ATOMINSTITUT

qBOUNCE with neutrons:

Airy Functions & Gravity Resonance Spectroscopy

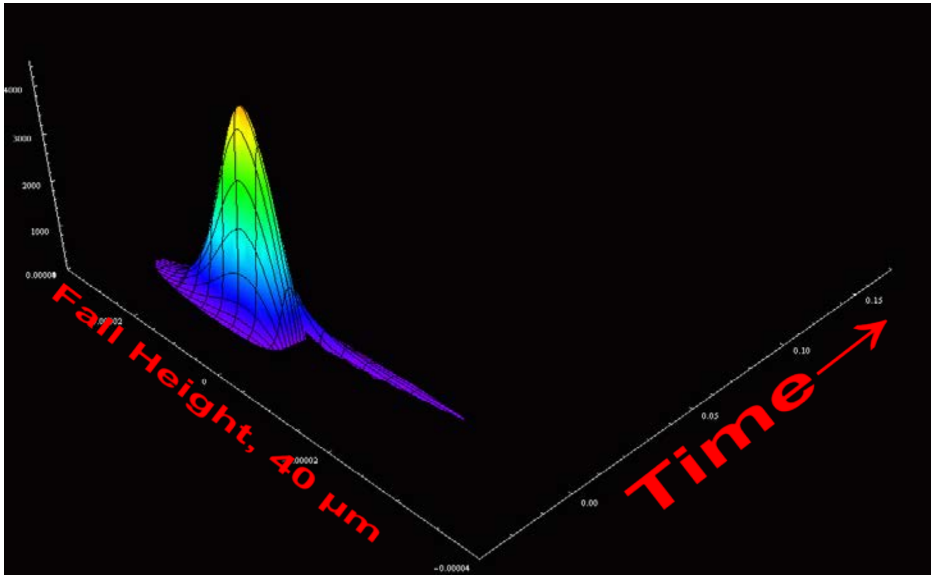
Hartmut Abele

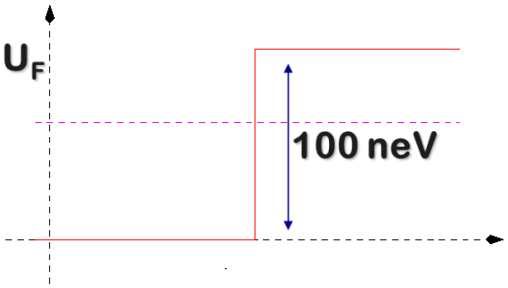
Vancouver, Testing Gravity 2017

27 January 2017

*q*BOUNCE

- A simple quantum mechanical system





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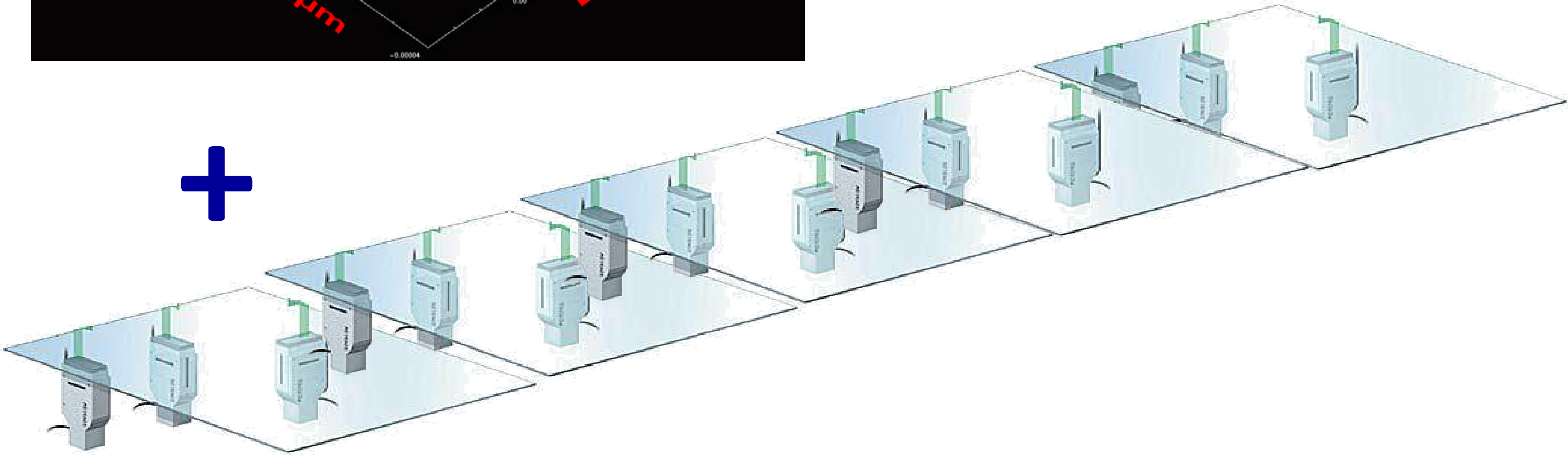
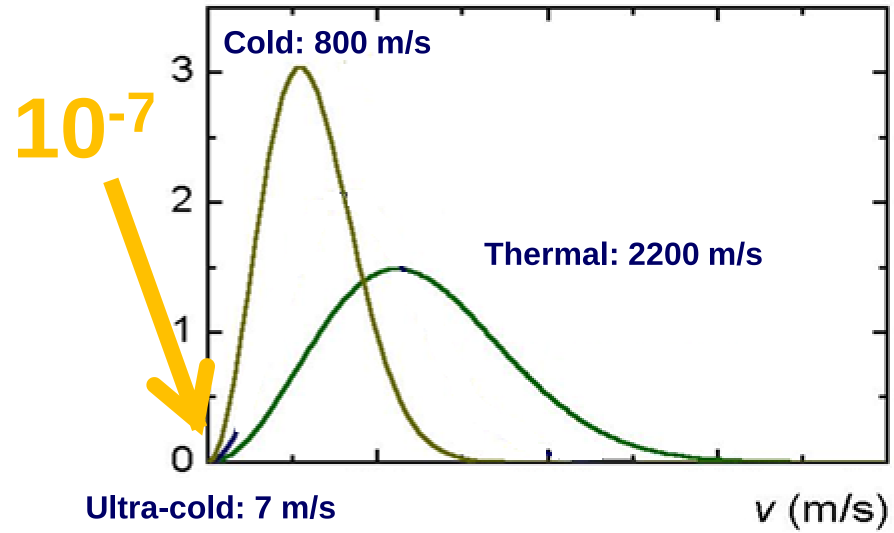
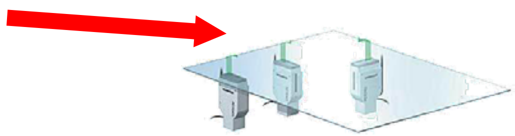



NEUTRONS
FOR SCIENCE
ESRF



- **Fission Neutrons: 2 MeV**
- **Thermal Neutrons: 25 meV**
- **Cold Source: 4 meV**
- **Ultra-cold Neutrons: 100 neV**
- **Gravity experiment: 2 peV**



Tobias Jenke

PF2 – ILL

- Ultra-cold Neutrons
- v = (7±1)m/s

Tobias Jenke

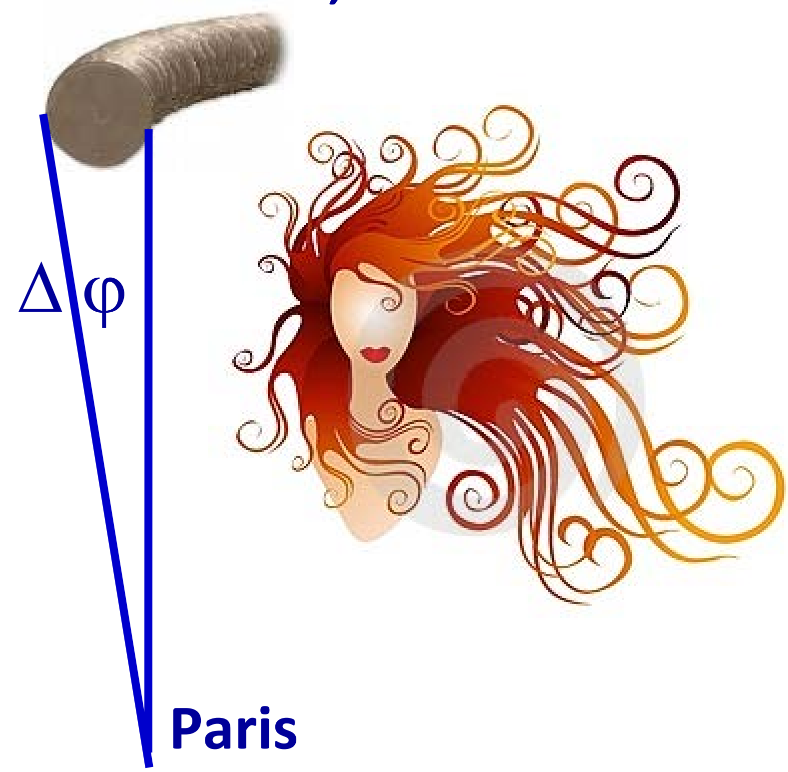
Peter Geltenbort

Why Neutrons?

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

- <u>Energy $\Delta E = 10^{-21}$ eV</u>
  - Search for an electric dipole moment
  - Ramsey's Spectroscopy Method of Separated Oscillating Field

- **By a hair's breadth**
  - **New York, Vancouver**



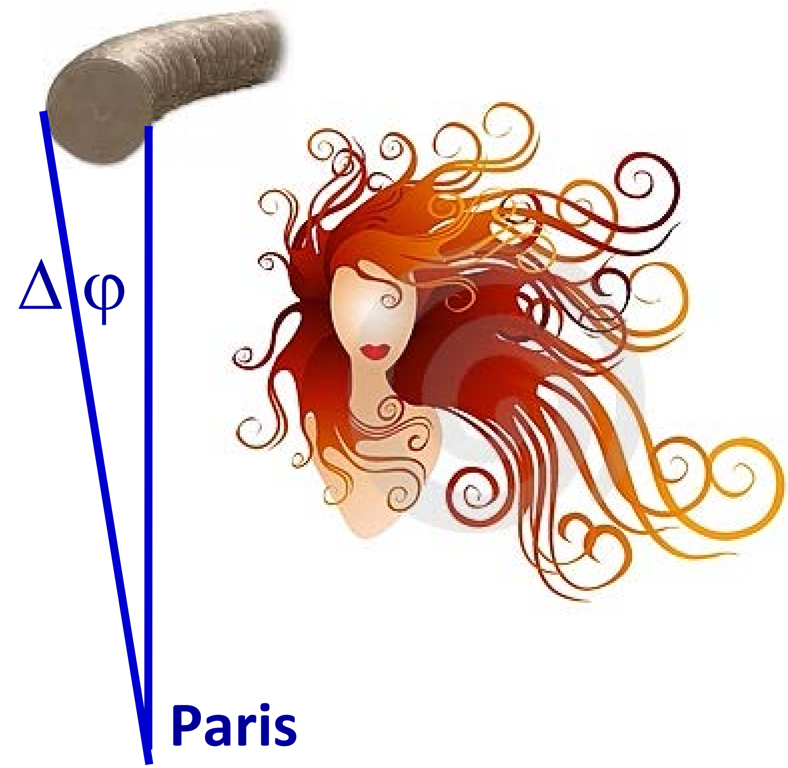
Observables: more than a dozen related to particle physics and cosmology

Review Article:
H.A., The neutron. Its properties and basic interactions, Prog. Part. Nucl. Phys. 60 1-81 (2008)

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

- Energy $\Delta E = 10^{-21}$ eV
  - Search for an electric dipole moment
  - Ramsey's Spectroscopy Method of Separated Oscillating Field
- <u>Momentum $\Delta p/p = 10^{-11}$</u>
  - Search for a non-zero charge of the neutron new method: Ramsey Spectroscopy

- **By a hair's breadth**
  - **New York**



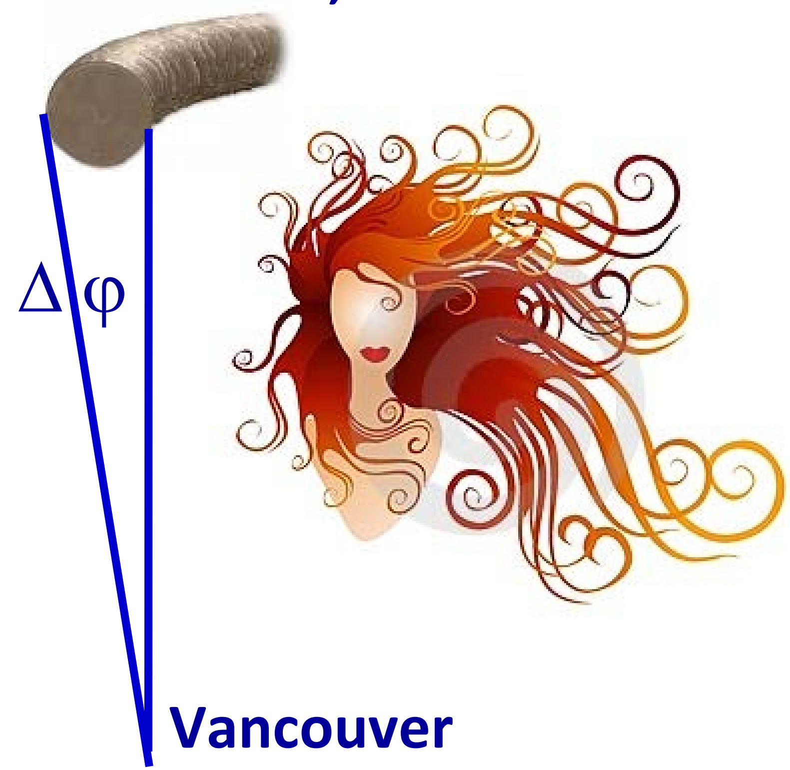
Observables: more than a dozen related to particle physics and cosmology

Review Article:
H.A., The neutron. Its properties and basic interactions, Prog. Part. Nucl. Phys. 60 1-81 (2008)

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

- Energy $\Delta E = 10^{-21}$ eV
- Momentum $\Delta p/p = 10^{-11}$
- Angle $\Delta\ \varphi = 10^{-11}$ rad
  - TU Wien Neutron Interferometer
- Decay rate: 10^{6} /s/m
  - Standard Model Tests complementary to LHC studies
- Neutral
- Polarisability extremely small

- **By a hair's breadth**
  - **New York, Paris**



Observables: more than a dozen related to particle physics and cosmology

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Casimir Force and Van der Waals Force

Atom

- Example Rb

  Energy shift for Rb Atom at r = 1 µm distance to surface

$$a_0 = 2,3 \times 10^{-23}$$
$$V(r) = \frac{3\hbar c}{2\pi}\frac{a_0}{r^4}$$
$$= 0.6 \text{ peV}$$

Spectroscopy with cold and ultra-cold neutrons
H.A. T Jenke, G Konrad
EPJ Web of Conferences 93, 2015

Neutron

- Casimir force absent
- Polarizability extremely small:

$$a_n = 11.6 \times 10^{-4}\,\text{fm}^3$$
$$D = 4\pi\varepsilon_0 a_n E$$
$$= 6 \times 10^{-41}\,\text{eV} \times E\left[\frac{\text{V}}{\text{m}}\right]$$
$$= 10^{-18}\ \text{peV}$$

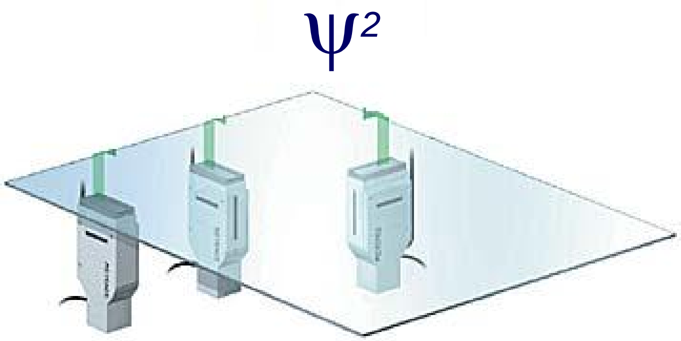
Aim: gravity experiments with neutrons with a sensitivity level of 10^{-21} eV = 10^{-9} peV

Outline of my talk: free fall at short distances

- ***q*****Bounce -** Quantum Bouncing Ball:
  - Mathematical description with Airy-Functions
- Measurements of Airy-Wave-Functions in the gravity potential of the Earth
  - Fall height: 30µm
  - Mirror, polished glass
- Gravity Resonance Spectroscopy
  - Aim: $\Delta E = 10^{-21}$ eV
- Test of Newton's Law at short distances
  - Search for hypothetical gravity-like forces, effects of string theories, higher dimensional field theories etc.
  - Limits on theories describing the expansion of the universe

*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

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

AiryAi & AiryBi

M. Pitschmann

Schroedinger Equation

Two linearly independent solutions of

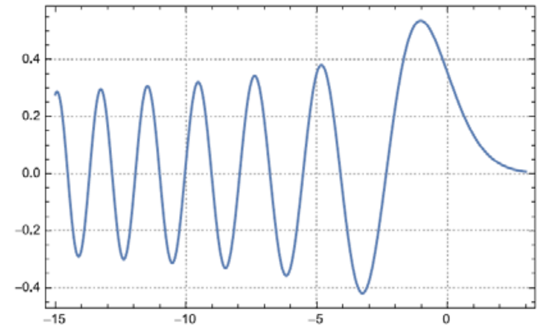
$$\frac{d^2\tilde{\psi}_n(\xi)}{d\xi^2} - \xi\,\tilde{\psi}_n(\xi) = 0$$

are the *Airy functions*

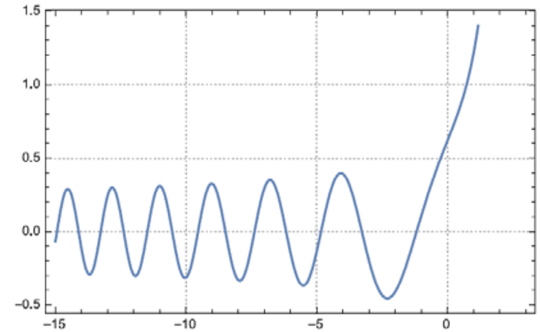
$$Ai(\xi) = \frac{1}{\pi}\int_0^\infty \cos\left(\frac{t^3}{3} + \xi t\right) dt$$

$$Bi(\xi) = \frac{1}{\pi}\int_0^\infty \left[\exp\left(-\frac{t^3}{3} + \xi t\right) + \sin\left(\frac{t^3}{3} + \xi t\right)\right] dt$$

$Ai(\xi)$



$Bi(\xi)$



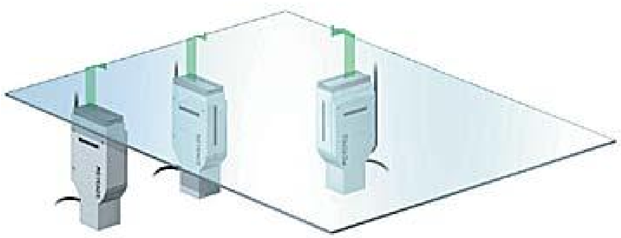
Asymptotic Forms

$$\lim_{\xi\to\infty} Ai(\xi) \simeq \frac{e^{-\frac{2}{3}\xi^{3/2}}}{2\sqrt{\pi}\,\xi^{1/4}} \quad , \quad \lim_{\xi\to-\infty} Ai(\xi) \simeq -\frac{\sin(\frac{2}{3}|\xi|^{3/2} + \frac{\pi}{4})}{\sqrt{\pi}\,|\xi|^{1/4}}$$

$$\lim_{\xi\to\infty} Bi(\xi) \simeq \frac{e^{\frac{2}{3}\xi^{3/2}}}{\sqrt{\pi}\,\xi^{1/4}} \quad , \quad \lim_{\xi\to-\infty} Bi(\xi) \simeq -\frac{\cos(\frac{2}{3}|\xi|^{3/2} + \frac{\pi}{4})}{\sqrt{\pi}\,|\xi|^{1/4}}$$

*q*BOUNCE: Quantum States in the Gravity Potential

- Energy Eigenvalues are given by the Zeros of AiryAi



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

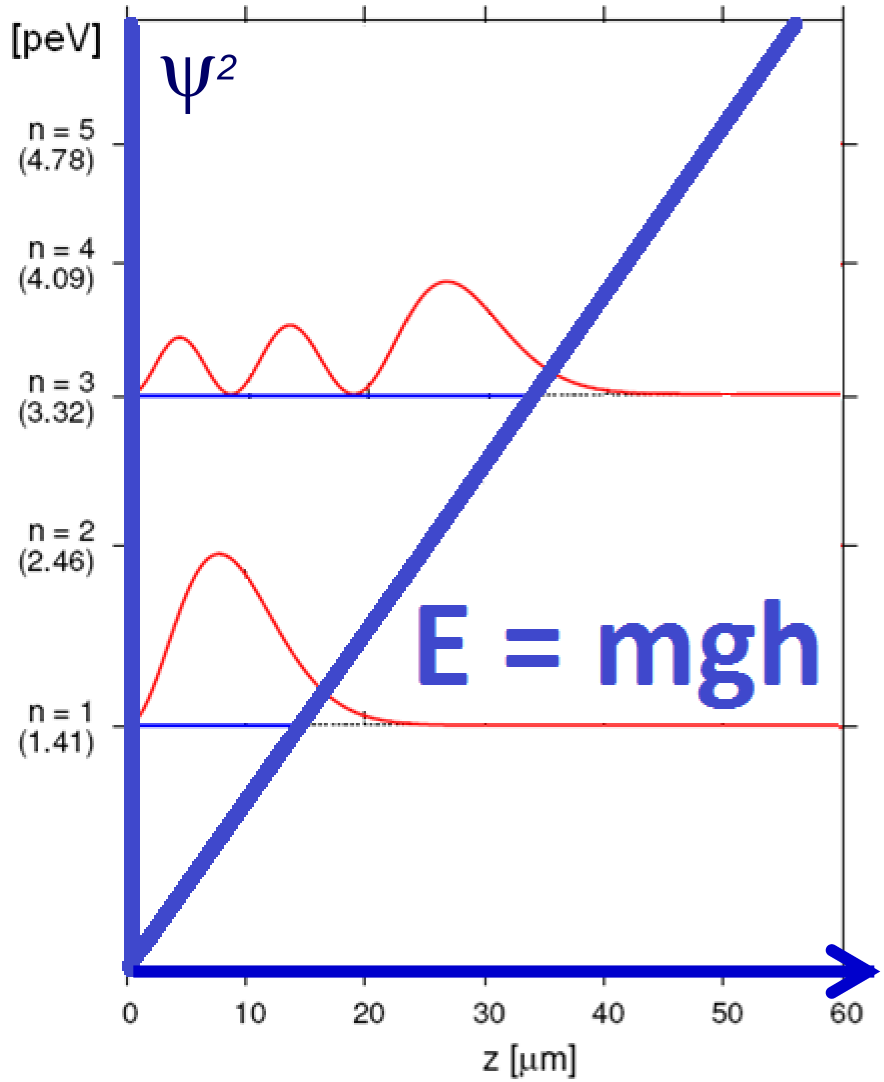
- Zeros, Energy & Ψ

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

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

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

- Bound State

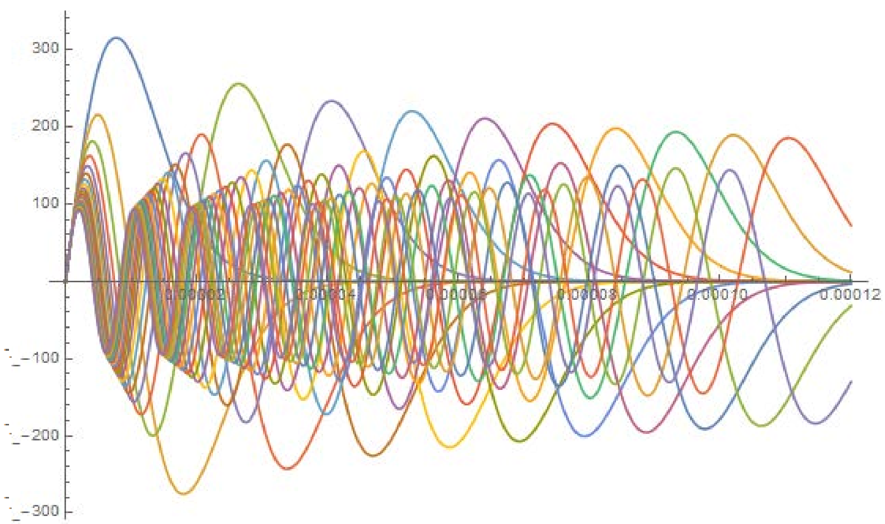


The time dependent case

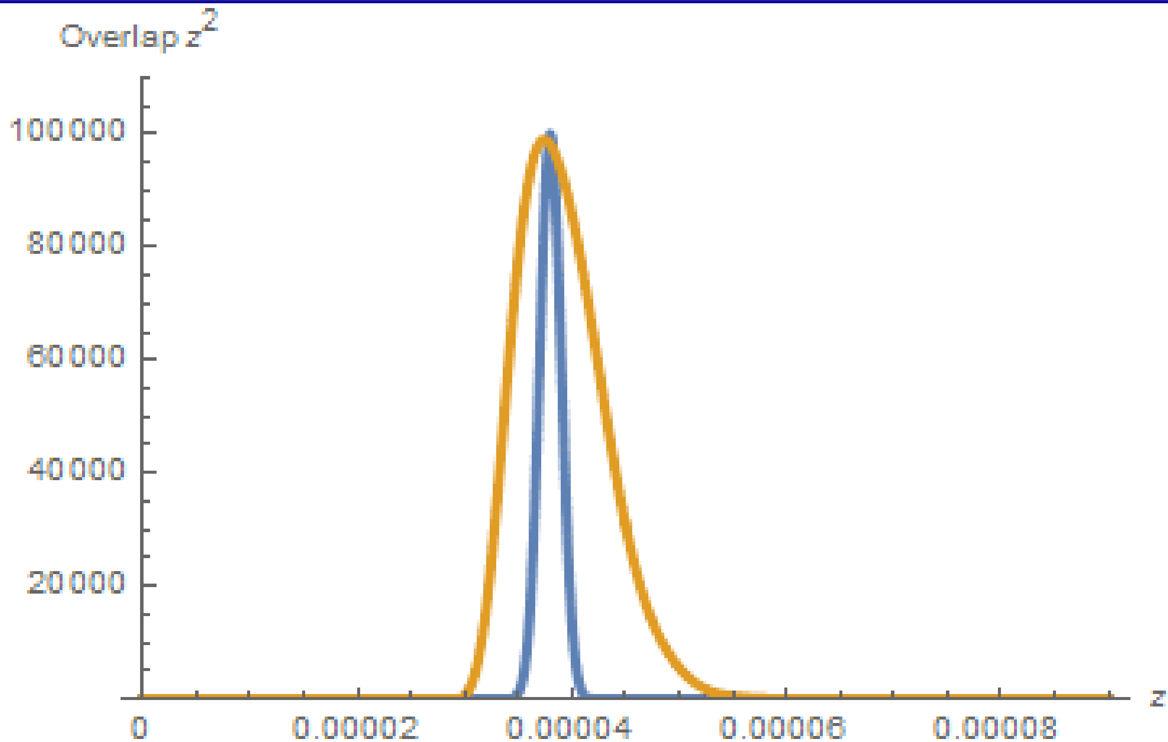
- the time dependent Schrödinger equation

$$i\hbar\frac{\partial\Psi}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2\Psi}{\partial z^2} + mgz\Psi$$

- separate variables $\Psi_n(z,t) = e^{-iE_n t/\hbar}\psi_n(z)$
- general solution $\Psi(z,t) = \sum_{n=0}^{\infty} c_n e^{-iE_n t/\hbar}\psi_n(z)$ $\qquad c_n = \int_0^{\infty} \Psi(z,0)\psi_n(z)dz$



"Fourier"-Airy Series



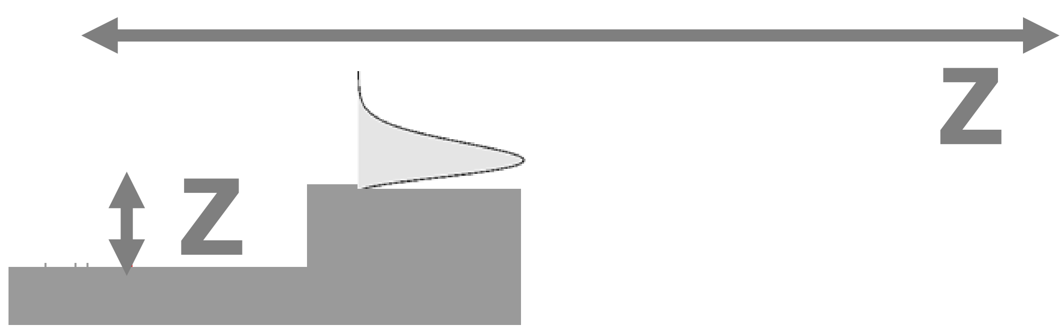
$$\Psi_1(\tilde{z},t) = c_1 Ai_1(\tilde{z}) \times e^{-i(E_1/\hbar)\times t}$$

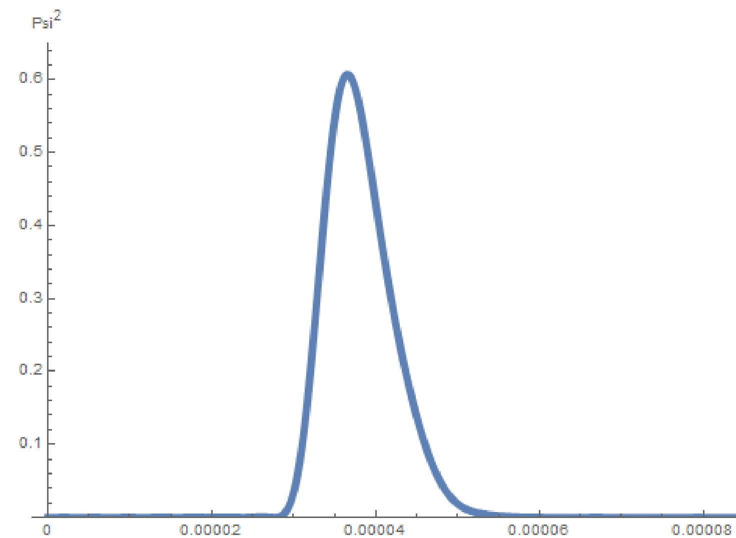
$$\Psi_2(\tilde{z},t) = c_2 Ai_2(\tilde{z}) \times e^{-i(E_2/\hbar)\times t}$$

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

$$\ldots$$

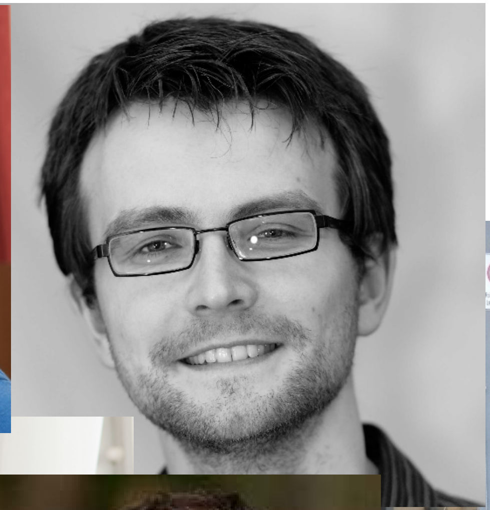
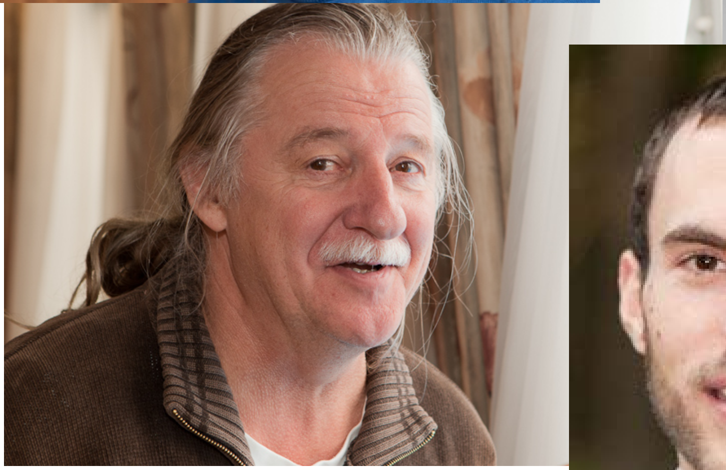
$$\Psi(\tilde{z},t) = \sum_{n=1}^{\infty} Ai_n(\tilde{z}) \times e^{-i(E_n/\hbar)\times t}$$

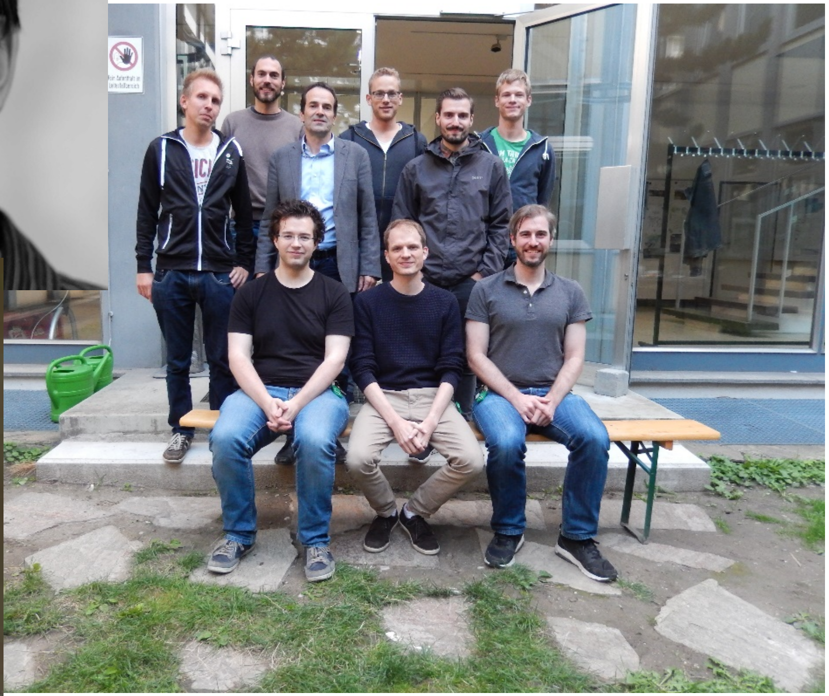




The Team at Atominstitut

- Gravity tests with quantum objects
  - T. Jenke, G. Cronenberg, H. Filter, K. Mitsch, Martin Stöger, Tamara Putz, P. Geltenbort (ILL), M. Heumesser, H. Lemmel, M. Thalhammer, T. Rechberger, P. Schmidt, J. Herzinger, Collaboration ILL (P. Geltenbort), HD (U. Schmidt)

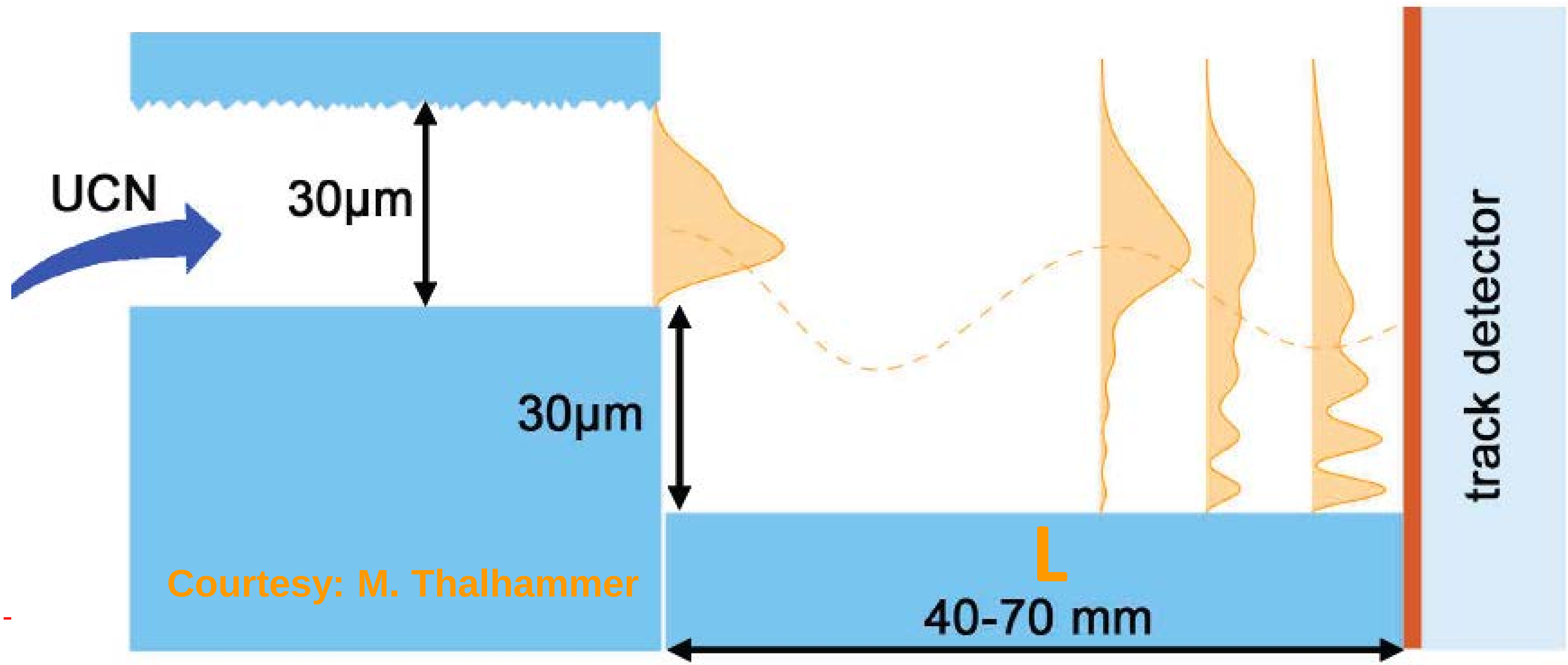


M. Thalhammer, T. Jenke et al.

- Snapshots with spatial resolution detectors ~ 1.5 µm

$$\Psi(z,t) = \sum_{n=0}^{\infty} c_n e^{-iE_n t/\hbar} \psi_n(z)$$

$$\psi_n(z) \sim Ai[\frac{z}{z_0} - \frac{E_n}{E_0}]; c_n = \int_0^{\infty} \Psi(z,0)\psi(z)dz$$



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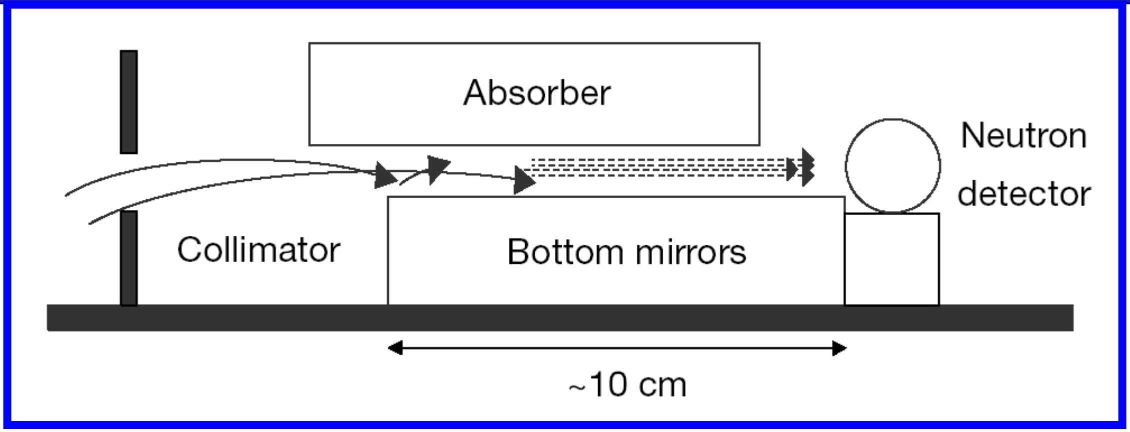
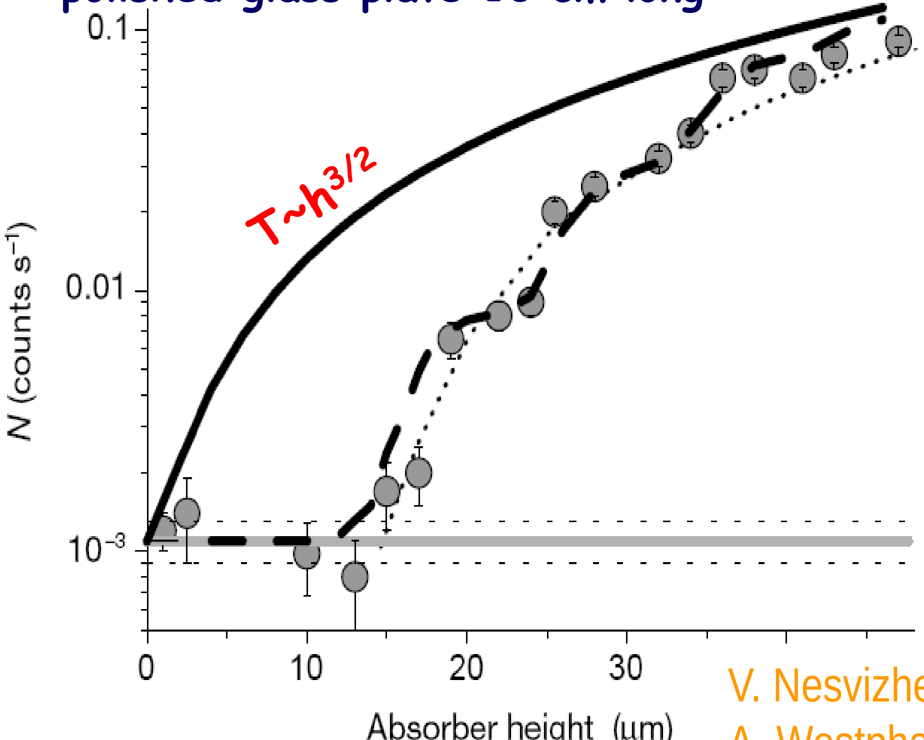
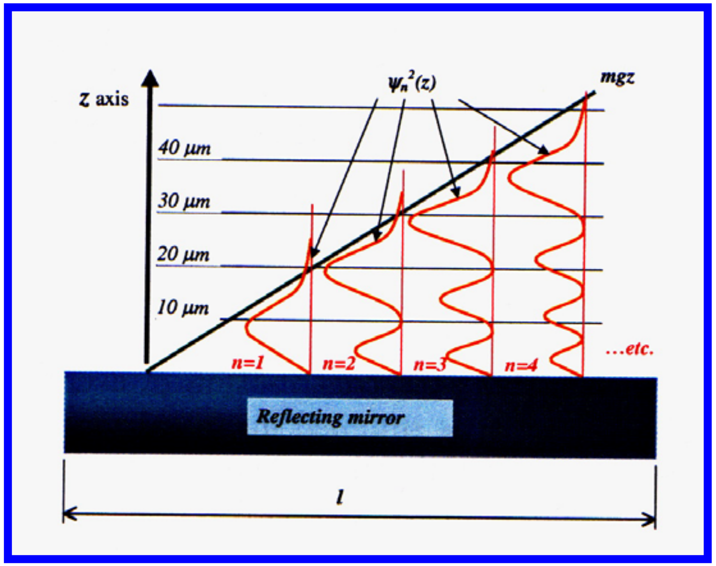
2002: Observation of Bound Quantum States



Neutron mirror:
polished glass plate 10 cm long

V. Nevizhevsky, H.A. et al., Nature 415 299 (2002).

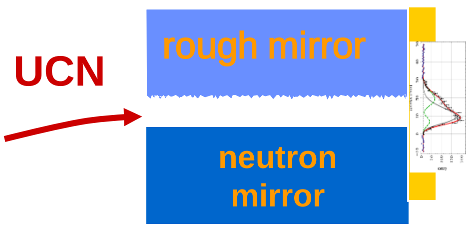


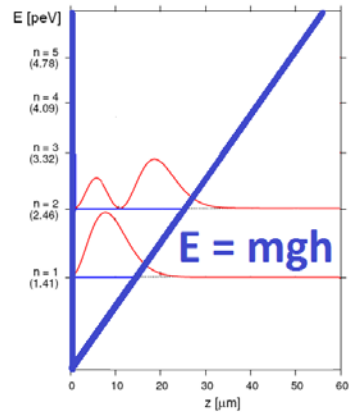


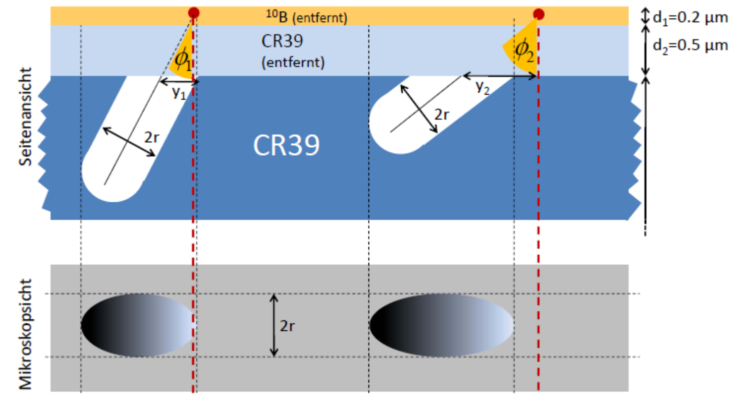
V. Nesvizhevsky, H.A. et al., Eur. Phys. Lett. (2005)
A. Westphal, H.A. et al., Eur. Phys. Lett. (2007)

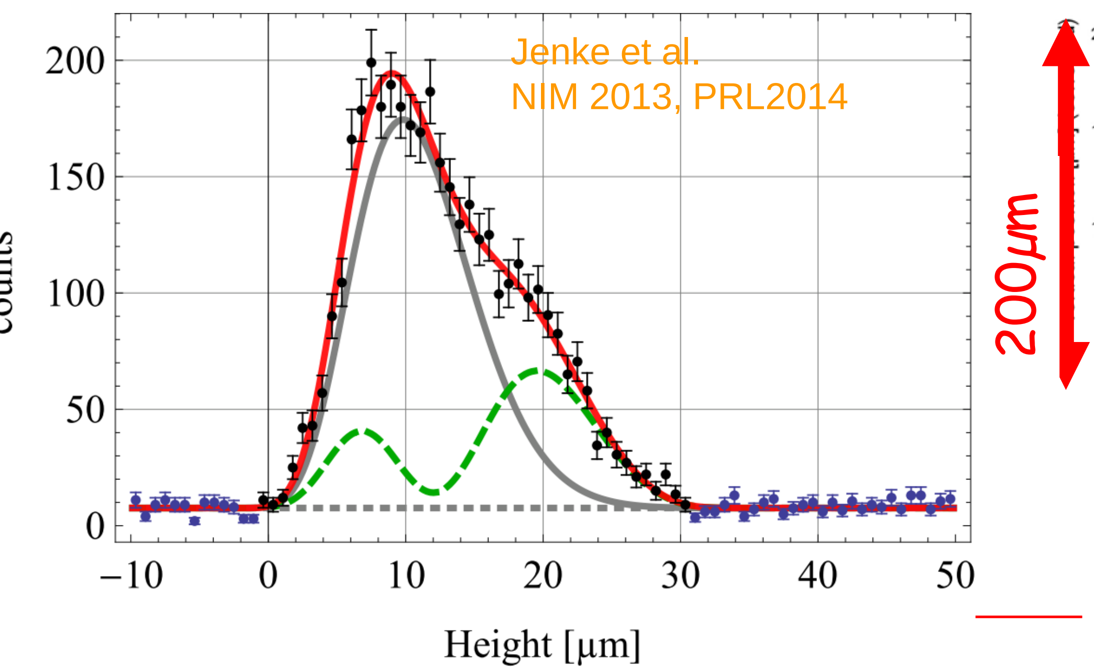
Airy - Quantum States 1 & 2

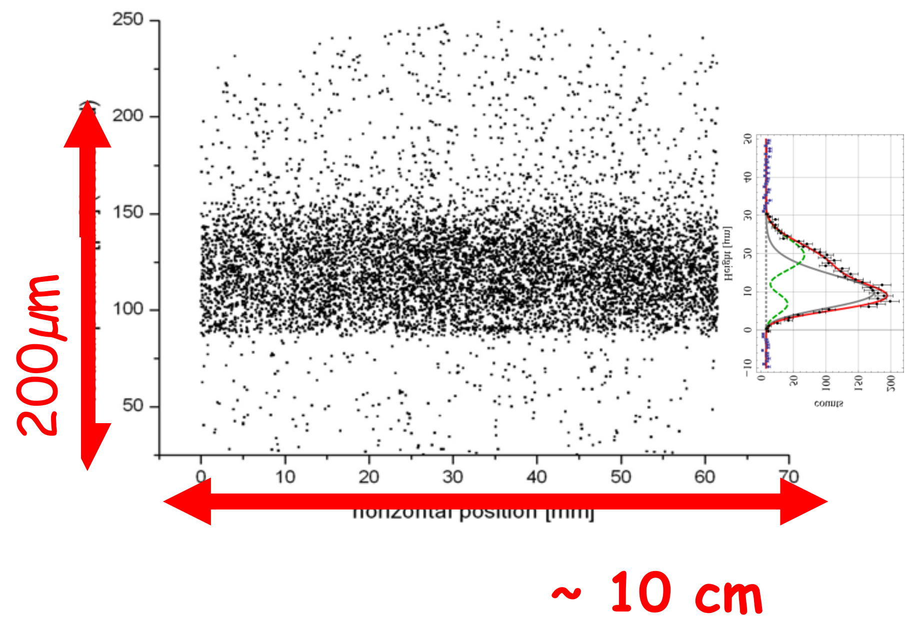
$$n + {}^{10}B \rightarrow {}^{7}Li^{*} + \alpha$$









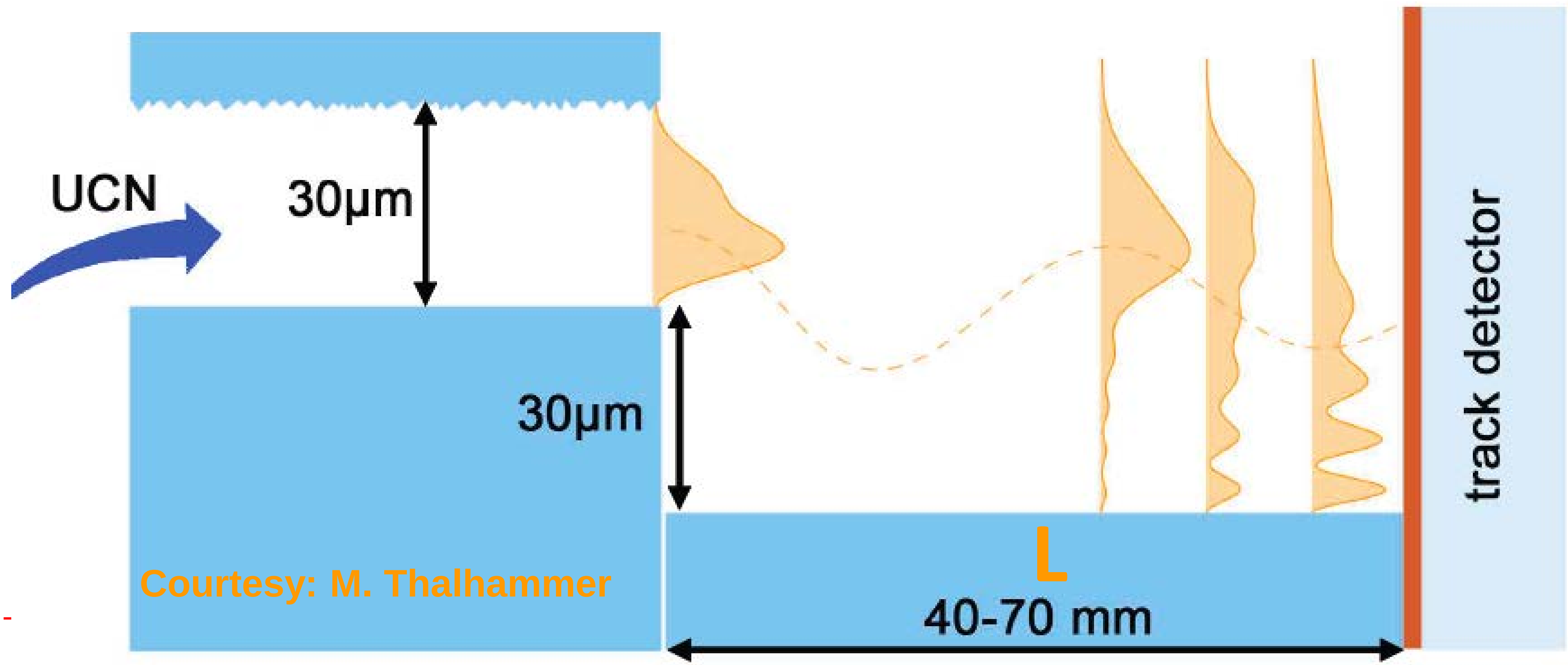


M. Thalhammer, T. Jenke et al.

- Snapshots with spatial resolution detectors ~ 1.5 µm

$$\Psi(z,t) = \sum_{n=0}^{\infty} c_n e^{-iE_n t/\hbar} \psi_n(z)$$

$$\psi_n(z) \sim Ai[\frac{z}{z_0} - \frac{E_n}{E_0}]; c_n = \int_0^{\infty} \Psi(z,0)\psi(z)dz$$



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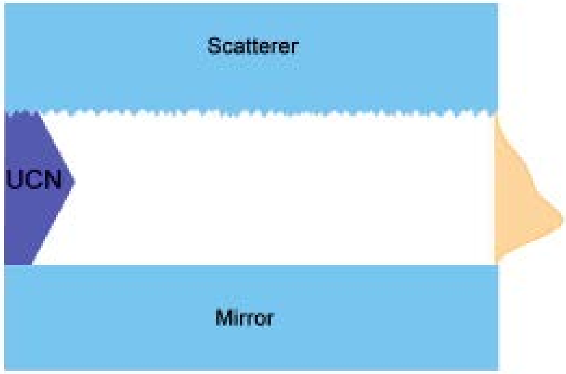
Preparation L = 0



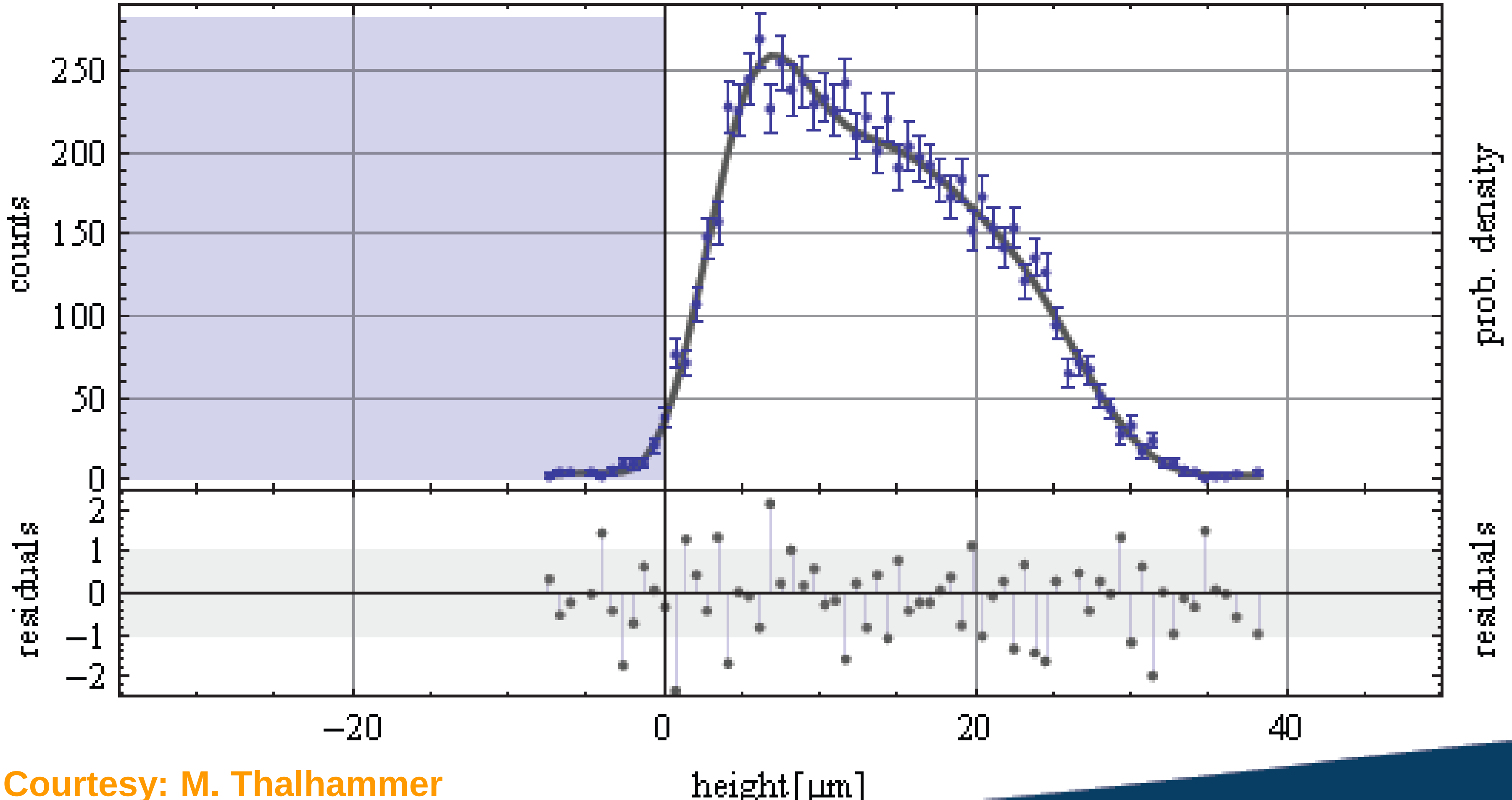
$$|\Psi_I(z,t_1)|^2 = \sum_n |C_n(t_1)|^2 \cdot |\psi_n(z)|^2$$

$|c_1|^2 = 48\%$,

$|c_2|^2 = 40\%$,

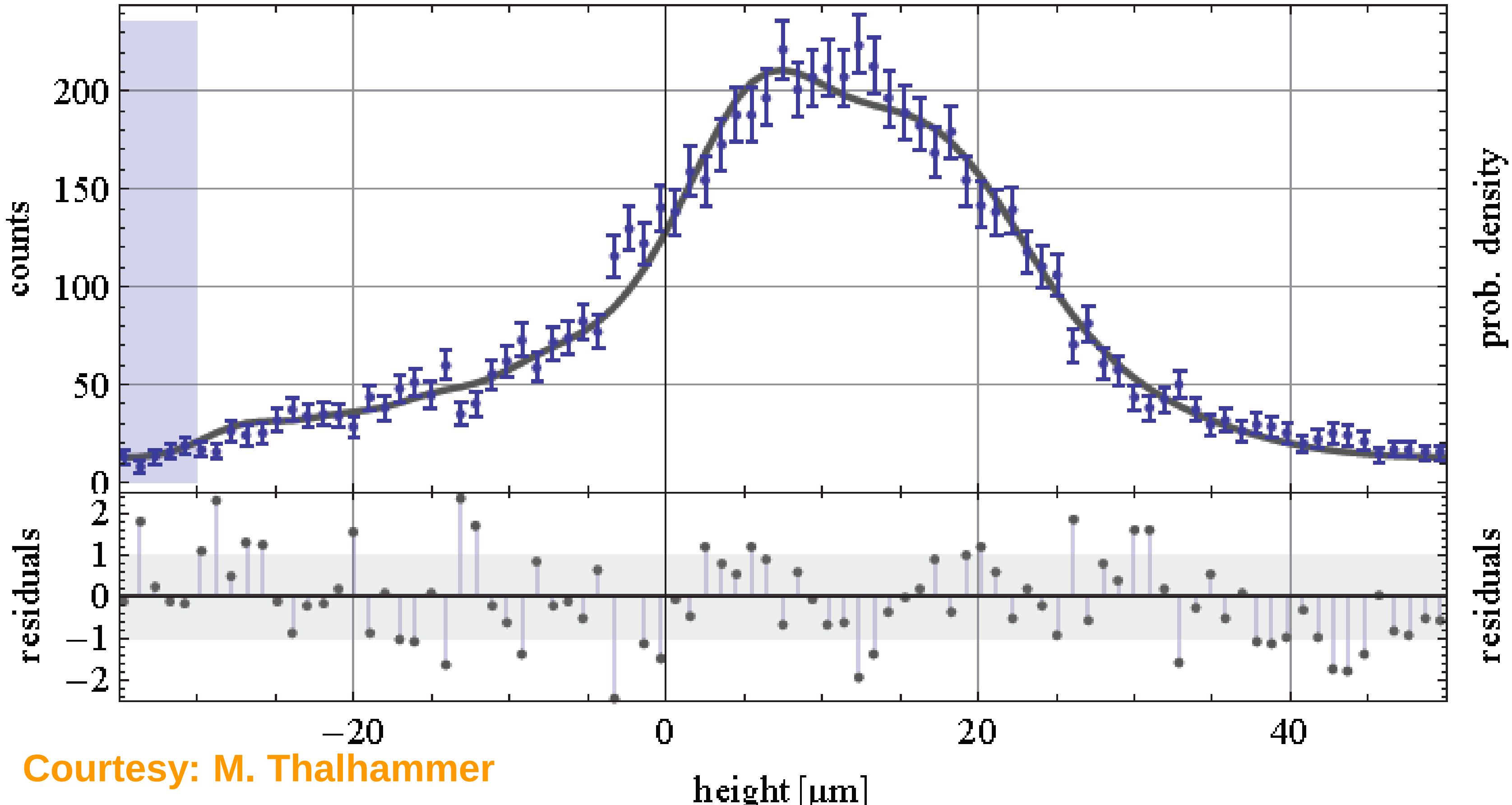
$|c_3|^2 = 12\%$,

preliminary



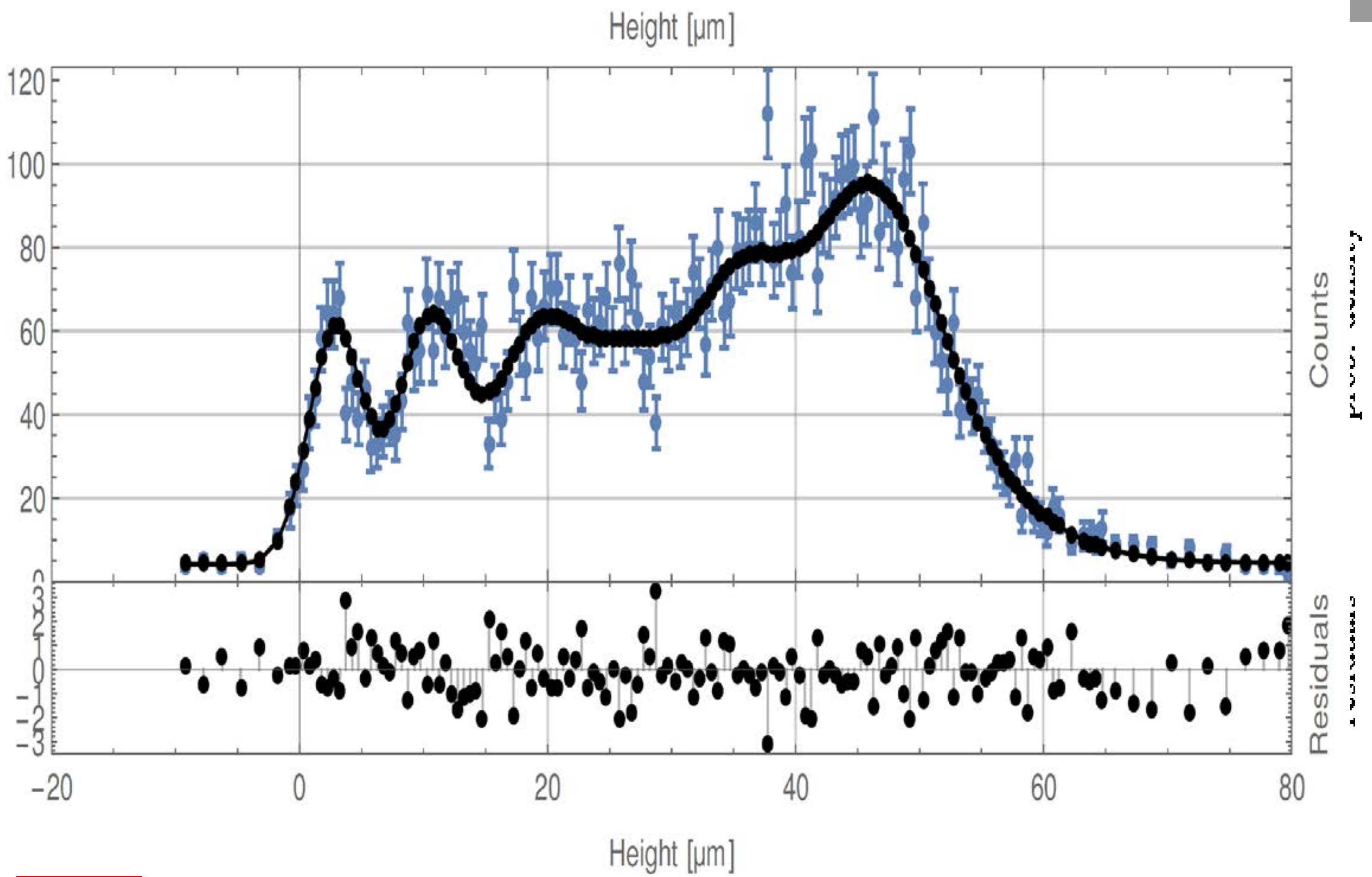
Courtesy: M. Thalhammer

2nd bounce, 2nd turning point, L = 41 mm



Courtesy: M. Thalhammer

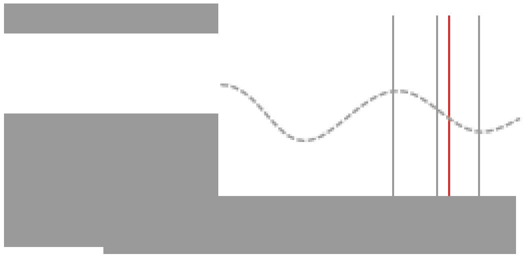
Move downwards, L = 51 mm

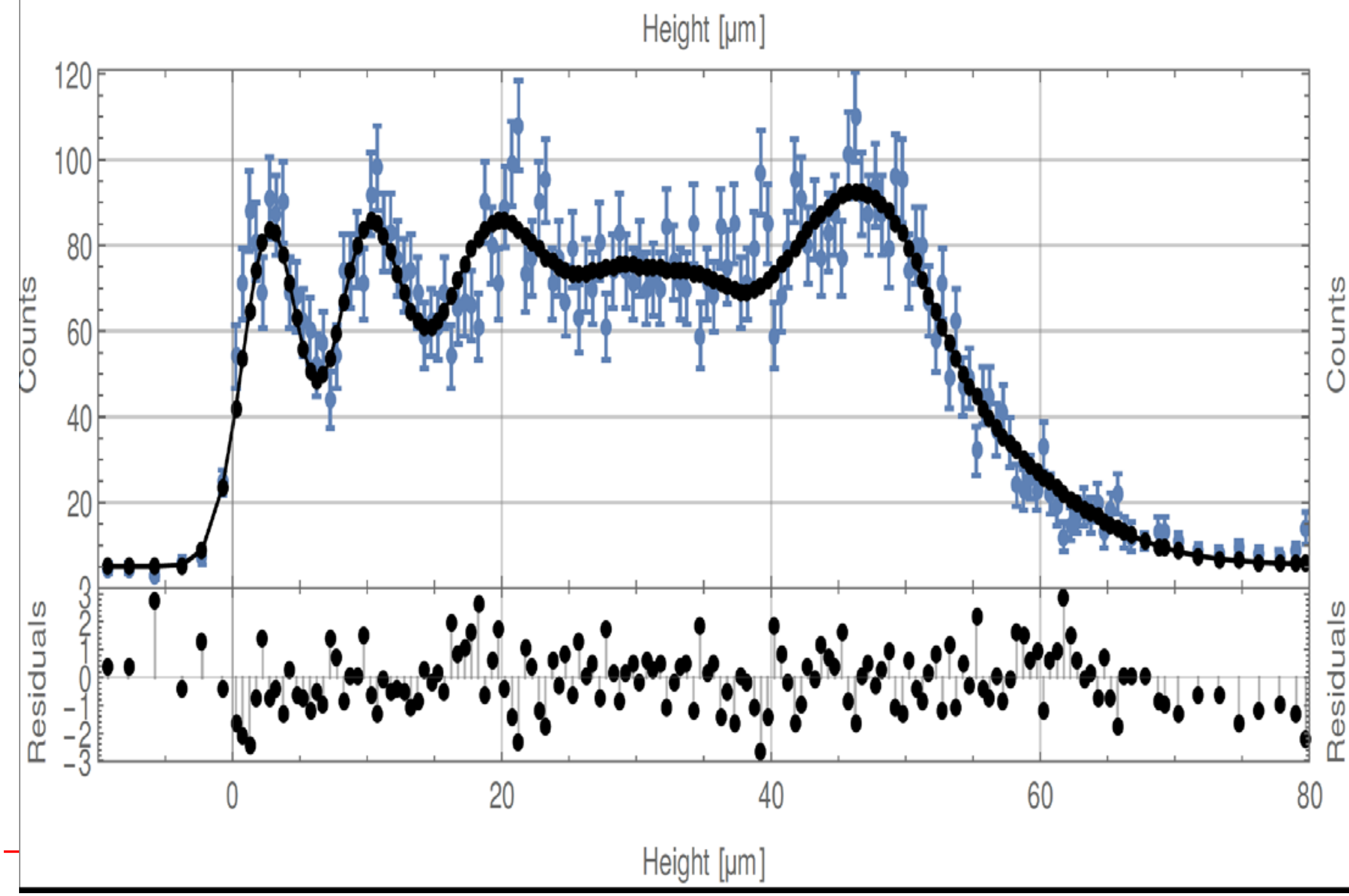


Courtesy: M. Thalhammer

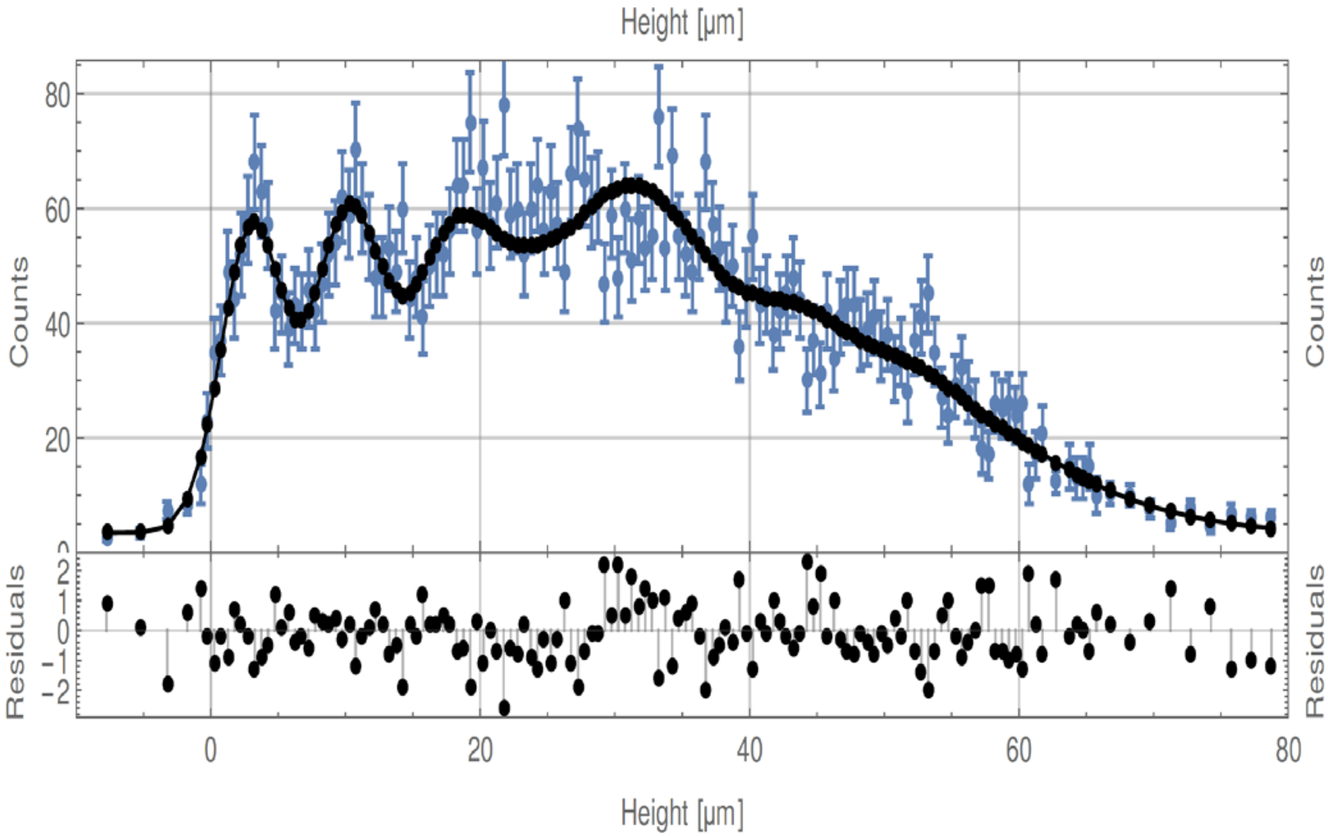
L = 54 mm

54 mm



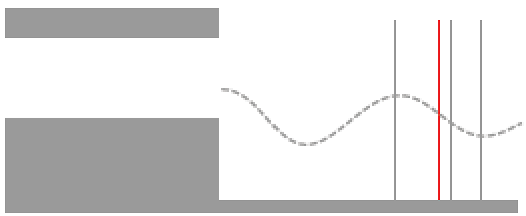


L = 61 mm

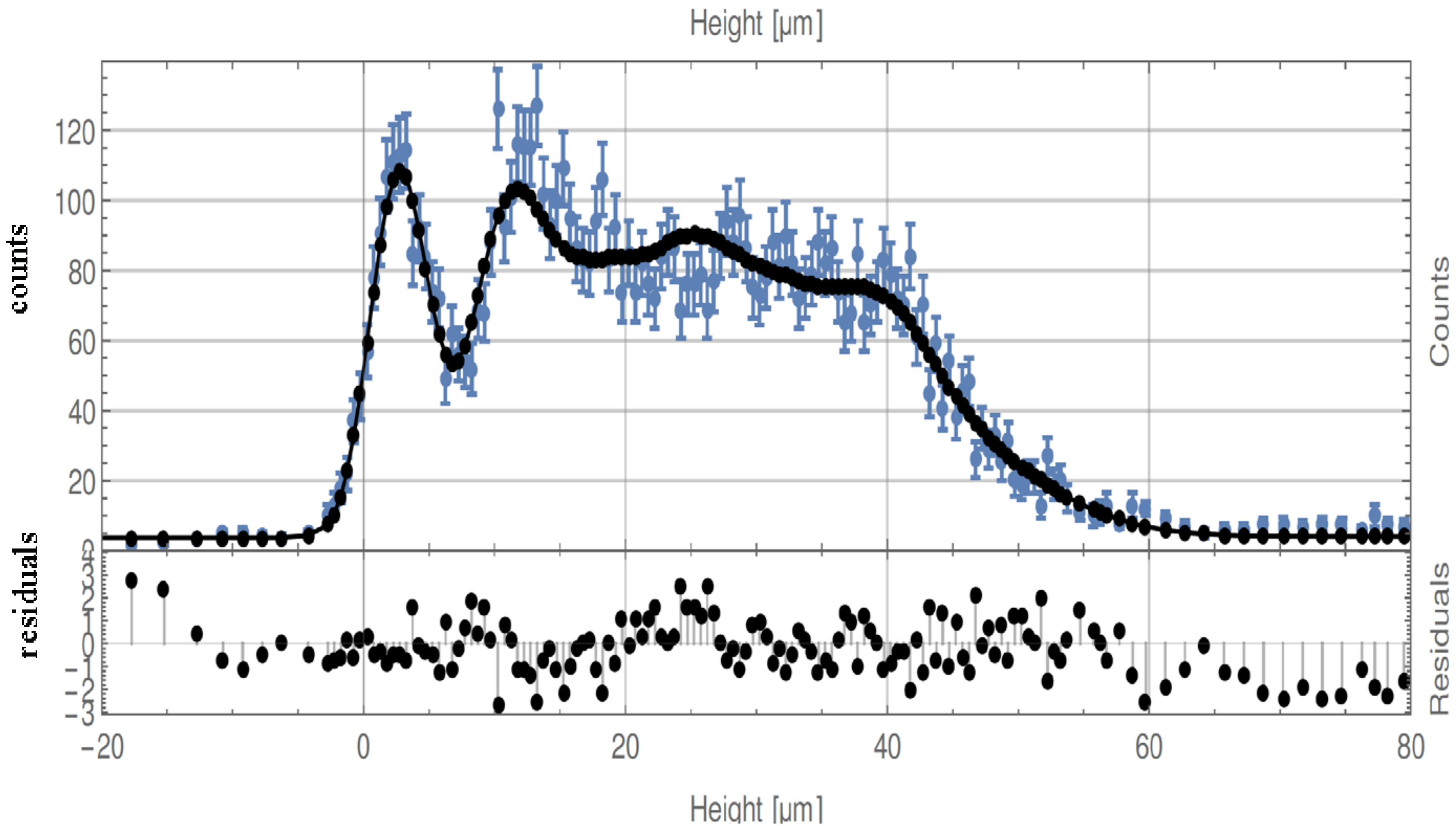


Height [μm]
80
60
40
20
0
Counts
Counts
2
1
0
-1
-2
Residuals
Residuals
0
20
40
60
80
Height [μm]

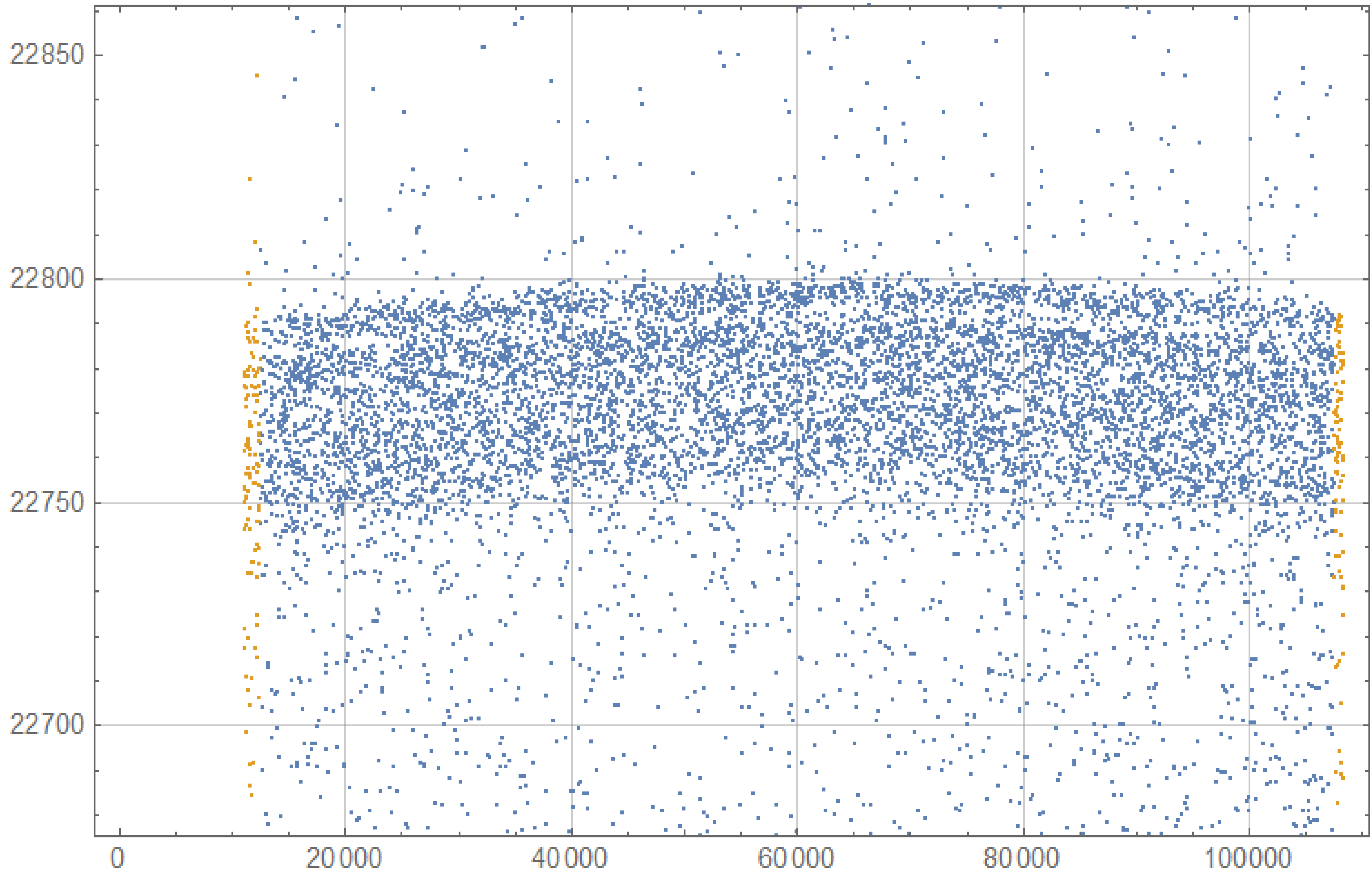
L = 51 mm @ 20 µm



- Parameters: Norm, Bg, sigma, c2,c3,h



Raw Data, 20 µm Step



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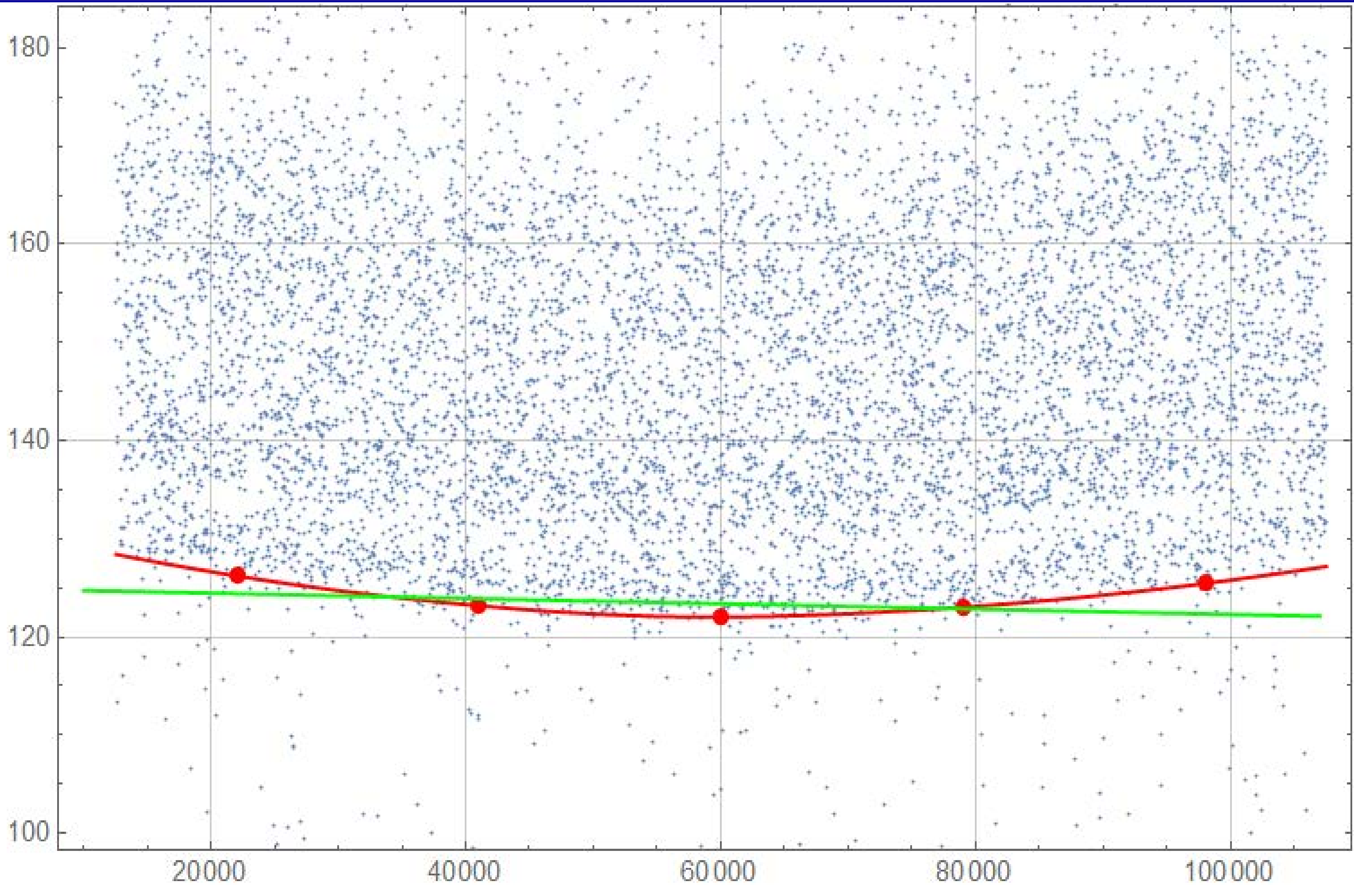
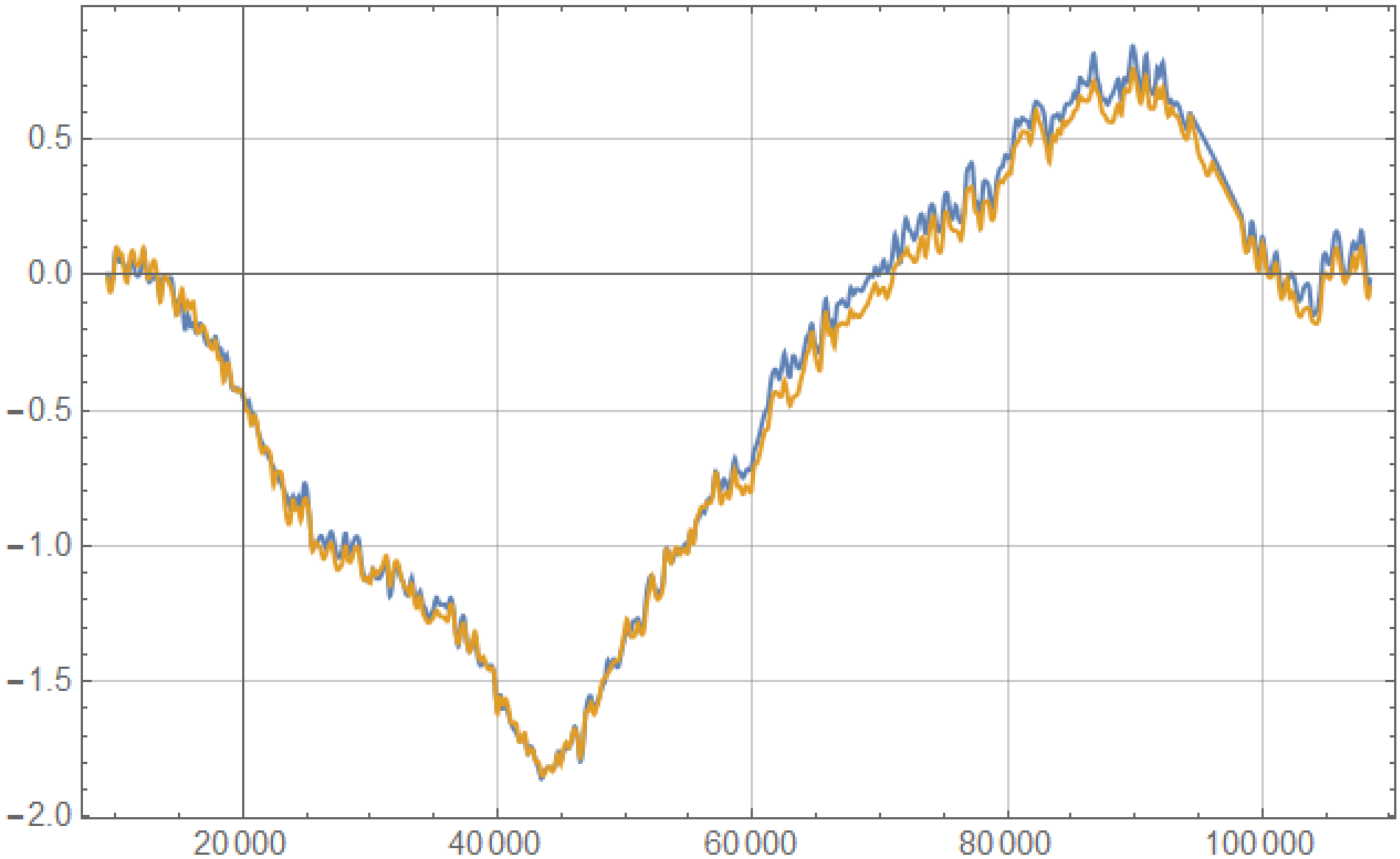
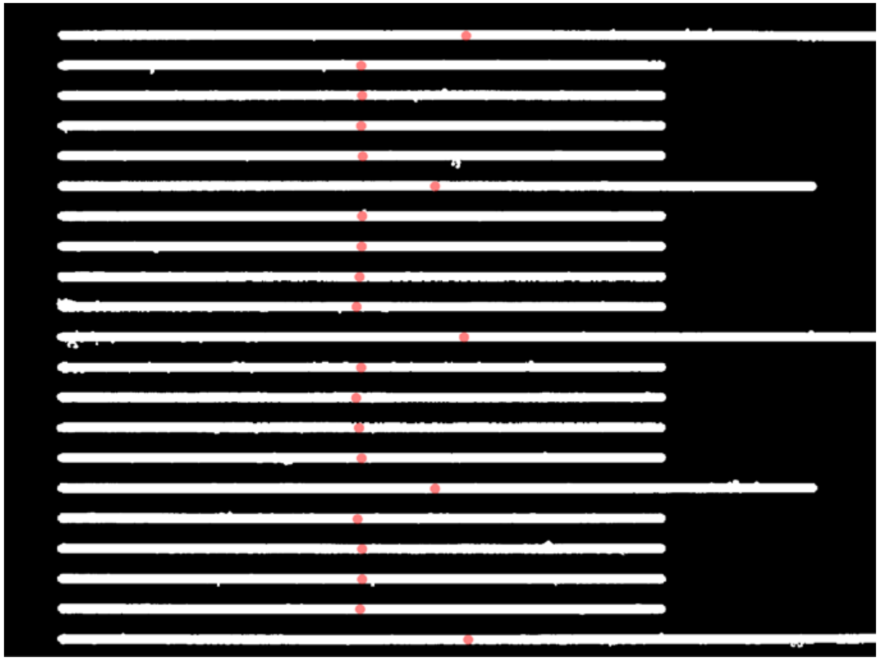


Lateral Deviation of Microscope Table Movement from Line Motion



Microscope Calibration

- Line pattern calibration 0.1 µm on 200 µm, DKD
- Dot pattern r = 2.5 µm

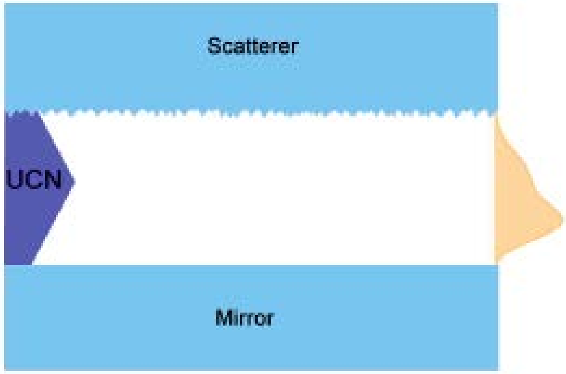


Preparation L = 0

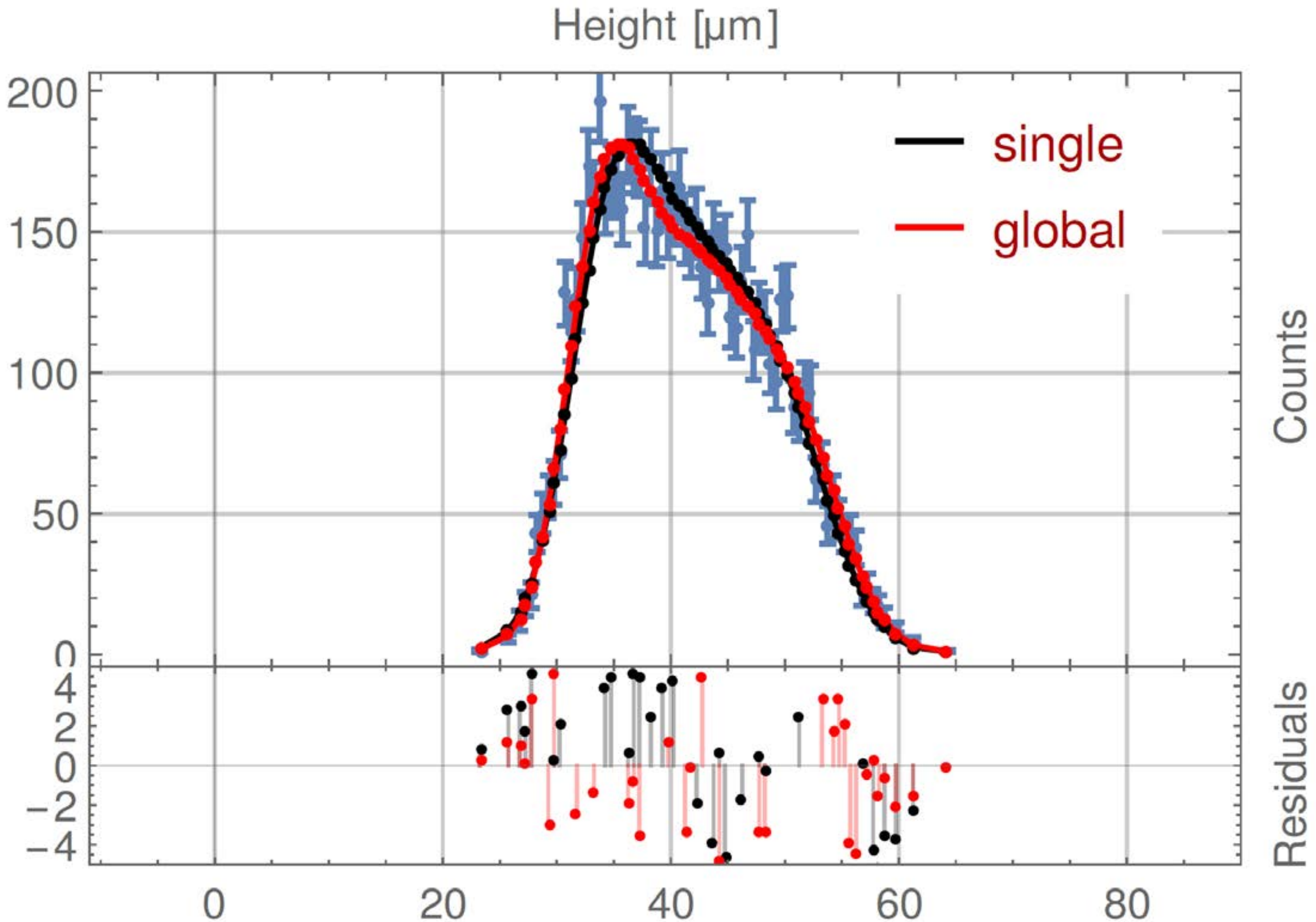
local $|c_1|^2 = 48\%$, global $|c_1|^2 = 50\%$

$|c_2|^2 = 40\%$, $|c_2|^2 = 40\%$

$|c_3|^2 = 12\%$, $|c_3|^2 = 10\%$

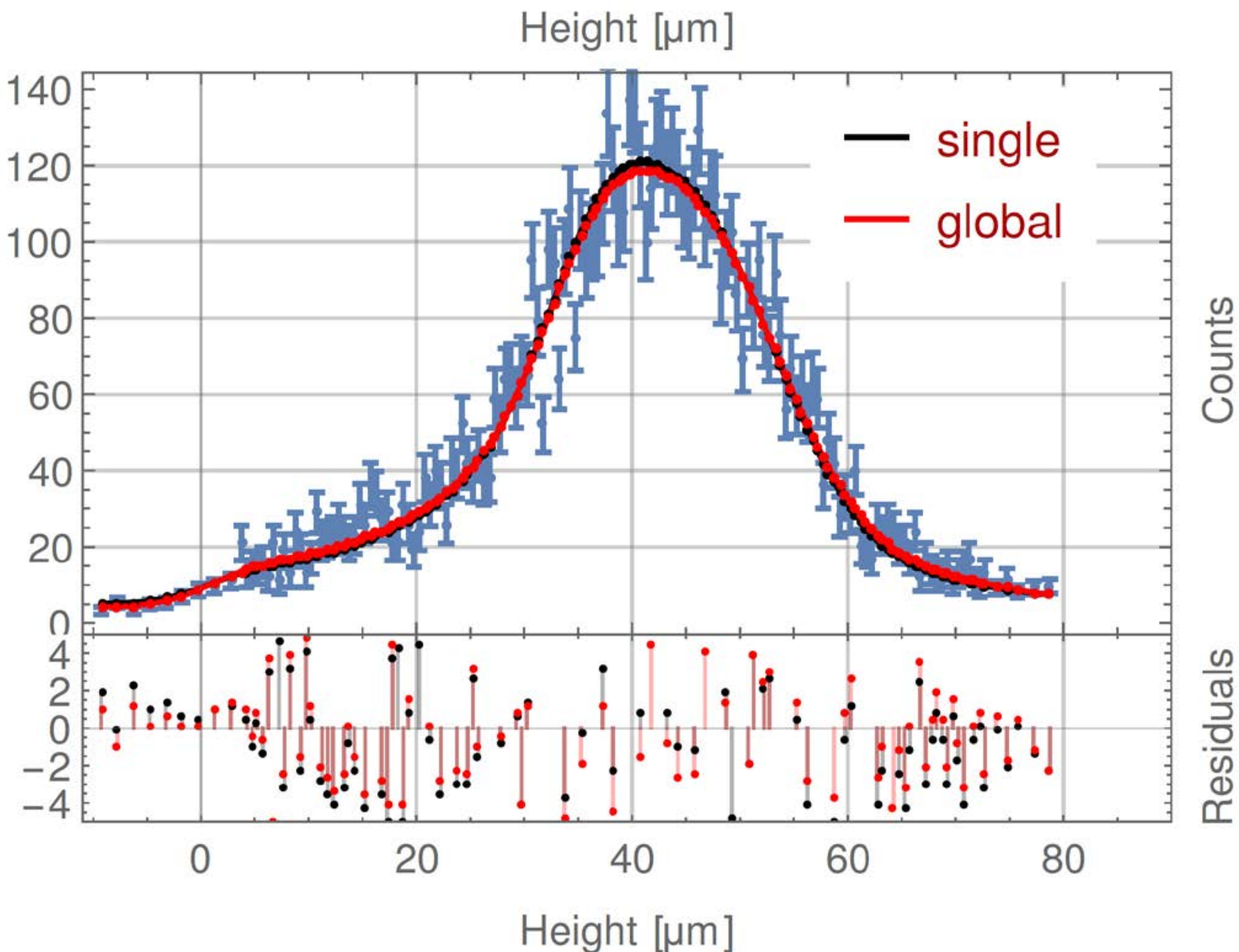


$$|\Psi_I(z, t_1)|^2 = \sum_n |C_n(t_1)|^2 \cdot |\psi_n(z)|^2$$

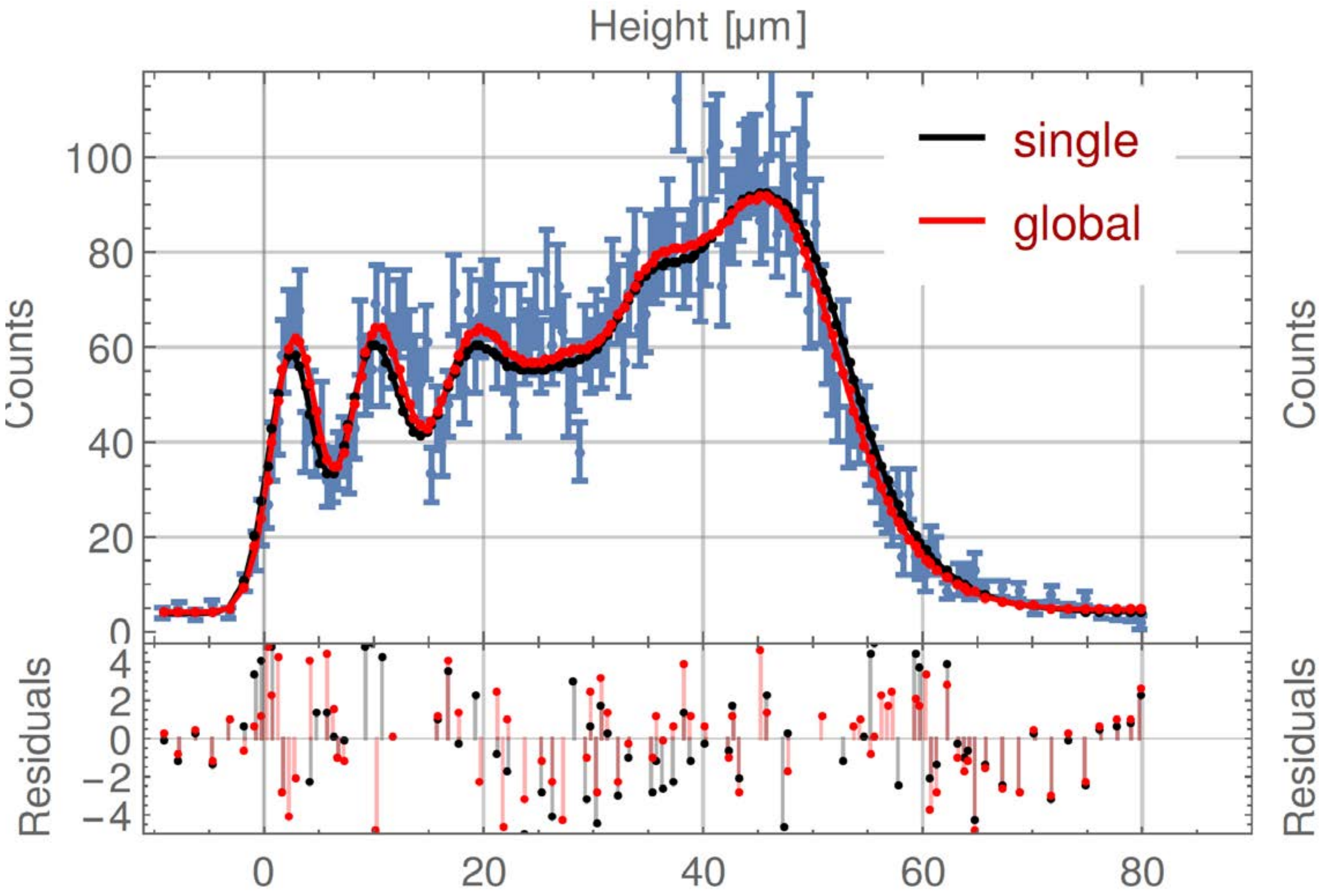


Courtesy

2nd bounce, 2nd turning point, L = 41 mm

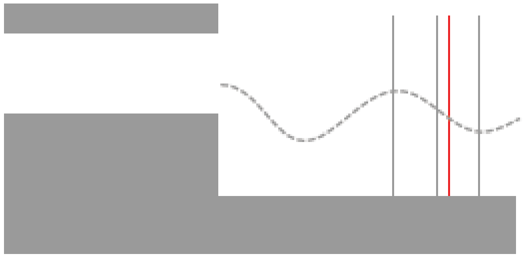


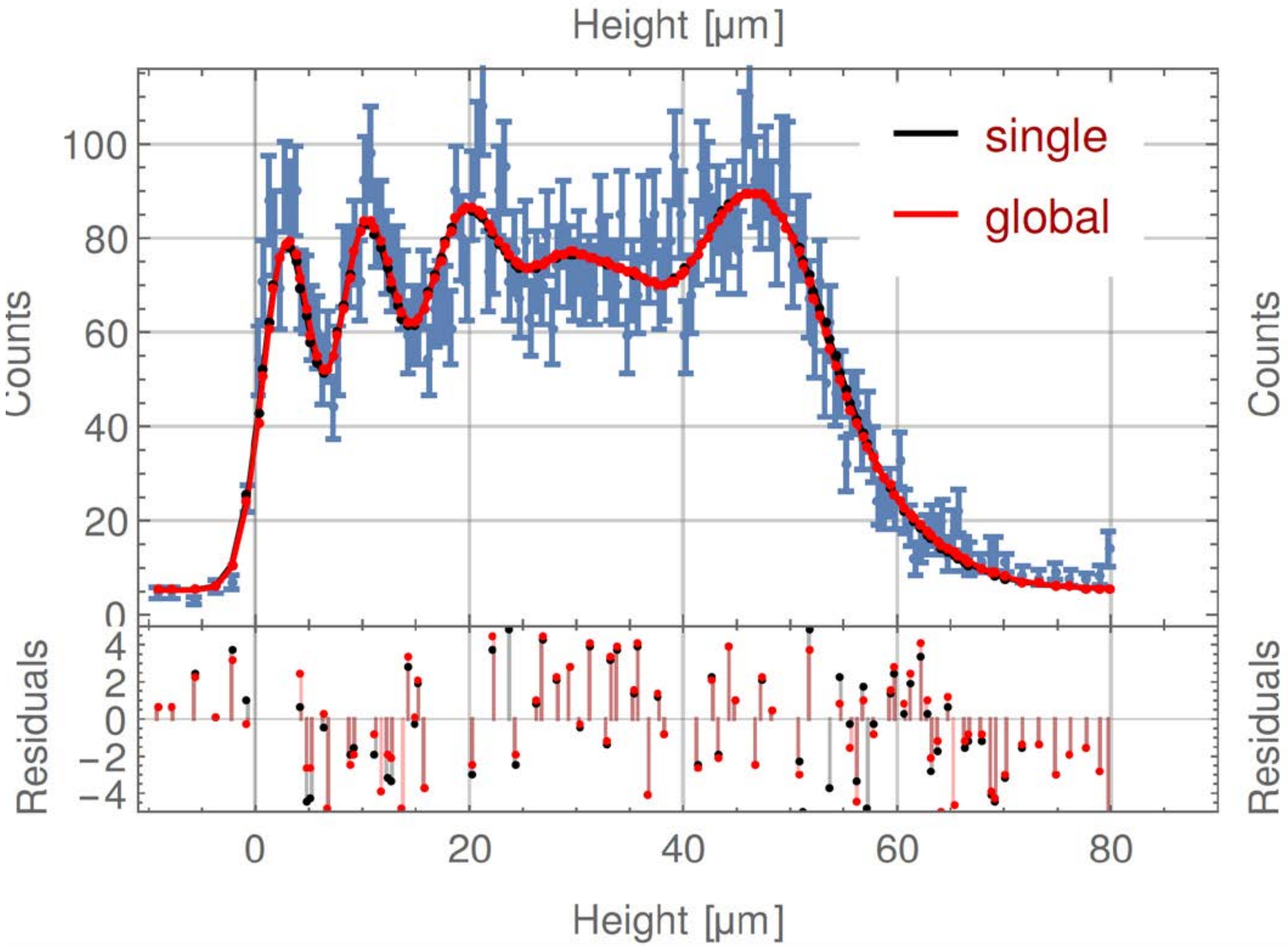
Move downwards, L = 51 mm



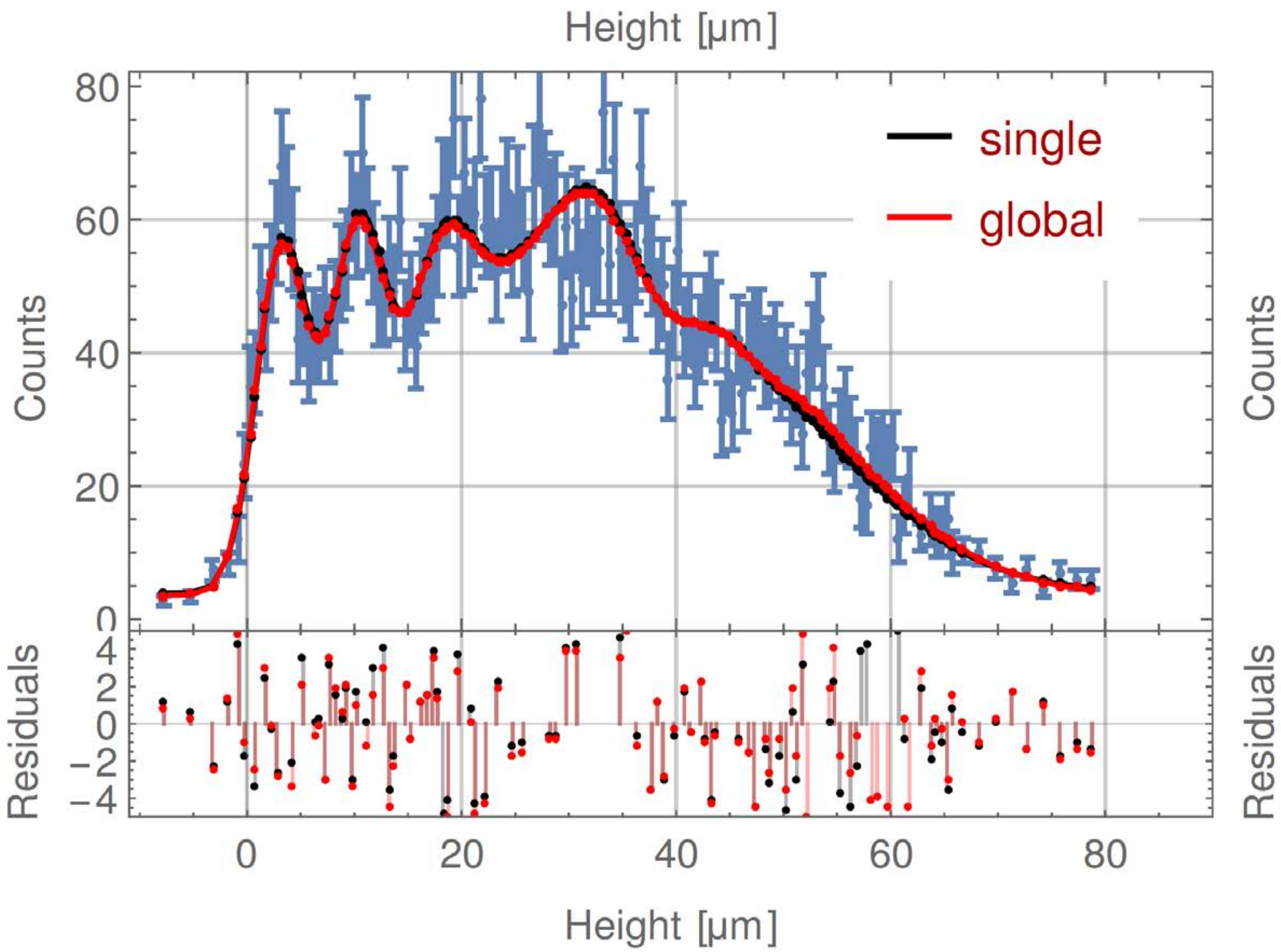
L = 54 mm

54 mm



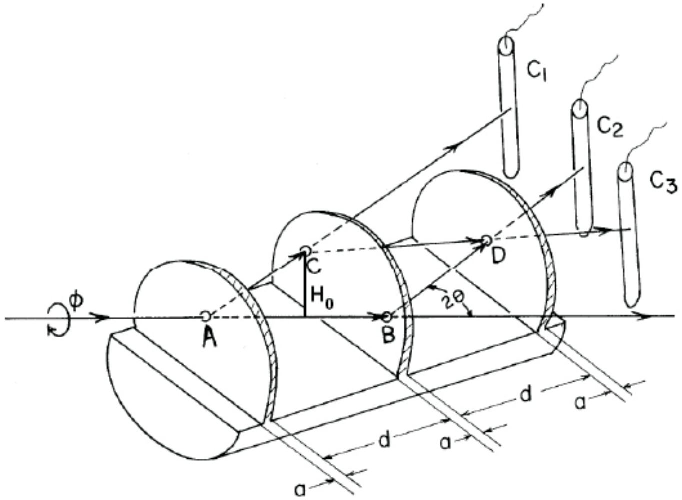

Height [μm]
single
global
100
80
60
40
20
0
Counts
Counts
4
2
0
−2
−4
Residuals
Residuals
0
20
40
60
80
Height [μm]

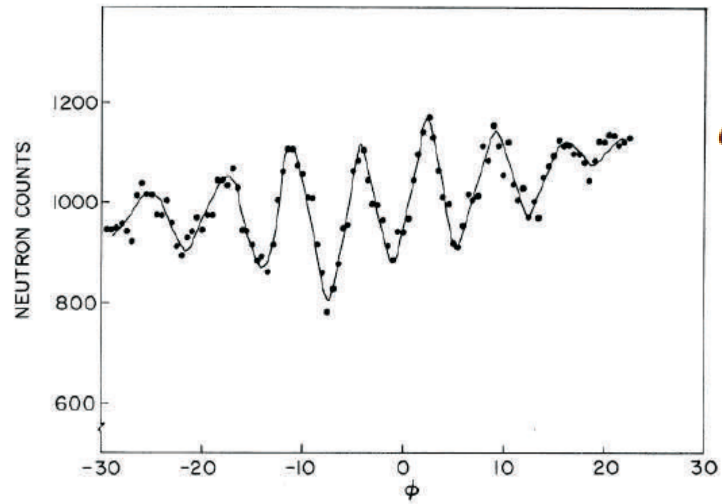
L = 61 mm



Height [μm]
80
60
40
20
0
Counts
single
global
4
2
0
−2
−4
Residuals
0
20
40
60
80
Height [μm]

Collela Overhauser Werner





$$q_{\mathrm{COW}} = 2\pi\lambda \frac{m_n^2}{h^2} g A_0$$

$$\begin{aligned} q_{\mathrm{grav}} &= \left(q_{\mathrm{exp}}^2 - q_{\mathrm{Sagnac}}^2\right)^{1/2} - q_{\mathrm{bend}} \\ &= (60.12^2 - 1.45^2)^{1/2} - 1.42\ \mathrm{rad} \\ &= 58.72 \pm 0.03\ \mathrm{rad.} \end{aligned}$$

$$E_0 = \frac{\hbar^2 k_0^2}{2m_n} = \frac{\hbar^2 k^2}{2m_n} + m_n g H(\phi),$$

$$\begin{aligned} \Delta\Phi_{\mathrm{COW}} &= \Phi_{\mathrm{ACD}} - \Phi_{\mathrm{ABD}} \\ &= \Delta k S \\ &\simeq -q_{\mathrm{COW}} \sin\phi \end{aligned}$$

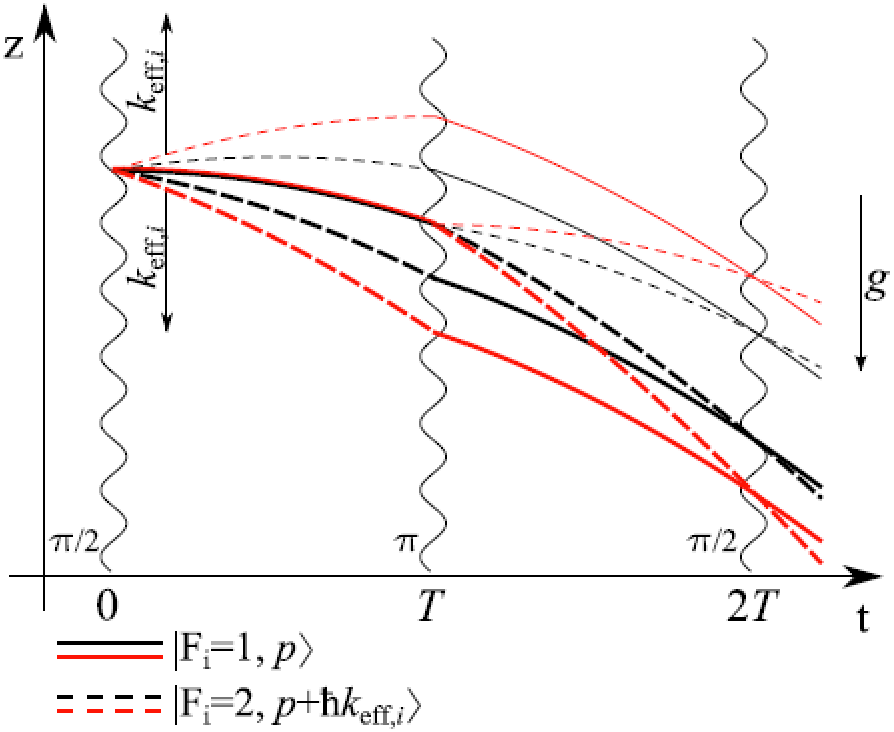
	Interfero-meter	λ (nm)	A_0 (cm^2)	q_{COW} (theory) (rad)	q_{COW} (exp.) (rad)	Agreement with theory (%)
Collela *et al* [1]	Sym. number 1	1.445(2)	10.52(2)	59.8(1)	54.3(2.0)	12
Staudenmann *et al* [25]	Sym. number 2	1.419(2)	10152(4)	56.7(1)	54.2(1)	4.4
		1.060(2)	7,332(4)	30.6(1)	28.4(1)	7.3
Werner *et al* [21]	Sym. number 2	1.417(1)	10.132(4)	56.50(5)	56.03(3)	0.8
(440)	Full range	1.078(6)	12.016(3)	50.97(5)	49.45(5)	3.0
	Rest. range	1.078(6)	12.016(3)	50.97(5)	50.18(5)	1.5
(220)	Full range	2.1440(4)	11.921(3)	100.57(10)	97.58(10)	3.0
	Rest. range	2.1440(4)	11.921(3)	100.57(10)	99.02(10)	1.5
Littrell *et al* [22]	Large sym.					
(440)	Full range	1.8796(10)	30.26(1)	223.80(10)	223.38(30)	0.6

WEP

- WEP: 10^{-13} level tested: Ti Be

$$\eta = 2\frac{|a_1 - a_2|}{|a_1 + a_2|}$$

- WEP: 10^{-7} level tested: ^{87}Rb and ^{39}K

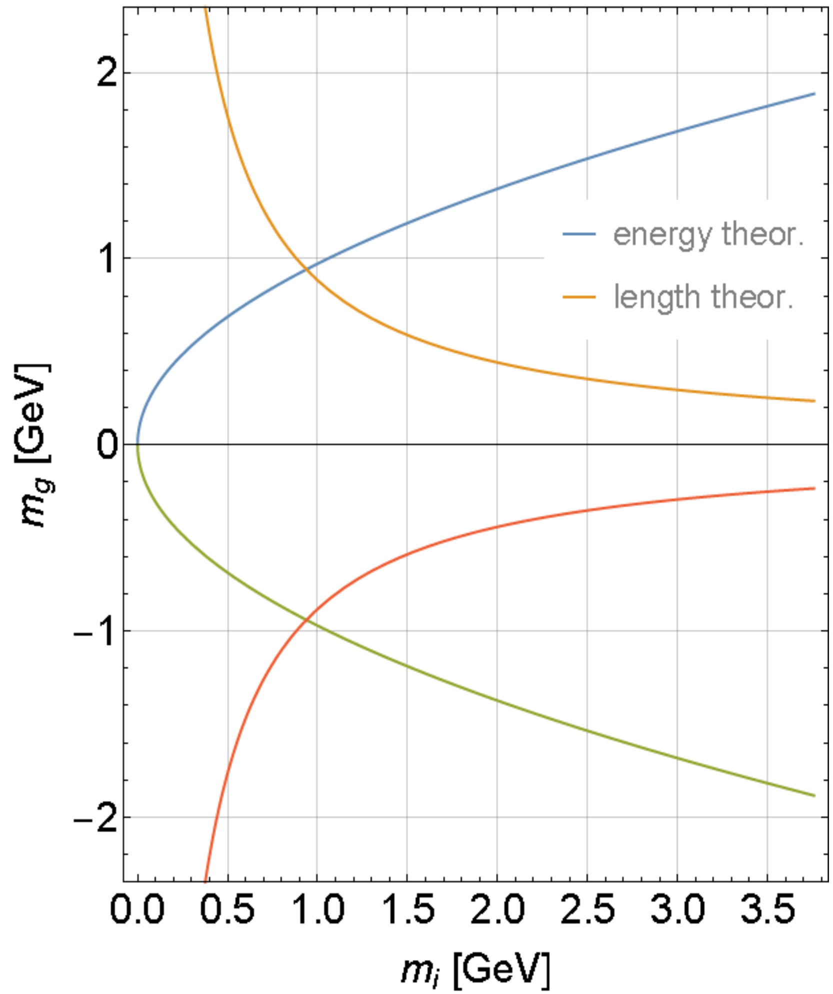


Quantum Aspects of the Bouncing Ball

- **WEP and *q*Bounce**
- Inertial and gravitational mass

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

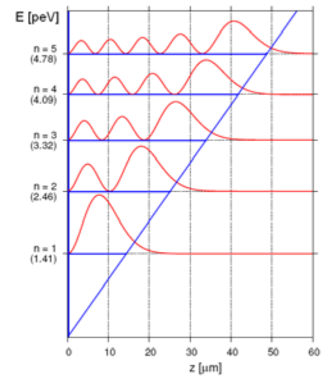
$$E_0 = -\left(\frac{\hbar^2 m_g{}^2 g^2}{2m_i}\right)^{1/3} = 0.602\,\mathrm{peV}$$



Gravity Resonance Spectroscopy

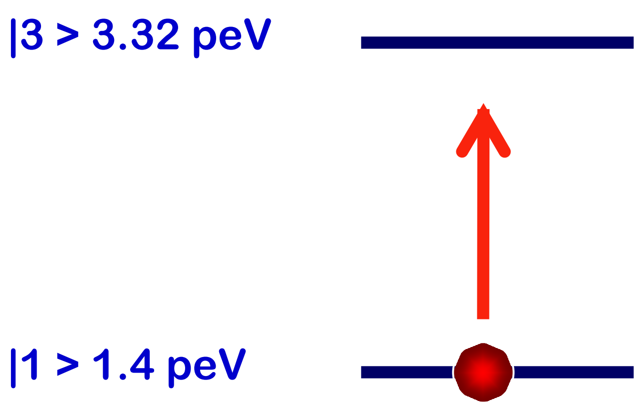
- Quantum System, 2-Level System
- Coupling

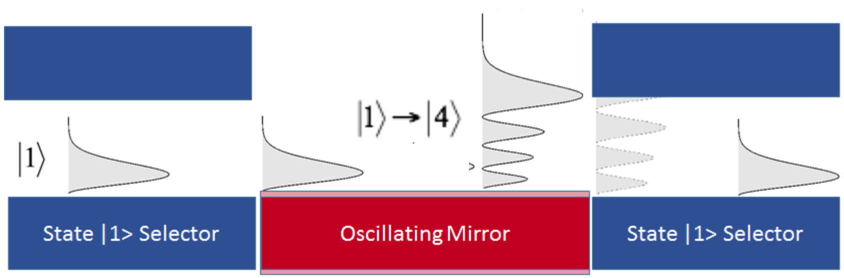
$$E = h\nu$$



- GRS: Neutron
  - gravity field of earth,
  - oscillating Mirror

  drives transitions

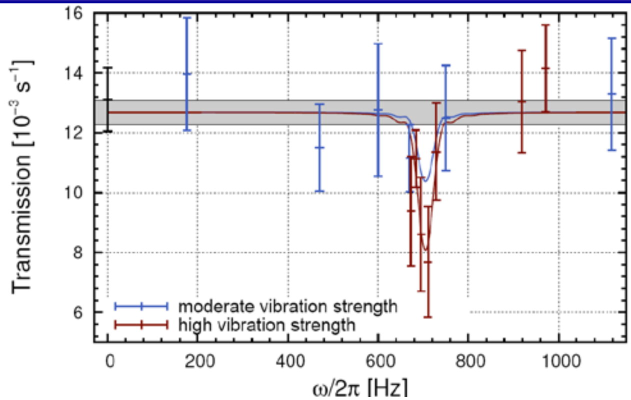


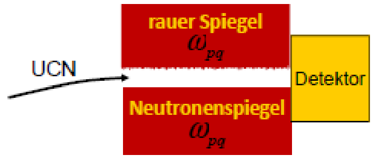


***q*Bounce: Vibrating mirror**

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

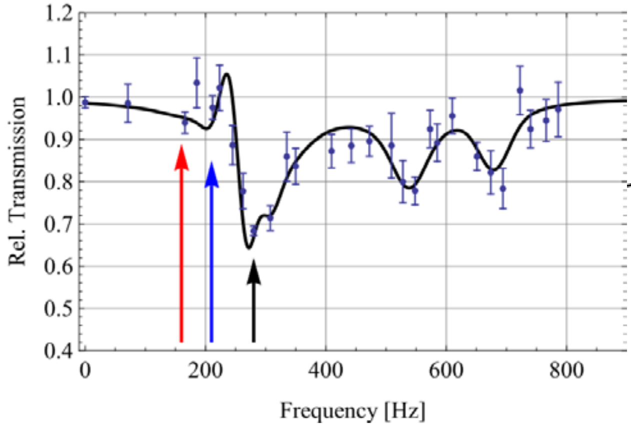
qBounce – Gravity Resonance Spectroscopy

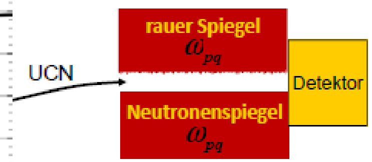




$|1> \leftrightarrow |3>$

- T. Jenke et al. NP 2011





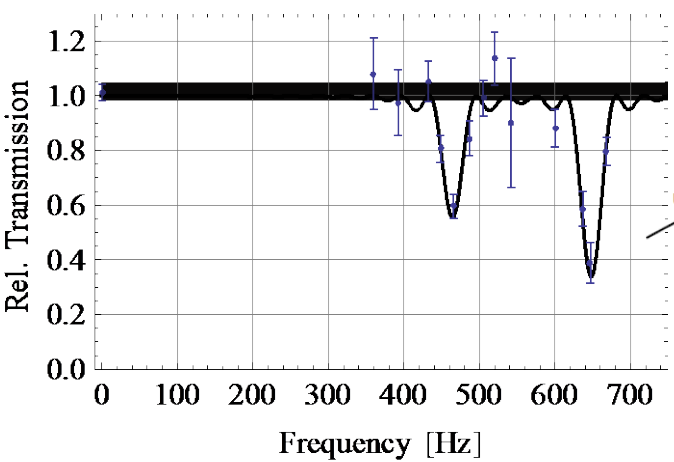
$|1> \leftrightarrow |2>$: 266 Hz

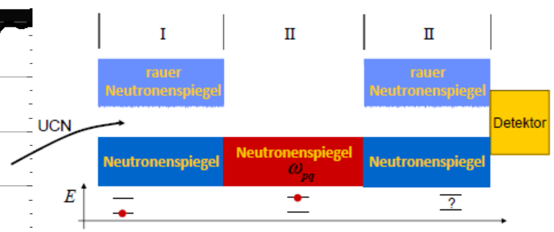
$|1> \leftrightarrow |3>$: 563 Hz

$|2> \leftrightarrow |3>$: 296 Hz

$|2> \leftrightarrow |4>$: 701 Hz

- T. Jenke et al. PRL 2014





$|1> \leftrightarrow |3>$: 462 Hz

$|1> \leftrightarrow |4>$: 647 Hz

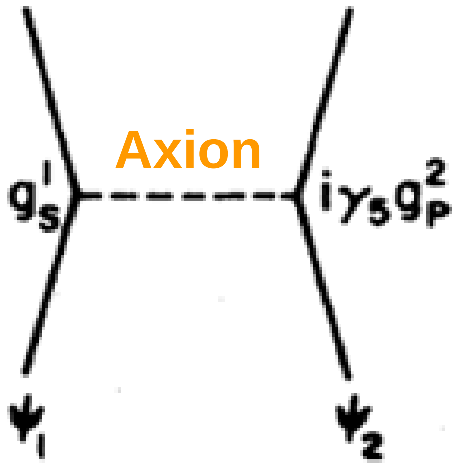
- C. Cronenberg et al.

Access: test of gravitation with quantum objects

- ***q*Bounce** gives access to all gravity-parameters[1]:
  - mass, distance, energy momentum, …
- ***q*Bounce** allows constraints on any possible new interaction at the level of sensitivity
- Observe or restrict dark matter / dark energy

[1]A. Ivanov, M. Pitschmann, PRD 2014

- Examples for Hypothetical gravity-like forces
  - Axions-exchange?
  - Chameleons?



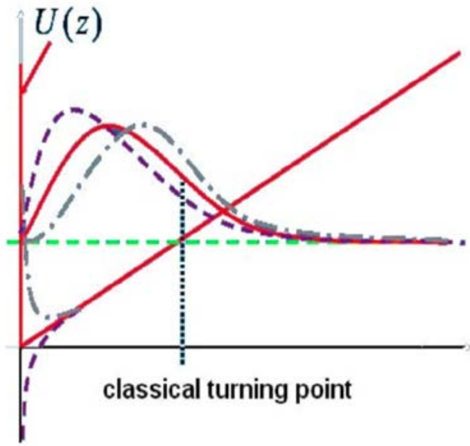
- limits on axion and chameleon fields:

T. Jenke et al., PRL 2014

Neutrons test Newton

$$\boxed{V(r) = G\frac{m_1 \cdot m_2}{r}\left(1 + \alpha \cdot e^{-r/\lambda}\right)}$$

- **Strength α**
- **Range λ**



Hypothetical Gravity Like Forces

Extra Dimensions:
The string and D_p-brane theories predict the existence of extra space-time dimensions
Infinite-Volume Extra Dimensions: Randall and Sundrum
Exchange Forces from new Bosons: a deviation from the ISL can be induced by the exchange of new (pseudo)scalar and vector bosons

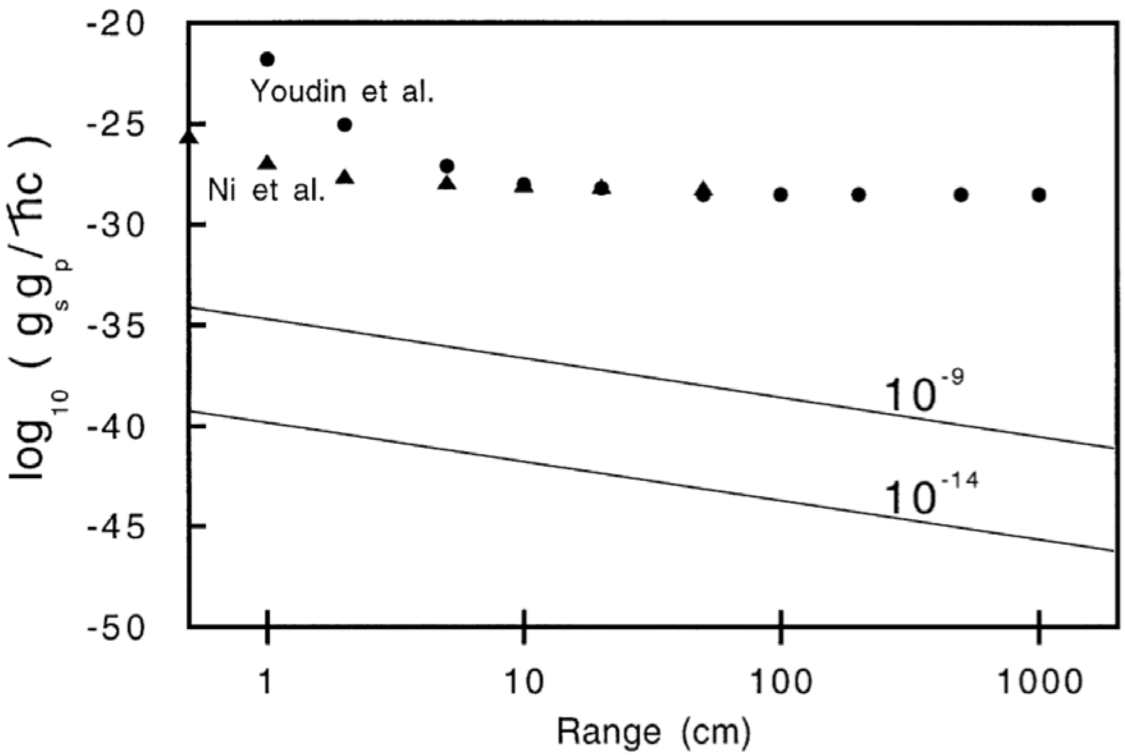
- **Axion - → 0.2 μm < λ < 0.2 cm**
- **Scalar boson. Cosmological consideration**
- **Bosons from Hidden Supersymmetric Sectors**
- **Gauge fields in the bulk (ADD, PRD 1999) - - - - →$10^6 < \alpha < 10^9$**

Supersymmetric large Extra Dimensions (B.& C.) - - - - → $\alpha < 10^6$

Distinguishing axions from generic light scalars

- using EDM and fifth-force experiements
- Relation between

$$g_s^q g_p^q = \frac{m^2\,\bar{\theta}_{ind}}{f_a^2} \propto \frac{\bar{\theta}_{ind}}{\lambda^2}$$



Mantry, Pitschmann, Ramsey-Musolf
PRD 90, 054016 (2014)

Scalar without PQ Symmetry

General Scalar

NOT related to a *PQ symmetry* $\Longrightarrow$
couplings g_s, g_p and mass m are *a priori* **free parameters**

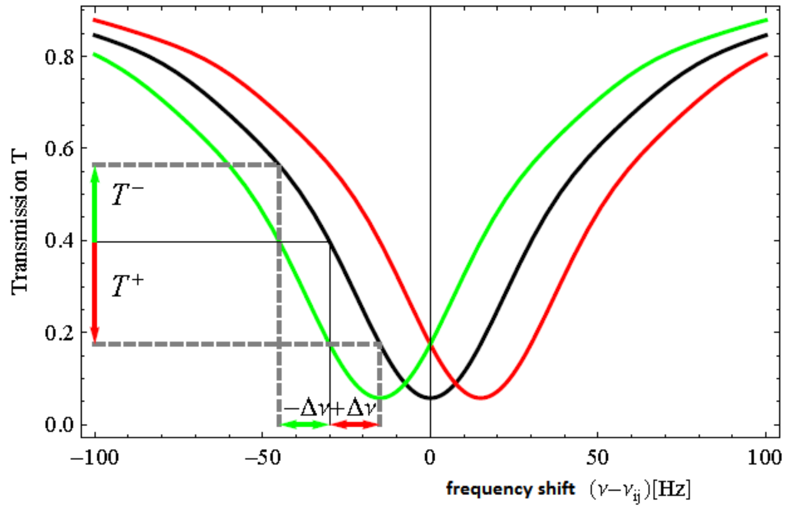
NO relation to QCD θ-term

EDM is induced by exchange of one scalar with coupling g_s and g_p – *CPV interaction*

Mantry, Pitschmann, Ramsey-Musolf
PRD 90, 054016 (2014)

Applications I:
Spin-dependant short-ranged interactions

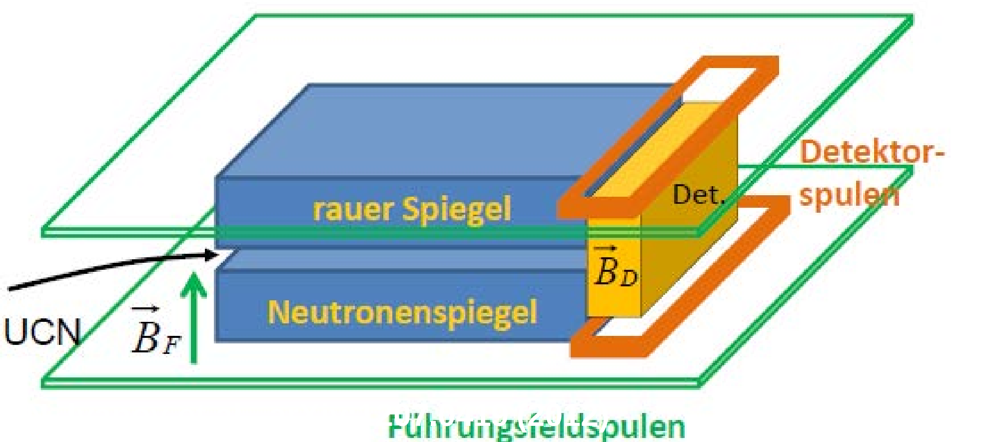
$$V_{\text{axion}} = \frac{g_s g_p \hbar}{8\pi m_n c} \vec{\sigma}\cdot\vec{n} \left(\frac{1}{\lambda r} + \frac{1}{r^2} \right)$$

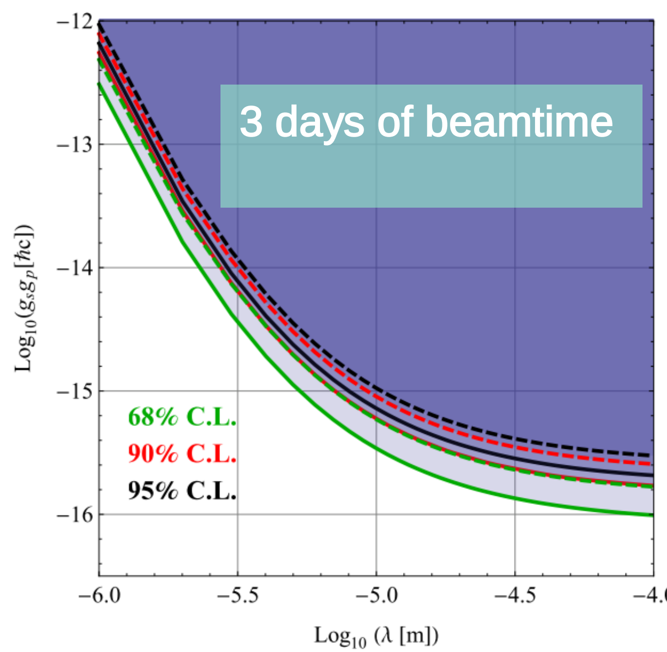


discovery potential [Setup 2010]:

$$g_s g_p / \hbar c \geq \frac{3 \cdot 10^{-16}}{\sqrt{days}}$$

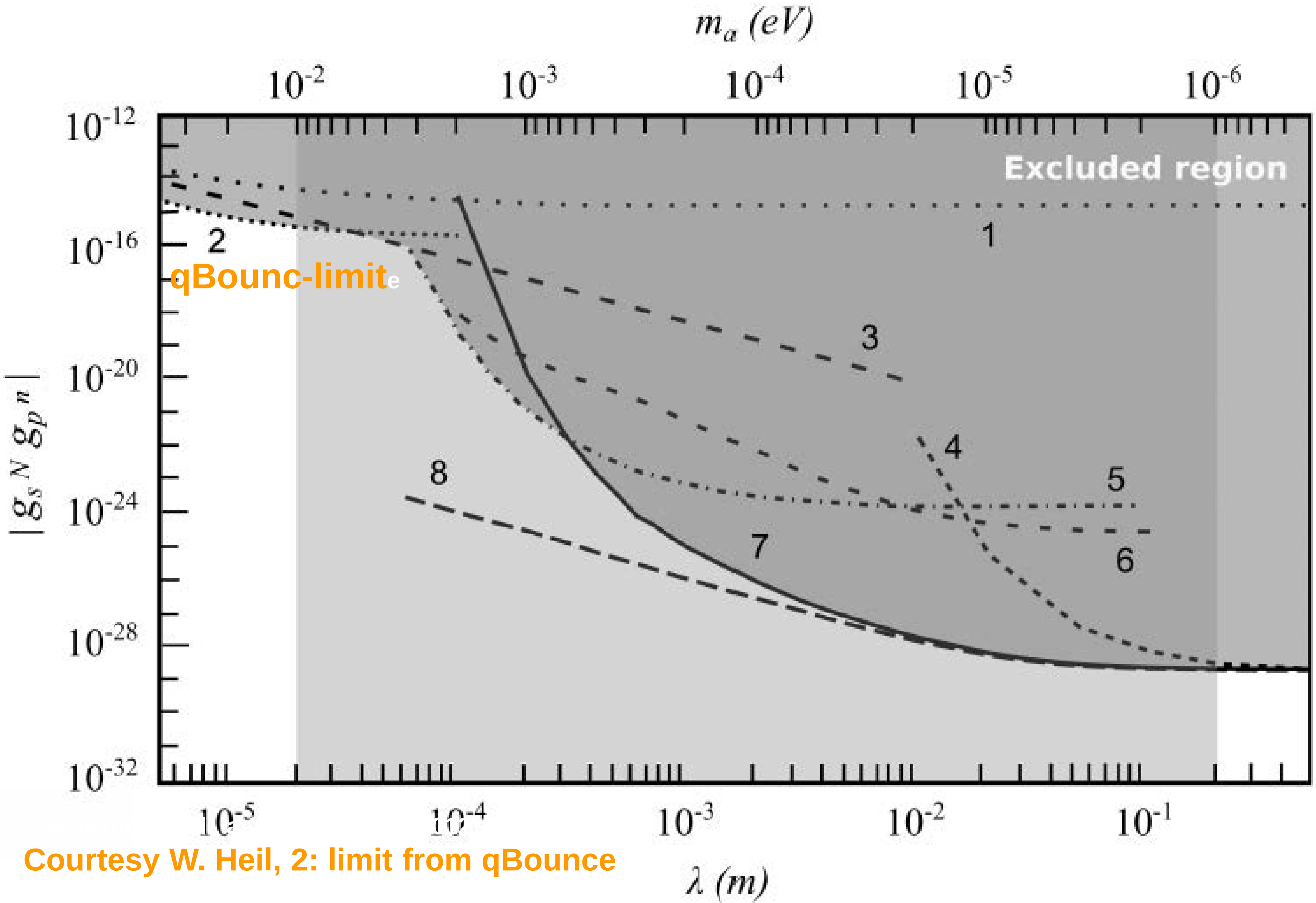
$(\lambda = 10\,\mu\text{m}, 68\%\,\text{C.L.})$





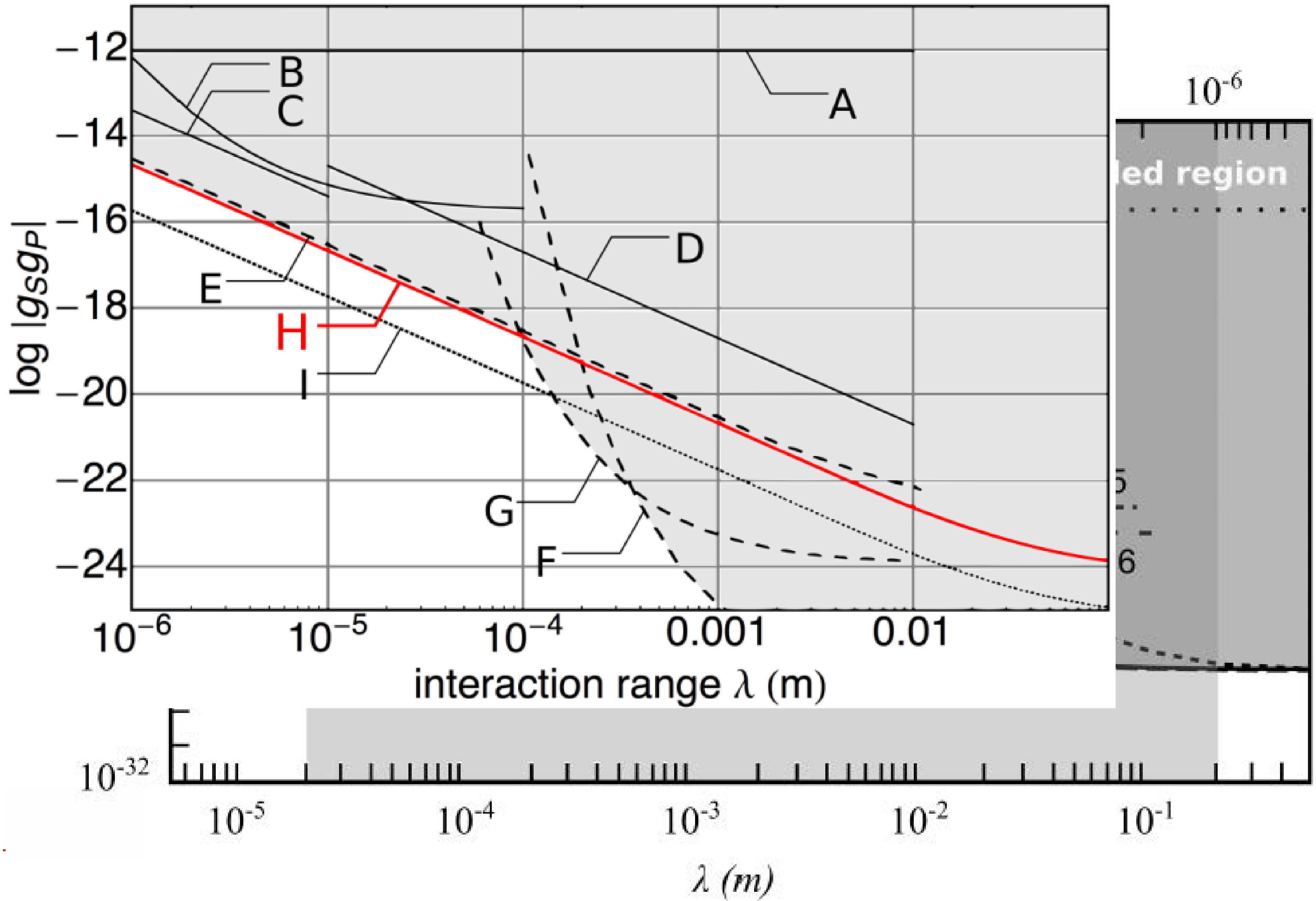
T. Jenke et al. PRL 2014

Axion-like forces



Courtesy W. Heil, 2: limit from qBounce

Axion-like forces

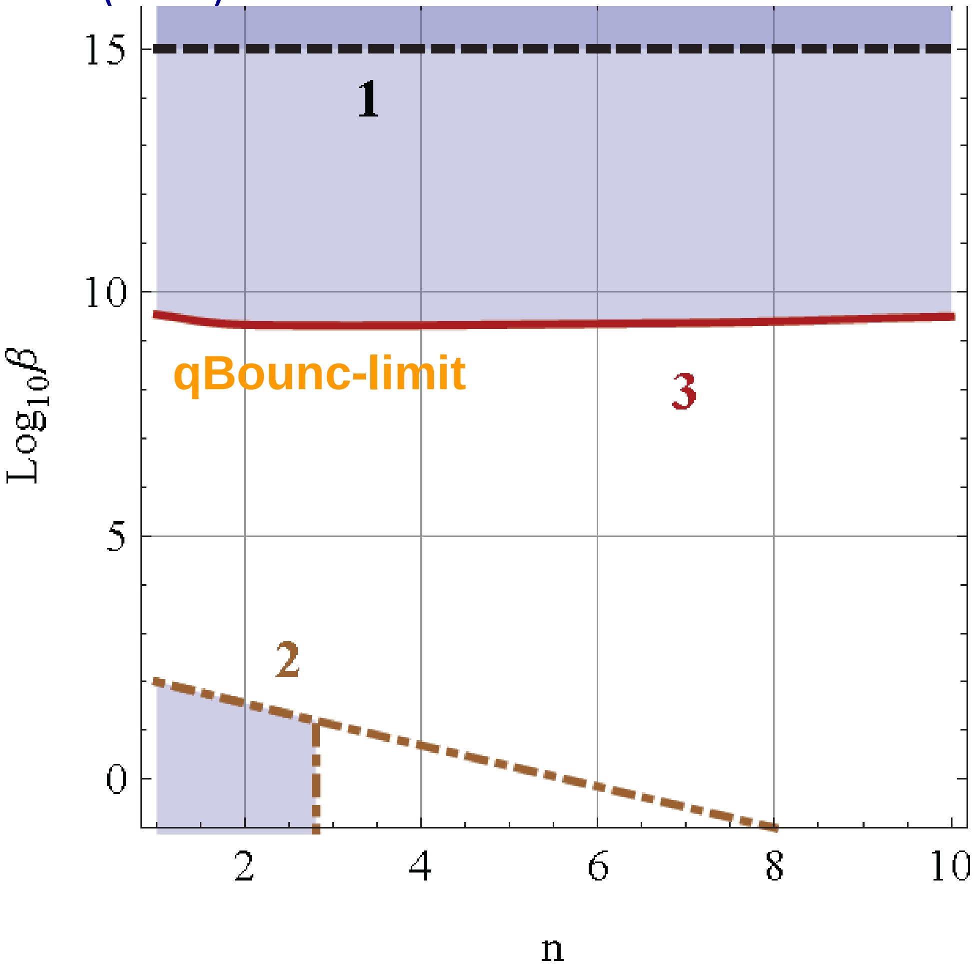


Experiments on the Planck Scale: $\beta^{-1} = M/M_{Pl}$

- Chameleon fields, J.Khoury, A. Weltmann, P.Brax et al.
  Phys. Rev. Lett. 93, 171104, PRD **70,** 123518 (2004)
- 2 Parameters β, n
- Λ self interation

$$V_{\text{eff}}(\phi) = V(\phi) + e^{\beta\phi/M_{\text{Pl}}}\rho.$$


PRL 107, 111301 (2011)



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

PHYSICAL REVIEW D **94**, 085005 (2016)

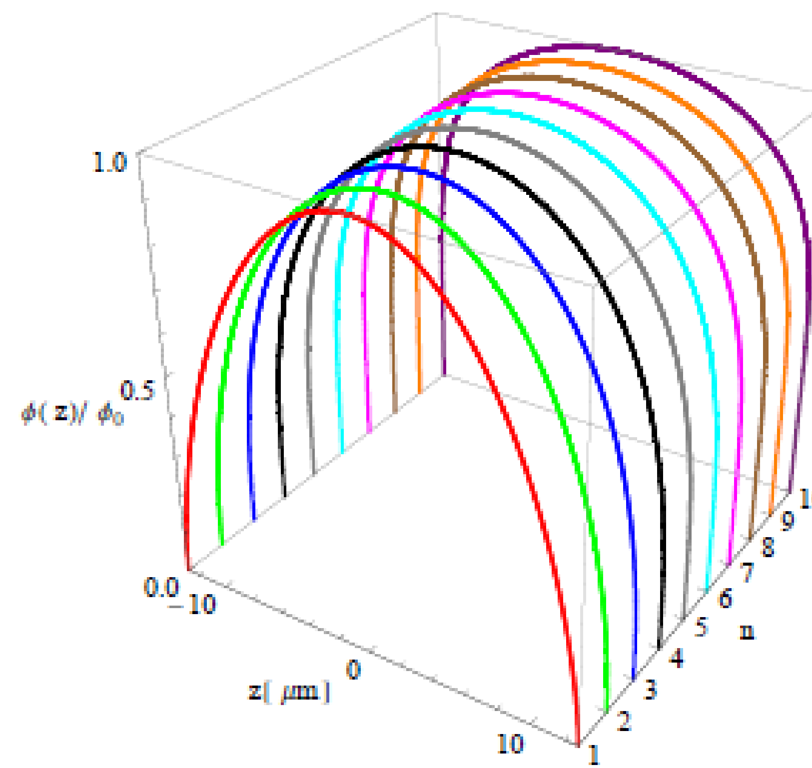
Exact solution for chameleon field, self-coupled through the Ratra-Peebles potential with $n = 1$ and confined between two parallel plates

Bounds on coupling β

- By comparing transition frequency with theoretical expectation:

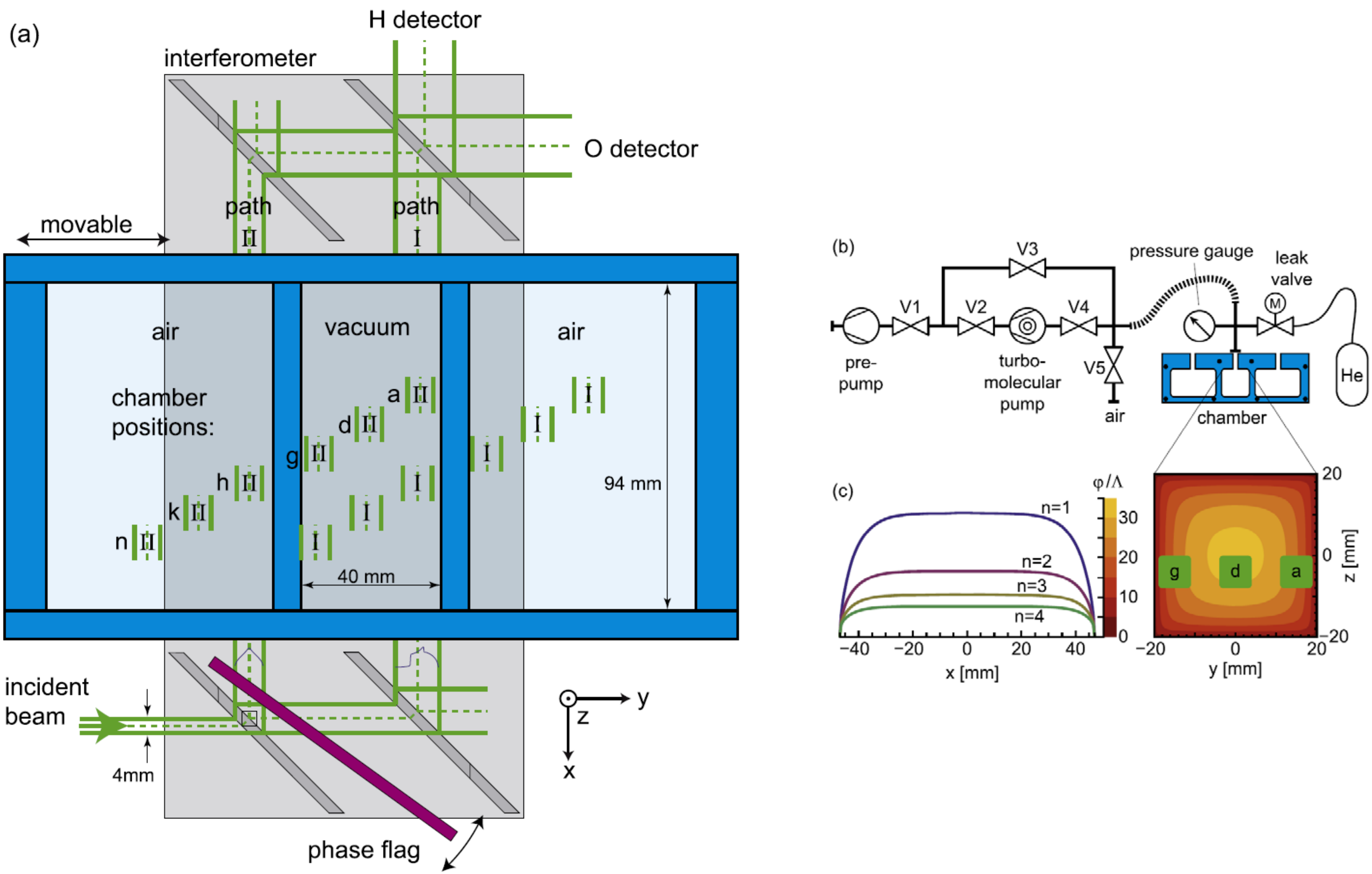
$$\omega_{ab} - \omega_{ab}^{\text{theo}} = \beta \frac{m}{M} \left(\langle a|\phi(z)|a\rangle - \langle b|\phi(z)|b\rangle \right)$$

- as long as $\beta > 10^5$
- Cite as: A. Ivanov et al., PRD, arXiv:1207.0419v1, PRD, 94 08005 (2016), arXiv:16



– FIG. 2: The profiles of a chameleon field, calculated in the strong coupling limit as the solutions of Eq.(81) in the spatial region $z^2 < \frac{d^2}{4}$ and $n \in [1, 10]$.

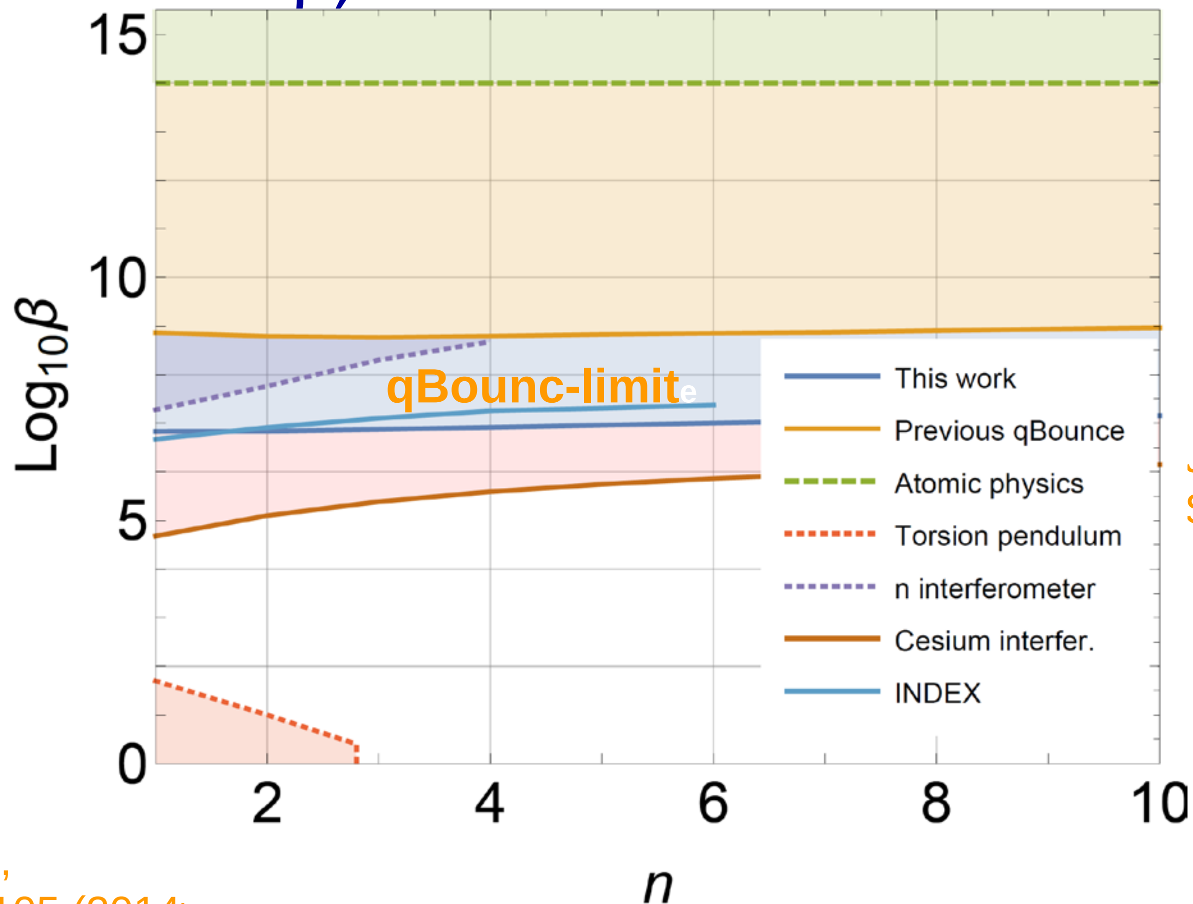
Chameleonfields & Neutron Interferometer



Dark Energy – Scalar Fields: G. Cronenberg

$$V_{\mathrm{eff}}(\phi) = V(\phi) + e^{\beta\phi/M_{\mathrm{Pl}}}\rho.$$

- Chameleon fields, Brax et al. PRD **70,** 123518 (2004)
- 2 Parameters β, n



J. Schmiedmayer, H.A. Science 2015

T. Jenke et al., PRL 112, 151105 (2014)

H. Lemmel et al., Physical Letters B 743, 310 (2015), Li et al., PRD (2016)

Dark Energy – Scalar Fields: G. Cronenberg

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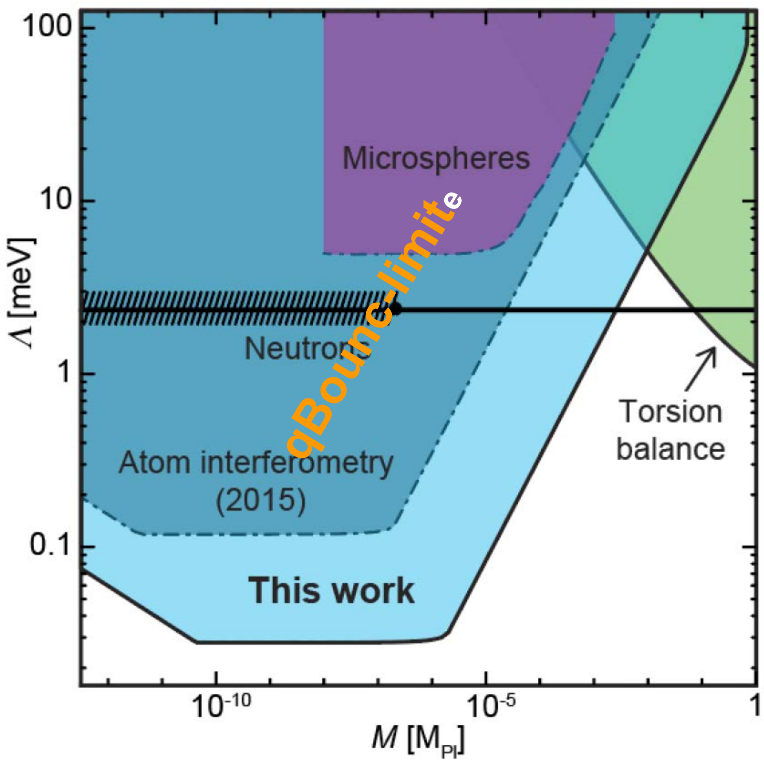
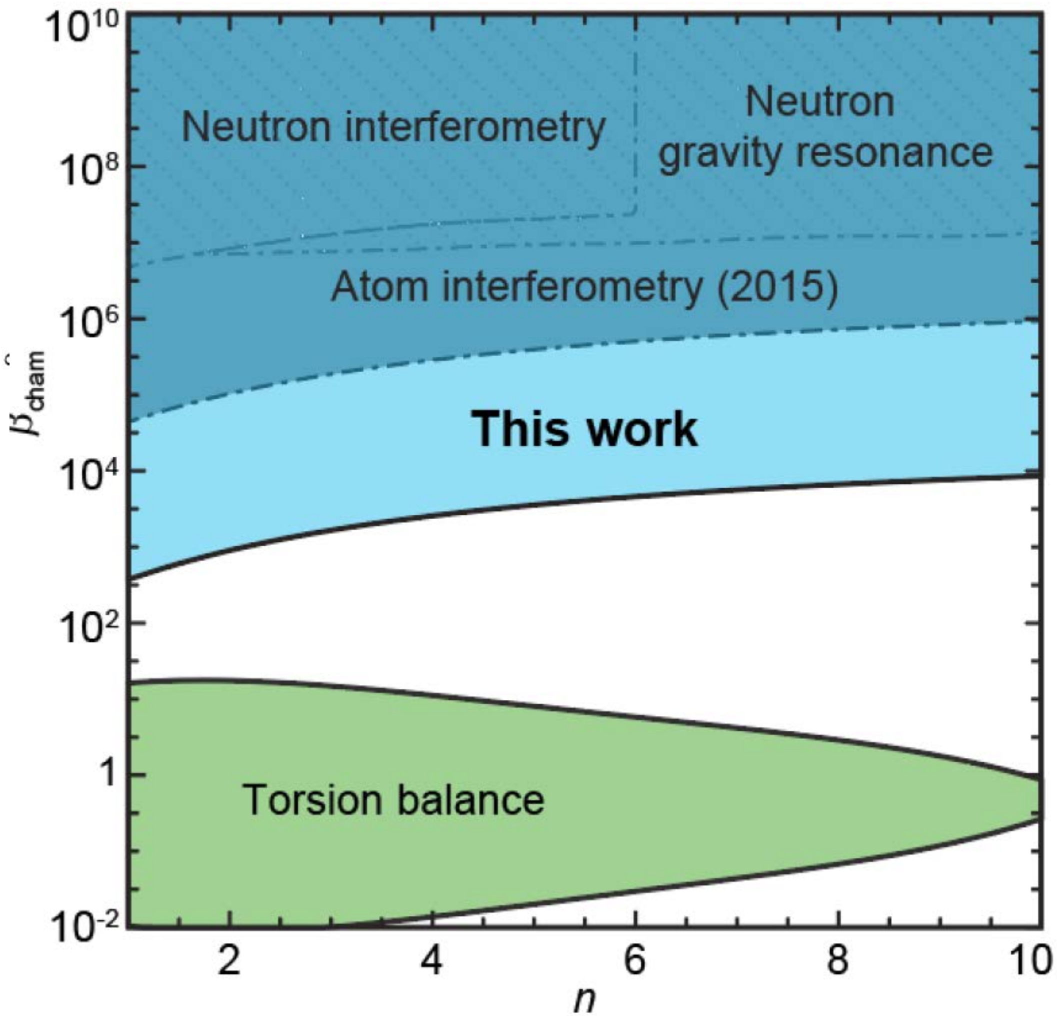
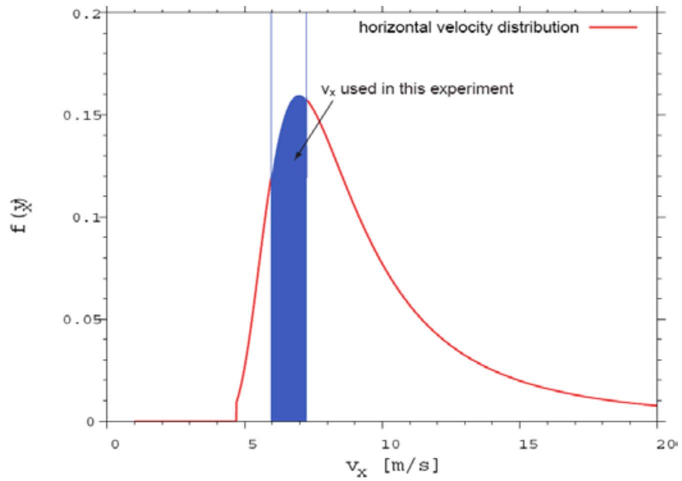


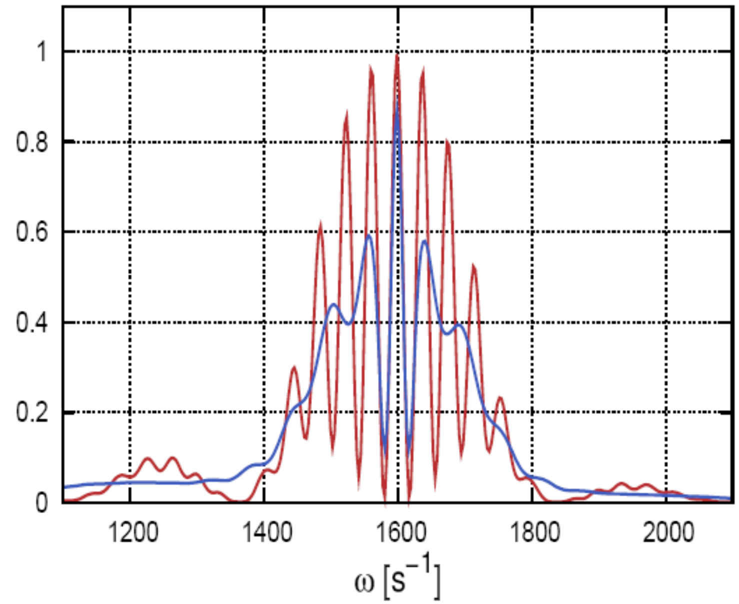


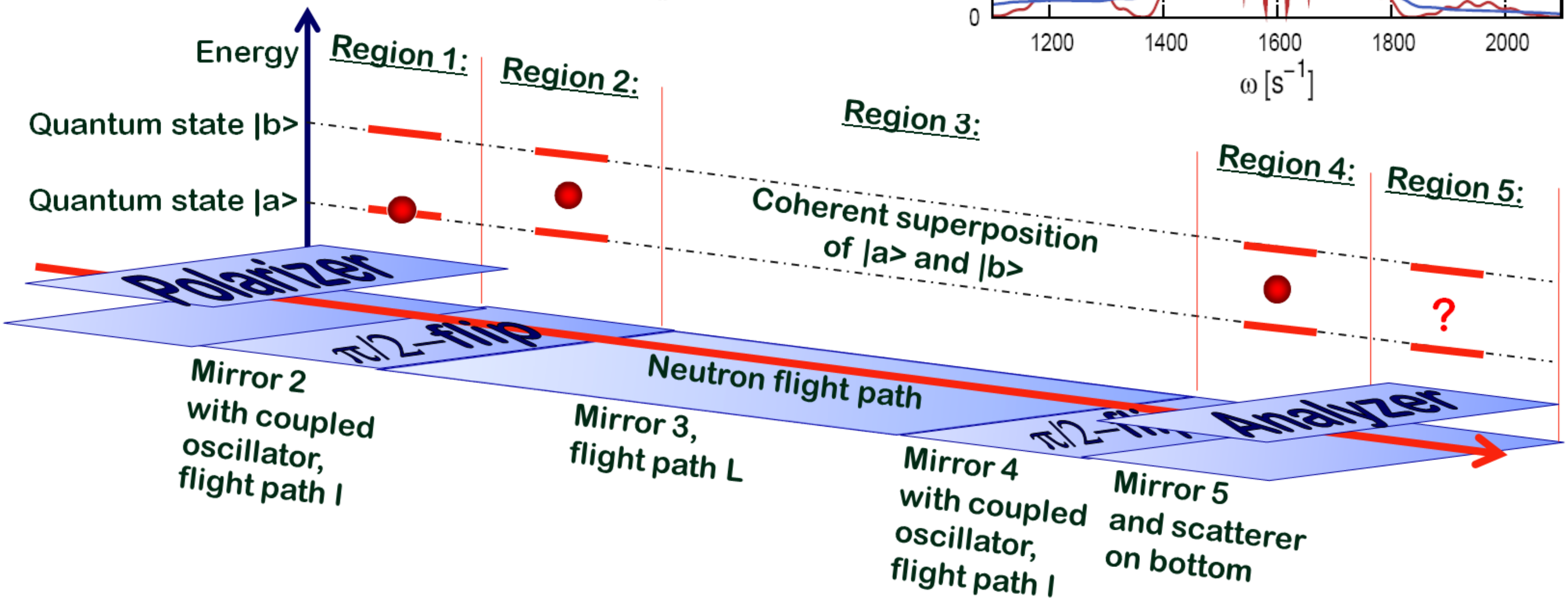
T. Jenke et al.,
PRL 112, 151105 (2014)

H. Lemmel et al., Physical Letters B 743, 31

The Future: Ramsey-Method

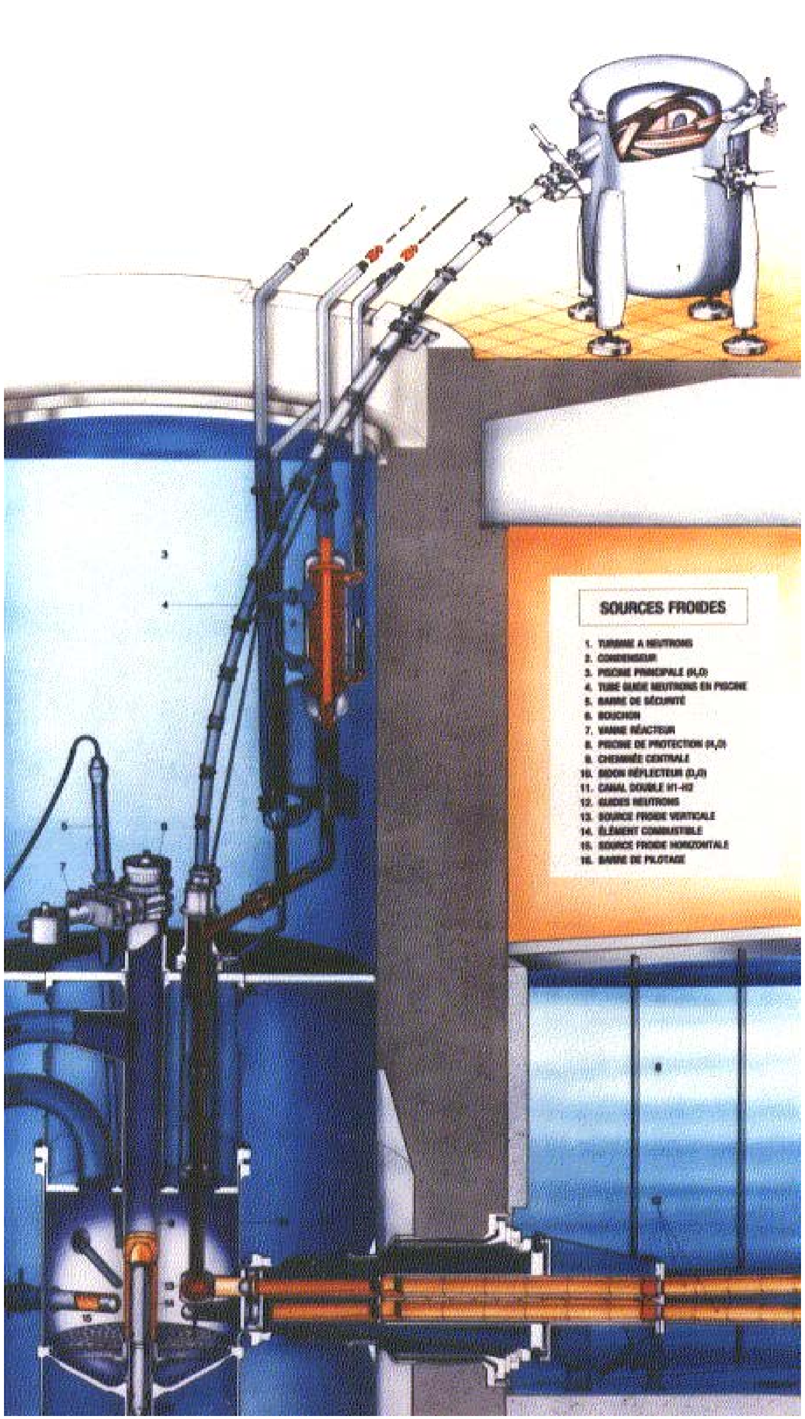


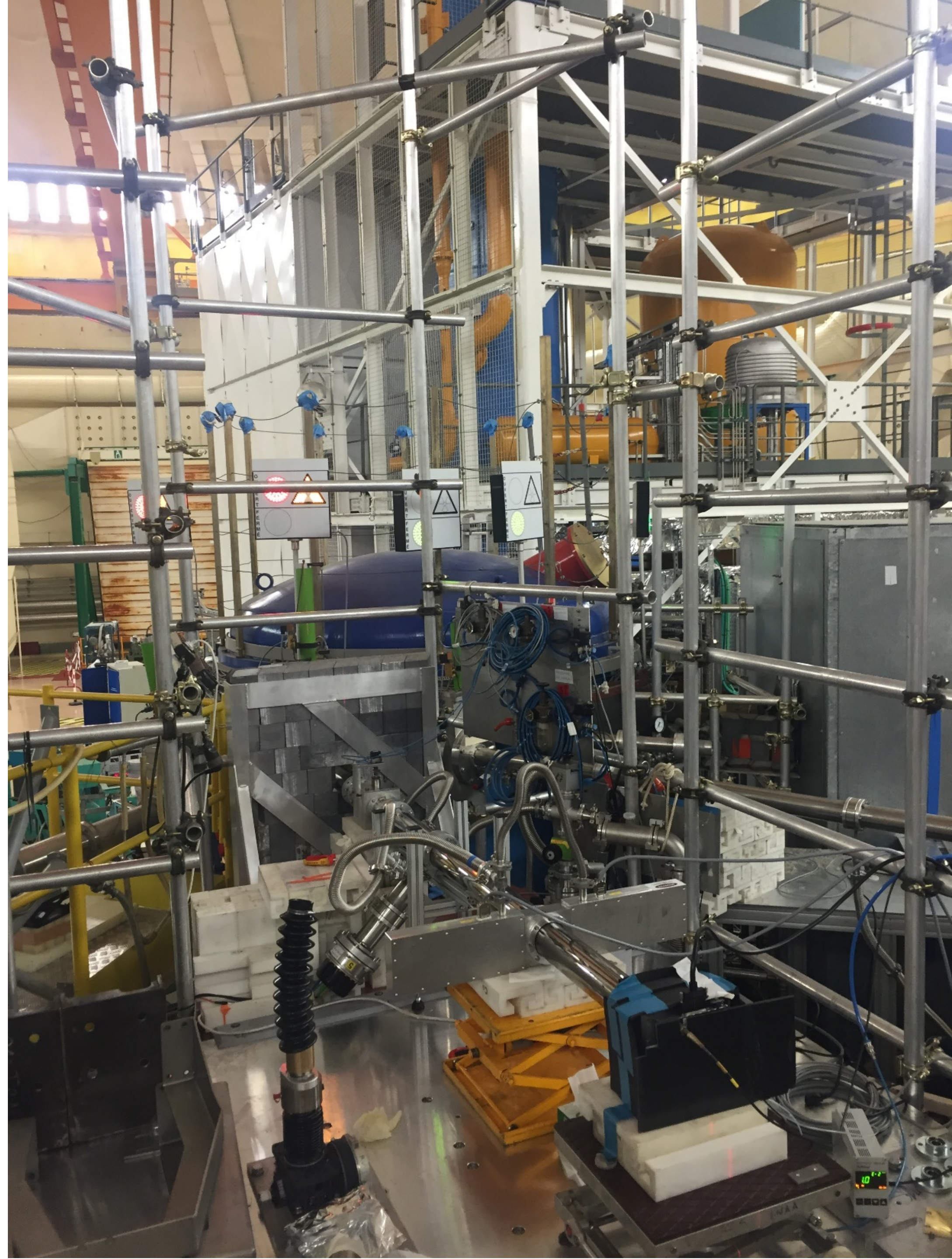


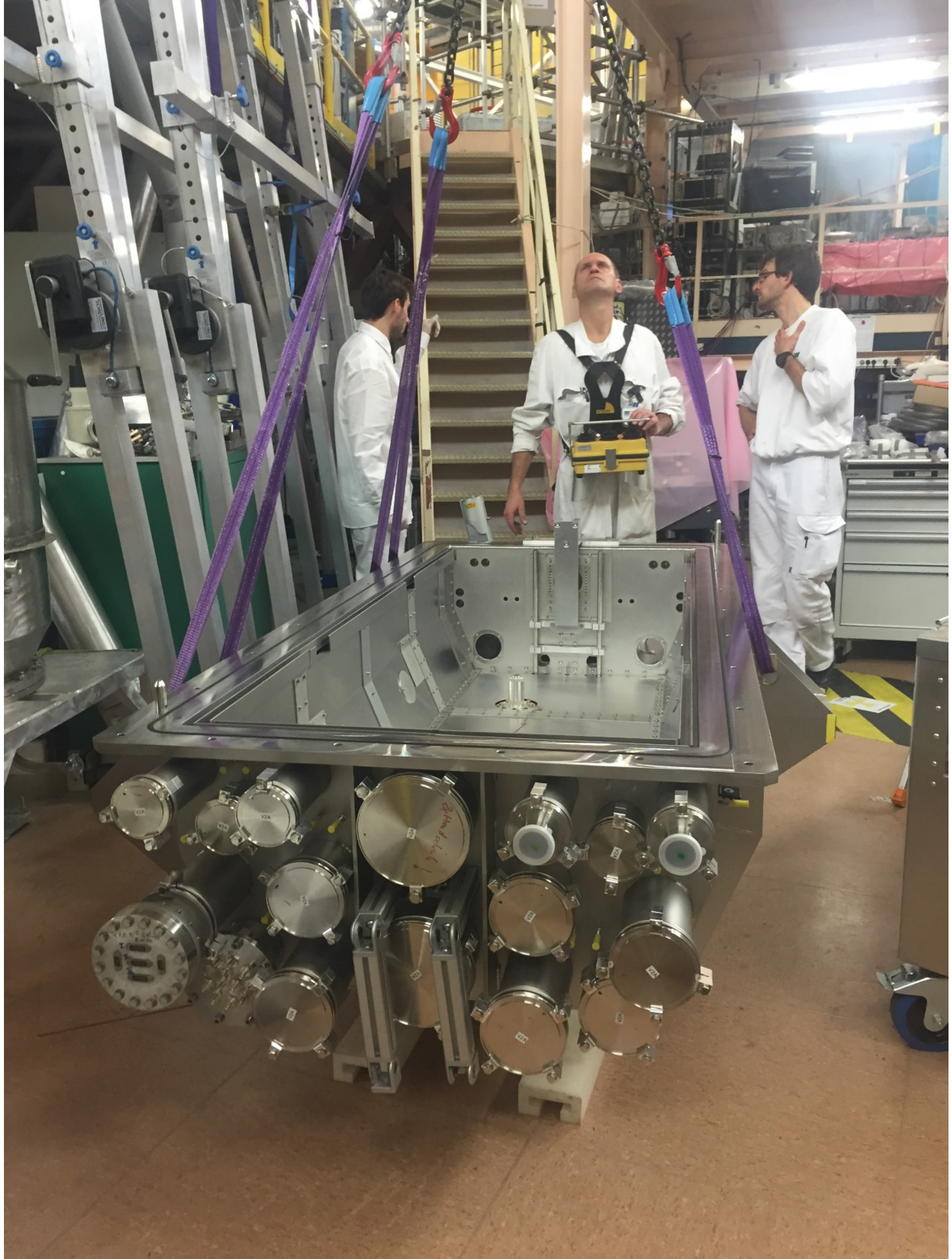


28.01.2017

qBOUNCE-Instrument from 2016


SOURCES FROIDES
1. TURBINE A NEUTRONS
2. CONDENSEUR
3. PISCINE PRINCIPALE (H_2O)
4. TUBE GUIDE NEUTRONS EN PISCINE
5. BARRE DE SÉCURITÉ
6. BOUCHON
7. VANNE RÉACTEUR
8. PISCINE DE PROTECTION (H_2O)
9. CHEMINÉE CENTRALE
10. BIDON RÉFLECTEUR (D_2O)
11. CANAL DOUBLE H1-H2
12. GUIDES NEUTRONS
13. SOURCE FROIDE VERTICALE
14. ÉLÉMENT COMBUSTIBLE
15. SOURCE FROIDE HORIZONTALE
16. BARRE DE PILOTAGE

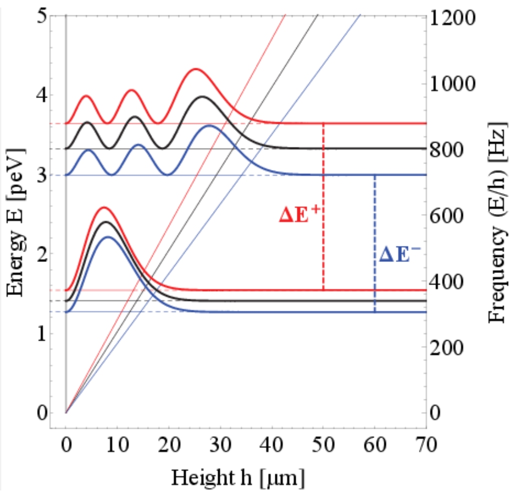


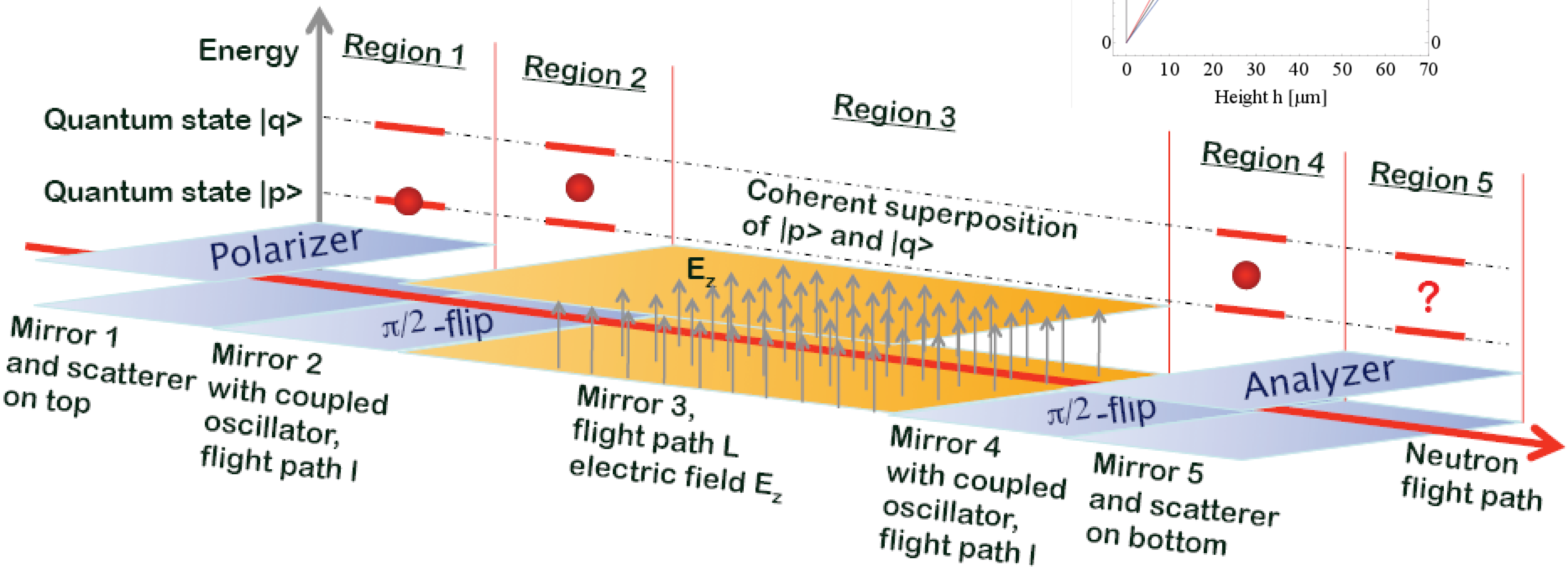



ZONE CONTRÔLÉE
NEUTRONS FOR SCIENCE

Charge quantization and the electric neutrality of the neutron.

- Since the Standard Model value for q_n *requires extreme fine tuning, the* smallness of this value may be considered as a hint for GUTs, where q_n *is equal to zero.*
- **Improve limit by two orders of magnitude**





Area A (electric fields)
Area A/E (magnetic shielding, measuring techniques)

… a need for best sources

Distance between electrodes on mirrors [µm]	Electric field [kV/mm]
24	52
51	39
76	33
100	27

discovery potential:

$$\delta q_n\left(t=1\,day\right)=3\cdot 10^{-20}q_e$$

using less than 10.000 neutrons…

The Neutron Physics Group at Atominstitut

- Gravity tests with quantum objects
  - G. Cronenberg, T. Jenke, J. Bosina, H. Filter, P. Geltenbort (ILL), A. Ivanov, H. Lemmel, M. Thalhammer, T. Rechberger, J. Herzinger, J. Micko, M. Pitschmann, P. Schmidt, U. Schmidt (HD), T. Lauer (TUM), Collaboration HD, TUM, ILL
- Neutron Beta Decay, PERC collaboration
  - J. Erhart, E. Jericha, D. Moser, P. Haydn, G. Konrad, M. Klopp, H. Saul, X. Wang, Collaboration with HD, MZ, TUM, ILL
- Interferometry
  - G. Badurek, H. Rauch, Y. Hasegawa, S. Sponar, T. Denkmayr, M. Zawisky, H. Geppert, B. Demirel,
- Neutron Radiography
  - M. Zawisky,
- N_TOF/USANS: E. Jericha, C. Weiß, H. Rauch, G. Badurek, H. Leeb, Griesmayer

Summary

- Visualization of Airy-Functions
  - Coherent Superposition of Airy-Functions
  - 30µm, 20µm

- Realization of Gravity Resonance Spectroscopy:
  - Coherent Rabi-Transitions,
  - $|1\rangle \rightarrow |2\rangle$
  - $|1\rangle \rightarrow |3\rangle$, see Nature Physics, 1 June 2011
  - $|2\rangle \rightarrow |3\rangle$, $|1\rangle \rightarrow |4\rangle$, $|2\rangle \rightarrow |4\rangle$
- New Tool for
  - A Search for a deviation from Newton's Law at short distances, where polarizability effects are extremely small ,
  - A quantum test of the equivalence principle
- Direct limits on axion coupling / chameleons at short distances,