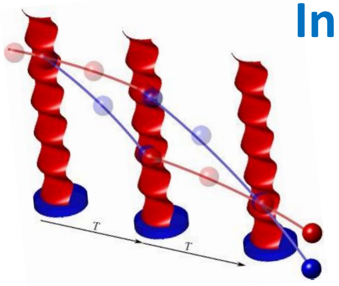
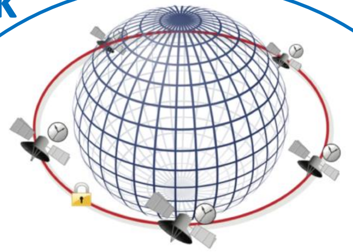
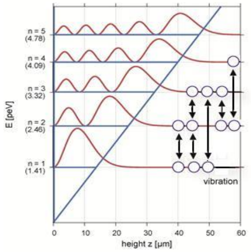
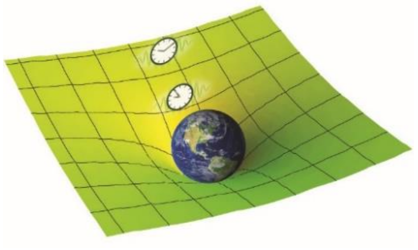
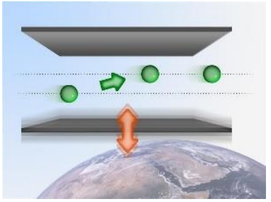
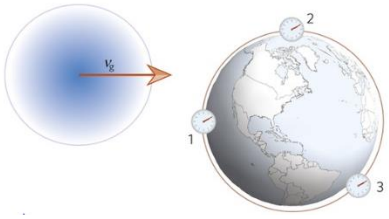
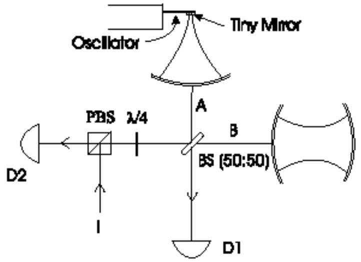
Gravitational wave detection with atomic clocks

IGOR PIKOVSKI

STOCKHOLM UNIVERSITY

Interplay between gravity and low-energy quantum systems

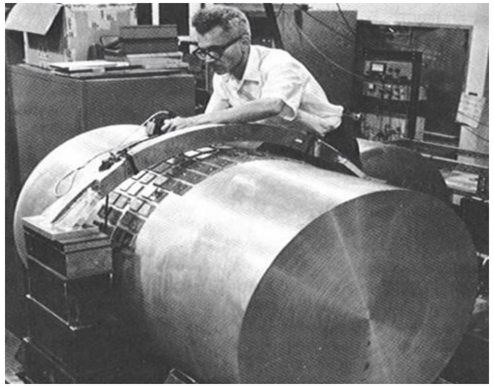
	Quantum systems as probes		Change in quantum behavior	
Expected physics	 Matter-waves to probe GWs	**In this talk**  Atomic clocks to probe GWs	 Quantized states of neutrons in gravity	 Quantum interference of clocks
Exotic models	 5th force / modified Newton law	 Dark matter searches	 Commutator deformations	 Gravitational wave function collapse

Overview

- Gravitational waves: frequency vs. phase measurements
- History of time keeping
- Atomic clocks
- Optical lattice atomic clock based gravitational wave detector
- Fundamental sensitivity and features
- Outlook

PhD and Postdoc positions open at SU (quantum optics, quantum info & interface with gravity, cosmology)
igor.pikovski@fysik.su.se

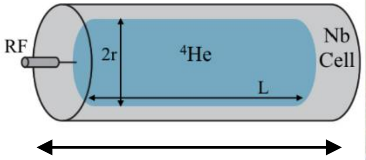
Detecting gravitational waves



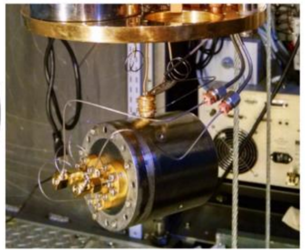
A. Resonant bar detectors: stretching of a material

New direction: Superfluid Helium opto-mechanical systems

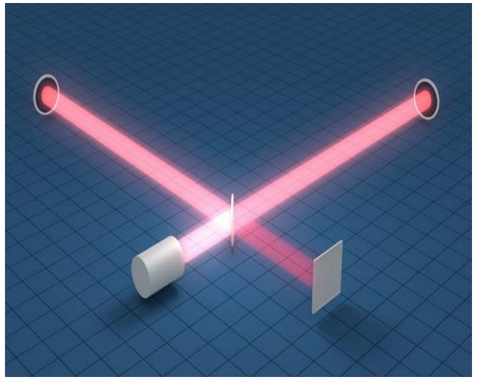
Singh, De Lorenzo, Pikovski, Schwab.
New J. Phys. 19, 073023 (2017)



$50cm$



$\sim 1kHz$



B. Free-space detectors: measuring distance

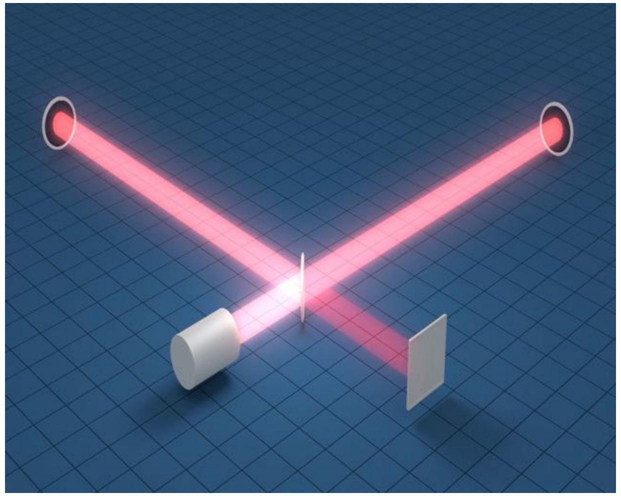
New direction: Atomic clocks and quantum control

Kolkowitz, Pikovski, Langellier, Lukin, Walsworth, Ye.
Phys. Rev. D 94, 124043 (2016)

LIGO principle: optical interferometry

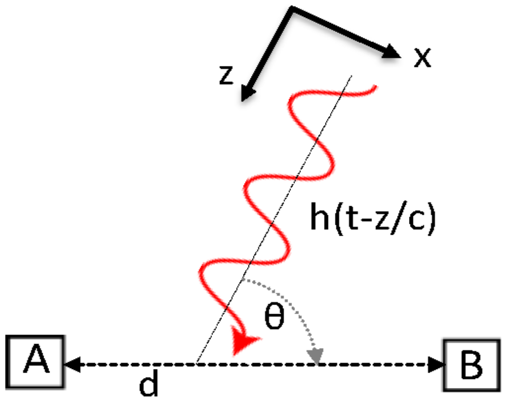
$$ds^2 = -c^2dt^2 + \big(1 + h(t,z)\big)dx^2 + \big(1 - h(t,z)\big)dy^2 + dz^2$$

Change in relative optical phase due to changes in distance



Distance from A to B in flat space: d

Light travel distance in presence of GW:



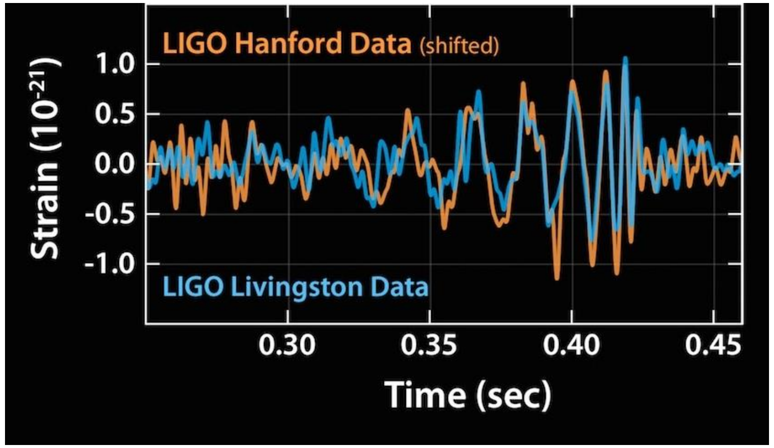
$$d + \frac{c}{2}(1+\cos\theta)\left[H(t) - H\left(t + \frac{d}{c}(1-\cos\theta)\right)\right]$$ where dH/dt=h

For $d \ll \lambda_{GW}$: $$\frac{\Delta d}{d} \approx h(t)$$ LIGO signal

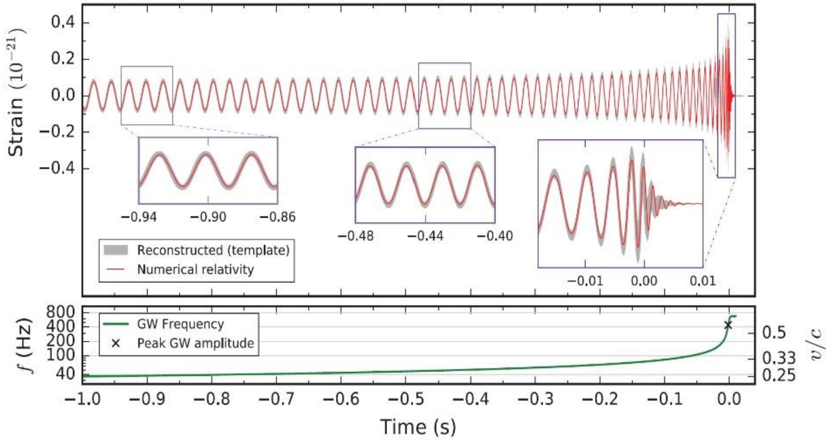
2 arms: cancellation of laser phase noise

Strain measured via changes in optical phase

LIGO detections

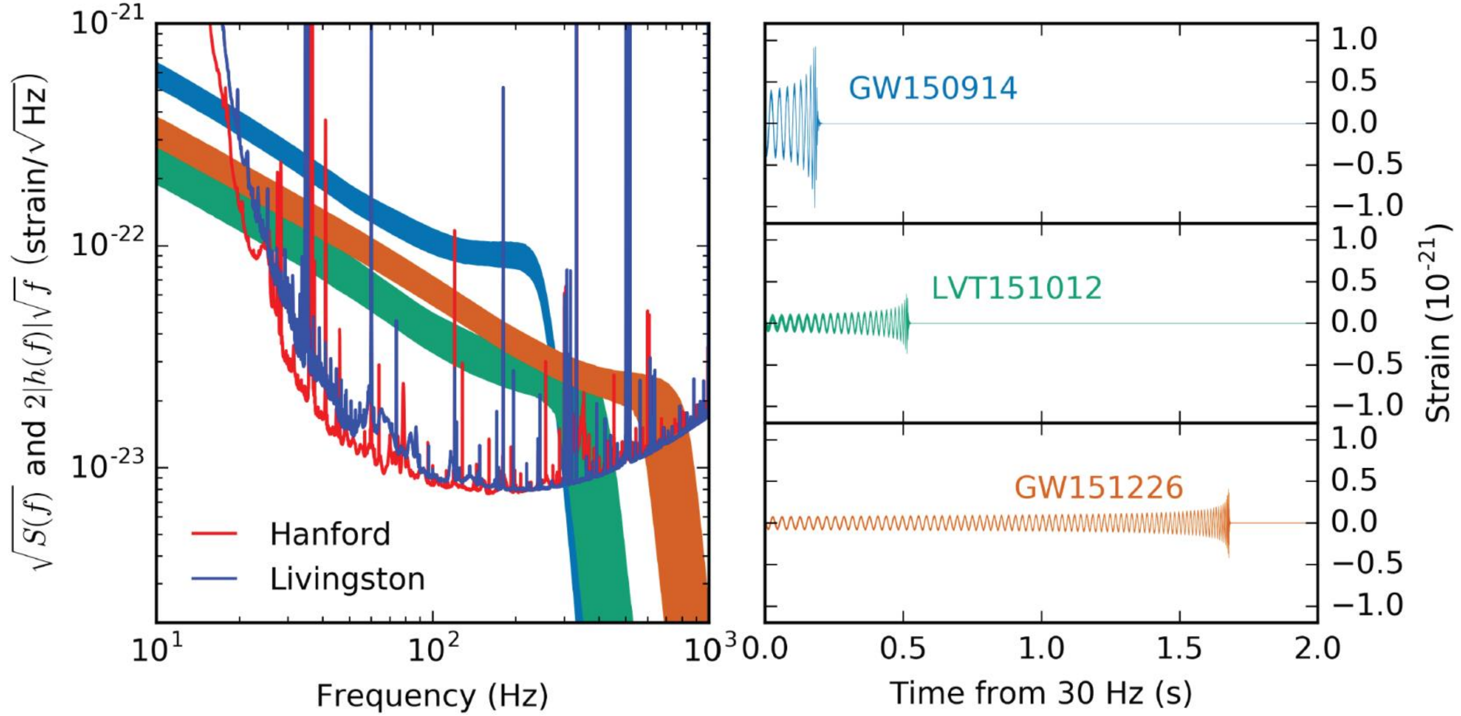


B. Abbott et al. PRL 116, 061102 (2016)



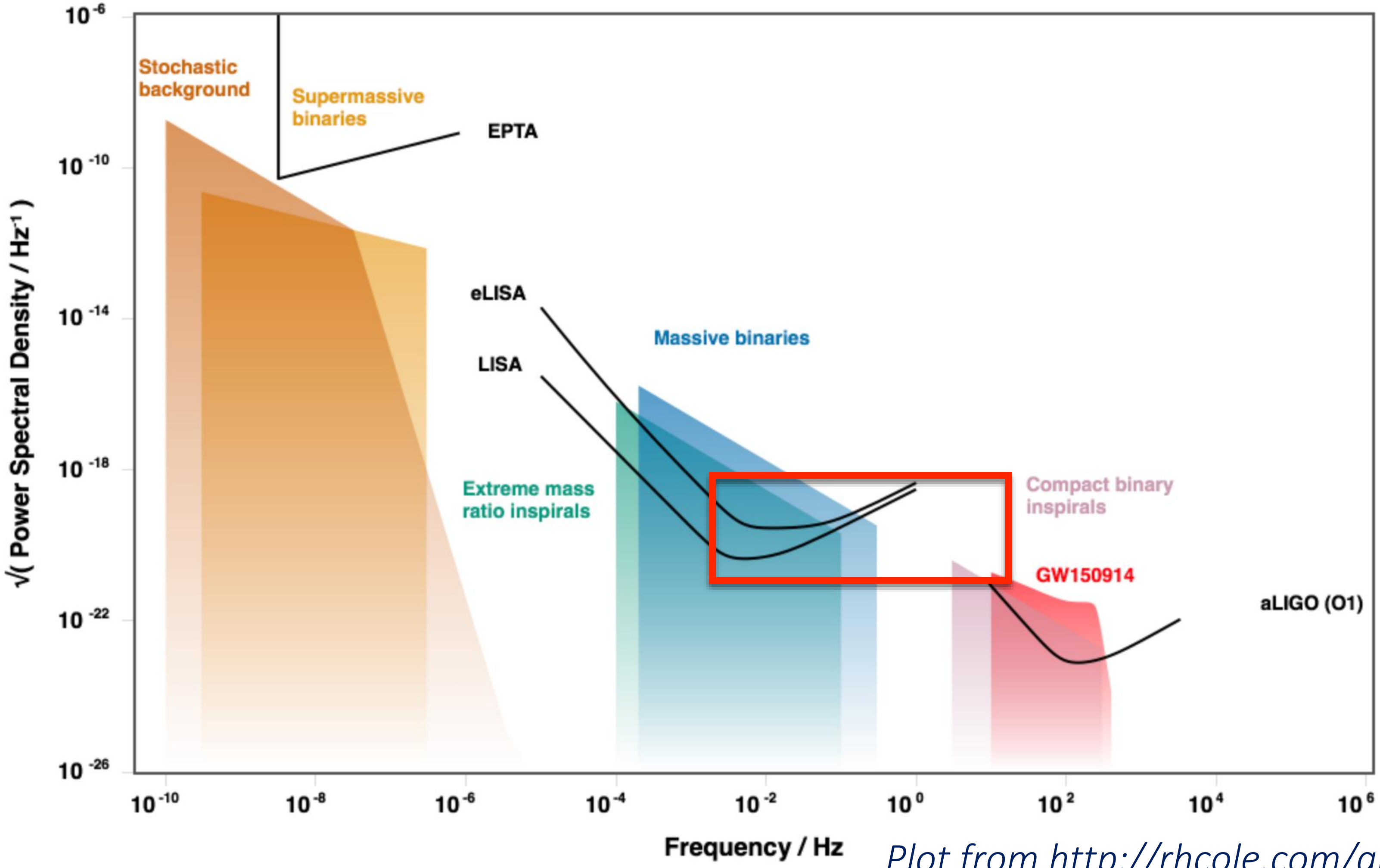
B. Abbott et al. PRL 116, 241103 (2016)

- Limited by photon shot noise at $f \gtrsim 200$ Hz
- On Earth: limited by gravity noise at $f \lesssim 40$ Hz



LIGO collaboration, https://dcc.ligo.org/P1600088/public/ (2016)

Current and future sensitivity



Plot from http://rhcole.com/apps/GWplotter

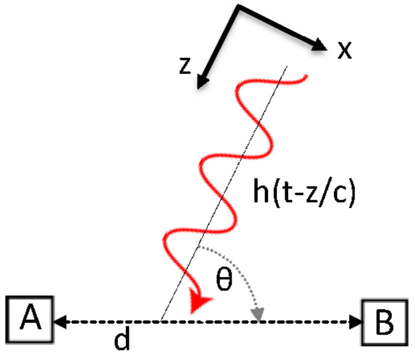
Here: atomic clock based detector in space

- Narrowband with competitive sensitivity
- Tunable in mHz – Hz range using techniques from quantum control
- Can bridge range between LISA and LIGO

Frequency measurements

Frequency measurements: Doppler shifts from gravitational waves

$$s = \frac{\Delta\nu}{\nu} = \frac{1+\cos\theta}{2}\left(h(t) - h(t + \frac{d}{c}(1-\cos\theta))\right)$$



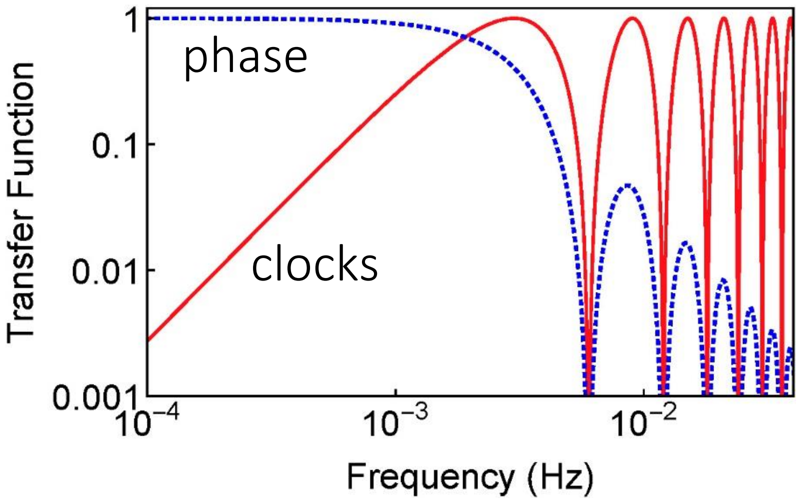
In Fourier space: $\tilde{s}^2(f) = \tilde{h}^2(f)T(f)$ T(f): detector transfer function

Clocks:

- Better signal for $f > c/d$
- Different measurement technique with other advantages

$$T_{phase} = \text{sinc}^2\left(\pi f \frac{d}{c}\right)$$

$$T_{clocks} = \sin^2\left(\pi f \frac{d}{c}\right)$$

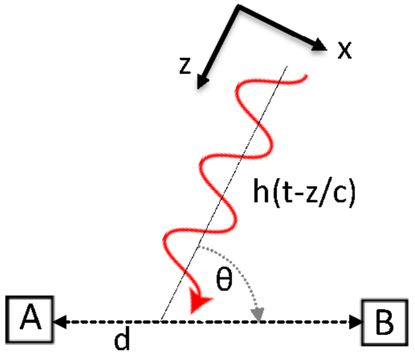


Also used in Pulsar Timing Array (f < μHz) *Hobbs et al. Class. & Quant. Grav. 27,* 084013 *(2010)*

Frequency measurements

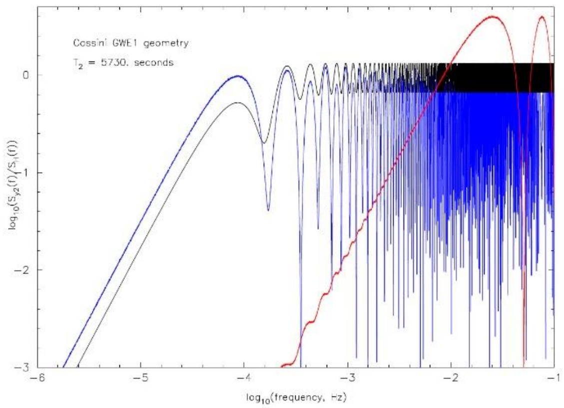
Frequency measurements: Doppler shifts from gravitational waves

$$s = \frac{\Delta\nu}{\nu} = \frac{1+\cos\theta}{2}\left(h(t) - h(t + \frac{d}{c}(1-\cos\theta))\right)$$



In Fourier space: $\tilde{s}^2(f) = \tilde{h}^2(f)T(f)$ T(f): detector transfer function

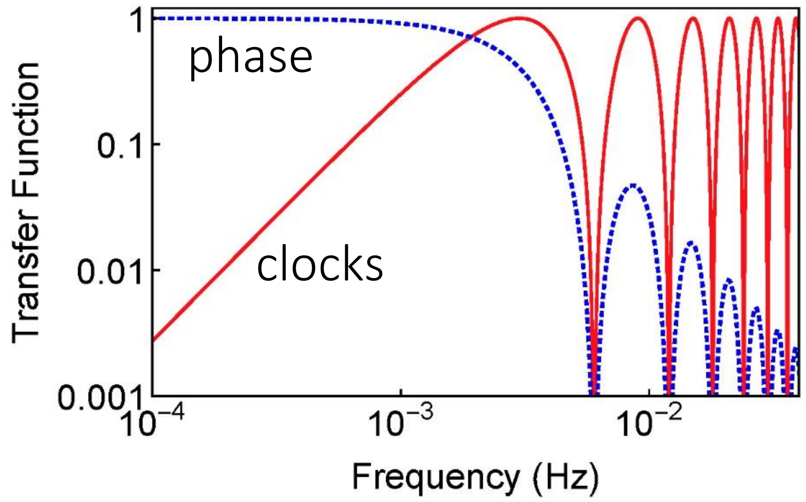
Same principle: Doppler Tracking



Armstrong, Living Rev. Relativity, 9, (2006)

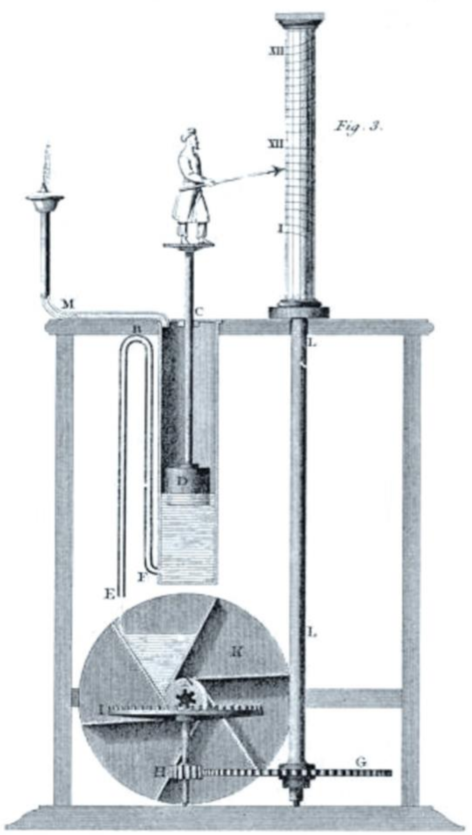
$$T_{phase} = \text{sinc}^2\left(\pi f \frac{d}{c}\right)$$

$$T_{clocks} = \sin^2\left(\pi f \frac{d}{c}\right)$$

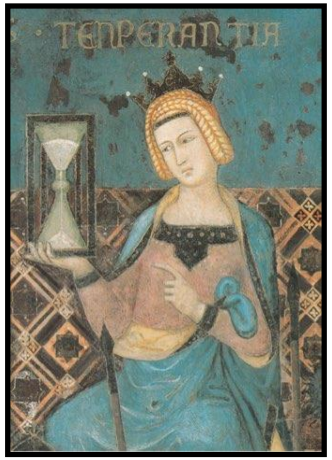


Measurement of time

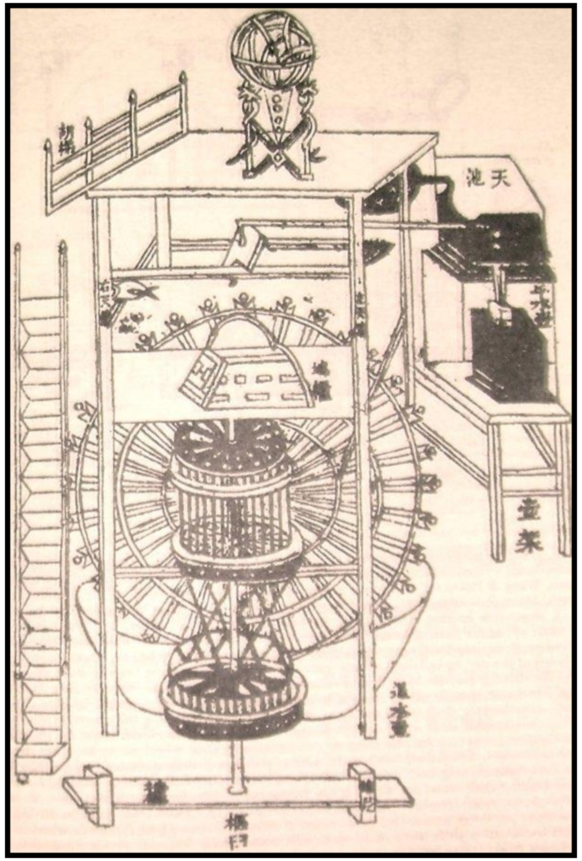
Persian water clock,
300 BC



Ctesibius's clepsydra,
250 BC



Painting of an hourglass,
Lorenzetti, 1338 AD

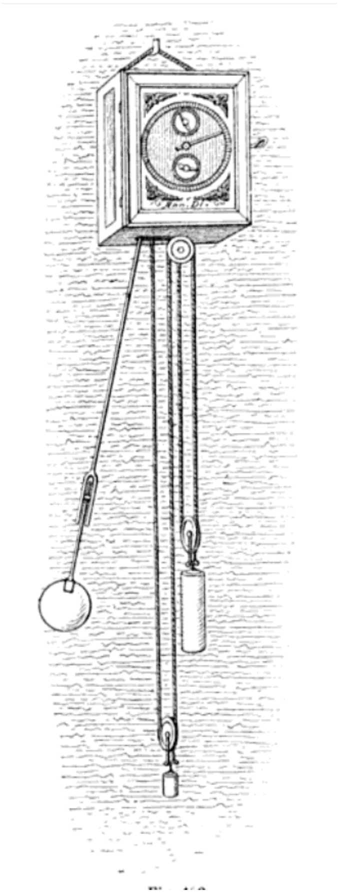


Su Song’s water clock,
1000 AD

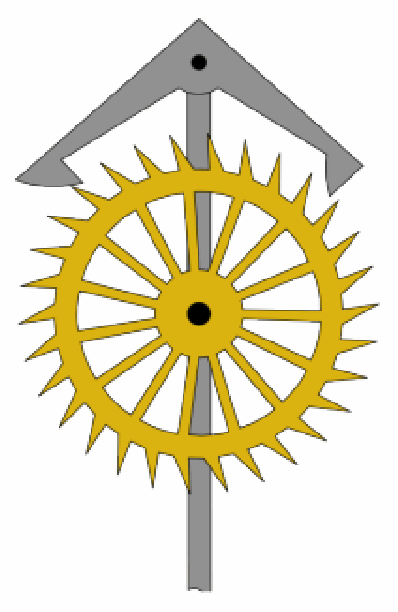
Image credit: wikipedia.org

1656: Invention of the pendulum clock

Christiaan Huygens
1629 - 1695



Huygens pendulum clock

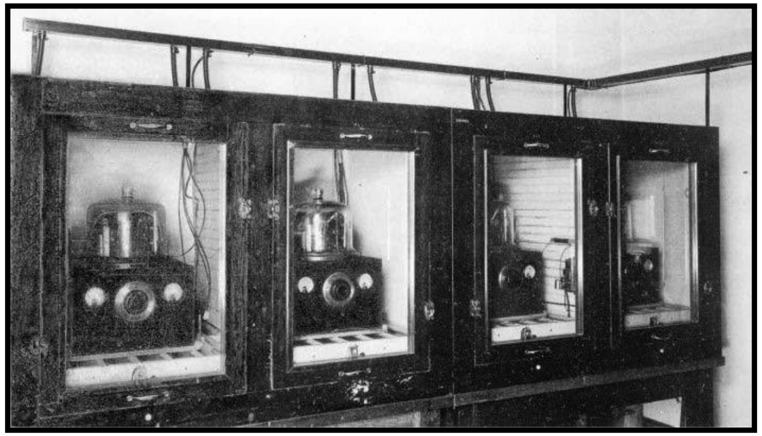


Escapement
(counter)

Image credit: wikipedia.org

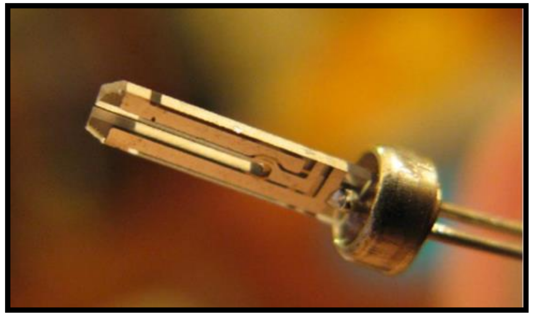
1921: Quartz oscillators invented

Applied voltage results in crystal oscillations, generating electric field



NIST 1929: Accurate to ~3 s in 1 year

$\sigma \sim 1x10^{-7}$

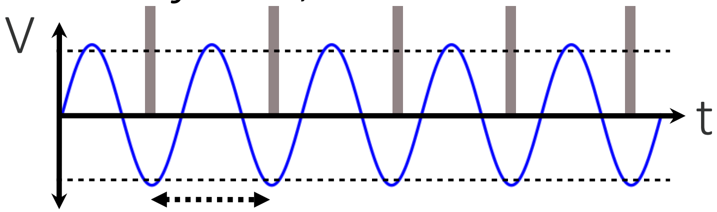


Modern day tuning fork

Accurate to ~0.5 s in 1 day

$\sigma \sim 6x10^{-6}$

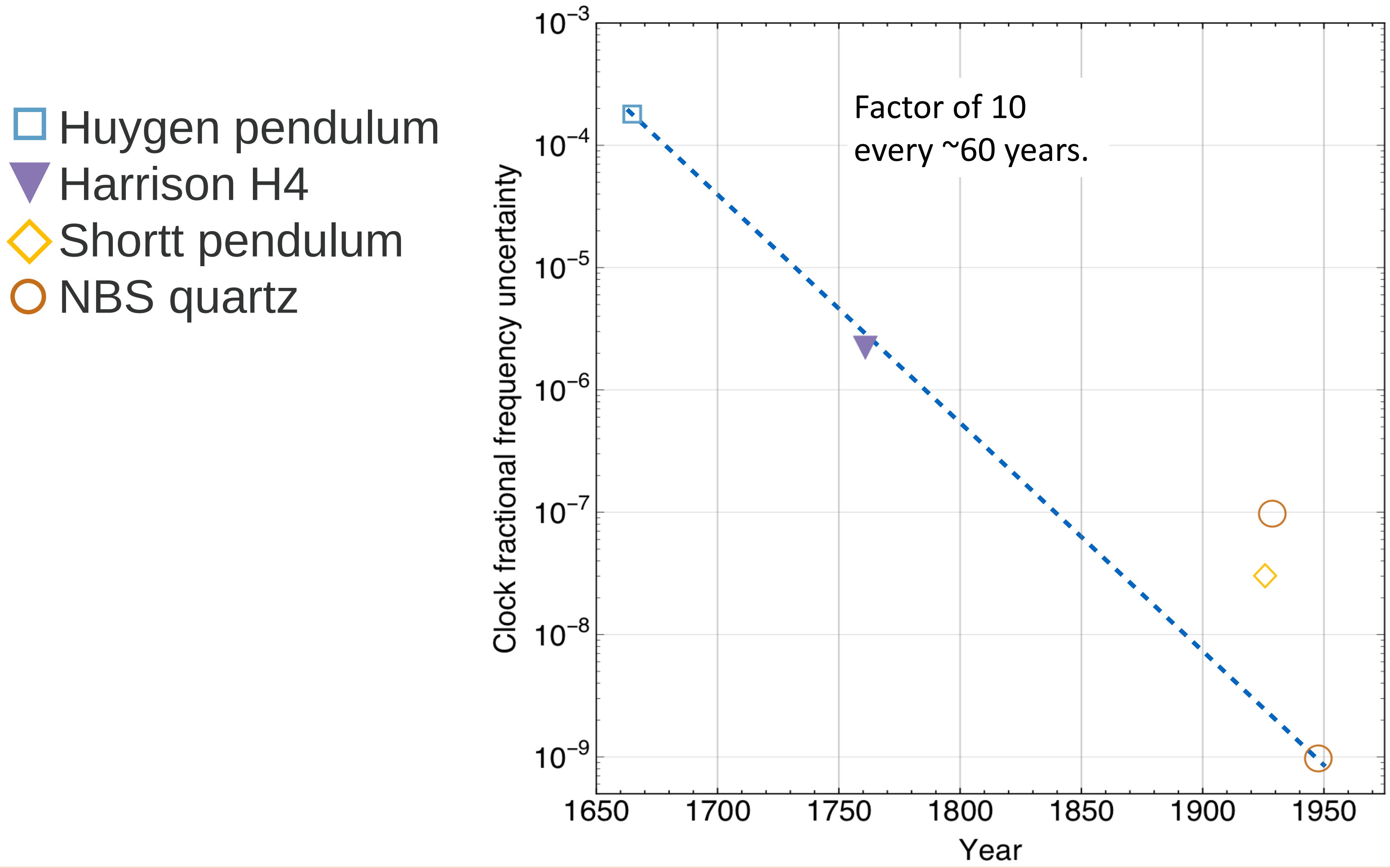
f = 32,768 Hz



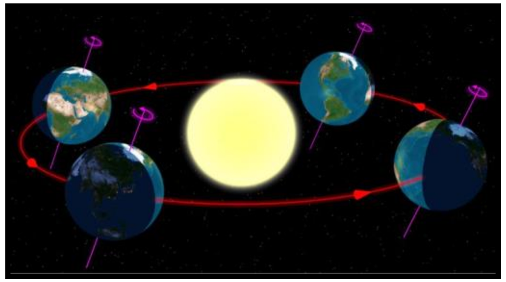
T ~ 30 microseconds

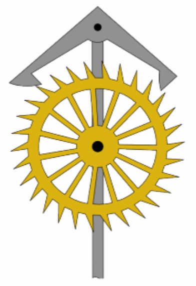
Image credit: wikipedia.org

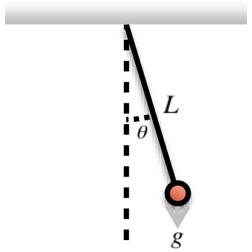
Clock progress, 1656 - 1949

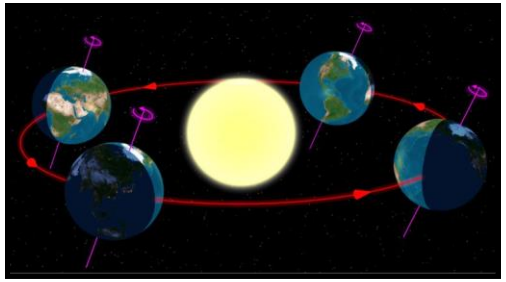


Components of a mechanical clock

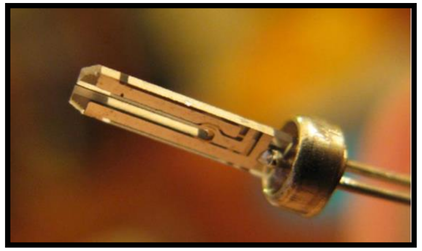




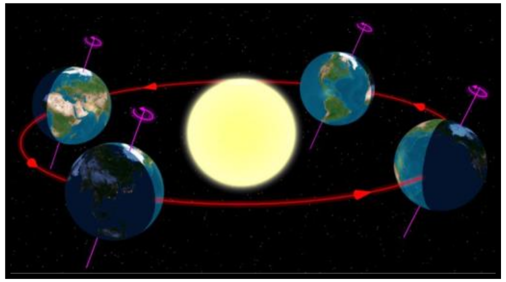




Counter



Local oscillator



Frequency reference

1955: First cesium atomic clock

Isidor Isaac Rabi

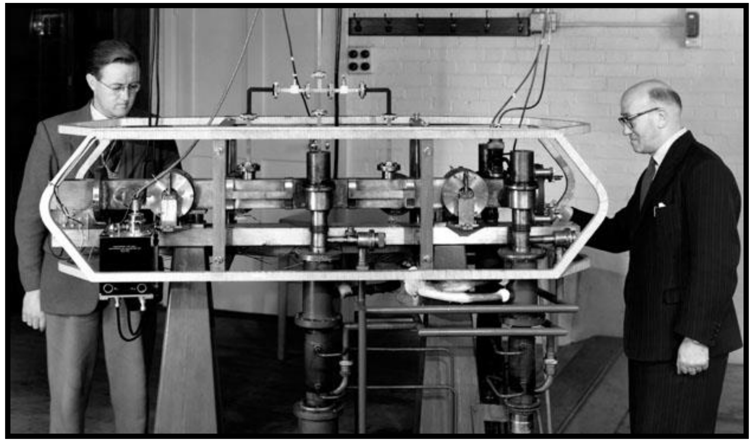
'COSMIC PENDULUM' FOR CLOCK PLANNED

Radio Frequencies in Hearts of Atoms Would Be Used in Most Accurate of Timepieces

DESIGN TERMED FEASIBLE

Prof. I. I. Rabi, 1944 Nobel Prize Winner, Tells of Newest Developments

NY Times,
Jan 21st, 1945



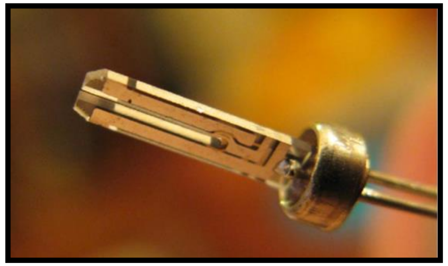
First cesium beam clock
Jack Parry, Louis Essen

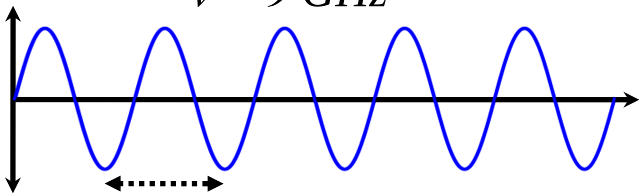
$\sigma \sim 1x10^{-10}$

(Accurate to ~3 s in 1000 years)

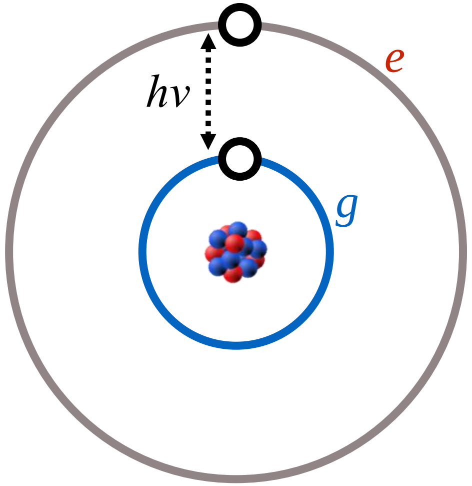
Principles of an atomic clock

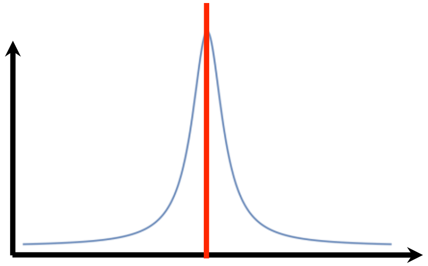
Counter





Local oscillator (LO)





Frequency reference

Atomic clocks

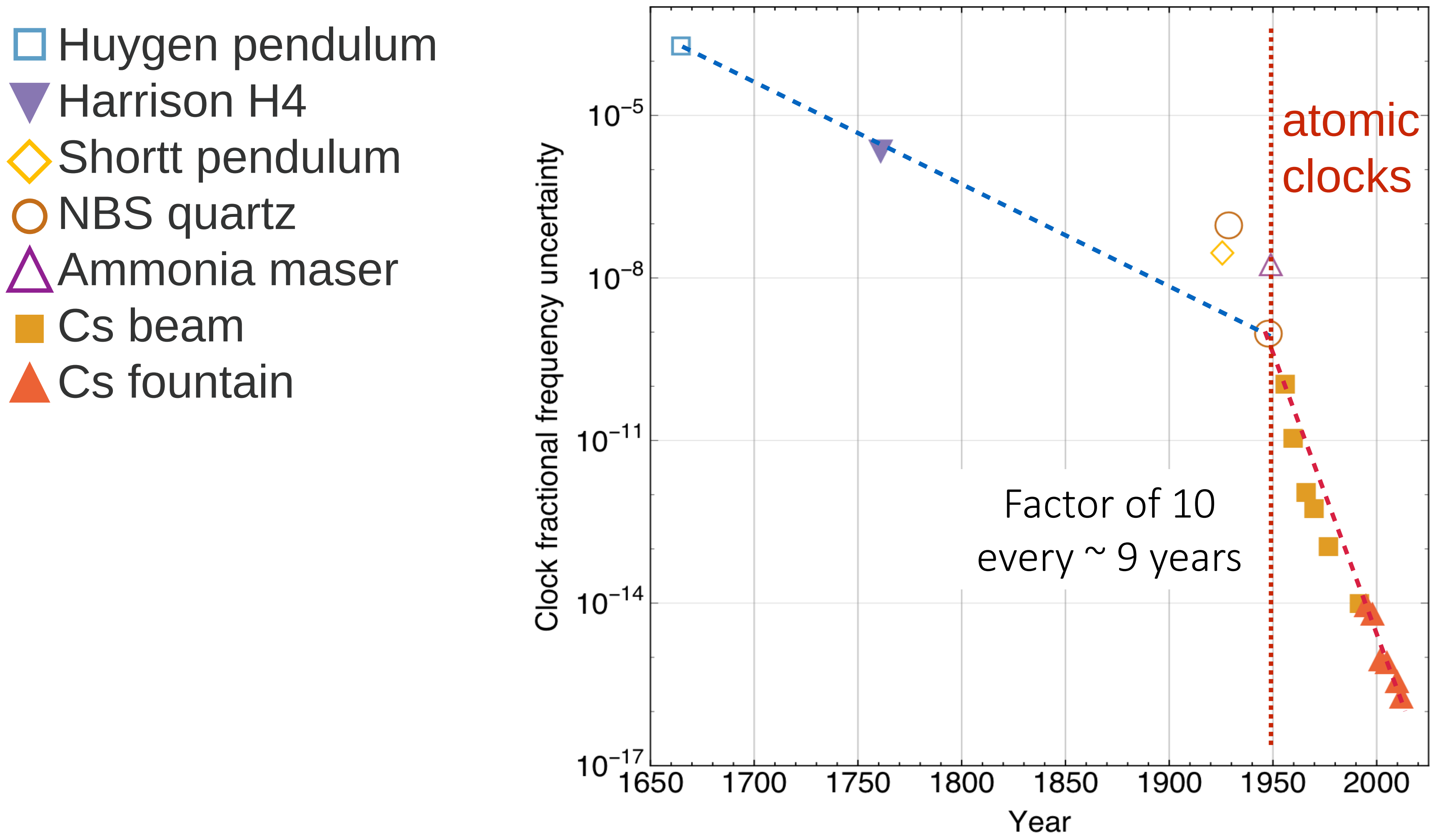
Fundamental limit: fractional frequency instability from projection noise (intrinsic randomness of n 2-level systems):

$$\sigma \approx \frac{\Delta\nu}{\nu_o} \times \frac{1}{SNR} = \frac{1}{\nu_o T \sqrt{n_a M}}$$

<u>**Best atomic clock will have:**</u>

- Narrow transition, and cold atoms
- Many atoms
- Long interrogation times
- Short dead times
- Well isolated atoms to avoid systematics

Clock progress, 1656 - 2016



Optical atomic clocks

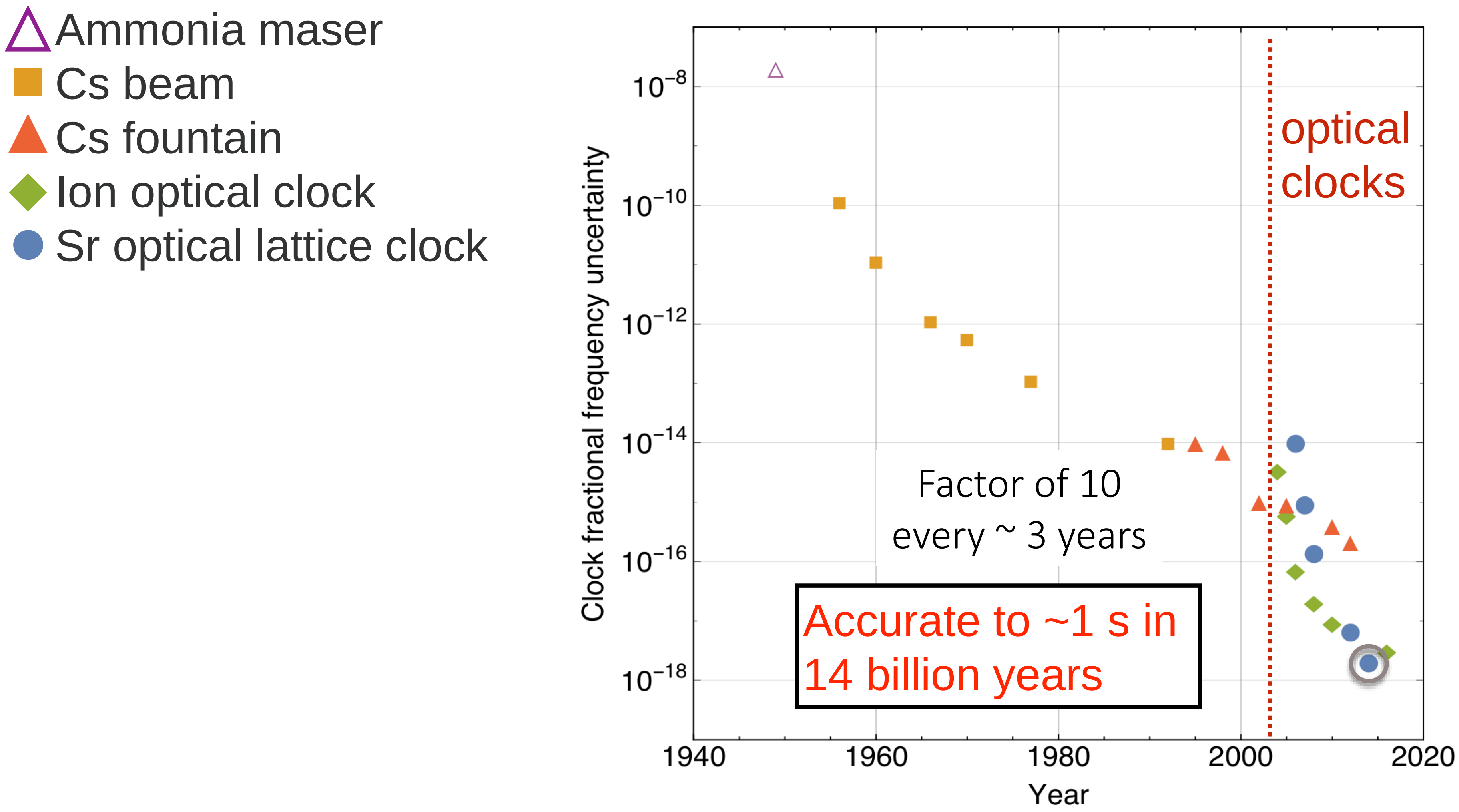
Fundamental limit: fractional frequency instability from projection noise (intrinsic randomness of n 2-level systems):

$$\sigma \approx \frac{\Delta \nu}{\nu_o} \times \frac{1}{SNR} = \frac{1}{\nu_o T \sqrt{n_a M}}$$

<u>Best atomic clock will have:</u>

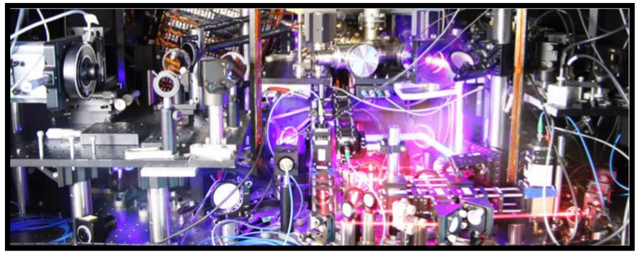
- Narrow transition, and cold atoms
- Many atoms
- Long interrogation times
- Short dead times
- Well isolated atoms to avoid systematics
- High frequency transition → Move from $\nu_o = 10^{10}$ Hz to $\nu_o = 10^{15}$ Hz

Atomic clock progress, 1949 - 2016



Optical lattice atomic clocks in a nutshell

Group of Jun Ye (JILA/CU Boulder)

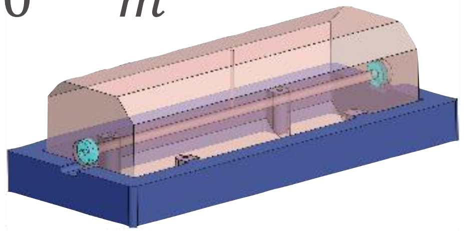


- Optical frequency

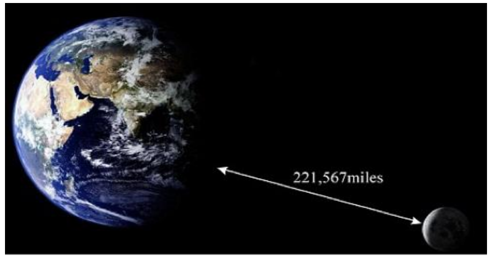
  Fractional frequency instability: $\sigma = \frac{\Delta\nu}{\nu} \times \frac{1}{SNR}$

- Ultra-stable laser

  Linewidth $26\, mHz, Q \sim 2 \times 10^{16}, \Delta L \sim 10^{-16} m$



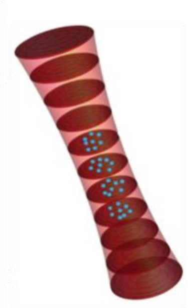
Coherent for ~10 earth-moon round trips

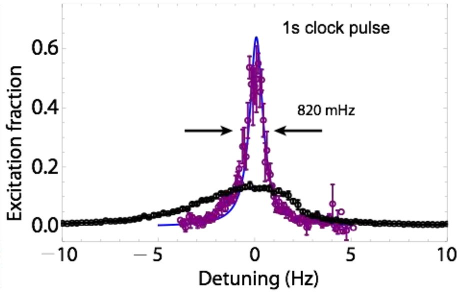


- Dipole forbidden transitions Sr^{87}

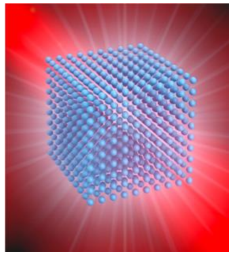
- Strong confinement

1D:

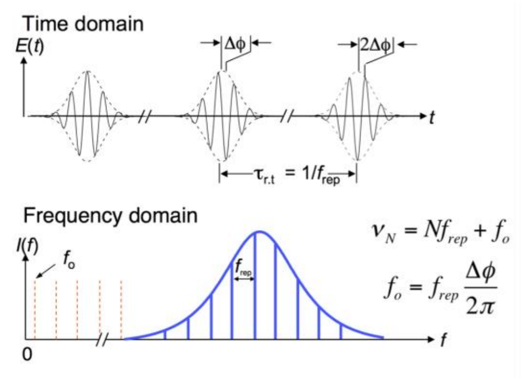




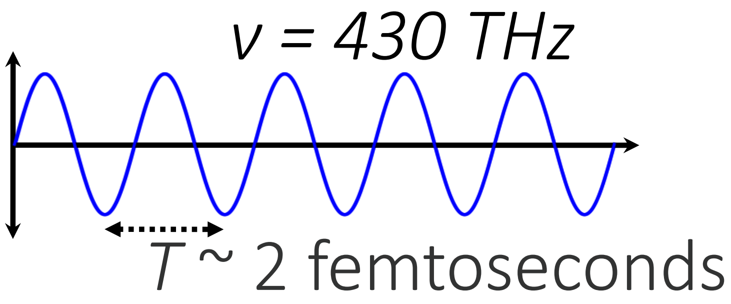
3D:



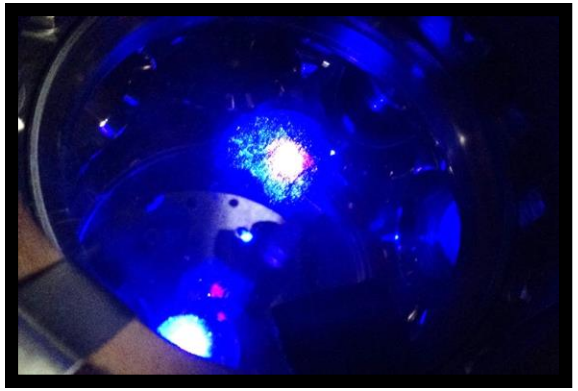
Optical lattice clock



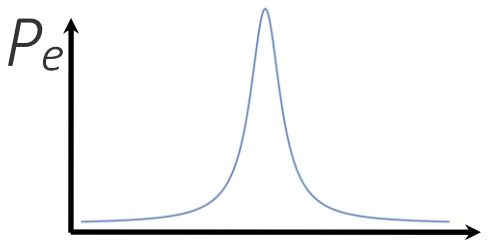
Counter:
Frequency Comb
(ability to count
optical oscillations)



Local oscillator (LO)



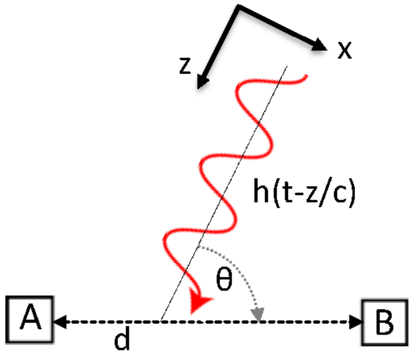
1 mHz linewidth



Frequency reference

Back to GWs: Frequency measurements

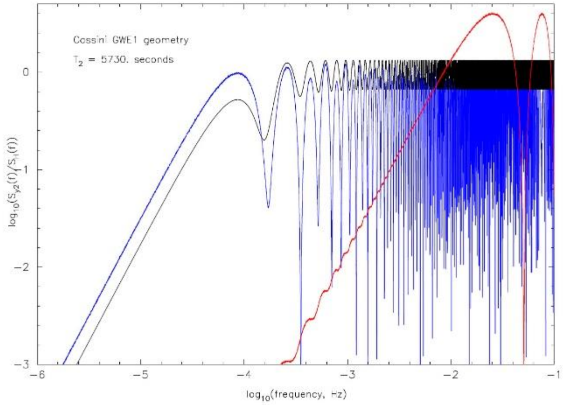
Frequency measurements: Doppler shifts from gravitational waves



$$s = \frac{\Delta\nu}{\nu} = \frac{1+\cos\theta}{2}\left(h(t) - h(t + \frac{d}{c}(1-\cos\theta))\right)$$

In Fourier space: $\tilde{s}^2(f) = \tilde{h}^2(f)T(f)$ T(f): detector transfer function

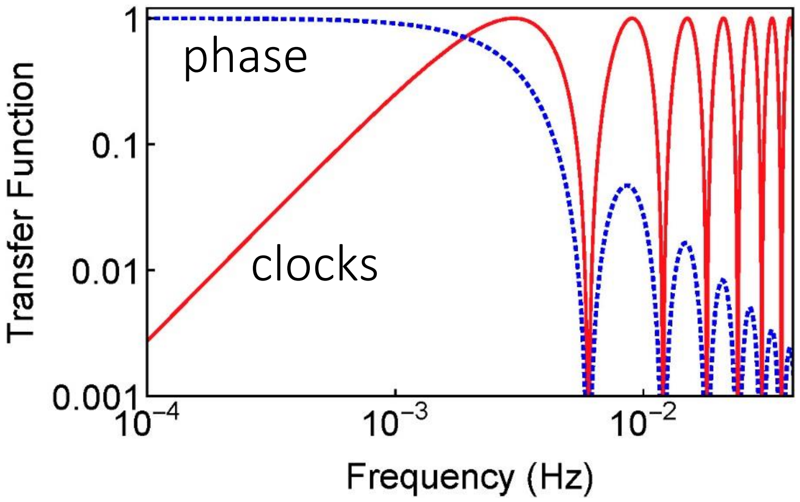
Same principle:
Doppler Tracking



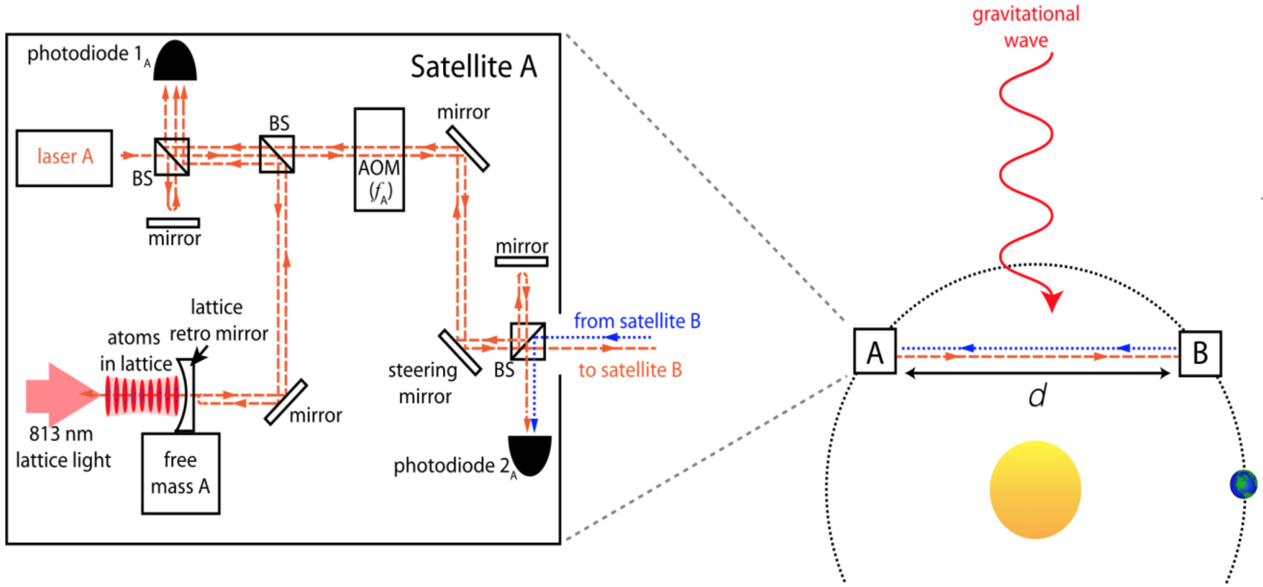
Armstrong, Living Rev. Relativity, 9, (2006)

$$T_{phase} = \mathrm{sinc}^2\left(\pi f \frac{d}{c}\right)$$

$$T_{clocks} = \sin^2\left(\pi f \frac{d}{c}\right)$$



Space-based setup using correlated spectroscopy



Two identical drag-free satellites separated from each other by d

On each satellite:

- strontium optical lattice clock
- ultra-stable laser
- free-floating reference mass

Light sent from satellite A to satellite B, where laser B is phase-locked to laser A

Doppler shift measured by spectroscopic clock comparison. For Ramsey time T:

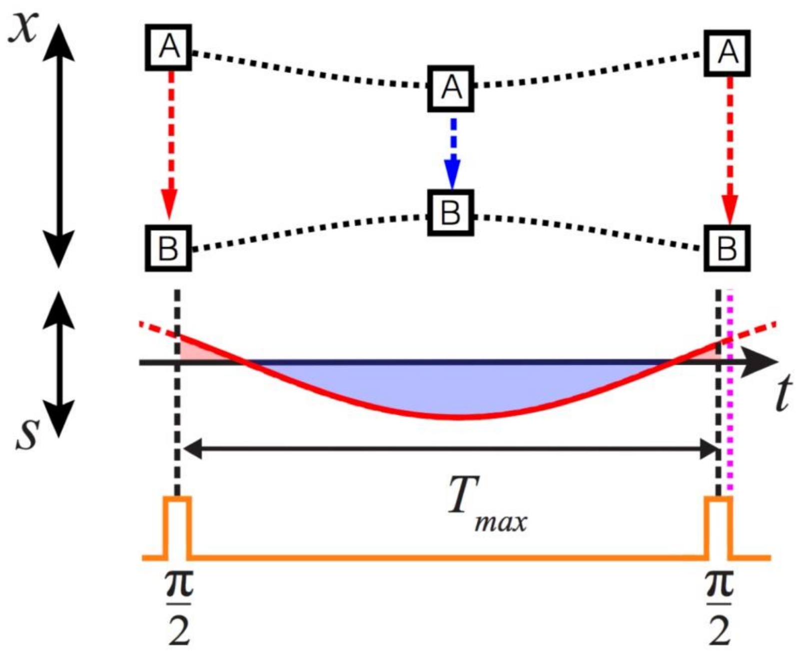
$$s^2 = h^2 \sin^2\left(\pi f \frac{d}{c}\right) \operatorname{sinc}^2(\pi f T)$$

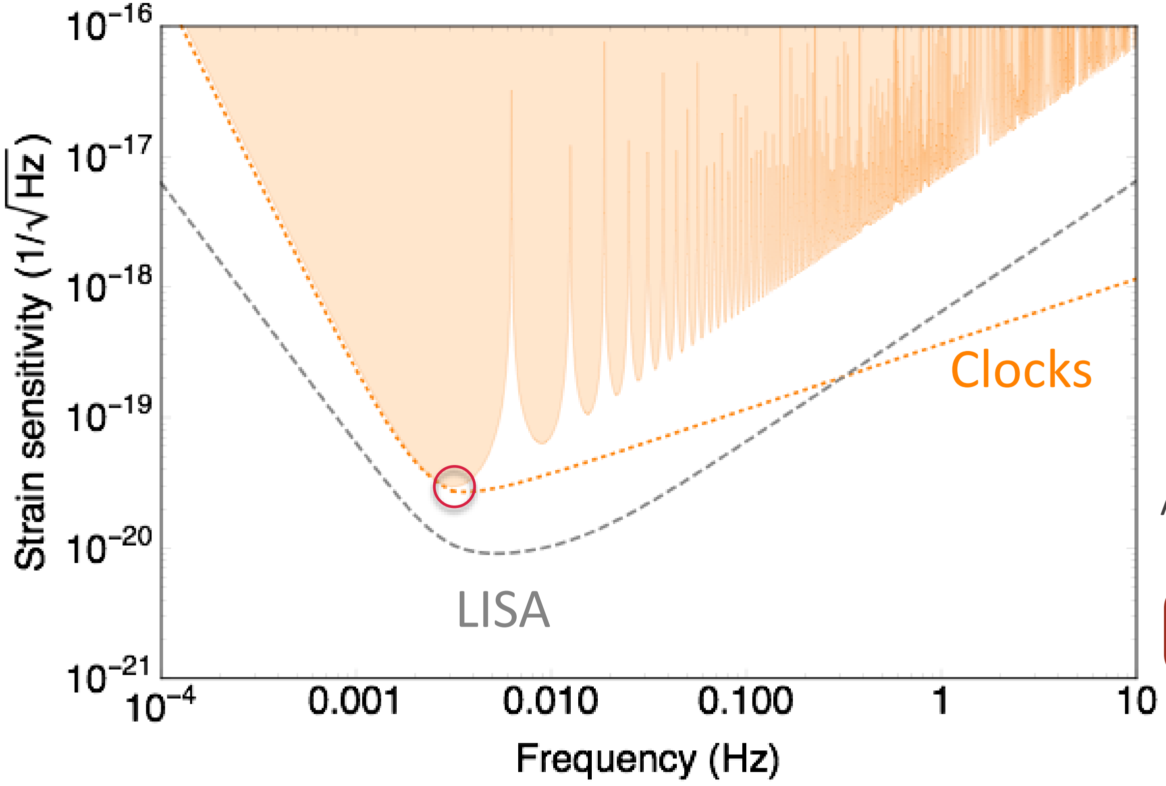
Sensitivity with Ramsey spectroscopy

Signal: $s_{Ramsey} = \frac{|\Delta\nu|}{\nu} = |h| \left| \sin\left(\pi f \frac{d}{c}\right) \mathrm{sinc}(\pi f T) \right|$

Noise: $\sigma_{min}(\tau) = \frac{1}{\nu}\sqrt{\frac{1}{T\,N}}$

Long Ramsey sequence:





$N = 7 \times 10^6$

# of Sr atoms

$d = 50 \times 10^6$ km

Satellite distance

$T_{max} = 160$ s

Atomic coherence time

$\sigma_{min} \sim 10^{-20}/\sqrt{\mathrm{Hz}}$

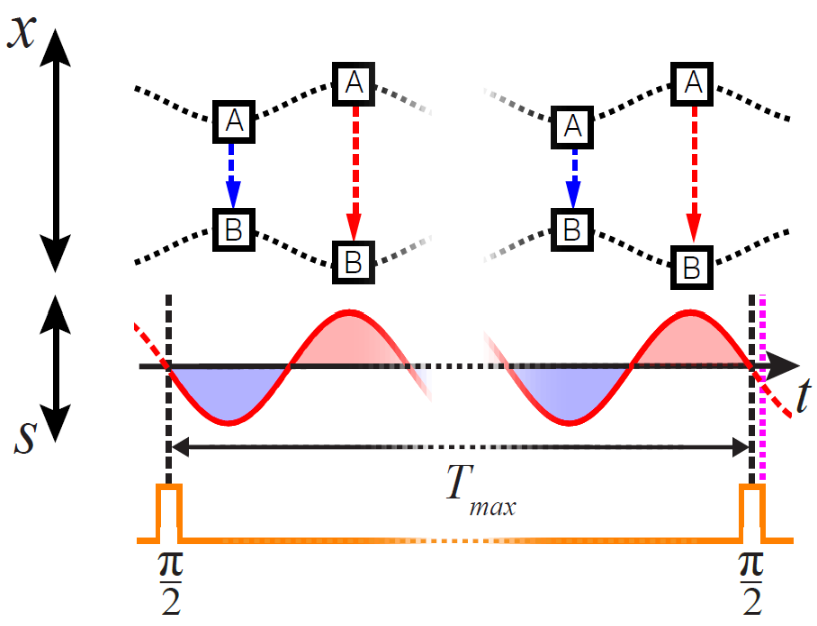
At $f = 1/2T_{max}$

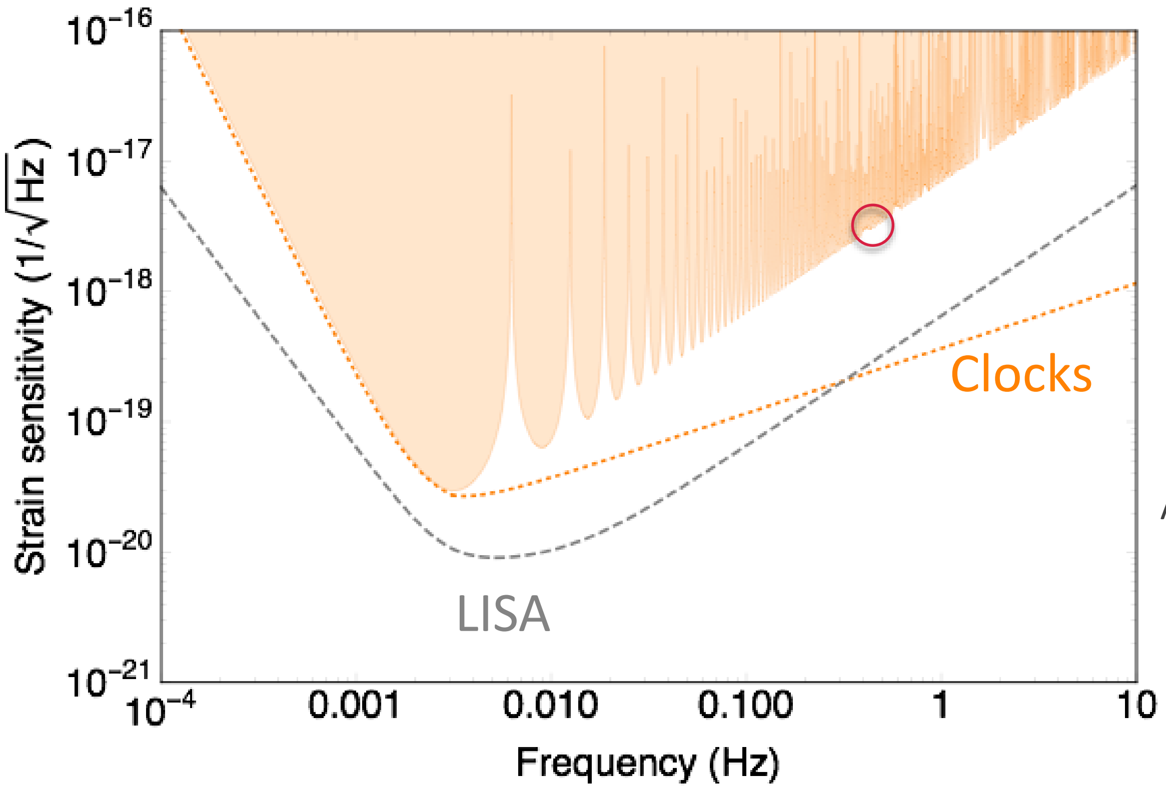
Sensitivity with Ramsey spectroscopy

Signal: $s_{Ramsey} = \frac{|\Delta\nu|}{\nu} = |h| \left| \sin\left(\pi f \frac{d}{c}\right) \mathrm{sinc}(\pi f T) \right|$

Noise: $\sigma_{min}(\tau) = \frac{1}{\nu}\sqrt{\frac{1}{T N}}$

Long Ramsey sequence:





$N = 7 \times 10^6$

\# of Sr atoms

$d = 50 \times 10^6$ km

Satellite distance

$T_{max} = 160$ s

Atomic coherence time

$\sigma \sim 10^{-18}/\sqrt{\mathrm{Hz}}$

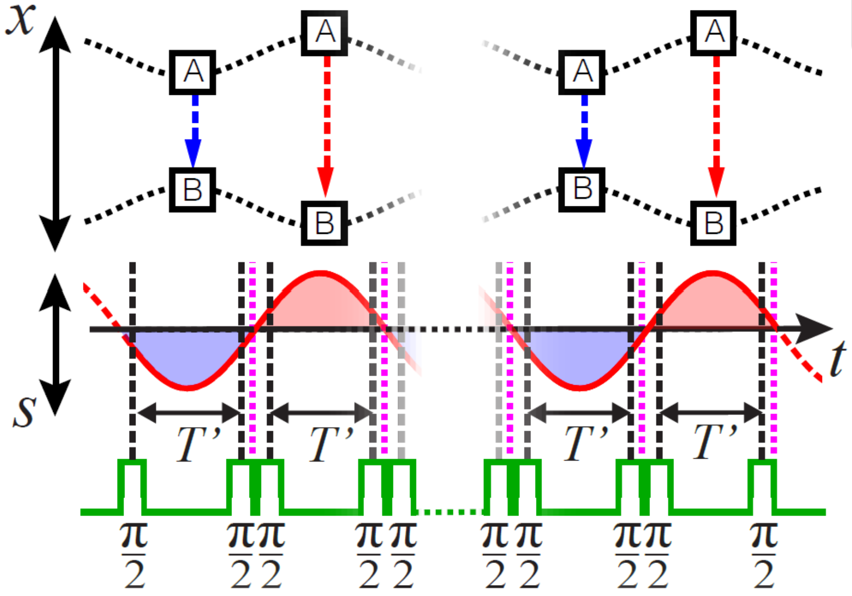
At $f = 160/2T$

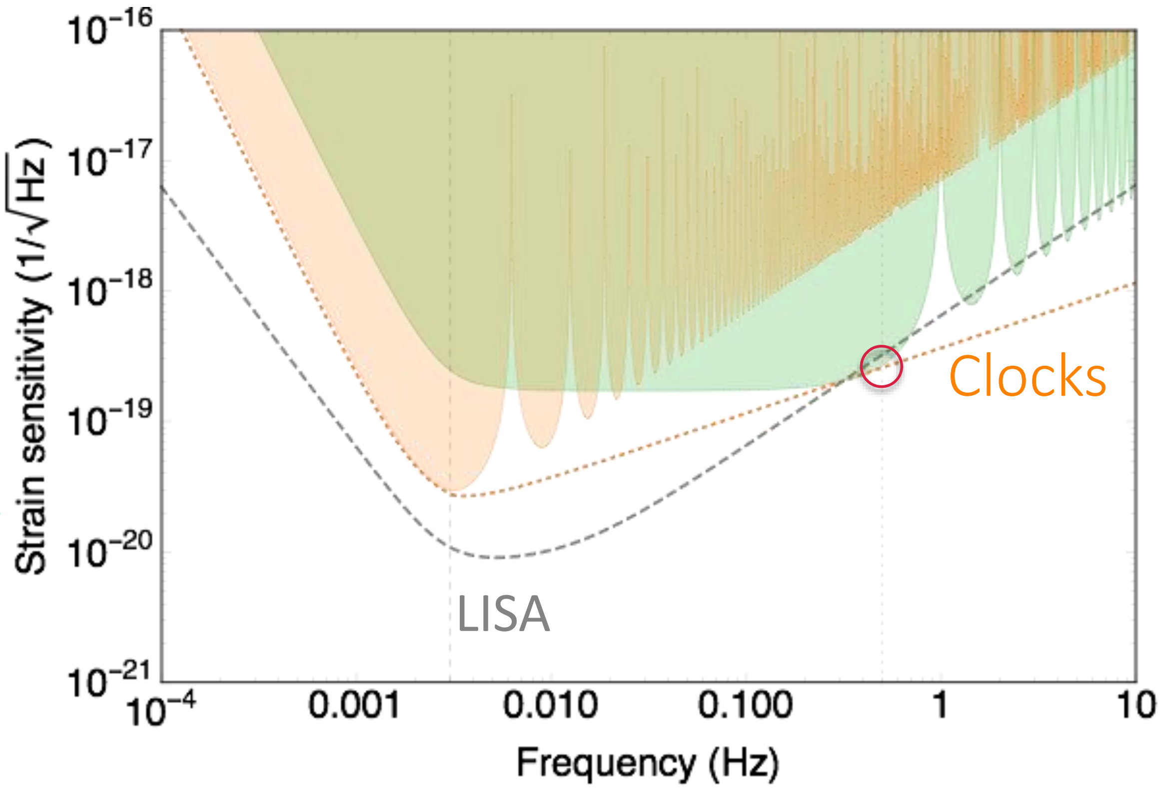
Sensitivity with Ramsey spectroscopy

Signal: $s_{Ramsey} = \frac{|\Delta\nu|}{\nu} = |h| \left| \sin\left(\pi f \frac{d}{c}\right) \operatorname{sinc}(\pi f T) \right|$

Noise: $\sigma_{min}(\tau) = \frac{1}{\nu}\sqrt{\frac{1}{T N}}$

Short Ramsey sequence:





$N = 7 \times 10^6$

\# of Sr atoms

$d = 50 \times 10^6$ km

Satellite distance

$T = 1$ s

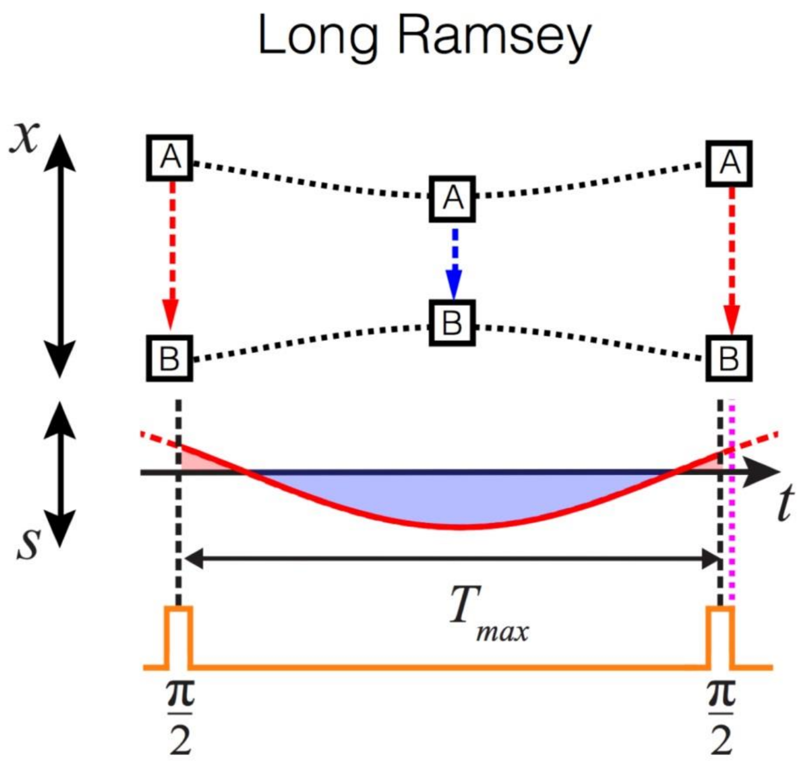
Ramsey time

$\sigma \sim 10^{-19}/\sqrt{\text{Hz}}$

At $f = 1/2T$

Frequency tuning: dynamical decoupling

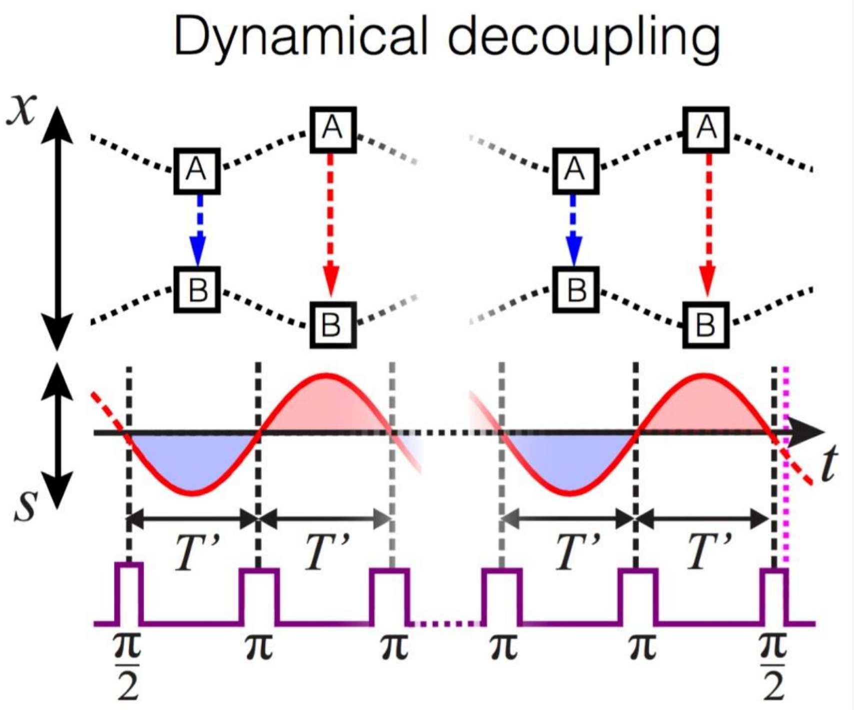
Can change spectroscopic read-out: use dynamical decoupling (DD) to move ideal sensitivity to other f



DD: match atomic read-out with high-frequency GW

$$s \rightarrow \bar{s} = \int dt\, s(t) F(t)$$

DD filter function

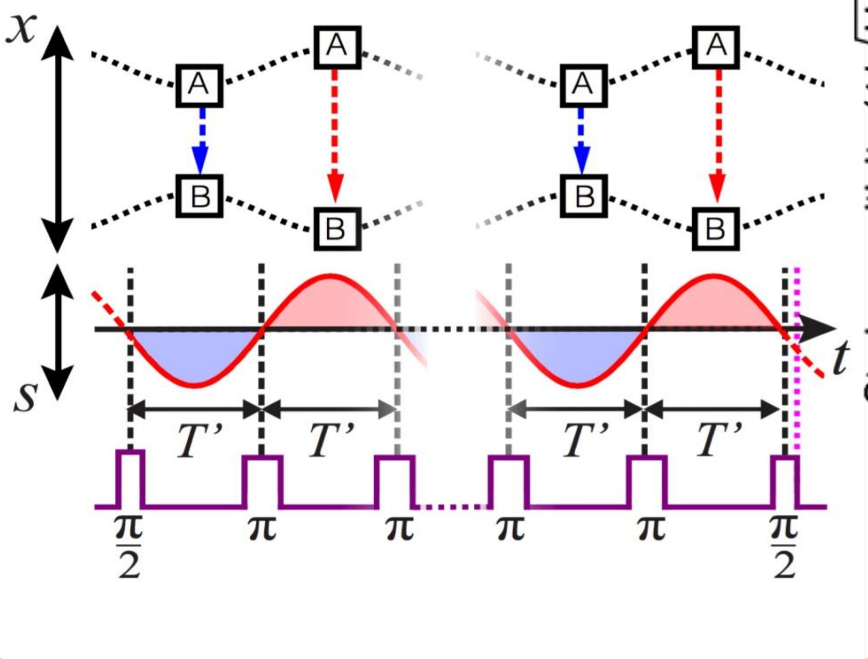


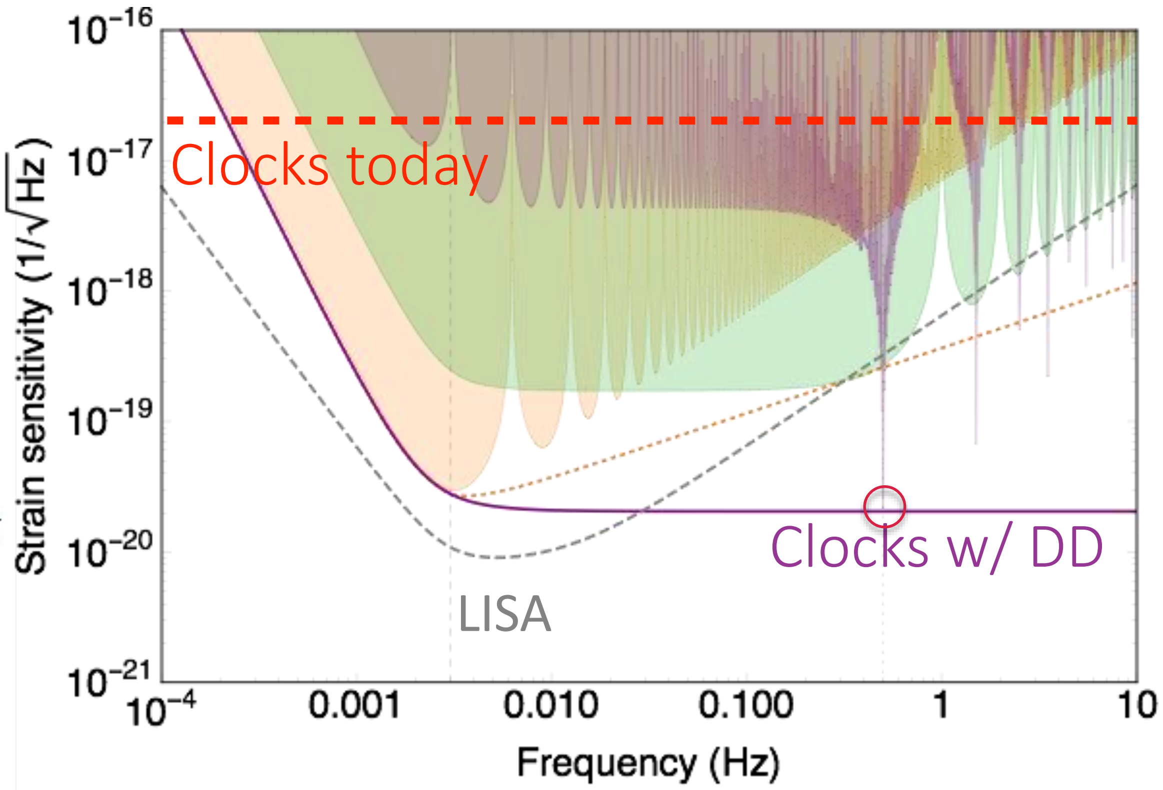
Sensitivity with Dynamical Decoupling technique

Signal: $s_{DD} = \int dt\, s(t) F(t)$ ← DD filter function matches specific GW frequency

Noise: $\sigma_{min}(\tau) = \frac{1}{\nu}\sqrt{\frac{1}{T\,N}}$

Dynamical decoupling sequence:





$N = 7 \times 10^6$

\# of Sr atoms

$d = 50 \times 10^6$ km

Satellite distance

$T = 1$ s

Ramsey time

$\sigma_{min} \sim 10^{-20}/\sqrt{\text{Hz}}$

At $f = 1/2T$

Optical power requirements

Laser noise enters through the phase-lock between satellites A and B. Total noise:

$$\sigma^2 = \frac{1}{(2\pi\nu)^2 T\tau}\left(\frac{1}{N} + \frac{1-e^{-B\tau}}{2}\frac{T}{\tau}\left(\frac{\Delta_L}{B} + \frac{h\nu}{P}B\right)\right)$$

atom projection noise   *laser linewidth*   *shot noise in PLL*

T: clock interrogation time

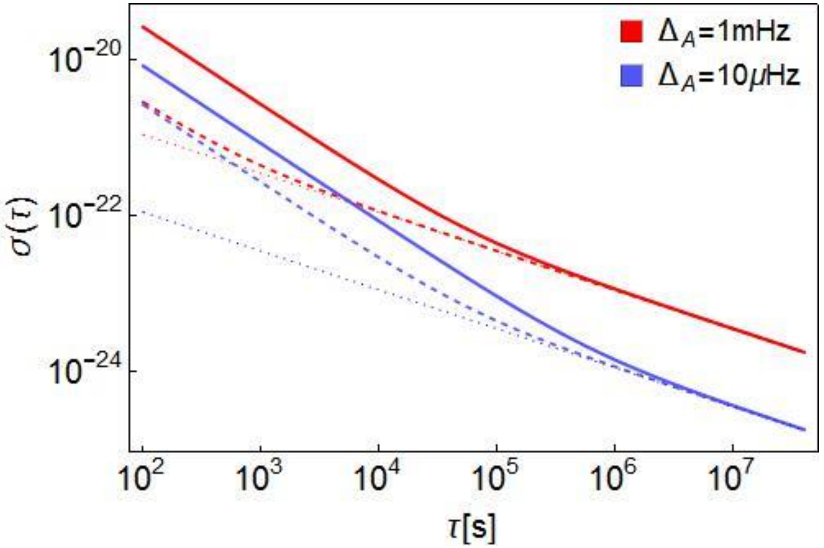
τ: total measurement time

N: # of atoms

B: phase-lock loop bandwidth

Δ_L: Laser linewidth

P: power



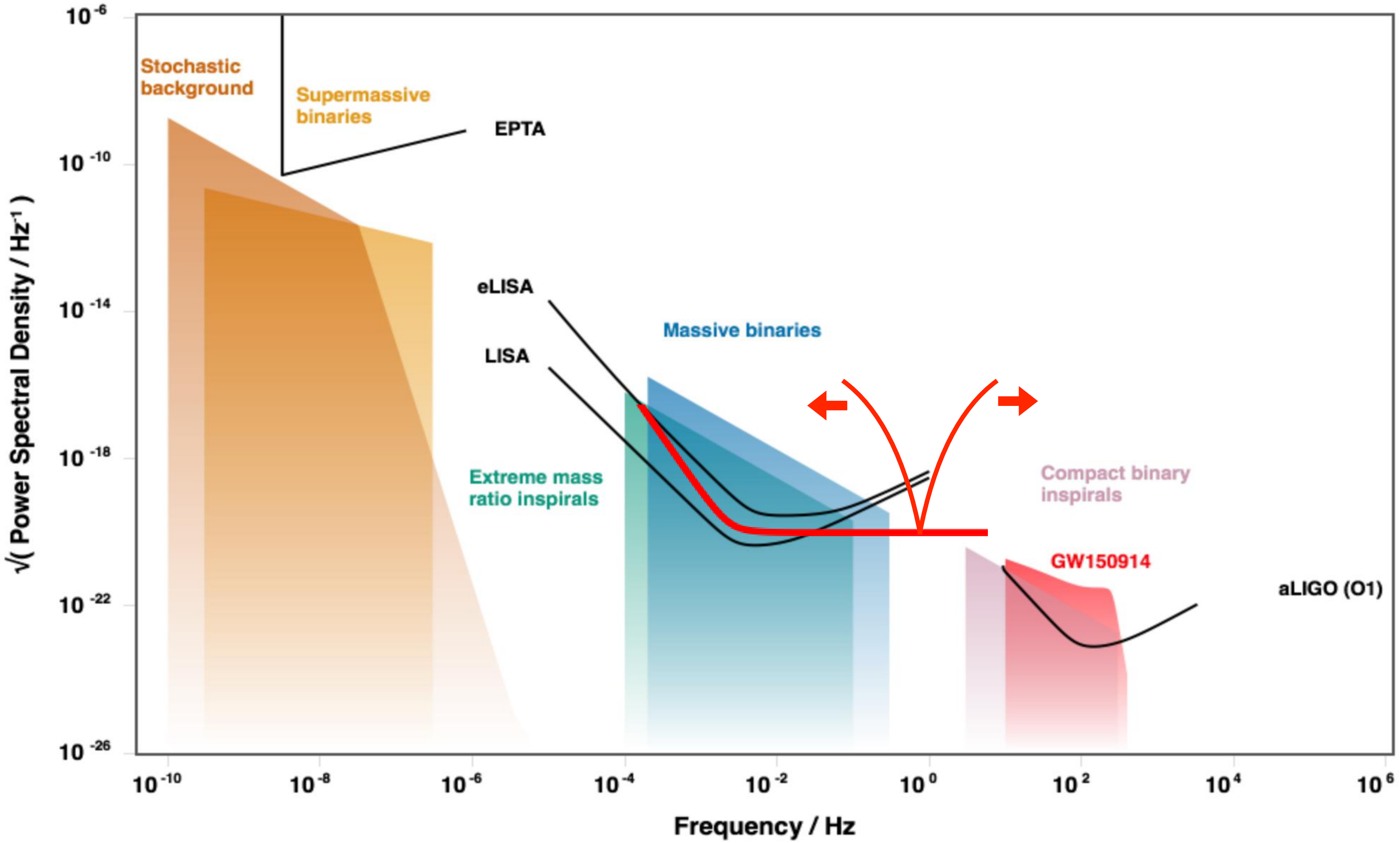
PLL: White frequency noise → white phase noise, averages down faster.

Atom projection noise limited after $\tau \lesssim 1$d for $\Delta_L = 1$ Hz, received laser power $P{\sim}10^{-10}$ W.

Emitted power for $d = 50\times10^6$ km: $P{\sim}1.4$ W.

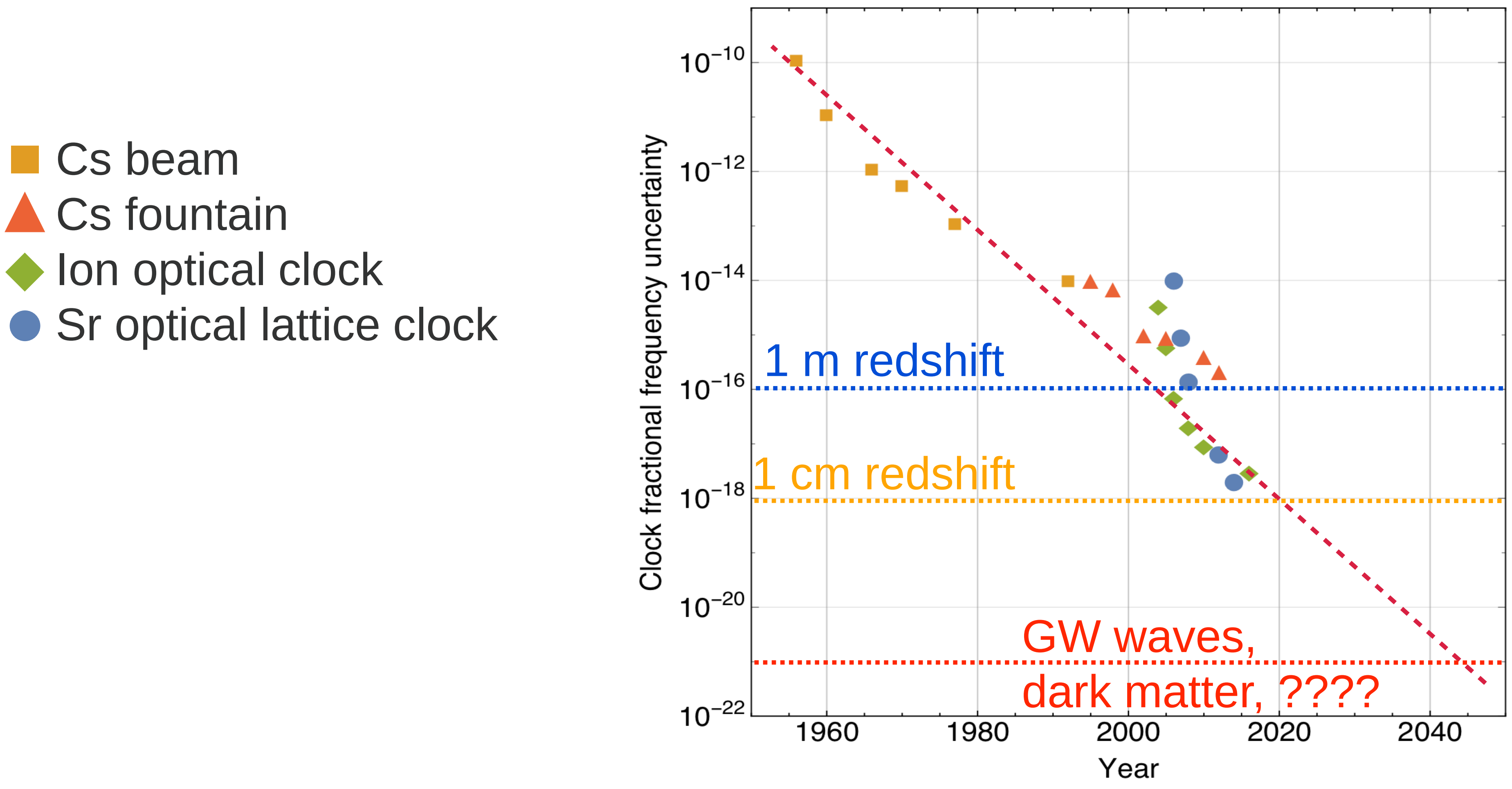
Sources

- Can bridge range between LISA and LIGO
- New and potentially strong sources possible in deciHz-range
- Can track inspirals throughout GW chirp



Plot from http://rhcole.com/apps/Gwplotter/

Fundamental physics with increased precision



Key advantages

- Different systems: utilize quantum control of atoms for frequency tunability
- Different detection method: not shot noise limited, but atom projection noise limited
- Optical power requirements very flexible
- Only 2 satellites required, due to low sensitivity to laser noise
- Can be hybridized with interferometric space missions like LISA, serves as a complementary detector

Potential future improvements

- Entangled atomic states (spin-squeezing, GHZ), can be used to bypass the standard quantum limit for short interrogation times: $\sqrt{N} \to N$

  Bohnet et. al., Nature Photonics 8, 731–736 (2014)

- Entanglement between clocks for further increase the sensitivity of a clock network based detector

  Komar et. al., Nature Physics 10, 582 (2014)

- Optimized clock measurement protocols.

  Kessler et. al., PRL 112, 190403 (2014)

- Switching to narrower clock transitions using other isotopes or atomic species.

  Santra et. al., PRL 94, 173002 (2005)

- Using LMT schemes of atomic fountains for better low-frequency sensitivity

  Norcia et. al., PRA 96, 042118 (2017)

Summary

- Optical lattice clocks can be used for GW detection, $h \sim 10^{-20}/\sqrt{Hz}$
- Effective Doppler shift measurement by correlated clock spectroscopy in space
- Tunability: ideal sensitivity in range 3 mHz – 10 Hz
- Narrow-band detection of continuous sources
- Possible future improvements from atomic technology and quantum control
- Sensitivities comparable to LISA with realistic improvement of ground-based clock technology, can be hybridized with LISA

S. KOLKOWITZ ET AL. PHYS. REV. D 94, 124043 (2016)

Acknowledgements (and thanks for the attention!)

Shimon Kolkowitz

Nick Langellier

Misha Lukin

Ron Walsworth

Jun Ye

HARVARD UNIVERSITY

ITAMP

JILA

& discussions with Avi Loeb, Mark Kasevich, Jason Hogan

University of Colorado **Boulder**

S. Kolkowitz, I. Pikovski, N. Langellier, M. D. Lukin, R. L. Walsworth, J. Ye.

PHYS. REV. D 94, 124043 (2016) [ARXIV:1606.01859]

The Branco Weiss Fellowship Society in Science