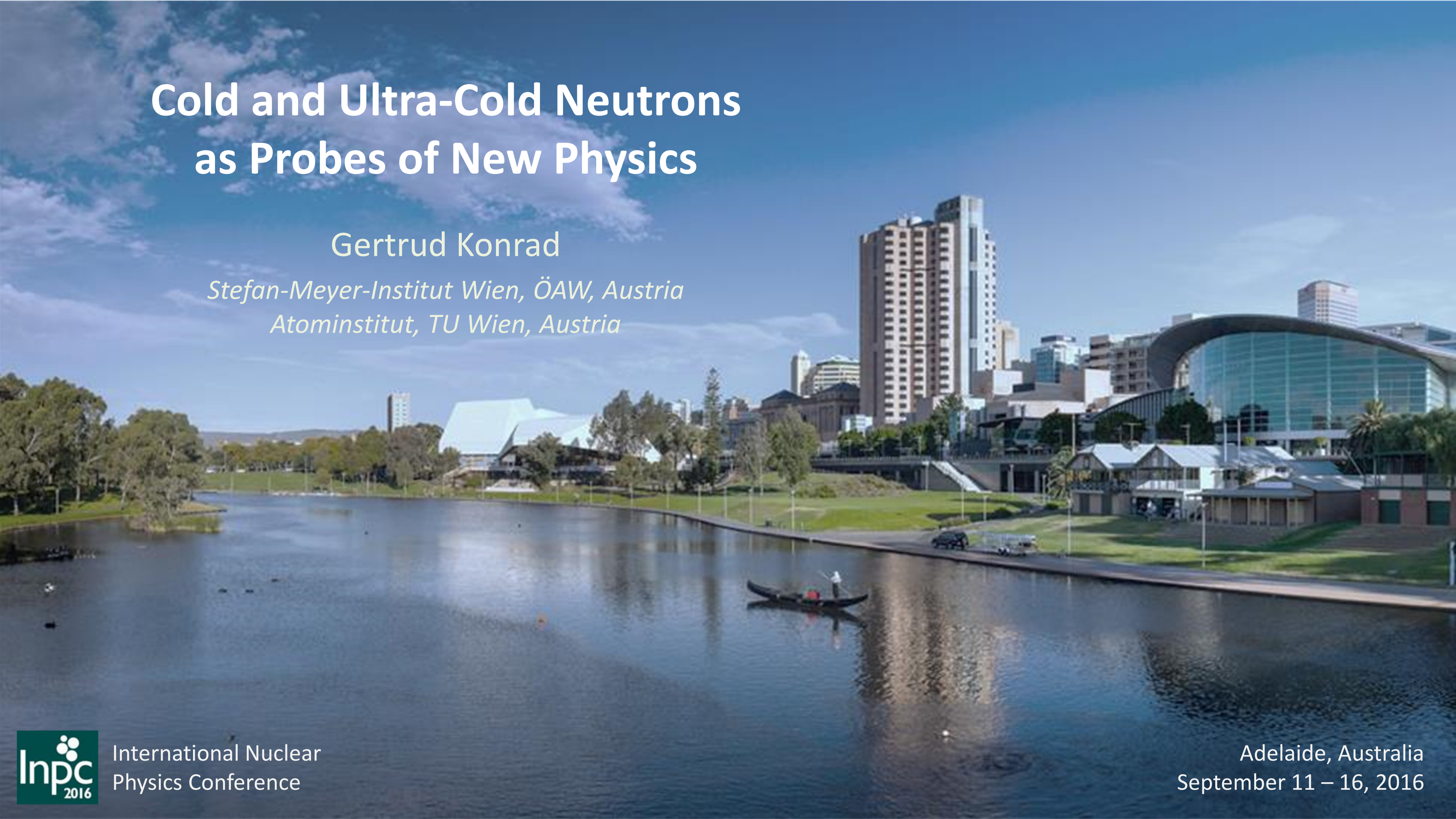


Cold and Ultra-Cold Neutrons as Probes of New Physics

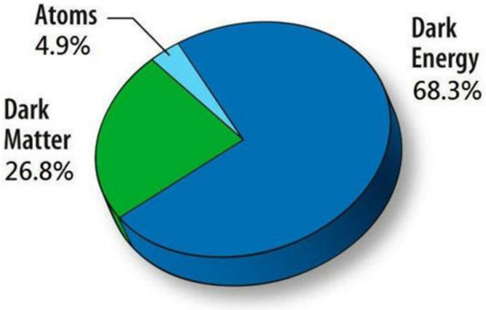
Gertrud Konrad

Stefan-Meyer-Institut Wien, ÖAW, Austria
Atominstitut, TU Wien, Austria

International Nuclear
Physics Conference

Adelaide, Australia
September 11 – 16, 2016

Composition of the Universe



Nature of DM?

- Axions
- WIMPs
- Sterile neutrinos
- Gravitinos
- Mirror matter

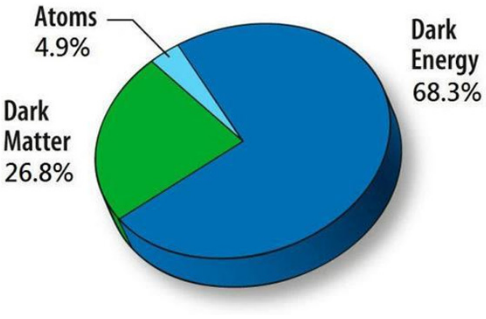
- Mirror matter

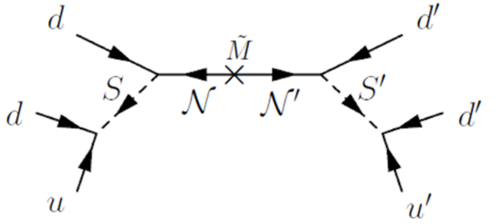
- etc.

1956 Lee & Yang: Phys. Rev. 104, 254 (1956)
mirror world can restore global parity symmetry

2001 Berezhiani, Comelli, & Vilante: Phys. Lett. B503, 362 (2001)
mirror matter as cosmological DM candidate, if $T'/T \ll 1$

Mirror dark matter





$$\varepsilon = \frac{\hbar}{\tau} < 6.6 \times 10^{-16}\text{eV}$$

$$\rightarrow \tau_{nn'} > 1\text{s}$$

Nature of DM?

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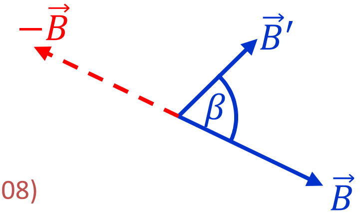
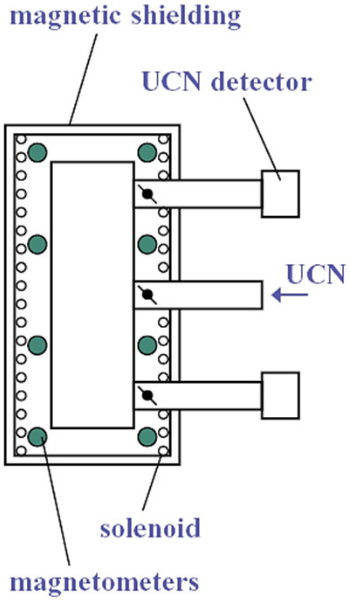
2006 Berezhiani & Bento: Phys. Rev. Lett. 96, 081801 (2006)
neutrons n can oscillate to mirror neutrons n'

Neutron – mirror-neutron oscillations

$$P_{nn'}(B,B',t) = p(B,B',t) + d(B,B',t) \cdot \cos\beta$$



B field variation:
$\pm$ 0.2 G up/down



A.P. Serebrov et al., Phys. Lett. B663, 181 (2008)

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$\tau_{nn'} > 414$ s (90 % C.L.), for $B' = 0$

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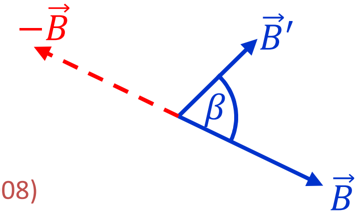

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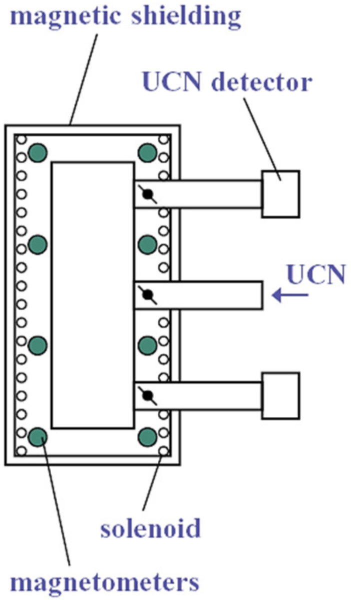

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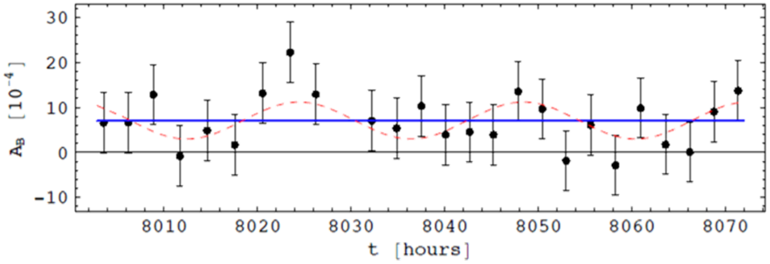
2012 *Re-analysis* Berezhiani & Nesti: Eur. Phys. J. C72, 1974 (2012)

$$A_B(t) = \frac{N_{-B}(t) - N_B(t)}{N_{-B}(t) + N_B(t)} = (7.0 \pm 1.3)\times 10^{-4} \rightarrow \tau_{nn'} \sim 2 - 10 \text{ s}, B' \sim 0.1 \text{ G}$$



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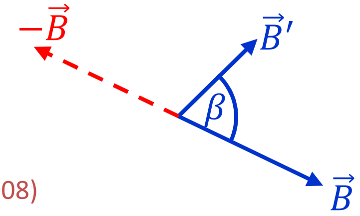

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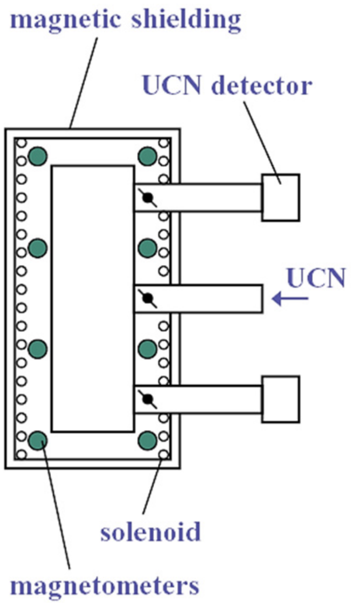

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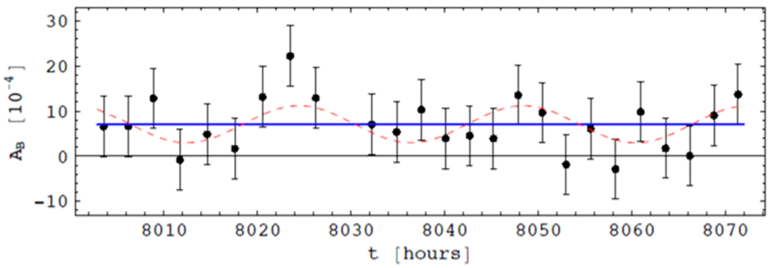


2009 Altarev et al.: Phys. Rev. D80, 032003 (2009)

$\tau_{nn'} > 12$ s (95 % C.L.), for $0 \leq B' \leq 12.5$ µT

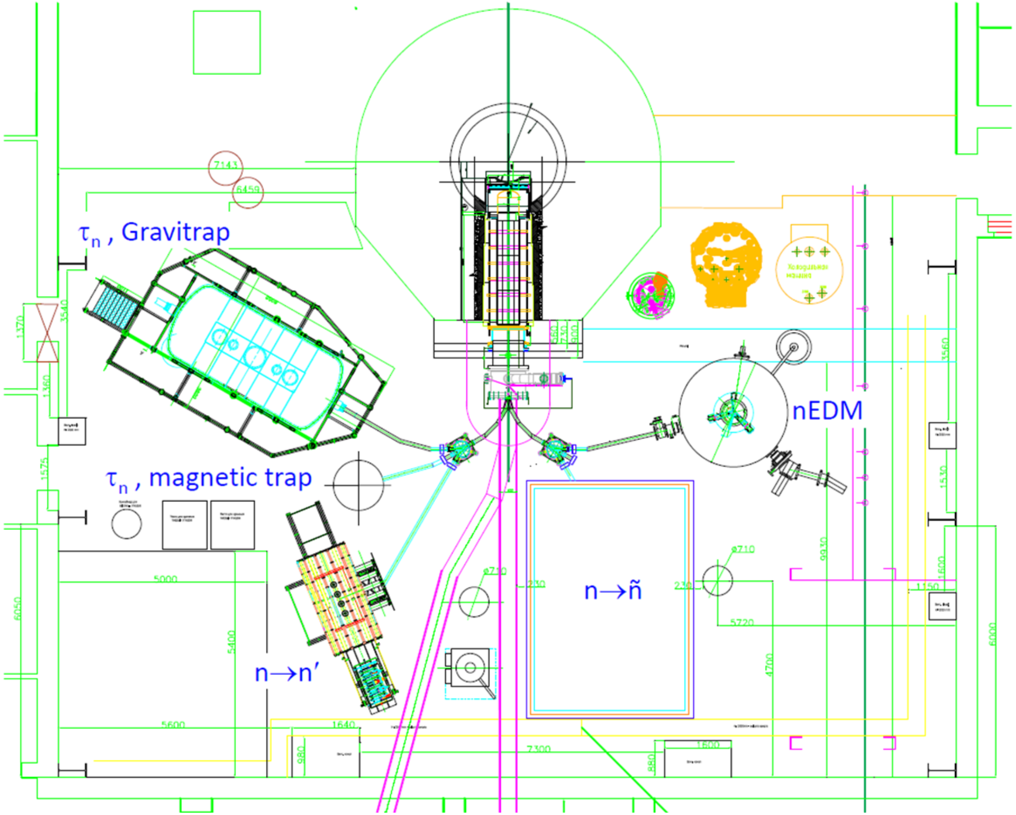
Neutron oscillations

Planned measurements:

- SNS (ORNL, Oak Ridge)

  → *Beam regeneration experiment*

- WWR-M (PNPI, Gatchina):
  - nn' oscillations



Based on A. Fomin, UCN Workshop, Mainz, 2016

Neutron oscillations

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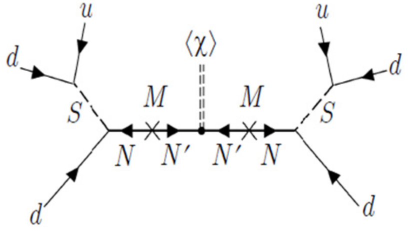
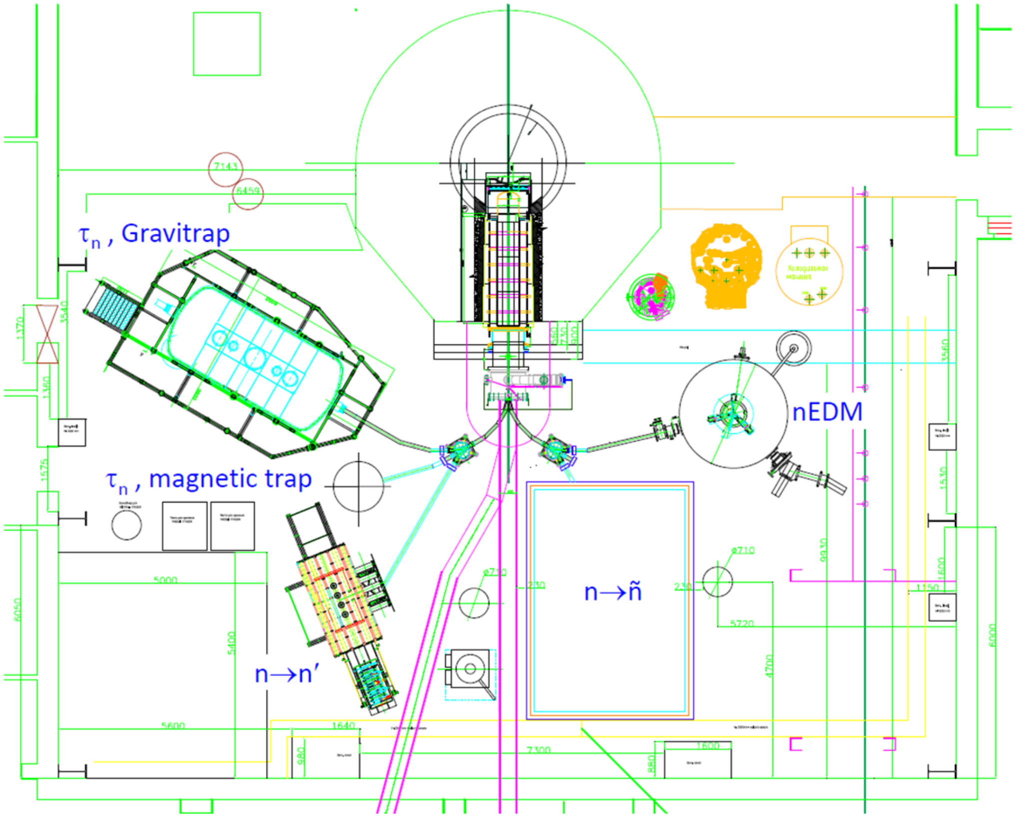
- WWR-M (PNPI, Gatchina):
  - nn' oscillations
  - $n\bar{n}$ oscillations

Fri 11:10 SY



$$\tau_{n\bar{n}} > 8.6 \times 10^7 \text{ s } (\Delta \boldsymbol{B} = \mathbf{2})$$



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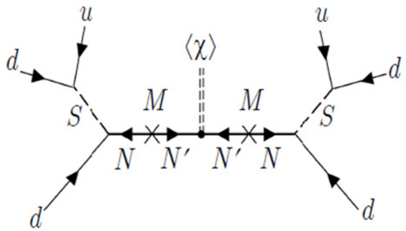
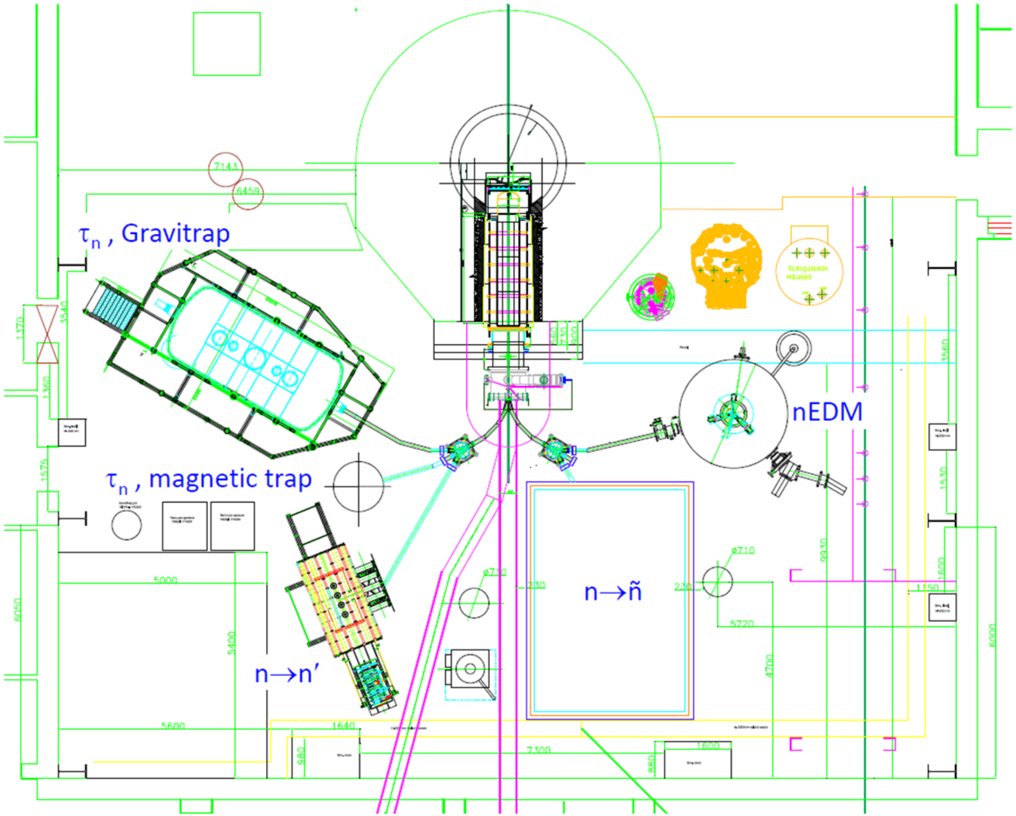


$$\tau_{n\bar{n}} > 8.6 \times 10^7 \text{ s } (\Delta \boldsymbol{B} = \mathbf{2})$$

- ESS (Lund):
  $n\bar{n}$ oscillations

K. Babu et al., arXiv:1310.8593



Based on A. Fomin, UCN Workshop, Mainz, 2016

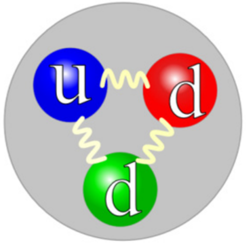
Outline

- Neutron – mirror neutron oscillations
- The neutron
  - Properties of the neutron
  - Neutron research facilities
- Neutrons as probes of (new) physics
  - Overview
  - Neutron β-decay
  - Neutron EDM
- Summary and Outlook

THE NEUTRON

Properties of the neutron

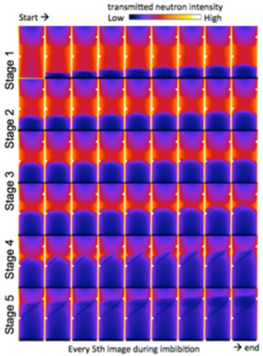
Property	Value
Charge q_n	< 1 ×10^{-21} e
Radius r_n	~ 1 fm
Mass m_n	939.565379(21) MeV/c^2
Mass difference $m_n - m_p$	1.29333217(42) MeV/c^2
Lifetime τ_n	(880.3±1.1) s
Spin	½
Magnetic dipole moment μ_n	-1.9130472(45) μ_{N}
Electric dipole moment d_n	< 2.9 ×10^{-26} e·cm
Electric polarizability α_n	118(11) ×10^{-5} fm^3
Magnetic polarizability β_n	37(12) ×10^{-5} fm^3



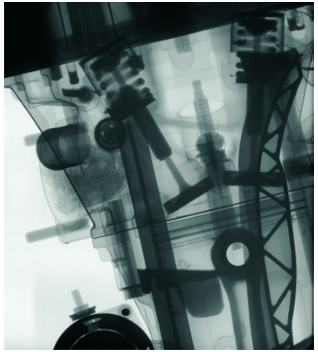
K.A. Olive et al. (Particle Data Group), Chin. Phys. C38, 090001 (2014)
D. Dubbers and M.G. Schmidt, Rev. Mod. Phys. 83, 1111 (2011)
F.E. Wietfeldt and G.L. Greene, Rev. Mod. Phys. 83, 1173 (2011)

Neutron research

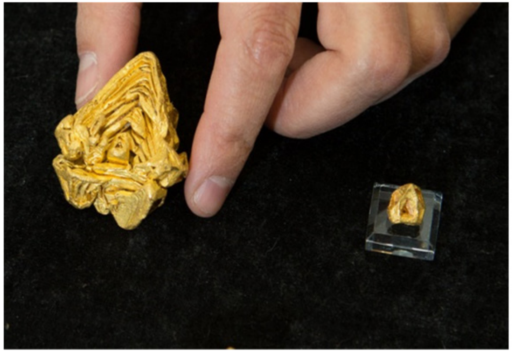
Geology



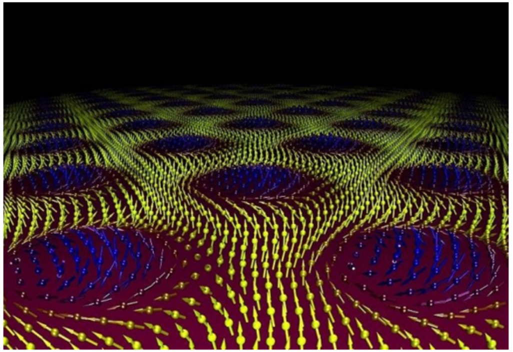
Engineering

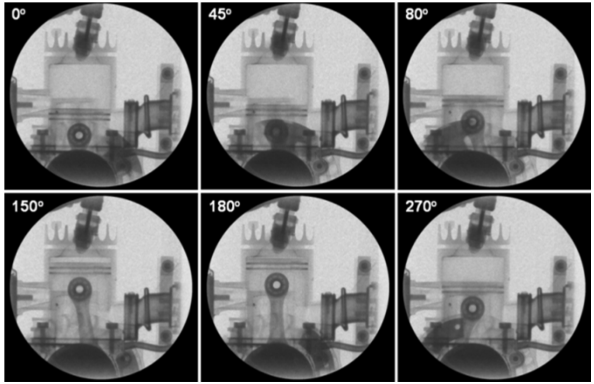


Crystallography

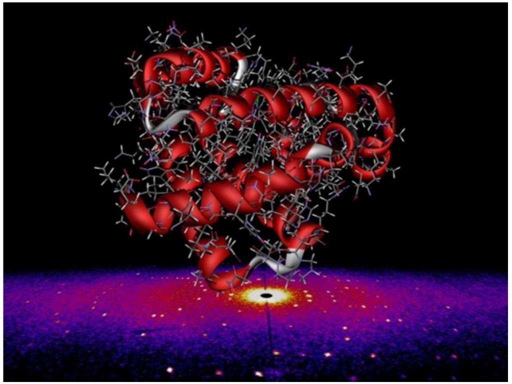


Magnetic materials

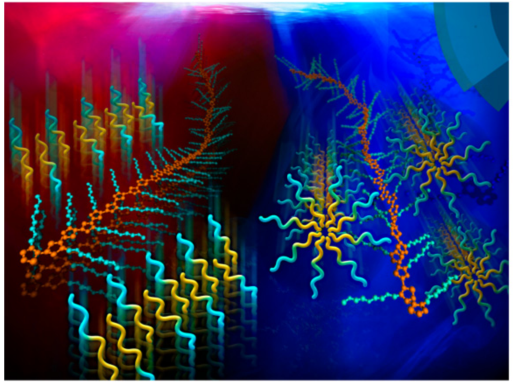




Engineering



Molecular biology



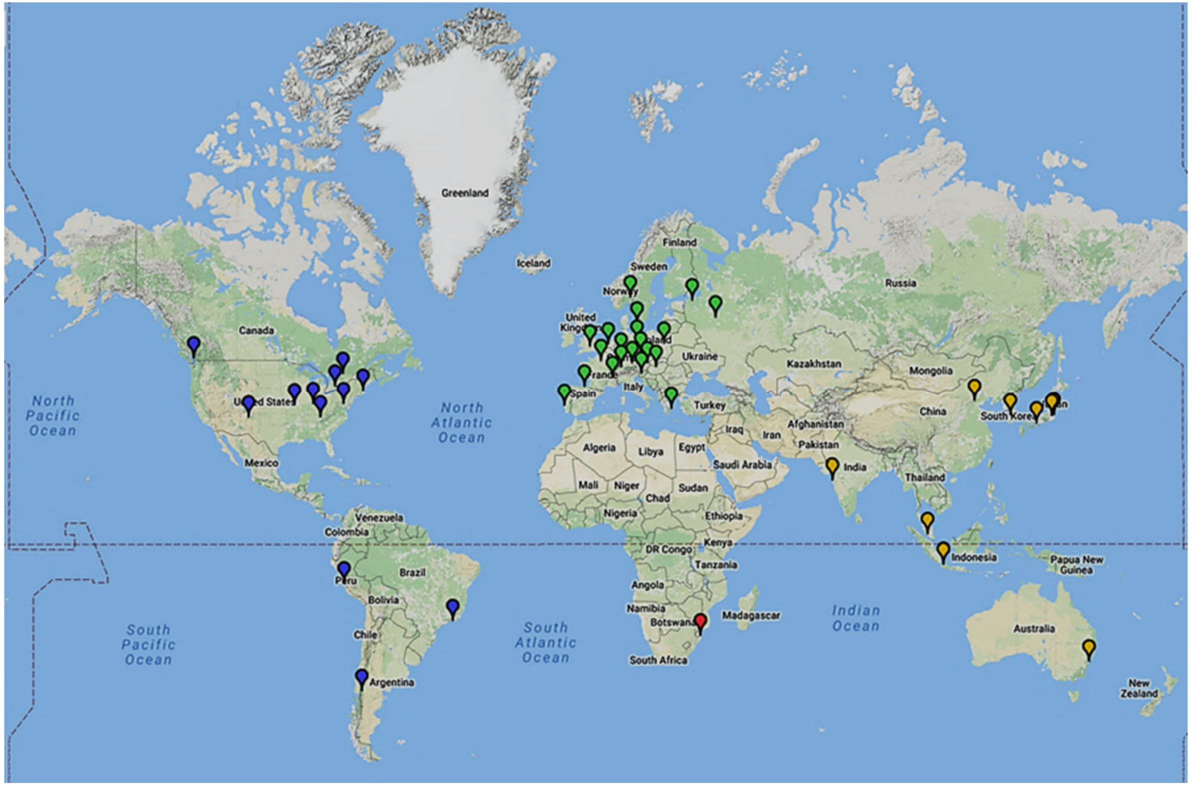
Energy research

and many more, in particular nuclear and particle physics

Neutron research facilities worldwide

Existing facilities:

- 9 North America
- 3 South America
- 19 Europe
- 1 Africa
- 8 Asia
- 1 Australia



Neutronsources.org

Neutron research facilities worldwide

Existing facilities:

- 9 North America
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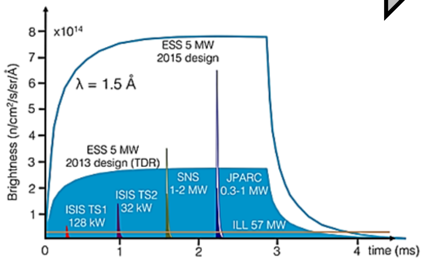
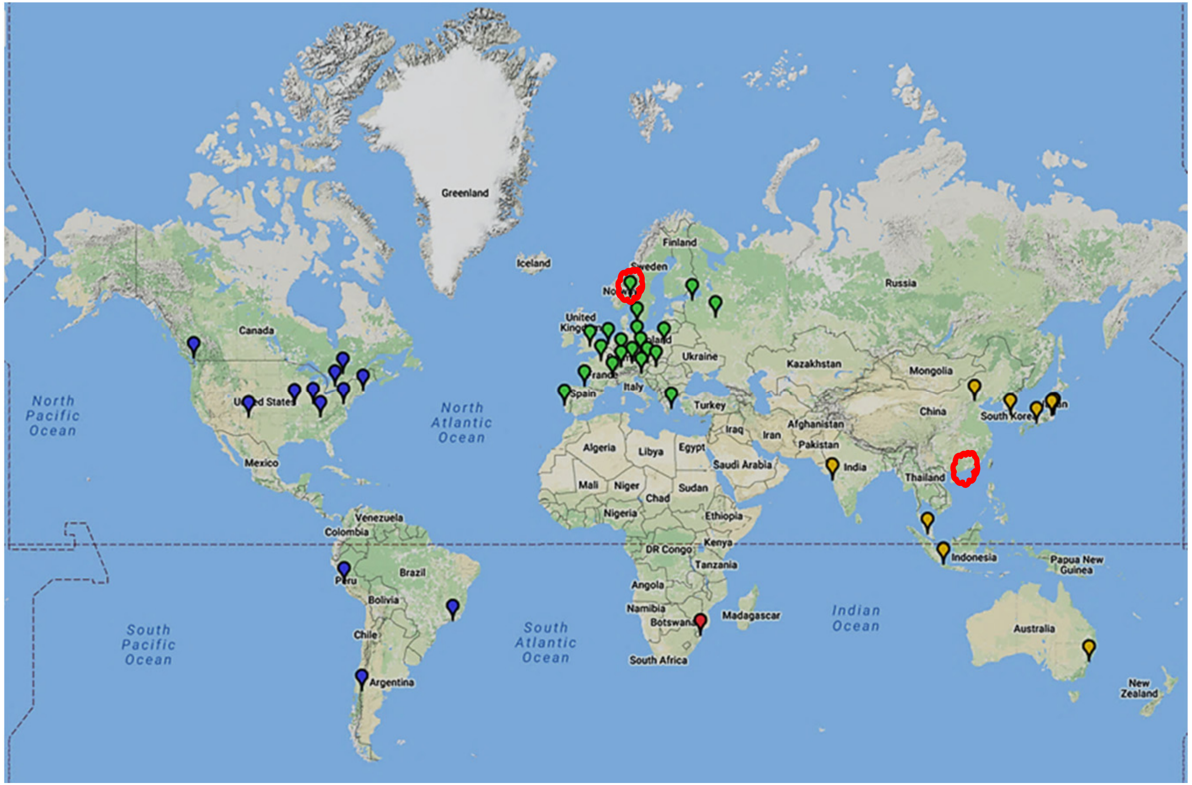
Under construction:

- CSNS (2018)
- ESS (2023)

SY 3



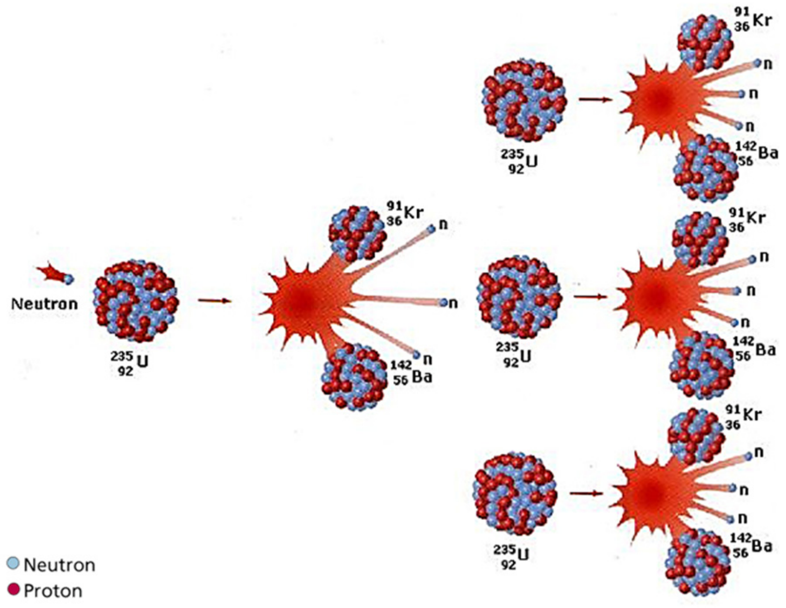
https://europeanspallationsource.se



Neutronsources.org

Neutron production

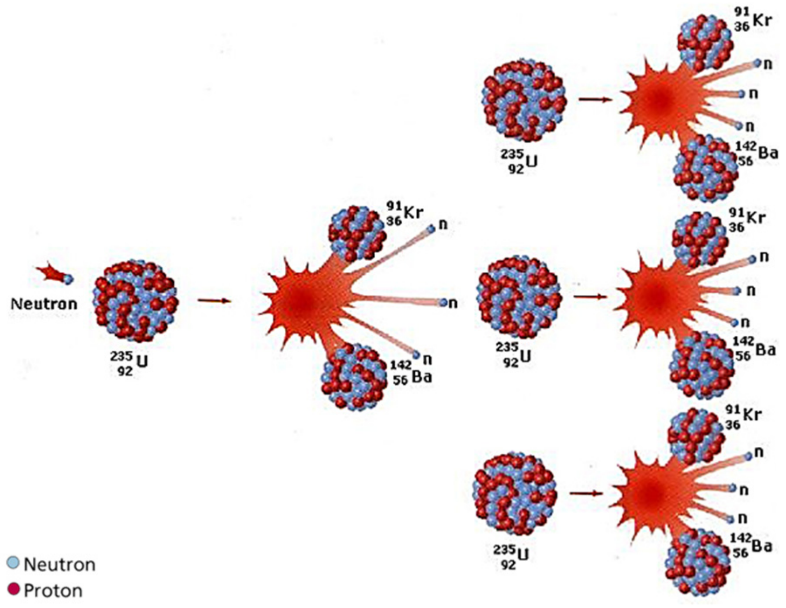
Nuclear fission



→ 1 – 2 neutrons /fission

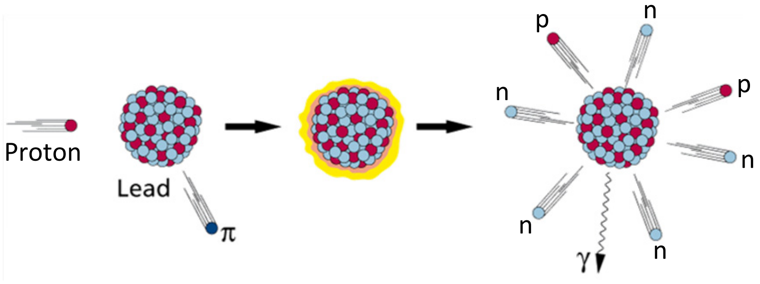
Neutron production

Nuclear fission



→ 1 – 2 neutrons /fission

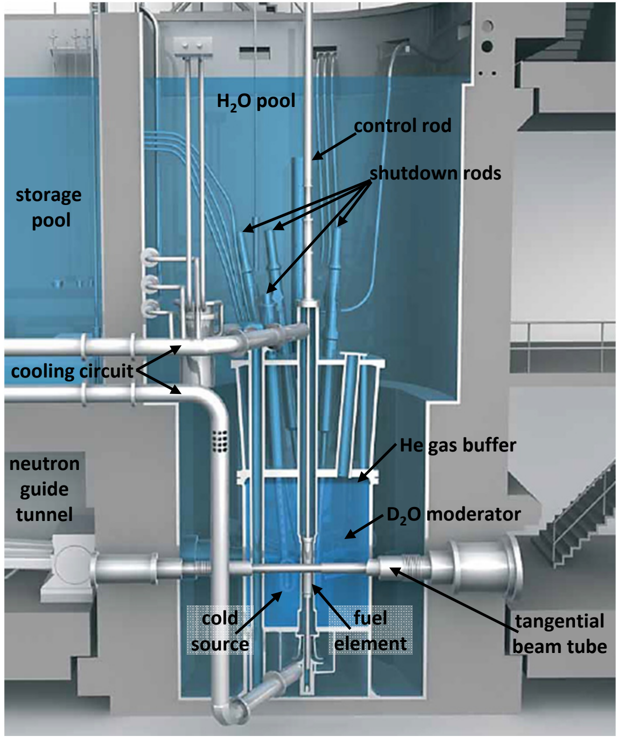
Spallation

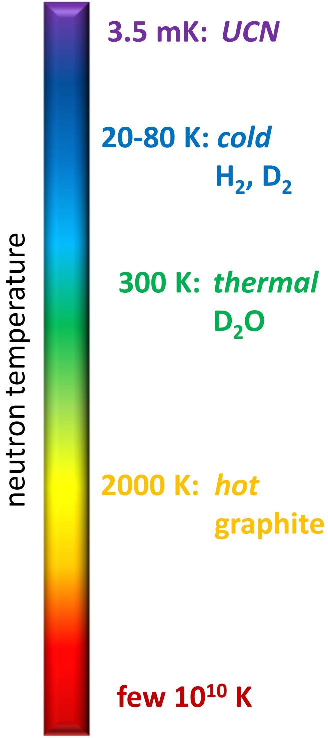


→ 30 – 40 neutrons /proton

Neutron sources

Research reactors: FRM II, 20 MW





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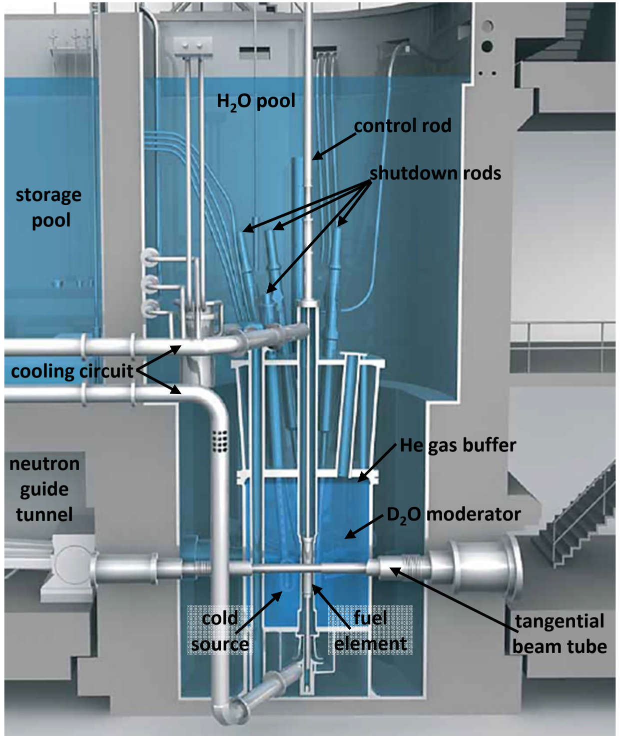
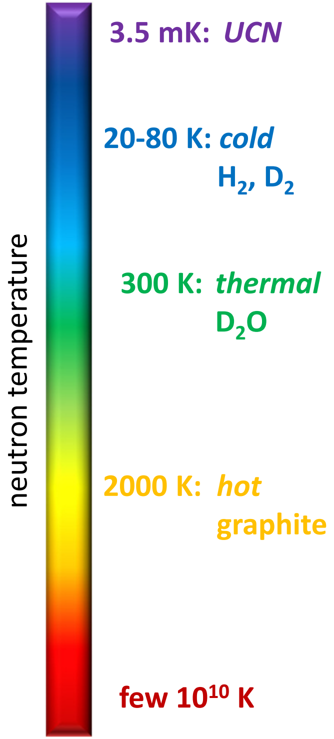




3.5 mK: *UCN*

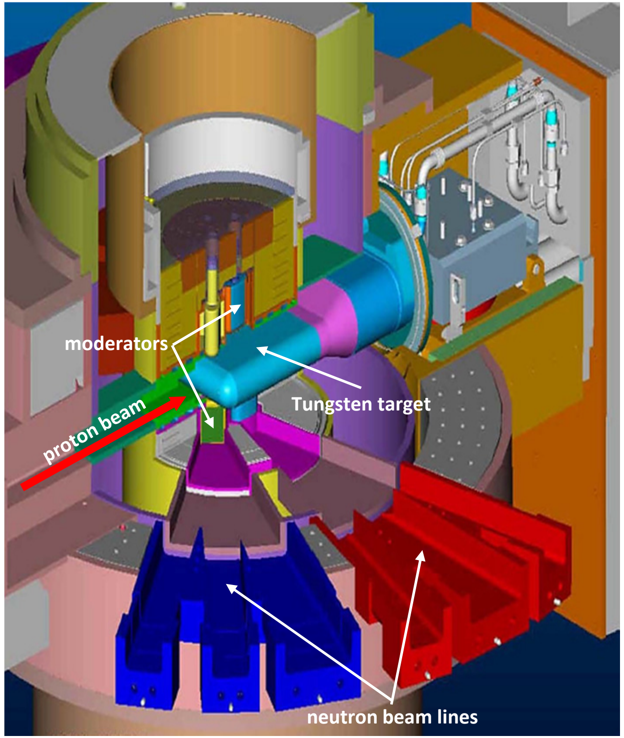
20-80 K: *cold*
H_2, D_2

300 K: *thermal*
D_2O

2000 K: *hot*
graphite

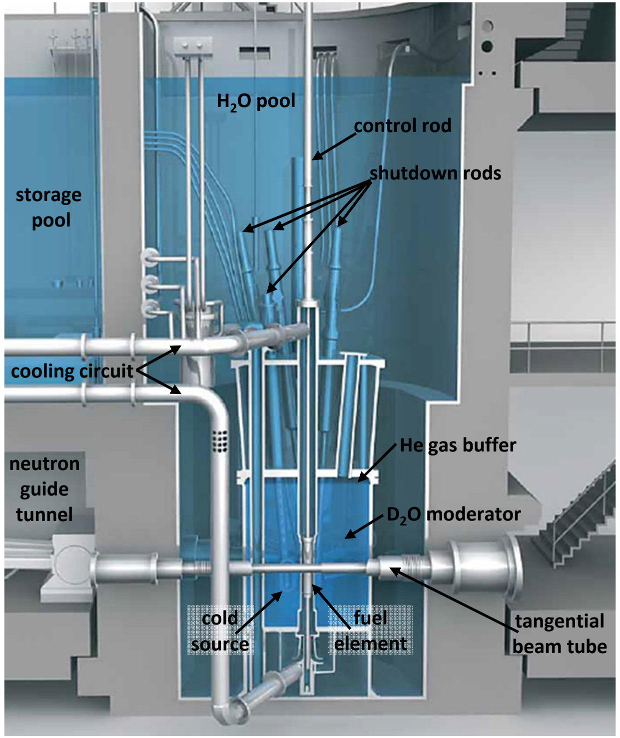
few 10^{10} K

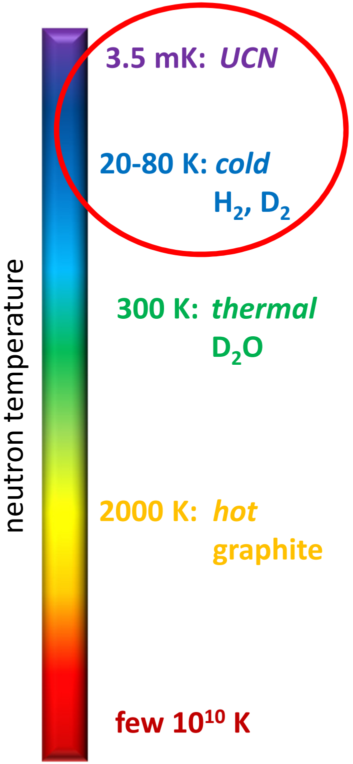
Spallation sources: SNS, 1.4 MW



Neutron sources

Research reactors: FRM II, 20 MW





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20-80 K: *cold* H_2, D_2

300 K: *thermal* D_2O

2000 K: *hot* graphite

few 10^{10} K

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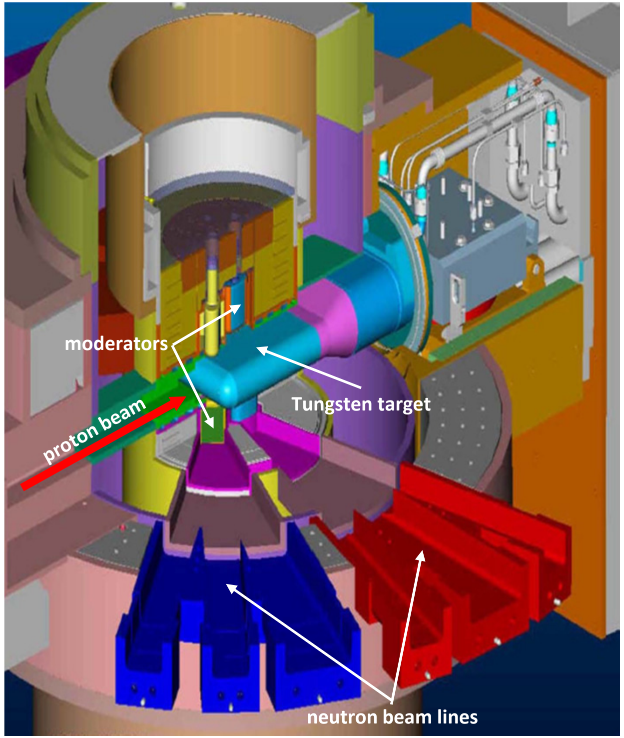
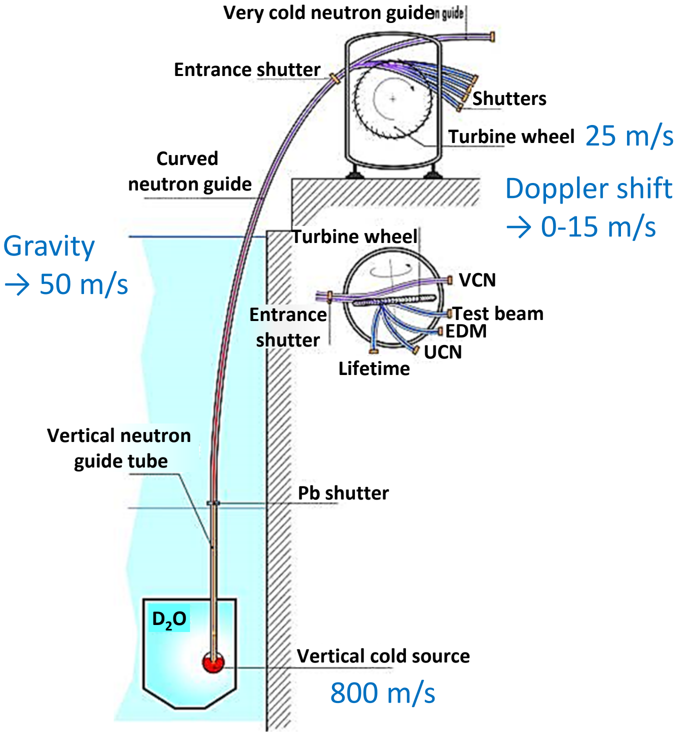


Production of ultra cold neutrons

Steyerl turbine source: PF2/ILL



A. Steyerl et al., Phys. Lett. 116 A, 347 (1986)

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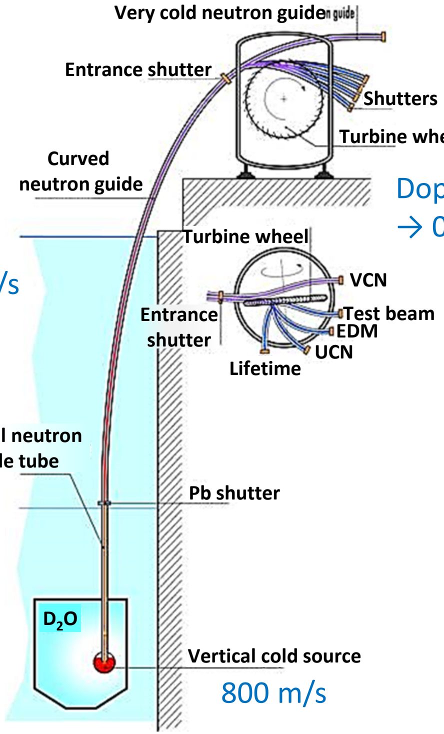


25 m/s

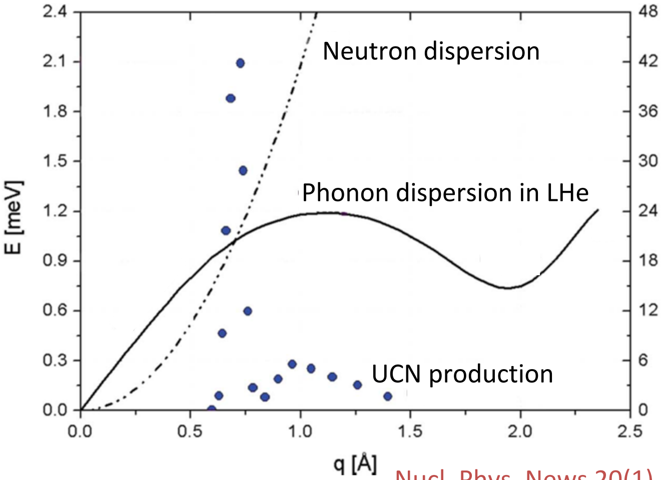
Doppler shift
→ 0-15 m/s

Gravity
→ 50 m/s

800 m/s

A. Steyerl et al., Phys. Lett. 116 A, 347 (1986)

Superthermal sources



Nucl. Phys. News 20(1), 23 (2010)

1 meV neutrons can excite single 0.7 /Å phonon
→ down-scattering to ~300 neV *UCN*

Source candidates: ^{4}D, ^{4}He, ^{15}N, ^{16}O, ^{208}Pb

high rate *high density*

UCN Sources worldwide

Type	Name	Density in cell	Useful ave. current (10^4 /s)	Source storage time (s)
Turbine	ILL Turbine	39	100 – 200	few s
LHe	ILL SUN-2	~15 peak (60 s, 30 l)	Max = 1, drain time ~150 s	200 (4 l, Fomblin, ~80 neV)
	RCNP/KEK	26	3.2	81 (Ni)
	SuperSUN	~150 peak (60 s, 30 l)	10 polarized	800 (12 l, 230 neV mag. trap)
	TRIUMF/KEK	600 polarized	~100 polarized	100 (NiP)
	PNPI	12000	7000	10 (from He @ 1.2 K)
SD$_2$	LANL	~50 (gatevalve) ~25 polarized	10 – 20 5 – 10 polarized	40
	PSI	~23 peak	~70 peak, 20 M/300 s = 6.7	~90
	Mainz	10	3.2	few s
	FRM II	~5000	6000	few s
	PULSTAR	>30	>10	few s

Tue 15:40 SY

Based on overview by A. Young, UCN Workshop, Mainz, 2016

NEUTRONS AS PROBES OF (NEW) PHYSICS

Neutron particle physics

- Neutron oscillations
  - → B number violation
  - → Mirror universes
- Neutron β-decay
  - → Electroweak SM
  - → BSM
- Neutron EDM
  - → Baryogenesis
  - → $\mathcal{C}P$ Violation
- Gravitational quantum levels
  - → Extra dimensions
  - → New forces
  - → Dark matter
  - → Fine structure constant α
- Neutron interferometry
  - → Fundamental tests of QM
  - → Chameleon
- Neutron charge
  - → $B - L$ Symmetry violation
- Neutron diffraction
  - → Spin-dependent short range interaction
- Neutron scattering
  - → Short range forces
- Hadronic weak interactions
  - → Non-perturbative limit of QCD
- Reactor neutrinos
  - → Light sterile neutrinos
- Etc.

H. Abele, Prog. Part. Nucl. Phys. 60, 1 (2008)
D. Dubbers and M.G Schmidt, Rev. Mod. Phys. 83, 1111 (2011)
B.R. Holstein et al., J. Phys. G 41(11) (2014), articles 114001 to 114007

Neutron particle physics

- Neutron oscillations
  - → B number violation
  - → Mirror universes

Fri 11:10 SY

- Neutron β-decay
  - → Electroweak SM
  - → BSM

Tue 16:35 SY
Fri 11:40 SY

- Neutron EDM
  - → Baryogenesis
  - → $\mathcal{C}P$ Violation

Tue 15:40 – 16:35 SY

- Gravitational quantum levels
  - → Extra dimensions
  - → New forces
  - → Dark matter
  - → Fine structure constant α

- Neutron interferometry
  - → Fundamental tests of QM
  - → Chameleon
- Neutron charge
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- Neutron diffraction
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- Neutron scattering
  - → Short range forces

Fri 11:25 SY

- Hadronic weak interactions
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Fri 11:00 NN

- Etc.

Fri 10:30 – 11:10 SY

Neutron particle physics

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  - → Dark matter
  - → Fine structure constant α

qBounce
GRANIT

- Neutron interferometry
  - → Fundamental tests of QM
  - → Chameleon

NIST
ATI

- Neutron charge
  - → $B - L$ Symmetry violation

UMZ
ATI

- Neutron diffraction
  - → Spin-dependent short range interaction
- Neutron scattering
  - → Short range forces
- Hadronic weak interactions
  - → Non-perturbative limit of QCD

NPDGamma

- Reactor neutrinos
  - → Light sterile neutrinos

Neutrino-4
STEREO

- Etc.

Neutron β-decay

Primordial nucleosynthesis

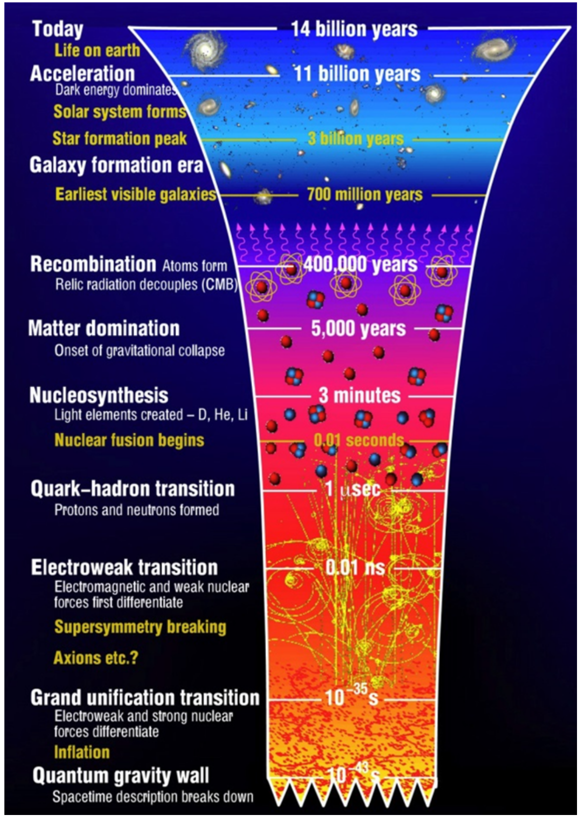
$t \ll 1\,\mathrm{s}: \quad n \approx p$

$t < 1\,\mathrm{s}: \quad n + e^{+} \leftrightarrow p + \bar{\nu}_e$

$n + \nu_e \leftrightarrow p + e^{-}$

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

$n/p = \exp(-\Delta m/kT)$



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

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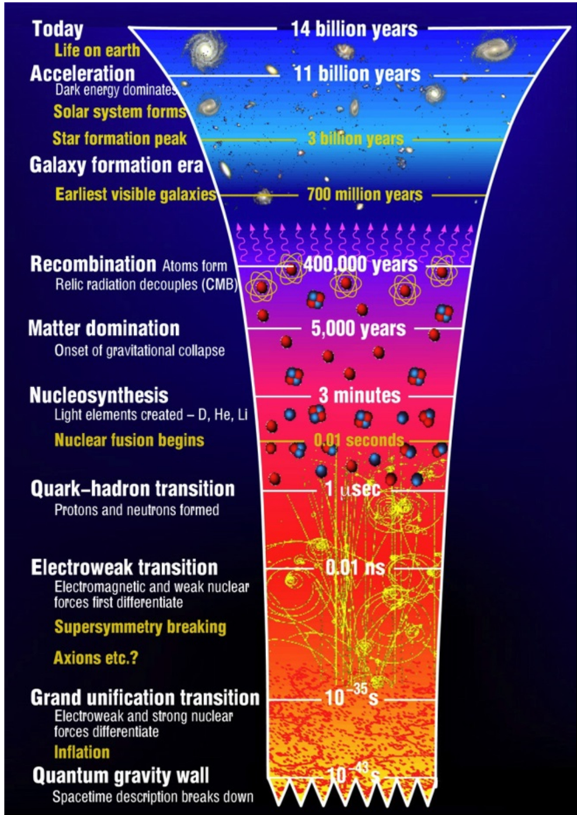
$$t_f \approx 2\,\mathrm{s}: \quad n/p = \exp\left(-\Delta m/kT_f\right) \approx 1/6$$



Primordial ^{4}He abundance

$t \ll 1\,\mathrm{s}:$ $\quad n \approx p$

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~~$n + \nu_e \leftrightarrow p + e^-$~~

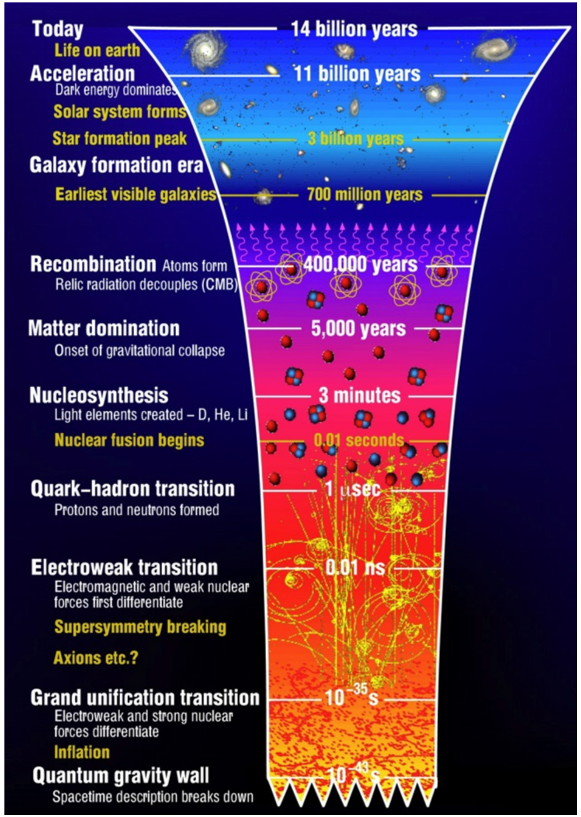
$$n \longrightarrow p + e^- + \bar{\nu}_e$$

$$n/p = \exp(-\Delta m/kT)$$

$t_f \approx 2\,\mathrm{s}:$ $\quad n/p = \exp\left(-\Delta m/kT_f\right) \approx 1/6$

$t_d \approx 150\,\mathrm{s}:$ $\quad n' \approx n \exp(-t_d/\tau_n),\ n + p = n' + p'$

$t = 150\,\mathrm{s}:$ $\quad Y_p = \dfrac{\text{He-4 mass}}{\text{total mass}} \approx \dfrac{2n'}{n' + p'}$



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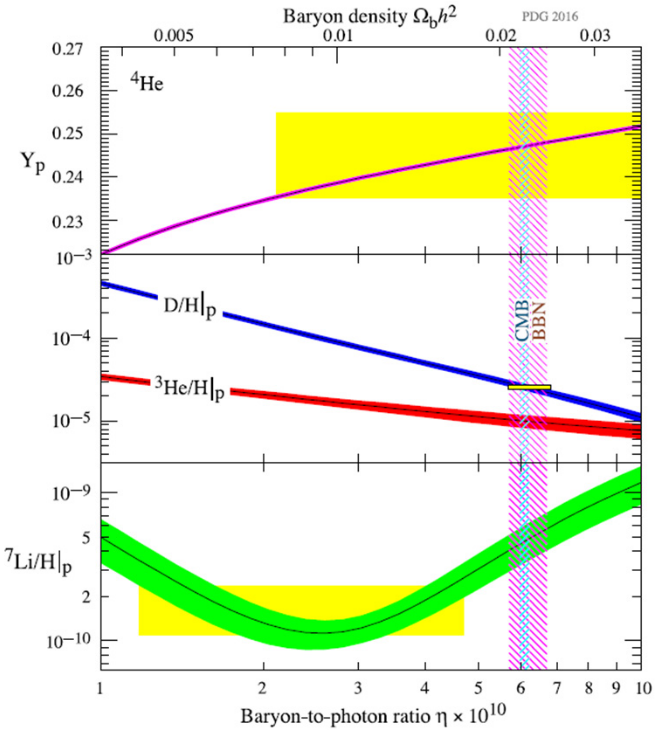
→ τ_n confirms $\eta = n_b/n_\gamma$ from cosmology



K.A. Olive et al. (Particle Data Group), Chin. Phys. C38, 090001 (2014)

Why investigate neutron β-decay?

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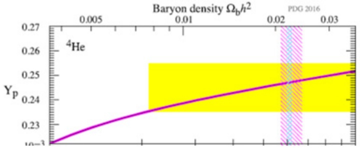
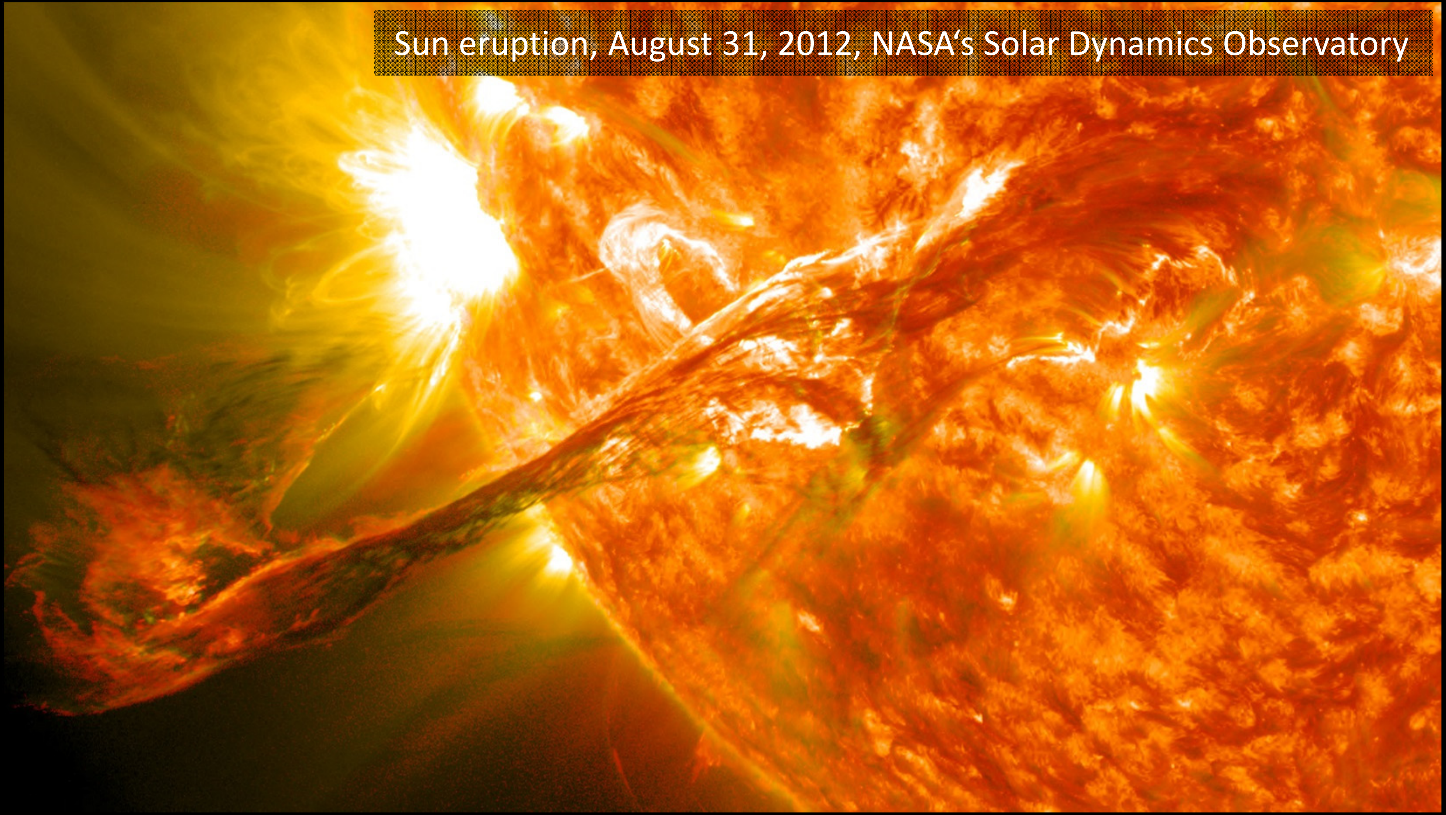


Energy generation within the Sun



Sun eruption, August 31, 2012, NASA‘s Solar Dynamics Observatory

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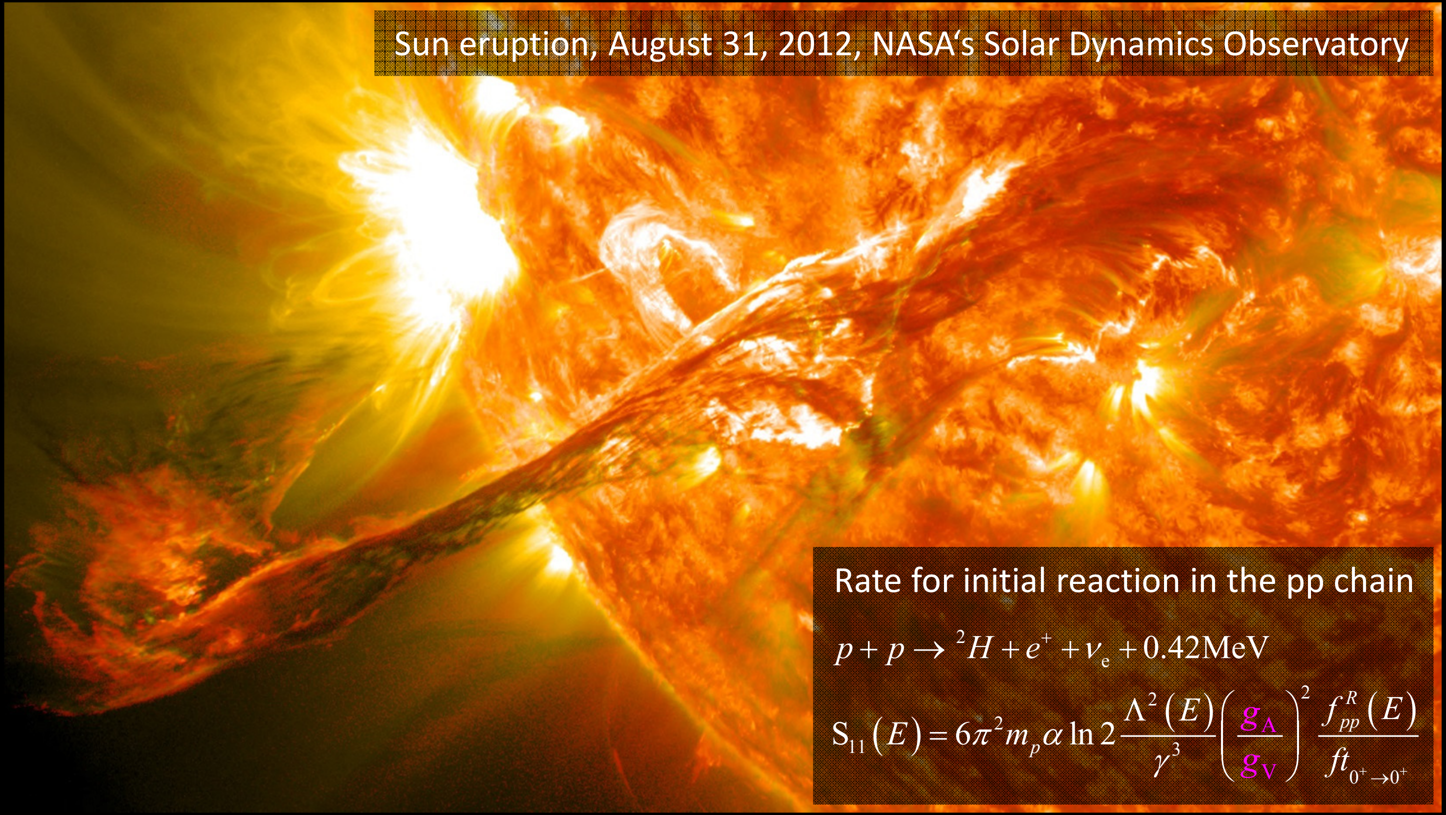


Sun eruption, August 31, 2012, NASA‘s Solar Dynamics Observatory

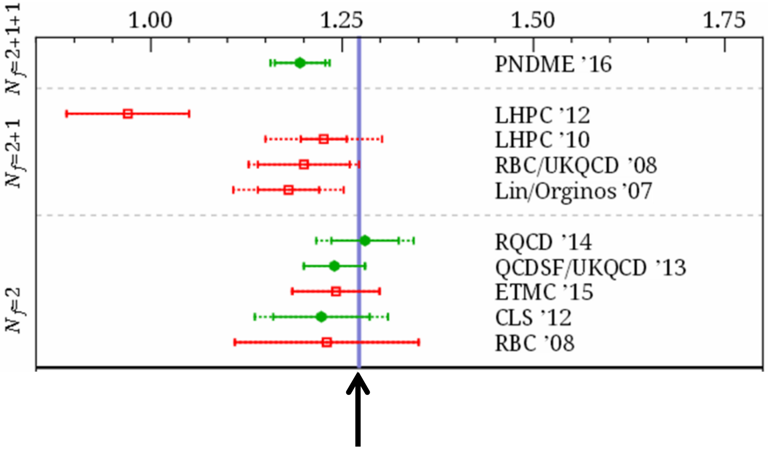
Rate for initial reaction in the pp chain

$$p + p \to {}^2H + e^+ + \nu_e + 0.42\text{MeV}$$

$$S_{11}(E) = 6\pi^2 m_p \alpha \ln 2 \frac{\Lambda^2(E)}{\gamma^3}\left(\frac{g_A}{g_V}\right)^2 \frac{f_{pp}^R(E)}{ft_{0^+\to 0^+}}$$

Current status of g_A / g_V

Lattice QCD

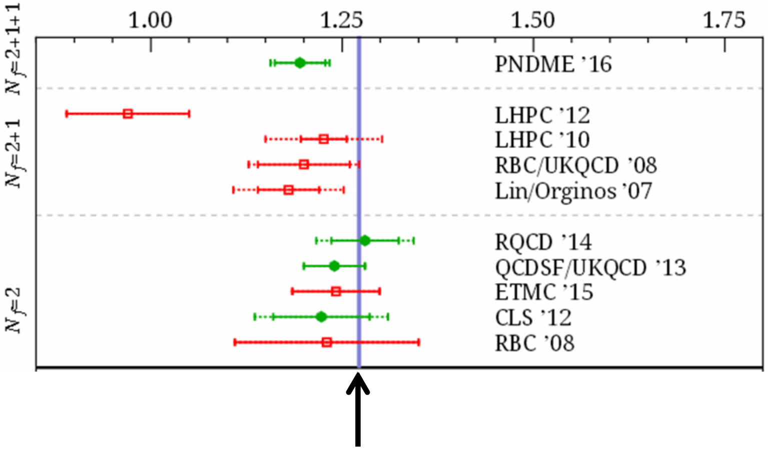


exp. (PDG 2015)

T. Bhattacharya et al., LA-UR-16-20522, arXiv:1606.07049 (2016)

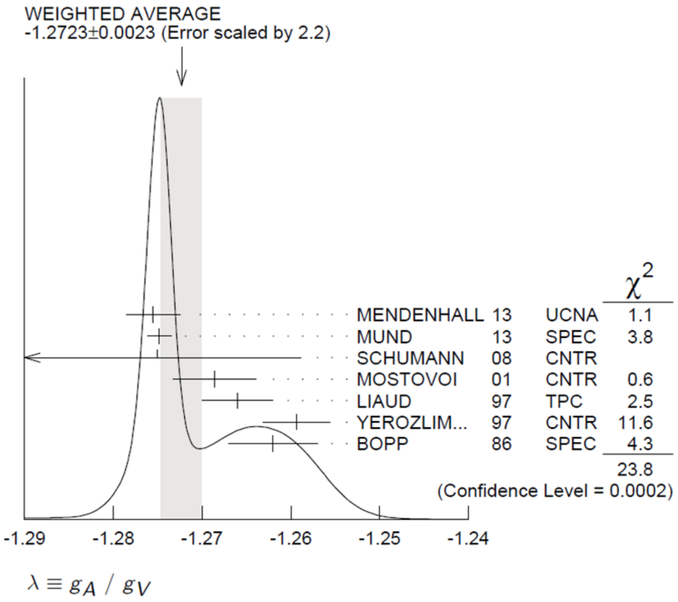
Current status of $g_{\mathrm{A}}/g_{\mathrm{V}}$

Lattice QCD



exp. (PDG 2015)

Neutron β-decay exp.



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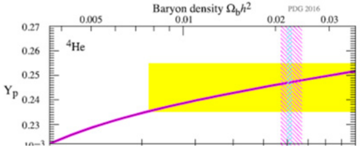

- Provide value of λ for other fields of research
  - Big Bang nucleosynthesis, energy generation in Sun, neutron star formation
  - detection efficiency of neutrino and LHC detectors
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Neutron β-decay

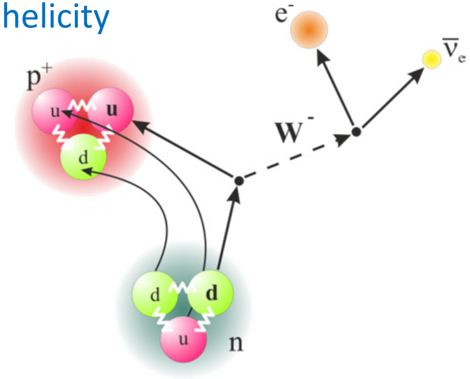
$\mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^- + \bar{\nu}_\mathrm{e} + 782.334\mathrm{keV}$:

- prototype of weak interactions
- described by $V-A$ theory: $H_{\mathrm{V-A}} = \frac{G_\mathrm{F} V_\mathrm{ud}}{\sqrt{2}} \langle \mathrm{p} | \gamma_\mu \left(1 + \frac{g_\mathrm{A}}{g_\mathrm{V}} \gamma^5 \right) | \mathrm{n} \rangle \langle \mathrm{e}^- | \gamma_\mu (1 - \gamma_5) | \nu_\mathrm{e} \rangle + \mathrm{h.c.}$

quark mixing

nucleon structure

helicity



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- lifetime:

coupling strength

$$\tau_\mathrm{n} = \frac{1}{|V_\mathrm{ud}|^2} \frac{(4908.7 \pm 1.9)\mathrm{s}}{\left(1 + 3|\lambda|^2\right)} = 880.3(1.1)\mathrm{s}$$

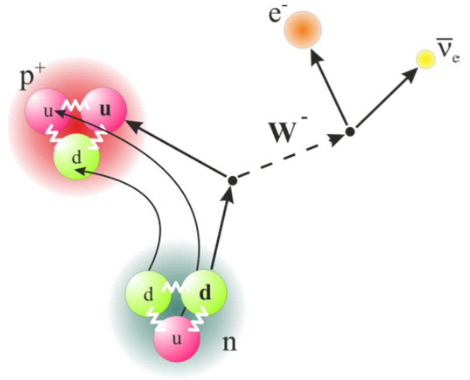
1×10^{-3}

Fri 11:40 SY

$$\lambda = g_\mathrm{A} / g_\mathrm{V}$$

$$g_\mathrm{V} = G_\mathrm{F} \cdot V_\mathrm{ud}$$

μ-decay



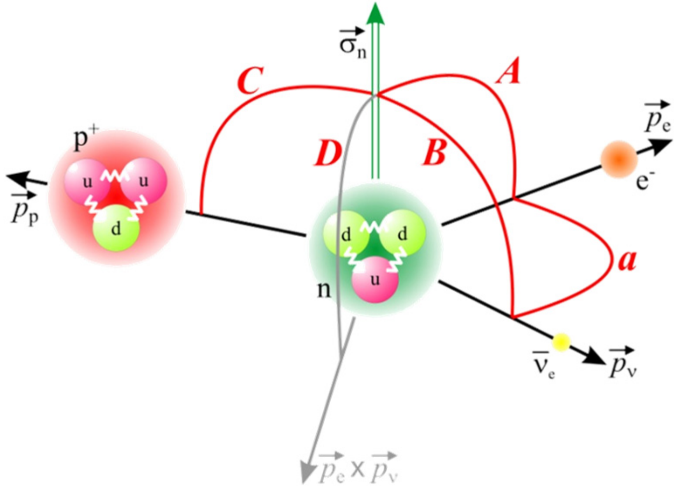
A. Czarnecki et al., PR D70, 093006 (2004)

The neutron alphabet

$$\frac{\mathrm{d}^3\Gamma}{\mathrm{d}E_\mathrm{e}\mathrm{d}\Omega_\mathrm{e}\mathrm{d}\Omega_\nu} = \frac{1}{2(2\pi)^5} \overbrace{G_\mathrm{F}^2 \left|V_\mathrm{ud}\right|^2 \left(1+3\left|\lambda\right|^2\right)}^{\propto\, \tau_\mathrm{n}^{-1}} p_\mathrm{e} E_\mathrm{e} \left(E_0 - E_\mathrm{e}\right)^2$$

$$\times\left[1 + a\frac{\vec{p}_\mathrm{e}\cdot\vec{p}_\nu}{E_\mathrm{e}E_\nu} + b\frac{m_\mathrm{e}}{E_\mathrm{e}} + \frac{\langle\vec{\sigma}_\mathrm{n}\rangle}{\vec{\sigma}_\mathrm{n}}\cdot\left(A\frac{\vec{p}_\mathrm{e}}{E_\mathrm{e}} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_\mathrm{e}\times\vec{p}_\nu}{E_\mathrm{e}E_\nu}\right)\right]$$

J.D. Jackson et al., PR106, 517 (1957)



The neutron alphabet *within SM*

$$\frac{\mathrm{d}^3\Gamma}{\mathrm{d}E_\mathrm{e}\mathrm{d}\Omega_\mathrm{e}\mathrm{d}\Omega_\nu} = \frac{1}{2(2\pi)^5} \overbrace{G_\mathrm{F}^2 |V_\mathrm{ud}|^2 \left(1+3|\lambda|^2\right)}^{\propto\, \tau_\mathrm{n}^{-1}} p_\mathrm{e} E_\mathrm{e} \left(E_0 - E_\mathrm{e}\right)^2$$

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$$\times\left[1 + a\frac{\vec{p}_\mathrm{e}\cdot\vec{p}_\nu}{E_\mathrm{e}E_\nu} + b\frac{m_\mathrm{e}}{E_\mathrm{e}} + \frac{\langle\vec{\sigma}_\mathrm{n}\rangle}{\vec{\sigma}_\mathrm{n}}\cdot\left(A\frac{\vec{p}_\mathrm{e}}{E_\mathrm{e}} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_\mathrm{e}\times\vec{p}_\nu}{E_\mathrm{e}E_\nu}\right)\right]$$

- 2 unknown parameters

  V_ud, $\lambda = g_\mathrm{A}/g_\mathrm{V}$

- 20 or more observables

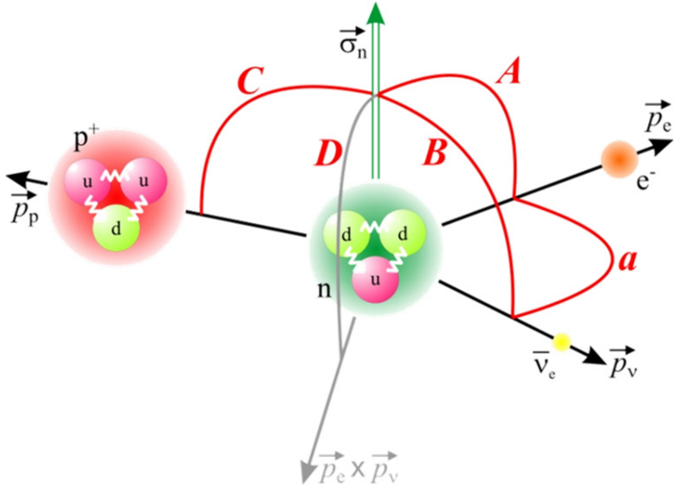
  τ_n, a, b, A, B, C, D, …

  $$a = \frac{1-|\lambda|^2}{1+3|\lambda|^2}\ , \qquad A = -2\frac{|\lambda|^2+\mathrm{Re}(\lambda)}{1+3|\lambda|^2}$$

  $$A(T_\mathrm{e}) = A\cdot\left(1+c+\underbrace{a_\mathrm{WM}\left(T_\mathrm{e},\lambda,f_2\right)}_{\approx 2\%}\right)$$

- yet unmeasured

  b, f_2



Current status of neutron alphabet

Observable	Standard Model	Status PDG 2015
Lifetime	$\tau_{\mathrm{n}} = \frac{1}{\lvert V_{\mathrm{ud}}\rvert^2} \frac{(4908.7 \pm 1.9)\,\mathrm{s}}{\left(1+3\lvert\lambda\rvert^2\right)}$	$\Delta\tau_n/\tau_n = 1 \times 10^{-3}$
Ratio of weak coupling constants	$\lambda = g_{\mathrm{A}}/g_{\mathrm{V}} = \lvert\lambda\rvert e^{i\phi}$	$\Delta\lambda/\lambda = 2 \times \boxed{10^{-3}}$
Electron-neutrino correlation	$a = \frac{1-\lvert\lambda\rvert^2}{1+3\lvert\lambda\rvert^2}$	$\Delta a/a = 3.9 \times \boxed{10^{-2}}$
Fierz interference term	$b = 0$	yet unmeasured
Beta asymmetry	$A = -2\frac{\lvert\lambda\rvert^2 + \lvert\lambda\rvert\cos\phi}{1+3\lvert\lambda\rvert^2}$	$\Delta A/A = 8 \times 10^{-3}$
Neutrino asymmetry	$B = 2\frac{\lvert\lambda\rvert^2 - \lvert\lambda\rvert\cos\phi}{1+3\lvert\lambda\rvert^2}$	$\Delta B/B = 3 \times 10^{-3}$
Proton asymmetry	$C = -0.27484(A+B)$	$\Delta C/C = 1.1 \times 10^{-2}$
Triple correlation	$D = 2\frac{\lvert\lambda\rvert\sin\phi}{1+3\lvert\lambda\rvert^2} \equiv 0 \qquad \phi = 180°$	$D = (-1 \pm 2) \times 10^{-4}$ $\phi = (180.02 \pm 0.03)°$

K.A. Olive et al. (Particle Data Group), Chin. Phys. C38, 090001 (2014)

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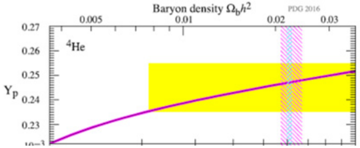

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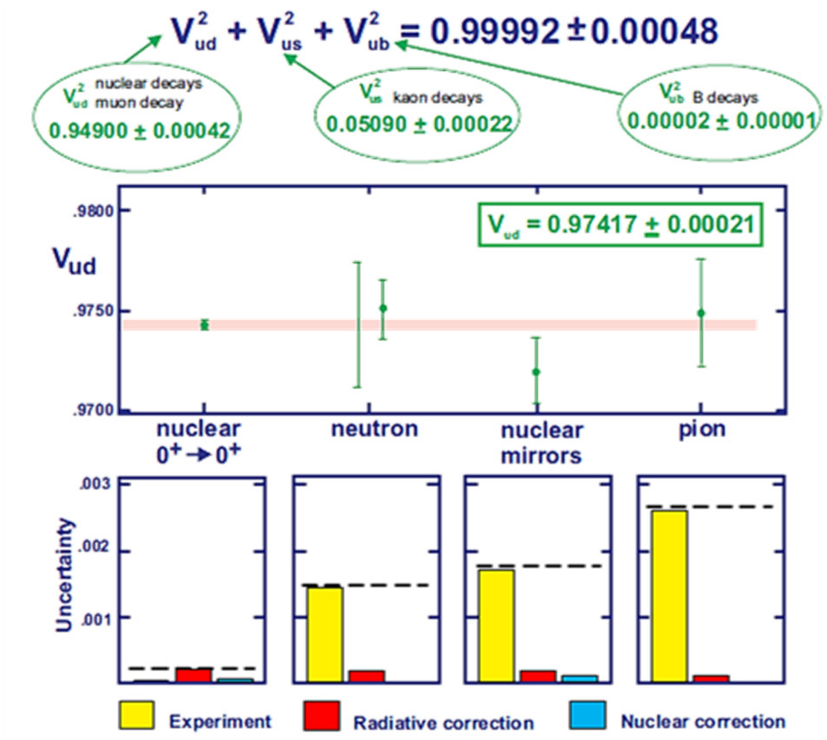
- Test the Standard Model of particle physics
  - self-consistency of the Standard Model
  - unitarity of Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix

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

Present best test of the Standard Model

$$1 \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 - (1 \pm 5) \times 10^{-4}$$

Current status of CKM unitarity



J.C. Hardy and I.S. Towner, Phys. Rev. C 91, 025501 (2015)
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Based on J. Hardy, Solvay Workshop, Brussels, 2014

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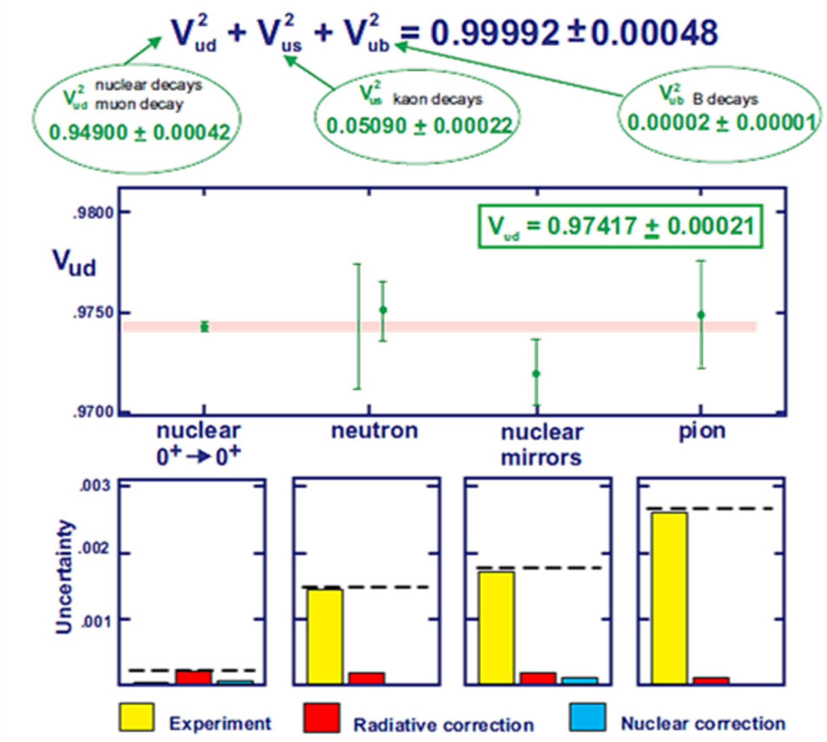
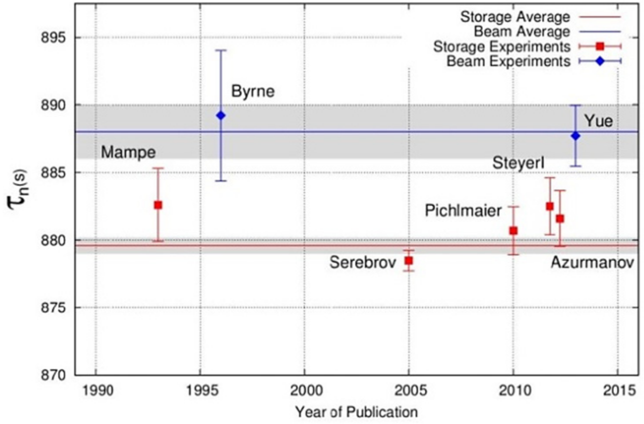


Current status of τ_n



→ *Beam* and *bottle* averages differ by ~3.8σ

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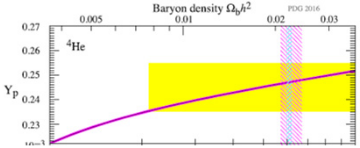

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- Search for `physics beyond´ and new symmetry concepts

The neutron alphabet *beyond SM*

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J.D. Jackson et al., PR106, 517 (1957)

$$\times\left[1+a\frac{\vec{p}_\mathrm{e}\cdot\vec{p}_\nu}{E_\mathrm{e}E_\nu}+b\frac{m_\mathrm{e}}{E_\mathrm{e}}+\frac{\langle\vec{\sigma}_\mathrm{n}\rangle}{\vec{\sigma}_\mathrm{n}}\cdot\left(A\frac{\vec{p}_\mathrm{e}}{E_\mathrm{e}}+B\frac{\vec{p}_\nu}{E_\nu}+D\frac{\vec{p}_\mathrm{e}\times\vec{p}_\nu}{E_\mathrm{e}E_\nu}\right)\right]$$

- 9 unknown parameters:

  V_ud, L_j, R_j, j=V, A, S, T
- 20 or more observables:

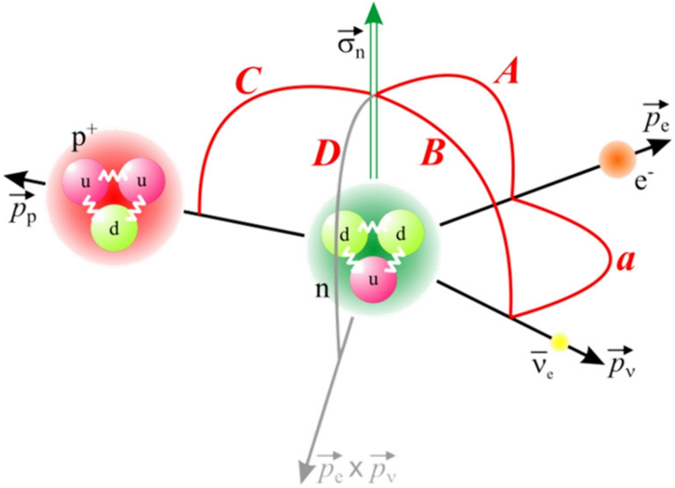
  τ_n, a, b, A, B, C, D, …

$$\xi a = \left|L_V\right|^2-\left|L_A\right|^2-\left|L_S\right|^2+\left|L_T\right|^2+\left|R_V\right|^2-\left|R_A\right|^2-\left|R_S\right|^2+\left|R_T\right|^2$$

$$\xi b = 2\Re\left(L_SL_V^*+3L_AL_T^*+R_SR_V^*+3R_AR_T^*\right)$$ yet unmeasured

$$\xi A = -2\Re\left(\left|L_A\right|^2+L_VL_A^*-\left|L_T\right|^2-L_SL_T^*-\left|R_A\right|^2-R_VR_A^*+\left|R_T\right|^2+R_SR_T^*\right)$$

$$\xi = \left|L_V\right|^2+3\left|L_A\right|^2+\left|L_S\right|^2+3\left|L_T\right|^2+\left|R_V\right|^2+3\left|R_A\right|^2+\left|R_S\right|^2+3\left|R_T\right|^2$$



F. Glück *et al.*, NP A593, 125 (1995)

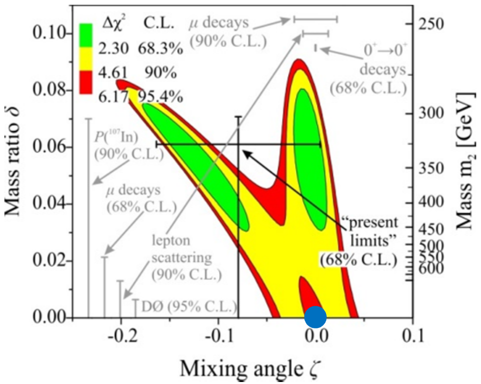
Sensitivity to `new physics´

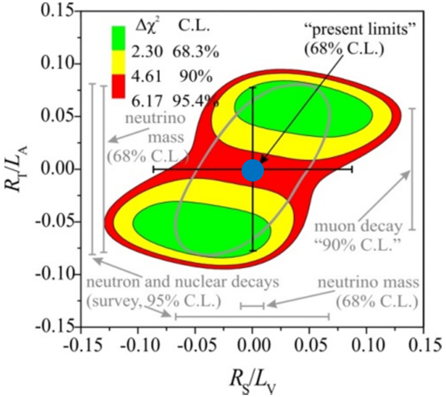
Right-handed $V + A$

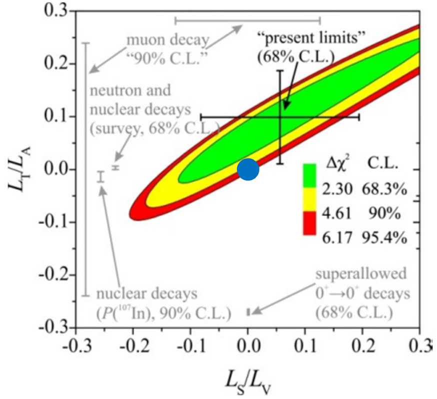
Right-handed S, T

Left-handed S, T

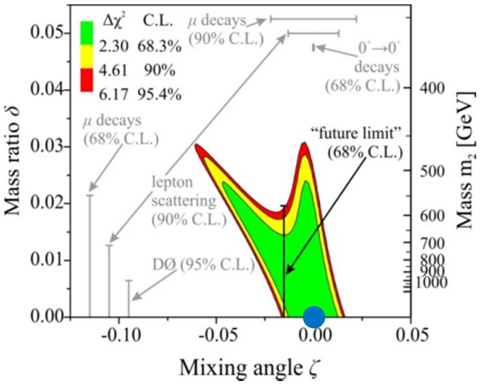
Present 2015

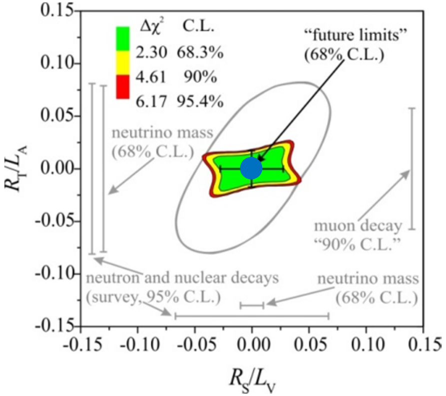


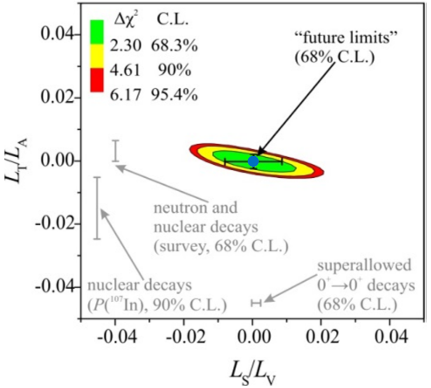




Future toy model







G. Konrad *et al.,* in: Proc. BEYOND 2010, World Scientific, 660, 2011, arXiv: 1007.3027v2 (2010)

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J.D. Jackson et al., PR106, 517 (1957)

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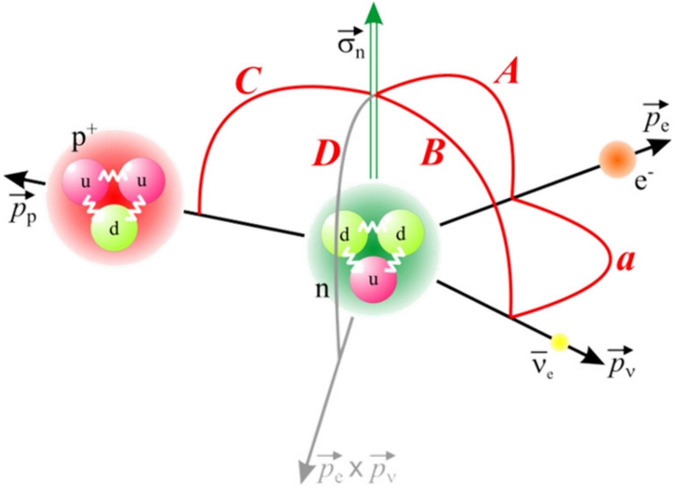
$$\xi A=-2\Re\left(\left|L_A\right|^2+L_VL_A^*-\left|L_T\right|^2-L_SL_T^*-\left|R_A\right|^2-R_VR_A^*+\left|R_T\right|^2+R_SR_T^*\right)$$

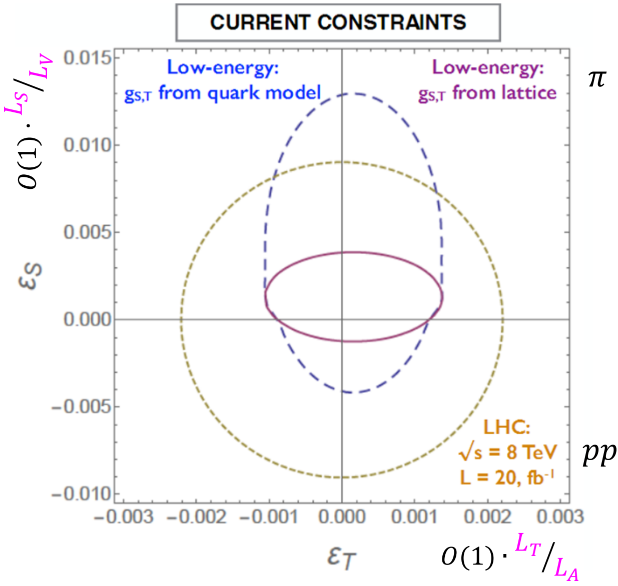
$$\xi=\left|L_V\right|^2+3\left|L_A\right|^2+\left|L_S\right|^2+3\left|L_T\right|^2+\left|R_V\right|^2+3\left|R_A\right|^2+\left|R_S\right|^2+3\left|R_T\right|^2$$



F. Glück *et al.*, NP A593, 125 (1995)

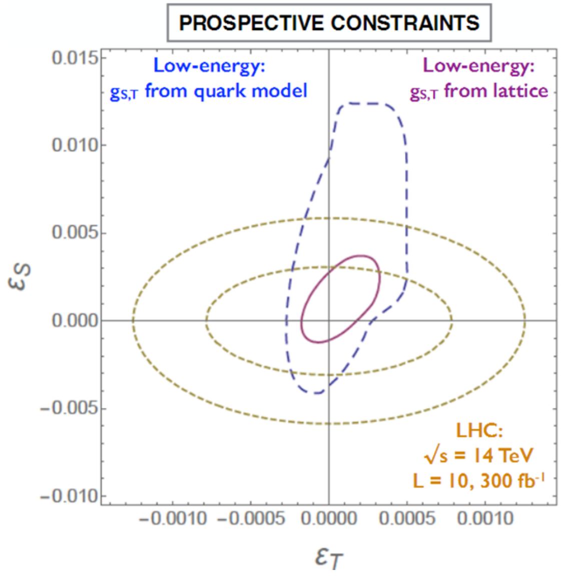
Prospects for *S* and *T* interactions in LHC era

$$d\Gamma_b = \left(1 + b\frac{m_e}{E_e}\right) d\Gamma_{\mathrm{SM}}$$



$\pi \rightarrow e\nu\gamma, 0^+ \rightarrow 0^+$

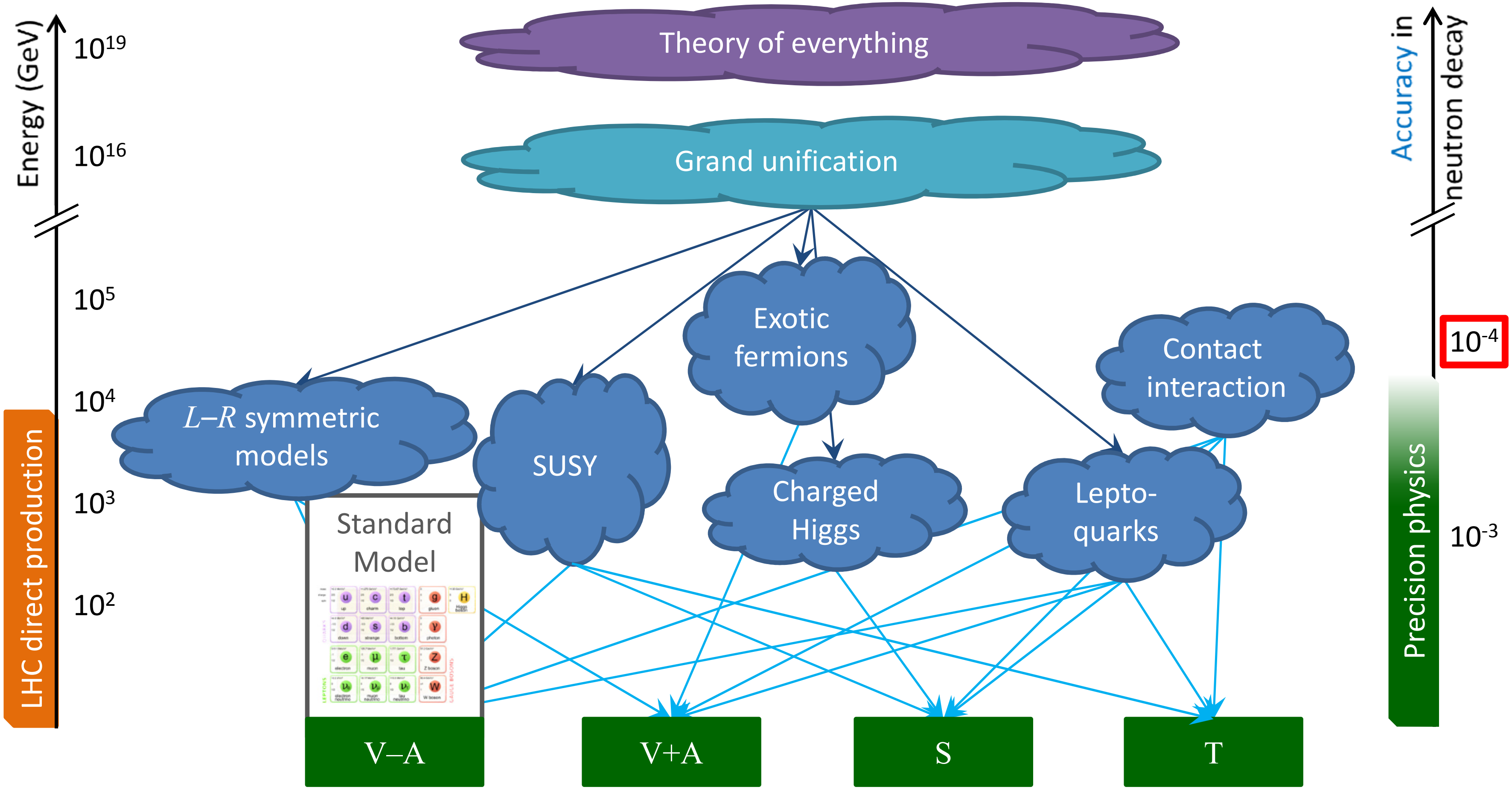
$pp \rightarrow e\nu + \mathrm{X}$



b, B, $b_{^6He}$
at 10^{-3} level

- ➢ 10^{-3} level b measurements complementary to improved LHC results

T. Bhattacharya et al., LA-UR-16-20522, arXiv:1606.07049 (2016)
see also: O. Naviliat-Cuncic & M. González-Alonso, Ann. Phys. (Berlin) 525 (2013) 600



Energy (GeV)

10^{19}

10^{16}

10^{5}

10^{4}

10^{3}

10^{2}

LHC direct production

Theory of everything

Grand unification

Exotic fermions

L–R symmetric models

SUSY

Contact interaction

Charged Higgs

Lepto-quarks

Standard Model

V–A

V+A

S

T

Accuracy in neutron decay

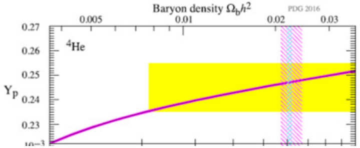
10^{-4}

10^{-3}

Precision physics

Why investigate neutron β-decay?

- Provide value of τ_n
  - primordial ^{4}He abundance

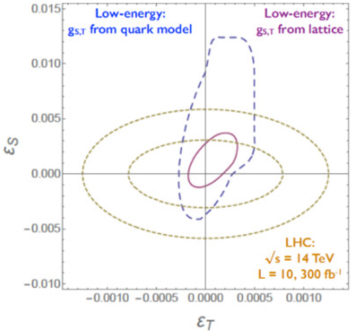


- Provide value of λ for other fields of research
  - Big Bang nucleosynthesis, energy generation in Sun, neutron star formation
  - detection efficiency of neutrino and LHC detectors
  - key benchmark for LQCD calculation of hadron structure (exascale computing)

- Test the Standard Model of particle physics
  - self-consistency of the Standard Model
  - unitarity of Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix

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

- Search for \`physics beyond´ and new symmetry concepts
  - right-handed admixtures, exotic scalar and tensor admixtures
  - left-right symmetry, supersymmetry (SUSY), leptoquarks, etc.
  - SUSY deviations from CKM unitarity ≥ 10^{-4} fall in LHC inaccessible region
  - 10^{-3} level b measurements complementary to improved LHC results



Why investigate neutron β-decay?

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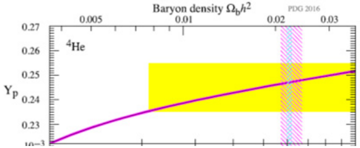

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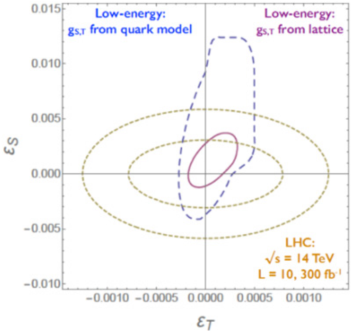
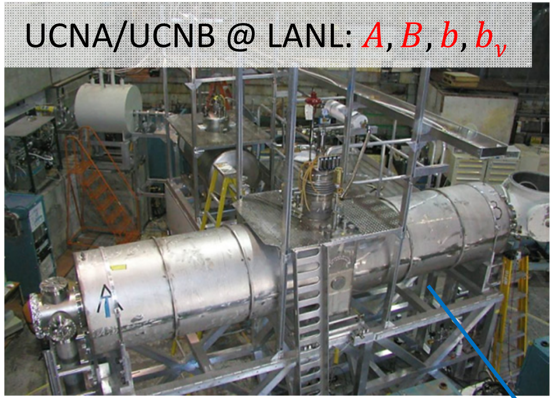
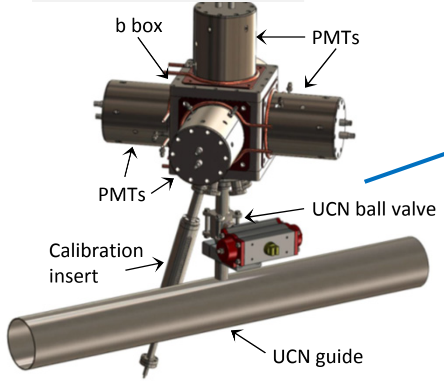


Experiments to measure Fierz term b

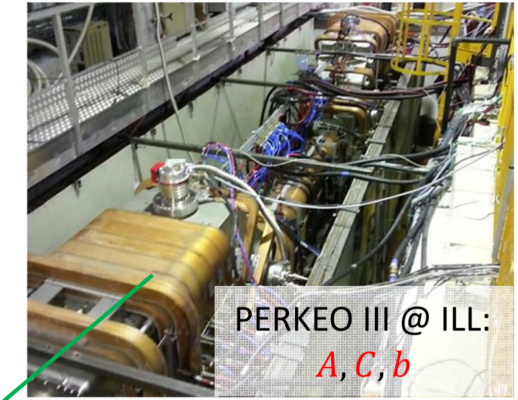
UCNA/UCNB @ LANL: A, B, b, b_ν



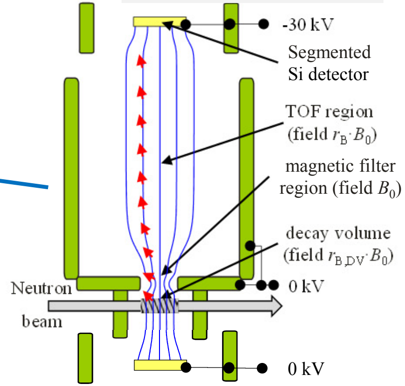
UCNb @ LANL: b



PERKEO III @ ILL: A, C, b

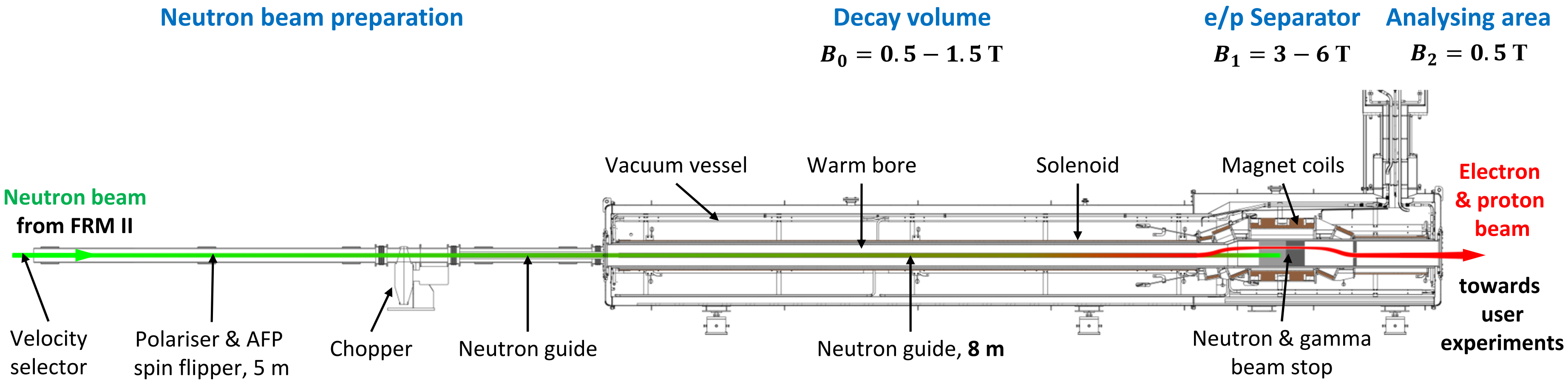


Nab @ SNS: a, b



New facility PERC @ FRM II

Tue 16:35 SY



Statistics	high flux $\phi=2\times10^{10}$ cm^{-2}s^{-1} and high decay rate = 1×10^{6} m^{-1}s^{-1}
Sensitivity	improved by up to 2 orders of magnitude to sub-10^{-4}-level
Systematics	$\leq 10^{-4}$ for e^{-}), especially $\Delta P/P=10^{-4}$
Versatility	a, b, A, B, C, f_2, …
Status	manufacturing within 11, commissioning within 17 months

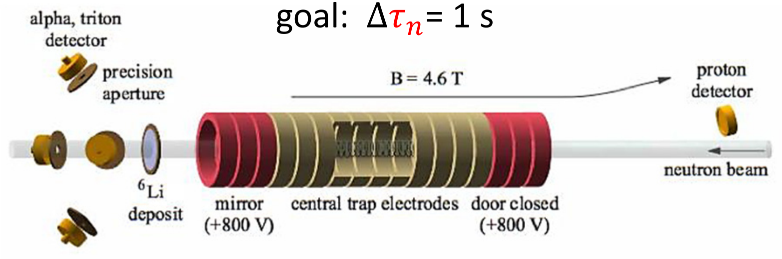
C. Klauser, PhD, TU Wien, 2013
C. Klauser et al, JPCS340, 012011 (2012)

D. Dubbers et al., NIM A 596, 238 (2008)
G. K. et al., J. Phys.: Conf. Ser. 340, 012048 (2012)

Experiments to measure τ_n

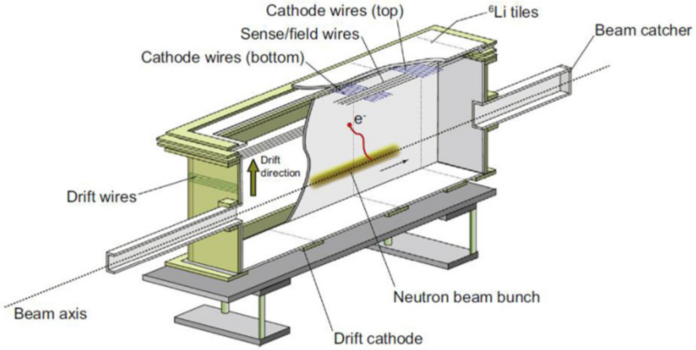
Beam method @ NIST

goal: $\Delta\tau_n = 1$ s

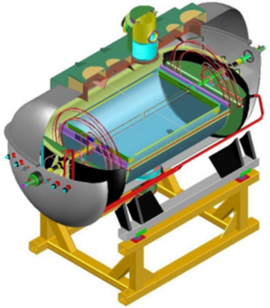


Beam method @ J-PARC

goal: $\Delta\tau_n = 1$ s

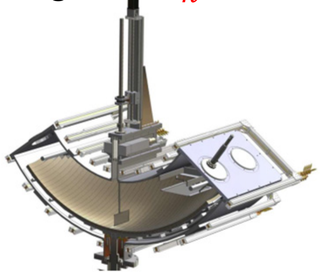


Big Gravitrap @ ILL



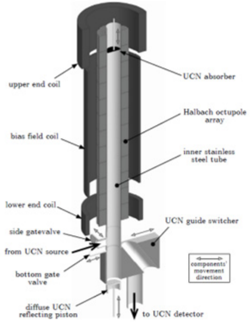
UCNτ @ LANL

goal: $\Delta\tau_n < 1$ s



HOPE @ ILL

goal: $\Delta\tau_n < 0.5$ s



PENeLOPE @ FRM II

goal: $\Delta\tau_n = 0.1$ s

Neutron EDM

EDM Reminder

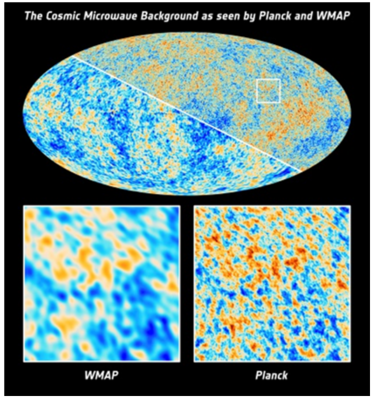
Baryon asymmetry of Universe

- Electroweak SM expectation:

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-18}$$

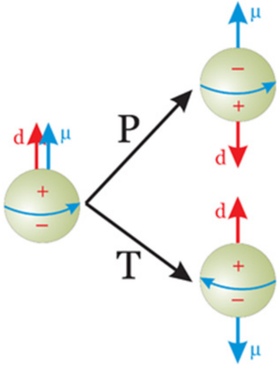
- Cosmological observation:

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$$



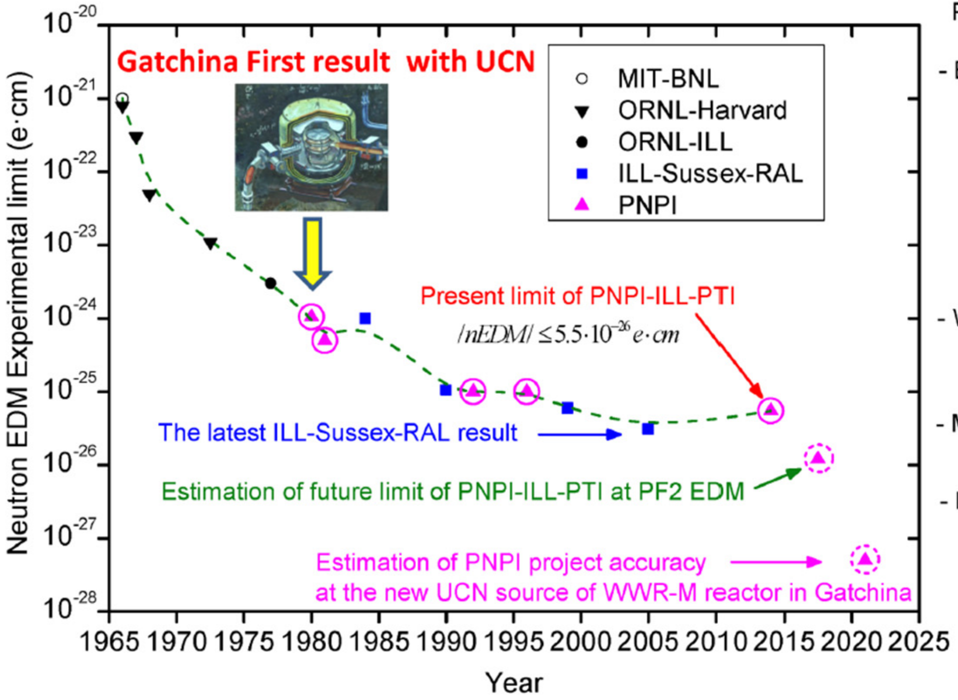
Sakharov criteria

1. Baryon number B violation
2. $\mathcal{C}$, $\mathcal{CP}$ violation
3. Thermal non-equilibrium



Non-zero EDM violates $\mathcal{T}$ and $\mathcal{CP}$

Neutron EDM experiments



Gatchina First result with UCN

Present limit of PNPI-ILL-PTI

$/nEDM/ \leq 5.5 \cdot 10^{-26} e \cdot cm$

The latest ILL-Sussex-RAL result

Estimation of future limit of PNPI-ILL-PTI at PF2 EDM

Estimation of PNPI project accuracy
at the new UCN source of WWR-M reactor in Gatchina

Theoretical
Prediction:

- Electromagnetic
- Weinberg Multi-Higgs
- Minimal SUSY

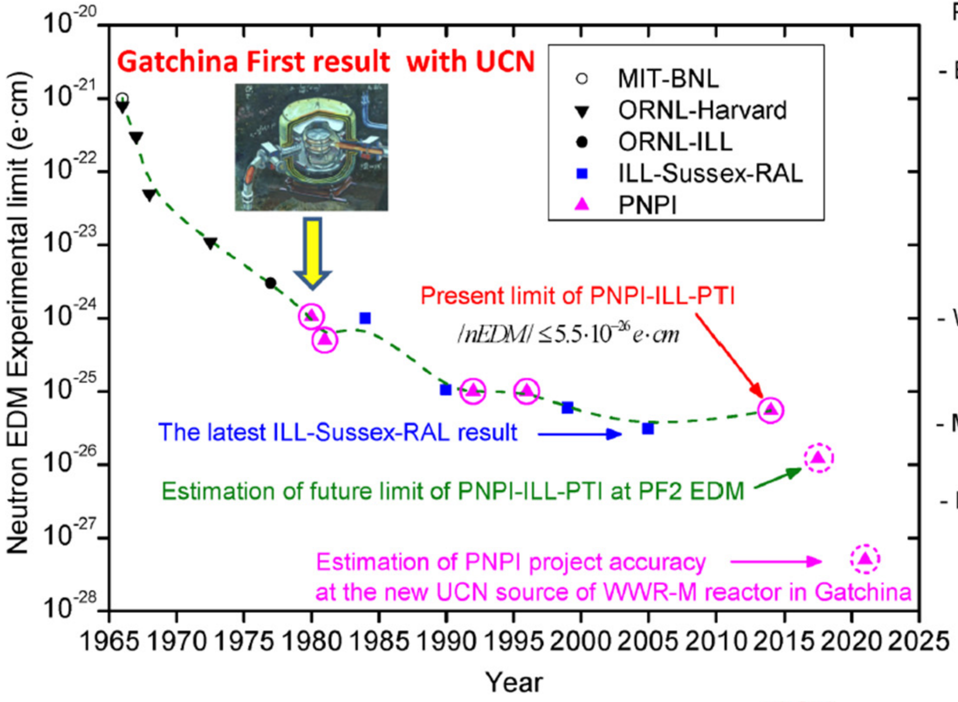
Cosmology

- Left-Right Symm.

UCN source at WWR-M reactor

Based on A. Serebrov, UCN Workshop, Mainz, 2016

Neutron EDM experiments



Theoretical
Prediction:

- Electromagnetic
- Weinberg Multi-Higgs
- Minimal SUSY

Cosmology

- Left-Right Symm.

UCN source at WWR-M reactor

nEDM @ PSI

2015 Pendlebury et al.:

Phys. Rev. D92, 092003 (2015)

$d_n < 2.9 \times 10^{-26}$ e·cm

2016 *expected* by end of year

$d_n < 1.16 \times 10^{-26}$ e·cm

n2EDM @ PSI

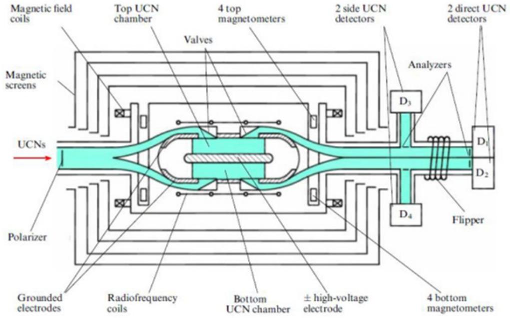
goal : $d_n < 5 \times 10^{-28}$ e·cm

Tue 15:40
– 16:20 SY

Based on A. Serebrov, UCN Workshop, Mainz, 2016

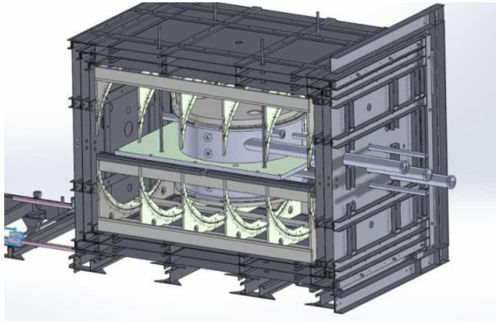
Neutron EDM experiments

PNPI-PTI-ILL @ ILL

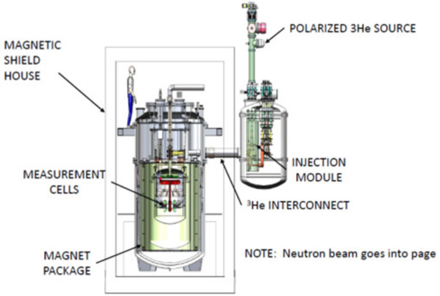


nEDM @ PSI

TUM/RAL/ILL @ ILL

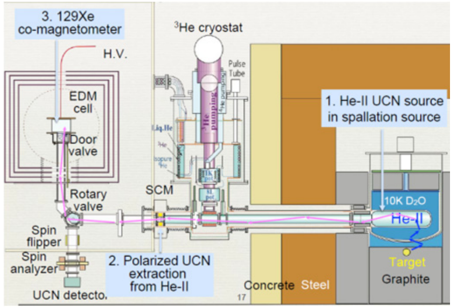


nEDM @ SNS

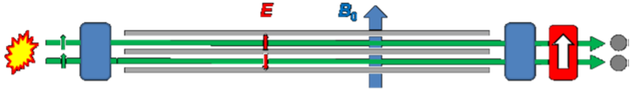


NOTE: Neutron beam goes into page

RCNP/TRIUMF



BeamEDM @ ESS



Summary and Outlook

- High-precision experiments with cold and ultra-cold neutrons address some of the unanswered questions in particle physics, astrophysics, and cosmology
- Neutron particle physics very versatile
- Large number of new neutron sources and experiments
- New facilities and technological developments now give window for significant improvement in precision by one to two orders of magnitude
- τ_n confirms $\eta = n_b/n_\gamma$ from cosmology
- Neutron alphabet deciphers the Standard Model of particle physics
- 10^{-3} level b measurements complementary to improved LHC results
- New limit on neutron EDM d_n < 2.9 $\times 10^{-26}$ e·cm (nEDM @ PSI)

Thanks to my colleagues @ SMI and TU Wien


ATI, Summer 2016