PhD Status Update:

Phase Noise Cancellation for Links in Networks of Optical Clocks

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from the "Quantum Sensing Group":
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Tuesday, 3rd June 2025 — MMS Annual Meeting

Outline

- Motivation:
  Dark matter detection with atomic clocks
- **Phase noise cancellation** (clock comparison)

Optical atomic clocks

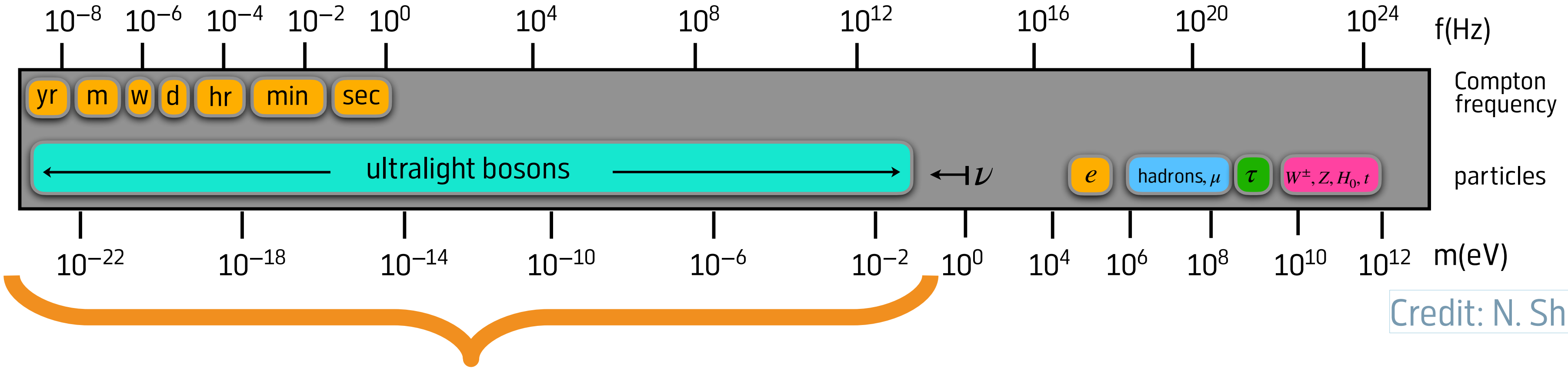
- Clock = periodic, well-known process in nature

  Currently: 1 second ≡
  Ceasium **mircowave** clock 'ticking' 9 192 631 770 times

- Optical clock:
  - Offer increased precision
    "higher frequency (>300THz) → higher precision"
  - Excite narrow optical transition O(<1Hz) with **finely tuned laser**

← My group's goal: build an optical clock

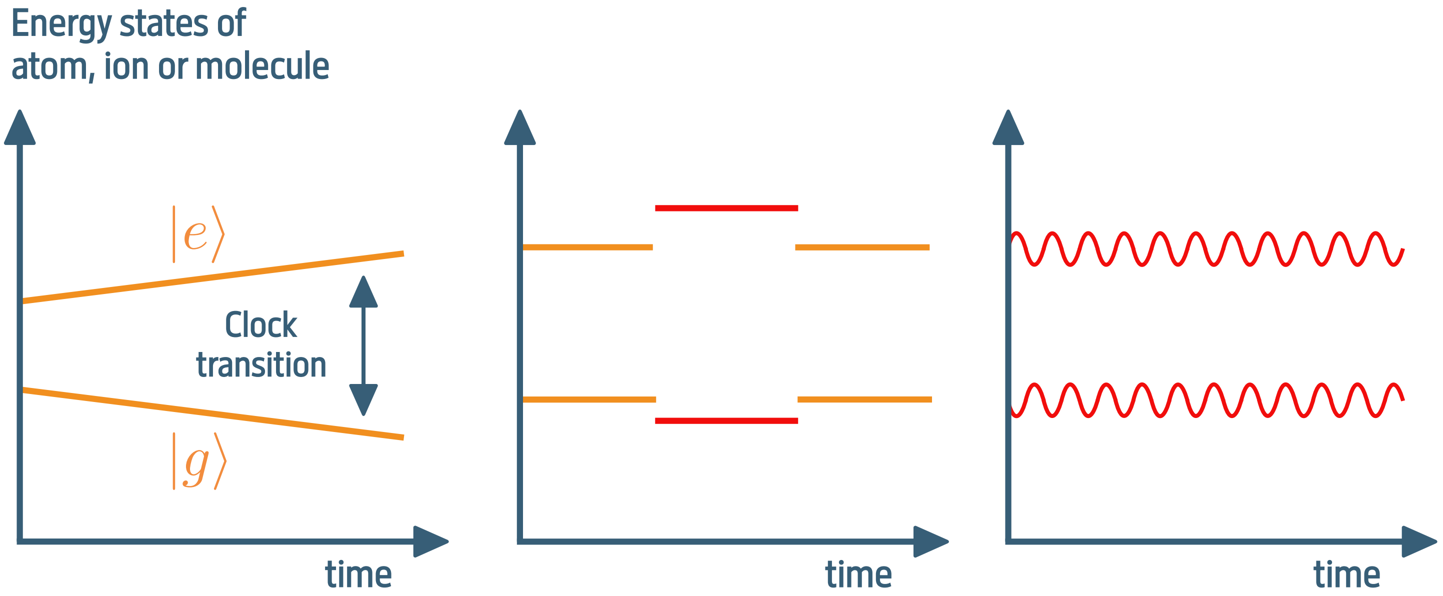
Motivation: Ultralight dark matter and α-variation



Credit: N. Sherrill

Our region of interest ~ coherently oscillating field

Motivation: Ultralight dark matter and α-variation



Fundamental constants (α, μ) vary slowly with time

Interaction with DM particles (transient events)

Interaction with DM particles (constant density in Earth's neighborhood)

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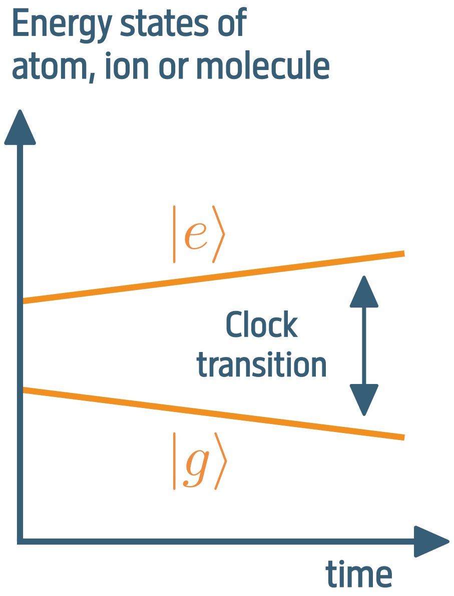

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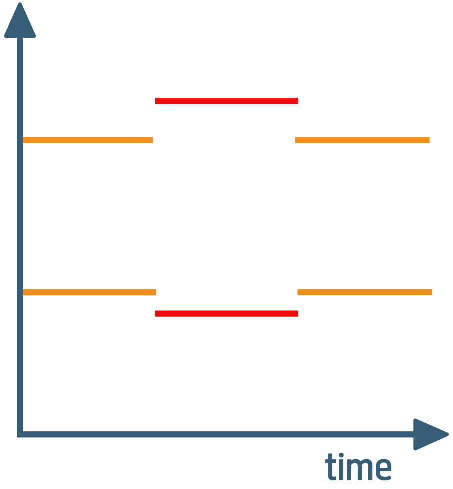
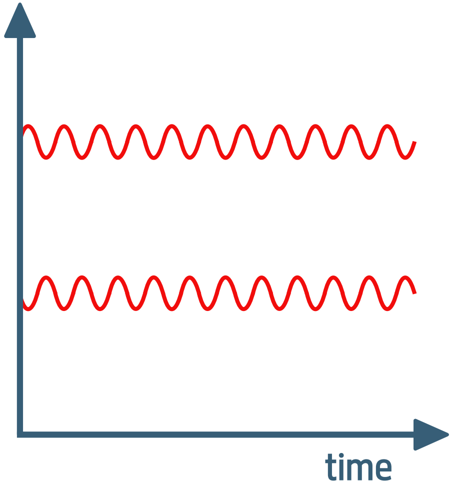


Interaction with DM particles (transient events)



Interaction with DM particles (constant density in Earth's neighborhood)

to **detect a variation** we **need to compare** to something stable, i.e. another clock:

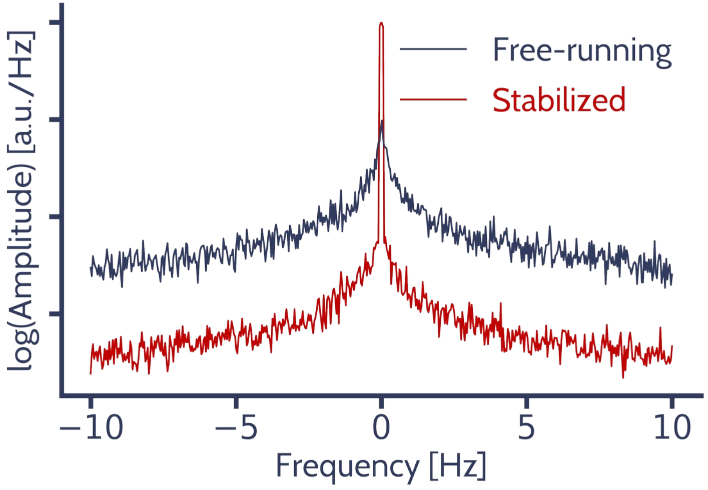
$$\nu_{\mathrm{clock1}} / \nu_{\mathrm{clock2}}$$

Phase noise from fiber transmission

- Clock comparison requires **frequency transmission: usually via fiber @ 1550nm**
- Vibrations, temperature fluctuations, optical components, ...

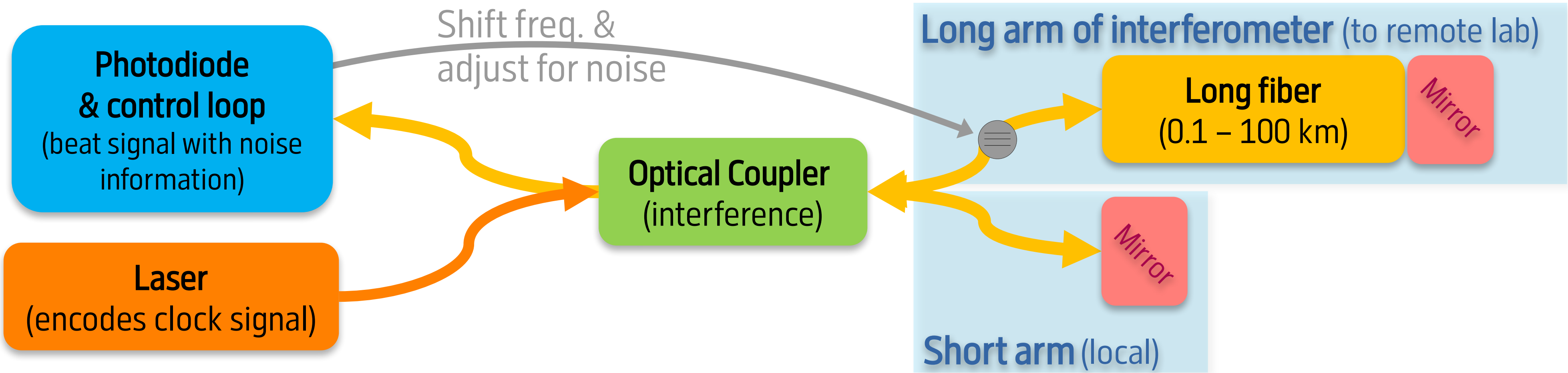
→ Phase noise ≙ **frequency instability**

Goal:

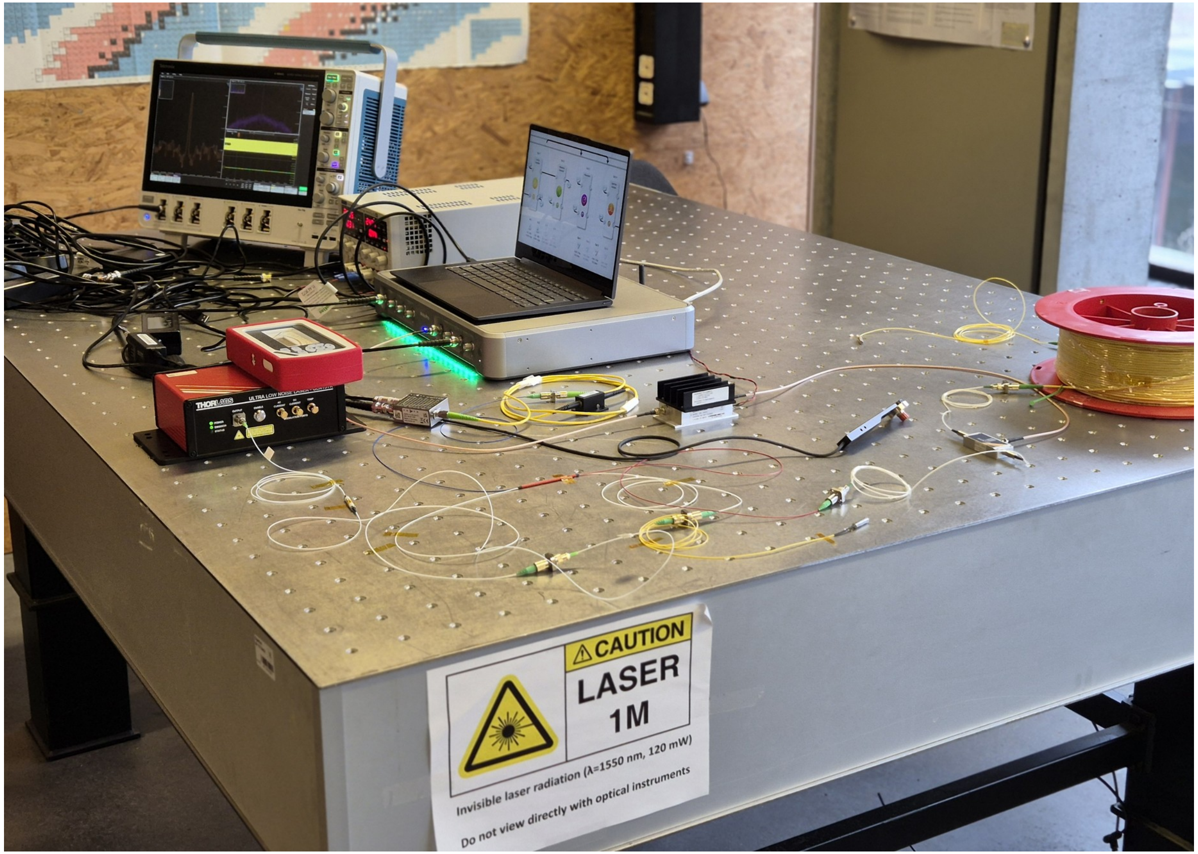


Phase noise cancellation (PNC)

...with a Michselson interferometer



PNC test setup stand



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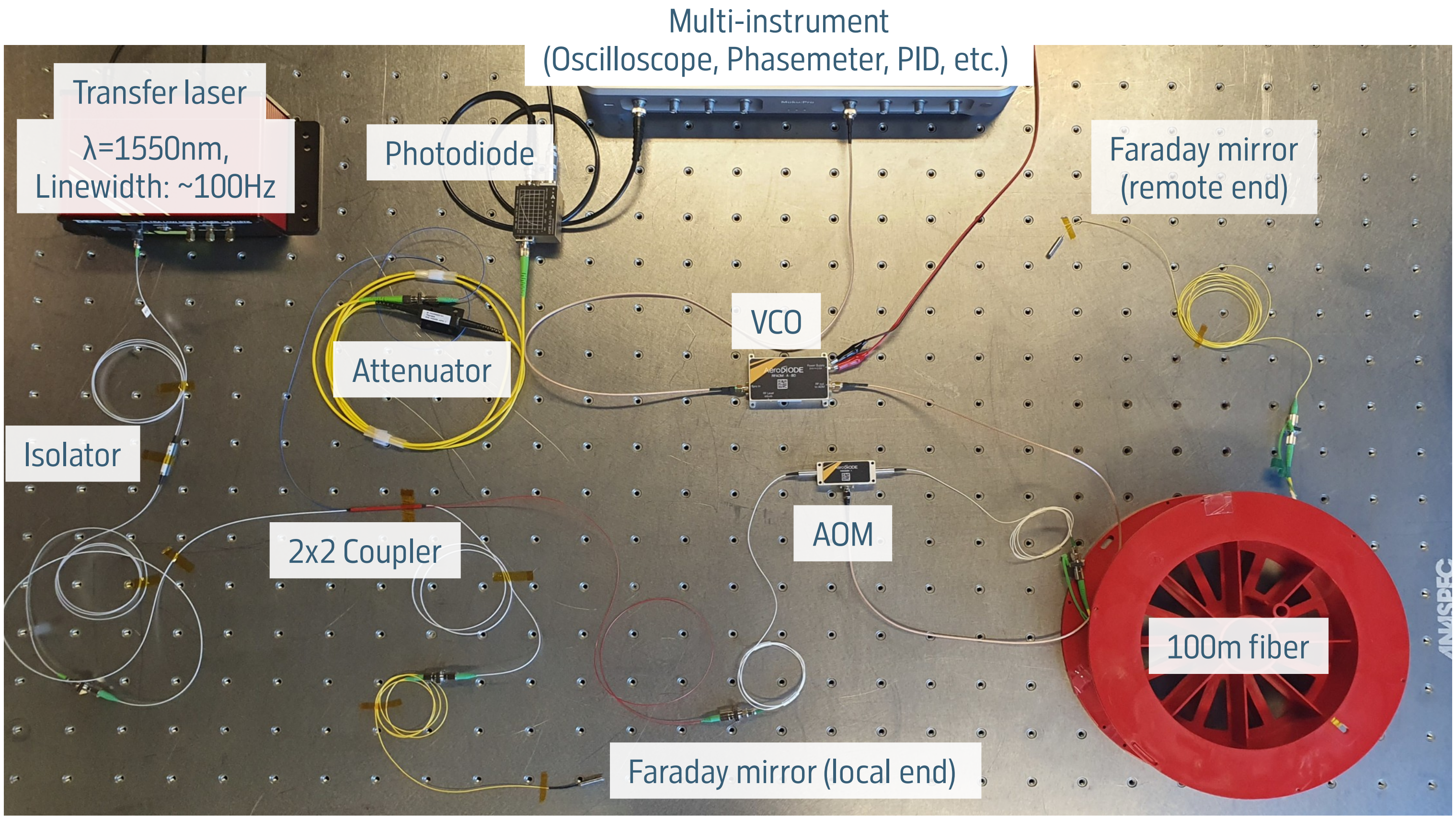


Fiber Michelson-interferometer uses RF beat note to identify & correct for phase noise

Goals and open questions

- Optimize performance
- Test longer 25km fiber connection
  (Physics Dept. Adlershof ⇔ Telekom Labs Berlin-Mitte)
- Make packaged, reproducible version
- Prepare lab for clock
- Dark matter sensitivity estimates

Thanks for your attention!

Backup

Backup: ULDM theory

QED Lagrangian

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi - q\bar{\psi}\gamma^\mu\psi A_\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

Lagrangian for a scalar field ϕ coupling to photon and electron fields

$$\mathcal{L}_\phi = (\partial_\mu\phi)(\partial^\mu\phi) - V(\phi) - g\phi\bar{\psi}\psi + \frac{q'\phi}{4}F_{\mu\nu}F^{\mu\nu}$$

Modified QED Lagrangian

$$\mathcal{L} \supset -\frac{1}{4}\left(1 - (\kappa\phi)^n d_\gamma^{(n)}\right)F_{\mu\nu}F^{\mu\nu} - m_e\left(1 + (\kappa\phi)^n d_{m_e}^{(n)}\right)\bar{\psi}\psi$$

Finestructure constant α and electron mass m_e effectively become functions of ϕ

$$\alpha(\phi) = \alpha_0\left(1 + (\kappa\phi)^n d_\gamma^{(n)}\right) \qquad m_e(\phi) = m_{e,0}\left(1 + (\kappa\phi)^n d_{m_e}^{(n)}\right)$$

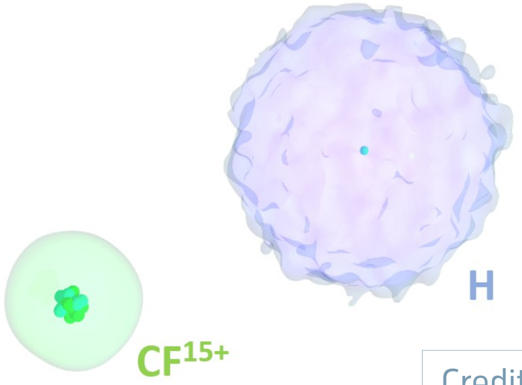
Coupling parameter

$$\kappa^n d_i^{(n)} = \frac{1}{\Lambda^n} \qquad \kappa = \sqrt{4\pi G} = \frac{1}{\sqrt{2}M_{\text{Pl}}}$$

D. Kimball, The Search for Ultralight Bosonic Dark Matter, 2023

Backup: Highly charged ions (HCIs)

- HCIs are interesting as **clock reference**, due to strong binding of electrons to the nucleus:
  - Suppression of systematic effects
  - Some transitions very sensitive to α
  - However: hard to produce & handle, most transitions in XUV



Credit: QSNET.org

Atom/Ion	$\lambda_{\text{transition}}$	K^{α}
Sr	698 nm	0.06
Yb^{+}	467 nm	-5.95
Cf^{15+}	618 nm	47
Cf^{17+}	485 nm	-43.05
^{229}Th	$\sim$8 eV	$\leq 10^5$

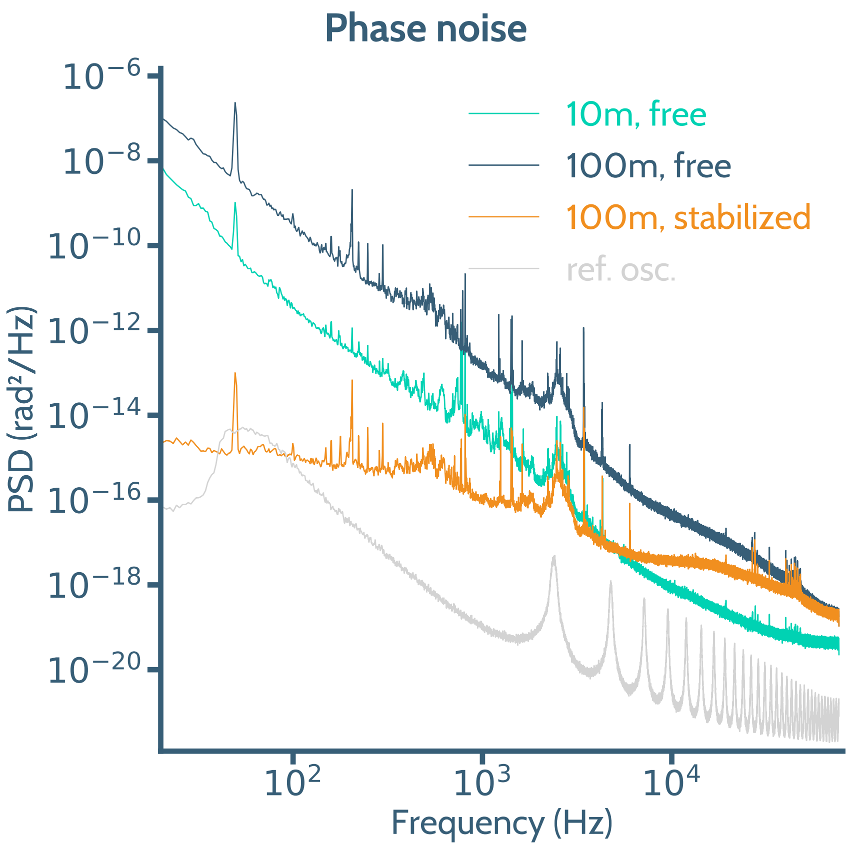
K^{α}: Enhancement factor

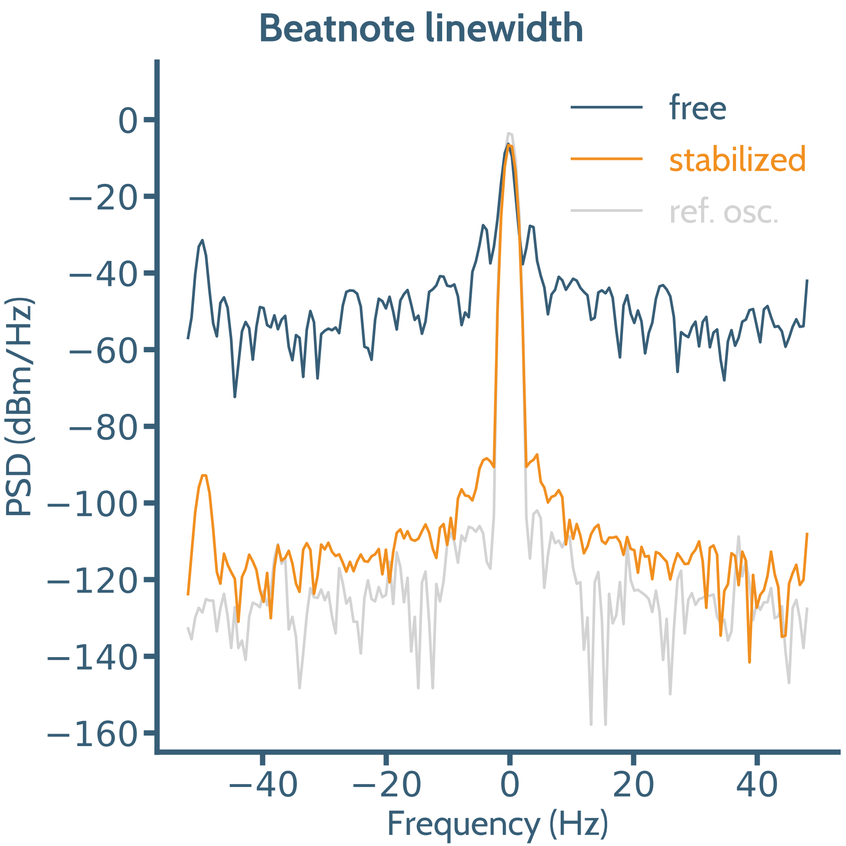
Backup: HCIs's suppression of systematics

Second-order Stark shift	$\sim 1/Z_a^4$
Blackbody shift	$\sim 1/Z_a^4$
Second-order Zeeman shift	suppressed[a]
Electric quadrupole shift	$\sim 1/Z_a^2$
Fine structure	$\sim Z^2 Z_a^3/(Z_{\text{ion}}+1)$
Hyperfine A coefficient	$\sim Z Z_a^3/(Z_{\text{ion}}+1)$

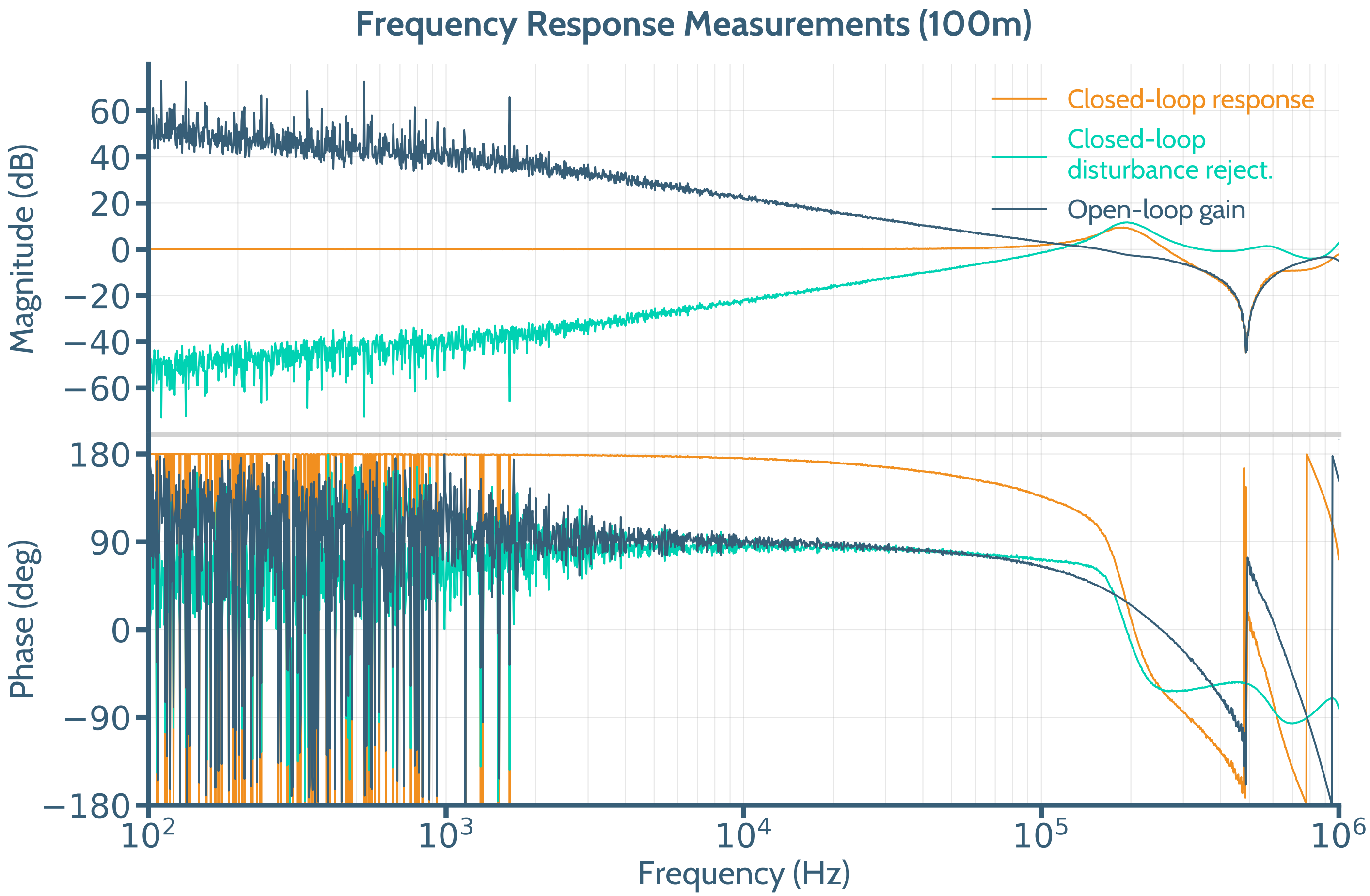
Berengut et al. 2012

Backup: PNC test setup - Performance

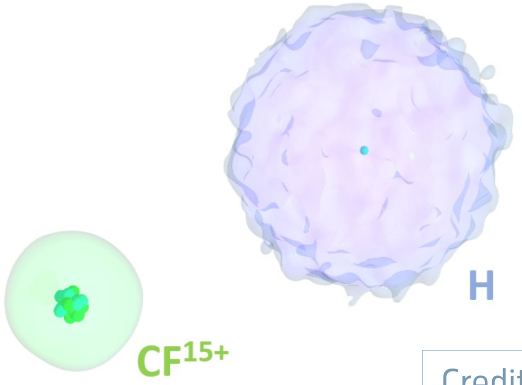




Backup: Loop characterization



Highly charged ions (HCIs)



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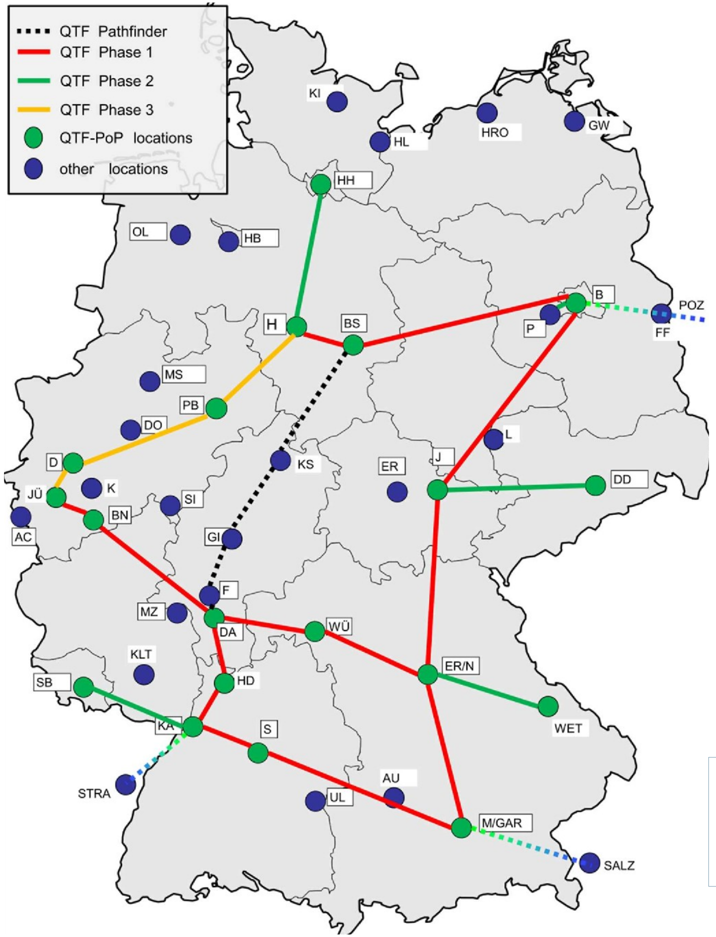
K^{α}: Enhancement factor

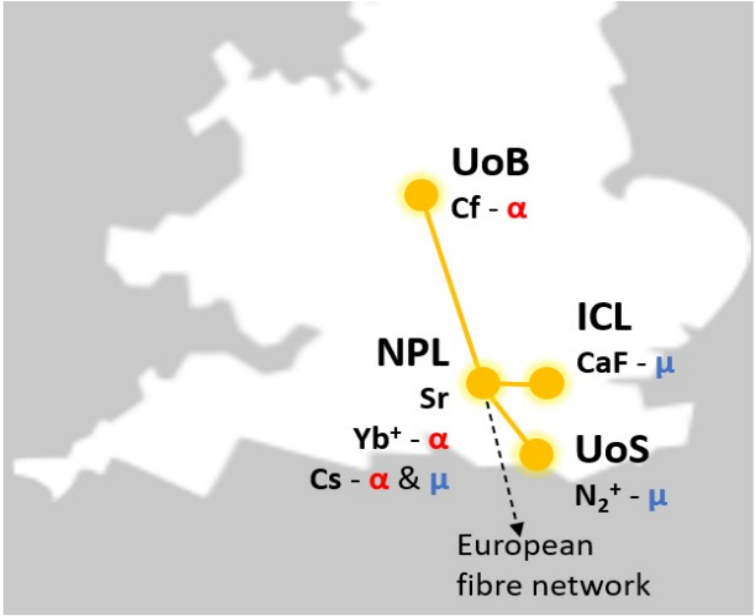
Backup: QTF-Backbone

- QTF:
  Quantum channel, time & frequency distribution



QTF-Backbone Proposal

Backup: QSNET



Clock	Kα	Kμ
Yb^+ (467 nm)	-5.95	0
Sr (698 nm)	0.06	0
Cs (32.6 mm)	2.83	1
CaF (17 μm)	0	0.5
N_2^+ (2.31 μm)	0	0.5
Cf^{15+} (618 nm)	47	0
Cf^{17+} (485 nm)	-43.5	0

Barontini et al., 2022