TECHNISCHE UNIVERSITÄT WIEN

Gravity resonance spectroscopy,

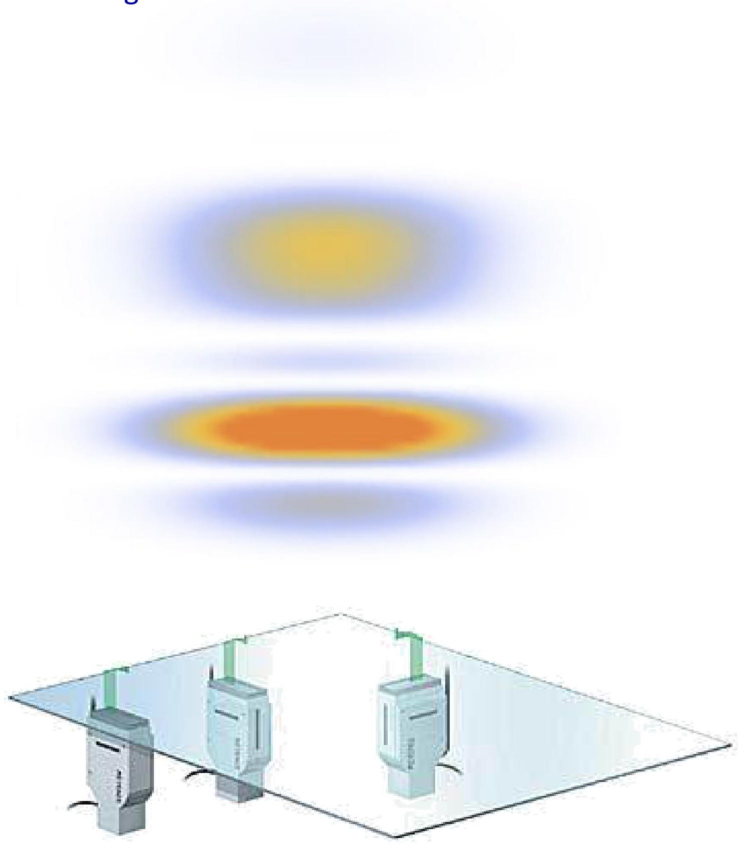
Lorentz violation, beyond-Riemann and entropic gravity

HARTMUT ABELE

HUMBOLDT KOLLEG 2022

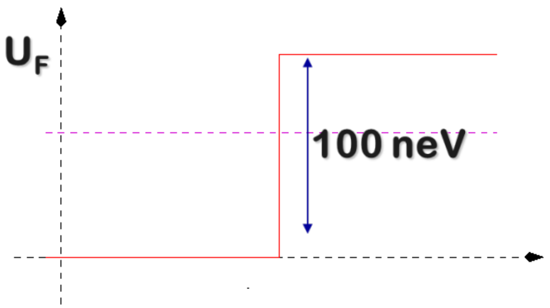
Free Fall at Short Distances

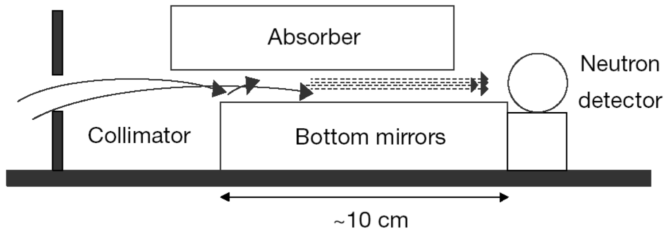
- A simple quantum mechanical system
  - A neutron with mass and spin
    - falling in the Earth's gravity potential
  - and a neutron reflector
    - made out of glass



Abele, Jenke, Lemmel, Nature 2019

- Reactor neutrons at ILL
  - 25 meV
- Ultra-cold Neutrons
  - @PF2 – ILL: T. Jenke
  - v = (7±1)m/s
  - U_F ~ 100 neV, 1…6 peV





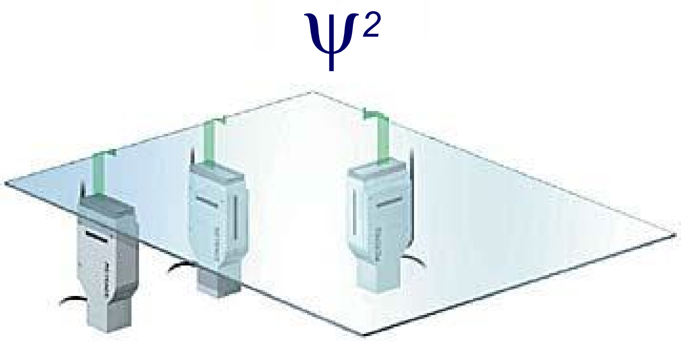
Nesvizhevsky et al.
Nature 415 299 (2002), Phys. Rev. D 67 102002 (2003).

*q*Bounce: Quantum States in the Gravity Potential

- Schrödinger Equation

$$-\frac{\hbar^2}{2m}\frac{d^2\Psi}{dz^2} + mgz\Psi = E\Psi$$

$$-\frac{\hbar^2}{2m}\frac{d^2\psi}{dx^2} = E\psi$$



- Characteristic length and energy scale

$$z_0 = -\left(\frac{\hbar^2}{2m_i m_g g}\right)^{1/3} = 5.87\,\mu\text{m} \qquad E_0 = -\left(\frac{\hbar^2 m_g{}^2 g^2}{2m_i}\right)^{1/3} = 0.602\,\text{peV}$$

- Change of variable $\tilde{z} = -\frac{z}{z_0} - \frac{E}{E_0}$

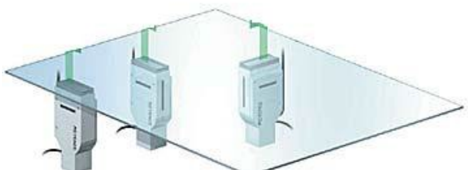
- Airy‘s Equation, and general Solution with AiryAi and AiryBi

$$-\frac{d^2\Psi}{d\tilde{z}^2} + z\Psi = 0 \qquad \psi(z) = aA_i(z) + bB_i(z)$$

*q*BOUNCE: Quantum States in the Gravity Potential

- Energy Eigenvalues are given by the Zeros of AiryAi

$$\tilde{z} = -\frac{z}{z_0} - \frac{E}{E_0} \qquad E_0 = -\left(\frac{\hbar^2 m_g{}^2 g^2}{2m_i}\right)^{1/3}$$



$$AiryAi(-\frac{E}{E_0}) = 0$$

Zeros of A_i	
1	-2.33810
2	-4.08794
3	-5.52055
4	-6.78670
5	-7.94413
6	-9.02265
7	-10.04017

$$E_1 = (2.33810)\left(\frac{\hbar^2 m g^2}{2}\right)^{\frac{1}{3}}$$

$$E_2 = (4.08794)\left(\frac{\hbar^2 m g^2}{2}\right)^{\frac{1}{3}}$$

$$E_3 = (5.52055)\left(\frac{\hbar^2 m g^2}{2}\right)^{\frac{1}{3}}$$

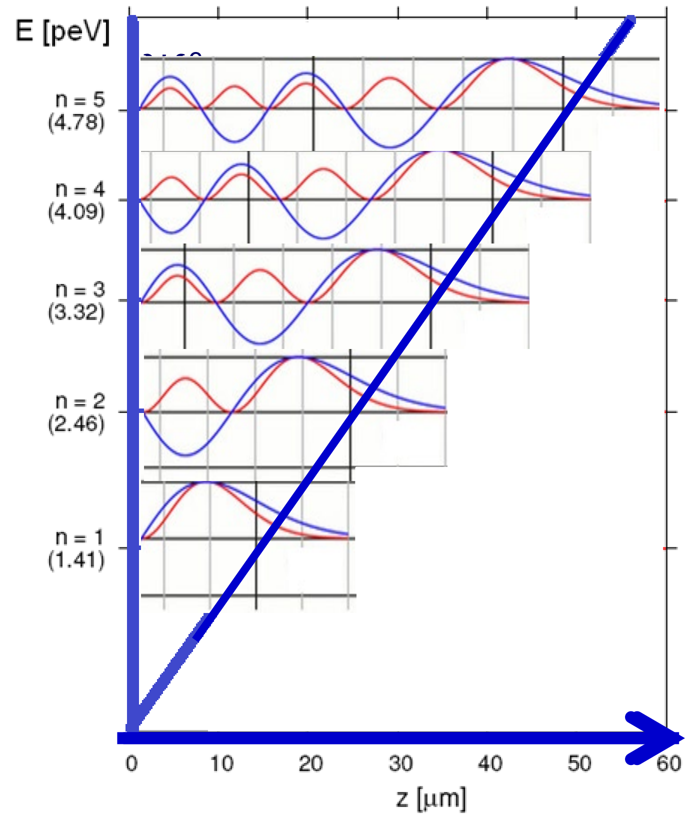
$$\Psi_1(\tilde{z},t) = c_1 Ai_1(\tilde{z}) \times e^{-i(E_1/\hbar)\times t}$$

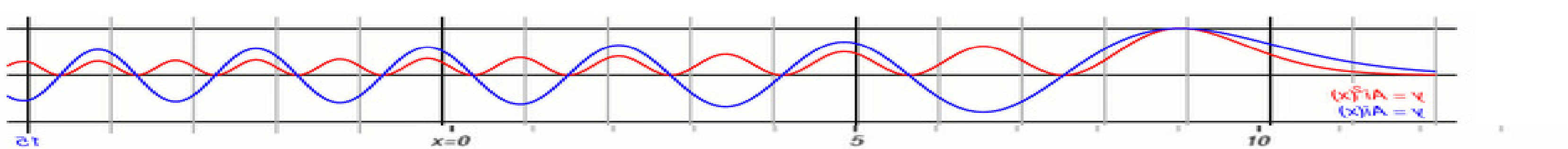
$$\Psi_2(\tilde{z},t) = c_2 Ai_2(\tilde{z}) \times e^{-i(E_2/\hbar)\times t}$$

$$+\ \Psi_3(\tilde{z},t) = c_3 Ai_3(\tilde{z}) \times e^{-i(E_3/\hbar)\times t}$$

$$\ldots$$

$$\Psi(\tilde{z},t) = \sum_{n=1}^{\infty} Ai_n(\tilde{z}) \times e^{-i(E_n/\hbar)\times t}$$





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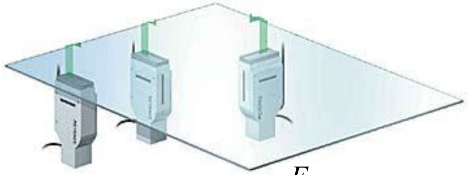

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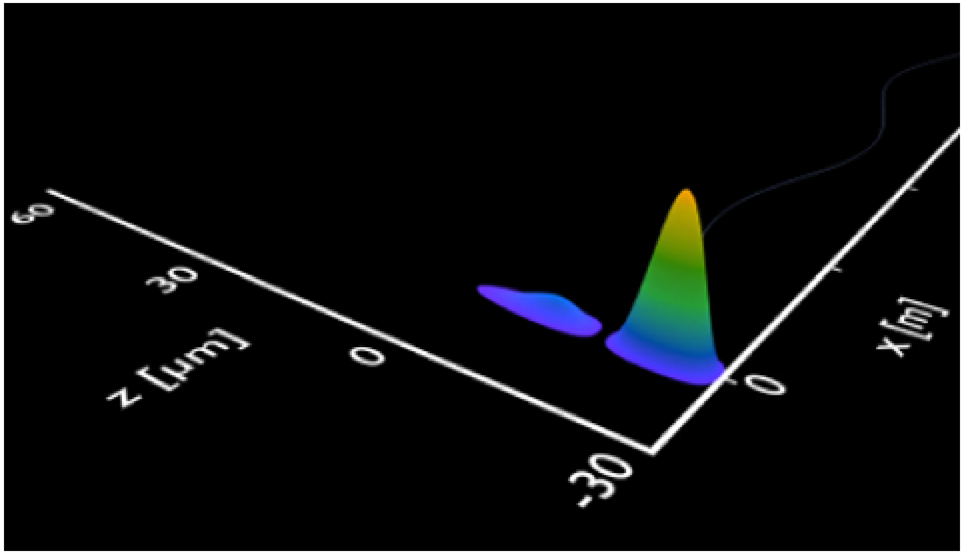
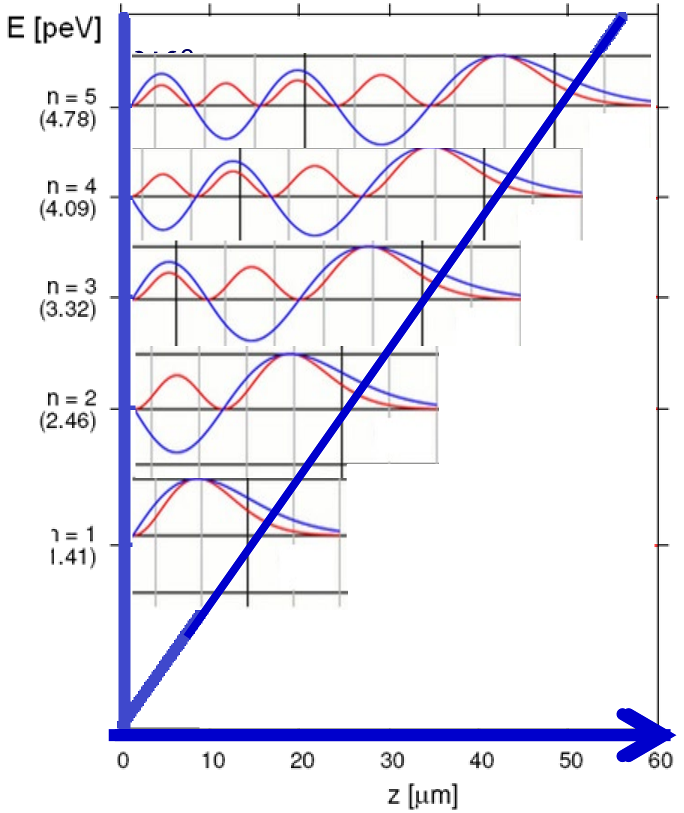
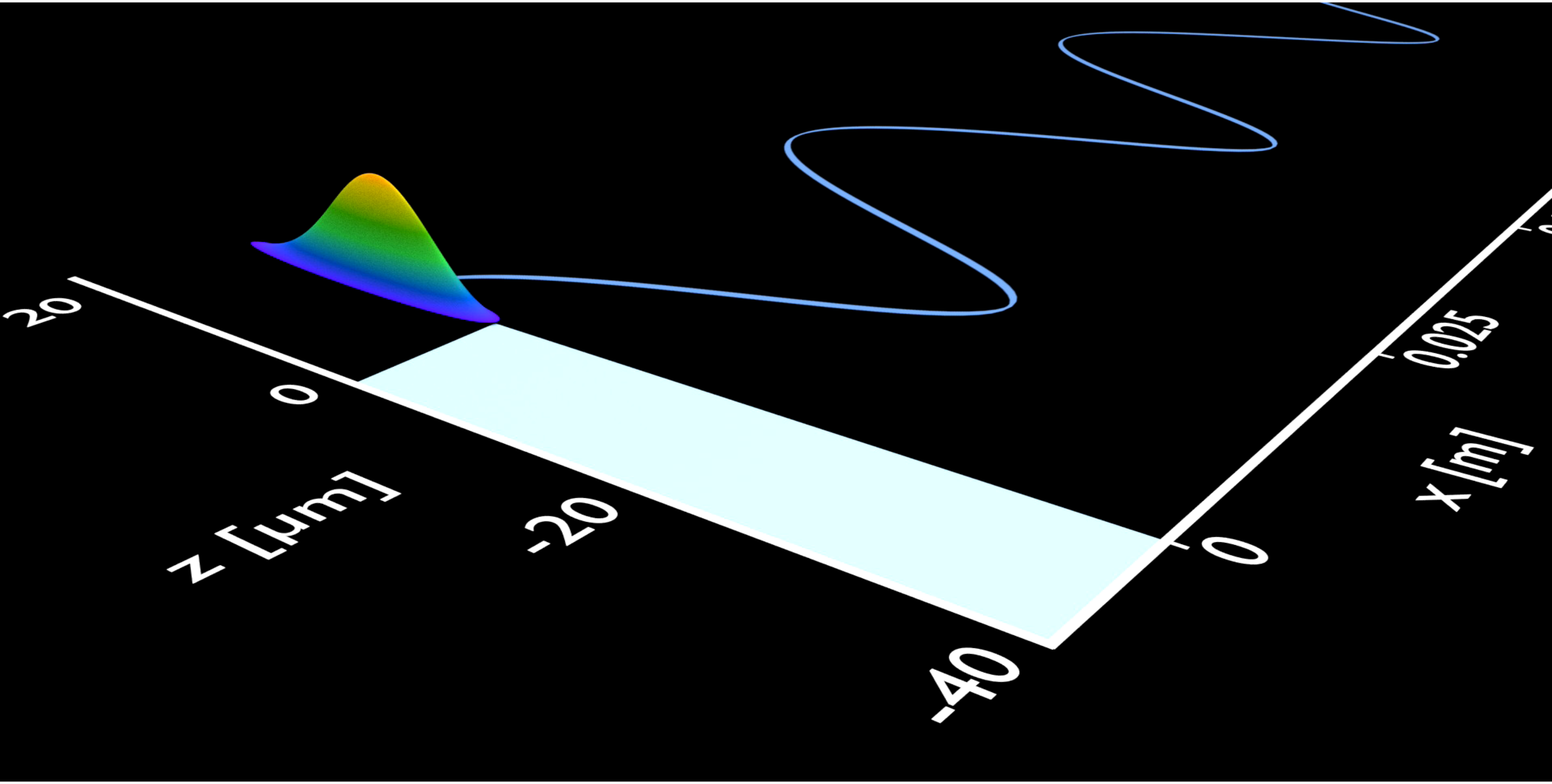
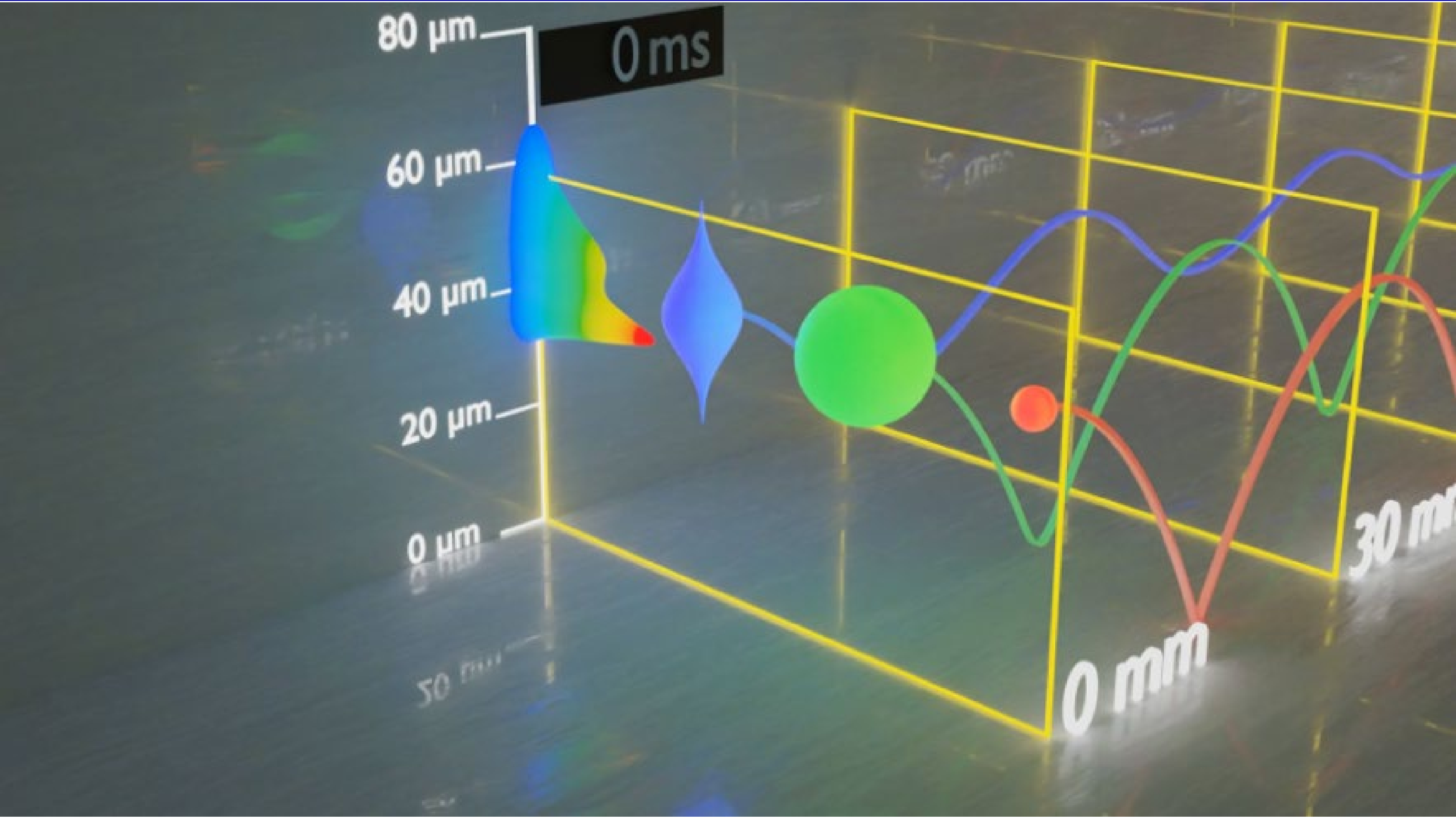




*q*BOUNCE



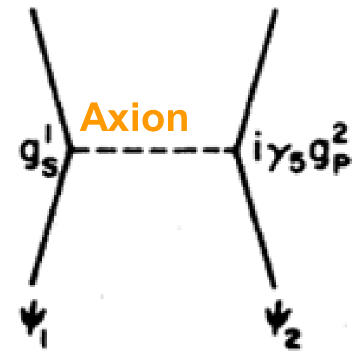
qBB



A neutron as an ideal object

- A neutron
  - is neutral
  - has small polarizability
  - probes small distances on the nm … µm – scale
  - gives access to gravity-parameters:
    - **mass, distance, energy momentum, torsion**
  - couples to scalar fields (if there is a coupling)
  - allows constraints on any possible new interaction at the level of sensitivity
    - Examples for hypothetical gravity-like forces or
    - **Dark Matter / Dark Energy fields**
    - **Chameleons? Symmetrons?**
  - has a spin
    - **Axions-exchange?**

Hypothetical New Interaction



- Is Lorentz Invariance violated?
  - Probing of violation of Lorentz invariance by ultracold neutrons in the Standard Model Extension
  - AN Ivanov, M Wellenzohn, H Abele, Phys. Lett. B, Physics Letters B 797, 134819 (2019)
- What about gravity theories based on geometries other than those of Riemann, Riemann-Cartan, etc. ("beyond-Riemann gravity")
  - Quantum gravitational states of ultracold neutrons as a tool for probing beyond-Riemann gravity, A. Ivanov, M. Wellenzohn, H. Abele, Phys. Lett. B. 822 (2021) 136640
- Is gravity an entropic force (E. Verlinde)
  - Decoherence-free entropic gravity: Model and experimental tests, AJ Schimmoller, G McCaul, H Abele, DI Bondar, Physical Review Research 3, 033065 (2021)

Addressing Quantum States

- State selector: put a neutron in the ground state |1>
- Resonant transition |1> $\rightarrow$ |x>, |2> $\rightarrow$ |x>, GRS
- Two mirror system:
  - tune energy levels
  - Charge of the neutron, J. Bosina
- Superposition of quantum states, the phase factor
  - Investigation of spacetime & cosmology
  - Search for hypothetical gravity-like interactions
  - By using the techniques of quantum interference via resonance spectroscopy

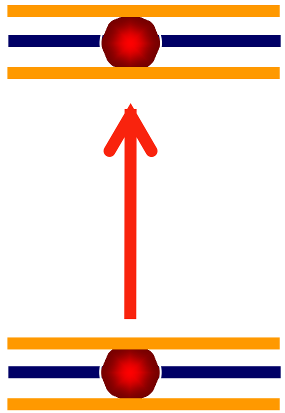
Frequency: Resonance Spectroscopy

- Quantum System, 2-Level System
- Coupling

$$E = h\nu$$

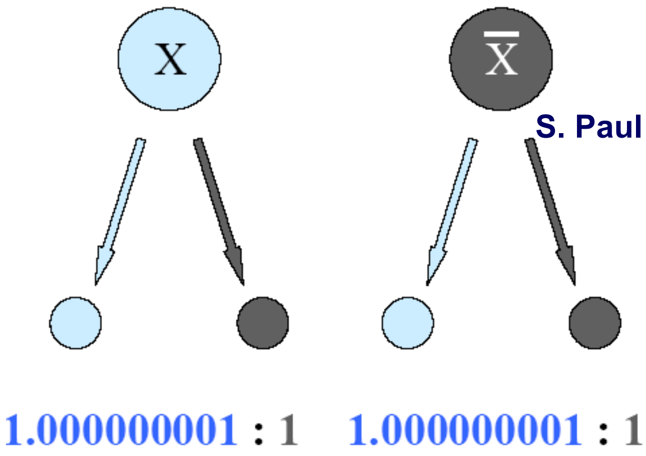
- Example:
  - NMR:
    - Magnetic Moment in
    - outer magnetic field
    - RF-field drives Transitions
  - Rabi – Spectroscopy
  - Ramsey Spectroscopy: Clocks, Spin Echo, EDM

$$4d_n E_{el} = \Delta\omega\hbar$$

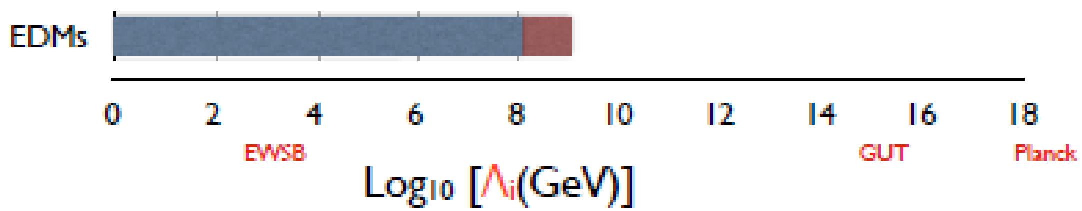


The electric dipole moment

- CP violation process: Why do we observe matter
  - Theory Standard Model: Baryons/Photons ~ 10^{-18}
  - Experiment: Baryons/Photons ~ 10^{-9}

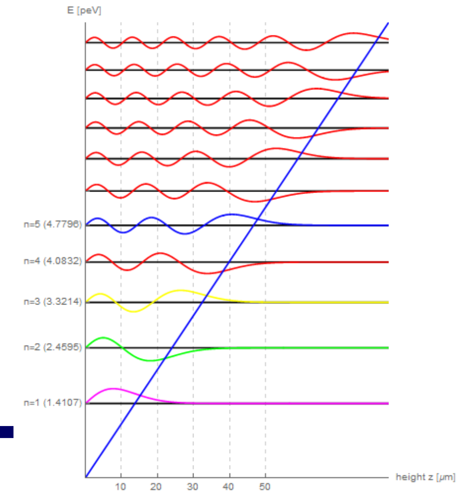


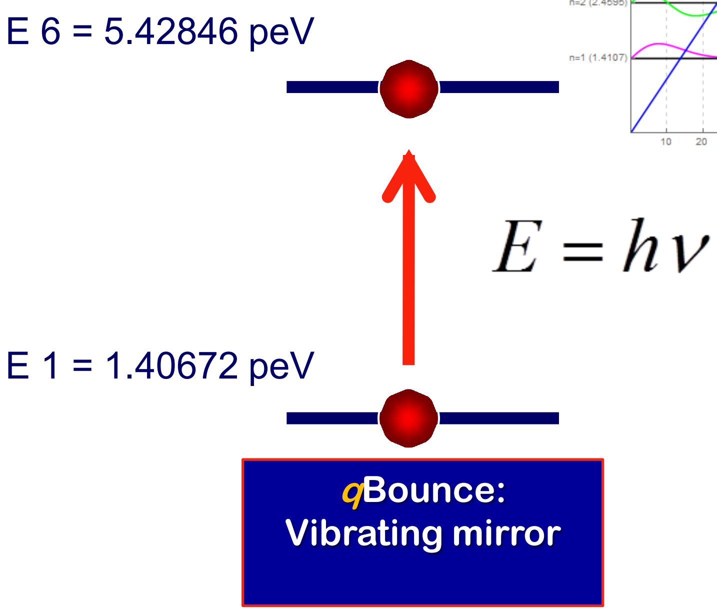
- Tool for new physics
  - EDM is pratically zero in the SM
  - Reach for new particles much higher than LHC
  - Range for EDM (Virigliano, Ramsey-Musolf)



Gravity Resonance Spectroscopy

- Quantum System, multi-Level System
- Coupling: Oscillating Mirror





- GRS: Neutron
  - Gravity field of the earth
  - Oscillating mirror

    drives transitions
- No lasers, no coupling to electromagnetic potential

Demonstration Gravity Resonance Spectroscopy: Jenke et al., Nature Physics 2011

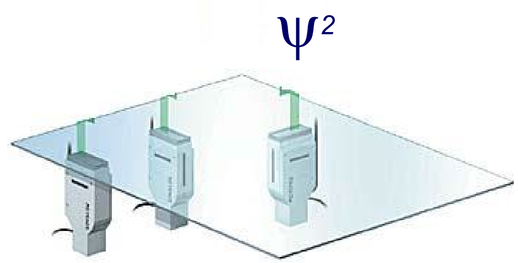
*q*BOUNCE: Quantum States

- Schrödinger Equation

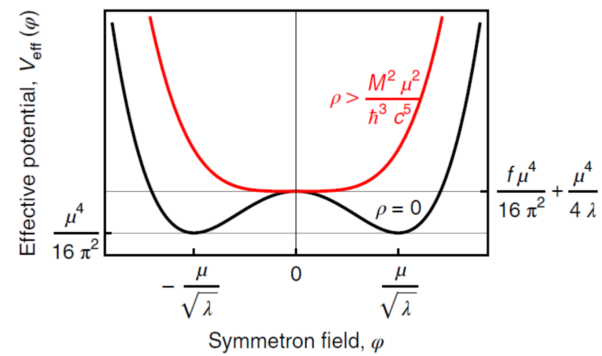
$$DM: -\frac{\hbar^2}{2m}\frac{d^2\psi}{dz^2} + mgz + V(Axion) = E\psi$$

$$DE: -\frac{\hbar^2}{2m}\frac{d^2\psi}{dz^2} + mgz + V(\Phi) = E\psi$$

$$-\frac{\hbar^2}{2m}\frac{d^2\psi}{dx^2} = E\psi$$



Hypothetical New Interaction



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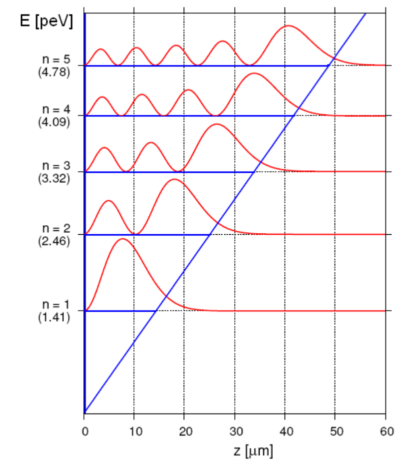
- Change of variable $\tilde{z} = -\frac{z}{z_0} - \frac{E}{E_0}$



- Airy's Equation, and general Solution with AiryAi and AiryBi

$$-\frac{d^2\Psi}{d\tilde{z}^2} + z\Psi = 0 \qquad \psi(z) = aA_i(z) + bB_i(z)$$

T. Jenke et al., Gravity Resonance Spectroscopy constrains dark matter and dark energy scenarios, Physical Review Letters 112, 151105 (2014)

Acoustic Rabi oscillations between gravitational quantum states and impact on symmetron dark energy, G Cronenberg, et al., Nature Physics 14 (10), 1022-1026 (2018)

*q*BOUNCE as a tool for probing of beyond-Riemann gravity

- Effective non–relativistic potential of beyond-Riemann gravity interactions
  - For the experimental analysis of the BRG and LV interactions by using the quantum gravitational states of UCNs Kostelecký and Li proposed

$$\mathrm{H} = \mathrm{H}_0 + \Phi_{\mathrm{RG}} + \Phi_{\mathrm{BRG}} = \frac{\vec{p}^{\,2}}{2m} - m\vec{g}\cdot\vec{z} + \Phi_{\mathrm{nRG}} + \Phi_{\mathrm{nBRG}},$$

$$\Phi_{\mathrm{nBRG}} = H_{\phi} + H_{\sigma\phi} + H_{g} + H_{\sigma g},$$

where the operators H_j for $j = \phi, \sigma\phi, g$ and σg are equal to [6]

$$H_{\phi} = (k^{\mathrm{NR}}_{\phi})_n \vec{g}\cdot\vec{z} + (k^{\mathrm{NR}}_{\phi p})^j_n \frac{1}{2}\Big(p^j(\vec{g}\cdot\vec{z}) + (\vec{g}\cdot\vec{z})p^j\Big) + (k^{\mathrm{NR}}_{\phi pp})^{jk}_n \frac{1}{2}\Big(p^j p^k(\vec{g}\cdot\vec{z}) + (\vec{g}\cdot\vec{z})p^j p^k\Big),$$

$$H_{\sigma\phi} = (k^{\mathrm{NR}}_{\sigma\phi})^j_n \sigma^j(\vec{g}\cdot\vec{z}) + (k^{(NR)}_{\sigma\phi p})^{jk}_n \frac{1}{2}\sigma^j\Big(p^k(\vec{g}\cdot\vec{z}) + (\vec{g}\cdot\vec{z})p^k\Big) + (k^{\mathrm{NR}}_{\sigma\phi pp})^{jk\ell}_n \frac{1}{2}\sigma^j\Big(p^k p^\ell(\vec{g}\cdot\vec{z}) + (\vec{g}\cdot\vec{z})p^k p^\ell\Big),$$

$$H_g = (k^{(NR)}_g)^j_n g^j + (k^{(NR)}_{gp})^{jk}_n p^j g^k + (k^{(NR)}_{gpp})^{jk\ell}_n p^j p^k g^\ell,$$

$$H_{\sigma g} = (k^{\mathrm{NR}}_{\sigma g})^{jk}_n \sigma^j g^k + (k^{\mathrm{NR}}_{\sigma gp})^{jk\ell}_n \sigma^j p^k g^\ell + (k^{\mathrm{NR}}_{\sigma gpp})^{jk\ell m}_n \sigma^j p^k p^\ell g^m.$$

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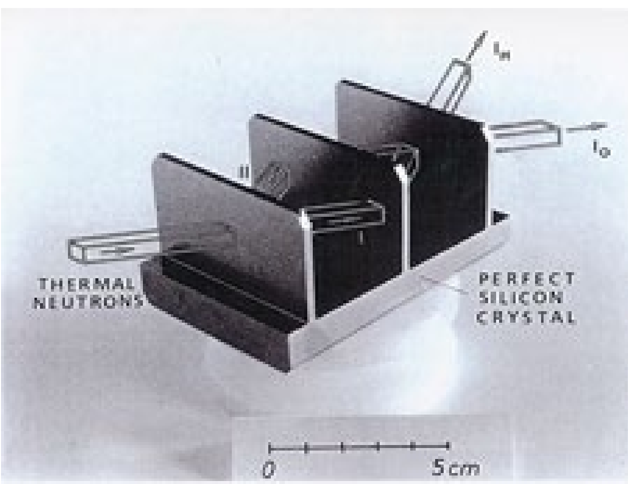
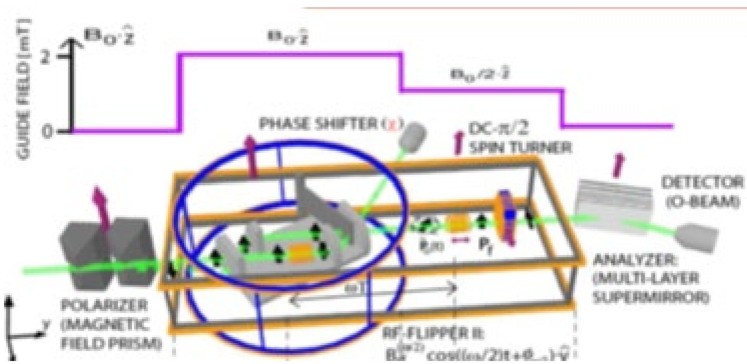
- Effective non–relativistic potential of beyond-Riemann gravity interactions
  - For the experimental analysis of the BRG and LV interactions by using the quantum gravitational states of UCNs Kostelecký and Li propose [6]

$$\mathrm{H} = \mathrm{H}_0 + \Phi_{\mathrm{RG}} + \Phi_{\mathrm{BRG}} = \frac{\vec{p}^{\,2}}{2m} - m\vec{g}\cdot\vec{z} + \Phi_{\mathrm{nRG}} + \Phi_{\mathrm{nBRG}},$$

$$\delta H = (k_{\phi}^{\mathrm{NR}})_n \vec{g}\cdot\vec{z} + (k_{\sigma\phi}^{\mathrm{NR}})_n^j \sigma^j \vec{g}\cdot\vec{z} + (k_{\sigma g}^{\mathrm{NR}})_n^{jk} \sigma^j g^k$$





$$A_+ = \frac{1}{\sqrt{2}}\left(\langle +|_{z'} + \langle -|_{z'}\right)\cdot\frac{1}{\sqrt{2}}\left(e^{i\phi_+}|+\rangle_{z'} + e^{i\phi_-}|-\rangle_{z'}\right)$$

$$\frac{g_n}{g} = 1 - \frac{(k_{\phi}^{\mathrm{NR}})_n}{m_n} \quad (k_{\phi}^{\mathrm{NR}})_n < 1\times10^{-2}\ \mathrm{GeV} \quad |(k_{\phi}^{\mathrm{NR}})_n + (k_{\sigma\phi}^{\mathrm{NR}})_n^j \hat{s}^j| < 2.5\times10^{-2}\ \mathrm{GeV}$$

*q*BOUNCE as a tool for probing of beyond-Riemann gravity

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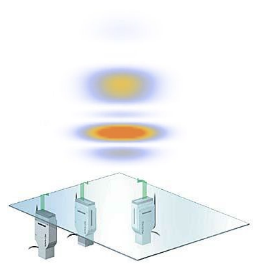
- qBOUNCE + GRS



$$\frac{g_n}{g} = 1 - \frac{(k_\phi^{\mathrm{NR}})_n}{m_n}$$

$$\delta H = (k_\phi^{\mathrm{NR}})_n \vec{g}\cdot\vec{z} + (k_{\sigma\phi}^{\mathrm{NR}})_n^j \sigma^j \vec{g}\cdot\vec{z} + (k_{\sigma g}^{\mathrm{NR}})_n^{jk} \sigma^j g^k$$

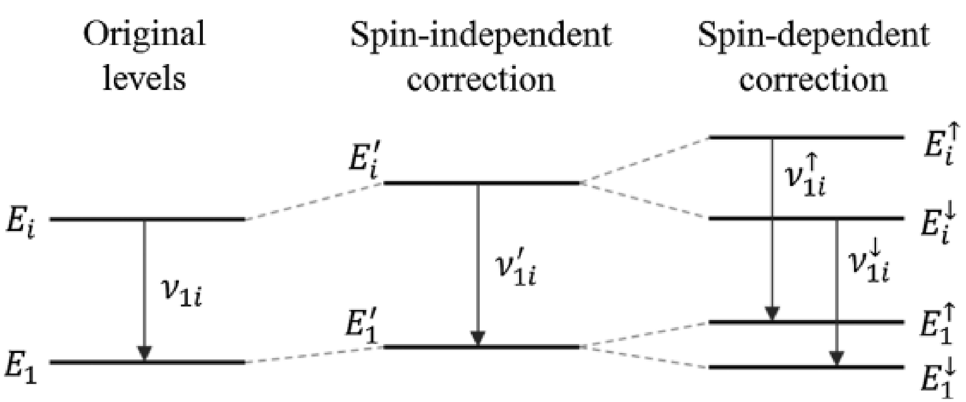


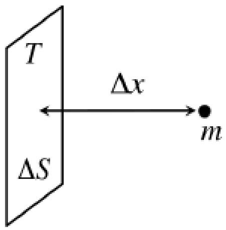
FIG. 1. Splitting of the neutron energy levels.

$$\left|(k_\phi^{(\mathrm{NR})})_n\right| < 10^{-3}\ \mathrm{GeV}$$

Quantum gravitational states of ultracold neutrons as a tool for probing beyond-Riemann gravity, A. Ivanov, M. Wellenzohn, H. Abele, Phys. Lett. B. 822 (2021) 136640

Verlinde: Gravity as entropic force

- **Black holes**



$$\Delta S = 2\pi k_B,\ \Delta x = \frac{\hbar}{mc}$$

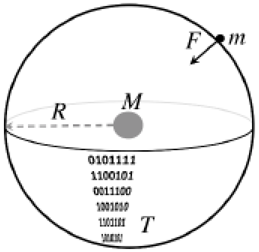
$$\Delta S = 2\pi k_B \cdot \frac{mc}{\hbar}\Delta x,\ F\Delta x = T\Delta S$$

- Relationship between temperature and acceleration

$$k_B T = \frac{1}{2\pi}\frac{\hbar a}{c} \quad \Rightarrow F = m \cdot a$$

- Entropy and information, N (Bits)

$$N \sim A,\ N = \frac{Ac^3}{G\hbar}$$



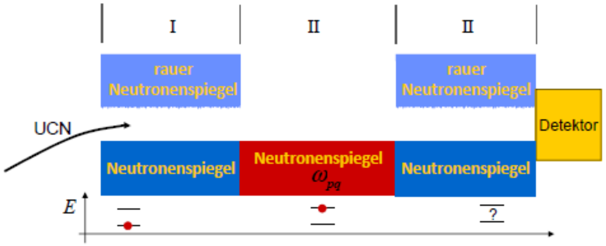
- Energy E is equally distributed, Bits N:

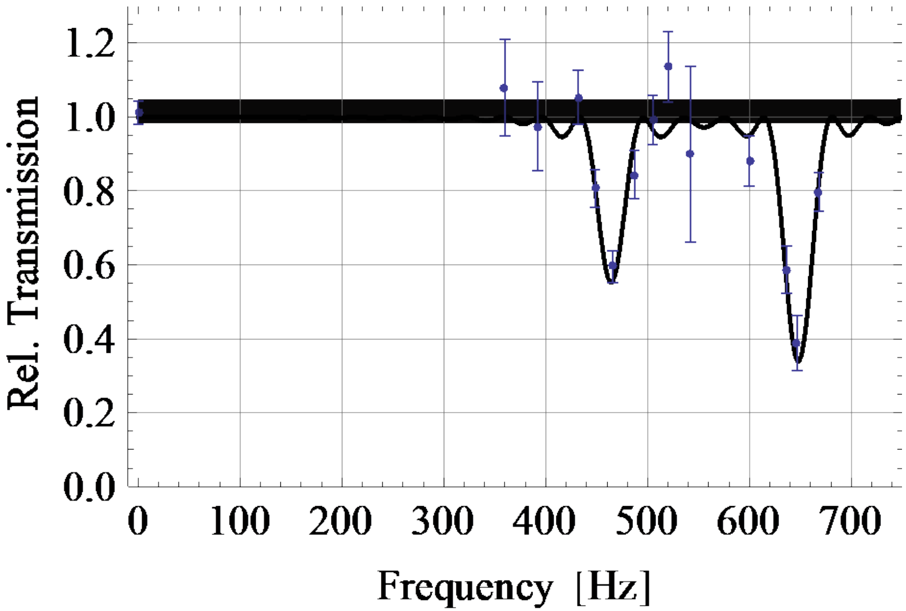
$$E = \frac{1}{2}Nk_B T,\ E = Mc^2,\ A = 4\pi R^2$$

$$F = G\frac{Mm}{R^2}$$

*q*BOUNCE and decoherence-free entropic gravity

- Problems:
  - entropic forces are by nature too noisy and thus destroy quantum coherence
  - it could be modeled as an environment in an open quantum system. Small objects must be very strongly coupled to the gravity environment.
  - But the strong coupling must lead to ample wave function collapse and quantum decoherence.
  - However, such decoherence is not observed in cold neutron experiments. Thus, entropic gravity cannot be true.





$$\nu_{13} = 463.74^{+1.05}_{-1.10}\,\mathrm{Hz}$$

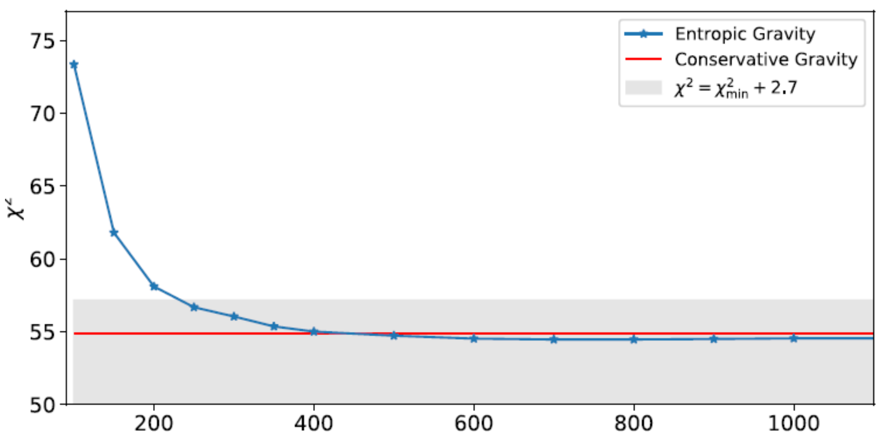
$$\nu_{14} = 648.24^{+1.46}_{-1.53}\,\mathrm{Hz}$$

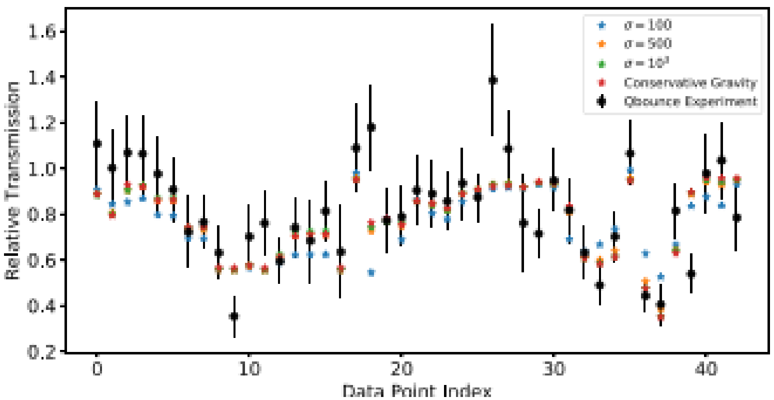
*q*BOUNCE and decoherence-free entropic gravity

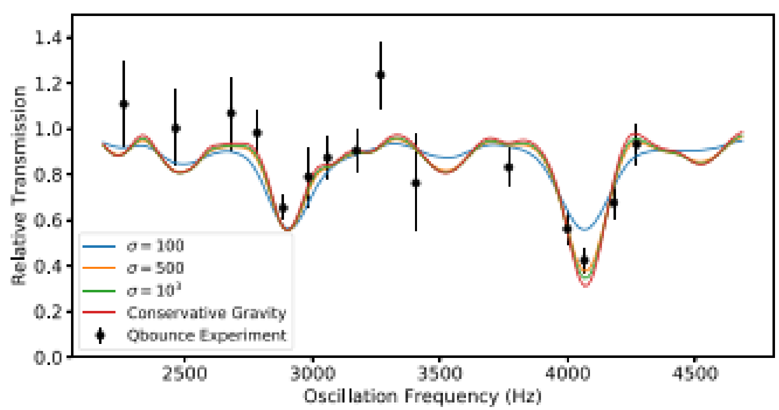
$$\frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar}\left[\frac{\hat{p}^2}{2m}, \hat{\rho}\right] + \mathcal{D}(\hat{\rho}) \qquad \mathcal{D}(\hat{\rho}) = \frac{mgx_0\sigma}{\hbar}\left\{\exp\left(-\frac{i\hat{x}}{x_0\sigma}\right)\hat{\rho}\exp\left(+\frac{i\hat{x}}{x_0\sigma}\right) - \hat{\rho}\right\}$$

$$x_0 = \left(\frac{\hbar^2}{2m^2 g}\right)^{1/3}$$

- D. Bondar suggested, arbitrarily low decoherence can be achieved by simply increasing the positive dimensionless coupling constant σ, which is a free parameter of this model. In the limit σ → ∞, the model recovers Newtonian gravity as a potential force.







AJ Schimmoller, G McCaul, H Abele, DI Bondar, Physical Review Research 3, 033065 (2021)

*q*BOUNCE and Lorentz Violation (LV), mgSME

- Lorentz violation must arise spontaneously in such a way that the LV coefficients are treated as dynamical fields that acquire nonzero vacuum expectation values.
- Schrödinger Equation

$$LV: -\frac{\hbar^2}{2m}\frac{d^2\psi}{dz^2} + mgz + V(LV - terms) = E\psi$$

Gravitational Searches for Lorentz Violation with Ultracold Neutrons

C. A. Escobar[1,*] and A. Martín-Ruiz[2,3,†]

$$H_{\rm NR} = \frac{1}{2}mc^2 h_{00} - h_{0k}p^k c - \frac{1}{4m}h_{00}p^2 - \frac{1}{2m}h_{jk}p^j p^k.$$

$$V_1 = \frac{1}{2}mc^2 h_{00},$$
$$V_2 = -c\left(h_{0k}\hat{p}^k + \frac{1}{2}h_{0k,k}\right),$$
$$V_3 = -\frac{1}{4m}\left(h_{00}\delta_{ij}\hat{p}^i\hat{p}^j + h_{00,i}\hat{p}^i + \frac{1}{4}h_{00,ii}\right),$$
$$V_4 = -\frac{1}{2m}\left(h_{jk}\hat{p}^j\hat{p}^k + h_{jk,j}\hat{p}^k + \frac{1}{4}h_{jk,jk}\right),$$

$$S = S_{\rm EH} + S_{\rm LV} + S_\psi.$$

$$S_{\rm LV} = \frac{1}{2\kappa}\int e\left(-uR + s^{\mu\nu}R^T_{\mu\nu} + t^{\mu\nu\alpha\beta}C_{\mu\nu\alpha\beta}\right)d^4x,$$

$$c^n_{\mu\nu} = \bar{c}^n_{\mu\nu} + \tilde{c}^n_{\mu\nu} \text{ and } s_{\mu\nu} = \bar{s}_{\mu\nu} + \tilde{s}_{\mu\nu}$$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu},$$

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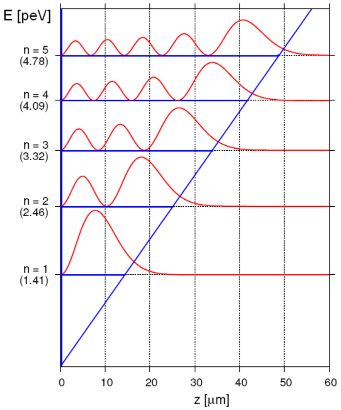
qBOUNCE and Lorentz Violation (LV), mgSME

- Ivanov

$$i\frac{\partial\psi}{\partial t} = \mathrm{H}\psi \quad , \quad \mathrm{H} = -\frac{1}{2m}\Delta + mgz + \Phi_{\mathrm{nLV}}$$

$$\delta\nu_{pq} = \frac{1}{2\pi\hbar}\int_0^\infty dz\,\left(\psi_p^\dagger(z)\Phi_{\mathrm{nLV}}\psi_p(z) - \psi_q^\dagger(z)\Phi_{\mathrm{nLV}}\psi_q(z)\right)\mathrm{Hz},$$



$$S = S_{\mathrm{EH}} + S_{\mathrm{LV}} + S_\psi.$$

$$S_{\mathrm{LV}} = \frac{1}{2\kappa}\int e\left(-uR + s^{\mu\nu}R^T_{\mu\nu} + t^{\mu\nu\alpha\beta}C_{\mu\nu\alpha\beta}\right)d^4x,$$

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$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu},$$

$$|2\bar{c}^n_{zz} + \bar{c}^n_{00}| < 2.2\times 10^{-3}.$$

transitions $|q\uparrow\rangle \to |p\uparrow\rangle$ or $|q\downarrow\rangle \to |p\downarrow\rangle$

$$\delta\nu_{pq} = \left\{(2\bar{c}_{zz} + \bar{c}_{00}) - \left[\left(4\bar{d}_{0z} + 2\bar{d}_{z0} - \varepsilon_{zmn}\bar{g}_{mn0}\right)\delta_{z\ell} + \varepsilon_{\ell mn}\bar{g}_{mn0} - 2\varepsilon_{z\ell m}(\bar{g}_{m0z} + \bar{g}_{mz0})\right]\langle S_\ell\rangle\right\}\frac{E_p - E_q}{6\pi}\,\mathrm{Hz},$$

$$\delta\nu_{31} = (2\bar{c}^n_{zz} + \bar{c}^n_{00})\frac{E_3 - E_1}{6\pi\hbar}\,\mathrm{Hz} = 154.341\,(2\bar{c}^n_{zz} + \bar{c}^n_{00})\,\mathrm{Hz},$$

$$\delta\nu_{41} = (2\bar{c}^n_{zz} + \bar{c}^n_{00})\frac{E_4 - E_1}{6\pi\hbar}\,\mathrm{Hz} = 215.747\,(2\bar{c}^n_{zz} + \bar{c}^n_{00})\,\mathrm{Hz},$$

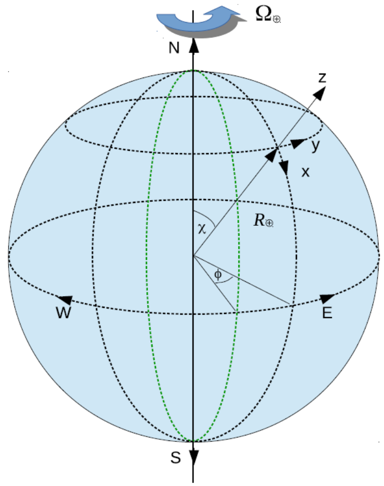
*q*BOUNCE and Lorentz Violation, the CANONICAL SUN–CENTERED FRAME

- For the transition of unpolarized UCN

$$\left|\sin^2\chi\,(\tilde{c}^n_{XX}+\tilde{c}^n_{YY})+2\,\cos^2\chi\,\tilde{c}^n_{ZZ}+\tilde{c}^n_{00}\right|<2.2\times10^{-3}$$

$$\left|(1+\sin^2\chi)\,\tilde{c}^n_{Q}+5\,m\,\tilde{c}^n_{ZZ}\right|<2.2\times10^{-3}m$$

$$|\tilde{c}^n_{ZZ}|<4.4\times10^{-4}$$



- Transition of polarized UCN

$$\delta\nu_{pq} = \left\{\left[\sin^2\chi(\tilde{c}^n_{XX}+\tilde{c}^n_{YY})+2\,\cos^2\chi\,\tilde{c}^n_{ZZ}+\tilde{c}^n_{00}\right]+\sin\chi(\tilde{g}^n_{X0Y}-\tilde{g}^n_{Y0X})\langle S_x\rangle\right\}\frac{E_p-E_q}{6\pi}\,\mathrm{Hz},$$

$$\delta\nu_{pq} = \left\{\left[\sin^2\chi(\tilde{c}^n_{XX}+\tilde{c}^n_{YY})+2\,\cos^2\chi\,\tilde{c}^n_{ZZ}+\tilde{c}^n_{00}\right]+\sin\chi\cos\chi\,(\tilde{g}^n_{X0X}+\tilde{g}^n{}_{Y0Y}-2\,\tilde{g}^n{}_{Z0Z})\,\langle S_y\rangle\right\}\frac{E_p-E_q}{6\pi}\,\mathrm{Hz},$$

$$\delta\nu_{pq} = \left\{\left[\sin^2\chi(\tilde{c}^n_{XX}+\tilde{c}^n_{YY})+2\,\cos^2\chi\,\tilde{c}^n_{ZZ}+\tilde{c}^n_{00}\right]-\cos\chi(4\,\tilde{d}^n_{0Z}+2\,\tilde{d}^n_{Z0})\,\langle S_z\rangle\right\}\frac{E_p-E_q}{6\pi}\,\mathrm{Hz}$$

$$\left|\tilde{b}^n_Z-m\,(\tilde{d}^n_{Z0}-\tilde{g}_{XY0})-\tilde{H}^n_{XY}\right|<\frac{1}{\cos\chi}\times10^{-24}\,\mathrm{GeV}$$

- Example of numerical analysis:

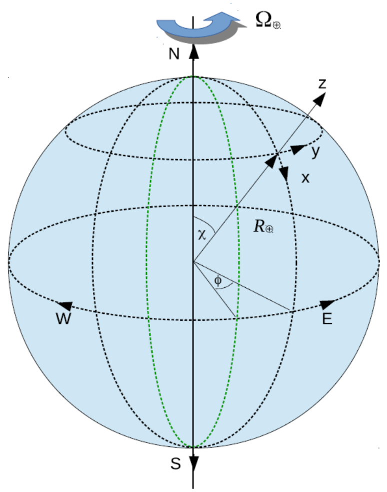
$$\delta\nu_{41} = 229.624\left\{(1+\sin^2\chi)\,\tilde{c}^n_Q+5\,m\,\tilde{c}^n_{ZZ}+\sin\chi\,m\,(\tilde{g}^n_{X0Y}-\tilde{g}^n_{Y0X})\langle S_x\rangle\right\}\mathrm{Hz},$$

$$\delta\nu_{31} = 229.624\left\{\left[(1+\sin^2\chi)\,\tilde{c}^n_Q+5\,m\,\tilde{c}^n_{ZZ}+\sin\chi\cos\chi\,\tilde{g}^n_Q\,\langle S_y\rangle\right\}\mathrm{Hz},$$

qBOUNCE and Lorentz Violation, the CANONICAL SUN–CENTERED FRAME

- For the 2019 sensitivity of qBOUNCE we get

$$\left|5\, m\, \bar{c}^n_{ZZ} + \sin\chi\, m\, (\bar{g}^n_{X0Y} - \bar{g}^n_{Y0X})\langle S_x\rangle\right| < 2.1\times 10^{-3}\,\mathrm{GeV},$$
$$\left|5\, m\, \bar{c}^n_{ZZ} + \sin\chi\cos\chi\, \tilde{g}^n_Q\, \langle S_y\rangle\right| < 2.1\times 10^{-3}\,\mathrm{GeV},$$
$$\left|5\, m\, \bar{c}^n_{ZZ} - \cos\chi\left(4\, \tilde{d}^n_Z + 2\, \bar{H}^n_{XY}\right)\langle S_z\rangle\right| < 2.1\times 10^{-3}\,\mathrm{GeV}$$



- With $|\bar{c}^n_{ZZ}| < 4.4\times 10^{-4}$ we get

$$\left|\bar{g}^n_{X0Y} - \bar{g}^n_{Y0X}\right| < 10^{-4},$$
$$\left|\tilde{g}_Q\right| < 1.3\times 10^{-4}\,\mathrm{GeV},$$
$$\left|\tilde{d}^n_Z + \frac{1}{2}\,\bar{H}^n_{XY}\right| < 2.3\times 10^{-5}\,\mathrm{GeV},$$

- Neutron Sector:

Combination	Result
$\lvert\bar{c}^n_{ZZ}\rvert$	$< 4.4\times 10^{-4}$
$\lvert\bar{c}^n_{XX}\rvert$	$< 2.2\times 10^{-4}$
$\lvert\bar{c}^n_{ZZ}\rvert$	$< 2.2\times 10^{-4}$
$\lvert\bar{g}^n_{X0Y} - \bar{g}^n_{Y0X}\rvert$	$< 10^{-4}$
$\lvert\tilde{g}_Q\rvert$	$< 1.3\times 10^{-4}$ GeV
$\lvert\tilde{d}^n_Z + \frac{1}{2}H_{XY}\rvert$	$< 2.3\times 10^{-5}$ GeV
$\lvert\tilde{b}^n_Z\rvert$	$< 1.4\times 10^{-24}$ GeV

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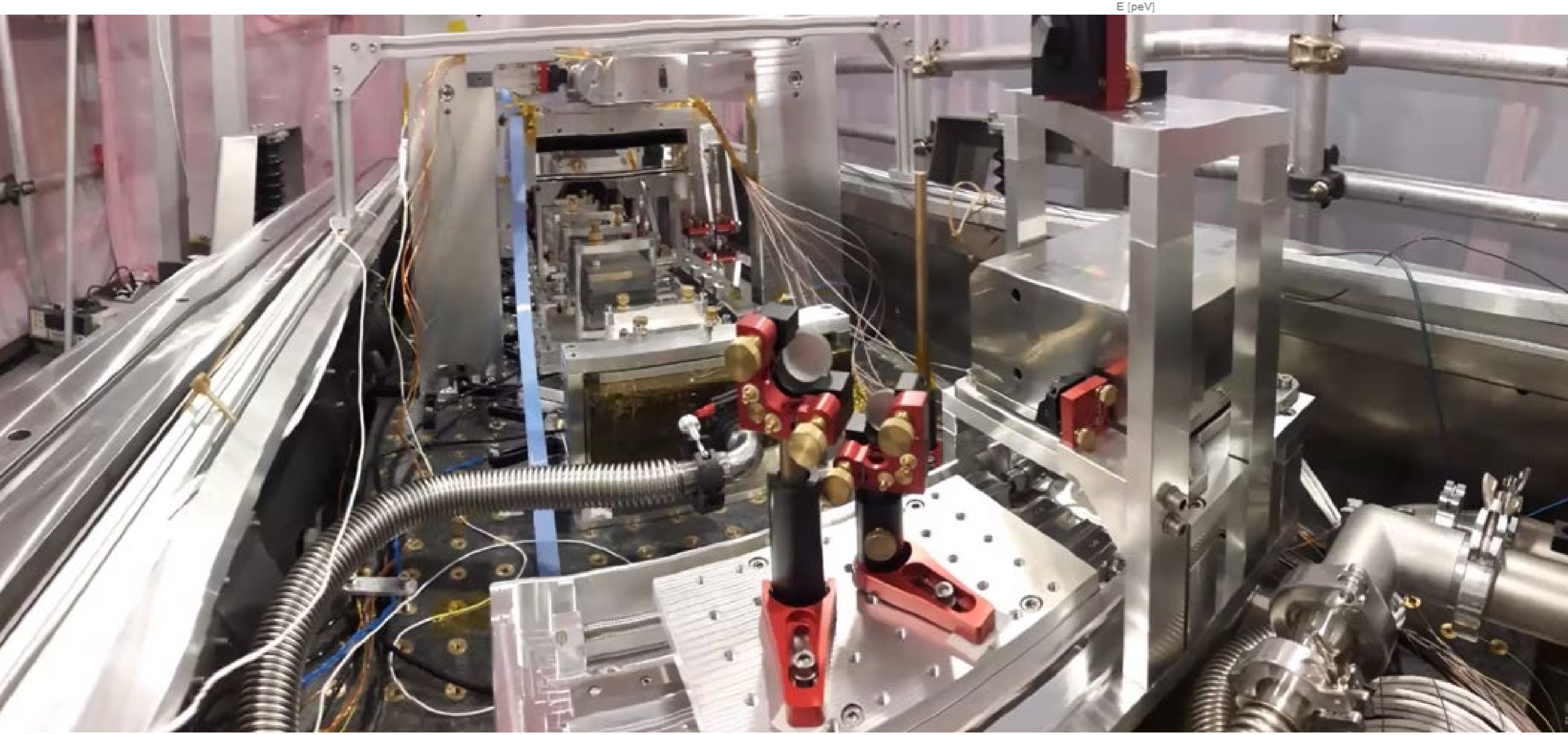
Motivation for high precision tests with neutrons:
extreme sensitivity or precision

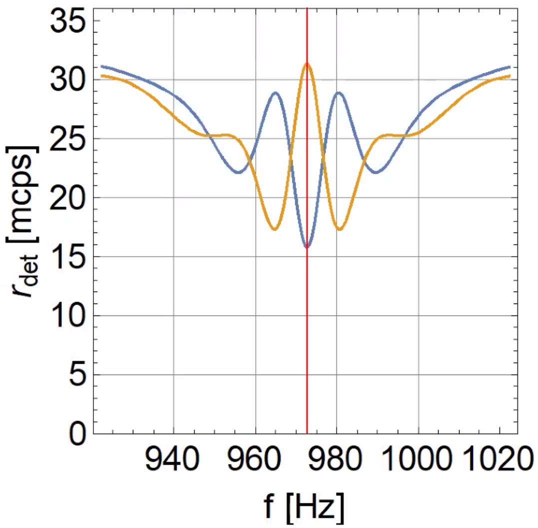
- Energy $\Delta E = 10^{-21}$ eV
  - Search for an electric dipole moment, neutron
  - $d_n < 3 \times 10^{-26}$ ecm
  - Ramsey's Spectroscopy Method of Separated Oscillating Field by NMR
- Energy $\Delta E = 10^{-16}$ eV
  - Ramsey's Spectroscopy Method of Separated Oscillating Field by GRS
  - (Jenke, Rechberger, Bosinar, Micko, Sedmik, HA)
- Energy $\Delta E = 4 \times 10^{-18}$ eV, ACME
  - Search for an electric dipole moment, electron (ThO), $d_e < 9 \times 10^{-29}$ ecm
- Energy $\Delta E = 2 \times 10^{-15}$ eV
  - Rabi's Spectroscopy Method by GRS

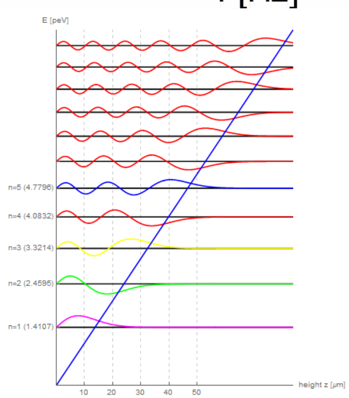
Jakok Micko + Tobias Jenke: experiments in 2020/21

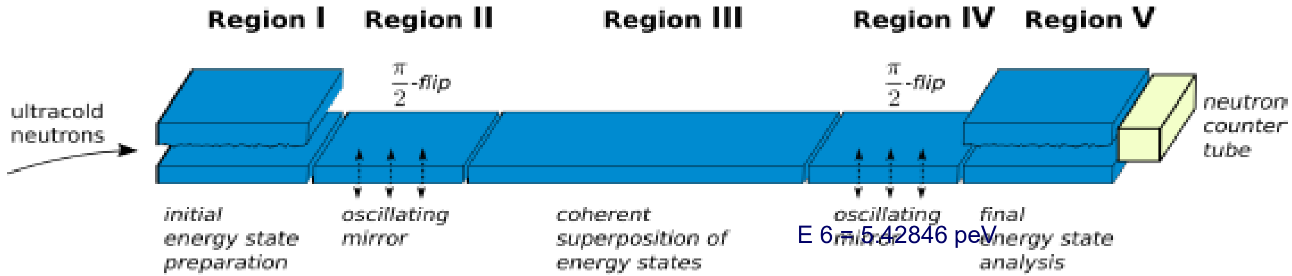
E [peV]

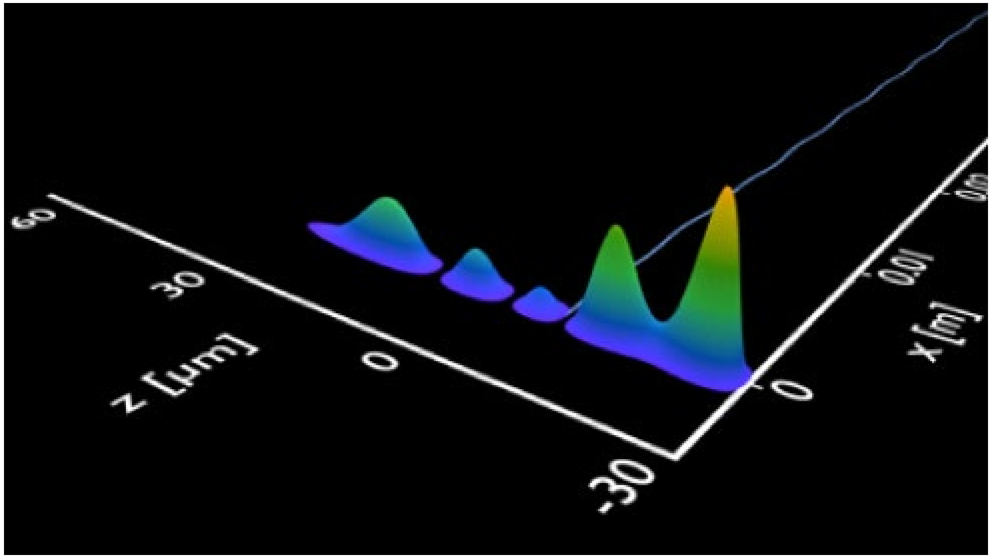


Micko/Jenke: first Results, Transition 1> → 6> @ 972 Hz









Movie: R. Neubacher

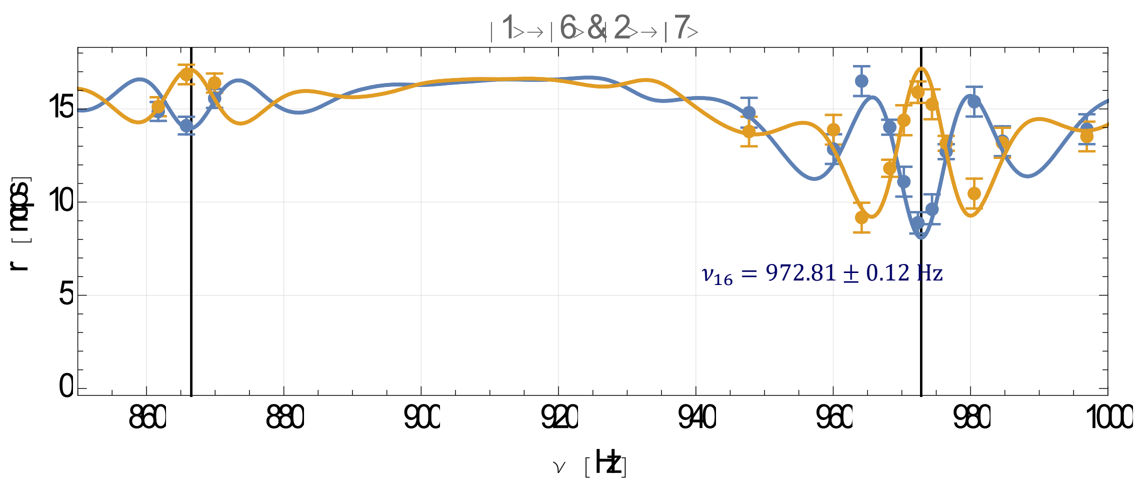
- Measure in phase (blue)
- Measure out of phase (yellow)
- Measure, where gradient is largest

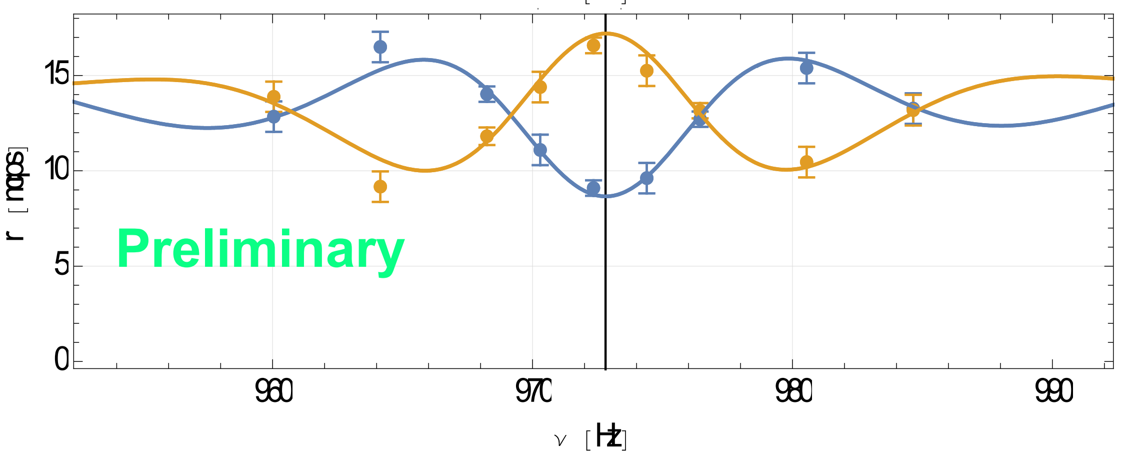
Reflect on all sufaces

- velocities in range [4;11] m/s (2021)
- Neutron mirror pseudo potential: 100 neV
- Length of setup 0.948 m
- Distance between mirrors ≈ 30 μm
- Steps in height between mirrors < 0.5 μm
- Typical count rates (no oscillation): $r \approx 20$ mcps
- Alignment relative to g: 10 μrad

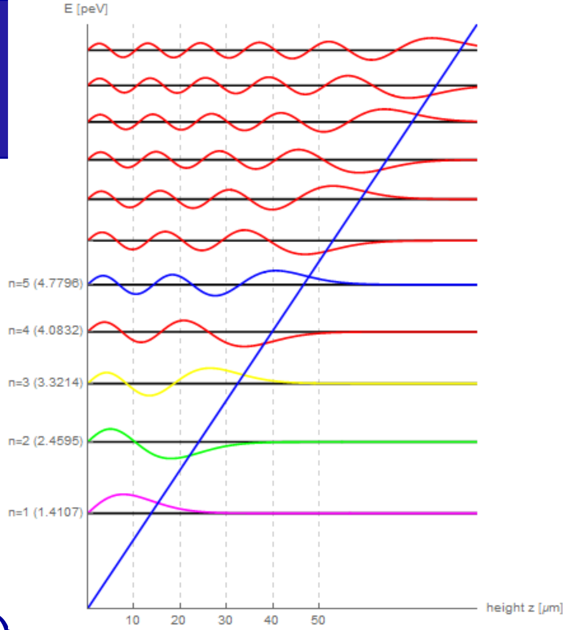
J. Micko: Cycle 2 in 2021@ILL:

- Frequency sweep with π phase
- Highest sensitivity: points measured at highest slope (and in the central dip)





J. Micko: Systematic effects (included)



$$E_{ij} = \sqrt[3]{\frac{\hbar^2 m_g^2 g^2}{2m_i}} \left(\mathrm{AiZ}(i) - \mathrm{AiZ}(j)\right)$$

- Spectator shift (numerical):

$$\Delta\nu_{16} \approx +30 \text{ mHz} \approxeq +4.5 \cdot 10^{-4} \text{ m/s}^2$$

- Bloch-Siegert shift (numerical):

$$\Delta\nu_{BS} \approx +15 \text{ mHz} \approxeq +2.3 \cdot 10^{-4} \text{ m/s}^2$$

- Mirrors close to neutrons:

$$\Delta g \approx +5.3 \cdot 10^{-8} \text{ m/s}^2 \approxeq 3.5 \cdot 10^{-6} \text{ Hz}$$

- Rotating Earth: $\Delta g \approx -0.0165 \text{ m/s}^2 \approxeq -1.2 \text{ Hz}$

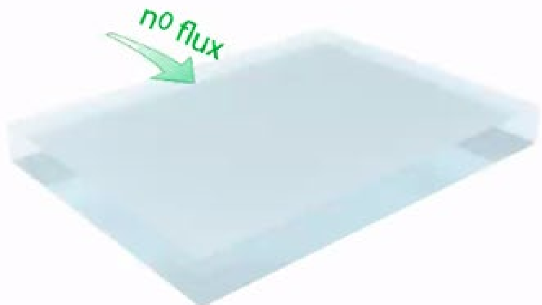
J. Micko: More effects?

- Misalignment? g decreases
- Coriolis/Sagnac are small
- Steps between regions? Lowers contrast, induces spectator shift
  small for |1> ->|6>
- Tidal forces? $\frac{\delta g}{g} \approx 10^{-6}$
- Time base off? Using Rb clock since 2020 (cross referenced with second clock referenced to GPS, agree to $< 10^{-10}$)
- Magnetic field gradient? Measured in situ and would eliminate resonance curve
- Finite mirror potential? $\mathrm{l} \approx 14\ \mathrm{nm}, \Delta E_{ij} < 1\ aeV$
- <u>Stat. Energy Sensitivity ΔE = 10^{-16} eV</u>

René Sedmik: Storage Solution

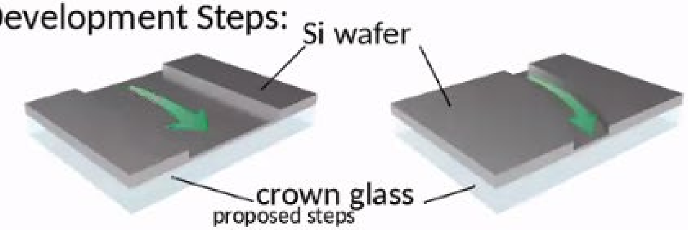
Ramsey GRS Outlook

current setup



$\tau \approx 70$ ms

Development Steps:



Future storage setup:

$\tau \approx 700$ s

Hypothetical improvement in sensitivity: **10^4**

Measurement options:
(spin-polarized or not)

$g_S^2,\ g_S g_P,\ g_P^2,\ g_V^2,\ g_A^2,\ g_T^2$

$g,\ e_n$ + WEP

$\bar{c}^n_{JJ},\ \bar{g}^n_{XTY} - \bar{g}^n_{YTX},$

$\tilde{g}^n_Q,\ \tilde{d}^n_Z,\ (k_\phi^{\mathrm{NR}})_{\mathrm{n}},\ \left|(k_{\sigma\phi}^{\mathrm{NR}})^J_{\mathrm{n}}\right|$

*q*Bounce Collaboration /Support

TU Wien Experiment

- René Sedmik
- Joachim Bosina
- Jakob Micko
- Joachim Bosina, Atominstitut TU Wien
- Sandeep Suresh Cranganore
- HA

TU Wien Theory

- Mario Pitschmann
- Andrey Ivanov
- Manfried Faber
- Martin Suda
- Christian Käding
- Ben Koch

ILL Grenoble

- Tobias Jenke
- Stephanie Rocchia
- Thomas Brenner

TU Wien

- Ivica Galic
- Roman Gergen

Tulane University

- Denys Bondar
- Alex Schimmoller
- Gerald McCaul

TU Munich / U Heidelberg

- Peter Fierlinger
- Ulrich Schmidt
- Torsten Lauer