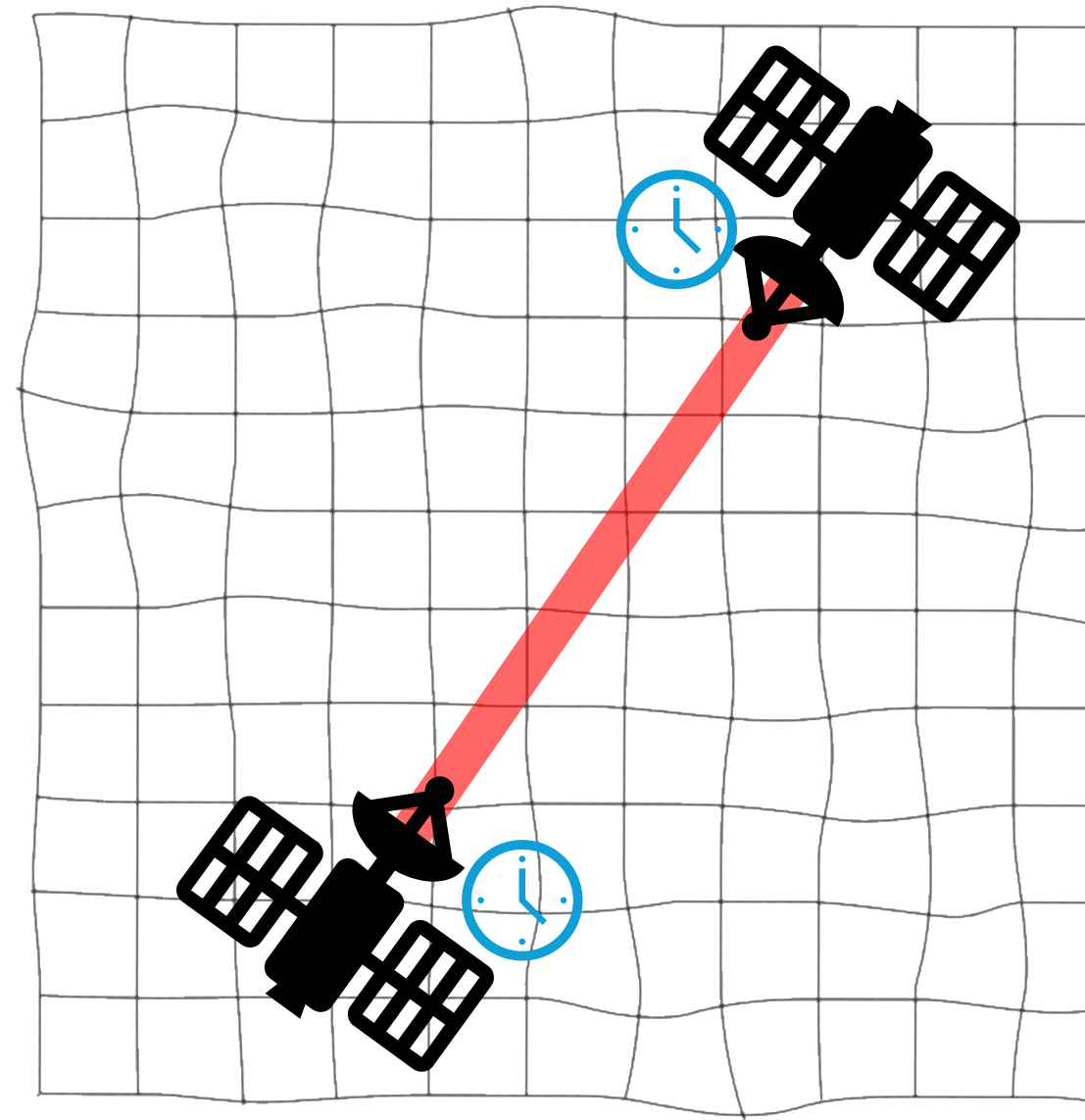


Gravitational Wave Astronomy with Optical Clocks

Dhruva Ganapathy,

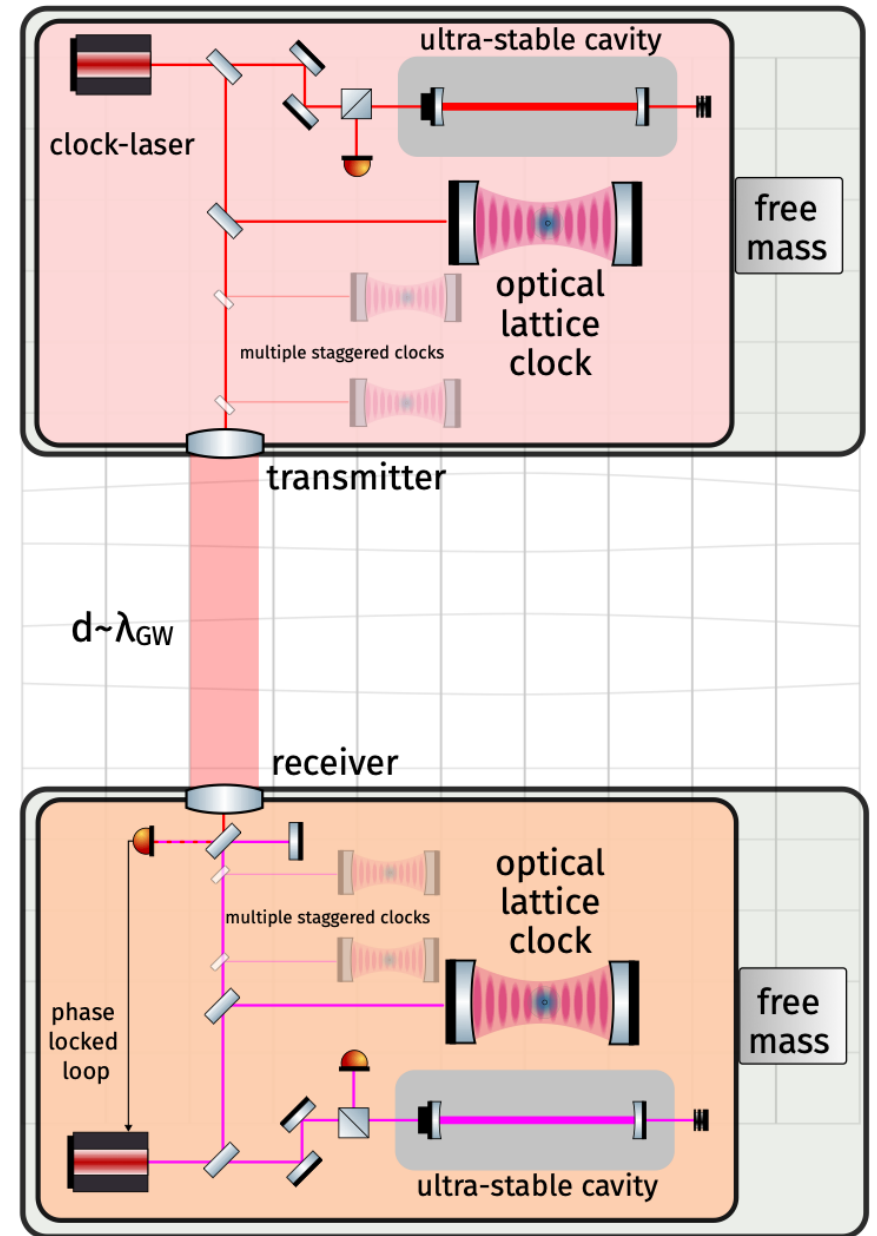
Divya Singh, Sammith Singamsetty and
Shimon Kolkowitz

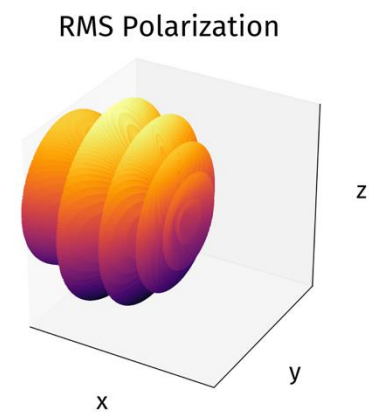
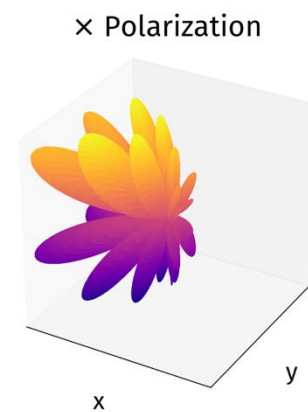
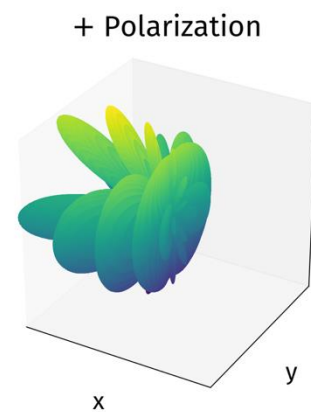
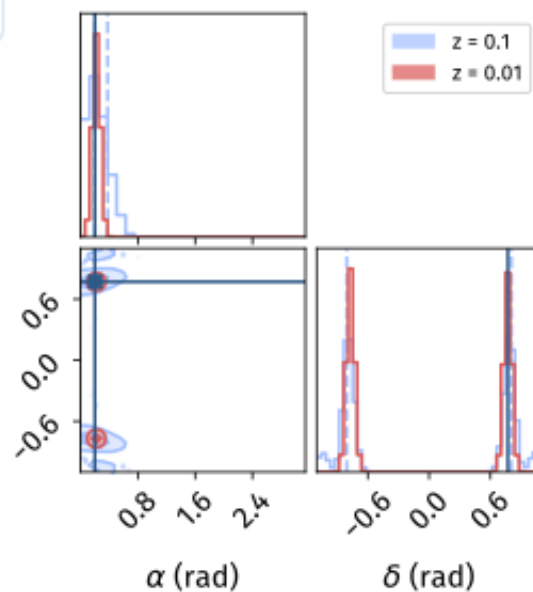
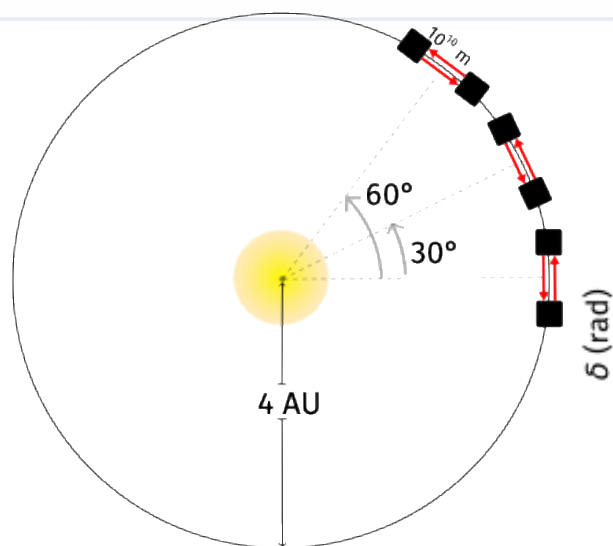
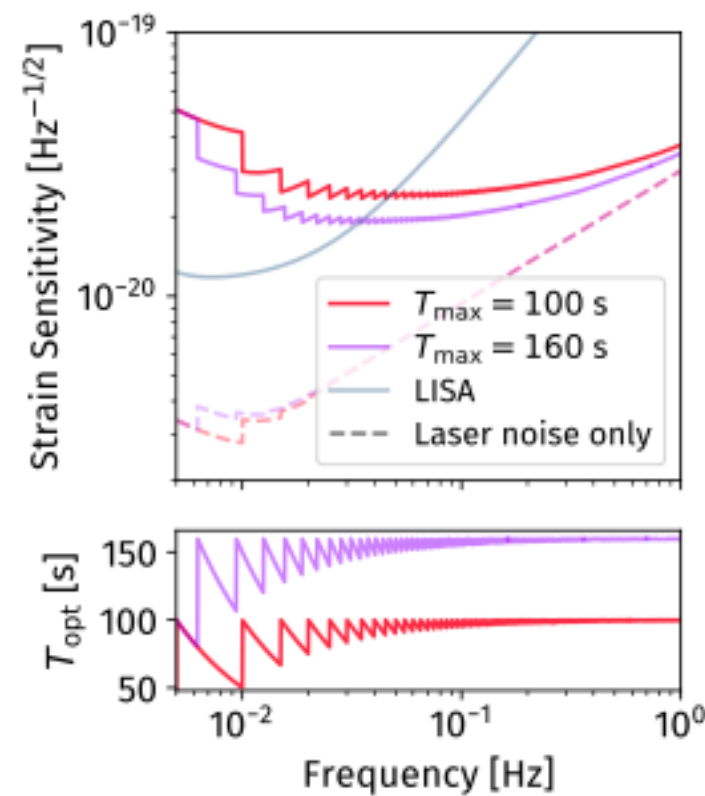
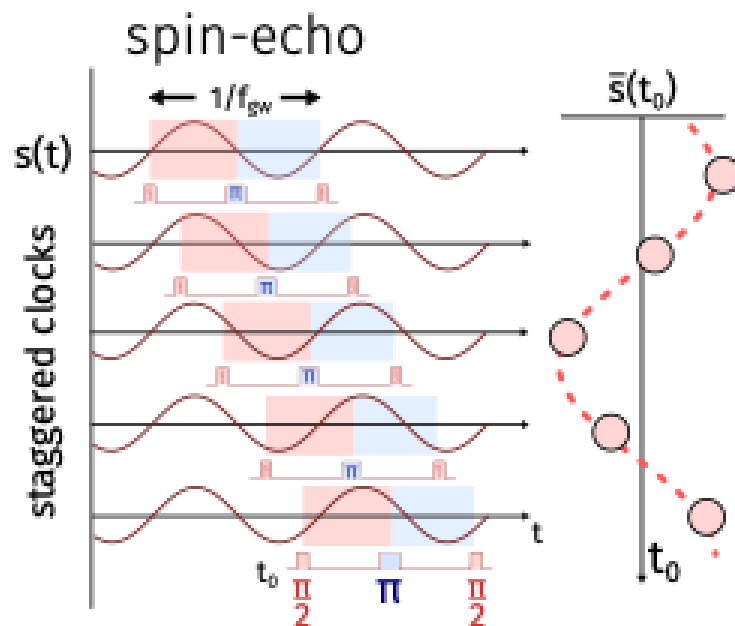


Detector Concept

Differential clock
measurements via
optical link across
satellites

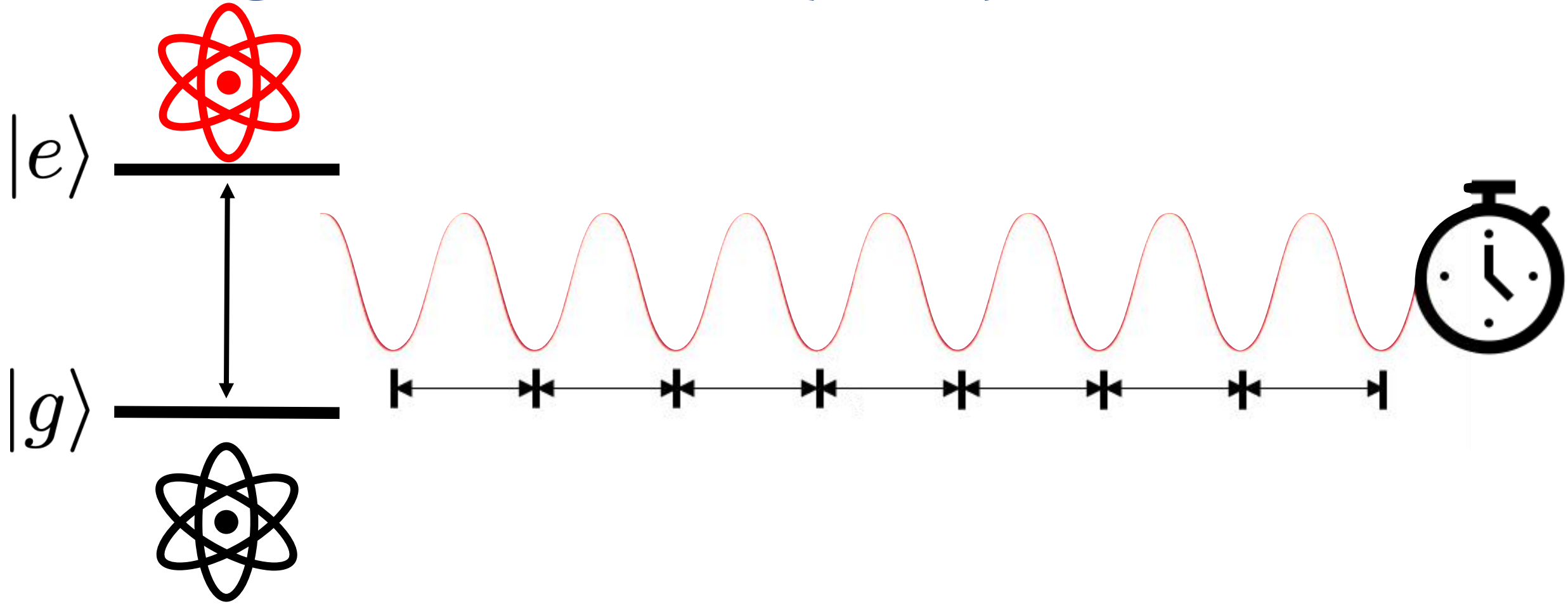
Atomic pulse sequences
tailored to AC signals





Optical Clocks

Using atoms as a frequency reference

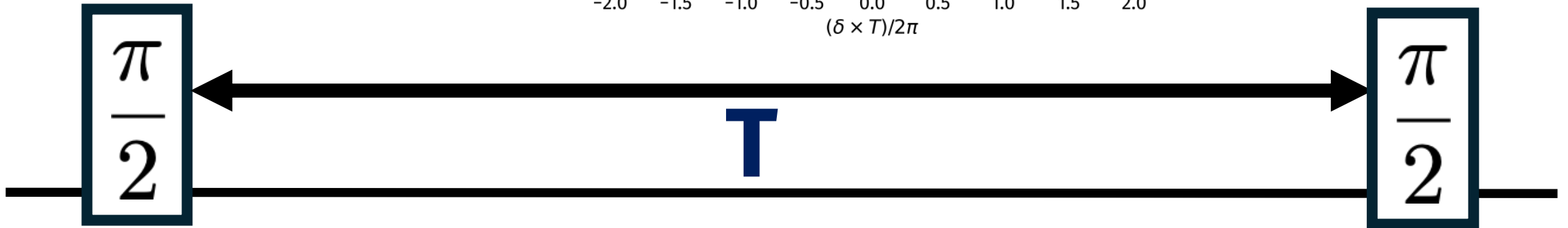
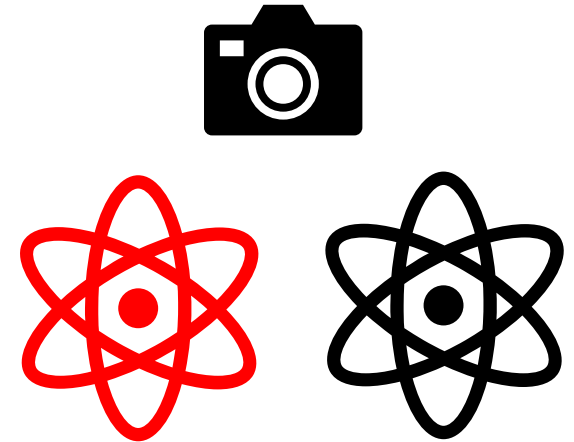
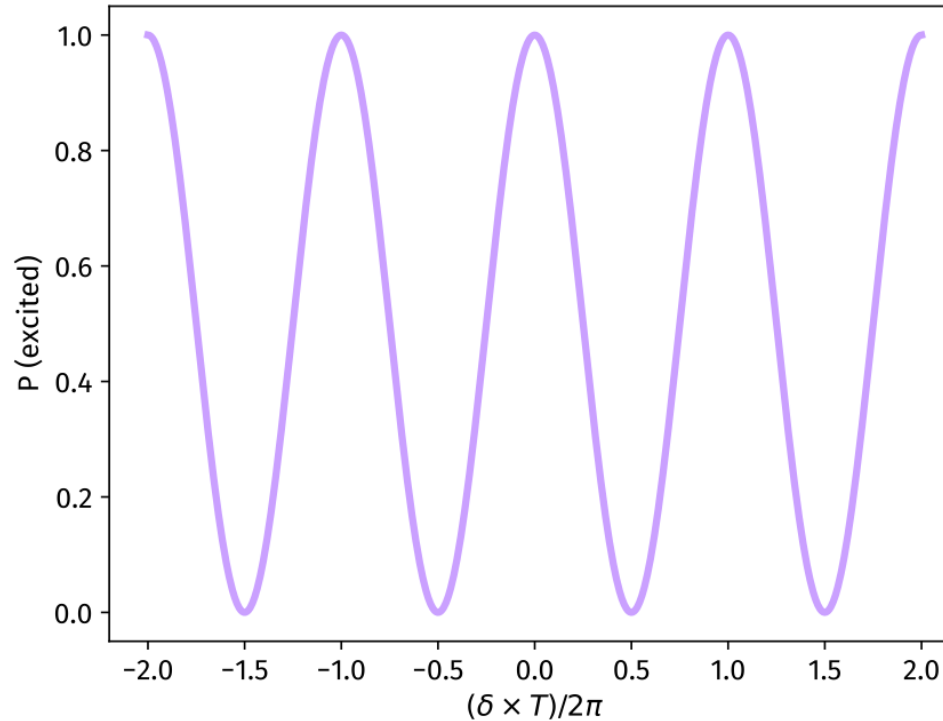


Ramsey Interferometry

Measures relative phase accumulated between lasers and atoms

Used for ultra-low frequency feedback to clock laser

Longer T = better sensitivity, but laser can lose coherence

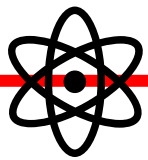


Differential Clock Comparisons

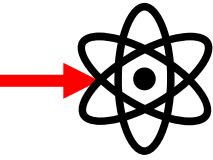
Going beyond laser coherence times

Ramsey phase includes contributions from common (laser noise) and differential signals

Clock
Laser

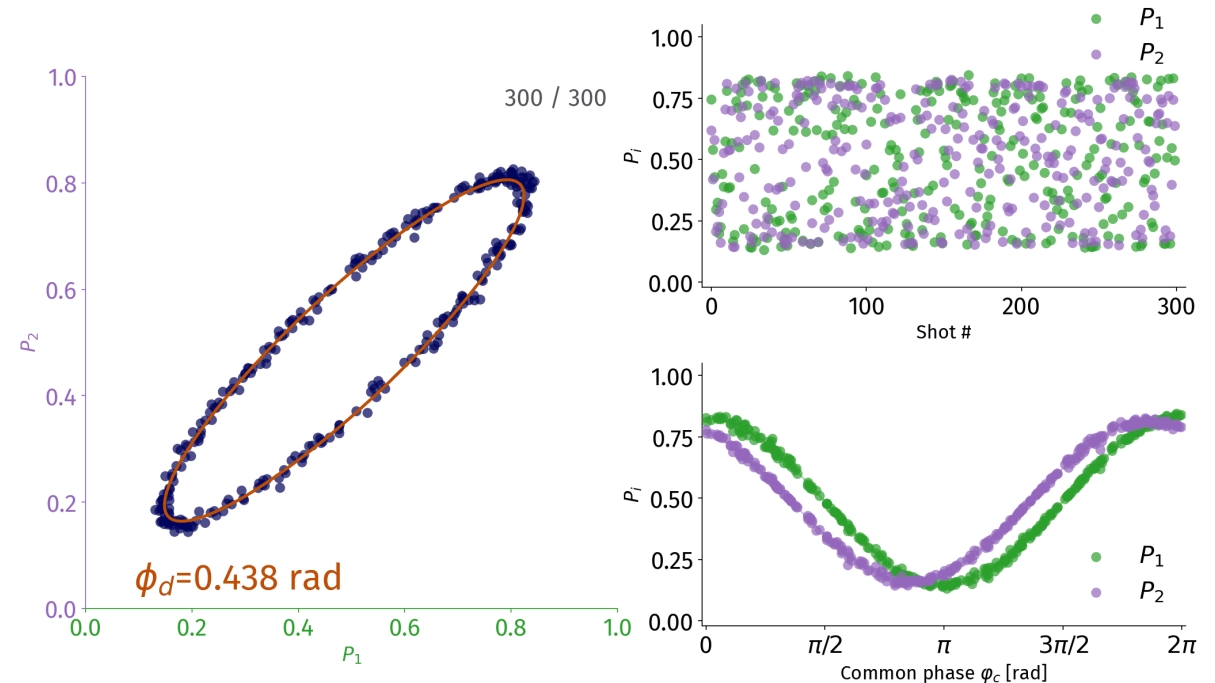


$$\phi_L$$



$$\phi_L + \phi_D$$

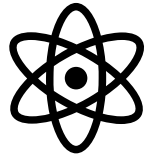
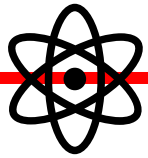
Individual shots have random phases, but the difference is well defined



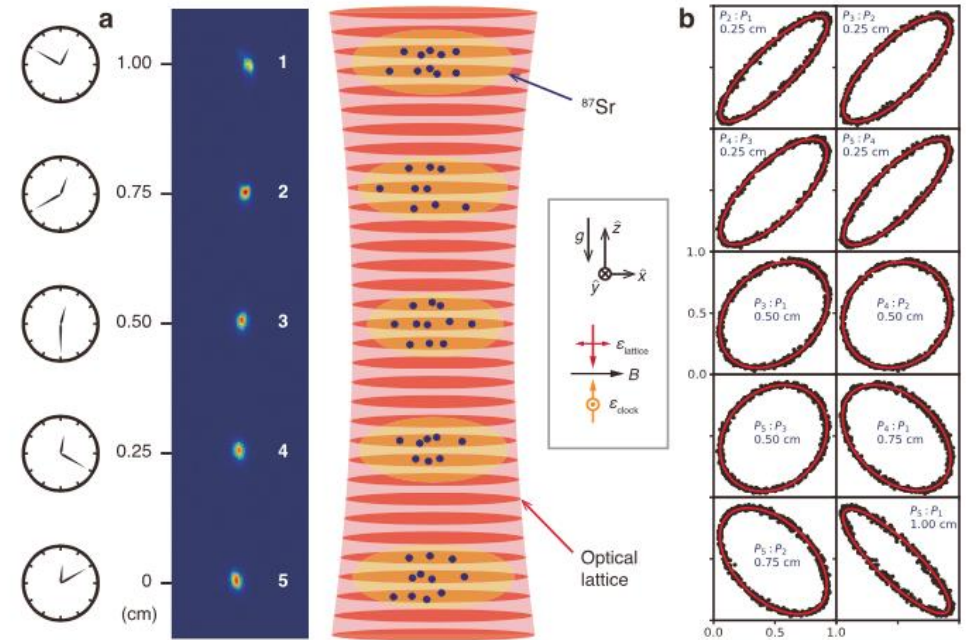
J. Dolde

Differential frequency signals

Clock
Laser

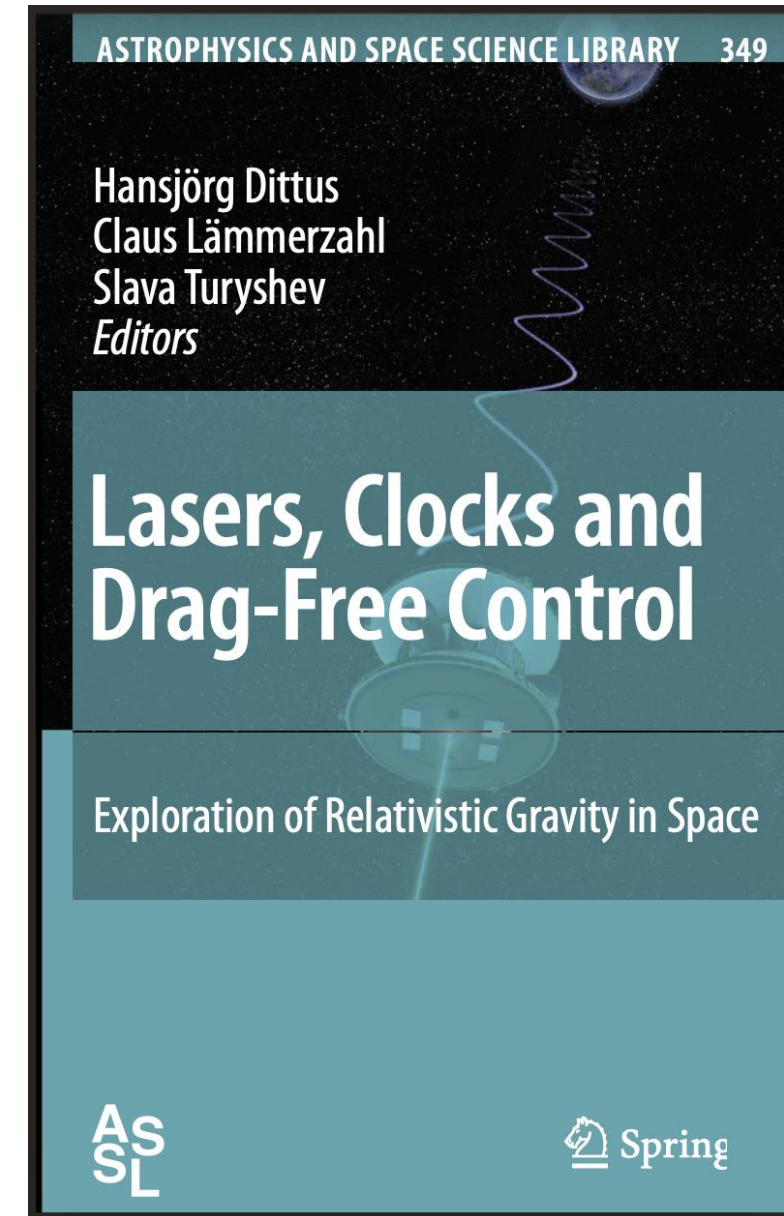
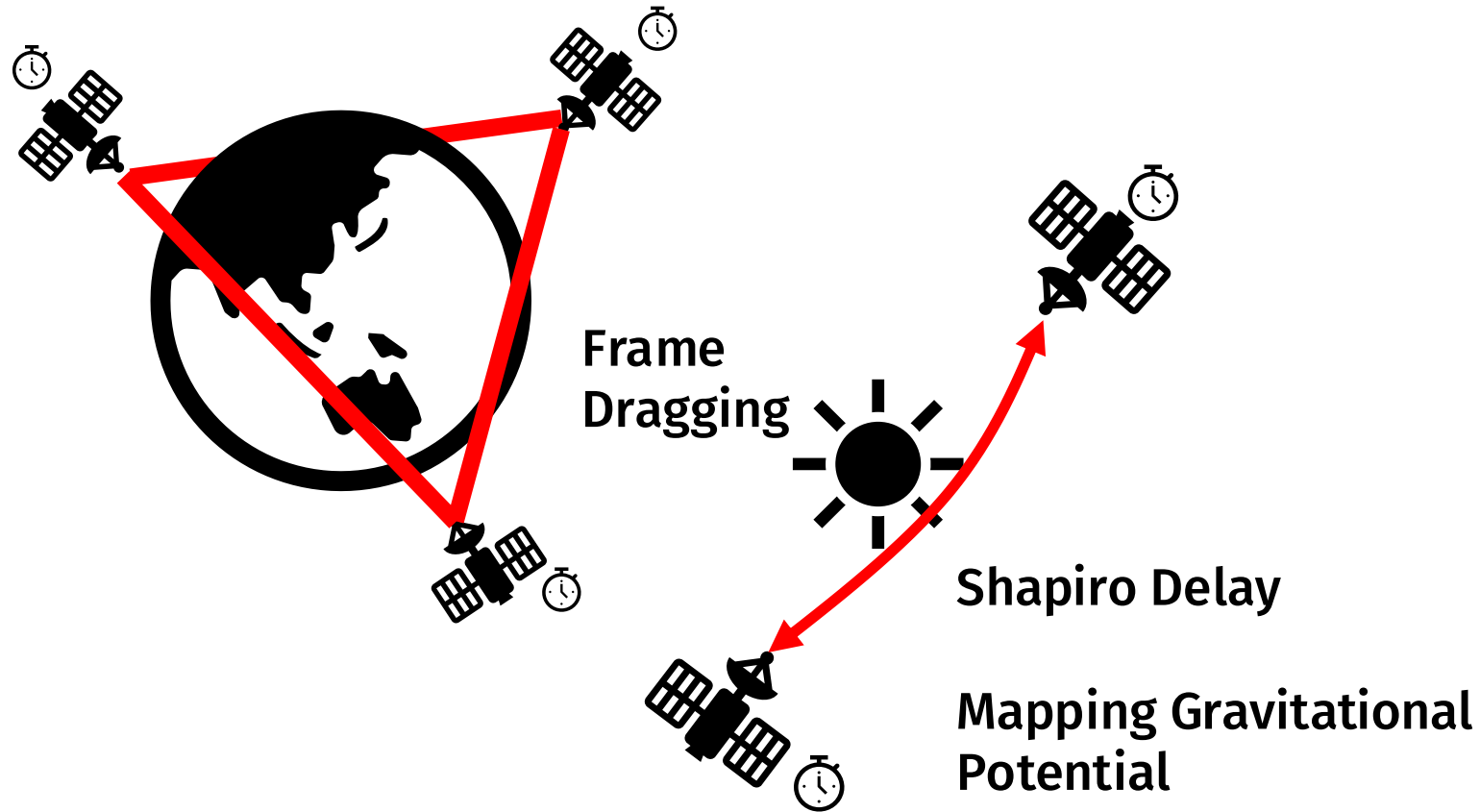


ϕ_D – frequency difference
between atoms, e.g. redshift
+
frequency signals that laser
picks up between the atoms
(GWs)



Zheng, X., Dolde, J., et al., 2023

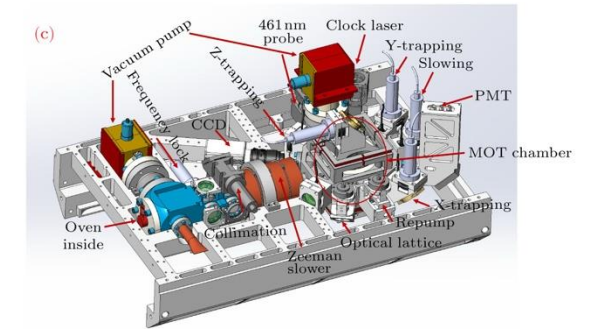
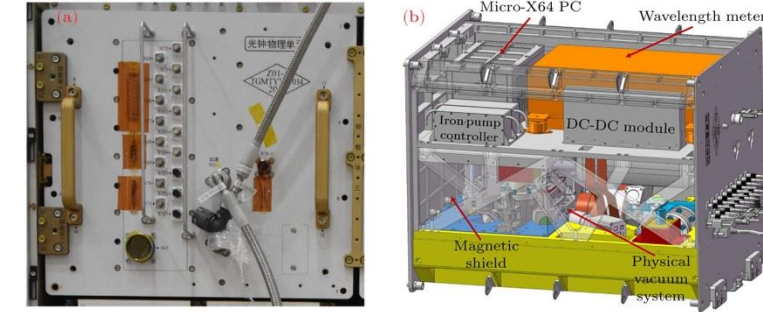
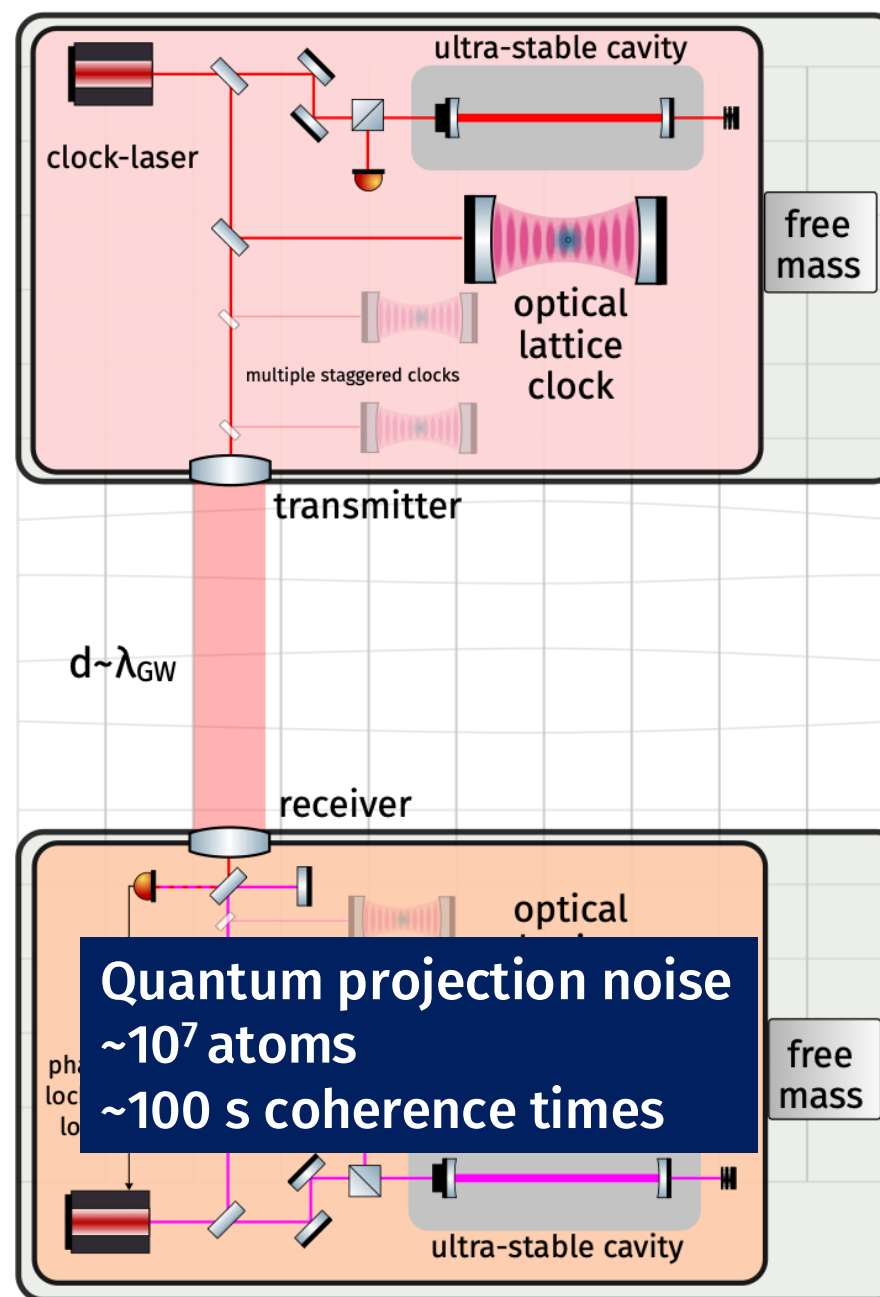
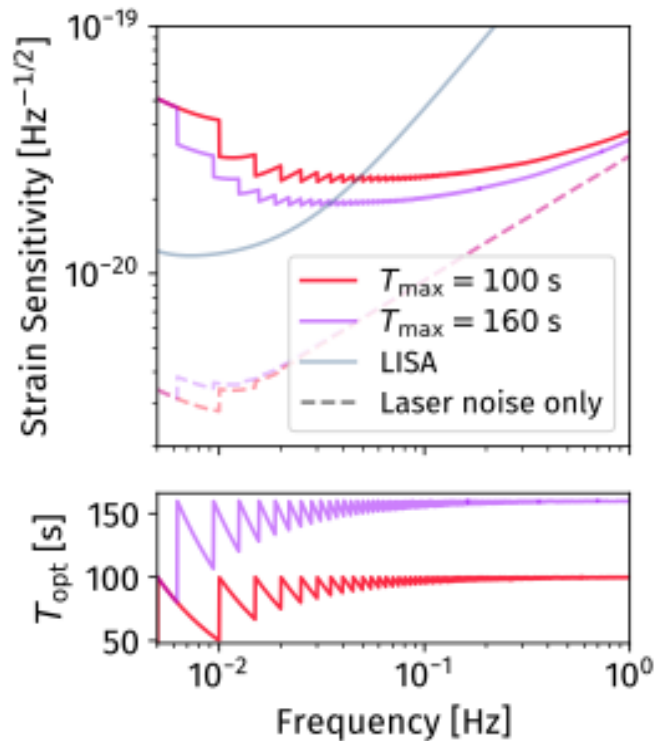
Clocks in Space for GR



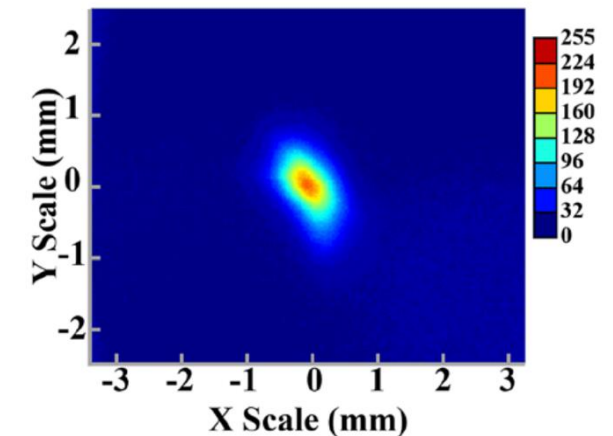
Technology Requirements

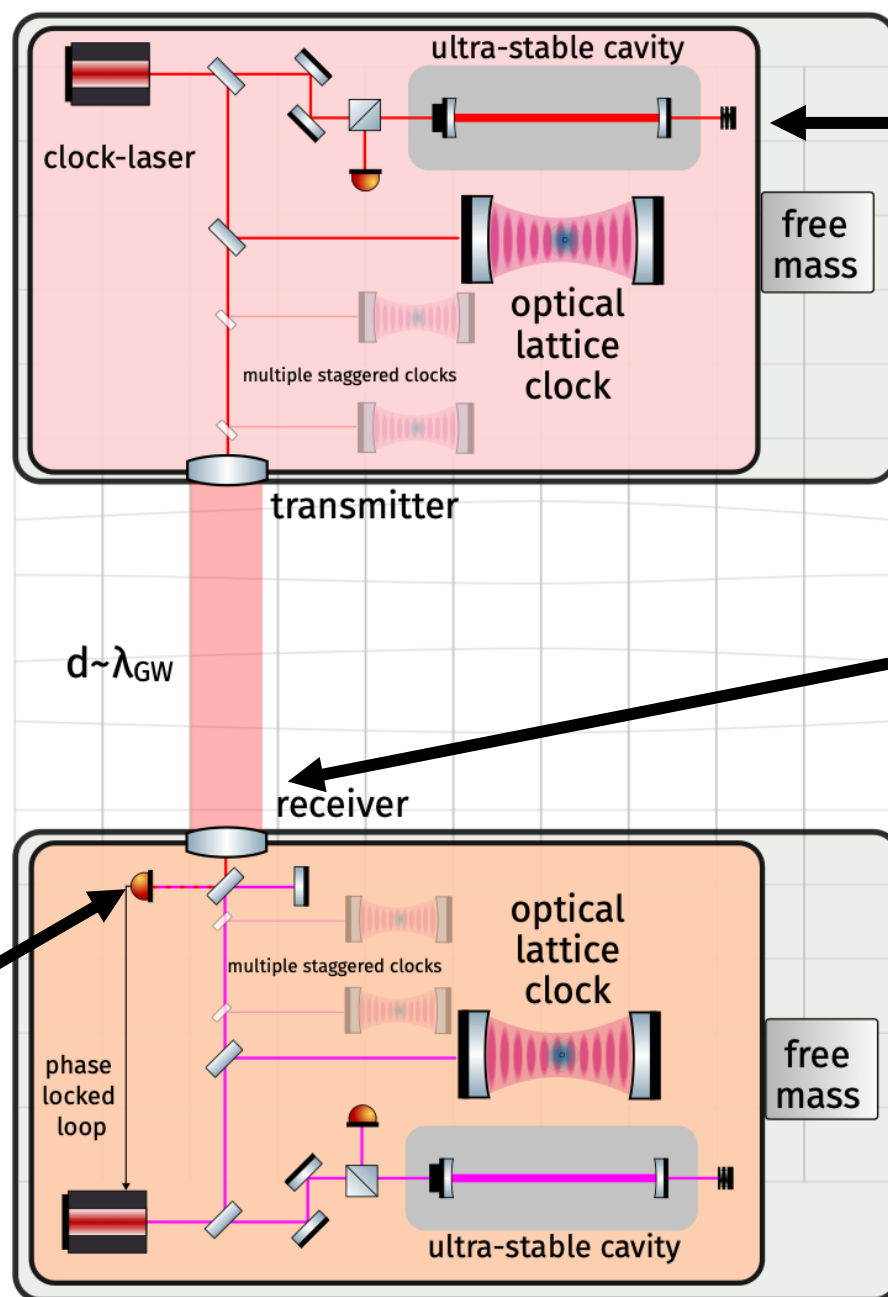
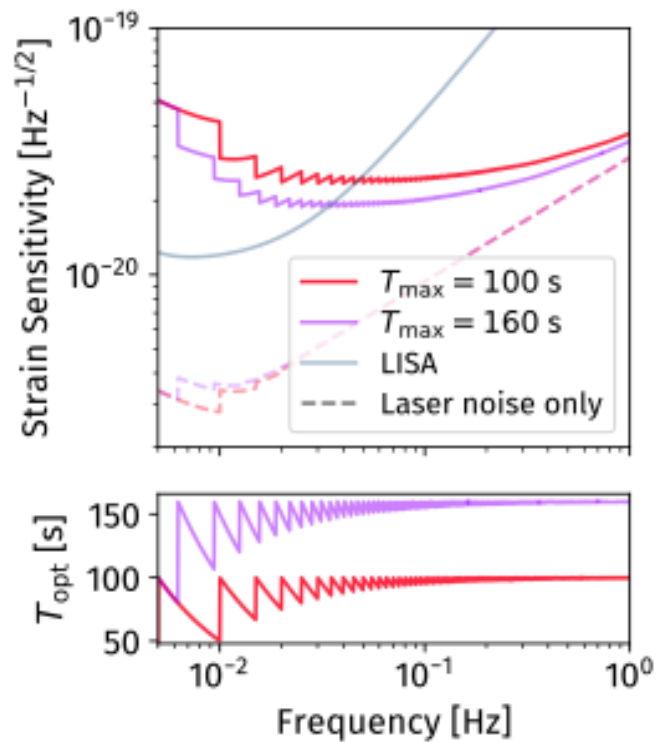
Optical Lattice Clocks in Space!

Need multiple clocks in single spacecraft to implement measurement protocols



J. Xia et al., Review of Scientific Instruments 96, 093201 (2025)

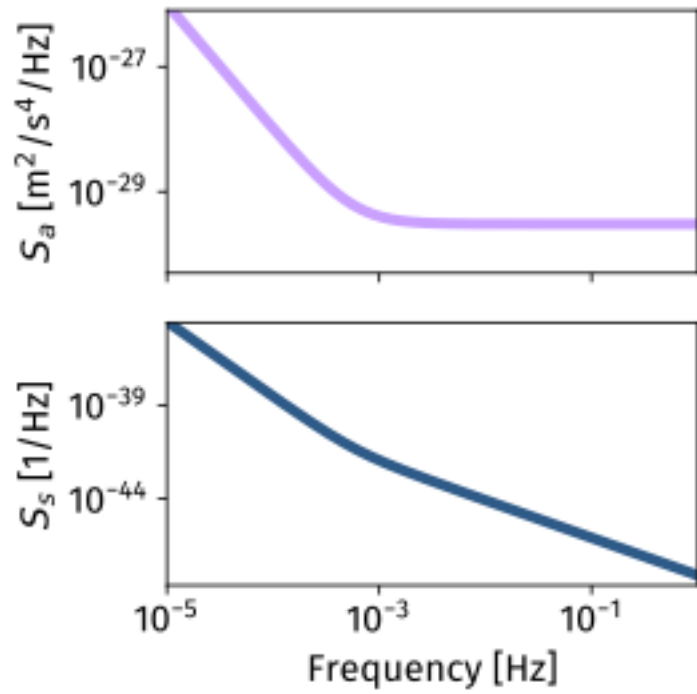




Lower linewidth = lower loop bandwidth, lower noise

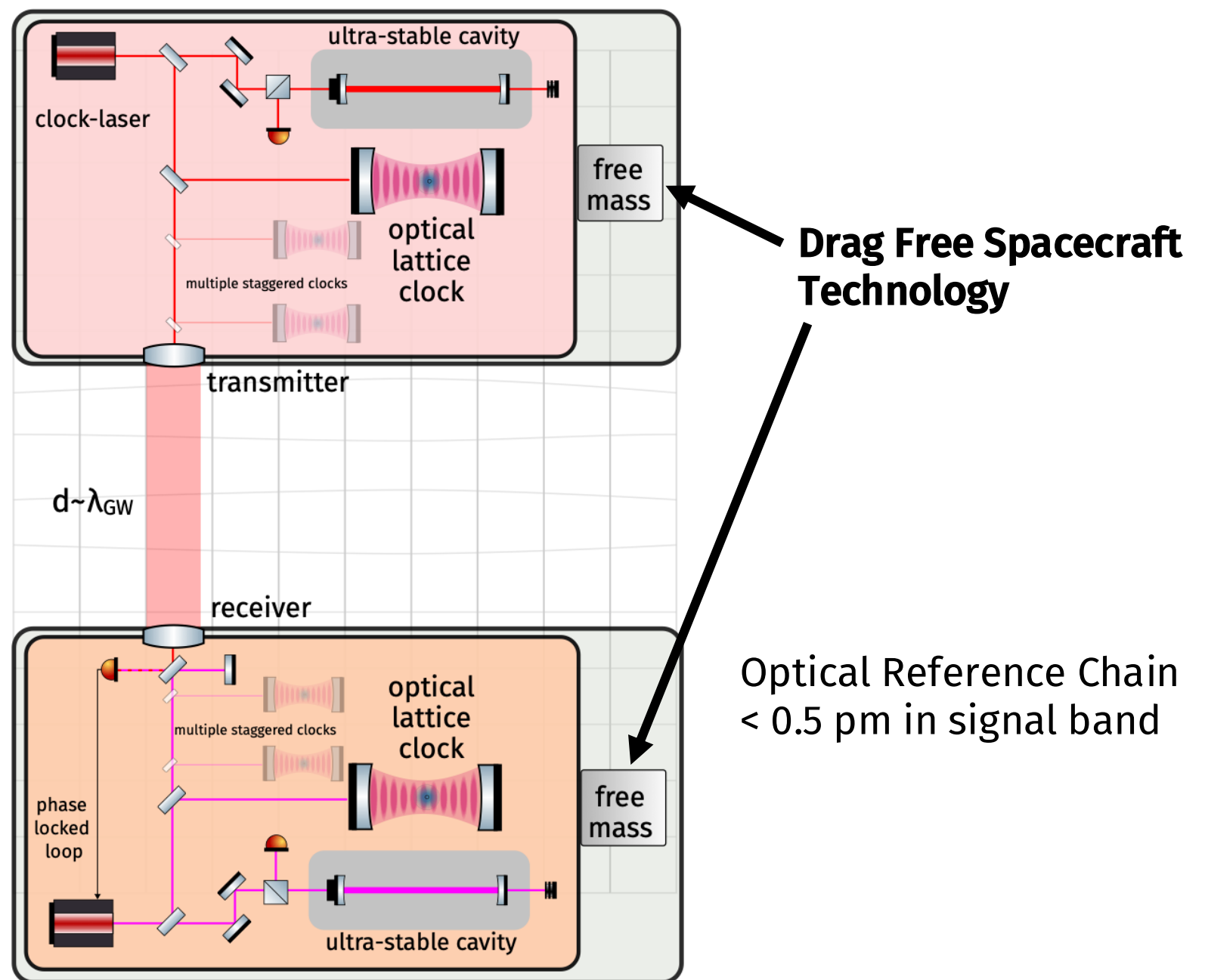
20-200 nW of optical power reqd. for laser noise to be subdominant

Shot Noise Limited Optical Link



LISA Pathfinder Data

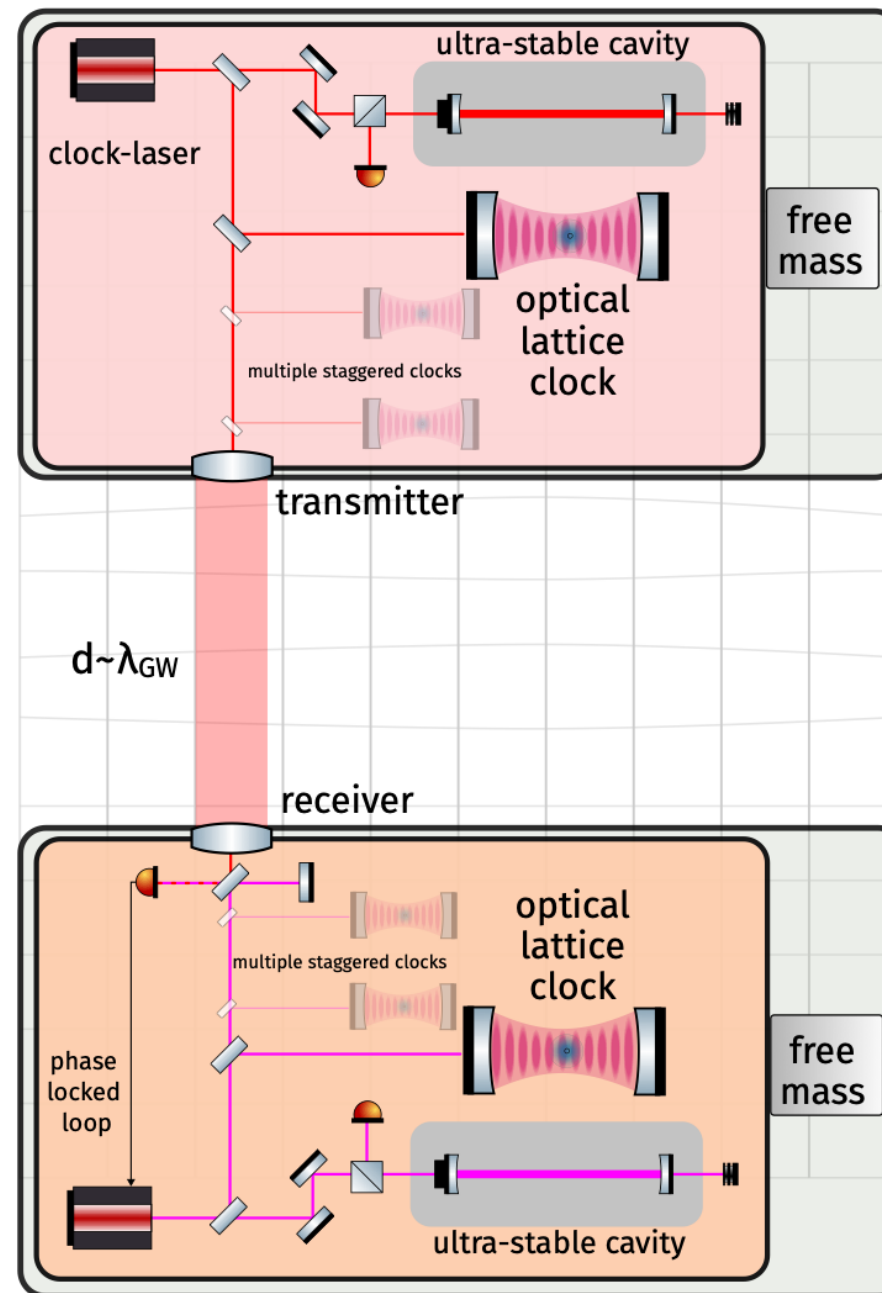
M. Armano et al., Phys. Rev. Lett. 120, 061101 (2018)



Clock Environment Stability

Blackbody radiation shielding < 0.1 mK in signal band

Magnetic field fluctuations < 10 pT in signal band



Optical lattice Req.

- Intensity fluctuations < 10^{-4}
- Frequency Fluctuations < 300Hz

arxiv 2606.05156



Divya
Singh



Sammith
Singamsetty



Shimon Kolkowitz

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