Probing the Frontier of Fundamental Physics:

New Matter, Forces, and Laws

QUPosium2024, Japan!

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

Hints Beyond the SM

Hints Beyond the SM

0. DARK MATTER BSM

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	?	

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	?	
6. Source of Matter/Anti-matter Asymmetry		Initial Conditions
7. Homogeneity/Flatness (Inflation)		

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	?	
6. Source of Matter/Anti-matter Asymmetry		Initial Conditions
7. Homogeneity/Flatness (Inflation)		
∞. GR UV Scale		Breakdown of Theory

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	?	
6. Source of Matter/Anti-matter Asymmetry		Initial Conditions
7. Homogeneity/Flatness (Inflation)		
∞. GR UV Scale		Breakdown of Theory

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

Beyond the Standard Model

Beyond the Standard Model

- At Higher Energy:
  1. New Heavy States
  2. Suppressed Operators/Rare Processes

Beyond the Standard Model

- At Higher Energy:
  1. New Heavy States
  2. Suppressed Operators/Rare Processes
- Weak Couplings:
  1. New Light States/Relics
  2. New Forces/Background Fields

Beyond the Standard Model

- At Higher Energy:
  1. New Heavy States
  2. Suppressed Operators/Rare Processes
- Weak Couplings:
  1. New Light States/Relics
  2. New Forces/Background Fields
- Violations of Principles
  1. Lorentz Invariance
  2. General Relativity
  3. Quantum Mechanics/QFT

Light Fields: Couplings

Spin 0, 1/2, and 1

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)

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 — $\bar{\psi}\gamma\gamma^5 A'\psi$

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 — $\bar{\psi}\gamma\gamma^5 A'\psi$

Spin 1/2 couplings (like matter):

mixing with ν — $\bar{\nu}\chi$

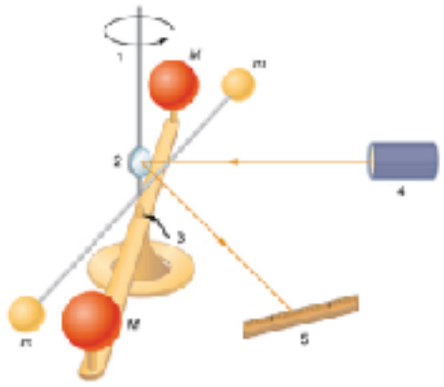
$\chi\chi$ couplings

Light Fields: Physical Effects

Forces!

EP violating

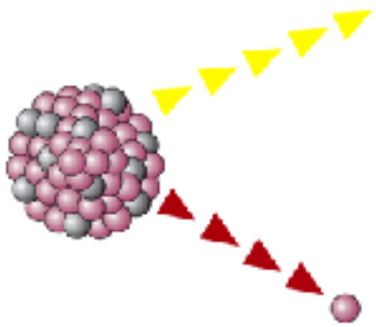
$$\frac{1}{r^2} \rightarrow \frac{e^{-mr}}{r^2} \text{ (range} \sim \frac{1}{m}\text{)}$$



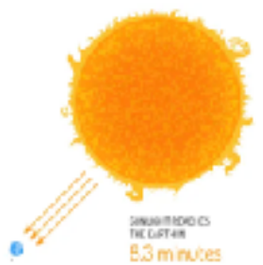
— Earth/Moon/Sun
— Earth/Lab
— Lab/Lab (cavendish)

Spin-dependent forces, polarized material

Nuclear (and atomic/hadronic) decays

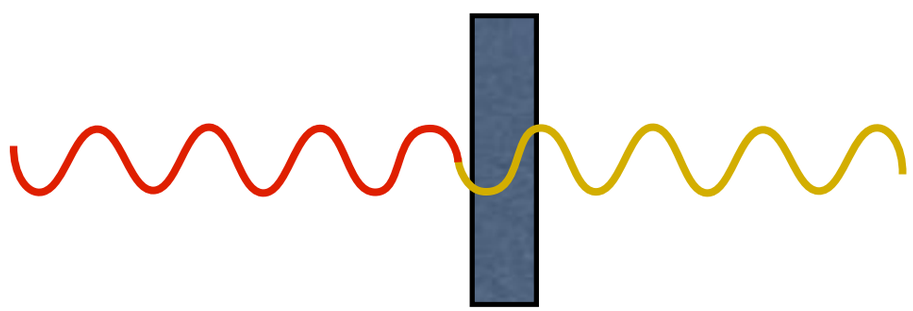


Solar/Stellar emission



Emission from core

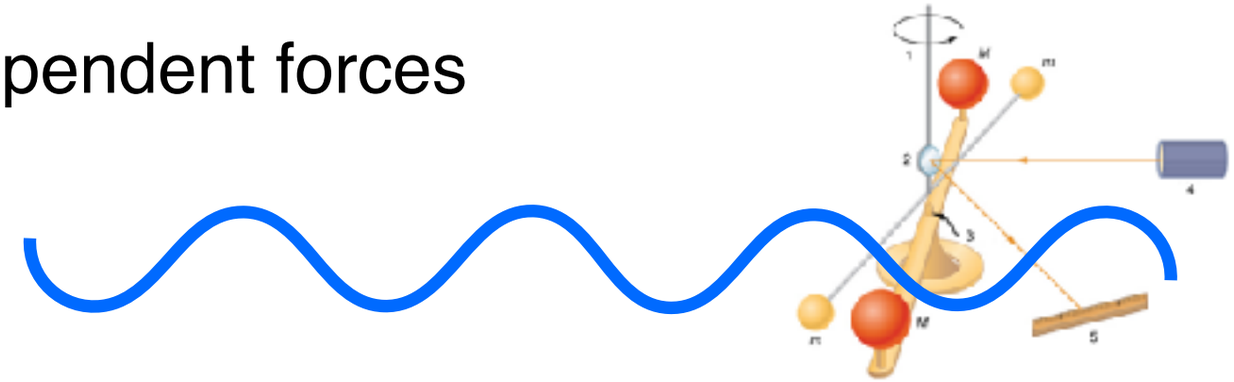
Conversion to/from photons/EM



Light Fields: Backgrounds

If it is Dark Matter, Dark Energy, or static

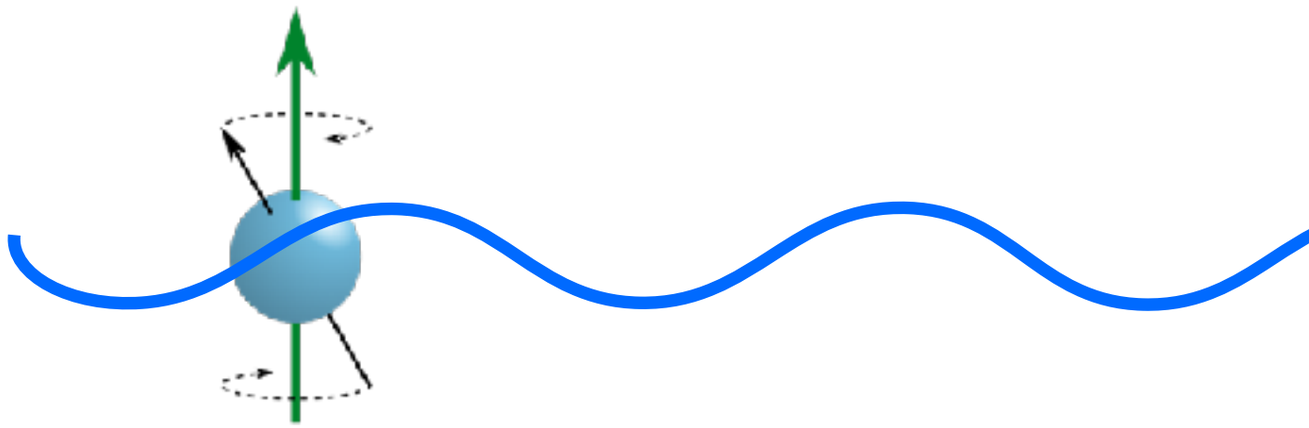
Time-dependent forces



DM robustly oscillates at a narrow frequency

Spin precession: fake B-field

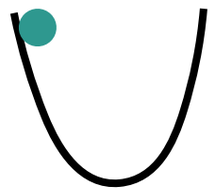
$$\vec{\nabla}\phi \cdot \vec{\sigma}$$

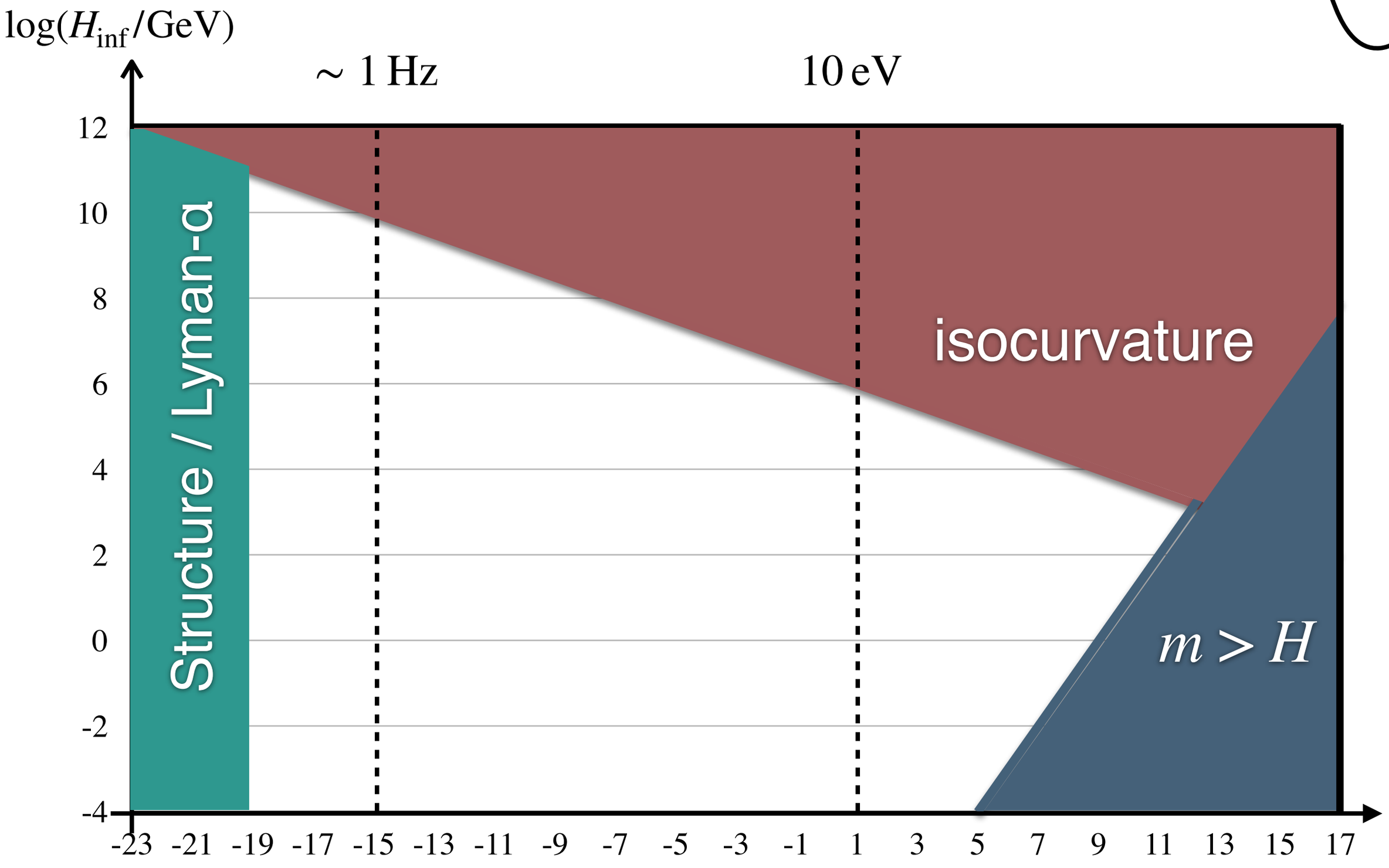


Photon polarization rotation

Sources change Fundamental Constants (mass/coupling)

Scalar DM: Misalignment





Light Fields: Couplings

Spin 2

coupling to $p/n/e$ — $h^{\mu\nu}\bar{\psi}\partial_{(\mu}\gamma_{\nu)}\psi$

coupling to γ kinetic — $h^{\mu\nu}F^{\lambda}_{\mu}F_{\lambda\nu}$

etc…

Now we can couple to light and *bend it*

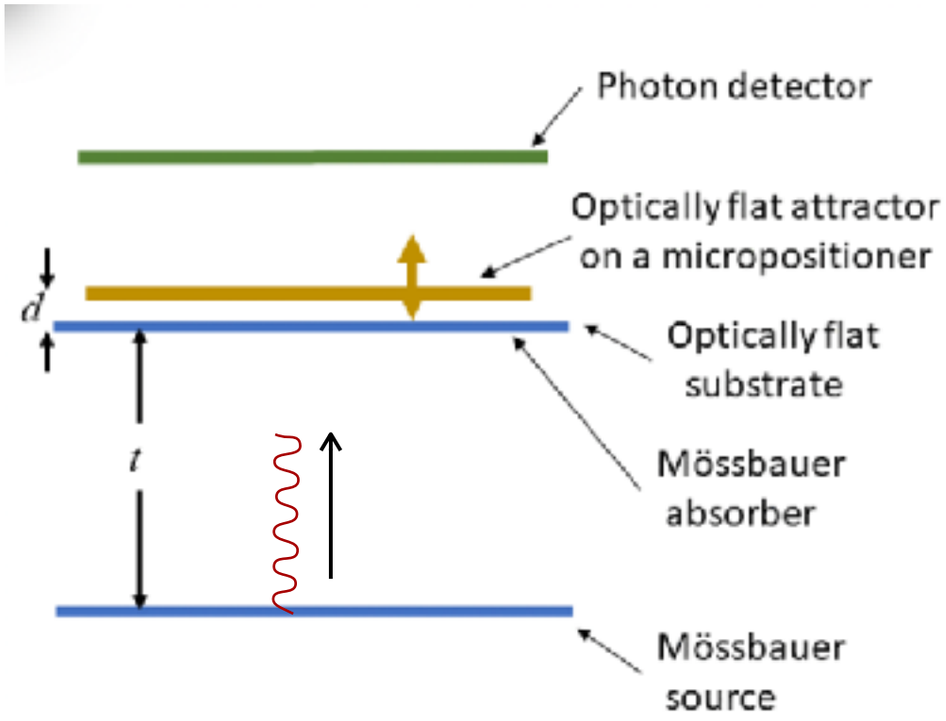
Force constraints keep effects very small

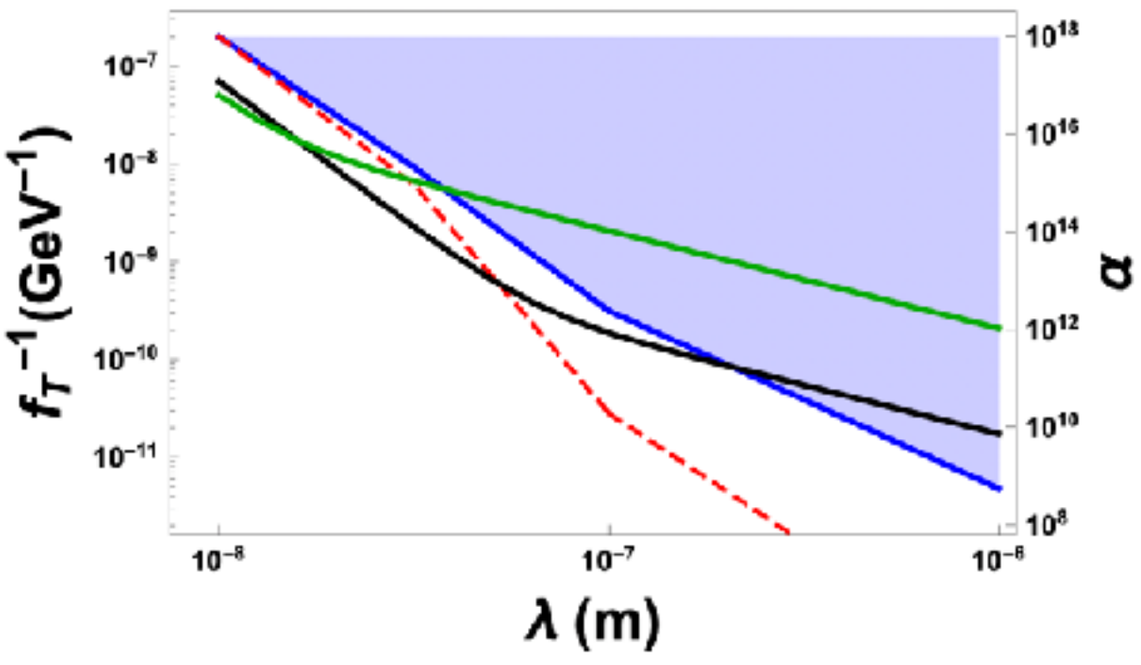
If from a typical field theory, confinement scale close — not a good candidate for light dark matter (occupation number < 1)

Spin-2 Fields: Redshift

Mossbauer:

Nuclide	E (eV)	$T_{1/2}$	Γ (eV)	Γ/E
$^{57}_{26}$Fe	14,413	98.3 ns	4.7×10^{-9}	6.4×10^{-13}
$^{73}_{32}$Ge	13,328	2.92 μs	1.6×10^{-10}	1.2×10^{-14}
$^{181}_{73}$Ta	6,237	6.05 μs	7.5×10^{-11}	1.2×10^{-14}
$^{67}_{30}$Zn	93,300	9.07 μs	5.0×10^{-11}	5.4×10^{-16}

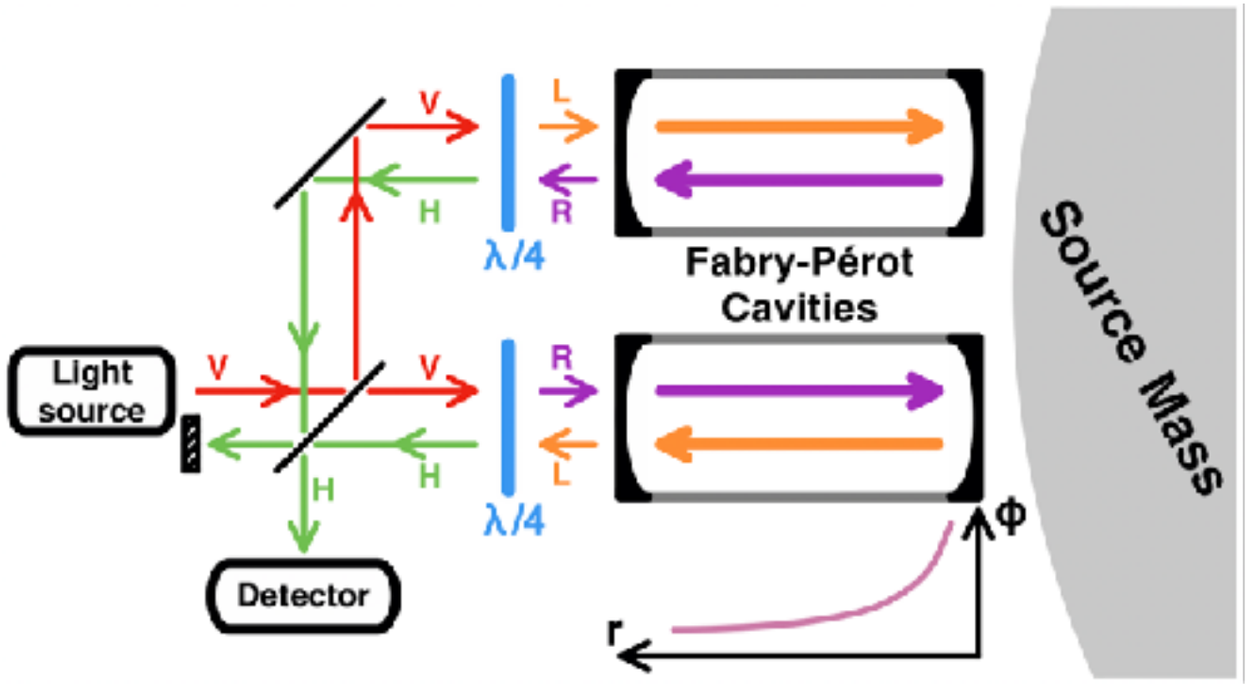




Attractor causes ‘blueshift’ of photon from Mossbauer line

Gratta, DEK, Rajendran, *Phys.Rev.D* 102 (2020) 115031

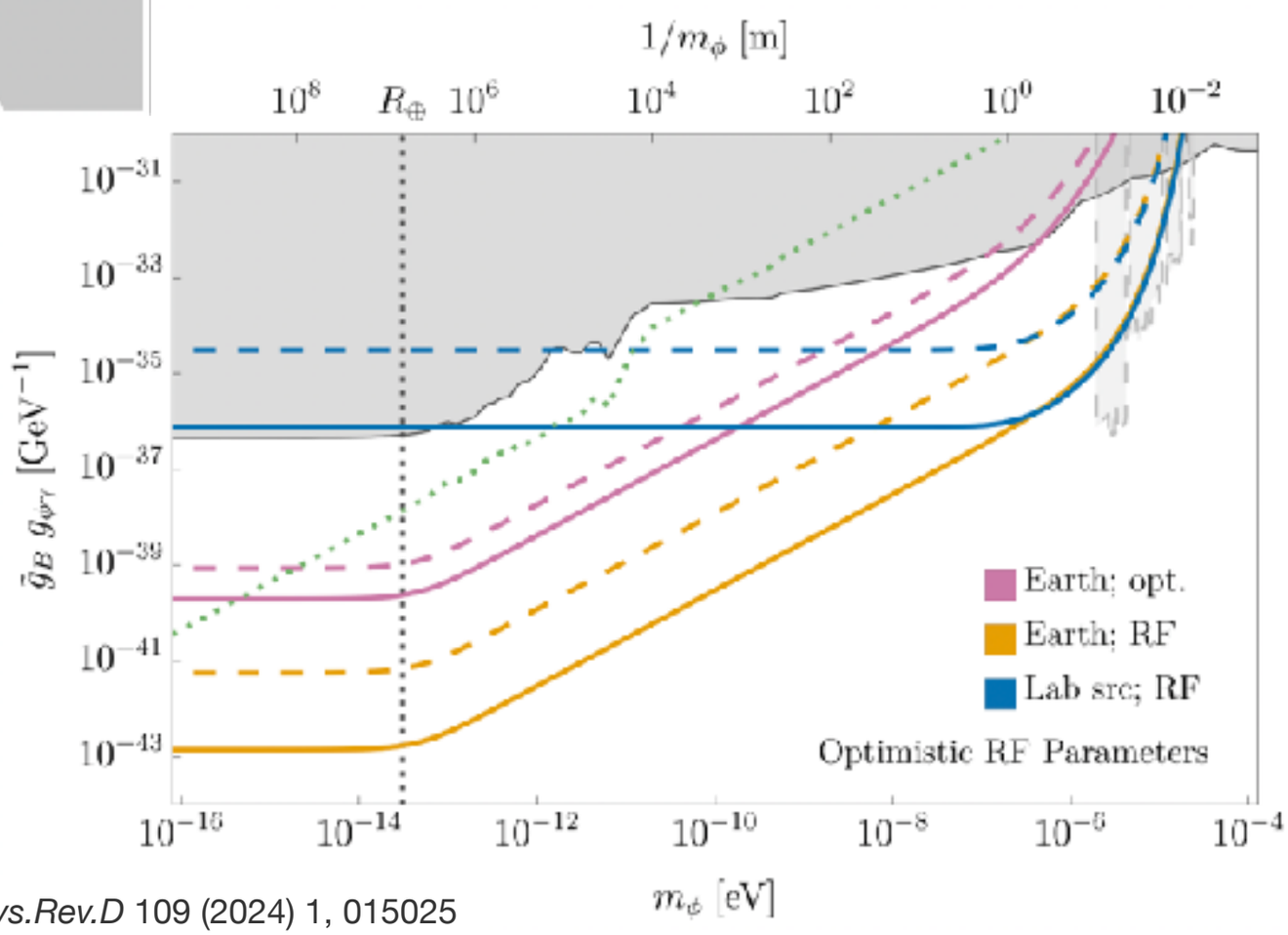
Monopole-Dipole Forces



Pseudo-scalar (ALP) with small CPV coupling

Field gradient causes polarization rotation in light

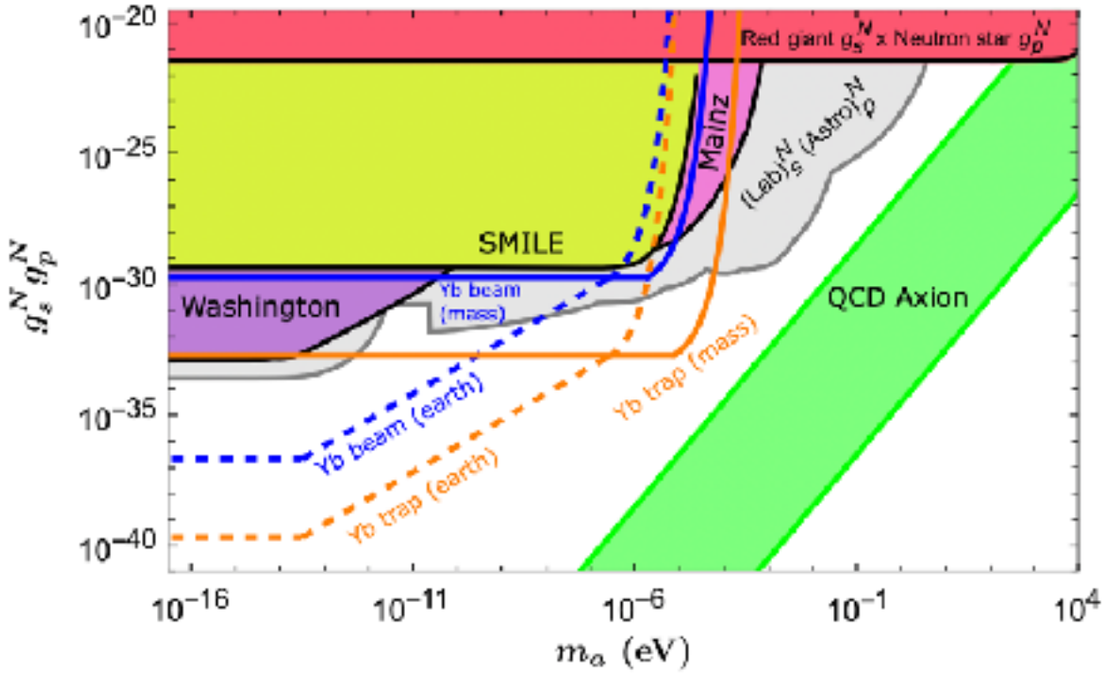
Source of field a mass in the lab or the Earth itself!



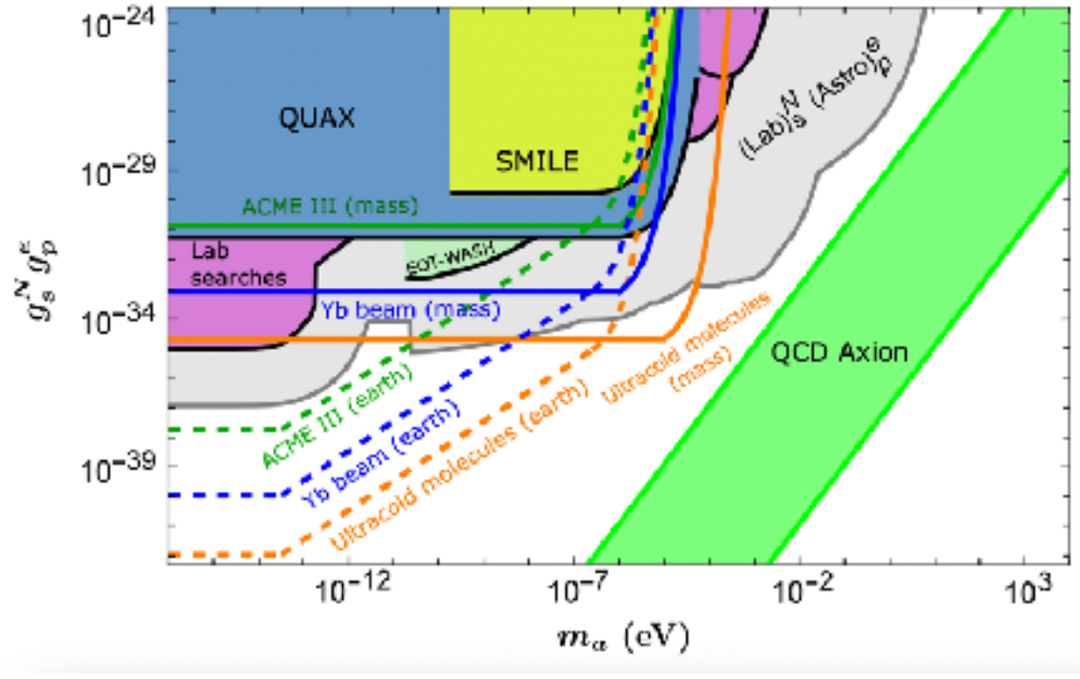
Fedderke, Thompson, Cervantes, Giaccone, Harnik, DEK, Rajendran, *Phys.Rev.D* 109 (2024) 1, 015025

Monopole-Dipole Forces

Spin precession detection:
ACME III molecules and other cold atoms & molecules with co-magnetometer states



Agrawal, Hutzler, DEK, Rajendran, Reig, *JHEP* 07 (2024) 133



Also storage rings:

Agrawal, DEK, Kim, Rajendran, Reig, *Phys.Rev.D* 108 (2023) 1, 015017

And atom interferometers:

Abe, Hogan, DEK, Overstreet, Rajendran, arXiv:2409.14793

Dark Energy

Dark Energy

Cosmological constant is the simplest: $$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{1}{M_p^2} \left(T_{\mu\nu} + g_{\mu\nu} \Lambda \right)$$

Dark Energy

Cosmological constant is the simplest: $$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{1}{M_p^2} \left(T_{\mu\nu} + g_{\mu\nu} \Lambda \right)$$

Cosmological constant is ridiculous:

In QFT, naive estimate $$\langle T_{\mu\nu} g^{\mu\nu} \rangle \sim M_p^4$$

naive minimum estimate $$\langle T_{\mu\nu} g^{\mu\nu} \rangle \sim (\mathrm{TeV})^4$$

measured value $$\langle T_{\mu\nu} g^{\mu\nu} \rangle \sim (10^{-3}\,\mathrm{eV})^4 \sim 10^{-123} M_p^4$$

Dark Energy

Cosmological constant is the simplest: $$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{1}{M_p^2} \left(T_{\mu\nu} + g_{\mu\nu} \Lambda \right)$$

Cosmological constant problem (paradox, enigma, puzzle, curiosity,…):

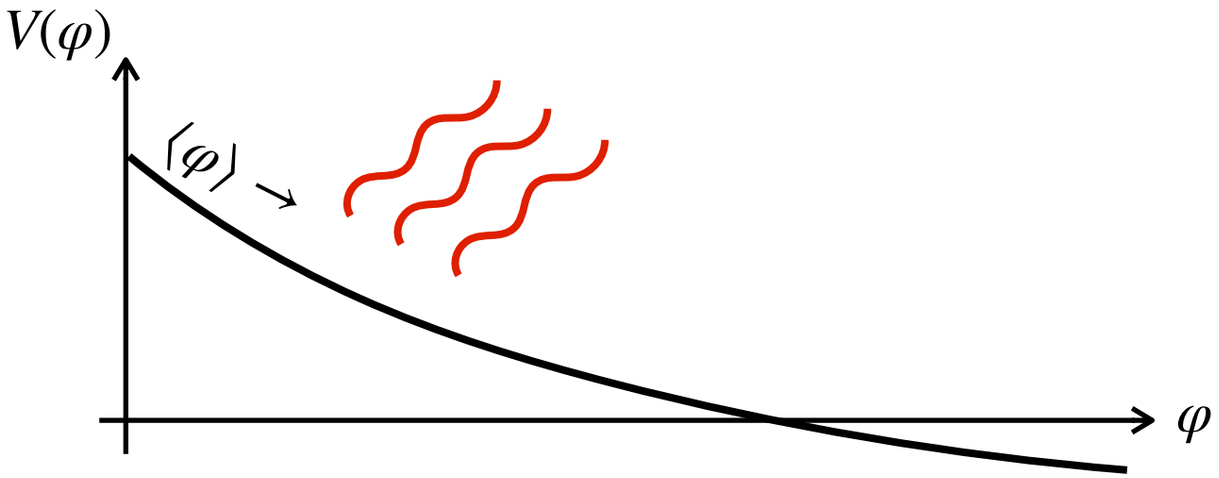
Quick solution — fine tuning accident? (one part in 10^{123})

No-mess solution — anthropic dependence, some kind of multiverse

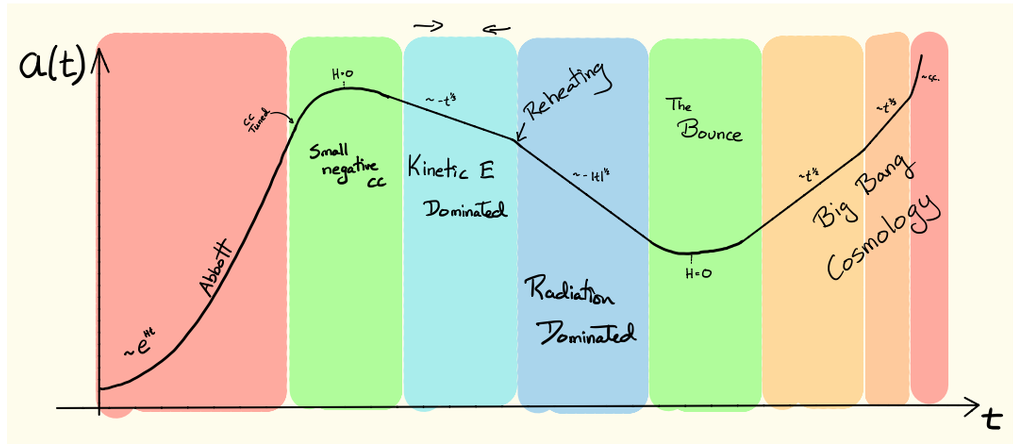
Leading dynamical solution — relaxation of value in early universe

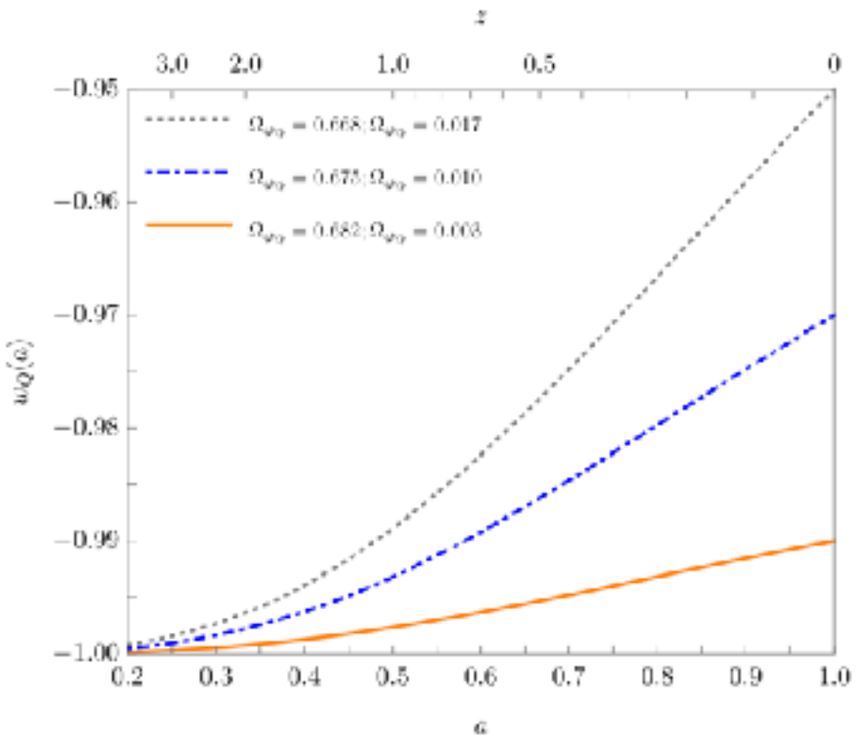
Dark Energy

rolling scalar field



Inflate, contract, reheat, bounce, expand





Dark Energy Equation of State

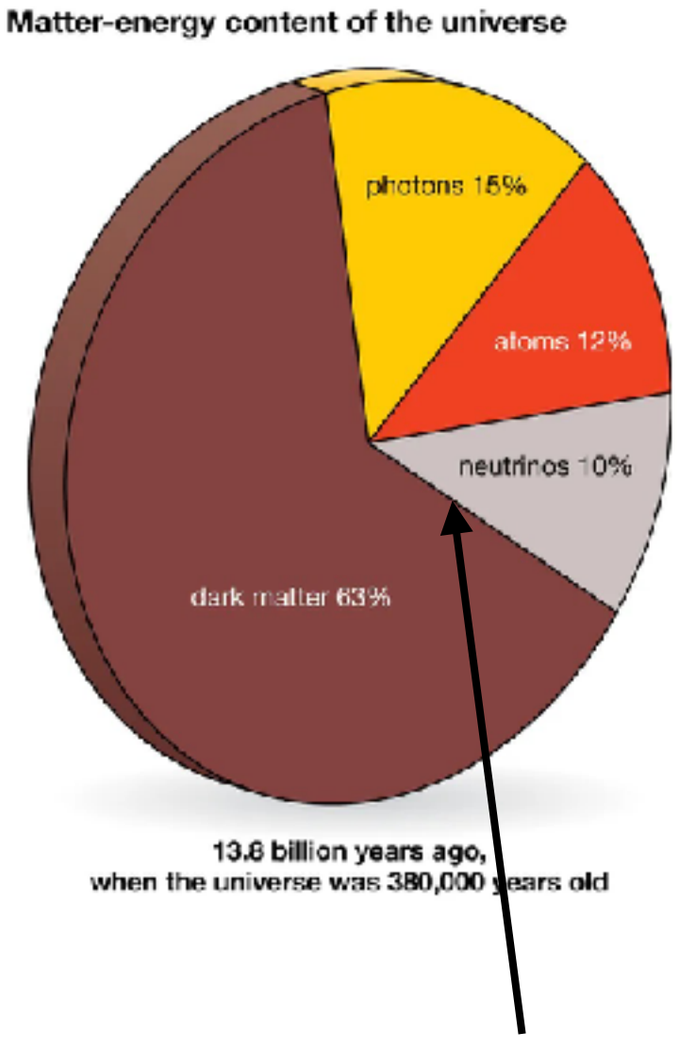
Dark energy: slowly evolving with:

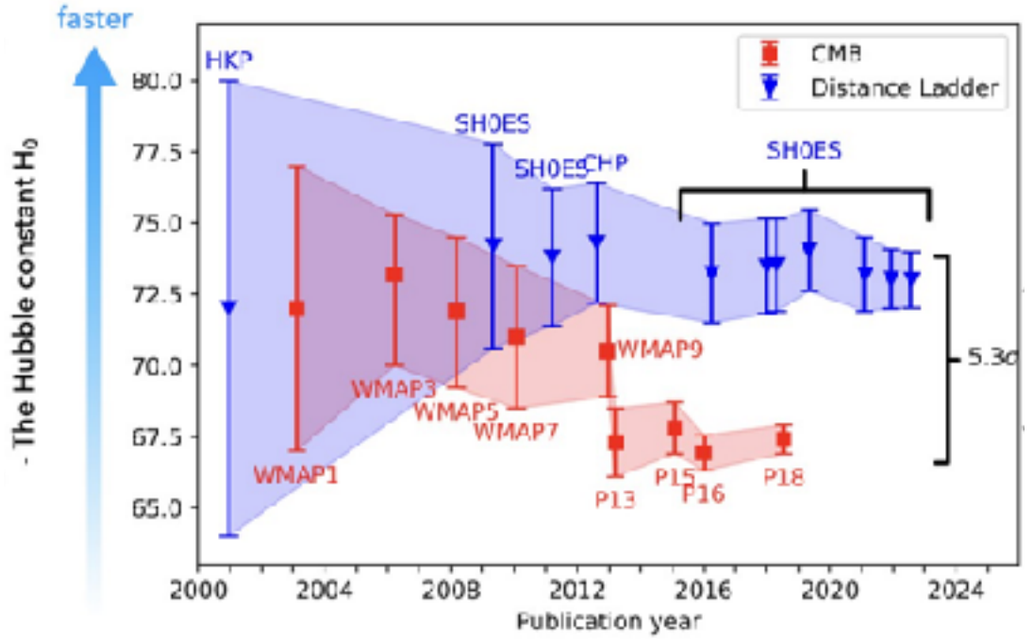
- Hubble friction
- Particle production

The latter —> dark radiation

Berghaus, Graham, DEK, Moore, Rajendran, *Phys.Rev.D* 104 (2021) 8, 083520

Dark Radiation





Hubble Tension may require additional radiation

Dark radiation at CMB — up to 100 GHz today

Dark radiation from dark energy — up to 1 THz today

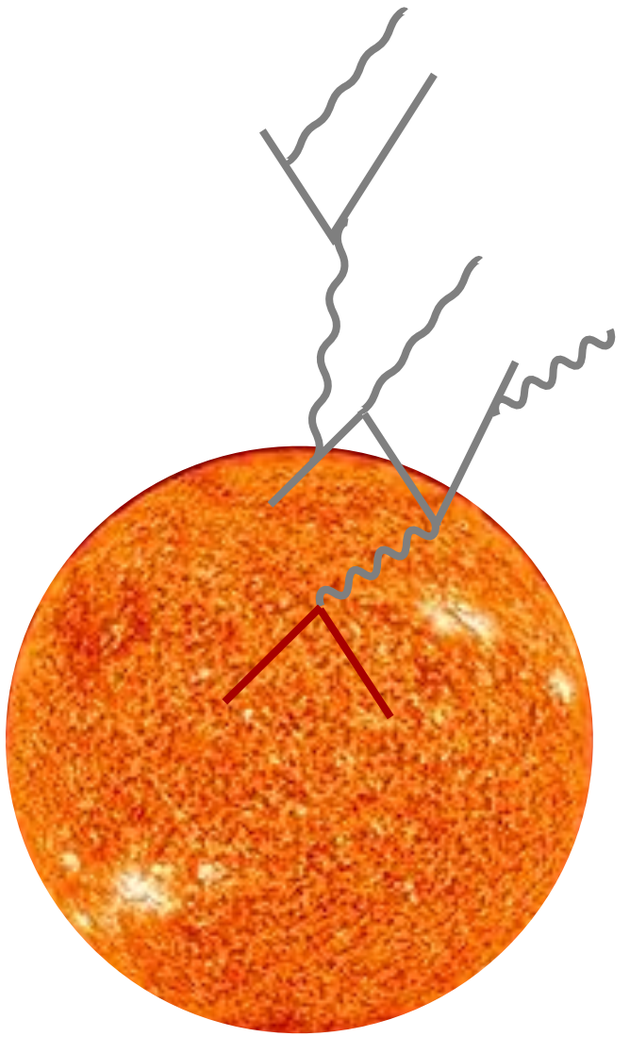
There is room here

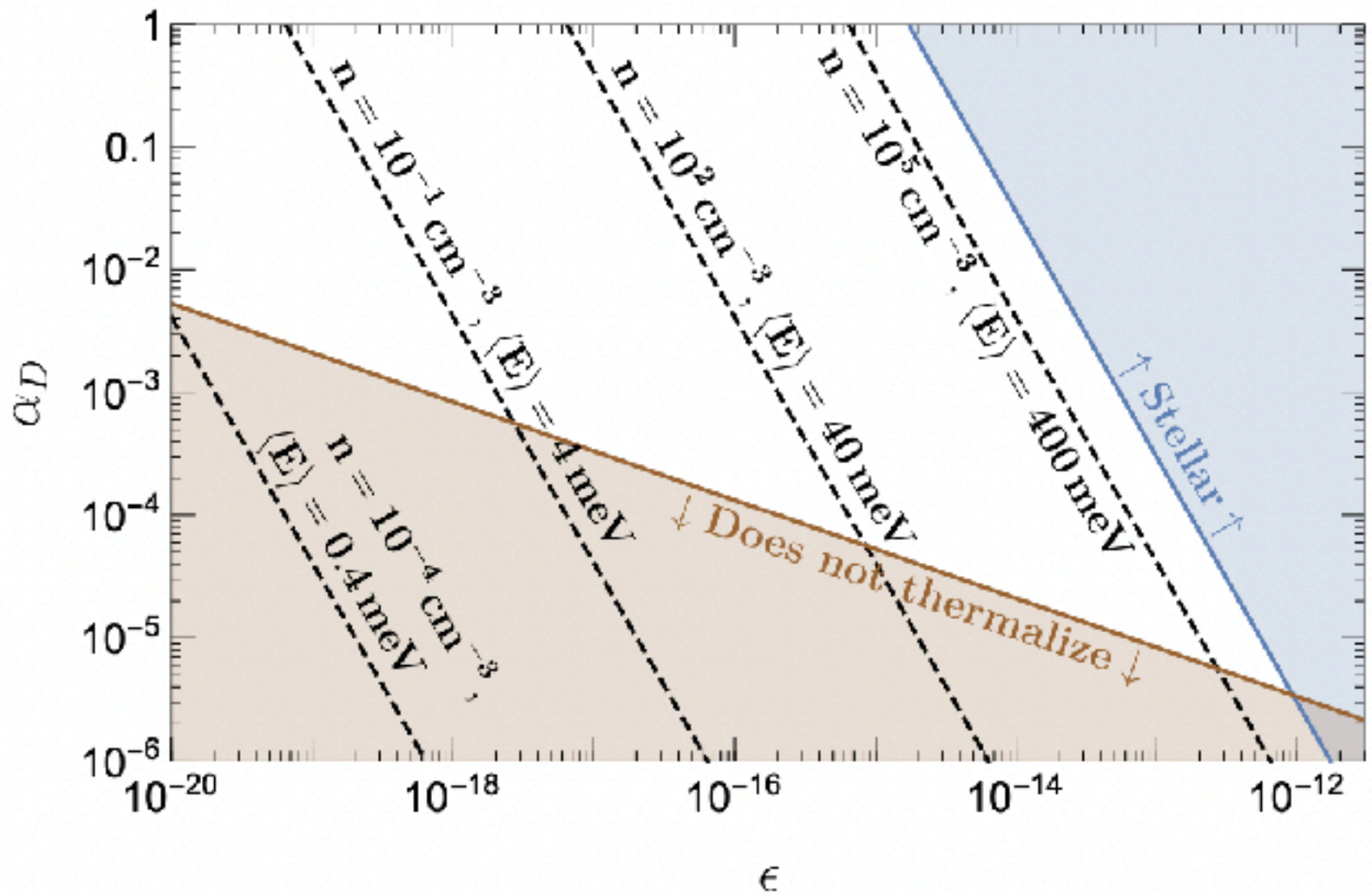
Dark radiation emitted from stellar cores, late-time decays (x-rays, gamma-rays, UHE)

Dark Radiation

Dark Solar Wind

Weakly coupled to us
strongly coupled to itself…

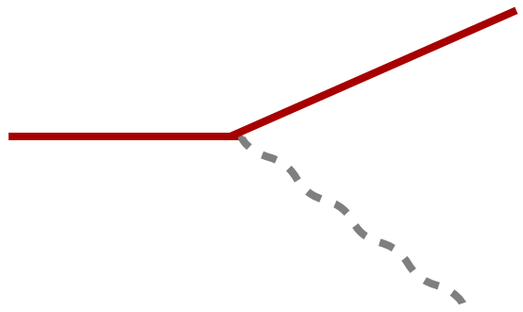




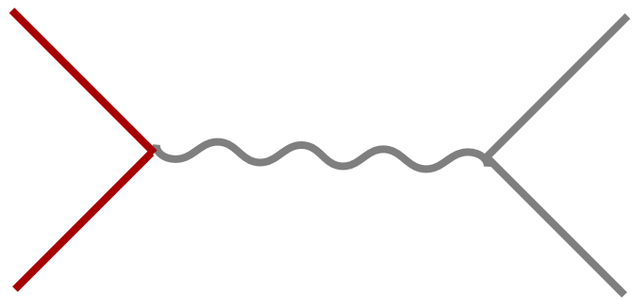
Chang, DEK, Rajendran, Ramani, Tanin, *Phys.Rev.Lett.* 129 (2022) 21, 211101

Violate SR: Backgrounds

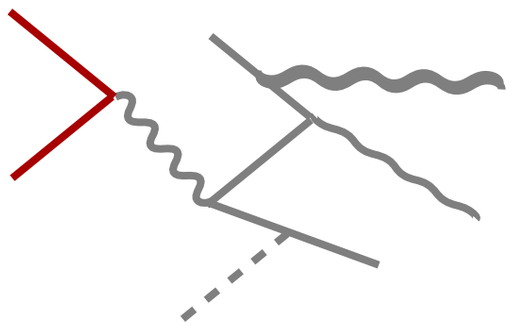
DM could be a gas of 1-particle type
(one new field added to the SM)



Dark sector could be 2-particles
(*e.g.*, mediator)



Dark sector could be many particles
(composite, inelastic)



Could it be zero particles?
('gross misunderstanding of gravity'?)

Ehrenfest

$$\left[\hat{q}_i, \hat{p}^j\right] = i\delta_i^j$$

for $H = \frac{p^2}{2m} + V(q)$

$$\partial_t q_i \;=\; i\left[H, q_i\right] \;=\; \frac{\partial H}{\partial p^i} \;=\; \frac{p_i}{m}$$

$$\partial_t p^i \;=\; i\left[H, p^i\right] = \;-\frac{\partial H}{\partial q_i} \;=\; -\frac{\partial V(q)}{\partial q_i}$$

(up to commutators)

Note: If there is a q_k without a p_k, we lose an e.o.m.

EM

classical: $$S = \int d^4x \mathscr{L} = \int d^4x \left[-\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - A_\mu J^\mu + \cdots \right]$$

Gauss' Law $$\frac{\delta S}{\delta A_0} = \underbrace{\partial_\mu F^{\mu 0}}_{\nabla \cdot E} - J^0 = 0$$

Ampere's Law $$\frac{\delta S}{\delta A_i} = \underbrace{\partial_\mu F^{\mu i}}_{\dot{E} + \nabla \times B} - J^i = 0$$

conjugate momenta:

$$\pi^i \equiv \frac{\delta \mathscr{L}}{\delta \dot{A}_i} = \partial^0 A^i - \partial^i A^0 \equiv - E^i$$

$$\pi^0 \equiv \frac{\delta \mathscr{L}}{\delta \dot{A}_0} = 0$$

Gauge freedom: choose: $A_0 = 0$

EM

From the Schrödinger Eq:

$$\partial_t \langle \mathbf{A} \rangle = i \langle \left[H, \mathbf{A} \right] \rangle = \langle \mathbf{E} \rangle$$

$$\partial_t \langle \mathbf{E} \rangle = i \langle \left[H, \mathbf{E} \right] \rangle = \langle \nabla \times \mathbf{B} - \mathbf{J} \rangle$$ Ampere's Law

Gauss' Law? $$G \equiv \nabla \cdot \mathbf{E} - J^0$$

Note: $$\left[H, G \right] = 0$$ (G's conjugate doesn't appear!)

Require: $$G \left| \psi \right\rangle_{\text{phys}} = 0$$

EM

Ampere's Law

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

Gauss' Law

$$G \equiv \nabla \cdot \mathbf{E} - J^0$$

$$G \left| \psi \right\rangle_{\text{phys}} = 0$$

EM

Ampere's Law $$\partial_t \langle \mathbf{E} \rangle = i \langle \left[H, \mathbf{E} \right] \rangle = \langle \nabla \times \mathbf{B} + \mathbf{J} \rangle$$

Gauss' Law $$G \equiv \nabla \cdot \mathbf{E} - J^0$$

$$G \left| \psi \right\rangle_{\text{phys}} = 0$$

Could instead require: $$G \left| \psi \right\rangle_{\text{phys}} = \rho_{\text{sh}}(\mathbf{x}) \left| \psi \right\rangle_{\text{phys}}$$

Appears as normal QED, with a static b.g. charge density

$$\langle \nabla \cdot \mathbf{E} - J^0 - \rho_{\text{sh}}(\mathbf{x}) \rangle = 0$$

GR: homogeneous

zero-mode only (FRW): $ds^2 = -N(t)^2 dt^2 + a(t)^2 d\mathbf{x}^2$

classical: $$S = \int d^4x\sqrt{-g}\,\Big(\; M_{\rm pl}^2 R \;+ \underbrace{\mathscr{L}_{\rm matter}(\phi)}_{g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi+\cdots}\Big) \;+\; S_{GHY}$$

$$\left.\frac{\delta S}{\delta N}\right|_{N=1} = a^3\left(6M_{\rm pl}^2\frac{\dot{a}^2}{a^2} - \frac{1}{2}\dot{\phi}^2 - V(\phi)\right) = 0$$ 1st Friedmann Eq

$$\left.\frac{\delta S}{\delta a}\right|_{N=1} = 3a^2\left(4M_{\rm pl}^2\left(\frac{\ddot{a}}{a} + \frac{\dot{a}^2}{2a^2}\right) + \frac{1}{2}\dot{\phi}^2 - V(\phi)\right) = 0$$ 2nd Friedmann Eq

GR: homogeneous

conjugate momenta:

$$\pi_a \equiv \frac{\delta \mathscr{L}}{\delta \dot{a}} = -\,6 M_{\rm pl}^2 \frac{a\dot{a}}{N} \qquad \pi_N \equiv \frac{\delta \mathscr{L}}{\delta \dot{N}} = 0 \qquad \pi_\phi = \frac{\delta \mathscr{L}}{\delta \dot{\phi}} = \frac{a^3}{N}\dot{\phi}$$

GR: homogeneous

conjugate momenta:

$$\pi_a \equiv \frac{\delta \mathscr{L}}{\delta \dot{a}} = -\,6M_{\rm pl}^2\,\frac{a\dot{a}}{N}$$

$$\pi_N \equiv \frac{\delta \mathscr{L}}{\delta \dot{N}} = 0$$

$$\pi_\phi = \frac{\delta \mathscr{L}}{\delta \dot{\phi}} = \frac{a^3}{N}\dot{\phi}$$

Hamiltonian:

$$H = \left[\pi\dot{a} + \pi_\phi\dot{\phi} - \mathscr{L}\right]_{\dot{a}=\cdots,\dot{\phi}=\cdots} = -\,\frac{N}{24M_{pl}^2 a}\pi^2 + \frac{N}{2a^3}\pi_\phi^2 + Na^3V(\phi)$$

$$= N\tilde{H}(\pi_a, a, \pi_\phi, \phi)$$

GR: homogeneous

Schrödinger eq:

$$i\frac{d}{dt}|\psi\rangle = N(t)\,\tilde{H}\,|\psi\rangle \qquad \rightarrow i\frac{d}{N(t)dt}|\psi\rangle = \tilde{H}\,|\psi\rangle$$

Simple choice: $N = 1$

GR: homogeneous

Schrödinger eq:

$$i\frac{d}{dt}|\psi\rangle = N(t)\,\tilde{H}\,|\psi\rangle \qquad \rightarrow i\frac{d}{N(t)dt}|\psi\rangle = \tilde{H}\,|\psi\rangle$$

Simple choice: $N = 1$

$\partial_t\langle a\rangle = i\langle[H,a]\rangle \rightarrow \langle\pi_a\rangle = \langle -6M_{\rm pl}a\dot{a}\rangle$ (choosing operator ordering wisely)

$\partial_t\langle\pi_a\rangle = i\langle\left[H,\pi_a\right]\rangle \rightarrow$

$$\longrightarrow \frac{\ddot{a}}{a} + \frac{1}{2}\left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{M_{\rm pl}^2}p$$ 2nd Friedmann Eq

$$p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

GR: homogeneous

1st Friedmann Eq? From classical:

$$0 = \frac{\delta S}{\delta N} = \frac{\delta \int \pi_a \dot{a} + \pi_\phi \dot{\phi} - N\tilde{H}}{\delta N} \longrightarrow \tilde{H} = 0$$

Simple fix: $\langle \psi | H | \psi \rangle = 0$

For classical states: $\tilde{H} = a^3 \left(3M_{\rm pl}^2 \left(\frac{\dot{a}}{a} \right)^2 - \rho \right) = 0$

$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

GR: homogeneous

Could choose: $\langle\psi|\tilde{H}|\psi\rangle = \mathbb{C}$

$\mathbb{C}$ is constant as $\left[\tilde{H},\tilde{H}\right] = 0$

For classical states: $\tilde{H} = a^3\left(3M_{\rm pl}^2\left(\frac{\dot{a}}{a}\right)^2 - \rho\right) = \mathbb{C}$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{3M_{\rm pl}^2}\left(\rho + \frac{\mathbb{C}}{a^3}\right)$$

behaves as another matter component

Katherine-Burns, DEK, Melia, Rajendran, arXiv: 2204.03043
DEK, Melia, Rajendran, arXiv: 2305.01798, 2307.09475

GR

$$S = \int d^4x \, (\underbrace{\sqrt{-g}\, M_{\rm pl}^2 R \;+\; \sqrt{-g}\, \mathscr{L}_{\rm matter}(\phi)}_{\mathscr{L}_g}) \;+\; S_{GHY}$$

classical:
$$\frac{\delta S}{\delta g_{\mu\nu}} = \sqrt{-g}\, \left(M_{\rm pl}^2 G^{\mu\nu} - T^{\mu\nu} \right) = 0$$

conjugates:
$$\frac{\delta \mathscr{L}_g}{\delta \dot{g}_{ij}} \equiv \pi^{ij}$$

$$\frac{\delta \mathscr{L}_g}{\delta \dot{g}_{0\mu}} = 0$$

GR

limit: $\mathbb{P}^i = 0$

if $\mathbb{H}(\mathbf{x}) > 0$ everywhere, then can do a spatial coordinate redefinition:

$$\frac{\mathbb{H}(\mathbf{x})}{\sqrt{-g}} \longrightarrow \frac{\overline{\mathbb{H}}}{\sqrt{-g}}$$

Del Grosso, DEK, Melia, Poulin, Rajendran, Smith, arXiv: 2405.06374

GR

limit: $\mathbb{P}^i = 0$

if $\mathbb{H}(\mathbf{x}) > 0$ everywhere, then can do a spatial coordinate redefinition:

$$\frac{\mathbb{H}(\mathbf{x})}{\sqrt{-g}} \longrightarrow \frac{\overline{\mathbb{H}}}{\sqrt{-g}}$$

$$ds^2 = -dt^2 + a(t)^2(\delta_{ij} + h_{ij})dx^i dx^j \qquad\qquad h = h_{ij}\delta^{ij}$$

at linear order $$T^{00}_{\rm sh} = (\overline{\rho}_{\rm sh} + \delta\rho_{\rm sh}) = \frac{\overline{\mathbb{H}}}{\sqrt{-g}} \simeq \frac{\overline{\mathbb{H}}}{a^3}(1 - h/2)$$

$$\text{or } \dot{\delta} = -\dot{h}/2$$

Del Grosso, DEK, Melia, Poulin, Rajendran, Smith, arXiv: 2405.06374

GR

limit: $\mathbb{P}^i = 0$

if $\mathbb{H}(\mathbf{x}) > 0$ everywhere, then can do a spatial coordinate redefinition:

$$\frac{\mathbb{H}(\mathbf{x})}{\sqrt{-g}} \longrightarrow \frac{\overline{\mathbb{H}}}{\sqrt{-g}}$$

$$ds^2 = -dt^2 + a(t)^2(\delta_{ij} + h_{ij})dx^i dx^j \qquad h = h_{ij}\delta^{ij}$$

at linear order $$T^{00}_{\rm sh} = (\overline{\rho}_{\rm sh} + \delta\rho_{\rm sh}) = \frac{\overline{\mathbb{H}}}{\sqrt{-g}} \simeq \frac{\overline{\mathbb{H}}}{a^3}(1 - h/2)$$

$$\text{or } \dot{\delta} = -\dot{h}/2$$

Evolves as pressure-less dust!

Del Grosso, DEK, Melia, Poulin, Rajendran, Smith, arXiv: 2405.06374

GR + EM

covariant derivatives

$$\nabla_\mu F^{\mu\nu} = (J^\nu + J^\nu_{\rm sh}) \qquad\qquad \nabla_\mu J^\mu_{\rm sh} = 0$$

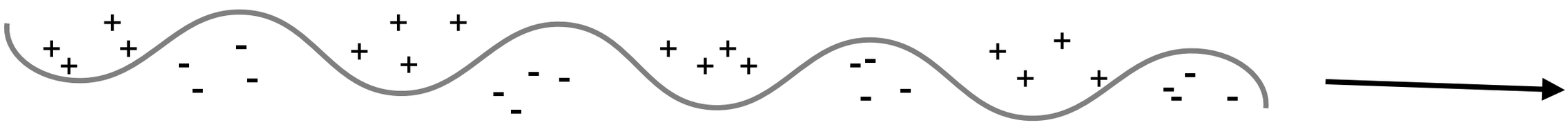
$$\sqrt{-g} J^\mu_{\rm sh} \equiv \{\mathbb{J}(\mathbf{x}), 0, 0, 0\}$$

time independent

$$J^\mu_{\rm sh} = \rho^{ch}_{\rm sh} v^\mu \qquad\qquad v^\mu = \{1, 0, 0, 0\}$$

synchronous gauge

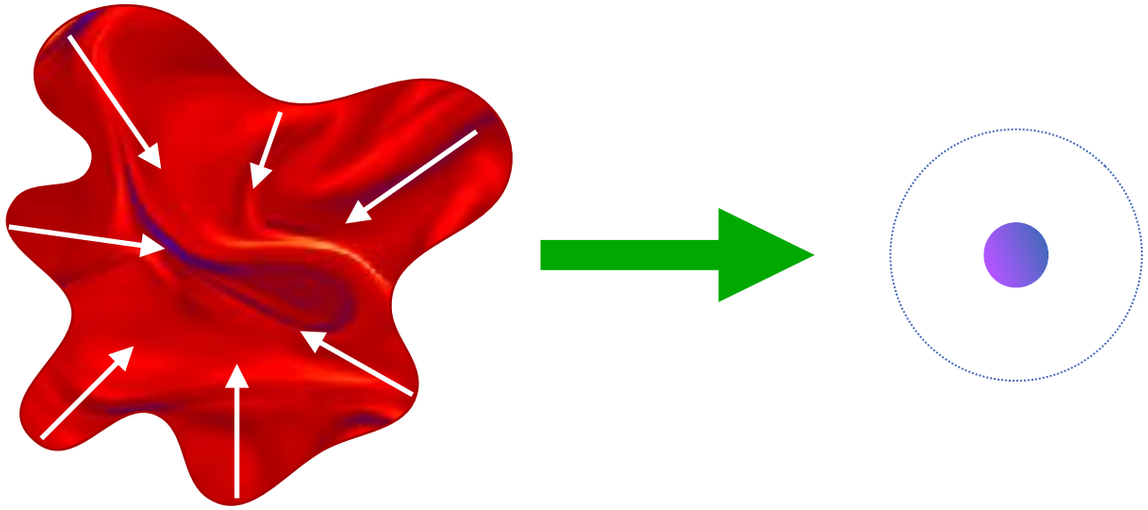
shadow charge density follows geodesics and
does not respond to electromagnetic fields



Del Grosso, DEK, Melia, Poulin, Rajendran, Smith, arXiv: 2405.06374

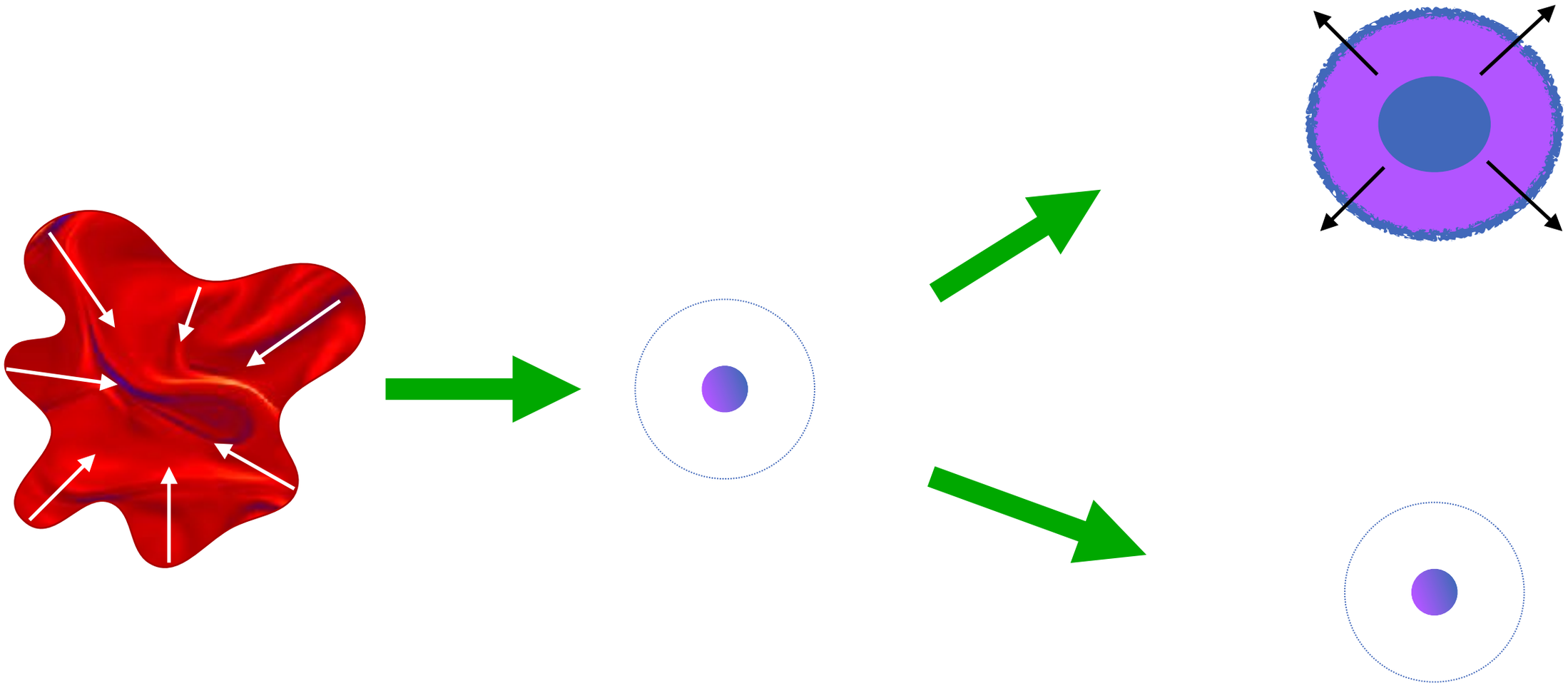
Violating GR

Where we are confident GR breaks down —
center of Black Hole collapse

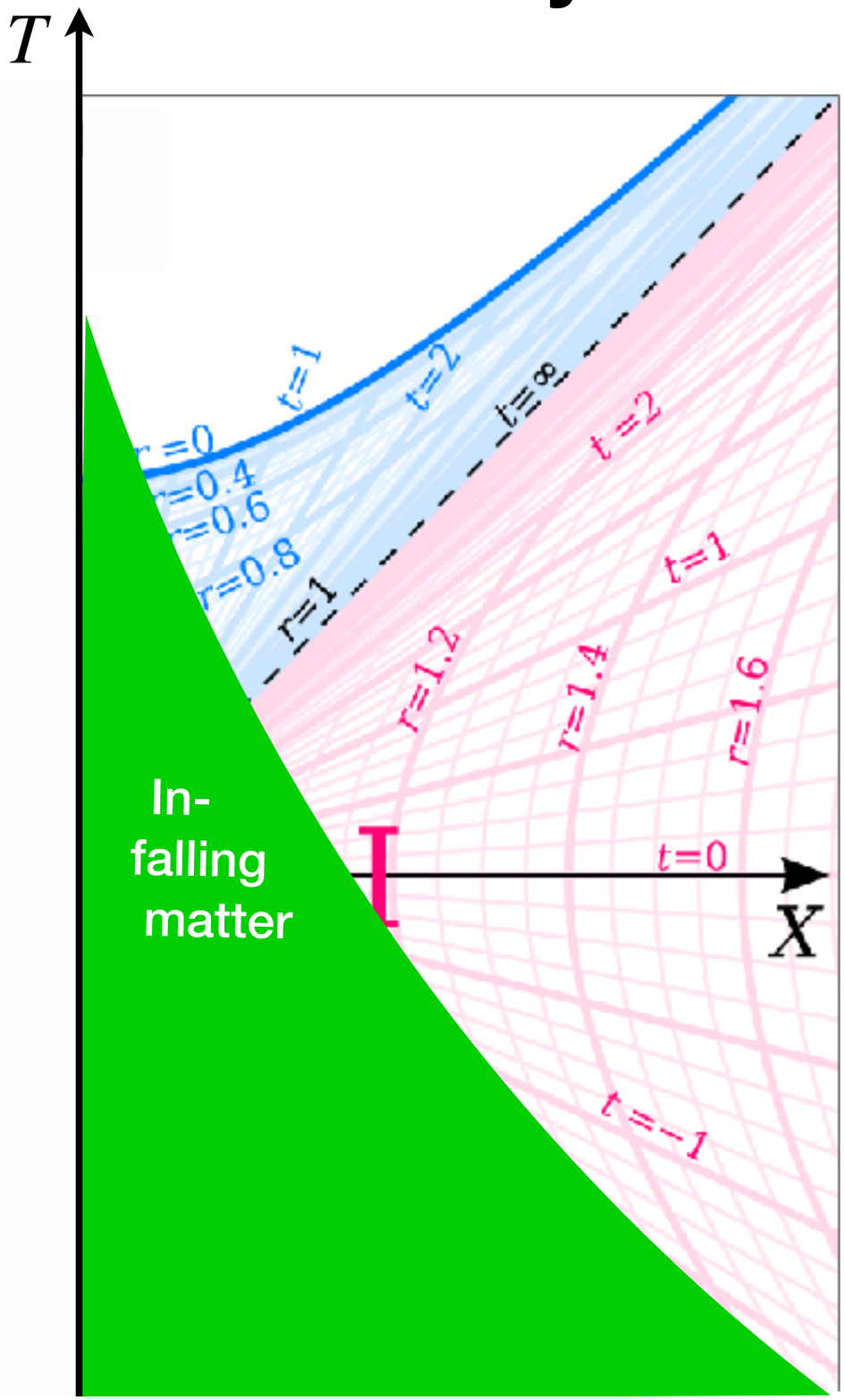


Violating GR

Where we are confident GR breaks down —
center of Black Hole collapse

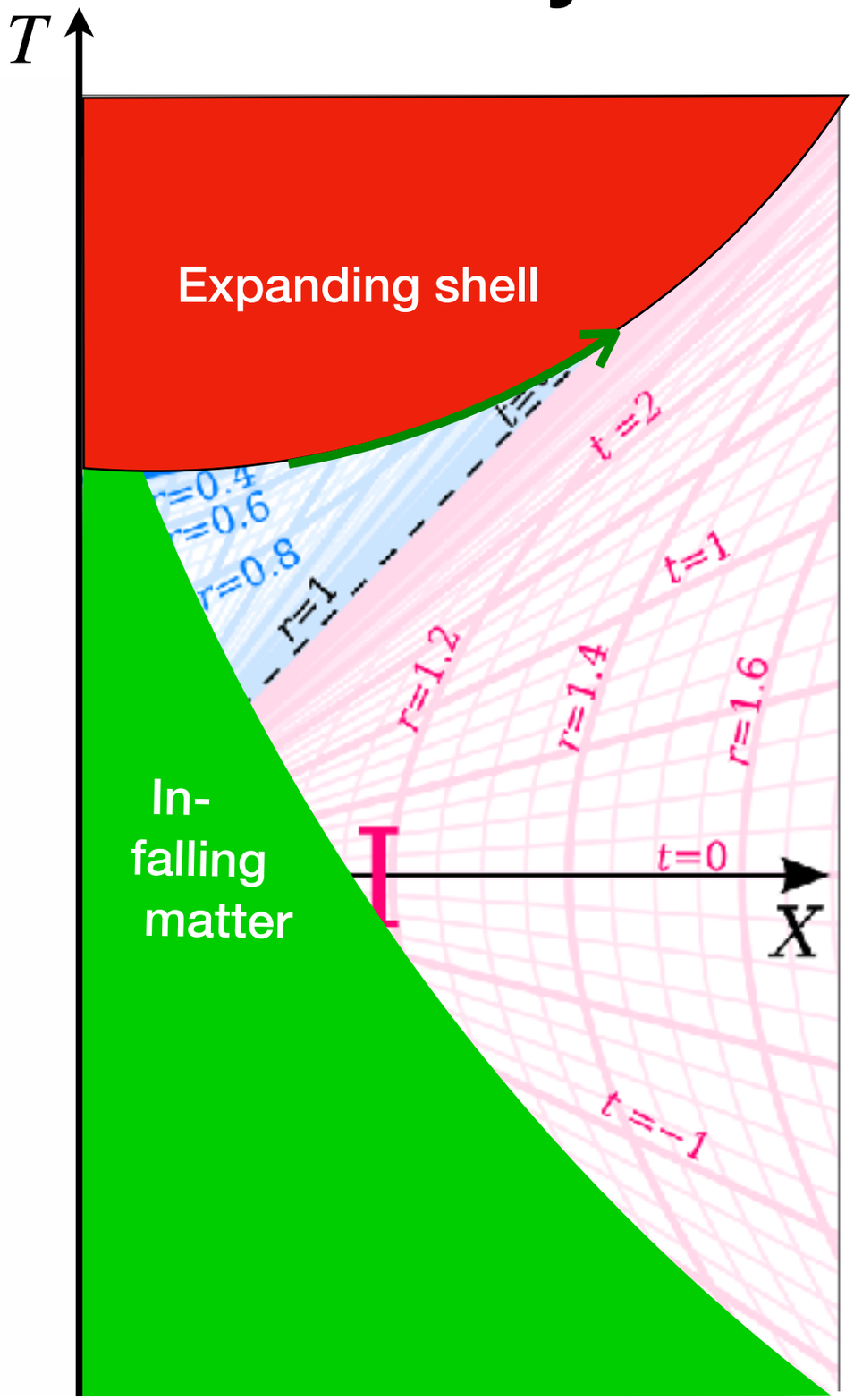


Causality-Preserving Expansion



In-falling matter collapses through horizon following GR trajectories.

Causality-Preserving Expansion



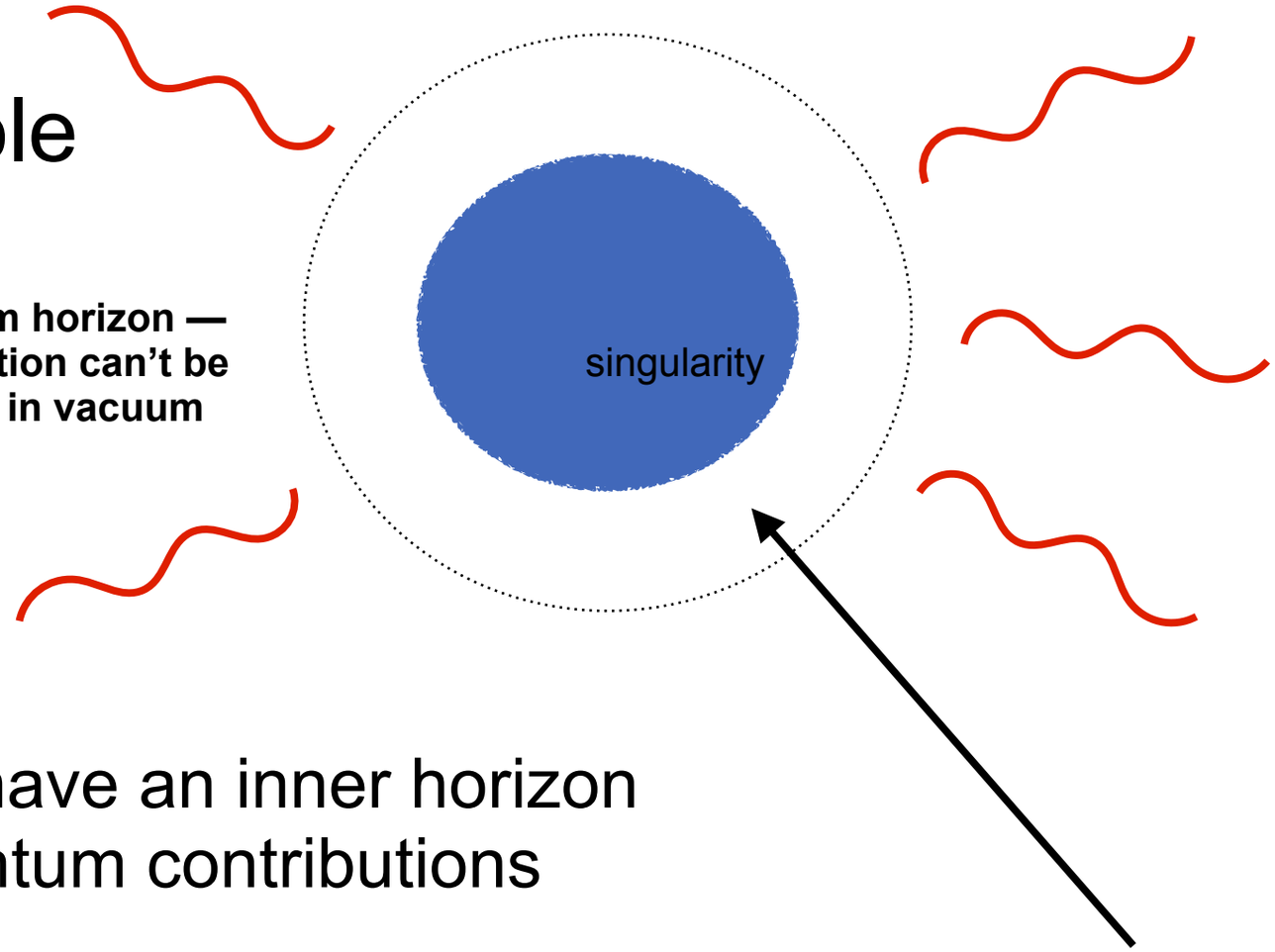
In-falling matter collapses through horizon following GR trajectories.

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

Geometry is convenient, but not fundamental.

Real Black Hole Firewall?

Rotating black hole

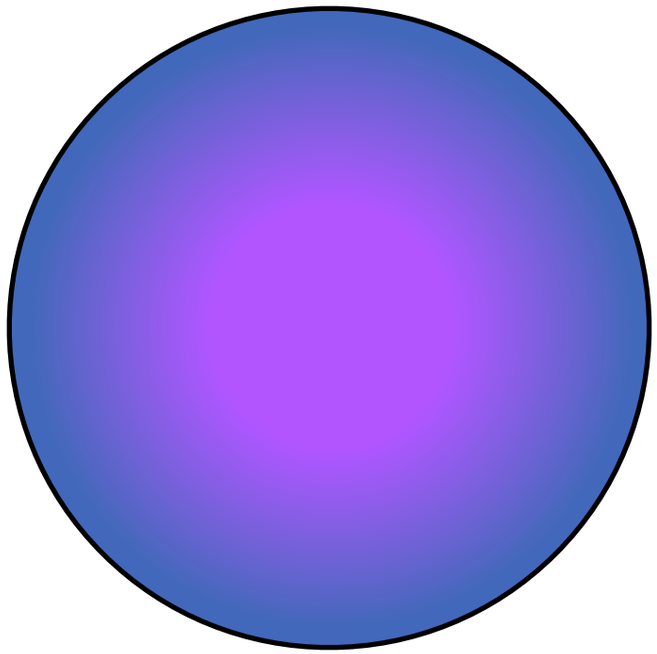


Spinning black holes have an inner horizon
with divergent quantum contributions

If Sagitarius A* has O(1) spin, it has an
inner firewall over 1,000,000 km across!

Signatures of Firewalls

Essentially impossible to see inside the photon sphere



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’?
Gravitational Wave Detectors

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

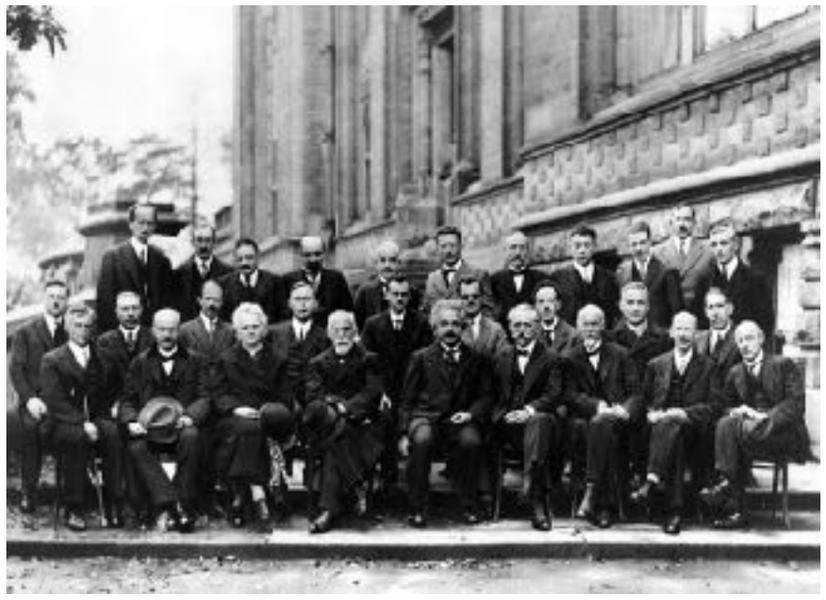
Even a small chance of seeing quantum gravity —
worth an all-out effort!!

Modify Quantum Mechanics?

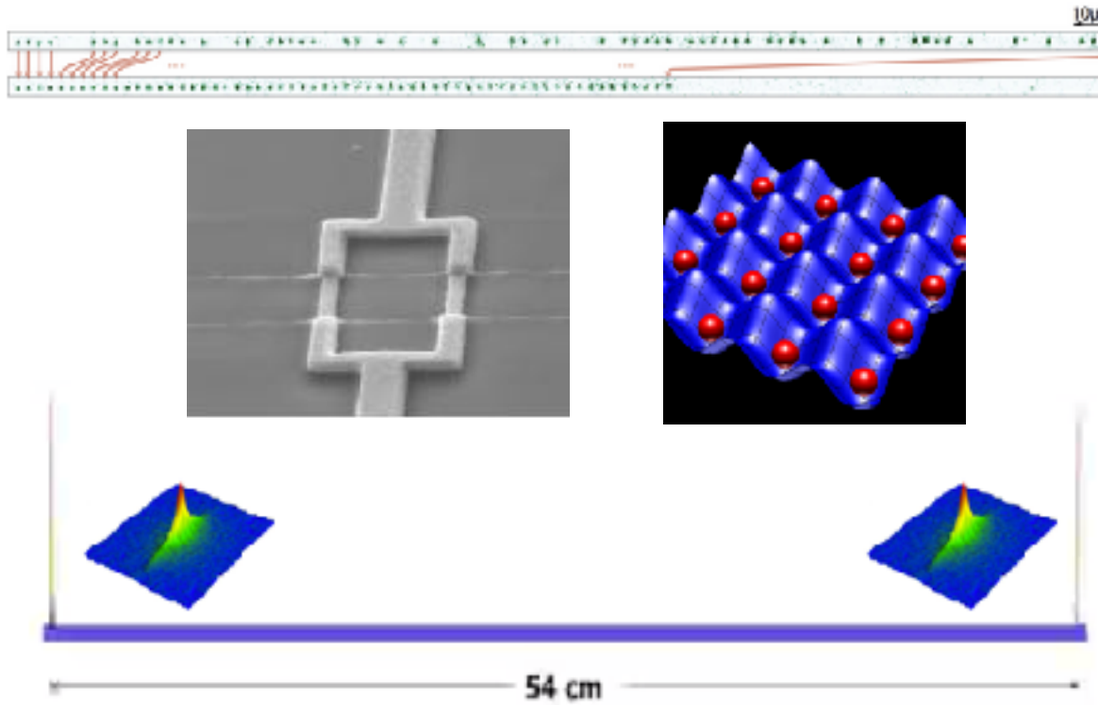
Why n(bergian)ot?

Modify Quantum Mechanics?

Why n(bergian)ot?



1927



2024

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:

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

DEK, Rajendran, *Phys.Rev.D* 105 (2022) 5, 055002

In Field Theory

Example: EM

"Linear" QFT $\mathscr{H} \supset eA_\mu J^\mu$

"Non Linear" QFT $\mathscr{H} \supset e\left(A_\mu + \epsilon\langle\chi|A_\mu|\chi\rangle\right)J^\mu$

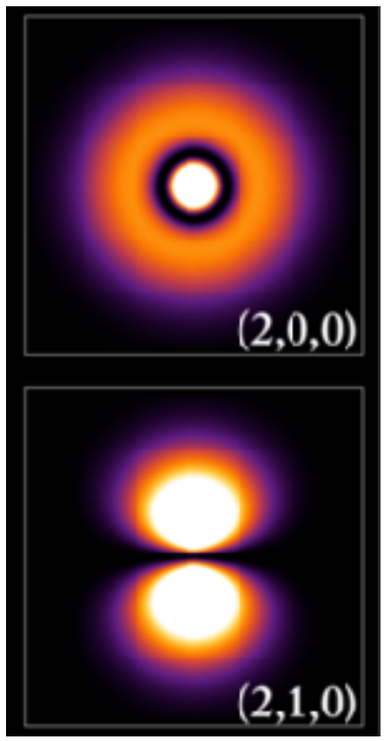
In Field Theory

Example: EM

"Linear" QFT $\mathscr{H} \supset eA_\mu J^\mu$

"Non Linear" QFT $\mathscr{H} \supset e\left(A_\mu + \epsilon\langle\chi|A_\mu|\chi\rangle\right)J^\mu$

Kibble wrote extensions like this (1978!)



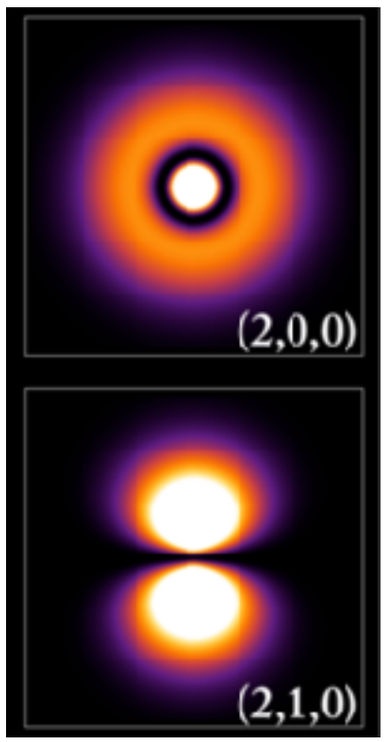
Constraints: Atomic Levels

What does this do to the Lamb Shift?

Say charged particles see their own w.f.:

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

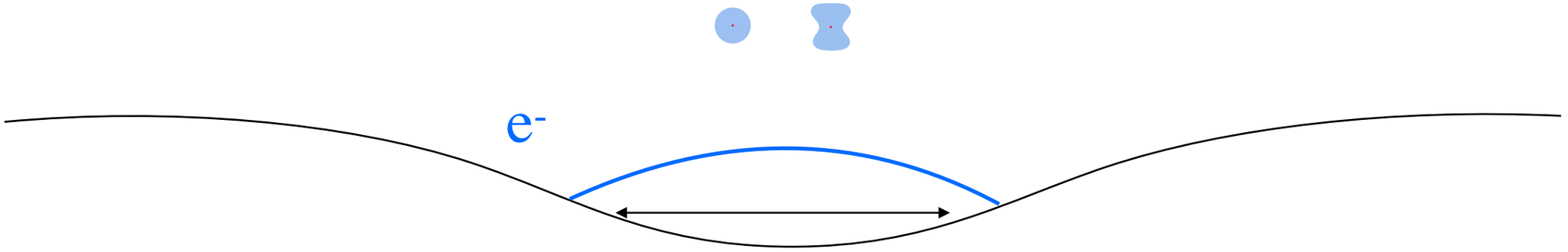
Constraints: Atomic Levels



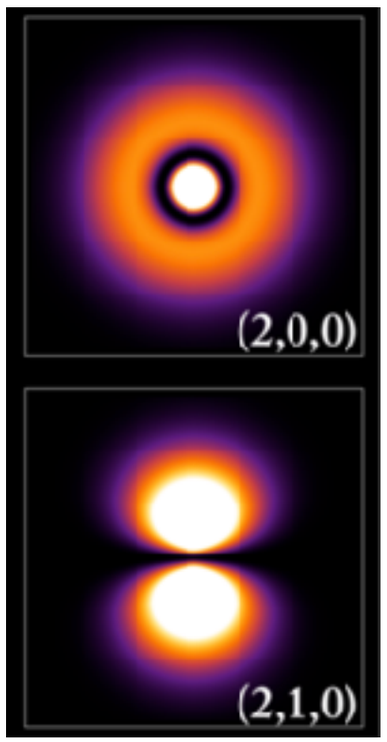
What does this do to the Lamb Shift?

Say charged particles see their own w.f.:

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



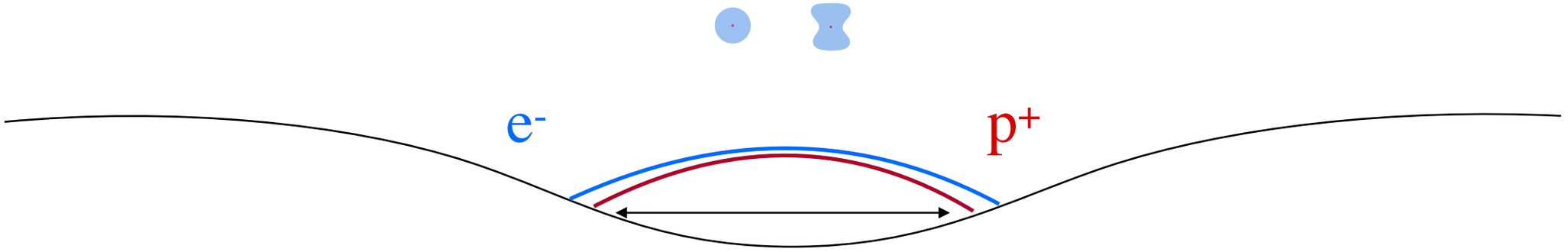
Constraints: Atomic Levels

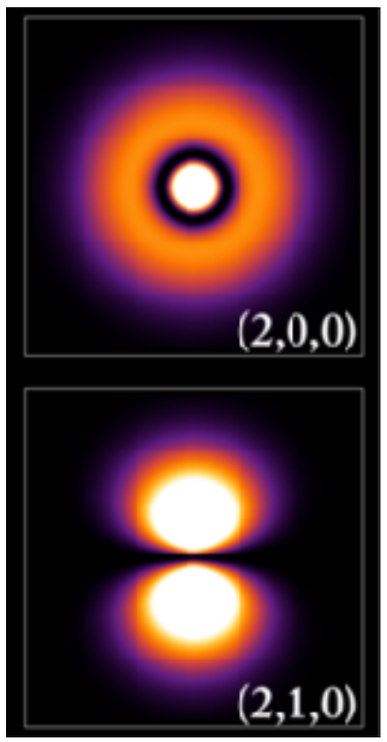


What does this do to the Lamb Shift?

Say charged particles see their own w.f.:

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



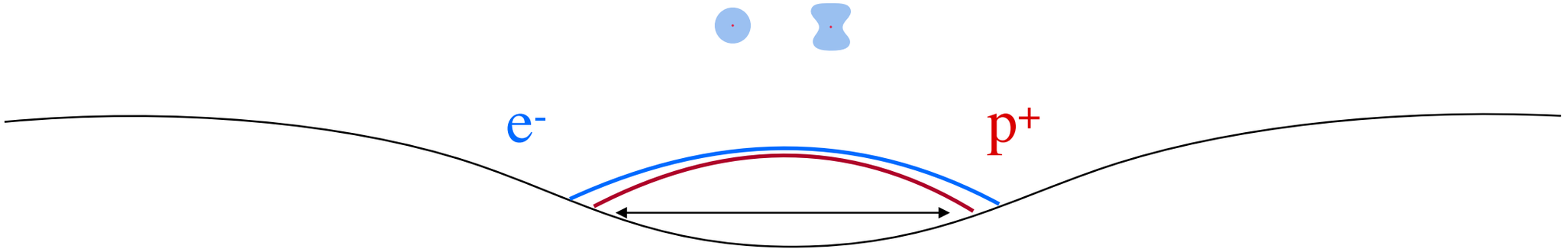


Constraints: Atomic Levels

What does this do to the Lamb Shift?

Say charged particles see their own w.f.:

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



Electron spread over the trap (micron) dilutes the electric field and thus the level splitting

Proton's wave function also produces a field that nearly **cancels the electron wave function**.

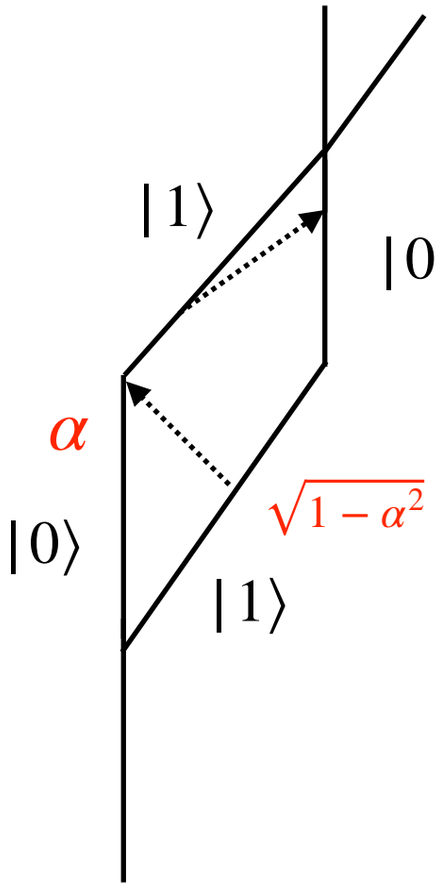
Key — center of mass coordinate cannot be separated from relative coordinate due to locality.

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

Experimental Tests: Local

Interferometry - interaction between paths

Take an ion - split its wave-function



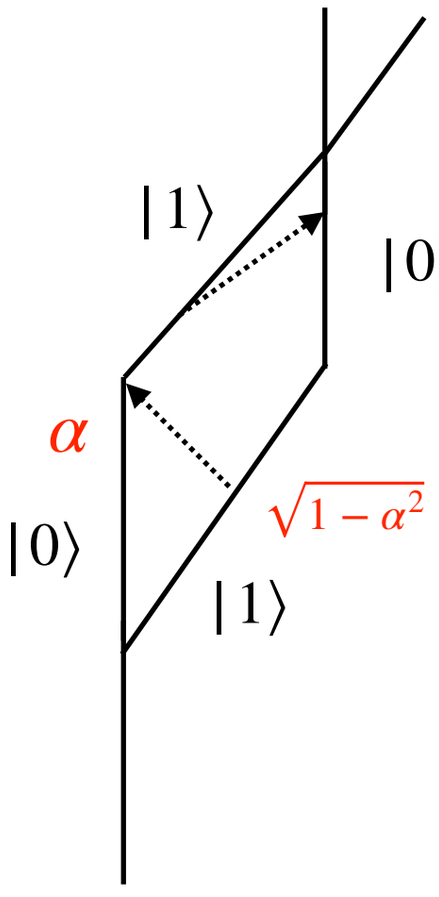
Coulomb Field of one path interacts with the other path

$$|\psi\rangle = \alpha|0\rangle + \sqrt{1-\alpha^2}\,|1\rangle$$

Experimental Tests: Local

Interferometry - interaction between paths

Take an ion - split its wave-function



Coulomb Field of one path interacts with the other path

$$|\psi\rangle = \alpha|0\rangle + \sqrt{1-\alpha^2}\,|1\rangle$$

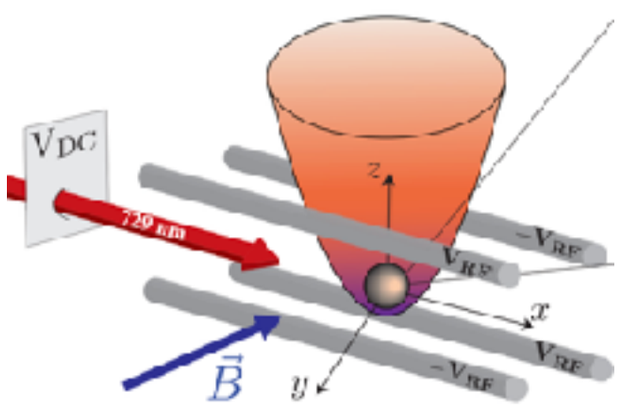
Gives rise to phase shift that depends on the intensity α^2 of the split

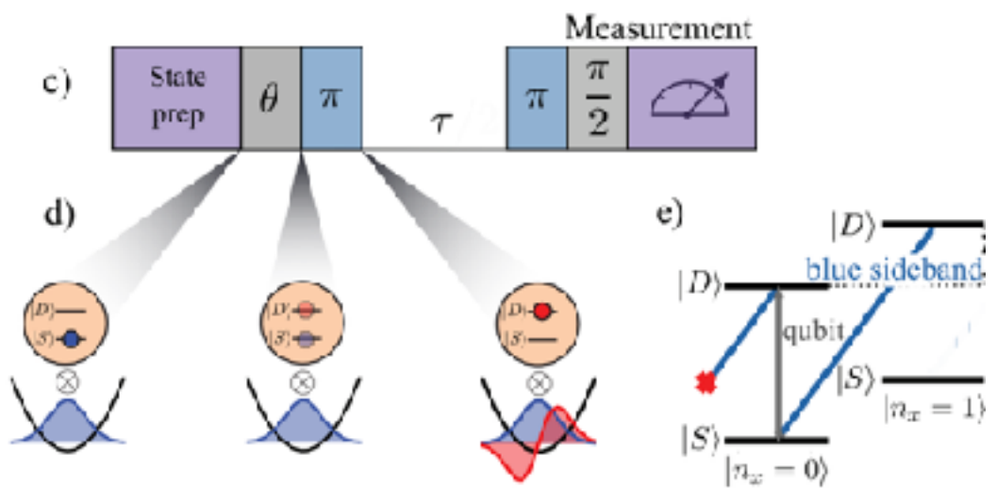
Could measure Born coefficients with a single measurement!

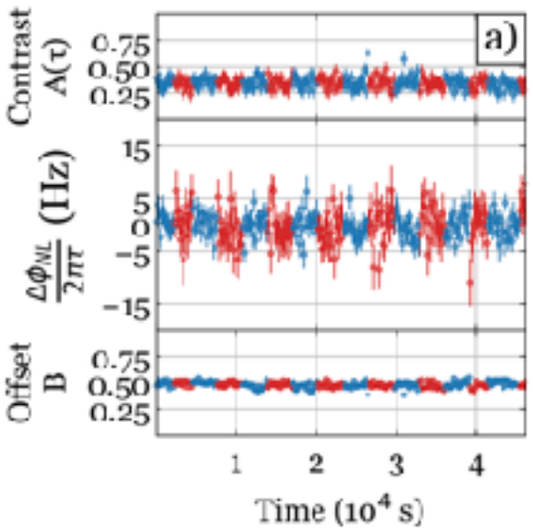
Test … Using a Vibrational Mode of a Trapped Ion

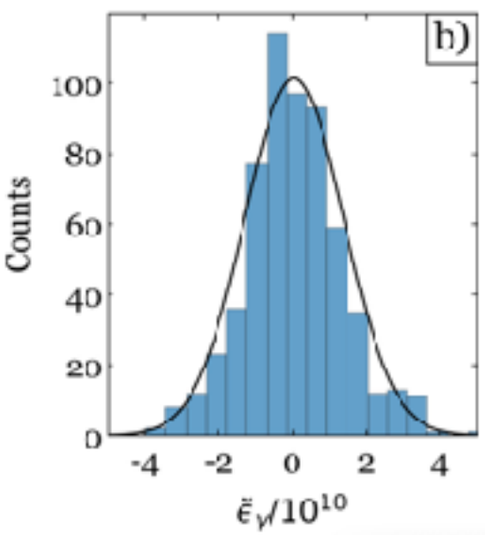
J. Broz, et al. (2022)

State: $|\psi\rangle = a|0\rangle + b|1\rangle$





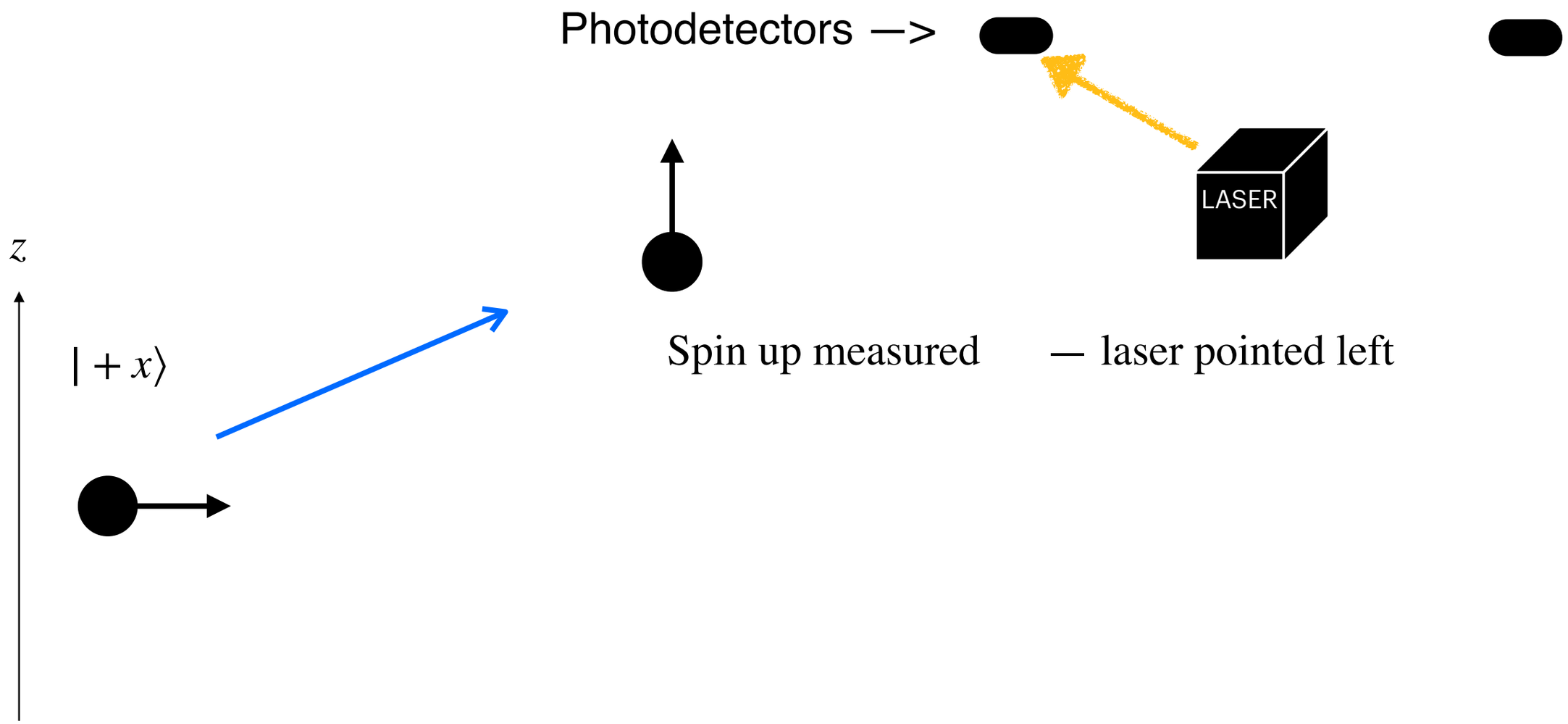




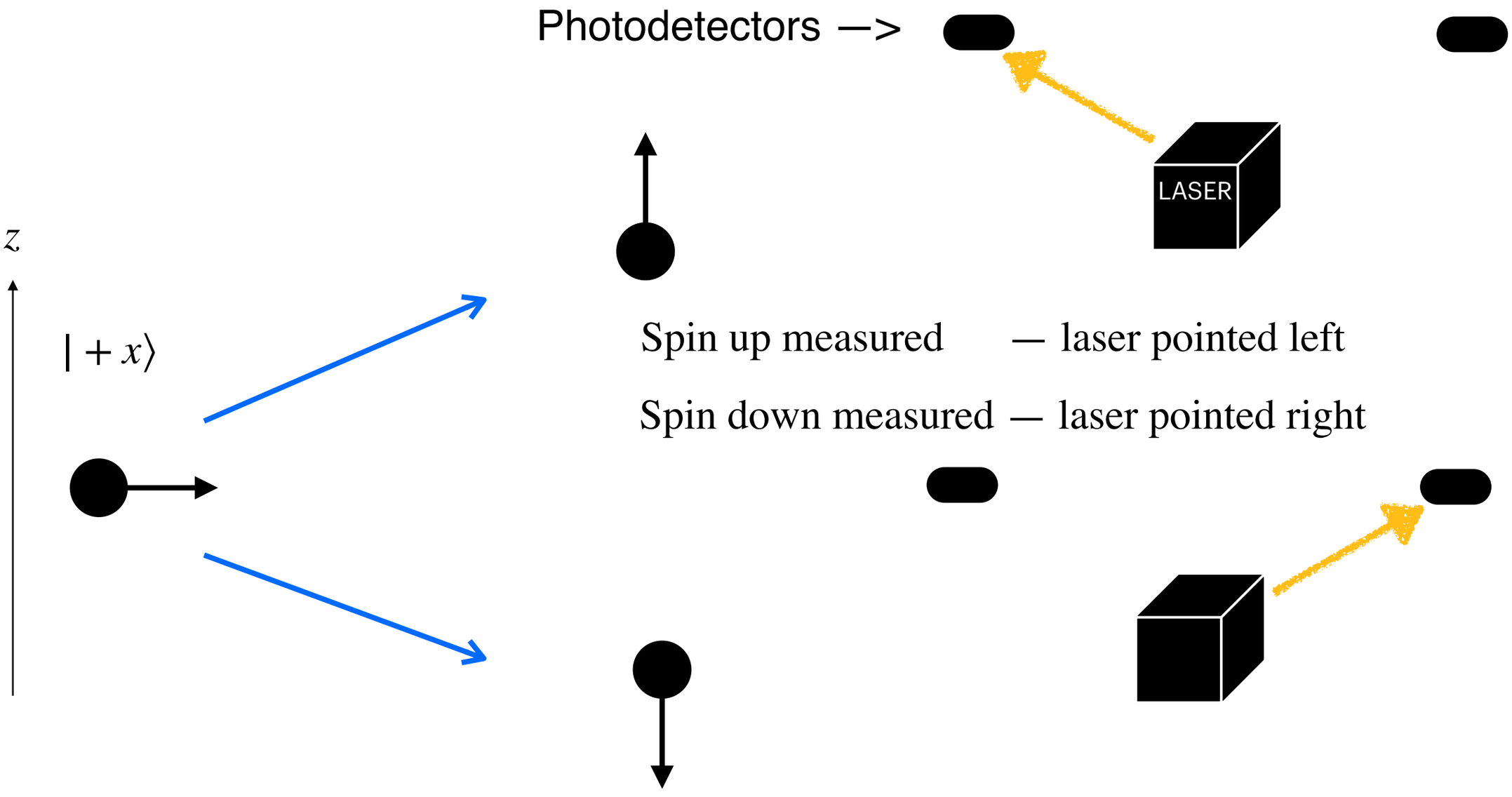
Non-linear phase: $\phi_{NL} = \epsilon_\gamma \alpha \frac{10a^2 + b^2}{30\sqrt{2\pi}\hbar x_0}\tau$

$$\epsilon_\gamma = 5 \pm 5.4 \times 10^{-12}$$

Linear Quantum Mechanics



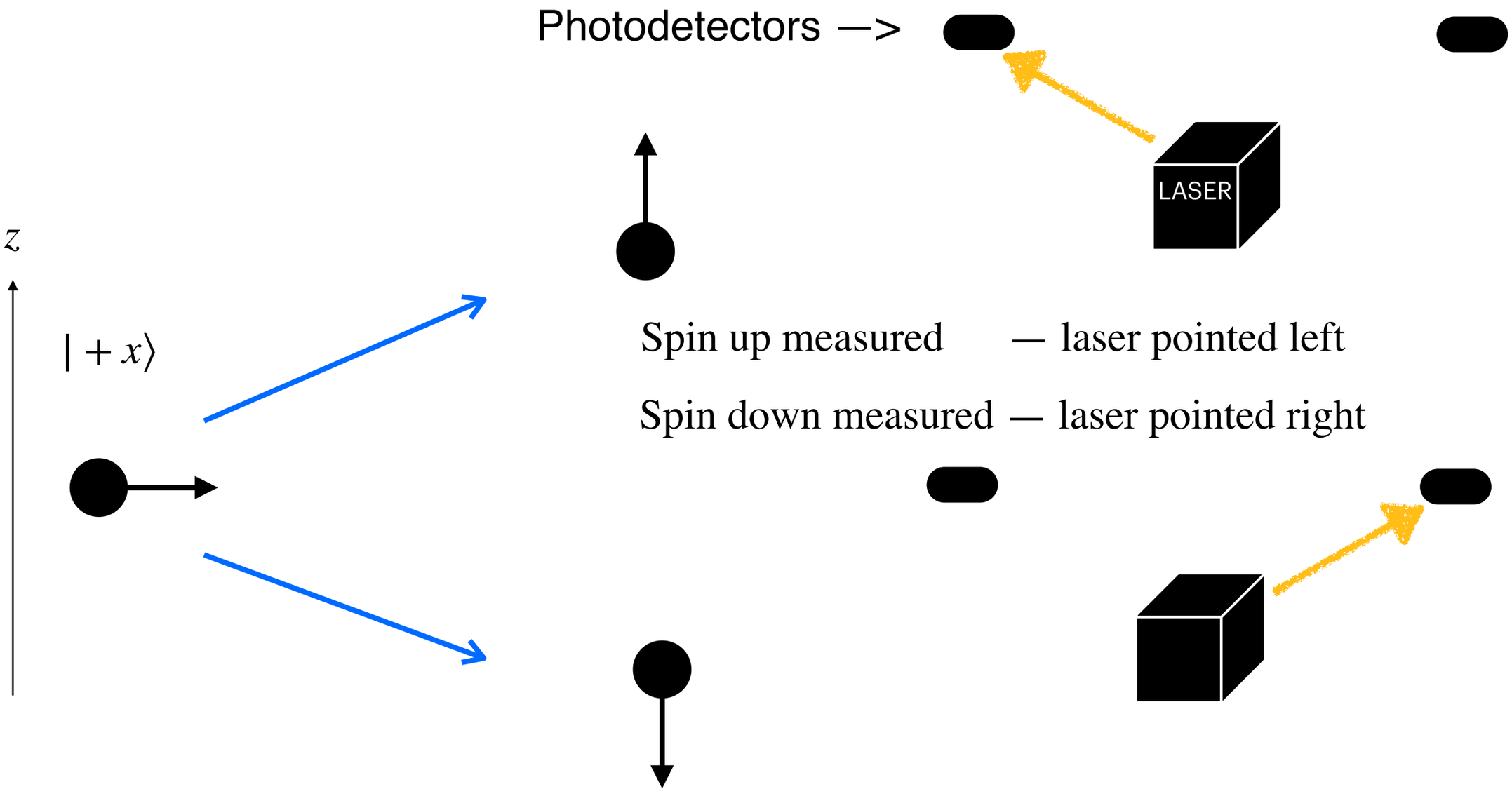
Linear Quantum Mechanics



Spin up measured — laser pointed left

Spin down measured — laser pointed right

Linear Quantum Mechanics



Spin up measured — laser pointed left

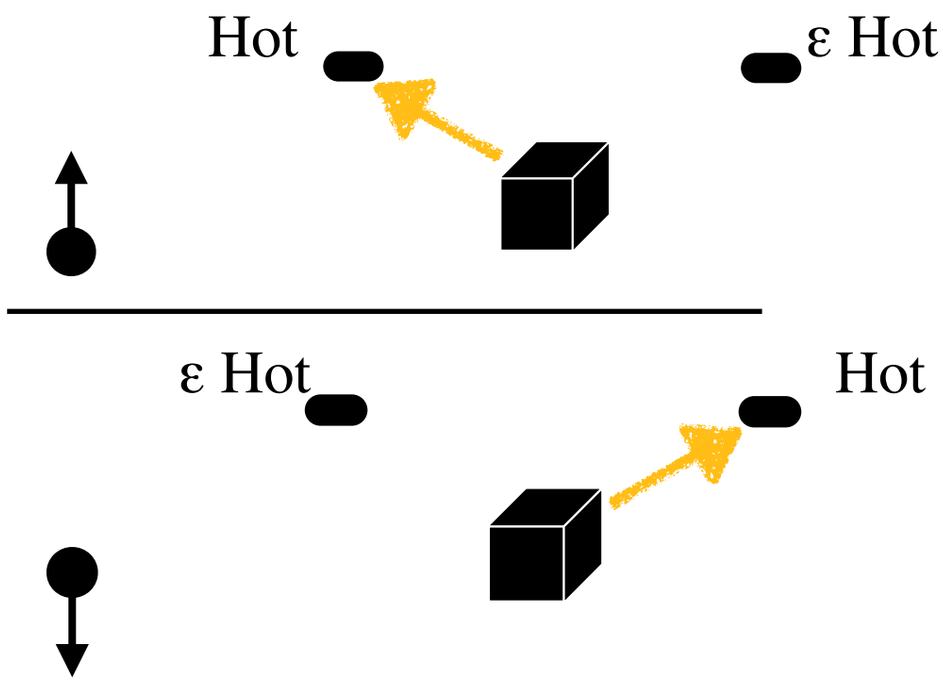
Spin down measured — laser pointed right

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

Non-Linear Quantum Mechanics

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

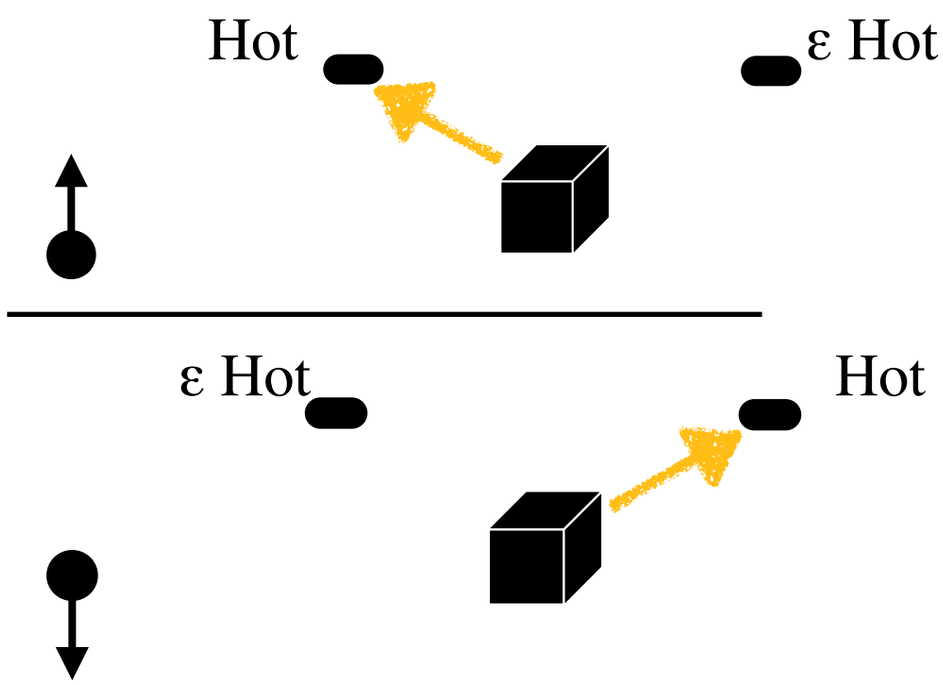
Which photodetectors light up?



Non-Linear Quantum Mechanics

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

Which photodetectors light up?



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

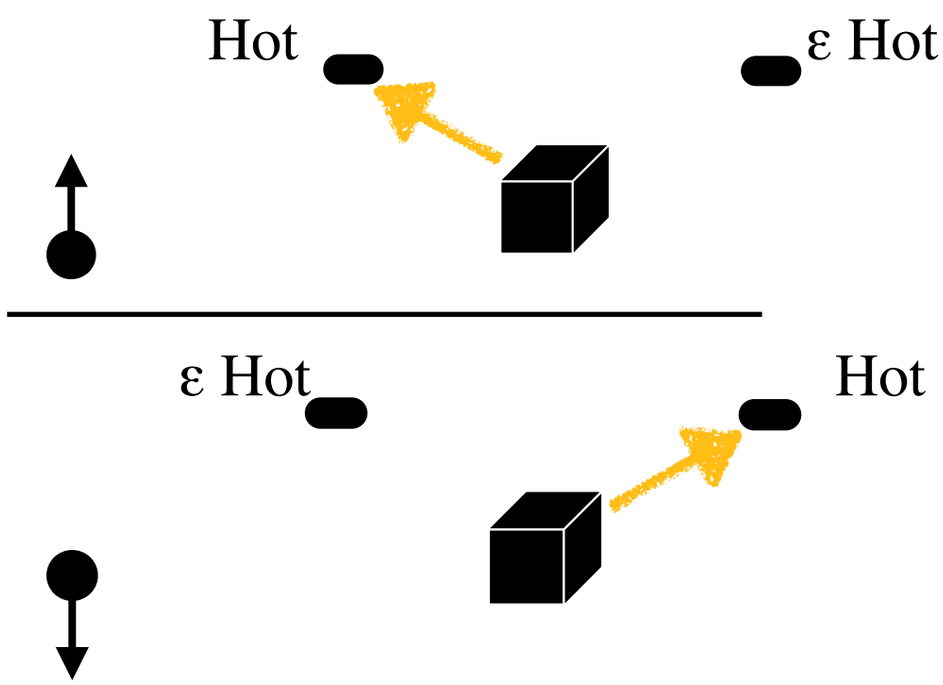
$$\langle \chi \,|\, A_\mu(x_R) \,|\, \chi \rangle \neq 0$$

Communication between “worlds”

Polchinski: “Everett Phone”

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”

Many crazier experiments…

Beyond the Standard Model

- At Higher Energy:
  1. New Heavy States
  2. Suppressed Operators/Rare Processes
- Weak Couplings:
  1. New Light States/Relics
  2. New Forces/Background Fields
- Violations of Principles
  1. Lorentz Invariance
  2. General Relativity
  3. Quantum Mechanics/QFT

In the era of Quantum Sensing!

Extras

Non-dynamical d.o.f.

Simple example: $\hat{H} = \frac{\hat{p}_1^2}{2m} + \frac{\hat{p}_2^2}{2m} + V(\hat{q}_2 - \hat{q}_1)$

Non-dynamical d.o.f.

Simple example: $\hat{H} = \frac{\hat{p}_1^2}{2m} + \frac{\hat{p}_2^2}{2m} + V(\hat{q}_2 - \hat{q}_1)$

$$Q = \frac{q_1 + q_2}{2} \qquad q = q_2 - q_1$$

$$P = p_1 + p_2 \qquad p = \frac{p_2 - p_1}{2}$$

$$\rightarrow H = \frac{P^2}{2M} + \frac{p^2}{2\mu} + V(q)$$

Non-dynamical d.o.f.

Simple example: $\hat{H} = \frac{\hat{p}_1^2}{2m} + \frac{\hat{p}_2^2}{2m} + V(\hat{q}_2 - \hat{q}_1)$

$$Q = \frac{q_1 + q_2}{2} \qquad q = q_2 - q_1$$

$$P = p_1 + p_2 \qquad p = \frac{p_2 - p_1}{2}$$

$$\rightarrow H = \frac{P^2}{2M} + \frac{p^2}{2\mu} + V(q)$$

$$[P, H] = 0 \qquad \hat{P}\,|\,P\rangle = P\,|\,P\rangle$$

Think of eigenstates of P as super-selection sectors

Non-dynamical d.o.f.

Simple example: $\hat{H} = \frac{\hat{p}_1^2}{2m} + \frac{\hat{p}_2^2}{2m} + V(\hat{q}_2 - \hat{q}_1)$

$$Q = \frac{q_1 + q_2}{2} \qquad q = q_2 - q_1$$

$$P = p_1 + p_2 \qquad p = \frac{p_2 - p_1}{2}$$

$$\rightarrow H = \frac{P^2}{2M} + \frac{p^2}{2\mu} + V(q)$$

$$[P, H] = 0 \qquad \hat{P}\,|P\rangle = P\,|P\rangle$$

Think of eigenstates of P as super-selection sectors

Can choose

$$\hat{P}\,|\psi\rangle_{\text{phys}} = 0$$

$$\hat{P}\,|\psi\rangle_{\text{phys}} = P\,|\psi\rangle_{\text{phys}}$$

$$\langle\psi|\,\hat{P}\,|\psi\rangle_{\text{phys}} = P$$

Non-dynamical d.o.f.

Next example: $$H = \frac{P^2}{2M} + \frac{p^2}{2\mu} + V(q) + \frac{P}{M}\overline{V}(q)$$

Still, $[P, H] = 0$

Non-dynamical d.o.f.

Next example: $$H = \frac{P^2}{2M} + \frac{p^2}{2\mu} + V(q) + \frac{P}{M}\overline{V}(q)$$

Still, $[P, H] = 0$

Again, can choose

$$\hat{P}\,|\psi\rangle_{\text{phys}} = 0$$

$$\hat{P}\,|\psi\rangle_{\text{phys}} = P\,|\psi\rangle_{\text{phys}}$$

$$\langle\psi|\,\hat{P}\,|\psi\rangle_{\text{phys}} = P$$

Measurement allows us to tell what super-selection sector we are in

GR

$$S = \int d^4x \, (\underbrace{\sqrt{-g}\, M_{\rm pl}^2 R \;+\; \sqrt{-g}\, \mathscr{L}_{\rm matter}(\phi)}_{\mathscr{L}_g}) \;+\; S_{GHY}$$

classical:

$$\frac{\delta S}{\delta g_{\mu\nu}} = \sqrt{-g}\, \left(M_{\rm pl}^2 G^{\mu\nu} - T^{\mu\nu} \right) = 0$$

conjugates:

$$\frac{\delta \mathscr{L}_g}{\delta \dot{g}_{ij}} \equiv \pi^{ij}$$

$$\frac{\delta \mathscr{L}_g}{\delta \dot{g}_{0\mu}} = 0$$

GR

EOM: $$\partial_t \langle \pi^{ij} \rangle \sim - \left\langle \frac{\delta H}{\delta \gamma_{ij}} \right\rangle \longrightarrow G^{ij} = 8\pi G T^{ij} \qquad \left(\frac{\delta S}{\delta g_{ij}} = 0 \right)$$

Four constraint equations

GR

EOM: $$\partial_t \langle \pi^{ij} \rangle \sim - \left\langle \frac{\delta H}{\delta \gamma_{ij}} \right\rangle \longrightarrow G^{ij} = 8\pi G T^{ij} \qquad \left(\frac{\delta S}{\delta g_{ij}} = 0 \right)$$

Four constraint equations

$$\langle \mathscr{H} \rangle = \mathbb{H} \longrightarrow M_{\rm pl}^{-2} \sqrt{-g}\, G^{00} - \sqrt{-g}\, T^{00} = \mathbb{H}$$

$$\langle \chi^i \rangle = \mathbb{P}^i \longrightarrow M_{\rm pl}^{-2} \sqrt{-g}\, G^{0i} - \sqrt{-g}\, T^{0i} = \mathbb{P}^i$$

GR

$$G^{00} = 8\pi G\left(T^{00} + \frac{\mathbb{H}}{\sqrt{-g}}\right)$$

$$G^{0i} = 8\pi G\left(T^{0i} + \frac{\mathbb{P}^i}{\sqrt{-g}}\right)$$

$$G^{ij} = 8\pi G T^{ij}$$

$$G^{\mu\nu} = 8\pi G(T^{\mu\nu} + T^{\mu\nu}_{\rm sh})$$

$$T^{\mu\nu}_{\rm sh} \equiv \frac{1}{\sqrt{-g}}\begin{pmatrix} \mathbb{H} & \mathbb{P}^1 & \mathbb{P}^2 & \mathbb{P}^3 \\ \mathbb{P}^1 & 0 & 0 & 0 \\ \mathbb{P}^2 & 0 & 0 & 0 \\ \mathbb{P}^3 & 0 & 0 & 0 \end{pmatrix}$$

$\mathbb{H}, \mathbb{P}^i$ are constrained functions

(identity) $\nabla_\mu G^{\mu\nu} = 0$

(EOM) $\nabla_\mu T^{\mu\nu} = 0$

$$\longrightarrow \nabla_\mu T^{\mu\nu}_{\rm sh} = 0 \longrightarrow \begin{aligned} \partial_0 \mathbb{H} + \partial_i \mathbb{P}^i &= 0 \\ \partial_0(g_{ij}\mathbb{P}^j) &= 0 \end{aligned}$$

GR

limit: $\mathbb{H}(\mathbf{x}) = \overline{\mathbb{H}} + \delta\mathbb{H}(\mathbf{x})$ $\mathbb{P}^i \equiv \delta\mathbb{P}^i$

$$ds^2 = -dt^2 + a(t)^2(\delta_{ij} + h_{ij})dx^i dx^j$$

Perturbative expansion around homogeneity

GR

limit: $\mathbb{H}(\mathbf{x}) = \overline{\mathbb{H}} + \delta\mathbb{H}(\mathbf{x})$ $\mathbb{P}^i \equiv \delta\mathbb{P}^i$

$$ds^2 = -dt^2 + a(t)^2(\delta_{ij} + h_{ij})dx^i dx^j$$

Perturbative expansion around homogeneity

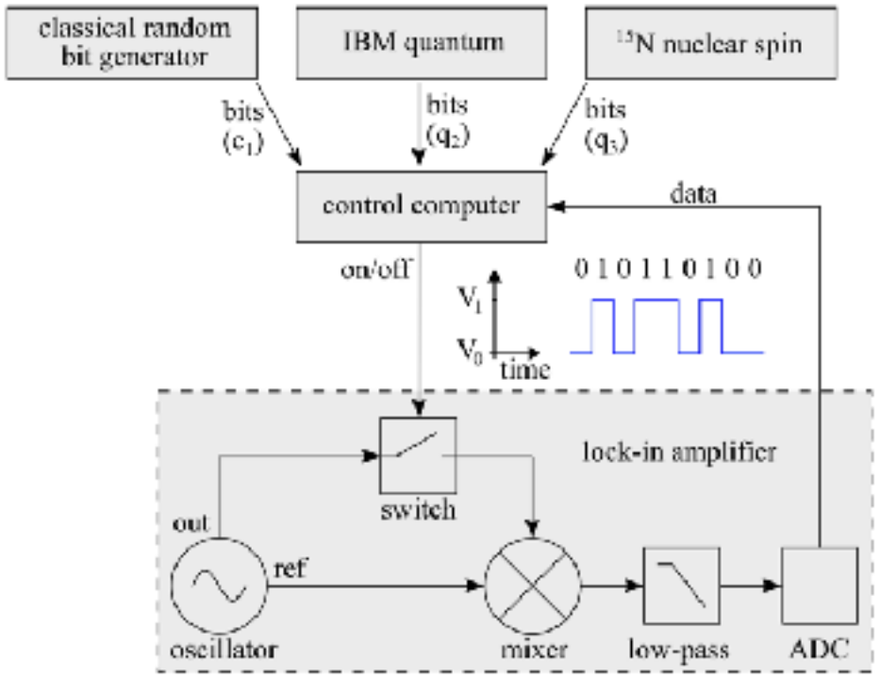
constraints: $\partial_0\mathbb{H} + \partial_i\mathbb{P}^i = 0$, $\partial_0(g_{ij}\mathbb{P}^j) = 0$ at linear order: $\partial_0(a^2\,\delta\mathbb{P}^j) = 0$

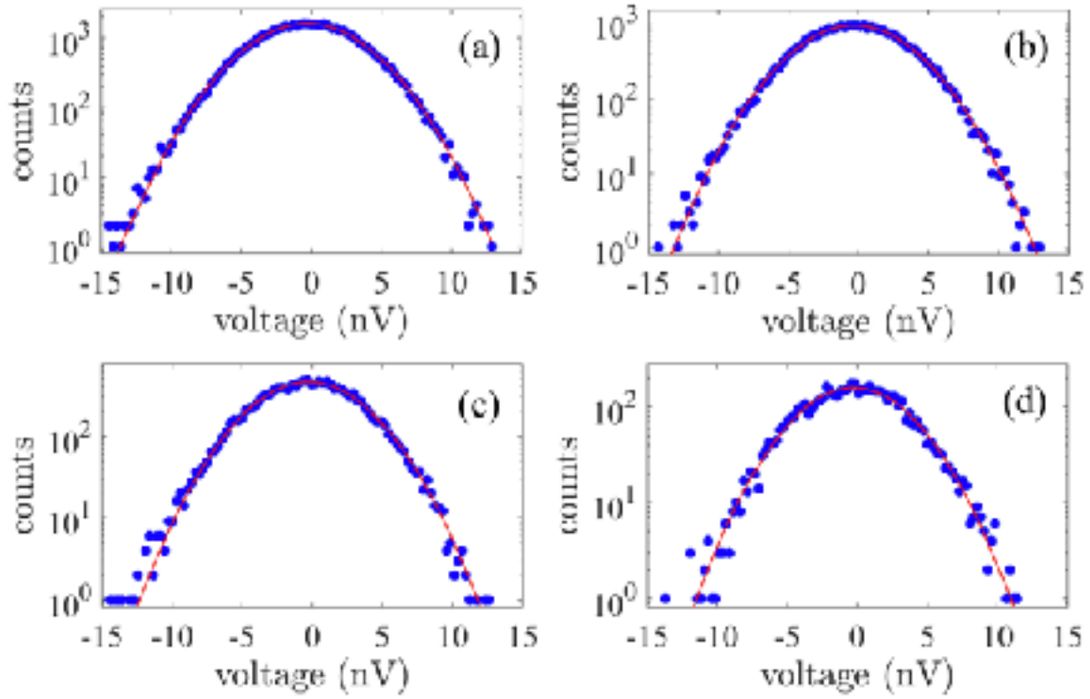
$\delta\mathbb{P}^i \sim a^{-2}$ and $\delta\mathbb{P}^i/\sqrt{-g} \sim a^{-5}$

Redshift quickly away outside horizon

Experimental limit on non-linear QM using a voltmeter and quantum bits

M. Polkovnikov, et al (2022)





$$|\epsilon_\gamma| \leq 4.7 \times 10^{-11}$$

O. Melnychuk, et al (2024) $|\epsilon_\gamma| \leq 1.5 \times 10^{-12}$ 90 % CL

Cosmological Sensitivity

What part of the wave function…

$$|\chi\rangle = \alpha\,|\mathrm{Us}\rangle + \beta\,|\mathrm{Them}\rangle$$

What part of the wave function…

$$|\chi\rangle = \alpha\,|\mathrm{Us}\rangle + \beta\,|\mathrm{Them}\rangle$$

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

$$|\chi\rangle = \alpha\,|\mathrm{Us}\rangle + \beta\,|\mathrm{Them}\rangle \rightarrow \langle\chi|A_\mu|\chi\rangle = |\alpha|^2\langle \mathrm{U}|A_\mu|\mathrm{U}\rangle + |\beta|^2\langle \mathrm{T}|A_\mu|\mathrm{T}\rangle$$

$$\langle\chi|A_\mu|\chi\rangle \rightarrow |\alpha|^2\langle \mathrm{U}|A_\mu|\mathrm{U}\rangle$$

$$\epsilon \rightarrow \epsilon_{\mathrm{eff}} \equiv \epsilon\,|\alpha|^2$$

What part of the wave function…

$$|\chi\rangle = \alpha\,|\mathrm{Us}\rangle + \beta\,|\mathrm{Them}\rangle$$

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

$$|\chi\rangle = \alpha\,|\mathrm{Us}\rangle + \beta\,|\mathrm{Them}\rangle \rightarrow \langle\chi|A_\mu|\chi\rangle = |\alpha|^2\langle \mathrm{U}|A_\mu|\mathrm{U}\rangle + |\beta|^2\langle \mathrm{T}|A_\mu|\mathrm{T}\rangle$$

$$\langle\chi|A_\mu|\chi\rangle \rightarrow |\alpha|^2\langle \mathrm{U}|A_\mu|\mathrm{U}\rangle$$

$$\epsilon \rightarrow \epsilon_{\mathrm{eff}} \equiv \epsilon\,|\alpha|^2$$

For $\alpha \ll \beta$, the wave function is dominated by something we are not a part of.
Can't turn on coherent fields over there.

Local exploitability completely determined by unchangeable
initial conditions dramatic difference from linear QM

Classical World?

$$|U(t)\rangle = |\ \rangle + \delta|\ \rangle \quad \textbf{Or} \quad |U(t)\rangle = \delta|\ \rangle + |\ \rangle$$

Are there natural quantum amplifiers, for e.g. in chaotic systems?

Classical World?

$|U(t)\rangle = |$ $\rangle + \delta |$ $\rangle$ **Or** $|U(t)\rangle = \delta |$ $\rangle + |$ $\rangle$

Are there natural quantum amplifiers, for e.g. in chaotic systems?

$\Delta x \sim 100\text{nm}$

Classical World?

$|U(t)\rangle = |$ 🌎 $\rangle + \delta |$ ■ $\rangle$ **Or** $|U(t)\rangle = \delta |$ 🌎 $\rangle + |$ ■ $\rangle$

Are there natural quantum amplifiers, for e.g. in chaotic systems?

$\Delta x \sim 100\text{nm}$

Changing classical evolution of a system requires coherent motion of N atoms

Probability that N atoms coherently move in some way: p^N

With $p \sim \mathrm{O}(1)$ scattering probability

Classical World?

$|U(t)\rangle = |$ 🌎 $\rangle + \delta |$ ■ $\rangle$ **Or** $|U(t)\rangle = \delta |$ 🌎 $\rangle + |$ ■ $\rangle$

Are there natural quantum amplifiers, for e.g. in chaotic systems?

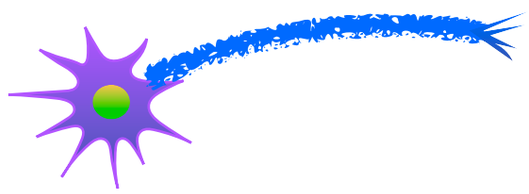
$\Delta x \sim 100$nm

Changing classical evolution of a system requires coherent motion of N atoms

Probability that N atoms coherently move in some way: p^N

With $p \sim$ O(1) scattering probability

What about the weather?
What about my brain??



100's + ions to get one neuron to fire

Classical World?

$|U(t)\rangle = |$ 🌎 $\rangle + \delta |$ ■ $\rangle$ **Or** $|U(t)\rangle = \delta |$ 🌎 $\rangle + |$ ■ $\rangle$

Are there natural quantum amplifiers, for e.g. in chaotic systems?

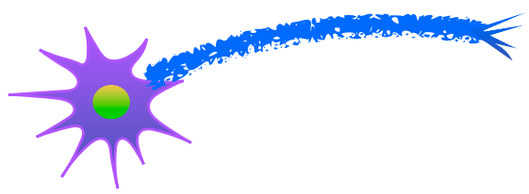
$\Delta x \sim 100$nm

Changing classical evolution of a system requires coherent motion of N atoms

Probability that N atoms coherently move in some way: p^N

With $p \sim$ O(1) scattering probability

What about the weather?
What about my brain??



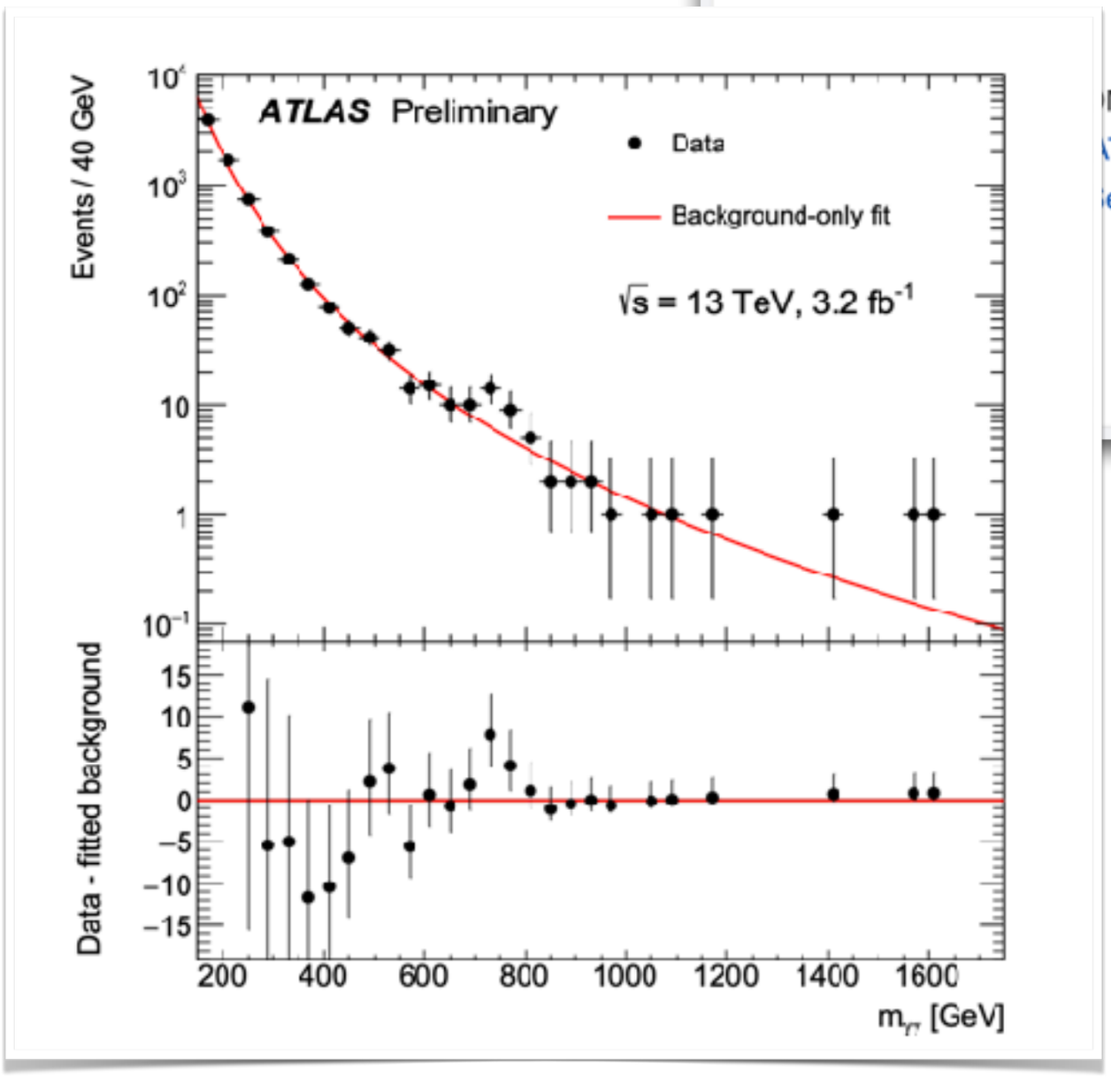
100's + ions to get one neuron to fire

$|U(t)\rangle = |$ 🌎 $\rangle + \delta |$ ■ $\rangle$ Reasonable

Quantum Amplifiers are Hard!

Natural Quantum Dilution

The ’750 GeV’ resonance!



Search for resonances decaying to photon pairs in 3.2 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

Dec 15, 2015

NF-2015-081
TLAS
erver

claim

reference search

562 citations

Have we been diluting our wave function on Earth for the past 100 years?

Tests for a Quantum-Diluted Earth

Look for coherent fields turned on in all parts of the wavefunction

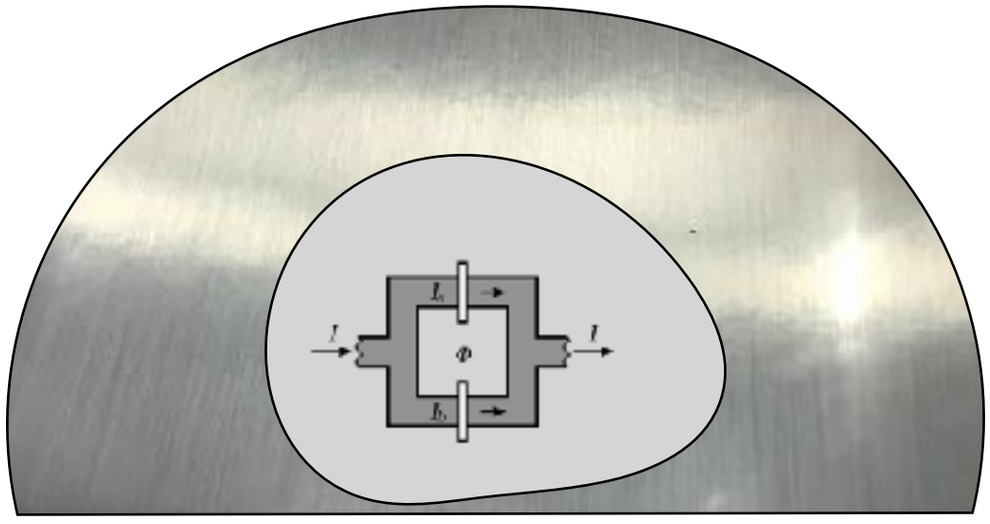
$$eJ^{\mu}(A_{\mu} + \epsilon_{\gamma}\langle A_{\mu}\rangle)$$

Tests for a Quantum-Diluted Earth

Look for coherent fields turned on in all parts of the wavefunction

$$eJ^{\mu}(A_{\mu} + \epsilon_{\gamma}\langle A_{\mu}\rangle)$$

Remove an ancient magnetic source in our part of the wave function and measure the field in that region.



$$|\,U(t)\rangle = |\ \rangle(\alpha\,|\,\text{missing magnetic material}\,\rangle + \beta\,|\,\text{magnetic material}\rangle)$$

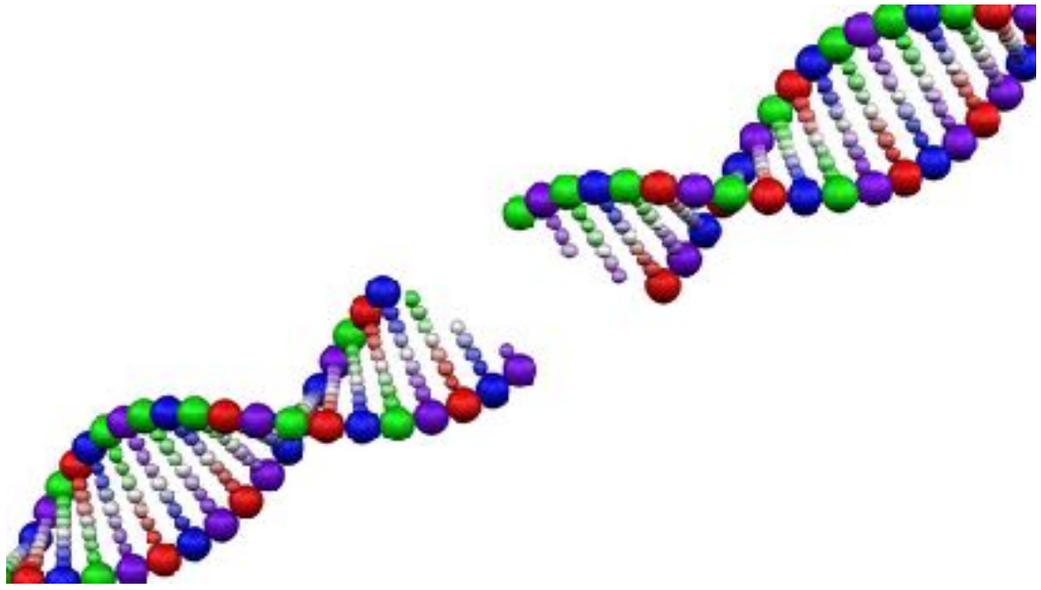
Could do the same with gravitational sources on Earth (*e.g.*, Bikini Atoll)

Evolutionary Dilution?

Is N ~ O(few) for evolution?

Maybe for RNA/DNA?

RNA formation?



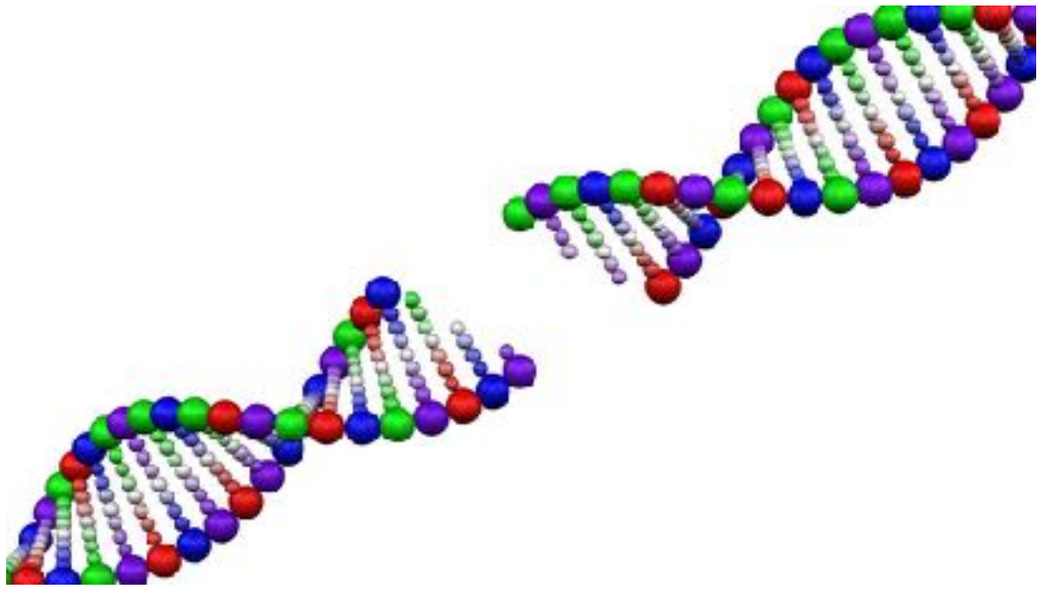
Is Evolution a quantum amplifier?!?

Evolutionary Dilution?

Is N ~ O(few) for evolution?

Maybe for RNA/DNA?

RNA formation?



Is Evolution a quantum amplifier?!?

$$|U(t=0)\rangle = \quad$$

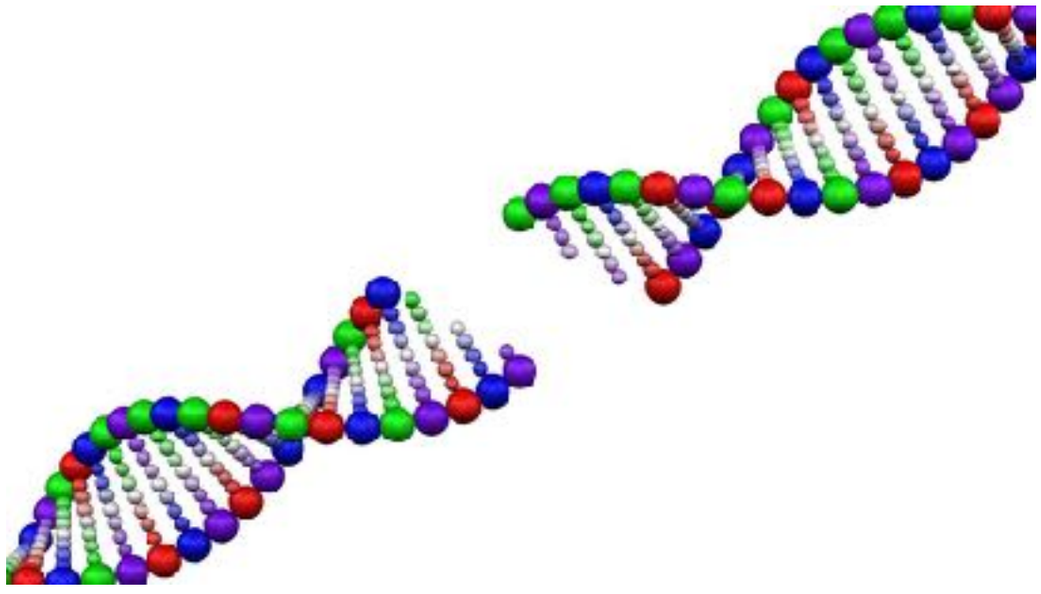
$$|U(t)\rangle = |\ \rangle(|\ \rangle + |\text{No life}\rangle + \ldots)$$

Evolutionary Dilution?

Is N ~ O(few) for evolution?

Maybe for RNA/DNA?

RNA formation?



Is Evolution a quantum amplifier?!?

$|U(t=0)\rangle =$

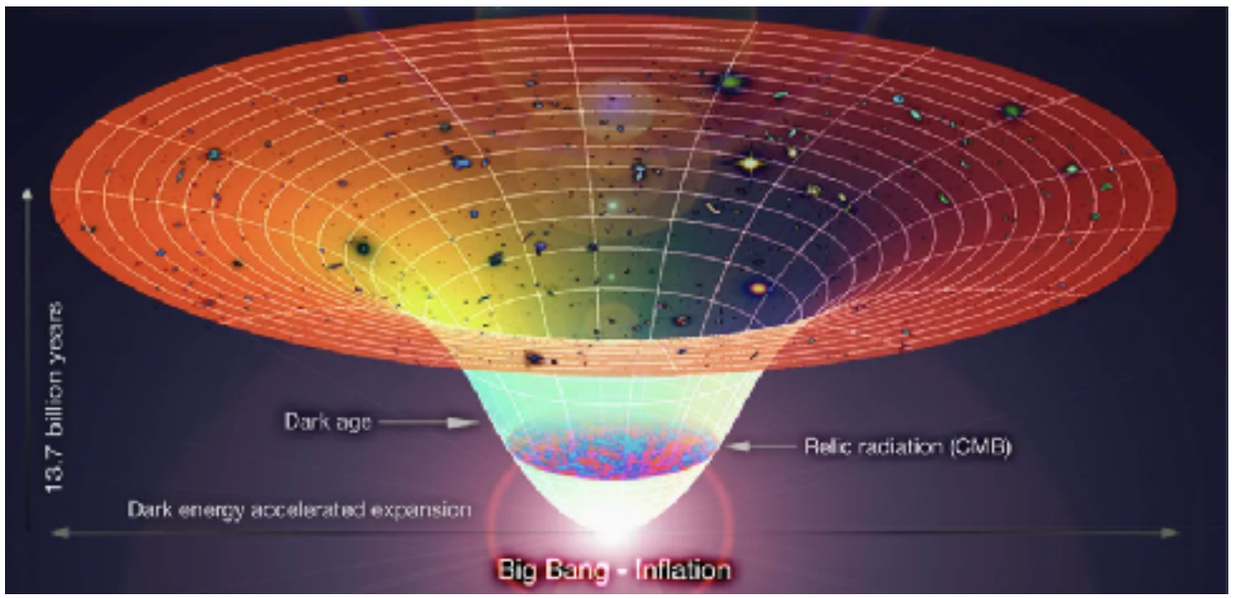
$|U(t)\rangle = |$ $\rangle(|$ $\rangle + |\text{No life}\rangle + \ldots)$

$|U(t=0)\rangle =$

$|U(t)\rangle = |$ $\rangle(|$ $\rangle + |$ $\rangle + \ldots)$

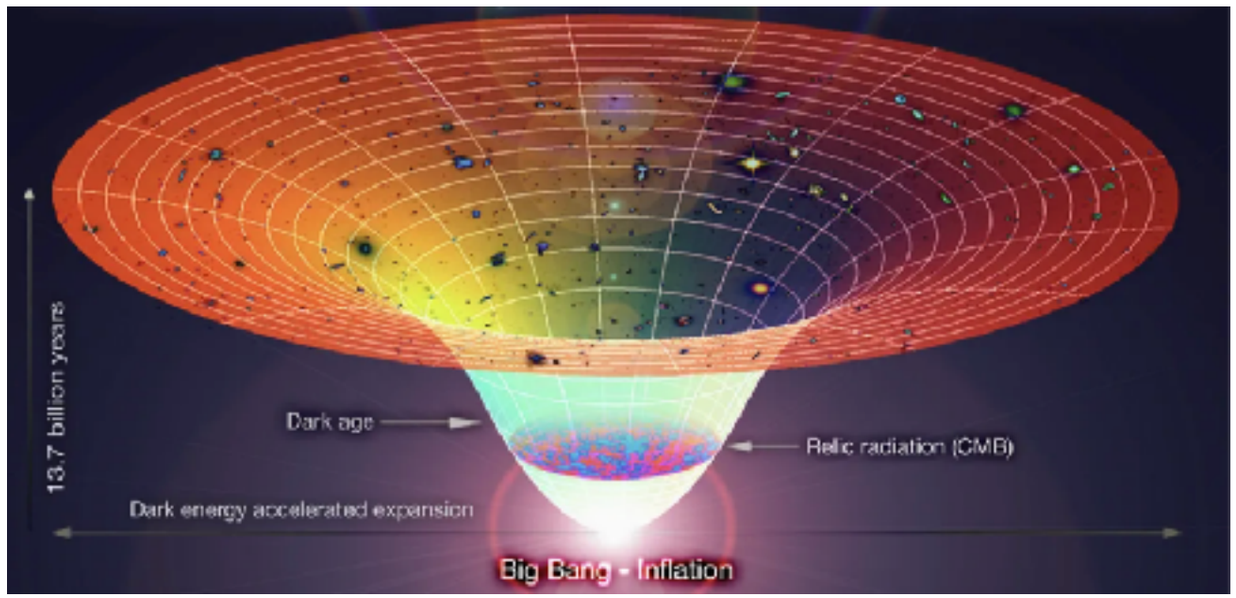
Cosmological Quantum Amplifier: Inflation

Standard cosmic inflation:
rapidly places quantum state in a homogenous and isotropic state
(Bunch-Davies Vacuum)



Cosmological Quantum Amplifier: Inflation

Standard cosmic inflation:
rapidly places quantum state in a homogenous and isotropic state
(Bunch-Davies Vacuum)



Homogeneous state becomes massive superposition of statistically similar Universes!

$$|\chi\rangle = \sum_i c_i |U_i\rangle, \;\; c_i \sim e^{-N}$$

Most of the Universe: The space-time point where the Earth is located is in intergalactic space

Tests for a Quantum-Diluted Universe(!)

Look for coherent fields turned on in all parts of the wavefunction

$$T^{\mu\nu}(g_{\mu\nu} + \epsilon_G \langle g_{\mu\nu} \rangle) + \cdots$$

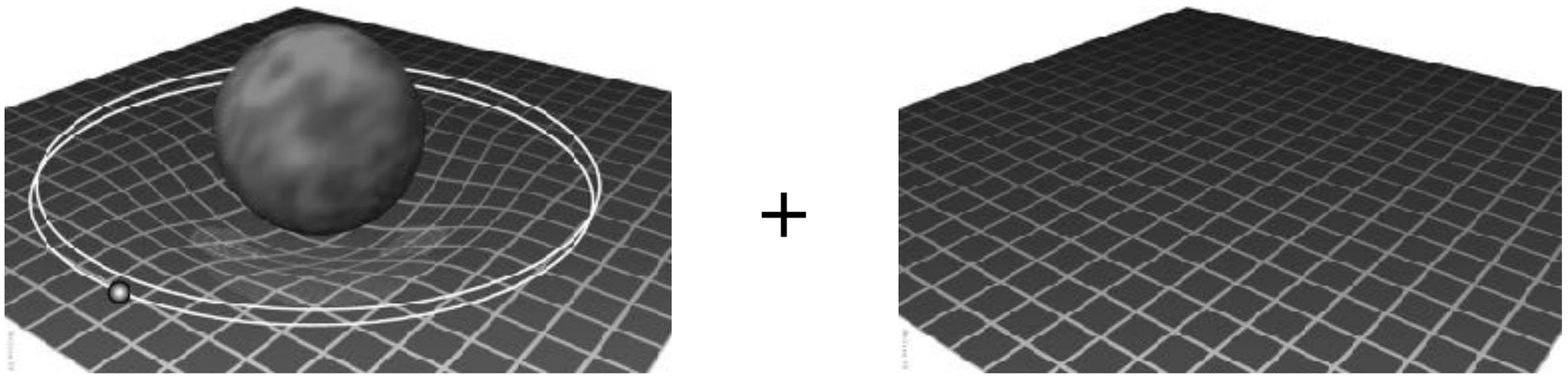
Objects in our part of the wave function will produce
different gravitational fields than the average

Tests for a Quantum-Diluted Universe(!)

Look for coherent fields turned on in all parts of the wavefunction

$$T^{\mu\nu}(g_{\mu\nu} + \epsilon_G \langle g_{\mu\nu} \rangle) + \cdots$$

Objects in our part of the wave function will produce
different gravitational fields than the average



Interfering metrics should also impact cosmological evolution — WIP

If we have a Classical Universe

Macroscopic superpositions can be produced at will.

Parallelize any computation:

If we have a Classical Universe

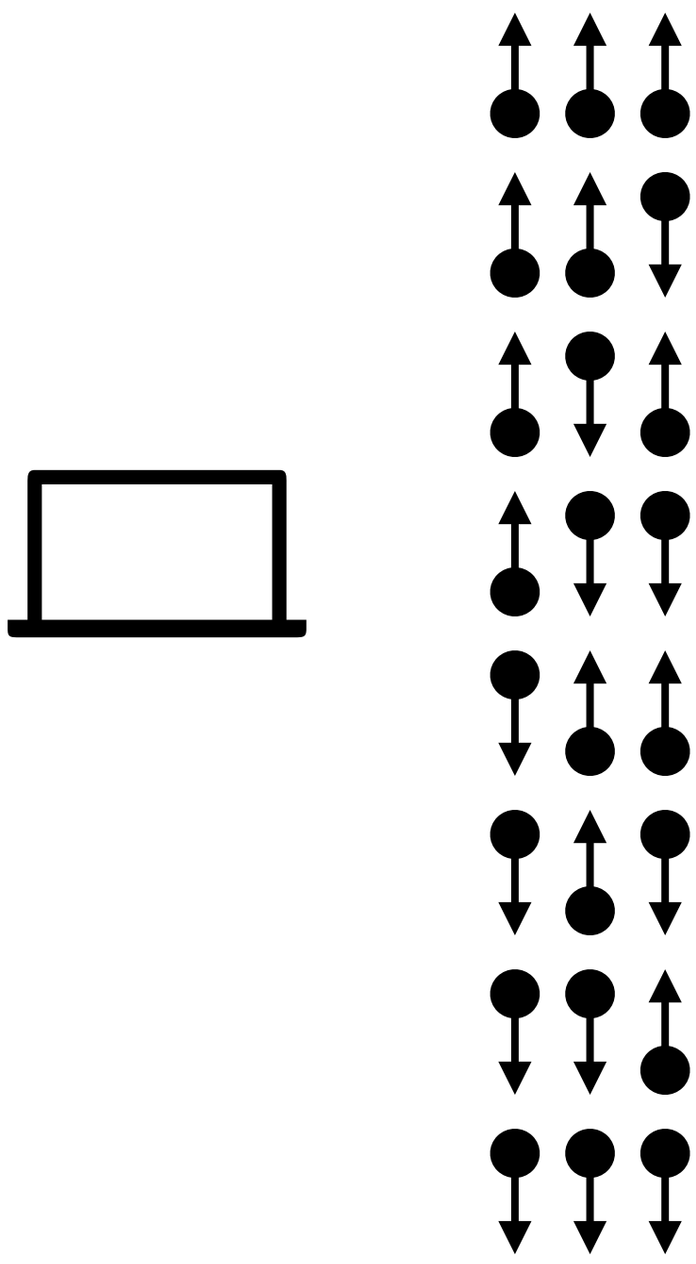
Macroscopic superpositions can be produced at will.

Parallelize any computation:

If we have a Classical Universe

Macroscopic superpositions can be produced at will.

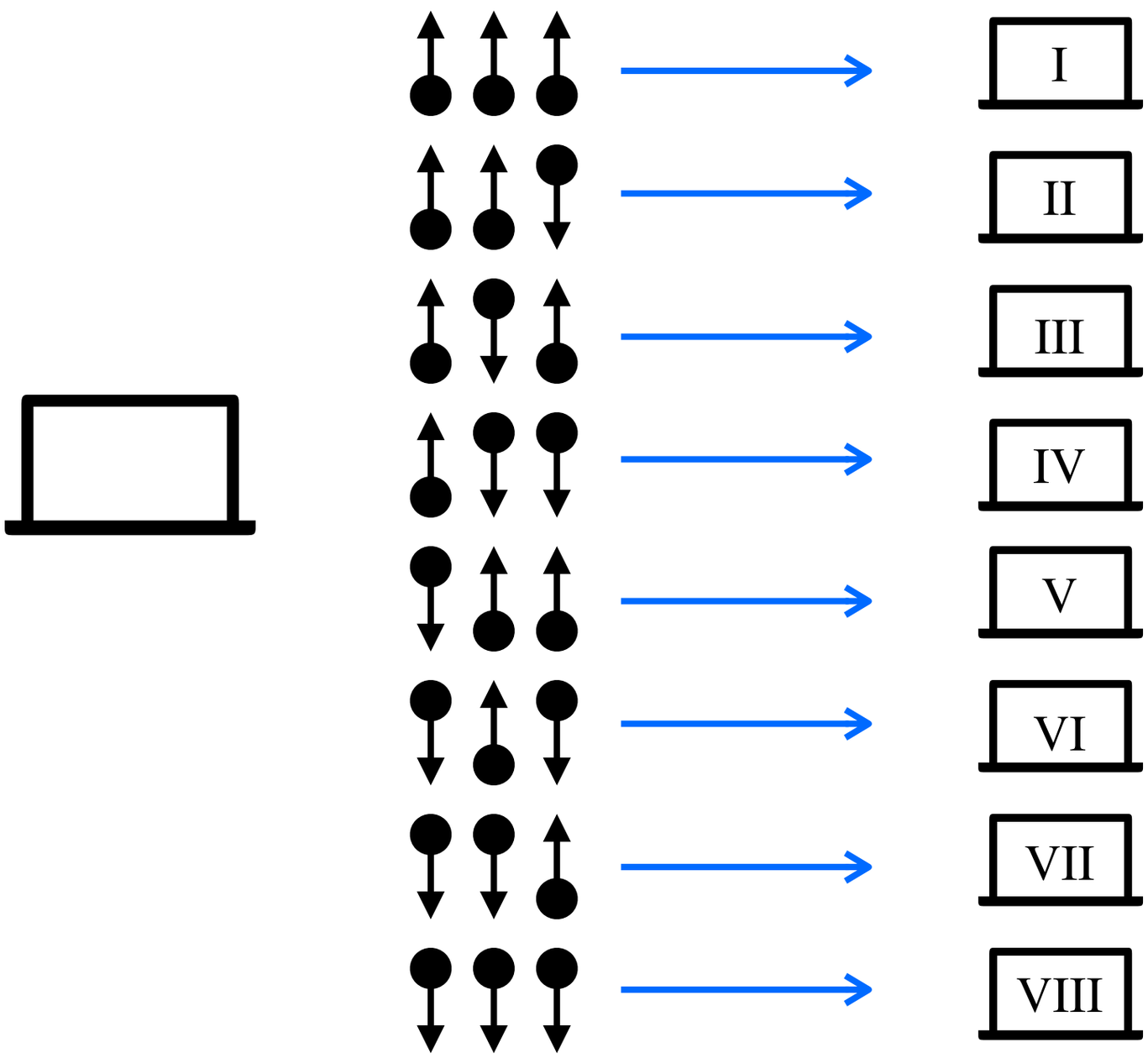
Parallelize any computation:



If we have a Classical Universe

Macroscopic superpositions can be produced at will.

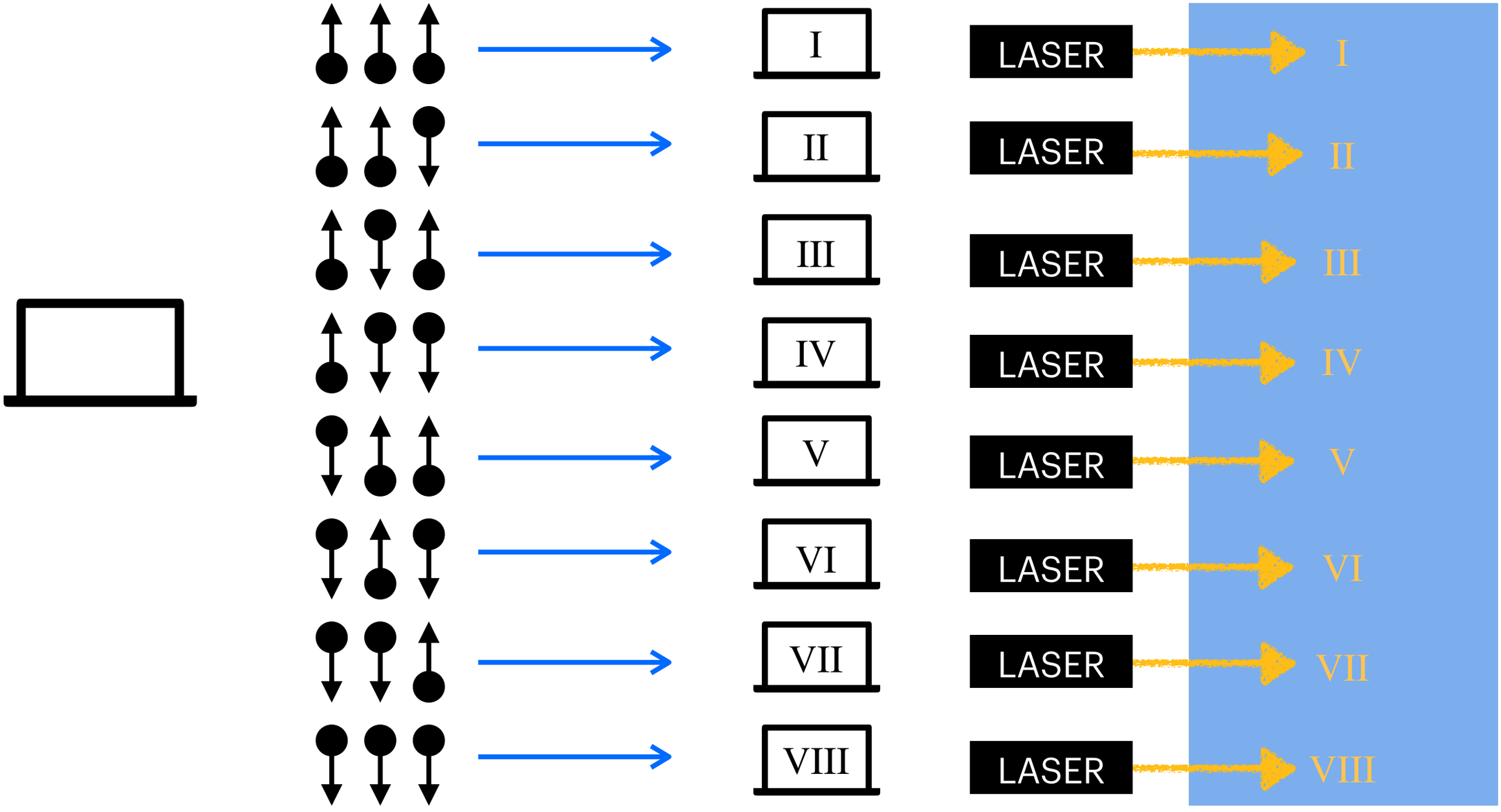
Parallelize any computation:



If we have a Classical Universe

Macroscopic superpositions can be produced at will.

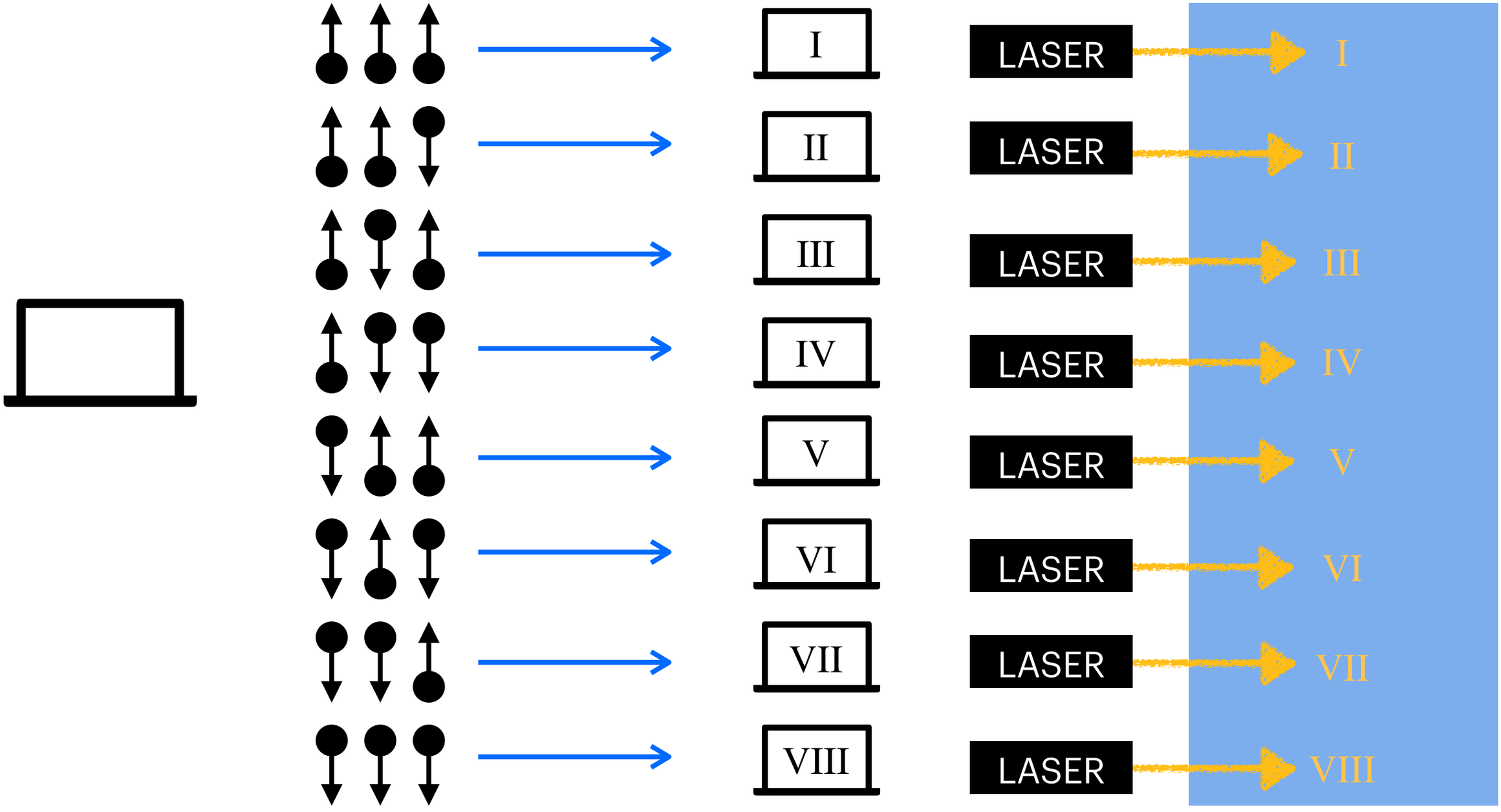
Parallelize any computation:



If we have a Classical Universe

Macroscopic superpositions can be produced at will.

Parallelize any computation:



Quantum Parallelizing!