Axiflavon Theory

Flavour and Dark Matter
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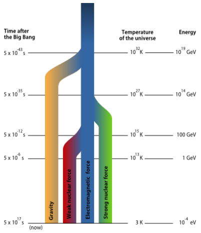
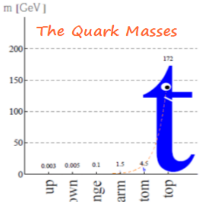
Calibbi, FG, Redigolo, Ziegler, Zupan, 1612.08040

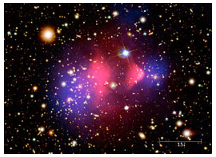
Physics Beyond the SM

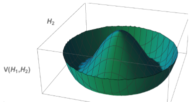
SM very successful, however explains by far not everything!

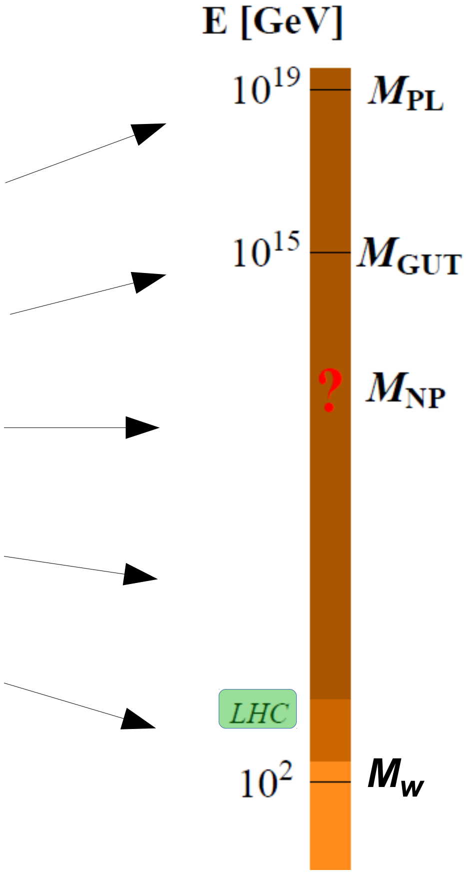
- Gravity $\not\subset$ SM
- Hierarchy Problem: $m_h << M_{PL}$
- Tiny Neutrino Masses
- Grand Unification of Forces?
- Hierarchical Flavor Structure
- Baryogenesis → Existence of Universe
- Dark Matter $\not\in$ SM
- Trigger for Symmetry-Breaking Potential?
- Strong CP Problem
- …





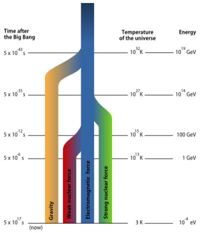


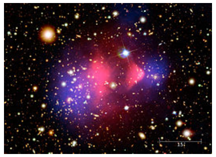




Physics Beyond the SM

Three of the Major Open Questions in Particle Physics





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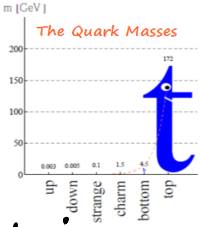
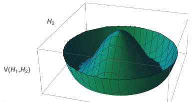
- Grand Unification of Forces?

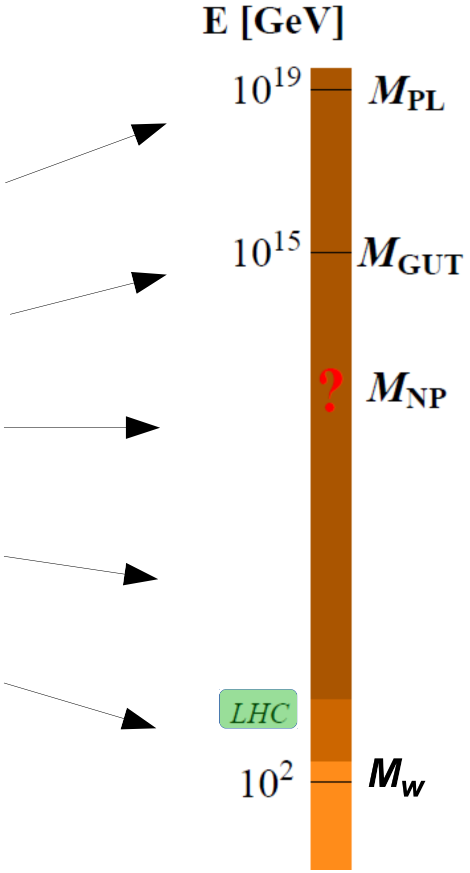


- Hierarchical Flavor Structure
- Baryogenesis → Existence of Universe
- Dark Matter $\not\in$ SM



- Trigger for Symmetry-Breaking Potential?
- Strong CP Problem

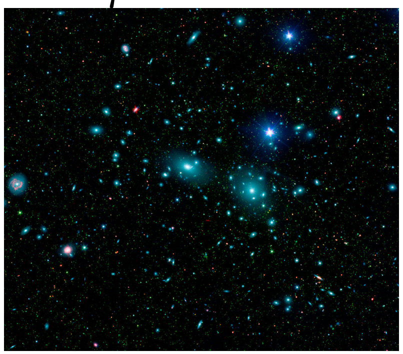
- ...



Dark Matter

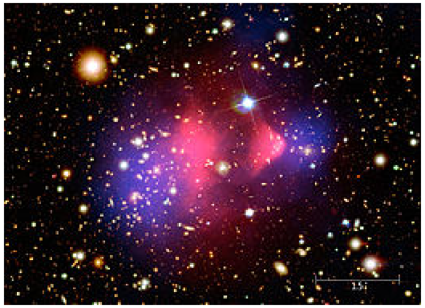
- Luminous matter cannot explain many observations

- luminous matter not sufficient to keep clusters bound



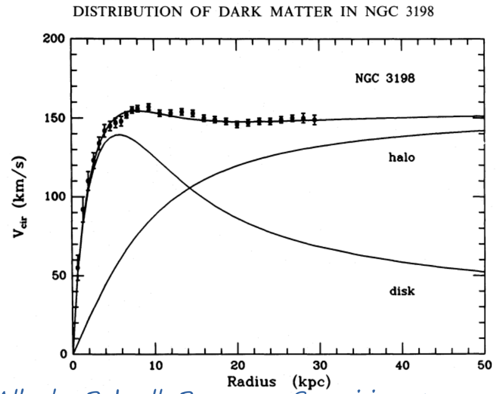
Coma Cluster, NASA, Zwicky

- Bullet Cluster:
  Optical observation (x-ray) vs. grav. lensing



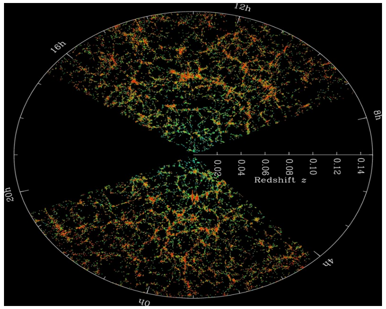
NASA, ...

- rotation curves of galaxies



Albada, Bahcall, Begeman, Sanscisi, APJ, 295, 305-313 (1985)

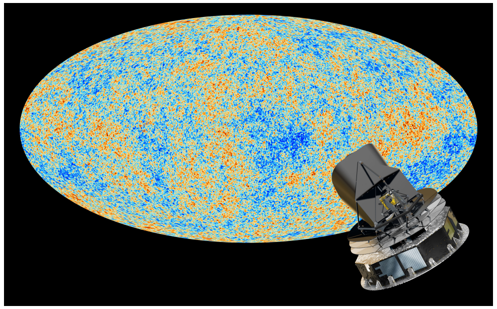
- large-scale structure formation



Sloan Digital Sky Survey

+ BBN, Lyman-α forest, ...

- CMB

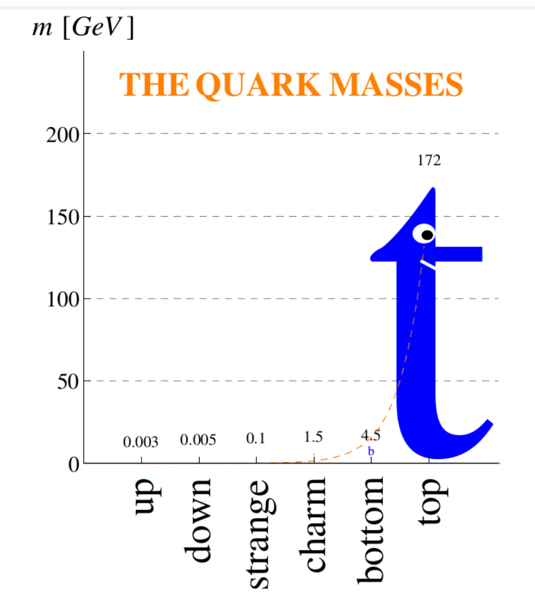


ESA

- All these observations can be explained by the presence of **Dark Matter**... What is its origin?

The Flavor Puzzle

- Large hierarchies in quark + lepton masses
  and in CKM matrix



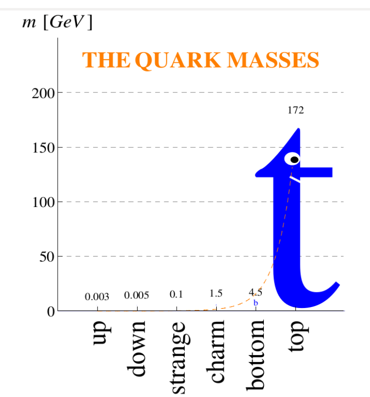
$$V_{\text{CKM}} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix} \qquad \lambda \sim 0.23$$

NuFIT 3.0 (2016)

$$|U|_{3\sigma} = \begin{pmatrix} 0.800 \to 0.844 & 0.515 \to 0.581 & 0.139 \to 0.155 \\ 0.229 \to 0.516 & 0.438 \to 0.699 & 0.614 \to 0.790 \\ 0.249 \to 0.528 & 0.462 \to 0.715 & 0.595 \to 0.776 \end{pmatrix}$$

Solution to The Flavor Puzzle

- Large hierarchies in quark + lepton masses and in CKM matrix ...

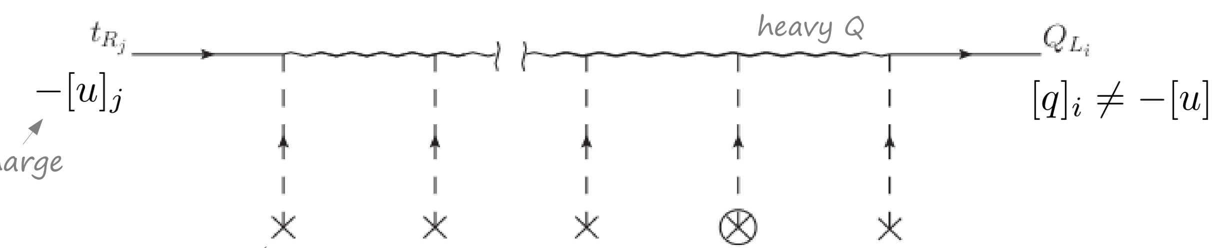


$$V_{\rm CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$

... can be addressed via horizontal $U(1)_H$ symmetry:

Froggatt-Nielsen mechanism: NPB 147, 277,...

- SM LH and RH fermions feature different $U(1)_H$ charges
- Mass terms only after $U(1)_H$ broken via VEV of scalar field: **flavon** Φ



$U(1)_H$ charge

Insertions of VEV $\langle\Phi\rangle \equiv v_\Phi > 0$

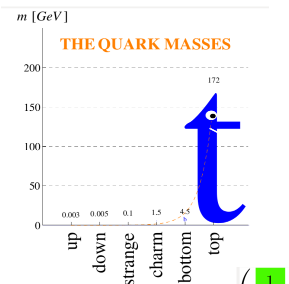
$\langle H\rangle \equiv v = 174\,\text{GeV}$

$Q_{U(1)_H}(\Phi) = -1$

$\rightarrow$ suppression by $v_\Phi/m_Q \ll 1$

Solution to The Flavor Puzzle

- Large hierarchies in quark + lepton masses and in CKM matrix ...



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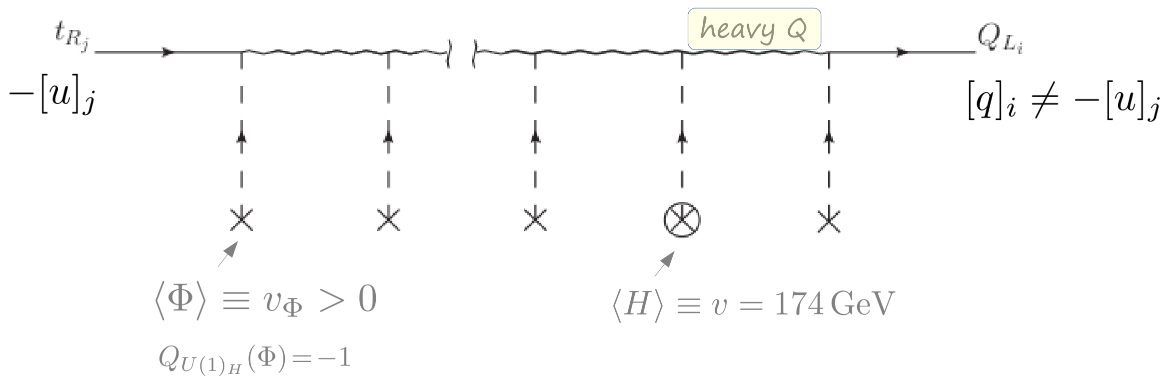


Integrate out heavy Q →
$m_Q \sim \Lambda \gtrsim v_\Phi$

$$\mathcal{L} = a^u_{ij}\; Q_i U^c_j\, H\, (\Phi/\Lambda)^{[q]_i + [u]_j} + \ldots$$

flavon Φ

a^q_{ij} : O(1) coefficient; all flavor structure comes from

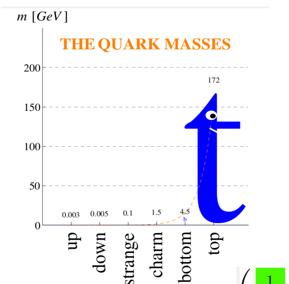
Yukawa couplings $y^{u,d,e}_{ij} = a^{u,d,e}_{ij}\,\epsilon^{[L]_i + [R]_j}$

$\epsilon \equiv v_\Phi/\Lambda$

$[L]_i = [q]_i, [R]_i = [u]_i, [d]_i$ (quarks)
$[L]_i = [l]_i, [R]_i = [e]_i$ (leptons)
$[L]_i, [R]_i > 0$

Solution to The Flavor Puzzle

- Large hierarchies in quark + lepton masses and in CKM matrix ...



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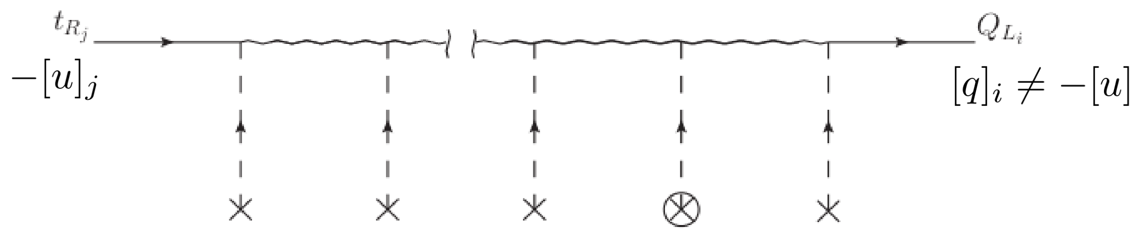


Yukawa couplings $\boxed{y_{ij}^{u,d,e} = a_{ij}^{u,d,e}\,\epsilon^{[L]_i+[R]_j}}$

LO in ε $\Rightarrow$
$$m_n = \frac{v}{\sqrt{2}}\,\frac{\left|\det \boldsymbol{a}_f^{(n)}\right|}{\left|\det \boldsymbol{a}_f^{(n-1)}\right|}\,\epsilon^{[L]_n+[R]_n}$$

Hierarchical structure:

$$\boxed{m_i/m_j \sim \epsilon^{[L]_i+[R]_i-[L]_j-[R]_j}}$$

$$\epsilon \equiv v_\Phi/\Lambda \sim \lambda \sim 0.23$$

LH rotations $\Rightarrow$
$$\boldsymbol{U}_f = (u_f)_{ij}\,\epsilon^{|[L]_i-[L]_j|}$$

$$u_f = \begin{pmatrix} 1 & \frac{(M_f)_{21}}{(M_f)_{11}} & \frac{(a_f)_{13}}{(a_f)_{33}} \\ -\frac{(M_f)^*_{21}}{(M_f)^*_{11}} & 1 & \frac{(a_f)_{23}}{(a_f)_{33}} \\ \frac{(M_f)^*_{31}}{(M_f)^*_{11}} & -\frac{(a_f)^*_{23}}{(a_f)^*_{33}} & 1 \end{pmatrix}$$

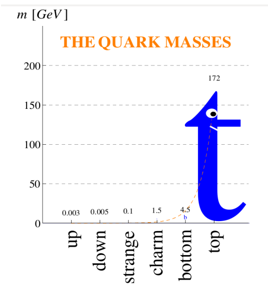
$$\boxed{(V_{\rm CKM})_{ik} = \sum_{j=1}^{3} (U_u^\dagger)_{ij}\,(U_d)_{jk} \sim \epsilon^{|[L]_i-[L]_k|}}$$

$\boldsymbol{a}_f^{(n)}$: remove rows + columns with i,j>n from $\boldsymbol{a}_f \equiv (a_{ij}^f)$

$(M_q)_{ij}$: minors of $\boldsymbol{a}_f$

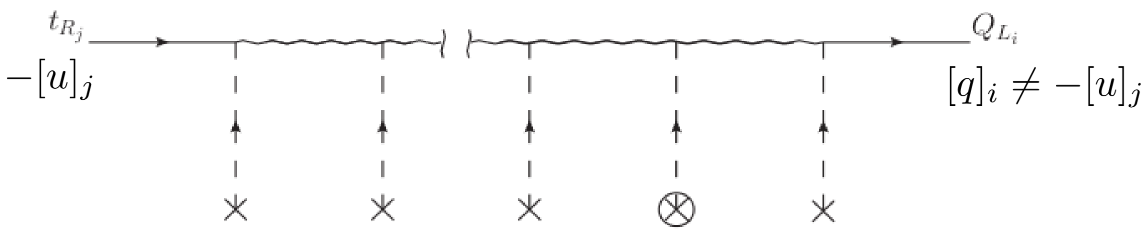
Solution to The Flavor Puzzle

- Large hierarchies in quark + lepton masses and in CKM matrix ...



... can be addressed via horizontal $\mathrm{U}(1)_H$ symmetry:

Froggatt-Nielsen mechanism: NPB 147, 277,...



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Hierarchical structure:

$$m_i/m_j \sim \epsilon^{[L]_i+[R]_i-[L]_j-[R]_j}$$

$$\epsilon \equiv v_\Phi/\Lambda \sim \lambda \sim 0.23$$

$$\begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$

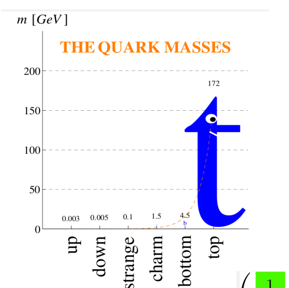
$$(V_{\mathrm{CKM}})_{ik} = \sum_{j=1}^{3} \left(U_u^\dagger\right)_{ij} \left(U_d\right)_{jk} \sim \epsilon^{|[L]_i-[L]_k|}$$

Fit to fermion masses and mixings $\rightarrow [L]_i, [R]_i$

uncertainties due to a_{ij}^f, overall normalization

Solution to The Flavor Puzzle

- Large hierarchies in quark + lepton masses and in CKM matrix ...



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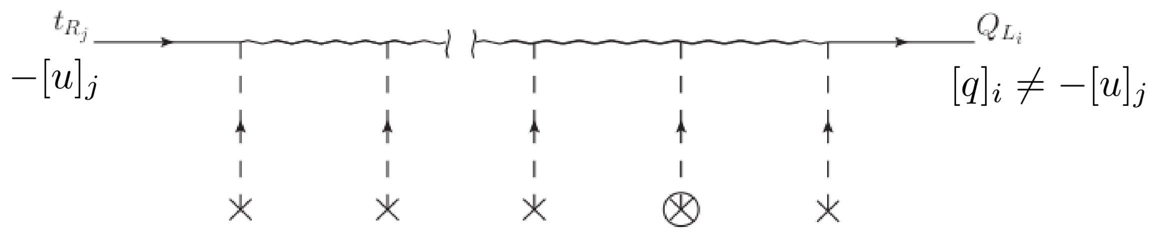

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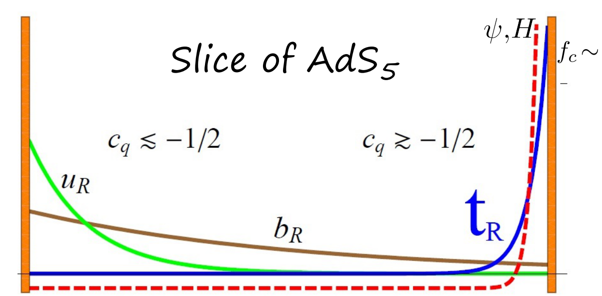
$$(V_{\rm CKM})_{ik} = \sum_{j=1}^{3} (U_u^\dagger)_{ij}\,(U_d)_{jk} \sim \epsilon^{|[L]_i-[L]_k|}$$

Naturally realized in warped extra dimensions/composite Higgs



Strong CP Problem

Why is the coefficient of the $\not{CP}$ operator $\mathcal{L}_{\rm SM} \supset \bar\theta \, \frac{\alpha_s}{8\pi} G_{a\mu\nu}\tilde G_a^{\mu\nu}$ so tiny?

- Limits on Neutron EDMs:

$$d_n \approx 3.6 \times 10^{-16} \bar\theta \, e\,{\rm cm}$$

$$|d_n| < 2.9 \times 10^{-26} e\,{\rm cm} \;(95\%{\rm CL})$$

$\Rightarrow |\bar\theta| \lesssim 10^{-10}$

Crewther, Vecchia, Veneziano, Witten, PLB 88, 123-127 (1979)
Baker et. al., hep-ex/0602020

- θ receives ($\mathcal{O}(1)$) contributions from two different sectors:

$$\bar\theta = \theta + \arg\det(M_u M_d)$$

Theta-vacua of QCD — Electroweak Sector

$|\bar\theta| \lesssim 10^{-10} \Rightarrow$ Fine-tuning problem!

No anthropic reasoning or the like: $\bar\theta \sim 0.01$ would be perfectly fine

Peccei-Quinn Axion Solution

Why is the coefficient of the $\cancel{CP}$ operator
$\mathcal{L}_{\rm SM} \supset \bar\theta \, \frac{\alpha_s}{8\pi} G_{a\mu\nu} \tilde G_a^{\mu\nu}$ so tiny?

- Promote $\bar\theta$ from parameter to dynamical variable:
  axion a = PNGB of spontaneously broken $U(1)_{PQ}$ symmetry
  → solves strong CP problem:

$\sigma \sim \frac{f}{\sqrt{2}} e^{ia/f}$

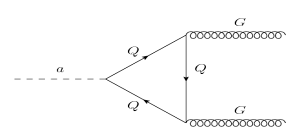
- $\mathcal{L} \supset \theta_0 \frac{\alpha_s}{8\pi} G\tilde G + \frac{\alpha_s}{4\pi} N \frac{a}{f} G\tilde G$

  Potential induced by QCD instantons

  → minimum CP conserving $\langle a \rangle = -af/(2N)\theta_0$ → $G\tilde G$ term vanishes

  Peccei, Quinn, PRL 38, 1440, Vafa, Witten, PRL 53, 535

- axion coupled to $G\tilde G$ via chiral anomaly



→ $a\, G\tilde G$

Wilczek, PRL 40, 279 (1978), Weinberg, PRL 40, 223 (1978)

A Unified Solution: The Axiflavon

- Can both frameworks be *unified*: 'single' solution for two problems?

$$\boxed{U(1)_H \leftrightarrow U(1)_{PQ}}$$

➡ embed **axion** and **flavon** in same complex scalar (single U(1))

don't gauge $U(1)_H$ of FN mech. ...

$$\Phi = \frac{1}{\sqrt{2}}(v_\Phi + \underbrace{\phi}_{\text{flavon}})e^{i\overbrace{a}^{\text{axiflavon}}/v_\Phi}$$

→ Solves strong CP problem: axiflavon $\hat{=}$ axion + solves flavor puzzle

$m_\phi \sim \mathcal{O}(v_\Phi)$ flavon heavy → integrate out

$m_a = 5.7\,\mu\text{eV}\left(\frac{10^{12}}{f_a}\right) \ll m_\Phi$ axiflavon = light PNGB, small mass induced by anomaly

di Cortona, Hardy, Pardo Vega, Villadoro, 1511.02867

$f_a = v_\Phi/2N$

see also: Ema, Hamaguchi, Moroi, Nakayama, 1612.05492, Wilczek, PRL 49, 1549 (1982), ...

The Axiflavon: Very Predictive

$$\Phi = \frac{1}{\sqrt{2}}(v_\Phi + \phi)e^{ia/v_\Phi}$$

flavon

axiflavon

$$\mathcal{L} = a^u_{ij}\ Q_i U^c_j\, H\, (\Phi/\Lambda)^{[q]_i+[u]_j} + \ldots$$

- **axiflavon** couplings to fermions $\mathcal{L}_{aff} = \lambda^f_{ij} a F_i F^c_j + \text{h.c.}$

non-universal (generation-dependent charges) → FCNCs

$$\lambda^{u,d,e}_{ij} = i([L]_i + [R]_j)\frac{v}{v_\Phi} y^{u,d,e}_{ij}$$

$$y^{u,d,e}_{ij} = a^{u,d,e}_{ij}\epsilon^{[L]_i+[R]_j}$$

- **axiflavon** couplings to gluons/photons $\mathcal{L} \supset \frac{\alpha_s}{8\pi}\frac{a}{f_a}G\tilde{G} + \frac{E}{N}\frac{\alpha_{\rm em}}{8\pi}\frac{a}{f_a}F\tilde{F}$

N = color anomaly

E = electromagnetic anomaly

$f_a = v_\Phi/2N$

$$N\delta_{ab} = \mathrm{Tr}\lambda_a\lambda_b Q_{PQ}$$

$$E = \mathrm{Tr} Q_{PQ} Q^2_{\rm em}$$

The Axiflavon: Flavor Constraints

$$\Phi = \frac{1}{\sqrt{2}}(v_\Phi + \boxed{\phi})e^{i\boxed{a}/v_\Phi} \qquad \mathcal{L} = a^u_{ij}\; Q_i U^c_j\, H\, (\Phi/\Lambda)^{[q]_i+[u]_j} + \ldots$$

flavon

axiflavon

- ***axiflavon*** couplings to <u>fermions</u> $\boxed{\mathcal{L}_{aff} = \lambda^f_{ij} a F_i F^c_j + \mathrm{h.c.}}$

non-universal (generation-dependent charges) → FCNCs

$$\boxed{\lambda^{u,d,e}_{ij} = i([L]_i + [R]_j)\frac{v}{v_\Phi} y^{u,d,e}_{ij}}$$

- *strong bounds from* ***Kaon Physics*** *($a\bar{s}d$ transitions):*

$$\Gamma(K^+ \to \pi^+ a) \simeq \frac{m_K}{64\pi}|\lambda^d_{21} + \lambda^{d*}_{12}|^2 B_s^2 \left(1 - \frac{m_\pi^2}{m_K^2}\right)$$

stringent limit: $\mathrm{BR}(K^+ \to \pi^+ a) < 7.3 \cdot 10^{-11}$

E787, E949

Kamenik, Smith, 1111.6402

$$\Rightarrow \boxed{\frac{1}{2}|\lambda^d_{21} + \lambda^{d*}_{12}| < 1.4 \cdot 10^{-13}}$$

define $|\lambda^d_{21} + \lambda^{d*}_{12}| \equiv 2\kappa_{sd}\sqrt{m_d m_s}/(2N f_a)$ $\Rightarrow$ $\boxed{f_a \gtrsim \frac{\kappa_{sd}}{N} \times 7.5 \cdot 10^{10}\,\mathrm{GeV}}$ $\left(m_a \lesssim \frac{N}{\kappa_{sd}} \times 7.6 \cdot 10^{-5}\,\mathrm{eV}\right)$

$\mathcal{O}(1)$ [model dependent]

$B_s = 4.6(8)$

NA62: $\mathcal{O}(10)$ improvement

The Axiflavon: Flavor Constraints

$$\Phi = \frac{1}{\sqrt{2}}(v_\Phi + \underbrace{\phi}_{\text{flavon}})e^{i\overbrace{a}^{\text{axiflavon}}/v_\Phi}$$

$$\mathcal{L} = a^u_{ij}\; Q_i U^c_j\, H\,(\Phi/\Lambda)^{[q]_i+[u]_j} + \ldots$$

- ***axiflavon*** couplings to <u>fermions</u> $\boxed{\mathcal{L}_{aff} = \lambda^f_{ij} a F_i F^c_j + \text{h.c.}}$

non-universal (generation-dependent charges) → FCNCs

$$\boxed{\lambda^{u,d,e}_{ij} = i([L]_i + [R]_j)\frac{v}{v_\Phi} y^{u,d,e}_{ij}}$$

- further bounds from **B-Physics** ($a\bar{b}s$ transitions):

$$\Gamma(B^+ \to K^+ a) \simeq \frac{m_B}{64\pi}|\lambda^d_{32} + \lambda^{d*}_{23}|^2 \left(f^K_0(0)\right)^2 \left(\frac{m_B}{m_b - m_s}\right)^2 \left(1 - \frac{m_K^2}{m_B^2}\right)^3$$

define $|\lambda^d_{32} + \lambda^{d*}_{23}| \equiv 2\kappa_{bs}\sqrt{m_b m_s}/(2N f_a)$ ➡ $\underbrace{\mathrm{BR}(B^+ \to K^+ a) \lesssim 10^{-6\div 8}}_{\text{Belle-II}}$ → $\boxed{m_a \lesssim \frac{N}{\kappa_{bs}} 10^{-1\div 2}\,\text{eV}}$

- Axion couplings as window to flavor dynamics (Kaon decay part. interesting)

$f^K_0(0) = 0.331$

The Axiflavon: Photon Couplings

$$\Phi = \frac{1}{\sqrt{2}}(v_\Phi + \boxed{\phi})e^{i\boxed{a}/v_\Phi}$$

flavon

axiflavon

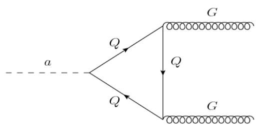
$$\mathcal{L} = a^u_{ij}\; Q_i U^c_j\, H\, (\Phi/\Lambda)^{[q]_i+[u]_j} + \ldots$$

- ***axiflavon*** *couplings to* ***gluons/photons*** $\boxed{\mathcal{L} \supset \frac{\alpha_s}{8\pi}\frac{a}{f_a} G\tilde{G} + \frac{E}{N}\frac{\alpha_{\rm em}}{8\pi}\frac{a}{f_a} F\tilde{F}}$ $f_a = v_\Phi/2N$

$$N = \frac{1}{2}\sum_i 2[q]_i + [u]_i + [d]_i$$

$$E = \sum_i \frac{4}{3}\left([q]_i + [u]_i\right) + \frac{1}{3}\left([q]_i + [d]_i\right) + [l]_i + [e]_i$$

N,E determined completely in terms of $U(1)_H$ charges



- *Can be directly related to fermion mass matrices:*

Froggatt, Nielsen: NPB 147, 277,...

$$\det m_u \det m_d = \alpha_{ud}\, v^6 \epsilon^{2N}$$
$$\det m_d / \det m_e = \alpha_{de}\, \epsilon^{\frac{8}{3}N - E}$$

$\det m_u \det m_d / v^6 \approx 5\cdot 10^{-20}\,;\ \det m_d/\det m_e \approx 0.7 \Rightarrow \boxed{E \approx 8/3N}$

Masses at μ=10⁹ GeV from Xing, Zhang, Zhou, 0712.1419

$$\alpha_{ud} = \det a_u \det a_d$$
$$\alpha_{de} = \det a_d / \det a_e$$

- *somewhat similar to DFSZ axion*

The Axiflavon: Photon Couplings

$$\Phi = \frac{1}{\sqrt{2}}(v_\Phi + \phi)e^{ia/v_\Phi}$$

flavon

axiflavon

$$\mathcal{L} = a^u_{ij}\; Q_i U^c_j\, H\, (\Phi/\Lambda)^{[q]_i+[u]_j} + \dots$$

- **axiflavon** couplings to <u>gluons/photons</u> $\mathcal{L} \supset \frac{\alpha_s}{8\pi}\frac{a}{f_a}G\tilde{G} + \frac{E}{N}\frac{\alpha_{\rm em}}{8\pi}\frac{a}{f_a}F\tilde{F}$ $\quad f_a = v_\Phi/2N$

$$N = \frac{1}{2}\sum_i 2[q]_i + [u]_i + [d]_i$$

$$E = \sum_i \frac{4}{3}\left([q]_i + [u]_i\right) + \frac{1}{3}\left([q]_i + [d]_i\right) + [l]_i + [e]_i$$

N,E determined completely in terms of $U(1)_H$ charges

- Can be directly related to fermion mass matrices:

$$\frac{E}{N} = \frac{8}{3} - 2\frac{\log\frac{\det m_d}{\det m_e} - \log\alpha_{de}}{\log\frac{\det m_u \det m_d}{v^6} - \log\alpha_{ud}} \xrightarrow[99.9\%]{|a_{ij}|\in[1/3,3]} \frac{E}{N} \in [2.4, 3.0]\,,\quad g_{a\gamma\gamma} \in \frac{[1.0, 2.2]}{10^{16}}\frac{m_a}{\mu\mathrm{eV}}$$

Rather sharp prediction for photon coupling, not too sensitive to O(1) changes in a_{ij}
(nor to explicit charge assignments)

$$\mathcal{L} \supset \frac{1}{4}g_{a\gamma\gamma}aF\tilde{F}$$

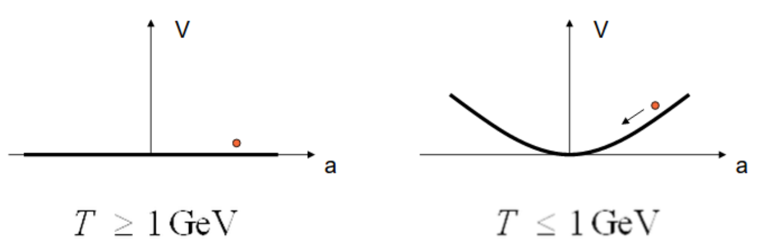
The Axiflavon: Dark Matter

- $U(1)_H$-breaking before inflation → vacuum realignment mechanism

  → axions as cold dark matter $\boxed{\Omega_{\rm DM} h^2 \approx 1 \times 10^{-7} \left(\frac{\rm eV}{m_a}\right)^{7/6} \theta^2}$

  misalignment angle

- Require $\Omega_{\rm DM} h^2 \approx 0.12$ → always possible (with θ<π) if $\boxed{m_a \lesssim 10^{-5} - 10^{-4}\,{\rm eV}}$



vacuum realignment

Sandbox Studio, Chicago with Ana Kova

axion-string density diluted by inflation

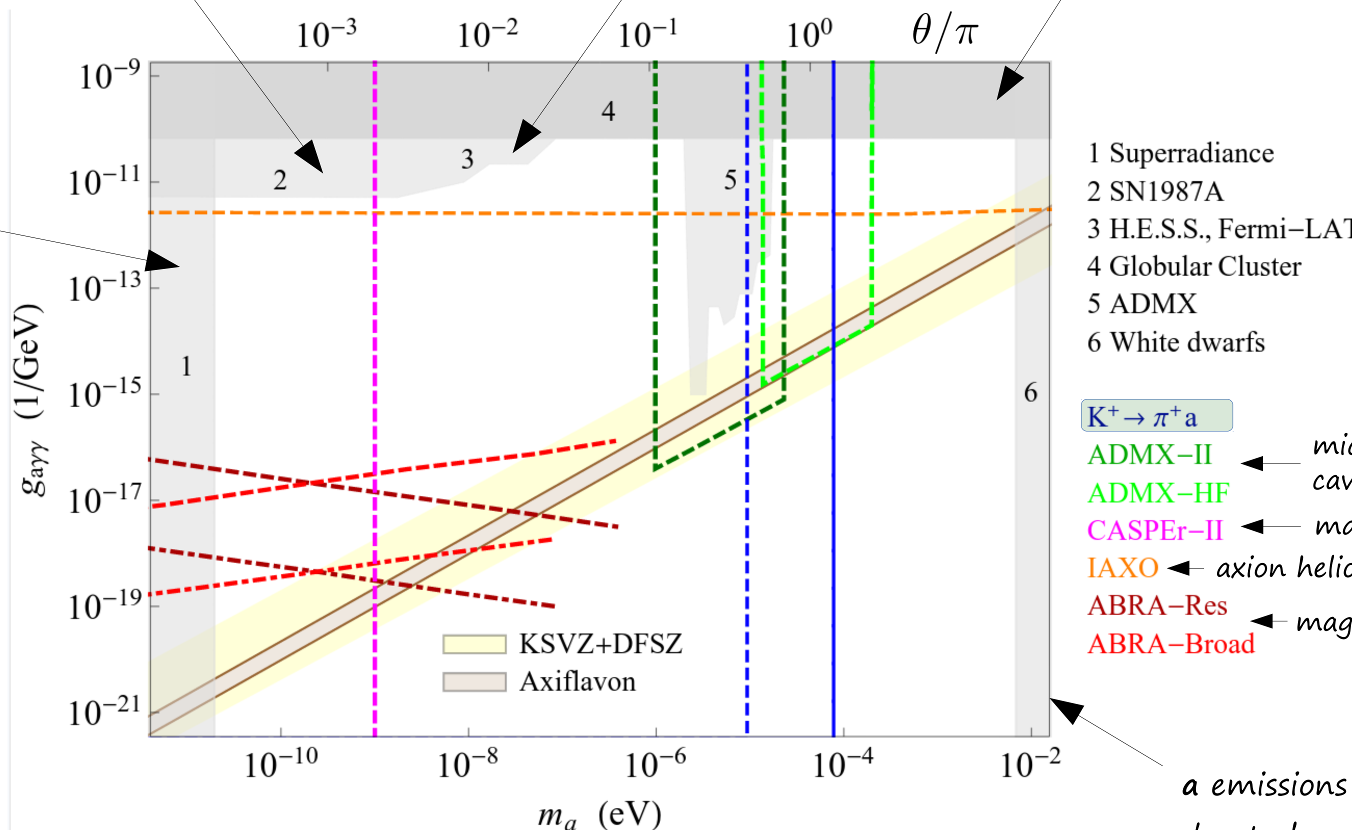
Summary of Constraints

Primakoff production of **a** in core of SN: $\gamma + Ze \leftrightarrow Ze + a$, converted to photons in galactic B field → gamma rays (SMM satellite)

Telescopes, searching for irregularities in γ-ray spectrum (γ-**a** oscil.)

Primakoff **a** losses affect stellar evolution (Globular Cluster)

a affects gravitational wave emission of rotating BH (rotating BEC of axions), imprint in spin vs. mass plots



microwave signal in cavity (strong B-field)

magnetic resonance exp.

axion helioscope (**a**->γ in B-field)

magn. flux in superc. loop

a emissions in white dwarfs due to bremsstrahlung → $a\bar{e}e$ coupling (WD cooling)

KSVZ, DFSZ: $|\frac{E}{N} - 1.92| \in [0.07, 7]$

PDG (2010)

Future Directions

- Explore impact of FN messengers on unification (à la unificaxion) and examine different UV completions

  Giudice, Rattazzi, Strumia, 1204.5465

- Look for further signatures, interactions with experimentalists from NA62: $K^+ \to \pi^+ a$ search with a almost massless is a new challenge

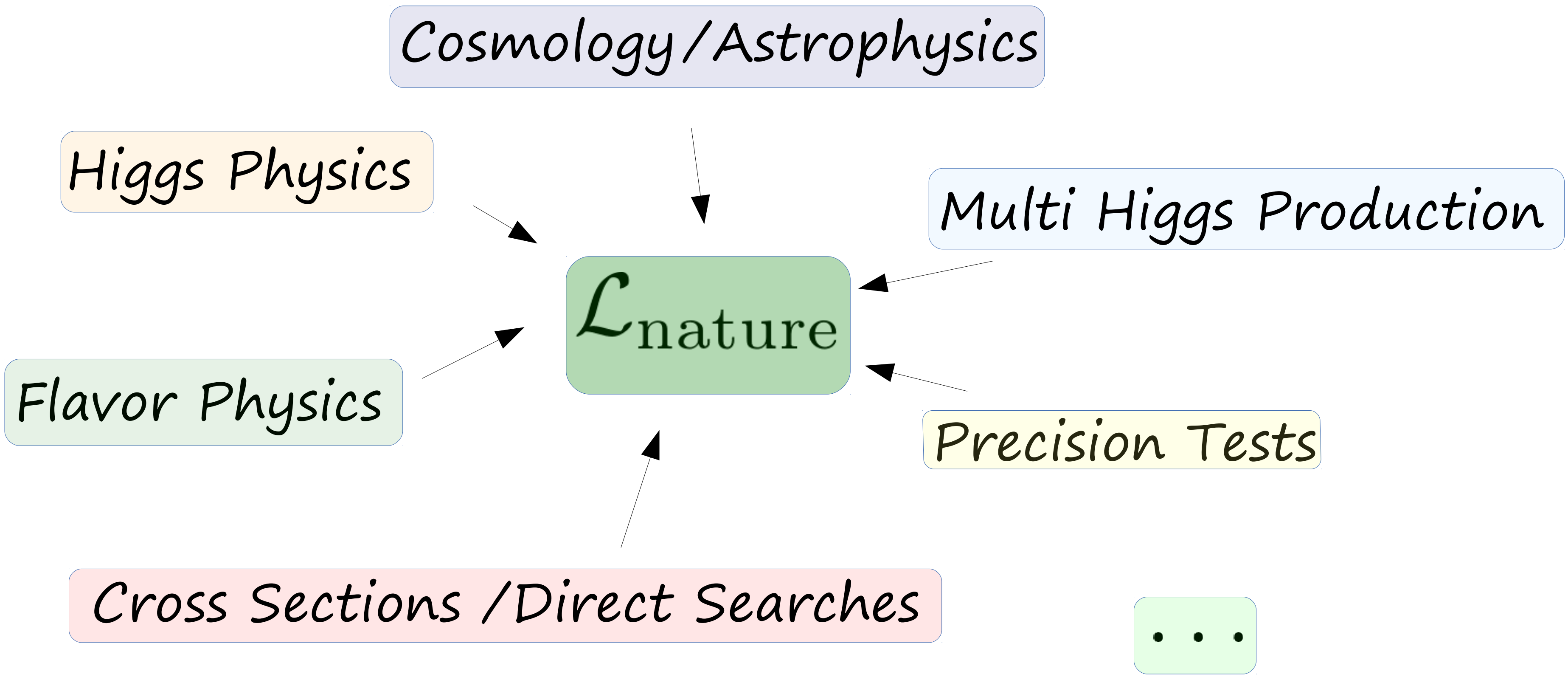
- Study embedding in supersymmetric scenario or PGBH setup

- ...

Conclusions

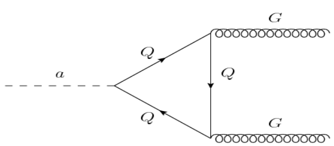
- Axiflavon solves *simultaneously* several of the problems of the SM within a very minimal and predictive model
- Solution to flavor puzzle considerably restricts axion properties, FCNCs → axion = window to generation of flavor hierarchies
- Complementary information from flavor, cosmology, axion searches: *probing interesting parameterspace in the future and potentially telling apart general axion solution from axiflavon*

Combined Effort



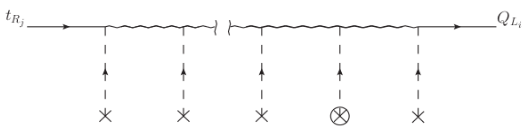
Conclusions

- Strong CP Problem



$\longrightarrow \; a\, G\tilde{G}$

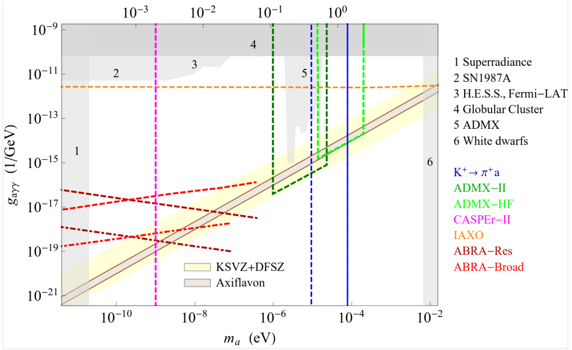
- Flavor Puzzle



$$\mathcal{L} = a^u_{ij}\; Q_i U^c_j\, H\, (\Phi/\Lambda)^{[q]_i+[u]_j} + \ldots$$

Axiflavon $\Phi = \frac{1}{\sqrt{2}}(v_\Phi + \phi)e^{ia/v_\Phi}$

- Dark Matter



Strong CP $\leftrightarrow$ Flavor $\leftrightarrow$ Cosmology