Beyond the Standard Model

Part I

Kwang Sik JEONG

Pusan National University, Korea

26th Vietnam School of Physics

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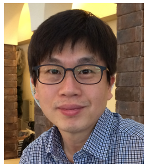
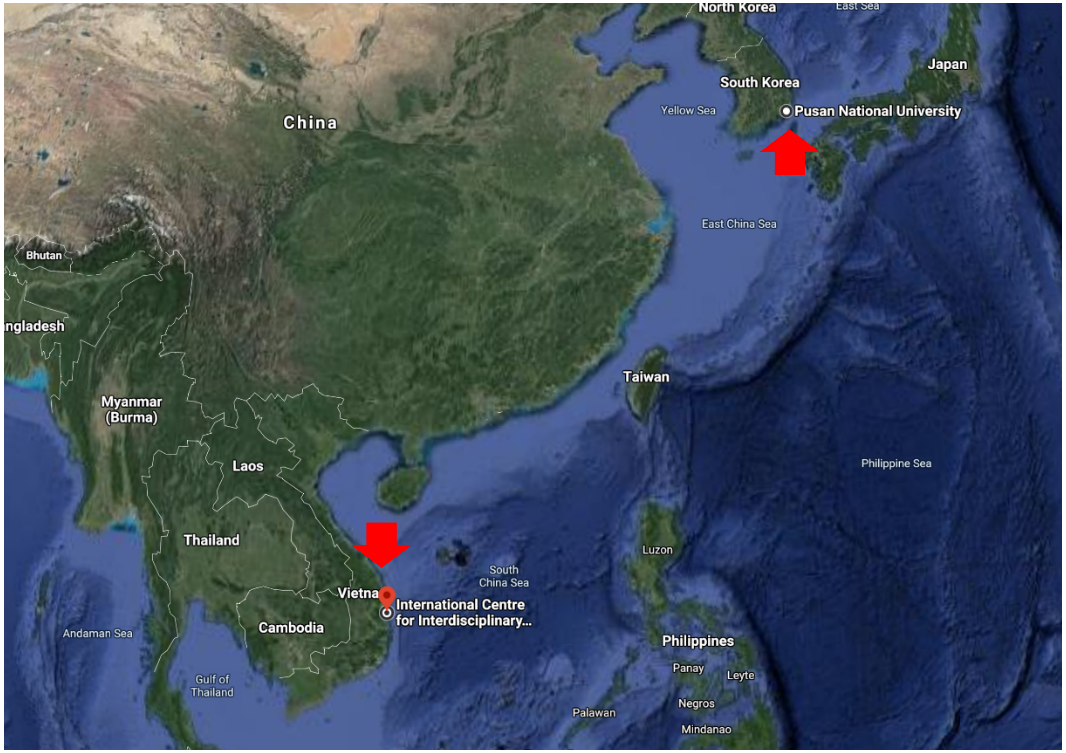




Lectures on BSM

- Why BSM?
- Axionic Extension
- Supersymmetric Extension

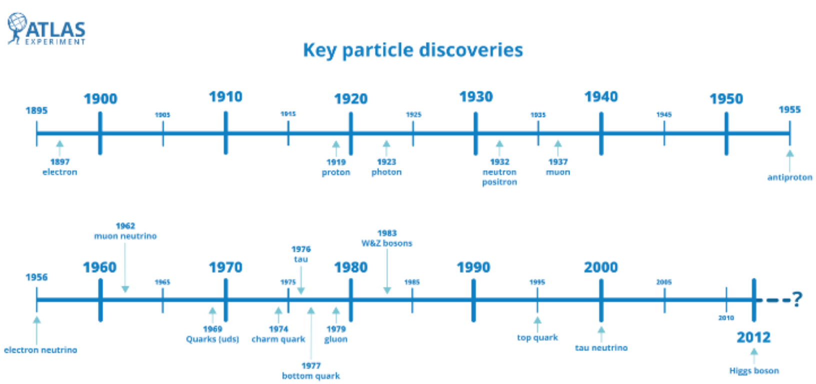
Lecture on SM by Cao Hoang Nam

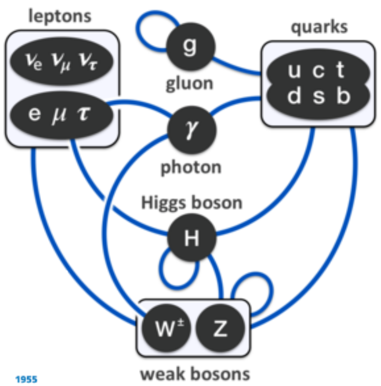
Standard Model

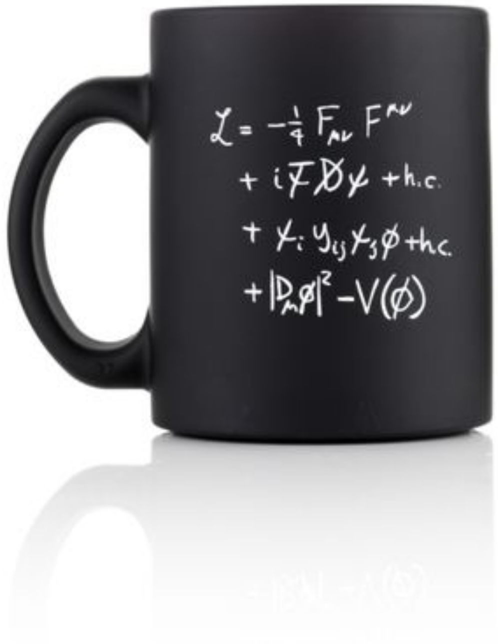
Theoretical Description of Nature

Standard Model of Particle Physics

- Successful at energy scales below TeV
  - 3 gauge symmetries: electromagnetic, weak, strong forces
  - 2 accidental global symmetries: B and L number stable proton, massless neutrinos
  - So far, all the collider measurements are in good agreement with SM predictions

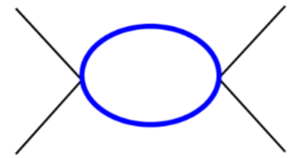






1-1. Introduction- SM

- Quantum Field Theory
  - Framework to describe elementary particles and their interactions
  - Theory: Action + Regularization + Renormalization



divergence in loop diagrams

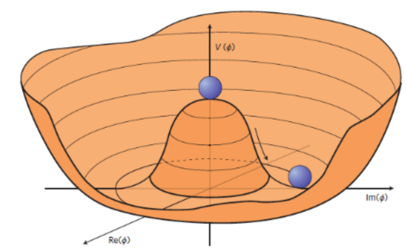
  - Symmetry: ΔS =(path-independent)

$$\langle \text{final}|\text{initial}\rangle = \int DA_\mu D\phi D\bar{\psi} D\psi \; e^{iS[A_\mu,\phi,\bar{\psi},\psi]}$$

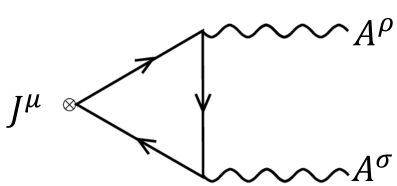
- Poincare symmetry: mass, spin
- Internal symmetry: charge

Symmetry breaking

- Spontaneous breaking: the ground state is not symmetric
- Anomaly: Breaking by quantum effects



due to fermions with chiral symmetry coupled to gauge fields



$$\Rightarrow \Delta L = \frac{c_\psi}{32\pi^2} F^{\mu\nu}\tilde{F}_{\mu\nu}$$

total derivative → relevant nonperturbatively

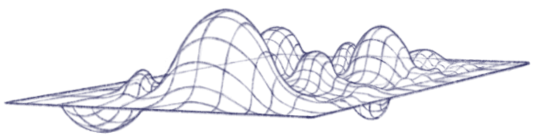
e.g. $B+L$ is anomalous under electroweak

gauge anomaly ↛ unitarity and renormalizability

Physical objects from fields

- Point-like particles elementary excitations

  Small linear perturbations of fields around the ground state

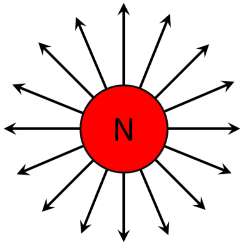


- Solitons

  Solution of the classical field equation $\delta S = 0$

  - Lumps of fields of finite size
  - Similar to particles, but without quantization
  - Existence and stability due to non-linearity of the field eqs

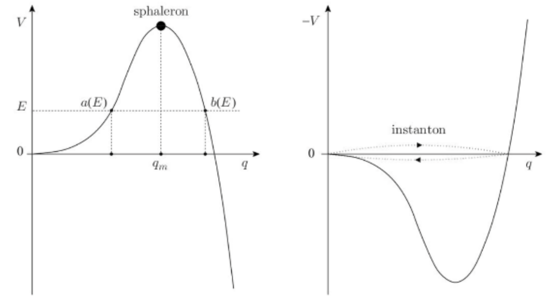
  e.g. magnetic monopole, domain wall, cosmic string, ...



(size) $\sim \frac{1}{m}$

(energy) $\sim \frac{m}{g}$

1-1. Introduction- SM



- **Instantons**

  Localized, finite-action solution of the Euclidean field eqs

  - Wick rotation $it \to \tau$

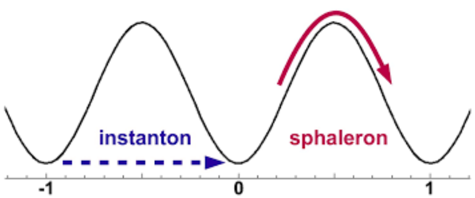
  $$S = \int dt \left(\frac{1}{2} m \left(\frac{dq}{dt}\right)^2 - V(q)\right) \to iS_E = \int d\tau \left(\frac{1}{2} m \left(\frac{dq}{d\tau}\right)^2 + V(q)\right)$$

  - Tunneling between quantum systems
  - Decay of a false vacuum by bubble nucleation

- **Sphalerons**

  Static, unstable, and finite-energy solution of the classical field eqs

  - Classical transition between vacua
  - Possible at high energy scales



Non-Abelian gauge theory: topologically non-trivial vacuum structure with an infinite number of ground states Chern-Simons number

Instantons → anomaly has physical effects

SM as Low Energy Effective Theory

- UV theory with renormalizable local operators

$$L = L_H(\phi_H, \phi_L) + L(\phi_L)$$

where ϕ_H (ϕ_L) are fields describing heavy (light) particles above (below) Λ

- Effective theory of light fields
  - Obtained by integrating out heavy fields: $\int D\phi_H D\phi_L e^{iS[\phi_H,\phi_L]}$
  - Below the cutoff scale Λ

$$L_{\text{eff}} = L(\phi_L) + \sum_{n,i} \frac{c_i^{(n)}}{\Lambda^{n-4}} O_i^{(n)}(\phi_L)$$

Dimensionless Wilson coefficients $c_i^{(n)}$

- Effects of heavy particles and high energy modes

- Effective theory of light fields
  - Contribution of the local operator $O_i^{(n)}$ to a process at energy scale $E \ll \Lambda$

$$c_i^{(n)} \left(\frac{E}{\Lambda}\right)^{n-4}$$

$n < 4$: relevant

$n = 4$: marginal

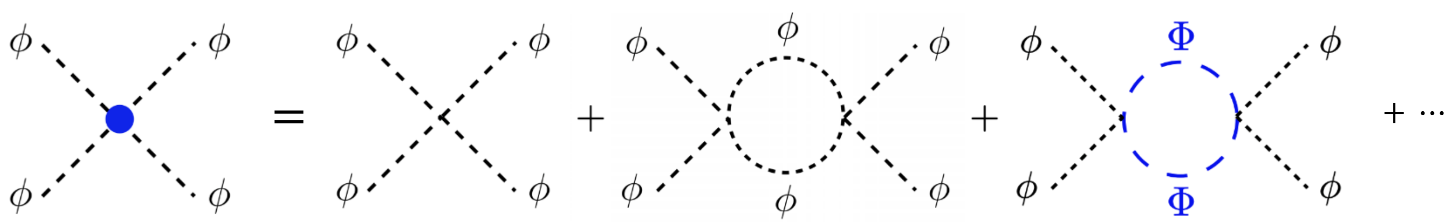
$n > 4$: irrelevant (non-renormalizable)

- Matching adjustment of coefficients

  Same physical predictions at low energy scales

$$\lambda_{\text{eff}}(\mu) = \lambda_{\text{full}}(\mu) + (\text{threshold corrections})$$

e.g.



- For a case of strongly coupled theory

  - Effective theory of relevant degrees of freedom e.g. hadrons in QCD

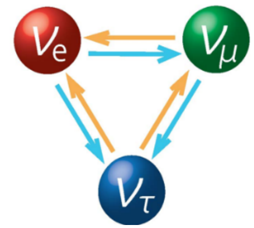
Why Beyond the SM?

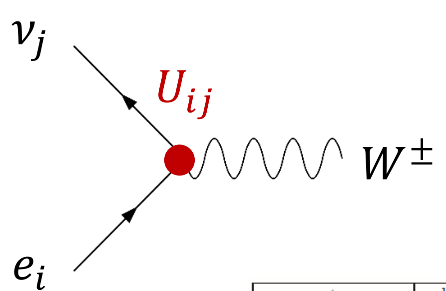
Experimental Evidences

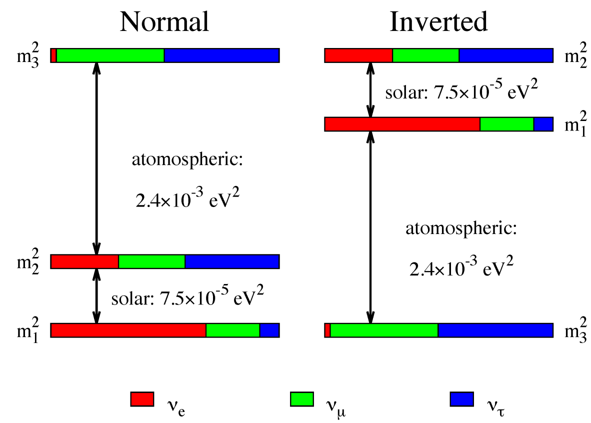
Physics beyond the Standard Model

Experimental evidences

- Neutrino Masses and Mixing
  - Neutrino oscillation experiments
  - Weak eigenstate = mixture of mass eigenstates







sign of from matter effects →

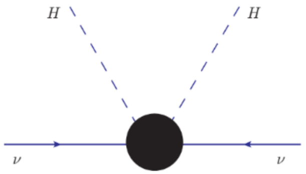
parameter	best fit $\pm1\sigma$	2σ	3σ
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.59^{+0.20}_{-0.18}$	7.24–7.99	7.09–8.19
Δm^2_{31} $[10^{-3}\text{eV}^2]$	2.45 ± 0.09 $-(2.34^{+0.10}_{-0.09})$	$2.28 - 2.64$ $-(2.17 - 2.54)$	$2.18 - 2.73$ $-(2.08 - 2.64)$
$\sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$	0.28–0.35	0.27–0.36
$\sin^2\theta_{23}$	0.51 ± 0.06 0.52 ± 0.06	0.41–0.61 0.42–0.61	0.39–0.64
$\sin^2\theta_{13}$	$0.010^{+0.009}_{-0.006}$ $0.013^{+0.009}_{-0.007}$	≤ 0.027 ≤ 0.031	≤ 0.035 ≤ 0.039

Cosmological observations

$\sum m_\nu < 0.1$ eV

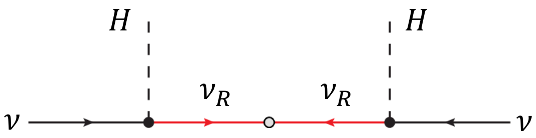
❖ Neutrinos are massless in the SM

- **Neutrino Masses and Mixing**



How to generate tiny neutrino masses?

- Majorana $\nu = \bar{\nu}$ $(\Delta L = 2)$
  - Seesaw mechanism: $L = y\,\bar{\ell}_L \tilde{H} \nu_R + \frac{1}{2} M_R \overline{\nu_R} \nu_R^c \;\rightarrow\; L_{eff} = \frac{y^2}{M_R} (\bar{\ell}_L \tilde{H})(\tilde{H}^T \ell^c)$

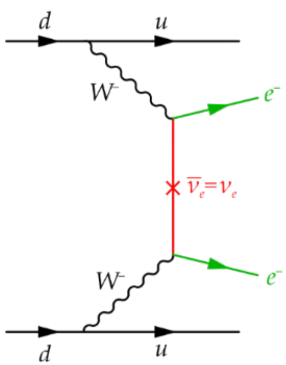


$$m_\nu \simeq \frac{y^2 \langle H \rangle^2}{M_R} \sim 0.1\text{eV}$$

seesaw scale: $M_R \sim y^2 \times 10^{14}$GeV

- Dirac $\nu \neq \bar{\nu}$ $(\Delta L = 0)$
  - Tiny Yukawa coupling: $L = y\,\bar{\ell}_L \tilde{H} \nu_R \;\rightarrow\; m_\nu = y\langle H \rangle \sim 0.1$eV

$\beta\beta 0\nu$ to test Majorana nature of neutrino:

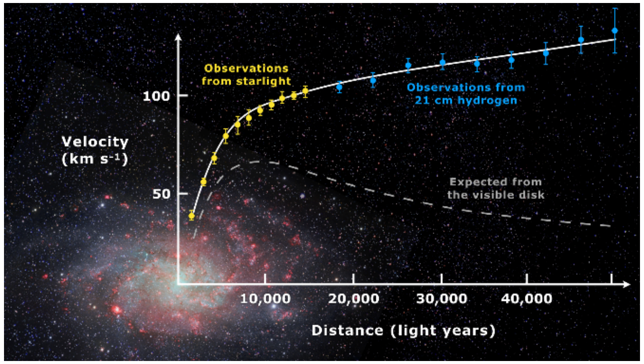


- Dark Matter

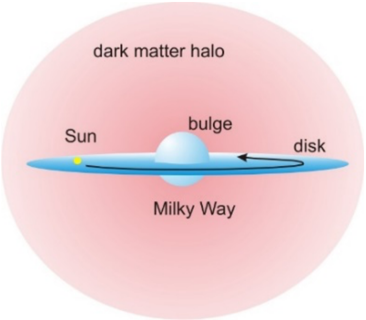
Lecture on DM by Kakizaki

Non-baryonic cold dark matter

- Observed motions of stars and galaxies
- Mass distribution measured with gravitational lensing



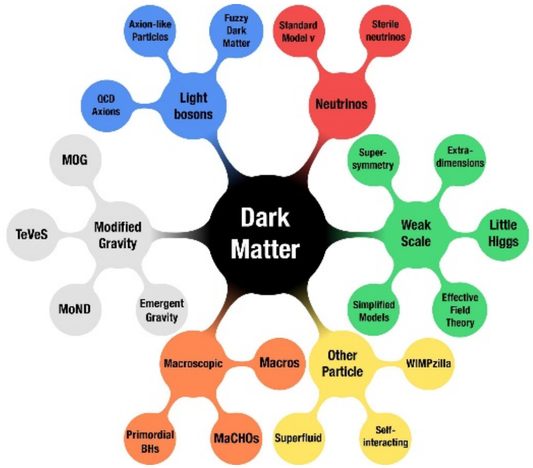
Rotation curve of galaxy



Bullet cluster: gravitional lensing + X-ray

❖ No candidate for cold dark matter in the SM

- Dark Matter
  - Various models in a broad range of masses
    - Stability + Production mechanism
  - Active researches on dark matter detection strategy

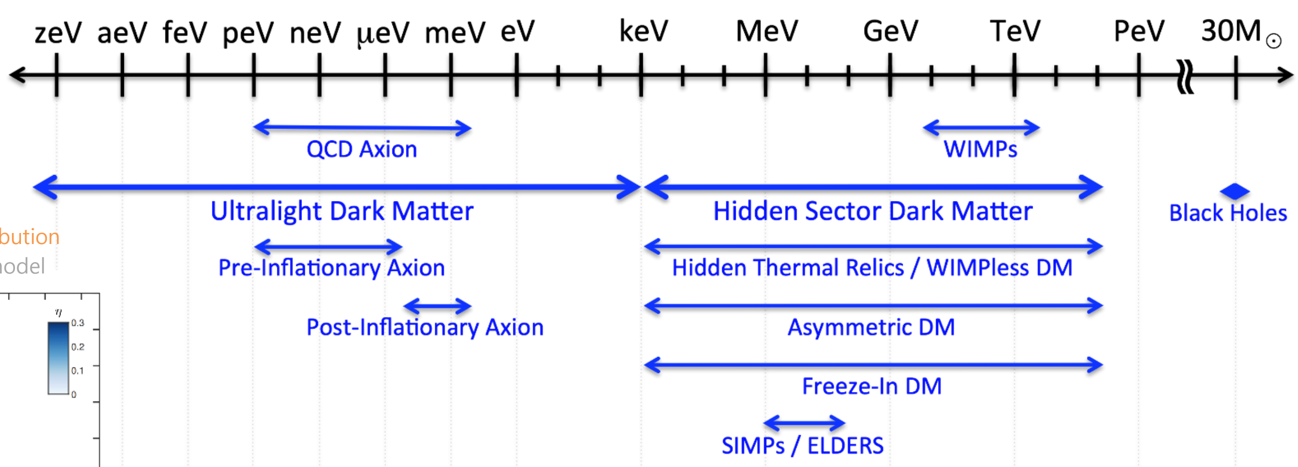


Dwarf galaxies

- Bosonic: de Broglie wavelength < kpc ⇒ heavier than 10^{-22}eV

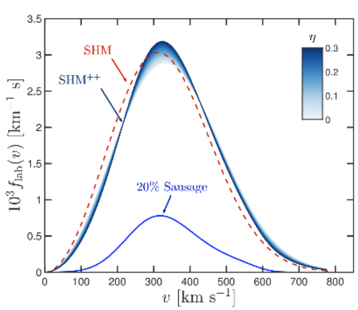
- Fermionic: phase space density limit by Pauli exclusion principle ⇒ heavier than about keV

If once thermalized: structure formation ⇒ heavier than keV



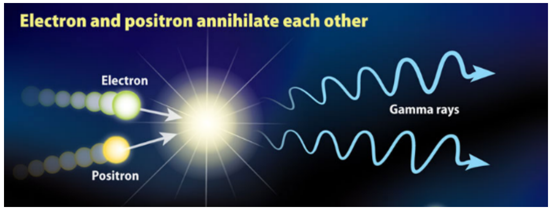
DM velocity distribution

Standard halo model

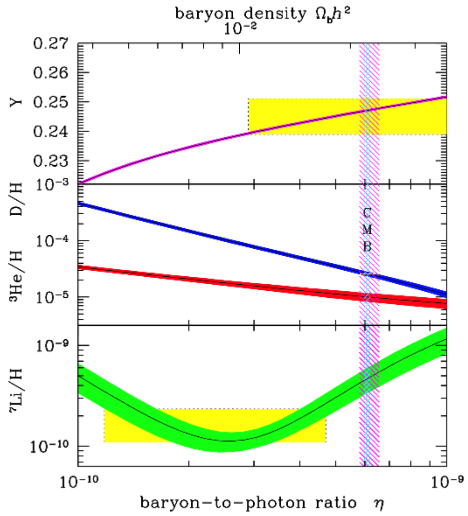


Evans, O'Hare, McCabe

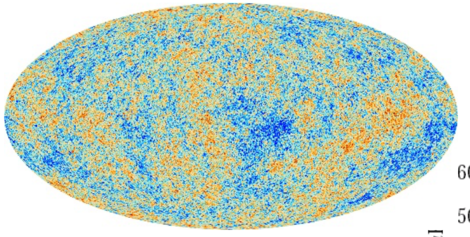
- Baryon Asymmetry
  - Non-observation of gamma ray burst from matter-antimatter annihilation



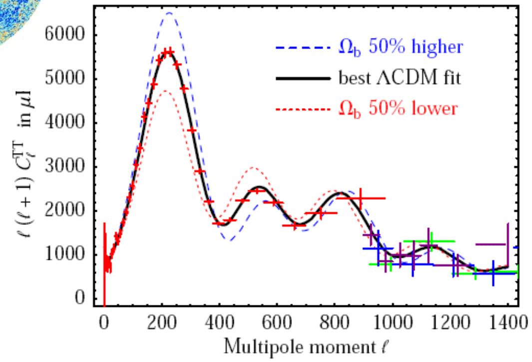
  - Big Bang Nucleosynthesis: abundance of light elements
  - Cosmic Microwave Background: sound speed of baryon-photon fluid



deuterium
helium-3,4,
lithium-7



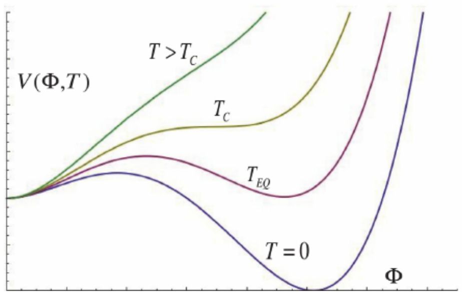
temperature anisotropy (angular scale)

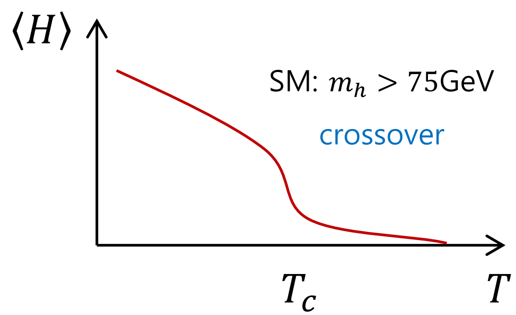


Sakharov conditions in CPT conserving background

❖ Baryogenesis requires B violation, C and CP violation, and B violating interactions out of thermal equilibrium ← Not enough in the SM

- **Baryon Asymmetry**
  - Electroweak phase transition: (free potential) = V +(thermal effects)





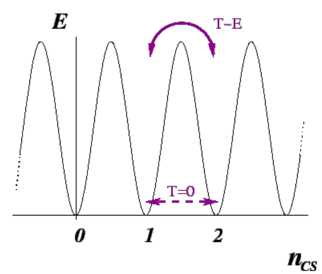
$$\Delta V_{\rm TH} \simeq \frac{1}{2} C_h T^2 h^2 - \frac{2}{3} E_h T h^3$$

$$C_h \simeq \frac{2m_W^2 + m_Z^2 + 2m_t^2}{4v^2} \simeq 0.16$$

$$E_h \simeq \frac{3(2m_W^3 + m_Z^3)}{8\pi v^3} \simeq 1.4 \times 10^{-2}$$

- Last period affecting baryon asymmetry

$B + L$ violation by rapid EW sphaleron transition in symmetric phase



- Baryogenesis scenarios
  - $B - L$ generation above the weak scale: Leptogenesis, Affleck-Dine, …
  - $B + L$ generation at the weak scale and rapid sphaleron decoupling:

    Electroweak baryogenesis c.f. electron EDM bound from ACME II

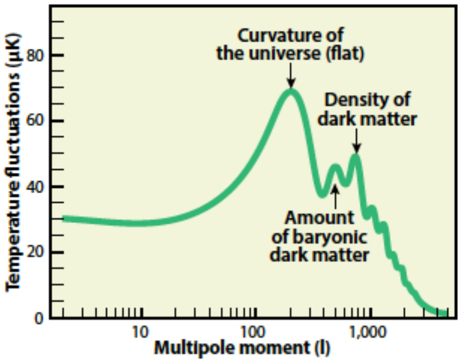
- **Cosmological Inflation**

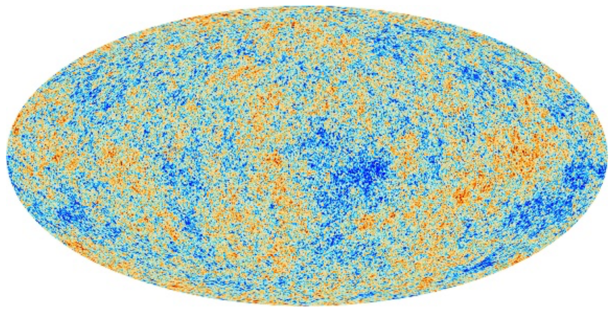
Exponential expansion & reheating in the early universe for the standard hot Big Bang model

- Homogeneous and isotropic universe on large scales
- Nearly scale-invariant, Gaussian density perturbations

power spectrum of density perturbation

$\log_k P_\rho(k) \sim 1$



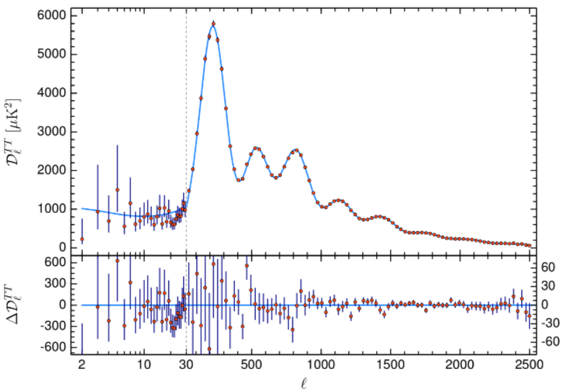


$\frac{\delta T}{T} \sim 10^{-5}$

sourced by density fluctuations

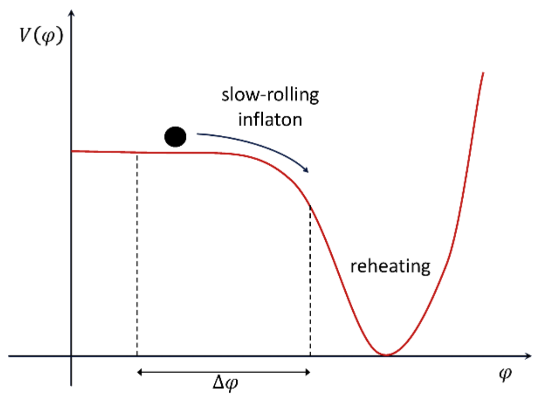
Temperature power spectrum

Planck 2018



❖ Difficult to implement inflation in the SM

- Cosmological Inflation
  - Slow-roll inflation



- Inflation during slow-roll era with $\epsilon \ll 1$ and $|\eta| \ll 1$

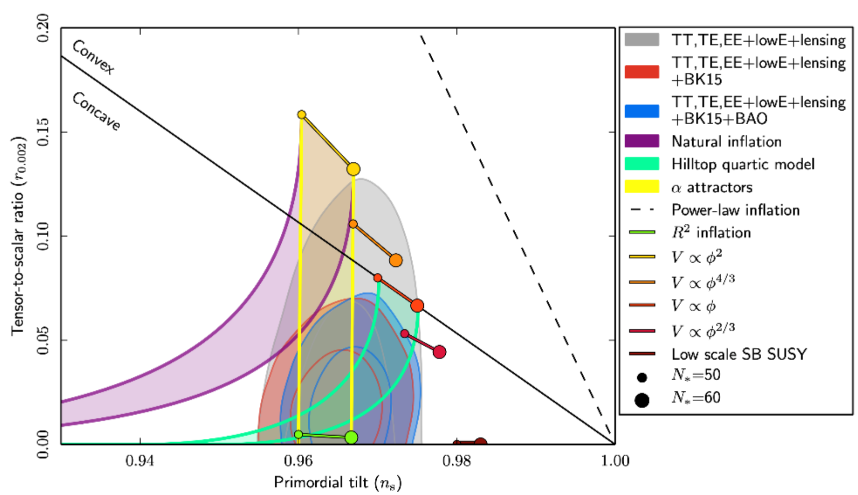
$$\epsilon \equiv \frac{1}{2} M_{Pl}^2 \left(\frac{V'}{V}\right)^2, \qquad \eta \equiv M_{Pl}^2 \frac{V''}{V}$$

- Coherent oscillations of inflaton to convert energy to SM particles → Reheating

- Planck constraints

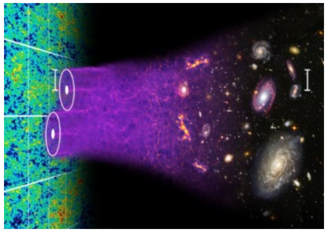
$$n_s \approx 1 + 2\frac{V''}{V} - 3\left(\frac{V'}{V}\right)^2$$

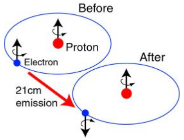
$$r = \frac{A_t}{A_s} \approx 8\left(\frac{V'}{V}\right)^2$$



1-2. Why BSM? Observational Hints

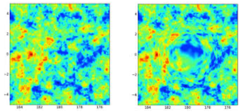
- **Content of the universe**
  - Baryon acoustic oscillations: power spectrum of galaxy fluctuations
  - Large scale structures: 21cm, Lyα, CMB lensing, galaxy clustering, …



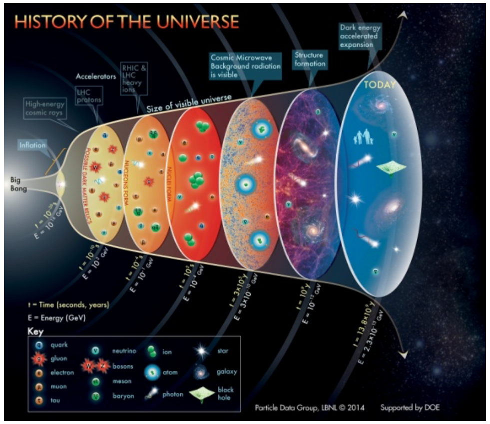


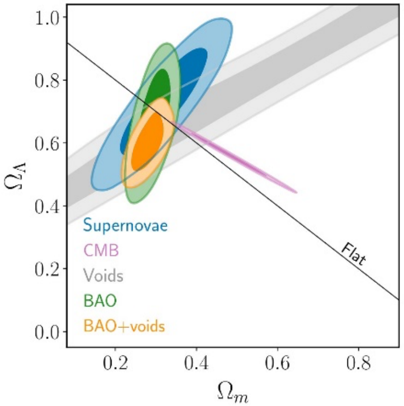
hyperfine transition of HI

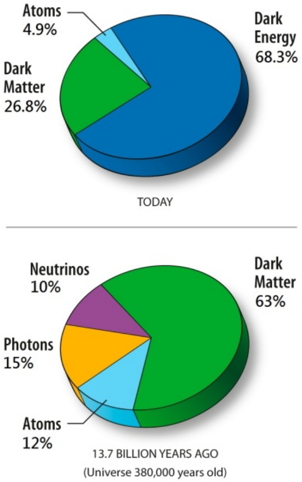
Lyman α transition of HI

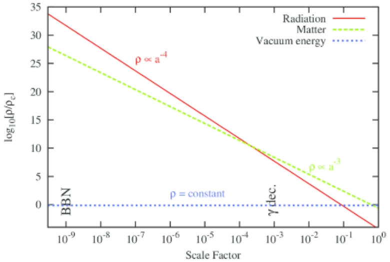


  - Supernovae probe of the cosmological expansion









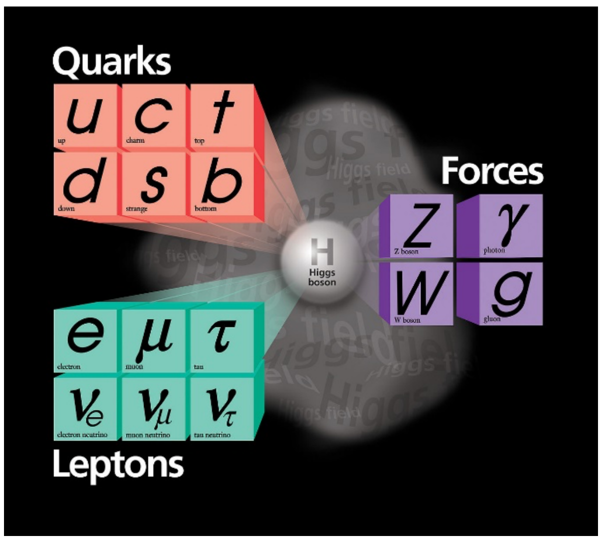
Why Beyond the SM?

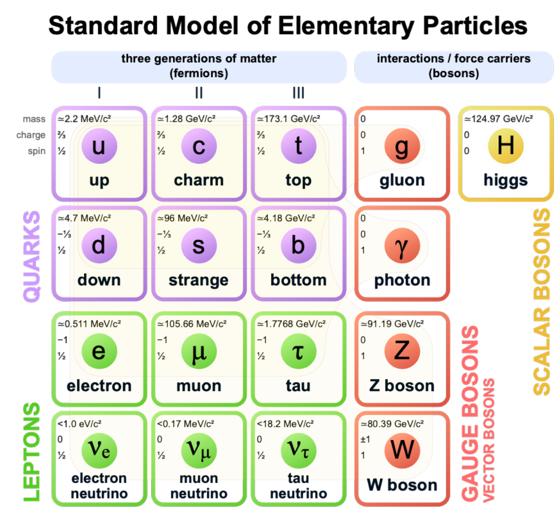
Theoretical Puzzles

- Standard Model Lagrangian

$$\boxed{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}}+\boxed{|D_\mu H|^2 - V(H)}+\boxed{i\bar{\psi}\sigma^\mu D_\mu\psi + y_{ij}H\psi_i\psi_j}$$

Gauge sector | Higgs sector | Fermion sector





Physics beyond the Standard Model

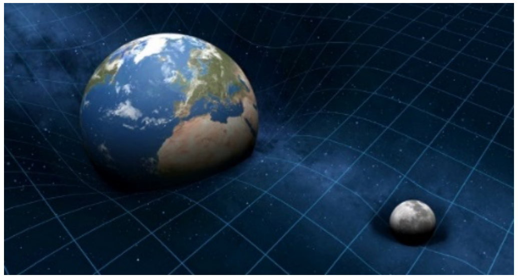
Theoretical Puzzles

- Quantum Gravity
  - General relativity

    - gravity = spacetime curvature

quantized

$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu}$$



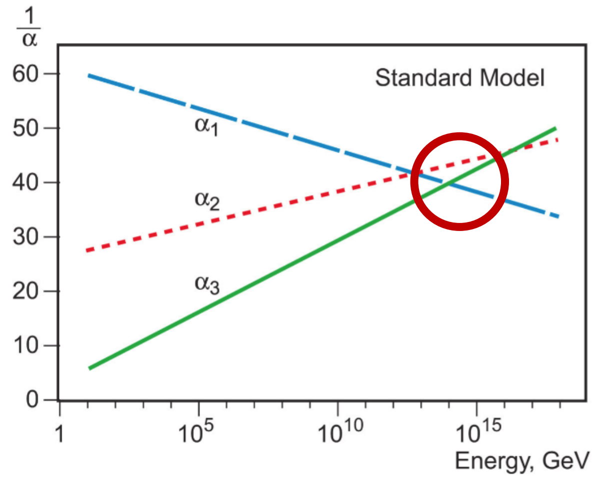
- Gravitational force becomes comparable to other forces at

  Planck scale: $M_{Pl} = 2.4\times10^{18}$GeV

  - Not renormalizable in QFT → String theory (?)

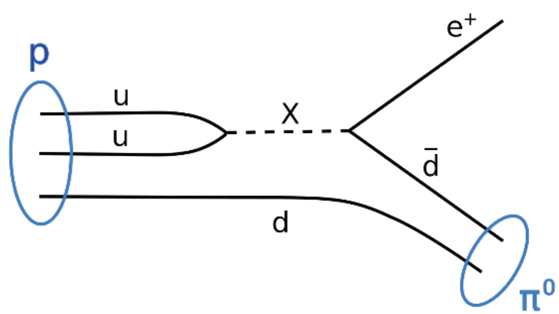
- Gauge Sector
  - SU(3)×SU(2)×U(1) for QCD and EW force
  - Grand Unification
    - Hint from renormalization group flow
    - Charge quantization (magnetic monopole)

      c.f. from anomaly cancellation? but scalars, Dirac fermions



  - Models: SU(5), SO(10), E_6, …
    - Proton decay by B and L violation mediated by heavy gauge bosons

      Unification scale: $\mathrm{M_{GUT}} \sim 10^{16}\mathrm{GeV}$



proton lifetime > 10^{33} years

$$M_{\rm GUT} > 10^{16}{\rm GeV}\left(\frac{g_{\rm GUT}^2}{0.5}\right)^{1/2}$$

- **Higgs Sector**
  - Scalar potential

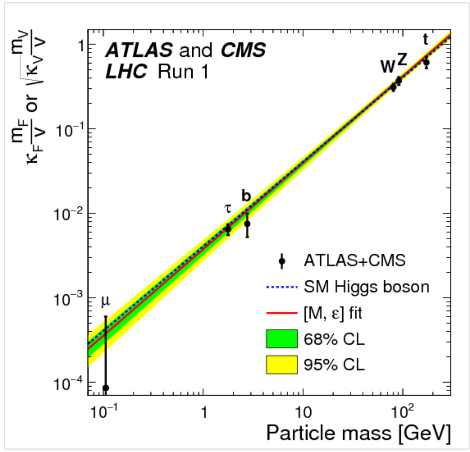
$$V = -\mu^2|H|^2 + \lambda|H|^4$$

the only mass parameter in the SM

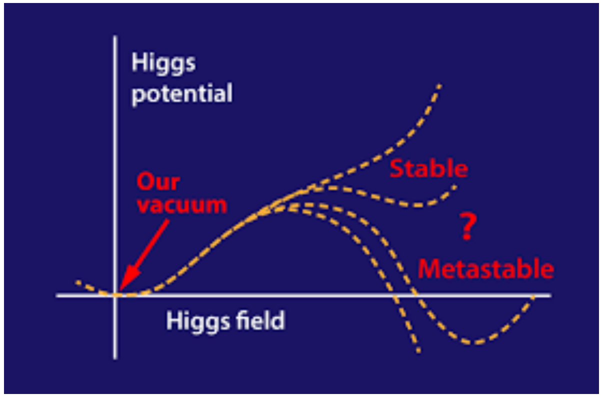
where $v = 246\text{GeV}$ and $m_h = 125\text{GeV}$

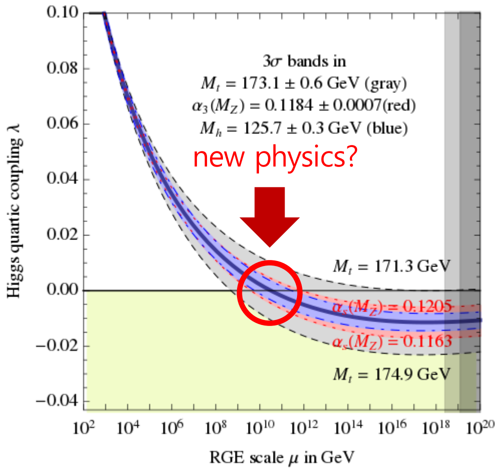
$\Rightarrow$ $\mu \simeq 88\text{GeV}$ and $\lambda \simeq 0.13$ at the weak scale

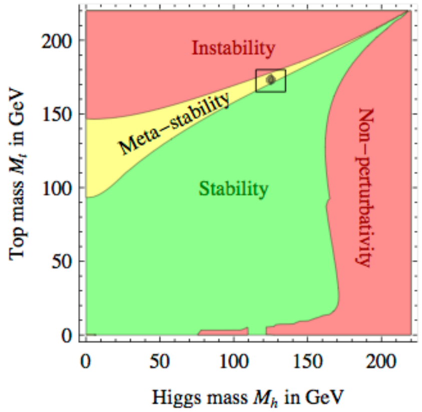
c.f. QCD scale: natural due to log running of α_3



- Vacuum stability: new physics at $M_{\lambda=0} \sim 10^{9-12}\text{GeV}$?

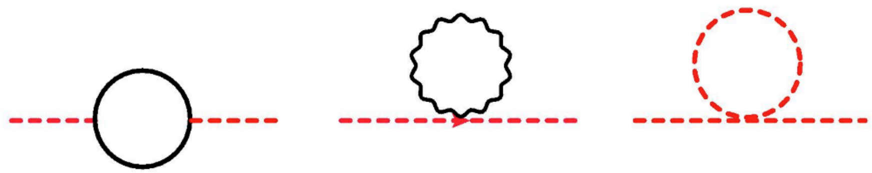






Degrassi et al

- Higgs Sector
  - Radiative correction to the Higgs mass squared parameter μ^2



$$\delta\mu^2 = -\frac{y^2}{8\pi^2}\Lambda^2 + \frac{g^2}{8\pi^2}\Lambda^2 + \frac{\lambda}{8\pi^2}\Lambda^2$$

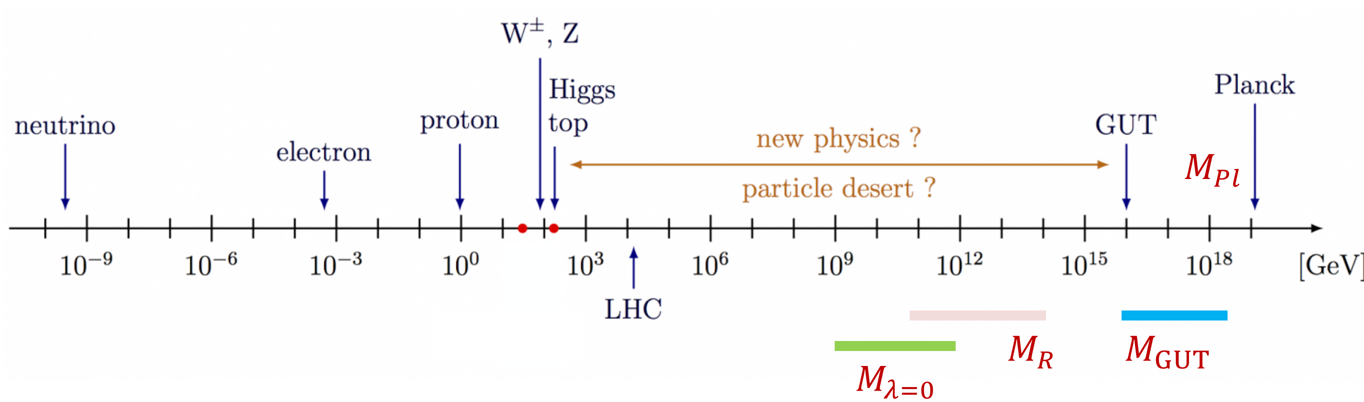
fermion | gauge boson | scalar boson

c.f. mass protection

- Gauge boson: Gauge symmetry
- Fermion: Chiral symmetry

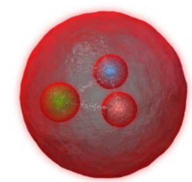
- EW hierarchy problem: sensitive to unknown UV physics

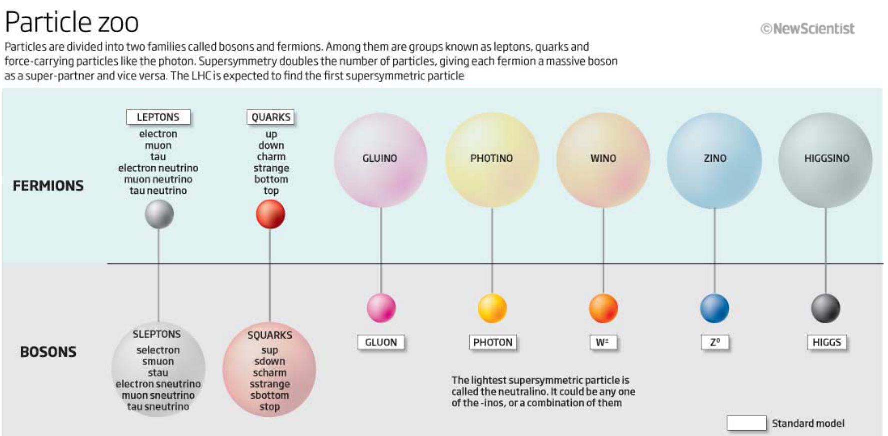
How to stabilize the weak scale?

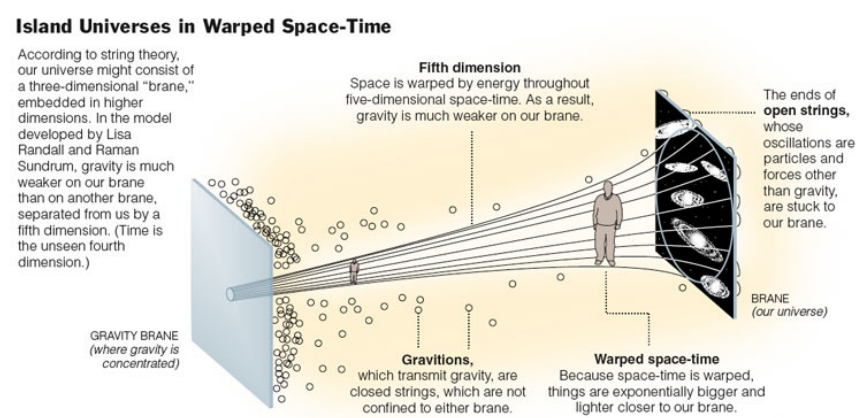


- Higgs Sector
  - Unnatural without new physics around TeV
    - EW naturalness has been considered as a guiding principle to BSM
    - Interesting ideas:

      Supersymmetry, Extra dimensions, Strong EWSB, …

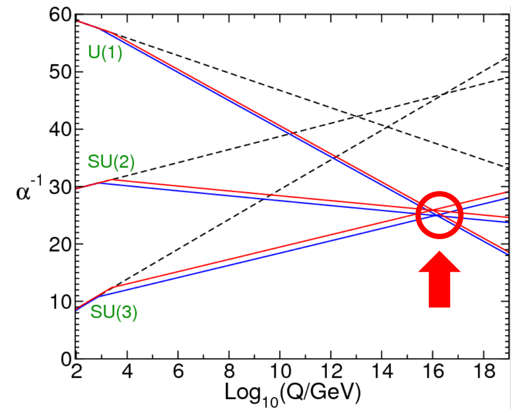




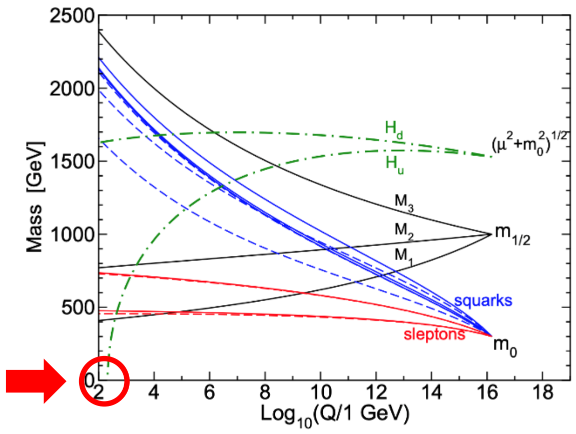


(often) WIMP as cold dark matter if realized around TeV

- Higgs Sector
  - Supersymmetry
    - Unique extension of the Poincare spacetime symmetry
    - Symmetry between boson and fermion



  - Weak scale SUSY superpartner particles around the weak scale
    - Natural solution to gauge hierarchy problem
    - Gauge coupling unification
    - WIMP dark matter: Lightest superparticle
    - Explanation of how EWSB occurs
    - Higgs quartic from gauge couplings
    - Local SUSY → Graviton



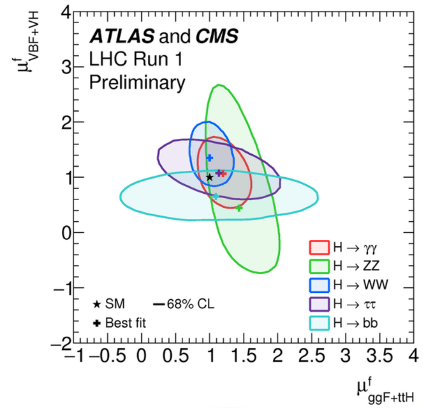
S. P. Martin

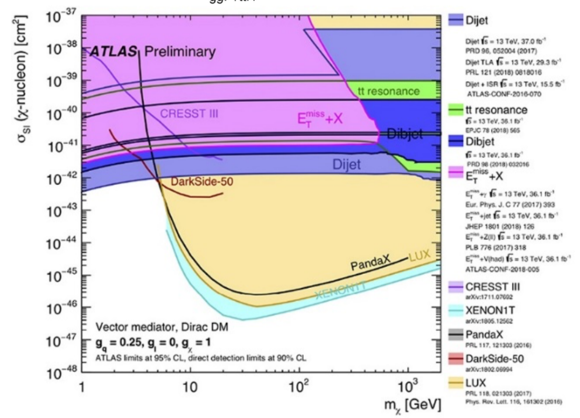
- **Higgs Sector**
  - LHC results so far
    - No significant deviations from the SM
    - No clear signals for BSM
  - Direct & indirect dark matter searches so far
    - No evidence of WIMP

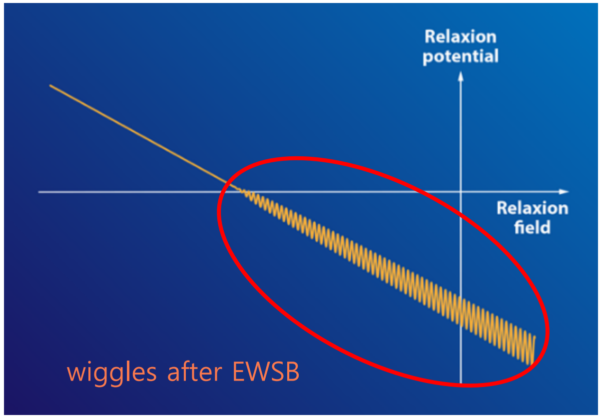
  - New approach

    Cosmological relaxation of the Higgs boson mass

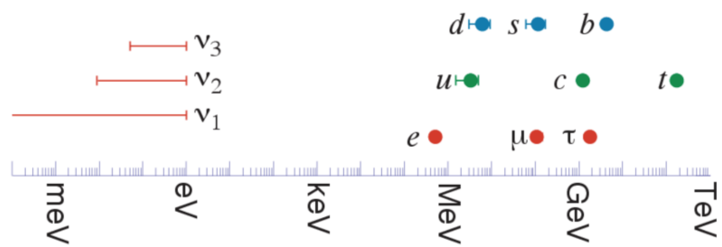
    - $\mu^2 = \mu^2(\phi)$: selection by slow-rolling relaxion







- Fermion Sector
  - Quarks and leptons
    - Mass hierarchy



  - Weak eigenstate = mixture of mass eigenstates
    - CKM matrix for quarks, PMNS matrix for leptons

    Flavor mixing and CP violation in charged weak current interactions

Quark	Lepton
$\lvert U_{CKM}\rvert \simeq \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$ 3 small angles	$\lvert U_{PMNS}\rvert \simeq \begin{pmatrix} 0.8 & 0.5 & 0.15 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$ 2 large angles and 1 small angle
CP phase: $\delta_{CKM} \simeq 1$	CP phase: $\delta \simeq -\frac{\pi}{2}$ (?)

1-3. Why BSM? Theoretical motivations

- Fermion Sector
  - Quark sector

    Why small mixing and hierarchical mass structure?

    - Continuous family symmetry spontaneously broken by flavon ϕ

      e.g. Froggatt-Nielson mechanism

      → Dynamical Yukawa couplings: $y_{ij} = \lambda_{ij}\left(\frac{\phi}{\Lambda}\right)^{n_{ij}}$ with $\lambda_{ij} = O(1)$

  - Lepton sector

    Why one small and two large mixing angles?

    Different from the quark sector

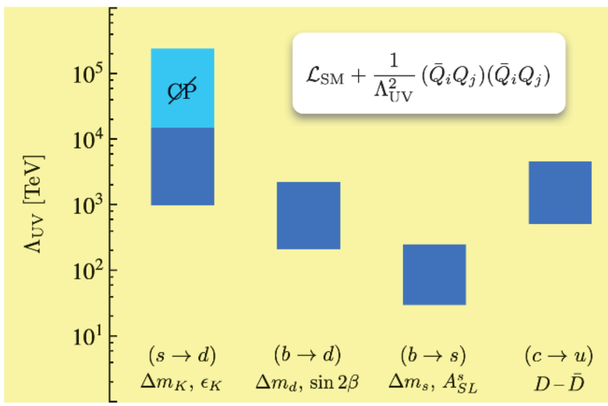
    - Fine-tuning? Non-Abelian discrete symmetries?
    - Seesaw + Froggatt-Nielson?

Gouvea , Vogel

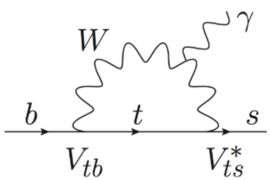
- Fermion Sector
  - GIM mechanism

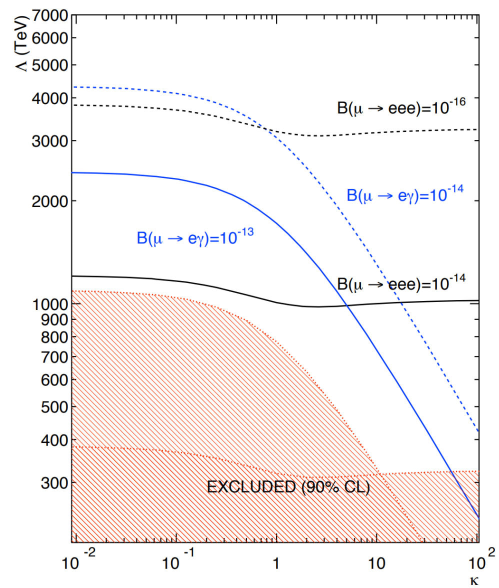
    No flavor-changing neutral current at tree-level in the SM (GIM)

    → Strong constraints on flavor and CP violations in BSM models



B. Grinstein

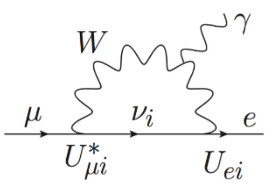




$$\frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu}$$

$$\frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\,(\bar{e}\gamma^\mu e)$$

Gouvea , Vogel



- Fermion Sector
  - CP violating phases in the QCD sector

    - $\delta_{\mathrm{CKM}} \sim \arg(\det[y_u y_u^{+}, y_d y_d^{+}]) \simeq 1.2 \pm 0.3$

    - $\bar{\theta} = \theta + \arg(\det[y_u y_d]) \leftarrow$ Physical if quarks are massive

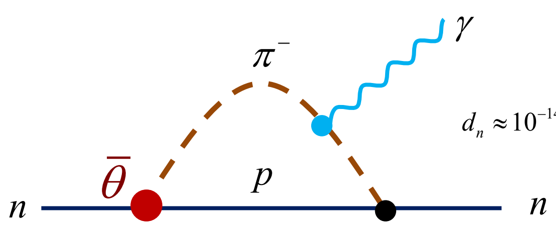
    topological QCD θ-term: $\Delta L = \frac{\theta}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu}$

    energy of θ-vacuum due to instantons

    c.f. θ-term of SU(2) → Rotated away by $\mathrm{U}(1)_{B+L}$ transformation

  - Smallness of electric dipole moments

    - Neutron EDM bound



$$d_n \approx 10^{-14} \frac{m_u m_d}{(m_u + m_d) m_s} \bar{\theta}\ e \cdot cm \quad \Rightarrow |\bar{\theta}| < 10^{-10}$$

1-3. Why BSM? Theoretical motivations

- Fermion Sector
  - Strong CP problem: How to make QCD CP-conserving?

    - Peccei-Quinn solution

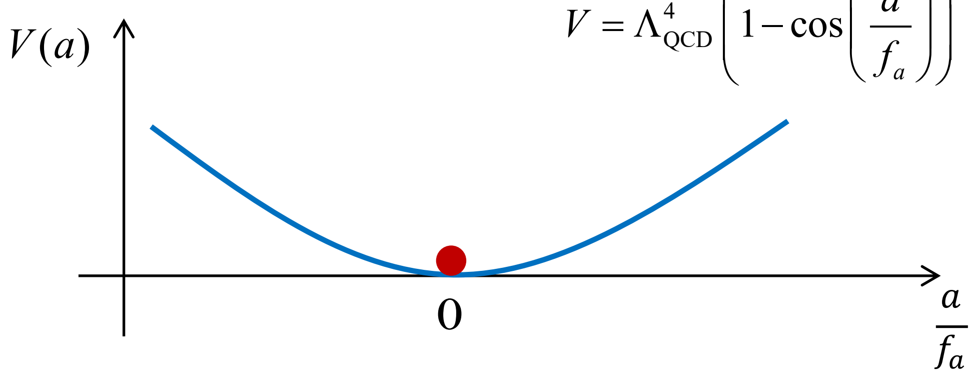
    Promote to $\bar{\theta}$ a field, axion, anomalous coupled to gluons

$$\frac{1}{32\pi^2}\frac{a}{f_a}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

    Properties of the axion determined by the decay constant f_a

  - Axion potential from QCD instantons after the QCD phase transition

$$V = \Lambda_{\mathrm{QCD}}^4\left(1-\cos\left(\frac{a}{f_a}\right)\right)$$



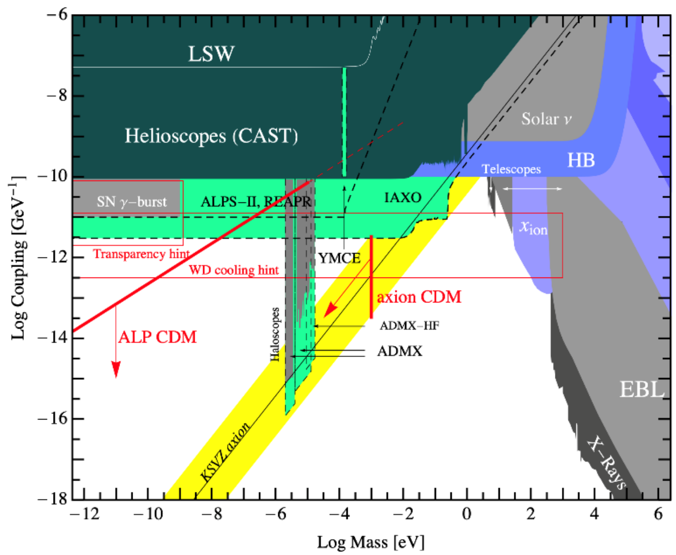
dynamical cancellation

$$\bar{\theta} = \frac{\langle a\rangle}{f_a}=0$$

- Fermion Sector
  - Axion properties

mass	axion-nucleon	axion-photon (model-dependent)
$m_a \sim 5\times10^{-6}\left(\frac{10^{12}\mathrm{GeV}}{f_a}\right)\mathrm{eV}$	$g_{aNN} \sim 10^{-12}\left(\frac{10^{12}\mathrm{GeV}}{f_a}\right)$	$g_{a\gamma\gamma} \sim 10^{-15}\left(\frac{10^{12}\mathrm{GeV}}{f_a}\right)\mathrm{GeV}^{-1}$

- Axion searches:

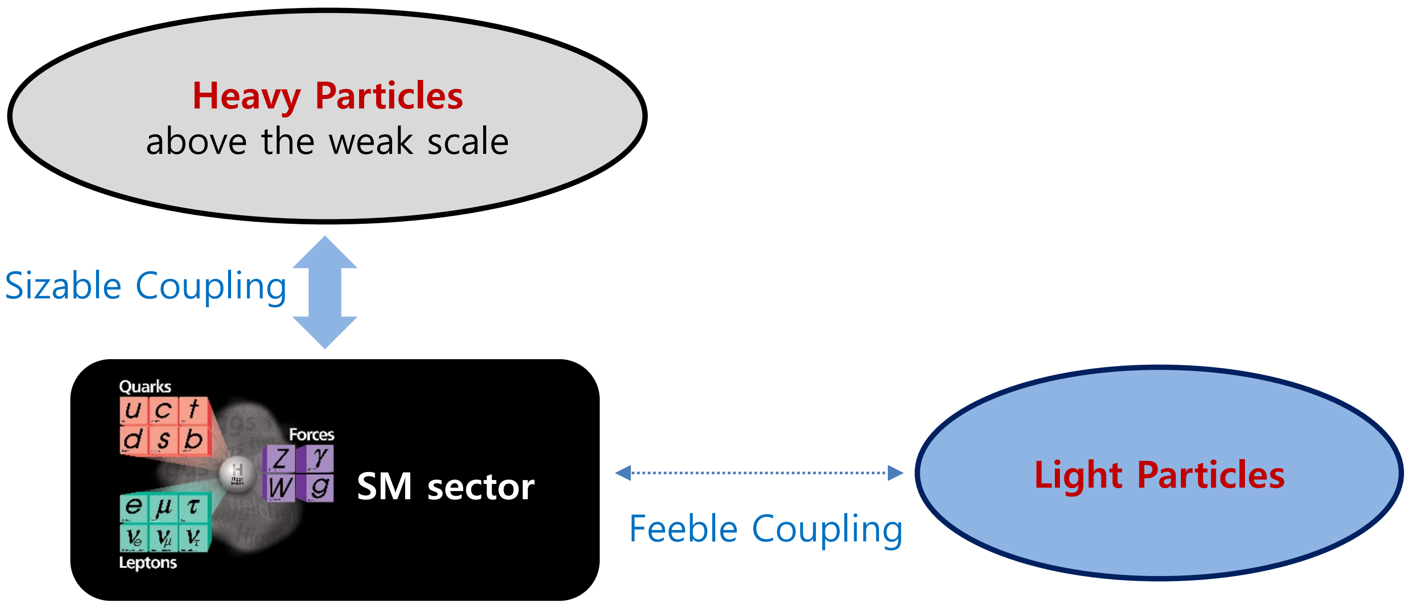


- Axion is cosmologically stable for large f_a → Dark matter candidate

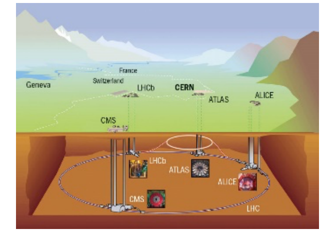
Extension of the SM

BSM Models

- Extension of the SM
  - SM
    - Not a complete description of nature
    - Experimental results: only small deviations from the SM below TeV
  - How to extend the SM? renormalizable interactions

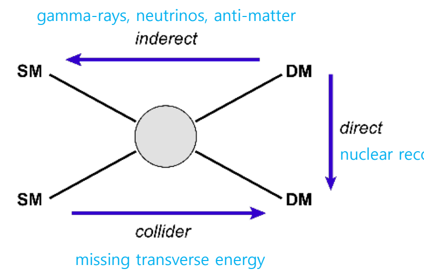


- Extension of the SM
  - Heavy particles with sizable coupling to the SM
    - Supersymmetry, extra dimensions, hidden strong forces, …
    - Constraints from collider searches for new particles, dark matter searches



Below the cutoff scale:

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d \geq 5, k} \boxed{\alpha_k^{(d)}} \left(\frac{1}{\boxed{\Lambda}} \right)^{d-4} \mathcal{O}_k^{(d)}$$



Experimental constraints on flavor and CP violations

Constraints from measured Higgs mass and couplings

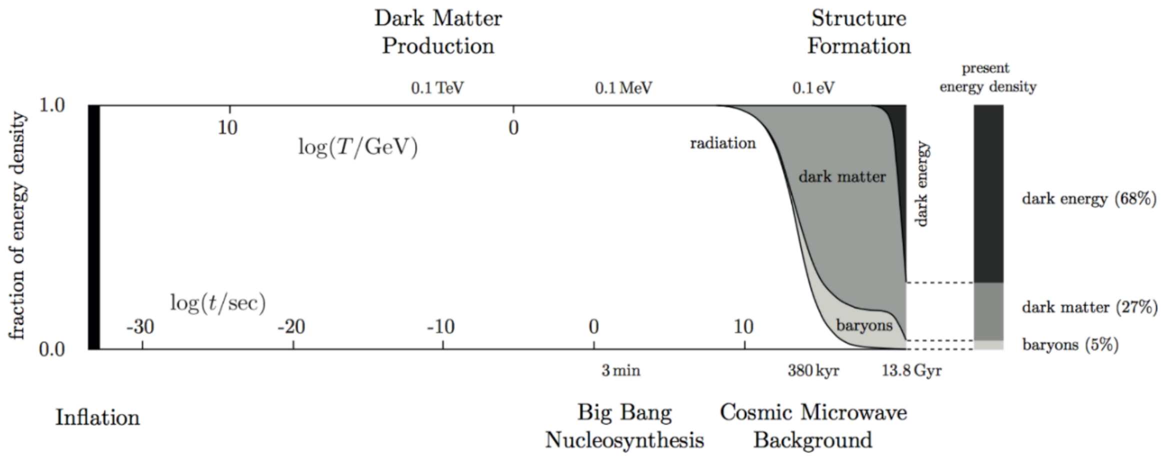
$d = 5$: only one operator without counting flavors

$d = 6$: 64 independent operators

- Extension of the SM
  - Light particles feebly coupled to the SM
    - Portal framework: Interaction between SM and Dark sectors

Dark Higgs	Sterile Neutrino	Dark Photon	Axion
$\lambda S^2 H^\dagger H$	$yLHN$	$\epsilon F'_{\mu\nu} B^{\mu\nu}$	$\frac{\phi}{f} F_{\mu\nu} \tilde{F}^{\mu\nu}$

- Solution to SM puzzles
- Cosmological importance



Part II and III

BSM

- Two BSM scenarios
  - **Axionic Extension**
    - Light scalar particles feebly coupled to the SM
    - Light scalar from continuous shift symmetry
  - **Supersymmetric Extension**
    - Heavy particles above the weak scale with sizable coupling to the SM
    - Supersymmetry to remove the UV sensitivity of scalar fields

Let's discuss how to resolve the puzzles of the SM within those scenarios!