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

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NSF
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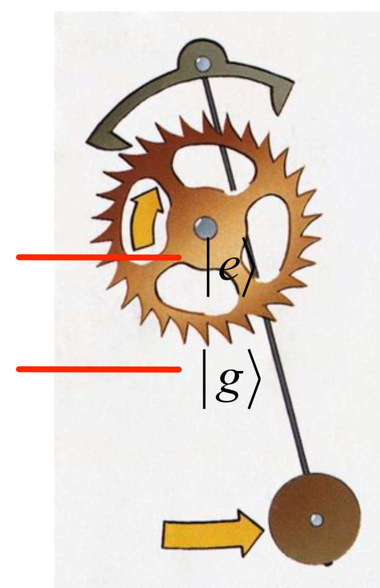
Overview

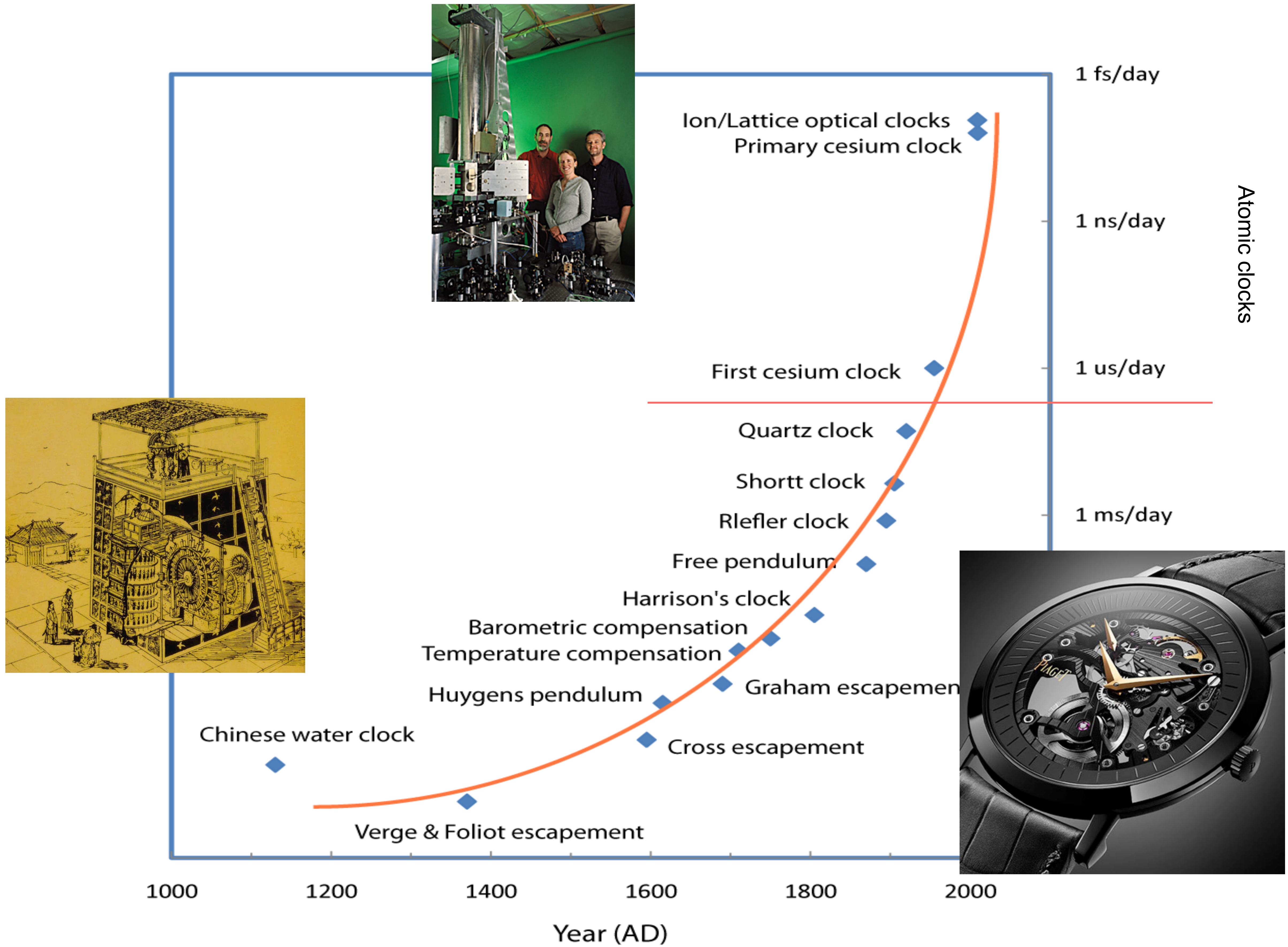
- Atomic clocks as quantum sensors
- Atomic clocks and exotic physics
  - Dark matter
  - Quantum gravity signals from black hole mergers ?
  - Anthropic constraints on transients

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)


The Nobel Prize in Physics 1989
Precision measurements using atomic beams and ion traps
The traps of Paul and Dehmelt
Ramsey and the atomic clocks
An Isolated Atomic Particle at Rest in Free Space

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)

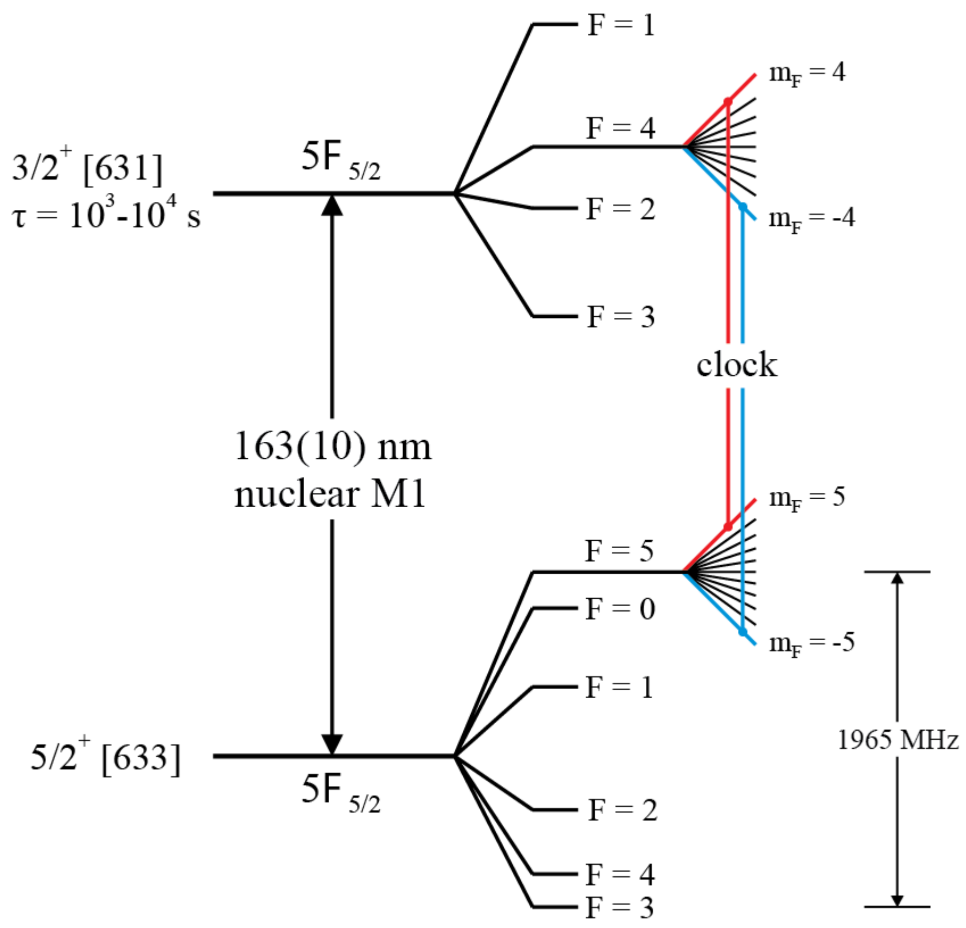


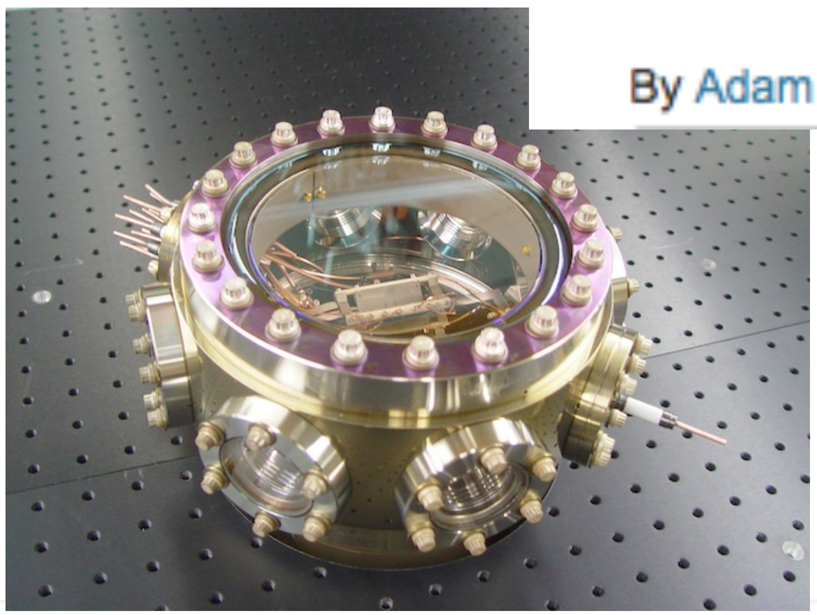
TABLE I. Estimated systematic error budget for a $^{229}Th^{3+}$ clock using realized single-ion clock technologies. Shifts and uncertainties are in fractional frequency units $(\Delta\nu/\nu_{clk})$ where $\nu_{clk} = 1.8$ PHz. See text for discussion.

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

WIRED

Laser-Tuned Nuclear Clock Would Be Accurate for Billions of Years

By Adam Mann March 20, 2012 | 5:28 pm | Categories: Physics



questcequilmanque

You've managed to find the single most depressing scientific endeavor of all time: Spend years of research trying to make an ultra-precise clock more precise. If they succeed, only electrons will notice. What's the suicide rate among these people?

Clocks and exotic physics

Conventional physics perturbations are well characterized.
If there is some new physics – we could use the clock as a discovery tool

Fundamental constants

Fundamental constant is any parameter **not** determined by the theory in which it appears

- Standard model: 28 parameters (masses, α, $\hbar$,c,…)
- Cosmology: +12 parameters (e.g., Hubble)

SM: constants are constant
BSM: constants become dynamical variables (fields)
can vary in space and time

Reviews:

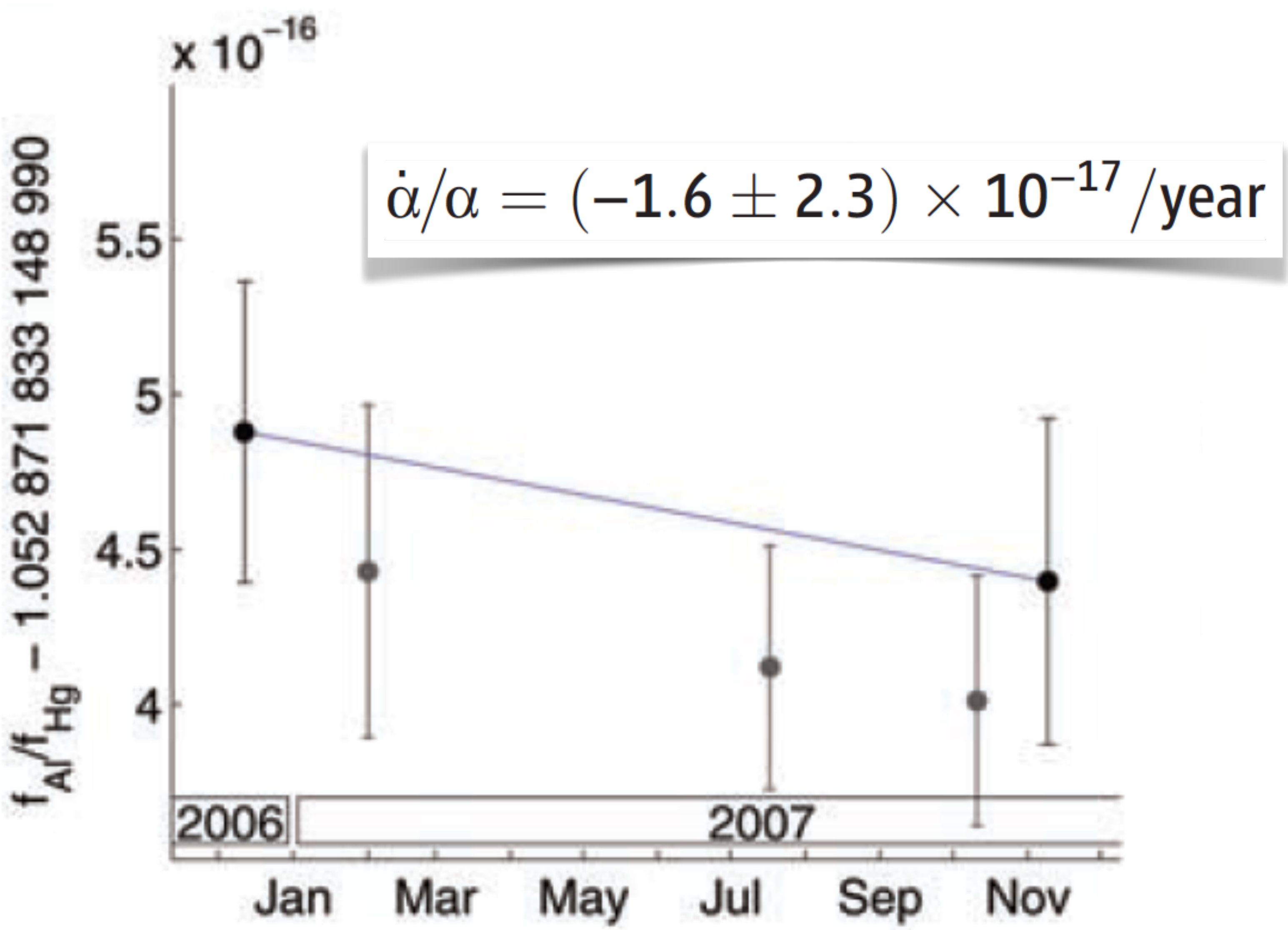
J.-P. Uzan, Living Rev. Relativ. 14, (2011)
J.-P. Uzan, Comptes Rendus Phys. 16, 576 (2015)

Slow drifts of fundamental constants

$$\nu_{\text{clock}}\left(\alpha, \frac{m_q}{\Lambda_{\text{QCD}}}, \frac{m_e}{m_p}\right)$$

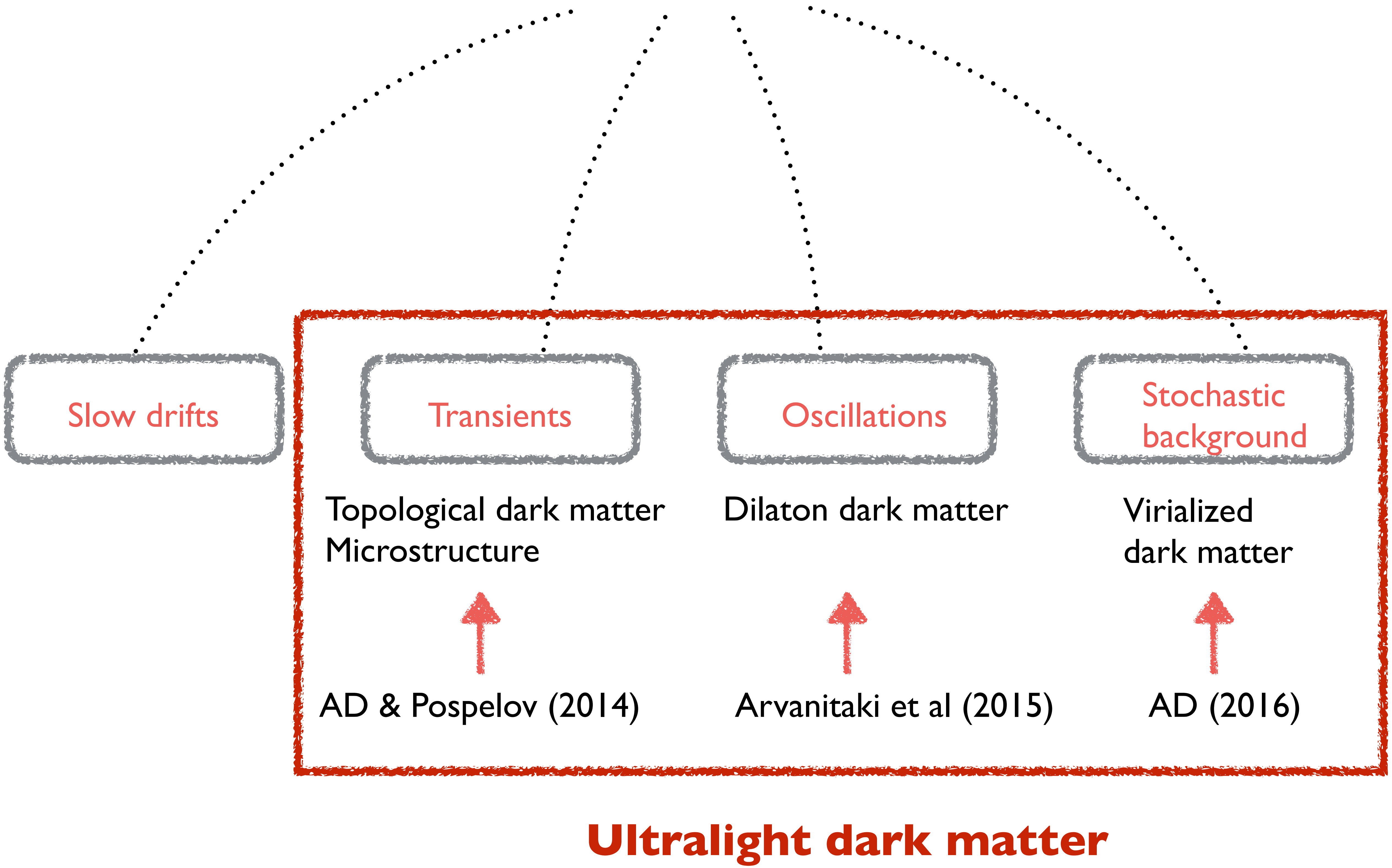
$$\frac{\delta\nu(t)}{\nu_0} = \sum_{X=\text{fnd consts}} K_X \frac{\delta X(t)}{X} = K_\alpha \frac{\delta\alpha(t)}{\alpha} + \ldots$$

Compare ratio of frequencies of two clocks with different sensitivities



T. Rosenband, et al. Science 319, 1808 (2008)

Variations of fundamental constants



Dark matter

Dark matter signatures and atomic clocks

Clocks monitor atomic transition frequencies

These depend on fundamental constants

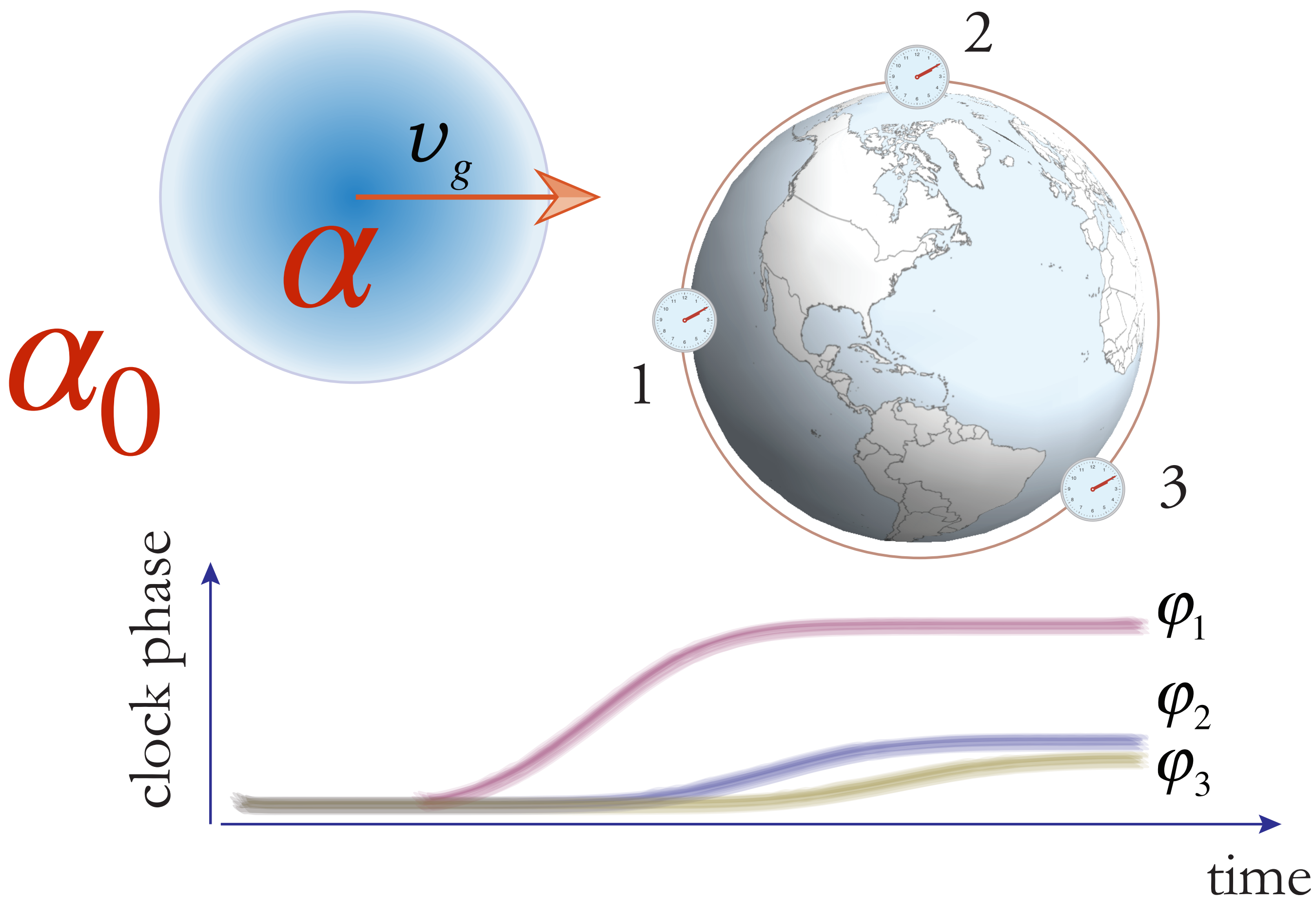
$$\Rightarrow$$

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

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

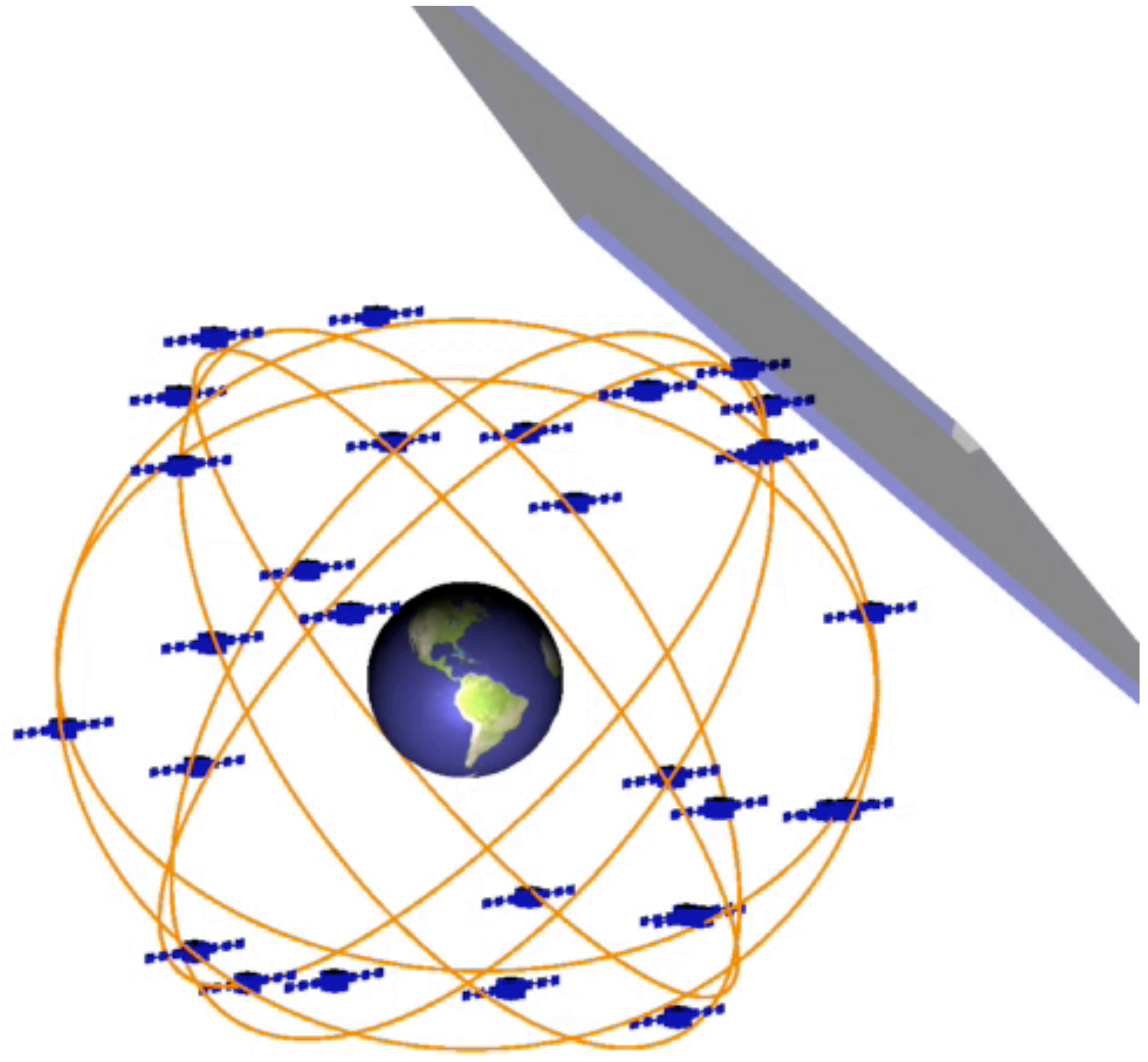
Hunting for topological dark matter with atomic clocks

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



Monopole or Q-ball signature

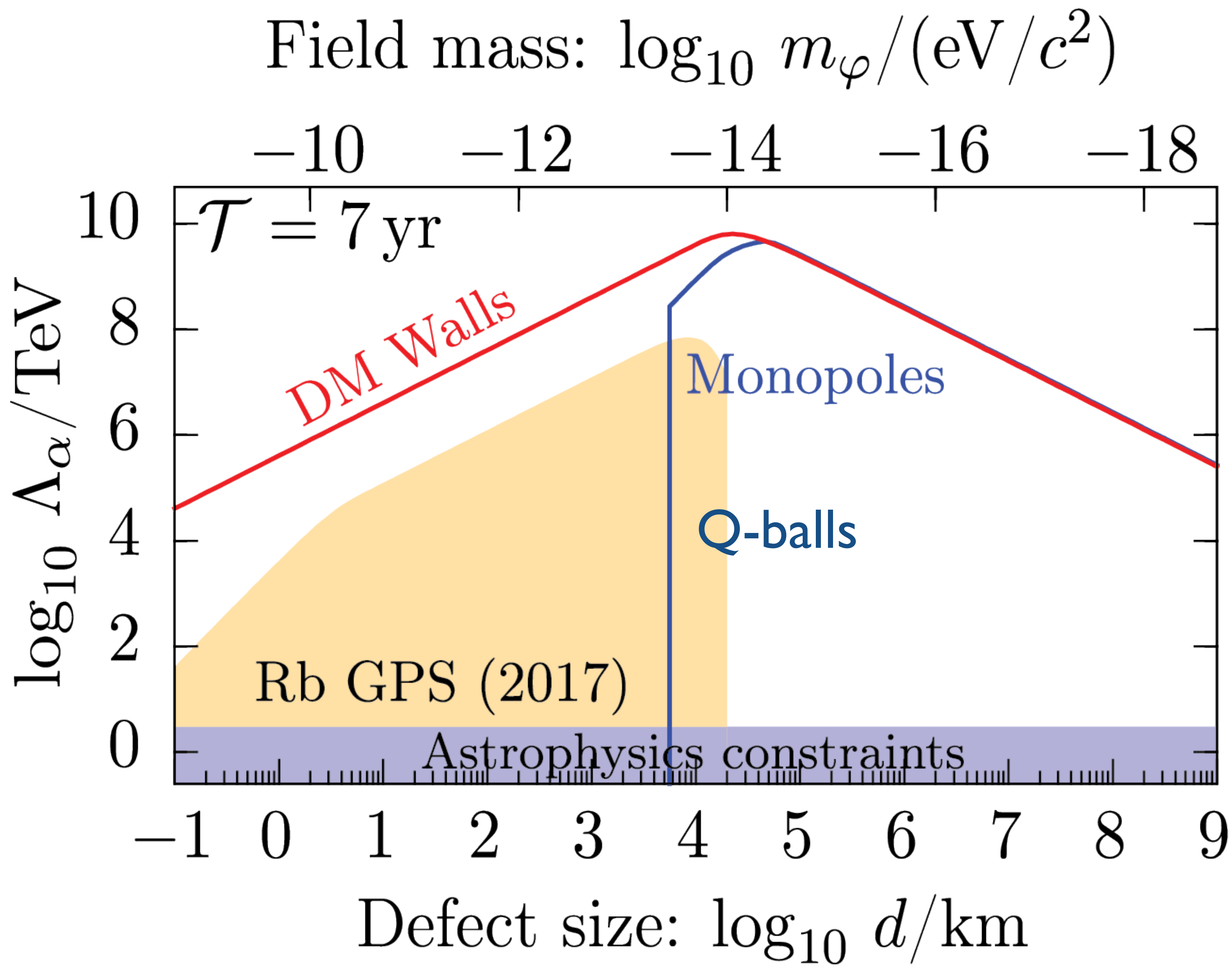
Domain wall GPS sweep



Credit: Conner Dailey

Largest human-built dark matter detector (~50,000 km)

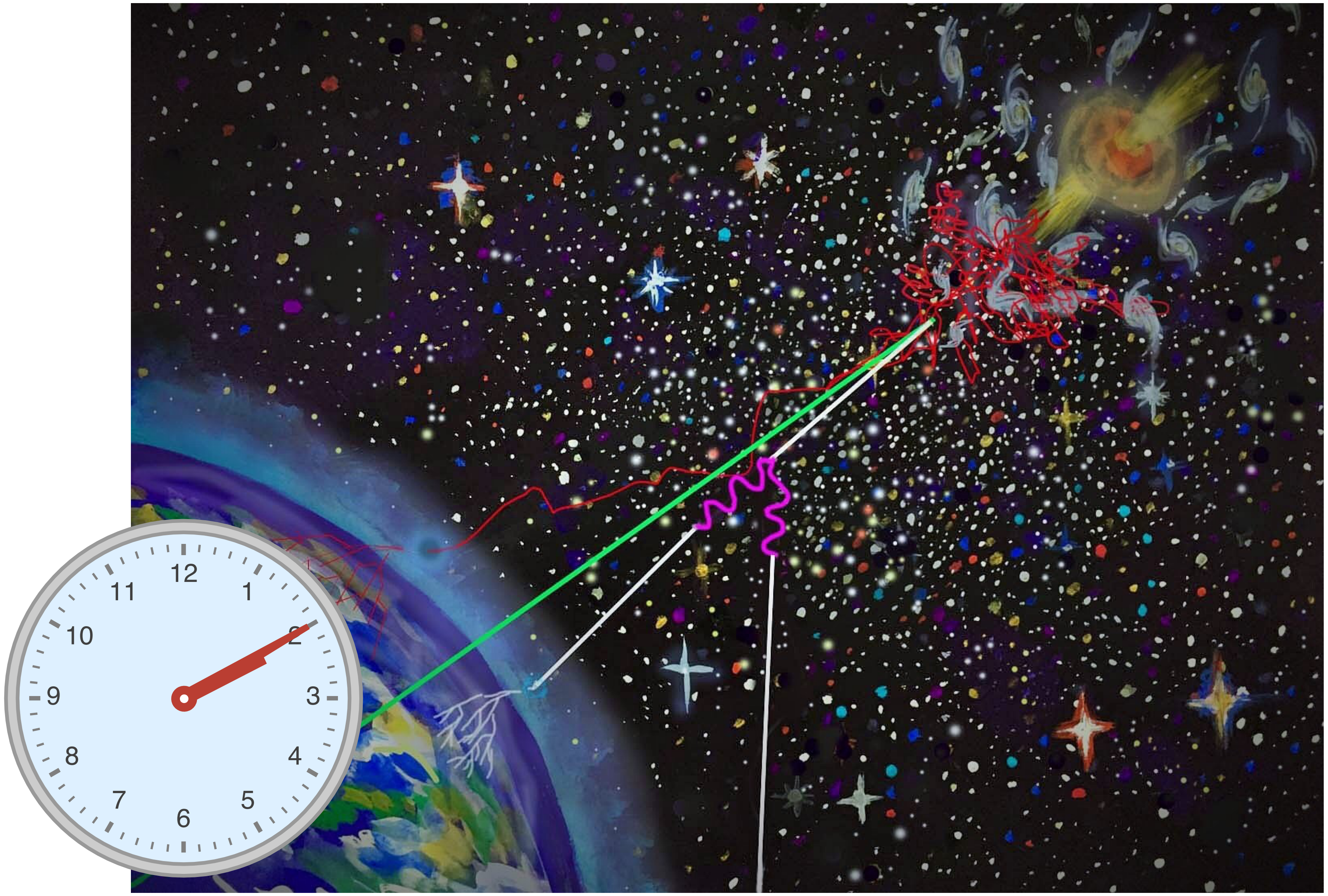
GPS.DM discovery reach



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

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

Sourced exotic fields



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

nature astronomy

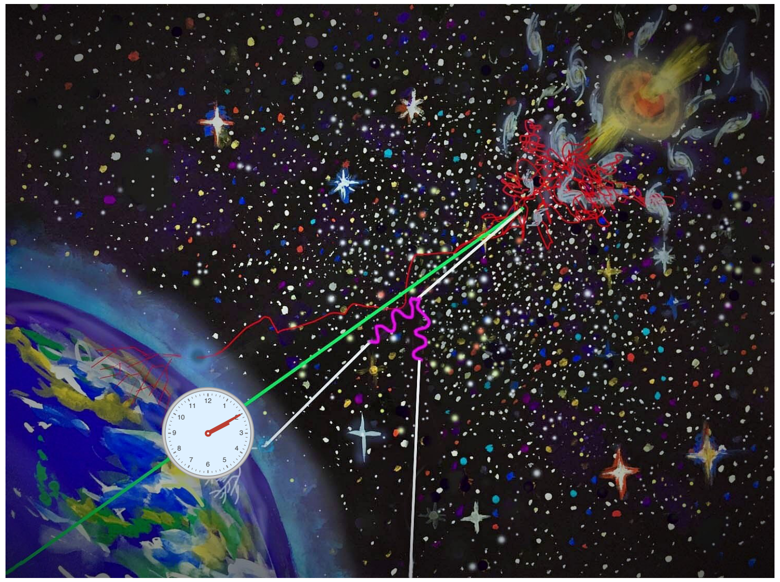
Check for updates

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]✉

Nature Astronomy, 5, 150–158 (2021)

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 (yet) sensitive to gravitational waves

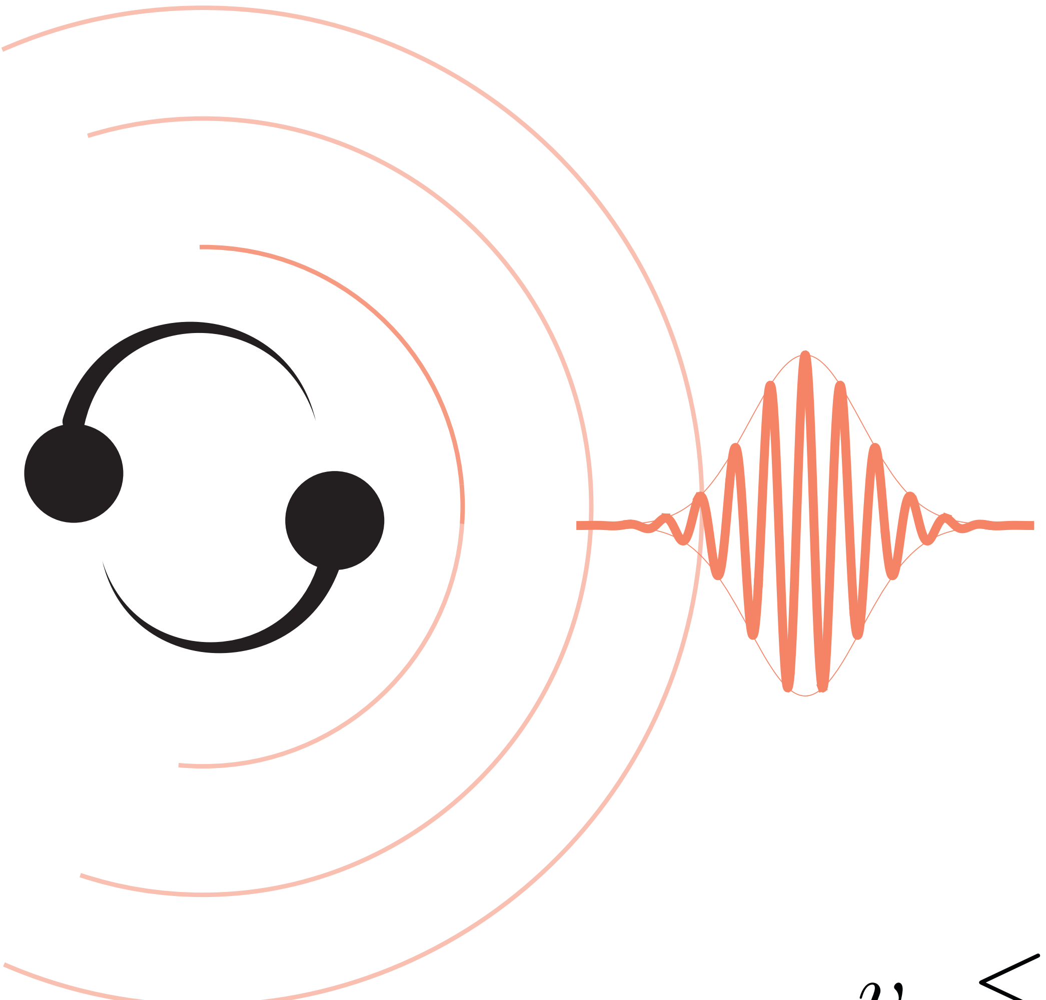
- Exquisite sensitivity to “new” physics beyond Standard model (BSM)
- Focus on exotic, BSM, scalar fields:
  - abundant in BSM theories [axions, dilatons, relaxions, etc]
  - can solve the hierarchy & strong-CP problems
  - dark-matter candidates

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

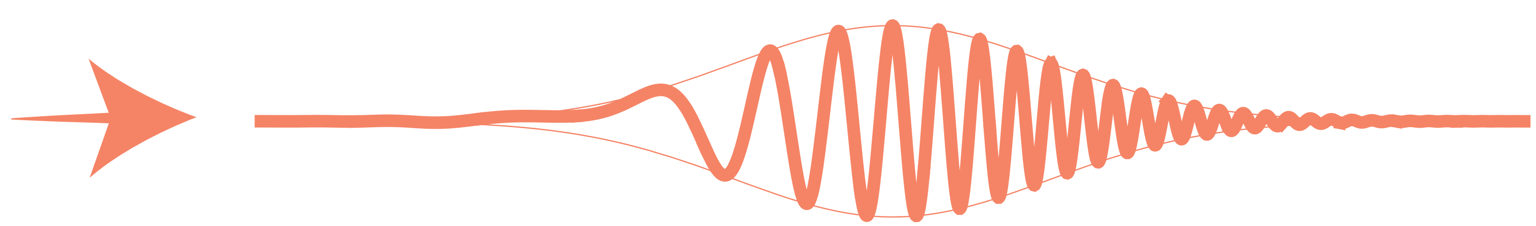
A pragmatic observational approach based on energy arguments:

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



$\Rightarrow$ Signal at the sensor?

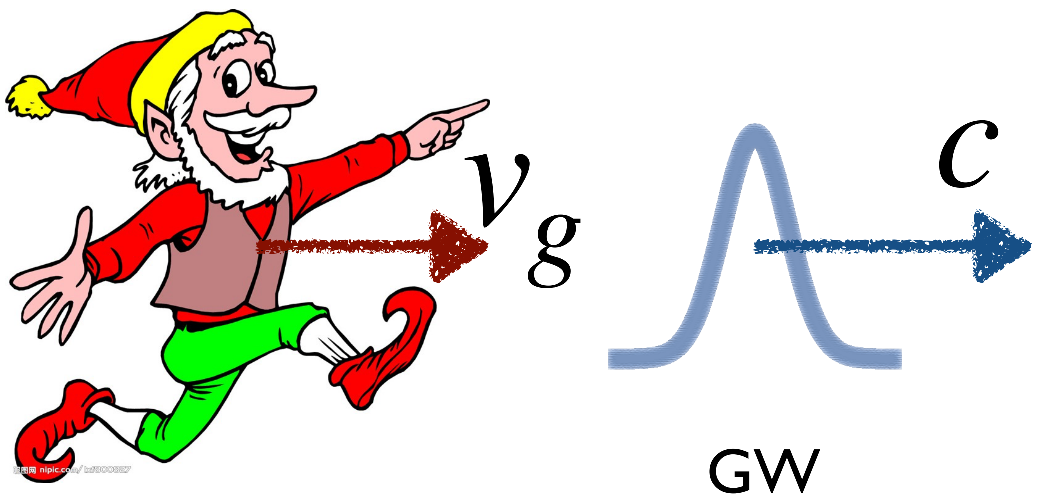
$$v_g \lesssim c$$



Nearly universal wave-form independent of the production mechanism

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

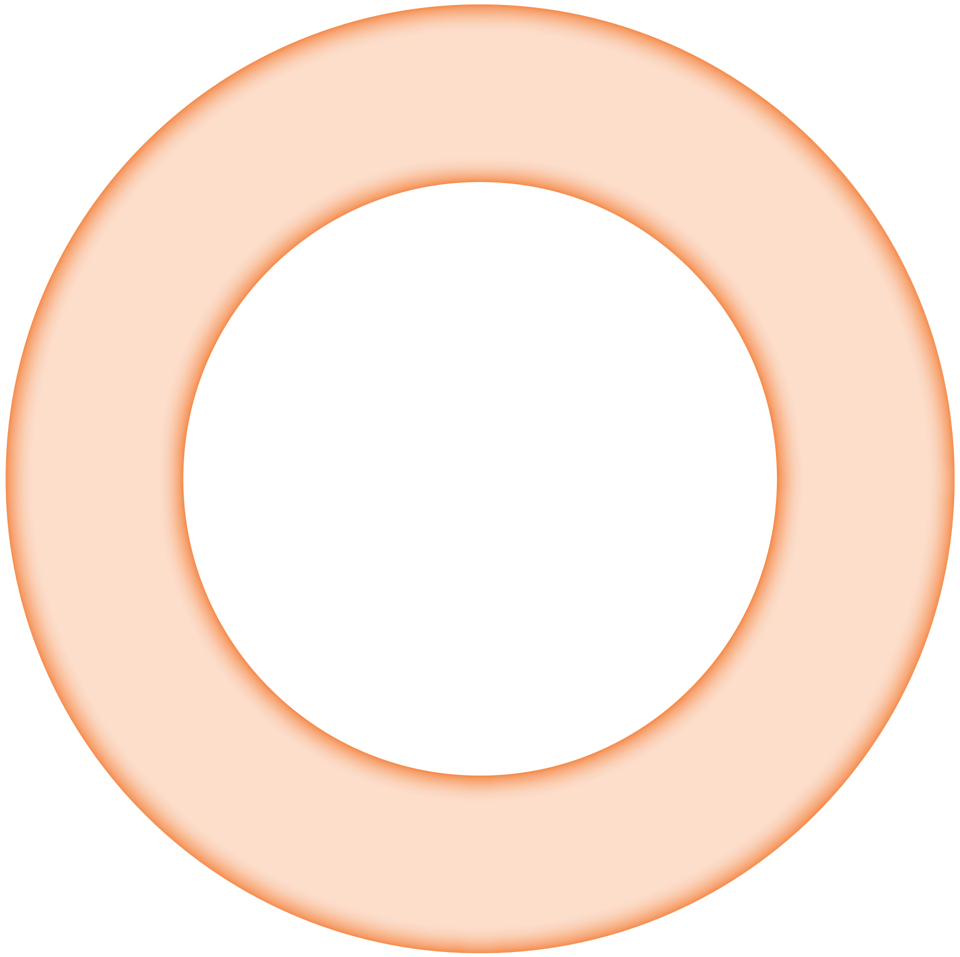
ELFs must be **ultralight**

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



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

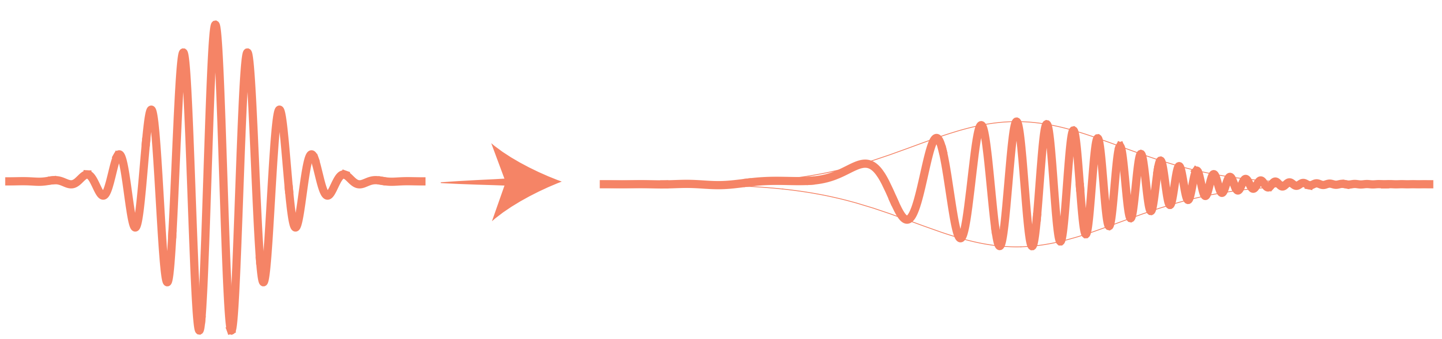
Scalar waves are like E&M waves

"Internal" refractive index (ultrarelativistic scalars)

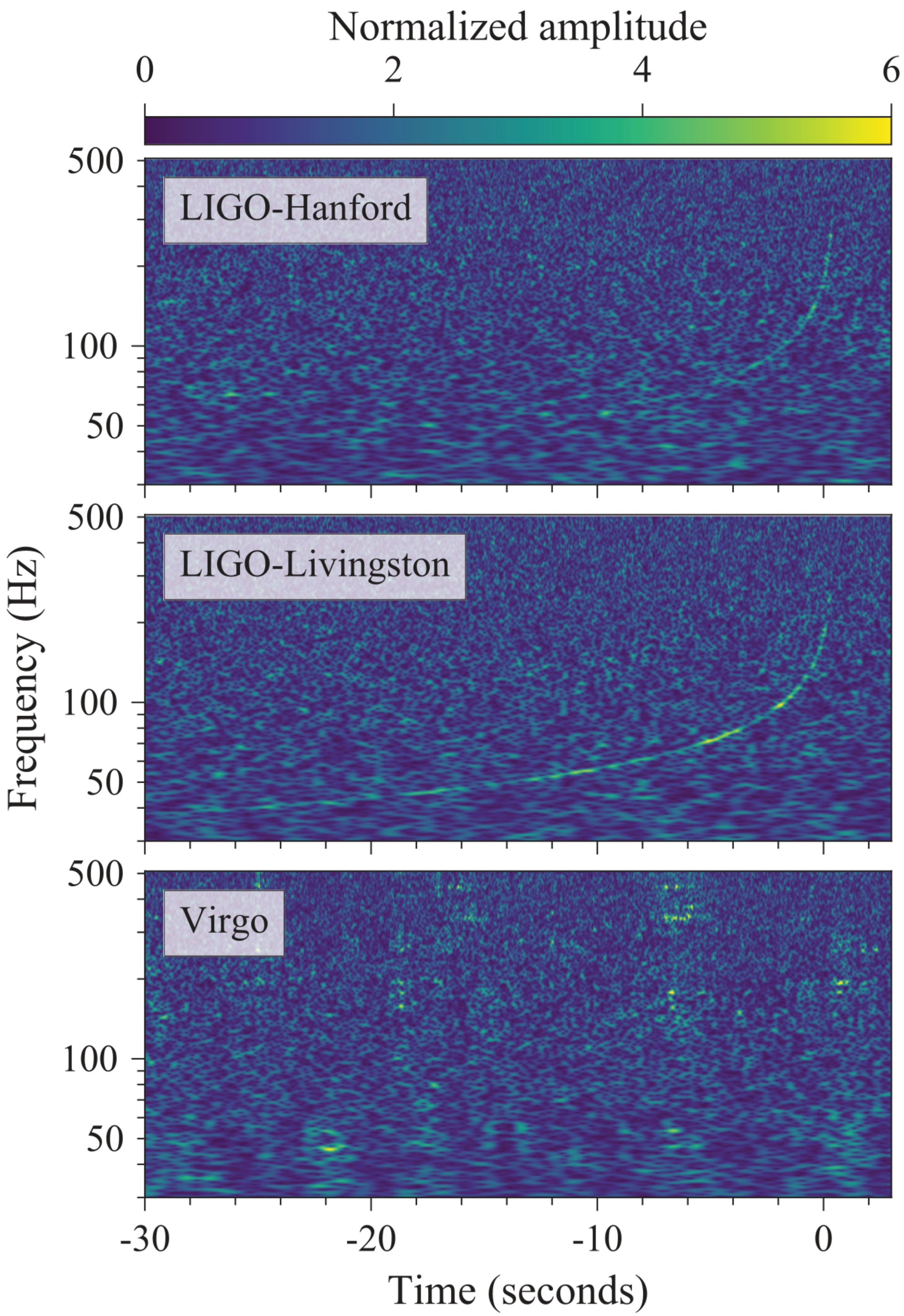
$$n(\omega) \approx 1 - \frac{1}{2}\frac{mc^2}{\hbar\omega}$$

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

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

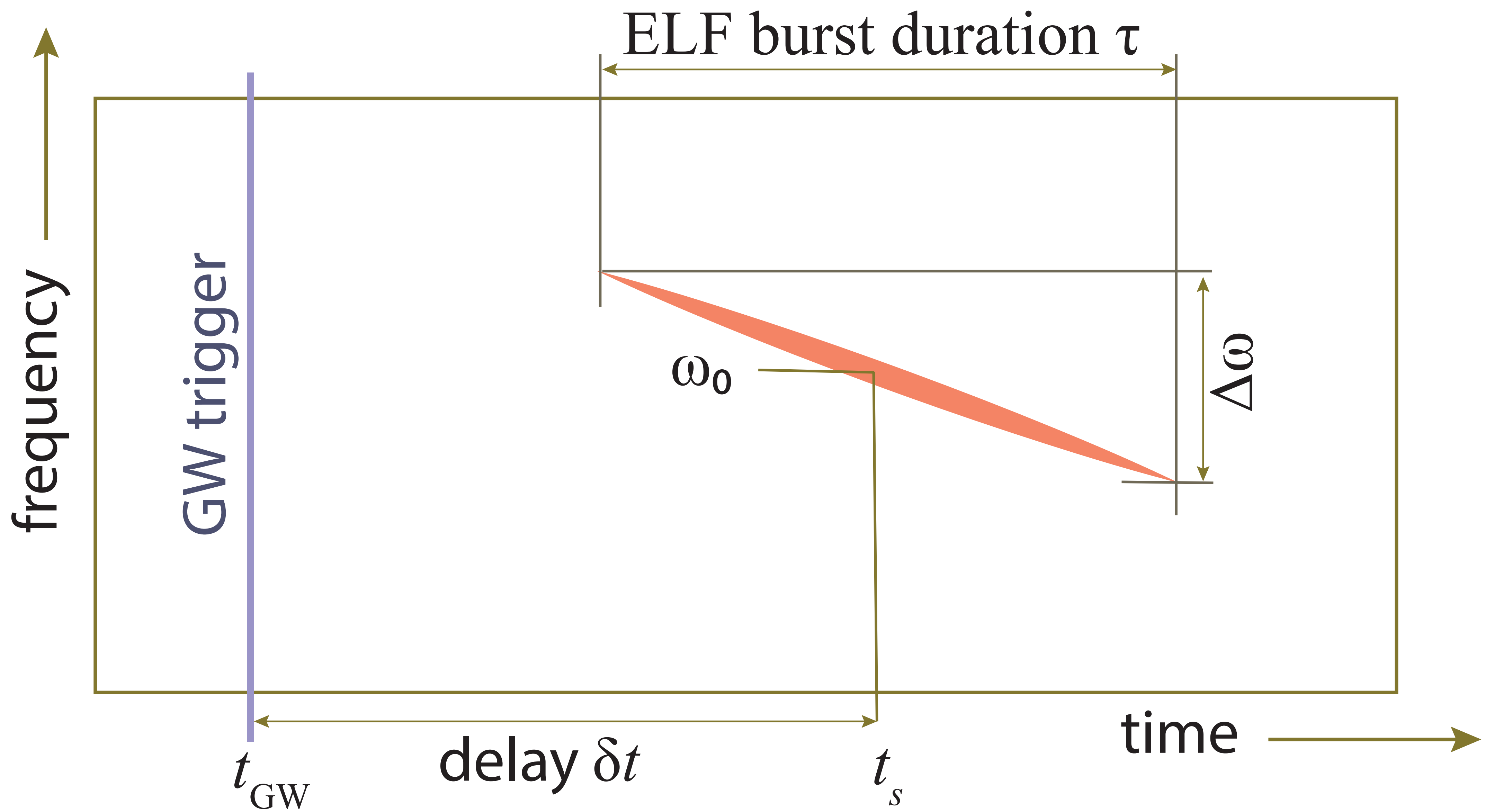


LIGO style time frequency map



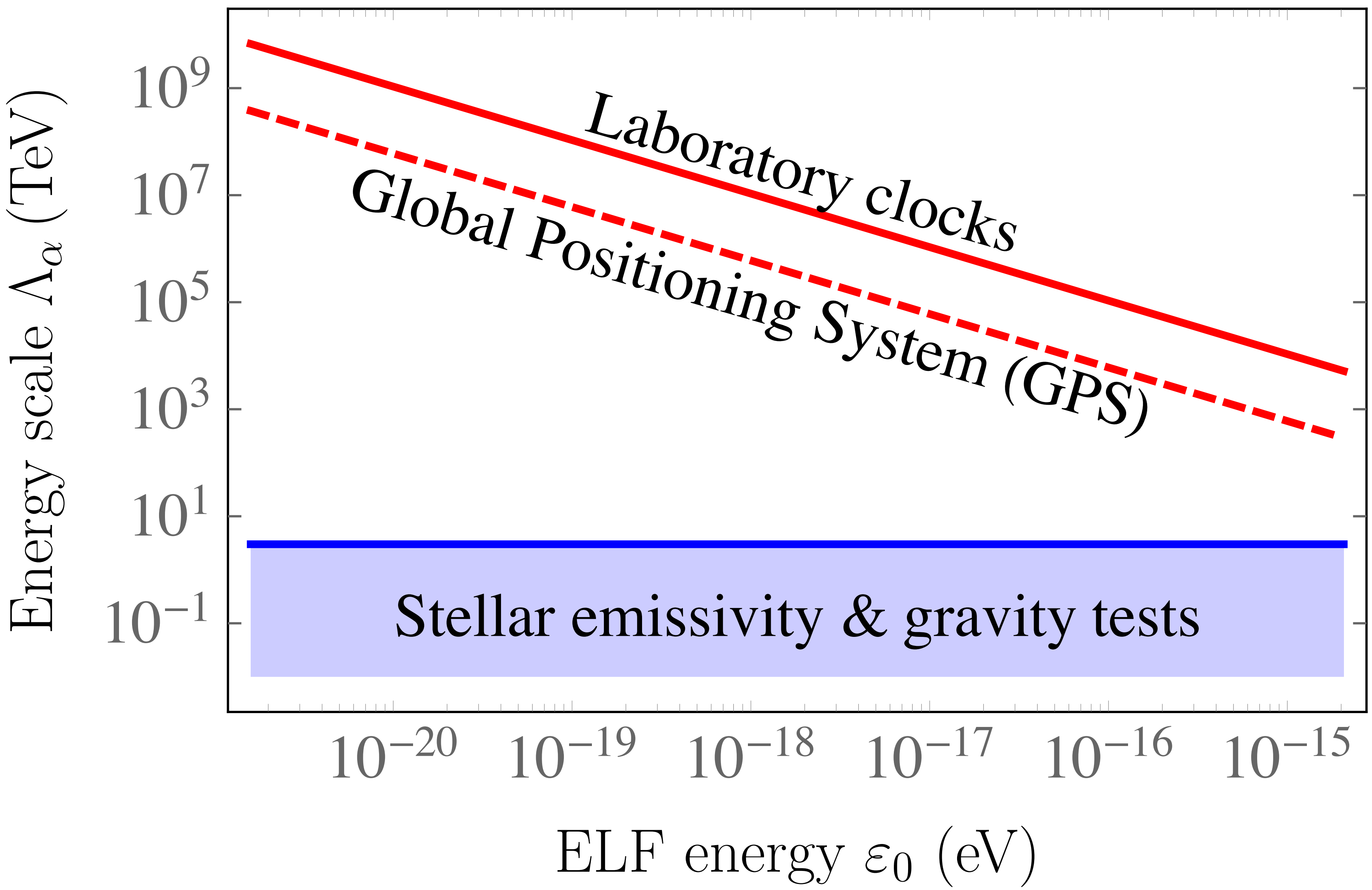
1. Chop data stream into equal chunks,
2. Discrete Fourier Transform in each window
3. Each tile = (window time stamp, frequency)
4. Compute power spectral density in each tile

ELF power spectrum template



Anti-chirp is independent of the production mechanism

Projected sensitivity GW170817 (NS+NS)

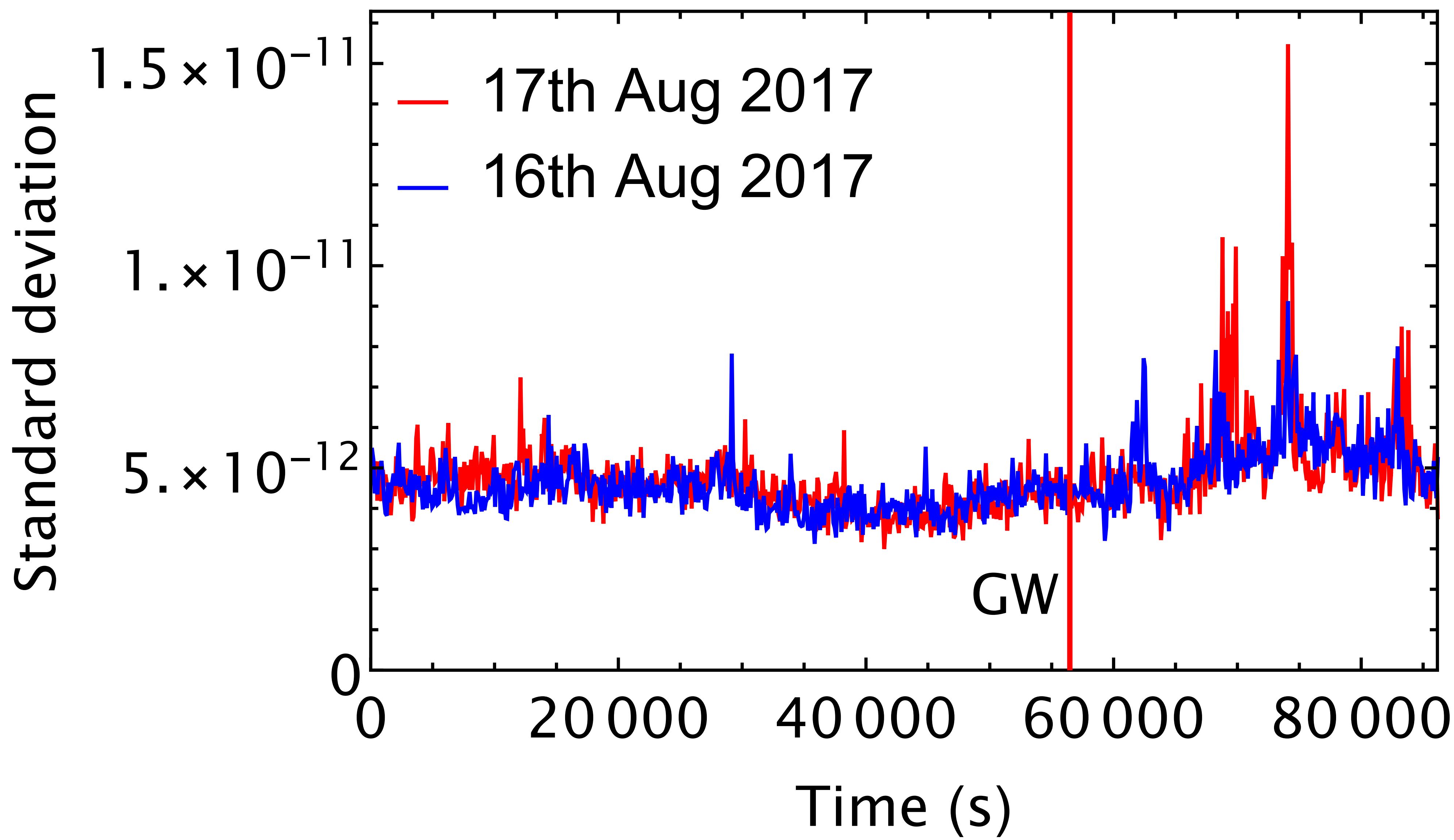


$\Delta E_{\mathrm{ELF}} = 0.1\, M_\odot c^2$

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

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

Clock noise for GW170817



Excess noise coincides with an increased solar flux activity

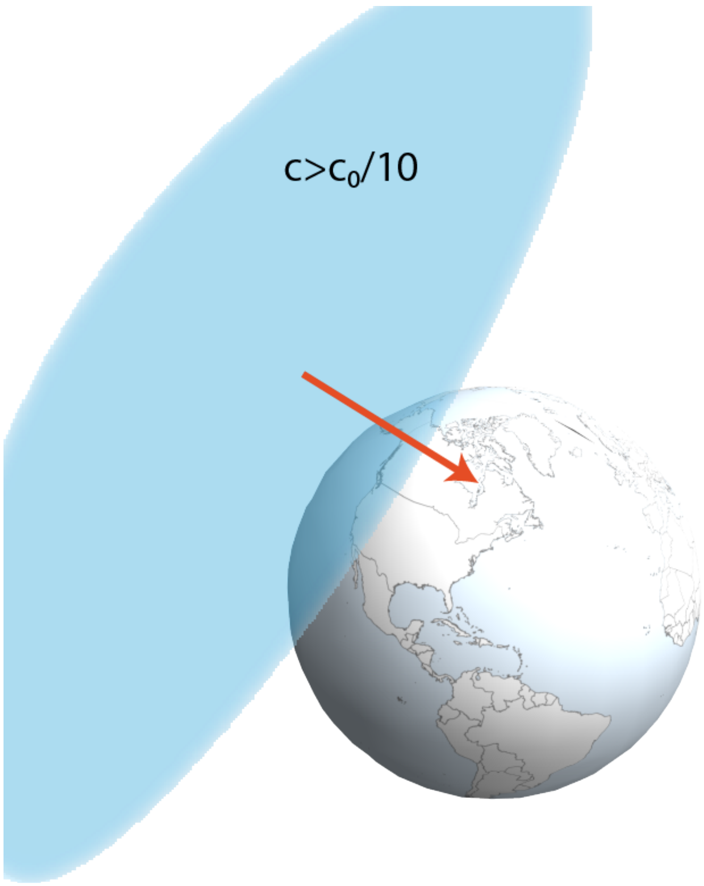
Anthropic constraints on *transient* variation of alpha

Dergachev, Tran Tan, Varganov & Derevianko, 2202.04228

Anthropic principle

- "Observation selection effect"
- Life can emerge and be sustained only in a narrow range of values of fundamental constants
- Nucleosynthesis of carbon-12
- All previous constraints are on slow-varying fundamental constants

- What about transients?
- GPS clocks only ~20 years of archived data.
- Lifeforms on Earth ~ 4 bln years



Mr. Tompkins in Wonderland

George “Big Bang” Gamow

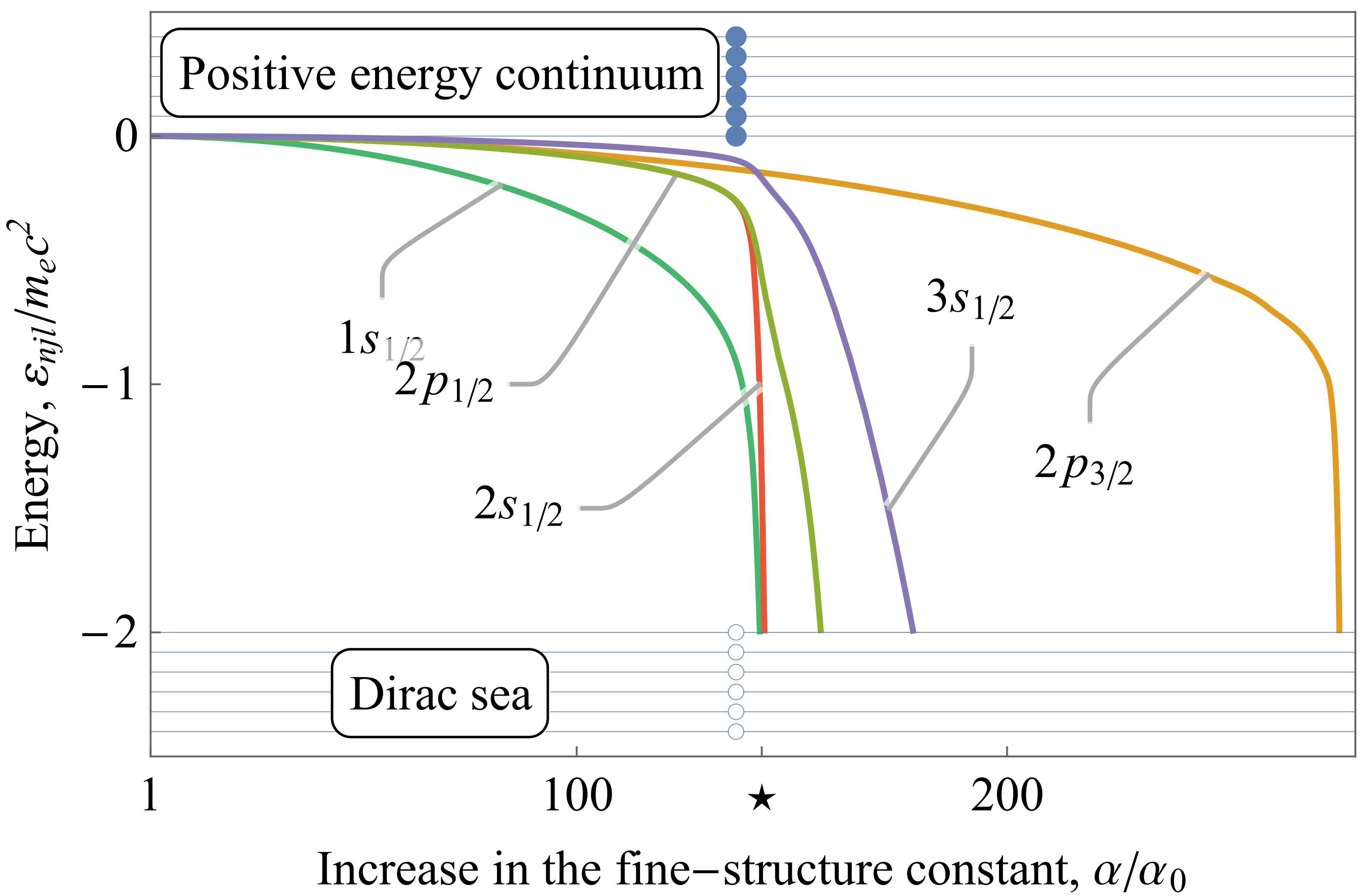
What would happen if speed of light were smaller?

At $c = 25$ mph would life be even possible?

Hydrogen atom goes boom

$$\varepsilon_{1s_{1/2}}/m_e c^2 = \sqrt{1-\alpha^2} - 1$$

Point-like nucleus

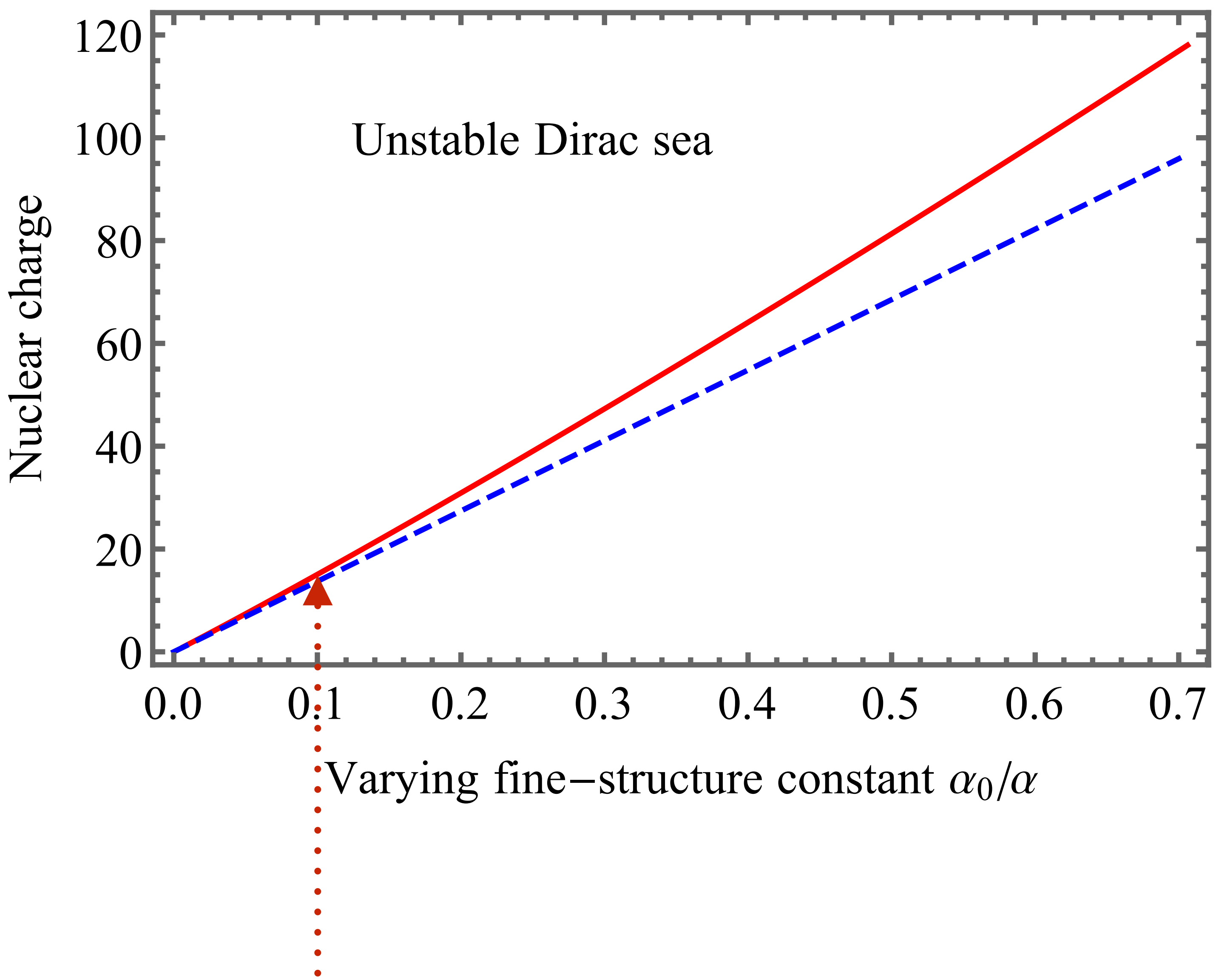


With finite-size proton

Truncation of Mendeleev periodic table

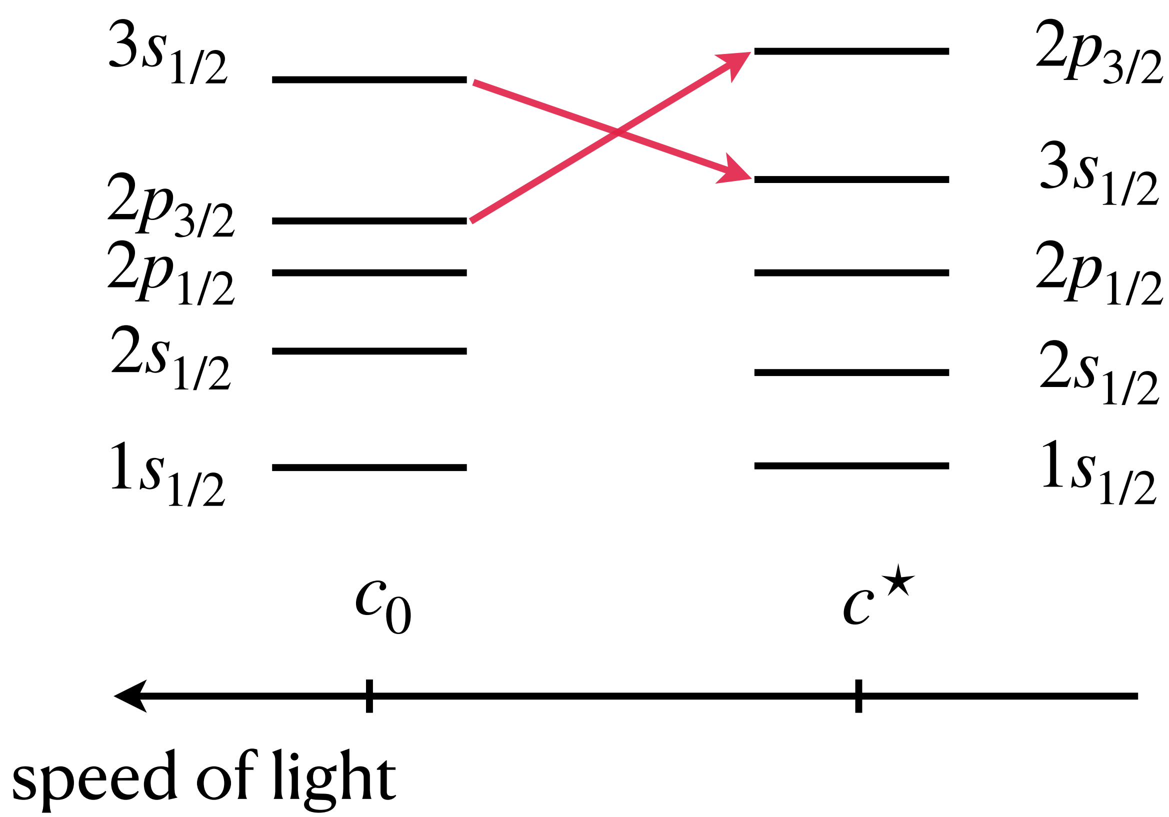
$$\frac{v}{c} \sim \alpha Z$$

1s electron speed



If α increases ten-fold, the periodic table shrinks to elements from hydrogen to sulphur

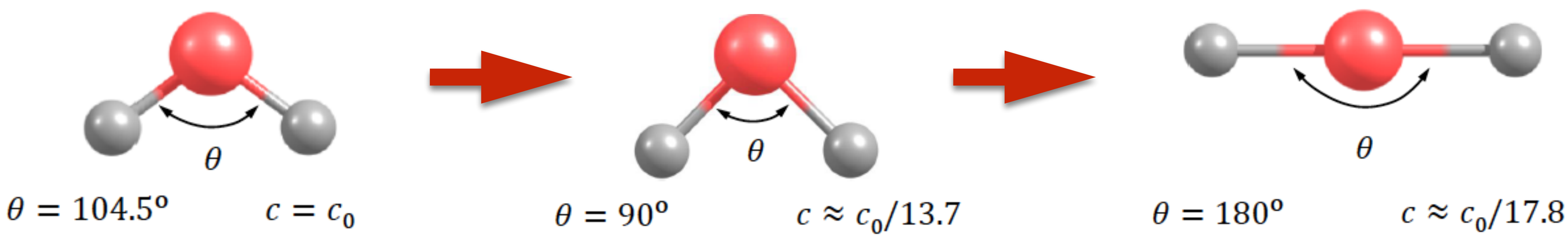
Neon-based life?



Aufbau principle of atomic structure

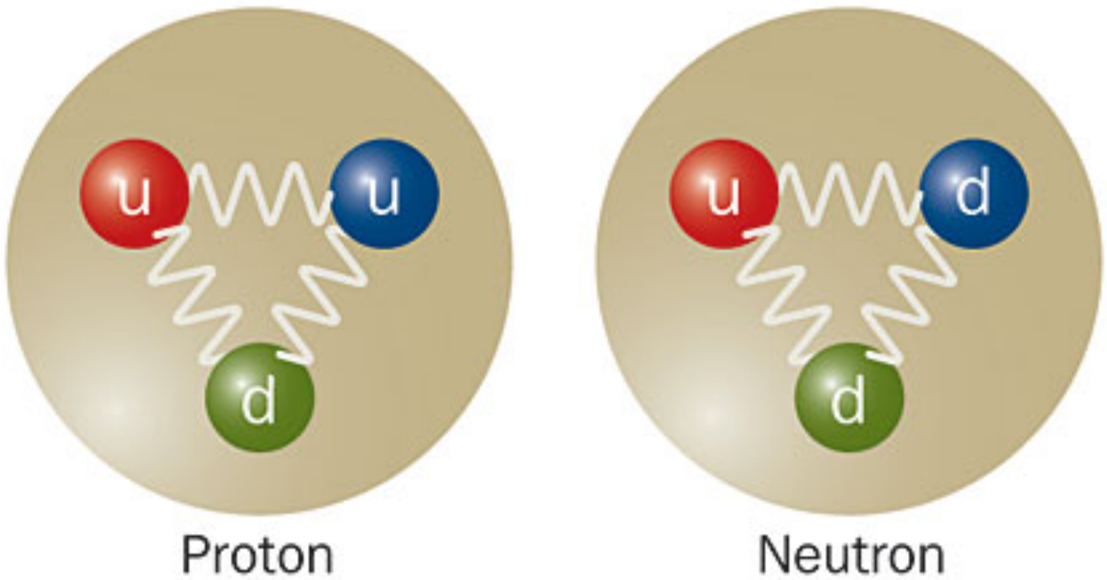
At $c < c_0/10$ neon is no longer chemically inert and becomes carbon-like

H_2O looses its magic



Linear water molecule does not have dipole moment = no longer a universal solvent

Proton goes boom



p-n mass difference =
cancellation between electromagnetic ($\propto \alpha$) energy and quark mass splitting

Borsanyi et al., Science 347, 1452 (2015)

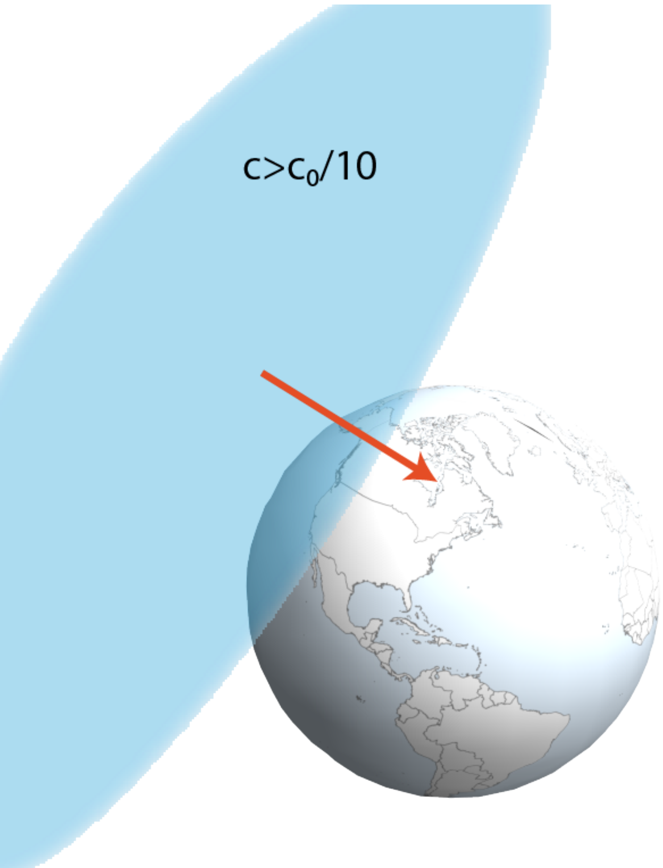
$\alpha \rightarrow 10\alpha_0$ spoils this balance
=> radioactivity and atomic electron capture by protons

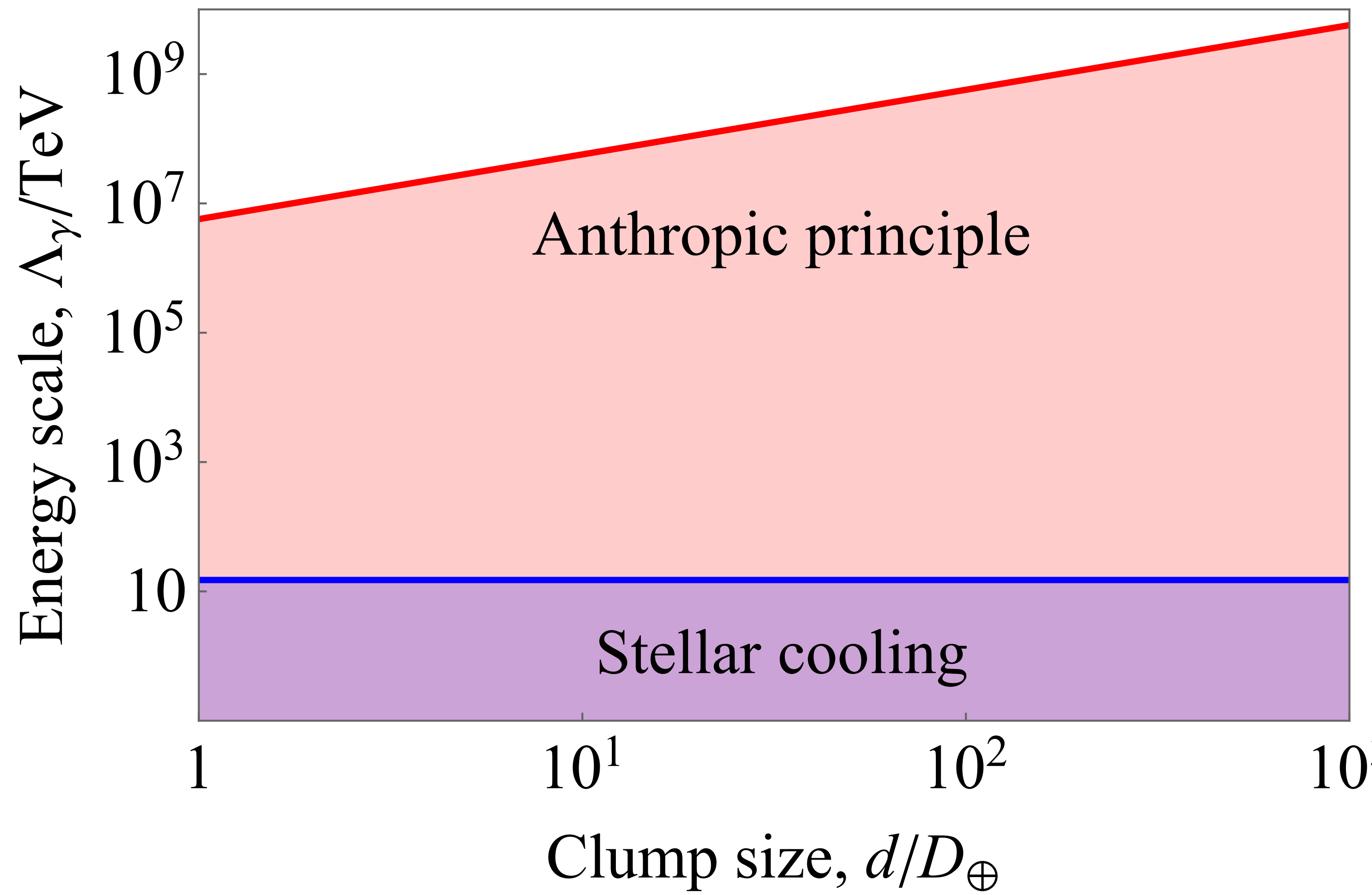
Timescale for these decays and capture?

Thanks to A. Kusenko and M. Pospelov

Anthropic constraints on DM clumps

Lifeforms as DM detectors





$$\mathscr{L} \supset \frac{1}{4\Lambda_\gamma^2} F_{\mu\nu}^2 \phi^2$$

Summary