New physics and atomic clocks

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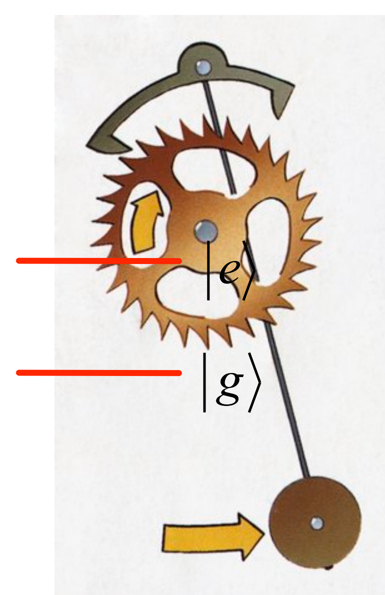
Overview

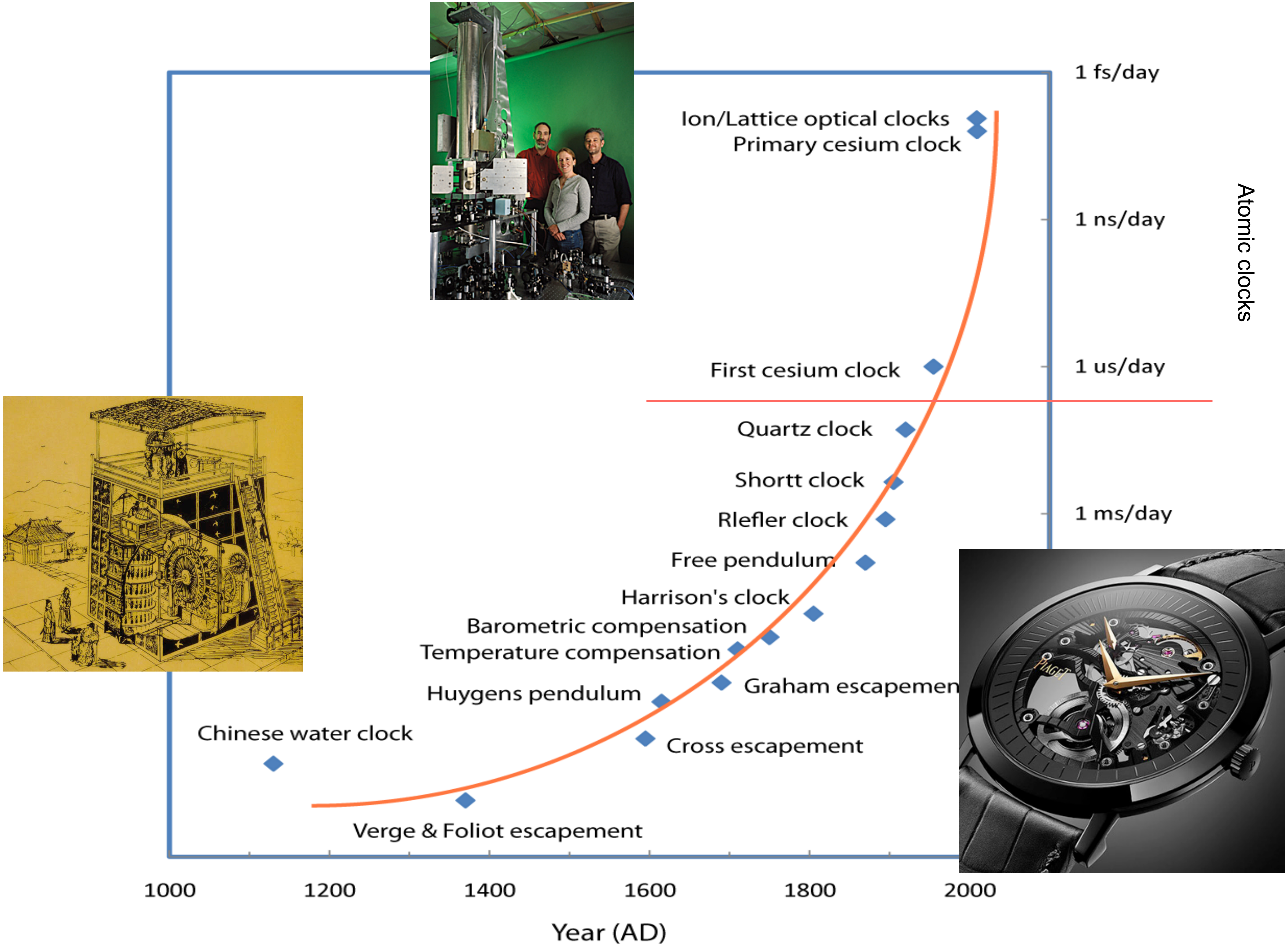
- Atomic clock as quantum sensors
- Atomic clocks and exotic physics
  - Dark matter
  - Quantum gravity signals from black hole mergers

How do we tell time?

Time = (number of oscillations) x (fixed & known period)



$$\nu_{\text{clock}} = \frac{E_e - E_g}{h}$$


1 fs/day
1 ns/day
1 us/day
1 ms/day
Atomic clocks
Ion/Lattice optical clocks
Primary cesium clock
First cesium clock
Quartz clock
Shortt clock
Rlefler clock
Free pendulum
Harrison's clock
Barometric compensation
Temperature compensation
Graham escapemen
Huygens pendulum
Cross escapement
Chinese water clock
Verge & Foliot escapement
1000
1200
1400
1600
1800
2000
Year (AD)

Example of evaluating accuracy

Single-Ion Nuclear Clock for Metrology at the 19th Decimal Place

C. J. Campbell, A. G. Radnaev, A. Kuzmich, V. A. Dzuba, V. V. Flambaum, and A. Derevianko

Phys. Rev. Lett. 108, 120802 (2012)

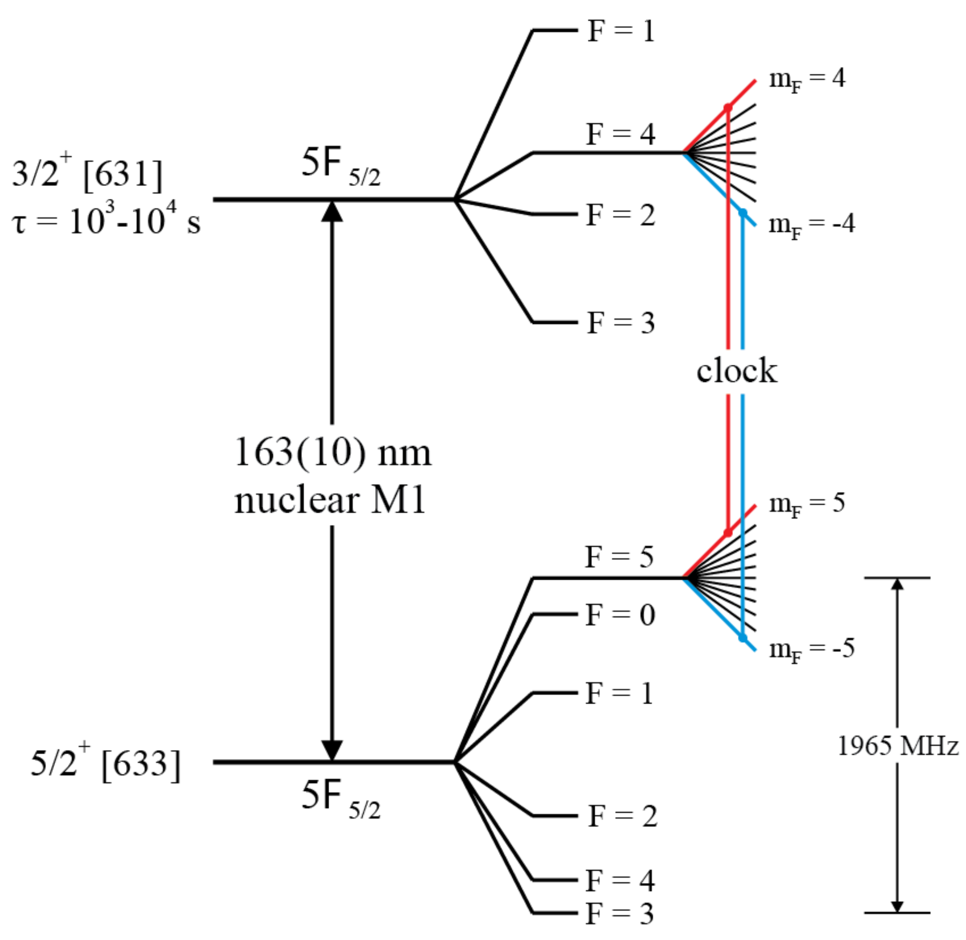
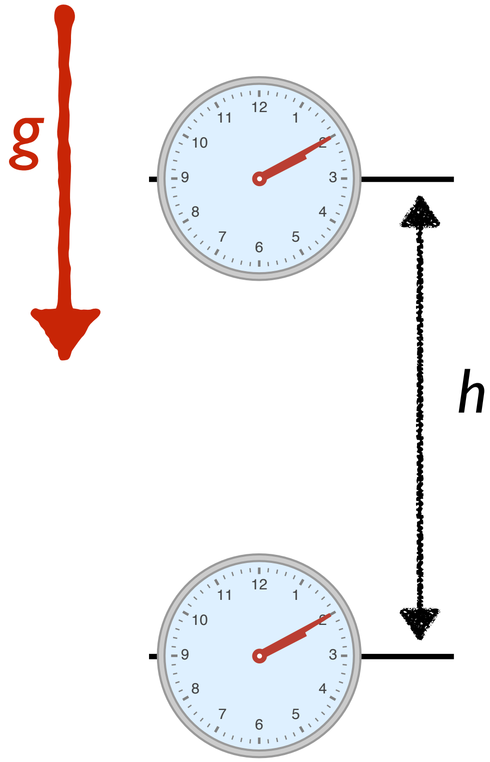


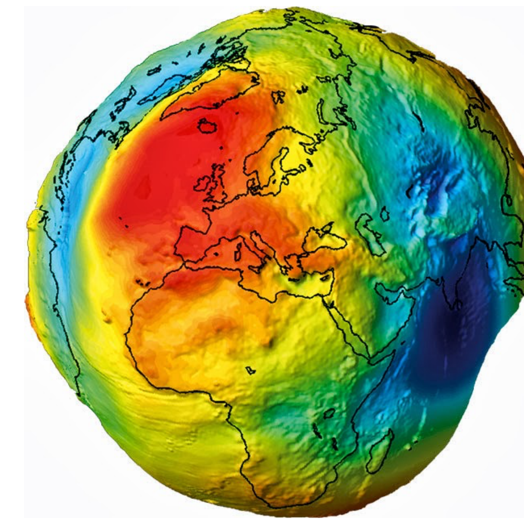
TABLE I. Estimated systematic error budget for a ^{229}Th^{3+} clock using realized single-ion clock technologies. Shifts and uncertainties are in fractional frequency units ($\Delta\nu/\nu_{clk}$) where $\nu_{clk} = 1.8$ PHz. See text for discussion.

Effect	|Shift| (10^{-20})	Uncertainty (10^{-20})
Excess micromotion	10	10
Gravitational	0	10
Cooling laser Stark	0	5
Electric quadrupole	3	3
Secular motion	5	1
Linear Doppler	0	1
Linear Zeeman	0	1
Background collisions	0	1
Blackbody radiation	0.013	0.013
Clock laser Stark	0	$\ll 0.01$
Trapping field Stark	0	$\ll 0.01$
Quadratic Zeeman	0	0
Total	18	15

Relativistic geodesy



$$\frac{\Delta\nu_{\text{gravity}}}{\nu_0} = \frac{gh}{c^2} \quad \Rightarrow \quad 10^{-18} \approx 1\,\text{cm}$$



Geoid = equipotential surface for gravitational field

Atomic clock performance enabling geodesy below the centimetre level

W. F. McGrew[1,2], X. Zhang[1,3], R. J. Fasano[1,2], S. A. Schäffer[1,4], K. Beloy[1], D. Nicolodi[1,2], R. C. Brown[1,8], N. Hinkley[1,2,9], G. Milani[1,5,6], M. Schioppo[1,10], T. H. Yoon[1,7] & A. D. Ludlow[1,2*]

Nature **564**, 87 (2018)

In two independent ytterbium optical lattice clocks, we demonstrate unprecedented values of three fundamental benchmarks of clock performance… Near the surface of Earth, clock comparisons at the 10^{-18} level provide a resolution of one centimetre along the direction of gravity, so the performance of these clocks should enable geodesy beyond the state-of-the-art level.

“Exotic” physics sensors

- Variation of fundamental constants
- Dark matter searches
- Gravitational wave detectors
- Lorentz invariance & EP tests
- Multi-messenger astronomy
- ….

Search for new physics with atoms and molecules

M. S. Safronova, D. Budker, D. DeMille, Derek F. Jackson Kimball, A. Derevianko, and Charles W. Clark
Rev. Mod. Phys. **90**, 025008 – Published 29 June 2018

Dark matter

Dark matter signatures and atomic clocks

Clocks monitor atomic transition frequencies

These depend on fundamental constants

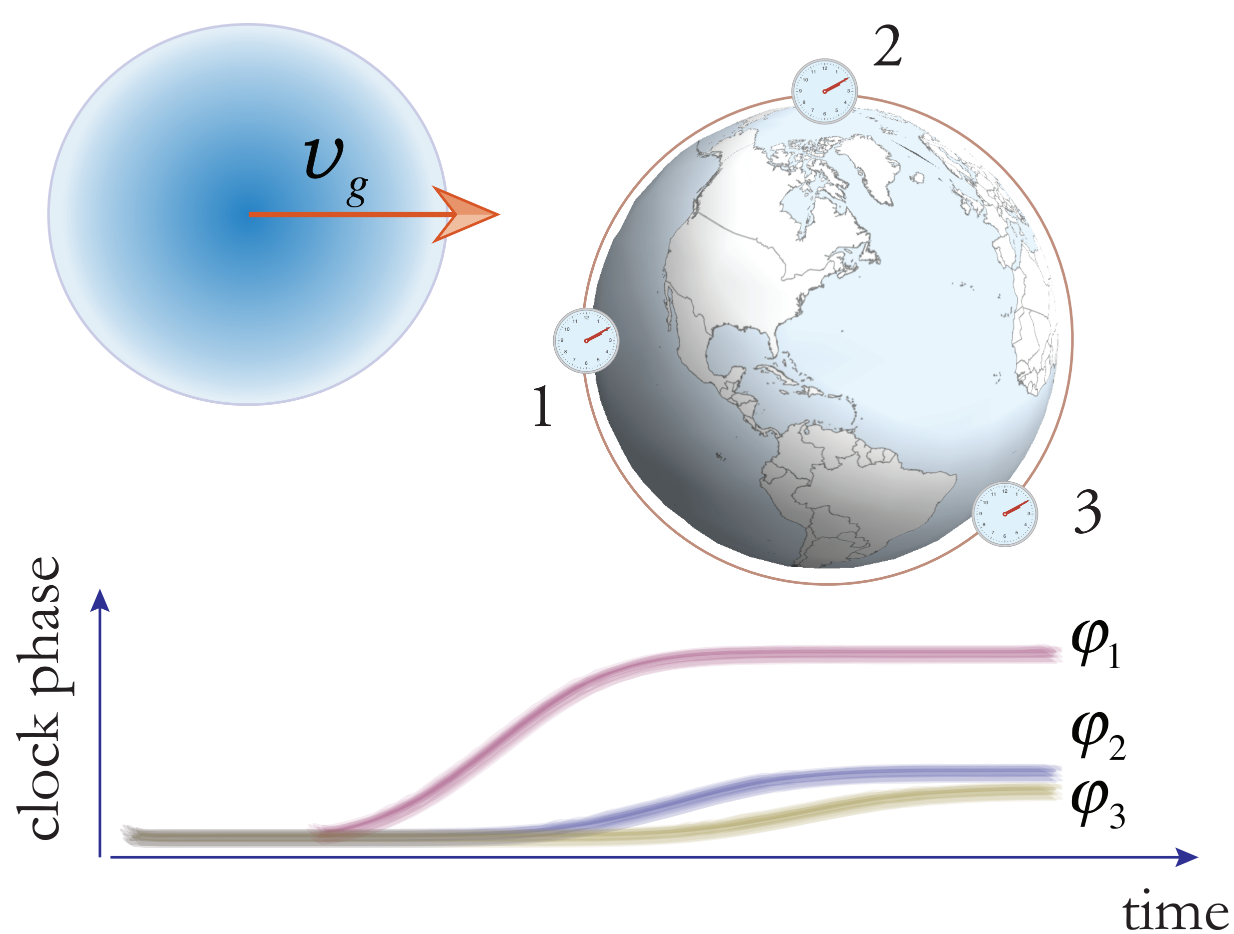
$$\Rightarrow$$

Search for variation of fundamental constants
that is consistent with DM models

nature physics
LETTERS
PUBLISHED ONLINE: 17 NOVEMBER 2014 | DOI: 10.1038/NPHYS3137

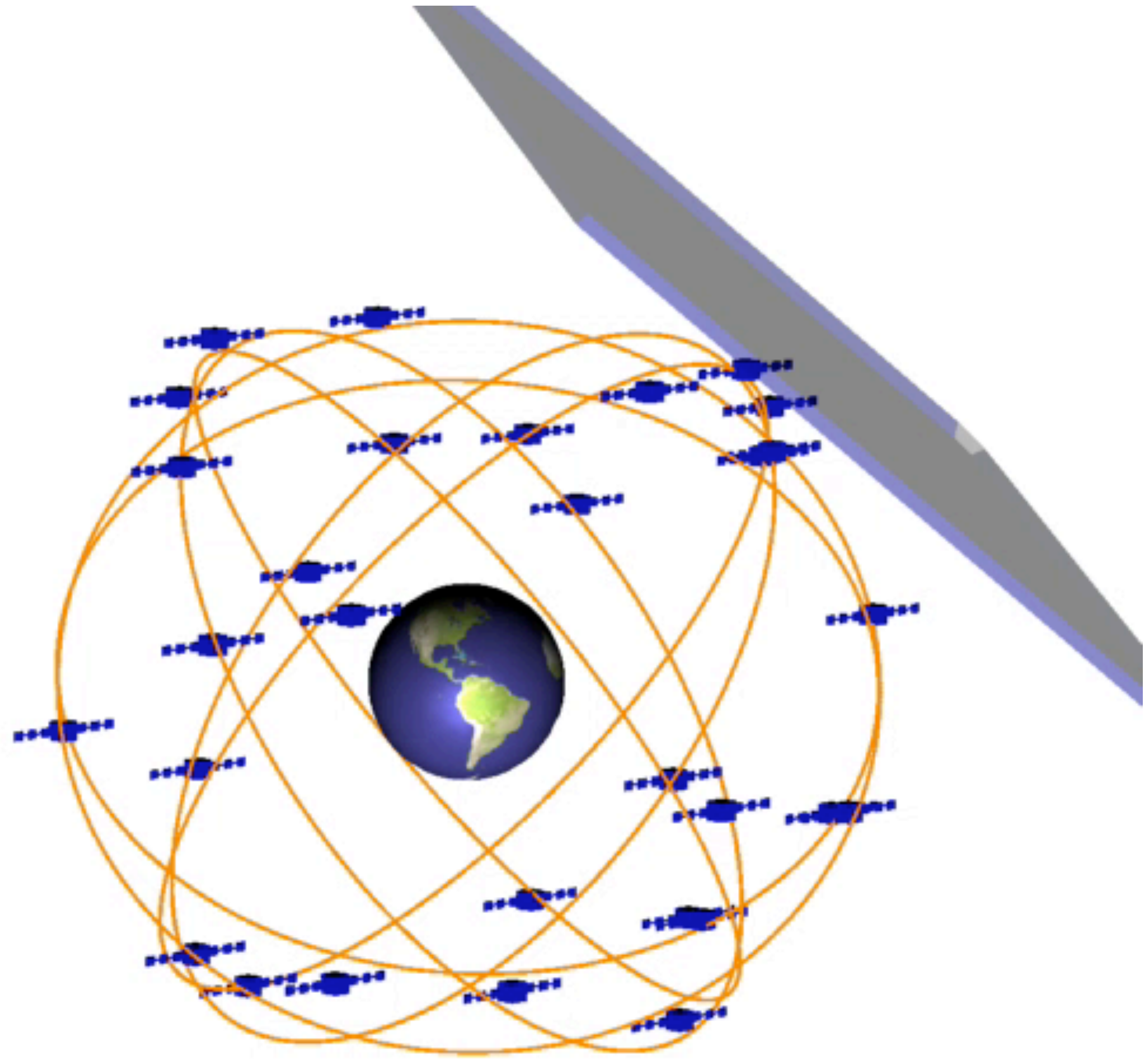
Hunting for topological dark matter with atomic clocks

A. Derevianko[1*] and M. Pospelov[2,3]



Monopole or Q-ball signature

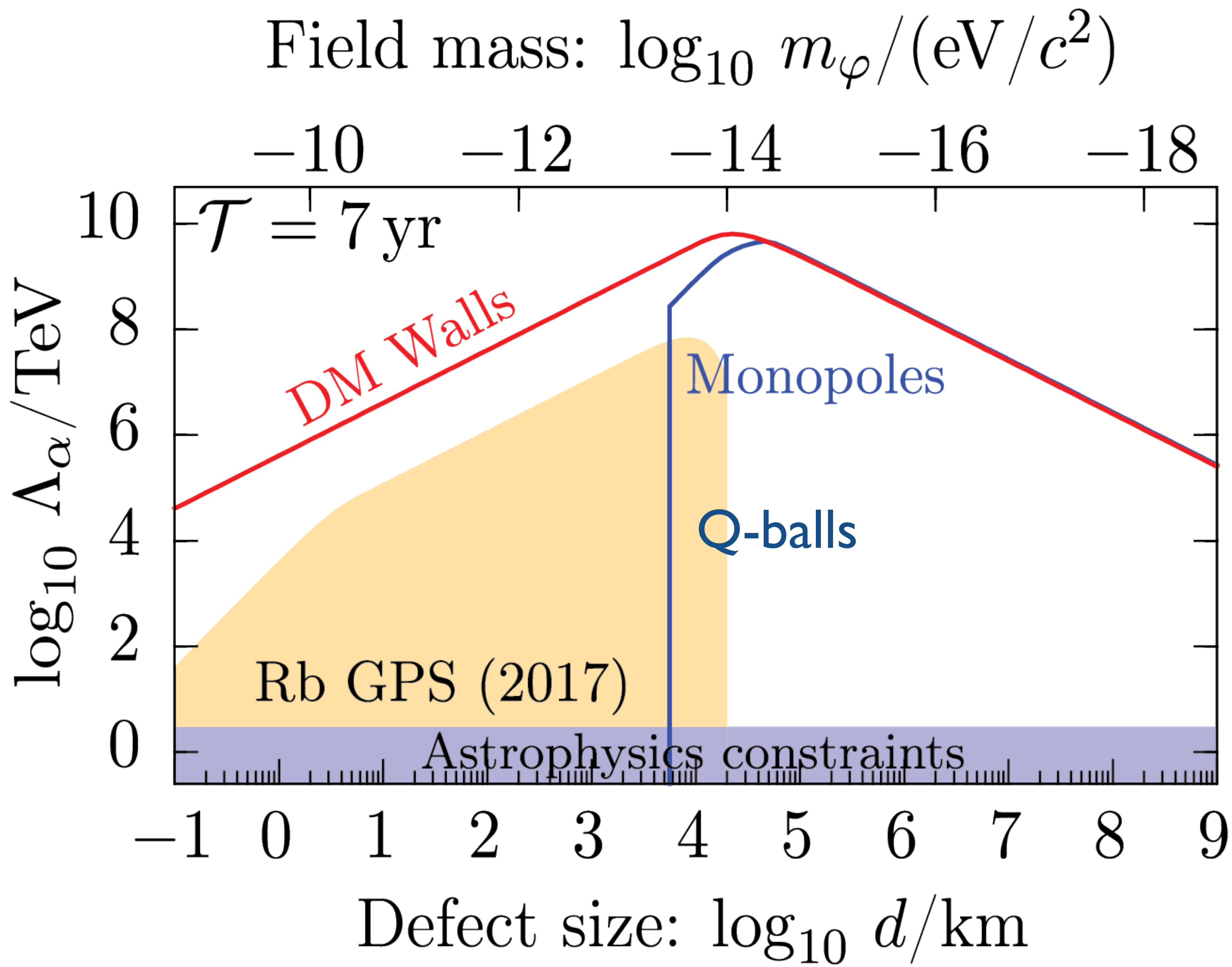
Domain wall GPS sweep



Credit: Conner Dailey

Largest human-built dark matter detector (~50,000 km)
GPS.DM collaboration
~20 years of archival GPS data

GPS.DM discovery reach

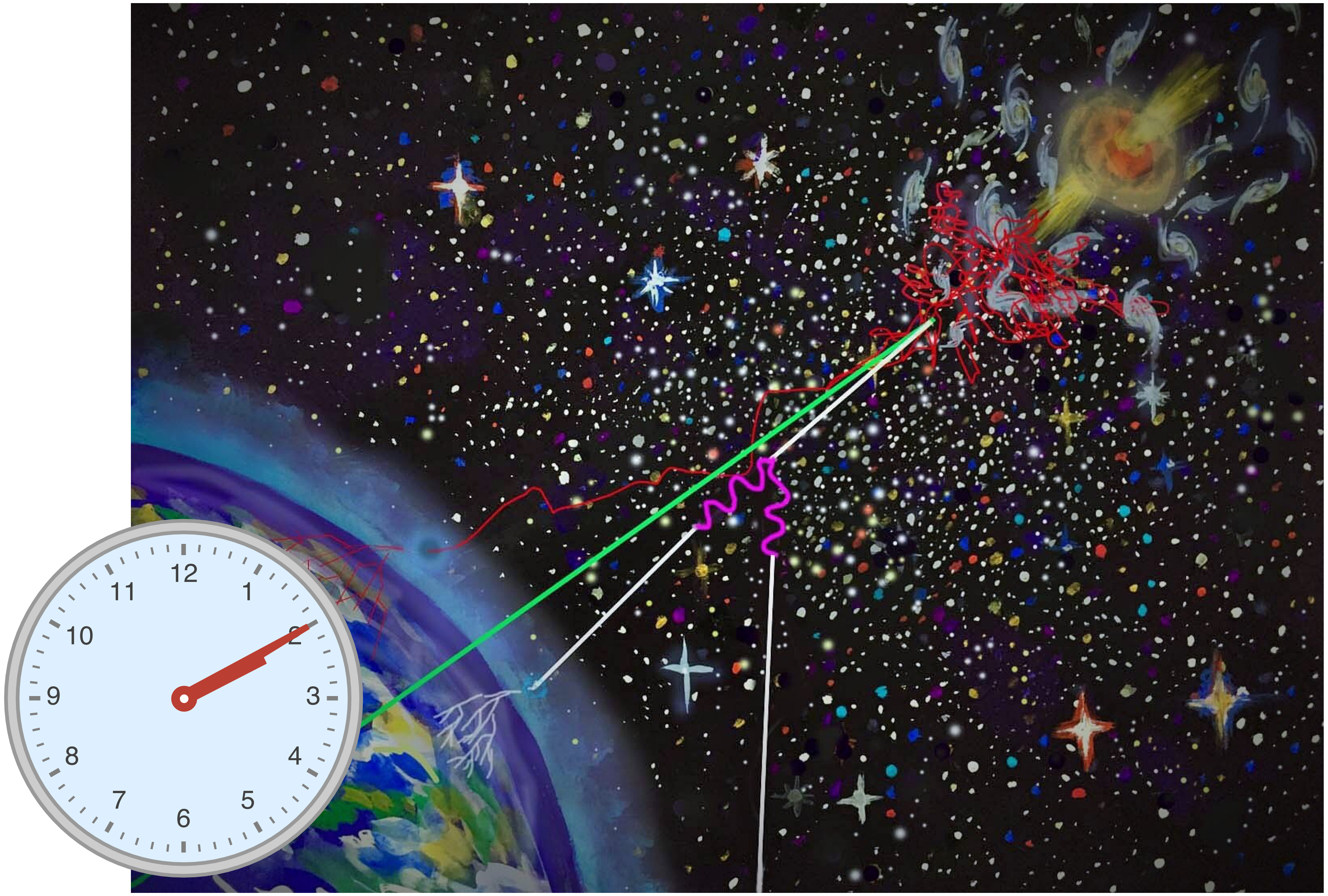


B. M. Roberts, G. Blewitt, C. Dailey, and A. Derevianko, PRD 97, 83009 (2018)

Nature Commun. **8**, 1195 (2017)

Current efforts: Tyler Daykin

Sourced exotic fields

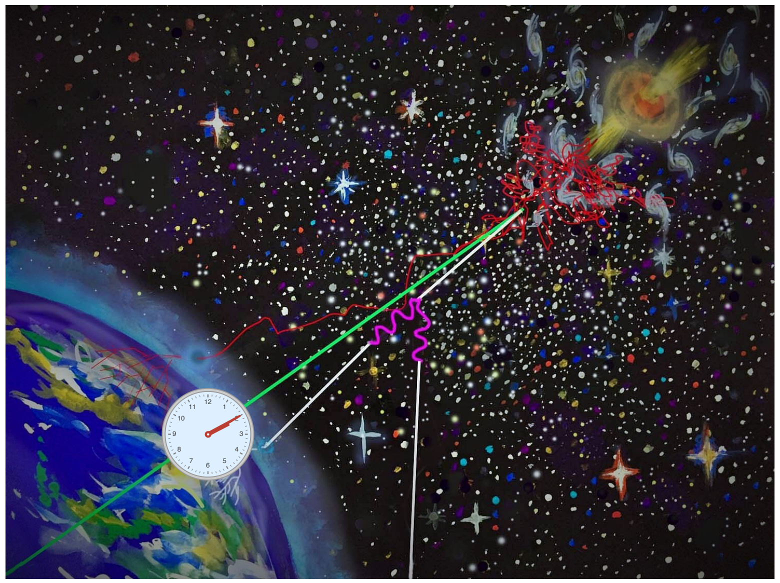


LETTERS
https://doi.org/10.1038/s41550-020-01242-7
nature astronomy

Quantum sensor networks as exotic field telescopes for multi-messenger astronomy

Conner Dailey[1], Colin Bradley[1], Derek F. Jackson Kimball[2], Ibrahim A. Sulai[3], Szymon Pustelny[4], Arne Wickenbrock[5] and Andrei Derevianko[1]✉

Multi-messenger astronomy



GW170817

Merger of two neutron stars (Aug 17, 2017)

Host galaxy 40 megaparsecs away

Trigger: gravitational waves detected by LIGO–Virgo

The source was observed in a comprehensive campaign across the electromagnetic spectrum
- in the X-ray, ultraviolet, optical, infrared, and radio bands
- over hours, days, and weeks.

Can we see the merger in the GPS atomic clock data?

Exotic Low-mass Fields (ELFs)

- Modern clocks are not sensitive to gravitational waves

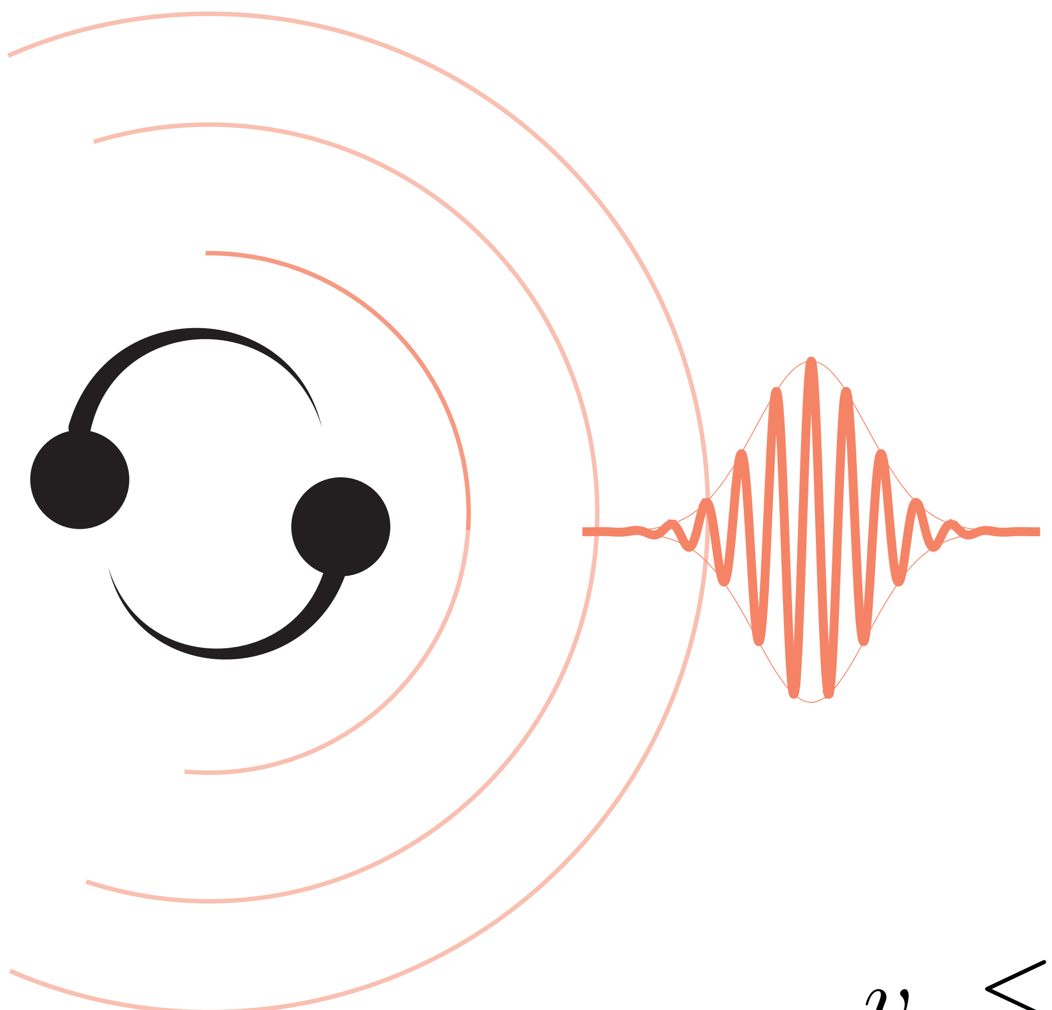
- Exquisite sensitivity to "new" physics beyond Standard model (BSM)
- Focus on exotic, BSM, scalar (S=0) fields:
  - abundant in BSM theories [axions, dilatons, relaxions, etc]
  - can solve the hierarchy & strong-CP problems
  - dark-matter candidates

ELFs as a signature of quantum gravity?

- Coalescing singularities in black hole mergers?
  yet unknown theory of quantum gravity
- Scalar-tensor gravity.
  BH and NS immersed in the scalar field. Modes can be excited during the merger.
  Dynamic scalarization + monopole scalar emission
- Scalar fields can be trapped in neutron stars - released during the merger
- Clouds of scalars (superatoms) around black holes
  up to 10% of BH mass is in the cloud
- Direct production
  (e.g., $\gamma + \gamma \to \phi + \phi$ or $N + N \to N + N + \phi + \phi$)

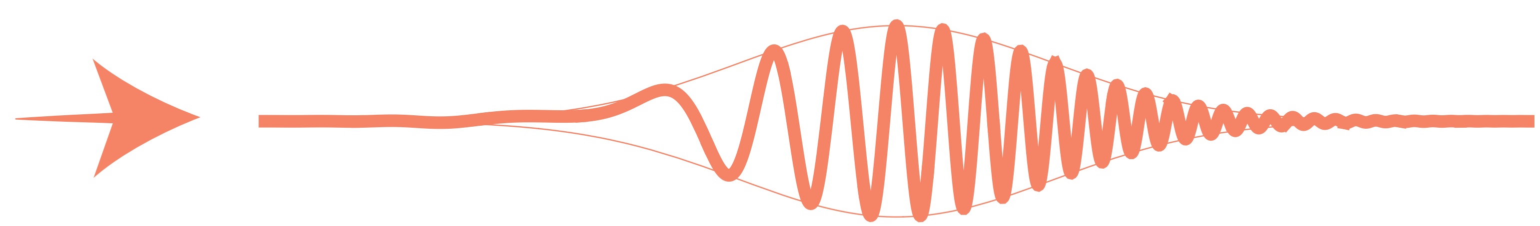
A pragmatic observational approach based on energy arguments:

ELF channel energy $\Delta E =$ fraction of $M_{\odot} c^2$



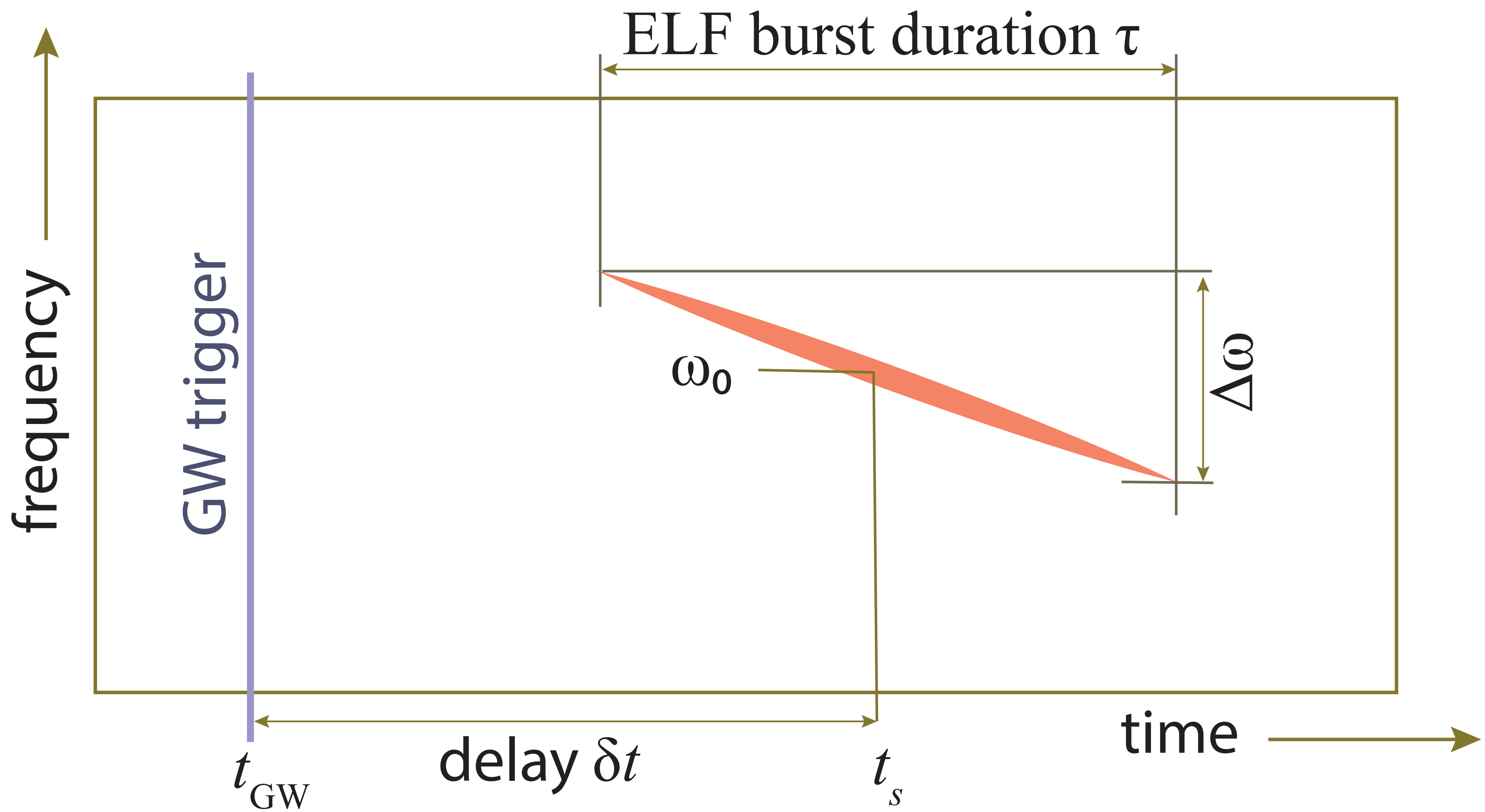
$\Rightarrow$ Signal at the sensor?

$$v_g \lesssim c$$



Nearly universal wave-form independent of the production mechanism

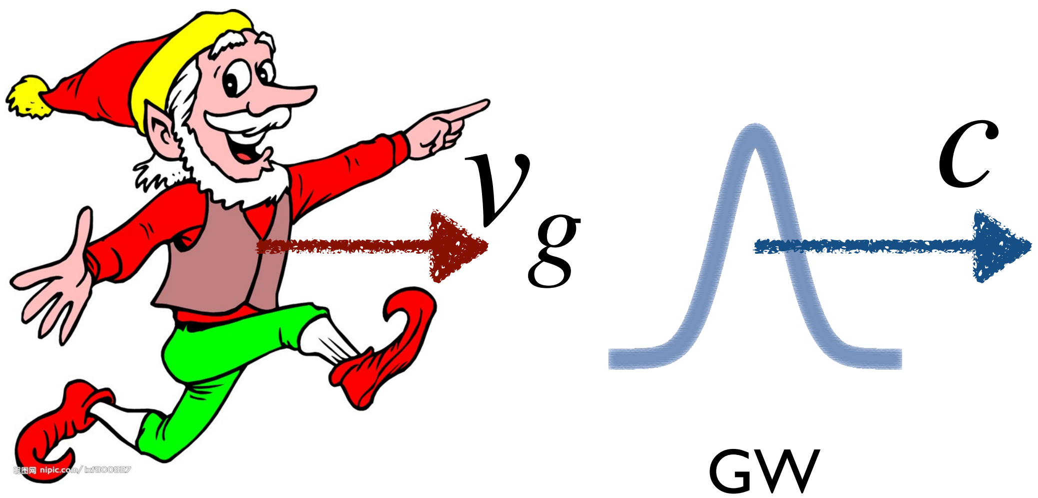
ELF power spectrum template



Anti-chirp is independent of the production mechanism

What kind of ELFs can we detect?

Gravitational wave travels @ c over 10^8 light-years



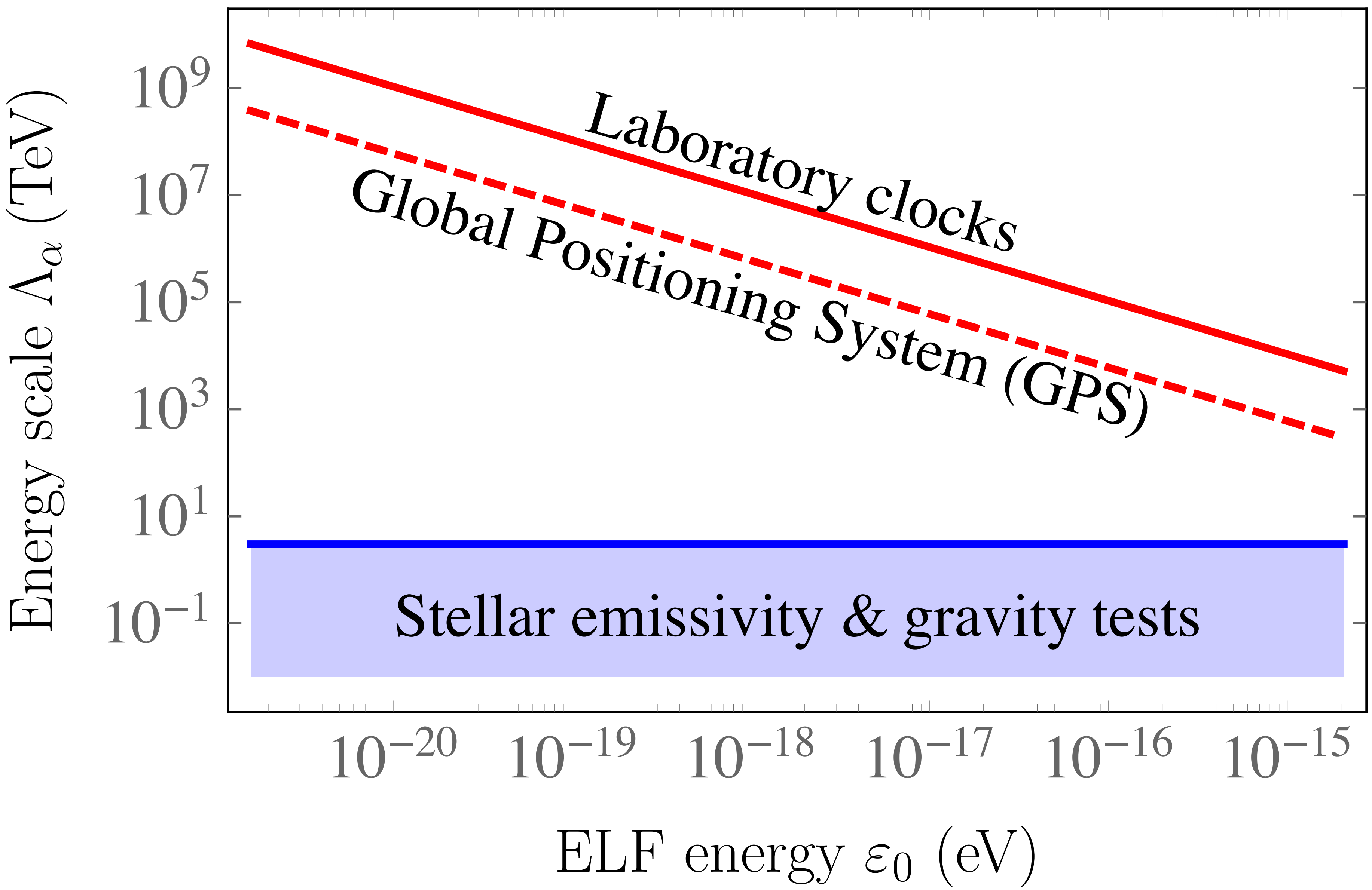
Reasonable time delay < a week $\Rightarrow v_g \approx c$

1. ELFs must be **ultrarelativistic**: $mc^2 \ll \varepsilon = \hbar\omega$

2. For a clock, $\max(\omega) = 2\pi$ Hz $\Rightarrow m \ll 10^{-14}\,\mathrm{eV}$

   ELFs must be **ultralight**

Projected sensitivity GW170817 (NS+NS)



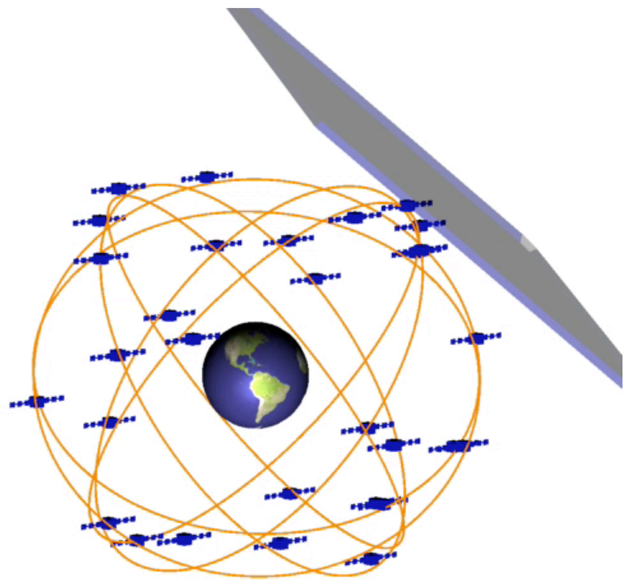
$\Delta E_{\mathrm{ELF}} = 0.1\, M_\odot c^2$

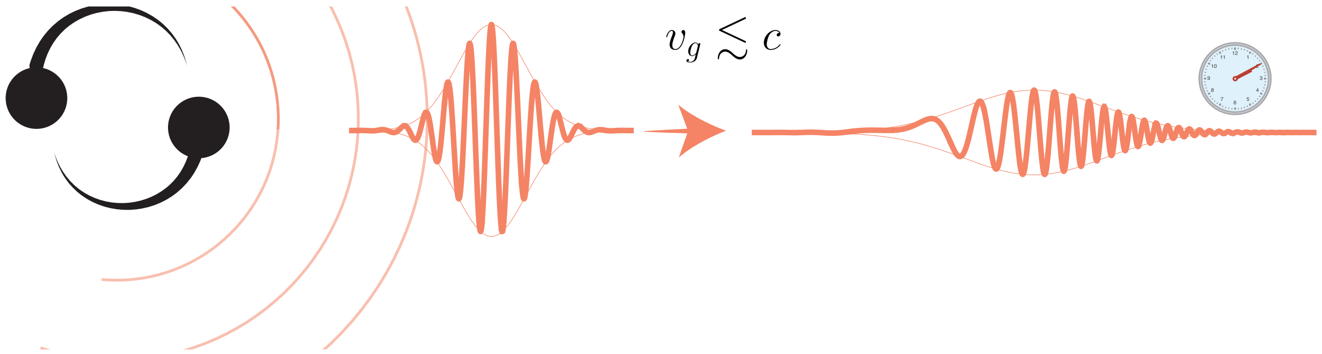
$R = 40\,\mathrm{Mpc}$

$$\mathscr{L} \supset \left(-\frac{m_e c^2 \bar{\psi}_e \psi_e}{\Lambda_{m_e}^2} + \frac{1}{4\Lambda_\alpha^2} F_{\mu\nu}^2 \right) \phi^2$$

Data analysis results both from GPS and GNOME to appear soon…

Summary





Other ideas?

How can we test non-commutativity of space and time?