

q BOUNCE: Using Gravity Resonance Spectroscopy for Dark Energy and Dark Matter searches

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UCNs

- Fermi potential $E_F > 0$ for many materials
- Ultra cold neutrons:
 - Reflect on all surfaces
 - velocities in range < 8 m/s
- $m_n g \approx 100$ neV/m
- $\mu_n \approx 60$ neV/T

Substance	E_F (neV)	v_c [m/s]
^{58}Ni	335	8.00
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
Ti	-49.7	-

Trapped on a mirror

- With gravity: trapped on mirror

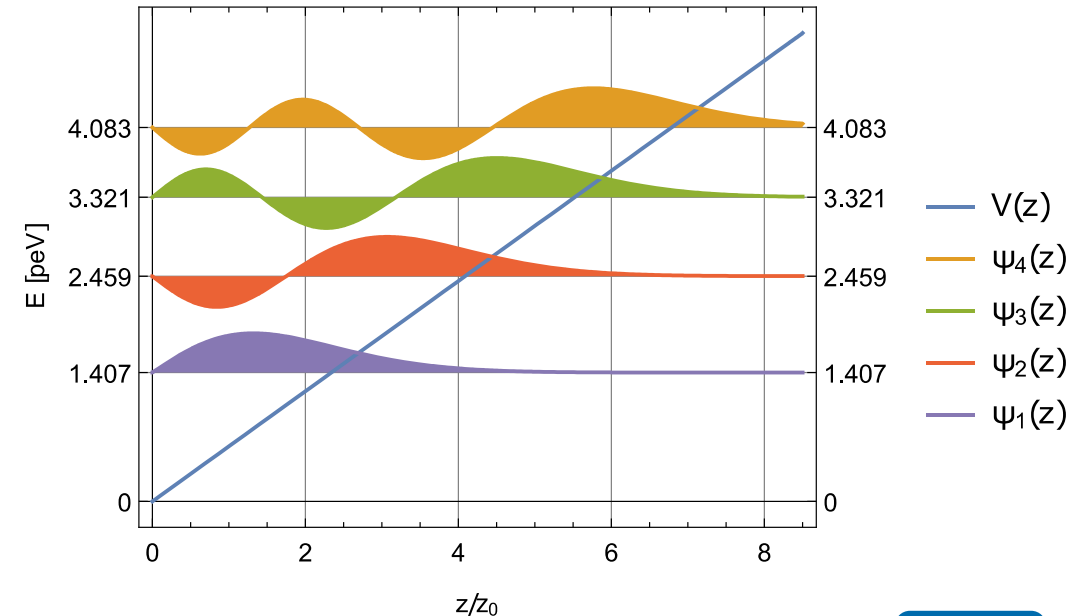
$$i\hbar \frac{d}{dt} \psi = -\frac{\hbar^2}{2m_i} \frac{d^2}{dz^2} \psi + m_g g z \psi + E_F \Theta(-z) \psi$$

$$\psi(0) \approx 0$$

$$\psi_n \propto \text{AiryAi} \left(\frac{z}{z_0} - \frac{E_n}{m_g g z_0} \right)$$

$$E_n = -m_g g z_0 \text{AiryAiZero}(n)$$

$$z_0 = \sqrt[3]{\frac{\hbar^2 (m_g g)^2}{2m_i}} \approx 5.8 \mu\text{m}$$



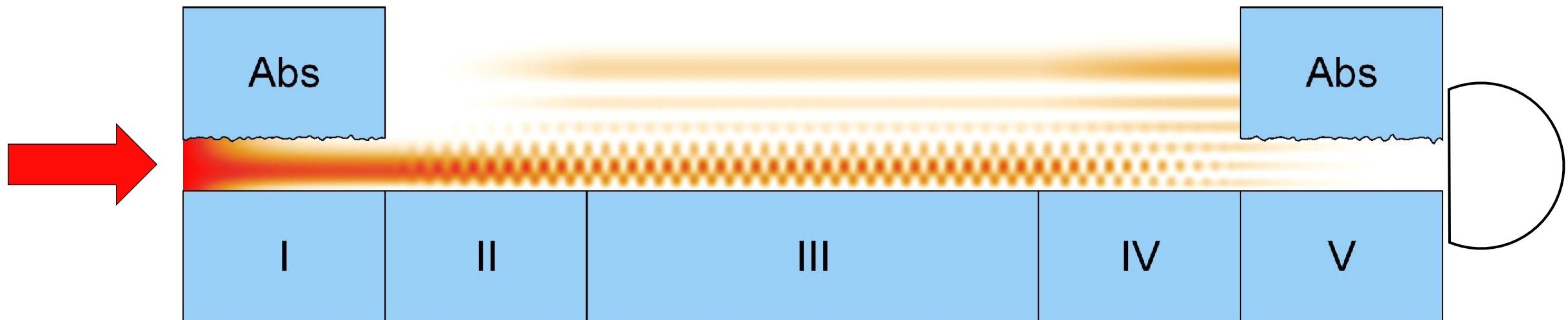
Driving transitions: Gravity Resonance Spectroscopy (GRS)

- Initial state $|1\rangle$
- $V(t|a, \omega, \phi) = E_F \Theta(a \sin(\omega t + \phi) - z)$
- Final state $|\psi\rangle = a|1\rangle + b|n\rangle + \dots$
- Analytical solution for 2 states
numerical calculation for more

$\frac{\omega_{mn}}{2\pi}$ [Hz]	m=1	2	3	4	5	6	7
n=1	0	254.535	462.925	647.101	815.462	972.345	1120.36
2		0	208.39	392.566	560.927	717.81	865.82
3			0	184.176	352.537	509.42	657.431

Overview of the qBounce Ramsey GRS setup

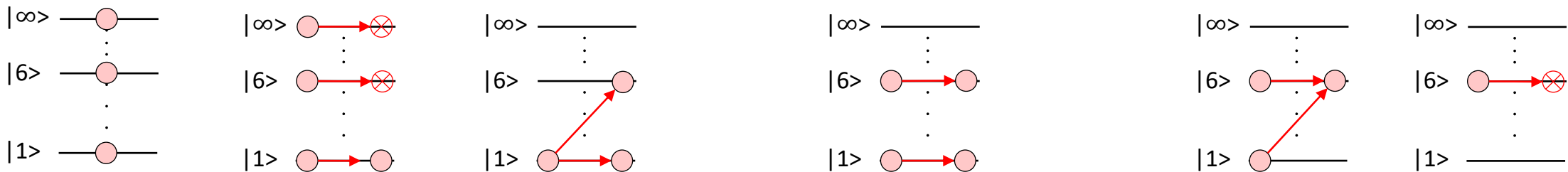
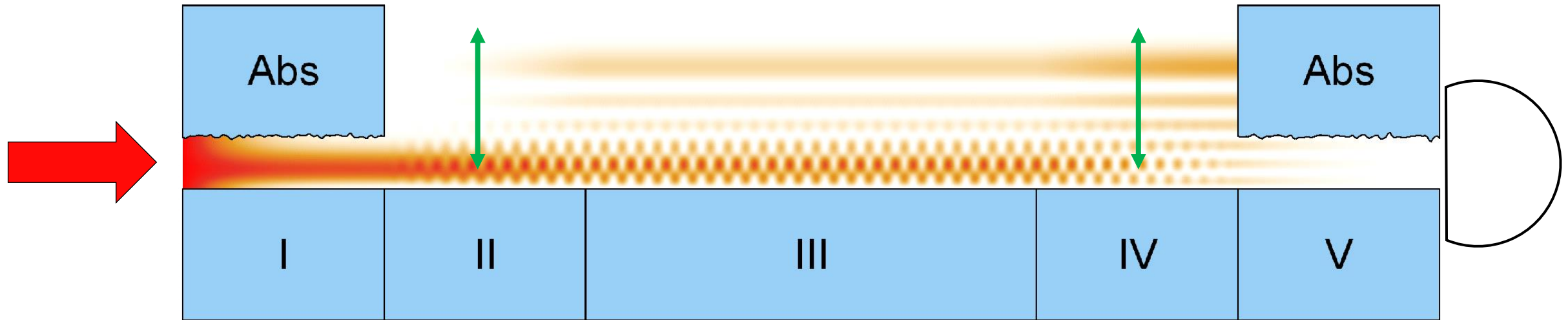
- Length of setup 0.948 m
- Distance between mirrors $\approx 30 \mu\text{m}$
- Steps in height between mirrors $< 0.5 \mu\text{m}$
- Absorbers select states



Overview of Ramsey GRS

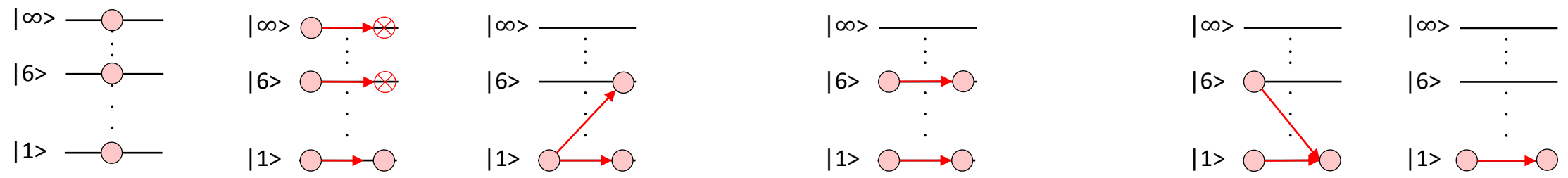
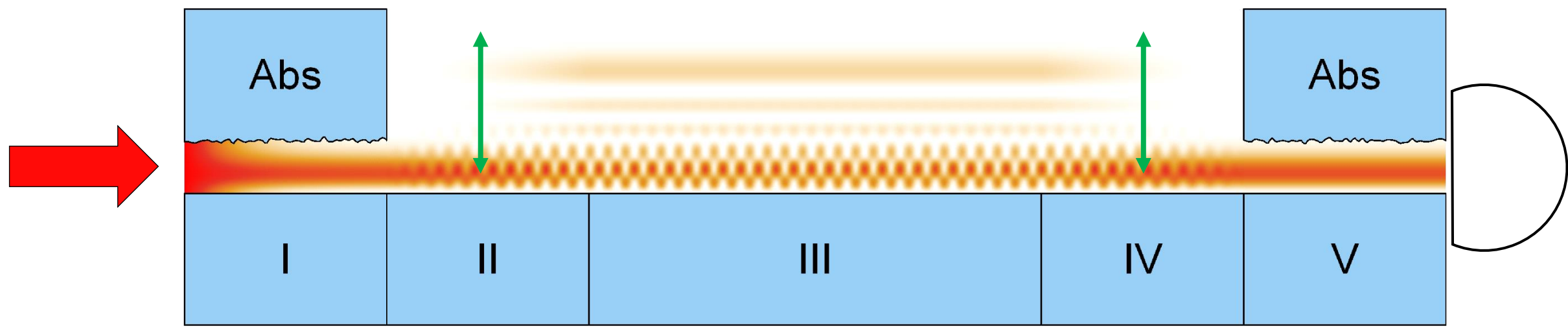
- I: $|\psi\rangle = |1\rangle$
- II: $|\psi\rangle = 50\% |1\rangle + 50\% |6\rangle$
- III: $|\psi\rangle = \frac{1}{\sqrt{2}}(e^{-i\frac{E_1}{\hbar}t} |1\rangle + e^{-i\frac{E_6}{\hbar}t} |6\rangle)$

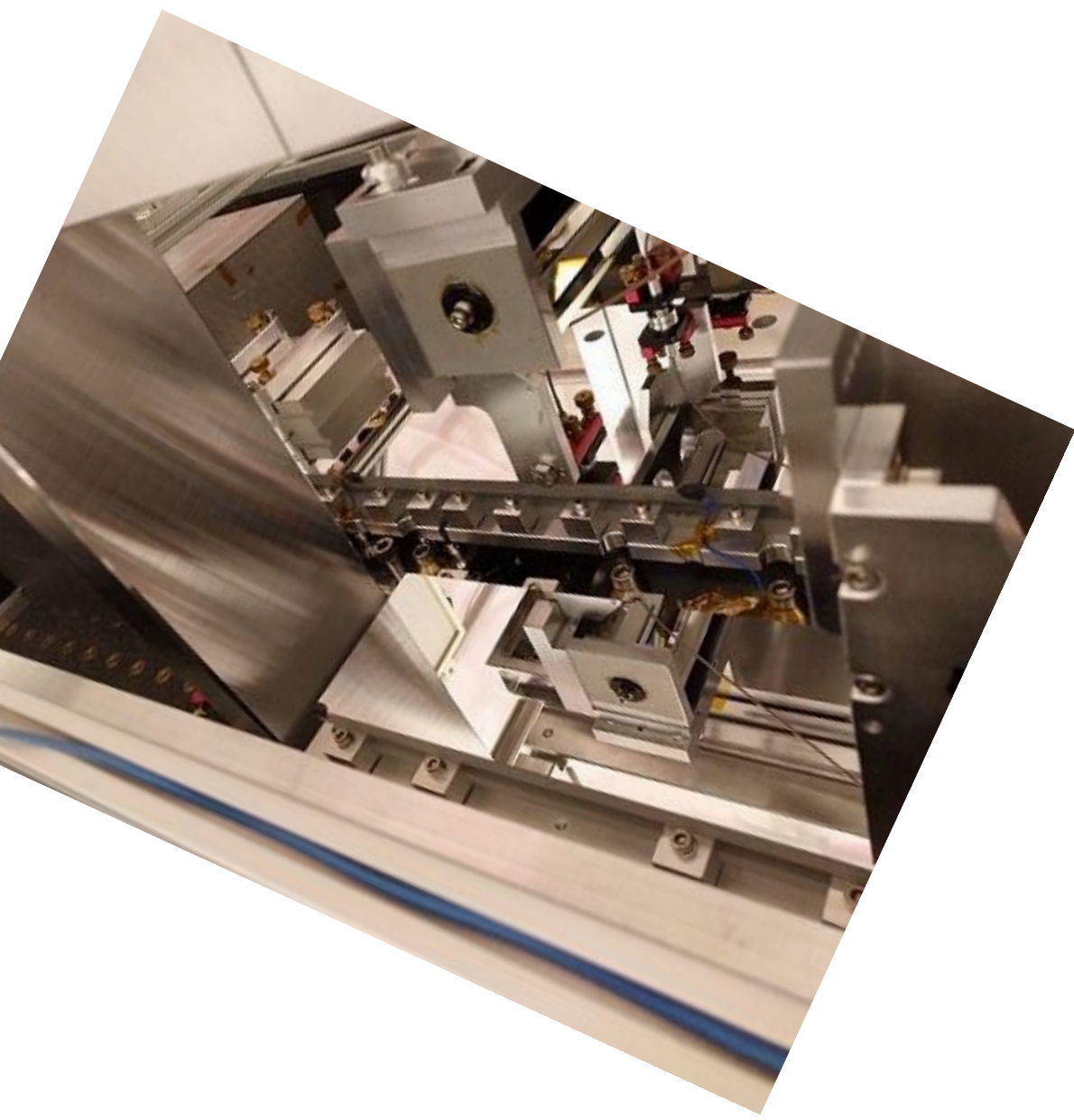
- IV: $|\psi\rangle = |6\rangle$
- Transmission is measured
- Oscillation: $a \sin(\omega t + \phi_{II/IV})$



π phase between oscillations of II & IV

- End of I: $|\psi\rangle = |1\rangle$
- End of II: $|\psi\rangle = 50\% |1\rangle + 50\% |6\rangle$
- III: $|\psi\rangle = \frac{1}{\sqrt{2}}(e^{-i\frac{E_1}{\hbar}t} |1\rangle + e^{-i\frac{E_6}{\hbar}t} |6\rangle)$
- $\Delta\phi = \pi$
- IV: $|\psi\rangle = |1\rangle$



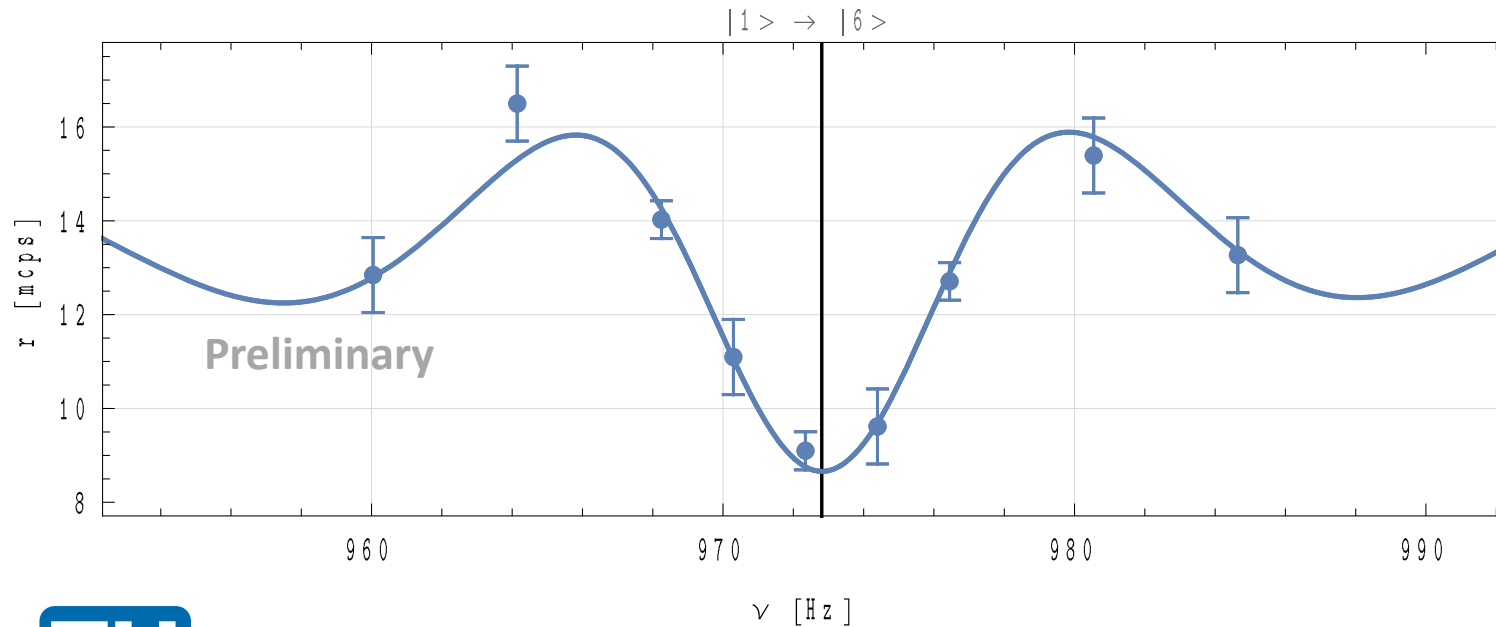




Cycle 2 in 2021@ILL:

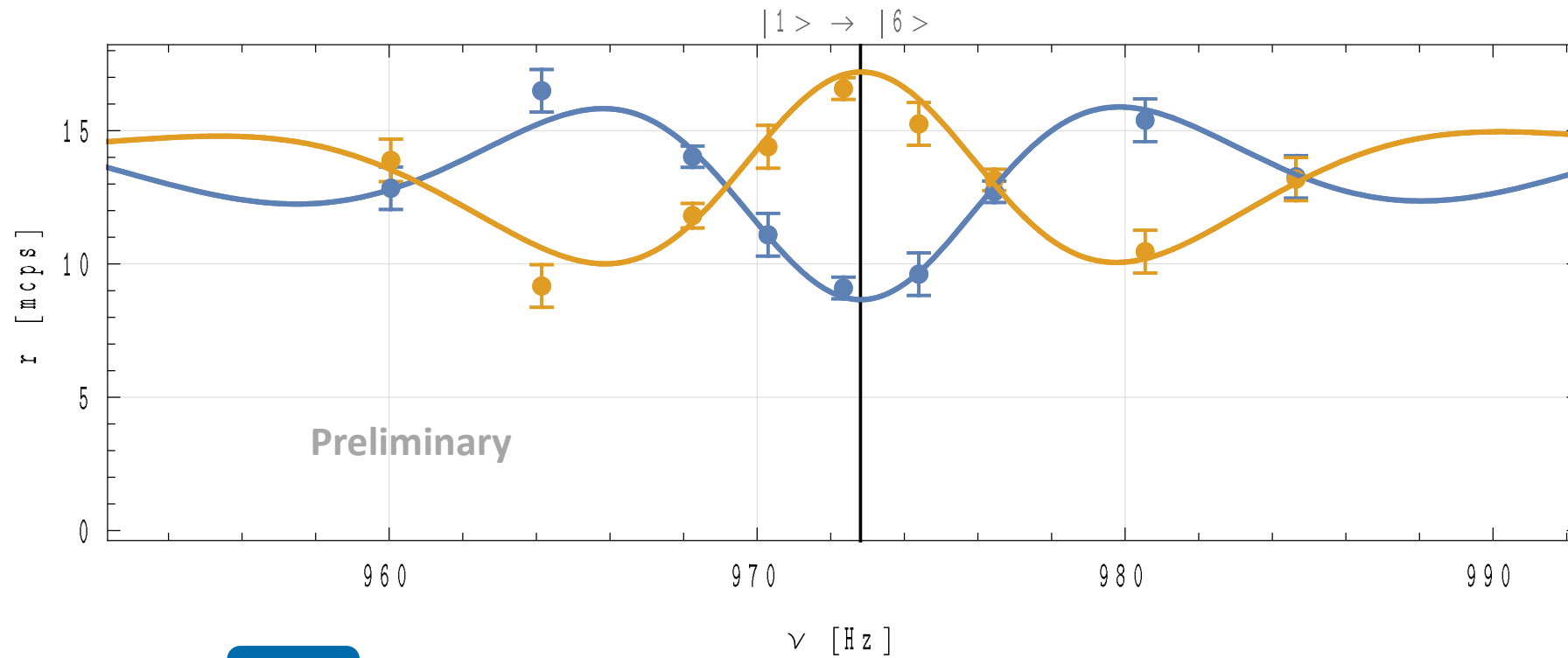
- Use constant oscillation strength $a\omega$ from $\frac{\pi}{2}$ flip
- Sweep frequency to determine resonance

$$\frac{r}{r_0} \approx 1 - 2 \cos^2\left(\frac{a\omega V}{2}\tau\right) \sin^2\left(\frac{a\omega V}{2}\tau\right) \left(1 + \cos\left(2\pi(\nu - \nu_0)\left(T + 2\frac{\tan\left(\frac{a\omega V}{2}\tau\right)}{a\omega V}\right) + \Delta\phi\right)\right)$$



Cycle 2 in 2021@ILL:

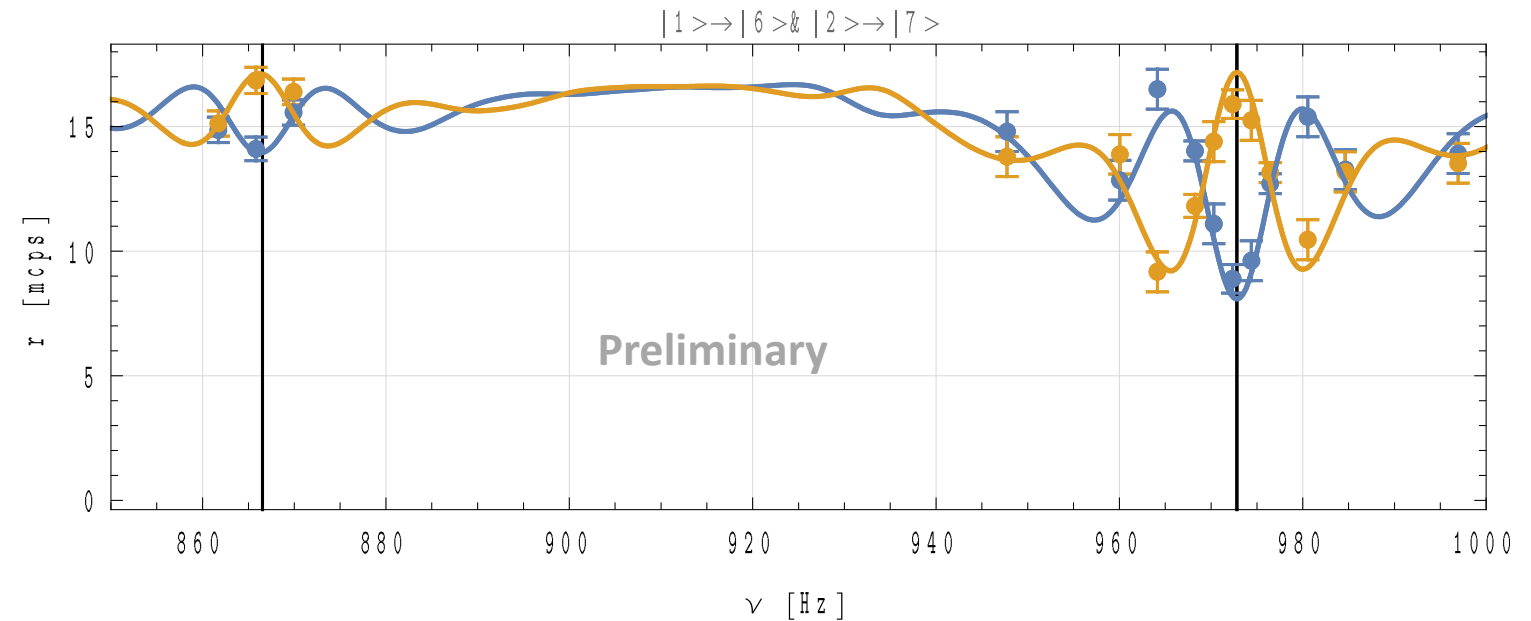
- Frequency sweep with π phase
- Highest sensitivity: only points on highest slope (and in the central dip)



Combined fit

$$E_{ij} = \sqrt[3]{\frac{\hbar^2 m_g^2 g^2}{2m_i}} (A_i Z(i) - A_i Z(j))$$

$$\chi^2 = 74.4$$
$$n_{eff} = 73$$



Systematic effects

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

- Spectator state shift (numerical):

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

- Bloch-Siegert shift (numerical):

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

- Mirrors close to neutrons:

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

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

Phase offset

- Close to resonance: $P(\nu) \approx \frac{1}{2} \left(1 - \cos \left(\frac{\pi}{w} (\nu - \nu_0) + \Delta\phi \right) \right)$
 - $\Rightarrow \Delta\phi = -\Delta\nu \frac{\pi}{w}$
- Measured using external interferometer to $\Delta\phi \approx \pm 0.5^\circ$
- Agrees with function generator to within 1°

Rotating Earth

- Hamilton operator in a rotating frame:

$$\hat{H} = \frac{\mathbf{p}^2}{2m_i} + V(\mathbf{r}) - \mathbf{L} \cdot \boldsymbol{\Omega}$$

$$V(\mathbf{r}) = -\frac{GM m_g}{r} = -\frac{m_g r_0^2 g_0}{r}, \quad \Omega \approx \frac{2\pi}{24h} \approx 7.3 \cdot 10^{-5} \text{ rad/s}$$

- Expansion around neutron mirror surface gives:

$$E_{nl\xi} = -A_i Z(n) \left(\frac{\hbar^2 m_g^2 \left(g_0 - \frac{L_l^2}{m_i m_g r_0^2} \right)^2}{2m_i} \right)^{\frac{1}{3}} + \hbar\omega\xi + \frac{L_l^2}{2 m_i r_0^2} - m_g r_0 g_0$$

$$g = g_0 - \frac{m_i}{m_g} \left(2\omega v_y \sin \chi + r_0 \omega^2 \sin^2(\chi) + \frac{v^2}{r} \right)$$

Some further considerations

- Misalignment? g decreases
- Coriolis/Sagnac effect
- Steps between regions? Lowers contrast, induces spectator shift
small for $|1\rangle \rightarrow |6\rangle$
- Tidal forces? $\frac{\delta g}{g} \approx 10^{-6}$
- As a frequency reference Rb clock
- Finite mirror potential? $l \approx 14 \text{ nm}, \Delta E_{ij} < 1 \text{ aeV}$

New Interactions

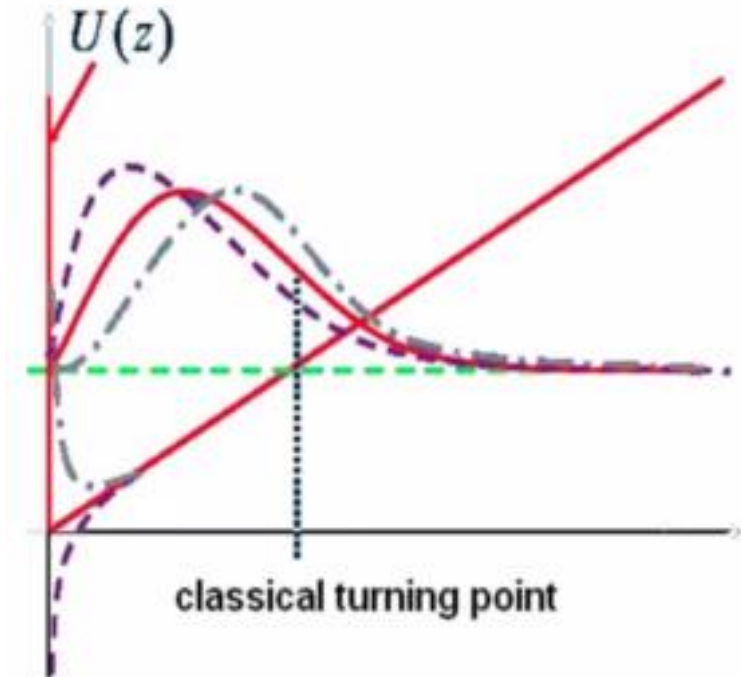
- Model predicts interaction
- Energy shift of a state can be calculated to first order:

$$\delta E_n^{(1)} = \langle n | \hat{V} | n \rangle$$

- 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



New Interactions

- Axion:

- $V(r) = \hbar^2 g_s g_p \frac{\sigma \cdot r}{8\pi m_M} \left(\frac{1}{\lambda r} + \frac{1}{r^2} \right) e^{-\frac{r}{\lambda}}$
- Spin dependent
 - Guidefield+spin dependent detector

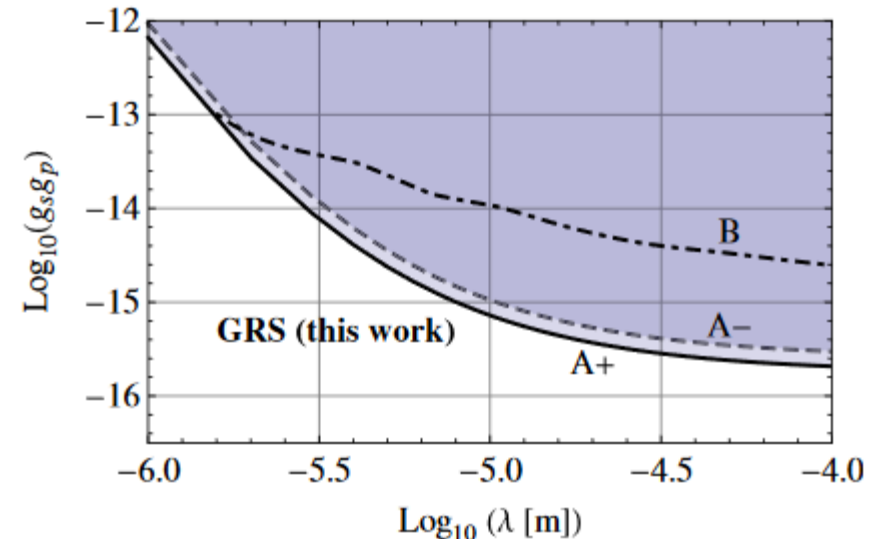
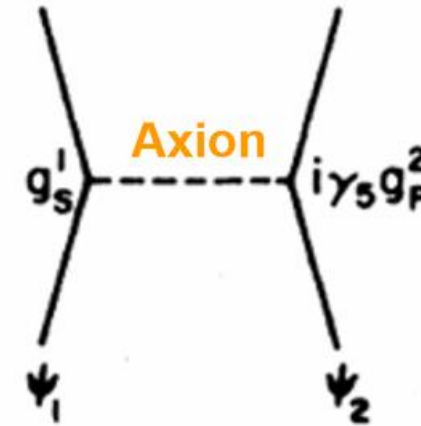
[Gravity Resonance Spectroscopy Constrains Dark Energy and Dark Matter Scenarios, T. Jenke et al., Phys. Rev. Lett. 112, 151105, <https://doi.org/10.1103/PhysRevLett.112.151105>]

- WEP test

- Charge of the neutron:

- $V(r) = m g z + q E_z z$
- Direct shift of g

- Chameleon field/Fifth forces



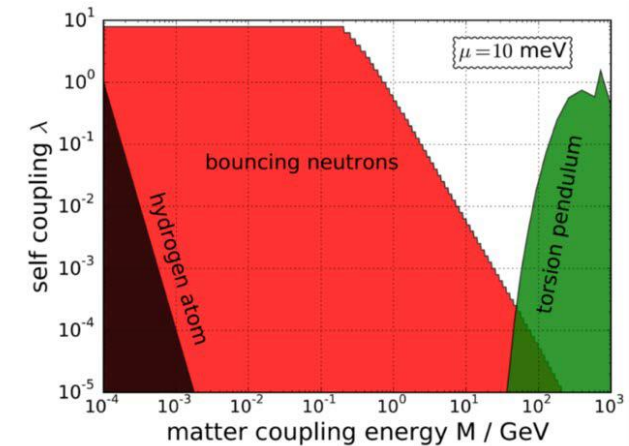
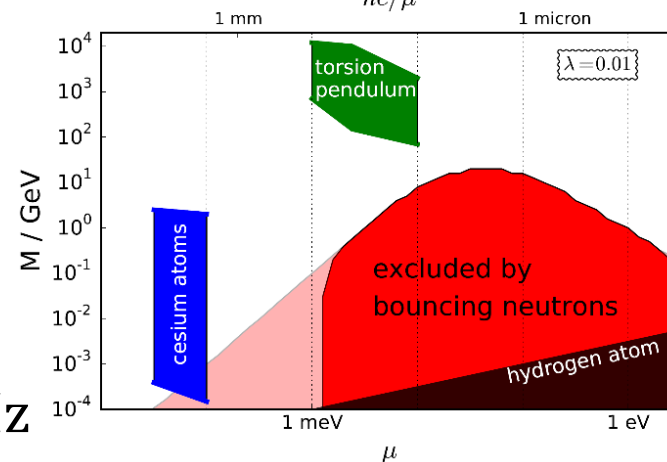
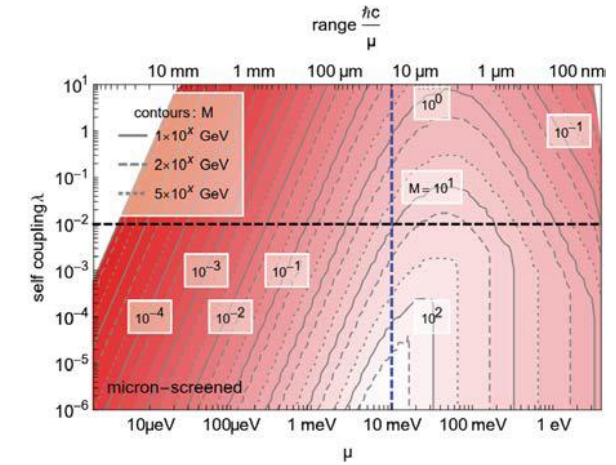
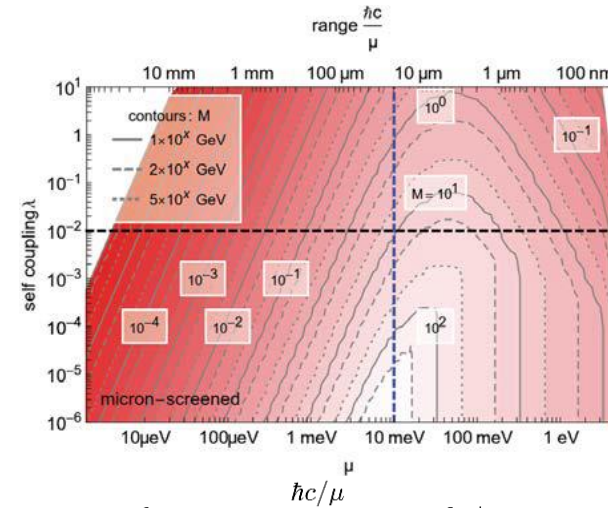
Symmetron dark energy

- $V(z) = mgz + \frac{mc^2}{2M} \varphi(z)^2$
- VEV for symmetron field $\varphi \neq 0$
- Screened by mass(density) inside matter

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>

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

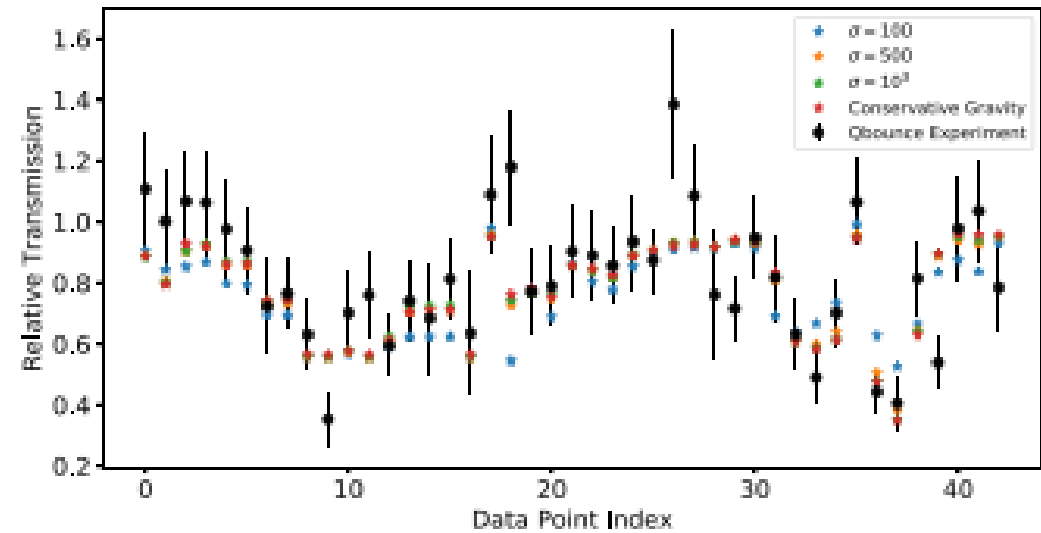
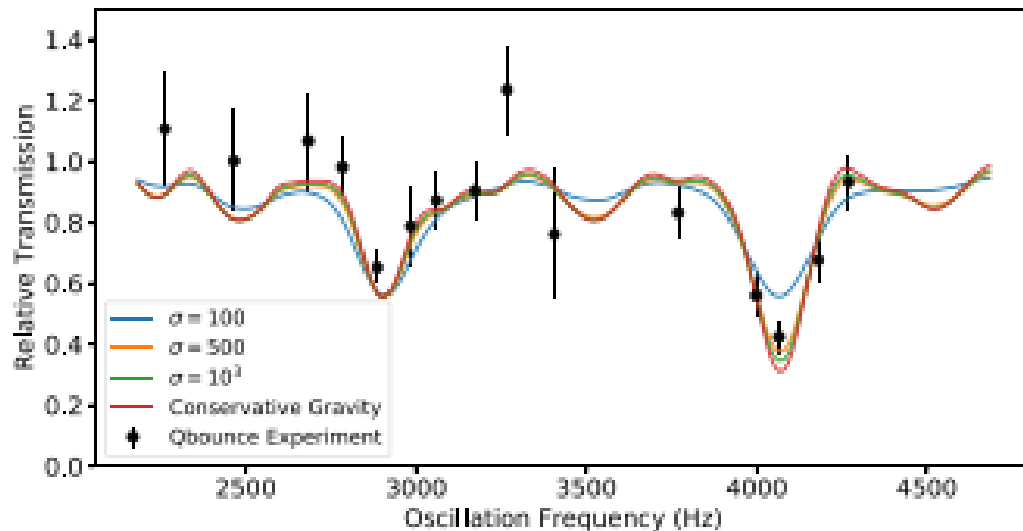


Entropic Gravity

- Proposed as a model for all gravitating bodies as an origin of gravity
[Verlinde, E. On the origin of gravity and the laws of Newton. *J. High Energ. Phys.* **2011**, 29 (2011). [https://doi.org/10.1007/JHEP04\(2011\)029](https://doi.org/10.1007/JHEP04(2011)029)]
- Has been criticised for decoherence, as shown in
[Decoherence-free entropic gravity: Model and experimental tests
A. Schimoller et al. arXiv:2012.10626 ,Phys. Rev. Research 3, 033065 (2021)]
not ruled out by experiments
- Can be investigated by looking at the coherence only

Entropic Gravity

- Using Rabi data from 2018 to determine coupling strength σ
- Currently analysing Ramsey dataset



Conclusion

- Transitions : $|1\rangle \rightarrow |6\rangle$ and $|2\rangle \rightarrow |7\rangle$
- Relative precision: $\frac{\delta g}{g} \approx 10^{-4}$
- Analysis ongoing:
 - one more transition $|2\rangle \rightarrow |8\rangle$
- High precision tests of model specific predictions:
 - Charge of the neutron
 - Spin dependent changes (up vs. down): Axions and Torsion
 - ...
- Combination of GRS and EM NMR
- Storage of gravity states in bottle

Thank you!

- qBOUNCE:
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 - Stephanie Rocca, ILL (PF2 responsible)
 - Thomas Brenner (PF2 technician)



