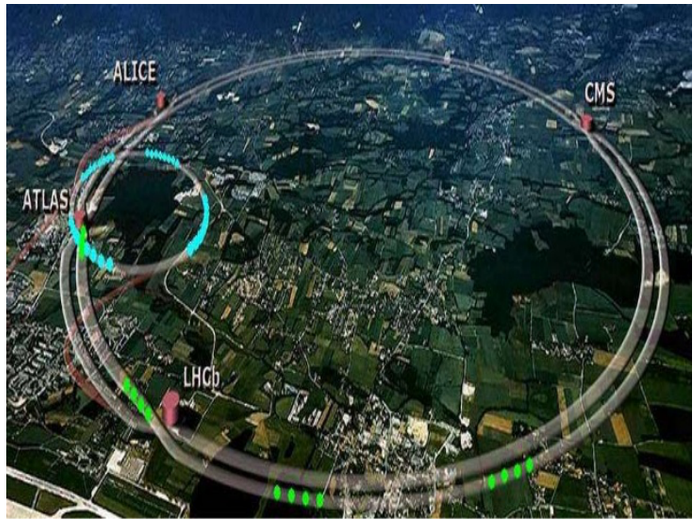
Fundamental Physics with Quantum Sensors

Surjeet Rajendran,
The Johns Hopkins University

Grand Challenge of High Energy Physics

Standard Model experimentally established



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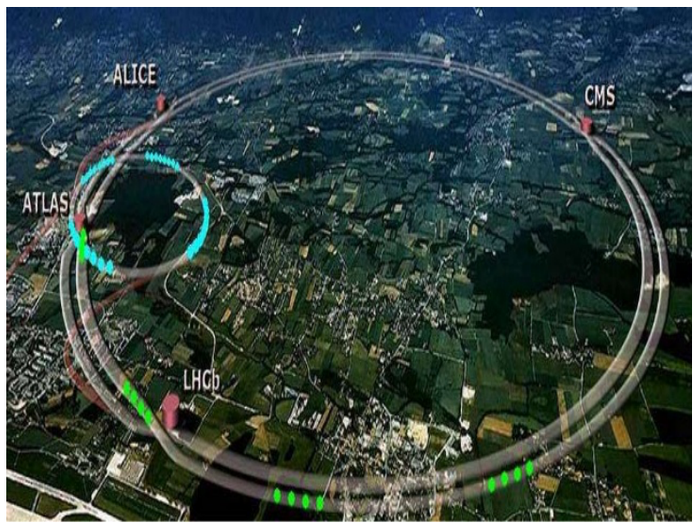
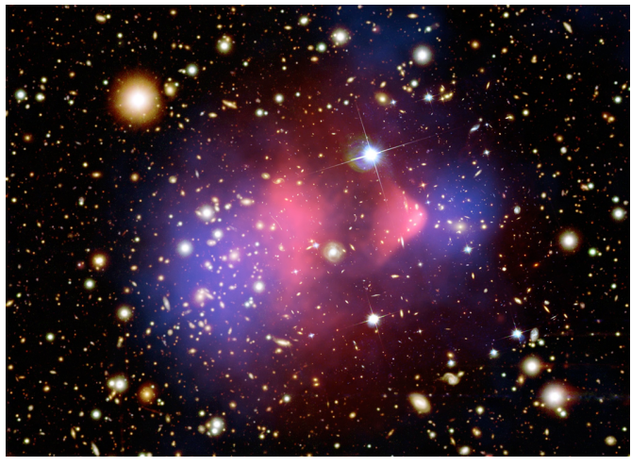
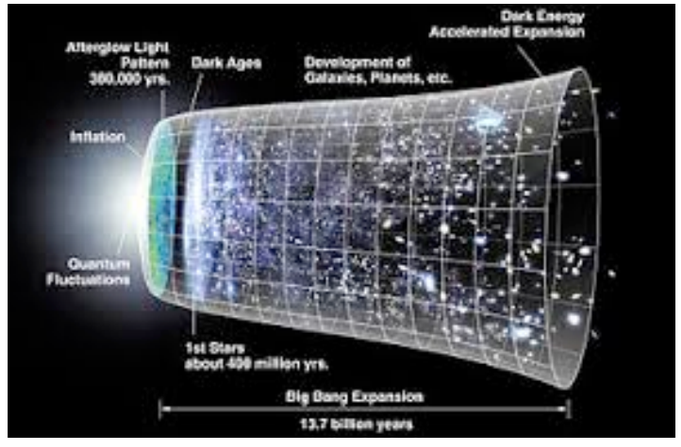


We know there is new physics out there

Matter?
Universe?



Dark Matter



Dark Energy

Hierarchy

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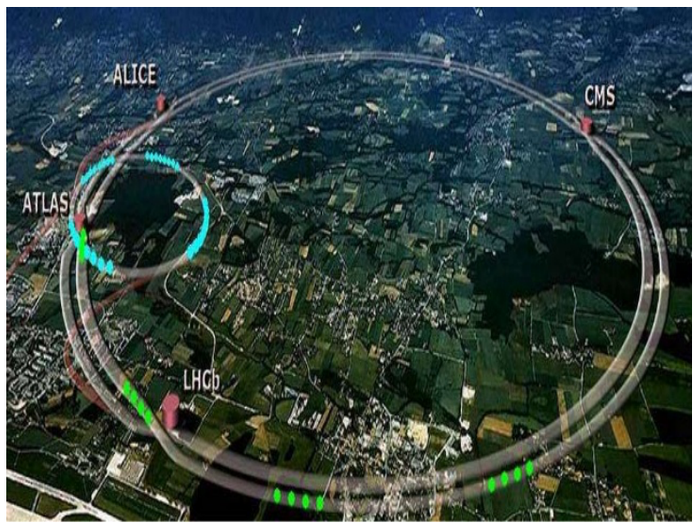

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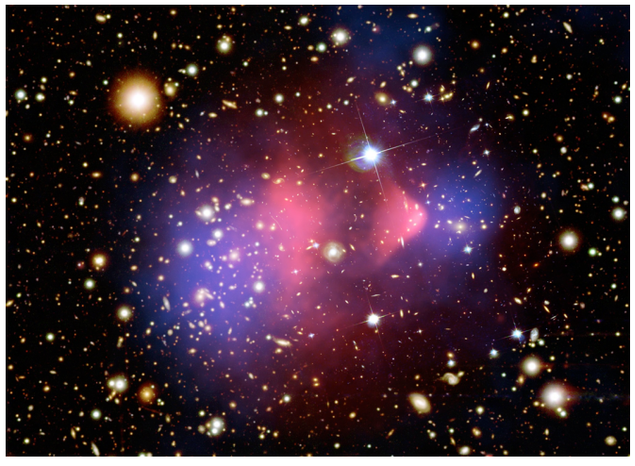

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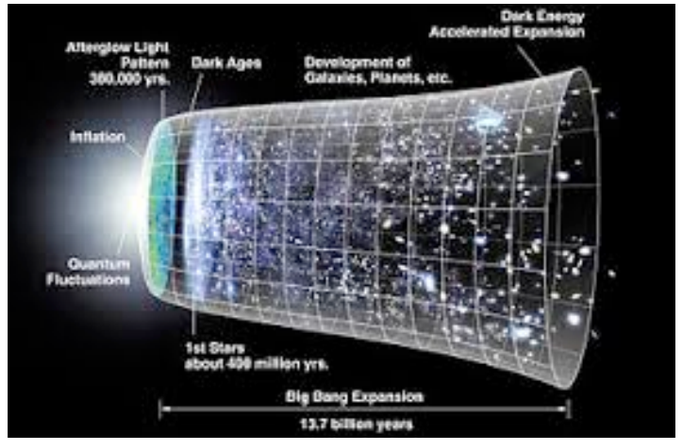

Dark Energy

Hierarchy

Where is this new physics?

Where is this New Physics?

Mass? Strength?

0 **Mass** **10^{19} GeV (Quantum Gravity)**

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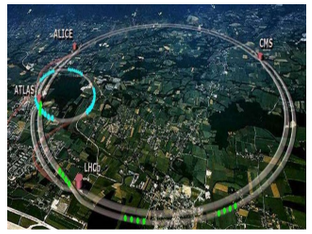
S t r e n g t h

Colliders



Gravity

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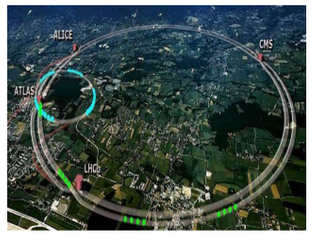

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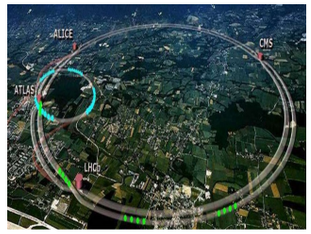

Gravitational Waves, Dark Matter, Dark Energy

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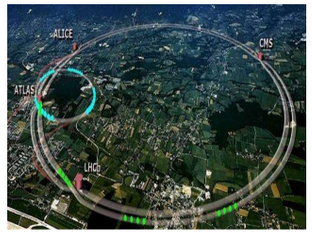

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Strong Physics Case

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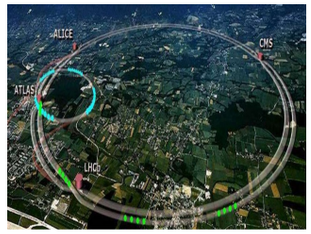

Gravitational Waves, Dark Matter, Dark Energy

Time ~ 10^{-23} s
Magnetic Field ~ 10^{-20} T

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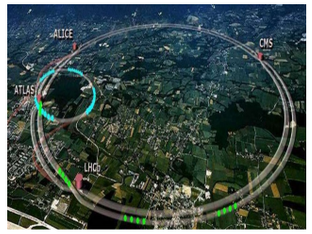

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How?

Quantum Sensors

How can we measure time ~ 10^{-23} s?

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Use Conventional Clock?

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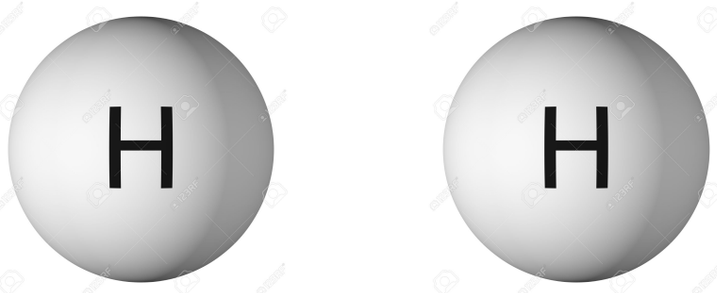

10^{80} H atoms in the universe, exactly identical

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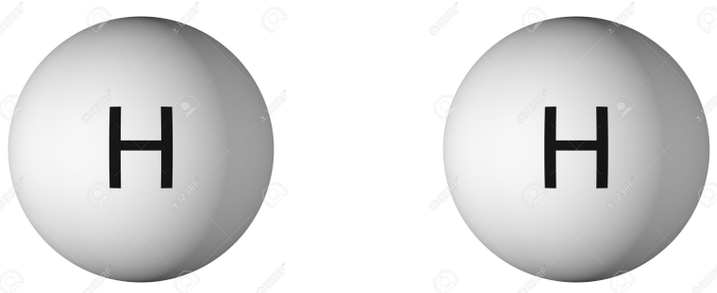

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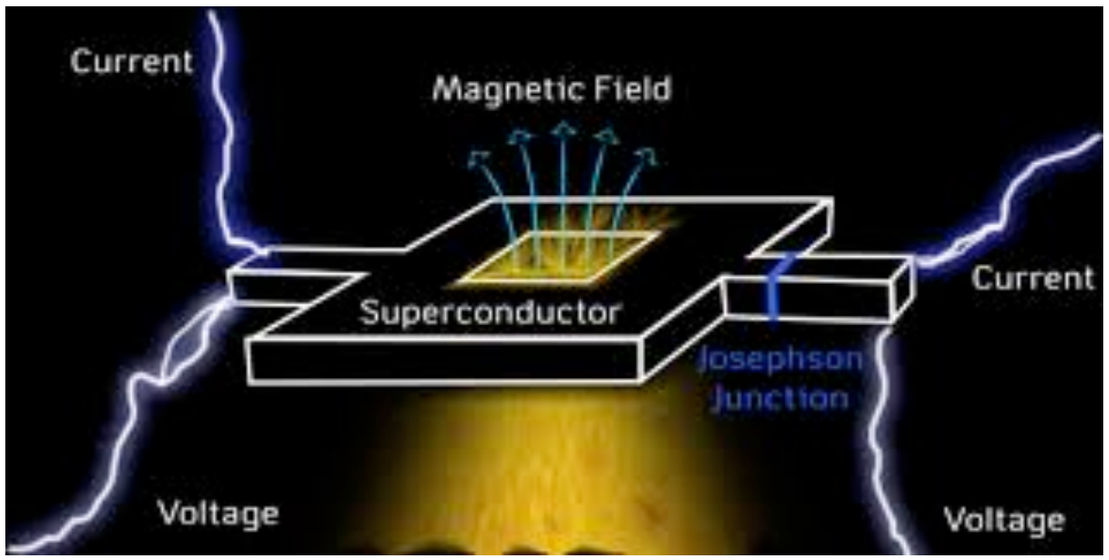
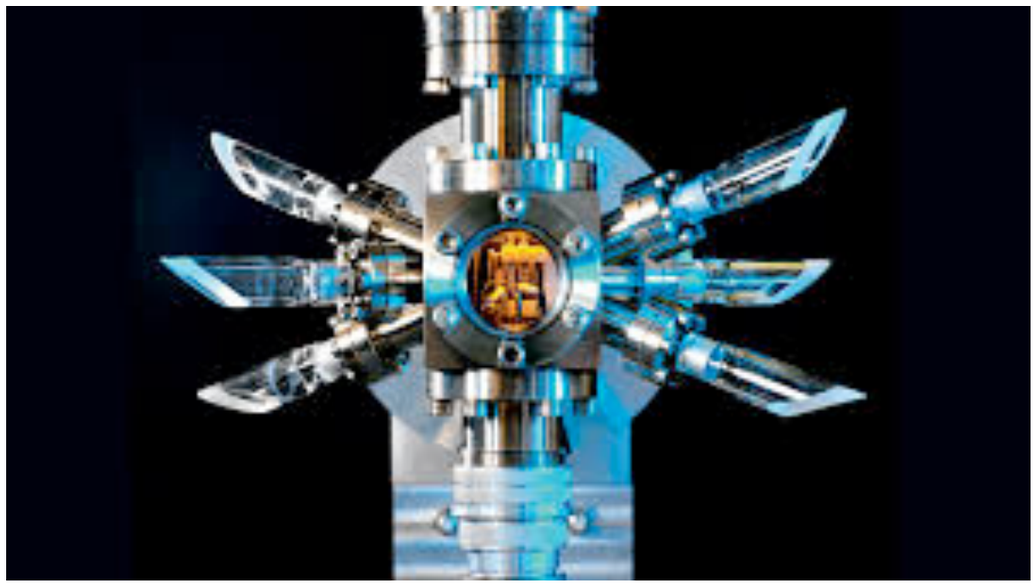
Atomic Clock: Atomic Energy levels for time

Quantum Sensors

Impressive developments in quantum sensors in the past two decades





$$\text{Magnetic Field} \lessapprox 10^{-16} \frac{\text{T}}{\sqrt{\text{Hz}}}$$

(SQUIDs, atomic magnetometers)

$$\text{Accelerometers} \lessapprox 10^{-13} \frac{\text{g}}{\sqrt{\text{Hz}}}$$

(atom and optical interferometers)

Rapid technological advancements

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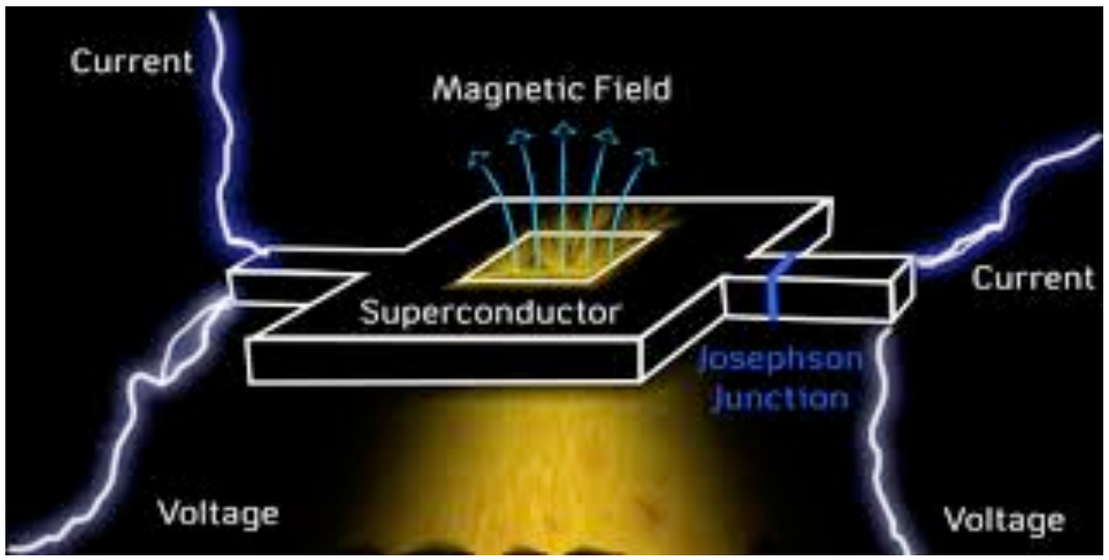

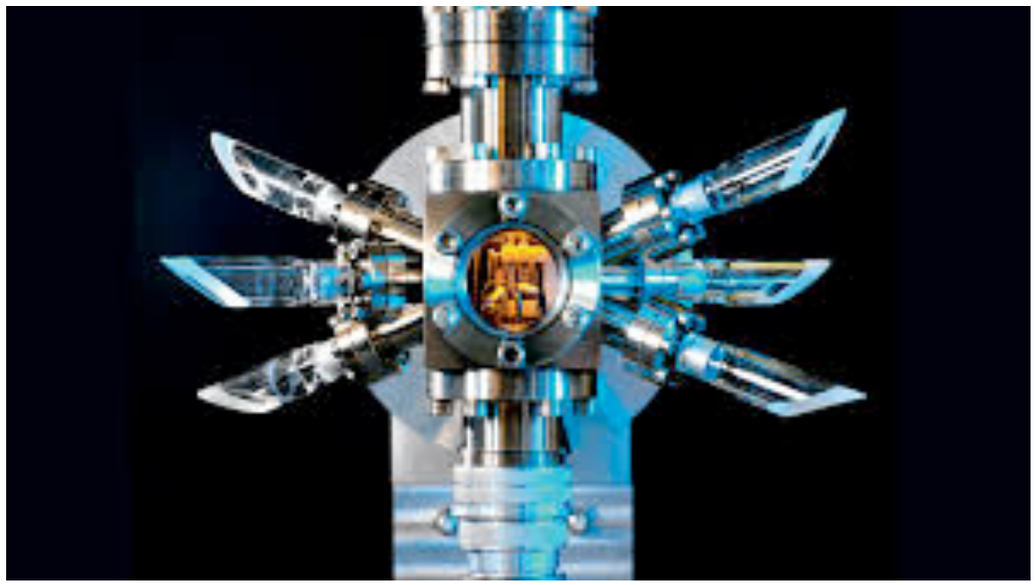

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Detect gravitational waves and probe dark sector?

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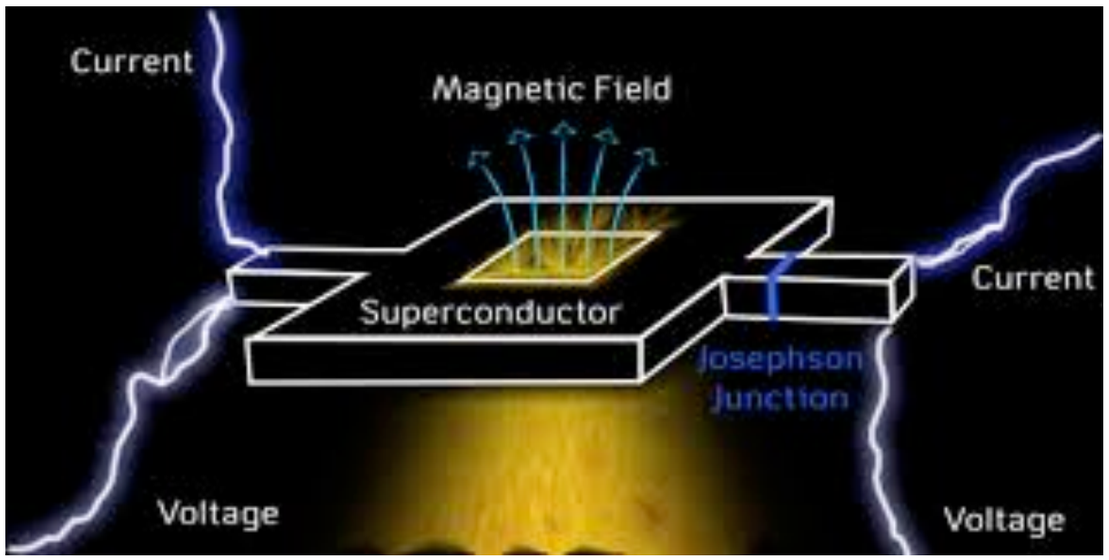

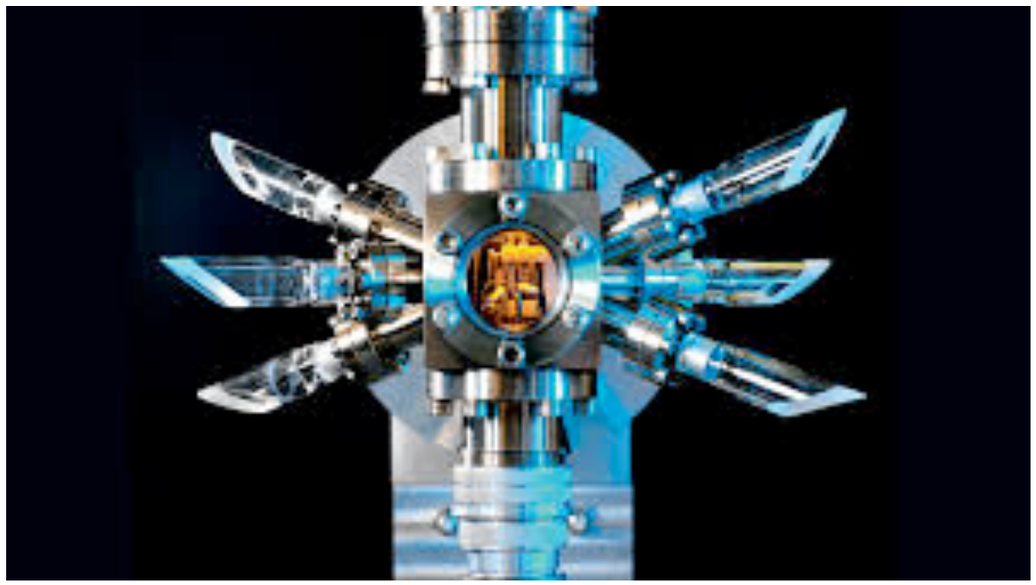

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Detect gravitational waves and probe dark sector?

Test quantum mechanics?

Outline

1. Gravitational Waves

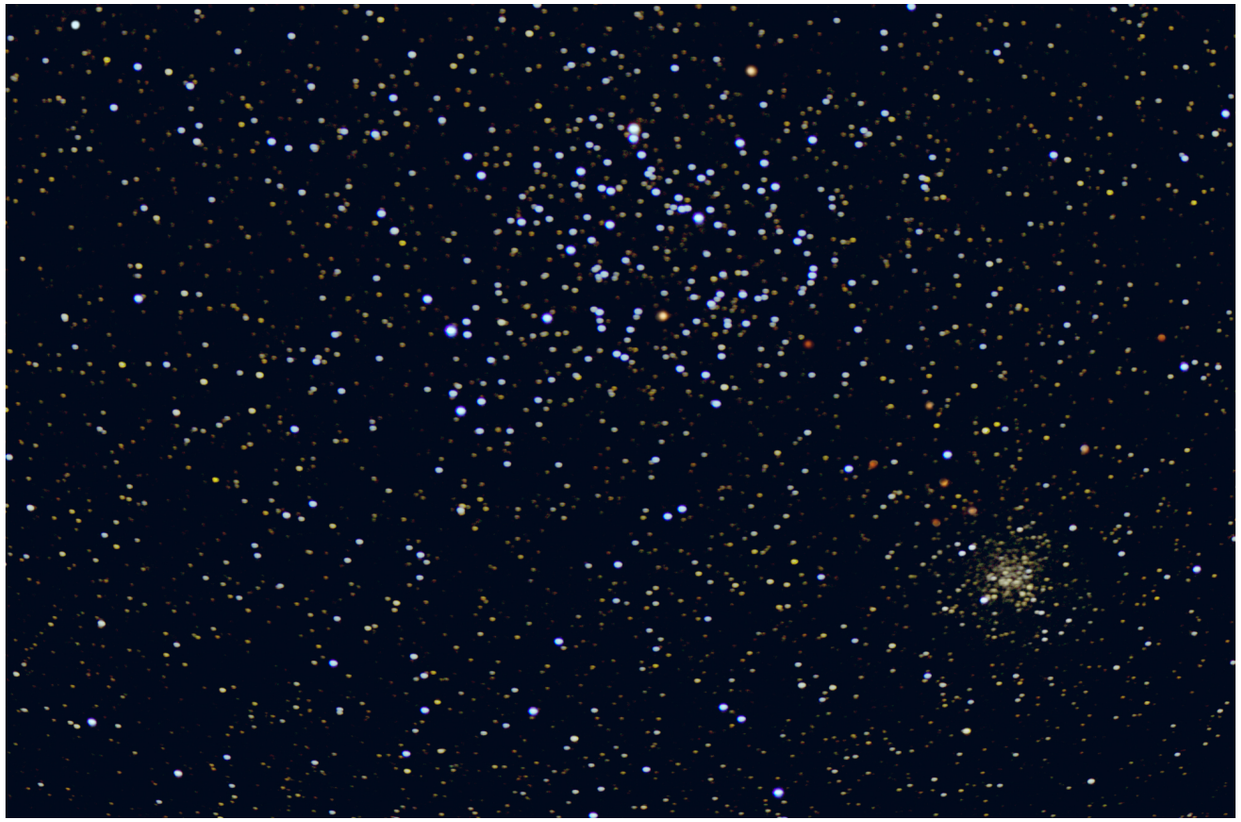
2. Dark Sector

3. Quantum Mechanics

4. Conclusions

Gravitational Waves

Gravitational Waves



Mostly learned about the universe through light

Discoveries in every frequency band

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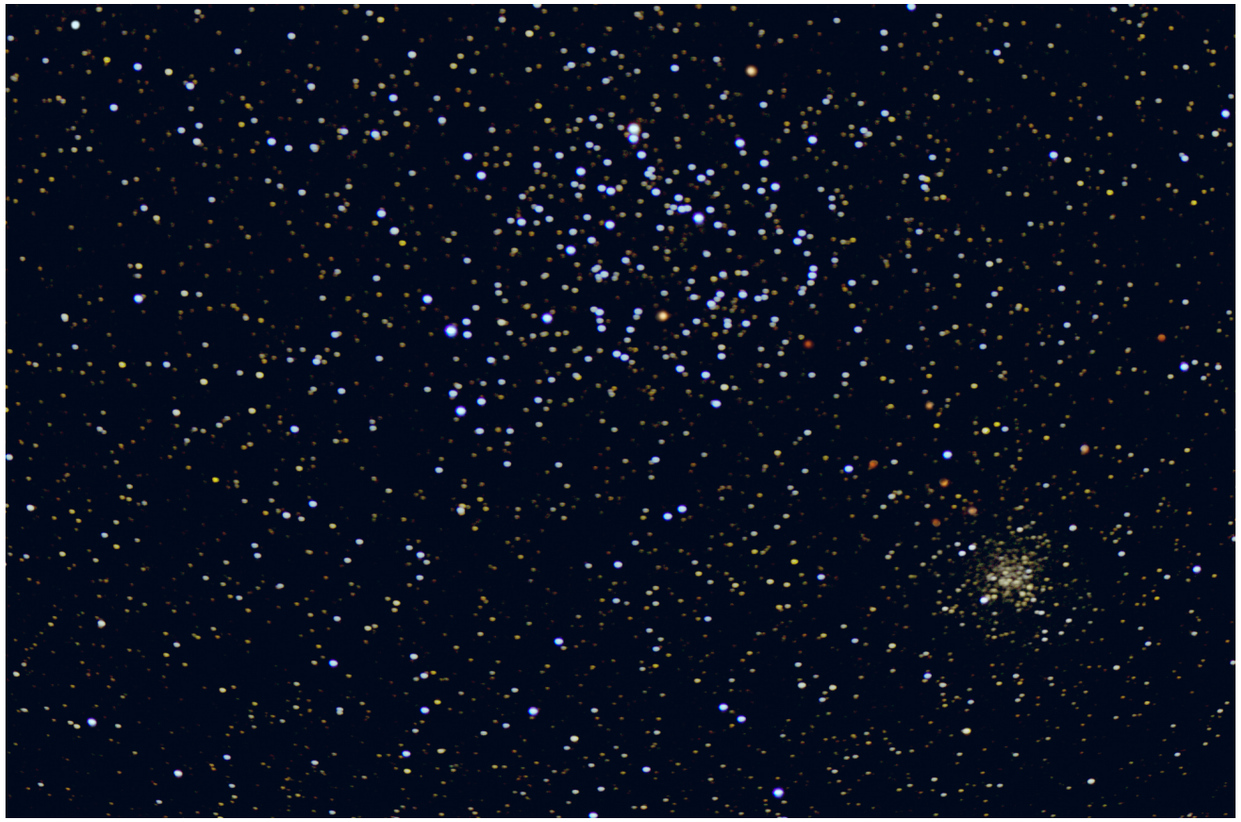

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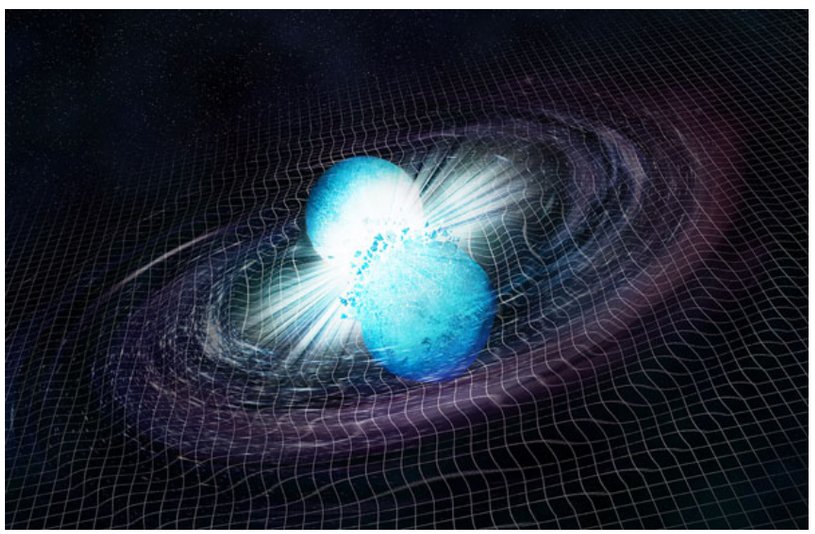
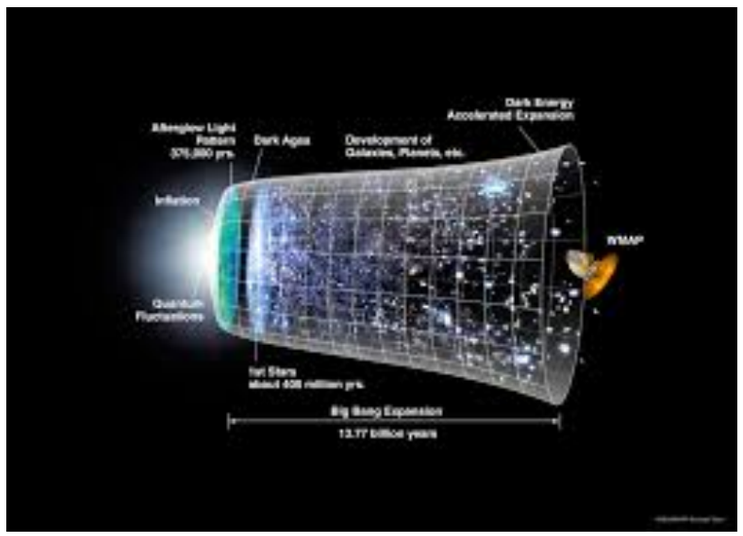
Known sources of gravitational waves that don't emit light





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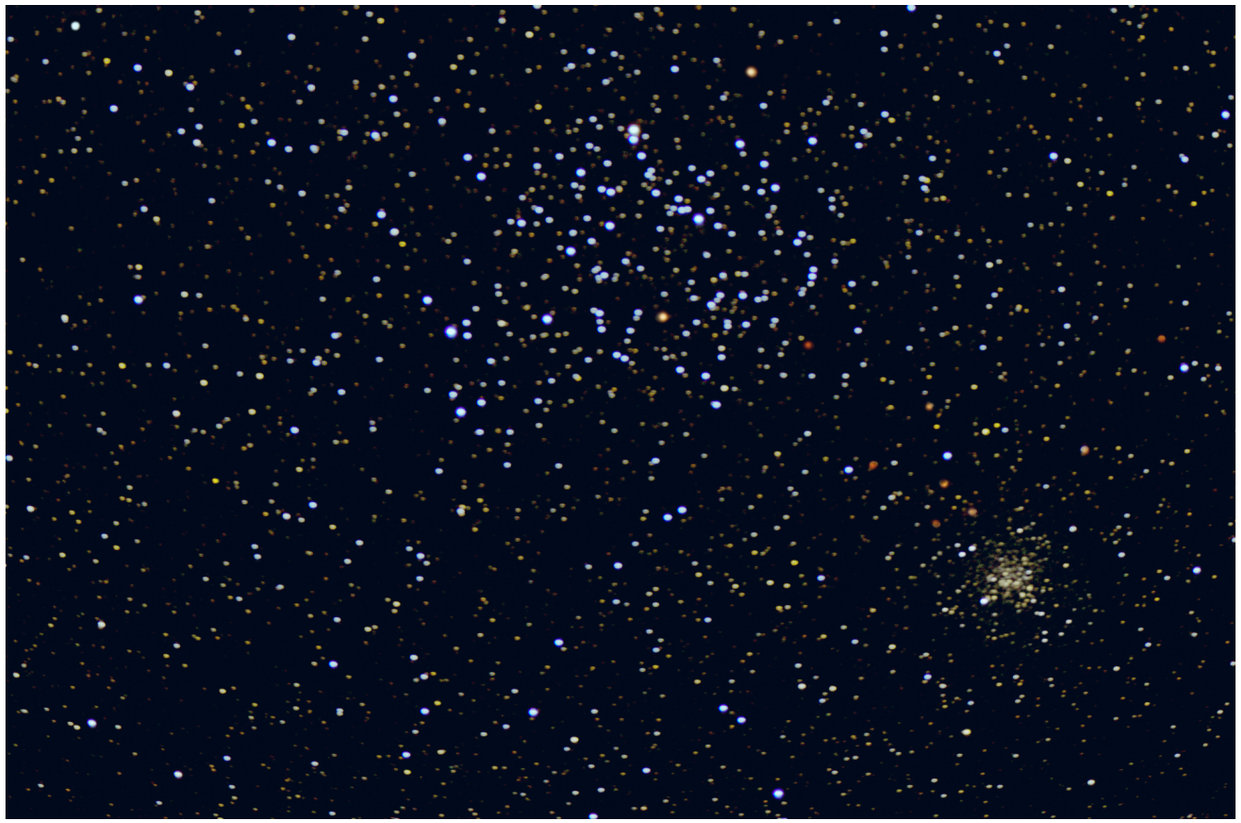

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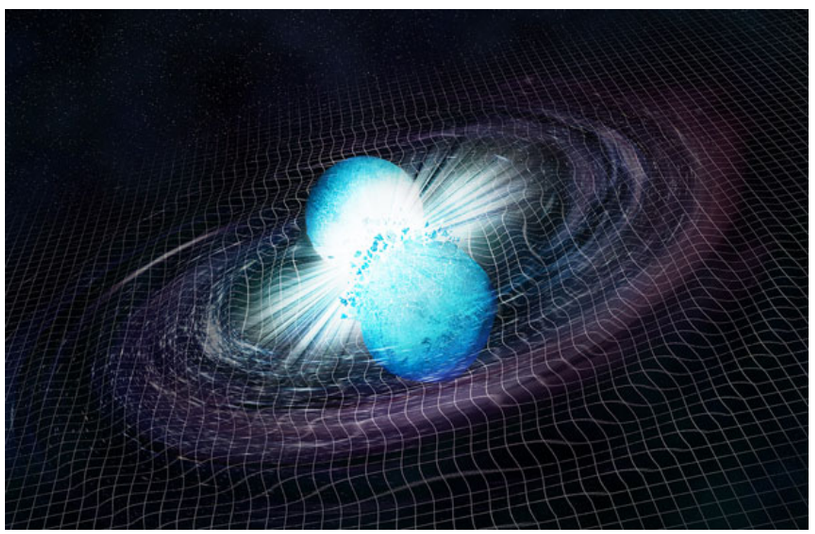
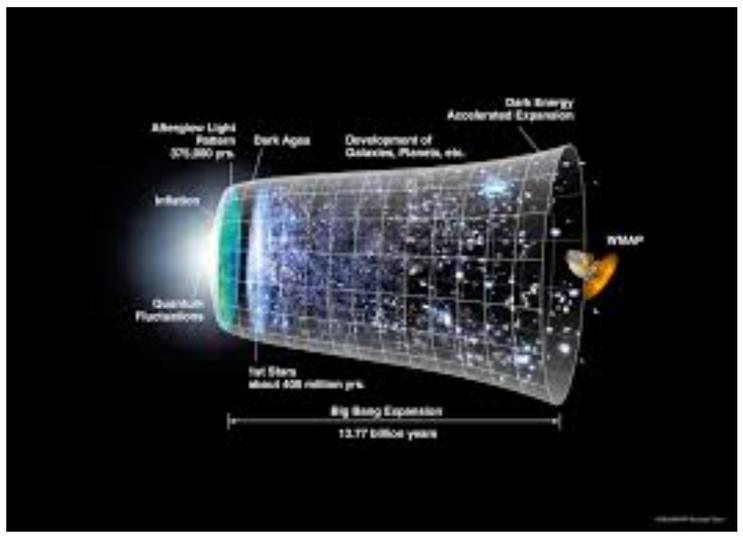
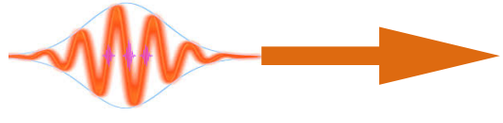




LIGO: 10 Hz - kHz. Other bands?

Gravitational Wave Detection

Protocol: Clocks across a baseline



A

L

B

Record Arrival Times

@ T, 2 T, 3T…

Null Result

Arrival at B: T+L, 2T +L, 3T+L…

Gravitational Wave

Arrival at B: T+L+ε, 2T +L-ε, 3T+L+ε…

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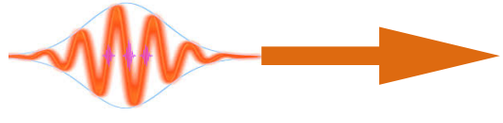

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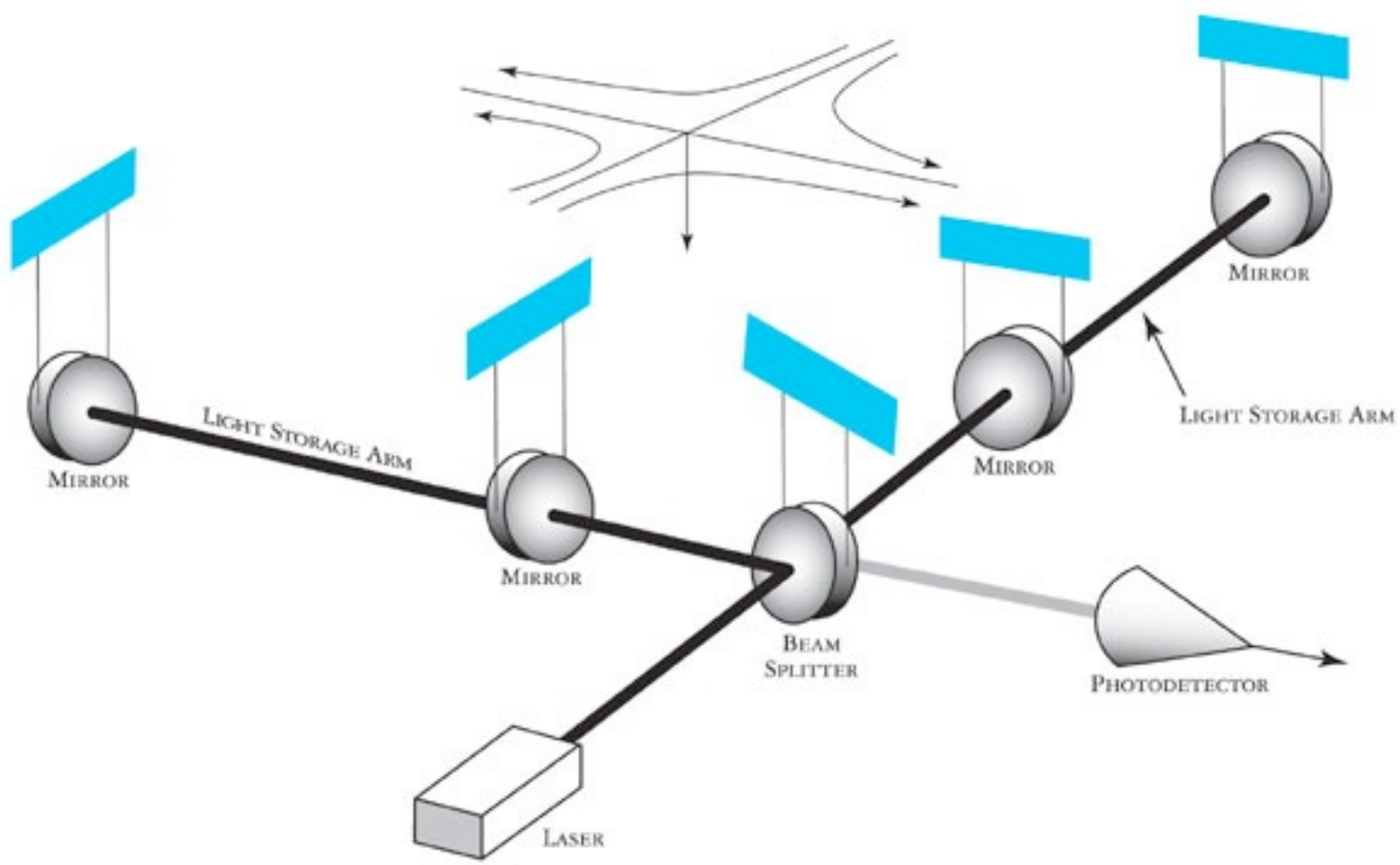
LIGO at 10 Hz - kHz. Other Frequencies?

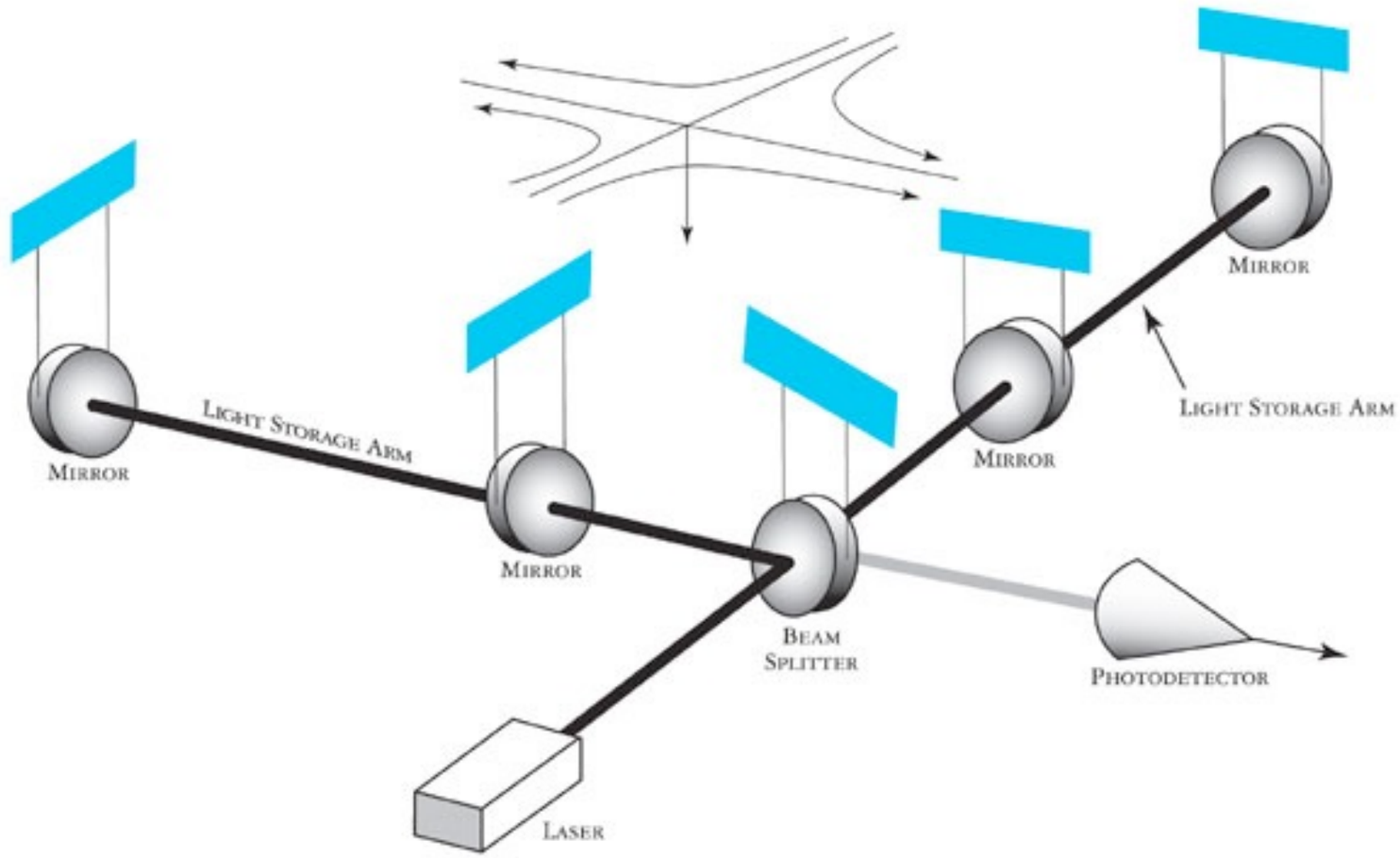
LIGO



Use optical interferometer to measure

Use vibration isolation

LIGO



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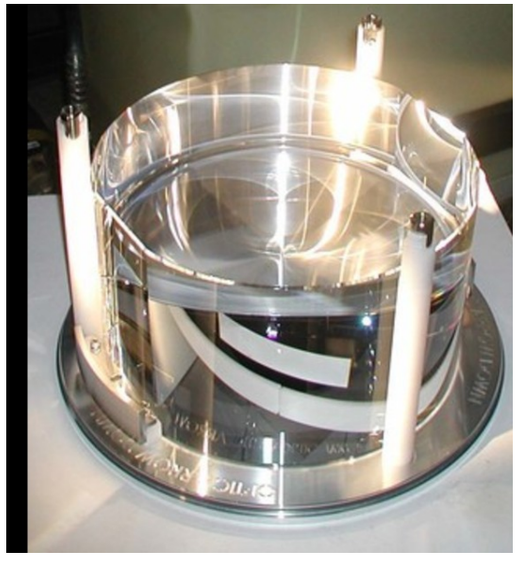
Problem: Large seismic activity below 10 Hz!

MAGIS



Take LIGO's mirrors

Drop them

Measure distance between them as they are falling

Gravitational wave still causes modulation
But, system completely vibration isolated!

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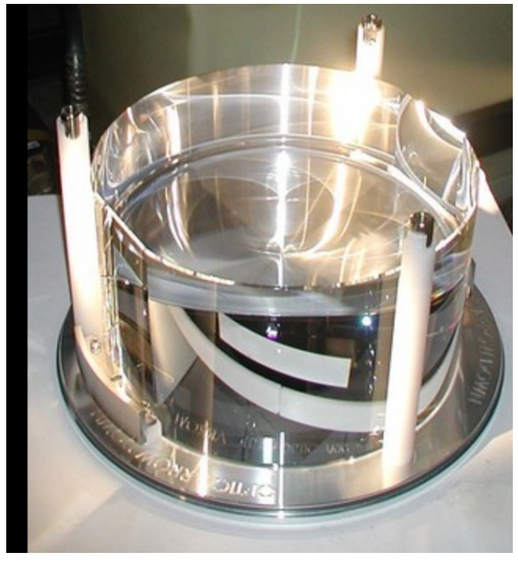

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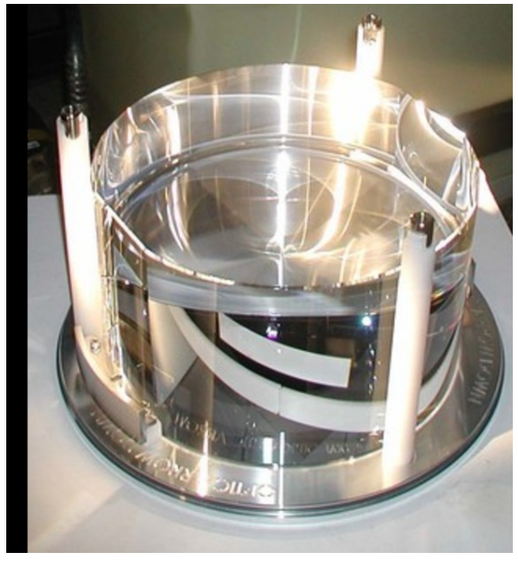

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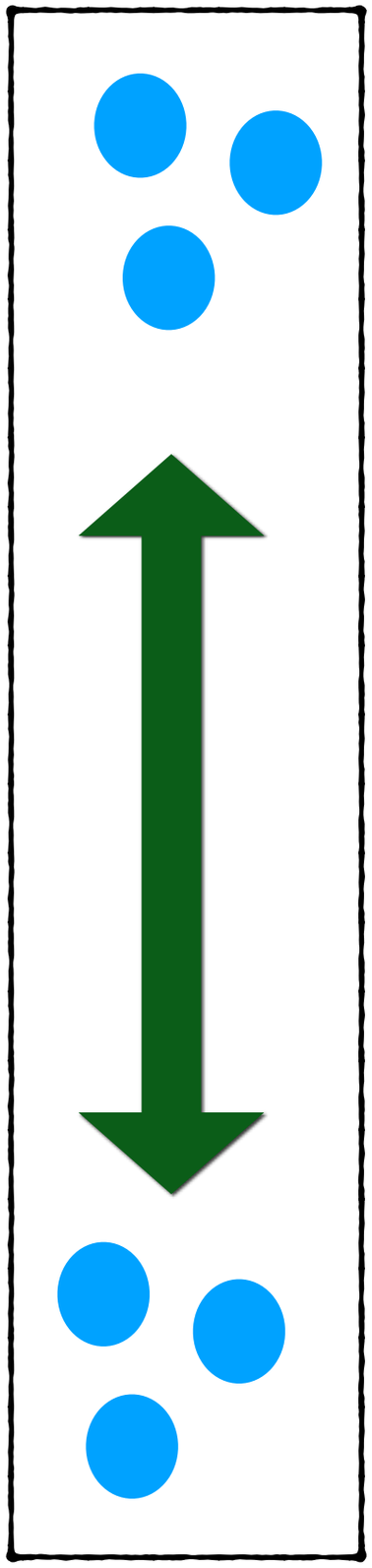
Atoms!

Atom Interferometers



Drop a cold cloud of atoms at the top and bottom of a ~ km long vertical mine shaft

Measure the relative acceleration between them the clouds when they are in free fall

Observe gravitational wave, no direct seismic noise

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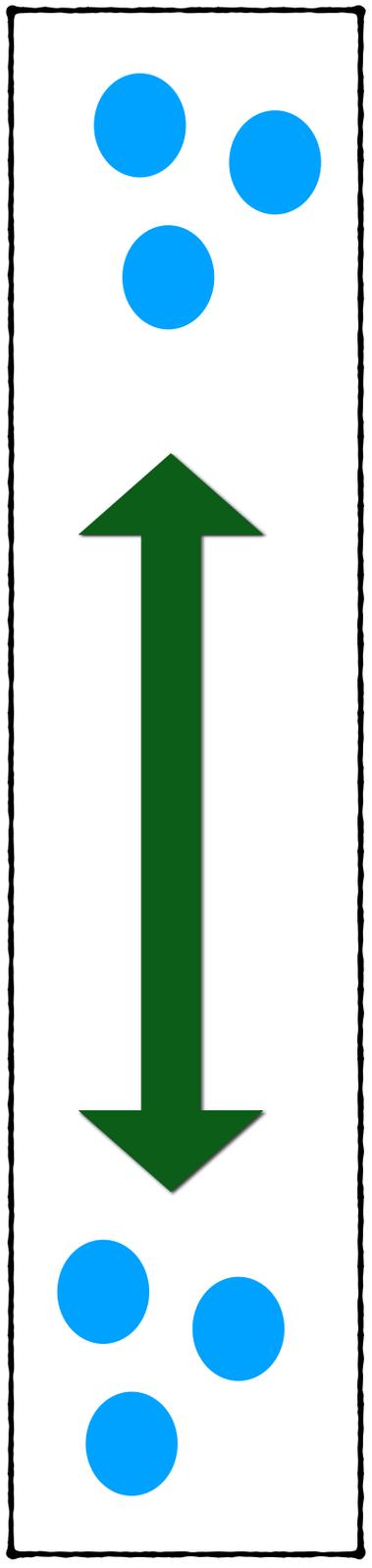

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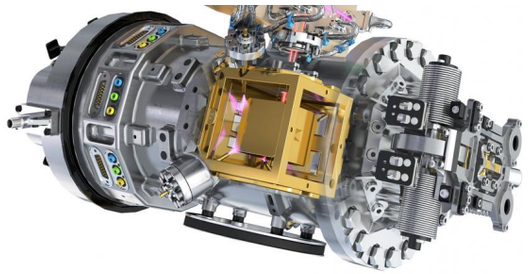
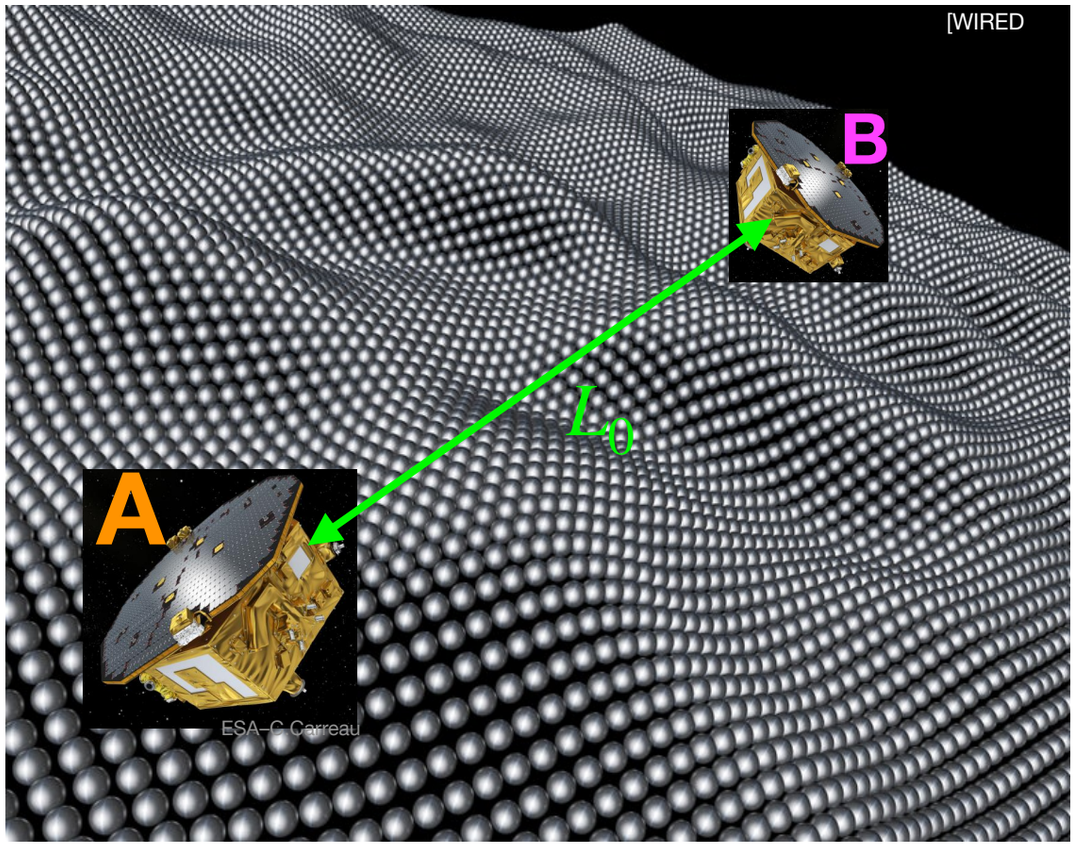
Use Atom Interferometry to measure distance between atoms
(Each atom is an atomic clock)

LISA

Satellites with drag-free test masses (TM)



Light travel time (= proper distance) between test masses is modulated by GW



Emitter (A) sends pulse at $t_A = t_0$;

receiver (B) gets pulse at $t_B = t_0 + \Delta t$:

$$\Delta t = L_0 \left(1 - \frac{h_0}{2}\,\mathrm{sinc}(\omega_{gw} L_0/2)\,\cos[\omega_{gw}(t_0 + L_0/2)]\right) + \mathcal{O}(h_0^2)$$

$$\longrightarrow L_0 \left(1 - \frac{h_0}{2}\cos[\omega_{gw} t_0]\right) + \mathcal{O}(h_0^2) \qquad [\omega_{gw} L_0 \ll 1]$$

GW strain amplitude

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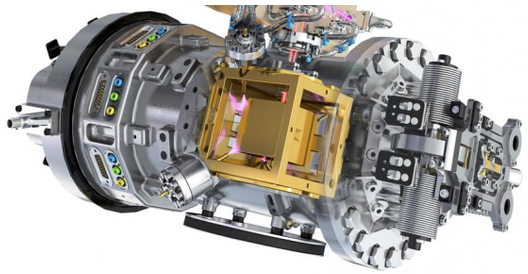

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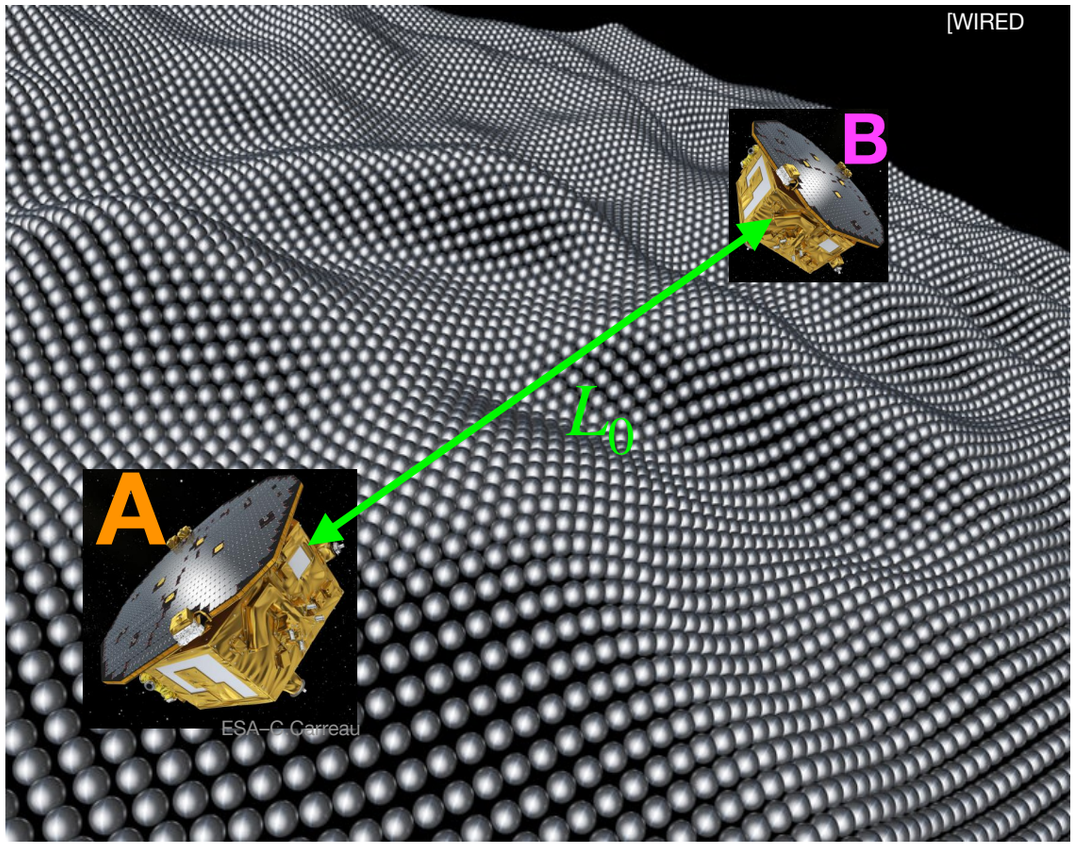

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GW strain amplitude

Demonstrated at mHz

Lower frequency?

Gravitational Waves @ μHz

Brighter gravitational waves at lower frequencies ($h \sim 10^{-17} - 10^{-18}$)

Stability?

$$h \sim 10^{-17} - 10^{-18}, L \sim 1\ \mathrm{AU} \implies \delta x \sim hL \sim 0.1\,\mu\mathrm{m}$$

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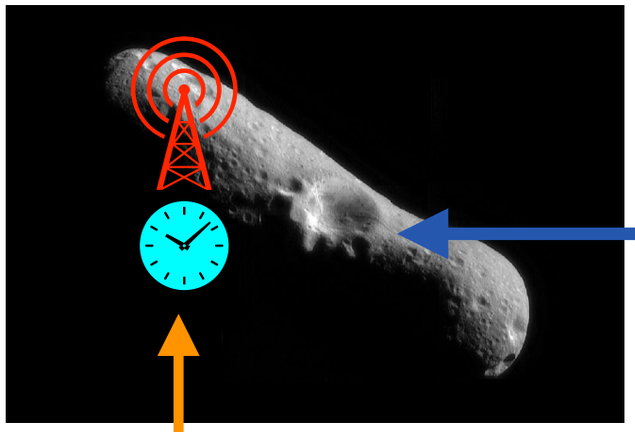
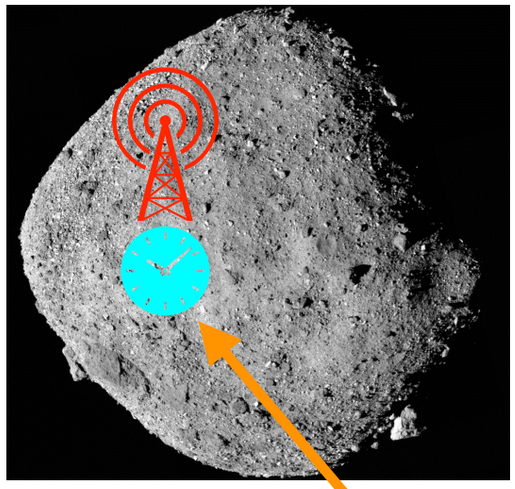


Deployed base station

Radio/Laser Range



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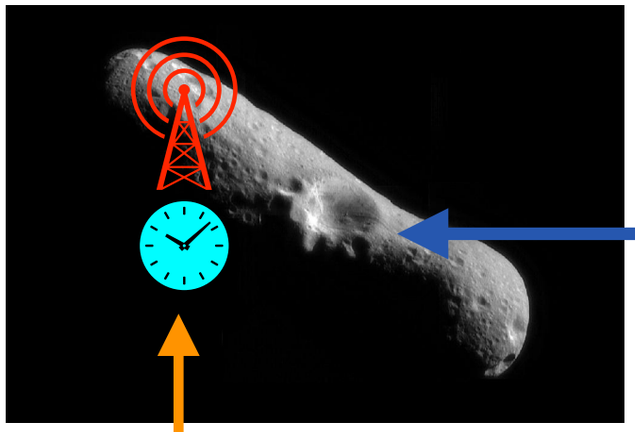
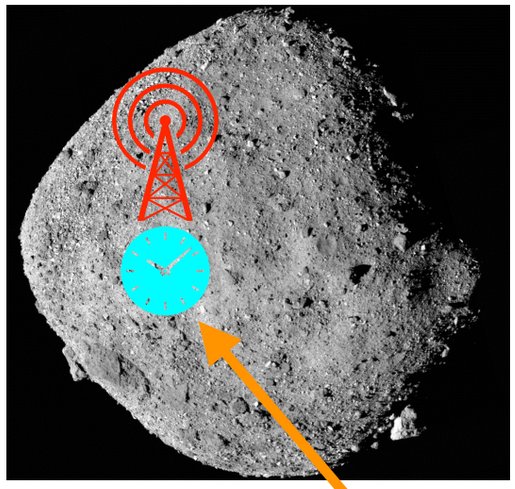


Radio/Laser Range



Land on Asteroids?

Do we have good enough atomic clocks?

Deployed base station

Deployed base station

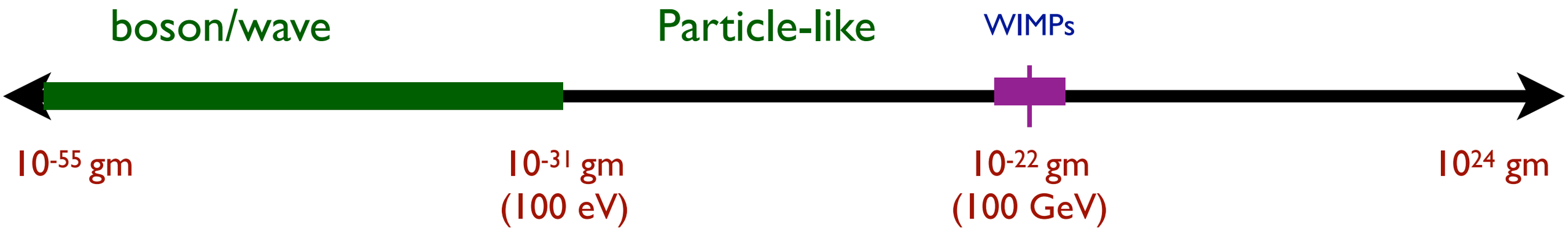
Is the asteroid surface/center of mass stable enough?

Likely Yes (need in-situ measurements)

Dark Matter

The Dark Matter Landscape

The Dark Matter Landscape



Many years of searching

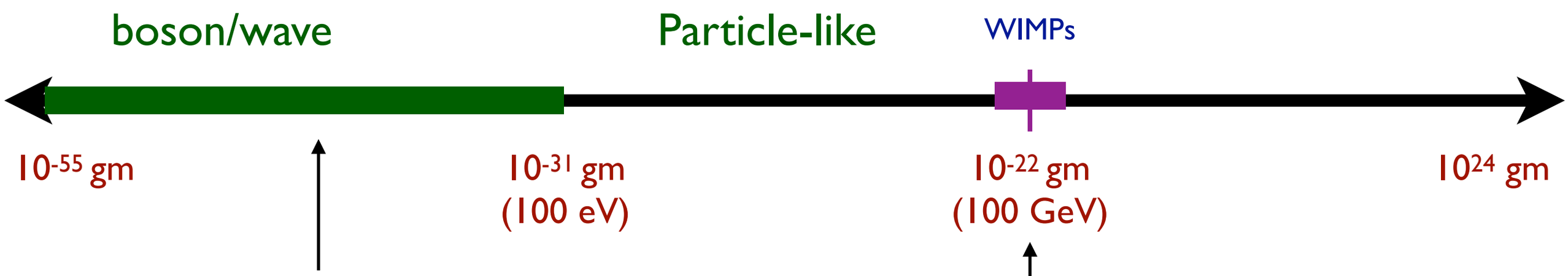
The Dark Matter Landscape

Large well-motivated parameter space

Hard to find through energy deposition

Many years of searching

The Dark Matter Landscape



Large well-motivated parameter space

Many years of searching

Hard to find through energy deposition

$$\text{Energy Density} = \text{Mass} \times \text{Number Density}$$

$$\text{Number Density} \propto 1/\text{Mass}$$

Dark matter waves

Observable Effects

What can the dark matter wave do?

Observable Effects

What can the dark matter wave do?

What can waves do?

Observable Effects

What can the dark matter wave do?

What can waves do?

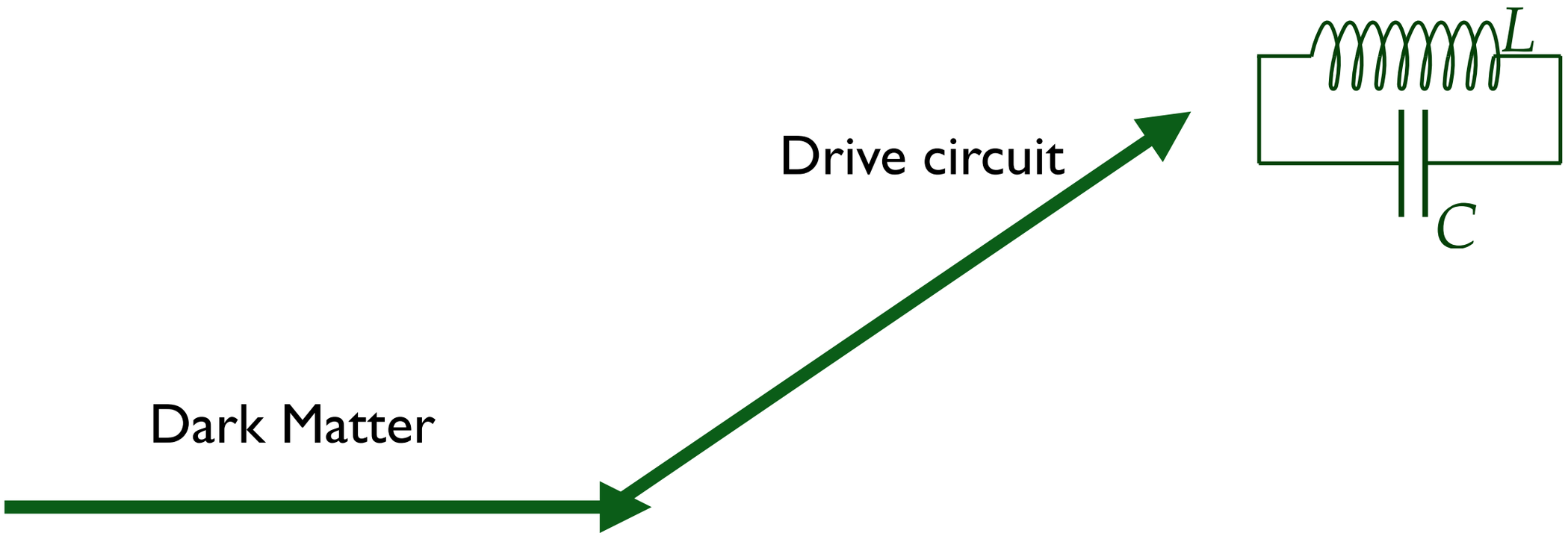
Dark Matter

Oscillating Dark Matter Wave

Observable Effects

What can the dark matter wave do?

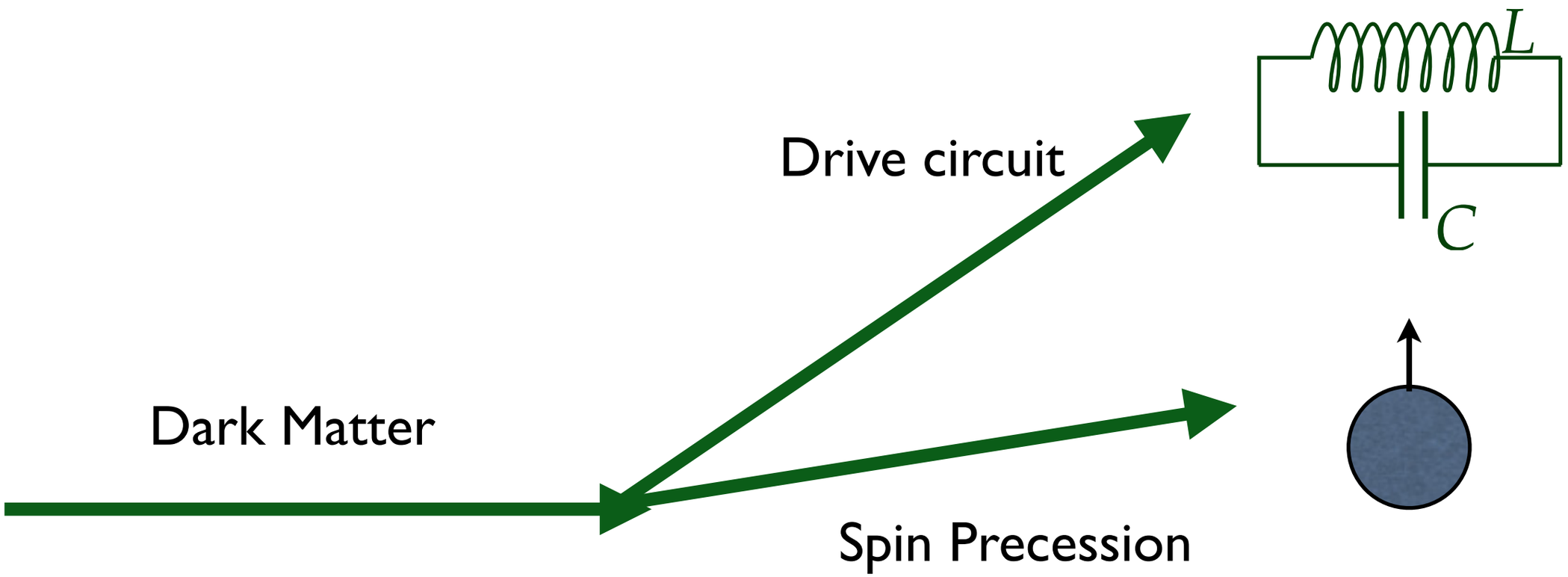
What can waves do?



Observable Effects

What can the dark matter wave do?

What can waves do?



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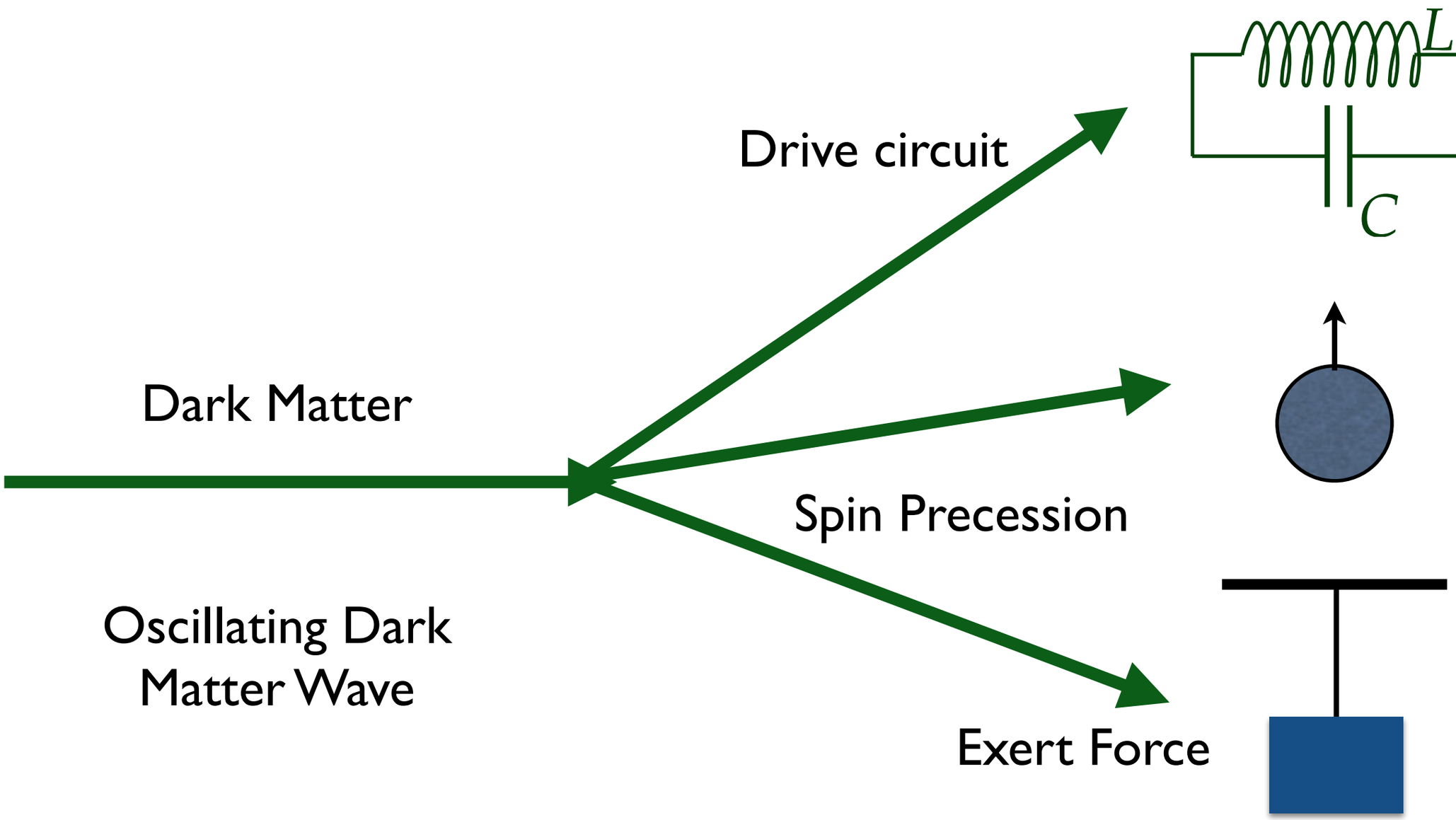

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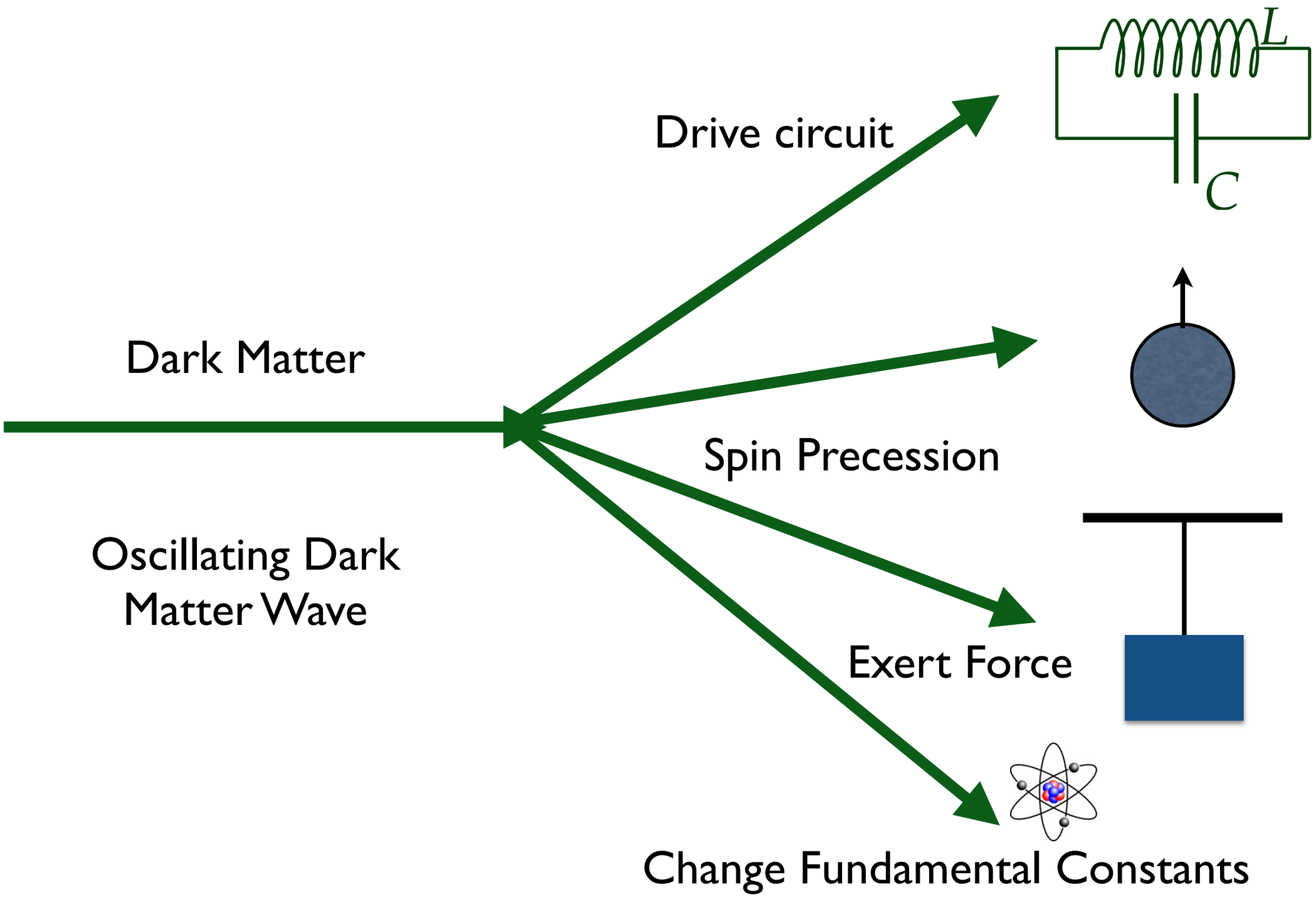

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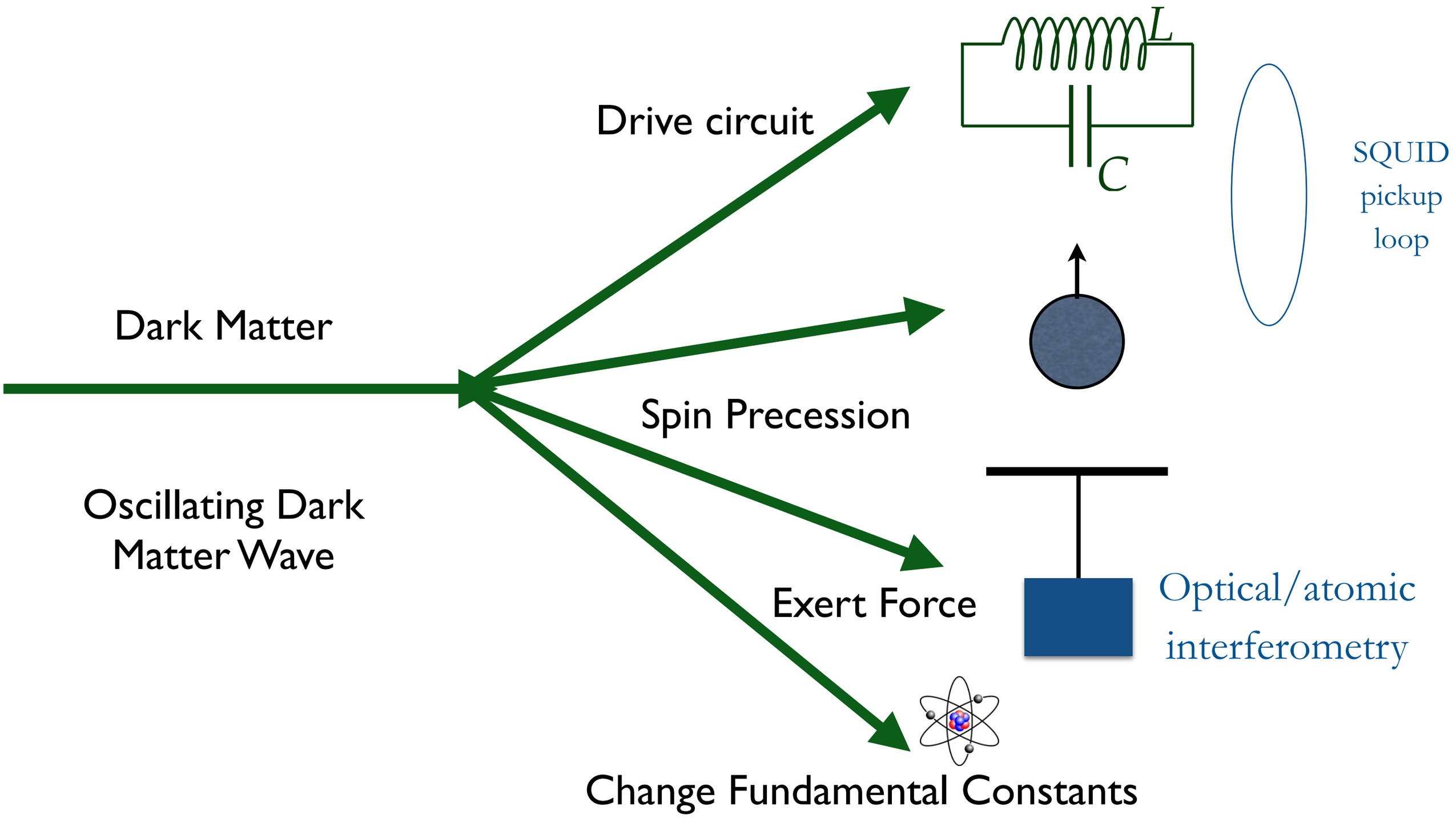
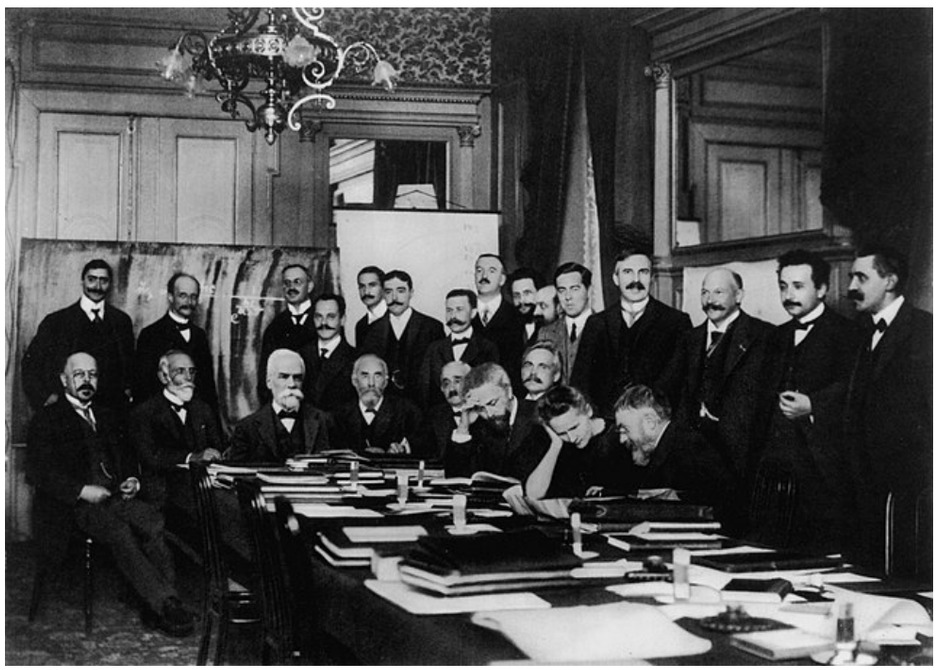


Quantum Mechanics

Why?

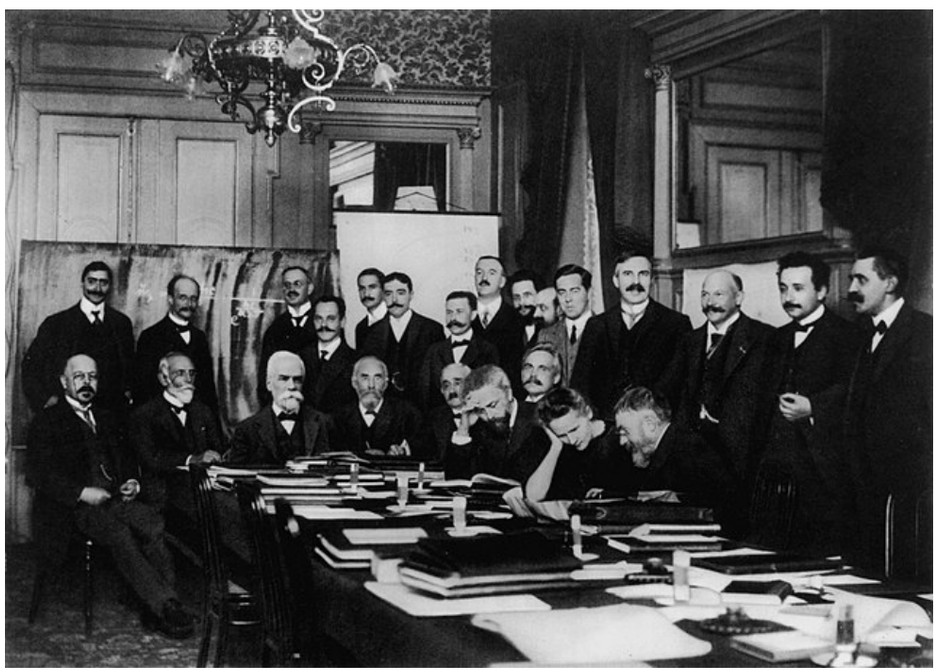
Why?



Quantum Mechanics

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

Why?



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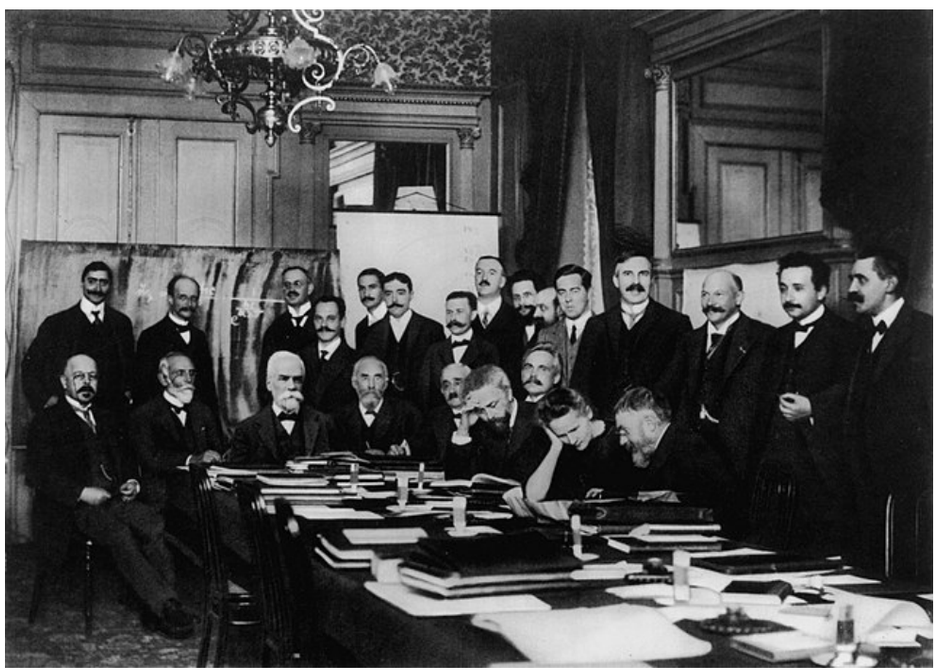
What?

Two Postulates of Quantum Mechanics

Probability **Linearity**

Why?



Quantum Mechanics

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Two Postulates of Quantum Mechanics

Probability → **Fact**

Linearity → **Why not?**

Causality and Entanglement

Trial Non-Linear Term

$$i\frac{\partial \Psi}{\partial t} = H_L \Psi + \epsilon \left(\Psi^2 + \Psi^{*2} \right) \Psi$$

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Entanglement is fundamental to quantum mechanics

$$\Psi\left(x, y; t\right) = \sum_{i,j} c_{ij}\left(t\right)\alpha_i\left(x\right)\beta_j\left(y\right)$$

Causality and Entanglement

Trial Non-Linear Term

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Entanglement is fundamental to quantum mechanics

$$\Psi\left(x, y; t\right) = \sum_{i,j} c_{ij}\left(t\right)\alpha_i\left(x\right)\beta_j\left(y\right)$$

Apply some local operation on x: $a_i(x)$ -> U $a_i(x)$

Does it instantly change the time evolution of y?

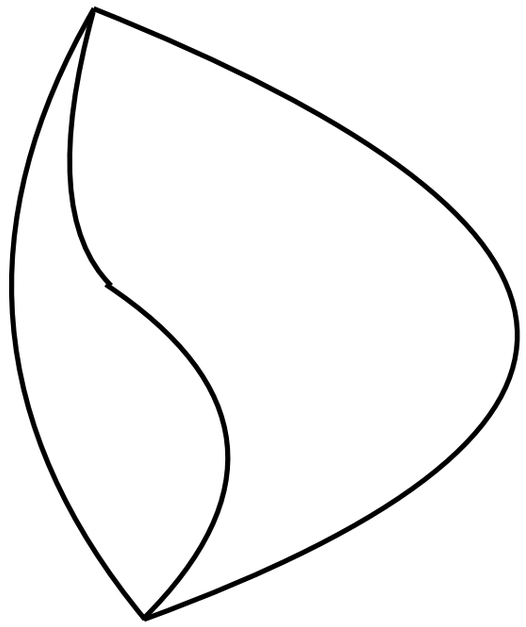
YES

Not causal

Causality and Non-Linearity

Linear Quantum Mechanics

Electron Coupled to Electromagnetism



Electron paths do not interact via electromagnetism

Causality and Non-Linearity

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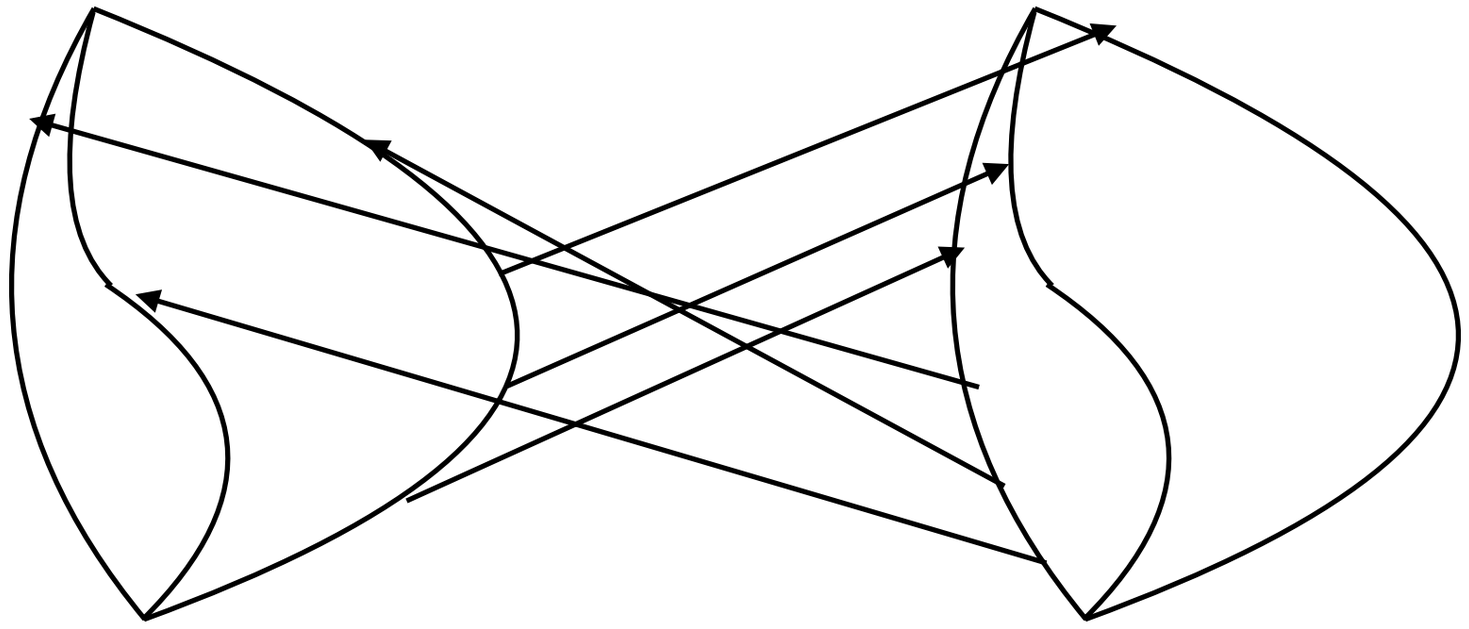

Electron paths do not interact via electromagnetism

Paths of two electrons interact causally (QFT)

Causality and Non-Linearity

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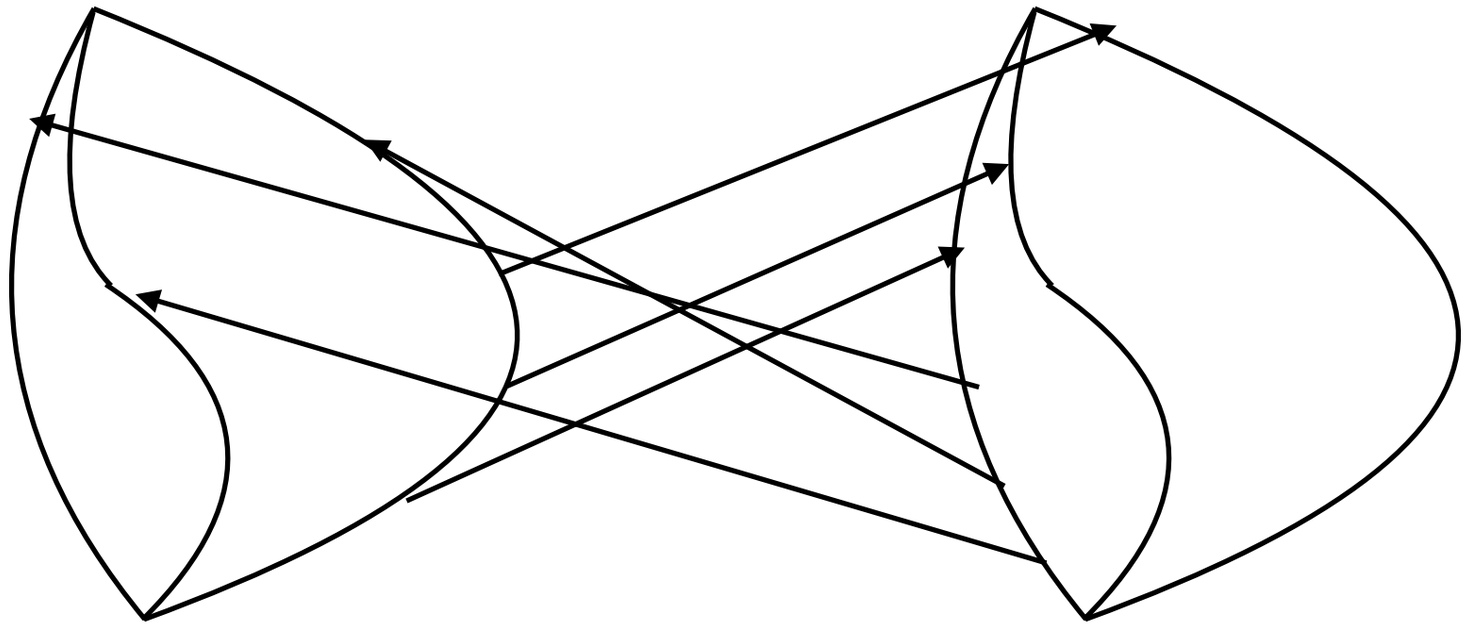


Electron paths do not interact via electromagnetism

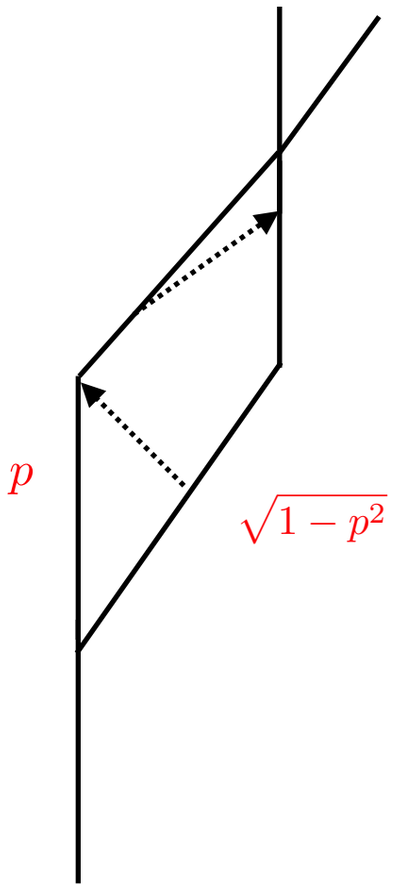
Paths of two electrons interact causally (QFT)

Why can’t path talk to itself?
Formulate directly into QFT

Experimental Tests

Interferometry - interaction between paths

Take an ion - split its wave-function



Coulomb Field of one path interacts with the other path

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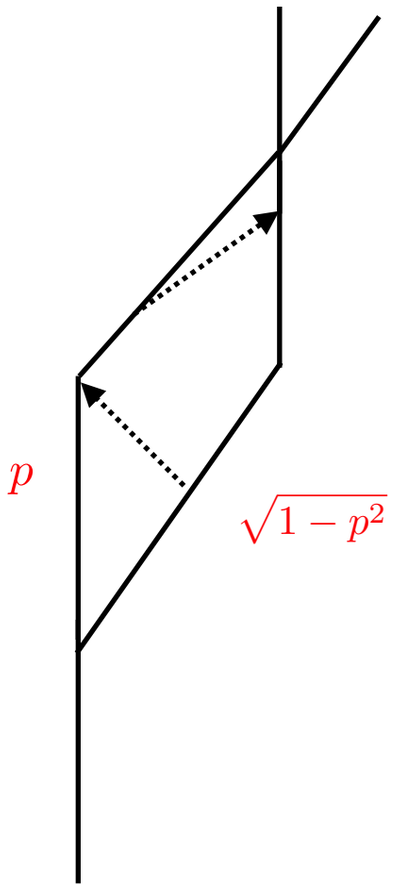


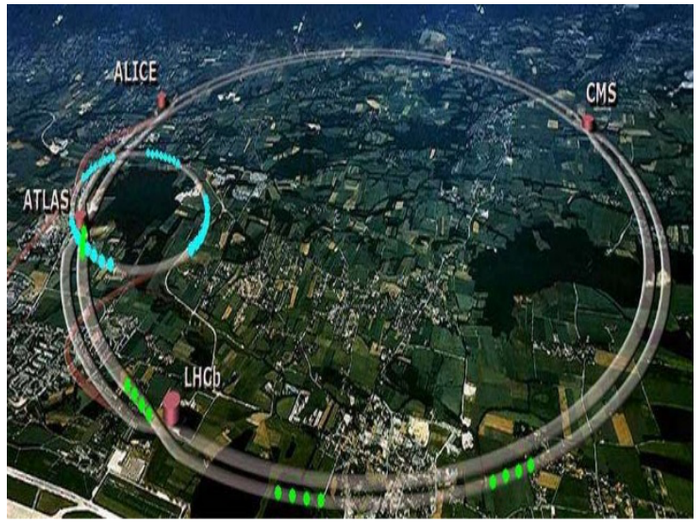
Coulomb Field of one path interacts with the other path

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

Use intensity dependence to combat systematics

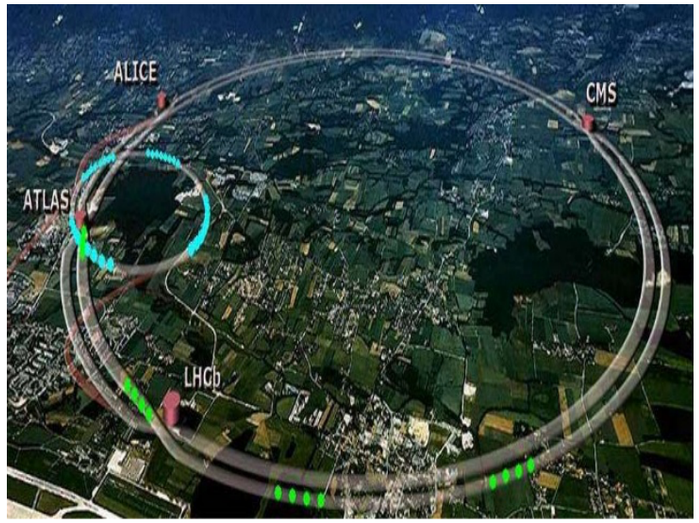
Conclusions

Technology Outlook



Dramatic Evolution in Colliders in the 20th century

Technology Outlook



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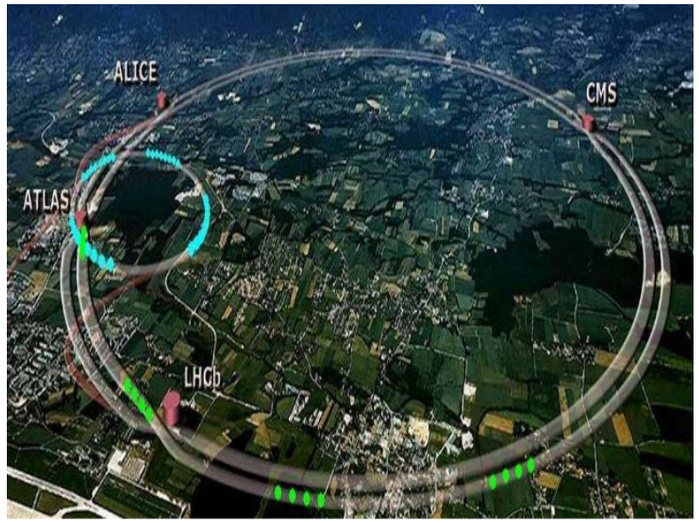
Why?

Technology Outlook



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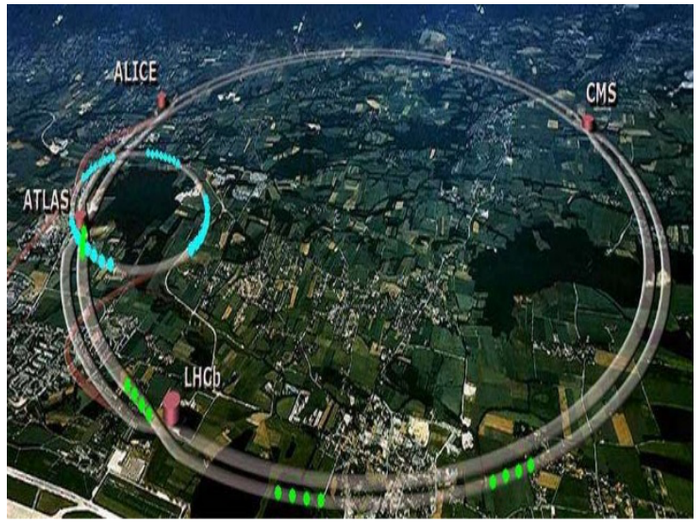

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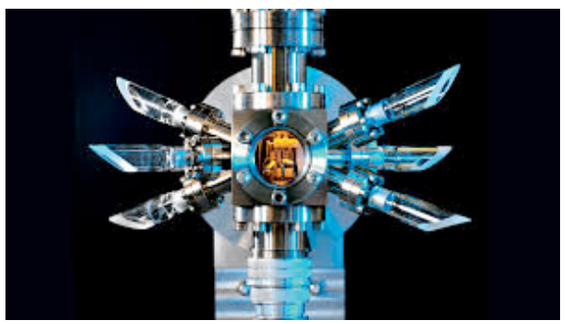
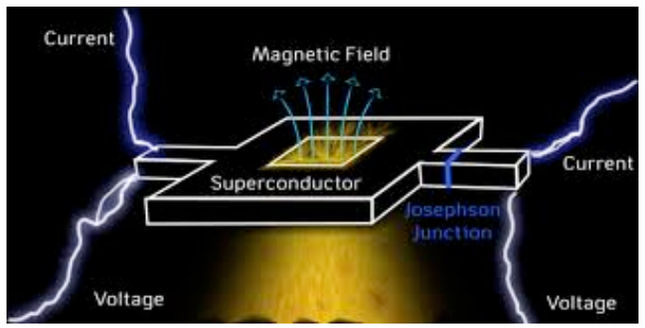
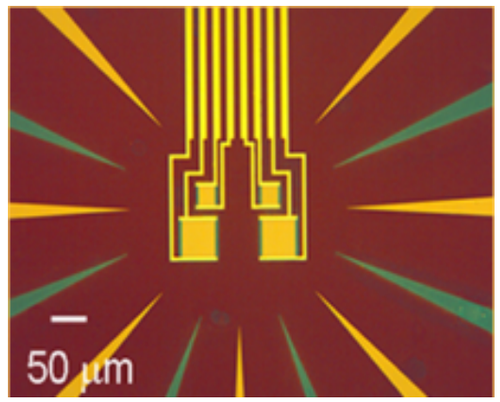
Now, at the anvil of quantum control







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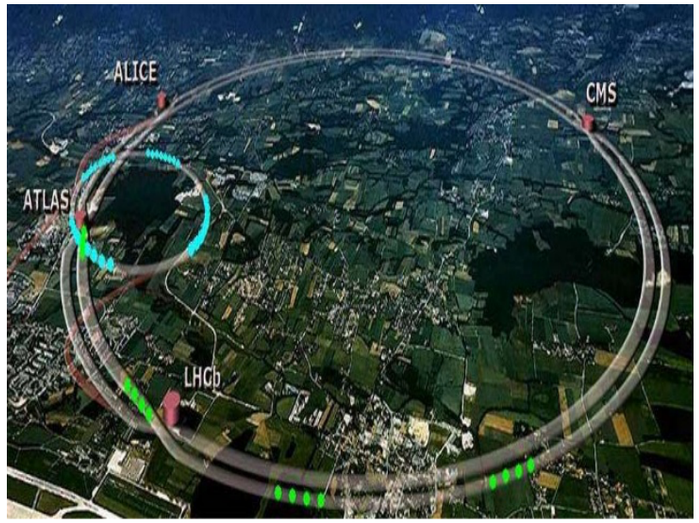

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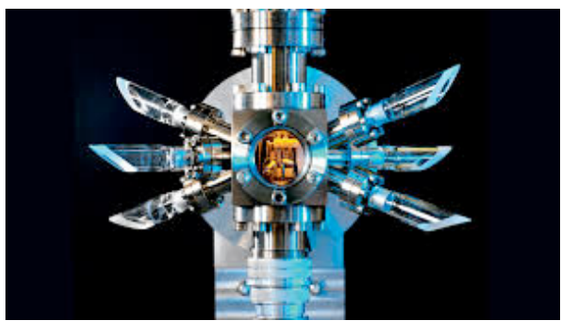

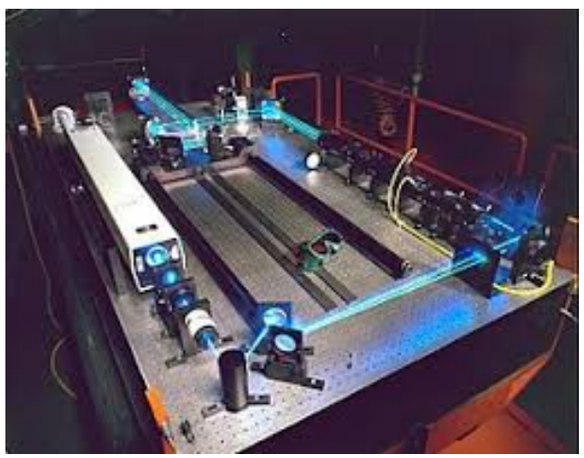

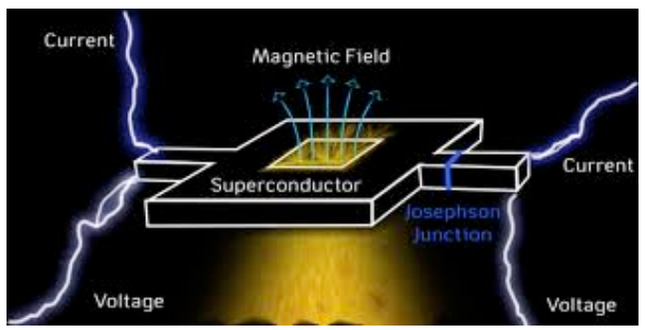

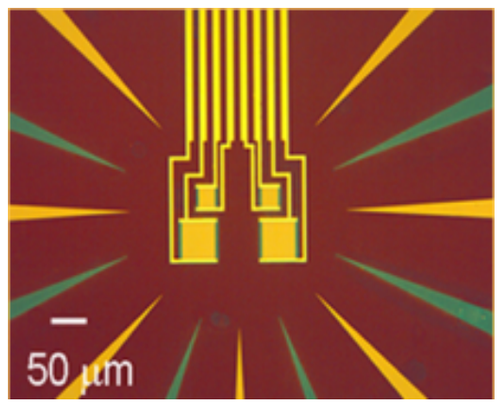

Time to find weakly coupled physics!

Probability

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Finite system has a finite set of energies

Continuous observables and symmetries

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Continuous observables and symmetries

} Deterministic Observables?

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Could an electron in an atom have a well defined position?

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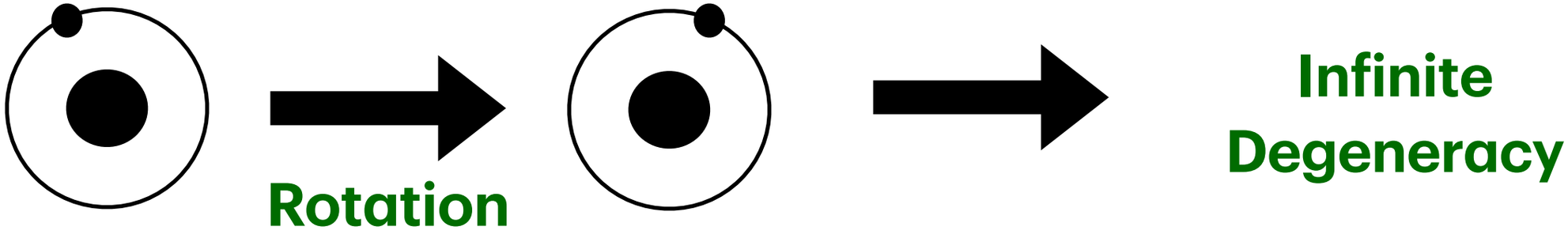

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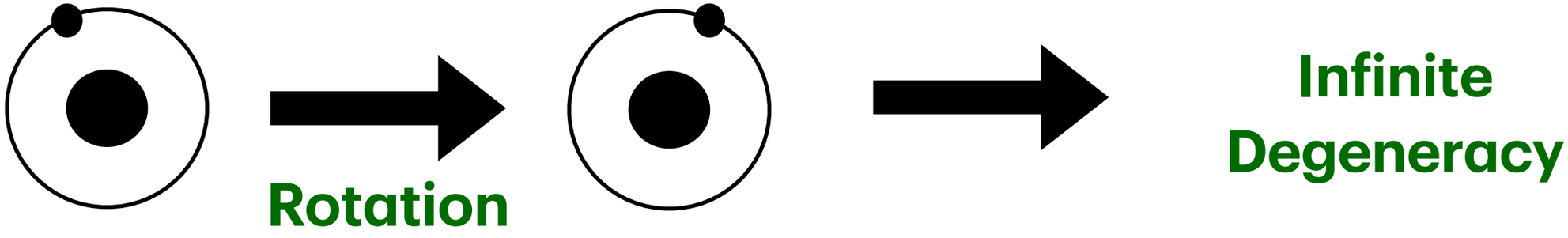

Quantum Mechanics

Sacrifice Determinism.

Preserve finite set of energy states, continuous symmetries and observables

Bell Inequalities, Kochen-Specker, SSC Theorems