The Many Frontiers of Particle Physics

LFC21

Strong Interactions from QCD to New Strong Dynamics
at the LHC and Future Colliders

David E Kaplan

The Standard Model and the Unknown

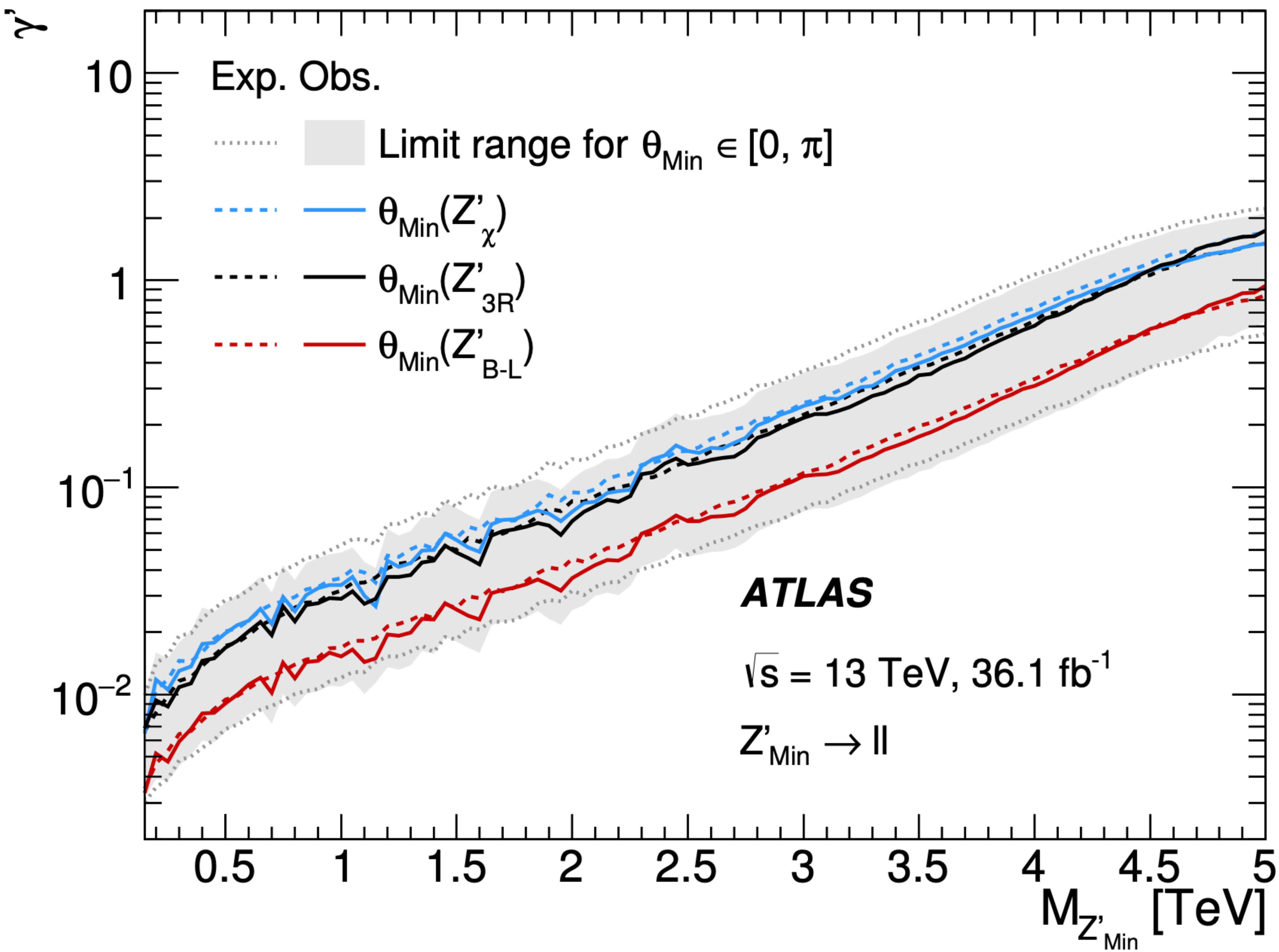
- At Higher Energy:
  1. New Heavy States (Particles or schmutz)
  2. Suppressed Operators $\frac{1}{M}\bar{\psi}\sigma_{\mu\nu}\psi F^{\mu\nu}$
- Weak Couplings:
  1. New Light States
  2. New Long-Range Forces
- Violations of Principles
  1. Lorentz Invariance — watch out for GR
  2. General Relativity — new fields?
  3. Quantum Mechanics — watch out for everything!

B-L Gauge Bosons

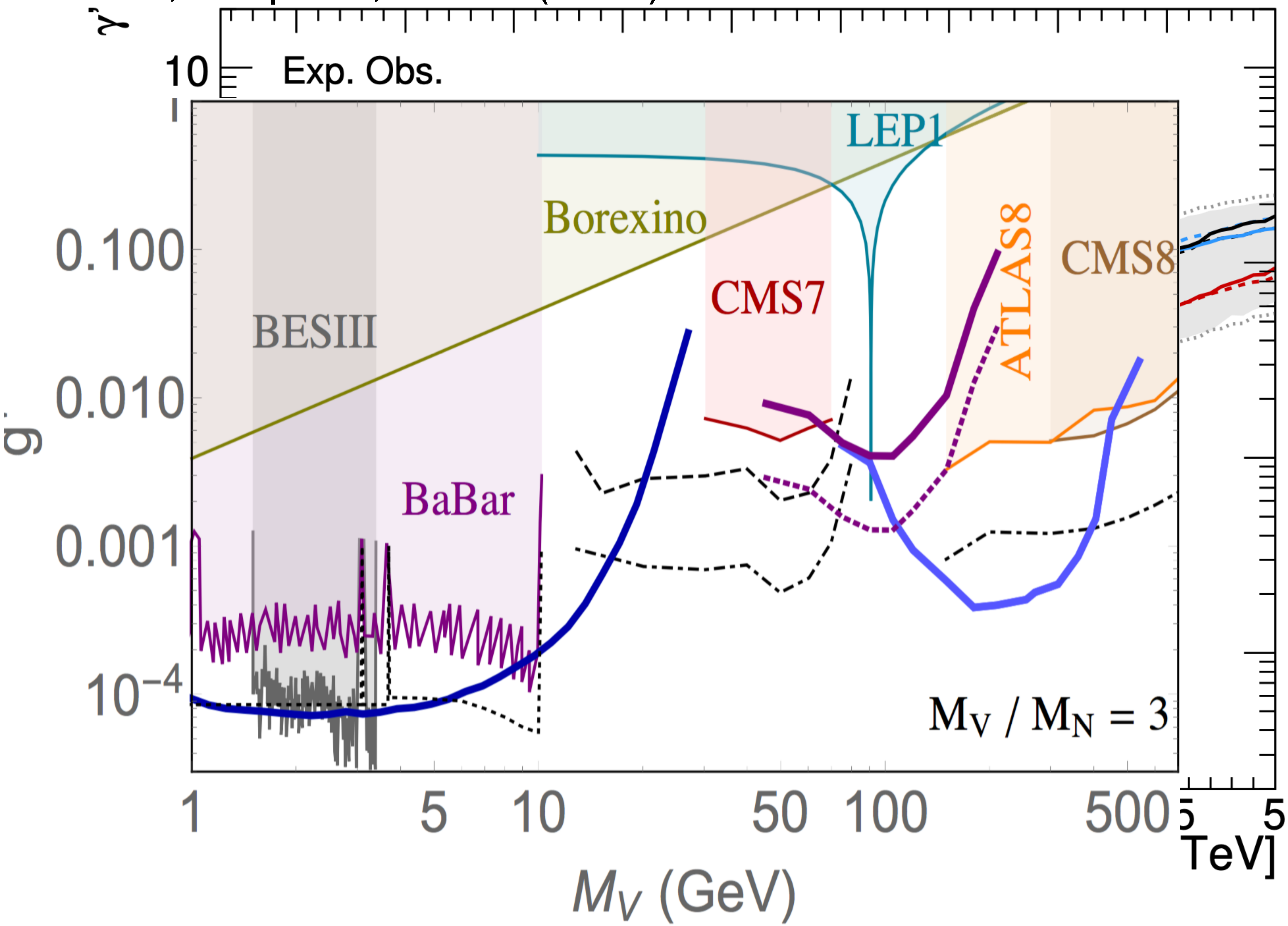
B-L: Natural New Force

- Preserved in the SM
- Anomaly cancellation suggests RH neutrinos
- Emerges from Left-Right models
- May be involved with Lepto-genesis, Supersymmetry-breaking, neutrino matter effects, …

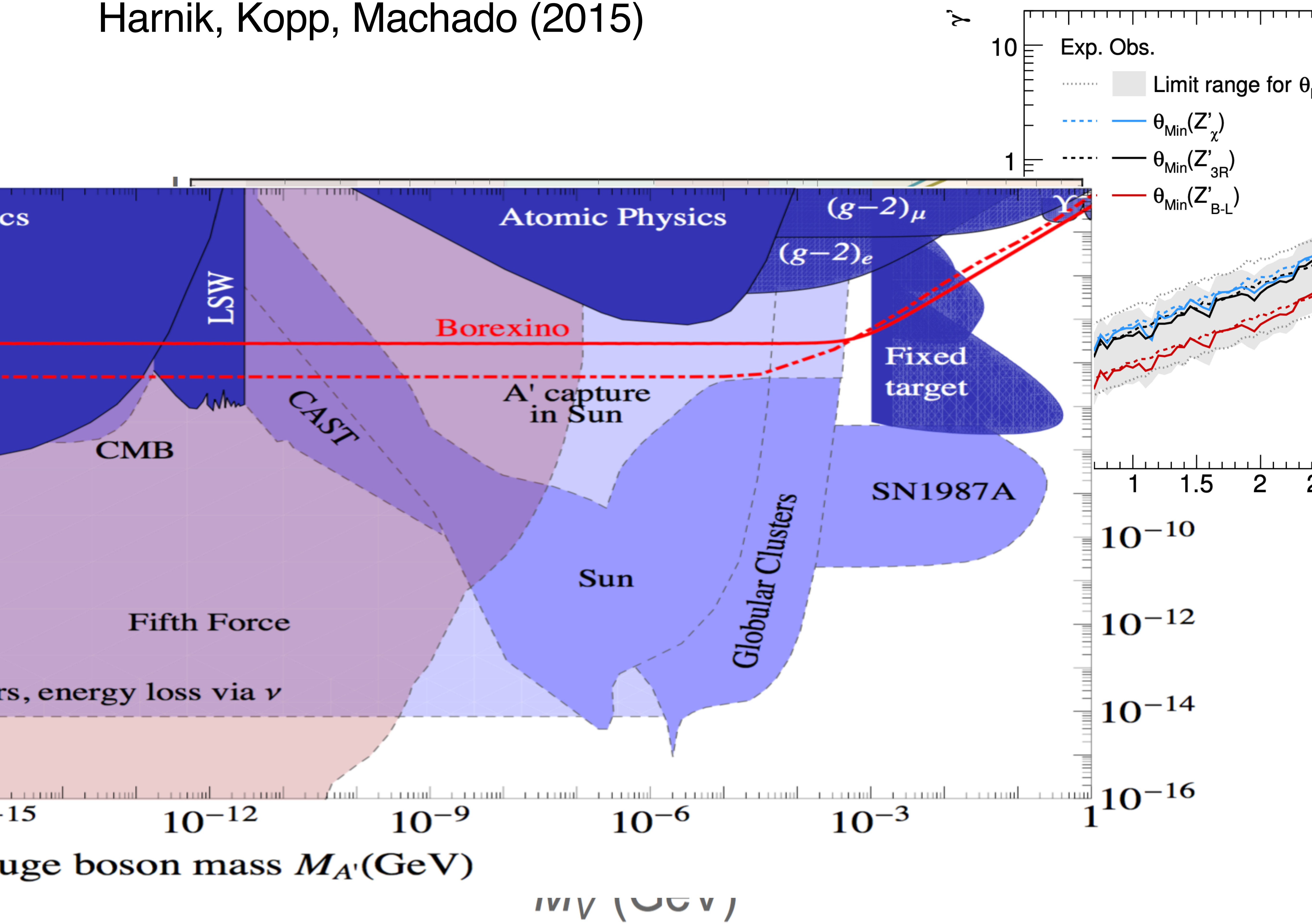
ATLAS, arXiv:1707.02424



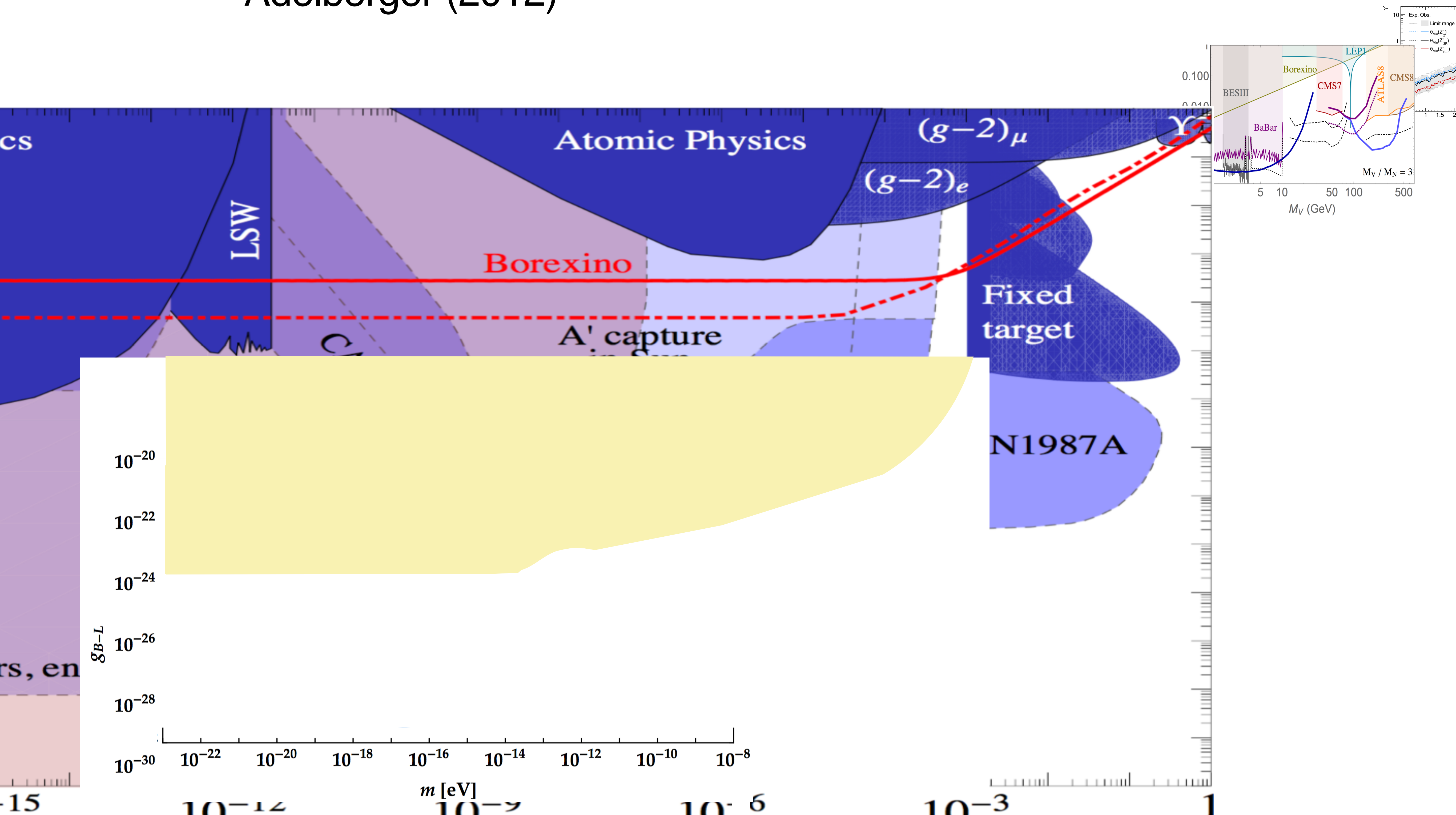
Batel, Pospelov, Shuve (2016)



Harnik, Kopp, Machado (2015)



Wagner, Schlamminger, Gundlach, Adelberger (2012)



But what are the ‘deep’ reasons to look for new physics?

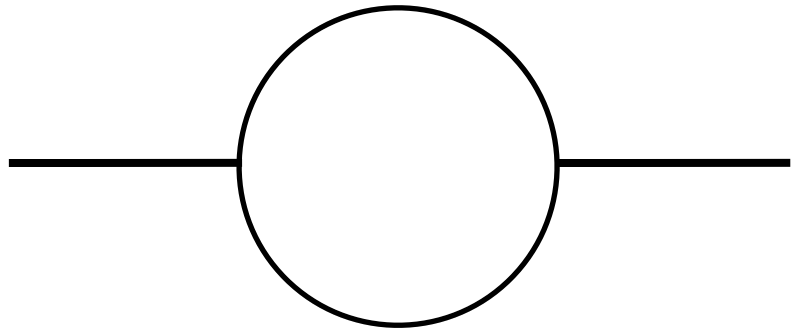
The Higgs

Deep Point

The Hierarchy Problem

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

$$m^2_{h_{\rm phys}} = m_0^2 + \delta m_h^2$$



This term gets contributions all the way to the Planck scale

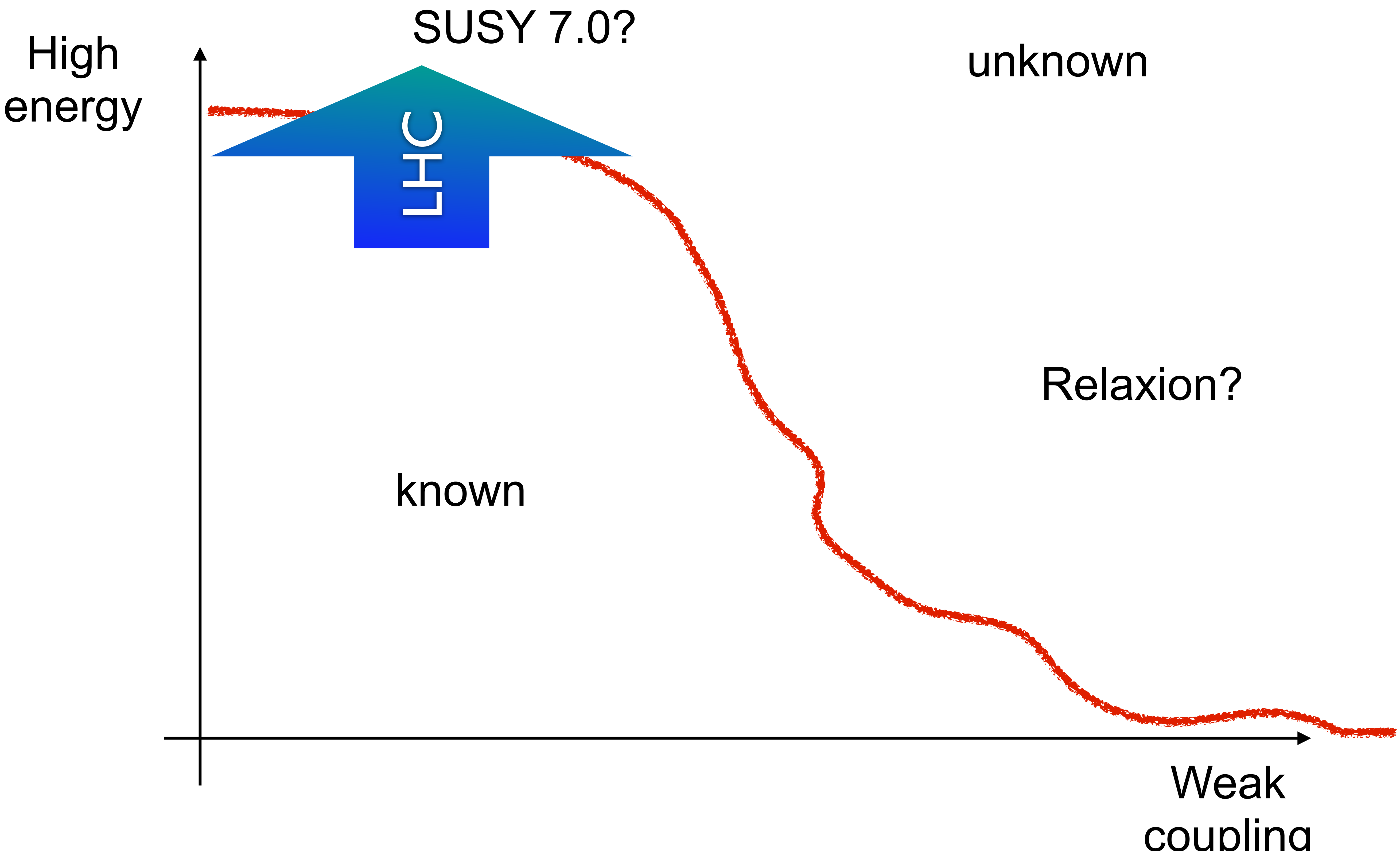
The Hierarchy Problem

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)

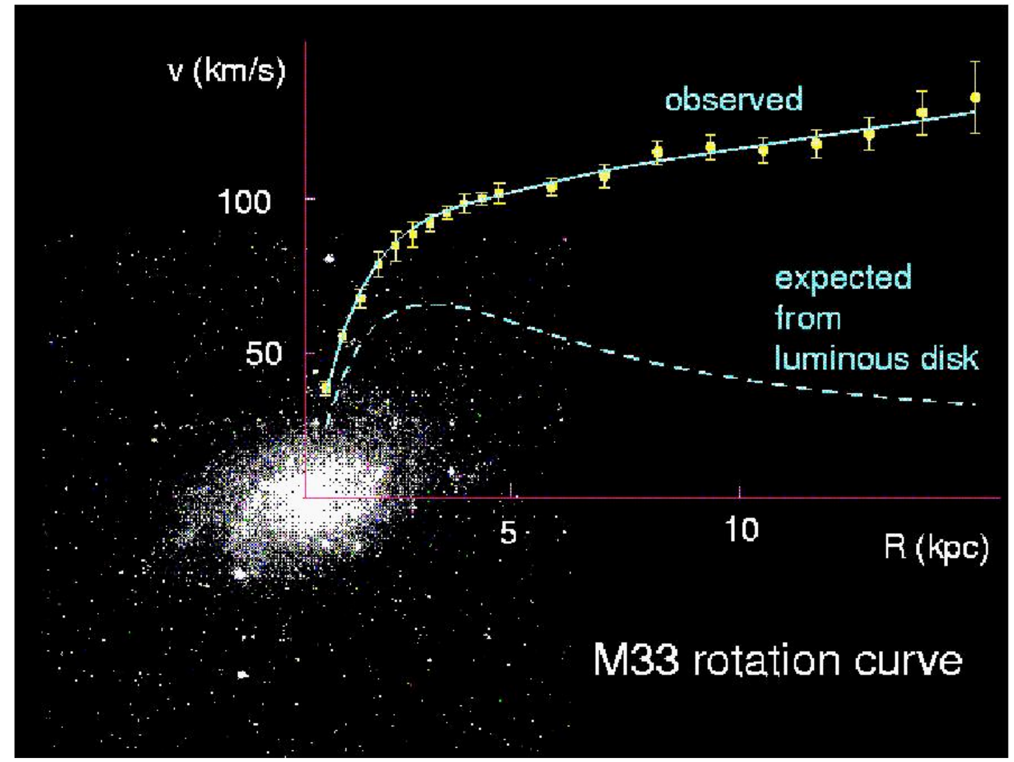
Search for the Physics

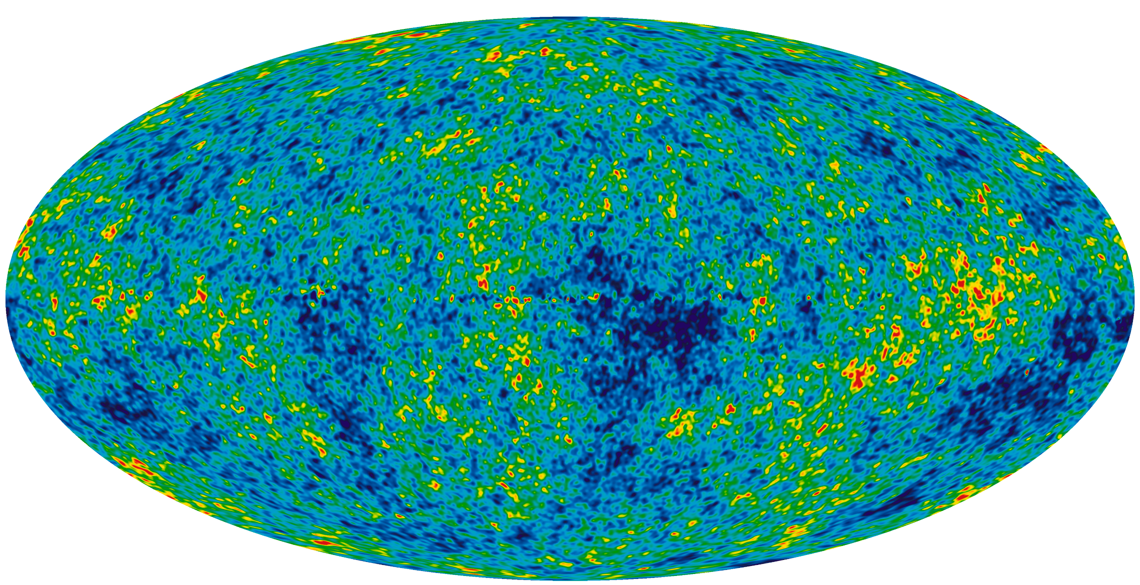


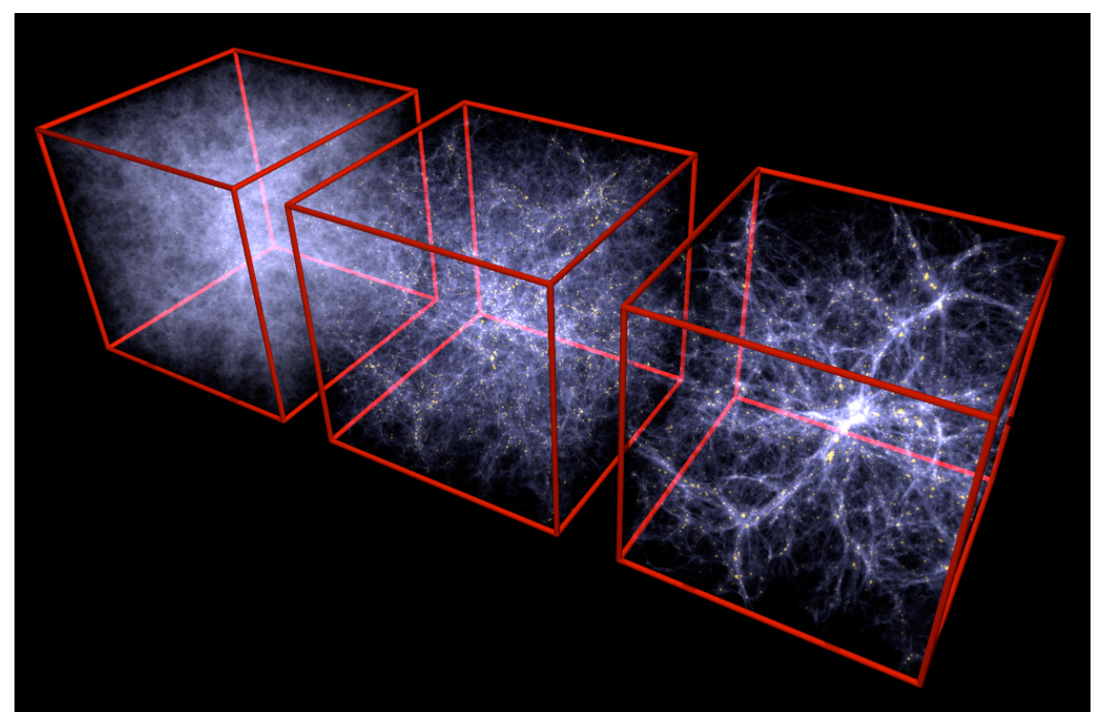
Dark Matter

Deep Point

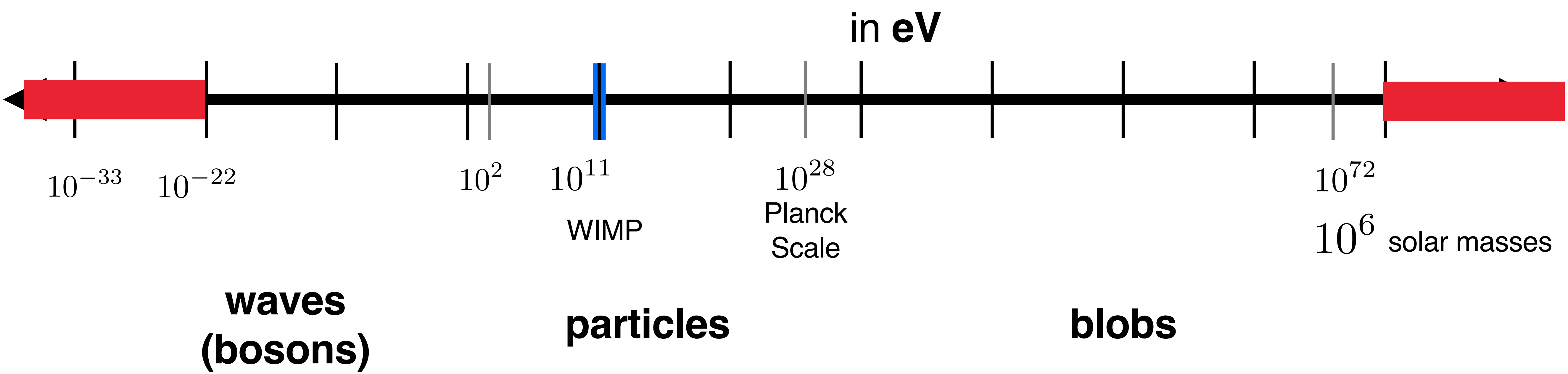
Dark matter exists!







The Mass of Dark Matter Bits



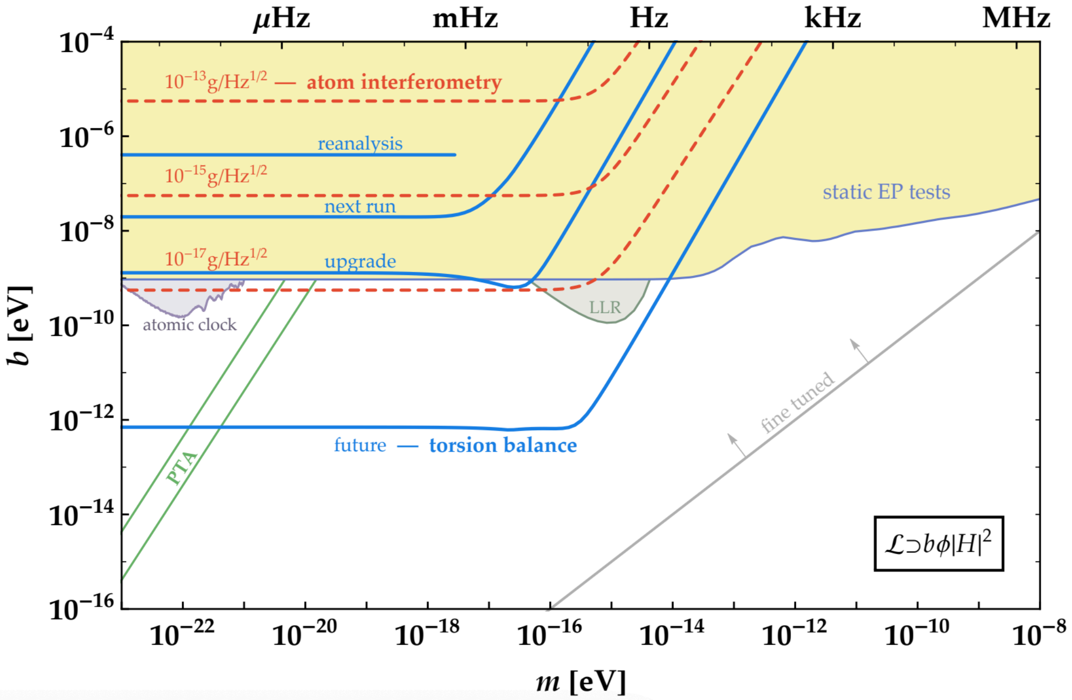
WIMP Miracle!?!?!?!?!?

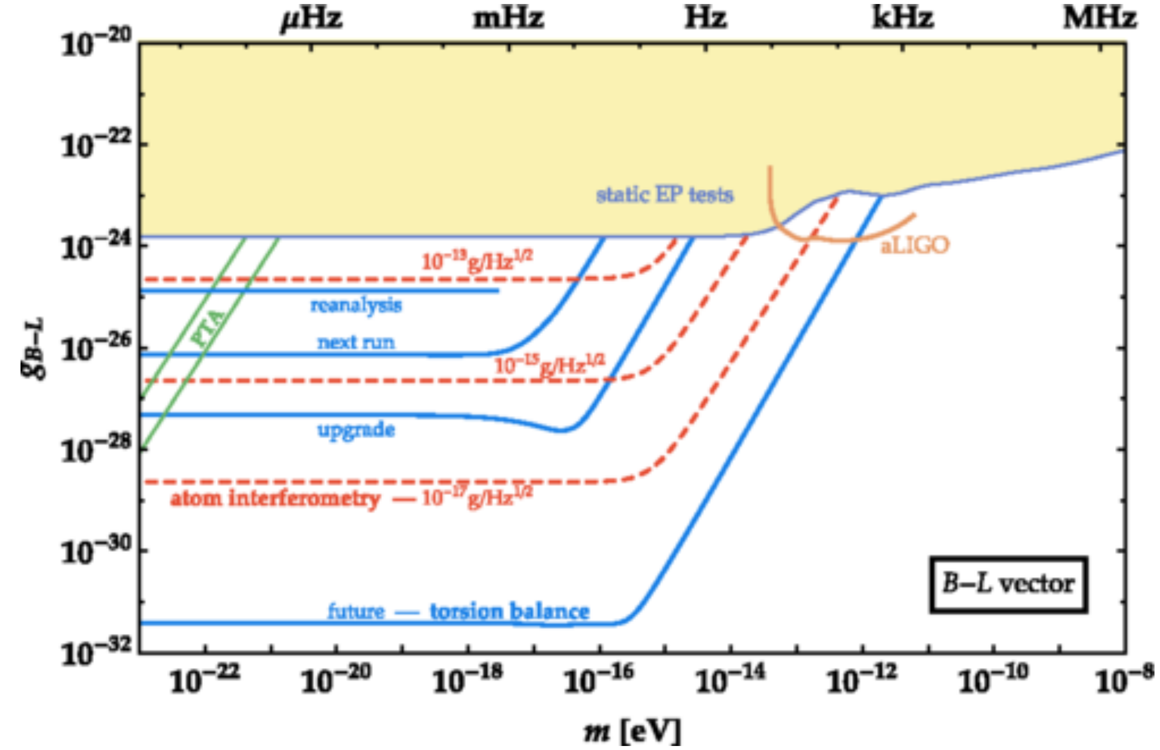
Freeze in, freeze in with mediator, vacuum misalignment, inflationary fluctuations, freeze in, out-of-equilibrium decays, dark nucleo-synthesis, black hole evaporation…

(model building is fine, but how do we search?)

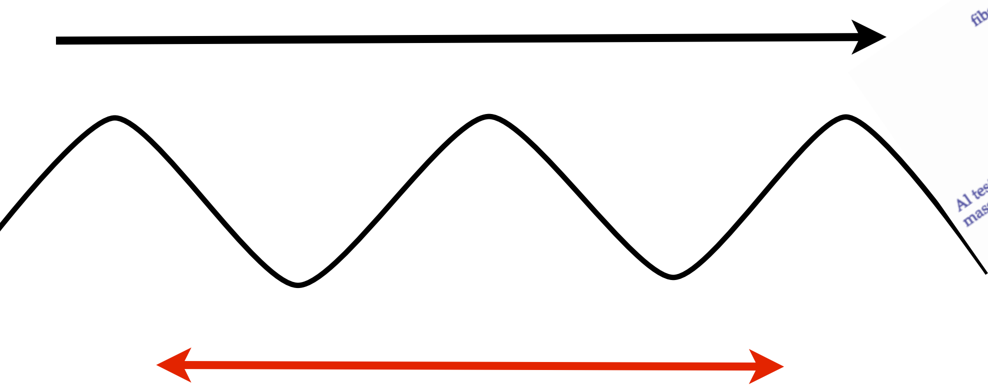
e.g., Light Bosons: Physical Effects

Spin	Type	Operator	Interaction	Oscillating DM Effects	Searches
0	Scalar	$\varphi h^\dagger h, \varphi \mathcal{O}_{SM}$	Higgs portal/dilaton	Electron mass, etc.	Atomic clocks, etc
				Acceleration	MAGIS, Eot-Wash, PTA
	Pseudo-scalar	$aG_{\mu\nu}\tilde{G}^{\mu\nu}$	Axion-QCD	Nucleon EDM	CASPEr, etc
		$aF_{\mu\nu}\tilde{F}^{\mu\nu}$	Axion-E&M	EMF along B field	ADMX, Abracadabra, etc
		$(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$	Axion-fermion	Spin torque	CASPEr, etc
1	Vector	$A'_\mu\bar{\psi}\gamma^\mu\psi$	Minimally coupled	Acceleration	MAGIS, Eot-Wash, PTA, LIGO
		$F_{\mu\nu}F'^{\mu\nu}$	Vector–photon mixing	EMF in vacuum	DM Radio, ADMX, etc
		$\bar{\psi}\sigma_{\mu\nu}\psi F'^{\mu\nu}$	Dipole operator	Spin torque	CASPEr, etc
	Axial-vector	$A'_\mu\bar{\psi}\gamma^\mu\gamma_5\psi$	Minimally coupled	Spin torque	CASPEr, etc
2	Tensor	$h'_{\mu\nu}T^{\mu\nu}$, etc	Gravity-like	Gravitational wave-like	LIGO, etc



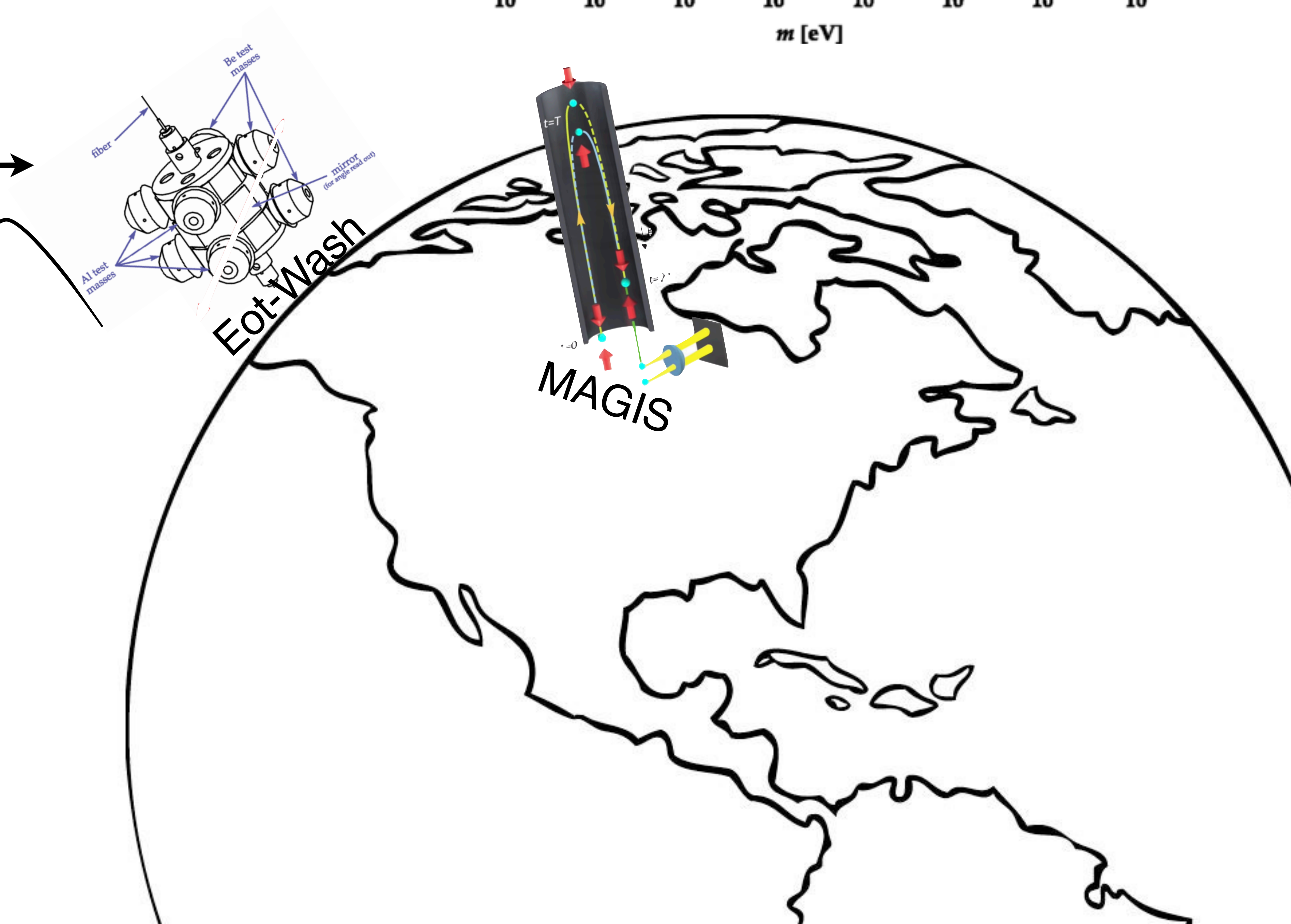


$$v \sim 10^{-3}$$

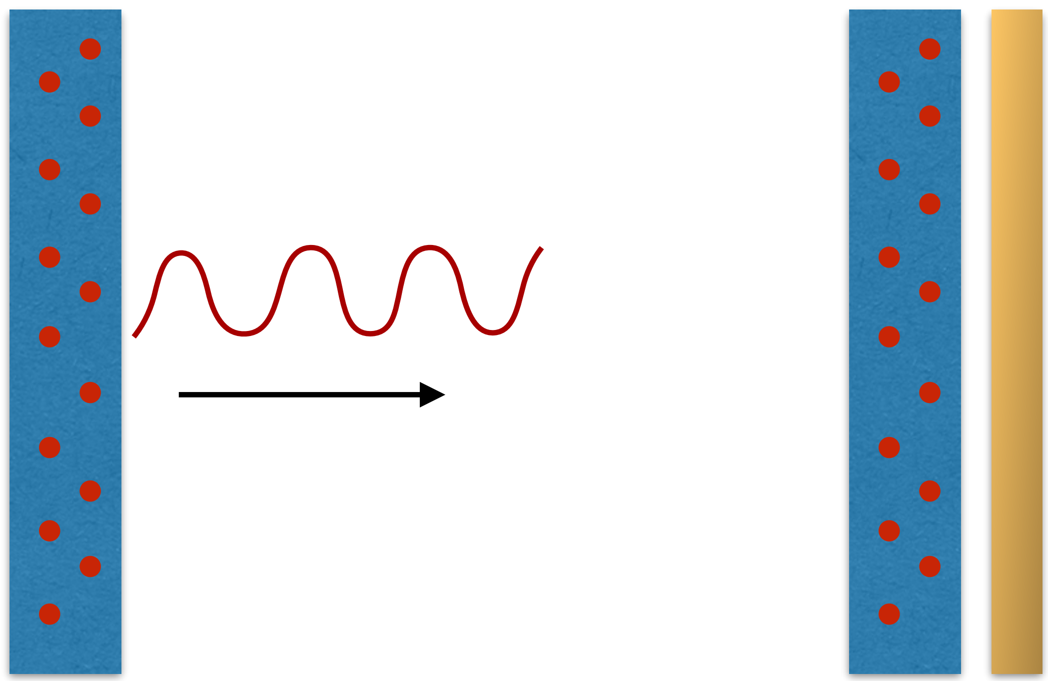


$$\lambda \sim 10^3 c/\omega$$

$$\omega \sim m$$



Light Scalars in the Spectrum: Mossbauer

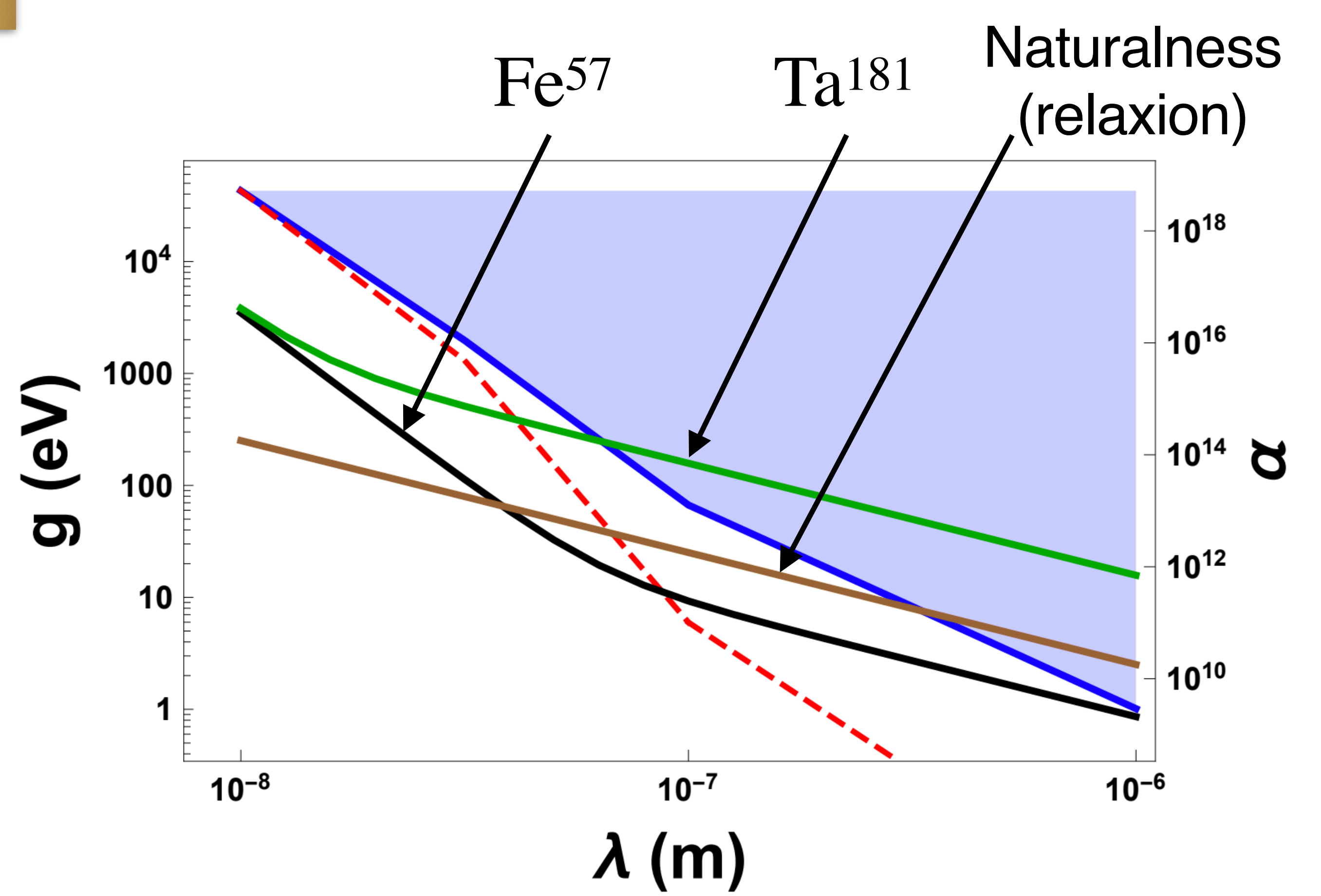


Atoms embedded in material can have nuclear transitions without recoil

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

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

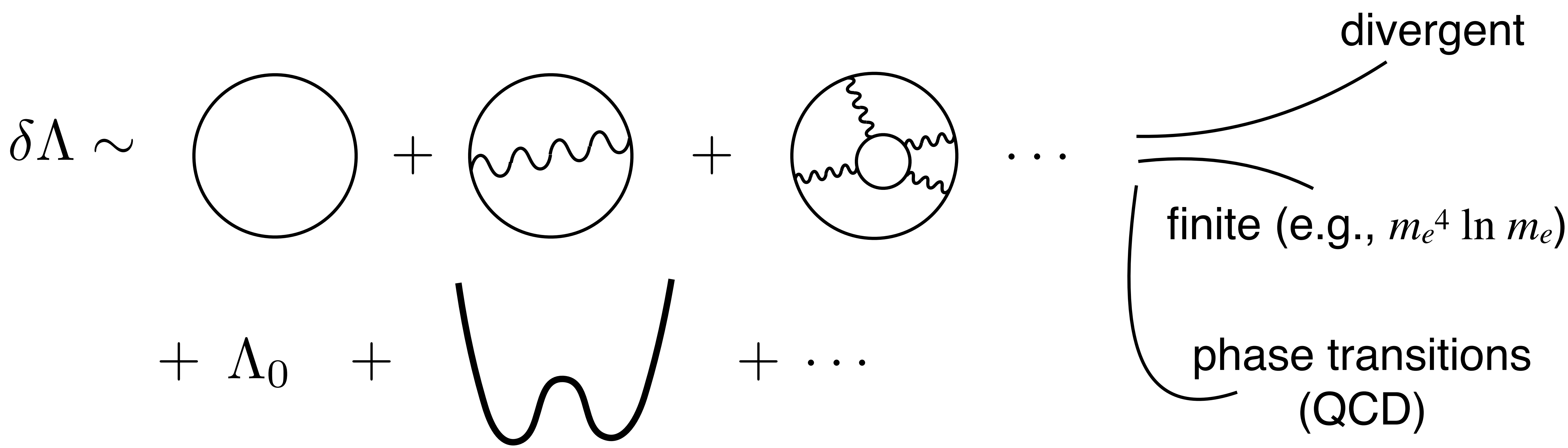
Scalar field (through Higgs portal) changes masses of nucleons and thus nuclear energy levels.



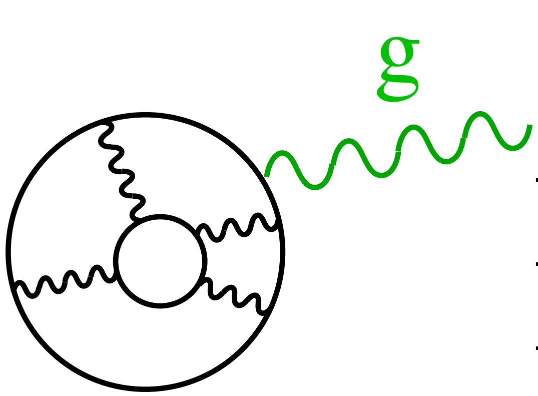
Dark Energy

Deep Point

Insane tuning of the cosmological constant.

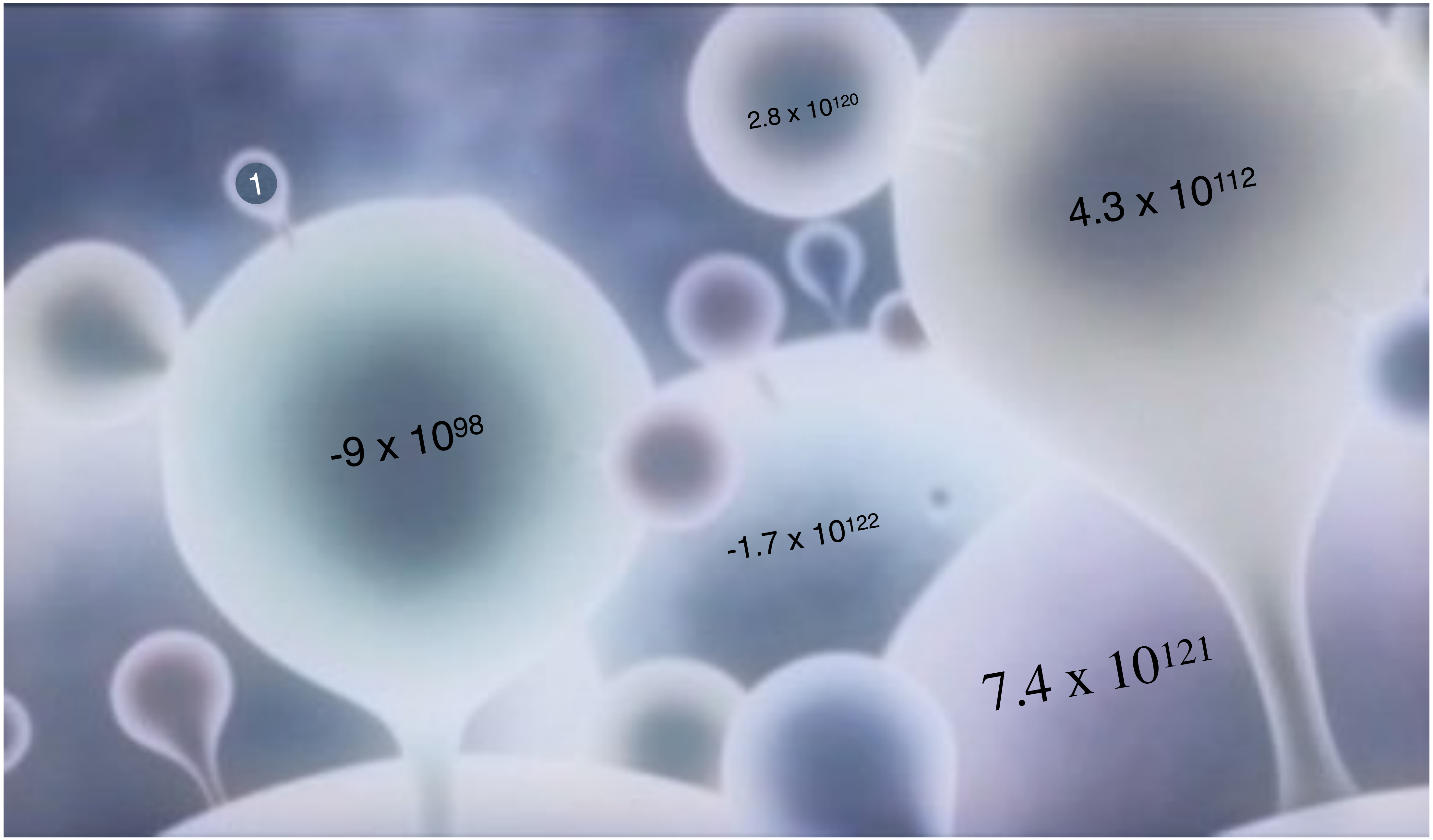


$\text{Naive}: M_{pl}^4 \sim 10^{123} \rho_{D.E.}$



- “Quantum gravity is weird…” (not at low energies)
- “How can you calc. when you are in curved space…” ($R << \Lambda$)
- “UV/IR dude…” (well that’s the problem)

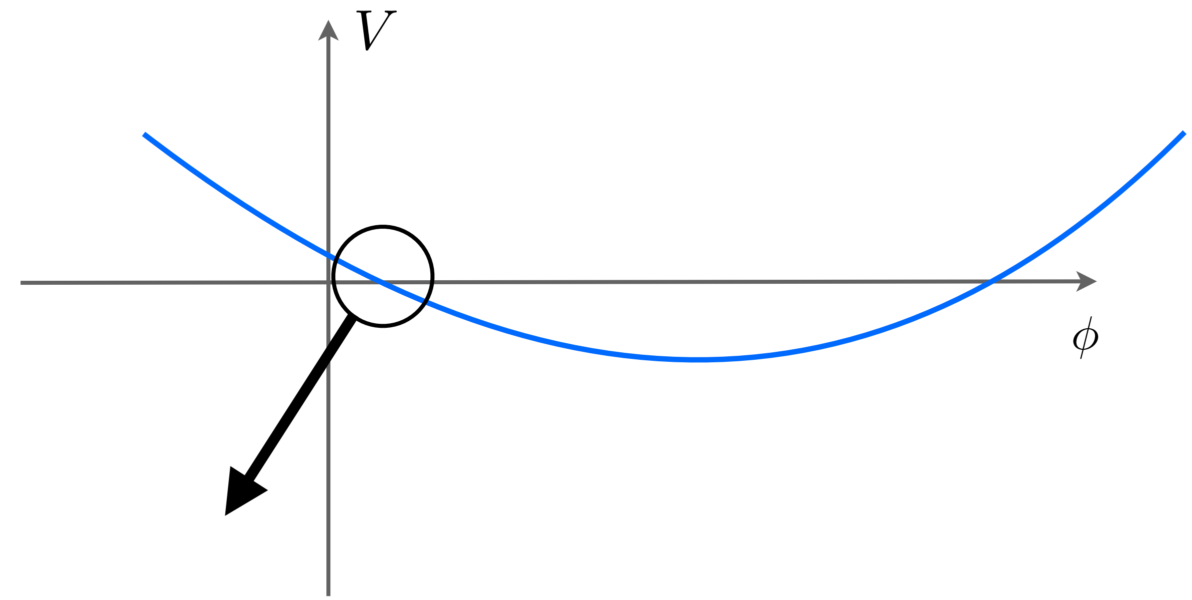
Explanation: It's Anthropic



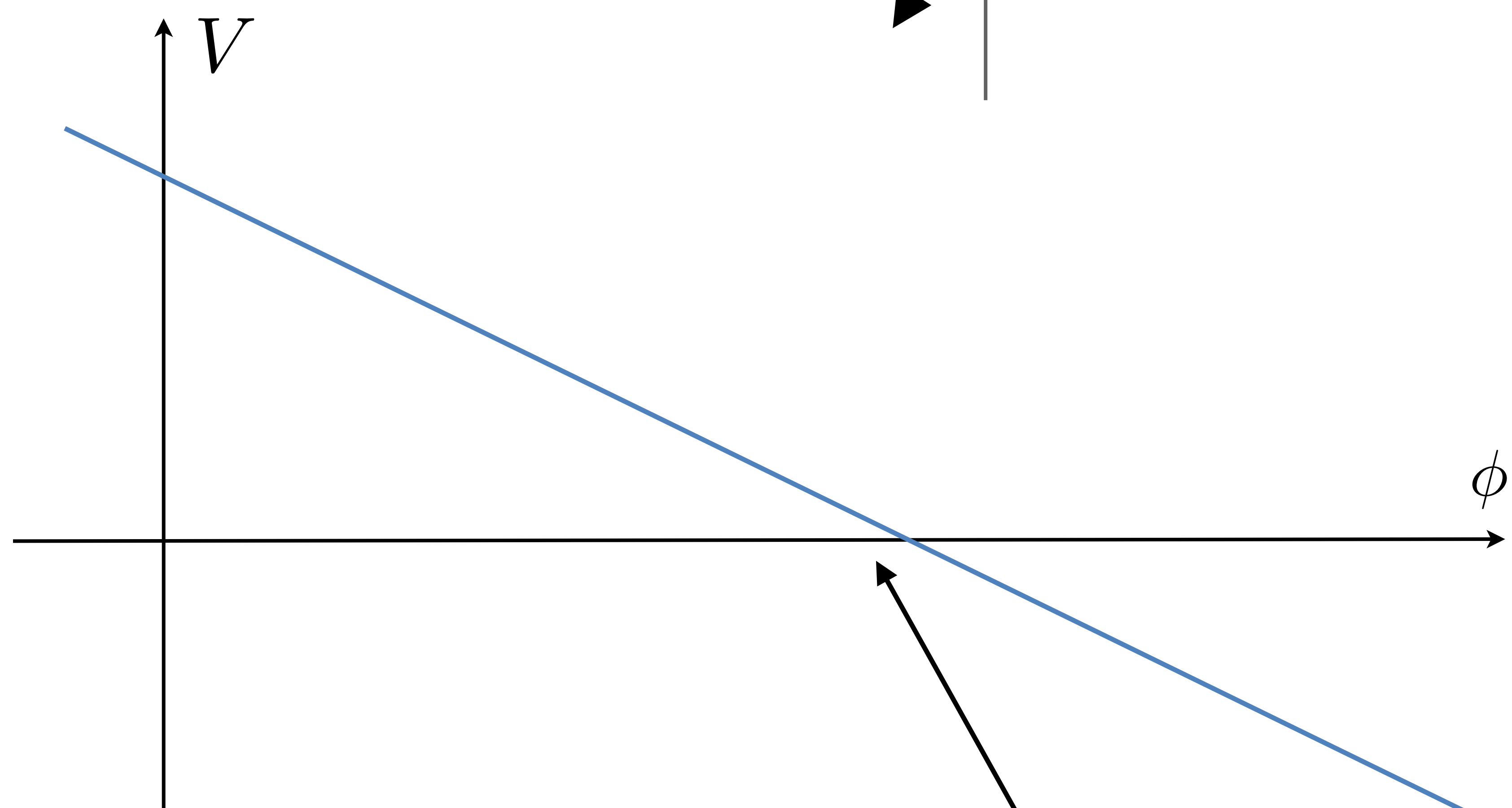
Structure only forms when CC is tiny… (assumes given $\delta\rho/\rho$)

A 'historical' solution

Simpler Explanation: Scan the CC with a light field



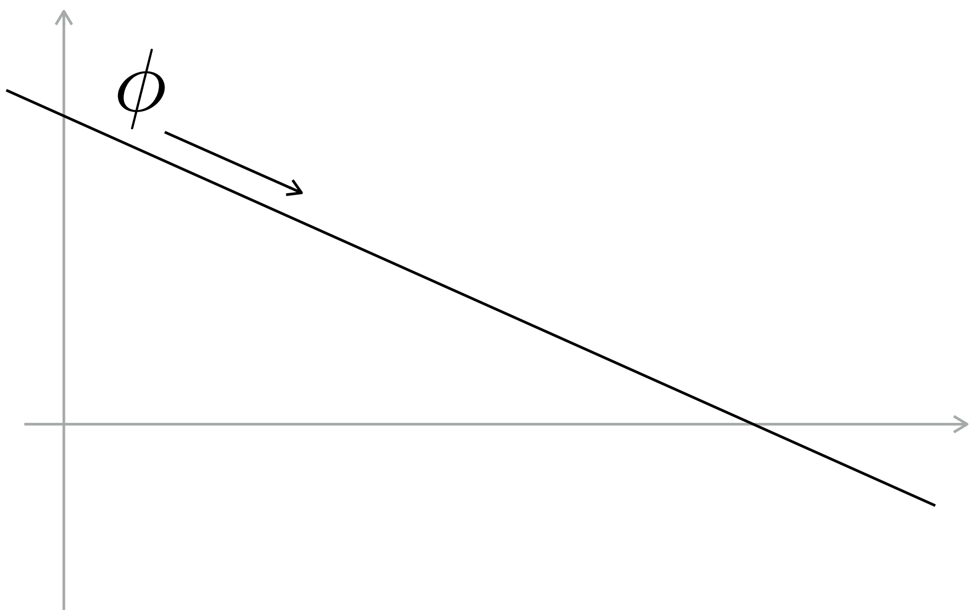
Must scan a large range of values!

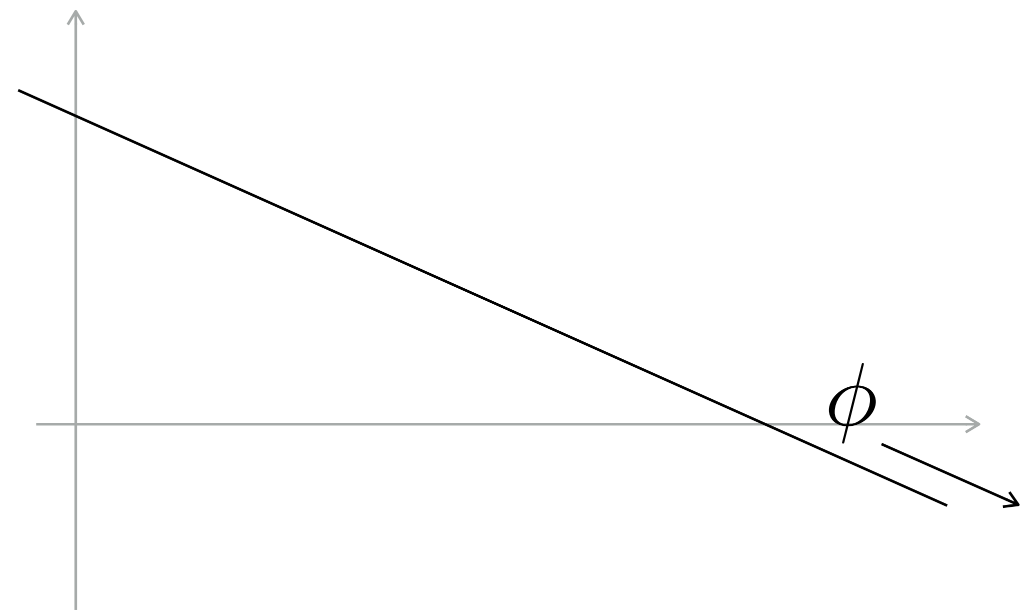


When does this happen?

Why are we here?

Relaxation





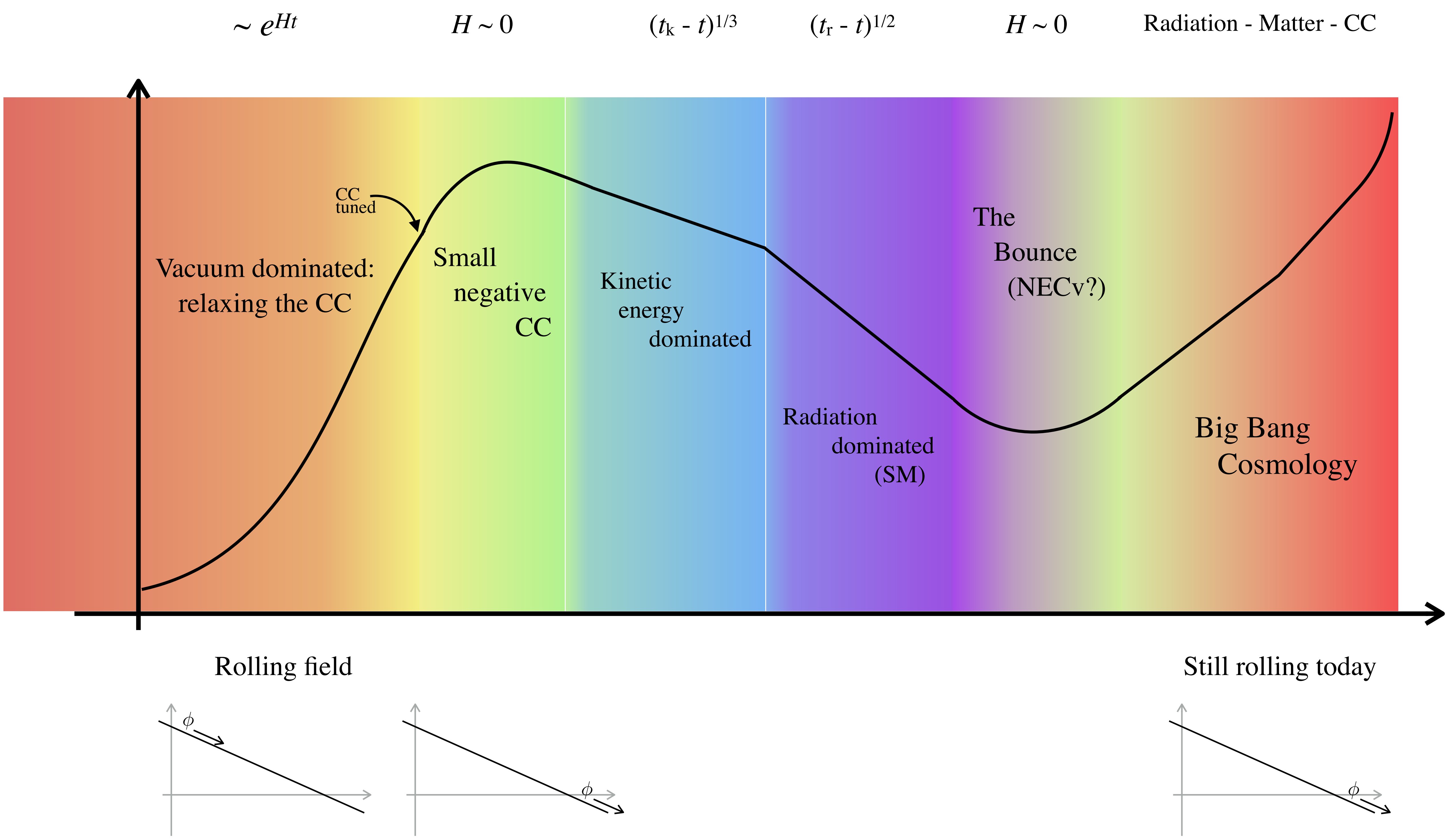
Slowly rolling field (with Hubble or other friction) over bazillions of Hubble times.

Universe massively inflated and mostly empty.

Soon after ϕ crosses zero vacuum energy, universe contracts

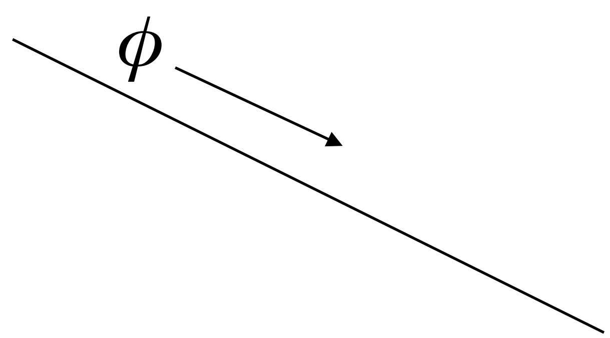
Make it expand and we are golden!

CC Relaxation and Universe History

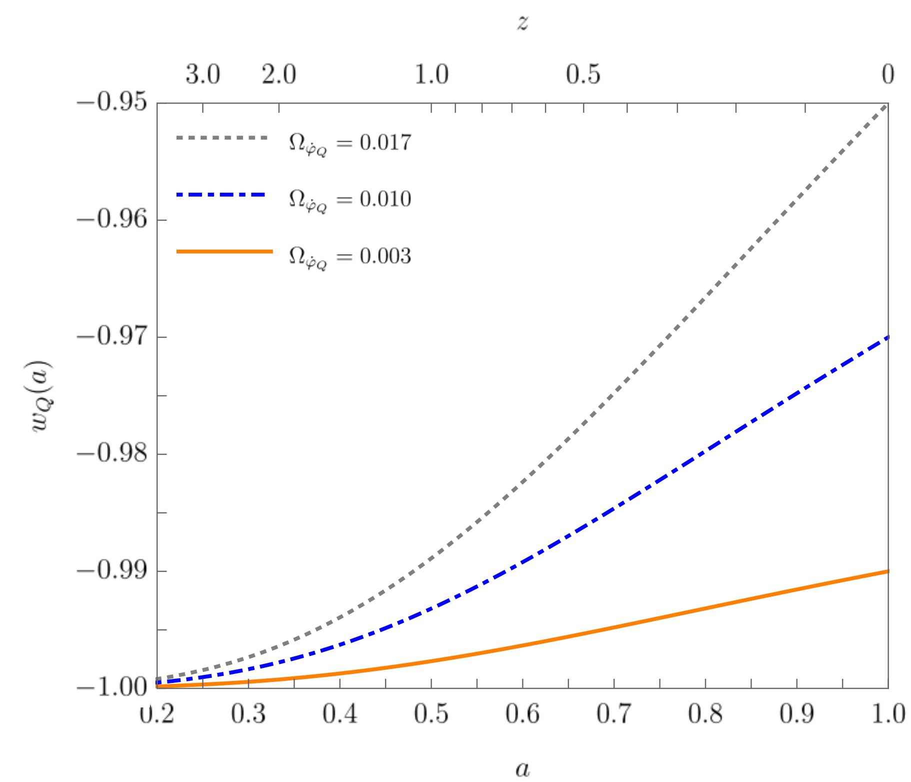


Rolling ϕ Today

Simple rolling scalar: Quintessence



$$w = \frac{\frac{\dot{\phi}^2}{2} - V}{\frac{\dot{\phi}^2}{2} + V}$$



$$m \lessapprox H = 10^{-43}\ \text{GeV}$$

Ultra-light field. Demand technical naturalness
=> axion-like, derivative interactions

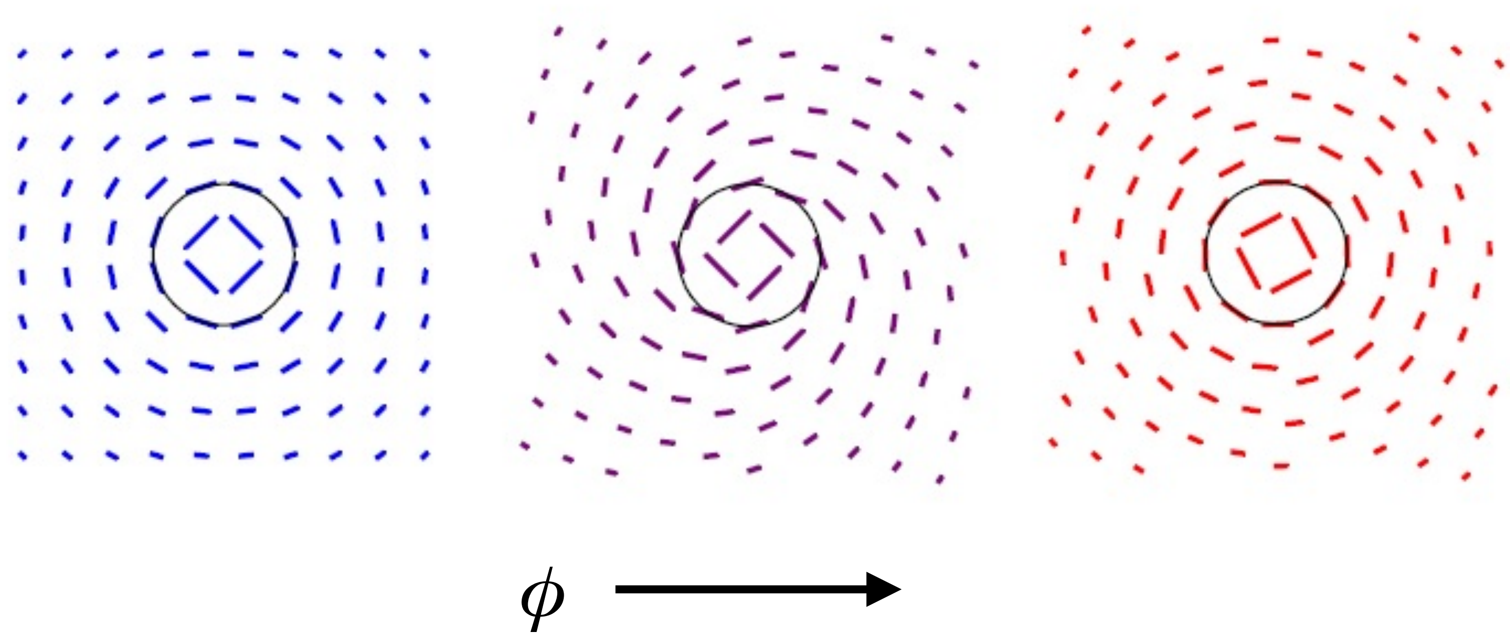
$$\mathcal{L} \supset C\phi + \frac{\partial_\mu \phi}{f_a}\bar{\psi}\gamma^\mu\gamma_5\psi + \frac{\phi}{f_a}F\tilde{F}$$

Kinetic Energy of Dark Energy < meV^4: **Direct Detection?**

Rolling ϕ Coupled to CMB

$$\frac{\phi}{f_\gamma} F\tilde{F}$$

$$\dot{\phi} \implies \text{Rotation of polarization of light}$$



The polarization of the CMB rotates as ϕ rolls

E-mode => B-mode

$$\frac{\dot{\phi}}{f_\gamma}\frac{1}{H} = \frac{\dot{\phi}}{\text{meV}^2}\frac{M_{pl}}{f_\gamma} \lessapprox 1$$

Current CMB Measurements already very constraining!

Future CMB polarization measurements (*e.g.*, CMB-S4, etc): $\delta w \left(\frac{M_{pl}}{f}\right)^2 < 2 \times 10^{-9}$!

Pogosian, Shimon, Mewes, Keating (2019)

Rolling ϕ Coupled to Fermions: Spin Precession

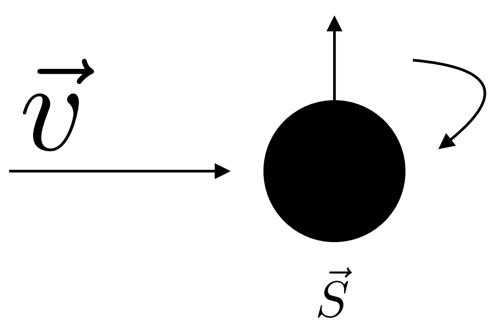
$$\frac{\partial_\mu \phi}{f_\psi} \bar{\psi} \gamma^\mu \gamma_5 \psi$$

$$H = \frac{\vec{\nabla}\phi}{f} \cdot \vec{\sigma}_\psi$$

Relative Motion between the dark energy and spin

Think of it as a new dark magnetic field

Like magnetic field, spin precesses about the direction of motion



Measure Spin Precession - similar to axion dark matter searches (CASPER)

Challenges: Signal is DC - need to combat low frequency noise, Dark energy is less abundant in galaxy than dark matter

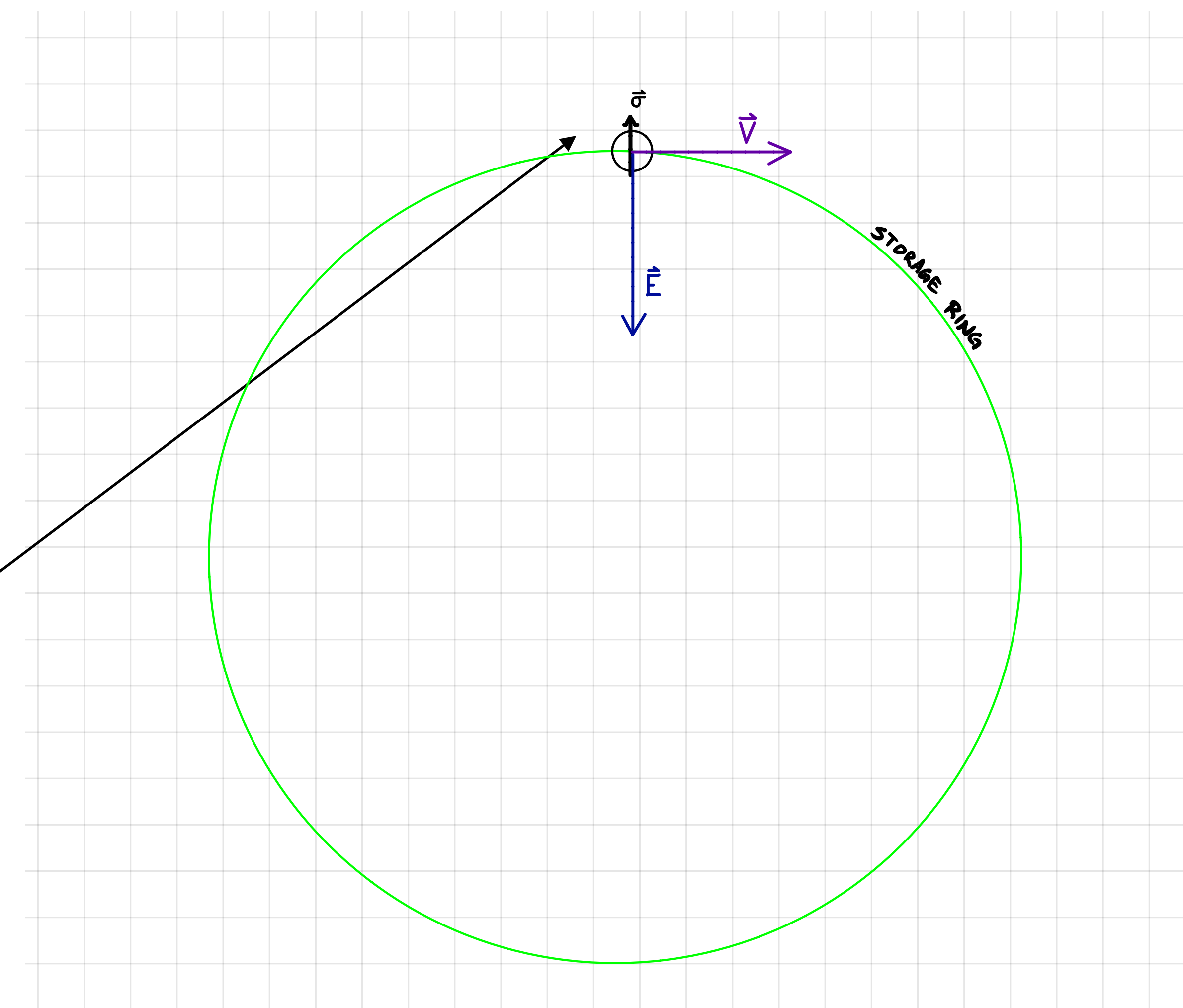
Advantage: Signal is coherent forever

Signatures: Spin Precession in Storage Ring

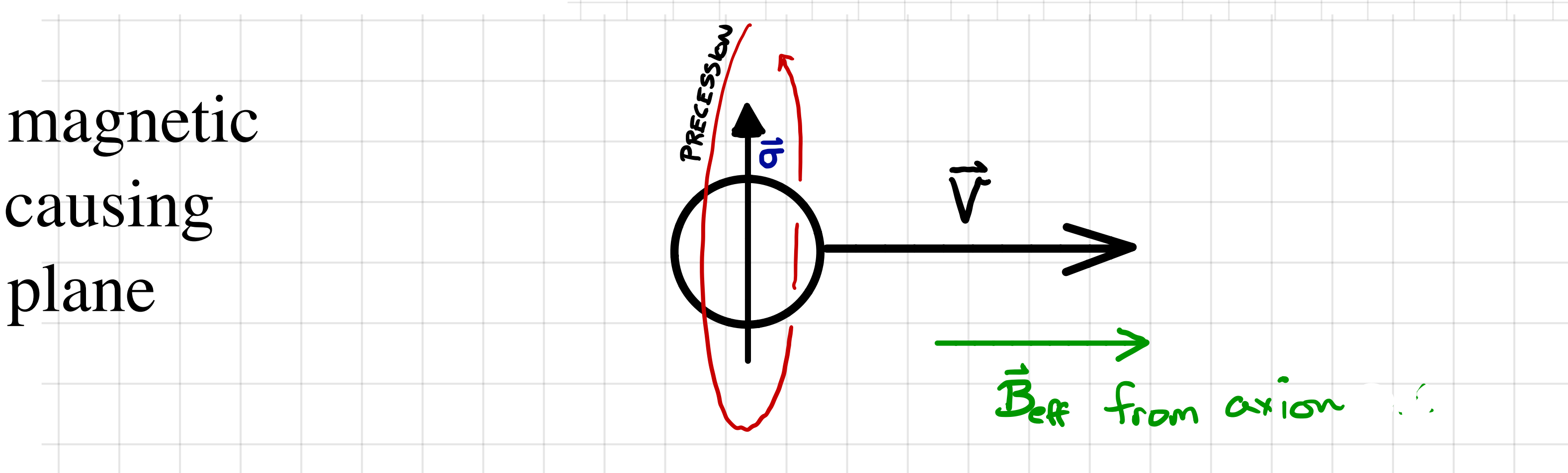
$$H = \frac{\vec{\nabla}\phi}{f} \cdot \vec{\sigma}_\psi$$

Cosmological axion field **homogeneous**, so gradient is velocity suppressed, but can use a **highly boosted** experiment!

Spin fixed to be radial at magic momentum without signal.

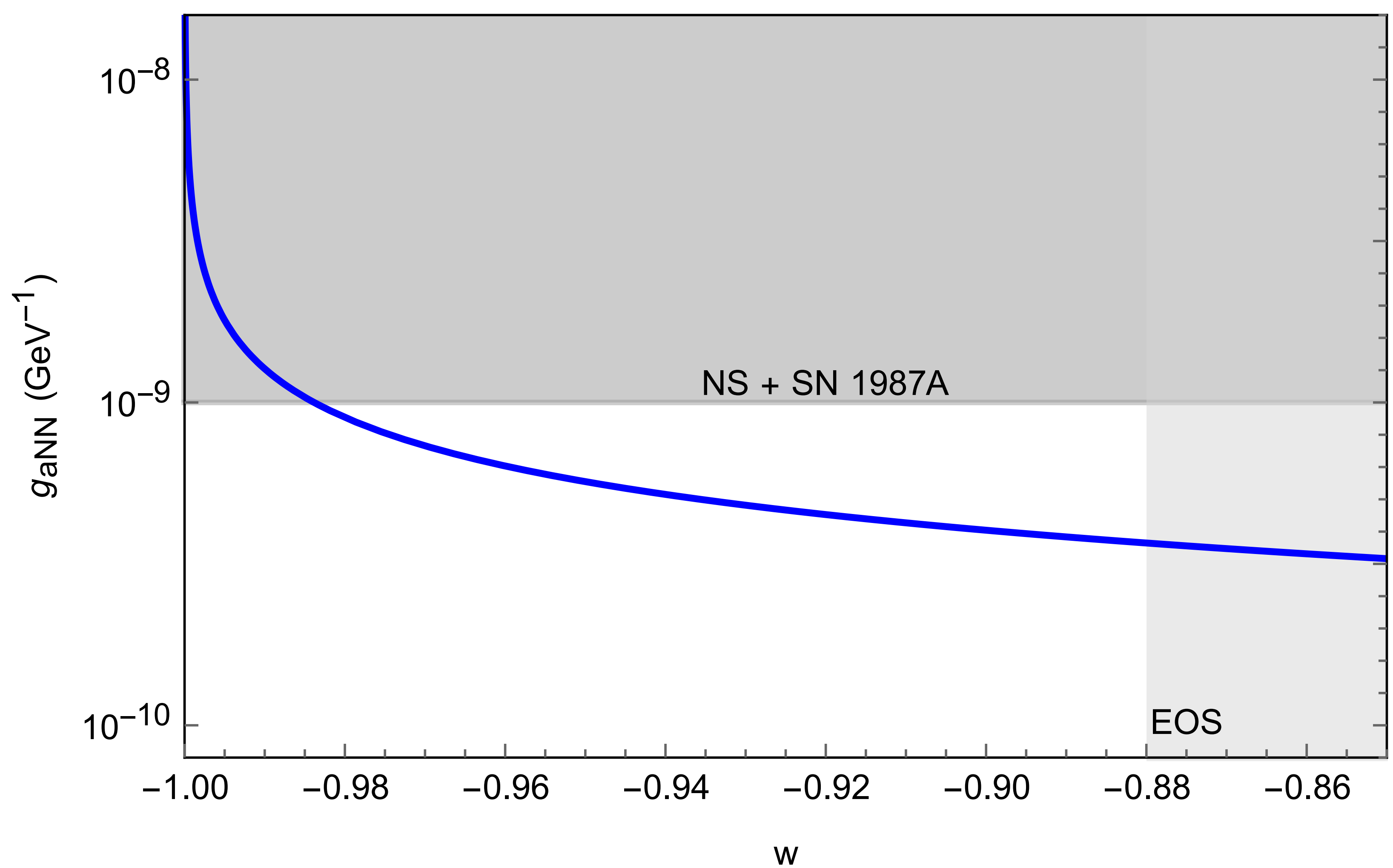


$\vec{\nabla}\phi$ acts as an effective magnetic field acting on the spin causing precession out of the plane



P Graham, S Haciömeroğlu, Z Omarov, S Rajendran, Y Semertzidis - 2005.11867

Projected Sensitivity



Stores protons for ~ 1000 s

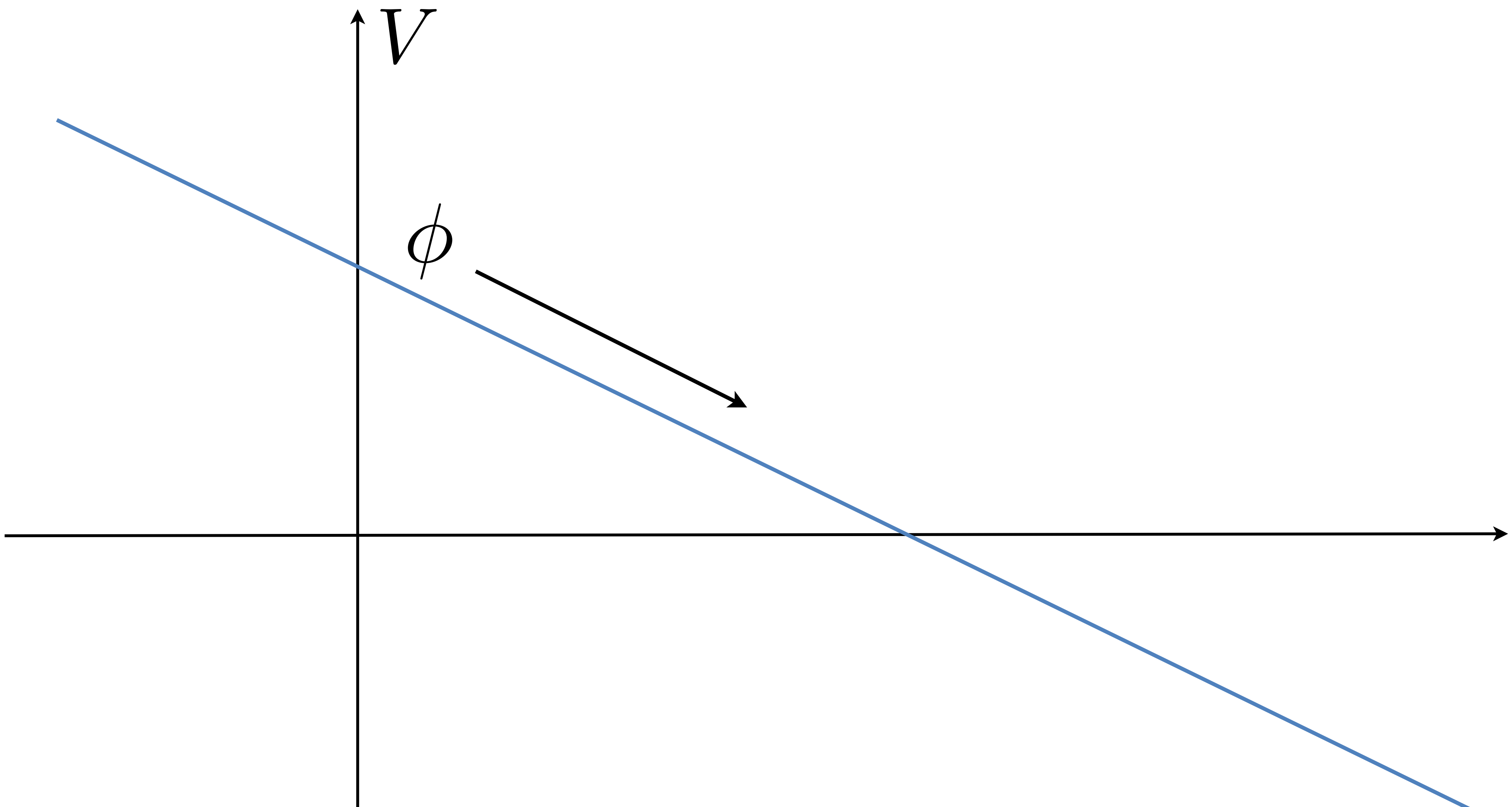
Measure spin precession to 10^{-6} rad

Lorentz Violation experiments also have comparable sensitivity

Dark Radiation

$$\ddot{\phi} + 3H\dot{\phi} + \Upsilon\dot{\phi} = g^3$$

New source of friction



Dark Radiation

Coupling rolling ϕ to, *e.g.*, pure YM

$$-\mathscr{L} = \frac{1}{2g^2}\,\mathrm{Tr}\,G_{\mu\nu}G^{\mu\nu} + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \frac{\phi}{f}\frac{\mathrm{Tr}\,G_{\mu\nu}\tilde{G}^{\mu\nu}}{16\pi^2} - g^3\phi$$

Can be show with a thermal bath of gluons, the friction:

$$\Upsilon \sim (N_c\alpha)^5\frac{T^3}{f^2}$$

Dark Radiation

Thus a thermal bath of YM produces a new source of friction for a rolling scalar field:

$$\ddot{\varphi} + 3H\dot{\varphi} + \Upsilon\dot{\varphi} = g^3 \qquad \text{with} \qquad \Upsilon \sim (N_c\alpha)^5 \frac{T^3}{f^2}$$

If $\Upsilon \gg H$, the friction extracts energy from the rolling field and dumps it into the thermal bath:

$$\dot{\rho}_{DR} = -4H\rho_{DR} + \Upsilon\dot{\varphi}^2$$

Assuming roughly steady state behavior ($\dot{T} = 0$, $\ddot{\phi} = 0$):

$$\dot{\phi} \simeq \frac{g^3}{\Upsilon} \qquad \text{and} \qquad T \sim \left(\frac{g^6 f^2}{H g_* N_c^5 \alpha^5}\right)^{1/7}$$

Dark Radiation

$$\dot{\phi} \simeq \frac{g^3}{\Upsilon} \qquad T \sim \left(\frac{g^6 f^2}{H g_* N_c^5 \alpha^5} \right)^{1/7} \quad \text{and} \quad \dot{\phi}^2 \sim \frac{H}{\Upsilon} \rho_{DR}$$

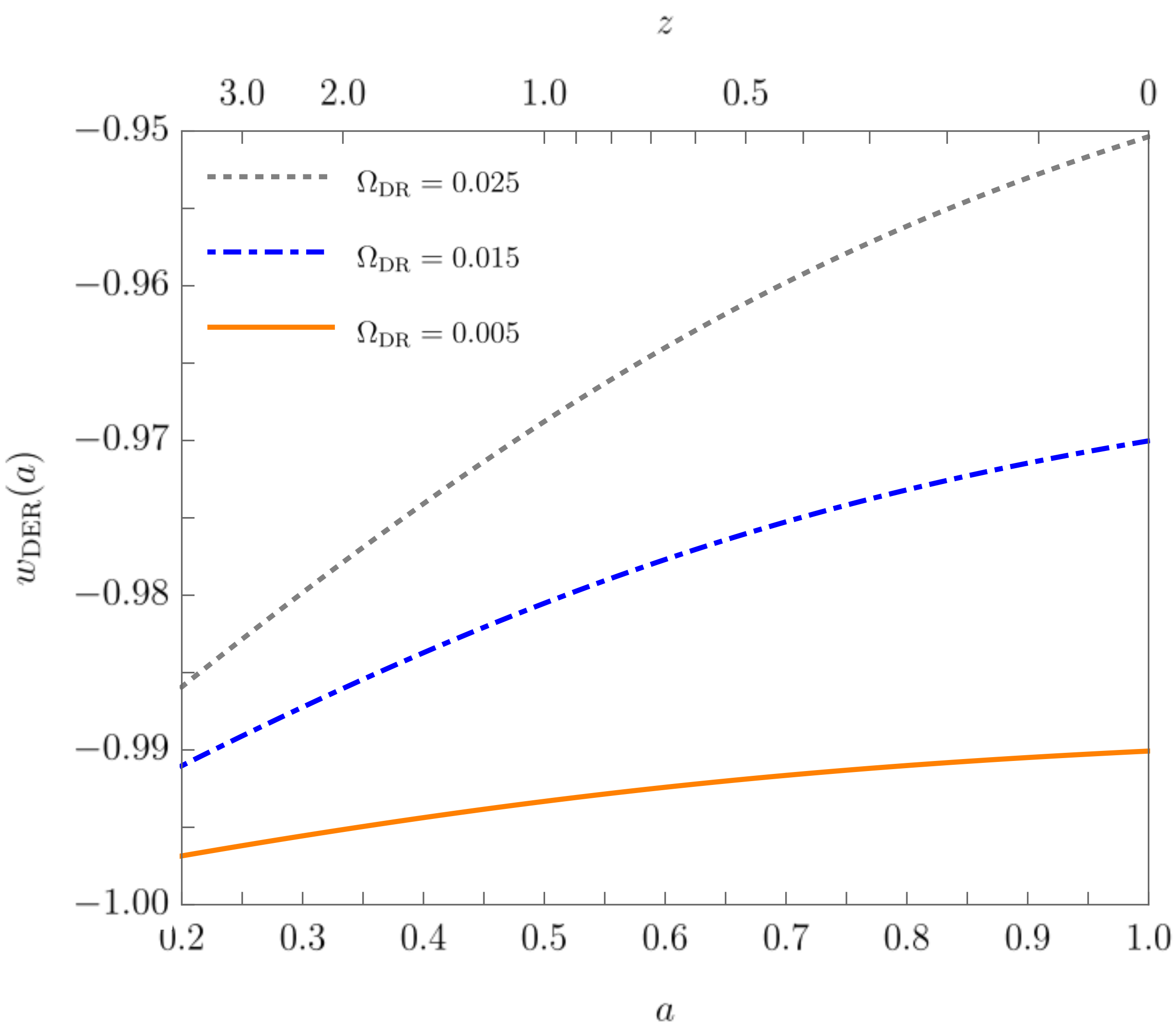
Thus, if $\Upsilon \gg H$, the dark radiation can be a significant component of dark energy while the kinetic energy is negligible.

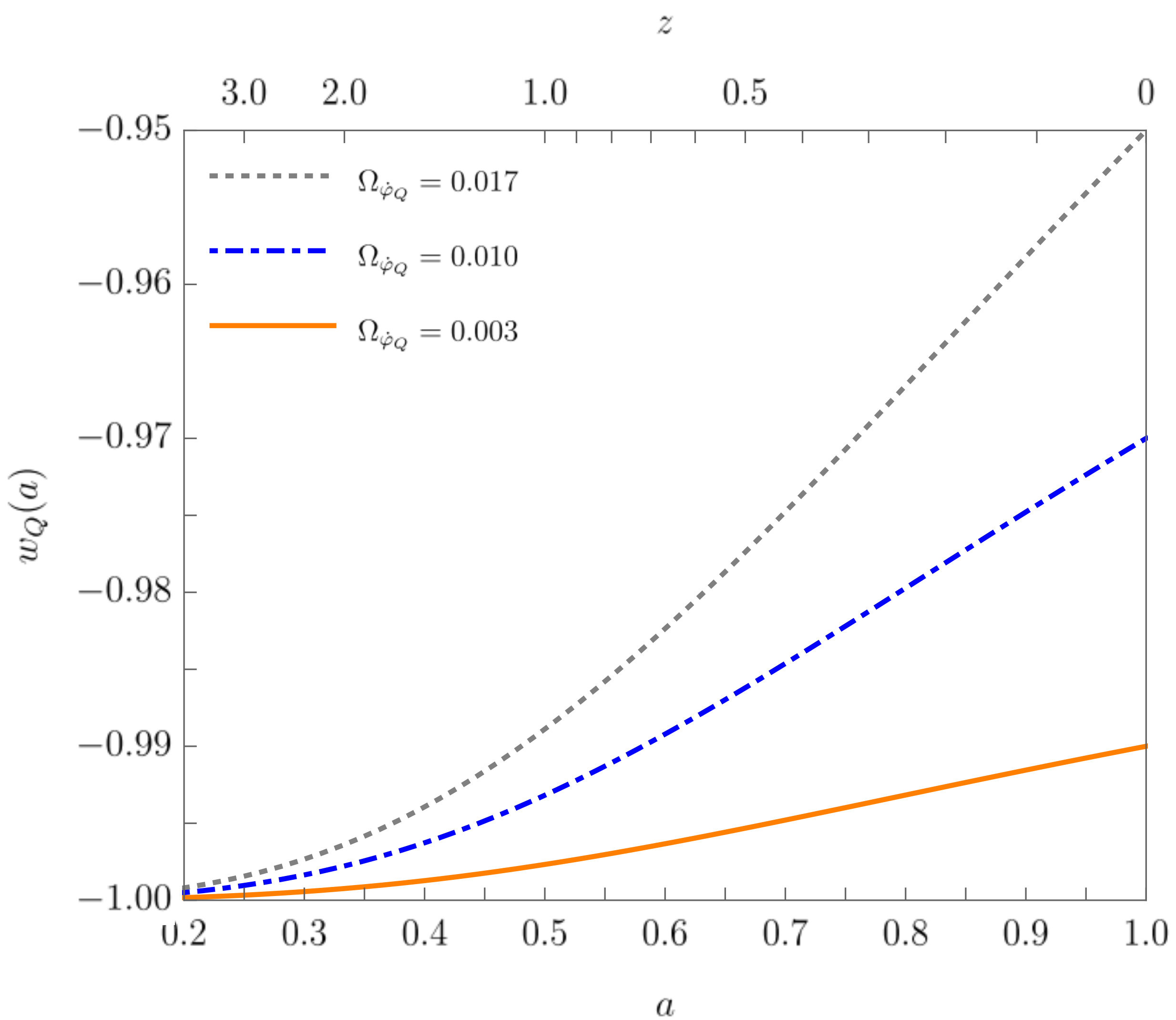
Coupling needs to be strong enough (low enough scale) — for example, if $T \sim \mathrm{meV}$ today, then $\Upsilon \gg H$ means $f \ll T\sqrt{T/H_0} \sim \mathrm{TeV}$ (hidden sector).

Cosmological Effects

Dark radiation does not affect CMB — large today, but meV vs. eV at recombination.

Significantly different from quintessence





Direct Detection

$$\frac{\bar{\psi}\psi G^2}{\Lambda^3}$$

Direct coupling to the Standard Model is dimension 7. Hard to probe

But dark sector doesn't have to be pure YM:

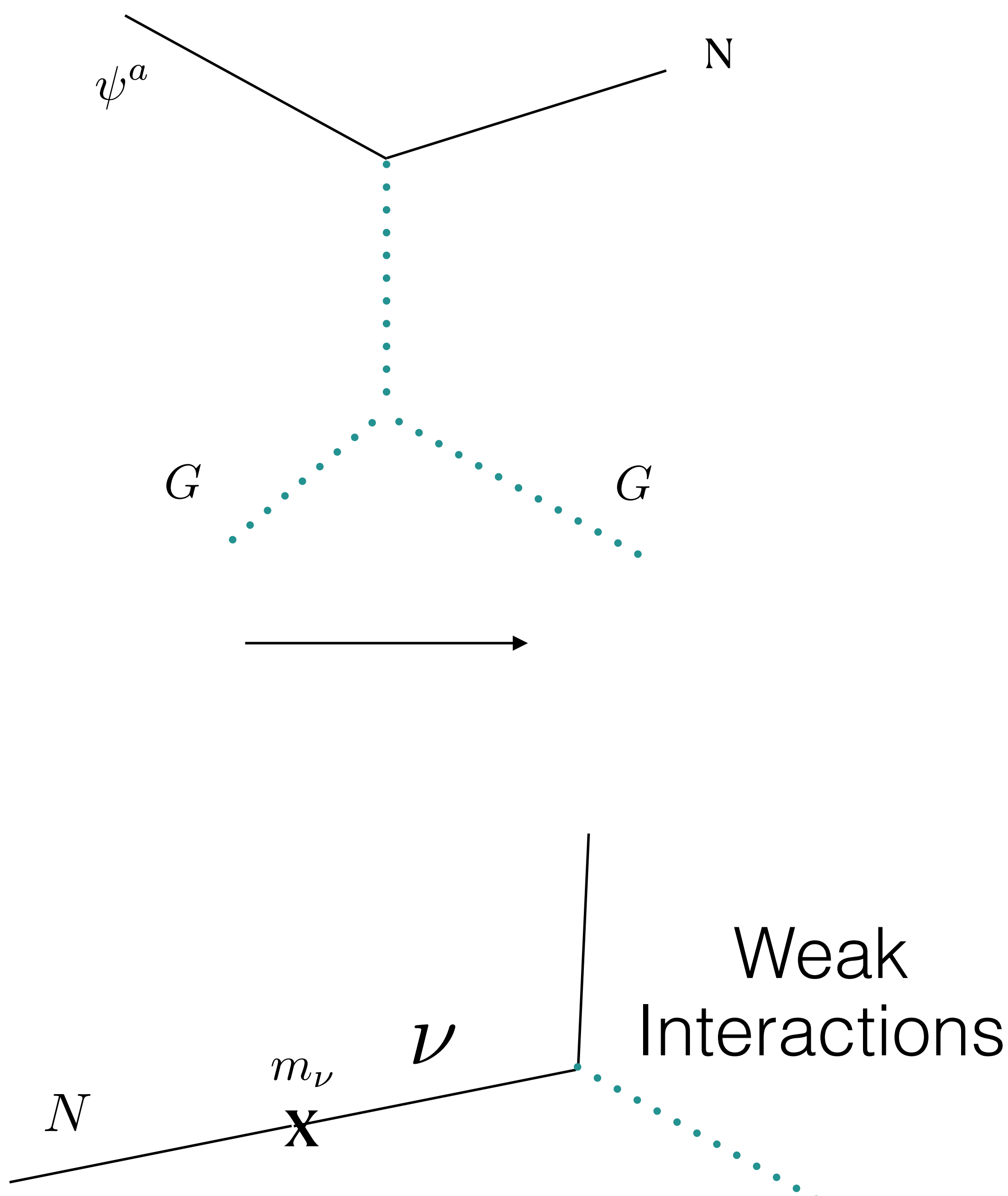
Fermions and hidden photons: $\mathcal{L} \supset \bar{\psi}\left(\gamma^\mu D_\mu + m\right)\psi$

Hidden photon mixing with our photon: $\epsilon F^{\mu\nu} F'_{\mu\nu}$

Fermions become milli-charged under E&M, while fundamental representation of non-abelian sector. Also hot gas of hidden photons.

Right Handed Neutrinos

$$\mathcal{L} \supset \frac{1}{f_N} G^a_{\mu\nu} \psi^a \sigma^{\mu\nu} N$$



Efficient (i.e. during the current age of the universe) conversion of energy from dark glue into right handed neutrino

Thermalized population of right handed neutrinos at meV energies

At low energy (meV), conversion of N to neutrino is not suppressed! So N behaves like a thermalized population of neutrinos - at meV temperatures!

10x the temperature of CvB

Direct Detection

Challenge: Detect meV scale milli-charged particles

No existing experiments - but plenty of upcoming ideas (e.g. using EM cavities to search for milli-charged particles)

Challenge: Detect meV scale hidden photons.

Leverage work done for single IR photon detection, use work done for dark matter detection in this mass range

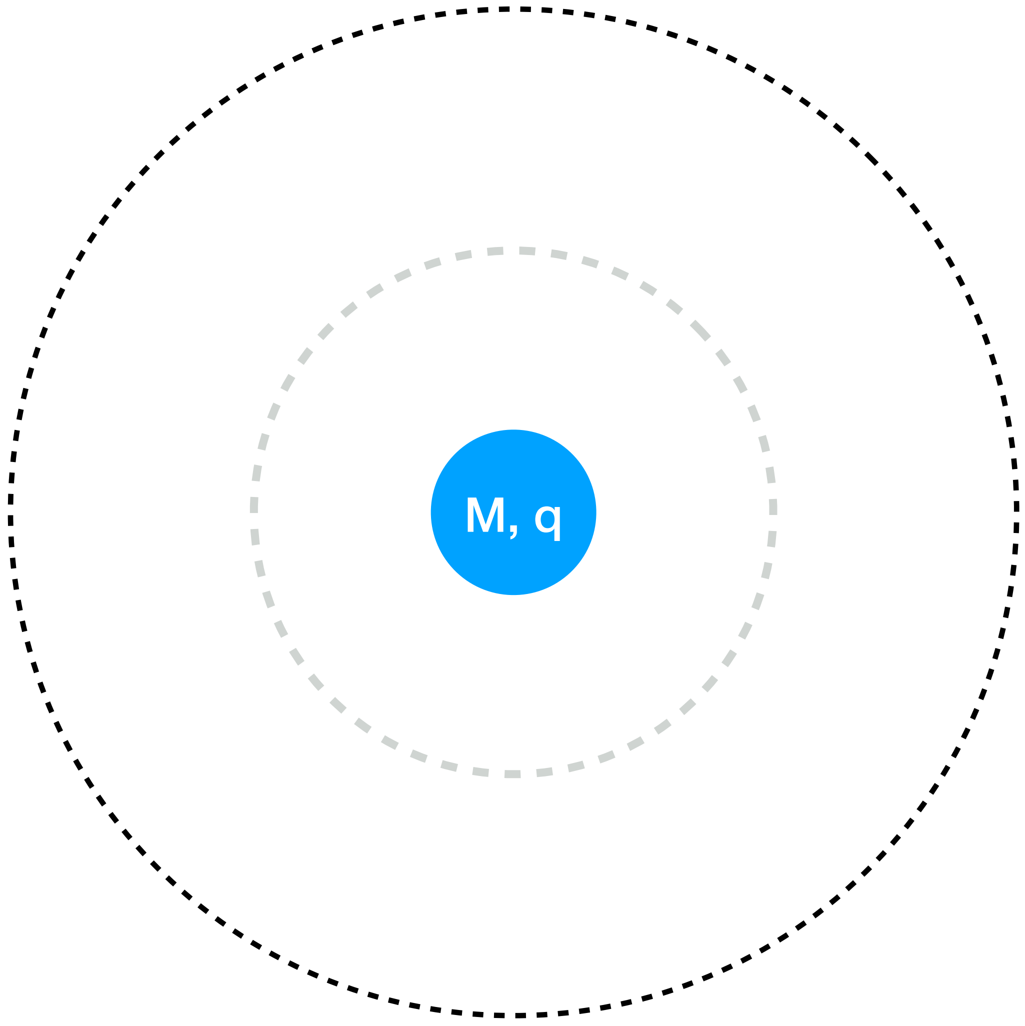
For neutrinos, this signal is significantly bigger than what PTOLEMY (tritium end point to detect CvB) looks for - but PLOLEMY is a very hard experiment

Interesting challenge for detection community!

Black Holes

Deep Point

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!

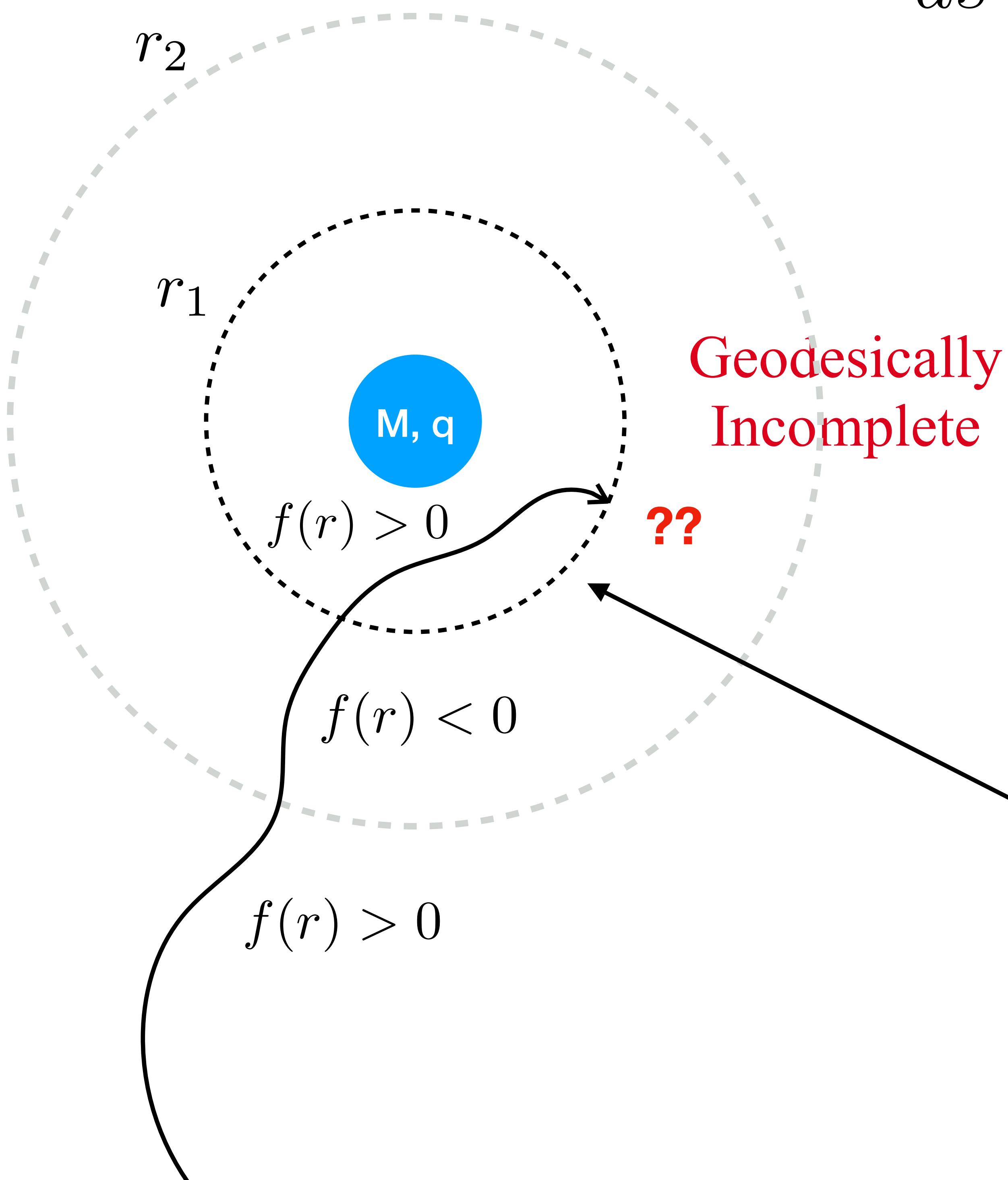
Cauchy Horizons in Charged BH

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

$$ds^2 = -f(r)dt^2 + \frac{1}{f(r)}dr^2 + r^2 d\Omega^2$$

$$f(r) = \frac{(r - r_1)(r - r_2)}{r^2}$$

$$r_{2/1} = GM \pm \sqrt{(GM)^2 - GQ^2}$$



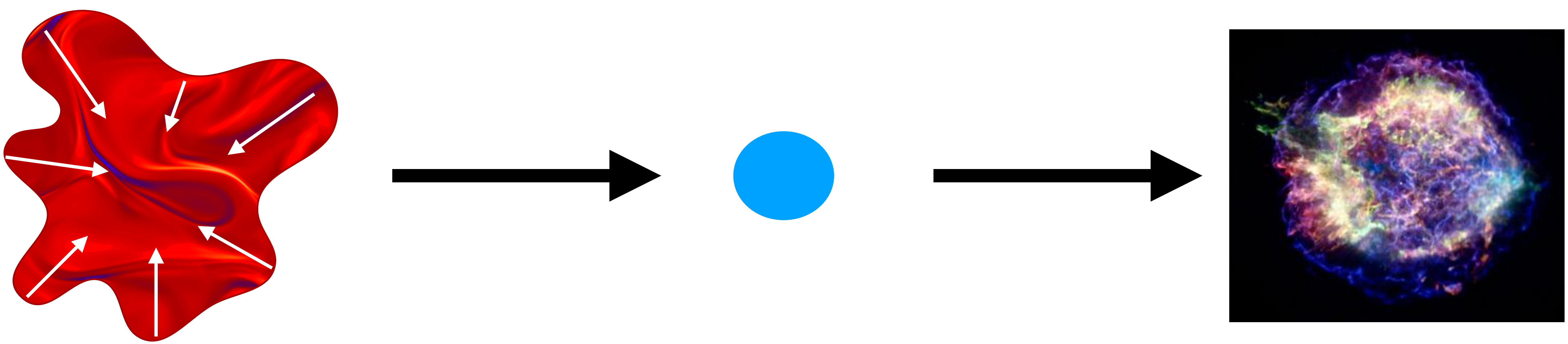
Vacuum energy divergences (and 'mass inflation') predict a **firewall** here

Argument for external Firewalls: Neutron Star Formation

Collapsing Matter (atoms)

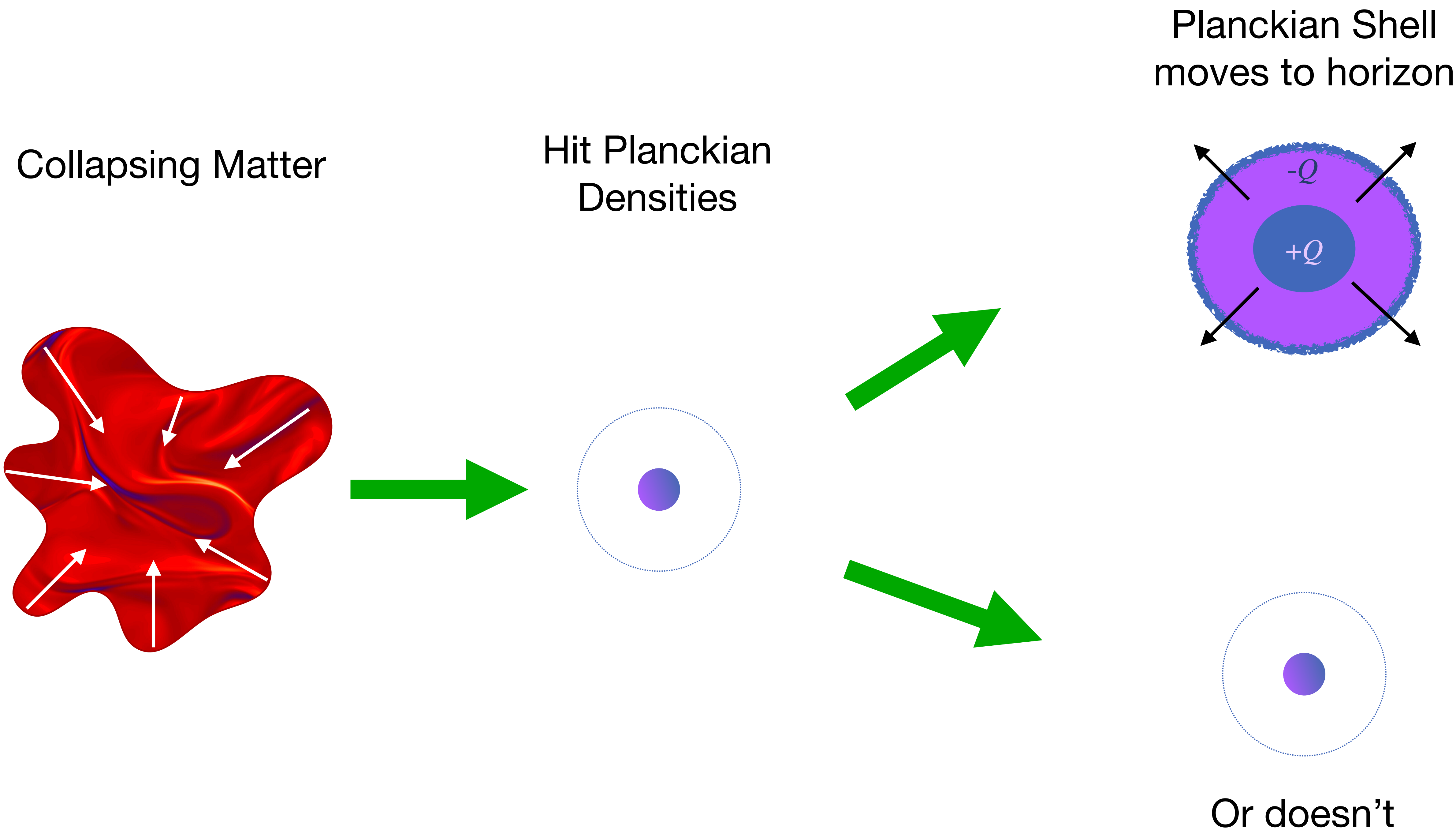
Hit High Density, Theory Breaks Down

New Phenomena: Need Nuclear Theory!



Falls to distance where high density, $(200\ \mathrm{MeV})^4$, is attained.

Black Hole Evolution



50-50 chance?

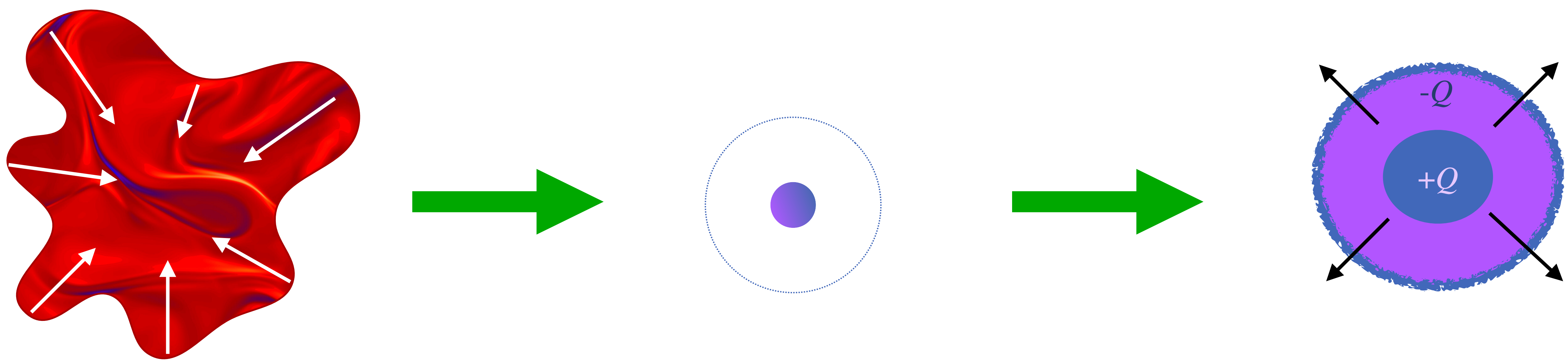
What Hamiltonian allows us to evolve through $r = 0$?

Firewall Formation

Collapsing Matter

Hit Planckian Densities

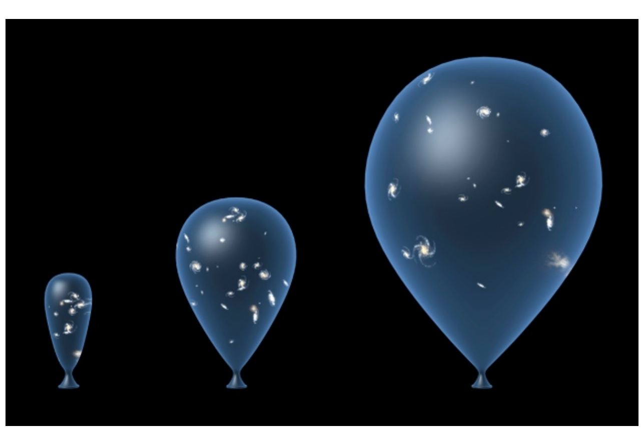
Planckian Shell moves to horizon



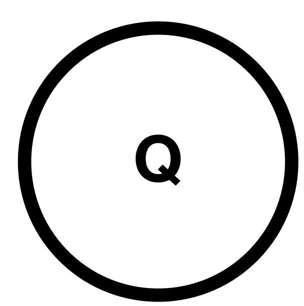
How large of a region can be at high density?

Negative binding energies from gravity allow for expansion at constant density without changing external mass

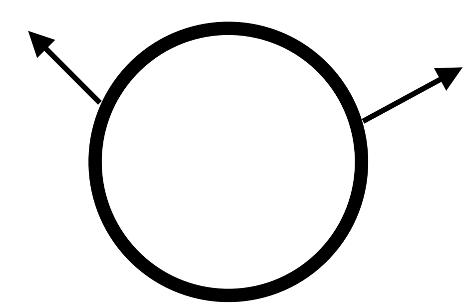
Inflation



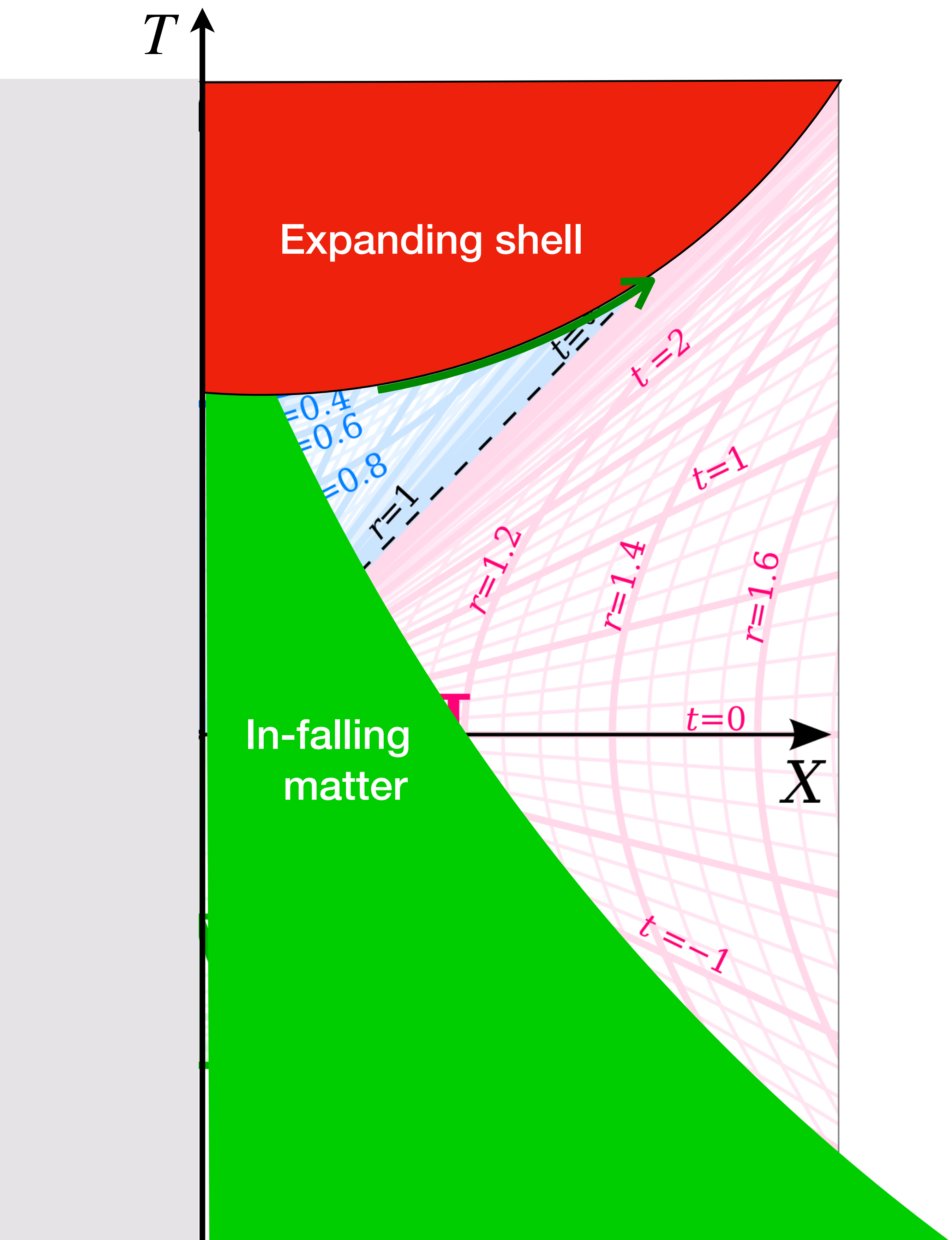
Mass Inflation

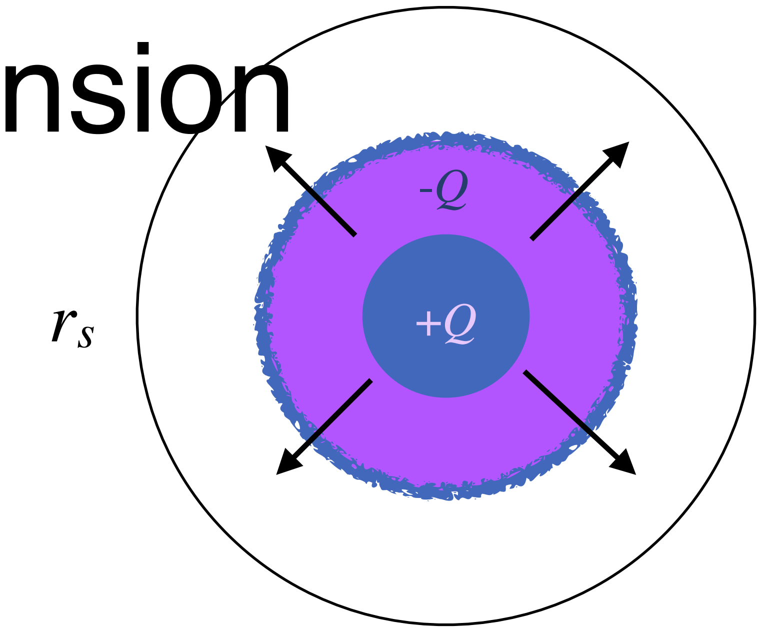


Firewalls



Causality-Preserving Expansion





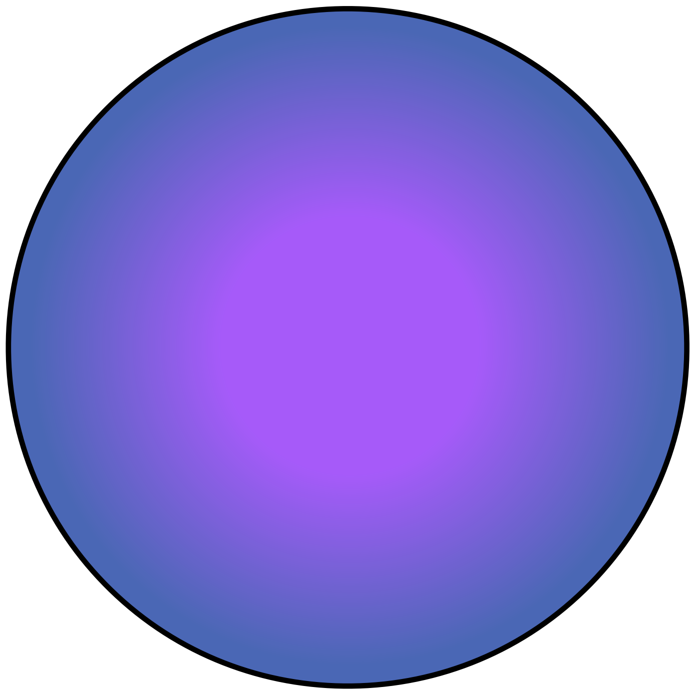
In-falling matter collapses through horizon following GR trajectories.

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

Nevertheless, no causality violation.

(Perhaps 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?

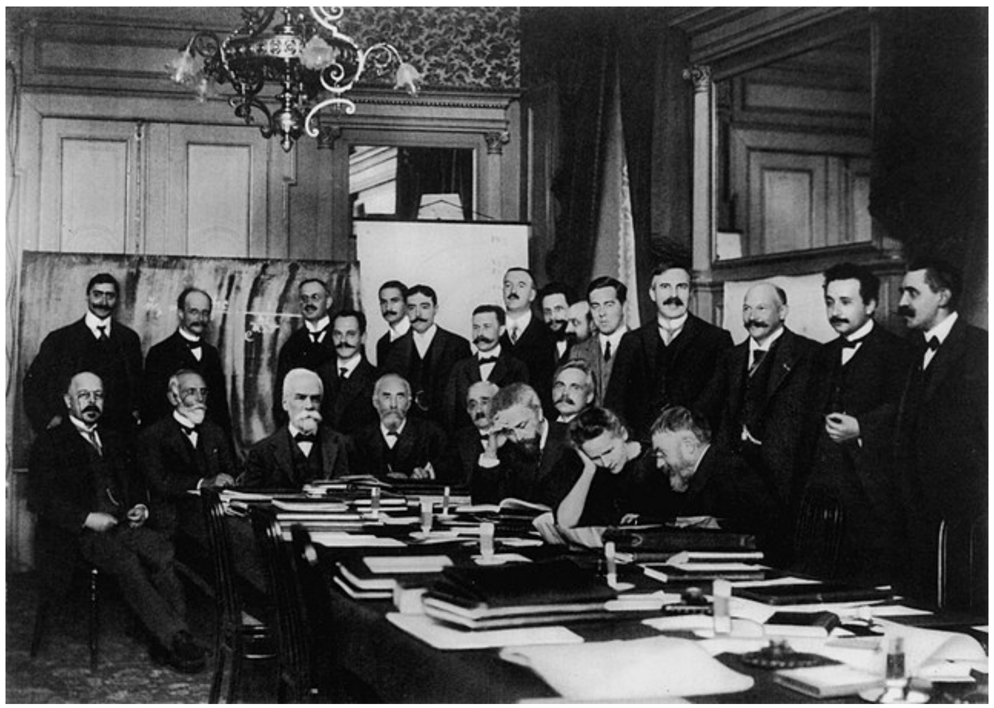
Electromagnet bursts from mergers at radio frequencies?
Multi-messenger?

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

Quantum Mechanics

Deep Point

Can quantum mechanics be modified?



Theory built on observations in the 1900s
Why should it be “the absolute truth”?

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

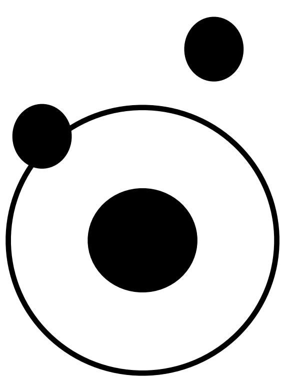
$$i\partial_t |\chi\rangle = \hat{H} |\chi\rangle$$

Or in position space:

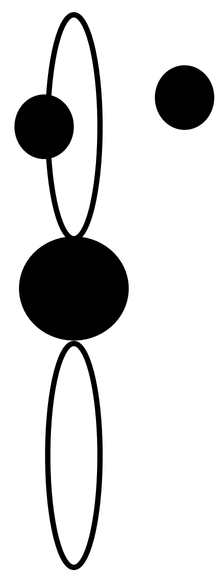
$$i\partial_t \Psi(t, \mathbf{x}) = H(\mathbf{x})\Psi(t, \mathbf{x})$$

Linearity

Wave-function does not interact with itself



Lamb Shift

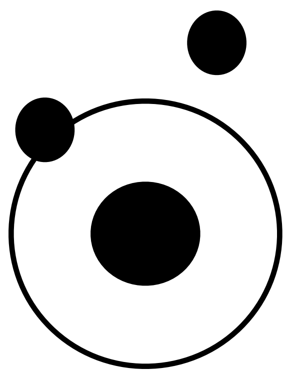


Degeneracies of the Hydrogen Atom

No self-energy of electron cloud
(Two different shapes - yet, same energy)

Another charged particle clearly sensitive to shape

Causality



Plenty of examples of causal non-linear theories

Causality Enforced by Green's Functions

$$\Box G\left(x;x'\right)=\delta^{(4)}\left(x-x'\right)$$

Linear Quantum Mechanics is basis independent

Local Interactions - Position Basis!

Causality issue? Use Position Basis!

Non Linear Quantum Mechanics in position basis leads to a natural embedding in local field theory

The Framework

Linear QFT Lagrangian

Non-Linear: Take any bosonic field and shift by term proportional to (state-dependent) expectation value

Example: Yukawa Theory

Linear QFT

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

$$\hat{\phi} \to \hat{\phi} + \epsilon \frac{\langle \chi | \hat{\phi} | \chi \rangle}{\langle \chi | \chi \rangle} \equiv \hat{\Phi}$$

Non Linear QFT

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

Gauge Theories and Gravitation

Linear QFT Lagrangian, Shift bosonic field by expectation value

$$\mathcal{L}_{EM} \supset eA_\mu J^\mu$$

$$A_\mu \to \frac{A_\mu + \epsilon_\gamma \frac{\langle \chi | A_\mu | \chi \rangle}{\langle \chi | \chi \rangle}}{1+\epsilon_\gamma} = B_\mu$$

$$\text{Notice: } A_\mu \to A_\mu + \partial_\mu \alpha \implies B_\mu \to B_\mu + \partial_\mu \alpha$$

Same Concept for gravitation — in interaction terms:

$$g_{\mu\nu} \to \frac{g_{\mu\nu} + \epsilon_G \frac{\langle \chi | g_{\mu\nu} | \chi \rangle}{\langle \chi | \chi \rangle}}{1+\epsilon_G} = \tilde{g}_{\mu\nu}$$

Look for perturbative solutions

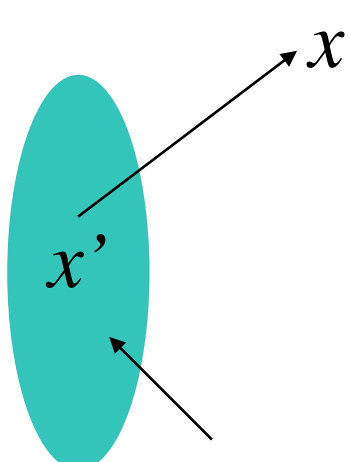
Single Particle

$$\mathcal{L} \supset y \Phi \bar{\Psi} \Psi = y \left(\phi + \tilde{\epsilon} \langle \chi | \phi | \chi \rangle \right) \bar{\Psi} \Psi$$

Suppose we have a ψ particle - how does its wave-function evolve?

To zeroth order, ψ just sources the ϕ field

Straightforward computation of expectation value



$$\langle \chi | \phi \left(x \right) | \chi \rangle = \int d^4 x' \psi^* \left(x' \right) \psi \left(x' \right) G_R \left(x - x' \right)$$

Charge Density of ψ

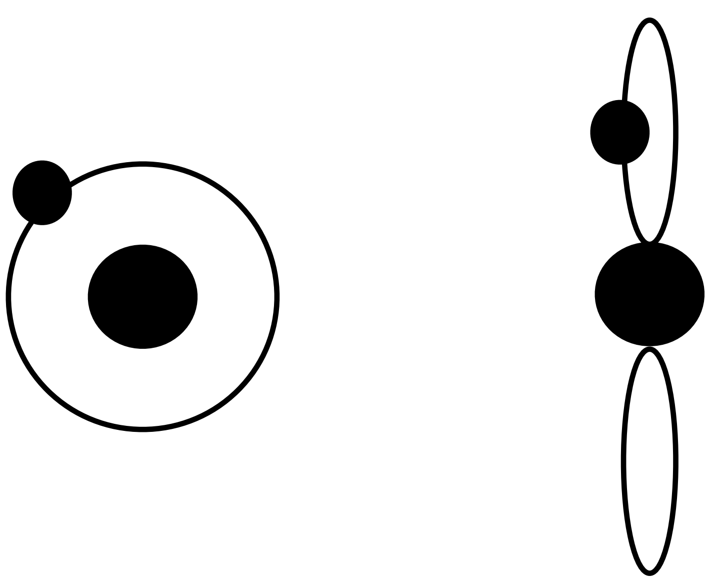
Causal Green's Function

Non-linear Schrodinger Equation

$$i\partial_t \Psi(t,\mathbf{x}) = \left(H(\mathbf{x}) + \epsilon \int d^4x' \Psi^*(x')\Psi(x')G_R(x;x') \right) \Psi(t,\mathbf{x})$$

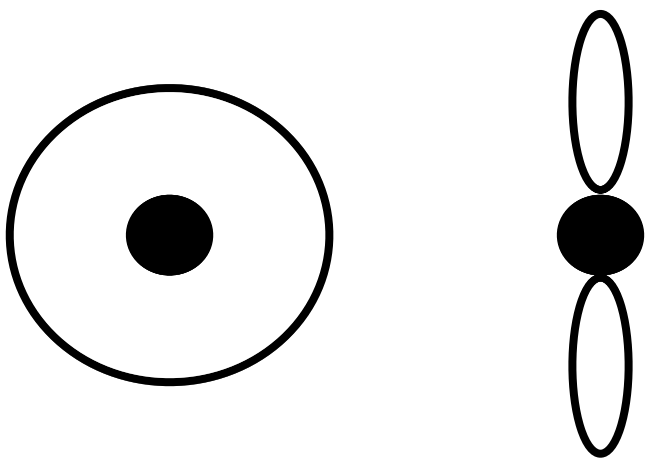
Single particle equation derived from field theory
Equation depends upon theory (Yukawa, EM, etc)

(Hermitian Form of Hamiltonian implies conserved norm)



Lamb Shift: Fixed Central particle, self interaction of wave-function breaks degeneracy of levels

Lamb Shift



Proton at Fixed Location, 2S and 2P electron have different charge distribution

Different expectation value of electromagnetic field — Level Splitting!

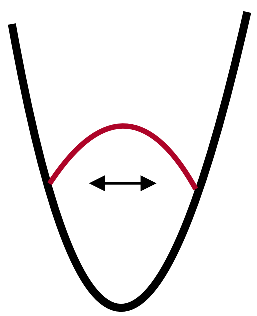
BUT: Cannot decouple center of mass and relative co-ordinates — Proton wave-function spread over region (e.g. trap size > 100 nm).

Expectation value of electromagnetic field diluted, especially for neutral atom!

$\varepsilon < 10^{-2}$

Leading Constraint?

For $\varepsilon > 0$ (repulsive interaction)



Too large a repulsion, Cant trap ion in trap:

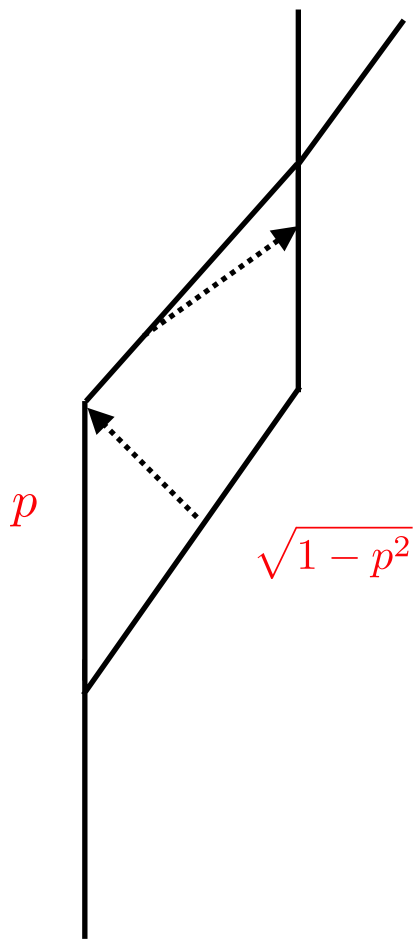
$$\varepsilon < 10^{-5}$$

No direct limit on $\varepsilon < 0$ (attractive interaction)
Perhaps from mapping of ion in trap?

Experimental Tests

Interferometry - interaction between paths

Take an ion - split its wave-function



Coulomb Field of one path interacts with the other path

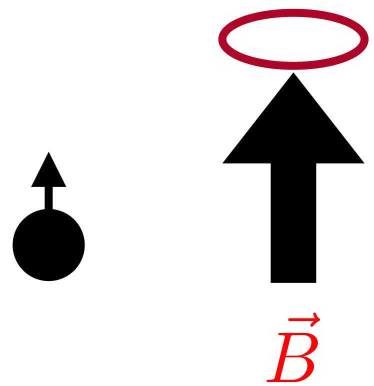
Gives rise to phase shift that depends on the intensity p of the split

Use intensity dependence to combat systematics

Data currently being taken by Haffner's group at Berkeley

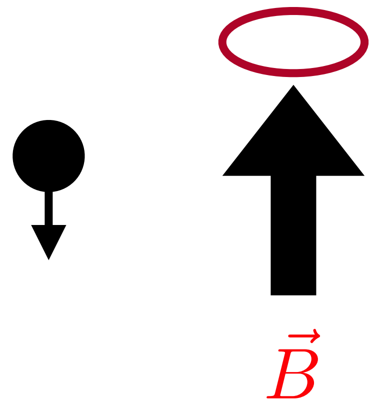
Experimental Tests

Key Point: Create macroscopic superposition
Create Expectation value of EM/Gravity
Search for Expectation value



On: $\{T, T + dT\}$
Off: $\{T + dT, T + 2\ dT\}$

SQUID
εB in $\{T + dT, T + 2\ dT\}$?



Off: $\{T, T + dT\}$
On: $\{T + dT, T + 2\ dT\}$

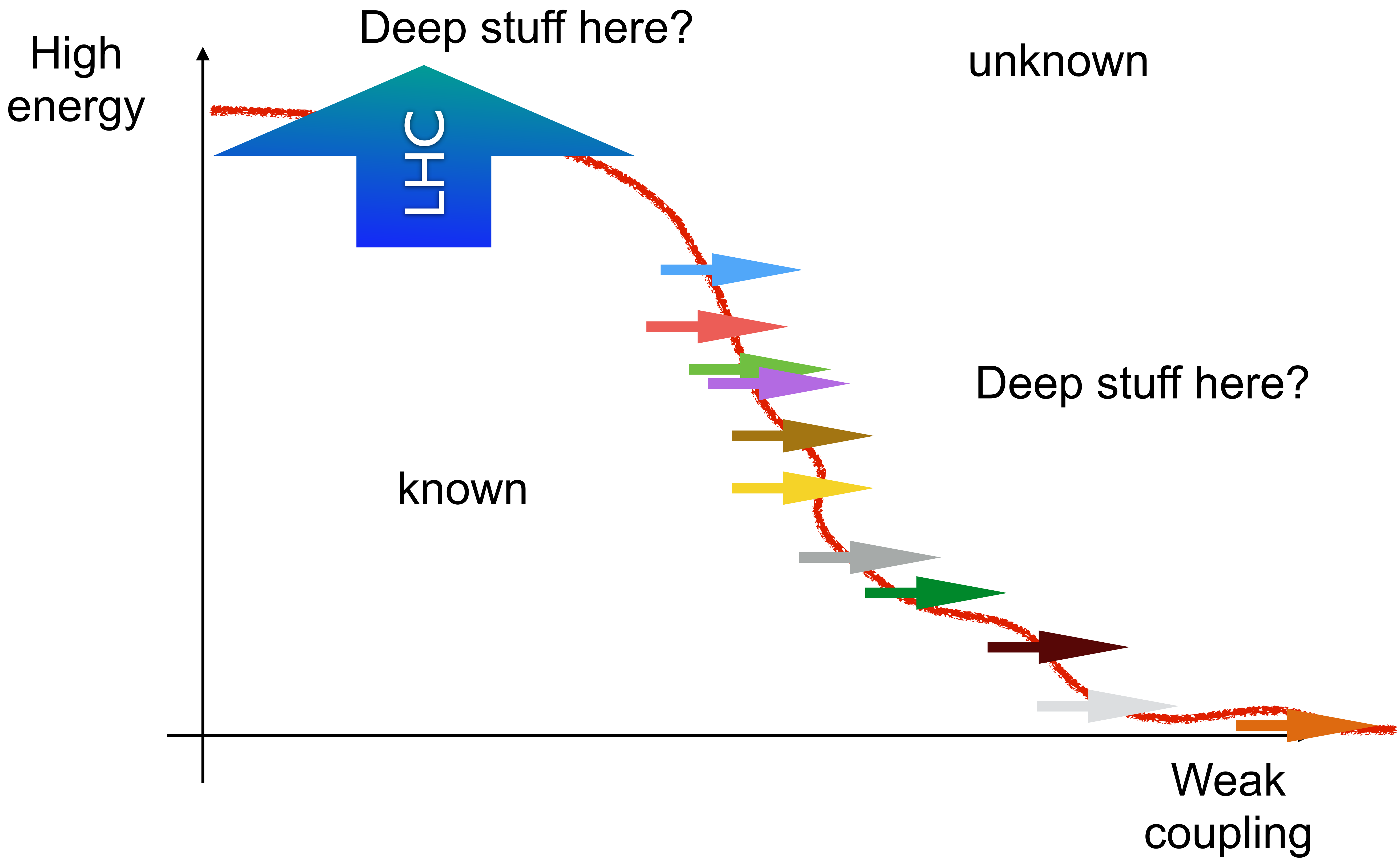
SQUID
εB in $\{T, T + dT\}$?

Experiments with E-fields (voltages) currently being done by Sushkov's group at BU

Similar tests can be done for the gravitational coupling

Rolling in the Deep

Search for New Physics



Thank You!