# Neutrons Ultra Froids (UCN)

- Propriétés des UCN
  - Découverte
  - Propriétés
  - Production
- Expériences avec des UCN
  - nEDM
  - Durée de vie du neutron
  - Etats quantiques du neutron dans le champ de pesanteur
  - « Galerie du chuchotement »

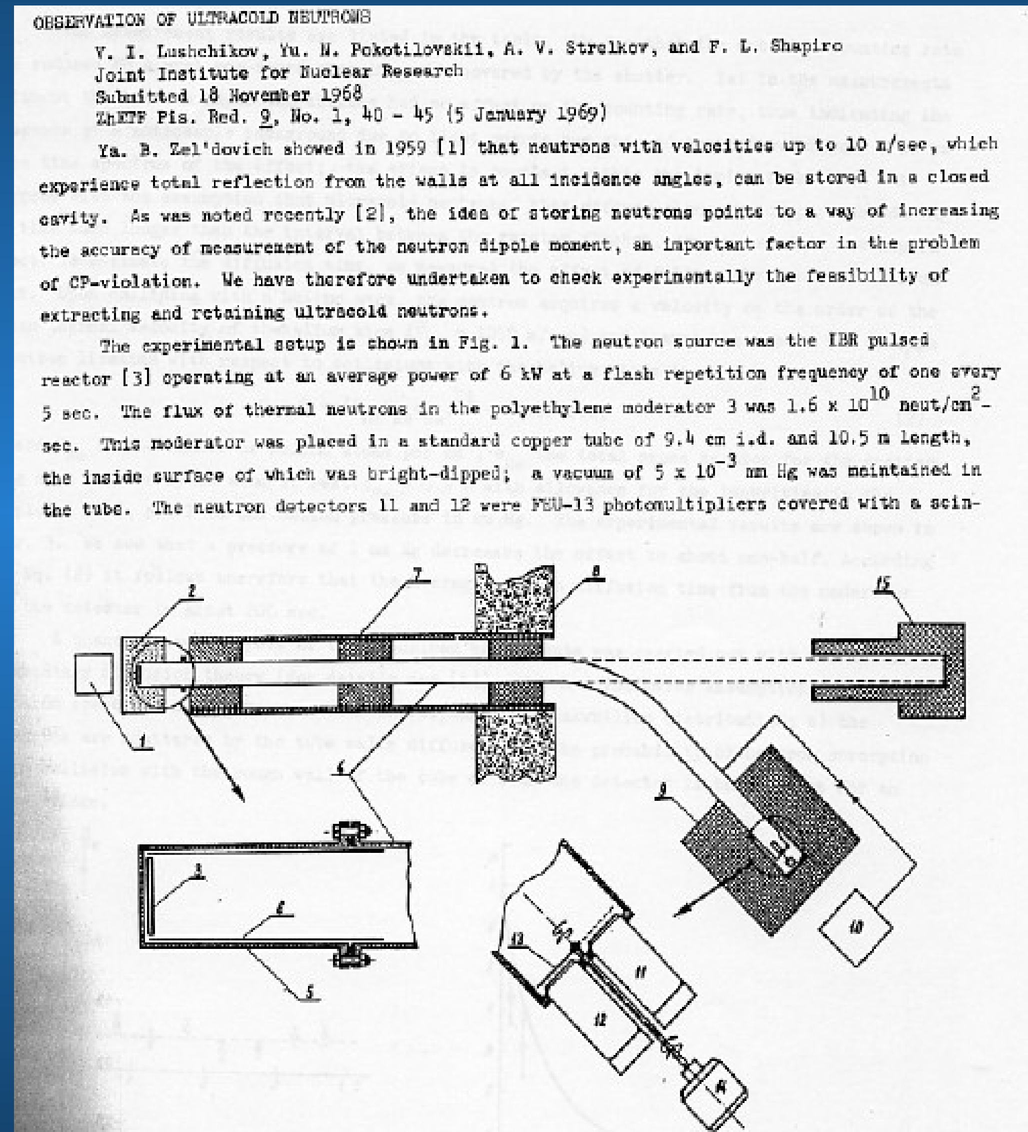
# Découverte expérimentale

Ya.B. Zeldovich,
*JETP* **36** (1959) 1952 :

« Les neutrons avec des vitesses inférieures à 10 m/s peuvent être confinés dans un volume ».

V.I. Luschikov, Yu.N. Pokotilovsky, A.V. Strelkov, F.L. Shapiro,
*JETP Lett* **9** (1969) 40

« Observation of ultracold neutrons »



OBSERVATION OF ULTRACOLD NEUTRONS

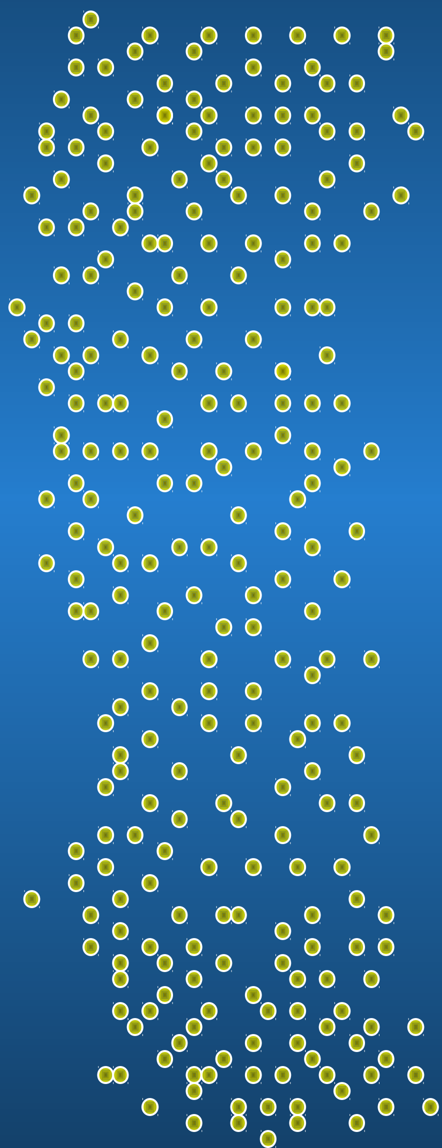
V. I. Lushchikov, Yu. N. Pokotilovskii, A. V. Strelkov, and F. L. Shapiro
Joint Institute for Nuclear Research
Submitted 18 November 1968
ZhETF Pis. Red. 9, No. 1, 40 - 45 (5 January 1969)

Ya. B. Zel'dovich showed in 1959 [1] that neutrons with velocities up to 10 m/sec, which experience total reflection from the walls at all incidence angles, can be stored in a closed cavity. As was noted recently [2], the idea of storing neutrons points to a way of increasing the accuracy of measurement of the neutron dipole moment, an important factor in the problem of CP-violation. We have therefore undertaken to check experimentally the feasibility of extracting and retaining ultracold neutrons.

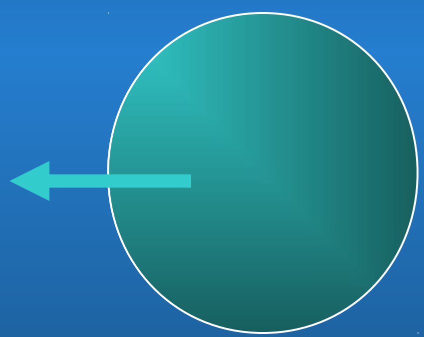
The experimental setup is shown in Fig. 1. The neutron source was the IBR pulsed reactor [3] operating at an average power of 6 kW at a flash repetition frequency of one every 5 sec. The flux of thermal neutrons in the polyethylene moderator 3 was 1.6 x $10^{10}$ neut/cm$^2$-sec. This moderator was placed in a standard copper tube of 9.4 cm i.d. and 10.5 m length, the inside surface of which was bright-dipped; a vacuum of 5 x $10^{-3}$ mm Hg was maintained in the tube. The neutron detectors 11 and 12 were FEU-13 photomultipliers covered with a scin-

# Potentiel de Fermi

Matière

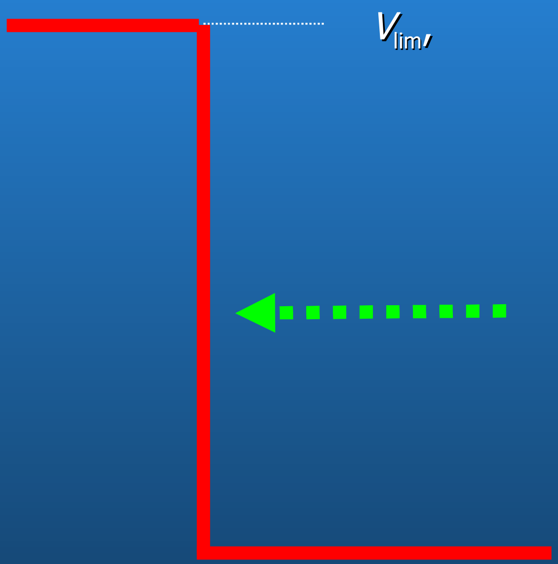


Neutron



Potentiel (de Fermi)
vu par neutron

$$U = \frac{2\pi h^2}{m} N b_{coh}$$



# Propriétés

## Interaction avec matière

~ 99.99 % – réflexion élastique

~ $10^{-4}$ – diffusion inélastique sur des phonons thermiques

~ $10^{-5}$ – absorption

$V_{UCN} \sim (1 \div 10)$ m/s

$E_{UCN} \sim 1$ neV

$H_{UCN}^{Earth's\ field} \sim 1$ m

$T \sim 1$ mK

d'où le nom UCN

| Matériel | $b_{coh}$, fm | Densité, g/cm$^3$ | $V_{lim}$, m/s |
|---|---|---|---|
| $D_2$ (liquide) | 13 | 0,15 | 3,82 |
| $D_2O$ | 18,8 | 1,1 | 5,57 |
| C (graphite) | 6,65 | 2,25 | 6,11 |
| C (diamant) | 6,65 | 3,52 | 7,65 |

# Deux problèmes majeurs

- Faible flux/densité

$$\eta = \frac{\int_0^{v_{\lim}} n(v)dv}{\int_0^{\infty} n(v)dv} = \frac{1}{8}\left(\frac{mv_{\lim}^2}{kT}\right)^2 \approx 10^{-11}$$

pour un spectre maxwellien et $T = 300$ K, $v_{\lim}(\mathrm{Cu}) = 5{,}67$ m/s

- (Pertes anomales)

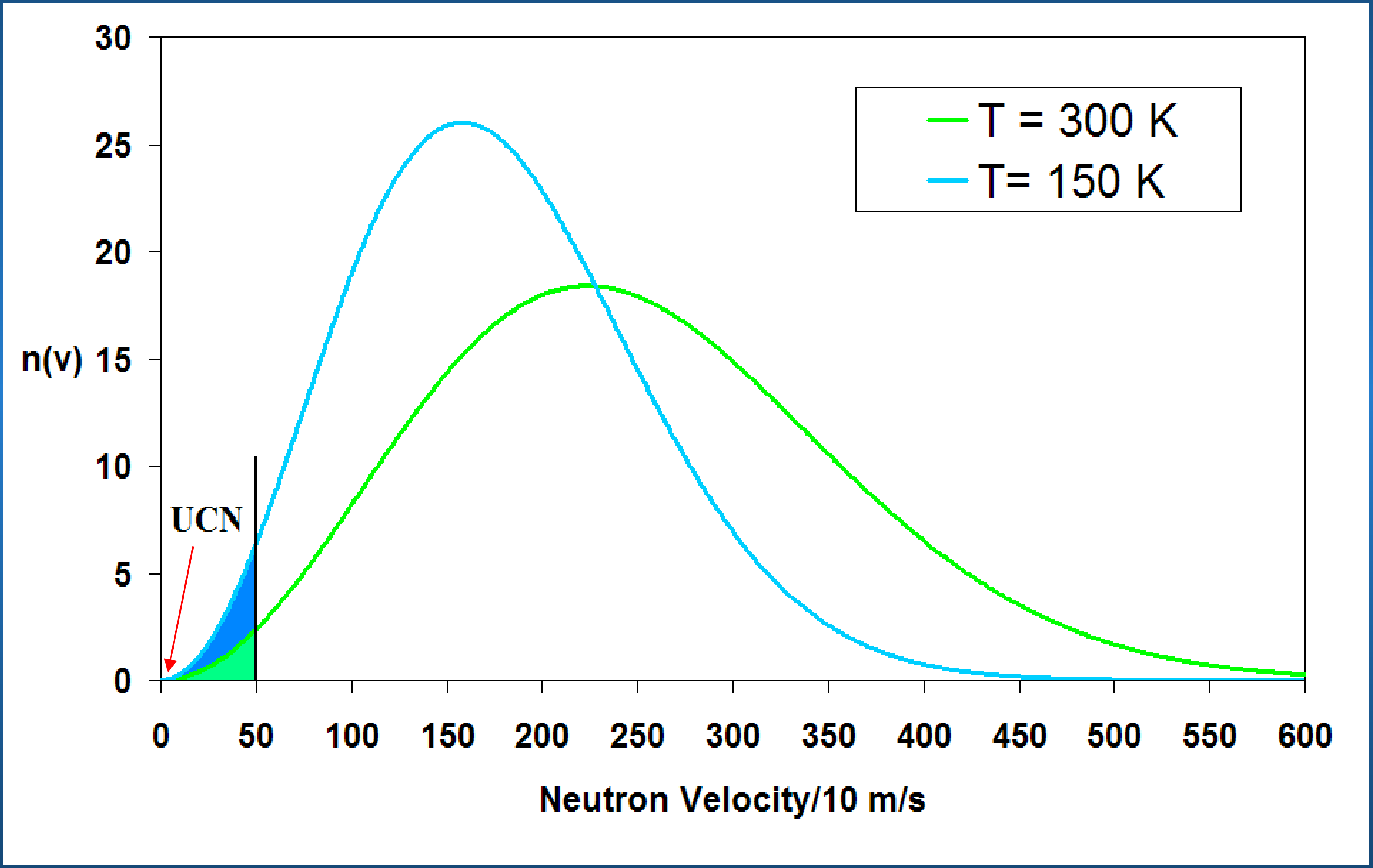
# Comment peut-on augmenter le flux ?

- Utiliser un modérateur froid
- Profiter du champ gravitationnel terrestre
- Les ralentir « mécaniquement »

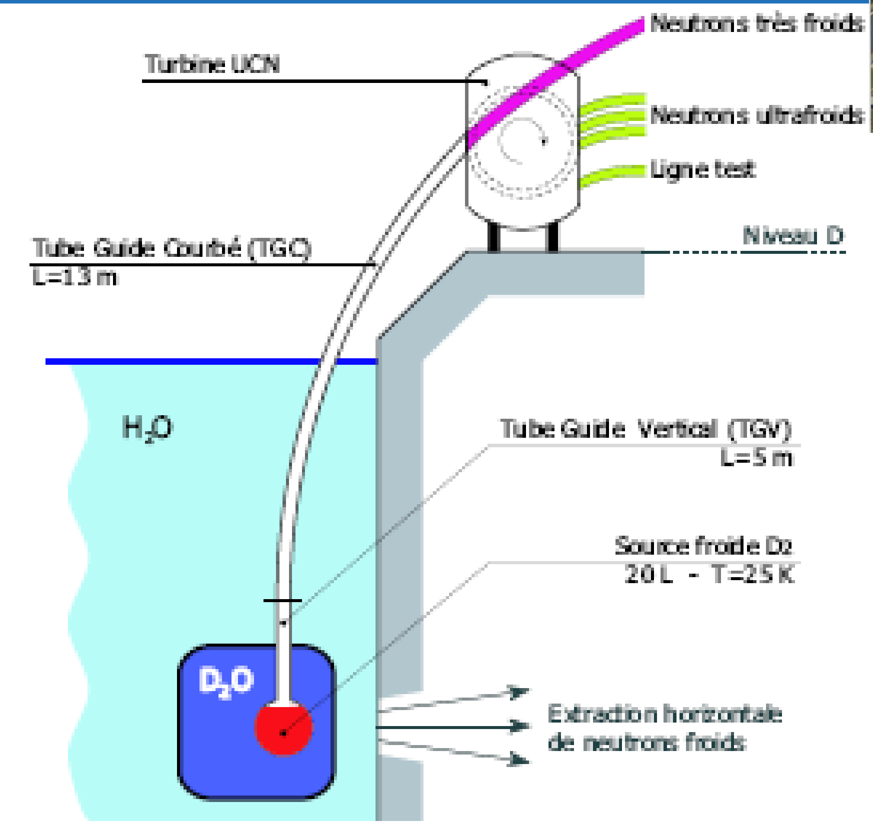
- Utiliser He superfluide

- Nanoparticules comme modérateur

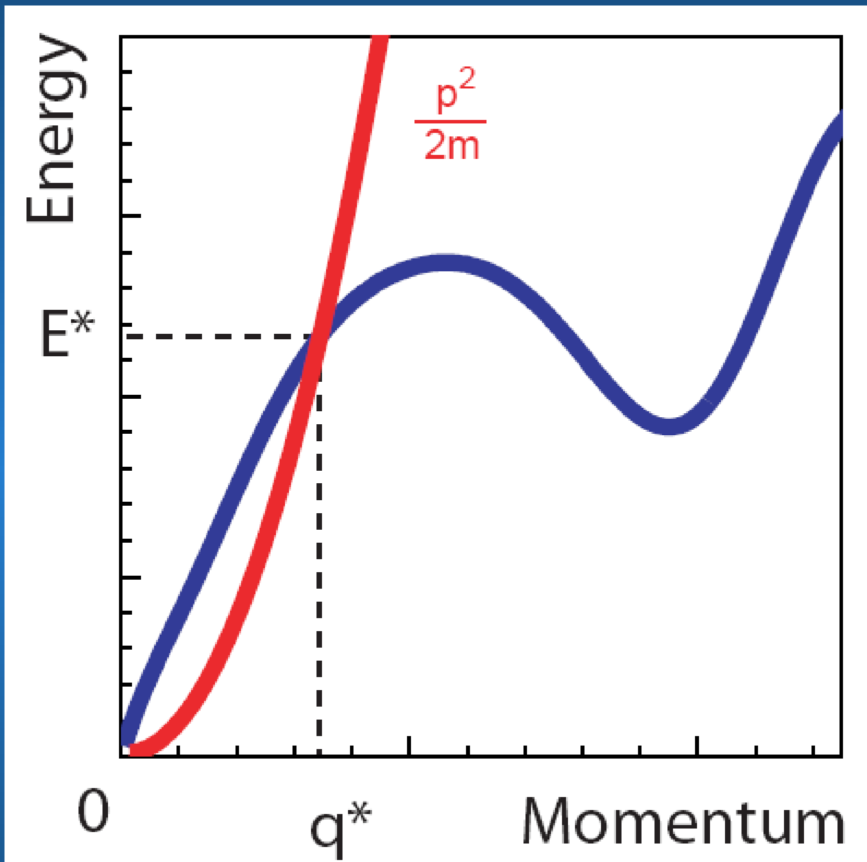
# L’importance du refroidissement des neutrons

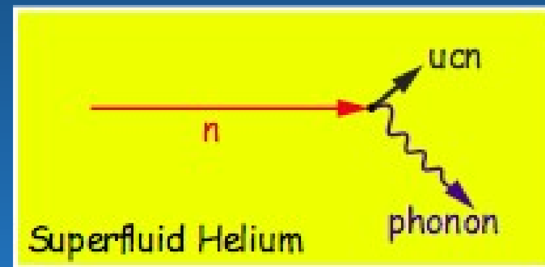


# UCN à l'ILL

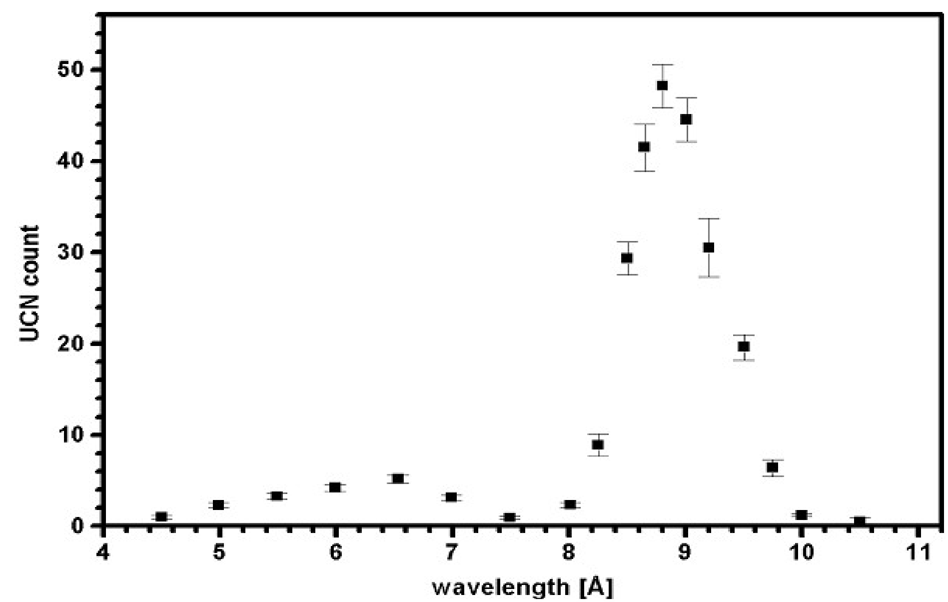

Neutrons très froids
Turbine UCN
Neutrons ultrafroids
Ligne test
Niveau D
Tube Guide Courbé (TGC)
L=13 m
$H_2O$
Tube Guide Vertical (TGV)
L=5 m
Source froide D2
20 L - T=25 K
$D_2O$
Extraction horizontale
de neutrons froids

# Production des UCN dans $^4$He superfluide (Bob Golub & Mike Pundlebury)




Problème :
Expériences in situ



# Physique avec des UCN

- « Propriétés » du neutrons
  - désintégration (durée de vie, asymétries, désintégration radiative…)
  - nEDM
- Neutrons comme outil
  - états quantiques dans le champ de pesanteur
  - états « centrifuges »

# Durée de vie du neutron

- Modèle Standard

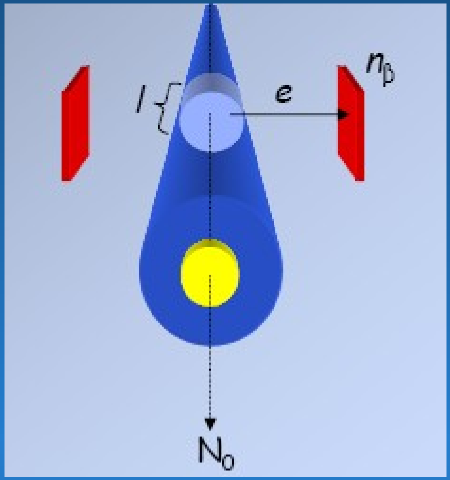
$$\left|V_{ud}\right|^2 = \frac{(4908 \pm 4)s}{\tau(1+3\lambda^2)} \qquad \lambda = \frac{g_A}{g_V}$$

$$\begin{pmatrix} d_w \\ s_w \\ b_w \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Astrophysique
  - cycle solaire
  - formation des étoiles à neutrons
  - nucléosynthèse primordiale
  - …

- <u>Expériences in-flight (CN) :</u>
  - Mesurer la radioactivité du faisceau des neutrons :

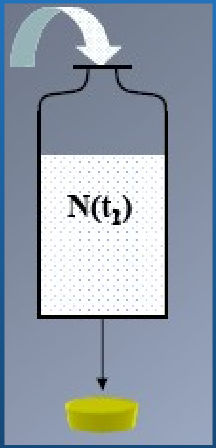
$$n_\beta = \frac{dN}{dt} = -\frac{N_0}{\tau_n} e^{-\frac{l}{v \cdot \tau_n}}$$




  - Deux mesures absolus

- <u>Expériences de stockage (UCN) :</u>
  - Measurer la diminution du nombre de neutrons directement :

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

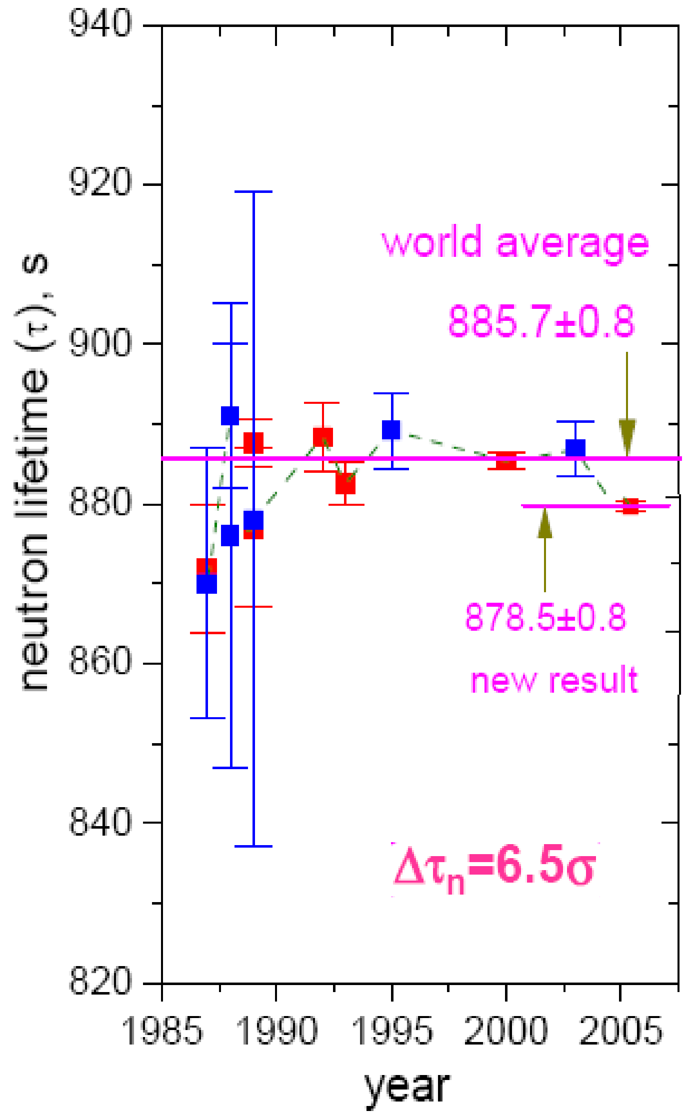



  - Deux mesures relatives, mais :

$$\tau_m^{-1} = \tau_n^{-1} + \tau_{loss}^{-1}$$

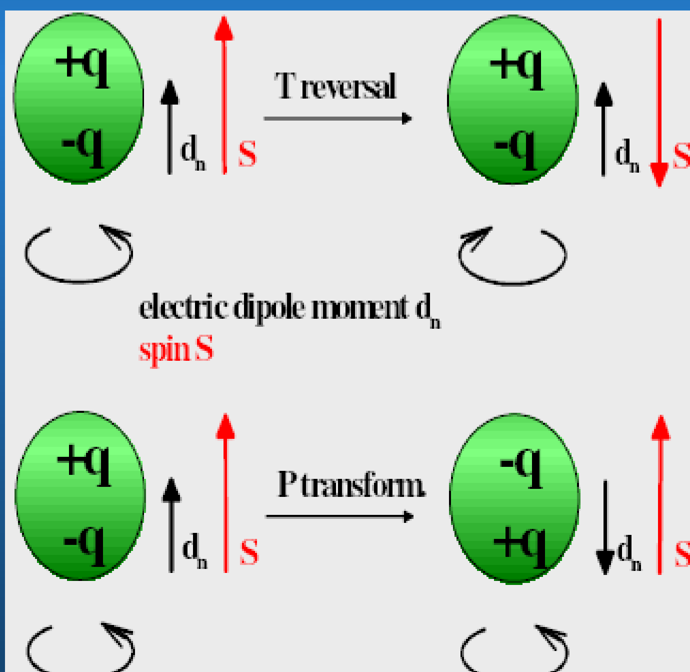
# Durée de vie du neutron (situation générale)

| Lifetime τ[s] | Method | Ref./Year |
|---|---|---|
| 878.5 ± 0.8 | Storage of ultra-cold neutrons | A. Serebrov et al. 2005 |
| 886.8 ± 3.42 | Neutron beam experiment | M.S. Dewey et al. 2003 |
| 885.4 ± 0.95 | Storage of ultra-cold neutrons | S. Arzumanov et al. 2000 |
| 889.2 ± 4.8 | Neutron beam experiment | J. Byrne et al. 1995 |
| 882.6 ± 2.7 | Storage of ultra-cold neutrons | W. Mampe et al. 1993 |
| 888.4 ± 3.1 ± 1.1 | Storage of ultra-cold neutrons | V. Nesvizhevski et al. 1992 |
| 878 ± 27 ± 14 | Neutron beam experiment | R. Kosakowski 1989 |
| 887.6 ± 3.0 | Storage of ultra-cold neutrons | W. Mampe et al. 1989 |
| 877 ± 10 | Storage of ultra-cold neutrons | W. Paul et al. 1989 |
| 876 ± 10 ± 19 | Neutron beam experiment | J. Last et al. 1988 |
| 891 ± 9 | Neutron beam experiment | P. Spivac et al. 1988 |
| 872 ± 8 | Storage of ultra-cold neutrons | A. Serebrov et al. 1987 |
| 870 ± 17 | Neutron beam experiment | M. Arnold et al. 1987 |
| 903 ± 13 | Storage of ultra-cold neutrons | Y.Y. Kosvintsev et al. 1986 |
| 875 ± 95 | Storage of ultra-cold neutrons | Y.Y. Kosvintsev et al. 1980 |
| 937 ± 18 | Neutron beam experiment | J. Byrne et al. 1980 |
| 881 ± 8 | Neutron beam experiment | L. Bondarenko et al. 1978 |
| 918 ± 14 | Neutron beam experiment | C.J. Christensen et al. 1972 |
| 885.8 ± 0.9 | world average 1998 | H. Abele 2000 |



# Moment électrique dipolaire du neutron (nEDM) – à la recherche de la violation de CP

$$\vec{d}_n = e\,\vec{r} = d_n\,\hat{s}$$



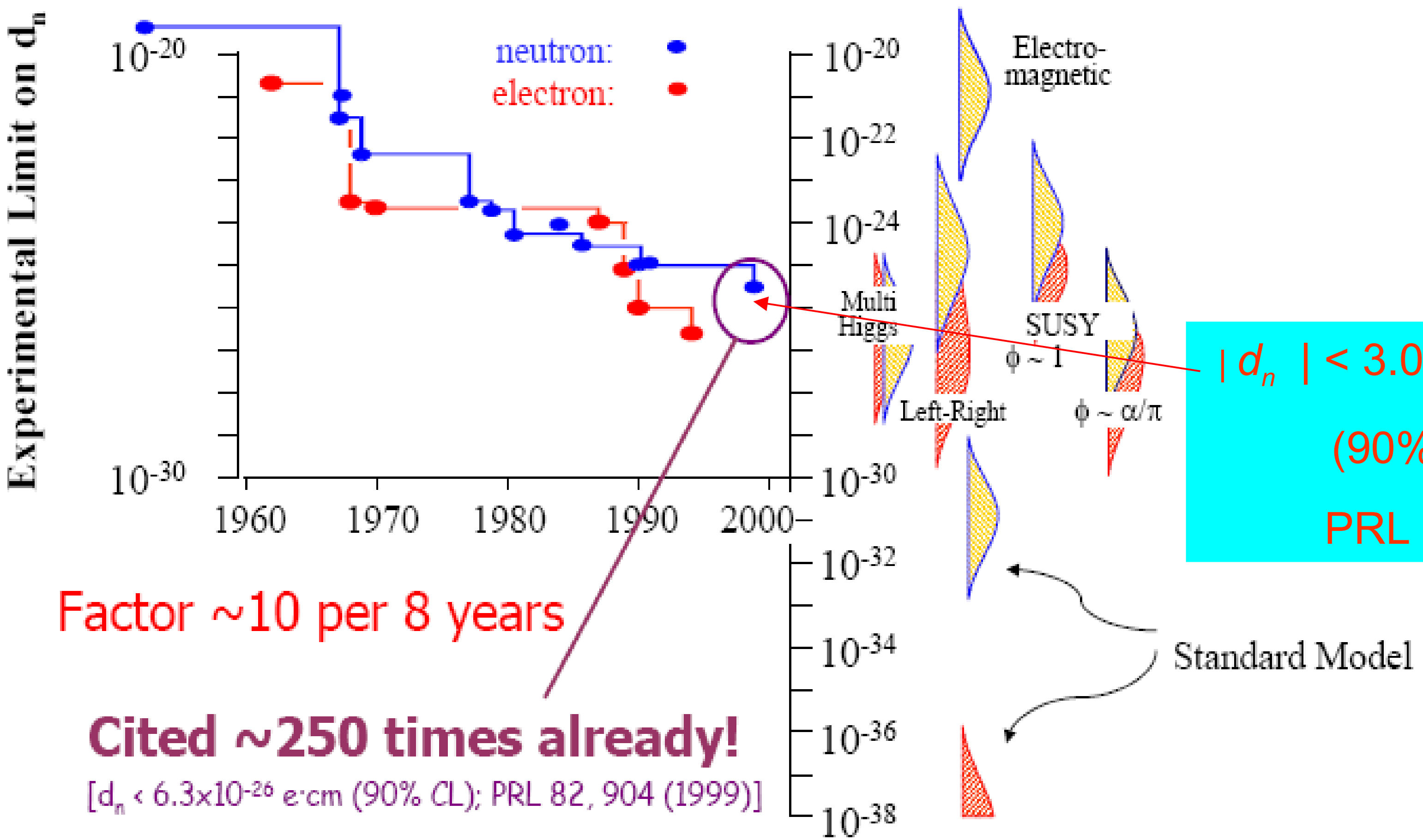

La violation de CP n’a été observée que dans les systèmes kaons et de B mesons neutres

L’existence de nEDM ≠ 0 implique

La violation de **P et de T**

Théorème CPT → violation de **CP**

# EDM limits: the first 50 years




$|d_n| < 3.0 \times 10^{-26}$ ecm

(90% C.L.)

PRL (2006)

Factor ~10 per 8 years

**Cited ~250 times already!**

[$d_n < 6.3 \times 10^{-26}$ e·cm (90% CL); PRL 82, 904 (1999)]

"It is fair to say that the neutron EDM has ruled out more theories (put forward to explain $K_0$ decay) than any experiment in the history of physics" R. Golub

# « Nouveaux » systèmes en mécanique quantique expérimentale

- États quantiques dans le champ de pesanteur
- États centrifuges

"Let us consider another possibility, an atom held together by gravity alone. For example, we might have two neutrons in a bound state. When we calculate the Bohr radius of such an atom, we find that it would be $10^8$ light years, and that the atomic binding energy would be $10^{-70}$ Rydbergs. There is then little hope of ever observing gravitational effects on systems which are simple enough to be calculable in quantum mechanics."

Brian Hatfield, in "Feynman Lectures on Gravitation" ;
R.P. Feynman, F.B. Morinigo, W.G. Wagner, Ed. Brian Hatfield

Addison-Wesley Publishing Company, 1995, p. 11

# Choix du système

Les états quantiques peuvent apparaître pour un neutron ultra froids

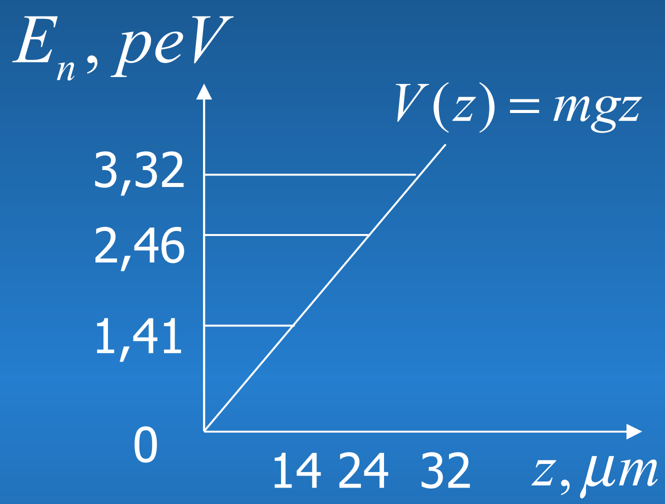
- une particule neutre
- d'une longue durée de vie
- d'une faible masse
- d'une faible énergie (température)

dans un puis formé par un miroir

- diffusion élastique à 99,99%
- absorption $10^{-5}$
- diffusion inélastique $10^{-4}$
- grande barrière de potentiel

et le champ de pesanteur

# Exercice de mécanique quantique




$$z_0 = \sqrt[3]{\frac{\hbar^2}{2gm^2}} = 5,87\ \mu\text{m}$$

$$E_n^{qc} \approx \sqrt[3]{\frac{m}{8}\left(\pi \hbar g\left(n-\frac{1}{4}\right)\right)^2}$$

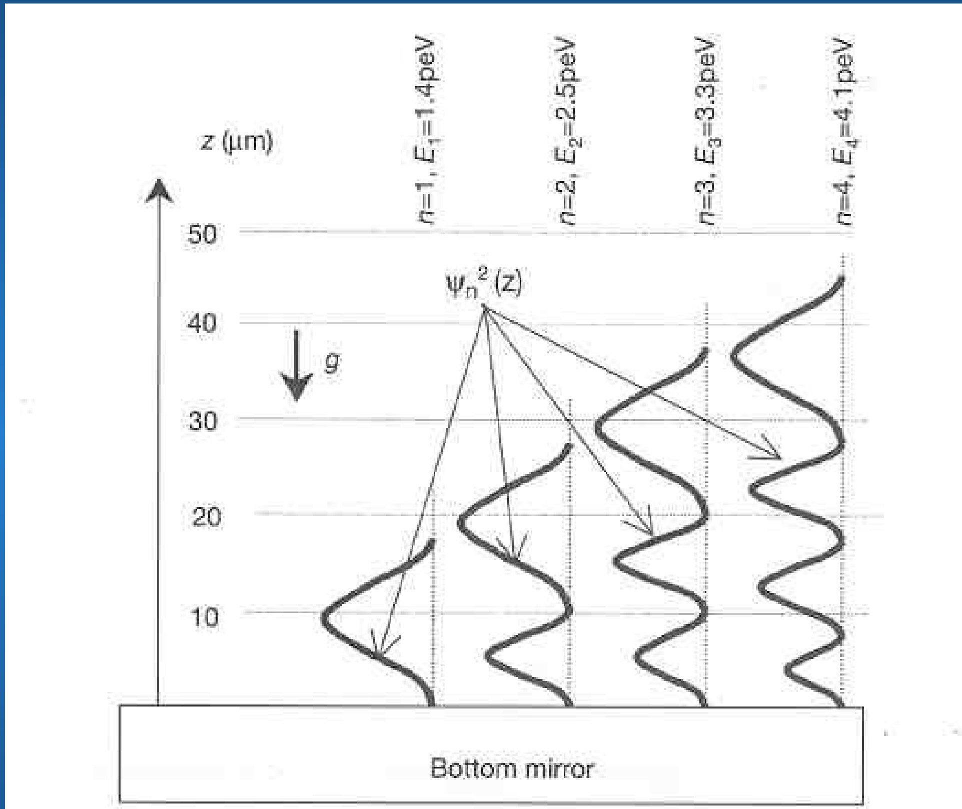
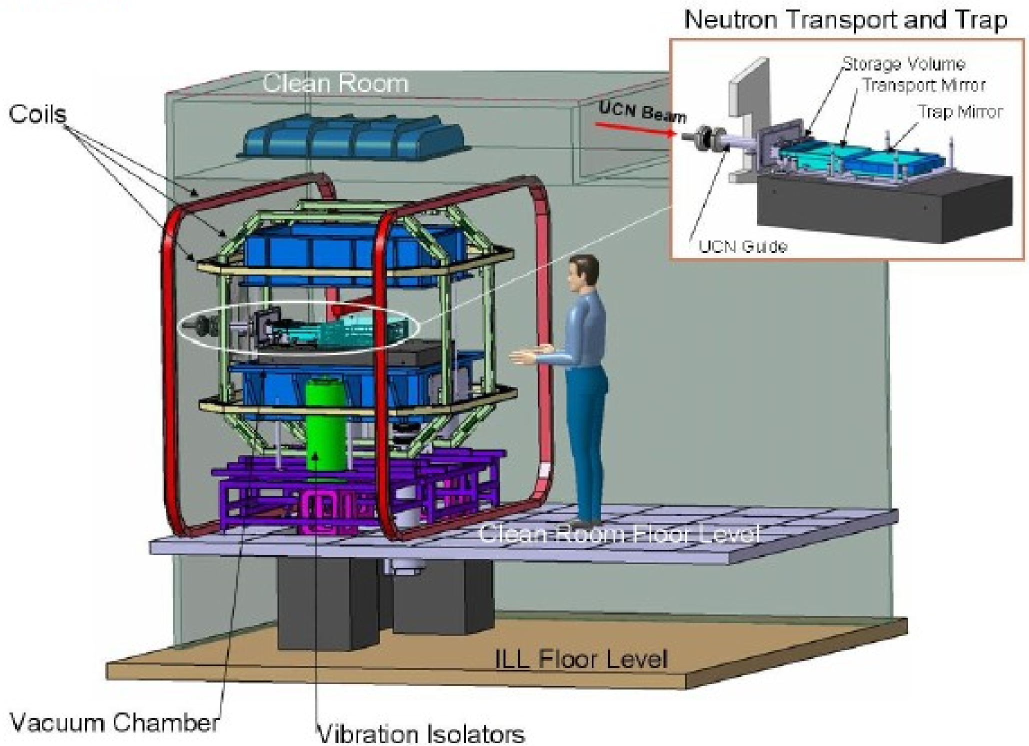


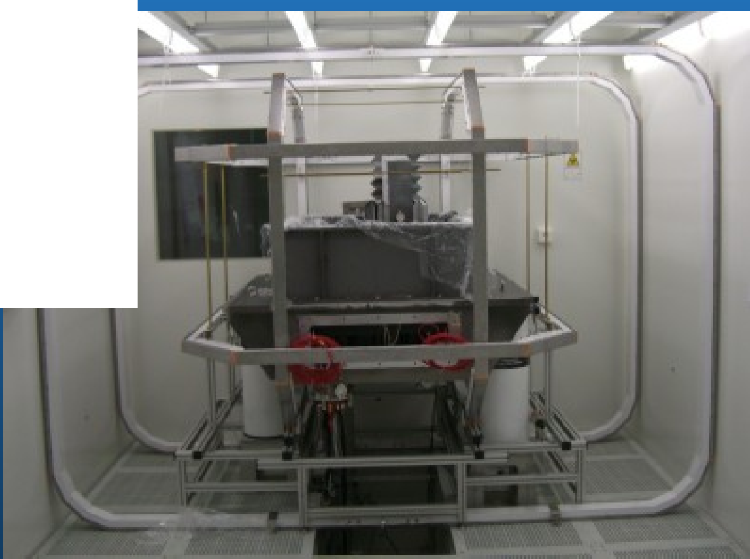

**Figure 1** Wavefunctions of the quantum states of neutrons in the potential well formed by the Earth's gravitational field and the horizontal mirror. The probability of finding neutrons at height $z$, corresponding to the $n$th quantum state, is proportional to the square of the neutron wavefunction $\psi_n^2(z)$. The vertical axis $z$ provides the length scale for this phenomenon. $E_n$ is the energy of the $n$th quantum state.

Granit
Gravitational Neutron Induced Transitions

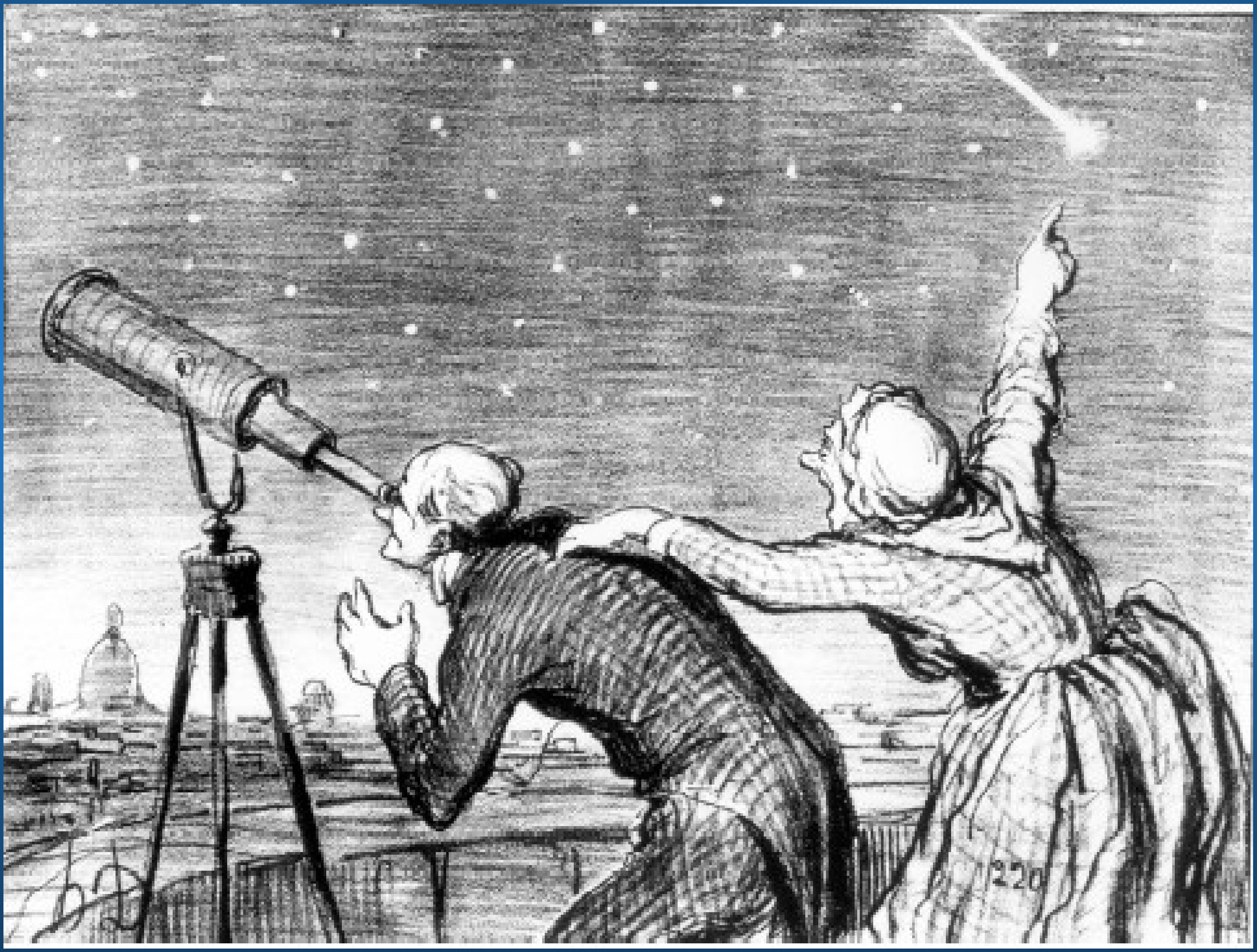
# GRANIT Spectrometer

## Global View



# Que cherche-t-on ?



# Physique de GRANIT

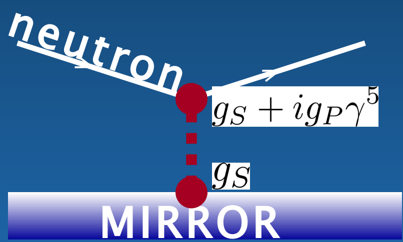
- Gravitation et la Mécanique Quantique
  - perte de la cohérence
  - localisation de la fonction d'onde (revivals)
  - la mécanique quantique « non commutative »
  - masse gravitationnelle vs masse inertielle
- Physique des particules
  - limites sur la 5e force (e.g. dimensions supplémentaires,…) ;

    Nesvizhevsky, Protasov, *Class. Quant. Grav.* **21** (2004) 4775
  - recherche de l'axion

    Baessler, Nesvizhevsky, Protasov, Voronin, *Phys. Rev*. **D75** (2007) 075006
- Physique appliquée
  - guide de neutrons
  - valve parfaite
  - étude des surfaces

# Sensitivity to extra short-range forces

Nesvizhevsky, Protasov, *Class. Quant. Grav.* **21** (2004) 4775



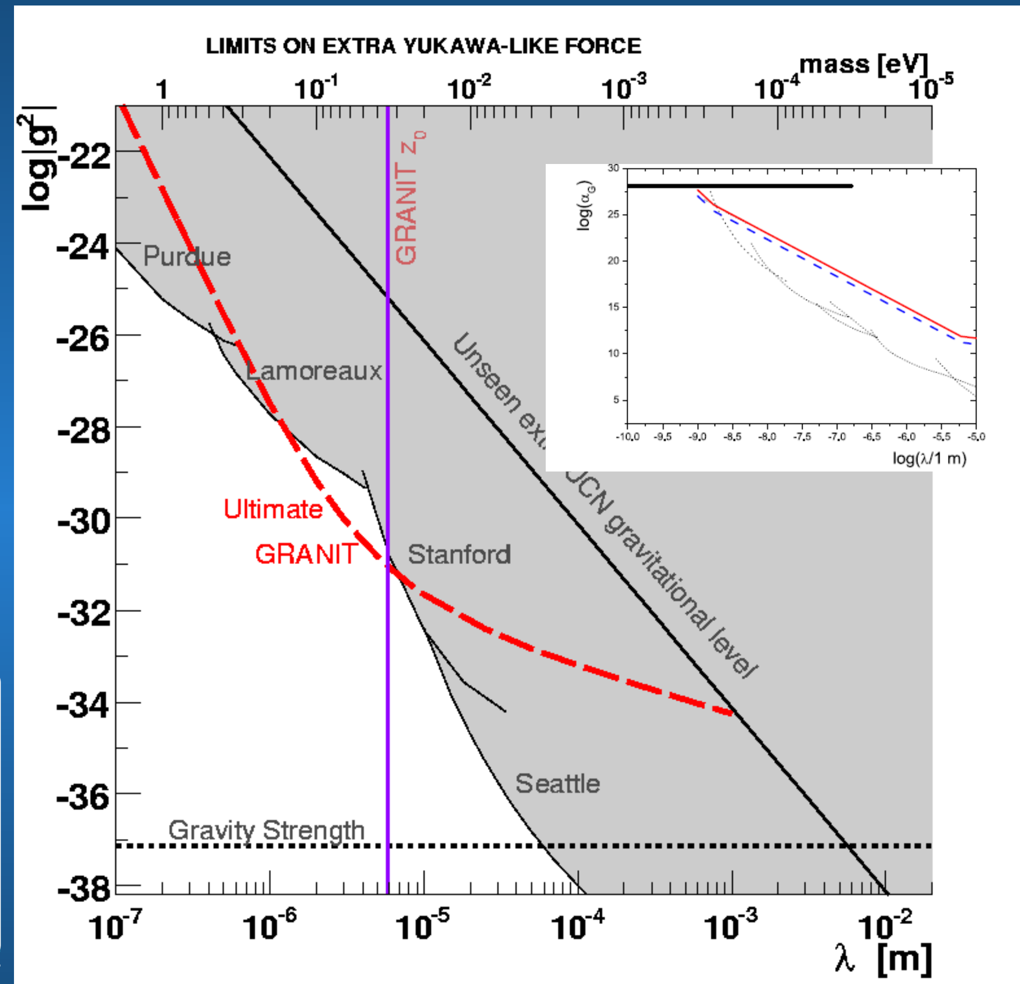

New light boson of mass M

- A new interaction between the neutron and the mirror with the range of

$$\lambda = \hbar c / M$$

**monopole-monopole coupling, spin-independent**

$$V_{SS}(z) = \frac{g_S^2}{2} \frac{\rho}{m} \; \hbar c \; \lambda^2 \; e^{-z/\lambda}$$

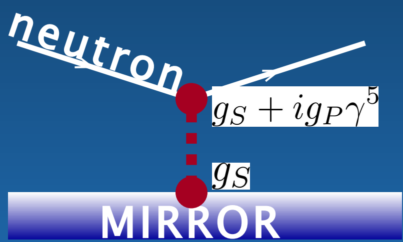



- Modification of the energy spectrum

PDG 2008

# Spin-dependent extra short-range forces

*S.Bäßler et al, Physical Review D 75(7): 075006(1-4).*



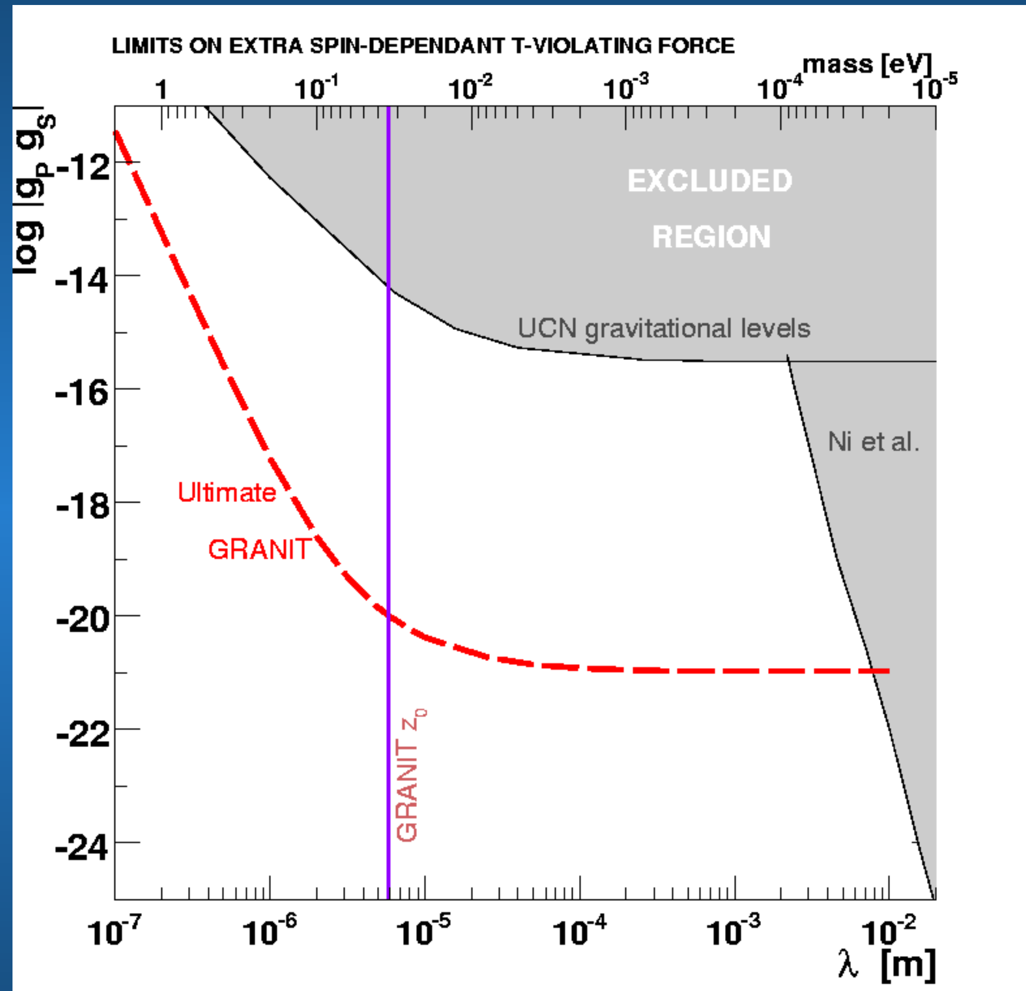

New light boson (axion) of mass M

- A new interaction between the neutron and the mirror with the range of

$$\lambda = \hbar c / M$$

**monopole-dipole coupling spin-dependant**

$$V_{SP}(z) = \frac{g_P g_S}{8} \frac{\rho}{m} \frac{(\hbar c)^2}{mc^2} \lambda \ \hat{\sigma_z} \ e^{-z/\lambda}$$

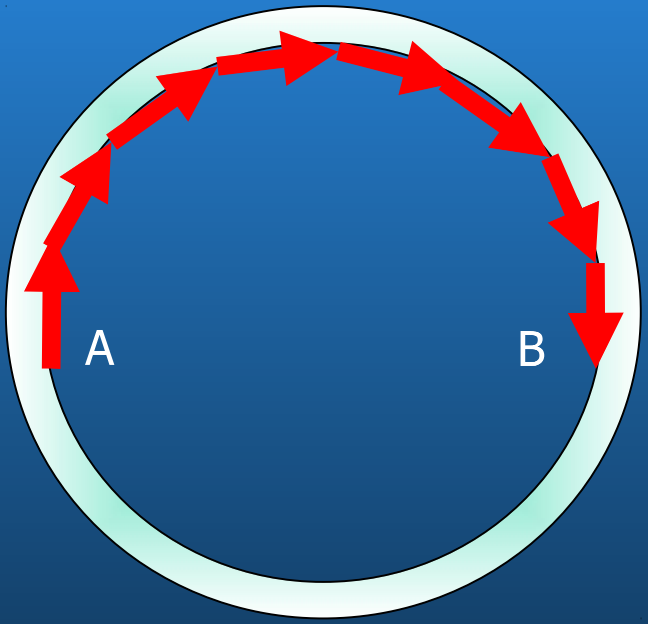



- Different spectra for spin up and spin down neutrons

# États « centrifuges »

## première réalisation d'une « galerie de chuchotement » pour des particules massives

St Paul est le centre spirituel de l'Angleterre: les discours du pape y sont lus et les événements les plus importants y sont célébrés. La façade occidentale, les clochers et la "Whispering Galery" (la galerie de chuchotement), qui rend tout chuchotement audible à de grandes distances, sont uniques.

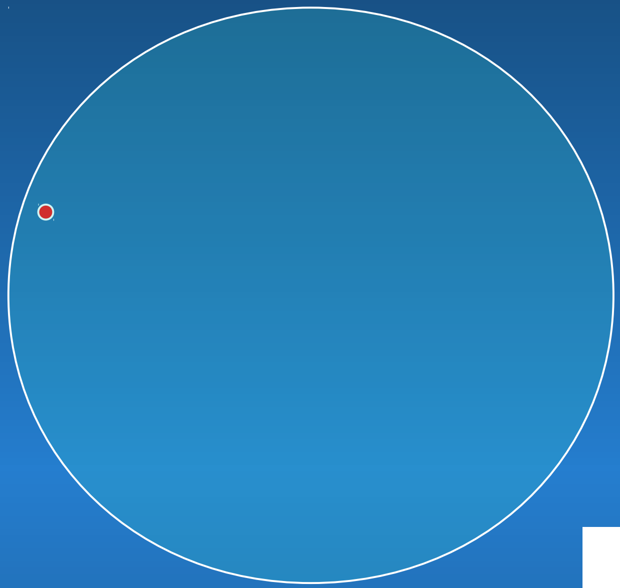



$$I(r_{AB}) \sim r_{AB}^{-1}$$


[1] J. W. Strutt Baron Rayleigh, *The Theory of Sound* (Macmillan, London 1878), Vol. 2.

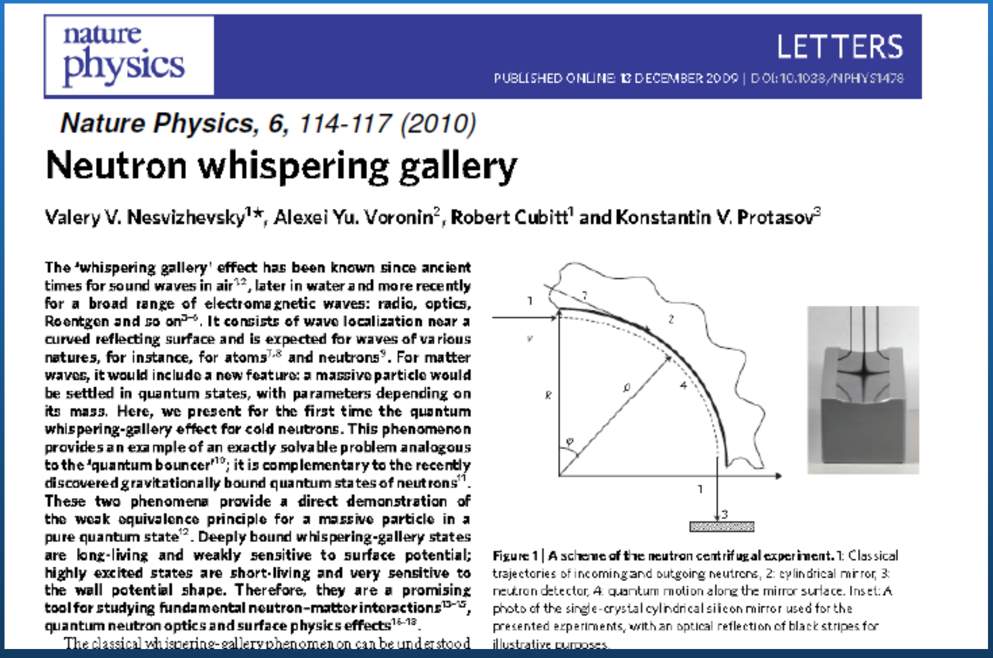
[2] L. Rayleigh, Philos. Mag. 27, 100 (1914).

# Et si l'on attrape une particule massive ?



On arrive à confiner une particule
Entre un mure et une barrière centrifuge

Un mouvement quantique



nature physics

LETTERS

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*Nature Physics*, 6, 114-117 (2010)

## Neutron whispering gallery

Valery V. Nesvizhevsky[1]*, Alexei Yu. Voronin[2], Robert Cubitt[1] and Konstantin V. Protasov[3]

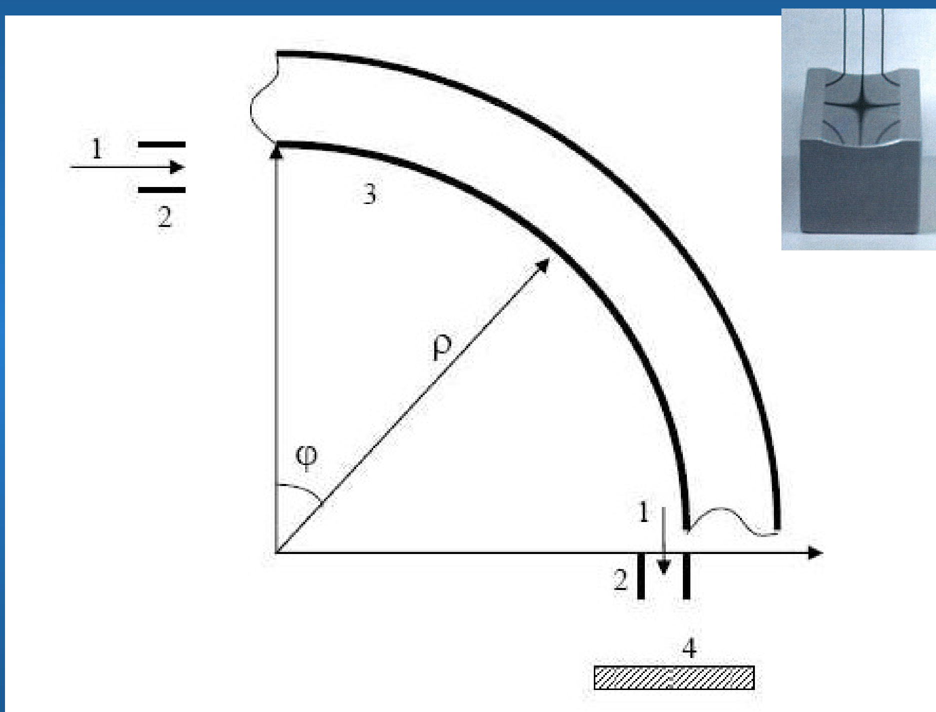
**The 'whispering gallery' effect has been known since ancient times for sound waves in air[1,2], later in water and more recently for a broad range of electromagnetic waves: radio, optics, Roentgen and so on[3–6]. It consists of wave localization near a curved reflecting surface and is expected for waves of various natures, for instance, for atoms[7,8] and neutrons[9]. For matter waves, it would include a new feature: a massive particle would be settled in quantum states, with parameters depending on its mass. Here, we present for the first time the quantum whispering-gallery effect for cold neutrons. This phenomenon provides an example of an exactly solvable problem analogous to the 'quantum bouncer'[10]; it is complementary to the recently discovered gravitationally bound quantum states of neutrons[11]. These two phenomena provide a direct demonstration of the weak equivalence principle for a massive particle in a pure quantum state[12]. Deeply bound whispering-gallery states are long-living and weakly sensitive to surface potential; highly excited states are short-living and very sensitive to the wall potential shape. Therefore, they are a promising tool for studying fundamental neutron–matter interactions[13–15], quantum neutron optics and surface physics effects[16–18].**

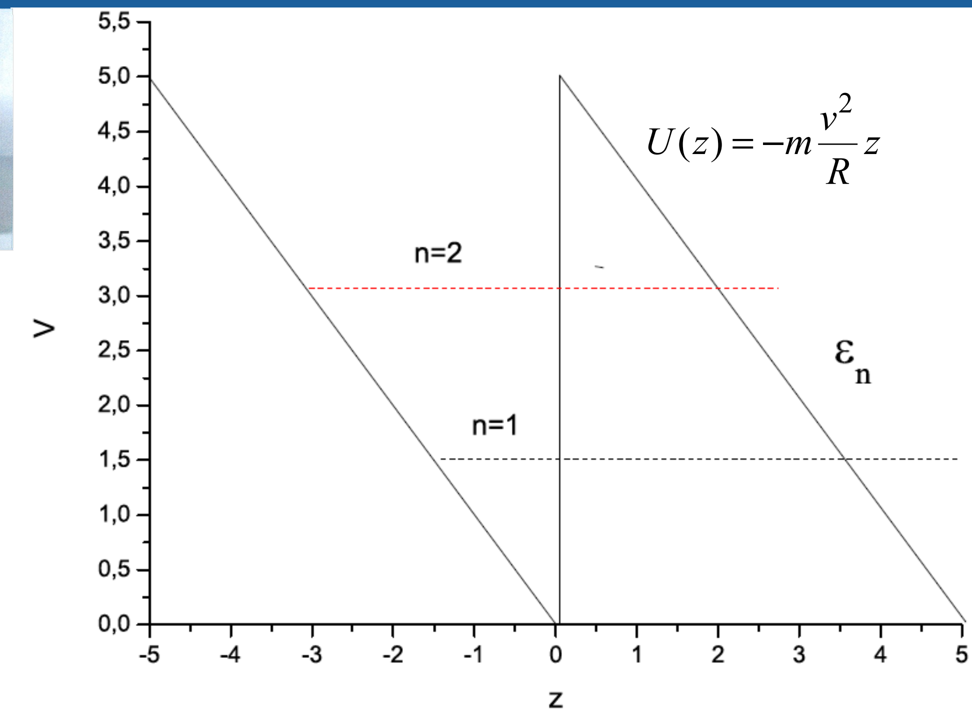
The classical whispering-gallery phenomenon can be understood

**Figure 1 | A scheme of the neutron centrifugal experiment.** 1: Classical trajectories of incoming and outgoing neutrons, 2: cylindrical mirror, 3: neutron detector, 4: quantum motion along the mirror surface. Inset: A photo of the single-crystal cylindrical silicon mirror used for the presented experiments, with an optical reflection of black stripes for illustrative purposes.

# États « centrifuges »

Les neutrons se mettent dans les états quasi stationnaires qui se désintègrent par l'effet tunnel à travers le miroir



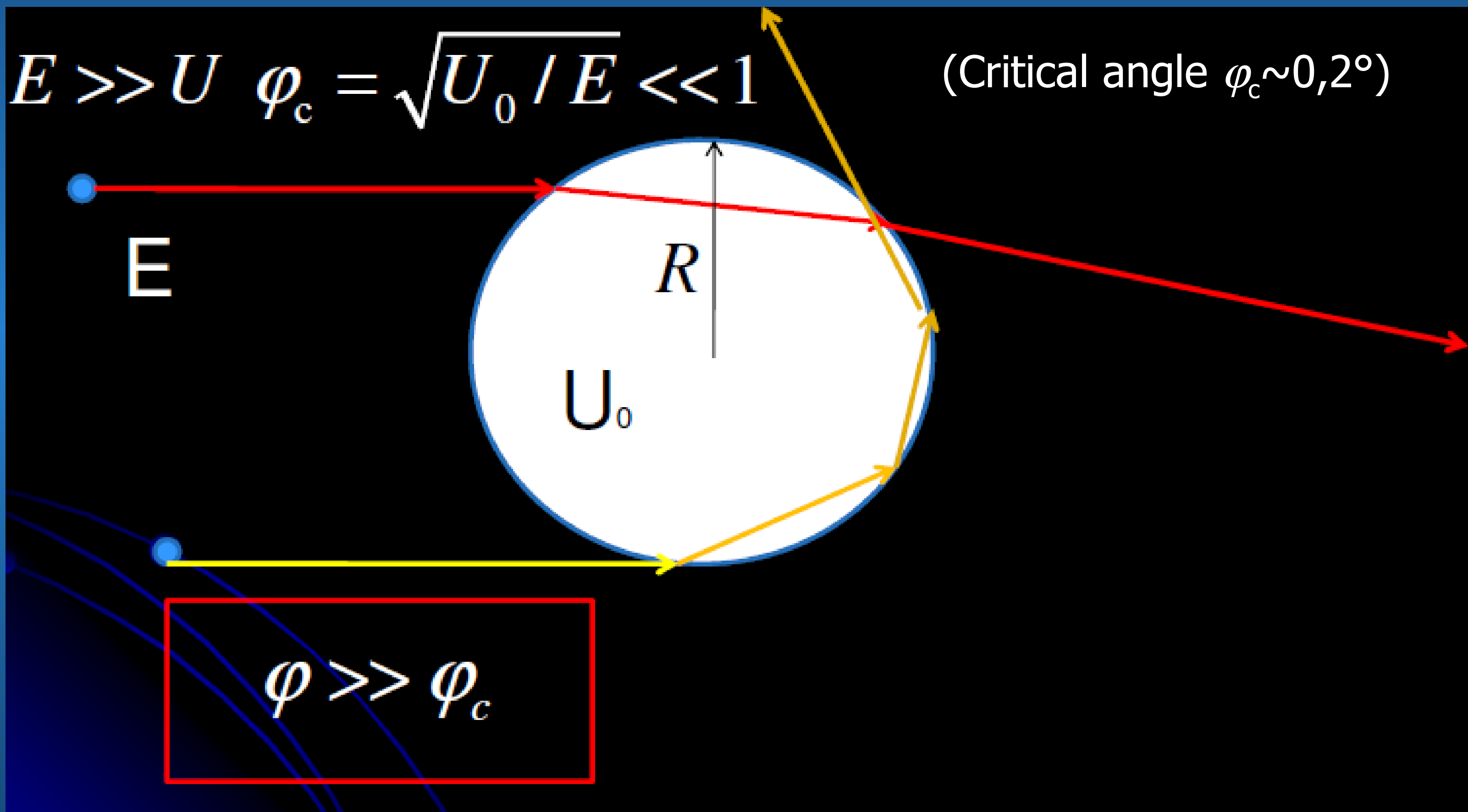




$$\Psi \propto \begin{cases} \mathrm{Bi}(z/l_0 - z_0) + i\mathrm{Ai}(z/l_0 - z_0) & z < 0 \\ \mathrm{Ai}(z/l_0) & z \geq 0 \end{cases}$$

; $\varepsilon_0 = \left(\frac{\hbar^2 M v^4}{2R^2}\right)^{1/3}$ -characteristic energy $l_0 = \left(\frac{\hbar^2 R}{2M^2 v^2}\right)^{1/3}$ -characteristic length

$z_0 = V_F / \varepsilon_0$ $V_F$ – mirror bulk Fermi potential

# Classical solution

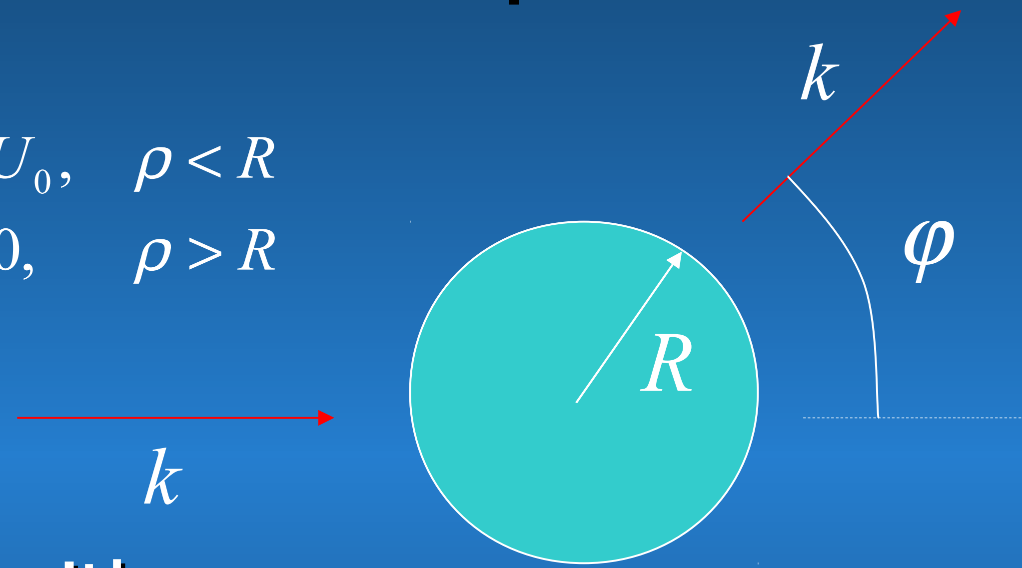



No classical refraction to big angles

# Formal QM solution of the problem

Potential

$$U(\rho) = \begin{cases} -U_0, & \rho < R \\ 0, & \rho > R \end{cases}$$




NB. We are working with

$$kR \approx 4\times 10^{8} >> 1 \qquad \frac{mU_0R^2}{\hbar^2} \approx 8\times 10^{8} >> 1$$

Born approximation can not be used

# Two dimensional scattering amplitude

$$f(k,\varphi) = \frac{1}{i}\sqrt{\frac{\hbar}{2\pi k}} \sum_{-\infty}^{+\infty} \left( S_m(k) - 1 \right) e^{im\varphi}$$

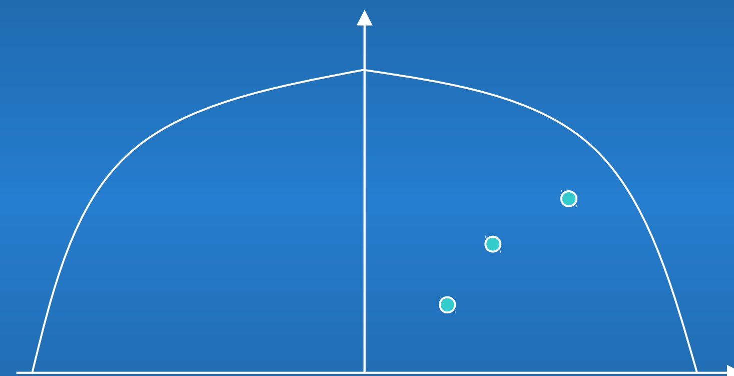
# With the scattering matrix

$$S_m(k) = \frac{N'_m(kR) + iJ'_m(kR) - \frac{\kappa}{k}\frac{J'_m(\kappa R)}{J_m(\kappa R)}\left[ N_m(kR) + iJ_m(kR) \right]}{N'_m(kR) - iJ'_m(kR) - \frac{\kappa}{k}\frac{J'_m(\kappa R)}{J_m(\kappa R)}\left[ N_m(kR) - iJ_m(kR) \right]}$$

with $\kappa = \sqrt{k^2 + 2MU_0}$

## And the sum is replaced by the integral ("Watson transformation")

$$f(k,\varphi) = \frac{1}{i}\sqrt{\frac{\hbar}{2\pi k}} \int_{-i\infty}^{+i\infty} \left(S_m(k) - 1\right) e^{im\varphi} dm$$



In the complex *m* -plane

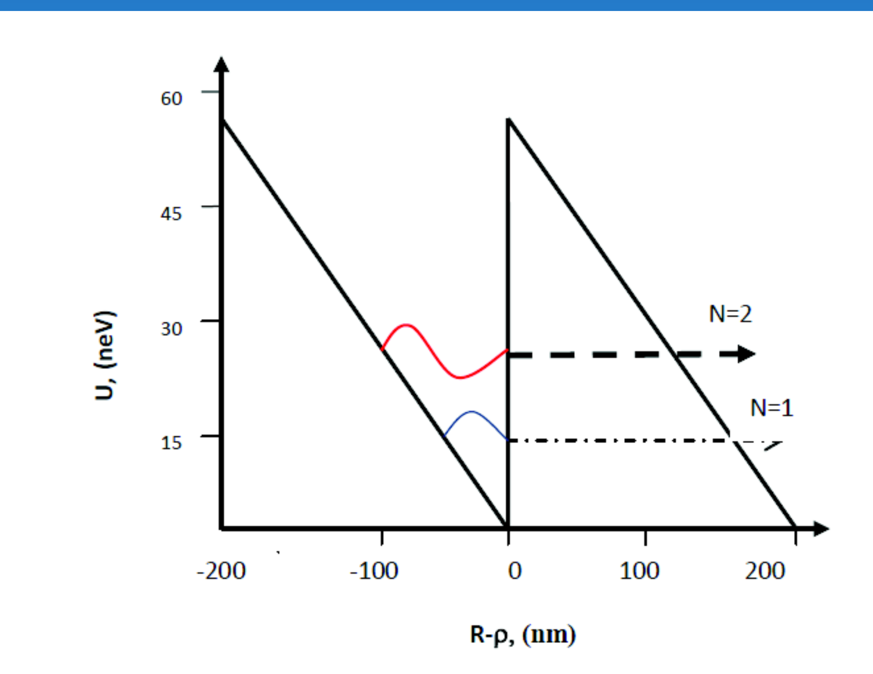
$$f(k,\varphi) \approx \sqrt{\frac{2\pi\hbar}{k}} \sum_i \mathrm{Res}\, S_{\mu_i}(k) e^{i \,\mathrm{Re}\, \mu_i \varphi} e^{-\mathrm{Im}\, \mu_i \varphi}$$

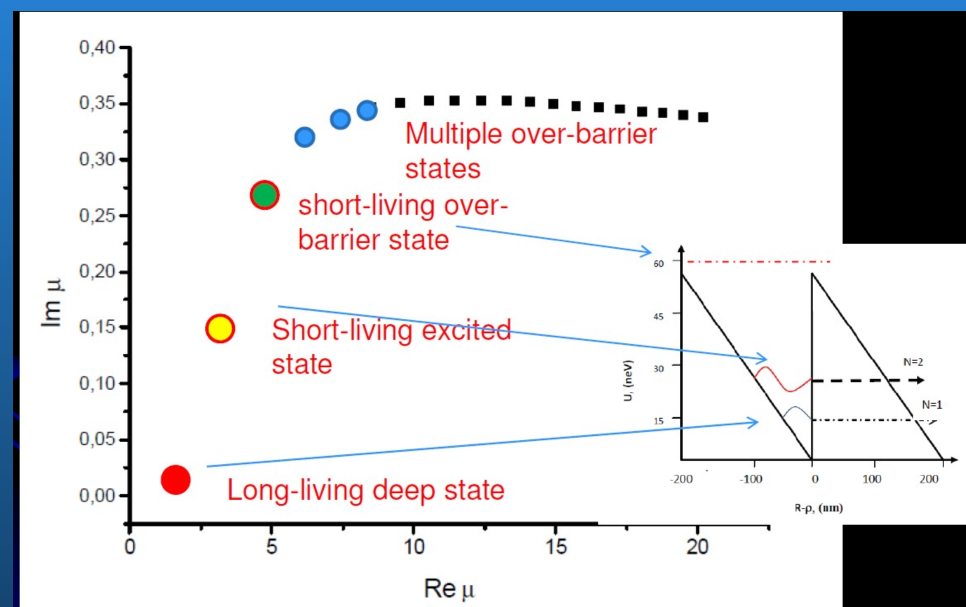
This is the sum over Regge poles

# Physical interpretation of Regge poles

$$U(\rho) = \frac{\hbar^2}{2M\rho^2}\left(m^2 - \frac{1}{4}\right) \approx \mathrm{Const} + \frac{\hbar^2}{2MR^2}\left(\left(m^2 - \frac{1}{4}\right) - \frac{2z}{R}\right)$$

with $\rho = R - z$

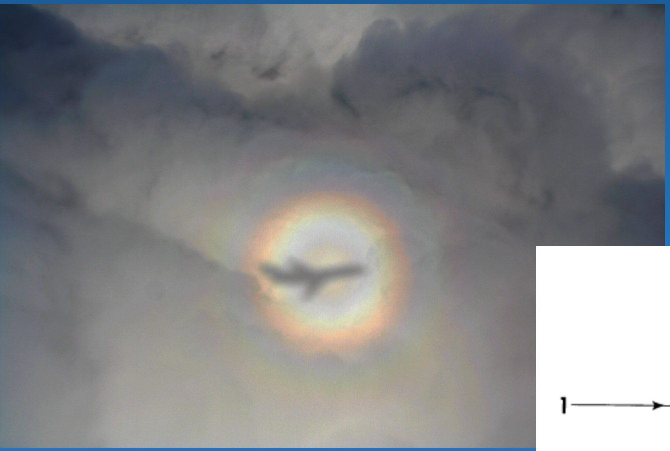


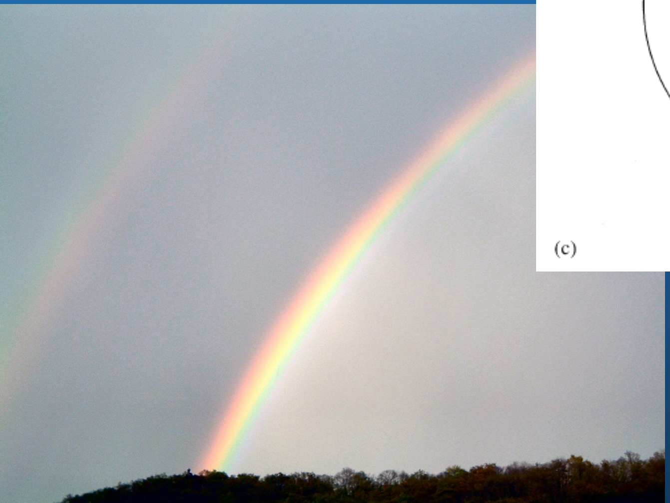



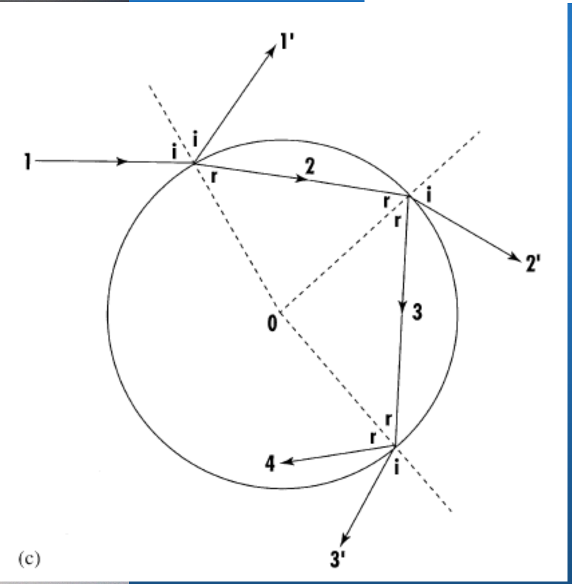
# Analogue exacte de l'arc-en-ciel/gloria (Nusseinzweig, 1969)

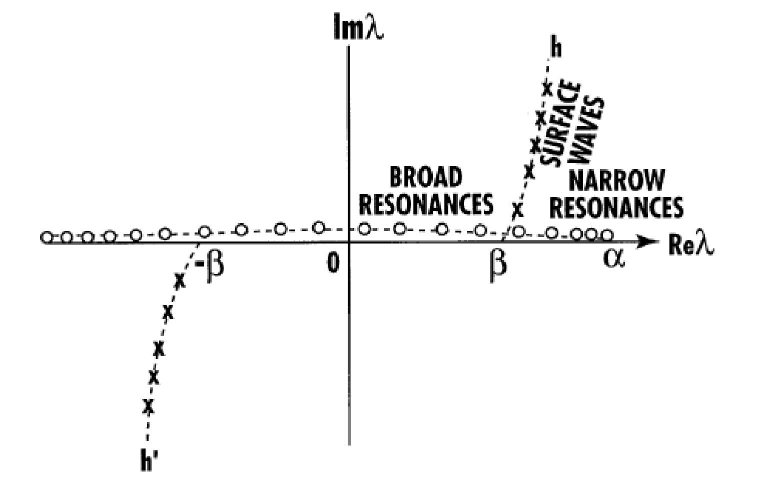
$$f(\beta,\theta) = \frac{i}{\beta} \sum_{m=-\infty}^{\infty} (-1)^m \int_0^{\infty} [1 - S(\lambda,\beta)] P_{\lambda-1/2}(\cos\theta) e^{2im\pi\lambda} \lambda \, d\lambda$$

$$S(\lambda,\beta) = -\frac{H_\lambda^{(2)}(\beta)}{H_\lambda^{(2)}(\beta)} \left\{ \frac{\ln' H_\lambda^{(2)}(\beta) - N \ln' J_\lambda(\alpha)}{\ln' H_\lambda^{(1)}(\beta) - N \ln' J_\lambda(\alpha)} \right\}$$



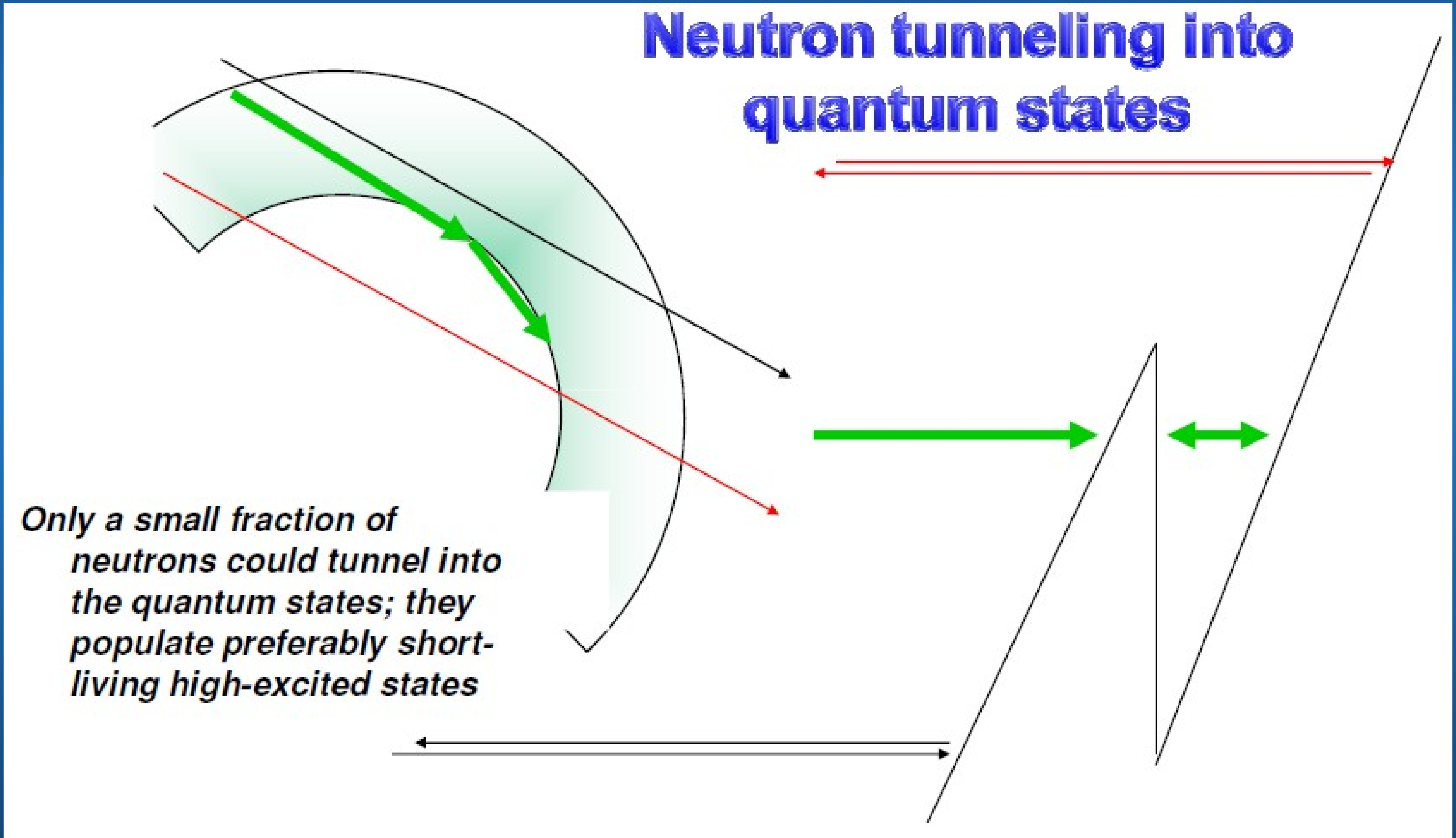




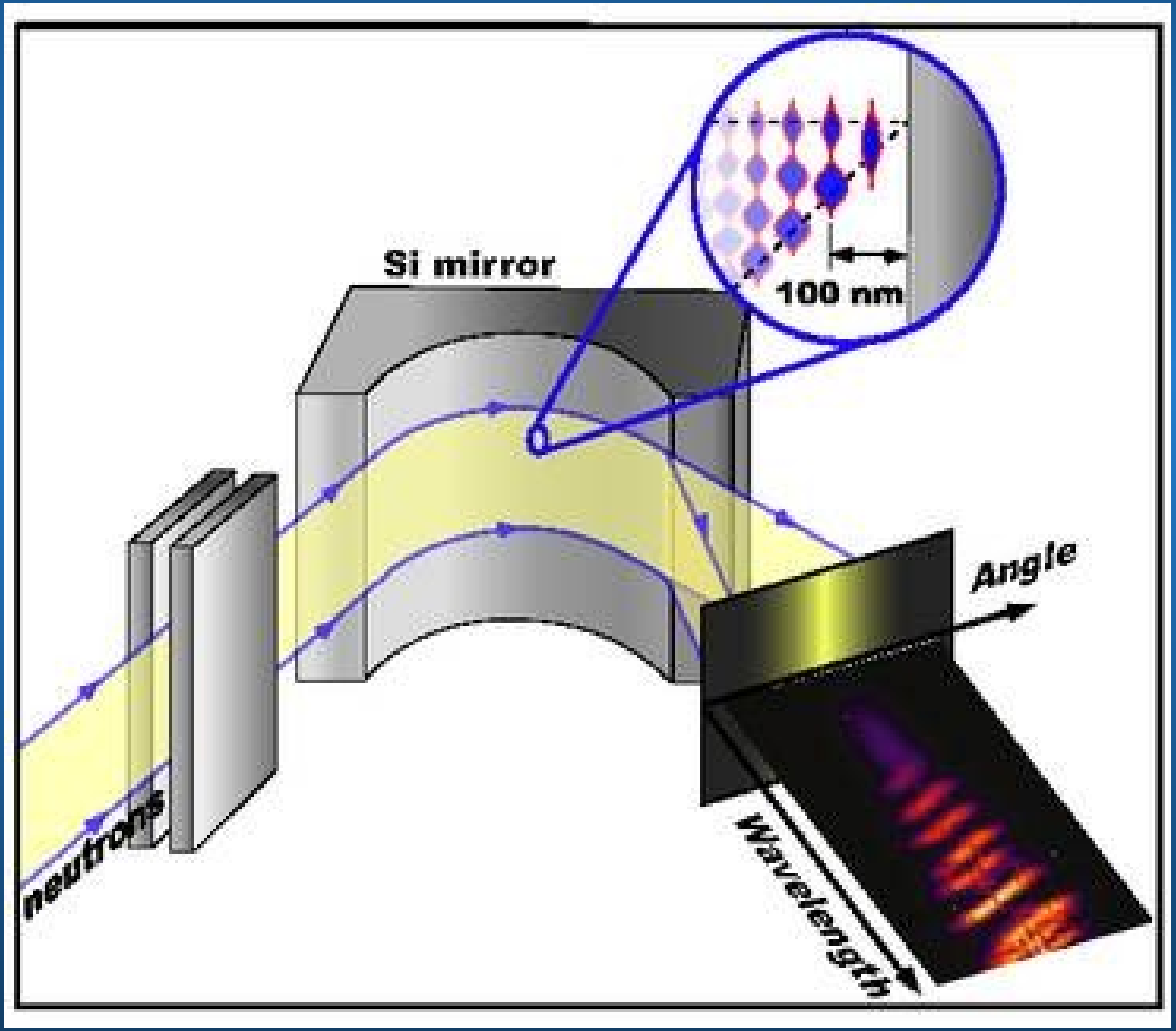




$$\lambda_n \approx \beta + \frac{x_n e^{i\pi/3}}{(2/\beta)^{1/3}} + \frac{i}{(N^2-1)^{1/2}}$$

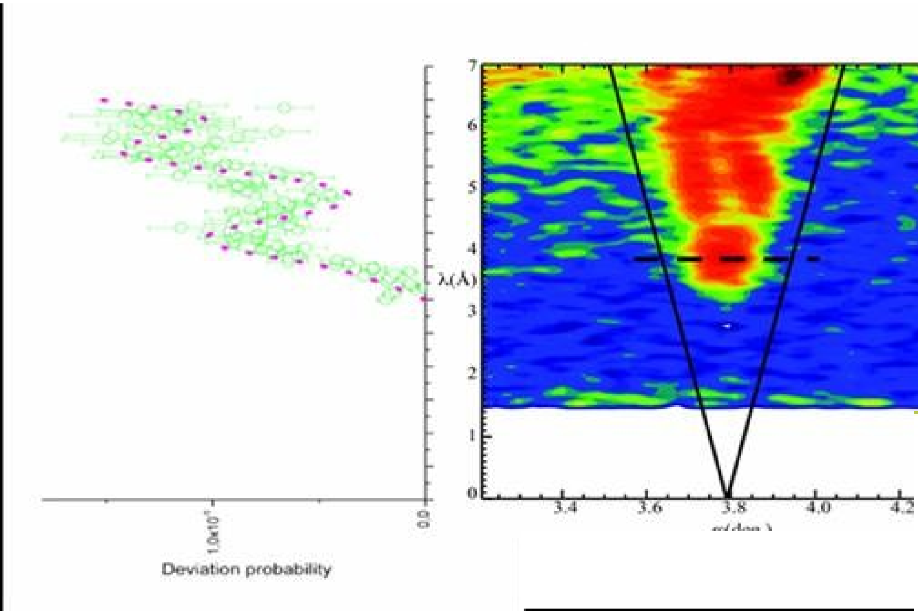
# How to populate these states?



# Schéma de l'expérience



# Premiers résultats

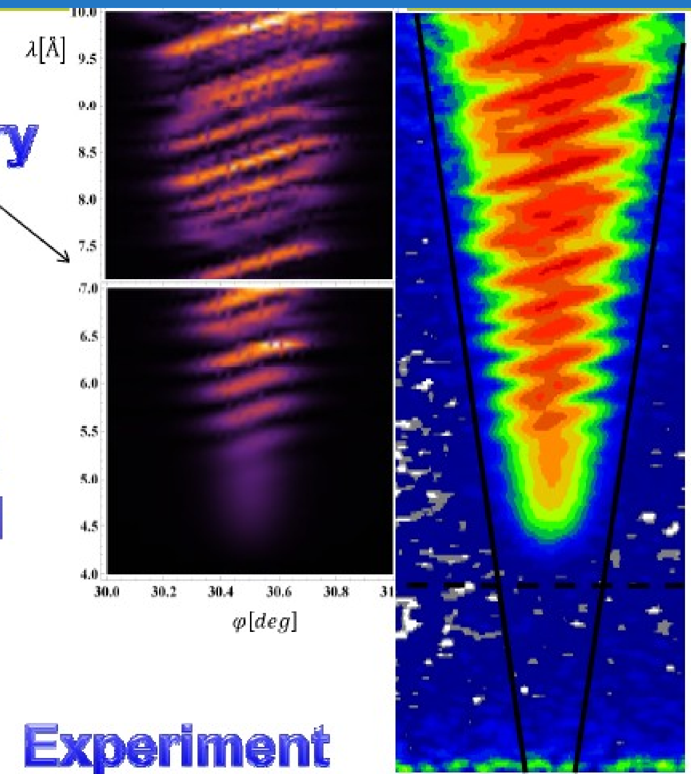



États faiblement liés

États profonds

Theory

Truncated cilyndrical mirror



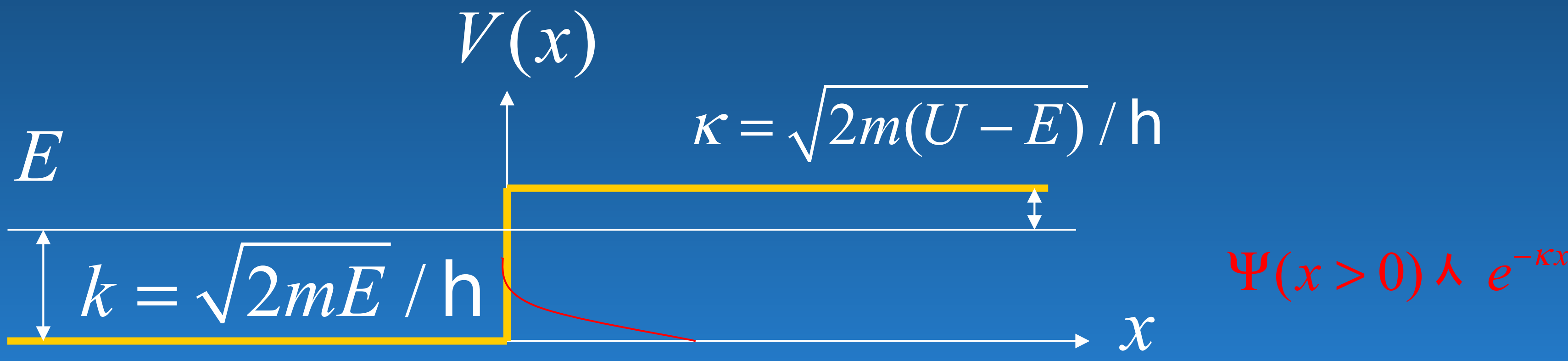

Experiment

Étude directe d'une équivalence entre la gravitation (GRANIT) et l'inertie (états « centrifuges »)

# Conclusions

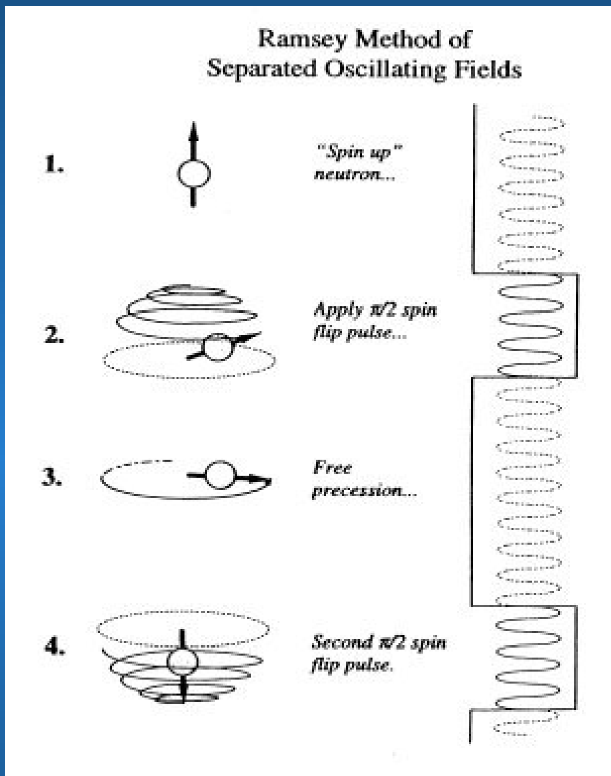
- La physique des UCN a apporté, à ces 40 ans, des résultats particulièrement importants
- Mise en place des nouvelles sources des UCN est en train d'ouvrir une nouvelle page dans ces études
- On aura besoin des belles idées et des bons physiciens

# Mécanisme de réflexion



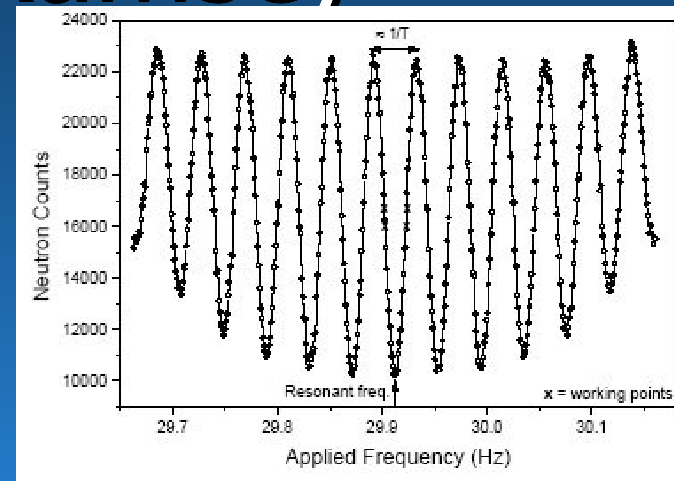

## Analogie avec l'optique – réflexion totale

# Méthode de Ramsey




T

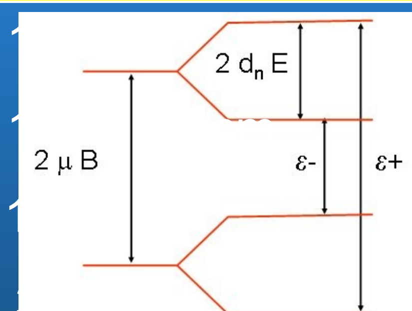
N ↑




$$H = 2(\mu_n \vec{I}.\vec{B} + d_n \vec{I}.\vec{E})$$

Valeurs expérimentales typiques :

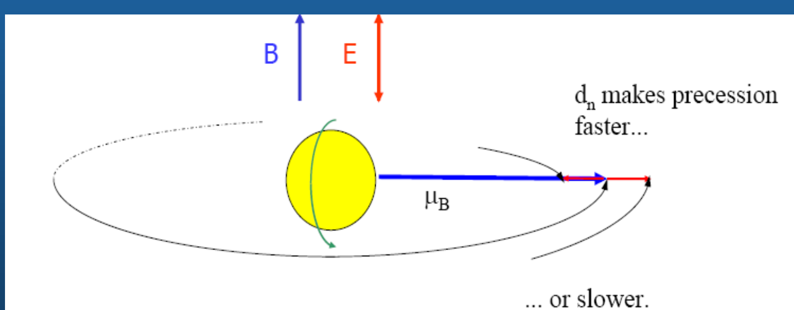
- B ~ 1
- E = 1
- T ~ 1
- $\nu_L$ ~



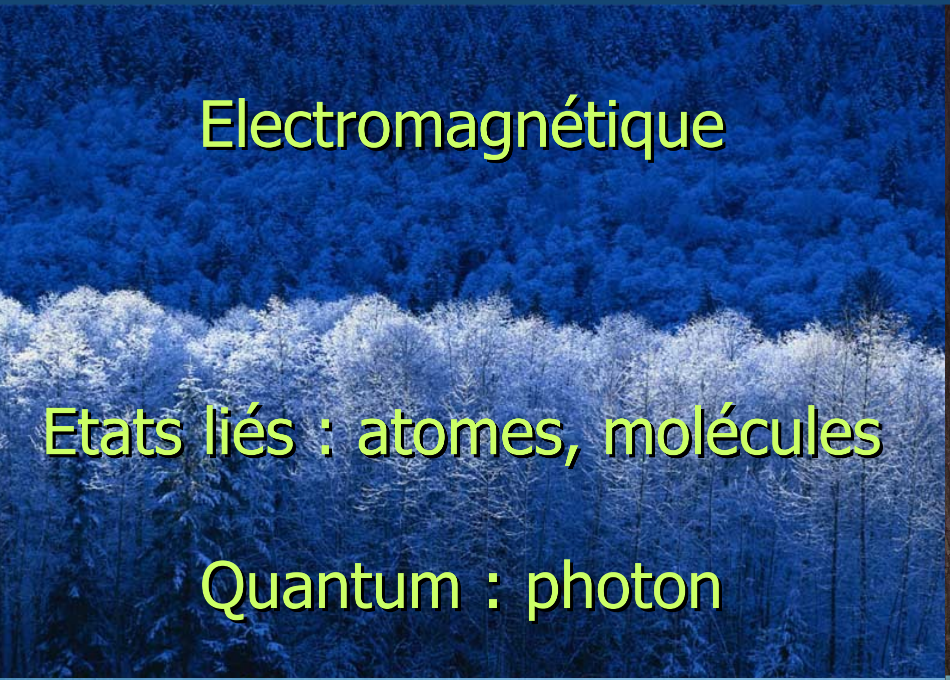

$$\Delta\nu = 4 d_n E/h$$

Pour $d_n = 10^{-27}$ e-cm et E = 15 kV/cm :

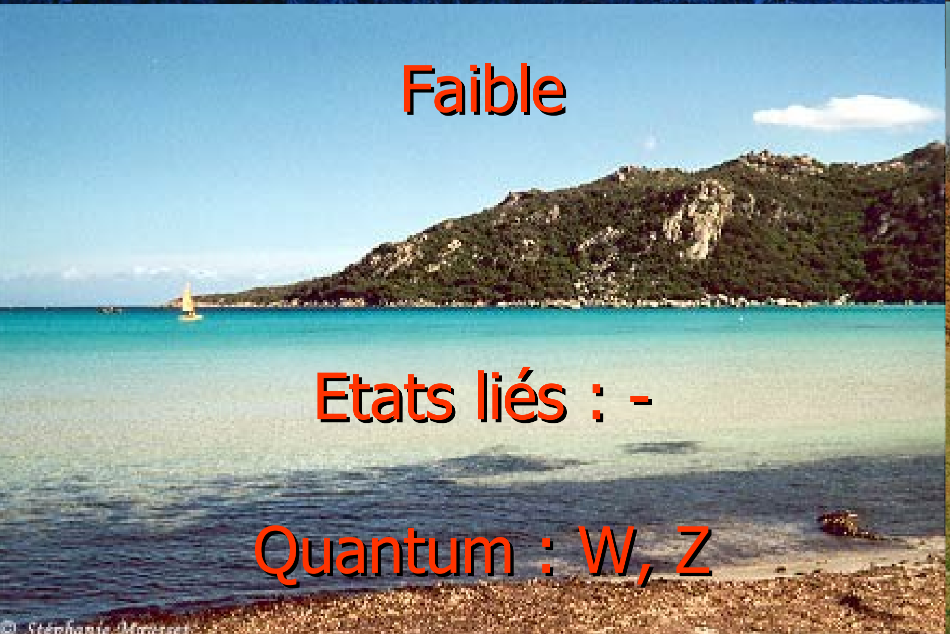
$\Delta\varepsilon \sim 6\ 10^{-23}$ eV ↔ $\Delta\nu \sim 10^{-8}$ Hz



# Quatre interactions







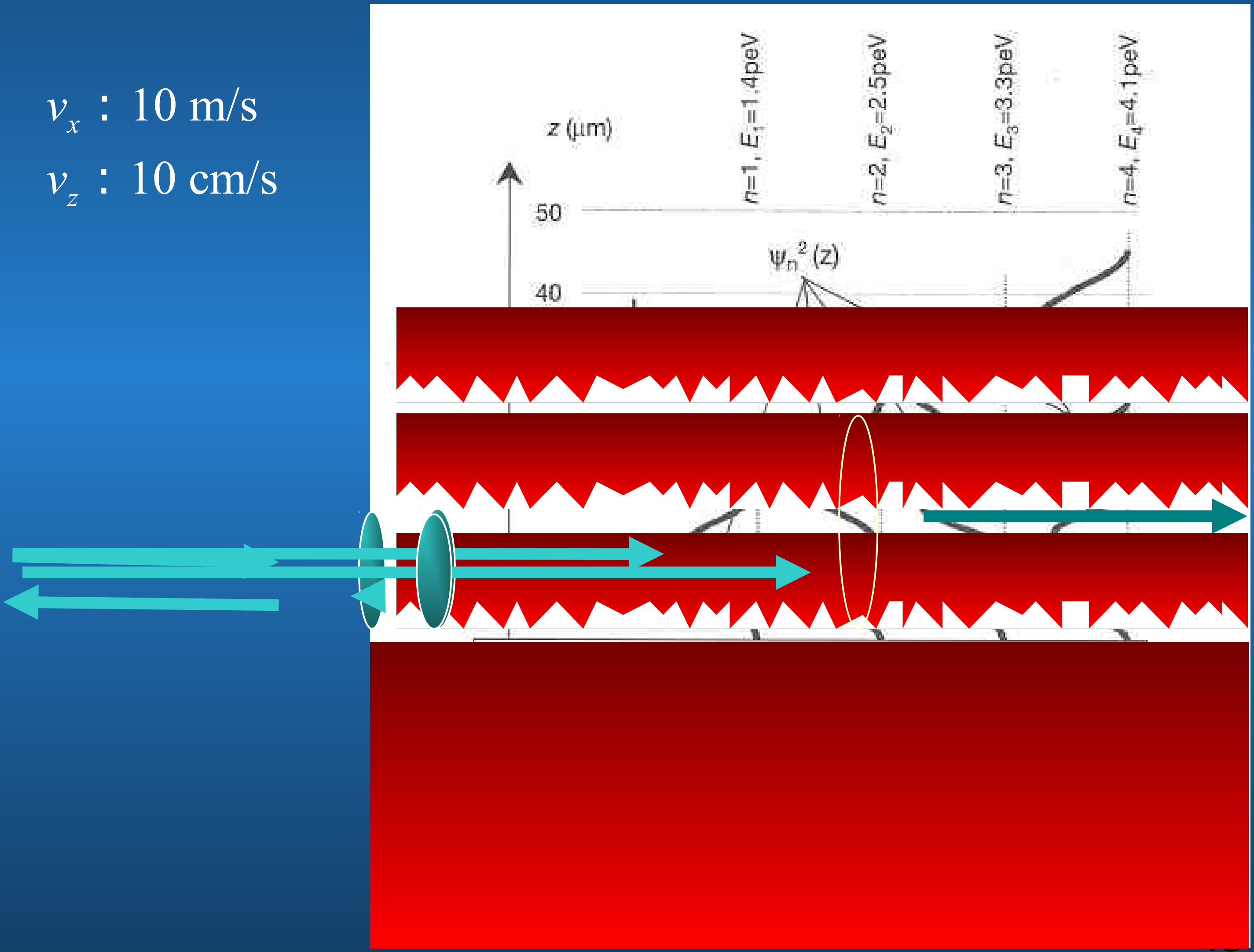

# Méthodes d’observation

- Méthode intégrale (recherche d’un paramètre avec un comportement discret)
- Méthode différentielle (visualisation de la fonction d’onde – « photo »)
- *Recherche des transitions entre les niveaux quantiques (GRANIT)*

# Méthode intégrale

$v_x$ : 10 m/s

$v_z$ : 10 cm/s



Idée de l'installation :

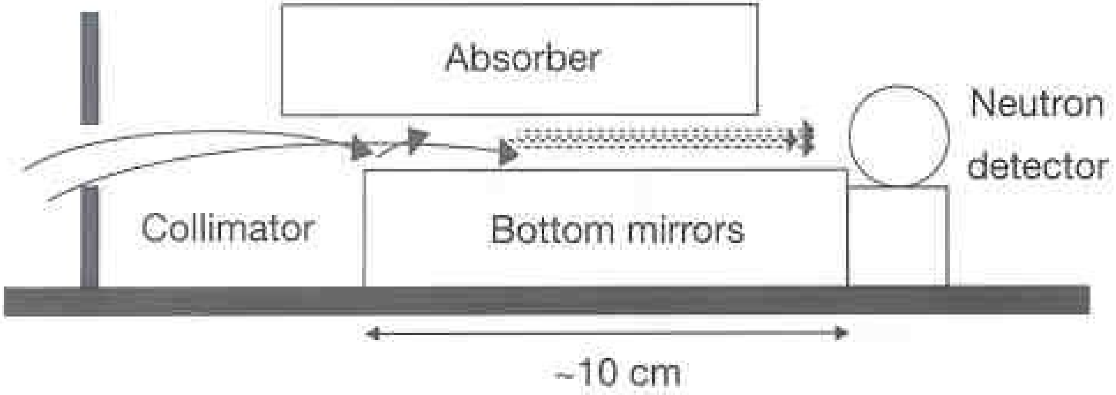
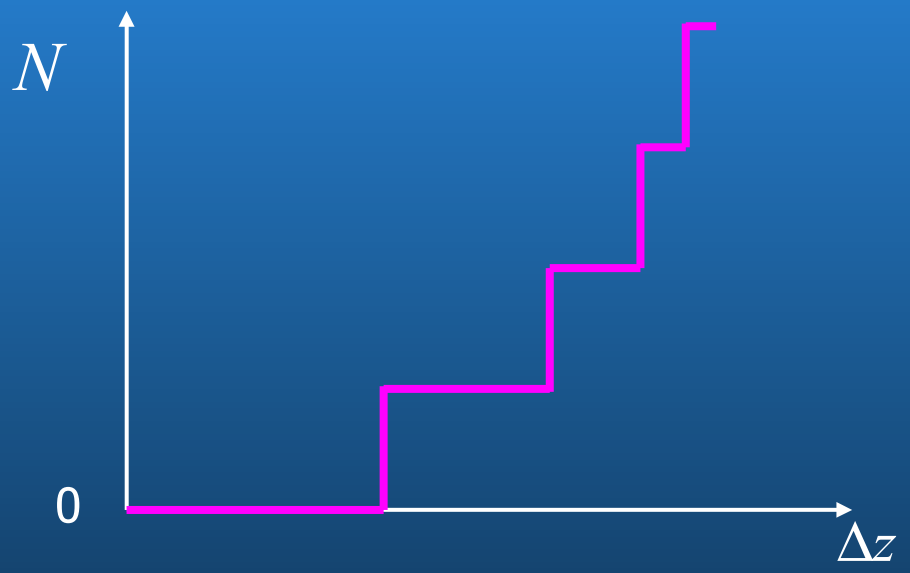


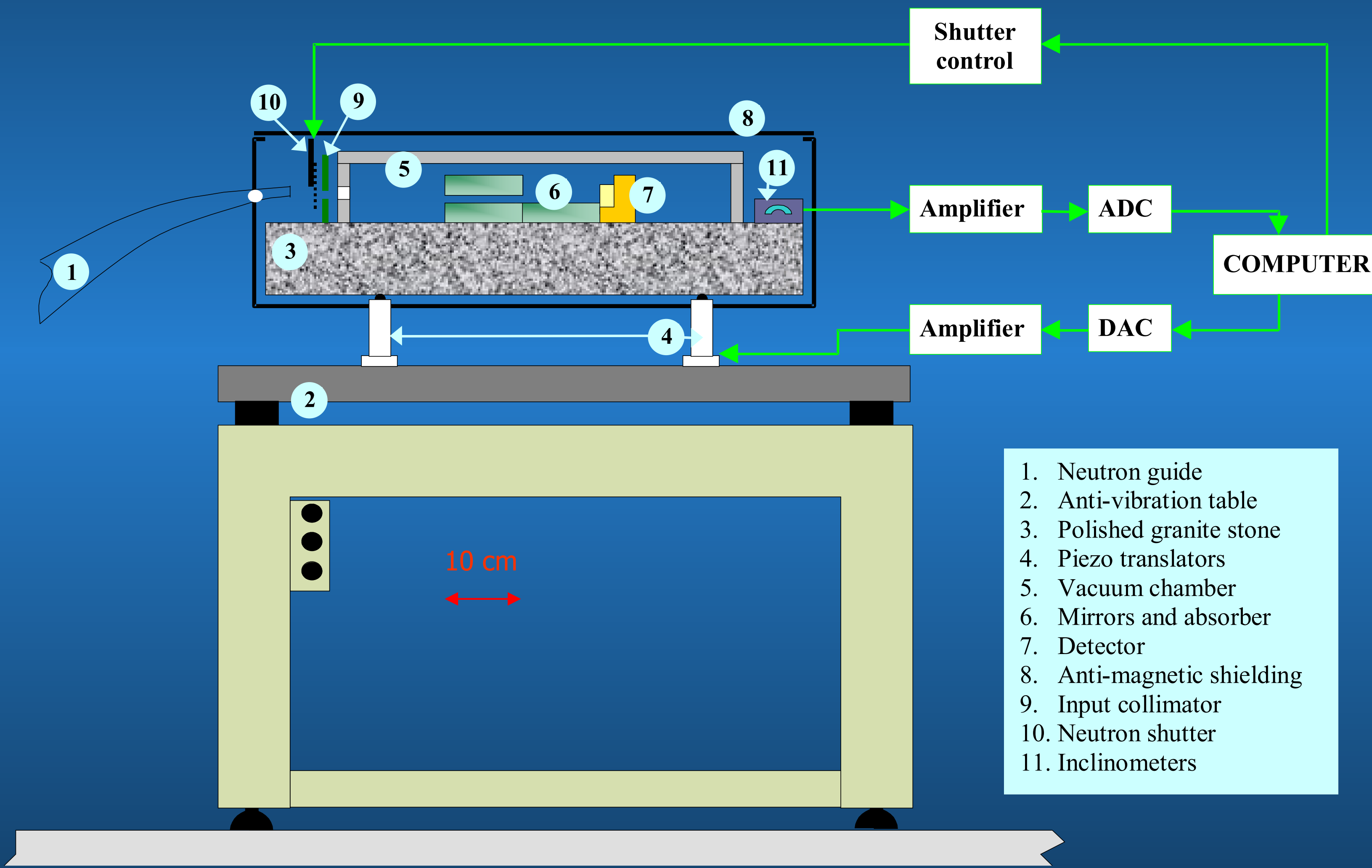

**Figure 2** Layout of the experiment. The limitation of the vertical velocity component depends on the relative position of the absorber and mirror. To limit the horizontal velocity component we use an additional entry collimator. The relative height and size of the entry collimator can be adjusted.

Résultat espéré (naïvement) :




$$N \sim \left(E_n^{\mathrm{qc}}\right)^{2/3} \sim \Delta z^{2/3} \text{ pour } \Delta z \to \infty$$

# Installation




1. Neutron guide
2. Anti-vibration table
3. Polished granite stone
4. Piezo translators
5. Vacuum chamber
6. Mirrors and absorber
7. Detector
8. Anti-magnetic shielding
9. Input collimator
10. Neutron shutter
11. Inclinometers

# Premiers résultats (1999)

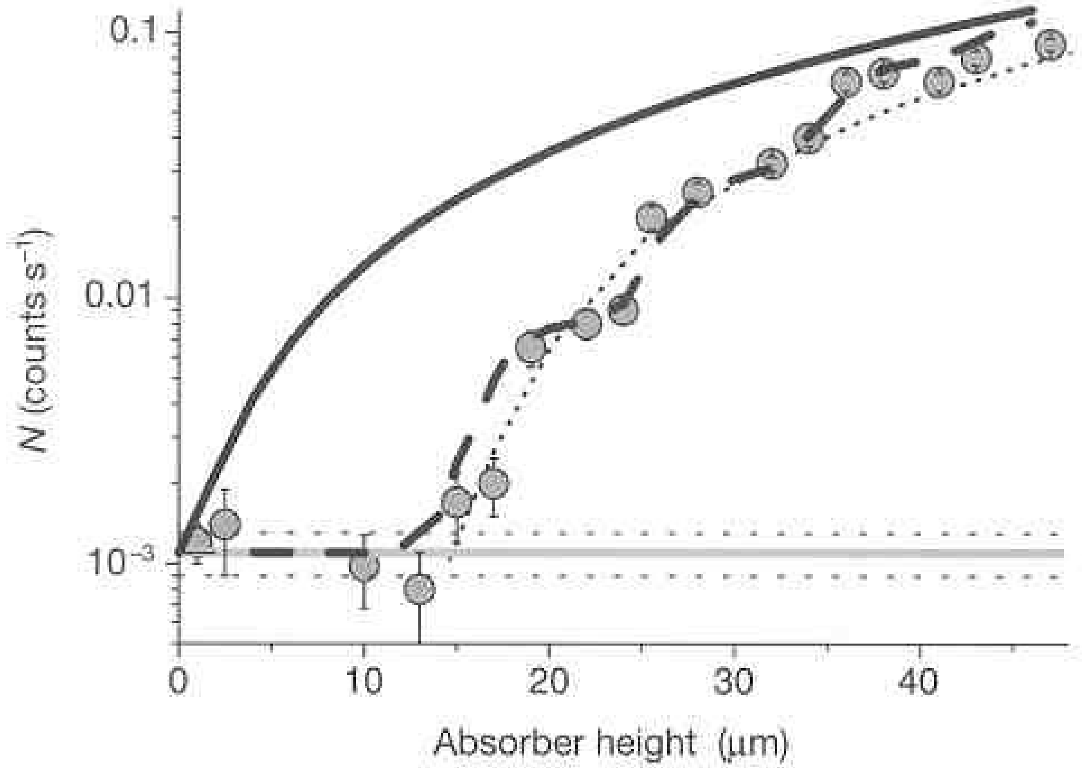
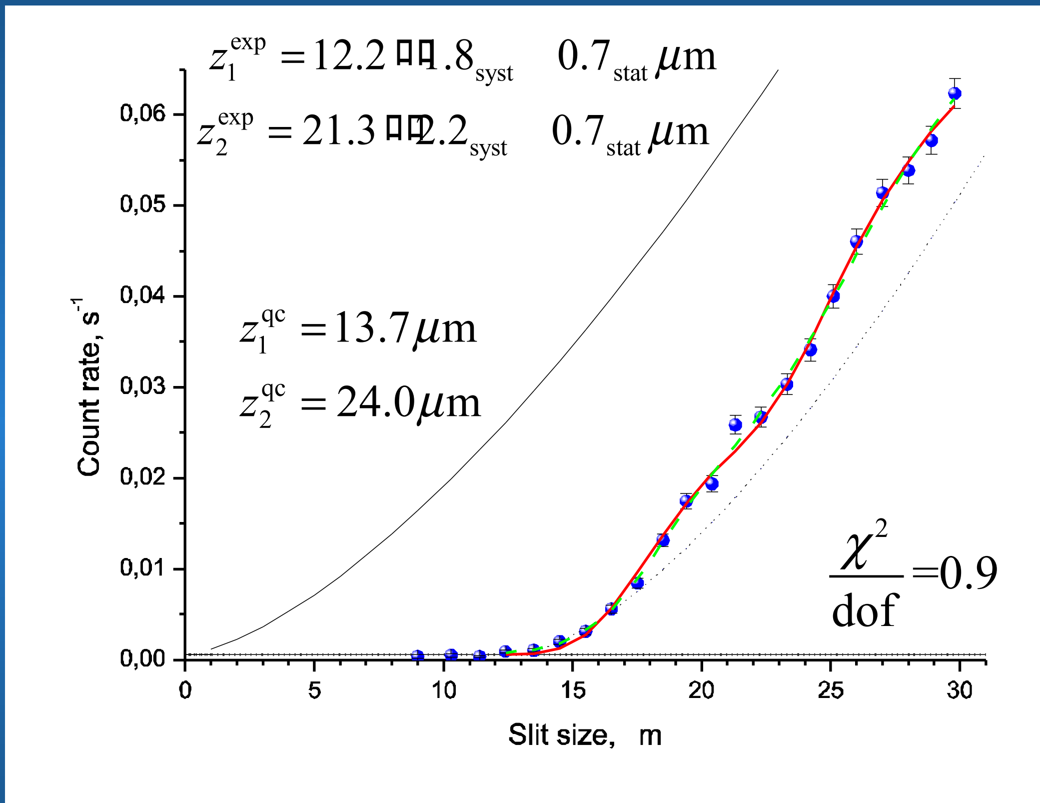


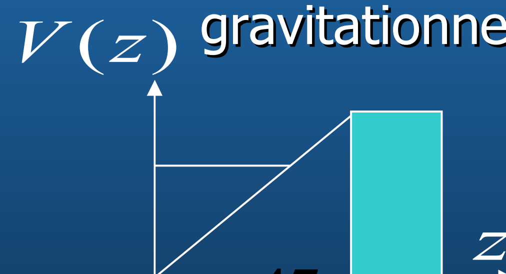

**Figure 4** The neutron throughput versus the absorber height at low height values. The data points are summed up in intervals of 2 μm. The dashed curve corresponds to a fit using the quantum-mechanical calculation, in which all level populations and the height resolution are fitted from the experimental data. The solid curve is again the full classical treatment. The dotted line is a truncated fit in which it is assumed that only the lowest quantum state—which leads to the first step—exists.

On voit l'état fondamental !!!

# Problème de la résolution



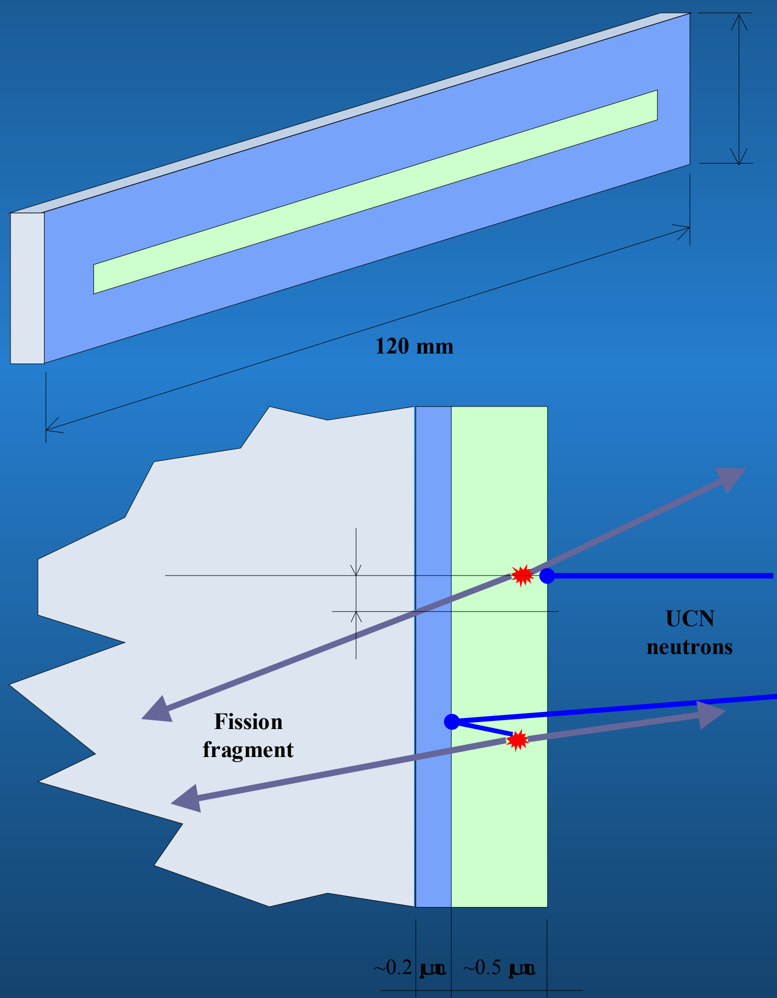

- Il existe une résolution minimale que l'on peut pas améliorer
- Cette résolution est directement liée au champ gravitationnel lui-même
- Elle est due à l'effet tunnel à travers de la barrière gravitationnelle

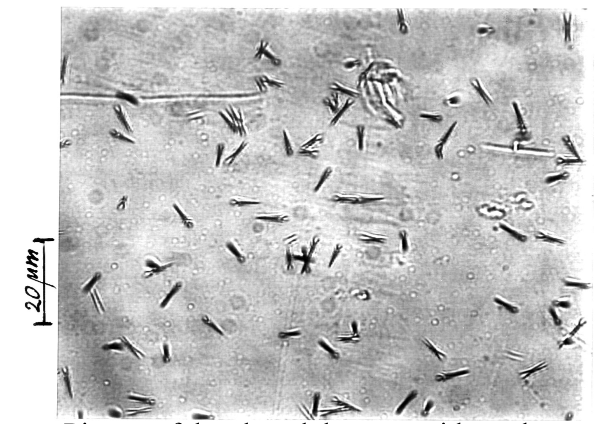



$$N(\Delta z) = \beta \sum_n \alpha_n \mathrm{Exp}\left( - \right) \mathrm{Exp}\left( -\frac{4}{3} \left( \frac{\Delta z - z_n}{z_0} \right)^{\frac{3}{2}} \right)$$

# « Photo » de la fonction d'onde

## (détecteur à haute résolution spatiale)

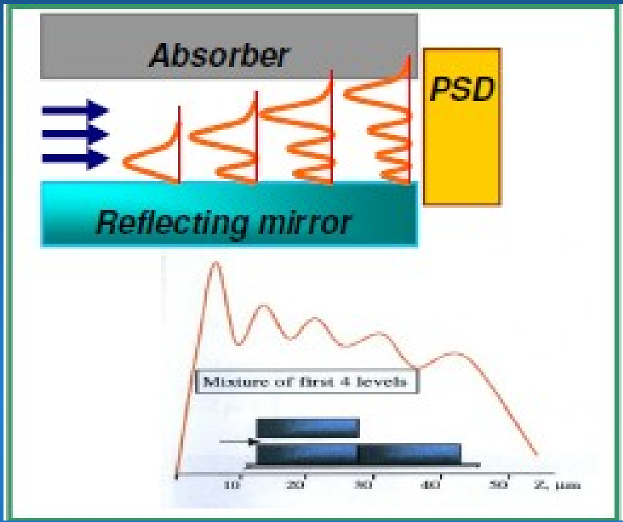


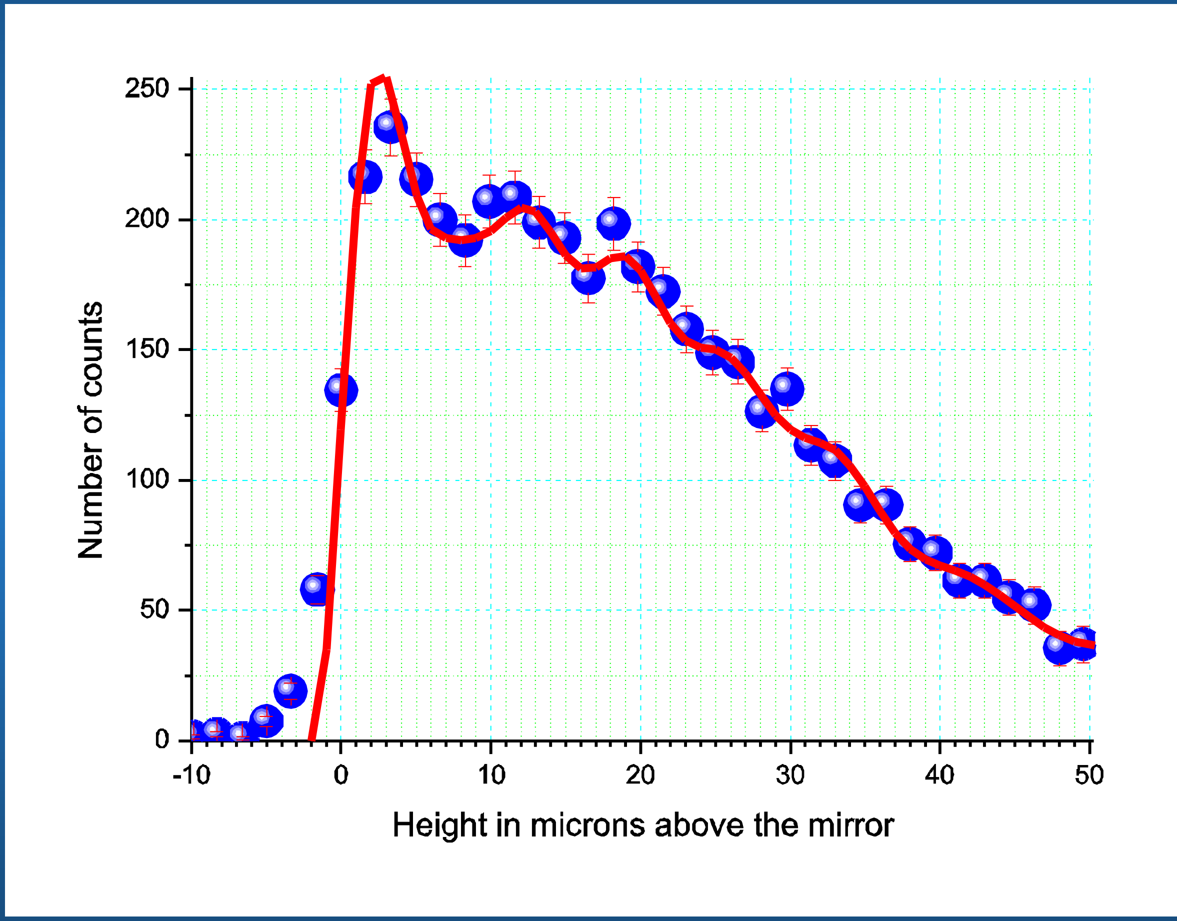



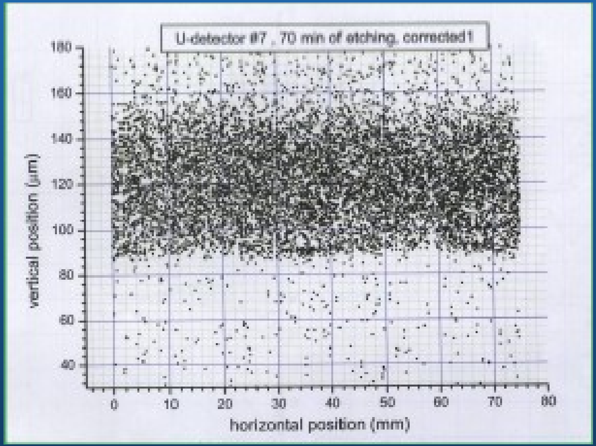

Picture of developed detector with tracks

# La première photo

Nesvizhevsky et al., J. Phys. **C40** (2005) 479

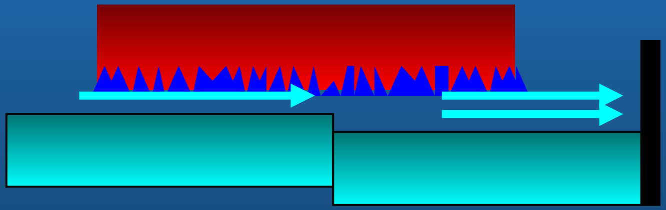


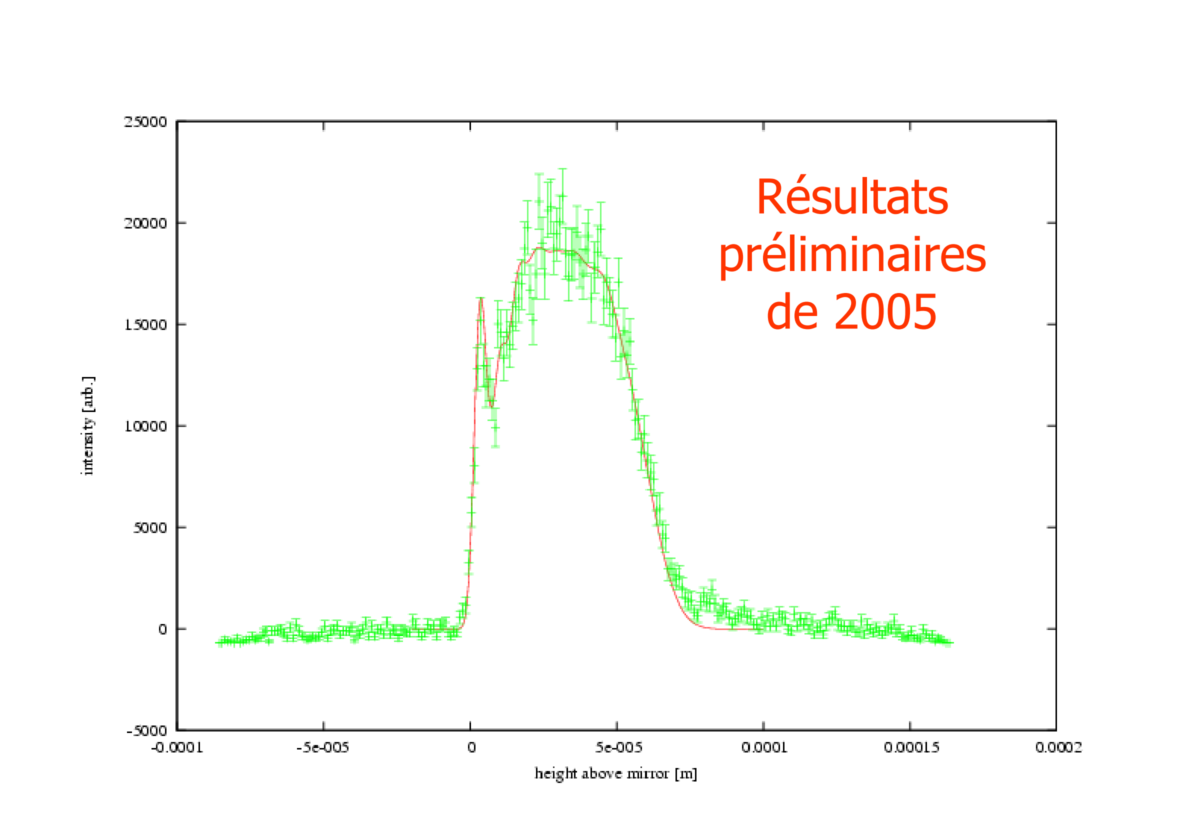



# La photo d'aujourd'hui

Pour se débarrasser de l'état fondamentale il faut modifier légèrement notre installation :





GRAvitational Neutron Induced Transitions

# Recherche des transitions résonnantes entre les niveaux quantiques

## Objectifs

- Obtenir la durée de vie du neutron dans un état quantique de l'ordre d'une seconde
- Observer les transitions résonnantes induites par le gradient du champ magnétique