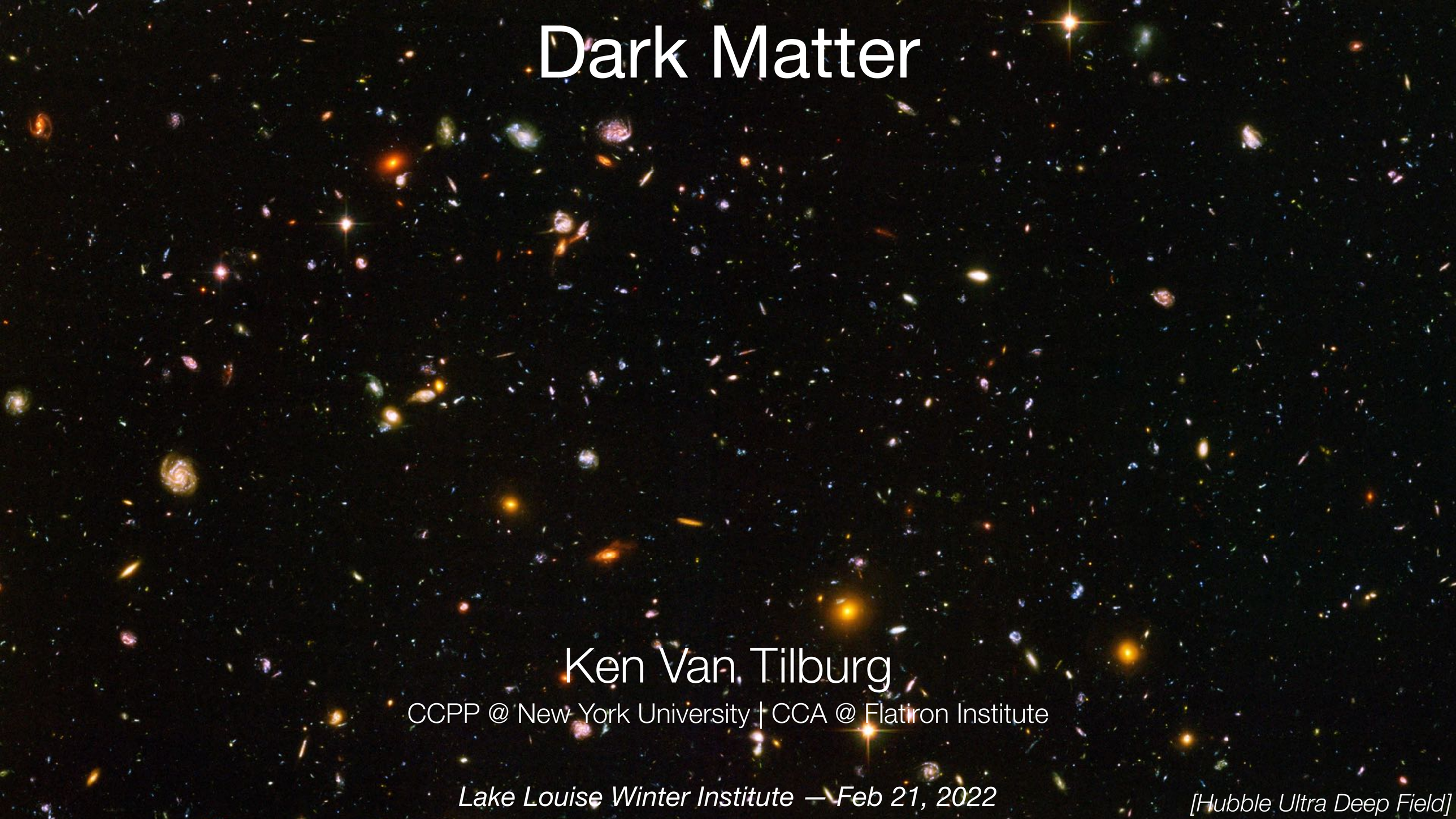
Dark Matter



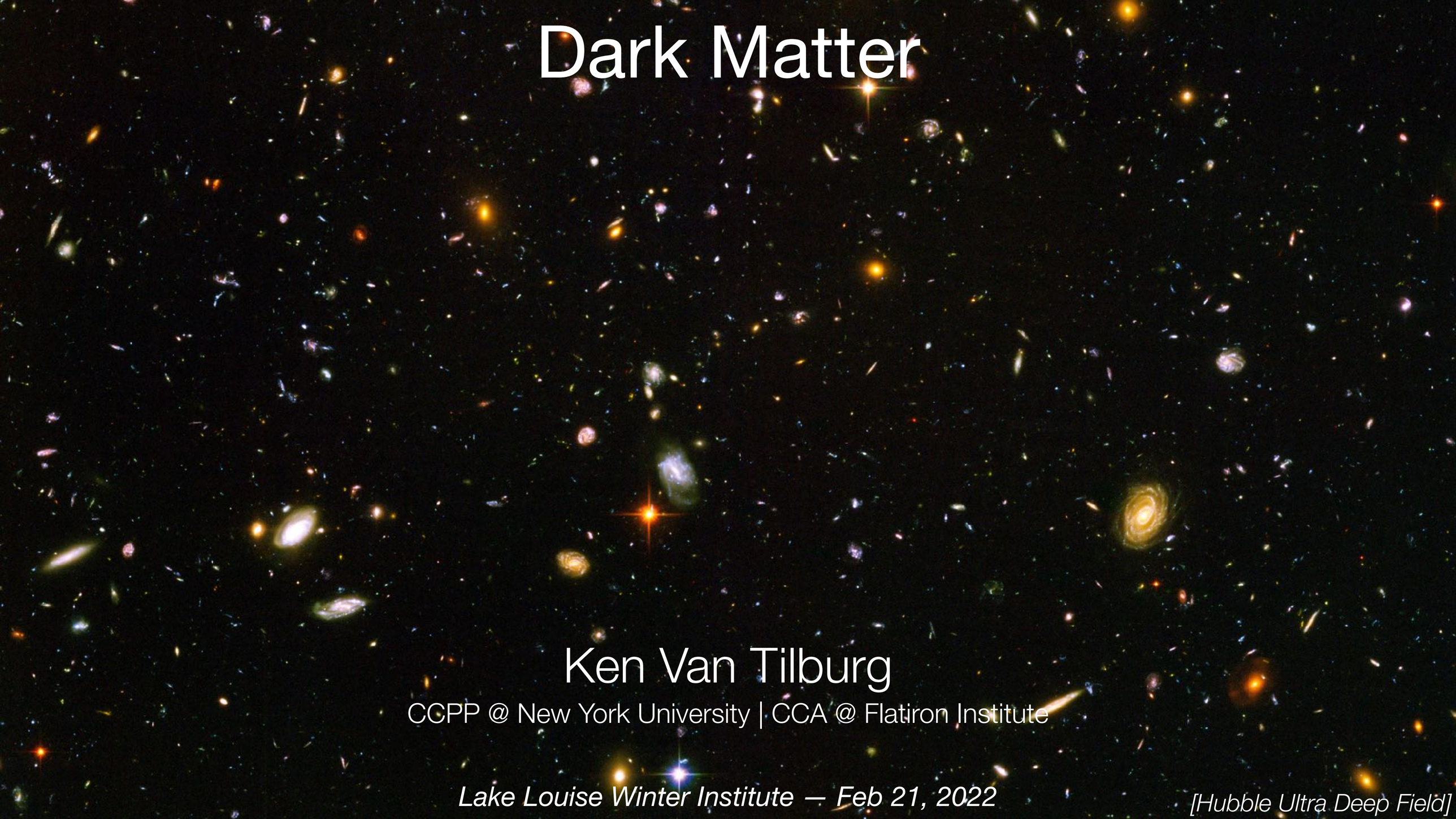
Ken Van Tilburg

CCPP @ New York University | CCA @ Flatiron Institute

Lake Louise Winter Institute — Feb 21, 2022

[Hubble Ultra Deep Field]

Dark Matter



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[Hubble Ultra Deep Field]

Not The Outline

Every dark matter theory and experiment

Not The Outline

Every dark matter theory and experiment

“… a wealth of information creates a poverty of attention.” —Herbert A Simon

Not The Outline

Every dark matter theory and experiment

"… a wealth of information creates a poverty of attention." —Herbert A Simon (1971)

The Outline

Almost no dark matter theory nor experiment

The Outline

The Outline

How does dark matter fit into theoretical particle physics?

The Outline

How does dark matter fit into theoretical particle physics?

↳ a serious question mark

The Outline

How does dark matter fit into theoretical particle physics?

↳ a serious question mark

The evidence for dark matter!

The Outline

How does dark matter fit into theoretical particle physics?

↳ a serious question mark

The evidence for dark matter!

↳ not a question mark

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↳ not a question mark

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↳ a guide for the first question

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General principles of precision-frontier dark matter detection

The Outline

How does dark matter fit into theoretical particle physics?

↳ a serious question mark

The evidence for dark matter!

↳ not a question mark

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↳ a guide for the first question

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↳ something I know something about

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The Central “Problem” of Fundamental Physics

Standard Model of cosmology and particle physics accurately describes*
every known experiment and observation to the measured and calculated precision

theoretical frontiers:

mathematical structures | theory breakdown | parametric puzzles | computational precision

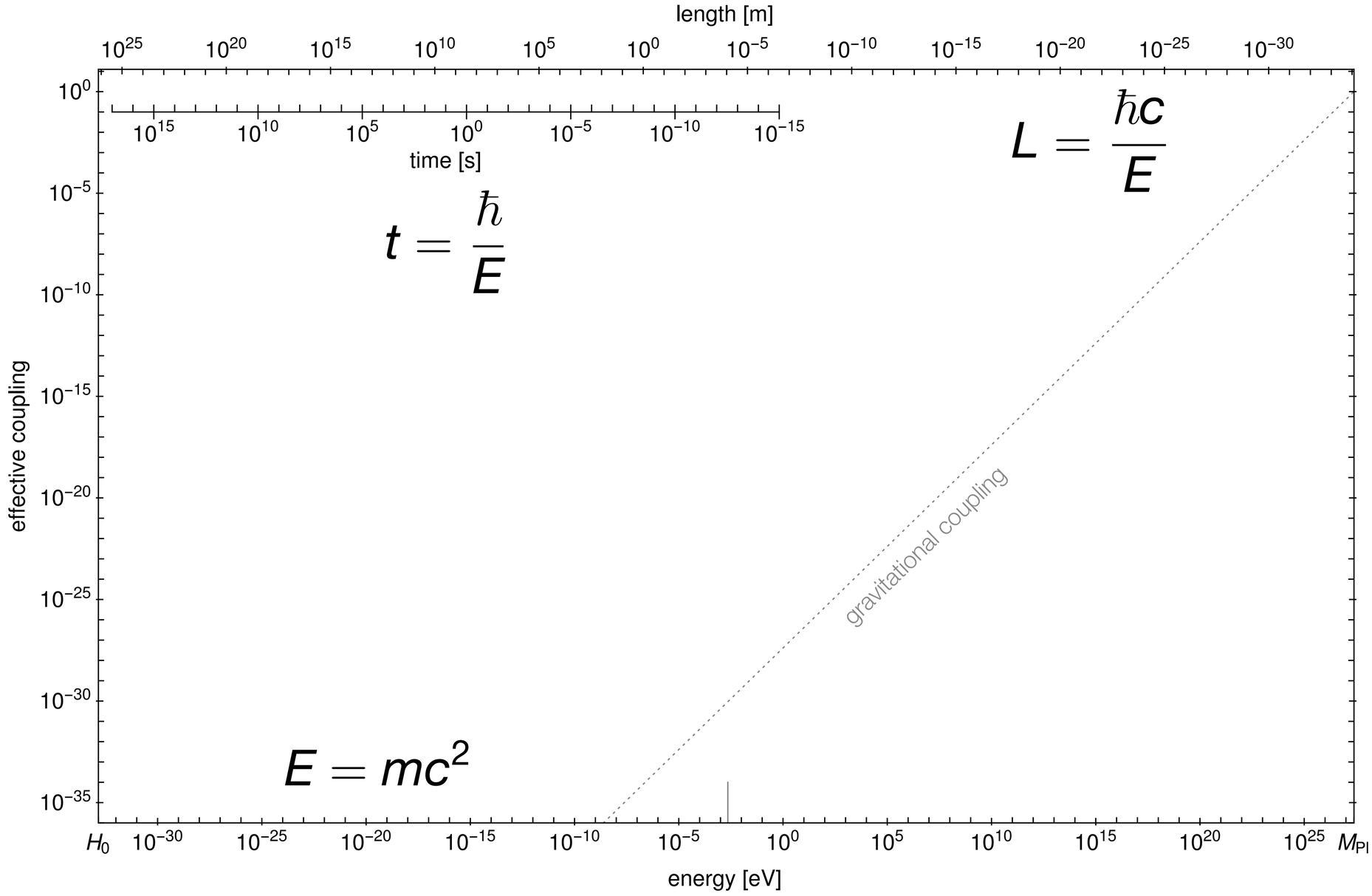
experimental frontiers:

high-energy | cosmic | intensity | precision

*parametrized unknowns:

dark matter | neutrino masses | baryon asymmetry | inflation

Scales in the Standard Model and Beyond



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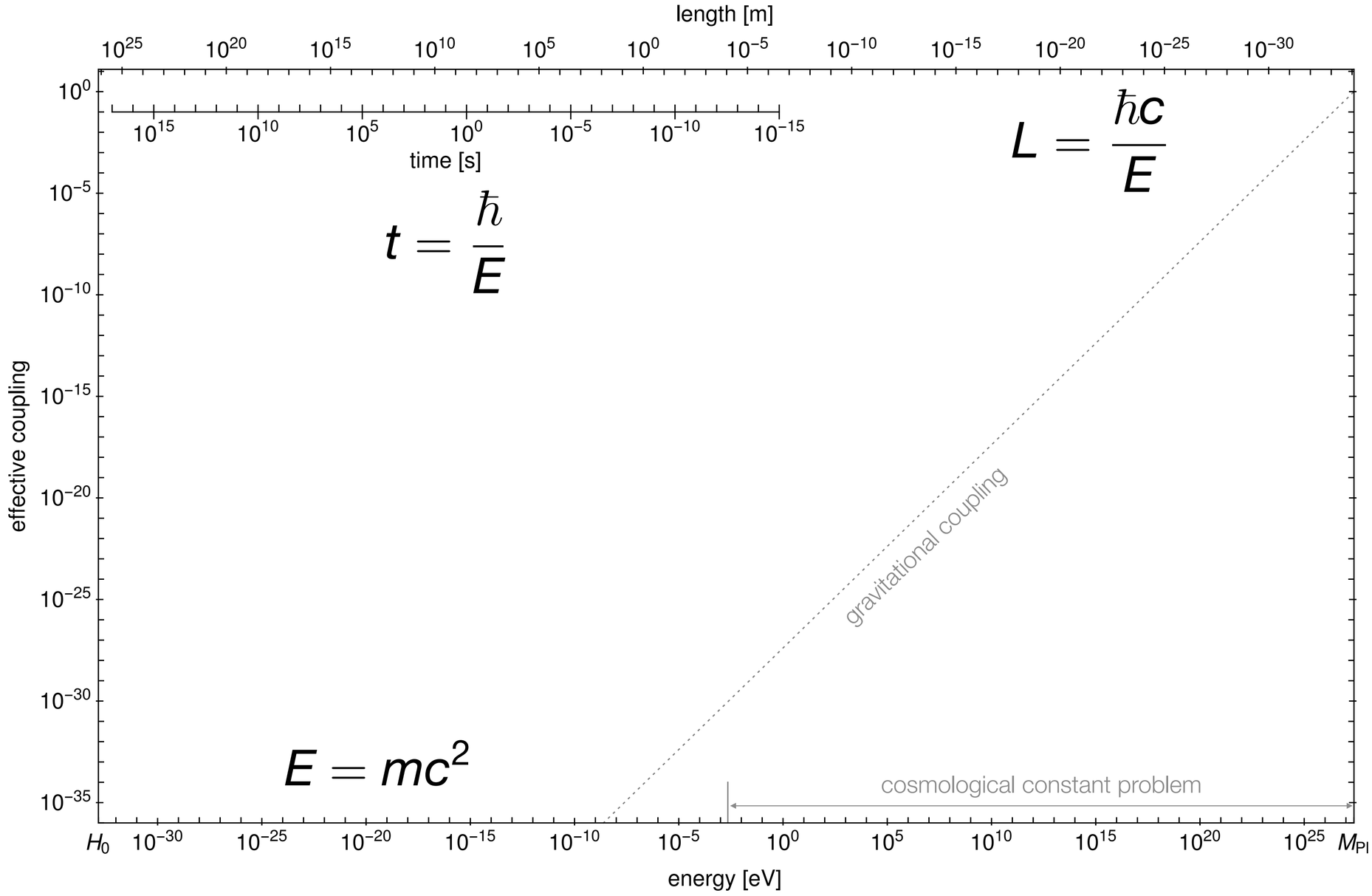

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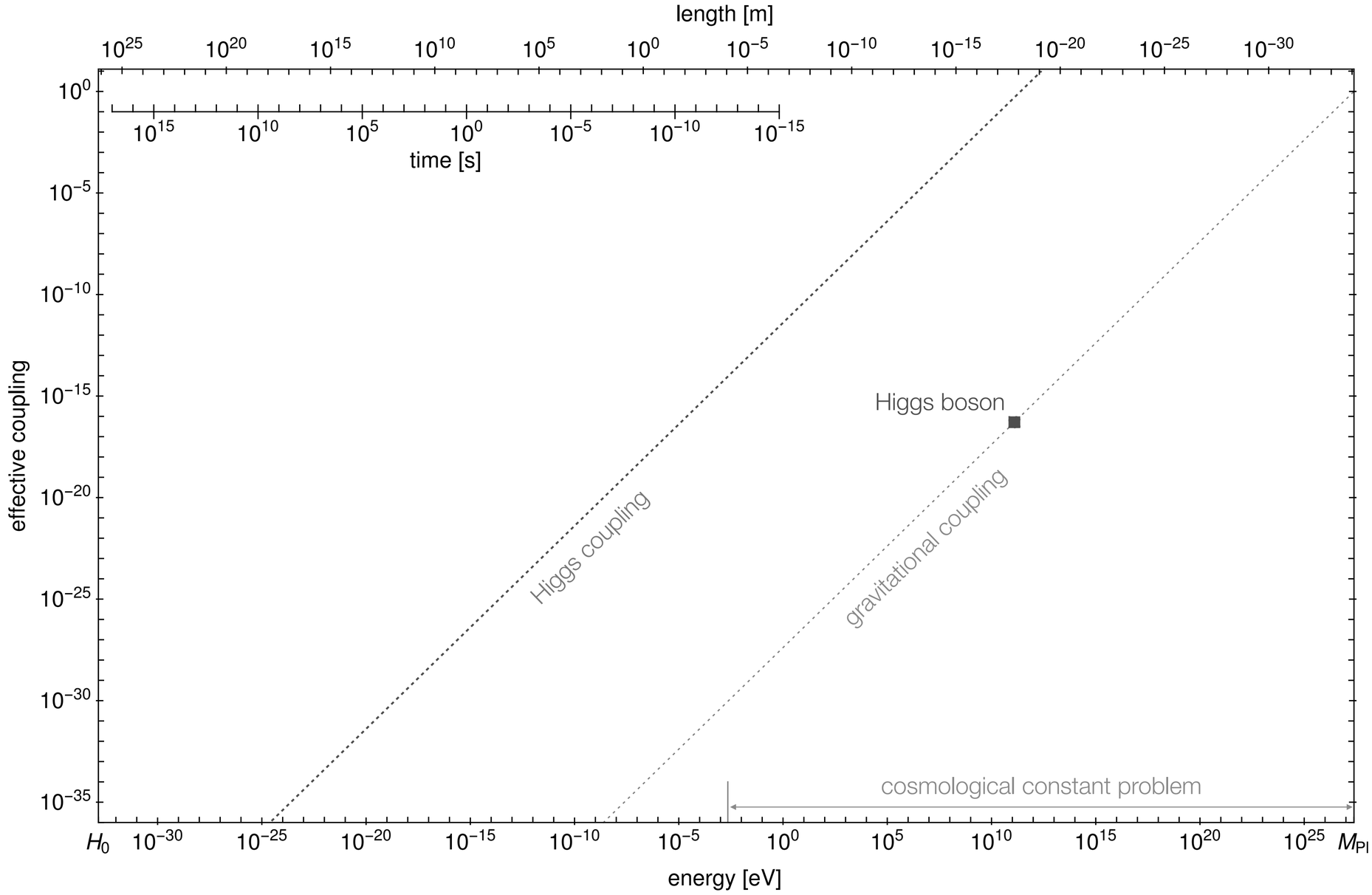

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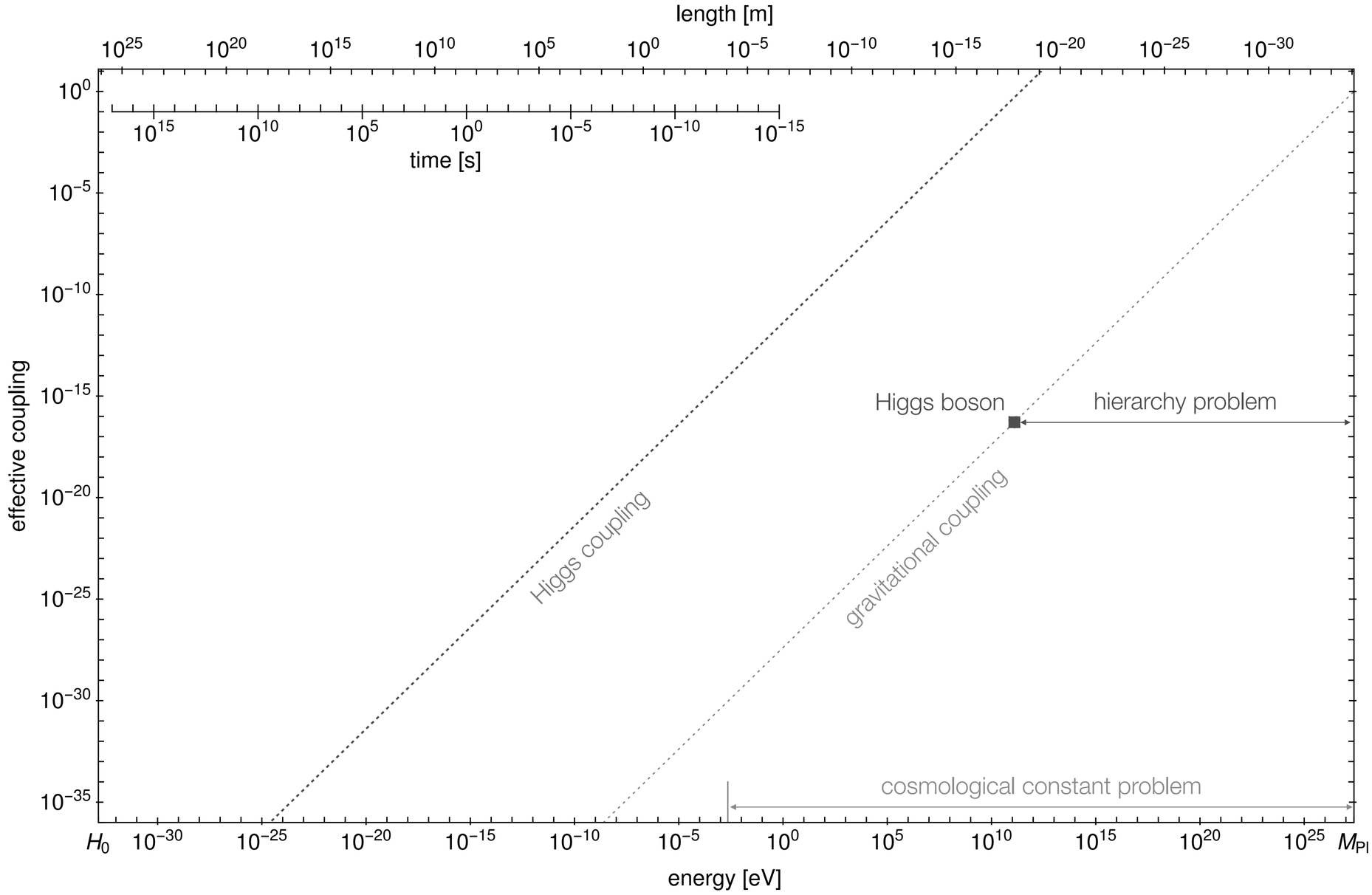

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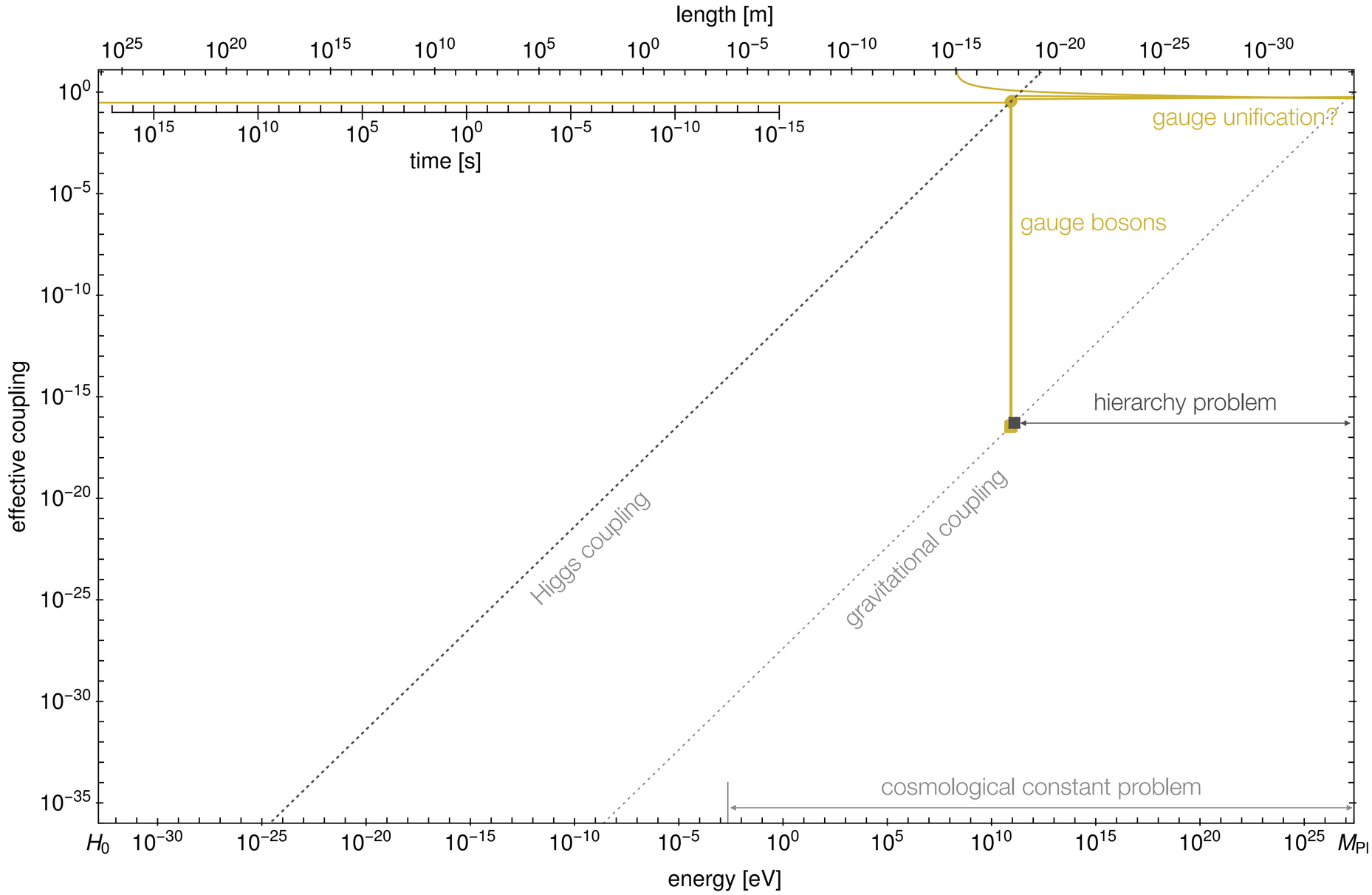

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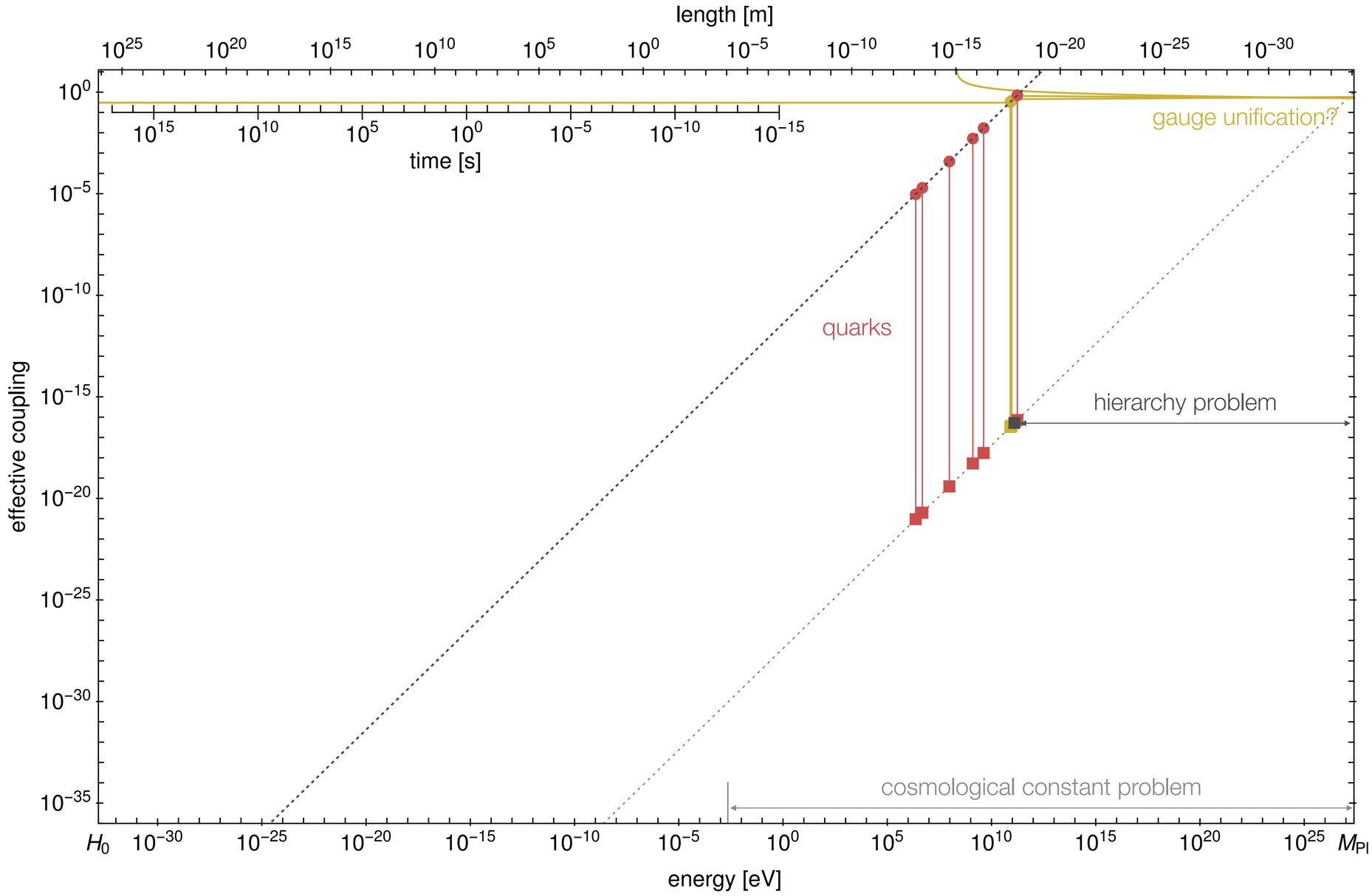

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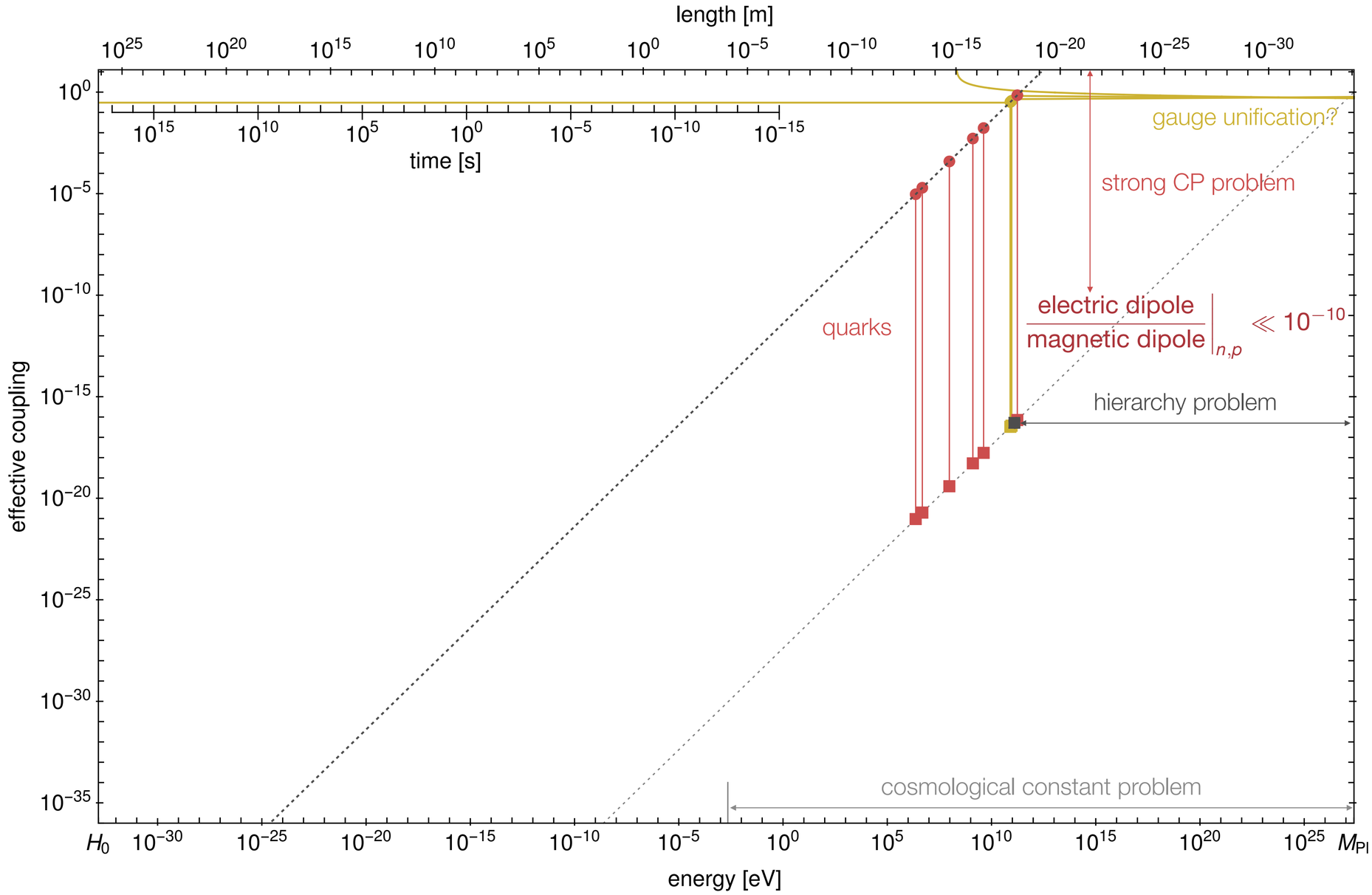

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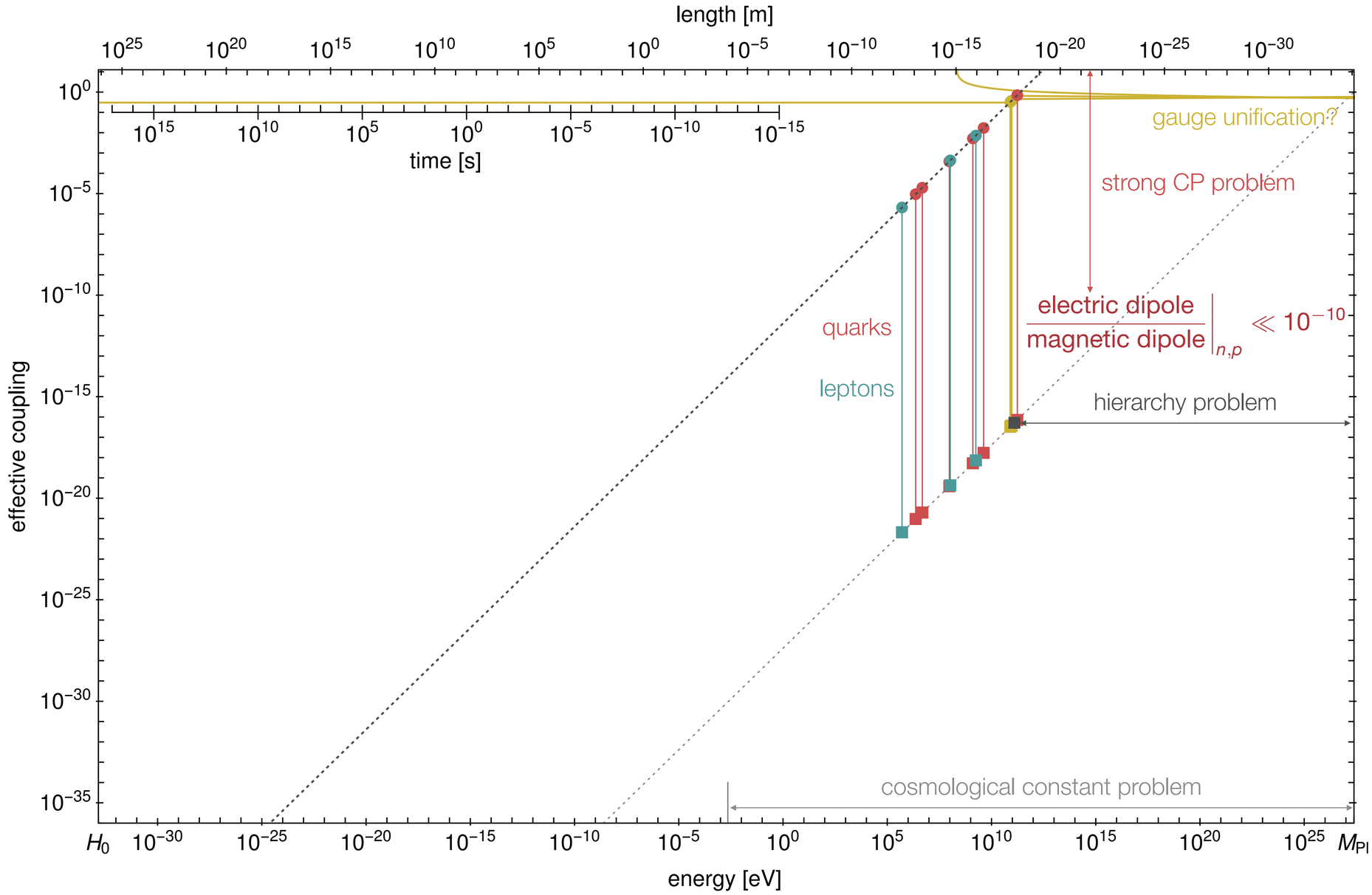

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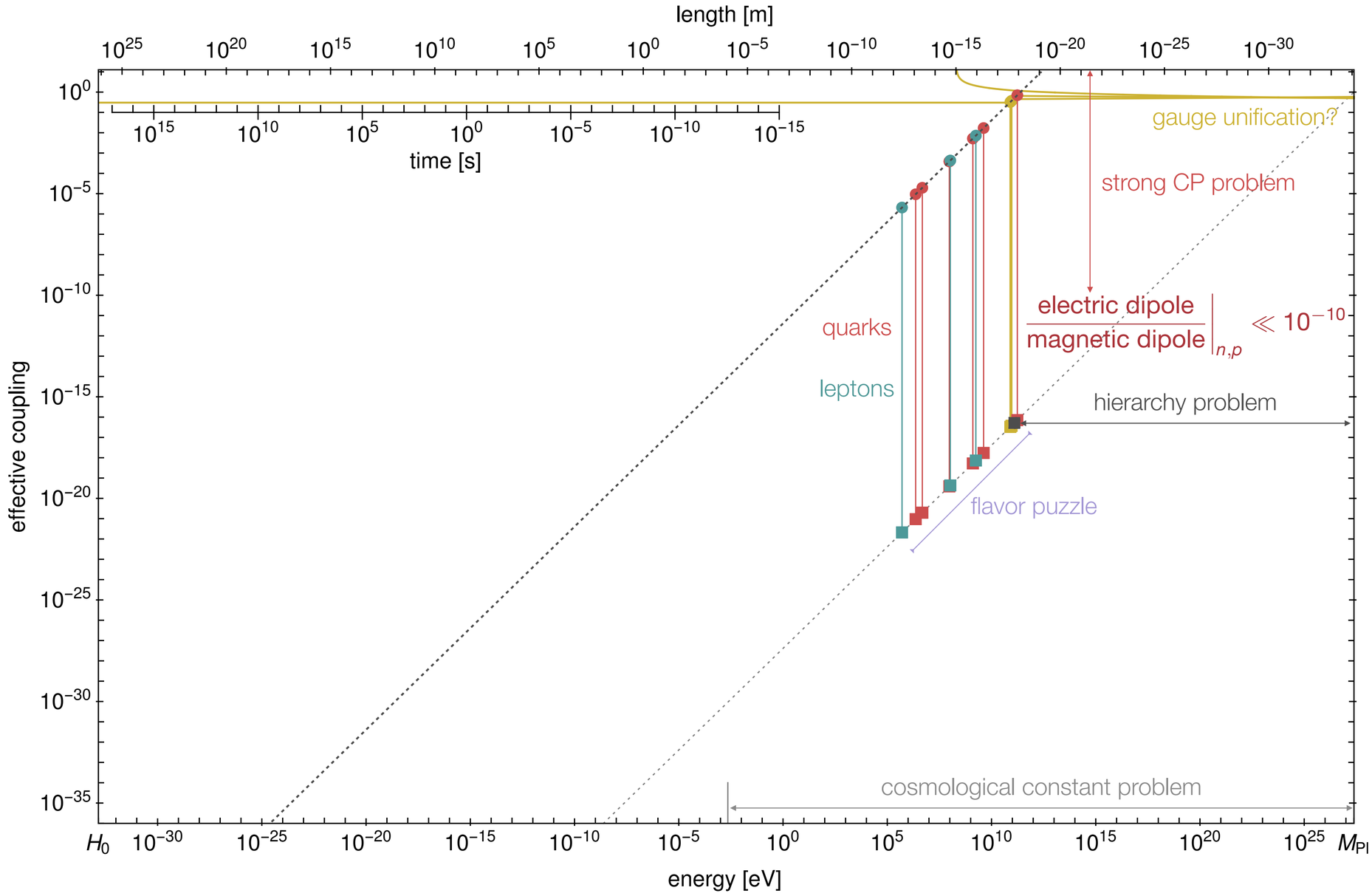

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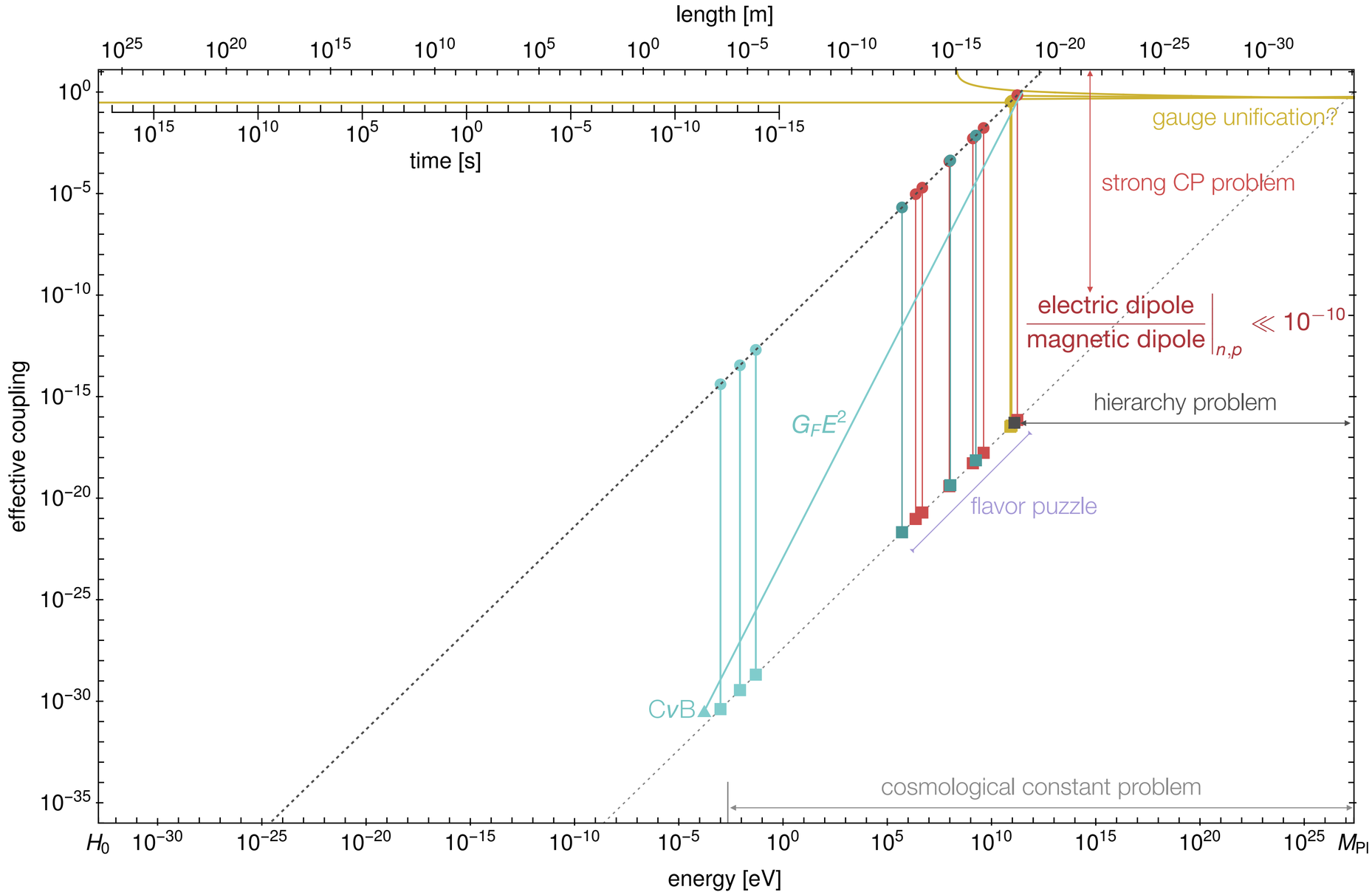

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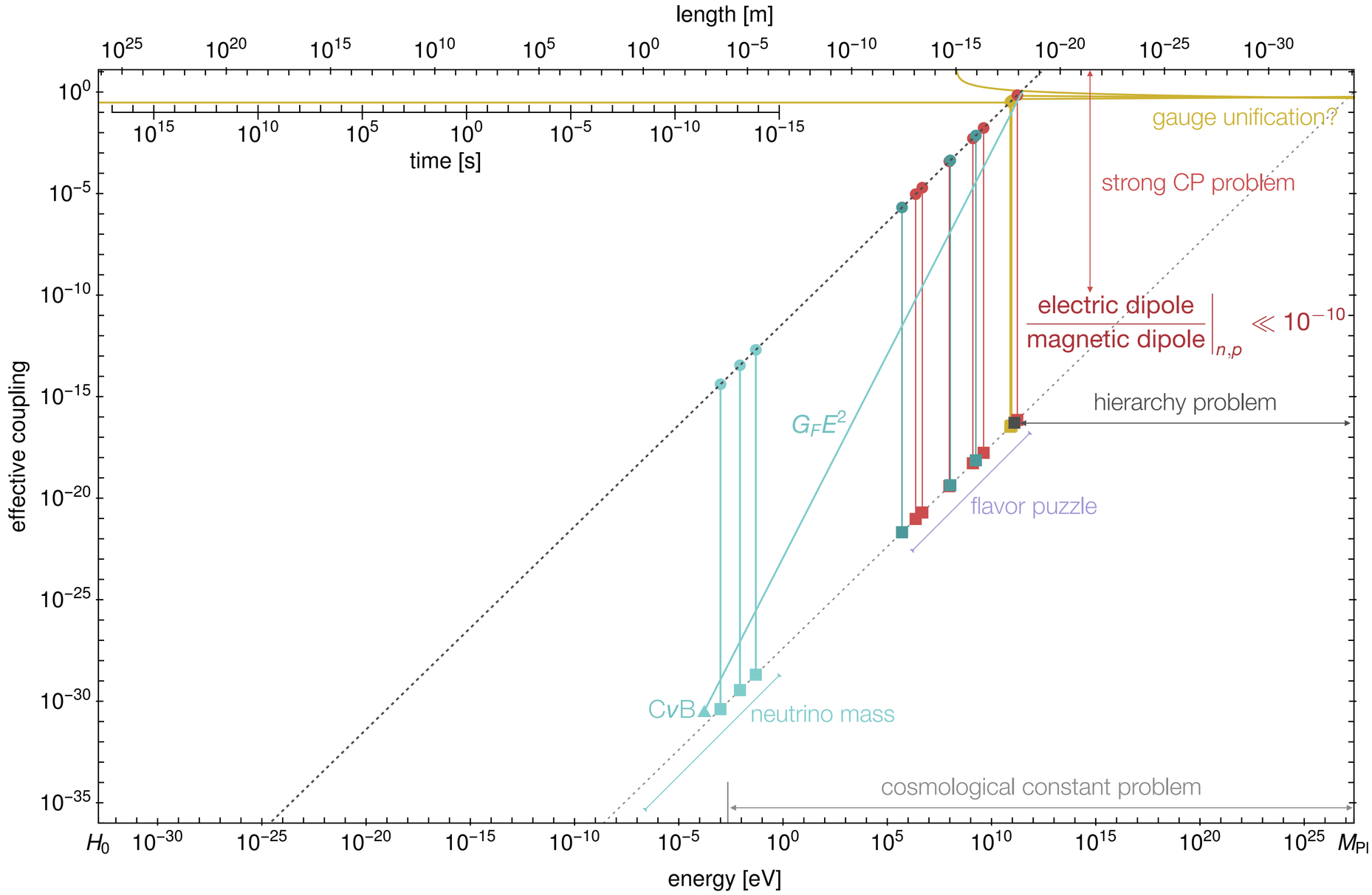

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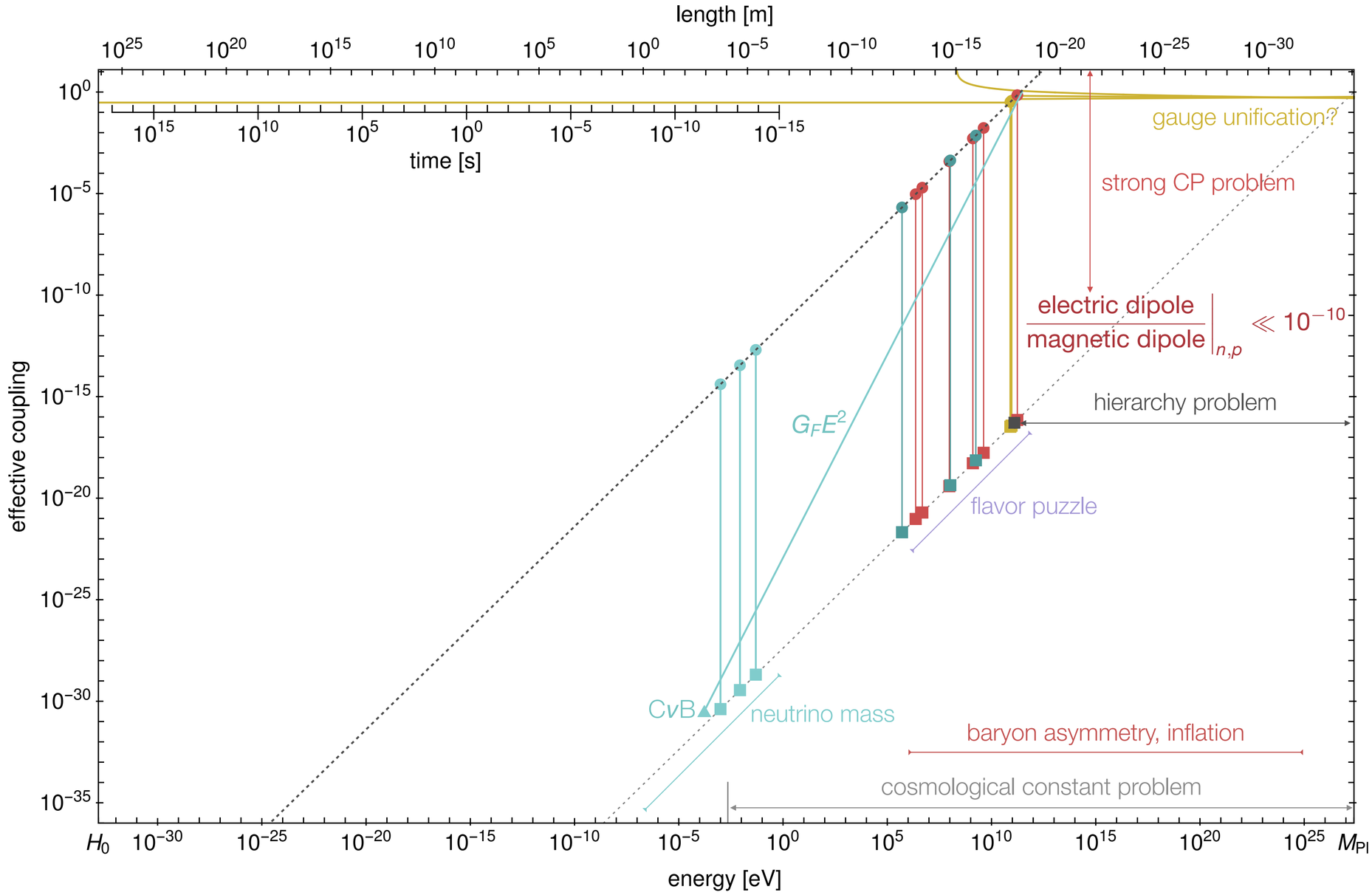

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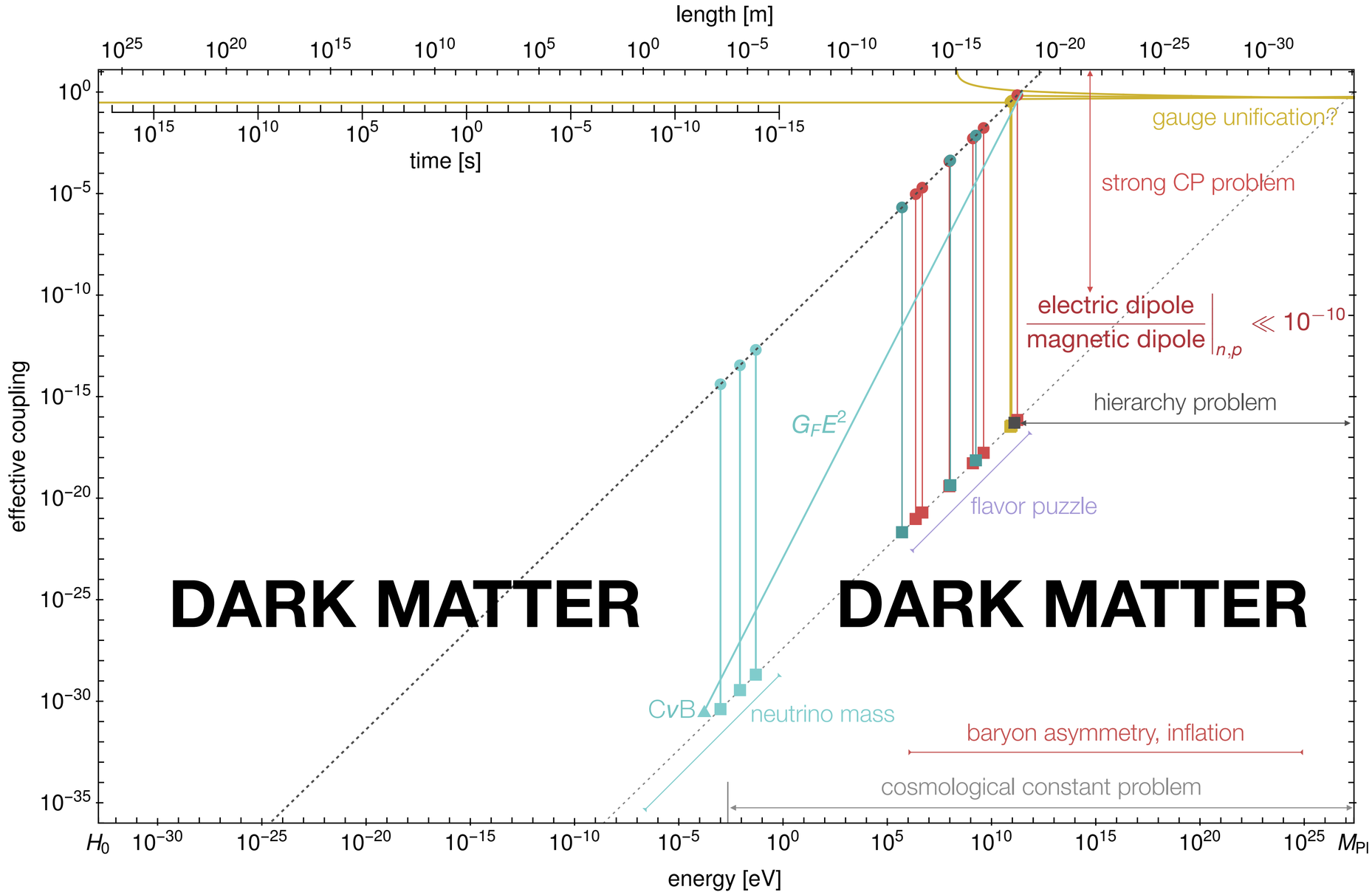
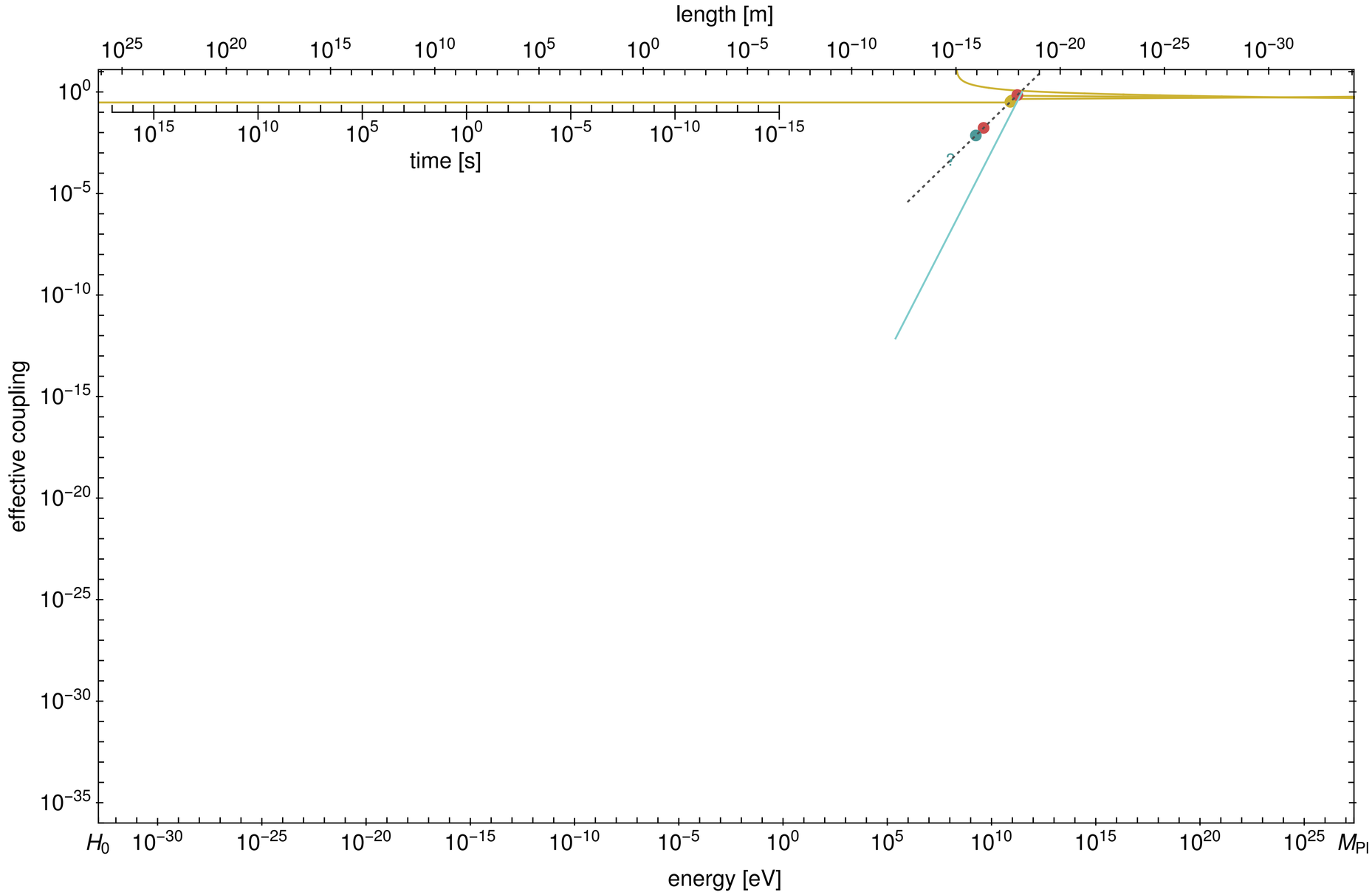


New Physics Frontiers



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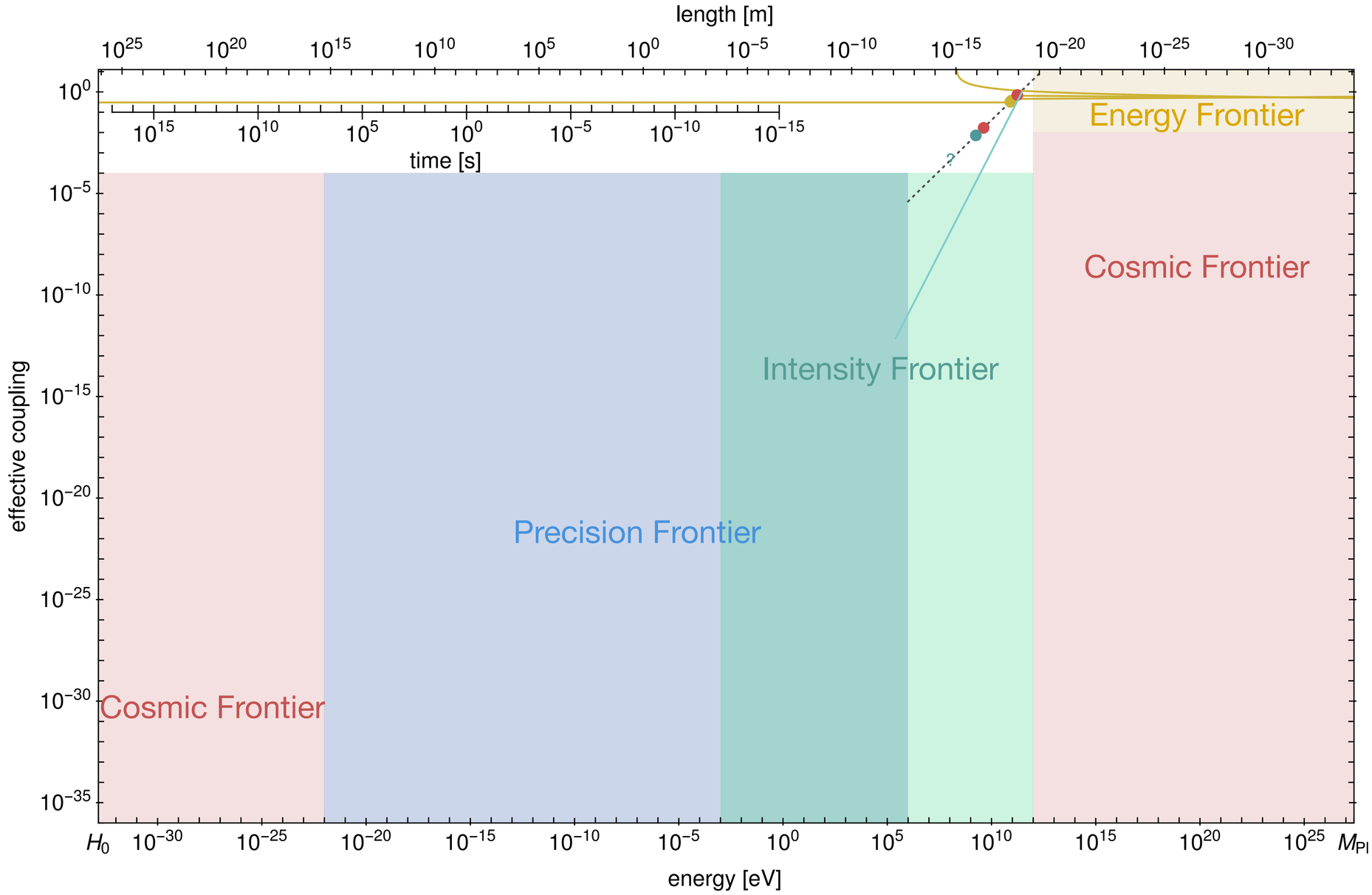

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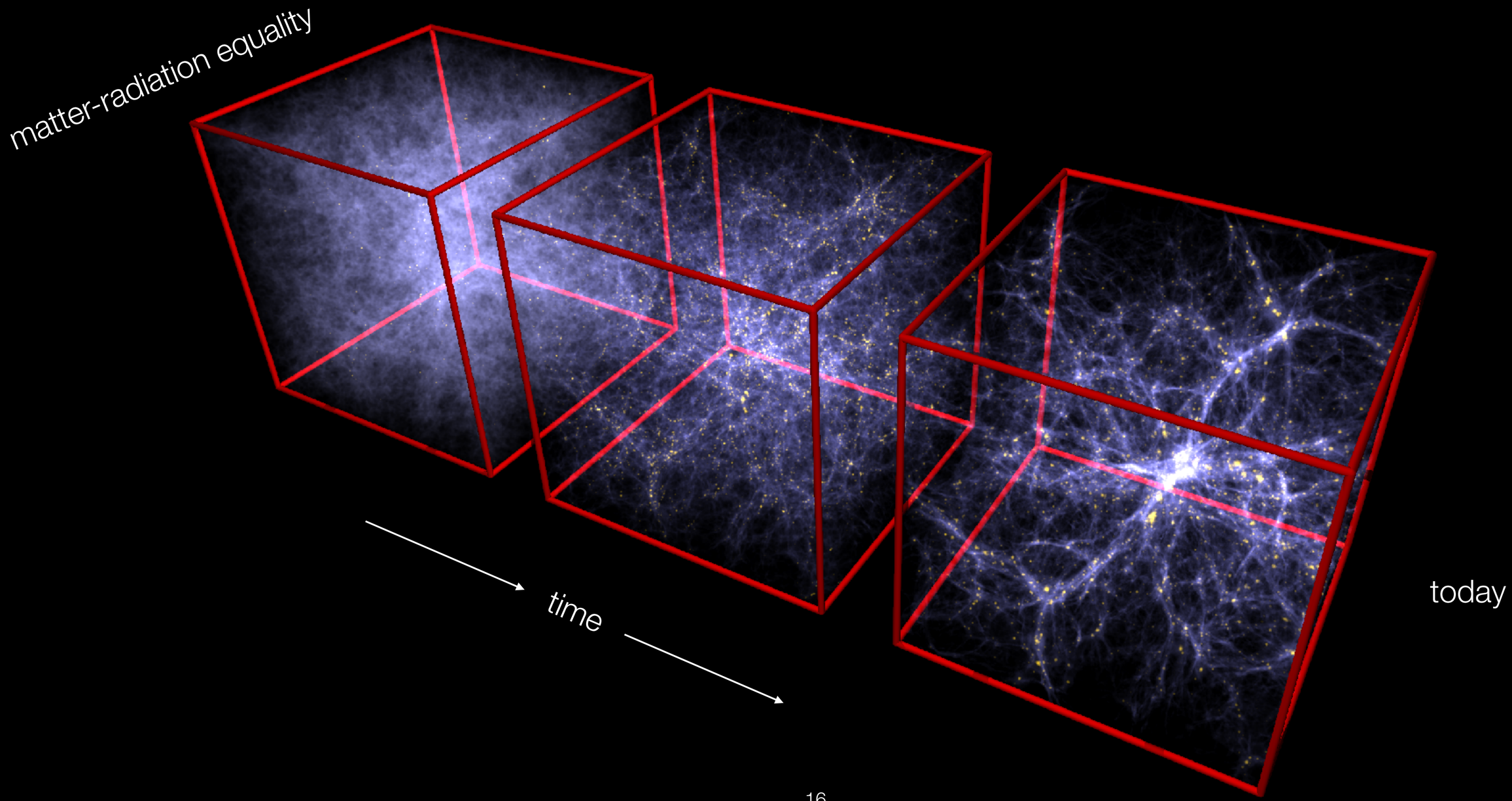
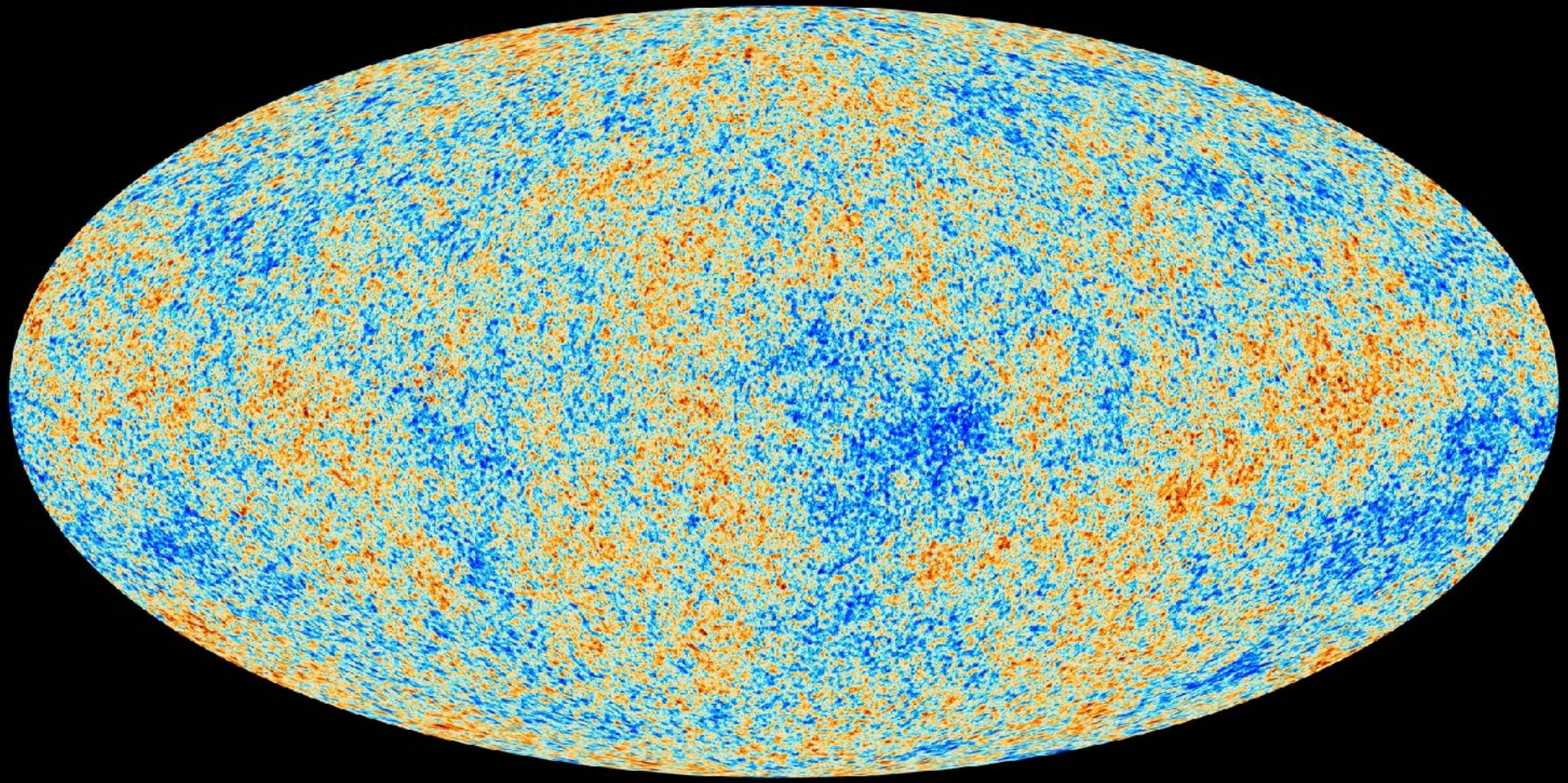
Growth of Dark Matter Density Fluctuations



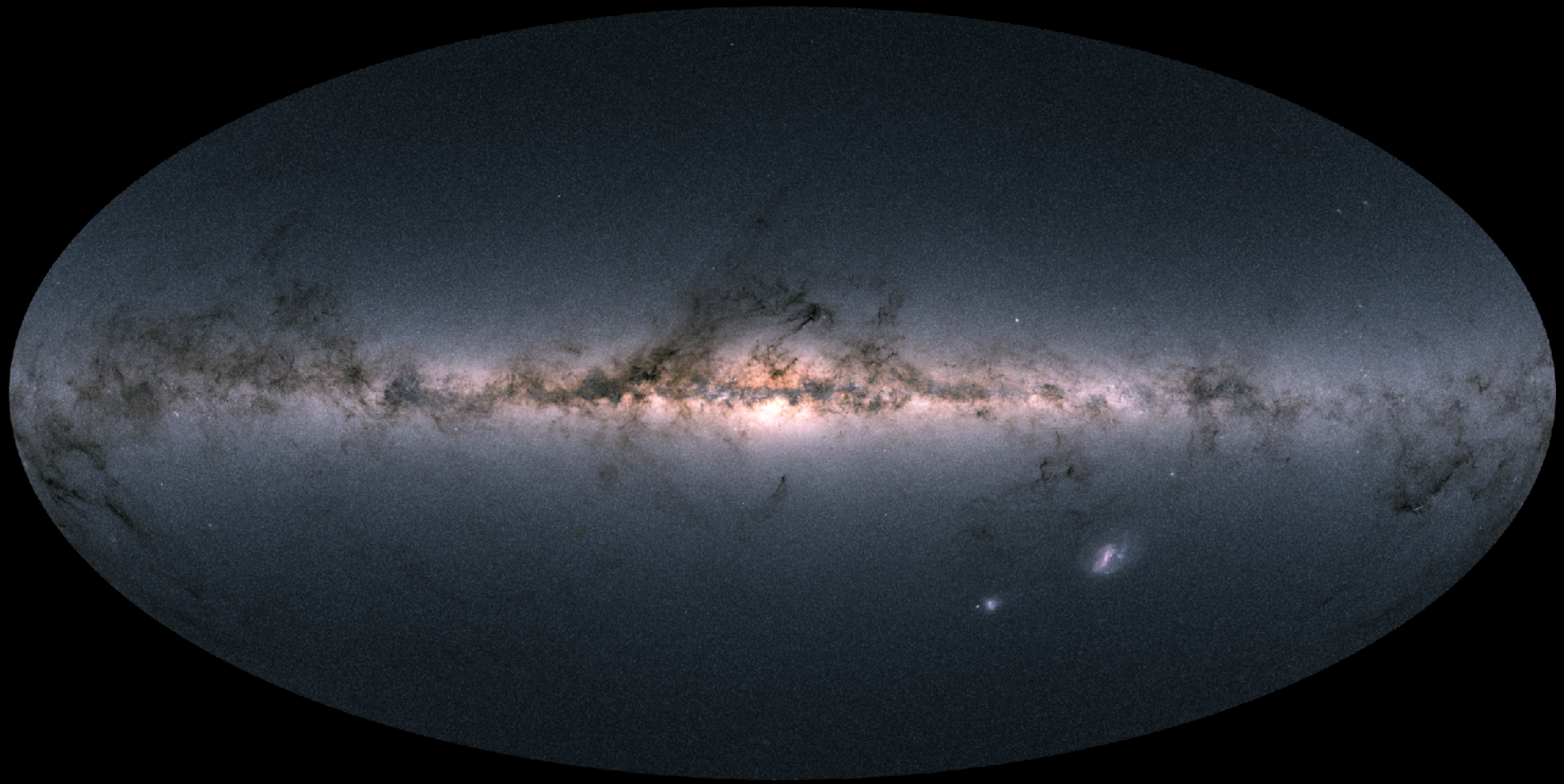
[MPA]

Large-Scale Dark Matter Density Fluctuations



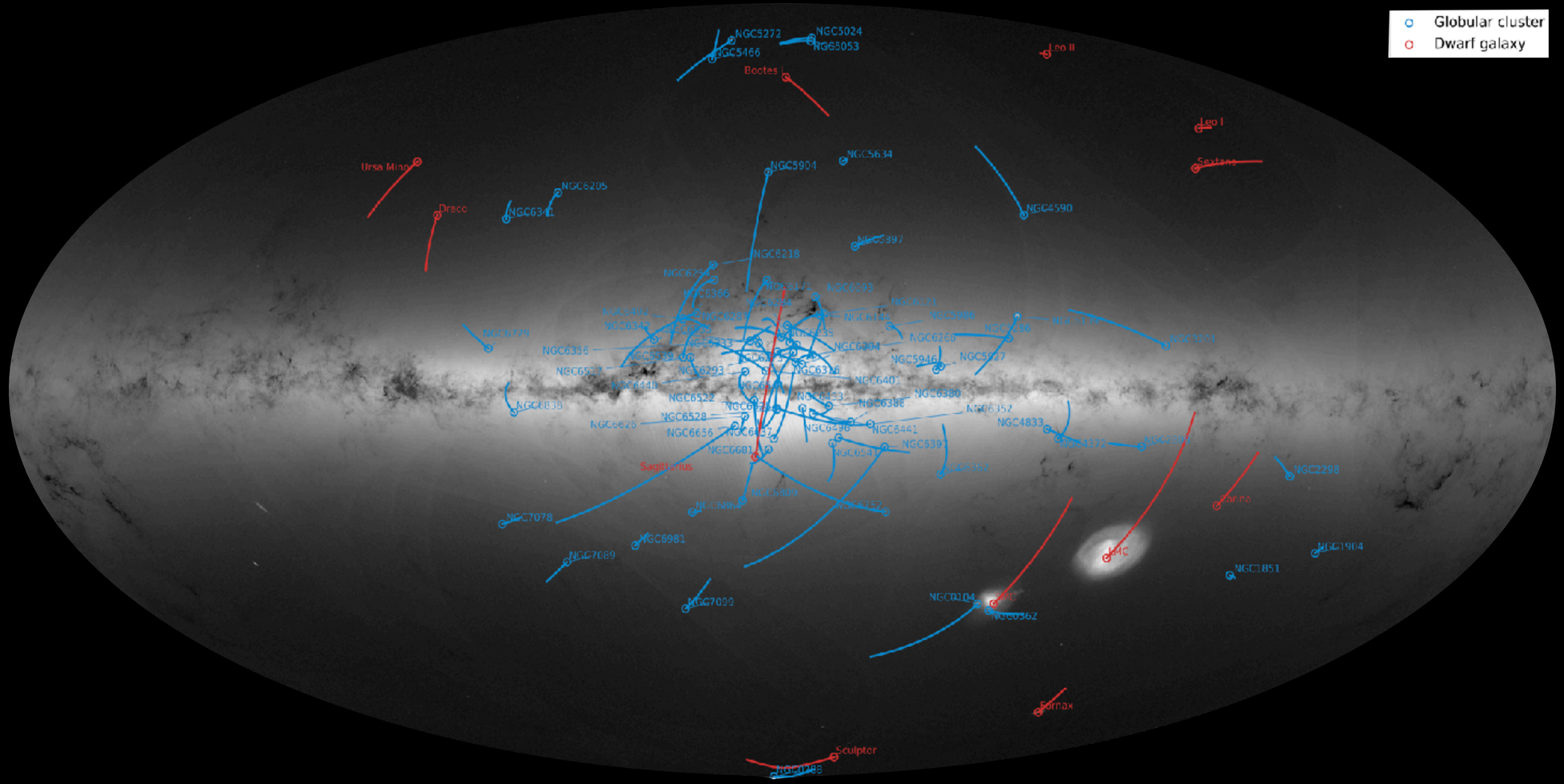
[Planck]

Small-Scale Dark Matter Density Fluctuations



[Gaia]

Small-Scale Dark Matter Density Fluctuations

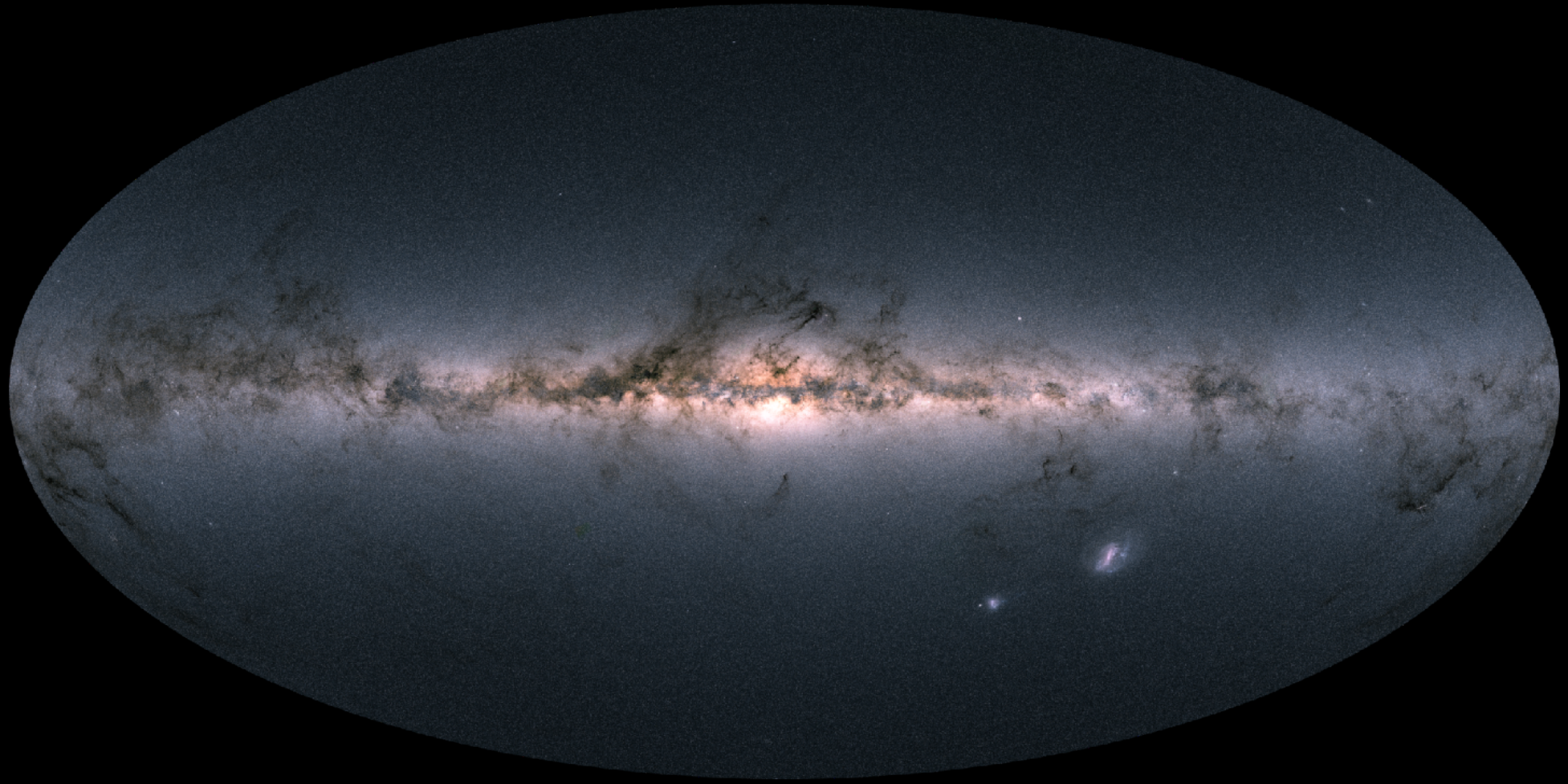


[Gaia]

Small-Scale Dark Matter Density Fluctuations

Theory: primordial fluctuations & DM microphysics

Observation: local & global



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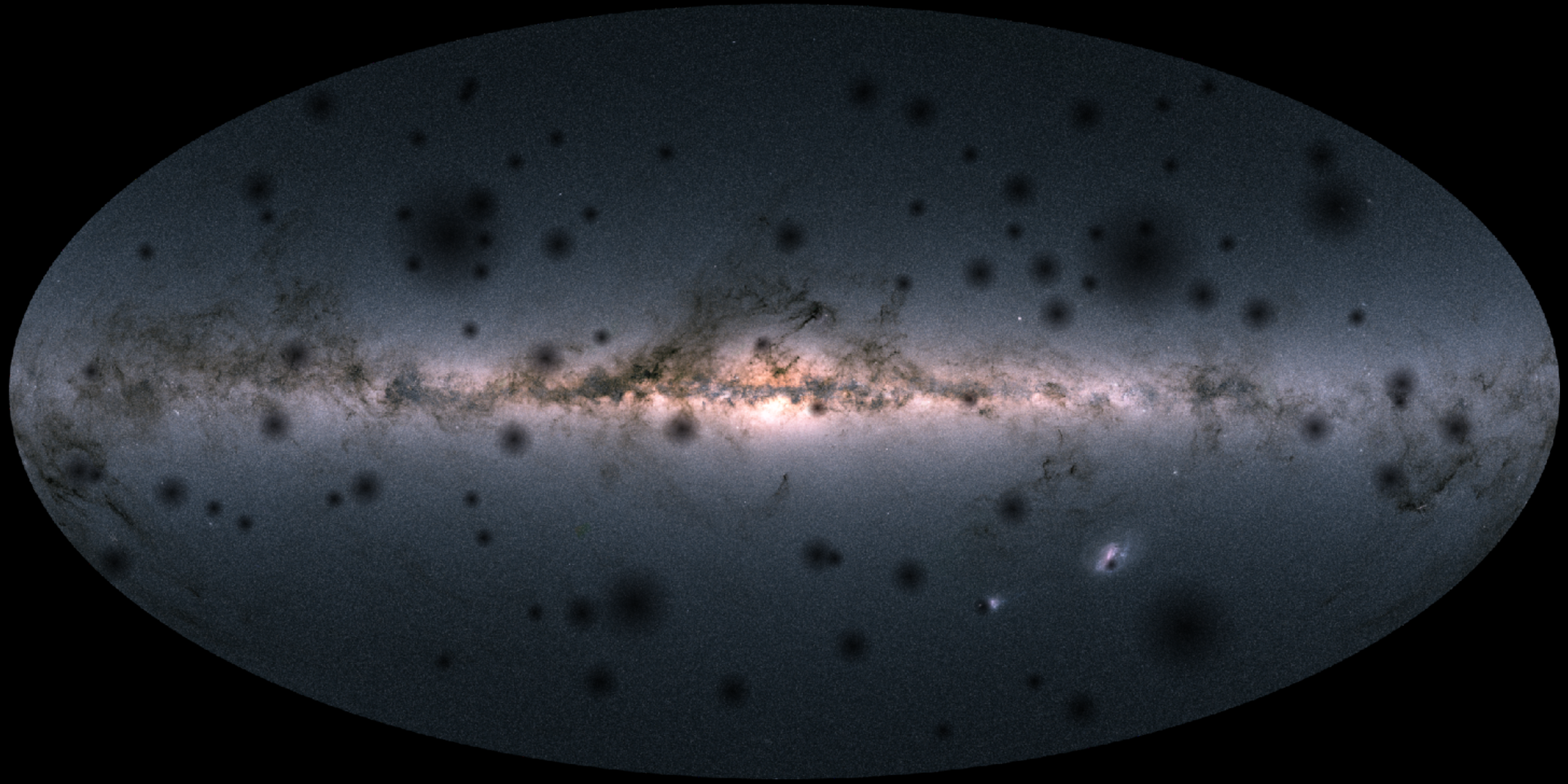
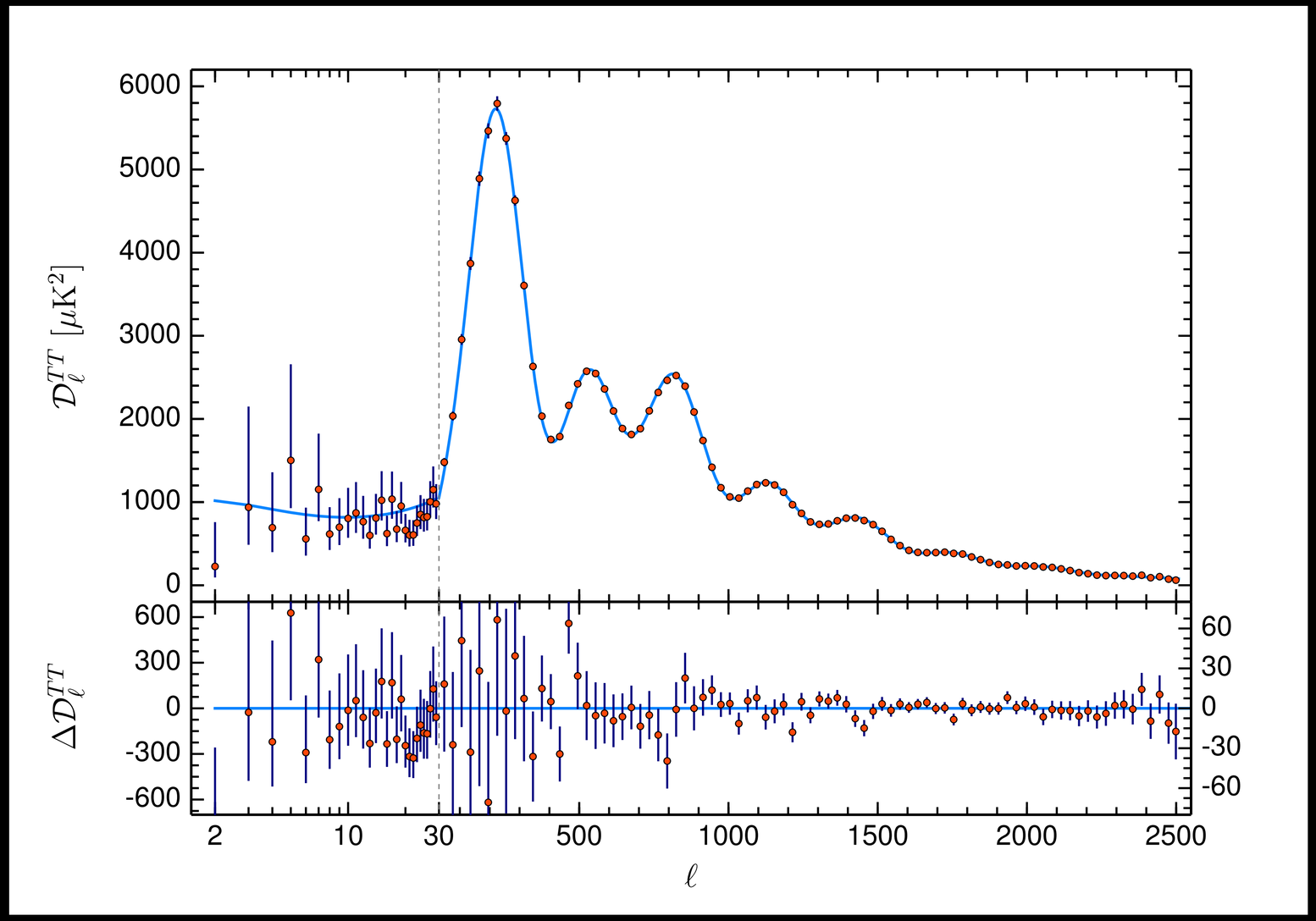
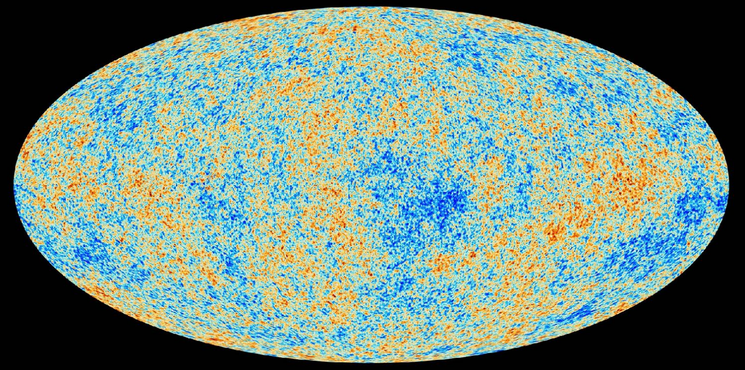


[Gaia]

Large-Scale Dark Matter Density Fluctuations





[Planck]

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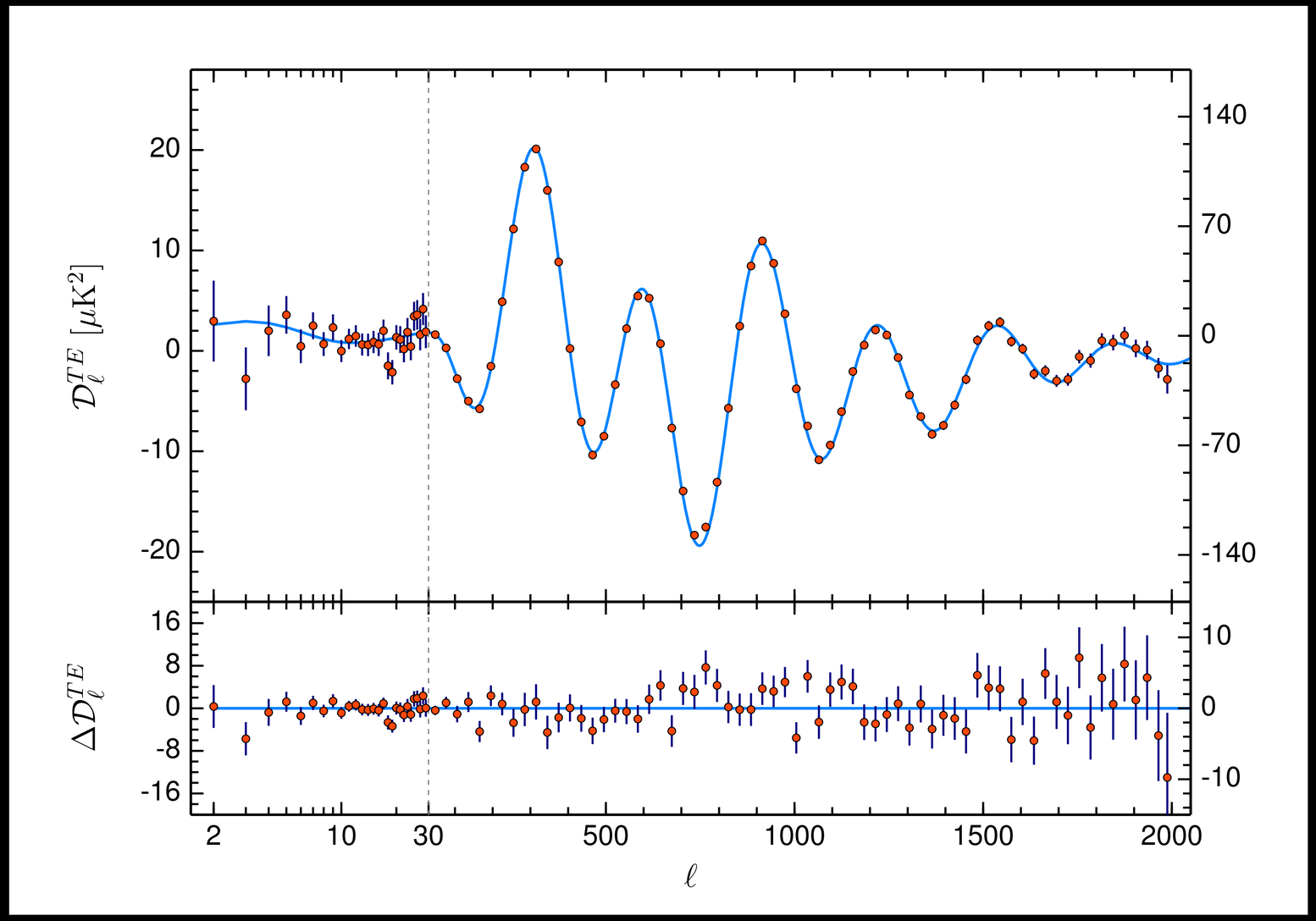

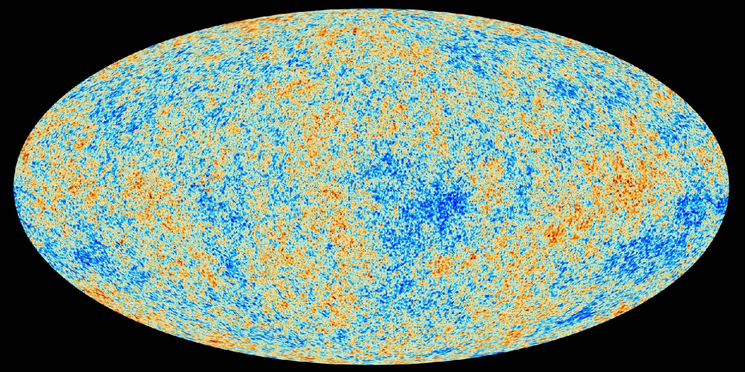

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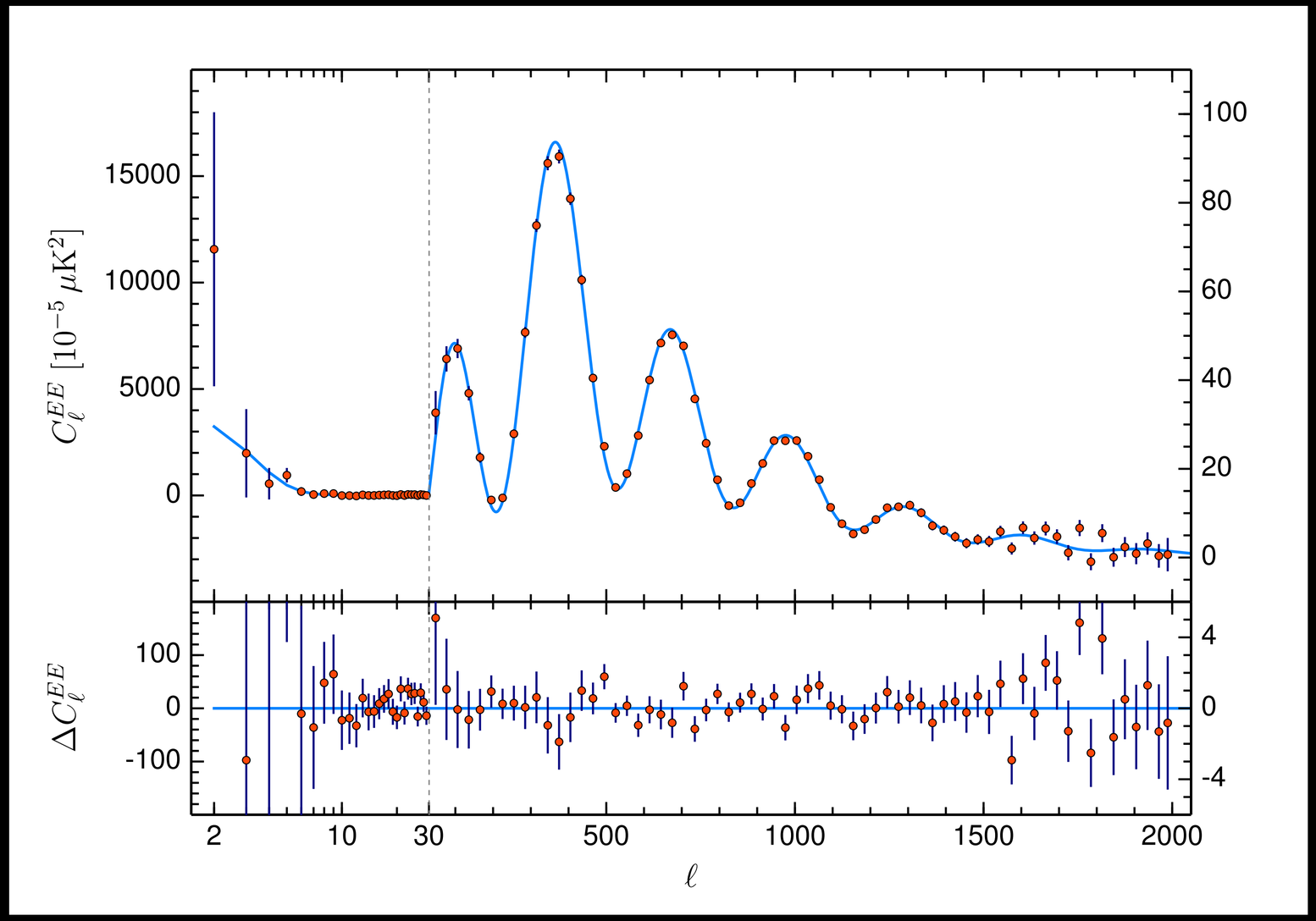

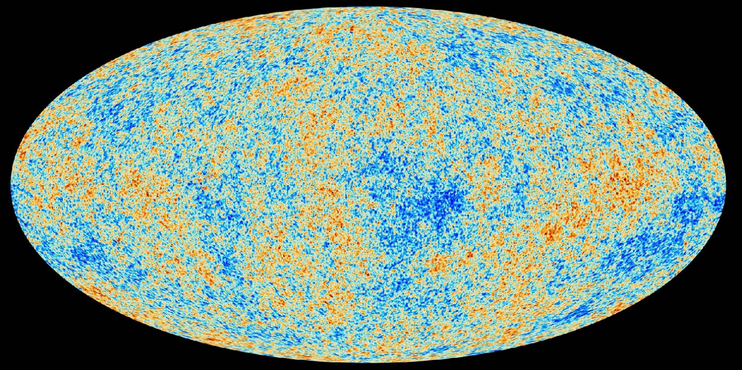

[Planck]

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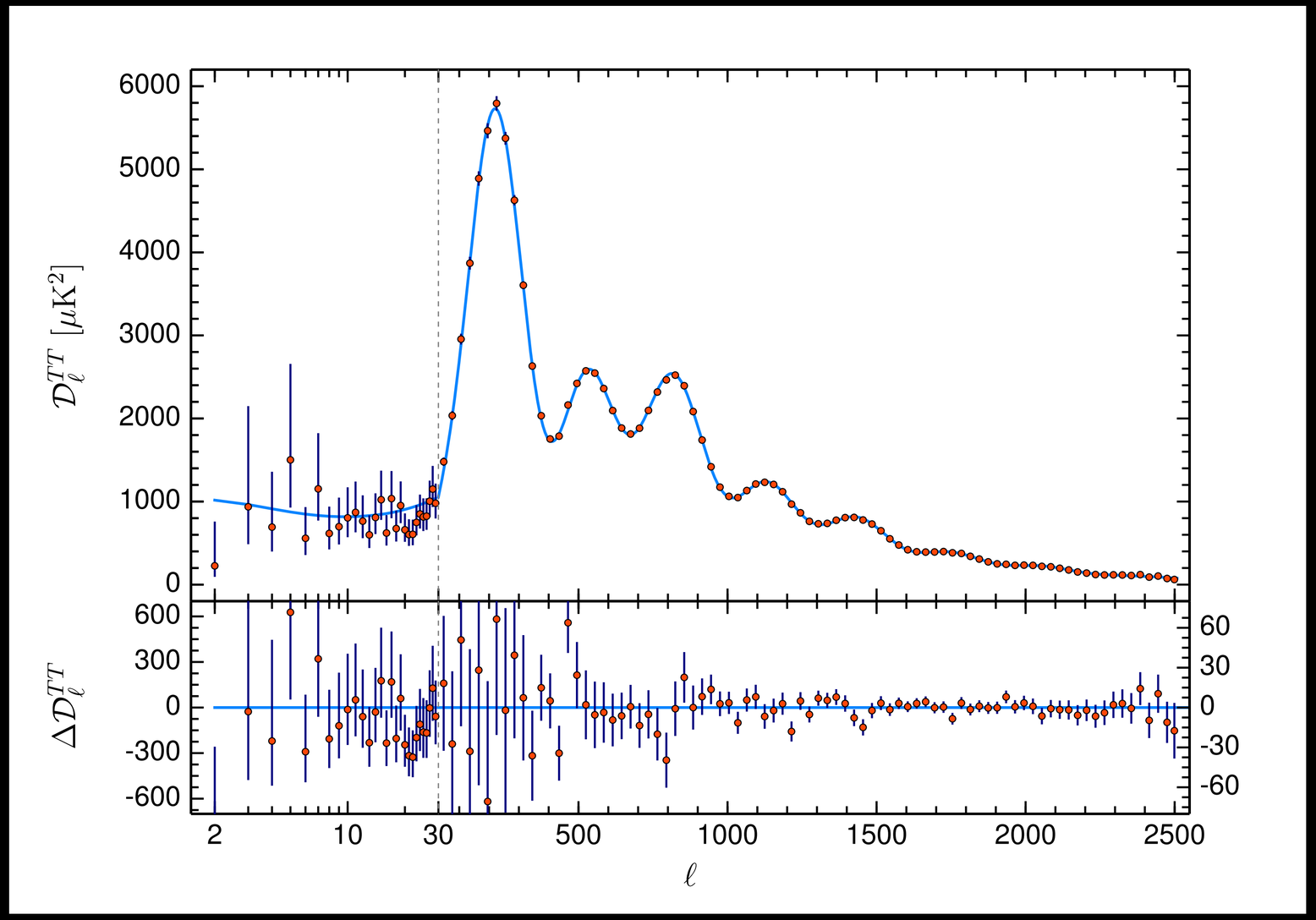
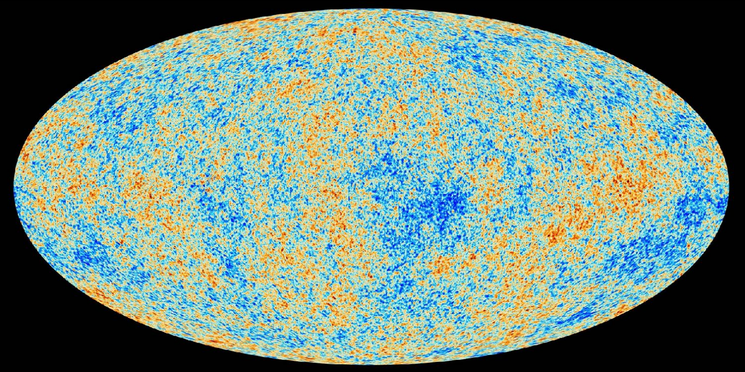
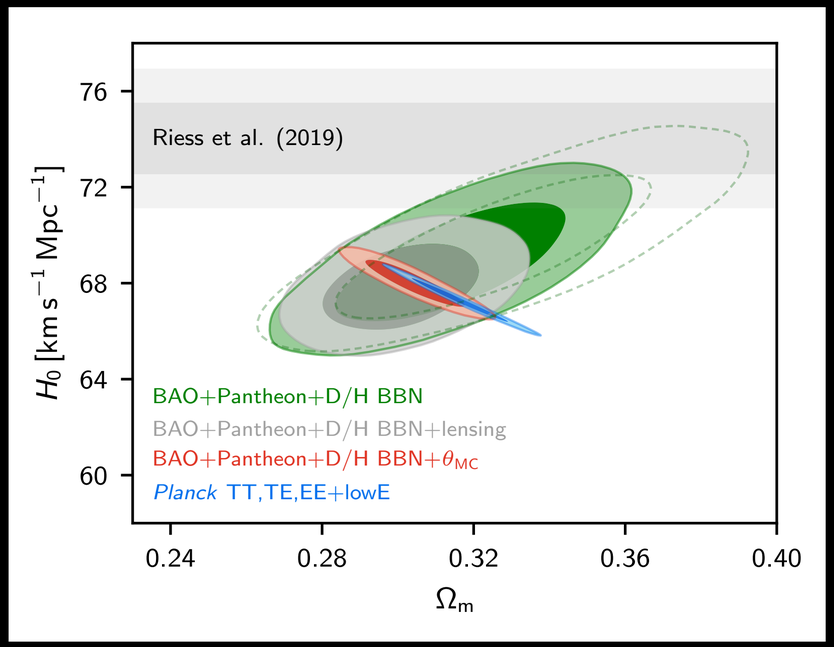




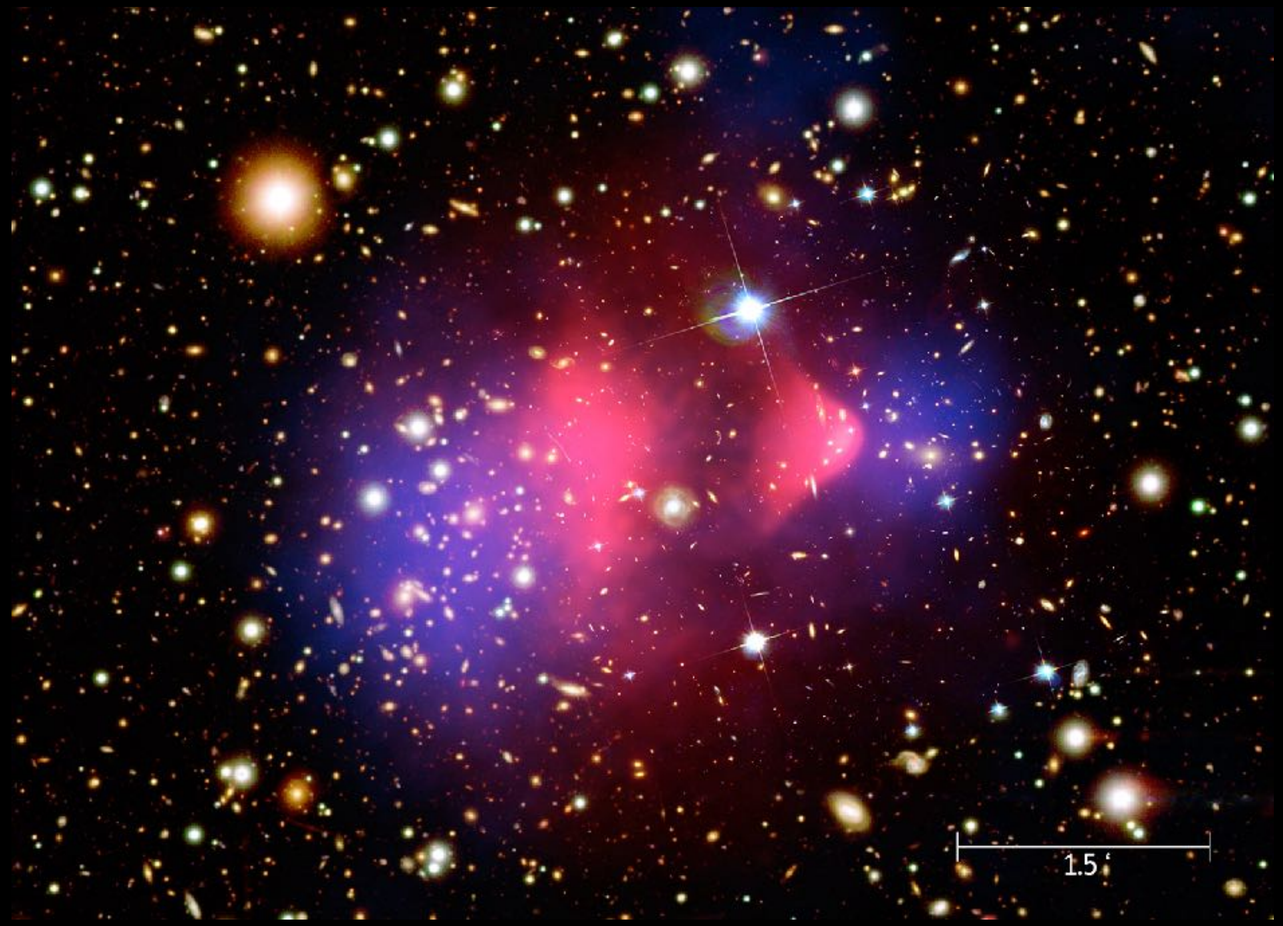


[Planck]

Large-Scale Dark Matter Overdensities

“If your experiment needs statistics, you ought to have done a better experiment.” — Ernest Rutherford

Large-Scale Dark Matter Overdensities



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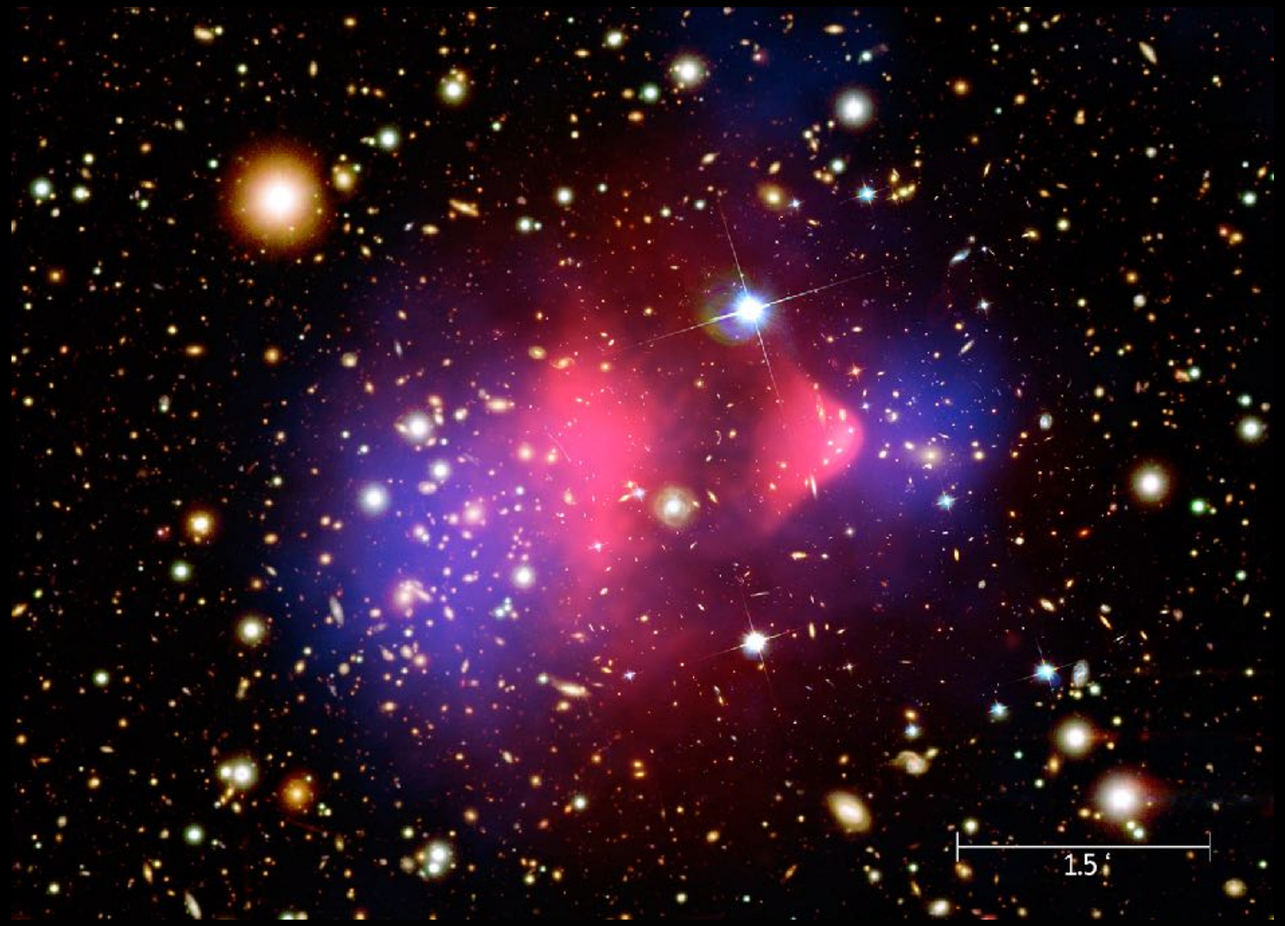

✓ abundance, location, kinematics

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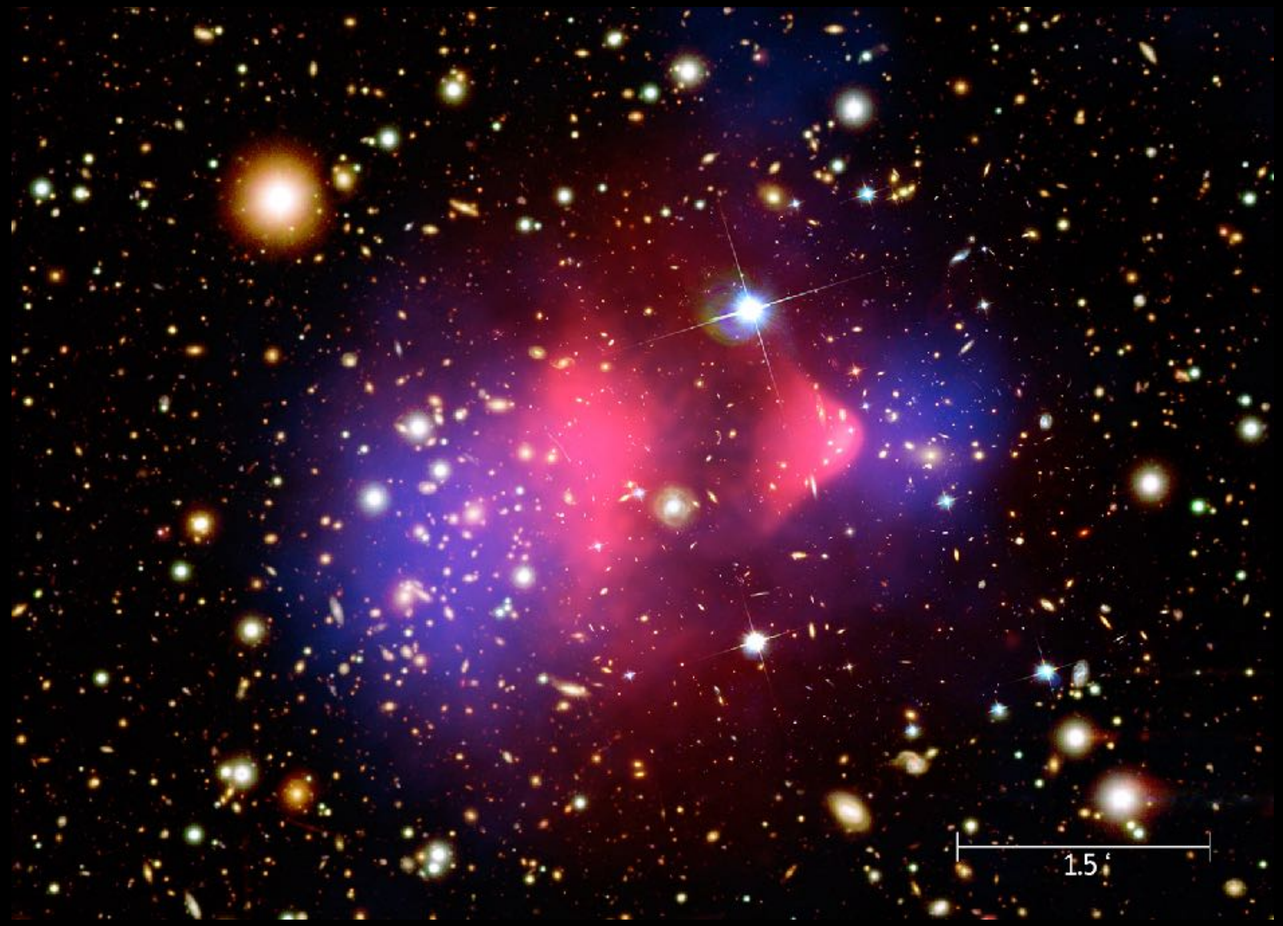
Large-Scale Dark Matter Overdensities



✓ abundance, location, kinematics

✗ mass, spin, non-gravitational interactions

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Enumerable Dark Matter Candidates

something else?

Weakly Interacting Massive Particle

stable by symmetry

thermal production: freeze-out, freeze-in

motivated by hierarchy problem

- ! allowed
- ! consistent
- ! produced
- ✓ testable
- ✓ anomaly, puzzle
- ✓ natural

mass $>$ keV

---

mass $<$ keV

Super Weakly Interacting Light Boson

meta-stable by lightness

non-thermal production: misalignment, inflationary fluctuation

motivated by strong CP problem, string theory, origin of SM masses and couplings

Enumerable Dark Matter Candidates

something else?

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$\text{mass} > \text{keV}$

$\text{mass} < \text{keV}$

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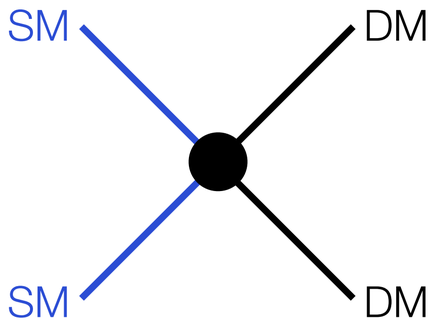

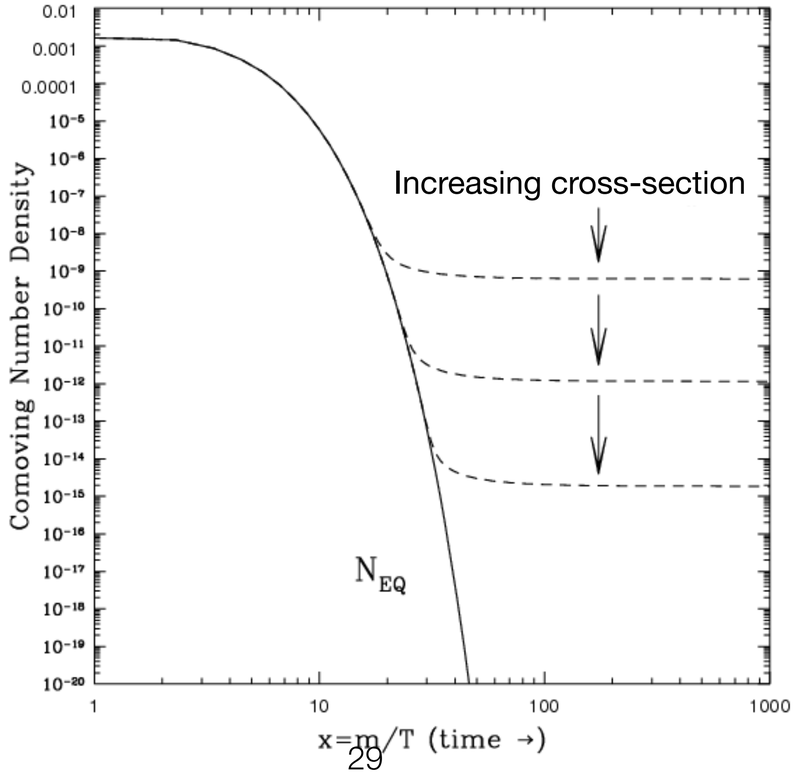

$$\frac{\Omega_{\rm WIMP}}{\Omega_m} \propto \frac{1}{\sigma_{\rm annihilation}} \approx \frac{1}{(20\,{\rm TeV})^{-2}}$$

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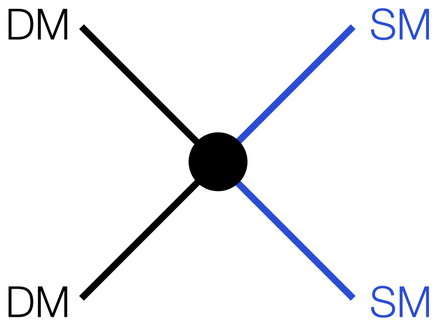

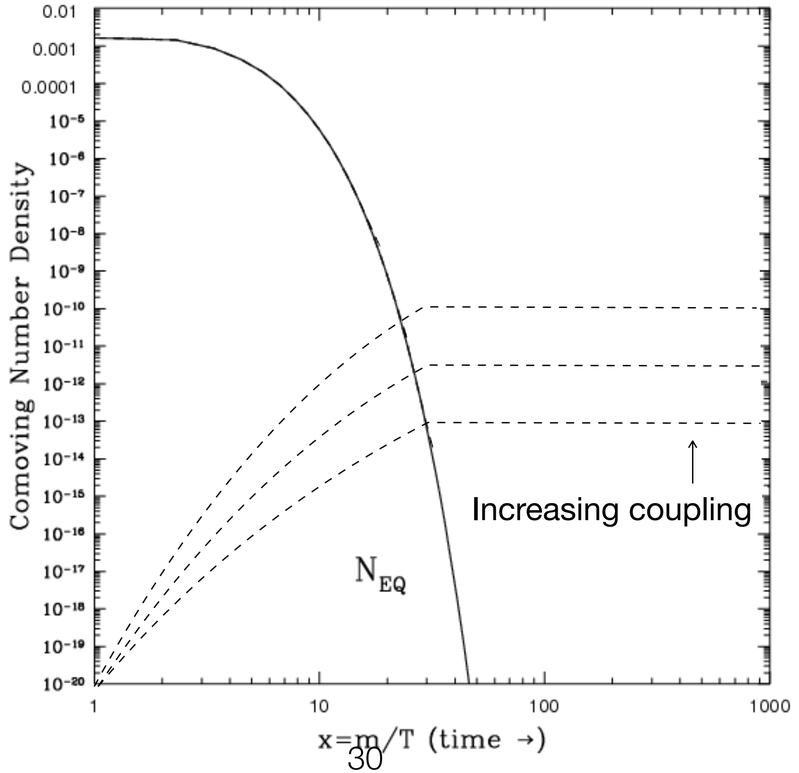

$$\frac{\Omega_{\rm WIMP}}{\Omega_m} \propto \frac{(\text{coupling})^2}{\text{mass}}$$

$$\approx \left(\frac{\text{coupling}}{10^{-12}}\right)^2 \frac{\text{GeV}}{\text{mass}}$$

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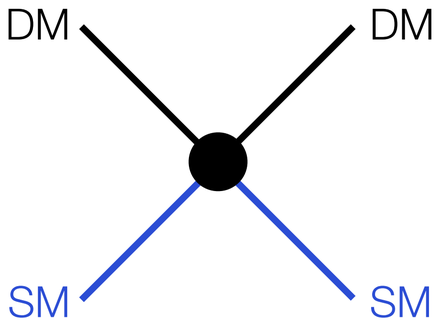

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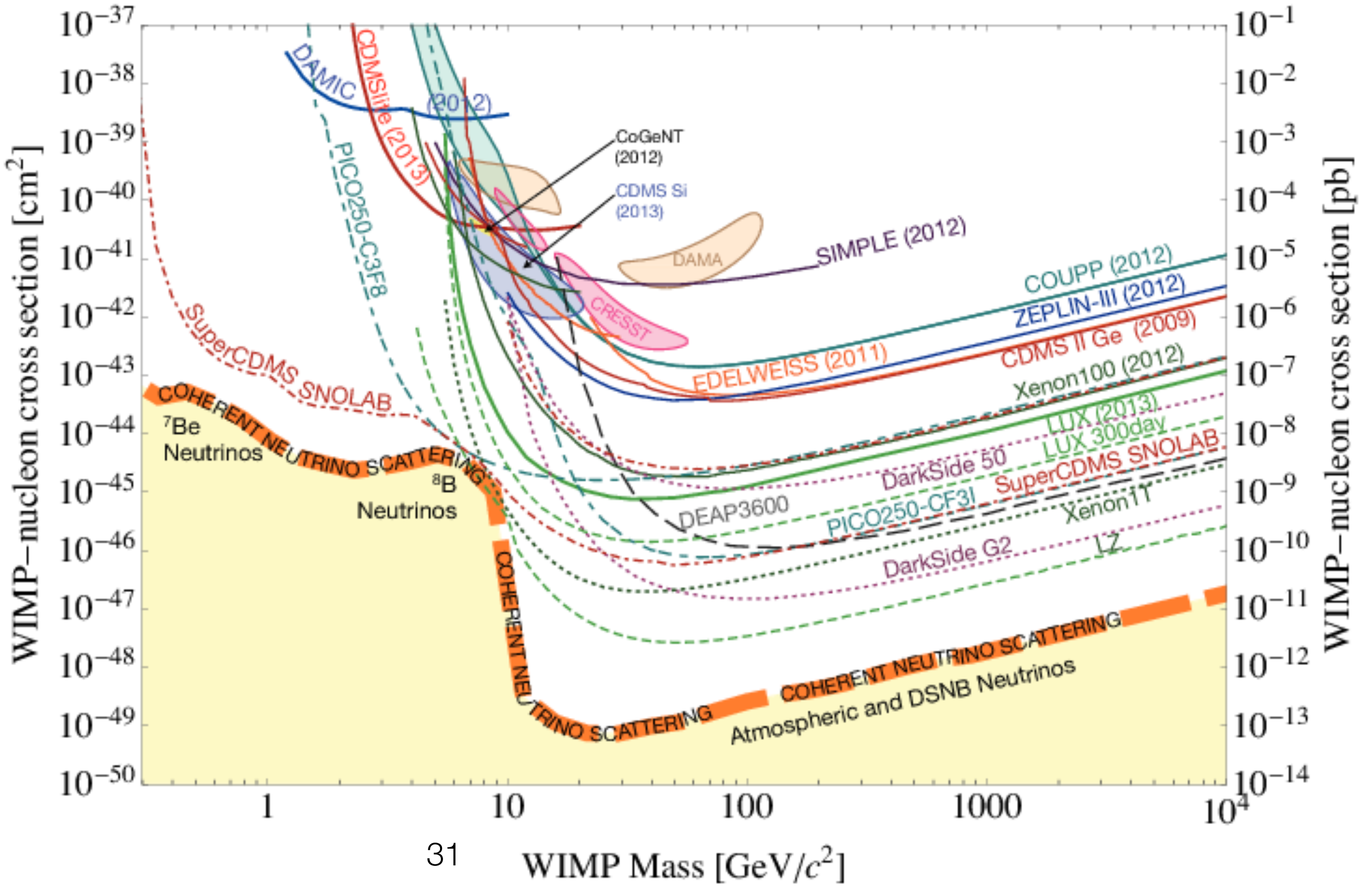

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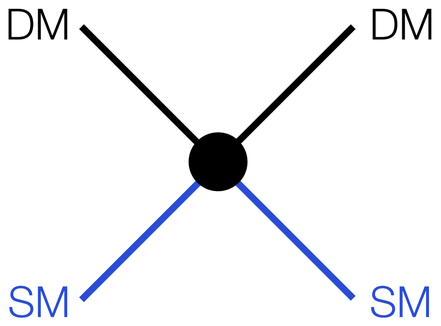

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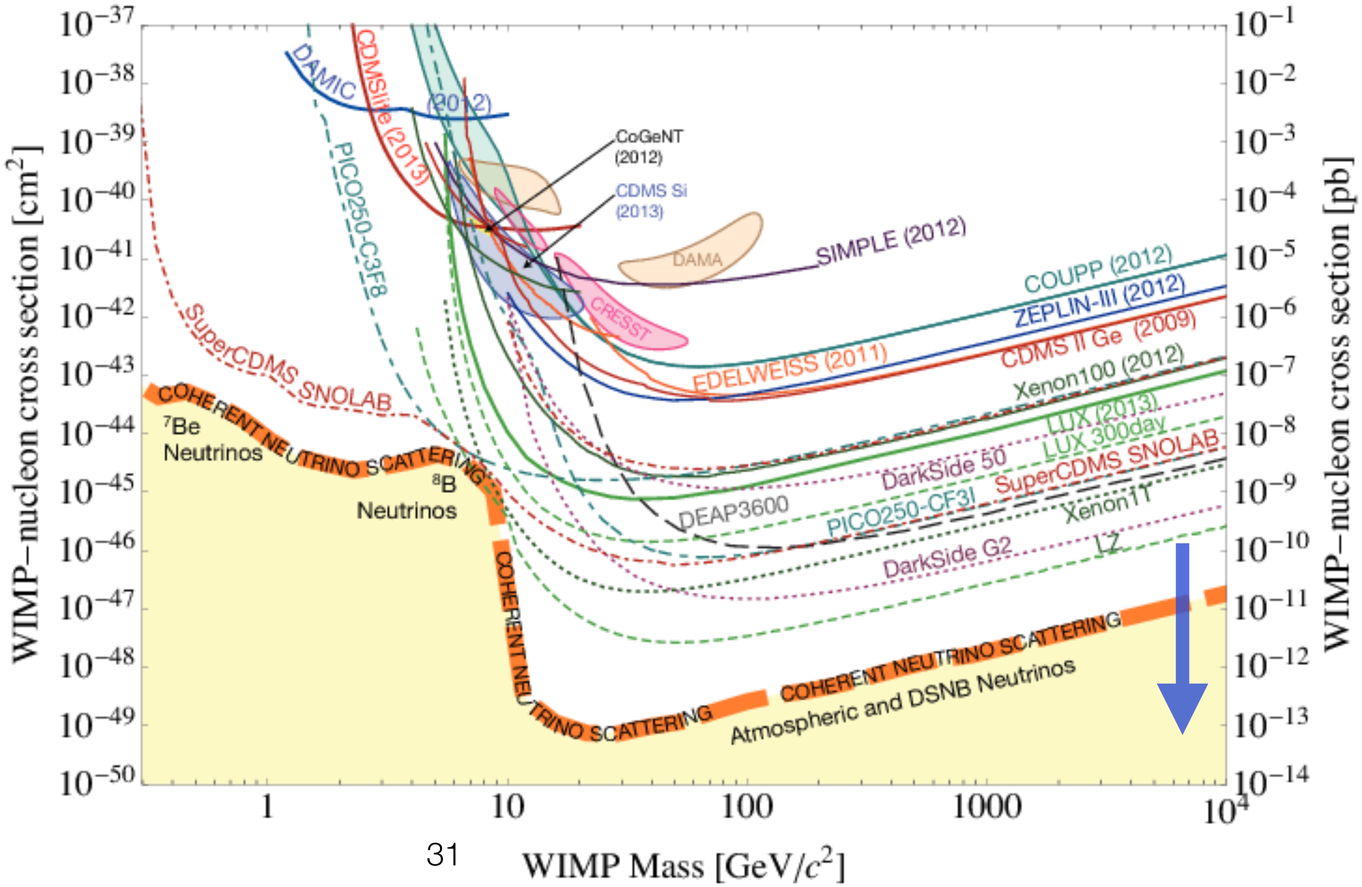

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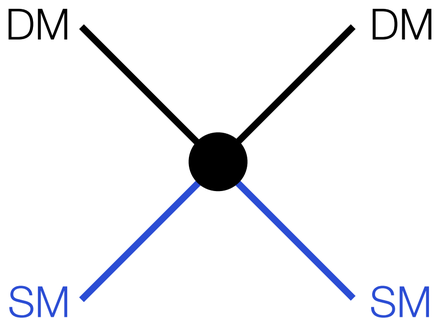

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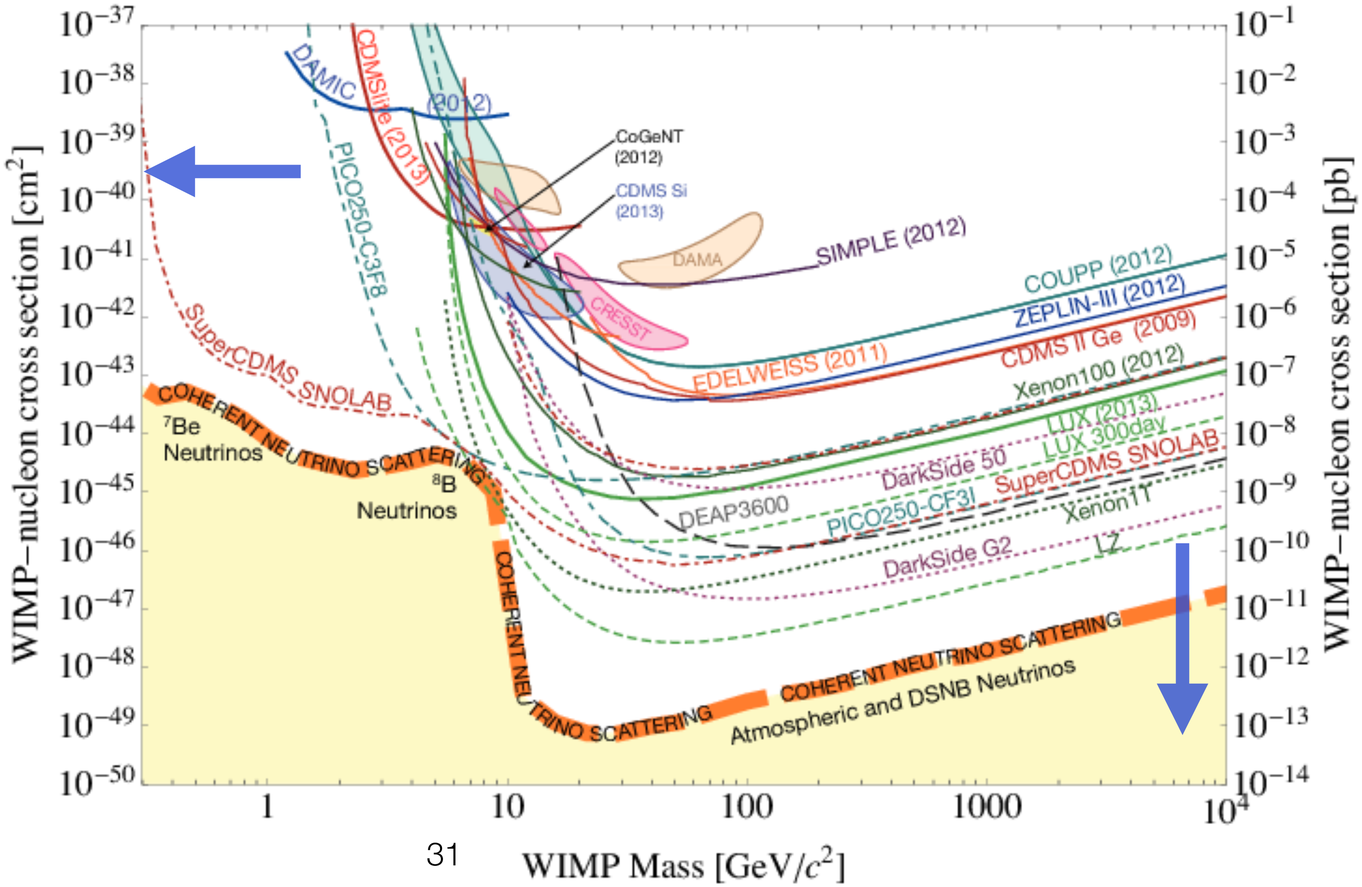

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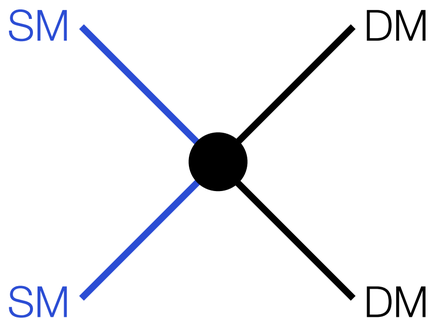
thermal production: freeze-out, freeze-in

motivated by hierarchy problem



Enumerable Bosonic Dark Matter Candidates

- ! allowed
- ! consistent
- ! produced
- ✓ testable
- ✓ anomaly, puzzle
- ✓ natural

Super Weakly Interacting Light Boson

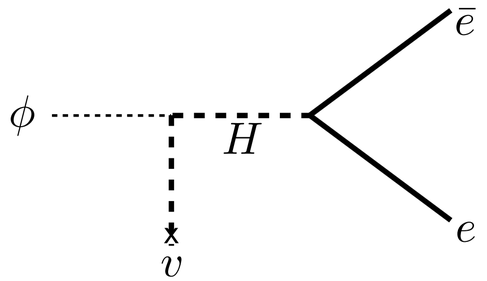
meta-stable by lightness

non-thermal production: misalignment, inflationary fluctuations

motivated by strong CP problem, string theory, origin of masses/couplings

Scalar	Pseudoscalar	Vector
$\phi\bar{e}e$ $\quad$ $\phi\bar{q}q$	$a\bar{e}i\gamma_5 e$ $\quad$ $a\bar{q}i\gamma_5 q$	$\epsilon A'_\mu J^\mu_{\rm EM}$
ϕF^2 $\quad$ ϕG^2	$aF\tilde{F}$ $\quad$ $aG\tilde{G}$	$gA'_\mu J^\mu_{B-L}$

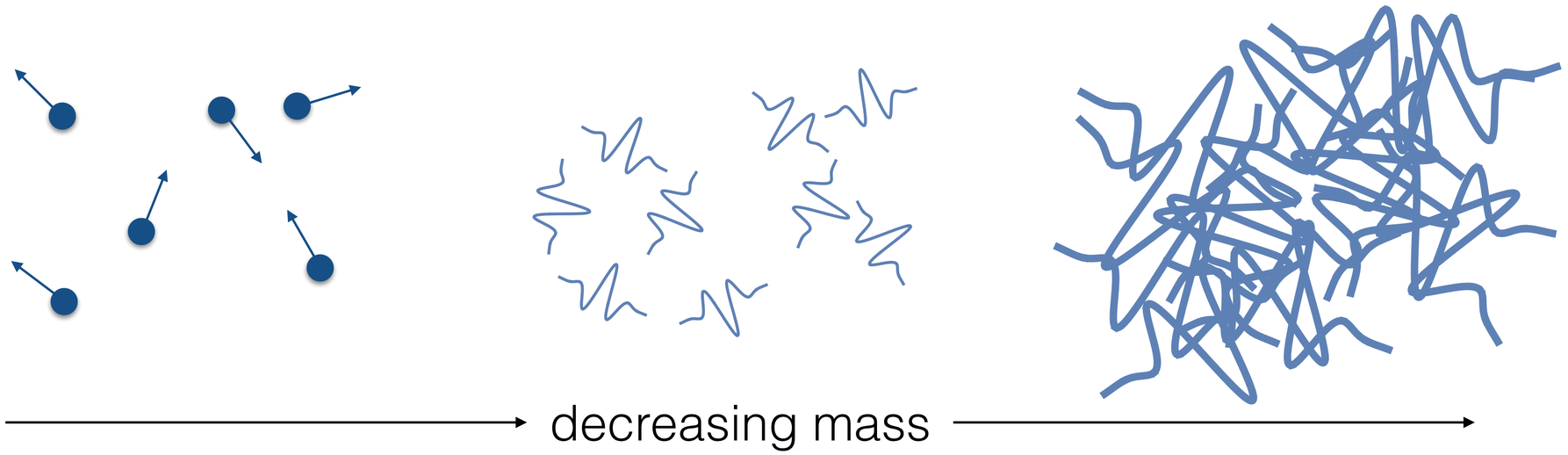
Higgs portal $A\phi|H|^2$



QCD axion

Light Bosonic Dark Matter as Classical Waves

$$\mathcal{L} = \frac{(\partial\phi)^2}{2} - \frac{m^2\phi^2}{2}$$



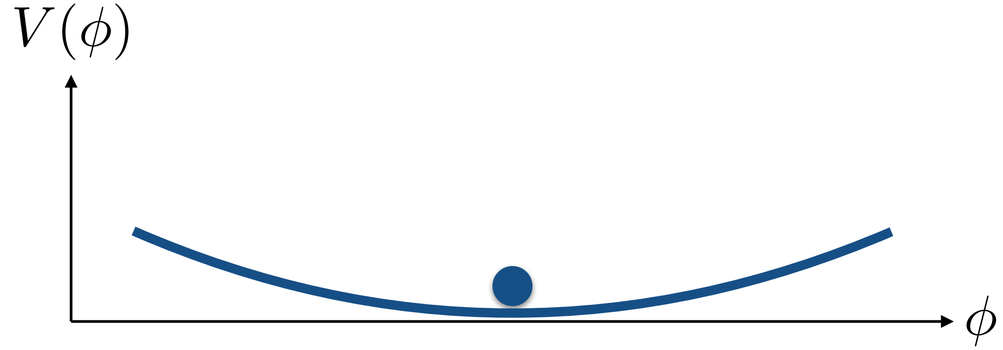
large occupation number: $\dfrac{\rho_{\rm DM}}{m^4\sigma_v^3} \sim 10^4 \left(\dfrac{\rm eV}{m}\right)^4$

large field amplitude: $\phi(t,\mathbf{x}) \simeq \underbrace{\dfrac{\sqrt{2\rho_{\rm DM}}}{m}}_{10^{-15}\, M_{\rm Pl} \left(\frac{10^{-15}\,\rm eV}{m}\right)} \cos\left(mt - m\mathbf{v}\cdot\mathbf{x} + \alpha\right) + \ldots$

Scalar Dark Matter Production in the early Universe

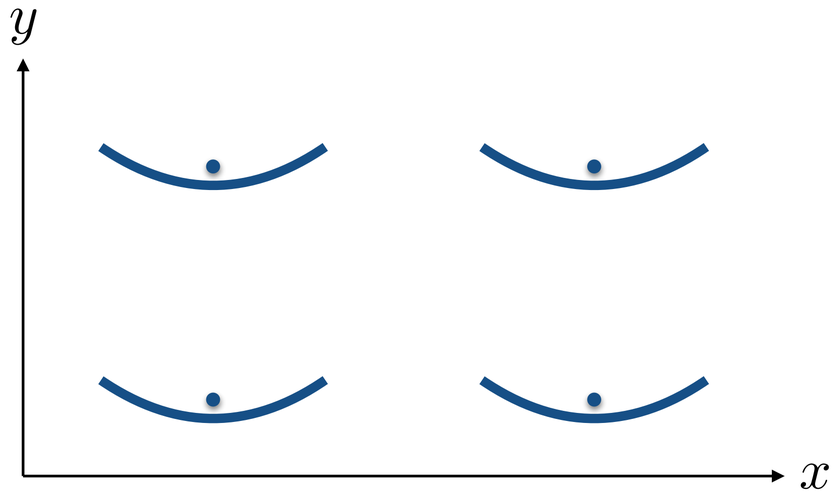
$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m^2 \phi^2$$

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi^2 = 0$$



dissipation ⟷ fluctuation

during inflation: misalignment



$$\phi_i \sim 10^{-2} M_{\rm Pl} \left(\frac{10^{-20}\,{\rm eV}}{m} \right)^{1/4}$$

(for free scalar field)

Scalar Dark Matter Production in the early Universe

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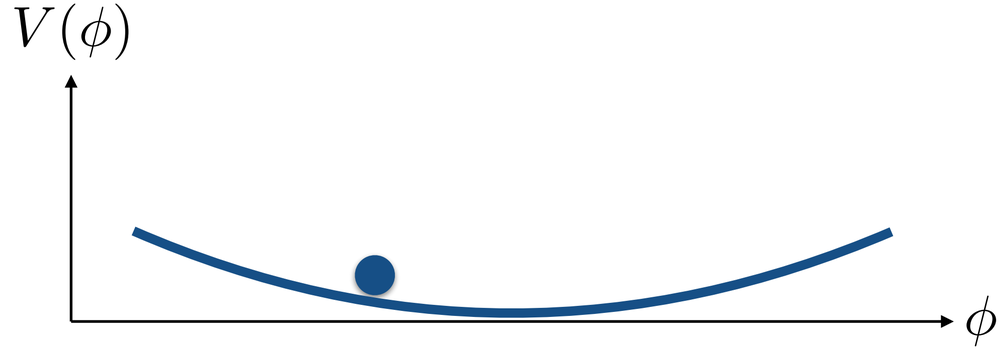
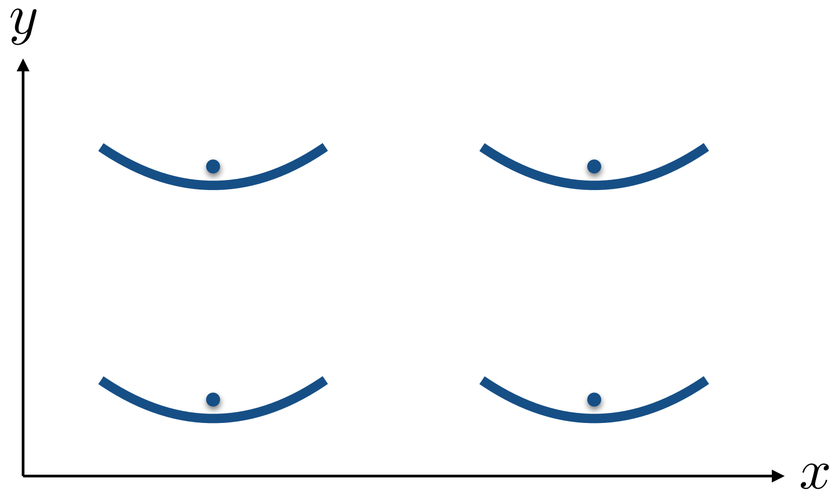


dissipation $\longleftrightarrow$ fluctuation

during inflation: misalignment



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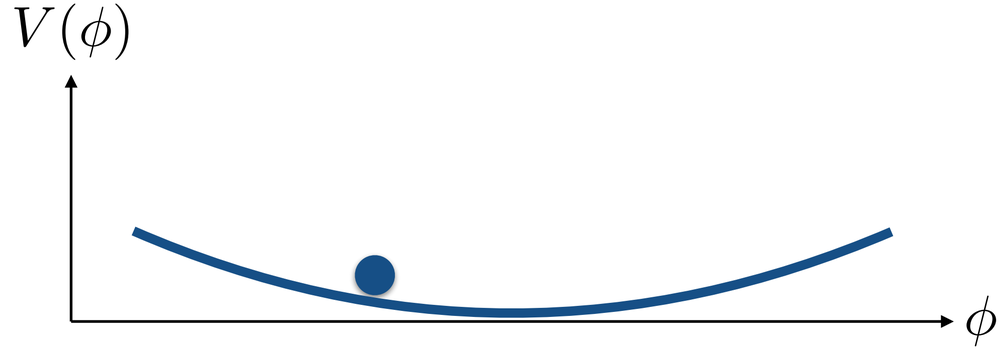
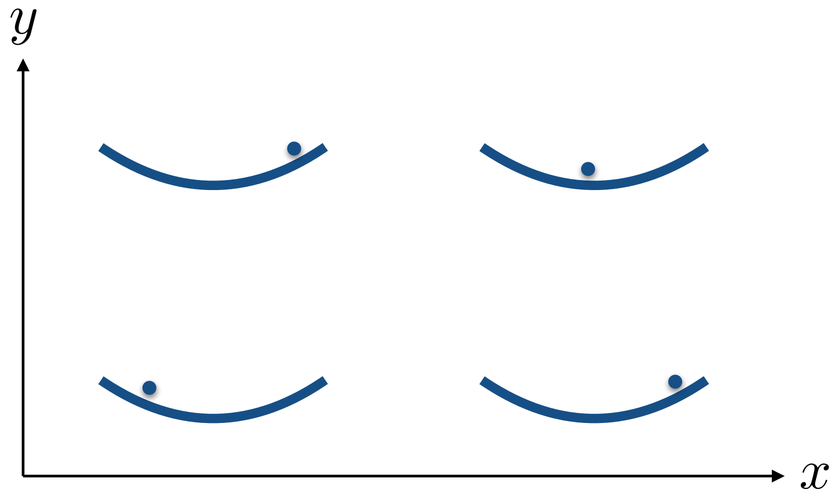


dissipation ⟷ fluctuation

during inflation: misalignment



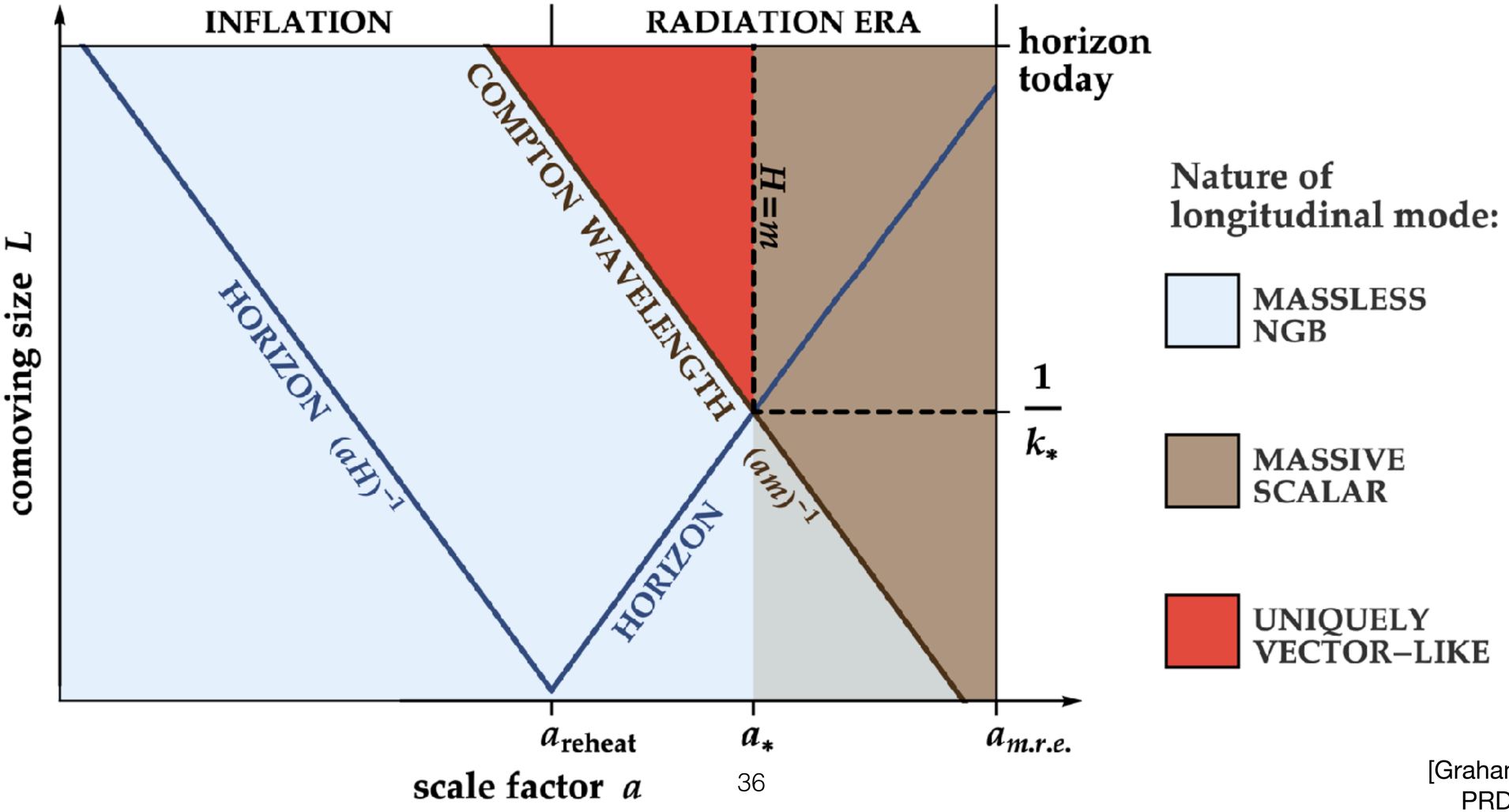
$$\phi_i \sim 10^{-2} M_{\rm Pl} \left(\frac{10^{-20}\,{\rm eV}}{m} \right)^{1/4}$$

(for free scalar field)

Vector Dark Matter Production in the early Universe

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{m^2}{2}A^{\mu}A_{\nu}$$

$$\frac{\Omega_{\rm vector}}{\Omega_m} = \sqrt{\frac{m}{6\times 10^{-6}\,{\rm eV}}}\left(\frac{H_{\rm I}}{10^{14}\,{\rm GeV}}\right)^2$$



[Graham, Mardon, Rajendran; PRD 93, 103520 (2016)]

Motivation “Metric” for Dark Matter Theories

- ! allowed
- ! consistent
- ! produced
- ✓ testable
- ✓ anomaly, puzzle
- ✓ natural

The Outline

How does dark matter fit into theoretical particle physics?

The evidence for dark matter!

A motivation “metric” for dark matter theories

General principles of precision-frontier dark matter detection

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How does dark matter fit into theoretical particle physics?

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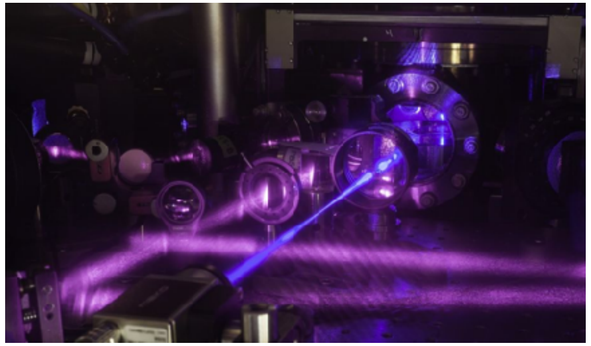
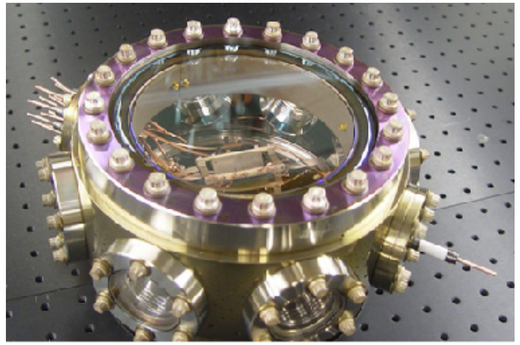
General principles of precision-frontier dark matter detection

Innumerable Probes

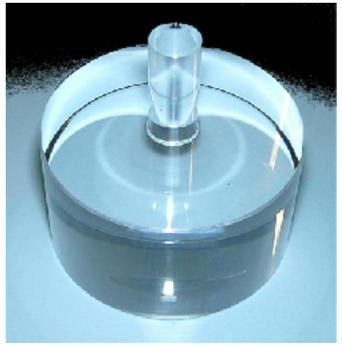
Atomic Clocks



Nuclear Clock

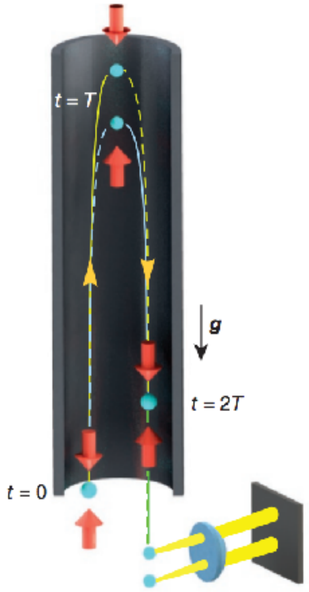


Acoustic Resonators



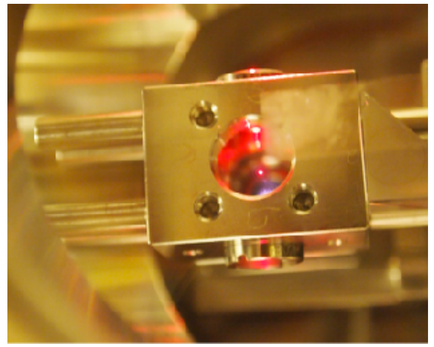
Molecular Resonators

Atom Interferometry

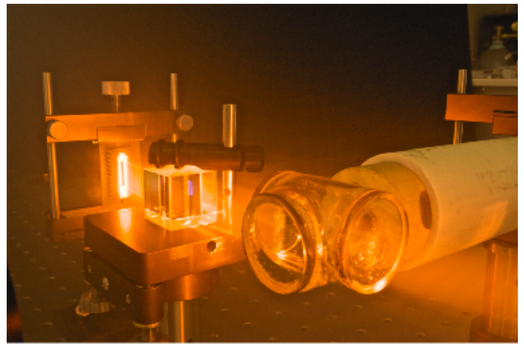


Laser Interferometry

Accelerometers

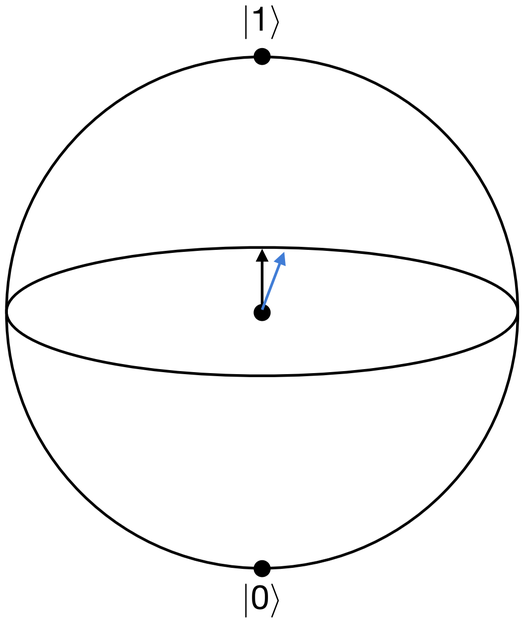


Spin Resonators

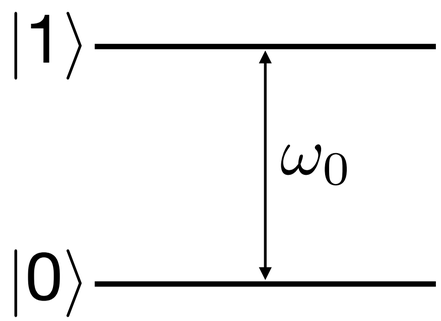


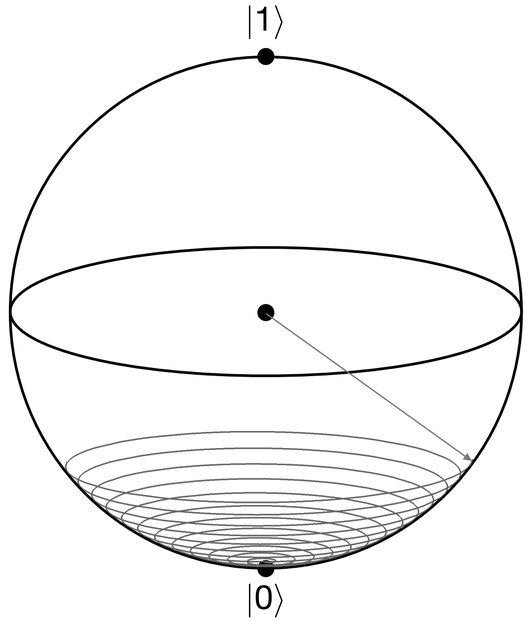
Precision Probe Classification

Two-Level System



Interferometer

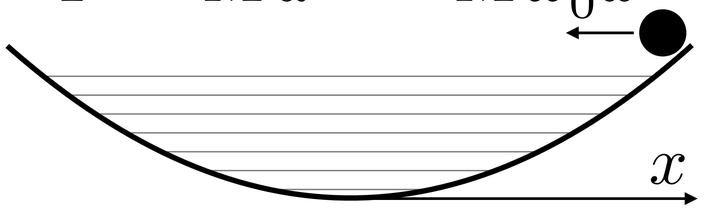




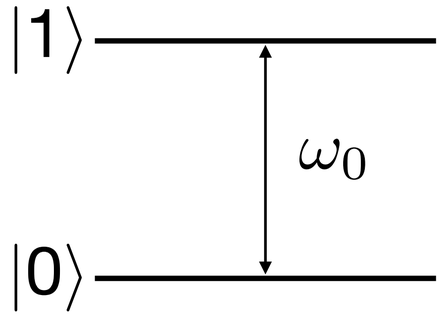
Resonator

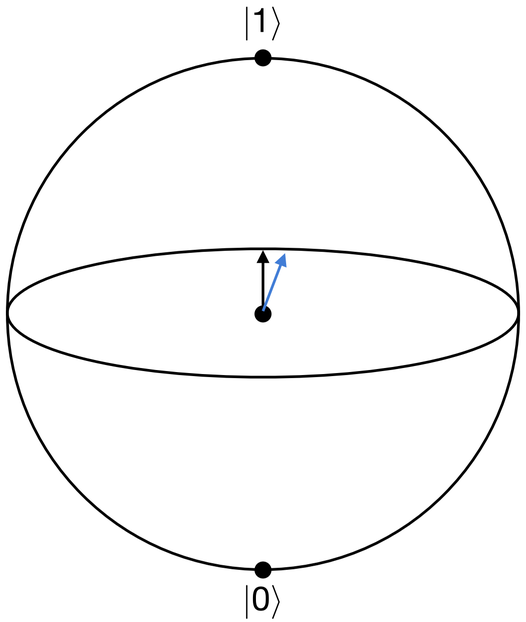
Generalized Harmonic Oscillator

$$F = Ma = -M\omega_0^2 x$$



Two-Level Interferometer



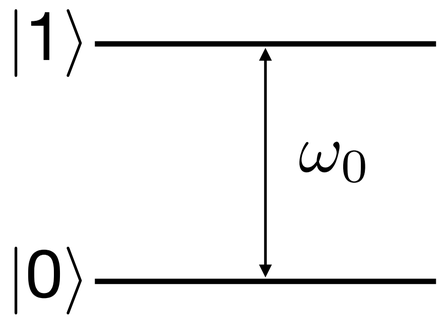


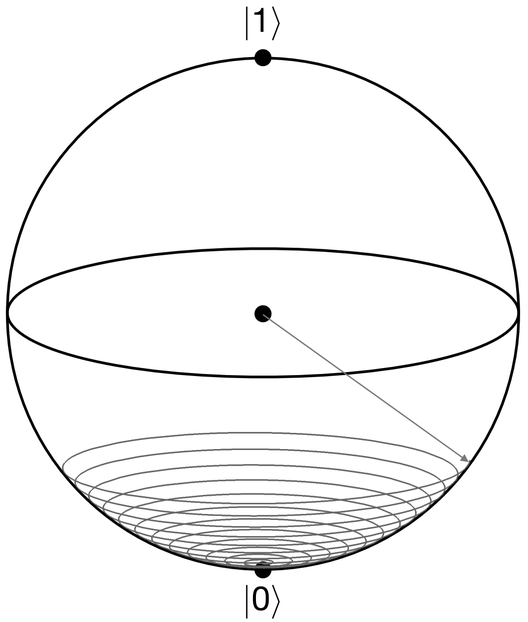
$$\left(|0\rangle + e^{i(\varphi+\Delta\varphi)}|1\rangle\right)^{\otimes N} \qquad \sigma_\varphi = \frac{1}{\sqrt{N}}$$

LIGO: $\Delta\varphi = h_{\text{strain}} k_\gamma L \qquad \sigma_{h_{\text{strain}}} = \frac{1}{\sqrt{N}} \frac{1}{k_\gamma L}$

Clock: $\Delta\varphi = (\omega_0 - \omega)\tau \qquad \sigma_{\frac{\Delta\omega_0}{\omega_0}} = \frac{1}{\sqrt{N}} \frac{1}{\omega_0 \tau}$

Two-Level Resonator





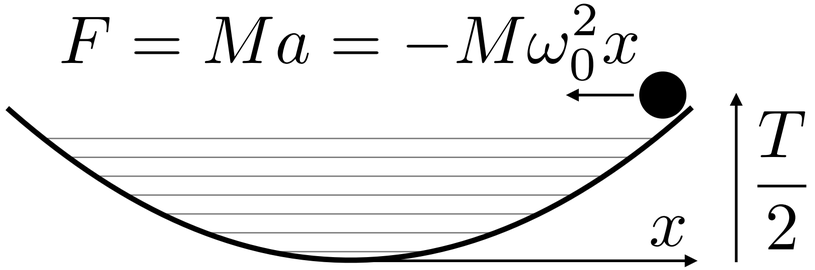
Width: $\frac{\omega_0}{Q}$

On resonance: $|0\rangle - (i\langle \Delta H \rangle t) e^{i\omega_0 t}|1\rangle$

Transverse readout: $\langle 0| + \langle 1|$ $\sigma_{\Delta H} = \frac{\omega_0}{Q\sqrt{N}}$

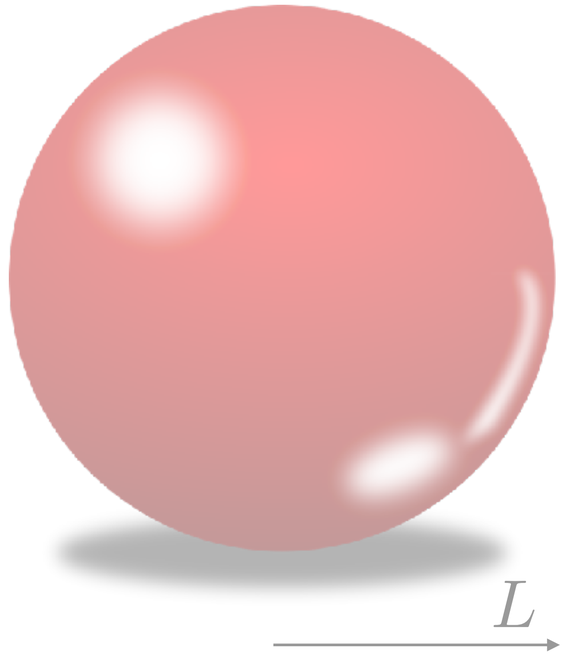
Absorption: $\Gamma_{\text{absorption}} = \frac{Q|\langle \Delta H \rangle|^2}{\omega_0}$ $\sigma_{\Delta H} = \sqrt{\frac{\omega_0 \sigma_\Gamma}{QN}}$

Generalized Harmonic Oscillator



$$\sigma_a = \sqrt{\frac{T}{M}\frac{\omega_0}{Qt}}$$

general for *any* linear system



$$a = h_{\rm strain}\omega^2 L \qquad \omega_0 = \frac{c_s}{L}$$

$$\sigma_{h_{\rm strain}} = \sqrt{\frac{T}{M}\frac{1}{Qc_s^2}\frac{\omega_0^4}{\omega^4}\frac{1}{\omega_0 t}}$$

Generalized Harmonic Oscillator

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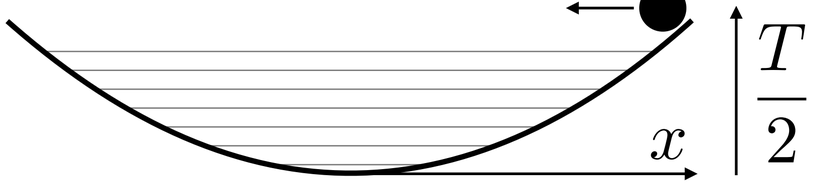

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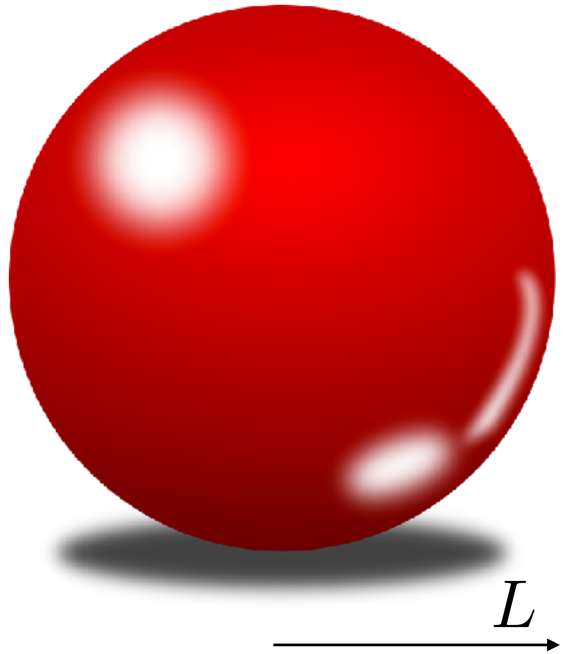

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Where is the Precision?

Spacetime coherence

$$\lambda_{\rm coh} \sim \frac{1}{m\sigma_v} \qquad \tau_{\rm coh} \sim \frac{1}{m\sigma_v^2}$$

Small dimensionless numbers

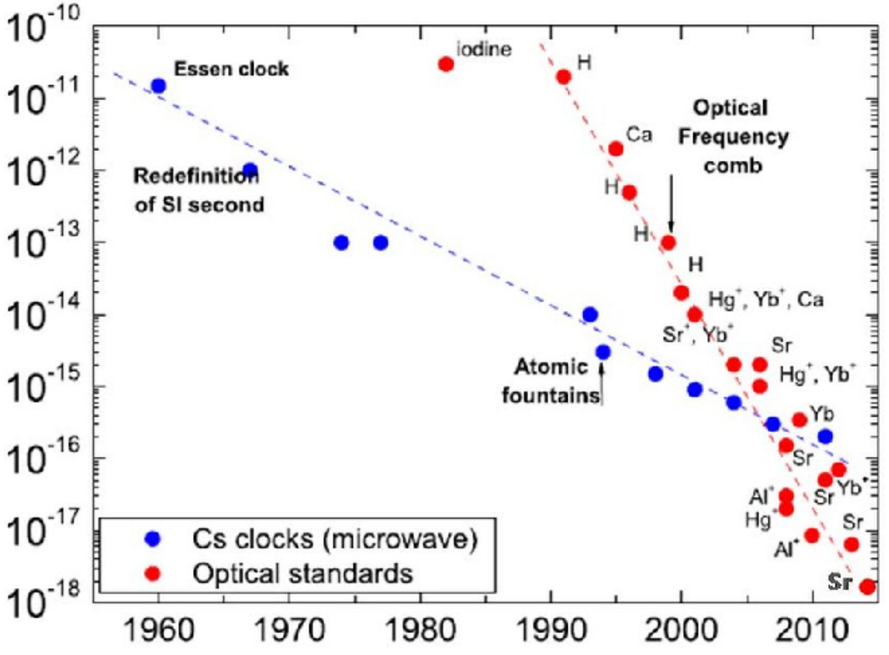
$$\frac{1}{\sqrt{N}} \qquad \frac{1}{N} \qquad \frac{1}{Q} \qquad \frac{T}{M}$$

Large dimensionless charges

$$\frac{M}{m_N} \qquad k_\gamma L \qquad \omega_0 \tau \qquad eBA$$

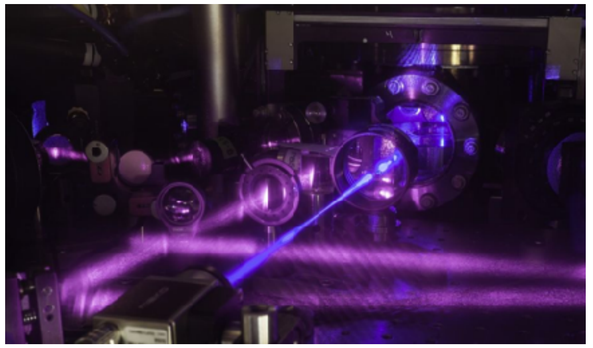
$$\frac{\rho_{\rm DM}}{m^4}$$

Engineering marvel

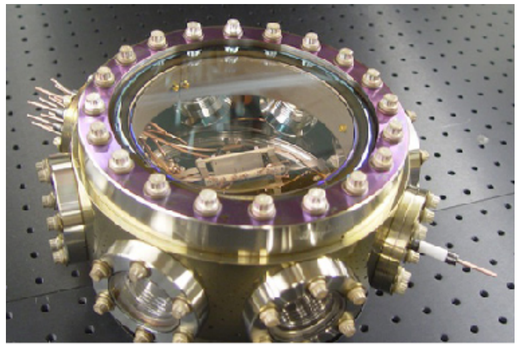


Innumerable Probes

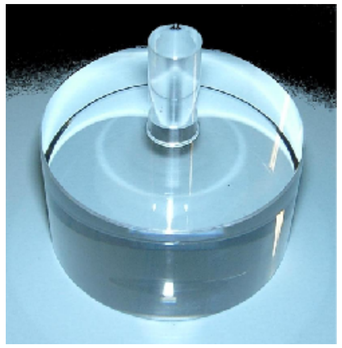
Atomic Clocks



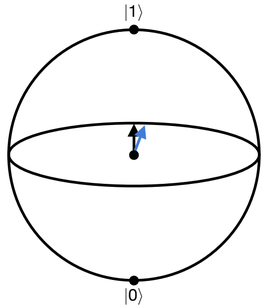
Nuclear Clock

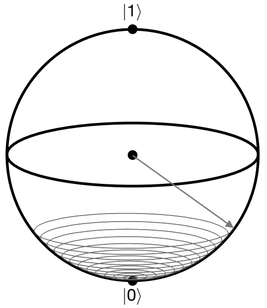


Acoustic Resonators

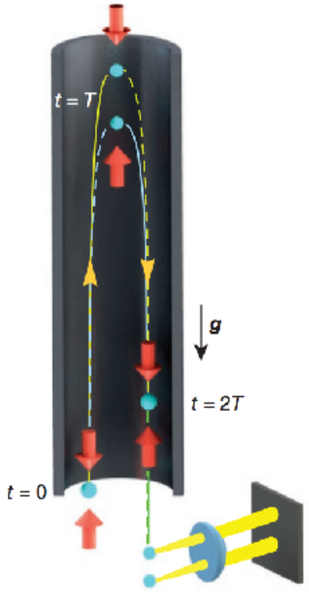


Molecular Resonators



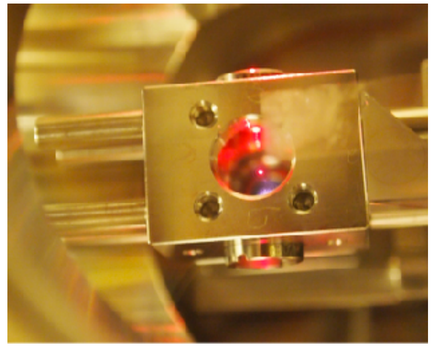


Atom Interferometry

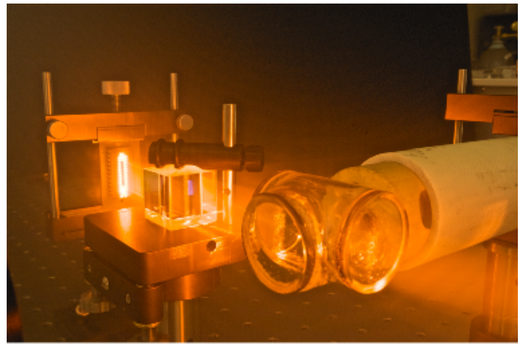


Laser Interferometry

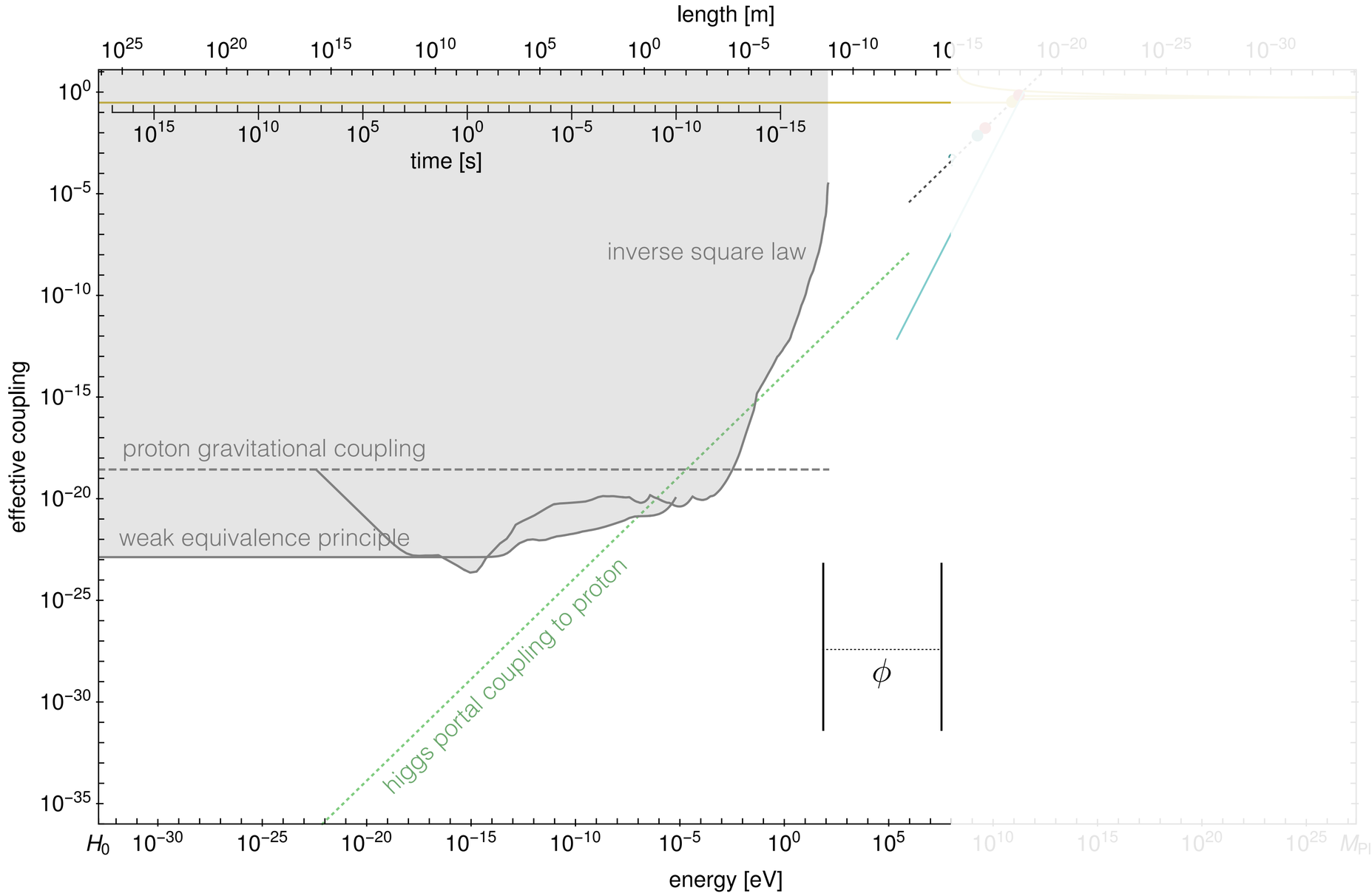
Accelerometers



Spin Resonators



Tests of Gravity



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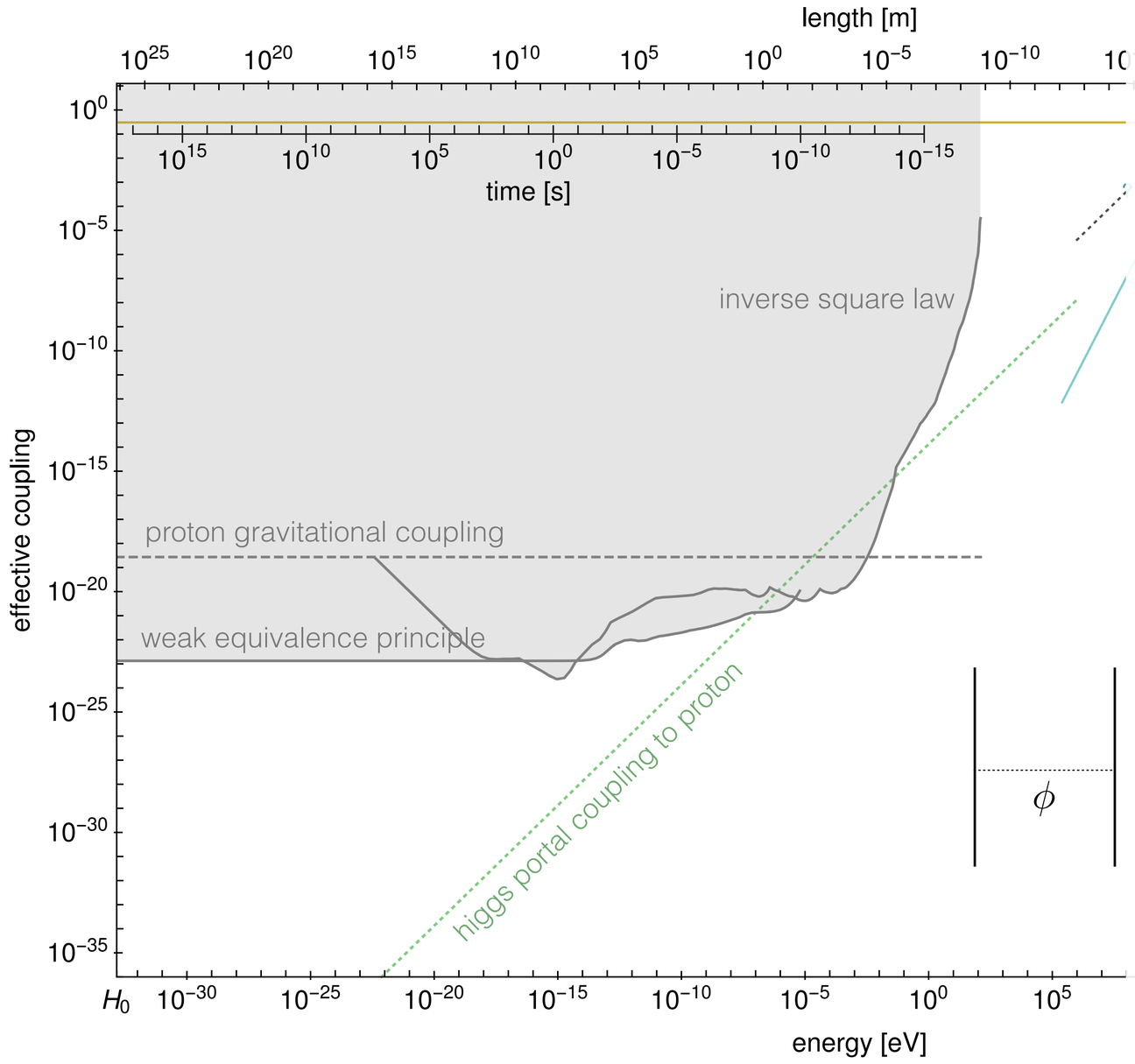
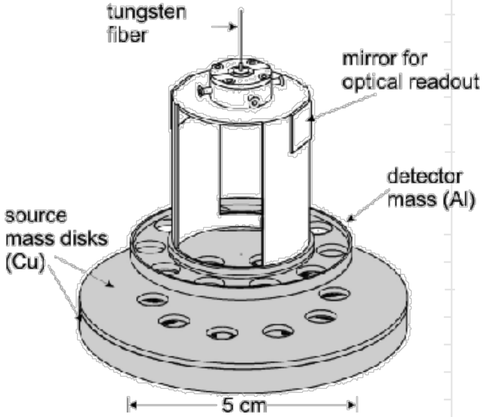
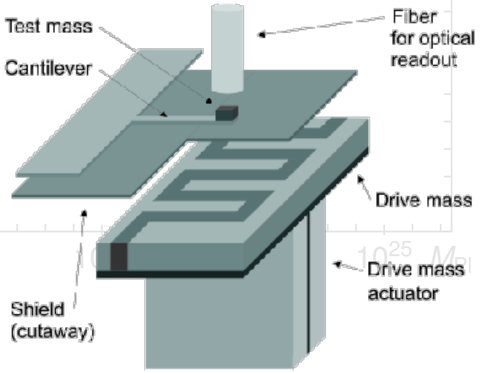


Lunar Laser Ranging

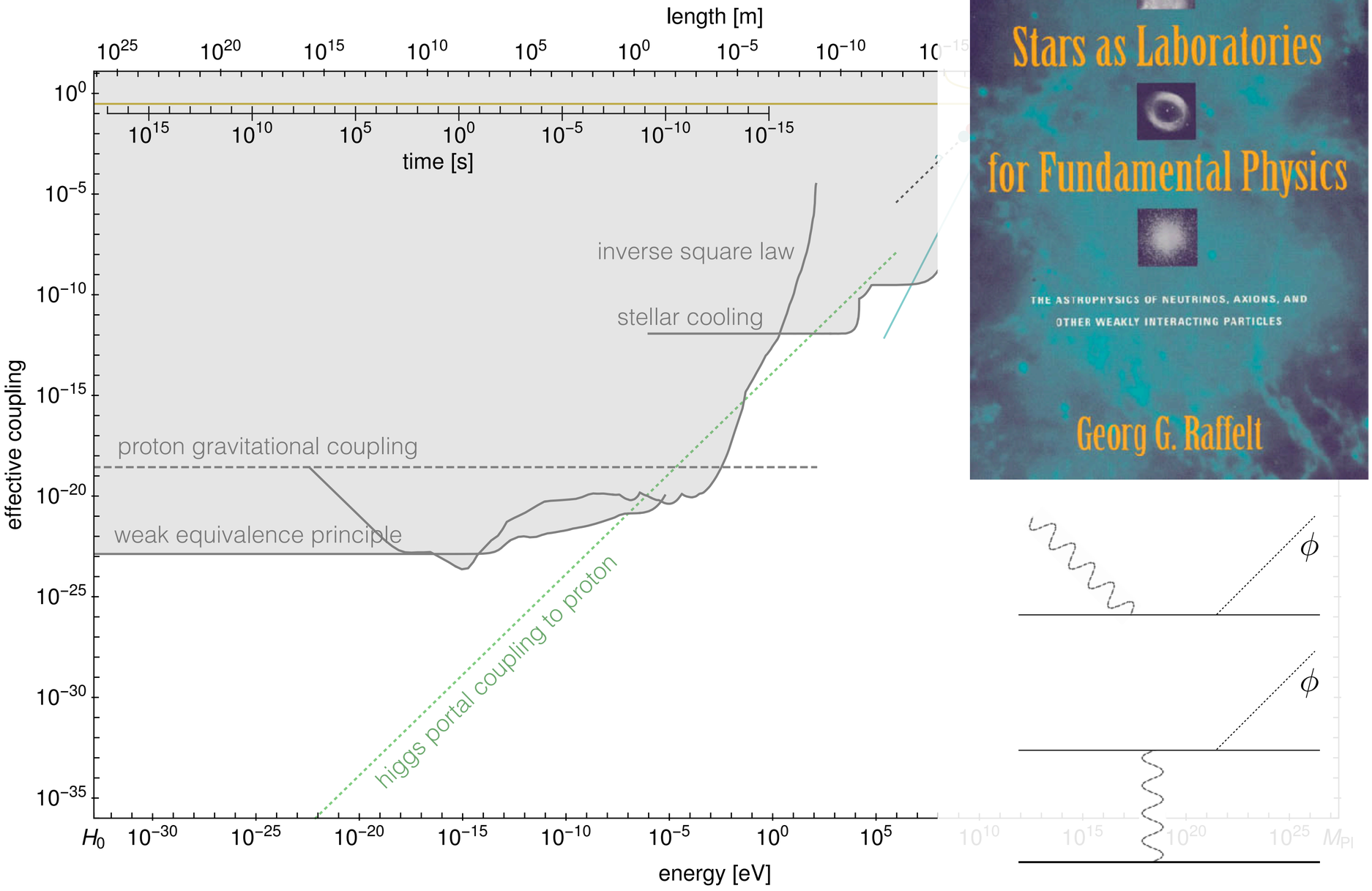
Torsion Balance



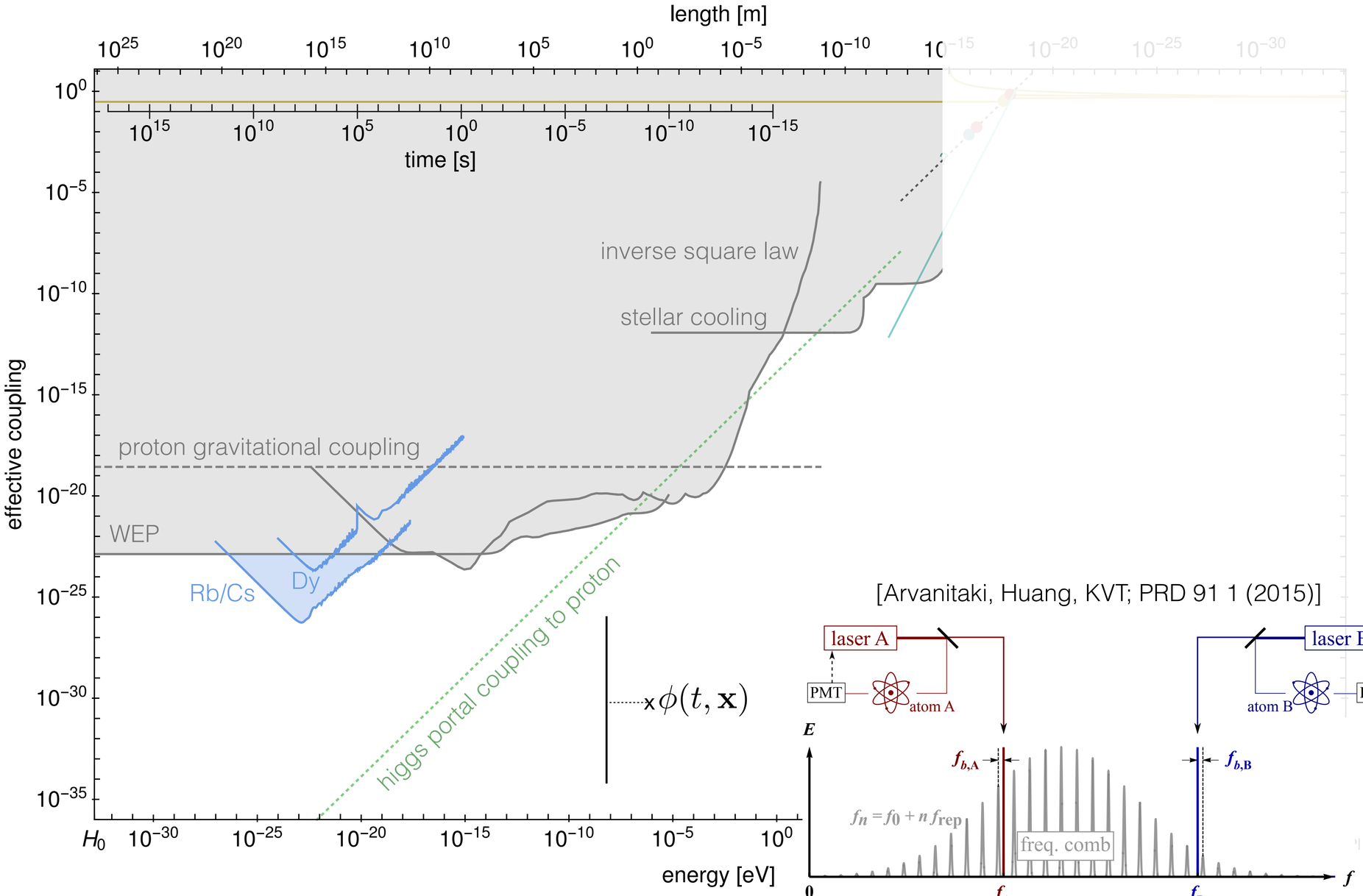
Cantilever



Stellar Cooling



Atomic Clocks

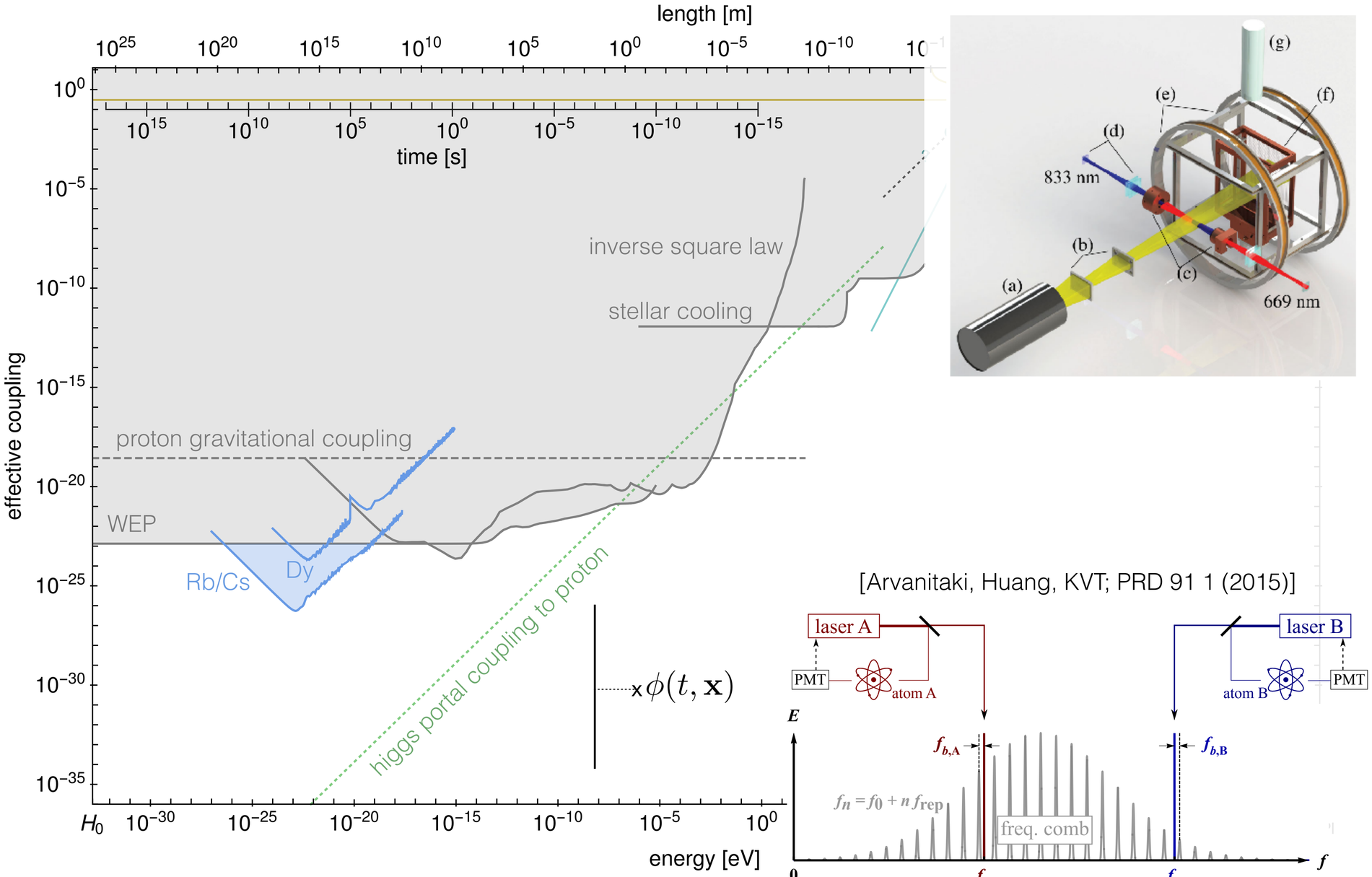


[Arvanitaki, Huang, KVT; PRD 91 1 (2015)]

Atomic Clocks

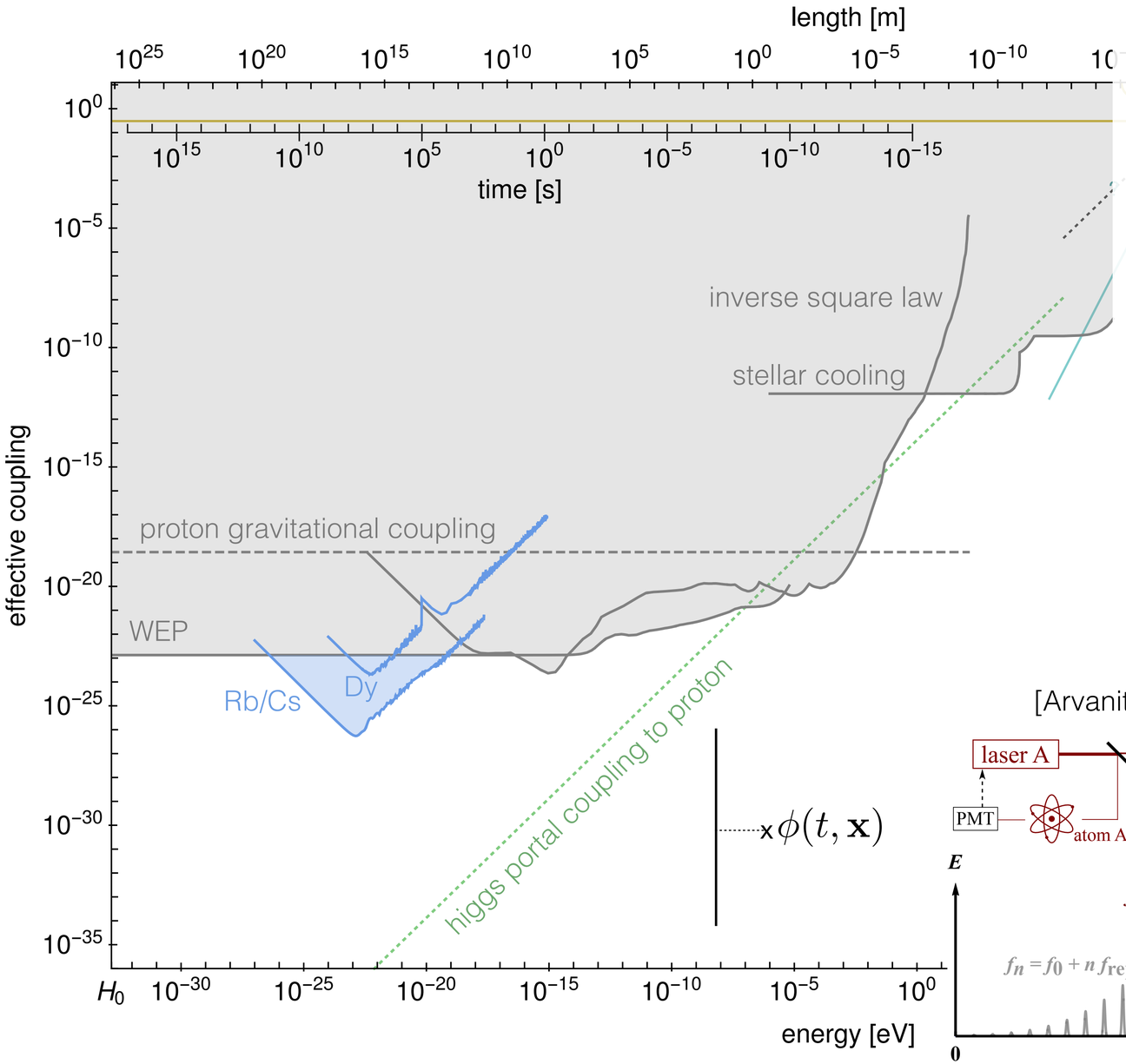
$^{162/1647}$Dy

[KVT, Budker, PRL 115 1 (2015)]



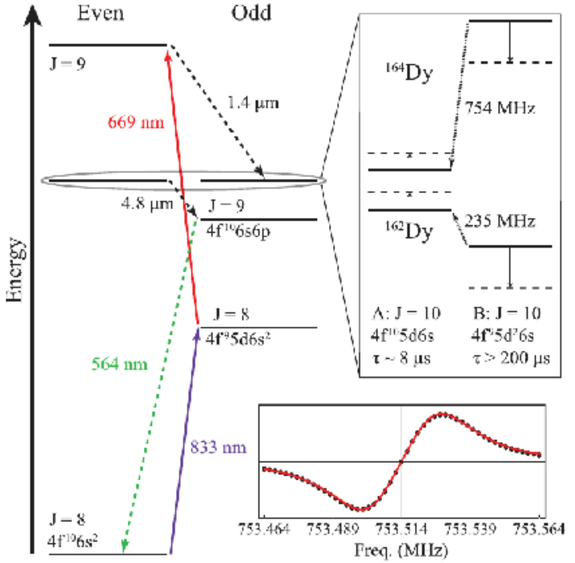
[Arvanitaki, Huang, KVT; PRD 91 1 (2015)]

Atomic Clocks

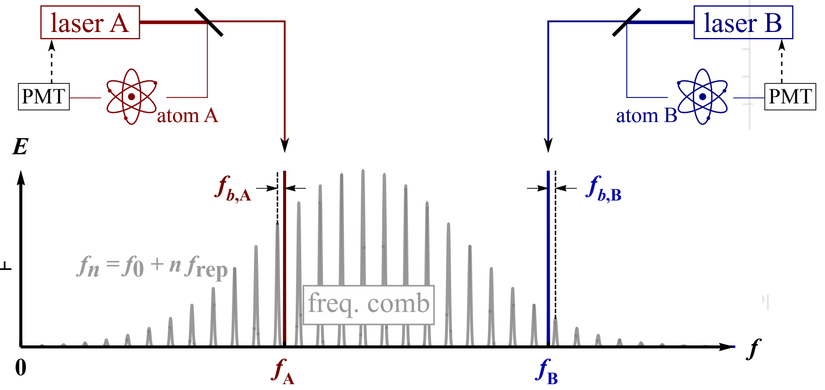


$^{162/164}$Dy

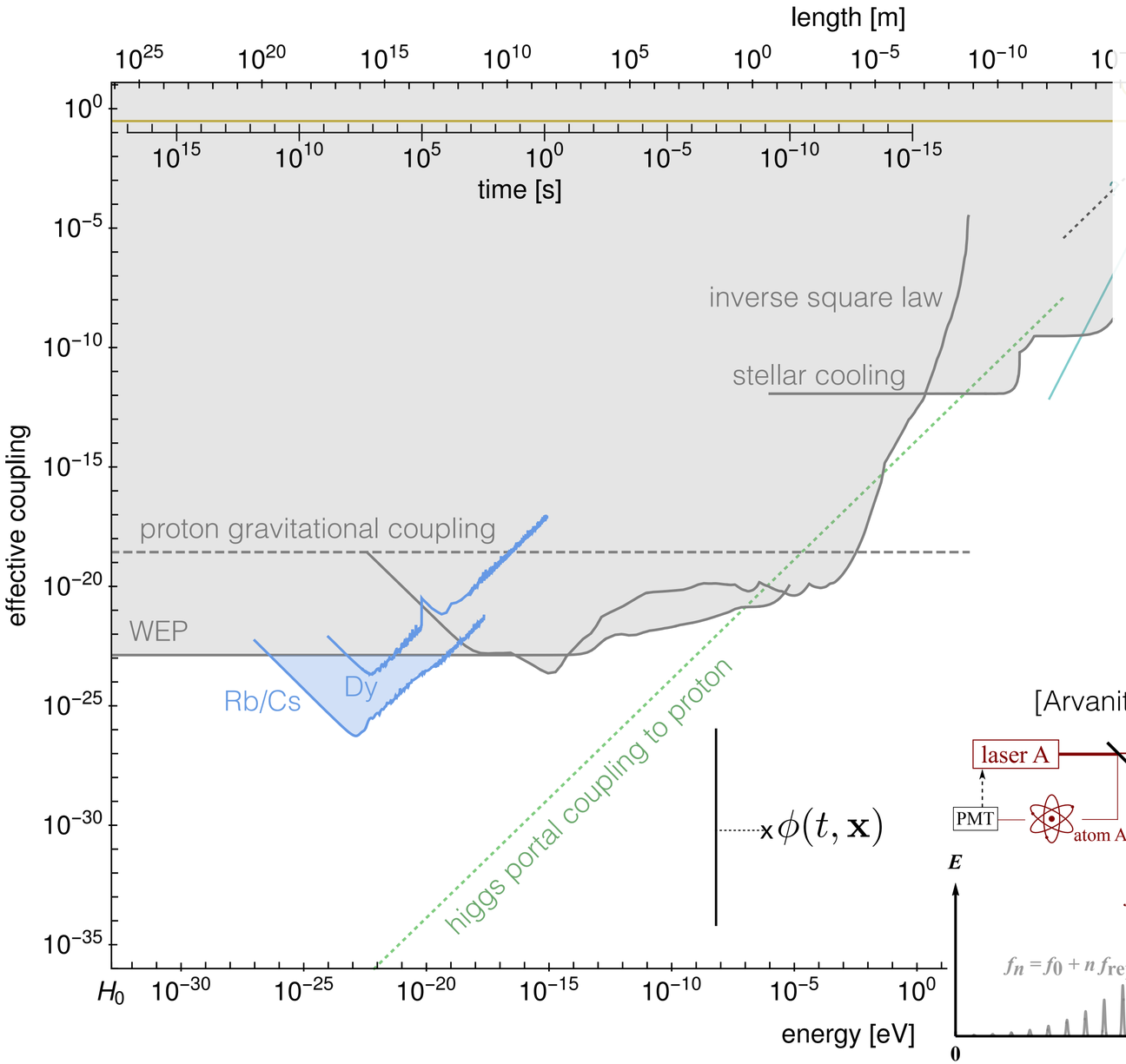
[KVT, Budker, PRL 115 1 (2015)]



[Arvanitaki, Huang, KVT; PRD 91 1 (2015)]

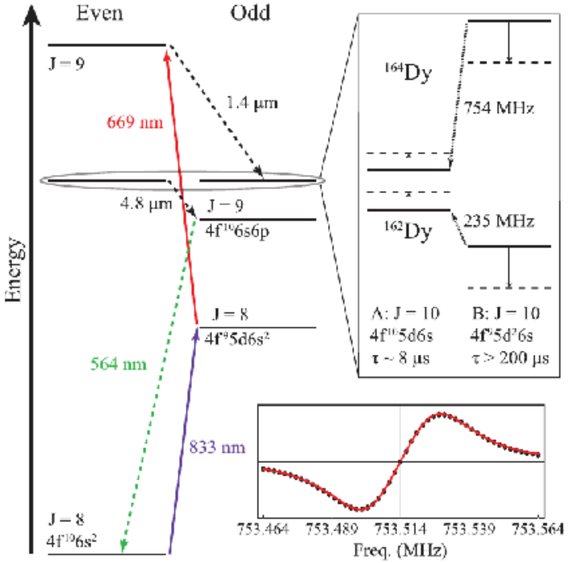


Atomic Clocks



$^{162/1647}$Dy

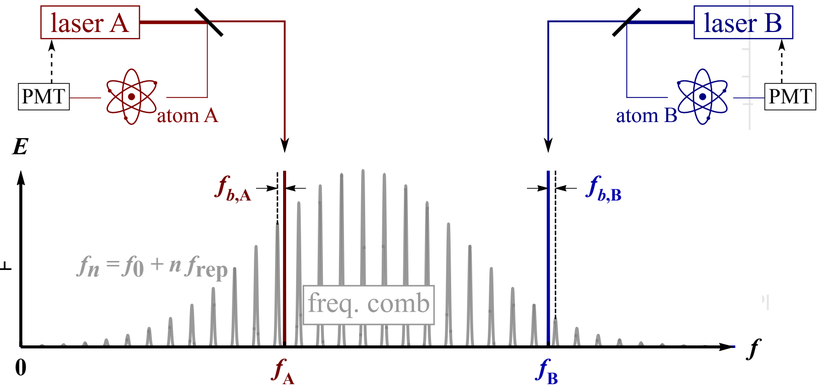
[KVT, Budker, PRL 115 1 (2015)]



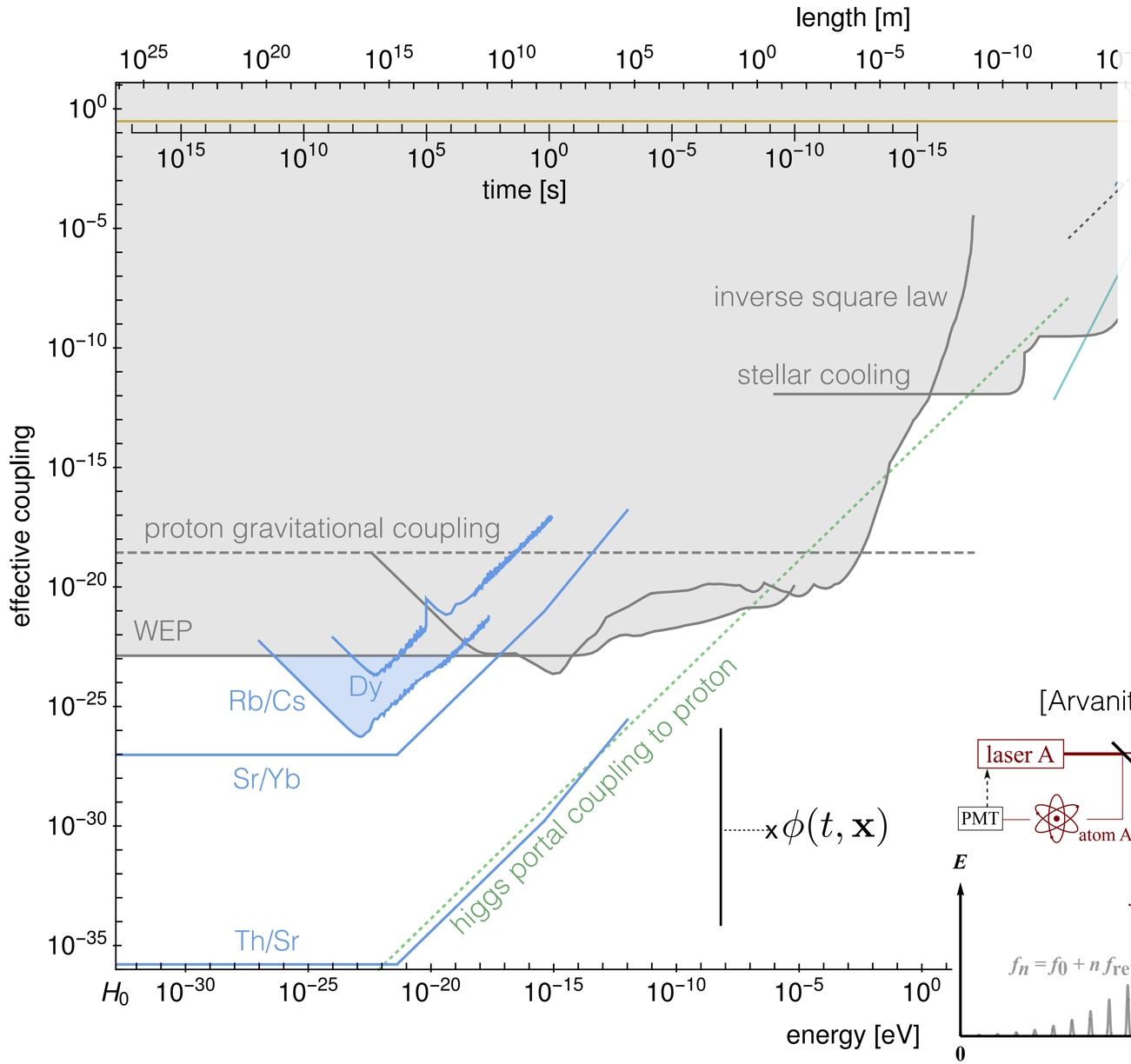
Rb/Cs

[Hees +, PRL 117 3 (2016)]

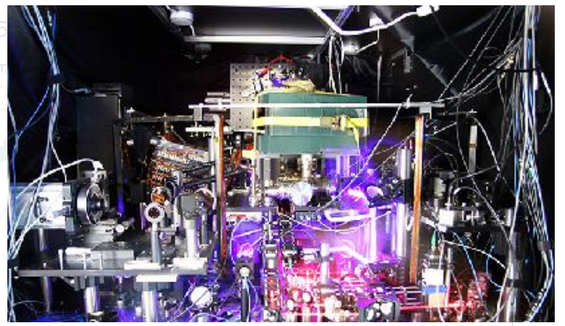
[Arvanitaki, Huang, KVT; PRD 91 1 (2015)]



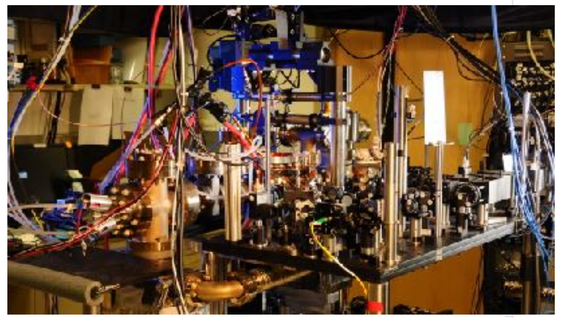
Near-Future Atomic & Nuclear Clocks



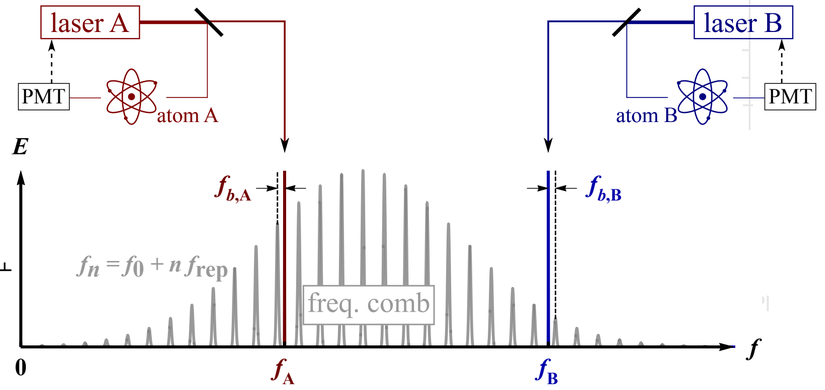
^{87}Sr (JILA)



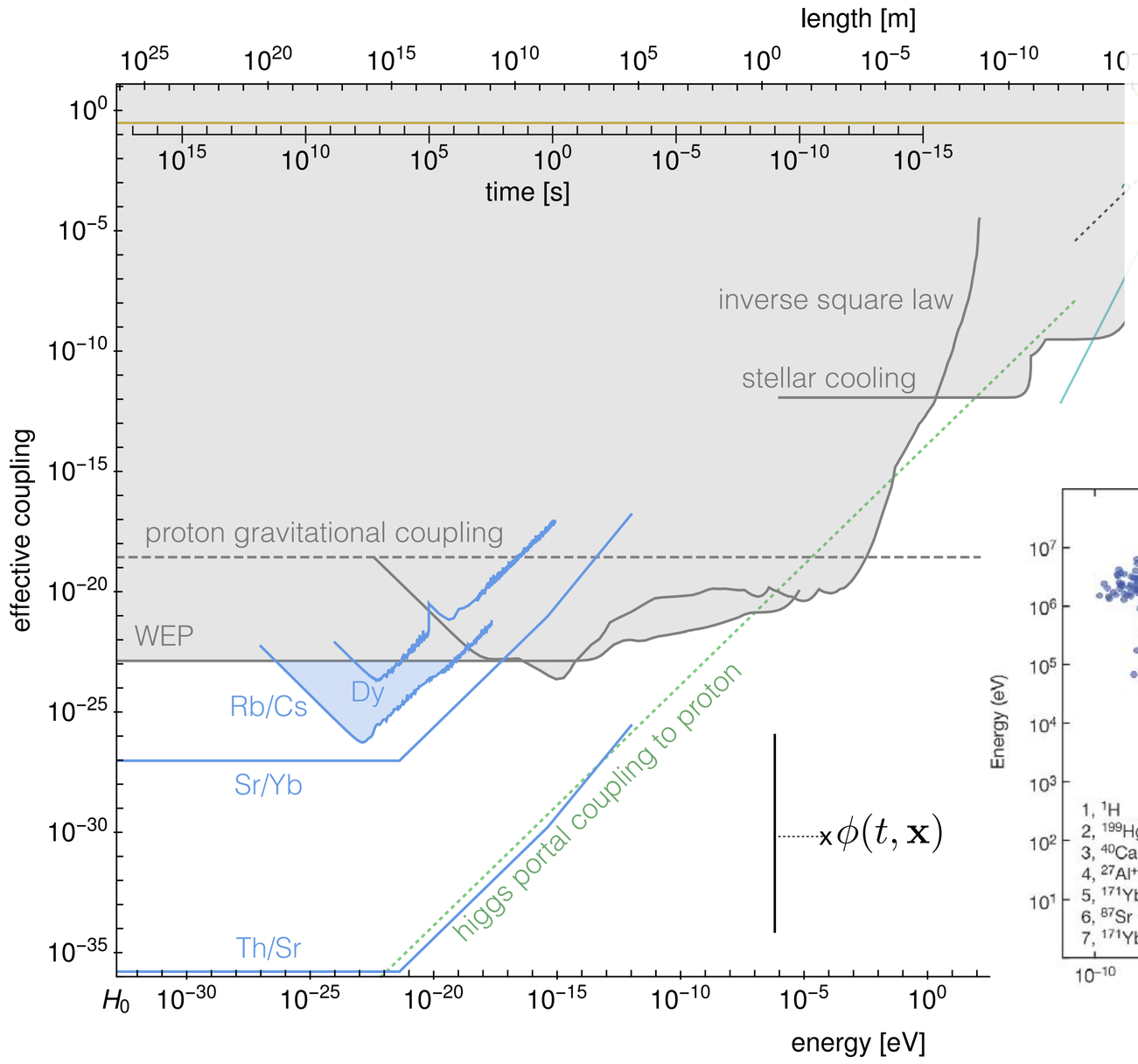
^{171}Yb (NIST)



[Arvanitaki, Huang, KVT; PRD 91 1 (2015)]



Near-Future Atomic & Nuclear Clocks



^{229}Th nuclear clock

$$\omega_0 = 8.28 \pm 0.17\,\mathrm{eV}$$

$$\frac{1}{\omega_0 \tau} \approx 10^{-20}$$

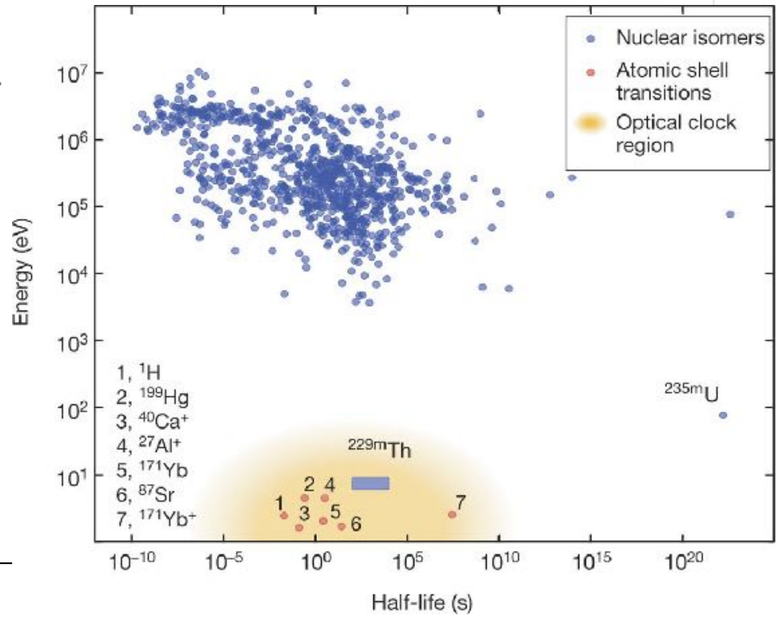
[Seiferle +, Nature (2019)]

Direct excitation imminent

UV lasers in development

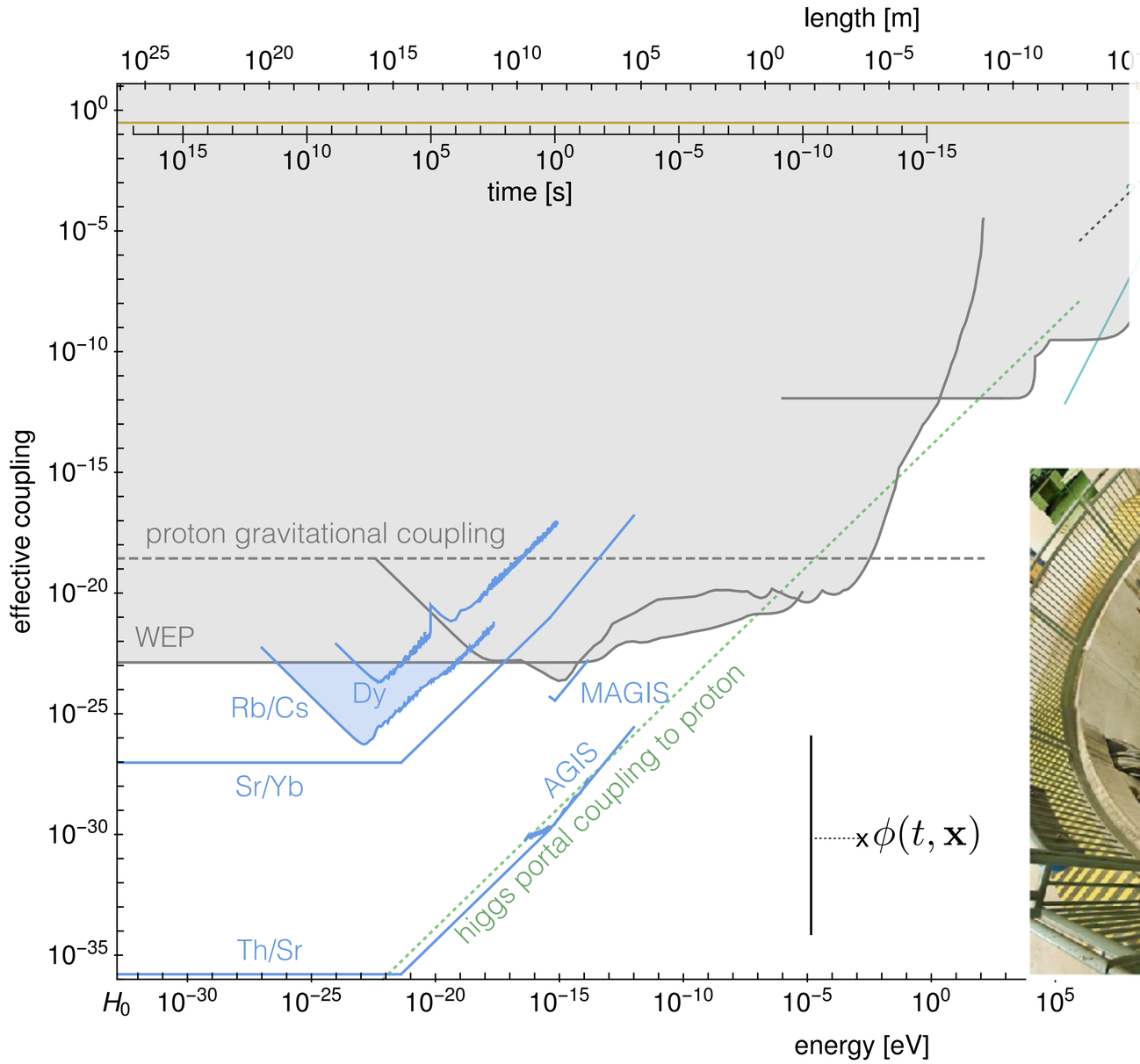
Reduction of systematics

Accidental cancellation

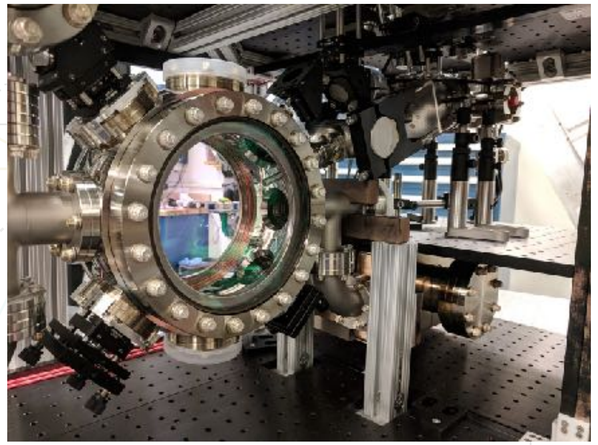


[von der Wense +, Nature (2016)]

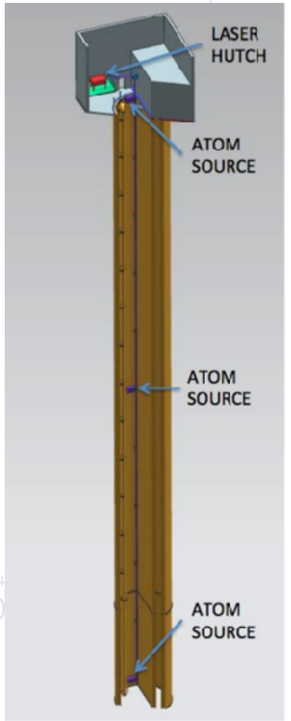
Atom Interferometry



MAGIS-100

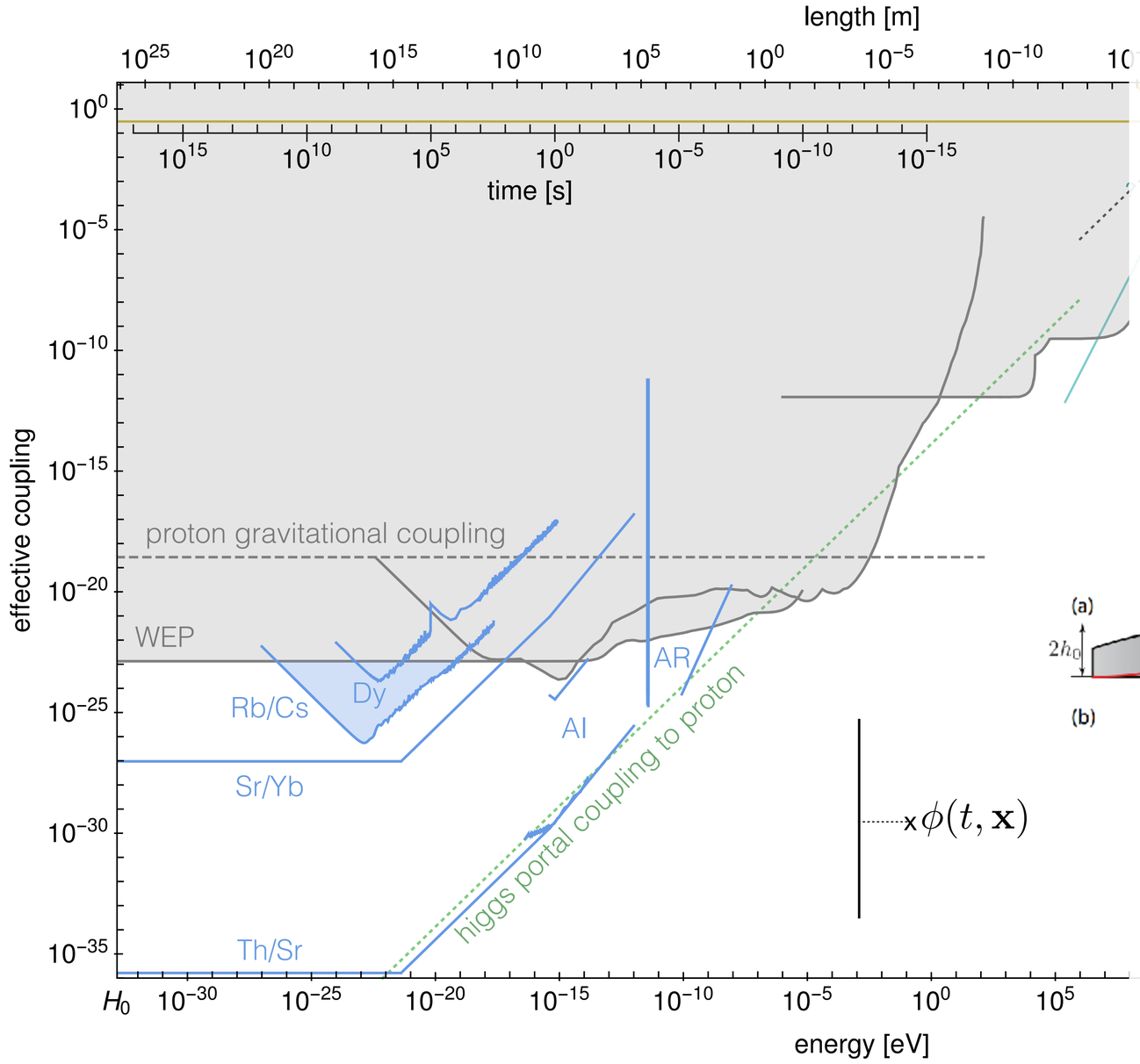


[Arvanitaki, Graham, Hogan, Rajendran, KVT; PRD 91 1 (2015)]

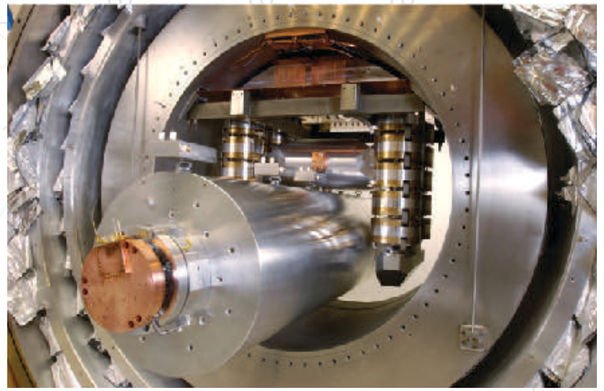


Acoustic Resonators

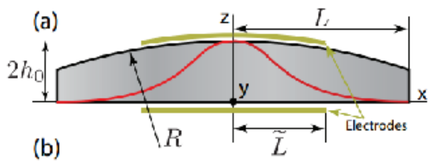
[Arvanitaki, Dimopoulos, KVT; PRL 116 3 (2016)]



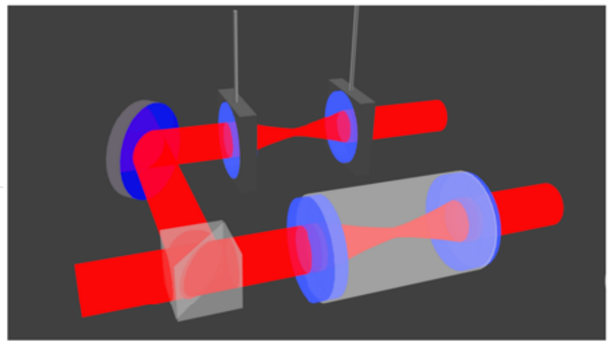
[Branca +; PRL 117 2 (2017]



[Goryachev +; PRD 90 10 (2014]

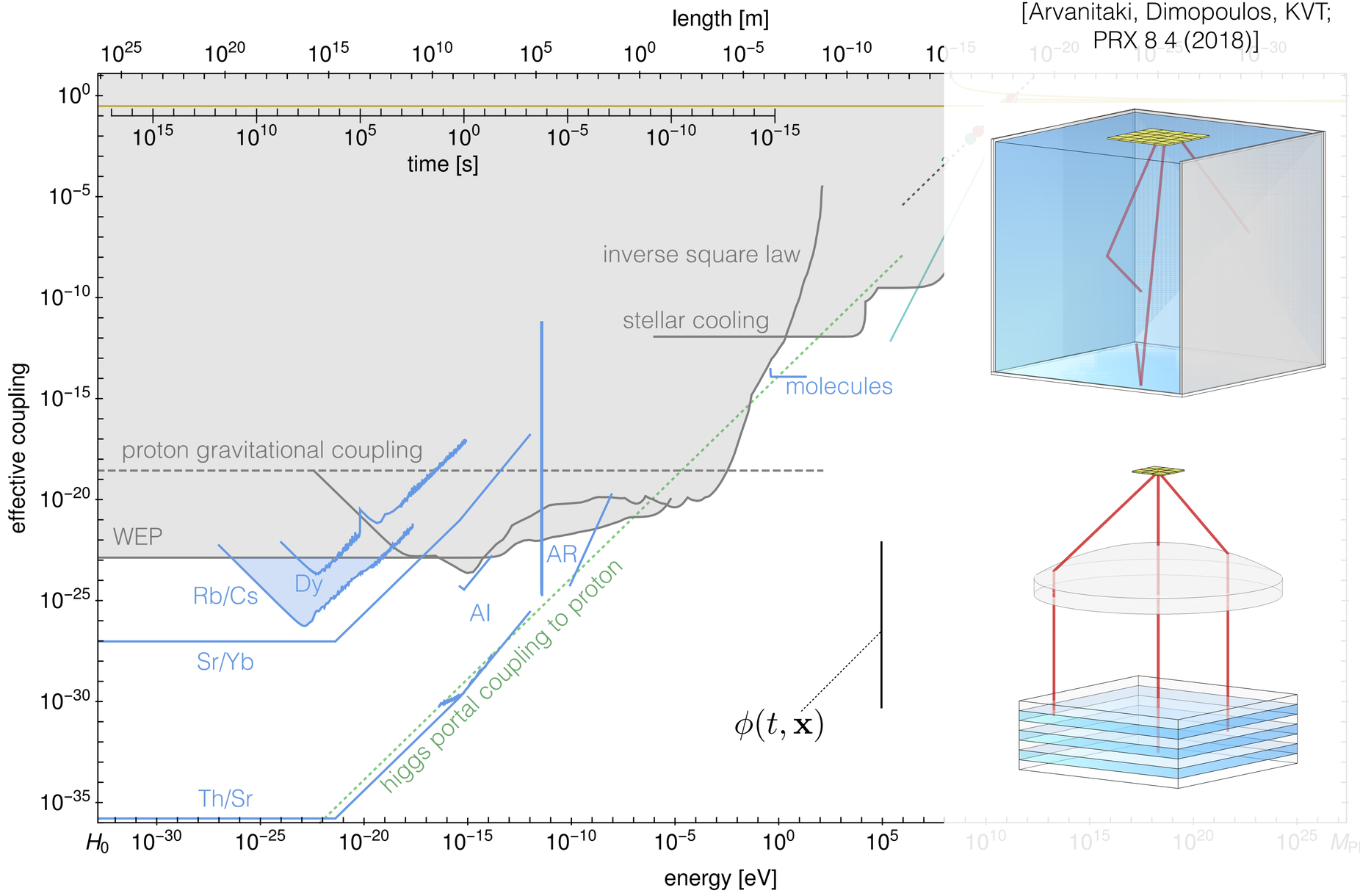


[Geraci +; PRL 123 3 (2019]



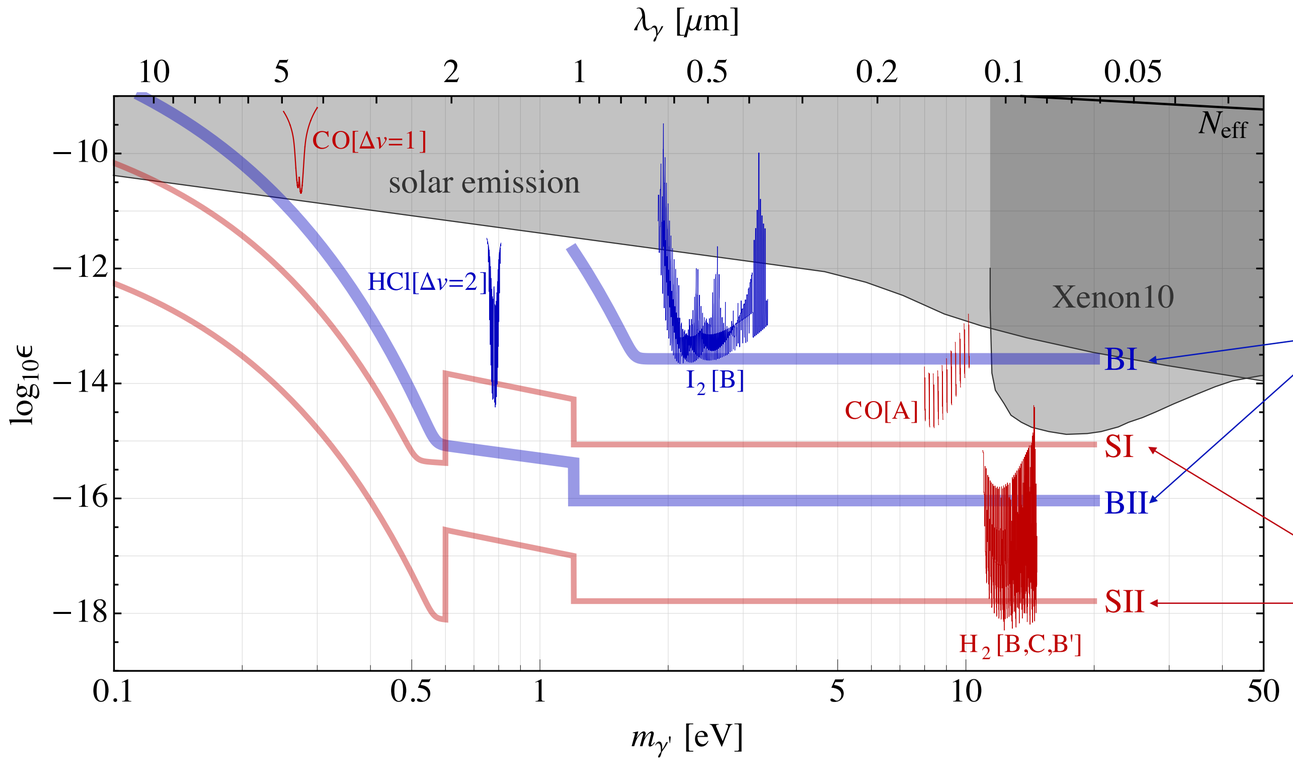
Resonant Absorption onto Molecules

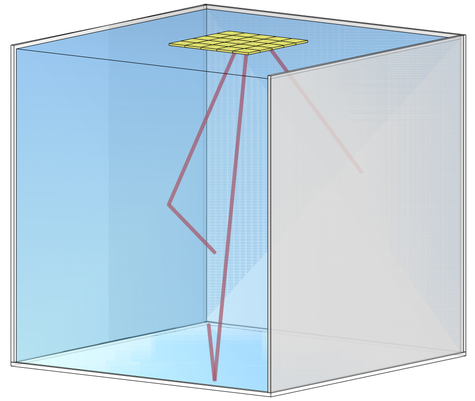
[Arvanitaki, Dimopoulos, KVT; PRX 8 4 (2018)]

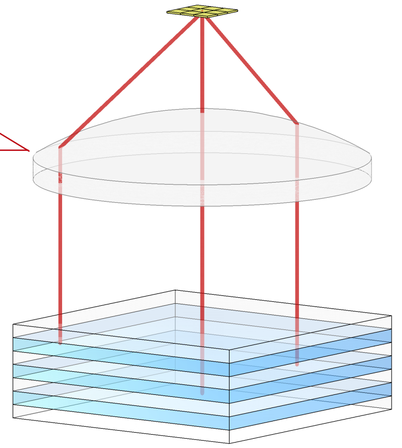


Molecular Absorption of Dark Photons

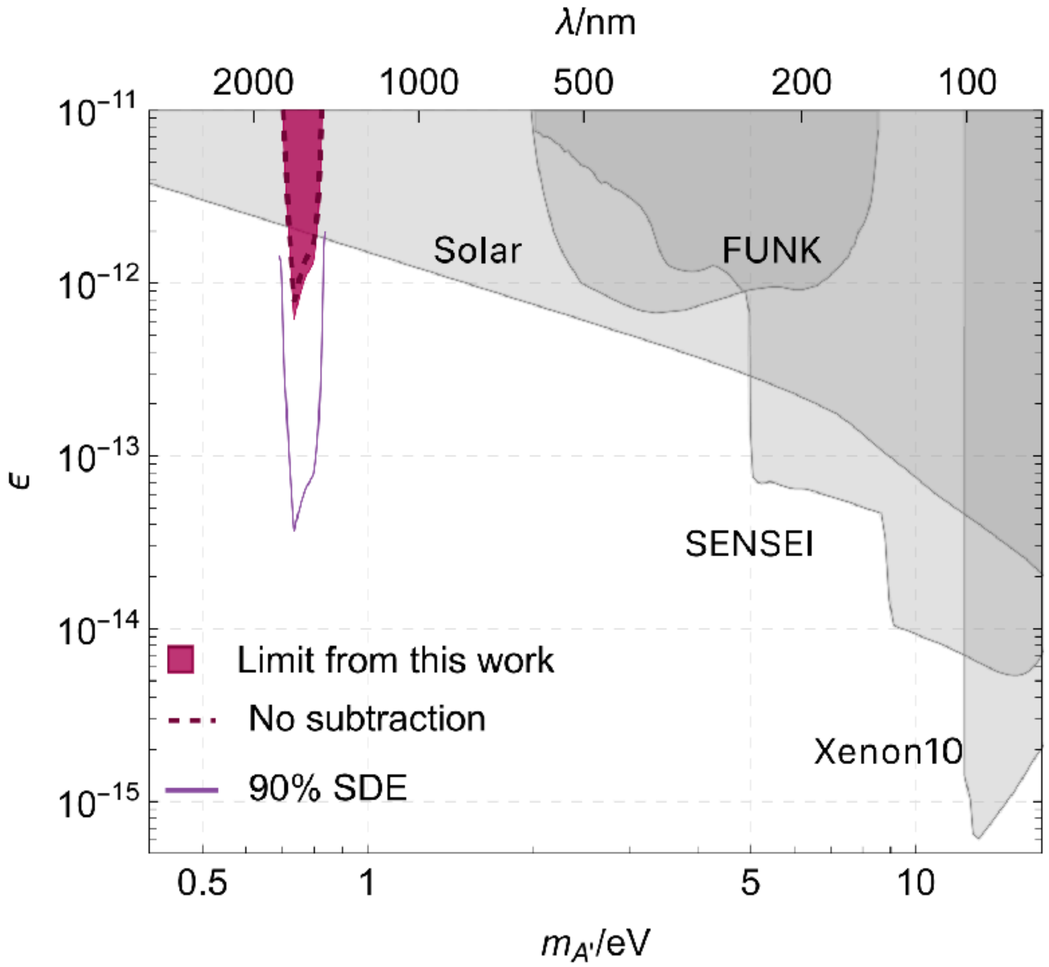
[Arvanitaki, Dimopoulos, KVT; PRX 8 4 (2018)]

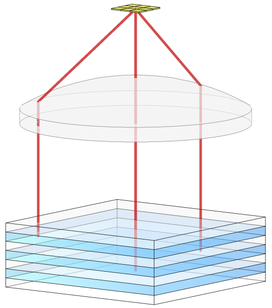






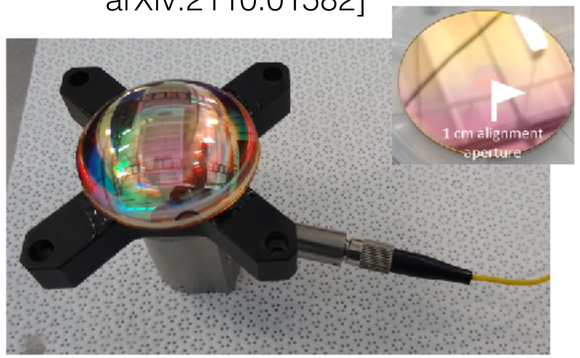
Absorption of Dark Photons

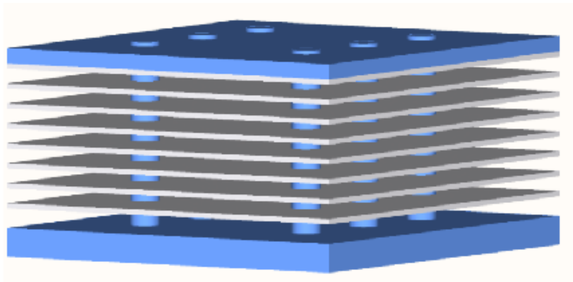


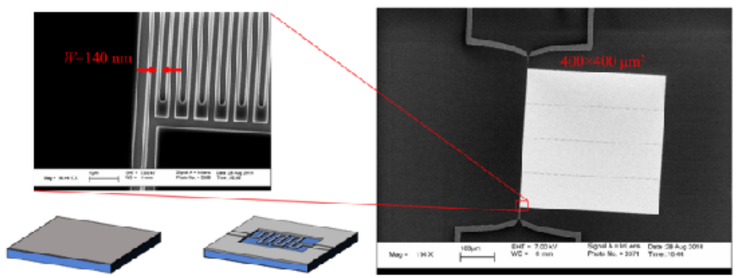


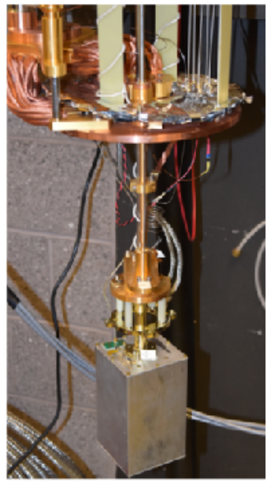
[Baryakhtar, Huang, Lasenby;
PRD 98 3 (2018)]

[Chiles, Charaev,
Lasenby, Baryakhtar, Huang, …,
KVT, …, Nam, Berggren;
arXiv:2110.01582]

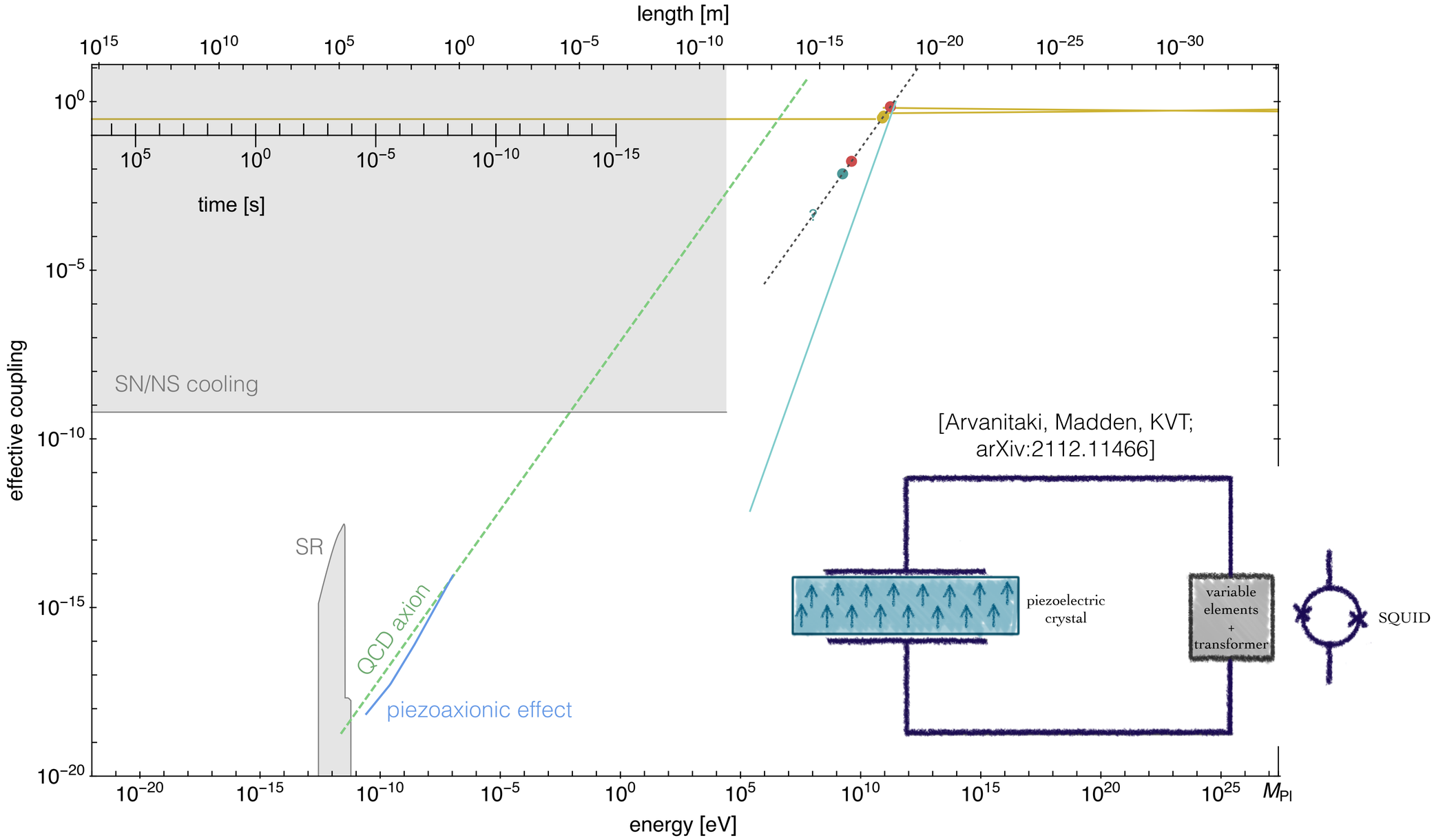




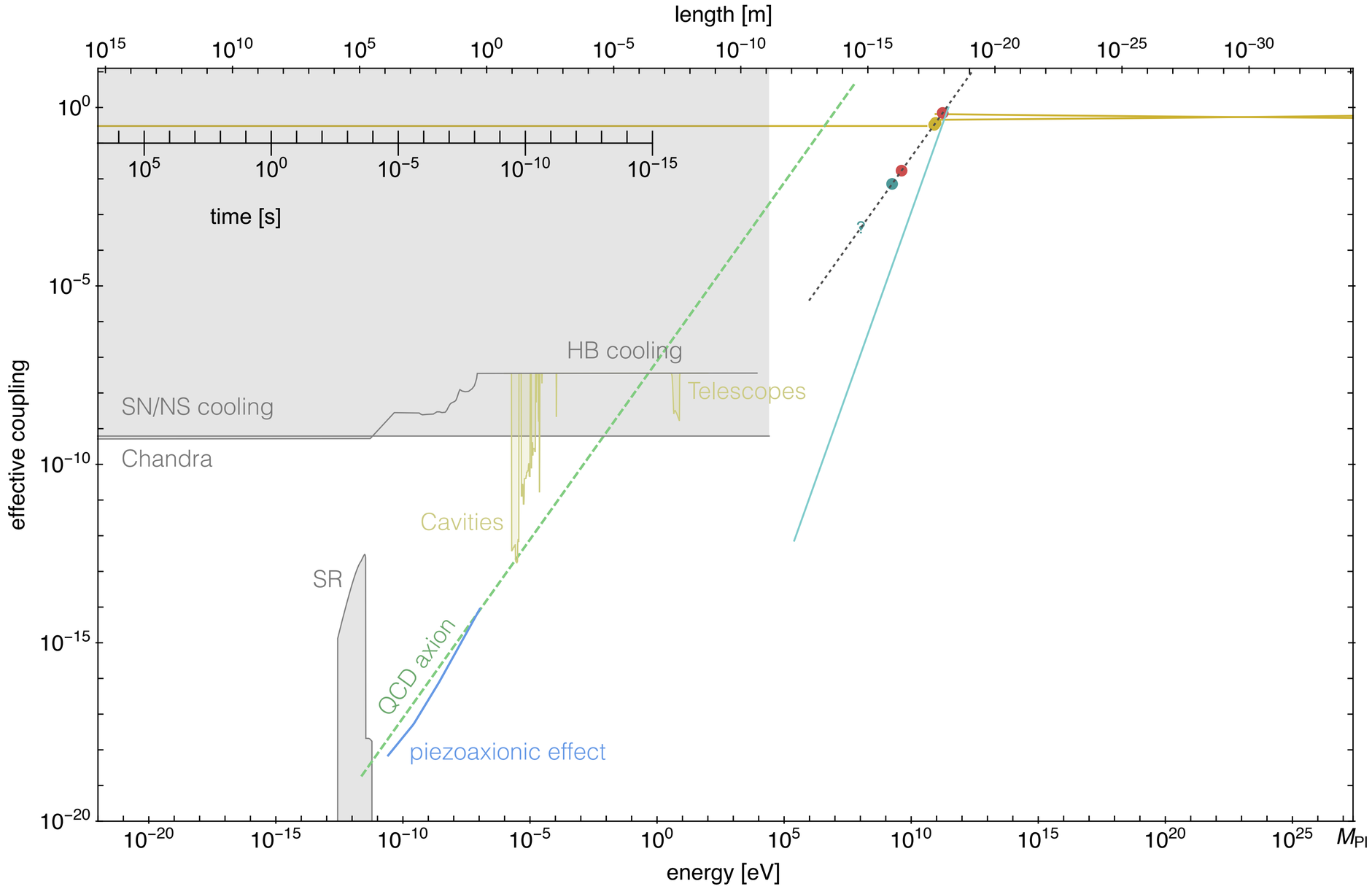




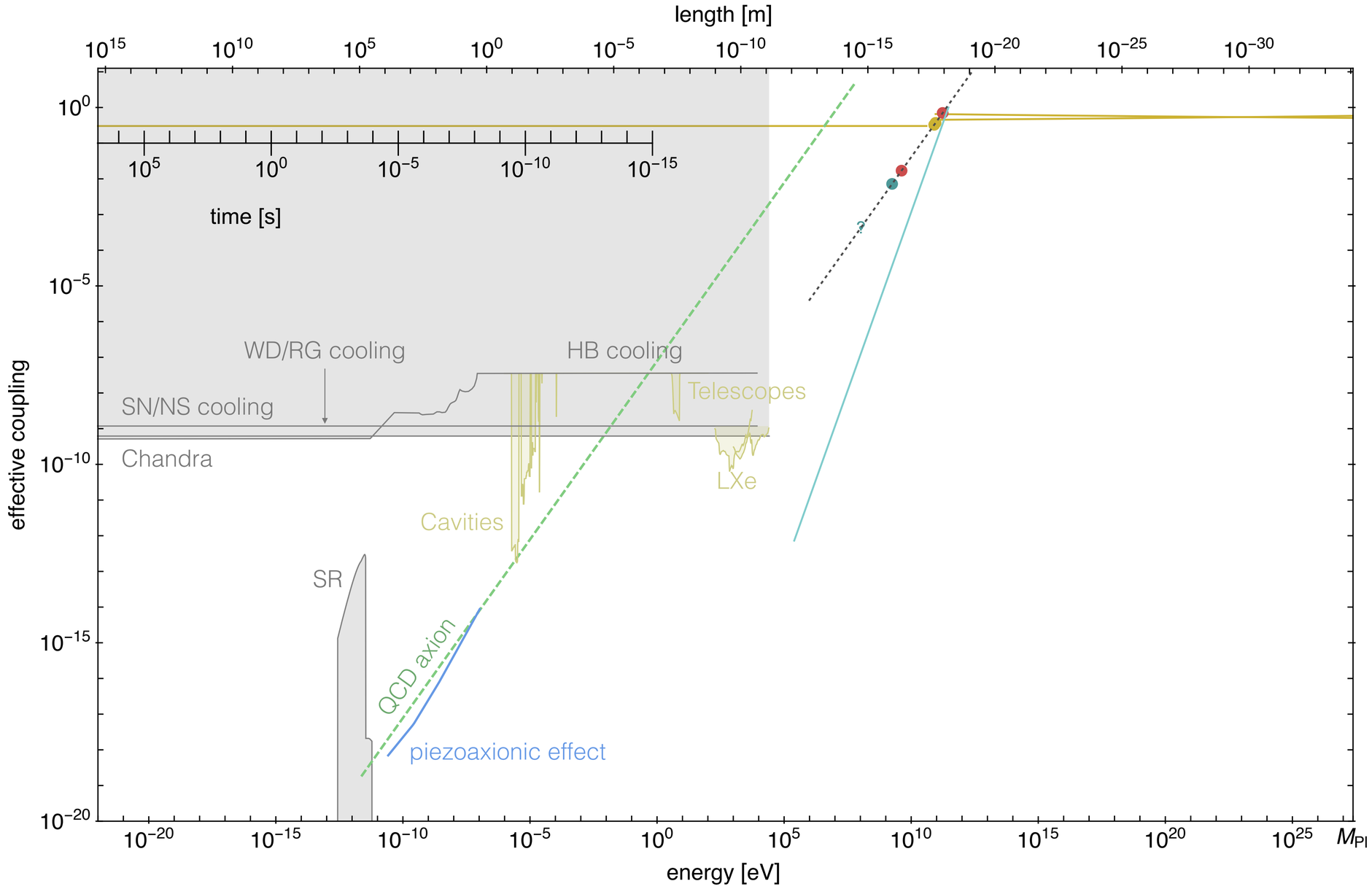
Axion Nuclear Coupling



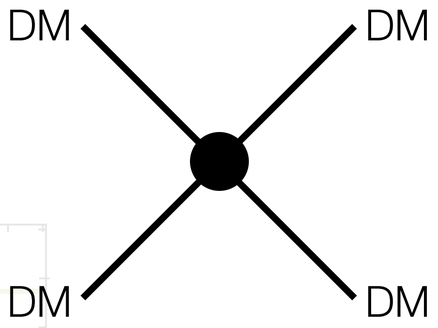
Axion Photon Coupling



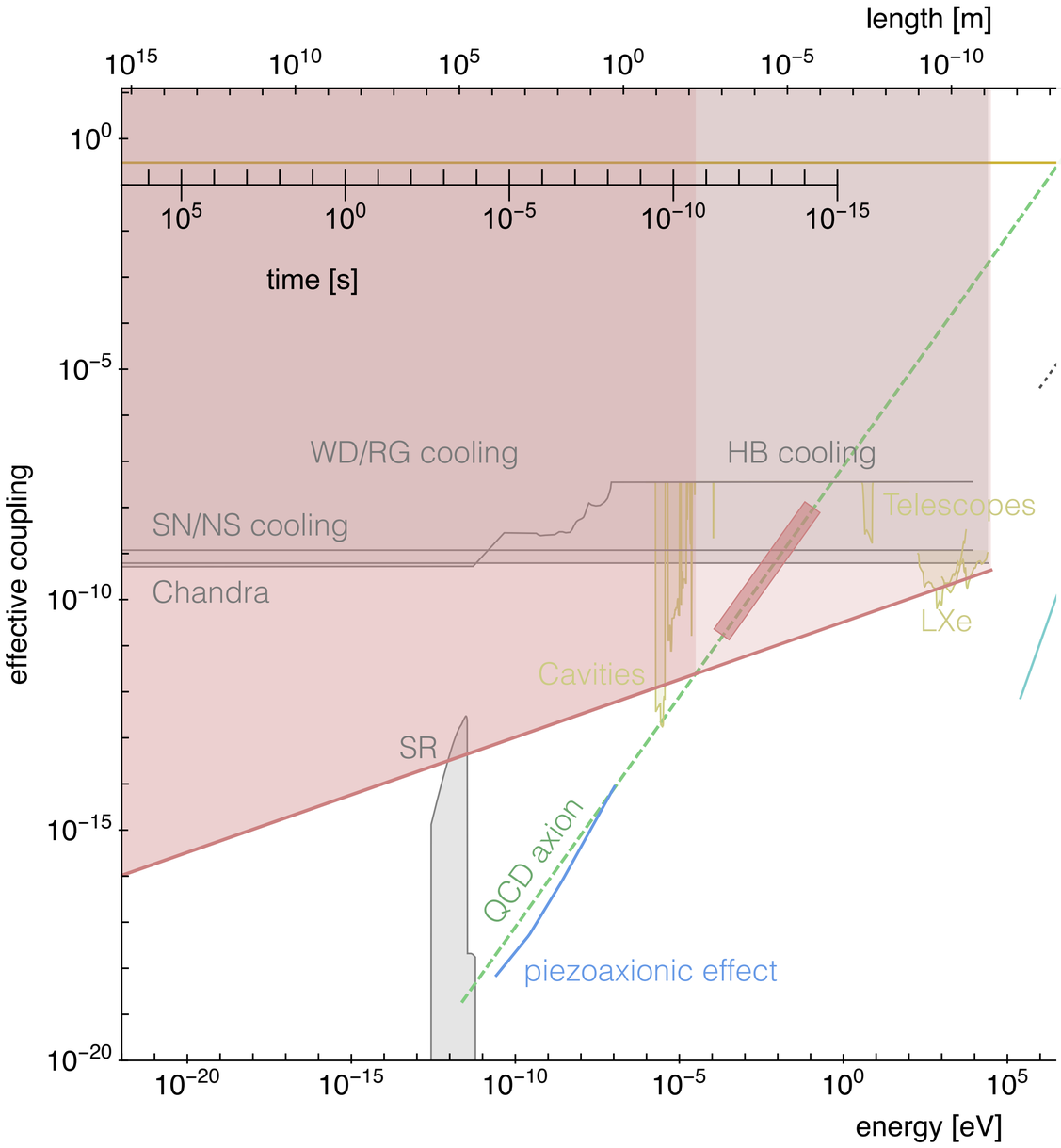
Axion Electron Coupling

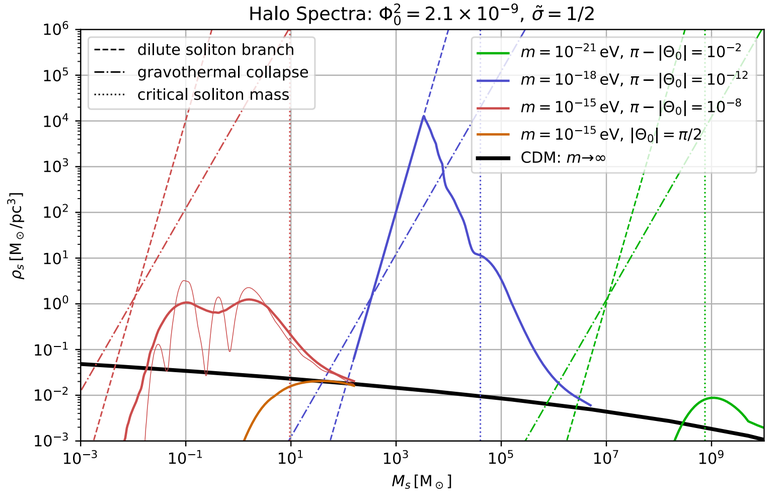


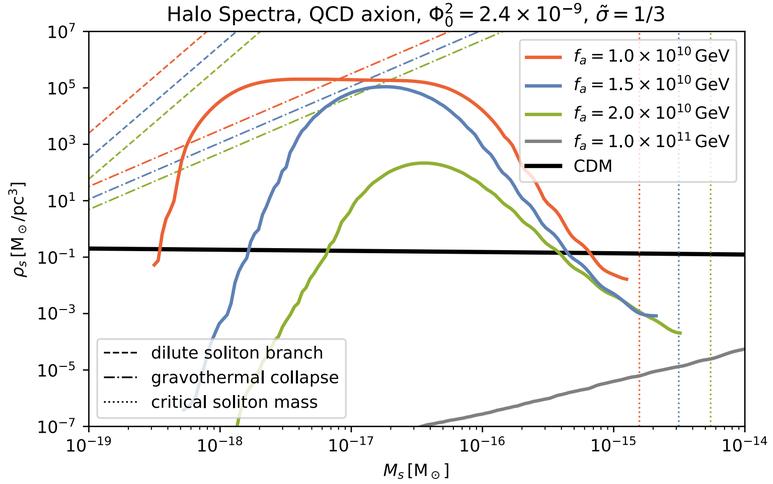
Compact Axion DM Structures



[Arvanitaki, Dimopoulos, Galanis, Lehner, Thompson, KVT; arXiv:1909.11665]







The Outline

How does dark matter fit into theoretical particle physics?

The evidence for dark matter!

A motivation “metric” for dark matter theories

General principles of precision-frontier dark matter detection

Future Outlook

Technological Improvements

Hard Engineering

Innovative Background Mitigation

Innovative Detection Concepts

Indirect Gravitational Probes

“Measure what is measurable, and make measurable what is not so.” — Galileo