Paul Scherrer Institut

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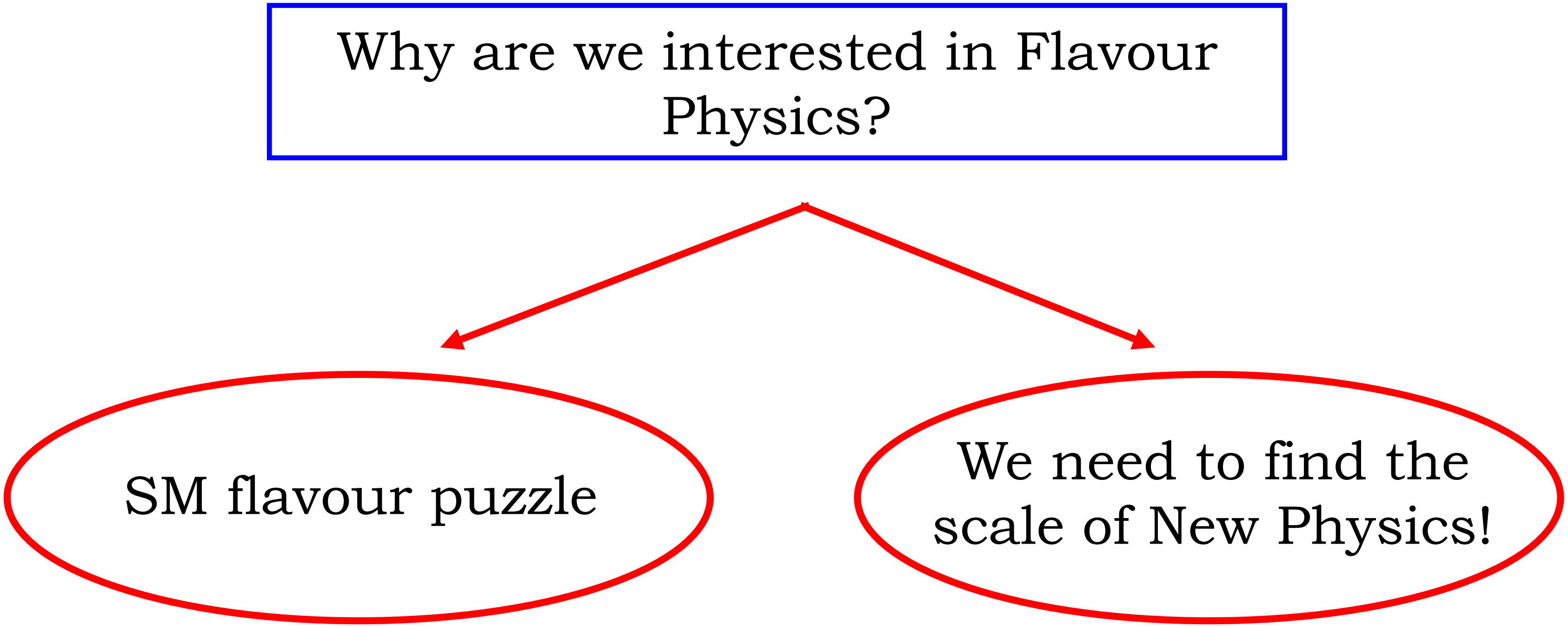
# Two ways of connecting flavour to Dark Matter: flavour portals and axiflavon

Lorenzo Calibbi
ITP CAS, Beijing

# Introduction



Why are we interested in Flavour Physics?

SM flavour puzzle

We need to find the scale of New Physics!

- Why three families?
- Why the hierarchies?

(*e.g.* $m_t / m_e = 3.4 \times 10^5$ )

- LHC found a SM-like Higgs
- No evidence of new phenomena
- We know there is new physics somewhere (DM, neutrino masses, baryogenesis etc.)

# SM flavour puzzle

Hierarchy of SM fermion masses and mixing

Up quarks:

$$\frac{m_c}{m_t} \approx \epsilon^4, \quad \frac{m_u}{m_t} \approx \epsilon^8$$

Down quarks:

$$\frac{m_s}{m_b} \approx \epsilon^3, \quad \frac{m_d}{m_b} \approx \epsilon^5$$

CKM matrix

$$V_{CKM} \approx \begin{pmatrix} 1 & \epsilon & \epsilon^3 \\ \epsilon & 1 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix}$$

$$\epsilon \approx 0.23$$

Hints for an organizing principle: is there a dynamical explanation?

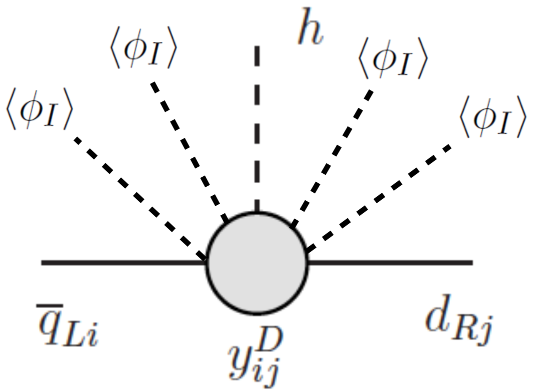
# Froggatt-Nielsen flavour models

- SM fermions charged under a new horizontal symmetry $G_F$
- $G_F$ forbids Yukawa couplings at the renormalisable level
- $G_F$ spontaneously broken by "flavons" vevs $\langle\phi_I\rangle$
- Yukawas arise as higher dimensional operators

Froggatt Nielsen '79
Leurer Seiberg Nir '92, '93

$$\mathcal{L}_{yuk} = y^U_{ij}\,\bar{q}_{Li}u_{Rj}\,\tilde{h} + y^D_{ij}\,\bar{q}_{Li}d_{Rj}\,h + \text{h.c.}$$

$$y^{U,D}_{ij} \sim \prod_I \left(\frac{\langle\phi_I\rangle}{M}\right)^{n^{U,D}_{I,ij}}$$



$\phi_I < M$ ⇨ $\epsilon_I \equiv \langle\phi_I\rangle/M$ small exp. parameter

$n^{U,D}_{I,ij}$ dictated by the symmetry

What is $G_F$ ?

# Froggatt-Nielsen flavour models

$G_F$ abelian or non-abelian, continuous or discrete

U(1), U(1)xU(1), SU(2), SU(3), SO(3), $A_4$ …

Froggatt Nielsen ’79; Leurer Seiberg Nir ’92, ’93; Ibanez Ross ’94; Dudas Pokorski Savoy ’95; Binetruy Lavignac Ramond ’96; Barbieri Dvali Hall ’95; Pomarol Tommasini ’95; Berezhiani Rossi '98; King Ross ’01; Ma ’02; Altarelli Feruglio ’05…

U(1) example

Chankowski et al. ‘05

$$(\mathcal{Q}_{q_1}, \mathcal{Q}_{q_2}, \mathcal{Q}_{q_3}) = (3,\, 2,\, 0)$$

$$(\mathcal{Q}_{u_1}, \mathcal{Q}_{u_2}, \mathcal{Q}_{u_3}) = (5,\, 2,\, 0) \quad \mathcal{Q}_\phi = -1$$

$$(\mathcal{Q}_{d_1}, \mathcal{Q}_{d_2}, \mathcal{Q}_{d_3}) = (4,\, 2,\, 2)$$

$$\Longrightarrow$$

$$y^u_{ij} = a^u_{ij}\, \epsilon^{\mathcal{Q}_{q_i} + \mathcal{Q}_{u_j}}$$

$$y^d_{ij} = a^d_{ij}\, \epsilon^{\mathcal{Q}_{q_i} + \mathcal{Q}_{d_j}}$$

$$\epsilon = \phi/M \approx 0.23$$

$$Y_u \sim \begin{pmatrix} \epsilon^8 & \epsilon^5 & \epsilon^3 \\ \epsilon^7 & \epsilon^4 & \epsilon^2 \\ \epsilon^5 & \epsilon^2 & 1 \end{pmatrix} \qquad Y_d \sim \begin{pmatrix} \epsilon^7 & \epsilon^5 & \epsilon^5 \\ \epsilon^6 & \epsilon^4 & \epsilon^4 \\ \epsilon^4 & \epsilon^2 & \epsilon^2 \end{pmatrix}$$

*M* can be interpreted as the mass scale of new degrees of freedom: the “flavour messengers”

# Low-energy flavour models

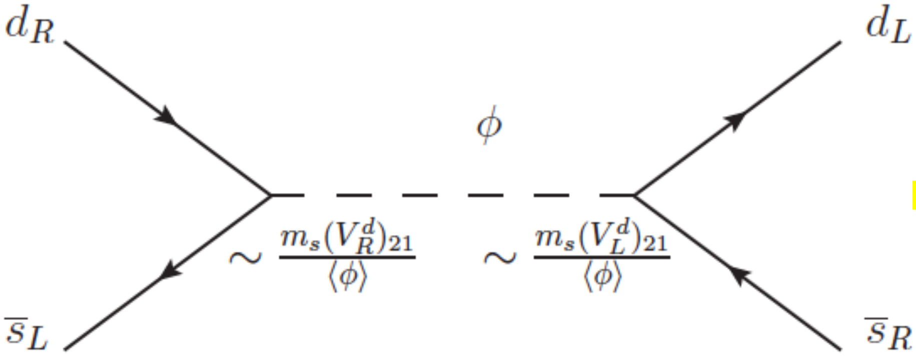
How light can the flavour dynamics be?

- Effective Yukawas imply fermion-flavon couplings

$$(m_f)_{ij} = a^f_{ij}\left(\frac{\langle\phi\rangle}{M}\right)^{n^f_{ij}}\frac{v}{\sqrt{2}} \quad\Longrightarrow\quad \mathcal{L}\supset n^f\,\frac{m_f}{\langle\phi\rangle}\,f_L f_R \phi$$

- Generically flavour violating
- FCNC induced at tree-level, but suppressed by small quark masses, *e.g.*:

Leurer Seiberg Nir ’92, ’93



$$\Longrightarrow\quad (\bar{s}_L d_R)(\bar{s}_R d_L)$$

- What if the flavour symmetry is local?

# Low-energy flavour models

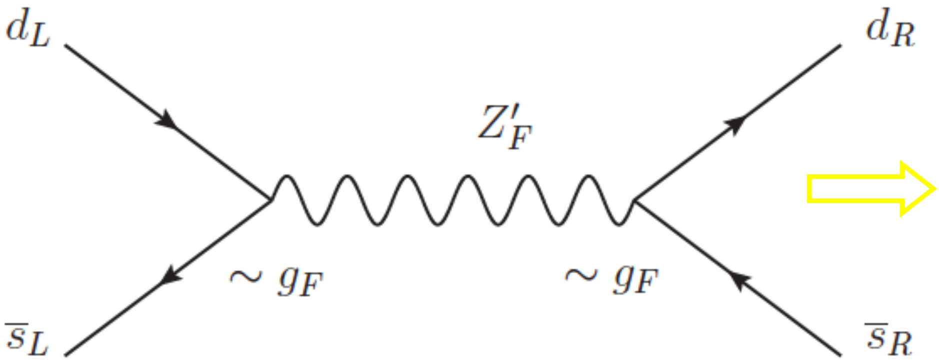
How light can the flavour dynamics be?

- Local flavour symmetry ⟹ flavour gauge bosons, *e.g.* abelian Z' :

$$\mathcal{L} \supset g_F \, \overline{f} \gamma^\mu (\mathcal{Q}_{f_L} P_L + \mathcal{Q}_{f_R} P_R) f \; Z'_\mu$$

- FV couplings to fermions (different generations have different charges)

- FCNC also arise at tree-level, *e.g.*:



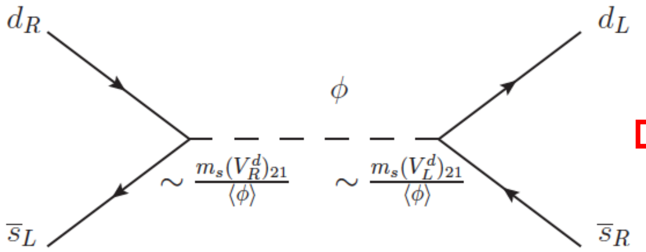
$$(\overline{s}_L \gamma^\mu d_L)(\overline{s}_R \gamma_\mu d_R)$$

- Additional contributions arise from the messenger sector

# FCNC bounds on FN models

**U(1) example:**

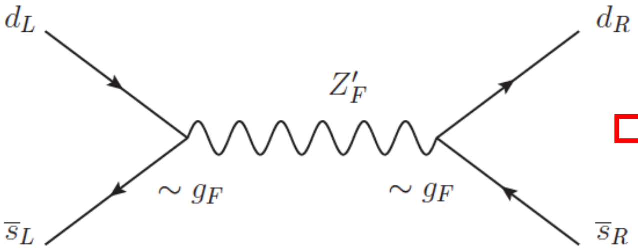
TeV-scale flavons are possible!



$$\Delta M_K : \; m_\phi \gtrsim 580 \text{ GeV}$$

$$\epsilon_K : \; m_\phi \gtrsim 2.3 \text{ TeV}$$

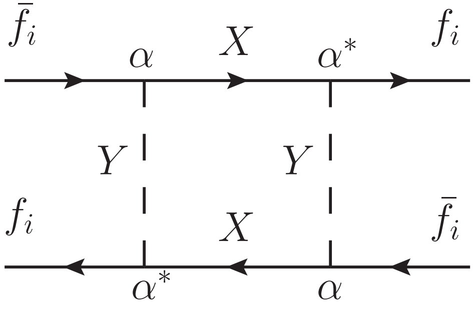
[with $\mathcal{O}(1)$ phases]



$$\Delta M_K : \; m_\phi \gtrsim \left(\frac{g_F}{10^{-3}}\right) \times 210 \text{ GeV}$$

$$\epsilon_K : \; m_\phi \gtrsim \left(\frac{g_F}{10^{-3}}\right) \times 3.3 \text{ TeV}$$

[with $\mathcal{O}(1)$ phases]



$$\Delta M_K : \; m_\phi \gtrsim 1.7 \text{ TeV}$$

$$\epsilon_K : \; m_\phi \gtrsim 27 \text{ TeV} \quad [\text{with } \mathcal{O}(1) \text{ phases}]$$

(indirect bounds from messenger sector)

LC Lalak Pokorski Ziegler ‘12

# Flavour Portal to Dark Matter

LC Crivellin Zaldivar ‘15

- DM must interact weakly with the SM, likely to be a SM singlet
- We introduce DM: fermionic SM singlets charged under $G_F$
- Flavour interactions are the only connection between dark and visible sector
- Global $G_F$ : DM and SM communicate only through flavon exchange
- Local $G_F$ : interactions can be also mediated by flavour gauge bosons

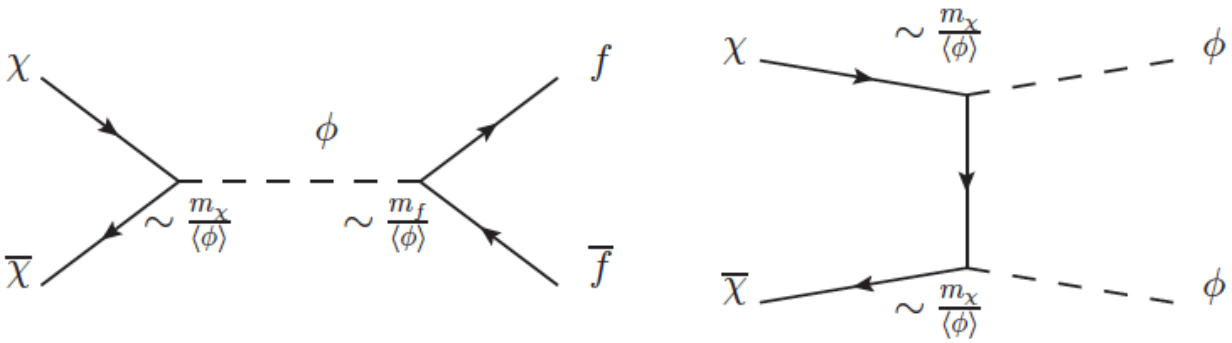
# Generic setup: flavon mediation

Global $G_F$

$$(m_f)_{ij} = a^f_{ij}\left(\frac{\langle\phi\rangle}{M}\right)^{n^f_{ij}}\frac{v}{\sqrt{2}} \qquad m_\chi = b_\chi\left(\frac{\langle\phi\rangle}{M}\right)^{n^\chi}\langle\phi\rangle \qquad m_\phi = k\langle\phi\rangle$$

$$\boxed{\mathcal{L} \supset n^f\frac{m_f}{\langle\phi\rangle}f_L f_R\phi + (n^\chi+1)\frac{m_\chi}{\langle\phi\rangle}\chi_L\chi_R\phi \;\equiv\; \lambda_f f_L f_R\phi + \lambda_\chi\chi_L\chi_R\phi}$$

DM annihilation to SM:



$$\langle\sigma^{\rm S}_\phi v\rangle \sim \frac{\lambda_\chi^2\lambda_f^2 m_\chi}{(4m_\chi^2 - m_\phi^2)^2 + \Gamma_\phi^2 m_\phi^2}T \qquad \langle\sigma^{\rm t}_\phi v\rangle \sim \frac{\lambda_\chi^4}{m_\chi^3}T$$

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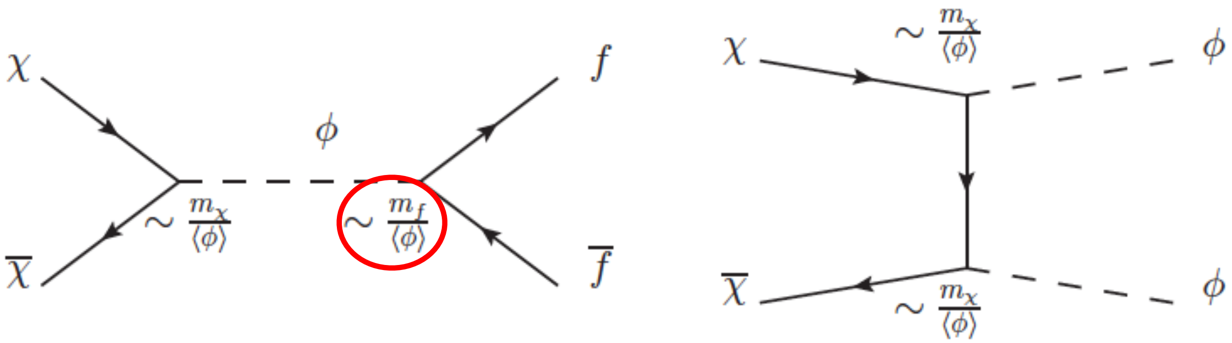

$$\langle\sigma^{\rm S}_\phi v\rangle \sim \frac{\lambda^2_\chi \lambda^2_f m_\chi}{(4m^2_\chi - m^2_\phi)^2 + \Gamma^2_\phi m^2_\phi} T \qquad \langle\sigma^{\rm t}_\phi v\rangle \sim \frac{\lambda^4_\chi}{m^3_\chi} T$$

annihilation to heavy flavours preferred

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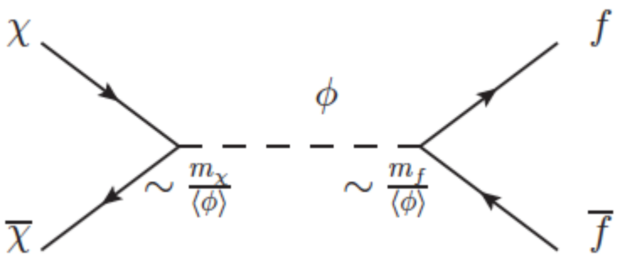
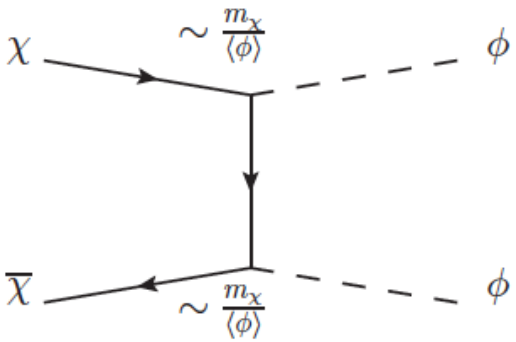
DM annihilation to SM:





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no coupling suppression

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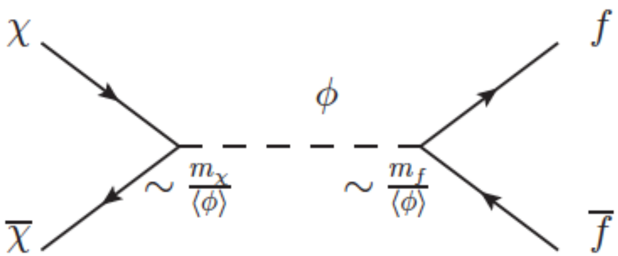
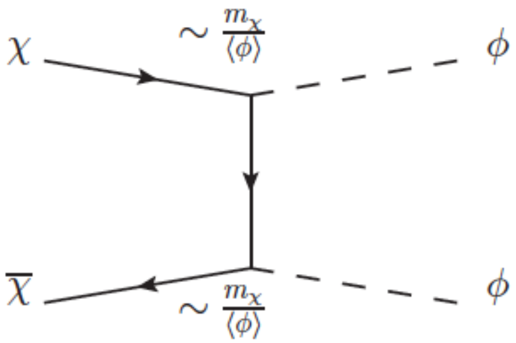
DM annihilation to SM:





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p-wave (velocity suppressed)

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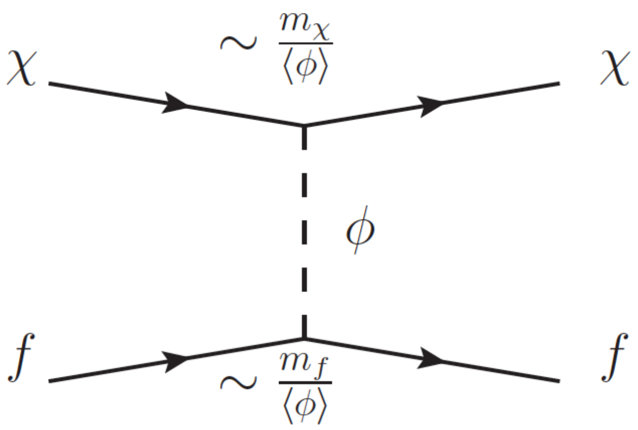
DM scattering with nuclei:



$$\sigma^{\rm SI}_\phi \sim \frac{\lambda_\chi^2 \lambda_{\phi N}^2}{m_\phi^4} \mu_{\chi N}^2$$

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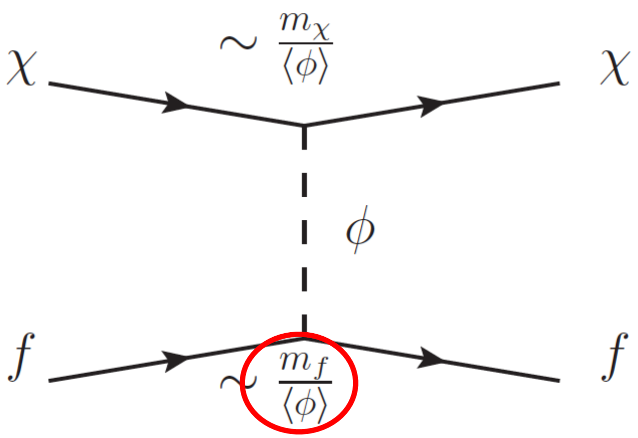


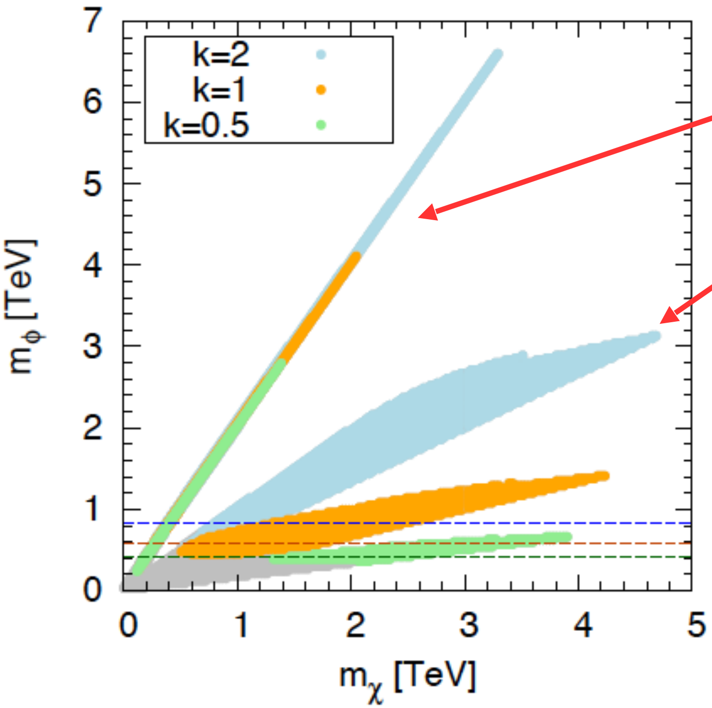
$$\sigma^{\rm SI}_\phi \sim \frac{\lambda^2_\chi\lambda^2_{\phi N}}{m^4_\phi}\mu^2_{\chi N}$$

suppressed by light quark masses/matrix elements

# Explicit example

Simple U(1)$_F$, only few parameters (besides O(1) coeffs.): $m_\phi$, $m_\chi$, $k \equiv m_\phi / \langle\phi\rangle$

$$\lambda_{ij}^{(u,d)} = a_{ij}^{(u,d)} (\mathcal{Q}_{q_i} + \mathcal{Q}_{(u_j,d_j)}) \epsilon^{\mathcal{Q}_{q_i} + \mathcal{Q}_{(u_j,d_j)}} \frac{v}{\langle\phi\rangle}$$



$\Omega_{\rm DM} h^2 \le 0.13$

Thermal freeze-out via flavour portal motivation for TeV-scale flavour dynamics!

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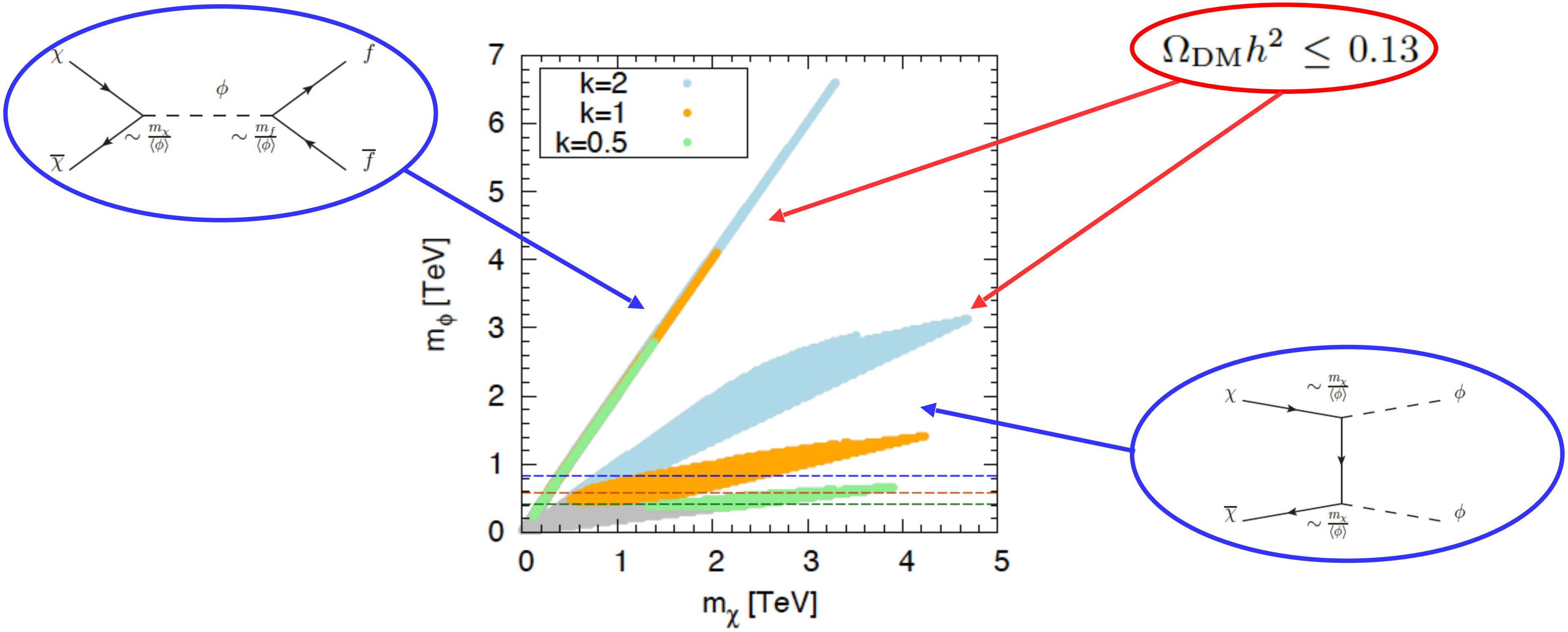

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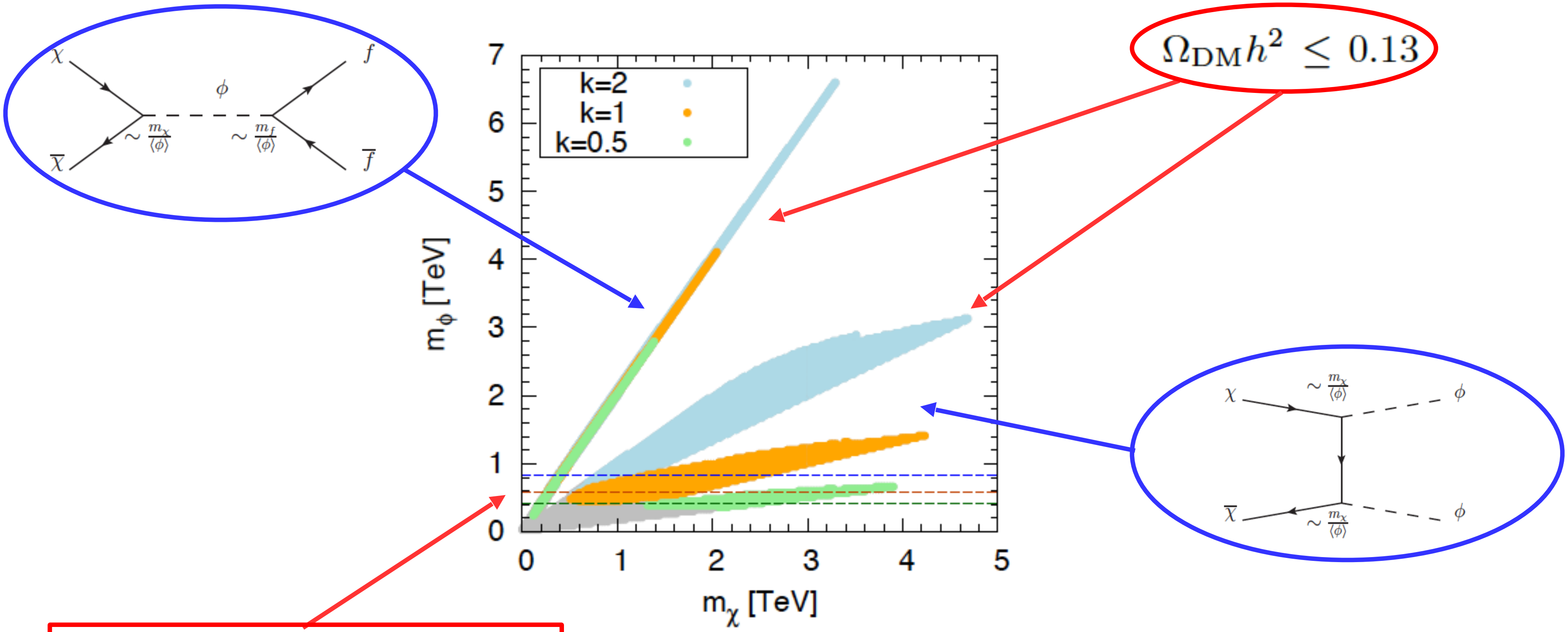

$\Omega_{\rm DM} h^2 \leq 0.13$

$m_\phi \gtrsim \sqrt{k} \times 580$ GeV

# Explicit example

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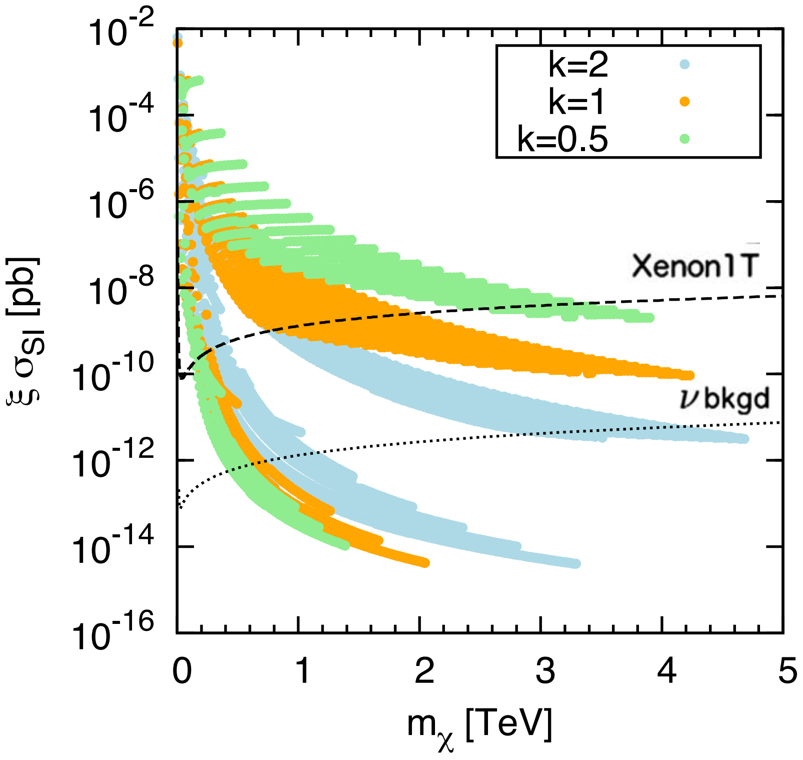
$$\lambda_{ij}^{(u,d)} = a_{ij}^{(u,d)}(\mathcal{Q}_{q_i} + \mathcal{Q}_{(u_j,d_j)})\epsilon^{\mathcal{Q}_{q_i}+\mathcal{Q}_{(u_j,d_j)}}\frac{v}{\langle\phi\rangle}$$



# Axiflavon

LC Goertz Redigolo Ziegler Zupan ‘16

- Another puzzle of the SM is the strong CP problem
- The strong CP problem is elegantly solved by an axion field
- The axion field can also provide the correct density of cold DM
- The axion is the PNGB of a colour-anomalous global U(1)
- Can we identify this symmetry with a Froggatt-Nielsen U(1)?

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Spoiler: Yes!

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Realisation of an old idea by Wilczek of using a subgroup of the global $U(3)^5$ flavour symmetry of the SM [as is the PQ U(1)]

Wilczek ’82

# The strong CP problem …

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?

- Limits on Neutron EDMs:

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

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

Crewther, Vecchia, Veneziano, Witten, PLB 88, 123-127 (1979)

Baker et. al., hep-ex/0602020

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

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

Theta-vacua of QCD

Electroweak Sector

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

borrowed from F. Goertz

# … and its 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:

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

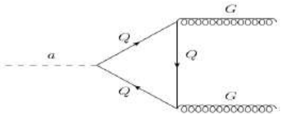
- $\mathcal{L} \supset \theta_0 \frac{\alpha_s}{8\pi} G\tilde G + \frac{\alpha_s}{4\pi} N \frac{a}{f} G\tilde G$

  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

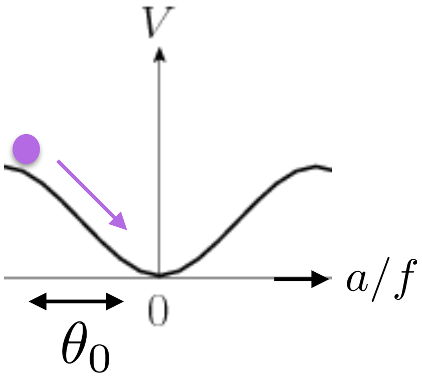


→ $a\,G\tilde G$

borrowed from F. Goertz

[axion essentially stable for $m_a \lesssim 20\,\mathrm{eV}$ ]

In early universe axion displaced from minimum



As universe expands axion rolls down and starts oscillating around minimum: energy stored in oscillations contributes to DM relic density

$$\Omega_{\mathrm{DM}} h^2 \approx 0.1 \left(\frac{10^{-5}\mathrm{eV}}{m_a}\right)^{1.18} \theta_0^2$$

Right abundance for $10^{-6}\ \mathrm{eV} \lesssim\ m_a\ \lesssim 10^{-4}\ \mathrm{eV}$

borrowed from R. Ziegler

# The axiflavon setup

The axion identified with the Nambu-Goldstone boson of a broken global FN U(1), *i.e.* as the phase of the flavon field → "axiflavon"

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

The axiflavon couples to the SM fermions exactly like the flavon:

$$\mathcal{L}_{aff} = \lambda^f_{ij} a F_i F^c_j + \text{h.c.} \qquad \lambda^{u,d,e}_{ij} = i([L]_i + [R]_j)\frac{v}{V_\Phi} y^{u,d,e}_{ij}$$

flavour violating!

And to gluons and photons via colour and electromagnetic anomalies:

$$\mathcal{L} = \frac{\alpha_s}{8\pi}\frac{a}{f_a}G\tilde{G} + \frac{E}{N}\frac{\alpha_{\rm em}}{8\pi}\frac{a}{f_a}F\tilde{F} \qquad f_a = V_\Phi/2N$$

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

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

[no contributions from messengers, vectorilike under U(1)]

Usual axion mass induced by the QCD anomaly:

$$m_a = 5.7\,\mu\text{eV}\left(\frac{10^{12}\text{GeV}}{f_a}\right)$$

# The axiflavon setup

$$\mathcal{L} = \frac{\alpha_s}{8\pi}\frac{a}{f_a}G\tilde{G} + \frac{E}{N}\frac{\alpha_{\rm em}}{8\pi}\frac{a}{f_a}F\tilde{F} \qquad\qquad f_a = V_\Phi/2N$$

Key observation: FN U(1) to reproduce observed Yukawas is necessarily anomalous and the coefficients are linked to the quark masses:

$$\det m_u \det m_d = \alpha_{ud}\, v^6 \epsilon^{2N}\,,$$

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

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

$$\Longrightarrow \quad \boxed{\frac{E}{N} = \frac{8}{3} - 2\,\frac{\overset{\approx -0.4}{\log\frac{\det m_d}{\det m_e}} - \overset{\mathcal{O}(1)}{\log\alpha_{de}}}{\underset{\approx -44}{\log\frac{\det m_u \det m_d}{v^6}} - \underset{\mathcal{O}(1)}{\log\alpha_{ud}}}}$$

Ibanez Ross '94, Bineutry Lavignac Ramond '94 '96

Sharp prediction for the coupling to photons $\frac{1}{4}g_{a\gamma\gamma}aF\tilde{F}$, independent of U(1) charges and little sensitive to O(1)s:

$$\boxed{\frac{E}{N} \in [2.4, 3.0] \quad \Longrightarrow \quad g_{a\gamma\gamma} \in \frac{[1.0, 2.2]}{10^{16}\text{GeV}}\frac{m_a}{\mu\text{eV}}}$$

Compare to DFSZ and KSVZ axions:

$|E/N| \in [0.3, 2.7]$ $\qquad$ $|E/N| \in [0, 6]$

$$m_a = 5.7\,\mu\text{eV}\left(\frac{10^{12}\text{GeV}}{f_a}\right)$$

# Axiflavon phenomenology

Stellar evolution bounds $f_a$ > $10^8$ GeV [natural DM window $10^{10}$ GeV < $f_a$ < $10^{13}$ GeV]

⇨ flavour processes considered before are suppressed

Despite the tiny couplings low-energy searches for rare processes are sensitive to flavour-violating decays to ultralight axiflavons! *E.g.*:

$K^+ \to \pi^+ a$ $\quad$ $B^+ \to K^+ a$ $\quad$ $\mu^+ \to e^+ a$

Small rates but strong constraints! Most stringent from Kaons:

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

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$$\mathrm{BR}(K^+ \to \pi^+ a) \simeq 1.2 \cdot 10^{-10} \left(\frac{m_a}{0.1\,\mathrm{meV}}\right)^2 \left(\frac{\kappa_{sd}}{N}\right)^2 \qquad \kappa_{sd}/N \sim \mathcal{O}(1)$$

$$\mathrm{BR}(K^+ \to \pi^+ a) < 7.3 \cdot 10^{-11} \quad \Rightarrow \quad f_a \gtrsim \frac{\kappa_{sd}}{N} \times 7.5 \cdot 10^{10}\,\mathrm{GeV}$$

E787, E949

Increased sensitivity ~70x is expected at NA62!

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$$K^+ \to \pi^+ a \qquad B^+ \to K^+ a \qquad \mu^+ \to e^+ a$$

Interesting effects in the lepton sector too:

$$\Gamma(\mu^+ \to e^+ a) \simeq \frac{m_\mu}{16\pi} |\lambda^e_{21} + \lambda^{e*}_{12}|^2 \qquad \lambda^e_{12} \sim \frac{m_\mu}{f_a}$$

for anarchical neutrinos

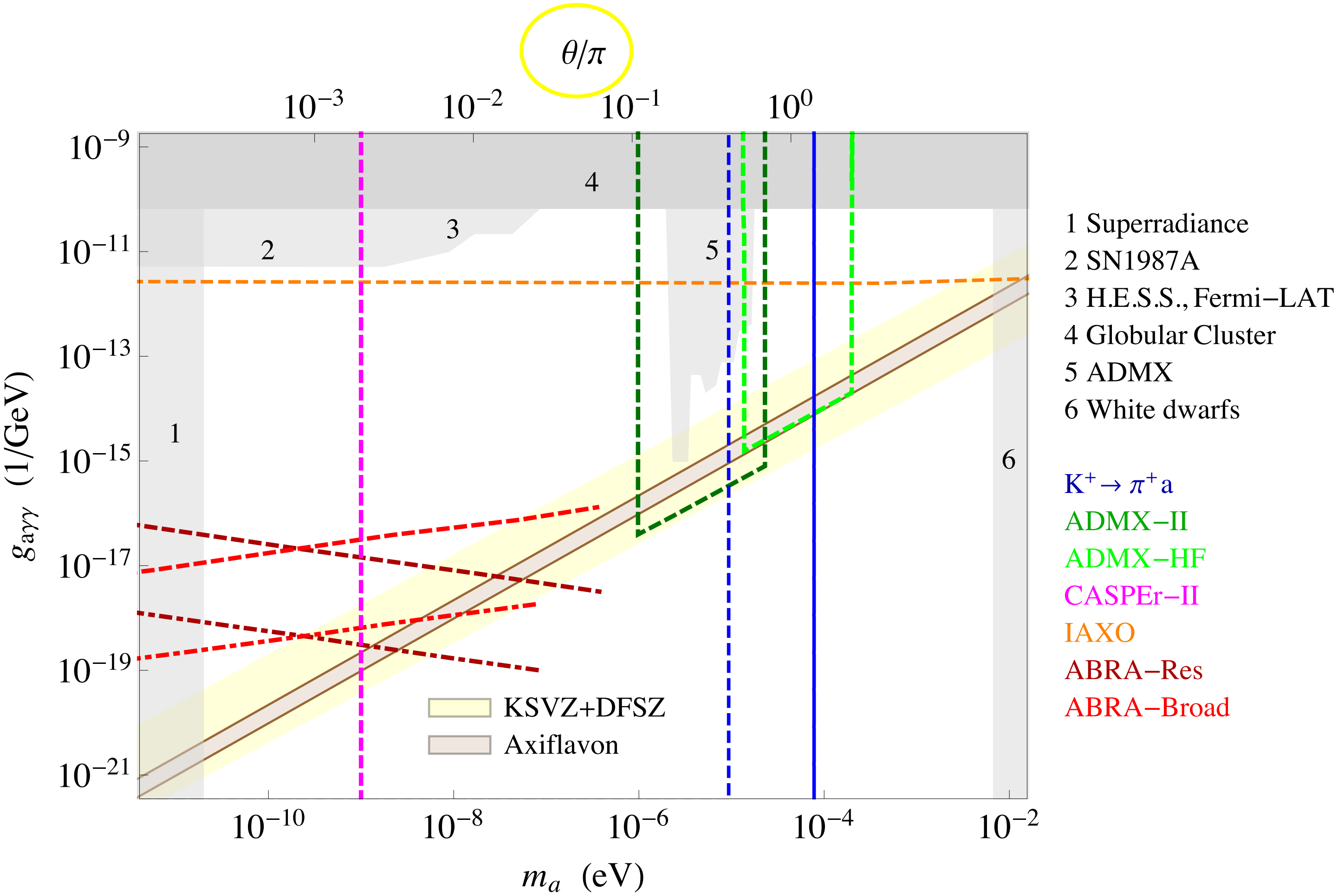
$$\mathrm{BR}(\mu^+ \to e^+ a) \simeq 2.4 \times 10^{-8} \left(\frac{m_a}{0.1\ \mathrm{meV}}\right)^2 \left(\frac{\kappa_{\mu e}}{N}\right)^2$$

Limit on muon decay to “Majoron”: $2.6\text{x}10^{-6}$, 30 years old! TRIUMF ‘86

# Axiflavon phenomenology

Axiflavon can be complementary tested at axion and flavour experiments!

$\frac{1}{4} g_{a\gamma\gamma} a F \tilde{F}$



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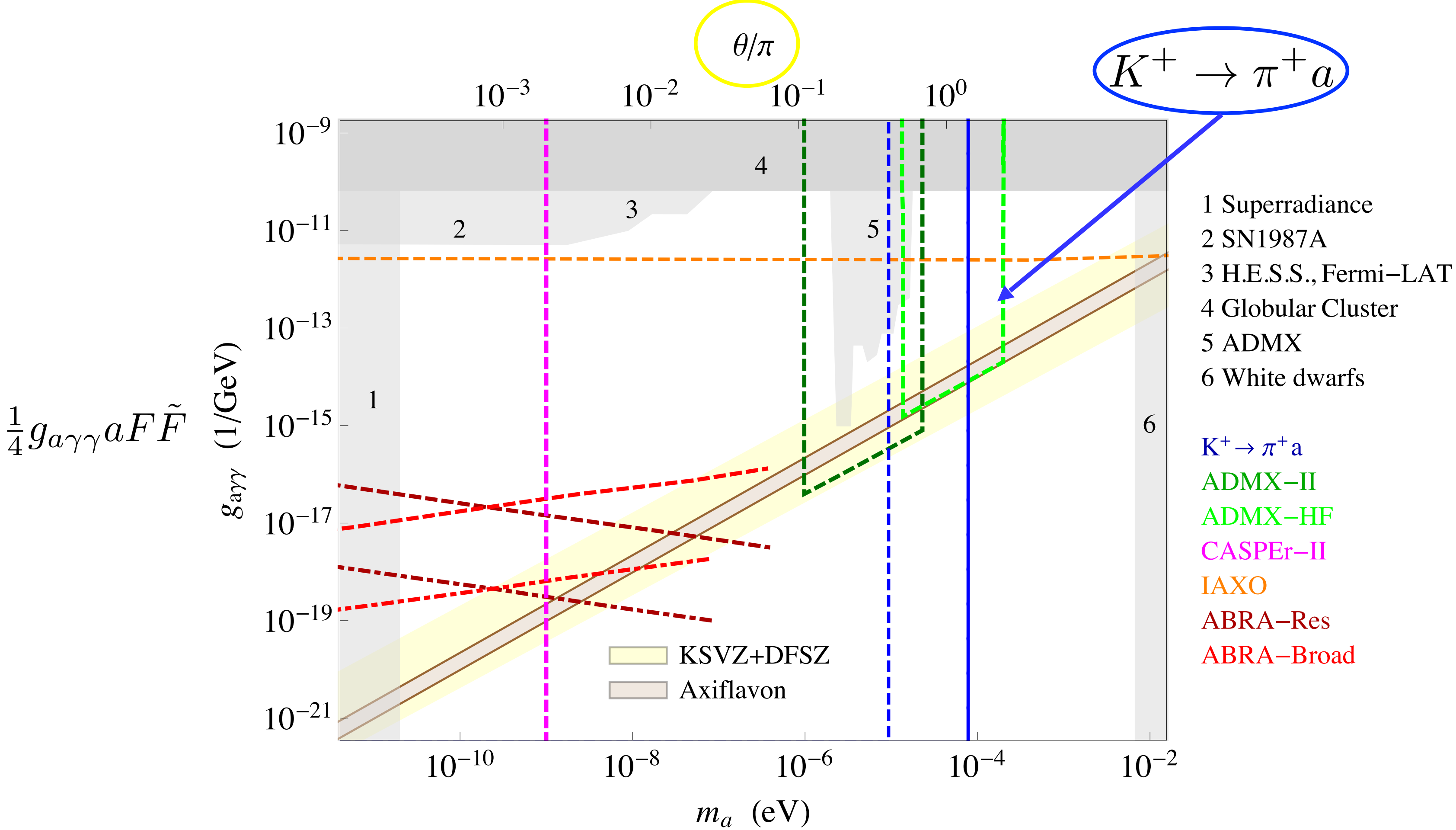

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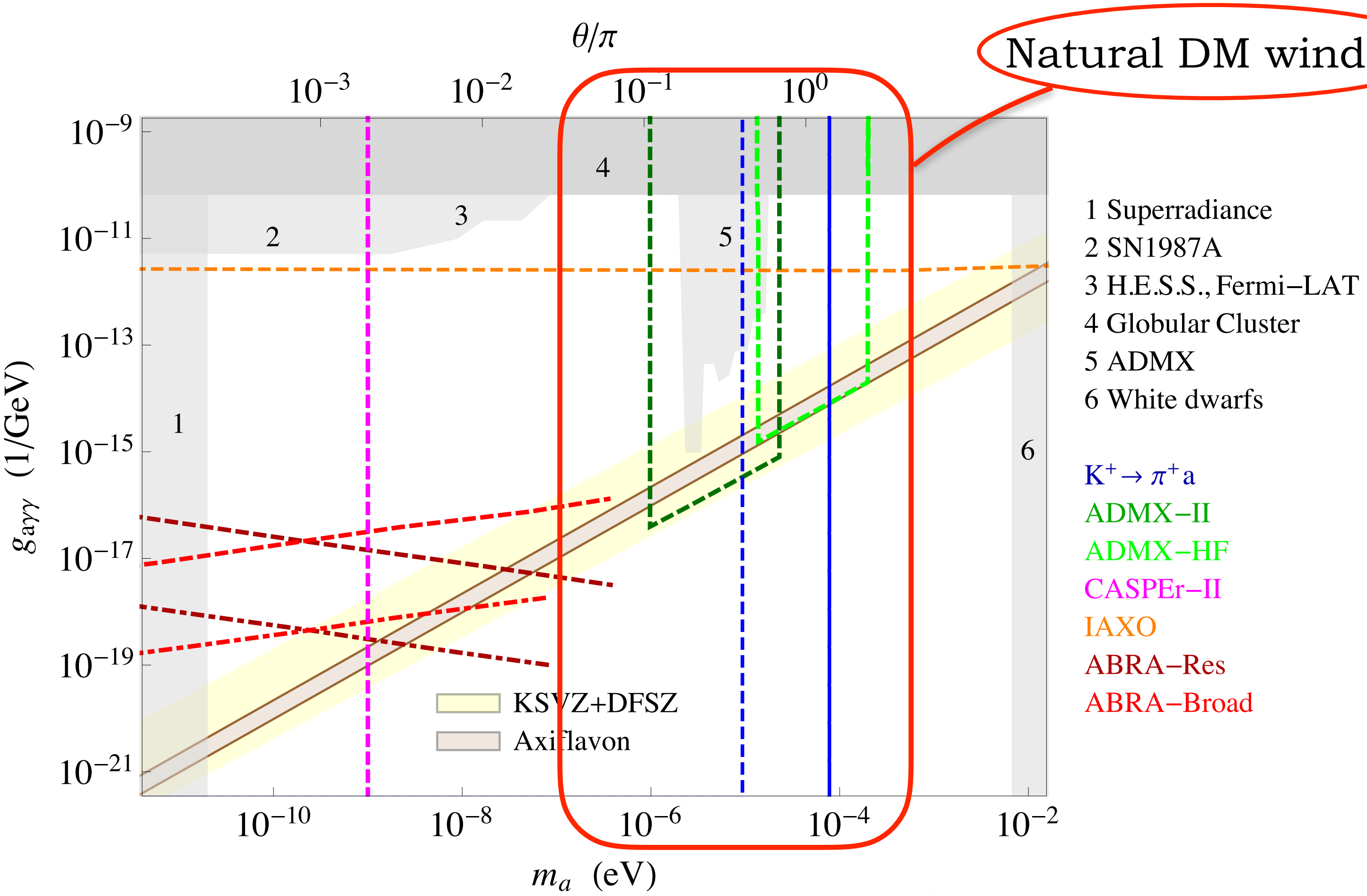
# Axiflavon phenomenology

Axiflavon can be complementary tested at axion and flavour experiments!

Natural DM window

$$\frac{1}{4} g_{a\gamma\gamma} a F \tilde{F}$$



$$m_a = 5.7\,\mu\text{eV}\left(\frac{10^{12}\text{GeV}}{f_a}\right)$$

# Conclusions

We discussed two ways of connecting
Flavour and Dark Matter

Flavour portal

Axiflavon

# Conclusions

Froggatt-Nielsen flavour models are possible explanation of hierarchies in fermion masses and mixing

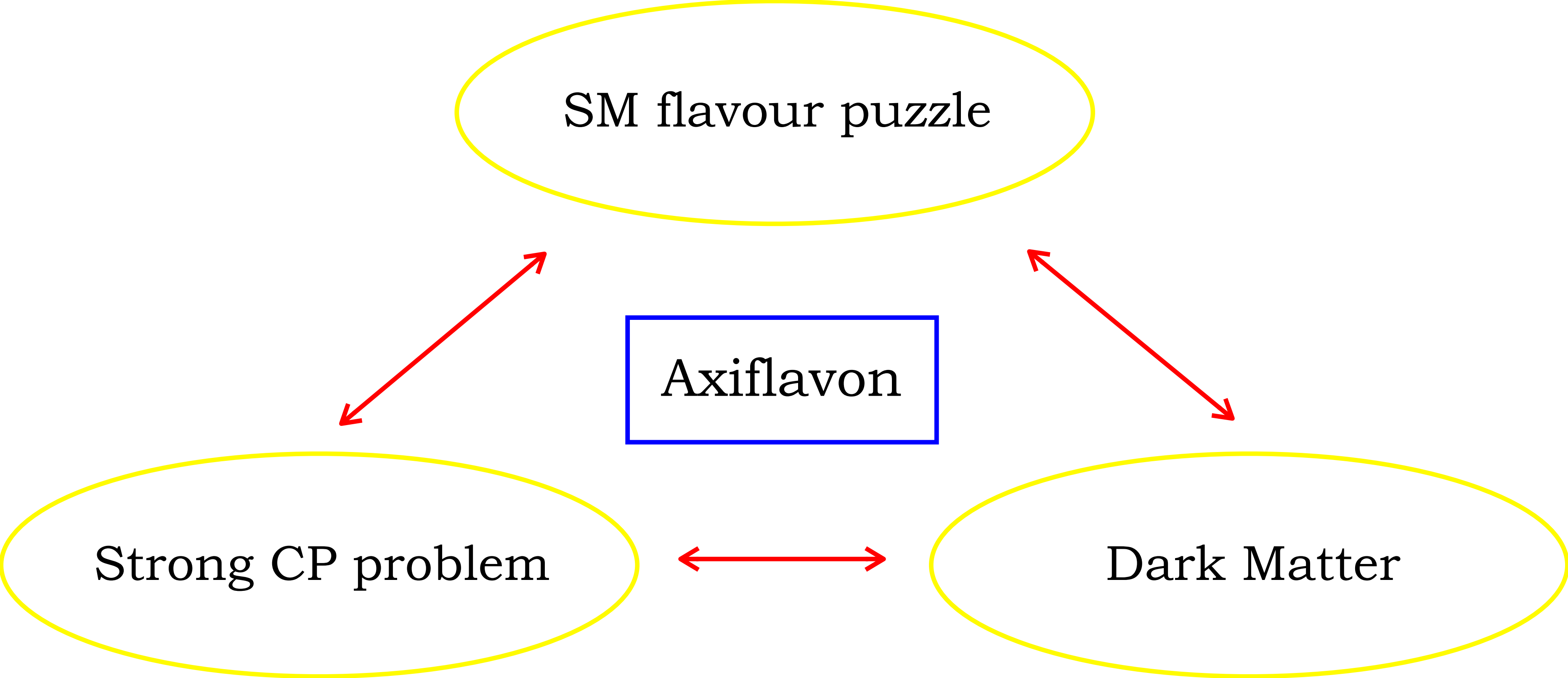
FCNC constraints still allows TeV-scale flavour dynamics

Dark Matter can be a thermal relic charged under the flavour symmetry only

No ad hoc quantum numbers: SM-DM interactions dictated by the flavour dynamics ("Flavour Portal")

Direct DM searches and flavour experiments can test this class of models

# Conclusions



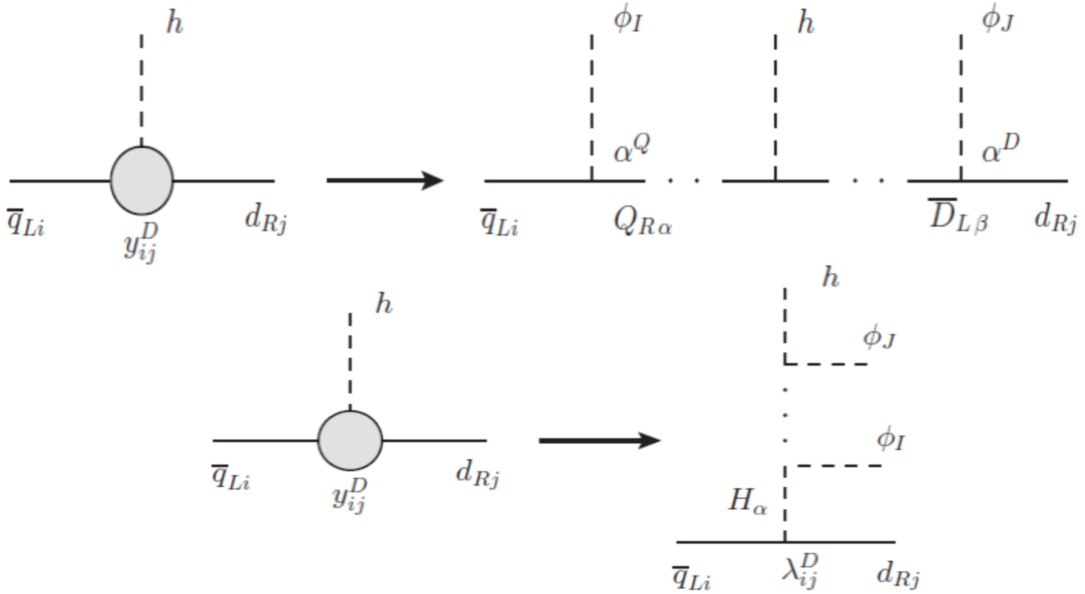
# 谢 谢

# Additional slides

# The messenger sector

- If smaller than $M_{Pl}$, $M$ can be interpreted as the mass scale of new degrees of freedom: the “flavour messengers”
- New fields in vector-like representations of the SM group and $G_F$-charged
- Effective Yukawa couplings generated by integrating out the messengers. Two possibilities: heavy fermions or heavy scalars:

see *e.g.* LC Lalak Pokorski Ziegler ‘12



Fermion UV Completion

“Higgs” UV Completion

⇒ messengers mix with SM fermions or scalar fields and induce FCNC

# Low-energy messengers

How light can the messenger sector be?

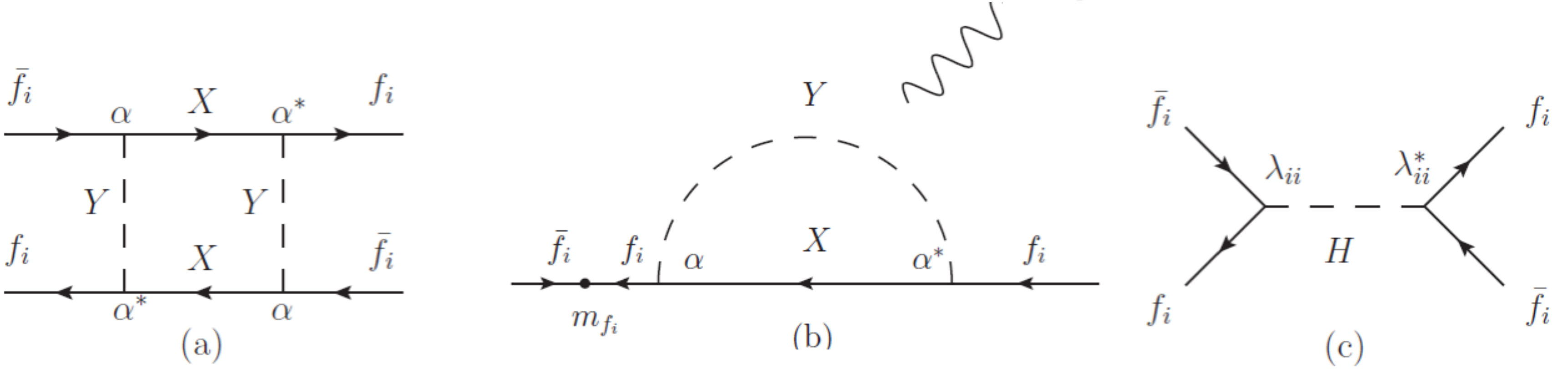
By construction always present couplings (with O(1) coeffs.) of the form:

FUVC

$$\mathcal{L} \supset \alpha^Q\, \overline{q}_{Li} Q_{R\alpha}\, \phi_I + \alpha^D\, \overline{D}_{L\beta} d_{Rj}\, \phi_J + \text{h.c.}$$

HUVC

$$\mathcal{L} \supset \lambda^D_{ij}\, \overline{q}_{Li} d_{Rj}\, H_\alpha + \text{h.c.}$$



$$\mathcal{L}_{eff} \supset \frac{|\alpha|^4}{16\pi^2 M^2} (\overline{f}_{Li} \gamma^\mu f_{Li})^2 \qquad \mathcal{L}_{eff} \supset \frac{|\alpha|^2}{16\pi^2 M^2} m_i \overline{f}_{Li} \sigma^{\mu\nu} f_{Ri} F_{\mu\nu} \qquad \mathcal{L}_{eff} \supset \frac{|\lambda_{ij}|^2}{M^2} (\overline{d}_{Li} d_{Rj})(\overline{d}_{Rj} d_{Li})$$

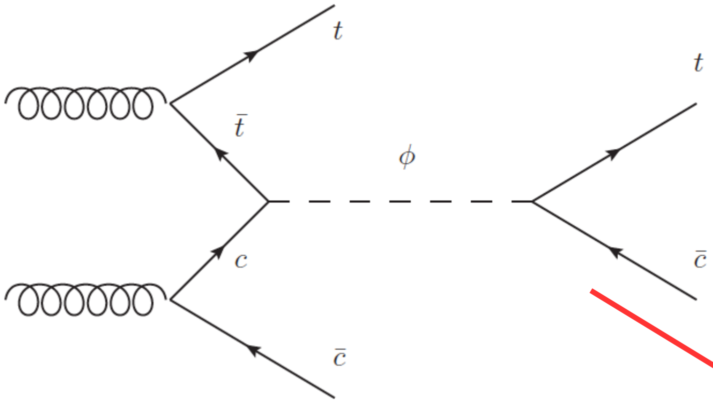
Flavour conserving ⇨ Flavour violating in the mass $d_{Li} \to d_{Li} + \sum_{j\neq i} \theta^{DL}_{ij} d_{Lj}$

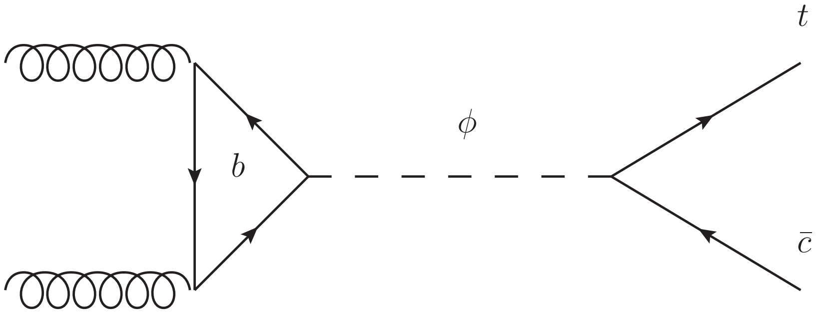
[ Abelian models: no cancellations (different O(1) coefficients) ]

LC Lalak Pokorski Ziegler ‘12

# Collider signatures?

Flavon production and decay → distinctive signatures, *e.g.* same-sign tops

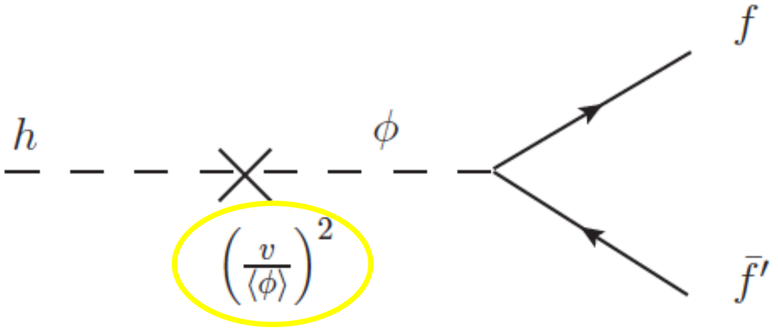




Low production at the LHC: 0.1 ($10^{-3}$) fb for 500 (1000) GeV flavon

Flavon-Higgs mixing → flavour-violating Higgs decays

$$\mathcal{L} \supset \ H^\dagger H \phi^\dagger \phi$$



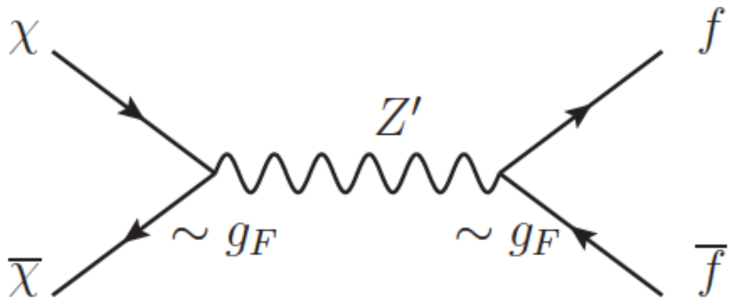
# Generic setup: flavour gauge bosons mediation

Local $G_F$

$$\mathcal{L} \supset \; g_F \, \overline{\chi} \gamma^\mu (\mathcal{Q}_{\chi_L} P_L + \mathcal{Q}_{\chi_R} P_R) \chi \; Z'_\mu + g_F \, \overline{f} \gamma^\mu (\mathcal{Q}_{f_L} P_L + \mathcal{Q}_{f_R} P_R) f \; Z'_\mu$$

DM annihilation to SM:

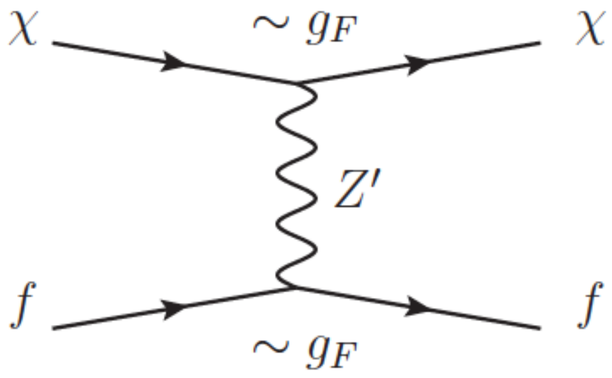
$$m_{Z'} = \sqrt{2} g_F \langle \phi \rangle$$



$$\langle \sigma_{Z'} v \rangle \sim \frac{g_F^4}{(m_{Z'}^2 - 4 m_\chi^2)^2 + \Gamma_{Z'}^2 m_{Z'}^2} m_\chi^2$$

no velocity suppression
no quark mass dependence

DM scattering with nuclei:

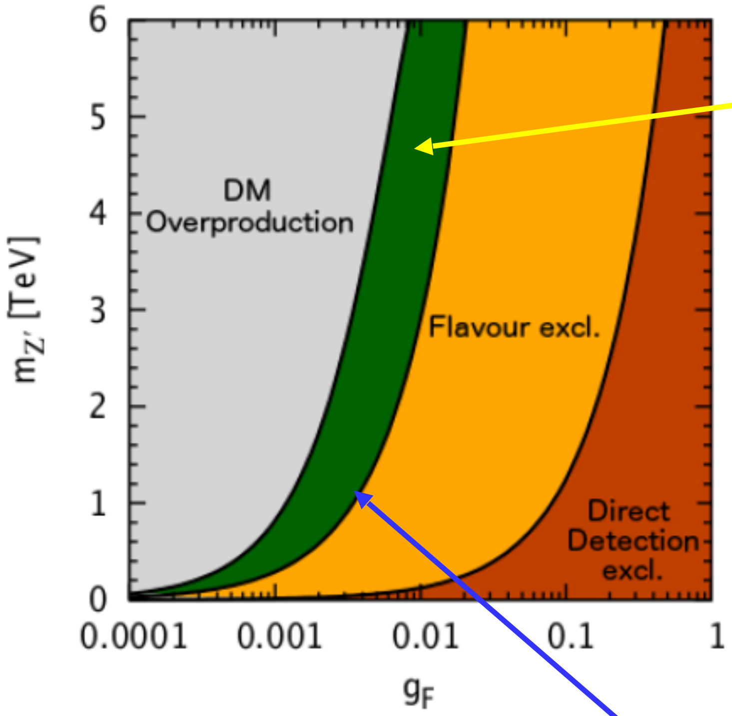


$$\sigma_{Z'}^{\rm SI} \sim \frac{g_F^2 \lambda_{Z'N}^2}{m_{Z'}^4} \mu_{\chi N}^2 \qquad \lambda_{Z'N} \propto g_F$$

# Explicit example

Local $U(1)_F$, relic density bound only fulfilled on the resonance: $m_\chi \approx m_{Z'}/2$

$m_\chi \approx m_{Z'}/2$



Viable region

$$m_{Z'} \gtrsim \left(\frac{g_F}{10^{-3}}\right) \times 210\ \text{GeV}$$