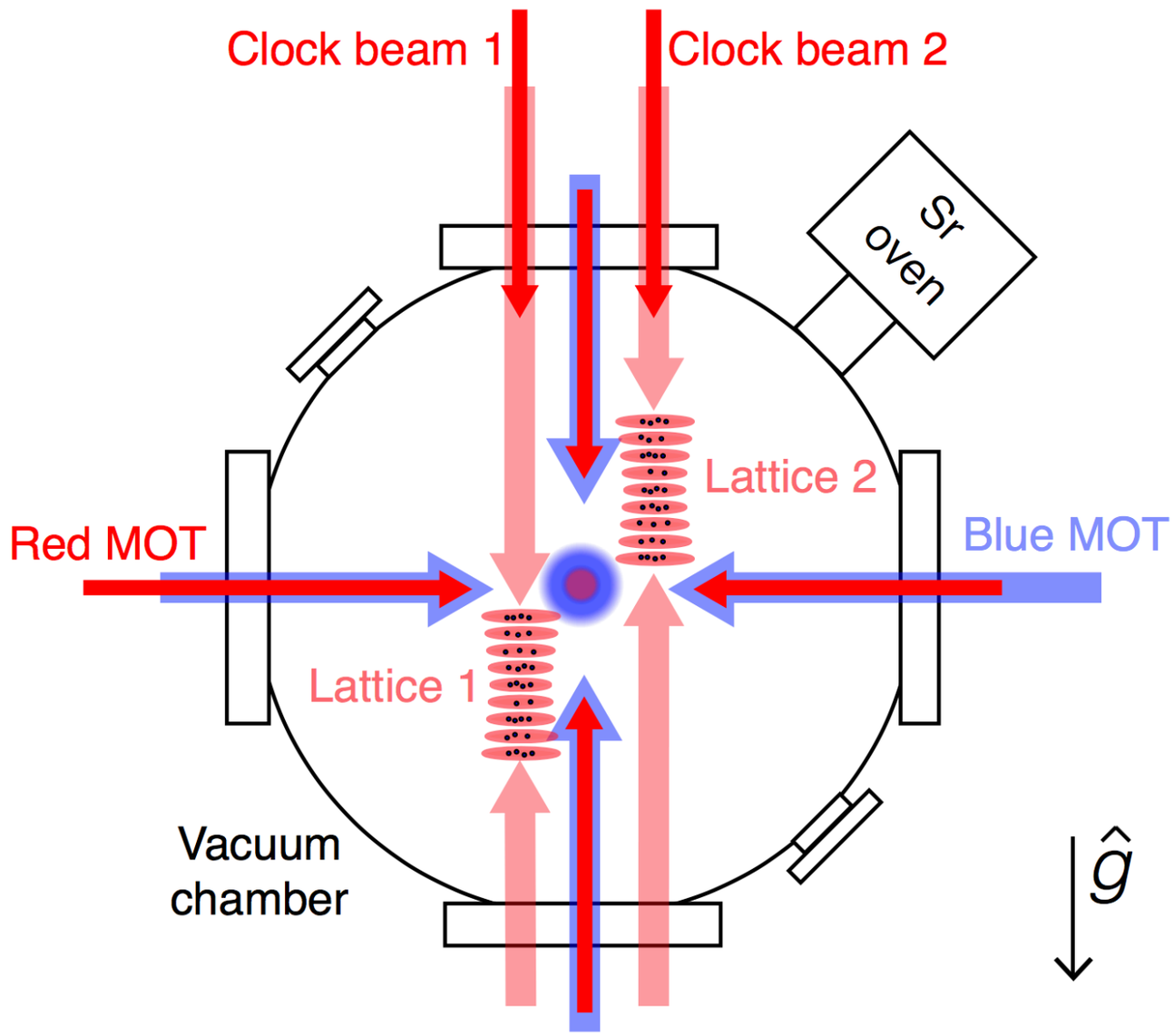
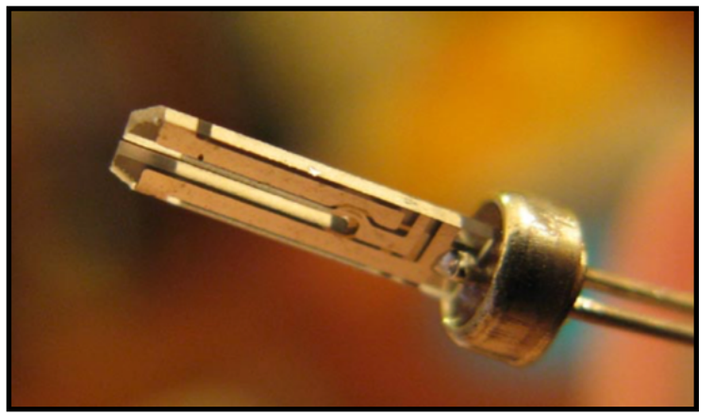
What's the difference?

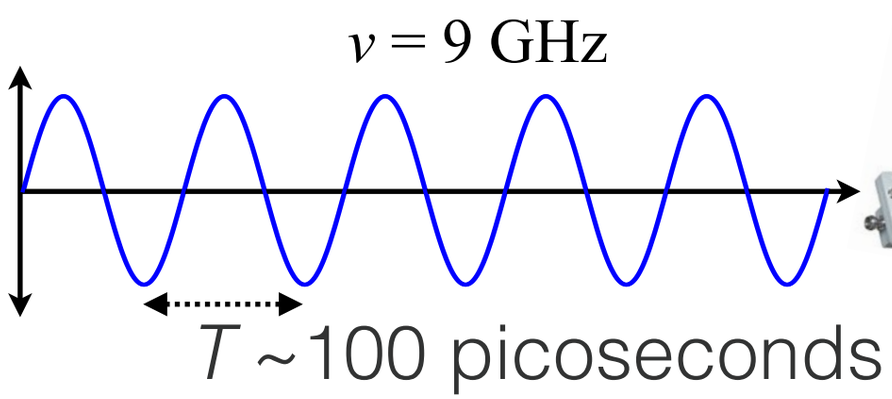
Prospects and applications for a multiplexed optical lattice clock

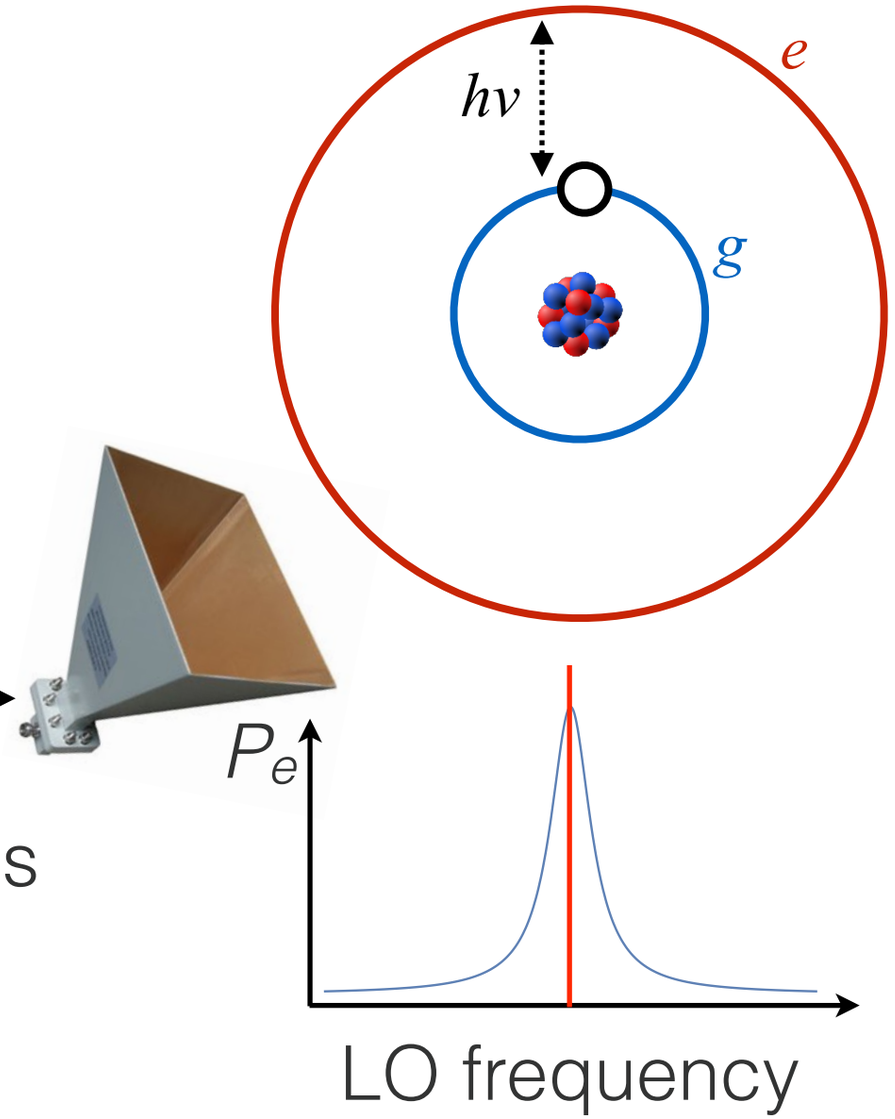


Shimon Kolkowitz
University of Wisconsin - Madison

Principles of an atomic clock





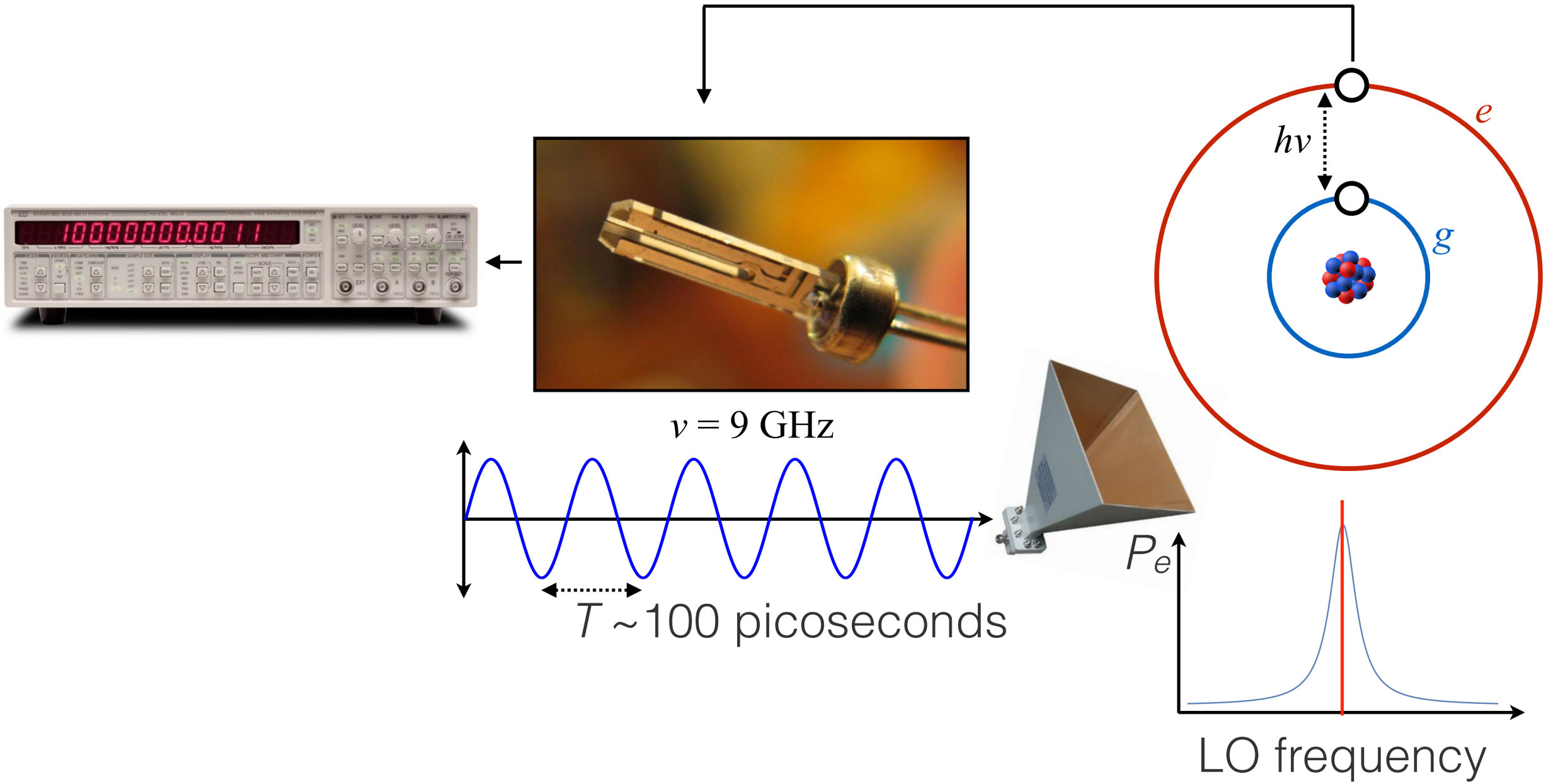


Counter

Local oscillator (LO)

Frequency reference

Principles of an atomic clock



Counter

Local oscillator (LO)

Frequency reference

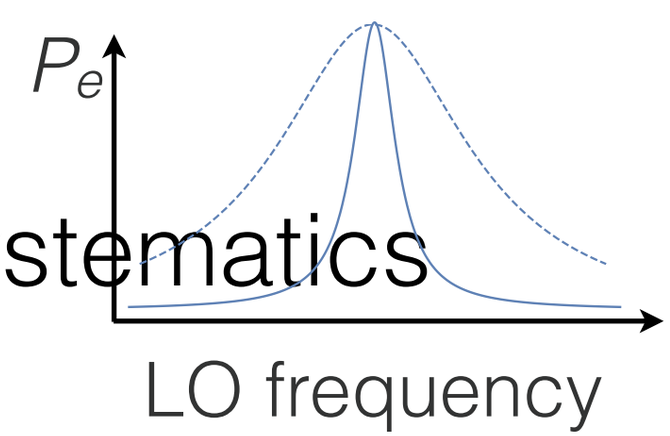
Atomic clocks

Fractional frequency instability from projection noise:

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

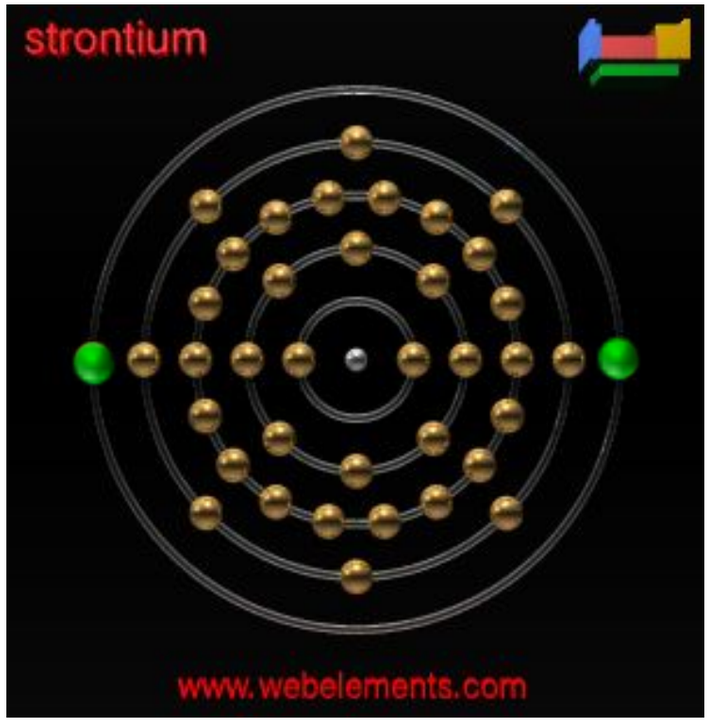
<u>Best atomic clock will have:</u>

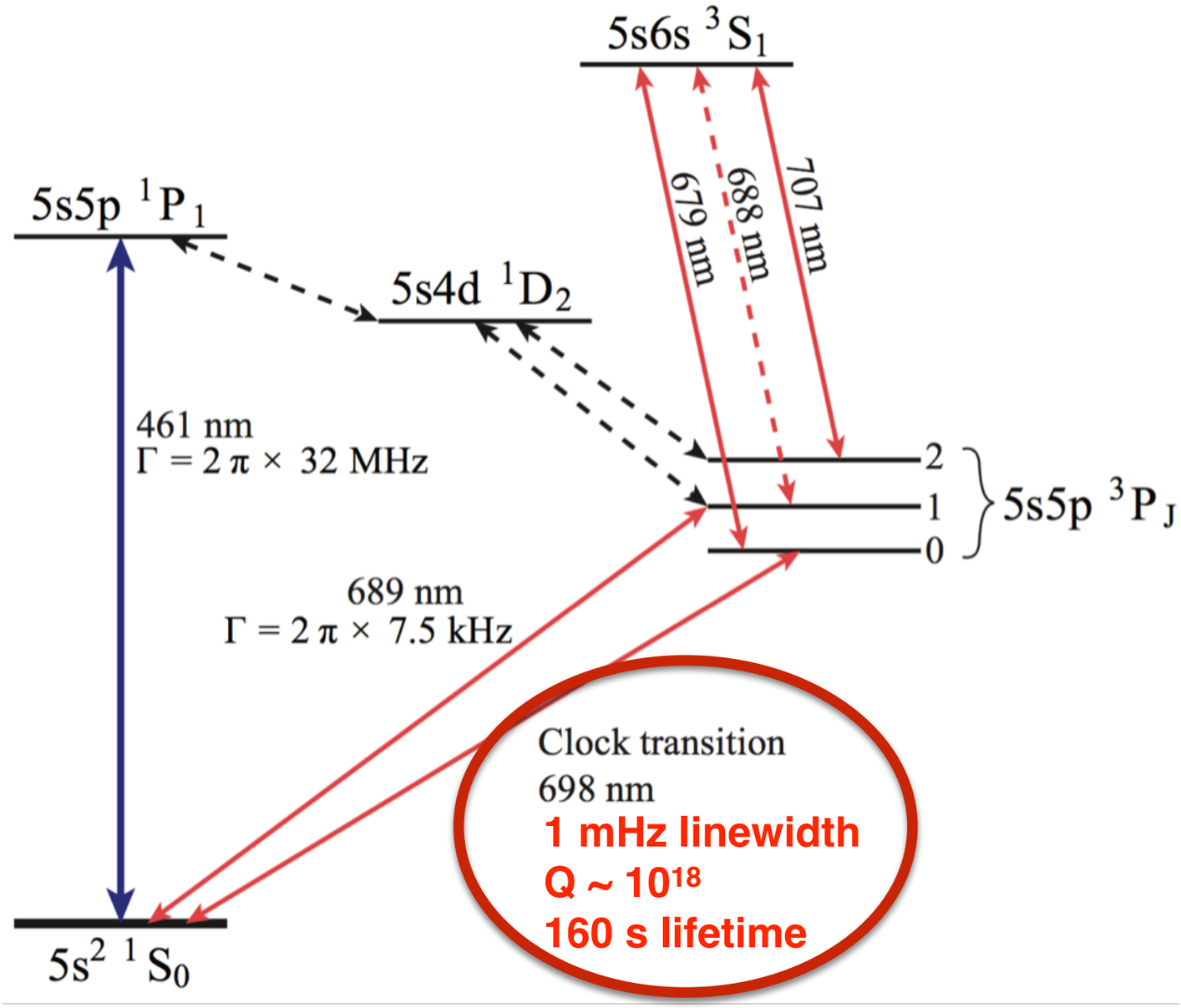
- Narrow transition, and cold, confined atoms
- Many atoms
- Long interrogation times
- Short dead times
- Well isolated atoms to avoid systematics
- High transition frequency

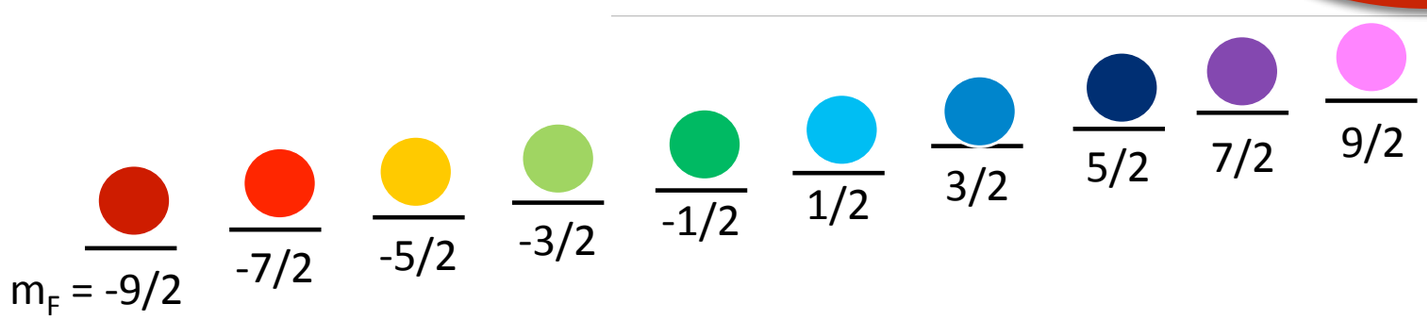


→ Move from $\nu_o = 10^{10}$ Hz to $\nu_o = 10^{15}$ Hz

^{87}Strontium

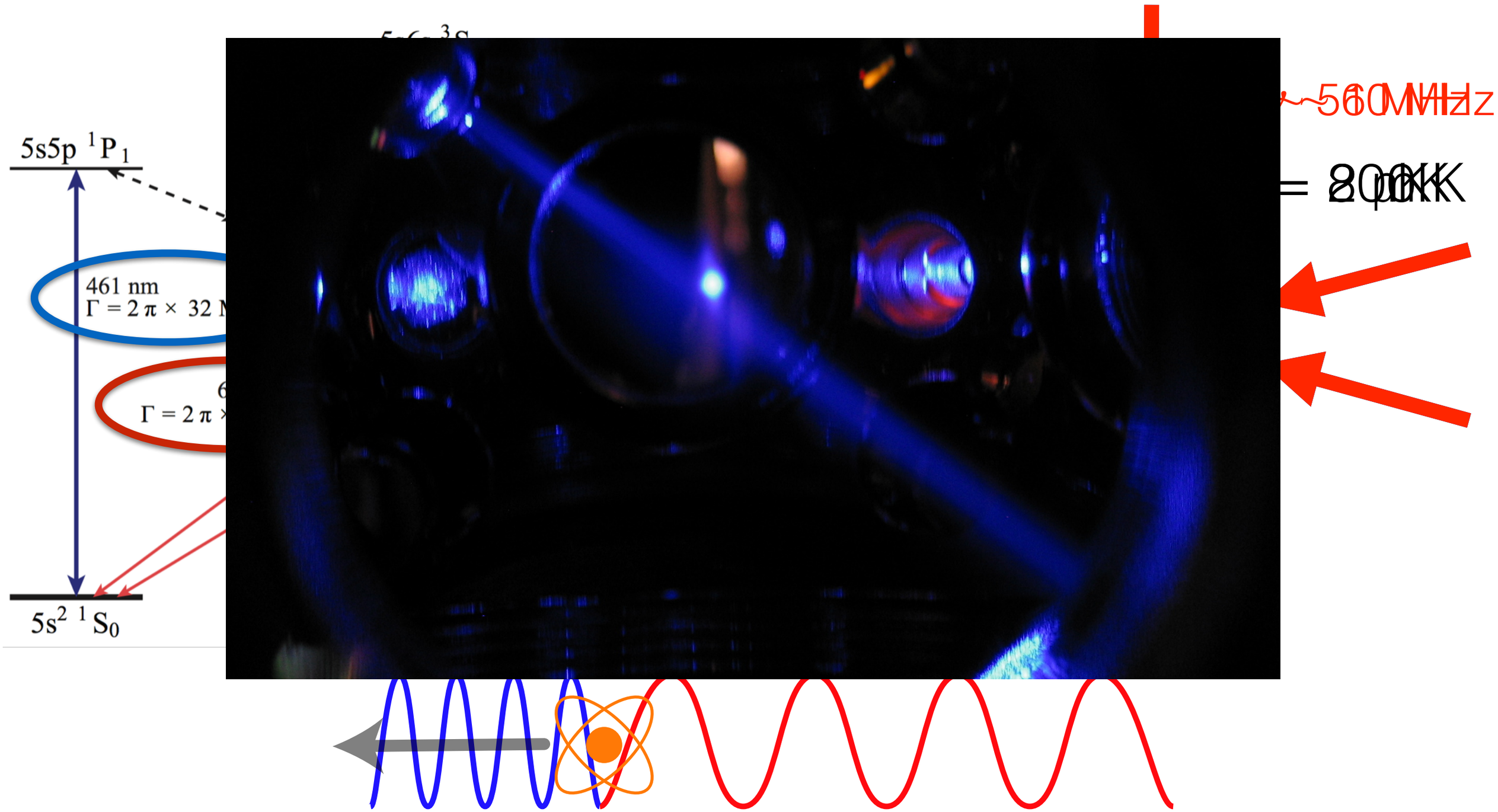




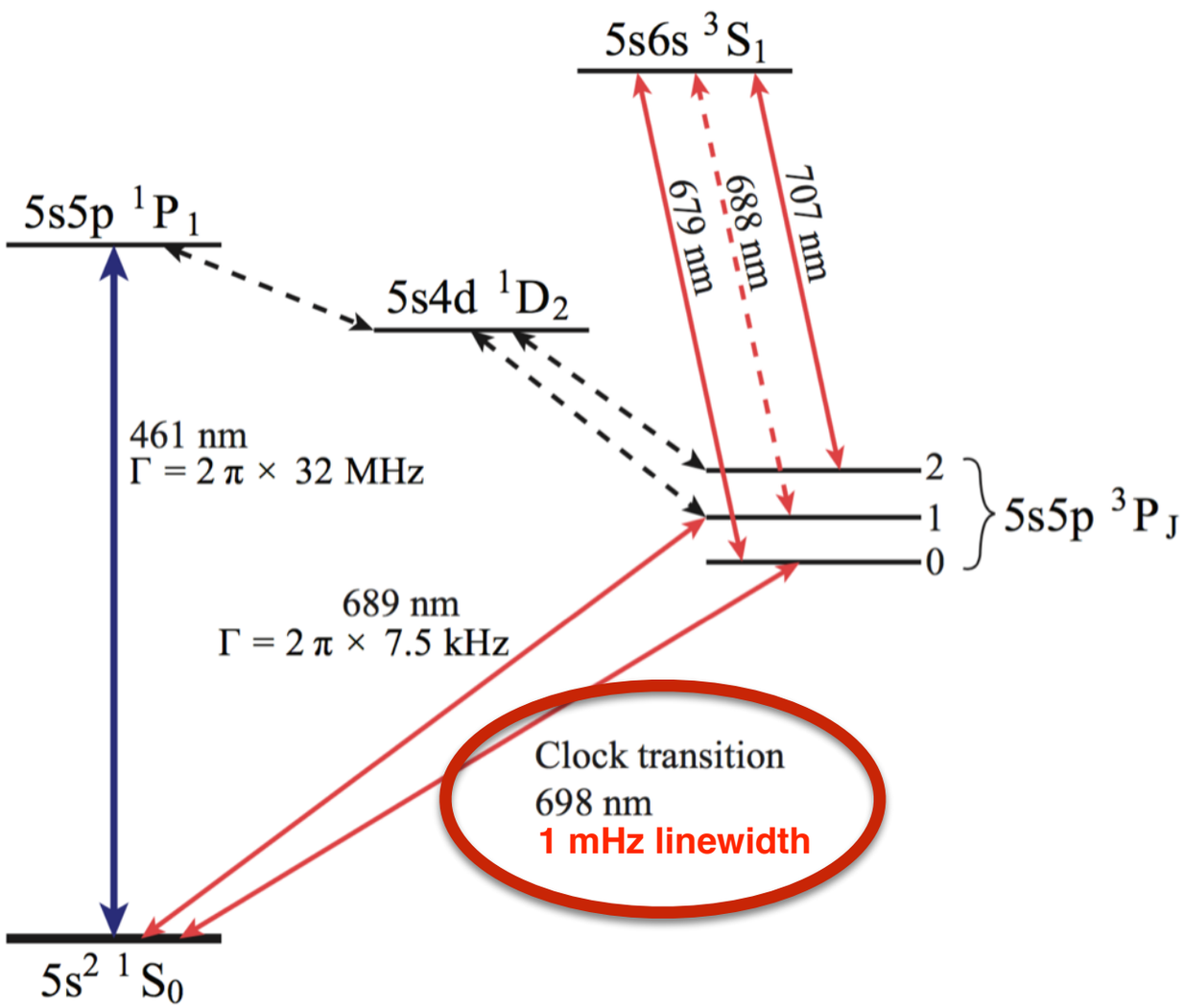


See Ludlow *et al., Reviews of Modern Physics* (2015) for other species of optical clocks

Laser cooling



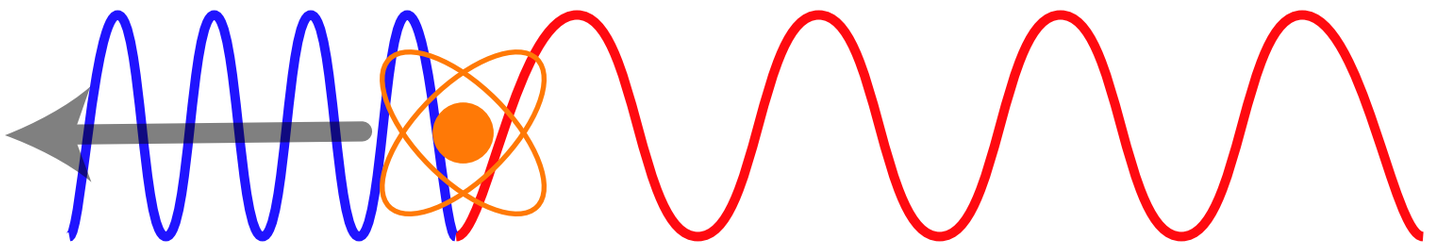
Laser cooling



T = 2 μK

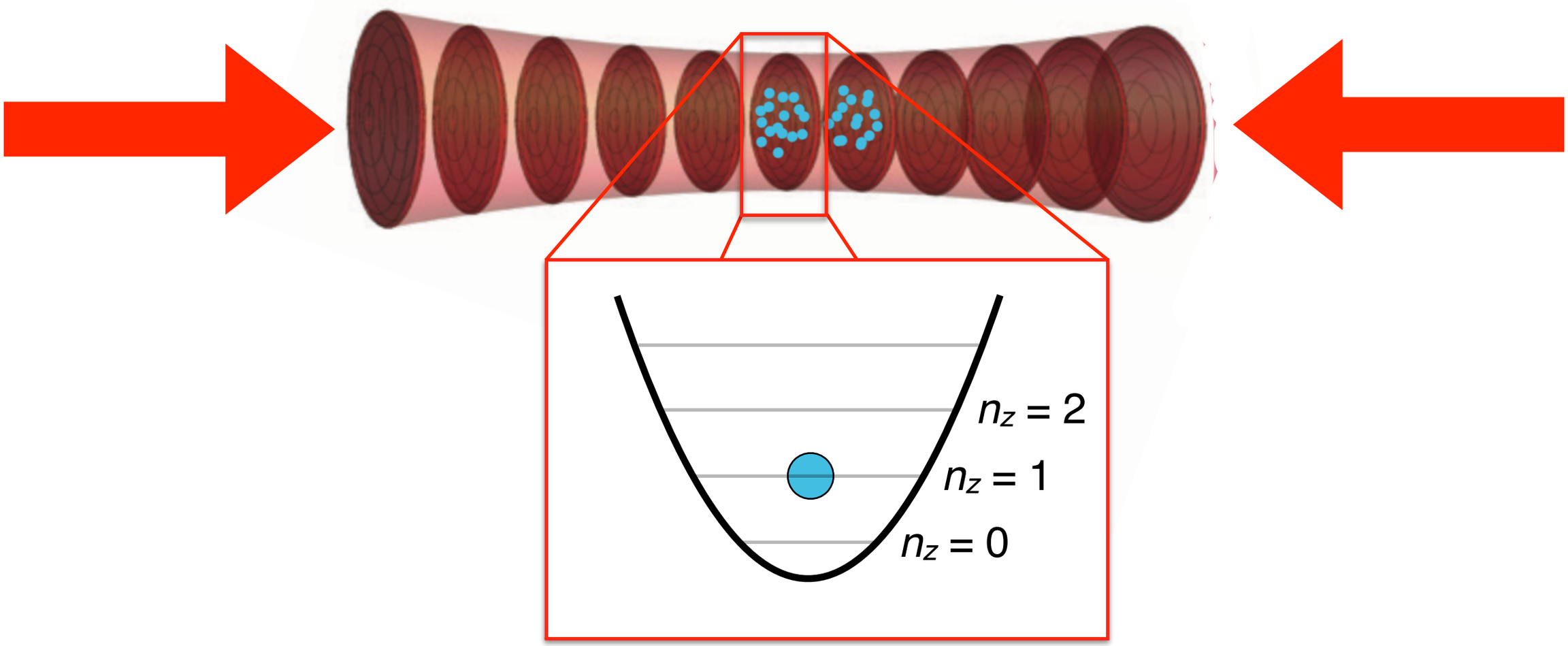
$\Delta\nu \sim 46$ kHz

Still too broad!

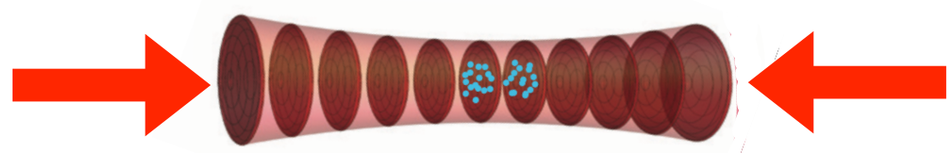


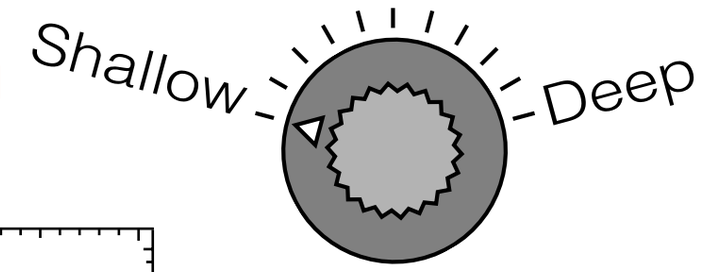
Optical lattice trap

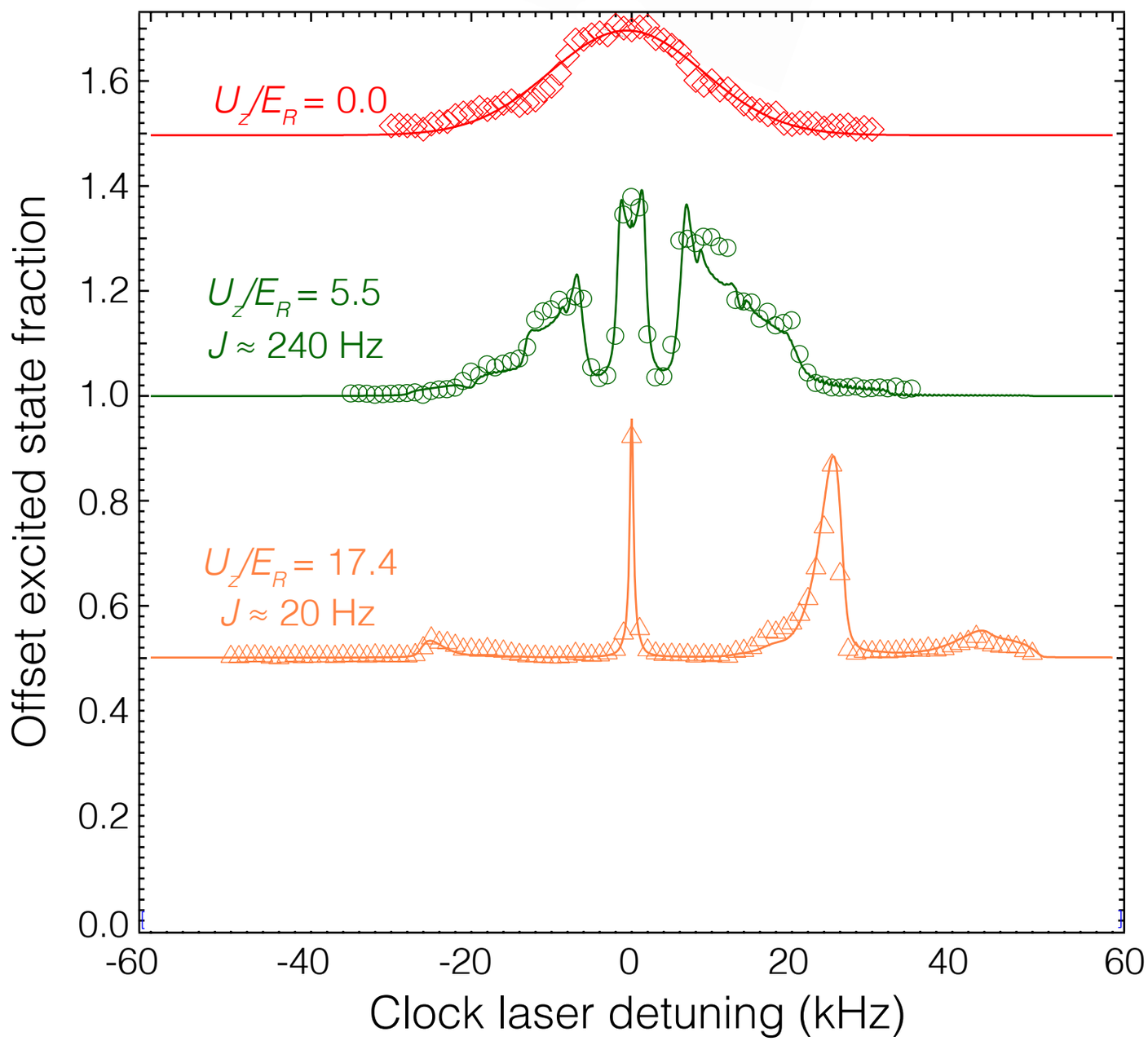
The solution?



Effect of optical lattice on clock transition

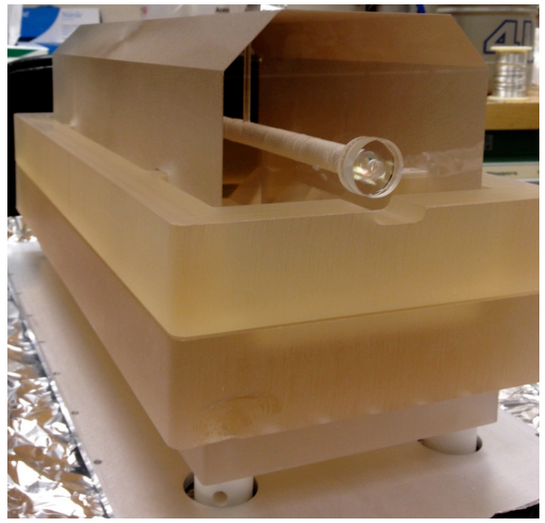


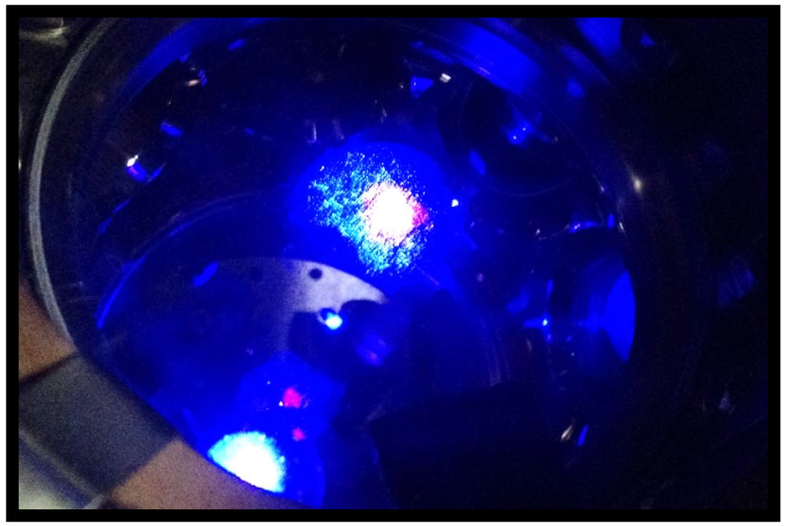


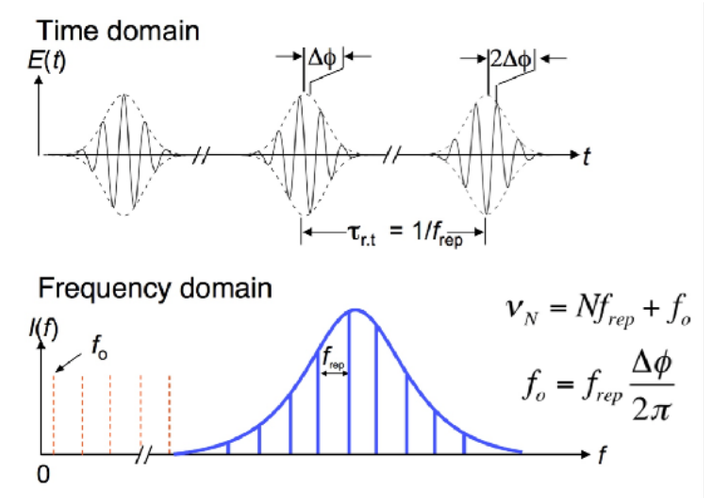


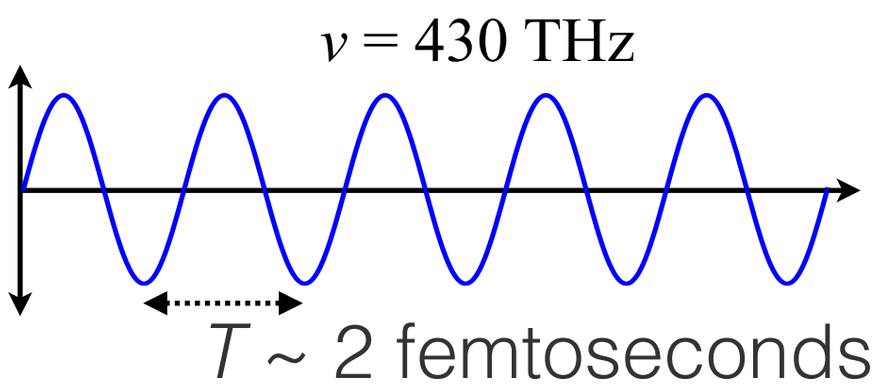
SK *et al., Nature* (2016)

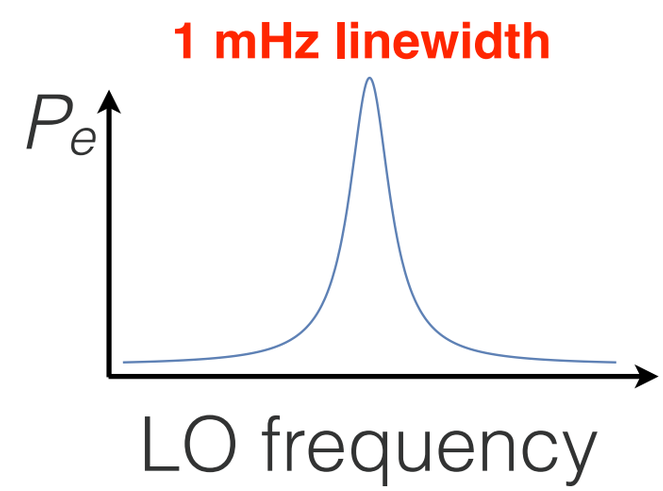
Optical lattice clock









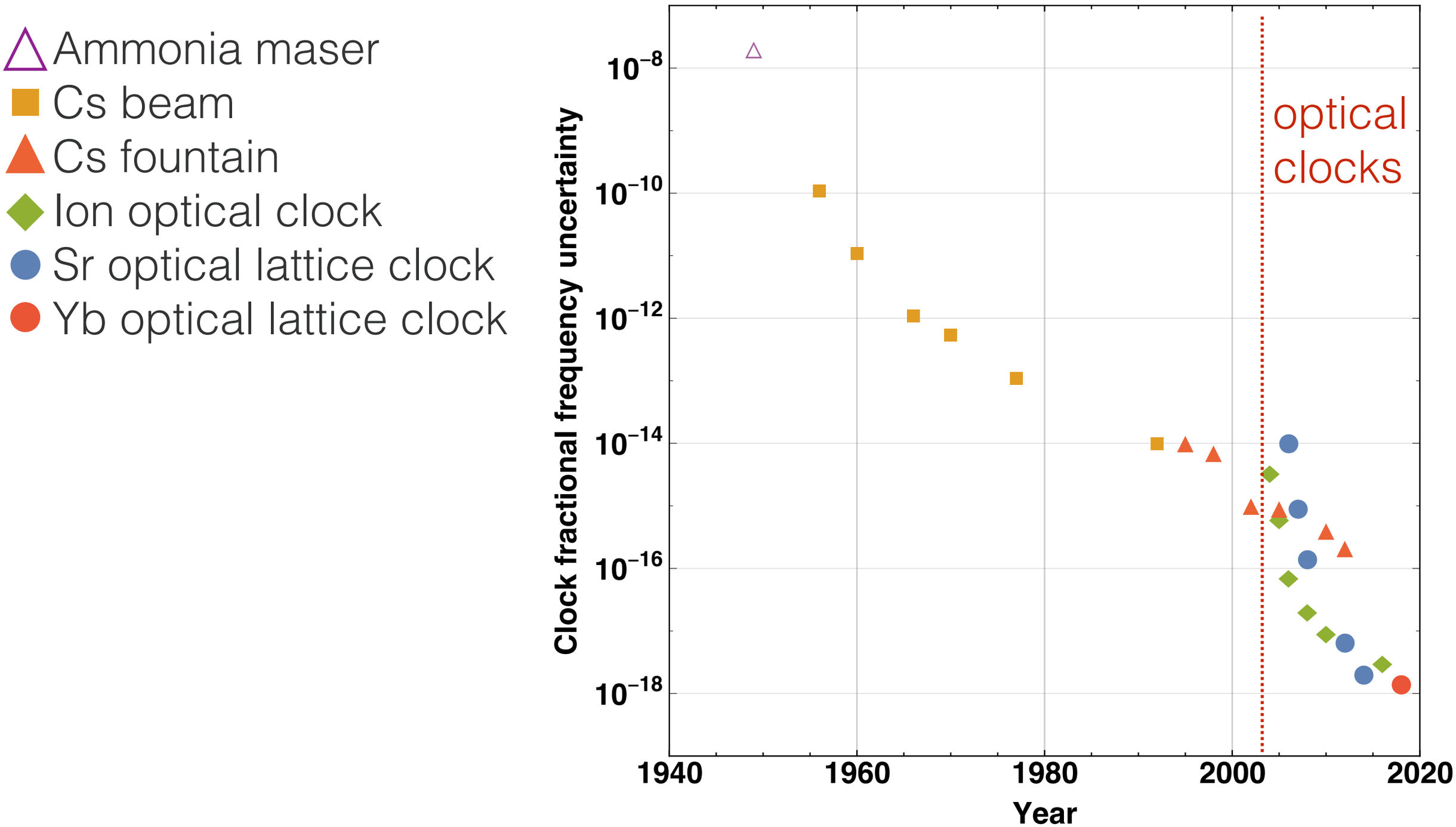


Counter

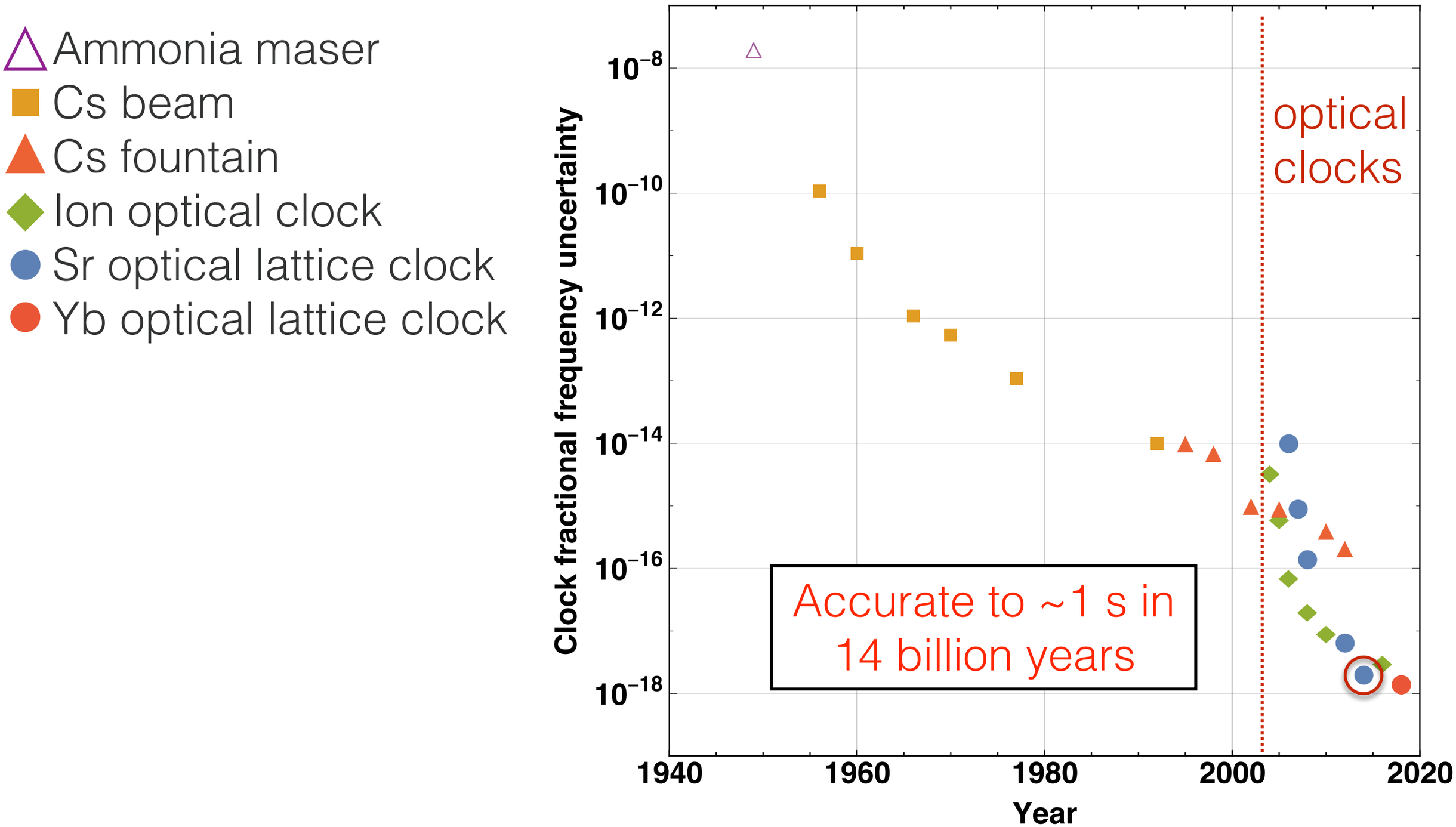
Local oscillator (LO)

Frequency reference

Atomic clock progress, 1949 - 2016

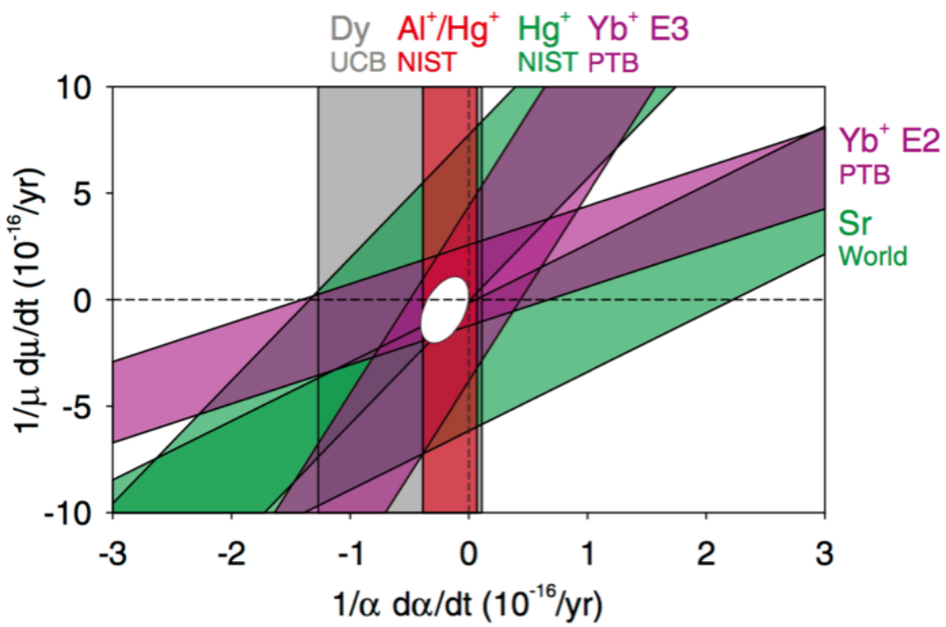


Atomic clock progress, 1949 - 2016

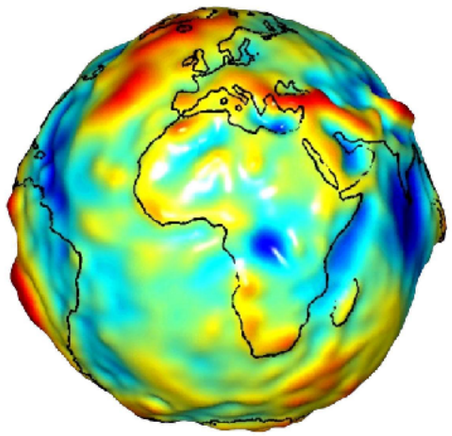


Novel applications of optical lattice clocks

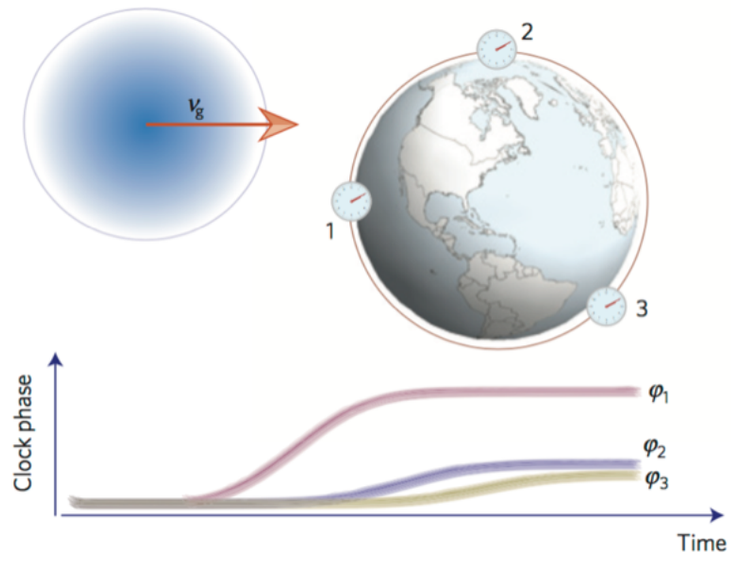
Searches for new physics



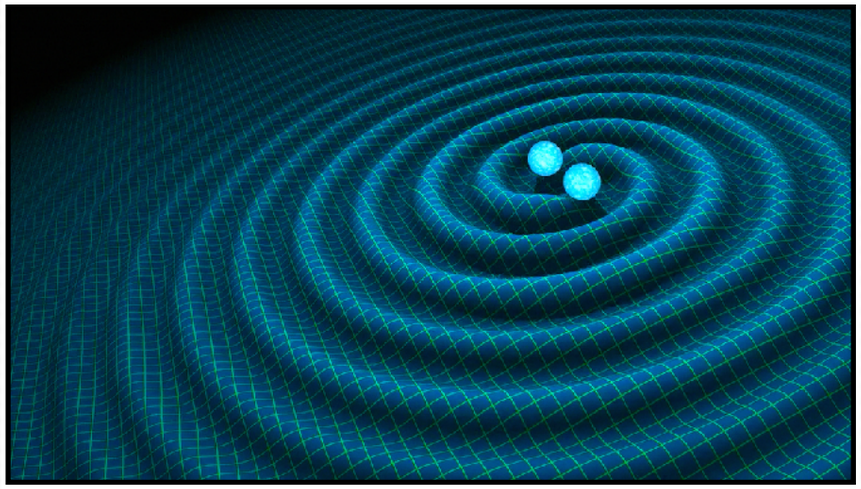
Geodesy



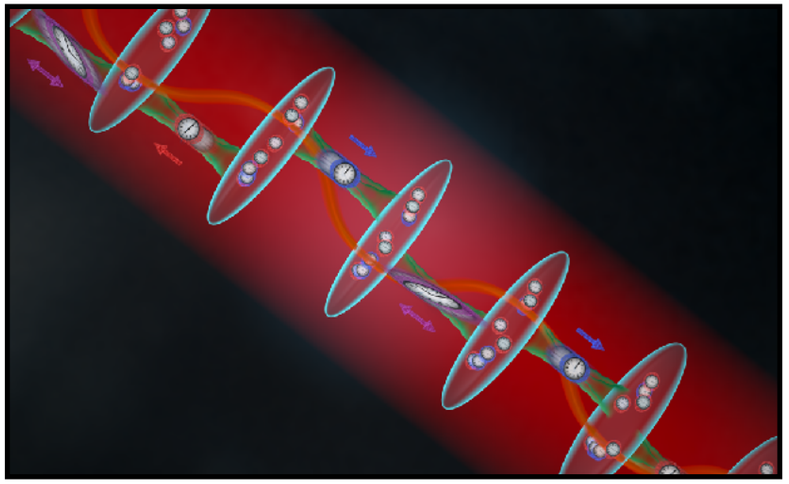
Dark matter detection



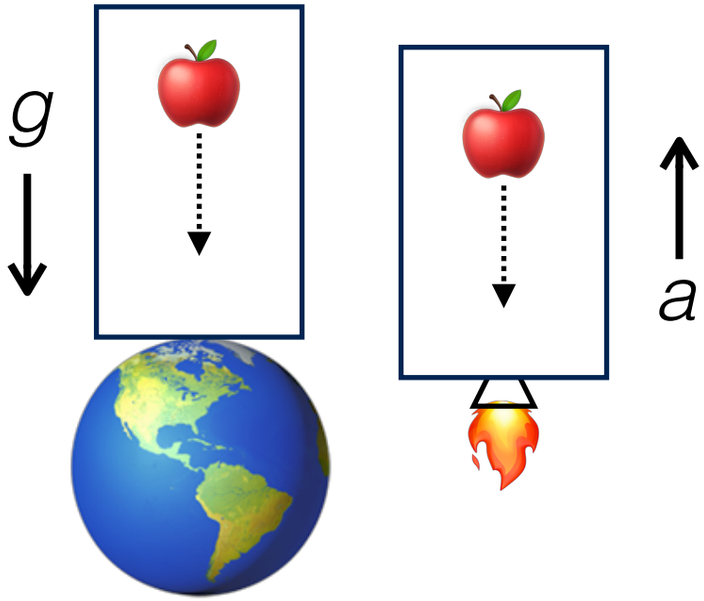
GW detection



Quantum simulation

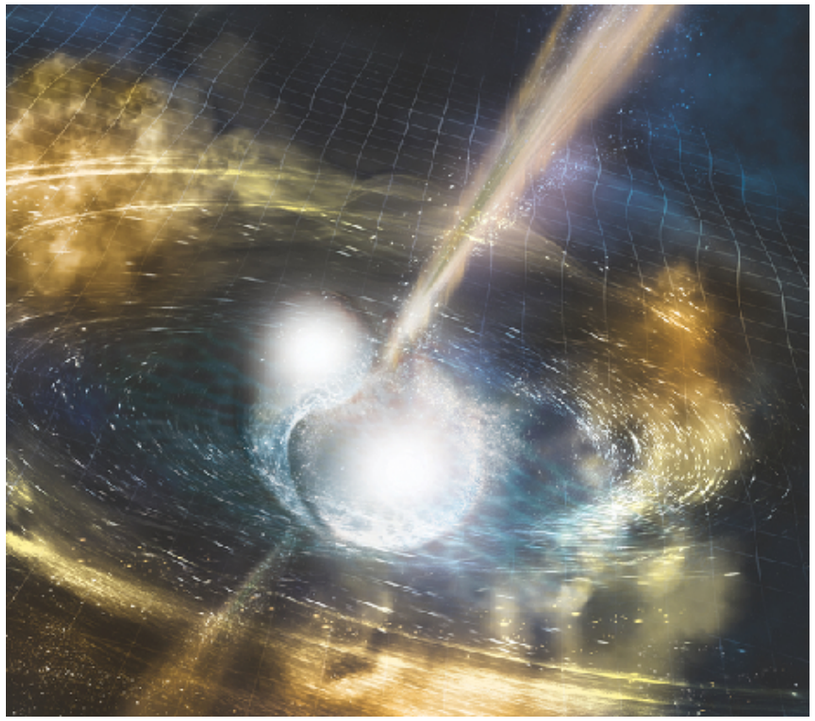


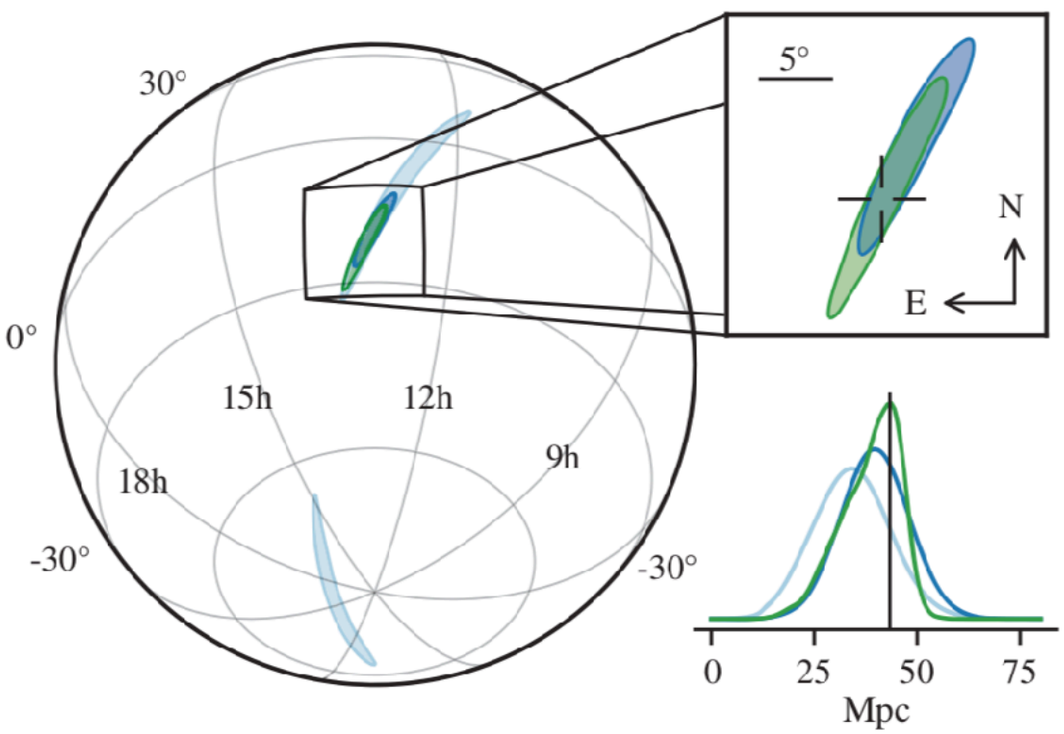
Tests of relativity

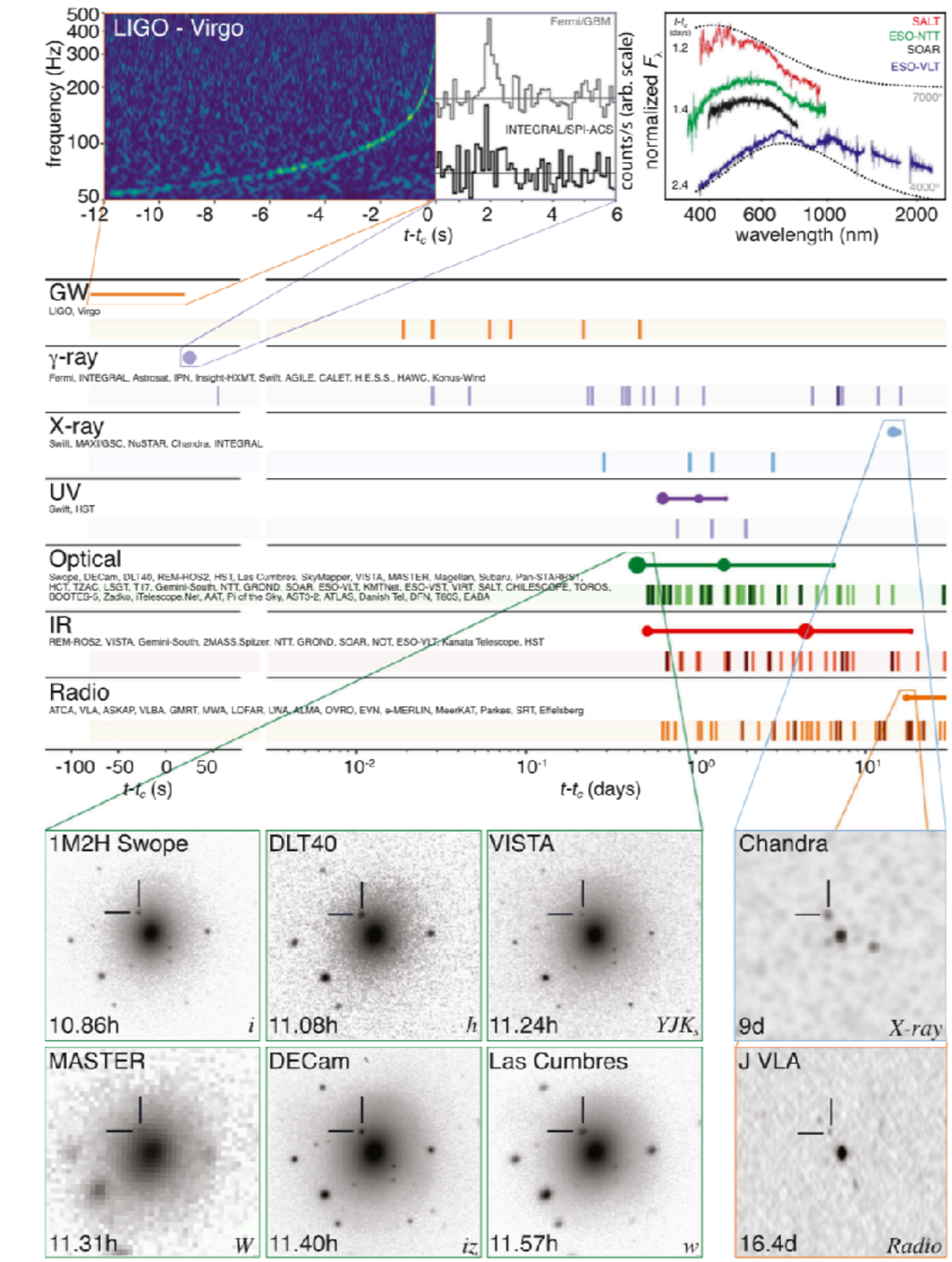


Huntemann *et al. PRL* (2014); Takano *et al. Nature Photonics* (2016); Dereviako, Pospelov, *Nature Physics* (2014)
SK *et al. PRD* (2016); SK *et al., Nature* (2017); Arms, Serna, *arXiv* (2016)

Gravitational wave detection - GW170817

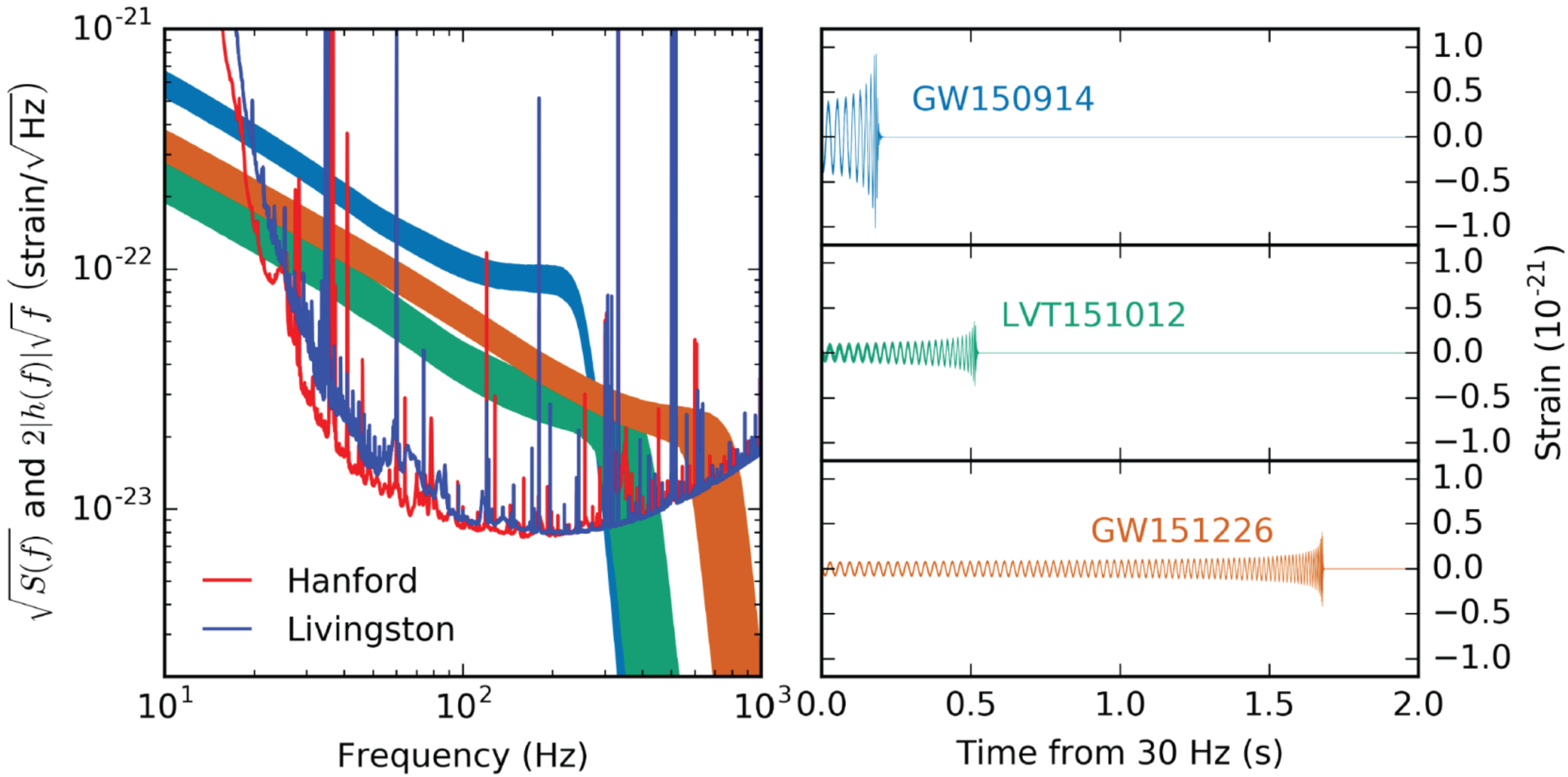






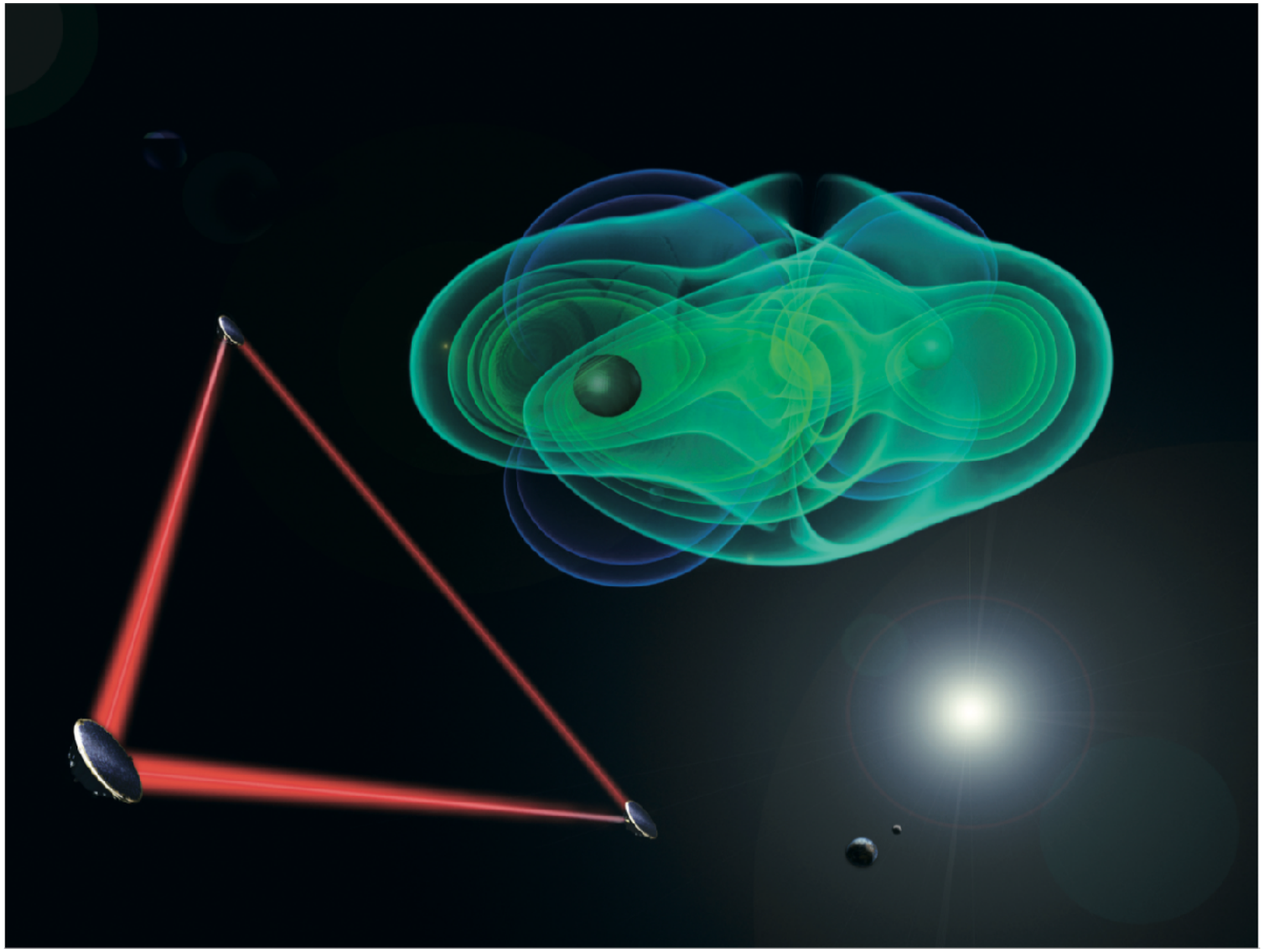
Abbott *et al.*, (LIGO collaboration + 1/3 world's astronomers), *AJL* (2017)

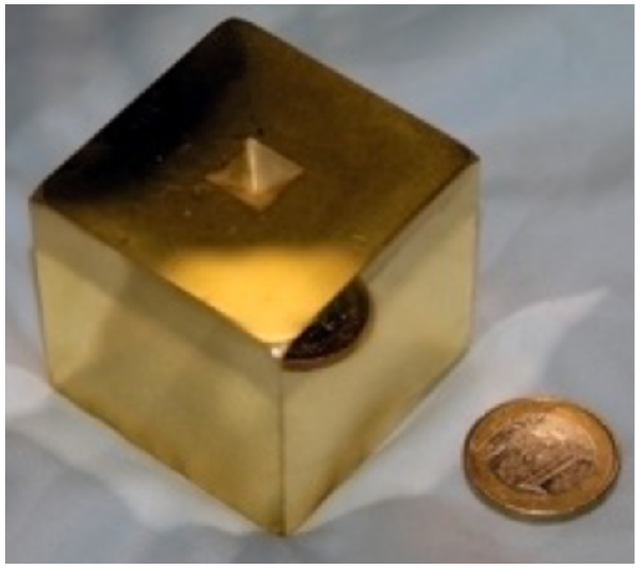
Gravitational wave detection - LIGO



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

LISA and eLISA



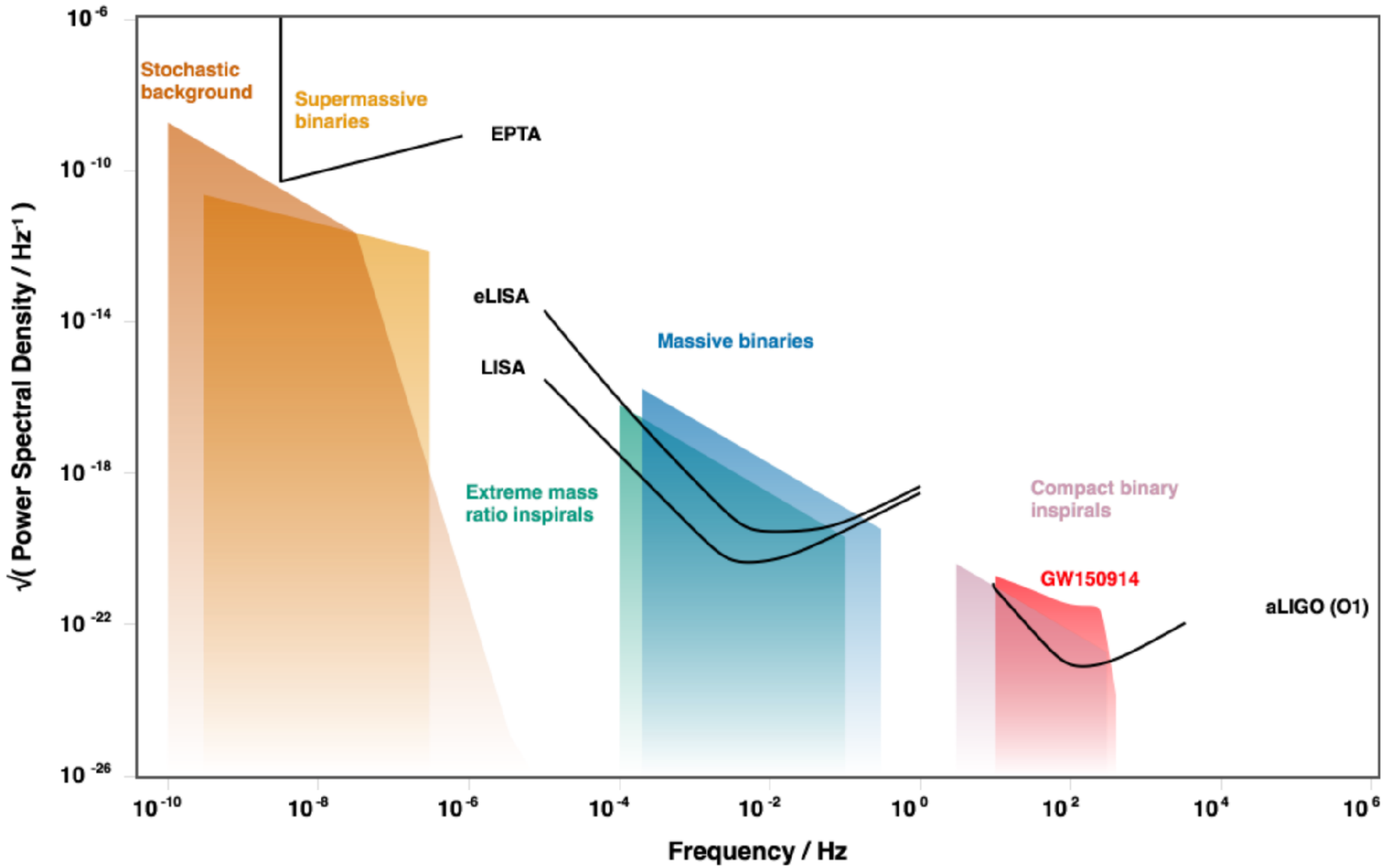


<u>LISA and eLISA:</u>

- Drag-free, space based version of LIGO
- $d = 5\text{x}10^9$ m arm length

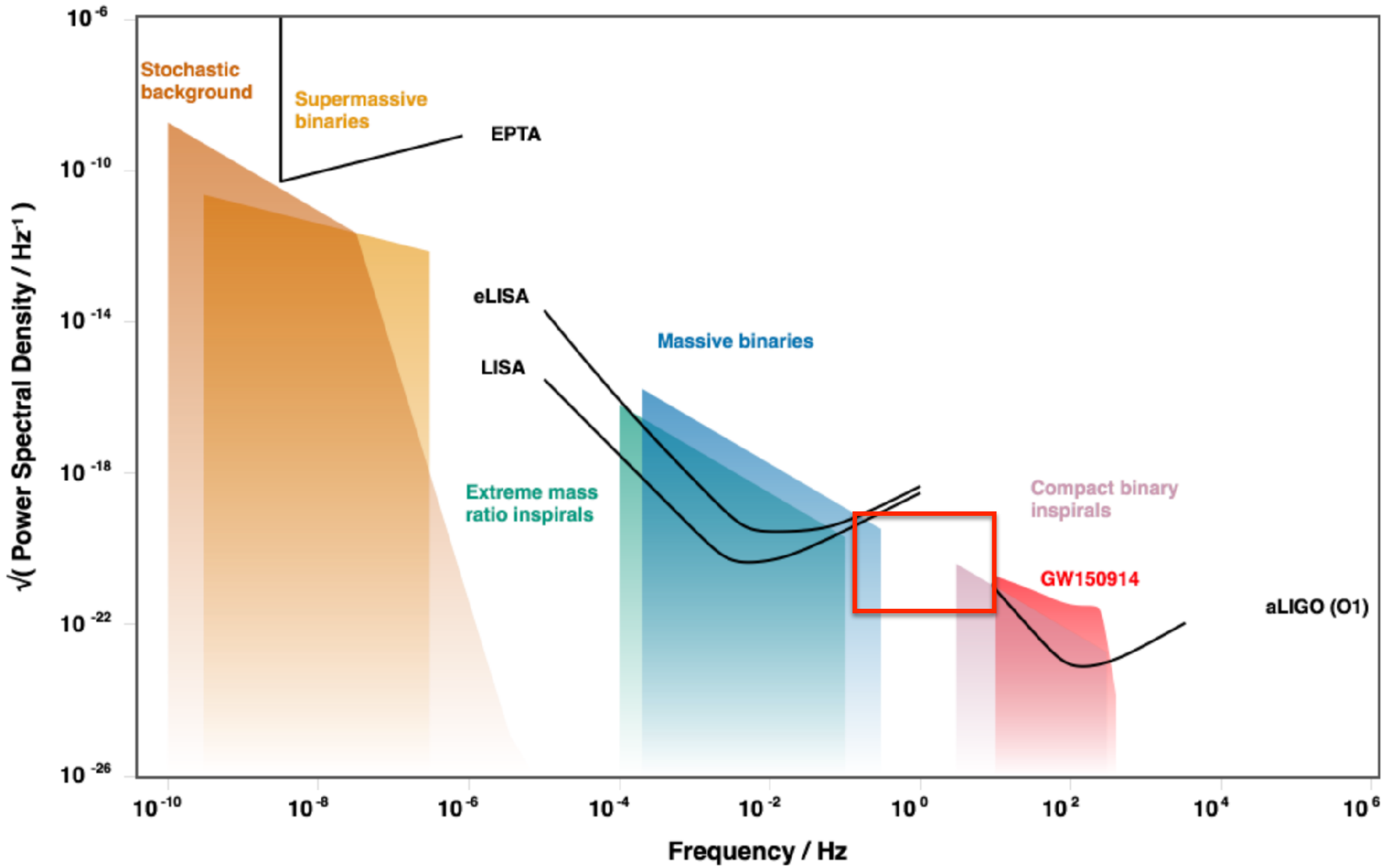
See e.g. Amaro-Seoane *et al.,* (LISA collaboration), *Classical and Quantum Gravity* (2012)

Gravitational wave detection



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

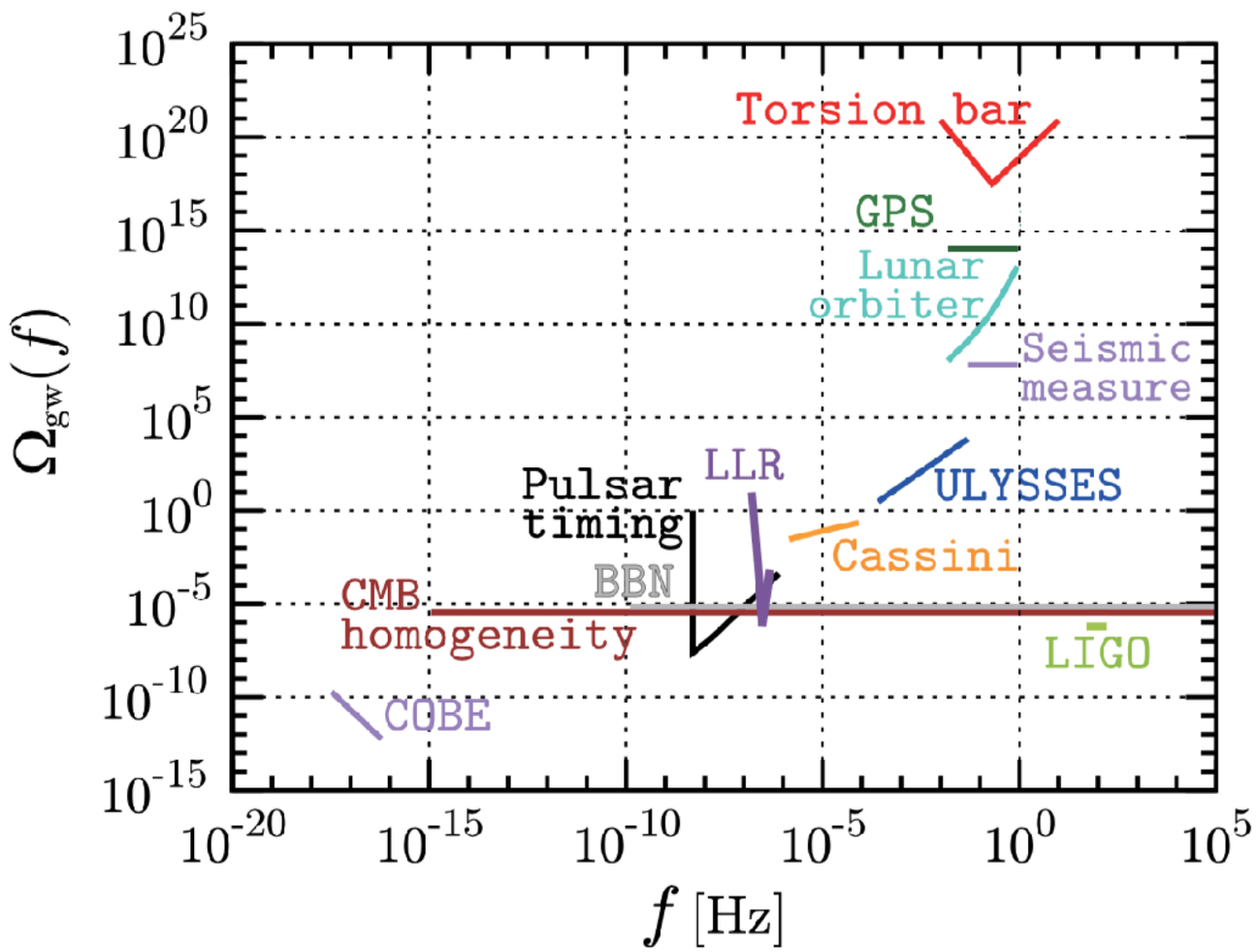
Gravitational wave detection

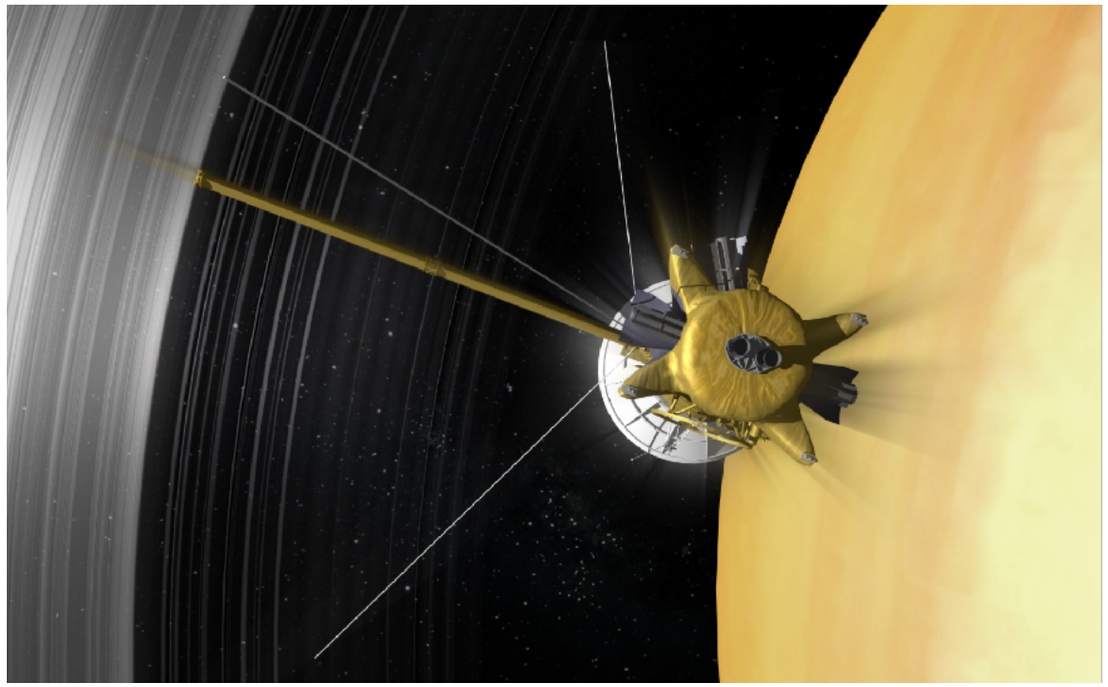


Plot from http://rhcole.com/apps/GWplotter/

Doppler tracking searches

Previous limits on GW density:

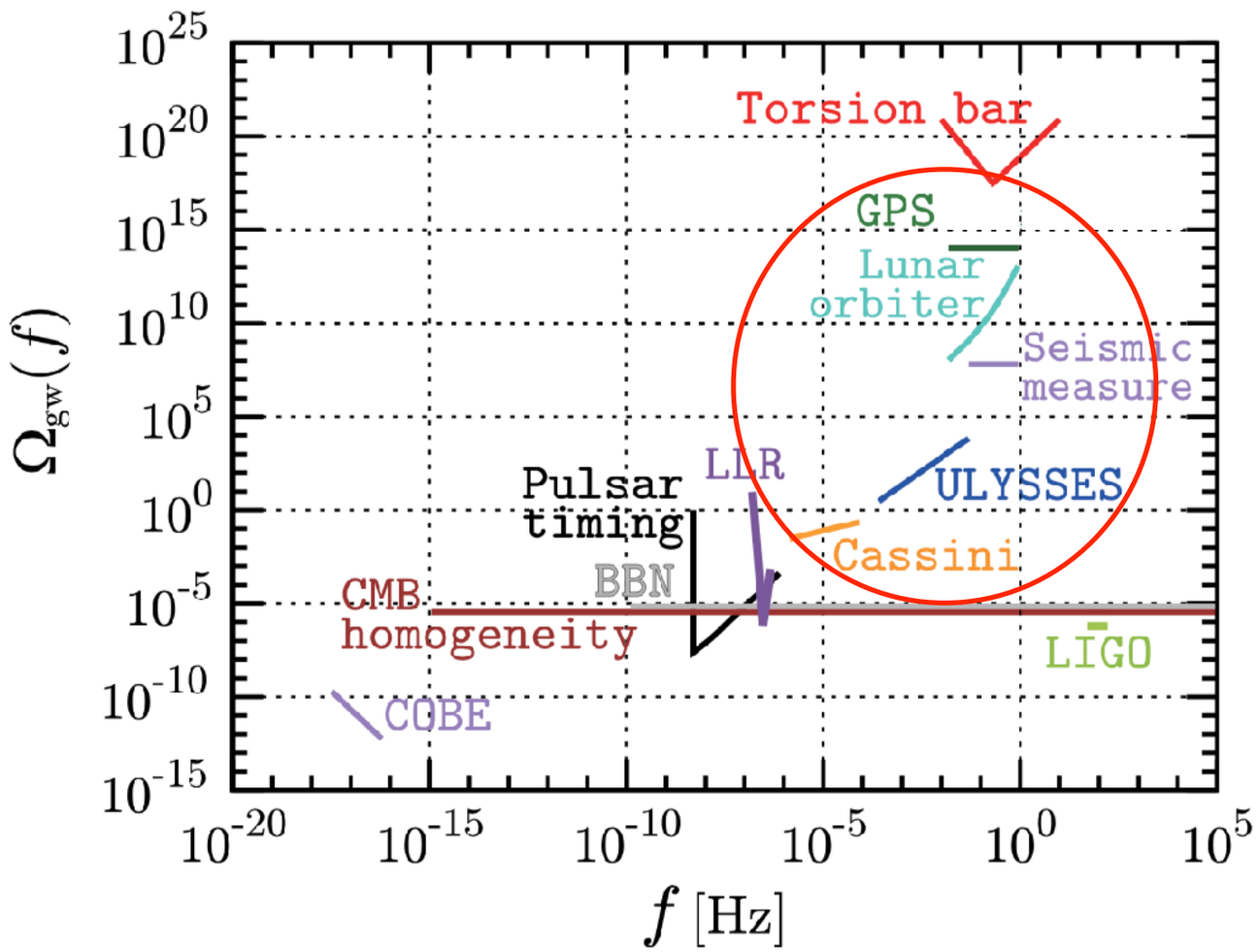




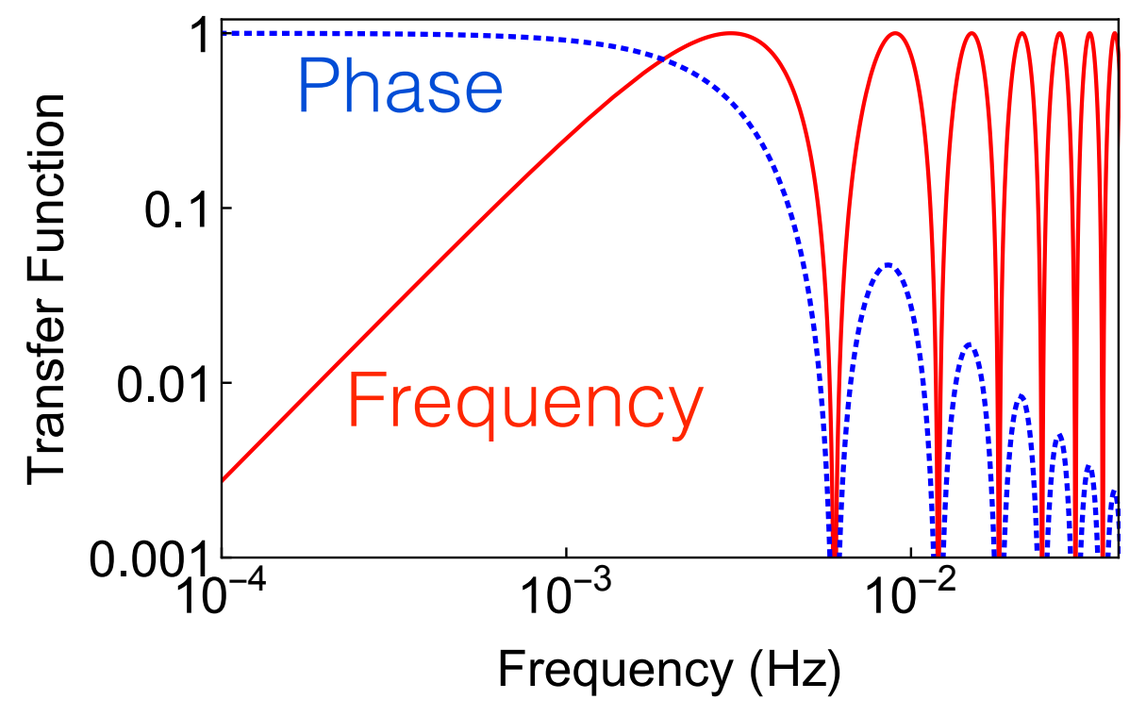
[1]Aoyama *et al.*, *PRD* (2014), [2]Image credit: NASA/JPL

Doppler tracking searches

Previous limits on GW density:

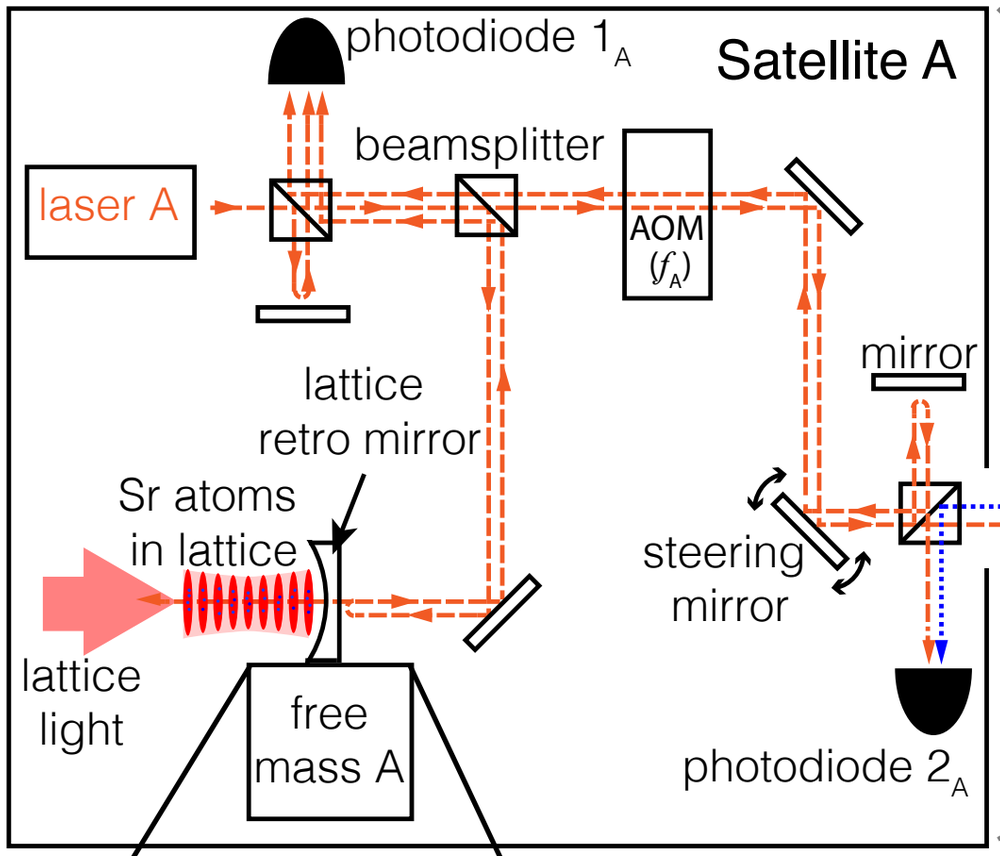


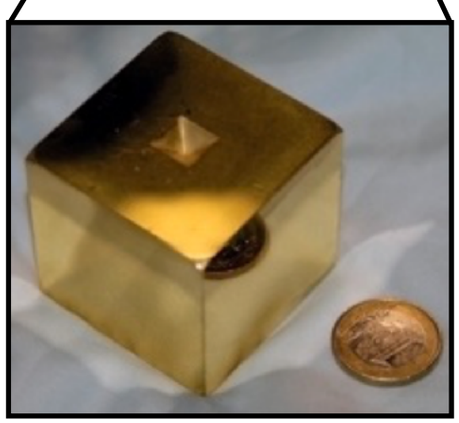
Detector transfer function:

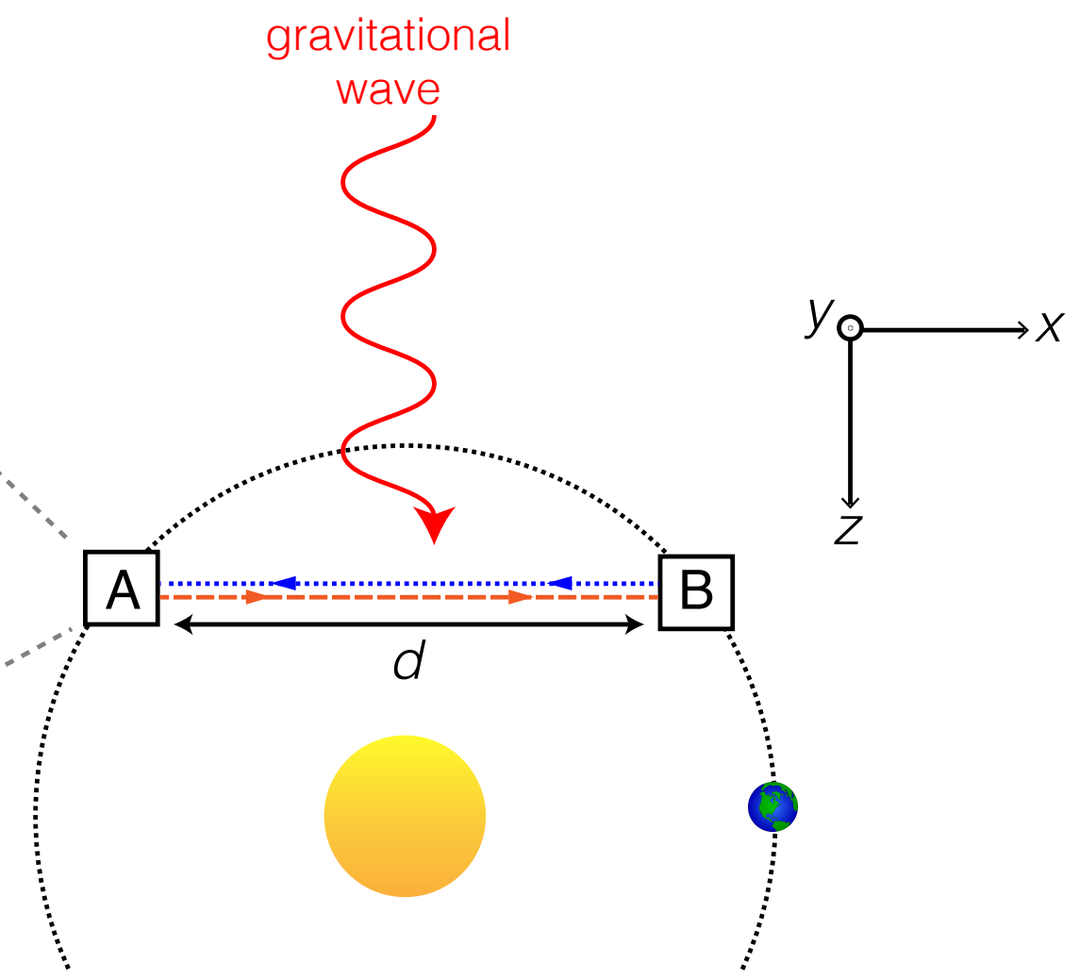


[1]Aoyama *et al.*, *PRD* (2014)

Gravitational wave detection with clocks







$$\sigma(\tau) = \left.\frac{\delta\nu}{\nu_o}\right|_\tau = \frac{\sqrt{\Delta_A}}{\nu_o\sqrt{2\pi\tau N}}$$

SK *et al., PRD* (2016), also Graham *et al., PRL* (2013), Vutha, *NJP* (2015), Loeb, Maoz, *arXiv* (2016)

Gravitational wave detection

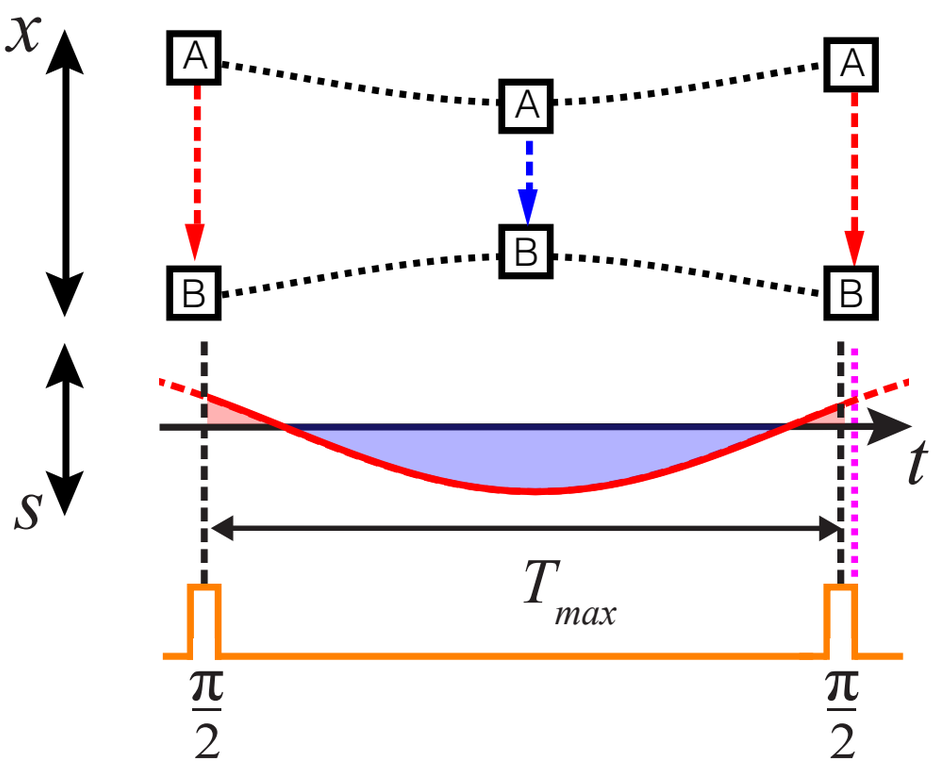
Clock based detector

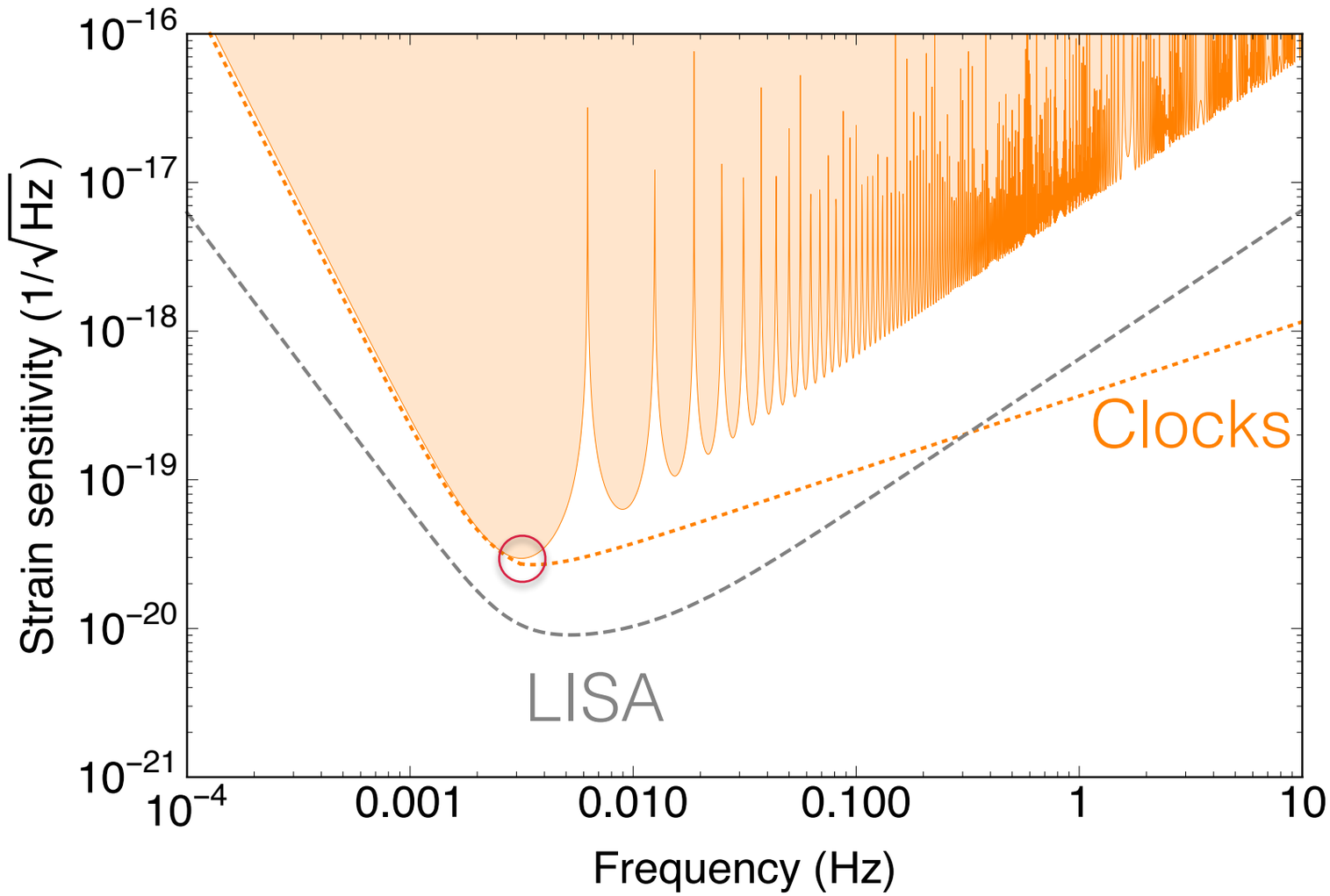
d = 5x10^{10} m arm length

N = 7x10^{6} Sr atoms per clock

160 s coherence time

Long Ramsey sequence:





SK *et al.*, *PRD* (2016)

Gravitational wave detection

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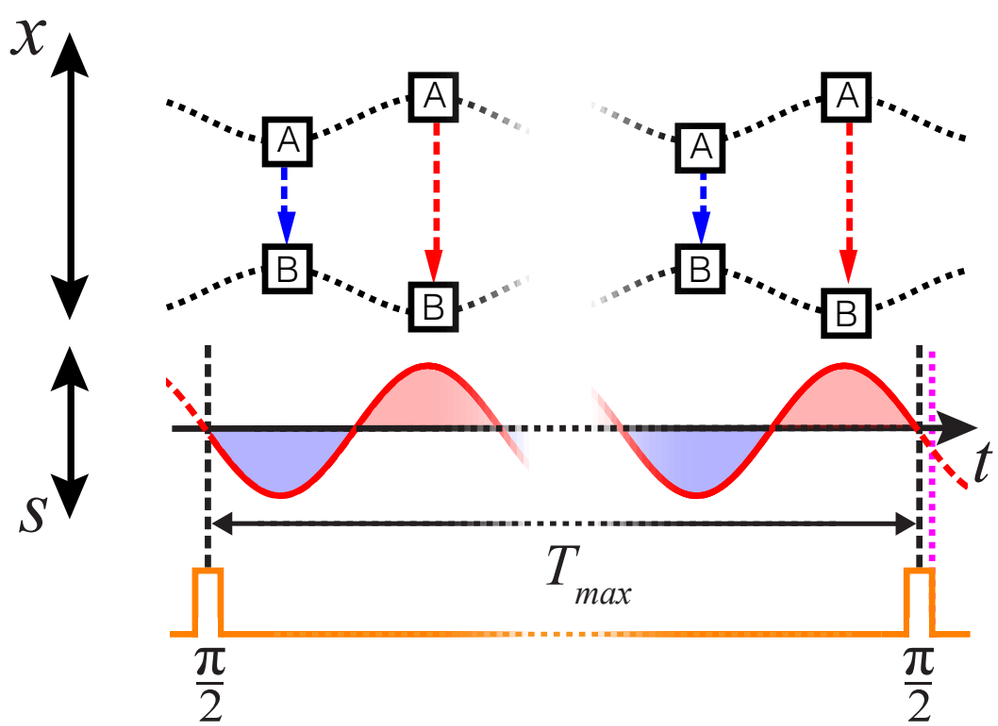
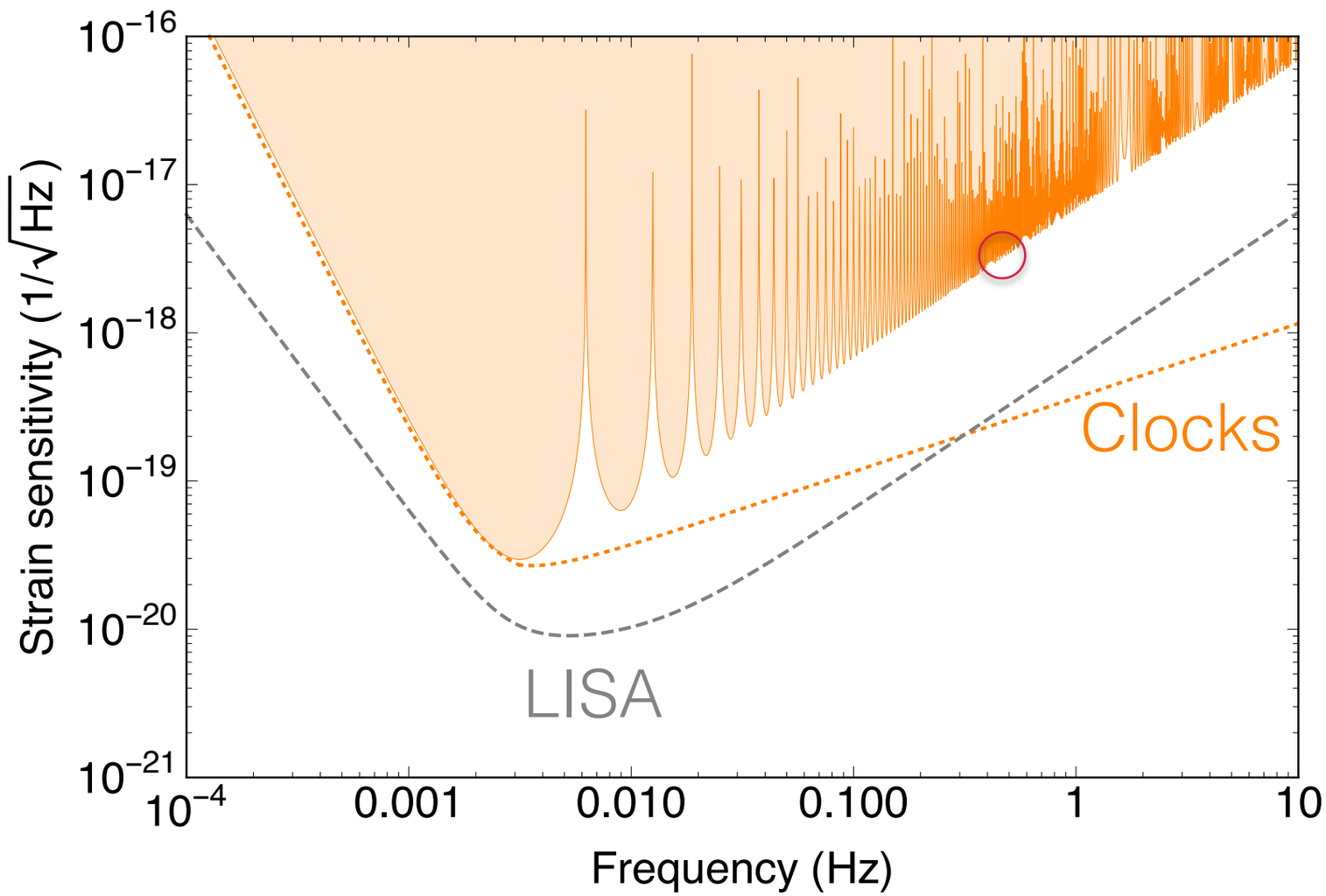




SK *et al.*, *PRD* (2016)

Gravitational wave detection

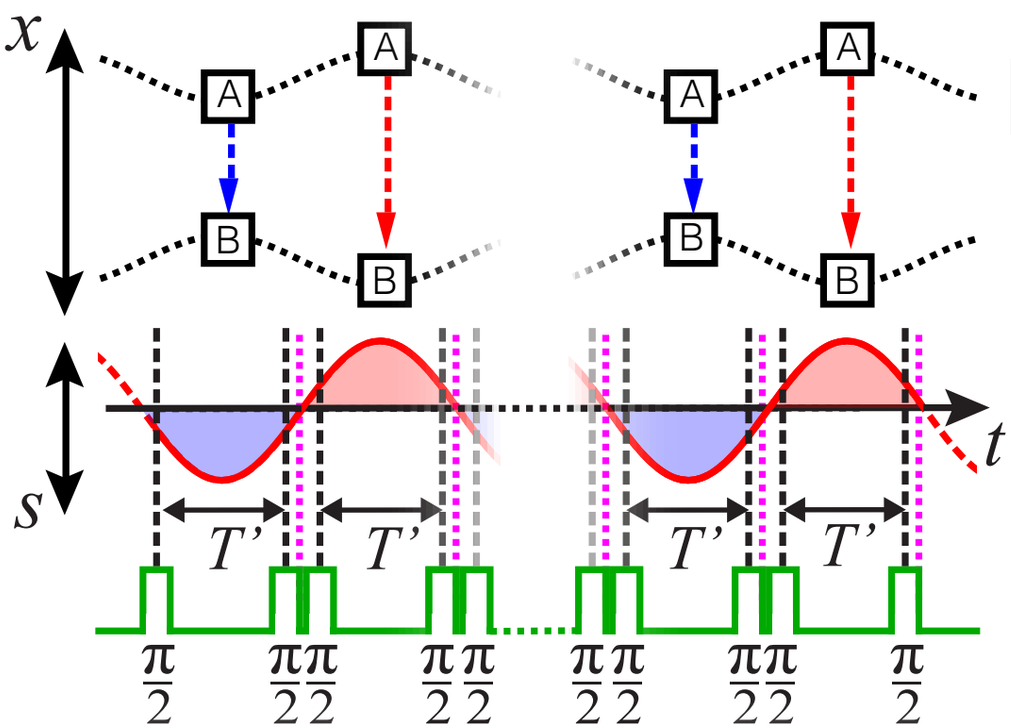
Clock based detector

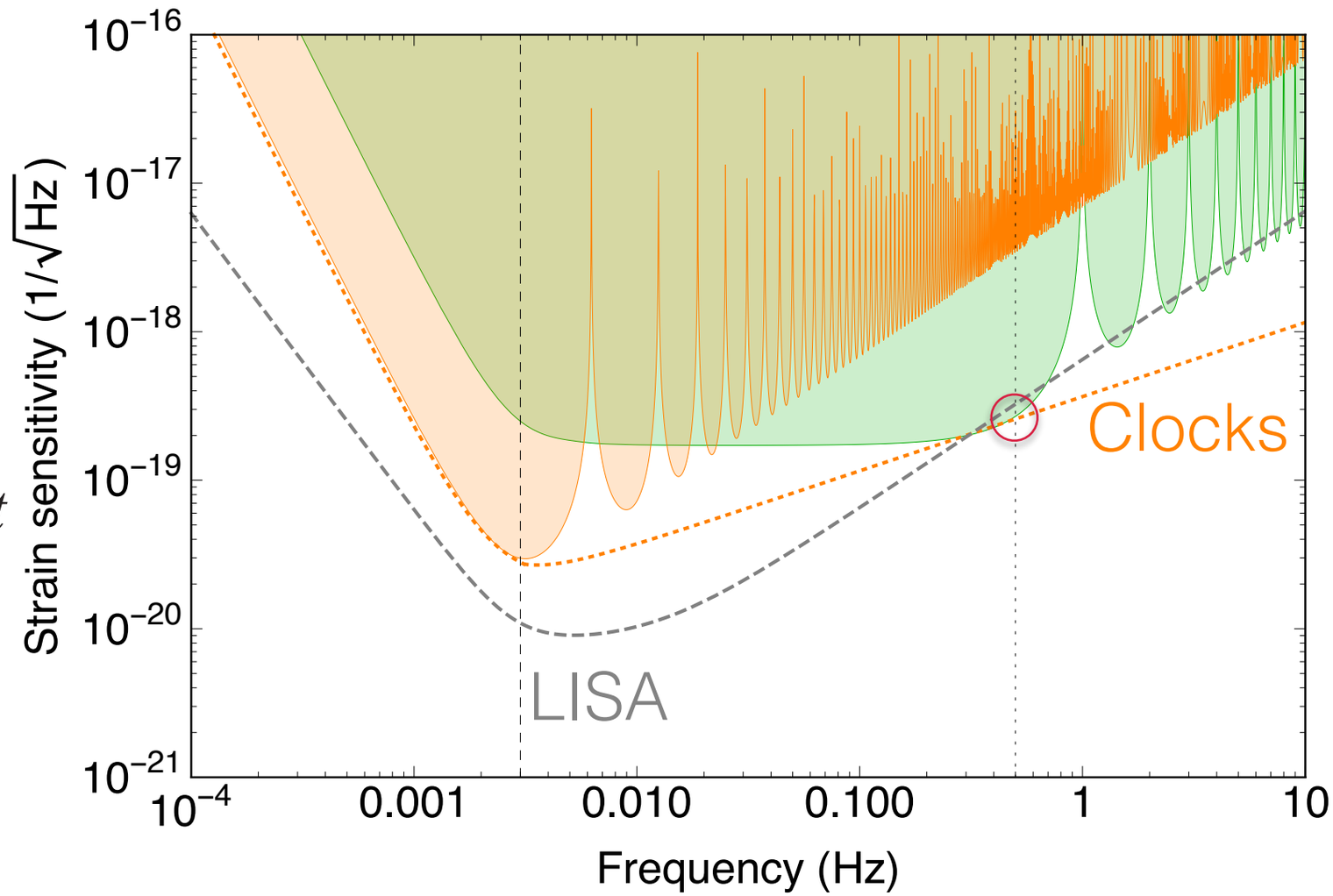
$d = 5\times10^{10}$ m arm length

$N = 7\times10^{6}$ Sr atoms per clock

160 s coherence time

Short Ramsey sequence:





SK *et al.*, *PRD* (2016)

Gravitational wave detection

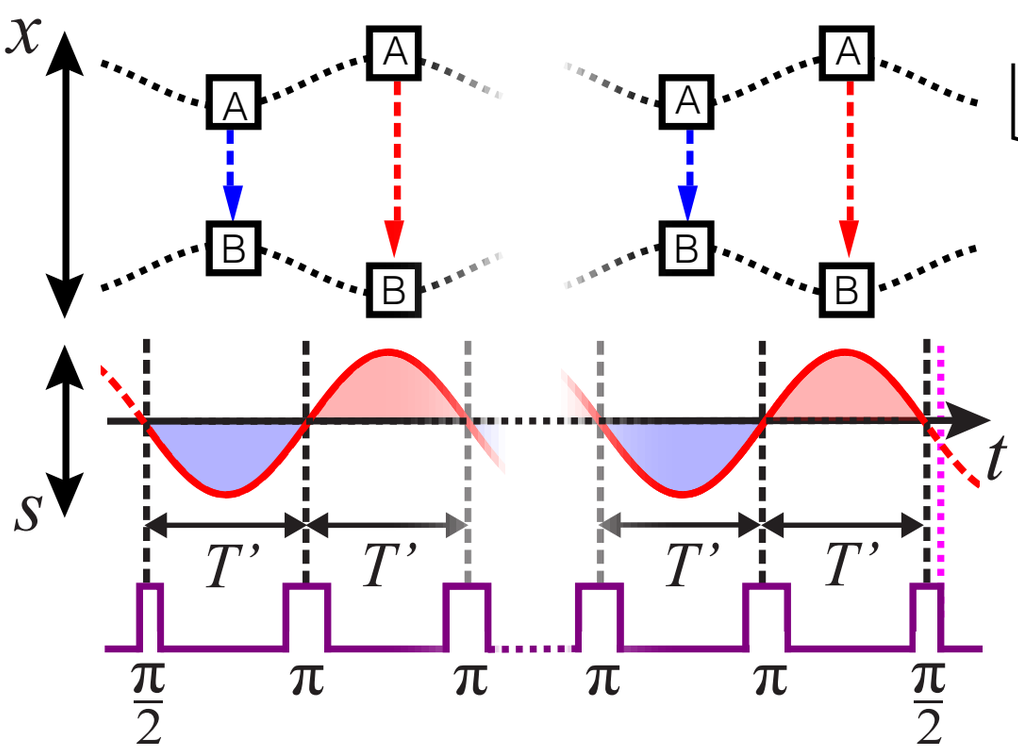
Clock based detector

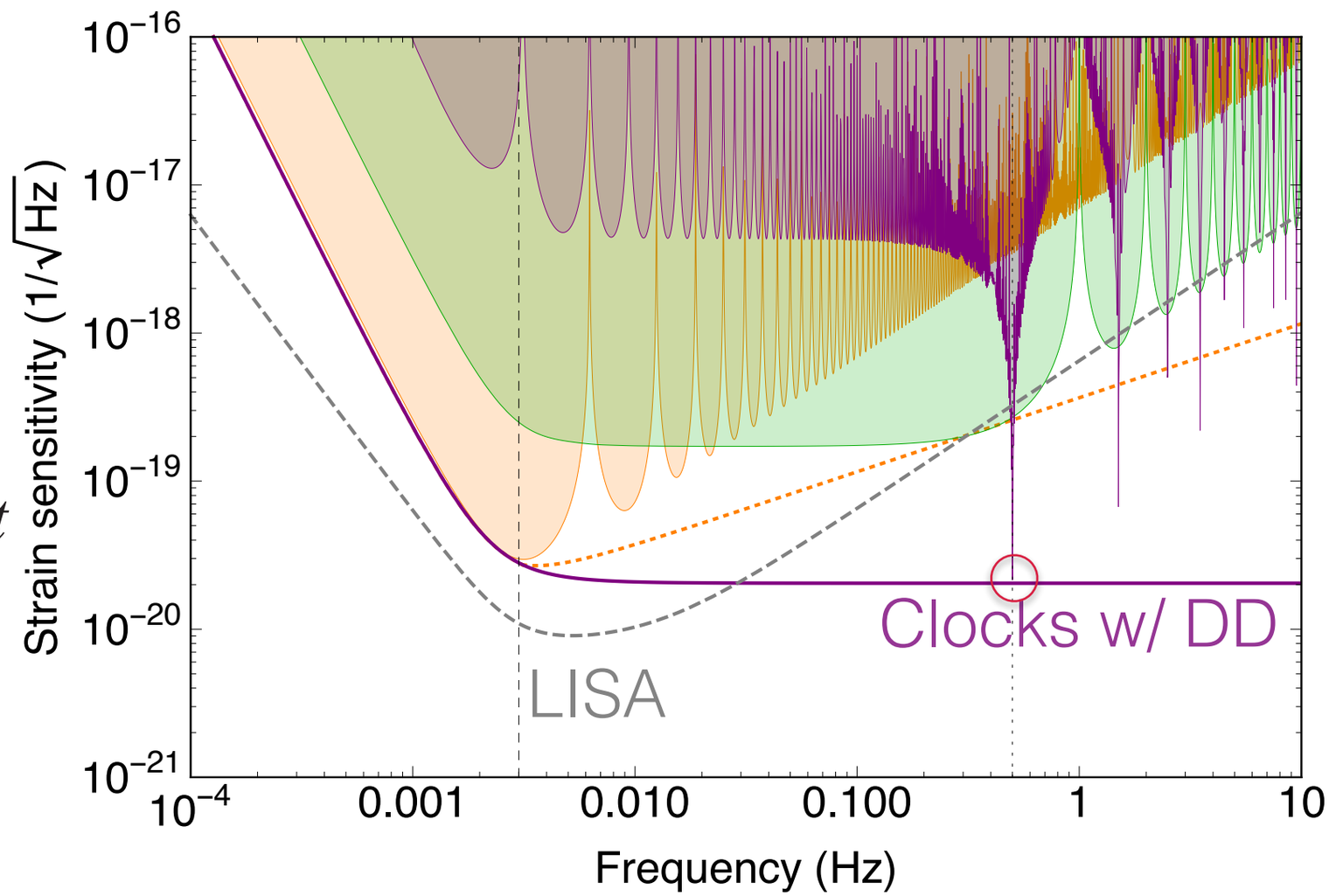
$d = 5\text{x}10^{10}$ m arm length

$N = 7\text{x}10^{6}$ Sr atoms per clock

160 s coherence time

Dynamical decoupling sequence:





SK *et al., PRD* (2016), see also Graham *et al., PRD* (2016)

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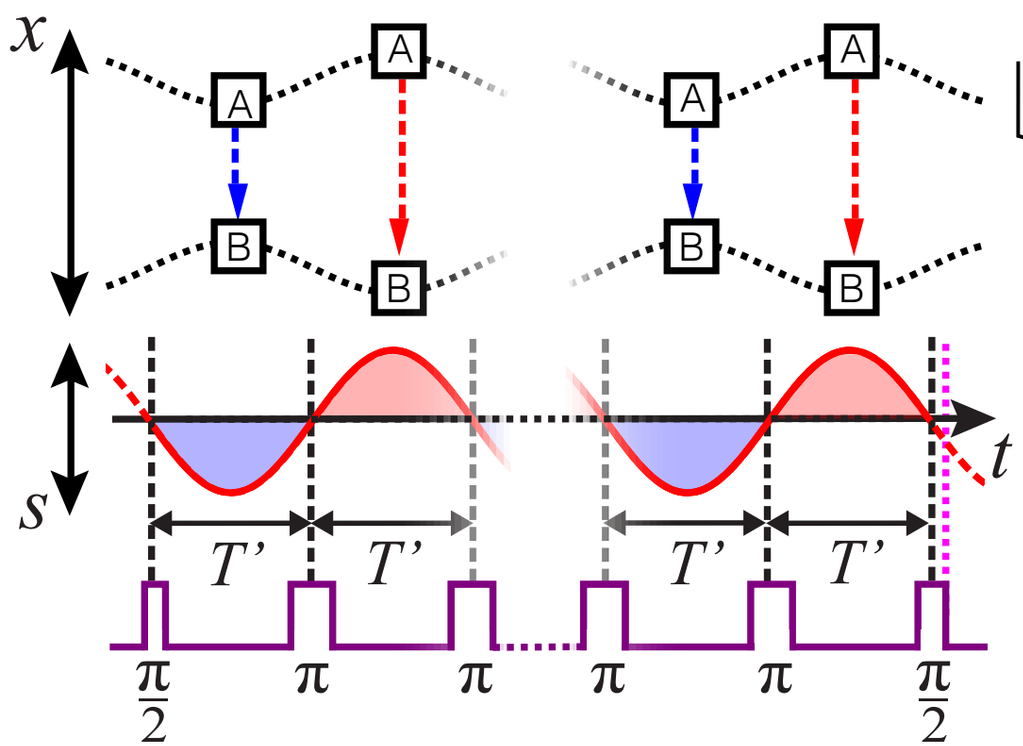

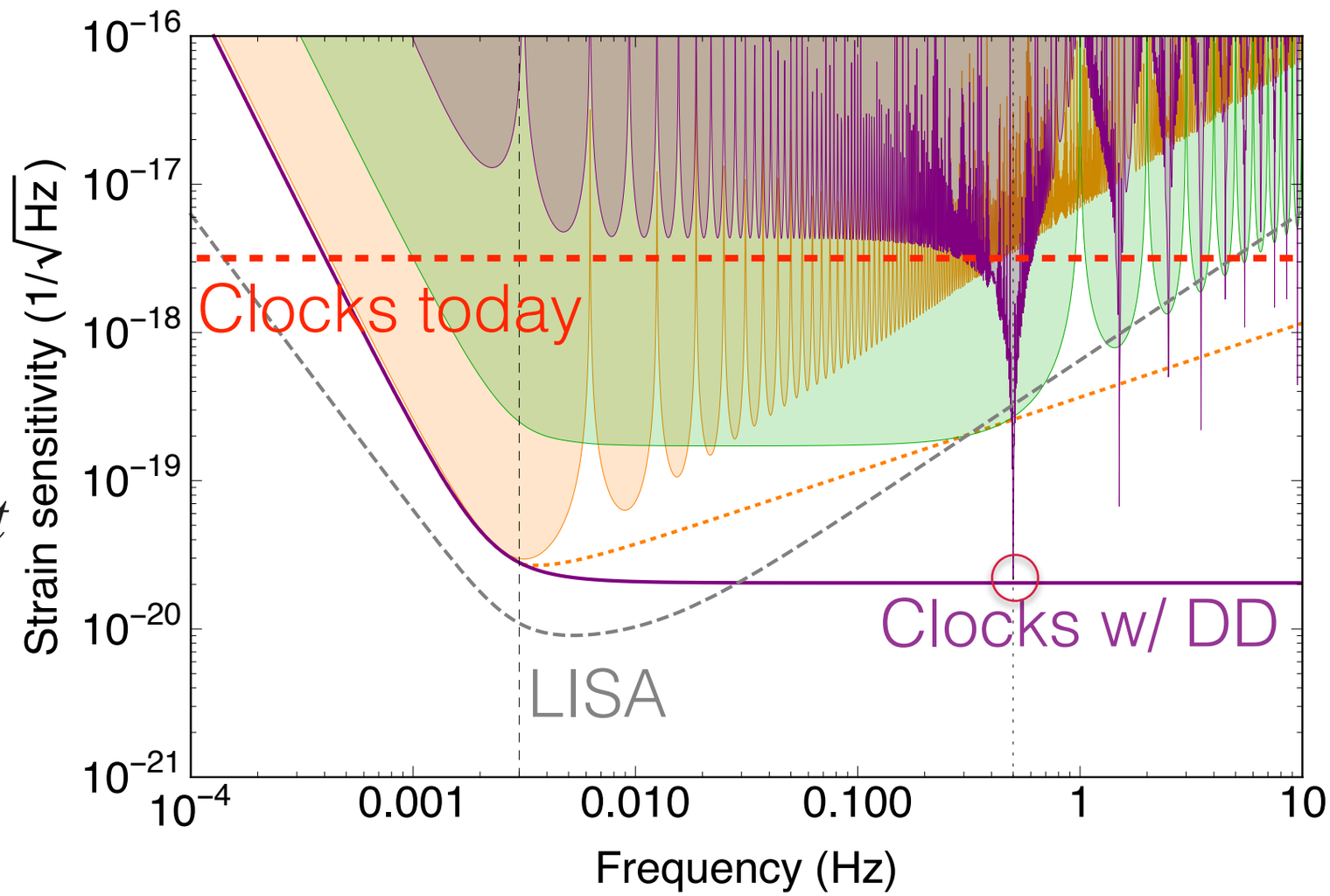

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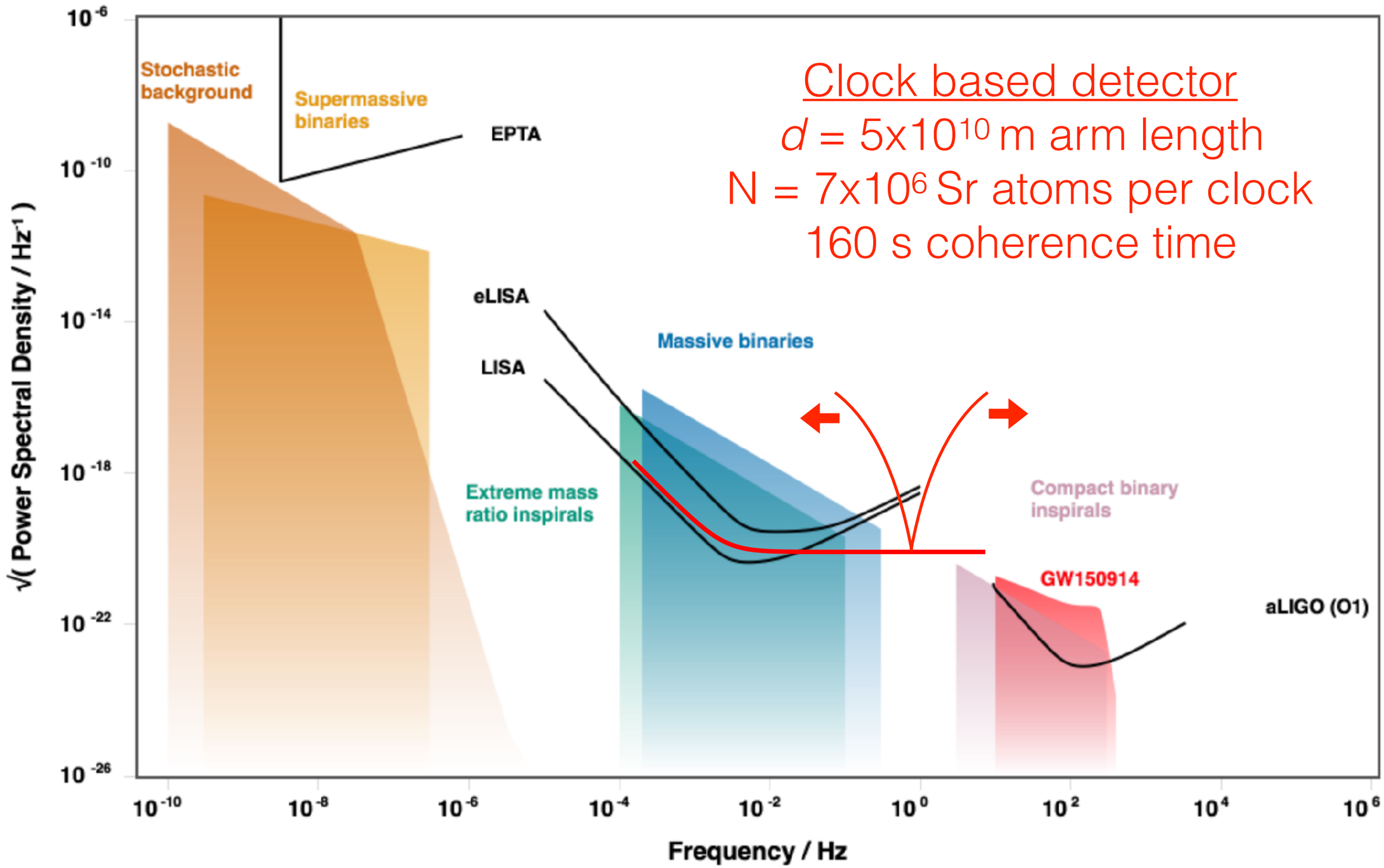

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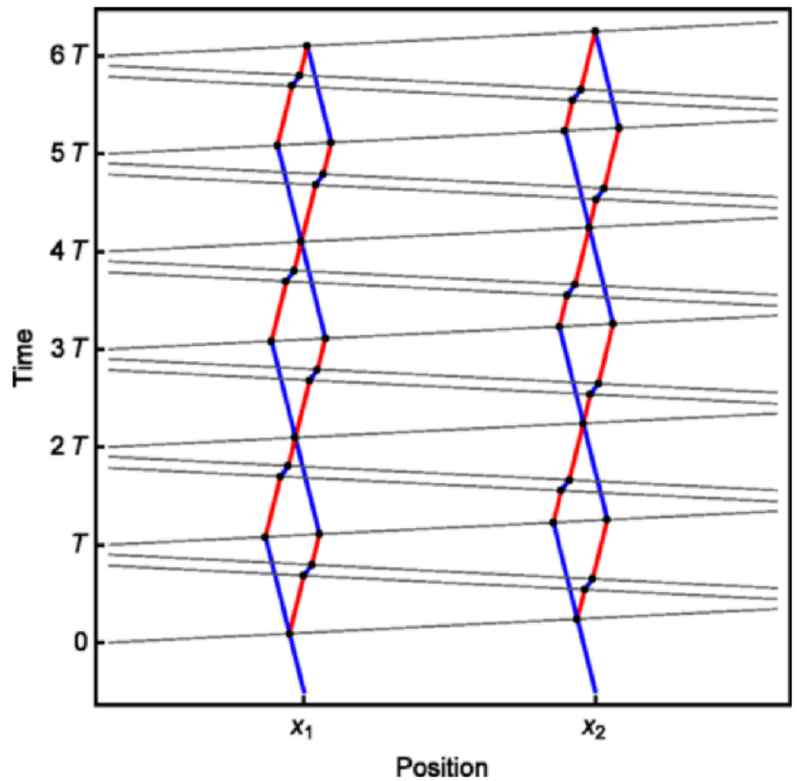
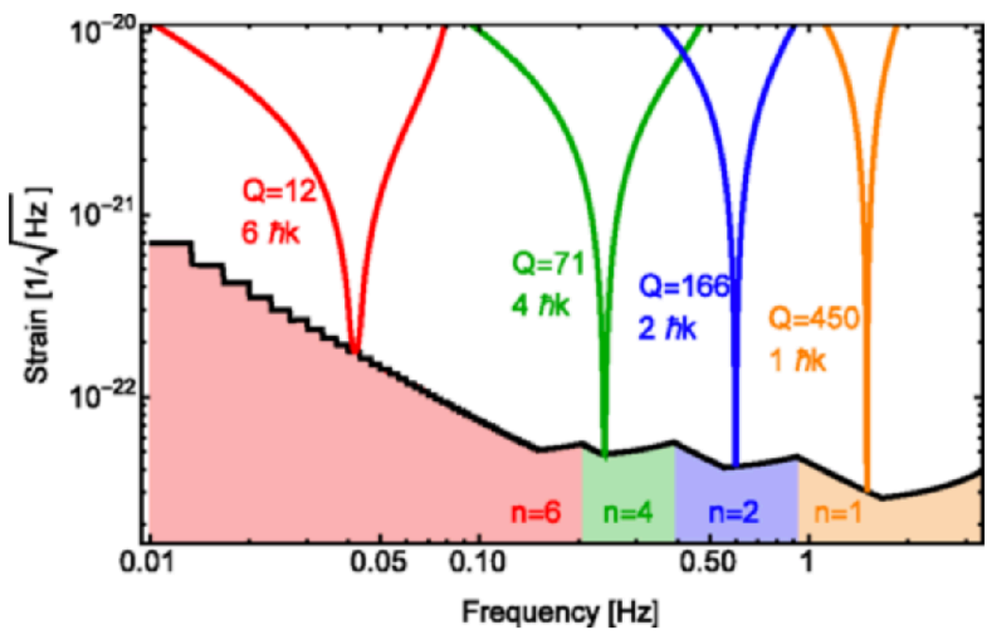
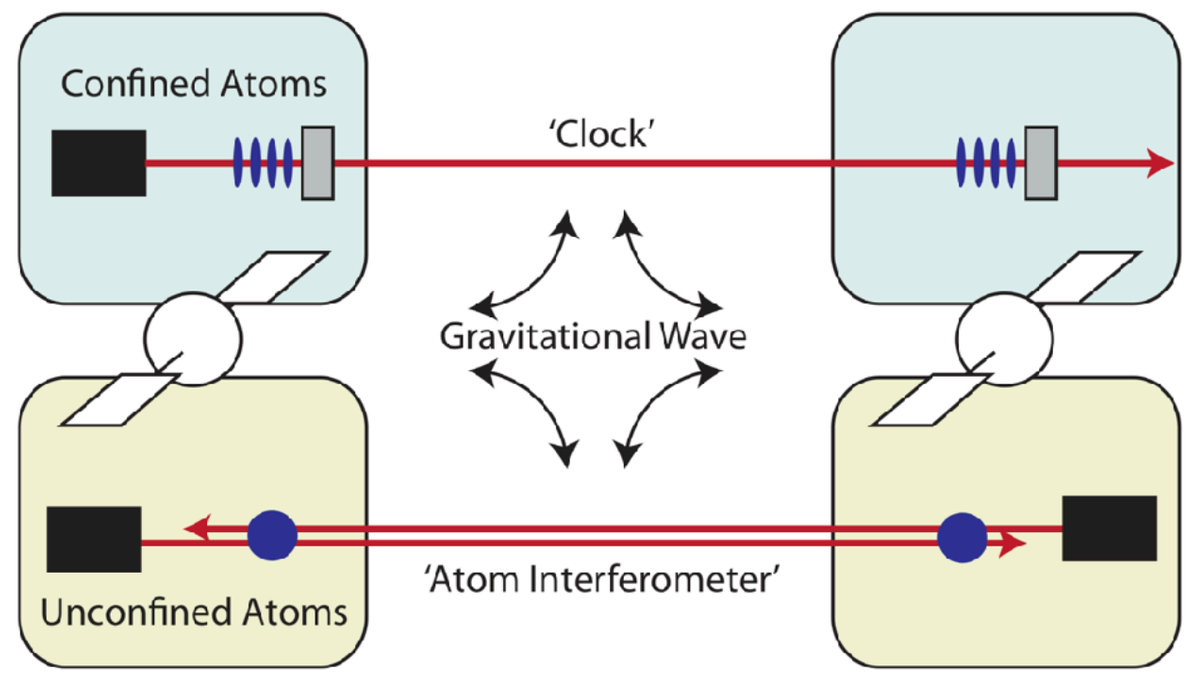
Atom interferometer-based GW detectors

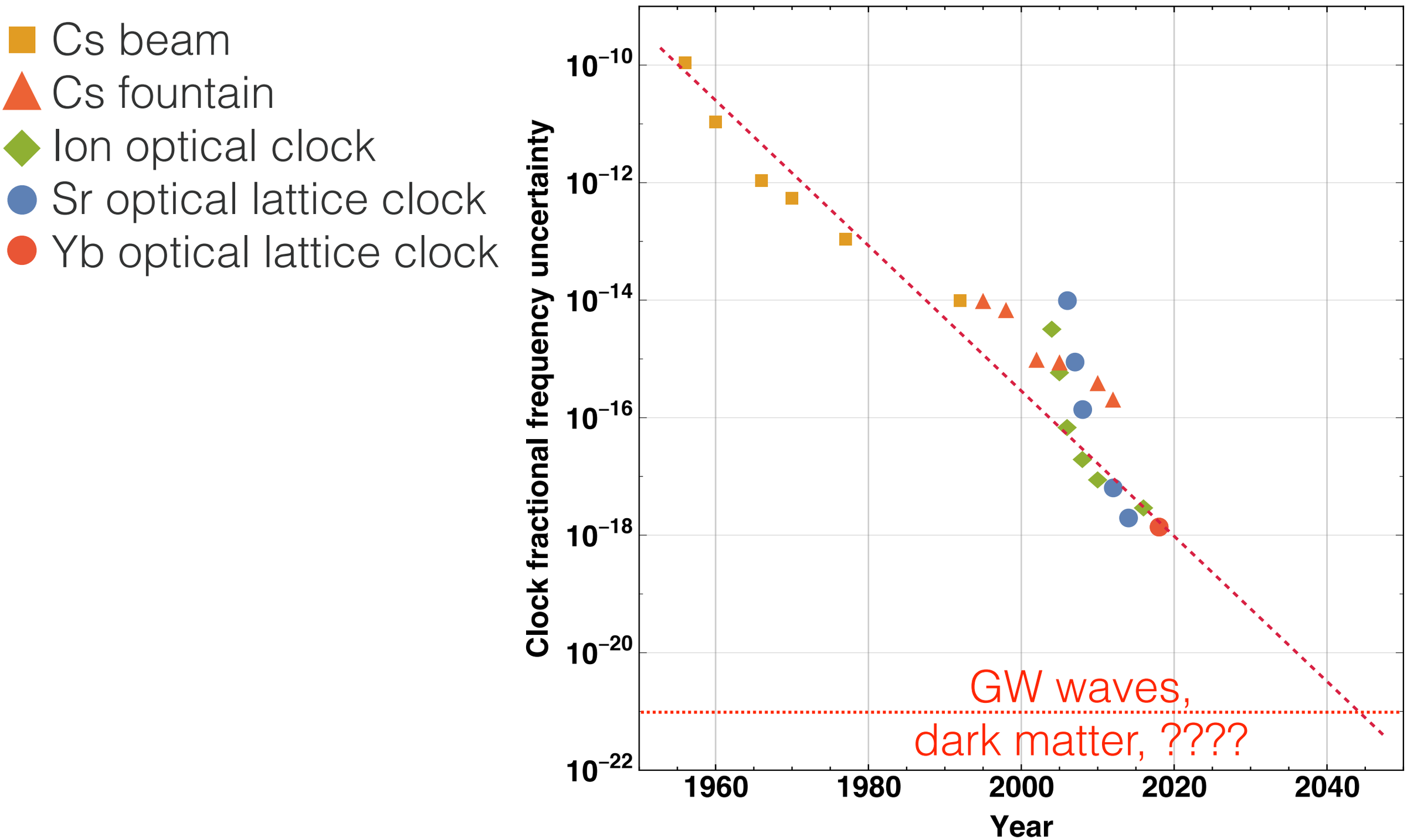






[1]Graham *et al., PRD* (2016), [2]Norcia *et al., PRA* (2017)

Novel applications of optical lattice clocks



Optical atomic clocks

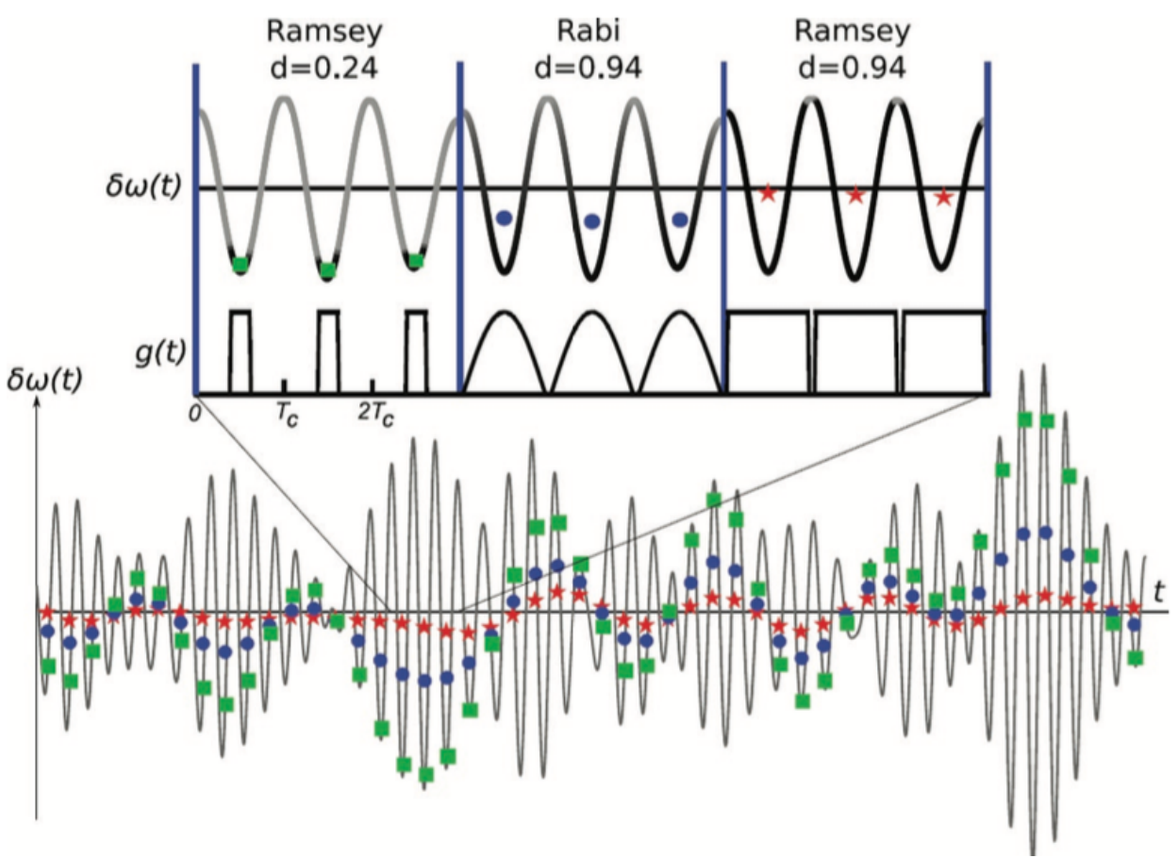
Fractional frequency instability from projection noise:

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

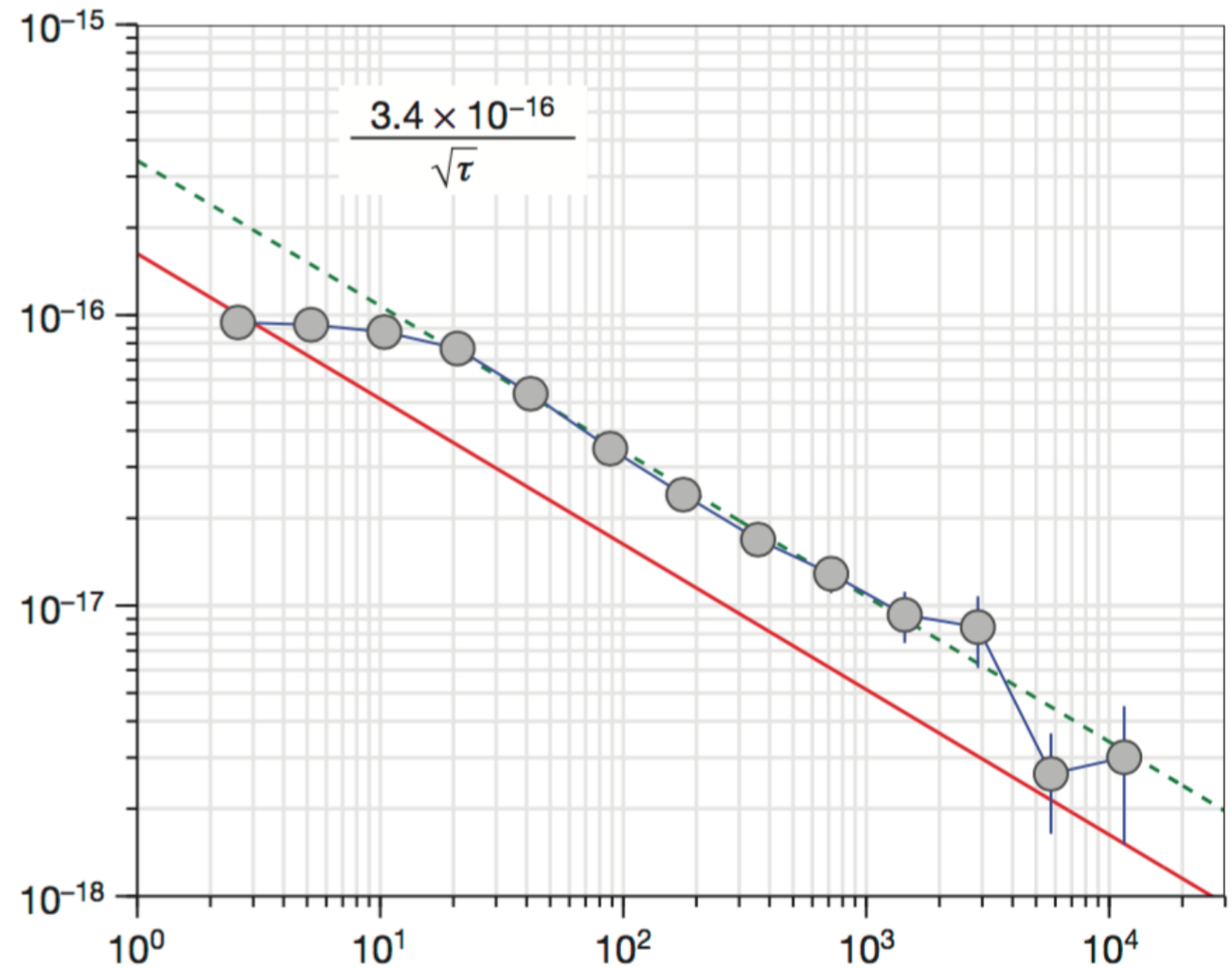
<u>Best atomic clock will have:</u>

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

The Dick Effect

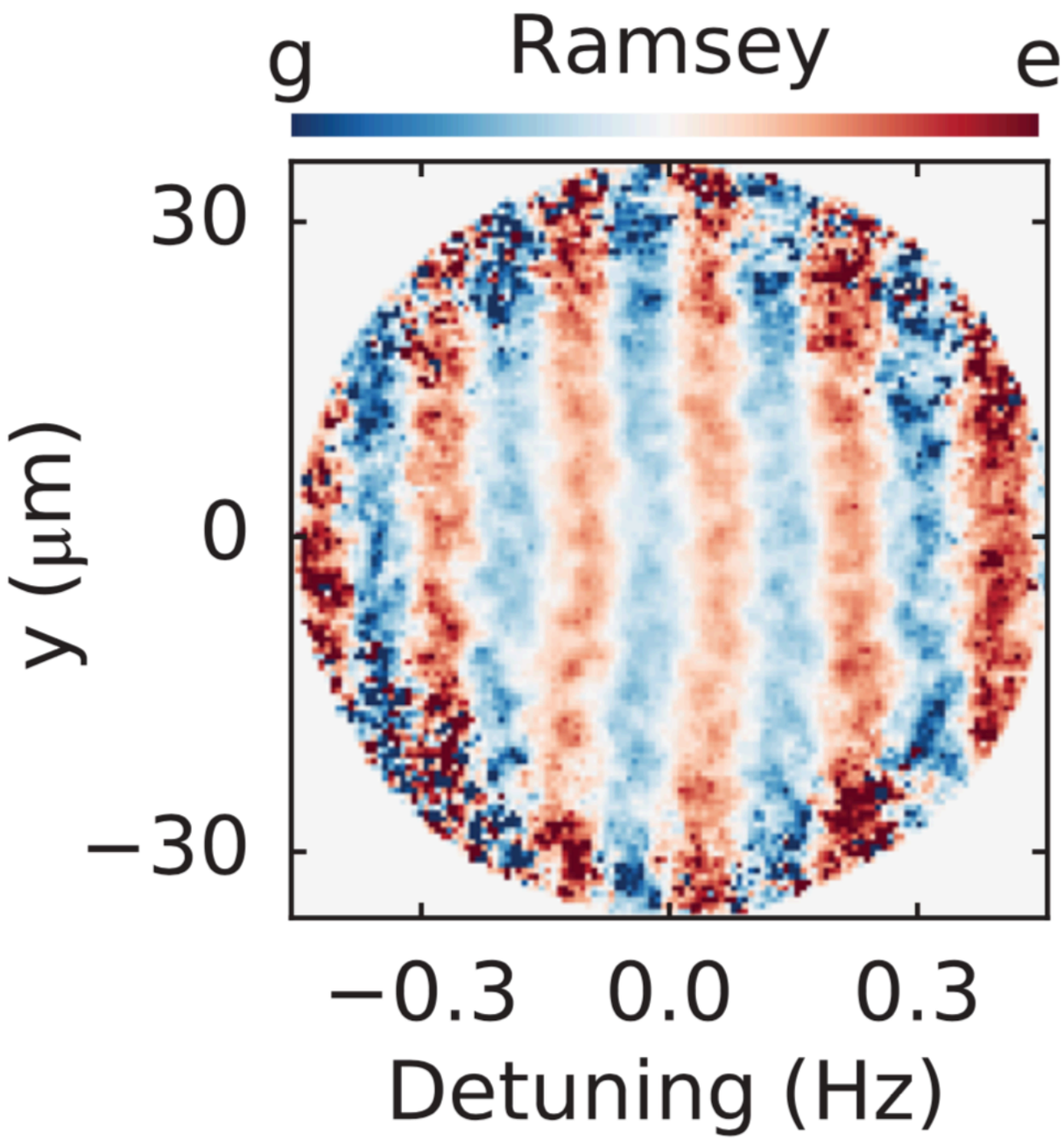


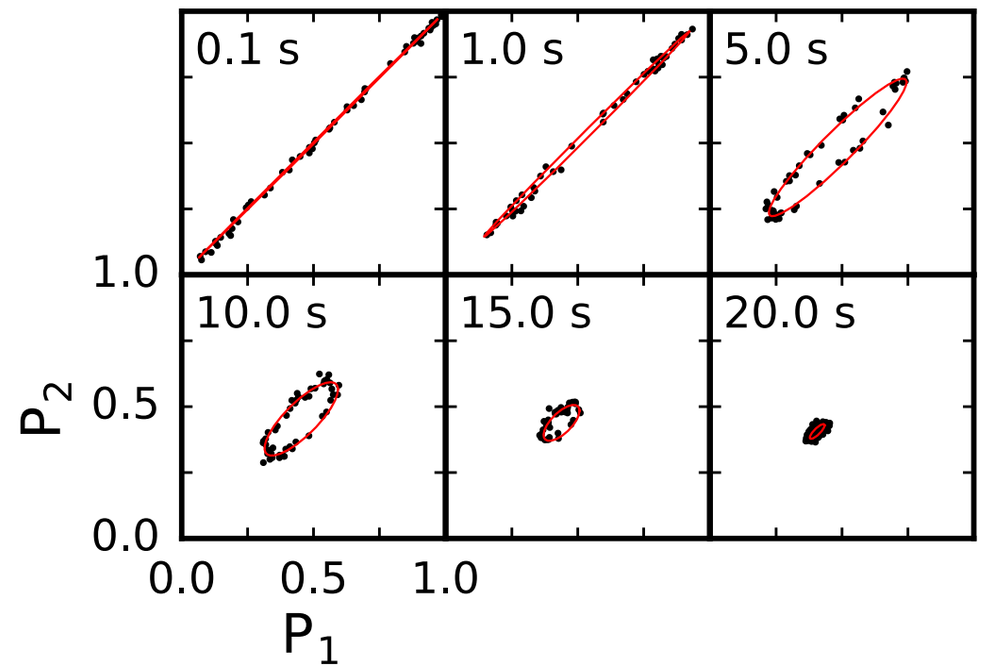
~2000 atoms,
160 ms interrogation:

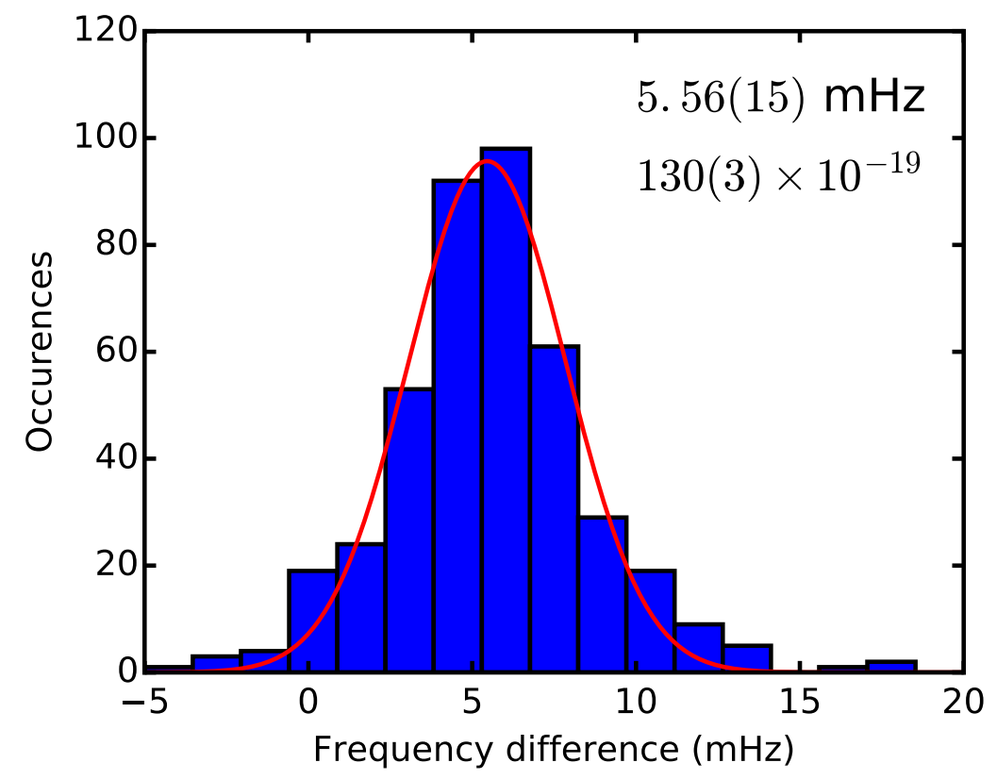


Westergaard *et al., IEEE Transactions on Frequency control* (2010), Bloom *et al., Nature* (2014)

Differential clock comparisons



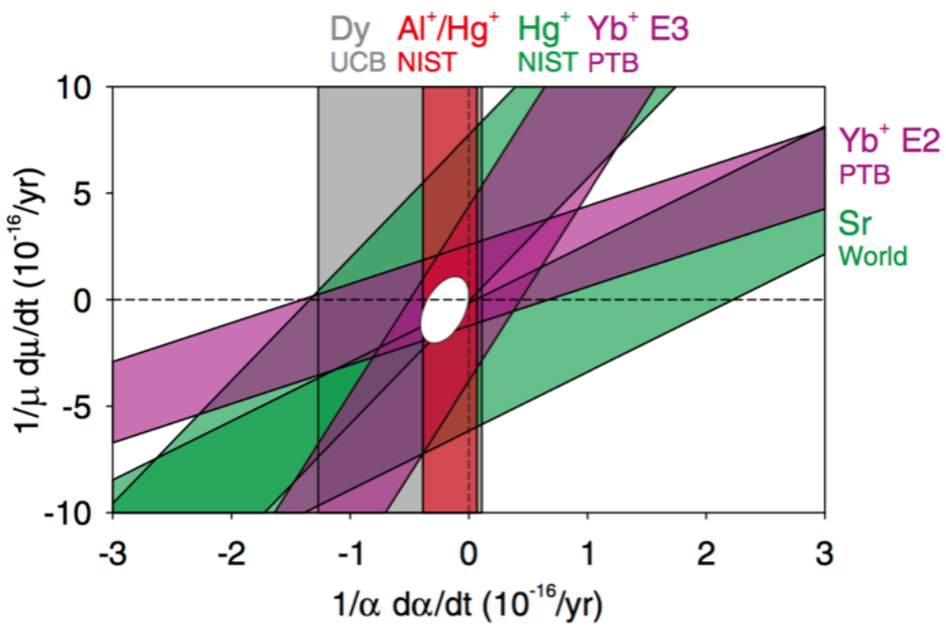




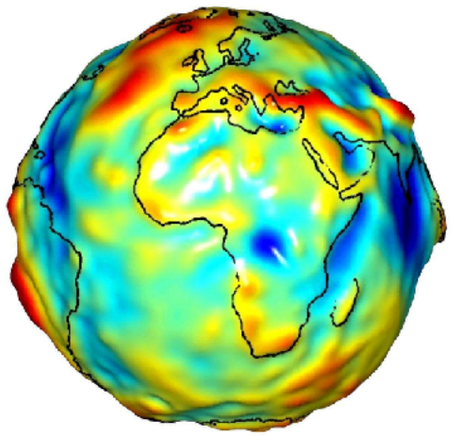
Marti *et al. PRL* (2018), see also Hume, Leibrandt *PRA* (2016)

Novel applications of optical lattice clocks

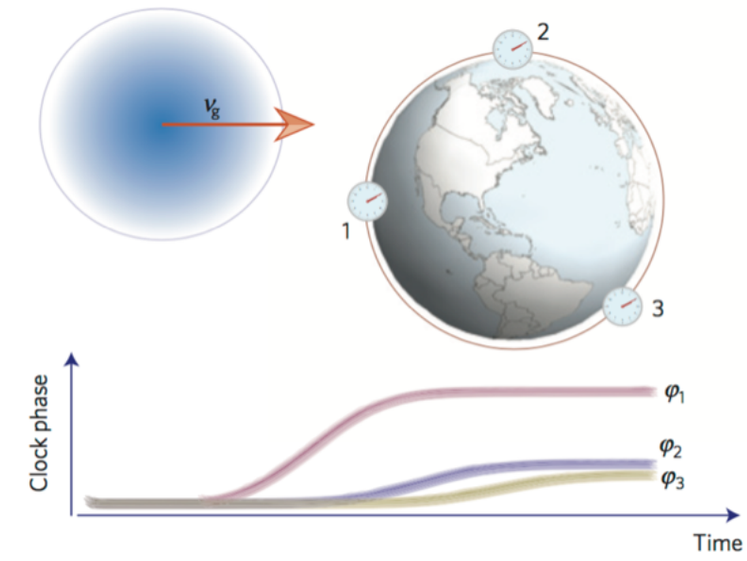
Searches for new physics



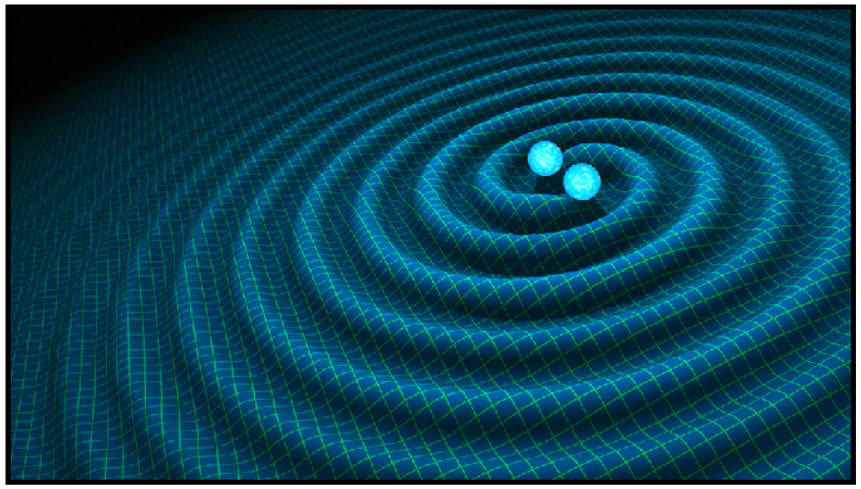
Geodesy



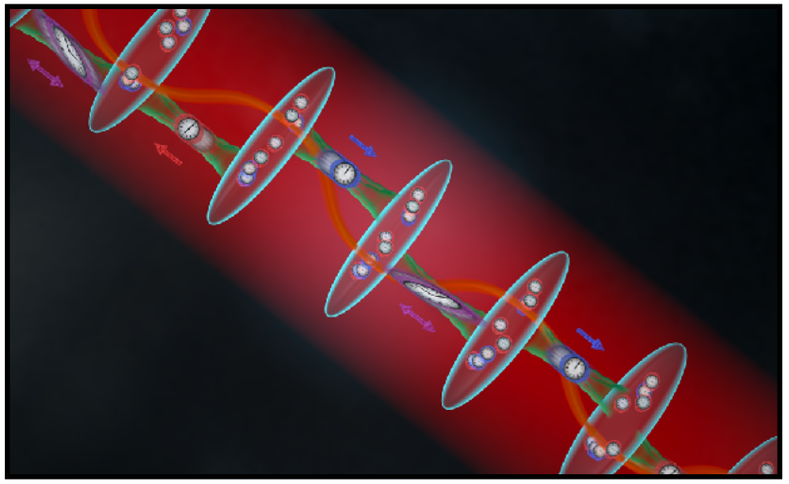
Dark matter detection



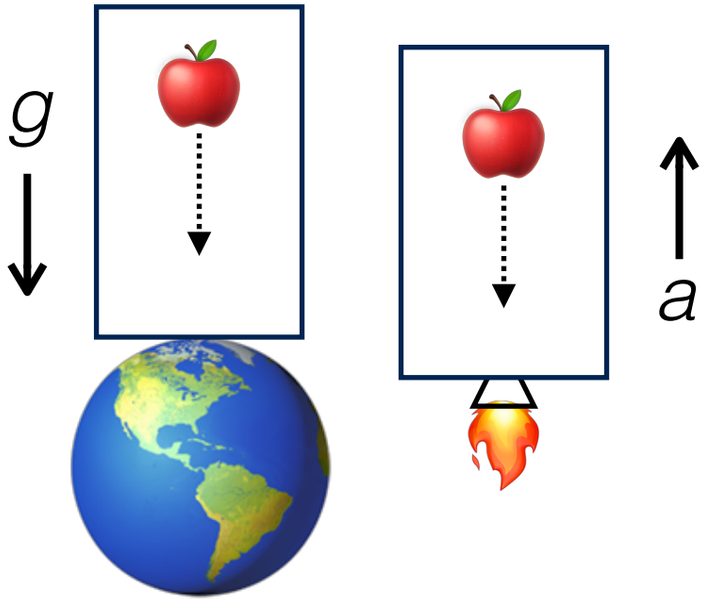
GW detection



Quantum simulation



Tests of relativity



Huntemann *et al. PRL* (2014); Takano *et al. Nature Photonics* (2016); Dereviako, Pospelov, *Nature Physics* (2014)
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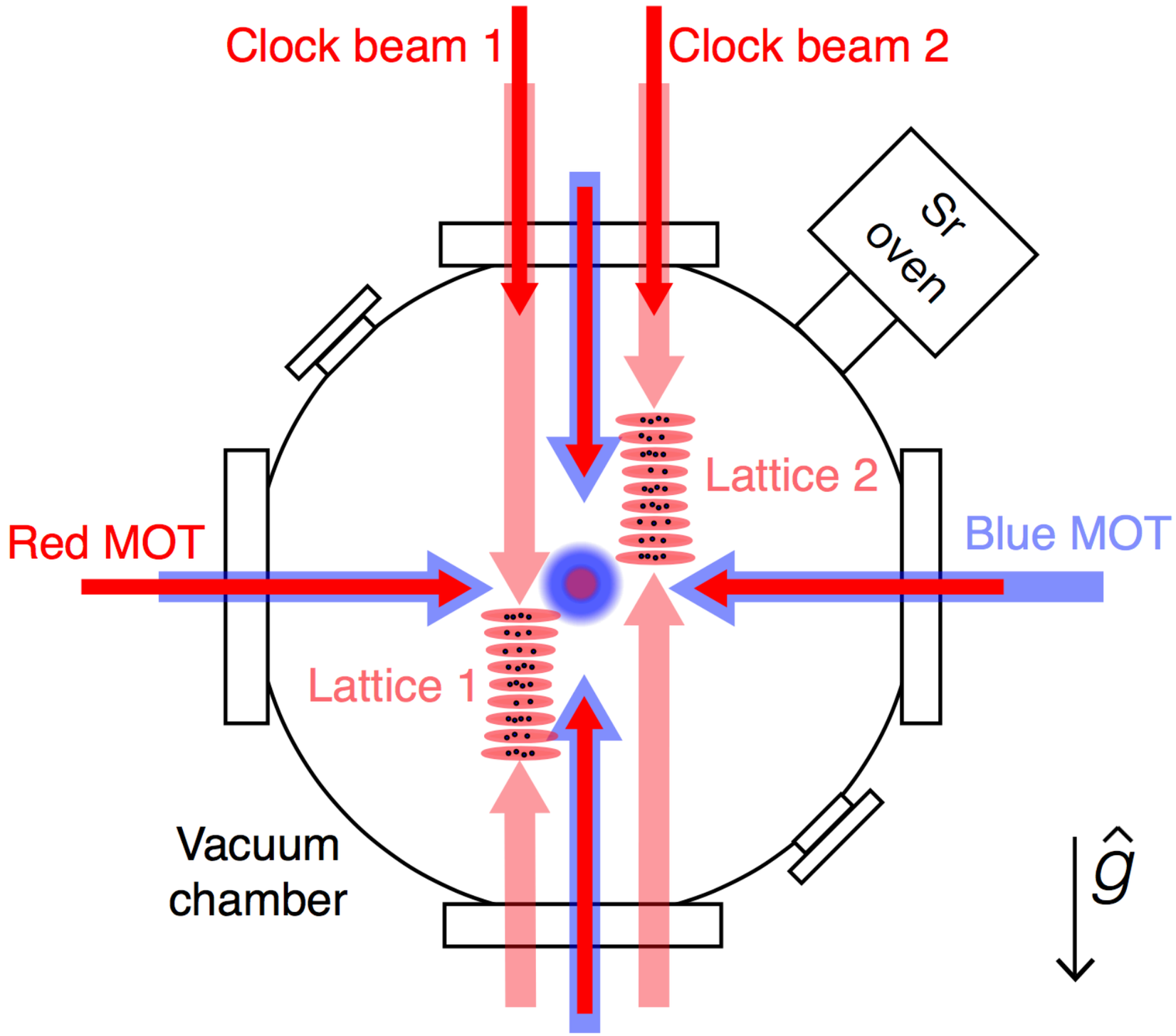
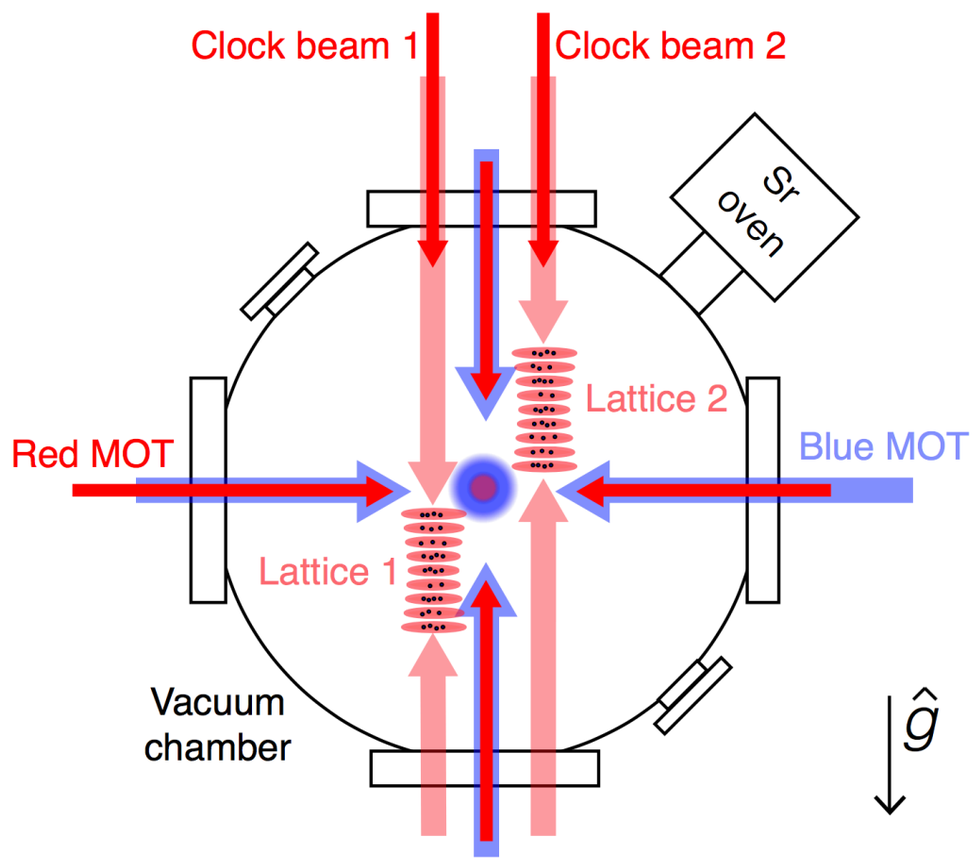
A multiplexed optical lattice clock

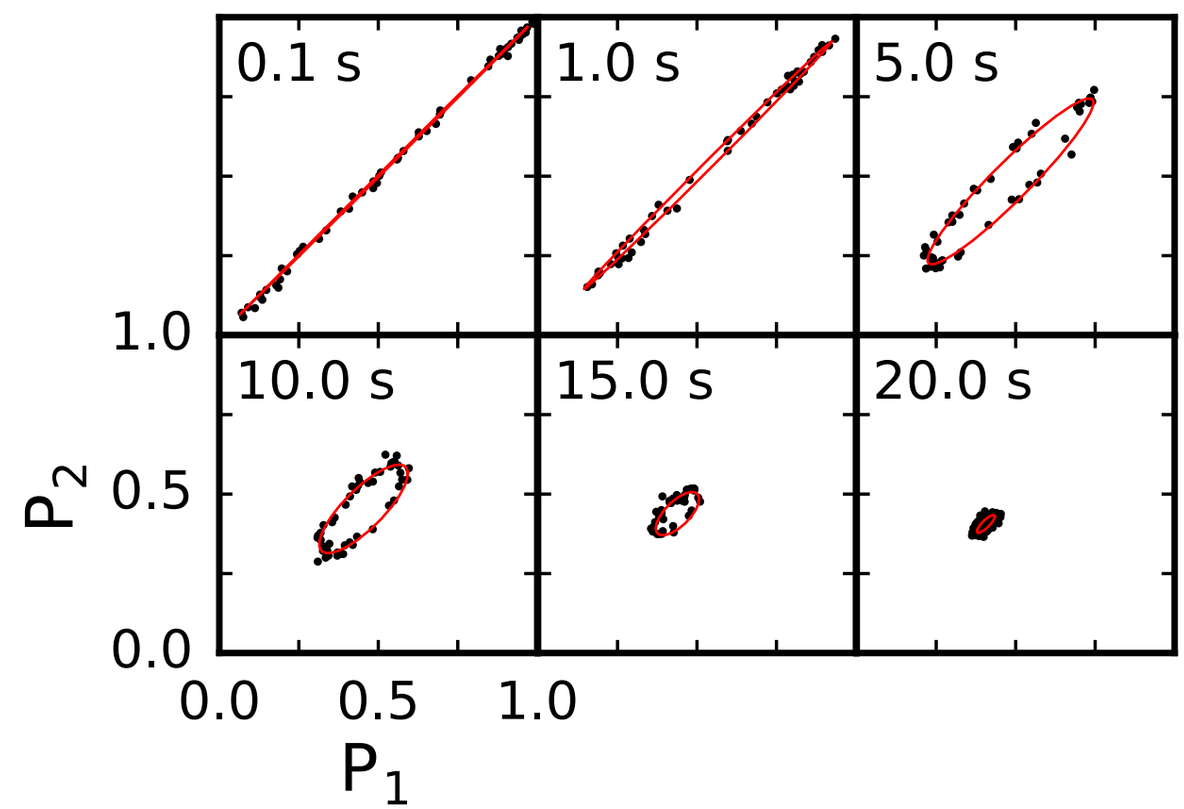


A multiplexed optical lattice clock

Challenges to achieving lifetime limited coherent interrogation:

- Clock laser coherence





Marti *et al. PRL* (2018)

A multiplexed optical lattice clock

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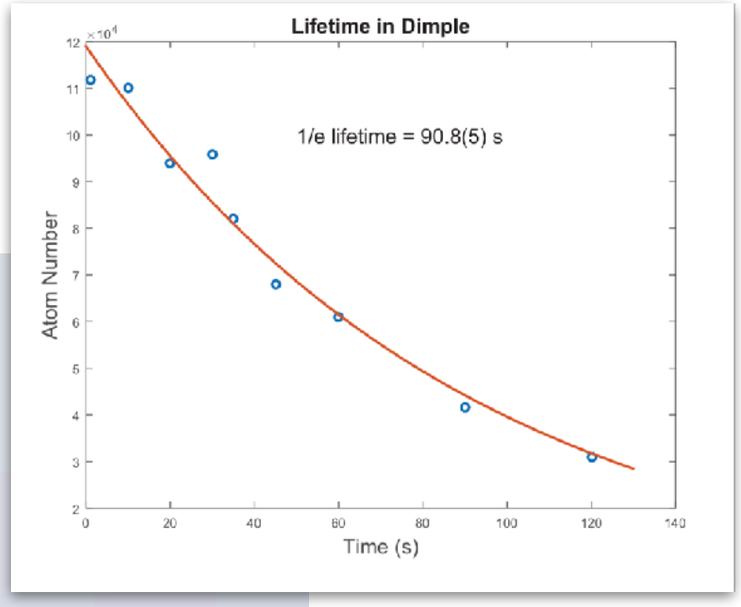

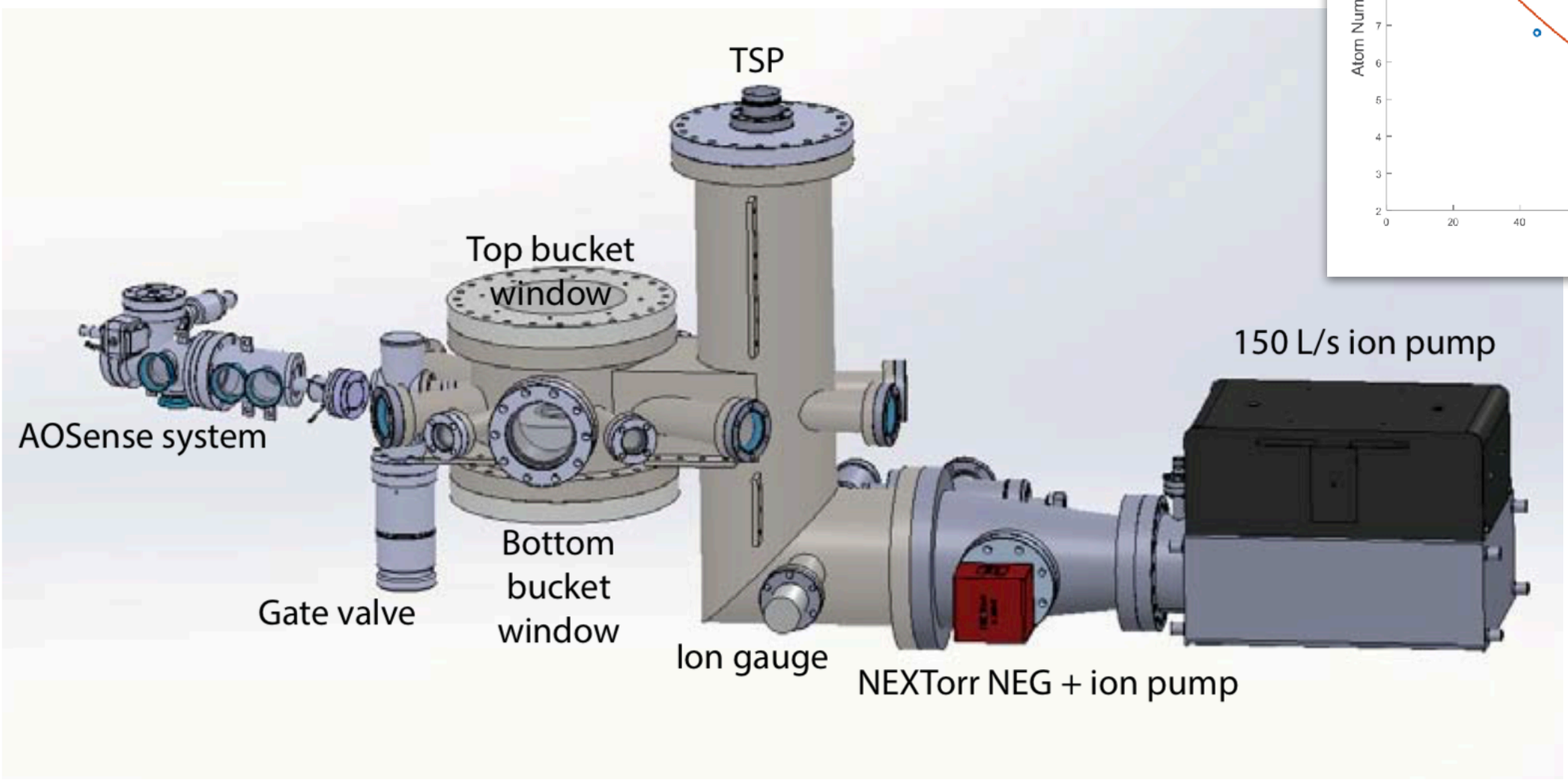

S. Campbell, *PhD Thesis, JILA* (2017)

A multiplexed optical lattice clock

<u>Challenges to achieving lifetime limited coherent interrogation:</u>

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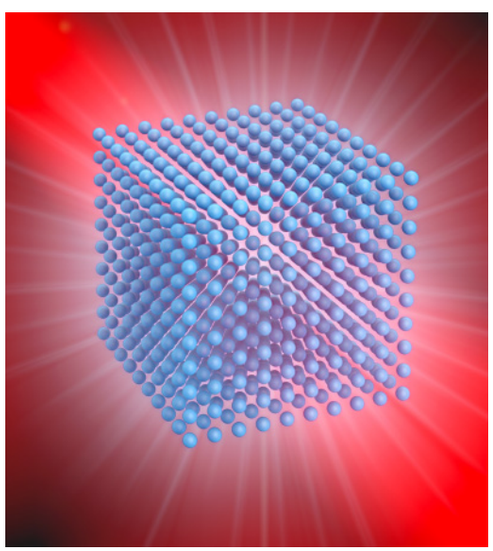
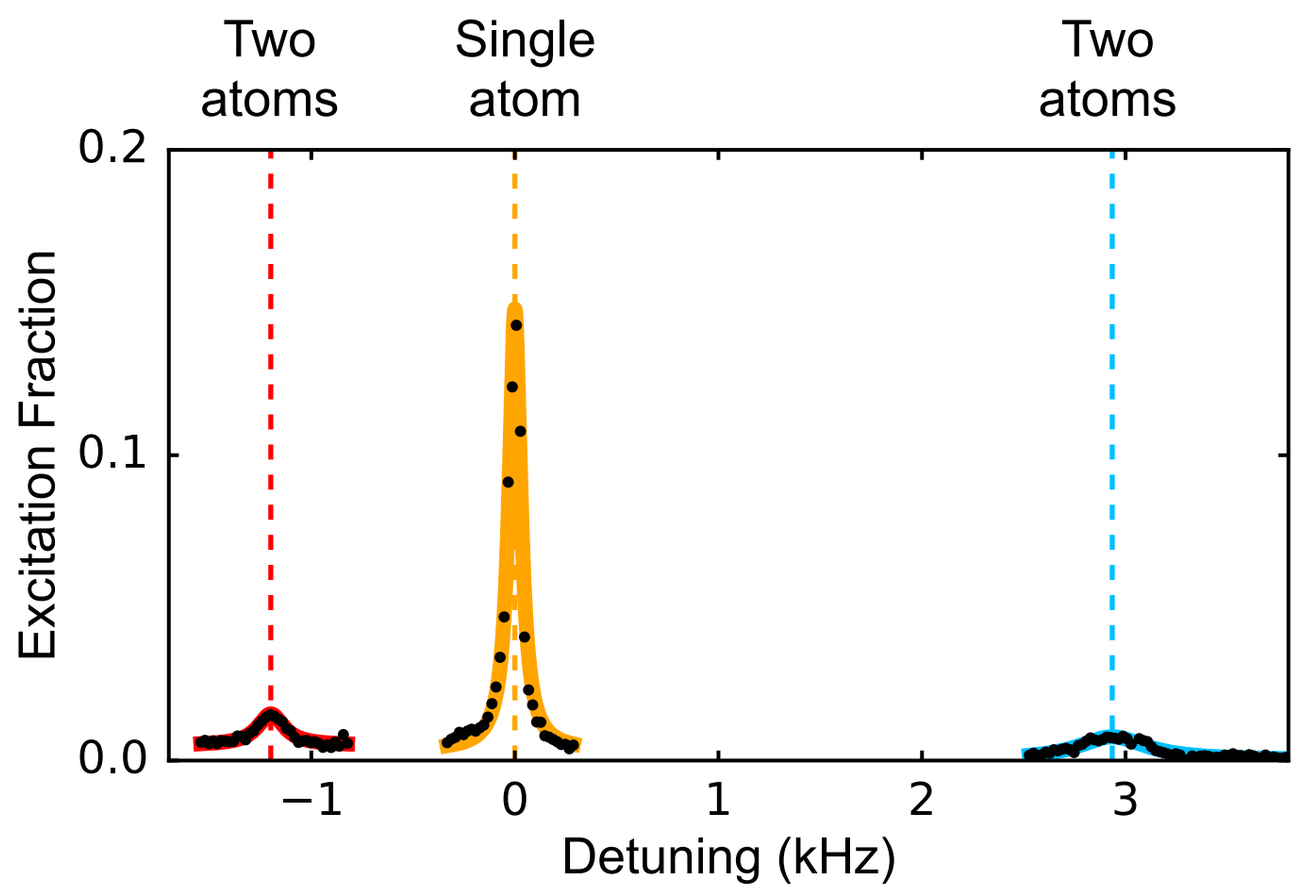
- Broadening due to Sr-Sr collisions





Campbell *et al., Science* (2017)

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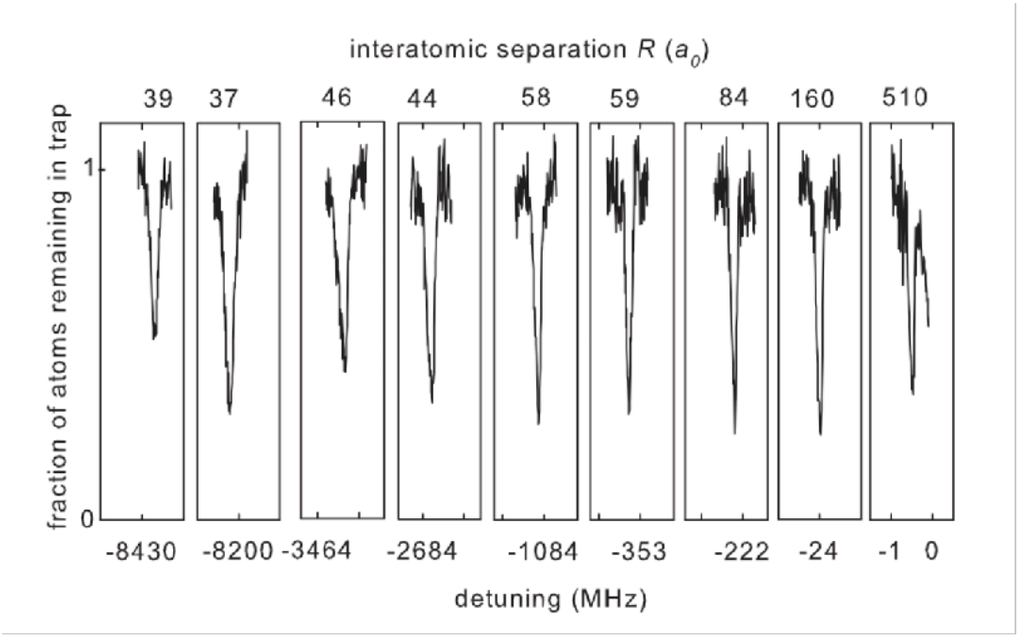

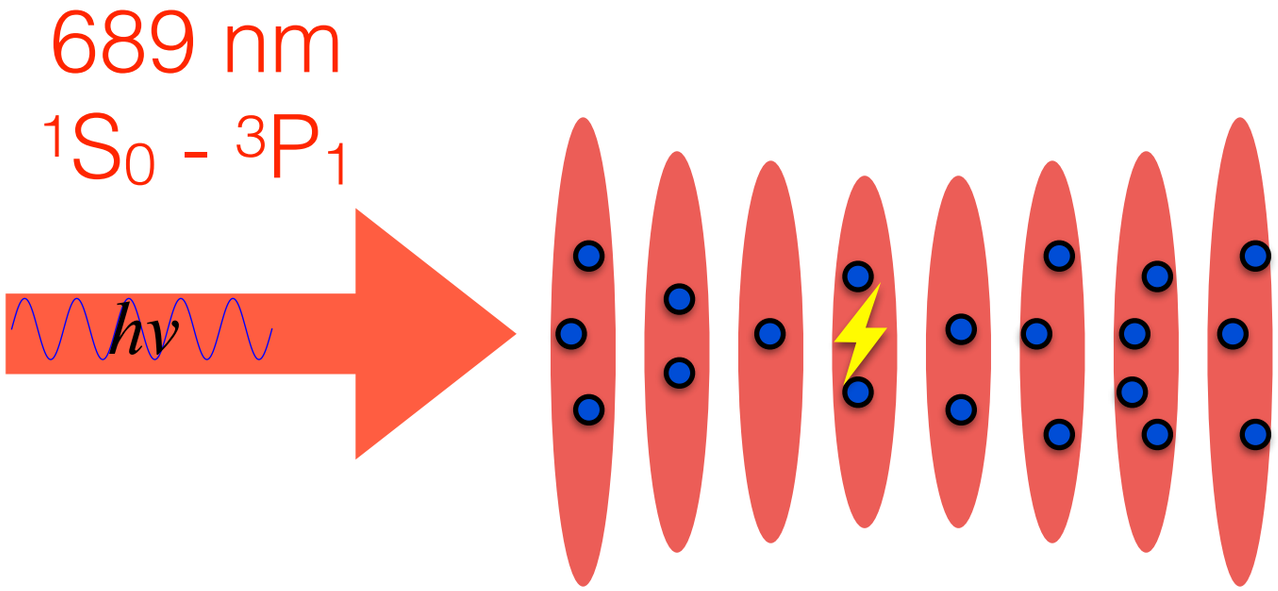

Zelevinsky *et al.*, *PRL* (2006)

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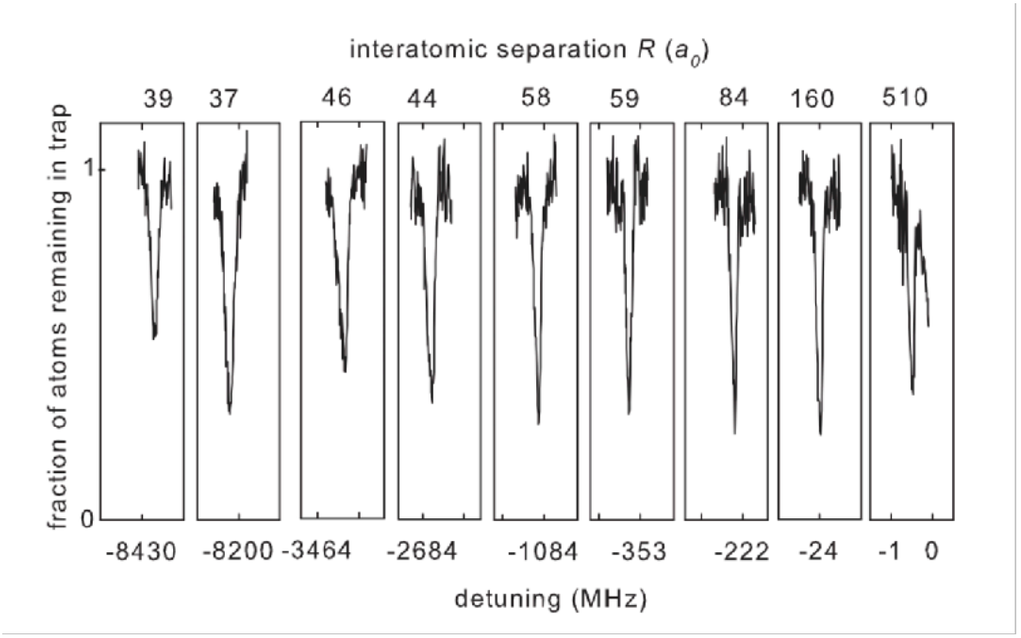

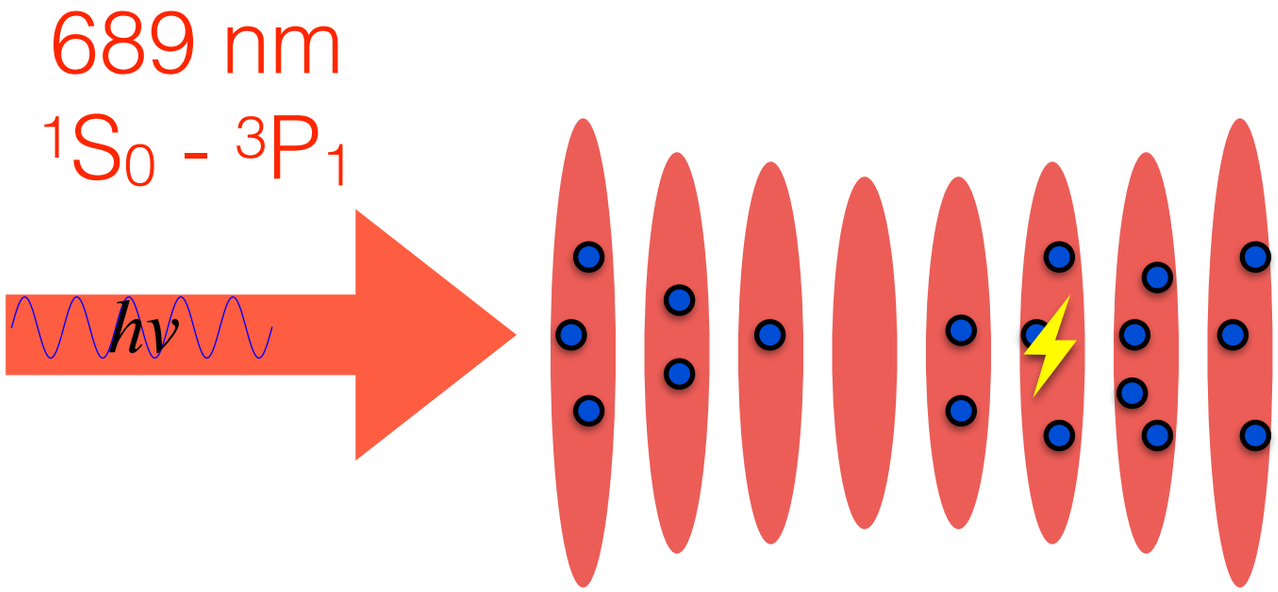

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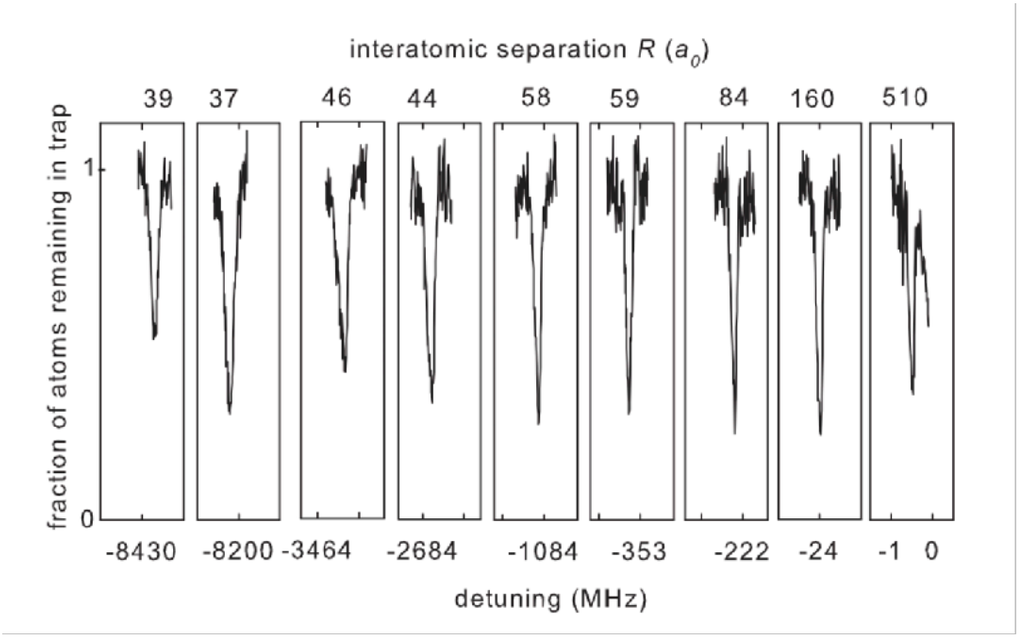

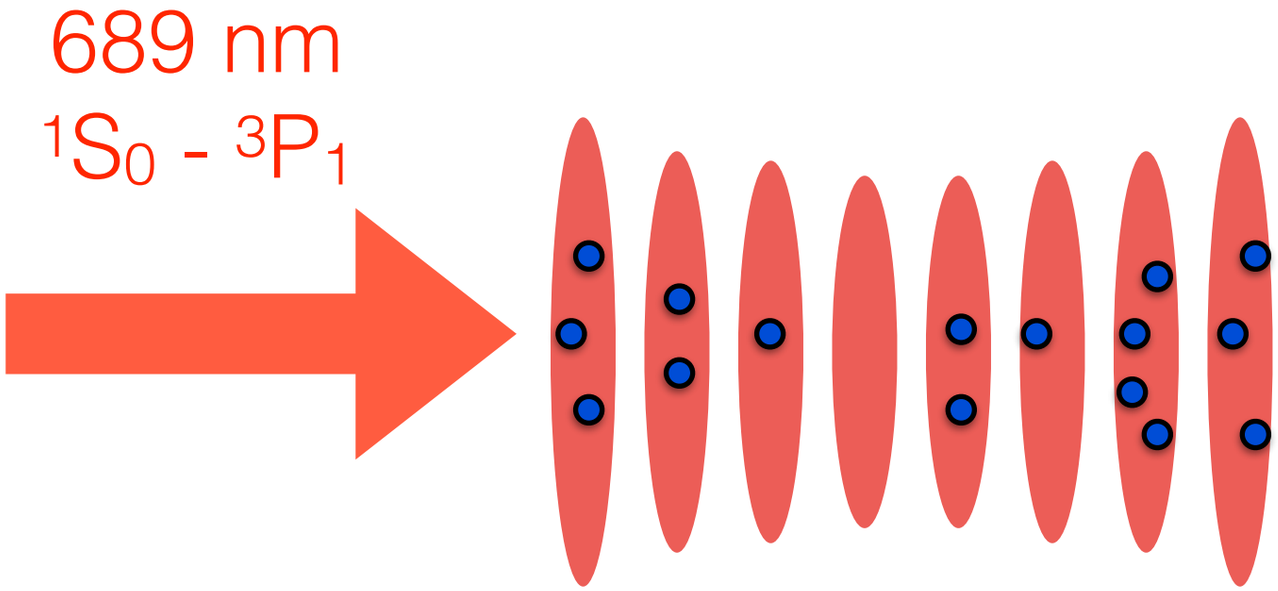

Zelevinsky *et al.*, *PRL* (2006)

A multiplexed optical lattice clock

Challenges to achieving lifetime limited coherent interrogation:

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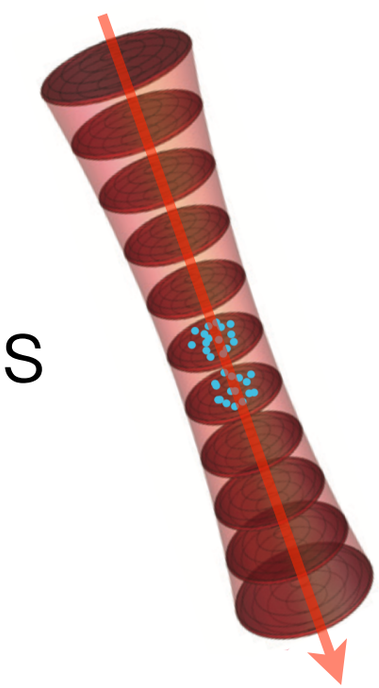
- Background gas collisions
- Broadening due to Sr-Sr collisions
- Raman scattering from lattice light

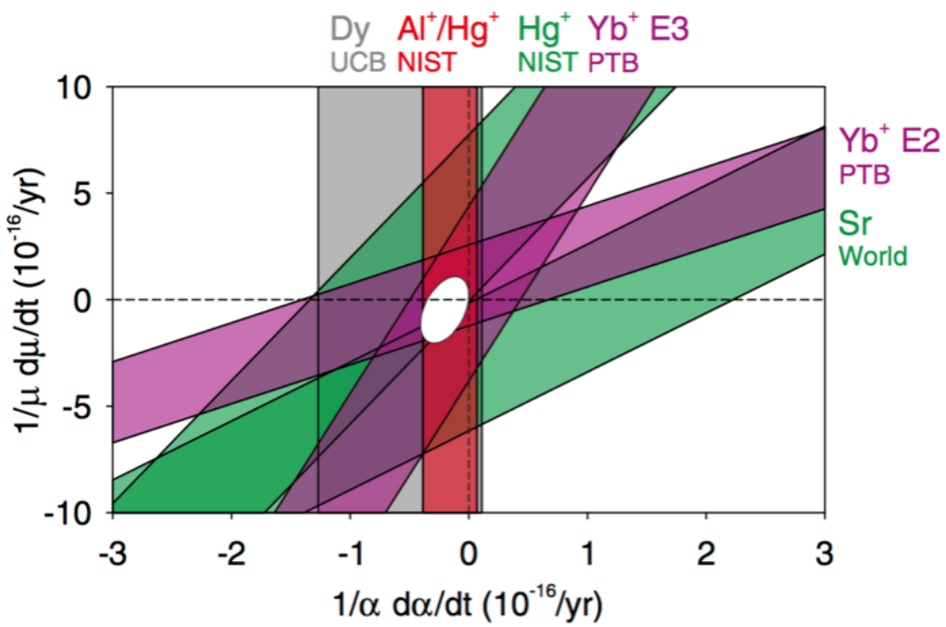
Weak vertical lattice
~100 s interrogation times



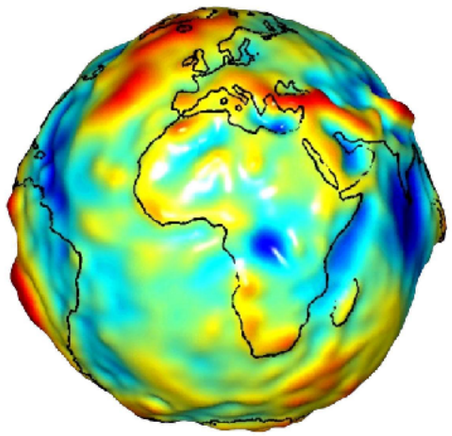
Dörscher *et al., PRA* (2018), Hutson *et al., in preparation*

Novel applications of optical lattice clocks

Searches for new physics



Geodesy



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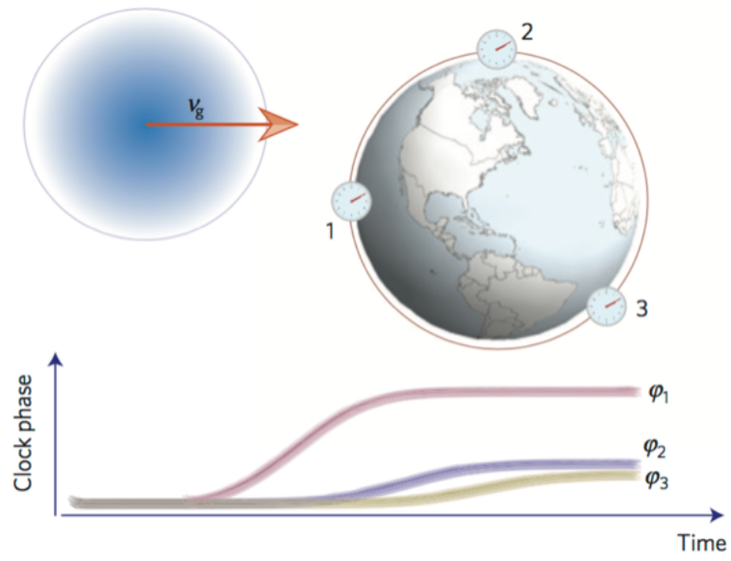
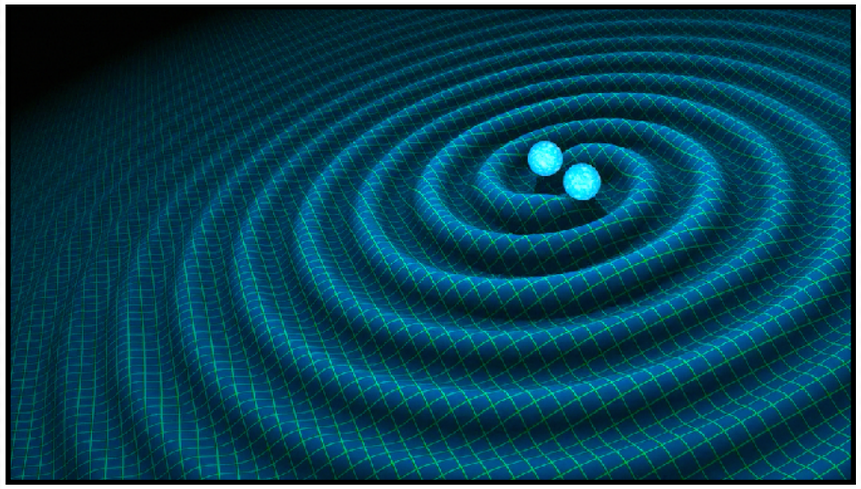
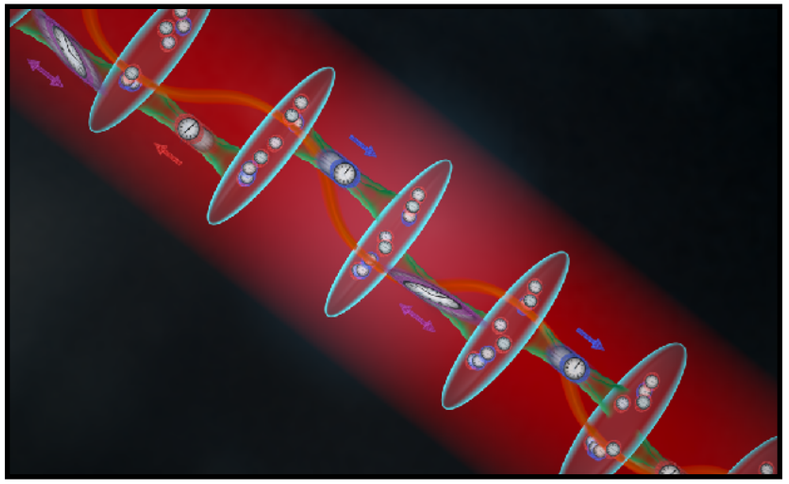


GW detection



Quantum simulation



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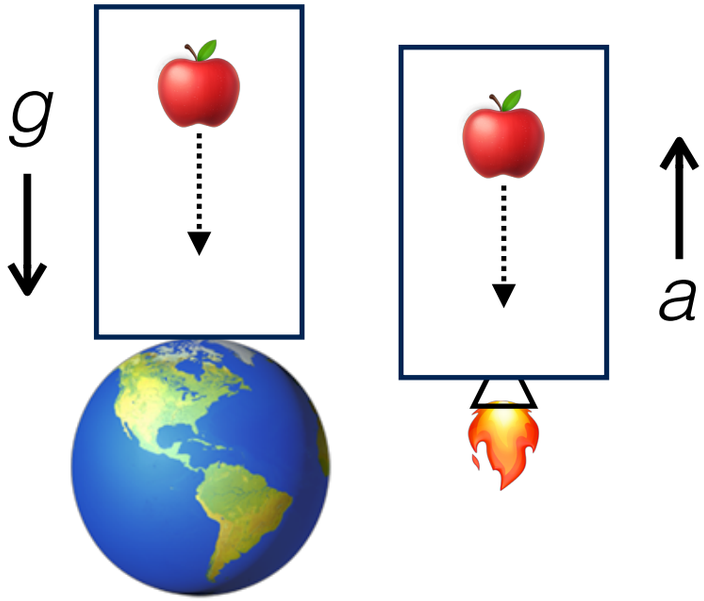

Huntemann *et al. PRL* (2014); Takano *et al. Nature Photonics* (2016); Dereviako, Pospelov, *Nature Physics* (2014)
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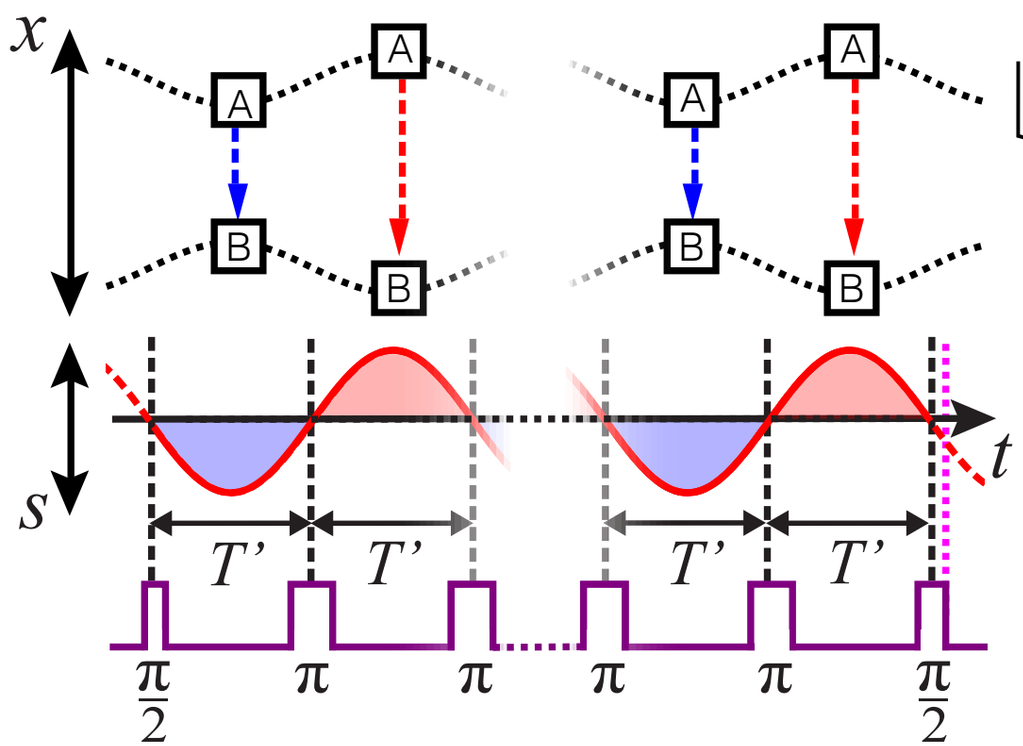

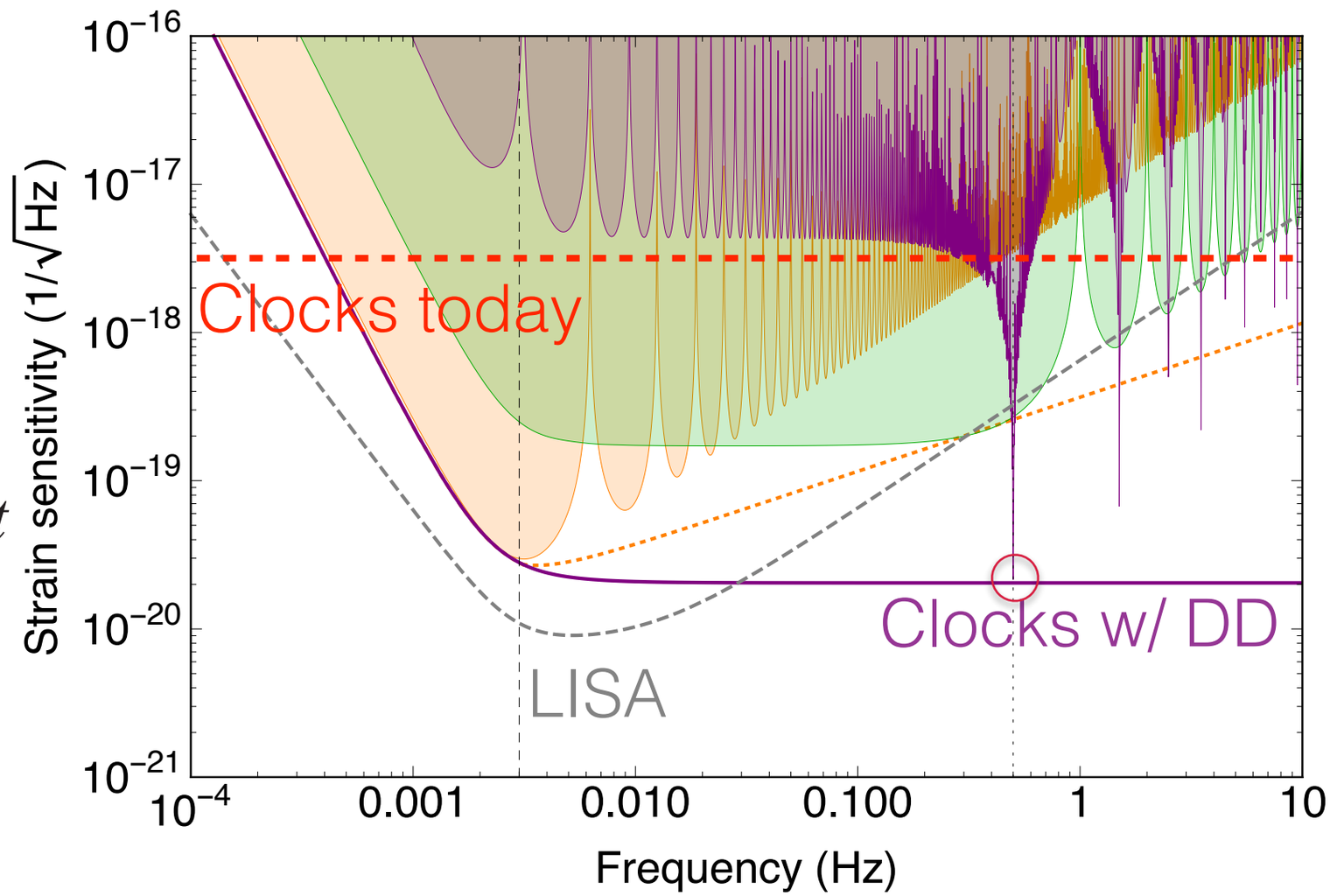

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Novel applications of optical lattice clocks

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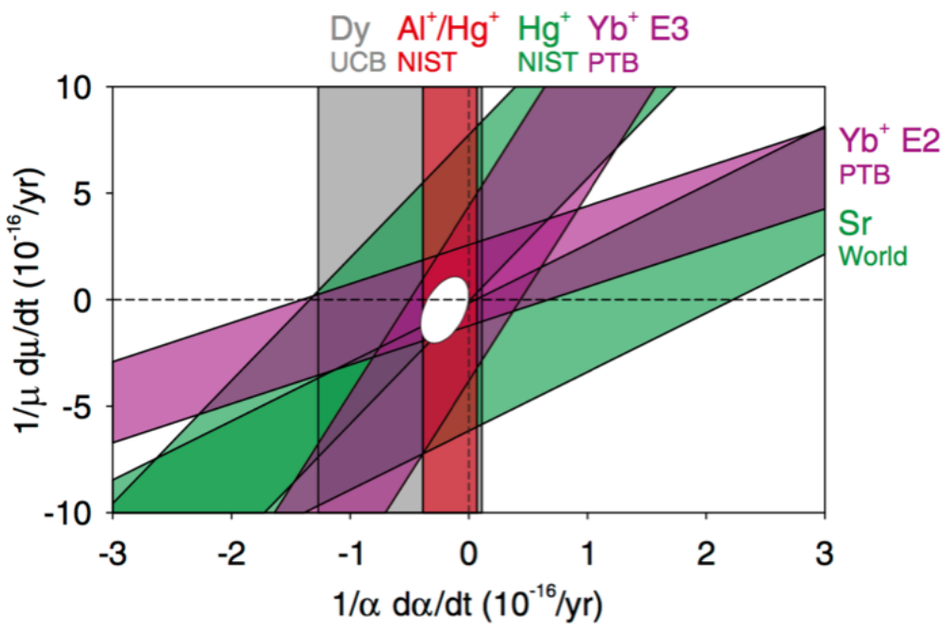
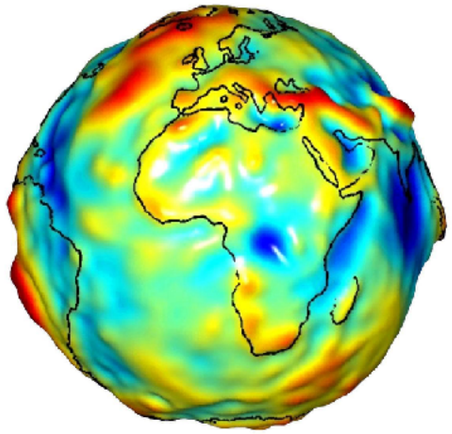
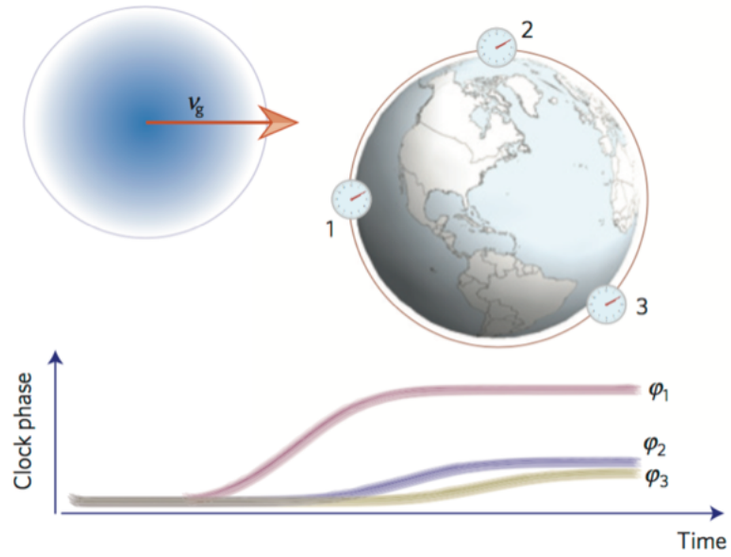


Geodesy



Dark matter detection



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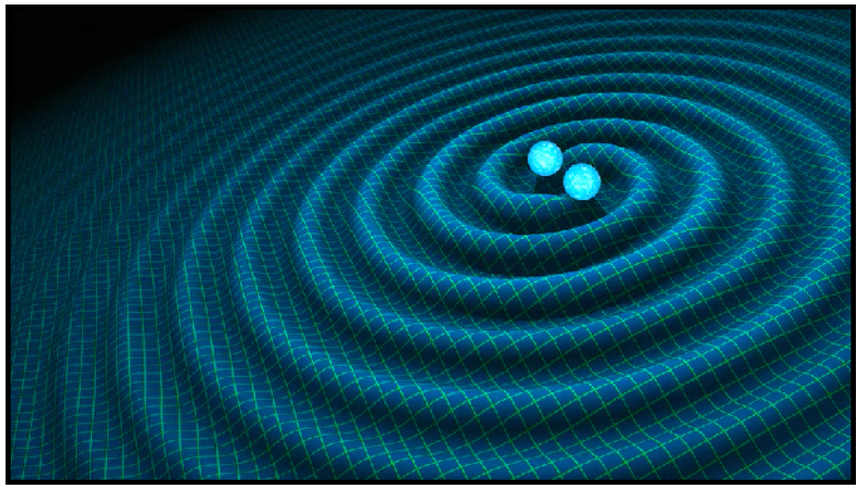

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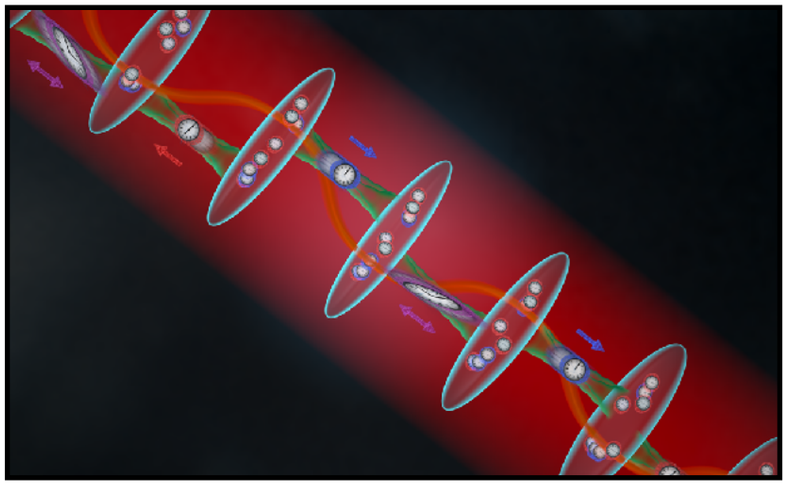

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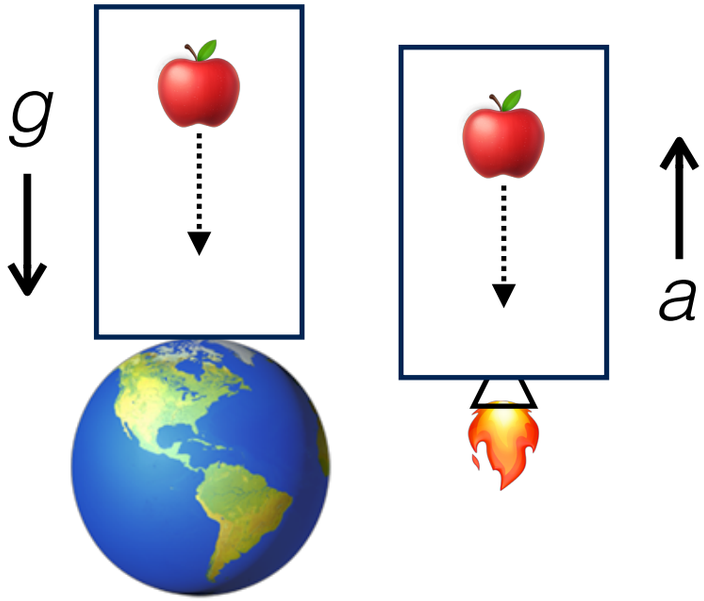

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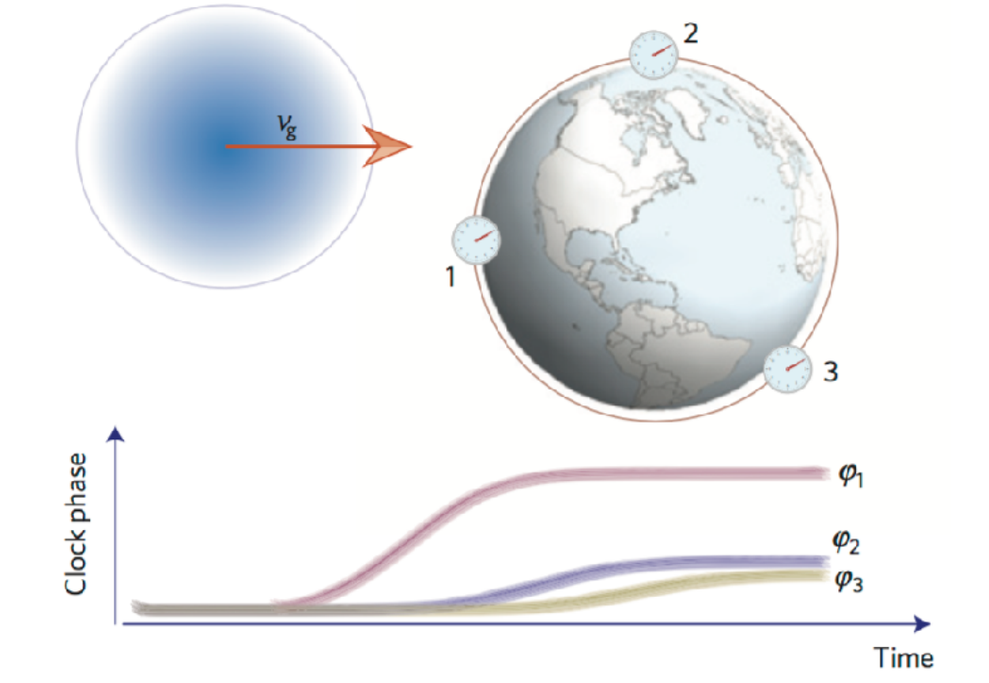
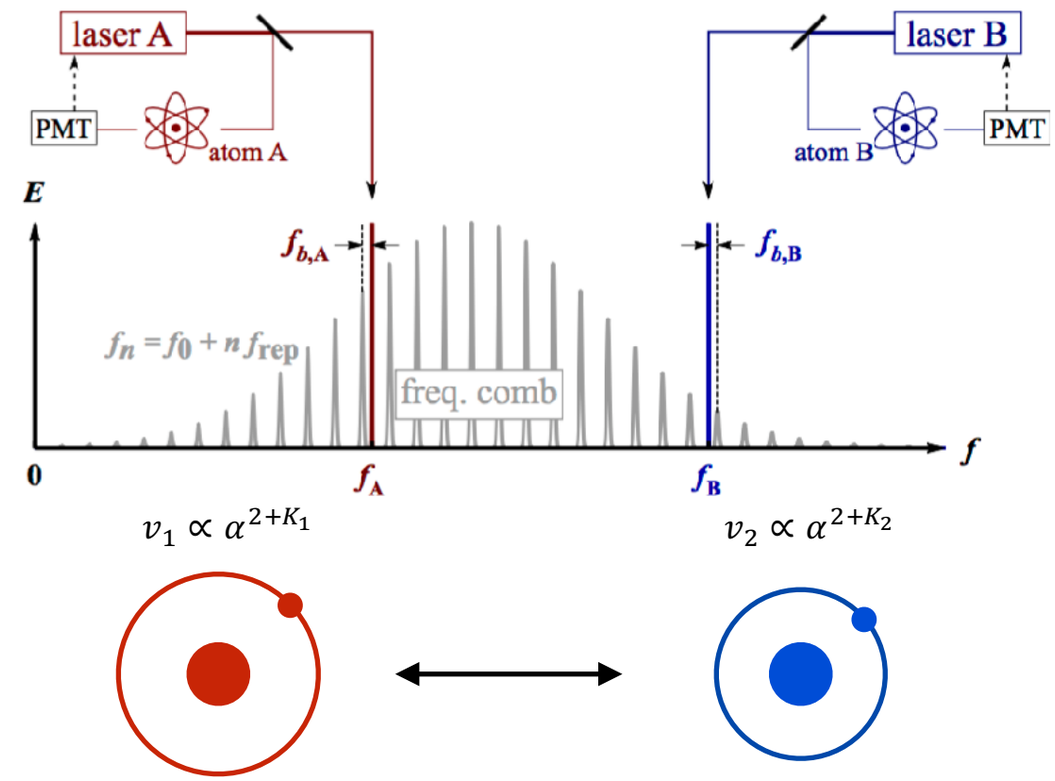
SK *et al. PRD* (2016); SK *et al., Nature* (2017); Arms, Serna, *arXiv* (2016)

Dark matter searches with atomic clocks

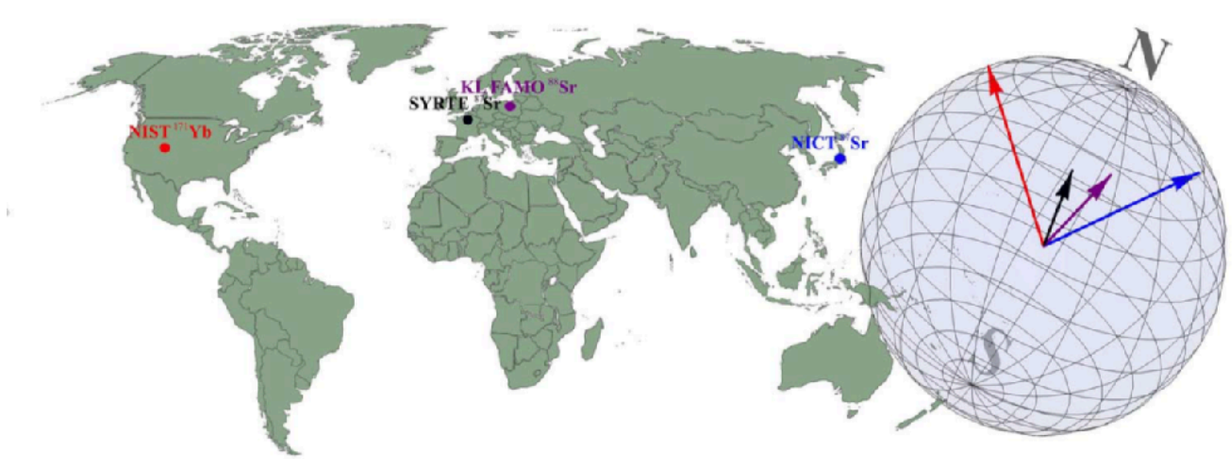
Long distance clock comparisons:



Multi-species comparisons:

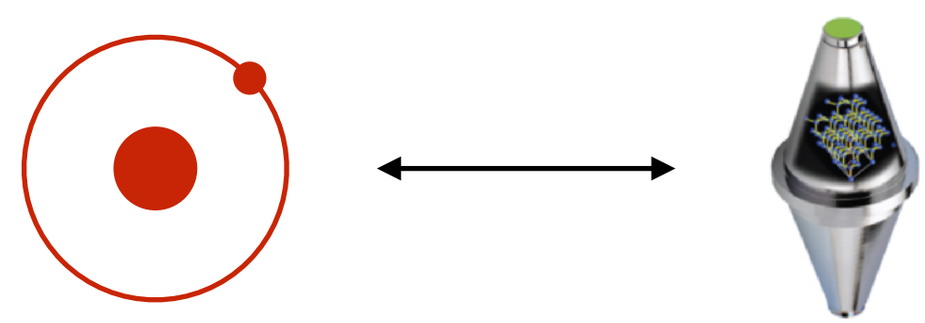


Atom-cavity comparisons:



$\nu_{Sr} \propto \alpha^2$

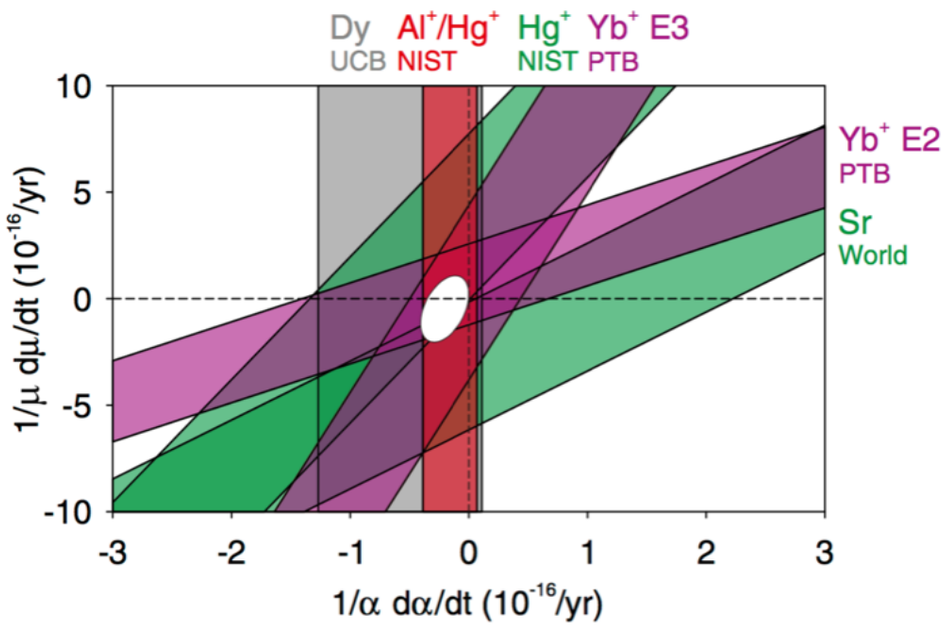
$\nu_{cav} \propto \frac{Nc}{2L} \propto \alpha$



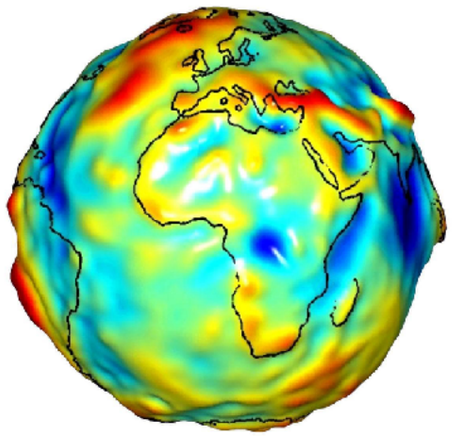
[1]Dereviako, Pospelov, *Nature Physics* (2014), [2]Arvanitaki *et al., PRD* (2015), [3]Wcisło *et al., Science Advances* (2018)

Novel applications of optical lattice clocks

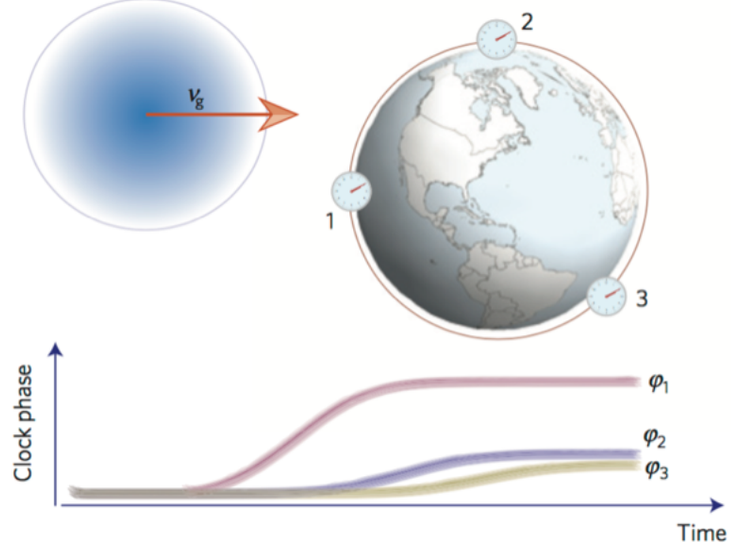
Searches for new physics



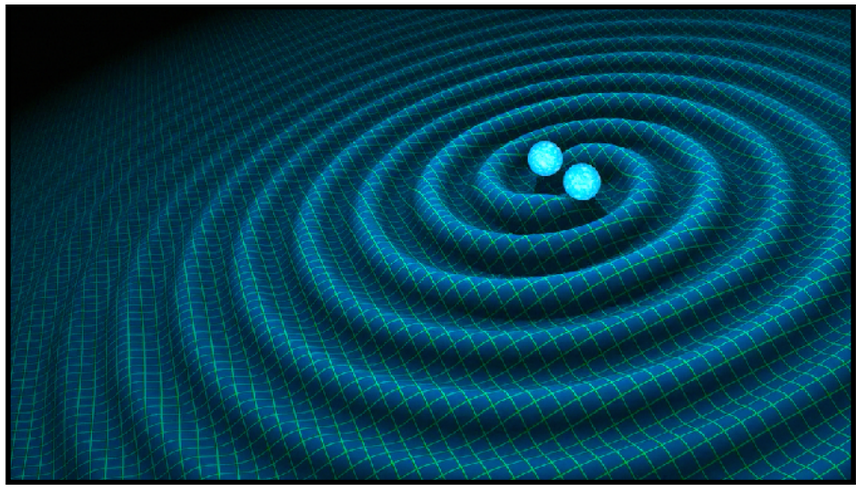
Geodesy



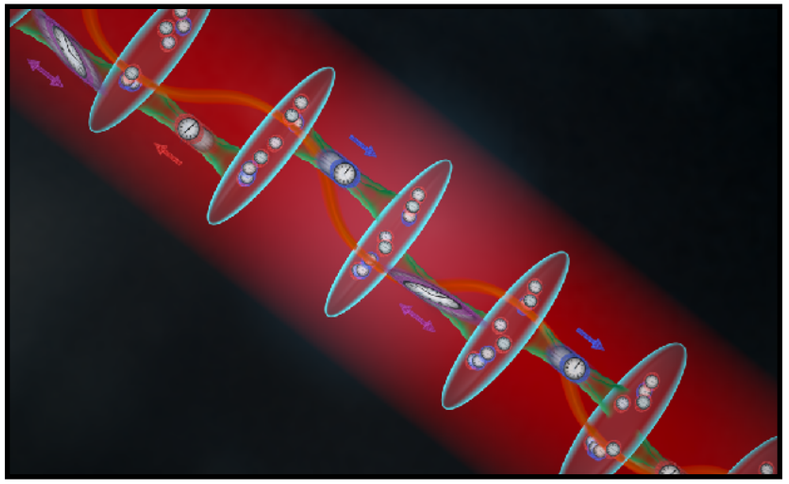
Dark matter detection



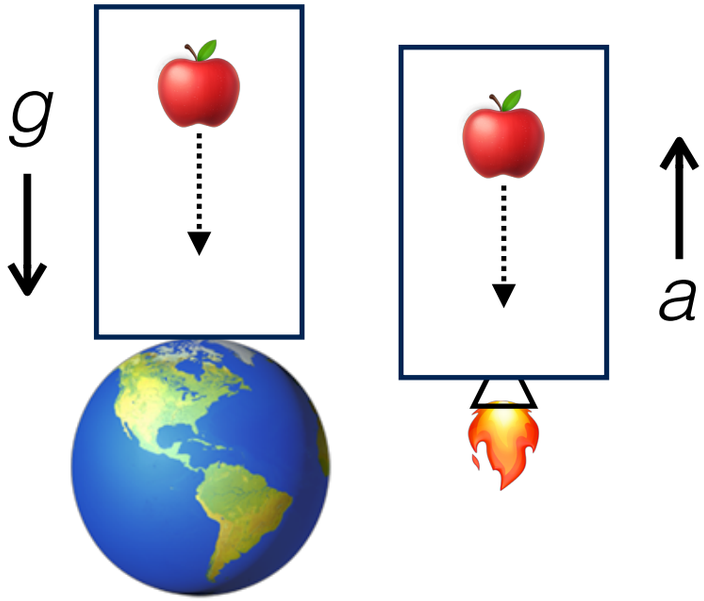
GW detection



Quantum simulation

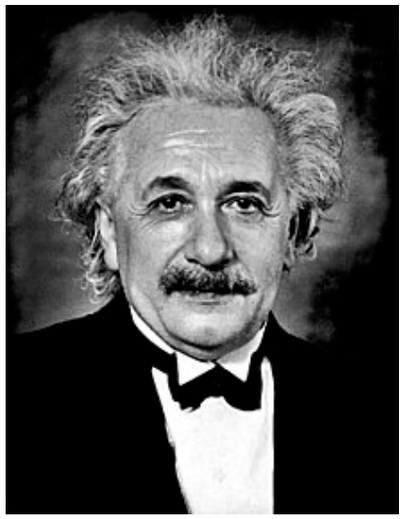


Tests of relativity

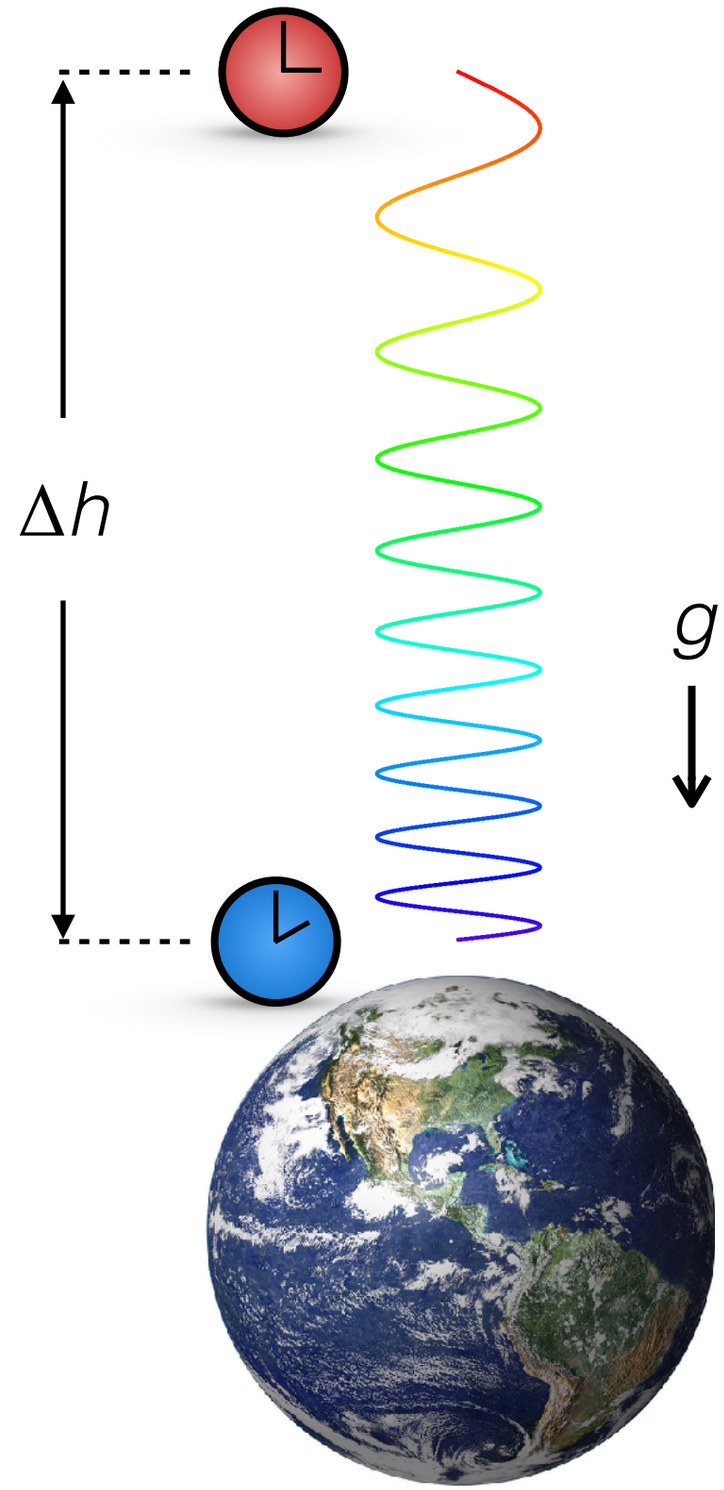


Huntemann *et al. PRL* (2014); Takano *et al. Nature Photonics* (2016); Dereviako, Pospelov, *Nature Physics* (2014)
SK *et al. PRD* (2016); SK *et al., Nature* (2017); Arms, Serna, *arXiv* (2016)

Gravitational redshift



$$\frac{\delta f}{f}_{GR} \approx \frac{\delta \lambda}{\lambda}_{GR} \approx \frac{g \Delta h}{c^2}$$



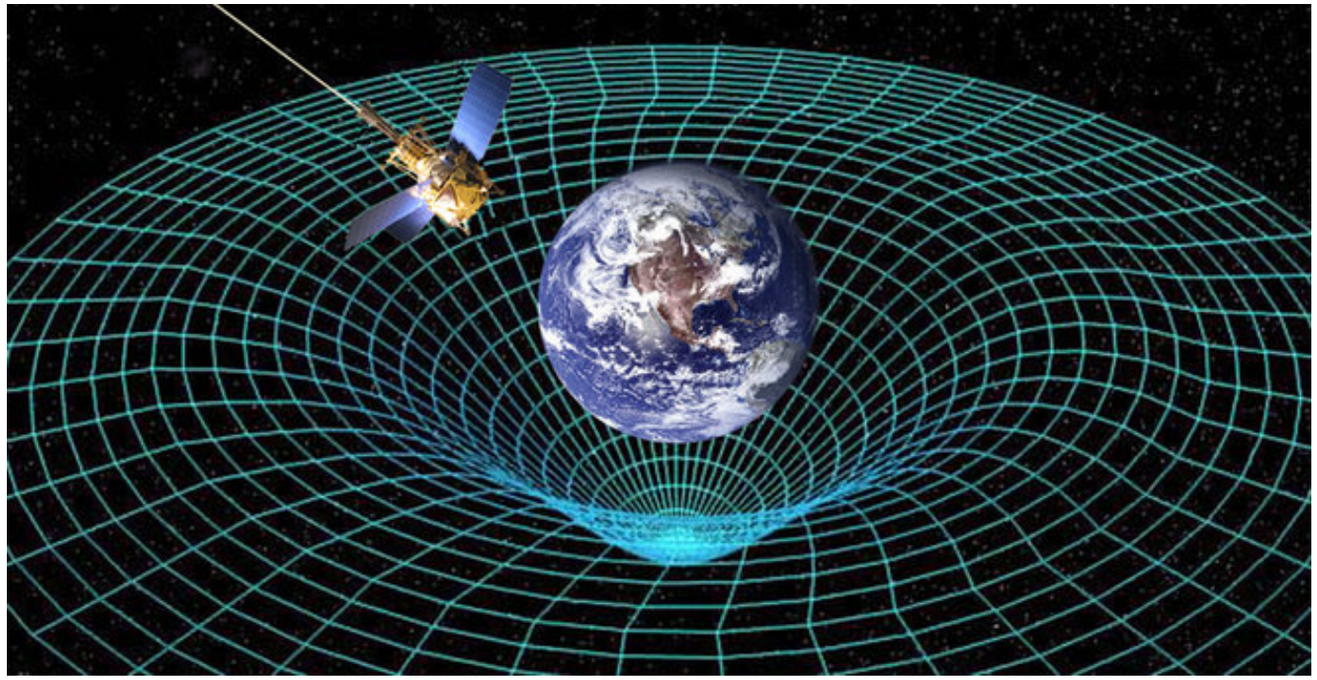
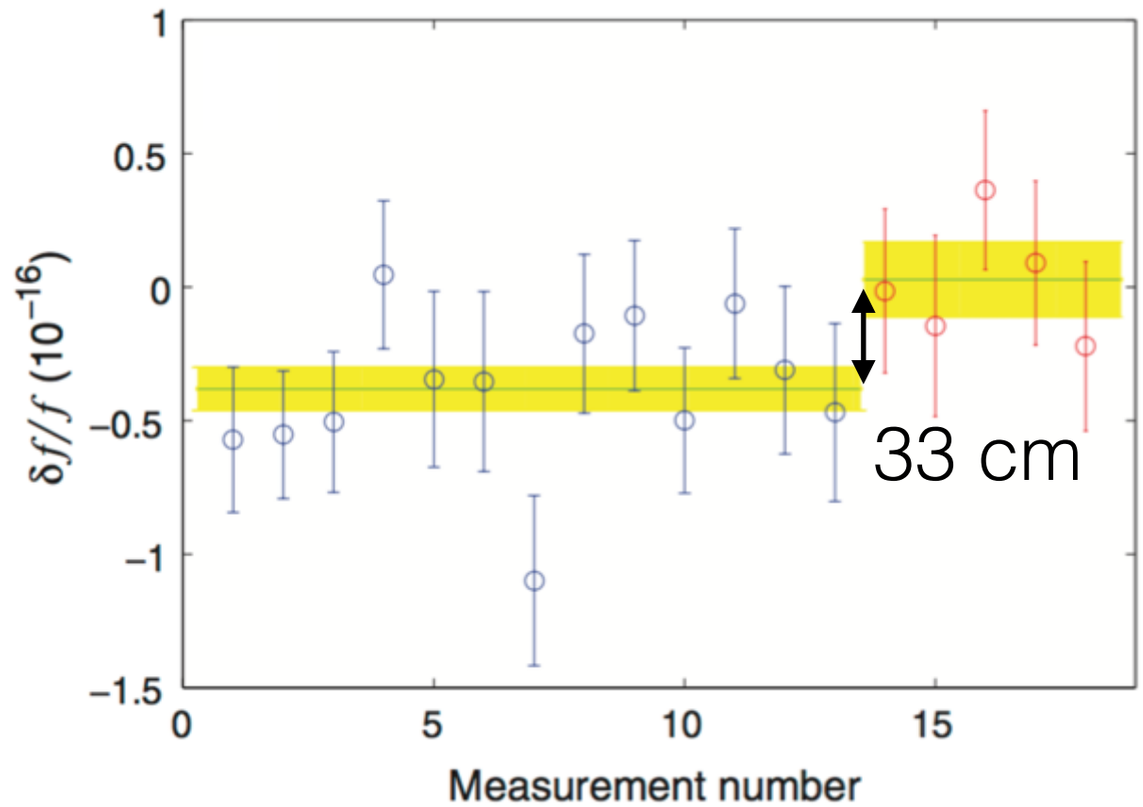


Image credits: wikipedia, space.com

2010: Tests of relativity in the lab

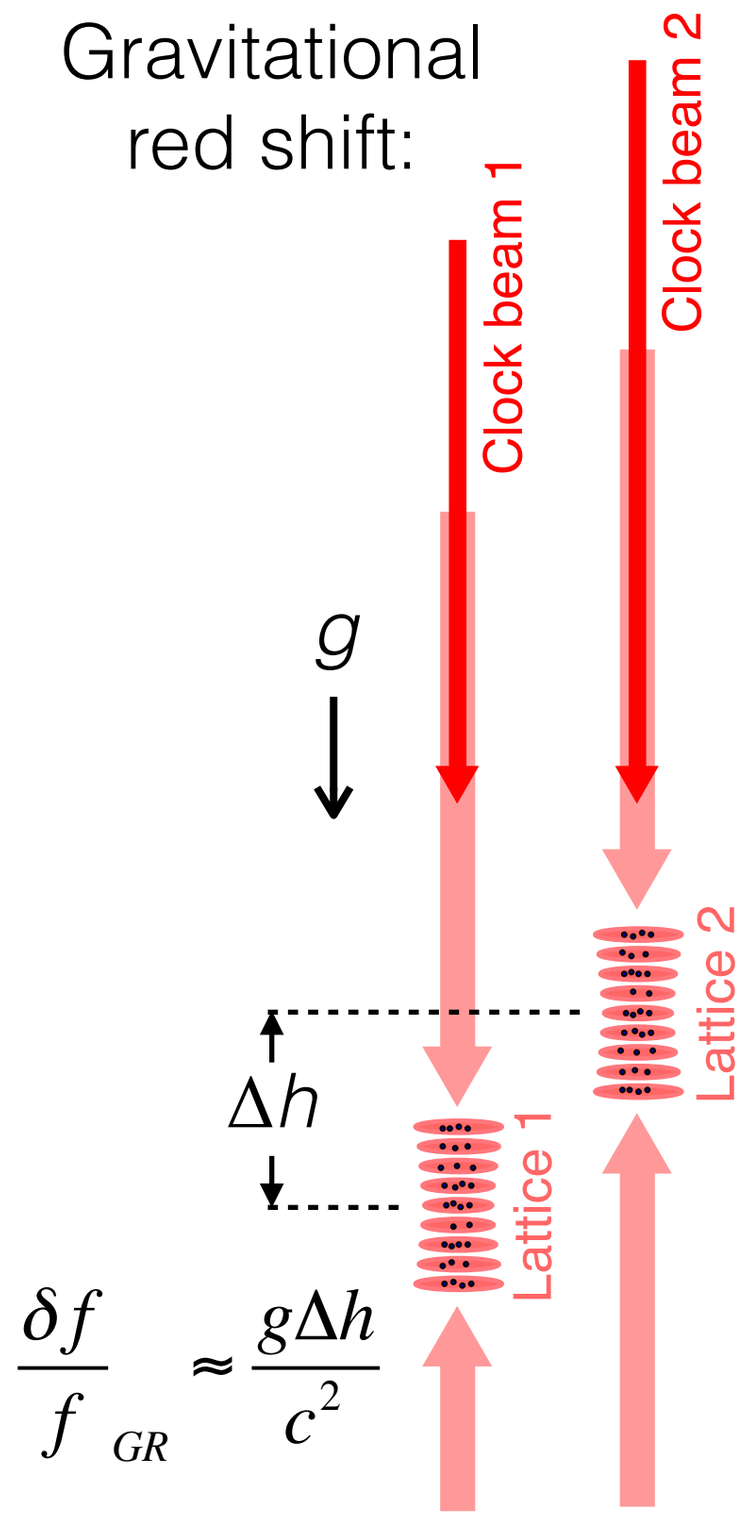


$\sigma \sim 5\times10^{-17}$

$$\frac{\delta f}{f}_{GR} \approx \frac{g\Delta h}{c^2}$$

Chou *et al., Science* (2010), nist.gov

Gravitational redshift at the mm scale



$$\frac{\delta f}{f}_{GR} \approx \frac{g\Delta h}{c^2}$$

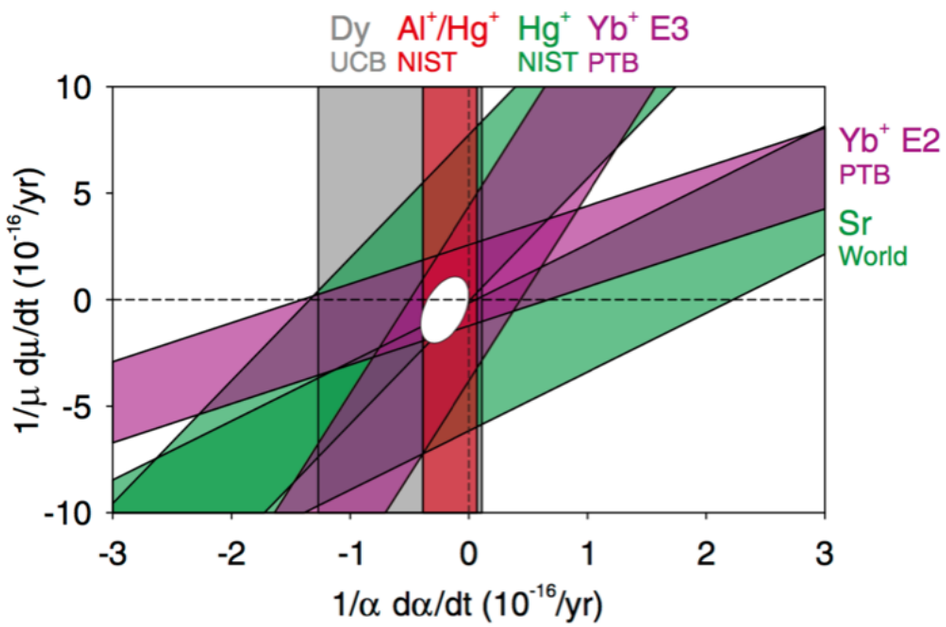
For Δl = 1 cm:

$$\frac{\delta f}{f}_{GR} = 1 \times 10^{-18}$$

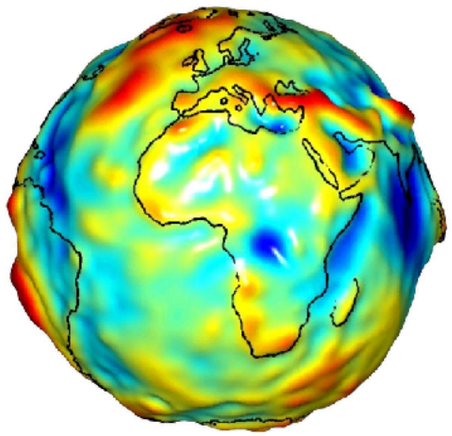
See e.g. Chou *et al., Science* (2010)

Novel applications of optical lattice clocks

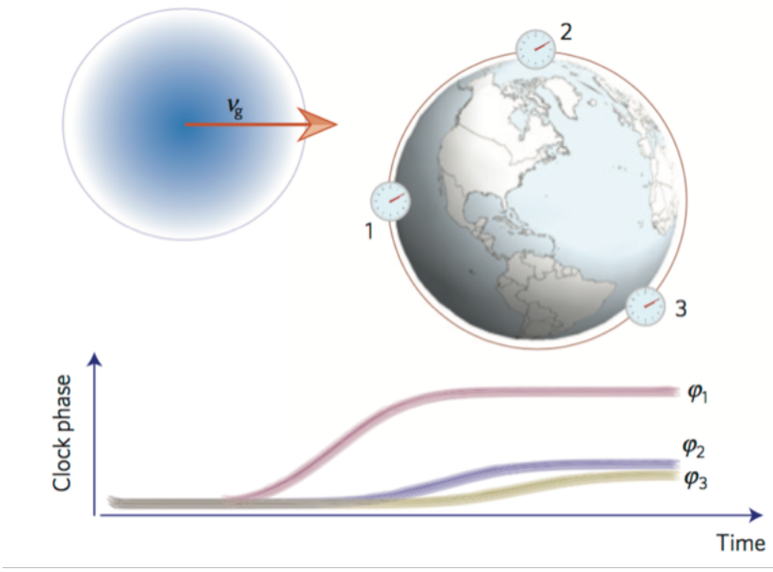
Searches for new physics



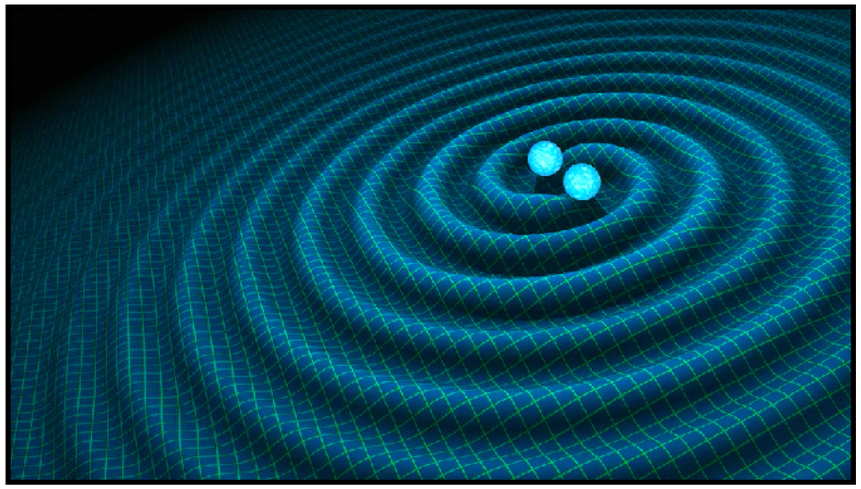
Geodesy



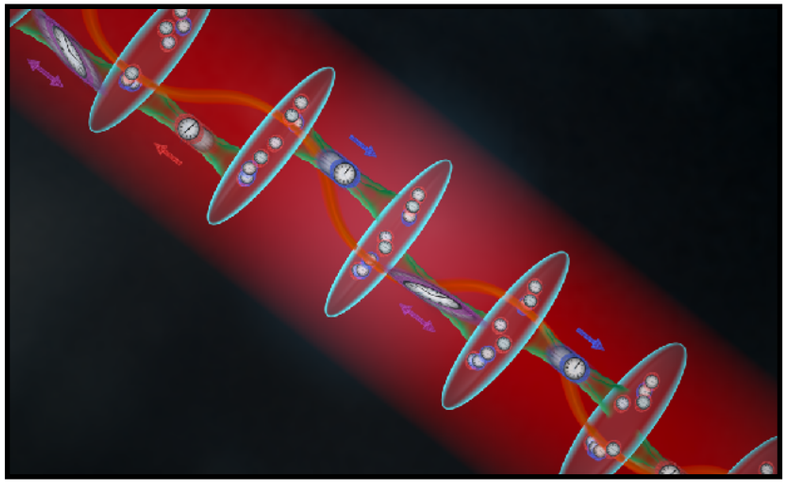
Dark matter detection



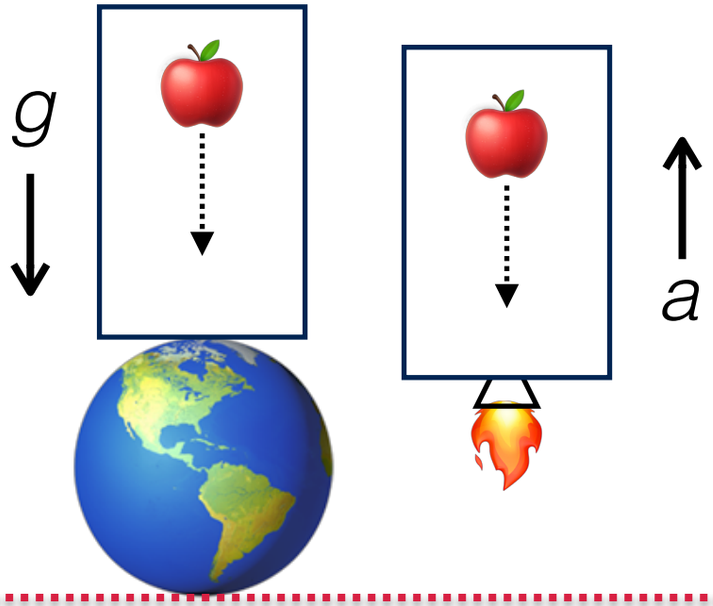
GW detection



Quantum simulation



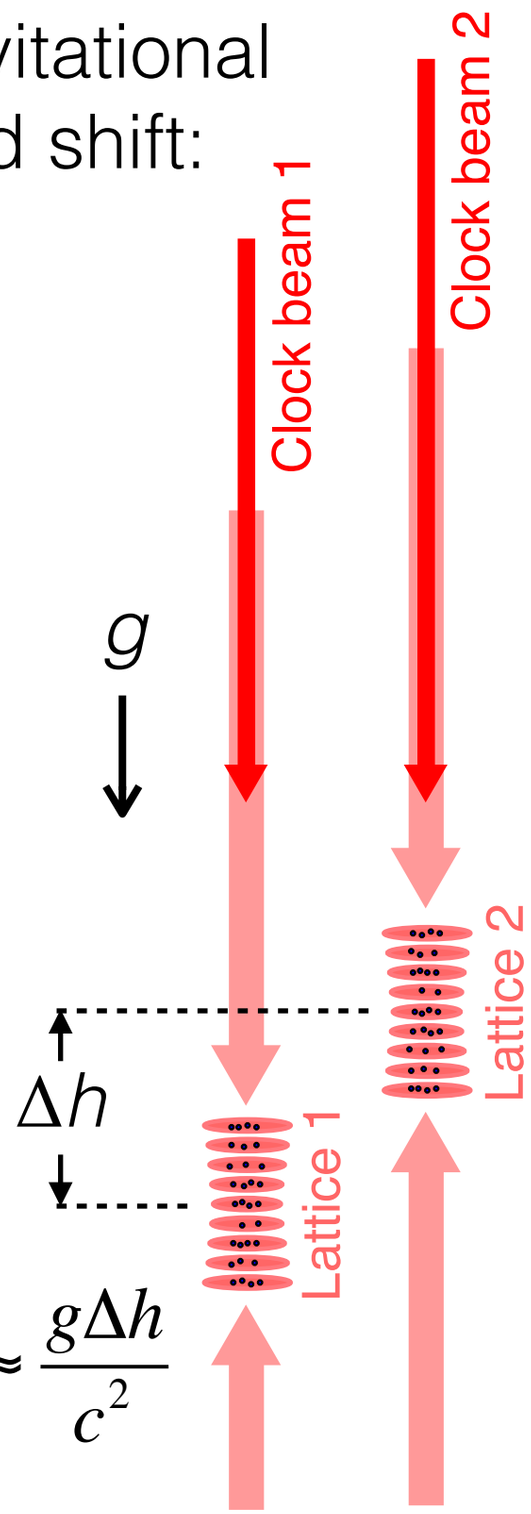
Tests of relativity



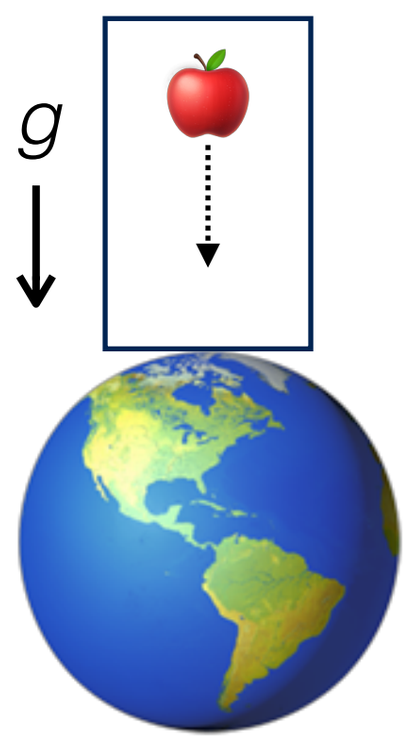
Huntemann *et al. PRL* (2014); Takano *et al. Nature Photonics* (2016); Dereviako, Pospelov, *Nature Physics* (2014)
SK *et al. PRD* (2016); SK *et al., Nature* (2017); Arms, Serna, *arXiv* (2016)

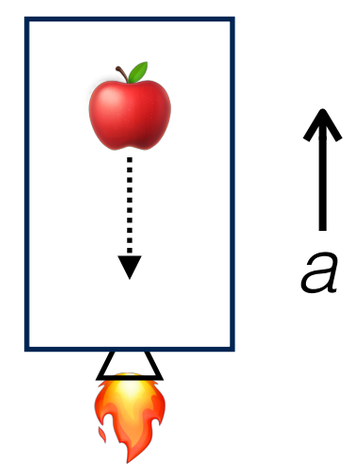
Einstein Equivalence Principle test

Gravitational red shift:



$$\frac{\delta f}{f}_{GR} \approx \frac{g\Delta h}{c^2}$$

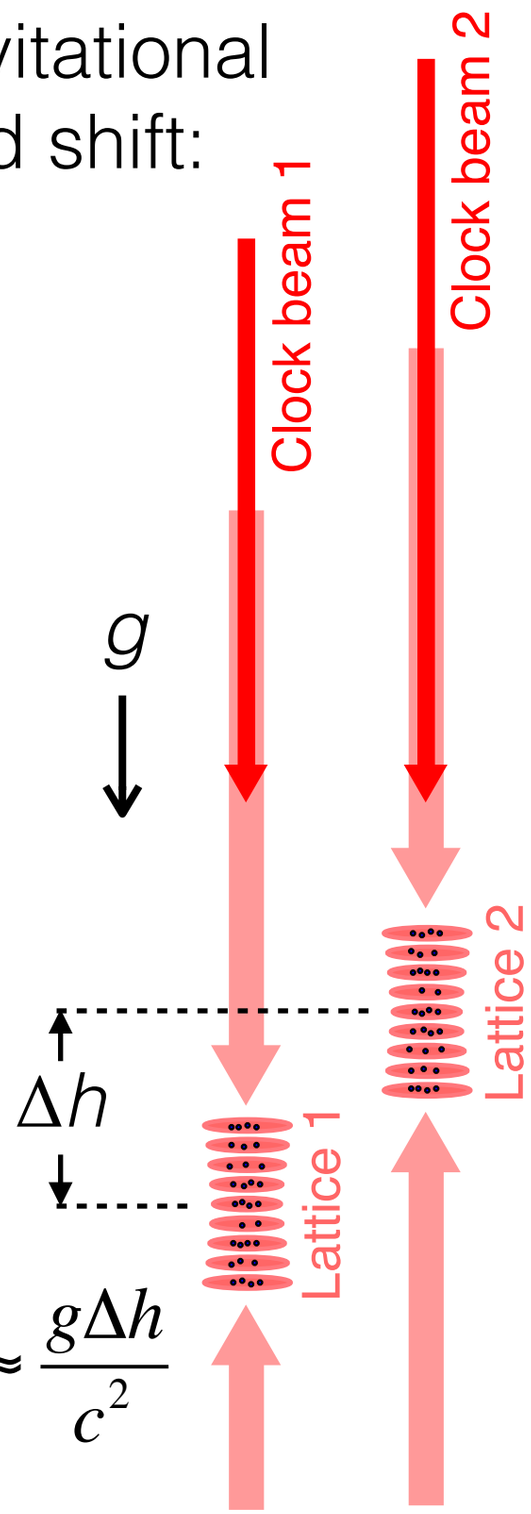




Arms, Serna, *arXiv* (2016)

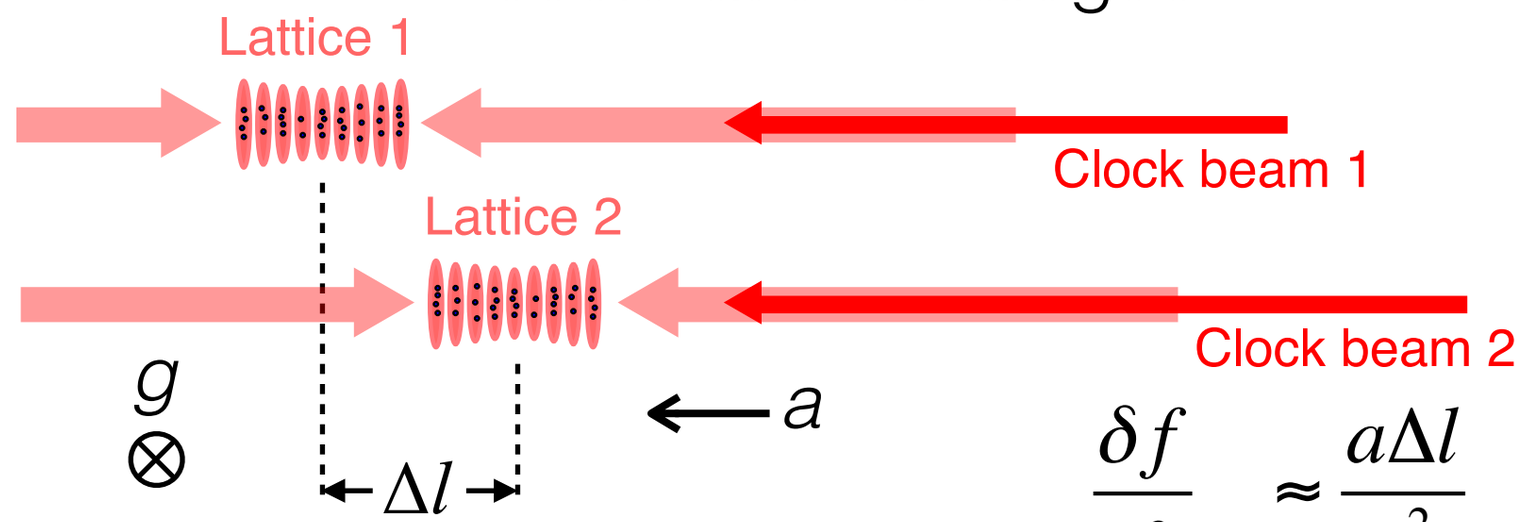
Einstein Equivalence Principle test

Gravitational red shift:

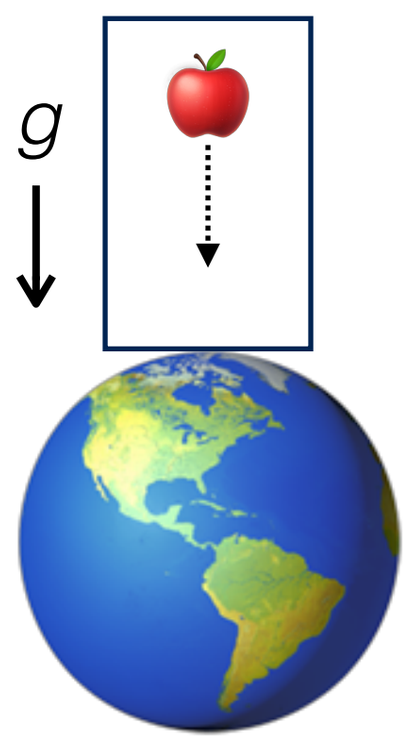


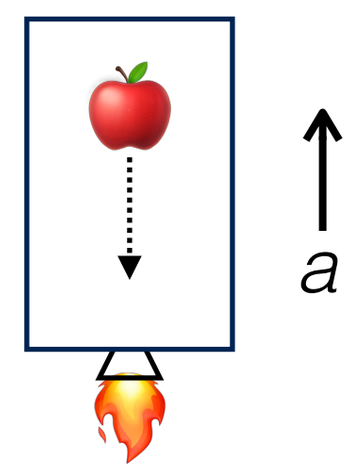
$$\frac{\delta f}{f}_{GR} \approx \frac{g\Delta h}{c^2}$$

Acceleration analogue:



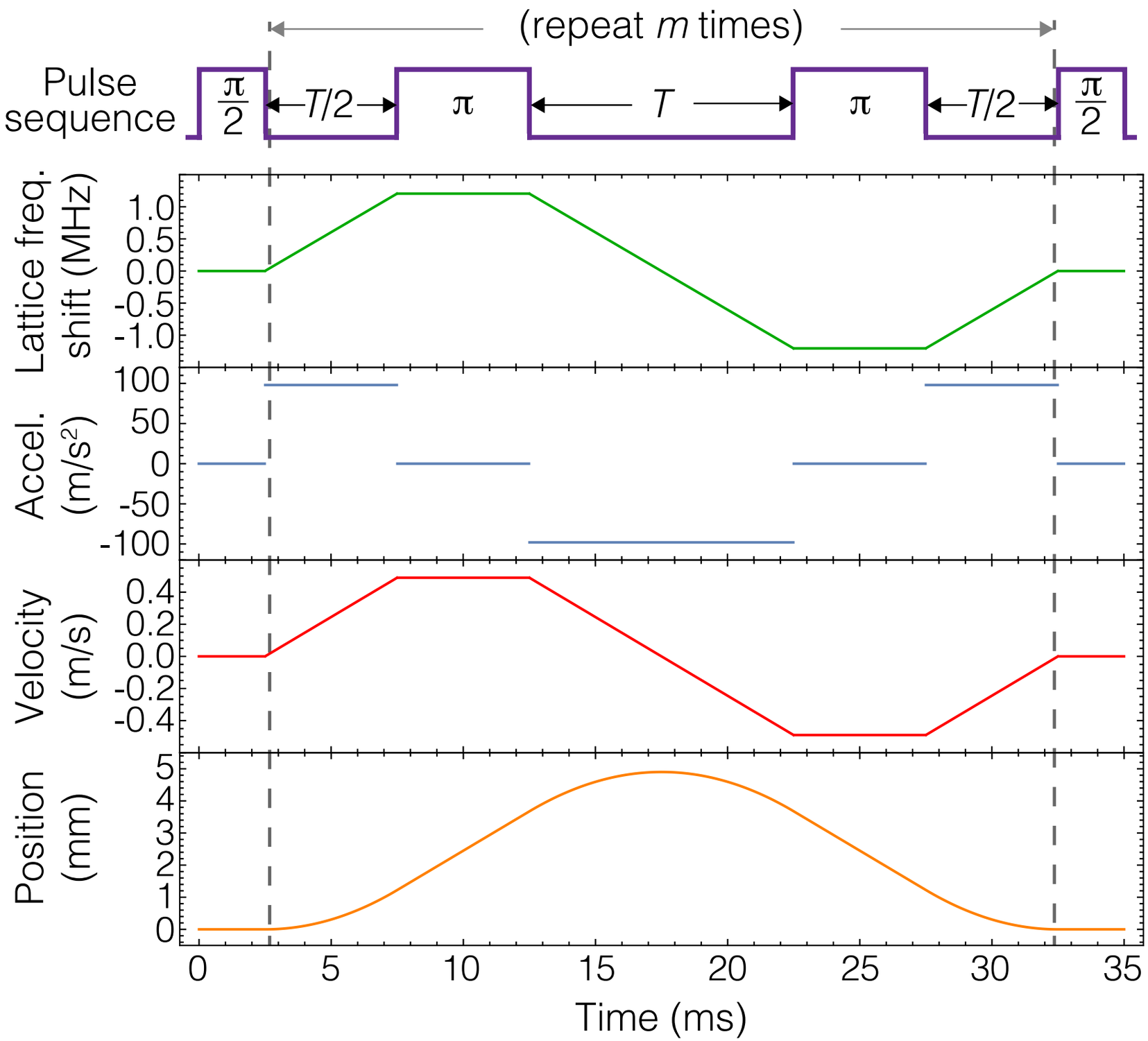
$$\frac{\delta f}{f}_{SR} \approx \frac{a\Delta l}{c^2}$$





Arms, Serna, *arXiv* (2016)

Einstein Equivalence Principle test



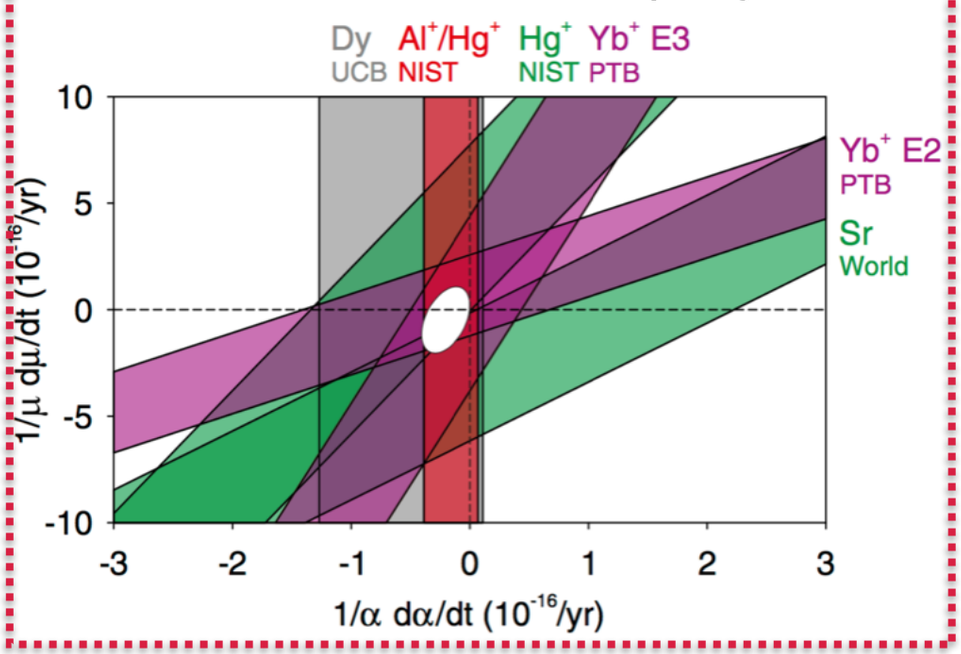
$$\frac{\delta f}{f}_{SR} \approx \frac{a\Delta l}{c^2}$$

For a = 10 g, Δl = 1 cm:

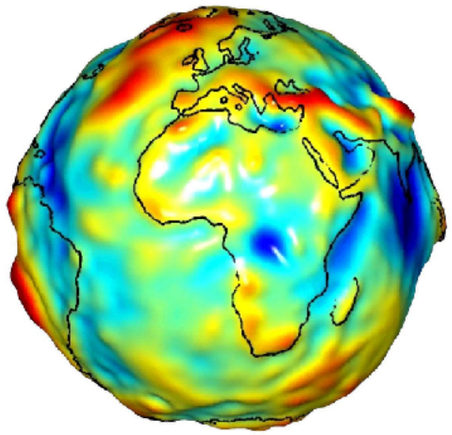
$$\frac{\delta f}{f}_{SR} = 1 \times 10^{-17}$$

Novel applications of optical lattice clocks

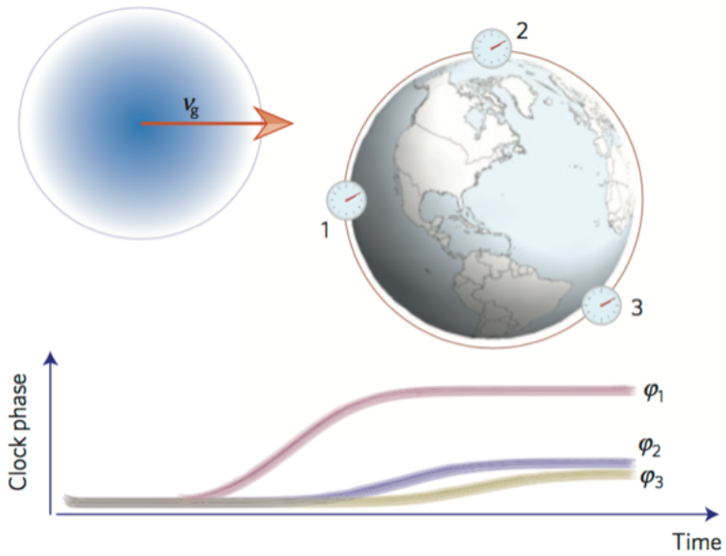
Searches for new physics



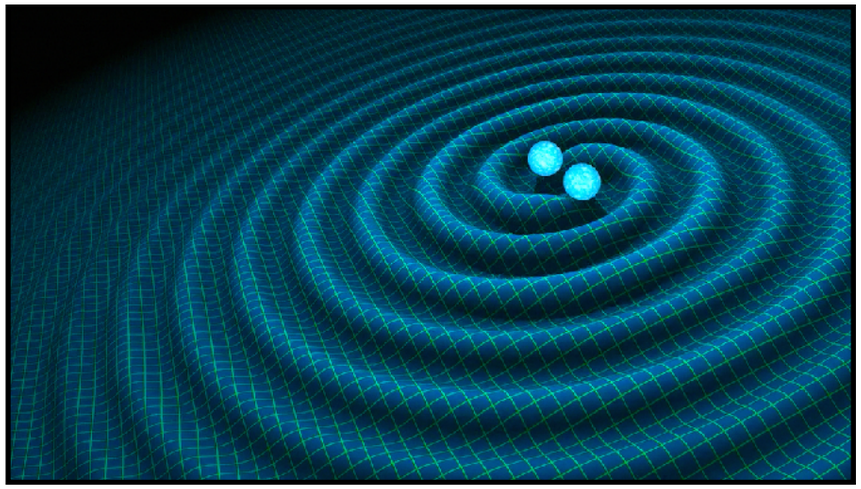
Geodesy



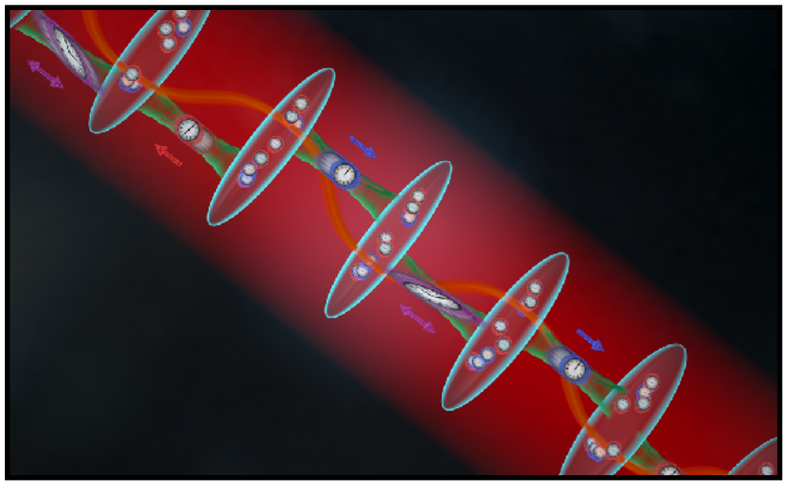
Dark matter detection



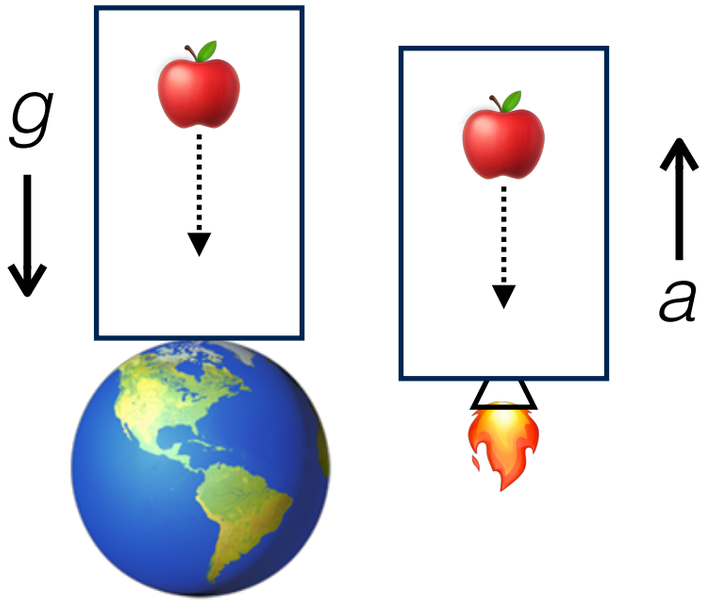
GW detection



Quantum simulation

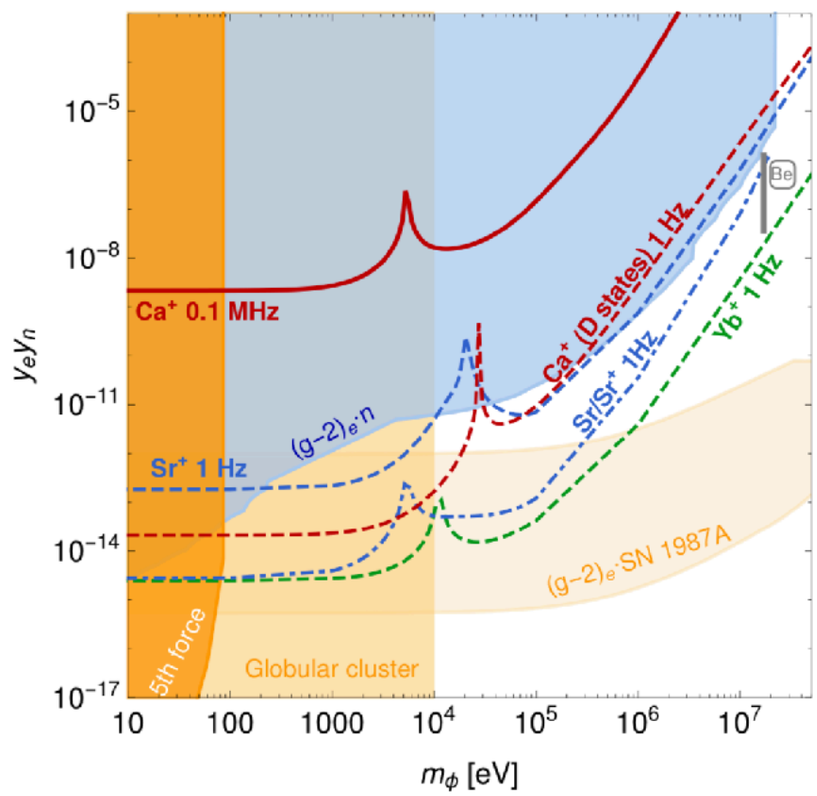


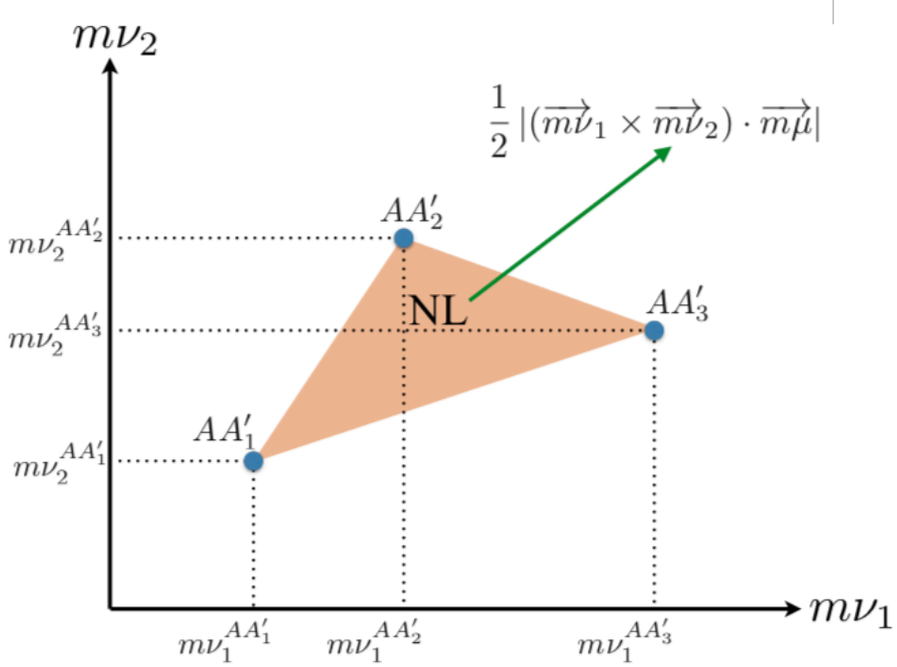
Tests of relativity



Huntemann *et al. PRL* (2014); Takano *et al. Nature Photonics* (2016); Dereviako, Pospelov, *Nature Physics* (2014)
SK *et al. PRD* (2016); SK *et al., Nature* (2017); Arms, Serna, *arXiv* (2016)

Isotope shift measurements





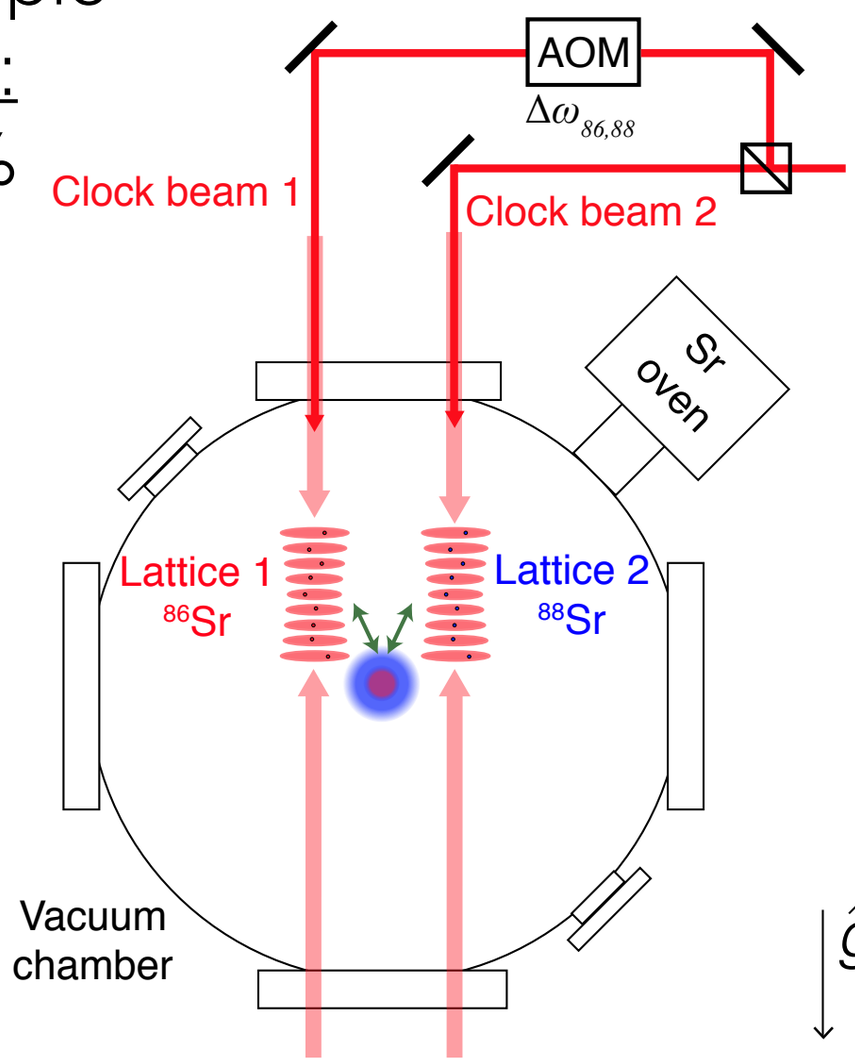
Stable Sr isotopic abundance:

^{88}Sr - 82.6%

^{87}Sr - 7.0%

^{86}Sr - 9.9%

^{86}Sr - 0.6%

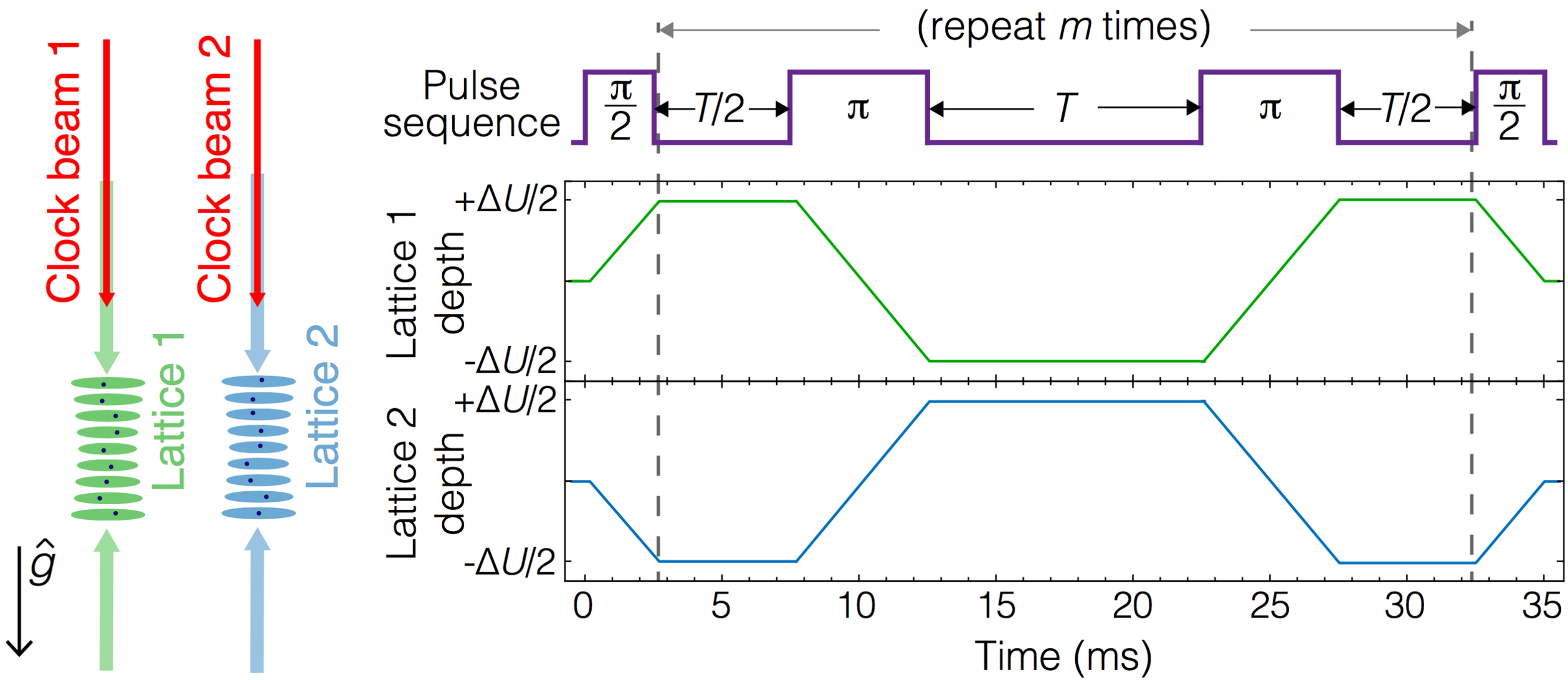


Berengut, *et al. PRL* (2018), see also Origlia *et al. arXiv* (2018), Katori *et al. Applied Physics Express* (2017), and Onishchenko *et al. arXiv* (2018)

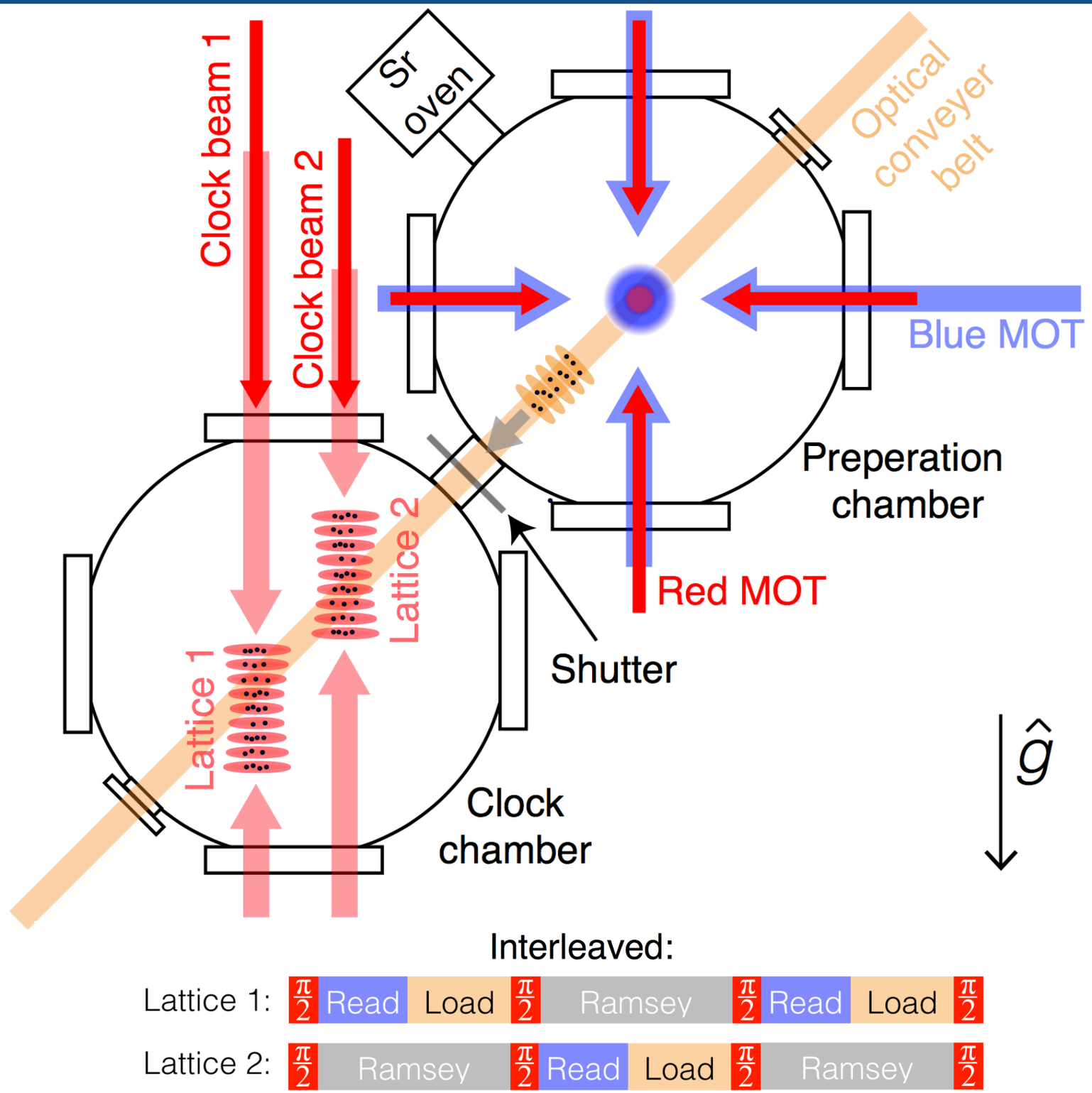
Characterizing limiting clock systematics

Lattice a.c. Stark shift:

$$\Delta\nu_{\text{lattice}} = U_o\{\Delta\kappa_s(f) + \Delta\kappa_v(f) m_f \xi \vec{k}\cdot\vec{B} + \left[3m_f^2 - F(F+1)\right](3|\vec{\epsilon}\cdot\vec{B}|^2 - 1)\Delta\kappa_t(f)\}$$



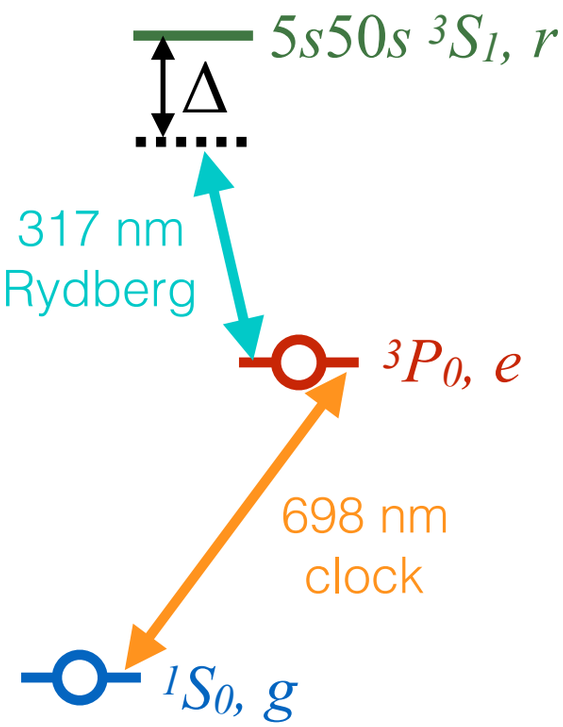
Other long term directions

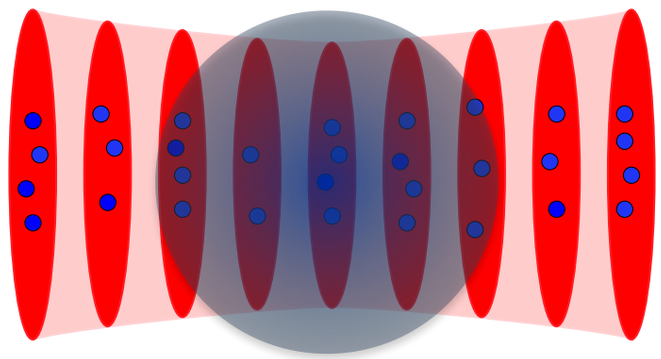


See also e.g. Schioppo *et al. Nature Photonics* (2017), and work by the Thompson and Schreck groups

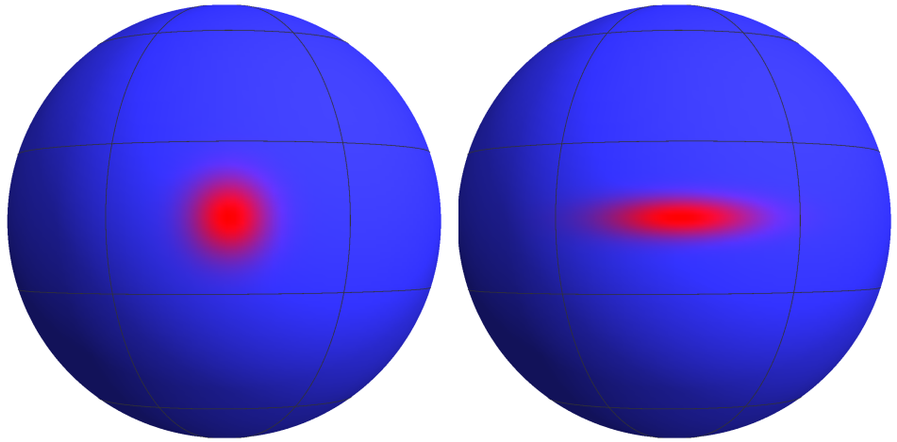
Quantum enhanced clocks

Introduce Rydberg interactions:

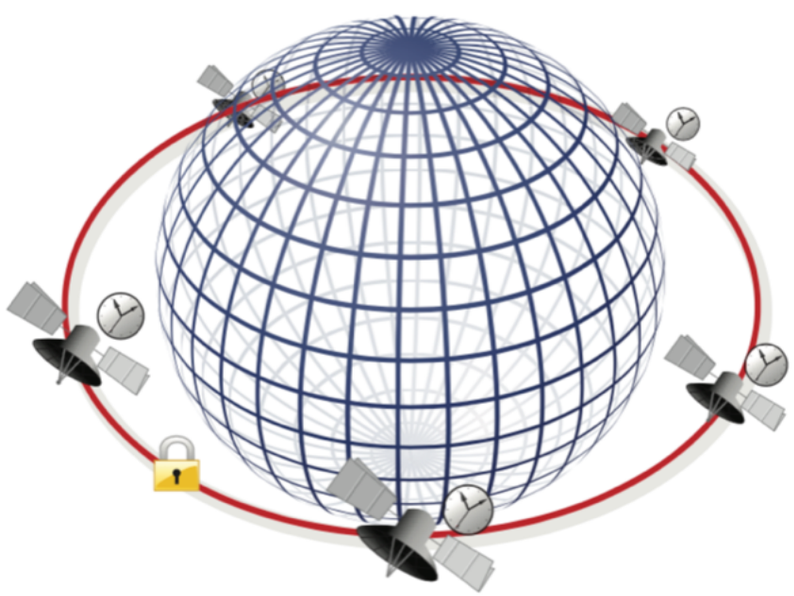


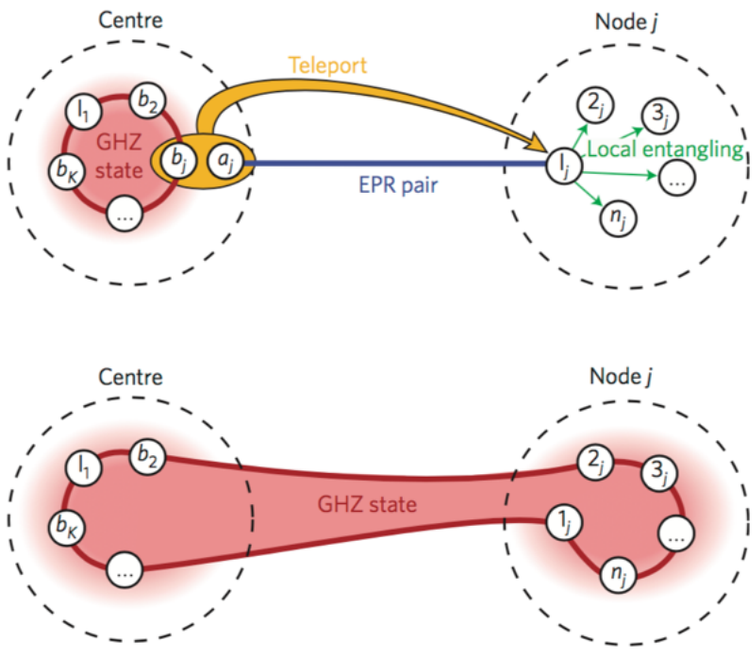


Spin squeezing:



Entangled clock networks:





[1]Gil *et al. PRL* (2014), [2]Komar *et al. Nature Physics* (2014)

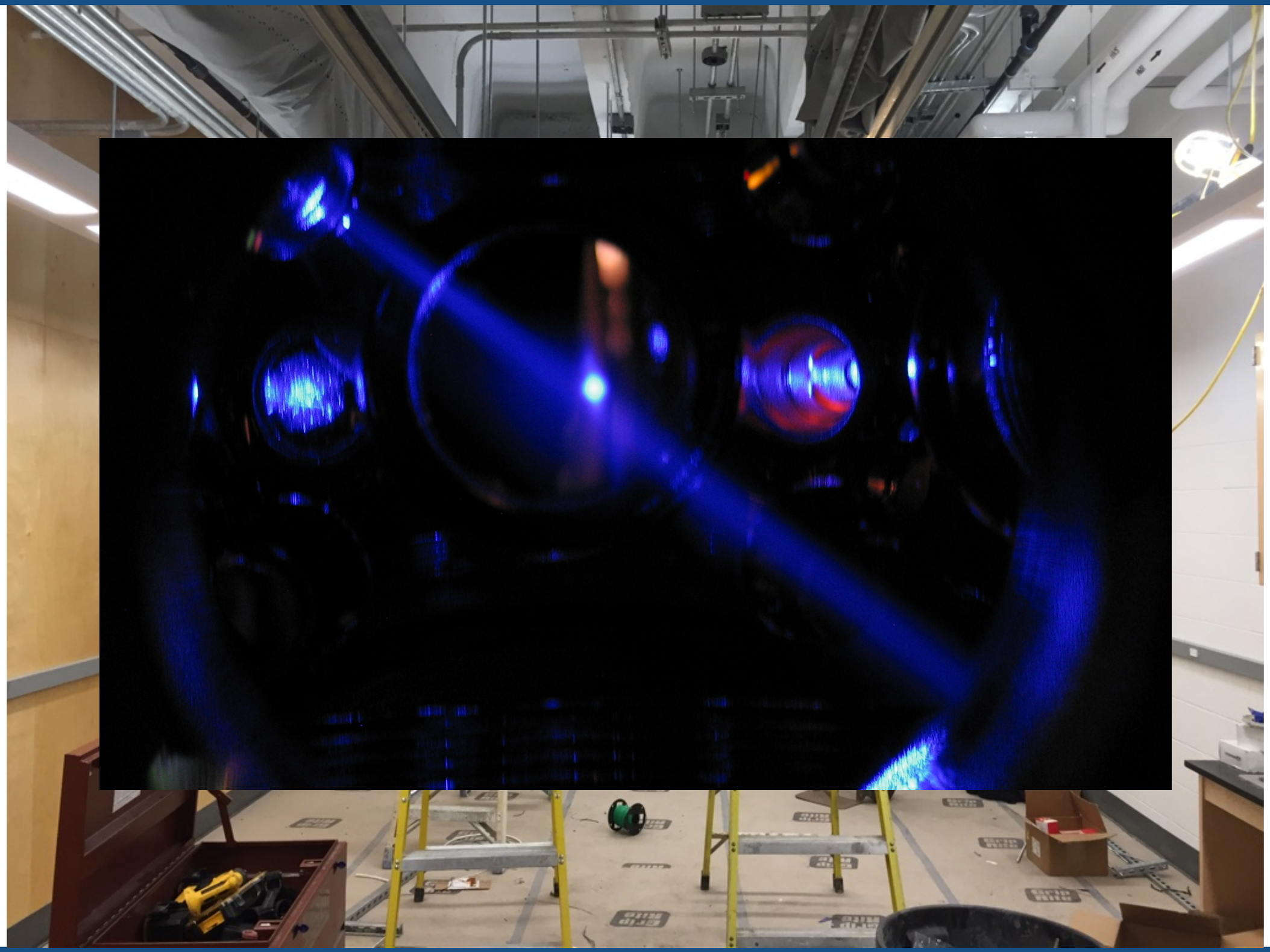
The Kolkowitz Lab in June:

The Kolkowitz Lab in July:

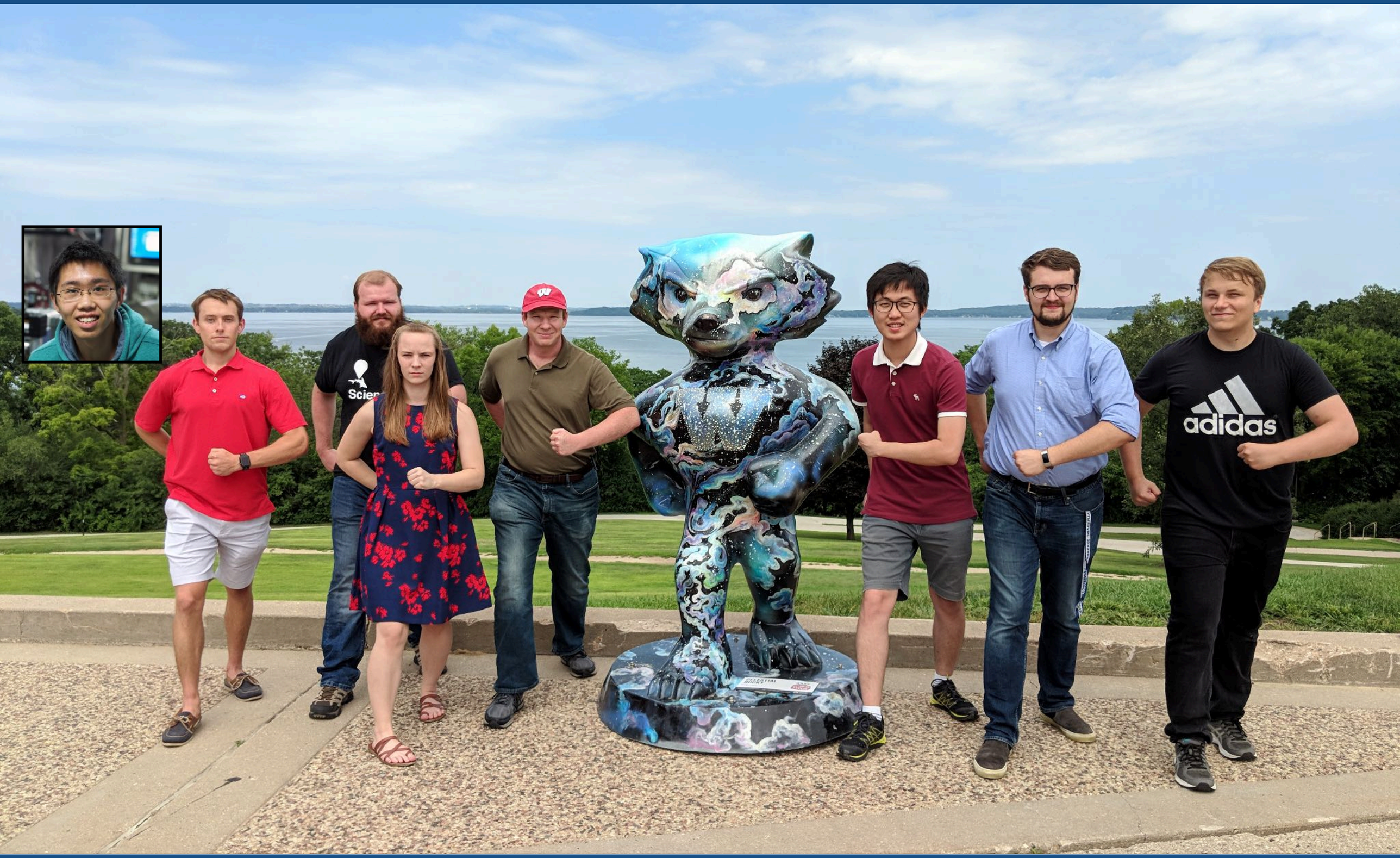
The Kolkowitz Lab the next day:

The Kolkowitz Lab last week:

The Kolkowitz Lab soon:



The Kolkowitz group



From left to right: Brett Merriman, Maxwell Granger, Megan Tabbutt, Shimon Kolkowitz, Buckingham U. Badger, Wangping Ren, Aedan Gardill, and Phillip Flinchum. Inset: Xin Zheng. Not Pictured: Matthew Cambria and Kelsey Jacobus.

And thank you all for your attention!