Day 3

Atomic clocks in the age of gravitational wave detectors

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What will we cover today?

- Dark matter and modified gravity
- Tests of general relativity (GR)
- Detection of gravitational waves
- Exotic field modality in multi-messenger astronomy
- Do not throw away outliers

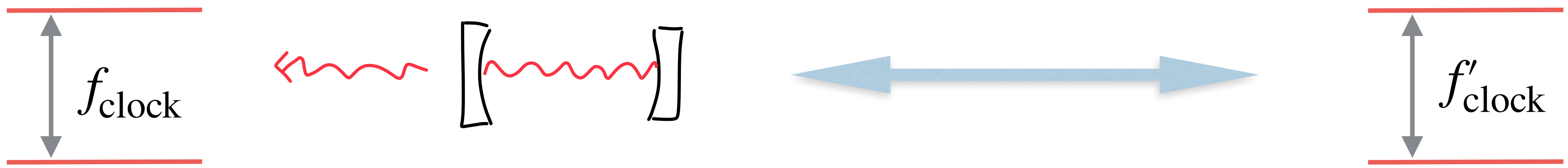
Atomic clocks as quantum sensors

- Quantum oscillator (qubit) is well protected from the traditional physics environmental perturbations

- Residual traditional physics perturbations are well characterized $\Longrightarrow$ low-level background

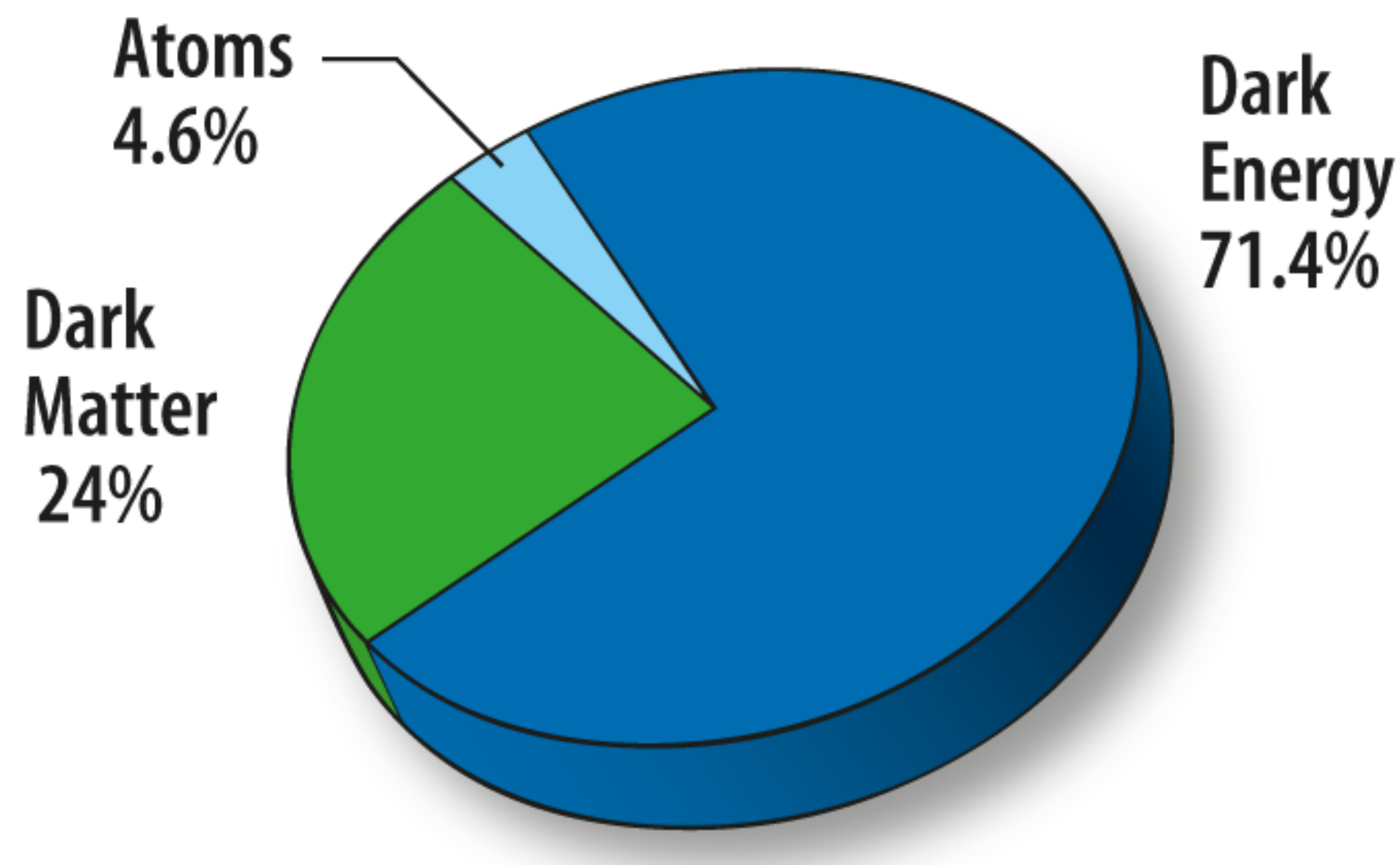
- Exotic physics can leave uncharacterized perturbations in atomic and cavity frequencies

Portals to exotic physics



- ➡ Exotic fields can change atomic/cavity frequencies
  [variation of fundamental constants by dark sector,…]
- ➡ Effects of special/general relativity on ticking rate
  [modified gravity,…]
- ➡ Comparison link - effective index of refraction
  [gravitational waves/dark sector,…]

Dark matter/dark energy



- DM: Handful of observational evidence from *gravitational* interactions on *galactic* scales
- Conventional paradigm = DM is made out of particles/fields
  - What is the microscopic composition?
  - Are there non-gravitational interactions?

Difficulties with particle dark matter paradigm

- Galactic core cusps vs observed flat density profiles
- Predicts too many satellite galaxies
- Does not explain alignment of satellite galaxies
- At odds with bosonic Tully-Fisher relation
- At odds with Renzo's rule
- Collisions of galaxies are too fast (DM has friction)

Alternative: modified gravity

On the largest and/or smallest scales, gravity acts in novel ways compared to the well-tested scales in the middle

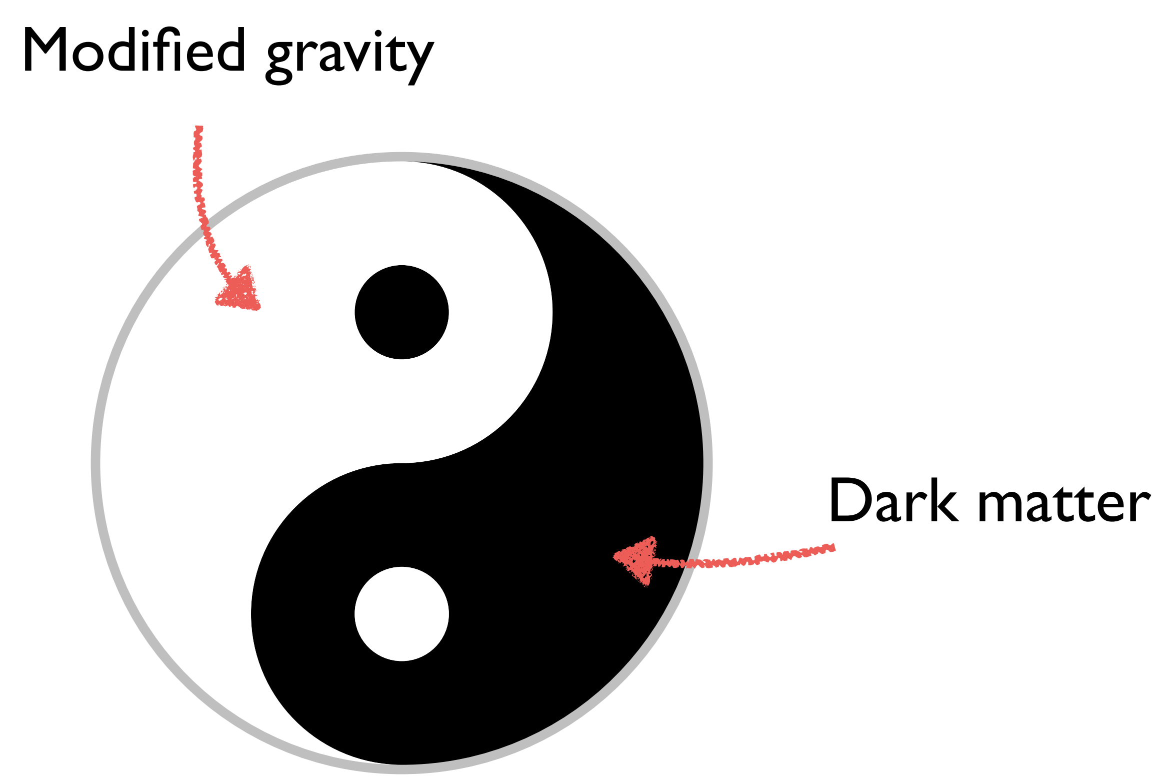
↓

Tests of General Relativity

- ☑ Galactic cores
- ☑ Number of satellite galaxies
- ☑ Alignment of satellite galaxies
- ☑ Bosonic Tully-Fisher relation
- ☑ Renzo's rule
- ☑ Collisions of galaxies

Difficulties: peaks in cosmic microwave background power spectrum, early universe, galaxy clusters

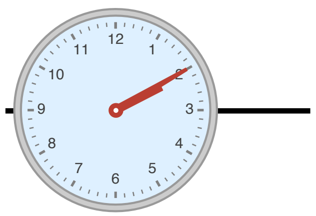
Duality?



We need to search for both manifestations

Tests of General Relativity

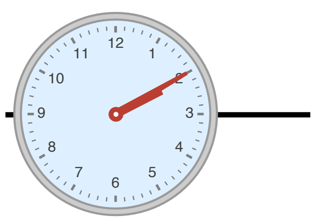
Testing GR with gravitational red shift



$U + \Delta U$

$$\frac{\Delta f_{\text{clock}}}{f_{\text{clock}}} = (1+\alpha) \times \frac{\Delta U}{U}$$

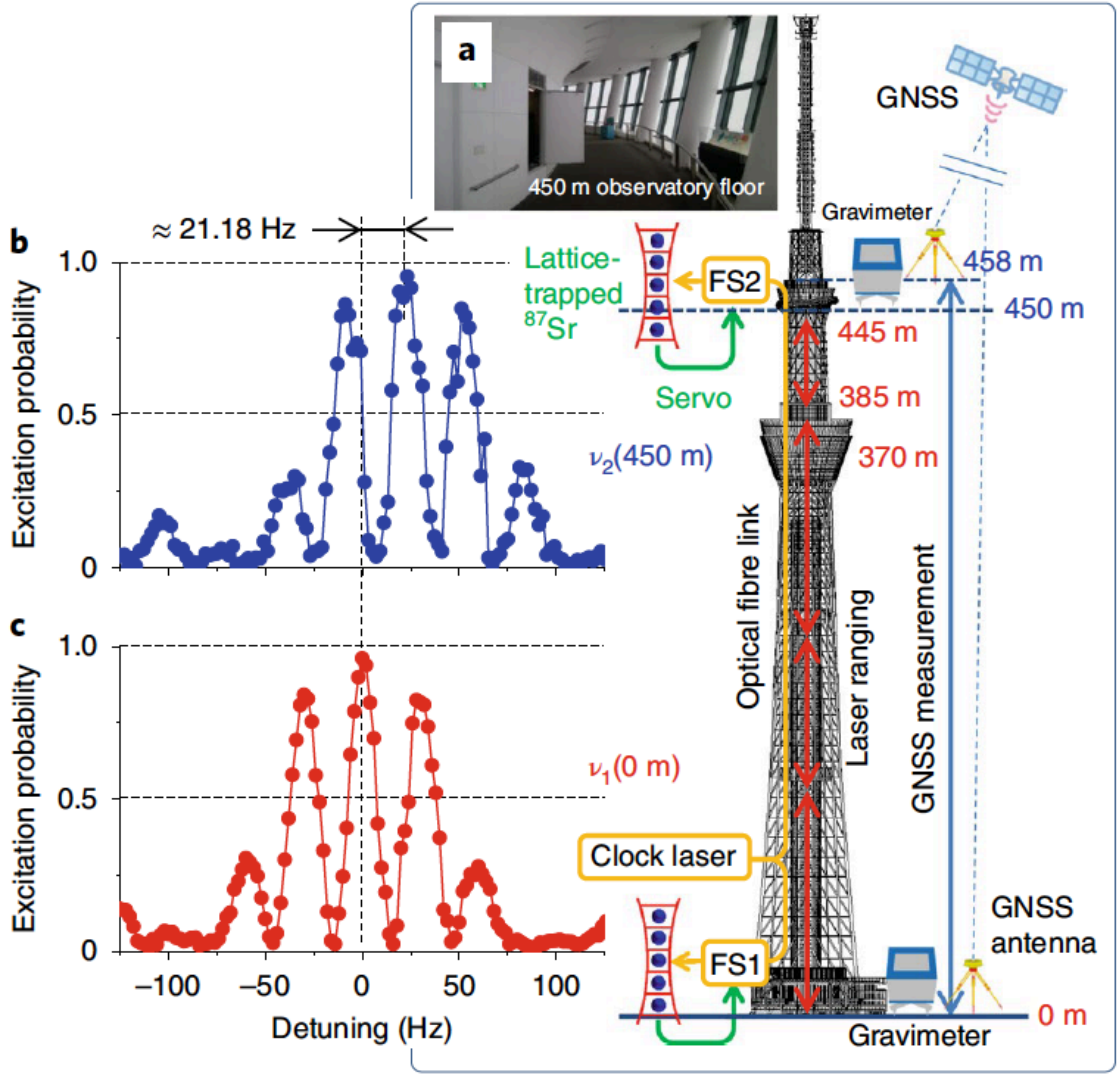
deviation from GR



U

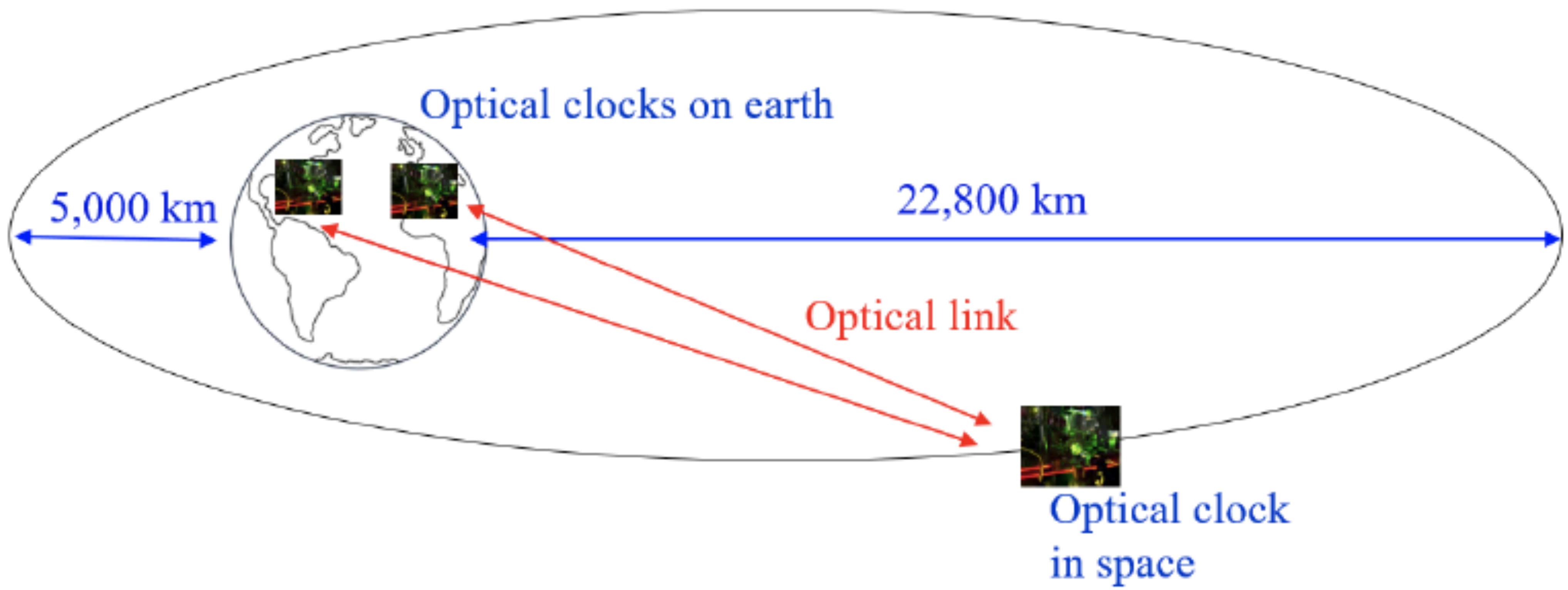
Best terrestrial:	$\lvert\alpha\rvert \lesssim 9 \times 10^{-5}$	Tokyo Skytree (optical clocks)	
Best constraints:	$\lvert\alpha\rvert \lesssim 0.19 \times 10^{-5}$	Galileo GNSS	*arXiv:1906.06161*
Proposed:	$\lvert\alpha\rvert_{\text{min}} \sim 10^{-9}$	FOCOS (Oats)	

Tokyo Skytree experiment



Takamoto, Ushijima, N. Ohmae, Yahagi, Kokado, Shinkai, & Katori, Nat. Photonics ***14****, 411 (2020)*

FOCOS (Fundamental physics with an Optical Clock Orbiting in Space)

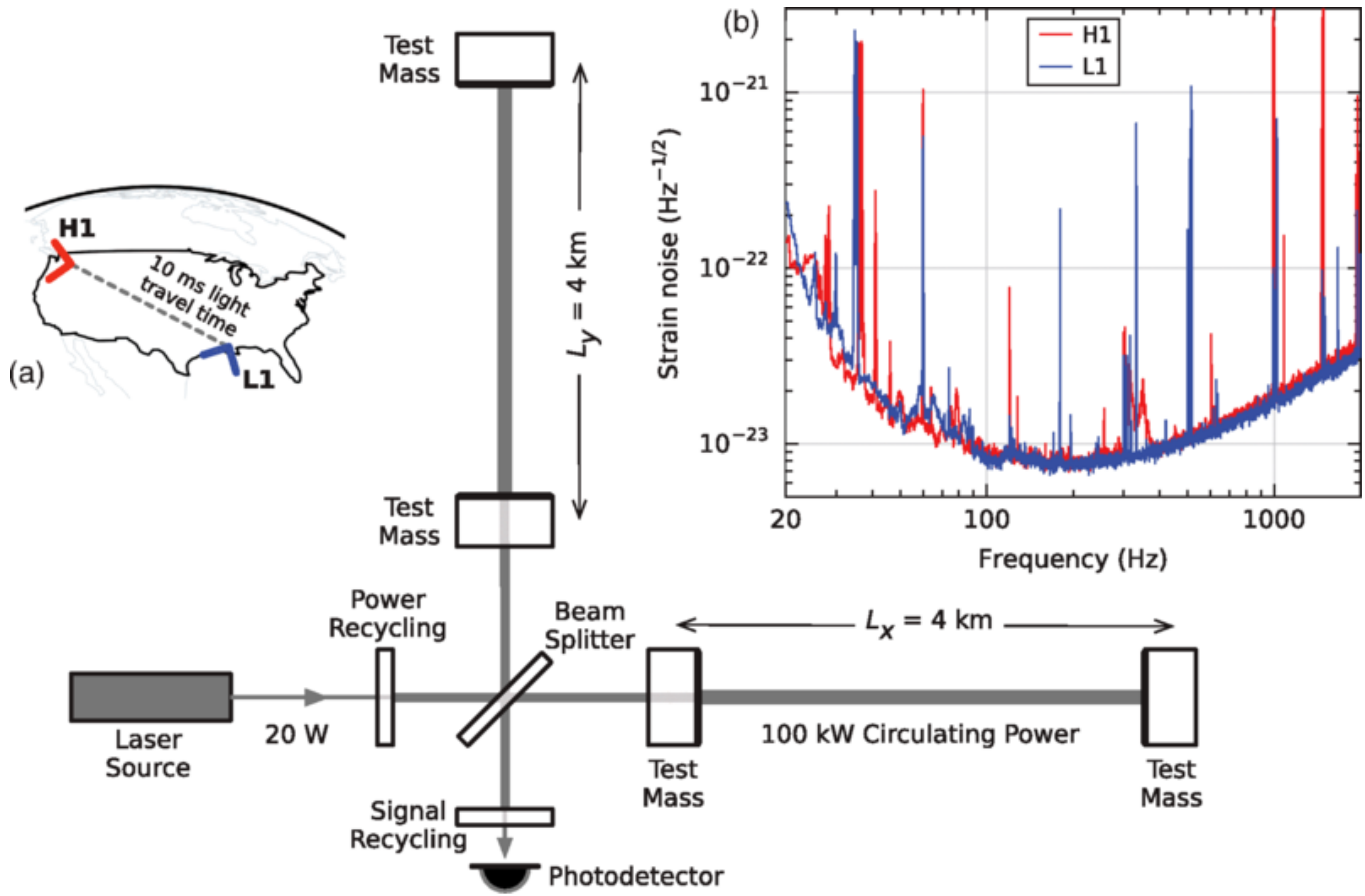


Highly elliptical orbit => variation in *U*
+ comparison with terrestrial clocks (fixed *U*)

Chris Oats ++

Gravitational waves (GW)

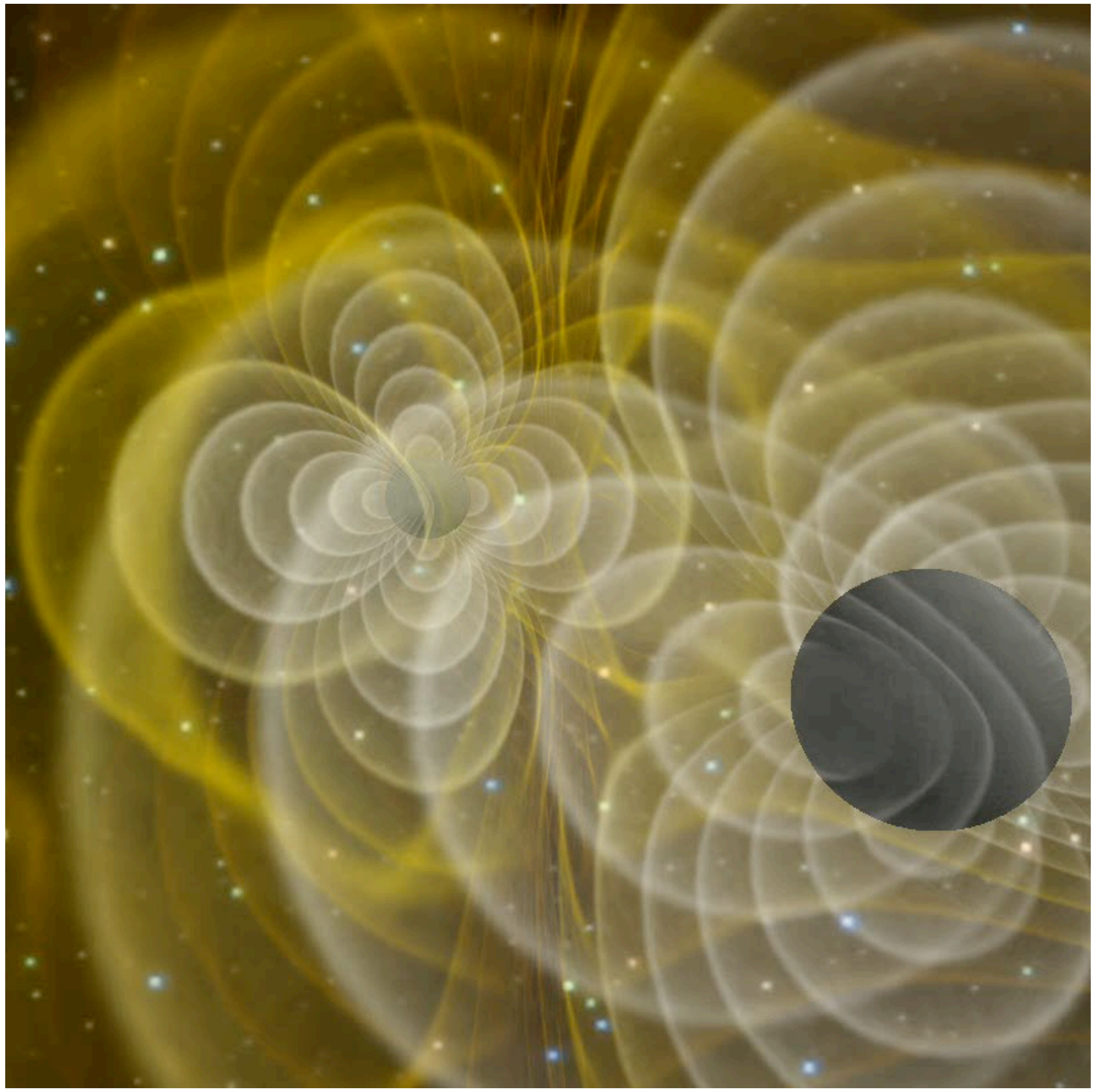
Laser Interferometer Gravitational-Wave Observatory (LIGO)

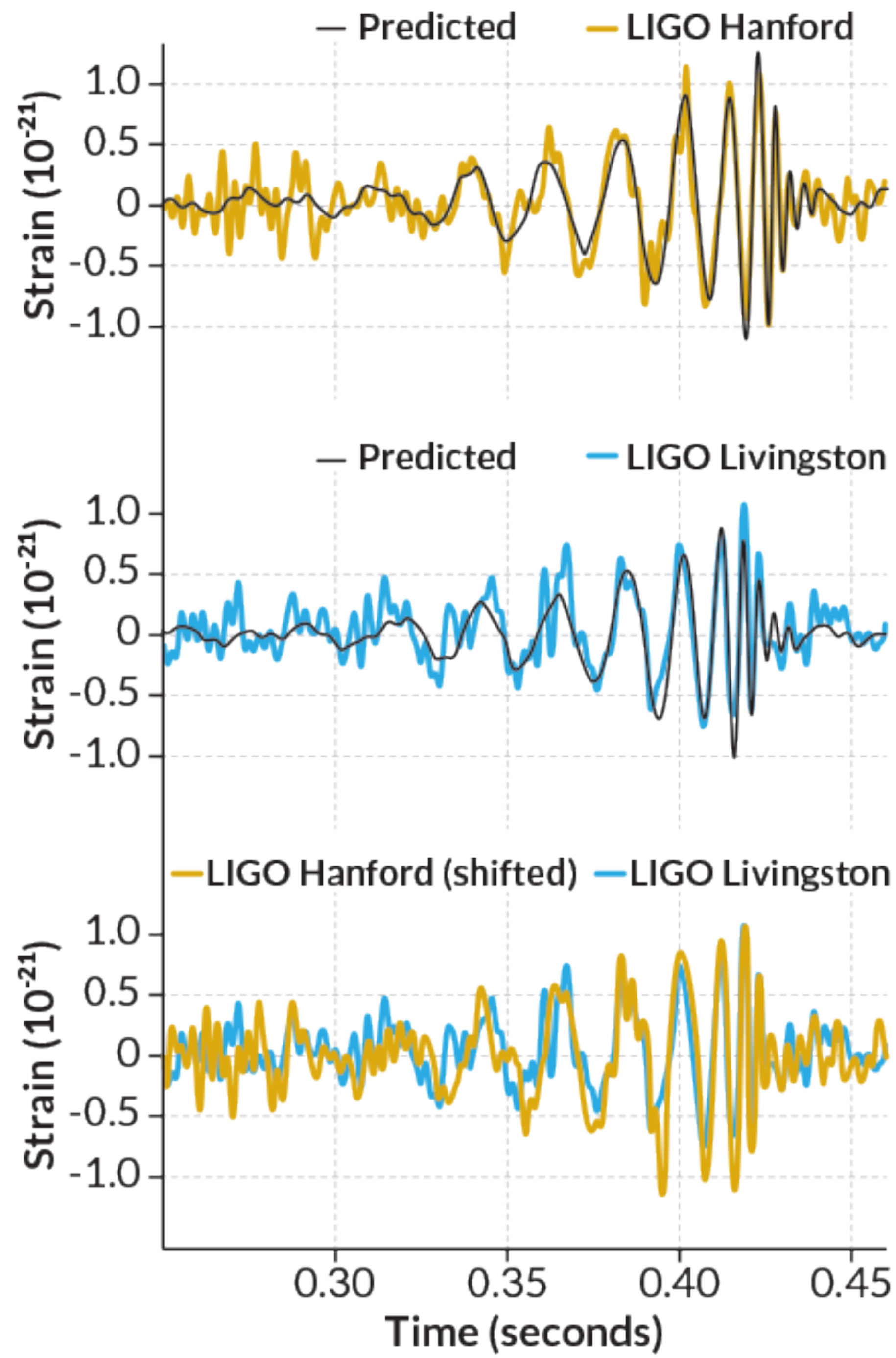


https://commons.wikimedia.org/w/index.php?curid=46922746

Black-hole merger & LIGO detection

Credit: NASA/C. Henze



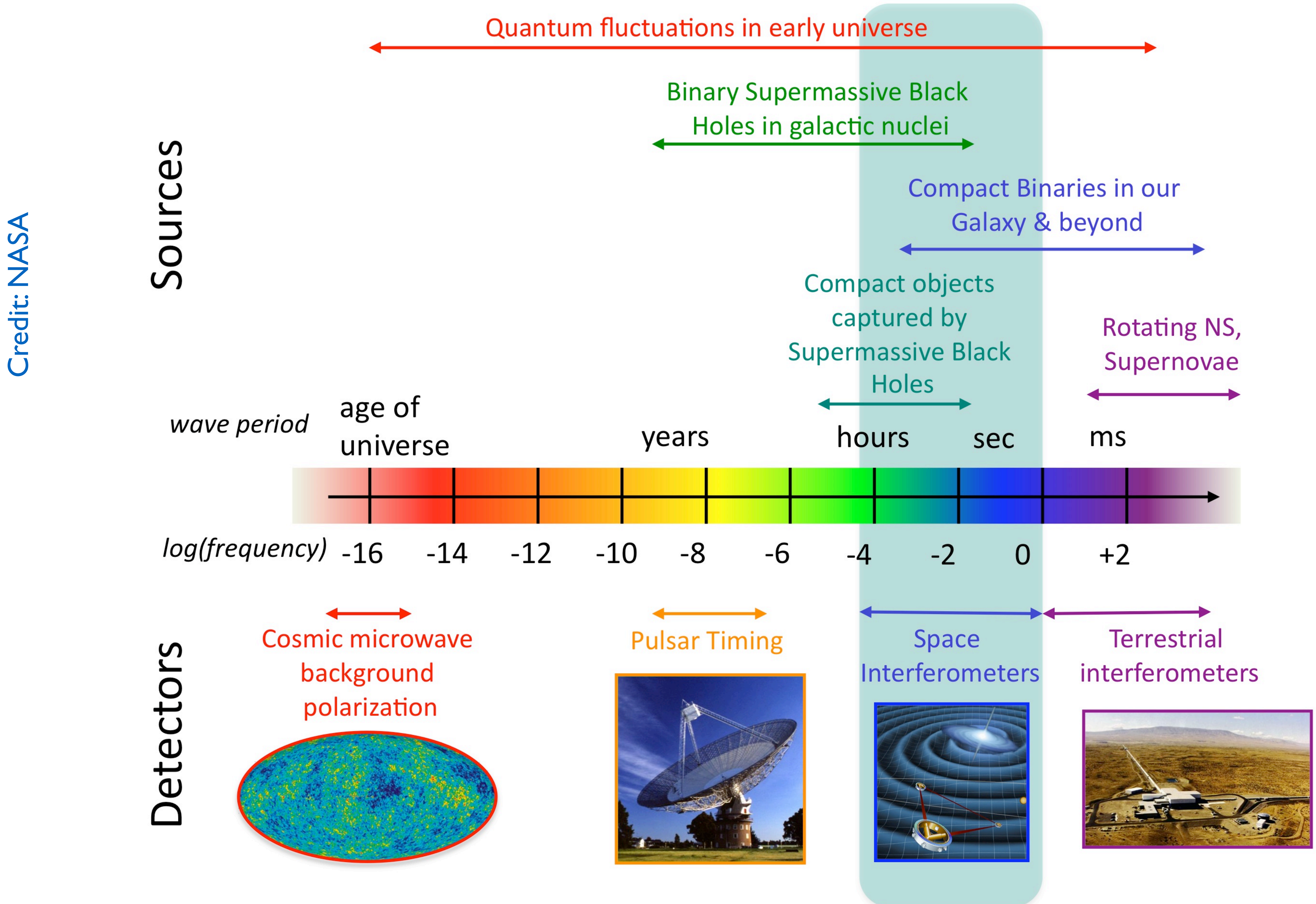


LIGO collaboration. Phys. Rev. Lett. 116, 61102 (2016)

So far ~20 GW events observed (as of 2021)

SNR ~ 5-7

The Gravitational Wave Spectrum



Some GR/GW basics

Line element
(Lorentz scalar)

$$\left(ds\right)^2 = g_{\mu\nu} dx^\mu dx^\nu$$

metric

$$x^\mu = \left(ct, \mathbf{r}\right)$$

Flat space time

$$g_{\mu\nu}^{(\text{flat})} = \text{diag}(1,-1,-1,-1)$$

$$\left(ds\right)^2 = \left(cdt\right)^2 - \left(dx\right)^2 - \left(dy\right)^2 - \left(dz\right)^2$$

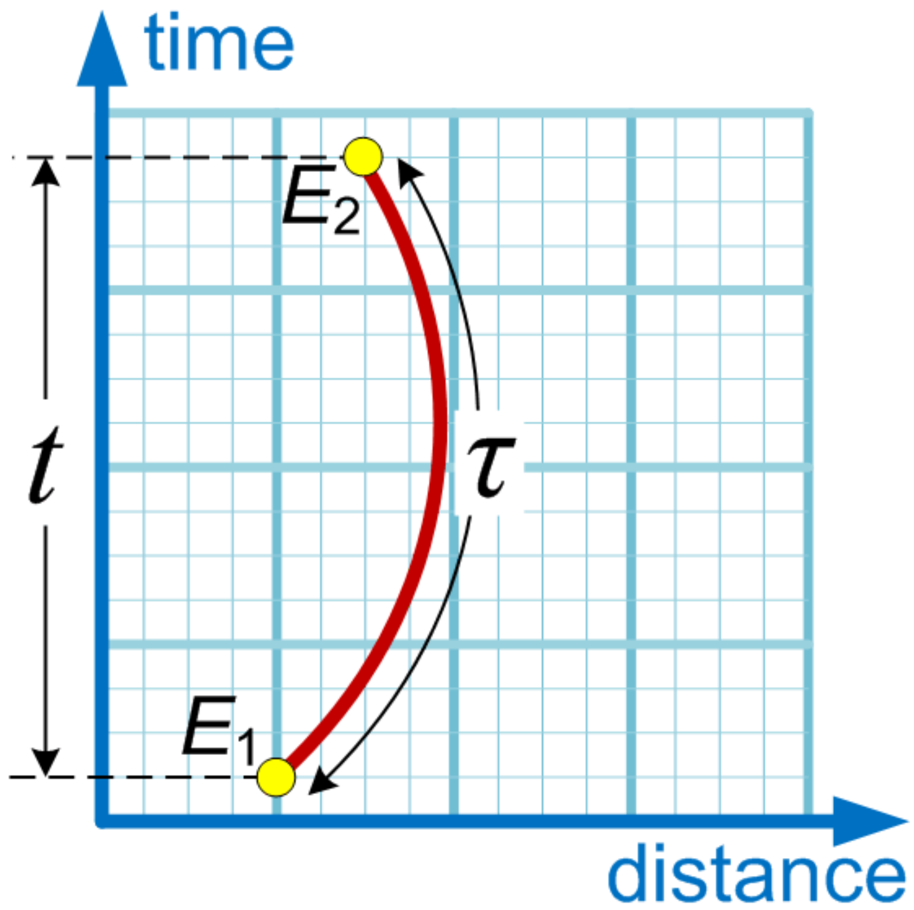
+ gravitational wave

$$g_{\mu\nu} = g_{\mu\nu}^{(\text{flat})} + h_{\mu\nu} \cos\left(\mathbf{k}\cdot\mathbf{r} - \omega t\right)$$

Strain ~10^{-21} (LIGO)

Proper time

Dr Greg, commons.wikimedia.org/w/index.php?curid=3812171



The dark blue vertical line represents an inertial observer measuring a coordinate time interval t between events E_1 and E_2. The red curve represents a clock measuring its proper time interval τ between the same two events.

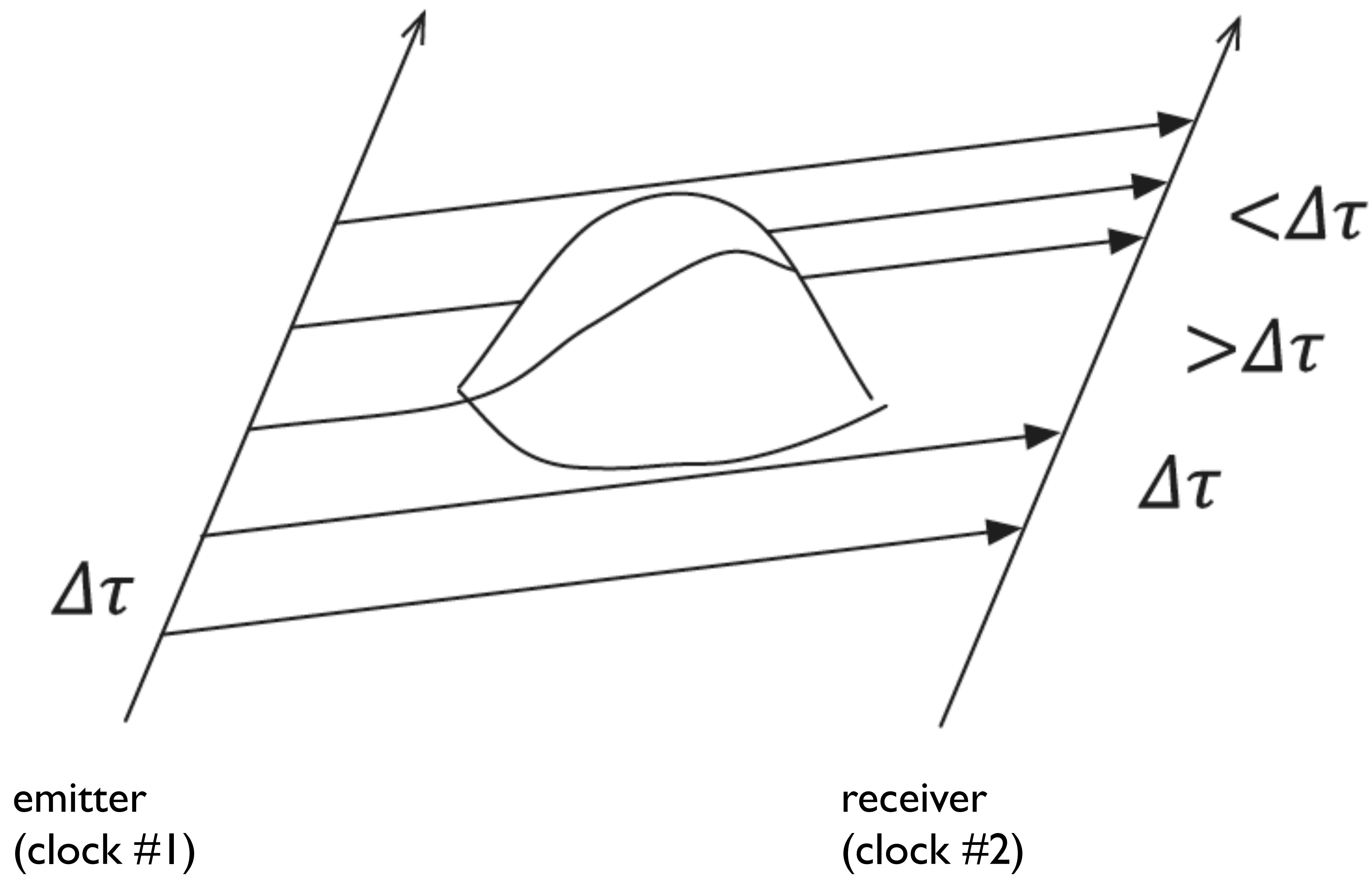
$$\tau = \int \sqrt{g_{00}}\, dt$$

For stationary clock in GW metric

$$g_{00} = 1 + h_{00}\cos\left(\mathbf{k}\cdot\mathbf{r} - \omega t\right)$$

$$\tau \approx t + \frac{1}{2} h_{00} \int \cos\left(\mathbf{k}\cdot\mathbf{r} - \omega t'\right) dt'$$

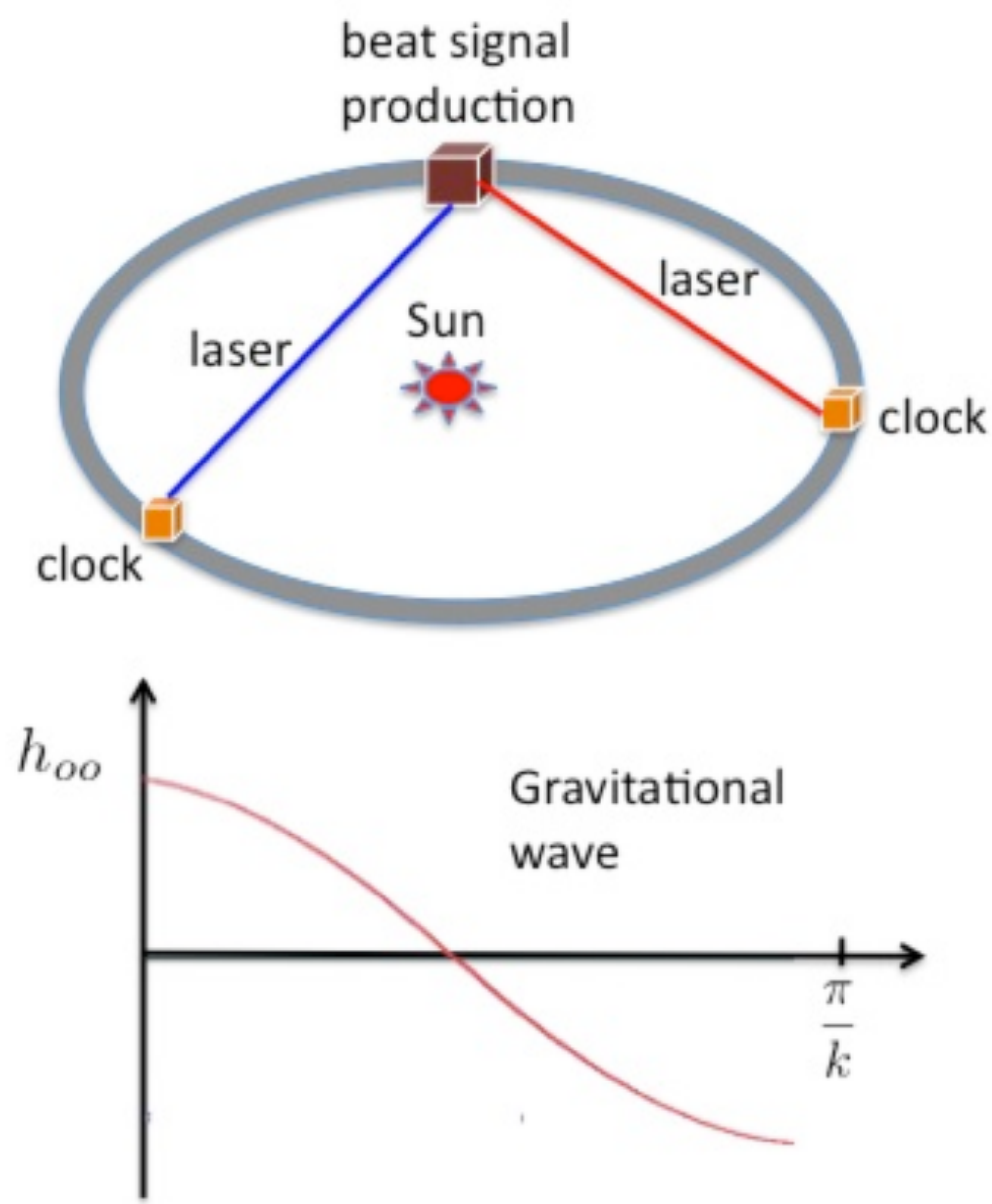
Clock comparison template in GR



Koop & Finn, PRD 96, 042118 (2014)

Emit pulses at regular time intervals and measure intervals b/w arriving pulses

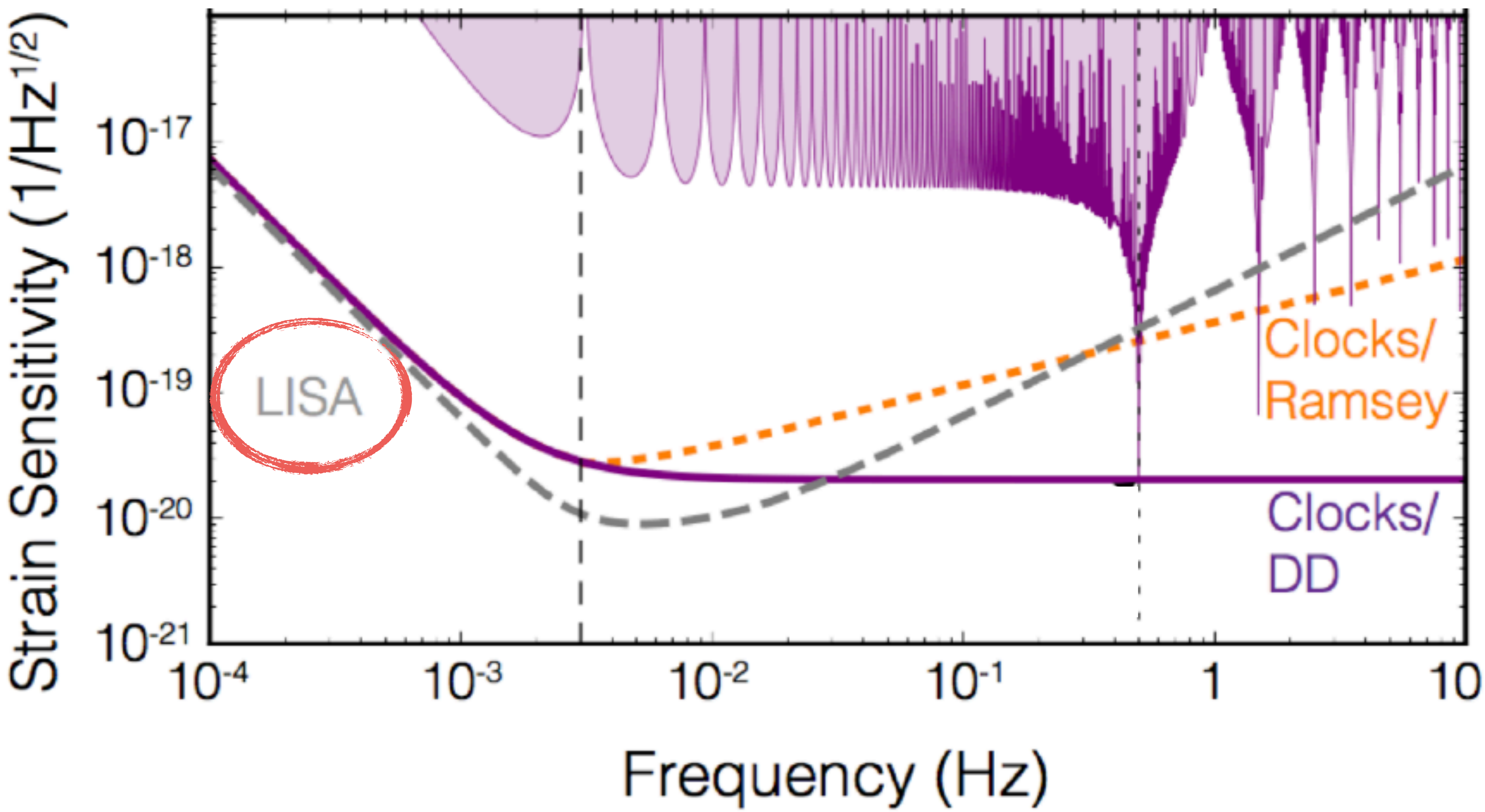
Loeb & Maoz proposal



$$\tau \approx t + \frac{1}{2} h_{00} \int \cos\left(\mathbf{k} \cdot \mathbf{r} - \omega t'\right) dt'$$

Loeb & Maoz arxiv astro-ph:1501.00996

Sr optical clock analysis



S. Kolkowitz et al., Phys. Rev. D 94, 124043 (2016)

Track GW in the intermediate frequency band between LISA and LIGO

Proposed clock space missions

- SAGE: Space Atomic Gravity Explorer
  Eur. Phys. J. D 73, 228 (2019)

- AEDGE: Atomic Experiment for Dark Matter and Gravity Exploration
  Eur. Phys. J. Quantum Technol. 7, 6 (2020)

SAGE and AEDGE: Primary goal is detection of gravitational waves
with secondary goals like dark matter detection and tests of quantum mechanics

- ACES: Atomic Clock Ensemble in Space (2015-2016)
  main objective is to demonstrate the performances of Cs fountain clock in the microgravity environment of the International Space Station (ISS).

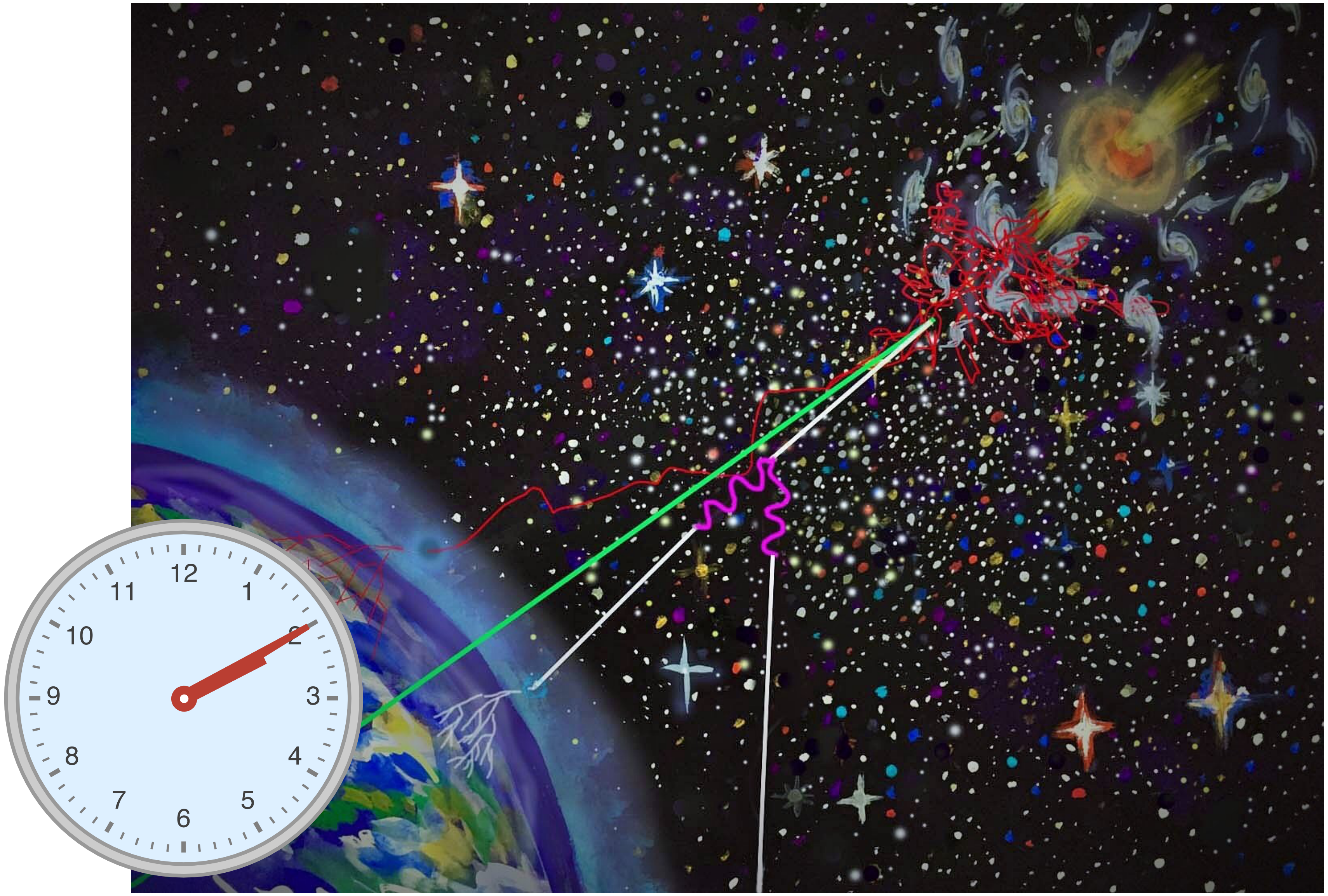
https://earth.esa.int/web/eoportal/satellite-missions/i/iss-aces

Exotic field modality in multi-messenger astronomy

ELF module overview

- Exotic low-mass fields (ELFs)
- ELF production mechanisms
- Expected signal and characteristic anti-chirp
- Discovery reach of existing networks
- Preliminary results from the GPS data

Sourced exotic fields



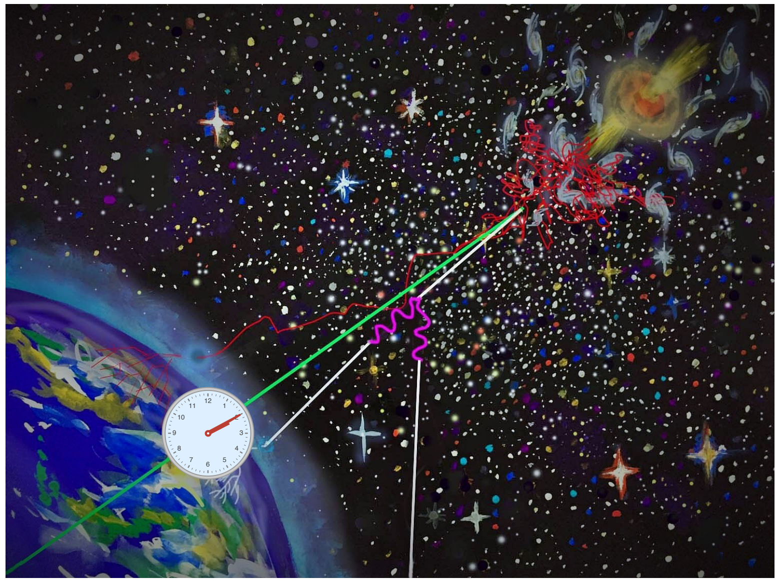
LETTERS
https://doi.org/10.1038/s41550-020-01242-7
nature astronomy

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] ✉

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 atomic clock data?

Exotic Low-mass Fields (ELFs)

- Modern clocks are **not** sensitive to gravitational waves
  (requires clock comparison over huge baselines)
- Exquisite sensitivity to "new" physics beyond the Standard model
- 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

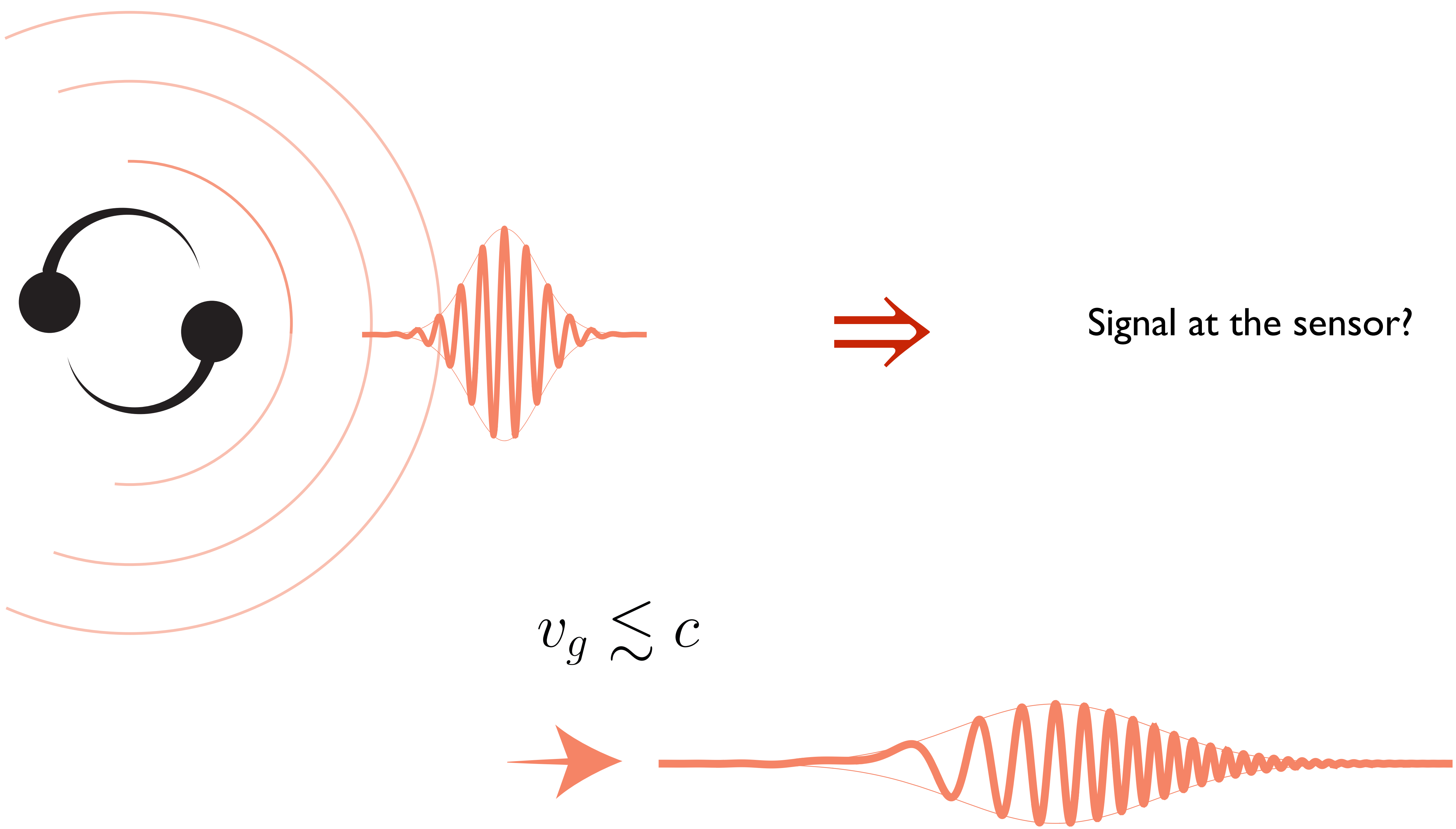
- Scalar fields can be trapped in neutron stars - released during the merger

- 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 $M_{\odot} c^2$



Generic wave-form independent of the production mechanism

Scalar bootcamp

Massive (mass m) and spin-less ($S = 0$) field

Relativistic Schrödinger eqn [Klein-Gorgon eqn]

$$\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\varphi - \nabla^2\varphi + \left(\frac{mc}{\hbar}\right)^2\varphi = 0$$

Solutions: the usual spherical and plane waves

$$\varphi \sim e^{i(\omega t - \mathbf{k}\cdot\mathbf{r})}$$

Relativistic energy-momentum relation => dispersion relation

$$\varepsilon = \hbar\omega = \left[\left(c\hbar k\right)^2 + \left(mc^2\right)^2\right]^{1/2}$$

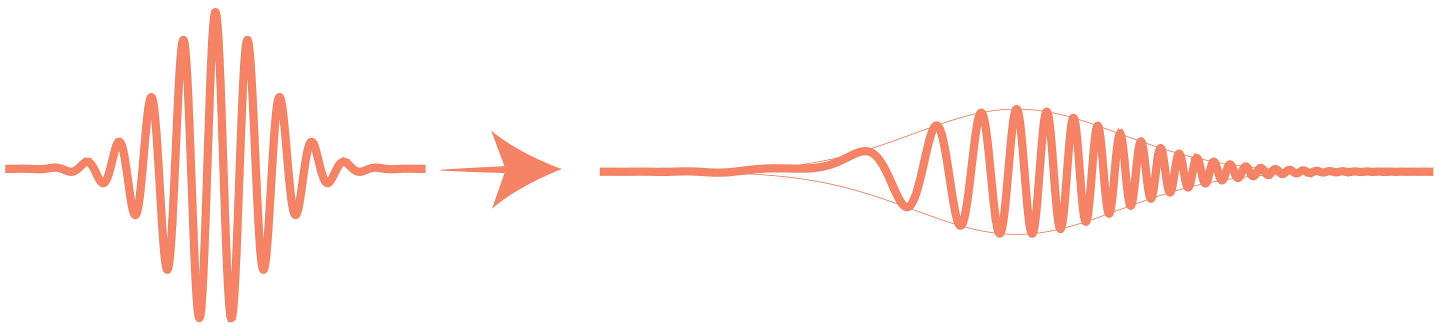
Scalar waves are like E&M waves

“Internal” refractive index (ultrarelativistic scalars)

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

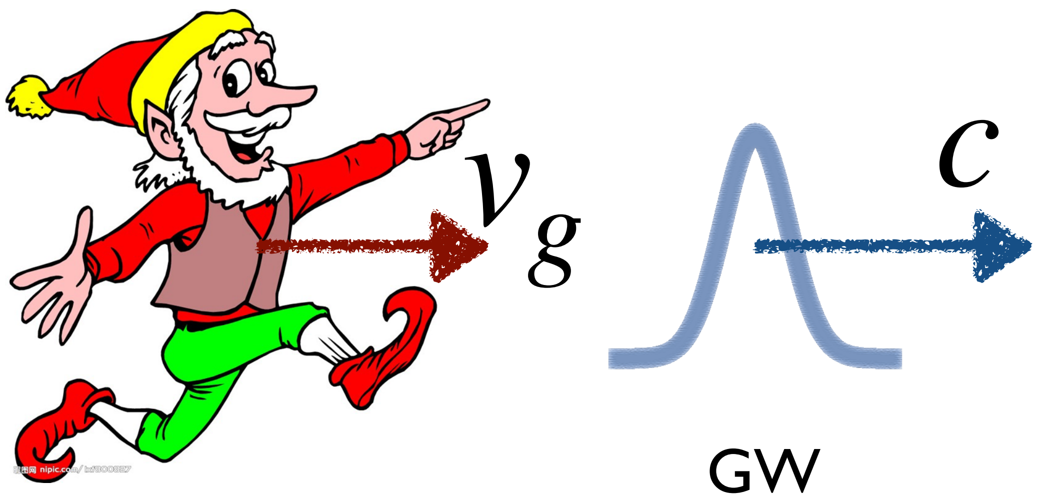
Most of Jackson E&M problems/intuition can be directly transferred

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



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 $\Rightarrow m \ll 10^{-14}\,\mathrm{eV}$

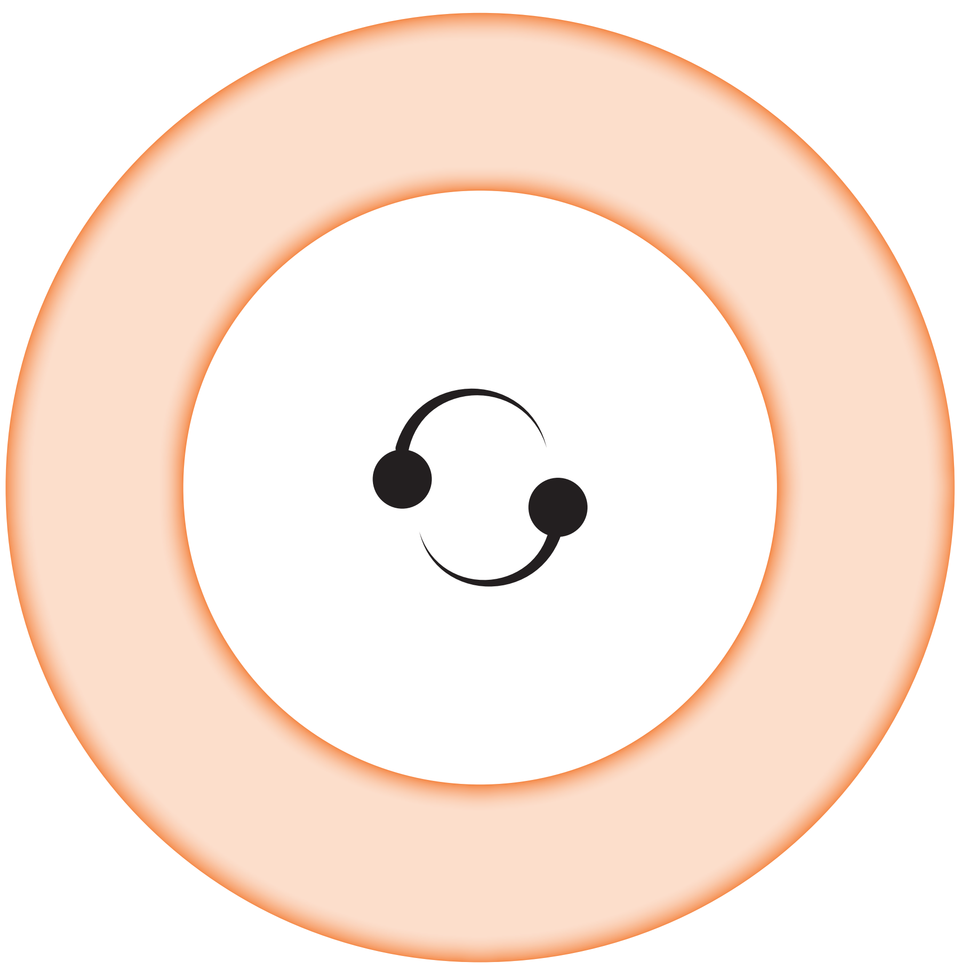
   ELFs must be **ultralight**

Energetics

Copious emission

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

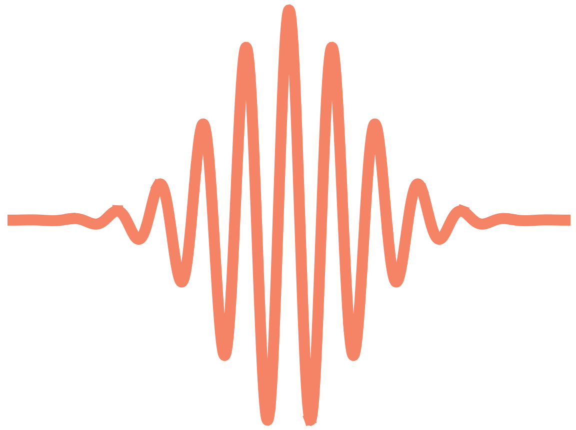
Large mode occupation numbers => classical field all the way to the sensor



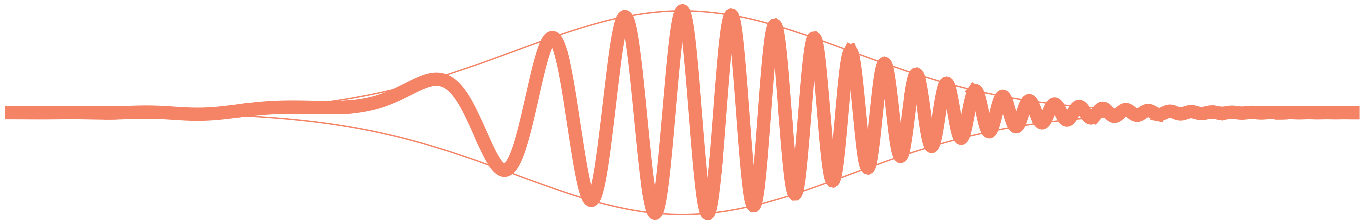
$$\varphi \sim \frac{1}{R} \quad \left(\sim \frac{1}{R^{3/2}} \text{with dispersion} \right)$$

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

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

Detailed analysis

$$\phi(t) \approx \frac{1}{R}\left(\frac{c\Delta E}{2\pi^{3/2}\omega_0^2\tau}\right)^{1/2} \exp\left(-\frac{(t-t_s)^2}{2\tau^2}\right) \times \cos\left(\omega_0(t-t_s) - \frac{\omega_0}{4\delta t}(t-t_s)^2\right)$$

Time lag between GW and ELF bursts

$$\delta t = \left(\frac{mc^2}{\varepsilon_0}\right)^2 \frac{R}{2c}$$

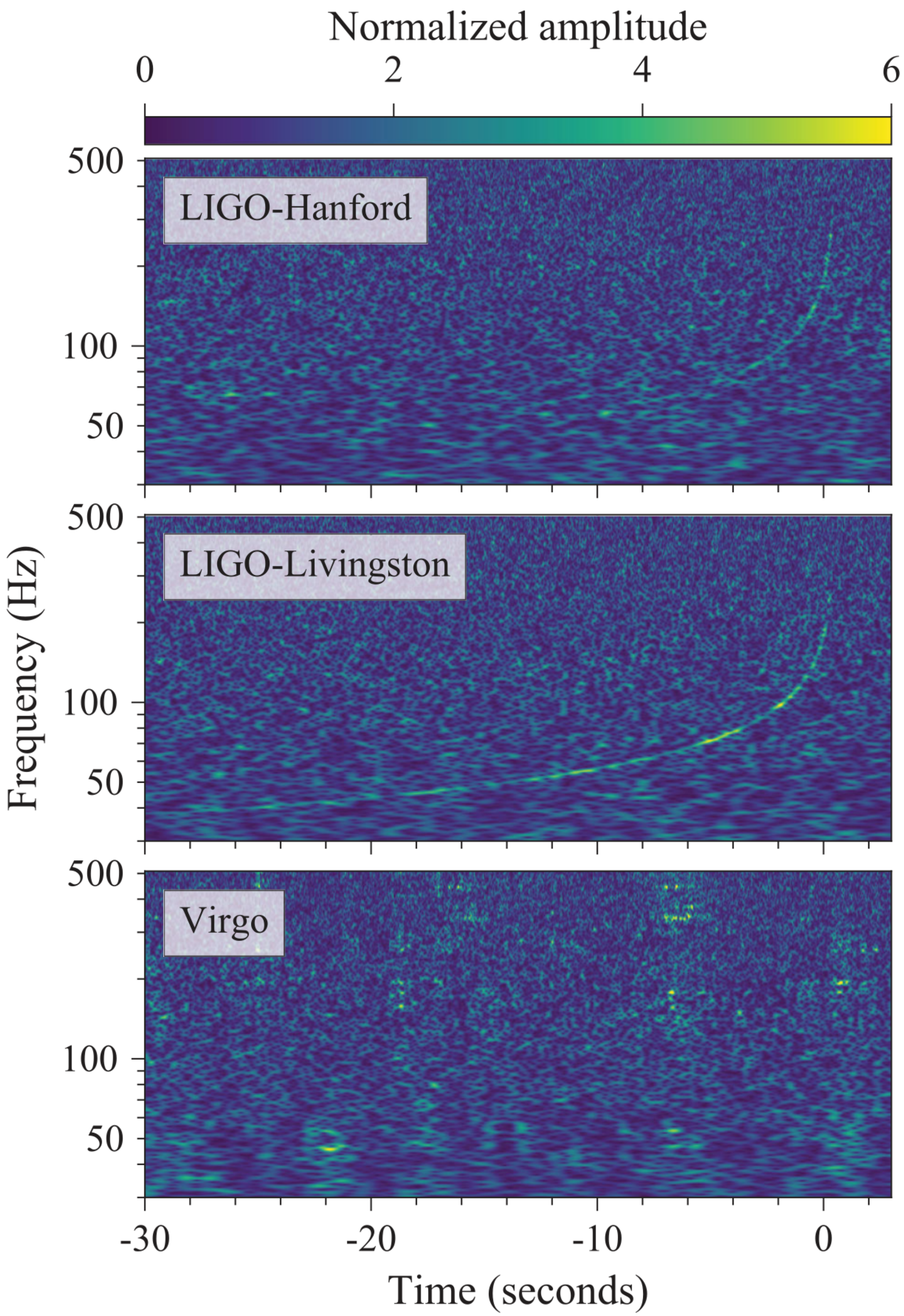
Duration at the sensor

$$\tau \approx 2\frac{\Delta\varepsilon}{\varepsilon_0}\delta t$$

Frequency slope

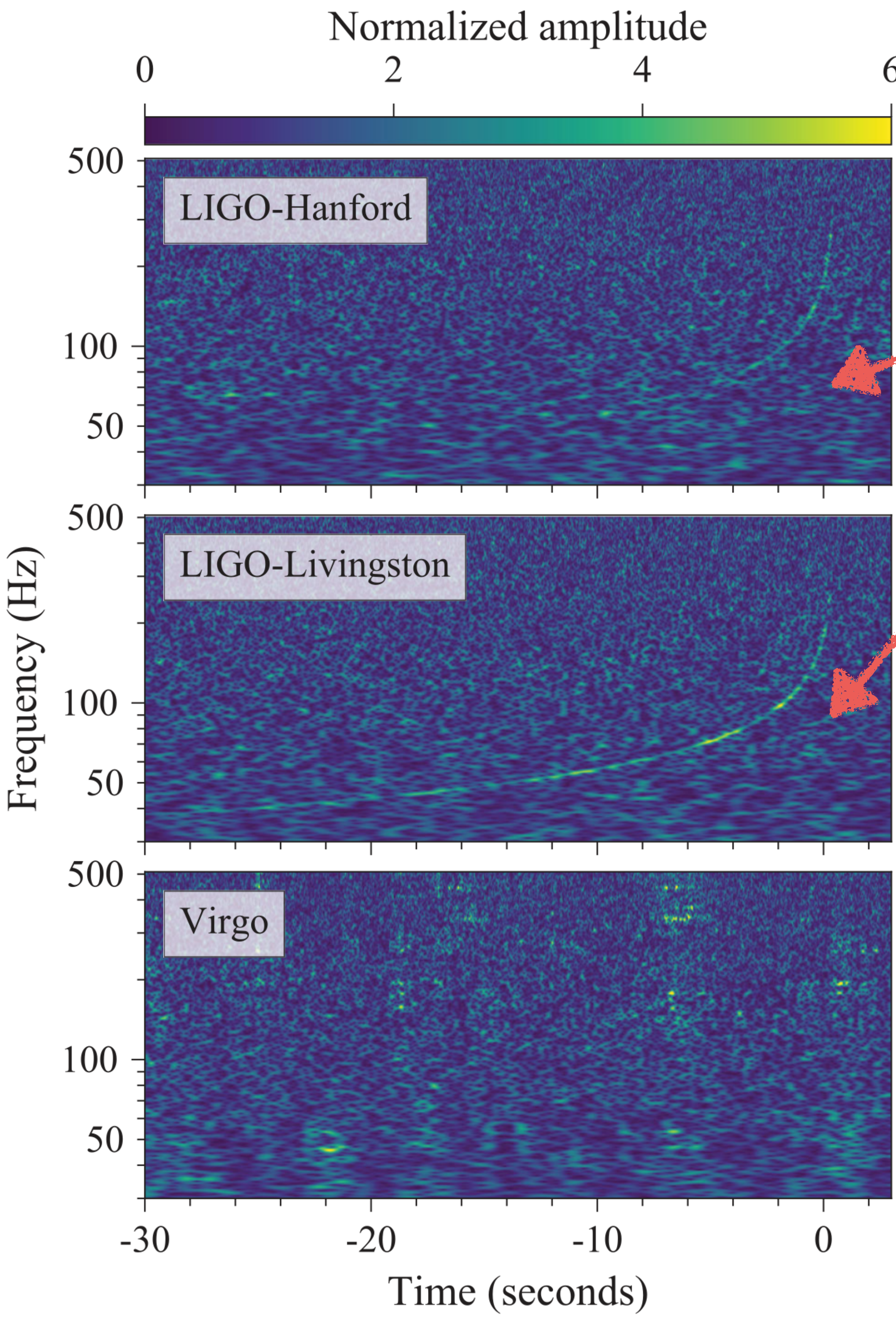
$$\frac{d\omega(t)}{dt} = -\frac{\omega_0}{2\delta t}$$

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

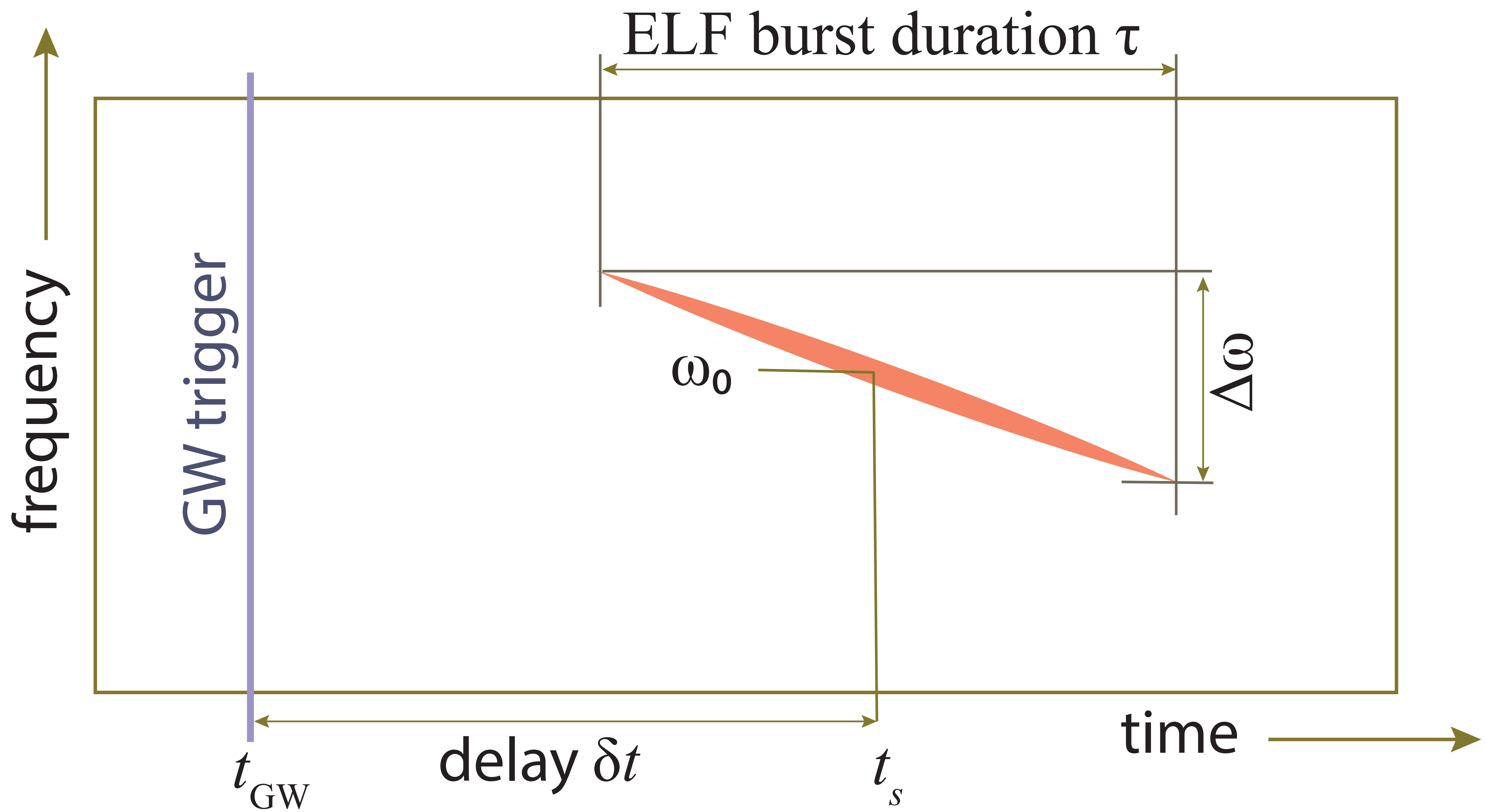
Power of the network



The same but time-shifted signal

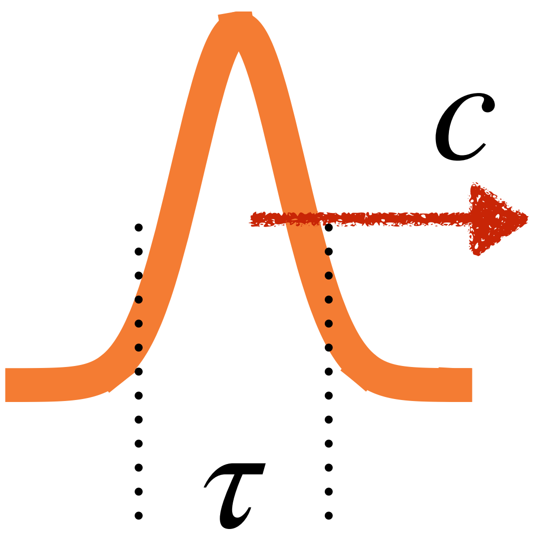
+ locating progenitor in the sky

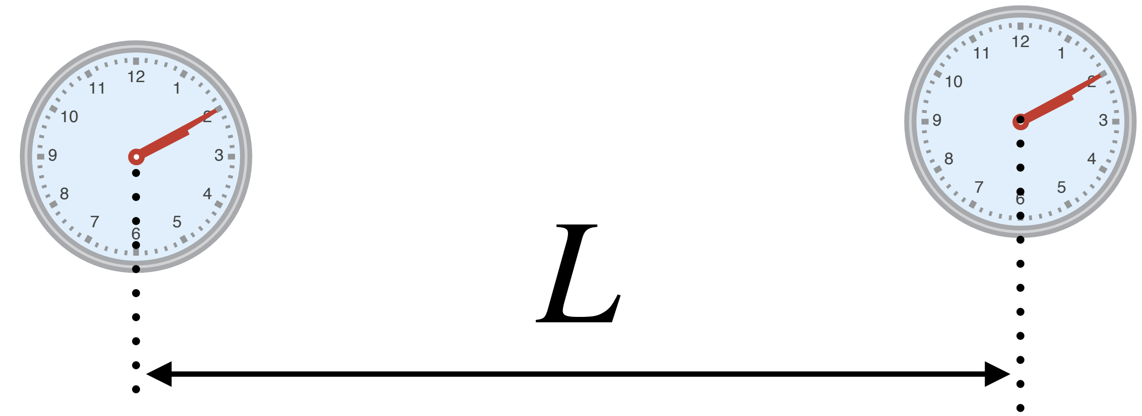
ELF power spectrum template



Anti-chirp is independent of the production mechanism

Network desiderata





Time resolution Δ_t

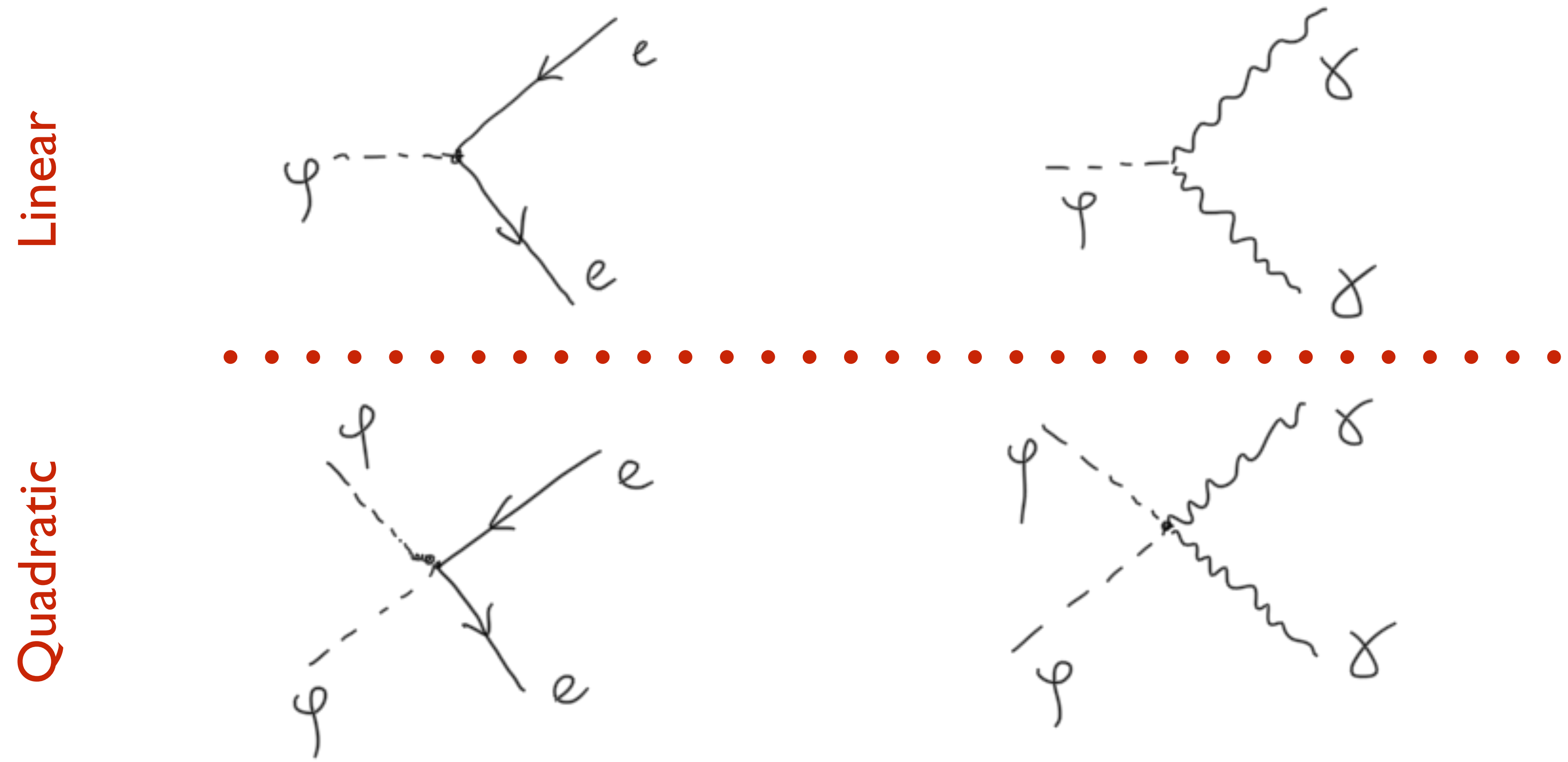
1. Resolve leading edge: $\Delta_t \ll L/c$
2. Resolve envelope: $\Delta_t \ll \tau$

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

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

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

Coupling ELFs to sensors

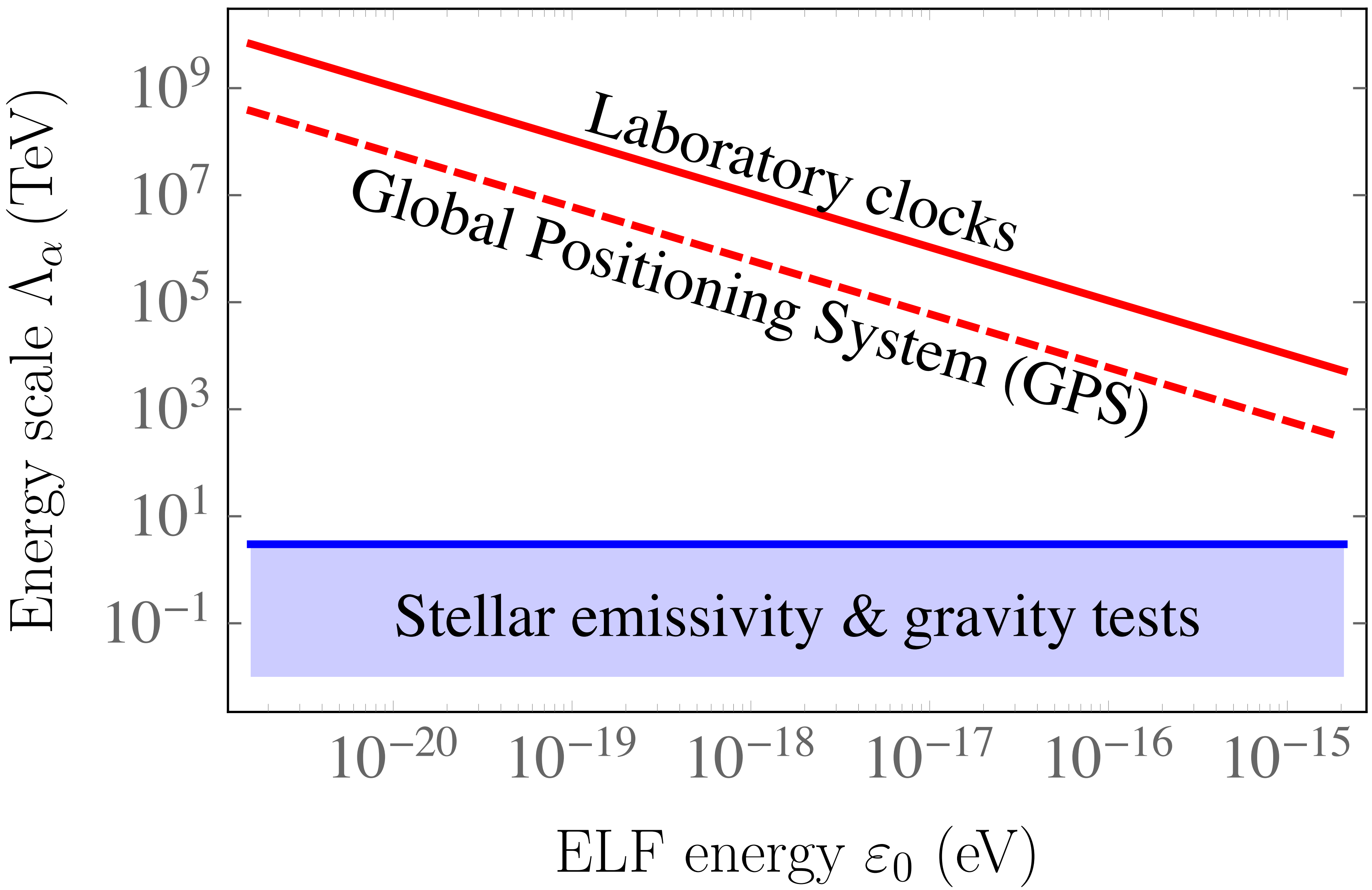


Induced variation in fundamental constants

$$\frac{\Delta\alpha}{\alpha} = \Gamma_{\alpha}\varphi(\mathbf{r},\mathbf{t}) \qquad \frac{\Delta m_e}{m_e} = \Gamma_{m_e}\varphi(\mathbf{r},\mathbf{t})$$

$\Rightarrow$ affects clock frequencies and the measured time

Projected sensitivity GW170817 (NS+NS)

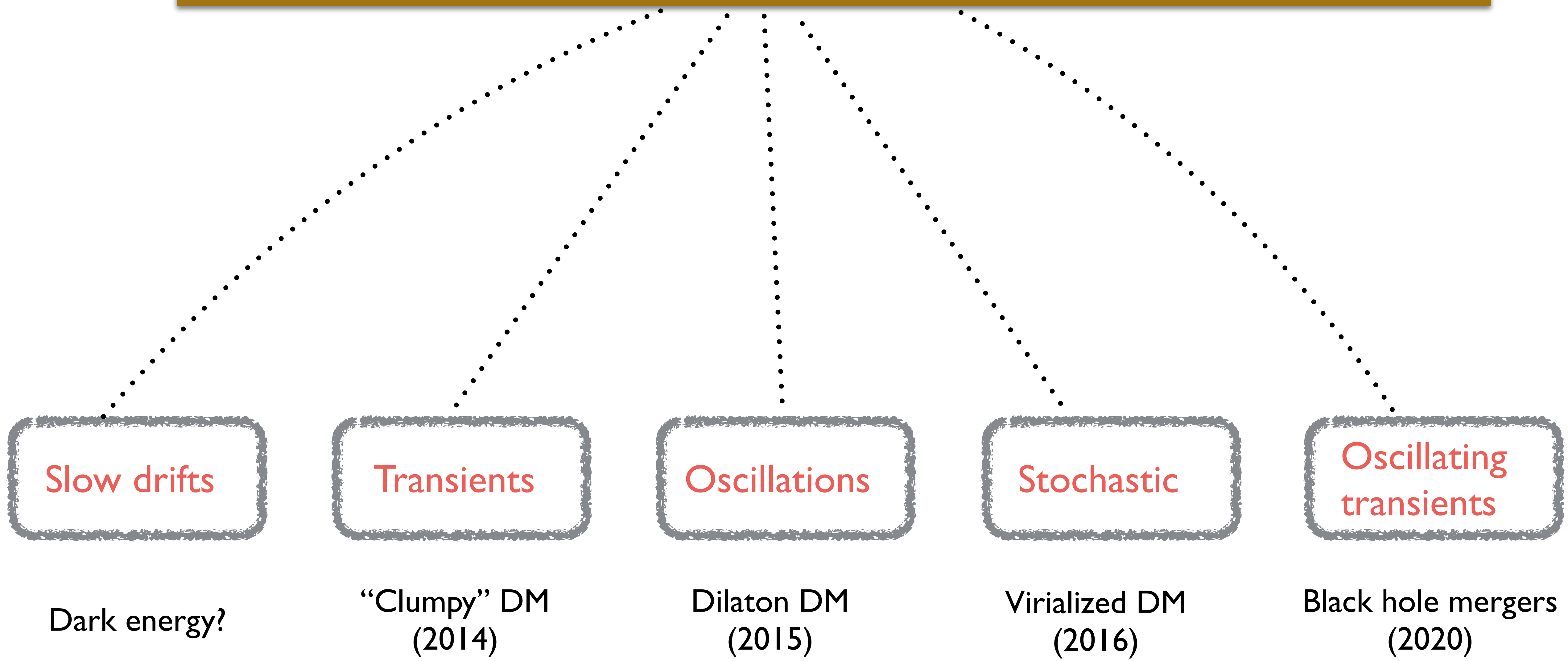


$\Delta E_{\mathrm{ELF}} = 0.1\, M_\odot c^2$

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

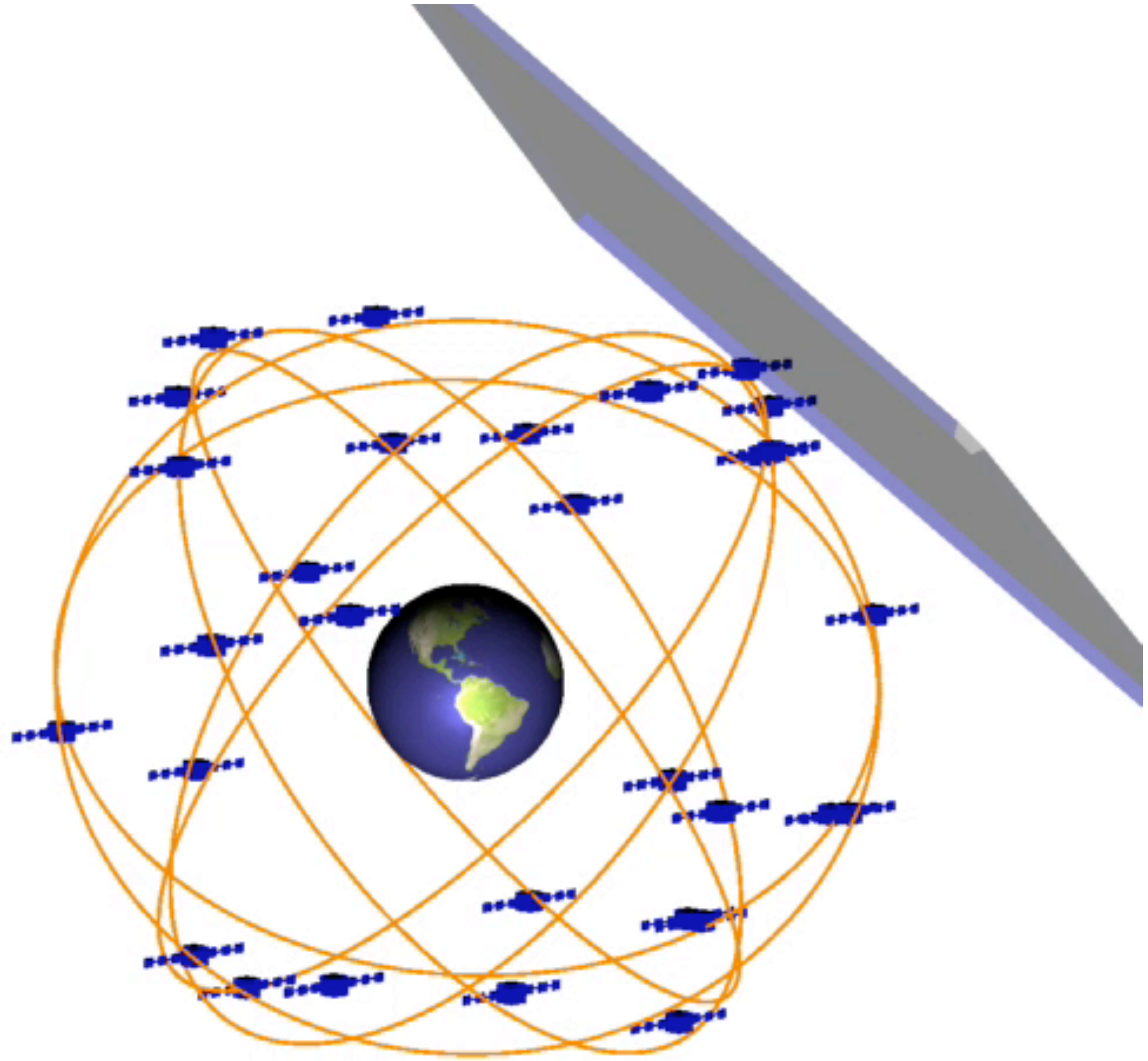
$$\mathscr{L} \supset \left(-\frac{m_e c^2 \bar{\psi}_e \psi_e}{\Lambda_{m_e}^2} + \frac{1}{4\Lambda_\alpha^2} F_{\mu\nu}^2 \right) \phi^2$$

Variations of fundamental constants (2021)



Preliminary results from GPS clocks

GPS.DM observatory



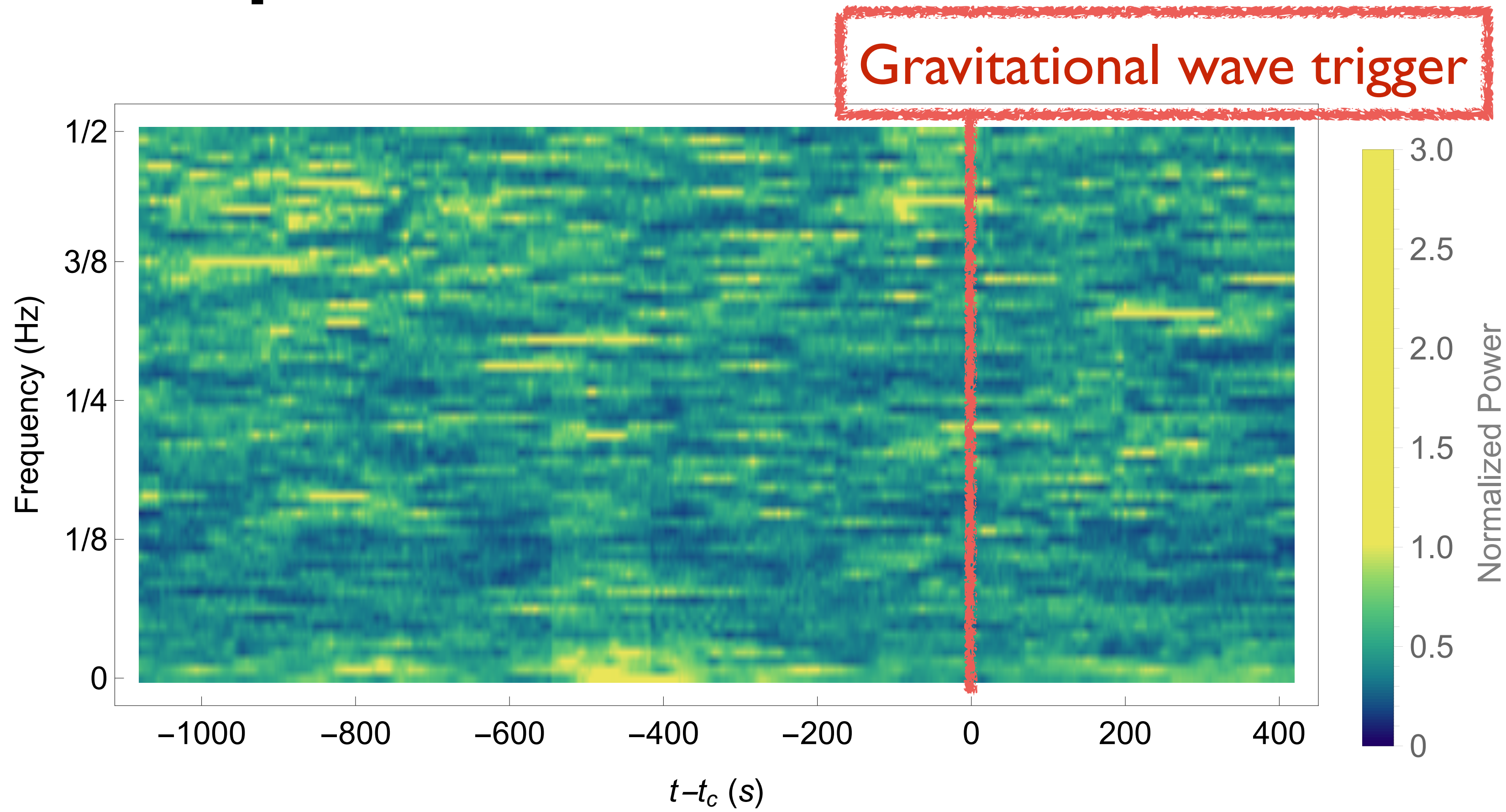
Credit: Conner Dailey

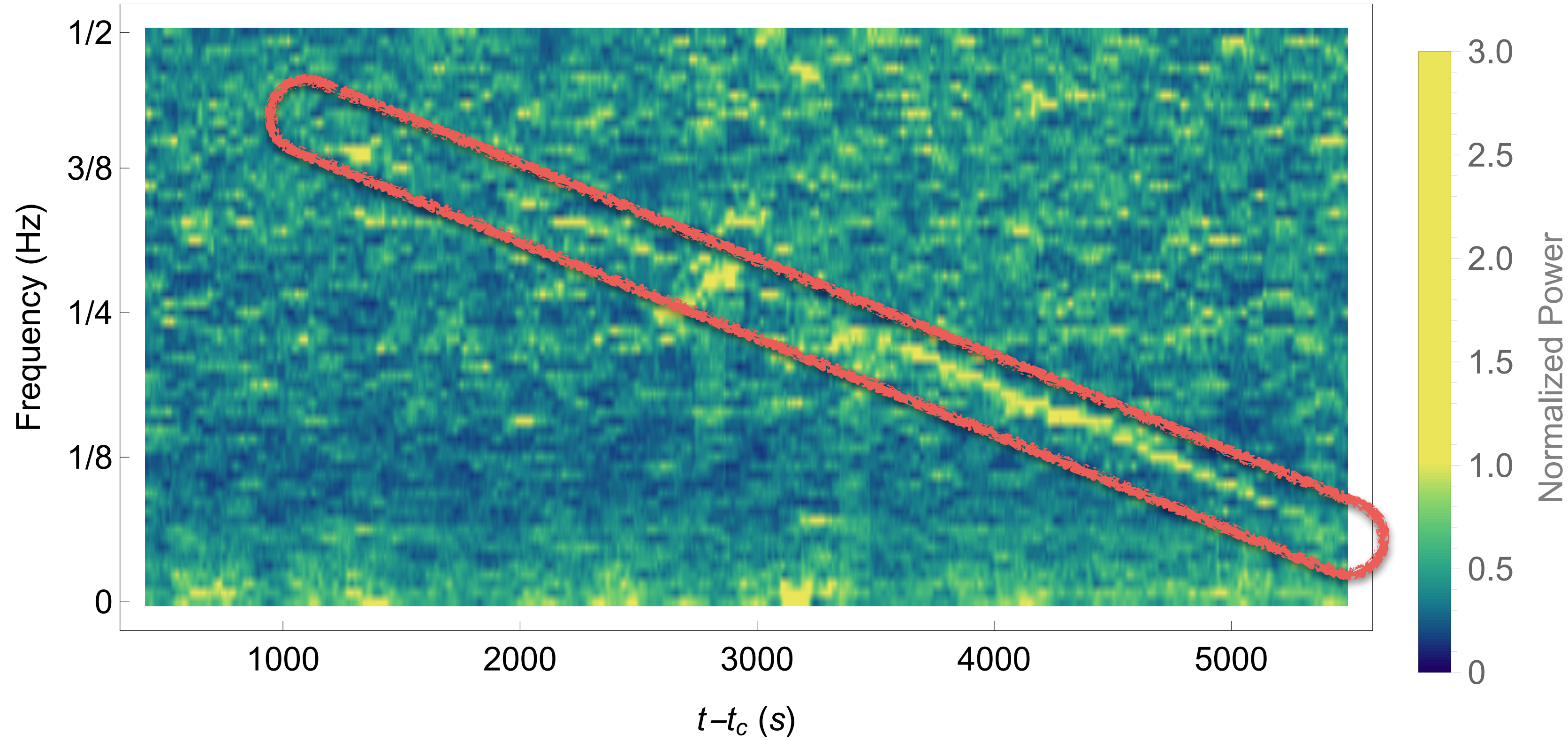
Mining ~20 years of archival data for atomic clocks onboard GPS satellites

30 second sampling time - need faster sampling rate for the ELF search

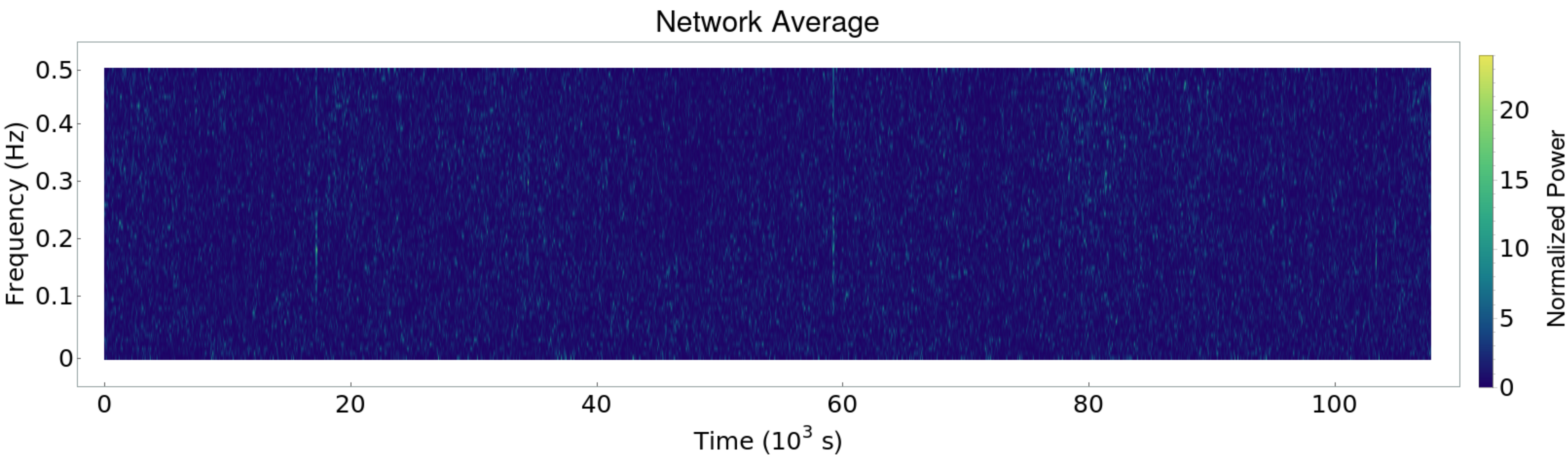
Excess power in GPS atomic clocks

1 second GPS data by G. Blewitt





Better $1\,\mathrm{s}$ data (Paul Reis, JPL)



- The "ELF signal" went away.
- Work in progress - still artifacts in 1s data.
- We can set limits on quadratic couplings.

Conner Dailey, MSc thesis, U. Nevada, Reno (2019)
Current efforts: Arko Pratim Sen

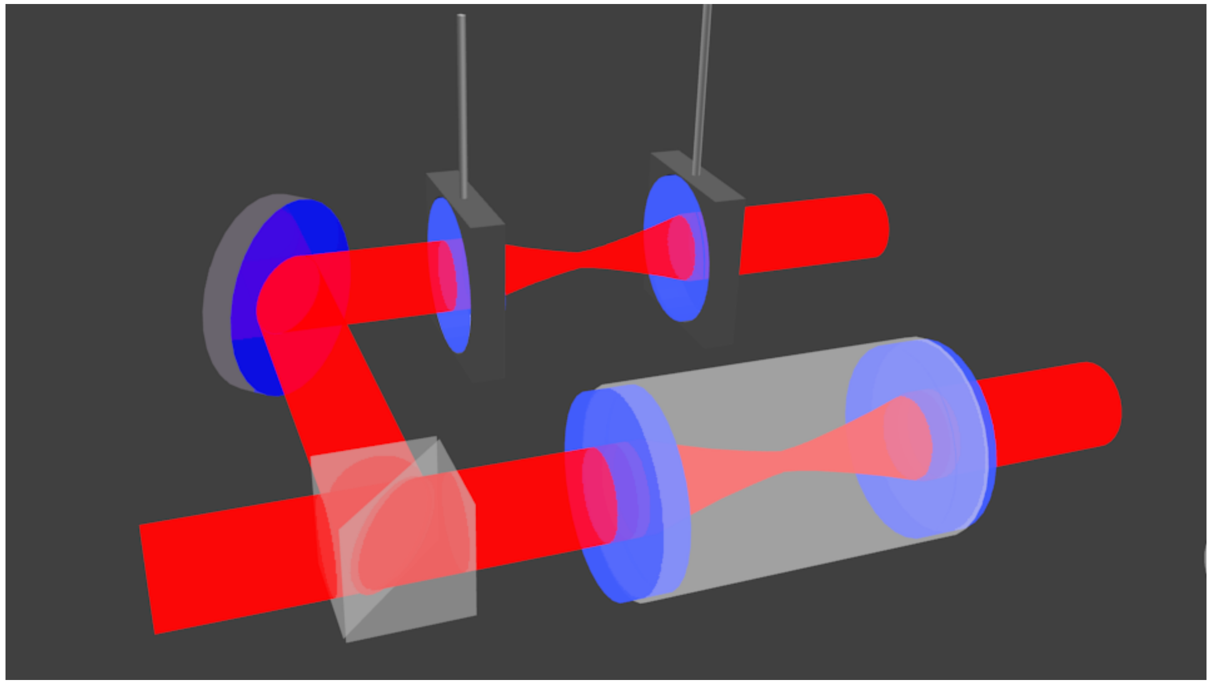
Cavities vs clocks

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

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

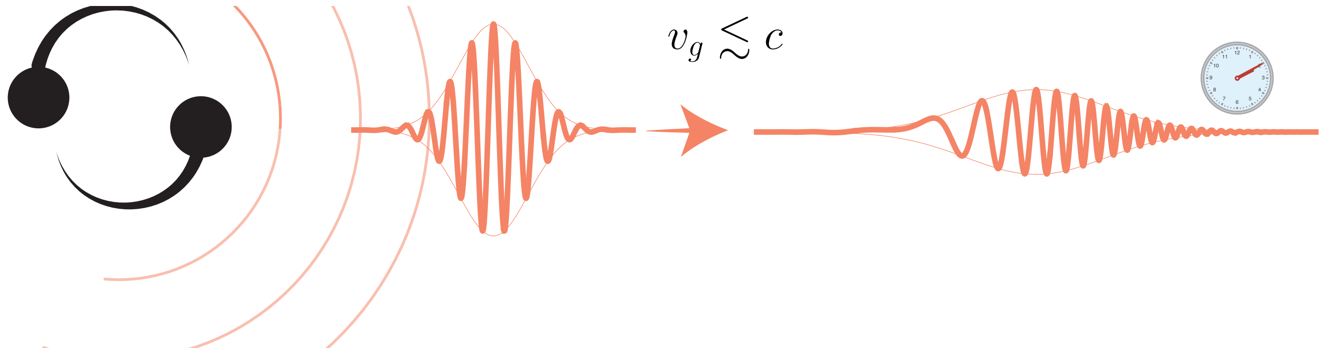
Cavities ~ 100 kHz. ELFs can be tracked!

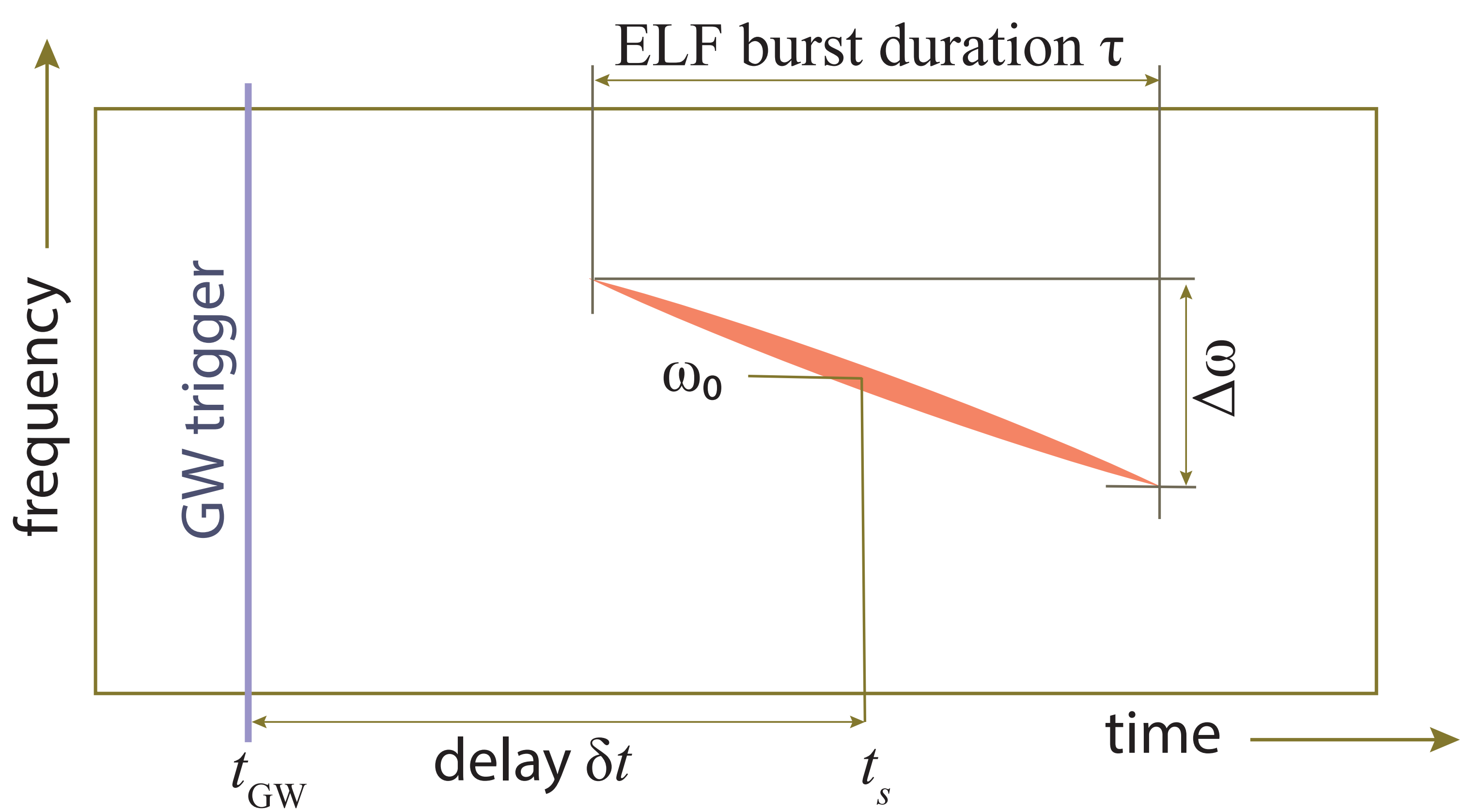
Campus-sized network ~ 3 km

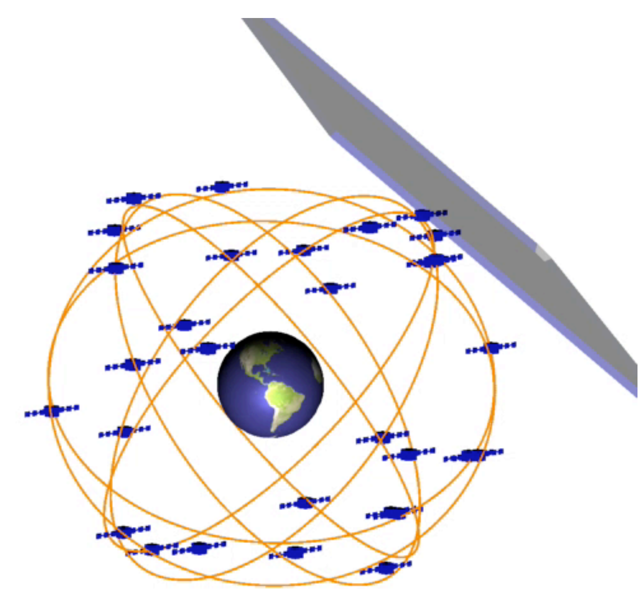


A. Geraci, C. Bradley, D. Gao, J. Weinstein, and A. Derevianko, PRL 123, 31304 (2019)

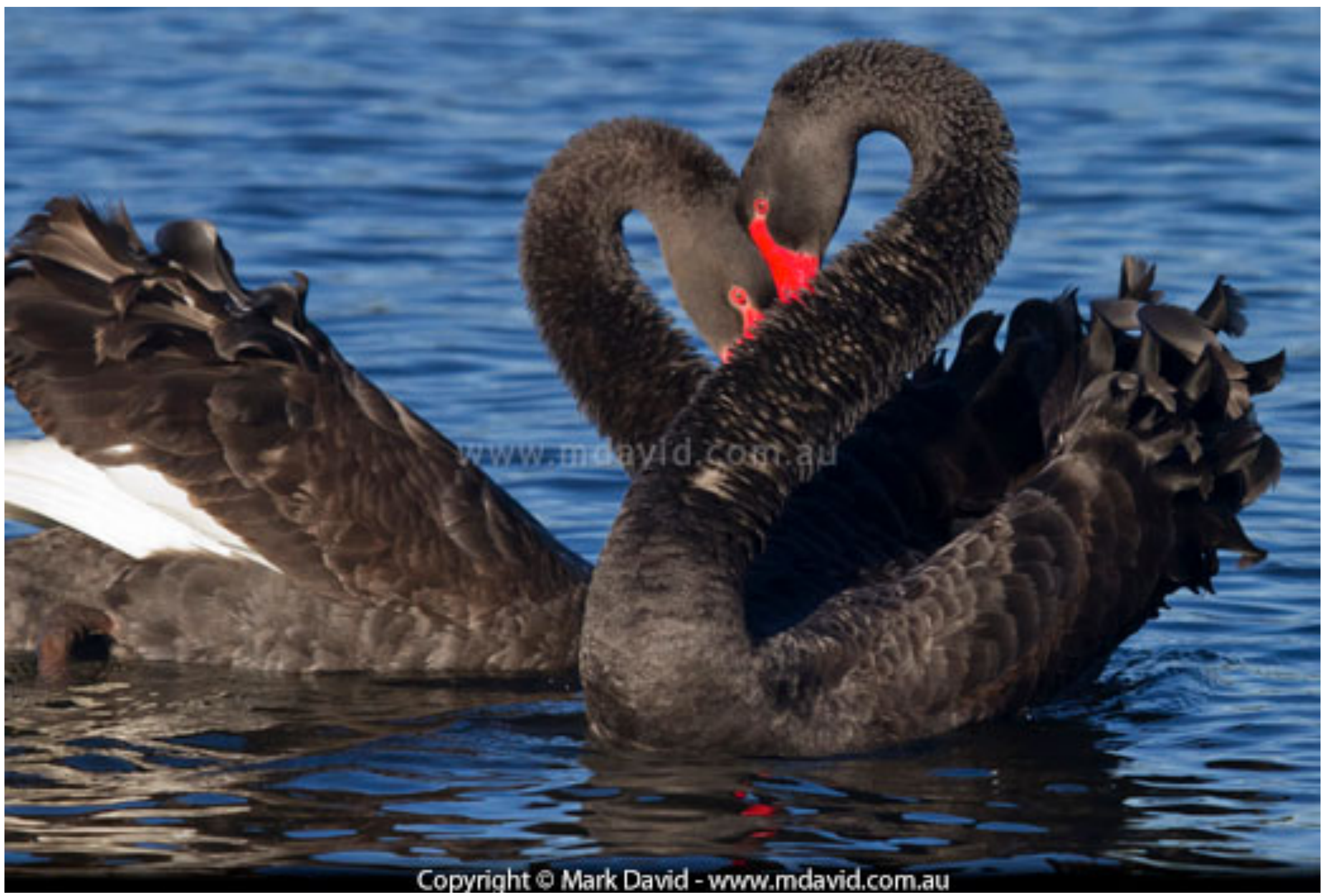
ELF summary


$v_g \lesssim c$

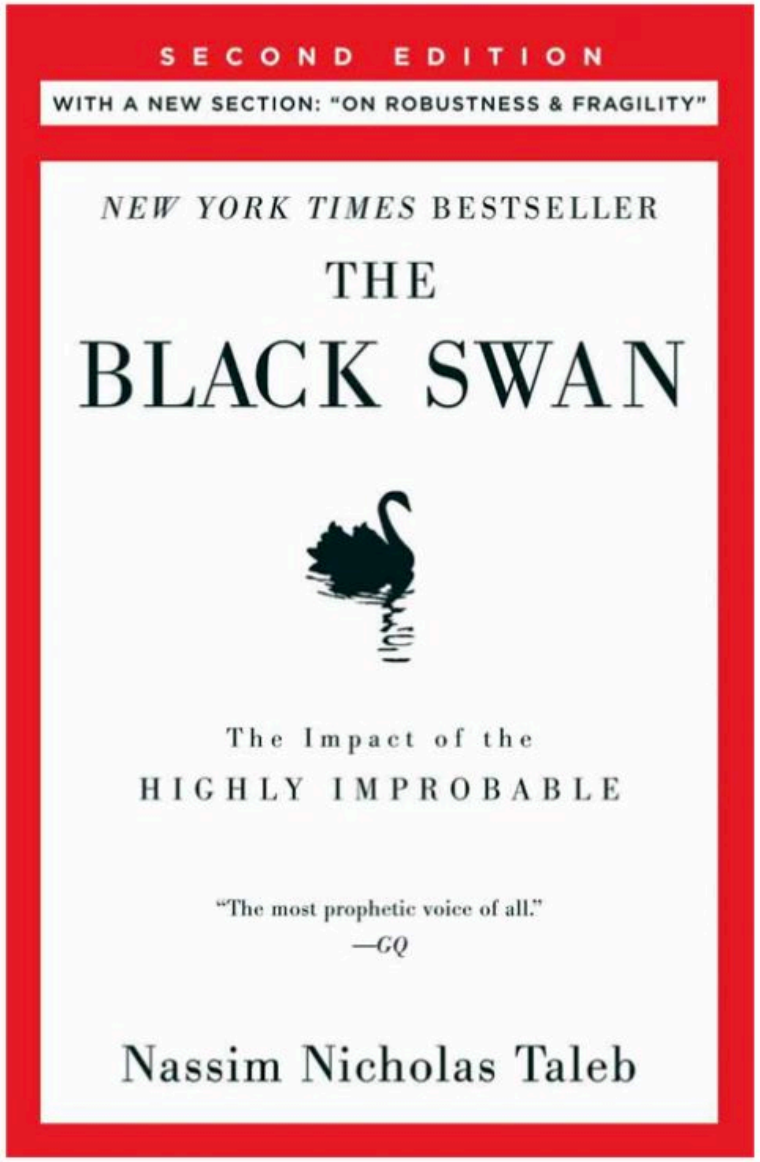

ELF burst duration τ
frequency
GW trigger
ω_0
$\Delta\omega$
t_{GW}
delay δt
t_s
time



Outliers: Black swan physics



Black swan physics

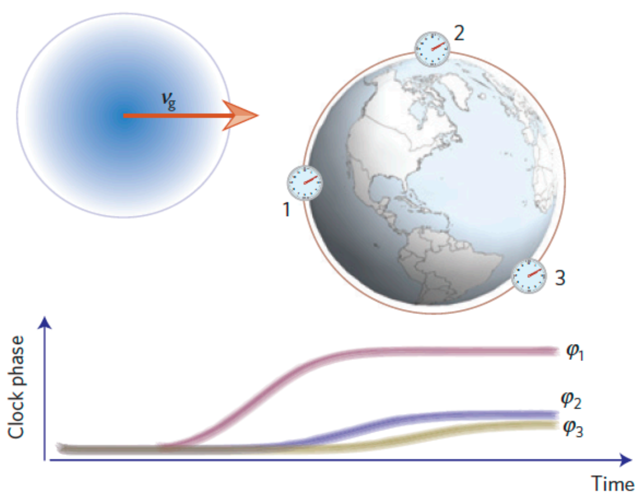


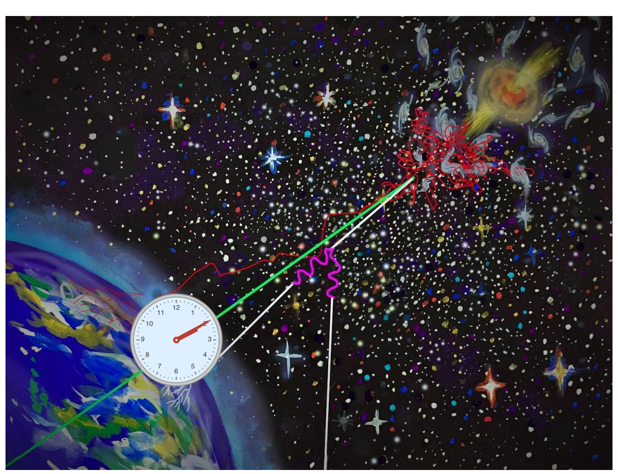
- Rare but dramatic events
  [both in time and frequency domains]
- Pragmatic empirical approach to data
- Data is the king. Make it public.
- Do not throw away outliers
  [unless you know technical reasons]

Budker & Derevianko, Physics Today 68, 10 (2015)

“Fundamental” physics sensors summary

$\dot{\alpha} \,\&\, \vec{\nabla}\alpha$





- Variation of fundamental constants
- Dark matter searches
- Gravitational waves
- Tests of general relativity
- Multi-messenger astronomy
- …