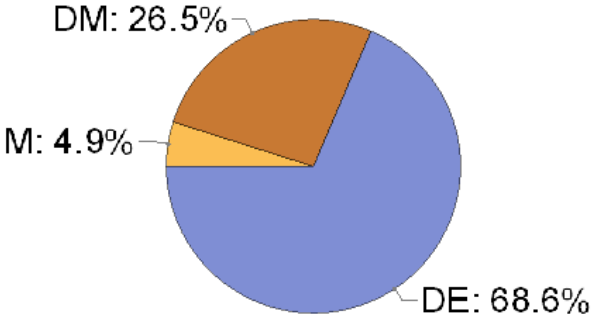
Sixteenth Marcel Grossmann Meeting

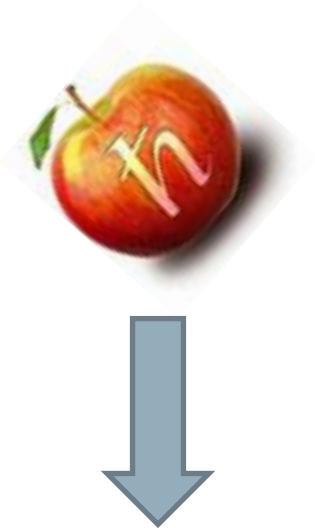
*q*BOUNCE: Ultra-cold neutrons bound by Earth's gravity field, a tabletop search for hypothetical gravity-like interactions

Jakob Micko
Institut Laue-Langevin
Atominstitut TU Wien

The Universe



Planck Data 2018



$F=10^{-36}$

Neutrons in gravitational field

- $\mathrm{i}\hbar\partial_t\psi = -\frac{\hbar^2}{2\mathrm{m_i}}\partial_\mathrm{z}^2\psi + \mathrm{m_g g z}\psi$
- No charge
- Small polarizability
  - Rb in 1µm distance of surface: 0.6 peV
  - n in 1µm distance of surface: 10^{-18} peV
- Mass interacts with Gravity

Modifications to Gravity

- No complete Quantum Theory of Gravity=>Effective Field Theory
- Theories with 3+n space dimensions =>V(r)~$\frac{1}{r^{1+n}}$
- Additional Yukawa like Potential => V(r)~$\frac{\alpha e^{-\frac{r}{\lambda}}}{r}$
- n in gravity field is in μm range

Neutrons

- Thermal neutrons 25 meV
- (ultra) (very) cold neutrons <25 meV
- Fermi (pseudo) potential: coherent scattering on nuclei in matter => Effective potential for neutron wavefunction $E_F \sim 100\ \mathrm{neV}$
- Matter can be used to store ultra-cold neutrons

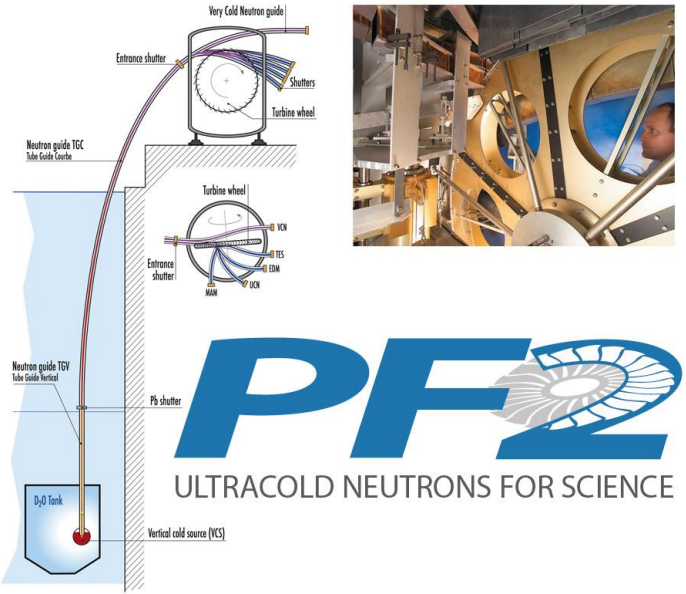
Fermi potentials

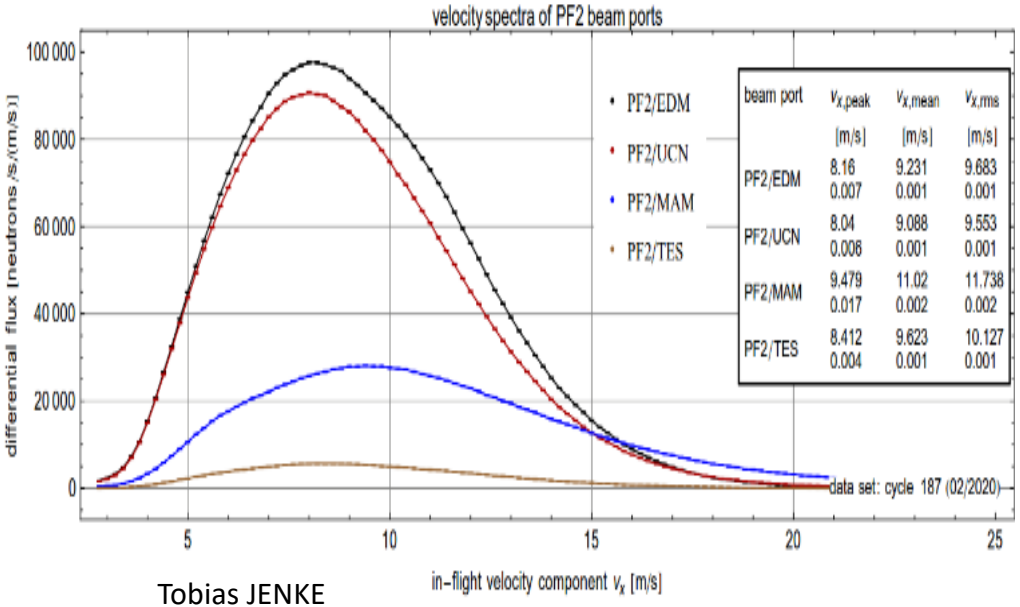
- critical velocity: reflection under all angles of incidence
- $E_F \approx 100$ neV
- $m_N g \approx 100$ neV/m
- $\mu_n \approx 60$ neV/T

Substance	E_F (neV)	v_c [m/s]
^{58}Ni	335	8.00
Ni	252	6.9
Be	252	6.9
C (diamond)	305	7.74
C (graphite)	175	5.8
Cu	165	5.6
Stainless Steel	~188	~6
Al	54.1	3.22
V	-8.34	-
Ti	-49.7	-

Ultracold Neutrons. A. Steyerl. 2020.

PF2 @ ILL





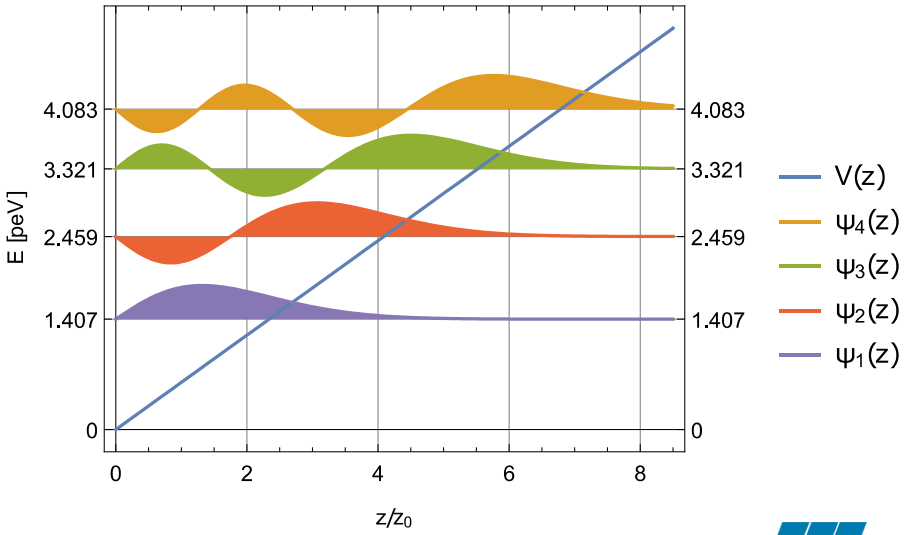
https://www.ill.eu/users/instruments/instruments-list/pf2/description/ultracold-neutron-facility

Tobias JENKE

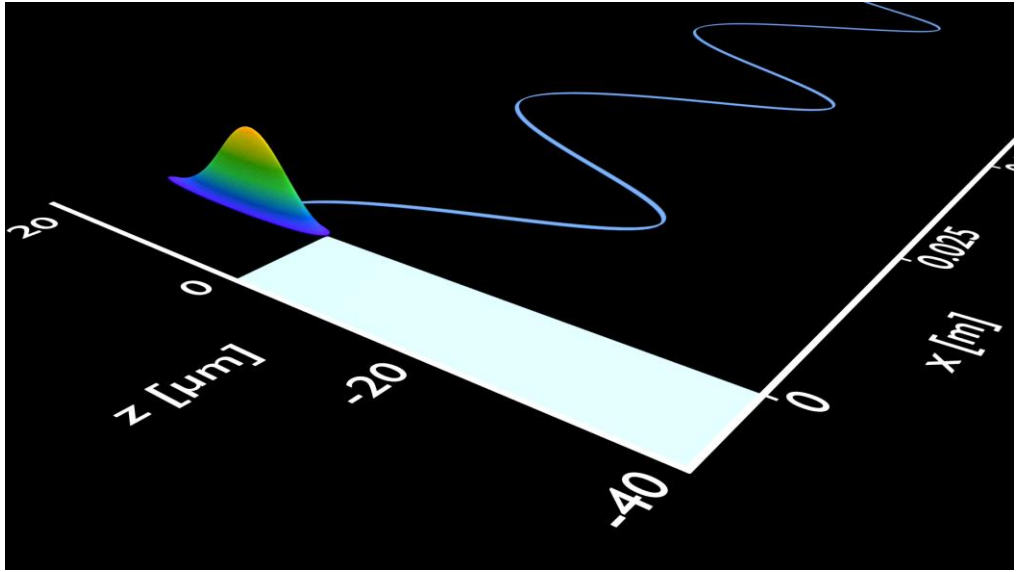
Public Talk of 103rd Scientific Council of the Institut Laue-Langevin 06/11/2020

Neutrons on a mirror

- Airy functions $\mathrm{Ai}\left(\frac{z}{z_0} - \frac{\mathrm{E}}{\mathrm{mgz_0}}\right)$
- $\mathrm{z_0} = \sqrt[3]{\frac{\hbar^2}{2\mathrm{m}^2\mathrm{g}}} \approx 5.87\mu\mathrm{m}$
- $\mathrm{mgz_0} \approx 0.60183 \pm 4 \cdot 10^{-5}\mathrm{peV}$
- $E_n = -mgz_0\ \mathrm{AiZero}(n)$
- $f \lesssim 1\ \mathrm{kHz} \sim 4\ \mathrm{peV}$



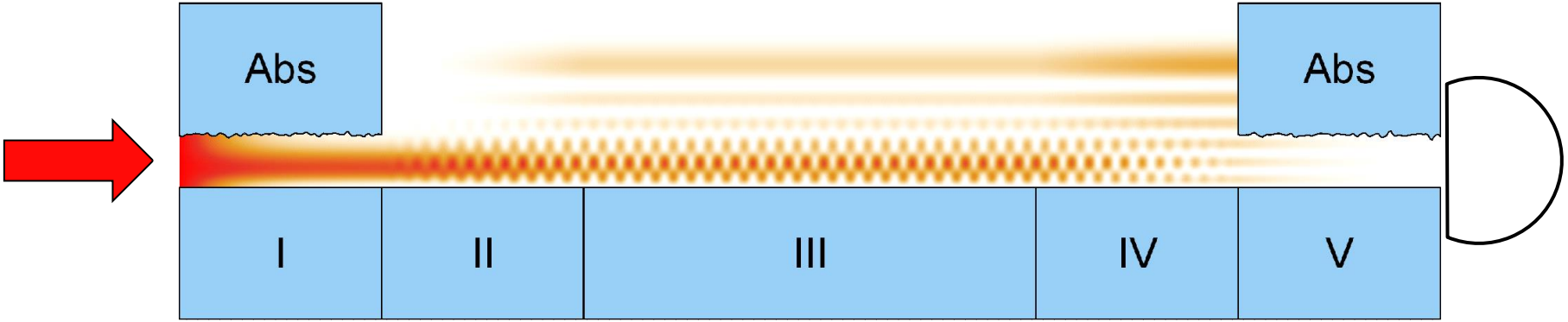
Time evolution of states

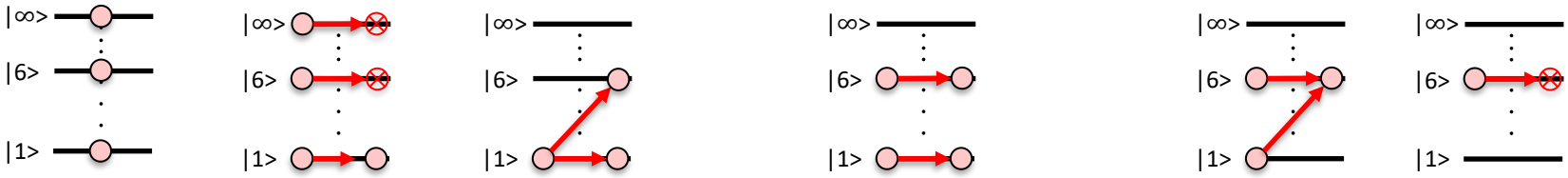


M. Thalhammer

Ramsey's Method with qBounce

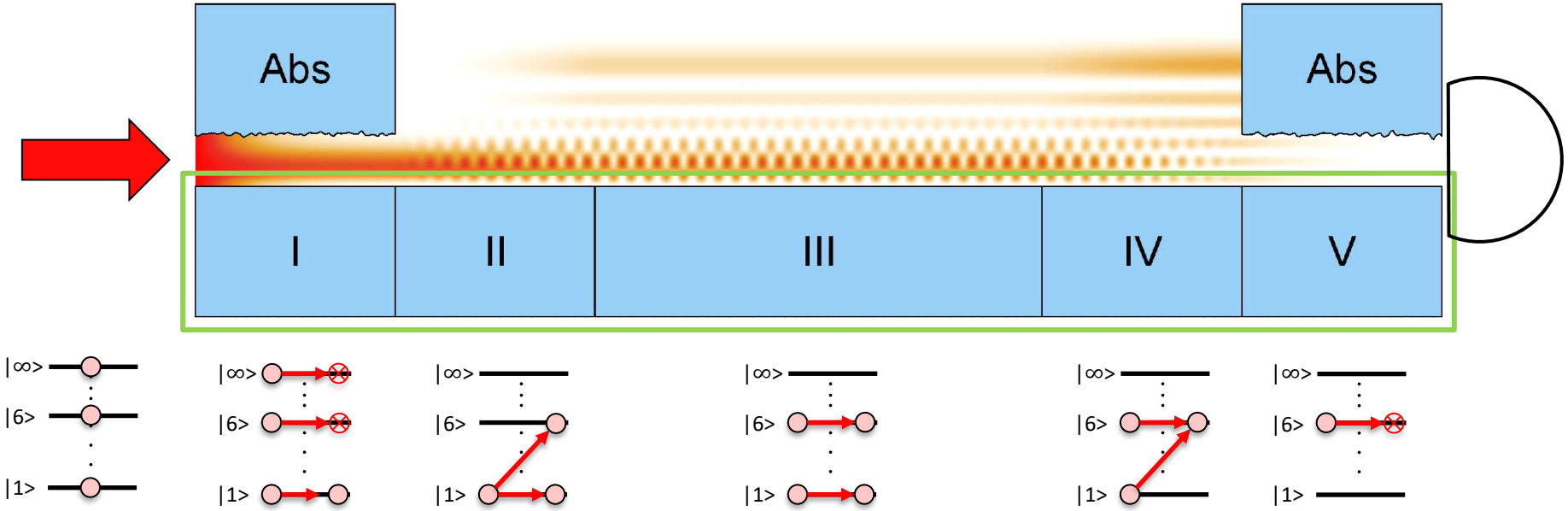
- UCNs enter from the left
- Neutron detector to the right
- Total length: 0.95 m





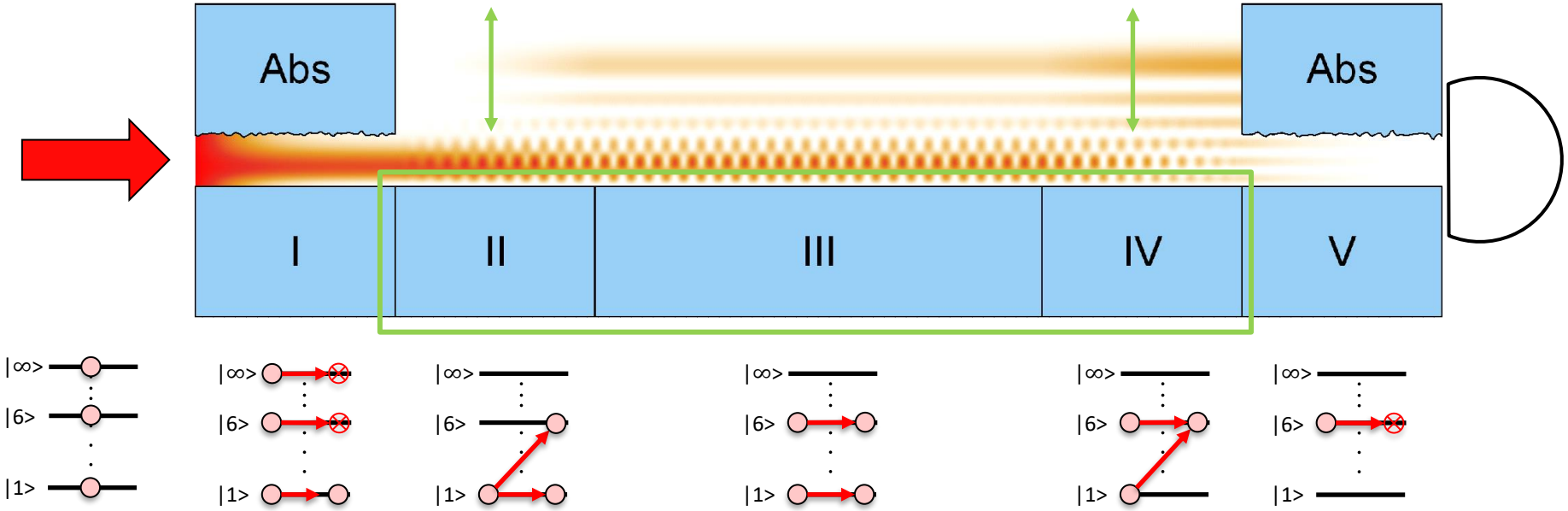
Ramsey's Method with qBounce

- Neutron mirrors, five different sections
- Bound states in gravitational potential
- Oszillations drive transitions



Ramsey's Method with qBounce

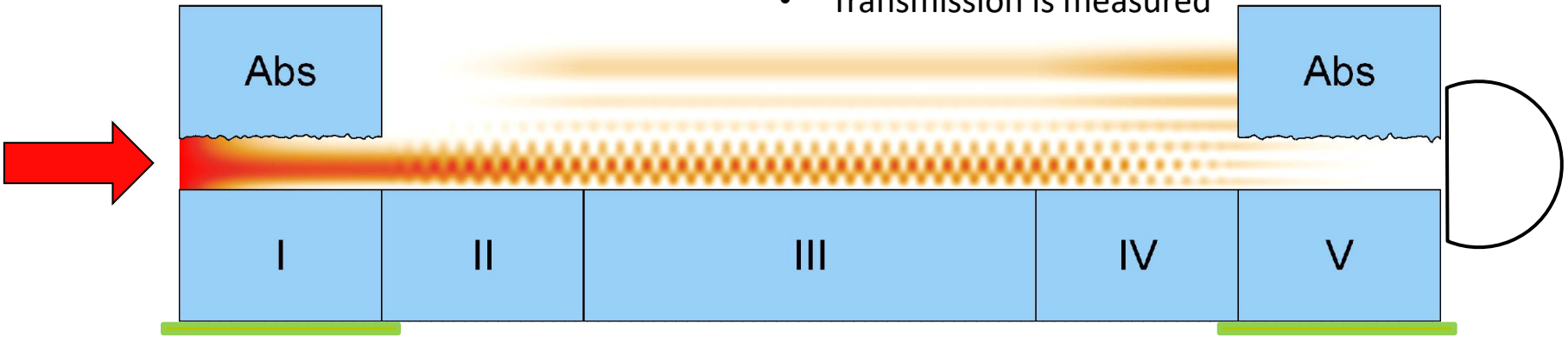
- II & IV induce transitions
- Free propagation in III
- Oscillation frequency determines final state

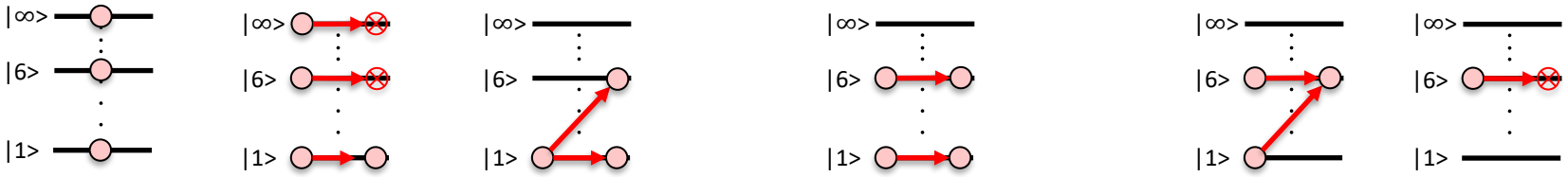


State selection

- Rough glass plates
- Scatter high energy states
- Height ≈ 25 µm above mirror
- End of I: Iψ>= I1>

- End of II: Iψ> = 50% I1> +50% I6>
- III: Iψ> =$\frac{1}{\sqrt{2}}(e^{-i\frac{E_1}{\hbar}t}$ |1>+ $e^{-i\frac{E_6}{\hbar}t}$ |6>)
- IV: Iψ> =|6>
- Transmission is measured





Transitions

- $i\hbar\partial_t\psi = -\frac{\hbar^2}{2m}\partial_z^2\psi + mgz\psi + V_0\Theta\left(-z + a\sin(\omega t + \varphi)\right)\psi$
- Experimental parameters:
  - Vibration strength $a\omega_{II}, a\omega_{IV}$
  - Vibration frequency f_{II}, f_{IV}
  - Relative phase φ_{II-IV}
- Systematic effects:
  - steps between mirrors -phase offset
  - frequency offset - tilt of mirrors

New Interactions

- Model predicts interaction (with screening)
- Energy shift of a state can be calculated to first oder:

$$\delta E_n^{(1)} = < n | \hat{V} | n >$$

- Difference of energies between two states is measured:

$$\delta E_{nm}^{(1)} = \delta E_n^{(1)} - \delta E_m^{(1)}$$

- Comparison with theoretical expectation leads to exclusion or discovery

Symmetron Dark Energy?

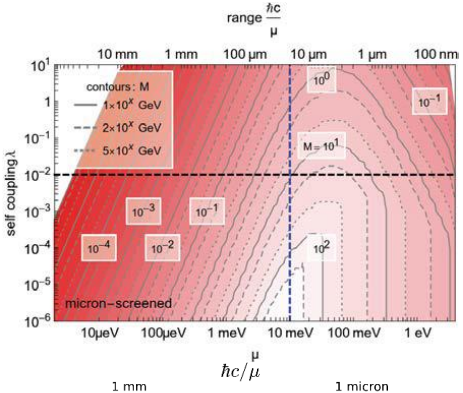
$$i\hbar\partial_t\psi = -\frac{\hbar^2}{2m_i}\partial_z^2\psi + \left(m_g g z + V_{DE}(z) + V_{DM}(z)\right)\psi$$

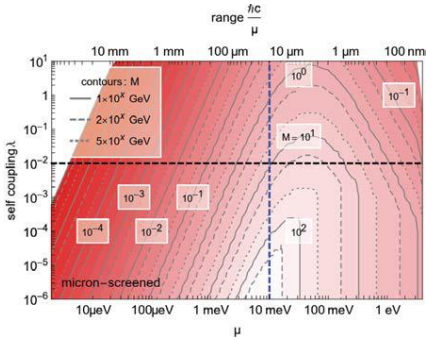
$$V_{eff} \sim \frac{\lambda}{4}\varphi^4 + \left(\frac{\rho}{2M^2} - \frac{\mu^2}{2}\right)\varphi^2 + \mu^4\left(\frac{1}{4\lambda} + \frac{1}{16\pi^2}\right)$$

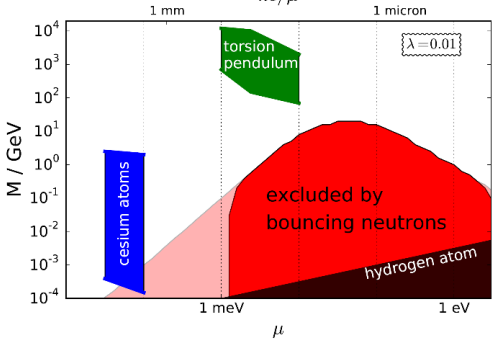
$$V_{DE} = \frac{m^2c^2}{2M^2}\varphi^2$$

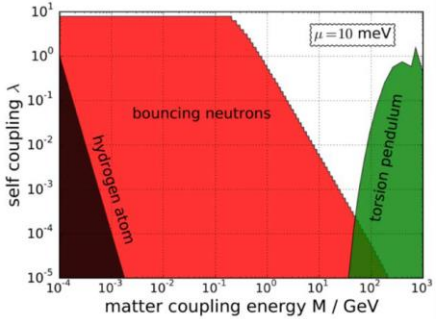
Cronenberg, G., Brax, P., Filter, H. *et al.* Acoustic Rabi oscillations between gravitational quantum states and impact on symmetron dark energy. *Nature Phys* **14,** 1022–1026 (2018).
https://doi.org/10.1038/s41567-018-0205-x

$\nu_{13} = 464 \pm 1.3\ \mathrm{Hz}, \nu_{14} = 649.8 \pm 1.8\ \mathrm{Hz}$

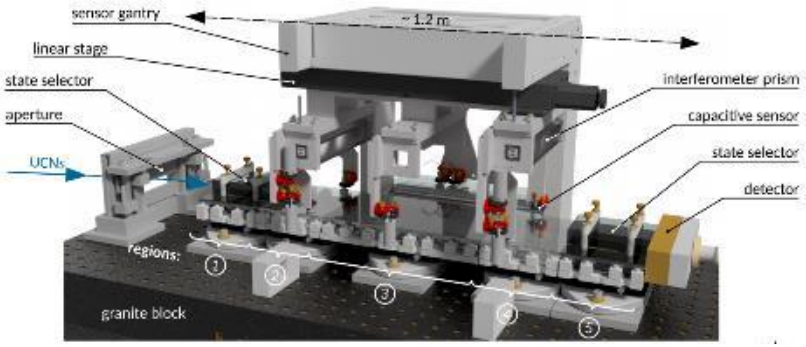


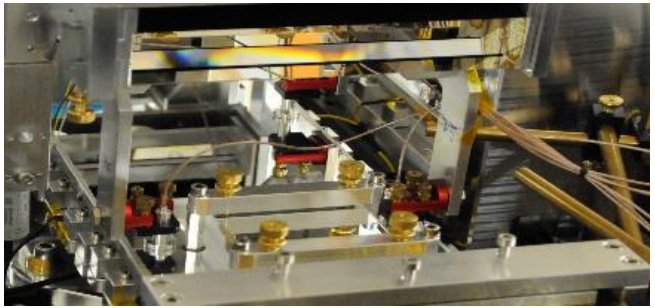






The Experiment





Tobias JENKE
Public Talk of 103rd Scientific Council of the Institut Laue-Langevin
06/11/2020

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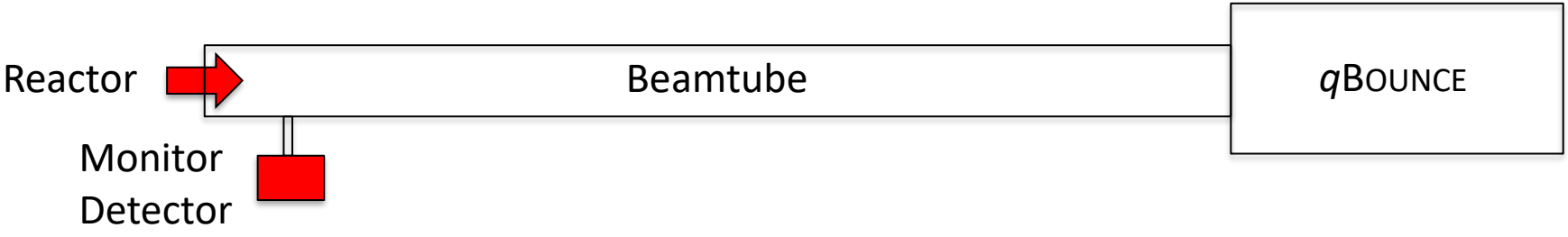
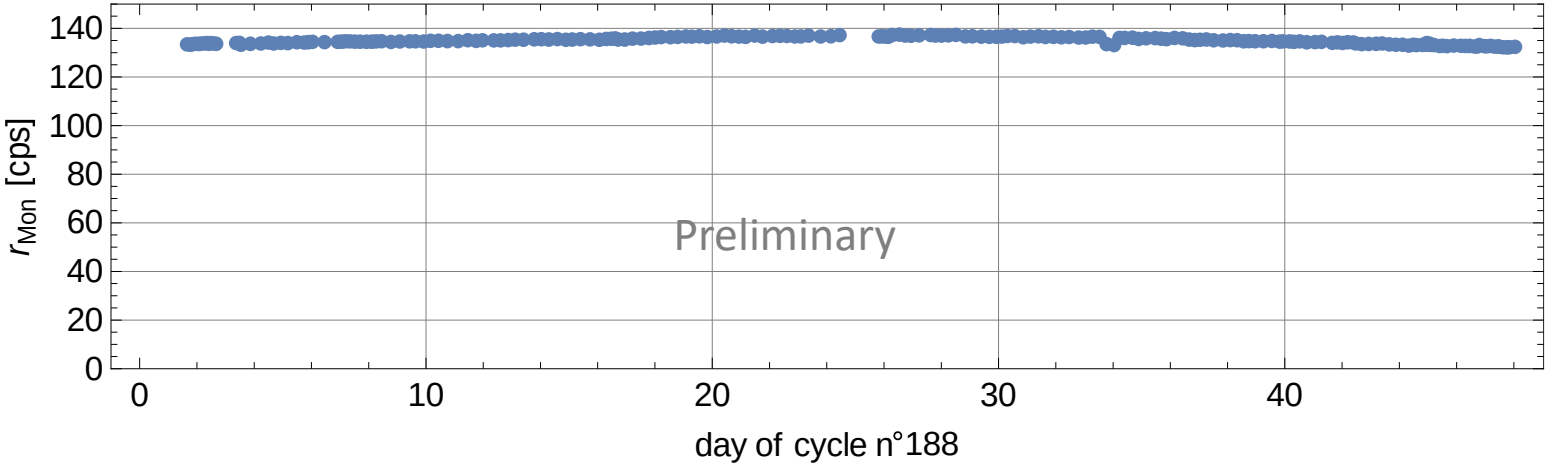
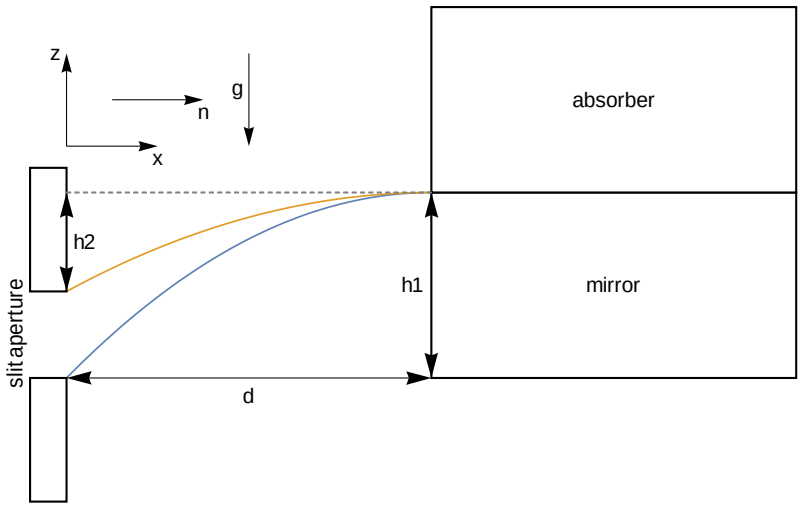
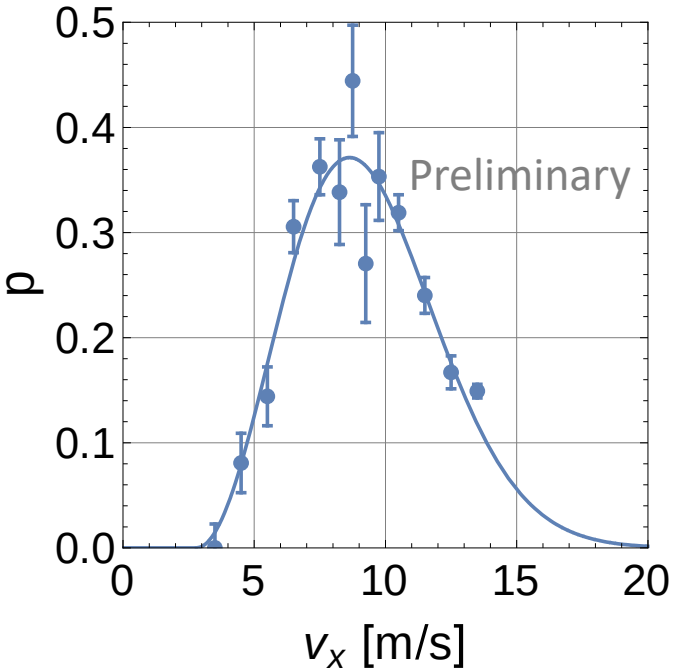

Reactor
Beamtube
qBOUNCE
Monitor
Detector


140
120
100
80
60
40
20
0
r_{Mon} [cps]
Preliminary
0
10
20
30
40
day of cycle n°188

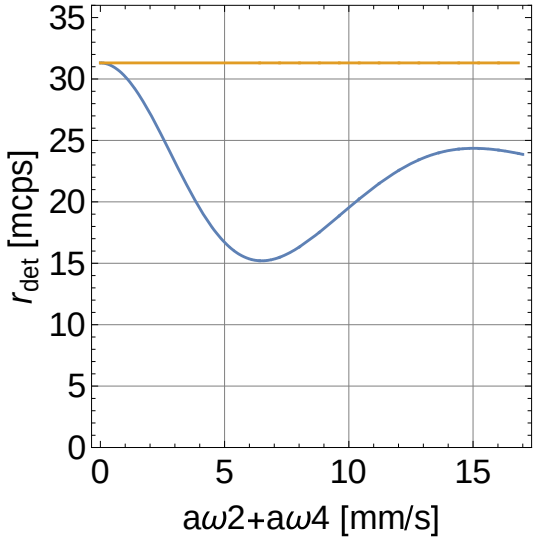
Velocity selection





Finding the transition |1>->|6>

- Highest contrast at „$\frac{\pi}{2}$-flip“ (spoiled by velocity)



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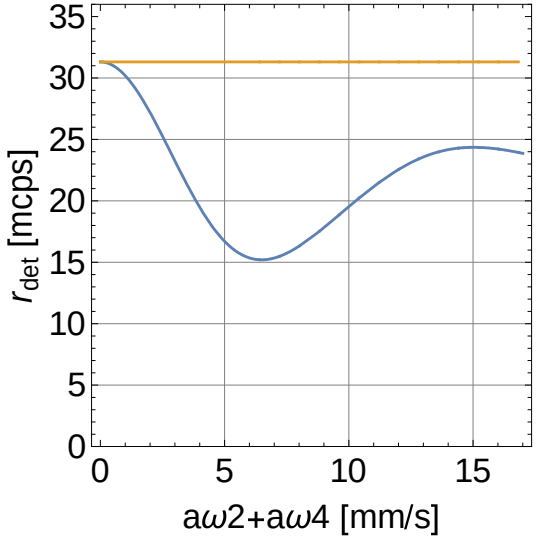
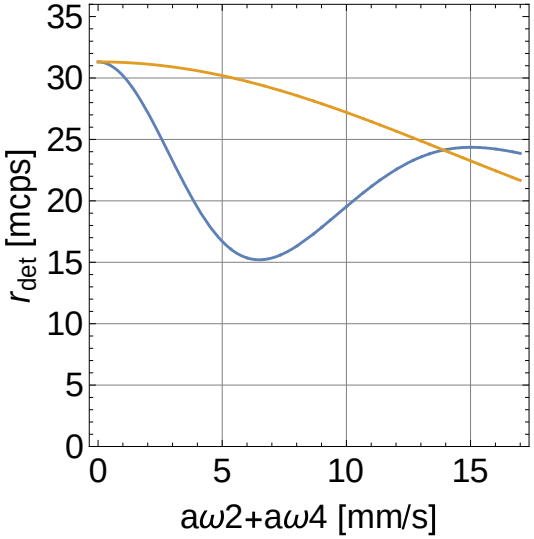
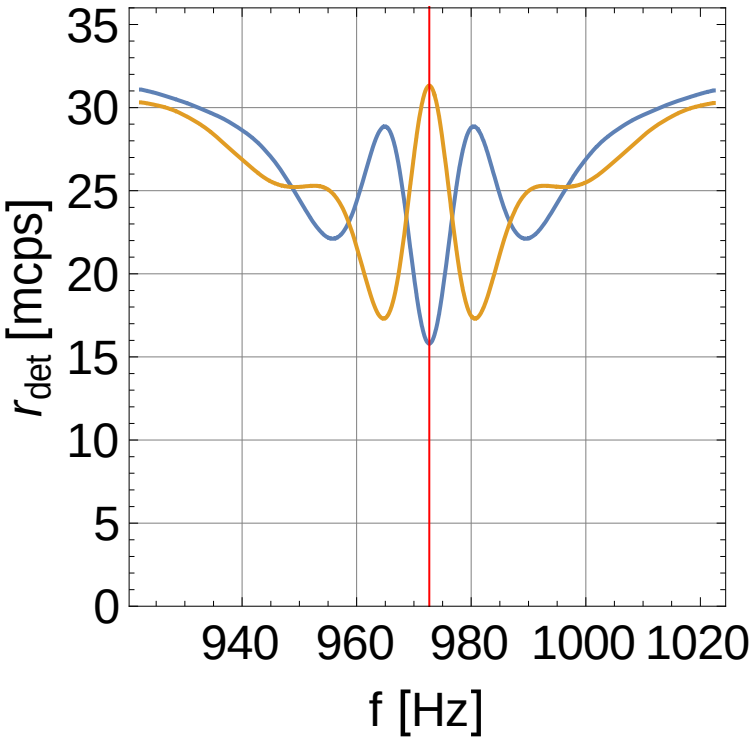
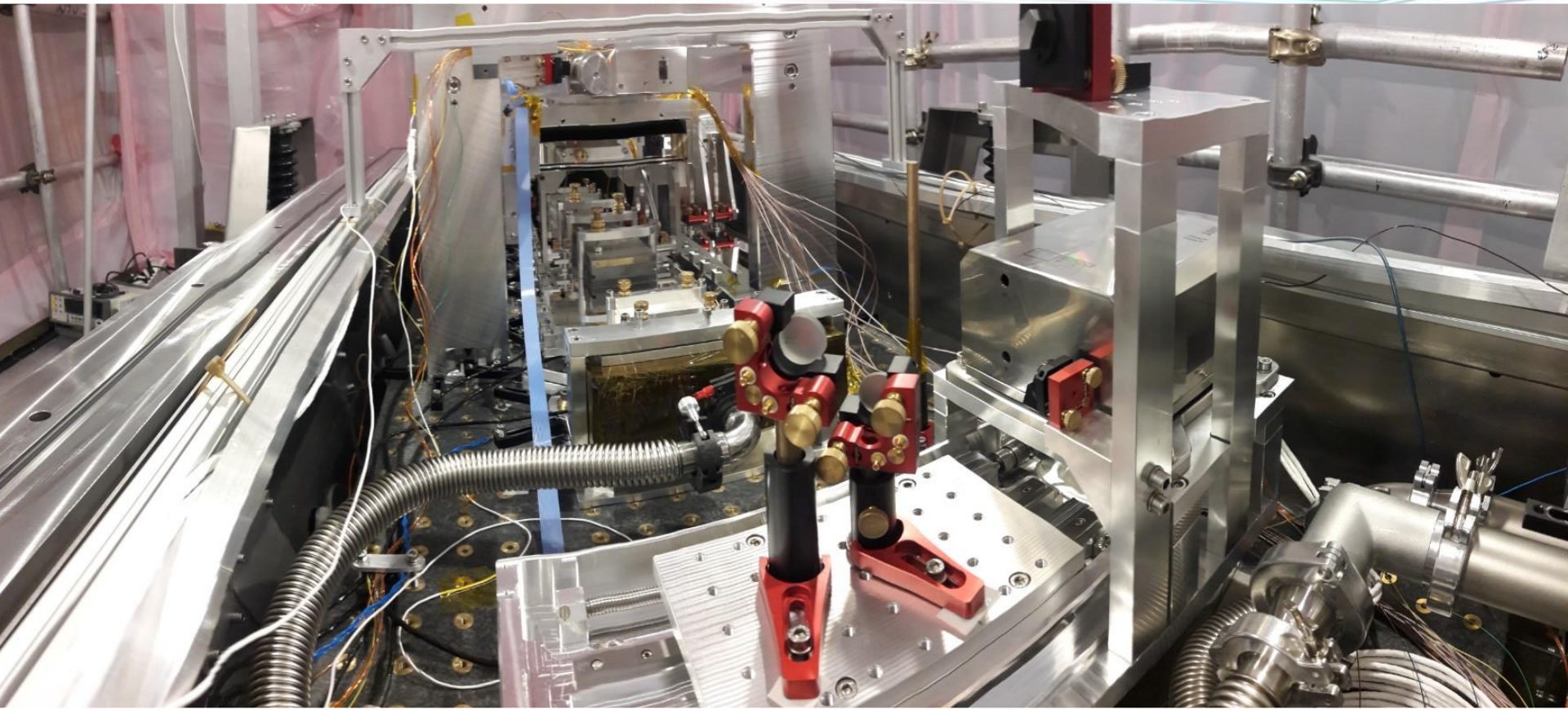




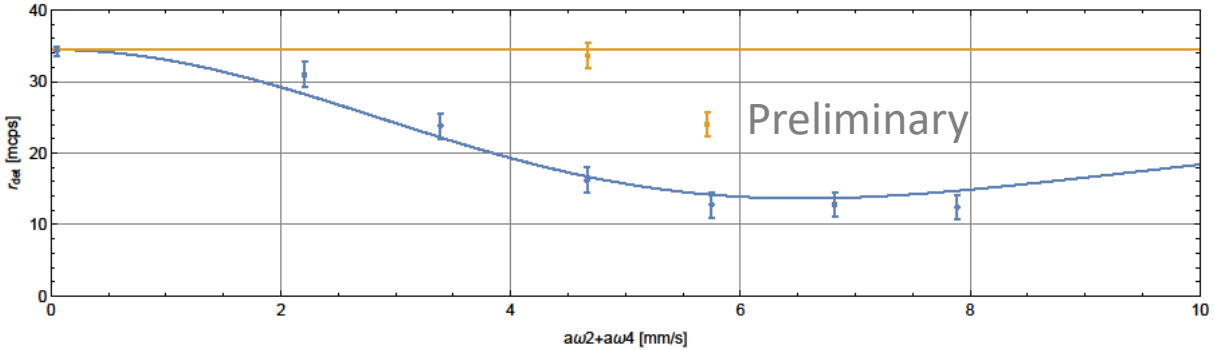
Finding the transition |1>->|6>

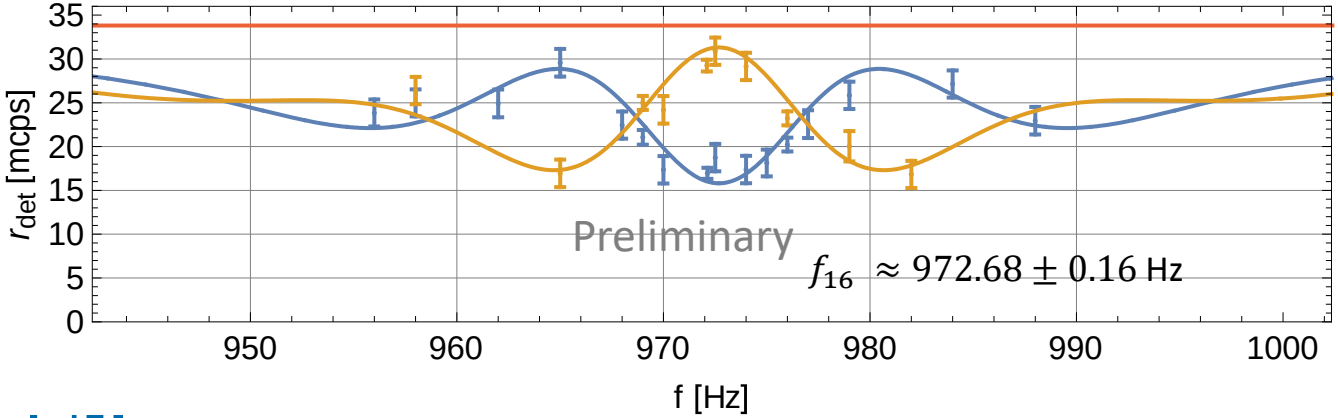
- Measure transition around $f_{1\to6} \approx 972$ Hz to find true transition frequency
- Keep vibration strength constant
- Avoid steps
- For highest sensitivity use highest slope



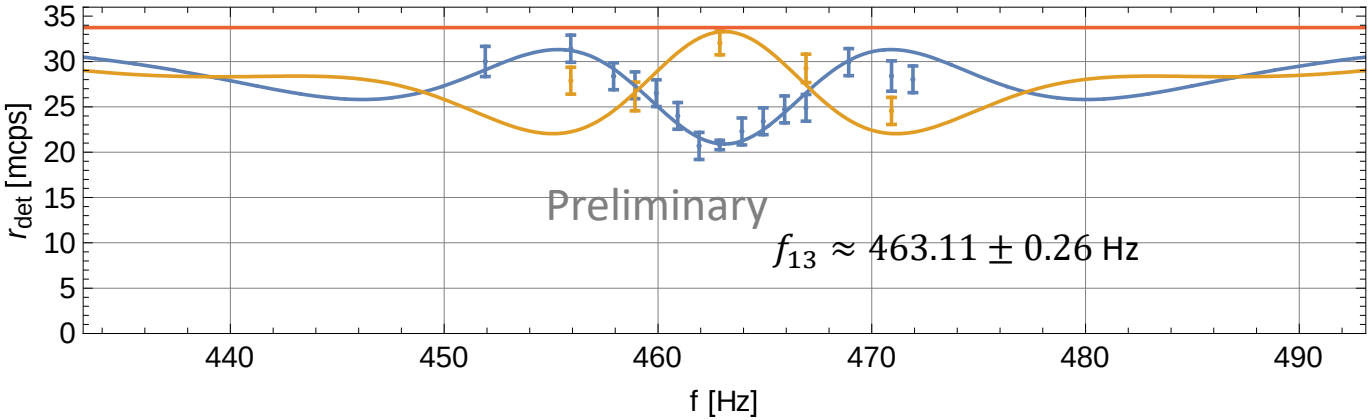


|1>->|6> 11.8-28.9.2020

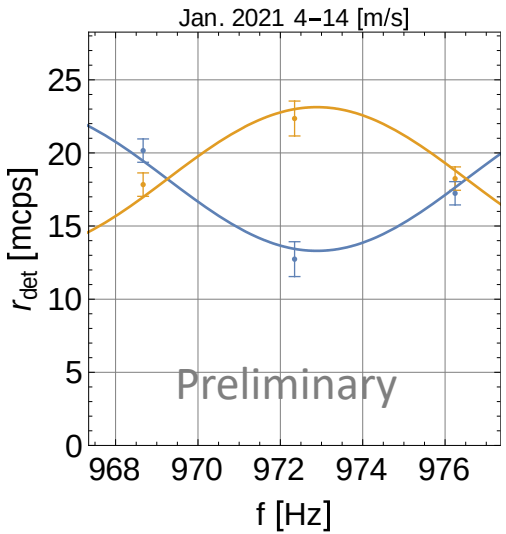


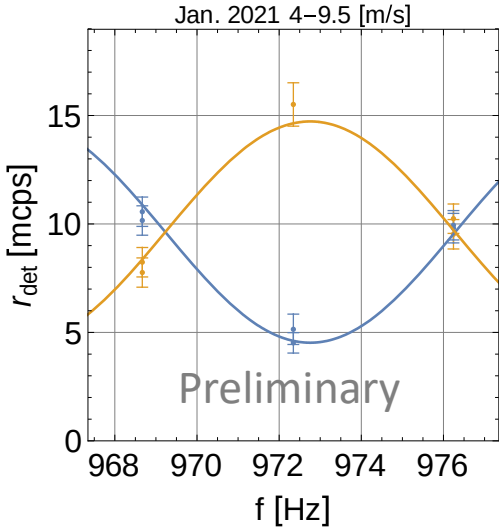


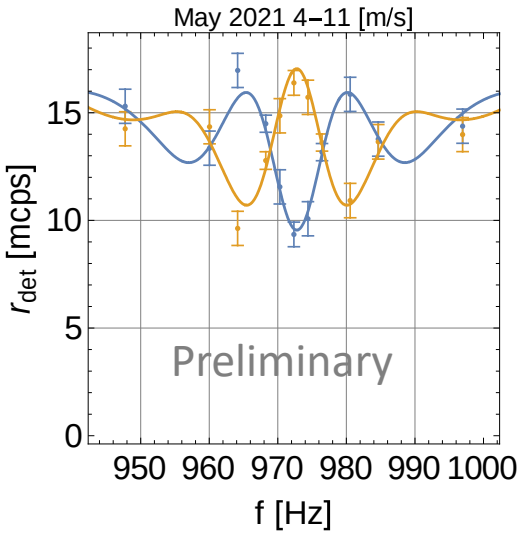
|1>->|3> 11.8-28.9.2020



2021: Jan & May(current) cycles

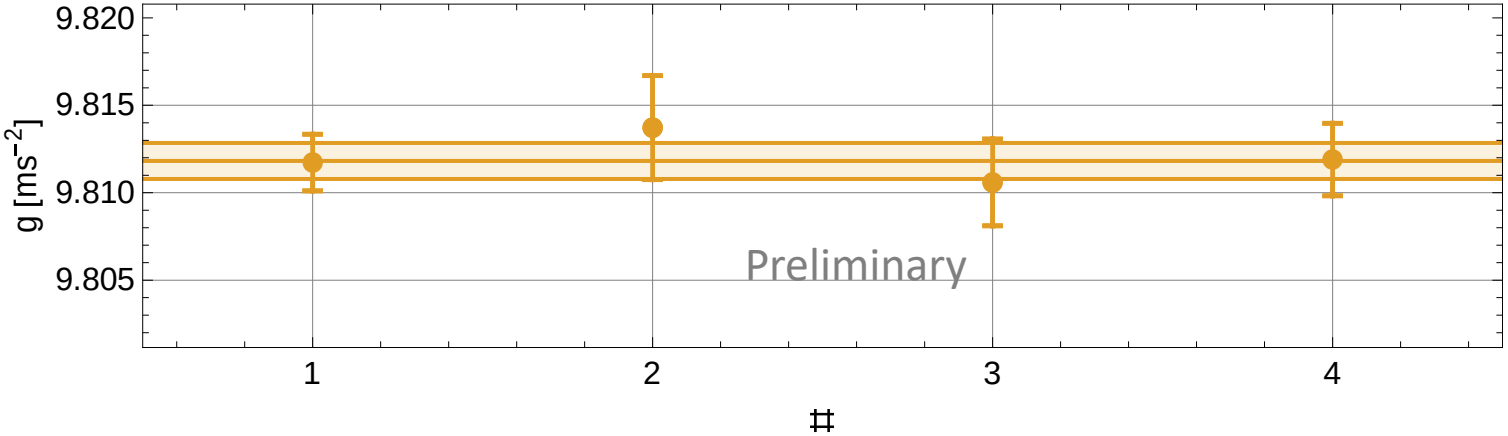






f [Hz]:	972.89 ± 0.20	972.76 ± 0.11	972.77 ± 0.14
Drop:	42 ± 6 %	69 ± 5 %	44 %

Summary



- Measured $g = 9.812 \pm 0.001\ \mathrm{m/s^2}$, $\Delta g/g = 1.05 \cdot 10^{-4}\ \mathrm{m/s^2}$ with transition |1> →|6>
- Investigated systematic effects (in progress)
- Improved stability of the experiment

Outlook

- Currently: Measuring transition $|1> \rightarrow |6>$ with a magnetic field to investigate Torsion.
- Later this year: (classical) measurement of g at PF2
- Testing the WEP with *q*BOUNCE
- Extend the capabilities to include neutron storage

Thank you

Collaboration between TU Wien and the ILL

- *q*BOUNCE:
  - Atominstitut:
    - Prof. Hartmut Abele
    - Post Doc: R.I.P Sedmik
    - PhD: Joachim Bosina
  - ILL:
    - PF2 Responsible: T. Jenke
    - PF2 Co-Responsible: S. Roccia
    - Technician: T. Brenner
- Students
  - Carina Killian
  - Andrej Brandalik
  - Veronika Kraus
  - Richard Bergmayr
  - Hippolyte Bartosz