Title: Optical frequency standards for gravitational wave detection

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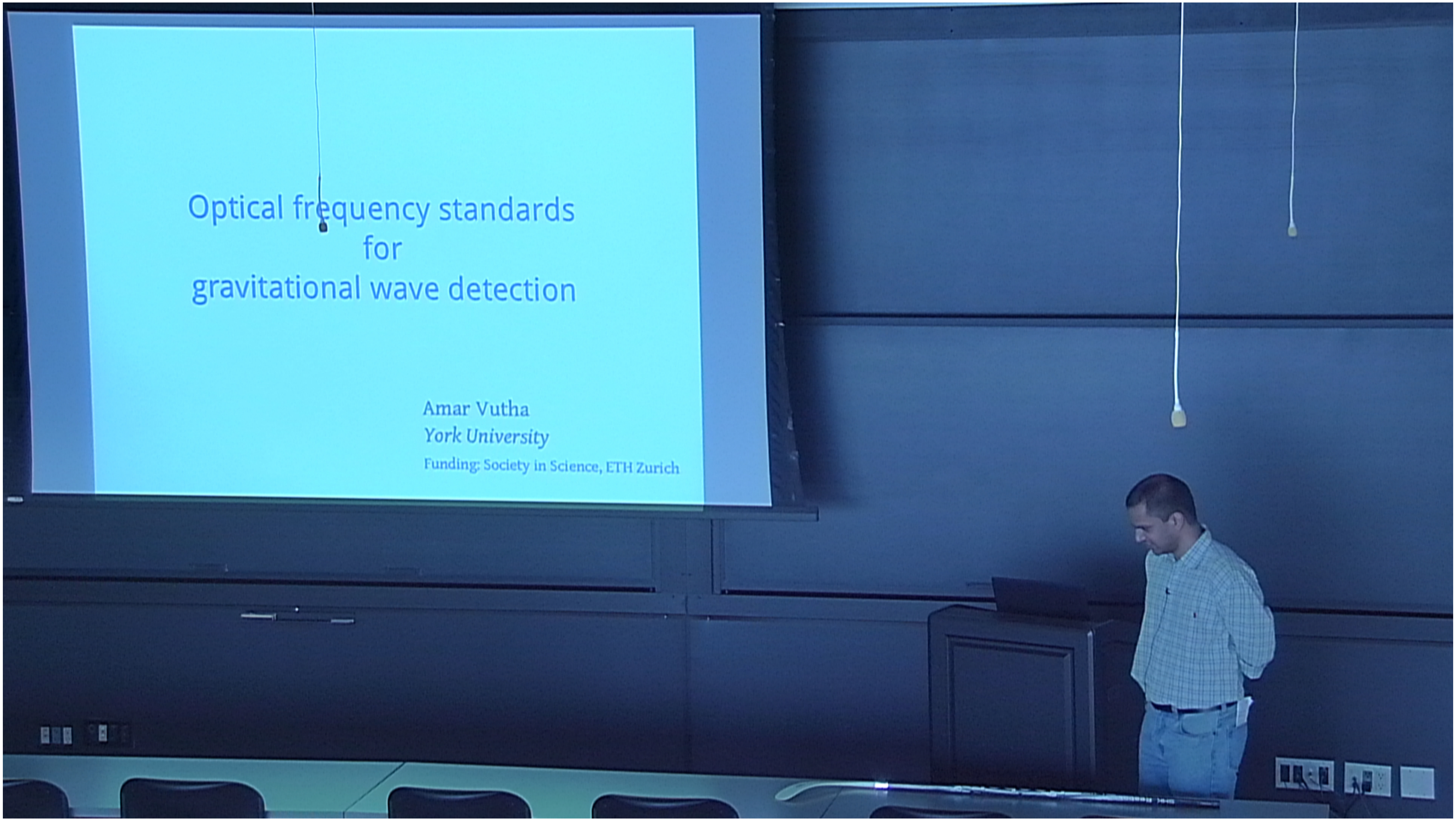
Abstract: <p>Gravitational waves (GW) imprint apparent Doppler shifts on the frequency of photons propagating between an emitter and detector of light. This forms the basis of a method to detect mHz GW using Doppler velocimetry between pairs of satellites [1]. The crucial component in such GW detectors is the frequency standard on board the emitting and receiving satellites. I will discuss how recent developments in atomic clock technology have led to devices that could be sufficiently sensitive to probe astrophysically interesting sources. I will present a design for a robust, space-capable optical frequency standard [2], that is being developed at York.</p>

<p>References</p>

<p>[1] JW Armstrong, Living Rev. Relativity 9, (2006), 1 [2] AC Vutha, arXiv:1501.01733 (2015)</p>


Optical frequency standards
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(collaboration: BP Das group, Indian Inst. of Astrophysics)

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Measurement of 2S-2P Lamb shift in hydrogen to shed light on proton radius puzzle

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Data-taking in progress, systematic effects being studied

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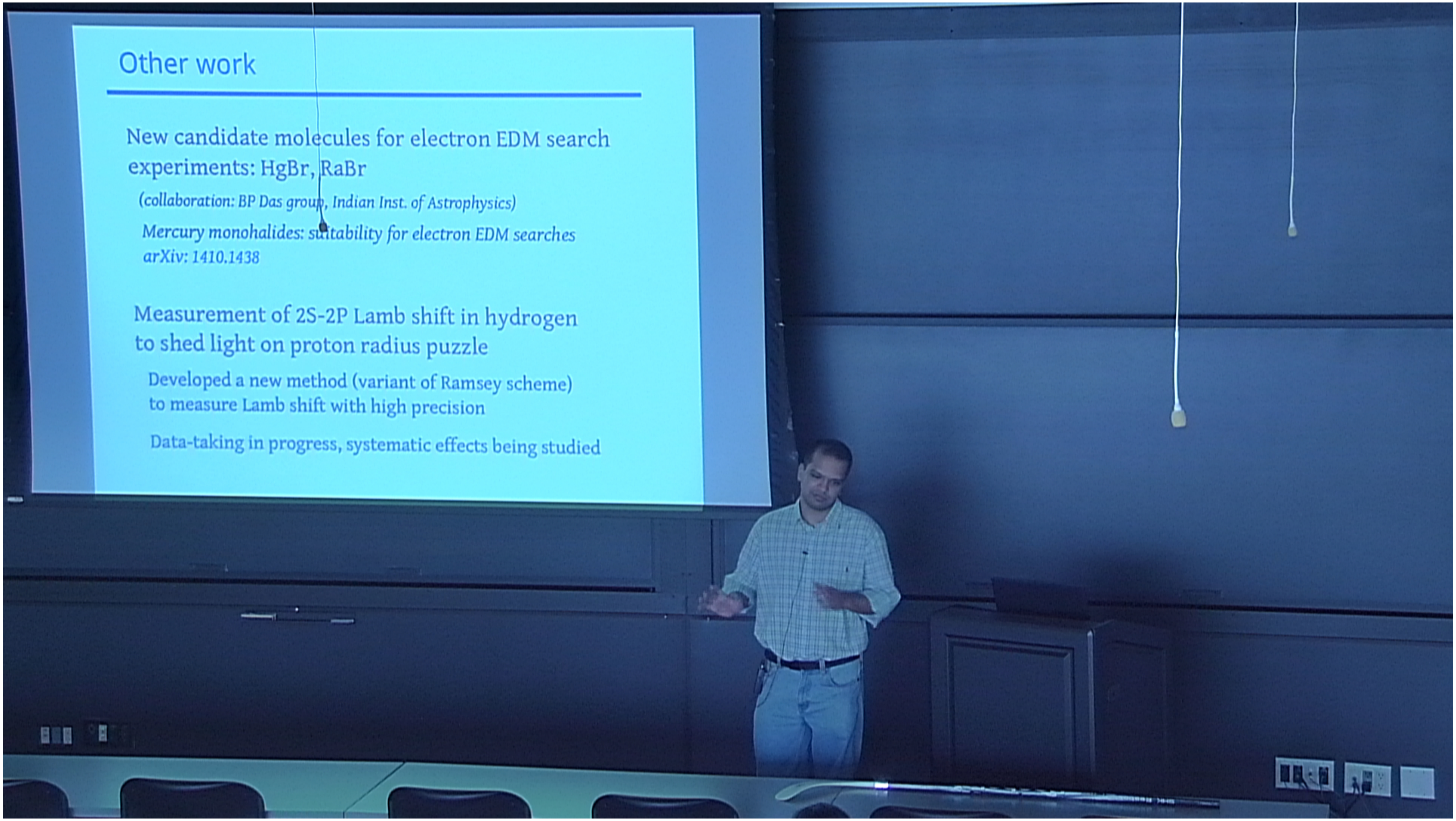
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Clocks

Clock = Oscillator + Frequency reference + Counter

Quartz watch = Electric circuit + Quartz crystal + Electric counter

Audio "clock" = Cello + Tuning fork + Electric counter

Optical clock = Laser + Atoms + Optical counter (frequency comb)

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What can you do with a good clock ?

Precise measurements

Accuracy of directly measuring	
length	10^{-9}
temperature	10^{-6}
mass	10^{-8}
frequency	10^{-17}

Ranging + Navigation — *distance = time x speed of light*

Communication — *accurate frequency synthesis*

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Performance of a frequency standard

Precision: $$\frac{\delta f}{f} \sim \frac{1}{f_0 \sqrt{N T \tau}}$$ FUNDAMENTAL LIMIT

- oscillation frequency (f_0)
- SNR factor = √N(atoms)
- coherence time (T)
- averaging time (τ)

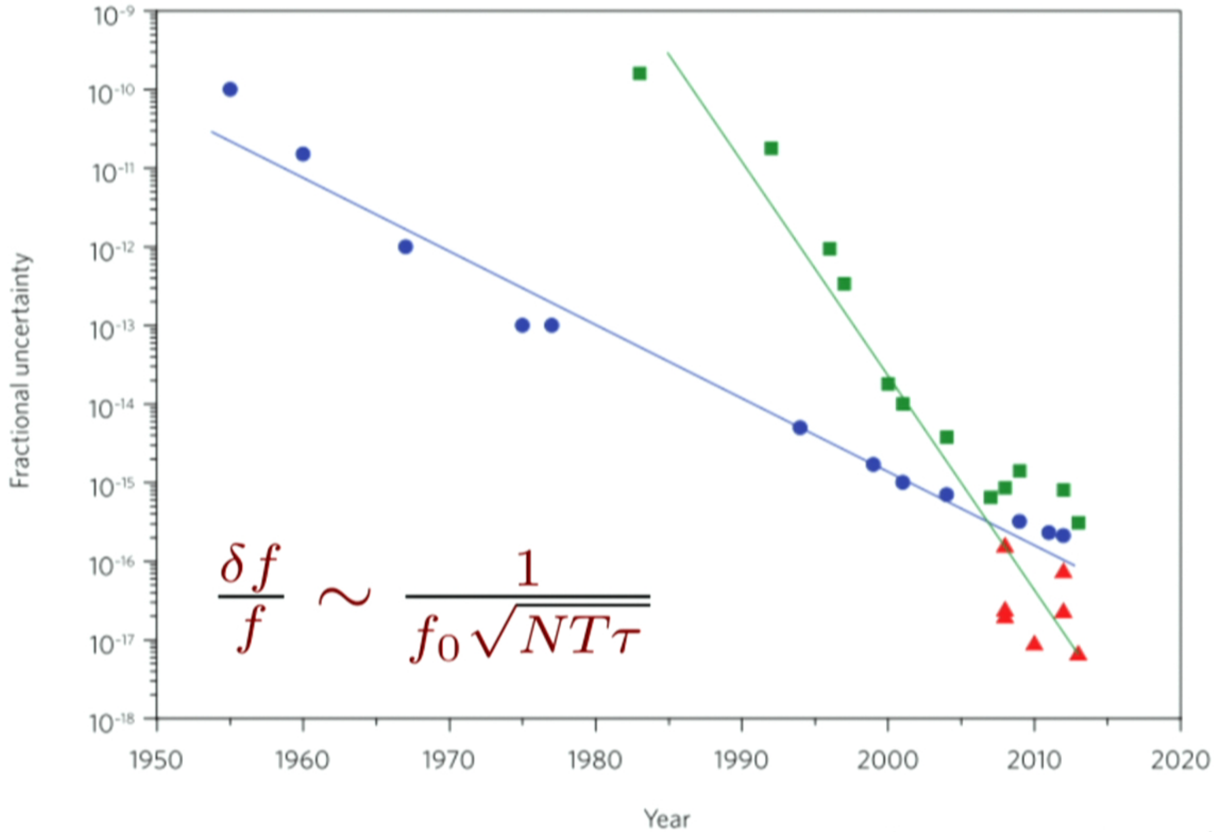
Accuracy: *determined by design*

Example: similar performance achieved with

optical lattice clocks .... $N \sim 10^4$

ion clocks .... N=1

State of the art



$$\frac{\delta f}{f} \sim \frac{1}{f_0\sqrt{NT\tau}}$$

Margolis, *Nature Physics* (2014)

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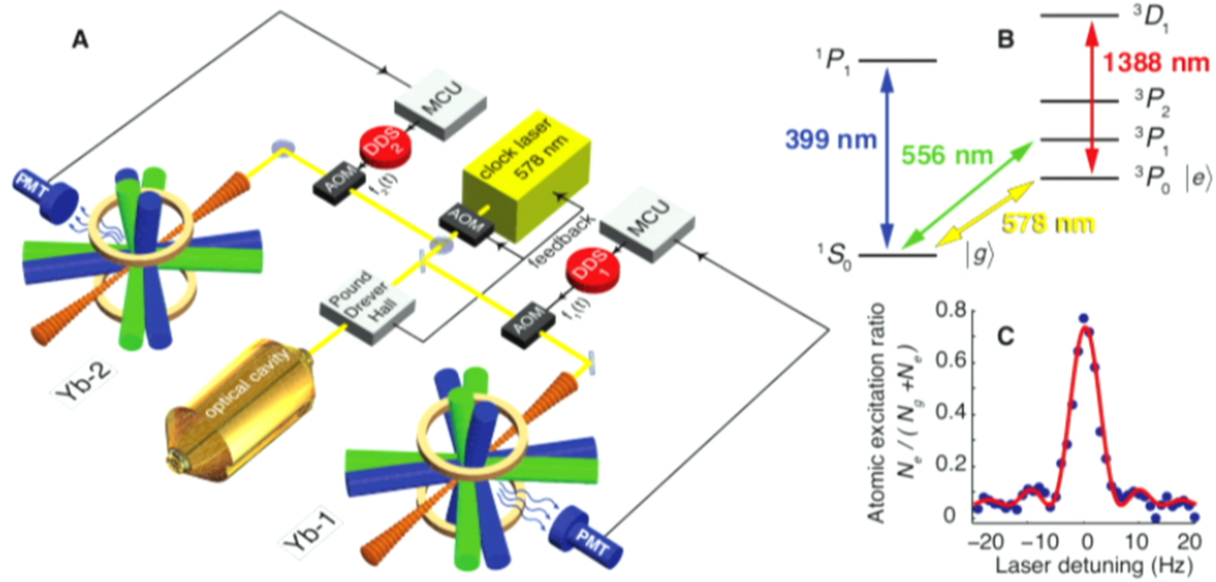


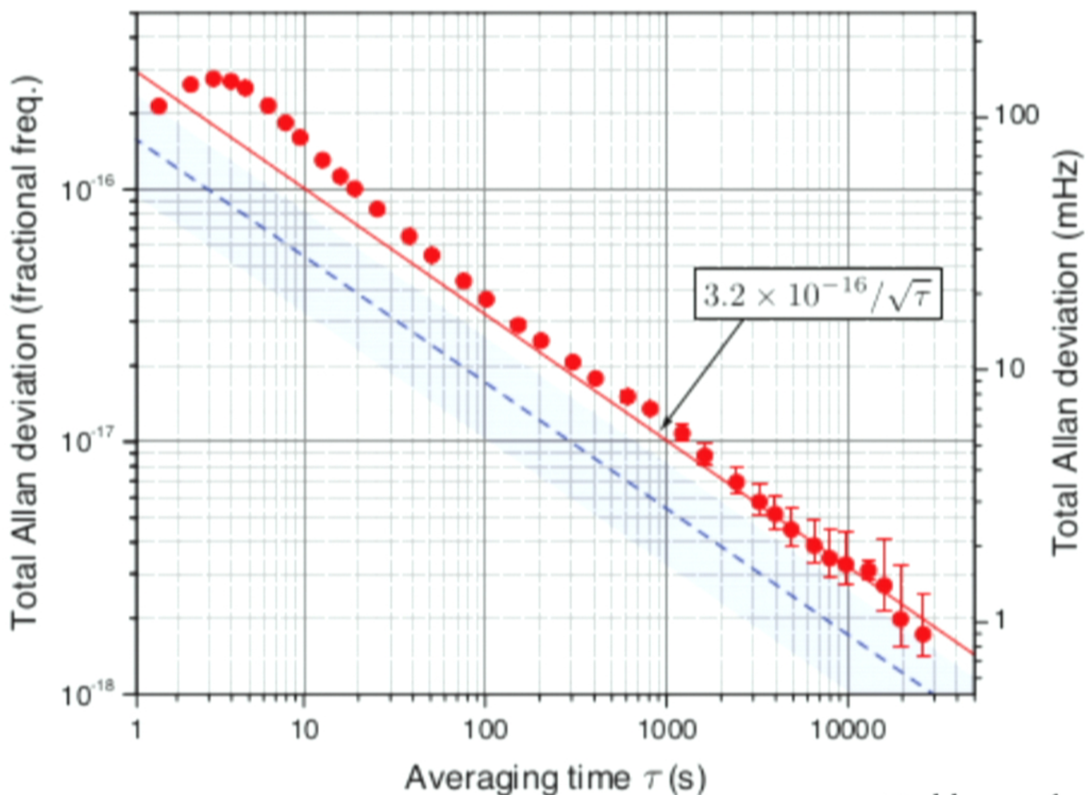
Hinkley *et al.*, Science (2013)

$$\frac{\delta f}{f} \sim \frac{1}{f_0 \sqrt{N T \tau}}$$

N ~ 10^4 atoms

T = 500 ms

State of the art: optical lattice clocks



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Gravity & clocks

Waterloo: 330 m + m.s.l.

$$\frac{\Delta\nu}{\nu} \simeq 10^{-14}$$ *(1000x sensitivity of optical clocks)*

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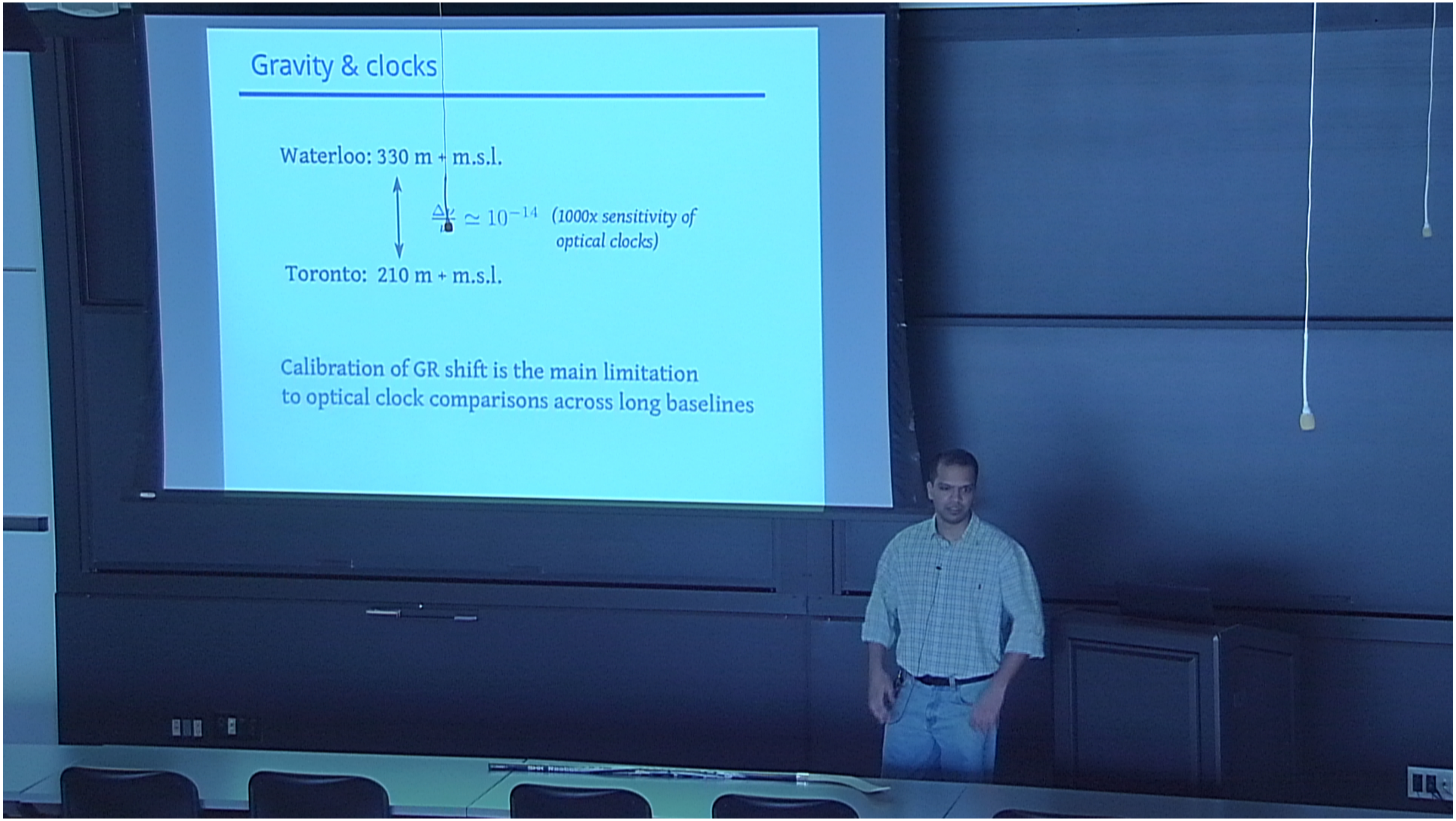
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GW effect on an emitter-receiver pair

$$ds^2 = dt^2 - (dz^2 + dx^2 + dy^2) - h_+[k(z-t)](dx^2 - dy^2) - 2h_\times[k(z-t)]dxdy$$

Conserved momenta are $p_z + p_t$, p_x, p_y

Photon momentum is a null vector p.p = 0

$$p = \left[\tfrac{\gamma}{2}(1+\delta); \alpha, \beta, \tfrac{\gamma}{2}(1-\delta)\right]$$

$$\alpha = p_0 \sin\theta\cos\phi$$
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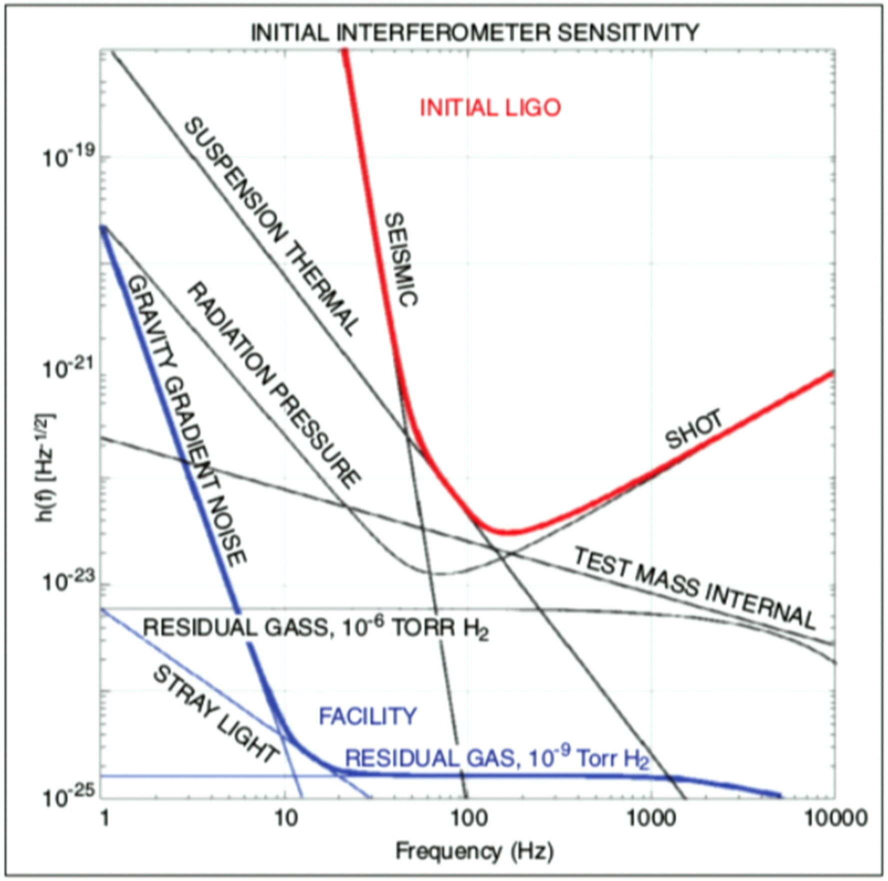
$$\frac{\nu_e}{\nu_r} = \frac{1+\delta_e}{1+\delta_d} \approx 1 + \sin^2\theta\,(\cos 2\phi\, h_+ + \sin 2\phi\, h_\times)$$

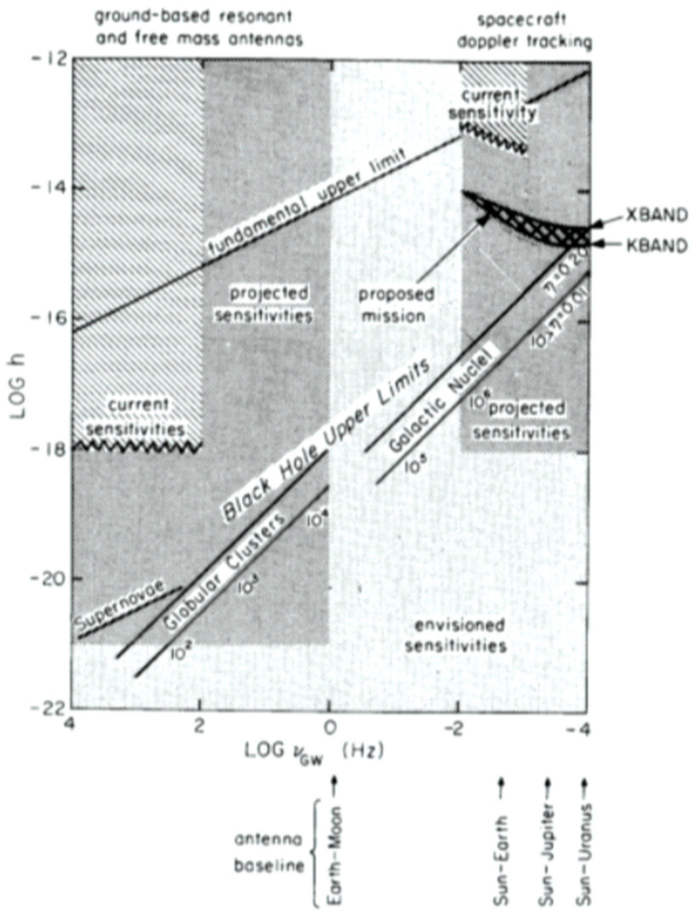
GW amplitude shows up in frequency differences

Terrestrial interferometers



Flanagan & Hughes, New J. Phys. (2005)

GW detection in the uHz - mHz band



Gravitational waves can be detected by precise Doppler measurements

Kaufman (1970),
Estabrook & Wahlquist (1975),
Smarr *et al.* (1983)

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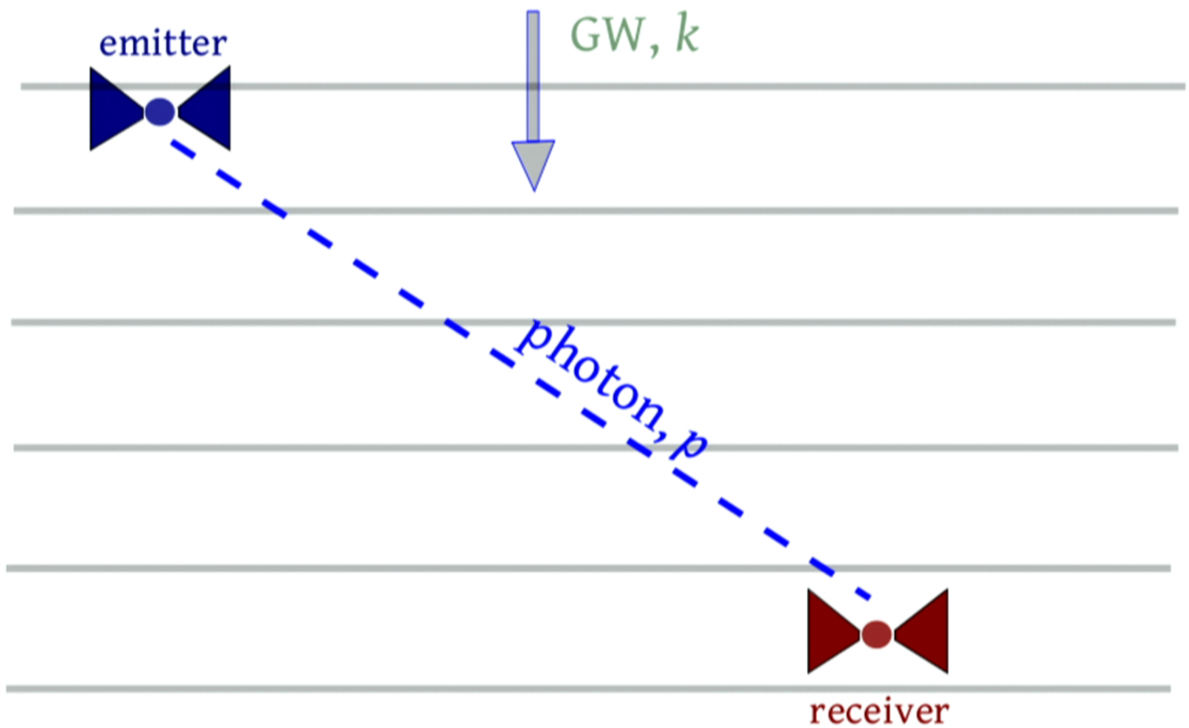

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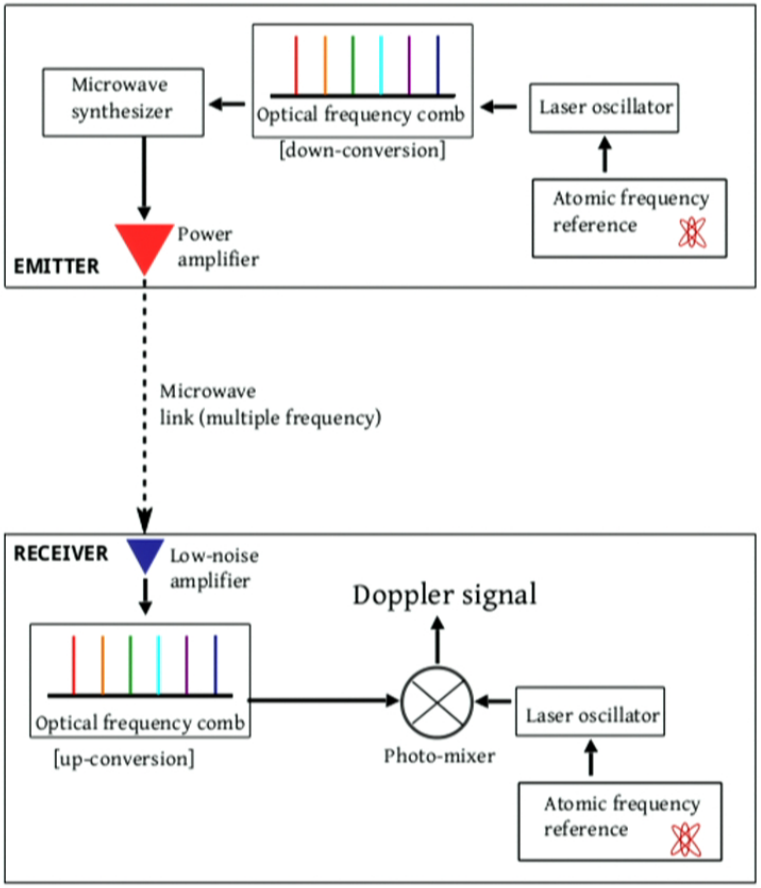
Frequency comparison scheme



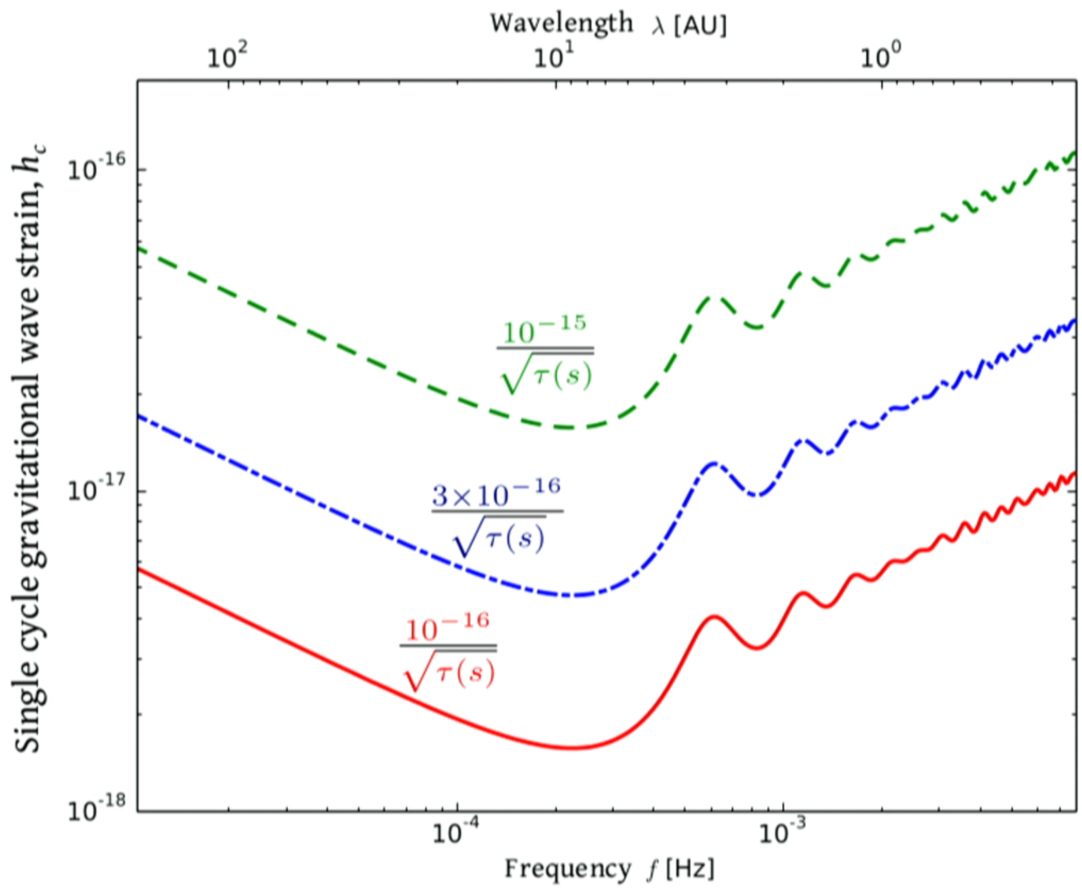
Absolute distance locking is not necessary

Multiple-frequency microwave link to suppress refractive index fluctuations

Possibly direct optical links in future

Compact frequency combs have been demonstrated
Papp et al., arXiv:1309.3525

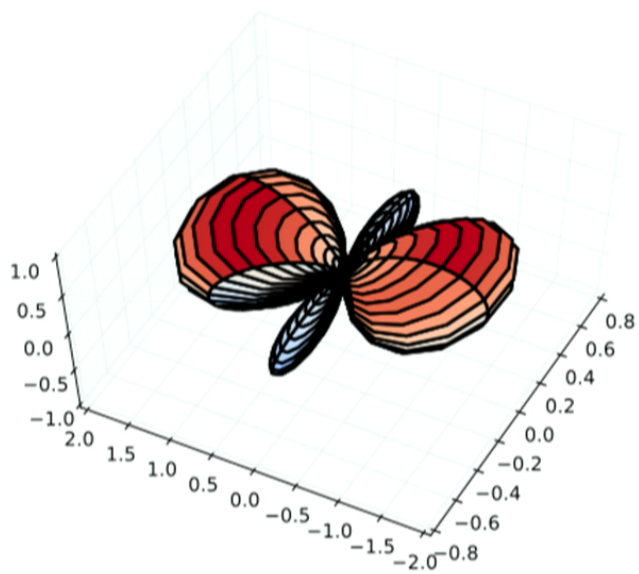
GW sensitivity of optical frequency standards

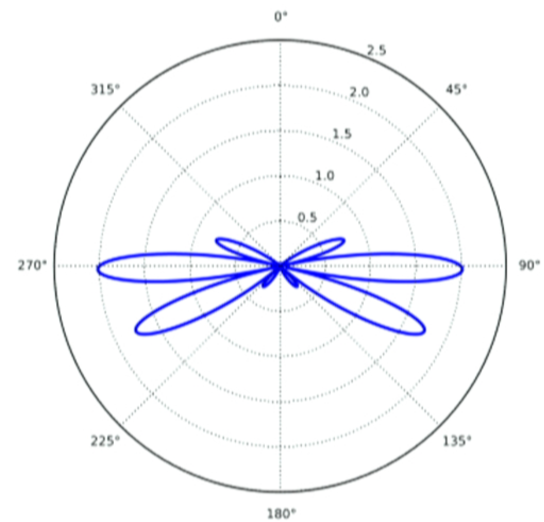


Clock arrays

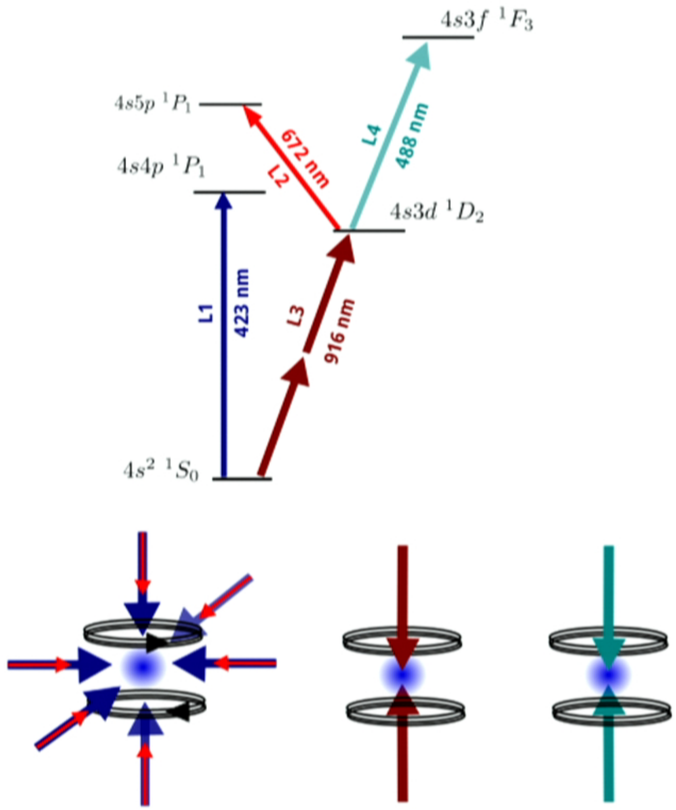
GW amplitude is linear in fractional frequency shift

Combined signals from different emitter-detector pairs can be used to improve directional sensitivity





Calcium 2-photon optical clock



2-photon clock transition is Doppler- and recoil-free

Doesn't need optical lattice => simpler architecture

Good prospects for portability and maintenance-free operation

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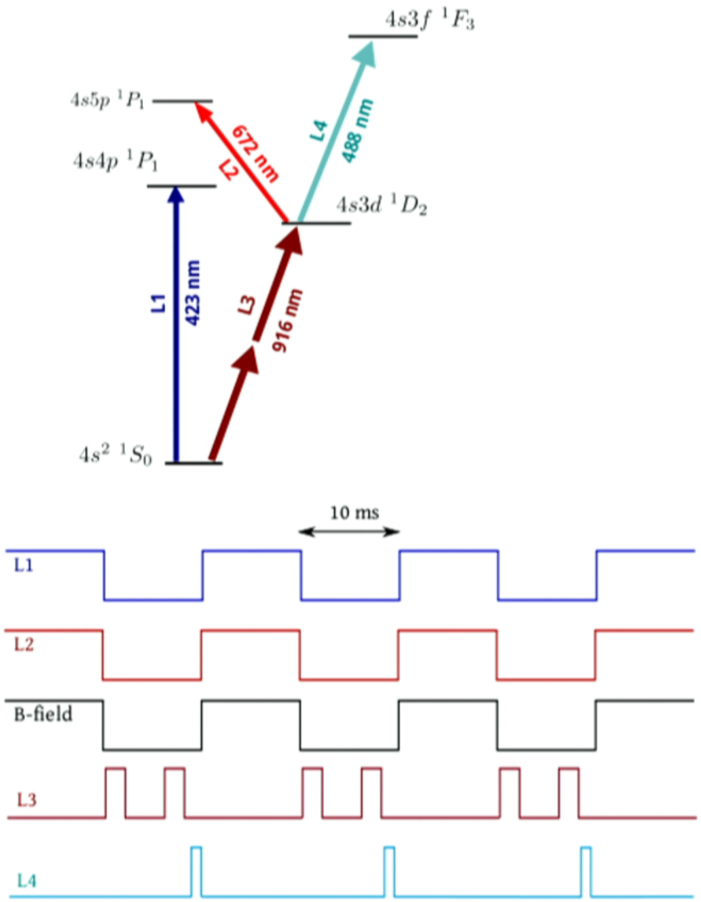

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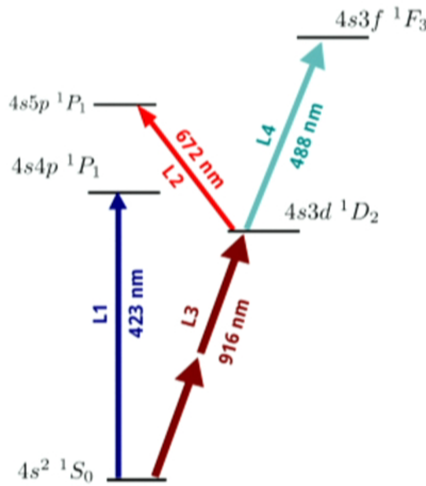

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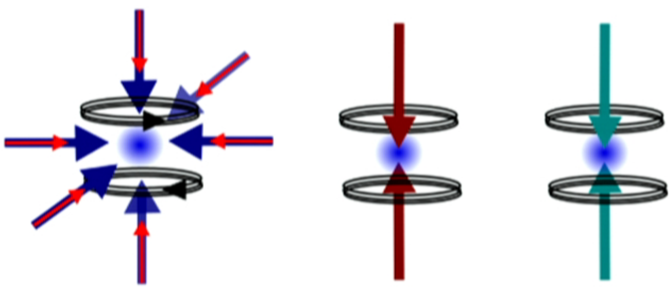

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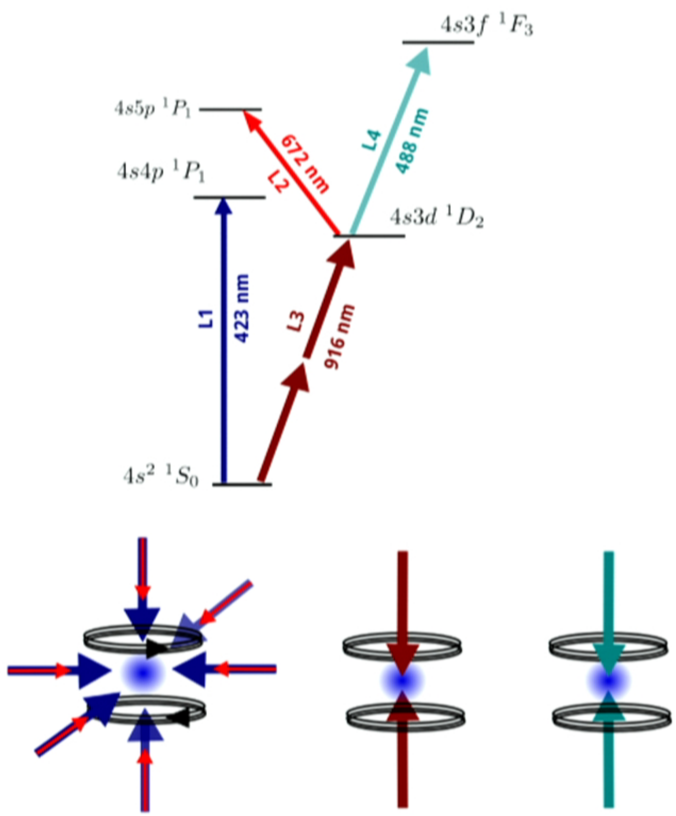

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Where next

Continuous clocks ?

$$\frac{\delta f}{f} \sim \frac{1}{f_0\sqrt{N\tau^2}}$$

Faster averaging, better performance