Flavor-specific scalar mediators

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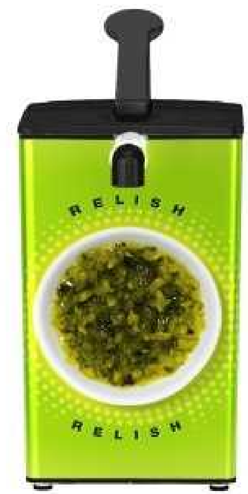
arXiv:1712.10022, arXiv:1812.05103

Light scalars,
flavor symmetries
and naturalness

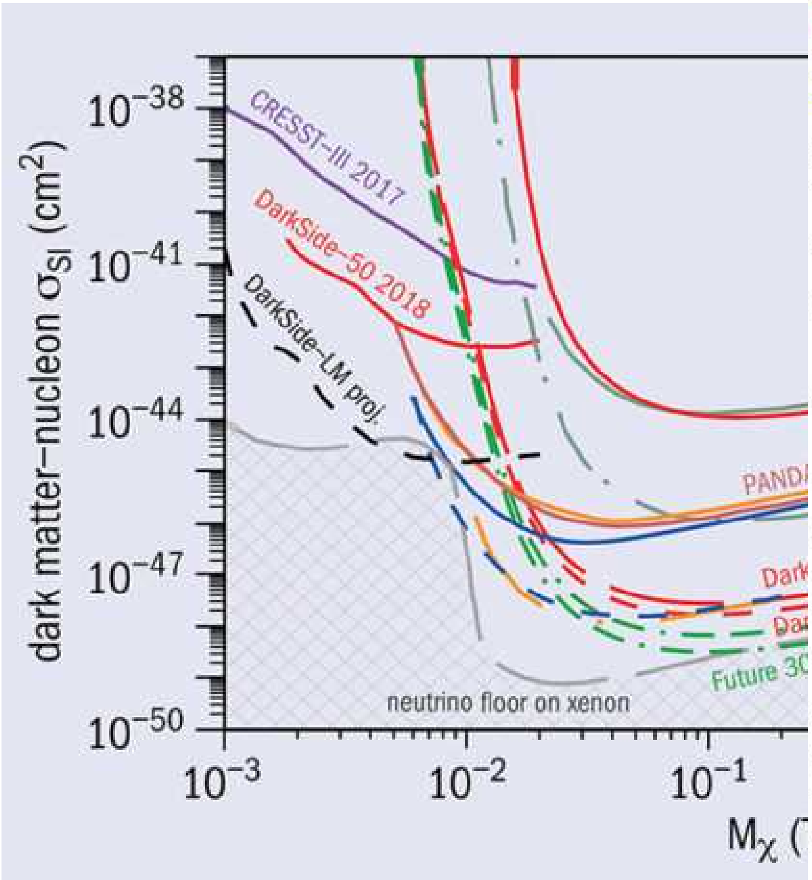


μ-specific scalars

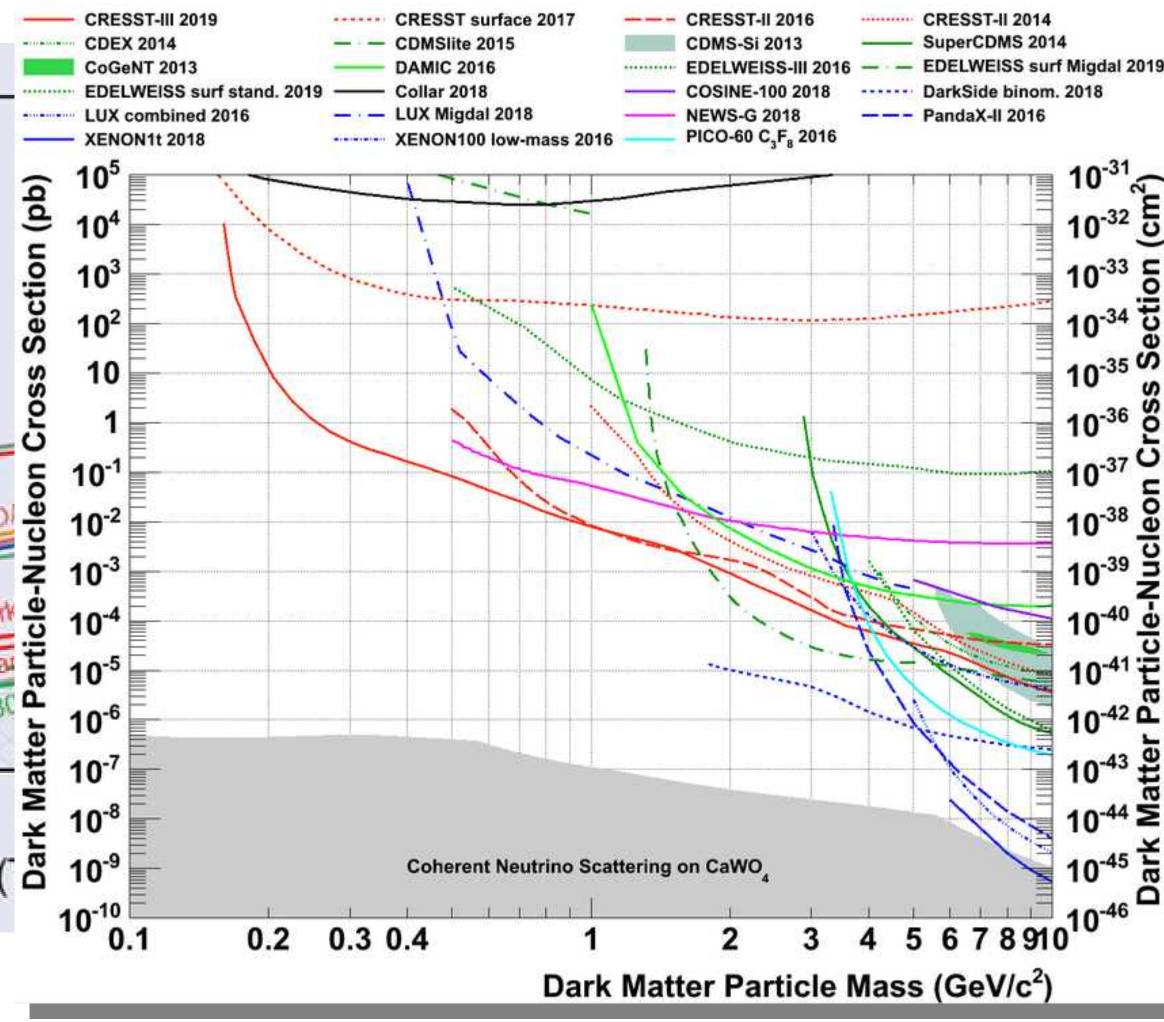
up-specific scalars

WIMP Direct Detection

CRESST Coll. 2019



CERN Courier 2018



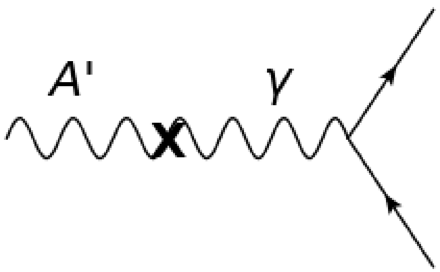
- Very strong direct detection constraints for weak-scale DM
- Constraints much weaker for $m_{DM} \lesssim 1$ GeV

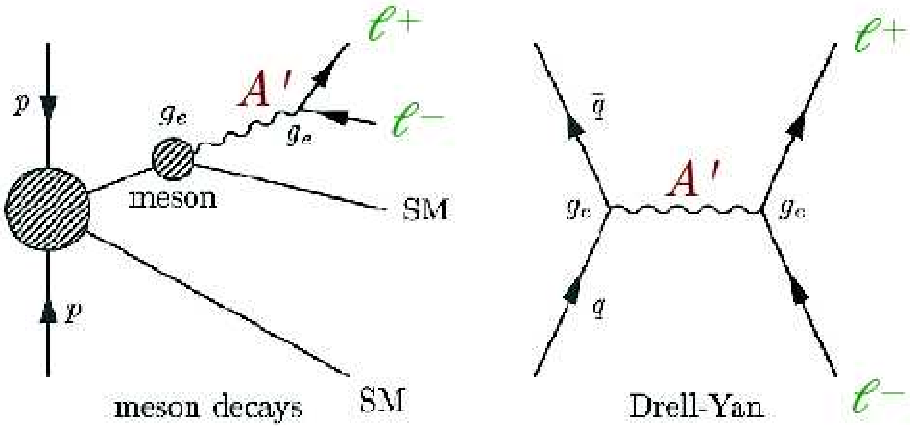
Light DM / light mediators

- Sub-GeV DM could evade direct detection bounds
- Relic density typically demands light mediator particles
- Examples of light mediators:
  - Gauge bosons (“dark photon”)
  - Scalars
  - Sterile neutrinos

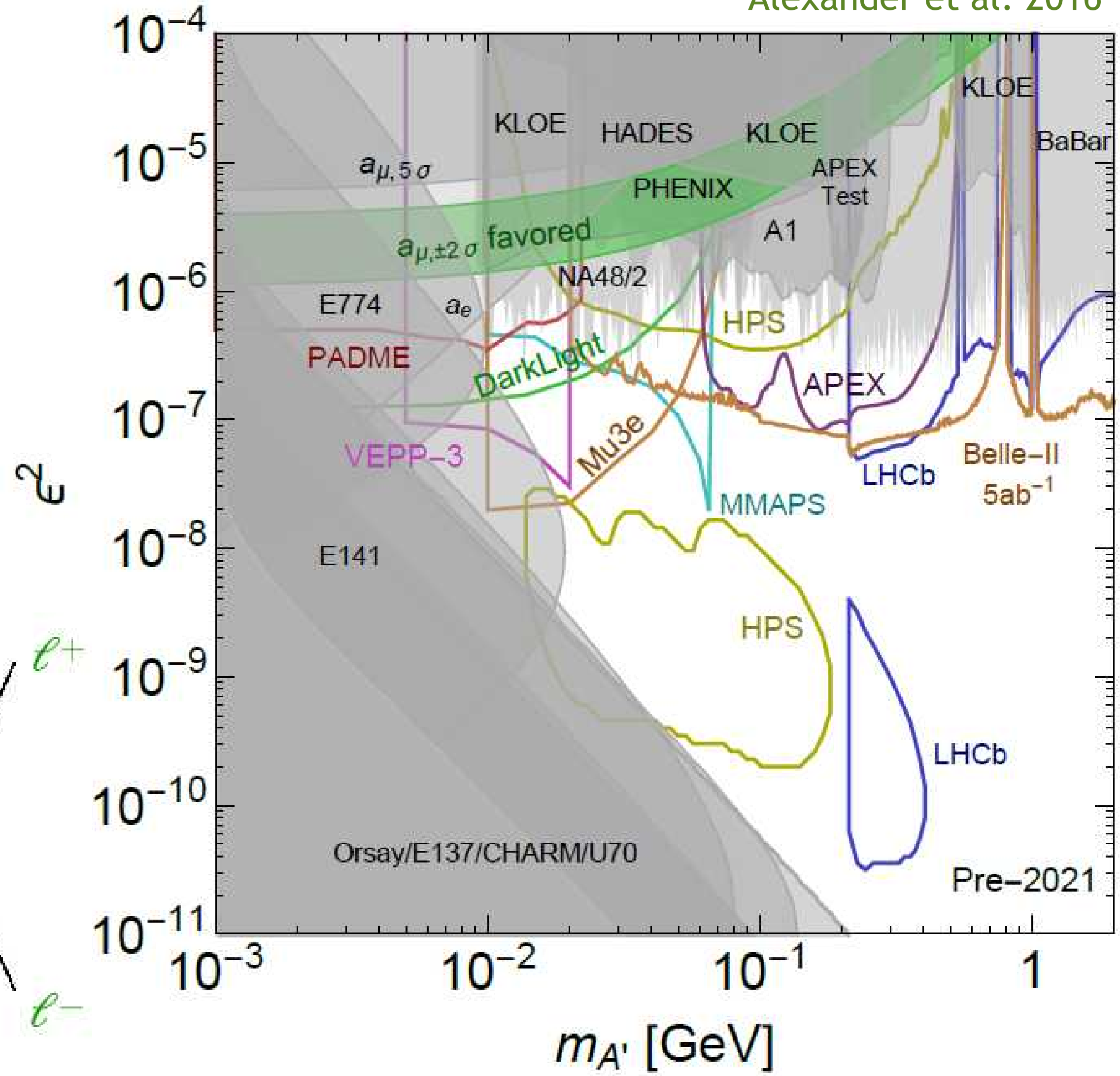
Dark photon

Kinetic mixing generates small coupling of A' to SM fermions





Alexander et al. 2016



Light scalars

- S is singlet under SM gauge symmetry
- Coupling to SM through dim-5 operators:

$$\mathcal{L}_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \left(\frac{c_S}{M} S \bar{Q}_L U_R H_c + \text{h.c.} \right) + \frac{d_S}{M} \partial_\mu S \bar{U}_R \gamma^\mu U_R$$
$$+ \frac{d'_S}{M} \left(i S \bar{U}_R \not{D} U_R + \text{h.c.} \right).$$

- SM flavor symmetry $U(3)_Q \times U(3)_U \times U(3)_D$
  broken by Yukawa couplings in SM:

$$\mathcal{L}_{\text{SM}} = i\bar{Q}_L \not{D} Q_L + i\bar{U}_R \not{D} U_R + i\bar{D}_R \not{D} D_R - \left(\bar{Q}_L Y_u U_R H_c + \bar{Q}_L Y_d D_R H + \text{h.c.} \right)$$

- $\mathcal{L}_S$ leads to additional breaking (through c_S, d_S, d'_S)

Minimal flavor violation

D'Ambrosio, Guidice, Isidori, Strumia, 2002

- **Idea:** flavor symmetry only broken by Yukawa couplings
- Treat Y_u, Y_d as spurion fields under $U(3)_Q \times U(3)_U \times U(3)_D$:

  $$Y_u \sim (3, \bar{3}, 1) \qquad Y_d \sim (3, 1, \bar{3})$$

  so that $-\left(\bar{Q}_L Y_u U_R H_c + \bar{Q}_L Y_d D_R H + \text{h.c.}\right)$ is invariant

- Transformation of S couplings:

$$\mathcal{L}_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_S^2 S^2 - \left(\frac{c_S}{M} S \bar{Q}_L U_R H_c + \text{h.c.}\right) + \frac{d_S}{M}\partial_\mu S \bar{U}_R \gamma^\mu U_R + \frac{d'_S}{M}\left(iS\bar{U}_R \not{D} U_R + \text{h.c.}\right).$$

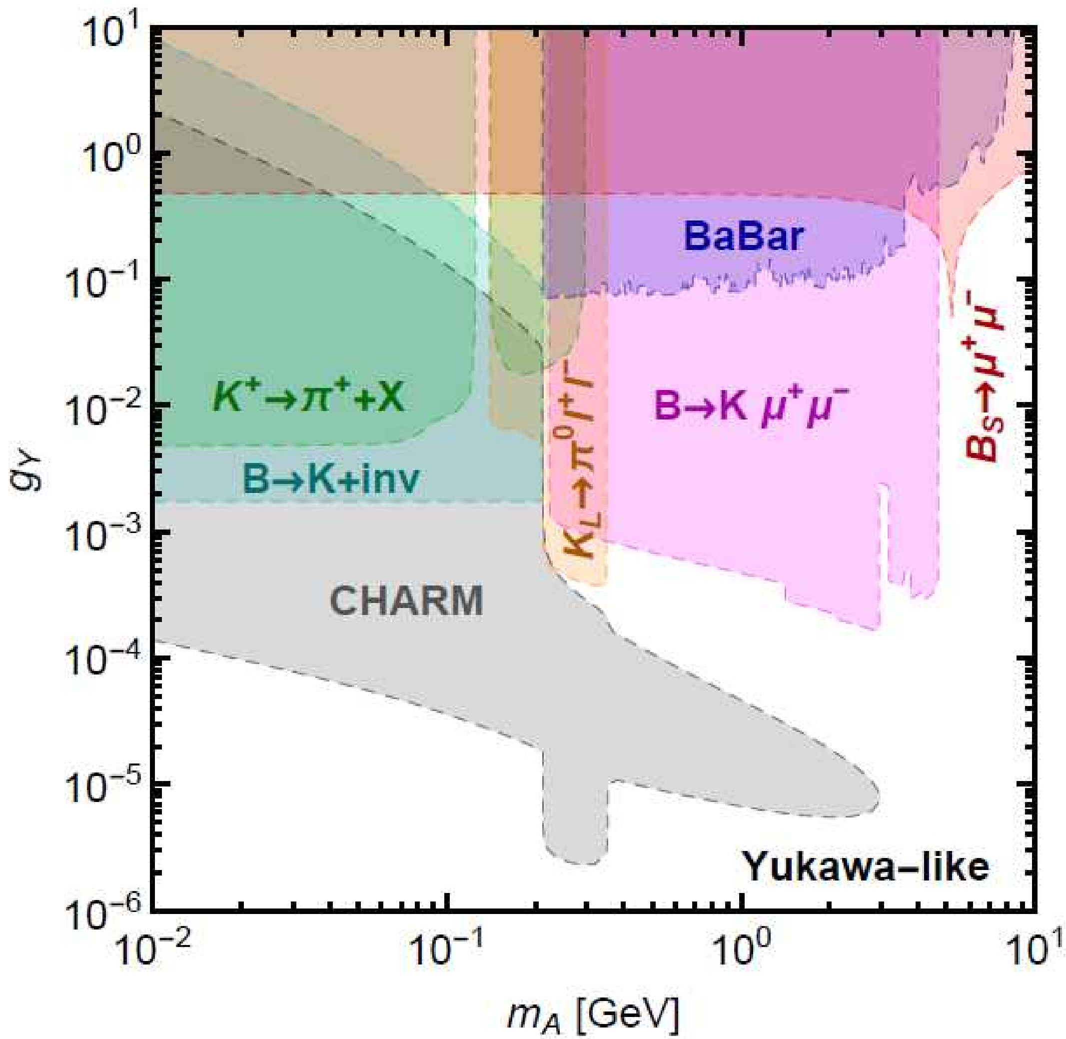
$$c_S \sim (3, \bar{3}, 1), \qquad c_S = c_1 Y_u + \ldots$$

$$d_S, d'_S \sim (1, 1, 1) \oplus (1, 8, 1). \qquad d_S = d_1 \mathbb{1} + d_2 Y_u^\dagger Y_u + \ldots$$

- S couplings are either **universal** or **dominantly to 3rd gen.**

Minimal flavor violation

- In MFV dominant constraints come from heavy-flavor mesons:

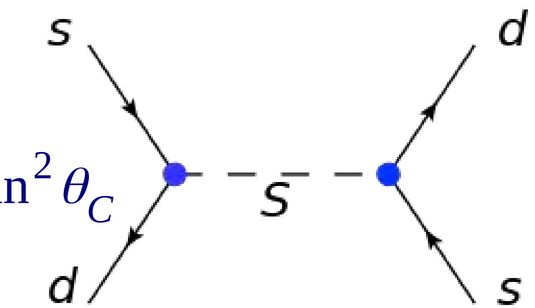


Dolan, Kahlhoefer, McCabe, Schmidt-Hoberg, 2014

Flavor alignment

- **MFV** ensures that FCNCs are under control

$\propto Y_s^\dagger Y_s \sin^2\theta_C$



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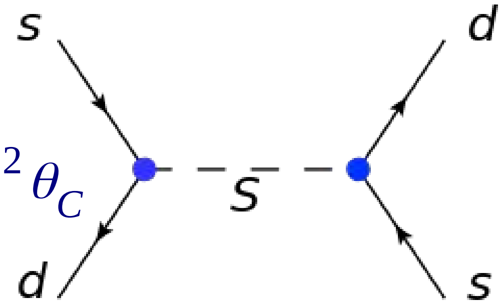

- Alternative: **Flavor alignment**
  a) Eliminate d_S, d'_S through field redefinition: $U_R \to U_R - (d'_S - i d_S) S U_R / M$

$$\mathcal{L}_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \left(\frac{c_S}{M} S \bar{Q}_L U_R H_c + \text{h.c.}\right) + \frac{d_S}{M} \partial_\mu S \bar{U}_R \gamma^\mu U_R$$
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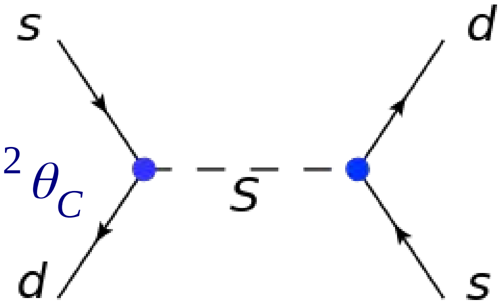
Flavor alignment



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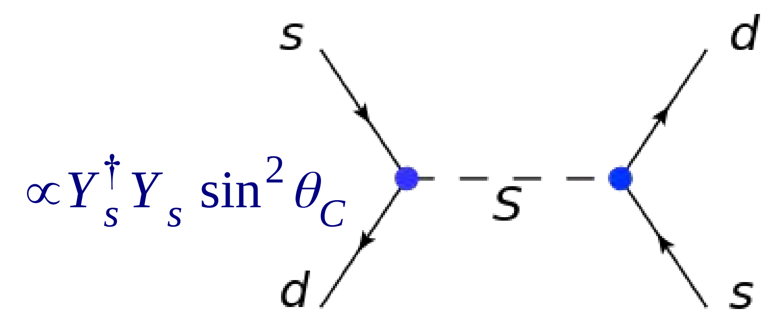
$\Rightarrow \quad c_S \to c_S - Y_u (d'_S - i d_S)$ + dim-6 operators

Flavor alignment



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b) c_S diagonal in mass basis, e.g. $c_S \propto \mathrm{diag}(1,0,0)$

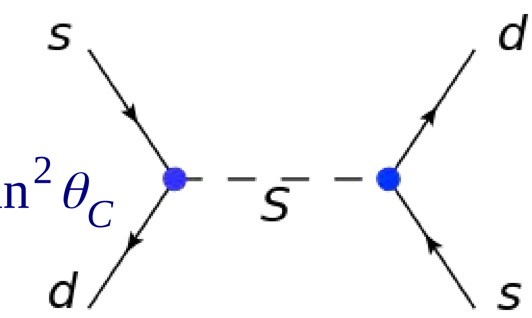
$$U(3)_Q \times U(3)_U \to U(1)_u \times U(2)_{ctL} \times U(2)_{ctR}$$

→ technically natural

Flavor alignment

- **MFV** ensures that FCNCs are under control

$\propto Y_s^\dagger Y_s \sin^2\theta_C$



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b) c_S diagonal in mass basis, e.g. $c_S \propto \text{diag}(1,0,0)$

$$U(3)_Q \times U(3)_U \to U(1)_u \times U(2)_{ctL} \times U(2)_{ctR}$$

→ technically natural

- Can be dynamically generated through extended scalar potential

Knapen, Robinson, 2015

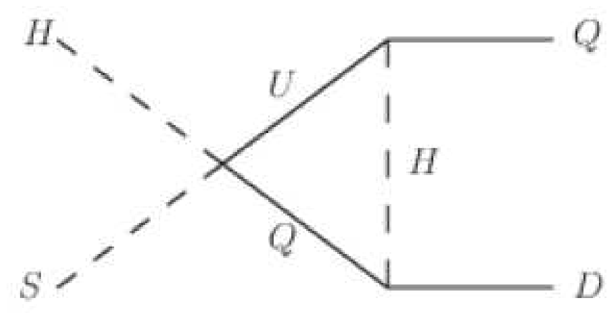
Flavor alignment

$$\mathcal{L} \supset -\frac{1}{2} m_S^2 S^2 - \left(\bar{Q}_L Y_u U_R H_c + \frac{c_S}{M} S \bar{Q}_L U_R H_c + \text{h.c.} \right)$$

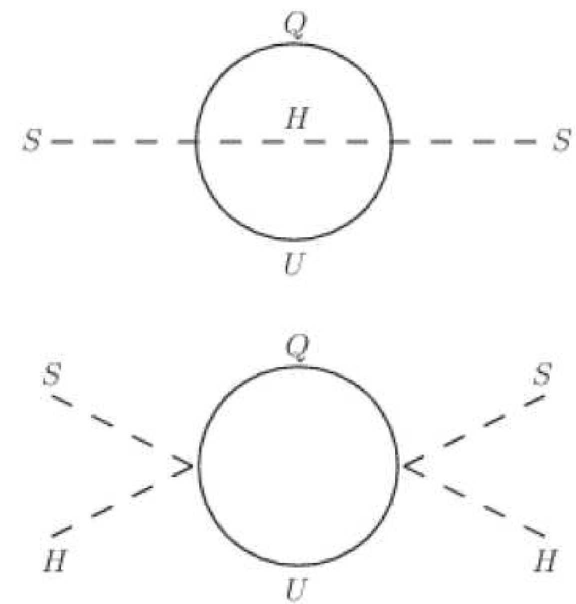
- c_S diagonal in mass basis → no FCNCs in up-sector

- FCNCs in down-sector induced at one-loop, suppressed by

$$\frac{1}{16\pi^2 M} \left(V_{\rm CKM}^\dagger (Y_u^D) c_S^\dagger V_{\rm CKM} Y_d^D \right)$$



Naturalness



- Corrections to scalar mass from scale M:

$$\delta m_S^2 \sim \frac{\mathrm{Tr}\, c_S^\dagger c_S}{(16\pi^2)^2} M^2$$

$$\delta m_S^2 \sim \frac{\mathrm{Tr}\, c_S^\dagger c_S}{32\pi^2} v^2$$

Requiring $\delta m_S^2 \lesssim m_S^2$

$$(c_S)^{ij} \lesssim \begin{cases} (3\times 10^{-3})\left(\dfrac{m_S}{0.1\,\mathrm{GeV}}\right)\left(\dfrac{5\,\mathrm{TeV}}{M}\right) \\ (7\times 10^{-3})\left(\dfrac{m_S}{0.1\,\mathrm{GeV}}\right) \end{cases}$$

- Naturalness constraints from scalar potential and quark masses lead to similar bounds on c_S

Naturalness

- Corrections to scalar potential from scale M:

$$\delta_{S^{2k}} \sim \frac{\mathrm{Tr}(c_S^\dagger c_S)^k}{(16\pi^2)^{k+1}} M^{4-2k}, \;\; k = 1, 2, \ldots$$

$$\delta_{S^{2k+1}} \sim \frac{\mathrm{Tr}(c_S^\dagger c_S)^k c_S^\dagger Y_u}{(16\pi^2)^{k+2}} M^{4-(2k+1)}, \;\; k = 0, 1, \ldots.$$

$\Rightarrow \quad v_S \approx -\frac{\delta_S}{m_S^2} \sim \frac{\mathrm{Tr}\, c_S^\dagger Y_u}{(16\pi^2)^2} \left(\frac{M}{m_S}\right)^2 M$ (small if c_S involves only first gen.)

Renormalizable UV completion

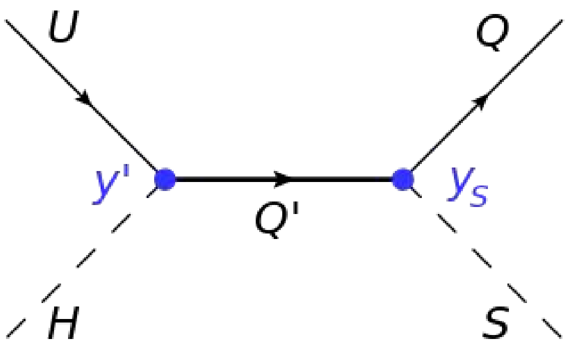
- Vector-quark model:

$$\mathcal{L}_{cs} = i\bar{Q}'_L \not{D} Q'_L + i\bar{Q}'_R \not{D} Q'_R - \left(y_S S \bar{Q}_L Q'_R + M \bar{Q}'_R Q'_L + y' \bar{Q}'_L H_c U_R + \text{h.c.}\right)$$

$$y_S \sim (3,1,1),$$

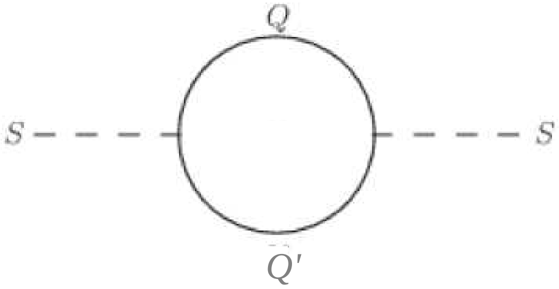
$$M \sim (1,1,1),$$

$$y' \sim (1,\bar{3},1).$$



- Naturalness:
  One-loop correction to m_S: $\quad (y_S)^{ij} \lesssim (4\pi)\dfrac{m_S}{M}$

  One-loop correction to m_H: $\quad (y')^{ij} \lesssim (4\pi)\dfrac{v}{M}$



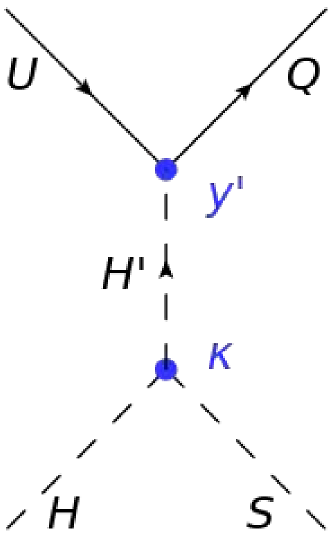
→ $c_S^{\text{eff}} \lesssim (2\times10^{-4})\left(\dfrac{m_S}{0.1\,\text{GeV}}\right)\left(\dfrac{5\,\text{TeV}}{M}\right)^2$ stronger by v/M compared to EFT

Renormalizable UV completion

- 2HDM: $\mathcal{L}_{C_H} = (D_\mu H')^\dagger (D^\mu H') - \frac{M^2}{2} H'^\dagger H' - (y' \bar{Q}_L H' U_R + \kappa S H^\dagger H' + \text{h.c.})$

$$y' \sim (3, \bar{3}, 1)$$

$$\kappa, M \sim (1,1,1)$$



- Naturalness: One-loop corrections m_S and m_H
  → similar to vector-quark model

μ-specific scalar

$$-\mathcal{L}_{\rm int} = \bar{L}_L Y_\ell E_R H + \frac{c_S}{M} S \bar{L}_L E_R H + \text{h.c.}$$

$c_S \propto \mathrm{diag}(0,1,0)$

Y_ℓ: $\quad U(3)_L \times U(3)_E \to U(1)_e \times U(1)_\mu \times U(1)_\tau$

c_S: $\quad U(3)_L \times U(3)_E \to U(1)_\mu \times U(2)_{e\tau L} \times U(2)_{e\tau R}$

After EWSB:

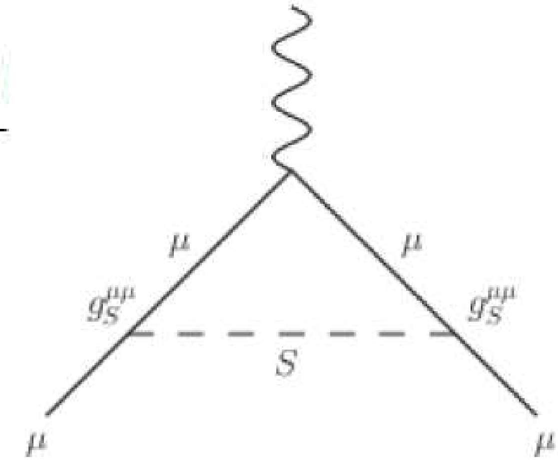
$$-\mathcal{L}_{\rm int} \supset S\bar{\mu}\left(\mathrm{Re}\, g_S^{\mu\mu} + i \mathrm{Im}\, g_S^{\mu\mu} \gamma^5\right)\mu$$

$$g_S^{\mu\mu} = \frac{(c_S)^{22} v}{\sqrt{2} M}.$$

Muon anomalous magnetic moment

- One-loop correction:

$$\Delta a_\mu = \frac{1}{8\pi^2}\int_0^1 dx \frac{(1-x)^2\left((1+x)\left(\mathrm{Re}\, g_S^{\mu\mu}\right)^2-(1-x)\left(\mathrm{Im}\, g_S^{\mu\mu}\right)^2\right)}{(1-x)^2+x\left(m_S/m_\mu\right)^2}$$



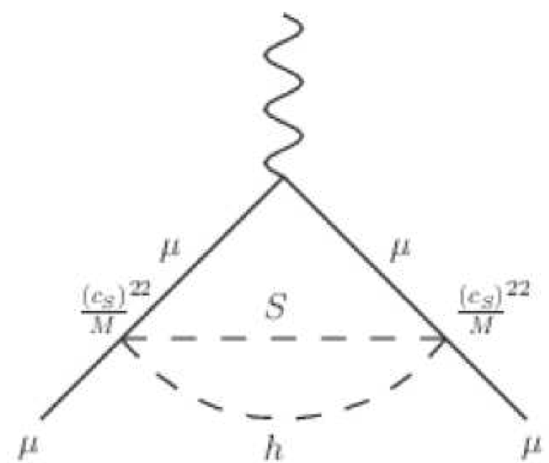
For $m_S \ll m_\mu$: $\Delta a_\mu \sim 3\left(g_S^{\mu\mu}/4\pi\right)^2 = 35\times 10^{-10}$

if $g_S^{\mu\mu} \sim 4\times 10^{-4}$

- Two-loop correction:

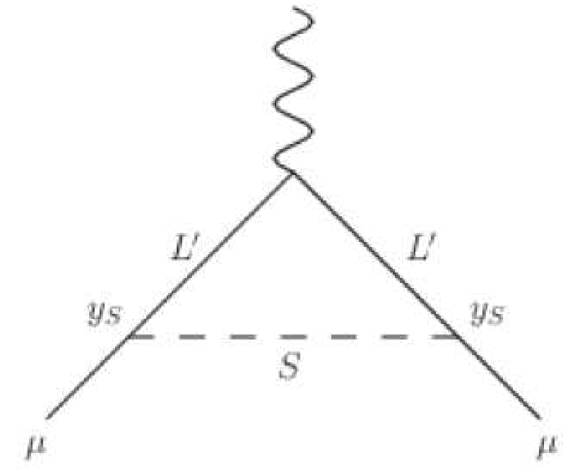
$$\frac{(\Delta a_\mu)_{2-\mathrm{loop}}}{(\Delta a_\mu)_{1-\mathrm{loop}}} \sim \frac{M^2}{8\pi^2 v^2}$$

subdominant for $M < 2$ TeV



Vector-lepton UV completion

$$-\mathcal{L} \supset M L'_L L'_R + y_S S L_L L'_R + y' L'_L H E_R + \mathrm{h.c.}$$



- Additional correction to Δa_μ suppressed by $(m_\mu/M)^2$

- Mixing between L'_R and μ_R

  $$\tan\theta = y'v/\sqrt{2}M$$

  constained by electroweak precision tests for $Z\mu\mu$ couplings

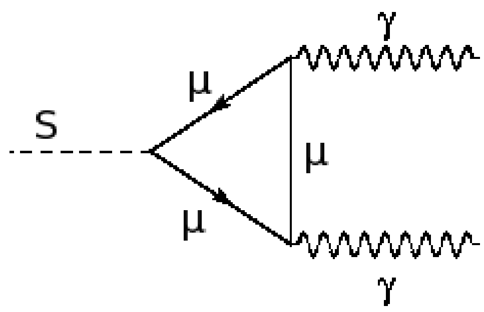
  $$\frac{y'v}{M} \lesssim 0.05$$

del Aguila, de Blas, Perez-Victoria, 2008
Freitas, Lykken, Kell, Westhoff, 2014

Bounds from lab experiments

- Decay $S \to \mu^+\mu^-$ for $m_S > 2m_\mu$

  $S \to \gamma\,\gamma$ for $m_S < 2m_\mu$



- Searches at beam-dump experiments:

  E137 (SLAC electron beam): production $\gamma^* \to \gamma\, S$ followed by $S \to \gamma\,\gamma$

  Future: SHiP, FASER, ... (p beams)
  COMPASS (μ beam)

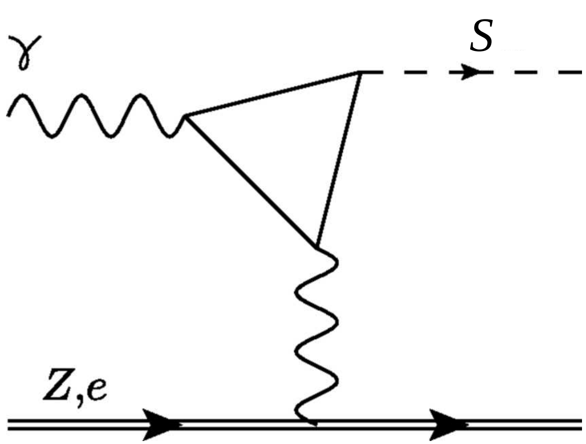
- High-energy collisions:

  BaBar: $e^+e^- \to \mu^+\mu^- S, \quad S \to \mu^+\mu^-$

  ATLAS: $Z \to \mu^+\mu^- S, \quad S \to \mu^+\mu^-$

Bounds from astrophysics

- Supernova cooling (SN 1987A)



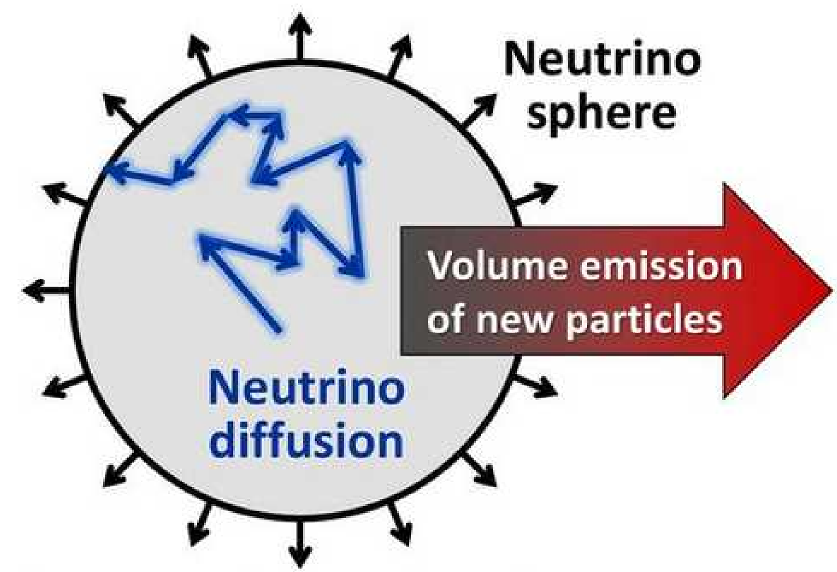
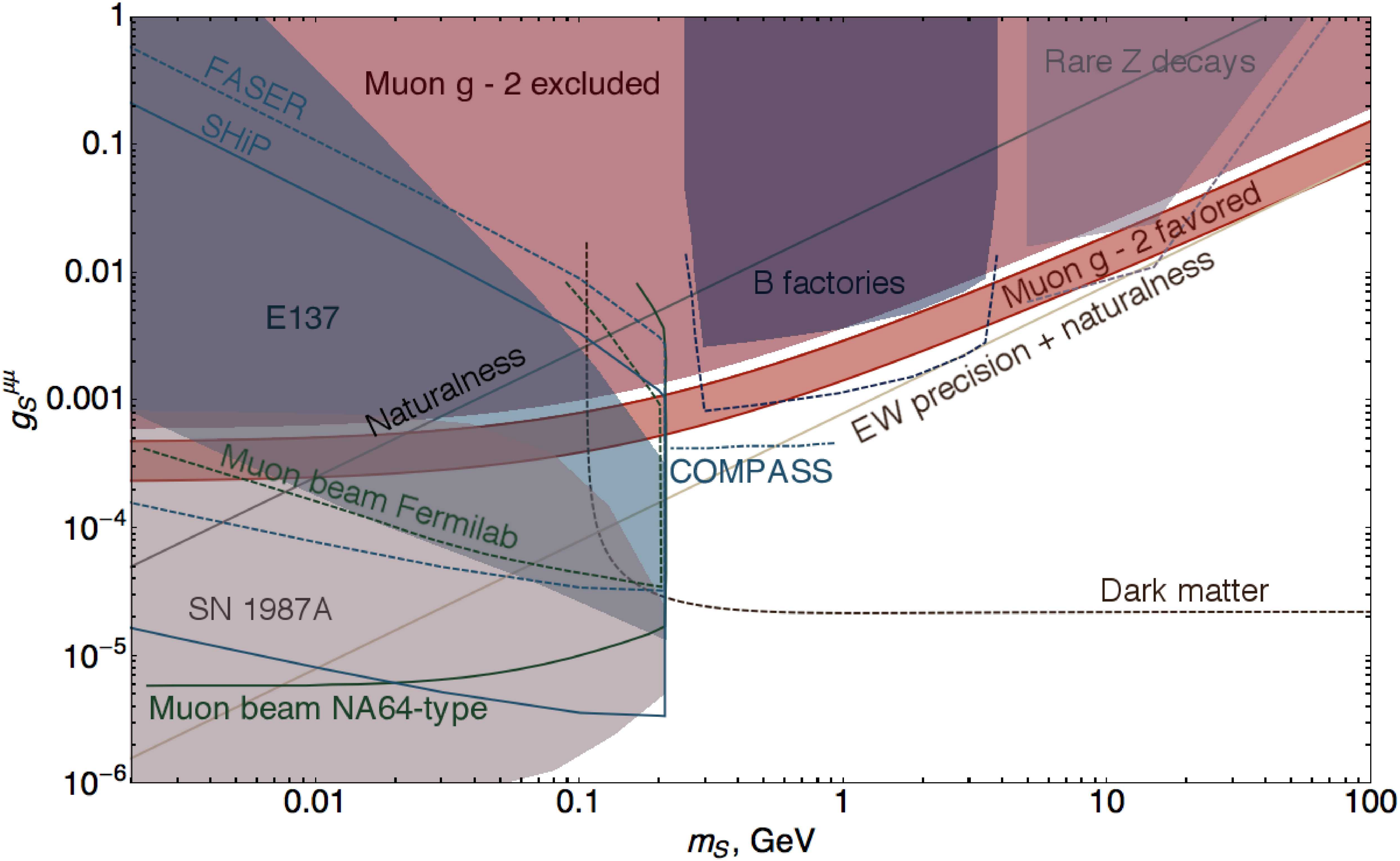


image credit: G. Raffelt

Dolan, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg, 2017

μ-specific scalar: Summary of bounds



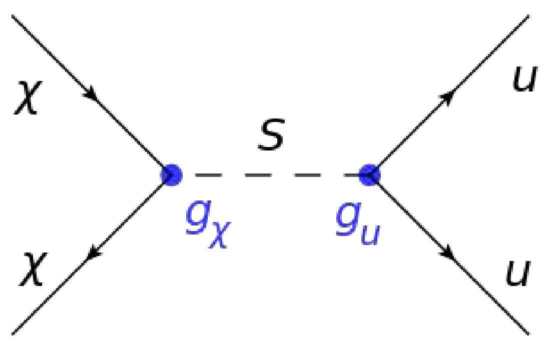
up-quark specific scalar

- Scalar DM mediator, coupled only to u quark

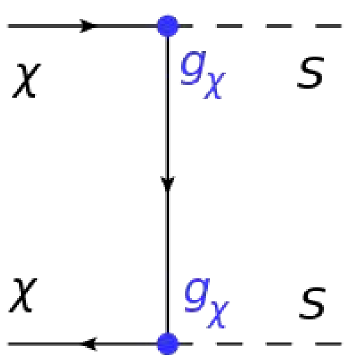
$$\mathcal{L} \supset i\bar{\chi}(\not{D} - m_\chi)\chi + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_S^2 S^2$$
$$- \left(g_\chi S \bar{\chi}_L \chi_R + \underbrace{\frac{c_S}{M} S \bar{Q}_L U_R H_c} + \text{h.c.} \right)$$

$$g_u S \bar{u}_L u_R \qquad g_u \equiv \frac{c_S v}{\sqrt{2}M}$$

- DM relic density from thermal freeze-out:



$m_S > m_\chi$



$m_S < m_\chi$

Couplings to hadrons

- For $m_S \sim O(\mathrm{GeV})$, S effective couples to hadrons
- Couplings to mesons from χPT:

$$\mathcal{L} \supset \frac{f^2}{4}\mathrm{tr}[(D_\mu\Sigma)^\dagger D^\mu\Sigma] + \frac{f^2}{4}\mathrm{tr}[\Sigma^\dagger\chi + \chi^\dagger\Sigma]$$

$$\chi = 2B\begin{pmatrix} m_u + g_u S & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_s \end{pmatrix}$$

- For $m_S > 900\ MeV$, need to include s-channel resonances (form factors)

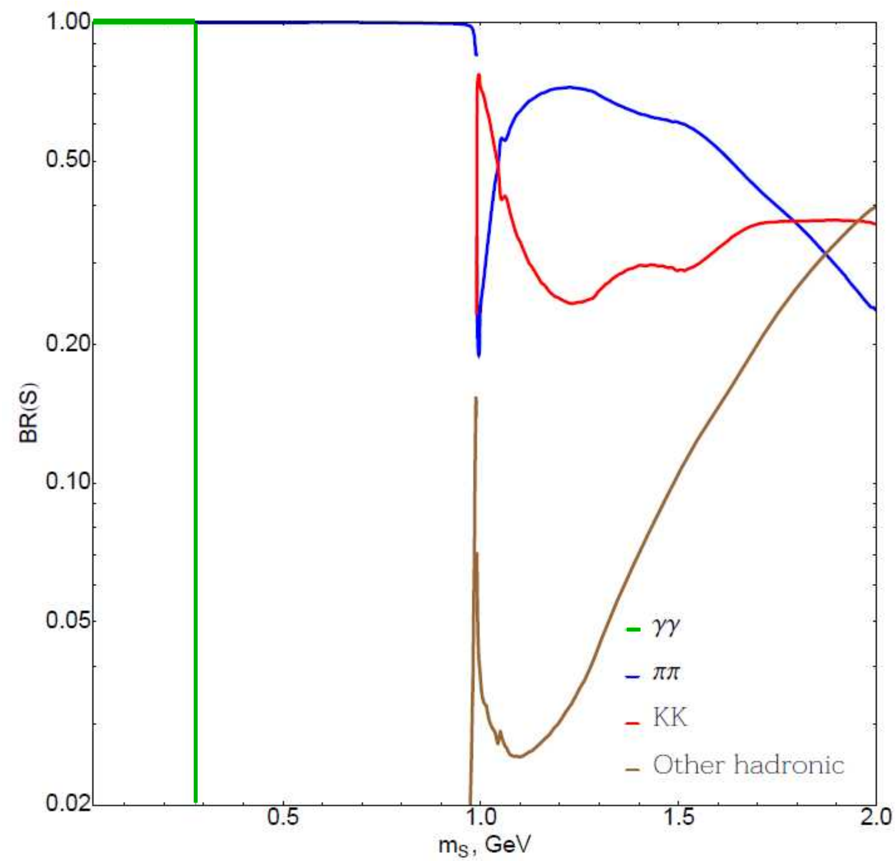
$$\langle\pi(p)\pi(p')|m_u\bar{u}u + m_d\bar{d}d|0\rangle = \Gamma_\pi(s)$$

$$\langle\pi(p)\pi(p')|m_u\bar{u}u - m_d\bar{d}d|0\rangle = \Omega_\pi(s)$$

Γ_π, Γ_K extracted from data, O(1) uncertainty

Monin, Boyarsky, Ruchaysiy, 2018
Winkler, 2018

Ω_π, Ω_K are unkown



Couplings to hadrons

- Couplings to nucleons:

$$y_{Spp} = g_u \langle p|\bar{u}u|p\rangle = g_u \frac{f^p_{Tu} m_p}{m_u} \approx 6.0\, g_u,$$

$$y_{Snn} = g_u \langle n|\bar{u}u|n\rangle = g_u \frac{f^n_{Tu} m_n}{m_u} \approx 5.1\, g_u$$

$f^p_{Tu} = 0.014,\ f^n_{Tu} = 0.012$ from lattice

Durr et al., 2015

Bounds from lab experiments

blue = current, red = future

- Meson decays $\eta \to \pi^0 S$, $S \to \gamma\gamma$ (MAMI)
  $S \to \pi\pi$ (KLOE, REDTOP)
  $S \to \chi\chi$ invisible (REDTOP?)

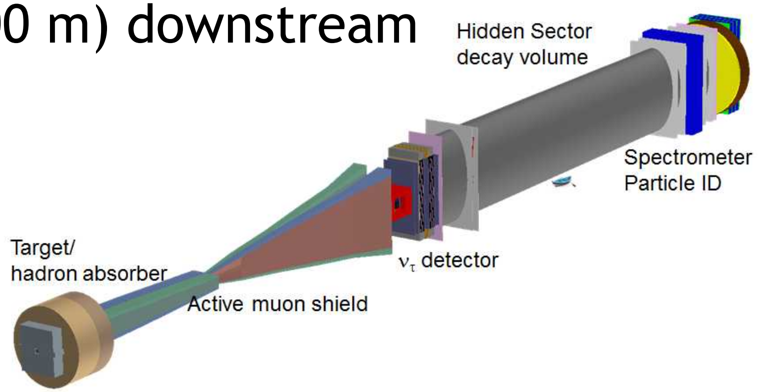
  $\eta' \to \pi^0 S$, $S \to \pi\pi$ (BES III, REDTOP?)

  $K^\pm \to \pi^\pm S$, $S \to \gamma\gamma, \chi\chi$ long-lived, invisible (E787, E949)

- Searches at beam-dump experiments:

  a) Production $\eta \to \pi^0 S$ followed by $S \to \gamma\gamma$ O(100 m) downstream (CHARM, SHip, FASER, ...)

  b) $\eta \to \pi^0 S$, $S \to \chi\chi$,
  χN scattering in far detector
  (MiniBooNE-DM, SBND)

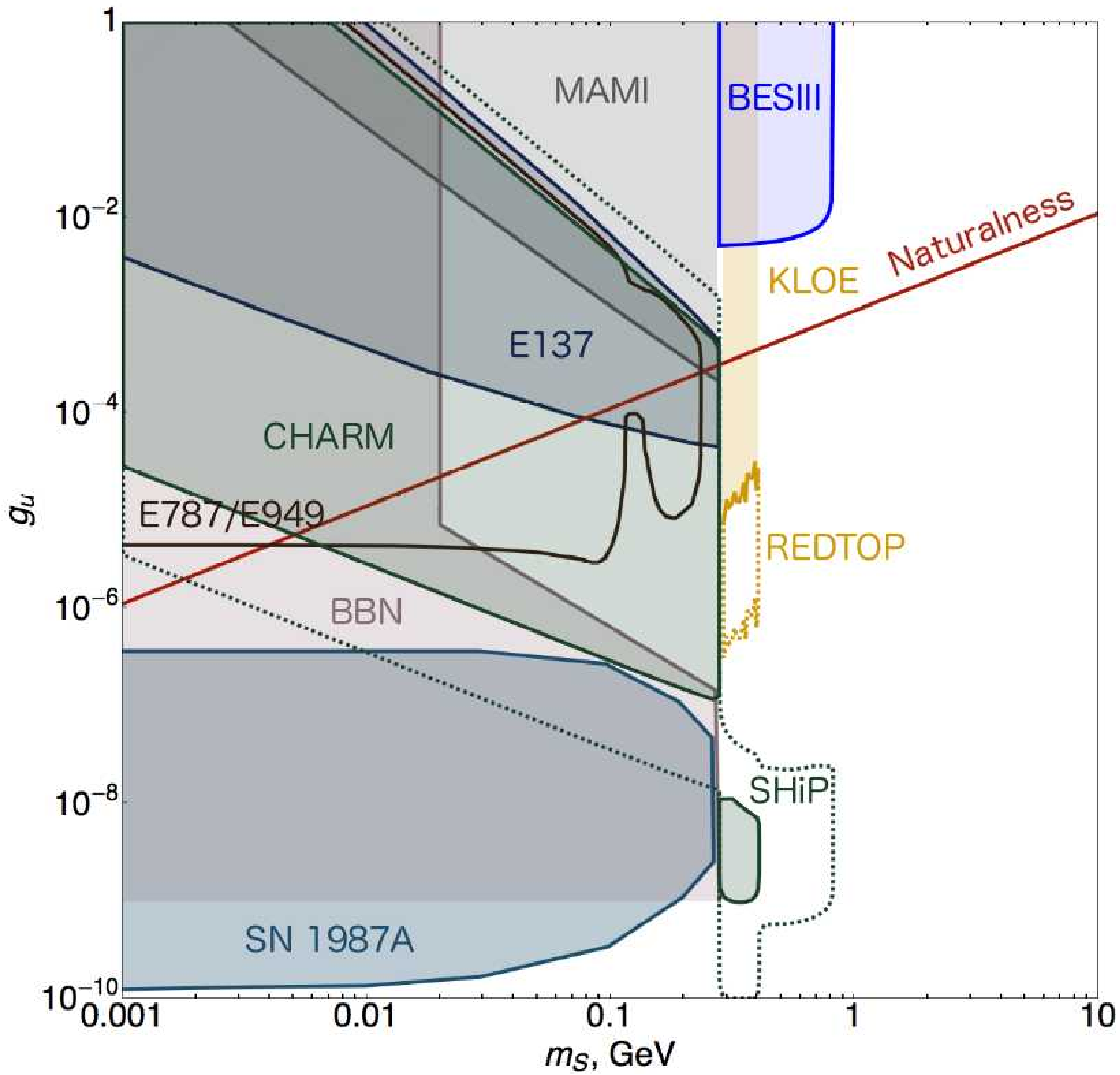


Bounds from astrophysics

- BBN: Millea, Knox, Fields, 2015
  - $m_S < 20\ \mathrm{MeV}$: S not fully kinetically decoupled during BBN → increased N_{eff}
  - $g_u < (2 \times 10^{-8}) \left(\frac{m_S}{\mathrm{GeV}} \right)^{-3/2}$ photons from late decay of S decrease $\eta = n_B / s$
  - Assume: S was in equilibrium at some point ($g_u \gtrsim 10^{-9}$)

- Supernova cooling (SN 1987A):
  - $g_u \gtrsim 10^{-10}$: enough S produced to cause significant cooling
  - $g_u \gtrsim 4 \times 10^{-8}$: re-absorption before leaving SN core
  - $m_S > 2 m_\pi$: S decays inside SN core

up-specific scalar: Summary of bounds



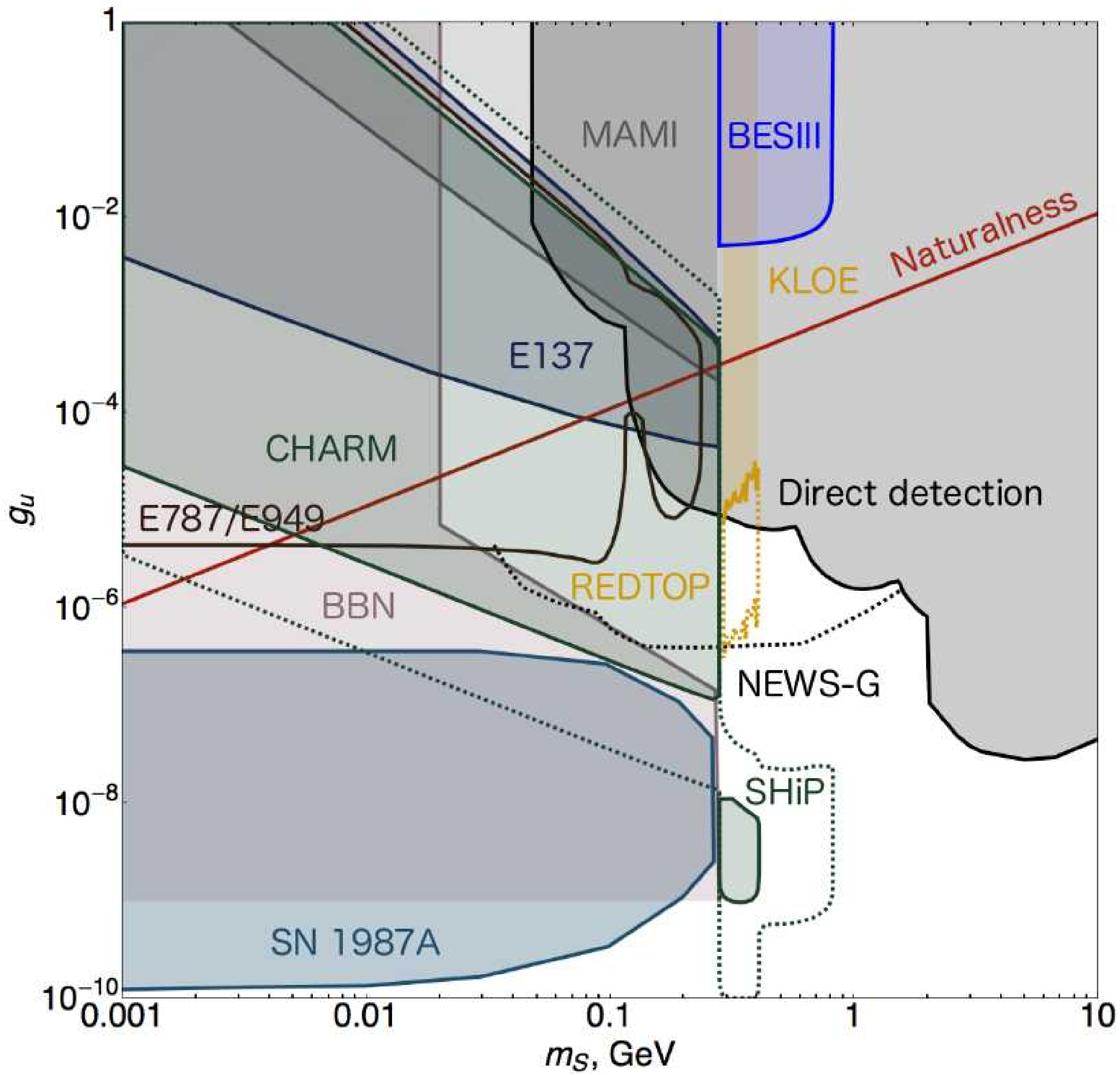
No DM

- Strong constraints for $m_S < 2m_\pi$
- O(1) couplings allowed for $m_S > 0.8$ GeV

Other bounds:

- n scattering only for lighter m_S
- EWPT depend on UV completion

up-specific scalar: Summary of bounds

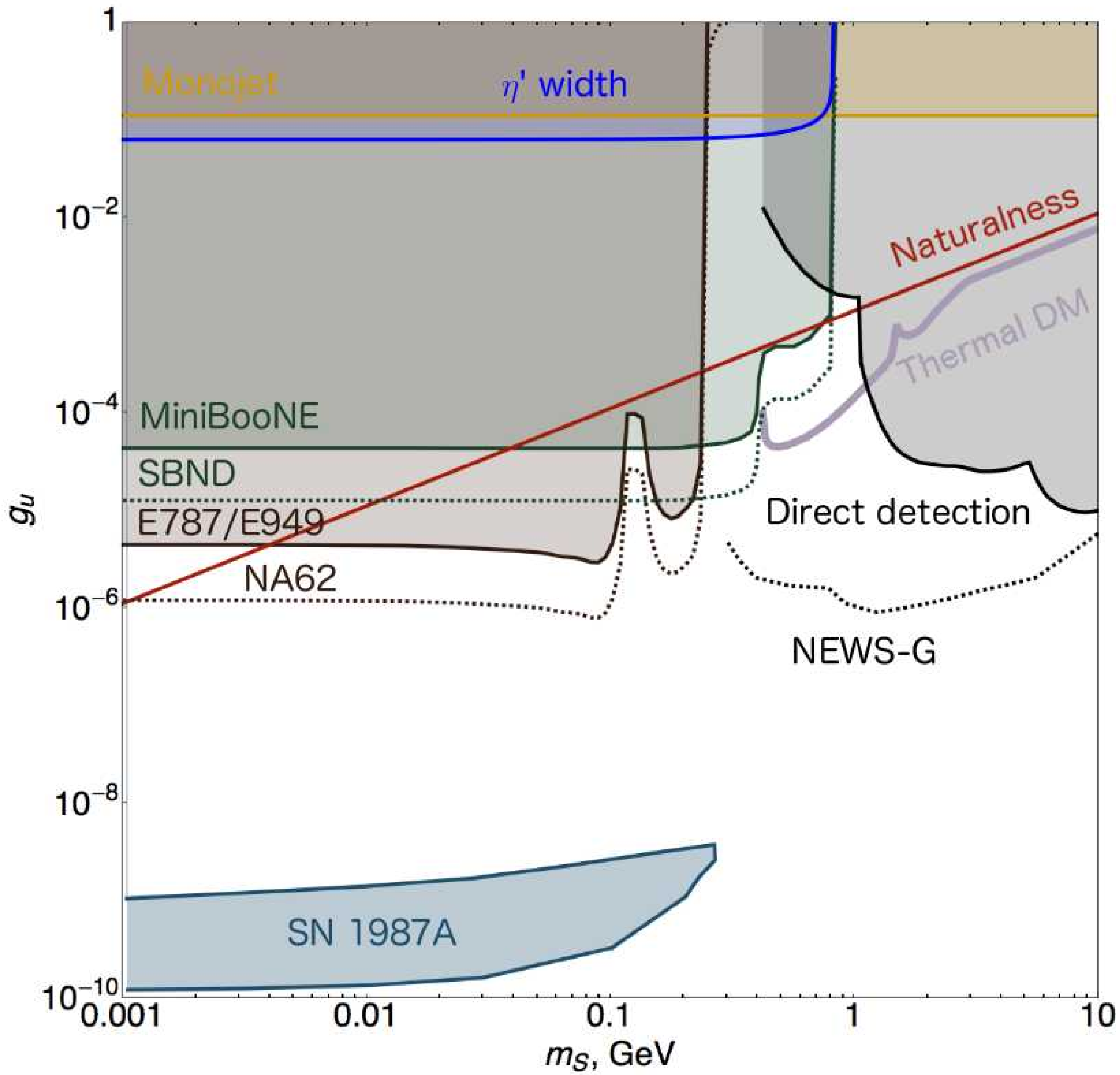


$m_\chi = 3m_S$

g_χ **set to match Ω_{DM}**

- Relic density independent of g_u
- Direct detection constraints from XENON1T, CRESST, CDMSlite, PICO (future: NEWS-G)
- Complementarity of χ and S searches

up-specific scalar: Summary of bounds



$m_\chi = m_S / 3, \ g_\chi = 1$

- Invisible decay evades bounds
- Monojet bounds from LHC
- Direct detection constraints from XENON1T, CRESST, CDMSlite, PICO (future: NEWS-G)
- $m_S < 2m_\pi$ would overproduce DM

Summary

- Light bosons could play a role as DM mediators and address flavor anomalies

- Generation-specific couplings to SM fermions are technically natural

- Naturalness puts constaints on scalar parameters

- μ-specific scalar could explain a_μ anomaly, but many expt. bounds

- light quark-specific:
  - O(1) couplings allowed by all bounds
  - Interesting phenomenology as DM mediator