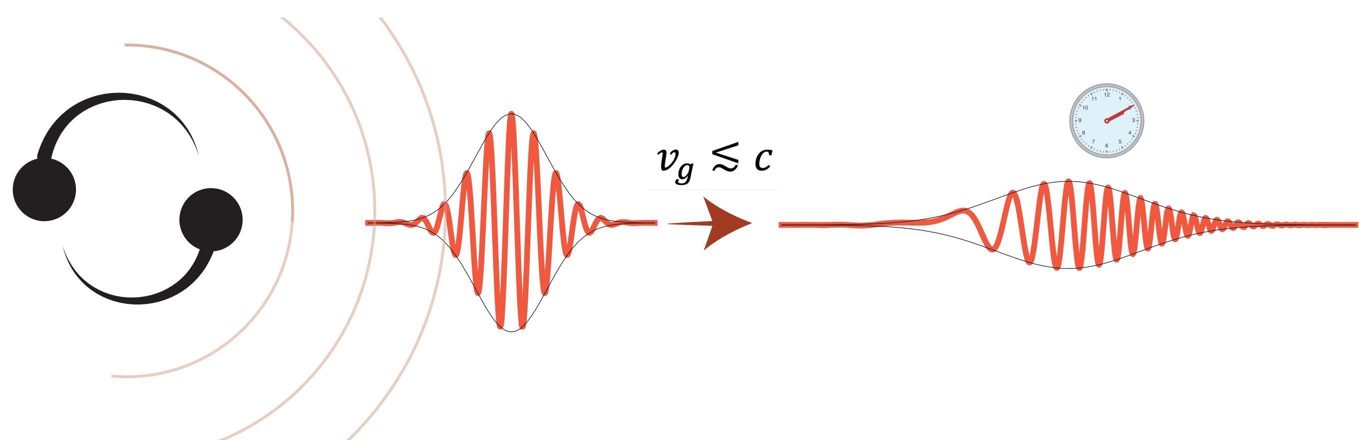
Quantum sensors and their networks as exotic field telescopes for multi-messenger astronomy

Andrei Derevianko
University of Nevada, Reno, USA



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NASA
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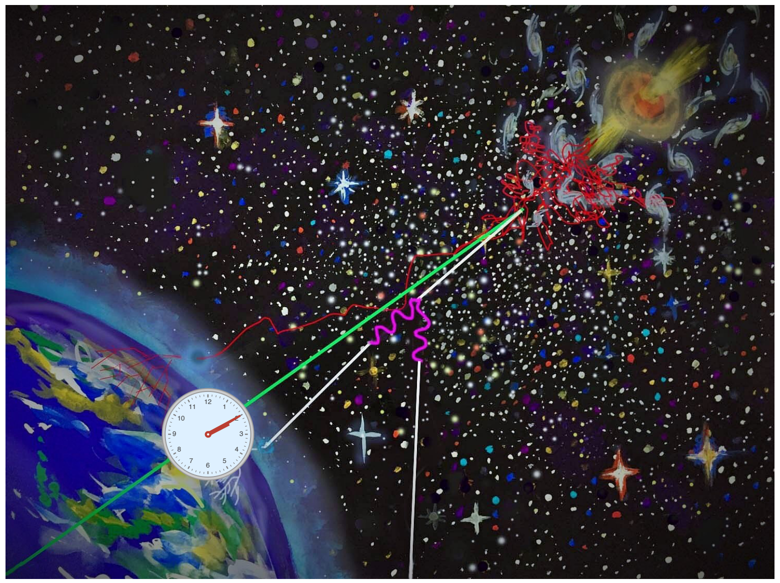
JOHN TEMPLETON FOUNDATION

Merger of two neutron stars (Aug 17, 2017)

Credit: ESO/L. Calçada. Music: Johan B. Monell (www.johanmonell.com)

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.

Direct detection of exotic physics messengers?

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

nature astronomy

Check for updates

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]✉

Nature Astronomy, 5, 150–158 (2021)

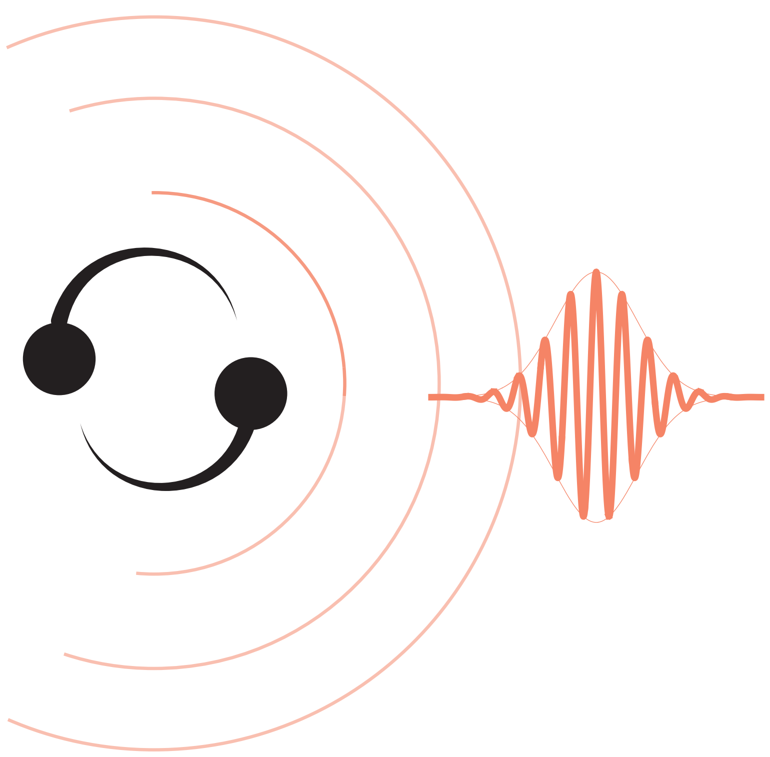
Arne Wickenbrock GNOME talk today @ 15:00

Exotic Low-mass Fields (ELFs) as exotic physics messenger

Exotic Low-mass Fields (ELFs)

Focus on exotic, BSM, (pseudo-) scalar fields:

- abundant in BSM theories [axions, dilatons, relaxions, etc]
- can solve the hierarchy (dilatons) & strong-CP problems (axions)
- dark-matter candidates

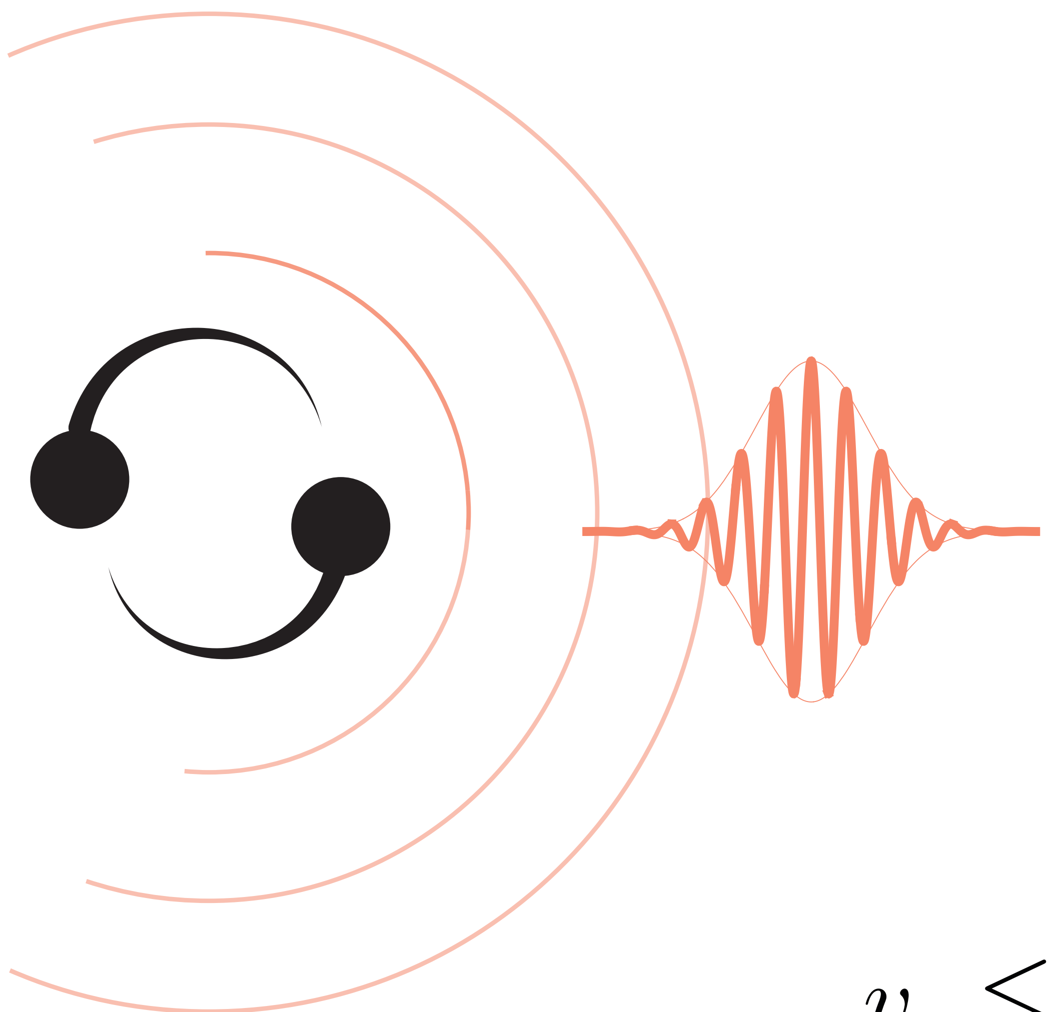


ELFs as a signature of quantum gravity?

- 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 $N + N \to N + N + \phi + \phi$)

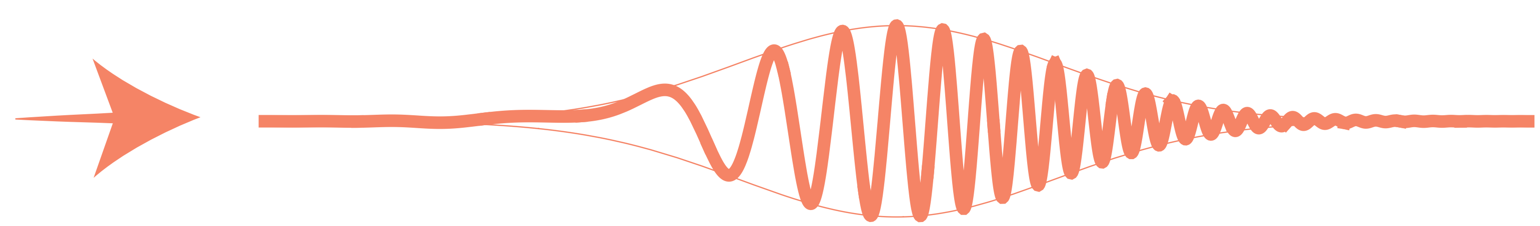
A pragmatic observational approach based on energy arguments:

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



$\Rightarrow$ Signal at the sensor?

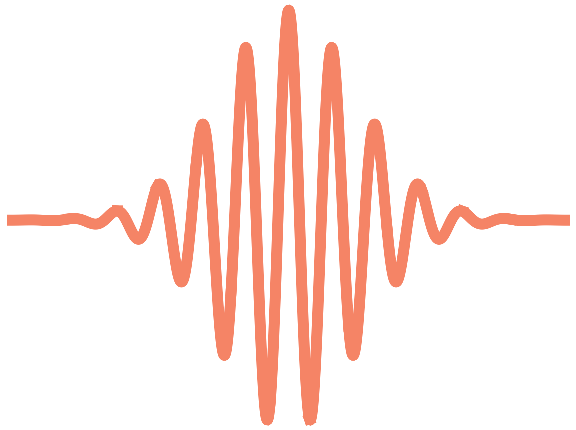
$$v_g \lesssim c$$



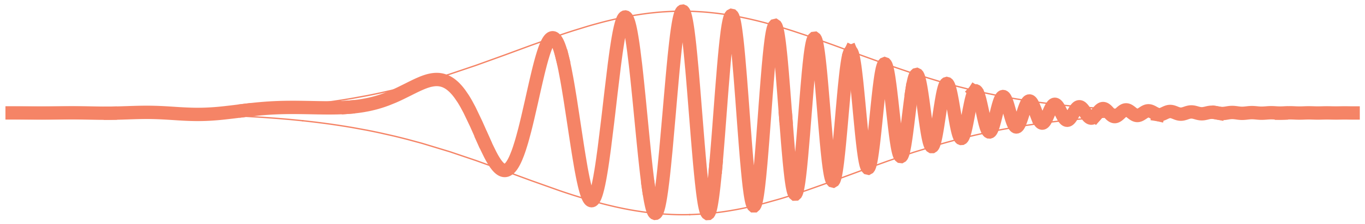
Nearly universal wave-form independent of the production mechanism

Anti-chirp signature

- Start with a Gaussian pulse (ω_0, τ_0)



- higher frequency ω have larger momenta $\hbar k \Rightarrow$
  Higher frequencies arrive earlier!

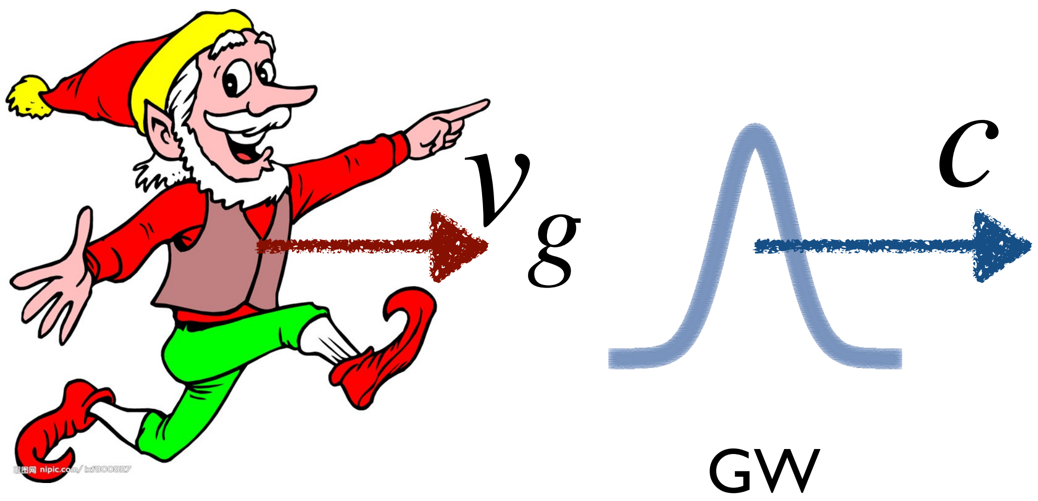


- Instantaneous frequency chirp

$$\frac{d\omega}{dt} < 0$$

What kind of ELFs can we detect?

Gravitational wave travels @ c over $\sim 10^8$ 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 $\Rightarrow m \ll 10^{-14}\,\mathrm{eV}$

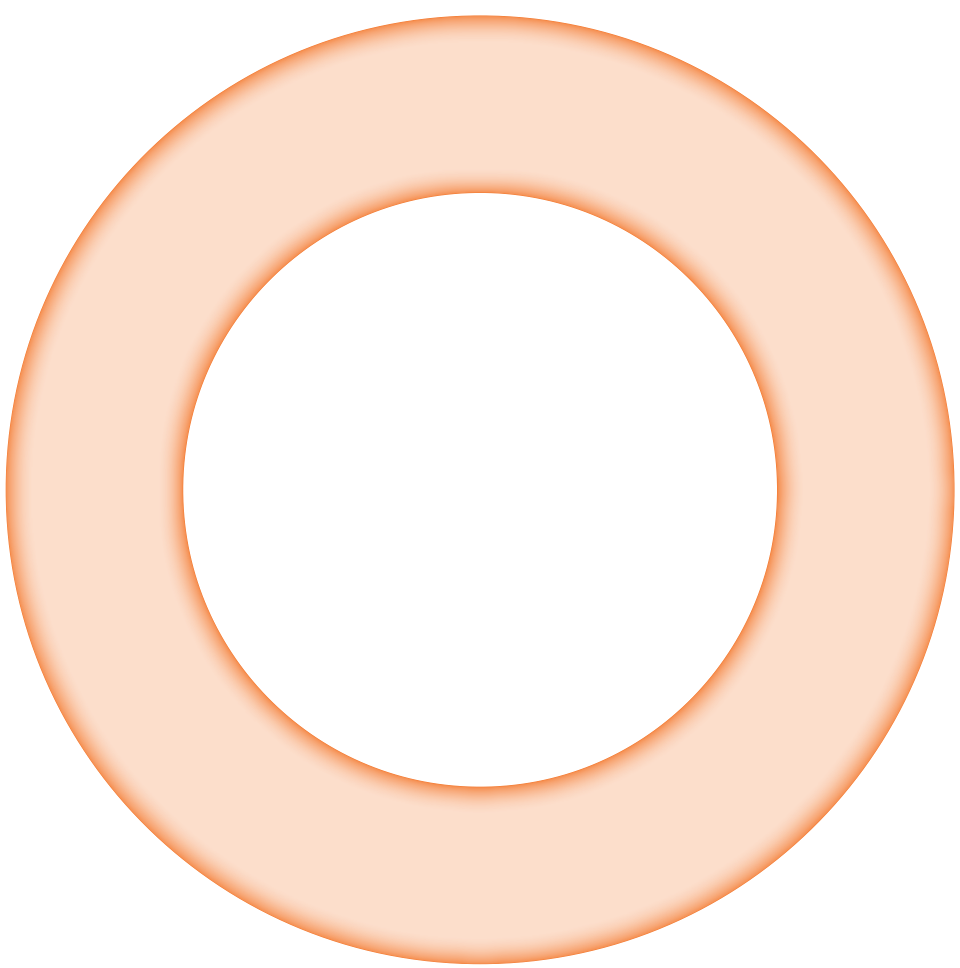
ELFs must be **ultralight**

Energetics

Copious emission

$$\frac{\Delta E = \text{fraction of } M_{\odot} c^2}{\varepsilon = 10^{-10}\,\text{eV}} \sim 10^{70}\,\text{ELFs}$$

Large mode occupation numbers => classical field all the way to the sensor



$$\varphi \sim \frac{1}{R} \quad \left(\sim \frac{1}{R^{3/2}} \text{with dispersion} \right)$$

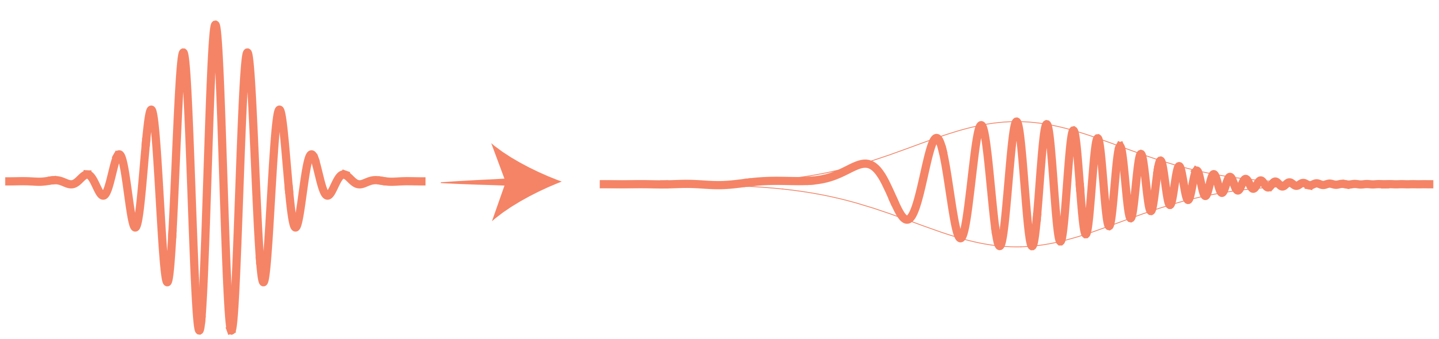
Scalar waves are like E&M waves

"Internal" refractive index (ultrarelativistic scalars)

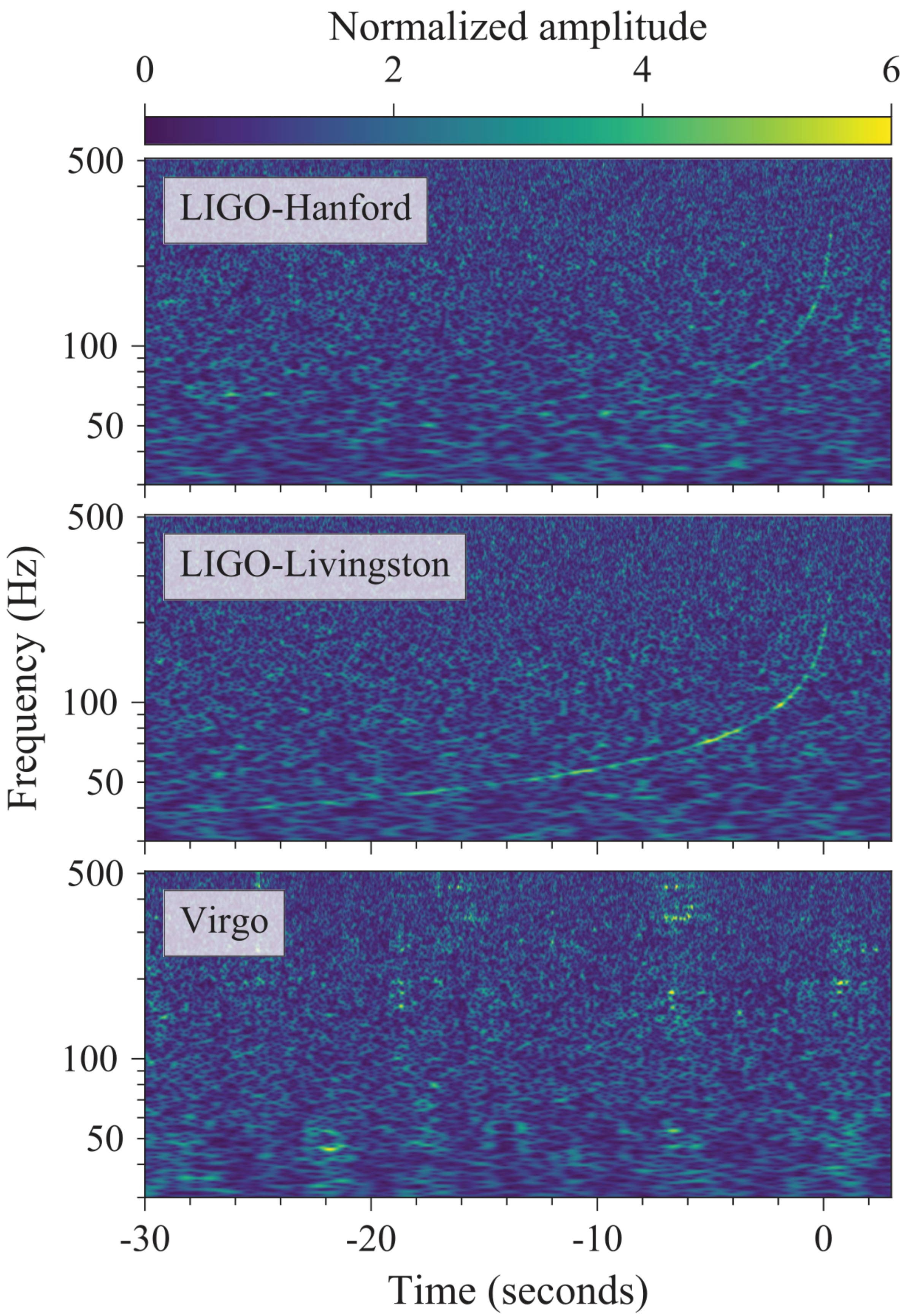
$$n(\omega) \approx 1 - \frac{1}{2}\frac{mc^2}{\hbar\omega}$$

Most of Jackson E&M problems/intuition can be directly transferred

- Group velocity $v_g \lesssim c$
- Dispersive propagation

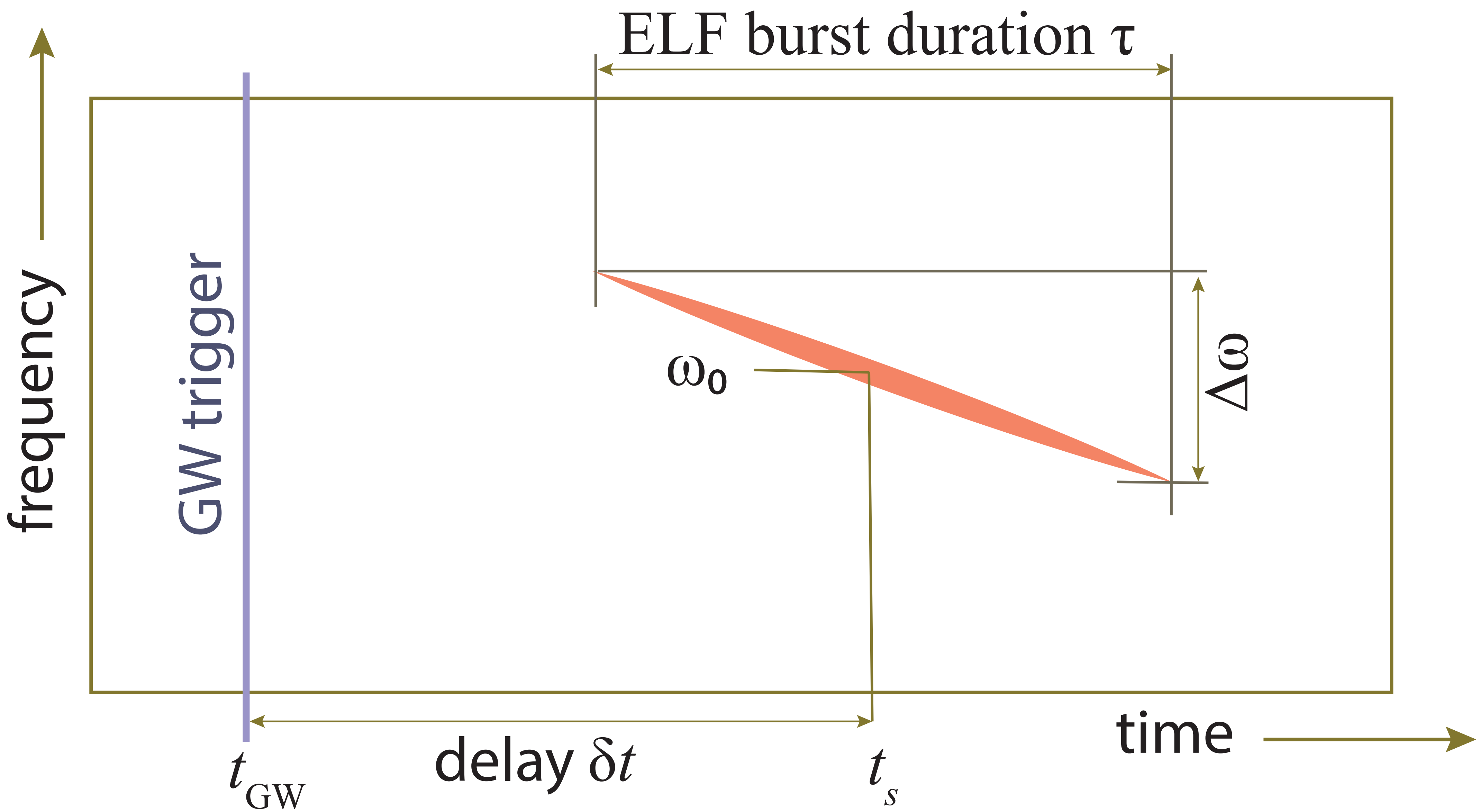


LIGO style time-frequency map



1. Chop data stream into equal chunks,
2. Discrete Fourier Transform in each window
3. Each tile = (window time stamp, frequency)
4. Compute power spectral density in each tile

ELF power spectrum template



Anti-chirp is independent of the production mechanism

Quantum sensors

Quantum sensors

A quantum sensor is any device whose performance relies on quantum mechanics to detect quantities of interest

- quantized energy levels
- superposition
- coherence
- quantum statistics
- entanglement/squeezing (QS 2.0)

Exquisite sensitivity gains

Examples:
atomic clocks, magnetometers, NV centers in diamond, interferometers, optomechanical oscillators, …

Atomic clocks and exotic physics

- Lock laser/mw frequencies in resonance with atomic transition frequencies
- Quantum oscillator is well protected from environment => exotic physics sensor

Exotic physics channel: variation of fundamental constants of nature

$$\nu_{\text{clock}}\left(\alpha, \frac{m_q}{\Lambda_{\text{QCD}}}, \frac{m_e}{m_p}\right) \quad \oplus \quad \mathscr{L} \supset \left(-\frac{m_e c^2 \bar{\psi}_e \psi_e}{\Lambda_{m_e}^2} + \frac{1}{4\Lambda_\alpha^2} F_{\mu\nu}^2\right)\phi^2$$

$$\frac{\delta\nu(t)}{\nu_0} = \sum_{X=\text{fnd consts}} K_X \frac{\delta X(t)}{X} = K_\alpha \frac{\delta\alpha(t)}{\alpha} + \ldots$$

↑

Sensitivity coefficients

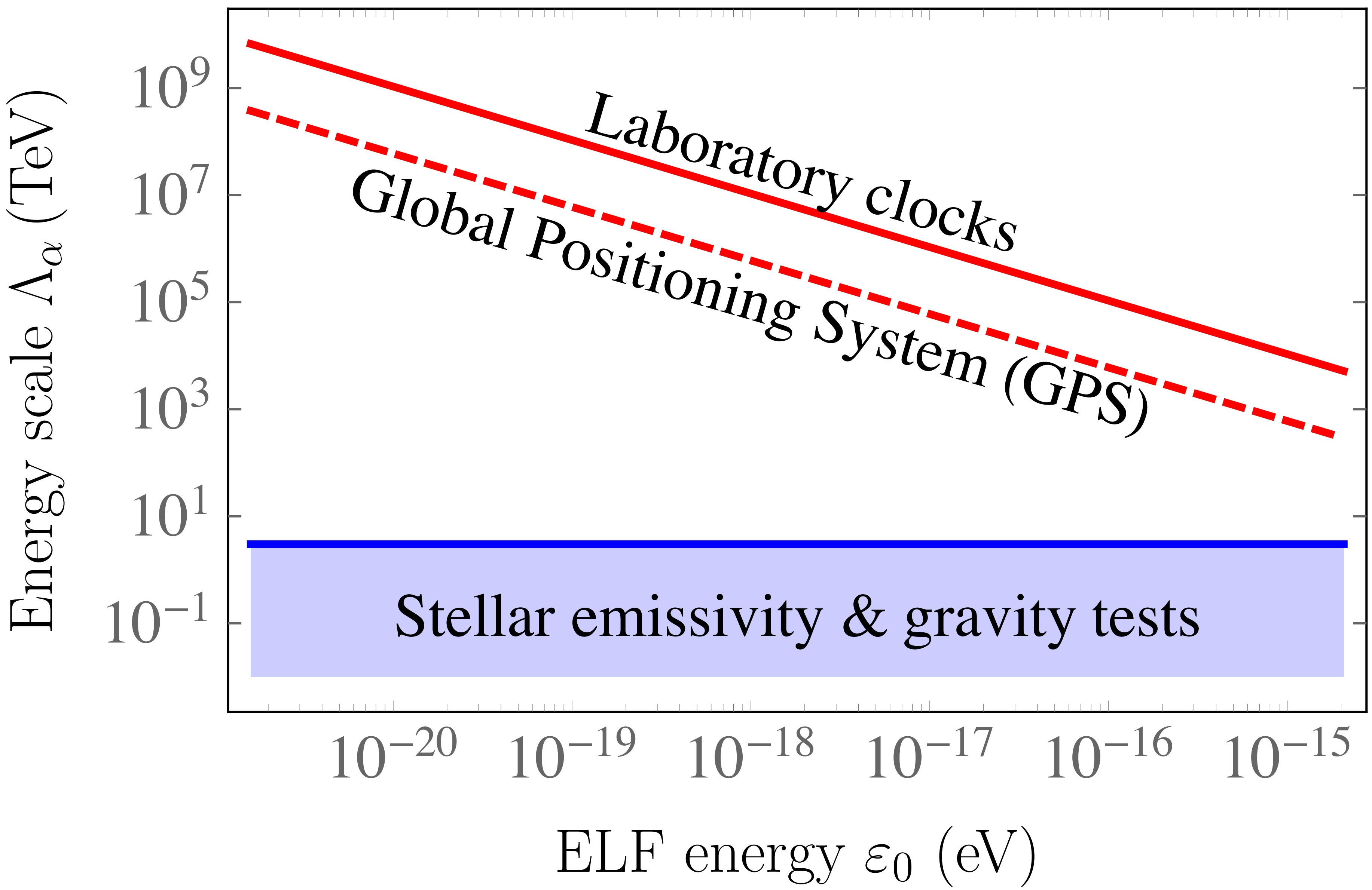
$K_\alpha \sim 2$ for atomic clocks

$K_\alpha \sim 10^4$ for ^{229}Th nuclear clocks

Regimes of variations of fundamental constants (circa 2020)

- **Slow drifts** — Dark energy?
- **Transients** — "Clumpy" DM, AD & Pospelov (2014)
- **Oscillations** — Dilaton DM, Arvanitaki++(2015)
- **Stochastic** — Virialized DM, AD (2016)
- **Oscillating transients** — Multi-messenger (2020)

Projected sensitivity GW170817 (NS+NS)

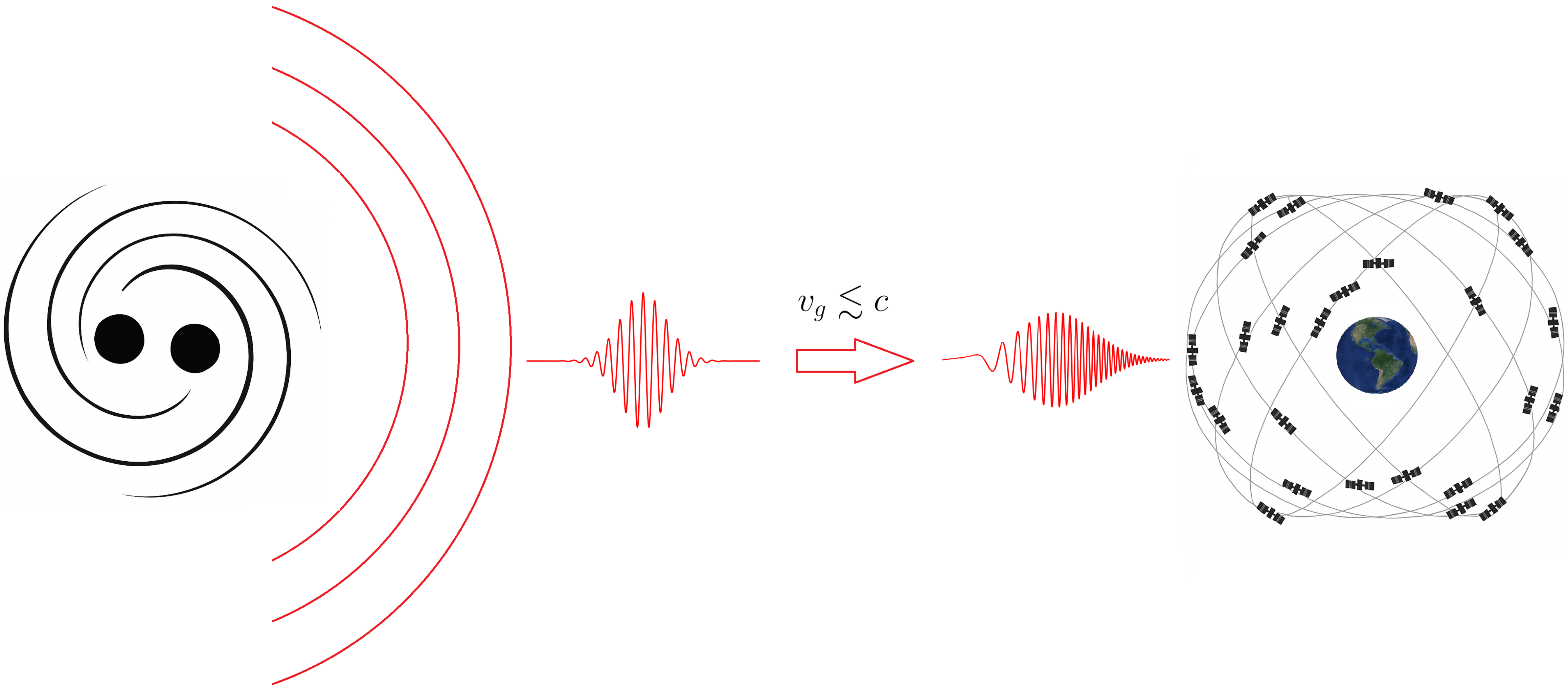


$\Delta E_{\mathrm{ELF}} = 0.1\, M_\odot c^2$

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

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

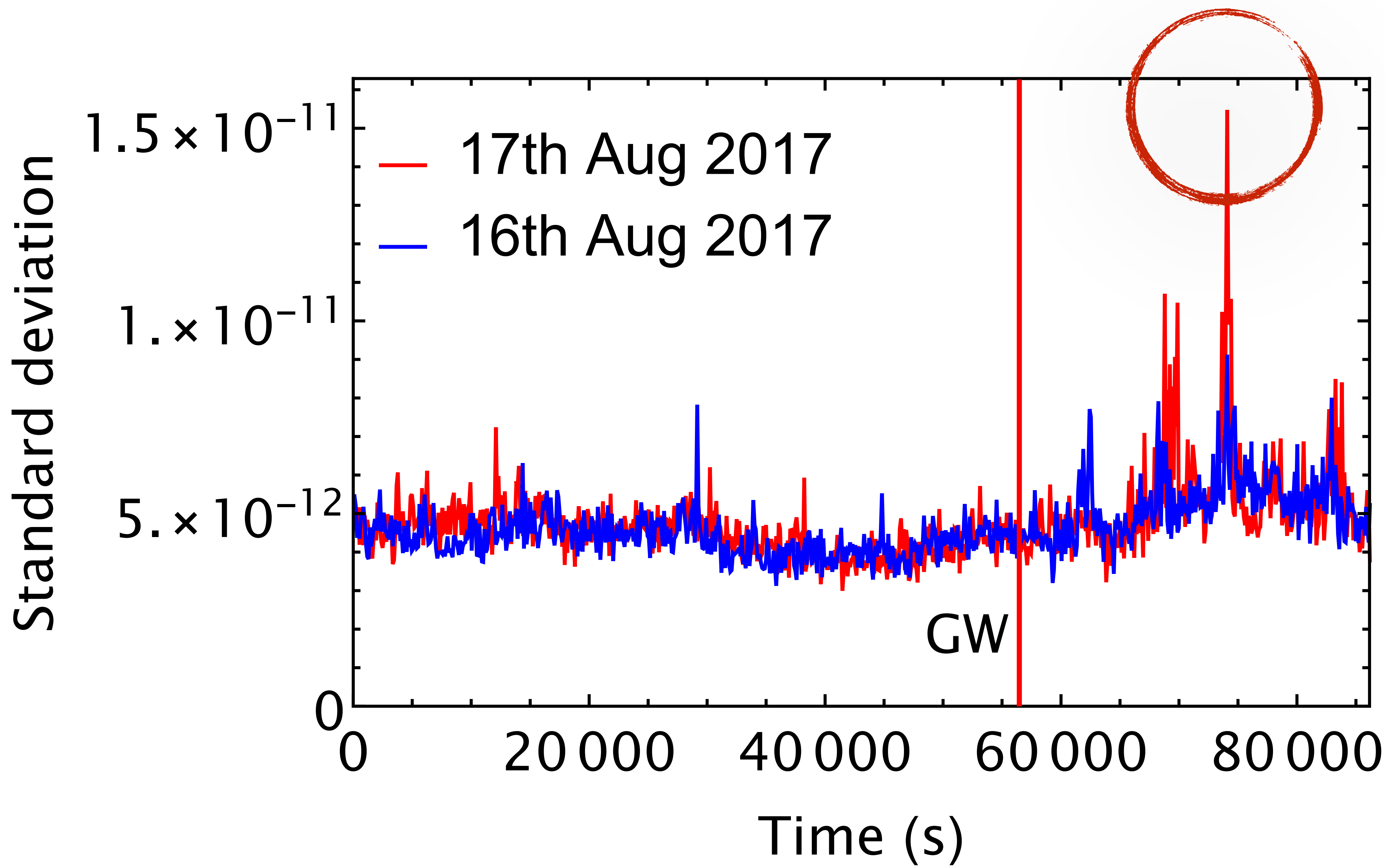
GPS constellation search for ELFs
BNS merger GW170817



Archival data from 27 Rb clock on GPS satellites referenced to a terrestrial H-maser

50,000 km distributed quantum sensor (no network resolution due to 1s sampling time)

GPS clock noise for GW170817

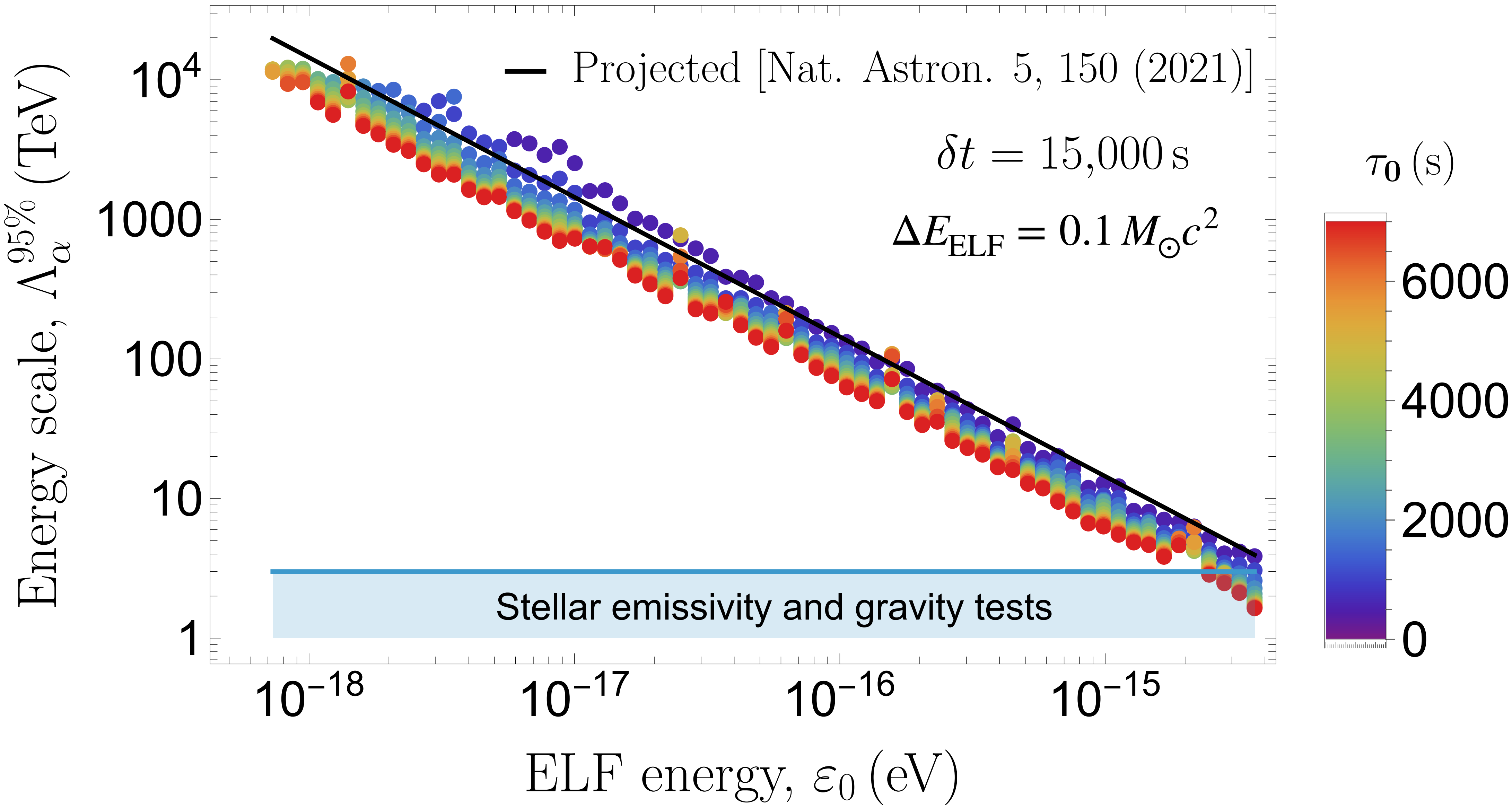


Excess noise coincides with an increased solar flux activity

Sen, Pfeffer, Ries, Blewitt, Derevianko J. Phys. Conf. Ser. 2889, 012003 (2024).

Limits on quadratic couplings GW170817

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

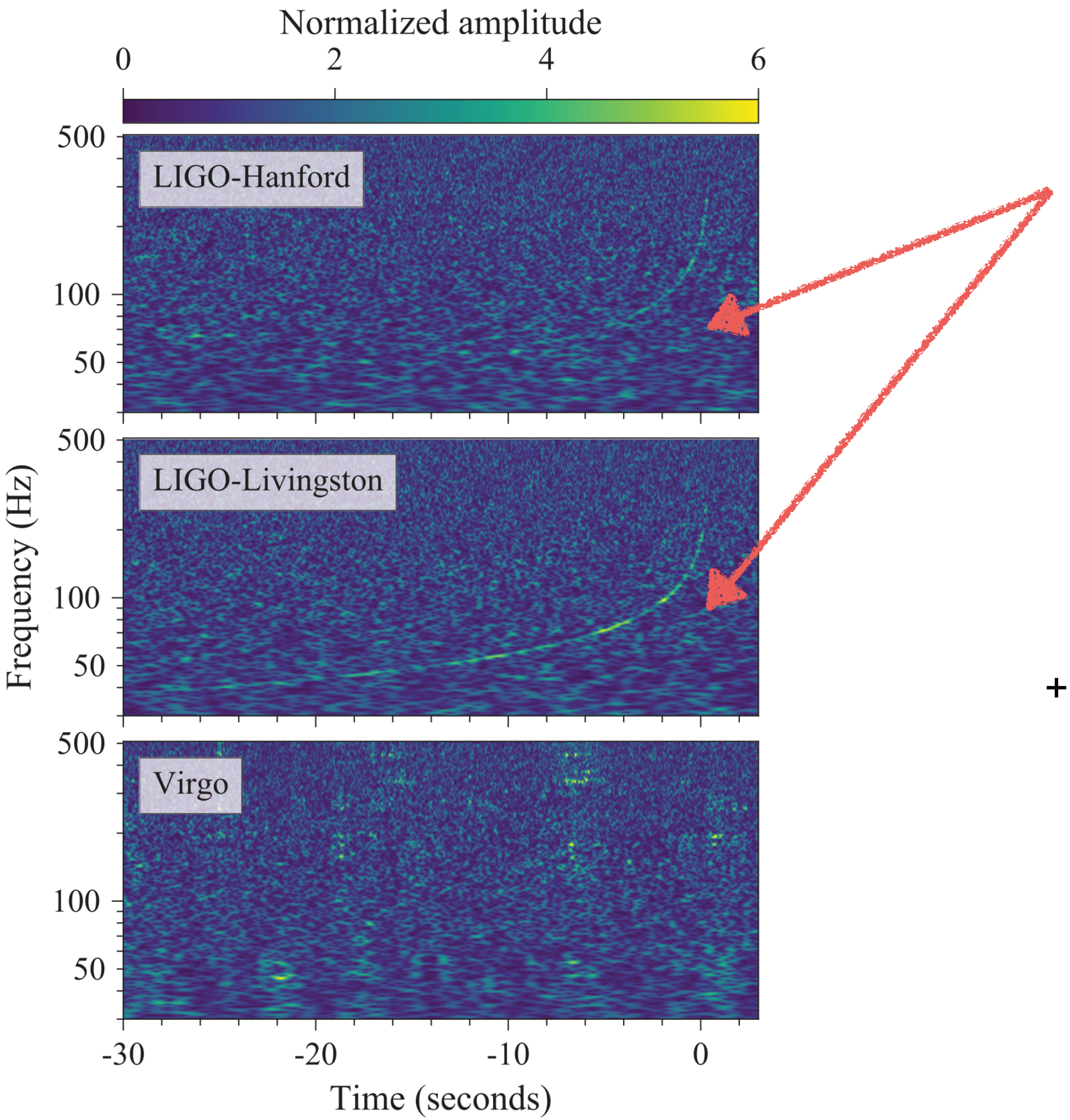


$$\mathscr{L} \supset \left(-\frac{m_e c^2 \bar{\psi}_e \psi_e}{\Lambda_{m_e}^2} - \frac{1}{4\Lambda_\alpha^2} F_{\mu\nu}^2 \right) \phi^2$$

GPS.ELF collaboration (2025)

Future prospects/ideas

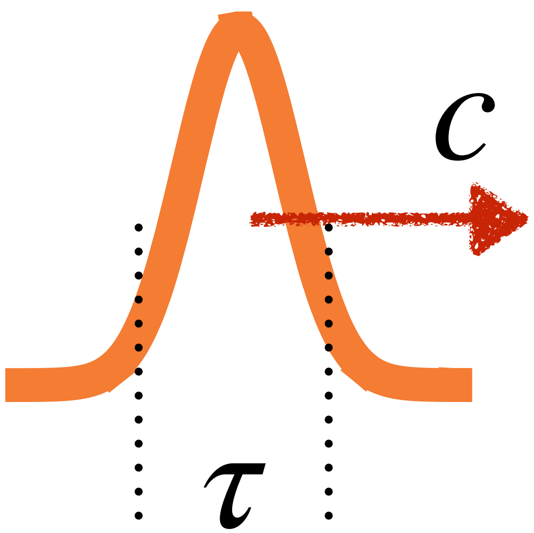
Power of the network

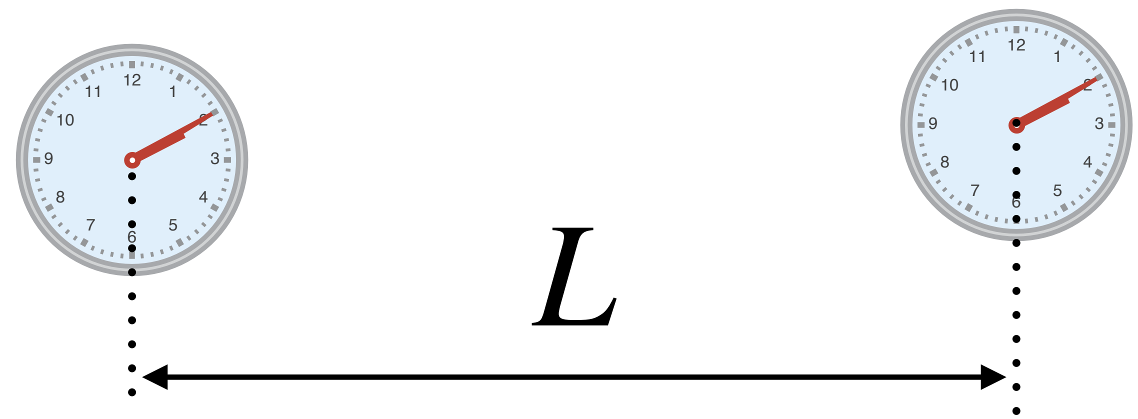


The same but time-shifted signal

+ locating progenitor in the sky

Network desiderata





Time resolution Δ_t

1. Resolve leading edge: $\Delta_t \ll L/c$
2. Resolve envelope: $\Delta_t \ll \tau$

GNOME: $L \sim 10{,}000\,\text{km}; \quad L/c \sim 40\,\text{ms}\,; \Delta_t = 1\,\text{ms}$

GPS: $L \sim 50{,}000\,\text{km}; \quad L/c \sim 0.2\,\text{s}\,; \Delta_t = 30\,\text{s} \rightarrow 1\,\text{s}$

GPS can't track the leading edge = compound multi-node sensor
all clocks must have the same signal

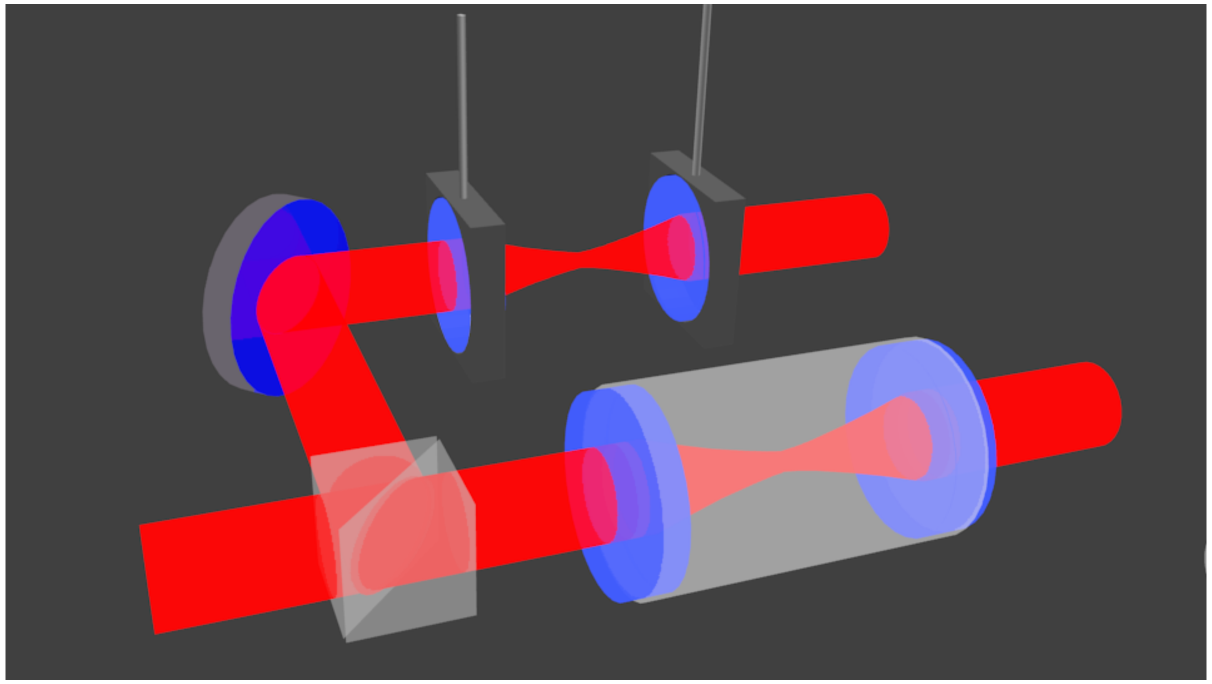
Cavities vs clocks

At c, ELF burst propagates across Earth in 40 ms.

Clock sampling rate is slow ~ Hz. Terrestrial network can not track ELFs.

Cavities ~ 100 kHz. ELFs can be tracked + sky location of progenitors!

Campus-sized network ~ 3 km



A. Geraci, C. Bradley, D. Gao, J. Weinstein, and A. Derevianko, PRL 123, 31304 (2019)

Catalogue of future search targets

Event Type	Electromagnetic	Cosmic Rays	Gravitational Waves	Neutrinos	Event Example
Solar Flare	✓	✓	-	•	SOL1942-02-28 [2]
Supernova	✓	•	•	✓	SN 1987A [3]
Neutron Star Merger	✓	-	✓	•	GW170817 [1]
Blazar	✓	•	-	✓	TXS 0506+056 [4]

BH+BH surprises: two events had X-ray counterparts