3RD TERRESTRIAL VERY-LONG-BASELINE ATOM INTERFEROMETRY WORKSHOP
AUGUST 20, 2025

Multimessenger Astronomy Beyond the Standard Model: New Window from Quantum Sensors

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Department of Physics and Astronomy
University of Delaware, Delaware

Q-SEnSE
An NSF Quantum Leap Challenge Institute

https://www.colorado.edu/research/qsense/

thorium nuclear clock

https://thoriumclock.eu/

NSF

Office of Naval Research
ONR
Science & Technology

erc
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Problems with the standard model

New physics is required due to observations: no Standard Model explanation

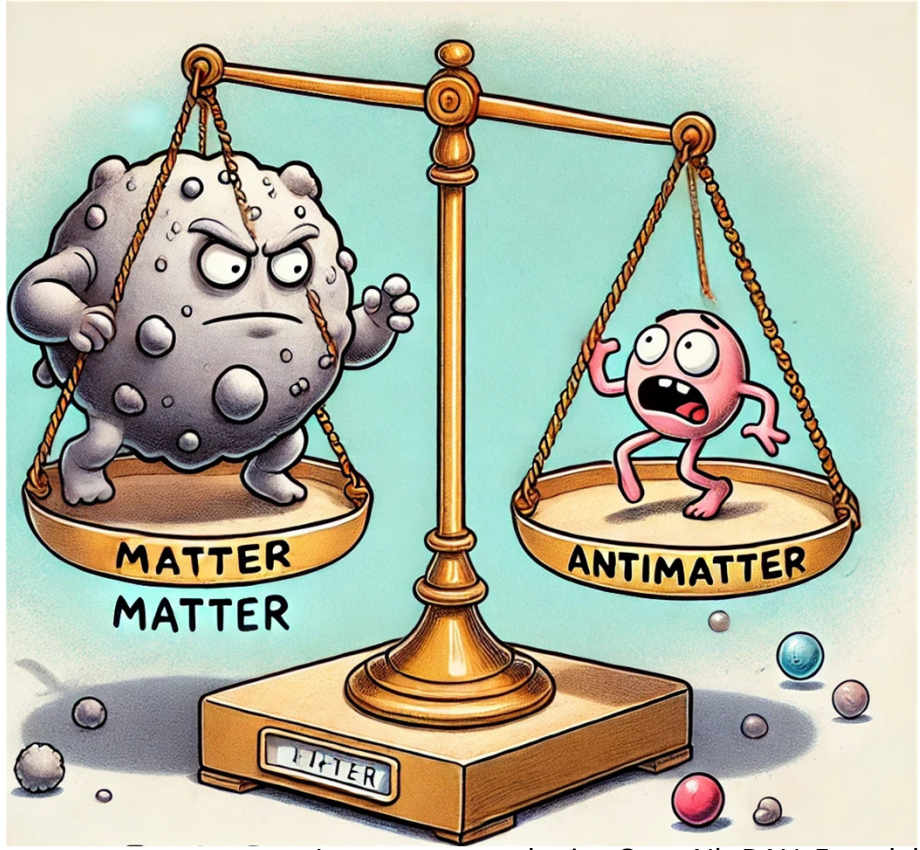
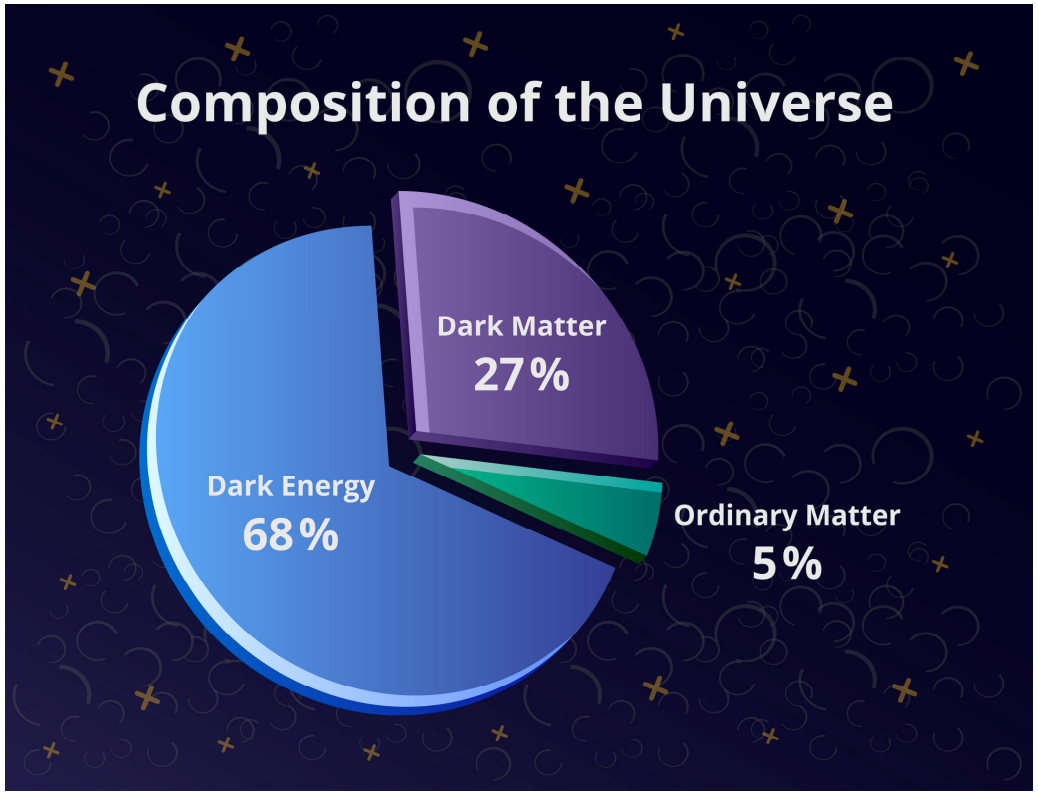


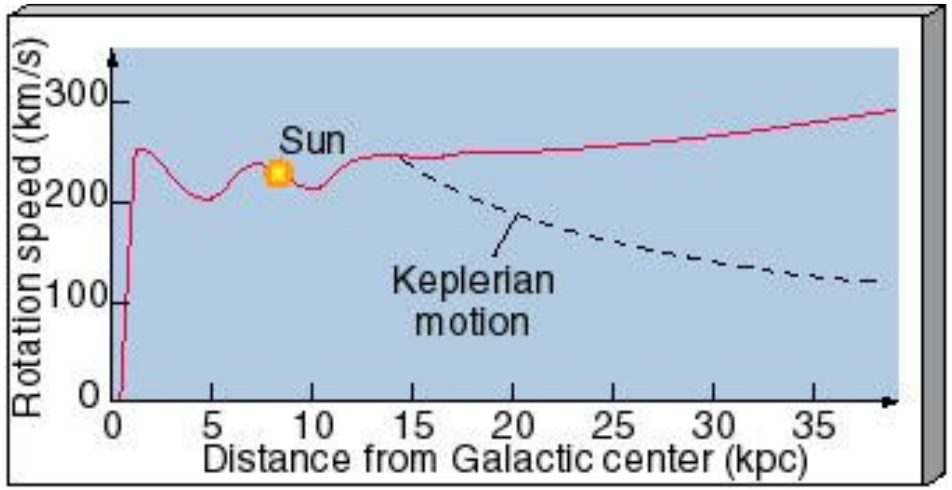
Image generated using OpenAI's DALL·E model



We do not know what the universe is made of

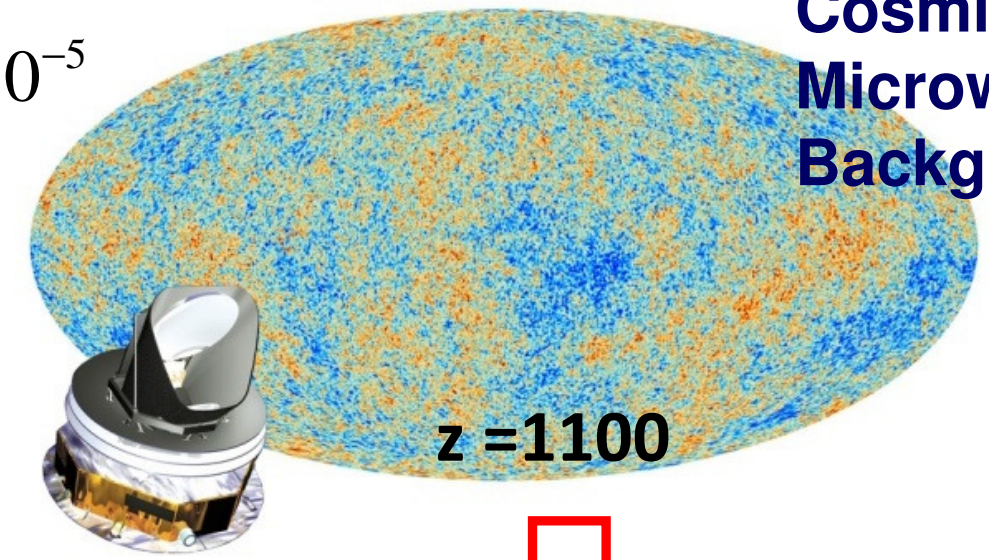
- Dark matter
- Matter-antimatter asymmetry
- Neutrino masses
- Accelerate expansion of the Universe (dark energy/cosmological constant?)

What is the experimental evidence for dark matter?

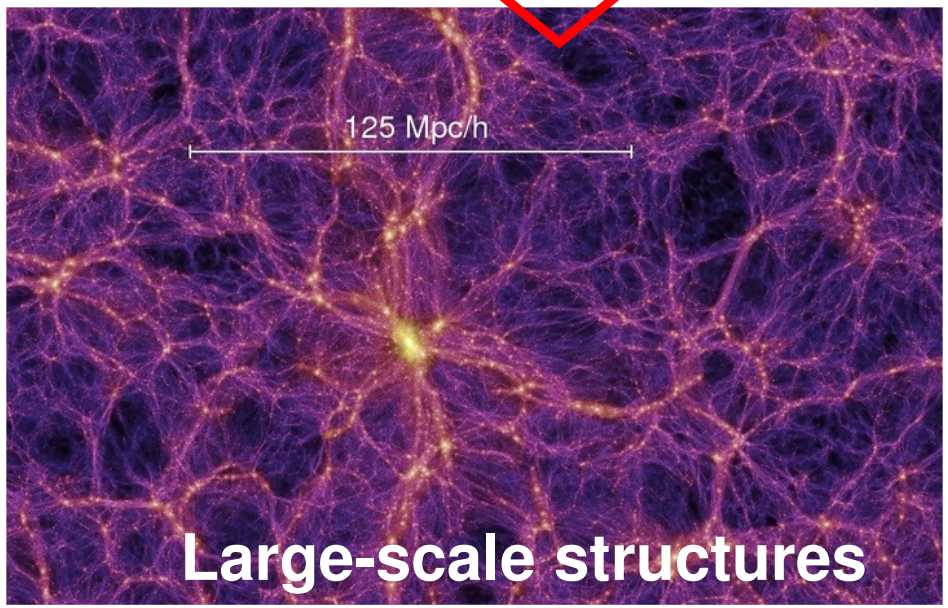


Rotation curves

$$\frac{\delta\rho}{\rho} \approx 10^{-5}$$

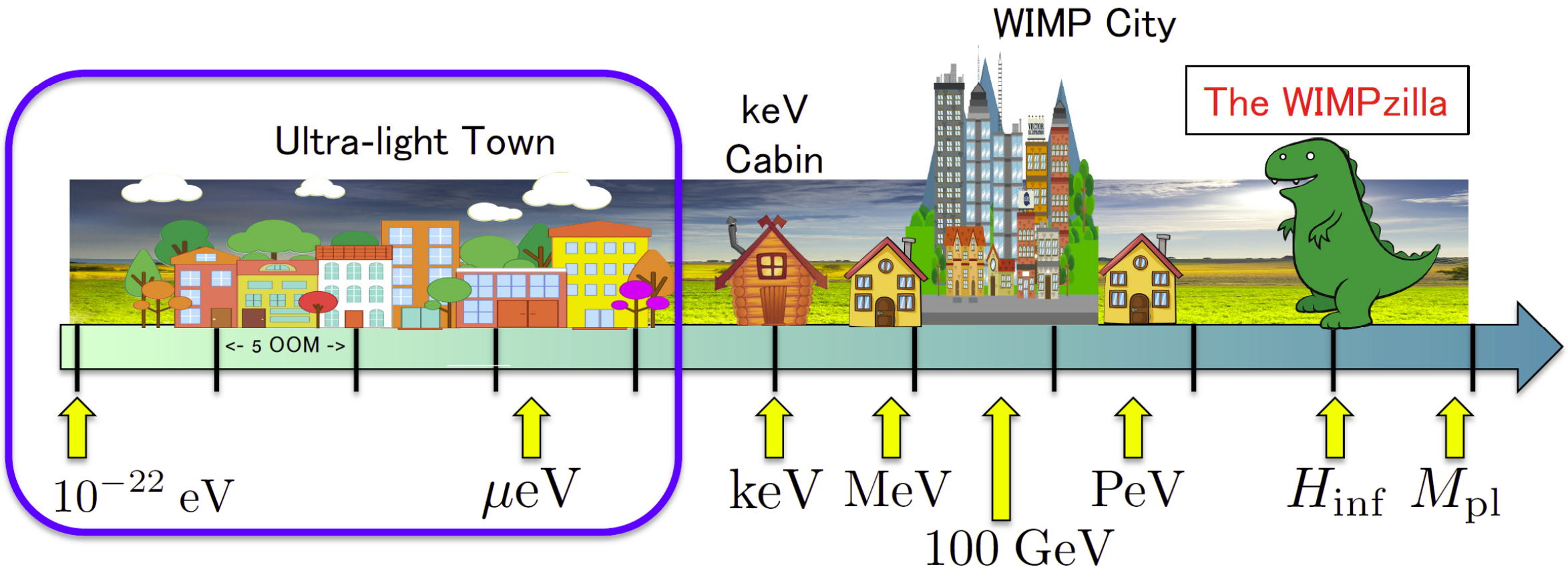


Cosmic Microwave Background



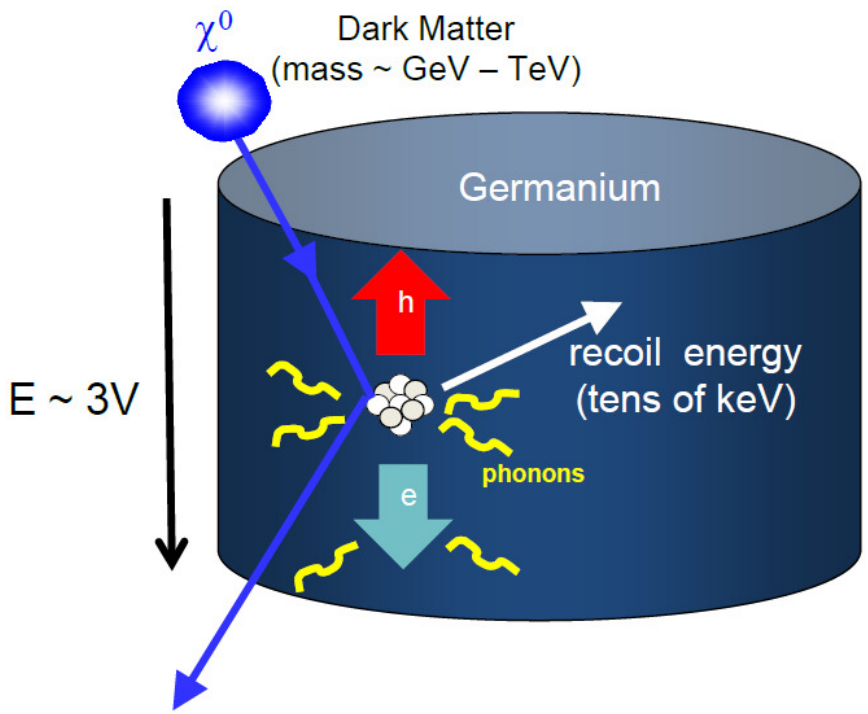
Slide from Andrew Long's 2018 LDW talk

The landscape of dark matter masses

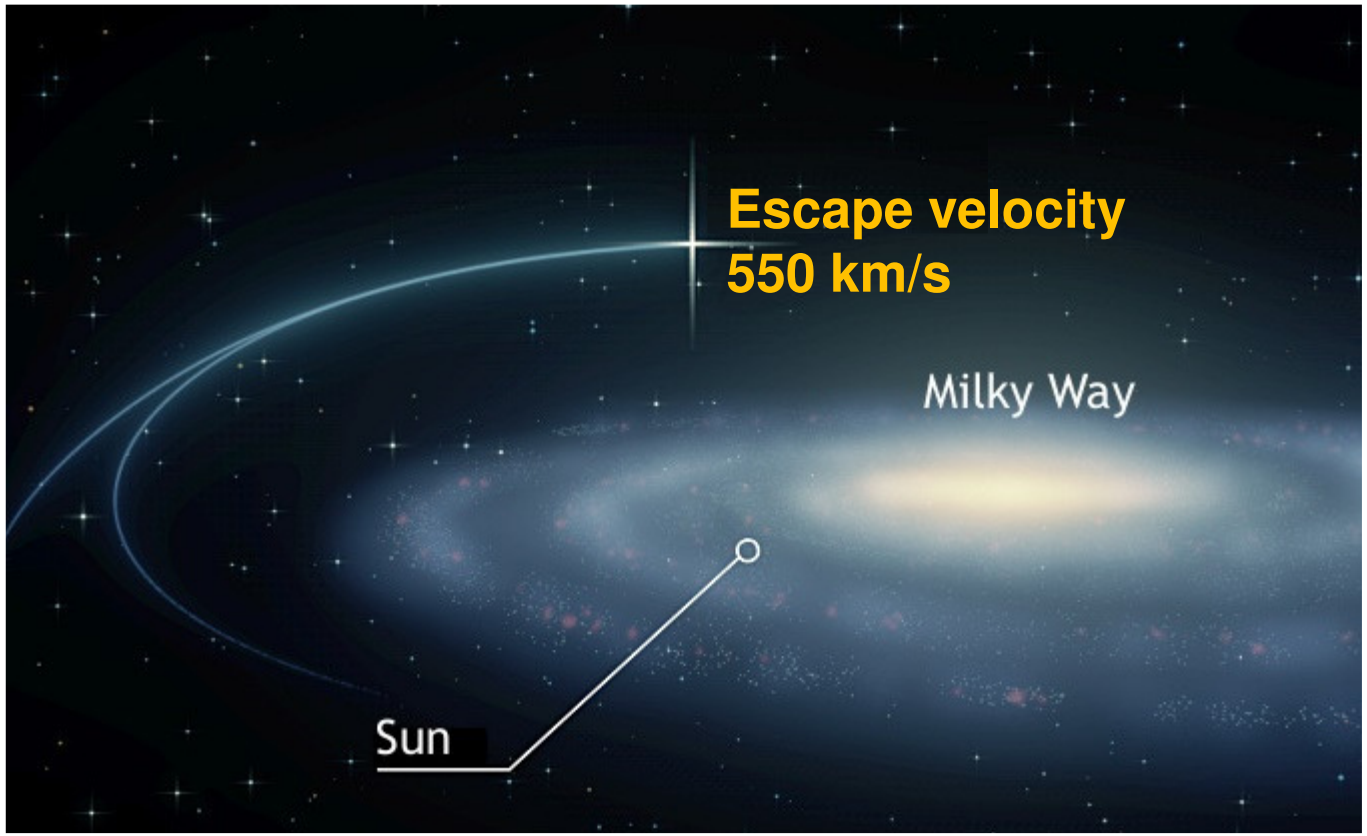


DARK MATTER DETECTION

Particle dark matter detection:
DM particle scatters and deposits energy
We detect this energy



Fermi velocity for DM with mass <10 eV is higher than our Galaxy escape velocity.



Ultralight dark matter has to be bosonic.

Image credits: CDMS: https://www.slac.stanford.edu/exp/cdms/
https://astronomynow.com/2016/04/14/speeding-binary-star-discovered-approaching-galactic-escape-velocity/

Ultralight dark matter detection

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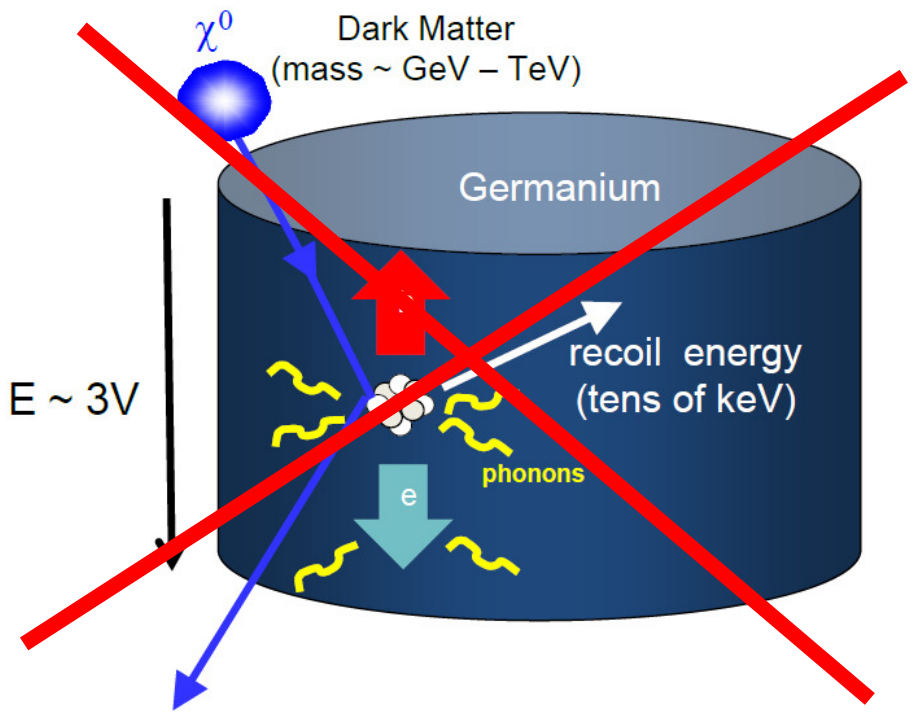

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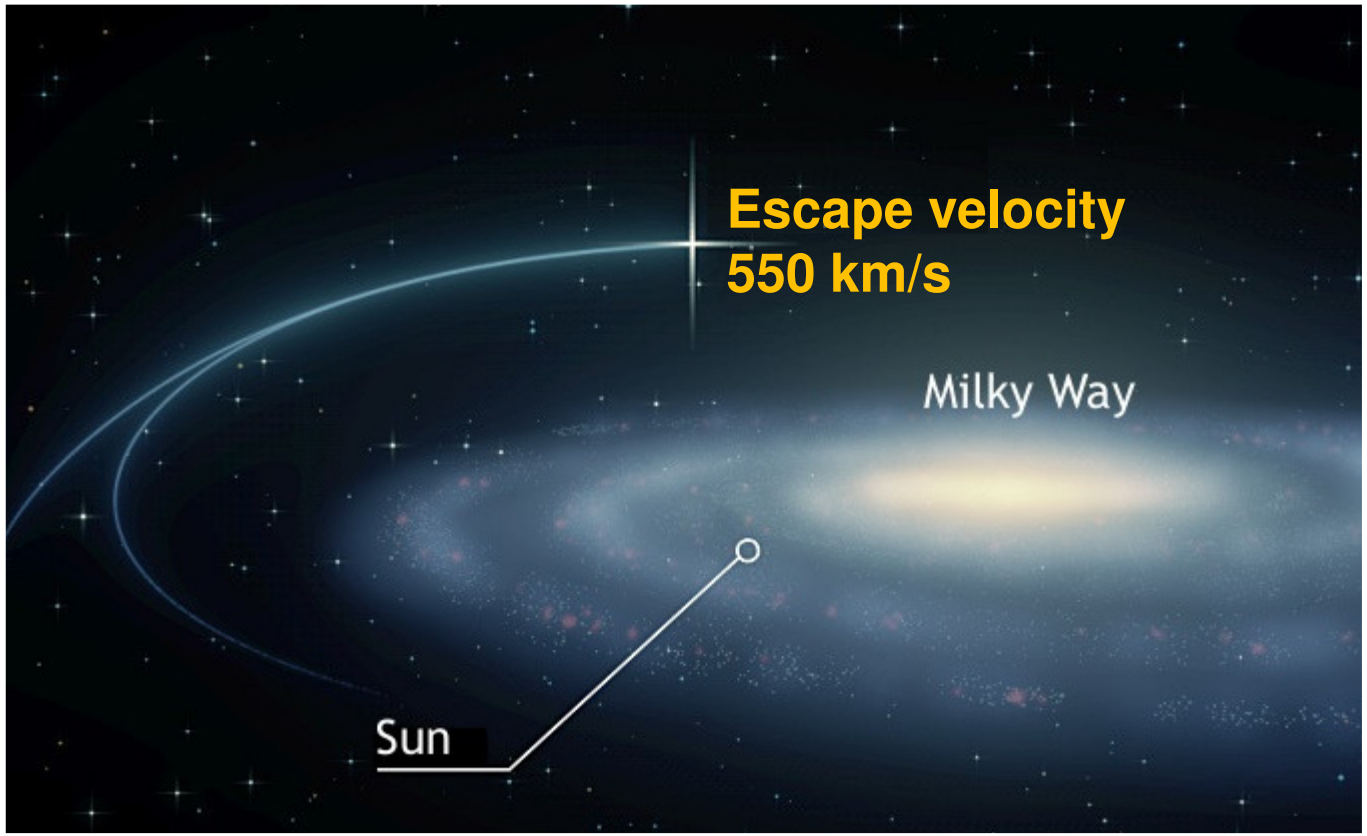

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https://astronomynow.com/2016/04/14/speeding-binary-star-discovered-approaching-galactic-escape-velocity/

Ultralight dark matter $(m_\phi \lesssim 10 \text{ eV})$

The key idea: ultralight dark matter (UDM) particles behave in a "wave-like" manner.

$$\phi(t) \approx \phi_0 \cos(m_\phi t)$$

$$\lambda_{\text{coh}} \sim 10^3 (2\pi / m_\phi c)$$

$$N_{\text{dB}} = n_\phi \lambda_{\text{coh}}^3 \gg 1$$

UDM: coherent on the scale of detectors or networks of detectors.

$$\phi_0 \sim \sqrt{2\rho_{\text{DM}}}/m_\phi$$

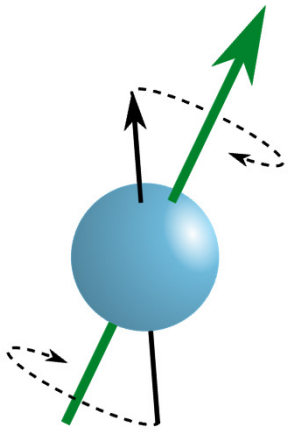
Dark matter field amplitude

Dark matter density

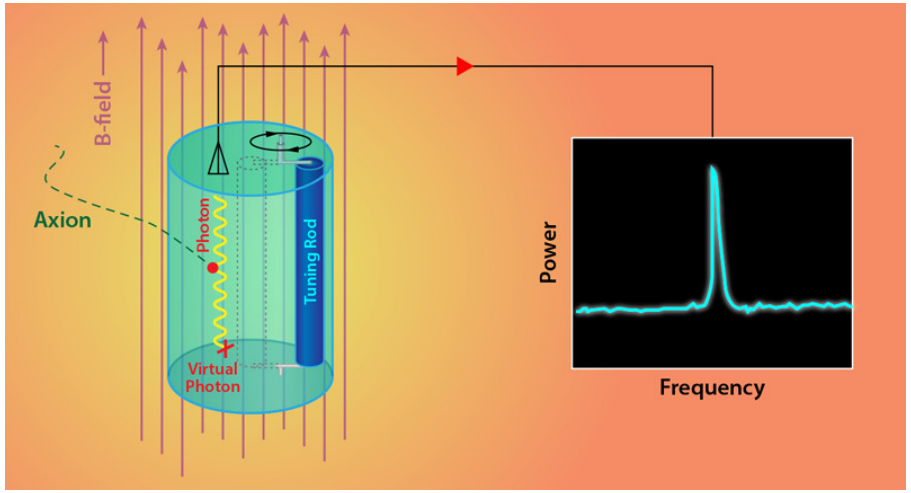
Dark matter mass

Need different detection strategies from particle dark matter.

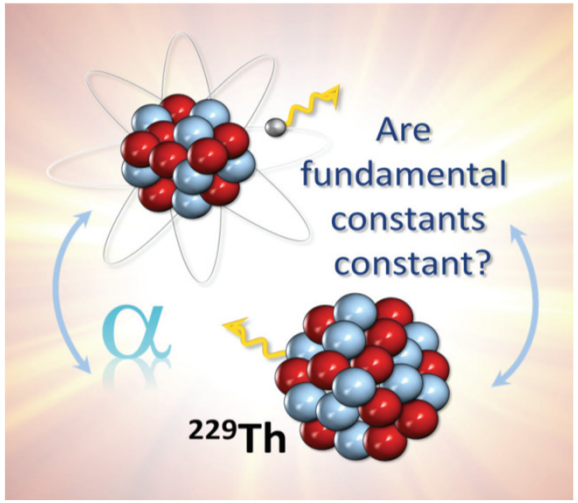
Observable effects of ultralight dark matter



Precession of nuclear or electron spins



Driving currents in electromagnetic systems, produce photons



Modulate the values of the fundamental "constants"

Induced equivalence principle-violating accelerations of matter

Detectors: Magnetometers, Microwave cavities, Trapped ions & other qubits, Atom interferometers, Laser interferometers (includes GW detectors), Optical cavities, Atomic, molecular, and nuclear clocks, Other precision spectroscopy

RMP 90, 025008 (2018)

Picture sources and credits: Wikipedia, Physics 11, 34 C. Boutan/Pacific Northwest National Laboratory; adapted by APS/Alan Stonebraker, modulate the values of the fundamental "constants" of nature

Scalar ultralight dark matter

Coupling of scalar UDM to the standard model:

$$\kappa = (\sqrt{2}M_{\rm Pl})^{-1}$$

$$\phi(t) \approx \phi_0 \cos(m_\phi t)$$

photons electrons gluons quarks

$$\mathcal{L}_{\rm int}^{\rm lin} = \kappa\phi \left\{ \left[\frac{d_e F_{\mu\nu}F^{\mu\nu}}{4} - d_{m_e} m_e \bar{\psi}_e \psi_e \right] - \left[\frac{d_g \beta_3 G^a_{\mu\nu} G^{a\mu\nu}}{2g_3} + \sum_{q=u,d,s} \left(d_{m_q} + \gamma_m d_g\right) m_q \bar{\psi}_q \psi_q \right] \right\}$$

$$\alpha \to \frac{\alpha}{1-\kappa d_e \phi(t)} \approx \alpha\left(1+\kappa d_e \phi(t)\right) \qquad m_e \to m_e + \kappa m_e d_{m_e} \phi(t)$$

Scalar UDM will cause **oscillations** of the electromagnetic fine-structure constant α, strong interaction constant and fermion masses

Dimensionless constants: $\alpha, \frac{m_e}{m_p}, \frac{m_q}{\Lambda_{\rm QCD}}$

Key point: different (types) of "clocks" have different sensitivity to different constants

Observable: "clock" frequency ratios

How to detect ultralight scalar dark matter with clocks?

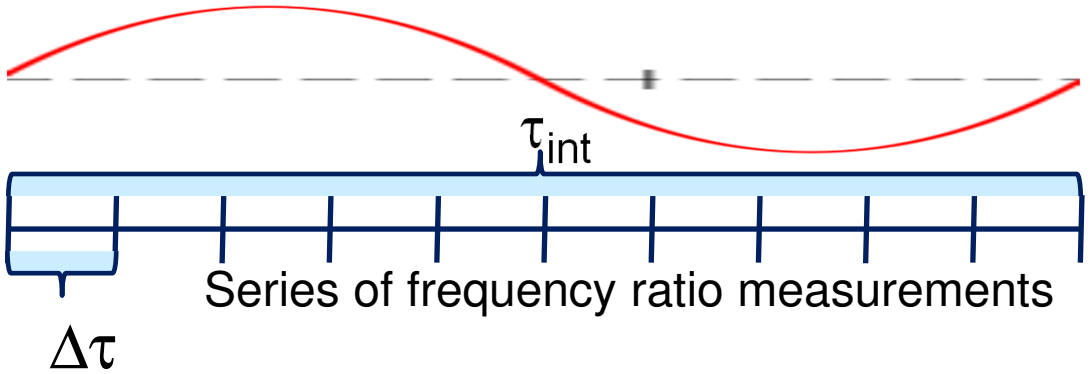
Dark matter field couples to electromagnetic interaction and "normal matter"

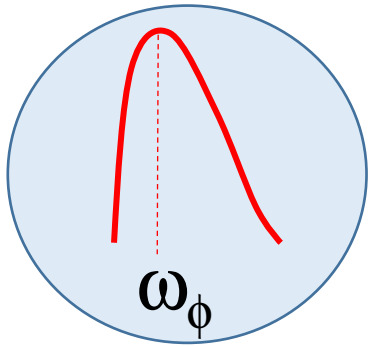
Fundamental coupling constants and mass ratios now oscillate

Atomic, molecular, nuclear energy levels will oscillate so clock frequencies oscillate

Measure ratios of clock frequencies over time (or clock to cavity)

Discrete Fourier transform of time series gives a frequency peak

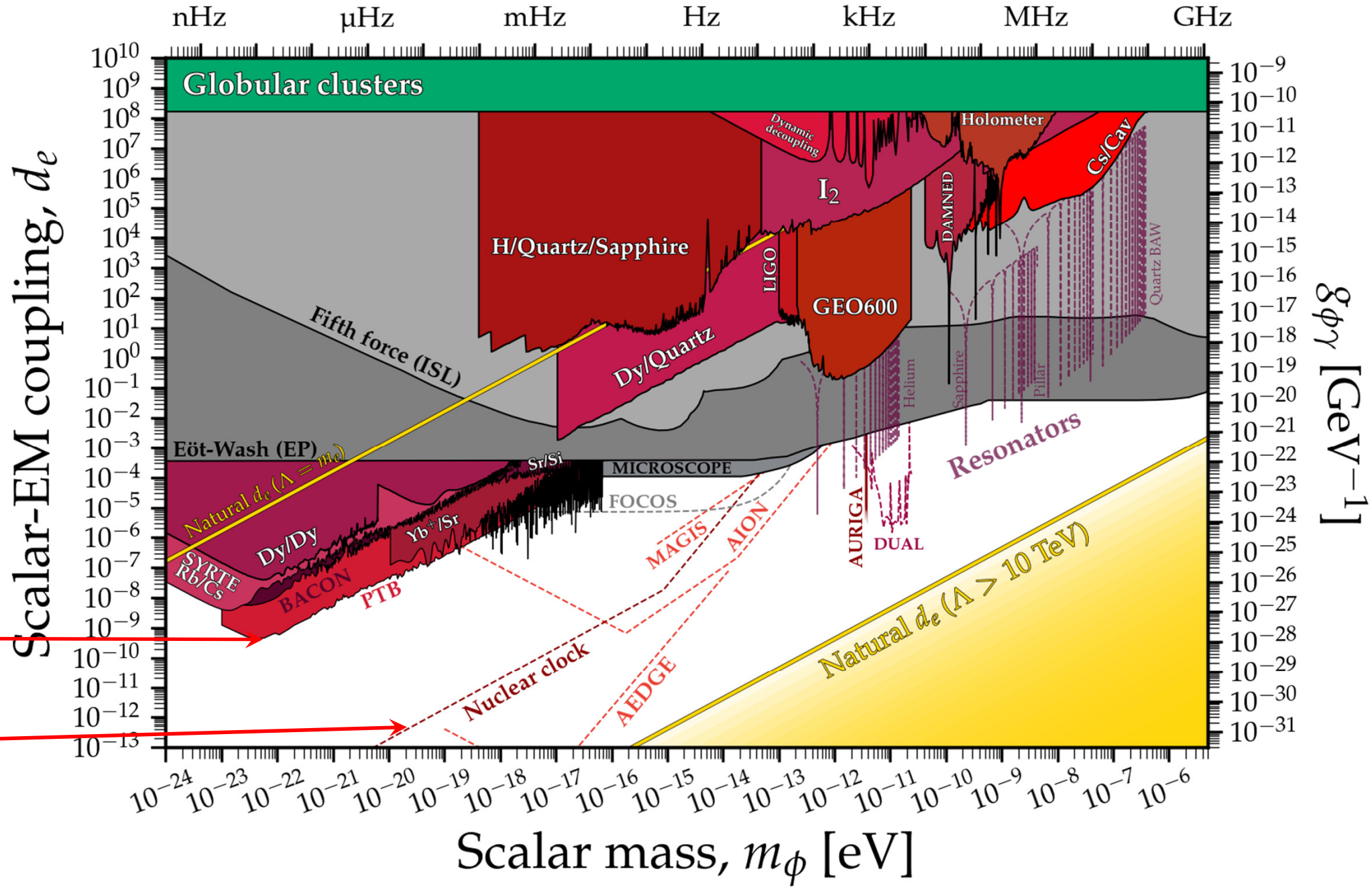




Dark matter Compton frequency

$f = 2\pi/m_\phi$ [Hz]	m_ϕ [eV]
1 MHz	4×10^{-9}
1 kHz	4×10^{-12}
1	4×10^{-15}
1 mHz	4×10^{-18}
10^{-6}	4×10^{-21}

$\phi F_{\mu\nu} F^{\mu\nu}$



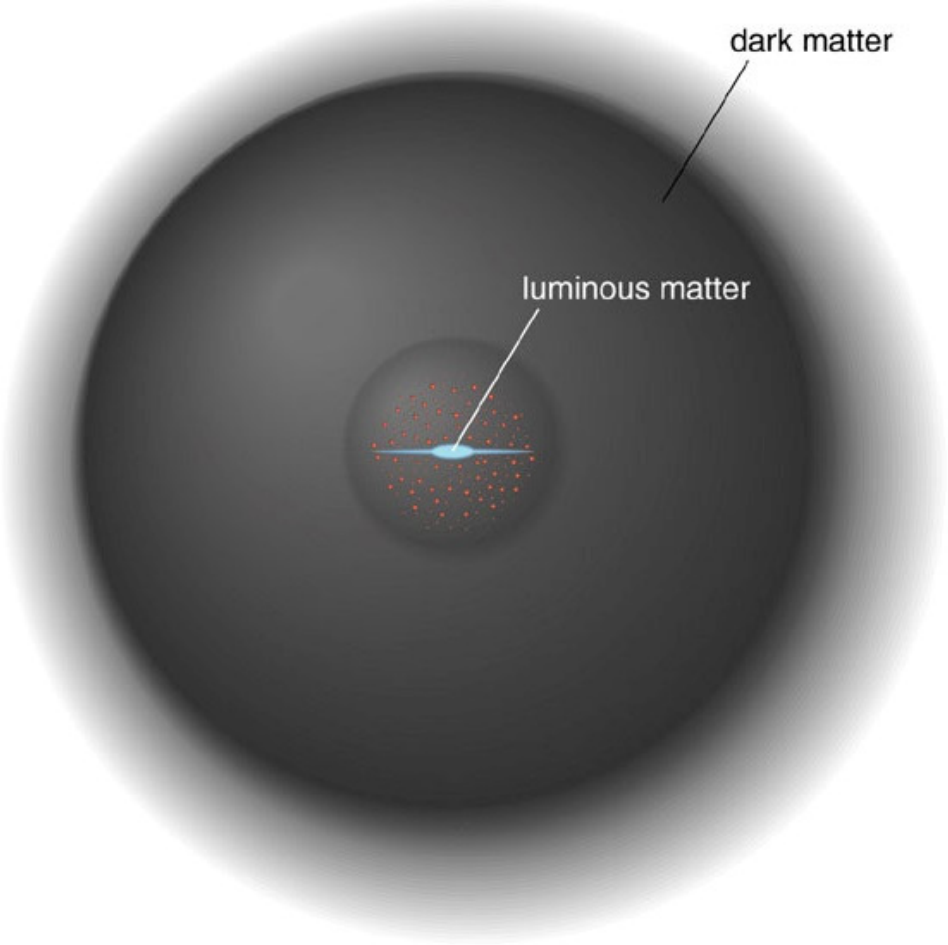
Present clock limits

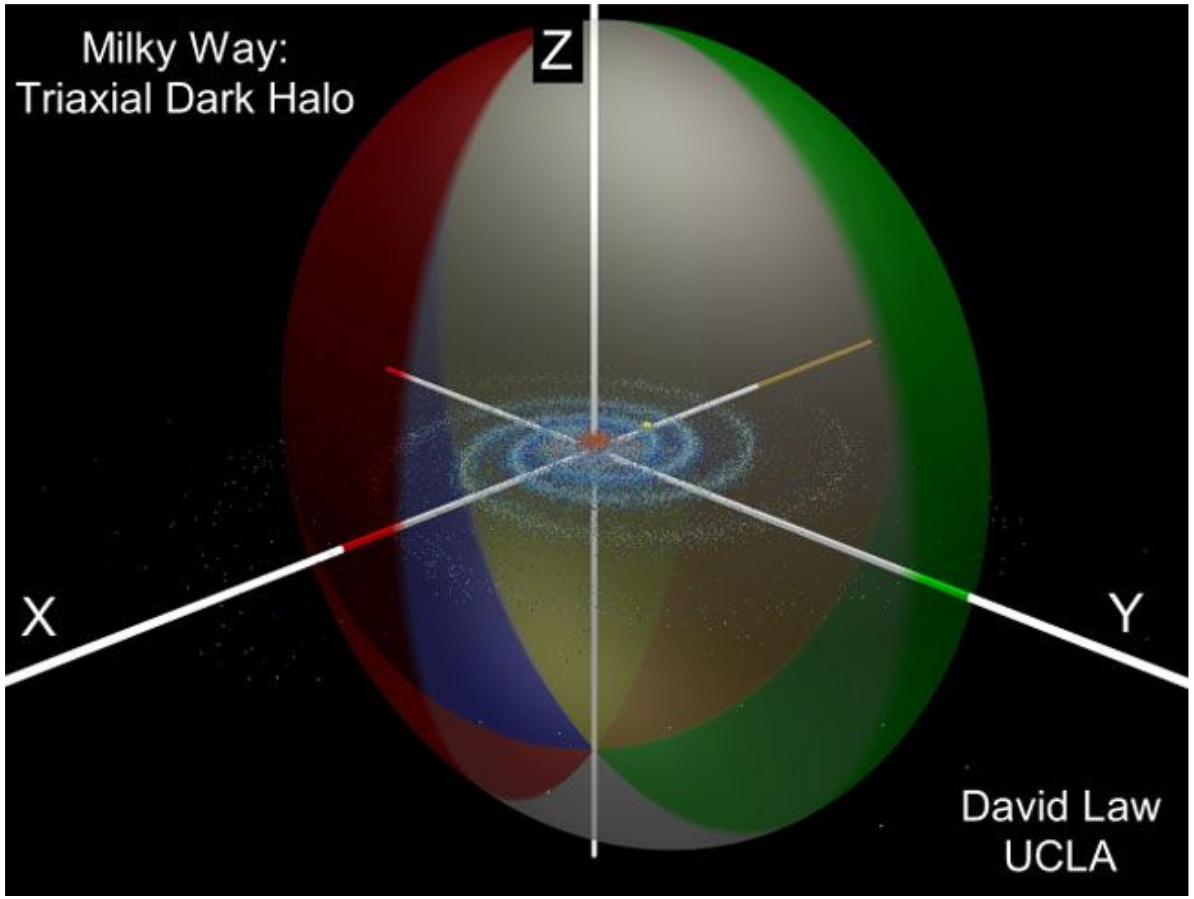
Projected clock limits

arXiv:2203.14915

Ultralight DM limits: https://cajohare.github.io/AxionLimits/

We do not know details of DM distribution in the Milky way or solar system





0.4 Gev/cm^3 average at Sun position (1 hydrogen atom per a few cm^3)

http://www.sjsu.edu/people/monika.kress/courses/sci255/

We do not know details of DM distribution in the Milky way or solar system

- Dark matter halos & remnants from other galaxies
- Stream(s)?
- Dark matter miniclusters (remnants of string decay)
- Compact objects (boson stars) … can explode
- "Gravitational atoms" Dark matter bound to stars, planets, etc.
- Special case of DM & rotating black holes

  Could eject dark matter in case of merges
- Topological defects
- …?

0.4 Gev/cm^3 average at Sun position (1 hydrogen atom per a few cm^3)

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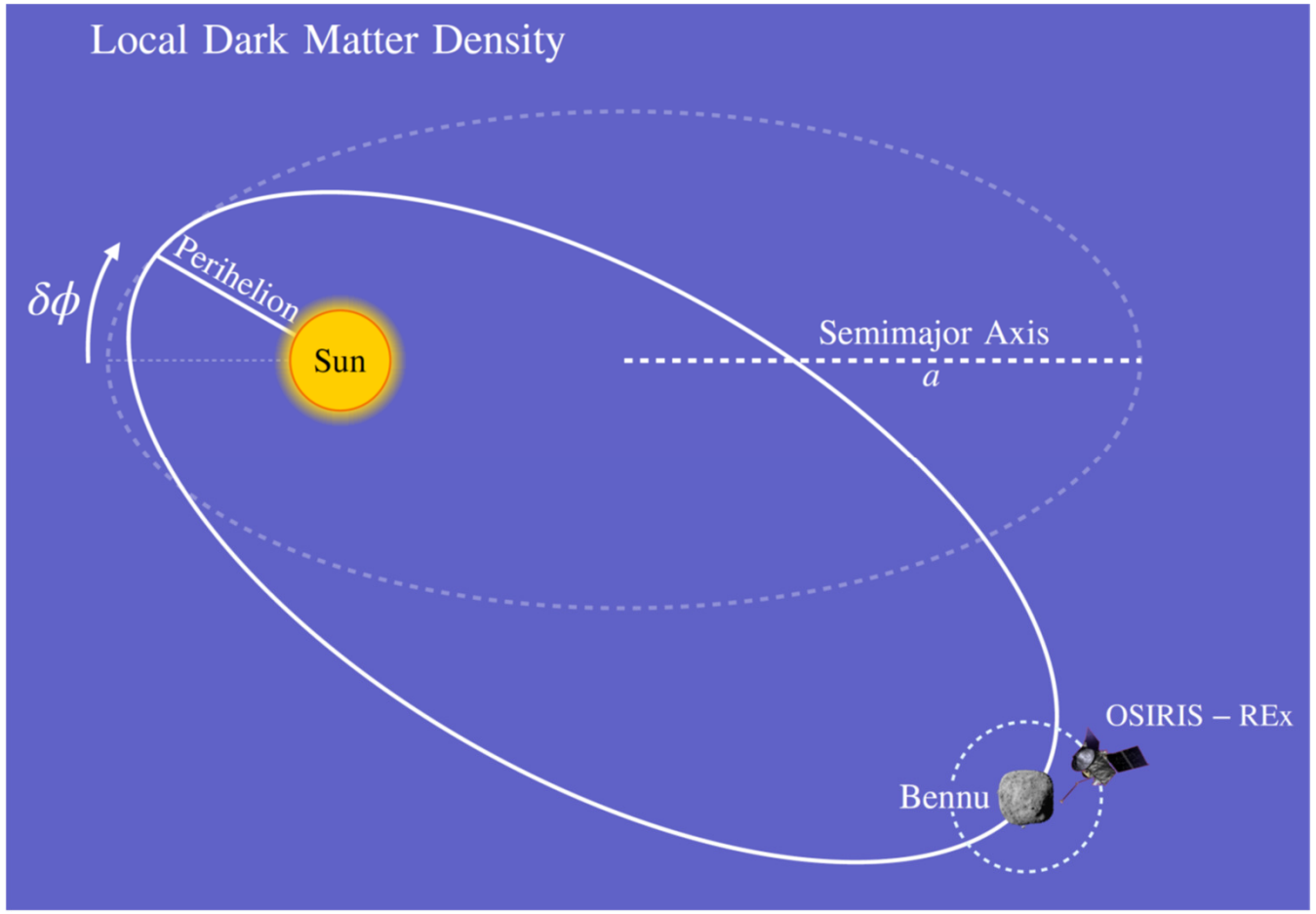
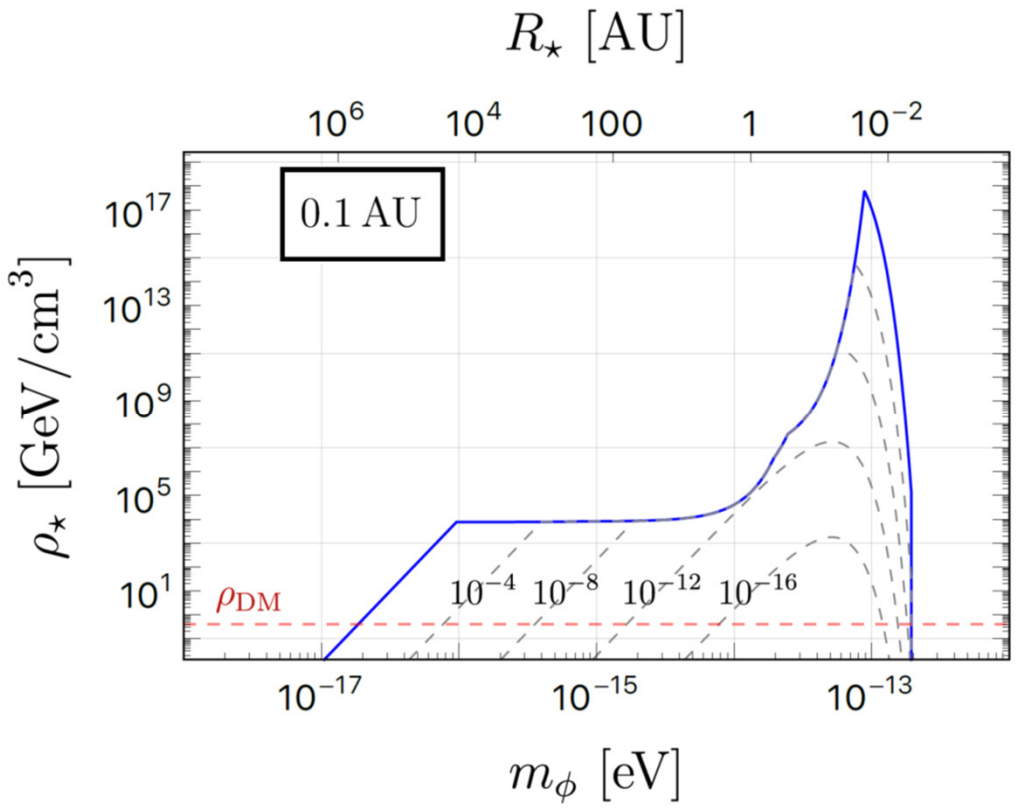
Constraints on Dark Matter and Cosmic Neutrino Profiles through Gravity

NASA mission to asteroid Bennu



Yu-Dai Tsai, Joshua Eby, Jason Arakawa, Davide Farnocchia, and Marianna S. Safronova, JCAP 02, 029 (2024)

Direct detection of ultralight dark matter bound to the Sun and Jupiter with space quantum sensors



Yu-Dai Tsai, Joshua Eby, Marianna S. Safronova, Nature Astronomy 7, 113 (2023).

Search for fast - oscillating fundamental constants with space missions

Dmitry Budker, Joshua Eby, Marianna S. Safronova, Oleg Tretiak, EPJ Quantum Technology 12, 39 (2025).

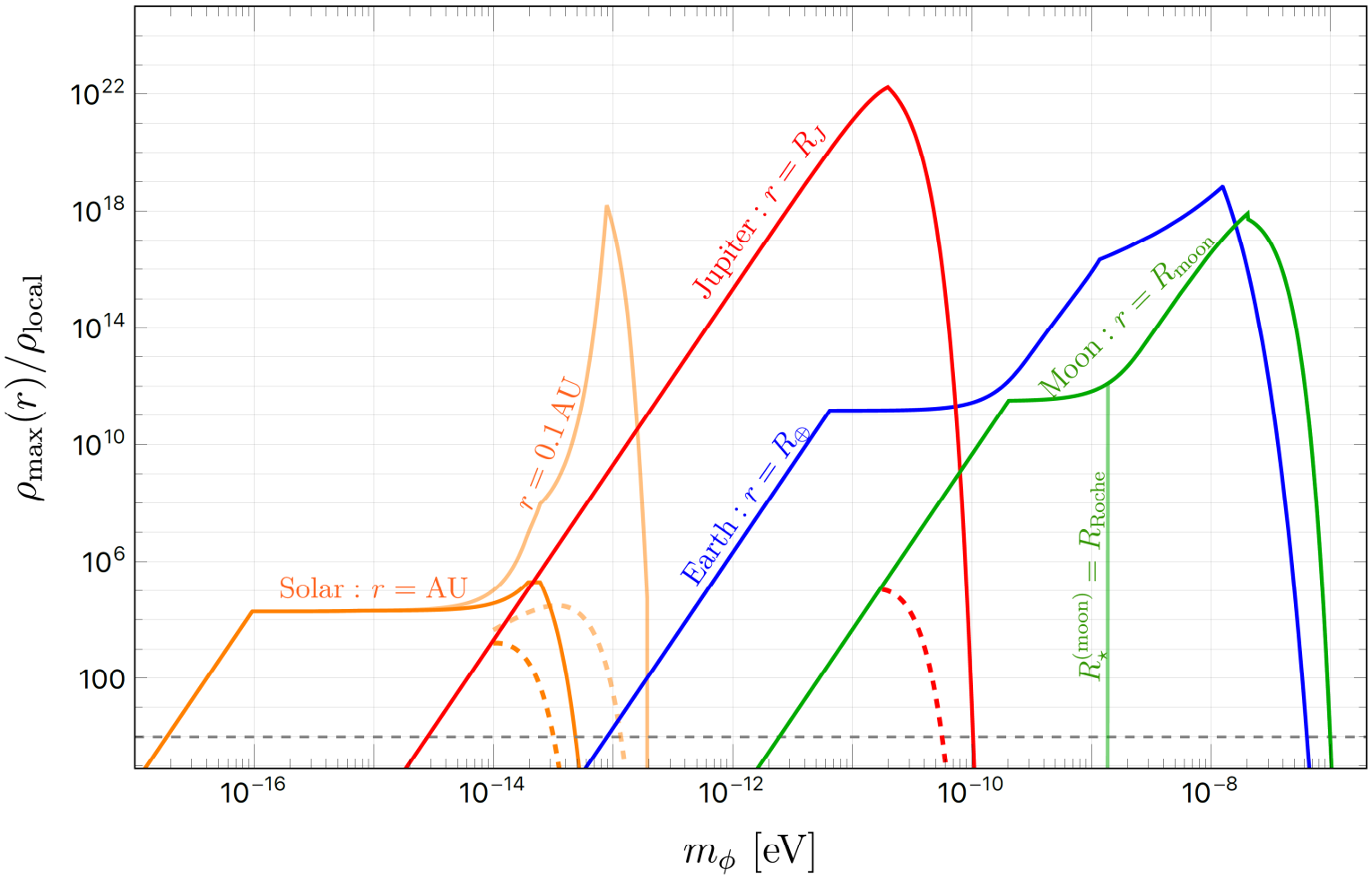
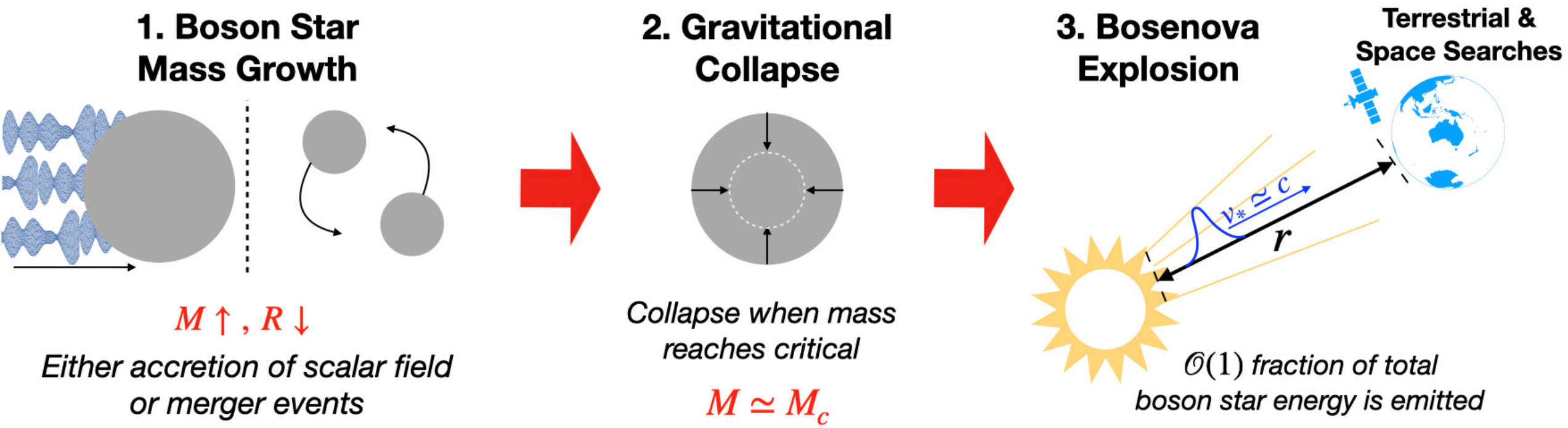


FIG. 1: Maximum gravitational atom density as a function of m_ϕ bound to the Sun (orange), Jupiter (red), Earth (blue) or moon (green). In each case the density is evaluated at a distance r from the center of the object as labeled. The dashed lines are the maximum density accumulated over 4.5 Gyr through the capture mechanism of [11].

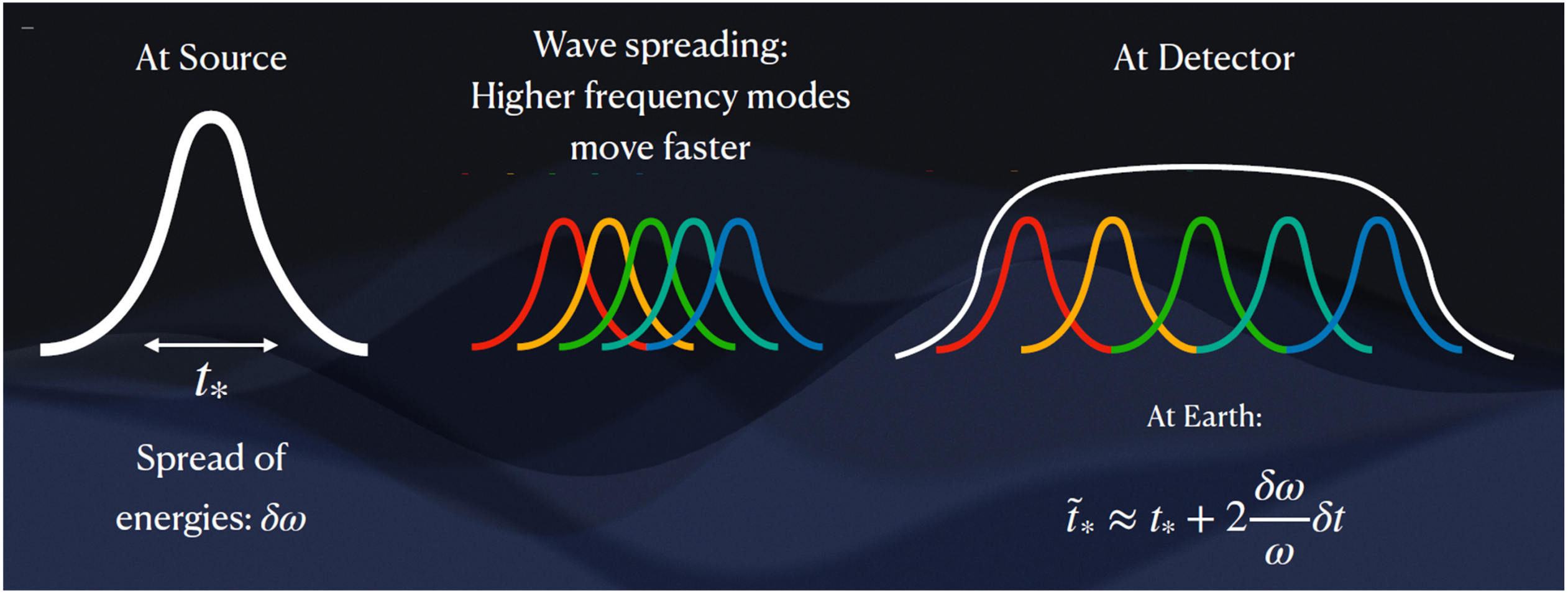
Transient dark matter signals: Boson star explosions and bosenova



Detection of Relativistic Scalar Bursts with Quantum Sensors, Jason Arakawa, Joshua Eby, Marianna S. Safronova, Volodymyr Takhistov, and Muhammad H. Zaheer, Phys. Rev. D 110, 075007 (2024).

Bosenovae with Quadratically-Coupled Scalars in Quantum Sensing Experiments, Jason Arakawa, Muhammad H. Zaheer, Joshua Eby, Volodymyr Takhistov, Marianna S. Safronova, J. High Energ. Phys. 2023, 42 (2023).

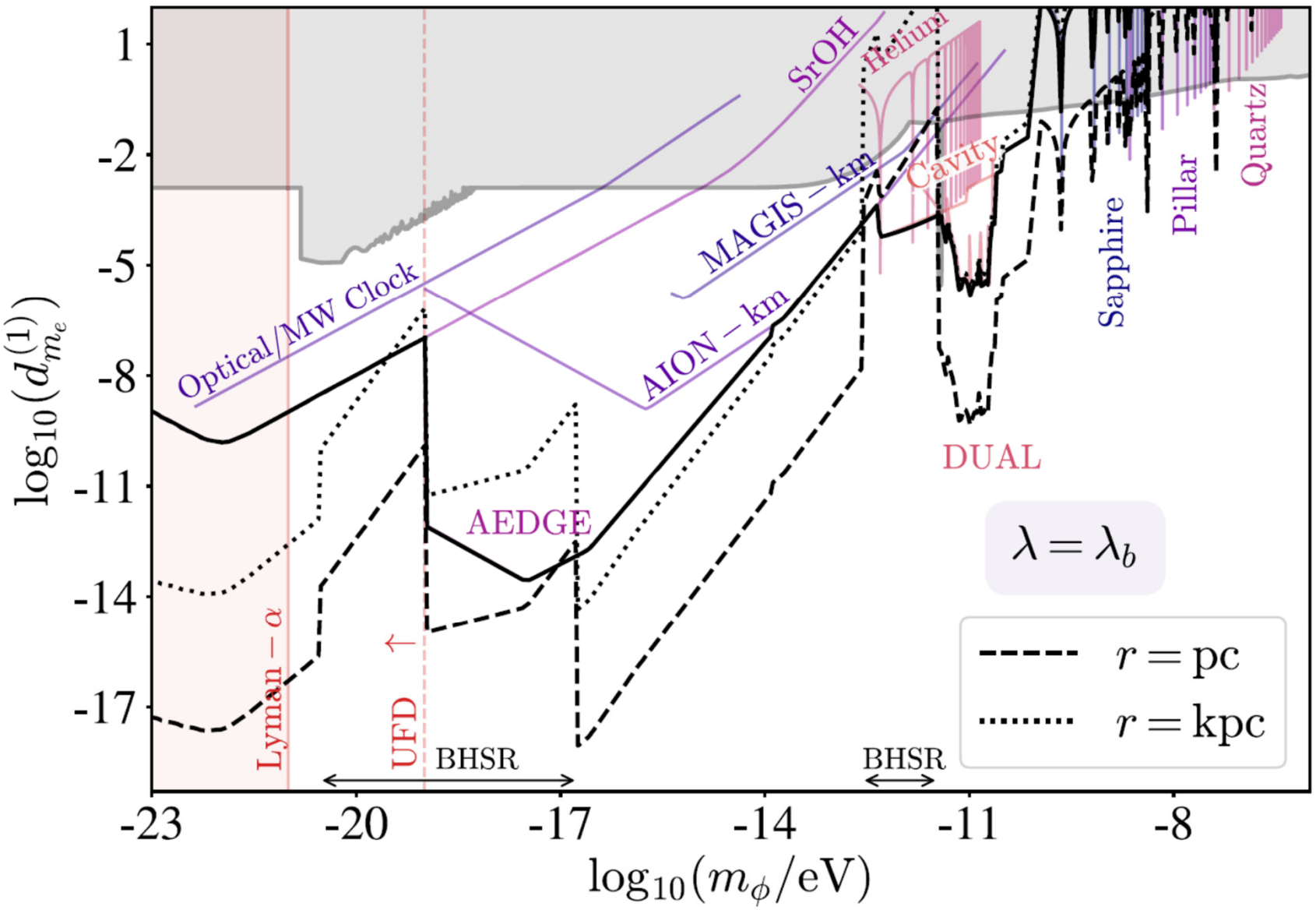
Wave spreading during propagation



Bosenova emission spectrum at source:

$$\bar{k} \simeq 2.4\, m_\phi$$
$$\delta k \simeq m_\phi$$

Bosenova signal lasts months to years



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New ideas in gravitational wave detection & multimessenger astronomy with atomic quantum sensors

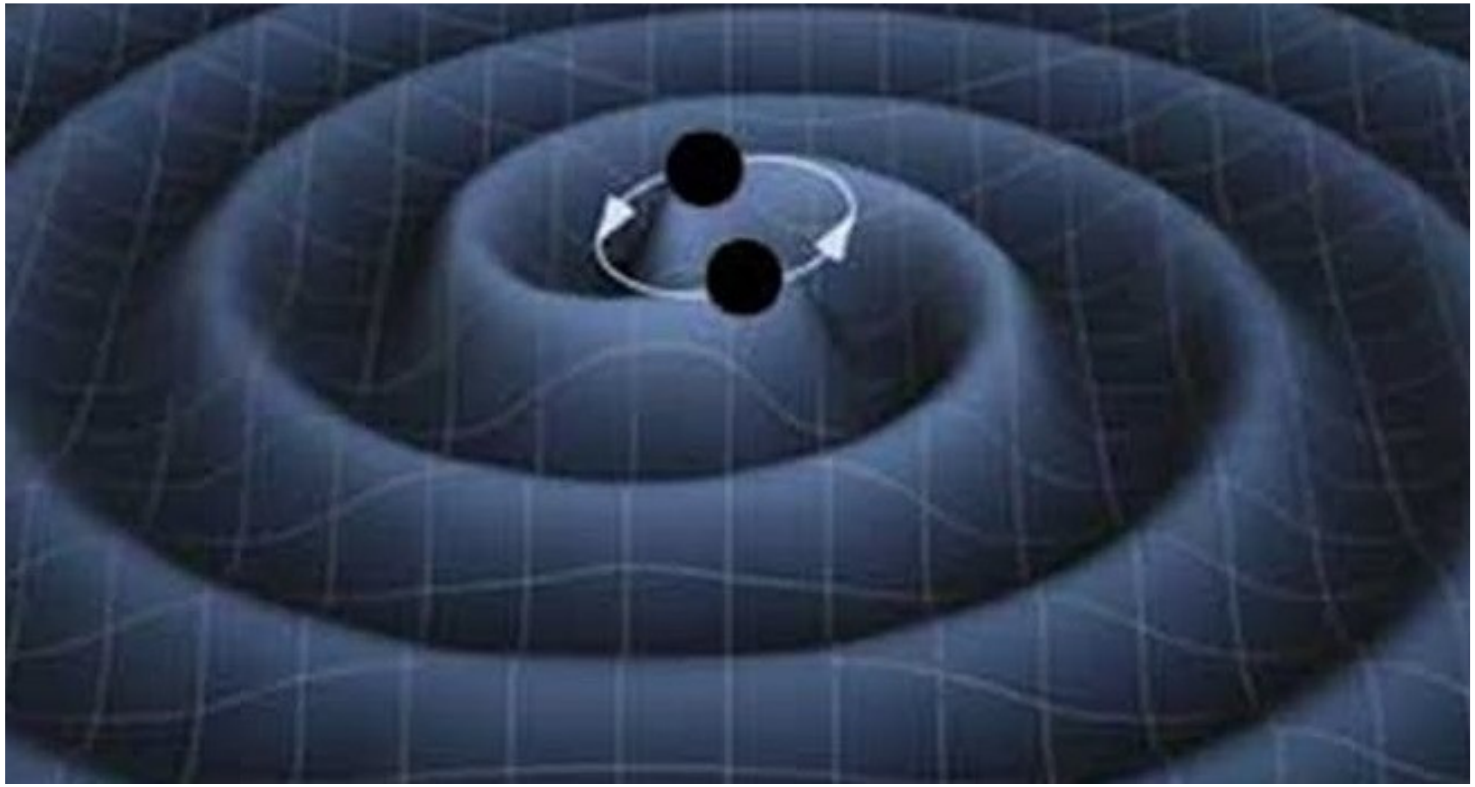
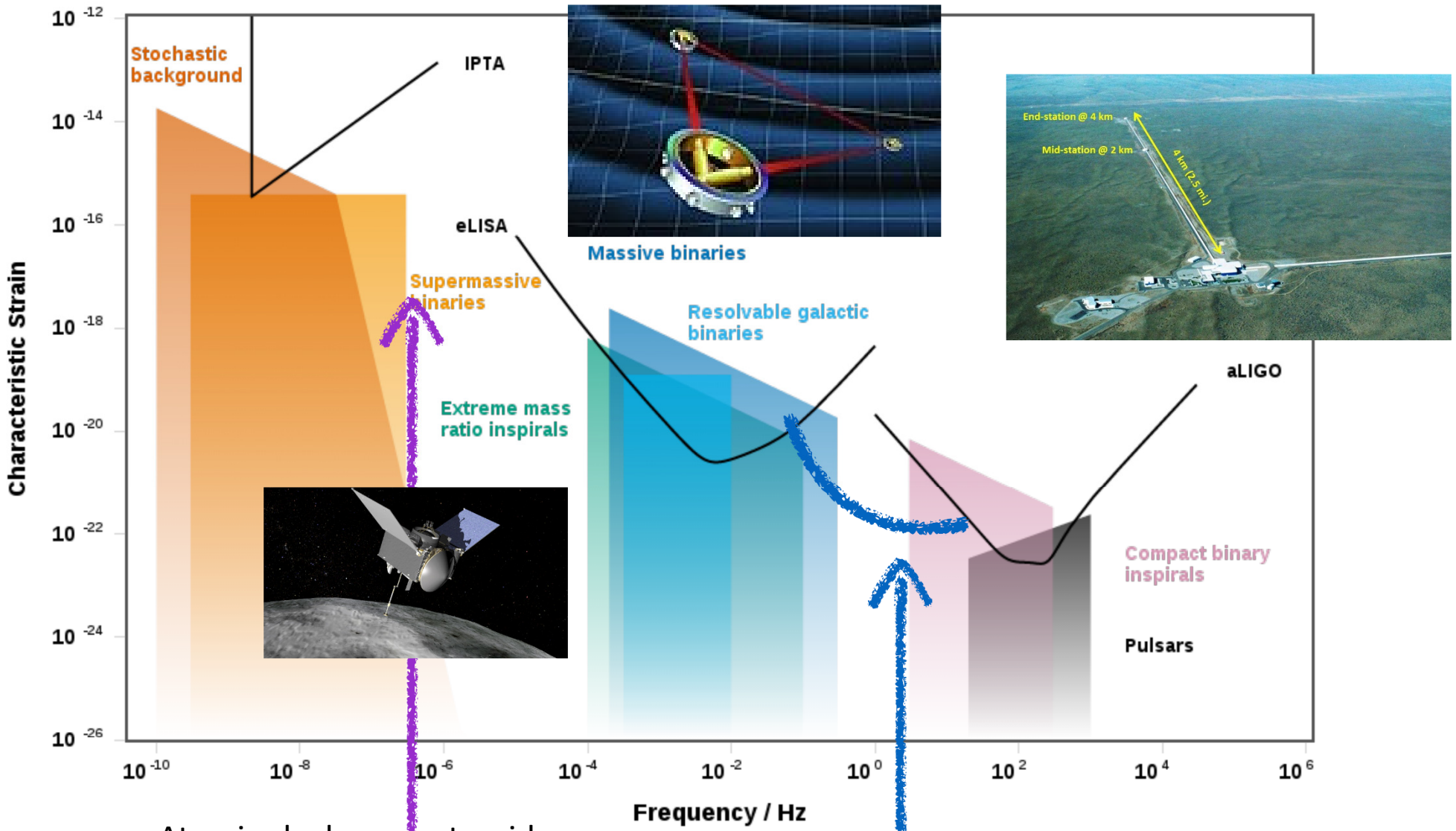


Figure is from Peter Graham's talk at KITP 2021: https://online.kitp.ucsb.edu/online/novel-oc21/



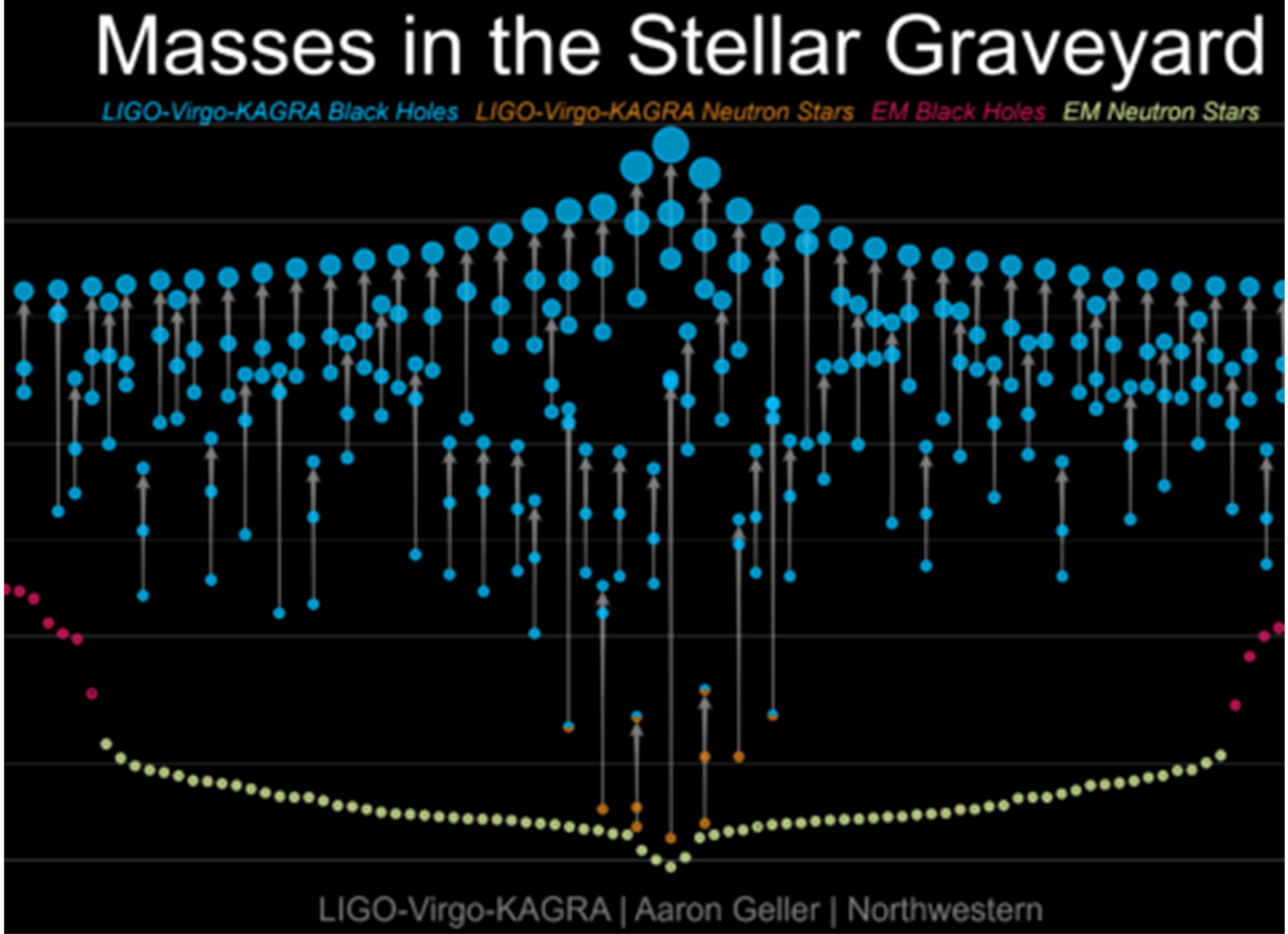
Atomic clocks on asteroids

PRD 105, 103018 (2022)

open band

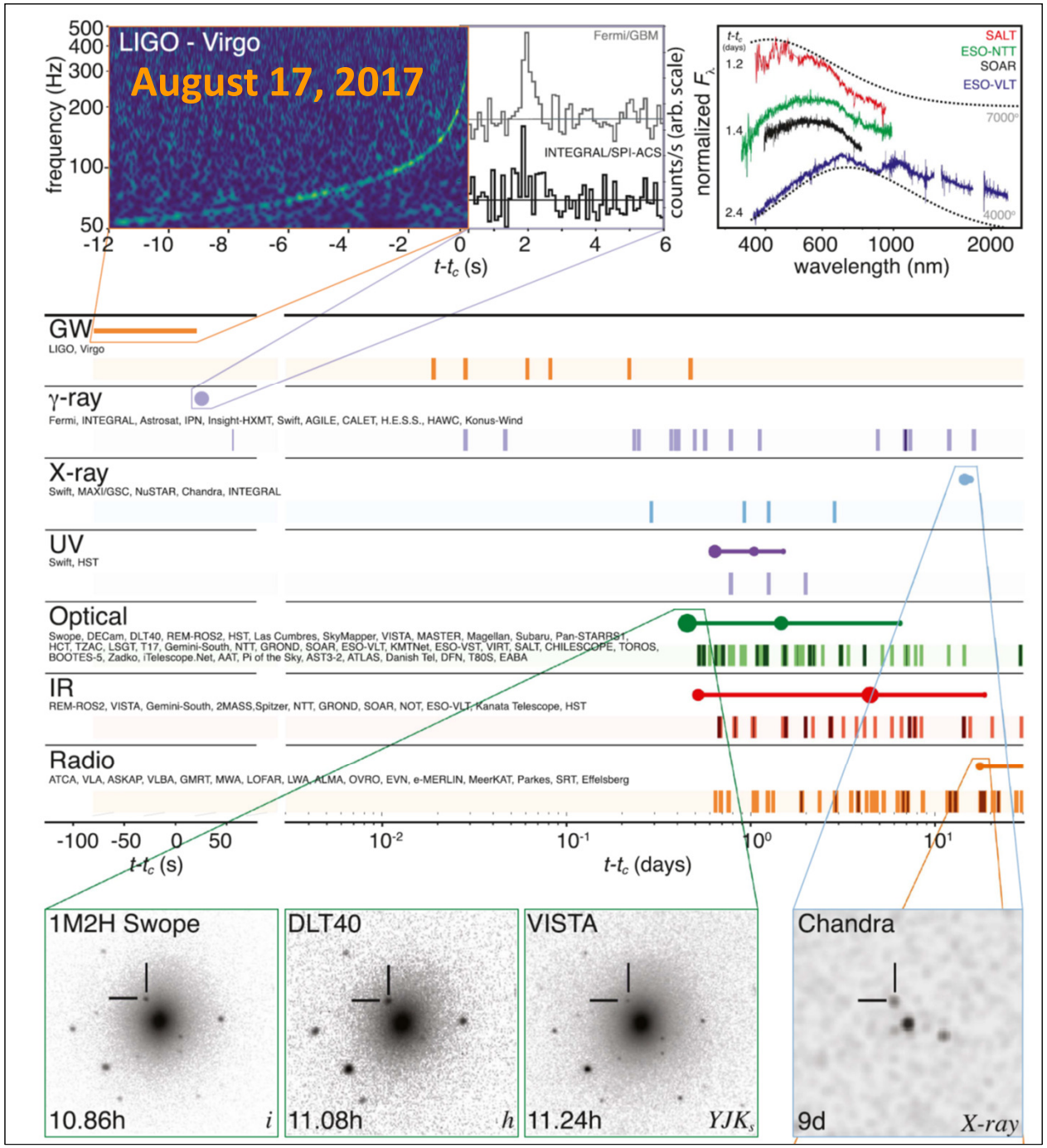
~ 10^{-7} Hz - 10^{-4} Hz

atoms (MAGIS, clocks, MIGA, AION…)


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Electromagnetic observations following GW170817 gravitation wave detection

Astrophysical Journal Letters, 848:L12 (2017)

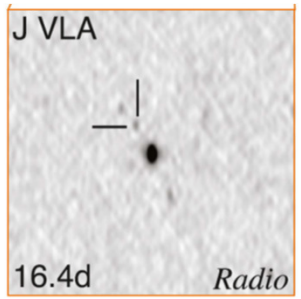


γ-ray burst 2 seconds later

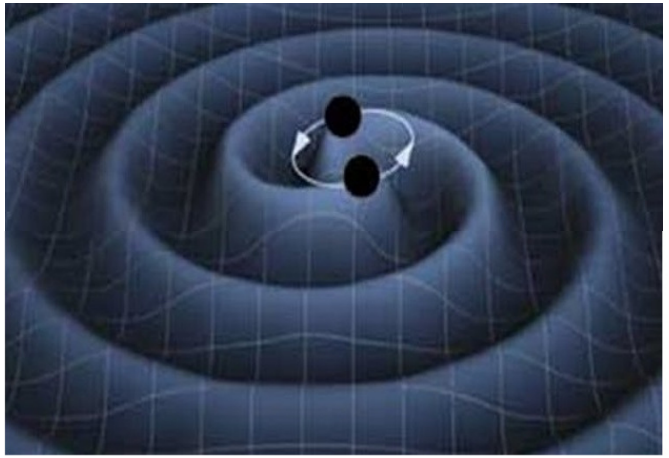
X-ray signal 9 days later

~ 11 hours to find optical source, following by UV and IR

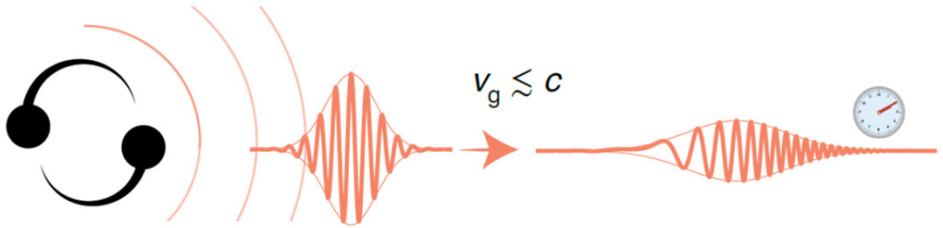
Radio wave signal 16 days later



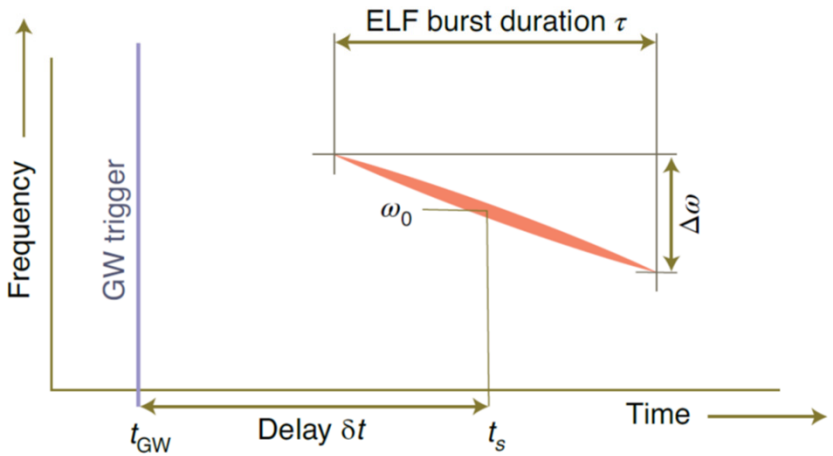
Transient dark matter signals: Quantum sensor networks as exotic field telescopes for multi-messenger astronomy



Bursts of exotic low-mass fields (ELFs) could be generated by cataclysmic astrophysical events, such as black-hole or neutron-star mergers, supernovae or the processes that produce fast radio bursts.



Effect of dispersion on the expected ELF signal at a precision quantum sensor.



- The leading edge of an ultrarelativistic ELF burst would propagate across Earth in ~40 ms.
- Magnetometers: 1-10 ms temporal resolution.
- Need longer baseline for clocks.

Conner Dailey, Colin Bradley, Derek F. Jackson Kimball, Ibrahim A. Sulai, Szymon Pustelny, Arne Wickenbrock and Andrei Derevianko, Nature Astronomy 5, 150 (2021)

A brief history of time delays

nature astronomy

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nature > nature astronomy > letters > article

Letter | Published: 02 November 2020

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

Conner Dailey, Colin Bradley, Derek F. Jackson Kimball, Ibrahim A. Sulai, Szymon Pustelny, Arne Wickenbrock & Andrei Derevianko

Nature Astronomy **5**, 150–158 (2021) | Cite this article

1613 Accesses | **20** Citations | **109** Altmetric | Metrics

Introduced coincident GW and Scalar Detection

Matters Arising | Published: 19 April 2024

Highlighting the back-action contribution of matter to quantum sensor network performance in multi-messenger astronomy

Yevgeny V. Stadnik

Nature Astronomy **8**, 434–438 (2024) | Cite this article

Comment pointing out SM matter back action effect that could be problematic for both detection and coincidence with GW:

Large time delays and critical screening

Matters Arising | Published: 19 April 2024

Reply to: Highlighting the back-action contribution of matter to quantum sensor network performance in multi-messenger astronomy

Andrei Derevianko, Derek F. Jackson Kimball & Conner Dailey

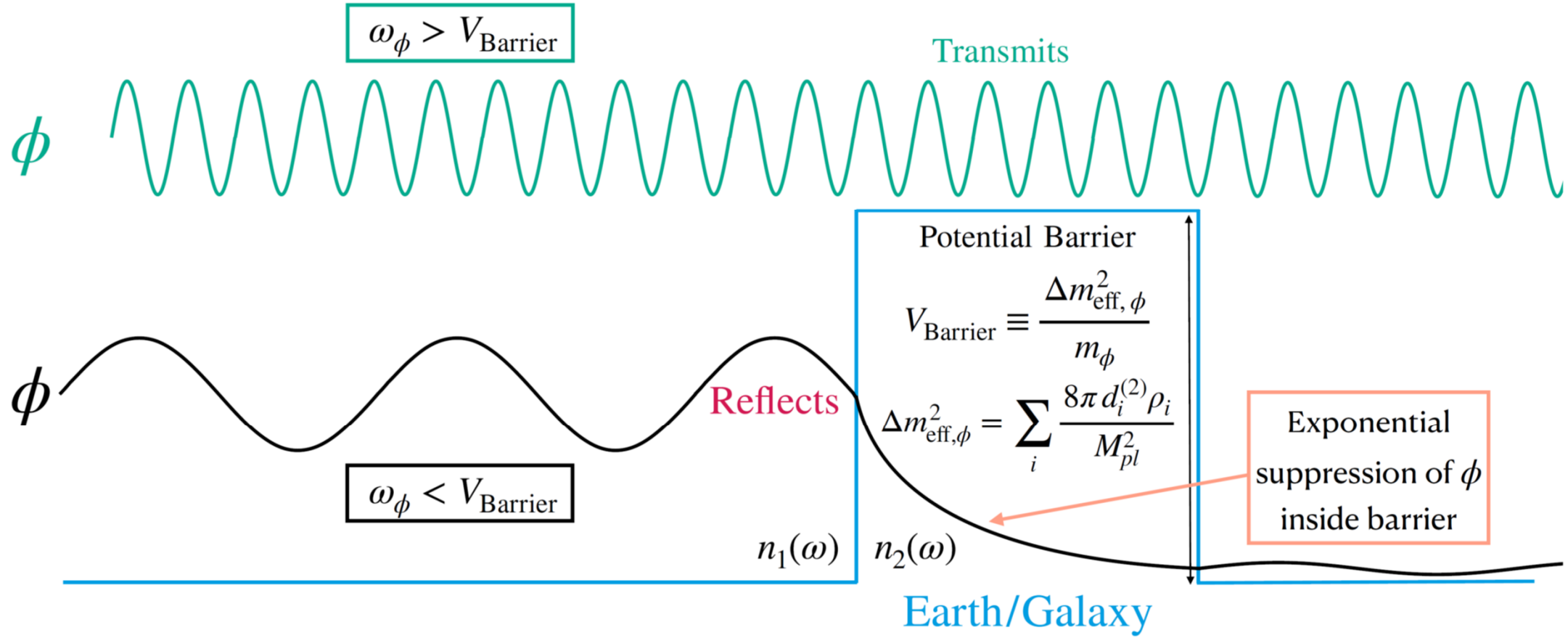
Nature Astronomy **8**, 432–433 (2024) | Cite this article

Claim: flip sign of coupling → problem doesn't arise

Rebuttal to arXiv:2112.02653v1

Responds to sign-flip claim: problems in QFT

Transient dark matter signals: quadratic couplings



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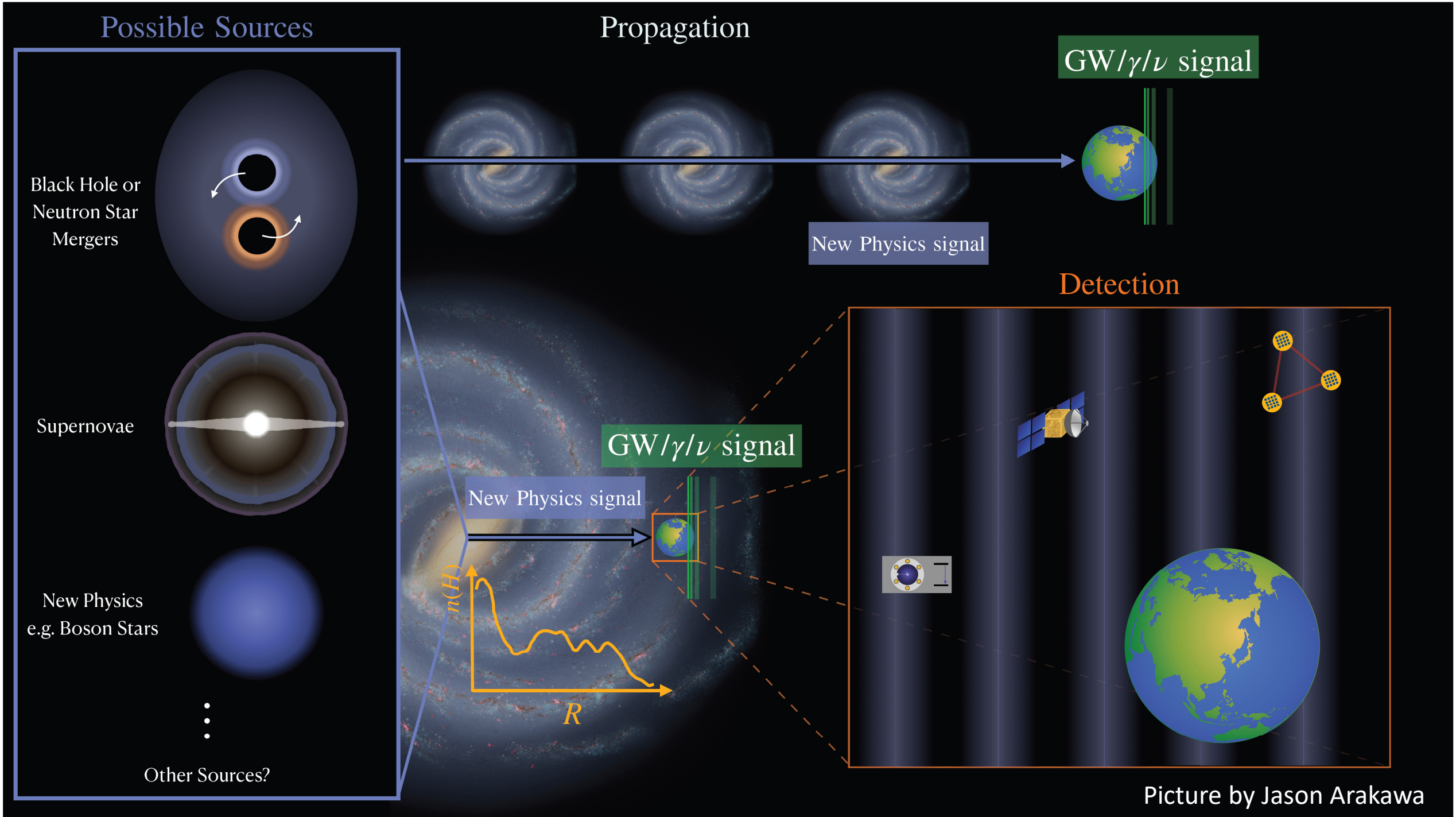
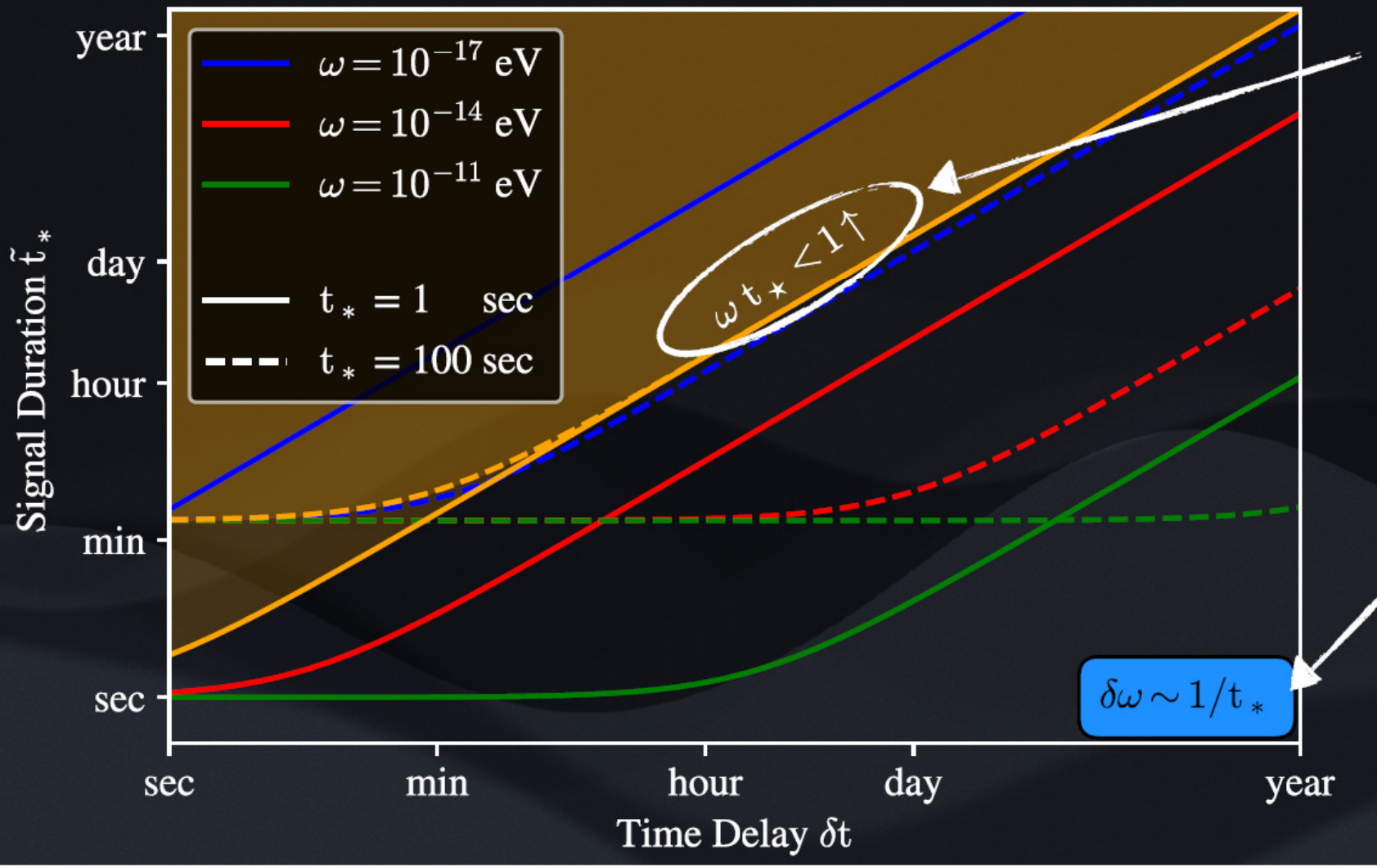

Possible Sources
Propagation
GW/γ/ν signal
Black Hole or
Neutron Star
Mergers
New Physics signal
Detection
Supernovae
GW/γ/ν signal
New Physics signal
New Physics
e.g. Boson Stars
n(H)
R
Other Sources?
Picture by Jason Arakawa

Signal duration $\tilde{t}_*$ vs Time delay δt

Slide by Jason Arakawa

J. Arakawa, M. H. Zaheer, V. Takhistov, M. S. Safronova, Joshua Eby, arXiv:2502.08716 (2025).

$$\tilde{t}_* \approx t_* + 2\frac{\delta\omega}{\omega}\delta t$$

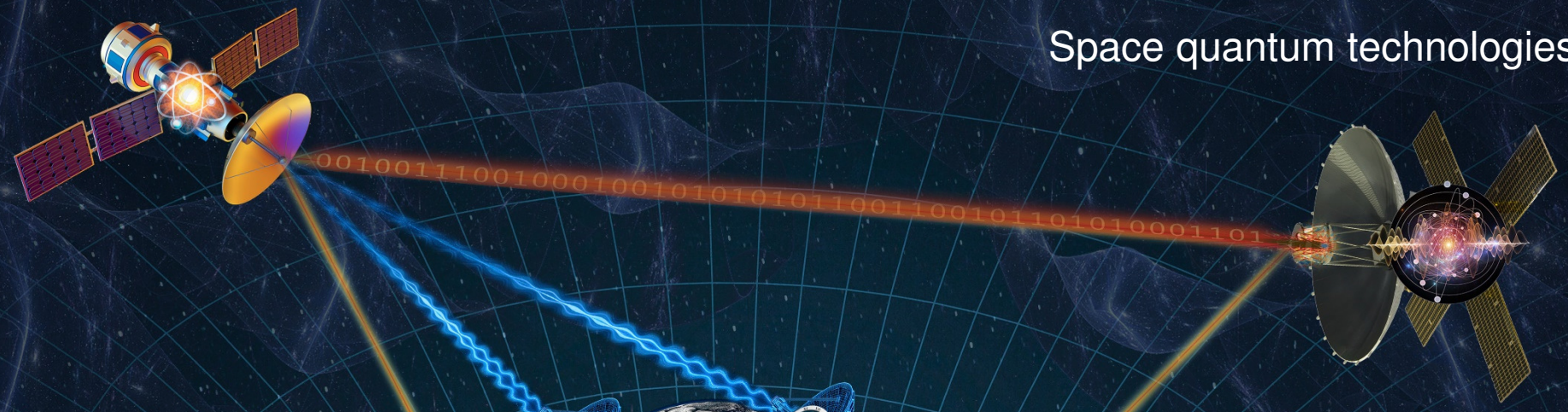


Uncertainty Principle

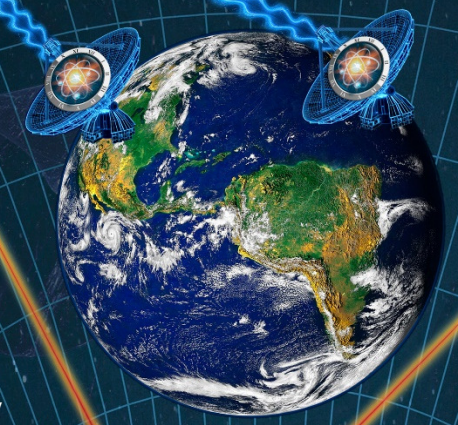
Taking example of minimum uncertainty

Figure by Hani Zaheer

Space Network of Quantum Sensors



Space quantum technologies



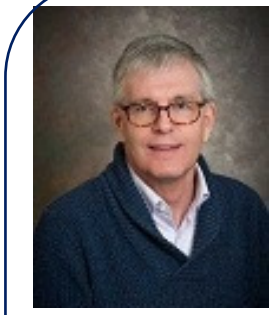
Fundamental Physics

Tests of quantum mechanics
Quantum vs. gravity
Tests of general relativity
Detection of gravitational waves in different wavelengths
The direct detection of dark matter and dark energy
Search for variation of fundamental constants
Searches for violation of symmetry laws

Earth-space optical time transfer
Intercontinental clock link via space
Trapped ion optical clock
Lattice based accelerometer
Atomic magnetometry space array
Hybrid optical lattice clock/atom interferometry facility
Space to space clock comparison
Cubesat quantum sensor network
Space - Earth- Moon optical time transfer
Improved Lunar laser ranging
Clock-based distance ranging demonstration
One-way navigation demonstration
Space - space and space - Earth quantum communications
Entanglement demonstration in space
GW atomic clock/interferometer pathfinder
Three-satellite optical link demonstration for GW prototype

UD team and collaborators

Online portal team



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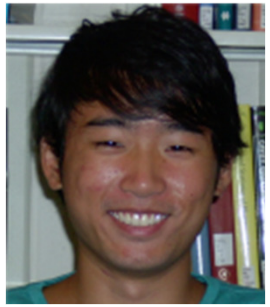

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