Ultralight Dark Matter Search with Space-Time Separated Atomic Clocks and Cavities

AIP Congress, Melbourne, December 2024

- Melina Filzinger, Ashlee Caddell, Dhruv Jani, Martin Steinel, Leo Giani, Nils Huntemann, BMR, arXiv:2312.13723
- Savalle *et al.*, Phys. Rev. Lett. **126**, 051301 (2021) [arXiv:2006.07055]
- BMR *et al.*, New J. Phys. **22**, 093010 (2020) [arXiv:1907.02661]
- BMR, Blewitt, Dailey, Murphy, Pospelov, Rollings, Sherman, Williams, Derevianko, Nature Comms. **8**, 1195 (2017)

Benjamin M. Roberts

School of Mathematics and Physics, University of Queensland, Australia

- Slides broberts.io/talks

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Dark Matter: What we know

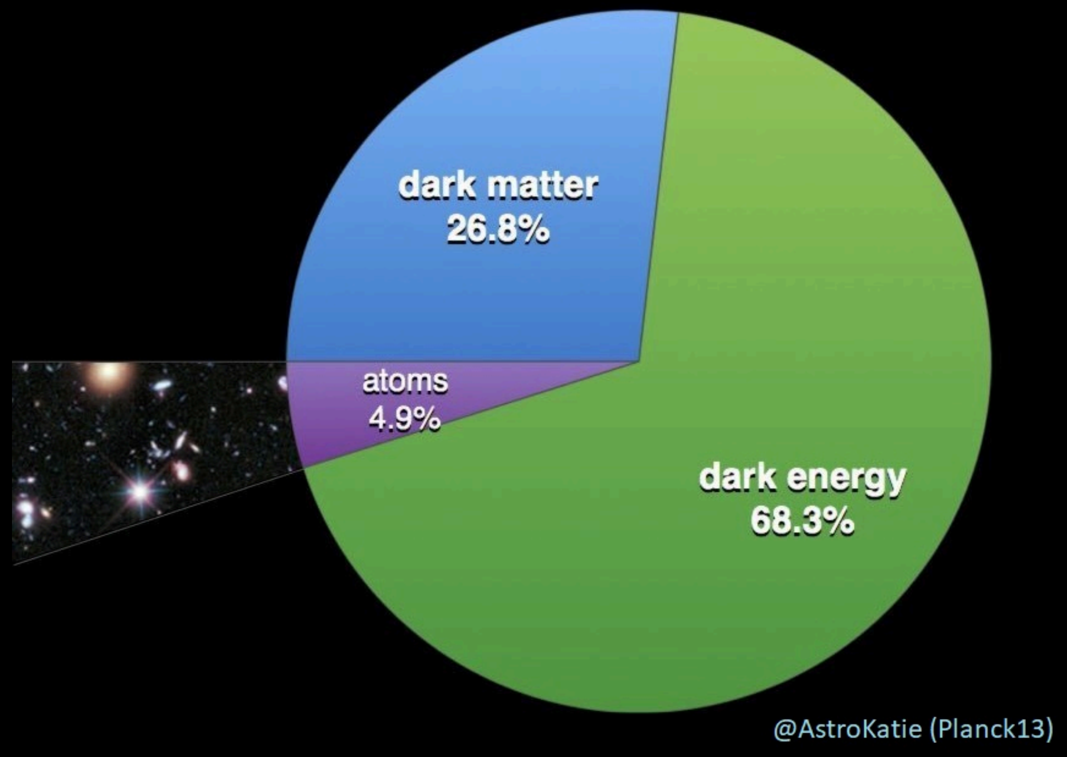
There's lots of it

It gravitationally clusters in halos around galaxies

(really, galaxies gravitationally cluster around DM)

Very strong evidence:

- Rotation curves, gravitational lensing, CMB
- Also: large scale structure, BAO etc.
- It's not strange for particles to not interact with light (e.g., neutrinos)



- ΛCDM model works extremely well
  - $\Omega_c = 0.2589(57)$ [Planck]

Dark Matter: What we don't know

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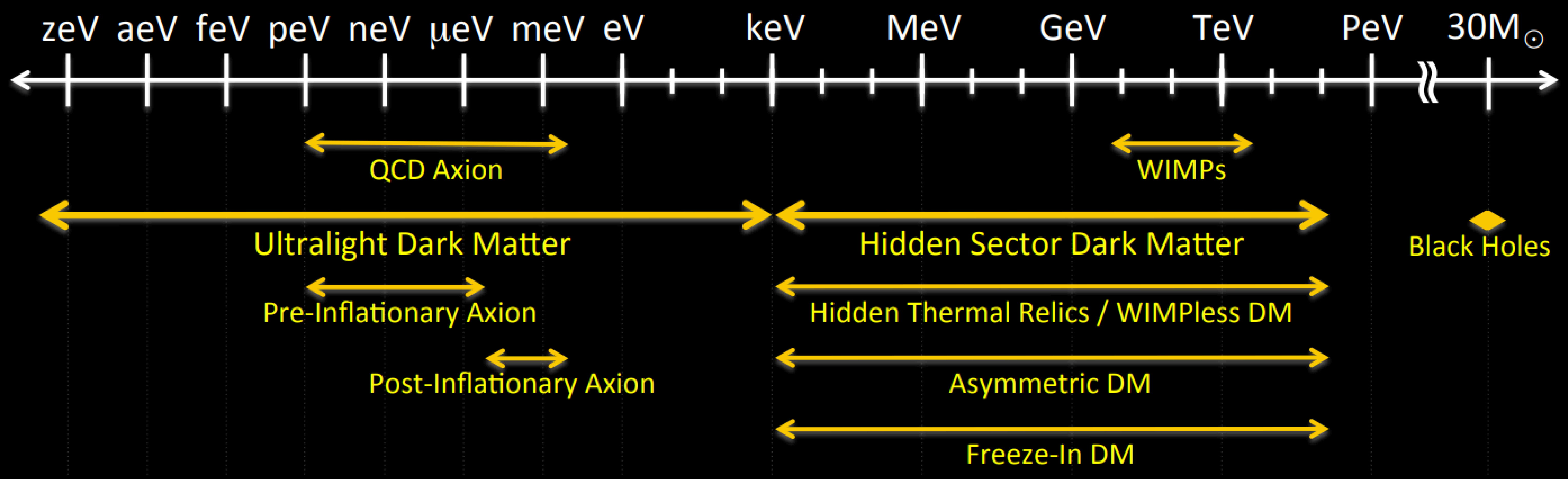

US "Cosmic Visions" report [arXiv:1707.04591]

- Possible mass range: 90 orders of magnitude!

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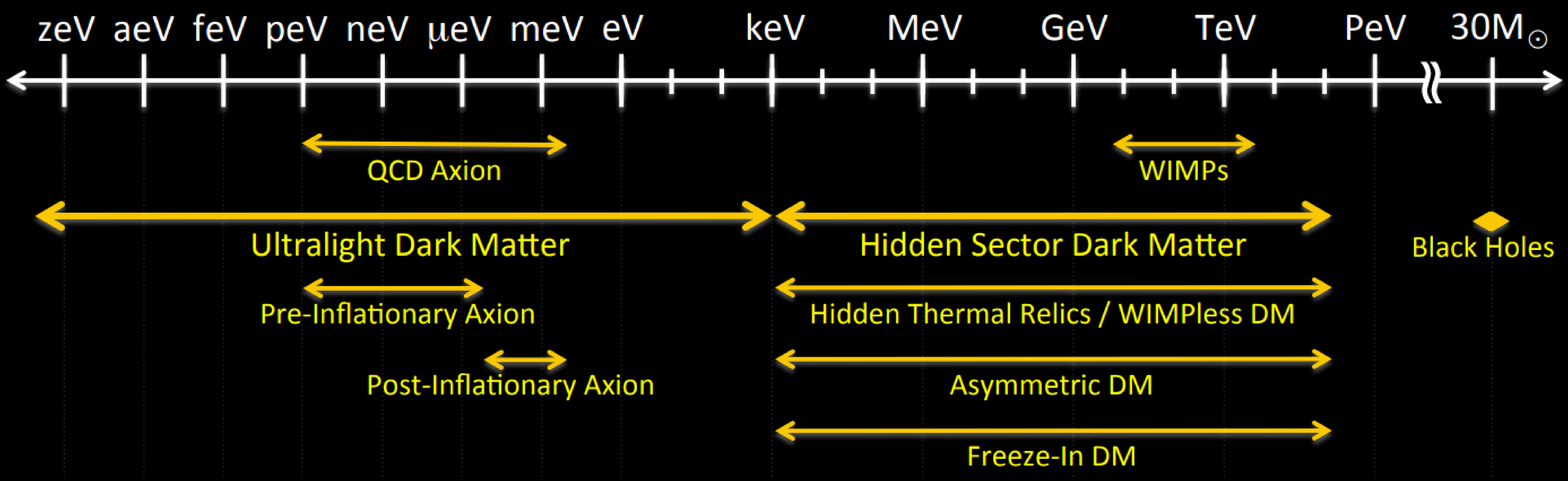

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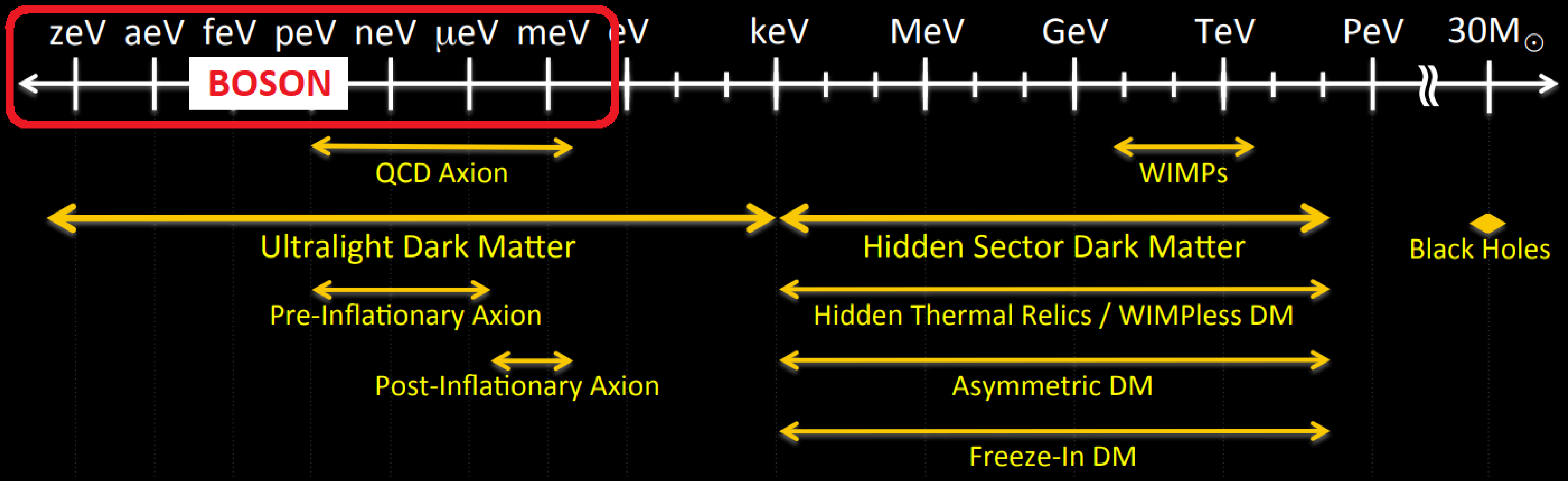

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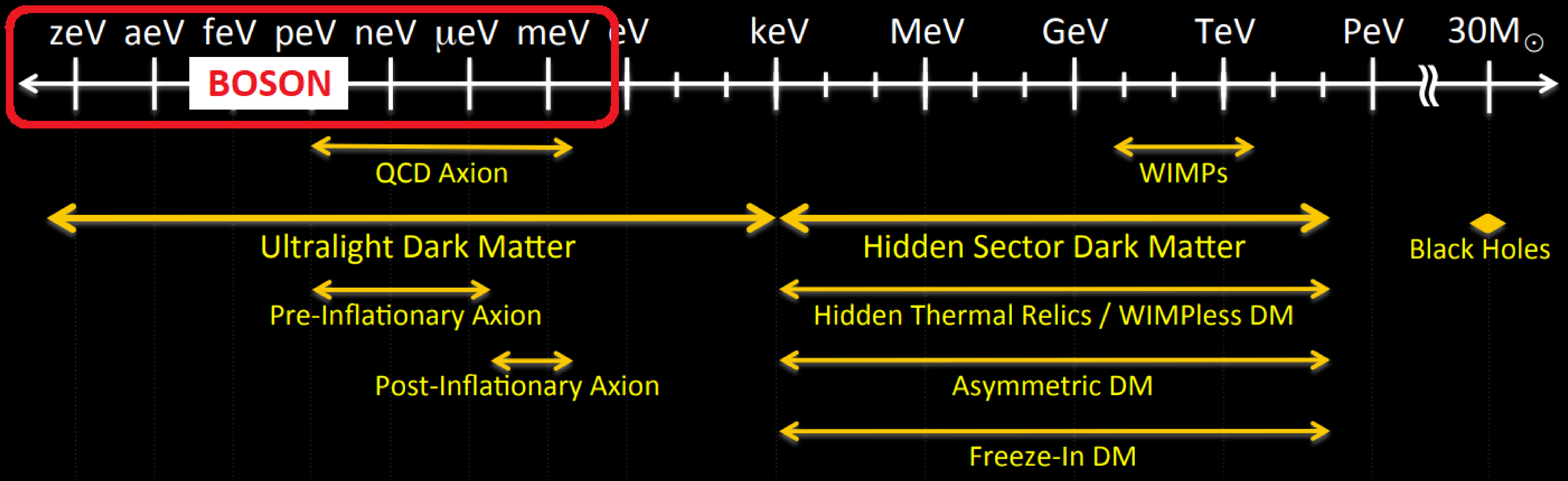

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- Fundamental particle: 50 orders (de Broglie to Planck)
- Vast majority of focus on WIMPs, but field is very wide

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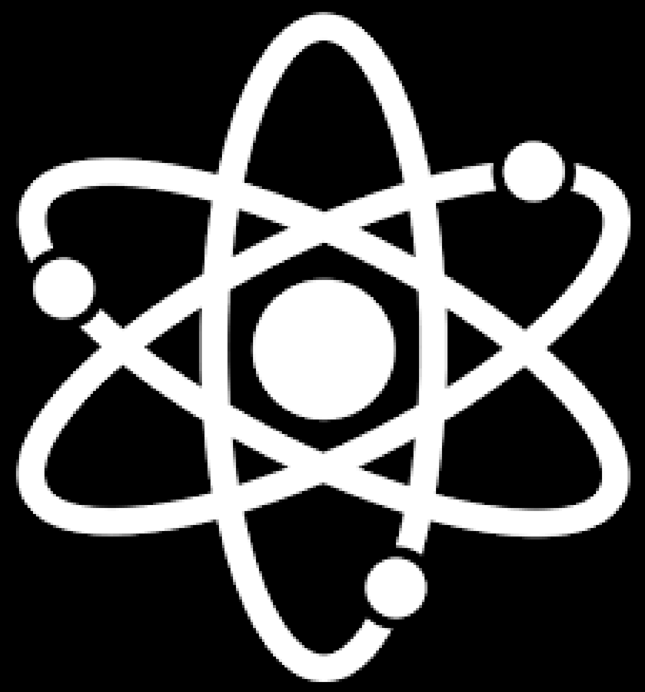
Mass drops below nuclear mass:



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  - Instead: electron recoils + ionisation
  - See Ashlee Caddell talk

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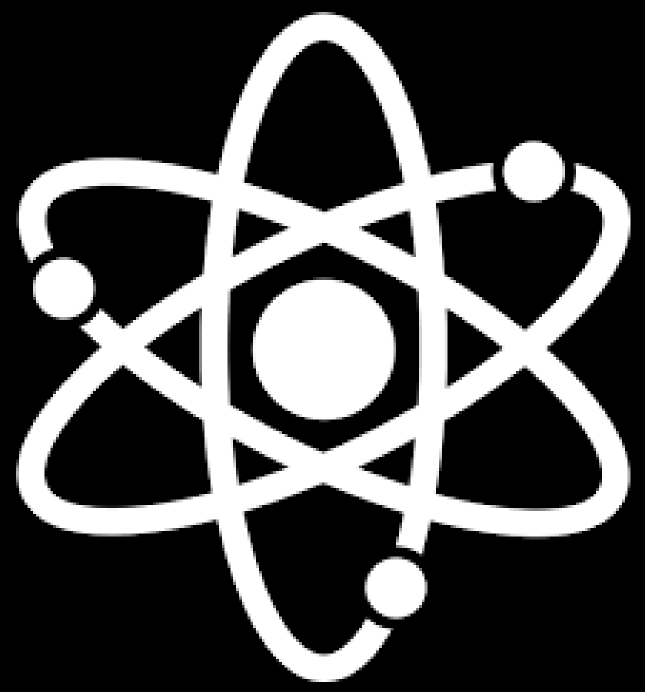

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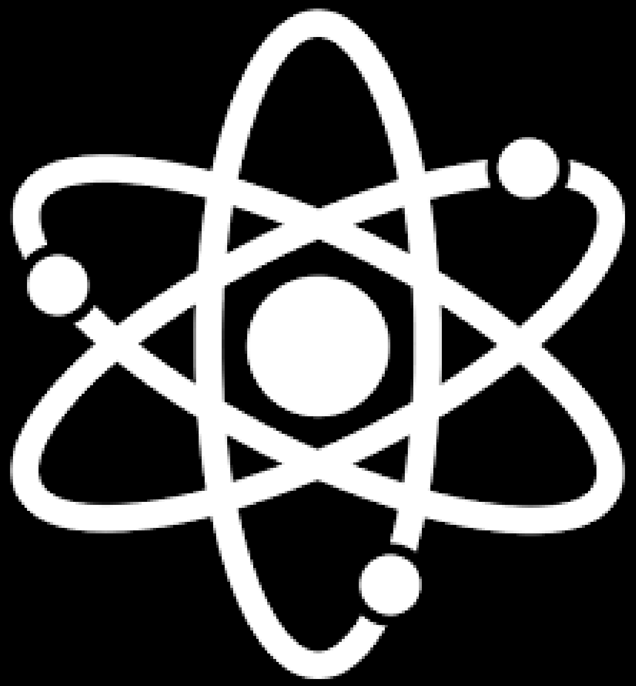

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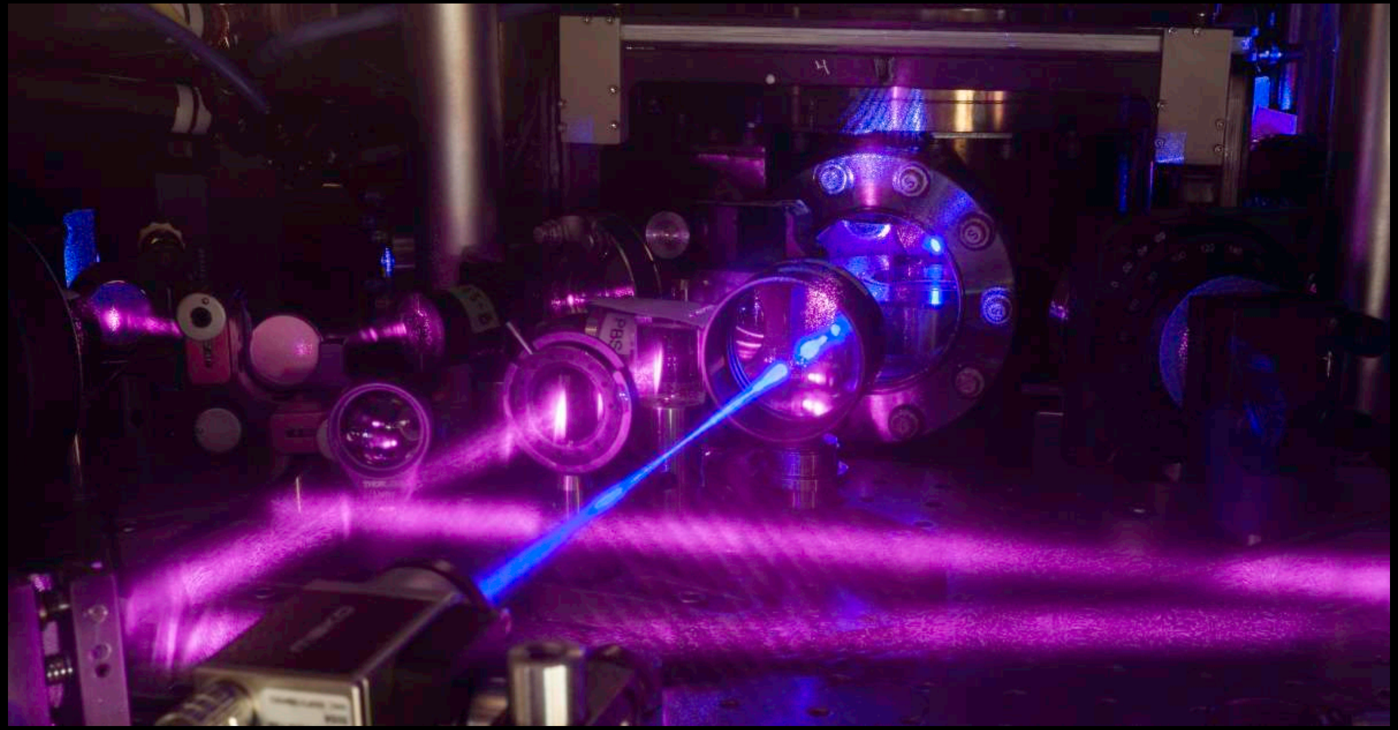

[JILA]

Mass drops below eV:

- Classical DM field
  - Quantum sensing (atomic clocks)

Ultralight Dark Matter

$$\rho_{\rm DM} \simeq 0.3\,\frac{\rm GeV}{\rm cm^3}$$

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3. Also: constant build-up (local over-densities)

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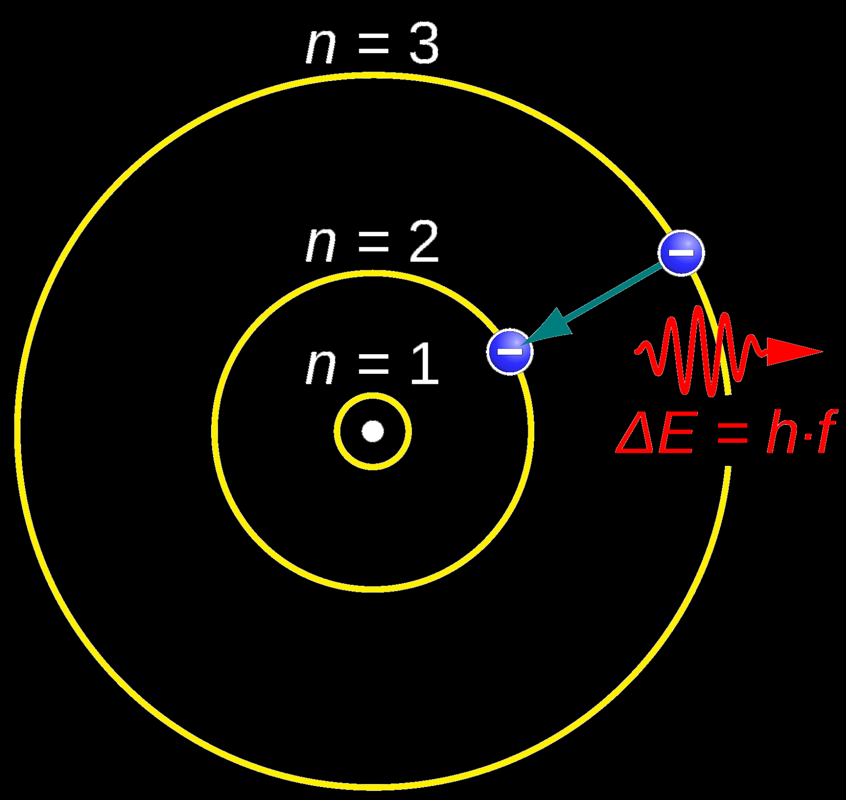

JabberWok [Wikimedia Commons]

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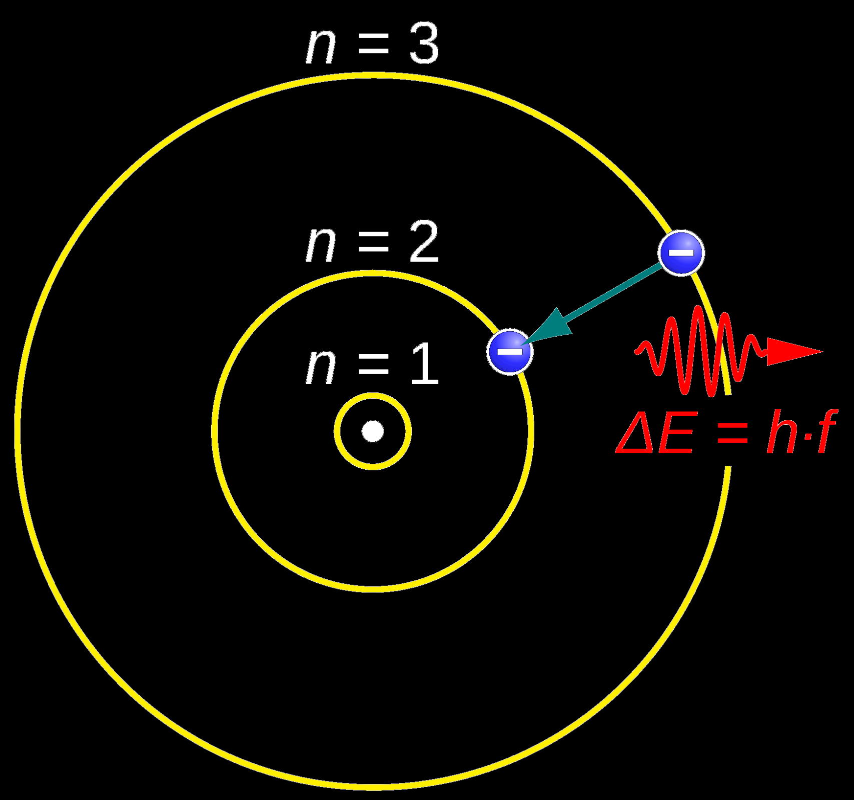

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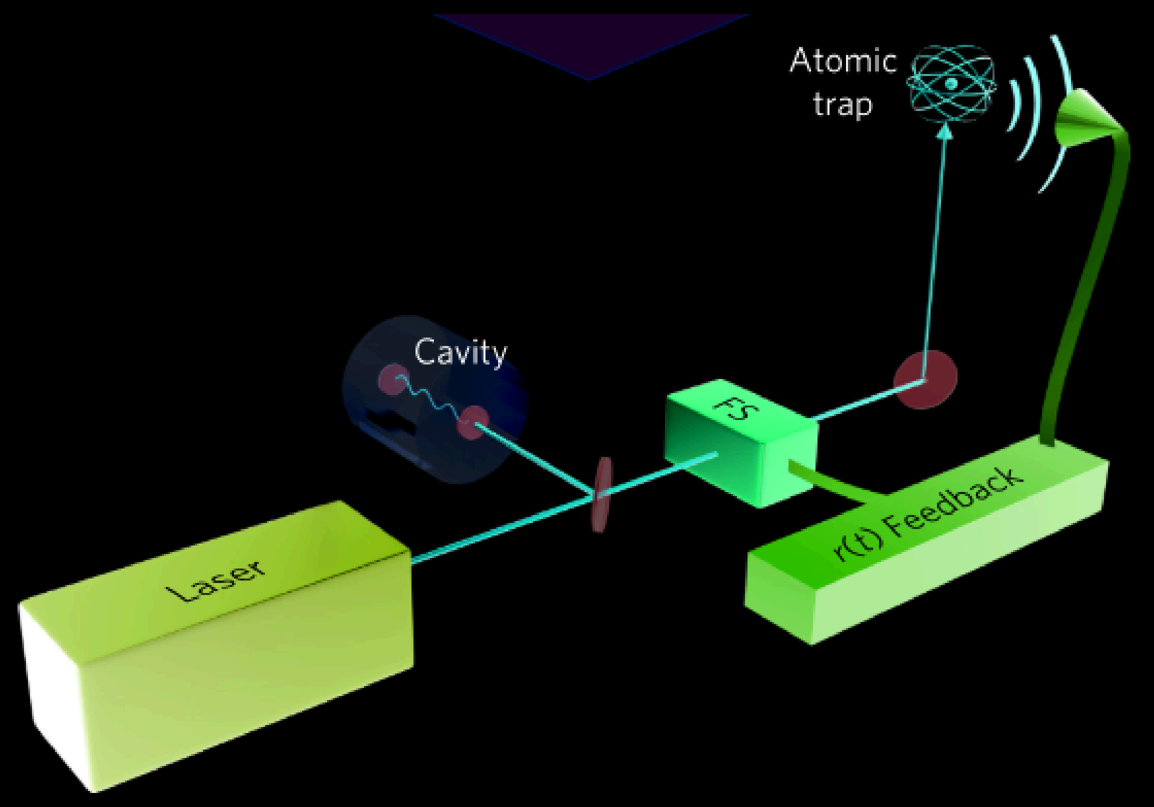

Wcislo, Science 2016

Compare frequency of oscillator to atomic transition

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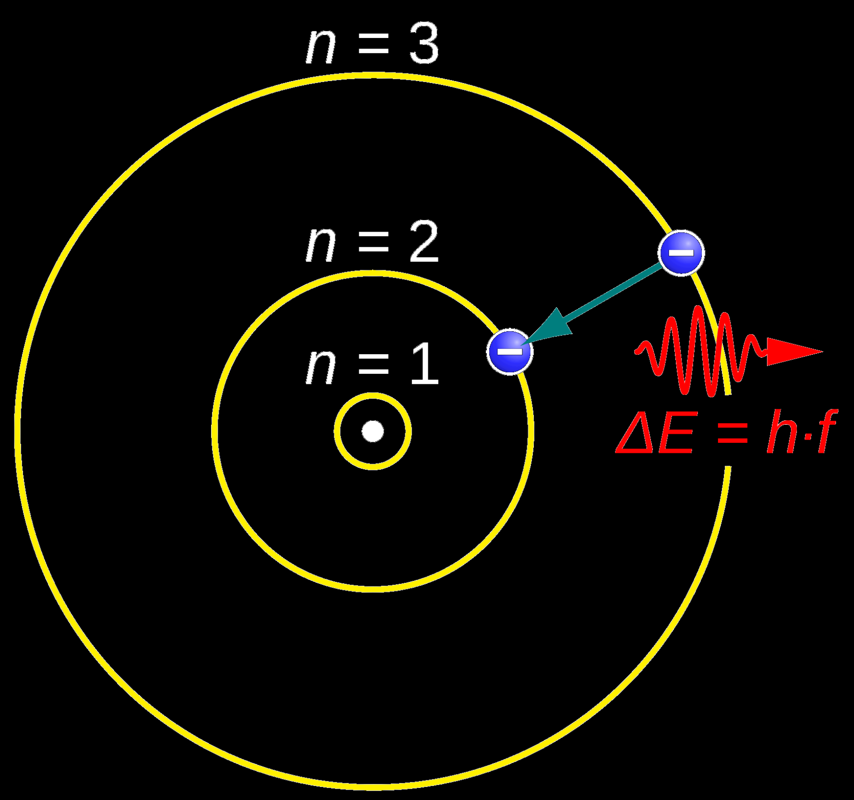

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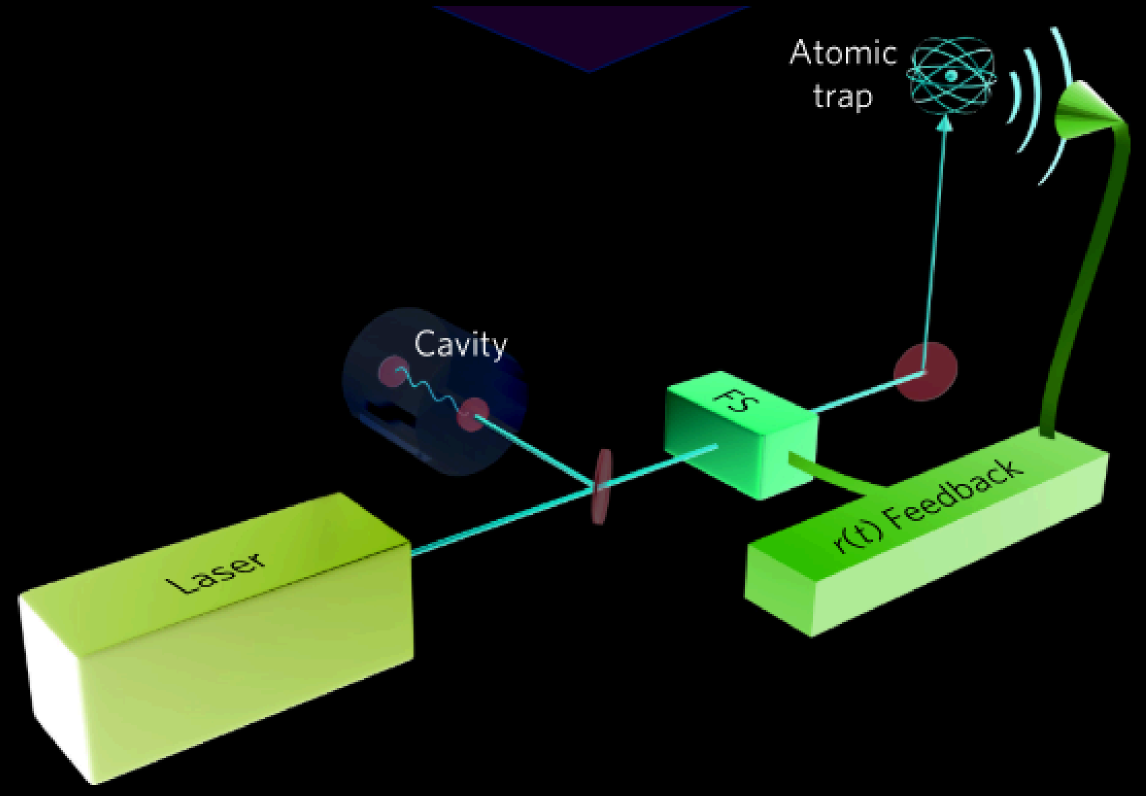

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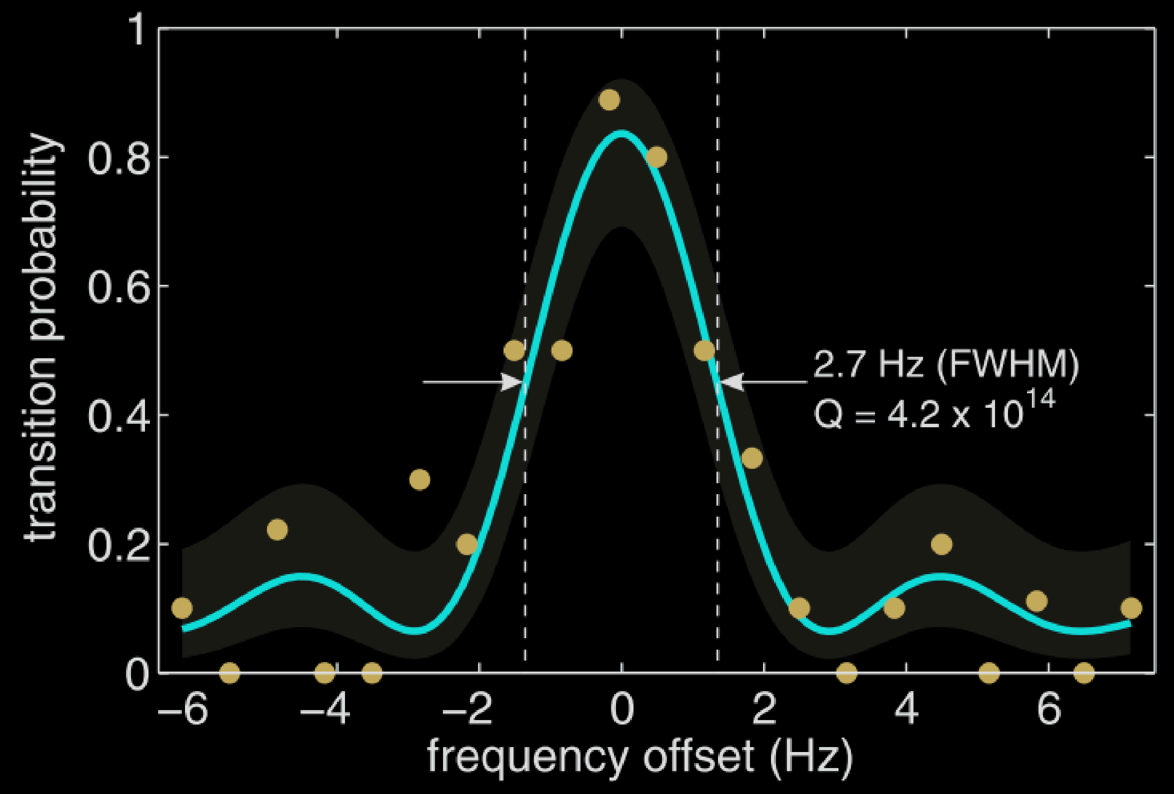
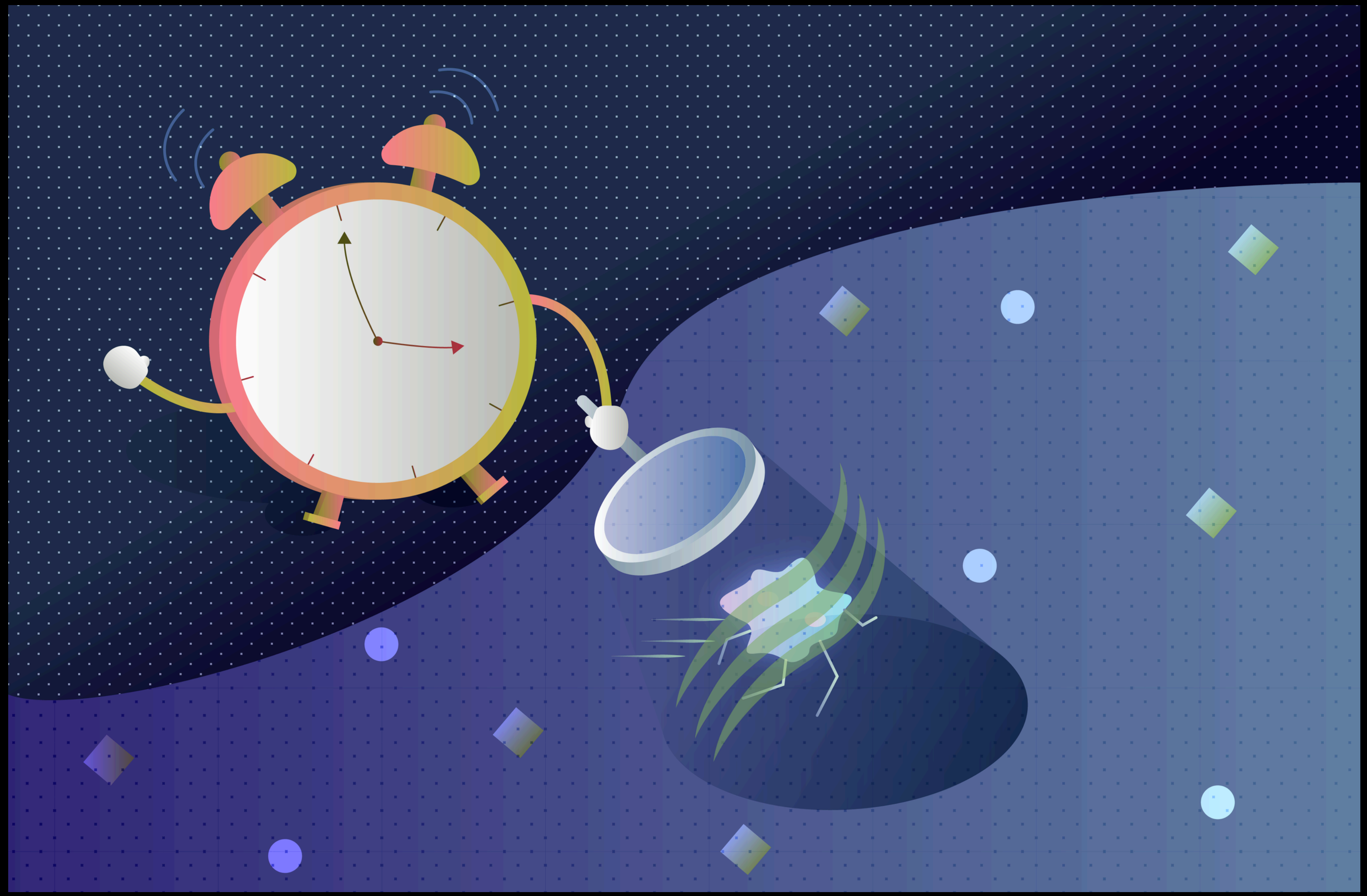


Choi, Phys. Rev. Lett. 2018

Lock on: Adjust local oscillator to maximum transition rate

"Listen" for DM field using atomic clocks



[N Hanacek/NIST]

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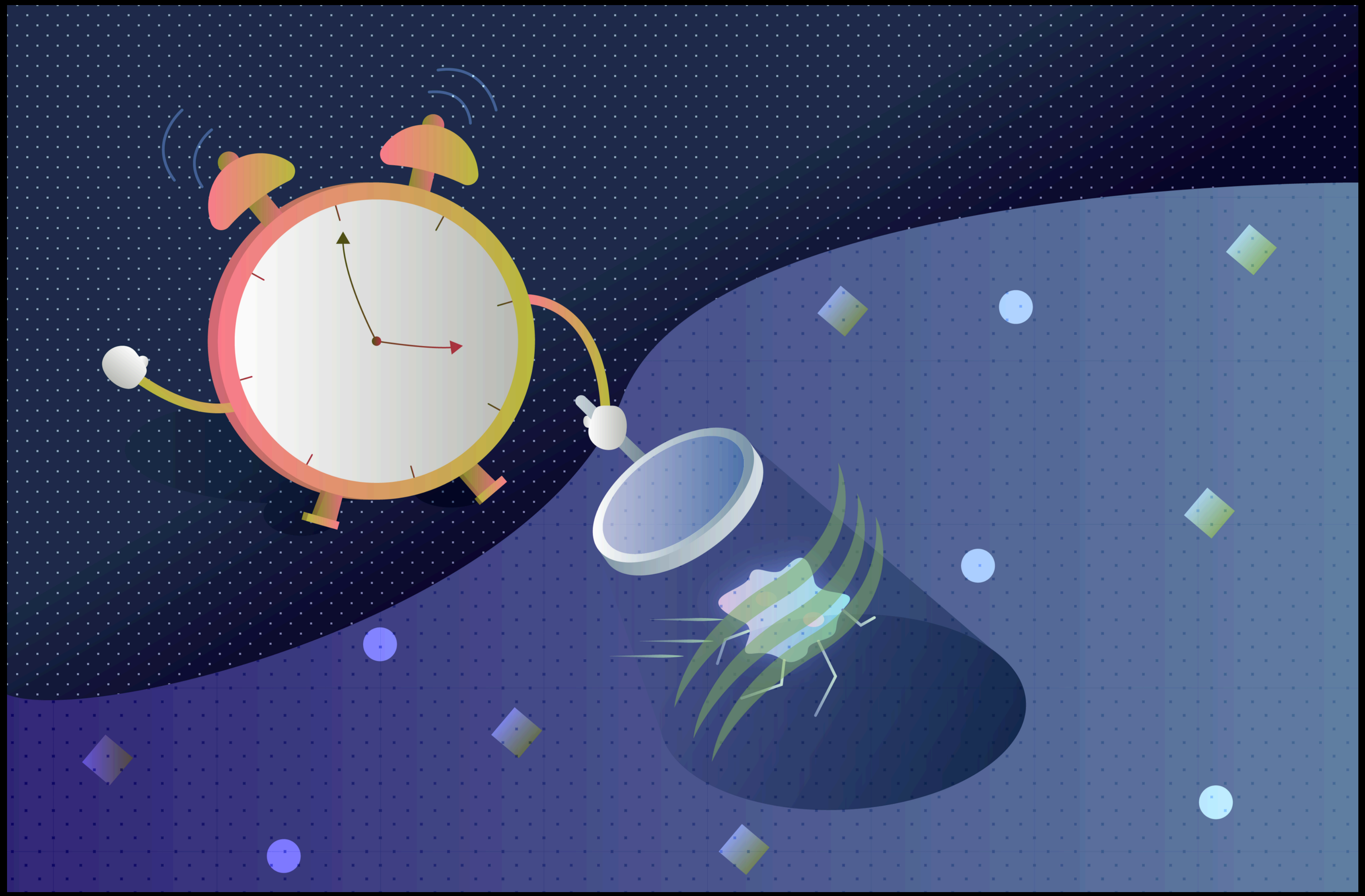

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- κ - model dependent parameter:

  $\Longrightarrow$ Different for different transitions
- Calculated: high-precision atomic theory

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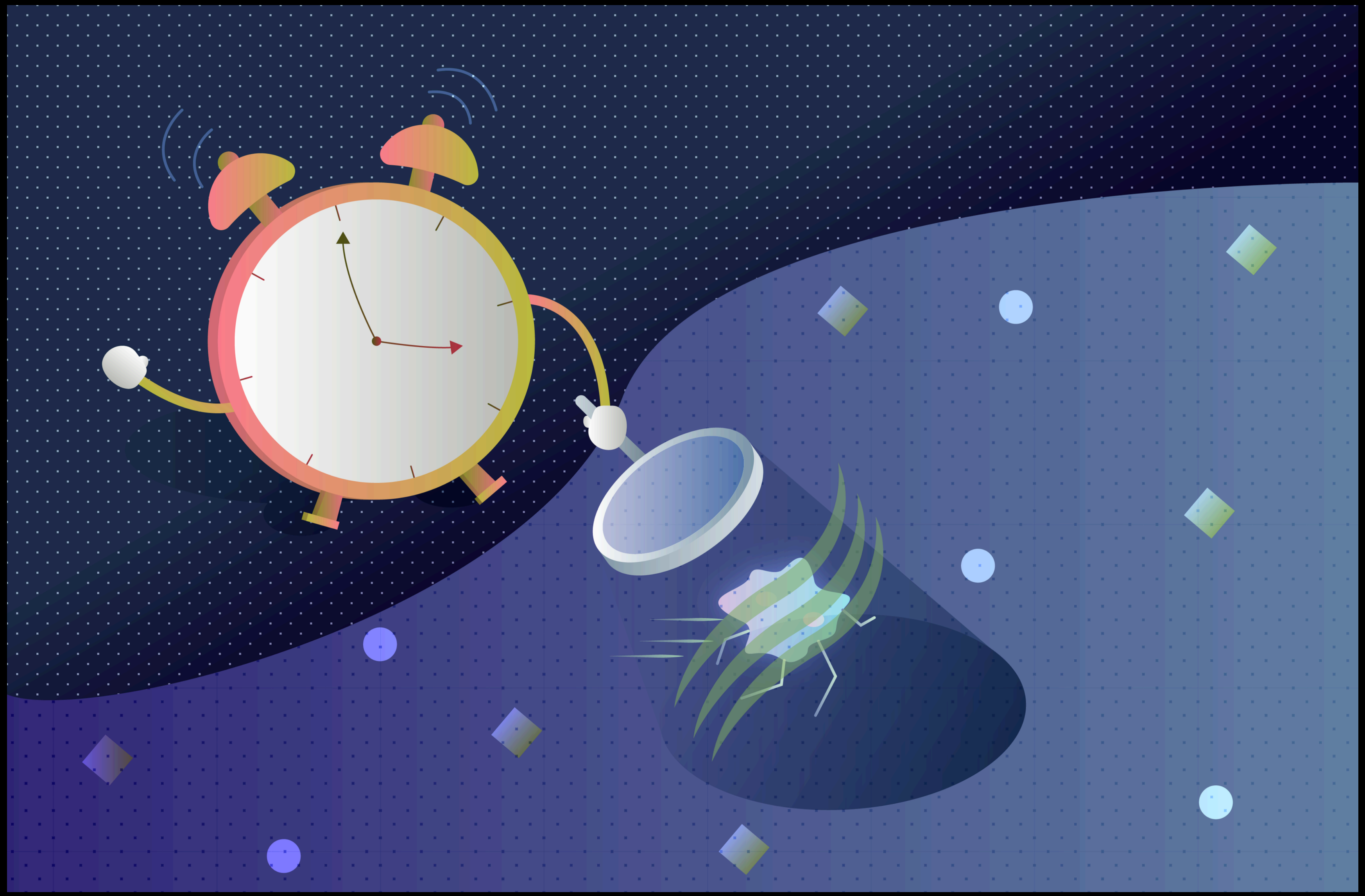

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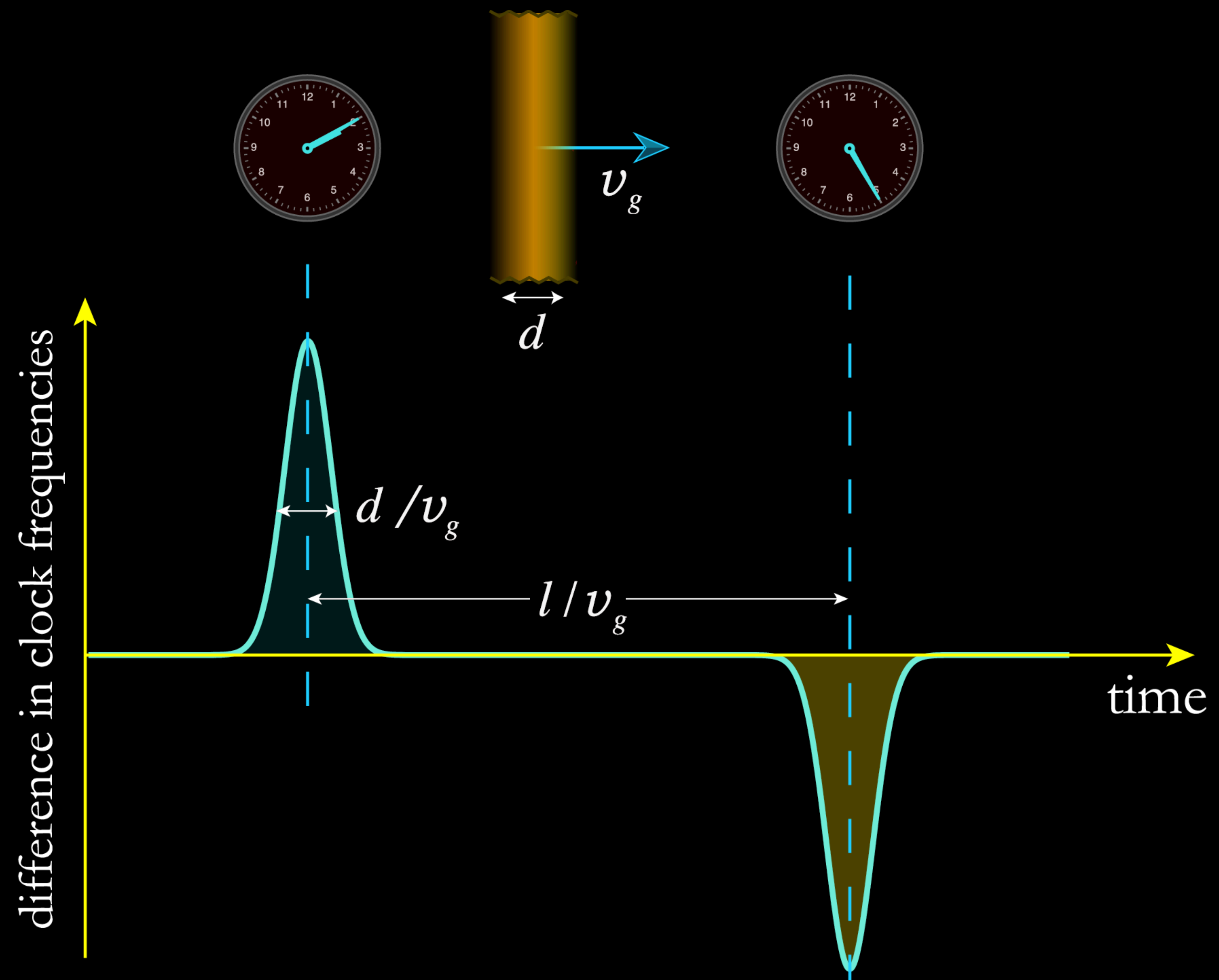
Example: variation of constants

$$\mathcal{L} = \phi F_{\mu\nu} F^{\mu\nu} \Longrightarrow \alpha \to \alpha + \phi_{\rm DM}(\vec{r}, t)$$

$$\kappa = \frac{{\rm d}(f/f_0)}{{\rm d}(\alpha/\alpha_0)}$$

Transient Signals



Derevianko + Pospelov, Nature Physics (2014)

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- May form "clumps": topological defects, Q-balls
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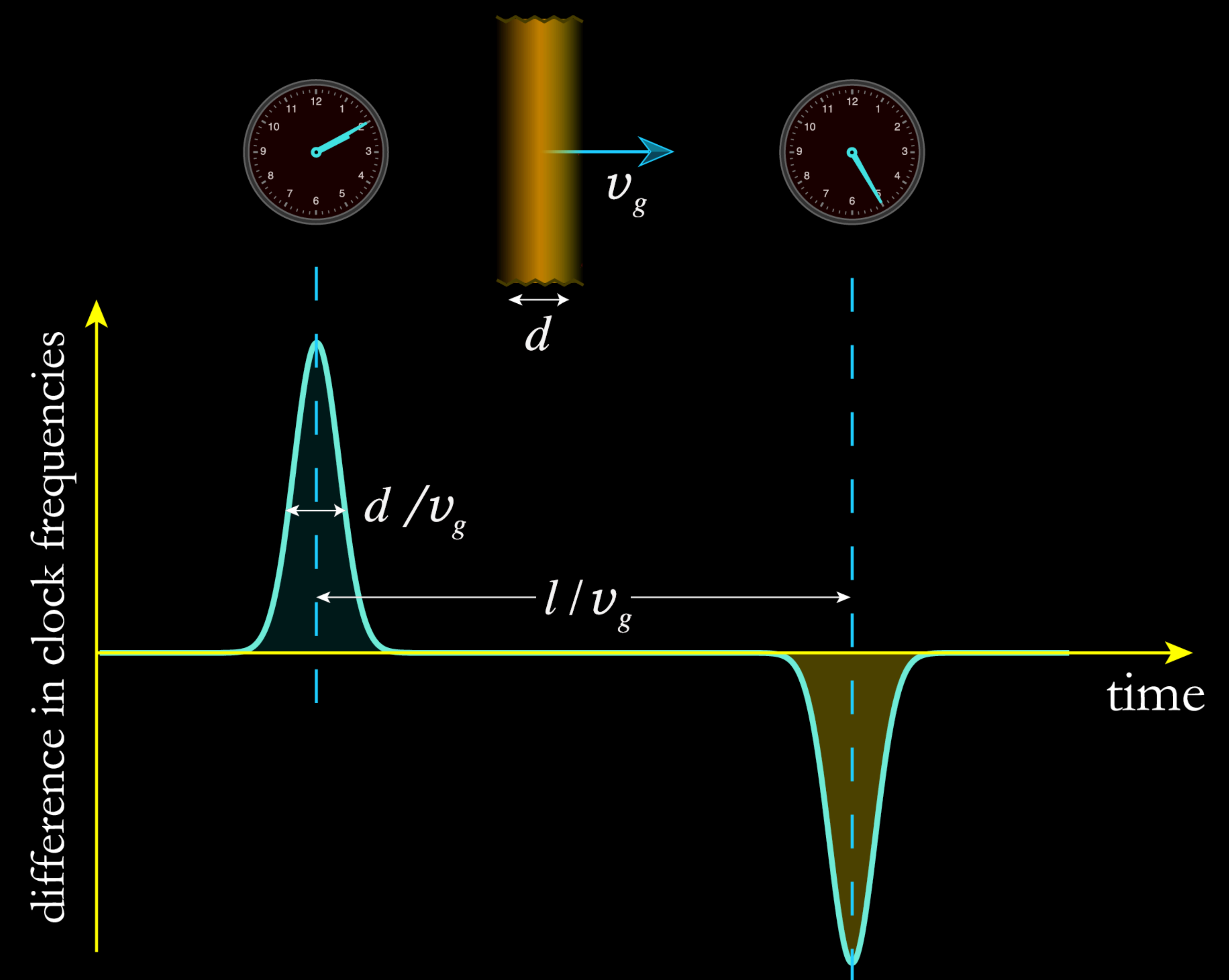

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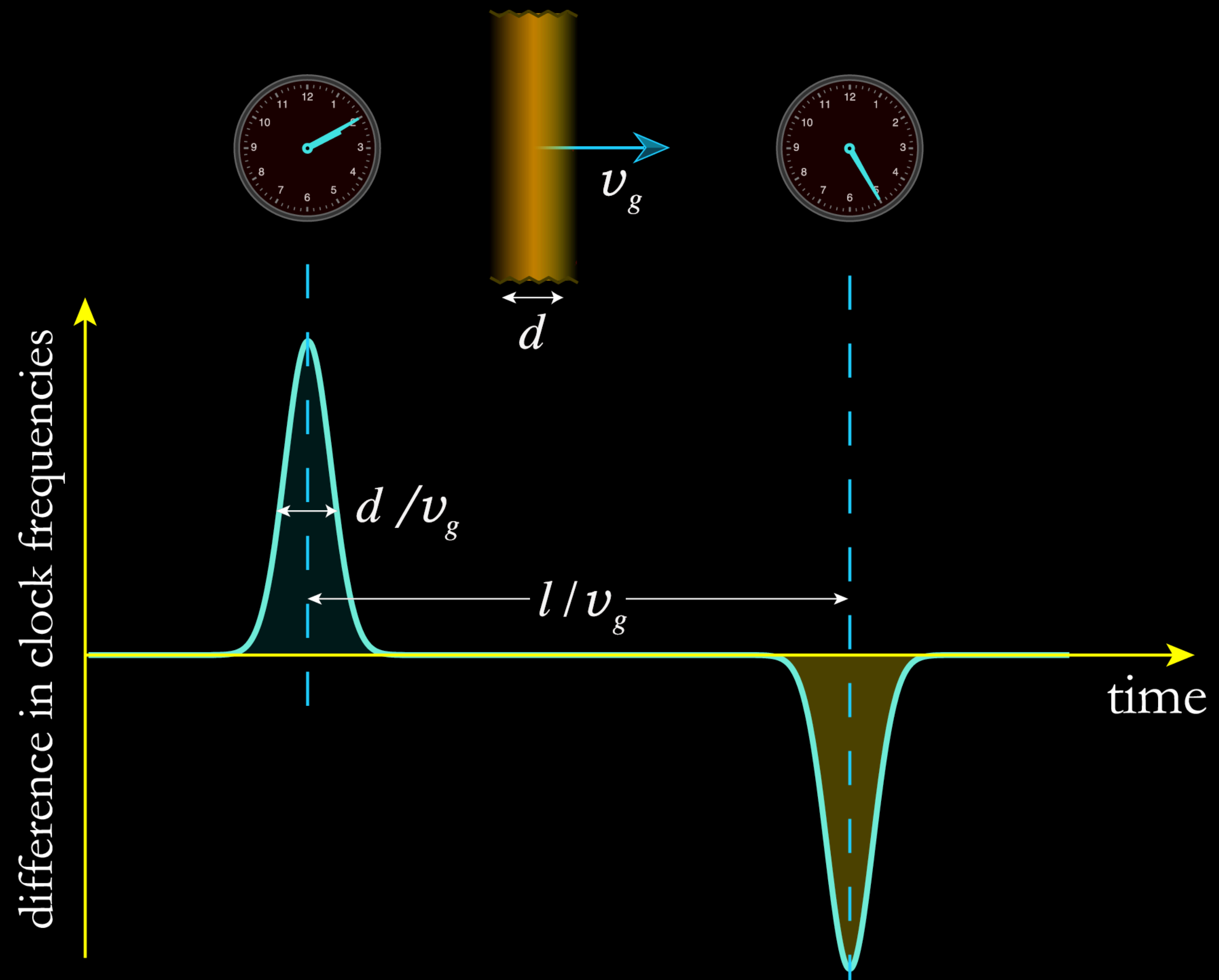

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- How to distinguish from noise?
  - Correlated signal across global network

GPS.DM

- 30 Cs, Rb atomic clocks
- Over 20 years of high-quality data
- Publicly available (JPL)
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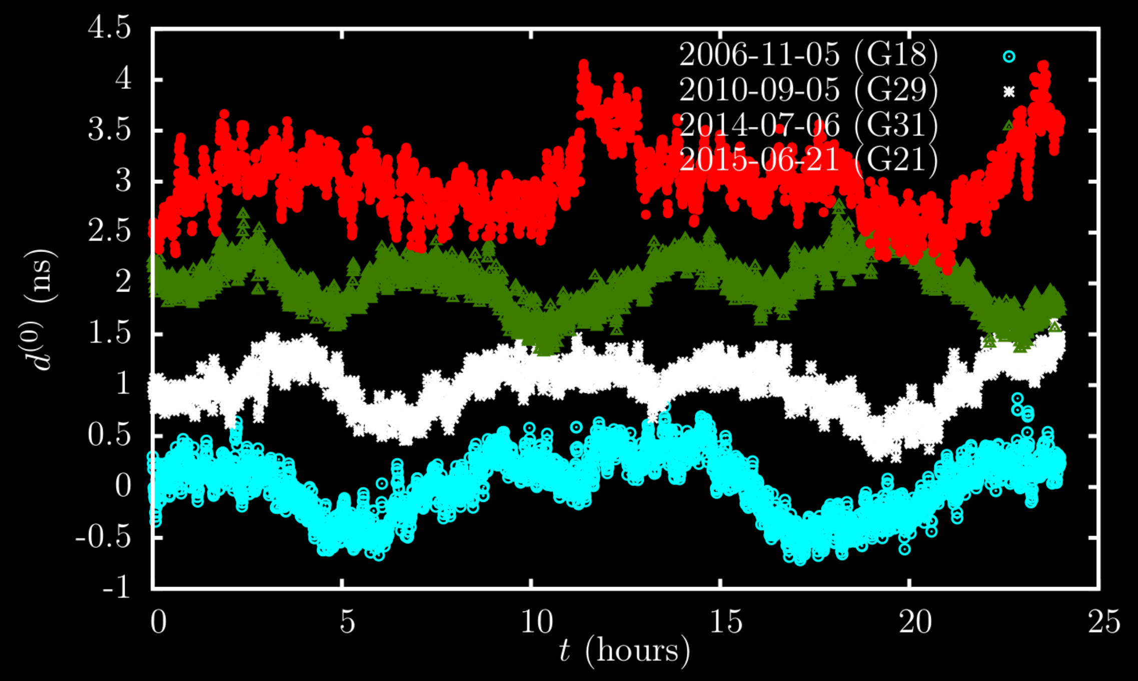

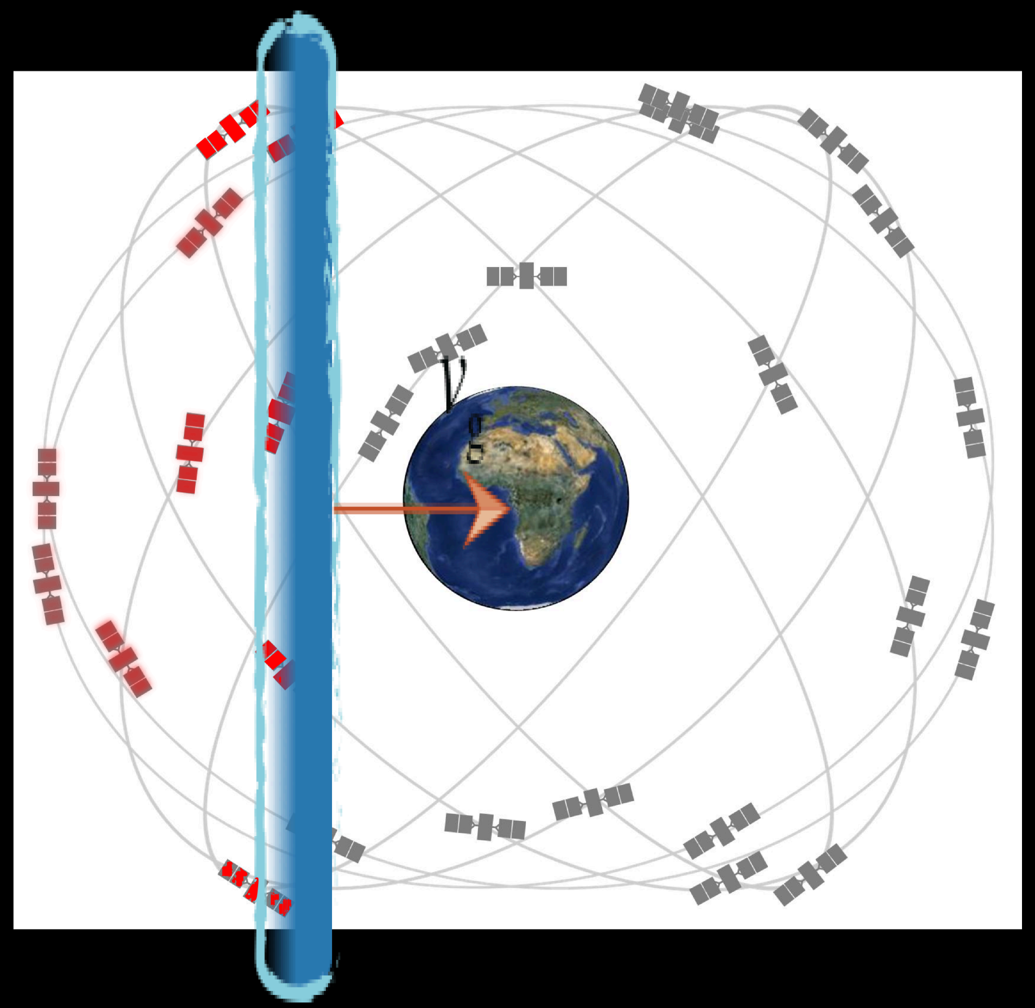

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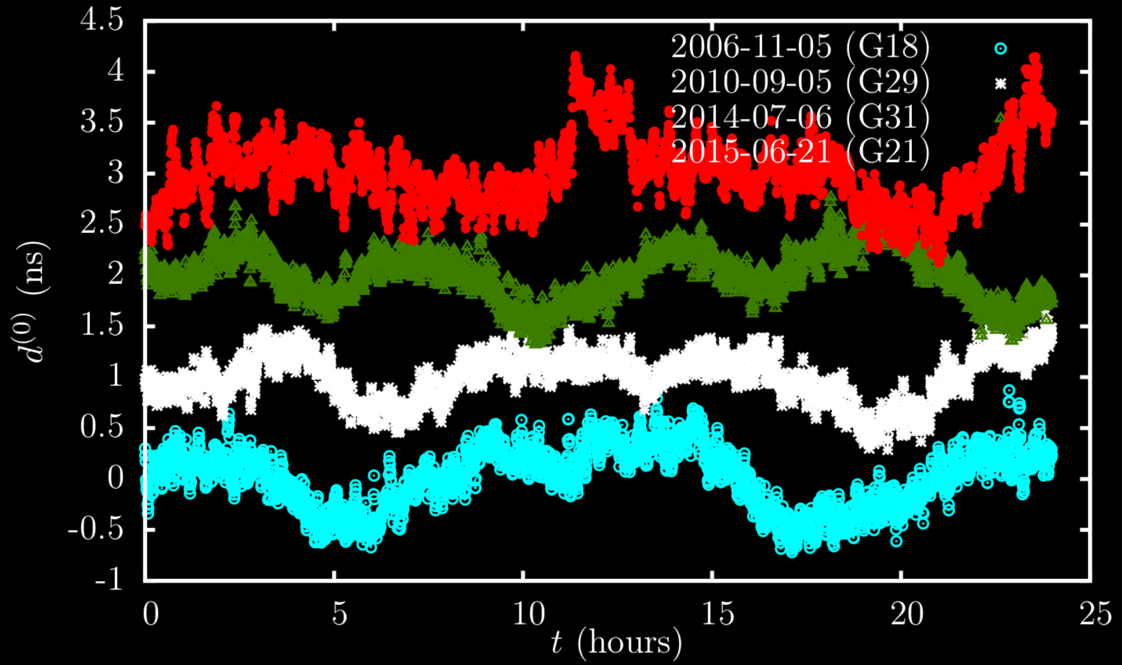
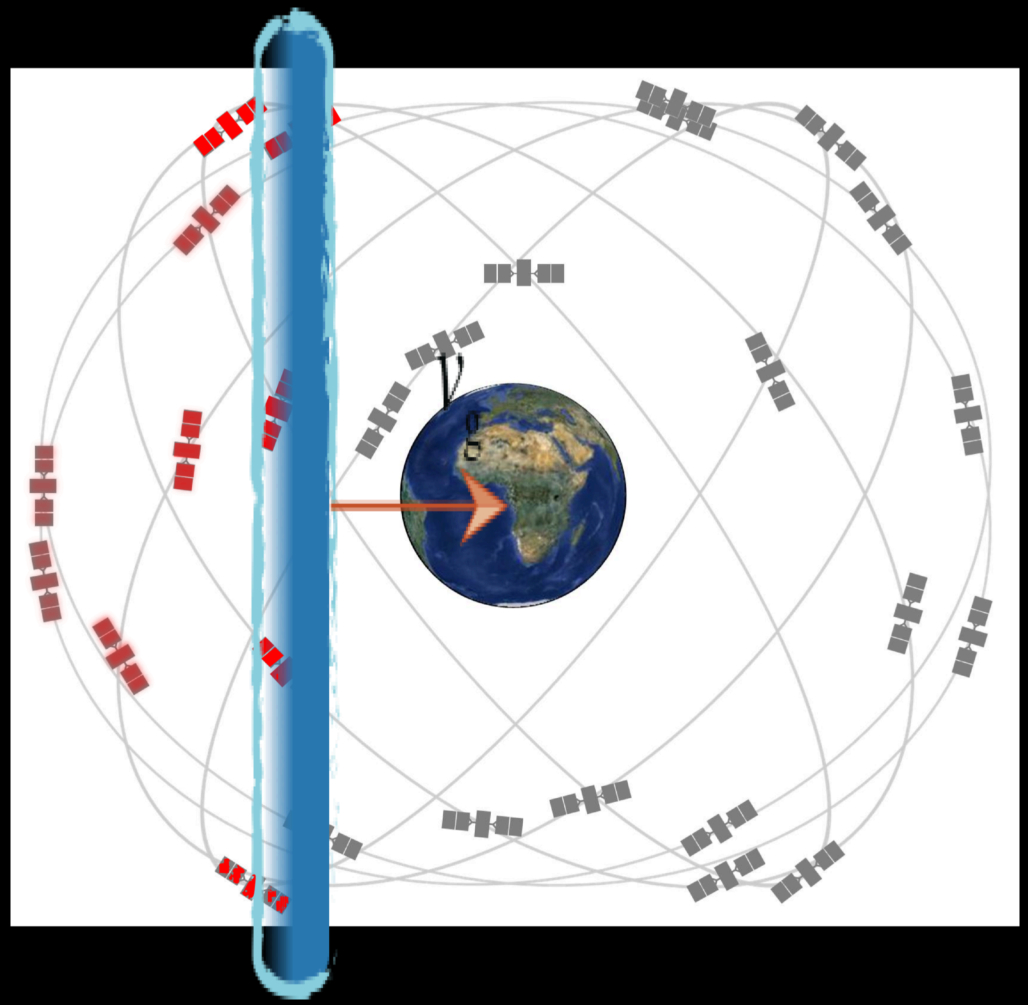
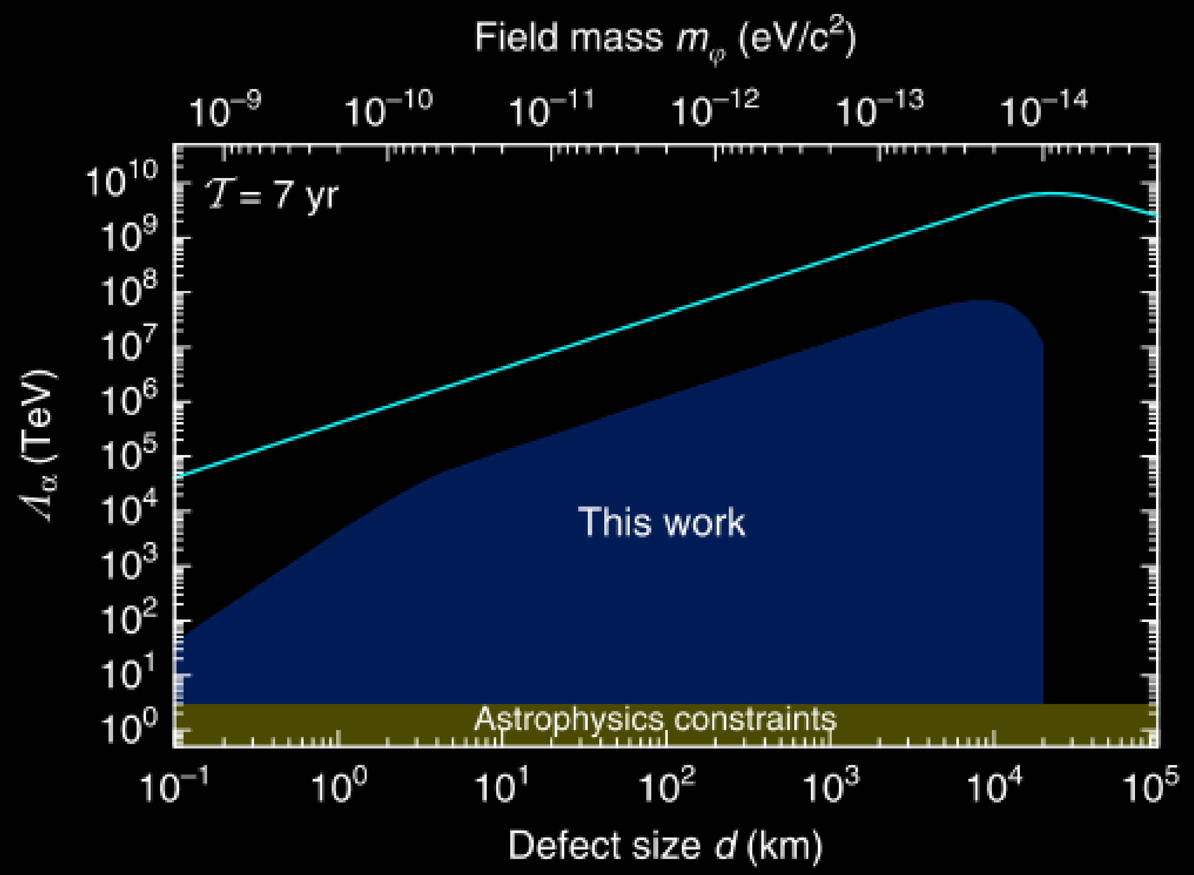
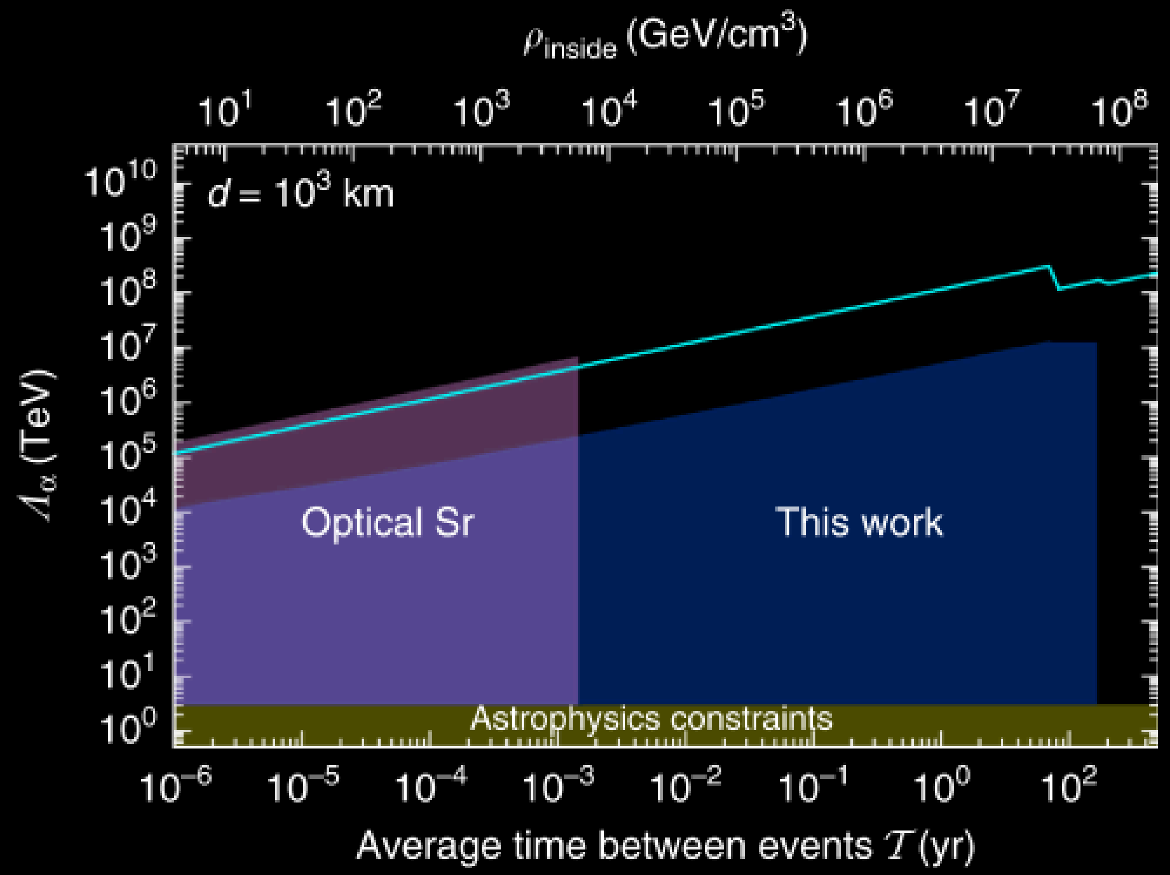


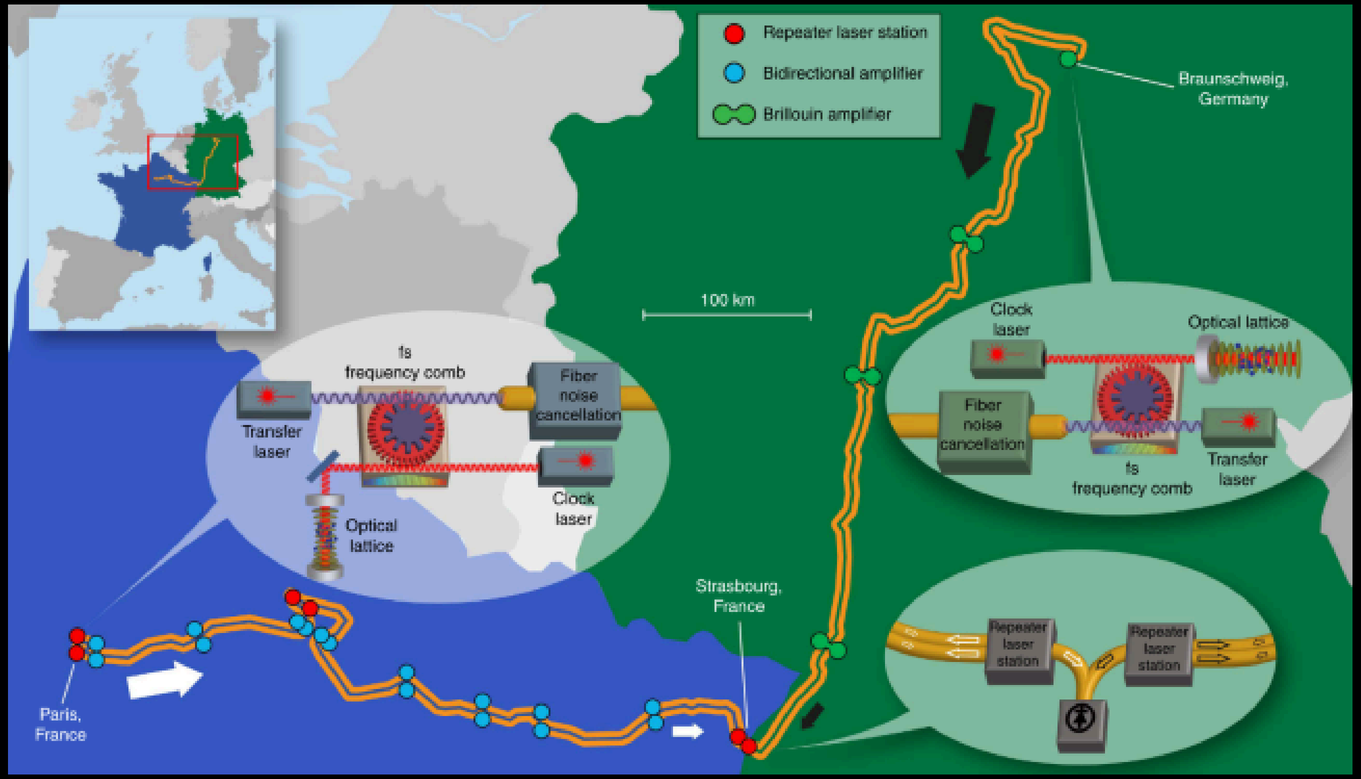






BMR, Blewitt, Dailey, Murphy, Pospelov, Rollings, Sherman, Williams, Derevianko, Nature Comms. (2017)

European Fibre-linked network



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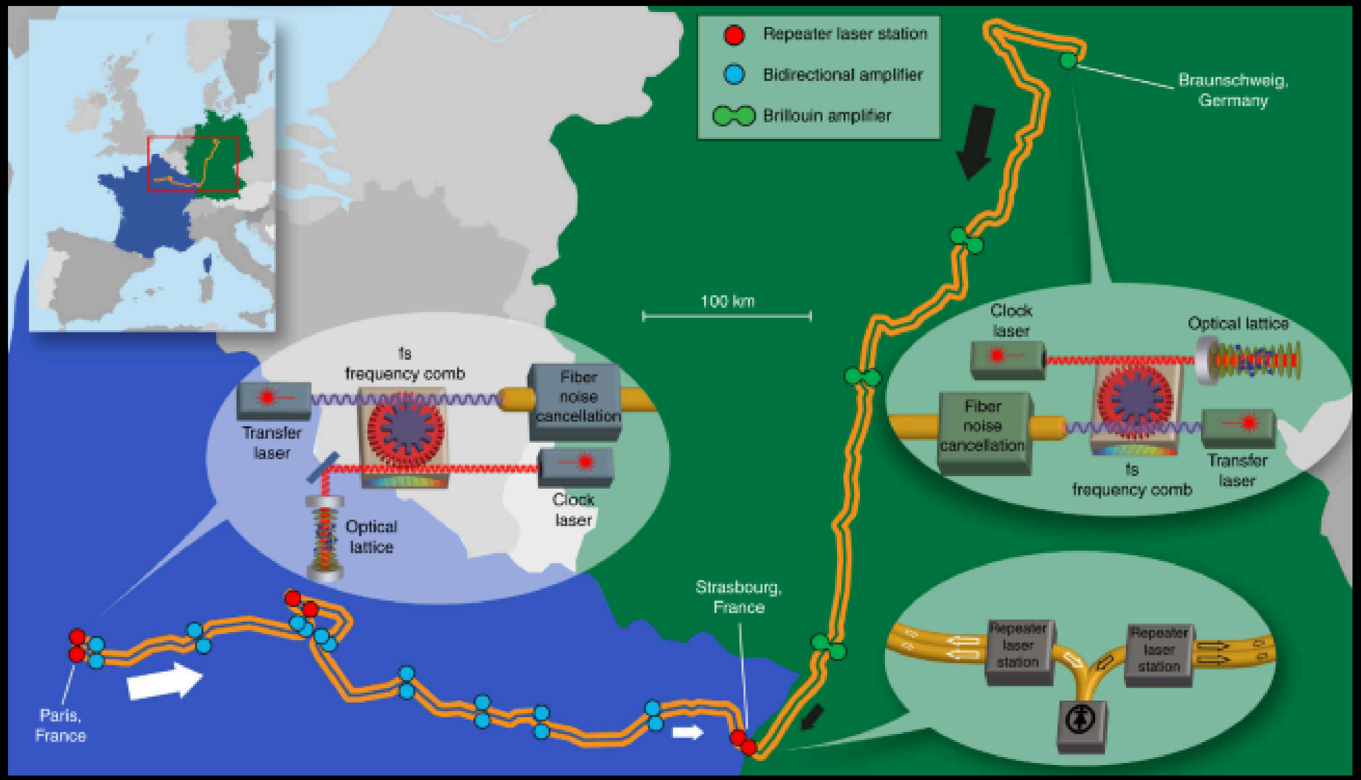

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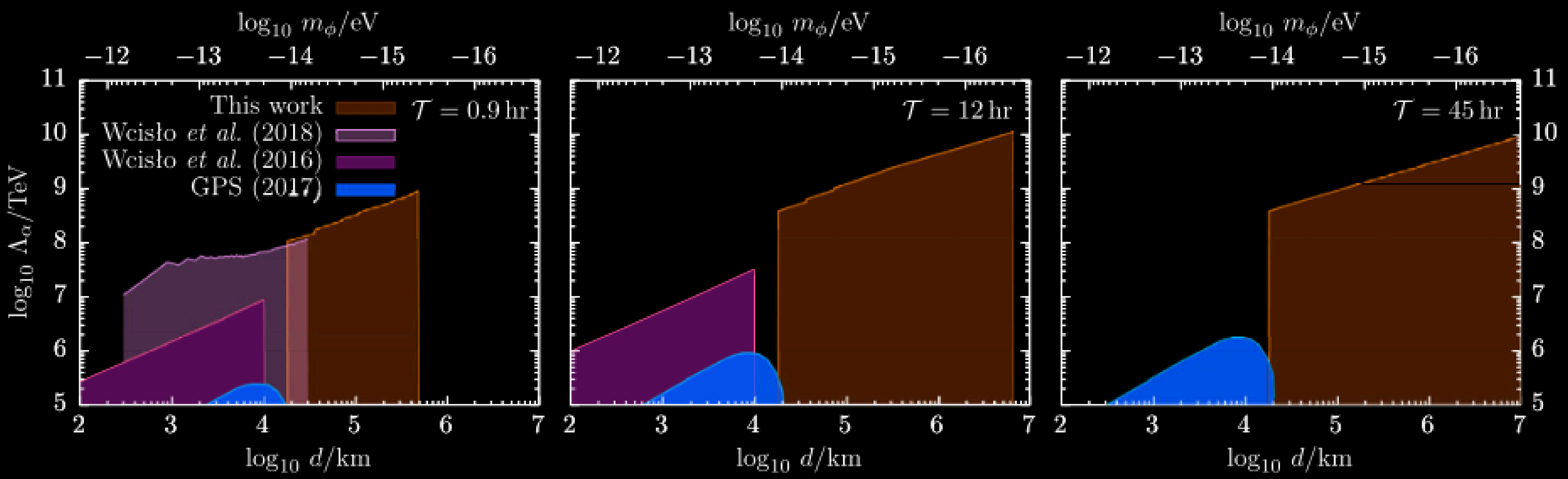

BMR, et al., N. J. Phys. (2020)

Oscillating Signals

- Filzinger, Caddell, Jani, Steinel, Giani, Huntemann, BMR, arXiv:2312.13723

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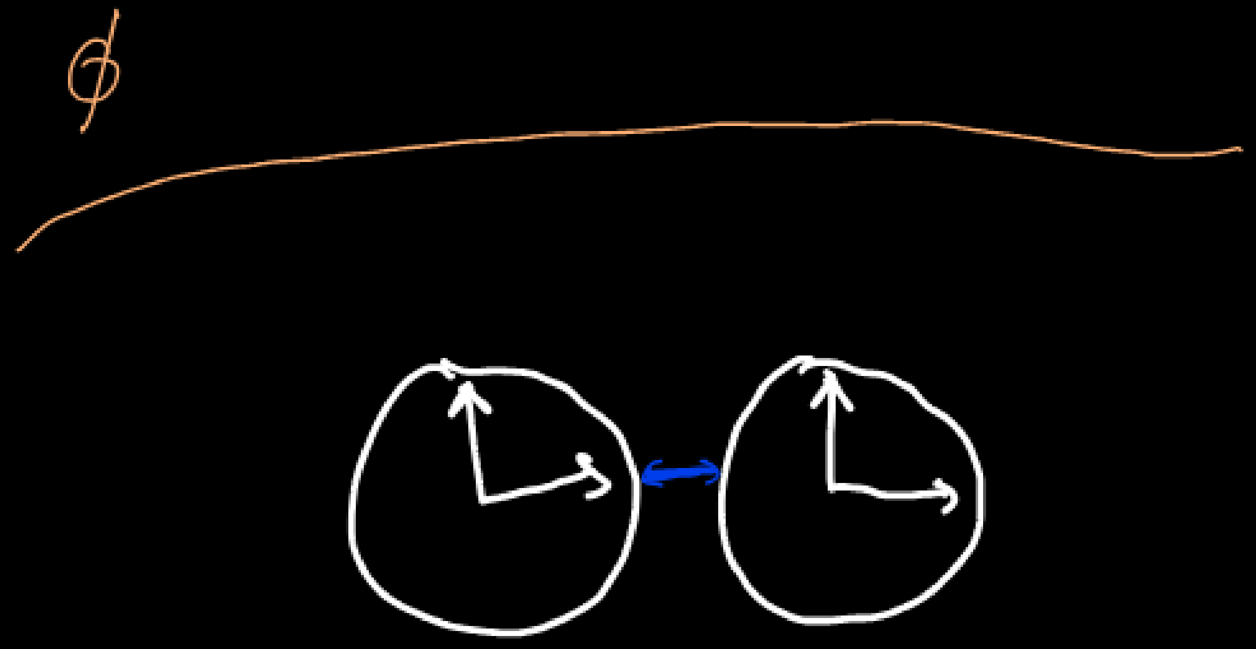
$$\frac{\delta(\nu_a/\nu_b)}{(\nu_a/\nu_b)} = \phi_0\,(\kappa_a - \kappa_b)\,\cos(\omega t)$$



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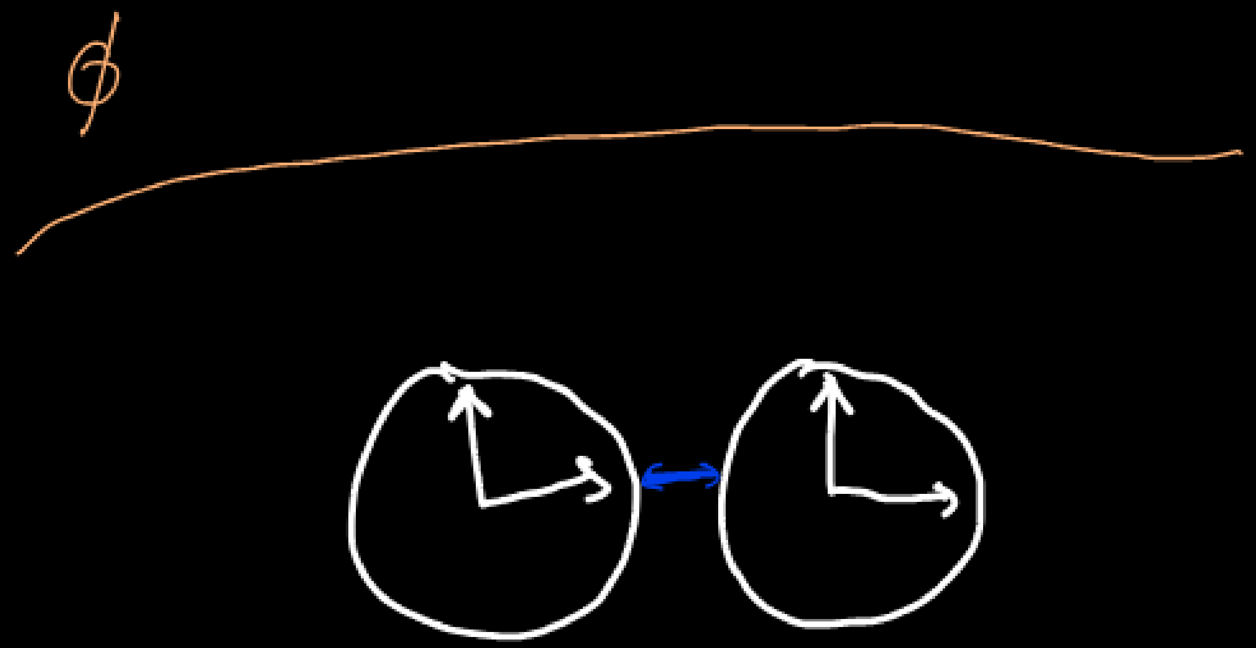
- e.g., Universal couplings



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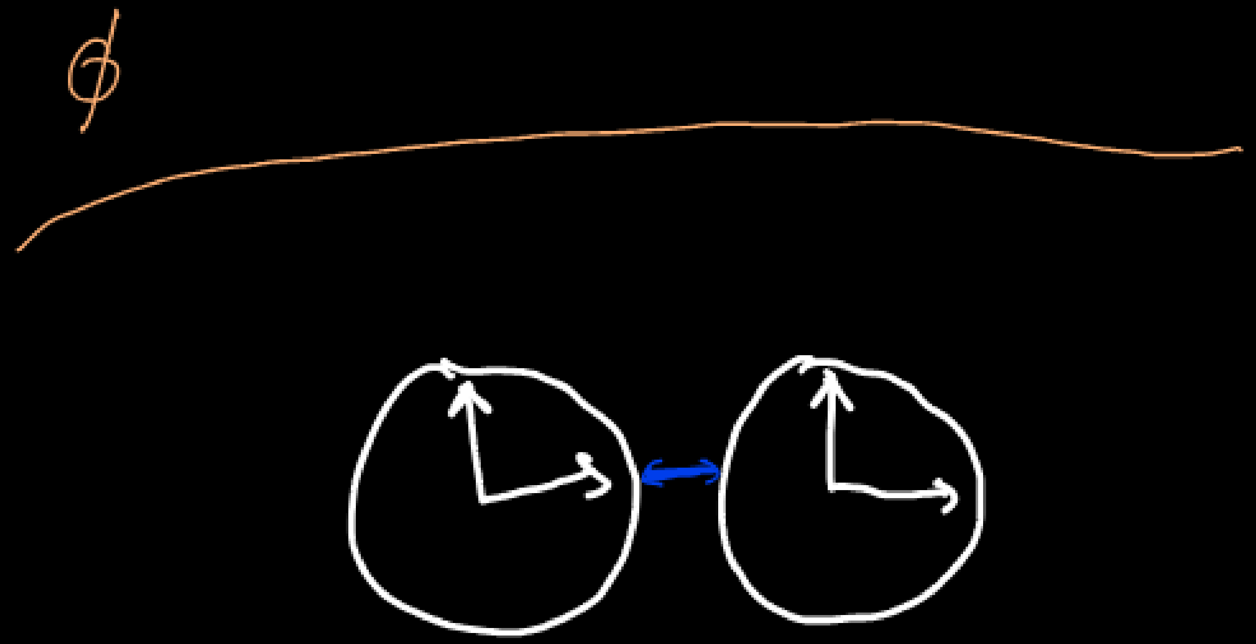
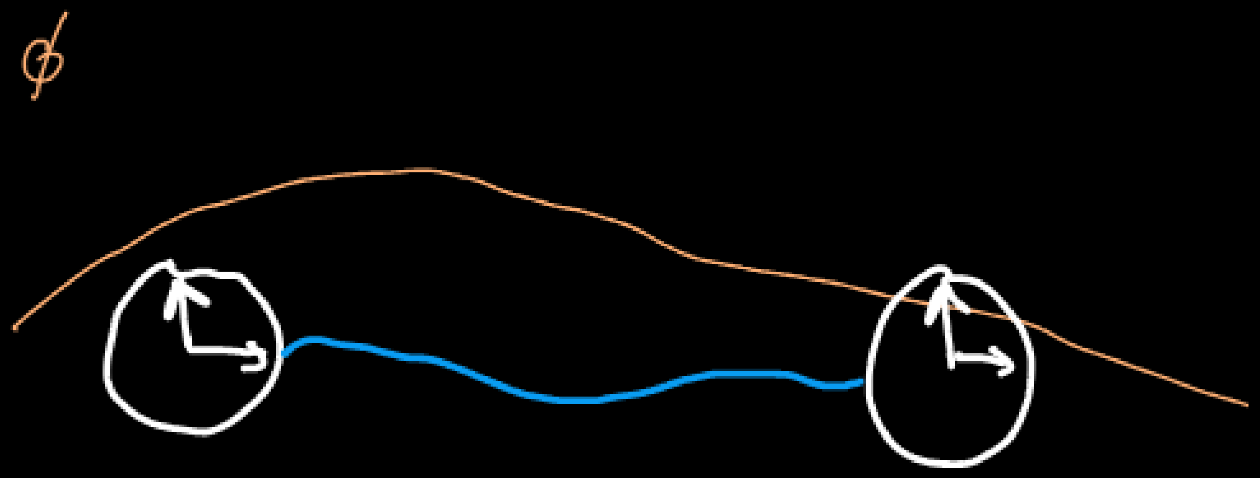


Separated (identical) sensors:

$$\frac{\delta(\nu_a/\nu_b)}{(\nu_a/\nu_b)} = \phi_0\,\kappa\,(\cos(\omega t) - \cos(\omega t - \delta))$$

$$\delta = \omega \Delta t - k_z D$$



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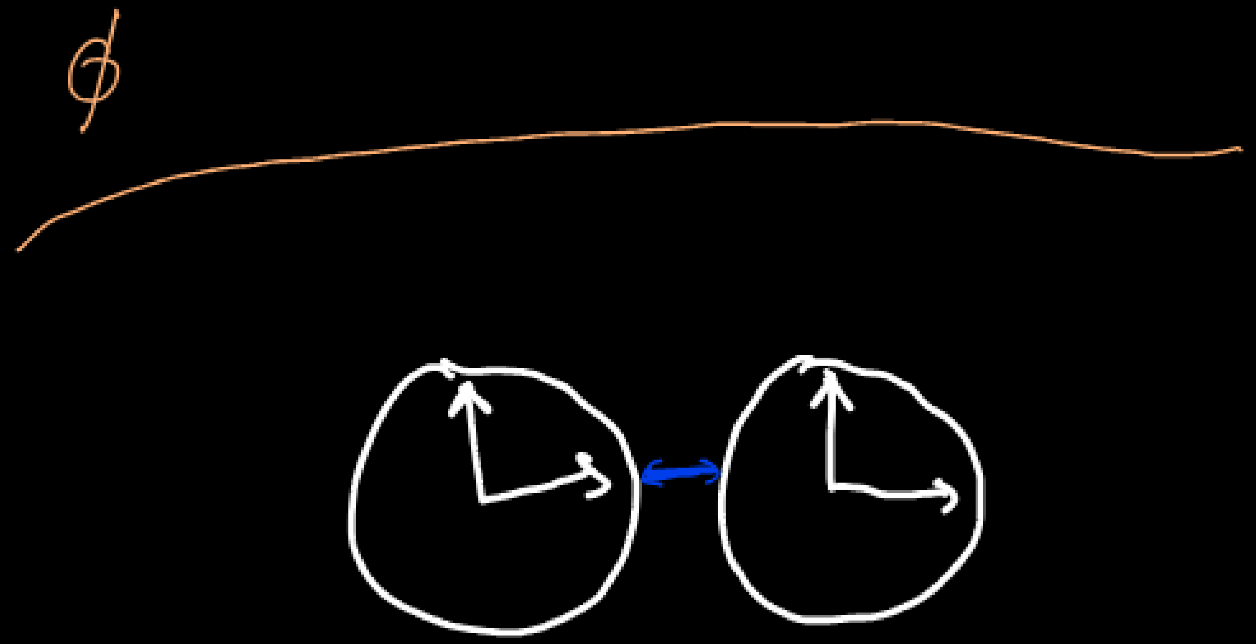

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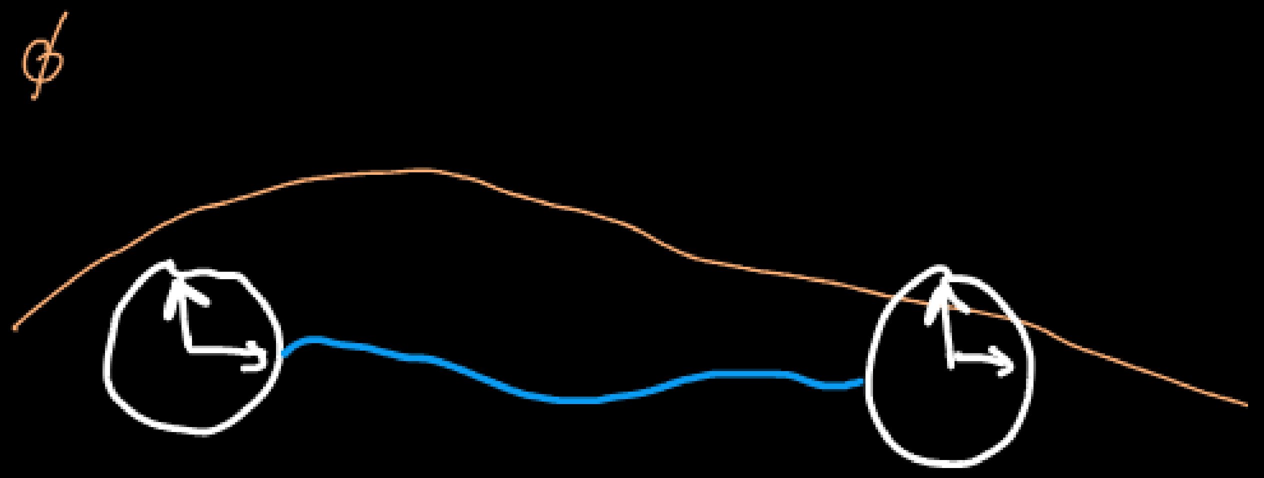
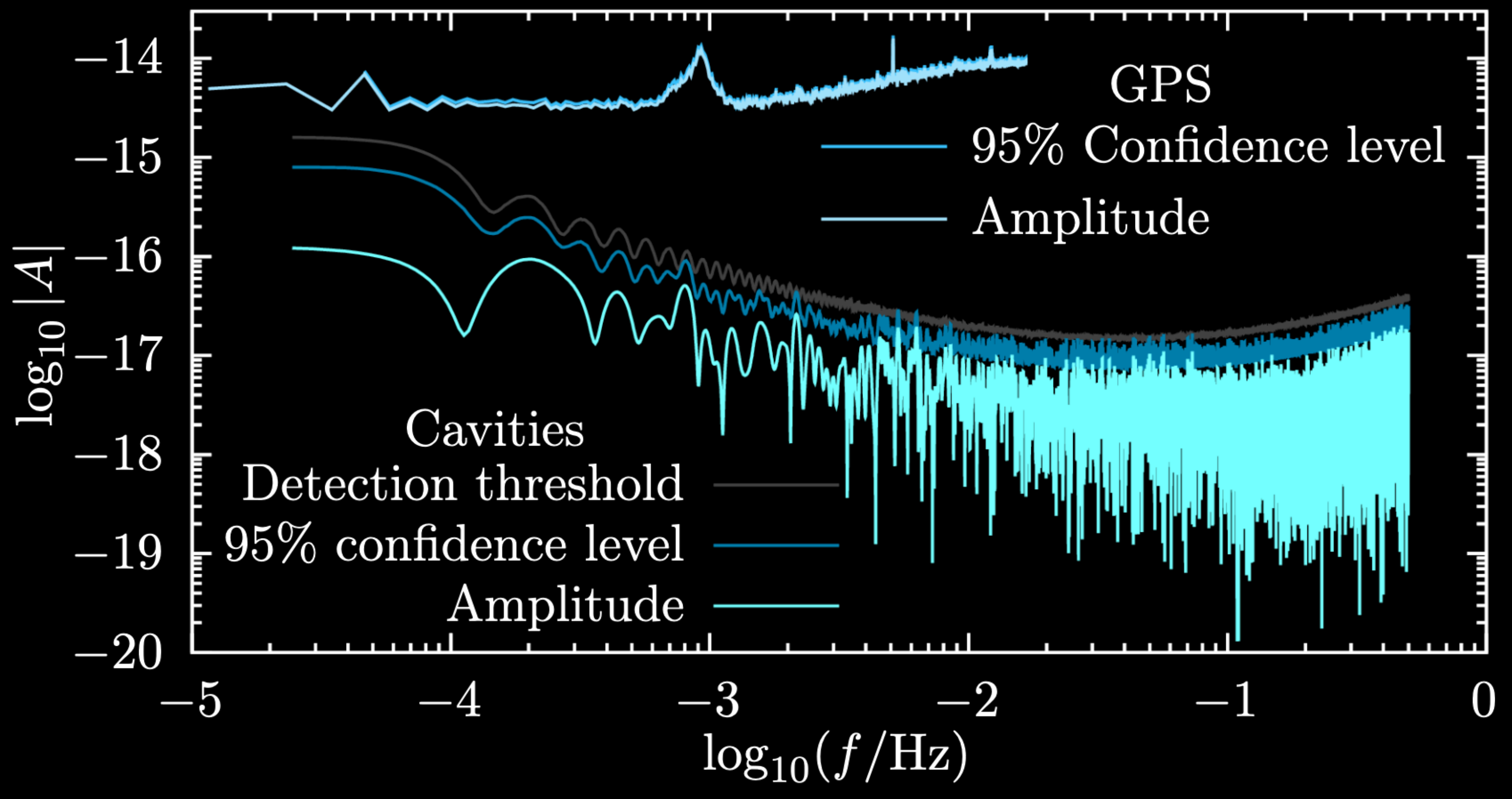
- Spatial and temporal component (depends on experiment)
- Allows access to unconstrained couplings
- Unique signals: scales with network size, daily modulation



Space-time separated sensors: initial results

- Filzinger, Caddell, Jani, Steinel, Giani, Huntemann, BMR, arXiv:2312.13723



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- Comparison of ultra-stable cavity lasers
- 750 km apart (2220 km Fibre cable: PTB to NPL via SYRTE)
- Sensitive to *spatial* phase shift

- Also: Data from GPS satellites (Rb clocks)
- Clocks less accurate, but setup sensitive to *temporal* term

- First constraints on d_{m_e} alone at low-frequency
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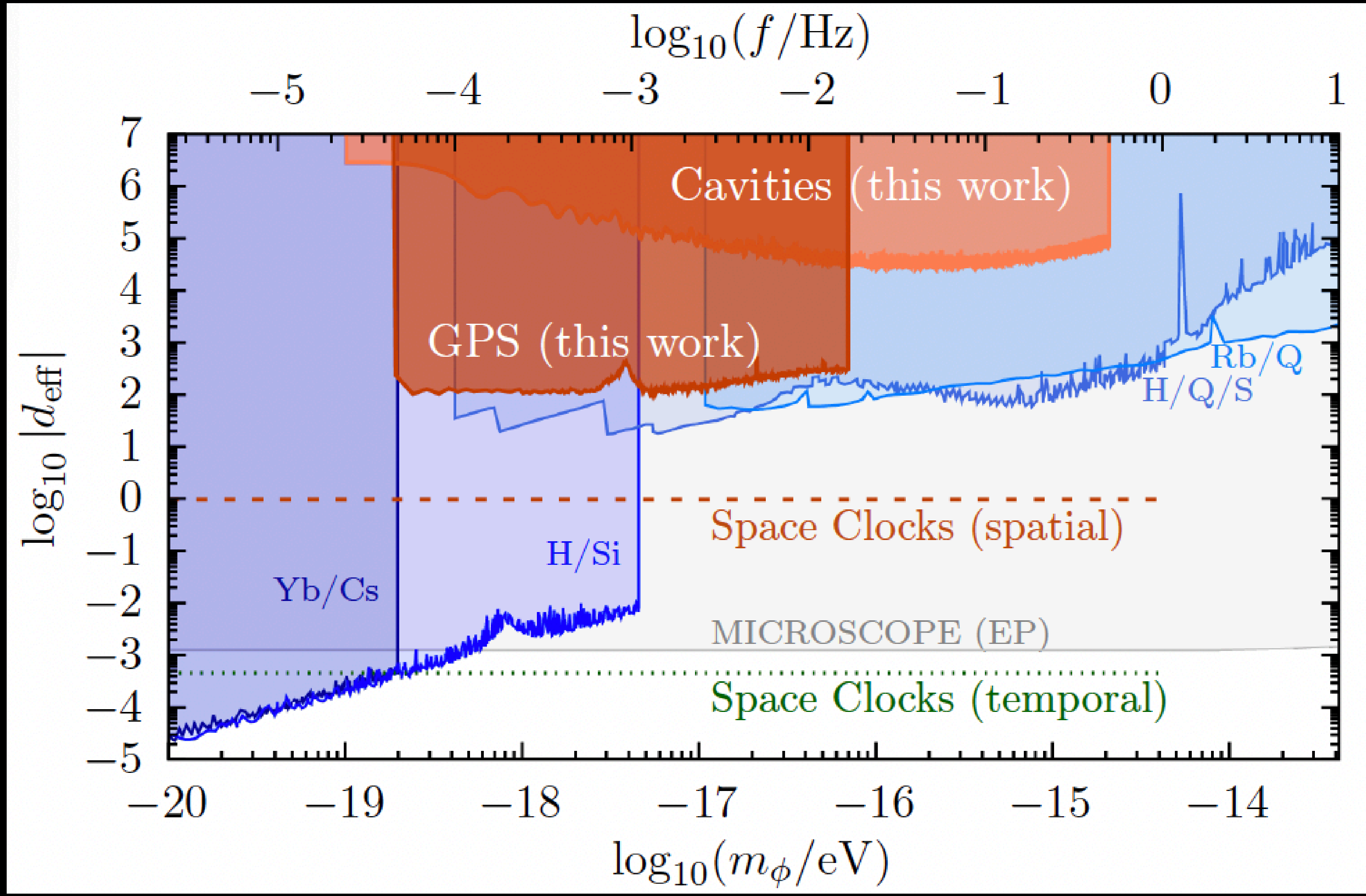

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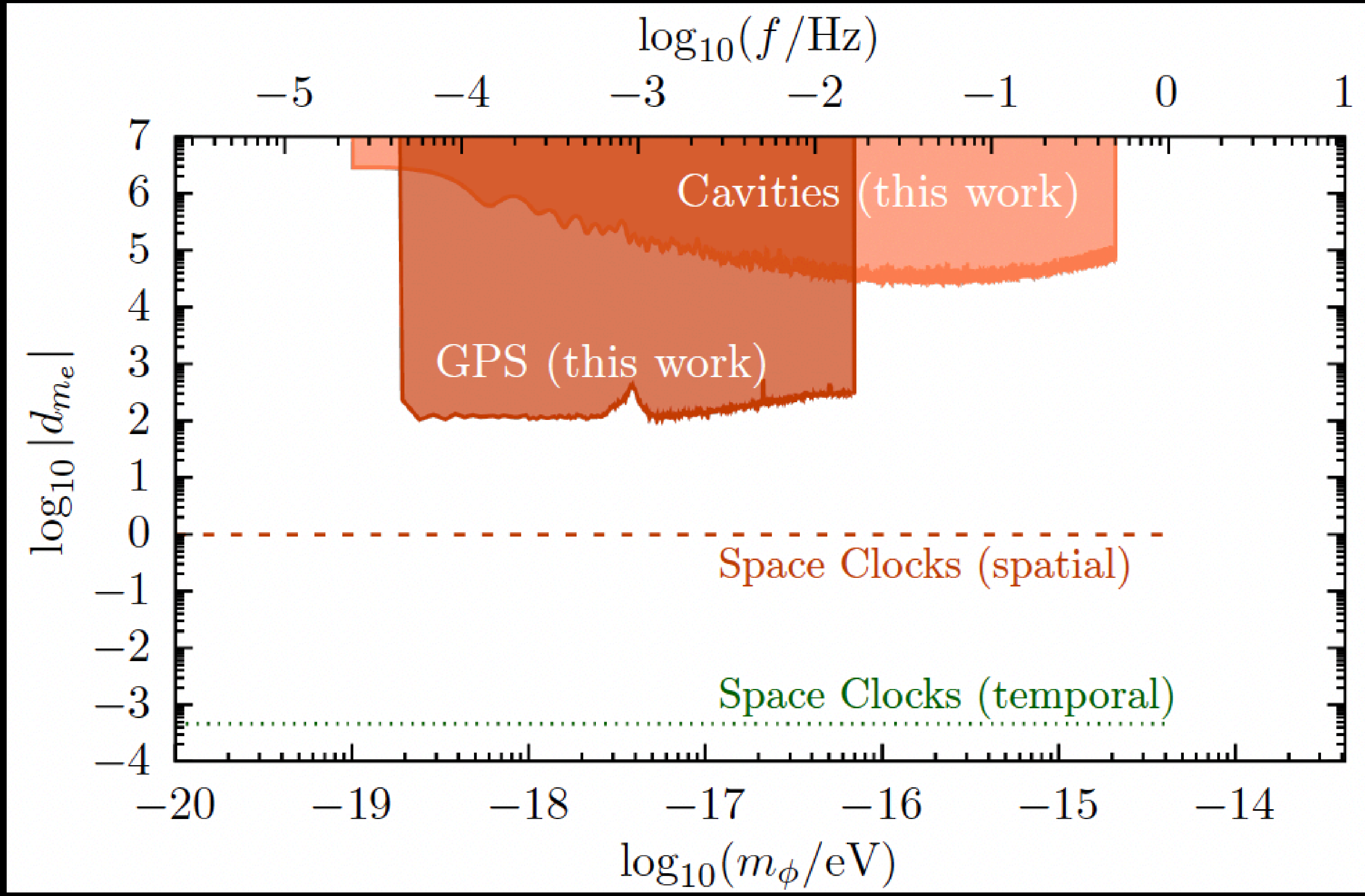

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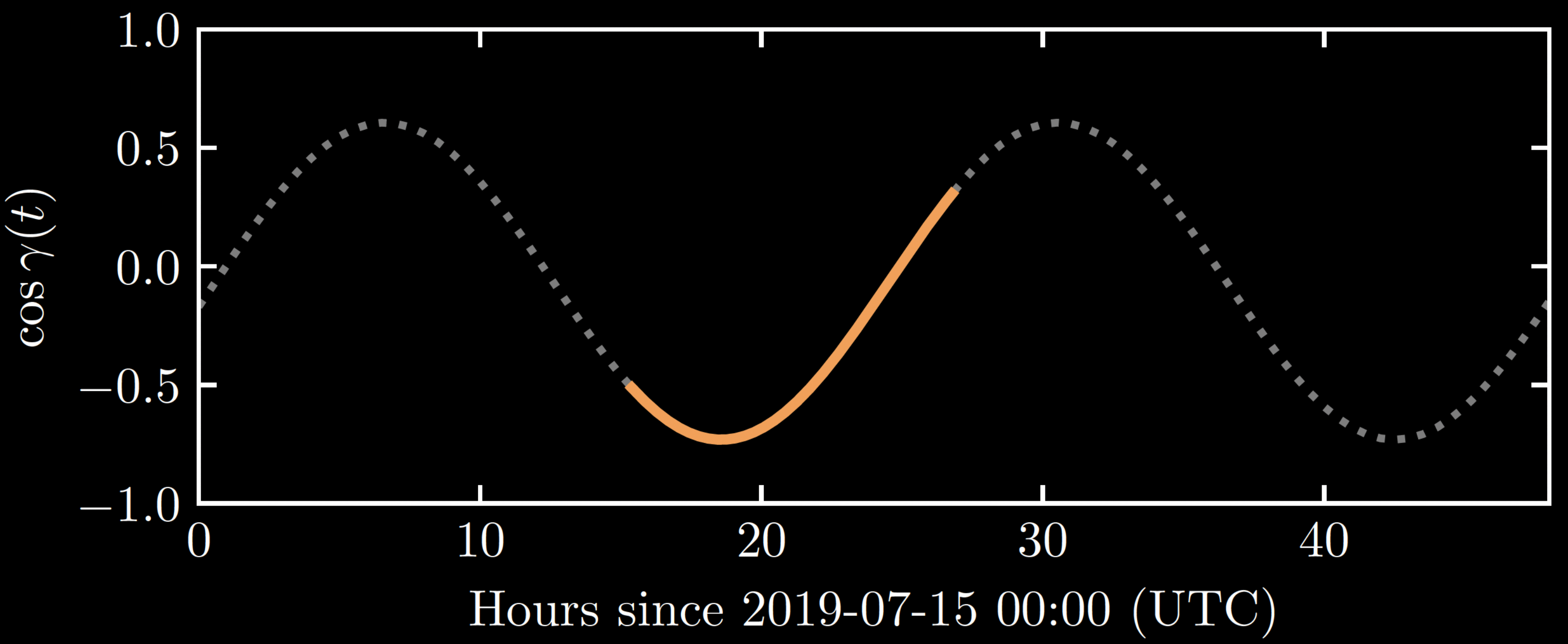

Conclusion

Ultralight dark matter

- Scalar coupling DM-SM: shift in atomic levels
- Monitor frequencies with atomic clocks

Space-time separated sensors

- Access to otherwise unconstrained couplings
- Unique signals: scale with network size, daily modulations

AIP Congress, Melbourne, December 2024

Benjamin M. Roberts

School of Mathematics and Physics,
University of Queensland, Australia

- Slides broberts.io/talks

- Caddell, Flambaum, BMR, Phys. Rev. D **108**, 083030 (2023)
- Savalle *et al.*, Phys. Rev. Lett. **126**, 051301 (2021)
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THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

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Extra

Scalar-SM?

- Overview: Hees *et al.*, PhysRevD.98.064051 (2018)

$$\mathcal{L}_{\text{int.}} = \phi\left[d_e\, F_{\mu\nu}F^{\mu\nu} + d_{m_f}\,\bar{\psi}\psi + d_g\, G^a_{\mu\nu}G^{a\mu\nu}\right]$$

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- nb: $d_e = d_\gamma = d_\alpha = 1/\Lambda_\gamma$

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- Nuclear moments + radius: depend on Λ_{QCD}, m_q

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- Optical clock

$$\omega \propto R_y\, F_{\text{rel}}(Z\alpha) \sim \alpha^{(2+K_{\text{rel}})} m_e$$

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- Microwave (hyperfine) clock

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- Cavity-stabilised laser

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