CQTA seminar
18.07.2024

Search for variation of fundamental constants with atomic clocks: Towards a highly charged ion clock

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Quantum sensing group
Prof. Dr. Steven Worm
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Outline

- Atomic clocks – principle and characteristics
- Why highly charged ion clocks?
- How to detect variations of the fundamental constants with clocks
- Planned experimental setup
- What are theoretical motivations for variation of the fundamental constants?
  → Scalar fields
- What physical phenomena could the scalar field represent?
  - Dark matter
  - Dark energy

Motivation – Temporal variation of fundamental constants

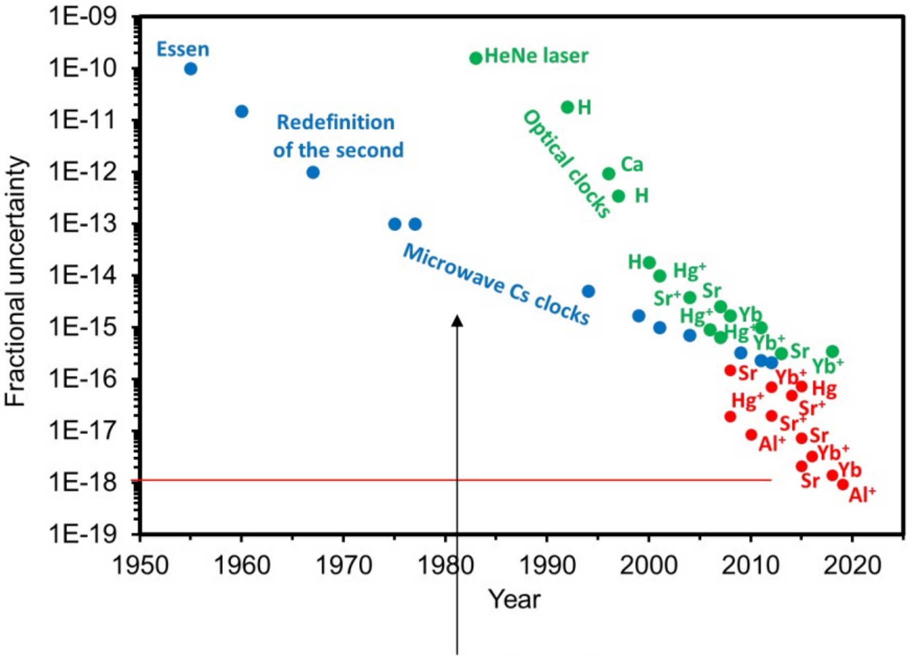
- Our experiment aims to measure a temporal variation of the fine-structure constant α
- Many different approaches to test time-variations in α
- Are physics the same everywhere and for all times in the universe?
- Energy running of couplings → why not also in time?

$\dot{\alpha}/\alpha\ (yr^{-1})$	Redshift	Method
$<0.5 \times 10^{-16}$	0.15	Oklo natural nuclear reactor
$< 3.4 \times 10^{-16}$	0.45	^{187}Re decay in meteorites
$< 10^{-16}$	0.2-3.7	Spectra of distant quasars
$< 10^{-19}$	0	Clock comparisons

C. Will, Living Rev Relativ. 9: 3, 2006

Evolution of atomic clocks

- Today one of the most precise measurement devices
- Current best clocks have fractional frequency uncertainty of $\Delta f/f \approx 10^{-18}$
- High-precision clocks used to test fundamental physics



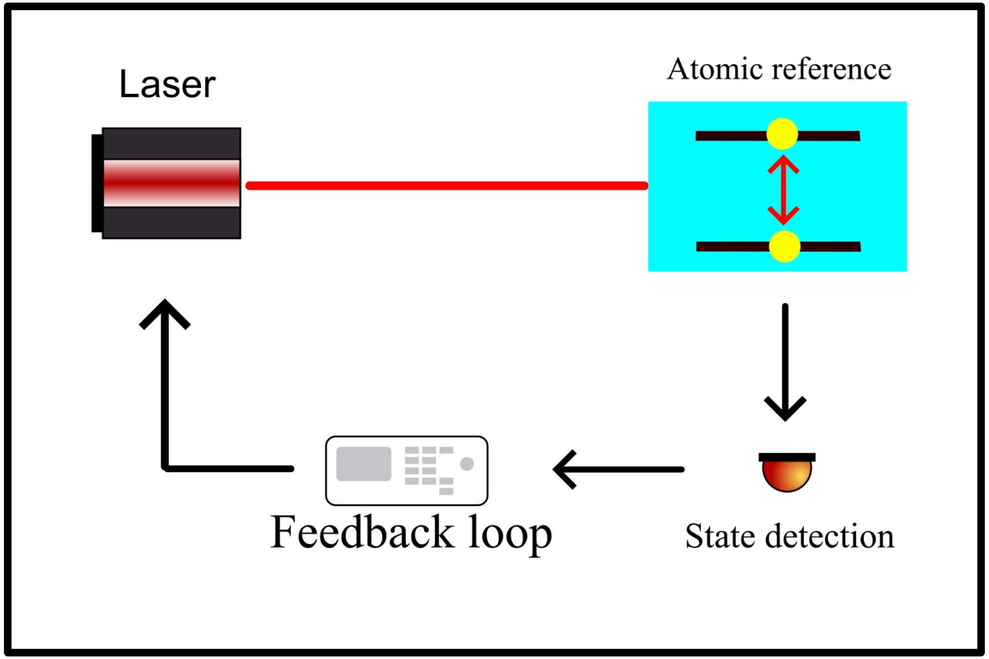
Current definition of the SI second

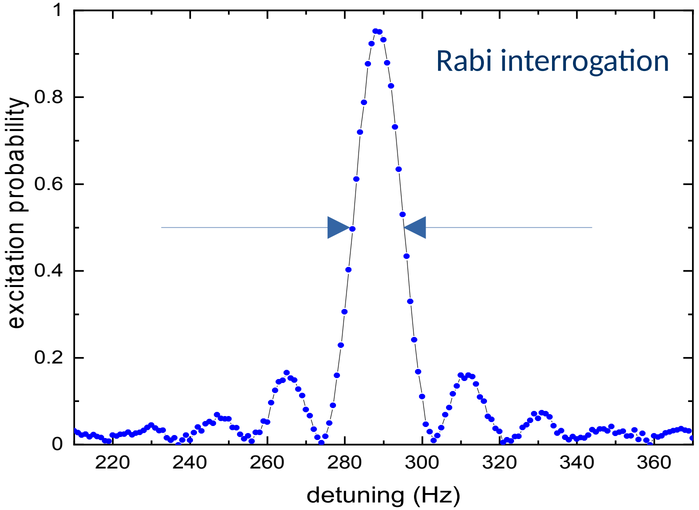
Testing fundamental physics with atomic clocks

Gravity	Fundamental constants

Testing Einstein's equivalence principle, in particular local Lorentz and position invariance	**Variation of fundamental constants might change clock frequency. Possibility to test many branches of high energy physics**

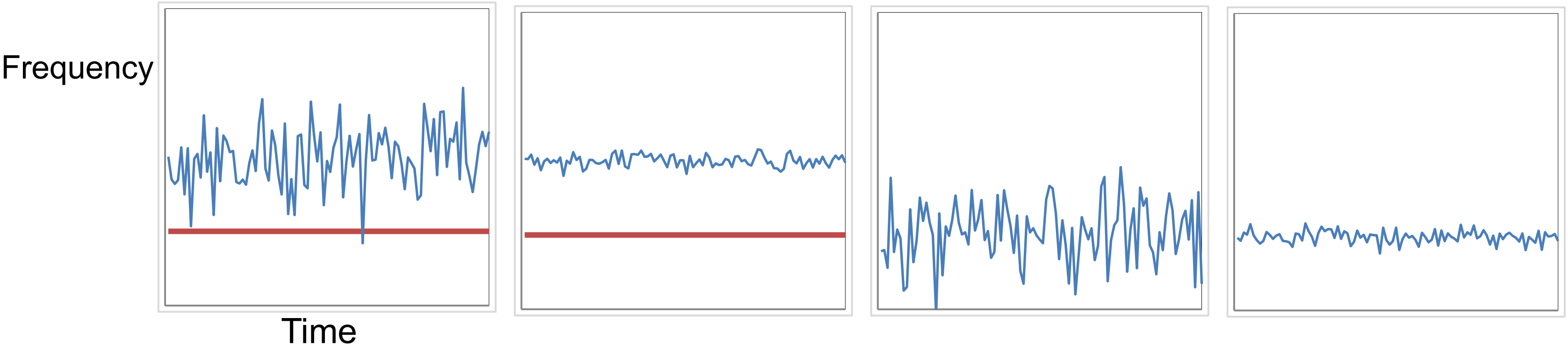
Atomic clocks – working principle





C. Lisdat,
Frontiers of Quantum Mechanics conference,
Bad Honnef, 2024

Clock characterization



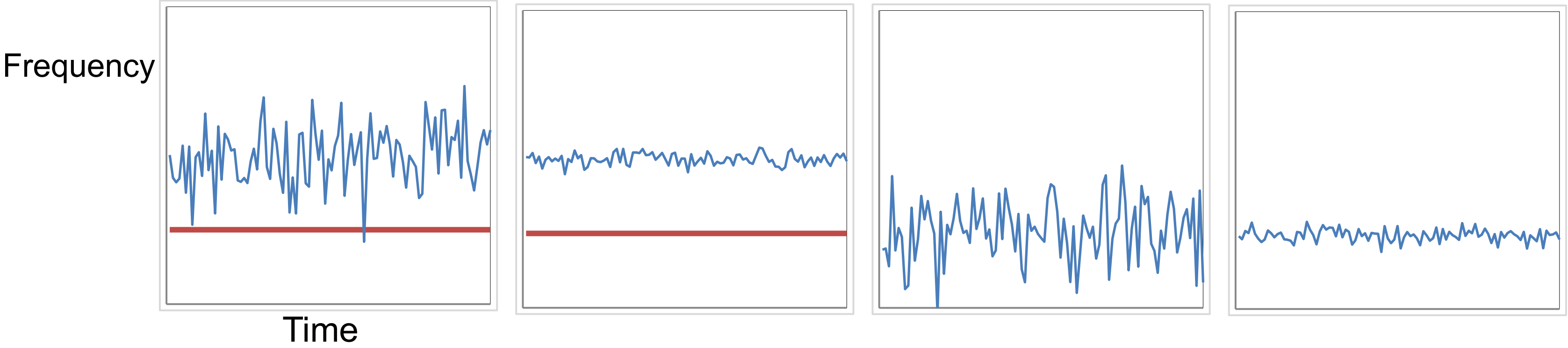
unstable, inaccurate | stable, inaccurate | unstable, accurate | stable, accurate

C. Lisdat, Frontiers of Quantum Mechanics conference, Bad Honnef, 2024

Stability → Statistical uncertainty → Quantum projection noise

Accuracy → Systematic uncertainty → Blackbody radiation, Doppler shifts, EM-effects, etc.

Clock characterization



unstable, inaccurate	stable, inaccurate	unstable, accurate	stable, accurate

C. Lisdat, Frontiers of Quantum Mechanics conference, Bad Honnef, 2024

Stability → Statistical uncertainty → Narrow optical transitions, many atoms, long operation times

Accuracy → Systematic uncertainty → Low sensitivity to external fields

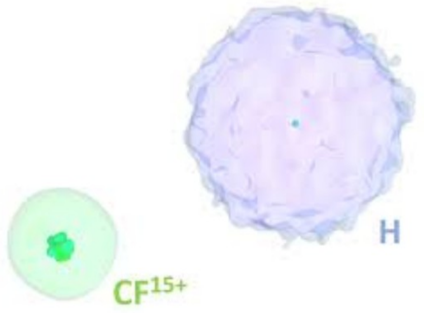
Why highly charged ions?

Highly charged ions

→ Strong binding energy of electrons to nucleus
→ Suppression of systematic shifts

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., PRA 86, 022517 (2012)



https://qsnet.org.uk/highly-charged-ion-clock/

+ High sensitivity to variations of α

Clock sensitivity to variation of fundamental constants

- Energy levels depend on α
with relativistic corrections $F_{rel}(\alpha)$
→ Complicated!

- Transition frequency can very generically be parametrized by α and sensitivity coefficient K

- How do we know the value of K?

→ Atomic spectra calculations
AMBiT, Flexible atomic code (FAC)

J. Berengut et al., arXiv:1805.11265

M. Gu, Can. J. Phys. 86: 675-689 (2008)

$$\nu = \nu(\alpha) = \nu_0 \alpha^K \quad \Rightarrow \quad \frac{d\nu}{d\alpha} = K \frac{\nu(\alpha)}{\alpha}$$

$$\Rightarrow \frac{d\nu}{\nu} = K \frac{d\alpha}{\alpha}$$

$$E(\alpha) = E_0 + q\left[\left(\frac{\alpha}{\alpha_0}\right)^2 - 1\right]$$

$$q = \frac{E(\delta) - E(-\delta)}{2\delta}$$

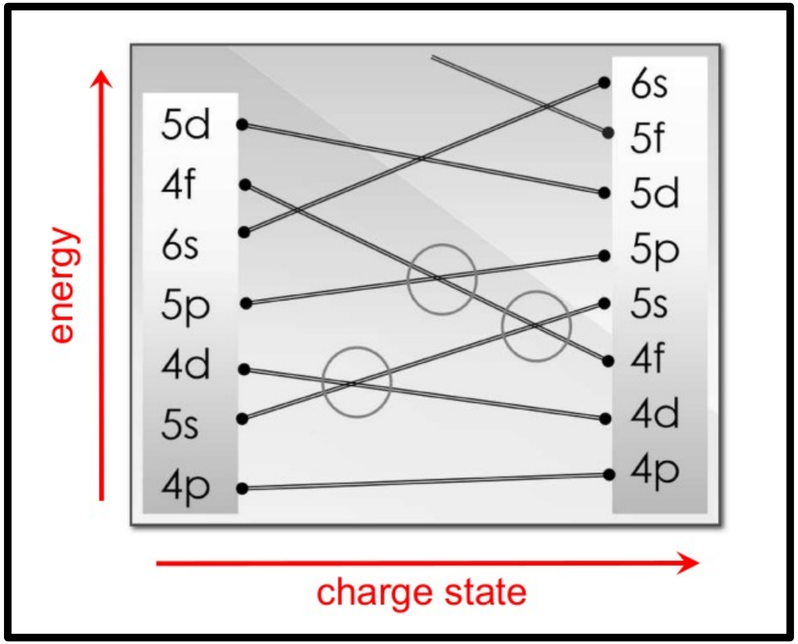
$$\rightarrow \boxed{K := \frac{2q}{E_0}}$$

Which ion to use?

<u>Demands on Ion:</u>

- narrow optical transition
  $\rightarrow$ **Level crossing**
- **High sensitivity to α-variations**
- Ideal: Cooling + readout transition

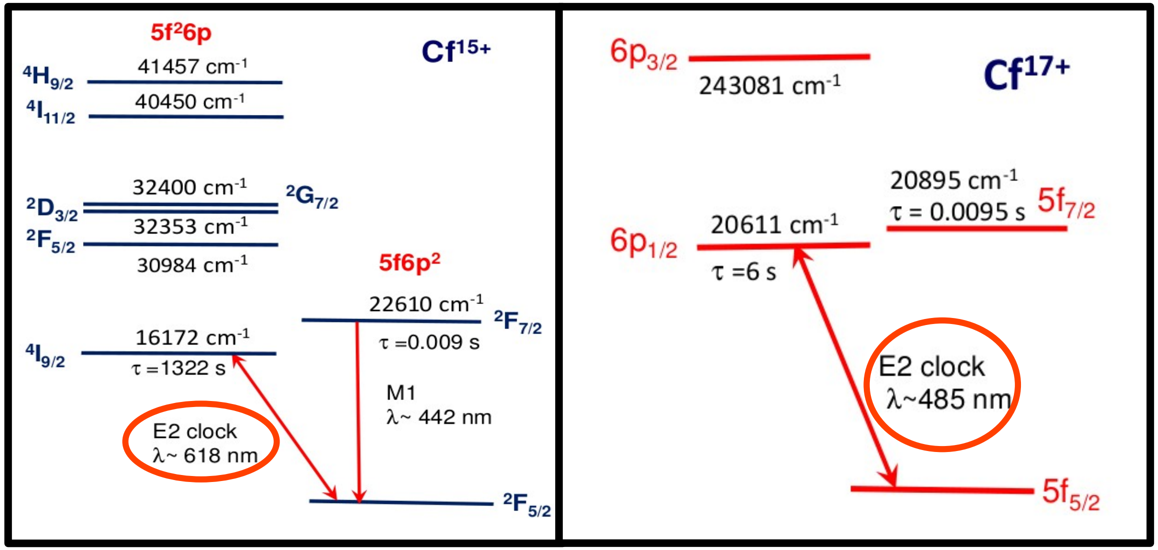
$$q \sim I_n \frac{(Z\alpha)^2}{n} = \frac{Z_a^2}{2n^2}\frac{(Z\alpha)^2}{n} \rightarrow \boxed{K := \frac{2q}{E_0}}$$



Kozlov et al., Rev. Mod. Phys 90, 045005 (2018)

J. C. Berengut et al., Phy Rev A 86, 022517 (2012)

Candidate ion: Cf^{15+}/Cf^{17+}

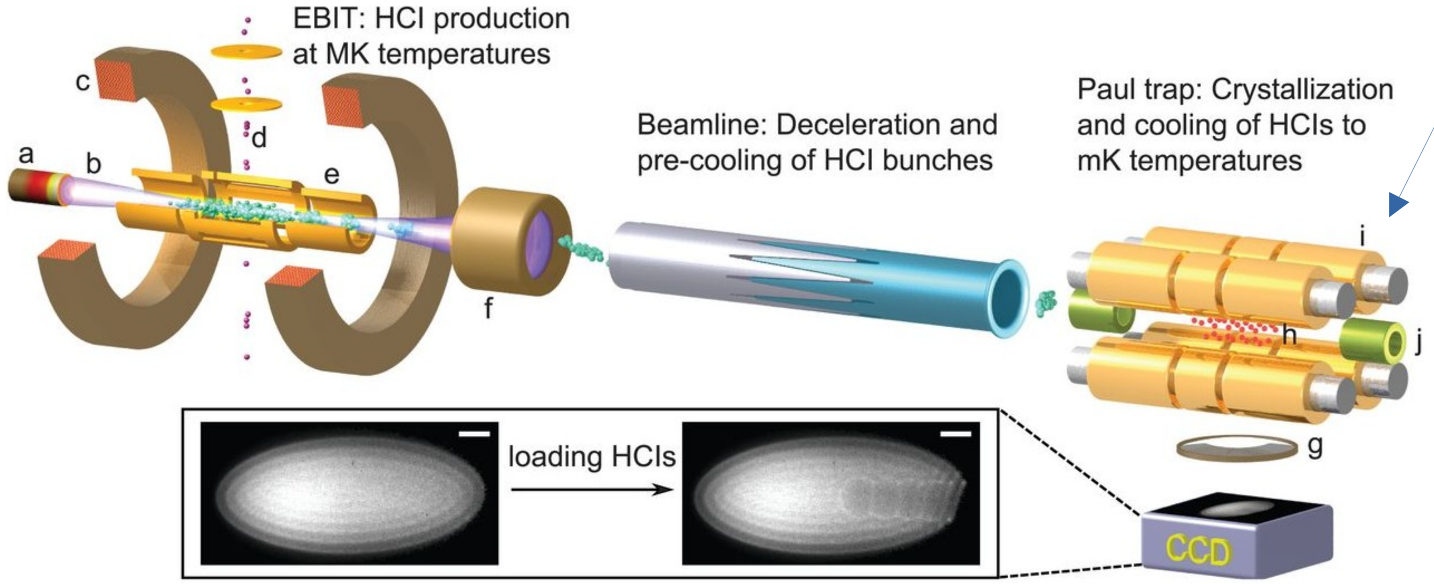


- Estimated K_α:
  $Cf^{15+} \rightarrow K_\alpha = 47$
  $Cf^{17+} \rightarrow K_\alpha = -43$
- Comparison:
  $Yb^+ \rightarrow K_\alpha = -5.95$
  Sr $\rightarrow K_\alpha = 0.06$
- Estimated accuracy:
  $\sigma_{sys} \sim 10^{-19}$
- Spectroscopy will be done soon at MPIK in Heidelberg in collaboration with J.Crespos group
  → DESY members:
  Lakshmi K. Sajith + Yang Yang

S. G. Porsev et al., Phy. Rev. A 102, 012802 (2020)

Barontini et al., EPJ Quantum Technol. 9, 12 (2022)

Highly charged ion clock



Sympathetic cooling with Be^+

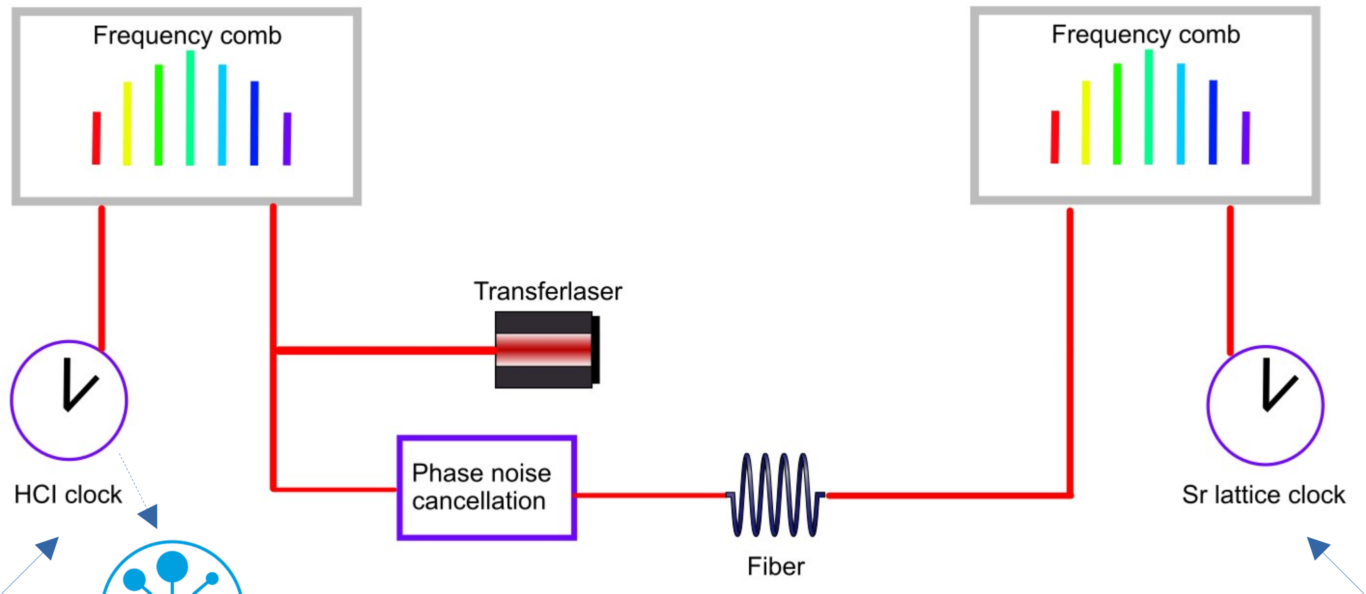
Interrogation with clock laser

Readout: Electron shelving/ Quantum logic spectroscopy

L. Schmöger et al., Science Vol 347, Issue 6227 (2015)

P. Micke et al., Nature 578, 2020

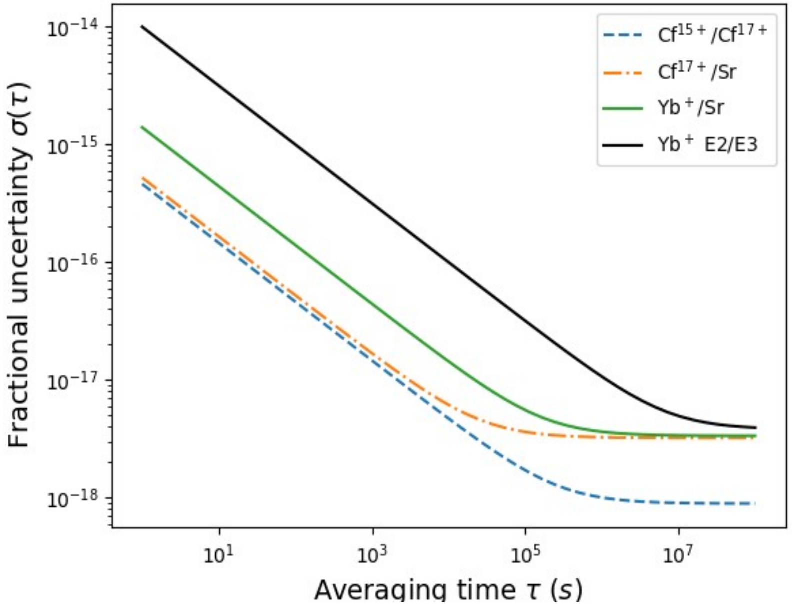
Planned experimental setup

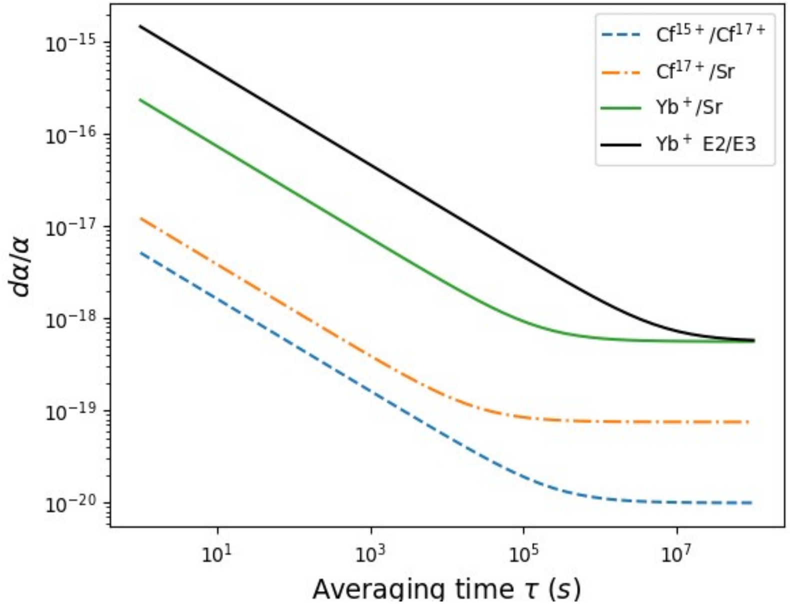


Will be built by our group

Currently built by M. Krutzik's group at HU

Estimated performance





Yb^{+}/Sr : Nathaniel Sherrill et al., New J. Phys. 25 093012 (2023)
Yb^{+} E2/E3: Filtzinger et al., PRL 130 25, 253001 (2023)

Current limit: $\mathbf{1/\alpha(d\alpha/dt) \sim 10^{-19}\ yr^{-1}}$

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- How to detect variations of the fundamental constants with clocks
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- **What physical phenomena could the scalar field represent**
    - **Dark matter**
    - **Dark energy**

Scalar fields in theories beyond the standard model

Scalar field ϕ(t)

Dark matter
(**Axion-like**, dilatonic, solitonic)

Dynamical dark energy
(Quintessence, Chameleon, ...)

Modified/Quantum Gravity
(Scalar-Tensor Gravity, String theory,...)

Many well-motivated ideas – we are interested in
the effective low energy coupling to the standard model fields

„Effective“ QED + scalar field

QED Lagrangian

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

Adding a scalar field which couples to photon and electron fields

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

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

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

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

Scalar field induced variation of α

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

$$A'_\mu = (1-(\kappa\phi)^n d_\gamma^{(n)})^{-1/2} A_\mu$$

$$q\bar{\psi}\gamma^\mu\psi A'_\mu = \underbrace{q(1-(\kappa\phi)^n d_\gamma^{(n)})^{-1/2}}_{q_{eff}}\bar{\psi}\gamma^\mu\psi A_\mu$$

ϕ-dependent expression for fine-structure constant

$$\boxed{\alpha(\phi) = \frac{q_{eff}^2}{4\pi} = \alpha\,(1+(\kappa\phi)^n d_\gamma^{(n)})}$$

Varying constants due to scalar field

$$\alpha(\phi) = \alpha_0 \left(1 + (\kappa\phi)^n d_\gamma^{(n)}\right)$$

$$\alpha_S(\phi) = \frac{g_{eff}^2}{4\pi} = \alpha_S \left(1 + (\kappa\phi)^n d_g^{(n)}\right)$$

$$\frac{\Delta\alpha_j}{\alpha_j} = (\kappa\phi)^n d_{\gamma/g}^{(n)}$$

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

$$m_{q_i}(\phi) = m_{q_i,0}\left(1 + (\kappa\phi)^n d_{m_{q_i}}^{(n)}\right)$$

$$\frac{\Delta m_j}{m_j} = (\kappa\phi)^n d_{m_j}^{(n)}$$

Possible sources of variation of α

Scalar field ϕ(t)

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$$

EOM for scalar field in flat FLRW spacetime

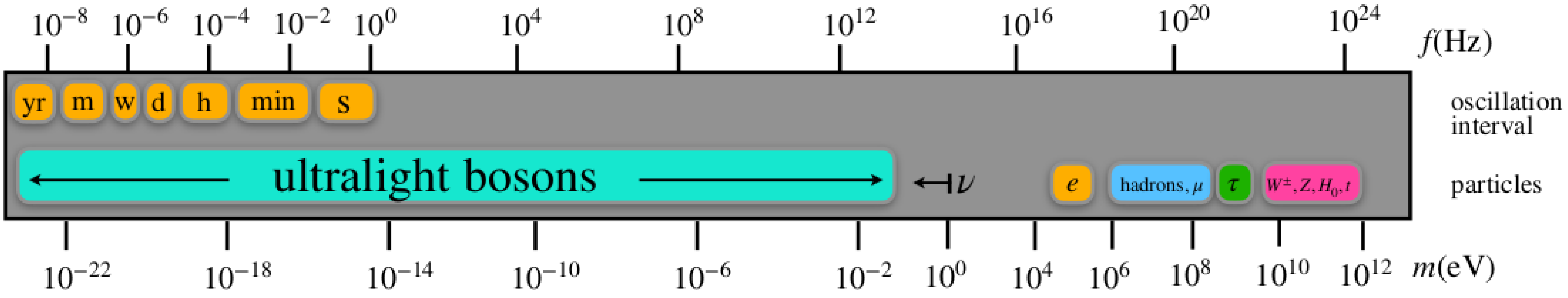
$H \ll m$ → Dark matter, field oscillates

$H_0 \sim 10^{-33}$ eV

$H \geq m$ → Dark energy, field evolves on cosmological timescales

The inverse of H and m are the characteristical timescales of expansion and field evolution!

Dark matter



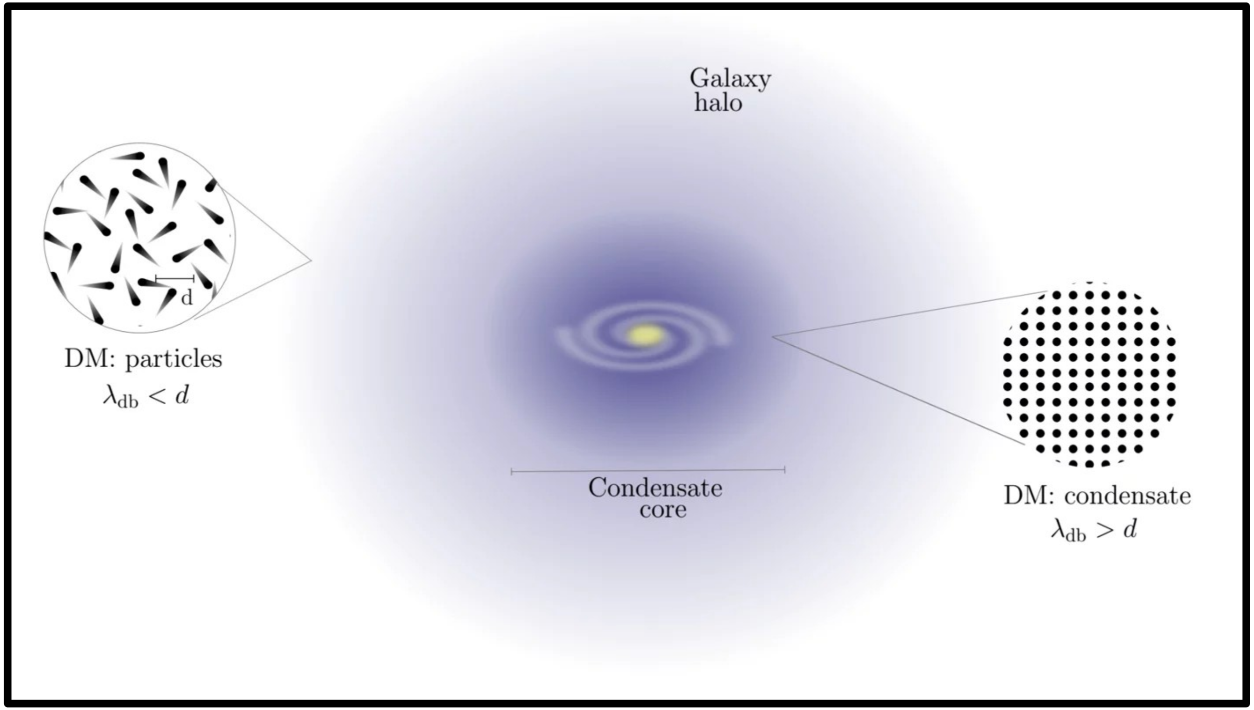
$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0 \xrightarrow{H \ll m} \phi(t) \approx \phi_0 \, cos(m_\phi t)$$

EOM for scalar field in flat FLRW spacetime

Oscillation frequency: $f \sim m_\phi$

Ultra light dark matter

- Ultra light dark matter (ULDM)
  → CDM on large scales while overcoming the small-scale problems (Cusp-core, missing satellites)
- ULDM forms Bose-Einstein condensate / Superfluid
- Condensation within galaxies
  → coherent oscillations
  Why coherent?



E. Ferreira, Astron A. Rev. 29/1, 2021

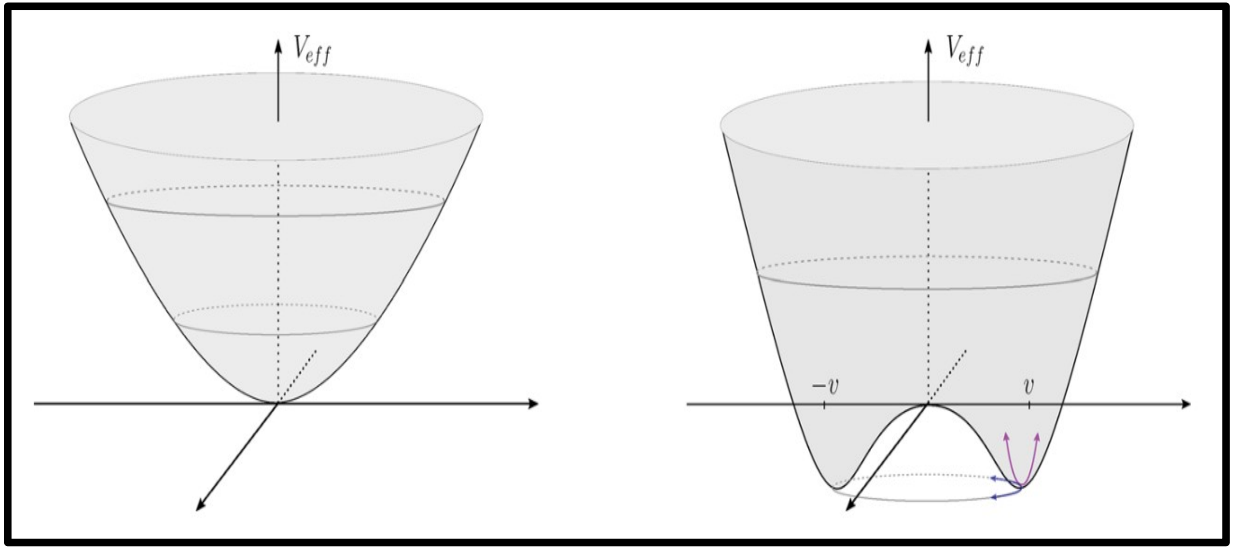
BEC: Field theoretic description

- Condensation: Spontaneous symmetry breaking of global U(1) symmetry by the ground state
- All particles in ground state have the same phase
  → Coherence
- Superfluid → Phonons

E. Ferreira, Astron A. Rev. 29/1, 2021

$$\mathcal{L} = (\partial_\mu \Psi)^*(\partial_\mu \Psi) - m^2 \Psi^* \Psi - \frac{g}{2}(\Psi^* \Psi)^2$$

$$\Psi \to \Psi e^{i\alpha}, \quad \Psi^* \to \Psi e^{-i\alpha}$$



Constraining ULDM models with clock experiments

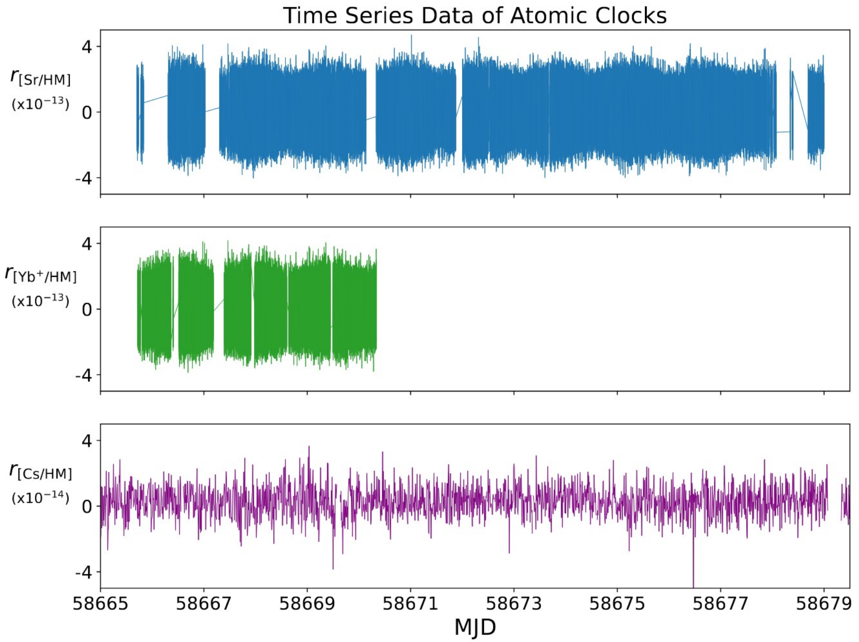
- Variation of fine-structure constant:

$$\frac{\Delta\alpha_j}{\alpha_j} = (\kappa\phi)^n d^{(n)}_{\gamma/g} \longrightarrow \boxed{\frac{d\alpha}{\alpha} = d_\gamma \ \kappa \ \phi_0 \ cos(m_\phi c^2/\hbar \ t)}$$

Comparing two clocks → Frequency ratio **R = ν₁/ν₂**

$$\frac{dR}{R} = \Delta K \frac{d\alpha}{\alpha} \longrightarrow \boxed{\frac{dR}{R} = \Delta K \frac{d\alpha}{\alpha} = \Delta K \ d_\gamma \ \kappa \ \phi_0 \ cos(m_\phi c^2/\hbar t)}$$

Comparing estimated performance to measurement of NPL

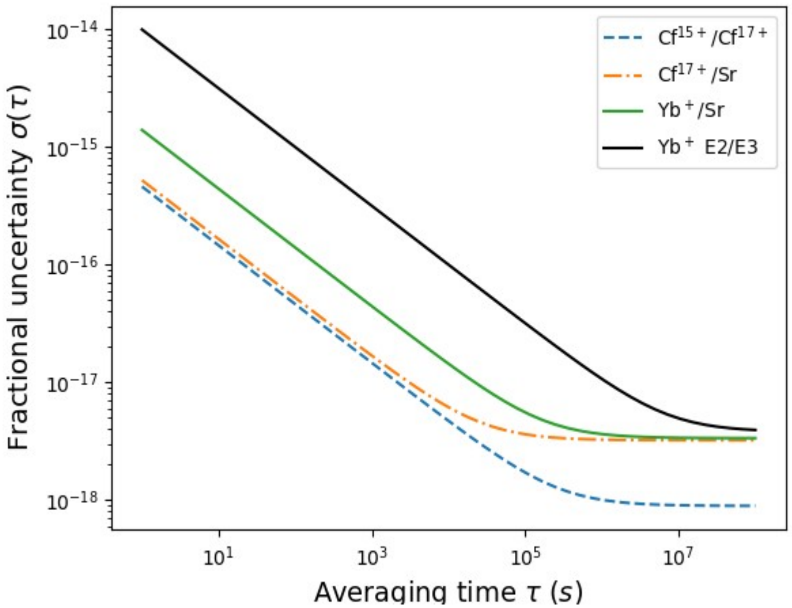


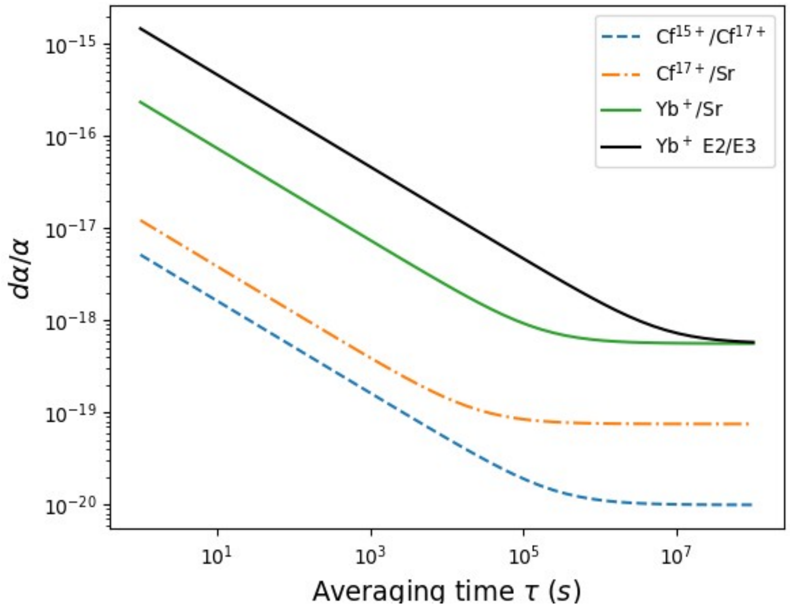
$$\boxed{\frac{dR}{R} = \Delta K \frac{d\alpha}{\alpha} = \Delta K \; d_\gamma \; \kappa \; \phi_0 \; cos(m_\phi c^2/\hbar t)}$$

Atom / Ion	$\lambda_{transition}$	σ_{sys}	N_{Atoms}	T_p	τ	K_α
Sr	698 nm	2×10^{-18}	10^4	0.5 s	1 s	0.06
Yb^+	467 nm	2.7×10^{-18}	1	0.5 s	1 s	-5.95
Cf^{15+}	618 nm	5.2×10^{-19}	1	0.5 s	1 s	47
Cf^{17+}	485 nm	1.01×10^{-18}	1	0.5 s	1 s	-43.05

Yb^+/Sr : Nathaniel Sherrill et al., New J. Phys. 25 093012 (2023)

Estimated performance

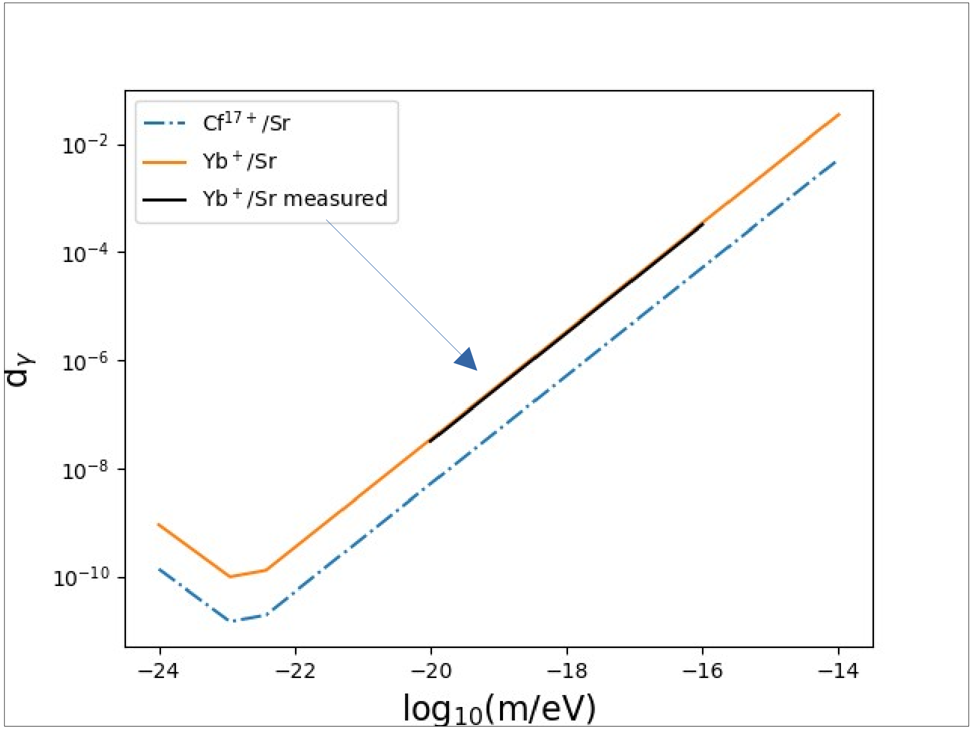




Yb^+/Sr : Nathaniel Sherrill et al., New J. Phys. 25 093012 (2023)
Yb^+ E2/E3: Filtzinger et al., PRL 130 25, 253001 (2023)

Current limit: $\mathbf{1/\alpha(d\alpha/dt) \sim 10^{-19}\ yr^{-1}}$

Testing ULDM with clocks



Yb^{+}/Sr : Nathaniel Sherrill et al., New J. Phys. 25 093012 (2023)

- Perform Monte Carlo simulations to estimate minimal signal Amplitude $A_{5\sigma}$
- Analysis with Lomb-Scargle Periodogram

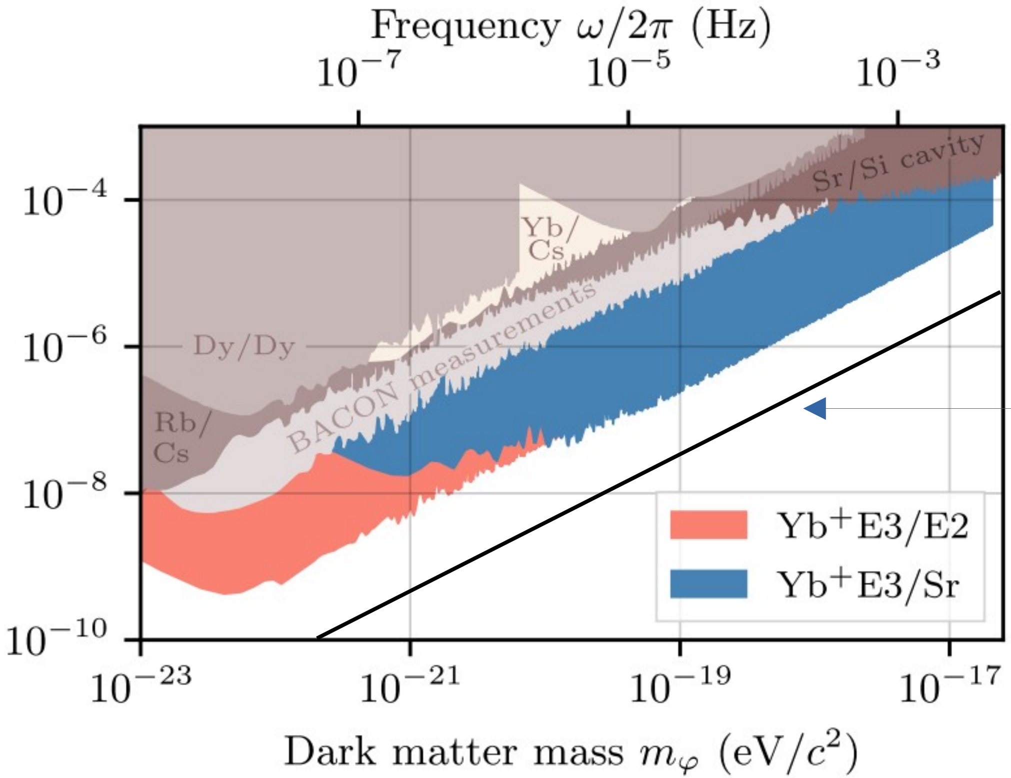
$$\boxed{d_\gamma = \frac{A}{\Delta K \ \kappa \ \phi_0}}$$

- Assumptions:
  - Simul. Measurement time: 1 yr
    Sampling time: 1 s
  - All DM in form of ULDM

$$\kappa = \sqrt{4\pi G} \qquad \phi_0 = \frac{\hbar}{mc}\sqrt{2\rho_{DM}}$$

$$\rho_{DM} = 0.4\ GeV/cm^3$$

Comparing to existing constraints

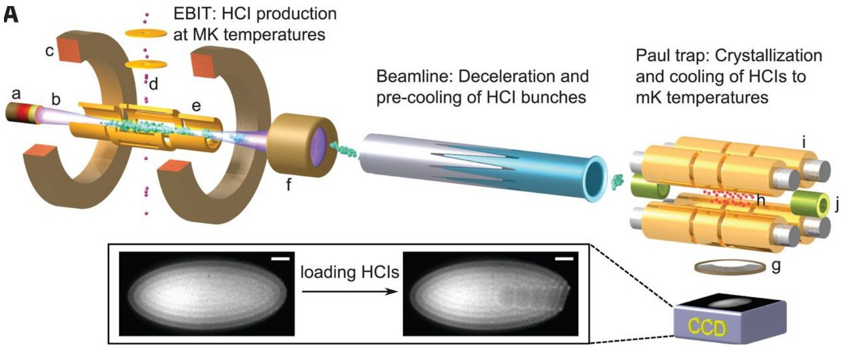


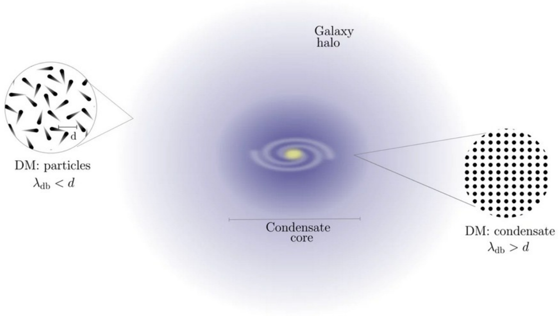
Estimated performance of Cf/Sr:
Possible enhancement of sensitivity of one order of magnitude

Yb^{+} E2/E3: Filtzinger et al., PRL 130 25, 253001 (2023)

Summary

- We are in the first steps of building up a highly charged ion clock at HU Berlin/DESY Zeuthen
- A highly charged ion clock promises an excellent accuracy + high sensitivity to variations of the fine-structure constant α
- Experiment offers the possibility to test many different fundamental physics models

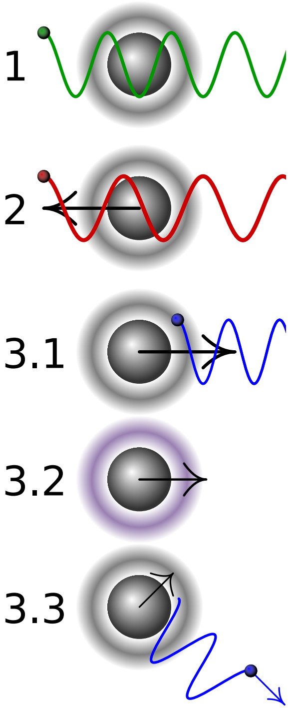


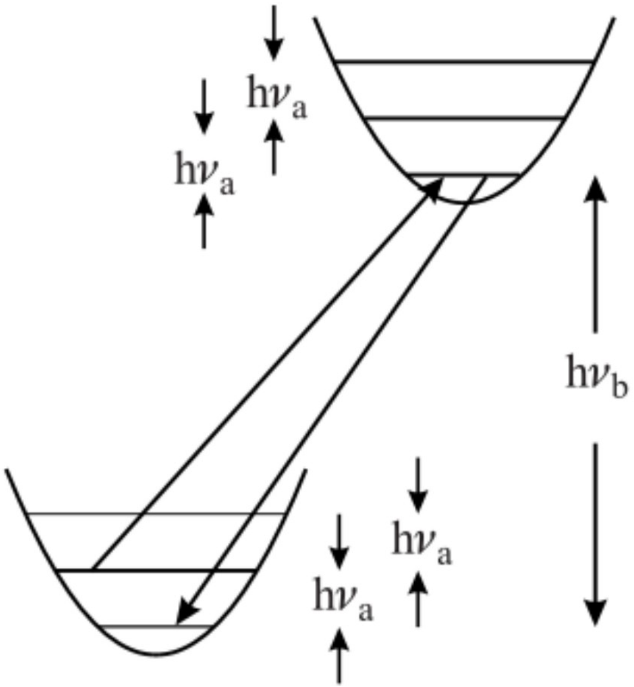


Thank you!

Backup

Laser cooling



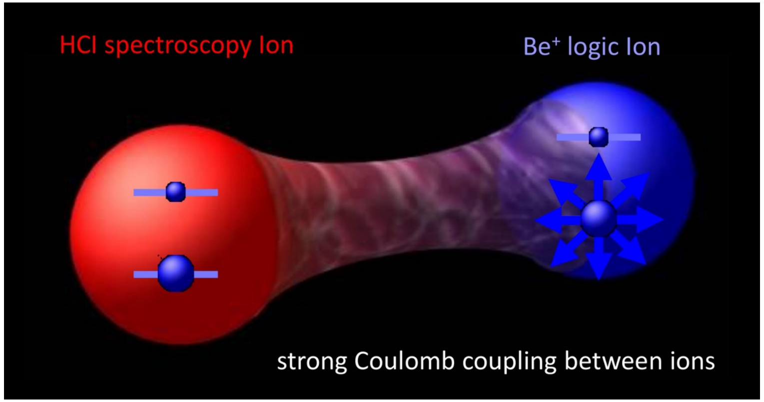


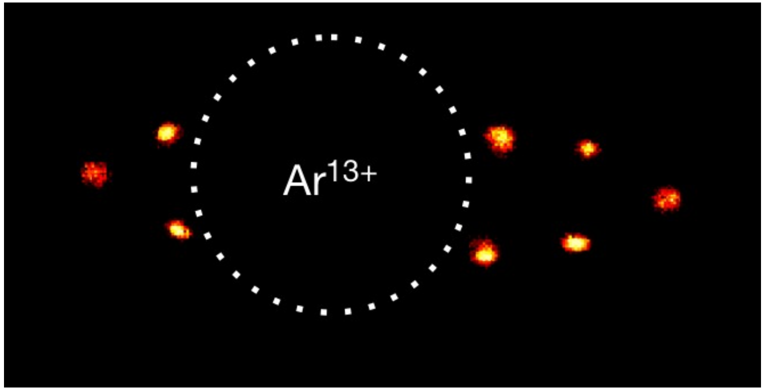
Sympathetic cooling

- Problem: HCI may not have a transition suitable for laser-cooling

- Cooling of HCI via Coulomb interaction with ion crystal Ions that can be directly laser-cooled are used to cool other ions

- Sympathetic cooling is said to be most efficient when charge/mass ratio of the cooling ion and the target ion are similar





P. Schmidt, Frequency Standards and Precision Measurements Summer School, 2023

P. Micke et al., Nature Vol. 578, 2020

Quantum logic spectroscopy

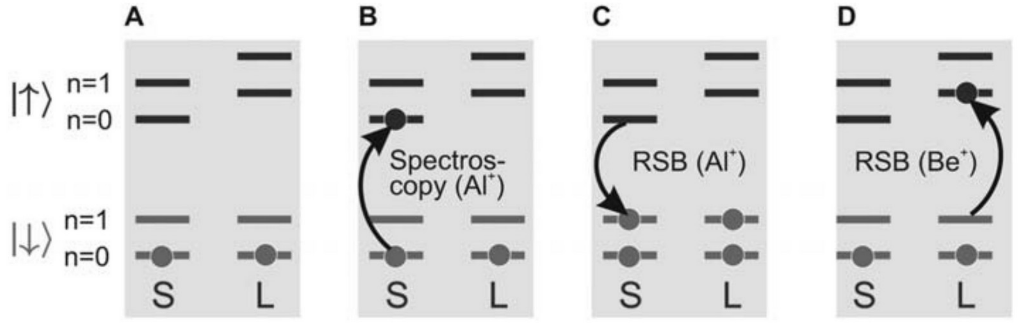
- How do we find out if the clock frequency is right with only a single ion?

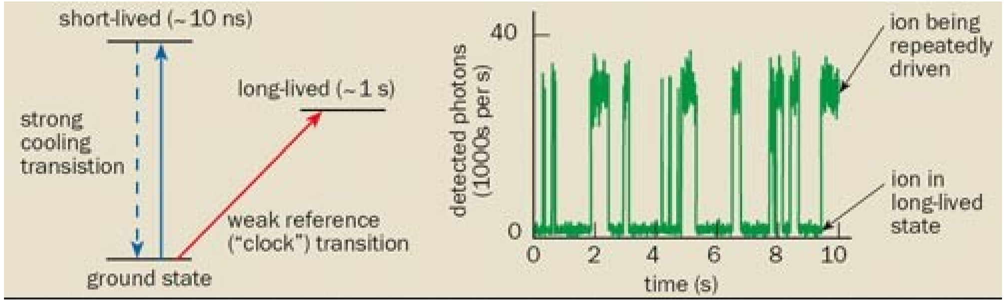
- Two-ion crystal shares common motional modes

- Application of red sideband pulses
  → transfer excitation from spectroscopy ion to logic ion

- Readout of logic ion via electron shelving

P. Schmidt et al., Science vol. 309, 2005

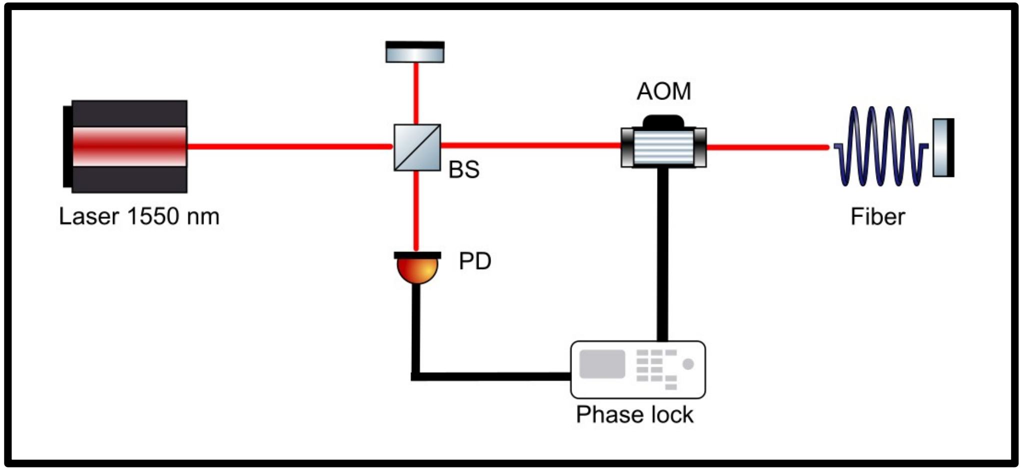




Phase noise cancellation

- Fiber based Michelson interferometer
- Phase locked loop
  → AOM (acousto-optical modulator) used to compensate for phase noise of transfer fiber

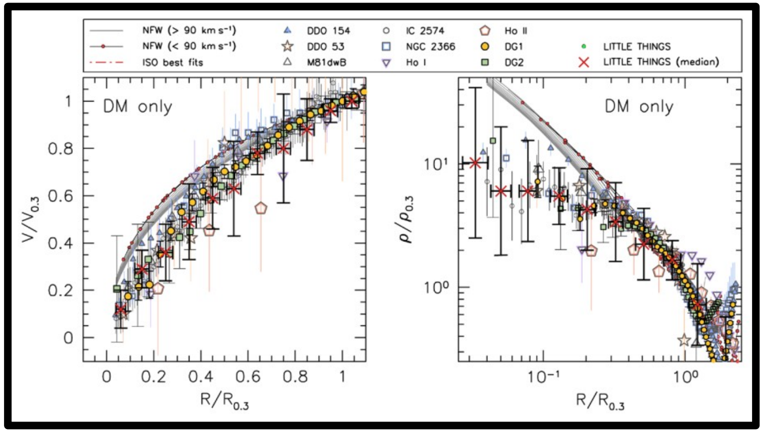
  → Constant phase relation between initial laser light and light after passing through fiber

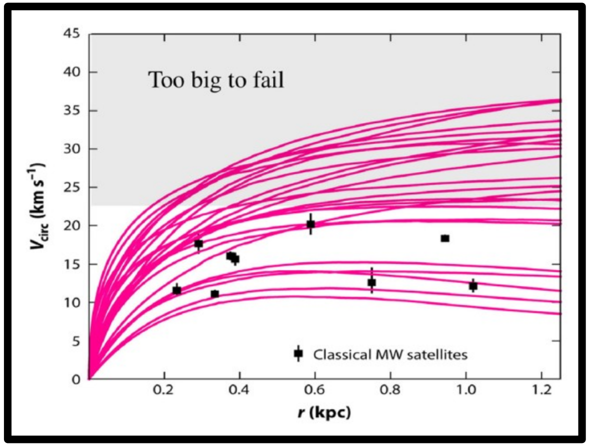


Ultra light dark matter

Some tension between Standard ΛCDM-cosmology and observations

- Cusp-core problem
- Missing satellites



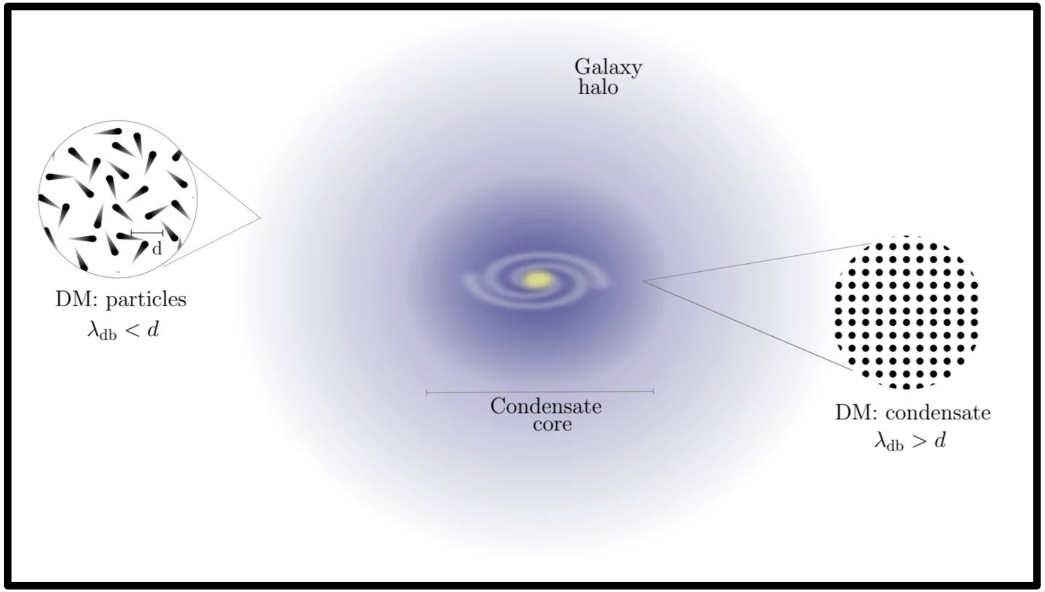


Fuzzy DM

- No Interaction → No superfluid, just BEC
- Now: P_{QP} counteracts gravity
- Small pertubations of BEC
  → Dispersion relation
  → Boundary scale for which stable condensation sets in:

  $\boldsymbol{\lambda_J \sim m^{-1/2} \cdot \rho^{-1/4}}$ (Jeans scale)

  For **m ~ $\mathbf{10^{-22}}$ eV** → **<u>$\boldsymbol{\lambda_J \sim}$ 3 kpc</u>**



Fuzzy DM

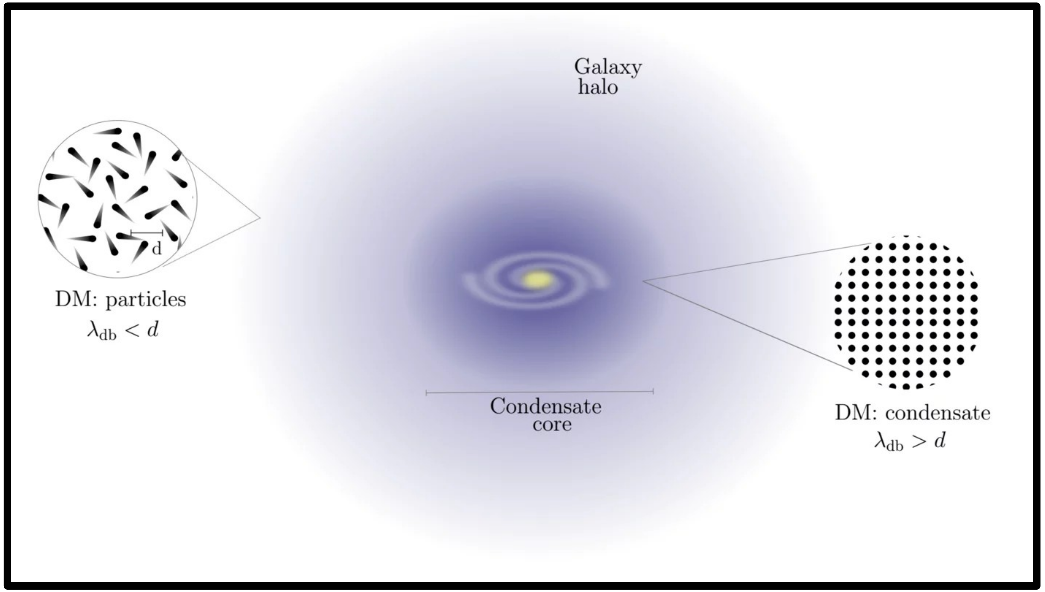
Adress small scale problems:

- Cusp-core problem
  - de Broglie wavelength of FDM must be smaller than radius of galaxies

$$\boxed{R \gtrsim \frac{1}{GMm^2}}$$

- Missing satellites problem
  - Smallest halos given by Jeans scale λ_J $\rightarrow$ Minimum allowed mass for subhalos

$$\boxed{M_J = \frac{4\pi}{3}\rho\left(\frac{1}{2}\lambda_J\right)^3}$$



Both problems can be solved for **$m \sim 10^{-22}$ eV**!

Standard Cosmology - ΛCDM

$$\boxed{\begin{aligned}\left(\frac{\dot{a}}{a}\right)^2 &= \frac{8\pi G}{3}\rho - \frac{k}{a^2}\,, \\ \frac{\ddot{a}}{a} &= -\frac{4\pi G}{3}(\rho + 3P)\end{aligned}}$$

Equation of state for Dark Energy, i.e. accelerated expansion:

$$\frac{P}{\rho} = \omega < -\frac{1}{3} \longrightarrow -1$$

Energy and momentum conservation

$$\nabla_\mu T^\mu_\nu = 0 \longrightarrow \dot{\rho} + 3\frac{\dot{a}}{a}(\rho + P) = 0$$

$$\longrightarrow \rho \propto a^{-3(1+w)}$$

- Negative pressure is necessary for accelerated expansion!
- If CC dominates the energy density of universe → $T_{\mu\nu}$ → 0
→ „Vacuum“ energy

Cosmological constant problem

- <u>Main problem</u>:
  - **GR**: Cosmological constant as vacuum energy is **absolute energy**
    QFT: Vacuum energy (Zero-point energy) is defined **relative**

  - Comparing the observed/predicted vacuum energies:

$$\rho_\Lambda^0 \sim \rho_c^0 = \frac{3H_0^2}{8\pi G} = \frac{3}{8\pi} H_0^2 M_P^2 \sim 10^{-47} GeV^4$$

$$|\rho_{\Lambda,th}^{EW}| \sim 10^8 GeV^4$$

$$\boxed{\left|\frac{\rho_\Lambda^0}{\rho_{\Lambda,Th}^{EW}}\right| \sim 10^{\underline{-55}}}$$

  - Is it even feasible to identify the two vacuum energies?

Dynamical dark energy

- Very generically: What happens when vacuum energy is dynamical?
- Energy and momentum conservation must still hold
- What conclusions can be drawn?

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G \, T_{\mu\nu} - \Lambda g_{\mu\nu}$$

$$\downarrow$$

$$T_{\mu\nu} \to \tilde{T}_{\mu\nu} \equiv T_{\mu\nu} - g_{\mu\nu} \, \rho_{\mathrm{vac}}$$

$$\downarrow$$

$$\nabla^\mu \left(G \, \tilde{T}_{\mu\nu} \right) = \nabla^\mu \, \left[G \left(T_{\mu\nu} - g_{\mu\nu} \, \rho_{\mathrm{vac}} \right) \right] = 0$$

Running vacuum models – 4 cases

Case 1: G= const. , ρ_{vac}=const. → Standard ΛCDM

Case 2: G= const., $\rho_{vac}\neq$const.

Case 3: G$\neq$const., ρ_{vac}=const.

→ Mixed conservation laws: Exchange of energy between matter and vacuum / G

Case 4: G$\neq$const., $\rho_{vac}\neq$const. → Mixed conservation law BUT: trade-off now between G and vacuum energy possible; Usual matter energy conservation also possible

Evolution of vacuum energy density

- Focus on **Case 2** (G= const., ρ_{vac}≠const)

- Mixed conservation law, energy exchange between vacuum and matter

- A solution to this equation is given by:

- This solution can also be derived from renormalization of the zero-point energy on curved space-time

$$\nabla^\mu \left(G \tilde{T}_{\mu\nu}\right) = \nabla^\mu \left[G \left(T_{\mu\nu} - g_{\mu\nu}\, \rho_{\rm vac}\right)\right] = 0$$

$$\dot{\rho}_{\rm vac} + \dot{\rho}_m + 3\, H \left(\rho_m + p_m\right) = 0$$

$$\rho_{\rm vac}(H) = \rho^0_{\rm vac} + \frac{3\nu}{8\pi}\, m^2_{\rm Pl}\left(H^2 - H_0^2\right)$$

Relation to variation of the fundamental constants

- Focus on **Case 2** (G= const., $\rho_{vac} \neq$ const)
- Running of vacuum energy parametrized by ν
- Departure from usual scaling of matter is also depending on ν

$$\boxed{\rho_{\rm vac}(H) = \rho^0_{\rm vac} + \frac{3\nu}{8\pi} m^2_{\rm Pl}\,(H^2 - H^2_0)}$$

$$\rho_m(z;\nu) = \rho^0_m\,(1+z)^{3(1-\nu)}$$

$$\rho^B_m = n_p\, m_p$$

$$n_p(z) = n^0_p\,(1+z)^{3(1-\nu)}$$

And/
Or

$$\boxed{m_p(z) = m^0_p\,(1+z)^{-3\nu}}$$

<u>Running of proton mass!</u>

Variation of fine-structure constant α

- Variation of proton mass also induces a variation of the QCD-scale parameter Λ_{QCD} itself:
- Strong coupling α_S depends on Λ_{QCD}
- Running now not only with usual renormalization scale μ_R but also with cosmic time
- How does this relate to fine-structure constant α?
  → Only in Grand unified theories, model-dependent

$$m_p \simeq c_{\mathrm{QCD}}\,\Lambda_{\mathrm{QCD}};$$

$$\alpha_s(\mu_R) = \frac{4\pi}{(11 - 2\,n_f/3)\,\ln\left(\mu_R^2/\Lambda_{\mathrm{QCD}}^2\right)}$$

$$\alpha_S(\mu_R) \to \alpha_S(\mu_R, H)$$