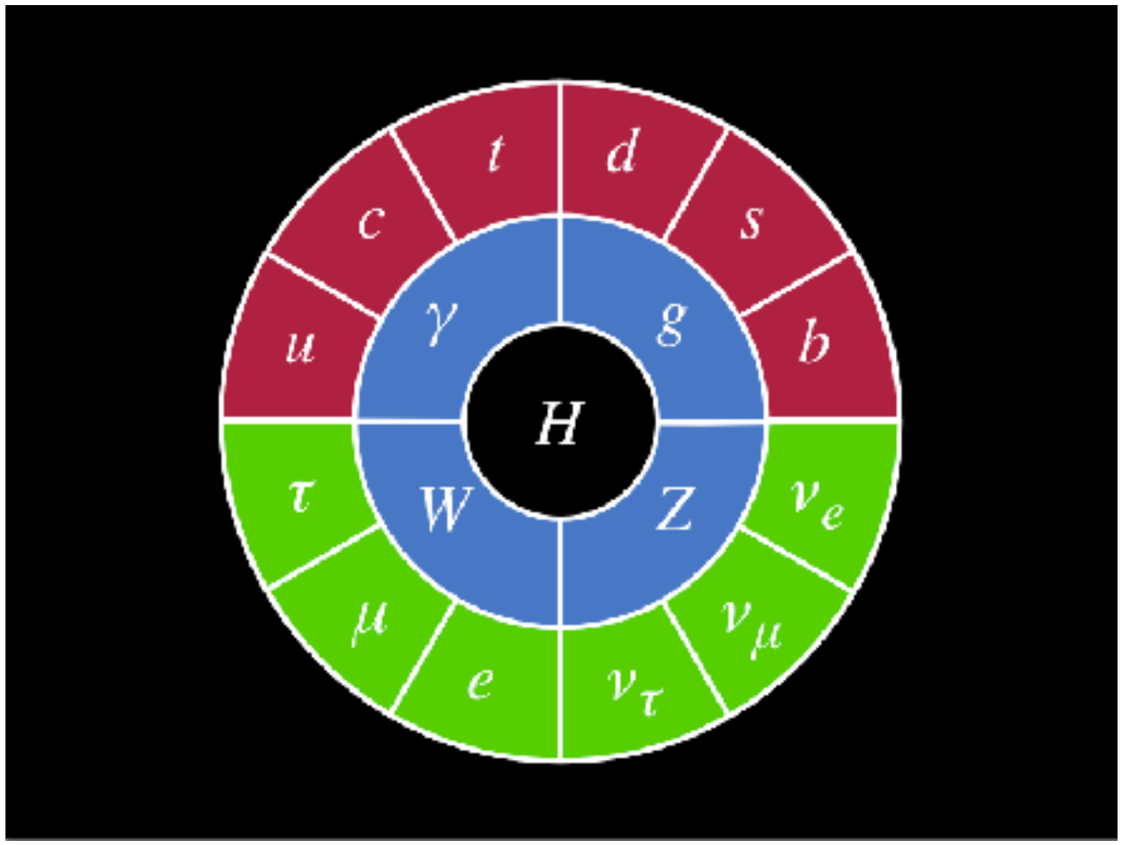
A Theory Perspective

Asimina Arvanitaki
Perimeter Institute for Theoretical Physics

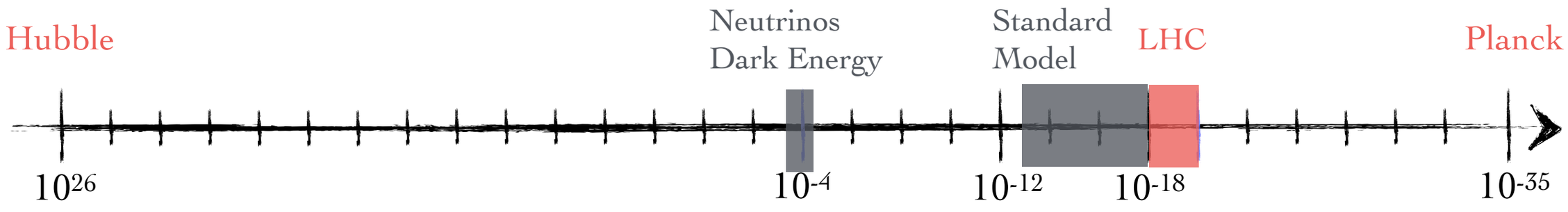
The Standard Model

$$\mathcal{L}_{SM} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ i \bar{\psi} \not{D} \psi$$
$$+ \bar{\psi}_i y_{ij} \psi_j \phi$$
$$+ |D_\mu \phi|^2 - V(\phi)$$
$$+ M_{pl}^2 R \quad - \rho_{vacuum}$$



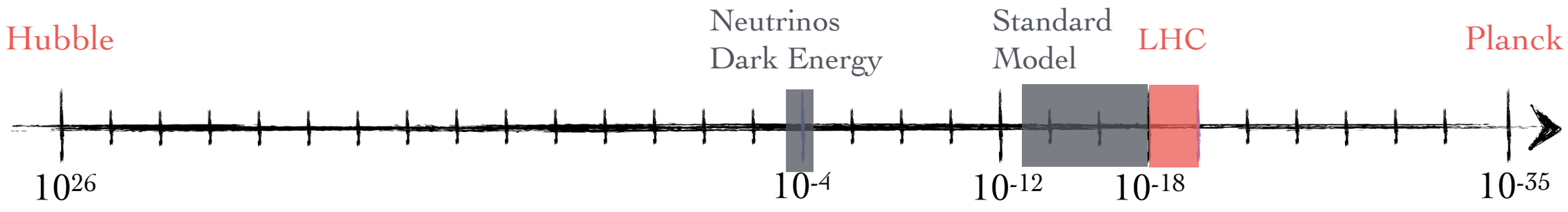
Contains ~20 particles and ~20 parameters

The Scales in our Universe



Scale in meters

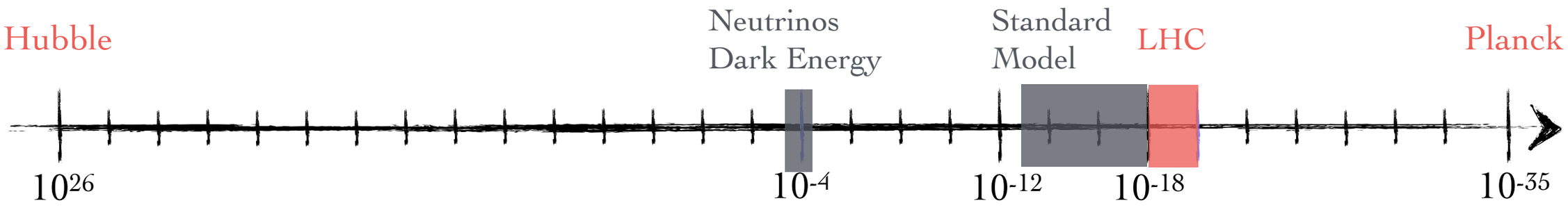
The Scales in our Universe



Scale in meters

The Cosmological Constant Problem
Why is the Universe so large?

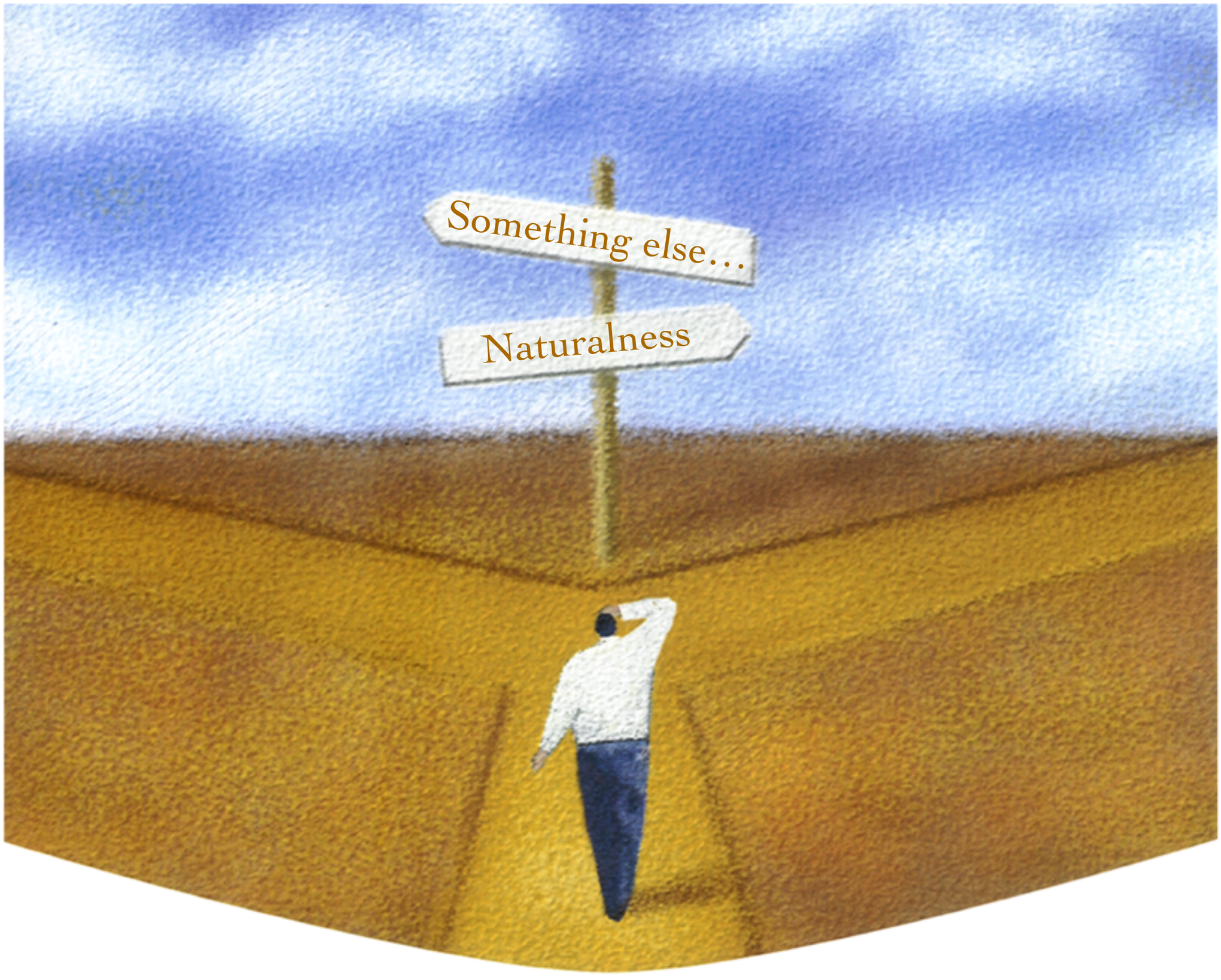
The Scales in our Universe



Scale in meters

The Hierarchy Problem
Why is Gravity so weak?

The Origin of Small Numbers



Small Numbers and Coincidences

Naturalness - Dynamics

Problem	Solution
Hydrogen Binding Energy	$E_b = \frac{1}{2}\frac{e^4}{(4\pi)^2} m_e$
Deuteron Binding Energy Nuclear Binding Energy	$E_b \approx \frac{1}{2}\frac{1}{(4\pi)^2}\frac{m_N}{2}$
π^+ - π^o mass difference	Symmetry/Dynamics
$K - \bar{K}$ mixing	Flavor Symmetry
Electron Mass	Chiral Symmetry

Small Numbers and Coincidences

Something else…

Problem	Solution
Earth-Sun Distance	Environmental Selection 10^{22} suns
7 eV line of ^{229}Th nucleus	"Look-elsewhere" effect
Solar-Lunar Eclipse	Plain Luck!
Cosmological Constant	Environmental Selection? 10^{500} universes!

Small Numbers and Beyond the Standard Model

- The gauge hierarchy problem

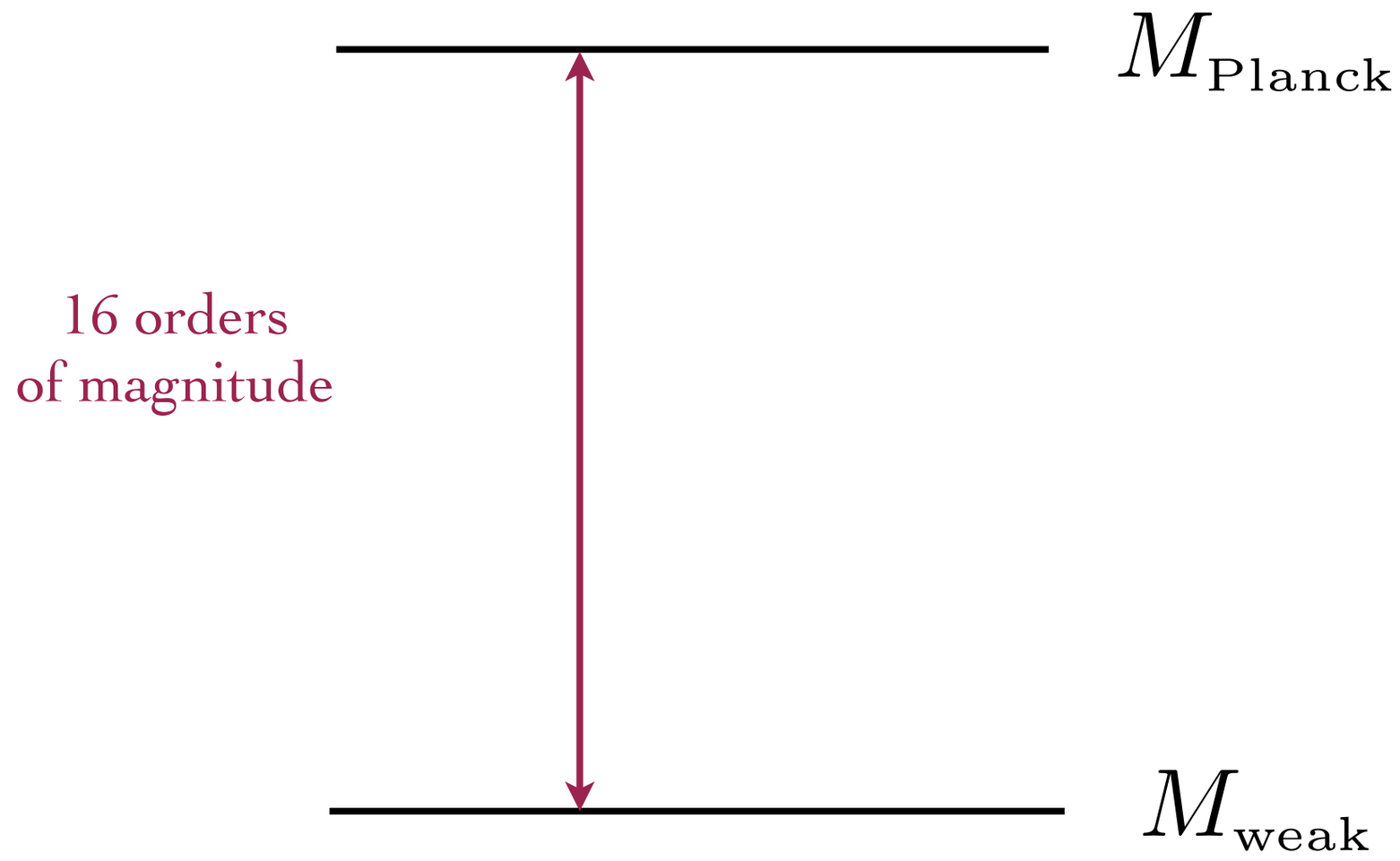
- The cosmological constant problem

- The strong CP problem

The hierarchy problem

$$M_{\text{Planck}} = G_{\text{Newton}}^{-\frac{1}{2}} = 10^{19}\ \text{GeV}$$

$$M_{\text{weak}} = G_{\text{Fermi}}^{-\frac{1}{2}} = 10^{3}\ \text{GeV}$$



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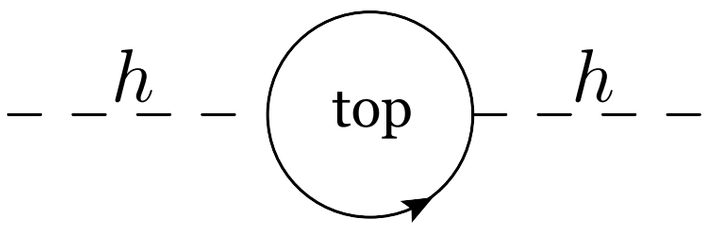
$$\frac{\text{————————}}{\text{————————}} \quad \frac{M_{\text{Planck}}}{M_{\text{weak}}}$$

In the Standard Model:

Quantum Corrections pull the weak scale up

Quantum Corrections in the Standard Model

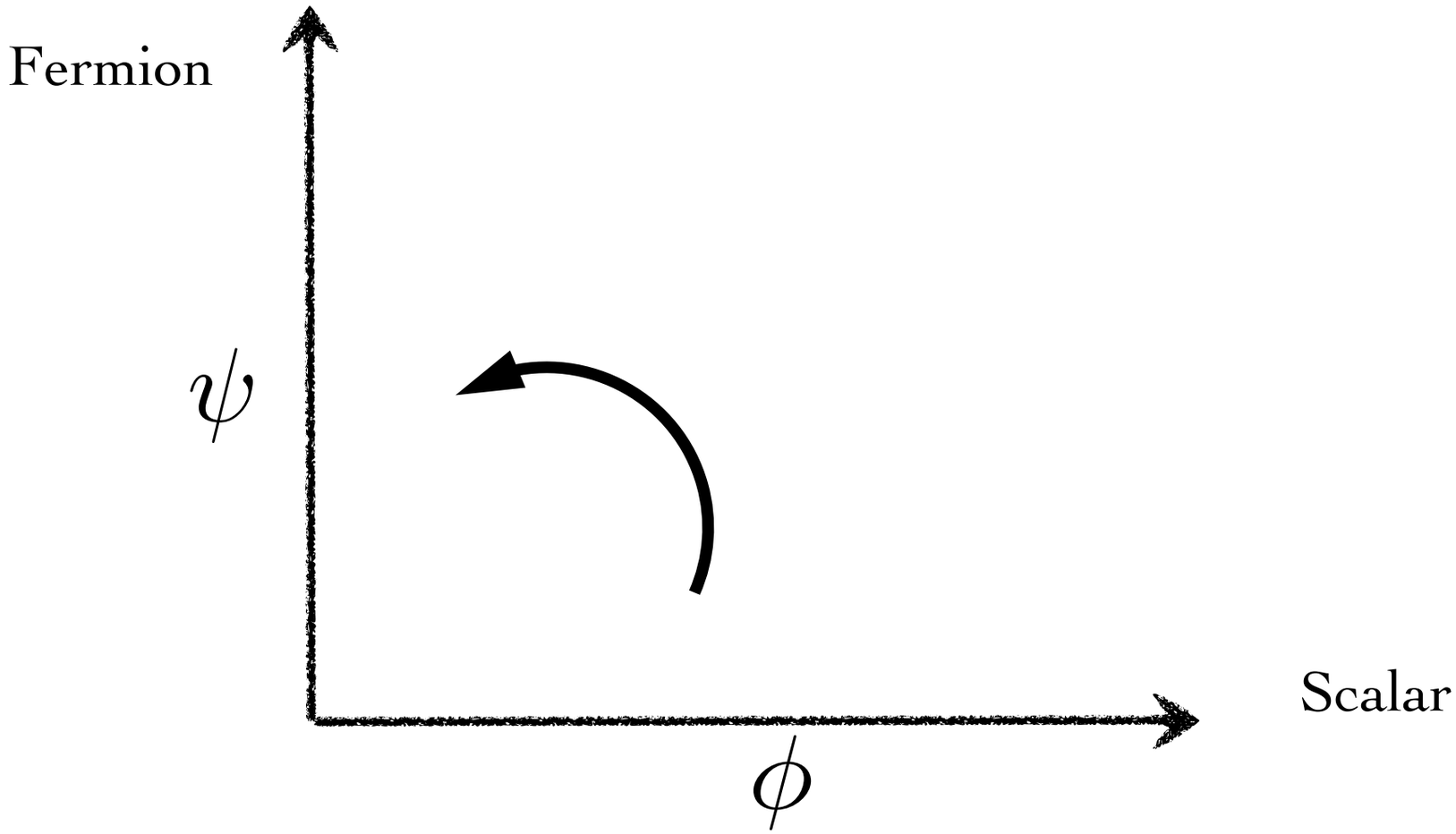
Note: $M_{weak} \sim \mathrm{m}_{\mathrm{higgs}}$



$$m^2_{\mathrm{higgs}} \propto M^2{}_{\mathrm{Planck}}$$

Need new symmetry to protect the Higgs in the Standard Model

A New Symmetry for the SM Higgs



Supersymmetric Standard Model

The Supersymmetric Standard Model

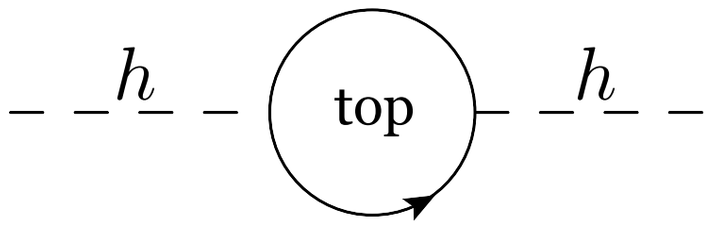
- New Symmetry: Supersymmetry

- New Particles: Superparticles

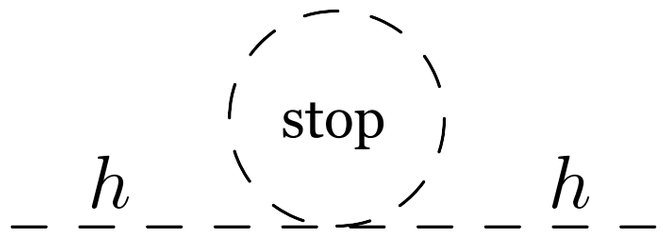
- Every particle has a superpartner:

lepton	→ slepton	} matter
quark	→ squark	
photon	→ photino	} force
gluon, W	→ gluino, Wino	
Higgs	→ Higgsino	

Superparticles and Quantum Corrections



$$\propto M^2_{\text{Planck}}$$

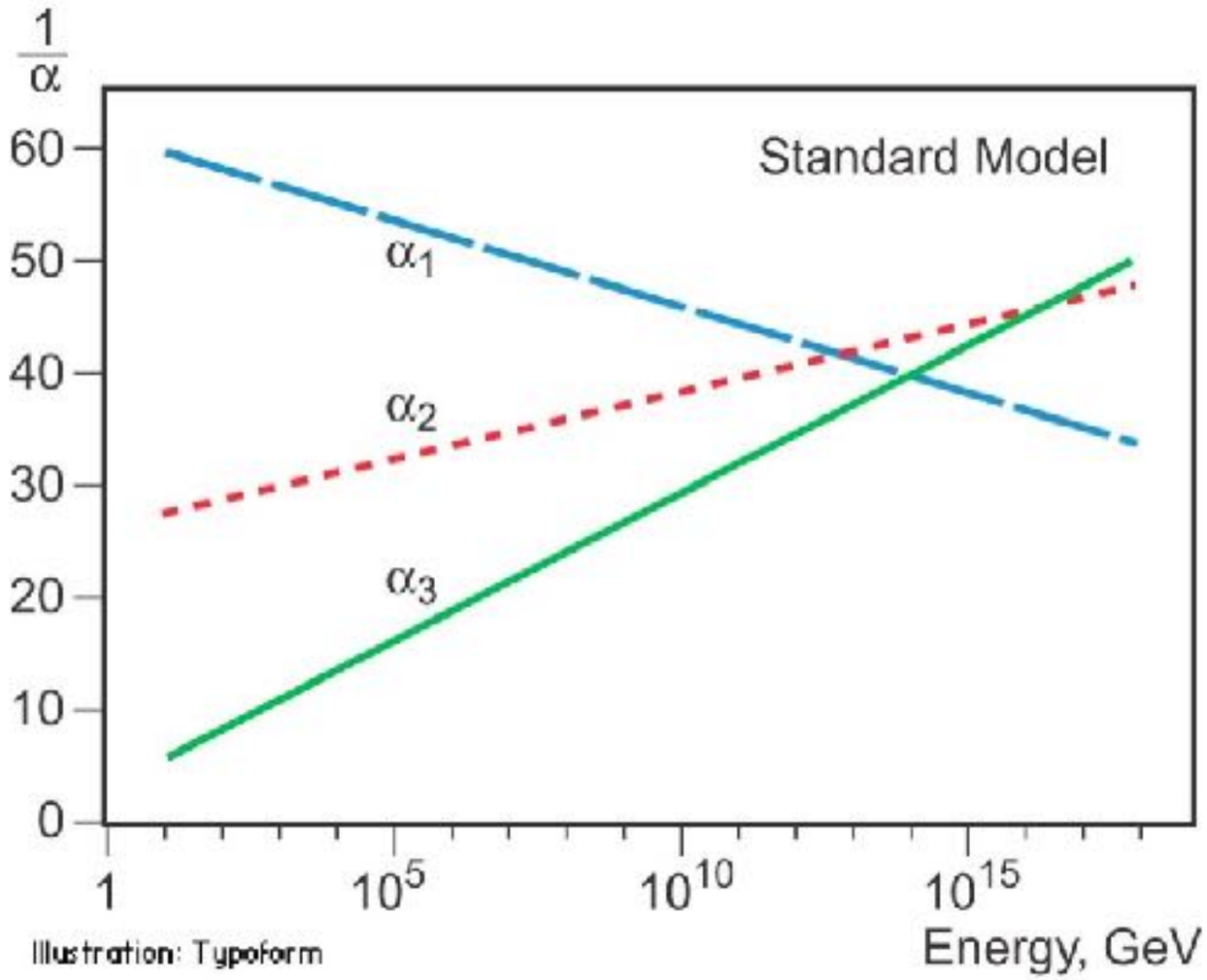


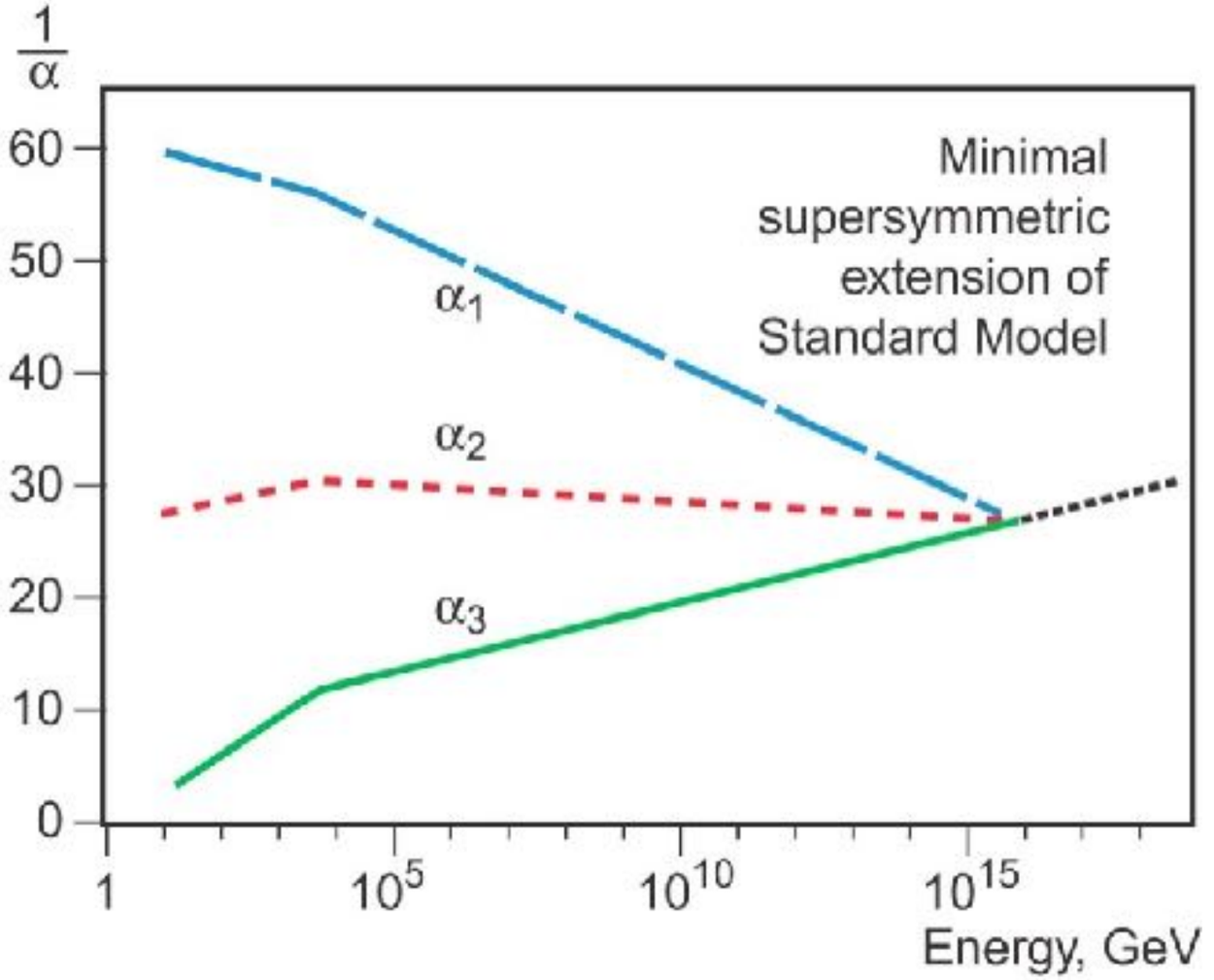
$$\propto -M^2_{\text{Planck}} + M^2_{\text{SUSY}}$$

$$\propto M^2_{\text{SUSY}}$$

If sparticles are at the weak scale so must be the higgs

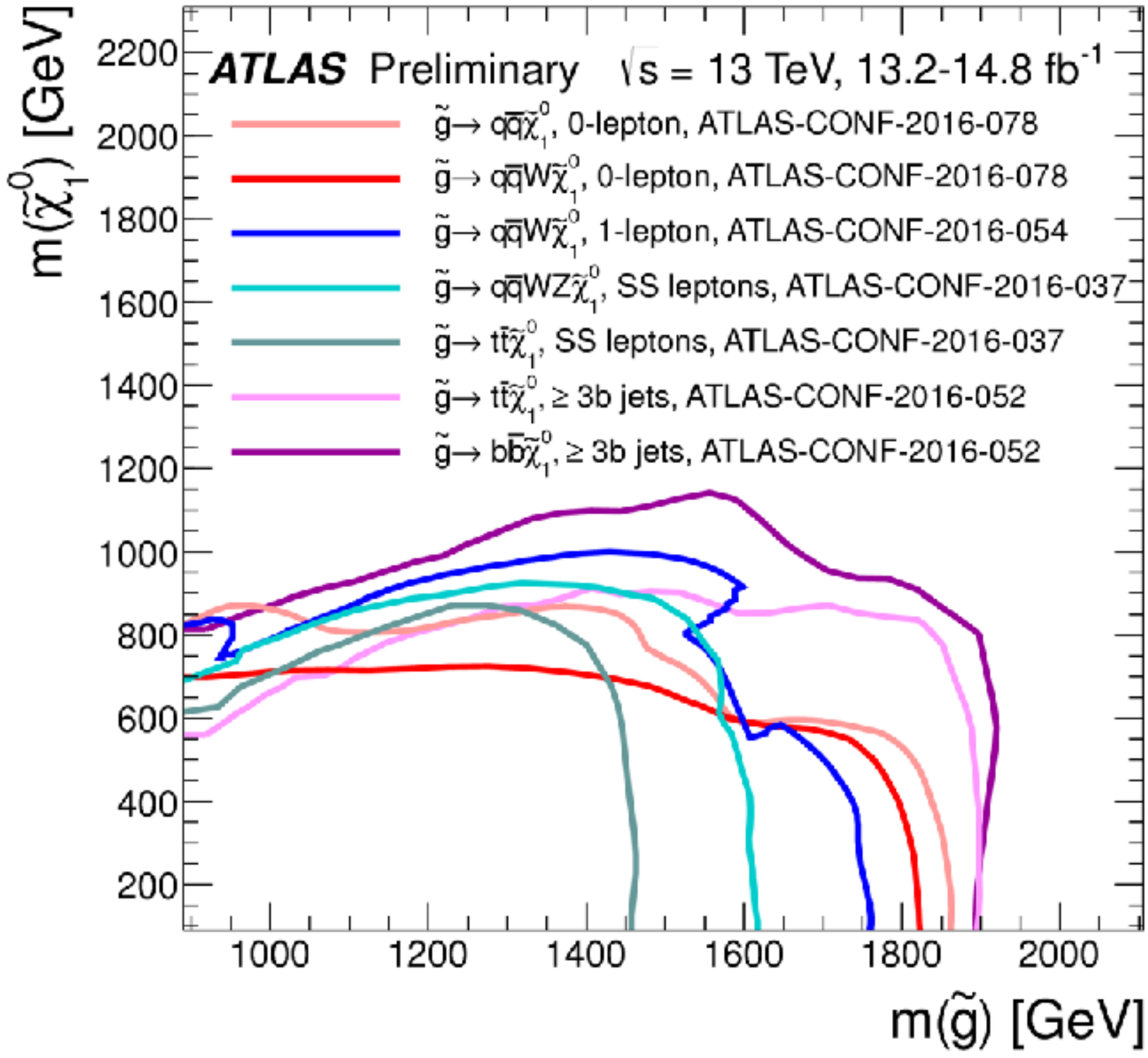
Gauge Coupling Unification





Experimentally verified in the early 1990s

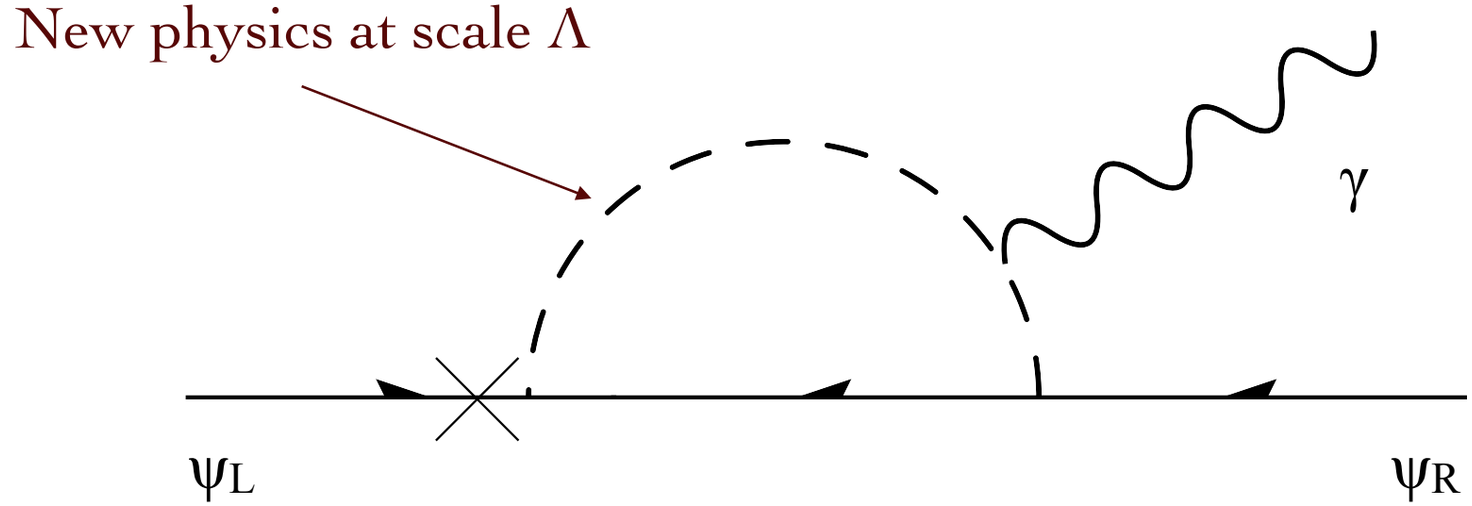
The Missing Superpartner Problem



EDM and the scale of new physics

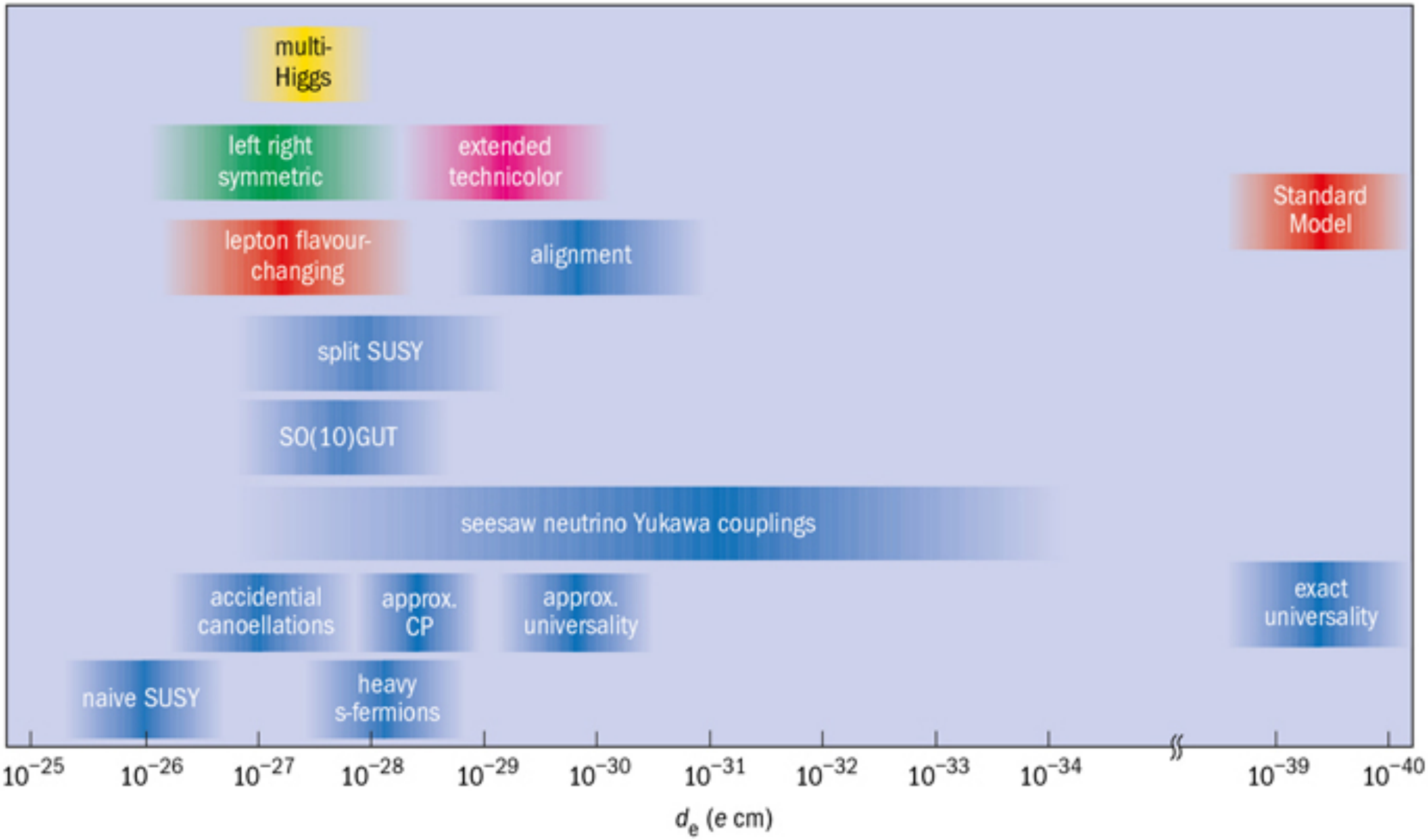
Electric Dipole Moment CP violating operator:

$$d_{\rm EDM}\ \bar{\psi}\sigma_{\mu\nu}\gamma^5\psi F^{\mu\nu}$$



EDM scales as $\quad d_{\rm EDM} \propto \dfrac{\mathrm{m}_\psi}{\Lambda^2}$

Reach in theory space



100 TeV: Highest Energy Collider proposed

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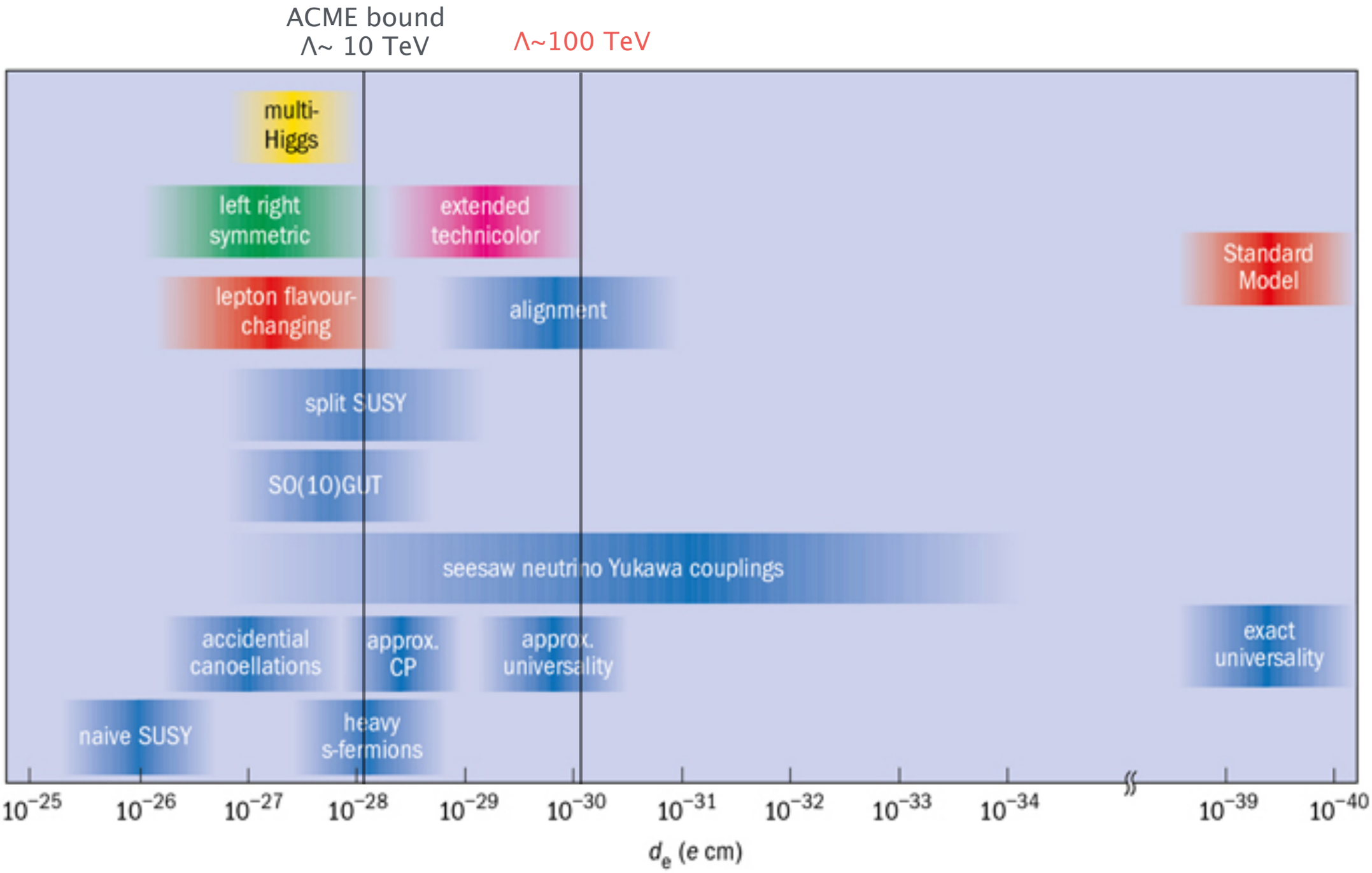

100 TeV: Highest Energy Collider proposed

The cosmological constant problem

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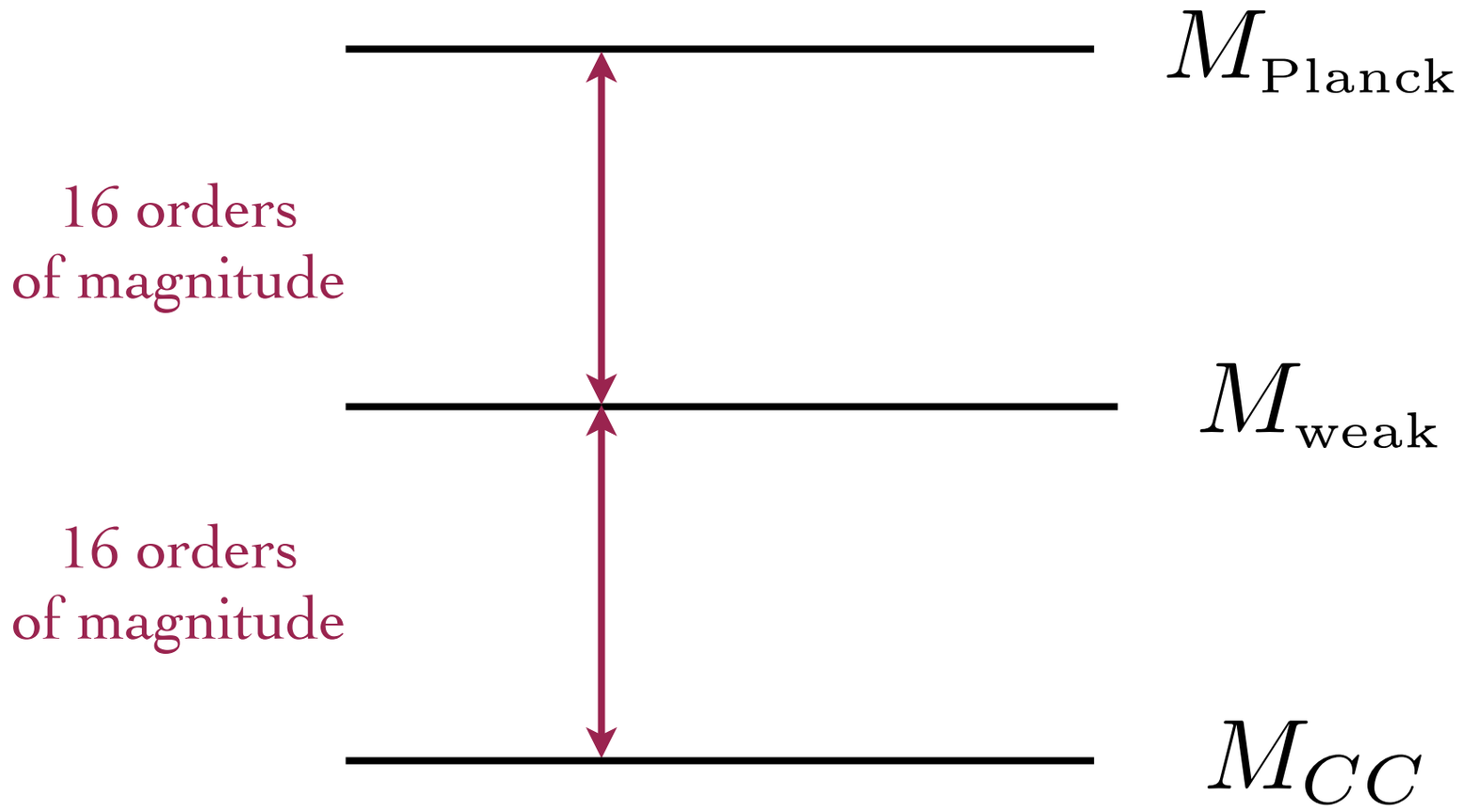
$$M_{\text{weak}} = G_{\text{Fermi}}^{-\frac{1}{2}} = 10^{3}\ \text{GeV}$$

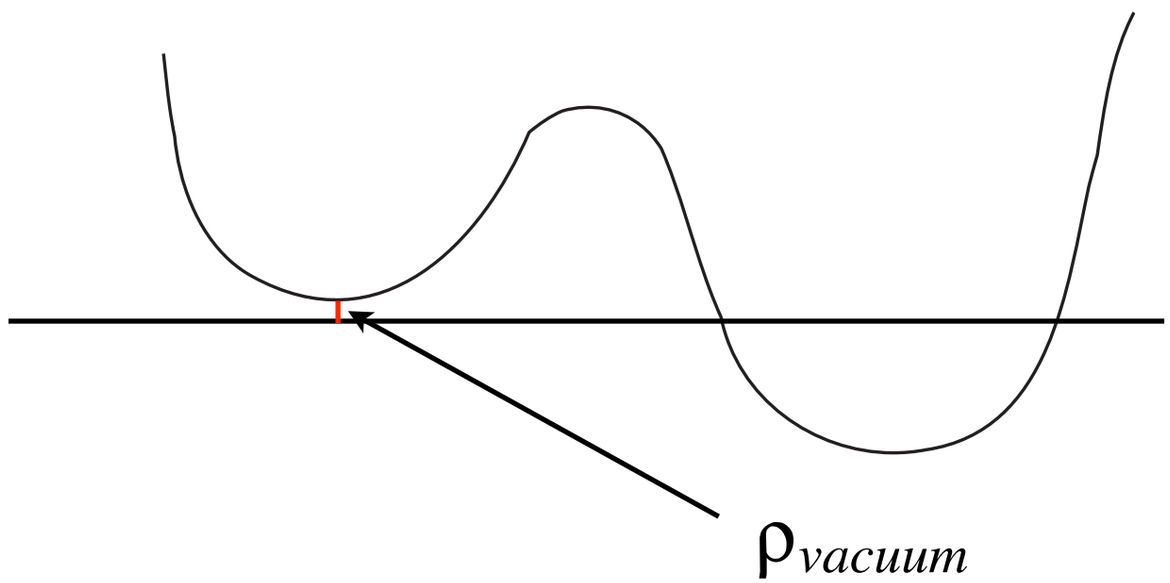
$$M_{CC} = \rho^{1/4}{}_{\text{vacuum}} = 10^{-12}\ \text{GeV}$$



Smallness of ρ_{vacuum} is critical for galaxies to form

In theories with few ground states (“vacua”)

each, is a different particle theory,
has different physical laws

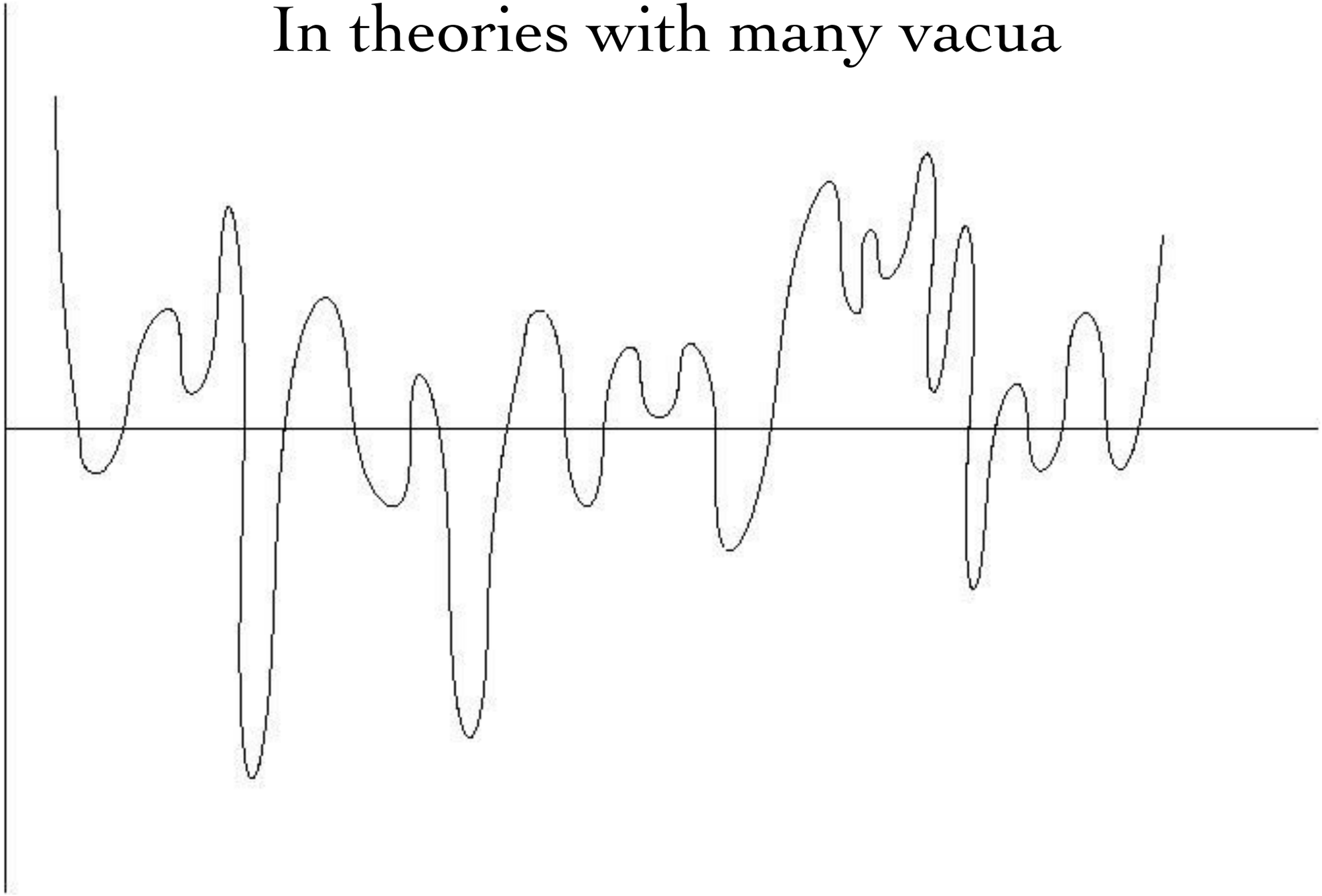


Getting $\rho_{vacuum} \sim (10^{-15} M_W)^4$

Looks like divine intervention!
Since any bigger value would rip apart galaxies

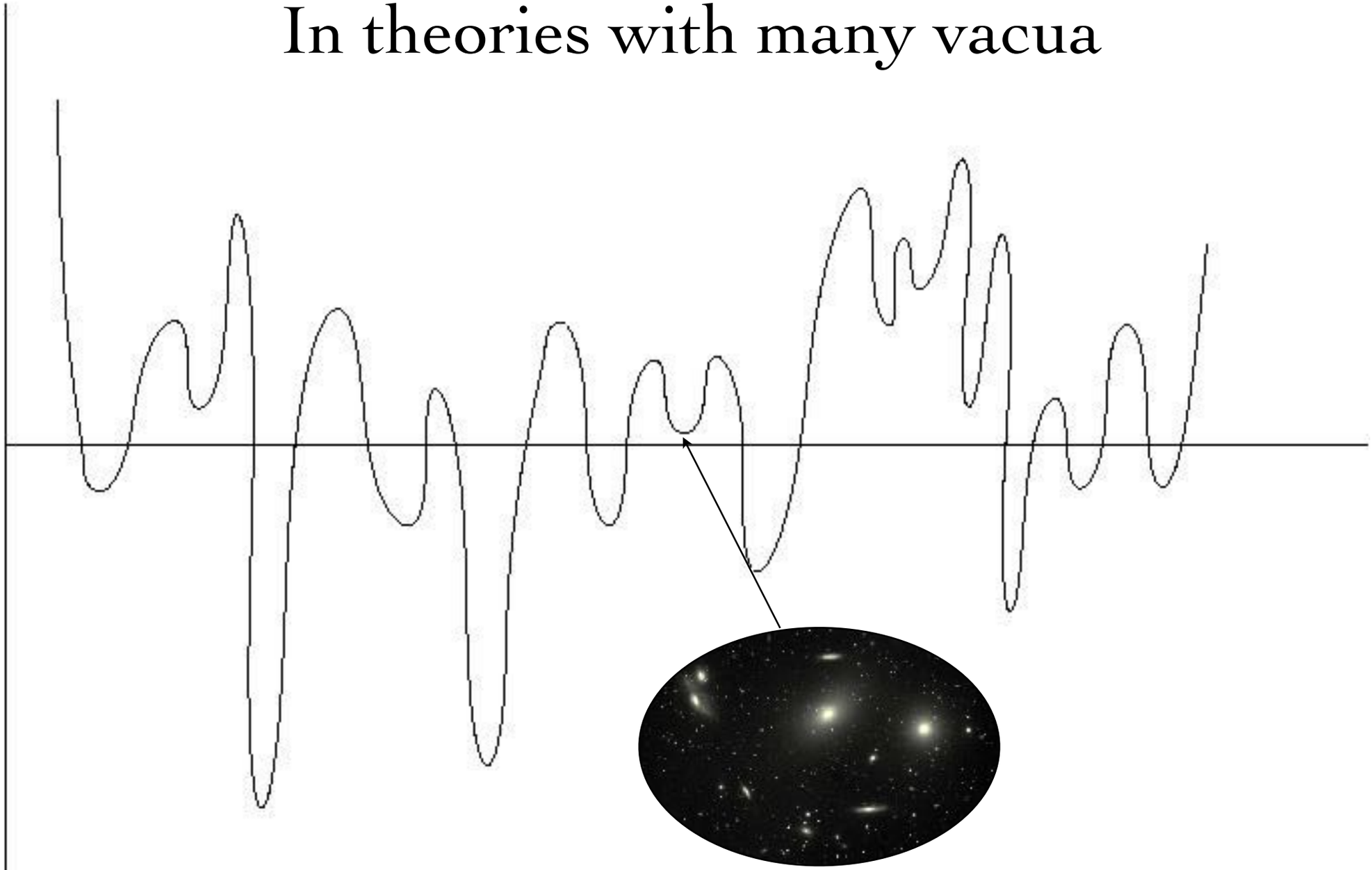
However... (Weinberg 1987)

In theories with many vacua



If there are enough vacua with different ρ_{vacuum} ,
the "structure" principle can explain
why we live in a universe with small, but nonzero, ρ_{vacuum}

In theories with many vacua



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One Solar System

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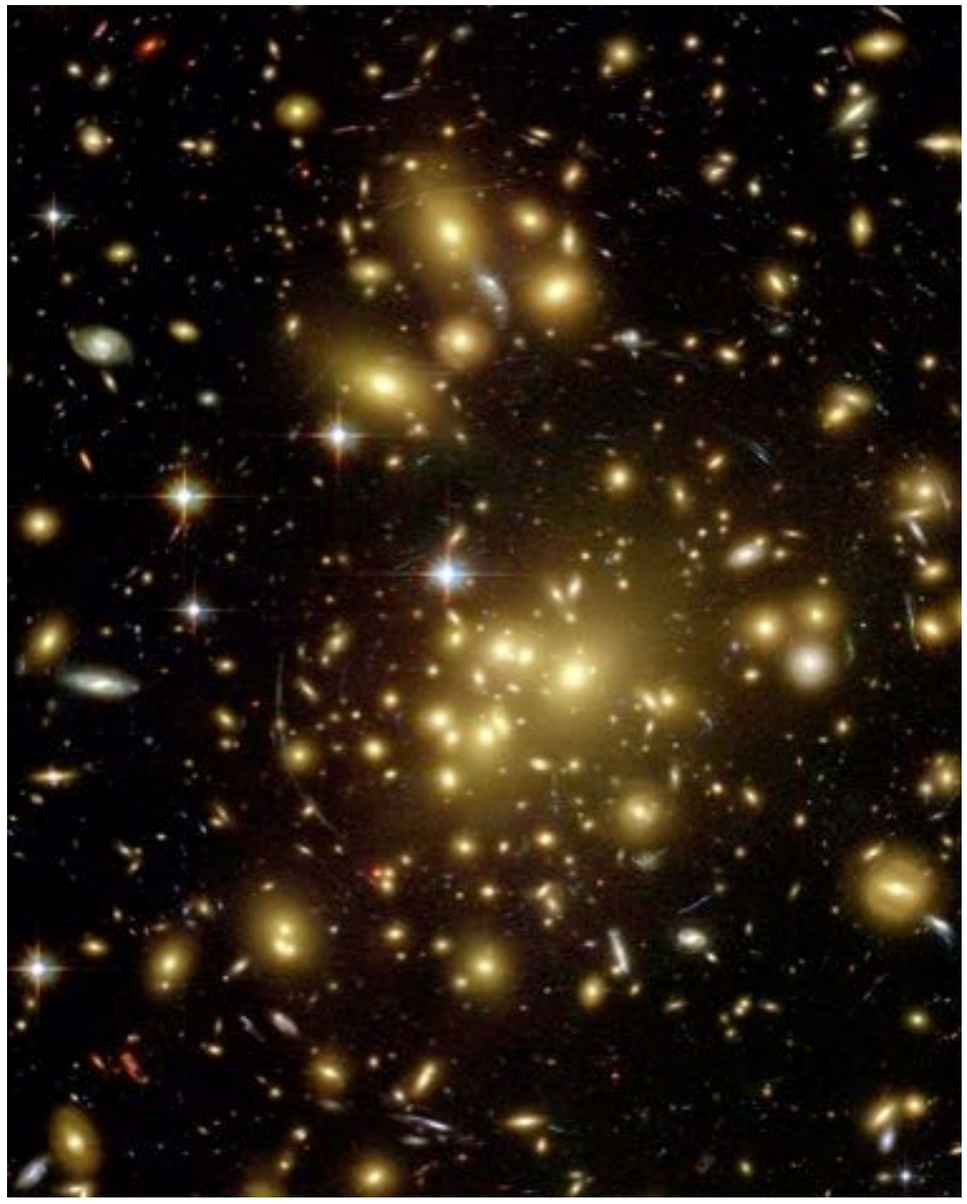
Many Solar Systems



One Solar System

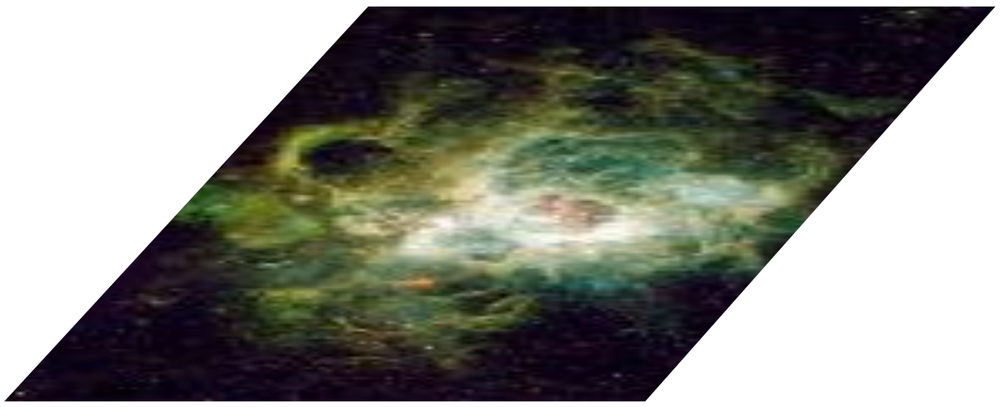
Many Solar Systems

‘Innumerable suns exist, innumerable earths revolve around these suns,
in a manner similar to the way the planets revolve around the sun.
Living beings inhabit these worlds’

Single Universe

The existence of Galaxies

$$\rho_{\text{vacuum}} \leq 10^{-120} M^4_{\text{Planck}}$$



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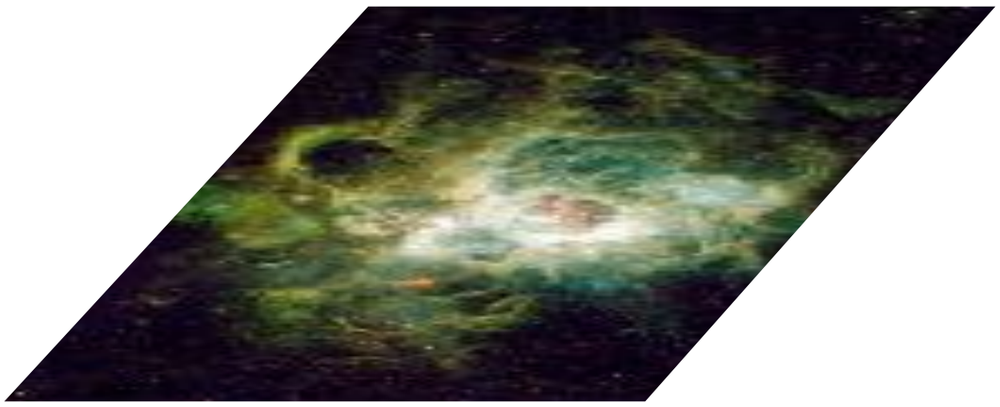

"Divine" Intervention

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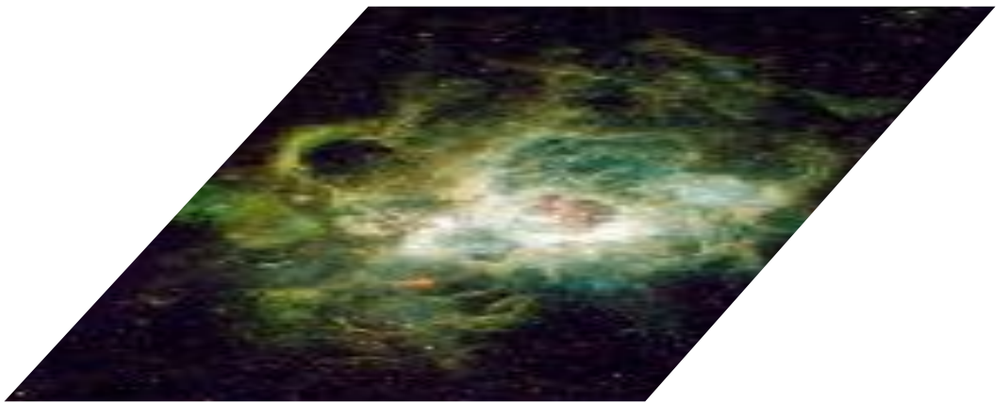

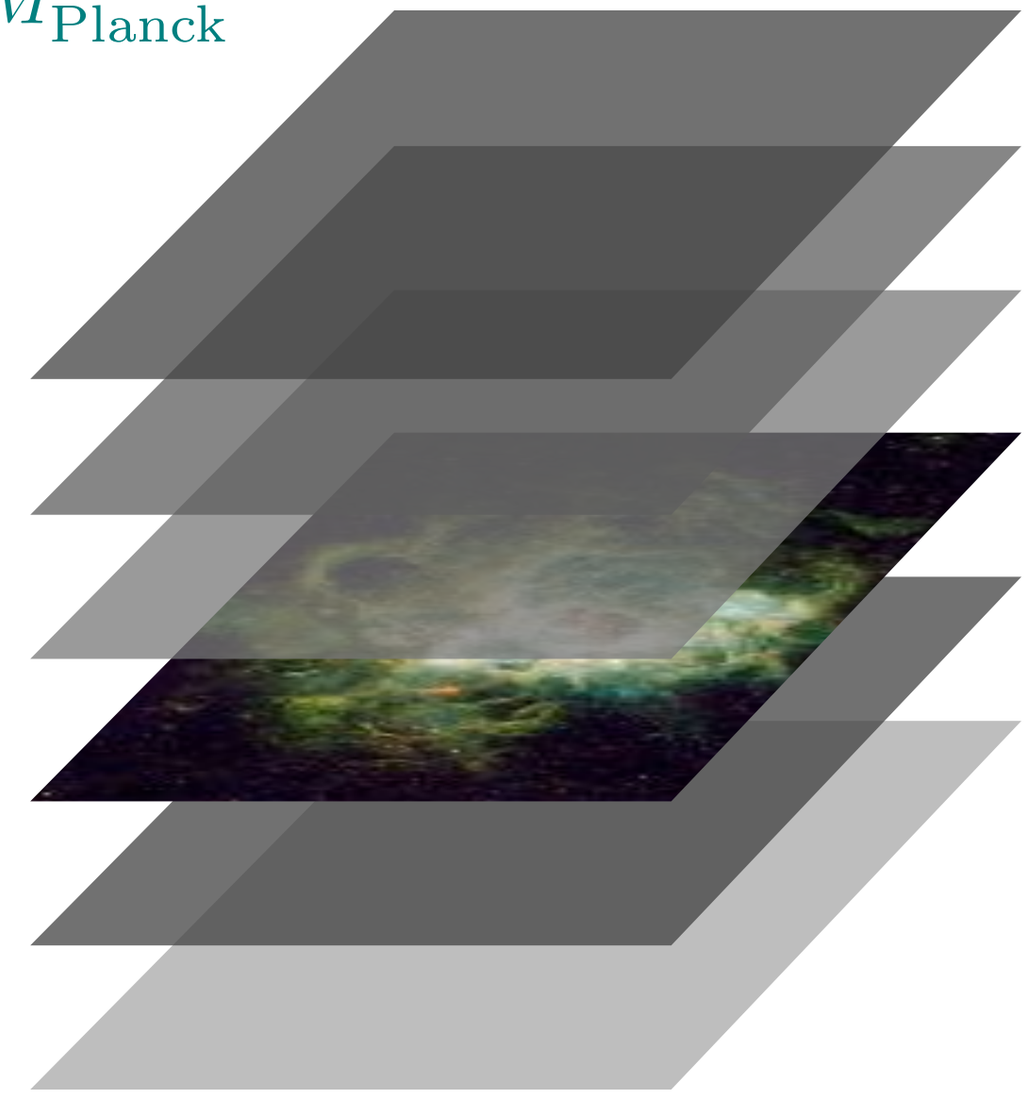

"Divine" Intervention

Environmental Selection

The Many Universes of String Theory

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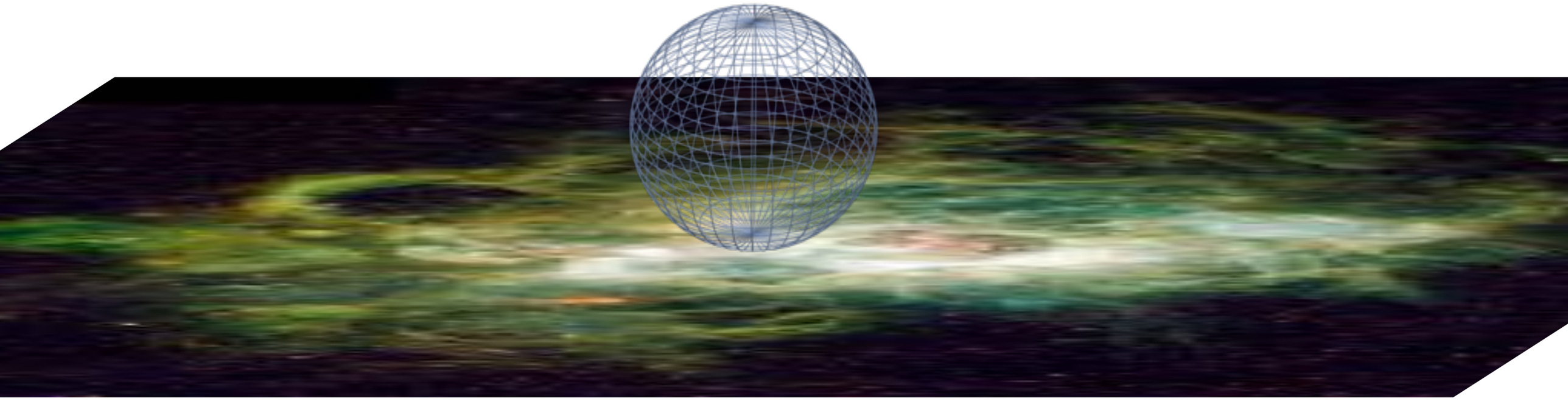

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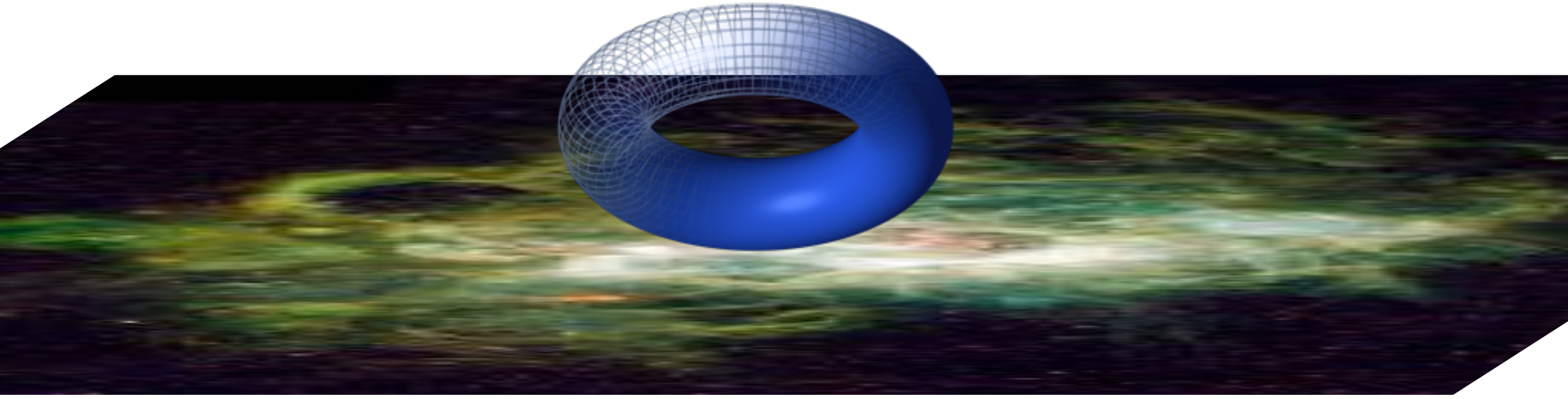

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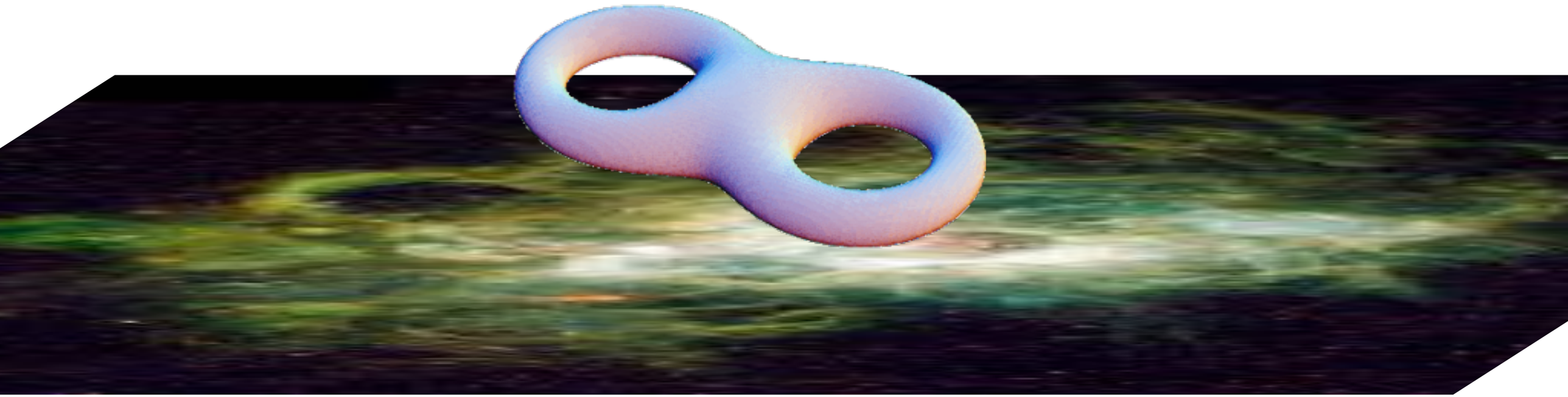

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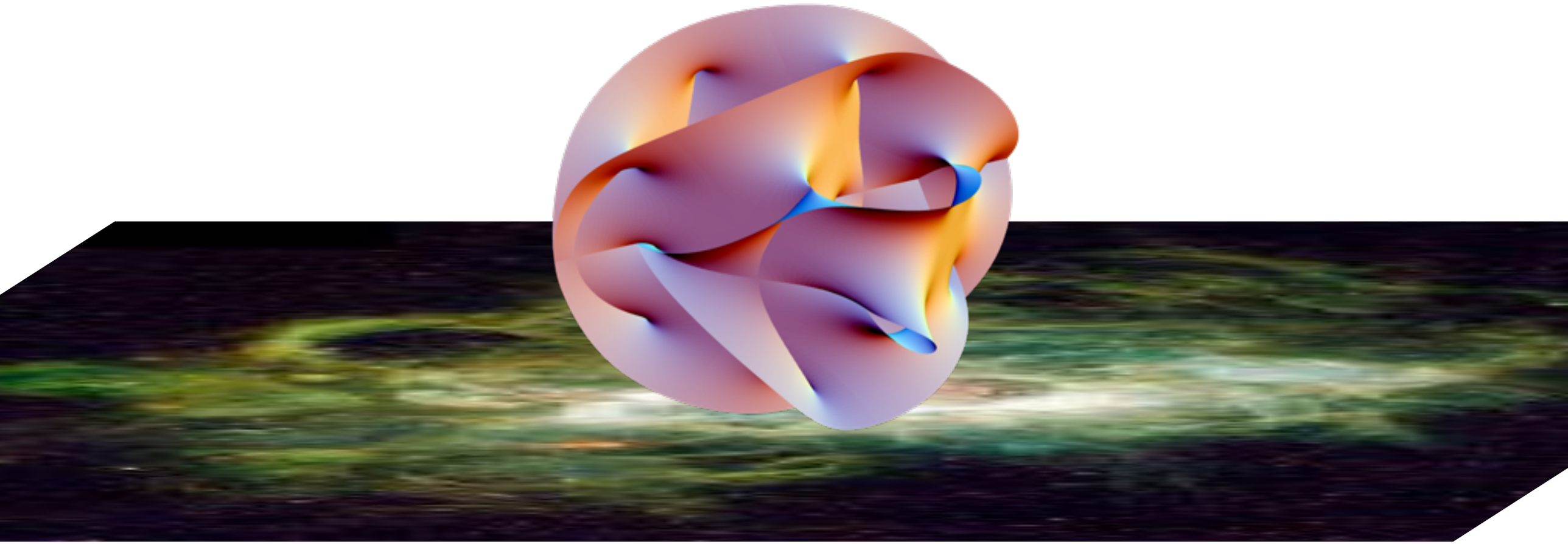

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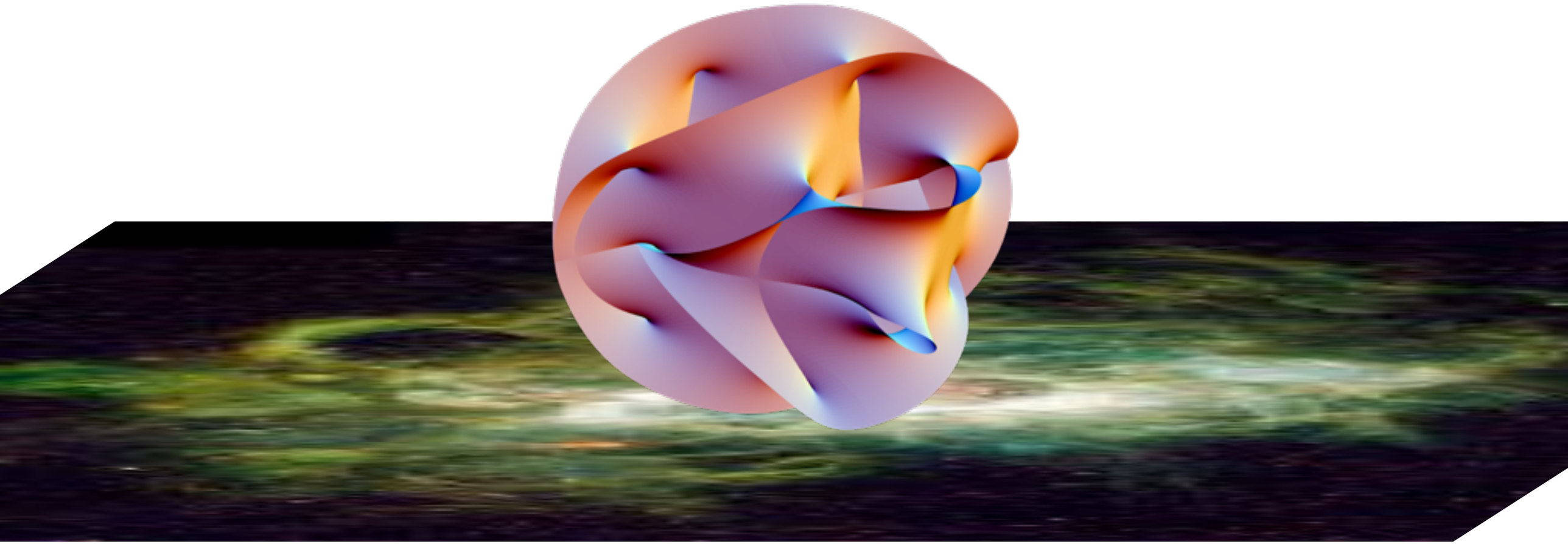
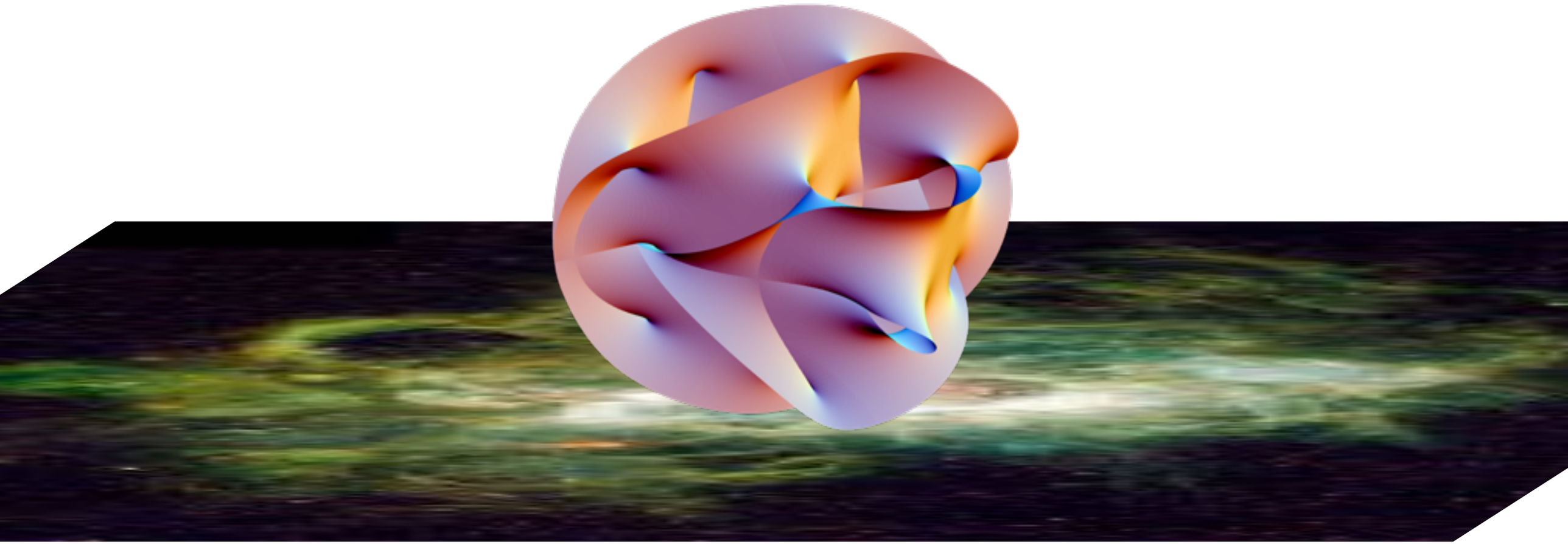


Extra dimensions of String Theory imply a Plenitude of Universes

Laws of Nature depend on the shape of the extra dimensions

The Many Universes of String Theory



Extra dimensions of String Theory imply a Plenitude of Universes

Complexity of Extra dimensions implies a Plenitude of Particles

Discovery of these particles would be indirect evidence for the Multiverse

Massless particles from topology

The Aharonov-Bohm Effect

Solenoid

Taking an electron around the solenoid

$$e \int A_\mu dx^\mu = e \times \text{Magnetic Flux}$$

while

$$\vec{B} = 0$$

Energy stored only inside the solenoid

Non-trivial gauge configuration far away carries no energy

Massless particles from topology

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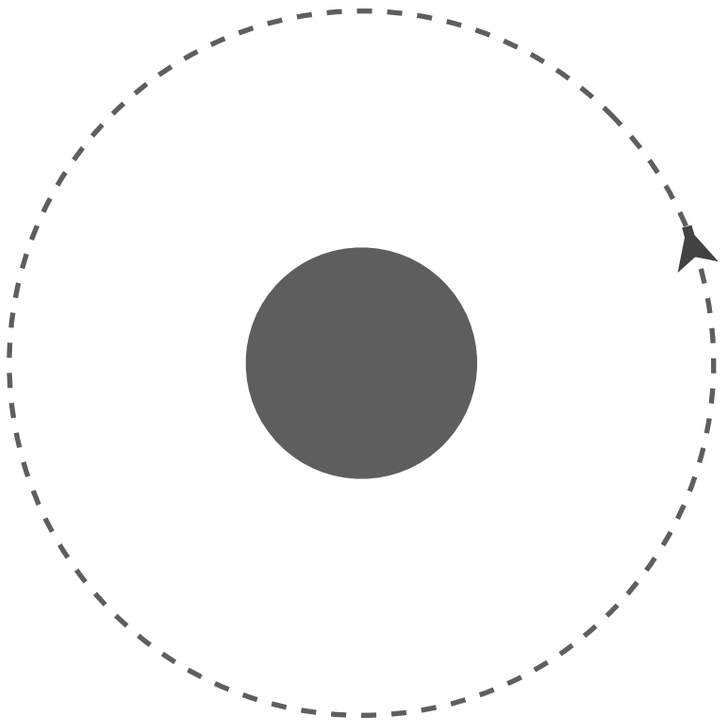

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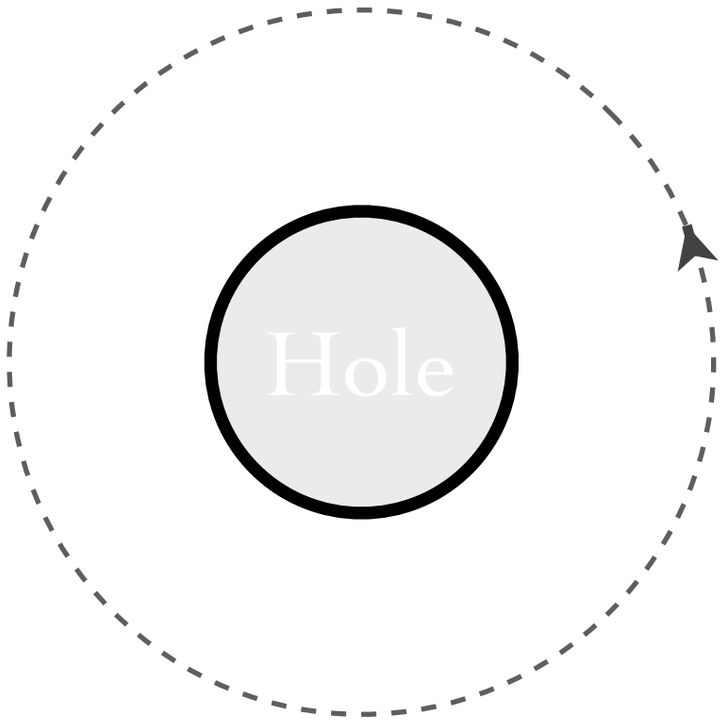

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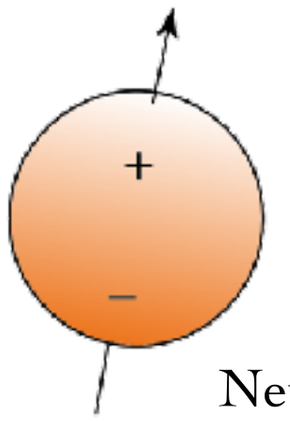
Non-trivial topology:
"Blocking out" the core still leaves a non-trivial gauge, but no mass

Why is the Electric Dipole Moment of the Neutron Small?

The Strong CP Problem and the QCD axion



Neutron EDM

$$\frac{g_s^2}{32\pi^2}\theta_s \vec{E}_s \cdot \vec{B}_s$$

EDM ~ e fm θ_s

Experimental bound: $\theta_s < 10^{-10}$

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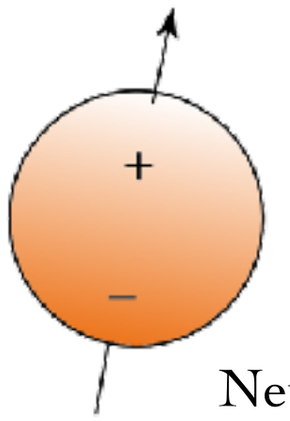

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Solution:

θ_s ~a(x,t) is a dynamical field, an axion

Axion mass from QCD:

$$\mu_a \sim 6 \times 10^{-11}\ \text{eV}\ \frac{10^{17}\ \text{GeV}}{f_a} \sim (3\ \text{km})^{-1}\ \frac{10^{17}\ \text{GeV}}{\text{f}_\text{a}}$$

f_a : axion decay constant

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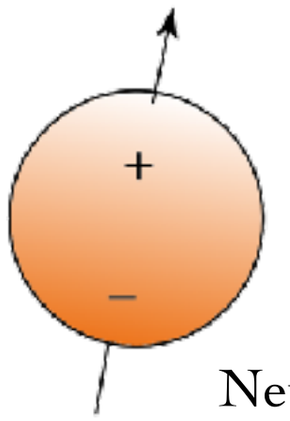

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f_a : axion decay constant

Mediates new forces and can be the dark matter

A Plenitude of Massless Particles

- Spin-0 non-trivial gauge field configurations: String Axiverse

- Spin-1 non-trivial gauge field configurations: String Photiverse

- Fields that determine the shape and size of extra dimensions as well as values of fundamental constants: Dilatons, Moduli, Radion

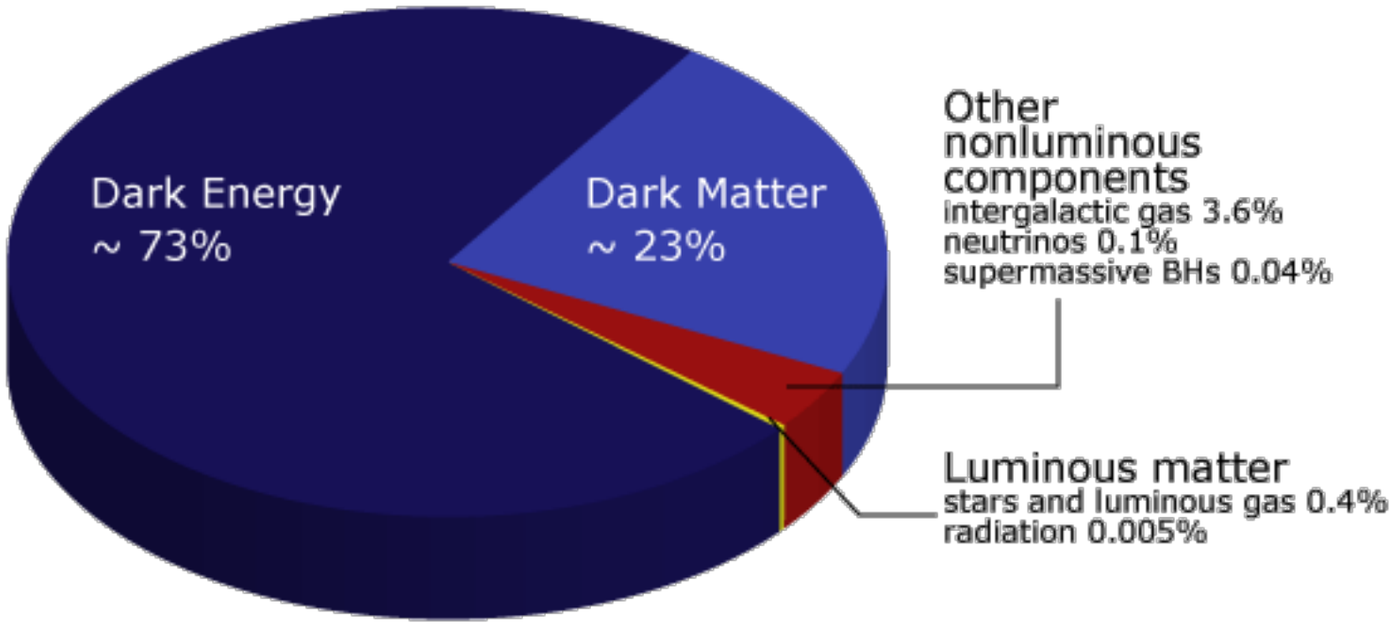
Properties of Plenitude of Particles from String Theory

- They couple very weakly to the Standard Model

- They can be extremely light

- They can mediate new forces and be the Dark Matter of the Universe

The Mystery of Dark Matter



Models of Dark Matter

- What is it made out of?

  Anything from 10^{-22} eV to 10^{70} eV in mass

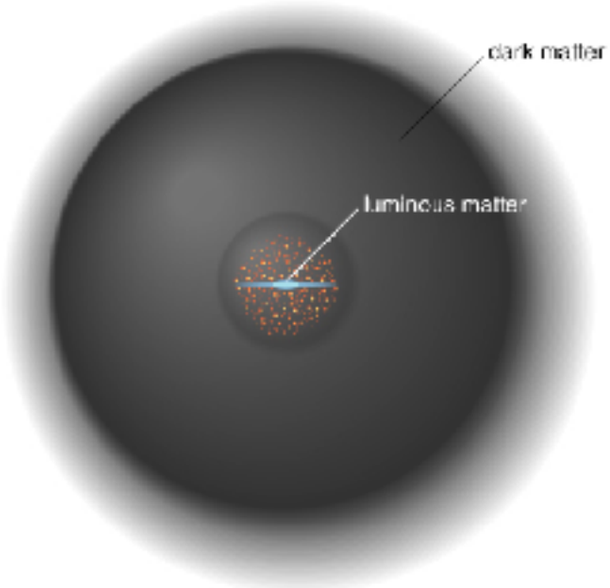
- How is it produced?

- Does it have interactions other than gravitational?

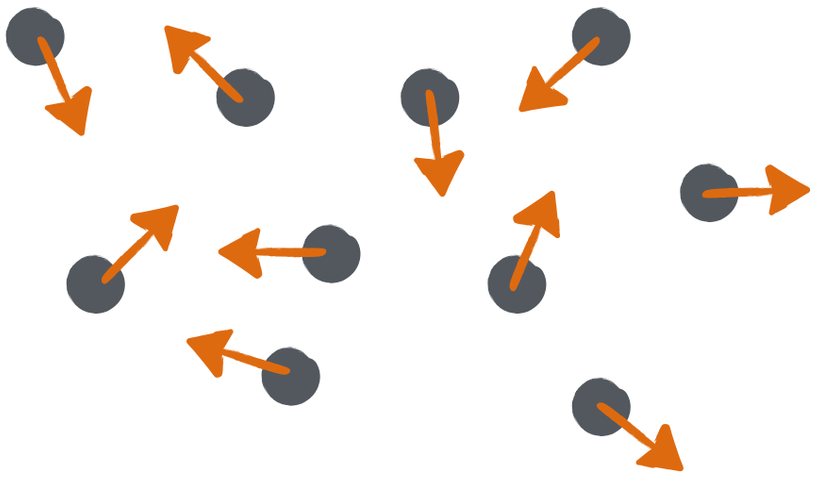
Axions, Moduli and Dark Photons have a production mechanism and interactions beyond gravitational with the SM

What If DM Is a Boson and Very Light?

Dark Matter Particles in the Galaxy



Usually we think of …



like a WIMP

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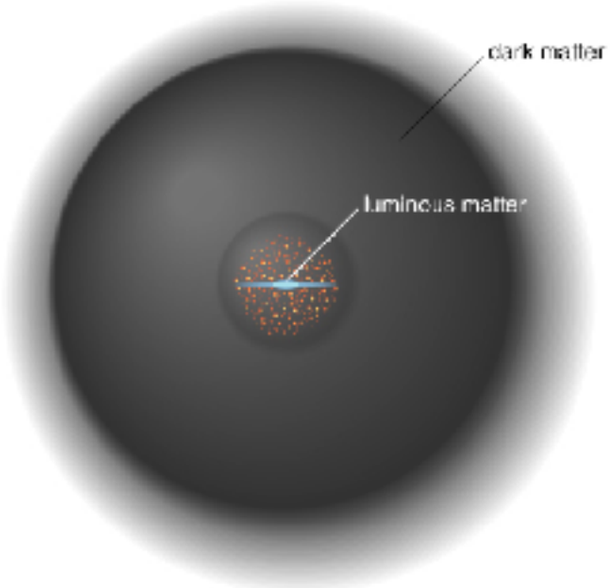

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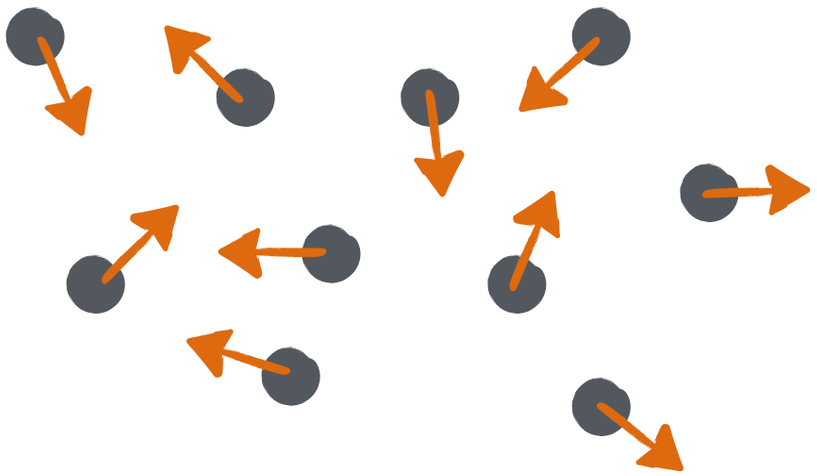
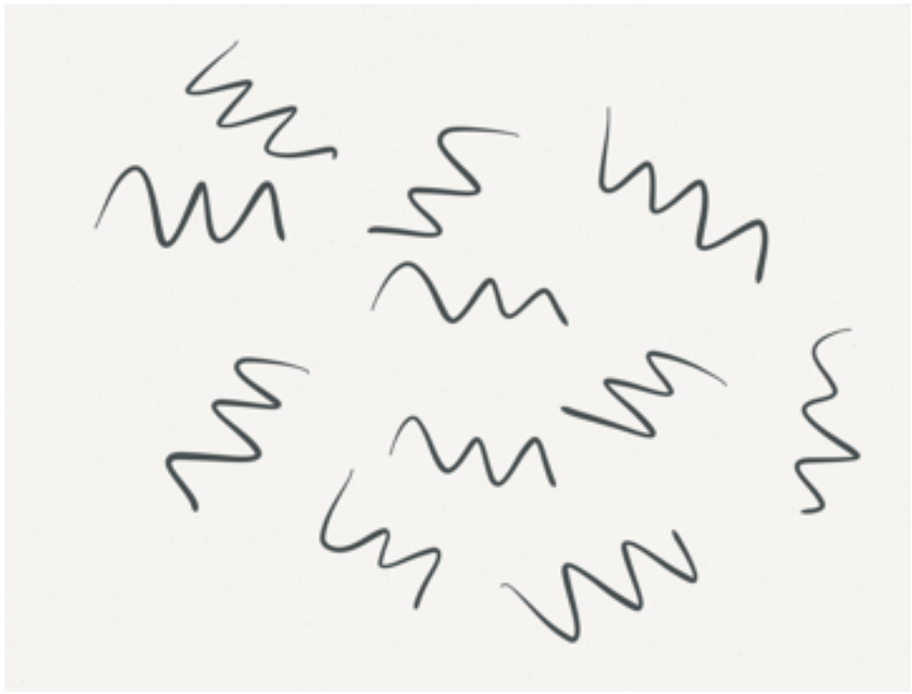


like a WIMP

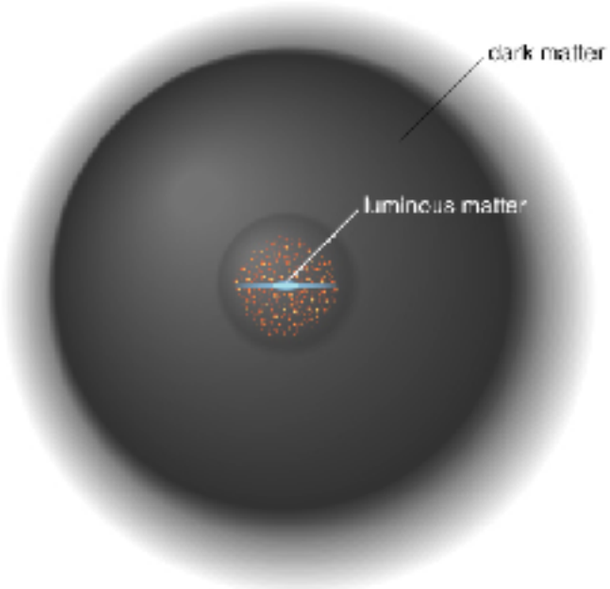
instead of…

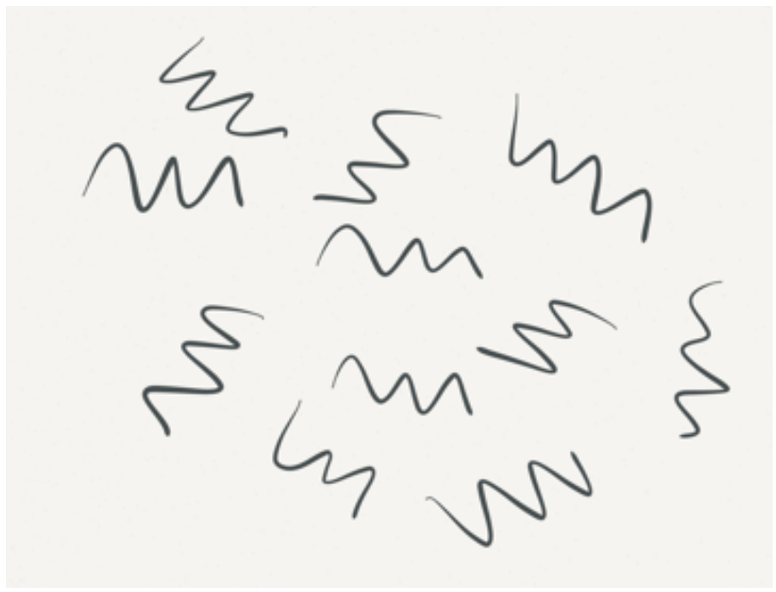


$$\lambda_{DM} = \frac{\hbar}{m_{DM} v}$$

What If DM Is a Boson and Very Light?

Dark Matter Particles in the Galaxy





Decreasing DM Mass

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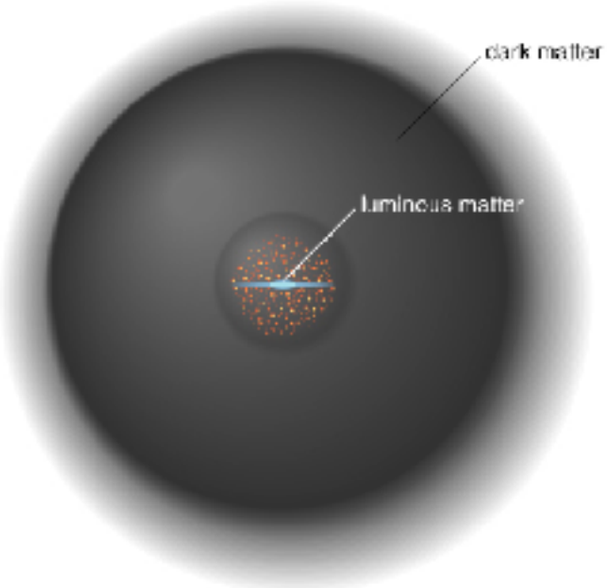
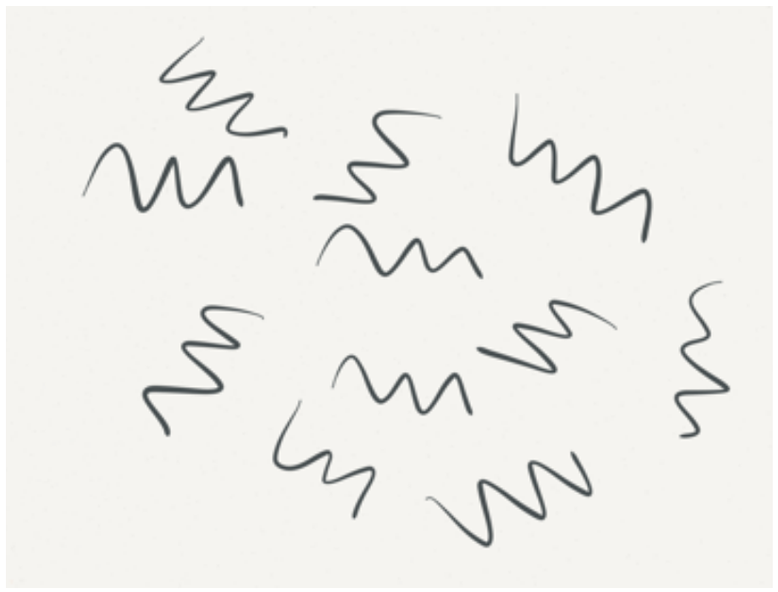




Decreasing DM Mass

$$\lambda_{DM} = \frac{\hbar}{m_{DM} v}$$

Equivalent to a Scalar wave

Going from DM particles to a DM "wave"

When $n_{DM} > \dfrac{1}{\lambda_{DM}^3}$

In our galaxy this happens when $m_{DM} < 1\ eV/c^2$

we can talk about DM $\phi(x,t)$ and locally

$$\phi(t) \approx \phi_0 \cos \omega_{DM} t$$

with amplitude

$$\phi_0 \propto \frac{\sqrt{\text{DM density}}}{\text{DM mass}}$$

with frequency

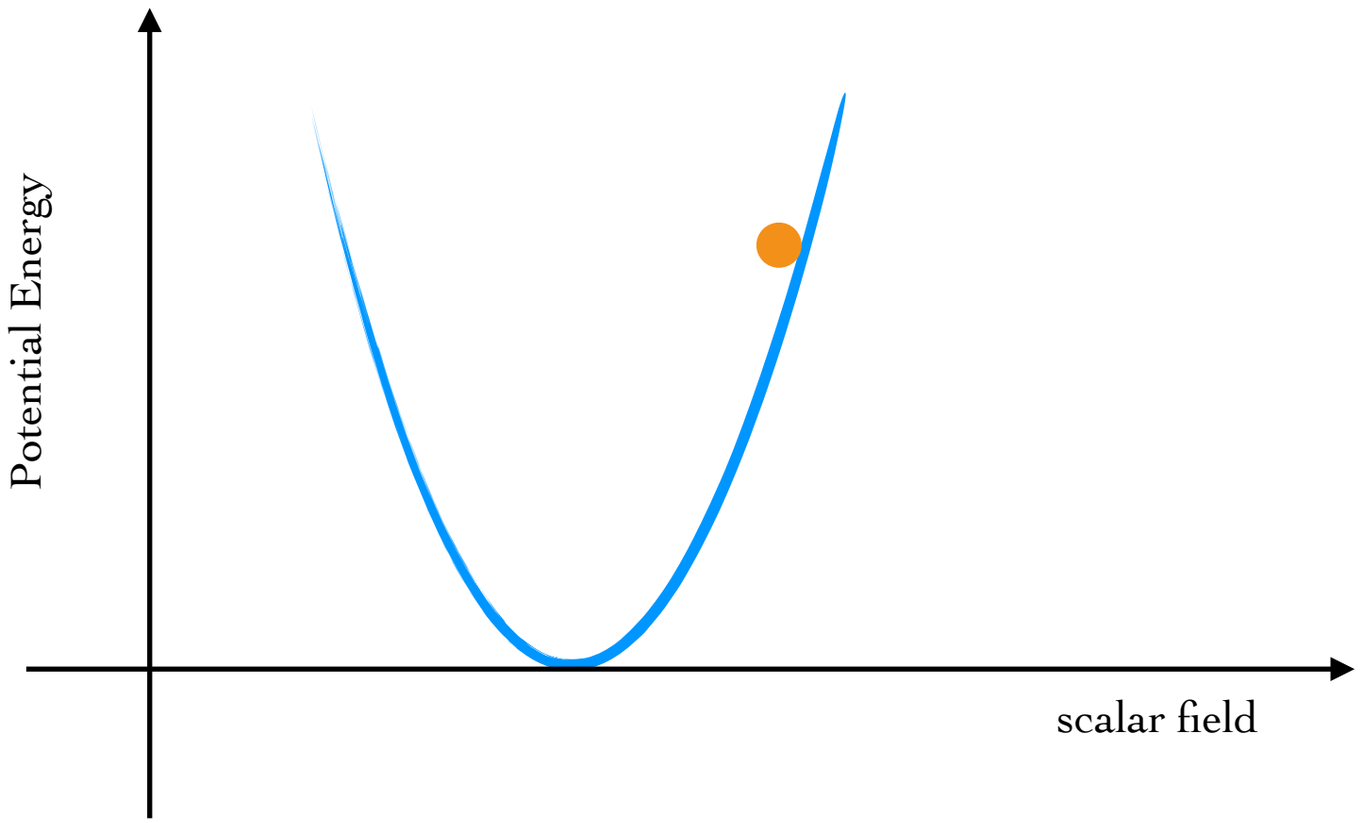
$$\omega_{DM} \approx \frac{m_{DM} c^2}{\hbar}$$

and finite coherence

$$\delta\omega_{DM} \approx \frac{m_{DM} v^2}{\hbar} = 10^{-6} \omega_{DM}$$

Light Scalar Dark Matter

- Produced by the misalignment mechanism



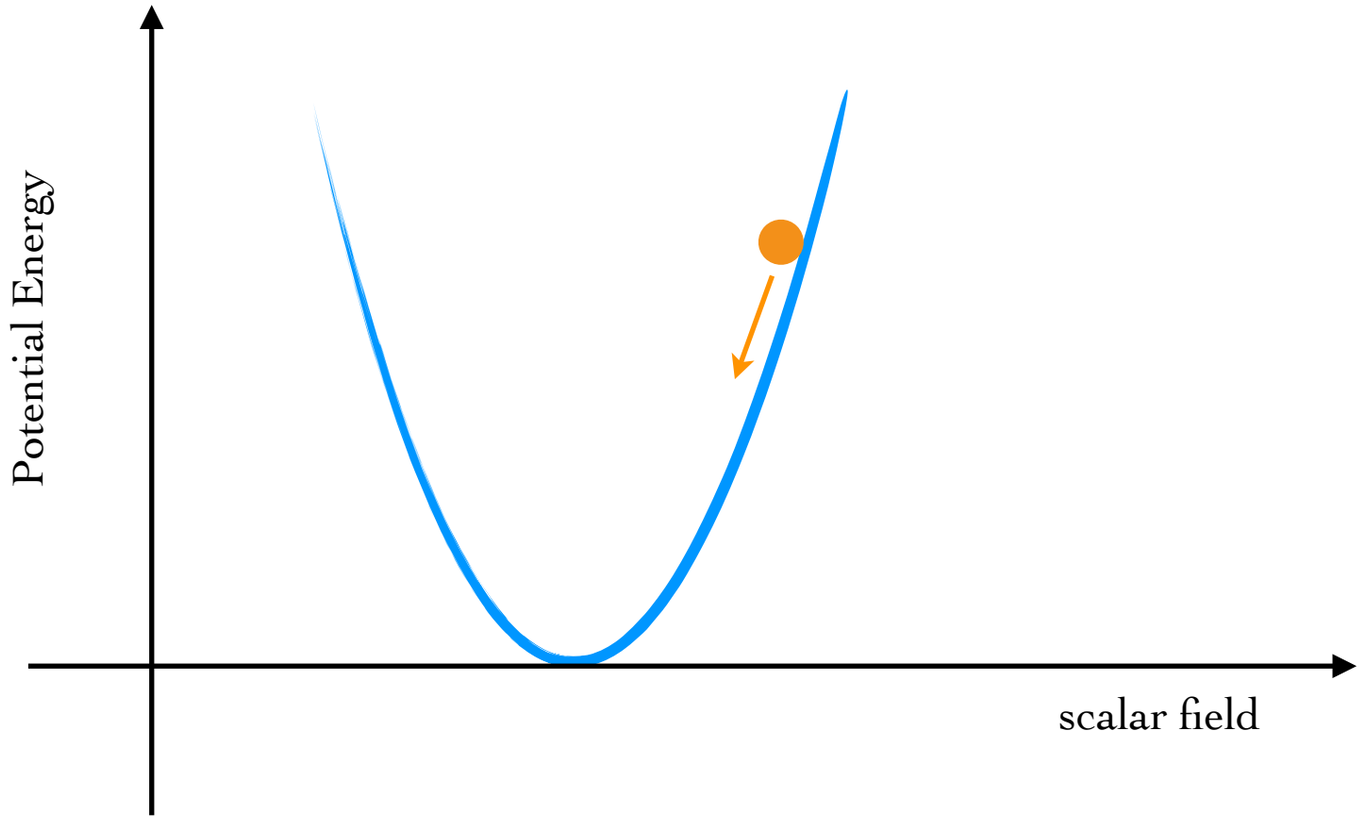
Frozen when:
Hubble > m_ϕ

Initial conditions set by inflation

*The story changes slightly if DM is a dark photon

Light Scalar Dark Matter

- Produced by the misalignment mechanism



Frozen when:
Hubble > m_ϕ

Oscillates when:
Hubble < m_ϕ

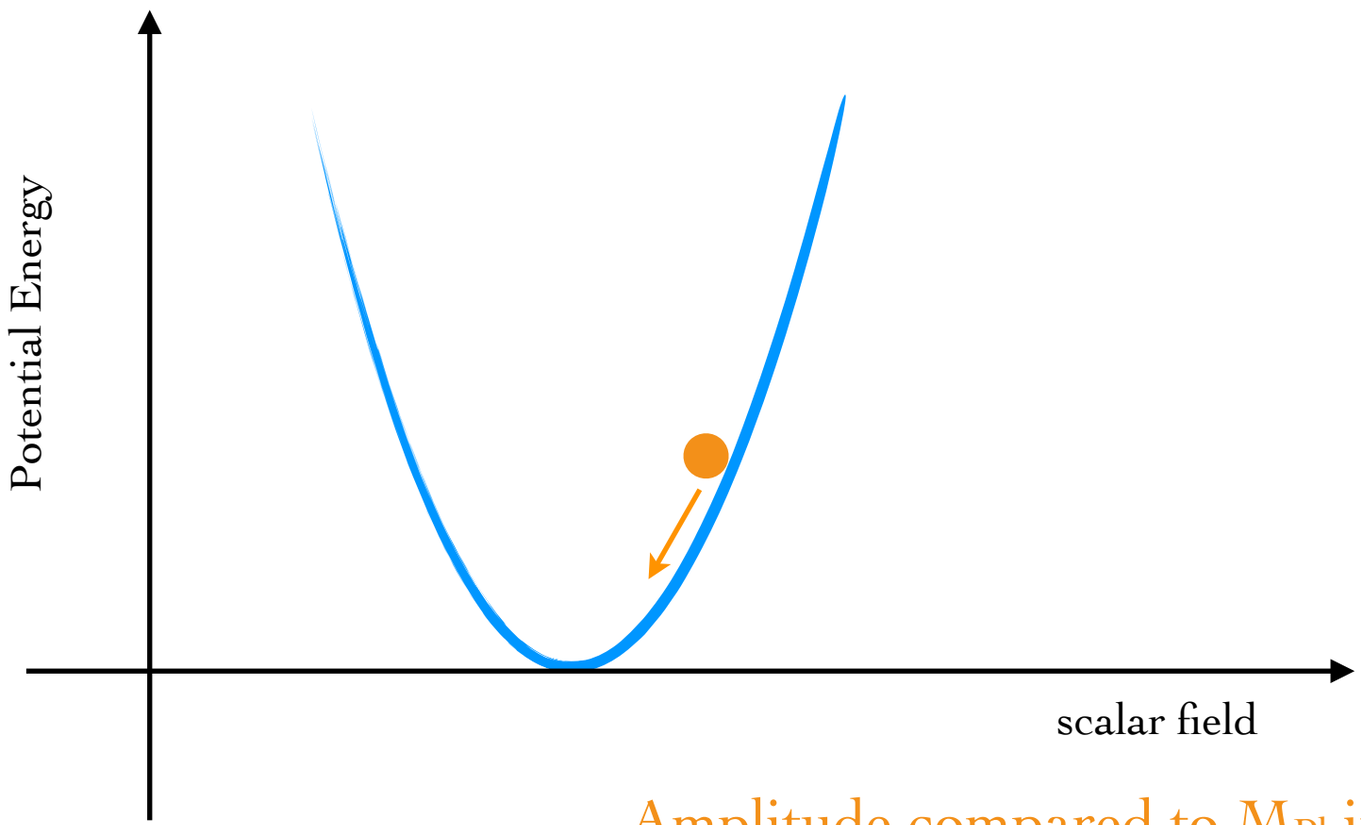
ρ_ϕ scales as a^{-3}
just like Dark Matter

Initial conditions set by inflation

*The story changes slightly if DM is a dark photon

Light Scalar Dark Matter Today

- If $m_\phi < 1$ eV, can still be thought of as a scalar field today



$m_\phi{}^2\, \phi_o{}^2\, \cos^2(m_\phi\, t) \sim \rho_\phi$

Coherent for $\upsilon_{vir}{}^{-2} \sim 10^6$ periods

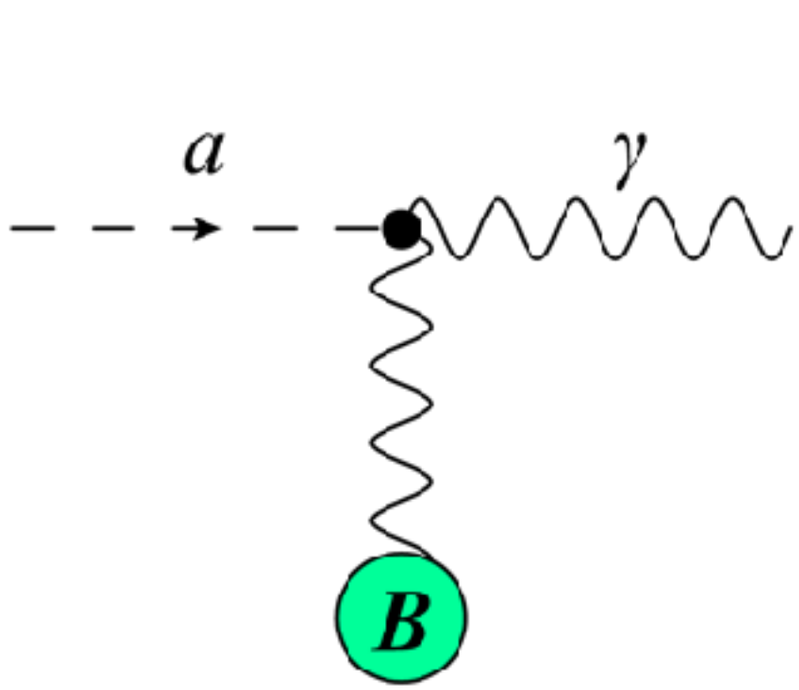
Amplitude compared to M_{Pl} in the galaxy:

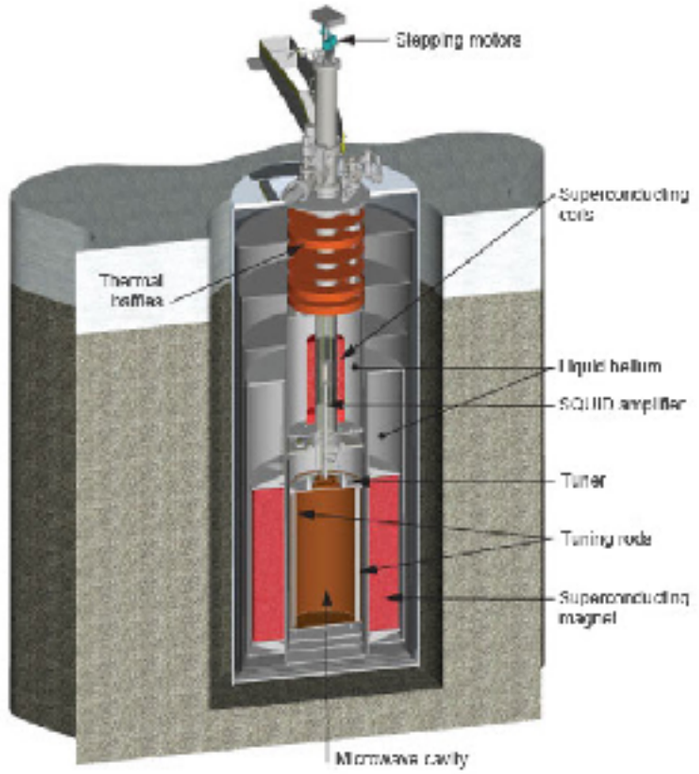
$$\kappa\phi_0 = \frac{\sqrt{8\pi\rho_\phi}}{m_\phi M_{\rm Pl}} = 6.4 \cdot 10^{13} \left(\frac{10^{-18}\,{\rm eV}}{m_\phi}\right)$$

Axion Dark Matter

Some examples

- Axion-to-photon conversion (ex. ADMX)





Cavity size = Axion size

Axion Dark Matter

Some examples

Monopole-Dipole Interaction

Mass with N nucleons Spin

Dipole-Dipole Interaction

N spins Spin

- Axion Force experiments (ex. ARIADNE)

Dark Photon Dark Matter

Some examples

- Detected if kinetically mixed with the photon

$$\mathcal{L} \supset \epsilon F_{EM} F_{DM}$$

- Detected like a photon (ex. DM Radio and ADMX)

$$\text{DM electric field} \sim \sqrt{\rho_{DM}} \sim 50 \text{ V/cm}$$

Moduli Dark Matter

- Couple non-derivatively to the Standard Model (as well axions with CP violation)

- Examples of couplings

$$\mathcal{L} = \mathcal{L}_{SM} + \sqrt{\hbar c}\frac{\phi}{\Lambda}\mathcal{O}_{SM}$$

$$\mathcal{O}_{SM} \equiv m_e e\bar{e},\ m_q q\bar{q},\ G_s^2,\ F_{EM}^2, ...$$

Fundamental constants are not really constants

Oscillating Fundamental Constants

AA, J. Juang, K. Van Tilburg (2014)

From the local oscillation of Dark Matter

Ex. for the electron mass:

$$d_{m_e}\sqrt{\hbar c}\frac{\phi}{M_{Pl}}m_e c^2 e\bar{e}$$

$M_{pl} = 10^{18}$ GeV
reduced Planck scale in energy

$$\frac{\delta m_e}{m_e} \approx \frac{d_{m_e}\phi_0}{M_{Pl}}\cos(\omega_{DM}t)$$

$$= 6.4\times 10^{-13}\cos(\omega_{DM}t)\left(\frac{10^{-18}\text{ eV}}{m_{DM}c^2}\right)\left(\frac{d_{m_e}}{1}\right)$$

d_{me} : coupling strength relative to gravity

Fractional variation set by square root of DM abundance

Need an extremely sensitive probe…

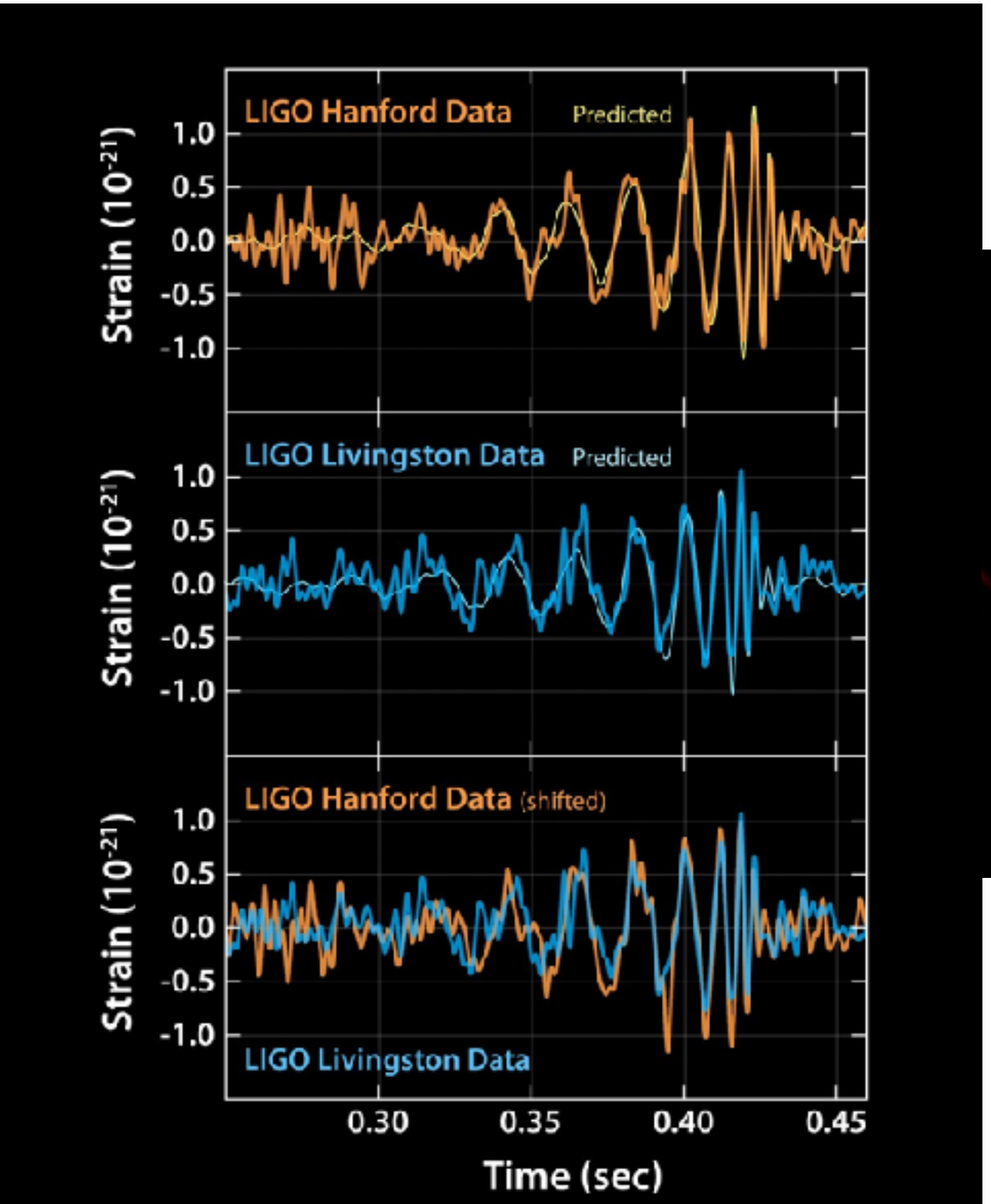
What happens if new physics only couples through gravity?

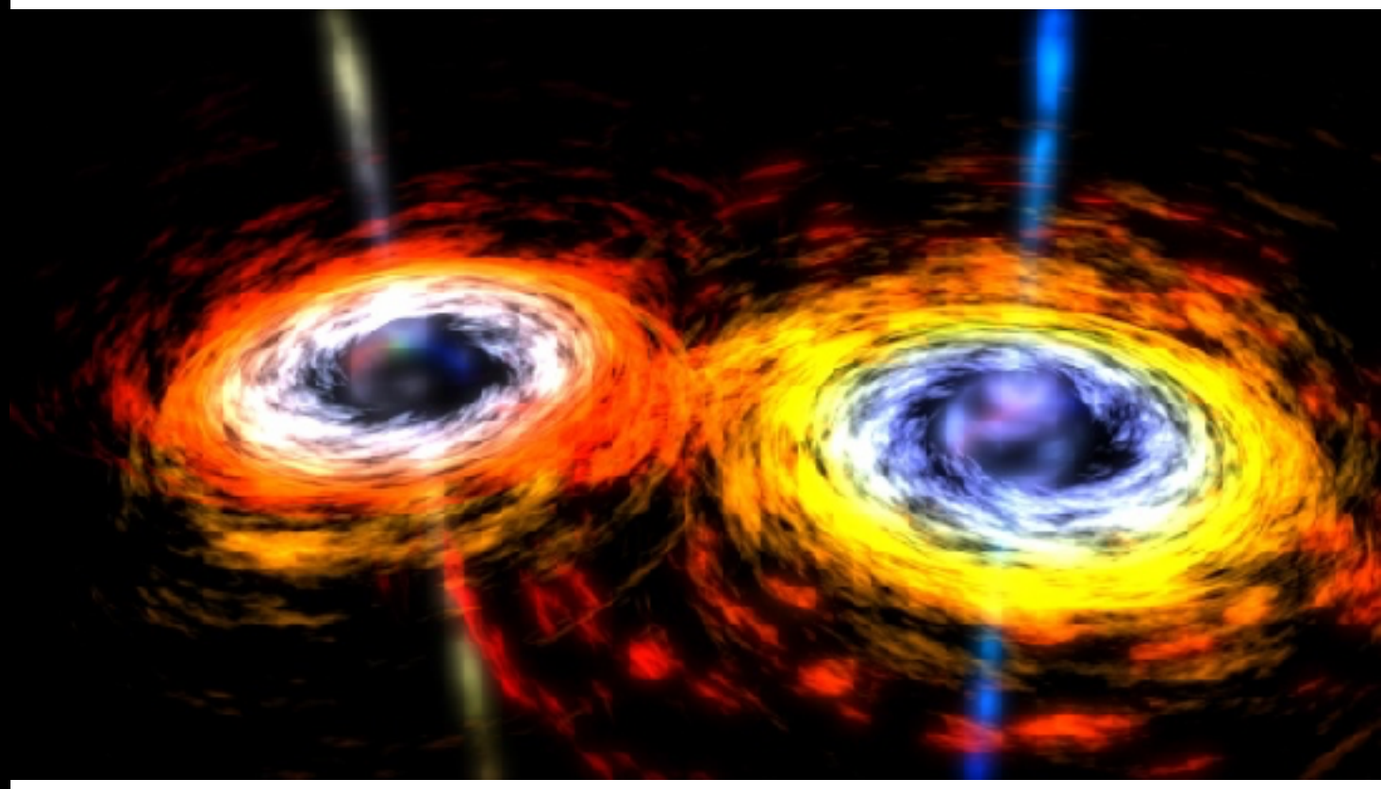
Black Holes as Nature's Detectors

1 km -10 billion km

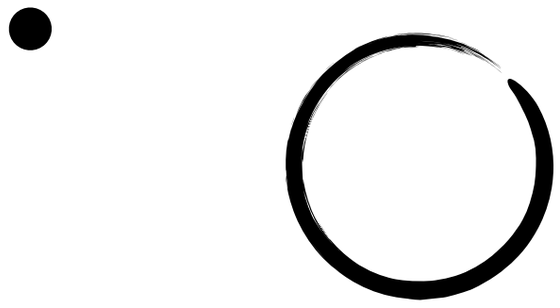
They can detect bosons of similar in size

September 14, 2015





Super-Radiance Cartoon



Super-radiant scattering of a massive object

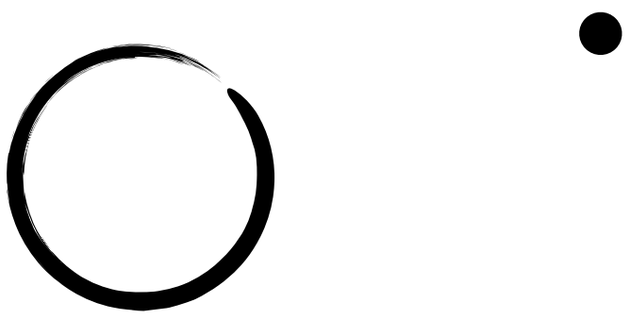
Super-Radiance Cartoon

Super-radiant scattering of a massive object

Super-Radiance Cartoon

Super-radiant scattering of a wave

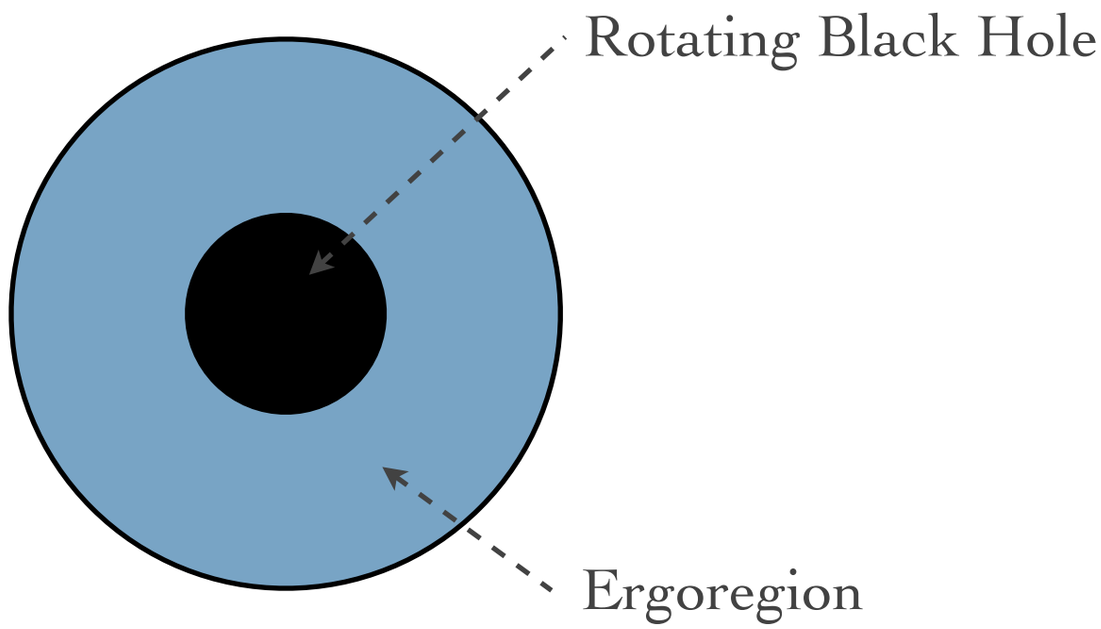
Super-Radiance Cartoon



Super-radiant scattering of a wave

Black Hole Superradiance

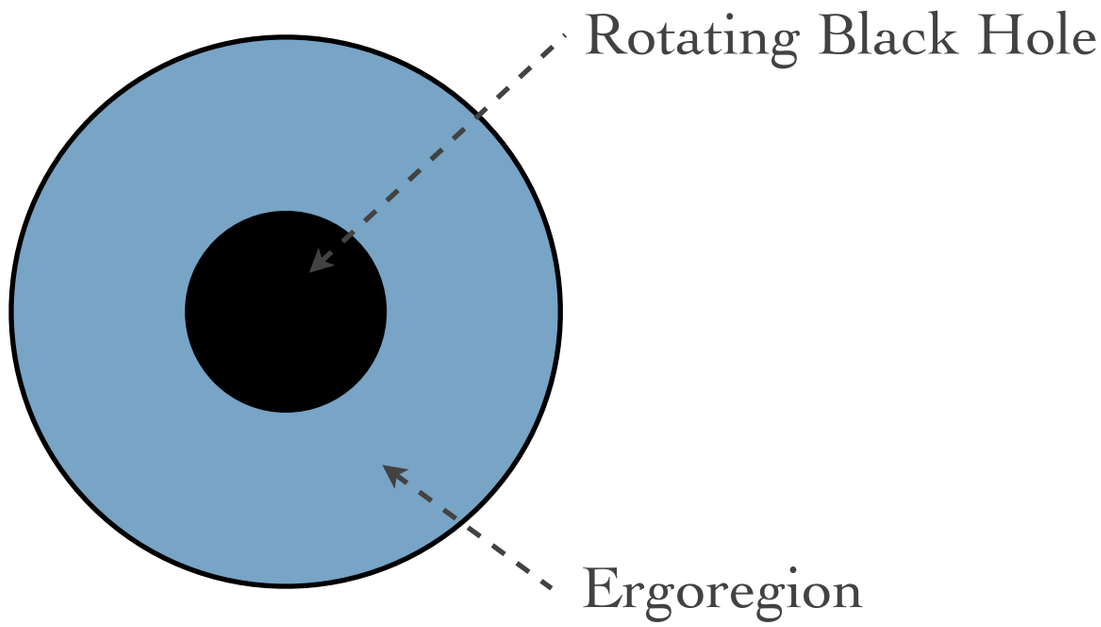
Penrose Process



Ergoregion: Region where even light has to be rotating

Black Hole Superradiance

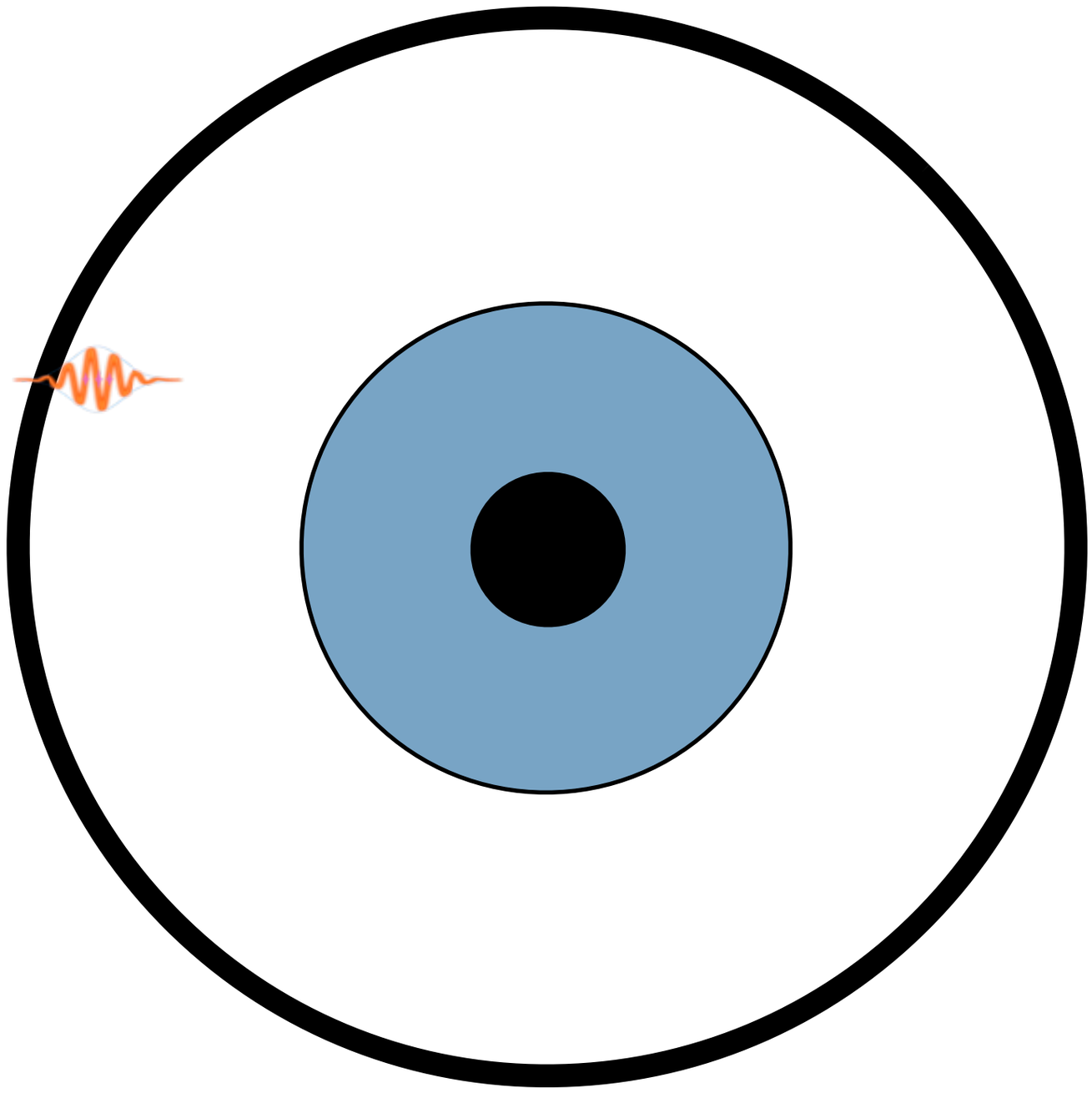
Penrose Process



Extracts angular momentum and mass from a spinning black hole

Black Hole Bomb

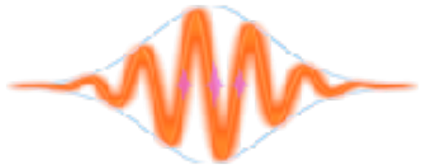
Press & Teukolsky 1972

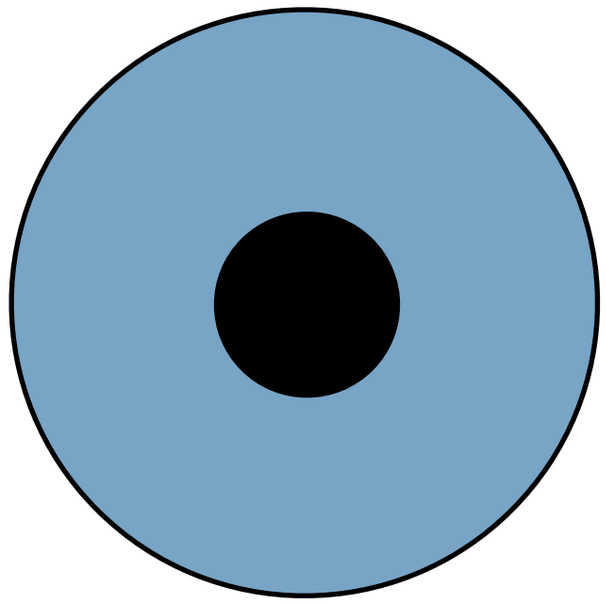


Photons reflected back and forth from the black hole
and through the ergoregion

Black Hole Bomb

Press & Teukolsky 1972

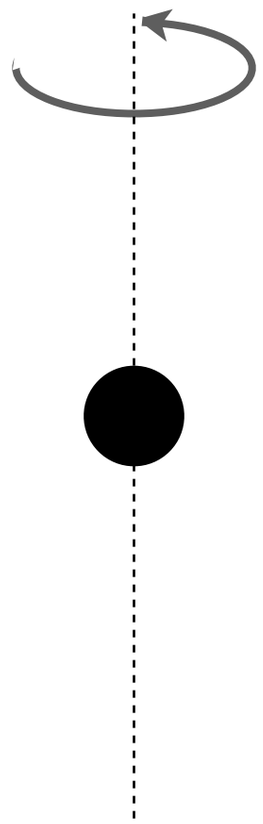




Photons reflected back and forth from the black hole
and through the ergoregion

Superradiance for a massive boson

Damour et al; Zouros & Eardley;
Detweiler; Gaina (1970s)



Particle Compton Wavelength comparable to the size of the Black Hole

Superradiance for a massive boson

Damour et al; Zouros & Eardley;
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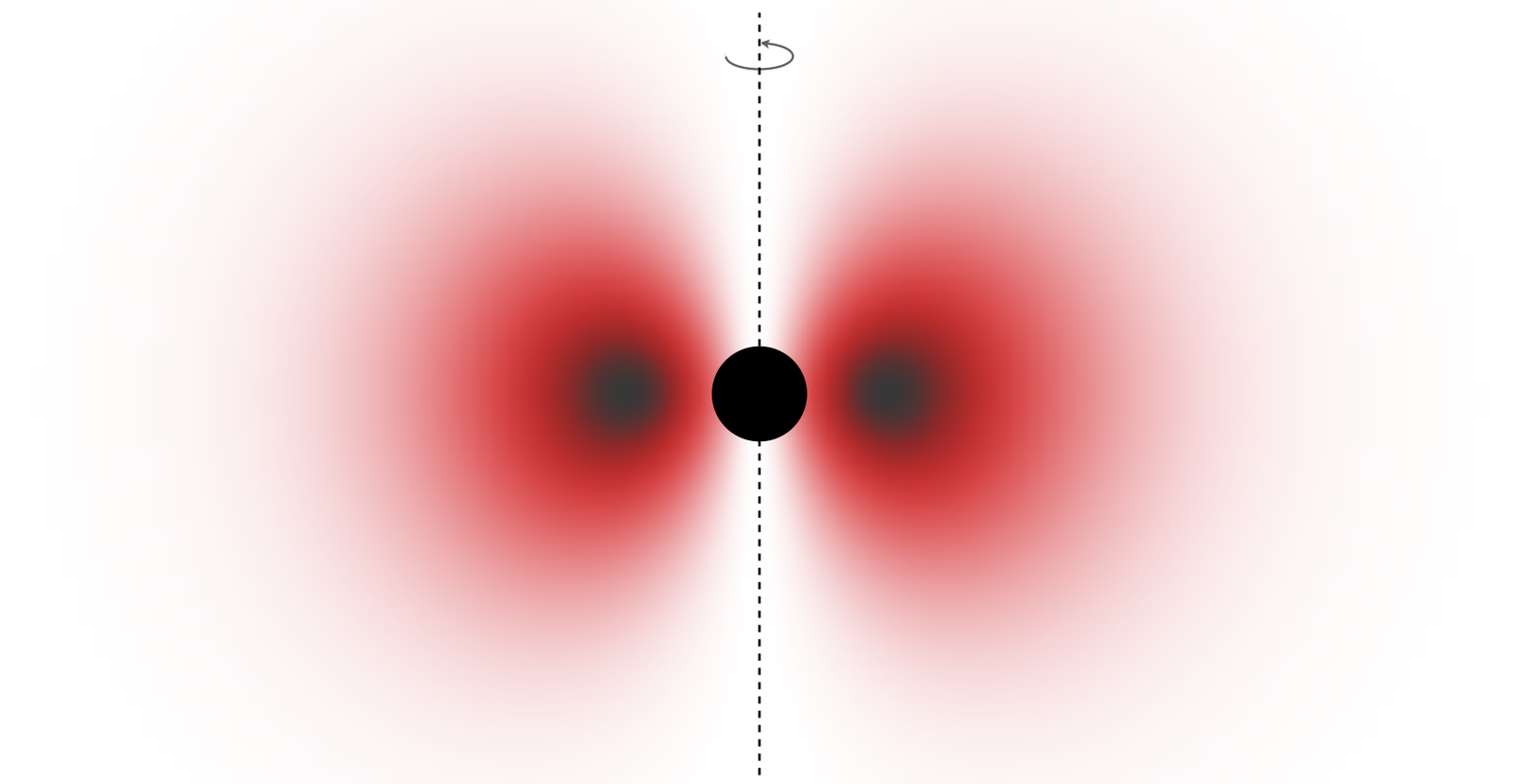
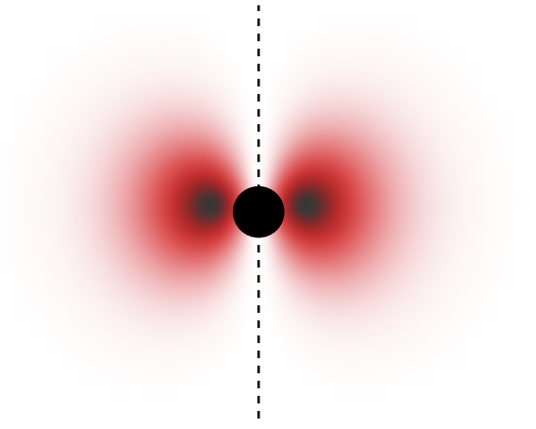


Particle Compton Wavelength comparable to the size of the Black Hole

Gravitational Atom in the Sky

The gravitational Hydrogen Atom



Fine-structure constant: $\alpha = G_{\rm N} M_{\rm BH} \mu_a = R_g \mu_a$

Principal (n), orbital (l), and
magnetic (m) quantum number for each level

$$E_{\rm binding} = -\frac{\alpha^2 \mu_a}{2n^2}$$

Main differences from hydrogen atom:

Levels occupied by bosons - occupation number $>10^{77}$

In-going Boundary Condition at Horizon

Key Points About Superradiance

- For light axions(weak coupling) equation identical to Hydrogen atom

- Boundary conditions different:
  - Regular at the origin ⟶ Ingoing (BH is absorber)
  - Hermitian ⟶ Non-hermitian

Superradiance Parametrics

Superradiance Condition

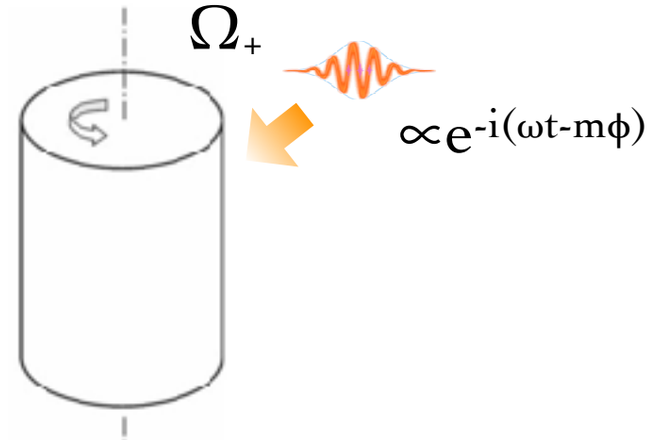
$$\omega_{\text{axion}} < m\,\Omega_{+}$$

m : magnetic quantum number

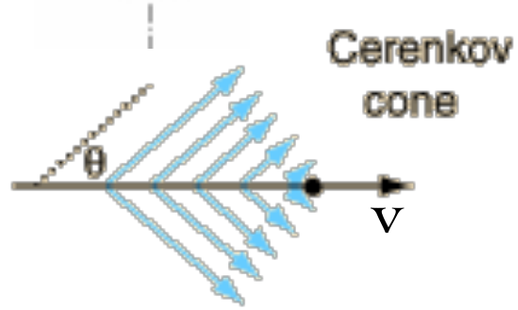
Ω_+ : angular velocity of the BH

Universal Phenomenon:

Superluminal rotational motion of a conducting cylinder



Superluminal linear motion - Cherenkov radiation $1/n(\omega) < v$



Condition can be extracted from requiring that $dA_{BH} > 0$

Superradiance Parametrics

Superradiance Rate

$\tau_{sr} \sim 0.6 \times 10^7 R_g$ for $R_g \mu_a \sim 0.4$

As short as 100 sec vs $\tau_{accretion} \sim 10^8$ years

When $R_g \mu_a >> 1$,

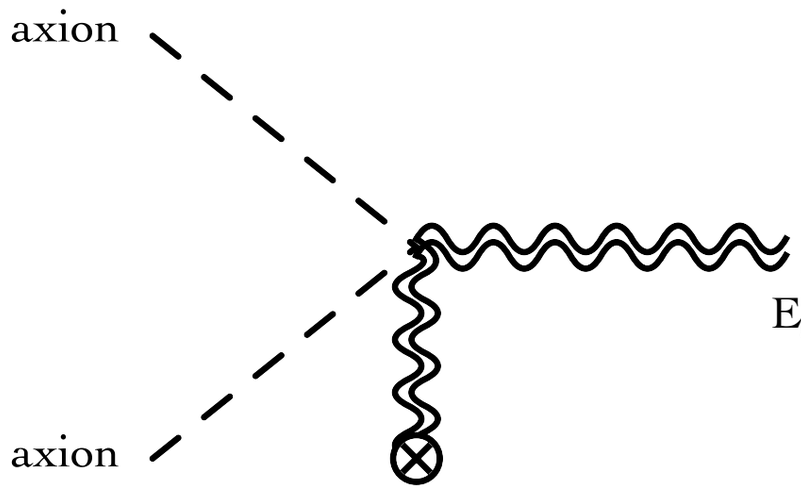
$$\tau_{sr} = 10^7 e^{3.7(\mu_a R_g)} R_g$$

When $R_g \mu_a << 1$

$$\tau_{sr} = \left(\frac{24}{a}\right)(\mu_a R_g)^{-9} R_g$$

Super-Radiance Signatures

GW annihilations



$$f = 10\,\mathrm{kHz} \times (\mu_a/10^{-11}\,\mathrm{eV})$$

$E_{graviton} \approx 2\ m_{axion}$ High frequency GWs

- Signal enhanced by the square of the occupation number of the state

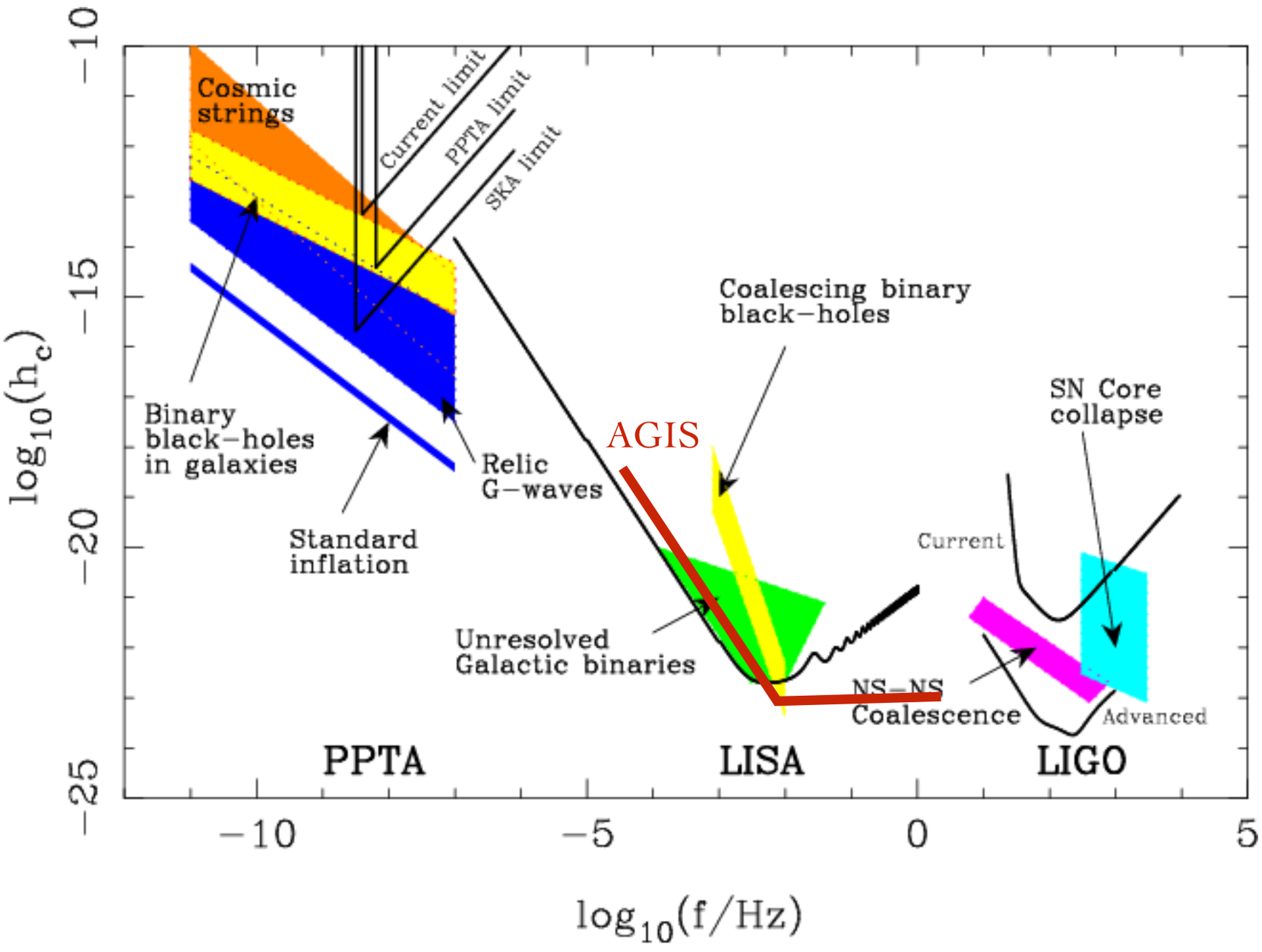
$$h_{\rm peak} \simeq 10^{-22} \left(\frac{1\,{\rm kpc}}{r}\right) \left(\frac{\alpha/\ell}{0.5}\right)^{\frac{p}{2}} \frac{\alpha^{-\frac{1}{2}}}{\ell} \left(\frac{M}{10 M_\odot}\right)$$

- Signal duration determined by the annihilation rate (can last thousands of years)

What will the Universe look like?

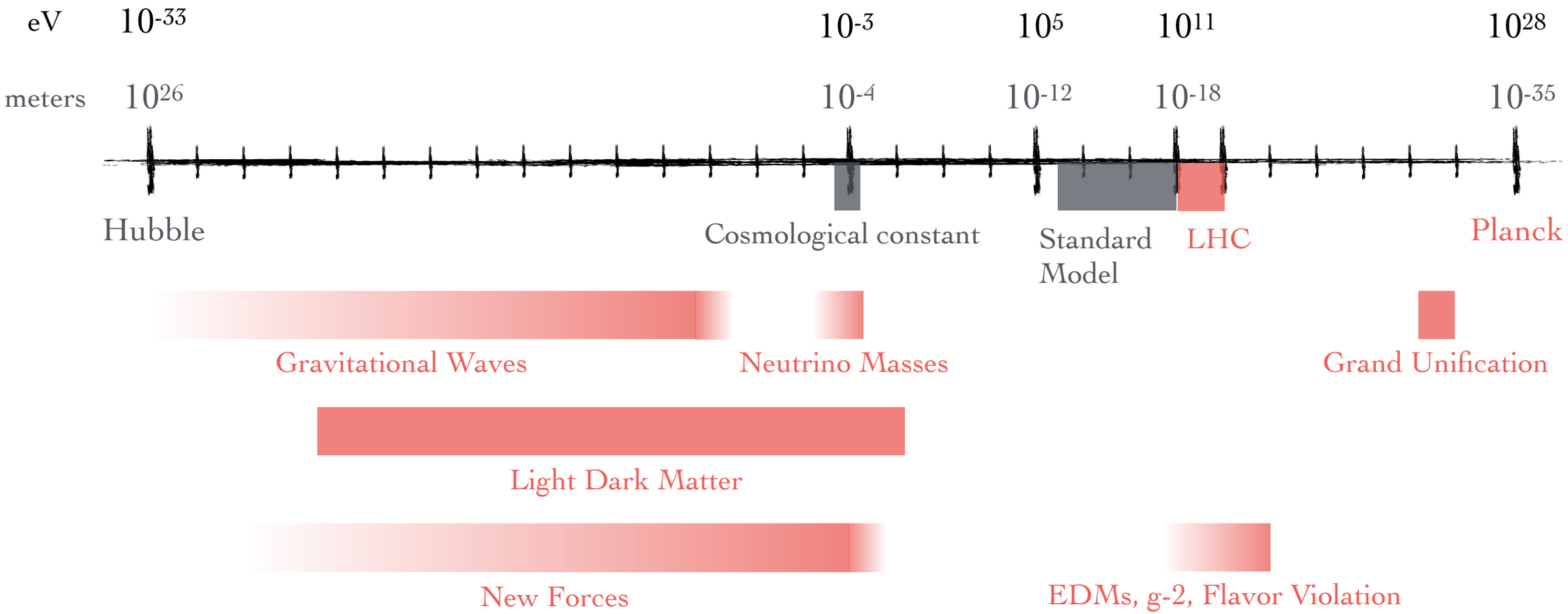
LIGO and PTA look at different frequencies:

Gravitational Wave Astronomy



Our new “eyes” for our Cosmos

The Scales in Our Universe



There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy.
- Hamlet