Physics of QSNET: Lecture 1

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QSNET

Networked quantum sensors for fundamental physics

UNIVERSITY OF SUSSEX

NPL National Physical Laboratory

UNIVERSITY OF BIRMINGHAM

Imperial College London

QTFP School 2023
University of Cambridge

Current fundamental physics

Over 100 years of theory and experiment support a description of nature based on two theories

$$\text{low energy world} \approx \text{GR} + \text{QFT}$$

This description includes several ***physical constants***

General Relativity

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- Contains 2 ***dimensionful*** *quantities*

Standard Model Lagrange density

$$\mathscr{L}_{\text{SM}} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + i\bar{\psi}^j \gamma^\mu D_\mu \psi^j + \left(\bar{\psi}^i_L V_{ij} \Phi \psi^j_R + \text{h.c.} \right) - |D_\mu \Phi|^2 - V(\Phi)$$

- Parametrized by 25 ***dimensionless*** *constants*
- Cannot be calculated directly — must be *measured*!

Physical constants

There are two types of physical constants:

- Dimensionful quantities: $G, \hbar, c, \ldots$
- Dimensionless constants: α, additional SM parameters, …

Dimensionful type *depend on choice of base units*

$[M]$ = unit of mass

$[L]$ = unit of length

$[T]$ = unit of time

Example $$F_g = G\frac{m_1 m_2}{r^2} \Rightarrow [G] = [M]^{-1}[L]^3[T]^{-2}$$

Exercise

$$G = \begin{cases} 6.67 \times 10^{-11}\mathrm{kg}^{-1}\mathrm{m}^3\mathrm{s}^{-2} & \text{SI units} \\ 6.70 \times 10^{-39}\mathrm{GeV}^{-2} & \text{natural units } (c = \hbar = 1) \end{cases}$$

Dimensionless constants are **pure numbers**, independent of convention ⇒ “fundamental constants”

Fundamental constants

Common examples:

$$\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c}, \mu = \frac{m_e}{m_p}$$

2018 CODATA values

E. Tiesinga et al., Rev. Mod. Phys. 93, 025010

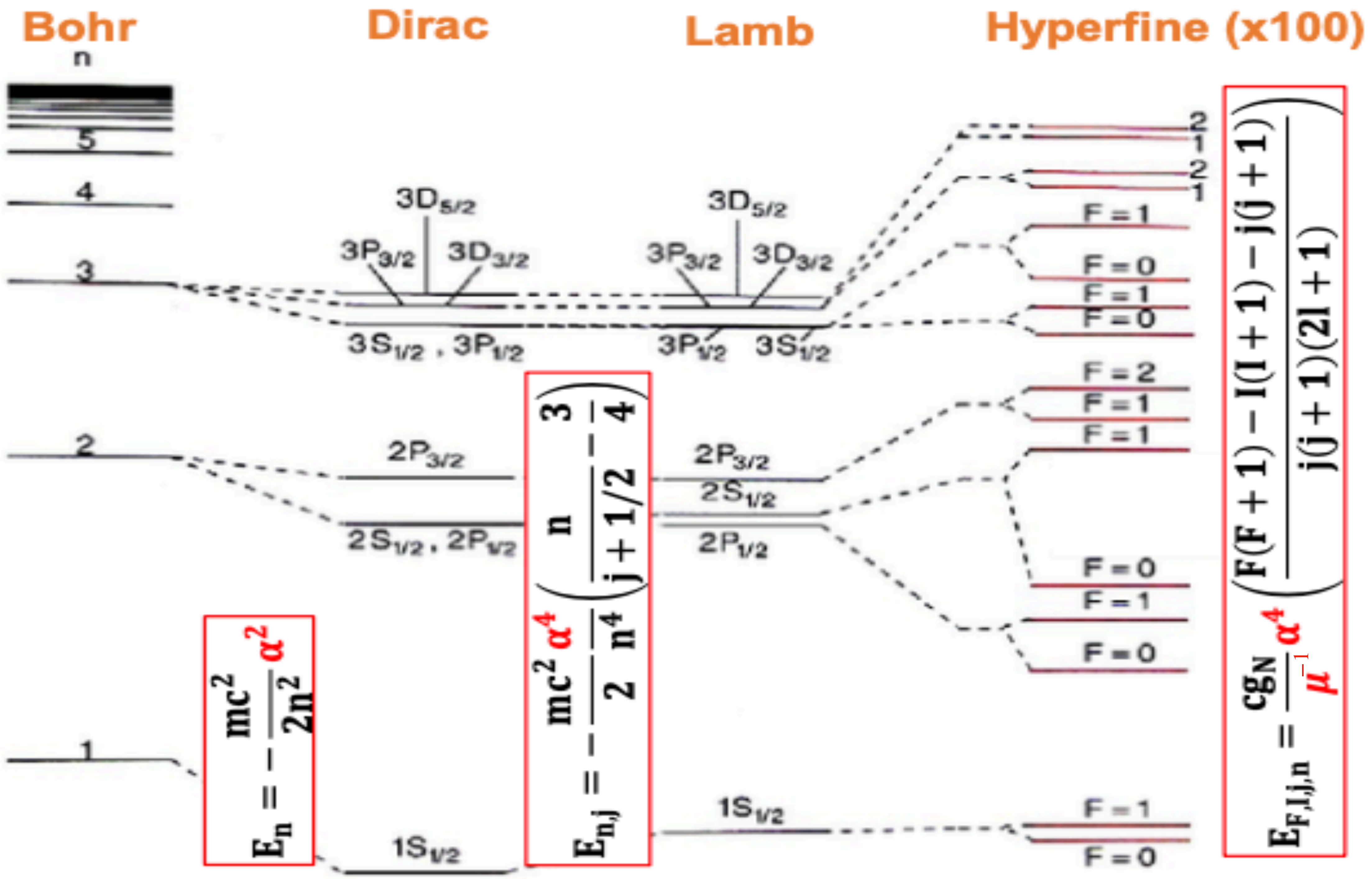
$$\alpha^{-1} = 137.035999084(21)$$

$$\mu^{-1} = 1836.15267343(11)$$

α, μ control the structure of matter!

Level structure	Scaling/R_∞
Bohr	1
Fine	α^K
Hyperfine	$\alpha^{2+K} \cdot \mu$
Vibrational (molecular)	$\mu^{\frac{1}{2}}$
Rotational (molecular)	μ

(Fig. from M. Keller)



Fundamental constants

Existence of fundamental constants naturally raises questions:

P. A. M. Dirac, Nature 139, 323 (1937)

- Why do they take values observed?
- Why are there so many of them?
- Why are there huge hierarchies?
- Do they exhibit numerological patterns/relations among each other?
- Can they be explained dynamically (i.e. from theories with no free parameters)?
- **Are they "only" numbers, or more generally, functions of spacetime?**

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Some approaches beyond the SM and GR (e.g. string theories) admit regimes where the constants can ***vary with time and space***

Reviews

J. Uzan, Living Rev. Rel. 14, 2 (2011)

C. J. A. P. Martins, Rep. Prog. Phys. 80, 126902 (2017)

How to describe varying constants for potential detection with **low-energy experiments**?

Effective description

How to capture signatures of varying constants?

1. Model phenomena explicitly
2. Use **effective field theory** (model independent)

EFT: ***new-physics (NP) effects captured by systematically parametrizing all possible additional couplings to known low-energy (LE) fields***

$$\mathscr{L}_{\mathrm{NP}}(F) = \underbrace{F}_{} \cdot \mathcal{O}^{F}_{\mathrm{LE}} \Rightarrow \boxed{\mathscr{L}_{\mathrm{EFT}} = \mathscr{L}_{\mathrm{LE}} + \sum_{F} \mathscr{L}_{\mathrm{NP}}(F)}$$

= (coupling strength, new field)

- NP terms typically treated as perturbations w.r.t. LE terms
- Search for influence of new in sensitive experiments

Bekenstein electrodynamics

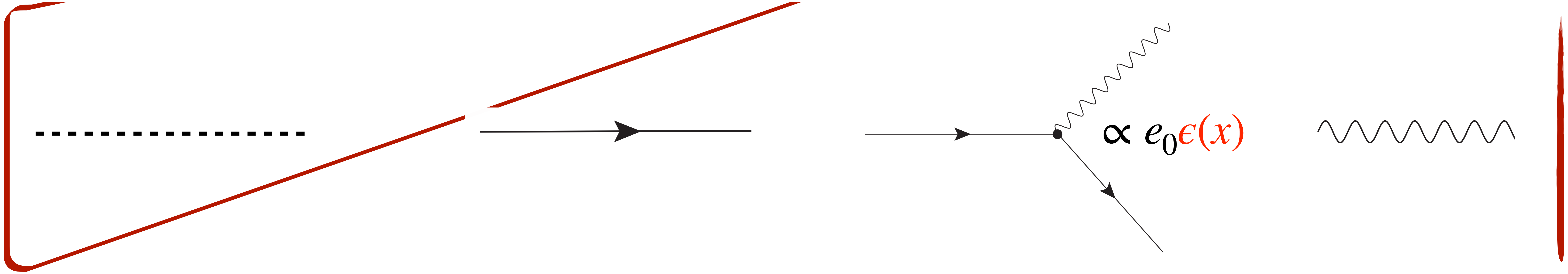
Electrodynamics with spacetime-dependent charge

J. D. Bekenstein, Phys. Rev. D 25, 1527 (1982)

$$e(x) = e_0 \epsilon(x)$$

$\epsilon(x) =$ scalar field

$$\mathscr{L} = \frac{1}{2}\frac{\Lambda^2}{\epsilon^2}(\partial_\mu \epsilon)^2 + \bar{\psi}_e(i\gamma^\mu \partial_\mu - m_e)\psi_e - e_0 \epsilon \bar{\psi}_e \gamma^\mu A_\mu \psi_e - \frac{1}{4}\widehat{F}_{\mu\nu}\widehat{F}^{\mu\nu}$$



Retains many properties of QFT, including gauge invariance:

$$\widehat{F}_{\mu\nu} = \left[\partial_\mu(\epsilon A_\nu) - \partial_\nu(\epsilon A_\mu)\right]/\epsilon$$

$$\epsilon A_\mu \rightarrow \epsilon A_\mu + \partial_\mu \chi$$

Bekenstein electrodynamics

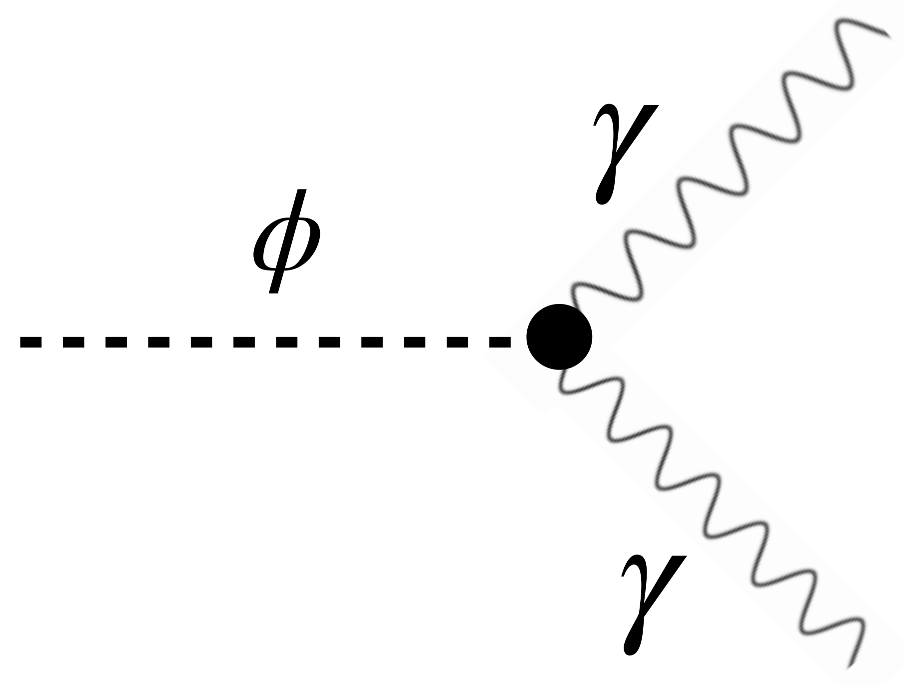
Expand about small variations $\epsilon(x) \approx 1 + \frac{\phi}{\Lambda}$: Exercise

$$\mathscr{L} \to \frac{1}{2}(\partial_\mu \phi)^2 + \bar{\psi}_e(i\gamma^\mu \partial_\mu - m_e)\psi_e - e_0 \bar{\psi}_e \gamma^\mu A_\mu \psi_e - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

conventional massless scalar + QED

$$-ie_0 \frac{\phi}{\Lambda}\bar{\psi}_e \gamma^\mu A_\mu \psi_e - \frac{1}{\Lambda}(\partial_\mu \phi)A_\nu F^{\mu\nu}$$

new interactions between ϕ, A_μ, ψ



Last line equivalent to $\frac{1}{2\Lambda}\phi F_{\mu\nu}F^{\mu\nu}$ Exercise

U. Danielsson et al., Nucl. Phys. B 919, 569 (2017)

Theory with a varying α equivalent to "usual" theories with additional interactions!

Bekenstein electrodynamics

Bekenstein's model motivated:

- A wave of theory generalizations
- Searches for α variations across measurements in cosmology, atomic physics, collider physics (**see reviews, slide 5**)

(see reviews, slide 5)

Primary effects of interest for atomic-clock-type searches

The relevant set of operators containing *ultralight scalar fields* multiplying Standard-Model terms

classified in EFT

(see, e.g.)

P. W. Graham et al., PRD 93, 075029 (2016)

Bottom line: signals for varying constants can be described by scalar fields interacting with "conventional matter"

Couplings to matter

Common terms considered for atomic-clock studies

$$\mathscr{L}^{\mathrm{NP}}_{\mathrm{clocks}} = -\left(\frac{\phi}{\Lambda}\right)^n \mathcal{O}_{\mathrm{SM}}$$

n = positive integer
Λ = scale of new physics
$\mathcal{O}_{\mathrm{SM}}$ = Standard-Model operator

Examples

$$\frac{\phi}{\Lambda_\gamma}\left(\frac{1}{4}F_{\mu\nu}F^{\mu\nu}\right) \qquad -\frac{\cancel{\phi}}{\Lambda_e}\left(m_e\bar{\psi}_e\psi_e\right)$$

$$\alpha \rightarrow \alpha(\phi)$$

$$m_e \rightarrow m_e(\phi)$$

$$\mu = m_e/m_p \rightarrow \mu(\phi)$$

Analogous couplings to, e.g. quarks, gluons, ... also present

Couplings to matter

How does this happen?

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \qquad A_\mu \to \frac{1}{e} A'_\mu$$

Exercise

$$\Rightarrow -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \to -\frac{1}{4e^2} F'_{\mu\nu} F'^{\mu\nu} = \left(\frac{1}{4\pi\alpha}\right)\left(-\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu}\right)$$

$\alpha = e^2/(4\pi)$
(natural units)

Combining SM and NP terms

$$\alpha \to \alpha(\phi) \approx \alpha \left(1 + \frac{\phi}{\Lambda_\gamma}\right)$$

$$\mu \to \mu(\phi) \approx \mu \left(1 + \frac{\phi}{\Lambda_e}\right)$$

Dynamical behavior of α, μ *linear* in dynamics of ϕ

Dynamics of ϕ

Scalar field equation of motion

$$(\partial_\mu \partial^\mu + m^2)\phi = 0 \;\Rightarrow\; \phi(x) = \phi_0 \cos(k \cdot x + \delta)$$

$$k^\mu = (E, \vec{k})$$
$$k^2 = m^2$$

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- *Often* interested in **time-dependent signals in nonrelativistic limit**

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$$\Rightarrow \phi(t) \approx \phi_0 \cos\left[m(1+\tfrac{1}{2}v^2)t + \delta\right]$$

$v \ll c \Rightarrow m$ **controls frequency of oscillations**

Exercise

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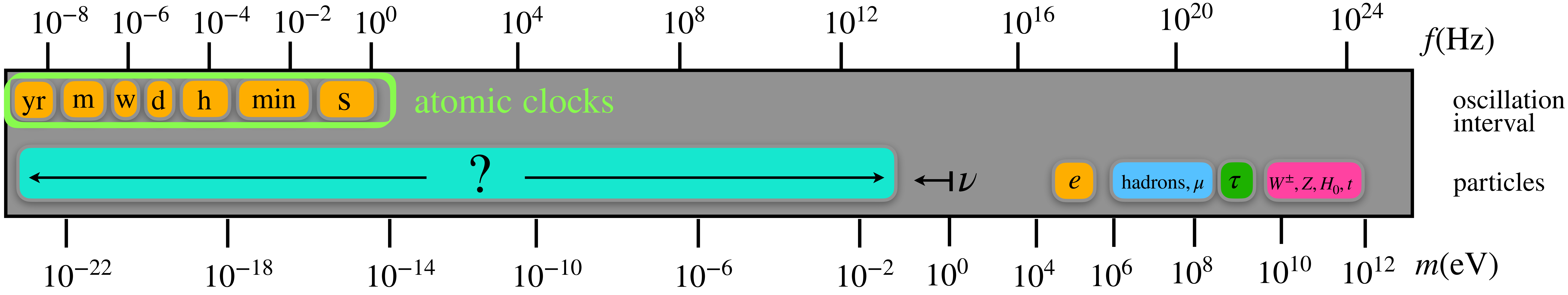

Dynamics of ϕ

Dynamics of ϕ

Oscillation of ϕ transmitted to constants: $\alpha(\phi) \approx \alpha \left[1 + \frac{\phi_0 \cos(mt + \delta)}{\Lambda_\gamma}\right]$ etc.

- Amplitude controlled by product ϕ_0/Λ_γ, frequency by field mass
- Distinct couplings + multiple fields enrich possibilities

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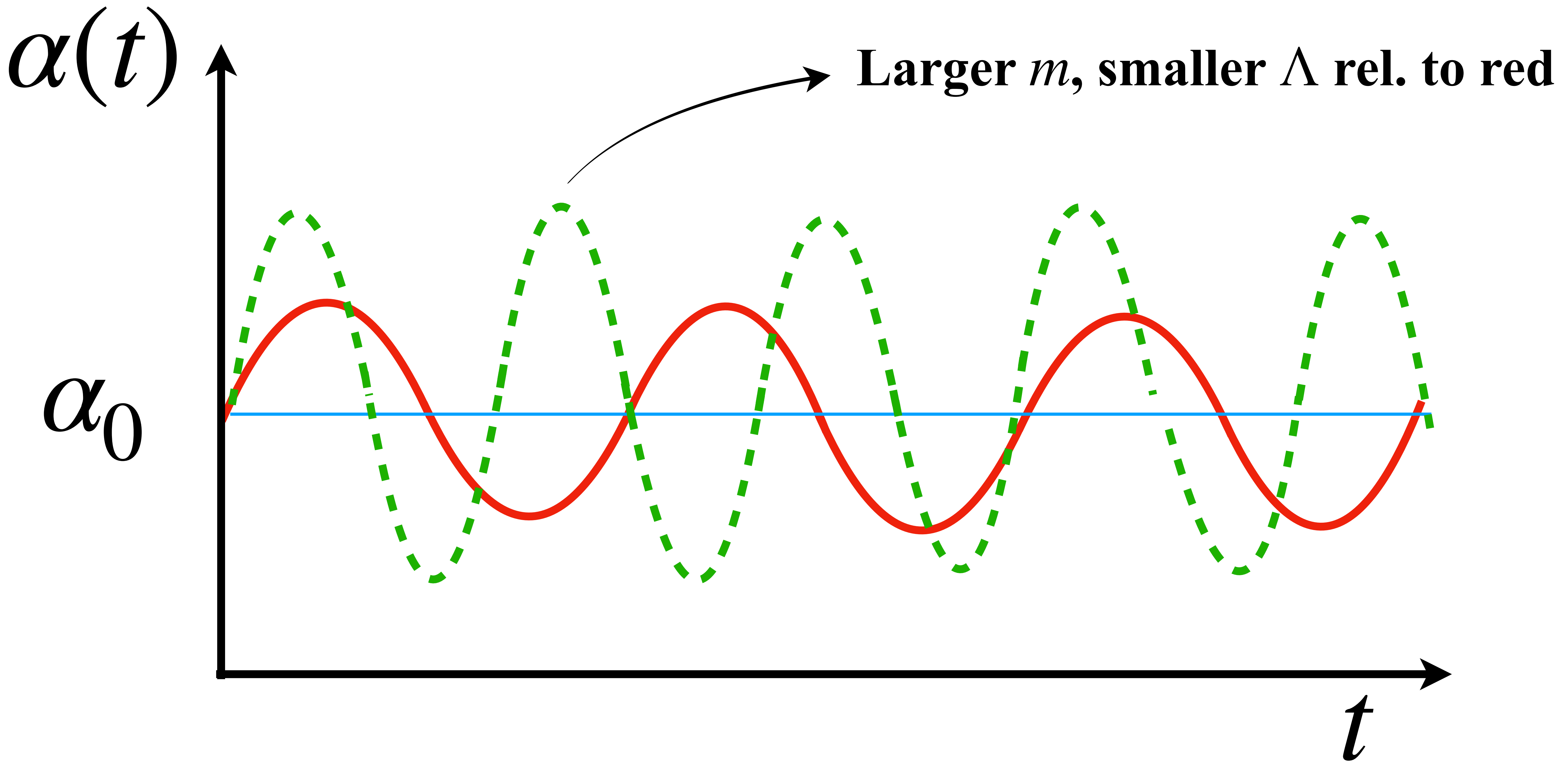

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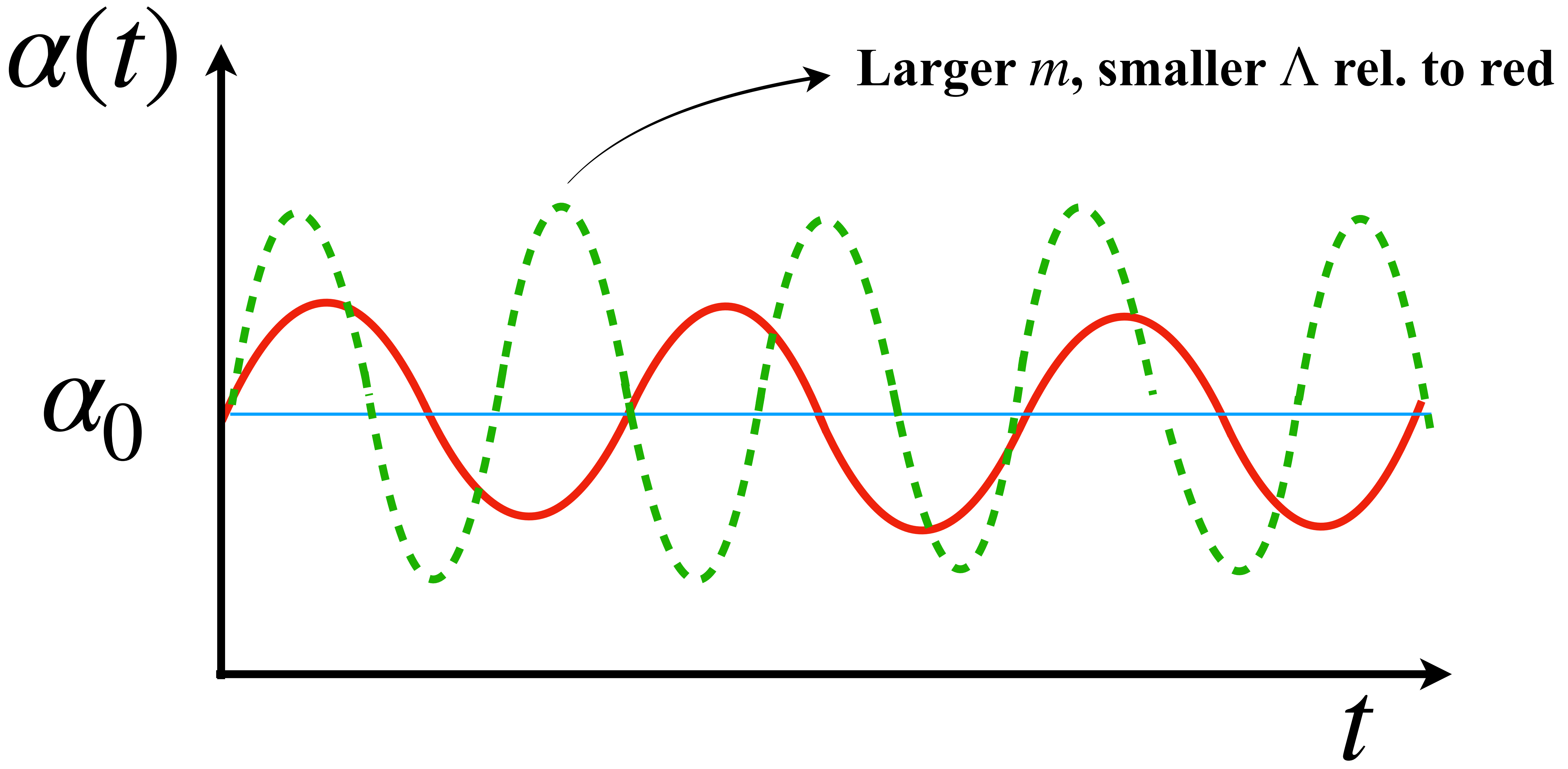
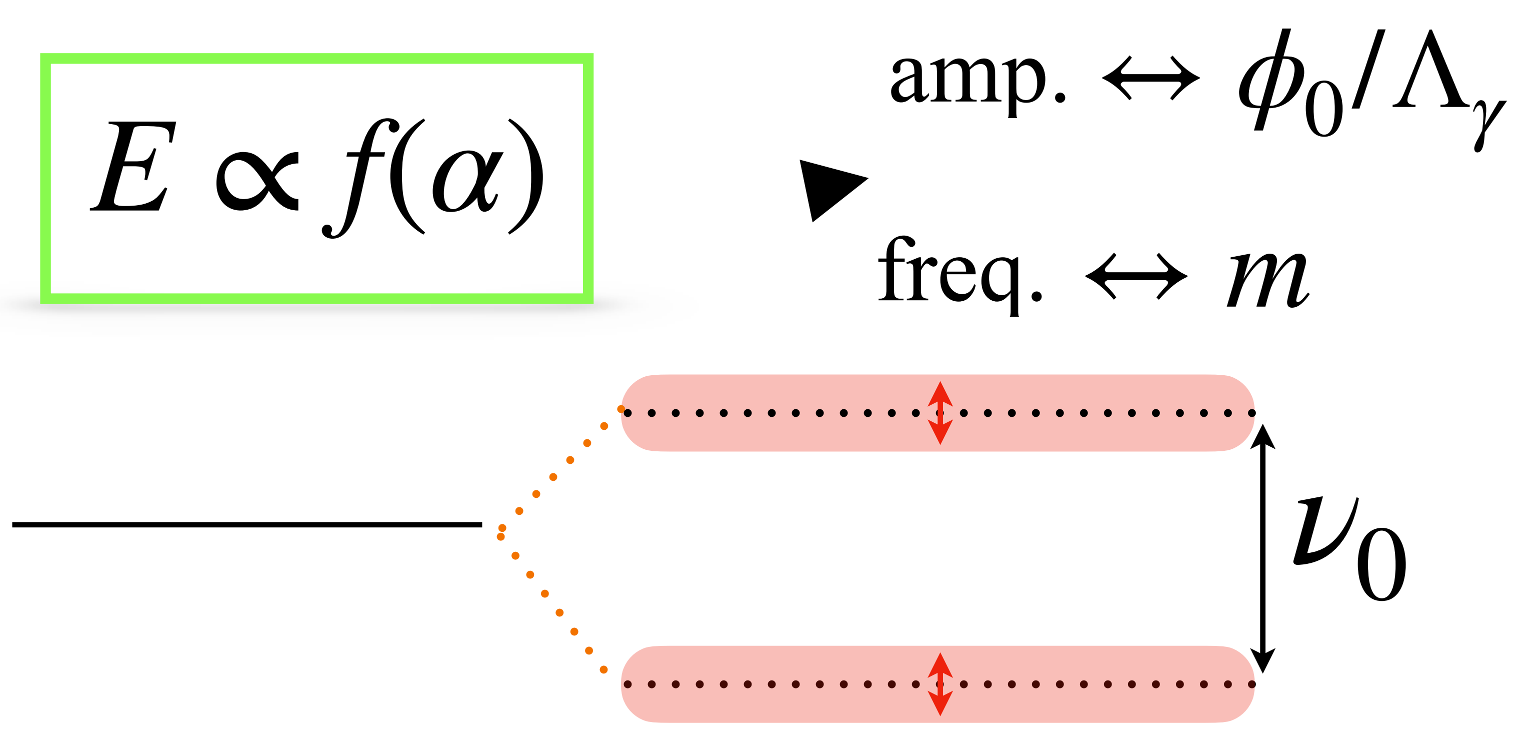


$E \propto f(\alpha)$



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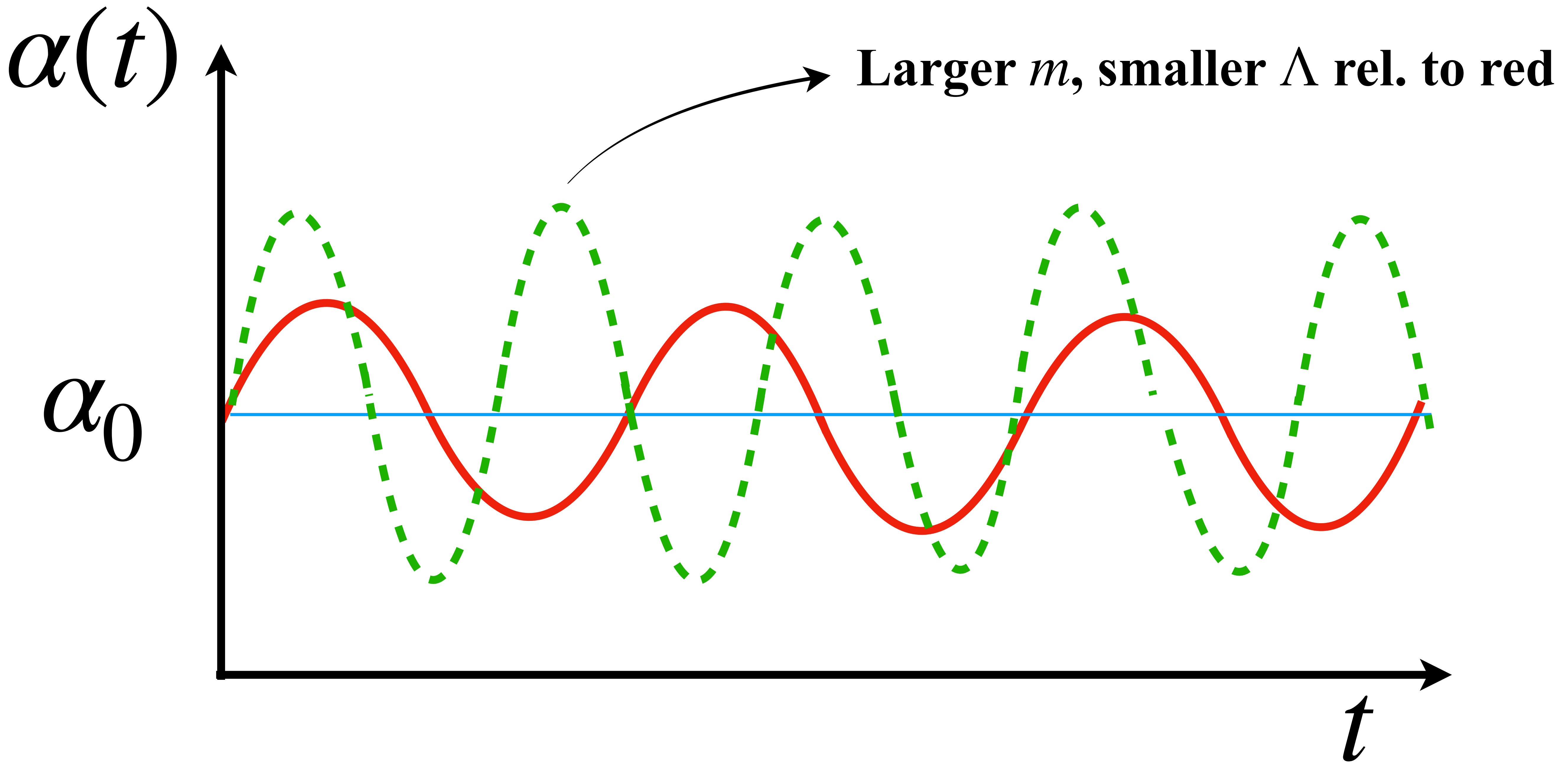
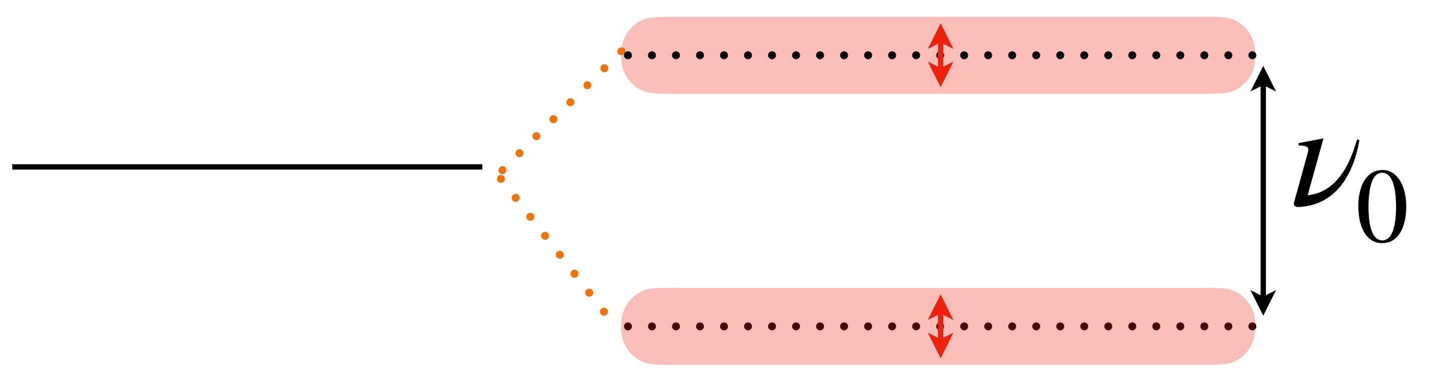


$\boxed{E \propto f(\alpha)}$

amp. $\leftrightarrow \phi_0/\Lambda_\gamma$

freq. $\leftrightarrow m$

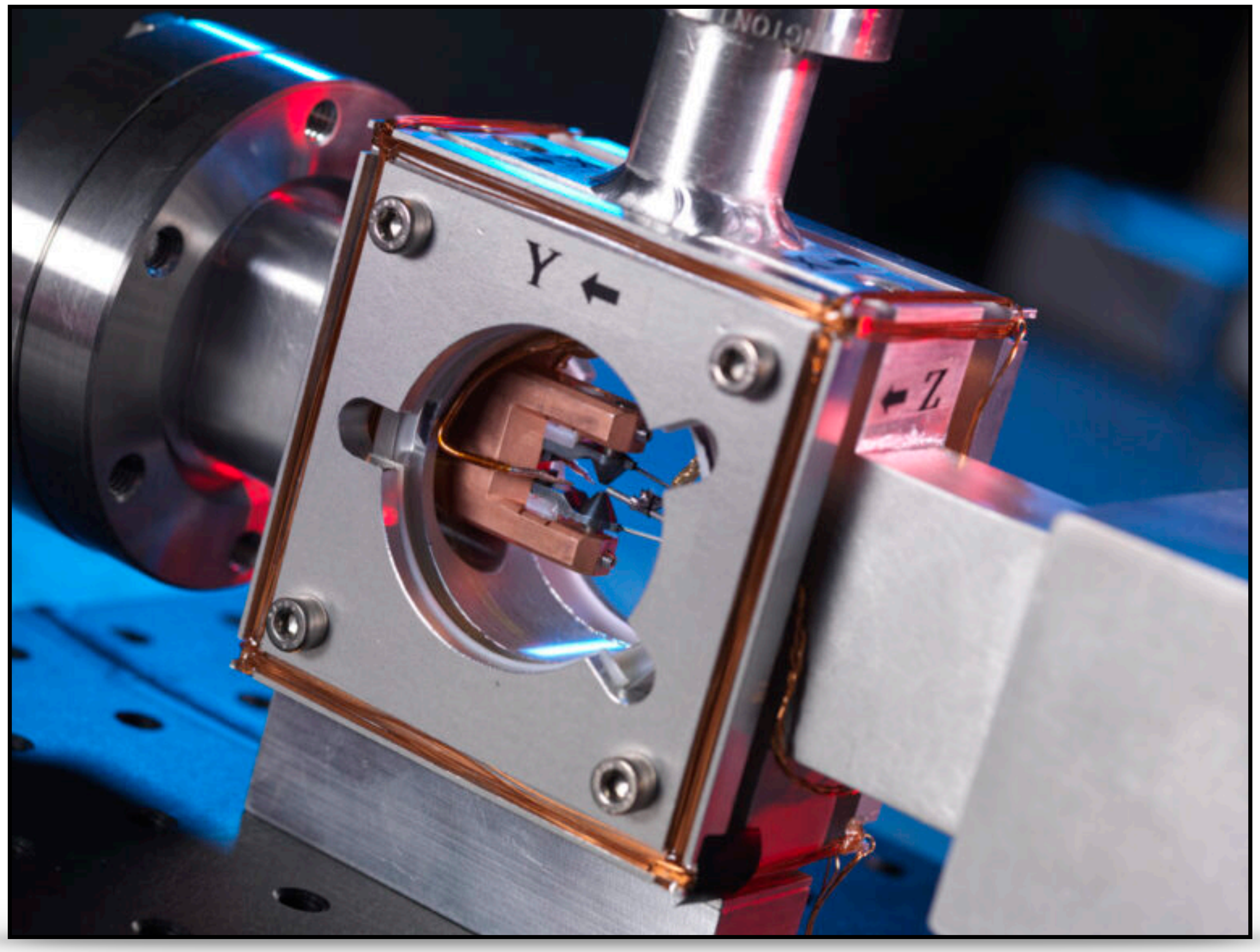


...but how does one measure with clocks?

Atomic clocks

Atomic clocks count cycles of EM radiation emitted from particular transitions

NPL Yb^+ optical clock



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Common examples

$$\nu_{\text{opt}} = A \cdot (cR_\infty) \cdot F_{\text{opt}}(\alpha)$$
$$\nu_{\text{MW}} = B \cdot (cR_\infty) \cdot \alpha^2 F_{\text{MW}}(\alpha) \cdot g_N \cdot \mu$$
$$\nu_{\text{vib}} = C \cdot (cR_\infty) \cdot \mu^{1/2}$$

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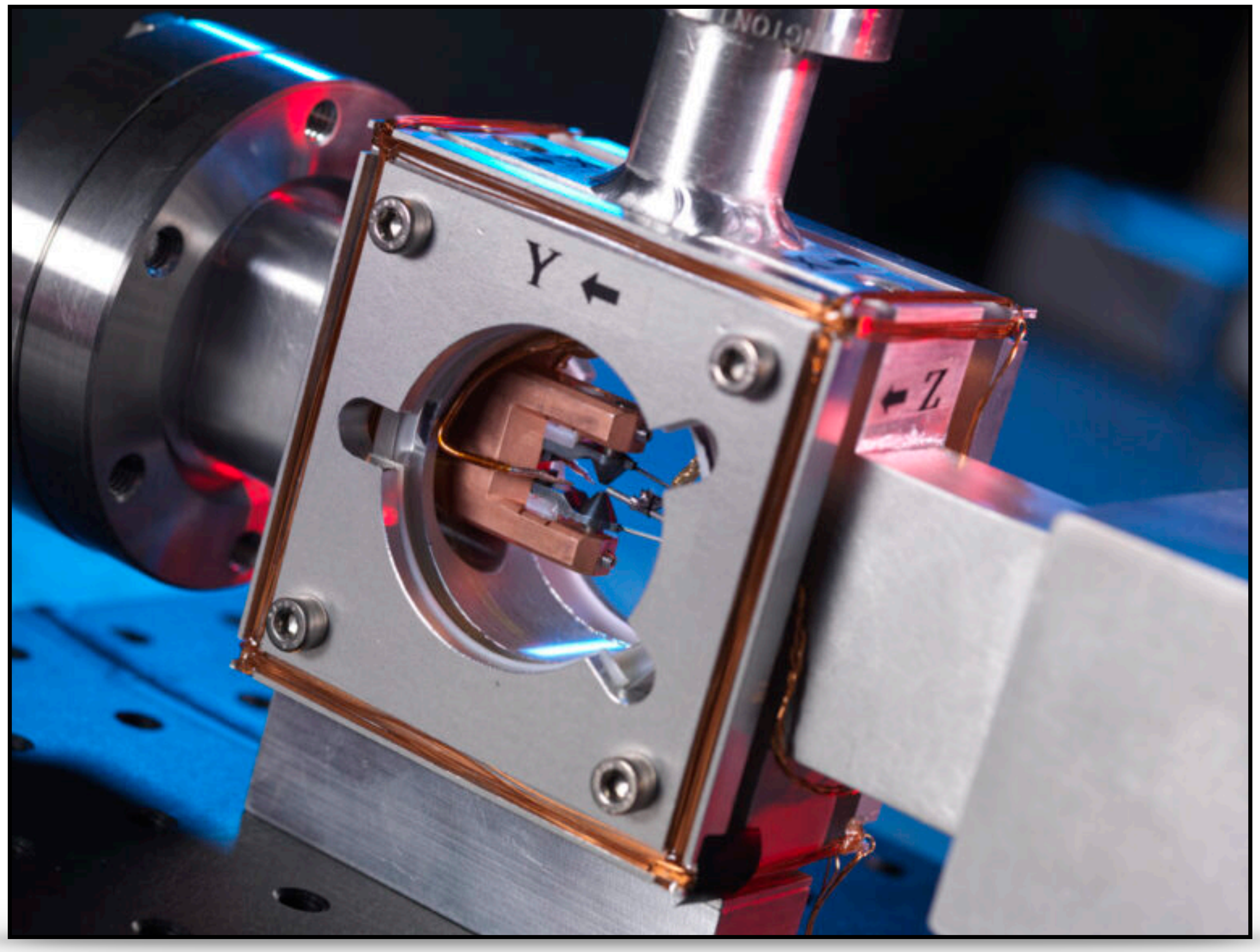

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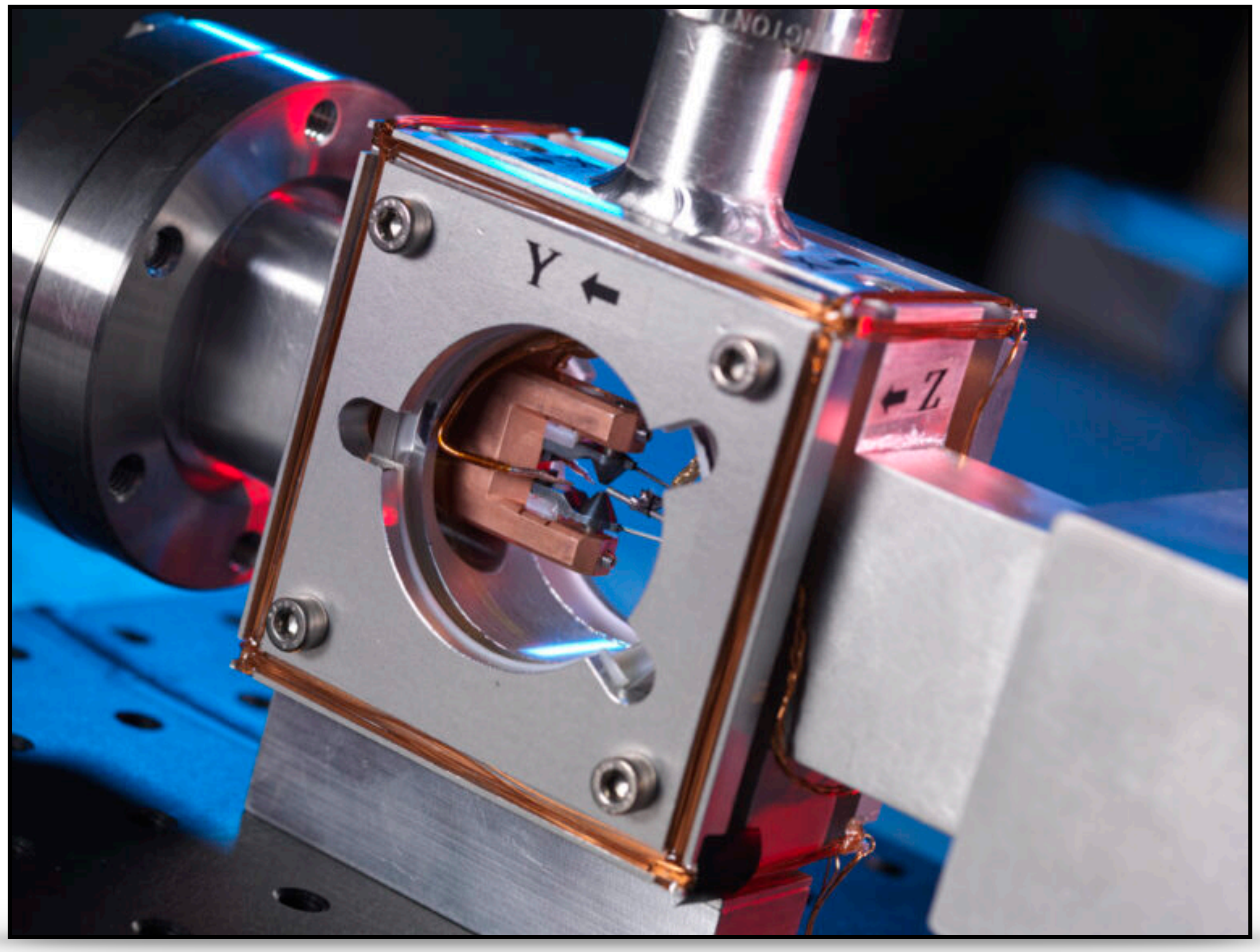

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$$K_g \equiv \frac{\partial \ln \nu}{\partial \ln g}$$

"sensitivity factor"
dependent on atom/transition

$$d\nu(g) = \frac{\partial \nu}{\partial g} dg \Leftrightarrow d\ln\nu = K_g \cdot d\ln g$$

V.V. Flambaum, V. A. Dzuba, Can. J. Phys. 87, 25 (2009)

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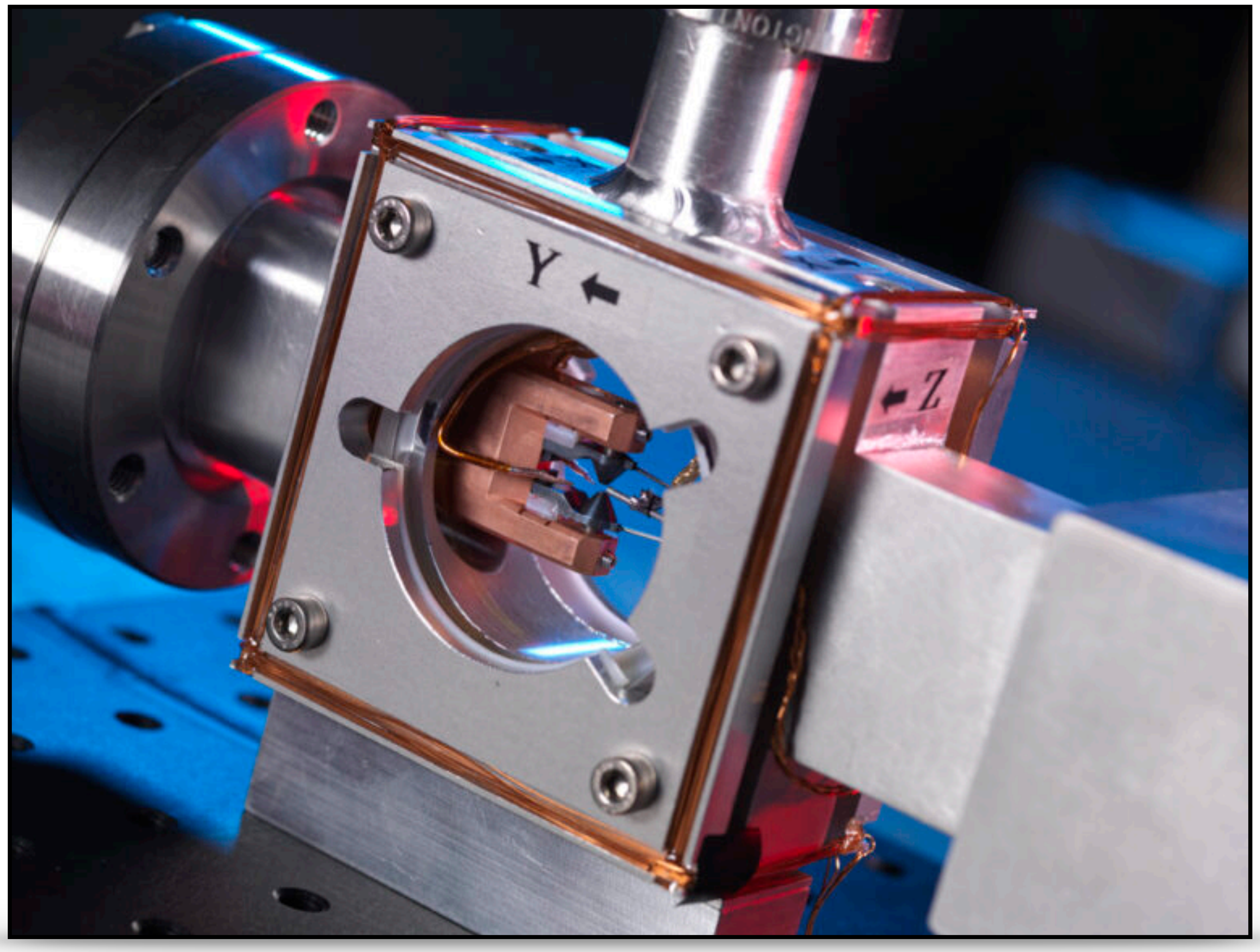

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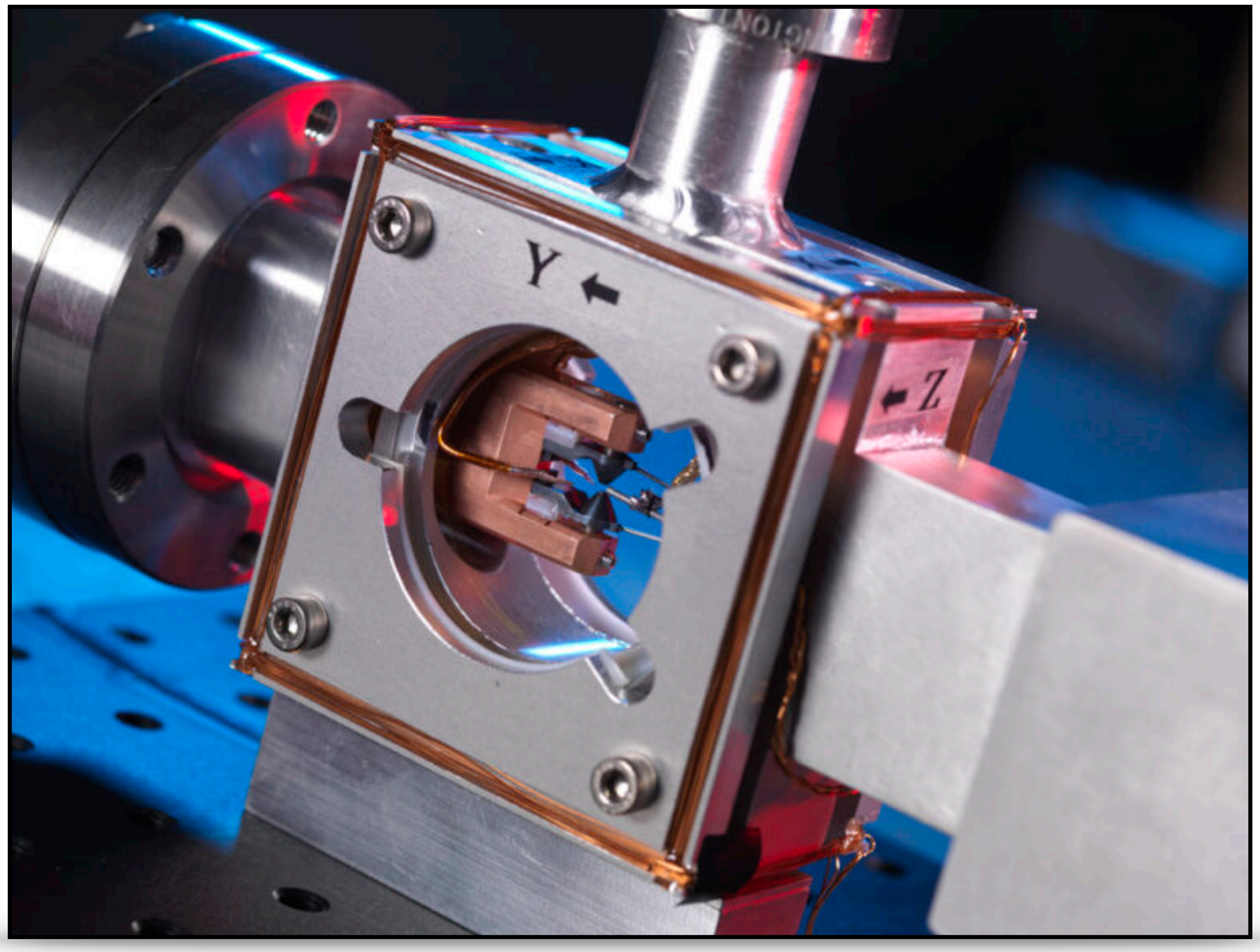

Measurements involve *comparisons*

- Cannot measure "absolute" variation
- Need a reference that has distinct sensitivity
- Ratio $r = \nu_1/\nu_2$ of two frequencies is dimensionless observable

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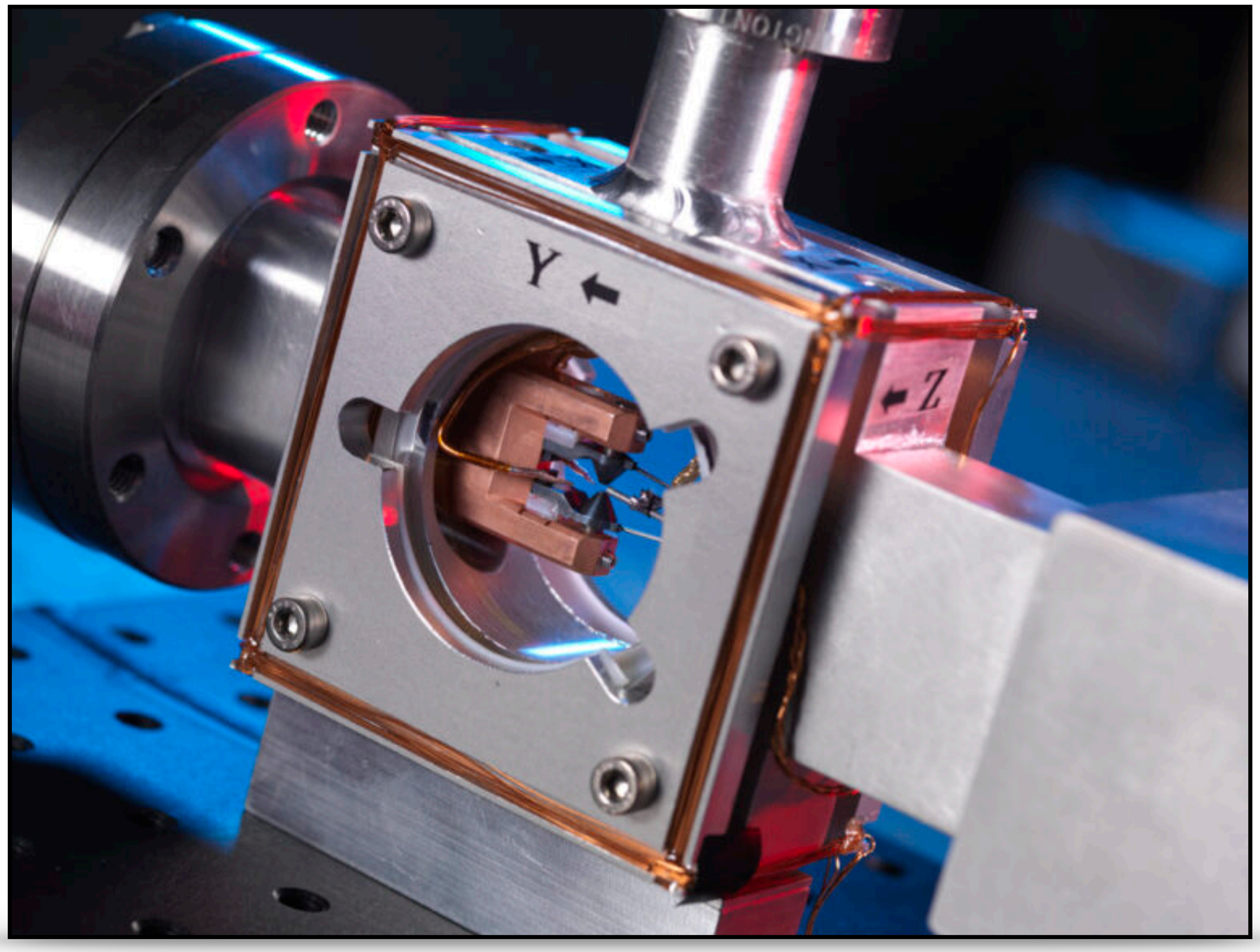

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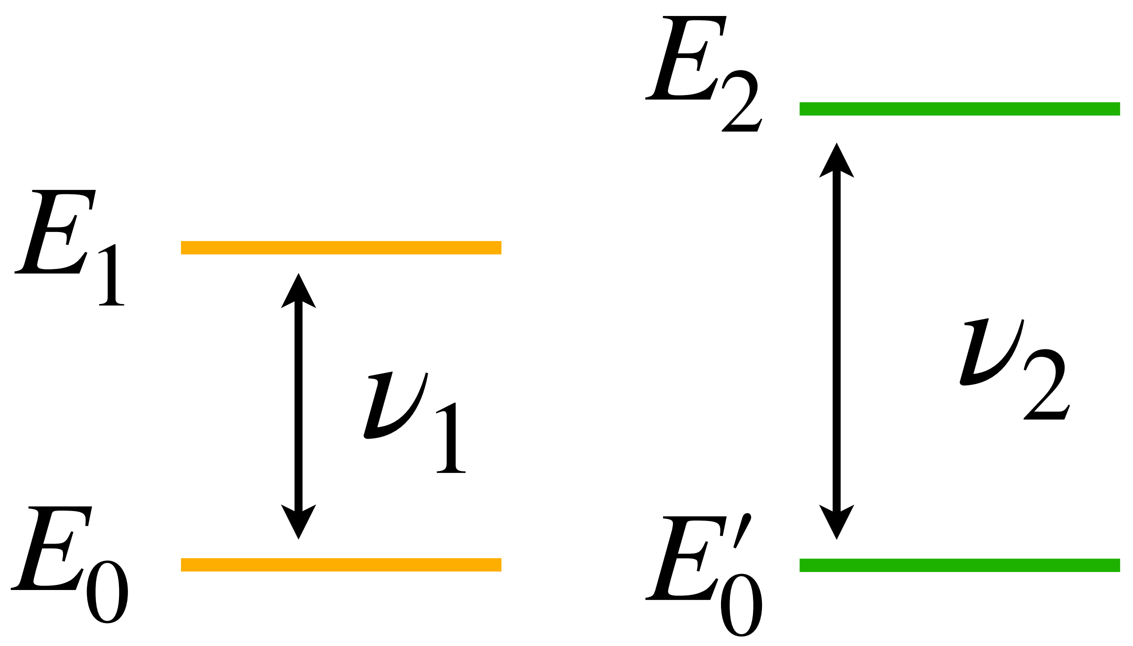
$$\left.\frac{\delta\nu}{\nu}\right|_{\text{Yb}^+} \approx 10^{-18}$$

"Off by 1 second after $T_{\text{Universe}} \approx 14$ billion yr"

Atomic clocks

The ratio of two clock transitions $\propto$ variation in dimensionless constants



$$\frac{\delta r}{r} = \sum_{g=\alpha,\mu,\cdots} \left(K_{g_1} - K_{g_2}\right) \frac{dg}{g}$$

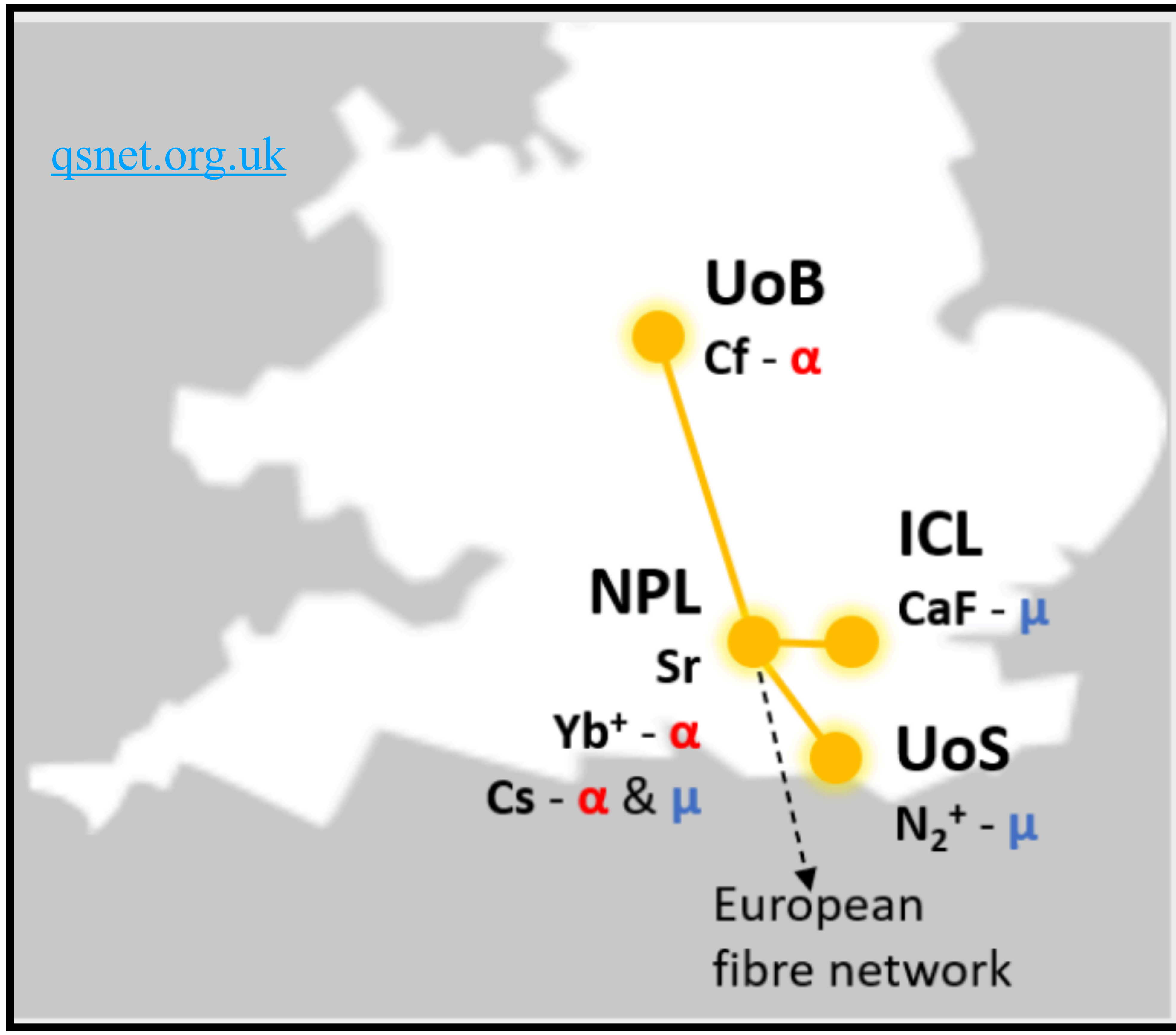
Exercise

- In general, ratio sensitive to a *linear combination* of FC variations
- Get additional enhancement from $\Delta K_g = K_{g_1} - K_{g_2}$
- Find atoms/transitions to maximize difference

QSNET

"A network of clocks for measuring the stability of fundamental constants"

G. Barontini et al., EPJ Quantum Technol. 9, 12 (2022)

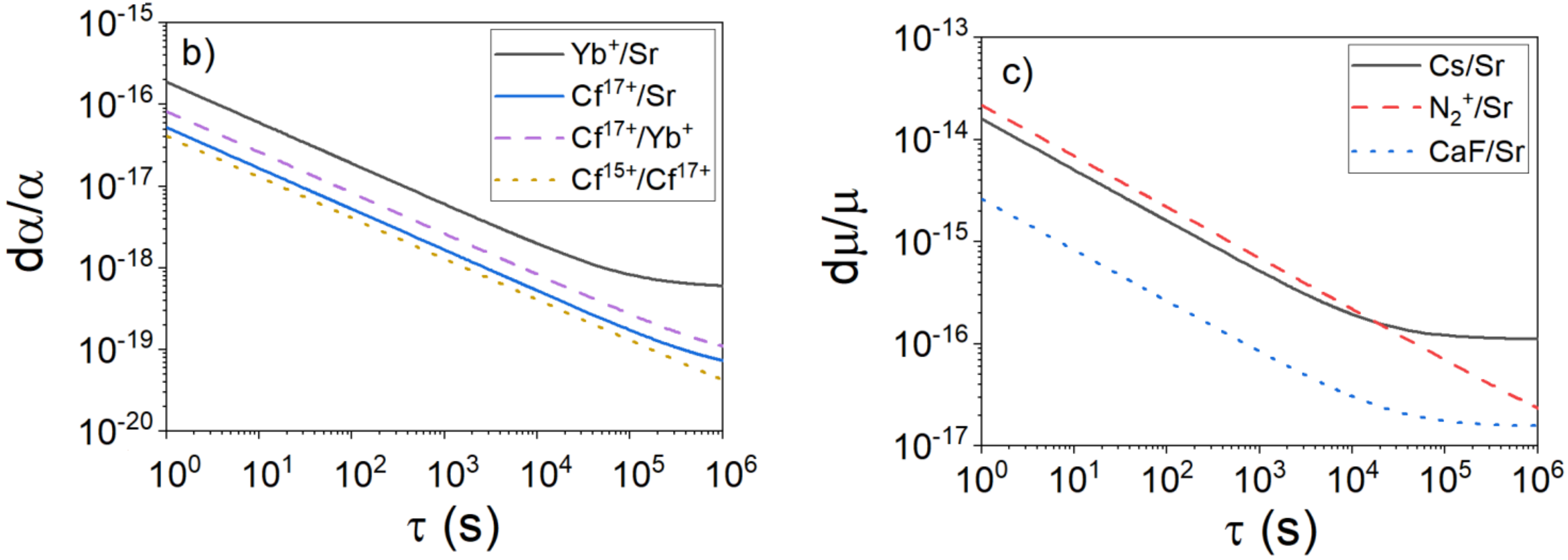


Clock	K_α	K_μ
Yb^+ (467 nm)	-5.95	0
Sr (698 nm)	0.06	0
Cs (32.6 mm)	2.83	1
CaF (17 µm)	0	0.5
N_2^+ (2.31 µm)	0	0.5
Cf^{15+} (618 nm)	47	0
Cf^{17+} (485 nm)	-43.5	0

Operational

Under construction

Projected QSNET sensitivities



Operational Yb^+, Sr, Cs **clocks at NPL have world-leading sensitivities**

Under construction Cf^+, CaF, N_2^+ **clocks bring improvements by > 1 order of magnitude**

Leading scalar-field interactions

Popular parametrization: leading couplings to QED + QCD:

$$\mathscr{L} = (\kappa\phi)^n \left(d_\gamma^{(n)} \frac{1}{4} F_{\mu\nu}F^{\mu\nu} - d_{m_e}^{(n)} m_e \bar{\psi}_e \psi_e \right) + \text{(analogous QCD terms)}$$

$$\kappa = \sqrt{4\pi G} = \left(\sqrt{2} M_P\right)^{-1}$$

$$\kappa^n d_j^{(n)} \leftrightarrow 1/\Lambda^n$$

- Operators normalized to reduced Planck mass M_P
- Couplings $d_j^{(n)}$ control oscillations

$$\alpha(\phi) = \alpha \left(1 + d_\gamma^{(n)} (\kappa\phi)^n \right) \Rightarrow \frac{\delta\alpha}{\alpha} = d_\gamma^{(n)} (\kappa\phi)^n$$

$$m_j(\phi) = m_j \left(1 + d_{m_j}^{(n)} (\kappa\phi)^n \right) \Rightarrow \frac{\delta m_j}{m_j} = d_{m_j}^{(n)} (\kappa\phi)^n \quad (j = e, u, d)$$

$$\Lambda_{\mathrm{QCD}}(\phi) = \Lambda_{\mathrm{QCD}} \left(1 + d_g^{(n)} (\kappa\phi)^n \right) \Rightarrow \frac{\delta\Lambda_{\mathrm{QCD}}}{\Lambda_{\mathrm{QCD}}} = d_g^{(n)} (\kappa\phi)^n$$

Leading scalar-field interactions

Parametrization of atomic frequency

V.V. Flambaum et al., Phys. Rev. D 69, 115006 (2004)

$$\nu = (\text{const.})\,(cR_\infty)\cdot\alpha^{K_\alpha}\cdot(m_e/\Lambda_{\rm QCD})^{K_\mu}\cdot(m_q/\Lambda_{\rm QCD})^{K_q}$$

$$\Rightarrow \quad \delta(\ln\nu) = K_\alpha\delta\ln\alpha + K_\mu\delta\ln\left(m_e/\Lambda_{\rm QCD}\right) + K_q\delta\ln\left(m_q/\Lambda_{\rm QCD}\right)$$

$$= K_\alpha d_\gamma^{(n)}(\kappa\phi)^n + K_\mu(d_{m_e}^{(n)} - d_g^{(n)})(\kappa\phi)^n + K_q(d_{m_q}^{(n)} - d_g^{(n)})(\kappa\phi)^n$$

Exercise

$$\Rightarrow \quad \boxed{\frac{\delta r}{r} = \Delta K_\alpha d_\gamma^{(n)}(\kappa\phi)^n + \Delta K_\mu(d_{m_e}^{(n)} - d_g^{(n)})(\kappa\phi)^n + \Delta K_q(d_{m_q}^{(n)} - d_g^{(n)})(\kappa\phi)^n}$$

What is $\delta r/r$ for QSNET clock ratios? Exercise

Application 1: particle dark matter

Decades of evidence strongly support the existence of **dark matter (DM)**

J. I. Read, J. Phys. G: Nucl. Part. Phys. 41 063101 (2014)

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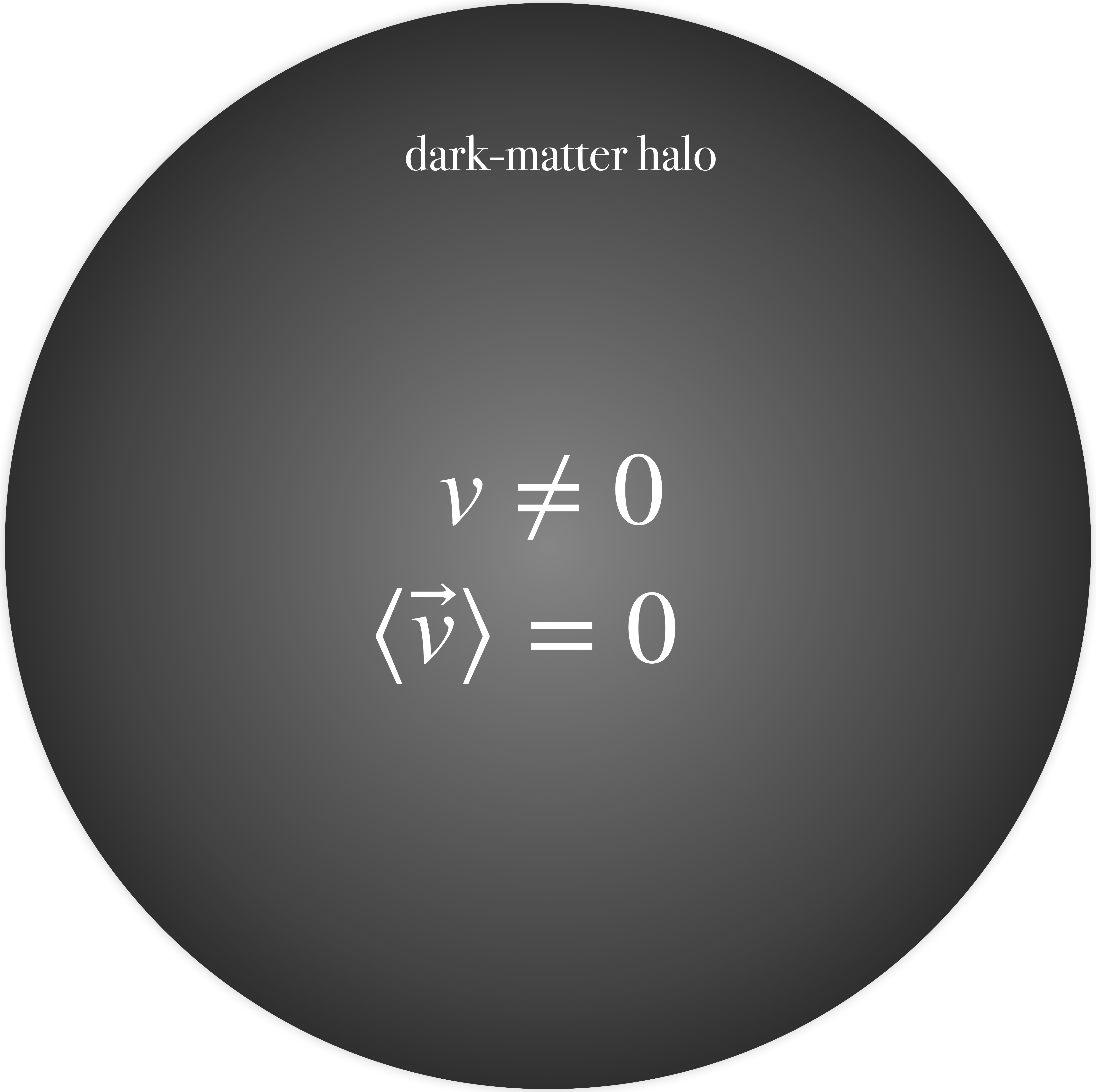
Galactocentric frame: *approx. isotropic velocity distribution*



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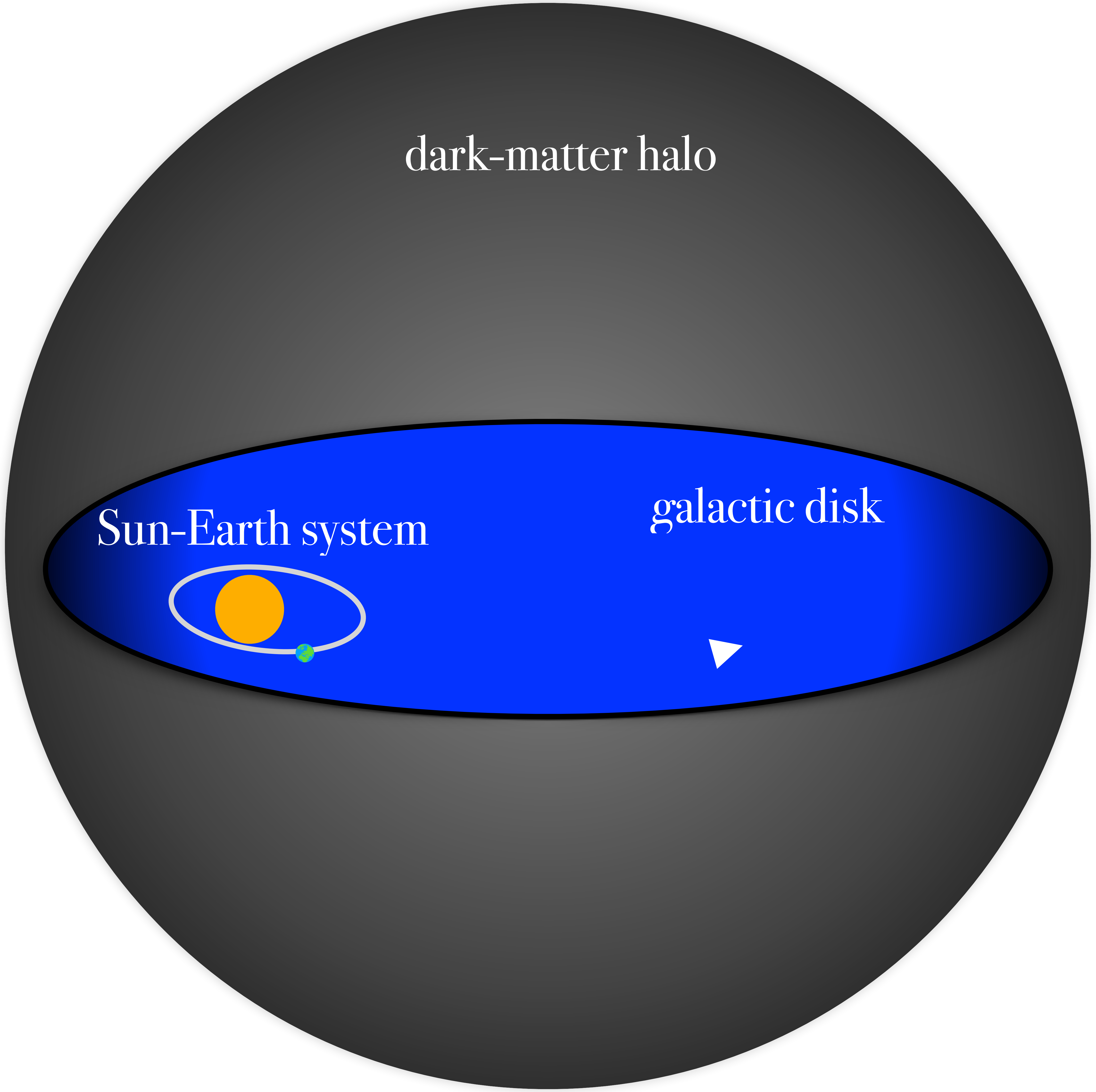

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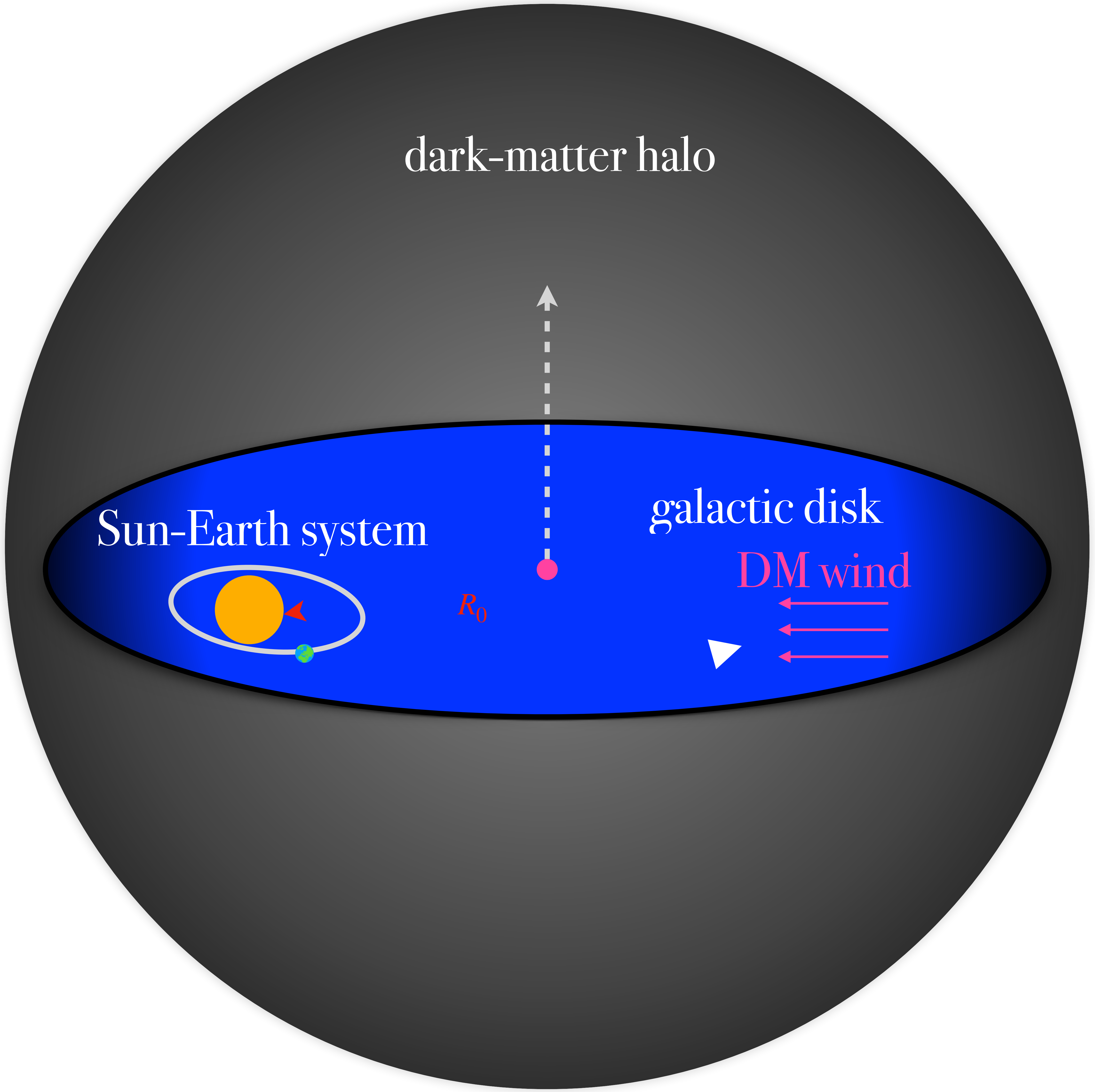
Application 1: particle dark matter

Decades of evidence strongly support the existence of **dark matter (DM)**

Galactocentric frame: *approx. isotropic velocity distribution*

Local (Earth-based) frame: *inferred* DM density* and DM "wind" velocity

$$\rho_{\rm DM}(R_0) \approx 0.3\ \mathrm{GeV/cm^3}$$
$$v_{\rm DM}^{\rm wind} \approx 10^{-3}c$$



J. I. Read, J. Phys. G: Nucl. Part. Phys. 41 063101 (2014)

Application 1: particle dark matter

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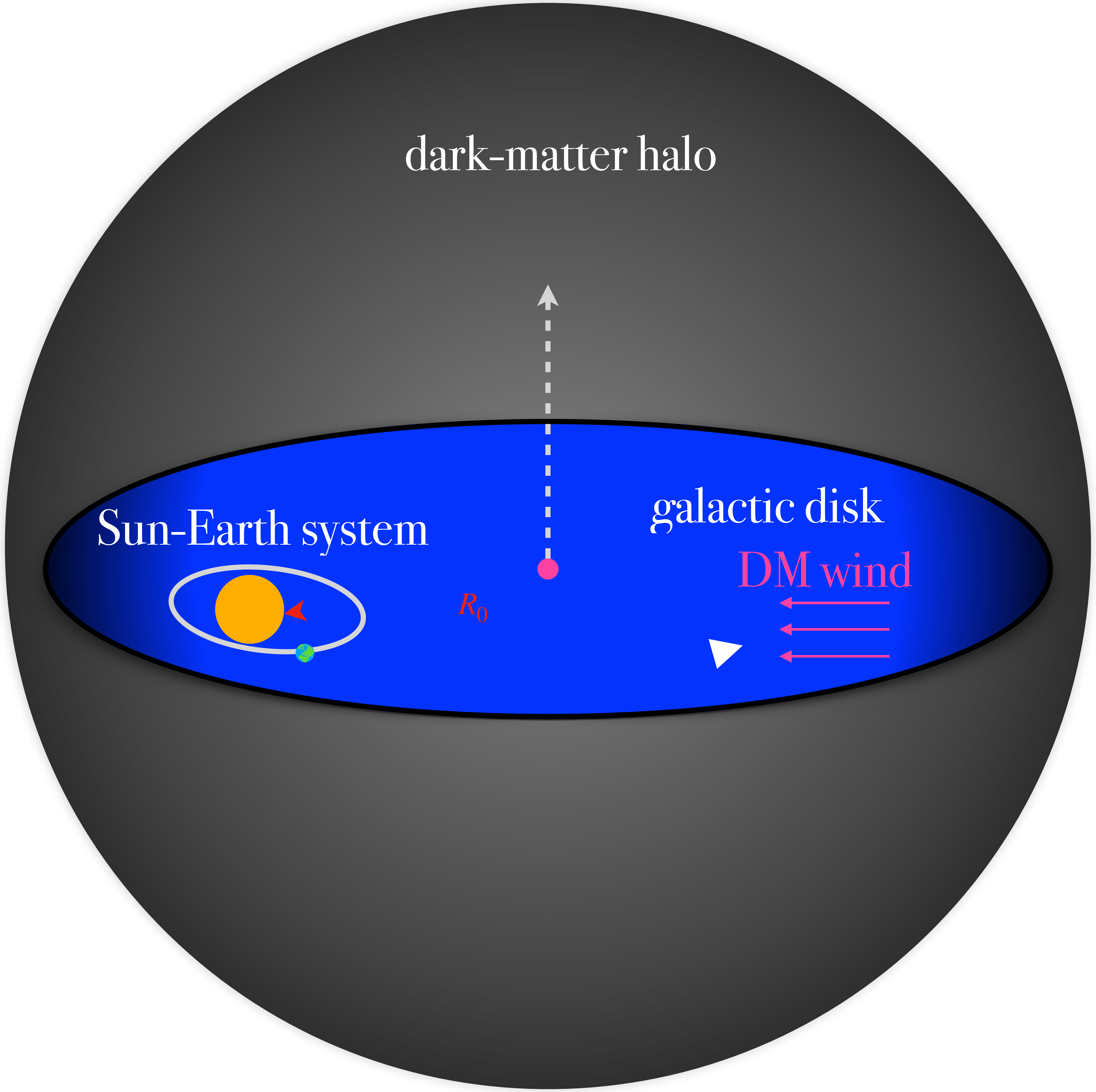

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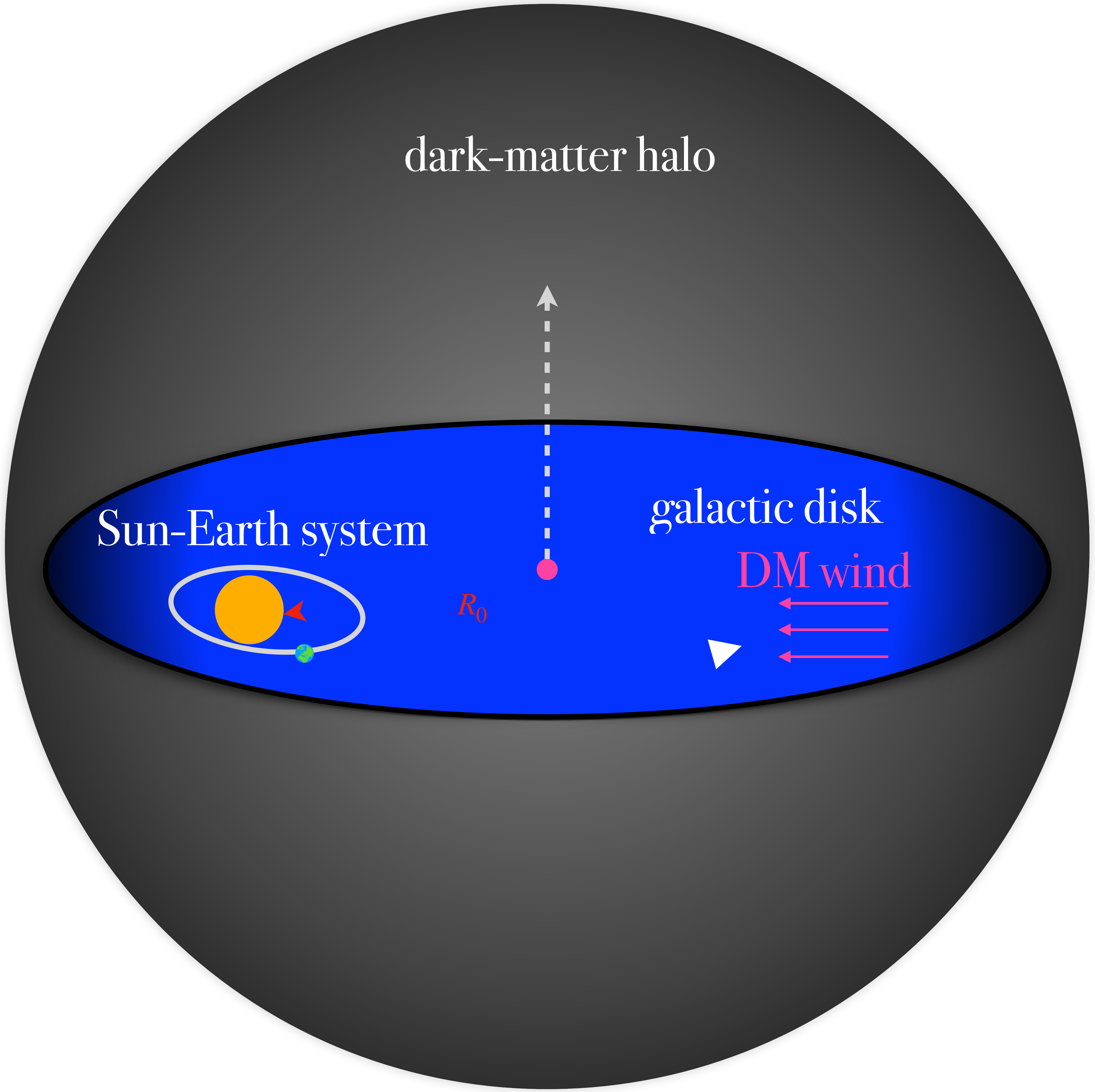

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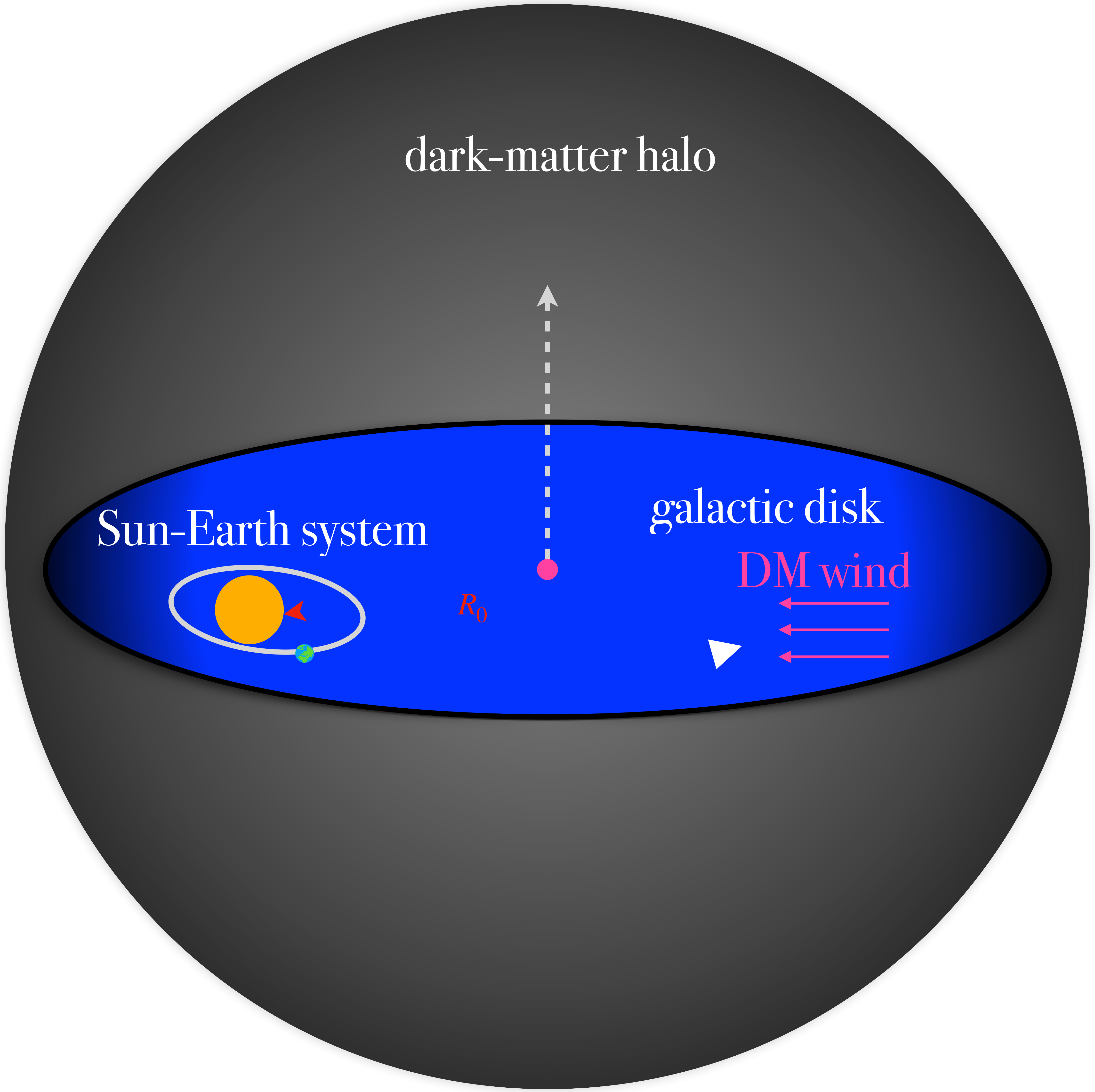
Note: *locally derived* ρ_{DM} estimates significantly less constrained!

$$\rho_{\mathrm{DM}}^{\mathrm{local}} \lesssim (10^4 - 10^6) \times \rho_{\mathrm{DM}}(R_0)$$

$\Rightarrow$ Implications for laboratory detection



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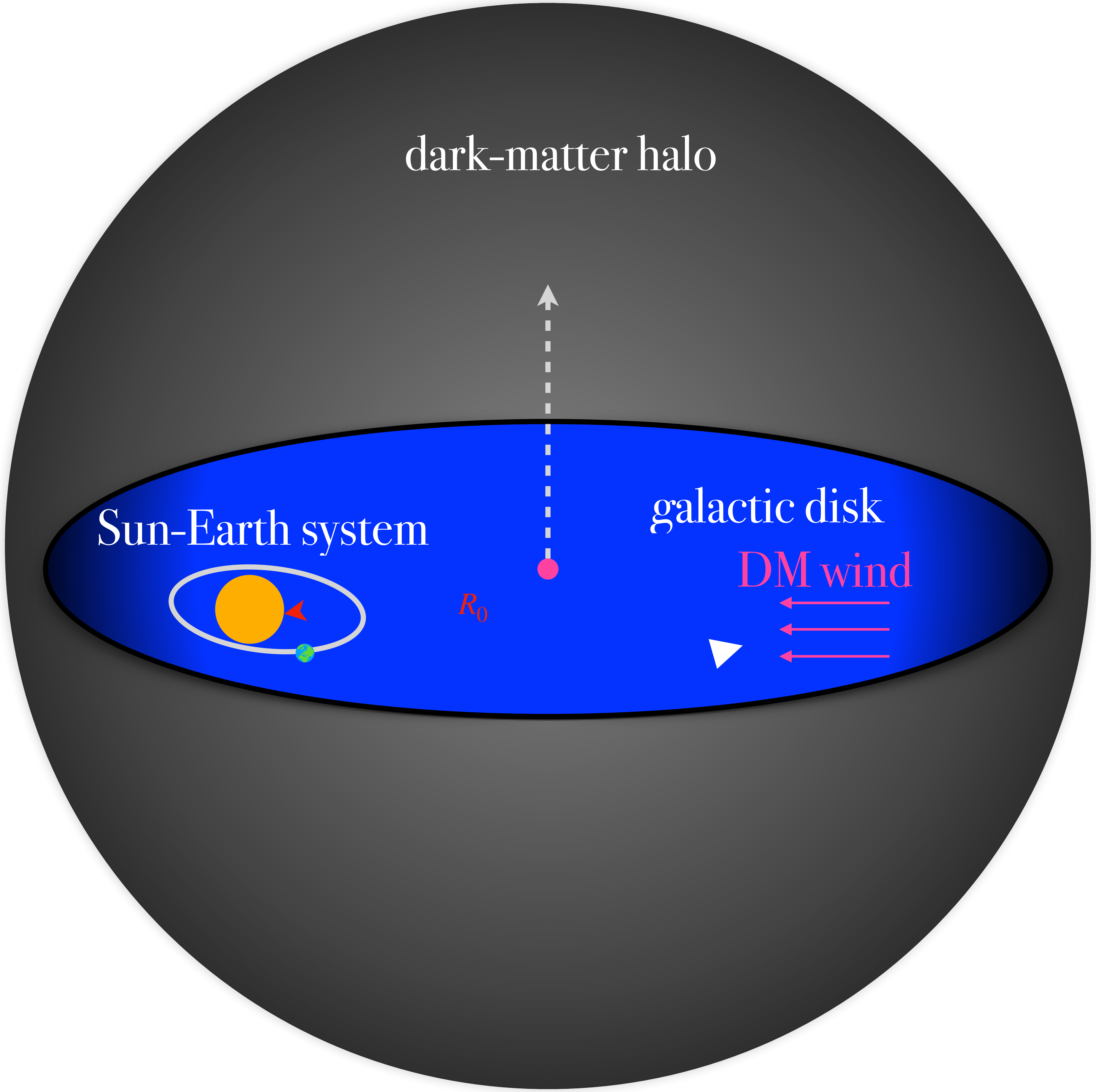
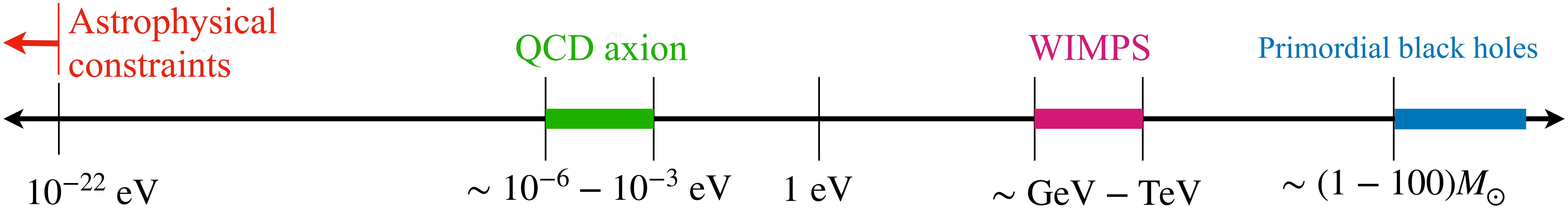
In a particular mass range, DM displays coherent-wave behavior



Ultralight DM

Range of dark-matter candidates is **enormous**



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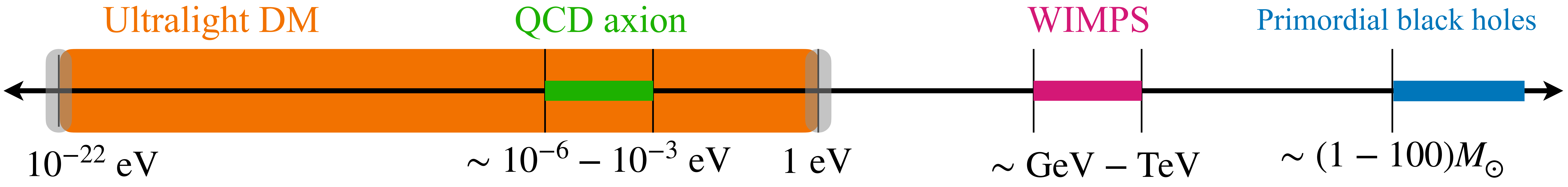

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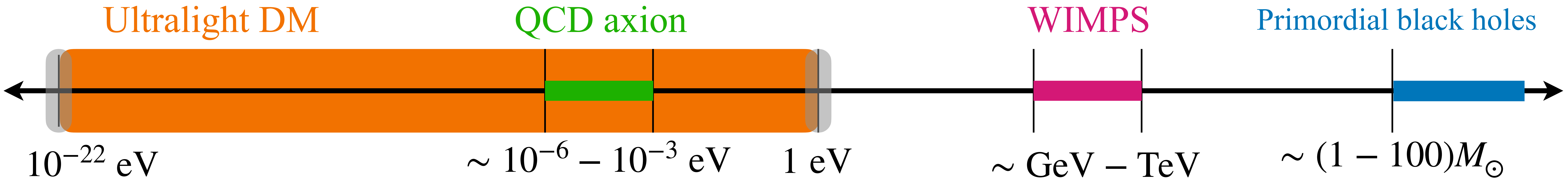

What *characterizes* mass range of ULDM?

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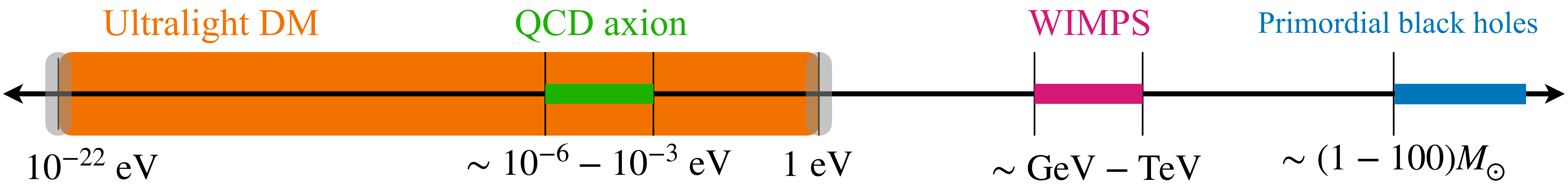

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- Upper limit: $\begin{cases} n \cdot \lambda_{\mathrm{DB}}^3 = \left(\frac{\rho_{\mathrm{DM}}}{m_{\mathrm{DM}}}\right) \cdot \left(\frac{2\pi}{m_{\mathrm{DM}} v_{\mathrm{DM}}}\right)^3 \gg 1 \\ \Rightarrow m \lesssim 1 \text{ eV} \end{cases}$

Exercise

Implies *bosonic* field

$\phi, \cancel{\psi}, A_\mu$

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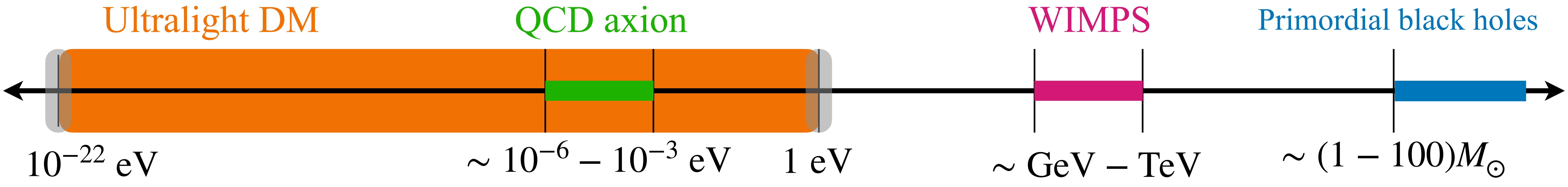

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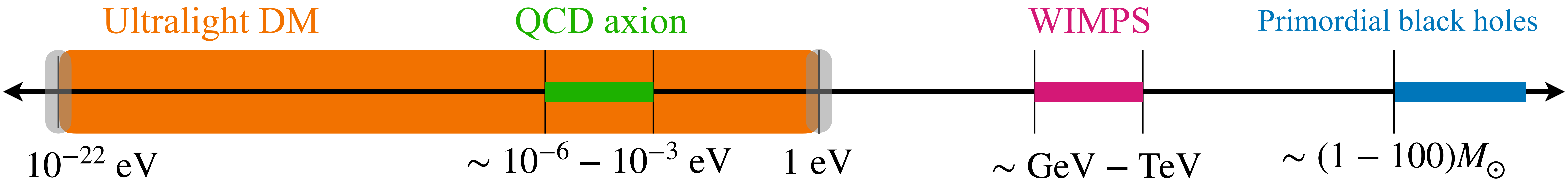
- Lower limit: $\begin{cases} \Delta x \Delta p \sim 1,\ \Delta x \sim 2 \times R_{\text{dwarf halo}} \approx 2 \times (1\text{kpc}),\ \Delta p \sim m v_{\text{dwarf halo}} \\ \Rightarrow m \gtrsim 10^{-22} \text{ eV} \end{cases}$

Exercise

Ultralight DM

Compton frequency tied to (rest) mass $$f_C = \frac{mc^2}{2\pi\hbar} \Rightarrow m = 2\pi f_C = \frac{2\pi}{T_C} \text{ (natural units)}$$

Ultralight DM



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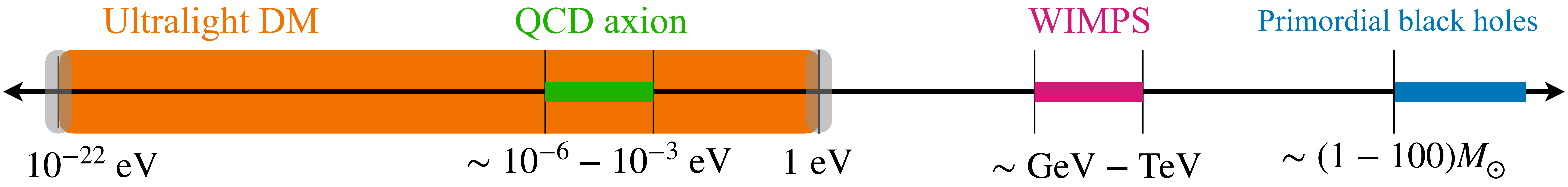

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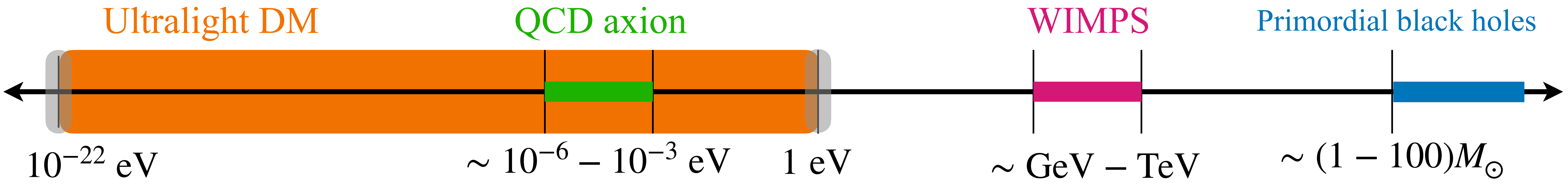
Exercise

ULDM = coherently oscillating scalar field!

$$\phi(\vec{x}, t) \approx \phi_0 \cos\left[m(1+\tfrac{1}{2}v^2)t + \delta(\vec{x}) \right]$$

Ultralight DM



Ultralight DM

DM known present in early universe:

- Typical treatment is scalar field evolving with FLRW metric
- Nonrelativistic time-averaged energy density gives prediction for field amplitude $\phi_0 = \sqrt{2\rho_{\mathrm{DM}}}/m$

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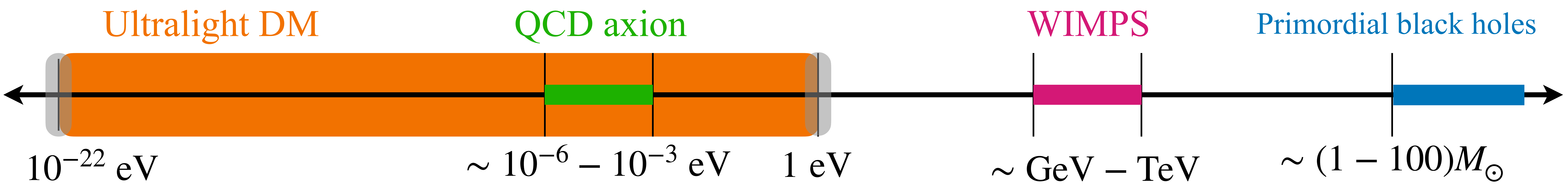

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$$\frac{\delta r}{r} = \sum_g \Delta K_g d_g^{(n)} (\kappa\phi)^n \quad \begin{cases} \dfrac{\sqrt{8\pi G \rho_{\rm DM}}}{m} \approx 6 \times 10^{-31} \dfrac{\rm eV}{m} \\ \text{oscillations up to n}^{\rm th} \text{ order harmonics of } m_\phi \end{cases}$$

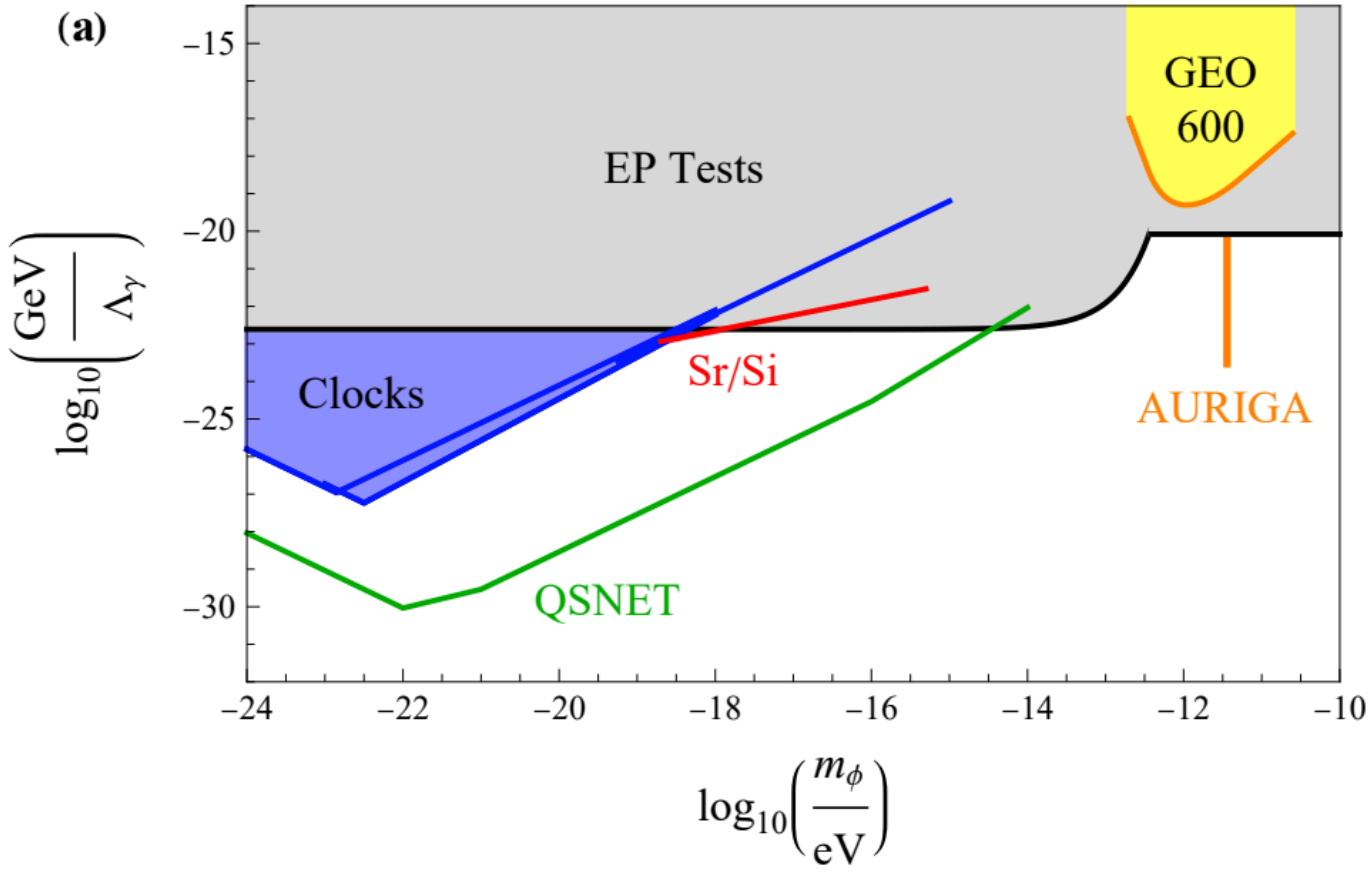
$$\kappa = \sqrt{4\pi G}$$

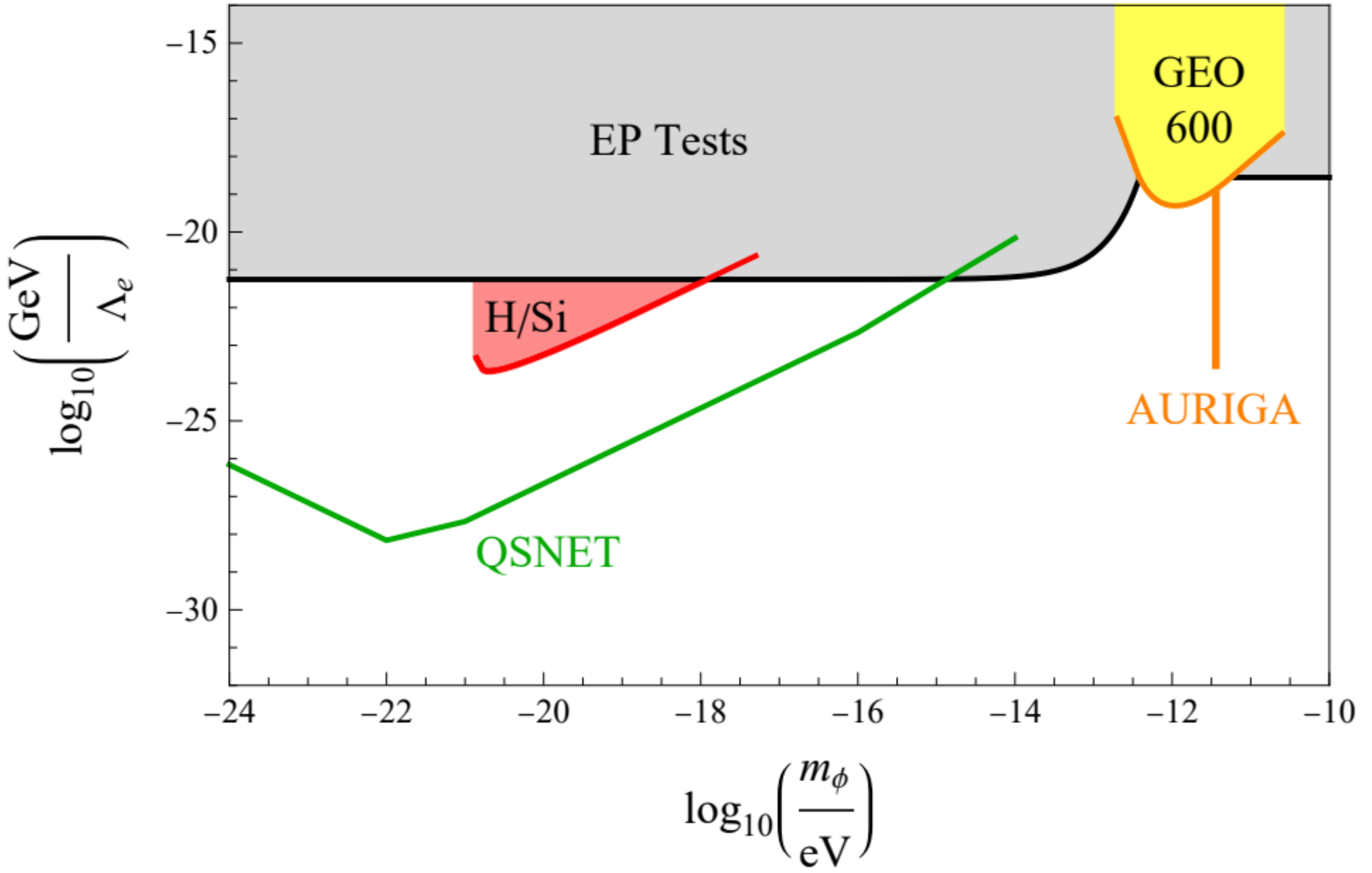
Exercise

Projected linear coupling constraints

$$(\kappa\phi)\, d_{\gamma}^{(1)} \frac{1}{4} F_{\mu\nu}F^{\mu\nu} \leftrightarrow \frac{\phi}{\Lambda_\gamma} \frac{1}{4} F_{\mu\nu}F^{\mu\nu}$$

$$-(\kappa\phi)\, d_{m_e}^{(1)} m_e \bar{\psi}_e \psi_e \leftrightarrow -\frac{\phi}{\Lambda_e} m_e \bar{\psi}_e \psi_e$$

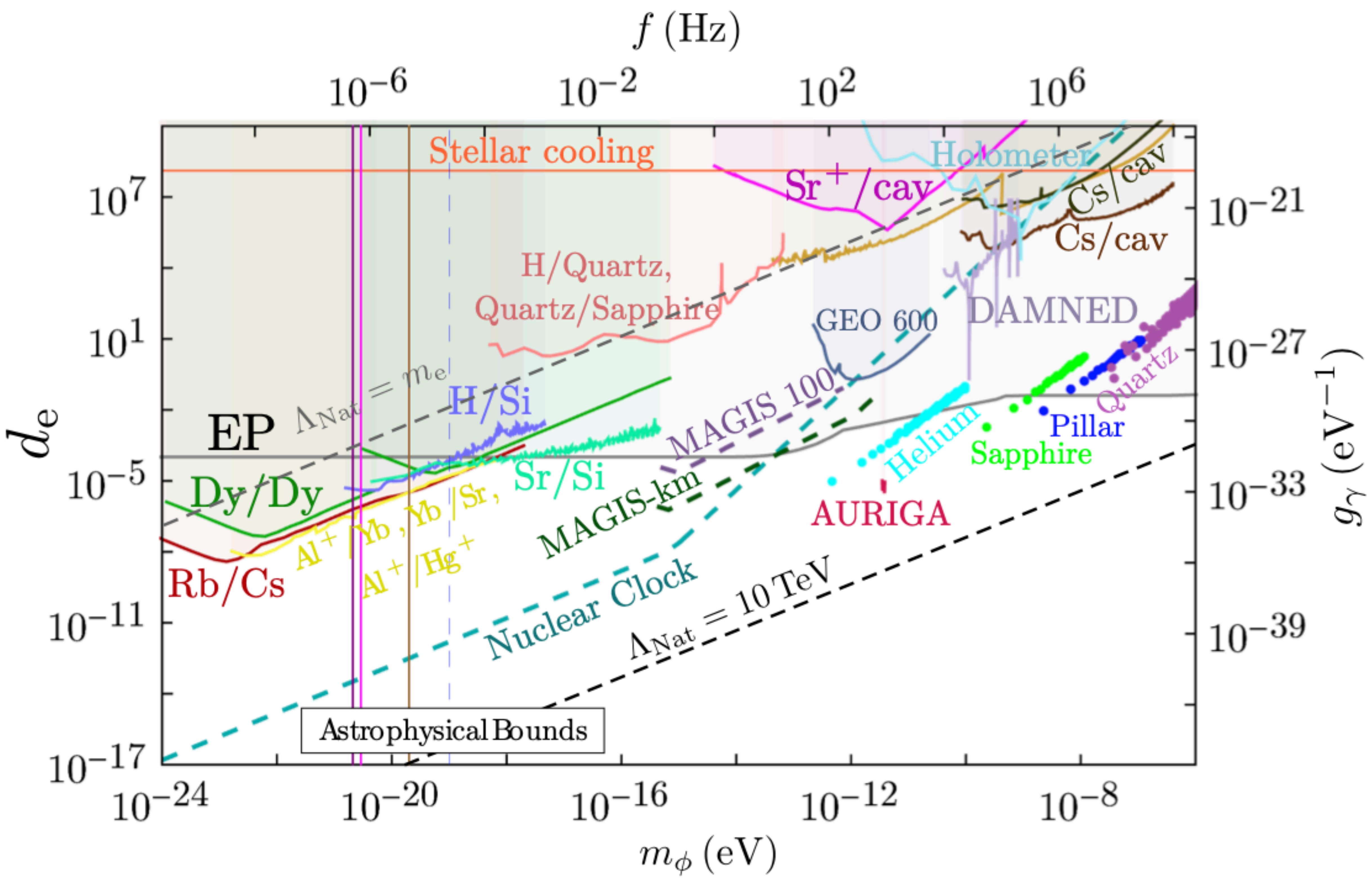




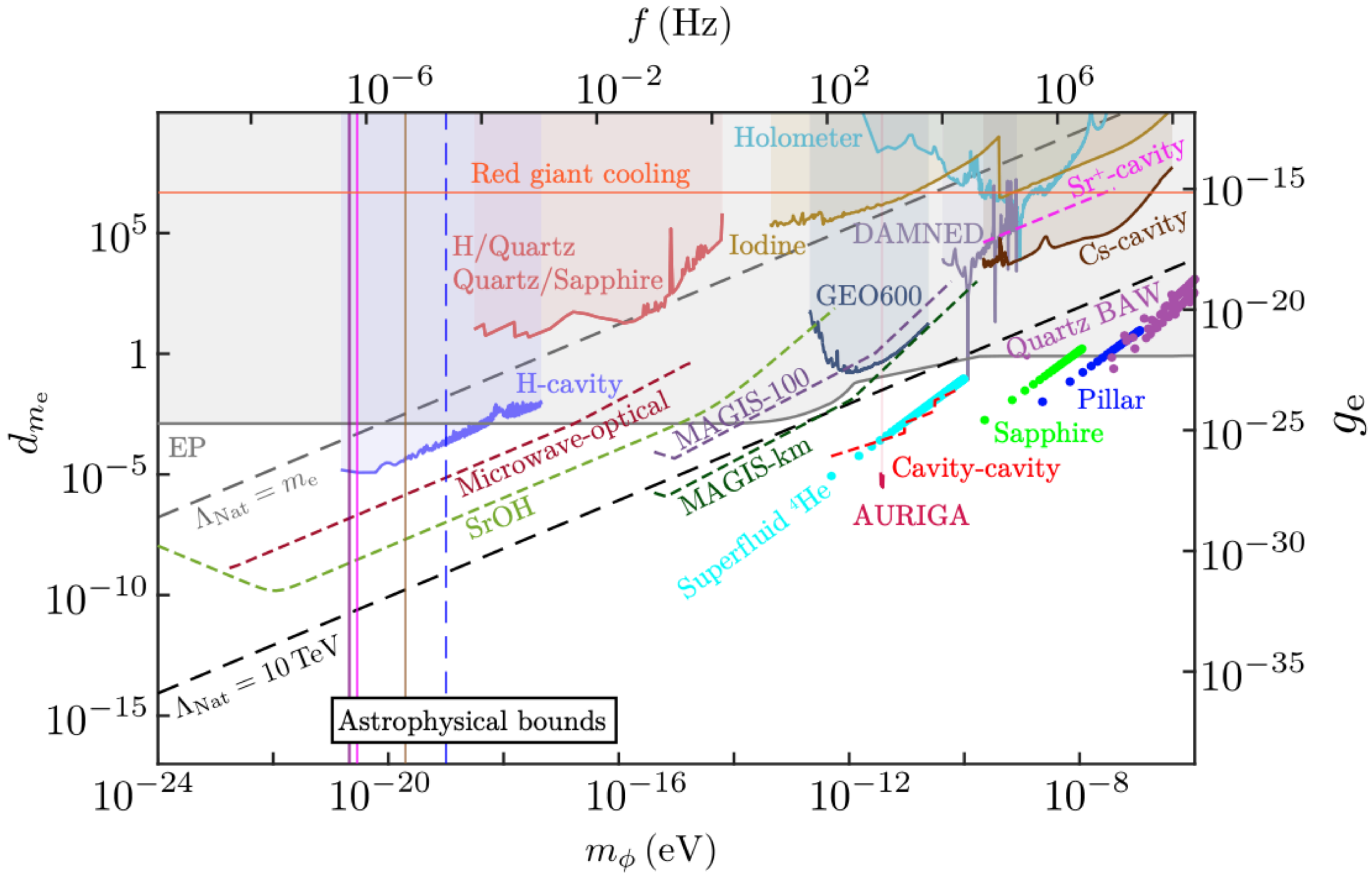
Sensitivity factors of QSNET clocks can increase existing constraints by over two orders in magnitude!

G. Barontini et al., EPJ Quantum Technol. 9, 12 (2022)

Constraints compilation



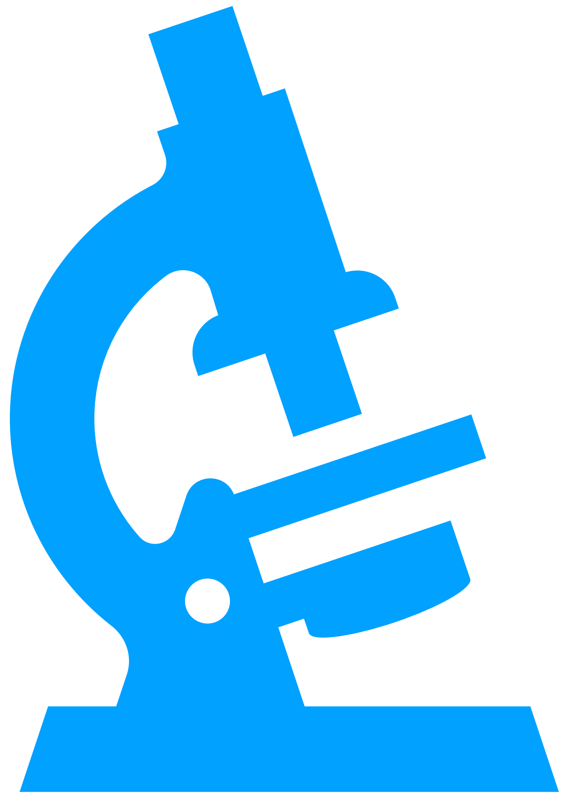
[New Horizons: Scalar and Vector Ultralight Dark Matter, 2022 Snowmass Summer Study]()



Application 2: Lorentz & CPT violation

Atomic clocks are also excellent probes of fundamental symmetries

Lorentz invariance: the laws of physics are independent of the relative velocity or orientation of an experiment in spacetime



Experiments observe system obeying the same laws of physics $\mathscr{L} \to \mathscr{L}$

Warning: does not mean different experiments will "measure the same thing"

$(\vec{v} = \vec{0}) \quad \tau = \tau_0$

$(\vec{v} \neq \vec{0}) \quad \tau = \tau_0/\gamma < \tau_0$

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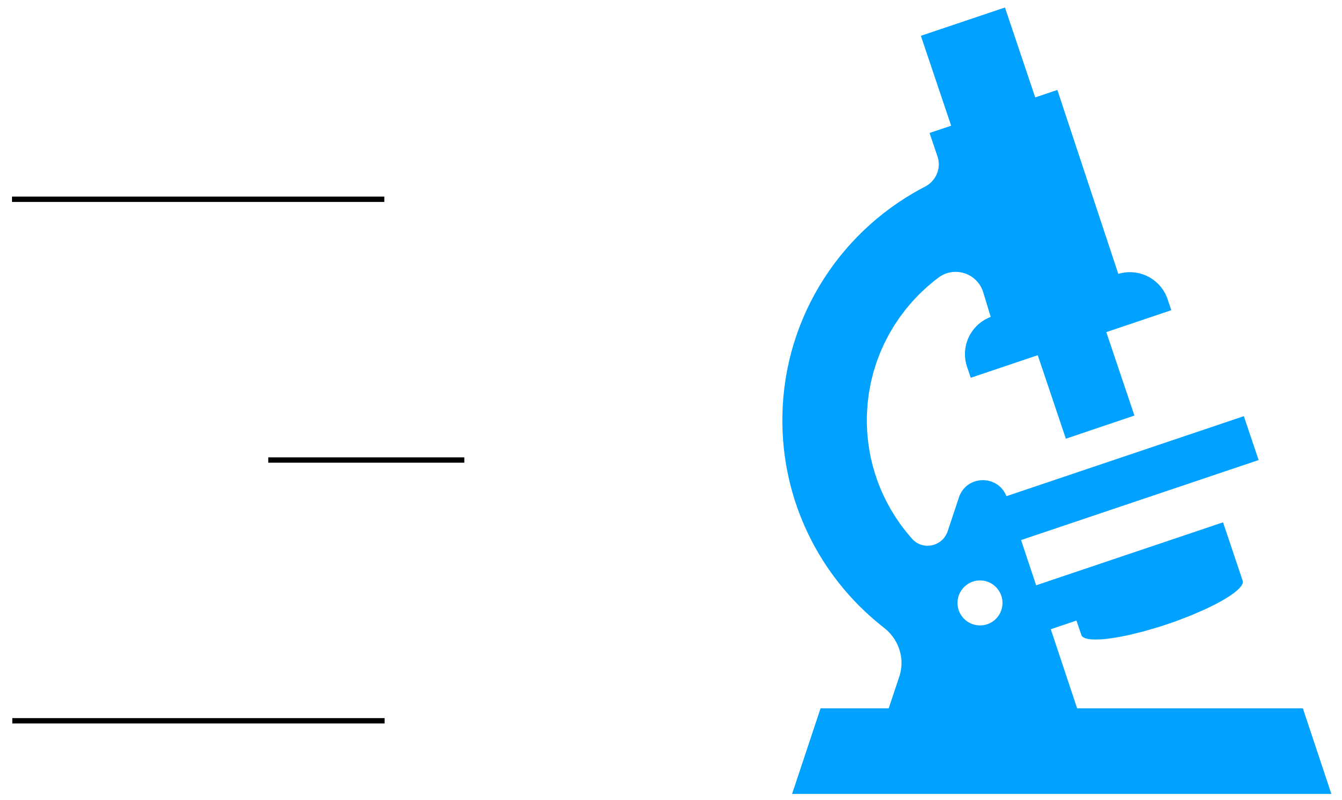

$\xrightarrow{\vec{v}}$ (boost)

Experiments observe system obeying the same laws of physics $\quad \mathscr{L} \rightarrow \mathscr{L}$

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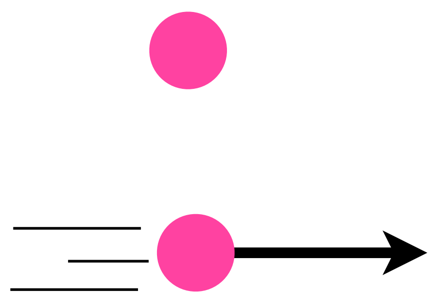

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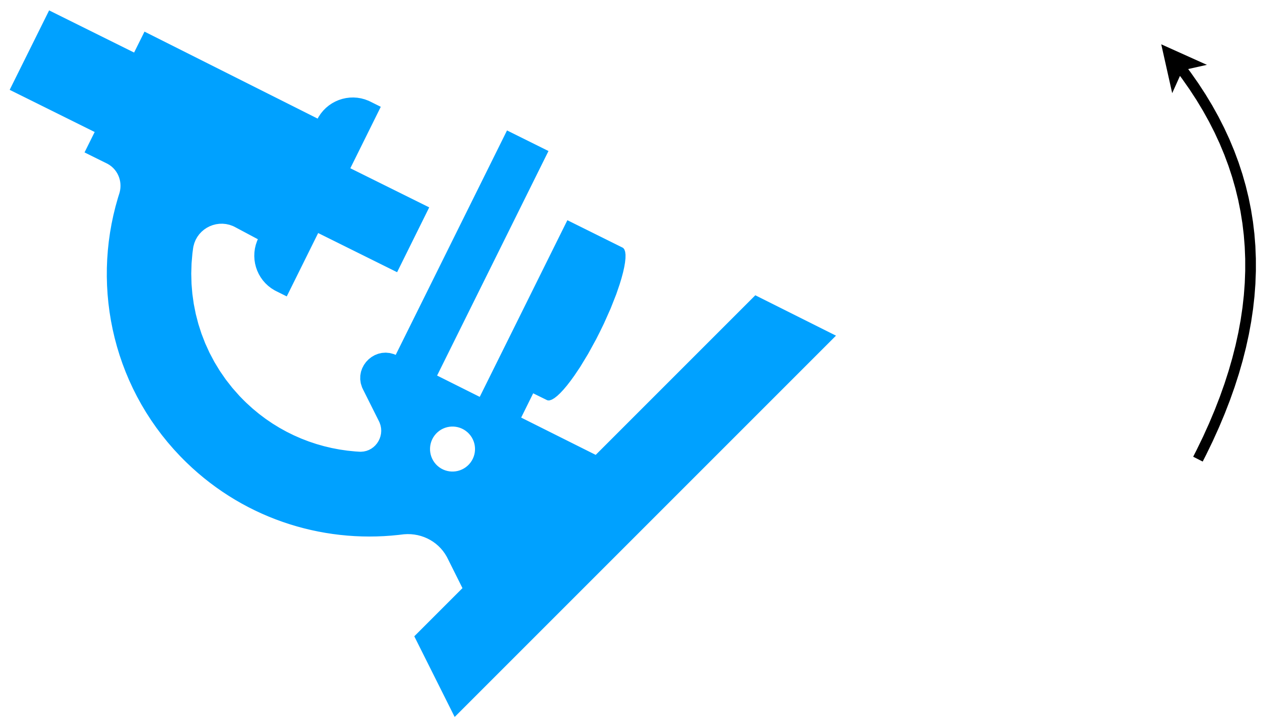

(rotation)

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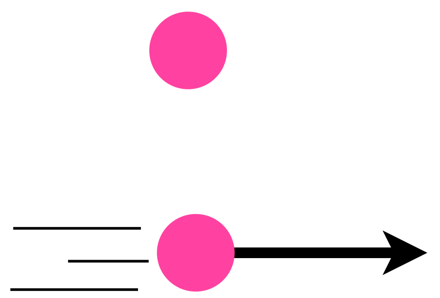

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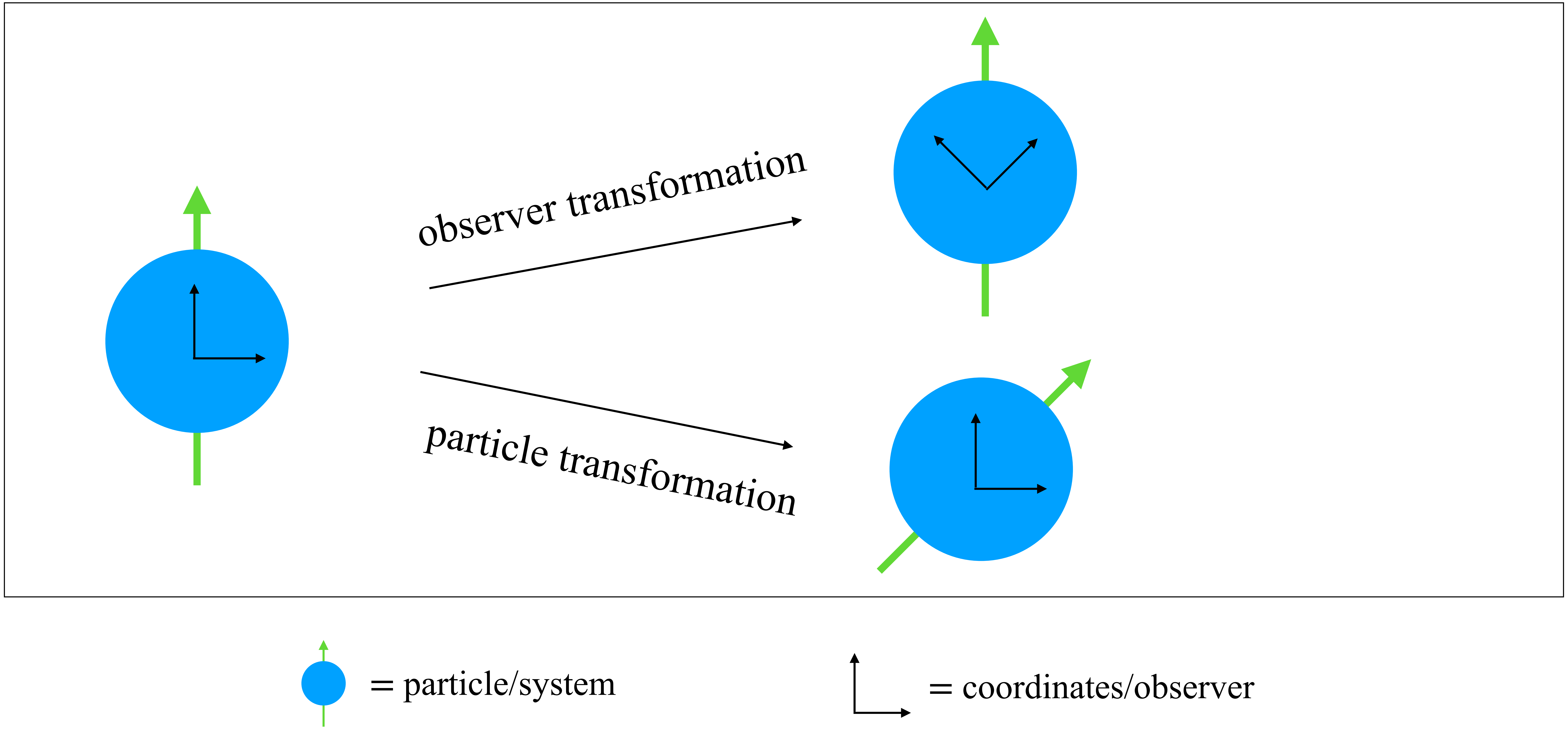
Observer vs. particle transformations

In Lorentz-*invariant* theories **observer** and **particle** transformations have indistinguishable effects



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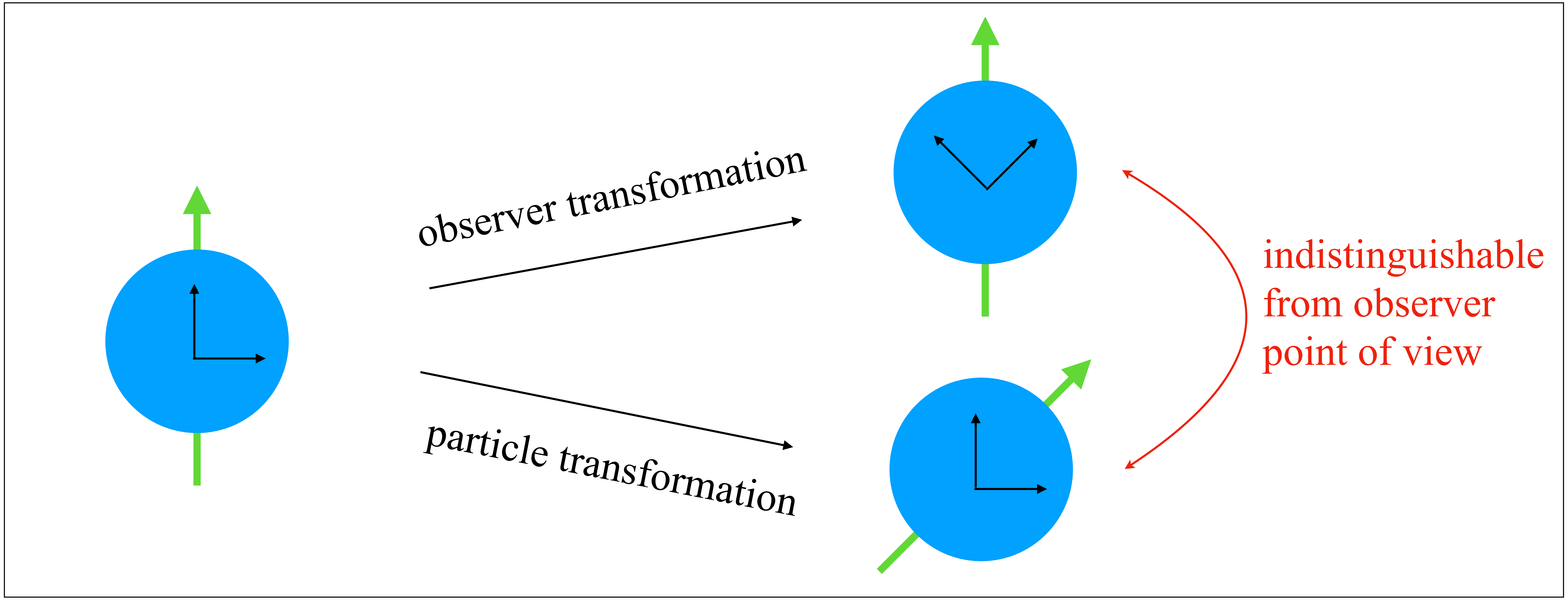
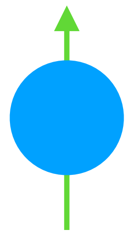
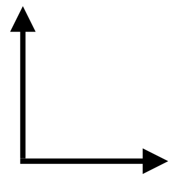


 = particle/system

 = coordinates/observer

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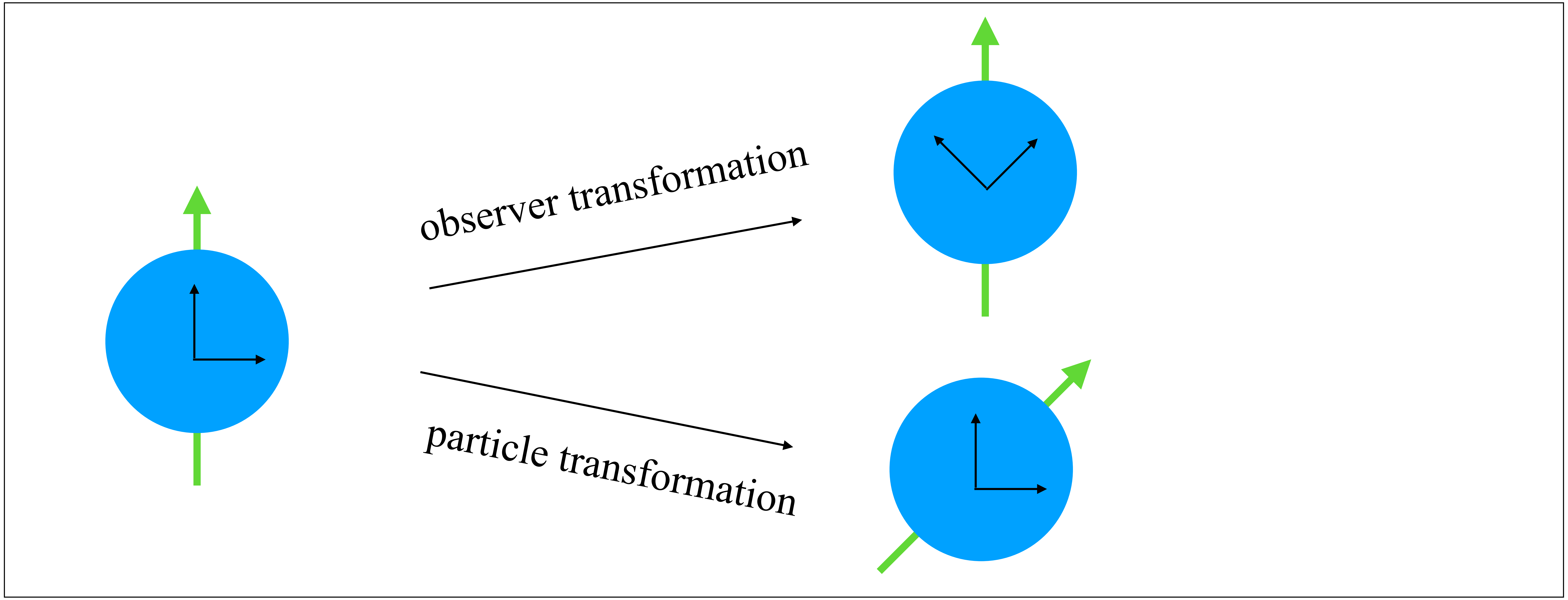
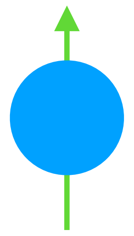
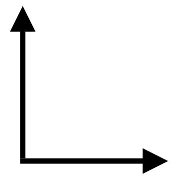
In Lorentz-*violating* theories **observer** and **particle** transformations are generically ***inequivalent***



 = particle/system

 = coordinates/observer

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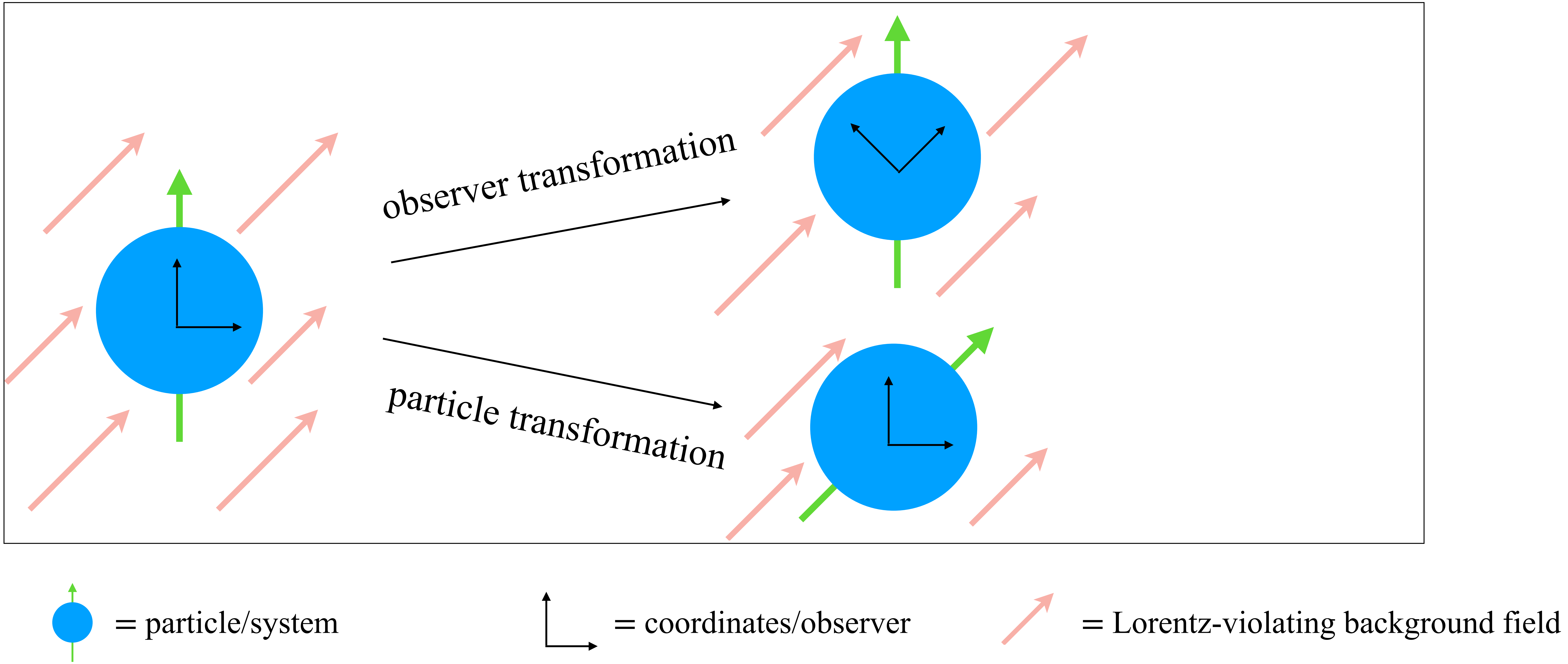

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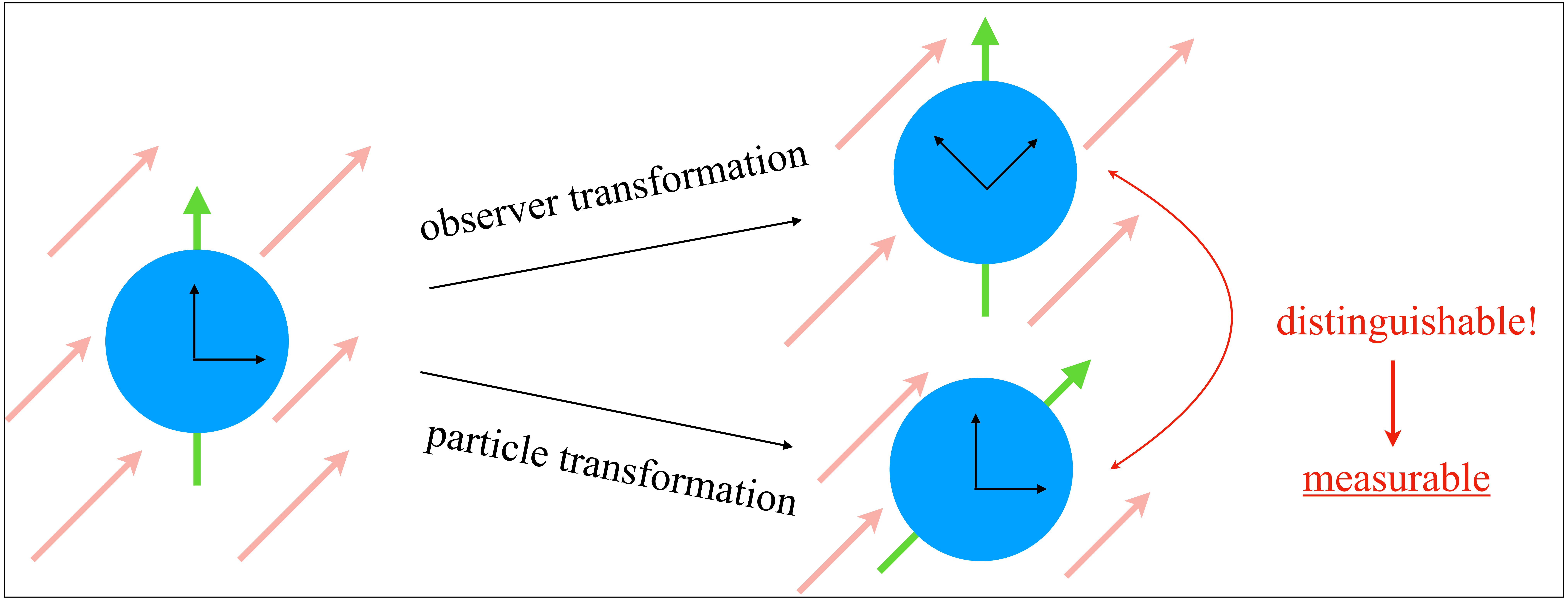
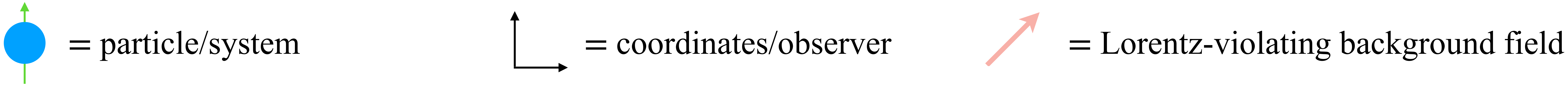




Standard-Model Extension (SME)

Lorentz- and CPT-violating effects are generically parametrized in an **EFT** known as the Standard-Model Extension (SME)

D. Colladay, V. A. Kostelecky, PRD 55, 6760 (1997); PRD 58, 116002 (1998);

$$\text{SME} = \text{SM} + \text{GR} + \text{LV}$$

Contains all possible terms that break Lorentz and CPT symmetry in **EFT**

$$\mathscr{L}_{\text{LV}} \supset k^{\mu\cdots}{}_{\nu\cdots}{}^{a\cdots}(x)\,\mathcal{O}_{\mu\cdots}{}^{\nu\cdots}{}_{a\cdots}(x)$$

V. A. Kostelecky, Z. Li PRD 103, 024059 (2021)

- Much more complex couplings possible
- Classified my mass dimension d

$d \leq 4$ "Minimal SME" e.g. $-a_\mu \underbrace{\bar{\psi}\gamma^\mu\psi}_{d=3} \Rightarrow [a_\mu] = \text{GeV}$

$d > 4$ "Nonminimal SME" e.g. $-\frac{1}{4}k^{\alpha\kappa\lambda\mu\nu} \underbrace{F_{\kappa\lambda}\partial_\alpha F_{\mu\nu}}_{d=5}$

Minimal SME properties

$SU(3) \times SU(2) \times U(1)$ structure	✓
$SU(2) \times U(1)$ breaking	✓
Renormalizability	✓
Spin statistics	✓
Observer Lorentz invariance	✓
Energy-momentum conservation	✓
Quantization	✓
Microcausality	✓
Particle Lorentz invariance	✗
CPT invariance	✗

Dominant effects for clocks

Electromagnetic interactions dominant

$$\mathcal{L}_{\mathrm{LV}}^{\mathrm{clocks}} \supset \frac{1}{2} i \bar{\psi} \widehat{\Gamma}_\nu \overleftrightarrow{D}^\nu \psi - \bar{\psi} \widehat{M} \psi \qquad \psi = \{\psi_e, \psi_p, \psi_n\}$$

$$\widehat{\Gamma}_\nu = \gamma_\nu + \widehat{c}_{\mu\nu}\gamma^\mu + \widehat{d}_{\mu\nu}\gamma_5\gamma^\mu + \widehat{e}_\nu + i\widehat{f}_\nu\gamma_5 + \tfrac{1}{2}\widehat{g}_{\lambda\mu\nu}\sigma^{\lambda\mu}$$

$$\widehat{M} = m + \widehat{a}_\mu\gamma^\mu + \widehat{b}_\mu\gamma_5\gamma^\mu + \tfrac{1}{2}\widehat{H}_{\mu\nu}\sigma^{\mu\nu}$$

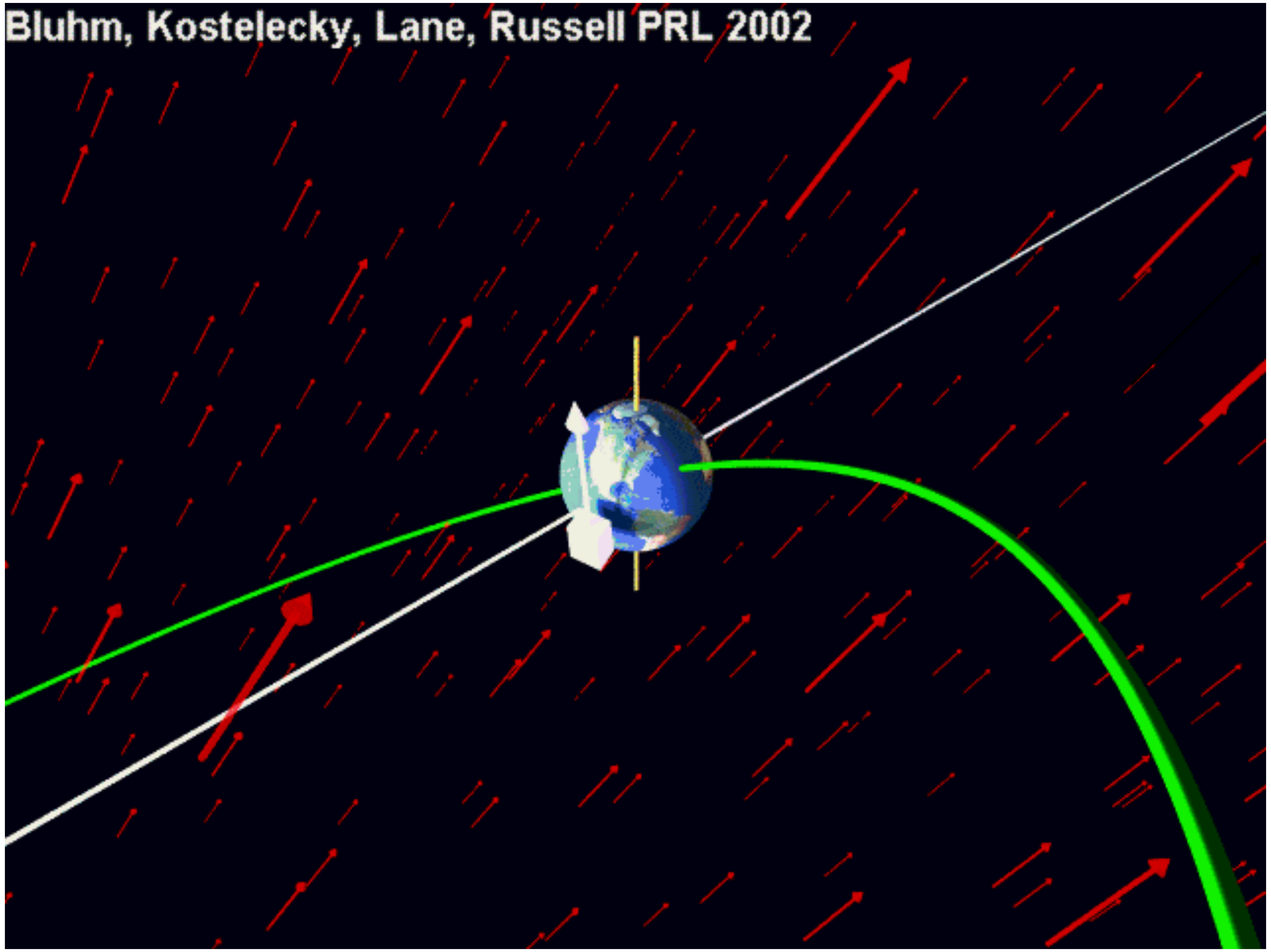
A small subset of effects studied to date

Basic procedure:

1. Construct full atomic perturbation $\qquad \delta h_{\mathrm{atom}} = \delta h_{\mathrm{electron}} + \delta h_{\mathrm{proton}} + \delta h_{\mathrm{nucleon}}$
2. Calculate shifted spectra & observables $\qquad \delta E_{\mathrm{atom}} = \langle F, m_F | \delta h_{\mathrm{atom}} | F, m_F \rangle$
3. Compare with experiment

Sidereal oscillations

Laboratories near and on the Earth's surface are typically noninertial



(Animation)

As Earth goes around the Sun, the orientation of the background field in the lab frame changes

$\Rightarrow$ Time dependence appears in lab observables

Convenient to choose inertial frame fixed on Sun to report constraints/ compare experiments from different labs

$$\sigma_{\rm LV} \approx \sigma_{\rm SM} + c_{\rm lab}(T_\oplus)\delta\sigma_{\rm LV}$$

$$c_{\rm lab}(T_\oplus) = c_{\rm sun}\cos(\omega_\oplus T_\oplus) + \cdots$$

sidereal frequency $\approx 2\pi/(23\text{ h }56\text{ min})$

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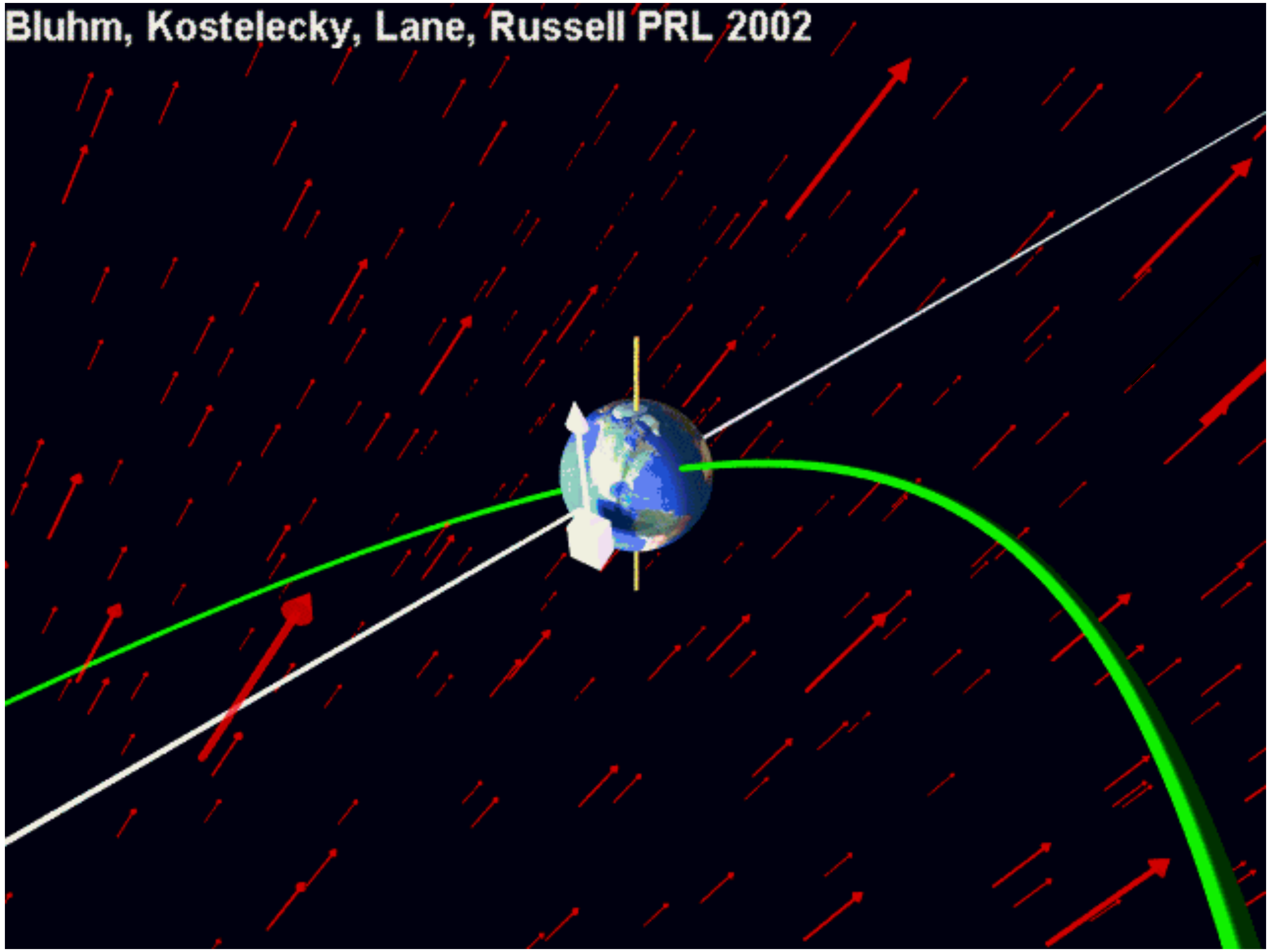

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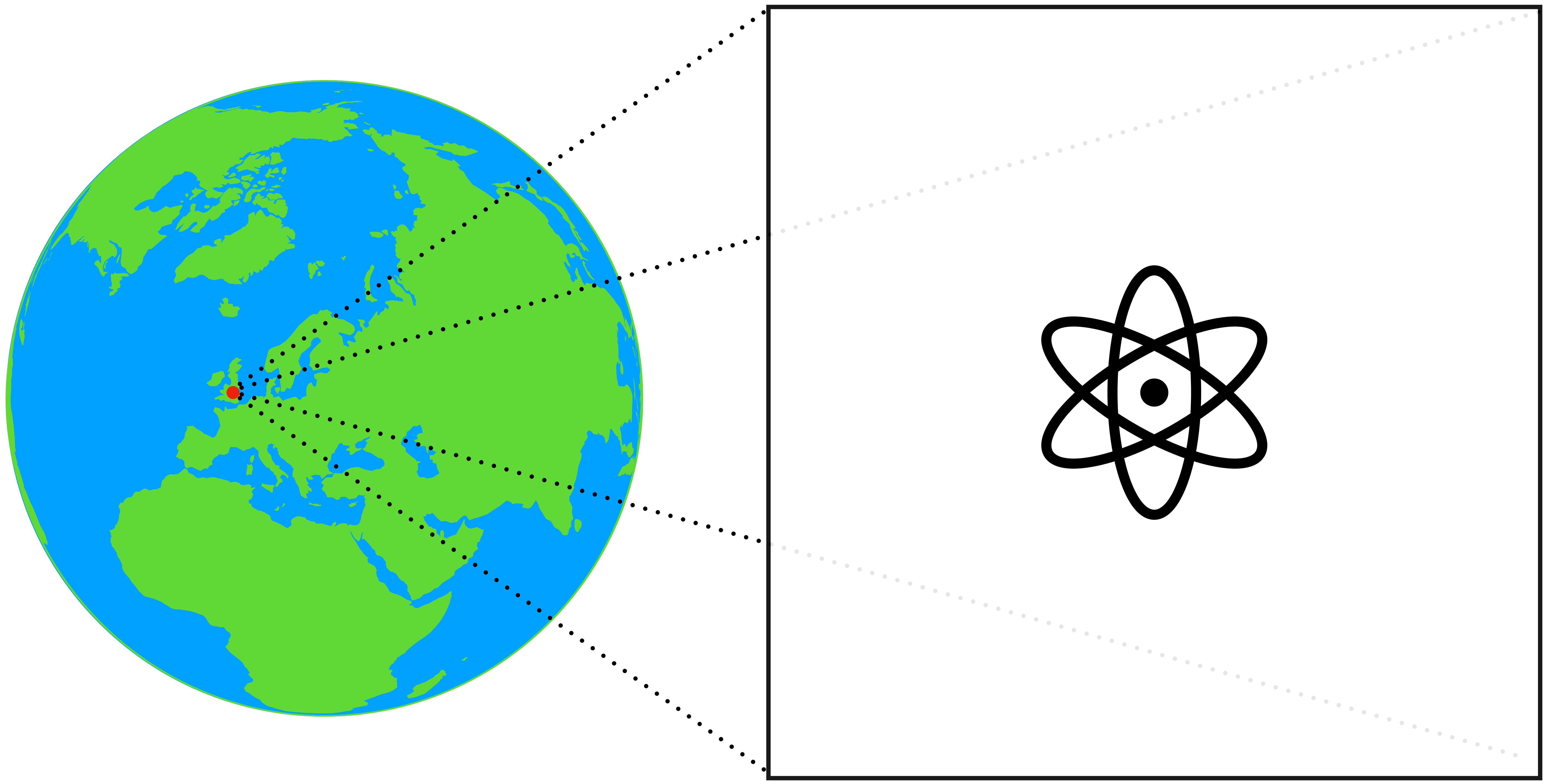
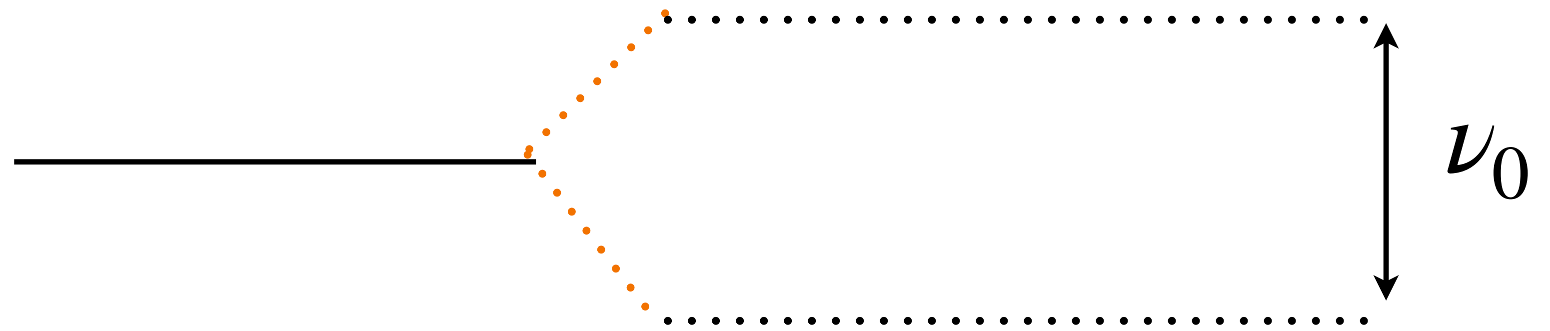
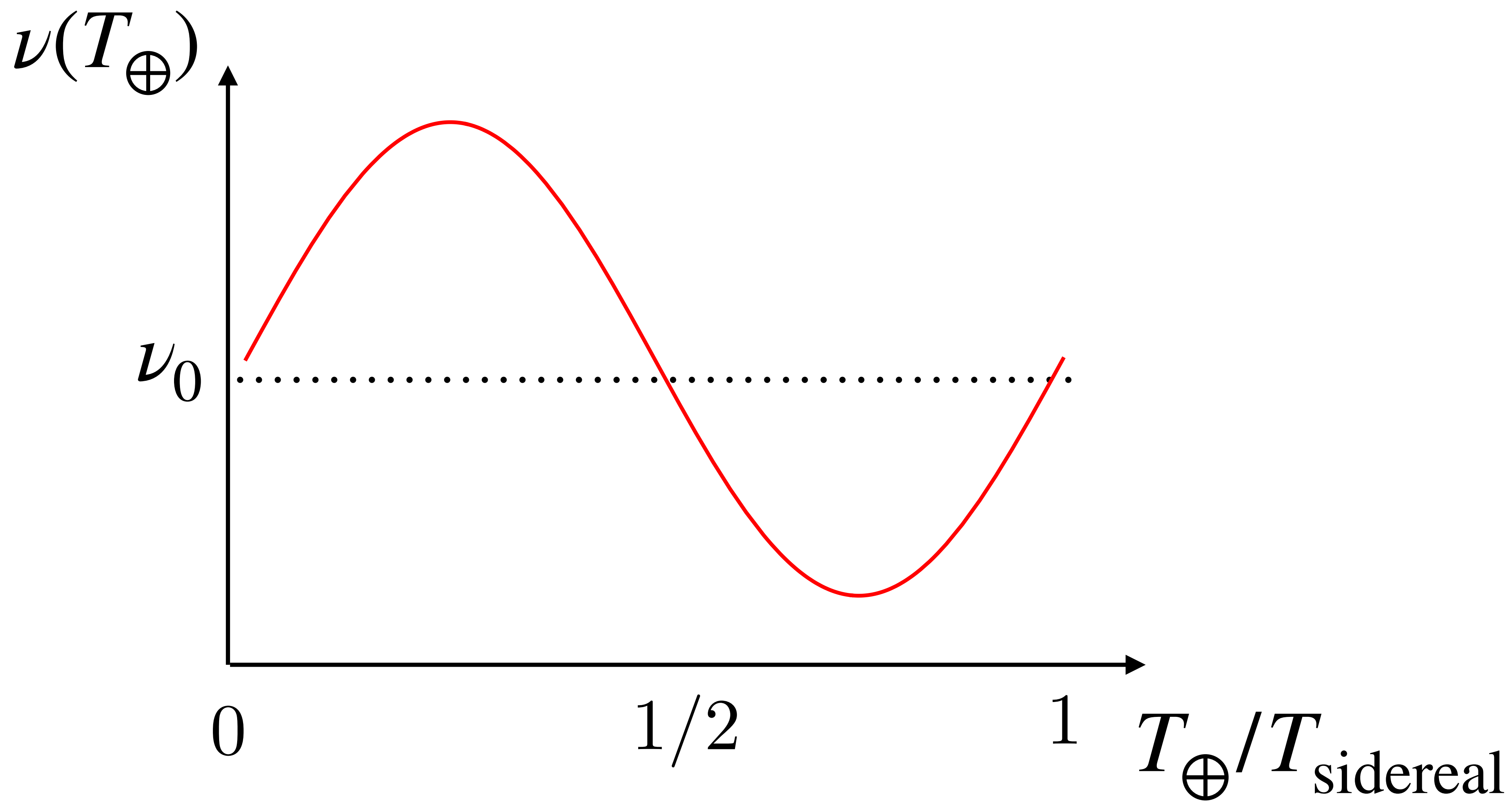
Laboratory signals

(Keynote animation)

Lab frame





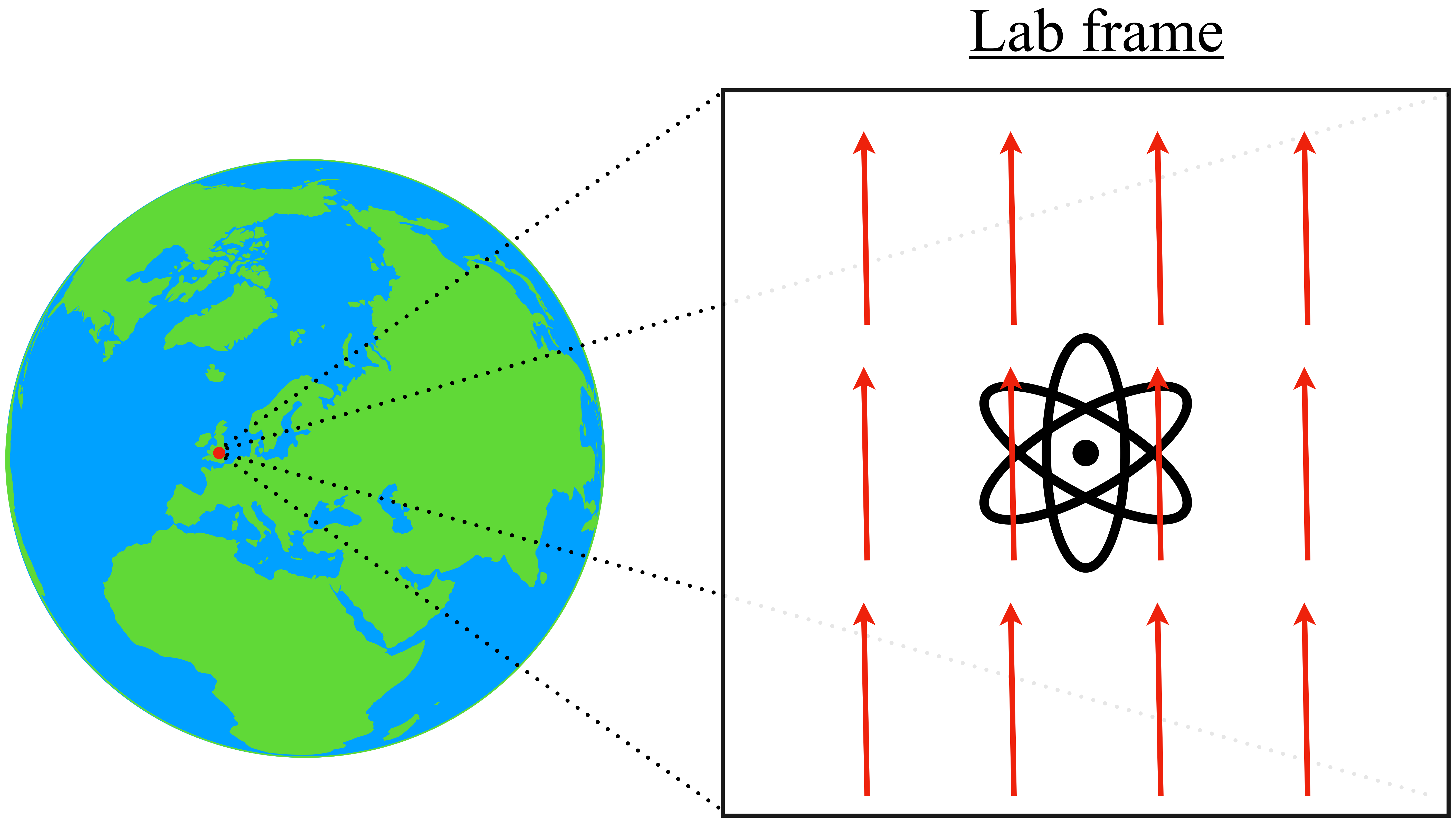


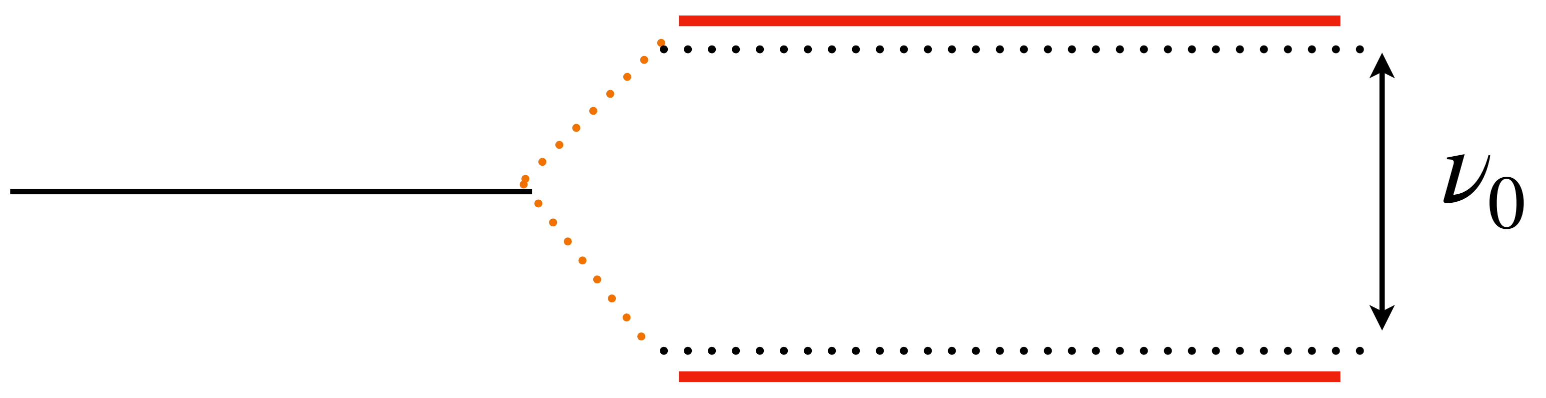
Clock ticking rate can depend on orientation of clock throughout the day

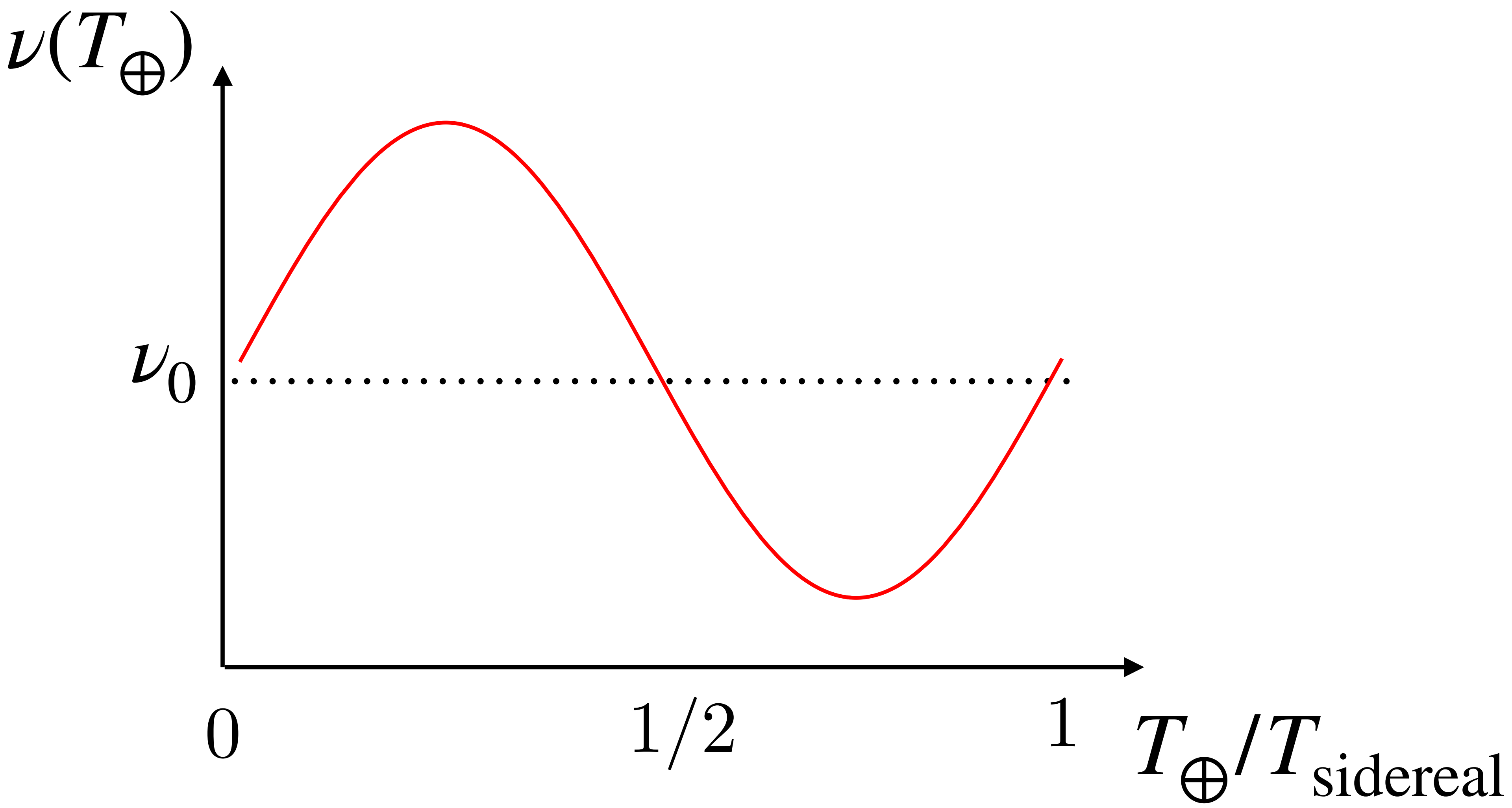
$\Rightarrow$ collect and bin clock data as function of sidereal time

Laboratory signals

(Keynote animation)







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Existing constraints

Constraints on LV/CPTV from clock-comparison experiments are among the most stringent

electrons	bounds	systems
$\lvert b_T \rvert$	$\lesssim \times 10^{-14}$-10^{-12} GeV	Cs, Tl, Dy, Yb
$\lvert b_J \rvert$	$\lesssim 10^{-29}$-10^{-27} GeV	K/He, Hg/Cs
H- and g-type	$\lesssim 10^{-27}$ GeV	H
$c_{\mu\nu}$	$\lesssim 10^{-21}$-10^{-13}	Yb, Ca, Dy
$\lvert \tilde{d}_J \rvert$	$< 10^{-22}$	Hg/Cs
nonminimal $5 < d < 8$	varied	H, $\overline{\mathrm{H}}$

nucleons	bounds	systems
$\lvert b_T \rvert$	$\lesssim 10^{-8}$-10^{-7} GeV	Cs, Tl
$\lvert \tilde{b}_J \rvert$	$\lesssim 10^{-34}$-10^{-27} GeV	He/Xe, Hg/Cs, K/He, H
H- and g-type	$\lesssim 10^{-33}$-10^{-27} GeV	He/Xe, H
$c_{\mu\nu}$	$\lesssim 10^{-29}$-10^{-20}	Ne/Rb/K, Be/H, Hg/He, Ne/H, Cs
$\lvert d_{TT} \rvert$	$\lesssim 10^{-8}$-10^{-7}	Cs, Tl
$\lvert \tilde{d}_J \rvert$	$\lesssim 10^{-28}$-10^{-25}	Hg/Cs
nonminimal $5 < d < 8$	varied	H, $\overline{\mathrm{H}}$, K/Rb/Ne, He/Xe

Experiments include:

- **Microwave clocks**
- **Optical clocks**
- Masers
- Magnetometers
- Optical resonators
- Atom interferometers

V. A. Kostelecky, N. Russell, Data Tables for Lorentz and CPT Violation

QSNET clock ratios allow competitive access to a variety of effects

Take-home messages

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3. **Ratios of QSNET clock transitions are proportional to FC variations**
   - Clock ratios can search for and constrain a variety of new physics, including violations of fundamental symmetries