Perspectives in Particle Physics

PHENO 2022

We're back!

David E Kaplan

Outline

Higgs
CC
Black Holes
QM

Fast, nutrient-dense.

Higgs

2014

The Hierarchy Problem

The Higgs mass in the standard model is sensitive to the ultraviolet.

Three approaches to explain:

- New symmetry or new dynamics realized at the electroweak scale. (SUSY, composite Higgs, EOFT)
- Dynamical Higgs mass with long relaxation period. (Relaxion)
- An anthropic explanation for fine tuning of ultraviolet parameters. (Multiverse)

Relaxion — Simplest

Standard Model plus QCD axion

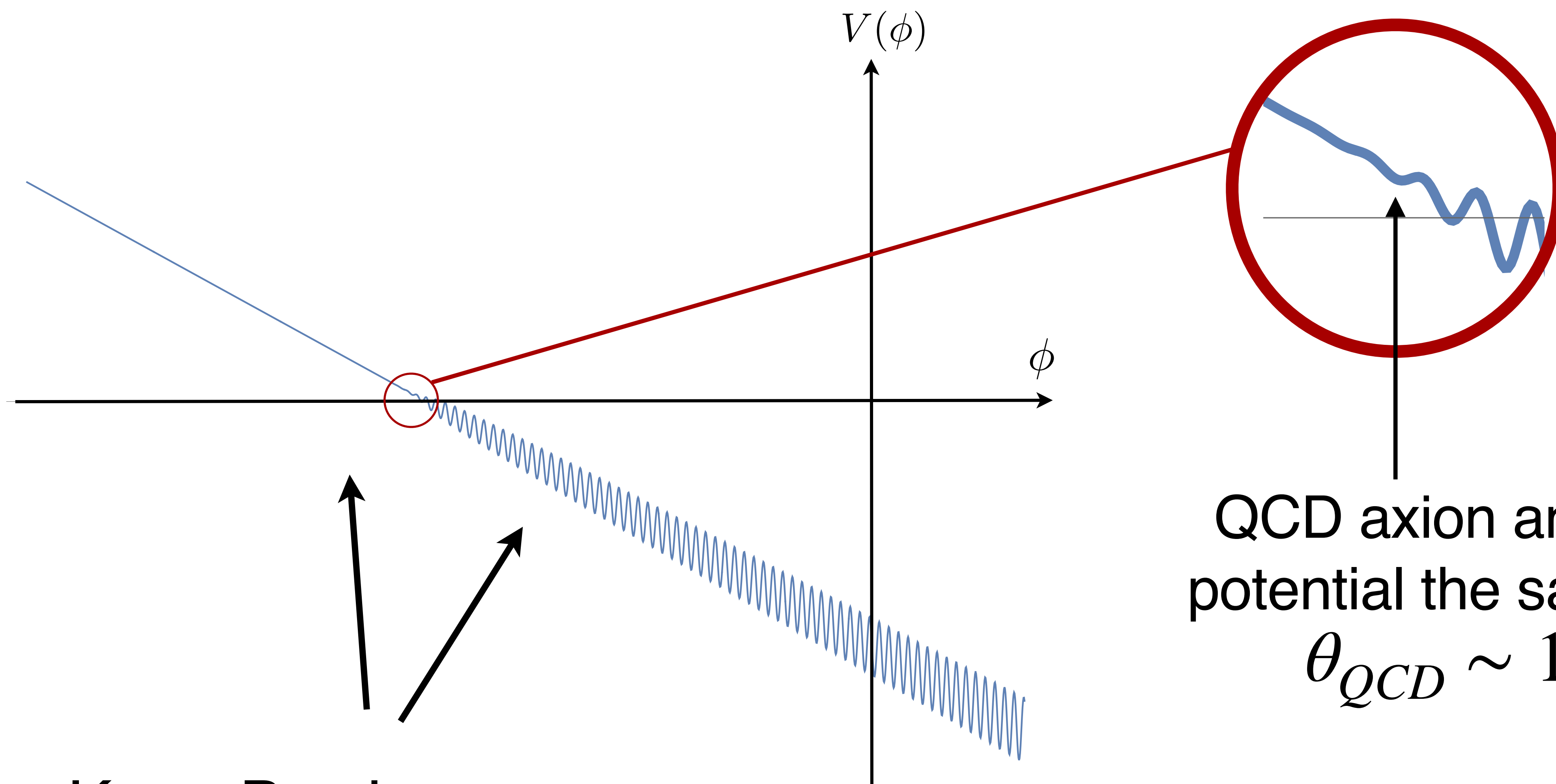
$$\mathcal{L} \supset (-M^2 + cM^2 \sin\frac{\phi}{F})h^2 + M^4 \sin\frac{\phi}{F} + \Lambda^4 \cos\frac{\phi}{f}$$

With: $F >> f$.

Principle: low cutoff $\longrightarrow$ long time evolution

Took 6 months to get anything to work

Relaxion Solution - Strong CP demise



QCD axion and linear potential the same size.

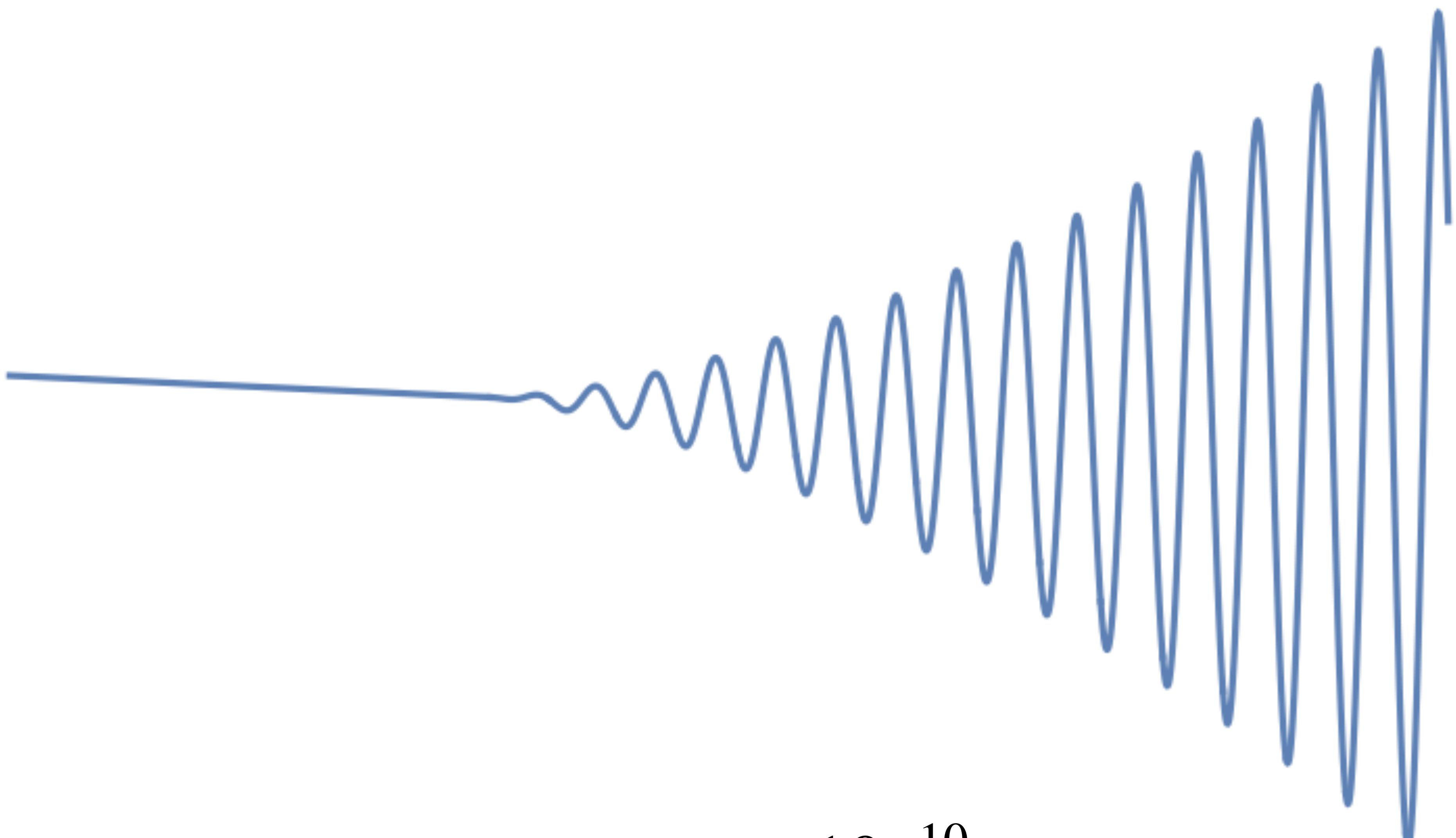
$\theta_{QCD} \sim 1$

Key: Barriers grow because they depend on the Higgs vev.

Relaxion solves both (model)

$$\mathcal{L} \supset (-M^2 + \kappa\sigma^2 + g\phi)|h|^2 + gM^2\phi + \cdots + \Lambda^4 \cos\frac{\phi}{f}$$

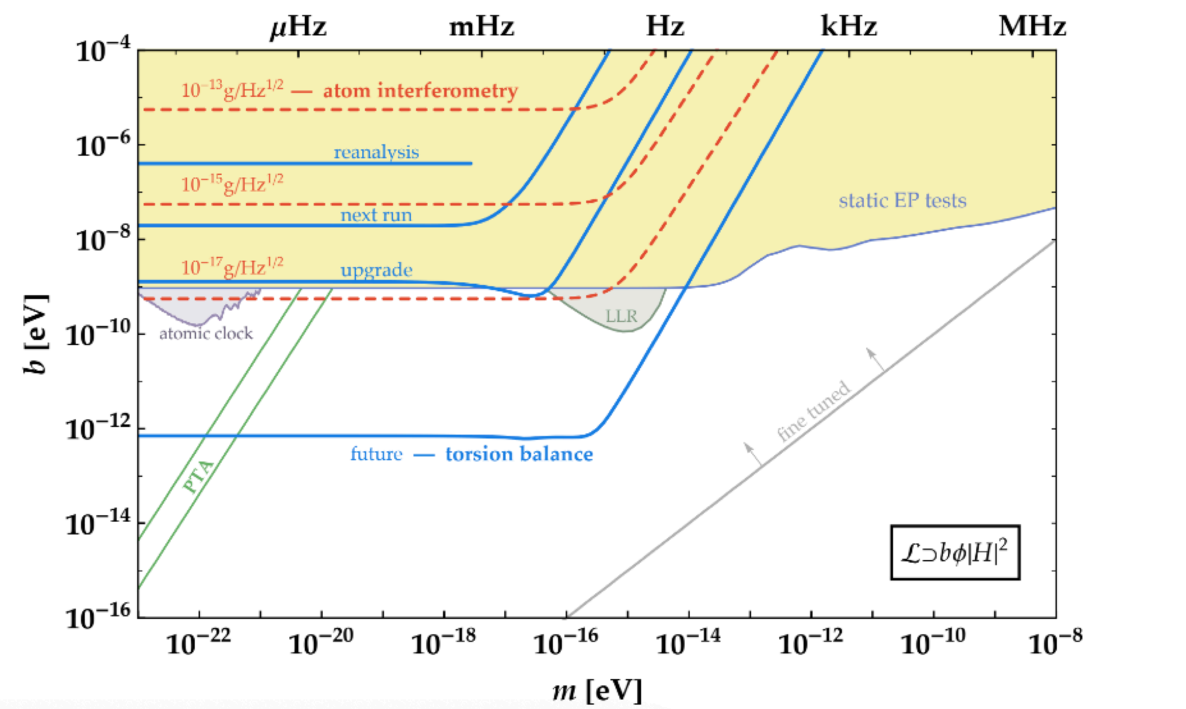
field that evolves after relaxion is trapped



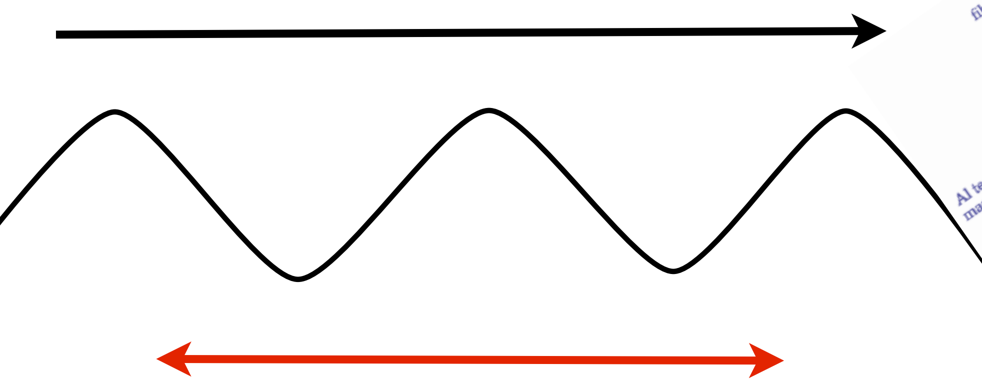
Small enough slope to relax Higgs vev to $10^{-10} \times v_{EW}$, then grow Higgs vev

Light Scalars: $b\phi|h|^2$

F. Piazza and M. Pospelov, "Sub-Ev Scalar Dark Matter Through the Super-Renormalizable Higgs Portal," Phys. Rev. D82 (2010) 043533.

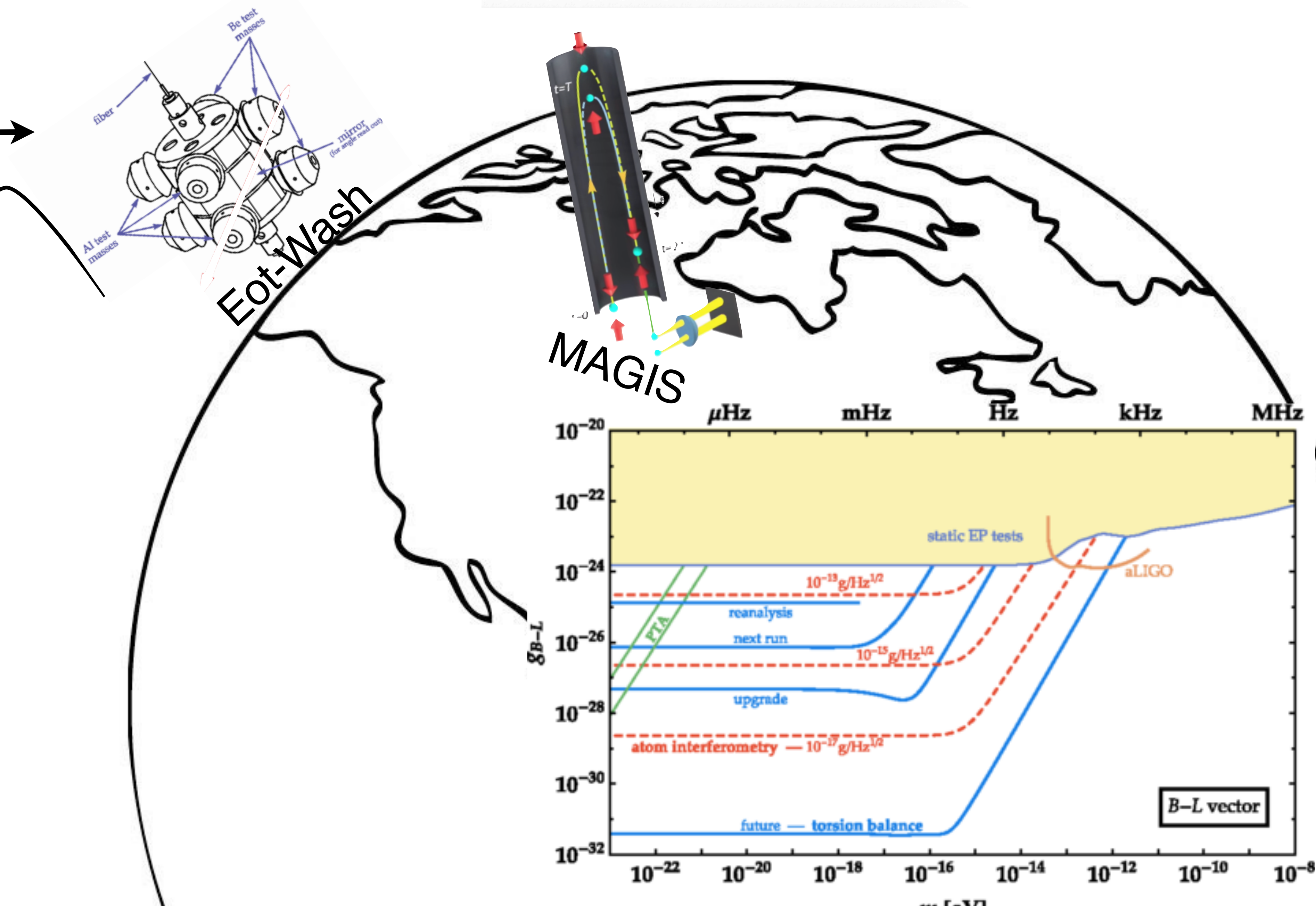


$$v \sim 10^{-3}$$

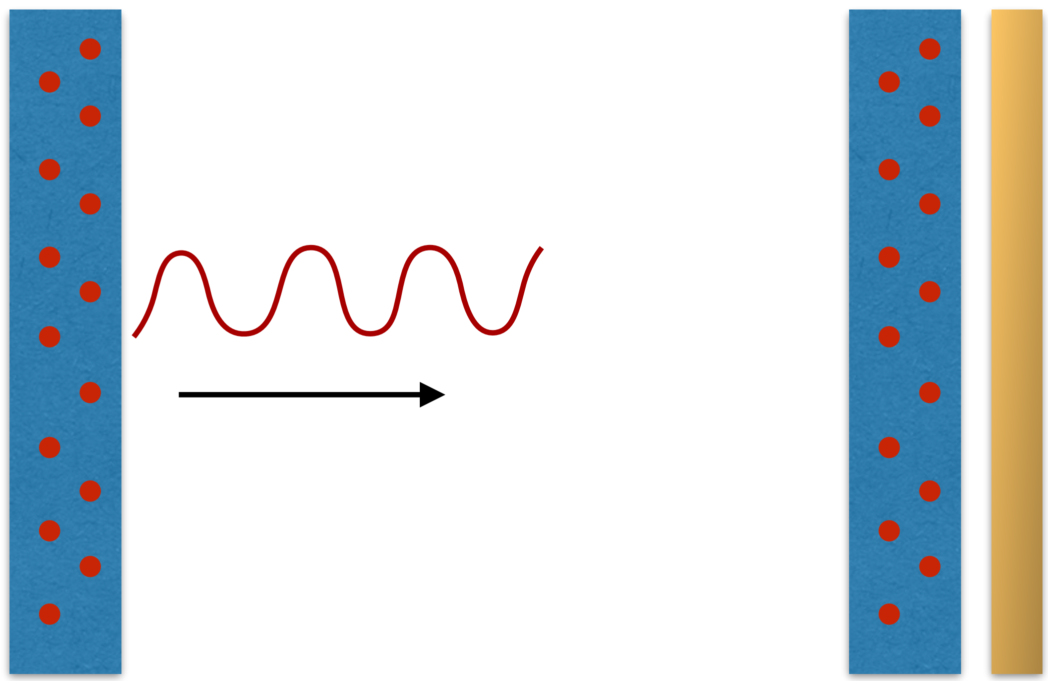


$$\lambda \sim 10^3 c/\omega$$

$$\omega \sim m$$



Light Scalars in the Spectrum: Mossbauer

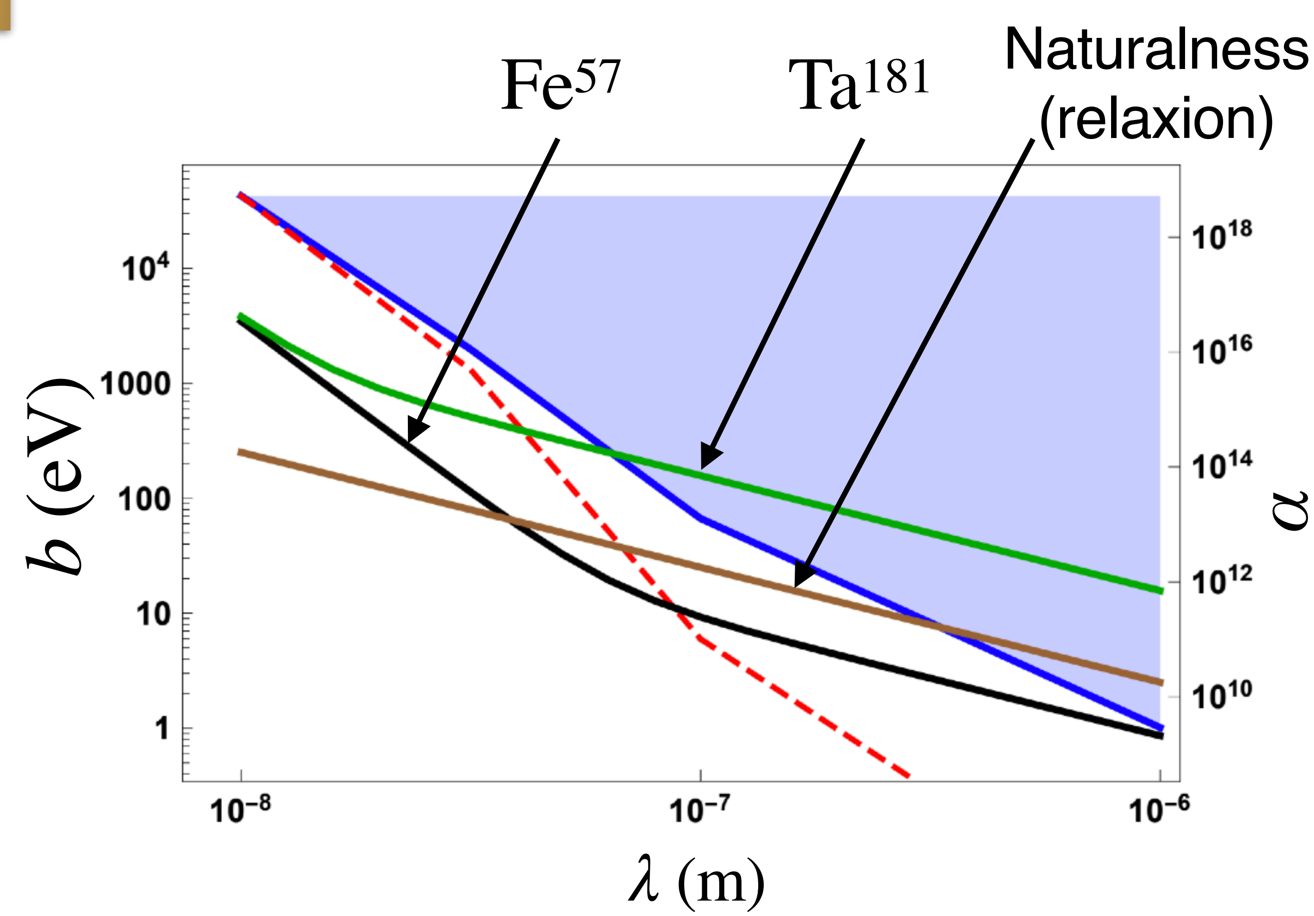


Atoms embedded in material can have nuclear transitions without recoil

Nuclear energy levels protected from EM fields via electrons and uniformity.

Plate of matter could source scalar field at 1-0.01 μm

Scalar field (through Higgs portal) changes masses of nucleons and thus nuclear energy levels.

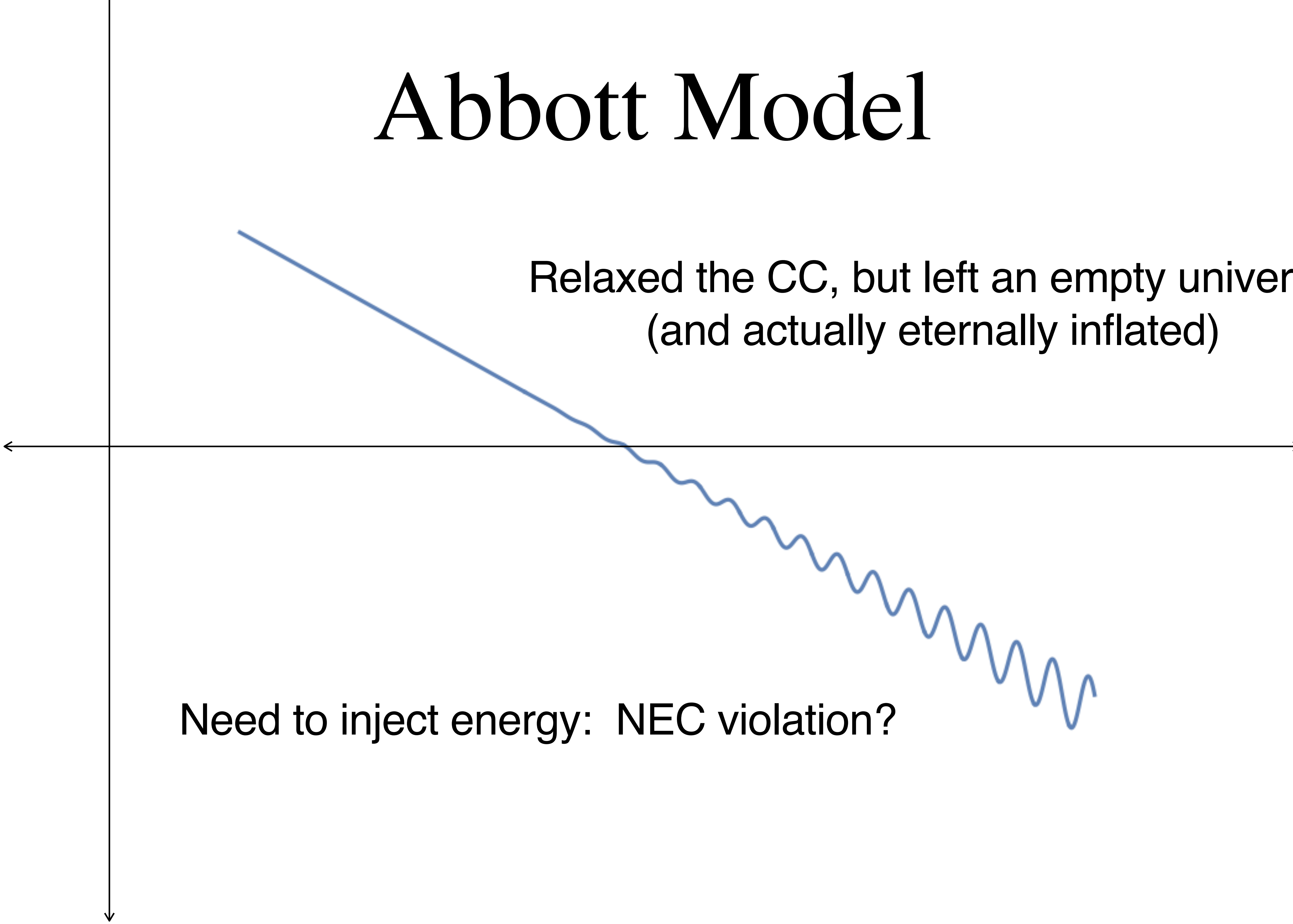


Search for the Physics

CC

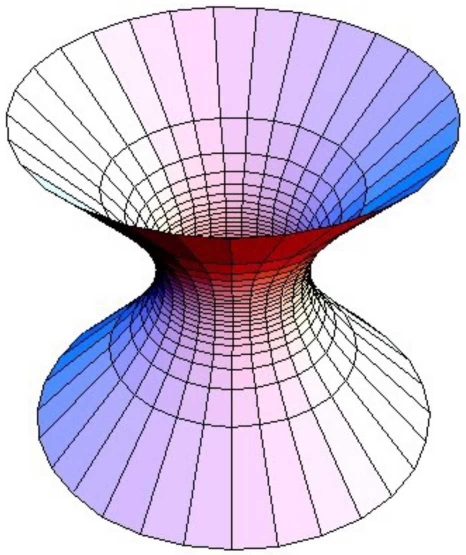
2015

Abbott Model

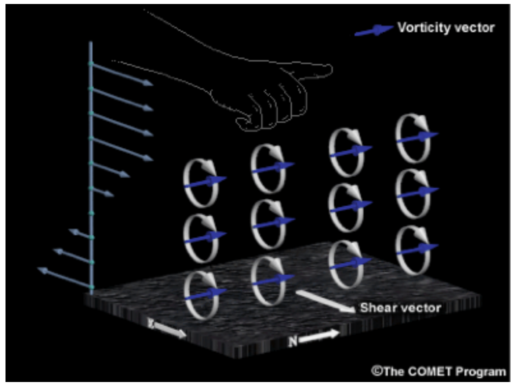


Relaxing the Cosmological Constant: a Proof of Concept: L Alberte, P Creminelli, A Khmelnitsky, D Pirtskhalava, E Trincherini (2016)

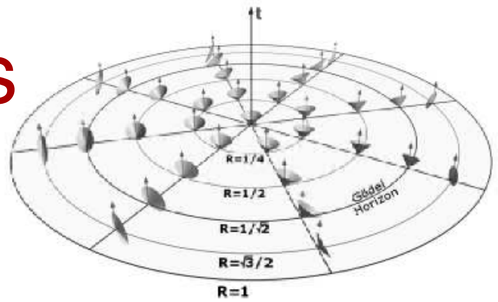
Solution: A Bounce



But NEC violation needed to bounce

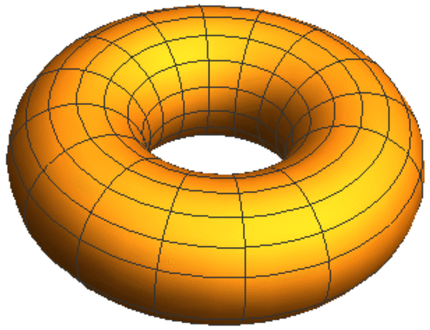


CTCs



Or vorticity!

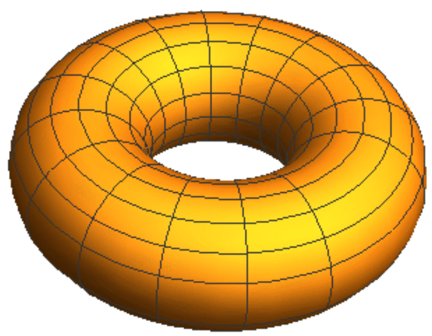
In compact space



NEC violation: Casimir

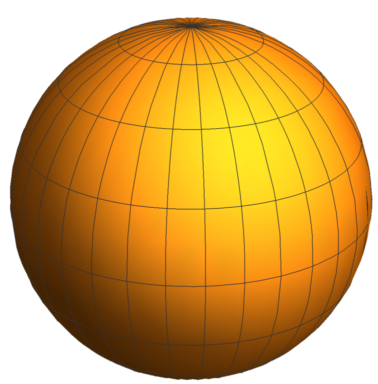
Solution: A Bounce

T3



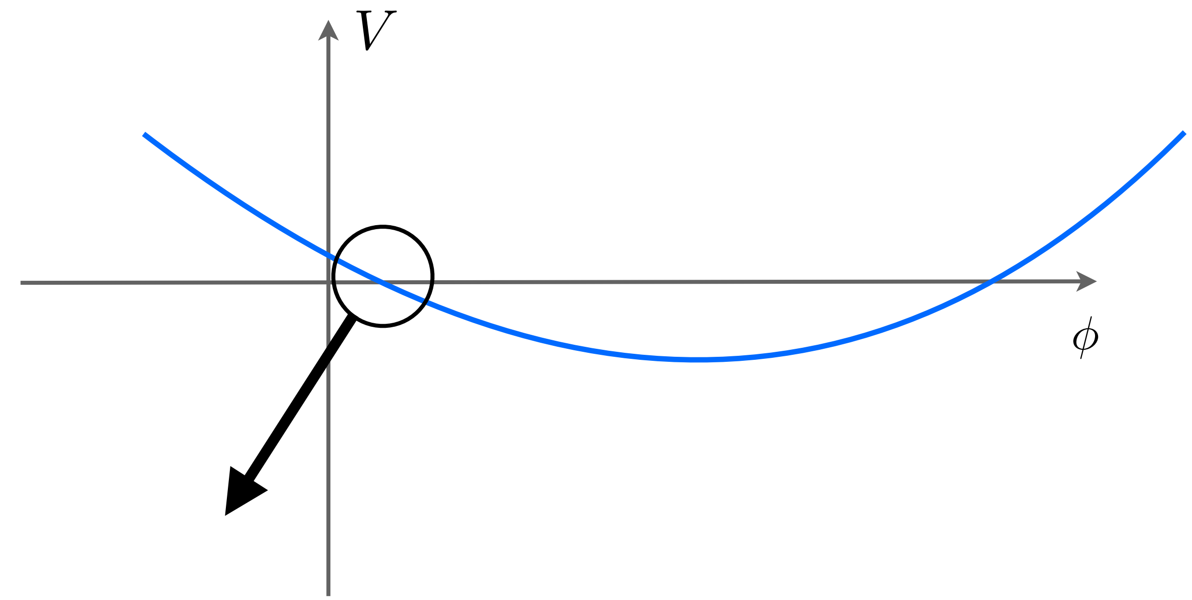
Need a lot of Casimir energy to stabilize — so many fields it renormalized the Planck scale down to the radius

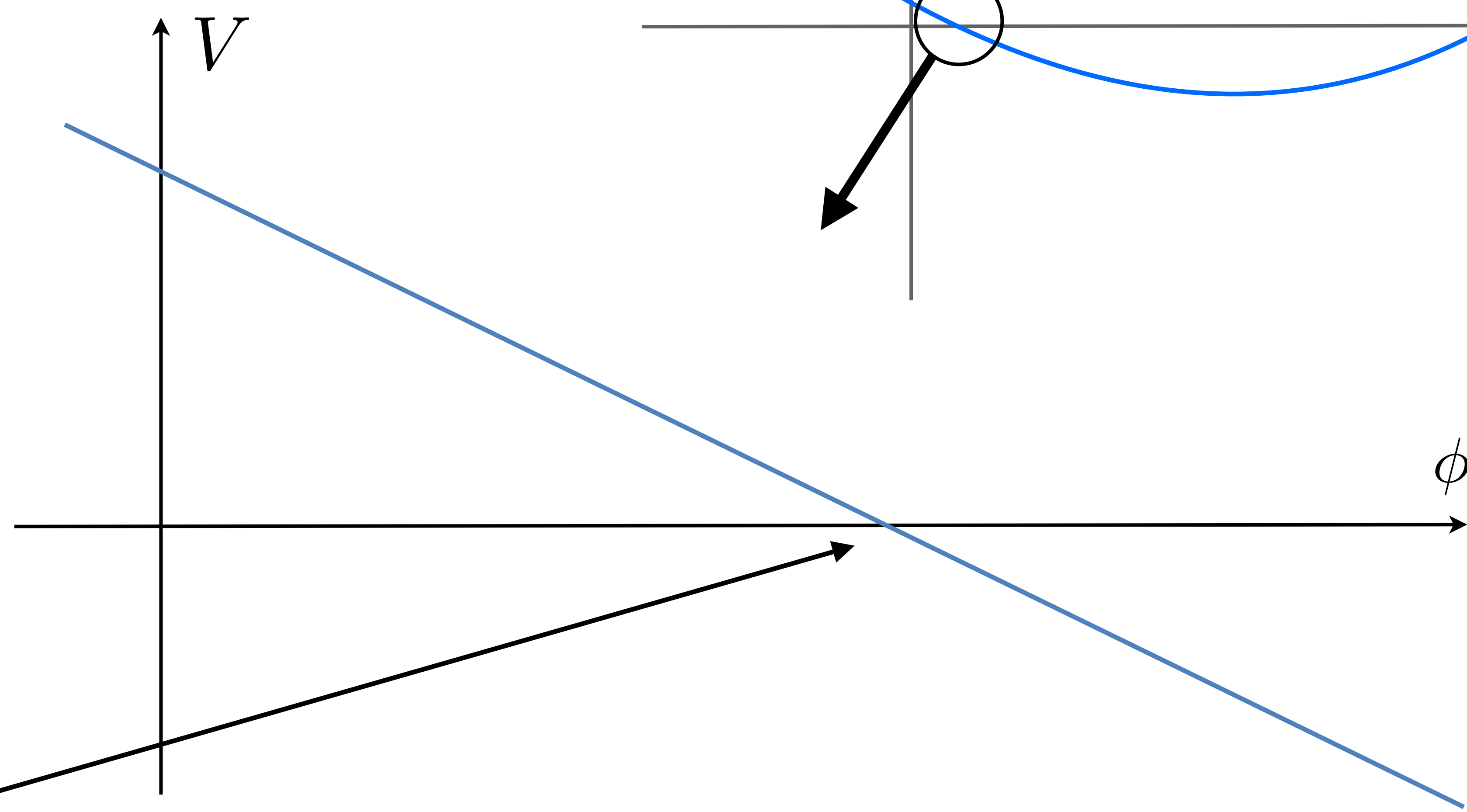
S3



If compact space has positive curvature, it provides most of the ‘NEC violation’, and Casimir needed is small.

Scanning — simple potential does the trick



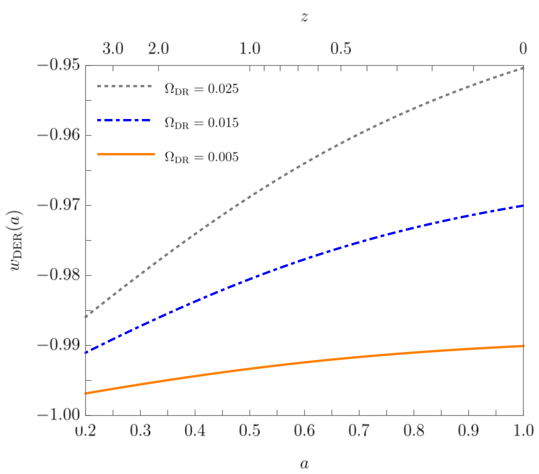


We are here because negative CC triggers crunch

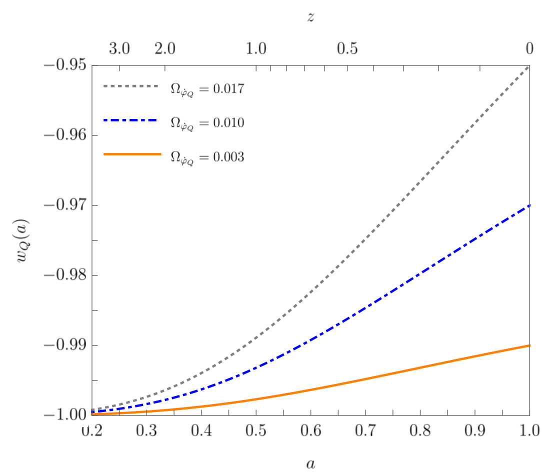
Better parametrics if we use friction $\frac{\phi}{f}G_{\mu\nu}\tilde{G}^{\mu\nu}$

It's Rolling Today!

thermal bath

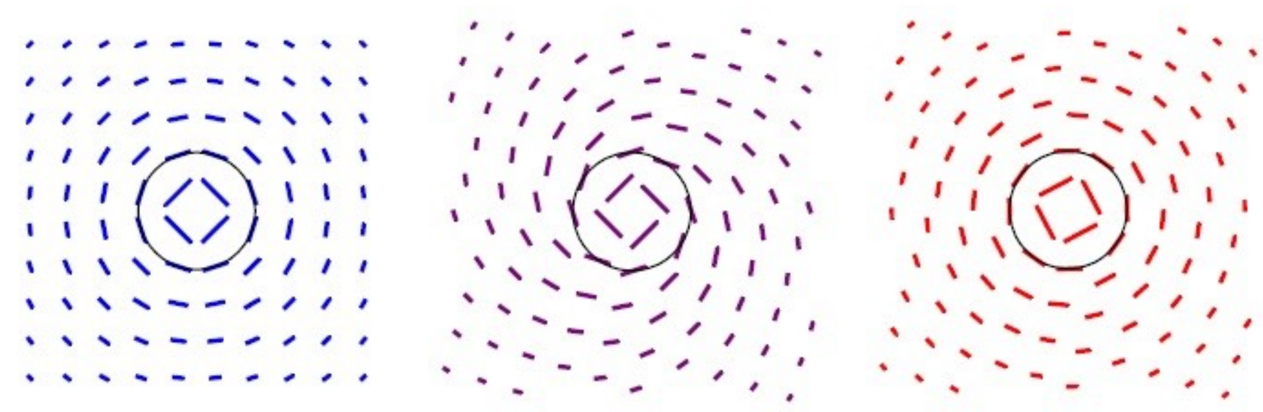


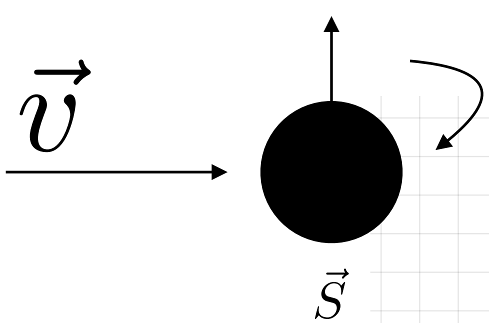
Hubble friction

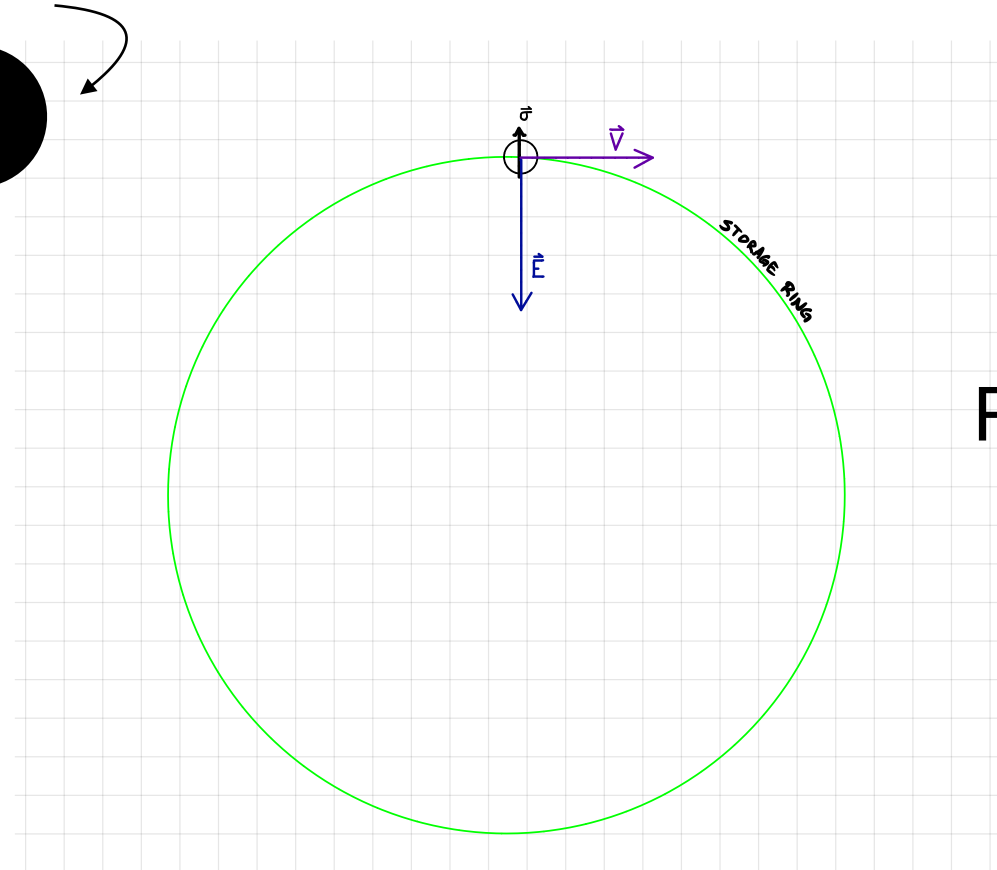


Cosmic evolution

CMB Bi-refringence







Precession of storage ring protons

Dark Energy Radiaton!

Up to 10x the temperature of CvB

Ho

2031: A Relaxation Space Odyssey

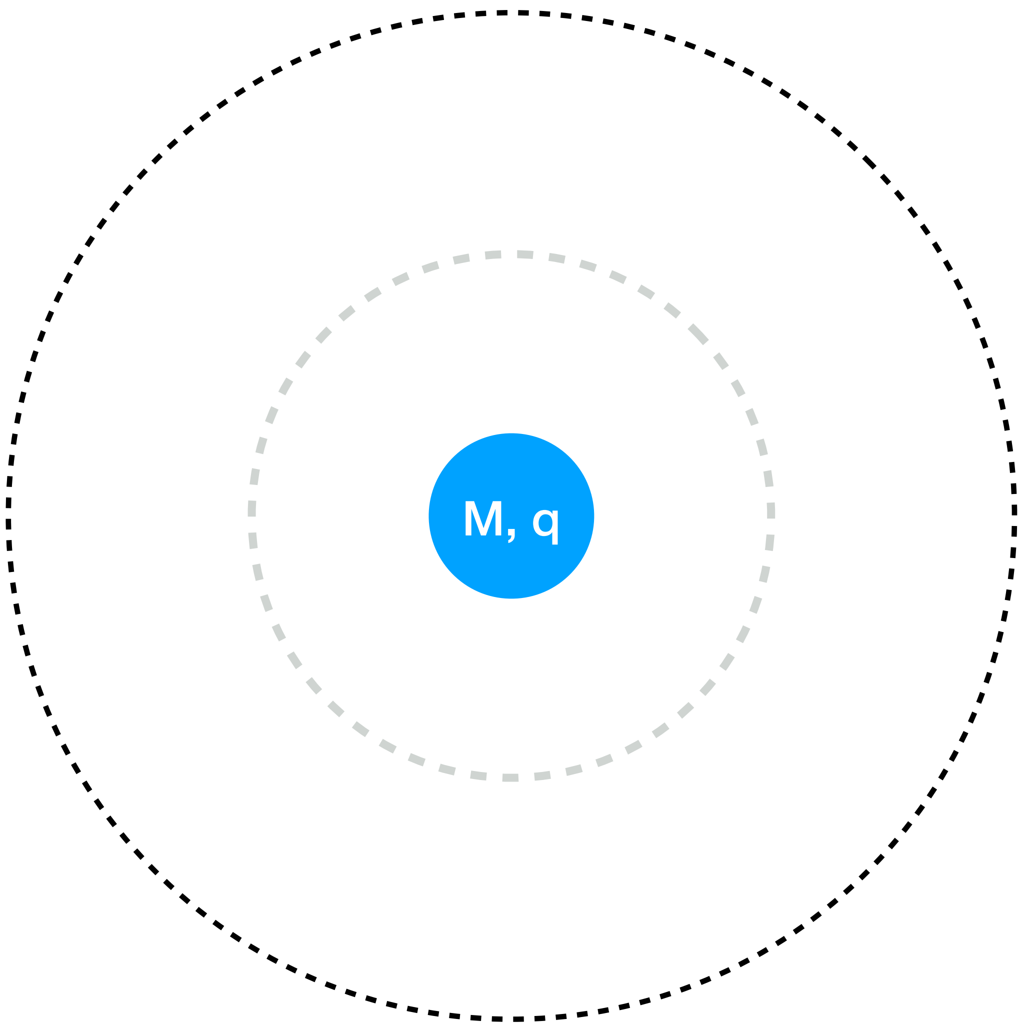
General searches for relativistic dark sectors warranted but challenging!

Black Holes

2016

Hawking Paradox

Classically, what falls into a black hole
(past the horizon), cannot get out.



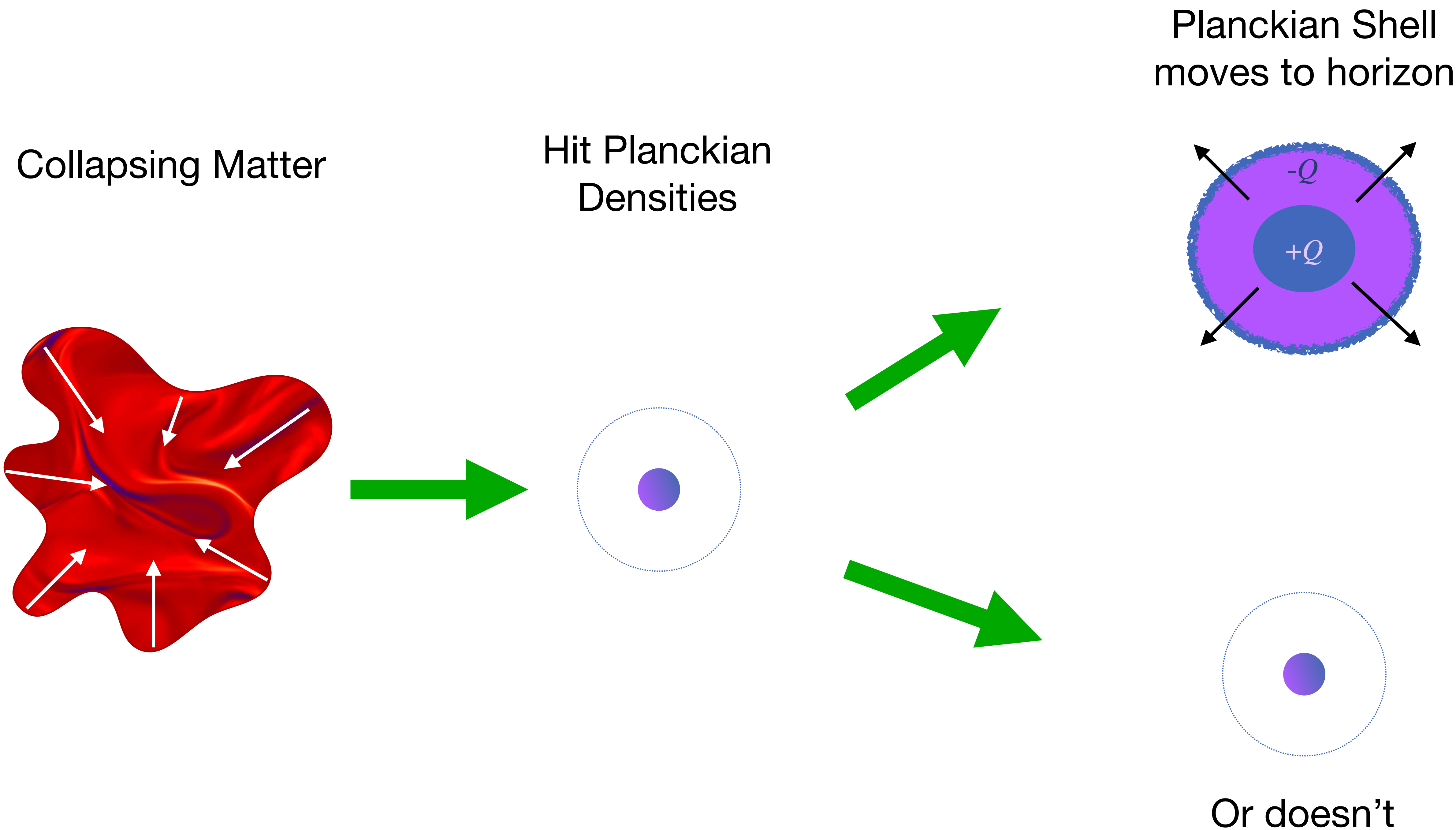
QM fluctuations near the horizon generate radiation that leaves the black hole:
—It has a temperature
—It has entropy proportional to area
—It shrinks

If the black hole shrinks to zero…
—How is unitary evolution maintained?
—Where is the entropy stored?
—Is GR violated??

Of course GR is violated - at the center!

What GR-violation can travel out?

Black Hole Evolution



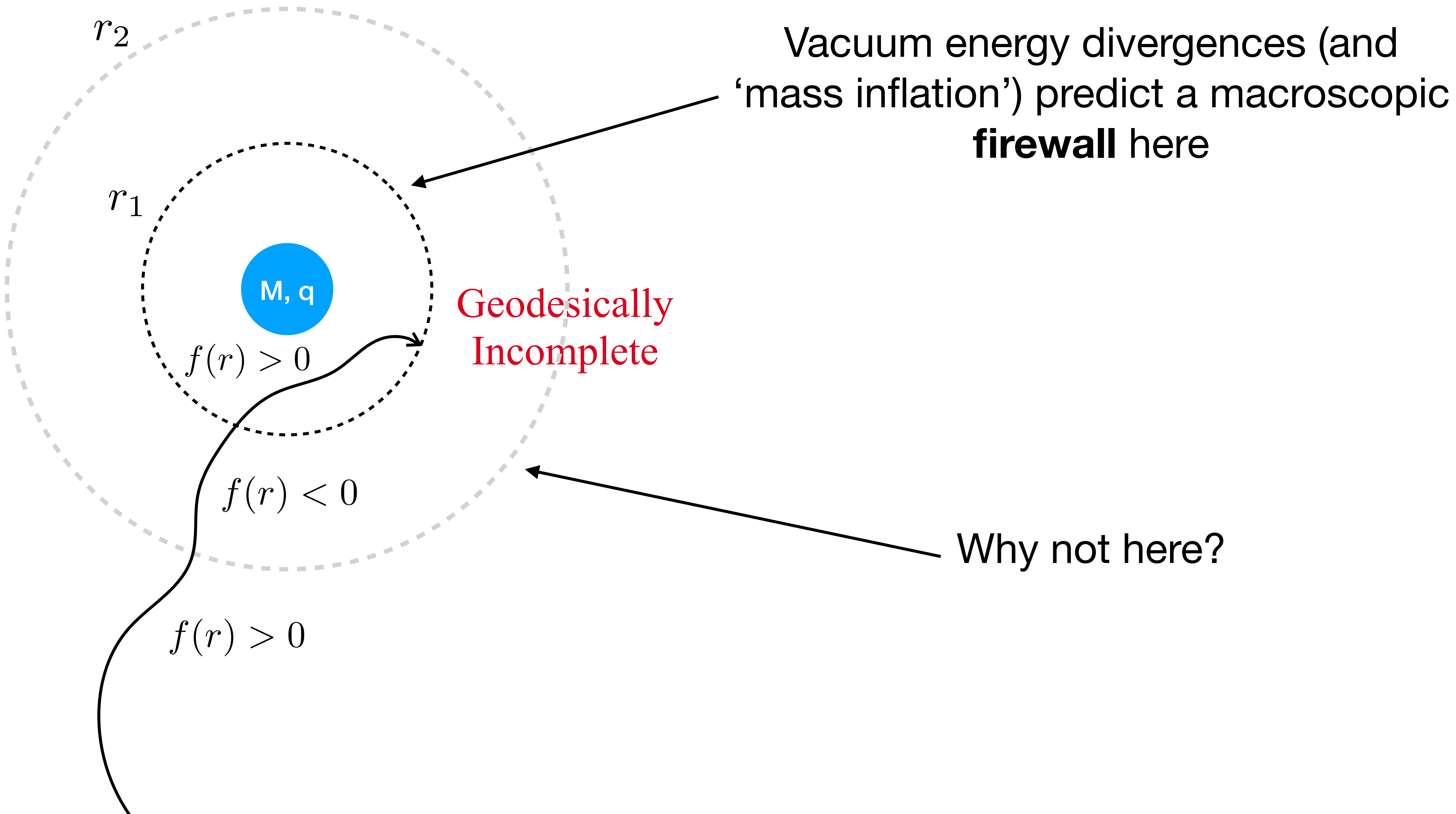
50-50 chance?

What Hamiltonian allows us to evolve through $r = 0$?

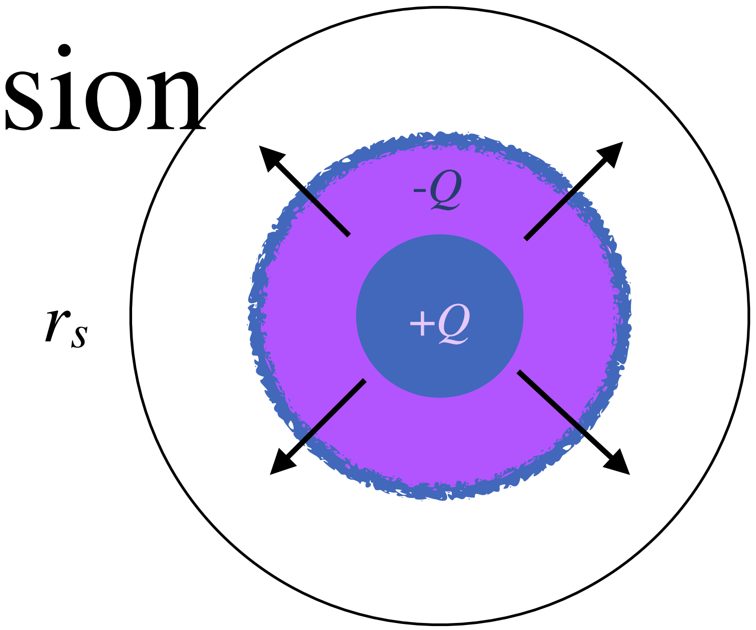
How large can the UV region be?

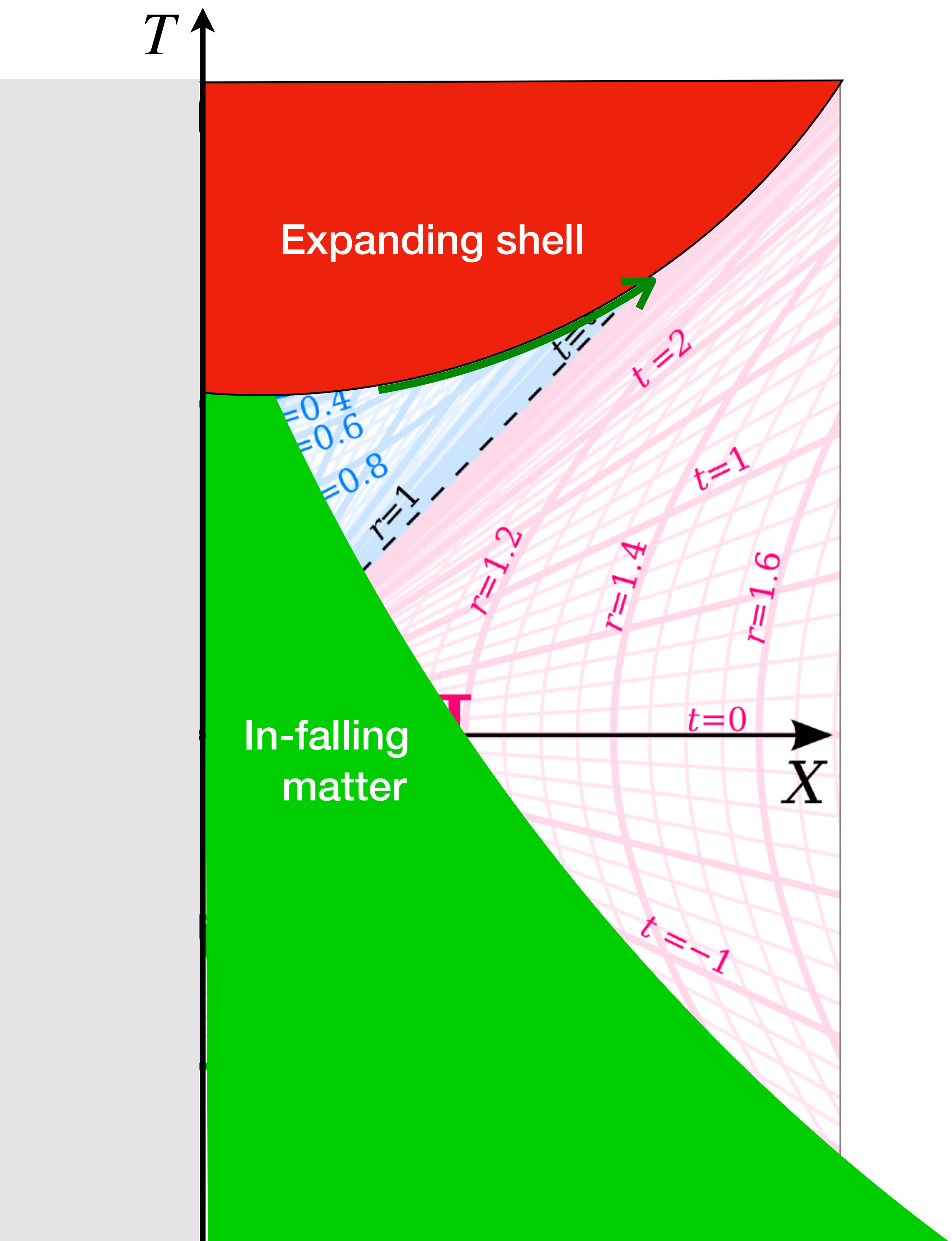
Cauchy Horizons in Charged BH

Charged and spinning black holes have a second (inner) horizon



Causality-Preserving Expansion





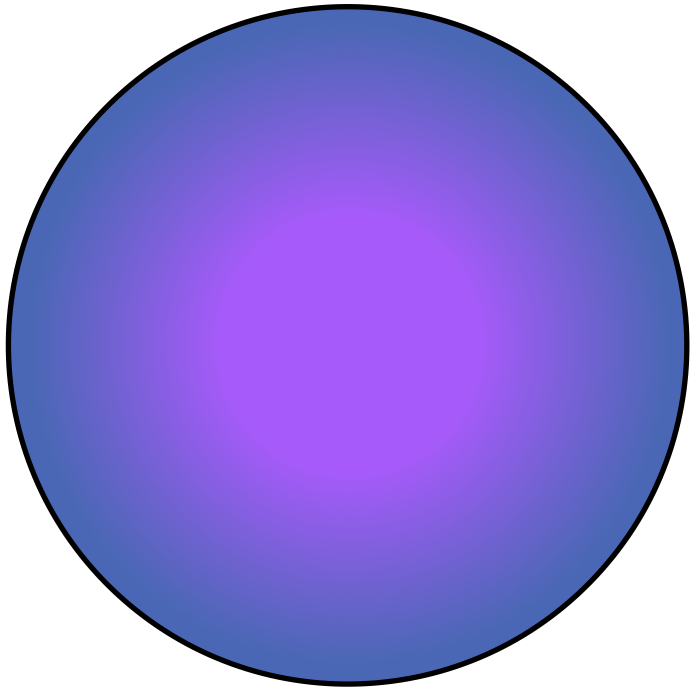
In-falling matter collapses through horizon following GR trajectories.

Out-going shell expands to the horizon along a space-like trajectory, violating GR.

Nevertheless, no causality violation.

(Geometry isn't fundamental — it's bookkeeping)

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?

Reflectivity of the horizon to EM and GW
LIGO? Radio?

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

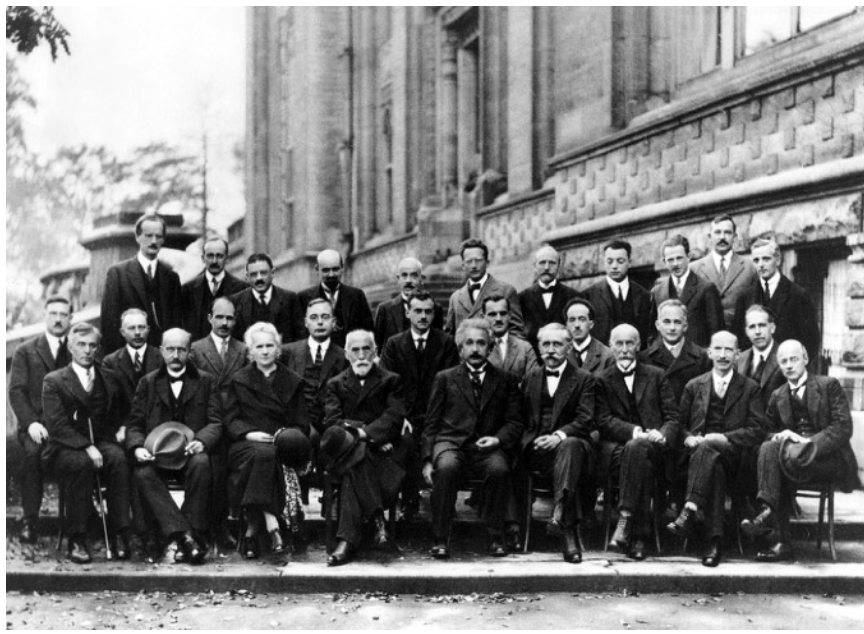
Even a small chance of seeing quantum gravity — isn’t it worth an all-out effort??

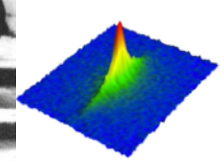
Quantum Mechanics

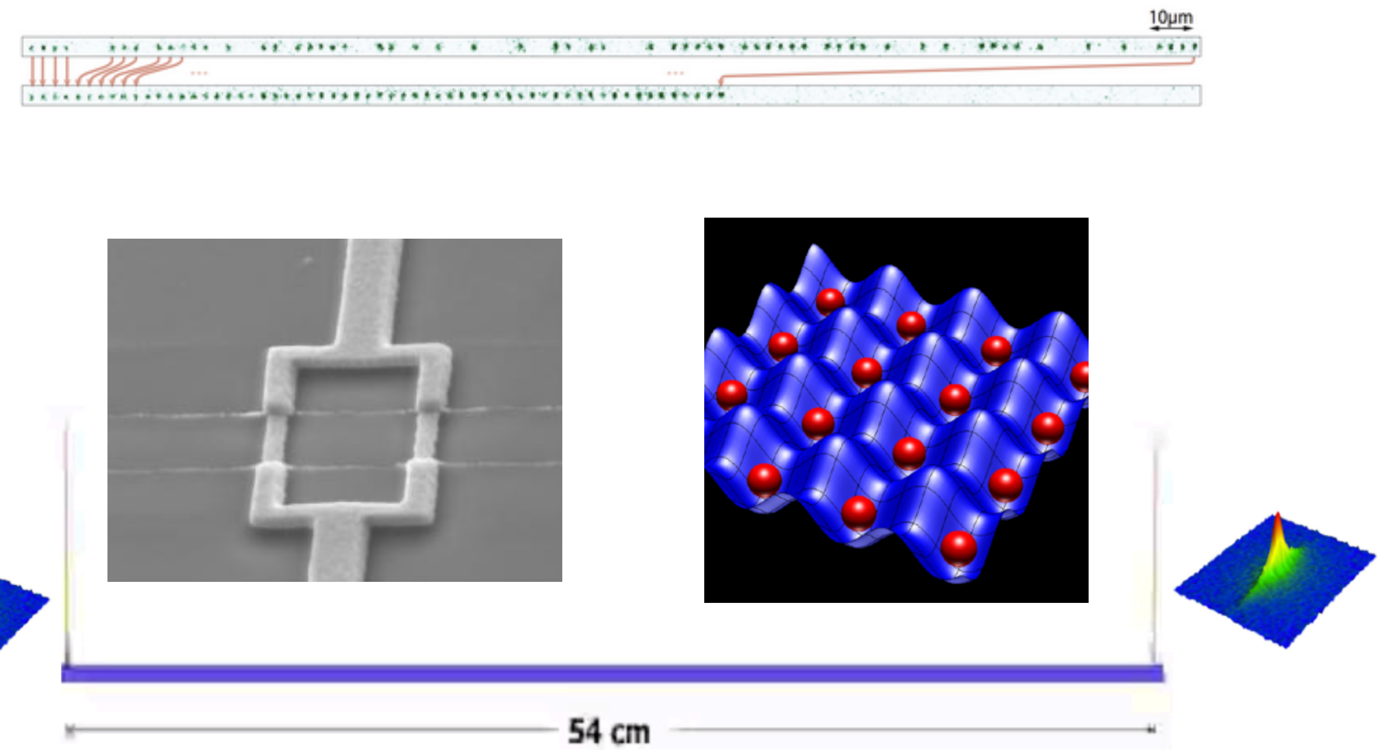
2010

Why Modify QM?

Why n(bergian)ot?







1927

2022

QM is the *only* known physical theory that is exactly linear

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

Non-Linear Time Evolution

The Schrödinger Equation (position space)

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

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

Our proposal:

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

Causality guaranteed by the retarded Green's Function. For a massless field:

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

In Field Theory

Example: Yukawa Theory (could be photon or graviton too)

Linear QFT

$$\mathscr{L} \supset y\hat{\phi}\hat{\bar{\psi}}\hat{\psi}$$

Non Linear QFT

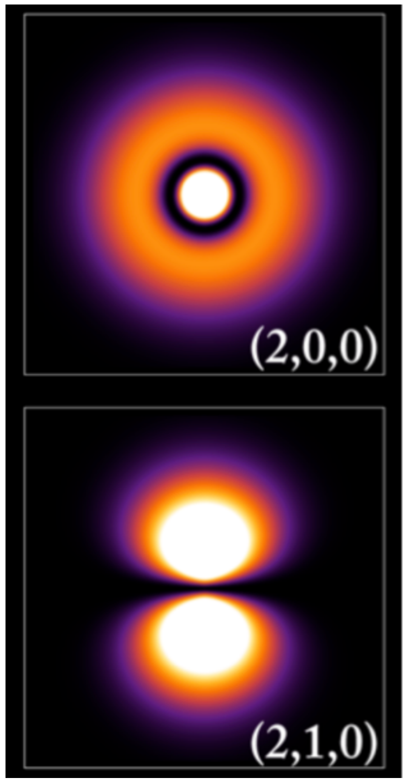
$$\mathscr{L} \supset y\left(\hat{\phi} + \epsilon\langle\chi|\hat{\phi}|\chi\rangle\right)\hat{\bar{\psi}}\hat{\psi}$$

$$S = \int d^4x\ \mathscr{L}(\phi(x), \partial_\mu\phi(x)) + \epsilon\left(\langle\chi|\hat{\mathscr{O}}_1|\chi\rangle(x)\ \mathscr{O}_2\left(\phi(x)\right) + \langle\chi|\hat{\mathscr{O}}_2|\chi\rangle(x)\ \mathscr{O}_1\left(\phi(x)\right)\right)$$

Kibble wrote extensions like this (1978!)

Strong Constraints?

What does this do to the Lamb Shift

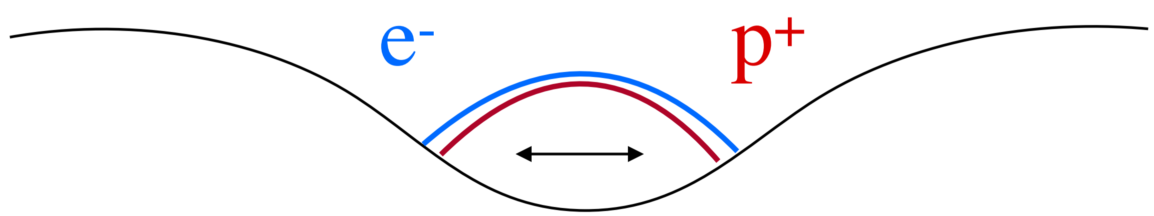


Proton at Fixed Location

2S and 2P electron have different charge distribution

Different expectation value of electromagnetic field

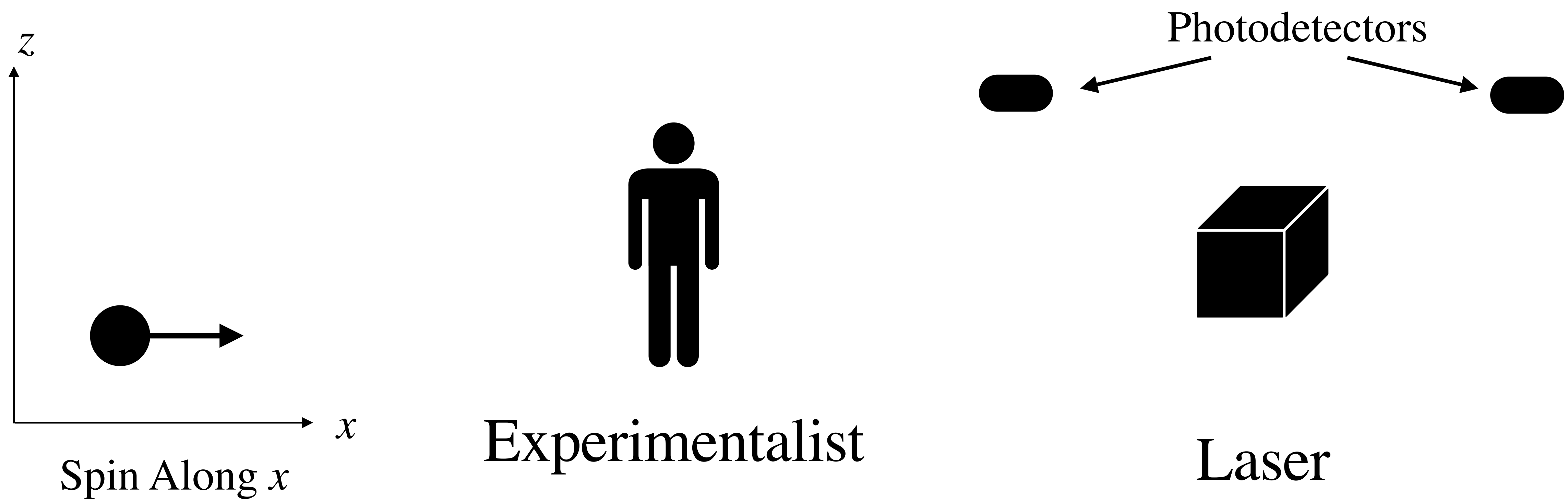
Level Splitting!



Proton wave-function is spread over some region (e.g. some trap size ~ 100 nm),
Expectation value of electromagnetic field diluted
In neutral atom - heavily suppressed, except at edges!

$$\epsilon_\gamma < 10^{-2}$$

Linear Quantum Mechanics



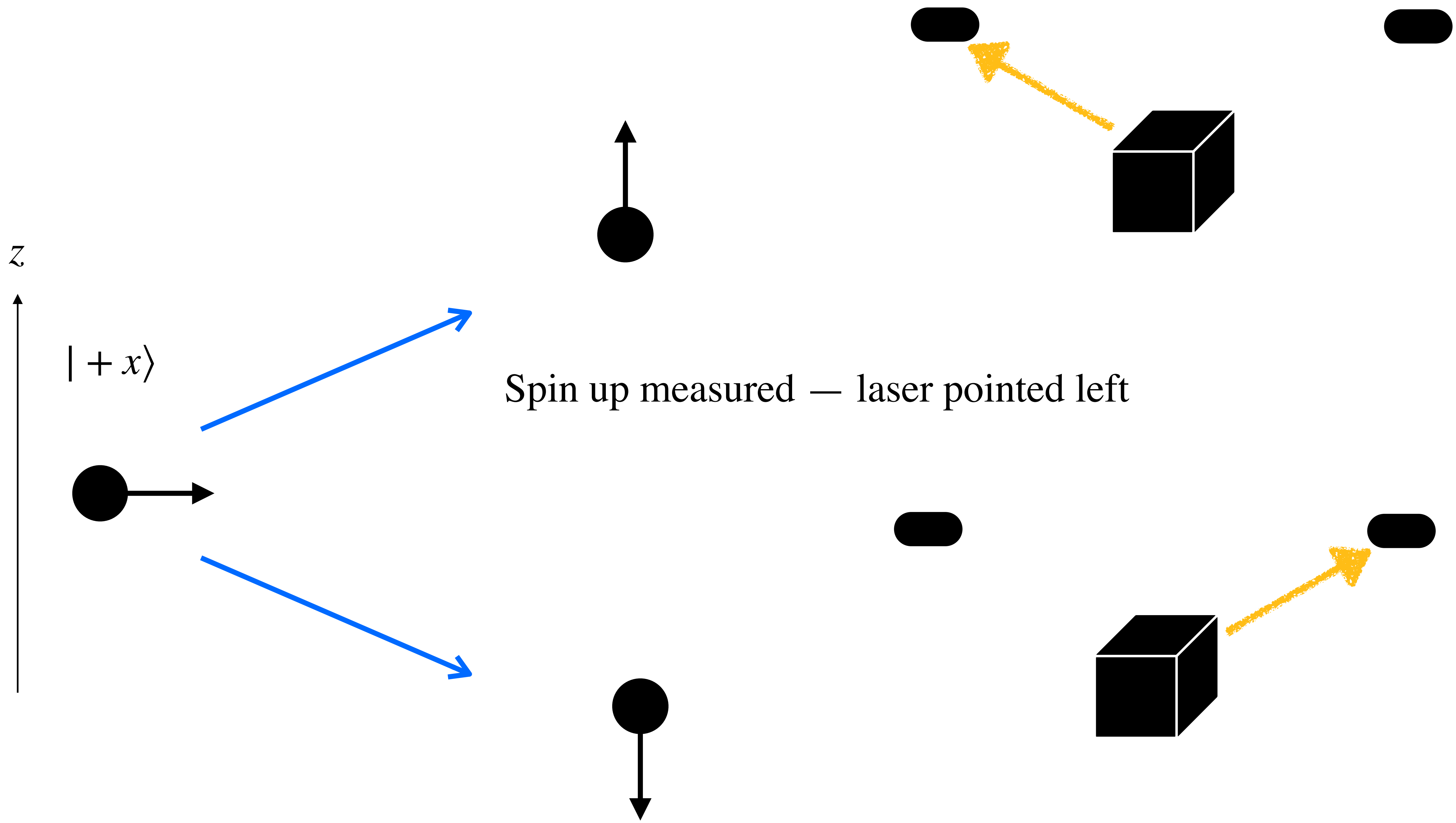
Initial State : $|\chi(0)\rangle$

Represents Full Quantum State (spin, experimentalist…)

Goal: Create Macroscopic Superposition

Method: Measure spin along z.
Depending upon outcome, send laser along different directions

Linear Quantum Mechanics

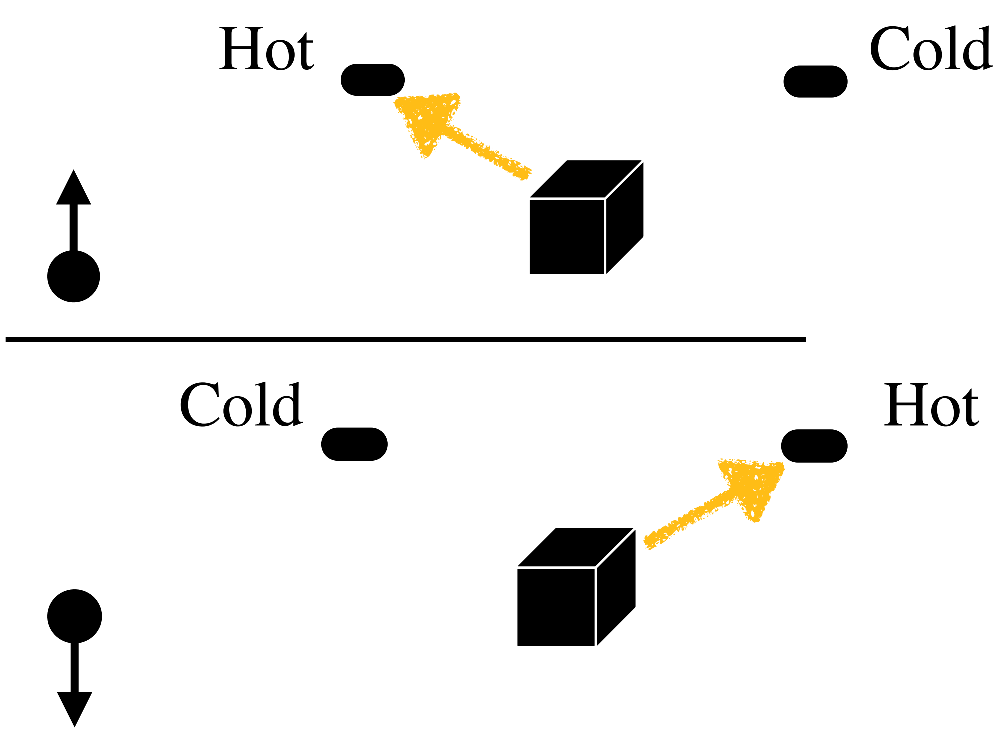


$$|\chi(t)\rangle = \frac{1}{\sqrt{2}}\left(|+z\rangle|L\rangle|Env_L\rangle + |-z\rangle|R\rangle|Env_R\rangle\right)$$

Linear Quantum Mechanics

Which photodetectors light up?

$$\mathscr{H} \supset eA_\mu J^\mu$$



Transition Matrix Elements

$$\langle +z | \langle L | \langle Env_L | A_\mu(x_L)\, J^\mu(x_L) | +z \rangle | L \rangle | Env_L \rangle \neq 0$$

$$\langle +z | \langle L | \langle Env_L | A_\mu(x_R)\, J^\mu(x_R) | +z \rangle | L \rangle | Env_L \rangle = 0$$

$$\langle L | A_\mu(x_R) | L \rangle = 0$$

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

Strange Kaplan

in the

MULTIVERSE OF MADNESS

Non-linearity visible despite Environmental De-coherence!
Polchinski: “Everett Phone”

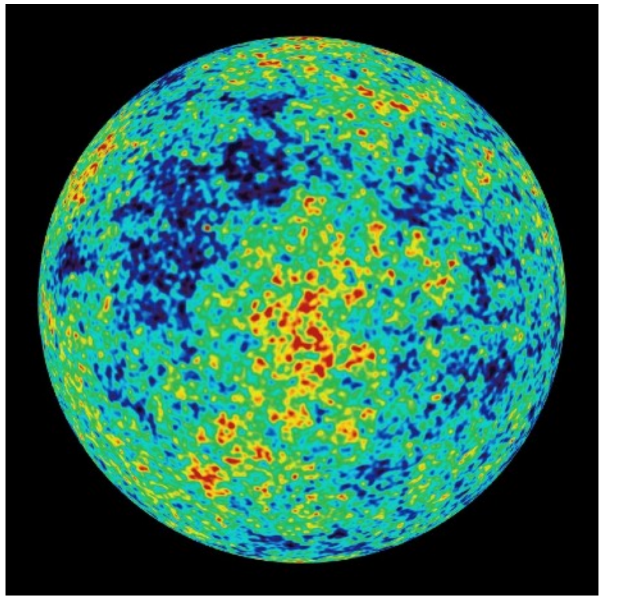
Non-Linearity and Cosmology

If $\quad |\chi\rangle = \alpha\,|\,\mathrm{Us}\rangle + \beta\,|\,\mathrm{Multiverse}\rangle$

For $\alpha \ll \beta$, the wave function is dominated by a different (combination of) metric(s).

For tiny α, entirely dominated by |Multiverse>

Standard Inflation: Quantum fluctuations!



Linear quantum mechanics is an attractor solution of inflation!!

Inflationary Metric Interference

$$g_{\mu\nu} \rightarrow \frac{g_{\mu\nu} + \epsilon_G \langle g_{\mu\nu} \rangle}{1+\epsilon}$$

Inflation: Expectation value is the average homogeneous FRW metric

Naive description:

$$g_s = -\left(1 - \frac{r_s}{r}\right) dt^2 + \frac{dr^2}{\left(1-\frac{r_s}{r}\right)} + r^2 d\Omega^2 \qquad \langle g \rangle = -dt^2 + dr^2 + r^2 d\Omega^2$$

Renormalize and Expand

$$g_{\text{eff}} \simeq \left[-(1 - \frac{R_s}{r})dt^2 + \left(1 + \frac{R_s}{r} + \left(\frac{R_s}{r}\right)^2 (1+\epsilon_G)\right) dr^2\right] + r^2 d\Omega^2$$

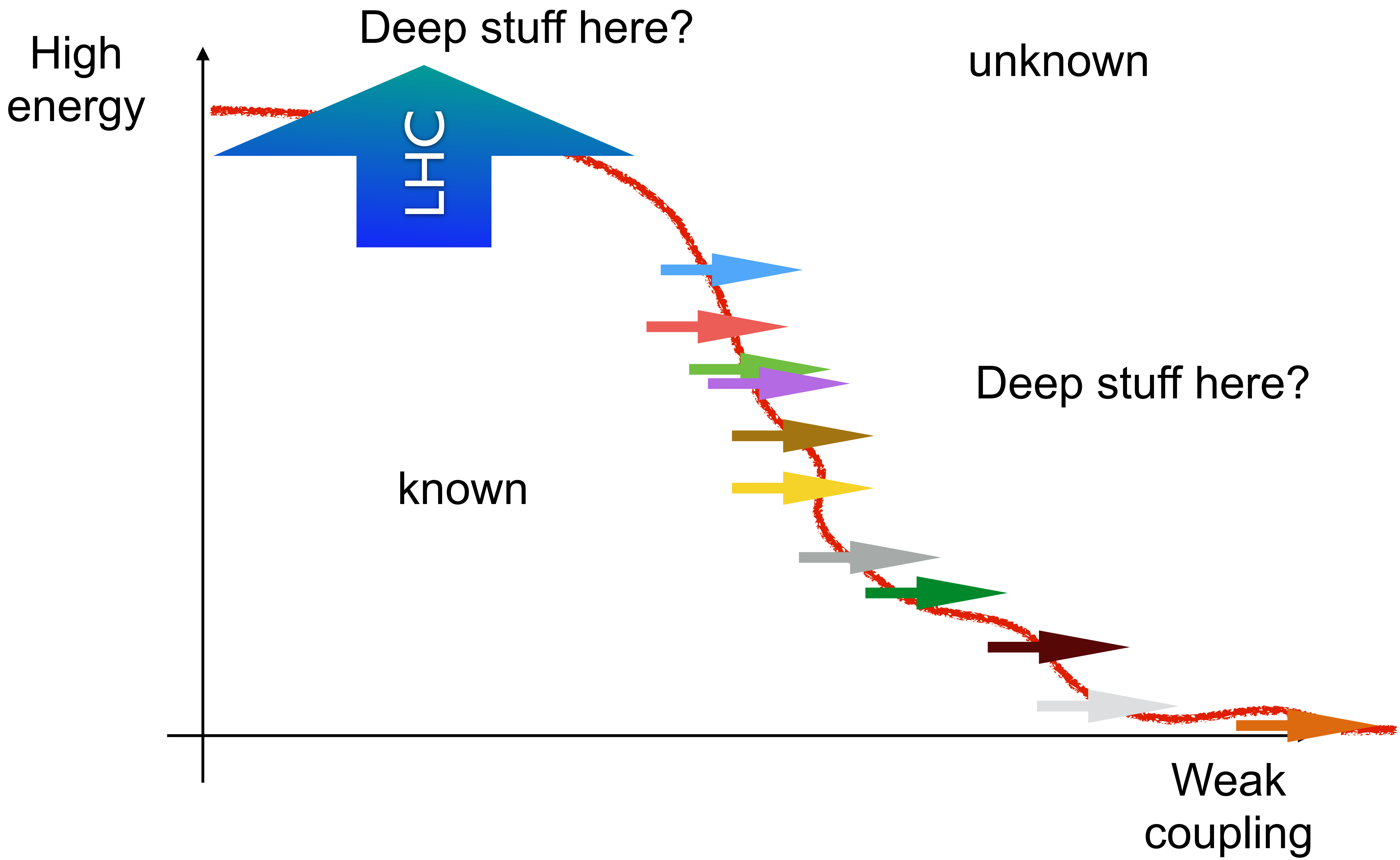
Looks like a long-distance modification of gravity!

$g_{tt} \rightarrow 0$ and $g_{rr} \rightarrow \infty$ at different values of r. *Vacuum fields blow up? Firewall?*

Modifications of cosmological evolution? Dark Energy? Dark Matter? Hubble Tension?

Perspective

Search for New Physics



Big problems are hard but worth it

They sometimes need **years** of thinking
to make real progress

Don’t give up - you can contribute
Don’t believe the experts, follow the science

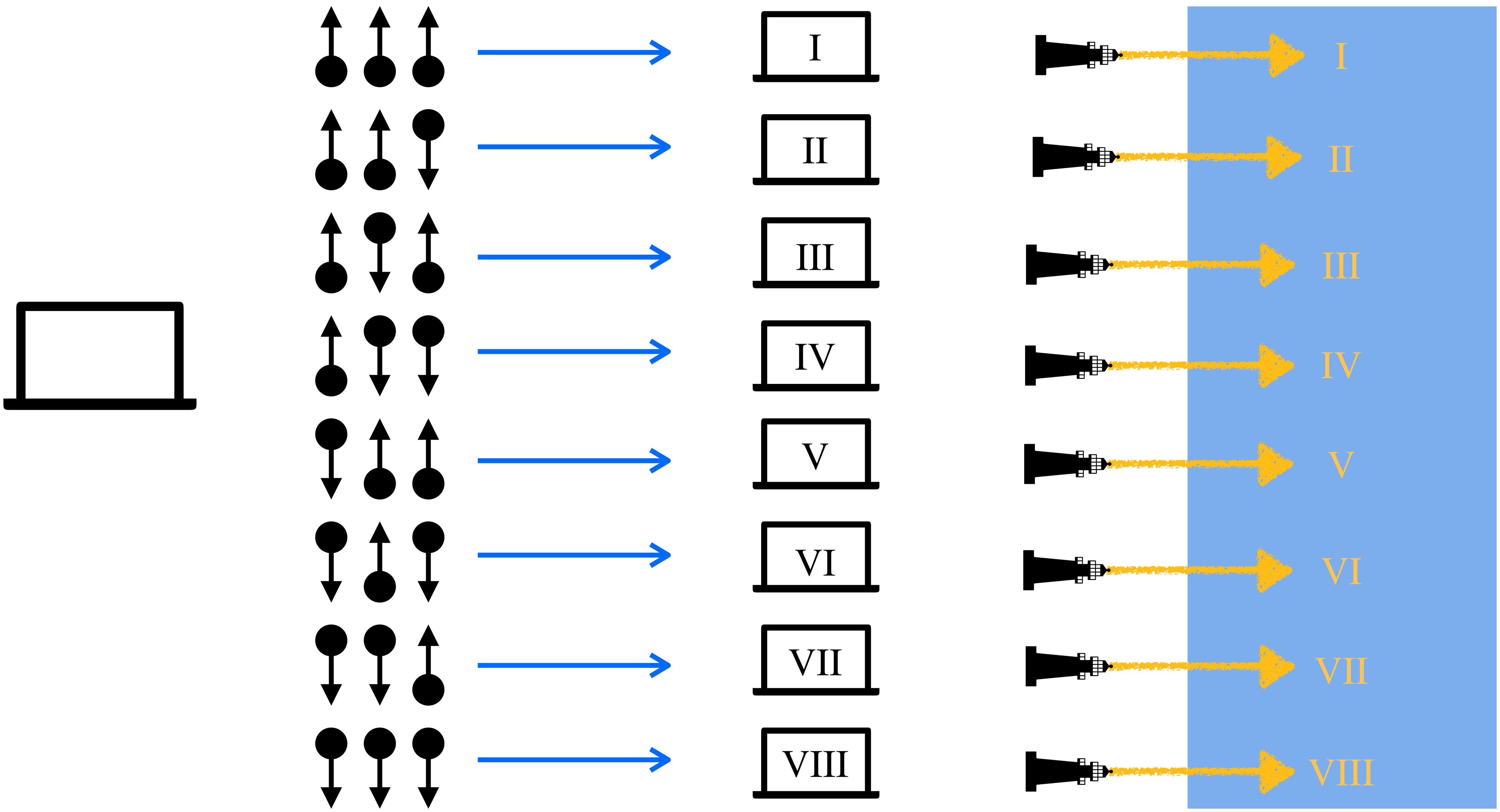
Thank You!

Extras

But if we have a Classical Universe

Macroscopic superpositions can be produced at will.

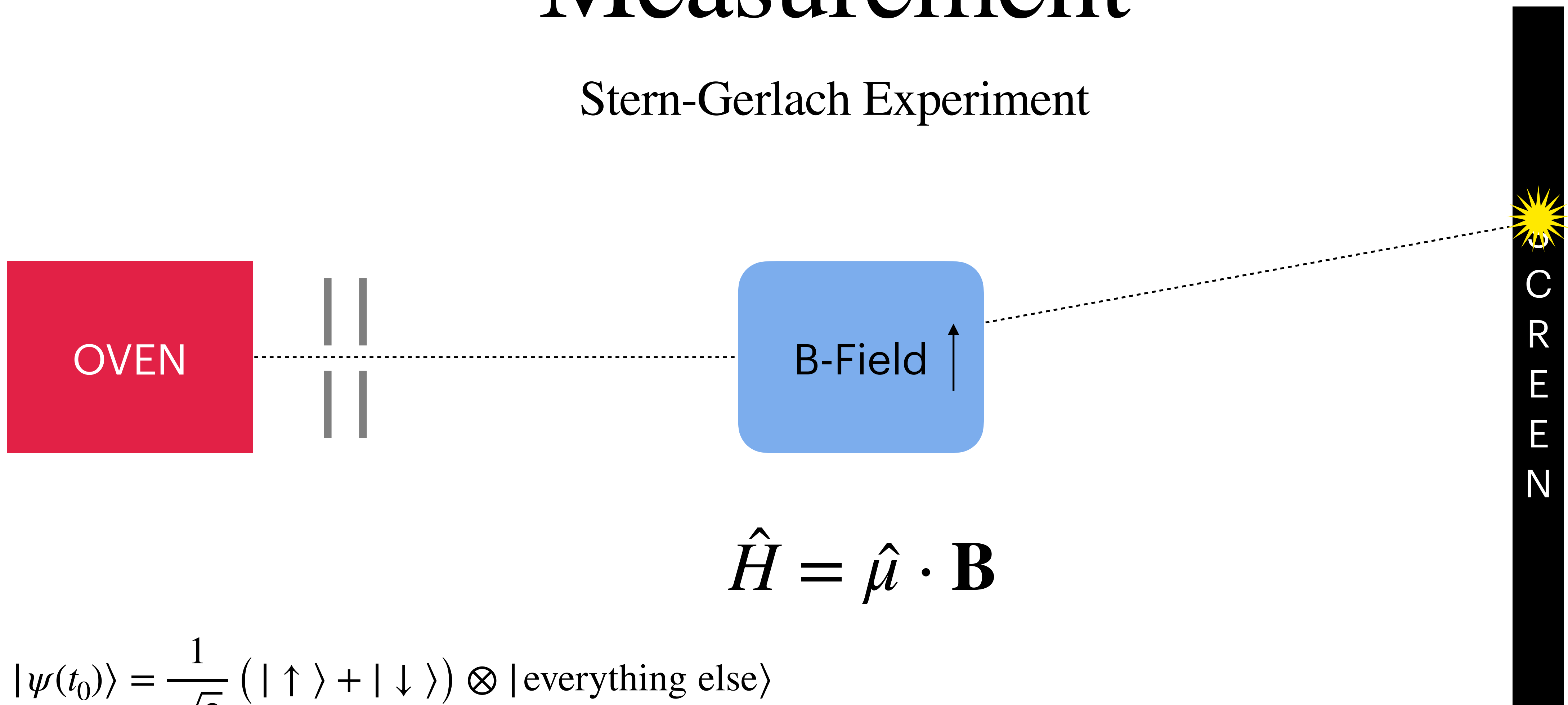
Parallelize any computation:



Quantum Computing!

Measurement

Stern-Gerlach Experiment



$$\hat{H} = \hat{\mu} \cdot \mathbf{B}$$

$$|\psi(t_0)\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\rangle + |\downarrow\rangle\right) \otimes |\text{everything else}\rangle$$

$$|\psi(t_f)\rangle = \left(|\uparrow\rangle\right) \otimes |\text{everything else}\rangle$$