BAD HONNEF PHYSICS SCHOOL, MAY 12, 2025

FRONTIERS OF QUANTUM METROLOGY FOR NEW PHYSICS SEARCHES

ATOMIC AND NUCLEAR CLOCKS

Dark matter searches with clocks
Clocks in space for fundamental physics

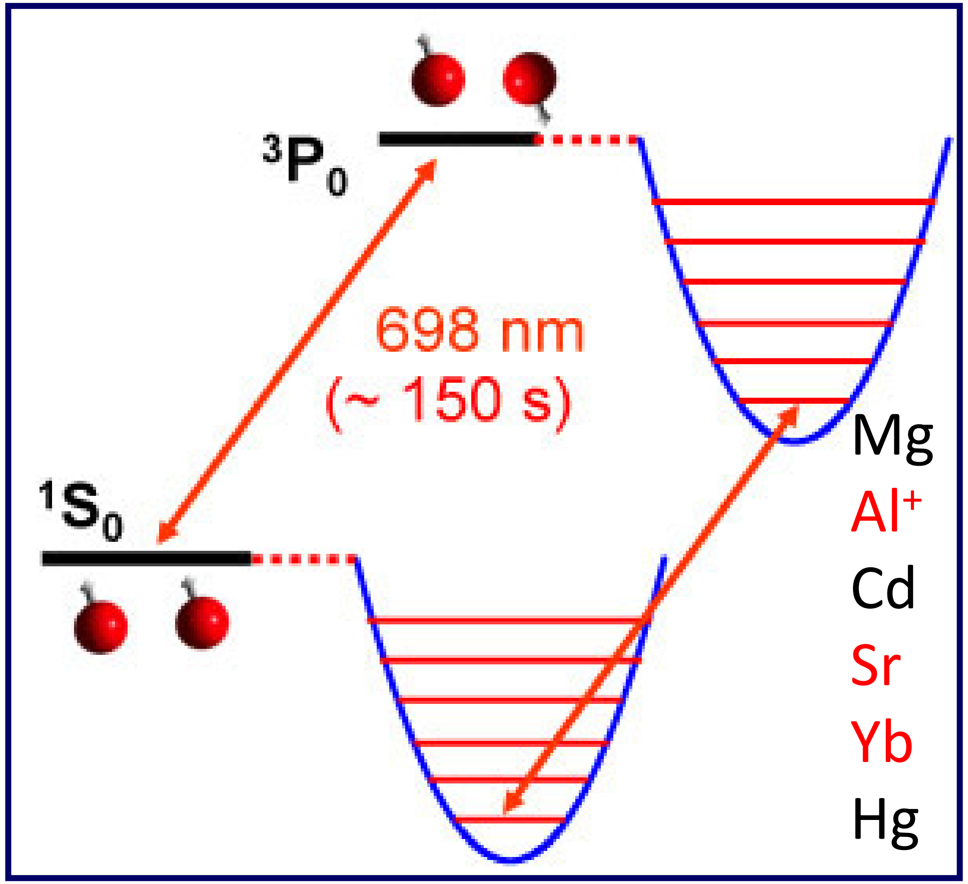
Marianna Safronova

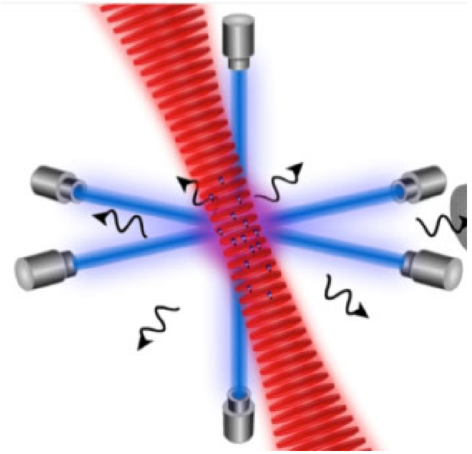
Q-SEnSE
An NSF Quantum Leap Challenge Institute
https://www.colorado.edu/research/qsense/

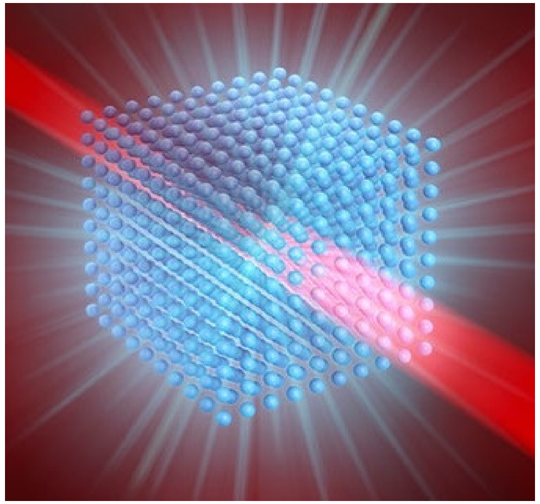
UNIVERSITY OF DELAWARE

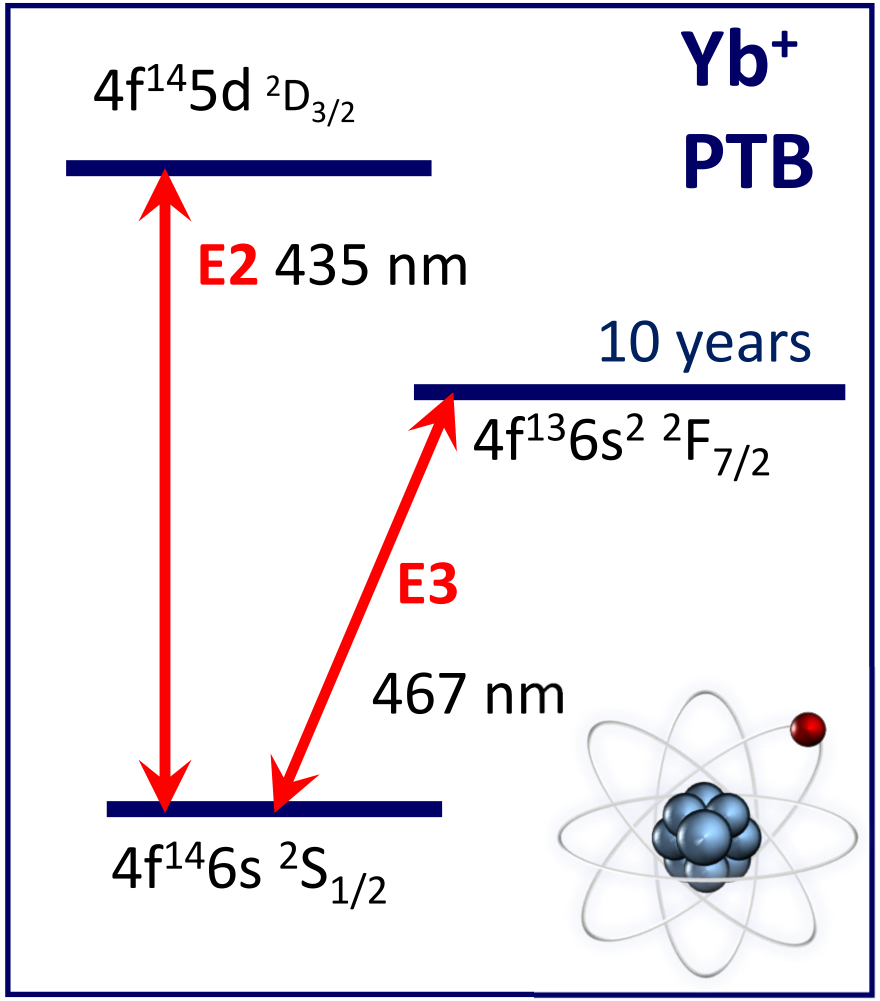
thorium nuclear clock
https://thoriumclock.eu/

Neutral atoms in optical lattice vs. trapped ion clocks









Strontium optical lattice neutral atom clock

Yb^+ single trapped ion clock

http://www.nist.gov/pml/div689/20140122_strontium.cfm

Clock instability
Quantum projection noise limit

$$\sigma_y(\tau) \approx \frac{1}{2\pi\nu_0}\frac{1}{\sqrt{NT\tau}}$$

Clock transition frequency

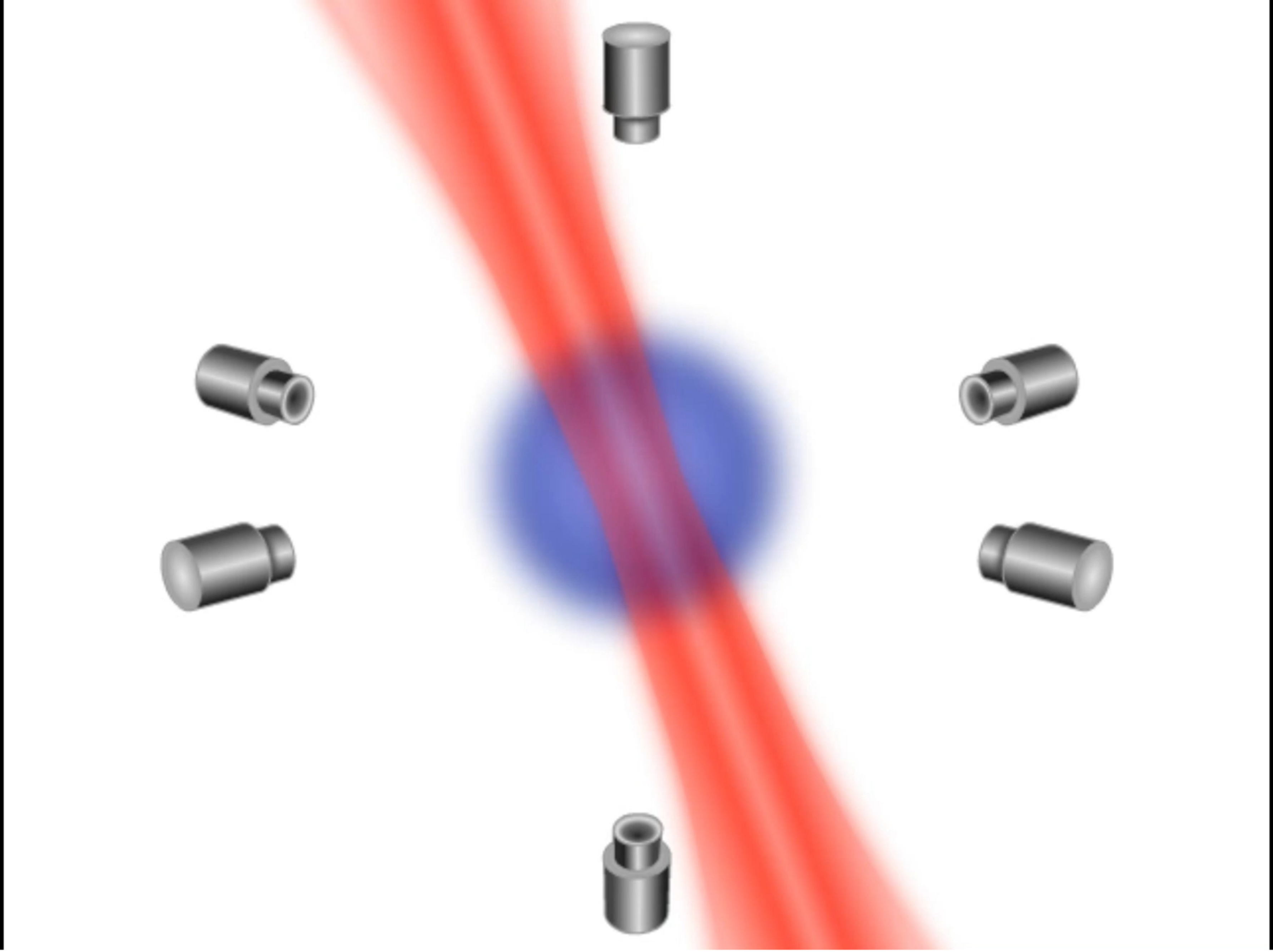
The number of atoms or ions used in a single measurement

N=1 (or a few) for ions now
1000 possible
N>1000 for neutral atoms

The averaging period

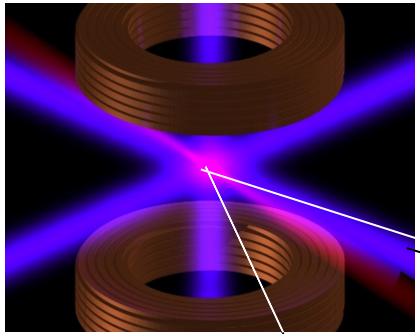
Duration of single measurement cycle

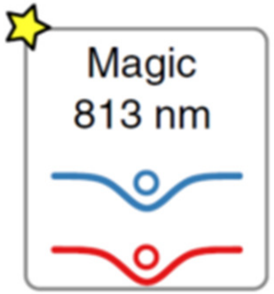
Limited by clock state lifetime and **laser stability**



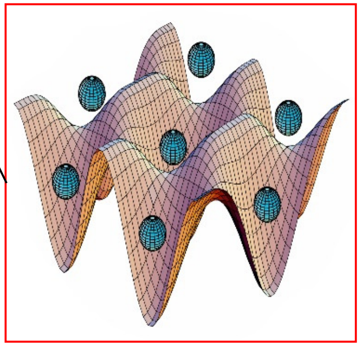
Animation credit: Jun Ye

Lattice clocks: magic wavelength



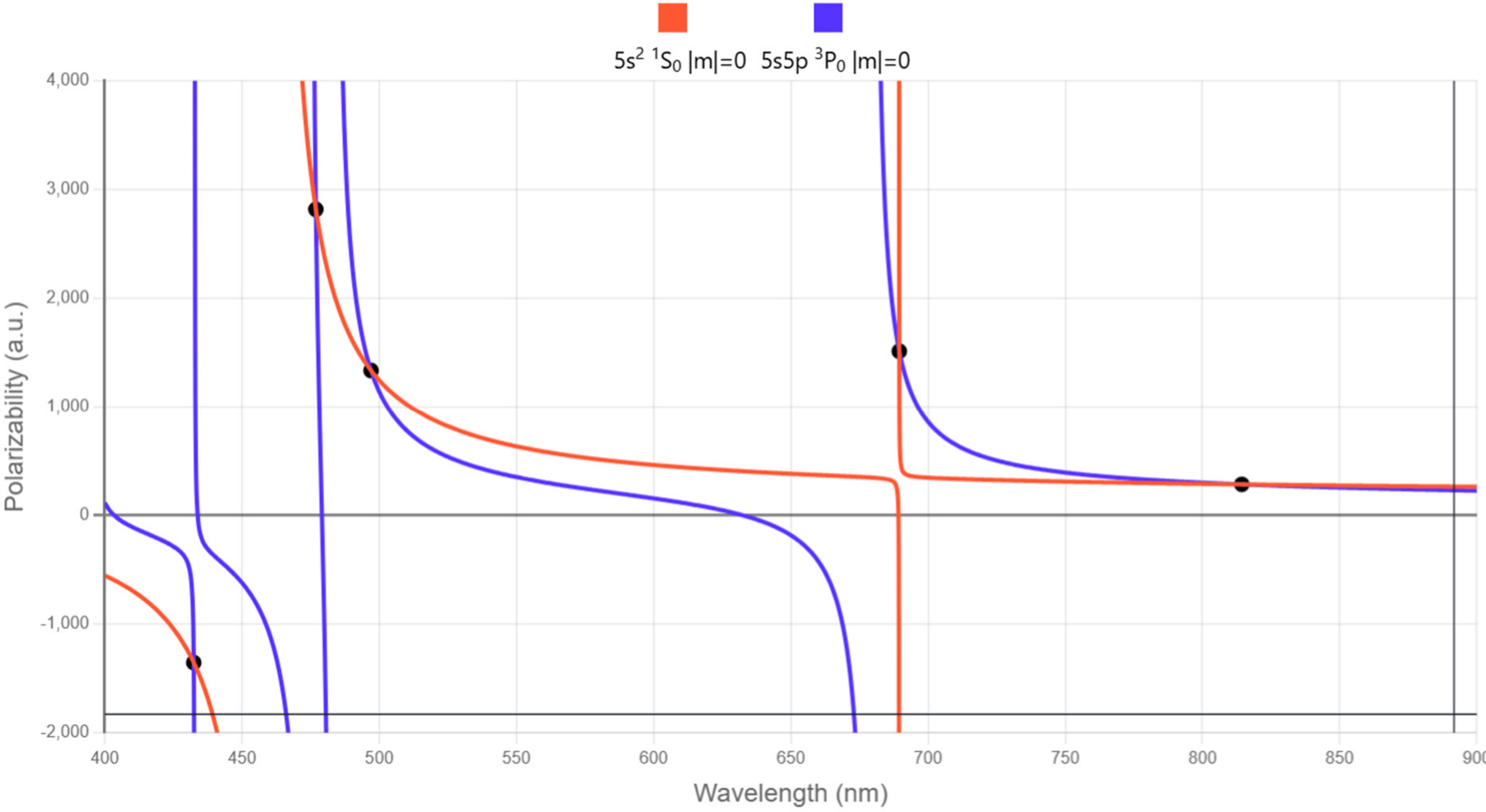


$$U \propto \alpha(\lambda)$$



Atom in state A sees potential U_A

Atom in state B sees potential U_B



Atomic data portal: https://www.udel.edu/atom

Image credits: NIST (Andrew Ludlow team, Yb clock, Steve Rolston)

Blackbody radiation shift

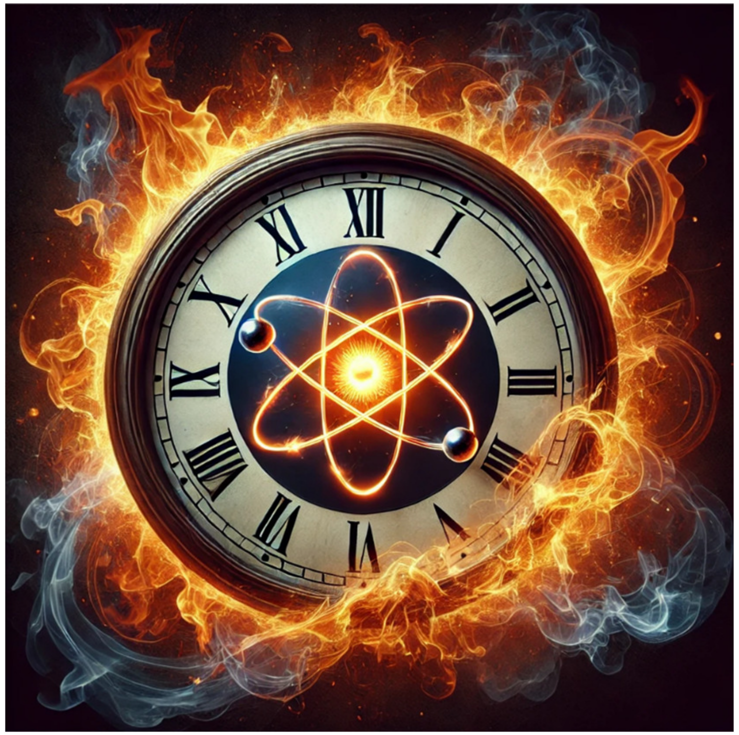
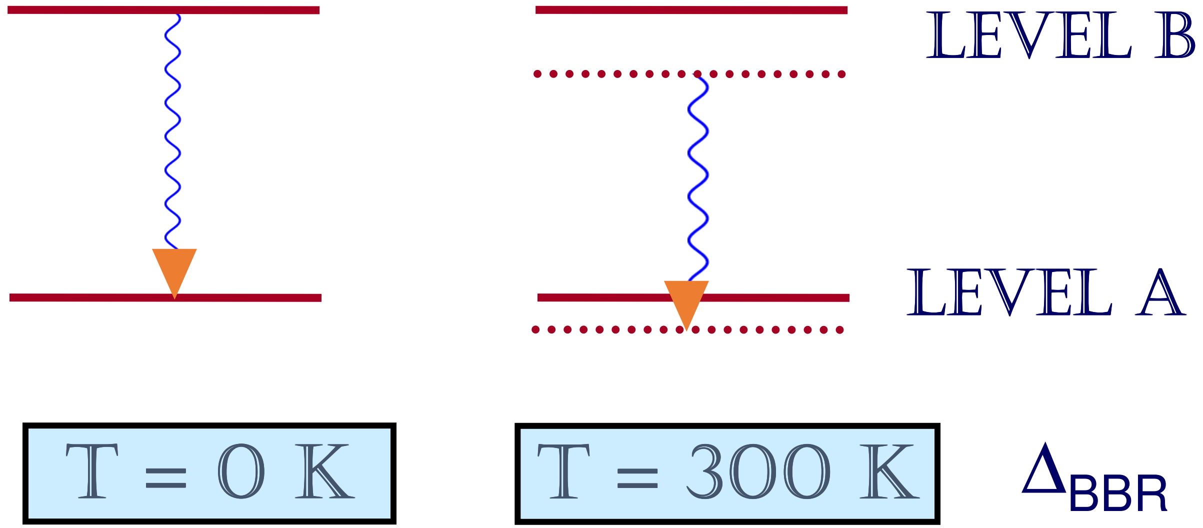


Image generated using OpenAI's DALL·E model



Transition frequency should be corrected to account for the effect of the black body radiation at T=300K.

Blackbody radiation shift

BBR shift of atomic level can be expressed in terms of a **scalar static polarizability** to a good approximation [1]:

$$\Delta\nu_{\mathrm{BBR}} = -\frac{1}{2}\alpha_0(0)(831.9V/m)^2\left(\frac{T(K)}{300}\right)^4(1+\eta)$$

Dynamic correction

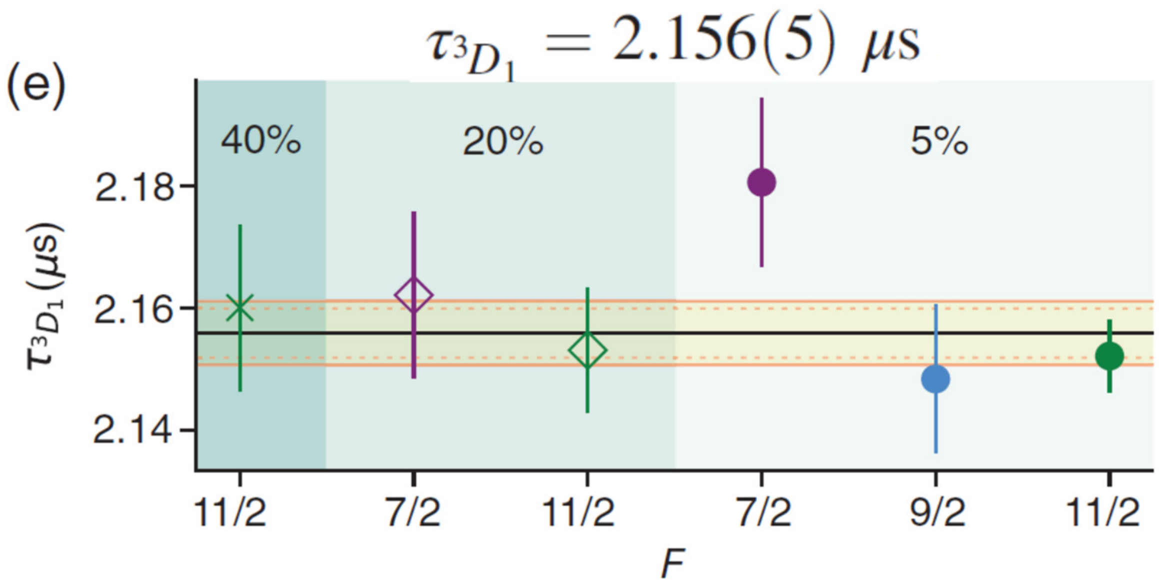
Dynamic correction is generally small. However it is 7% of the BBR in Sr. Multipolar corrections (M1 and E2) are suppressed by α^2 [1].

Vector & tensor polarizability average out due to the isotropic nature of field.

[1] Sergey Porsev and Andrei Derevianko, Physical Review A 74, 020502R (2006)

Contributions to dynamic BBR shift in Sr clock

Contribution	ΔE	y_n	D	$G_1(y_n)$	$\Delta\nu_{\mathrm{BBR}}$
$5s5p\ {}^3P_0 - 5s4d\ {}^3D_1$	3842	18.4	2.685(3)	0.009645	-0.15249(39)
$5s5p\ {}^3P_0 - 5s6s\ {}^3S_1$	14721	71	1.968(8)	0.000147	-0.00125(1)
$5s5p\ {}^3P_0 - 5s5d\ {}^3D_1$	20689	99	2.449(32)	0.000053	-0.00070(2)
$5s5p\ {}^3P_0 - 5p^2\ {}^3P_1$	20876	100	2.581(43)	0.000052	-0.00075(3)
$5s5p\ {}^3P_0 - 5s7s\ {}^3S_1$	23107	111	0.518(13)	0.000038	-0.00002
$5s5p\ {}^3P_0 - 5s6d\ {}^3D_1$	25368	122	1.165(31)	0.000029	-0.00009
Other					-0.0002
Total ${}^3P_0$					-0.1555(4)
Total ${}^1S_0$					-0.0028
Total ${}^3P_0$ - ${}^1S_0$					-0.1527(4)



Branching ratios computations for the extraction of ${}^3P_0$-${}^3D_1$ matrix element from the JILA lifetime measurement

	R
$5s5p\ {}^3P_0 - 5s4d\ {}^3D_1$	0.59529(60)
$5s5p\ {}^3P_1 - 5s4d\ {}^3D_1$	0.38622(39)
$5s5p\ {}^3P_2 - 5s4d\ {}^3D_1$	0.01849(2)

${}^3P_0$-${}^3D_1$ matrix element: 2.685(3) a.u.

PHYSICAL REVIEW LETTERS **133,** 023401 (2024)

Editors' Suggestion | Featured in Physics

Clock with 8×10^{-19} Systematic Uncertainty

Alexander Aeppli,[1,*] Kyungtae Kim,[1] William Warfield,[1] Marianna S. Safronova,[2] and Jun Ye[1,†]

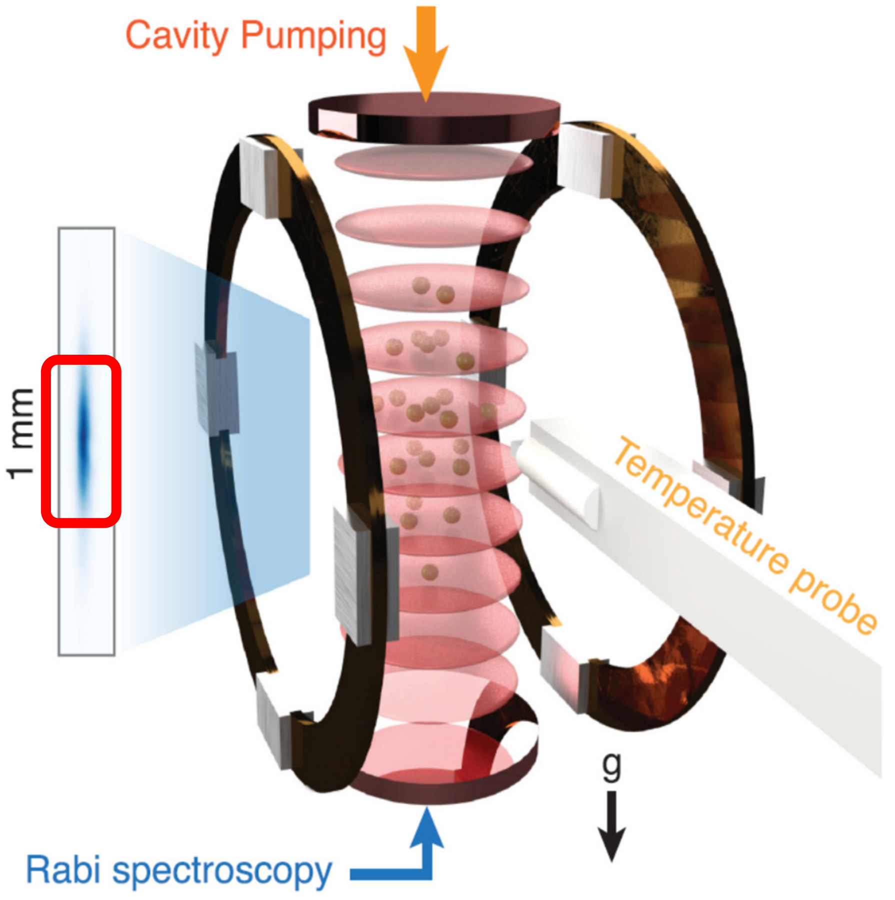
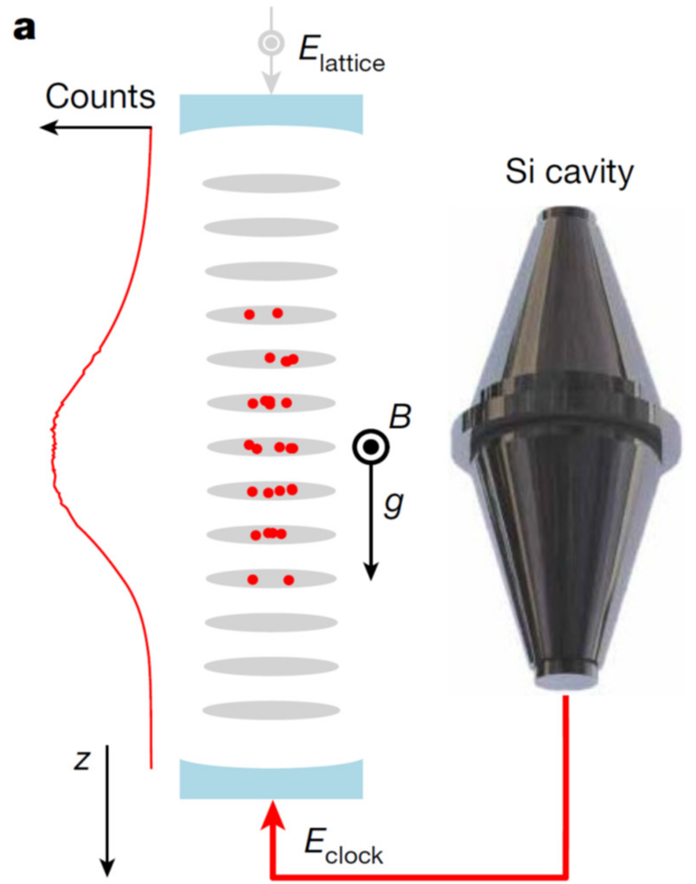


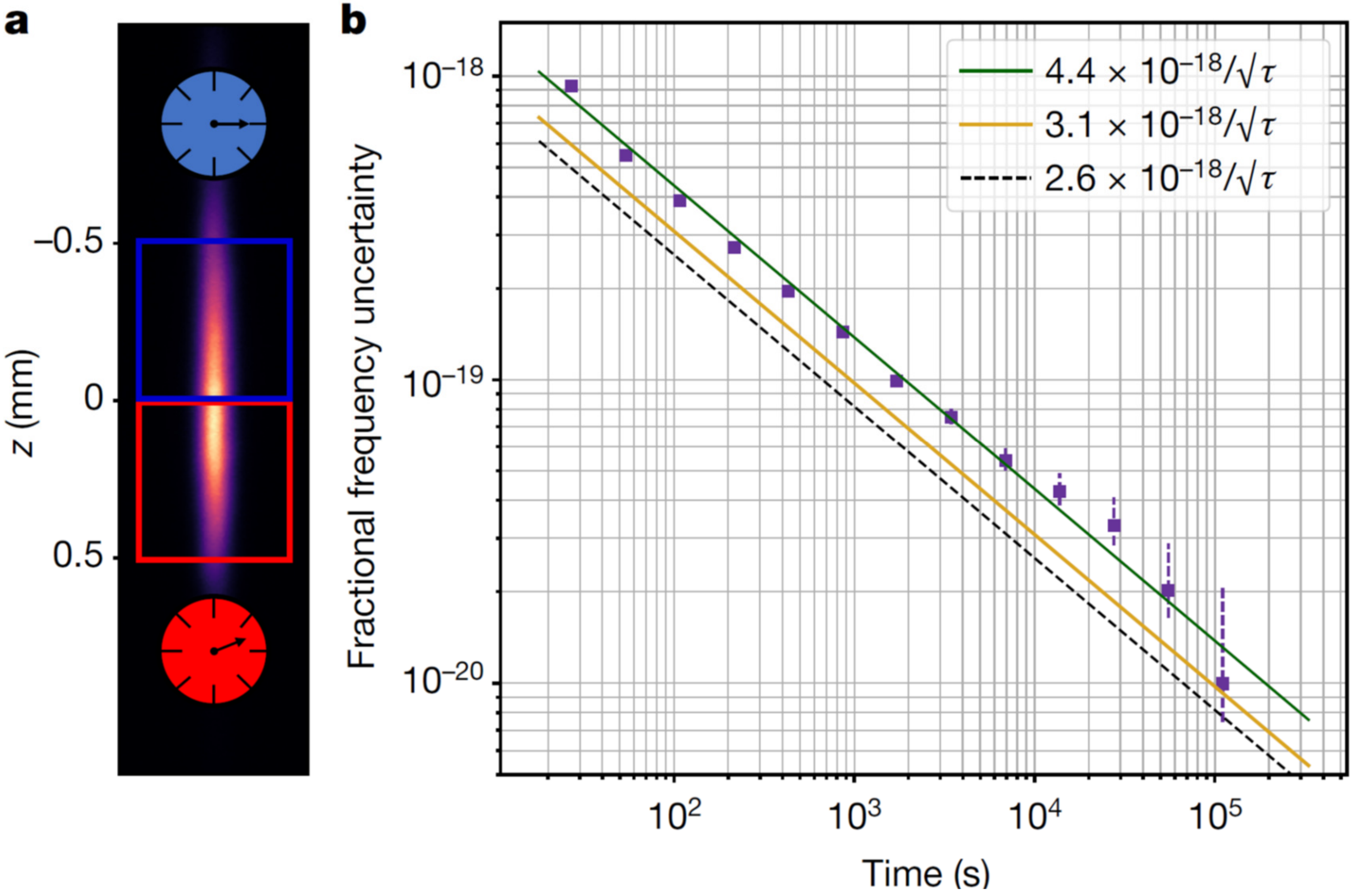
TABLE I. Fractional frequency shifts and uncertainties for the JILA 1D Sr optical lattice clock.

Shift name	Shift (10^{-19})	Uncertainty (10^{-19})
BBR	−48 417.2	7.3
Lattice light	−0.1	3.2
Second order Zeeman	−855.1	1.0
Density	−1.1	0.9
First order Zeeman	0.0	0.7
Background gas	−4.7	0.5
dc Stark	−1.0	0.1
Tunneling	0.0	<0.1
Minor shifts	0.0	<0.1
Total shift	−49 279.2	8.1

Resolving the gravitational redshift across a millimetre-scale atomic sample,

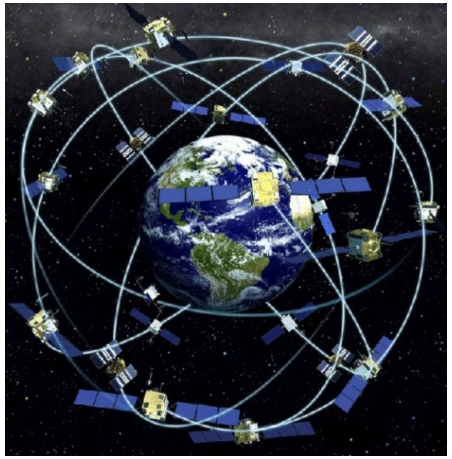
T. Bothwell, Kennedy, C., Aeppli, A., Kedar, D., Robinson, J., Oelker, E., Staron, A., and Ye, J., Nature 602, 420 (2022).



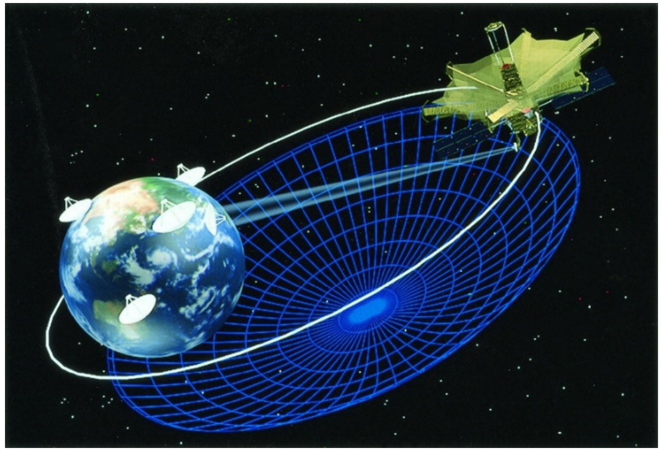


10^{-18} is reached in a few seconds!

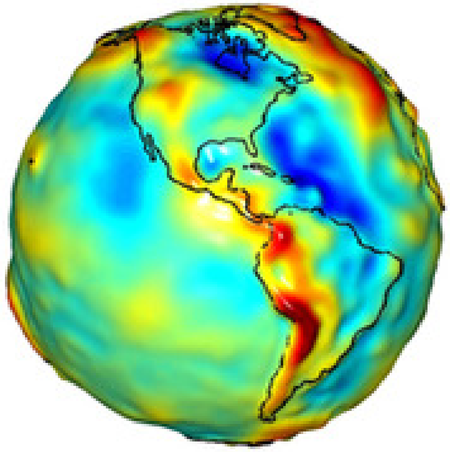
Applications of atomic clocks



GPS, deep space probes

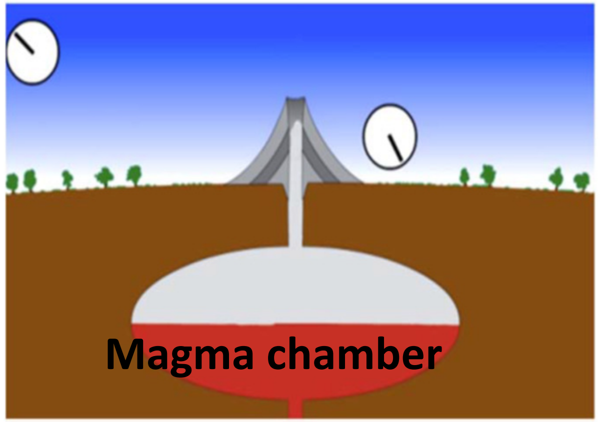


Very Long Baseline Interferometry

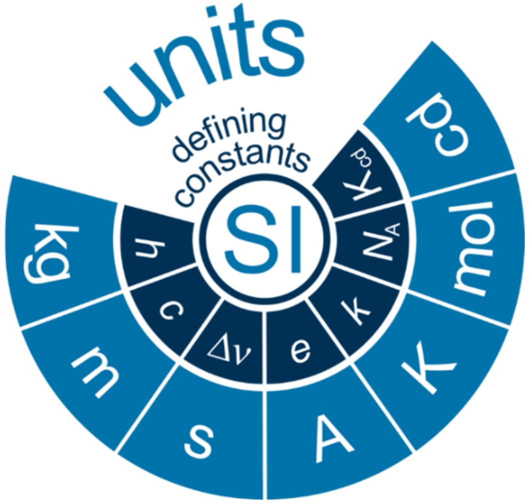


10^{-18}
1 cm
height

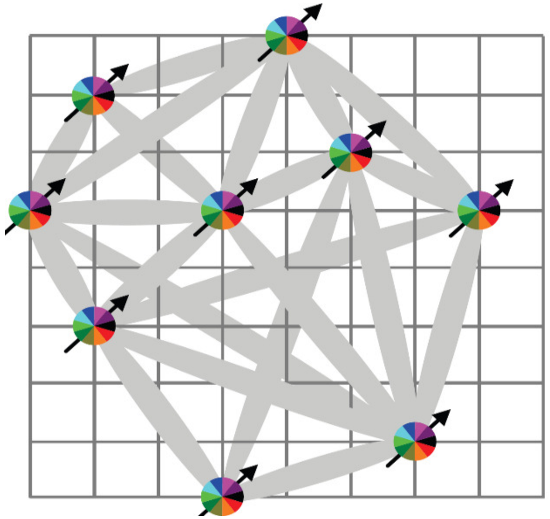
Relativistic geodesy



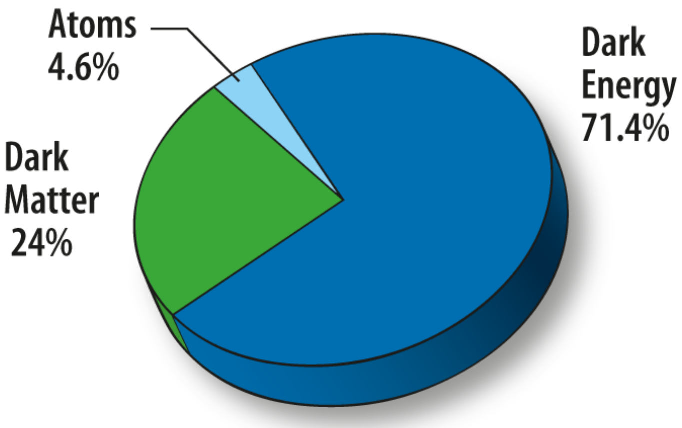
Gravity Sensor

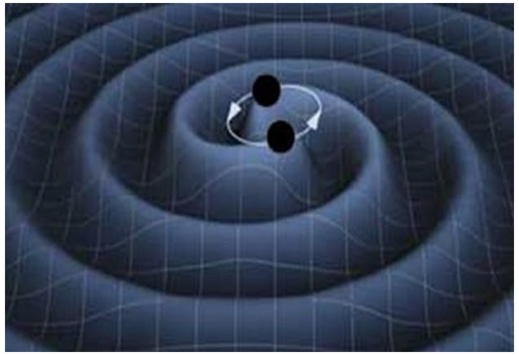


Definition of the second



Quantum simulation





Searches for physics beyond the Standard Model

Image Credits: NOAA, Science 281,1825; 346, 1467, University of Hannover, PTB, PRD 94, 124043, Eur. Phys. J. Web Conf. 95 04009

Why search for dark matter?


"Because it's there."
–George Mallory

What dark matter is not:
MACHOS hypothesis have been ruled out

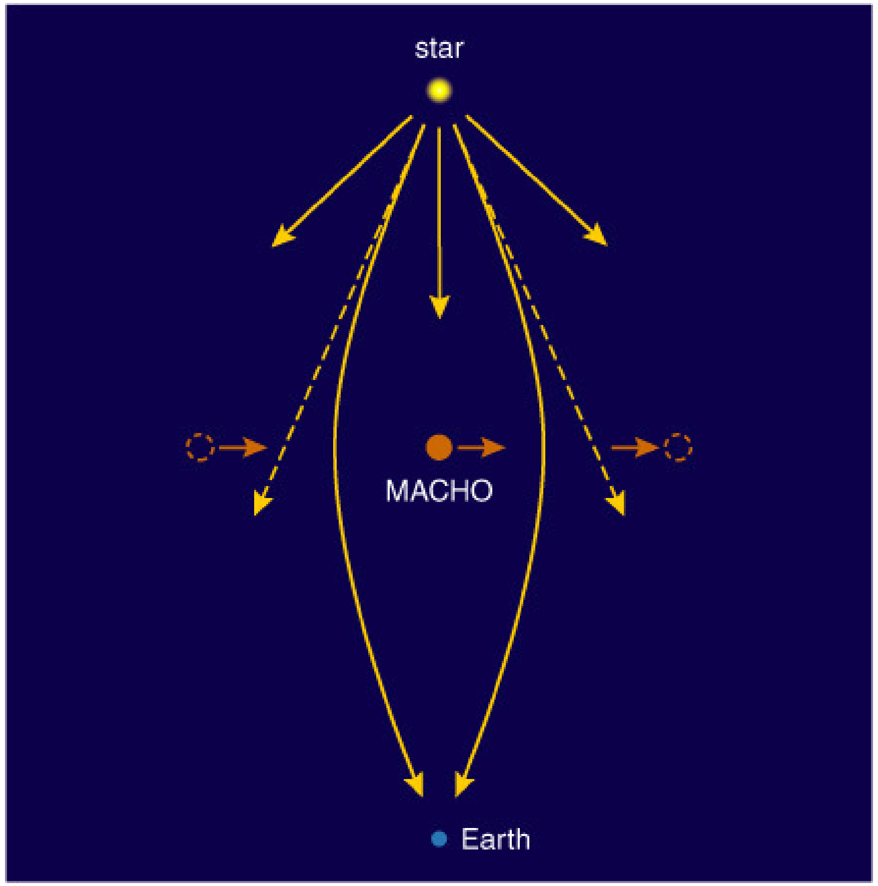
MACHOS: **MA**ssive **C**ompact **H**alo **O**bjects:

Dim stars (white dwarfs, drown dwarfs, neutron stars), black holes, Jupiter-sized planets, ...

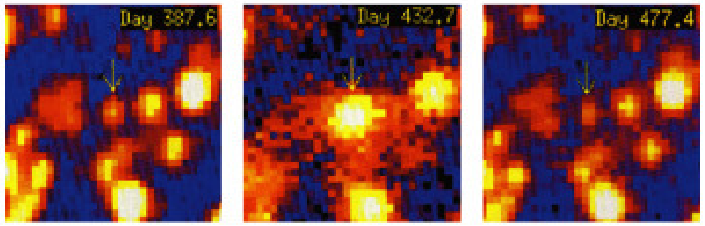
Not present at CMB
(except primordial black holes)

http://www.jcschroder.com/phy111/machos.htm

Searching for MACHOS with gravitational microlensing

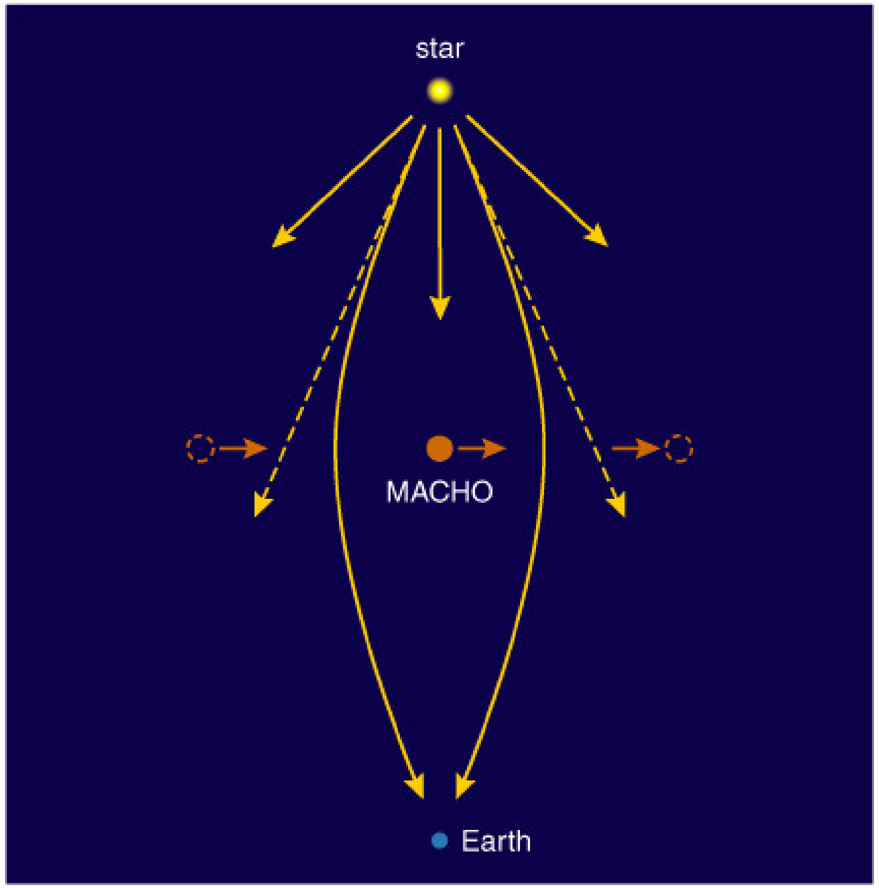


before during after



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

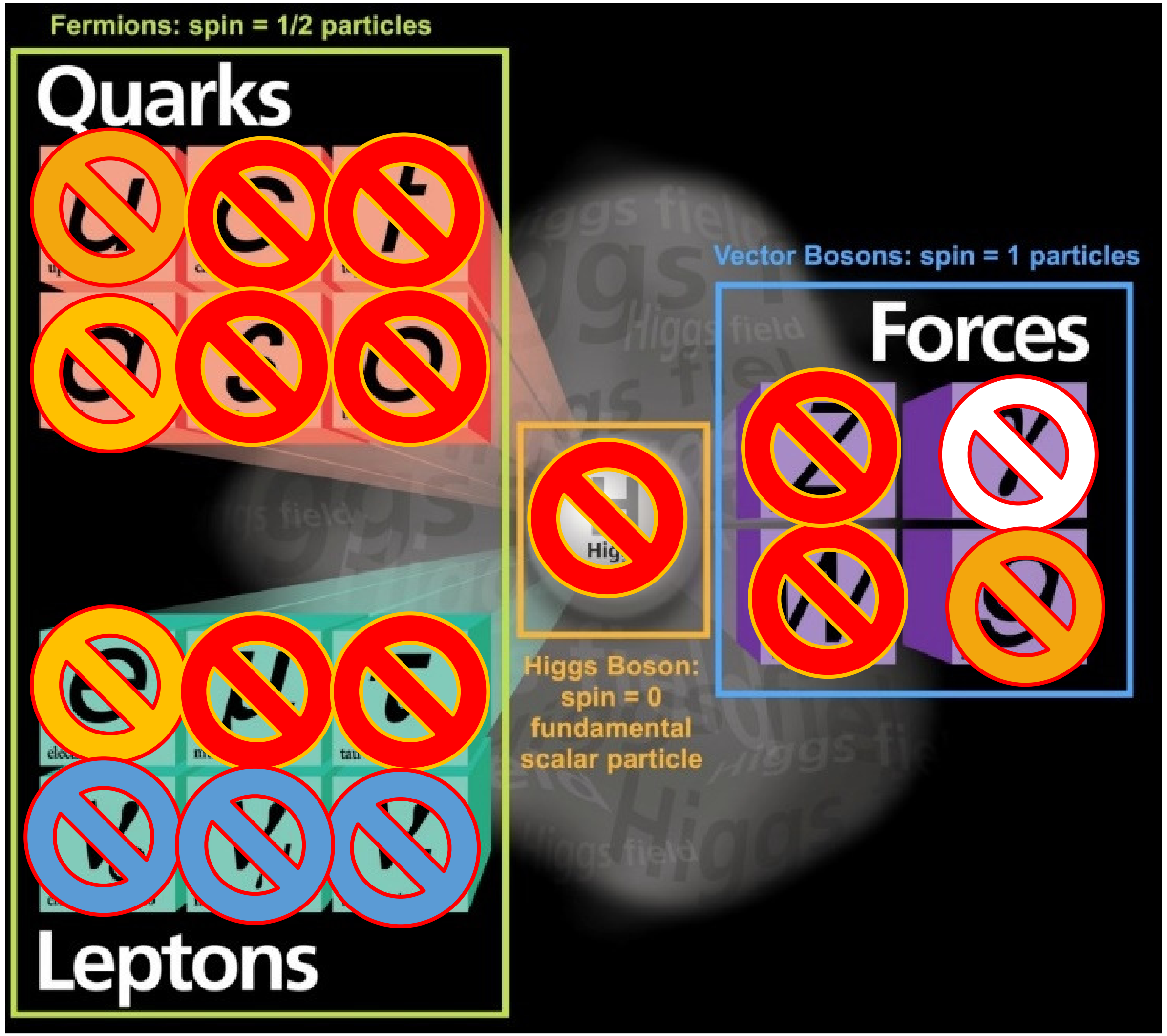
Searching for MACHOS with gravitational microlensing



Results: not enough MACHOS
to make dark matter (less then 8%)

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

Could elementary particles be cold dark matter?



Particle of light

Couple to plasma

Decay quickly

Hot dark matter

No known particle can be cold dark matter – Need to search for new particles.

Approaching dark matter theories

Top down:
Begin with theory motivation (hierarchy problem, strong CP problem.) develop model (SUSY [supersymmetry], axion) look for stable, neutral particle (LSP [light supersymmetric particle], axion)

Bottom up:
Motivated often by specific experimental anomalies, theories constructed. Implications for other experiments (and often SUSY)

Phenomenological: Motivated by considering whether a viable and detectable model could exist of a certain type.

Our most conservative idea for dark matter:
Some exotic particle that we have not yet detected
[note: it does not have to be just one particle]

Two most important parameters of such particles

(1) Mass and **(2) Strength of interaction with normal matter**

THE ZOOLOGY OF DARK MATTER

2015 perception

Three basic categories of dark matter:

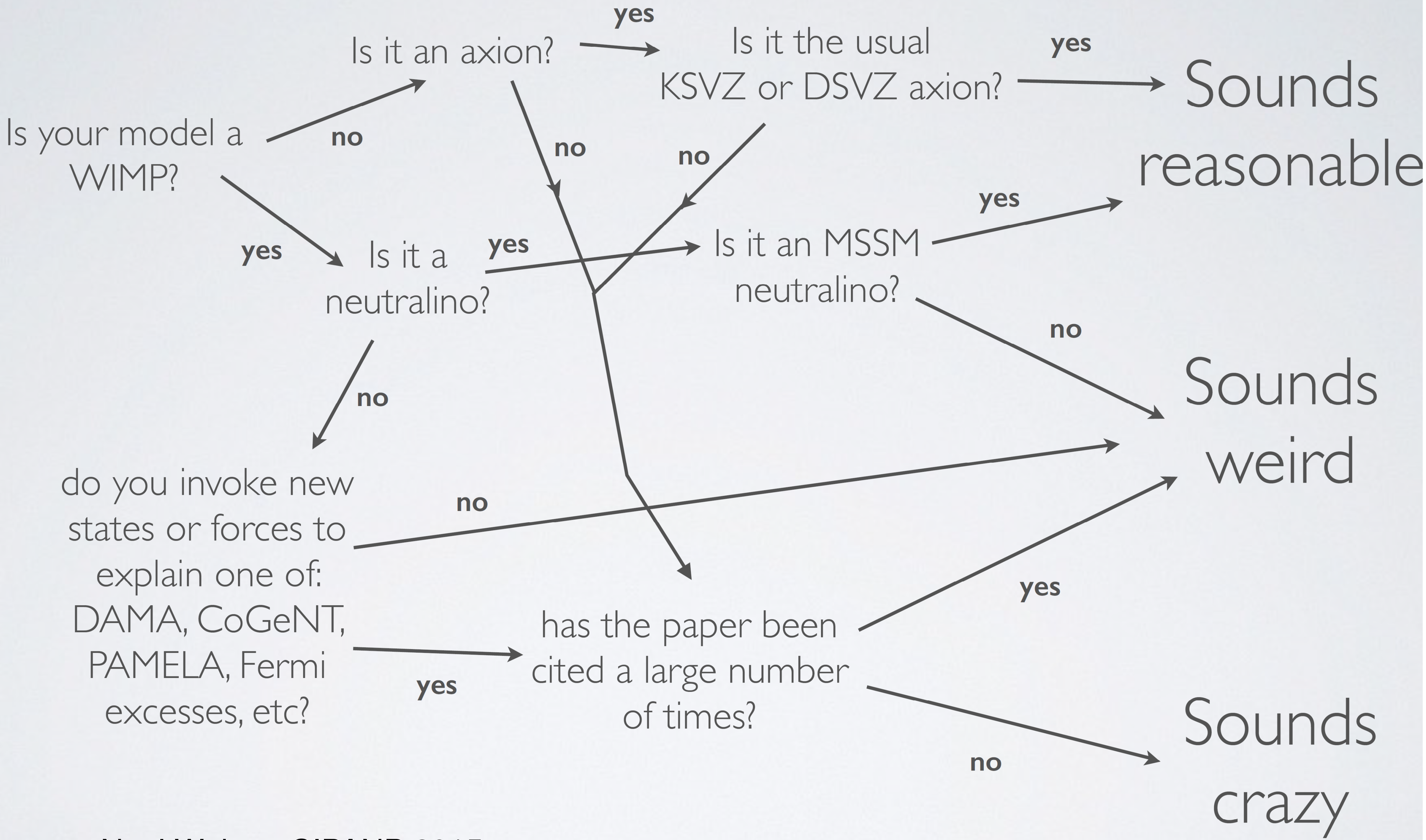
Reasonable   Weird   Crazy

sometimes also called "normal"

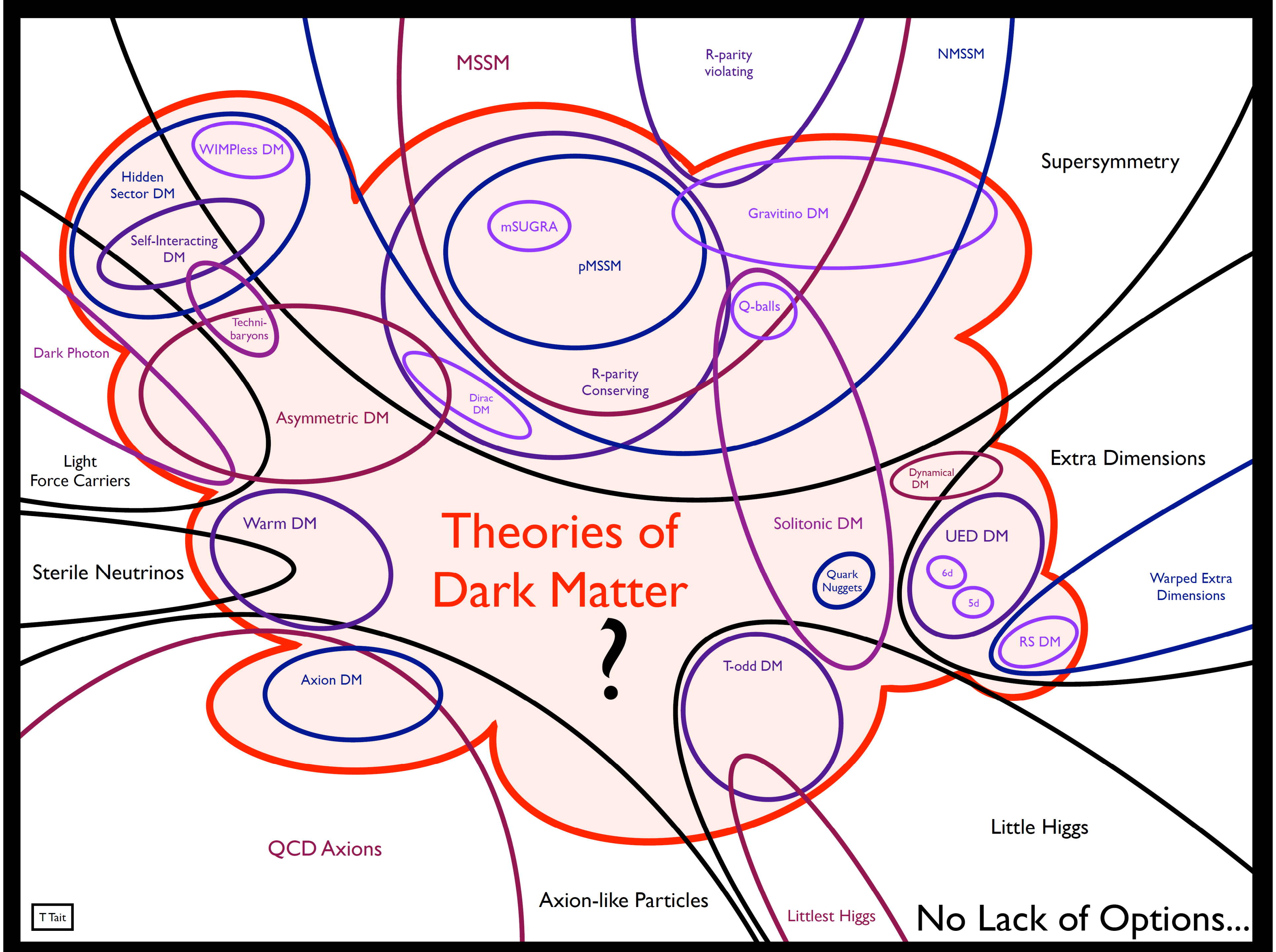
(also "obviously wrong")

Slide from Neal Weiner's (New York University) review on dark matter at the 2015 Conference on the Intersections of Particle and Nuclear Physics

2015 perception



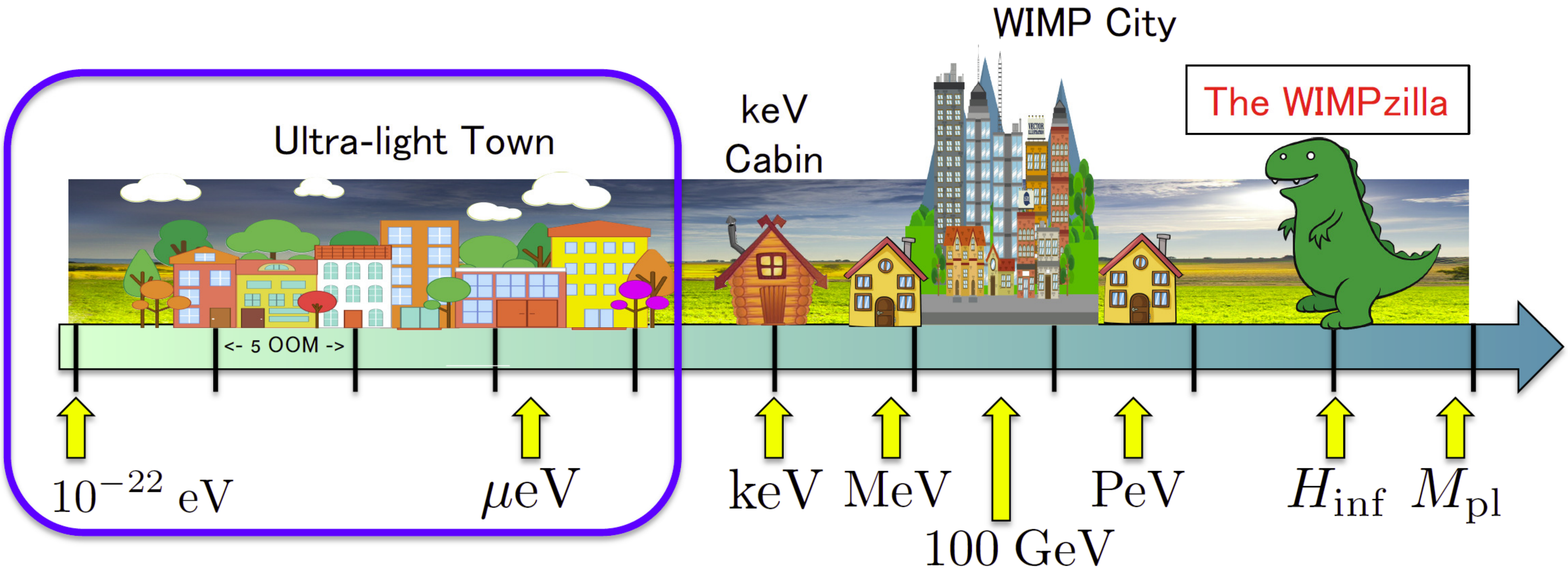
Neal Weiner, CIPANP 2015



MSSM
R-parity violating
NMSSM
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
Supersymmetry
Q-balls
Dark Photon
Asymmetric DM
Dirac DM
R-parity Conserving
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Theories of Dark Matter
?
Solitonic DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait
No Lack of Options...

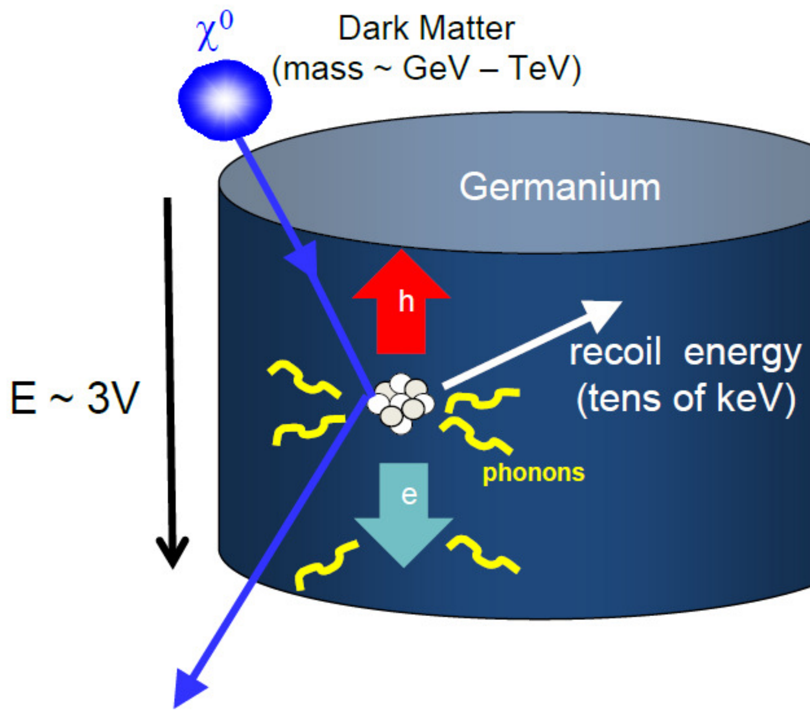
Slide from Andrew Long's 2018 LDW talk

The landscape of dark matter masses

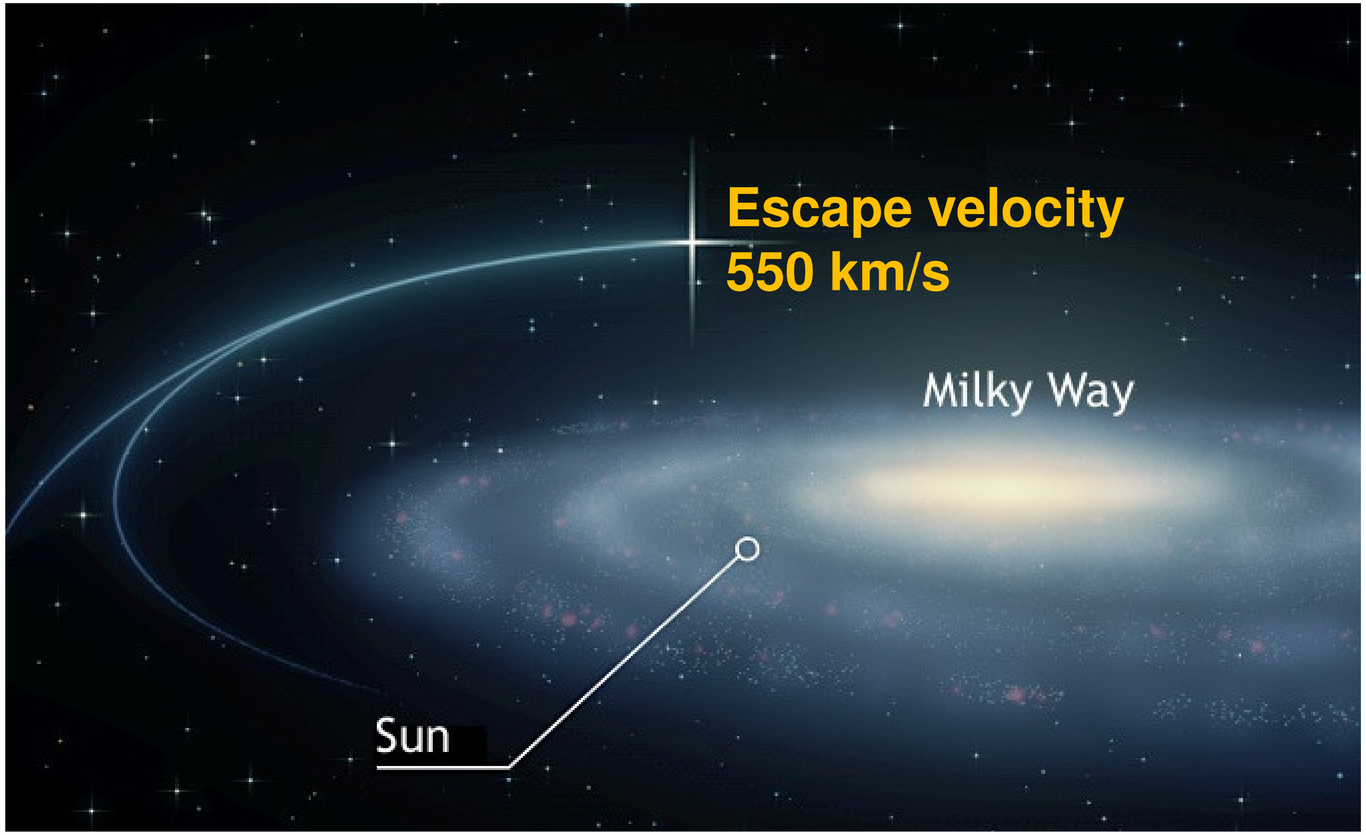


DARK MATTER DETECTION

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/

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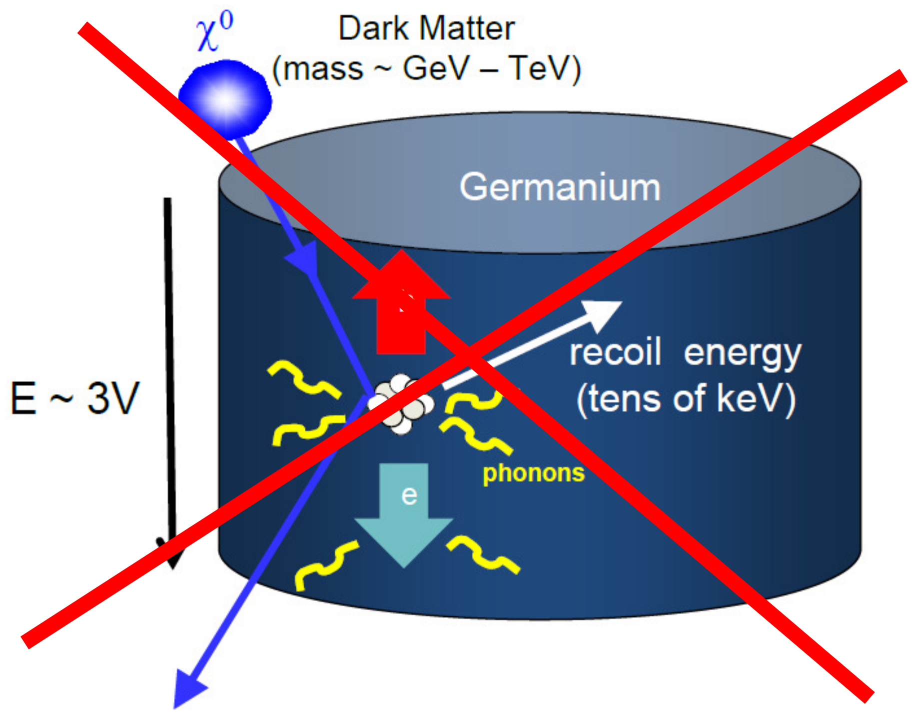

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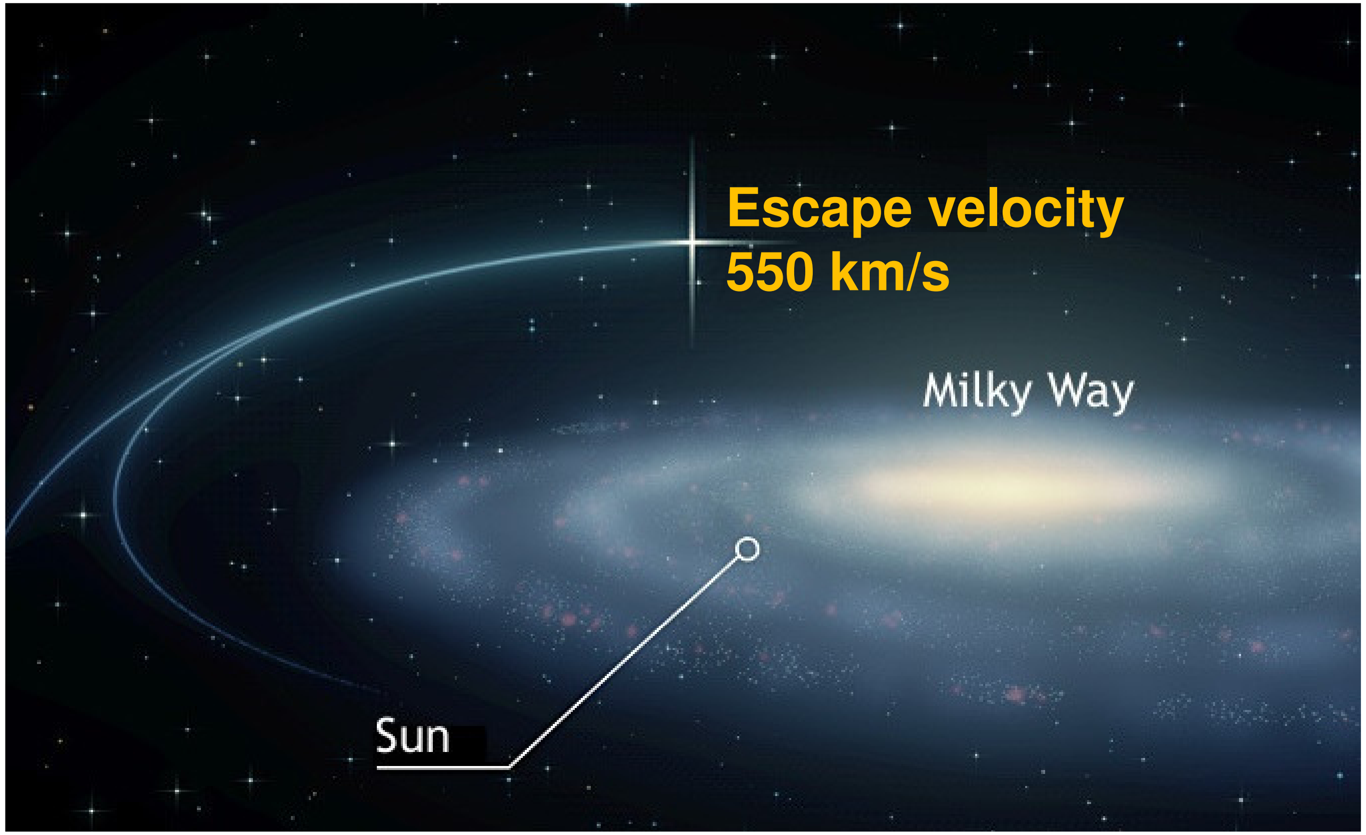

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https://astronomynow.com/2016/04/14/speeding-binary-star-discovered-approaching-galactic-escape-velocity/

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

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

$$\boxed{\phi(t) \approx \phi_0 \cos(m_\phi t)}$$

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

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

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

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

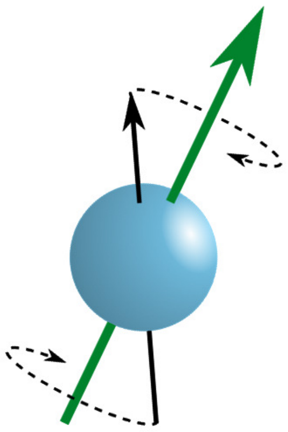
Need different detection strategies from particle dark matter.

Dark matter field amplitude

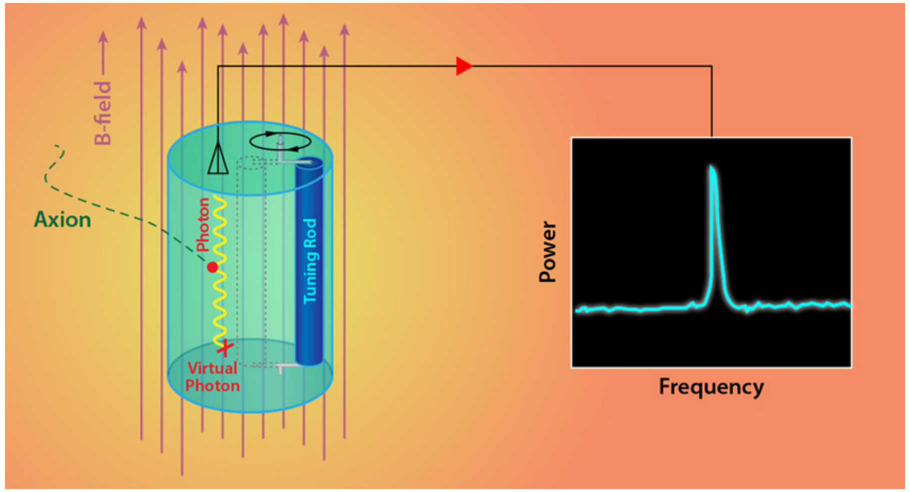
Dark matter density

Dark matter mass

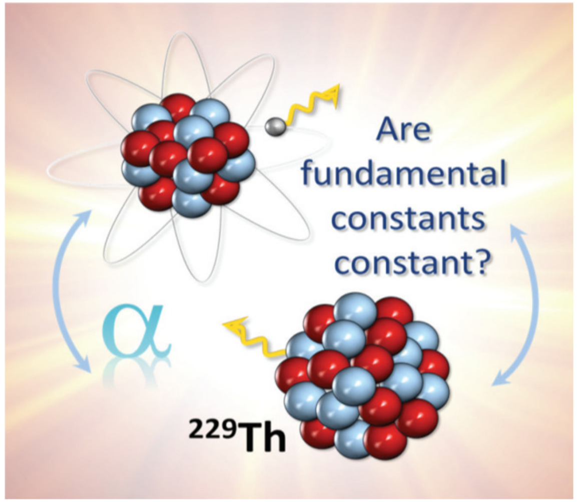
Observable effects of ultralight dark matter



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

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

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

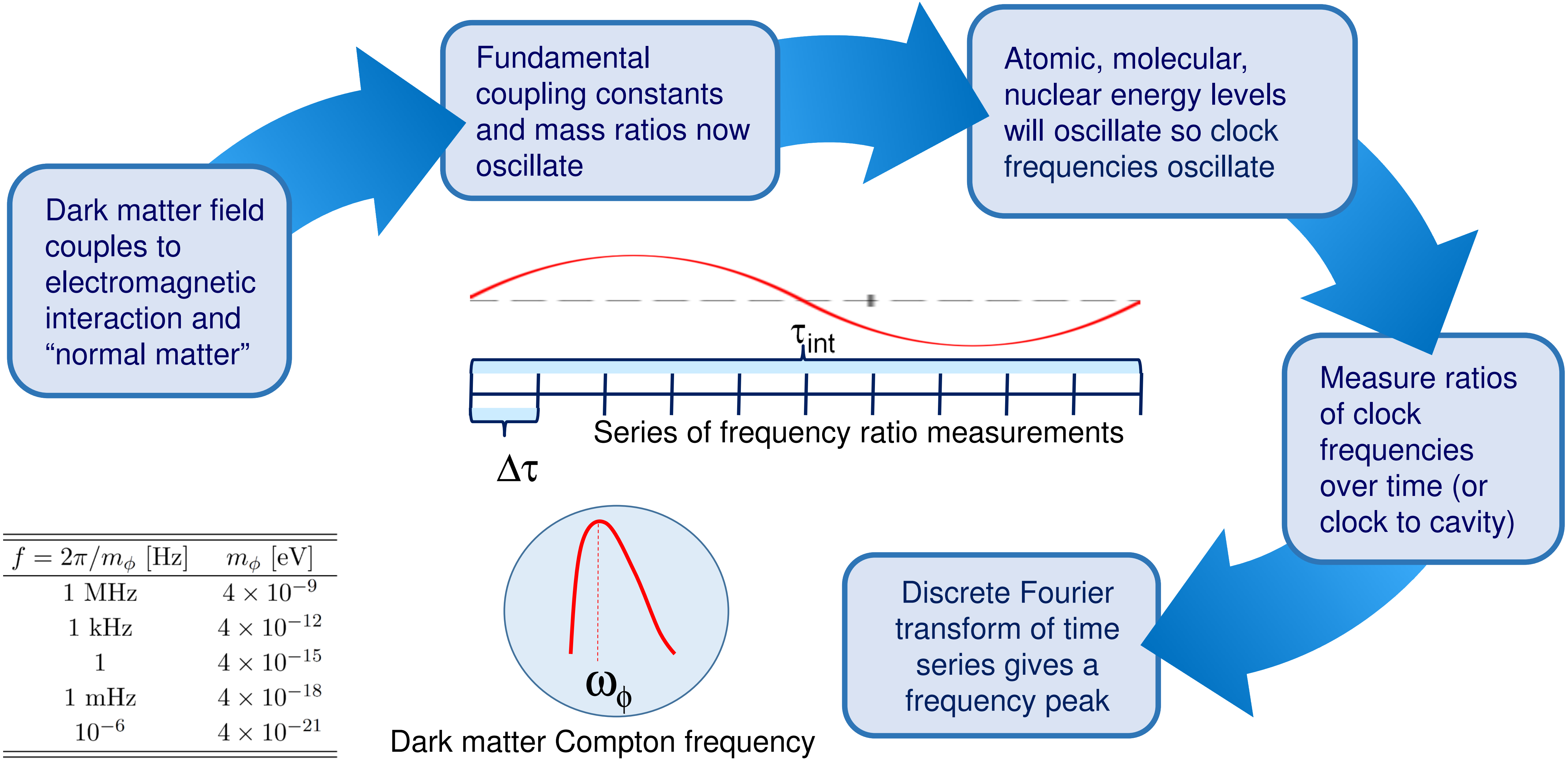
Scalar UDM will cause **oscillations** of the electromagnetic fine-structure constant α, strong interaction constant and fermion masses

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

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

Observable: clock frequency ratios

How to detect ULTRALIGHT dark matter with clocks?



$f = 2\pi/m_\phi$ [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}

Sensitivity of optical clocks to α-variation/dark matter

$$E = E_0 + \boldsymbol{q}\left(\frac{\alpha^2}{\alpha_0^2} - 1\right)$$

Enhancement factor

$$K = \frac{2q}{E_0}$$

Can calculate
with high accuracy

Need: large K for at least one for the clocks

Best case: large K_2 and K_1 of opposite sign for clocks 1 and 2

$$\frac{\partial}{\partial t}\ln\frac{\nu_2}{\nu_1} = (K_2 - K_1)\frac{1}{\alpha}\frac{\partial\alpha}{\partial t}$$

Frequency ratio
accuracy 10^{-18}

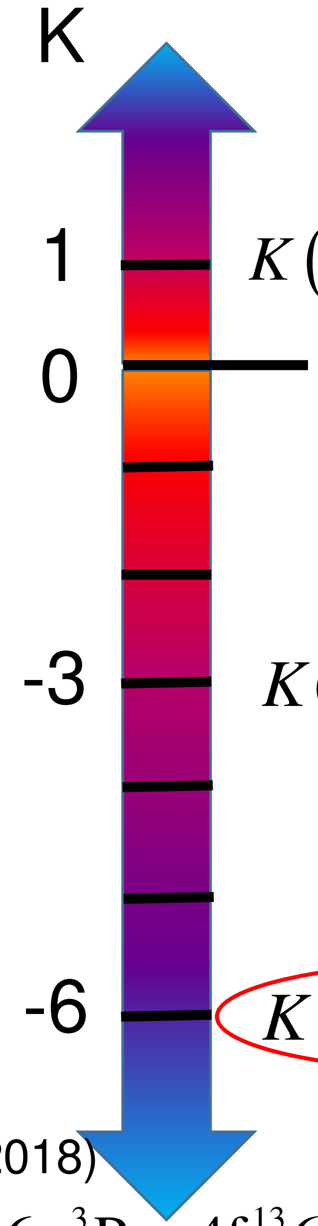
100

Test of α-variation

10^{-20}

Easier to measure large effects!

Enhancement (sensitivity) factor K for clocks



$K(Sr^{+}) = 0.4$

$K(Yb) = 0.3$

$K(Hg) = 0.8, \quad K(Yb^{+}E2) = 1$

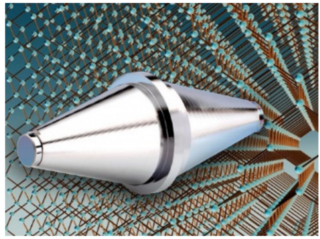
$K(Al^{+}) = 0.01, \; K(Sr) = 0.06, \; K(Ca^{+}) = 0.1$

$K(Hg^{+}) = -2.9$

$K(Yb^{+}E3) = -6$

Safronova et al., PRL120, 173001 (2018)

$K(Yb \;\; 4f^{14}6s6p\,^{3}P_{0} \text{ - } 4f^{13}6s^{2}5d\,) = 15$



Cavity K=1

Effective Sr/cavity K=1

$$\boxed{\frac{\partial}{\partial t}\ln\frac{\nu_2}{\nu_1} = (K_2 - K_1)\frac{1}{\alpha}\frac{\partial \alpha}{\partial t}}$$

Future clocks:

$K(Cf^{15+}/Cf^{17+}) \approx 110$

Nuclear clock $K = ?$

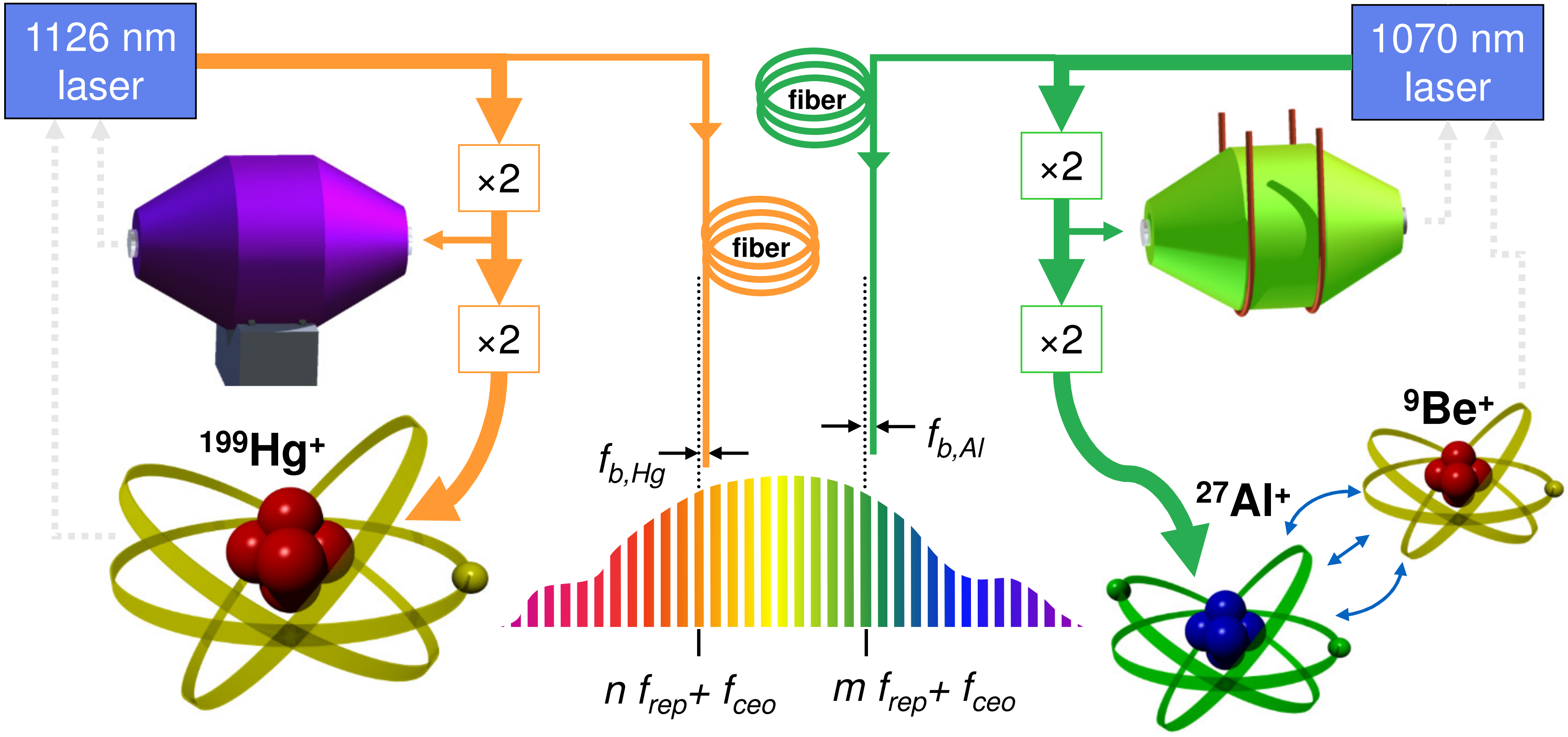
Observable: ratio of two clock frequencies

Measure a ratio of Al^+ clock frequency to Hg^+ clock frequency

$$\frac{\nu\left(Hg^+\right)}{\nu\left(\mathrm{Al}^+\right)}$$

$K(Hg^+) = -2.9$ Sensitivity factors

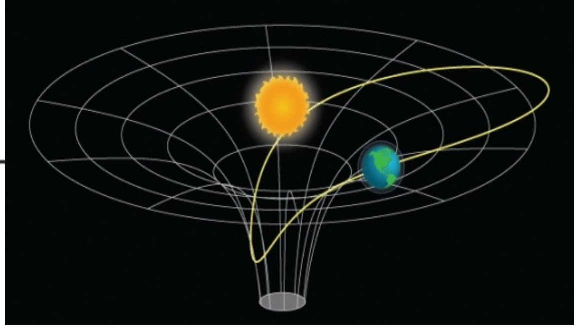
$K\left(Al^+\right) = 0.01$ Not sensitive to α-variation, used as reference



Picture credit: Jim Bergquist

Science 319, 1808 (2008)

PHYSICAL REVIEW LETTERS **126,** 011102 (2021)



Best limit on slow drifts of fundamental constants

Improved Limits for Violations of Local Position Invariance from Atomic Clock Comparisons

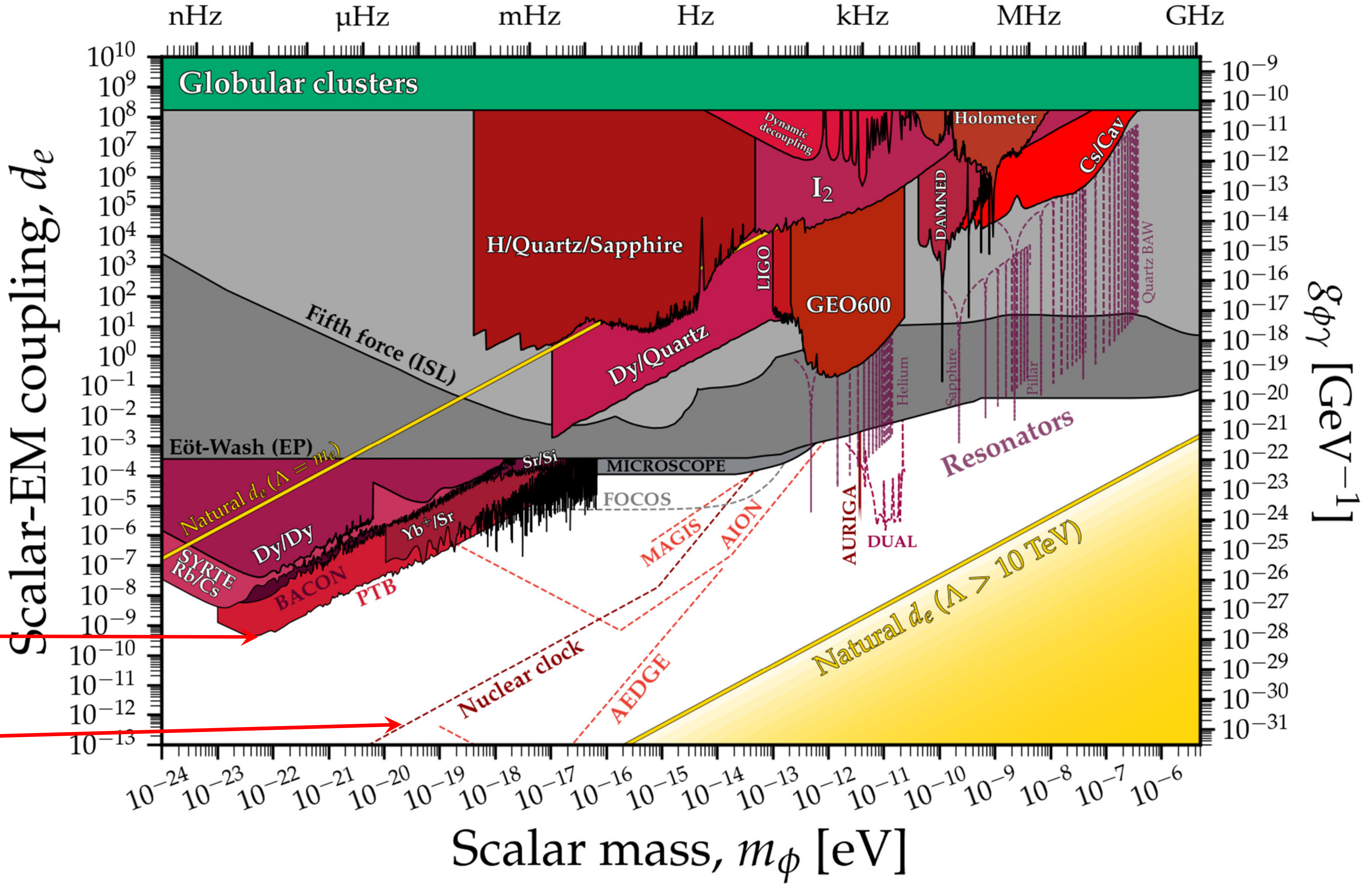
R. Lange, N. Huntemann,* J. M. Rahm, C. Sanner,† H. Shao, B. Lipphardt, Chr. Tamm, S. Weyers, and E. Peik
Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

(Received 13 October 2020; revised 23 November 2020; accepted 15 December 2020; published 6 January 2021)

We compare two optical clocks based on the ${}^2S_{1/2}(F=0) \rightarrow {}^2D_{3/2}(F=2)$ electric quadrupole (E2) and the ${}^2S_{1/2}(F=0) \rightarrow {}^2F_{7/2}(F=3)$ electric octupole (E3) transition of ${}^{171}\mathrm{Yb}^+$ and measure the frequency ratio $\nu_{\mathrm{E3}}/\nu_{\mathrm{E2}} = 0.932829404530965376(32)$, improving upon previous measurements by an order of magnitude. Using two caesium fountain clocks, we find $\nu_{E3} = 642121496772645.10(8)$ Hz, the most accurate determination of an optical transition frequency to date. Repeated measurements of both quantities over several years are analyzed for potential violations of local position invariance. We improve by factors of about 20 and 2 the limits for fractional temporal variations of the fine structure constant α to $1.0(1.1) \times 10^{-18}/\mathrm{yr}$ and of the proton-to-electron mass ratio μ to $-8(36) \times 10^{-18}/\mathrm{yr}$. Using the annual variation of the Sun's gravitational potential at Earth Φ, we improve limits for a potential coupling of both constants to gravity, $(c^2/\alpha)(d\alpha/d\Phi) = 14(11) \times 10^{-9}$ and $(c^2/\mu)(d\mu/d\Phi) = 7(45) \times 10^{-8}$.

$$\Delta\Phi/c^2 \approx 1.65 \times 10^{-10}$$

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



Present clock limits

Projected clock limits

arXiv:2203.14915

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

nature physics

LETTERS

PUBLISHED ONLINE: 17 NOVEMBER 2014 | DOI: 10.1038/NPHYS3137

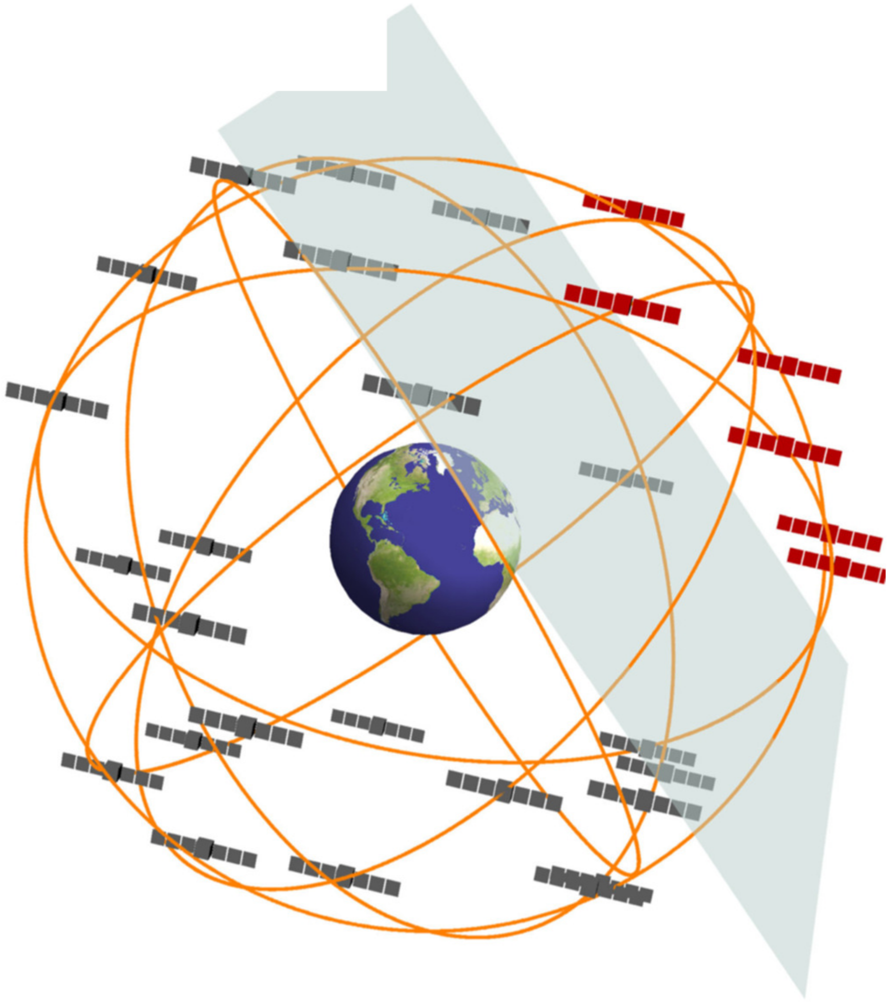
Transient variations

Hunting for topological dark matter with atomic clocks

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

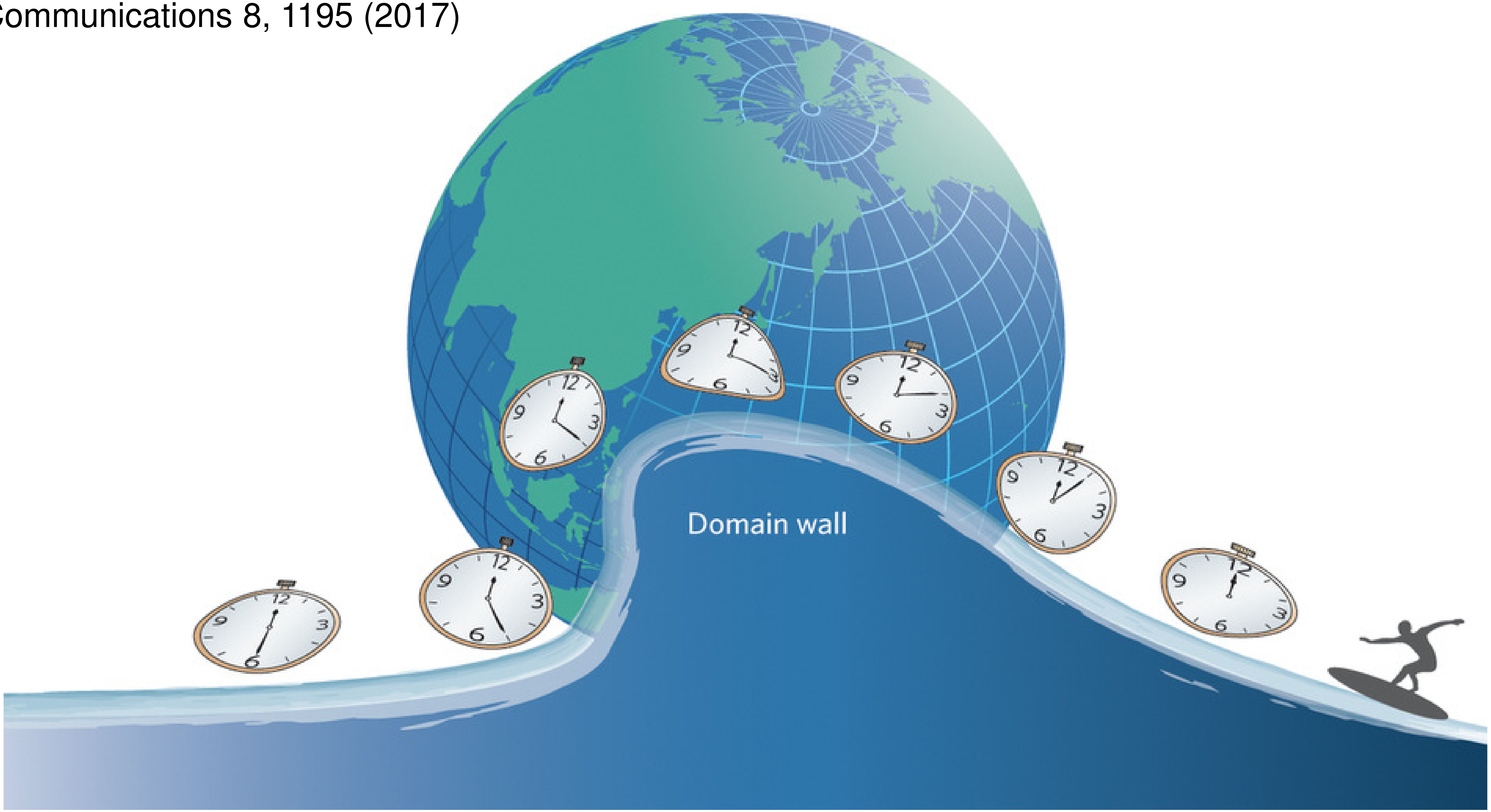
Dark matter clumps: point-like monopoles, one-dimensional strings or two-dimensional sheets (domain walls).

If they are large (size of the Earth) and frequent enough they may be detected by measuring changes in the synchronicity of a global network of atomic clocks, such as the Global Positioning System.



GPM.DM collaboration: Roberts at el., Nature Communications 8, 1195 (2017)

Nature Communications 8, 1195 (2017)

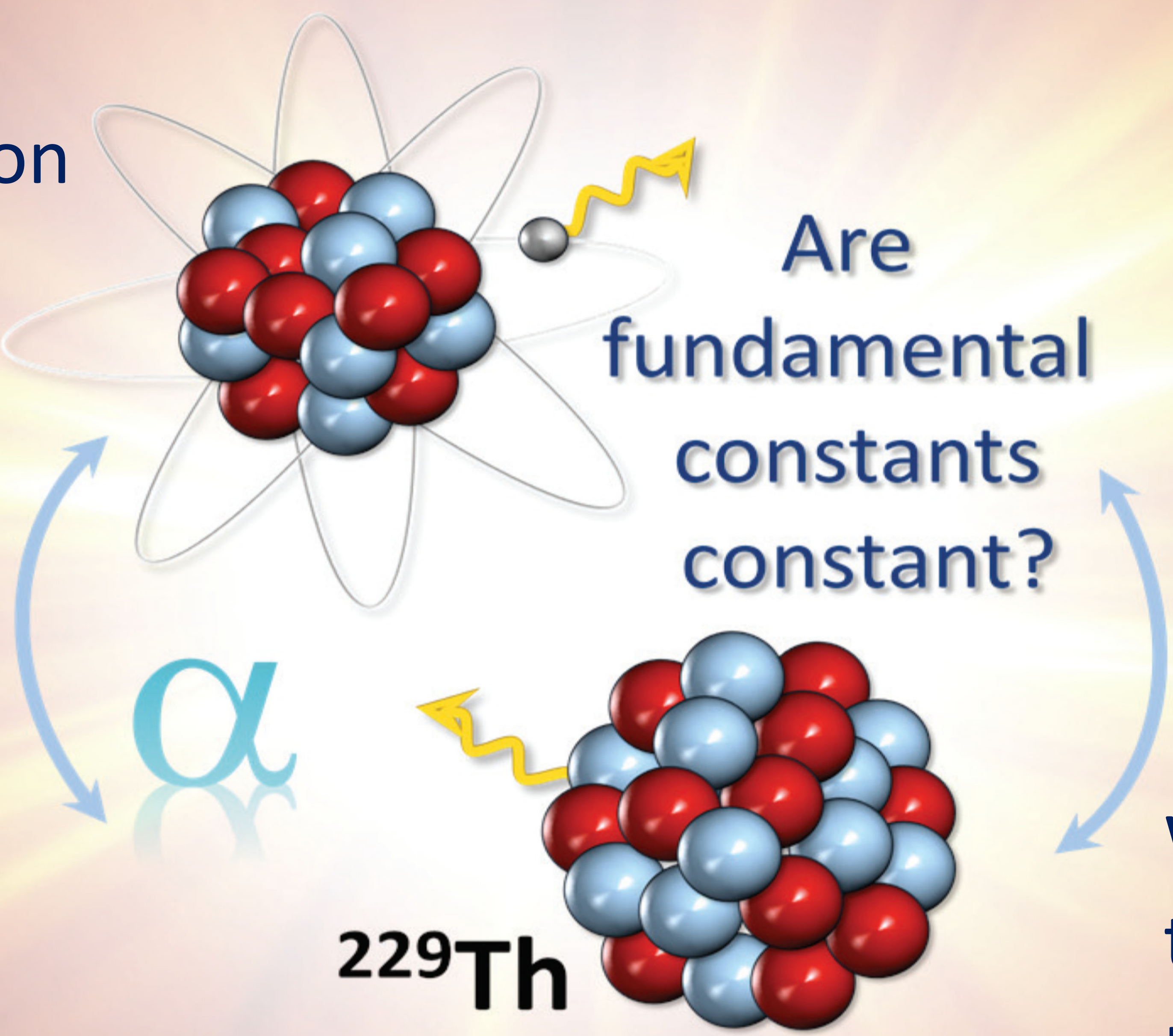


Topological dark matter may be detected by measuring changes in the synchronicity of a global network of atomic clocks, such as the Global Positioning System, as the Earth passes through the domain wall.

Rana Adhikari, Paul Hamiton & Holger Müller, Nature Physics 10, 906 (2014)

FROM ATOMIC TO NUCLEAR CLOCKS!

Clock based on transitions in atoms



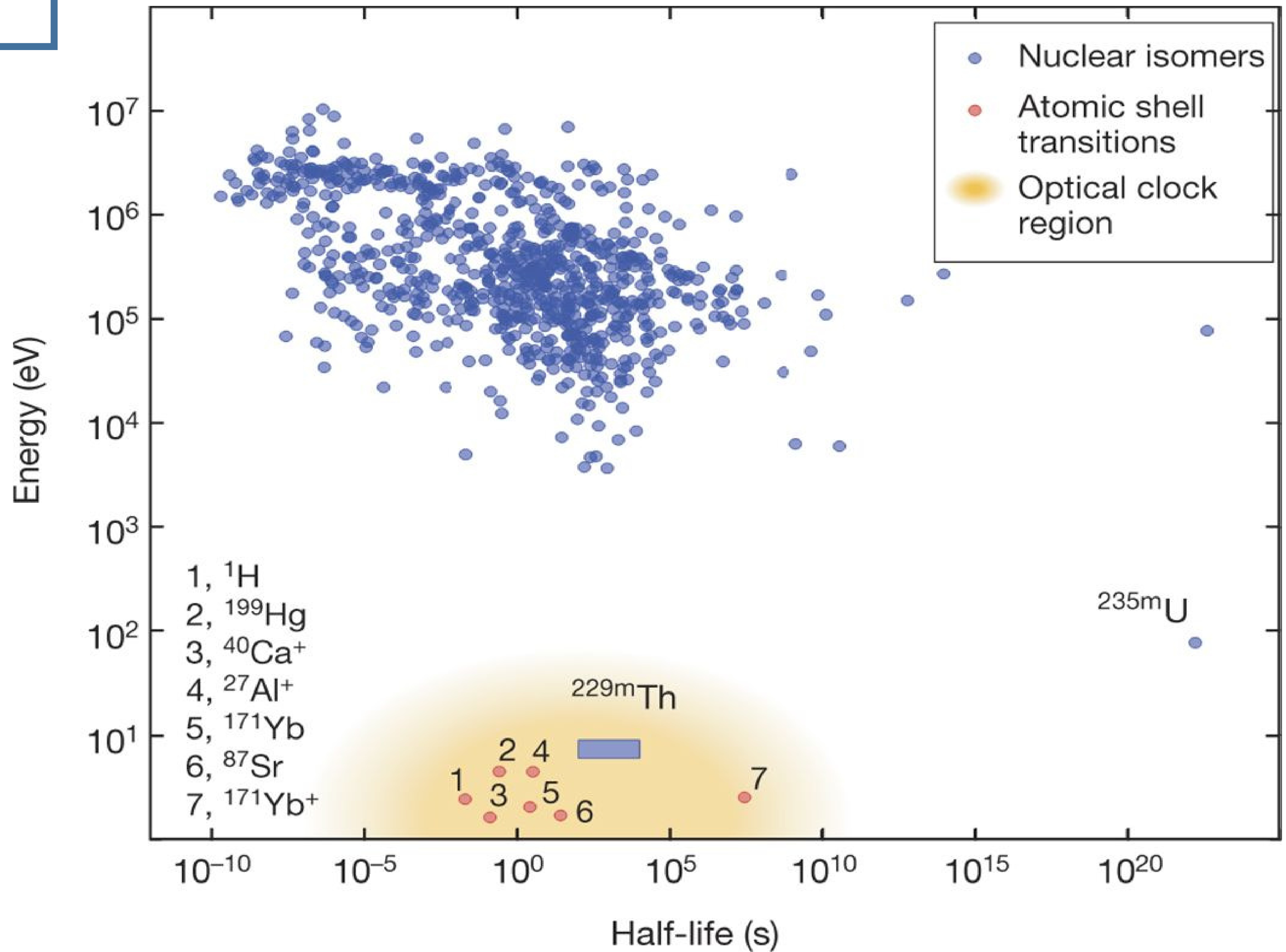
What about transitions in nuclei?

M. S. Safronova, Annalen der Physik 531, 1800364 (2019)

Nuclear clock

Obvious problem: typical nuclear energy levels are in MeV

Six orders of magnitude from ~few eV we can access by lasers!

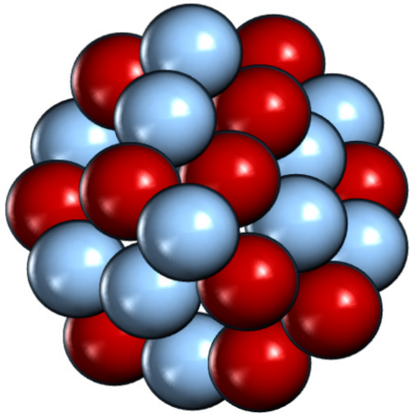


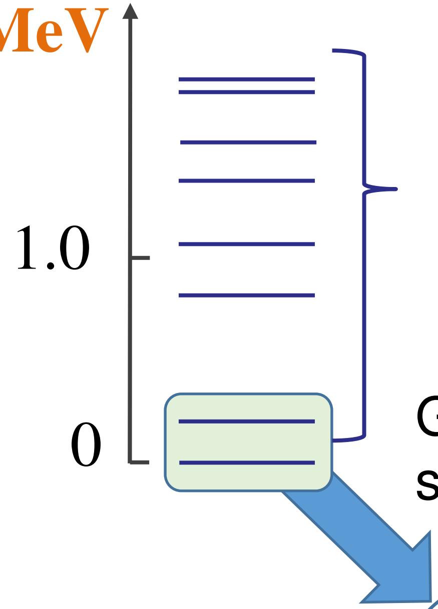
Nature 533, 47 (2016)

Obvious problem: typical nuclear energy levels are in MeV

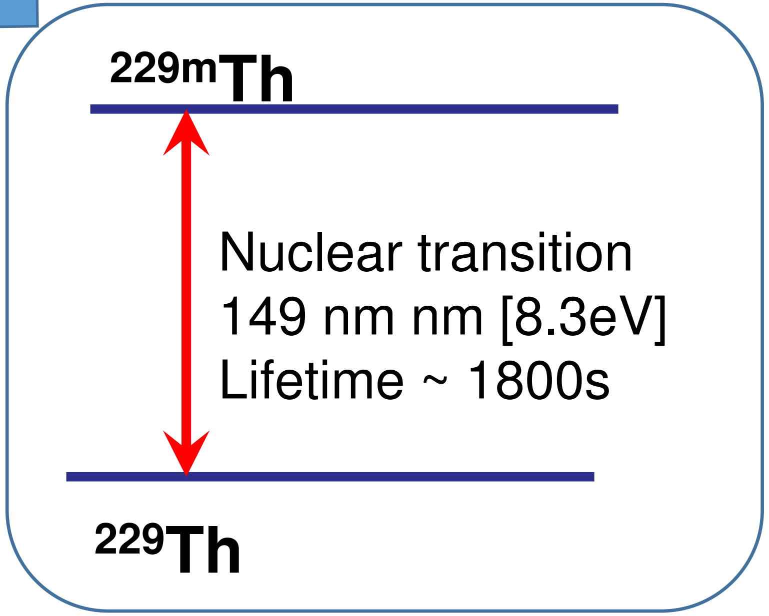
Six orders of magnitude from ~few eV we can access by lasers!

Atomic Nucleus





Only ONE exception!



Review & ERC Synergy project plan:

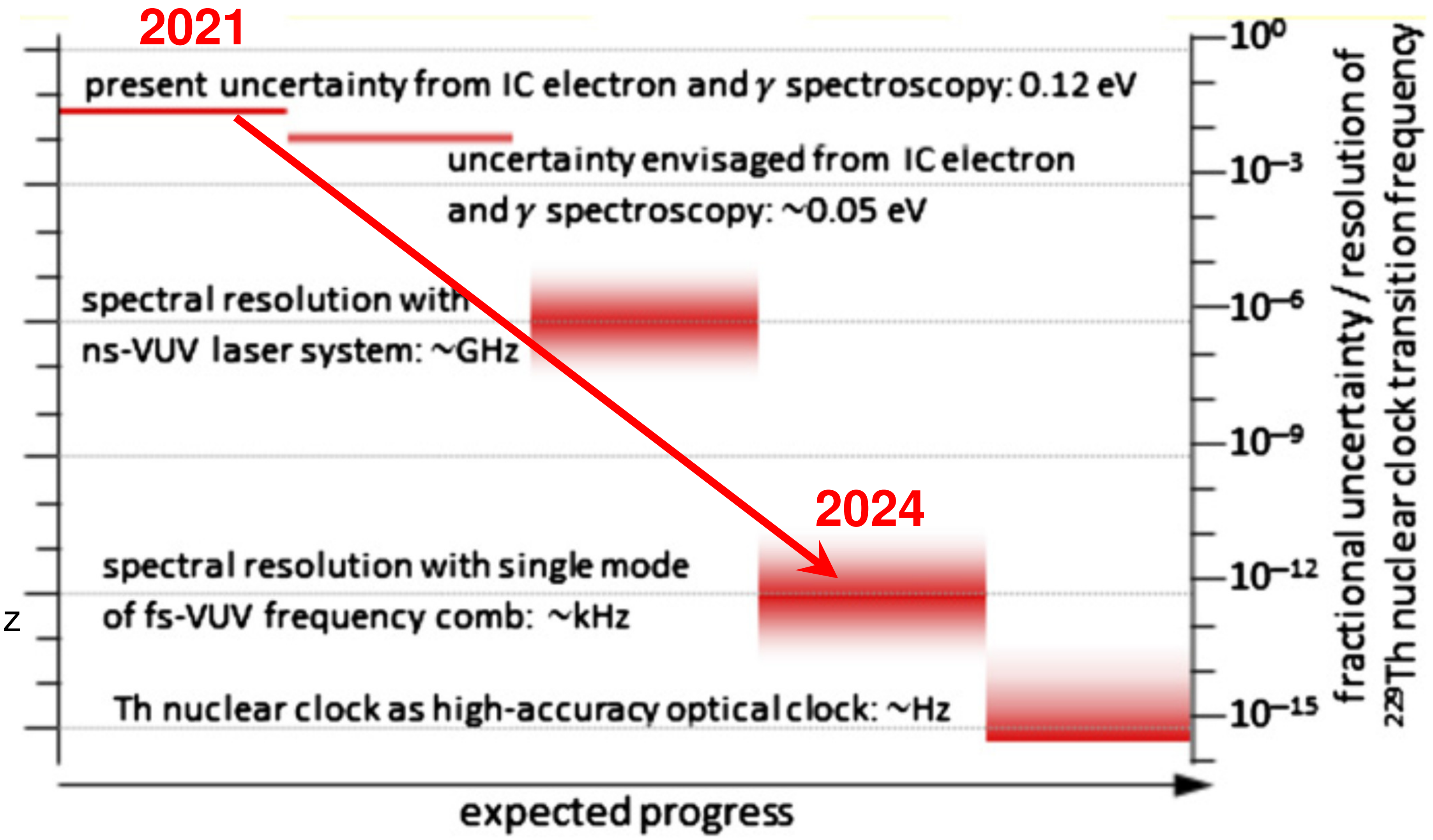
E. Peik, T. Schumm, M. S. Safronova, A. Pálffy, J. Weitenberg, and P. G. Thirolf, Quantum Science and Technology 6, 034002 (2021).

How to build a nuclear clock?

Nature 617, 706 (2023)

PRL 132, 182501 (2024)
PRL 133, 013201 (2024)

Nature 633, 63 (2024)
2 020 407 384 335(2) kHz

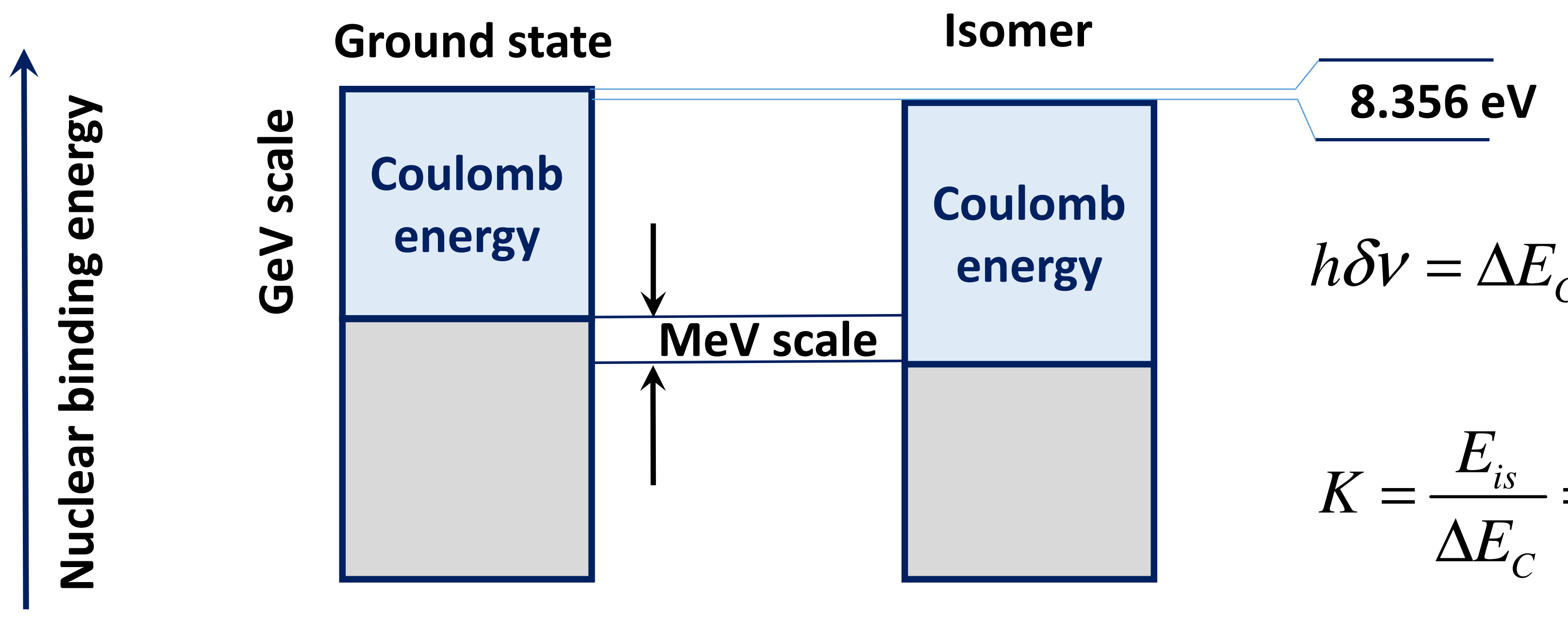


Quantum Science and Technology 6, 034002 (2021)

^{229}Th: very high sensitivity to variation of fundamental constants

"Unlikely cancellation" argument

V. V. Flambaum,
PRL 97, 092502 (2006)



Sensitivity to α variation

$$h\delta\nu = \Delta E_C \frac{\delta\alpha}{\alpha} \qquad \frac{\delta\nu}{\nu} = K\frac{\delta\alpha}{\alpha}$$

$$K = \frac{E_{is}}{\Delta E_C} = \frac{8.356\,eV}{\Delta E_C \approx MeV} \approx 10^5$$

Too much cancellation to compute Coulomb energy difference accurately enough:

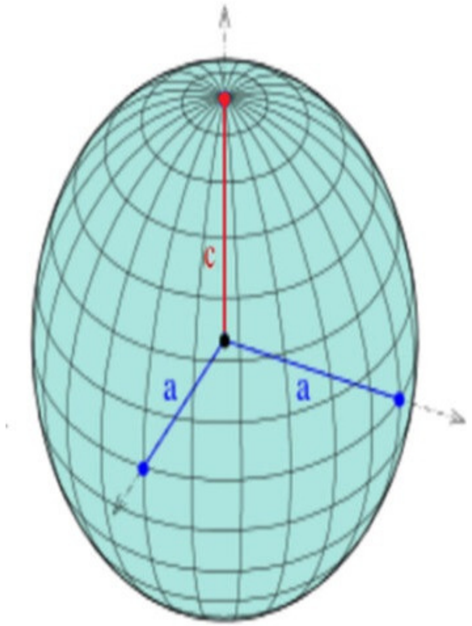
SkM∗ (HFB) model gave the Coulomb energy difference V_C = −0.307 MeV = (924.854 – 925.161) MeV
SIII (HFB) gave V_C = 0.001 MeV.

Elena Litvinova, Hans Feldmeier, Jacek Dobaczewski, and Victor Flambaum, Phys. Rev. C 79, 064303 (2009)

How to extract Coulomb energy difference from nuclear properties

J. C. Berengut, V. A. Dzuba, V. V. Flambaum, and S. G. Porsev, Phys. Rev. Lett. 102, 210801 (2009)

Geometric model: assume that both the ground state nucleus and the lowest-energy isomer are uniform, hard-edged, prolate ellipsoids. **Goal: express Coulomb energy vis observables nuclear properties.**



Prolate

$$e^2 = 1 - \frac{a^2}{c^2}$$

$$\langle r^2 \rangle = \int r^2 \rho(r) d^3 r = \frac{1}{5}\left(2a^2 + c^2\right)$$

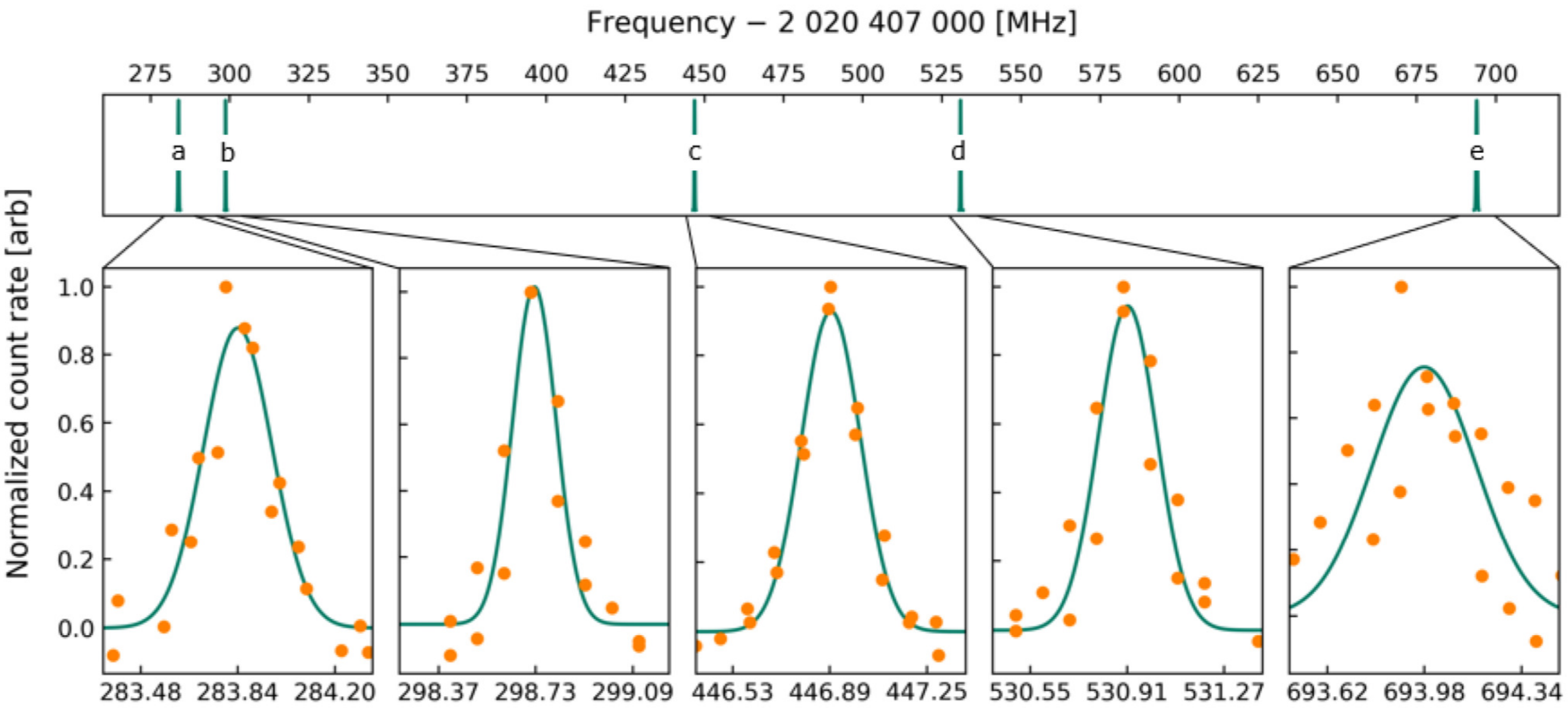
$$Q_0 = 2\int r^2 P_2(\cos\theta)\rho(r) d^3 r = \frac{2}{5}\left(c^2 - a^2\right)$$

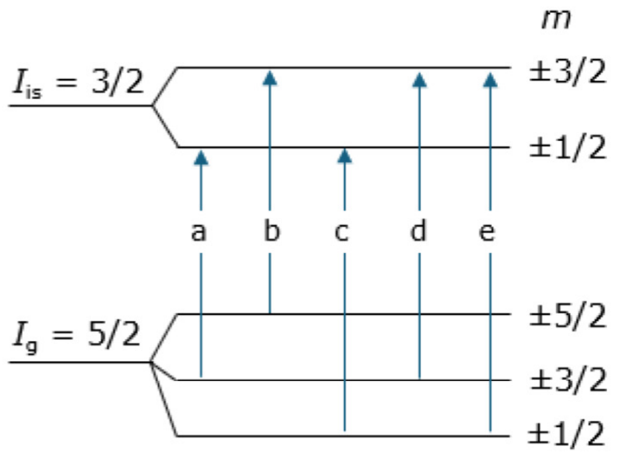
Use these expression to express a, c, and e via Q_0 and $\langle r^2 \rangle$ and compute Coulomb energy for ground state and isomer.

Coulomb energy: $$E_C = \frac{3}{5}\frac{q_e^2 Z^2}{R_0}\frac{\left(1-e^2\right)^{1/3}}{2e}\ln\left(\frac{1+e}{1-e}\right)$$

R_0 is the equivalent sharp spherical radius $R_0^3 = a^2 c$

Direct spectroscopic measurement of nuclear electric quadrupole structure





m_g	m_{is}	ν_{Th} [MHz]
3/2	1/2	2 020 407 283.847(4)
5/2	3/2	2 020 407 298.727(4)
1/2	1/2	2 020 407 446.895(4)
3/2	3/2	2 020 407 530.918(4)
1/2	3/2	2 020 407 693.98(2)

Result: measured ratio of the quadrupole moments is $Q_{is} / Q_g = 0.57003(2)$

Chuankun Zhang, Tian Ooi, Jacob S. Higgins, Jack F. Doyle, Lars von der Wense, Kjeld Beeks, Adrian Leitner, Georgy Kazakov, Peng Li, Peter G. Thirolf, Thorsten Schumm, Jun Ye, Nature 633, 63-70 (2024).

Calculation of Coulomb energy difference between ground state and isomer

$$\Delta E_C = \left\langle r^2 \right\rangle \frac{\partial E_C}{\partial \left\langle r^2 \right\rangle} \frac{\Delta \left\langle r^2 \right\rangle}{\left\langle r^2 \right\rangle} + Q_0 \frac{\partial E_C}{\partial Q_0} \frac{\Delta Q_0}{Q_0}$$

$$\Delta E_C = -485\,\mathrm{MeV} \frac{\Delta \left\langle r^2 \right\rangle}{\left\langle r^2 \right\rangle} + 11.3\,\mathrm{MeV} \left(\frac{Q_0^m}{Q_0} - 1 \right)$$

$$\left\langle r^2 \right\rangle := 5.756(14)^2$$

Angeli, K.P. Marinova, Atomic Data and Nuclear Data Tables 99, 69 (2013)

$$\Delta \left\langle r^2 \right\rangle = 0.0105(13)\mathrm{fm}^2$$

J. Thielking, M. V. Okhapkin, P. Głowacki, D.-M. Meier, L. von der Wense, B. Seiferle, C. E. Düllmann, P. G. Thirolf, and E. Peik, Nature (London) 556, 321 (2018).

M. S. Safronova, S. G. Porsev, M. G. Kozlov, J. Thielking, M. V. Okhapkin, P. Głowacki, D. M. Meier, and E. Peik, Phys. Rev. Lett. 121, 213001 (2018).

$$Q_{lab} = 3.11(2)\mathrm{eb}$$

S.G. Porsev, M.S. Safronova, M.G. Kozlov, Phys. Rev. Lett.127, 253001 (2021).
C. J. Campbell, A. G. Radnaev, and A. Kuzmich, Phys. Rev. Lett. 106, 223001 (2011)

$$\frac{Q_0^m}{Q_0} = 1.017912(17)$$

Chuankun Zhang, Tian Ooi, Jacob S. Higgins, Jack F. Doyle, Lars von der Wense, Kjeld Beeks, Adrian Leitner, Georgy Kazakov, Peng Li, Peter G. Thirolf, Thorsten Schumm, Jun Ye, Nature 633, 63 (2024). *Recalculated from the ratio of lab moments.

ESTIMATING SENSITIVITY OF TH NUCLEAR CLOCK TO α-VARIATION

$$\Delta E_C = -0.154(19)\,\mathrm{MeV} + 0.203(4)\,\mathrm{MeV} = 0.049(19)\,\mathrm{MeV}$$

$$K = \frac{\Delta E_C}{8.356\,\mathrm{eV}} = \underbrace{-18400(2300)}_{\langle r^2 \rangle\ \text{term}} + \underbrace{24300(400)}_{Q_0\ \text{term}} = 5900(2300)$$

Beeks at al., arXiv:2407.17300 (2024)

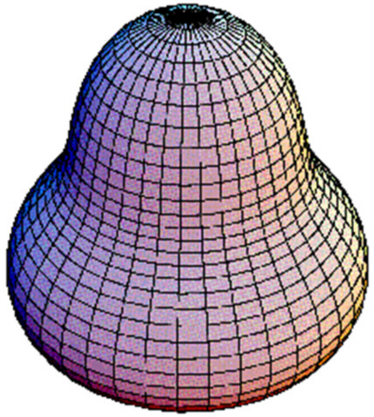
Why the value obtained using constant volume approximation [Pavel Fadeev, Julian C. Berengut , and Victor V. Flambaum, PRA 102, 052833 (2020)] predicted wrong quadrupole moment change and K=-8200(2500)?

We tested how the effect of a very small 0.06% volume change affects that ΔQ/Q: using

$V = 1.0055 \times V^m$ we get $\frac{\Delta Q_0}{Q_0} = 0.0179$ and with $V = V^m$ we get $\frac{\Delta Q_0}{Q_0} = 0.0075(20)$

Therefore, change in the quadrupole moment is extremely sensitive to the change in volume and it can not be used to compute K.

Octupole deformation



$$r(\theta) = R_s\left[1+\sum_{n=1}^{N}\beta_n Y_{no}(\theta)\right]$$

β_n are deformation parameters and $Y_{n0}(\theta)$ are spherical harmonics

R_s is defined by normalizing the volume to that of the spherical nucleus with equivalent sharp spherical radius R_0,

$$\int r\rho(r)\, d^3r = 1$$

For a pear shaped nucleus with quadrupole and octupole deformation, N = 3.

The Coulomb energy is given by

$$E_C = \frac{3}{5}\frac{q_e^2 Z^2}{R_0}\left(1-\frac{1}{4\pi}\beta_2^2-\frac{5}{14\pi}\beta_3^2\right)$$

The nuclear properties are related to the β coefficients via rms and Q_0 formulas

β_2 and β_3 are the quadrupole and octupole deformations, $O(\beta^3_n)$ terms are omitted.

$$K = 6300(2300)$$

What if octupole deformation changes?

Model changing octupole deformation between ground state and isomer:

Change in β_3 between isomer and ground state

$$1\% \rightarrow \Delta K = 2800$$
$$3\% \rightarrow \Delta K = 8600$$
$$5\% \rightarrow \Delta K = 14500$$

$$K = 6300+2800=9100$$
$$K = 6300 - 2800 = 3500$$

Larger β_3 of the isomer gives a positive change in K.
In this case, K will increase.

Estimate electric octupole moment $Q_{30} = 2\int r^3(\theta)P_3(\cos\theta)\rho(r)d^3r = 35 - 44\ \text{fm}^3$

β_2=0.22 obtained from experimental data, β_3 =0.11 - 0.145 from PRC 103, 014313 (2021)

Conclusions

- Need to measure <r^2> difference better
- Need to know at least the sign of the change in octupole deformation from ground state to isomer
- Higher moments can also be important! Charge distributions is important
- Need better model that can relate experimental quantities to Coulomb energy difference

Next decade of space research

What quantum technologies will be sent to space?

What new physics can one search for in space better then on Earth?

NASA Decadal Survey: Biological and Physical Sciences in Space
https://science.nasa.gov/biological-physical/decadal-survey
May 2023: Establishment of NASA Fundamental Physics Analysis group
https://www.jpl.nasa.gov/go/funpag

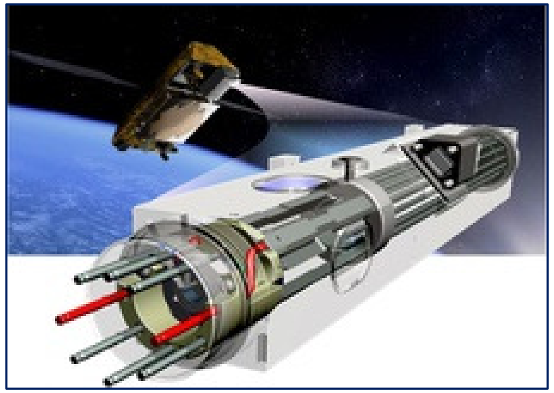
Europe: Community workshop on cold atoms in space (September 2021)
Cold Atoms in Space: Community Workshop Summary and Proposed Road-Map, Alonso et al., EPJ Quantum Technology 9, 1 (2022)

Image credits: NASA, ESA

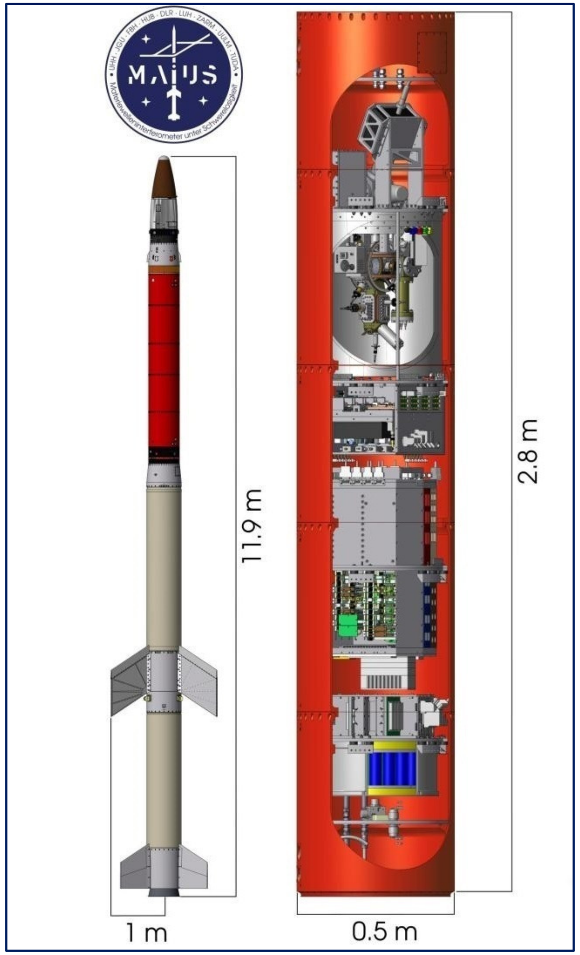
QUANTUM TECHNOLOGIES IN SPACE

GPS, “hot” atoms, Microwave, Cs or Rb

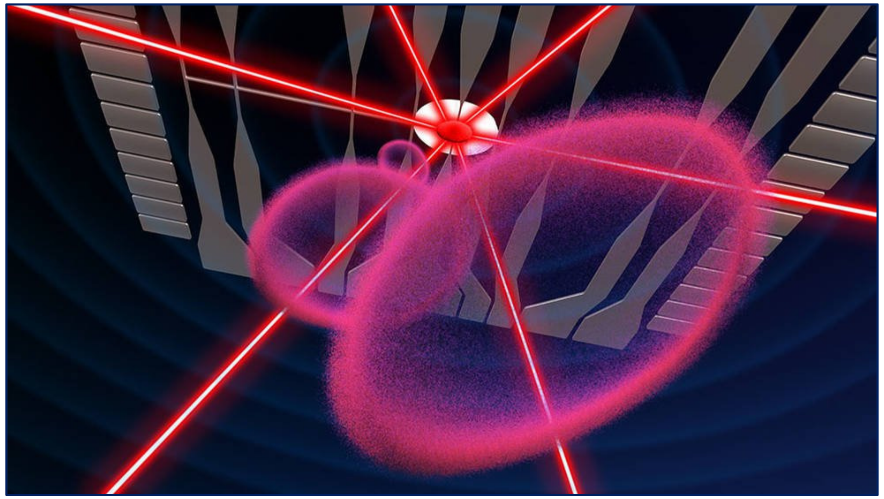
2017 CACES (Tiangong-2), China, microwave Rb cold atom clock



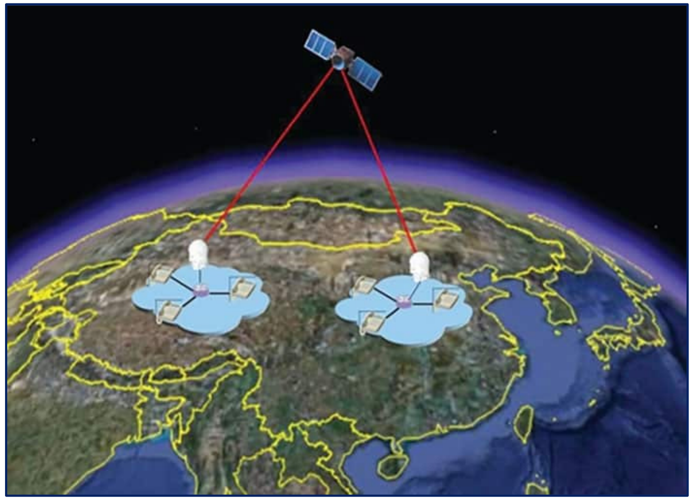
2019 NASA Deep Space Atomic Clock (DSAC), microwave, Hg^+ ions



2016 MAUS-1 sounding rocket, cold Rb atoms, BEC, atom interferometry, DLR



2018, Cold Atom Lab, ISS, NASA



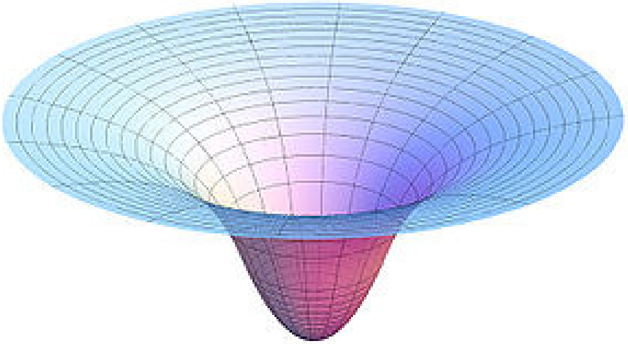
2016 QUESS, Entanglement distribution, China

Image credits: JPL, NASA, CMSE, NSSC, DLR/Leibnitz, University of Hannover

Why to search for new physics in space?

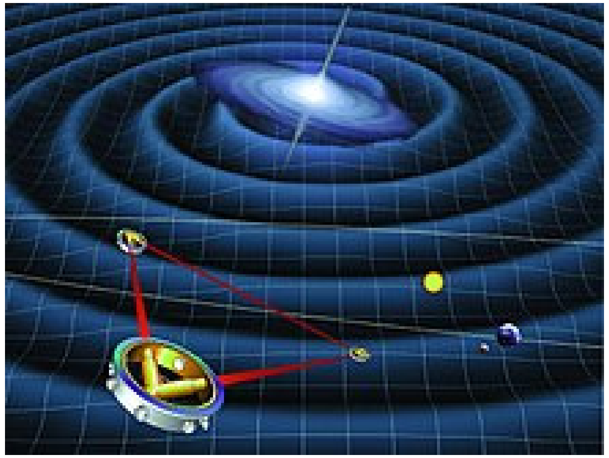
Quantum sensors in space enables discovery of new physics not possible on Earth
Many orders of magnitude improvements or principally different experiments are possible

Need to be away from Earth surface

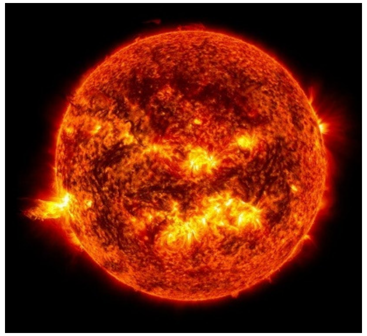


Tests of gravity are hindered by Earth gravity
Optical time transfer to link Earth clocks
Dark energy and some dark matter (screening)
Tests of fundamental postulates (WEP, LLI)

Need access to **variable gravitational potentials**



Long baselines: gravitational waves, dark matter (especially transients), dark energy



Sun: Dark matter halo bound to the Sun?
Extreme overdensities possible

Moon: laser ranging, low seismic activity, permanent cryogenic environment

Asteroids: test masses

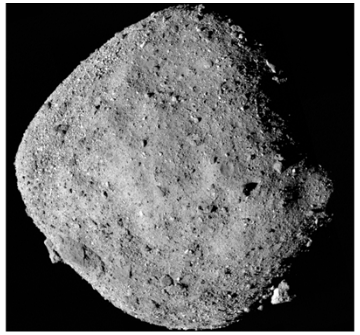
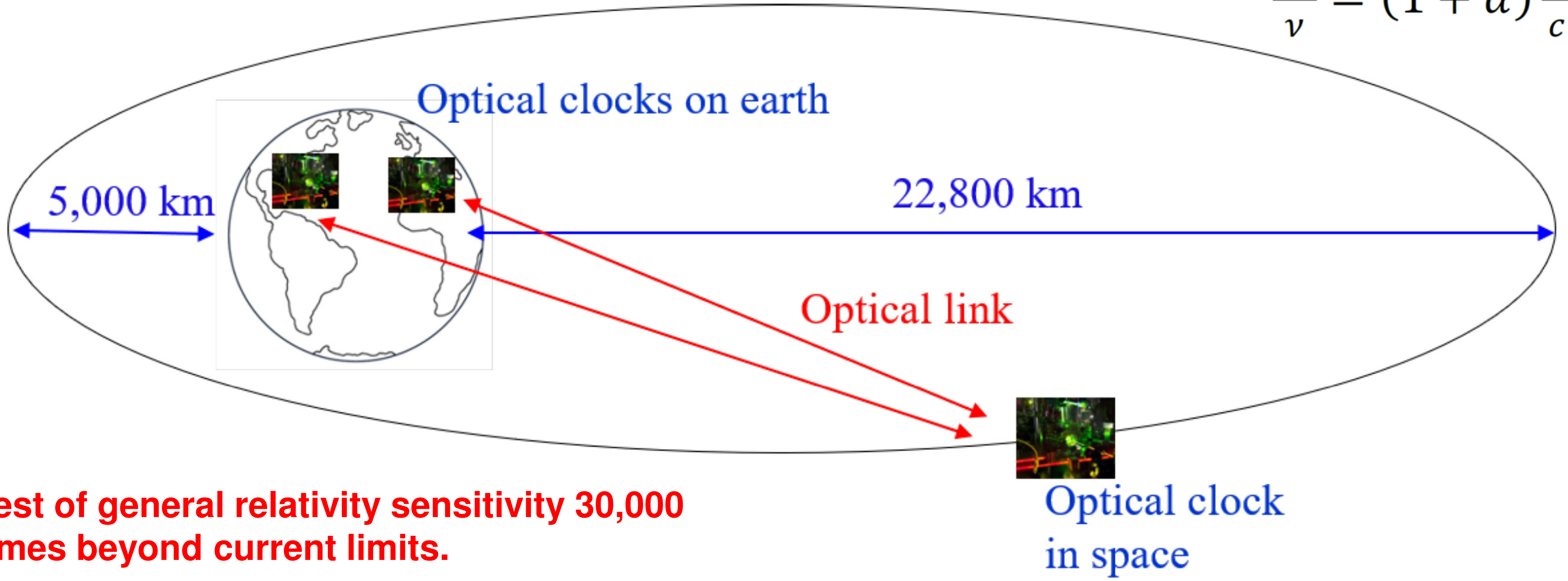


Image credits:
NASA, Wikipedia

Fundamental Physics with a State-of-the-Art Optical Clock in Space

Andrei Derevianko, Kurt Gibble, Leo Hollberg, Nathan R. Newbury, Chris Oates, Marianna S. Safronova, Laura C. Sinclair, Nan Yu, Quantum Sci. Technol. 7, 044002 (2022)

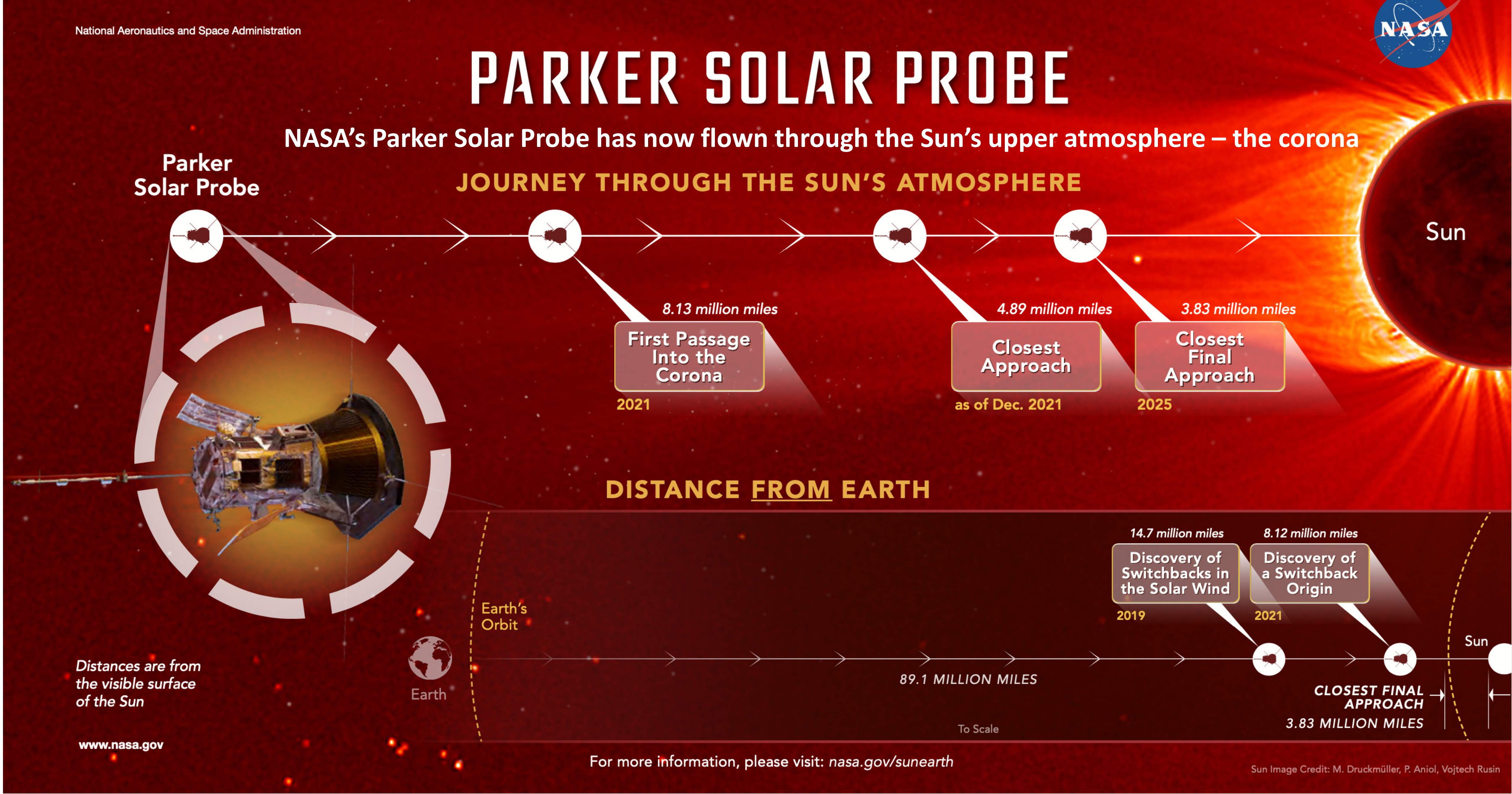
$$\frac{\Delta \nu}{\nu} = (1+\alpha)\frac{\Delta U}{c^2}$$



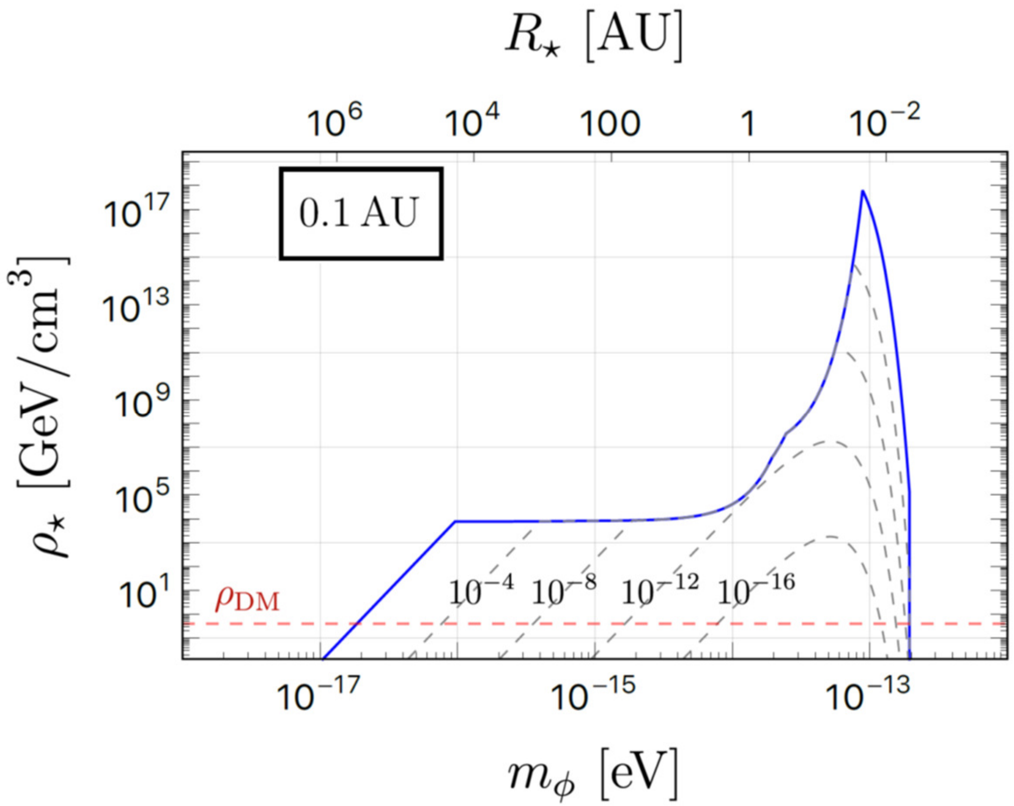
Test of general relativity sensitivity 30,000 times beyond current limits.

Schematic of the proposed mission to test Fundamental physics with an Optical Clock Orbiting in Space (FOCOS)

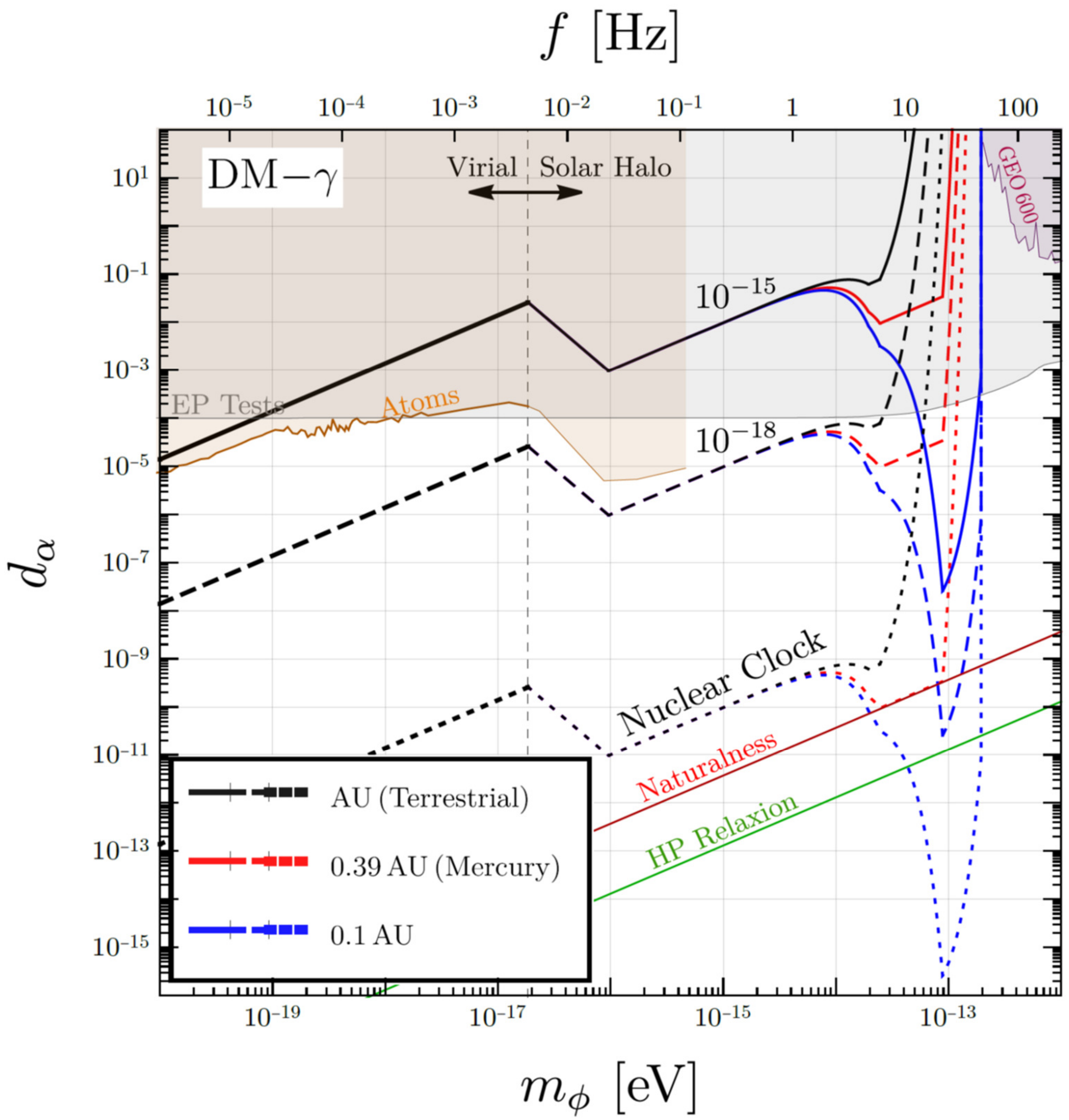
Image credit: NASA's Goddard Space Flight Center/Mary P. Hrybyk-Keith



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).

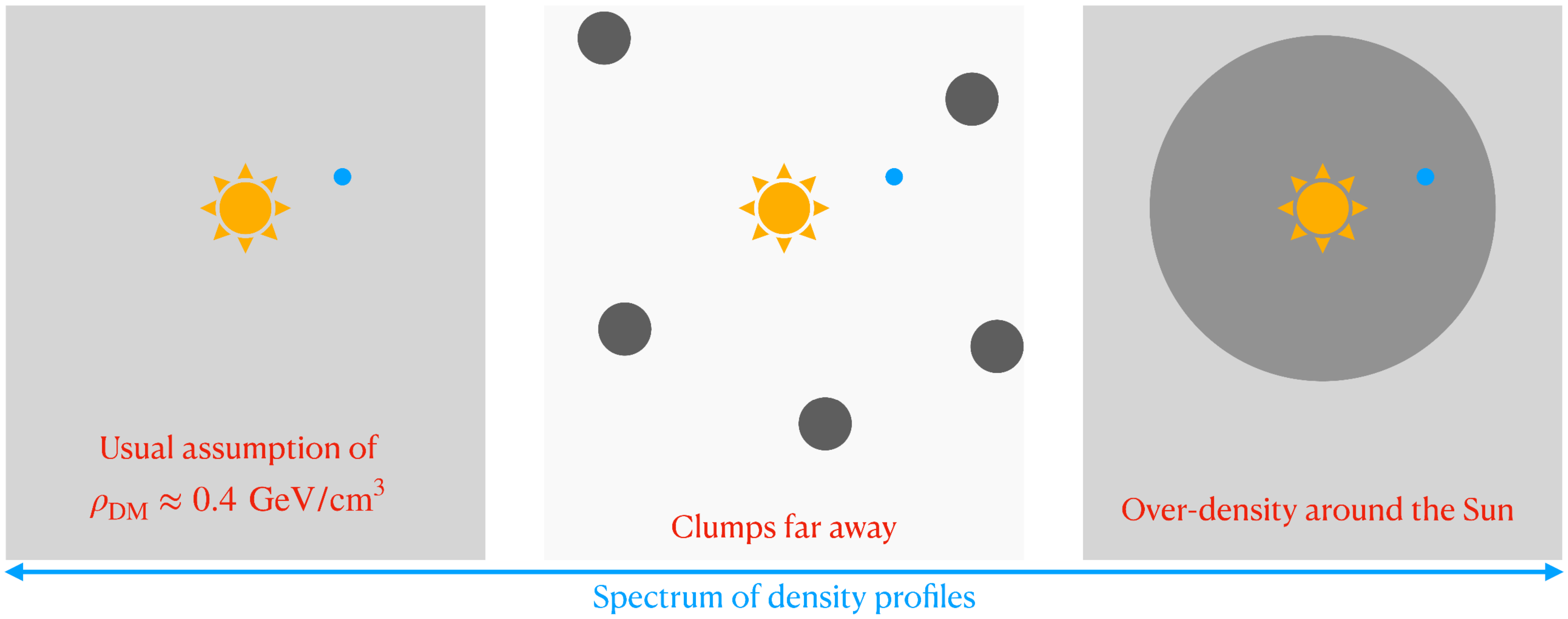


Estimated sensitivity reaches for ultralight dark matter (linear coupling) and bound to the Sun.

The blue, red, and black denote sensitivity for probes at the **distance of 0.1 AU**, probes at the orbit of Mercury, and for terrestrial clocks, respectively

Transient dark matter signals

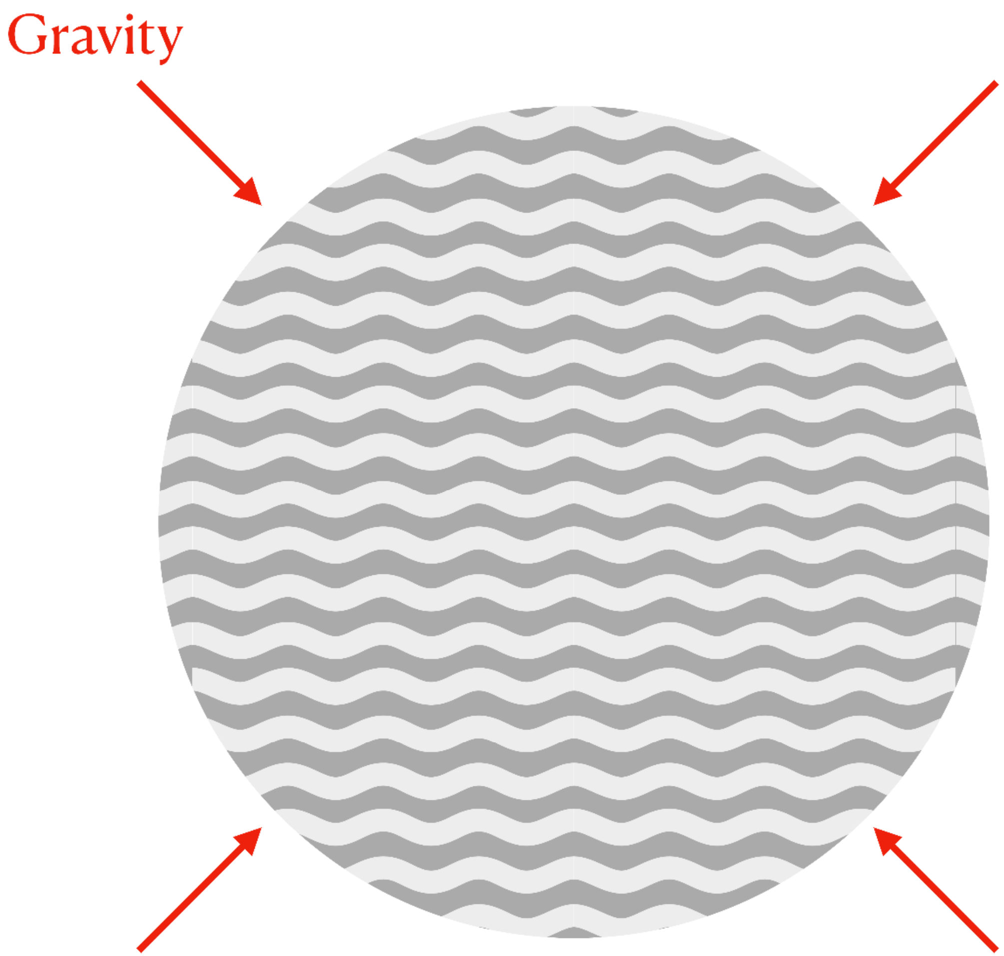
Beyond “dark matter blob” model



Picture credit: Jason Arakawa

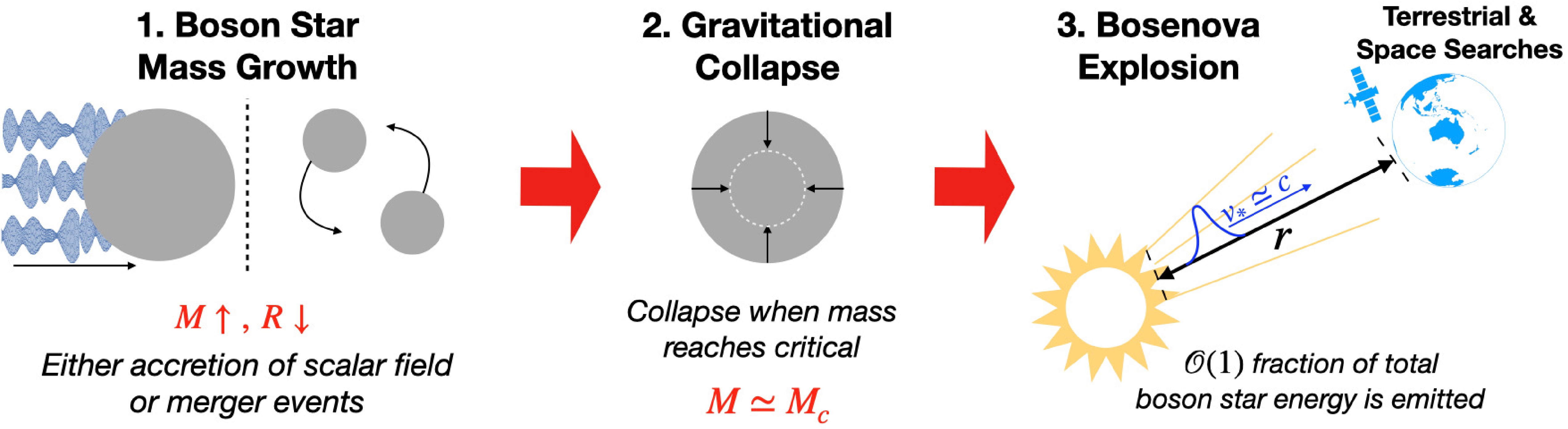
Compact dark matter objects
Bound states of ultralight dark matter

- ULDM can form gravitationally bound states$\rightarrow$ *Boson Stars*
- After reaching a critical mass, boson stars can explode
- We will be interested in these explosions



Picture credit: Jason Arakawa

Transient dark matter signals: Boson star explosions and bosenova

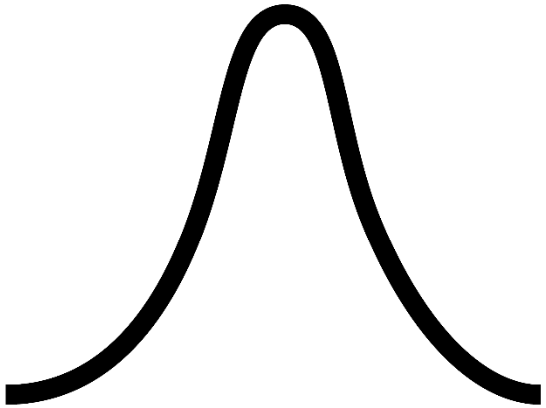


Detection of Relativistic Scalar Bursts with Quantum Sensors, Jason Arakawa, Joshua Eby, Marianna S. Safronova, Volodymyr Takhistov, and Muhammad H. Zaheer, Phys. Rev. D 110, 075007 (2024).

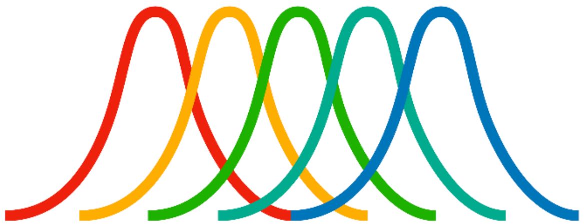
Coherence and wave spreading

Discrete Momentum Mode Example

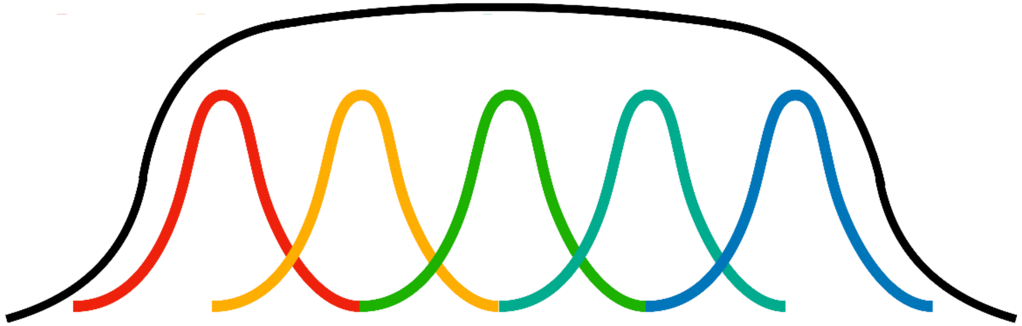
At Source
(Boson star)



Wave spreading:
Higher frequency modes
move faster



At Detector



Emitted momentum:

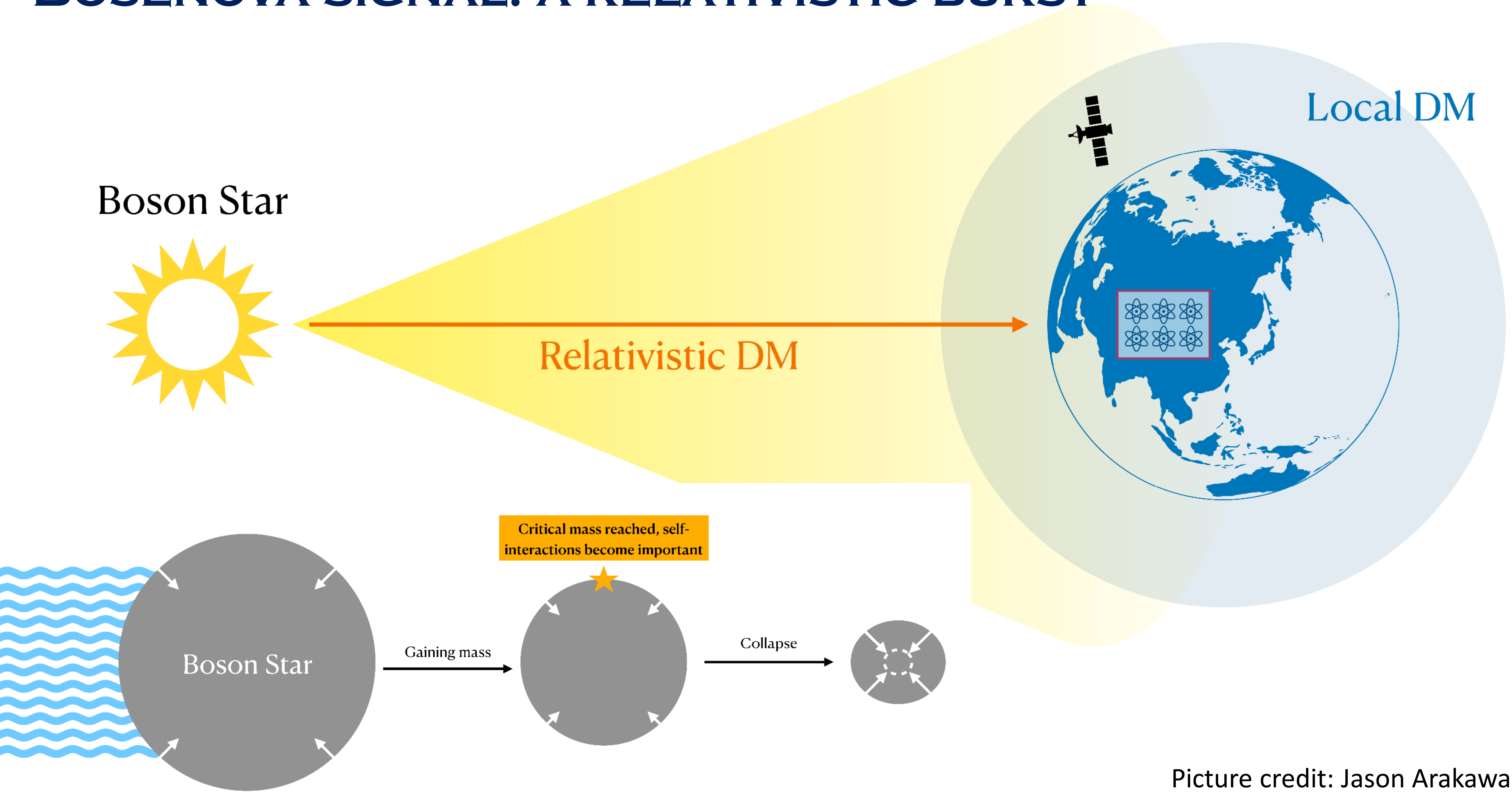
$$p_{\text{peak}} \sim \text{few} \times m_\phi$$

At Earth:

$$t_{\text{signal}} \sim \text{months to years}$$

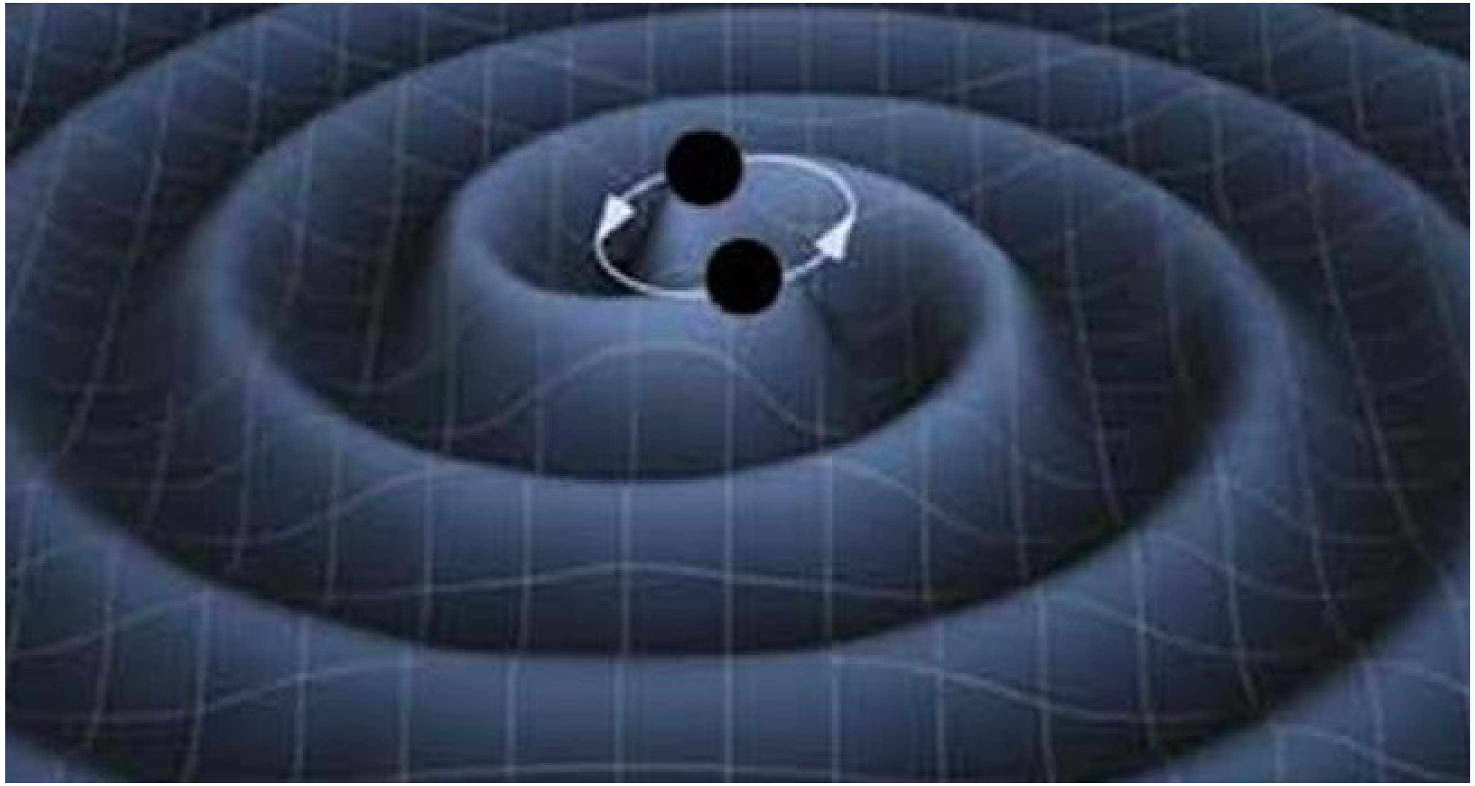
Slide credit: Jason Arakawa

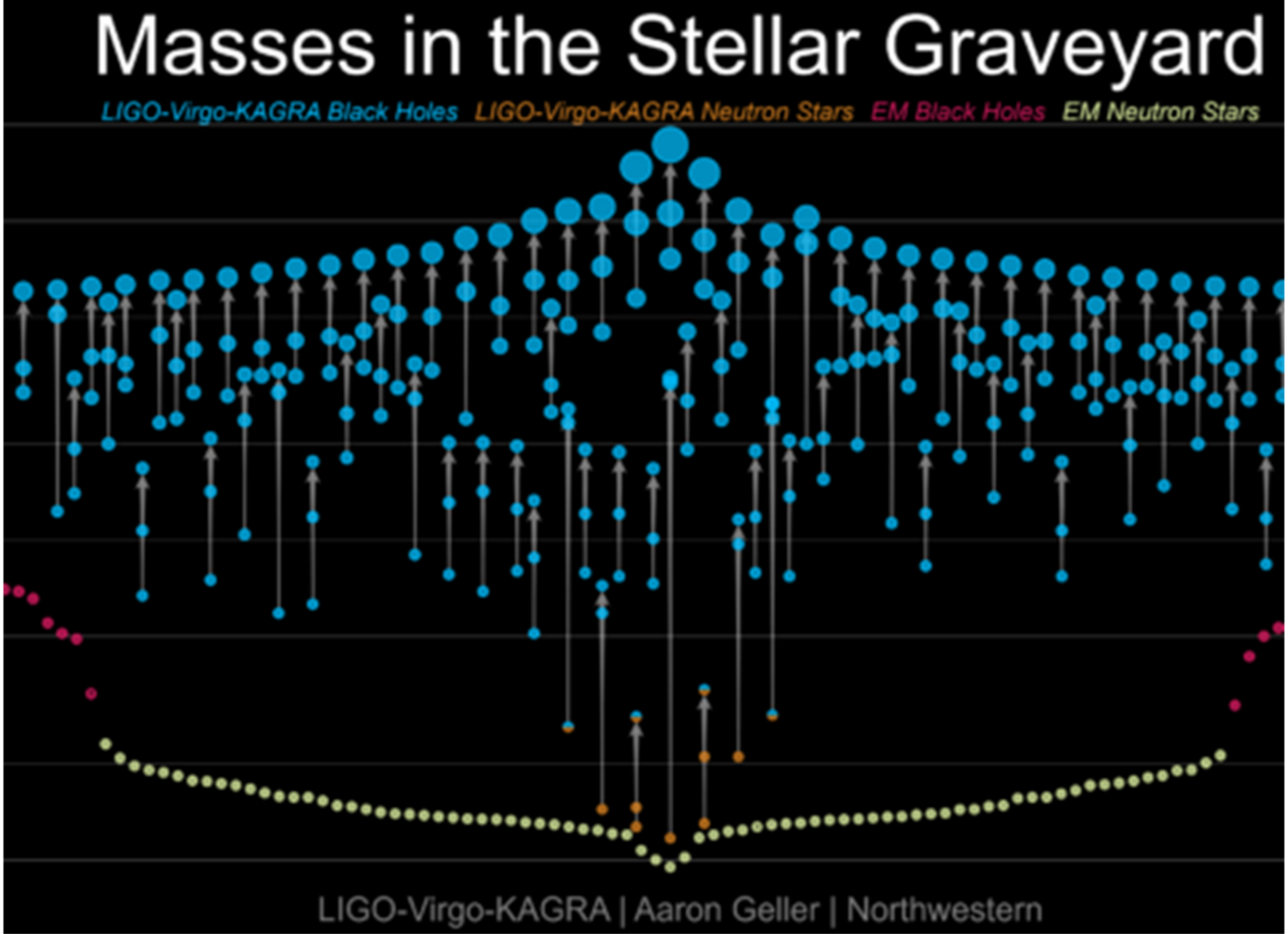
Bosenova signal: a relativistic burst

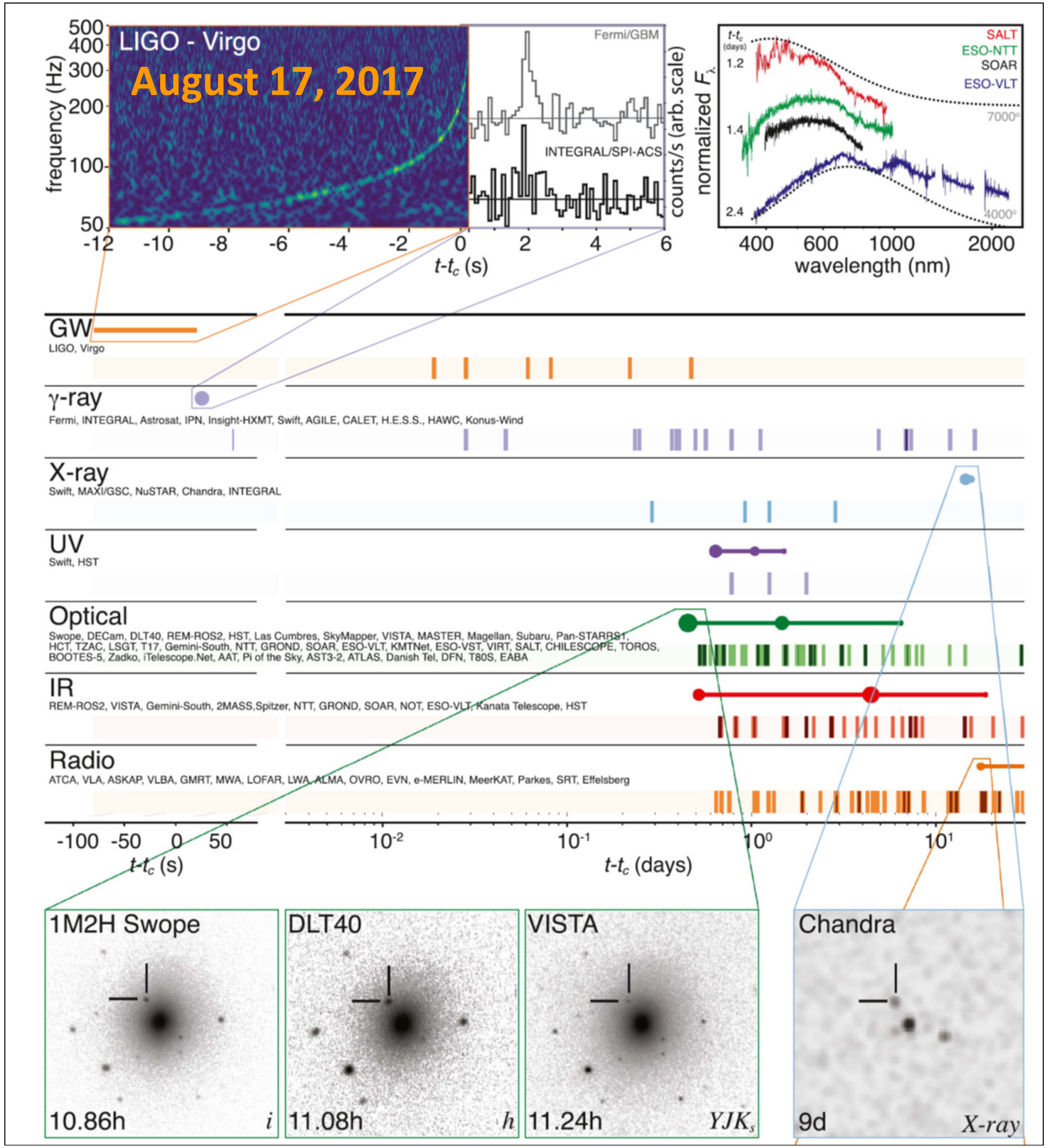


Picture credit: Jason Arakawa

MULTIMESSENGER ASTRONOMY WITH ATOMIC QUANTUM SENSORS




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

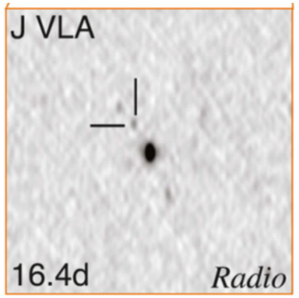
Astrophysical Journal Letters, 848:L12 (2017)

γ-ray burst 2 seconds later

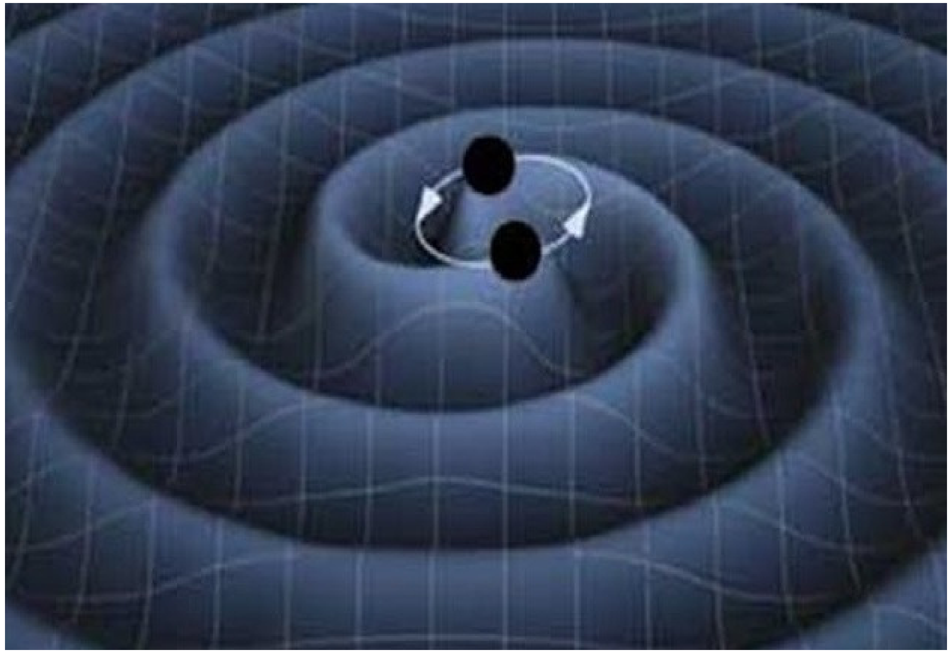
X-ray signal 9 days later

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

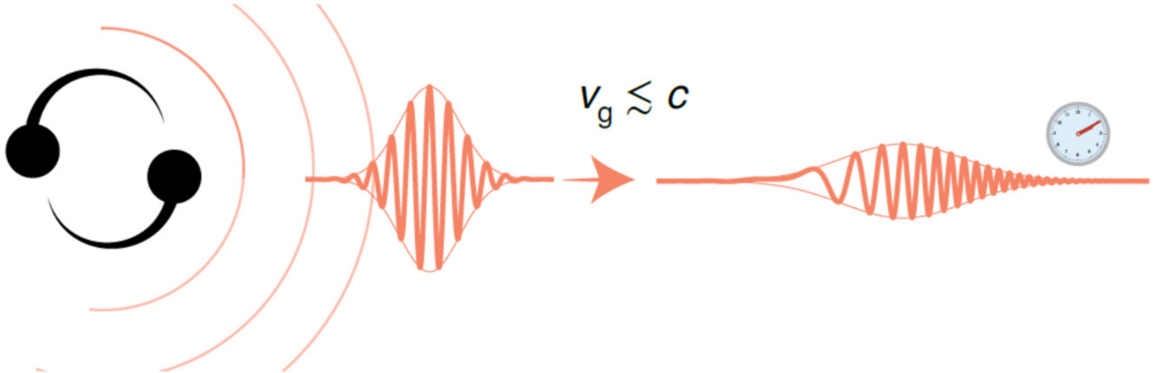
Radio wave signal 16 days later



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

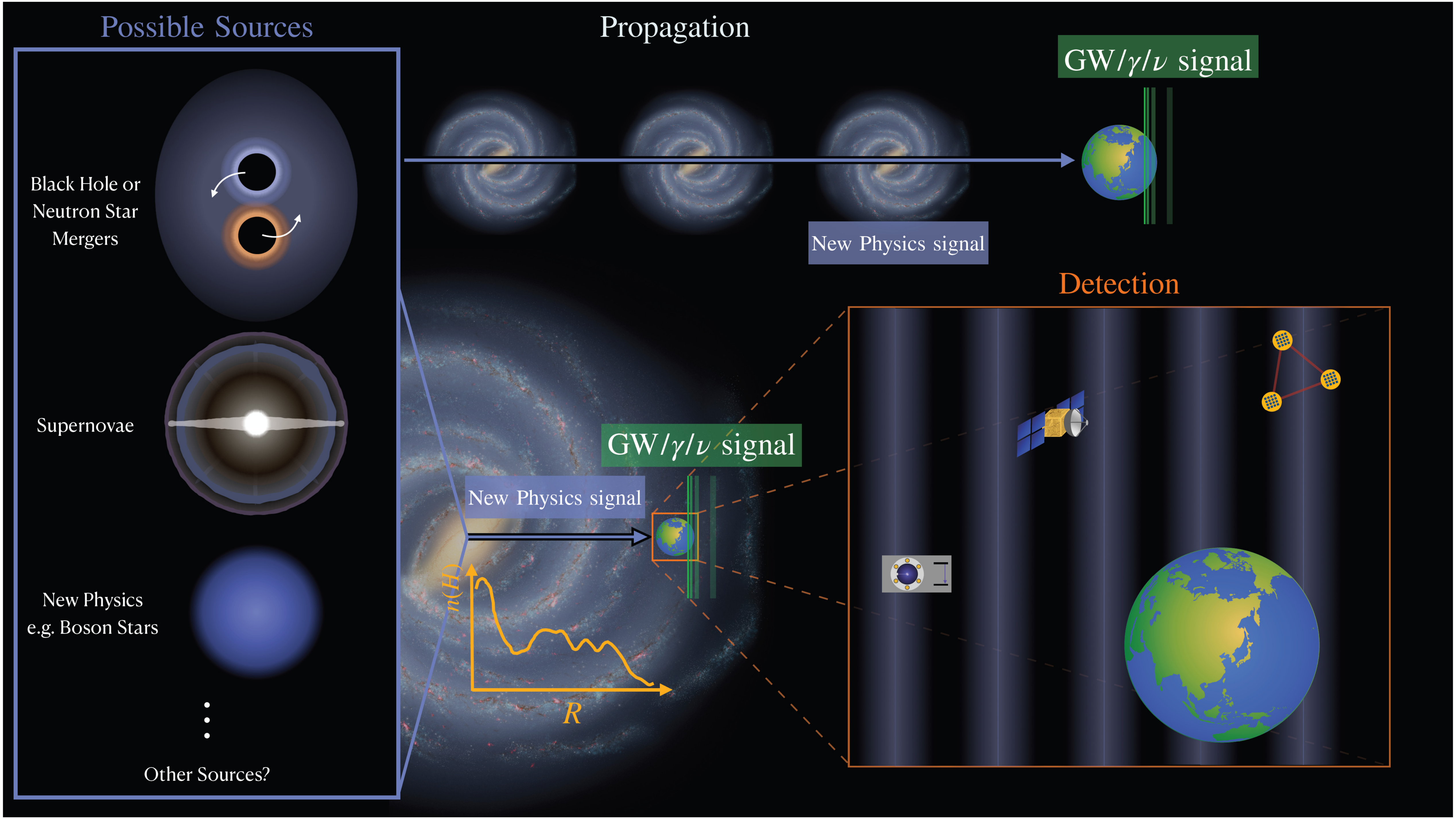


Bursts of exotic low-mass fields (ELFs) could be generated by cataclysmic astrophysical events, such as black-hole or neutron-star mergers, supernovae or the processes that produce fast radio bursts.



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

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


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
$n(H)$
New Physics
e.g. Boson Stars
R
Other Sources?

Resolving controversy: screening of the exotic fields with quadratic interactions

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

- Ultralight Bosons (ULB) can act as additional messengers for multi-messenger astronomy.

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

- Critical screening by the Earth and apparatus can make terrestrial experiments insensitive to ULBs.
- Screening can slow down ULB propagation through IGM and ISM, preventing multi-messenger astronomy on human timescales.

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

- Stadnik's statement relies on sign of $d_i^{(2)}$.
- There are ranges of $d_i^{(2)}$ where screening is irrelevant.
- For negative $d_i^{(2)}$, the group velocity can exceed 1 and time delay is in fact reduced.

Multimessenger Astronomy Beyond the Standard Model: New Window from Quantum Sensors, Jason Arakawa, M. H. Zaheer, V. Takhistov, M. S. Safronova, and Joshua Eby, arXiv:2502.08716 (2025).¶

QUADRATIC(ϕ^2) DARK MATTER COUPLINGS

$$\mathscr{L}_{\rm int}^{\rm quad} \supset \frac{4\pi\phi^2}{M_{\rm pl}^2}\left(d_{m_e}^{(2)} m_e \bar{e}e + \frac{d_e^{(2)}}{4} F_{\mu\nu}F^{\mu\nu} + \frac{d_g^{(2)}\beta(g_s)}{2g_s} G_{\mu\nu}^a G^{a\mu\nu}\right)$$

ϕ^2 coupling causes mass of ϕ to be dependent on density of normal matter nearby

$$\mathscr{L}_{\rm mass} = \frac{1}{2}(m^2 + \beta)\phi^2$$

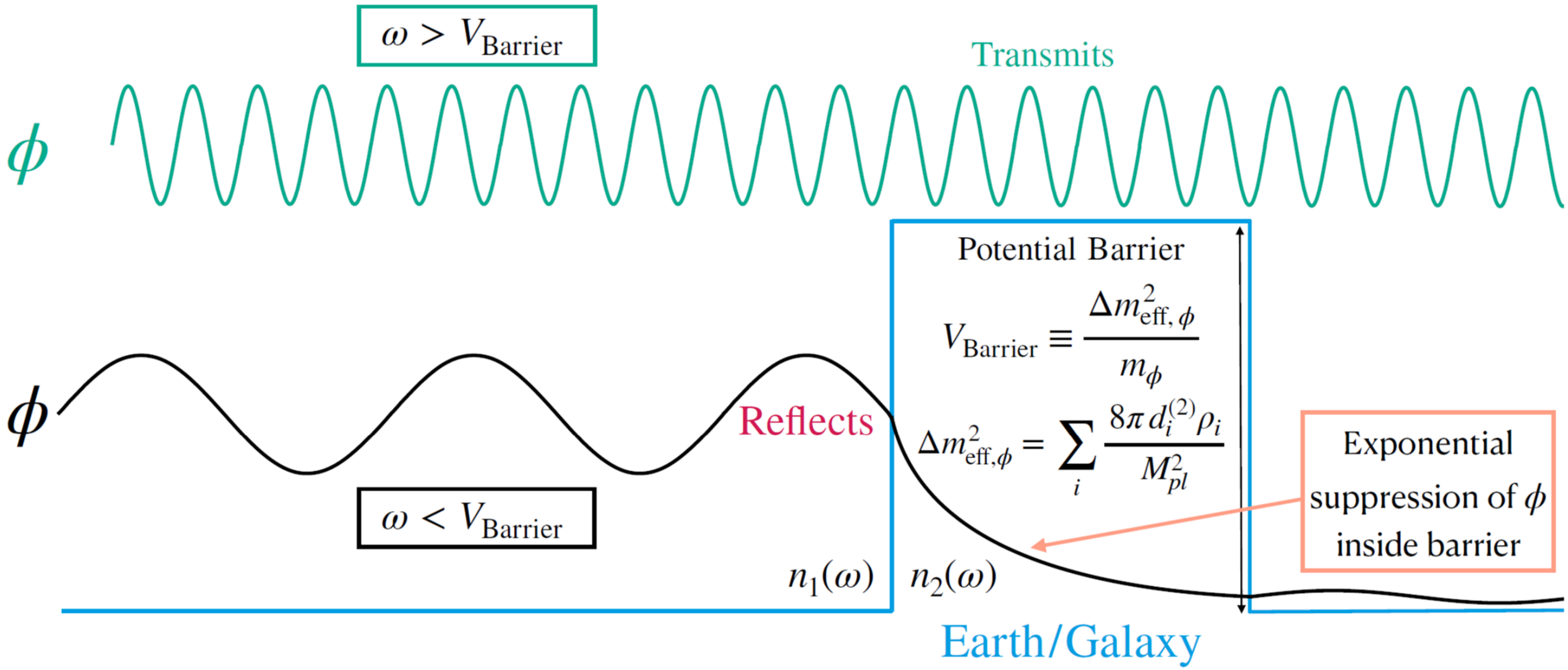
$$\beta \equiv \Delta m_{{\rm eff},\phi}^2(\phi) = \sum_i \frac{8\pi\, d_i^{(2)} \rho_{\rm i,SM}}{M_{pl}^2}$$

ϕ^2 coupling leads to the *screening* of ϕ

$$m_e(t) = m_{e,0}\left(1 + \frac{4\pi\, d_{m_e}^{(2)}}{M_{\rm pl}^2}\phi^2(t)\right) \qquad \alpha(t) = \alpha_0\left(1 + \frac{4\pi\, d_e^{(2)}}{M_{\rm pl}^2}\phi^2(t)\right) \qquad \alpha_s(t) = \alpha_{s,0}\left(1 + \frac{4\pi d_g \beta(g_s)}{2g_s M_{\rm pl}^2}\phi^2(t)\right)$$

Slide credit: Jason Arakawa

Screening of dark matter with quadratic interaction on Earth



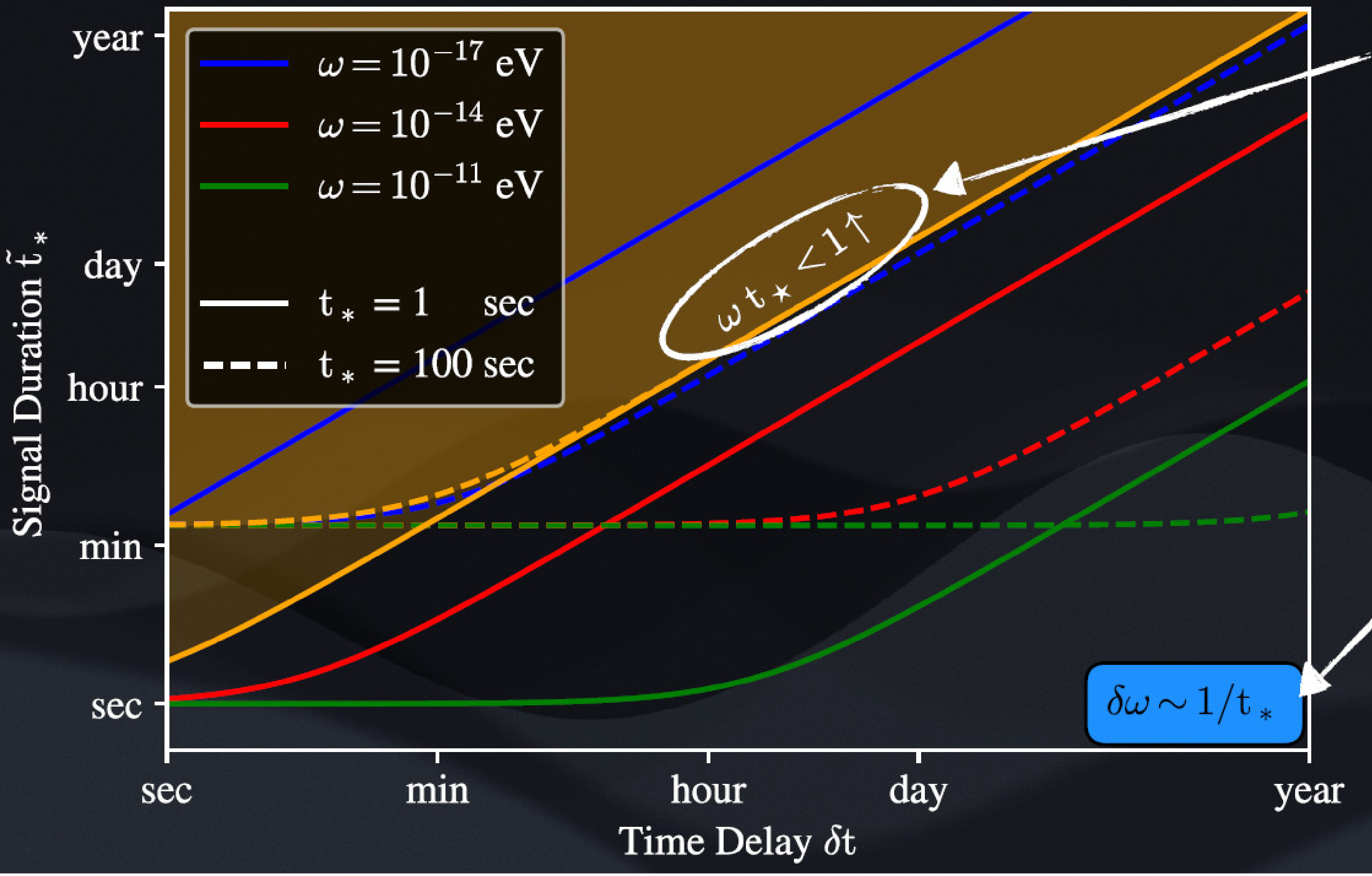
If the DM has kinetic energy greater than the height of the potential barrier, the DM will primarily reflect off the barrier, with an exponentially suppressed profile inside the Earth.

Jason Arakawa, Muhammad H. Zaheer, Joshua Eby, Marianna S. Safronova, Volodymyr Takhistov, J. High Energ. Phys. 2023, 42 (2024).

Slide by Jason Arakawa

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

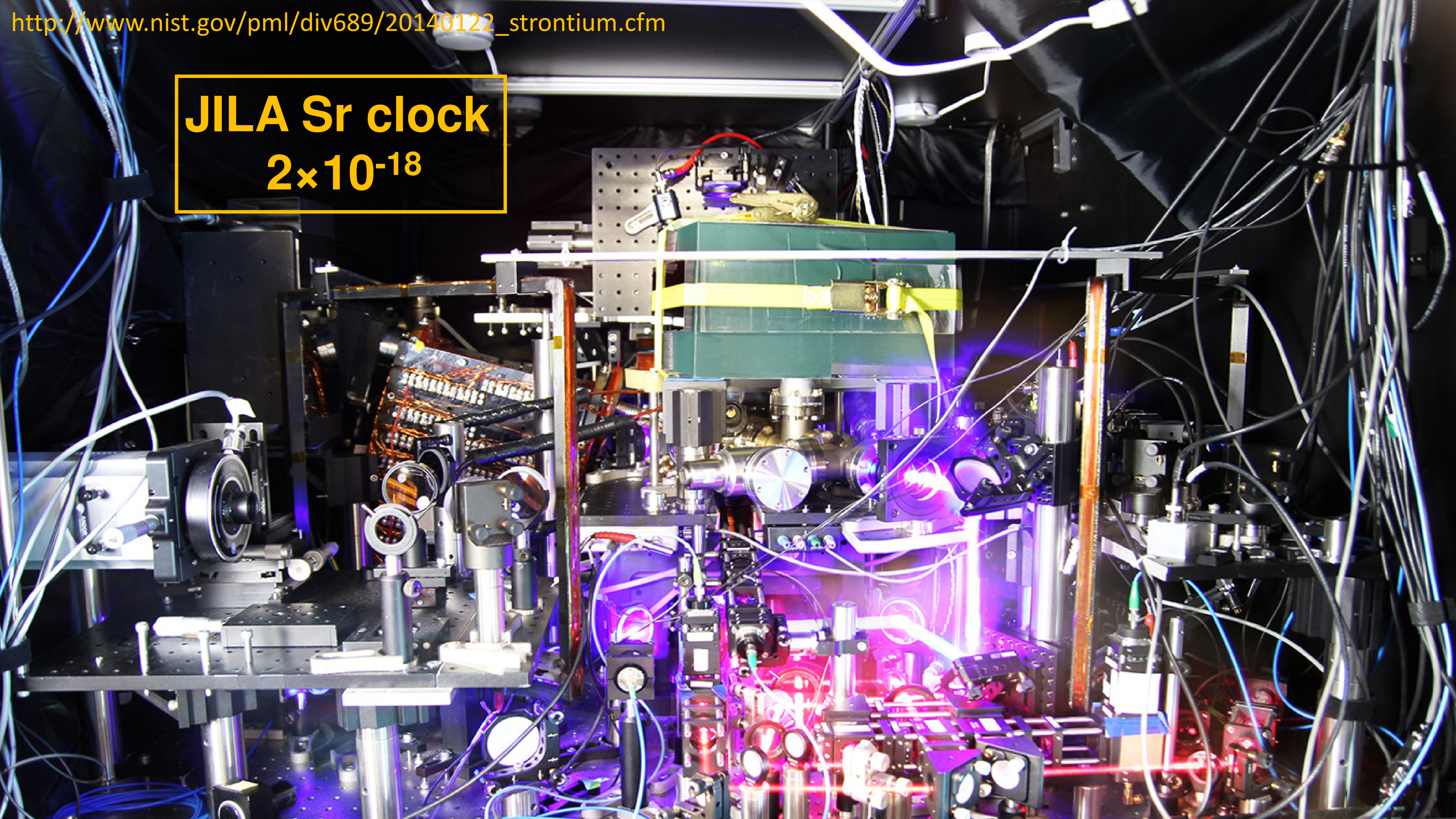
$$\tilde{t}_* \approx t_* + 2\frac{\delta\omega}{\omega}\delta t$$



Uncertainty Principle

Taking example of minimum uncertainty

Figure by Hani Zaheer


http://www.nist.gov/pml/div689/20140122_strontium.cfm
JILA Sr clock
2×10^{-18}

RESEARCH ARTICLE

ADVANCED QUANTUM TECHNOLOGIES
www.advquantumtech.com

Transportable Strontium Optical Lattice Clocks Operated Outside Laboratory at the Level of 10^{-18} Uncertainty

Adv. Quantum Technol. **2021**, 4, 2100015

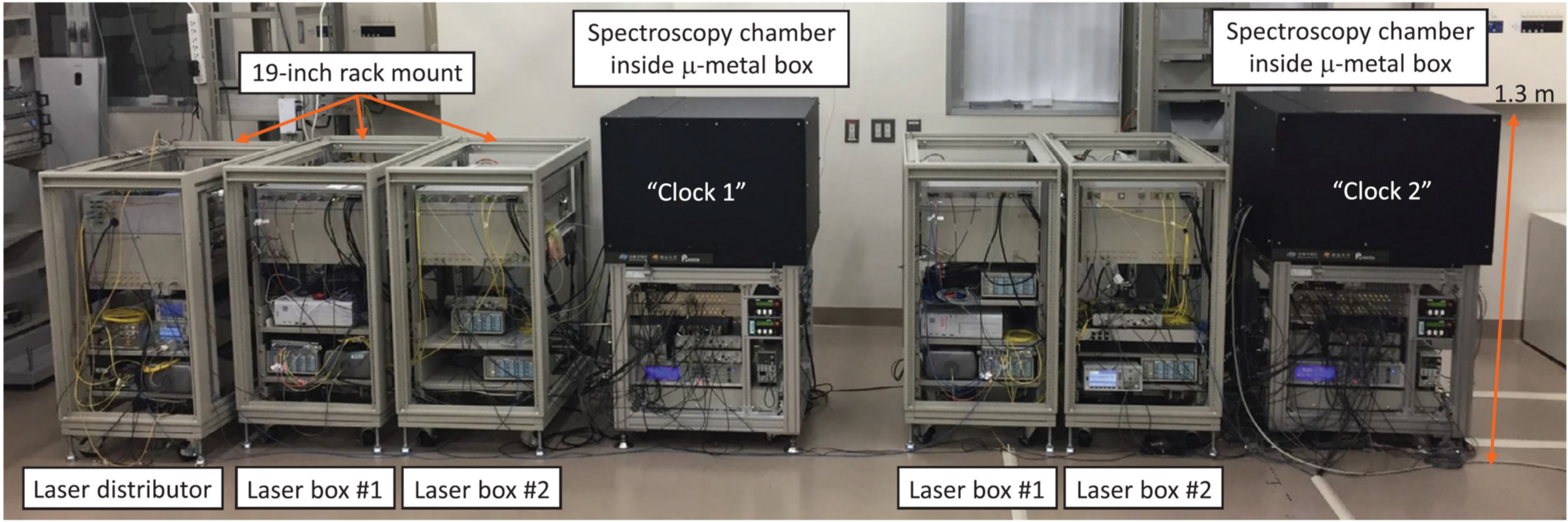
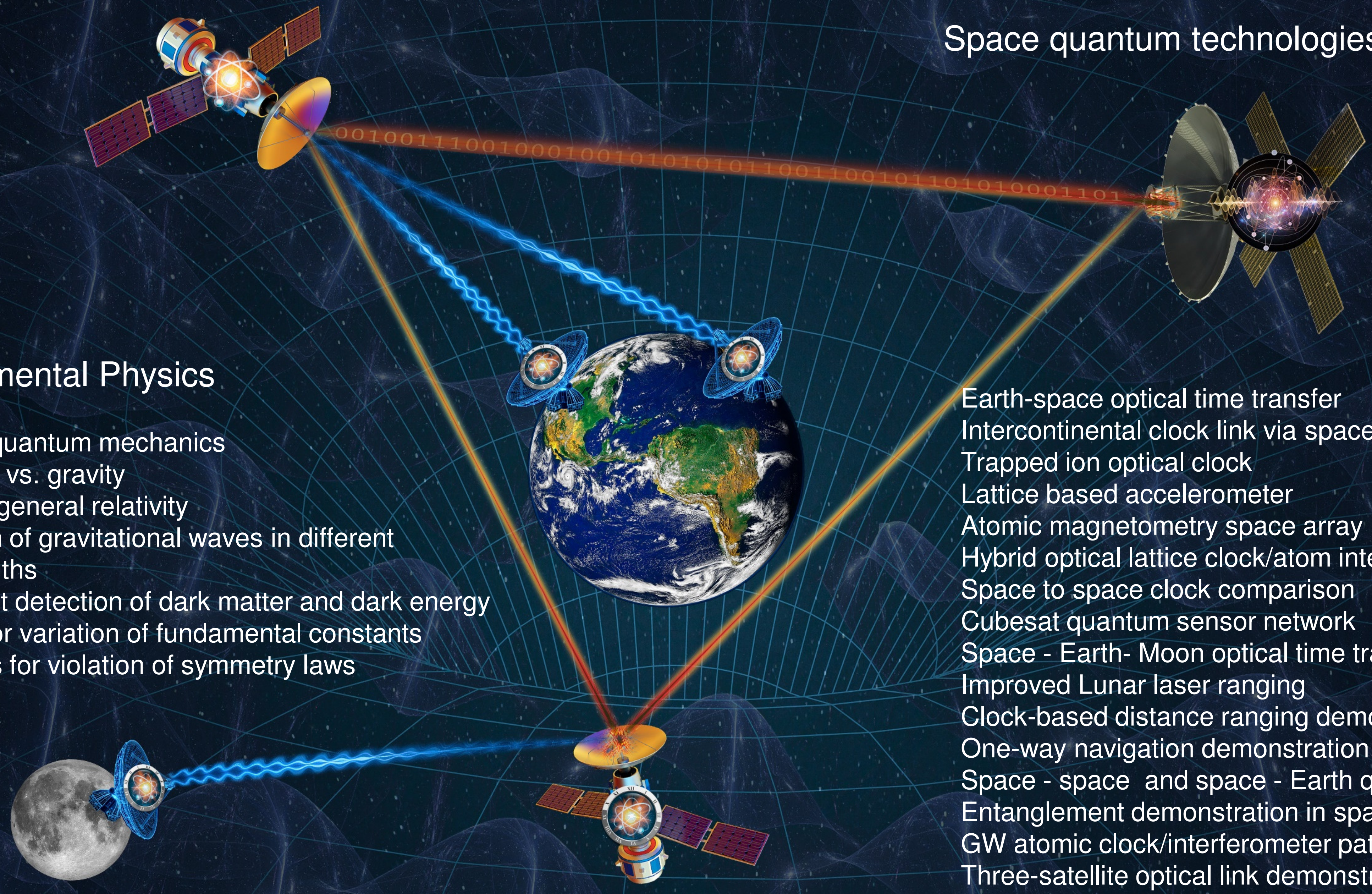


Figure 1. A pair of Sr optical lattice clocks placed at RIKEN laboratory.

Space Network of Quantum Sensors



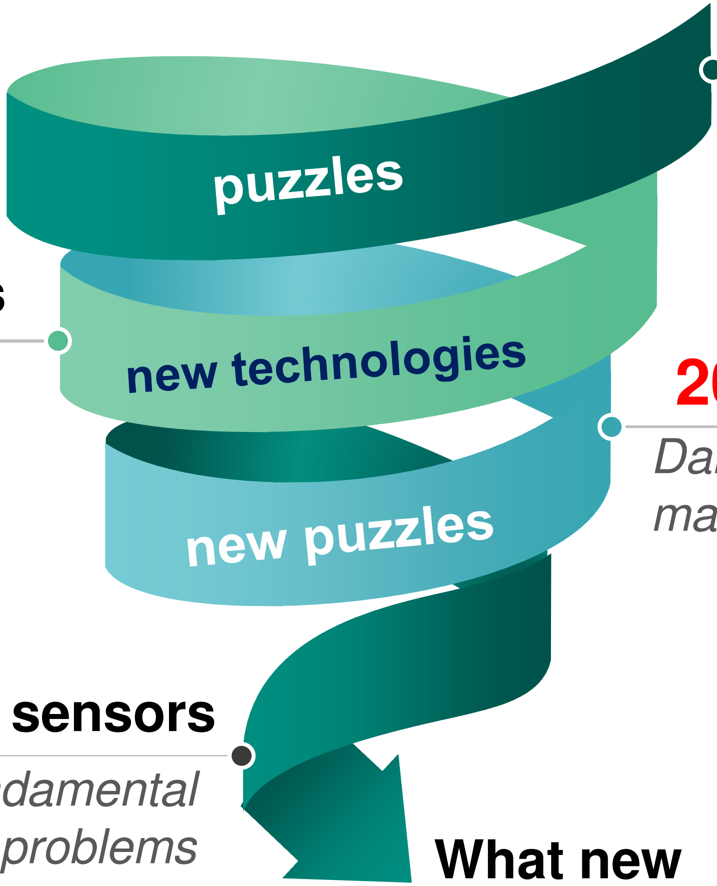
Space quantum technologies

- 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

Fundamental Physics

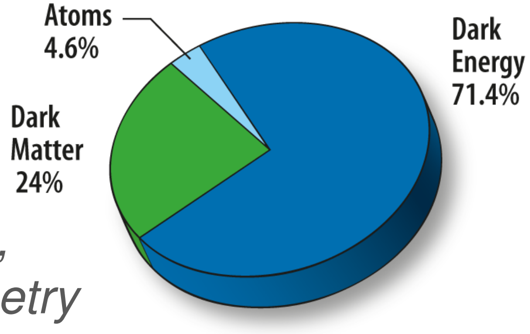
- Tests of quantum mechanics
- Quantum vs. gravity
- Tests of general relativity
- Detection of gravitational waves in different wavelengths
- The direct detection of dark matter and dark energy
- Search for variation of fundamental constants
- Searches for violation of symmetry laws

Fundamental physics and new technologies

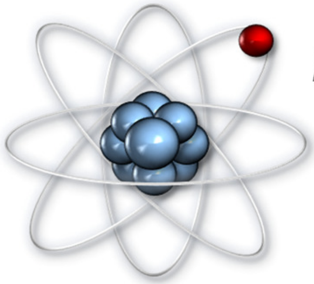


1925

Fundamental physics puzzles: atomic spectra, Stern-Gerlach experiment, etc., …



Quantum mechanics



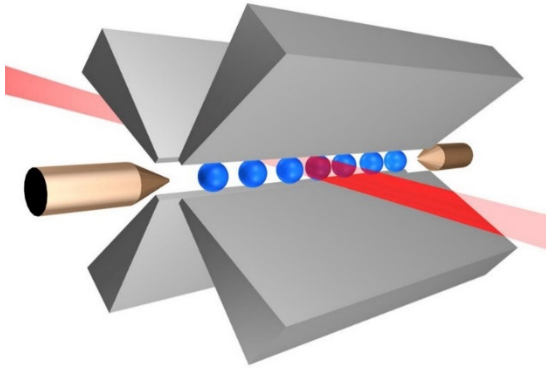
Result of solving 1925 fundamental physics problems

2025

Dark matter, dark energy, matter-antimatter asymmetry

Quantum sensors

Solving 2025 fundamental physics problems



What new technologies would that bring?

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