Open Questions in Fundamental Physics

Rencontres du Vietnam 2023

Windows on the Universe

Starting Point

Known fundamental laws:

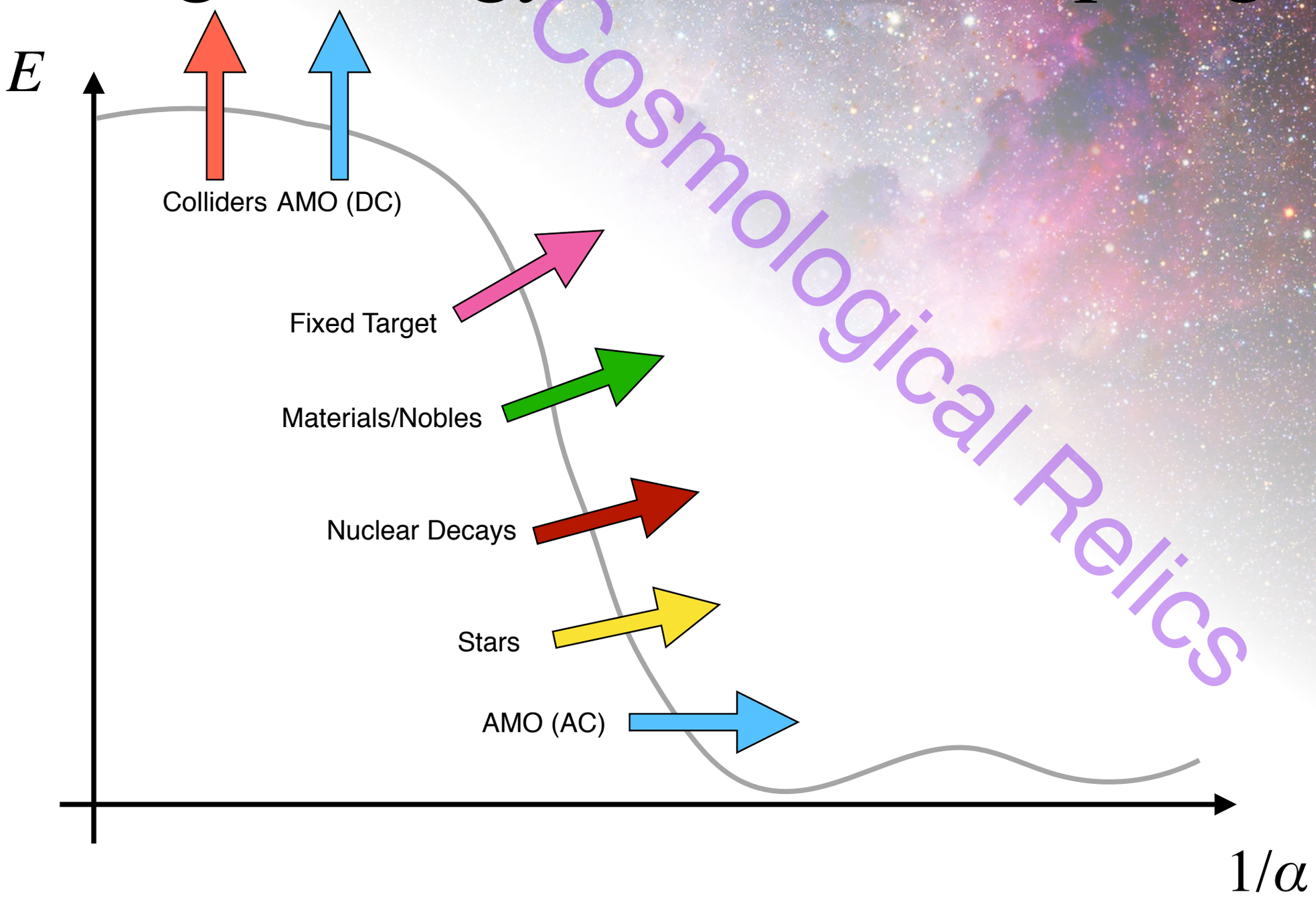
Quantum field theory

The Standard Model:

$$\mathscr{L} = \frac{1}{2}\bar{q}(i\partial_\mu + g_s G_\mu + gW_\mu + g'\frac{1}{3}B_\mu)\gamma^\mu q + \cdots + y_e h\bar{\ell}e + \cdots + m^2|h|^2 - \frac{1}{4}|h|^4 + \cdots$$

plus metric couplings to include General Relativity

The Frontier:
High Energy & Weak Coupling



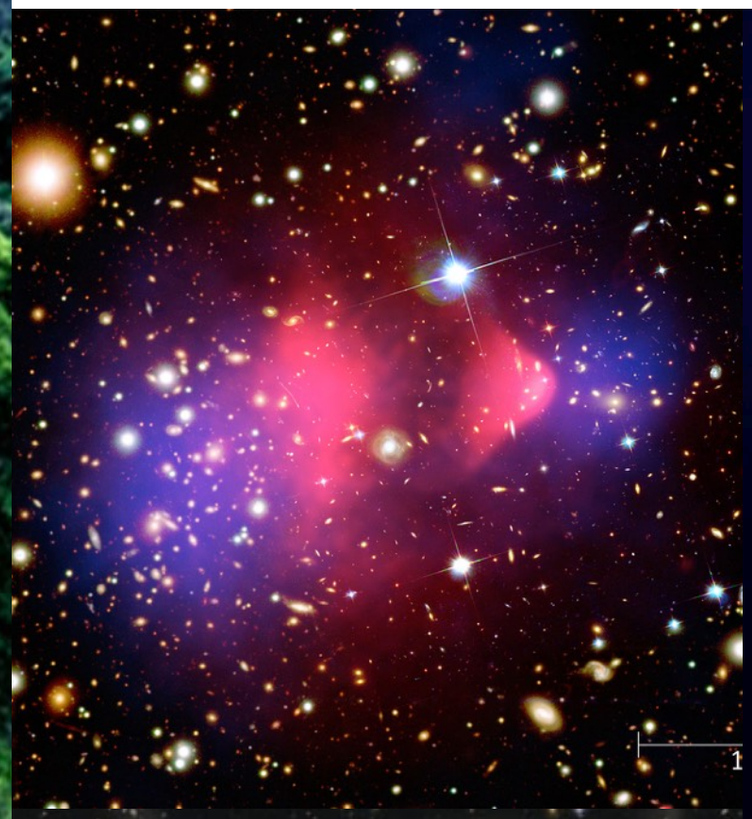
Hints Beyond the SM

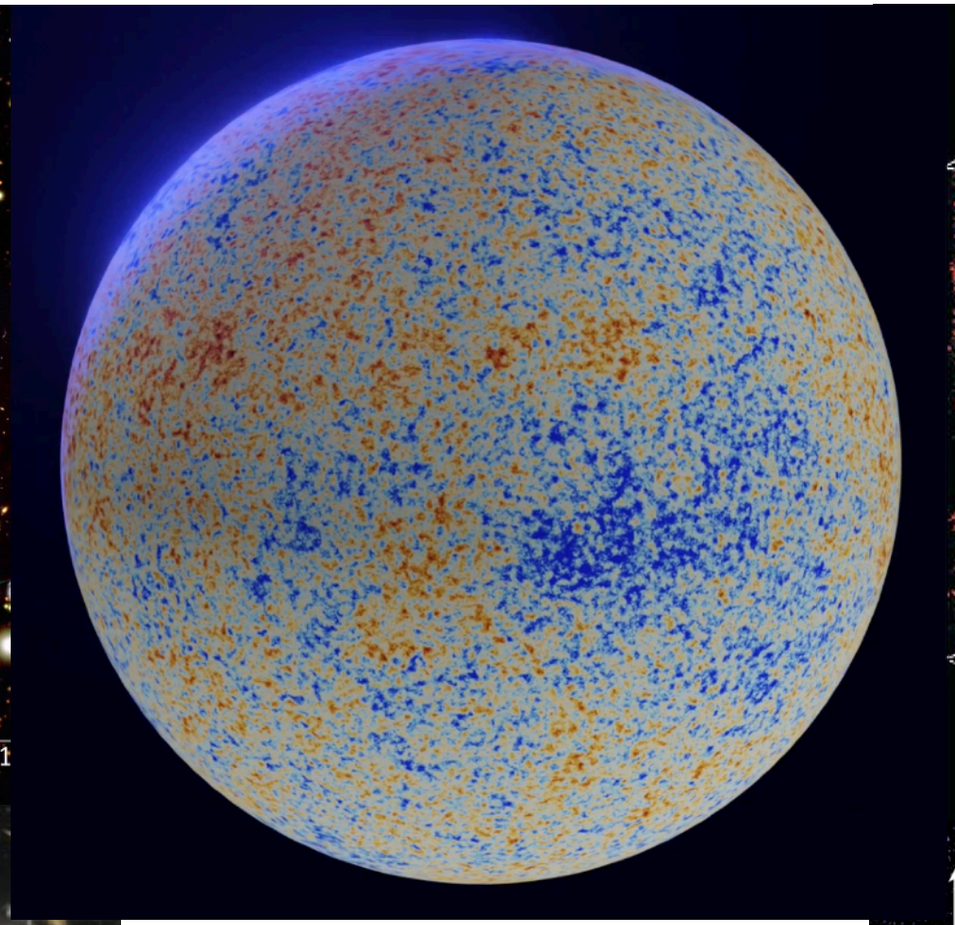
0.	**DARK MATTER**		BSM
1.	Cosmological Constant Problem	123	
2.	The Hierarchy Problem	32	
3.	The Strong CP Problem	10	Small Parameters
4.	Patterns in Fermion Masses	5	
5.	Neutrino Masses	?	

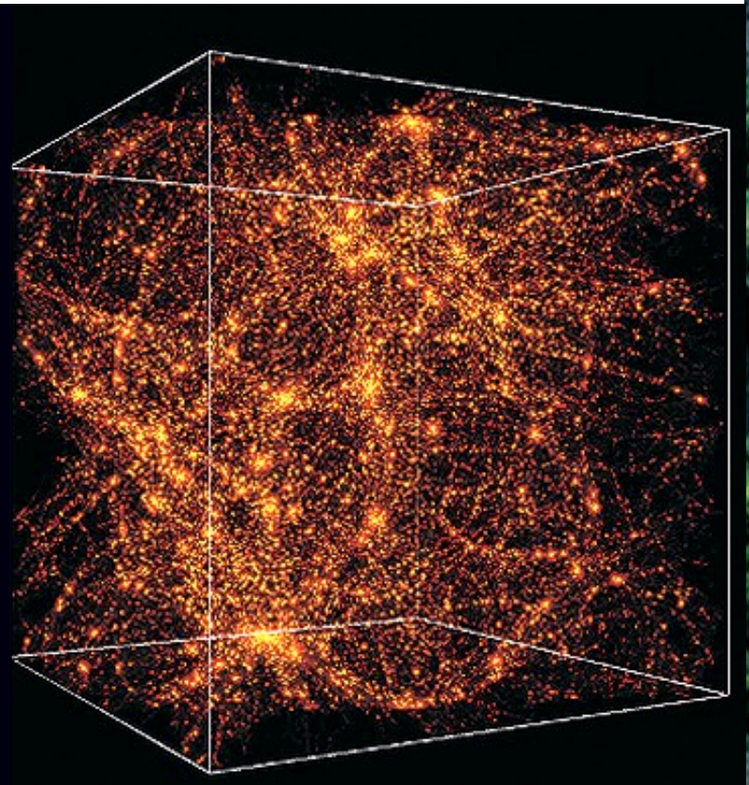
∞. GR UV Scale — Breakdown of Theory

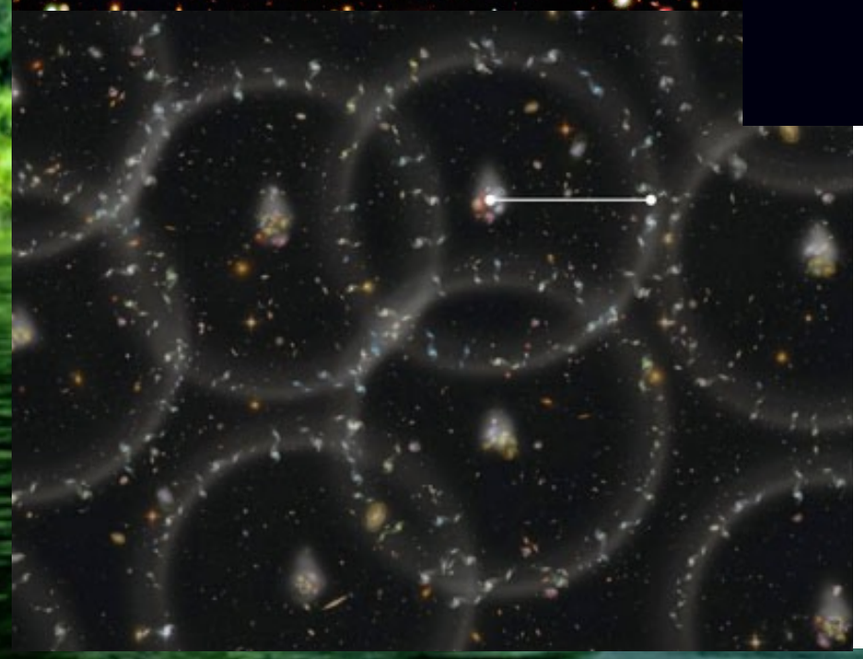
(also: Hubble tension, b-physics?, g-2?, Beryllium?, neutrinos, tons of astrophysics…) — Anomalies

Dark Matter

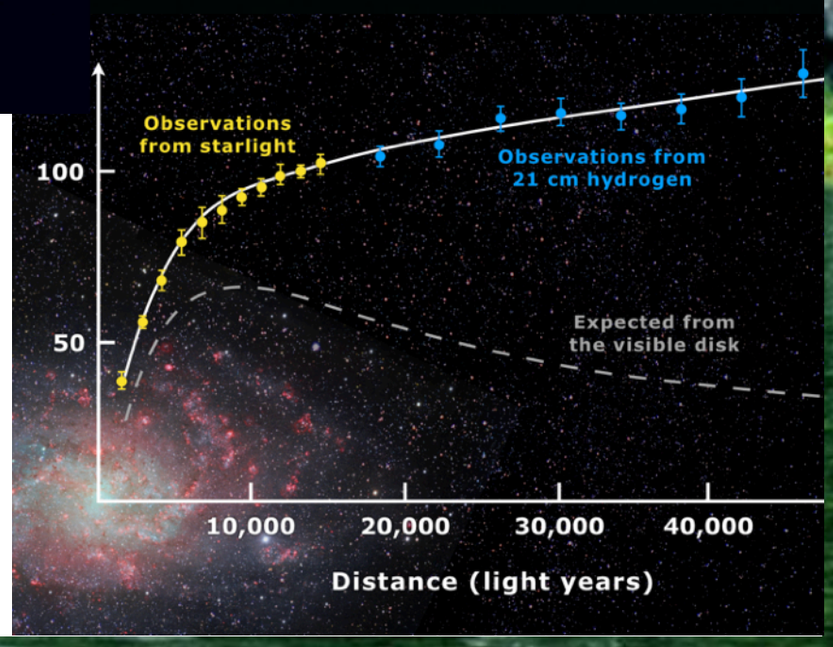








Dark matter's existence has been confirmed, but only gravitationally

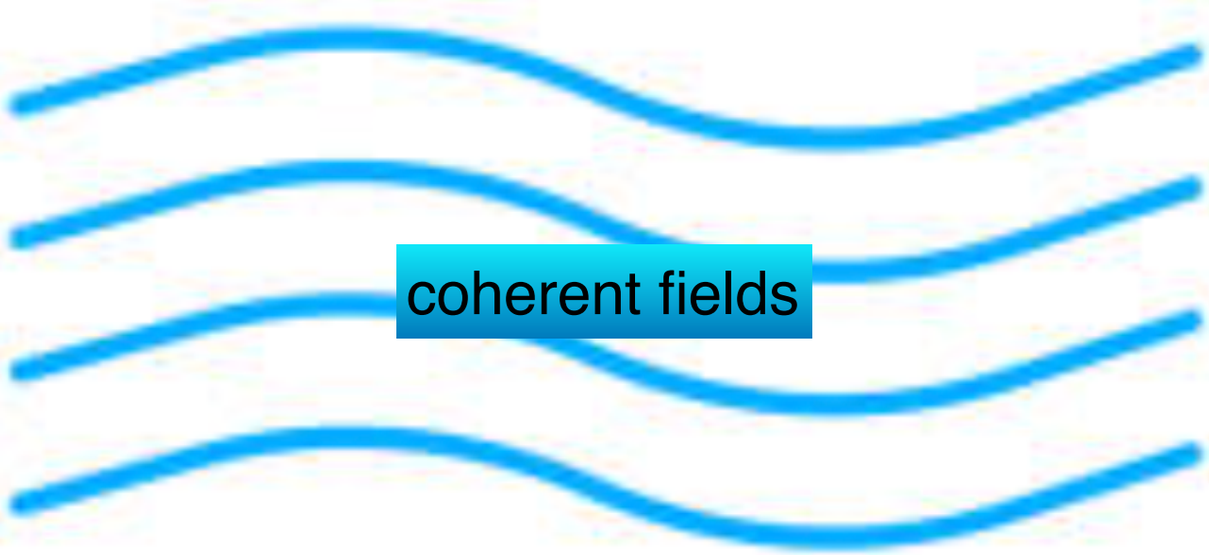


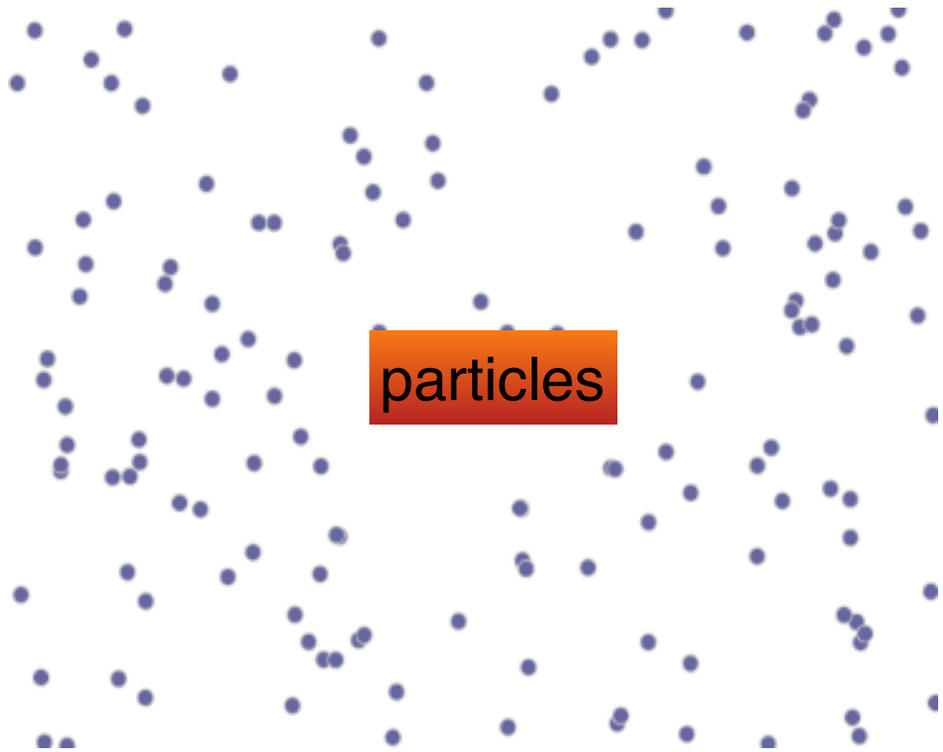
Dark Matter

MASS RANGE

macroscopic

$10^{-31} m_p$ spin 0 or spin 1 10 eV spin 0, 1/2, or 1 $10^{19} m_p$





Too much parameter space to search?
Huge mass range, but object type and coupling limited

Light Fields: Couplings

Spin 0, 1/2, and 1

Spin 0 (like h's or π)

coupling to $p/n/e$ mass — $\phi\bar{\psi}\psi$

coupling to $p/n/e$ spin — $\partial\phi\,\bar{\psi}\gamma\gamma^5\psi$

coupling to γ kinetic — ϕFF

coupling to γ spin — $\phi F\tilde{F}$

(CP even vs CP odd — naturalness)

Spin 1 (like γ or W/Z)

mixing with γ — FF'

new charge ($p/n/e$) — $\bar{\psi}\gamma A'\psi$

dark mag moment ($p/n/e$) — $\bar{\psi}\sigma\psi F'$

coupling to $p/n/e$ spin — $\bar{\psi}\gamma\gamma^5 A'\psi$

various to ν couplings

Spin 1/2 couplings (like matter):

mixing with ν — $\bar{\nu}\chi$

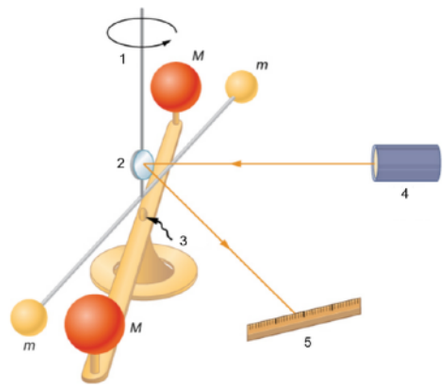
$\chi\chi$ couplings

Light Fields: Physical Effects

Forces!

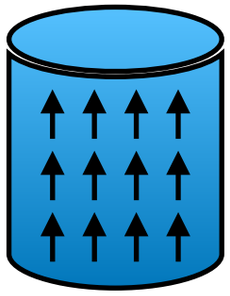
EP violating

$$\frac{1}{r^2} \rightarrow \frac{e^{-mr}}{r^2} \text{ (range} \sim \frac{1}{m}\text{)}$$

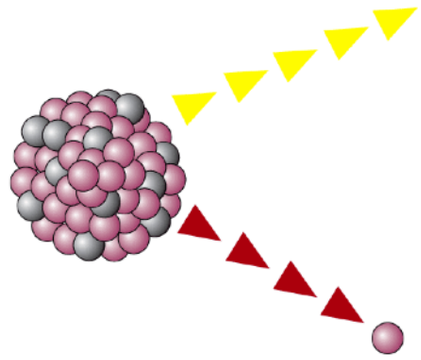


— Earth/Moon/Sun
— Earth/Lab
— Lab/Lab (cavendish)

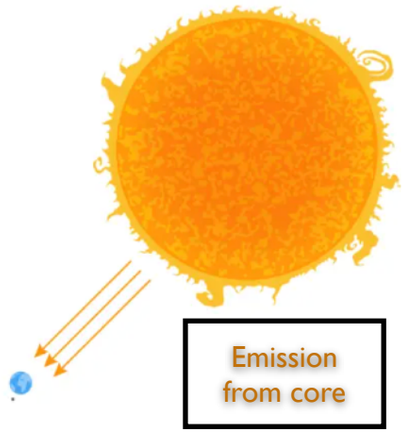
Spin-dependent forces
For polarized material



Nuclear (and atomic/hadronic) decays



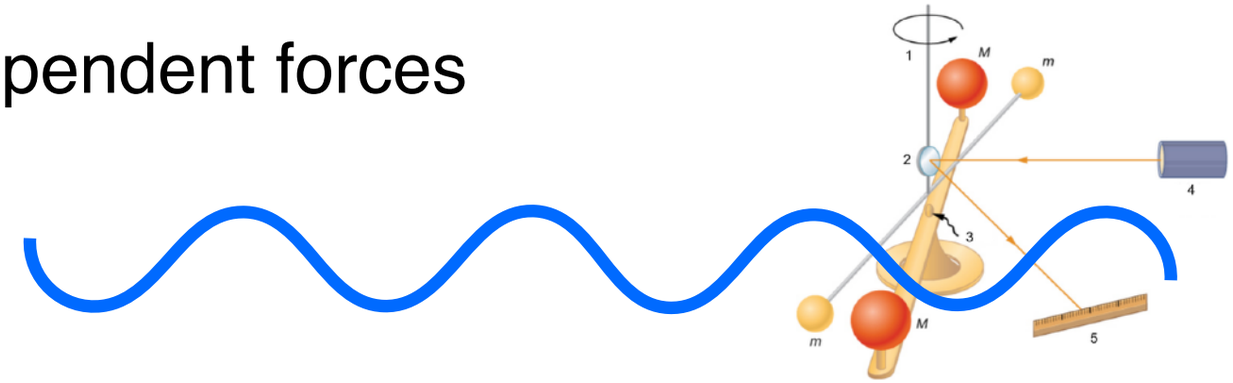
Solar/Stellar emission



Light Fields: Backgrounds

If it is Dark Matter, Dark Energy, or static

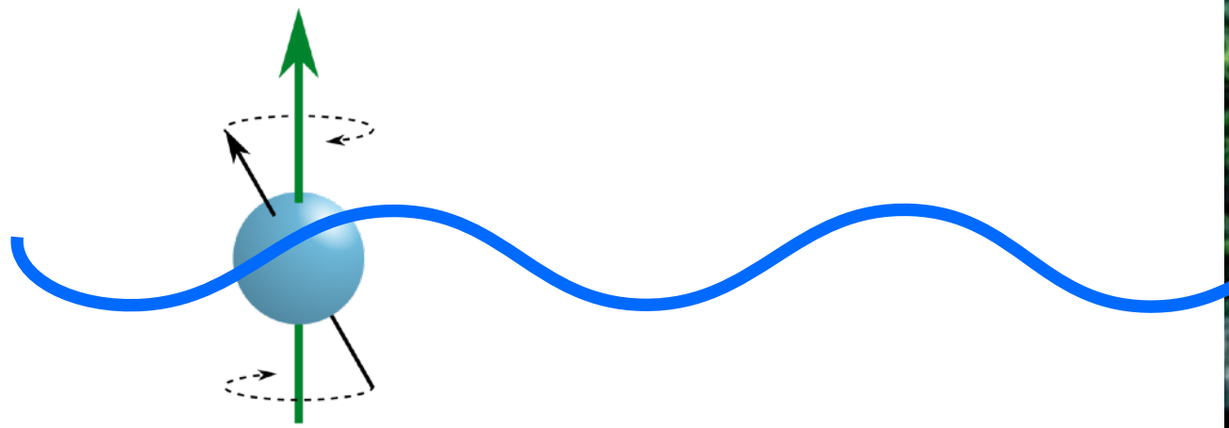
Time-dependent forces



DM robustly oscillates at a narrow frequency

Spin precession: fake B-field

$$\vec{\nabla}\phi \cdot \vec{\sigma}$$



Photon polarization rotation

Sources change Fundamental Constants (mass/coupling):

— atomic/molecular/nuclear spectroscopy: Static or dynamic!

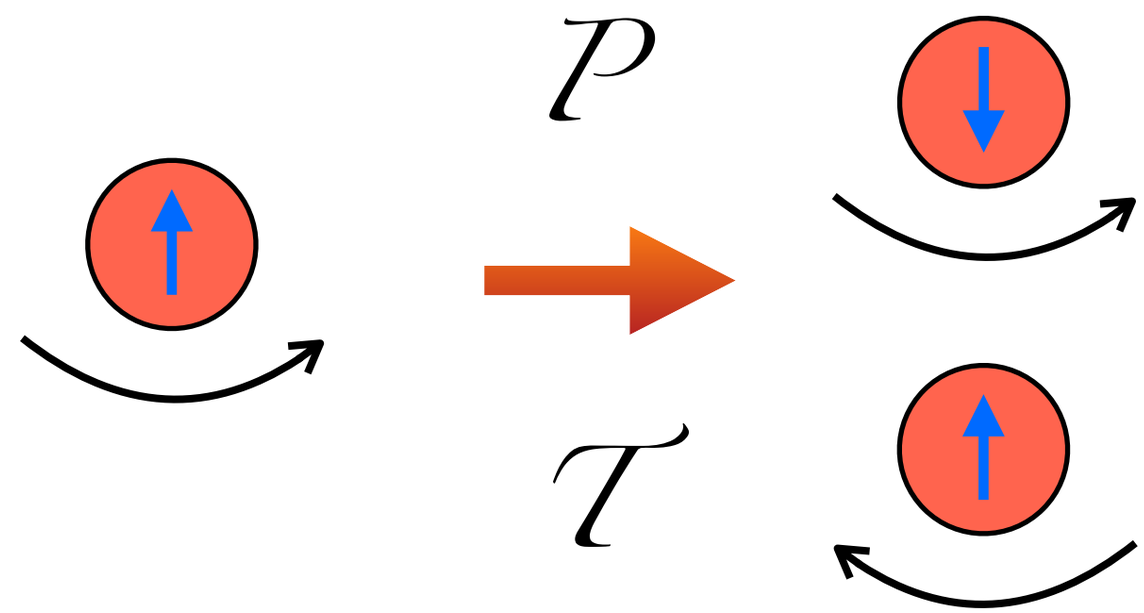
Heavy Fields

Heavy Fields (beyond colliders)

Higher-Dimension operators: Precision measurement!

EDMs

$$id_\psi \bar{\psi}\sigma\gamma^5\psi F$$



$d_e \sim$ 9 orders of magnitude above SM

$d_n \sim$ 5 orders of magnitude above SM

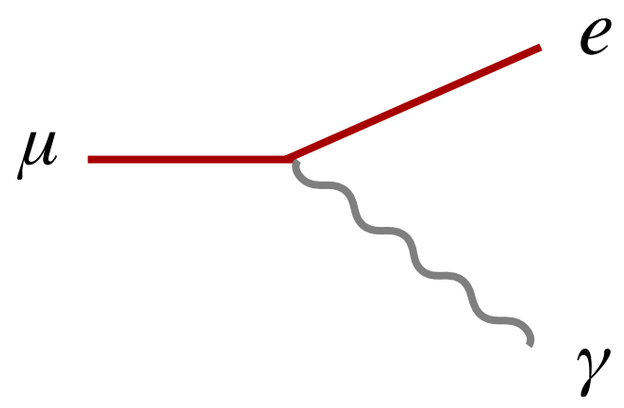
e.g., current constraints up to $d_n < \dfrac{m_n}{(10^6\,\mathrm{GeV})^2}$

Heavy Fields

Higher-Dimension operators: Precision measurement!

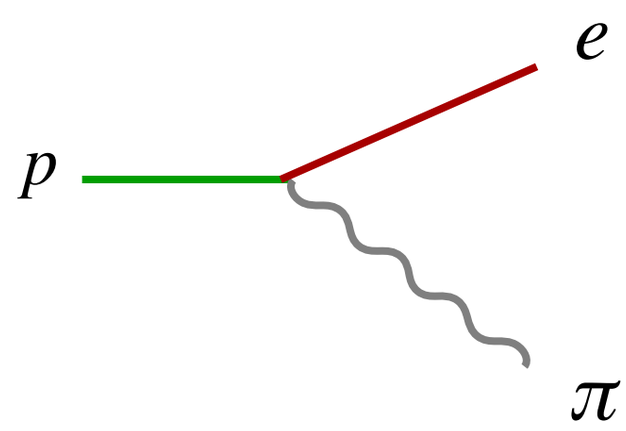
Produce ‘forbidden’ operators

FCNCs $e.g.,\ \mu \to e\gamma$



Bound on operator ~ 10^6 GeV

Proton decay $e.g.,\ p \to e\pi$



Bound on operator ~ 10^{15} GeV

Others B-physics effects, charge radius of the proton, etc…

Violating Special Relativity

Violations of SR (Lorentz Invariance) can often be parameterized by background fields

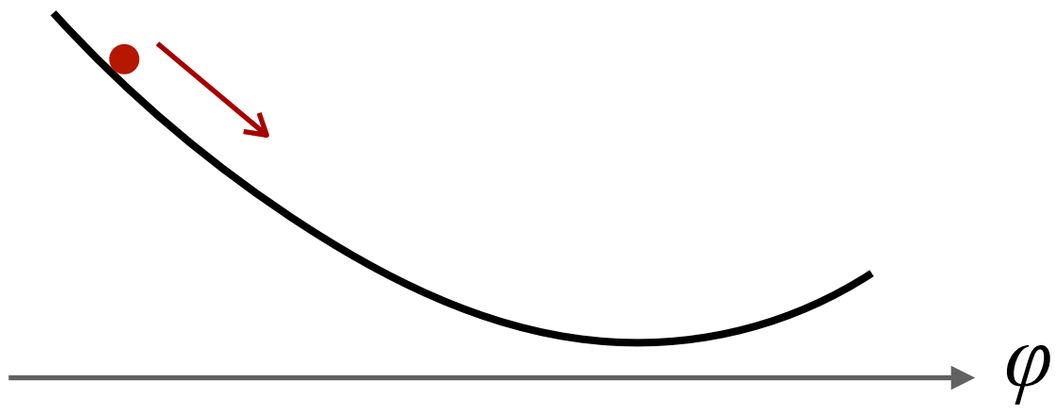
dynamic

static

DM

?

DE



Violating SR and Gauss

Classically:

$$\nabla \cdot \mathbf{E} = e\, J^0$$ Constraint (Gauss)

$$\partial_t \mathbf{E} = \nabla \times \mathbf{B} - e\mathbf{J}$$ Eq. of Motion (Ampere)

QM: Build Hamiltonian, but A_0 has no conjugate momentum

Weyl gauge: $A_0 = 0$

$$\hat{H} = \int d^3x \left(\hat{\mathbf{E}}^2 + \hat{\mathbf{B}}^2 + e\hat{\mathbf{A}} \cdot \hat{\mathbf{J}} \right)$$

$$\partial_t \langle \hat{\mathbf{E}} \rangle = i \left\langle \left[\hat{H}, \hat{\mathbf{E}} \right] \right\rangle = \left\langle \vec{\nabla} \times \hat{\mathbf{B}} - e\hat{\mathbf{J}} \right\rangle$$

No Gauss's Law —> put in by hand

Violating SR: Static charge b.g.

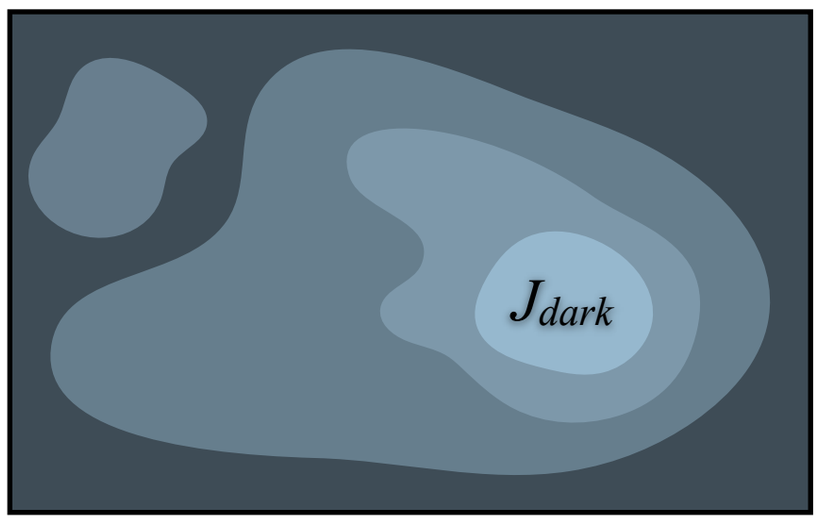
$$\mathcal{G} \equiv \nabla \cdot \mathbf{E} - eJ^0 \qquad \left[\hat{H}, \hat{\mathcal{G}}\right] = 0$$

thus can choose $\hat{\mathcal{G}}\,|\psi\rangle_{\text{phys}} = 0$

can also choose $\hat{\mathcal{G}}\,|\psi\rangle_{\text{phys}} = \mathcal{G}(\mathbf{x})\,|\psi\rangle_{\text{phys}}$

Can *interpret* $\mathcal{G}(\mathbf{x}) \equiv eJ^0_{dark}(\mathbf{x})$
background static dark charge

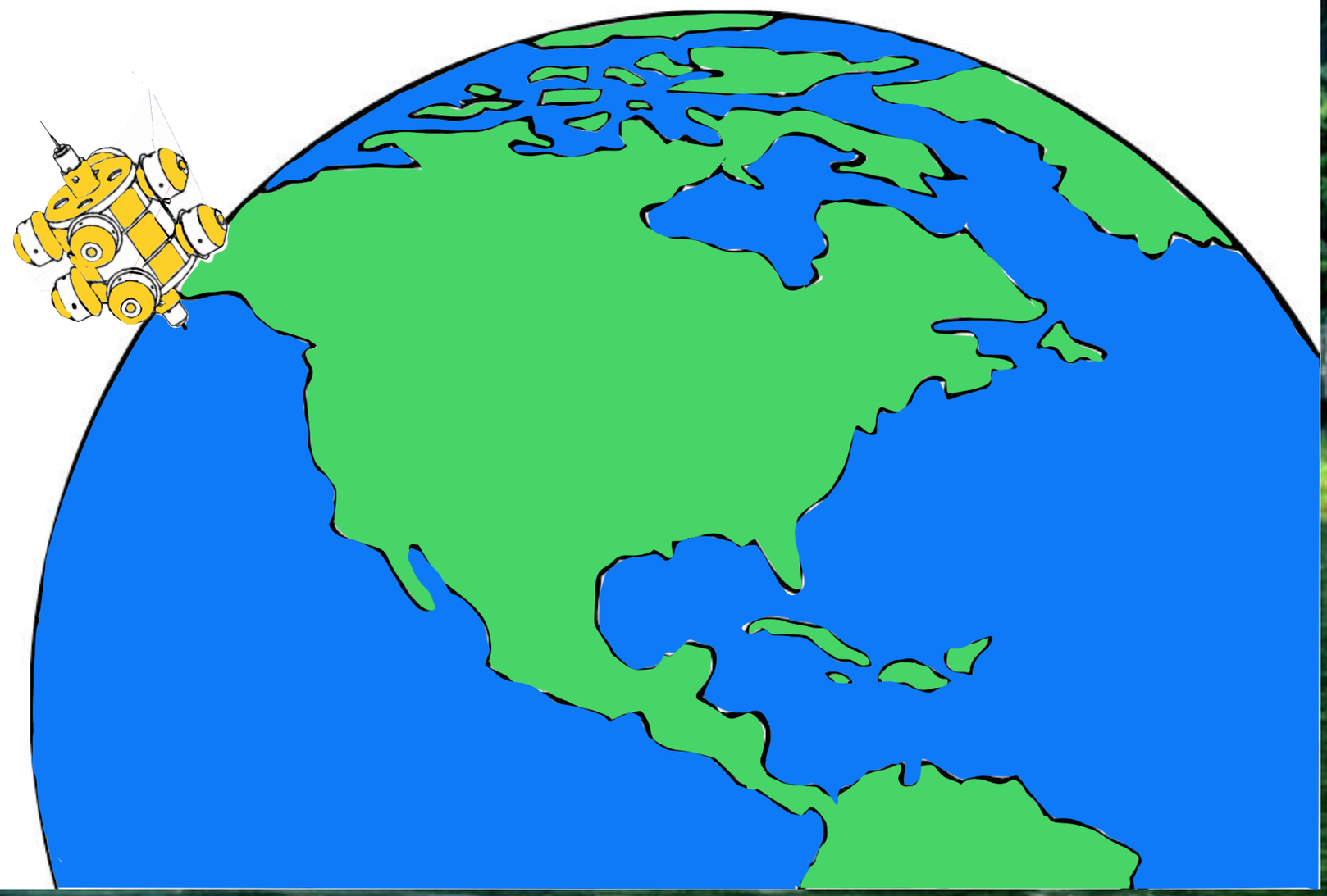
But entirely made of the EM field!



Violating General Relativity

Violations of GR (EP violation, etc) can often be parameterized by new long-range forces

Tests of GR have only been probed to length scales of 100μm, or 10^{31} x Planck length!



Violating GR and Friedmann

Classically:

$$\frac{\delta S}{\delta g_{00}} = 0 \longrightarrow a\dot{a}^2 = \frac{8\pi}{3} G_N a^3 \rho$$ 1st Friedmann (Constraint)

$$\frac{\delta S}{\delta g_{ii}} = 0 \longrightarrow 2a\ddot{a} + \dot{a}^2 = -\,8\pi G_N a^2 p$$ 2nd Friedmann (Eq. of motion)

QM: Hamiltonian density is (basically, synchronous gauge) $8\pi a^3 \rho - a\dot{a}^2$

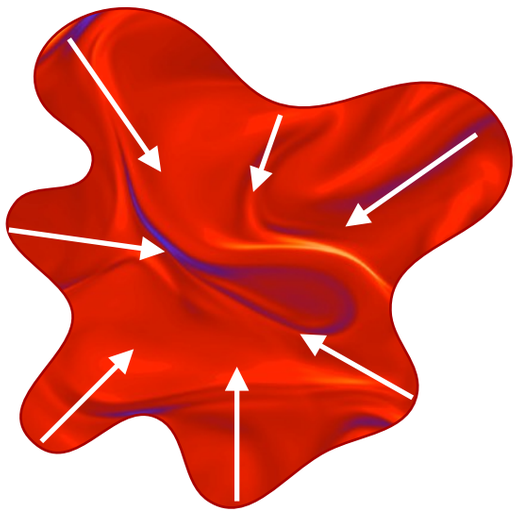
can choose $\hat{H}\,|\psi\rangle_{\text{phys}} = 0$ (Wheeler-deWitt)

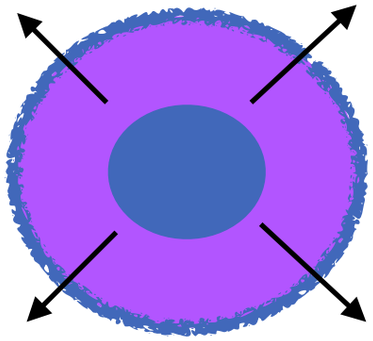
Instead, choose $\langle\psi|\,\hat{H}\,|\psi\rangle = ¶$ (constant)

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3}\rho - \frac{¶}{a^3}$$

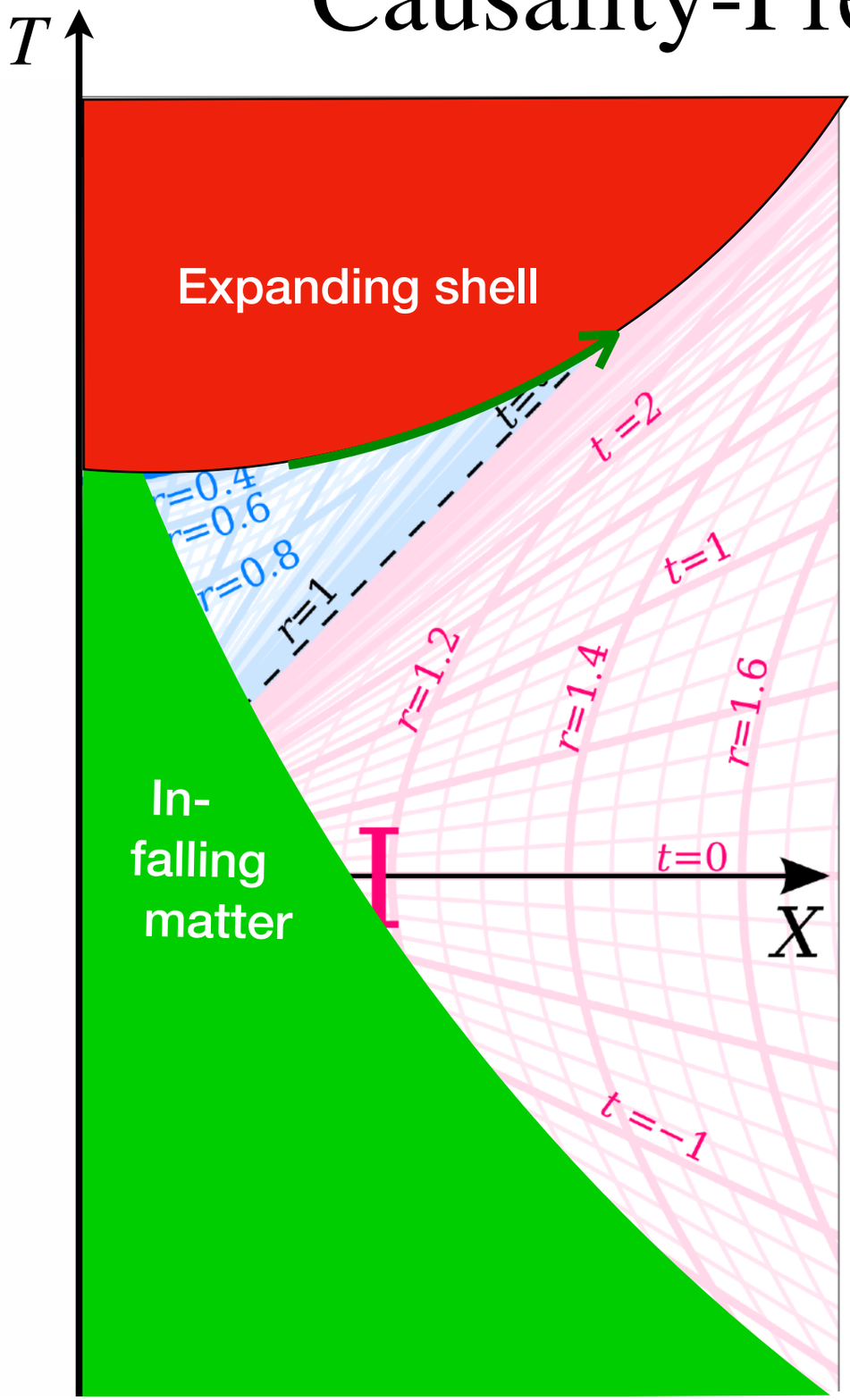
Quantum Gravity

Only place in the universe we are confident GR breaks down — center of Black Hole collapse





Causality-Preserving Expansion

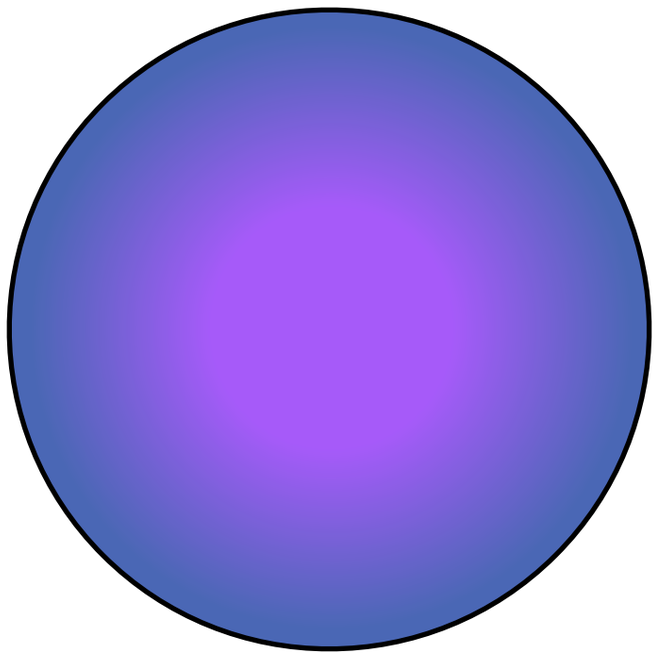


In-falling matter collapses through horizon following GR trajectories.

Out-going shell expands to the horizon along a space-like trajectory, violating GR, not causality.

Geometry is convenient, but not fundamental.

Signatures of Firewalls



Naked ‘Singularity’

Deviations from No Hair Theorem (GR & EM)
Event Horizon Telescope?

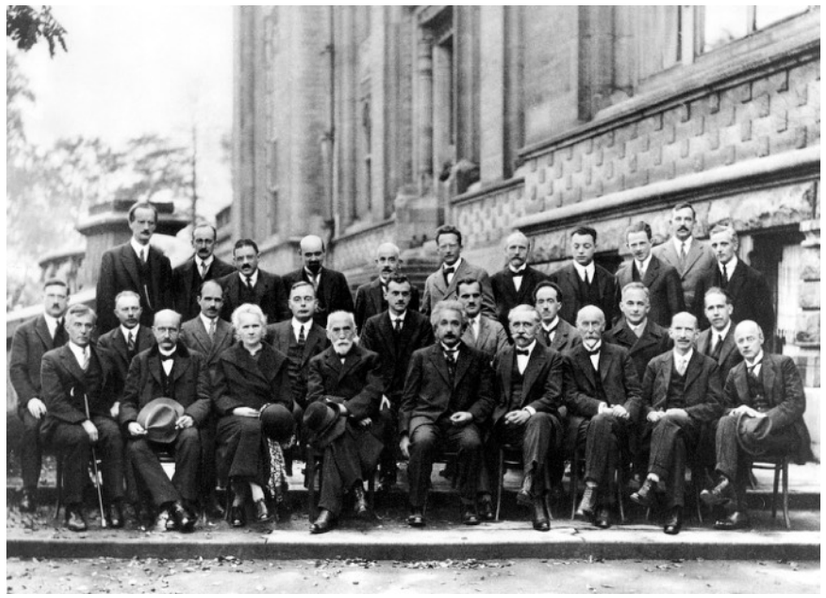
Ring-down of Quasi-Normal Modes set by Firewall physics, or delayed formation ‘glitch’?
Testable in Black Hole Mergers @ LIGO?

Electromagnet bursts from mergers at radio frequencies?
Multi-messenger?

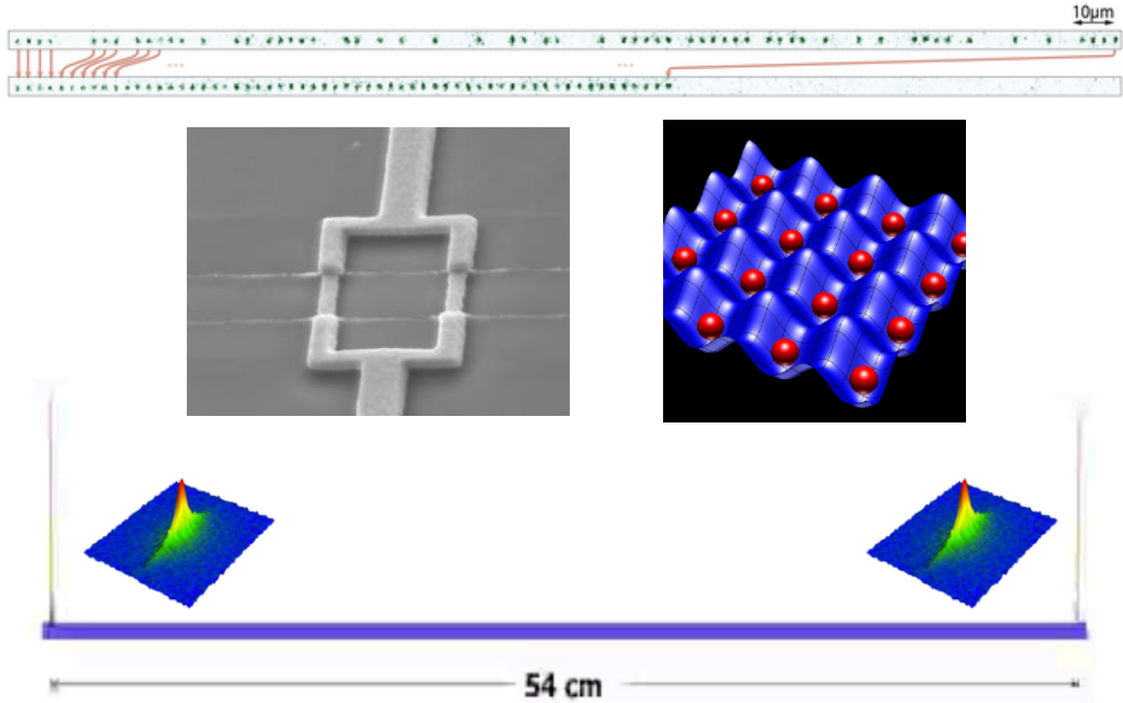
Even a small chance of seeing quantum gravity — isn’t it worth an all-out effort??

Modify Quantum Mechanics?

Why n(bergian)ot?



1927



2023

QM is the only known physical theory that is exactly linear

$$i\partial_t|\chi\rangle = \hat{H}|\chi\rangle$$

Non-Linear Quantum Mechanics

The Schrödinger Equation

$$i\hbar \frac{\partial}{\partial t}\psi(x) = H(\mathbf{x})\,\psi(x)$$

Weinberg's attempt (1989)

$$i\hbar \frac{\partial}{\partial t}\psi(x) = h(\psi^*, \psi)\,\psi(x)$$

Polchinski showed action at a distance with EPR pairs (1990)

Non-Linear Quantum Mechanics

Simple fix:

$$i\frac{\partial}{\partial t}\psi(x) = \hat{H}(\mathbf{x})\,\psi(x) + \epsilon\int d^4x'\,|\,\psi(x')\,|^2\,G_R(x'-x)\;\psi(x)$$

Causality guaranteed by the retarded Green's Function:

$$G_R(x-x') = \frac{\delta\left(t'-(t+|\,\mathbf{x}'-\mathbf{x}\,|)\right)}{|\,\mathbf{x}'-\mathbf{x}\,|}$$

In Field Theory

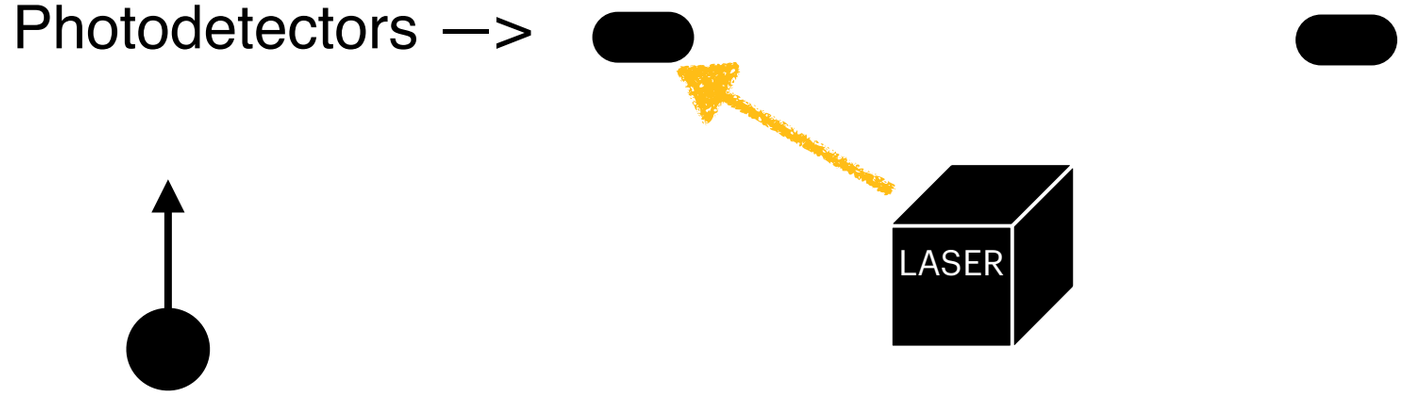
Example: Yukawa Theory

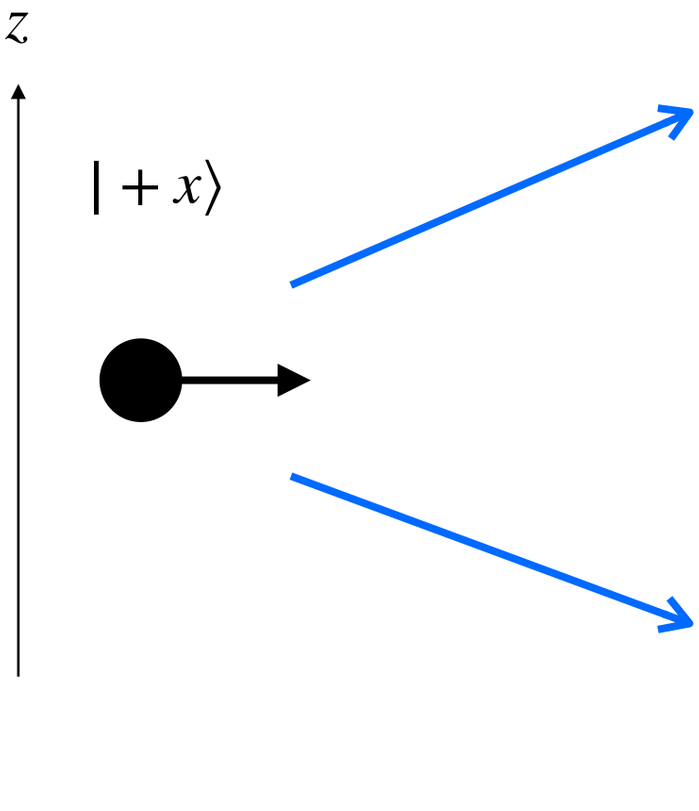
"Linear" QFT $\qquad \mathscr{H} \supset y\hat{\phi}\hat{\bar{\psi}}\hat{\psi}$

"Non Linear" QFT $\qquad \mathscr{H} \supset y\left(\hat{\phi} + \epsilon\langle\chi|\hat{\phi}|\chi\rangle\right)\hat{\bar{\psi}}\hat{\psi}$

Kibble wrote extensions like this (1978!)

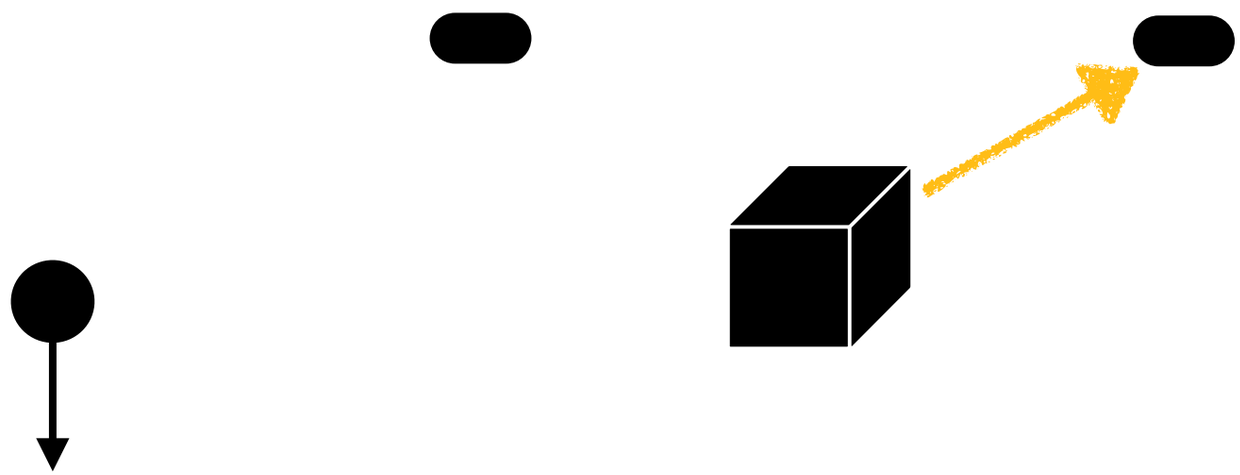
Linear Quantum Mechanics





Spin up measured — laser pointed left

Spin down measured — laser pointed right

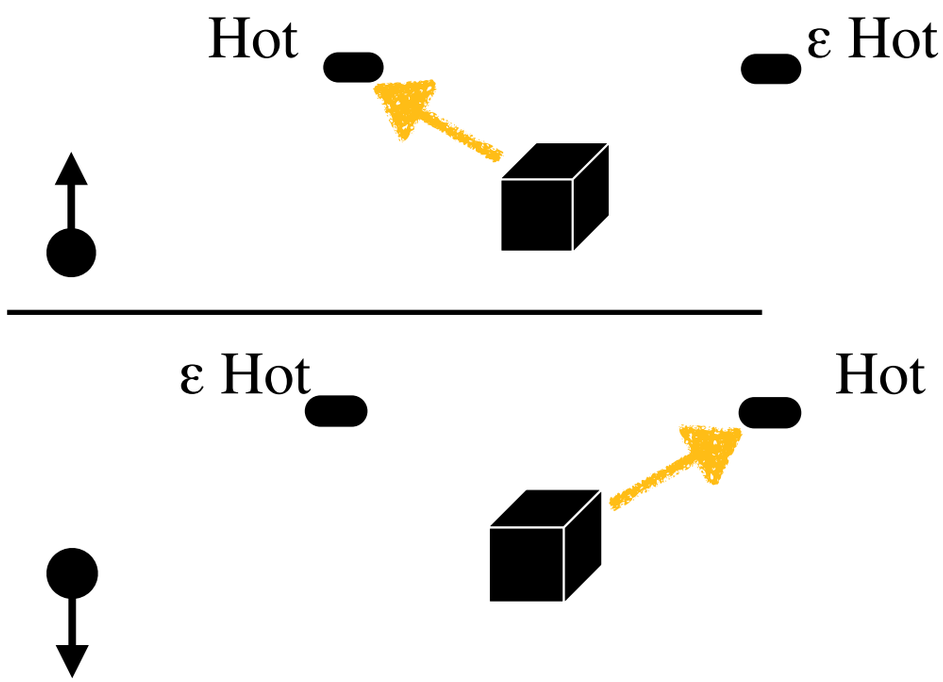


$$|\chi(t)\rangle = \frac{1}{\sqrt{2}}\left(|+z\rangle|L\rangle|Env_L\rangle + |-z\rangle|R\rangle|Env_R\rangle\right)$$

Non-Linear Quantum Mechanics

$$\mathscr{H} \supset e(A_\mu + \varepsilon\langle A_\mu \rangle)\, J^\mu$$

Which photodetectors light up?



$$\langle \chi \,|\, A_\mu(x_L) \,|\, \chi \rangle \neq 0$$

$$\langle \chi \,|\, A_\mu(x_R) \,|\, \chi \rangle \neq 0$$

Communication between “worlds”

Polchinski: “Everett Phone”

Time’s up


Thank You!