Probing Dark energy with neutrons

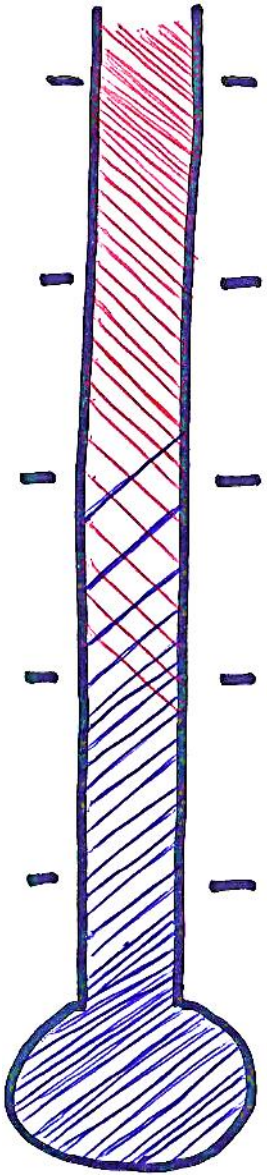
Guillaume Pignol

Habilitation à diriger les recherches,

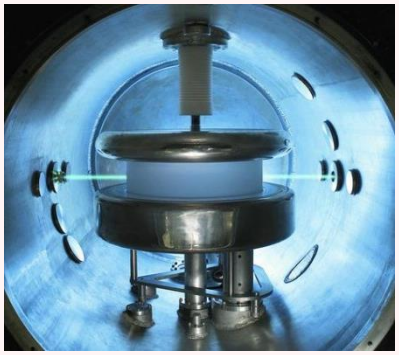
13 May 2015

LPSC Grenoble

neutrons and the Universe



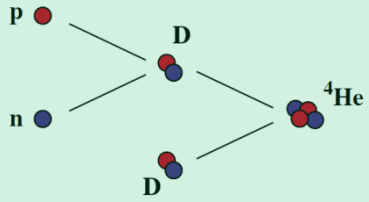
Baryogenesis



Search for the neutron electric dipole moment to explain the matter-antimatter asymmetry

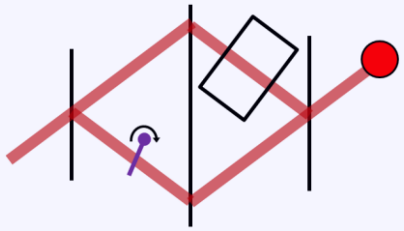
Nucleosynthesis

Measuring the neutron lifetime to predict the primordial production of light elements

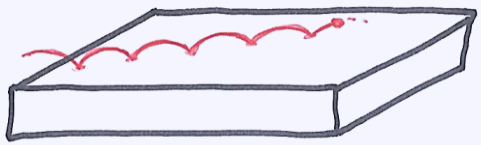


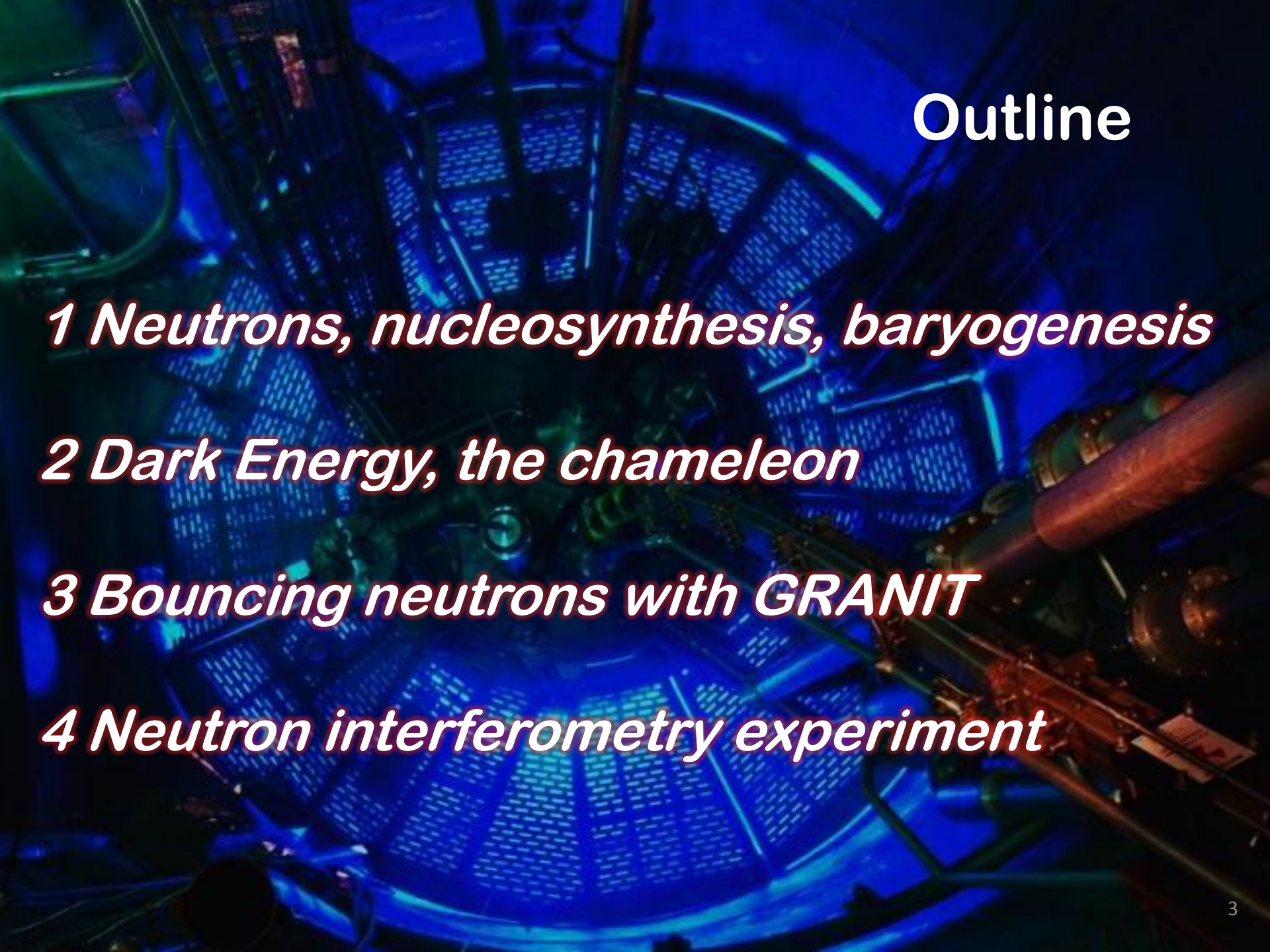
Dark energy

neutron interferometry



bouncing neutrons





Outline

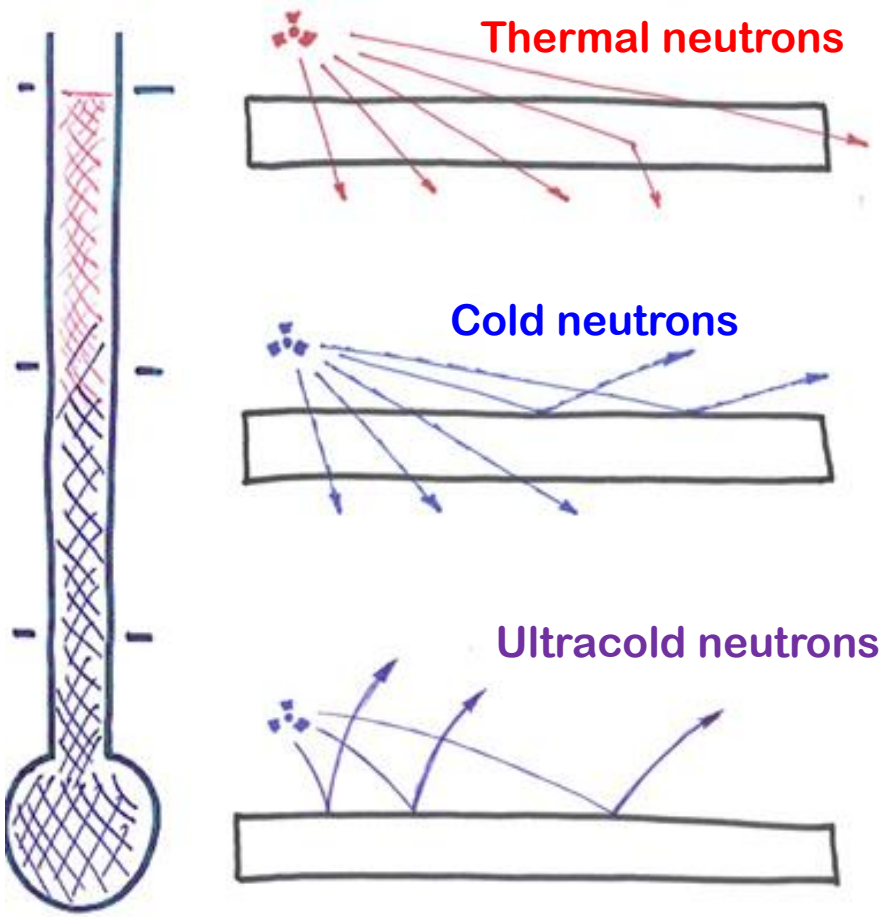
1 Neutrons, nucleosynthesis, baryogenesis

2 Dark Energy, the chameleon

3 Bouncing neutrons with GRANIT

4 Neutron interferometry experiment

Neutron optics, cold and ultracold neutrons



Cold neutrons

($\mathrm{E} < kT = 25$ meV)

have large wavelength

($\lambda > 0.2$ nm)

They behave like waves,

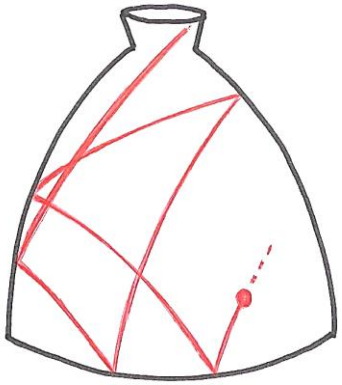
affected by the

Fermi potential of matter

(order of 100 neV)

Neutrons with energy < 100 neV,

are reflected by material walls they can be stored in material bottles.



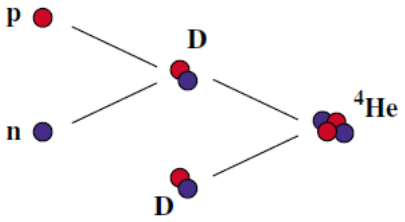
Big Bang nucleosynthesis

[Planck (2014)]

$$\eta_{\mathrm{CMB}} = (6.05 \pm 0.07) \times 10^{-10}$$

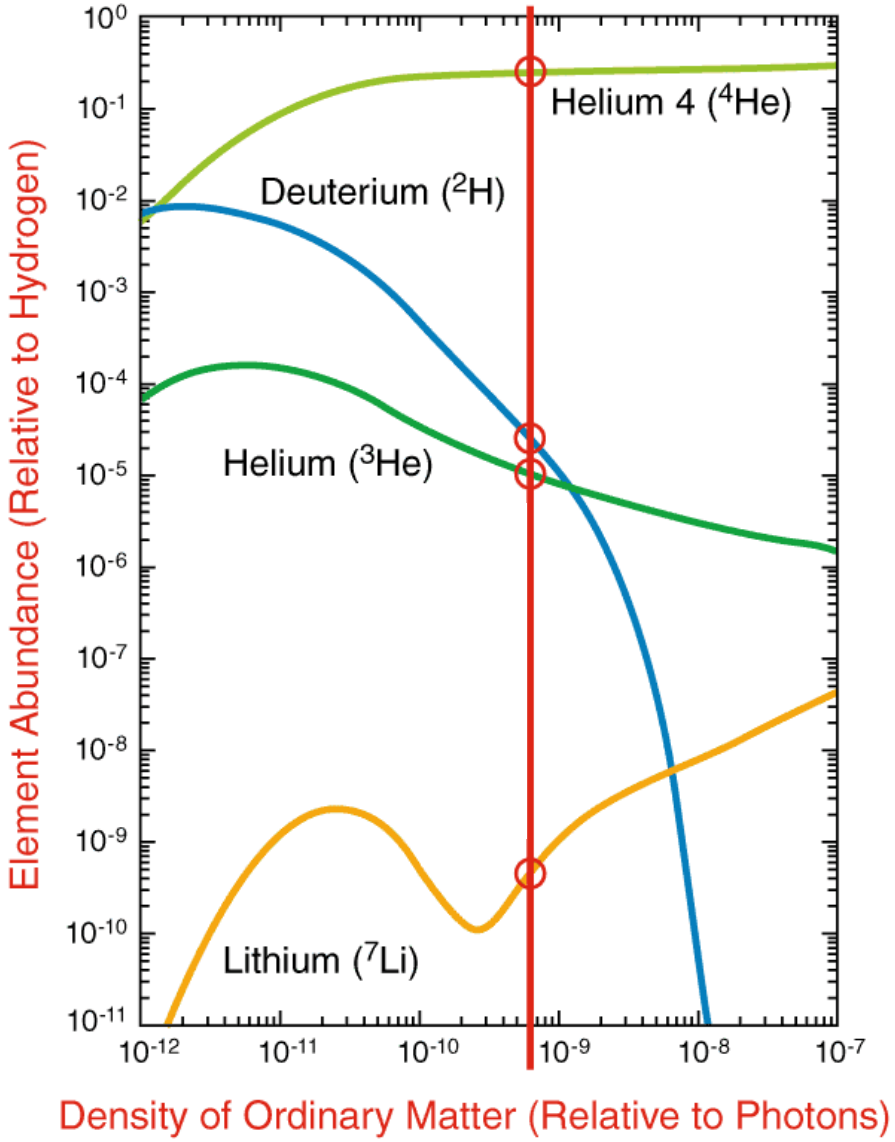
[Deuterium abundance from Lyα, Cooke et al (2014)]

$$\eta_{\mathrm{BBN}} = (6.0 \pm 0.1) \times 10^{-10}$$

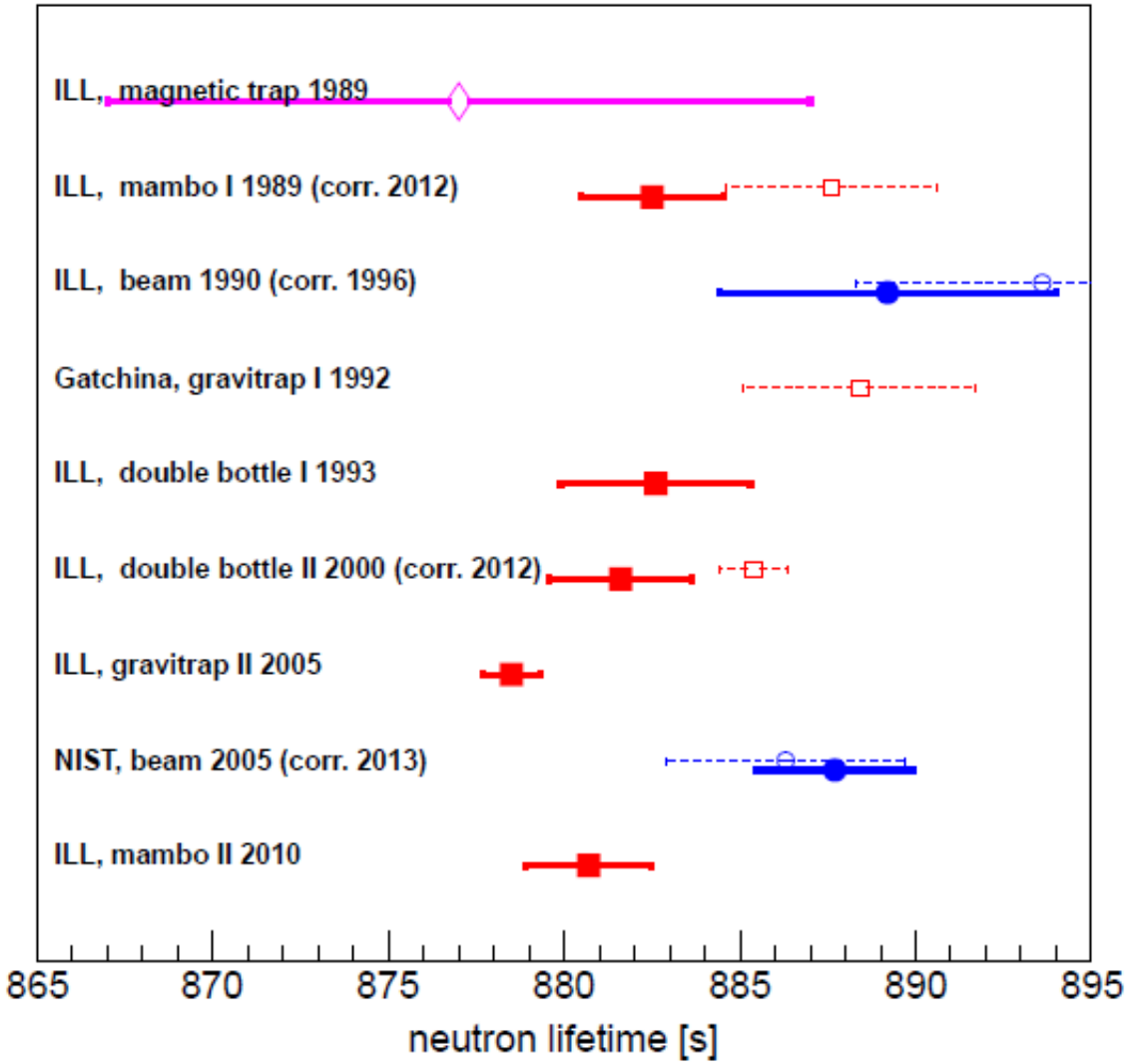


BBN calculations need to know the neutron lifetime:

$$\frac{\Delta(\mathrm{D/H})}{\mathrm{D/H}} = -1.6\frac{\Delta\eta}{\eta} + 0.4\frac{\Delta\tau_n}{\tau_n}$$



Current status on the neutron lifetime

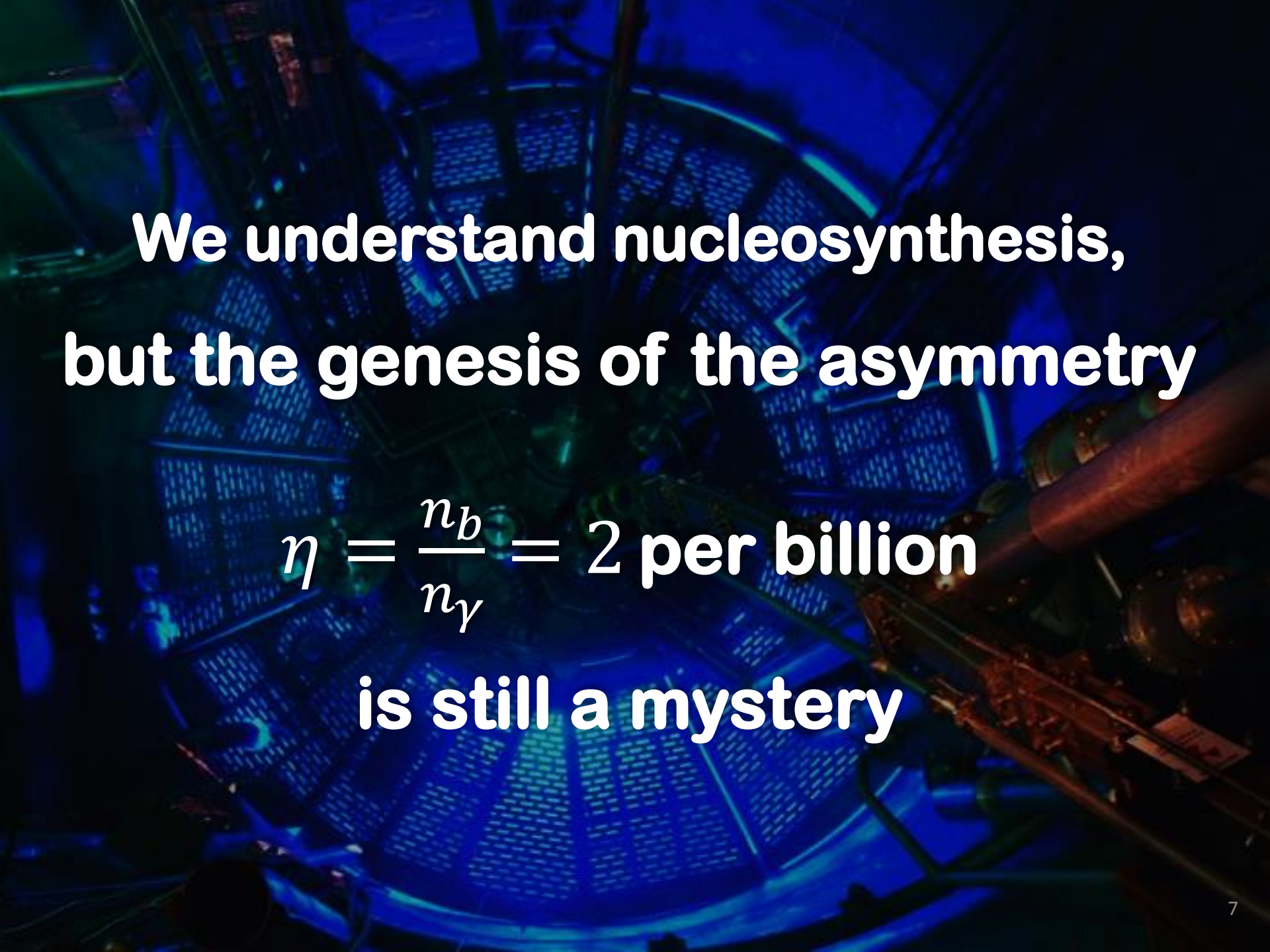


The 2015 situation

There is a 3.8 σ discrepancy

between the bottle method combination and the beam method combination.

To be continued…


We understand nucleosynthesis,
but the genesis of the asymmetry
$\eta = \frac{n_b}{n_\gamma} = 2$ per billion
is still a mystery

Baryogenesis: three Shakarov conditions

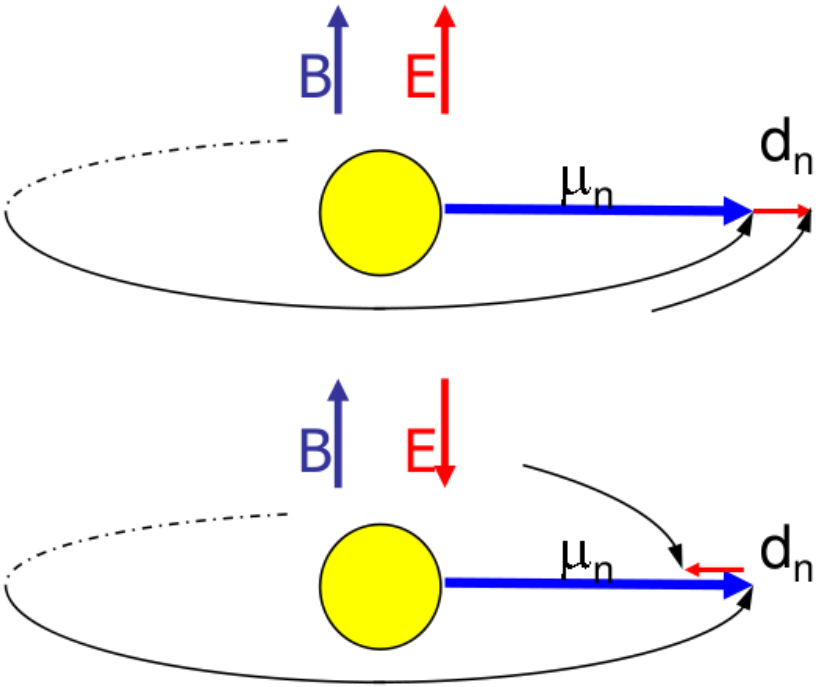
1 Departure from thermal equilibrium
at the electroweak phase transition?

2 Violation of B conservation
ok with SM sphaleron transitions

3 CP violation
requires new physics beyond the electroweak scale,
accessible by the next generation of EDM experiments

Principle of the nEDM measurement

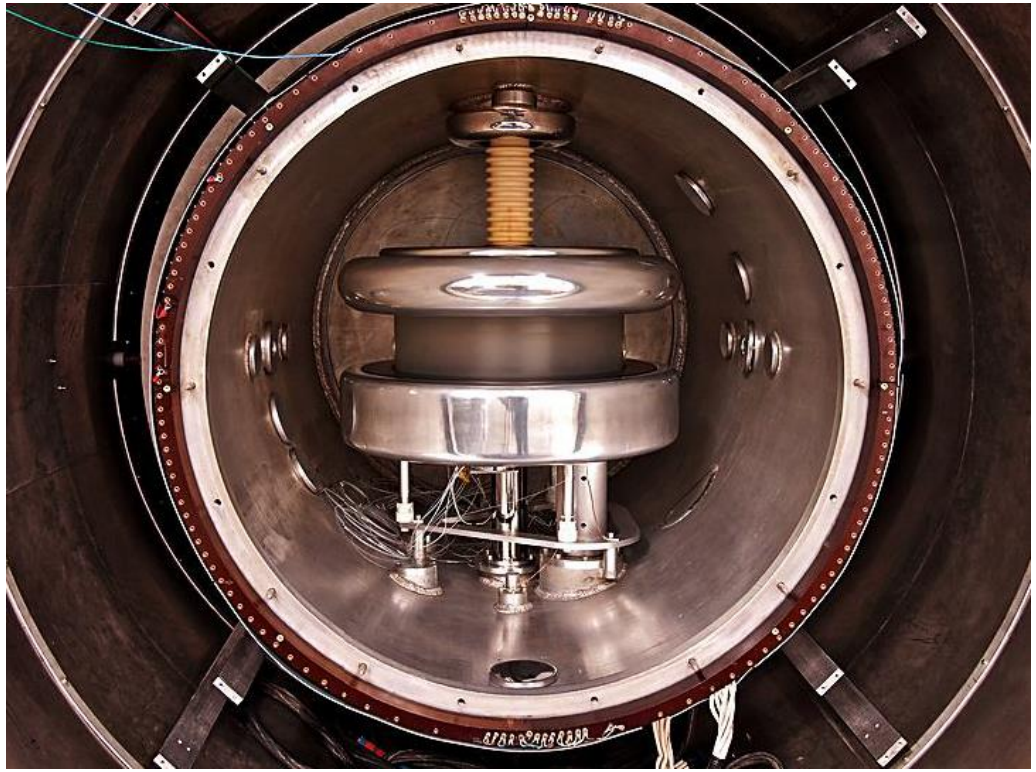
$$\hat{H} = -\mu_n \, B \, \hat{\sigma}_z - d_n \, E \, \hat{\sigma}_z = \pi\hbar \, f_L \, \hat{\sigma}_z$$



$$f_L(\uparrow\uparrow) - f_L(\uparrow\downarrow) = -\frac{2}{\pi\hbar} d_n \, E$$

A non-zero EDM violates T reversal
(thus violates CP symmetry)

The running nEDM apparatus



Electric field 150 kV / 12 cm

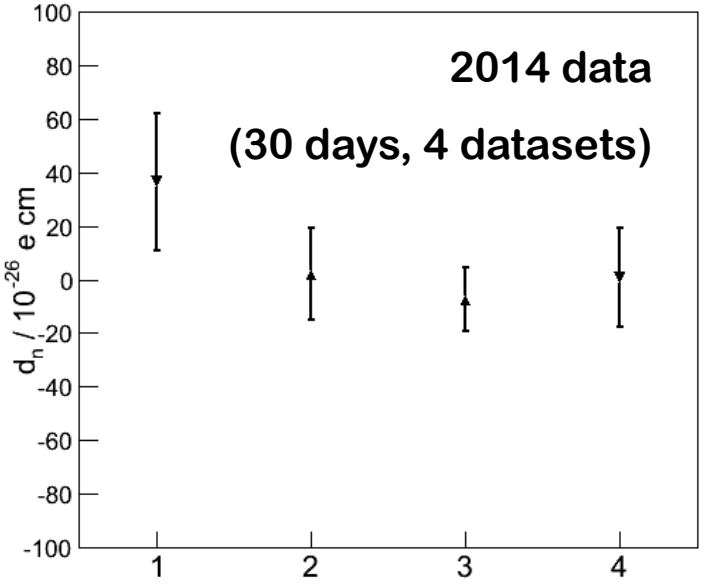
Shielded magnetic environment

B_0 = 1 μT Homogeneity < 10^{-3}
Time stability < 10^{-6}

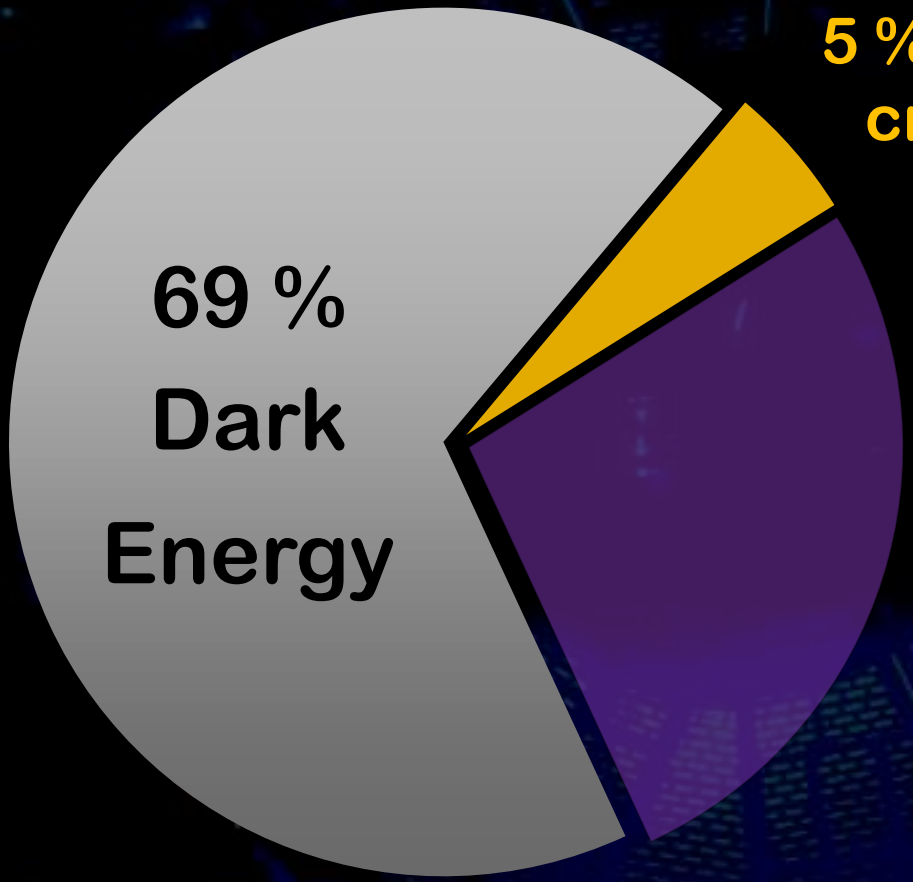
Operated at ILL (1998-2004), providing the world limit

$$|d_n| < 3 \times 10^{-26}\ e\ \text{cm}\ (90\%CL)$$

data taking at the PSI UCN source since 2012



Energy budget of the Universe in ΛCDM



5 % normal baryonic matter created by baryogenesis and nucleosynthesis

26% Dark Matter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The expansion of the Universe

E. Hubble 1929

$H_0 = 550\,\mathrm{km/s\,/Mpc}$

The Hubble law:
velocity = H_0 x distance

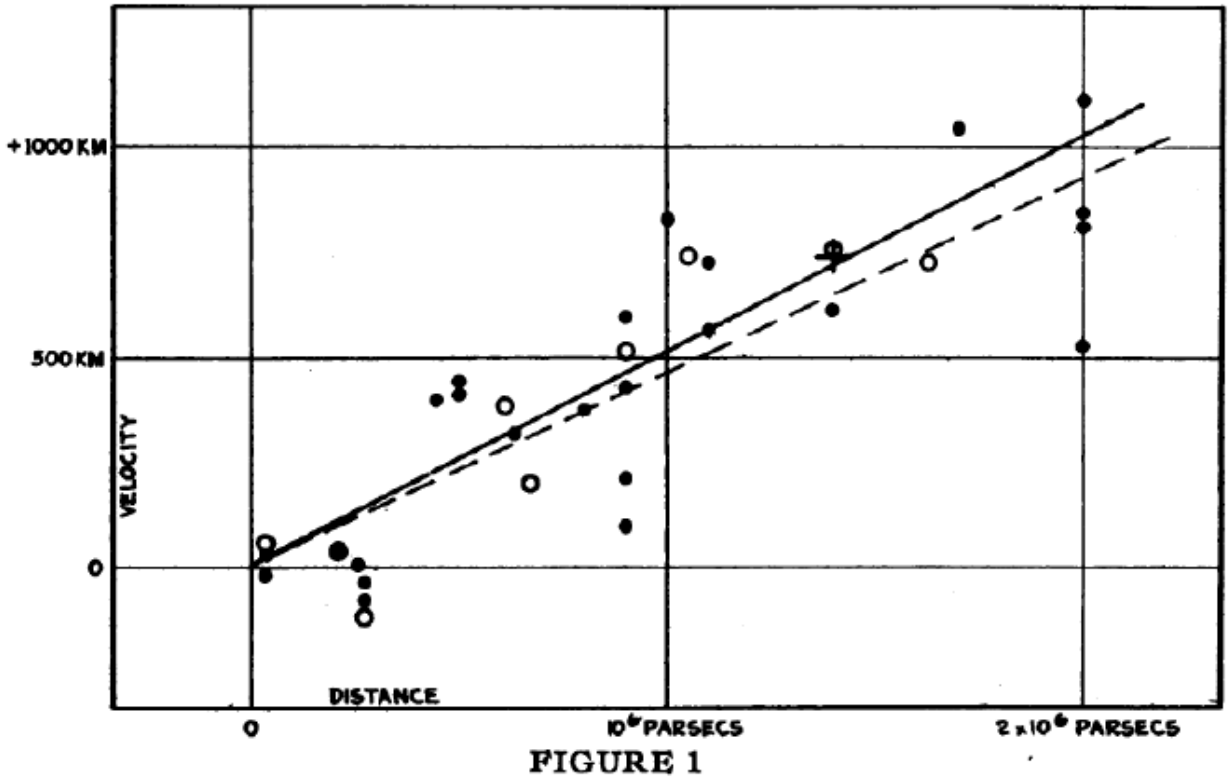
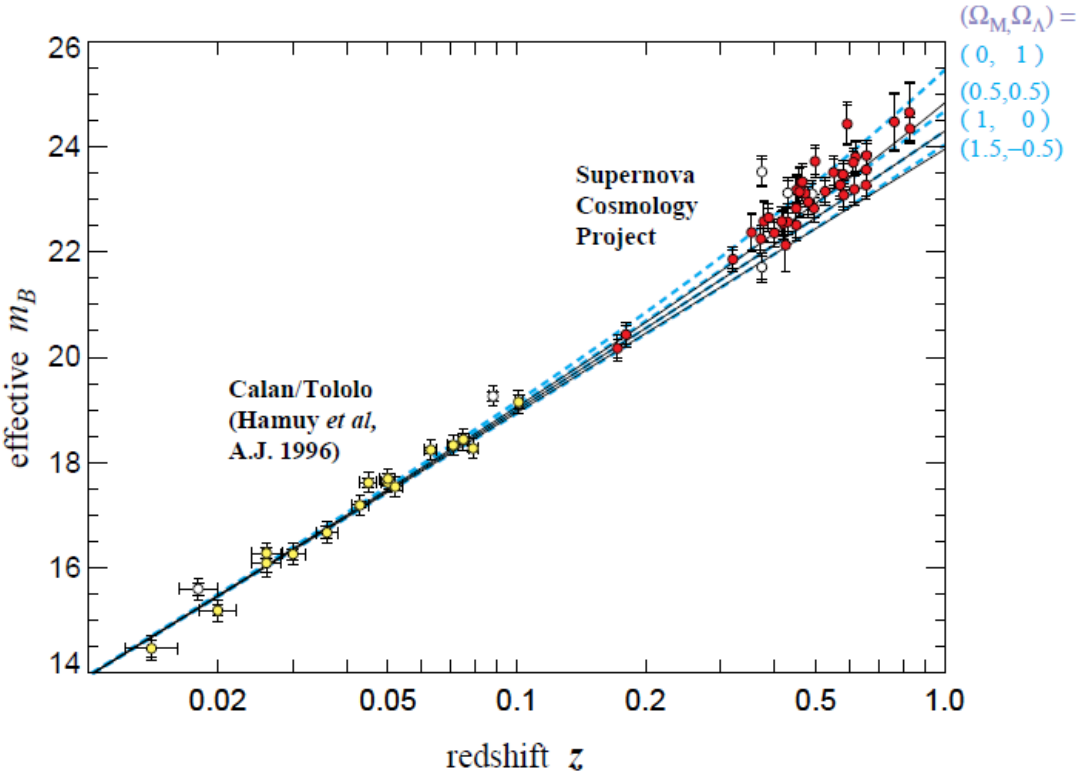


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

The expansion accelerates



S. Perlmuter *et al* (1999)
+ A. Riess *et al* (1998)

Friedmann equation

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\rho(1+3w)$$

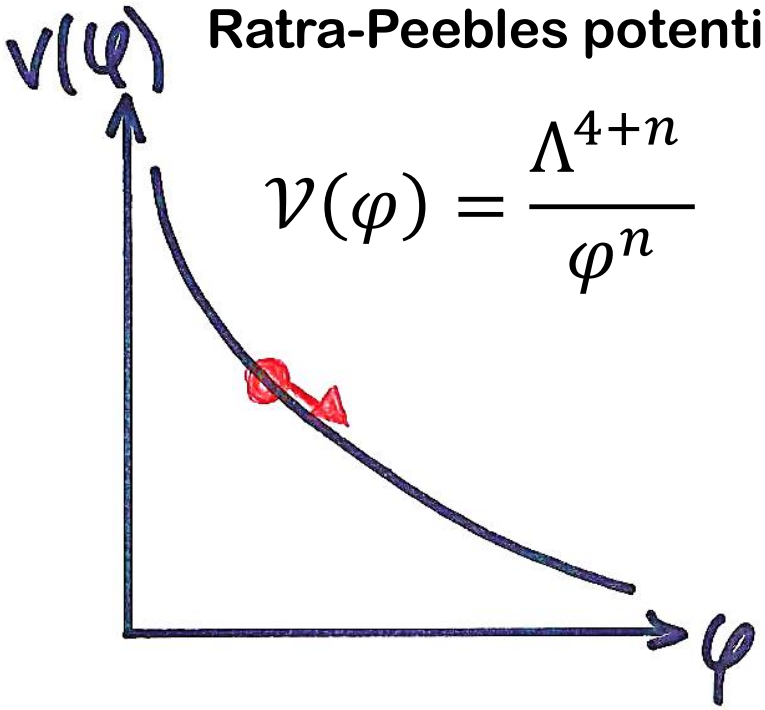
For a substance with an equation of state

$$p = w\,\rho$$

Acceleration requires

$$w < -1/3$$

Quintessence as Dark Energy



Ratra-Peebles potential

$$\mathcal{V}(\varphi) = \frac{\Lambda^{4+n}}{\varphi^n}$$

Dark Energy is (maybe) due to a cosmological scalar field φ

$$\ddot{\varphi} + 3H\dot{\varphi} + \mathcal{V}'(\varphi) = 0$$

$$w = \frac{p}{\rho} = \frac{\dot{\varphi}/2 - \mathcal{V}(\varphi)}{\dot{\varphi}/2 + \mathcal{V}(\varphi)}$$

Very low energy dynamics: $\Lambda \approx \rho_{\mathrm{DE}}^{1/4} = 2.4\ \mathrm{meV}$

Corresponds to a distance scale $\hbar c/\Lambda = 82\ \mu\mathrm{m}$

Should be possible to detect if φ couples to matter!

The Khoury-Weltman mechanism

A way to reconcile gravity tests and cosmology

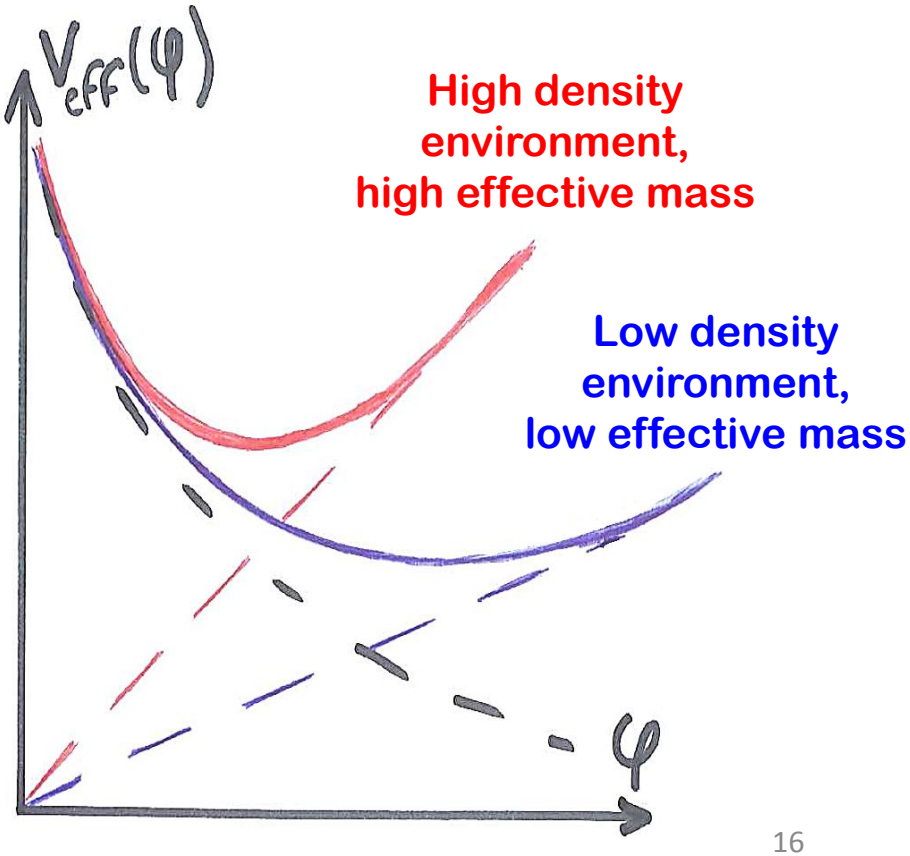
[Khoury & Weltman PRD 69 (2004)]

Recall: a massive Klein-Gordon field mediates a force with finite range $\hbar c/M$

$$\mathcal{V}_{\mathrm{KG}}(\varphi) = M^2\,\varphi^2$$

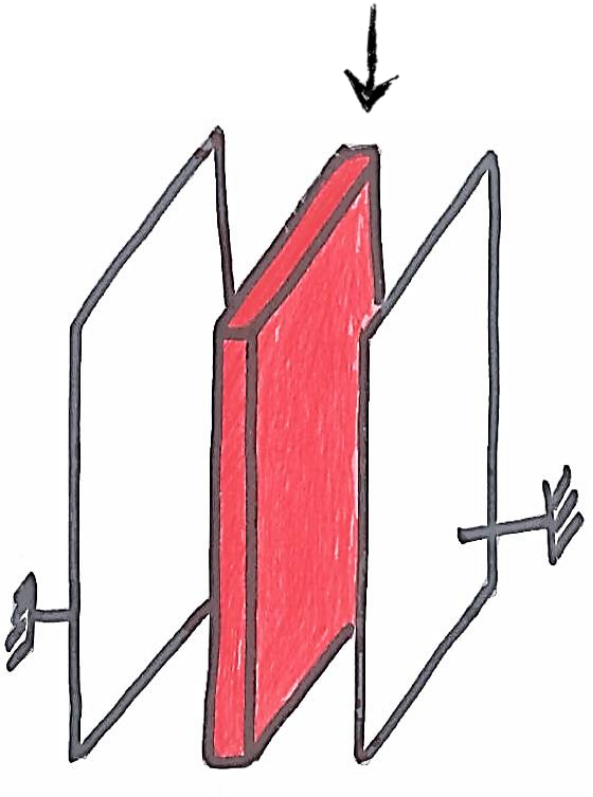
Quintessence field coupled with matter:

$$\mathcal{V}_{\mathrm{eff}}(\varphi) = \mathcal{V}(\varphi) + \frac{\beta\rho}{M_{\mathrm{Planck}}}\varphi$$



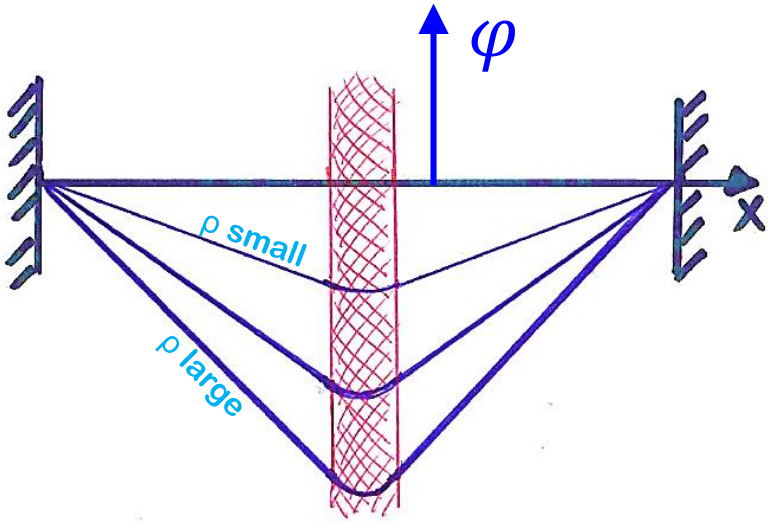
Understanding the chameleon mechanism

Plate with charge density ρ



Poisson equation for the electric potential

$$\Delta\varphi = \rho$$



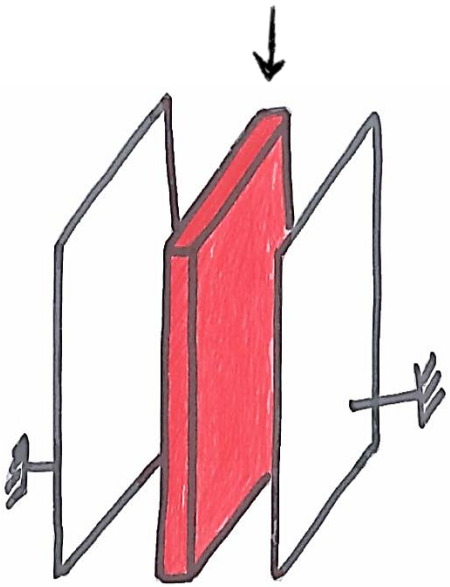
Electric field $\mathrm{d}\varphi/dx$ proportional to ρ

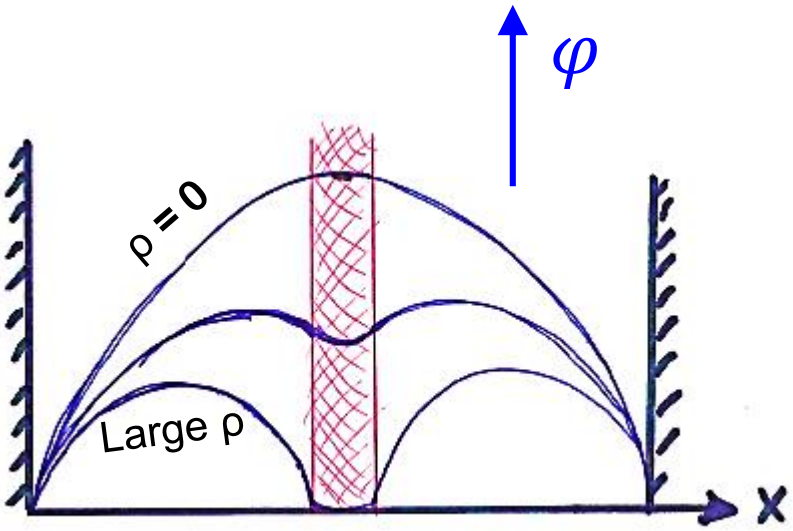
Understanding the chameleon mechanism

Nonlinear equation for the chameleon field

$$\Delta\varphi = -n\frac{\Lambda^{4+n}}{\varphi^{n+1}} + \frac{\beta}{M_{\text{Planck}}}\rho$$

Plate with mass density ρ





Saturation effect and screening mechanism. For large β the force between macroscopic bodies is independent of β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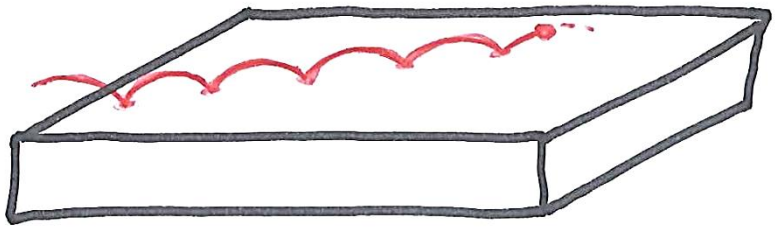
Bouncing neutrons: quantum states

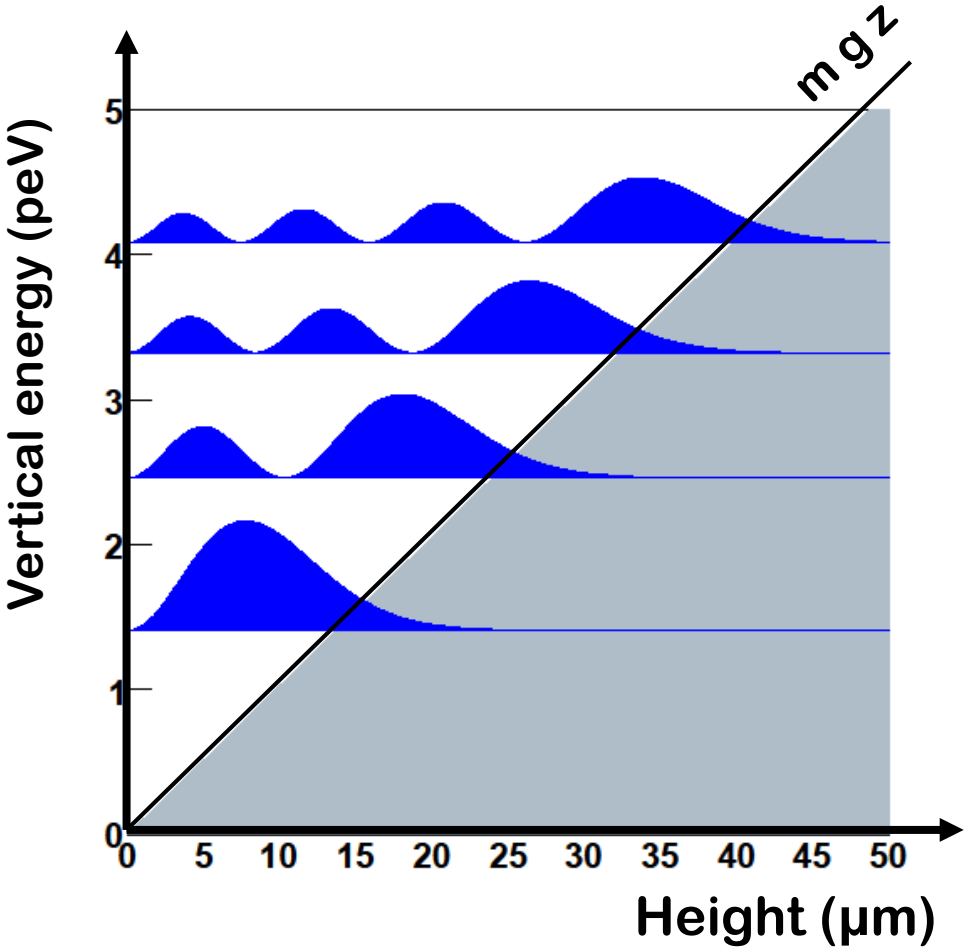
Neutrons with energy < 100 neV

can bounce above a glass mirror.

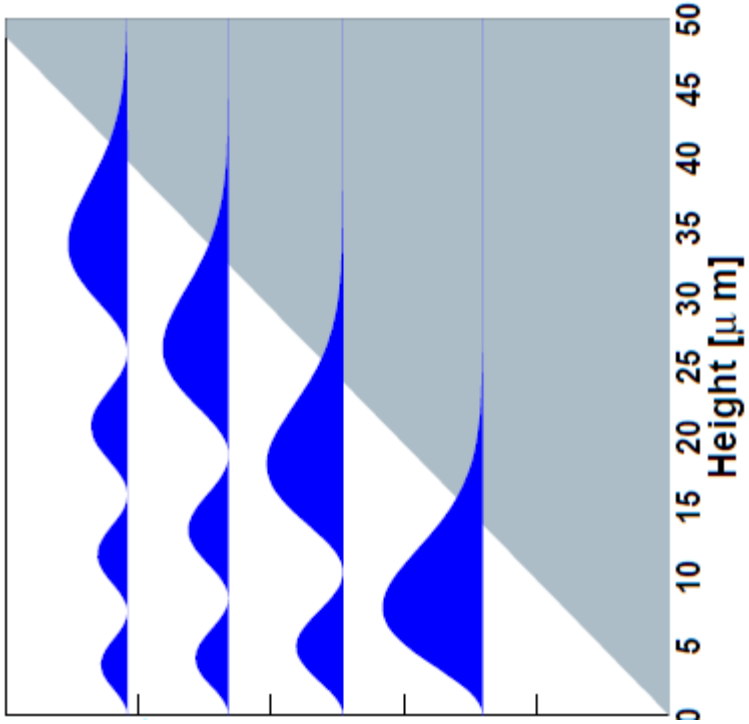


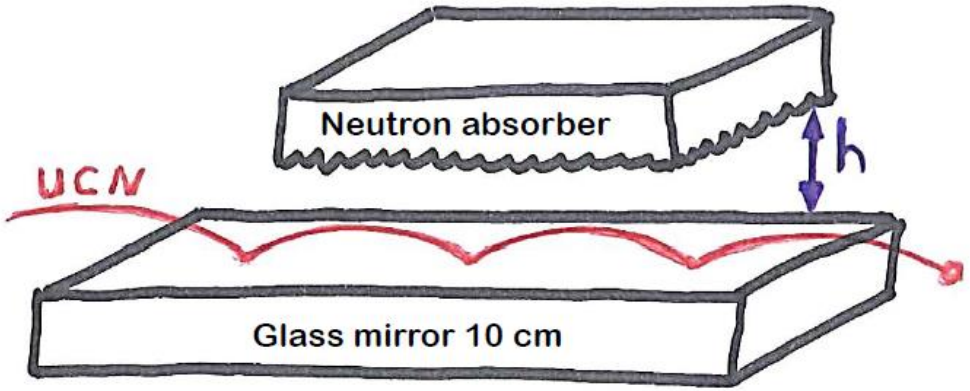
The vertical motion is a simple quantum well problem

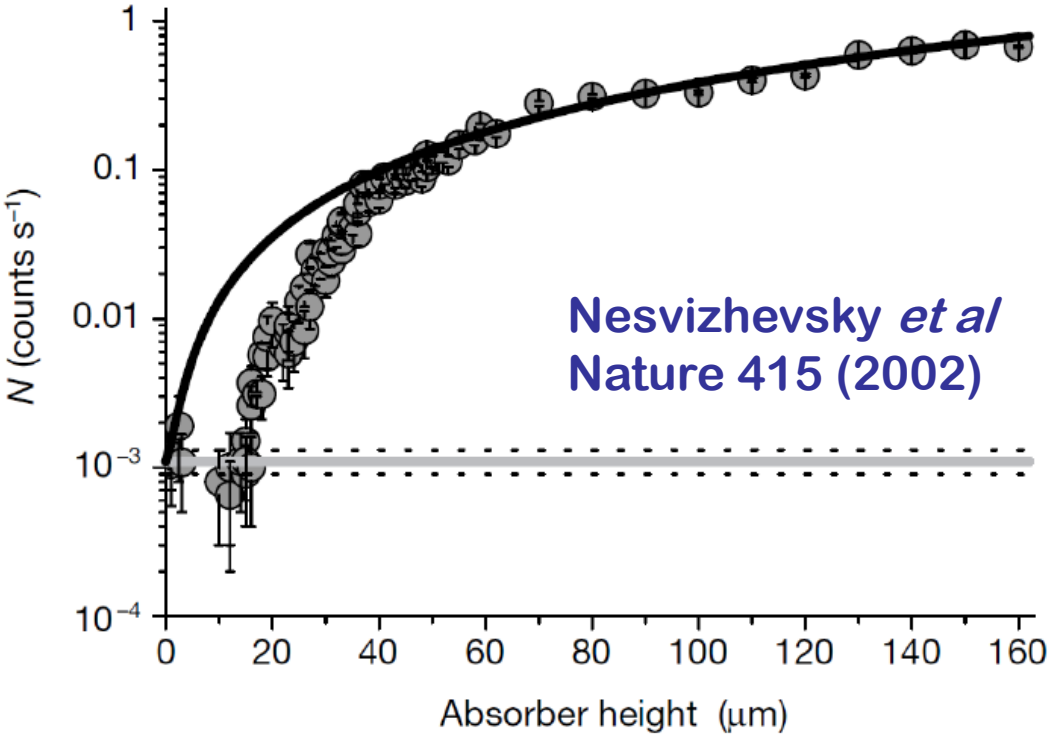
$$-\frac{\hbar^2}{2m}\frac{d^2\psi}{dz^2} + mgz\,\psi = E\,\psi$$



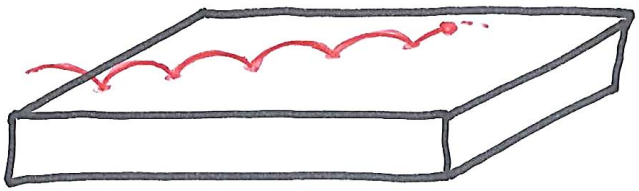
Discovery of the quantum states at ILL Grenoble



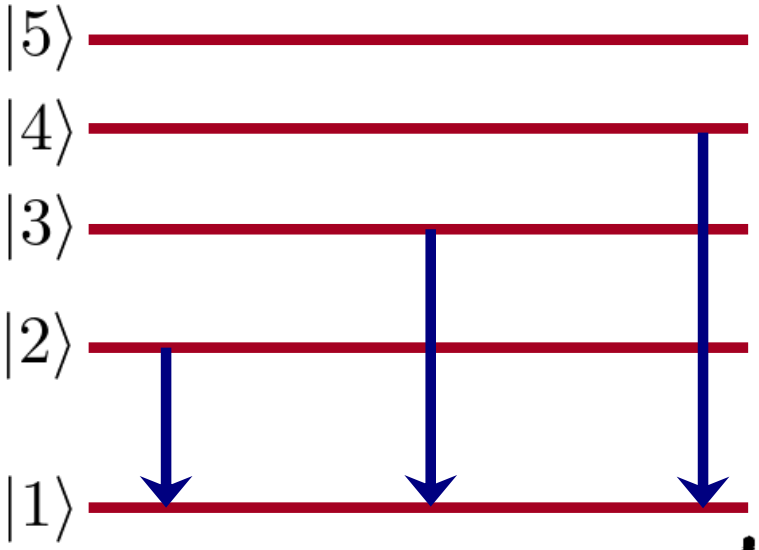




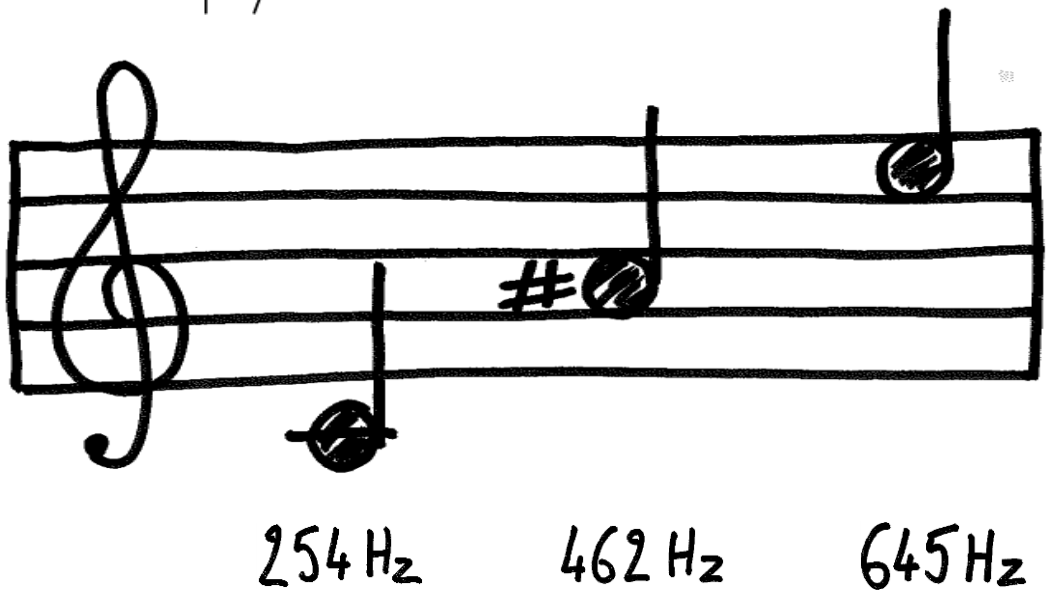
Bouncing neutron: quantum music



$$\Delta E = h \times f$$

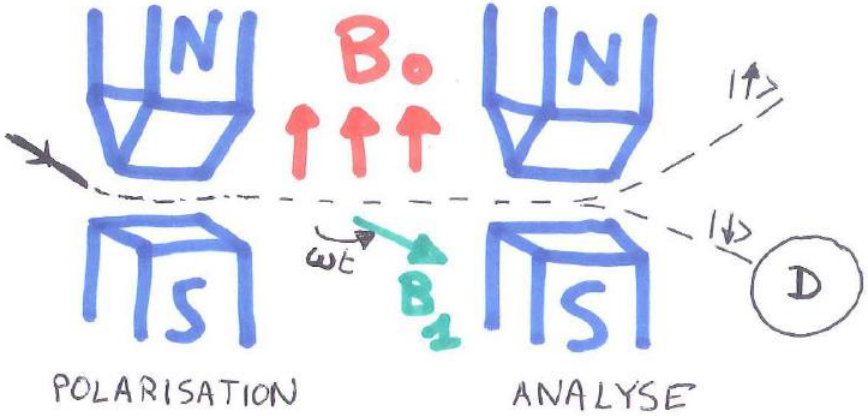


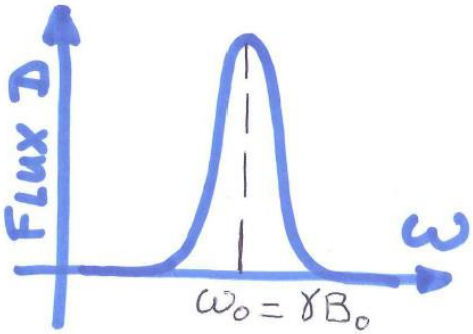
$$\frac{1}{2\pi}\sqrt[3]{\frac{mg^2}{2\hbar}} \times \begin{vmatrix} 1{,}75 \\ 3{,}18 \\ 4{,}45 \\ \vdots \end{vmatrix}$$



Gravity resonance spectroscopy

Rabi experiment (1939)



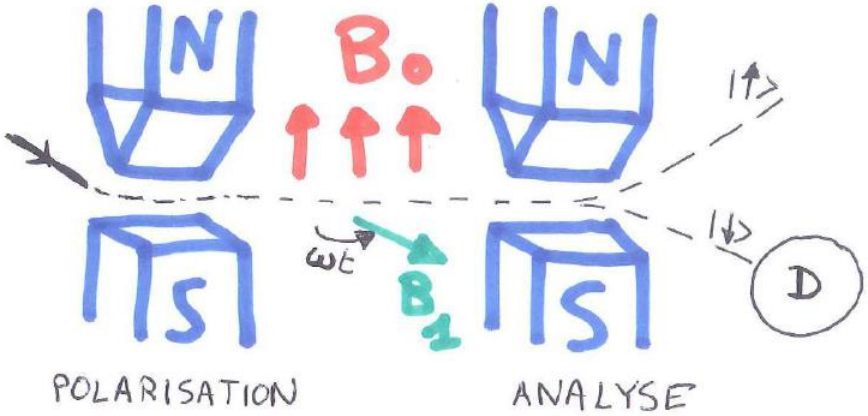


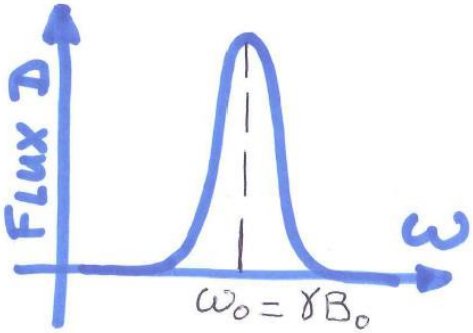
Rabi formula

$$P_{2\to 1} = \frac{\sin^2\left(\sqrt{\delta\omega^2 + \Omega^2}\, t/2\right)}{1 + \delta\omega^2/\Omega^2}$$

Gravity resonance spectroscopy

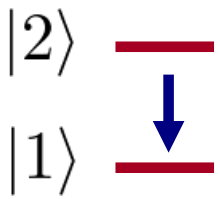
Rabi experiment (1939)





State selection

$|2\rangle$



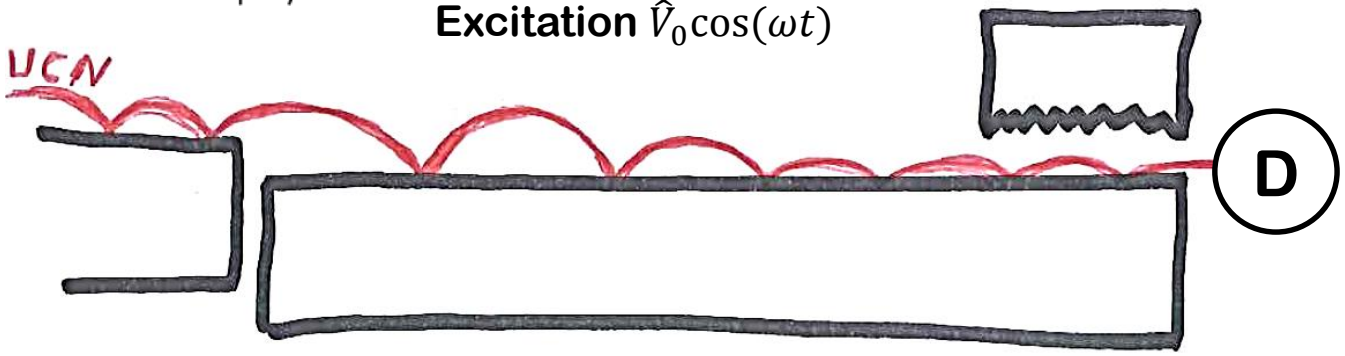
Excitation $\hat{V}_0 \cos(\omega t)$

$|1\rangle$ **?**

Rabi formula

$$P_{2\to 1} = \frac{\sin^2\left(\sqrt{\delta\omega^2 + \Omega^2}\, t/2\right)}{1 + \delta\omega^2/\Omega^2}$$

$$\Omega = \langle 2|\widehat{V_0}|1\rangle/\hbar$$

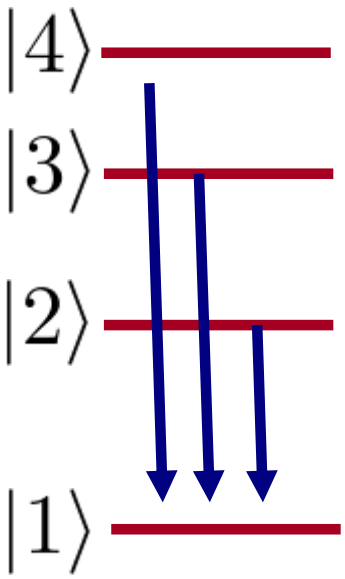


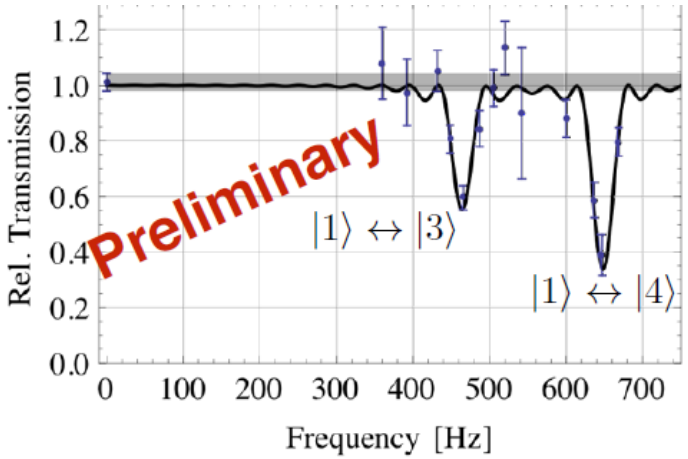
How to excite resonant transitions?

1) Mirror vibrations $h(t)$

$$\hat{V}(t) = -\frac{dh}{dt}\,\widehat{p_z}$$

qBounce



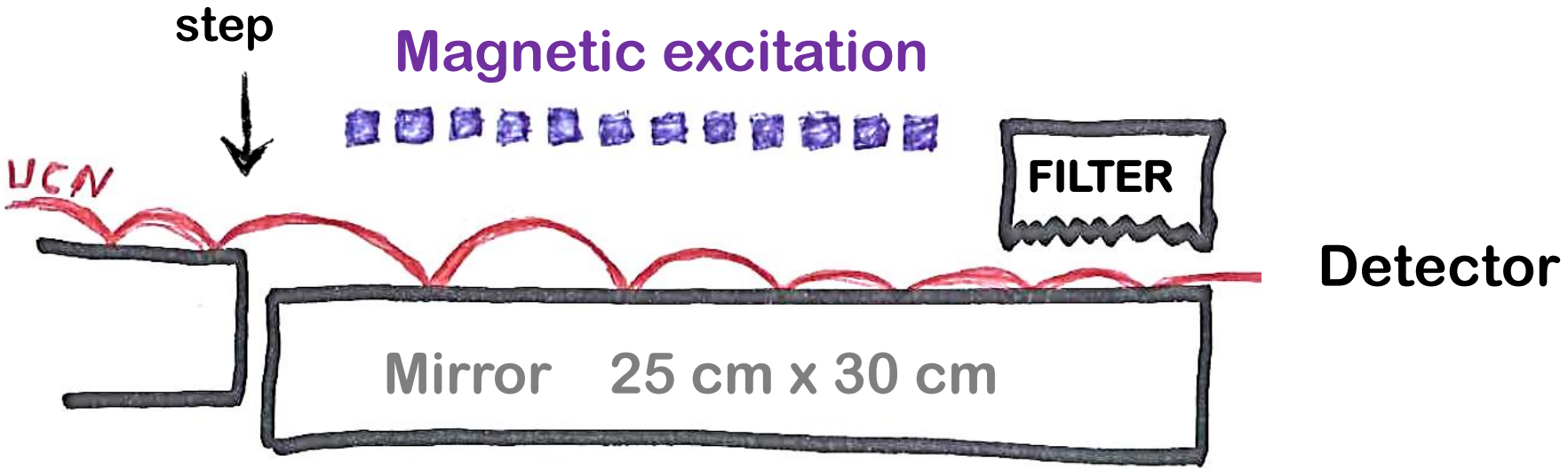


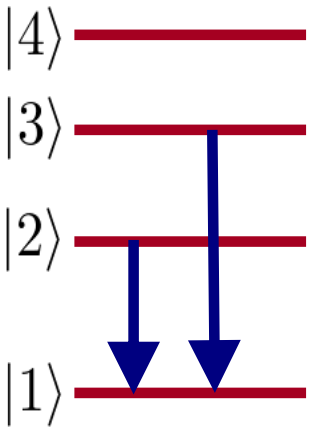
2) Magnetic excitation

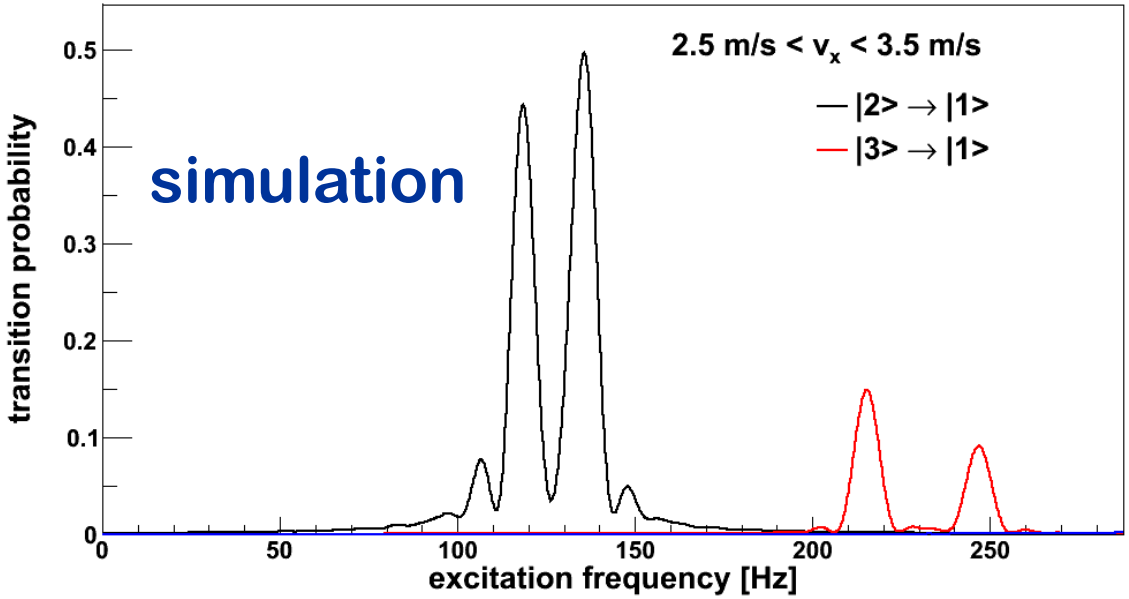
Grani
Gravitational Neutron Induced Transitions

$$\hat{V}(t) = \pm\mu\,|B|(t) \approx \pm\mu\frac{d|B|}{dz}(t)\,\hat{z}$$

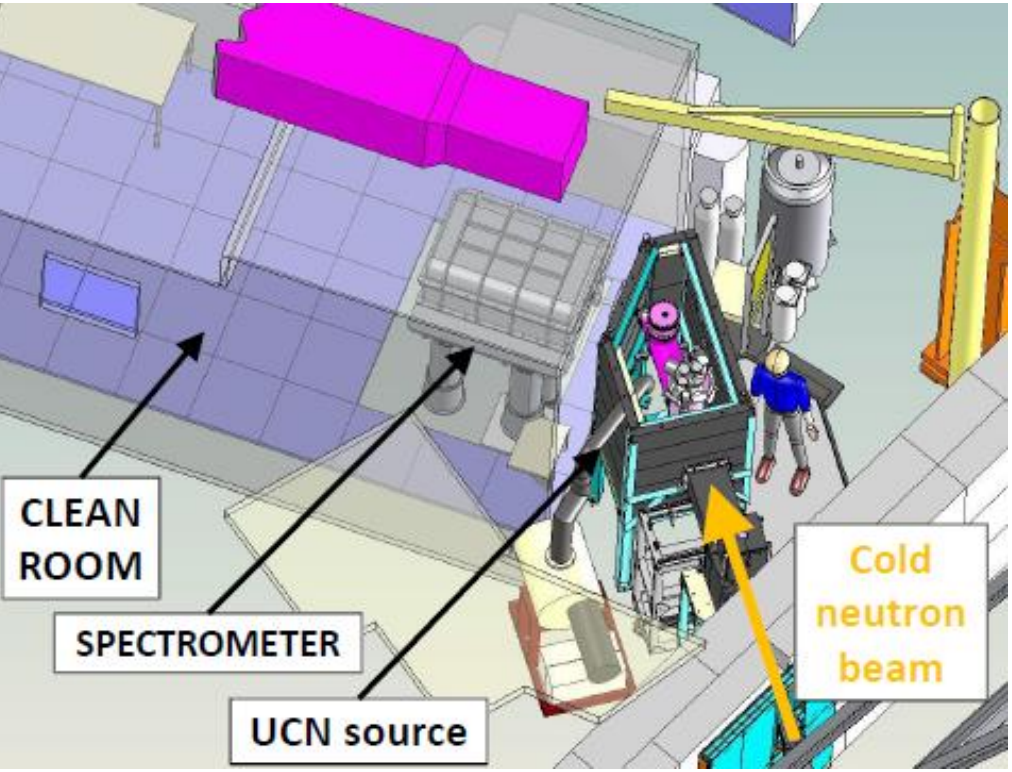
Resonant transitions in GRANIT

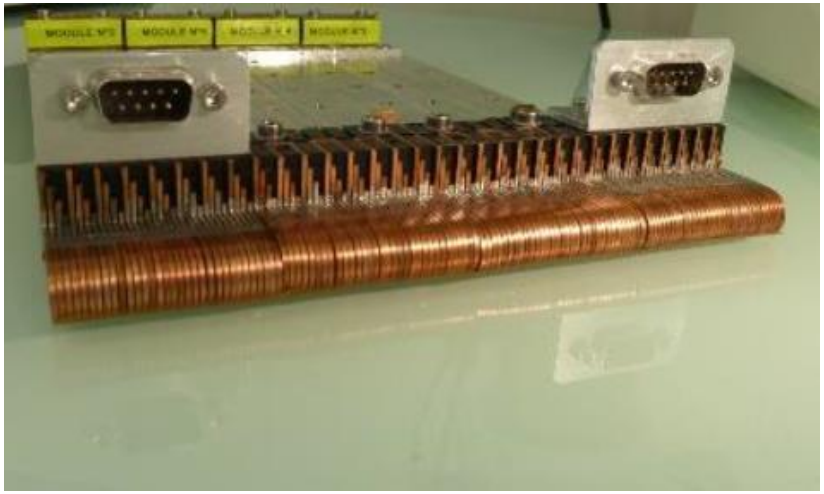






The GRANIT instrument
at ILL level C



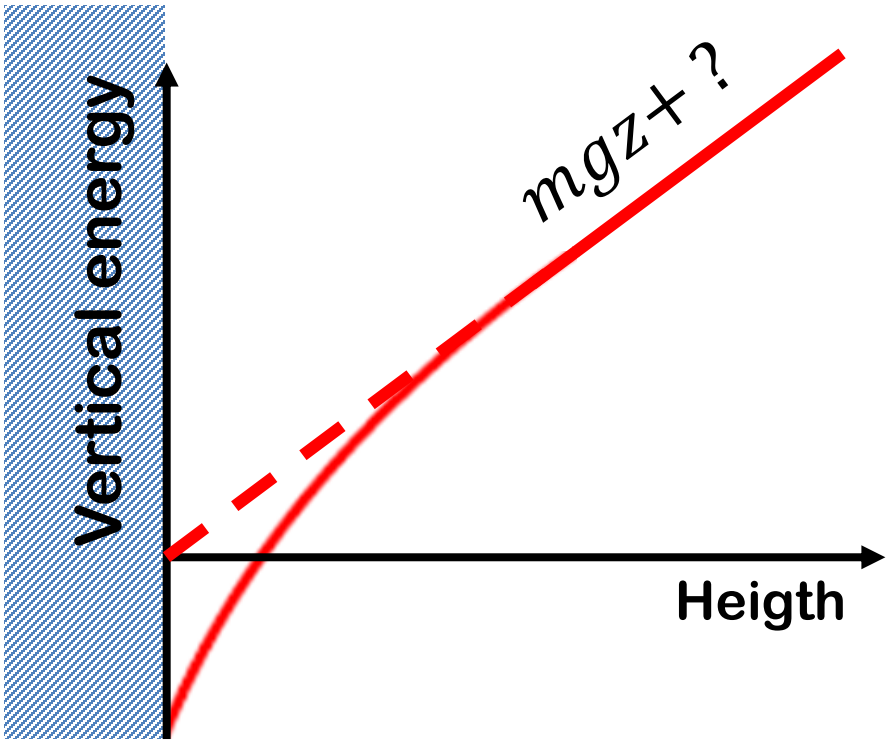


First UCNs in GRANIT in 2013.

Producing UCNs is a delicate art.

We are getting ready for measuring something interesting…

Searching for a fifth force



Consequences for the quantum states

1. **Squeezing of the wave functions**
2. **Dilatation of the energy spectrum**

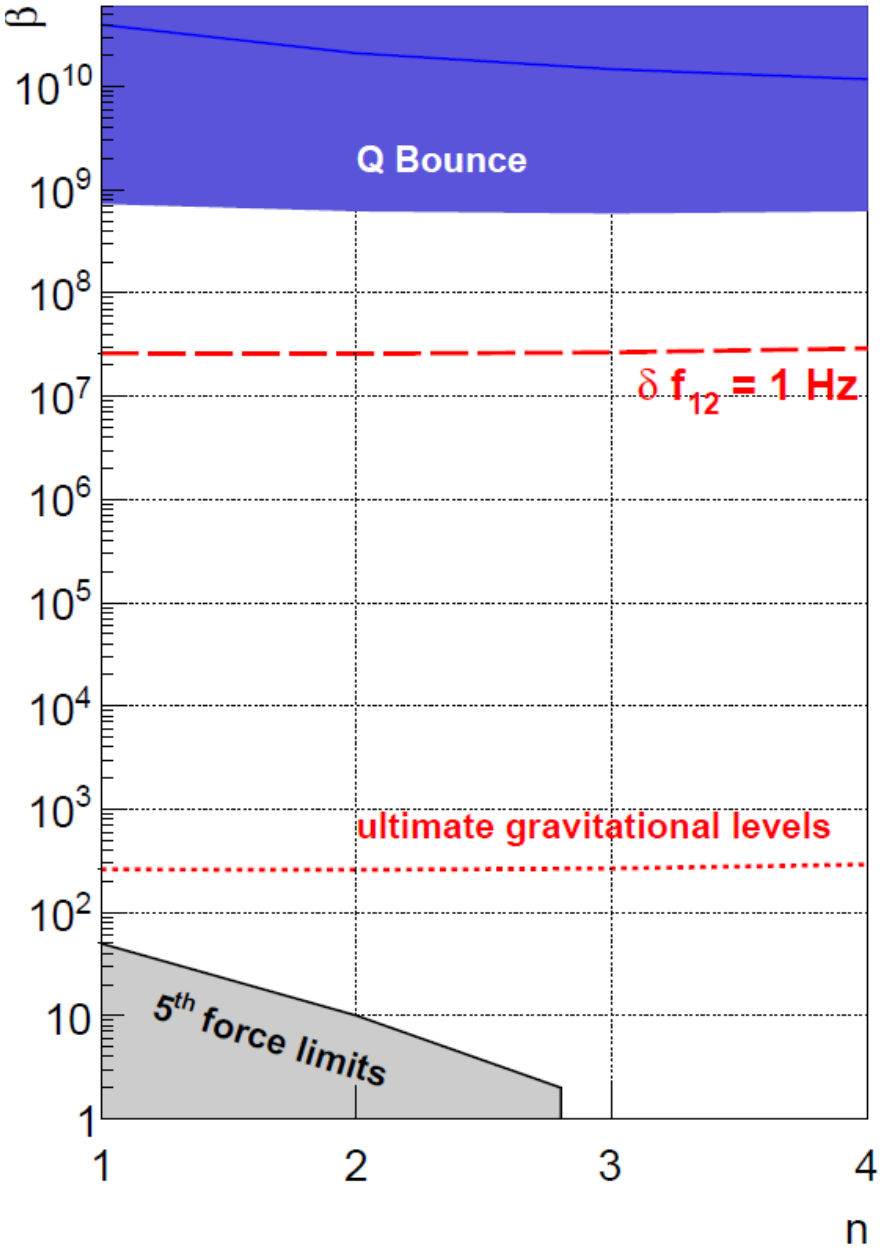
Chameleon case:

$$V(z) = mgz + \beta \frac{m}{M_{\text{Planck}}} \varphi(z)$$

Field profile above the mirror

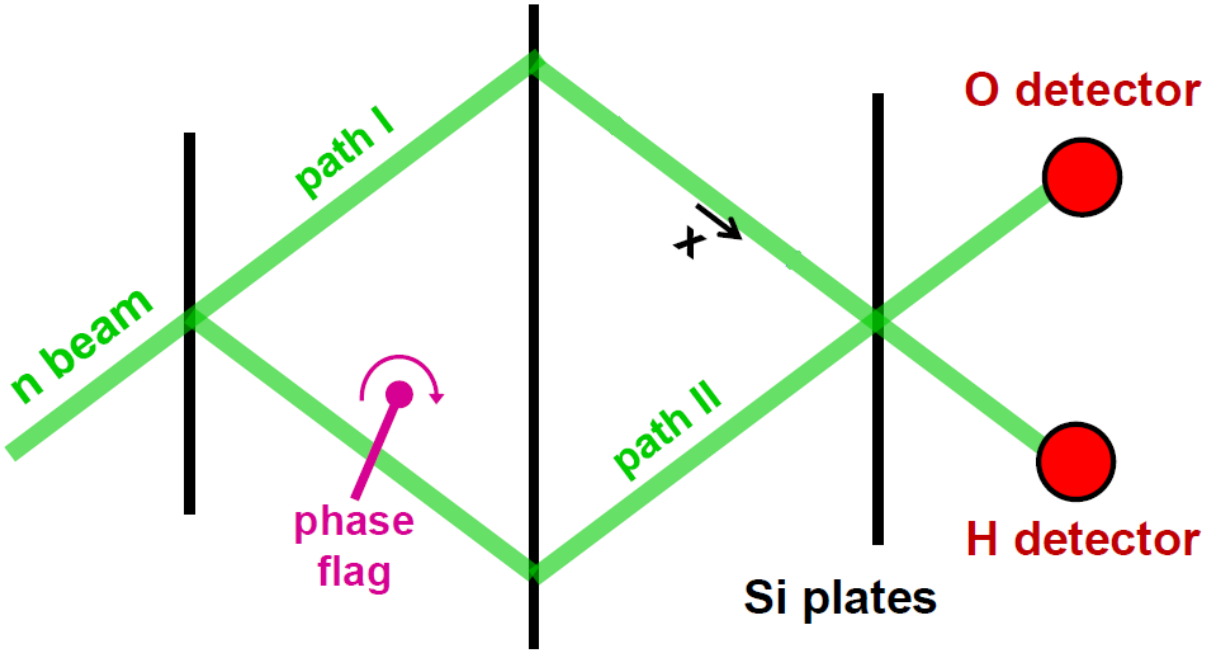
$$\varphi(z) = \Lambda(\Lambda z/\hbar c)^{2/2+n}$$

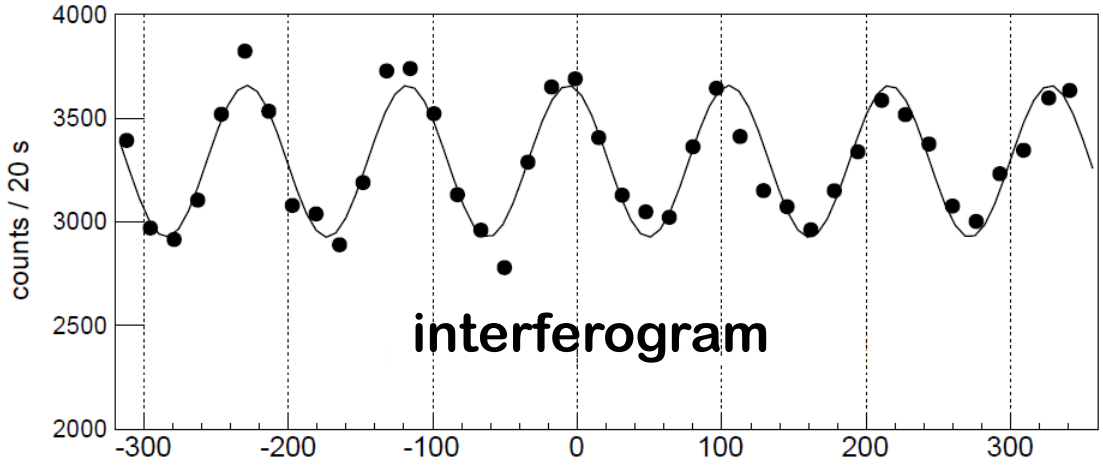
Bouncing neutron sensitivity to the chameleon



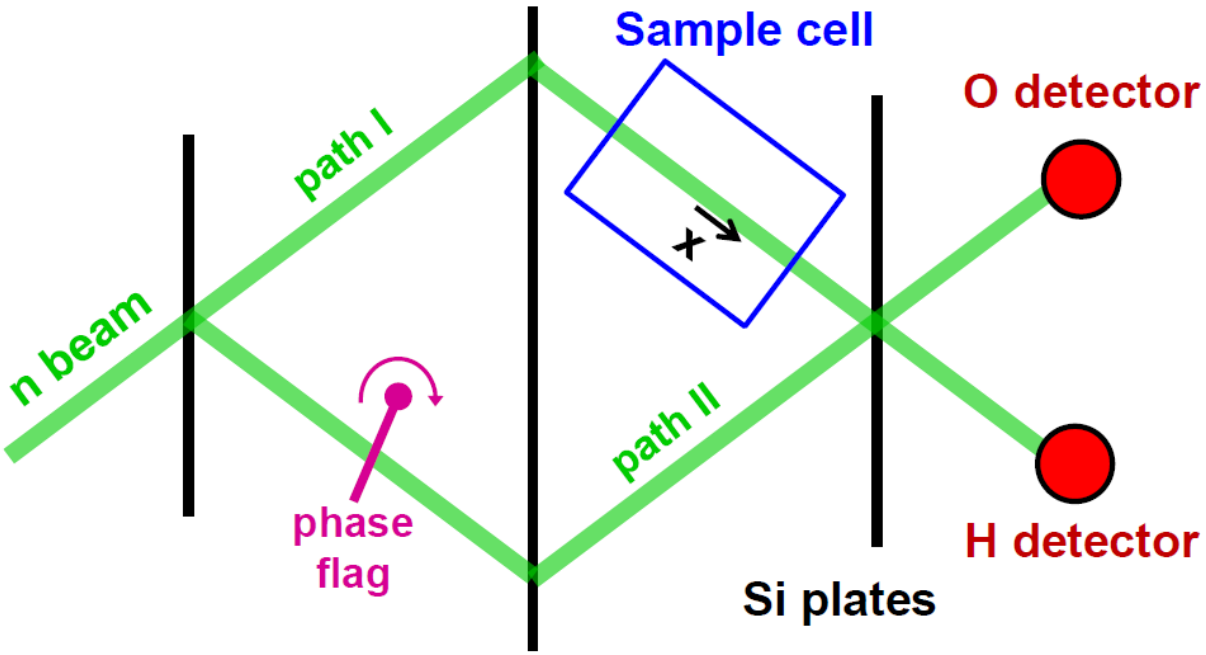

1 Neutrons, nucleosynthesis, baryogenesis
2 Dark Energy, the chameleon
3 Bouncing neutrons with GRANIT
4 Neutron interferometry experiment

Principle of neutron interferometry 1





Principle of neutron interferometry 2



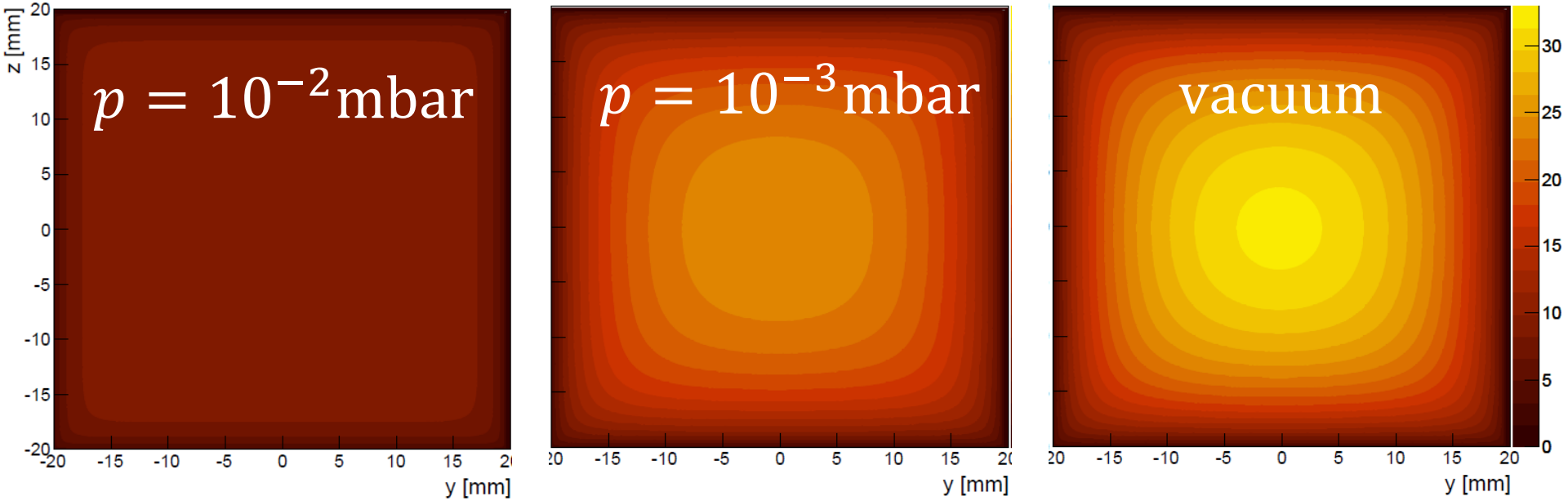
Phase shift due to the sample: $$\xi = -\frac{m}{k\hbar^2}\int V(x)\,dx$$

neutron potential in a chameleon field: $$V(x) = \beta\frac{m}{M_{\text{Planck}}}\varphi(x)$$

The chameleon cell

Idea:
the chameleon field in a cell exists only in vacuum,
it is suppressed by a small amount of gas (here helium)

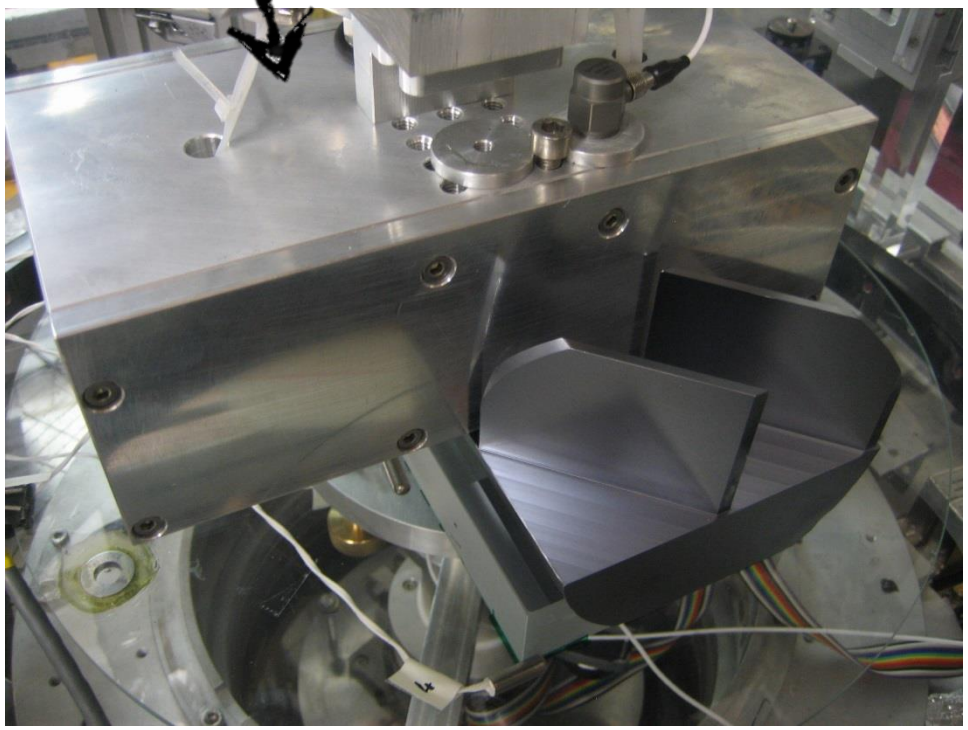
We plot the transverse field profile $\varphi(y,z)/\Lambda$



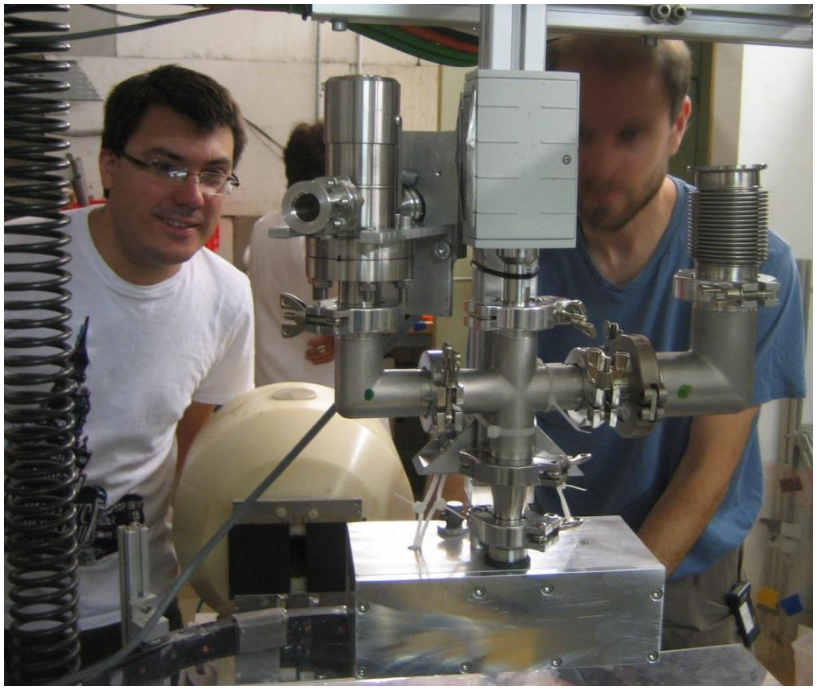
Numerical solution of the chameleon equation for $n = 1$ and $\beta = 5 \times 10^7$

The experiment at the S18 instrument (ILL)

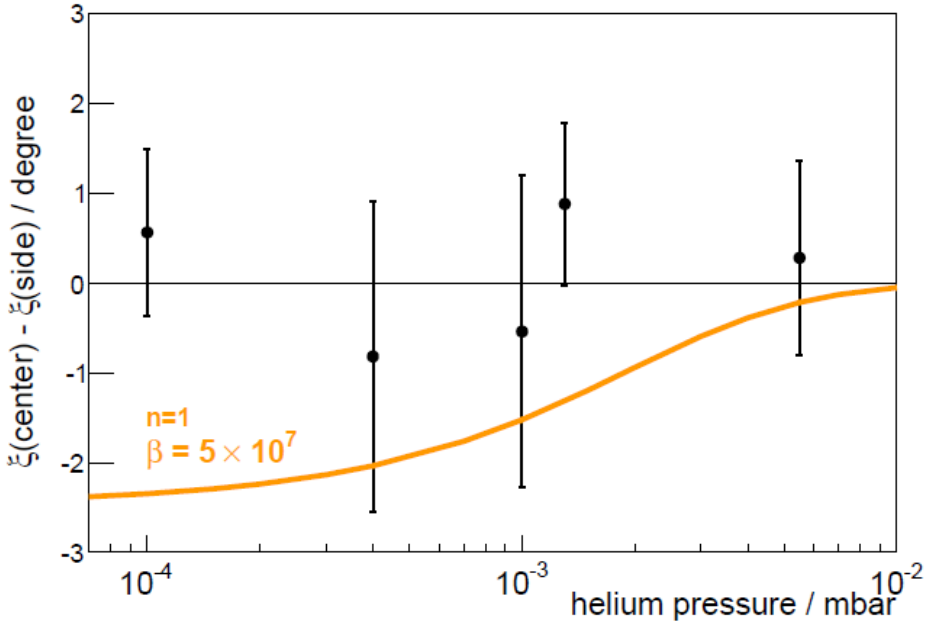
Dedicated vacuum chamber built by the Atominstitut in Vienna



Hartmut Lemmel

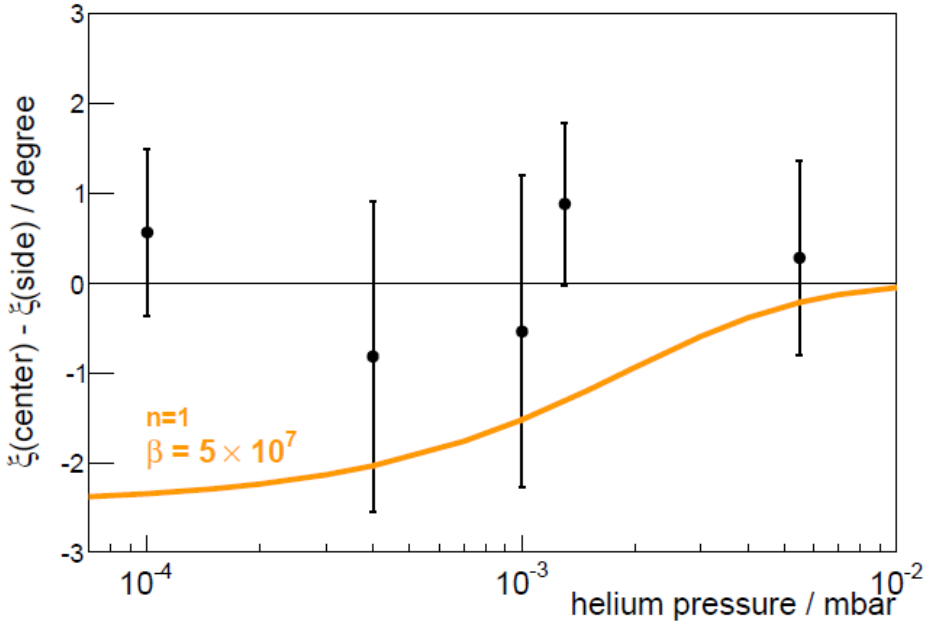


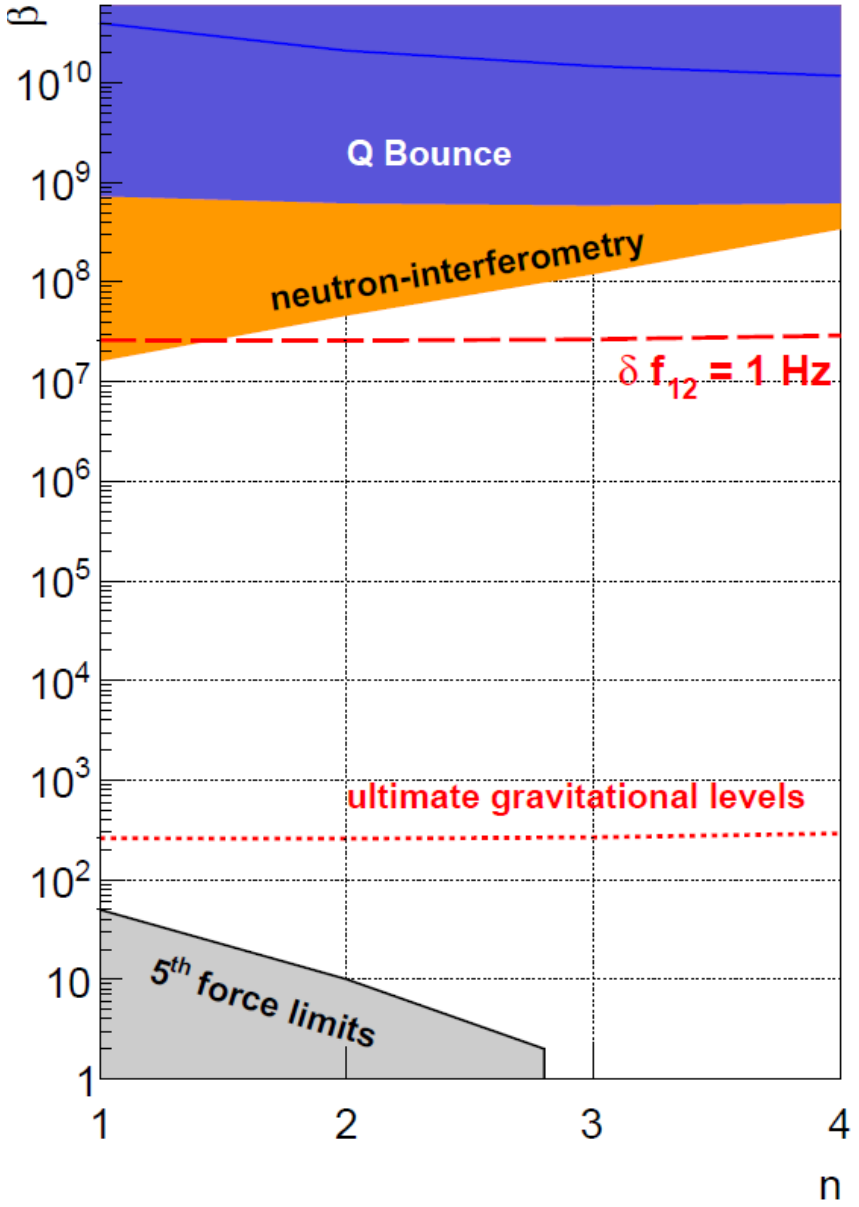
Results



We have measured the field profile,
by moving the vacuum cell,
as a function of the helium pressure

Results


ξ(center) - ξ(side) / degree
3
2
1
0
-1
-2
-3
n=1
β = 5 × 10^7
10^-4
10^-3
10^-2
helium pressure / mbar


β
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
Q Bounce
neutron-interferometry
δ f12 = 1 Hz
ultimate gravitational levels
5th force limits
1
2
3
4
n

Breaking news

Phys. Lett. B 743, 310 (2015)

Preprint arXiv:1502.03888

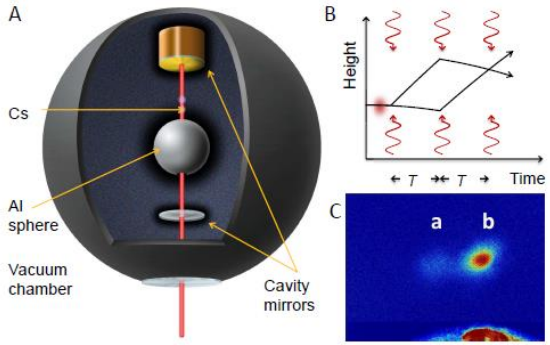
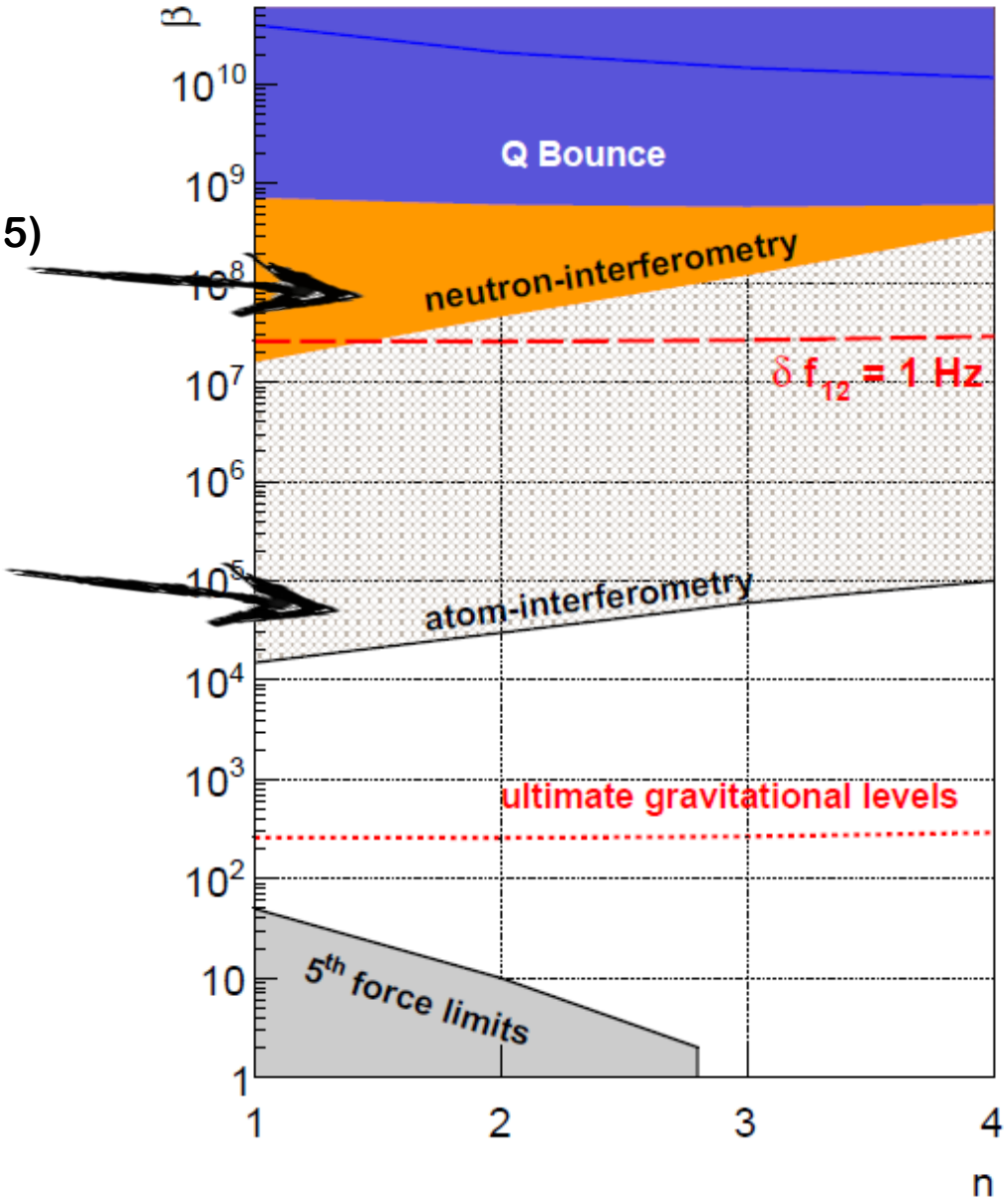
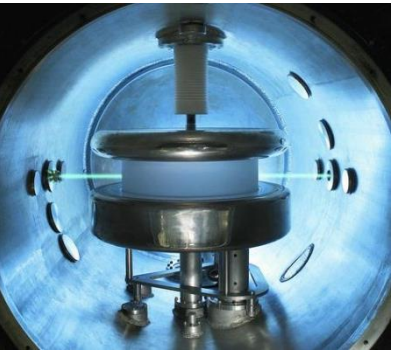


FIG. 1: (A): The vacuum chamber holds a pair of mirrors forming a Fabry-Pérot cavity and the aluminum (Al) source sphere. Laser beams pass a 1.5-mm radius hole in the $r_s = 9.5-$mm radius sphere. The chameleon field is suppressed close to the sphere, generating a field gradient. We form a Mach-Zehnder interferometer using cesium atoms from a magneto-optical trap (not shown). (B): Photons in three

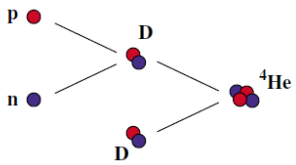


The end



10^{15} GeV
GUT epoch

100 GeV
Electroweak transition



1 MeV
nucleosythesis

1 eV

1 meV
Today