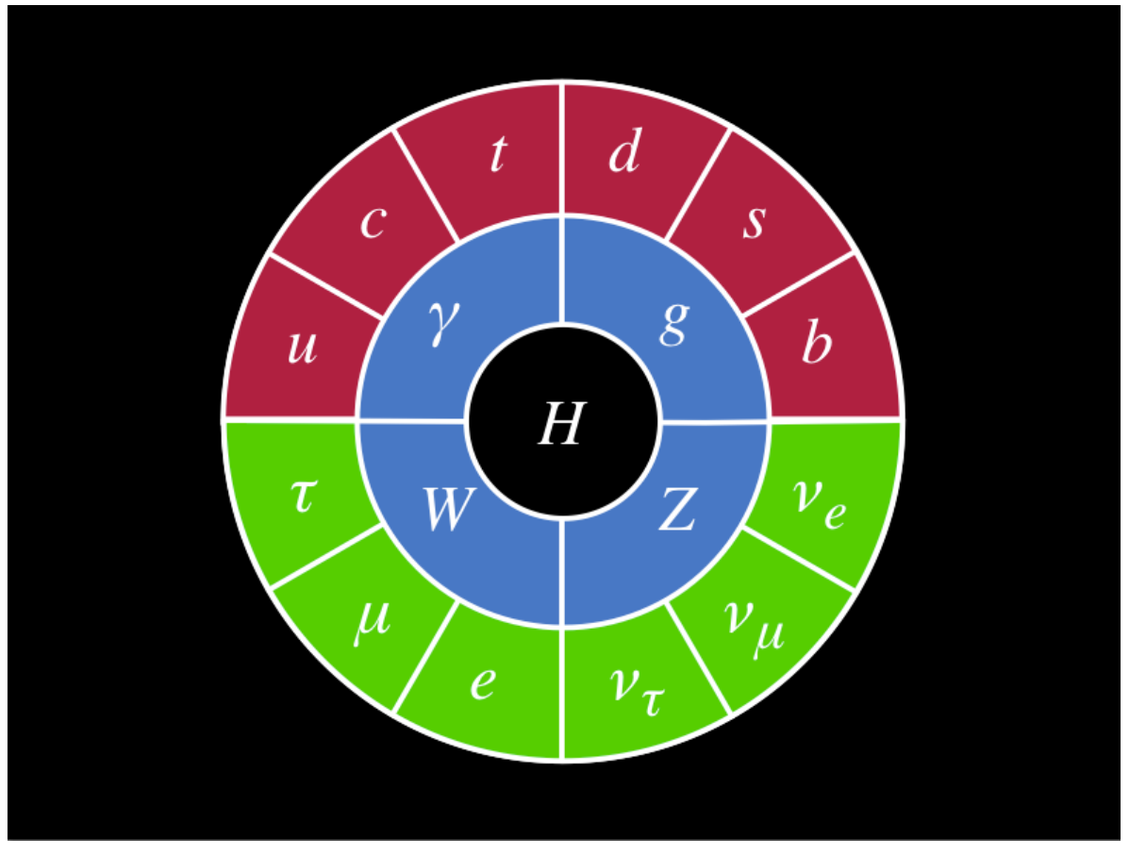
Particle Physics Circa 2021

Savas Dimopoulos

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

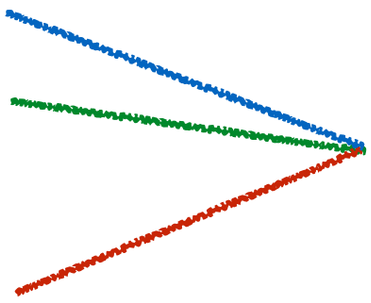
Beyond the Standard Model Motivations

- Dark Matter

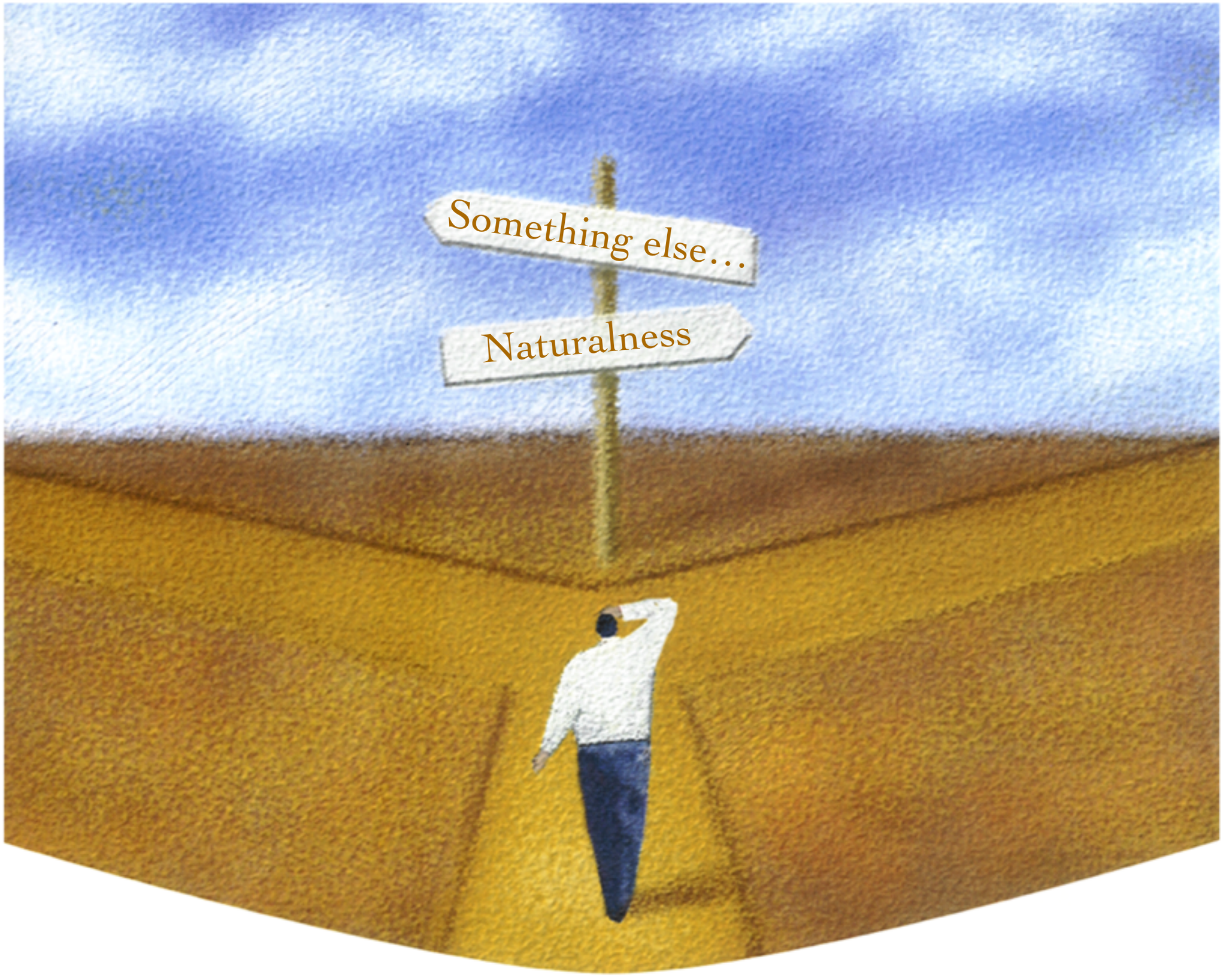
- Couplings and Particles of the Standard Model
  - Charge Quantization Puzzle
    - Hydrogen charge $\leq 10^{-22}$
  - Gauge Hierarchy Problem
    - $G_N \sim 10^{-33} G_F$
  - Cosmological Constant Problem
    - $\Lambda \sim 10^{-120} M_{Pl}^4$

Beyond the Standard Model Highlights

- Charge Quantization in GUTs — Georgi, Glashow 1974
  - $[Q_i, Q_j] = iQ_k f_{ijk}$
- Gauge Coupling Unification in TeV-SUSY GUTs — Georgi, Quinn, Weinberg 1974; SD, Raby, Wilczek 1981; SD, Georgi 1981



The Origin of Small Numbers



Small Numbers and Coincidences

Naturalness - Dynamics

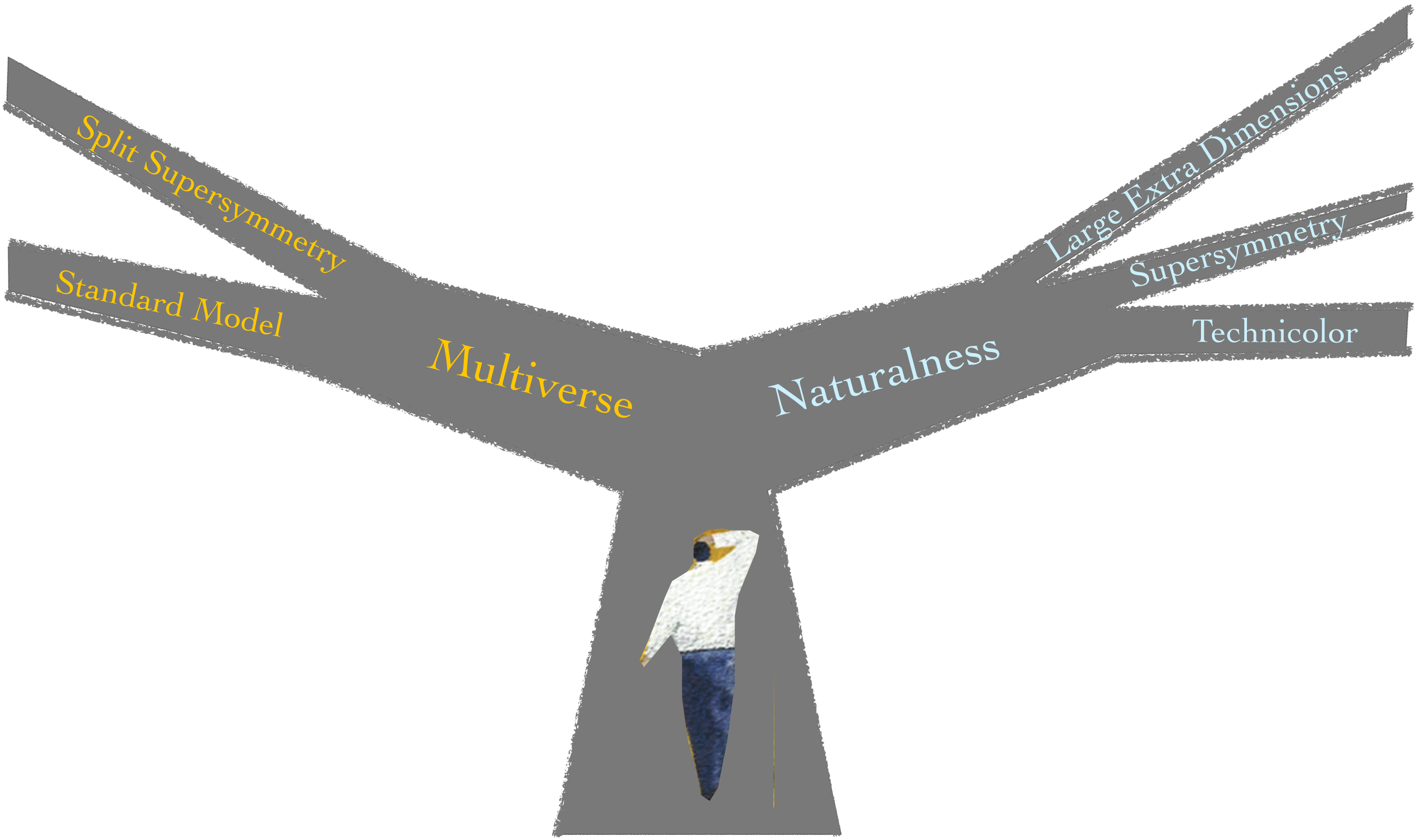
Problem	Solution
Hydrogen Binding Energy	$E_b = \frac{1}{2}\frac{e^4}{(4\pi)^2} m_e$
Deuteron Binding Energy Nuclear Binding Energy	$E_b \approx \frac{1}{2}\frac{1}{(4\pi)^2}\frac{m_N}{2}$
π^+ - π^o mass difference	Symmetry/Dynamics
$K - \bar{K}$ mixing	Flavor Symmetry
Electron Mass	Chiral Symmetry

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!

At the Crossroads



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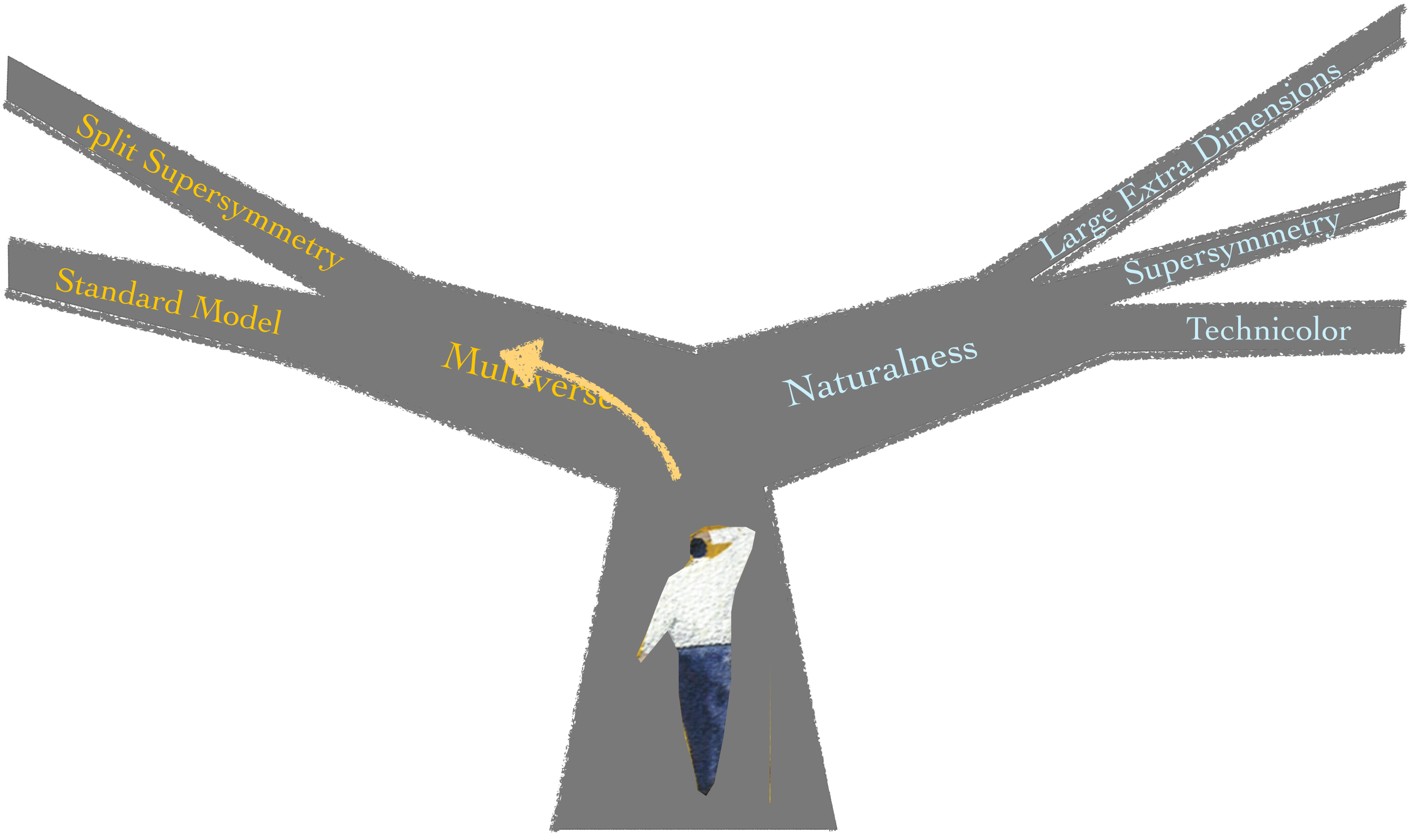


Will be using the terms
Multiverse, Landscape, Environmental and Anthropic Selection
interchangeably

Outline

- Natural approach to the gauge hierarchy problem

- Multiverse approach to the cosmological constant problem

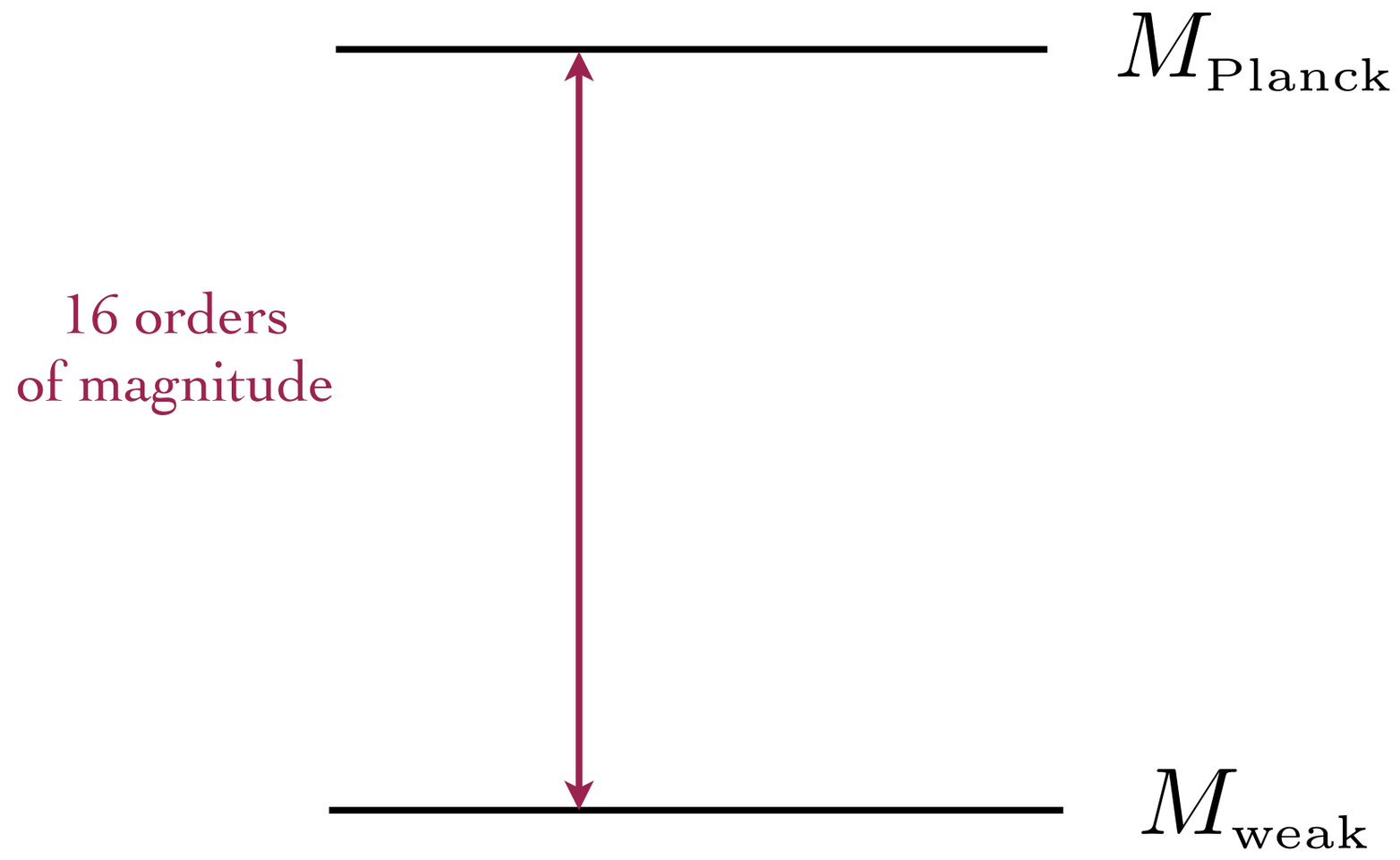
- The Multiverse, String Theory and a plenitude of particles
  - A plenitude of table-top experiments for a plenitude of particles

- Multiverse approach to the hierarchy problem
  - Mini-Split at a high energy collider

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

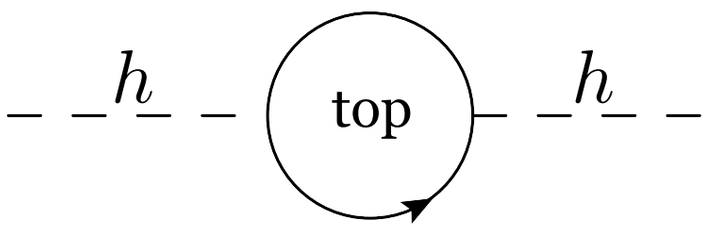
$$\frac{M_{\text{Planck}}}{M_{\text{weak}}}$$

In the Standard Model:

Quantum Corrections pull the weak scale up

Quantum Corrections in the Standard Model

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

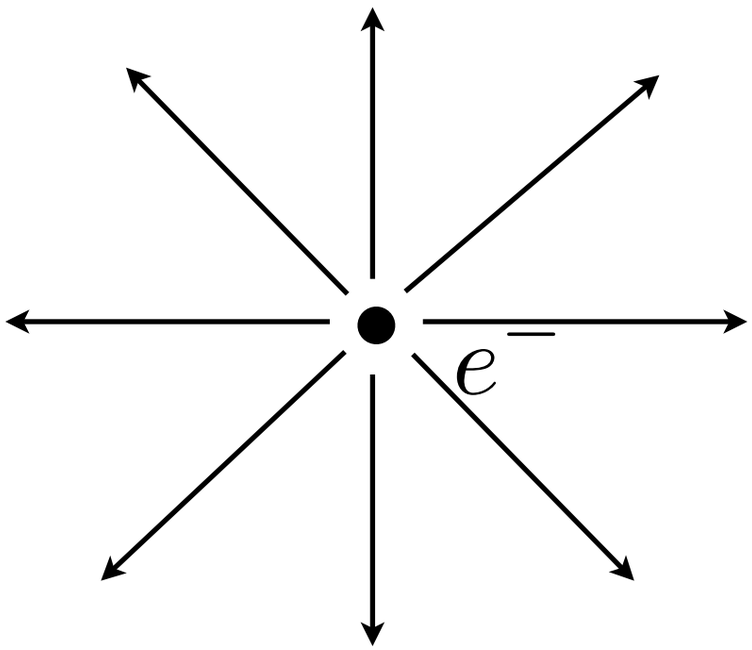


$$m^2_{\mathrm{higgs}} \propto M^2{}_{\mathrm{Planck}}$$

Need new symmetry to protect the Higgs in the Standard Model

A Historic Precedent for a New Symmetry

Non-relativistic electron self-energy



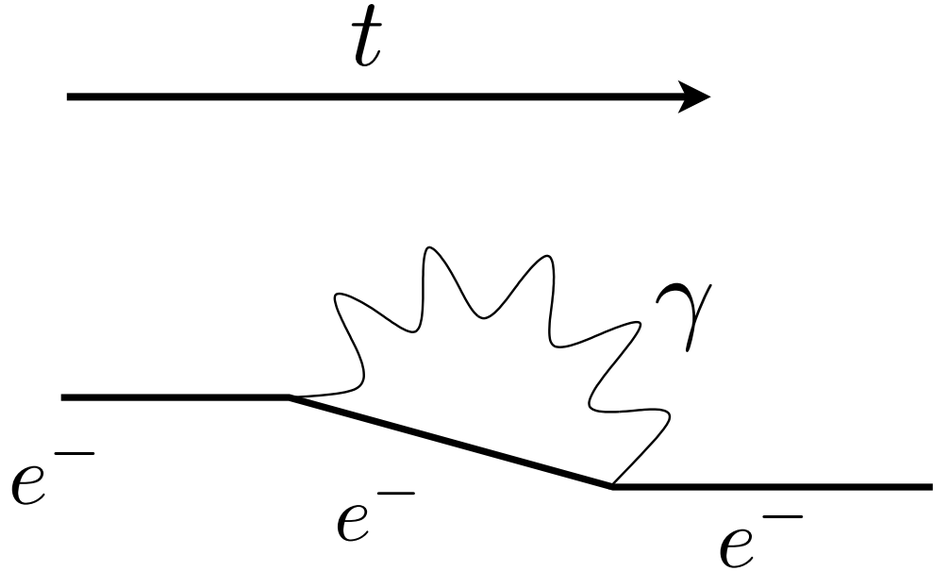
Classically

$$E = \frac{\alpha}{r_{\min}} = \alpha M_{\text{Planck}}$$

No understanding of why $m_{electron} \ll M_{Planck}$

The electron mass in quantum mechanics

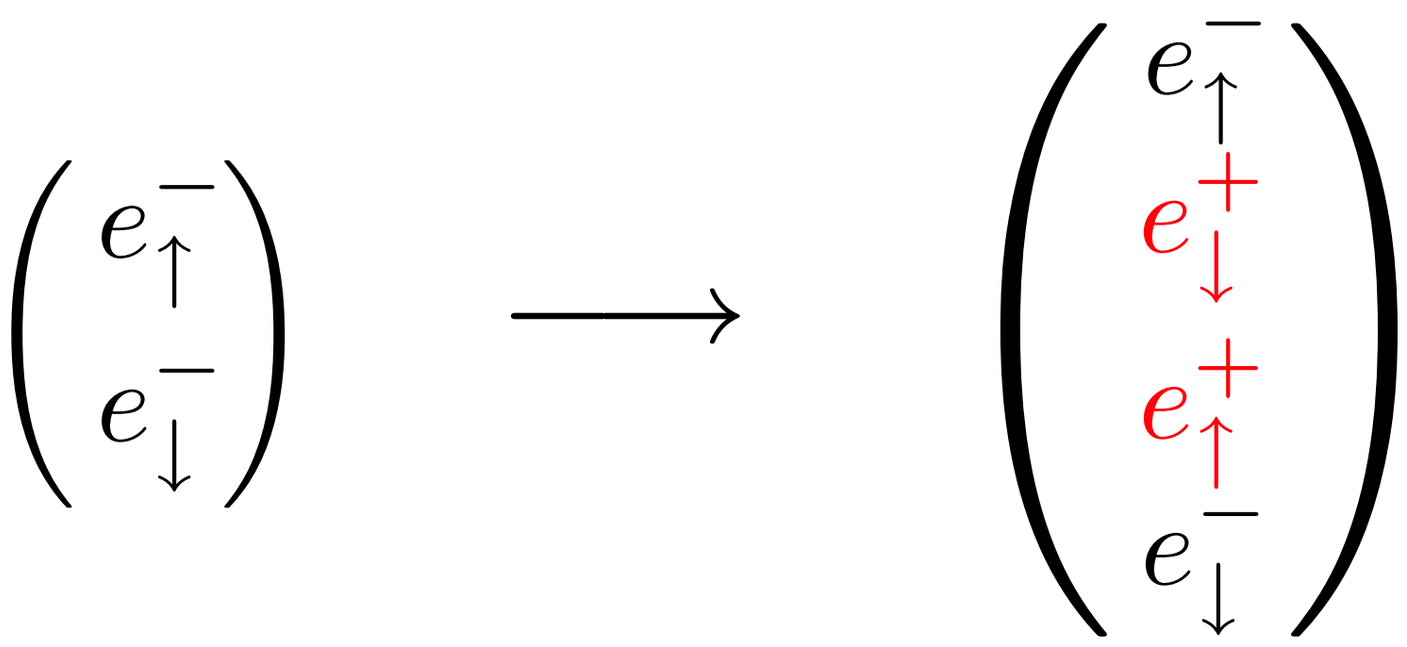
Without relativity



$$\alpha M_{\mathrm{Planck}}$$

A New symmetry for the Electron Mass: Lorentz Invariance

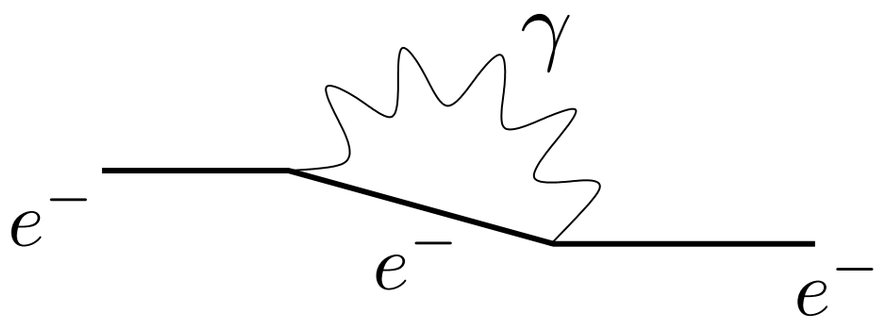
New Particle for the electron mass:
The positron



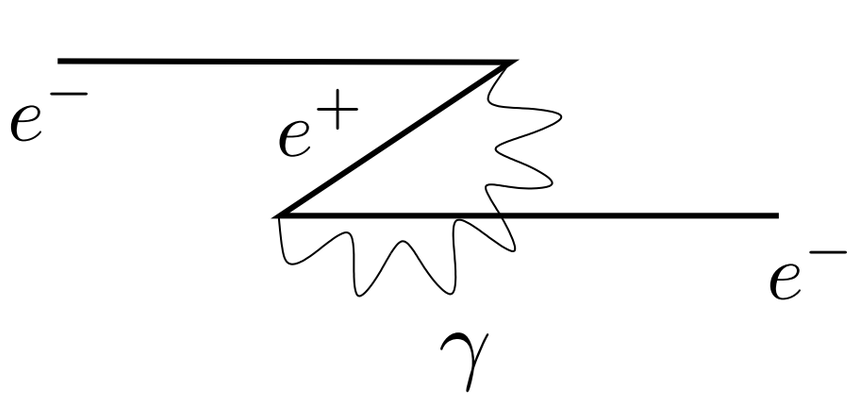
rotations

Lorentz

The Positron and Quantum Corrections



$$\alpha \left(M_{\text{Planck}} + m_e \log \frac{M_{\text{Planck}}}{m_e} \right)$$

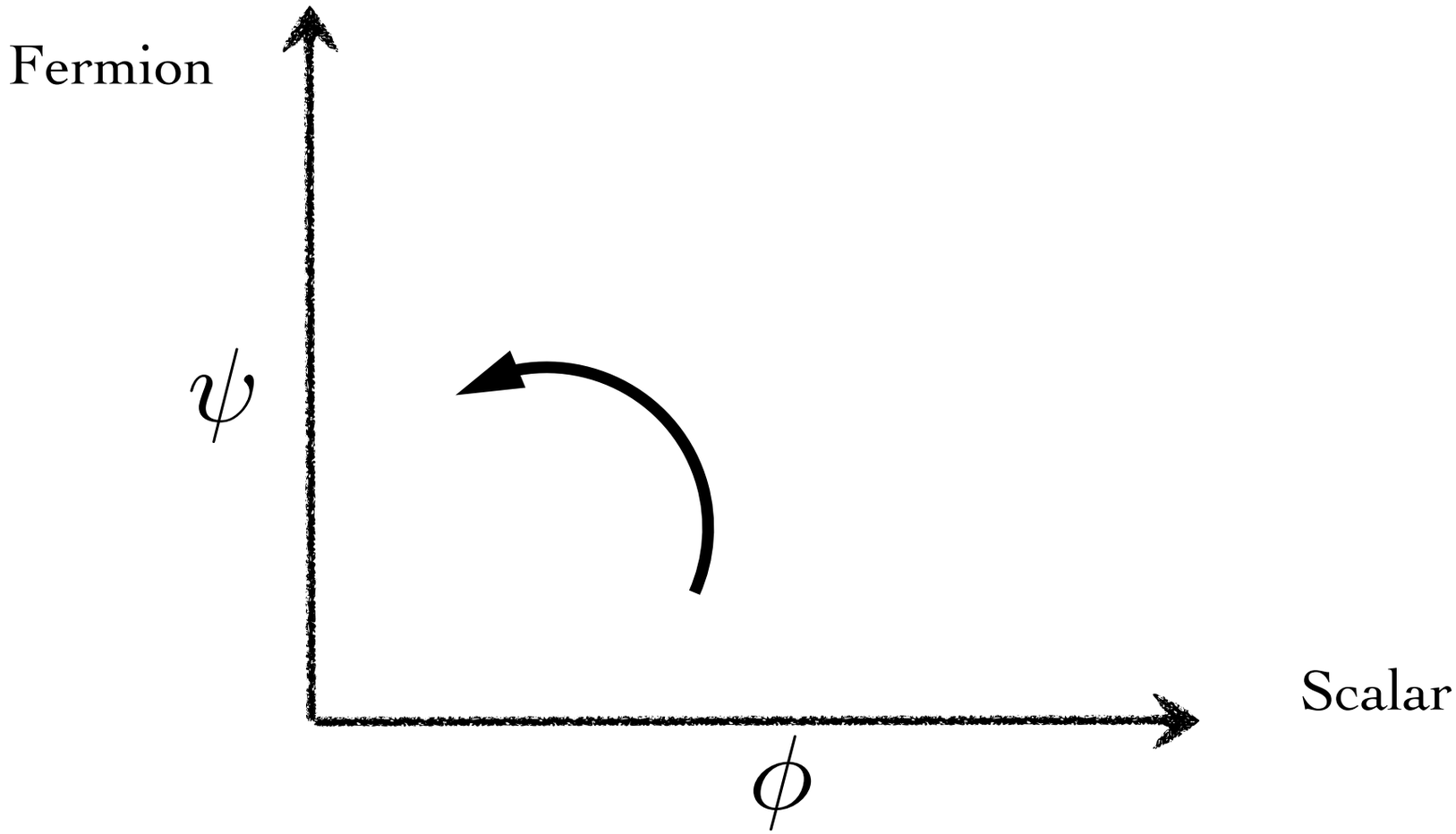


$$\alpha \left(-M_{\text{Planck}} + m_e \log \frac{M_{\text{Planck}}}{m_e} \right)$$

$$\boxed{\alpha \, m_e \, \log \frac{M_{\text{Planck}}^2}{m_e^2}}$$

No explanation why $m_e \ll M_{\text{Planck}}$ but once set, it's stable

A New Symmetry for the SM Higgs



Supersymmetric Standard Model

The Supersymmetric Standard Model

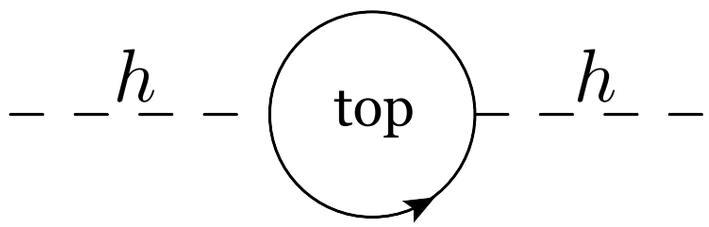
- New Symmetry: Supersymmetry

- New Particles: Superparticles

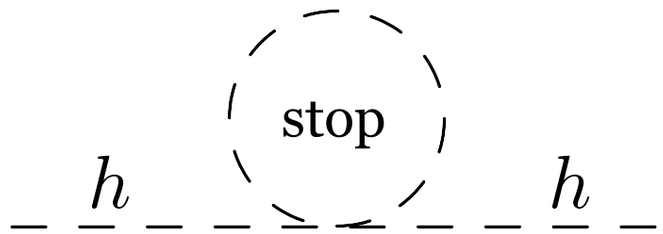
- Every particle has a superpartner:

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

Superparticles and Quantum Corrections



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

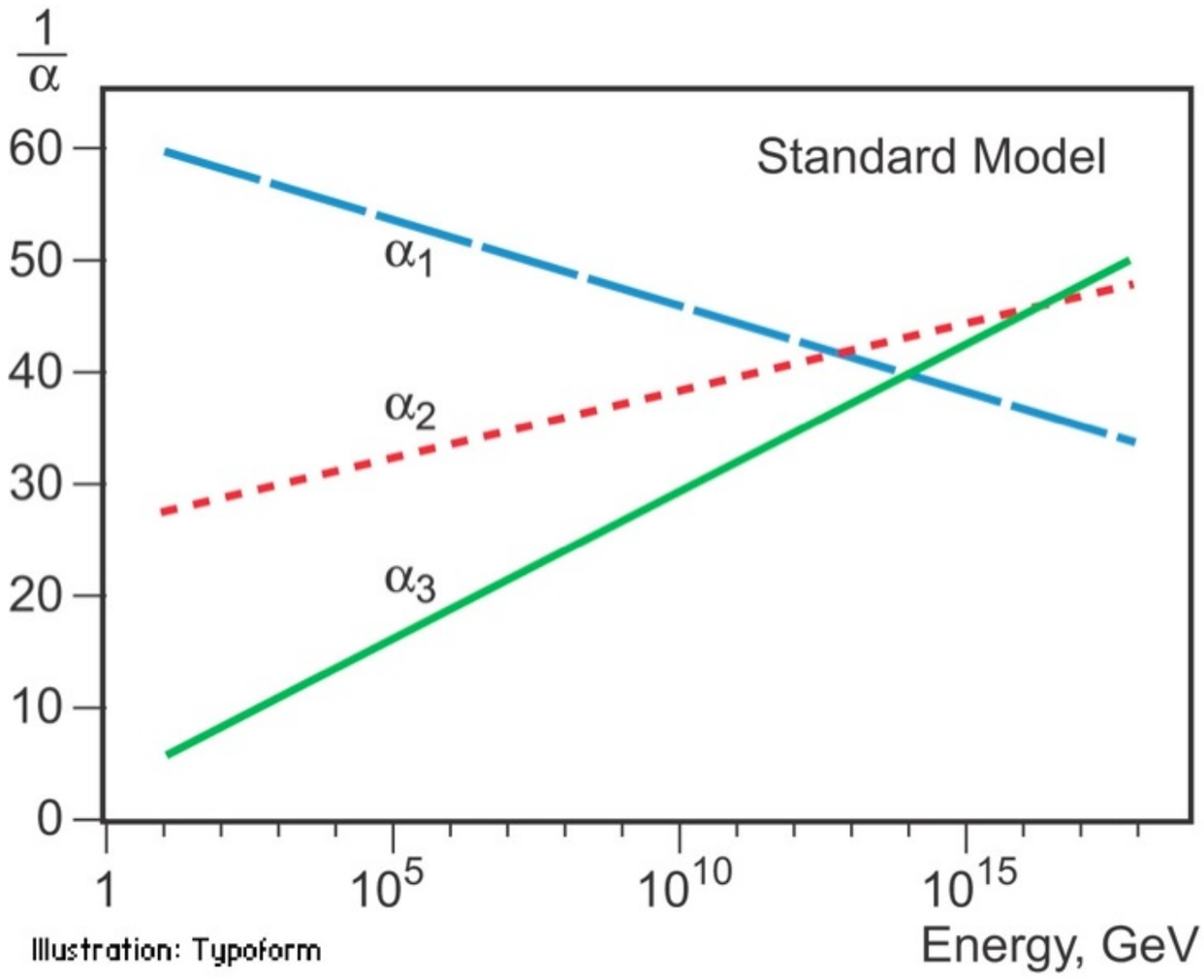


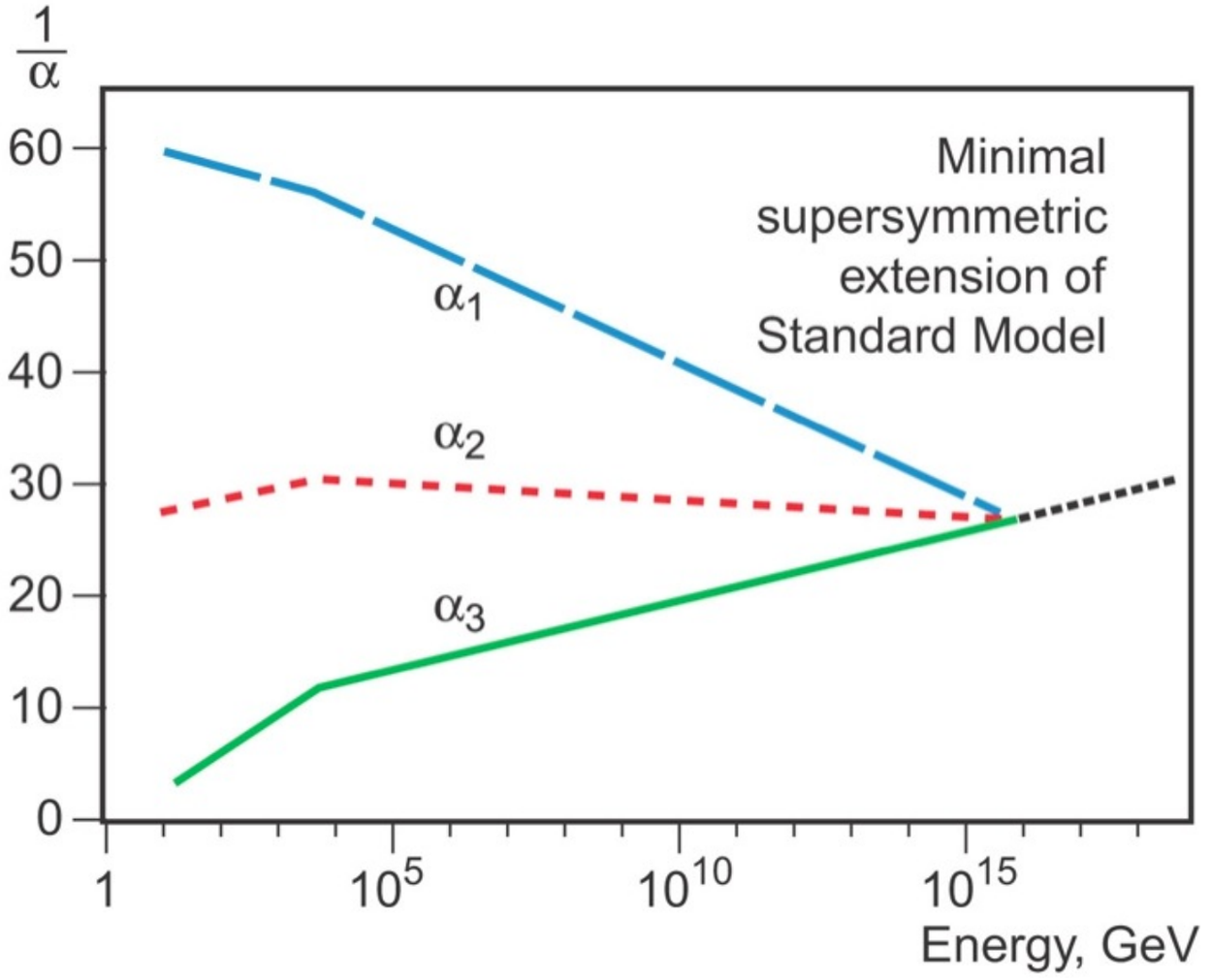
$$\propto -M^2_{\text{Planck}} + M^2_{\text{SUSY}}$$

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

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

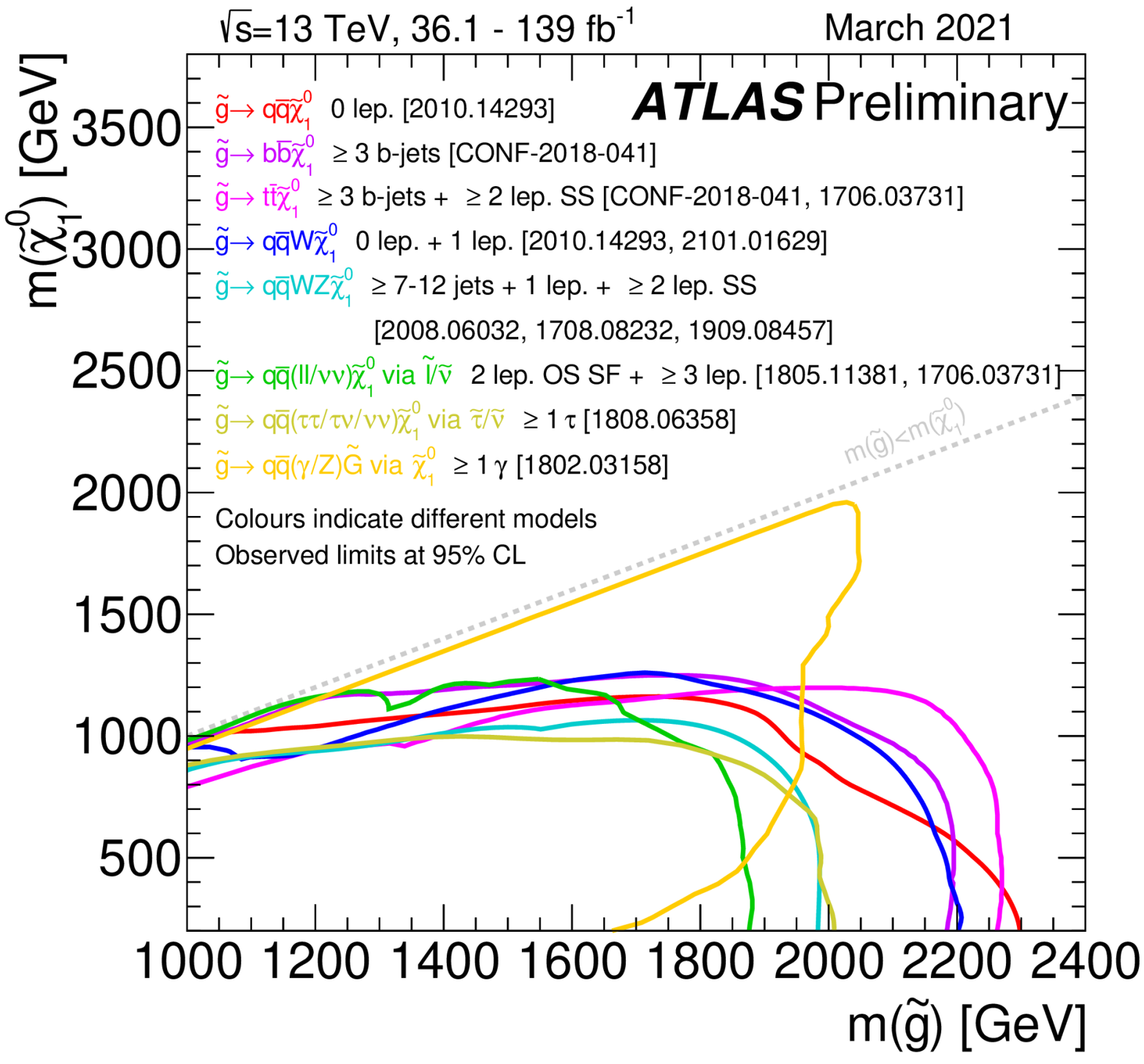
Gauge Coupling Unification





Experimentally verified in the early 1990s

The Missing Superpartner Problem



Outline

- Natural approach to the gauge hierarchy problem

- Multiverse approach to the cosmological constant problem

- The Multiverse, String Theory and a plenitude of particles
  - A plenitude of table-top experiments for a plenitude of particles

- Multiverse approach to the hierarchy problem

The cosmological constant problem

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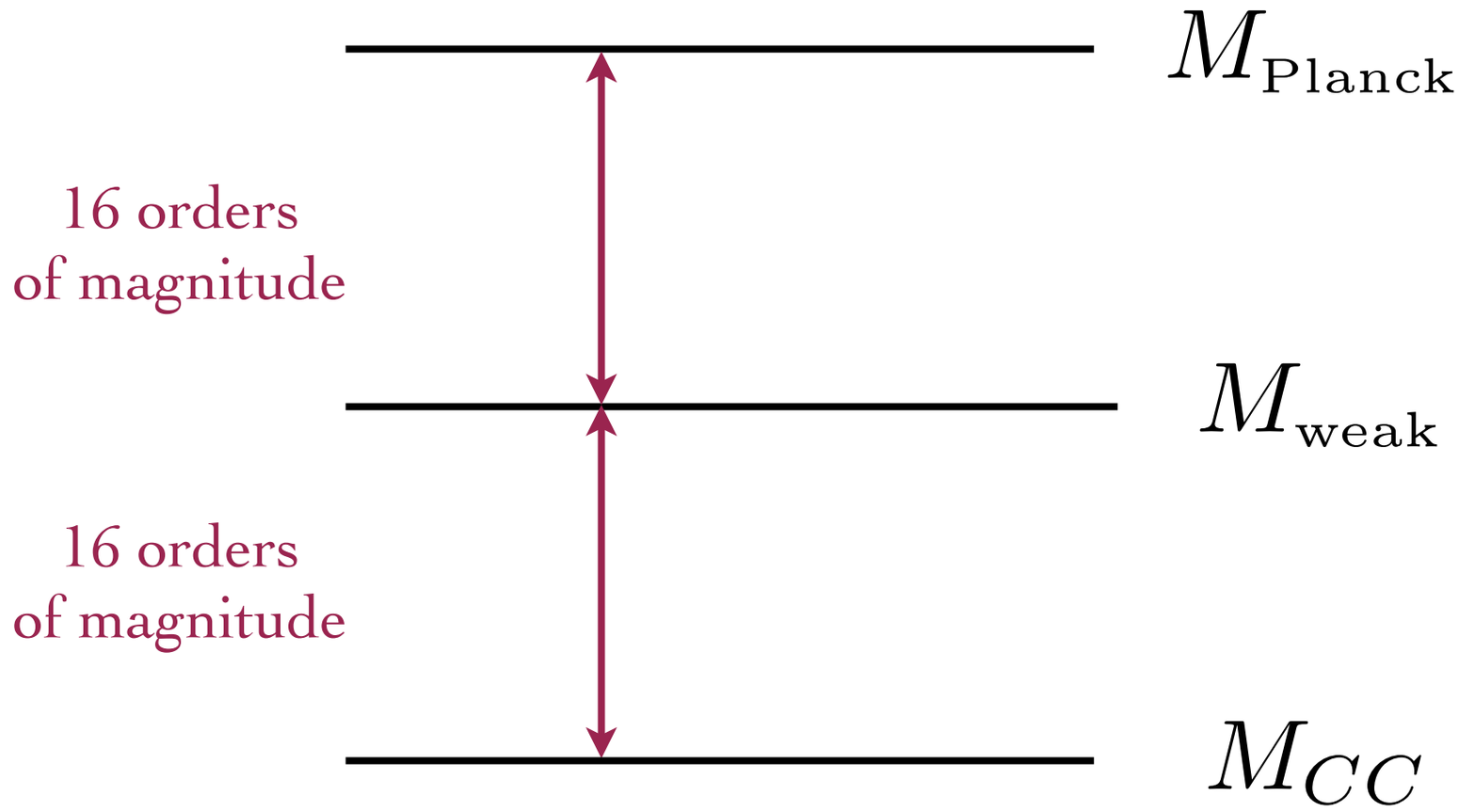
$$M_{\text{weak}} = G_{\text{Fermi}}^{-\frac{1}{2}} = 10^{3}\ \text{GeV}$$

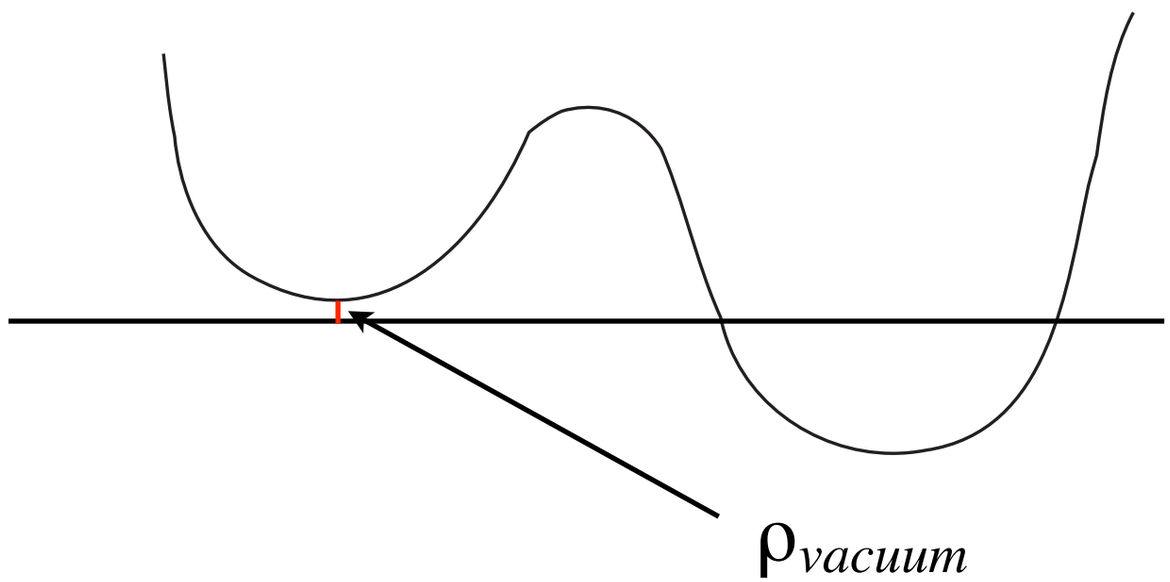
$$M_{CC} = \rho^{1/4}{}_{\text{vacuum}} = 10^{-12}\ \text{GeV}$$



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

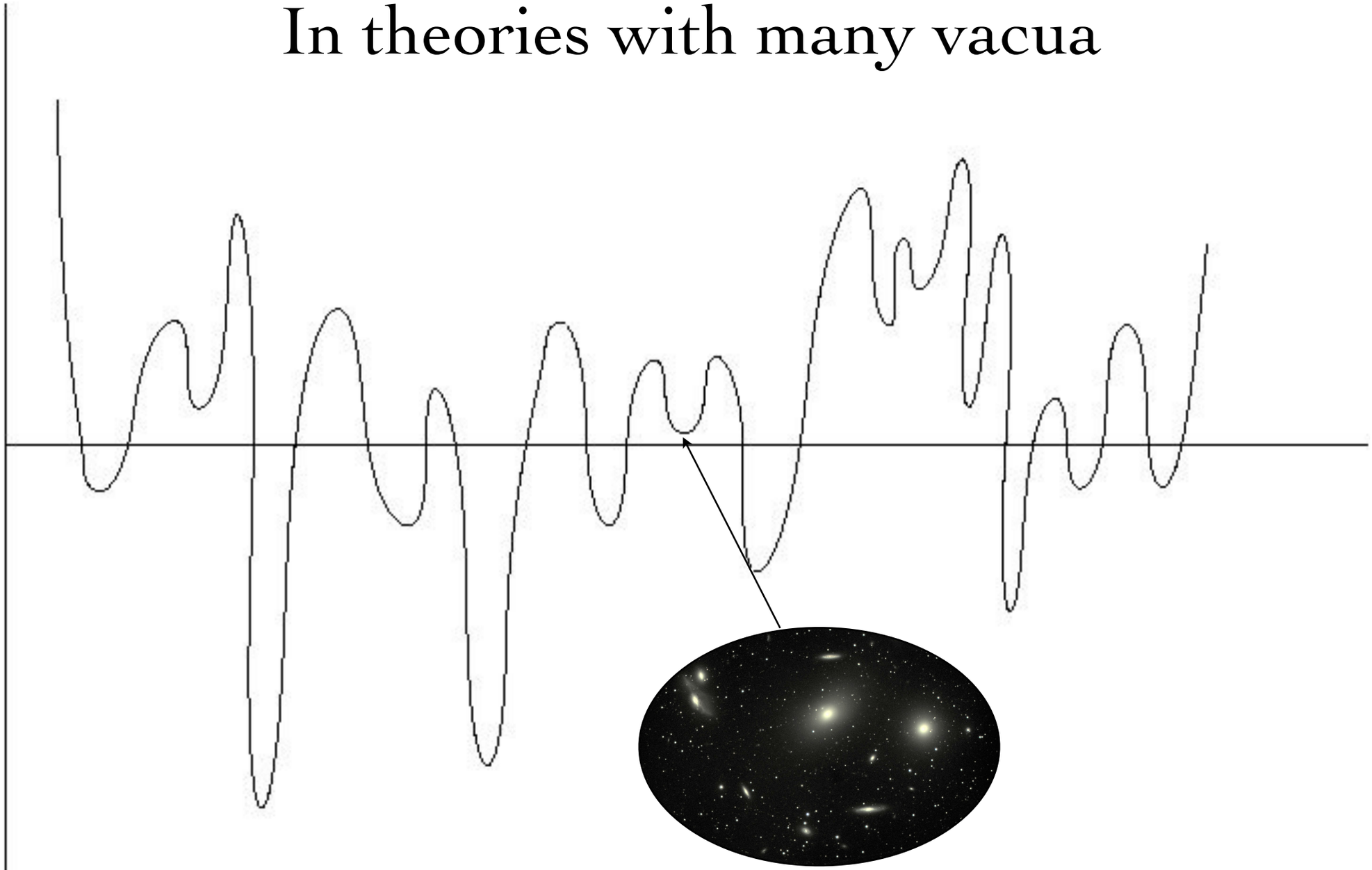


Getting $\rho_{vacuum} \sim (10^{-15} M_W)^4$

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 "galactic" principle can explain
why we live in a universe with small, but nonzero, ρ_{vacuum}

One Solar System

Many Solar Systems

One Solar System

Giordano Bruno,
February 17, 1600

Many Solar Systems

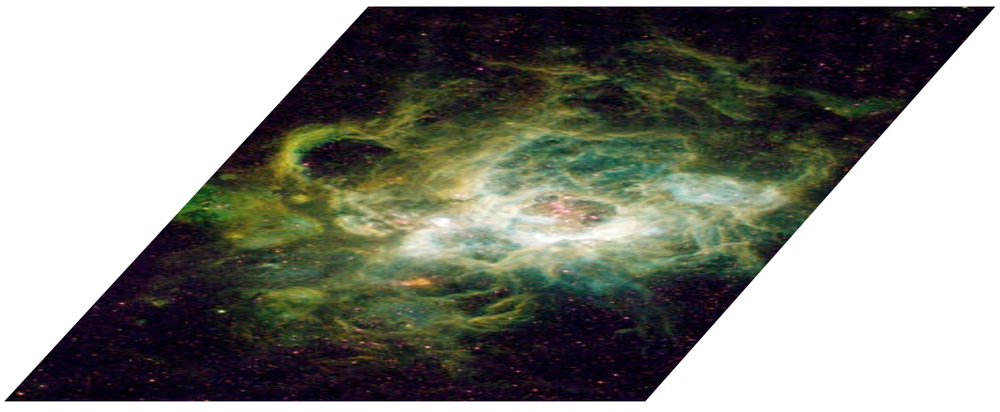
‘Innumerable suns exist, innumerable earths revolve around these suns,
in a manner similar to the way the planets revolve around the sun.
Living beings inhabit these worlds’

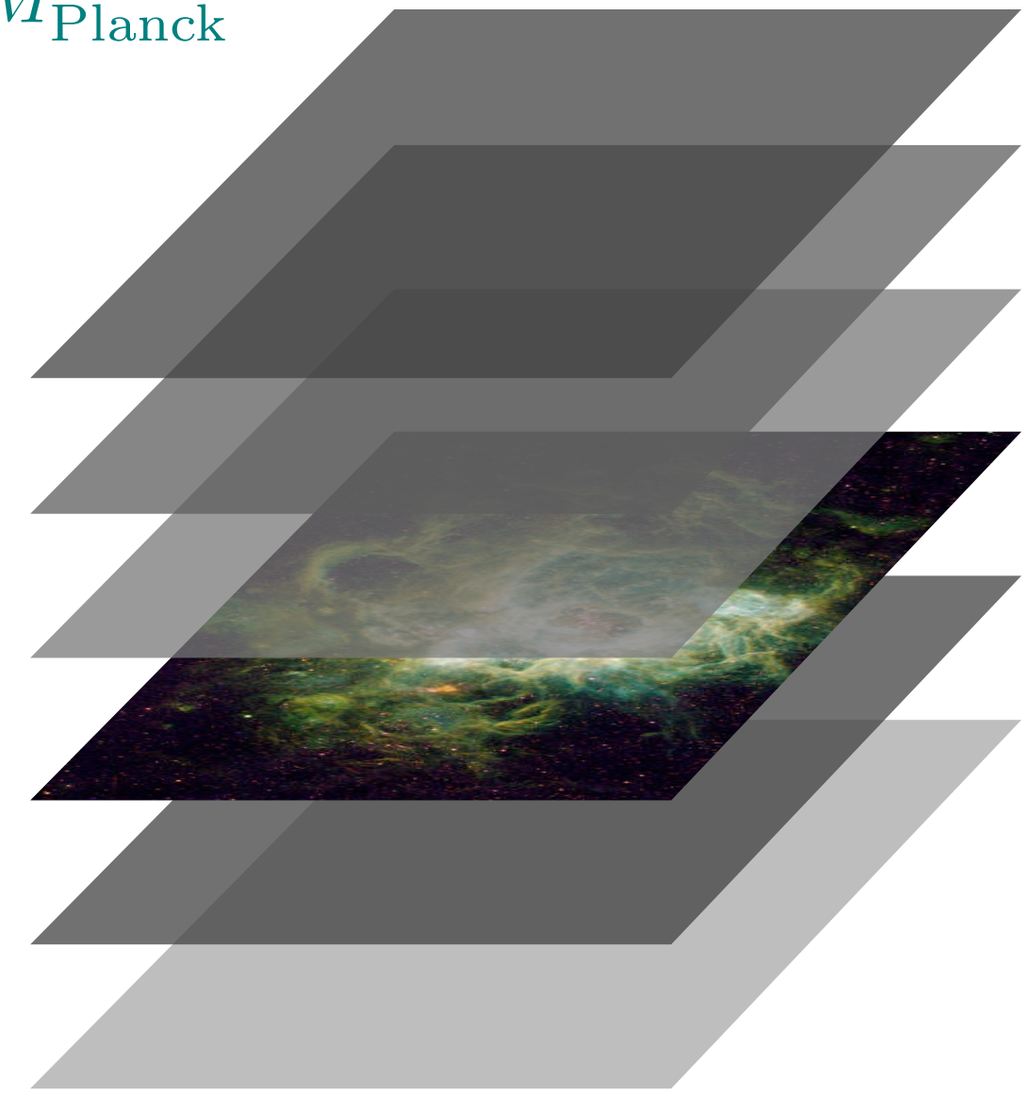
Single Universe

Many Universes

The existence of Galaxies

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





"Divine" Intervention

Environmental Selection

Analogies

Solar system	↔	Universe
Planetary Distances	↔	Vacuum Energy
Universe	↔	Multiverse
Telescope	↔	Precision and Collider Experiments

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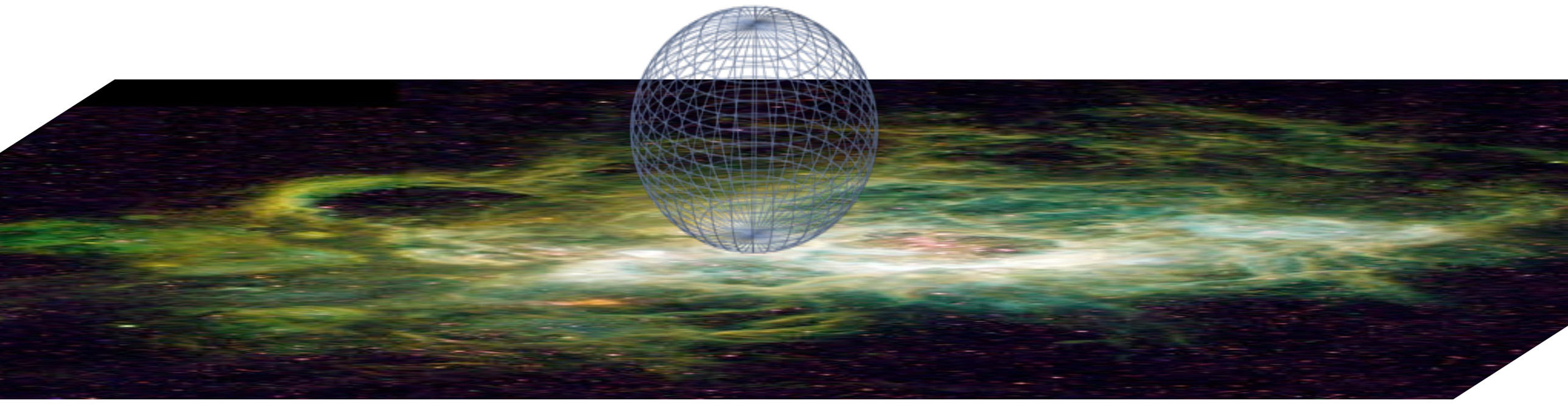
The Many Universes of String Theory



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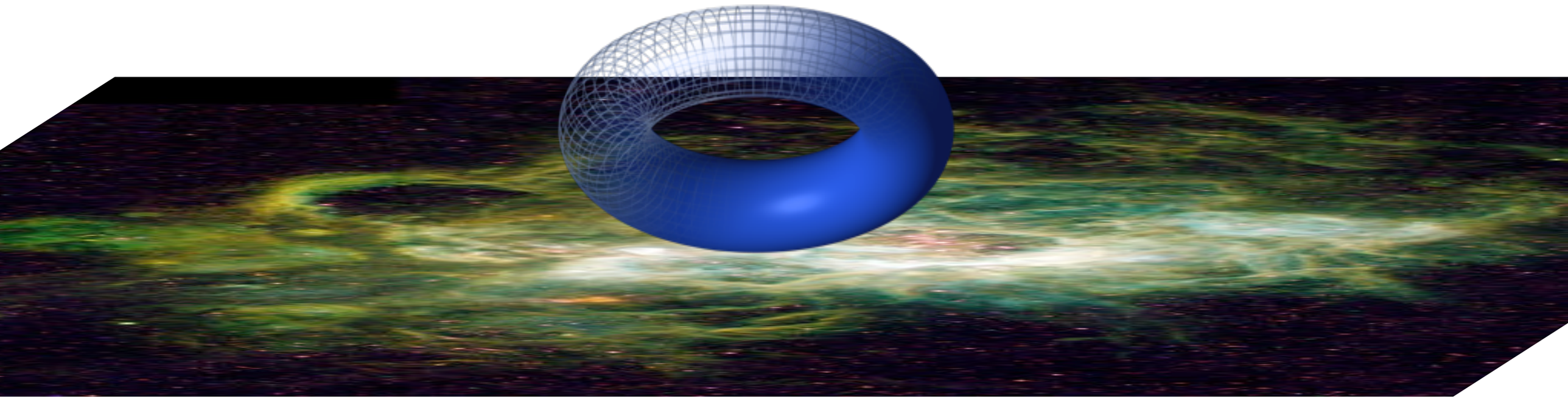

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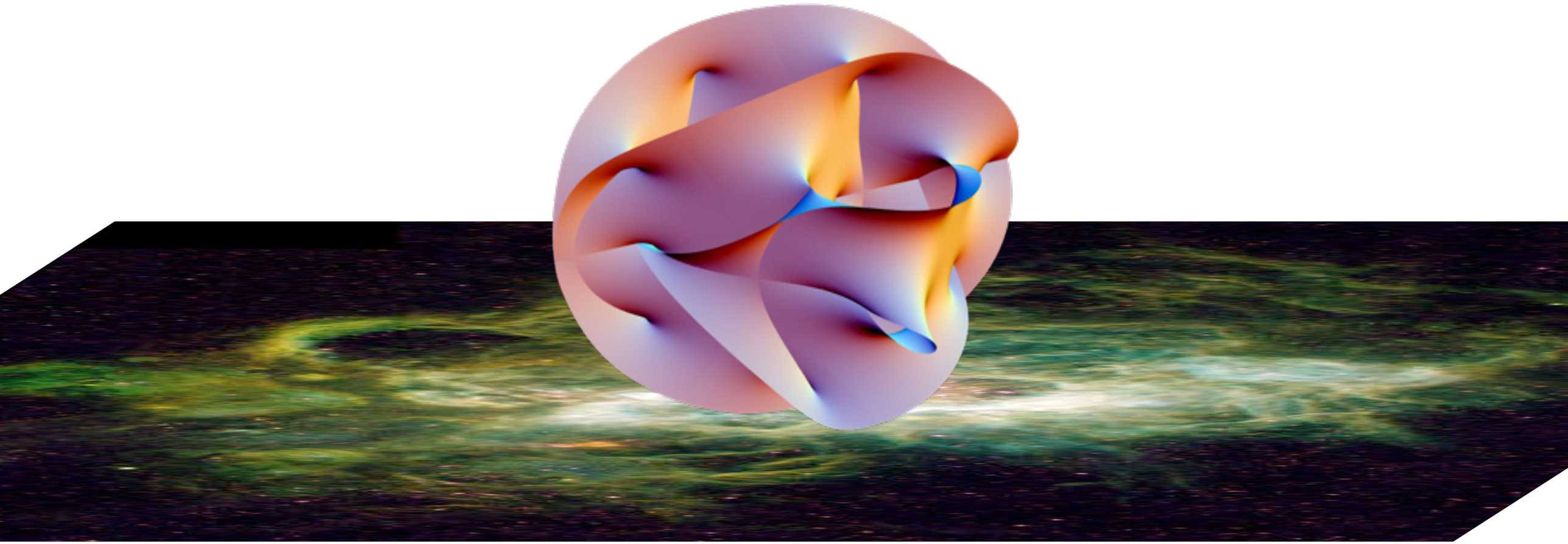


Extra dimensions of String Theory imply a Plenitude of Universes

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

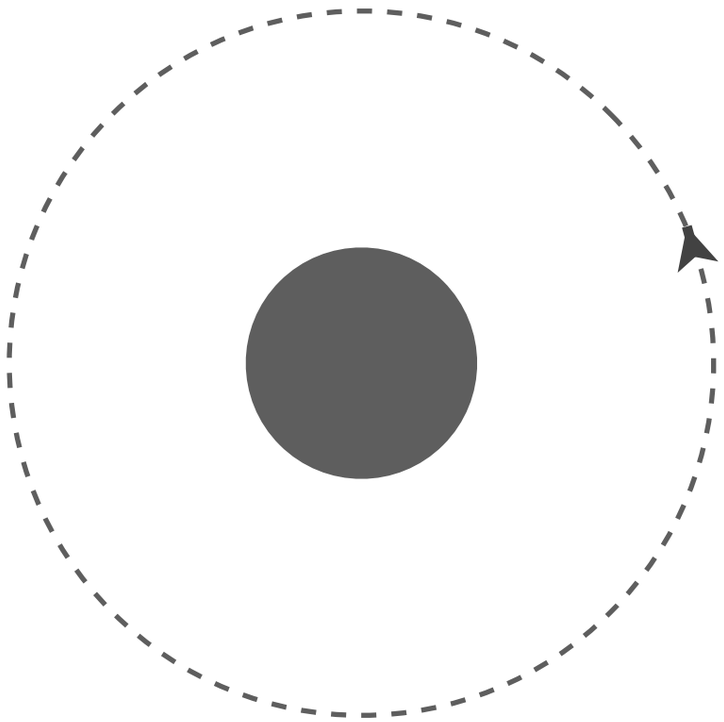
$$\vec{B} = 0$$

Energy stored only inside the solenoid

Non-trivial gauge configuration far away carries no energy

Massless particles from topology

The Aharonov-Bohm Effect



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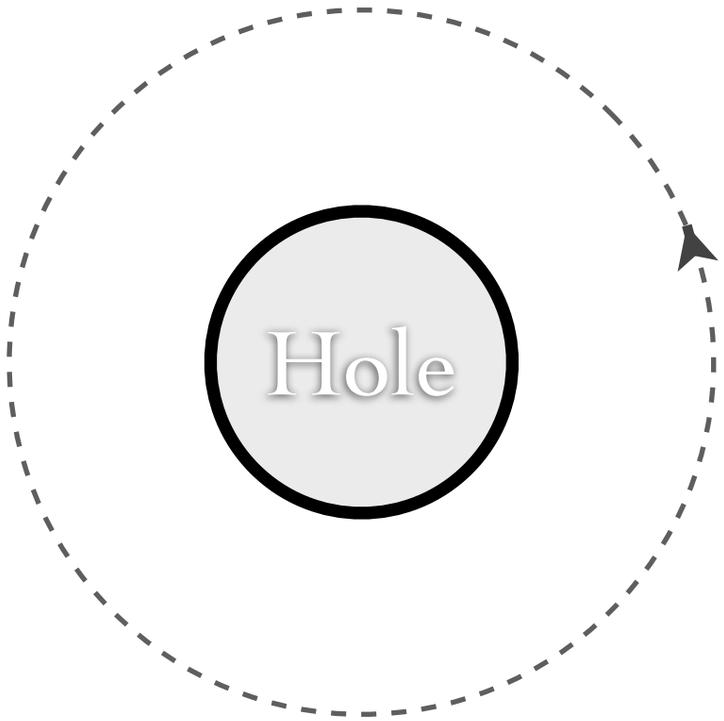


Taking an electron around the solenoid

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

while

$$\vec{B} = 0$$

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

String Axion mass and the QCD axion

$$\text{Particle Mass} \sim \frac{M_{\text{Planck}}^2 e^{-S/2}}{f_a}$$

Requirements on string theory for QCD axion
to solve the strong CP problem

$$\theta_{QCD} < 10^{-10}$$

String corrections < 10^{-10} × QCD

$$M_{Planck}^4 \; e^{-S} < 10^{-10} \times m_\pi^2 f_\pi^2$$

$S \gtrsim 200$ $\qquad\qquad$ $S \sim 2\pi / \alpha$

The QCD axion should not be special

There could be **many** light axions

A Plenitude of (Nearly) 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

- Higher dimensional graviton or modifications of gravity at short distances

Mass acquired by non-perturbative effects

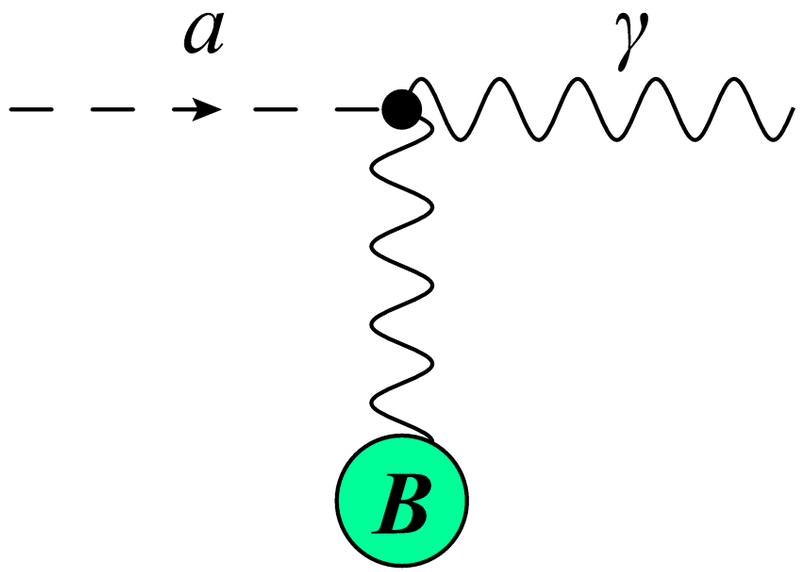
Signatures of a plenitude of particles

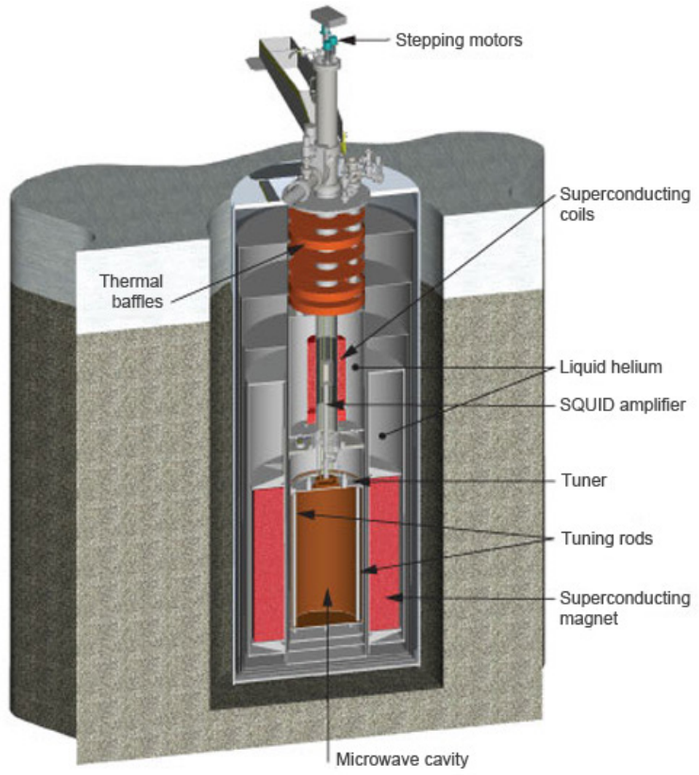
- They can mediate new forces
- They have astrophysical signatures
- They are excellent DM candidates

Axion Dark Matter

Some examples

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

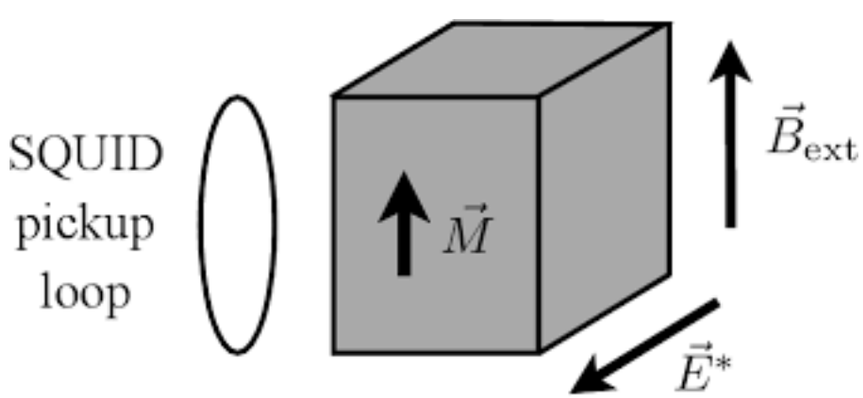




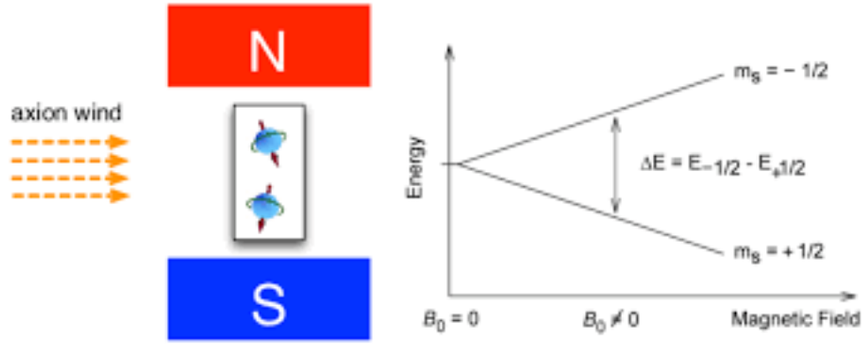
Cavity size = Axion size

Axion Dark Matter

- Spin precession experiments



EDM coupling of the axion

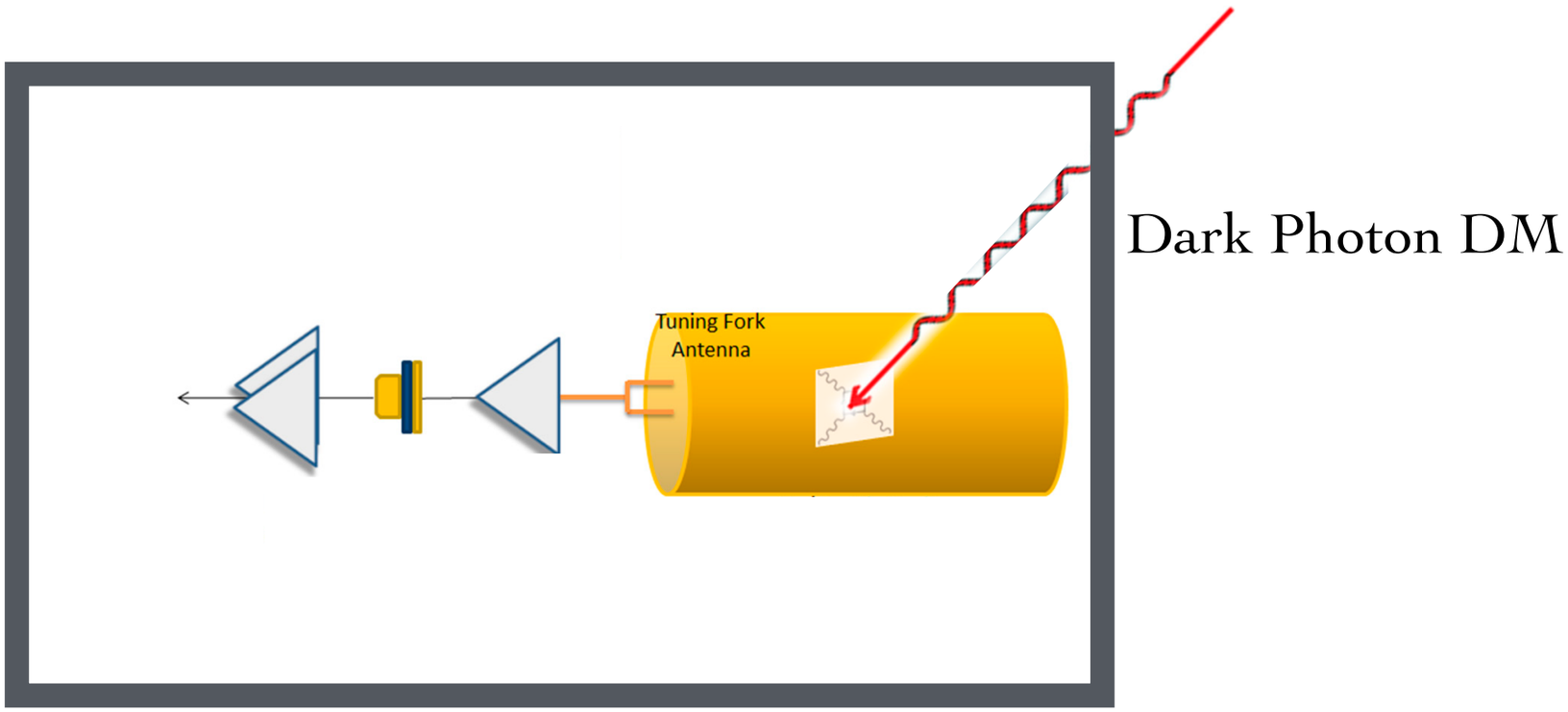


Spin coupling of the axion
axion wind

Dark Photon Dark Matter

Couples similarly to a photon

$$|\vec{E}'| \sim 50 \frac{V}{cm}$$



Moduli Dark Matter

Causes variation of fundamental constants

- Makes the energy splitting of atoms and nuclei oscillate in time
  - Atomic clocks and atom interferometry searches

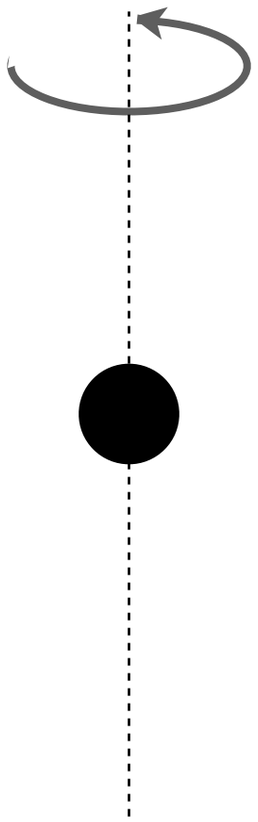
- Makes the size of atoms change in time
  - Resonant mass detectors and oscillator searches

Cosmology-independent signatures of all bosons

Black hole super-radiance

Damour et al; Zouros & Eardley; Detweiler; Gaina (Early 70s)

Arvanitaki, SD, Dubovsky, March-Russell, and Kaloper (2009)
Arvanitaki and Dubovsky (2010)



Particle Compton Wavelength comparable to the size of the Black Hole

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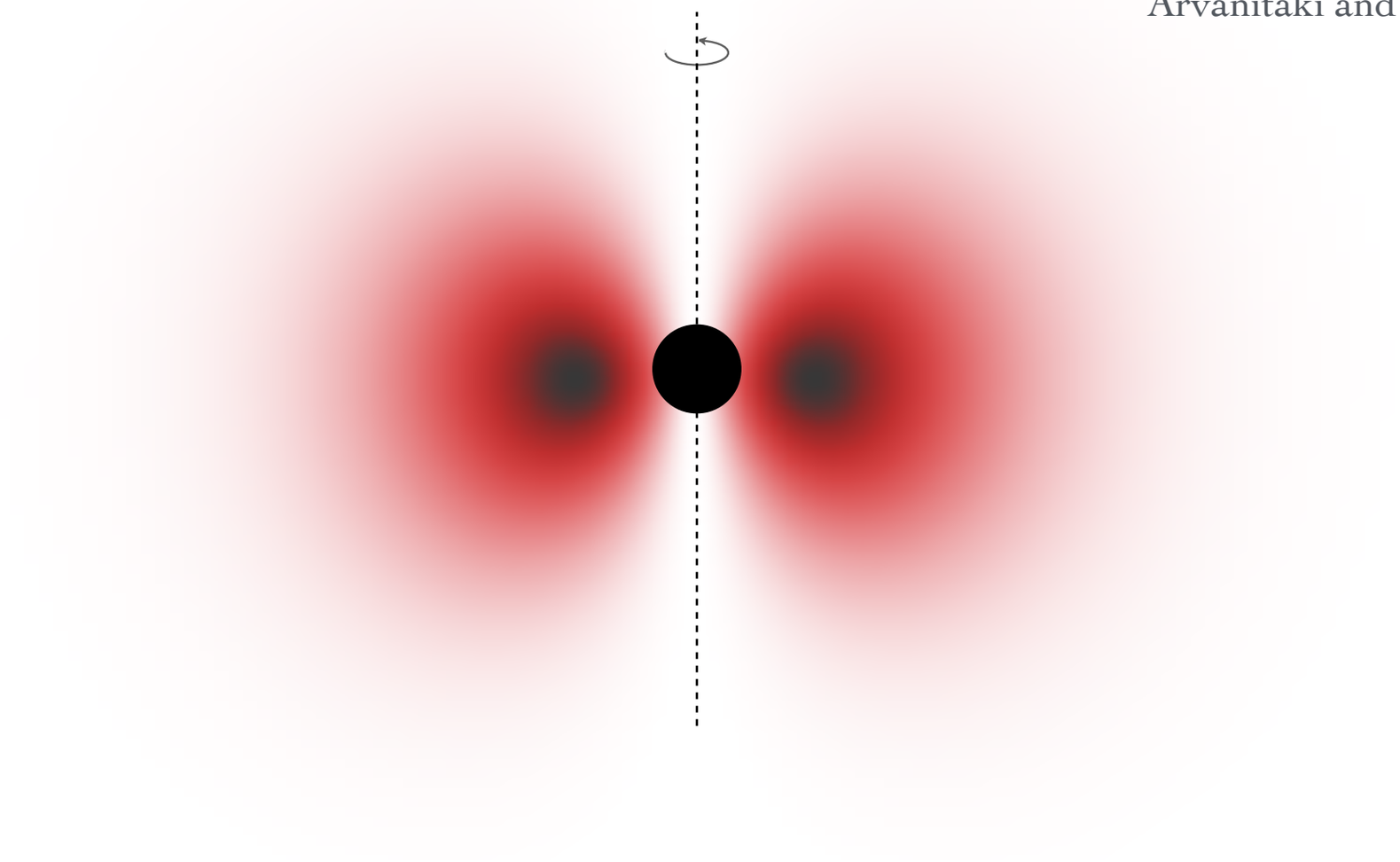

Particle Compton Wavelength comparable to the size of the Black Hole

Summary of Well Motivated Particles in String Theory

New Particle	Comes from	Couples to
Axion and Axion Like Particles	Topology of Extra Dimensions	Spin and Mass density, Light in a background field
Dilatons, Moduli, radion	Geometry of Extra Dimensions	Mass density, Fundamental constants
Dark Photons	Topology of Extra Dimensions	Mixes with the photon
Higher Dimensional Graviton	Extra Dimensions	Just like the graviton

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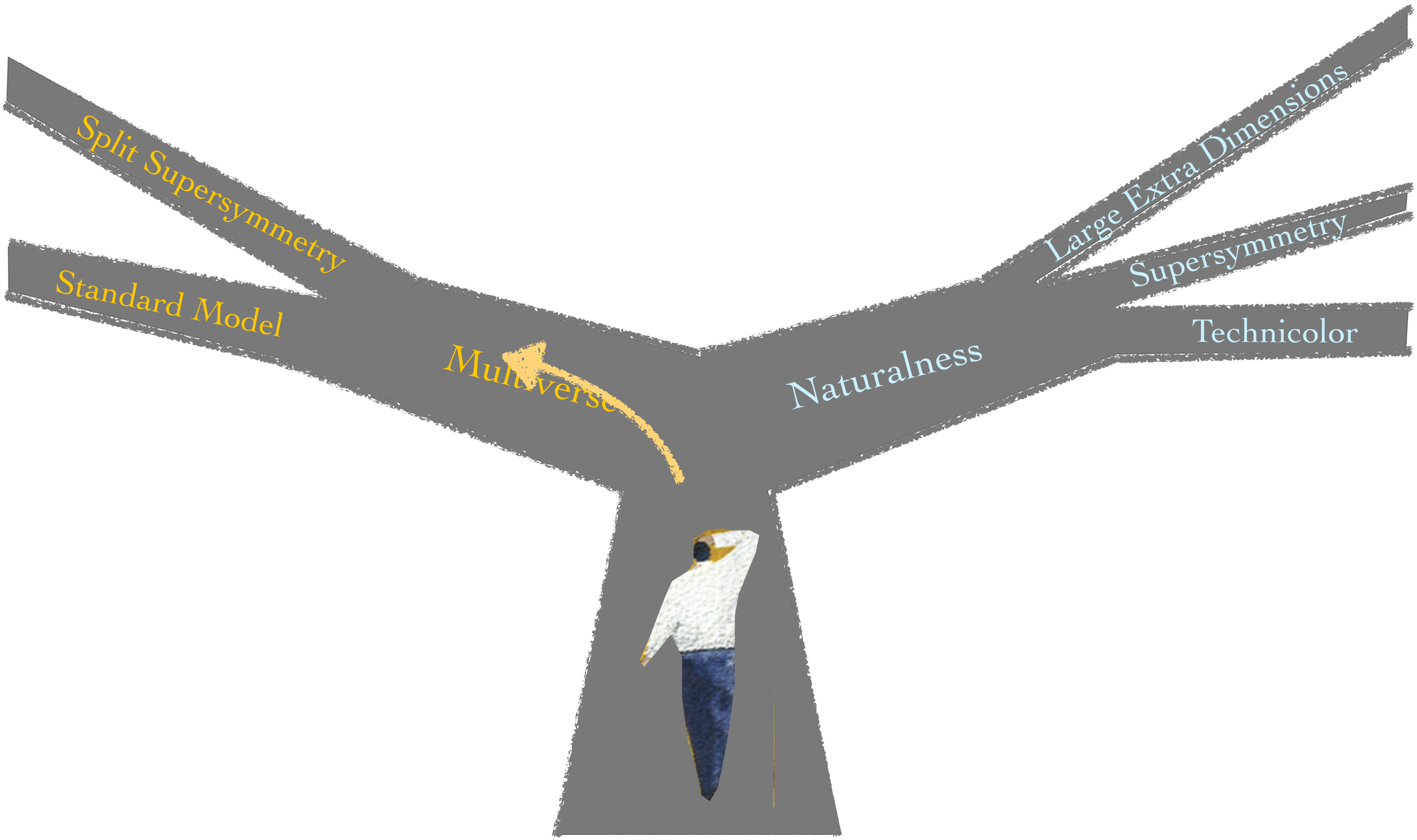
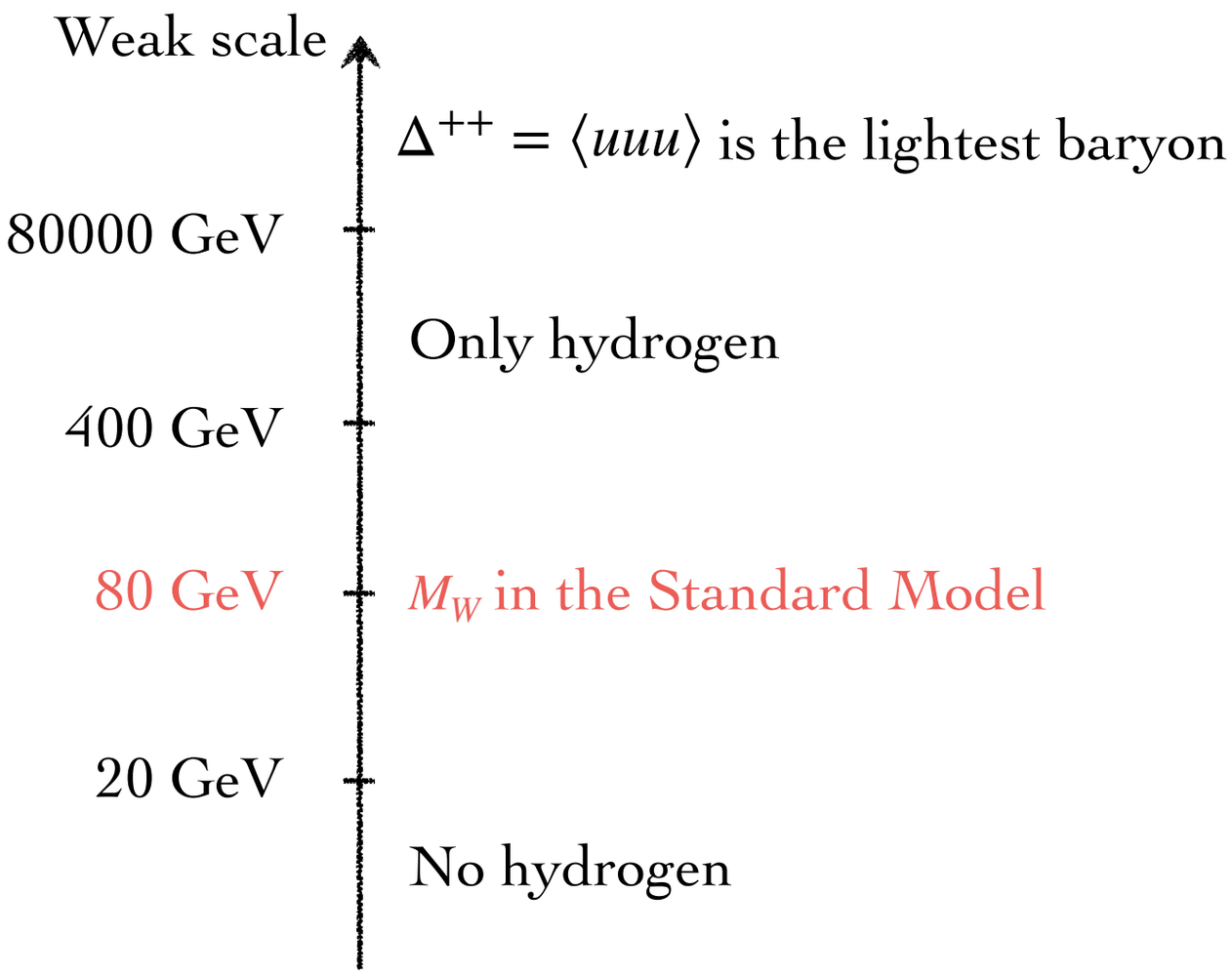
At the Crossroads



Is the weak scale anthropic?

Agrawal, Barr, Donoghue, Seckel 1997



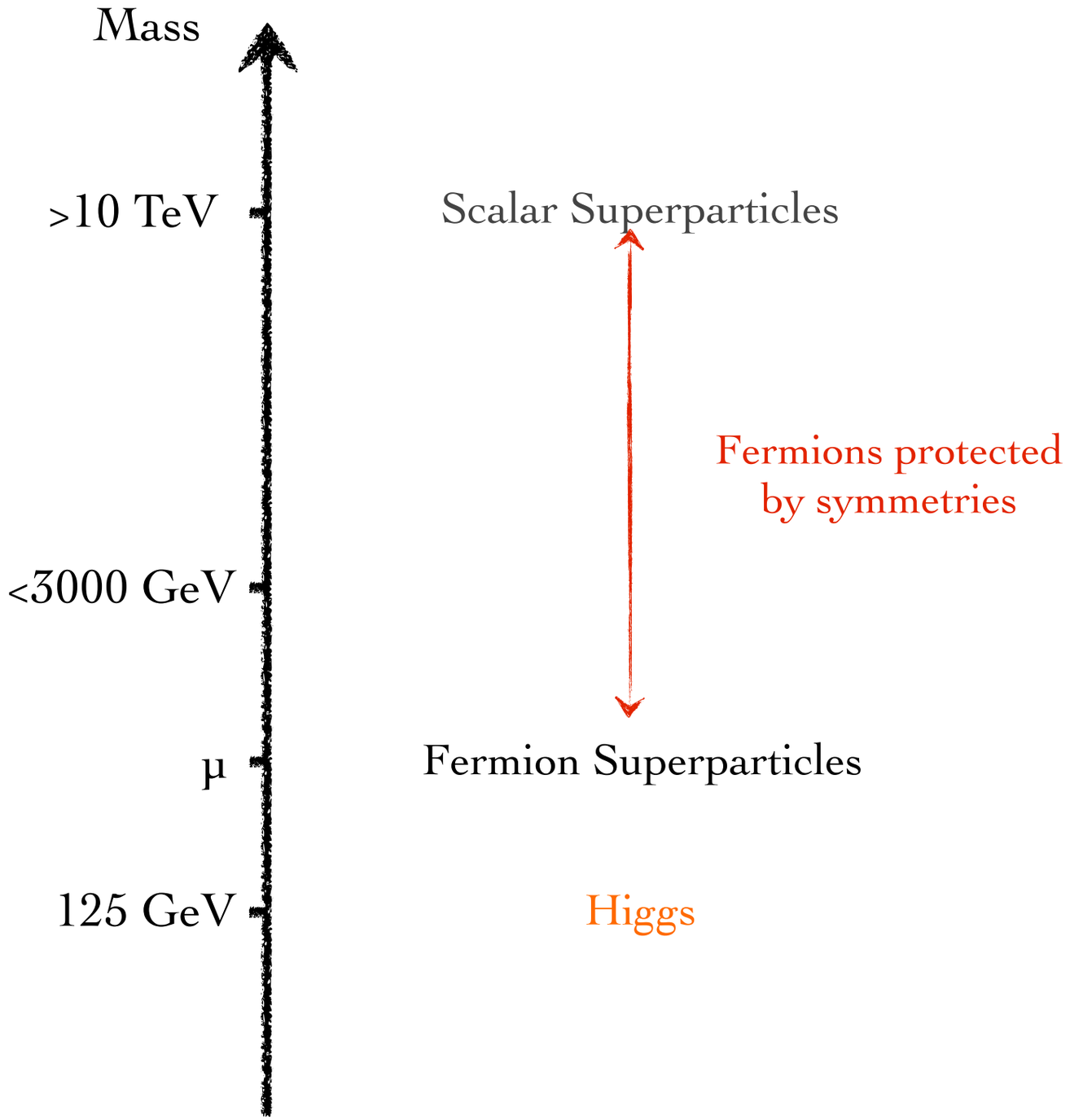
The weak scale is essential for the existence of atoms:
The "Atomic Principle"

Split Supersymmetry

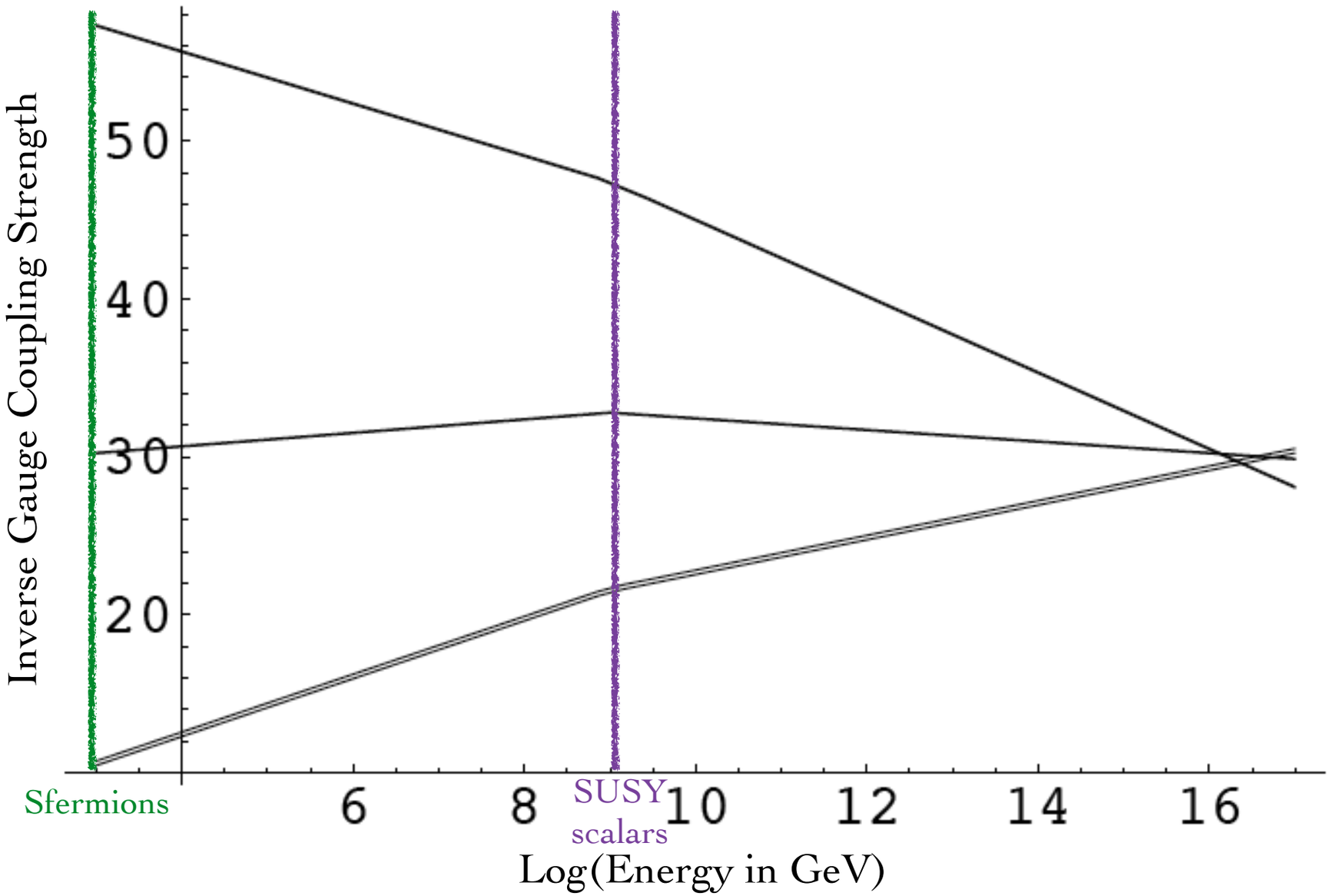
Arkani-Hamed, Dimopoulos (2004)
Giudice, Romanino (2004)

- Preserves successes of Dark Matter and gauge coupling unification

- Atomic Principle: One tuned light higgs



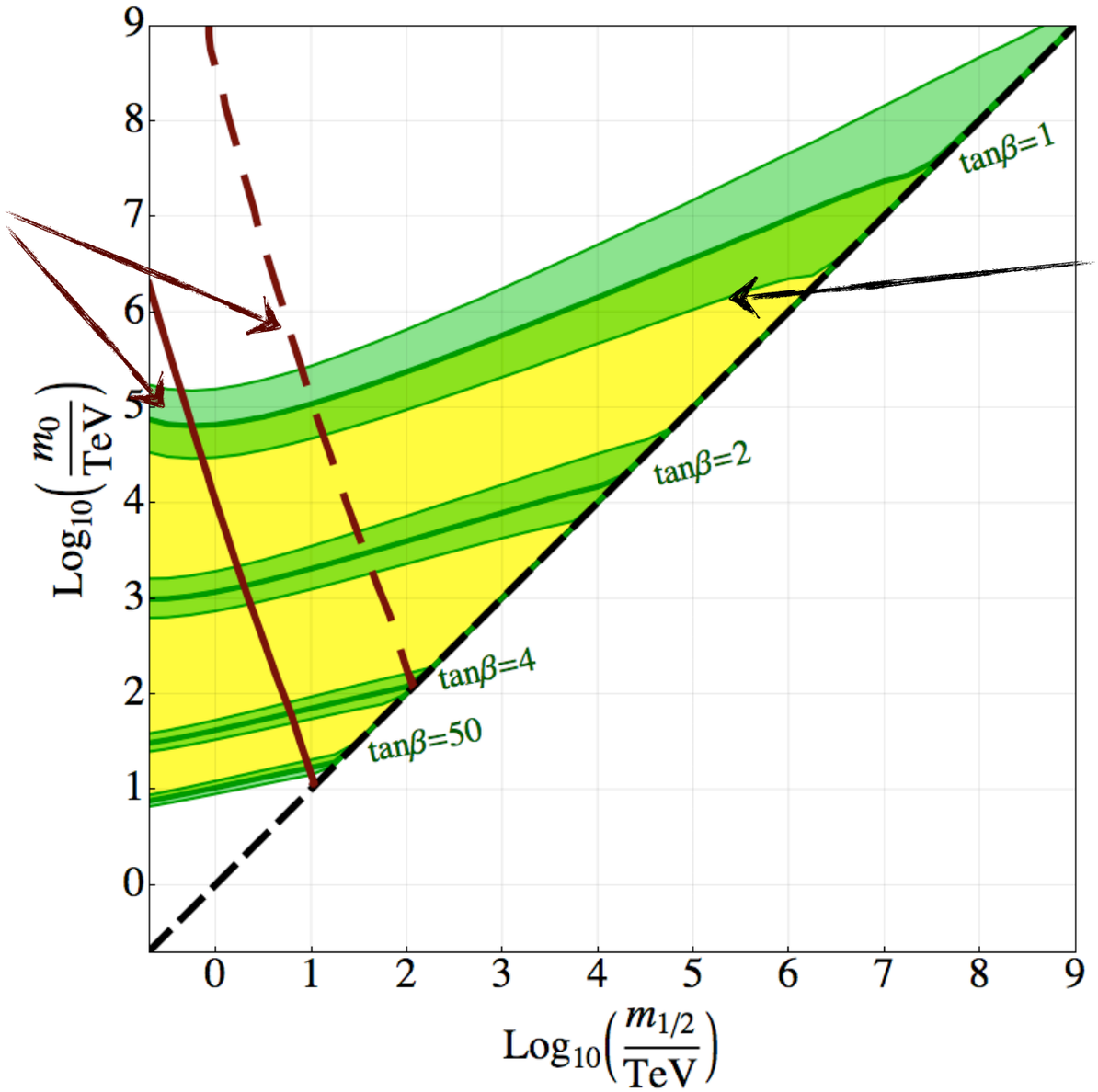
Unification in Split Supersymmetry



Works as well as ordinary Supersymmetry

The 125 GeV Higgs and Unification in Mini-Split

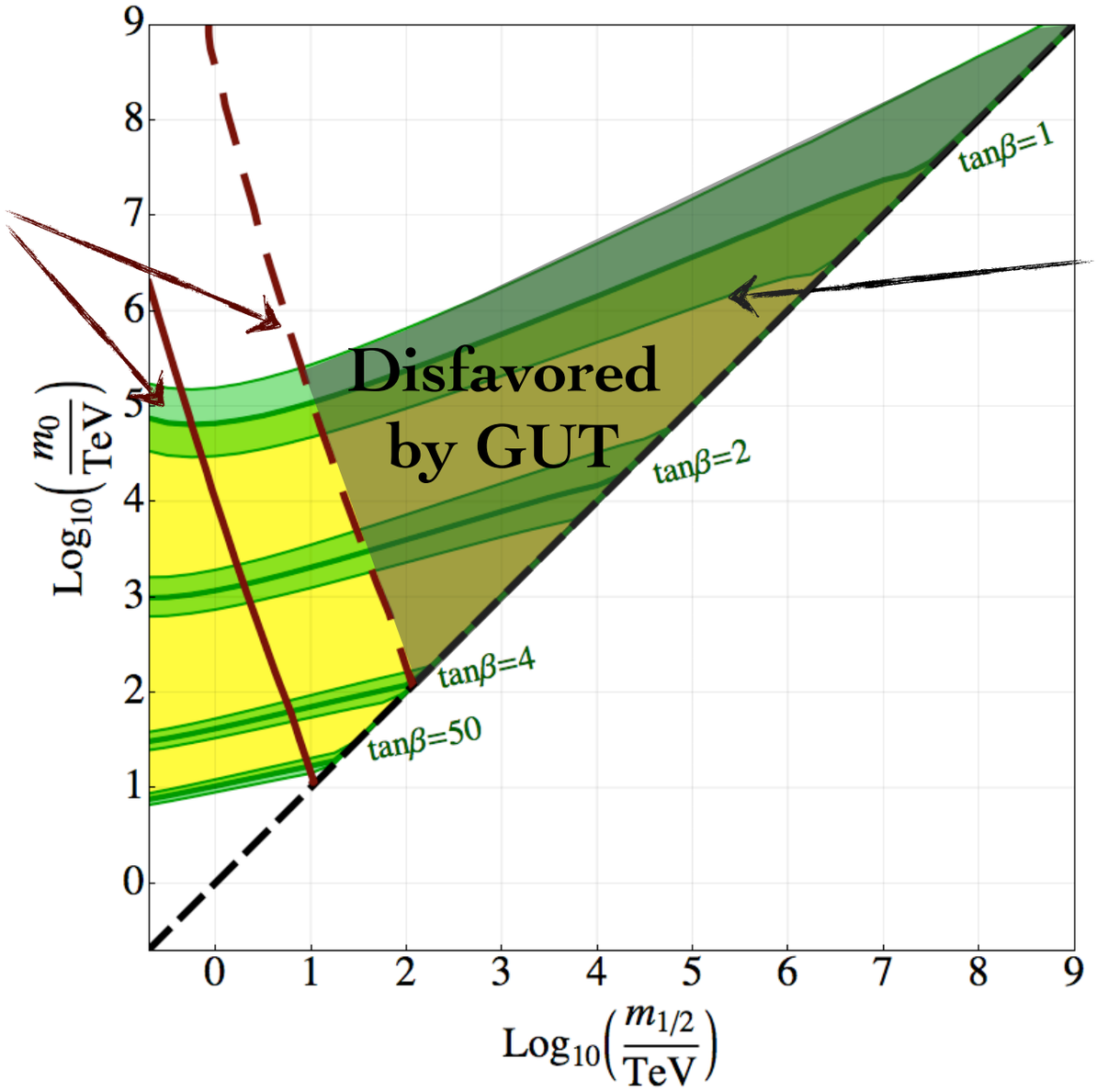
1σ and 2σ contours for unification



Parameter space for 125 GeV Higgs

The 125 GeV Higgs and Unification in Mini-Split

1σ and 2σ contours for unification



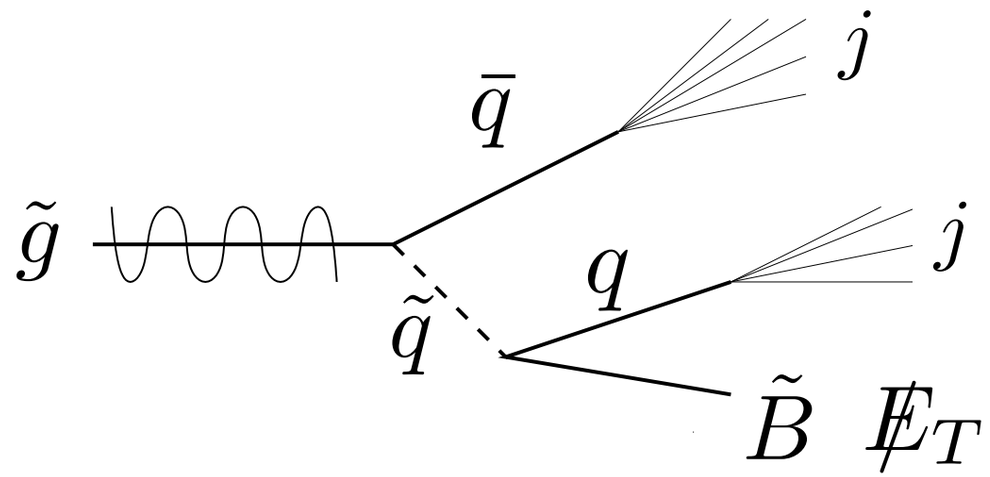
Parameter space for 125 GeV Higgs

- Higgsinos have to be lighter than 100 TeV for Unification

- The measured Higgs mass and gauge coupling unification motivate 100 TeV collider

Long-lived Gluinos

Gluino decay with displaced vertices
though the heavy scalars

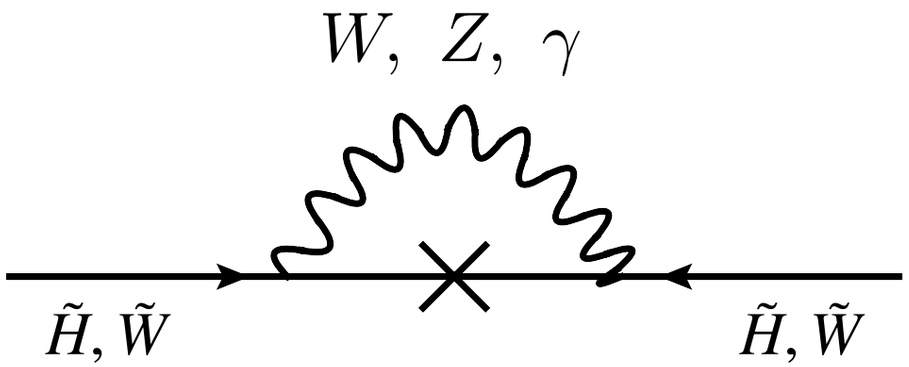


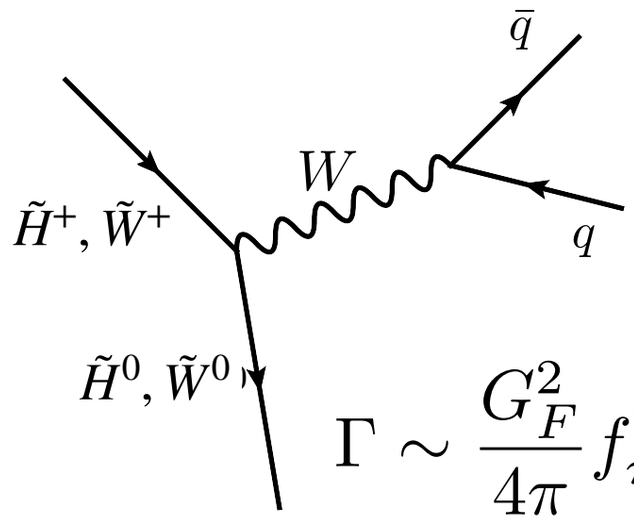
Signature:
2 jets and missing energy

Lifetime:

$$c\tau_{\tilde{g}} \simeq 3 \times 10^{-2}\ \mathrm{m} \left(\frac{1\ \mathrm{TeV}}{m_{\tilde{g}}}\right)^5 \left(\frac{M_{\mathrm{Susy}}}{10^4\ \mathrm{TeV}}\right)^4$$

Displaced Winos and Higgsinos





$$\Gamma \sim \frac{G_F^2}{4\pi} f_\pi^2 \Delta m^3$$

$$\Delta m \sim \frac{\alpha}{4\pi} M_Z$$

$\Delta M_{\tilde{W}} \approx 155 - 175$ MeV $\quad c\tau_{\tilde{W}} \sim 1$ cm

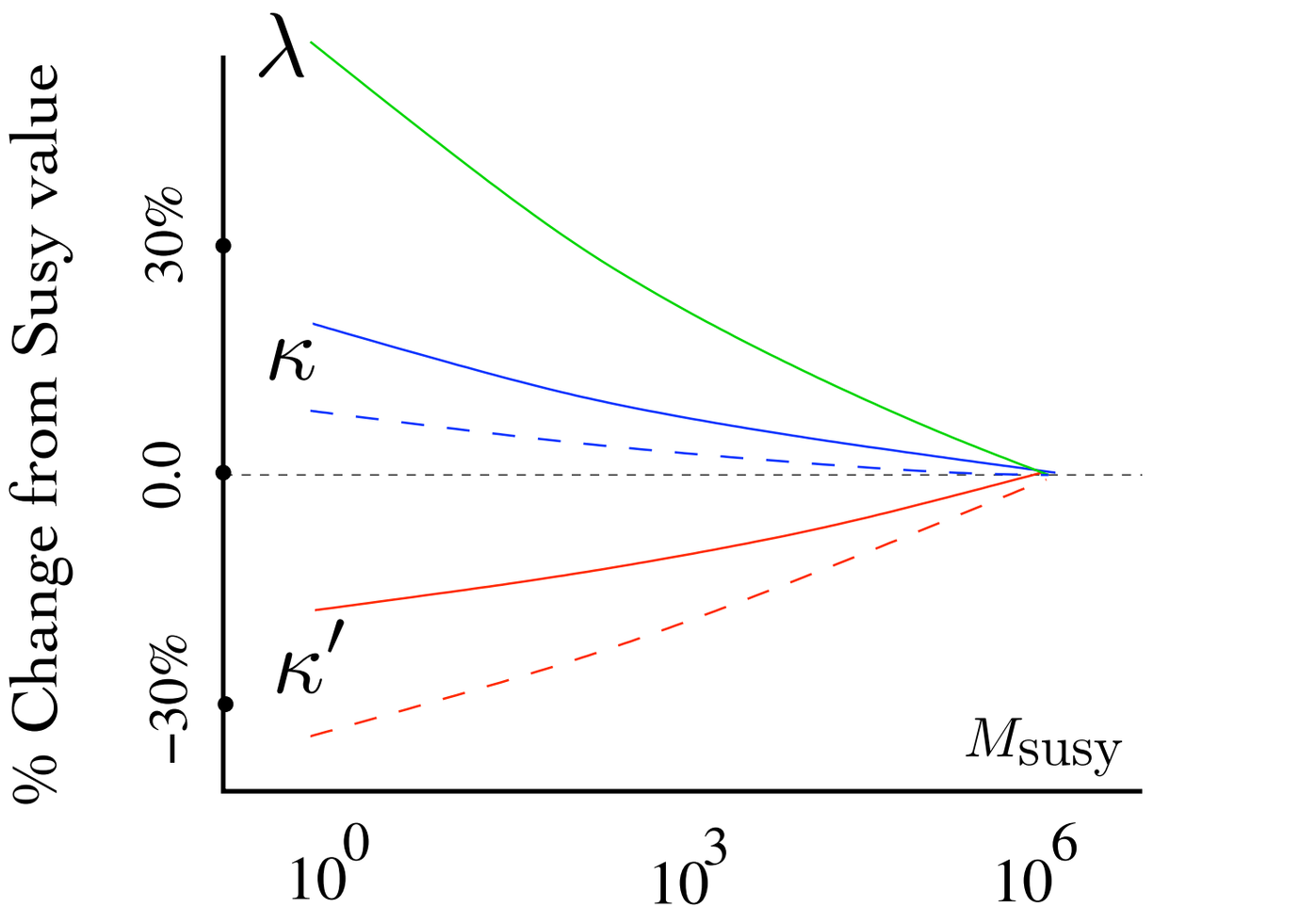
$\Delta M_{\tilde{H}} \approx 355$ MeV $\quad c\tau_{\tilde{H}} \sim 0.1$ cm

- The Wino or Higgsino can be the lightest sparticle

- 3 TeV Winos and 1 TeV Higgsinos remain excellent WIMP DM candidates

Electroweakinos and Higgsinos at the HEC

Gaugino and Higgsino Yukawa Coupling Unification

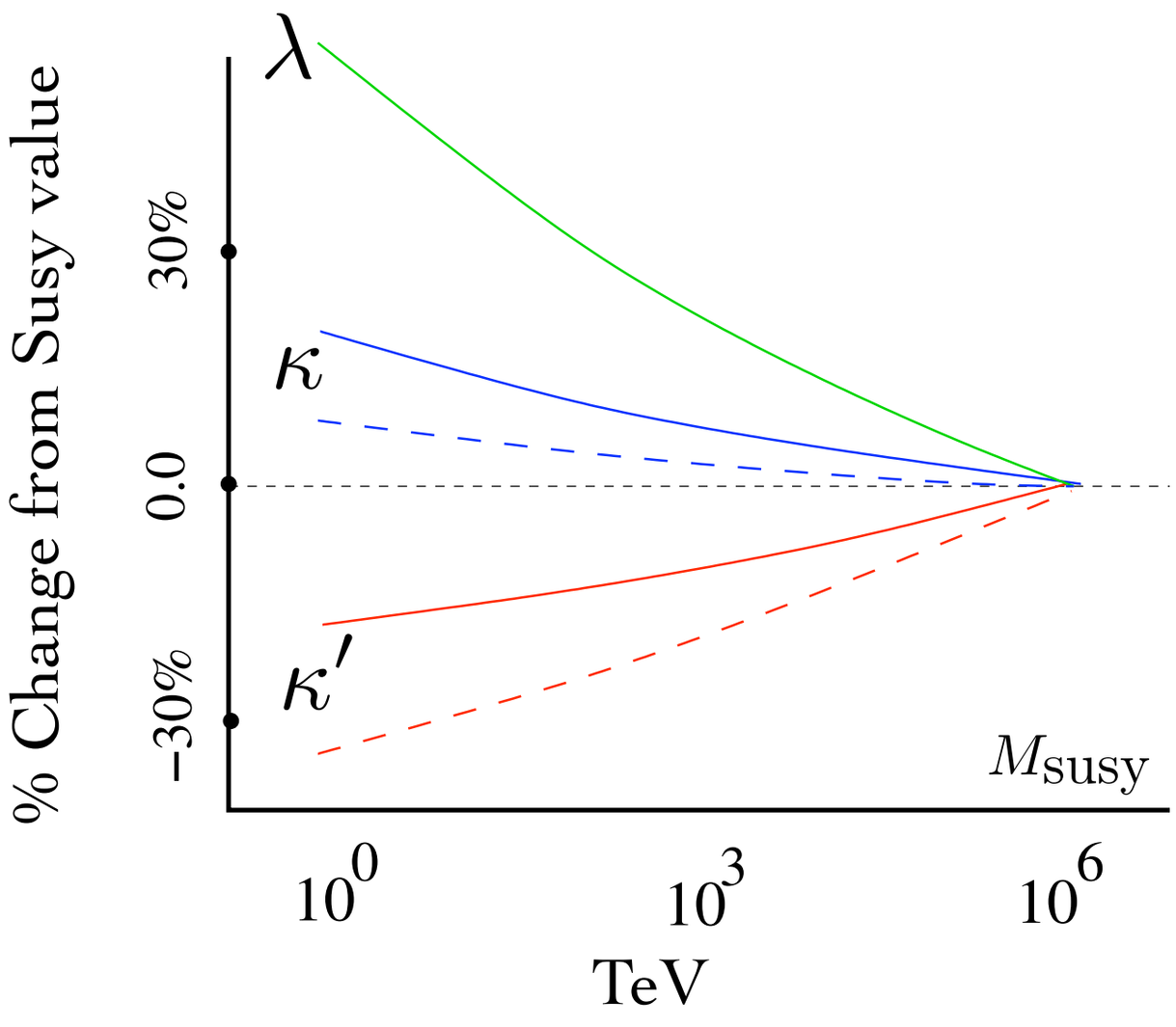


$\kappa_u H \widetilde{H}_u \widetilde{W} + \kappa_d H^\dagger \widetilde{H}_d \widetilde{W}$ $\quad$ $\kappa'_u H \widetilde{H}_u \widetilde{B} + \kappa'_d H^\dagger \widetilde{H}_d \widetilde{B}$

λ: Higgs Quartic

Electroweakinos and Higgsinos at the HEC

Gaugino and Higgsino Yukawa Coupling Unification



Combined with gluino lifetime measurement establishes supersymmetric origin of new particles

Mini-Split Phenomenology

- Displaced Gluinos at the LHC and HEC
- Displaced Winos and Higgsinos at the LHC and HEC
- Yukawa Coupling Unification at a HEC

What could be convincing evidence for the Multiverse?

I. 120 orders of magnitude tuning for the Cosmological Constant

Are we paying the price of ignoring it?

II. Fine tuned electroweak scale

Already problematic with the absence of new physics
at LEP, LHC, FCNCs, EDMs…

III. Two or more light axions or dark photons or moduli etc.

IV. Mini-Split at a High Energy Collider

Optimistic scenario

I. An anomaly gets confirmed

II. Small Scale Experiment or Astrophysical Observation discovery

III. High Luminosity LHC discovery

IV. A Zillionaire finances a Supercollider

V. Magnet technology development leads CERN to prioritize ~30 TeV collider in present tunnel and within ~10 years?!

Far from being untestable the Multiverse opens many opportunities for discoveries in novel small-scale, astrophysics, and collider experiments,