LEPTOQUARKS AND REAL SINGLETS

A RICHER SCALAR SECTOR BEHIND THE ORIGIN OF DARK MATTER

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Based on F. D'Eramo, N.K., F. Pobbe, A. Smolkovic, O. Sumensari: arXiv:2012.05743 [hep-ph]

IJS-F1 seminar, 14. January '21

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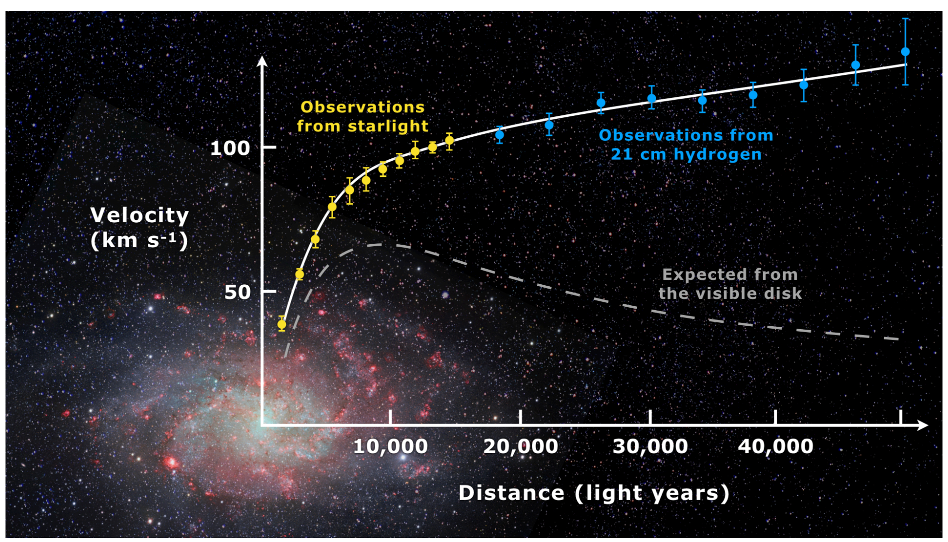
DARK MATTER

- The universe energy density in the LCDM model

$$\rho_0 = \rho_{\text{crit}} \left(\Omega_\Lambda + \Omega_c + \Omega_b\right)$$
$$= \frac{3H_0^2}{8\pi G_N^2} \left(0.70_{\text{Dark energy}} + 0.26_{\text{Dark matter}} + 0.04_{\text{Matter}}\right)$$

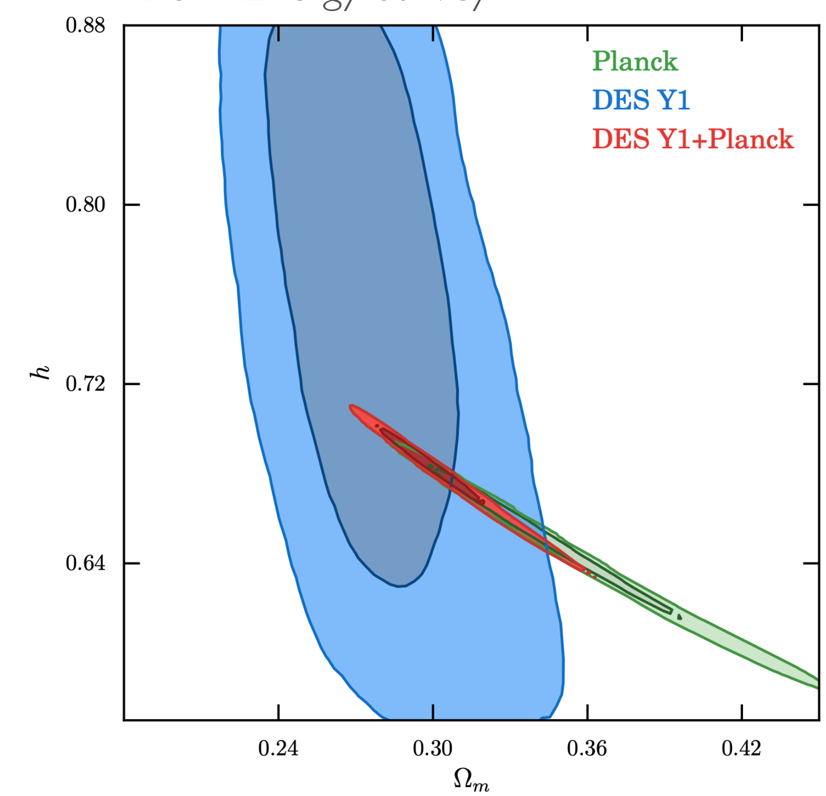
flat universe

- The existence of DM supported from galactic to cosmological scales



M33 rotation curve

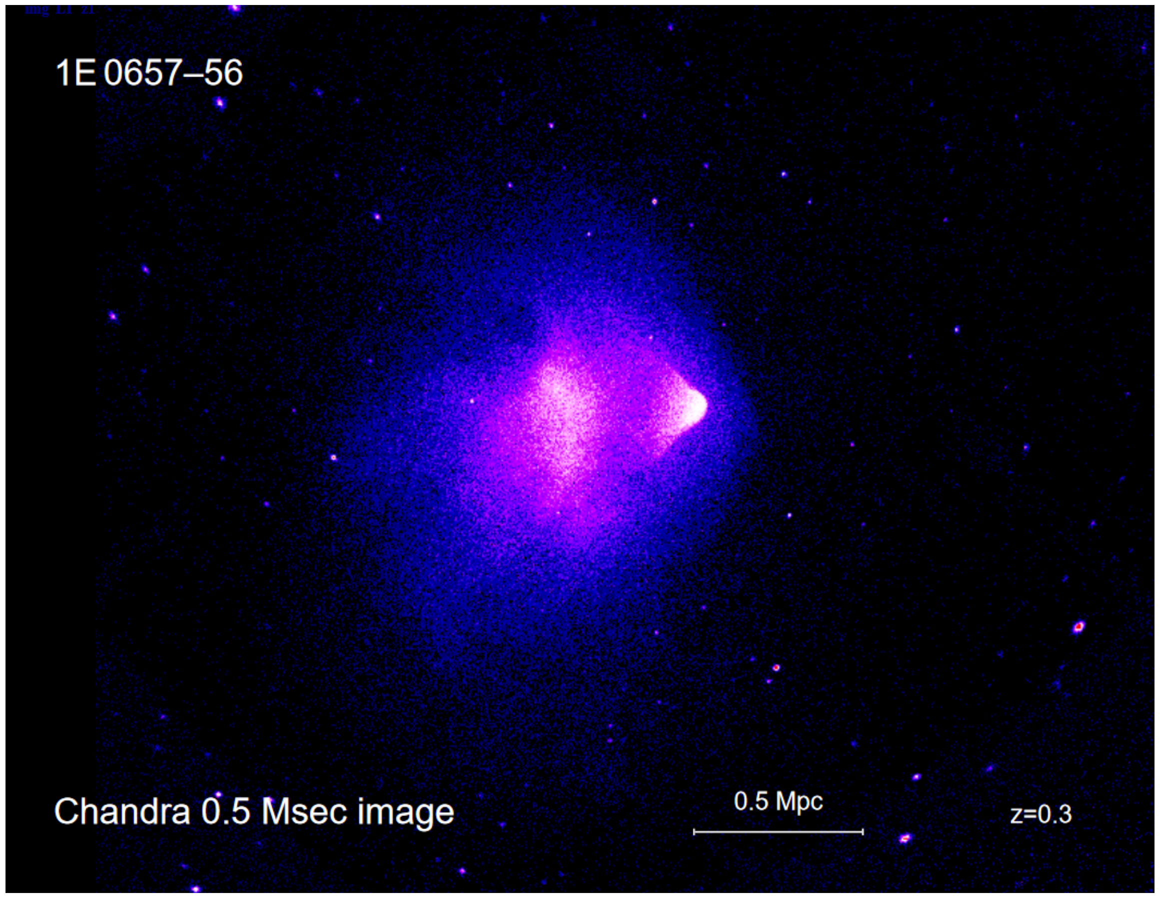
Dark Energy Survey

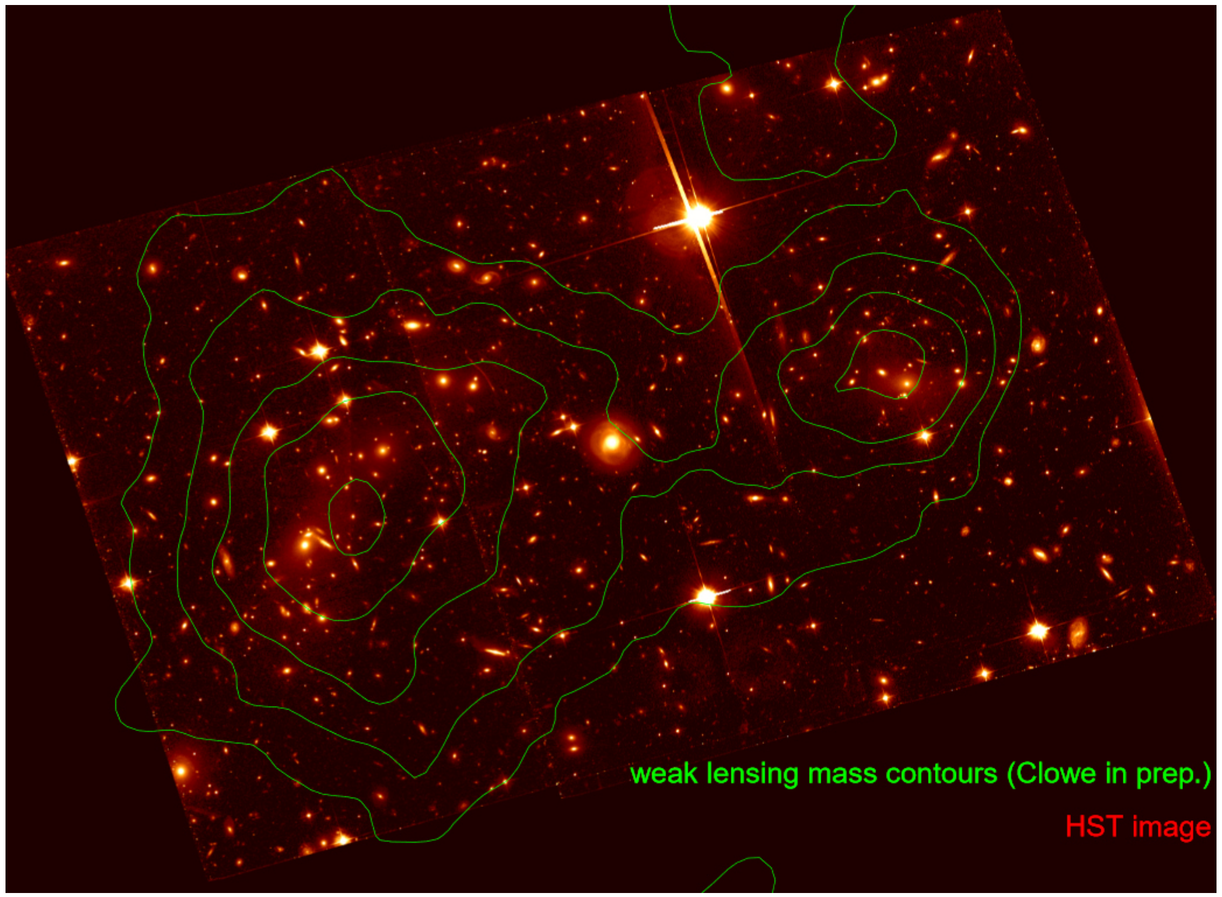


- Seeds structure formation in CMB

DARK MATTER

- Qualitative evidence





Gass Vs. Mass
in the Bullet cluster collision

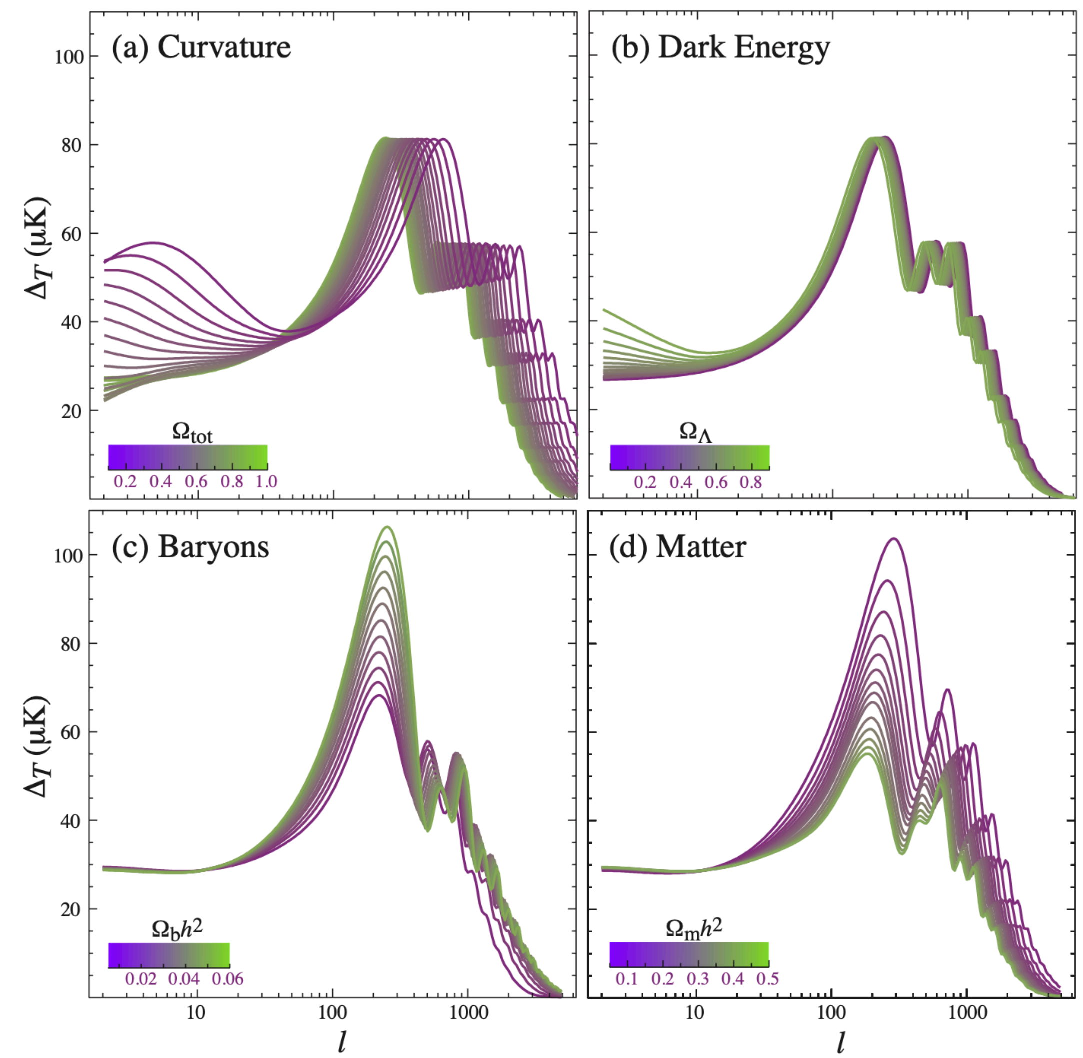
DARK MATTER

- Observed (gravitational) properties of DM

$$\Omega_c h^2 = 0.120 \pm 0.001 \qquad [h = H_0/(100\,\mathrm{km/s/Mpc}), \quad h^2 \approx 0.5]$$

Planck 2018

DM relic abundance



Hu, Dodelson, astro-ph/0110414

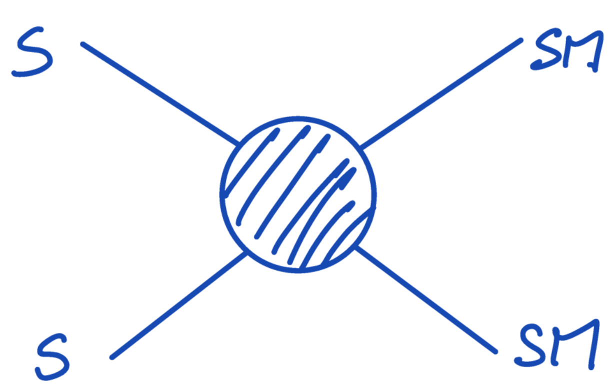
- Microscopic properties
  - ~ neutral
  - ~ stable
  - ~ mass $10^{-22} \ldots 10^{70}\,\mathrm{eV}$
  - ~ cold (neutrinos do not fit the bill)

DARK MATTER

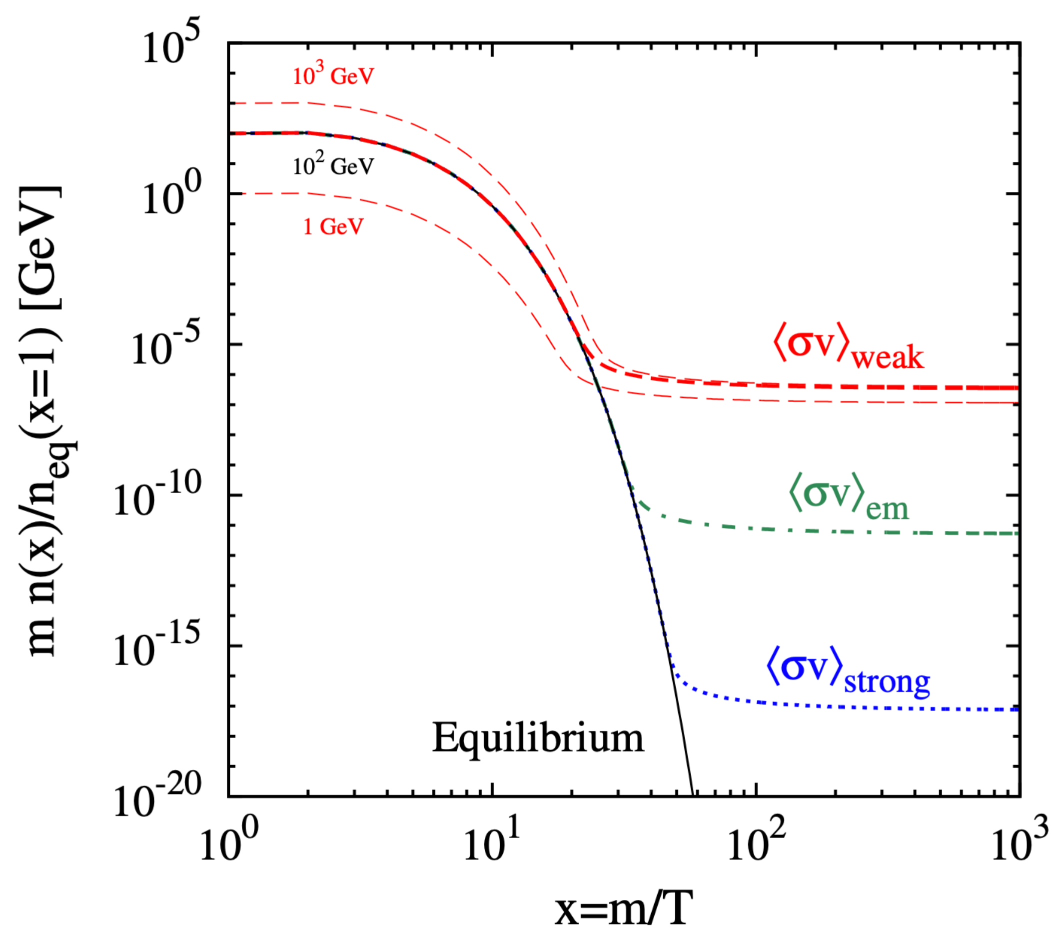
- Thermal decoupling (freeze-out) paradigm
  - ~ In the early universe DM particle S is in thermal equilibrium with the SM plasma. Equilibrium between S S ⇋ SM SM annihilations/creations.
  - ~ At T ~ 10 - 1000 GeV S decouples from the thermal bath - freezes out. The process determines the relic abundance.

$$\frac{\mathrm{d}n_S}{\mathrm{d}t} + 3Hn_S = -\langle \sigma v \rangle \left(n_S^2 - n_S^{\mathrm{eq}\,2} \right)$$

$$n_S^{\mathrm{eq}} = \left(\frac{m_S T}{2\pi} \right)^{3/2} \exp(-m_S/T)$$



$m_S, \sigma_{SS \to \mathrm{SM\,SM}}$

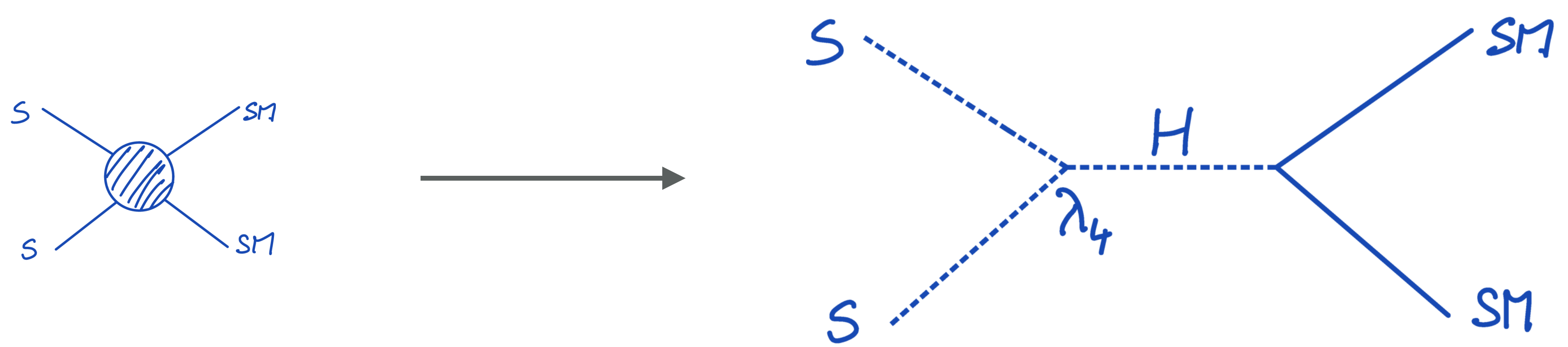


Steigman et al. '12

$\langle \sigma v \rangle_{\mathrm{WIMP}} \sim 3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$ gives approximately right relic abundance

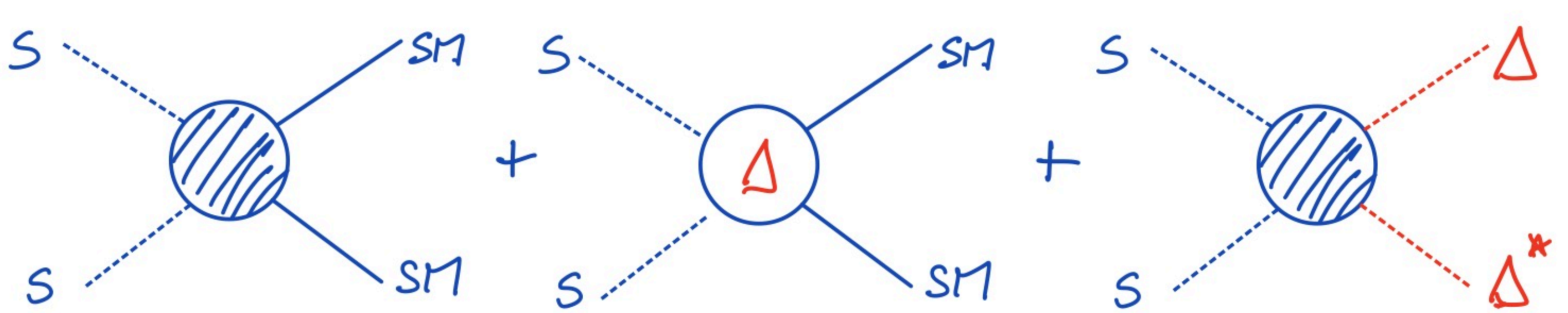
REAL SINGLET DM

- Simplest WIMP
  - ~ Singlet scalar S, stabilized by Z2 symmetry. Higgs portal ensures thermal contact with the SM.



  - ~ Simplistic scenario with two parameters: λ_4, m_S
  - ~ Strongly constrained by the LHC searches for H → invisible = $\nu\nu$, SS

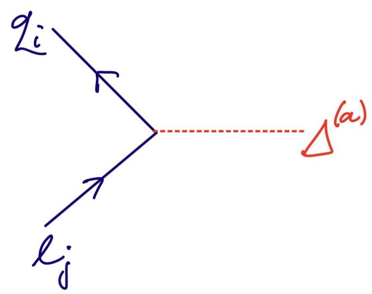
- Extend the model with a scalar leptoquark Δ



- Δ may solve the lepton flavour universality anomalies & $(g\text{-}2)_\mu$

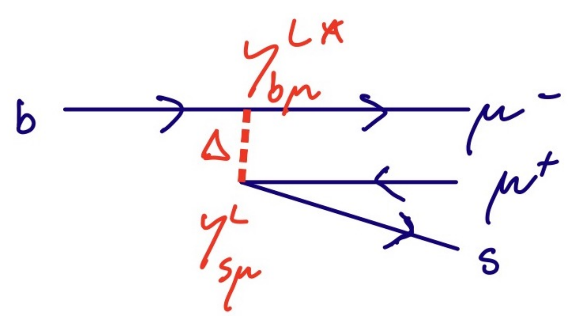
SCALAR LEPTOQUARK

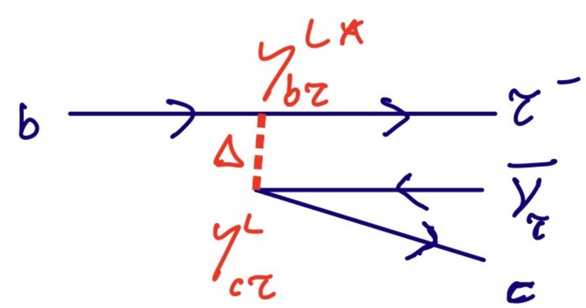
- Color triplets
  - ~ Allowed couplings to lepton-quark (also to quark-quark in some cases)

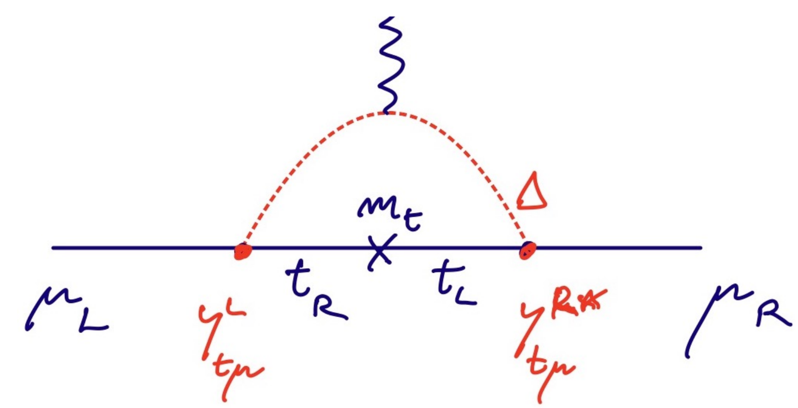


$$\mathcal{L}_{Yuk} = \bar{q}_i \left(y^R_{ij} P_R + y^L_{ij} P_L \right) \ell_j \; \Delta^{(a)} + h.c.$$

  - ~ Perfect candidates particle to address the Lepton Flavour Universality in *B* meson decays, magnetic moments. Meson mixing starts at 1-loop.



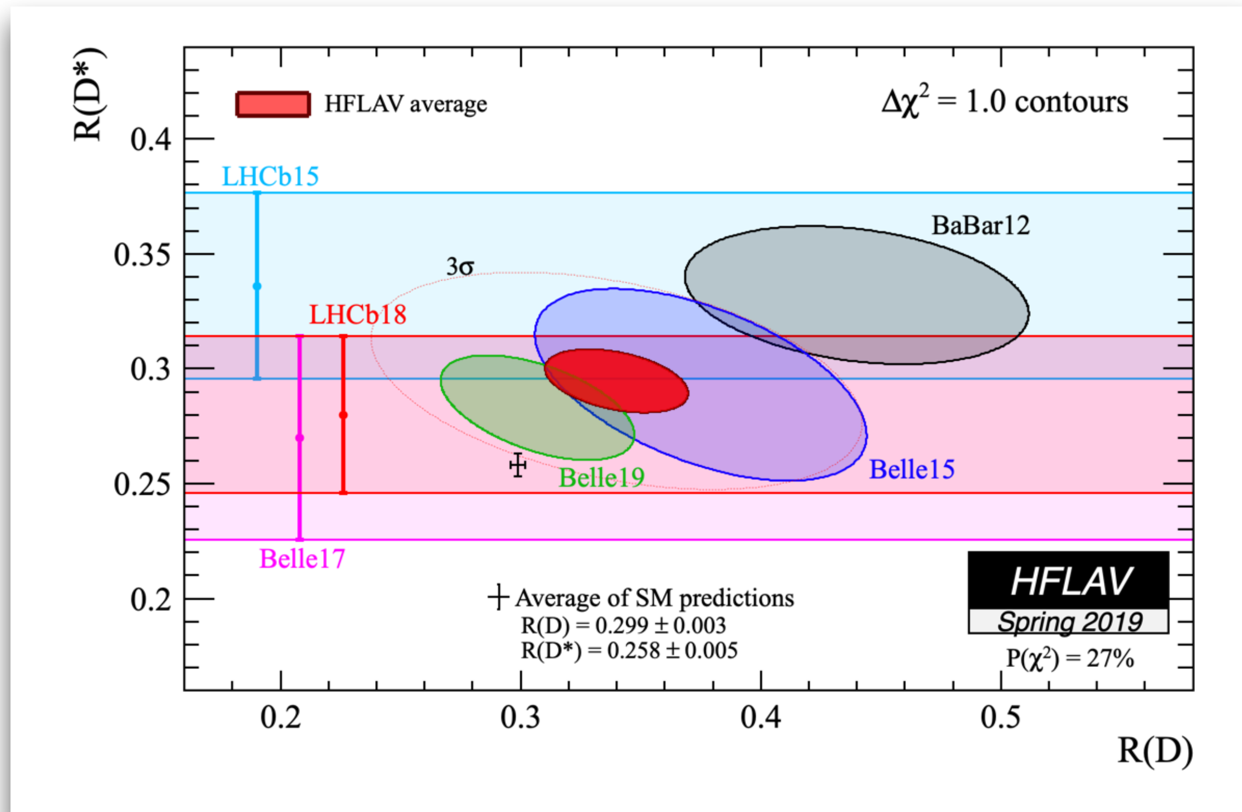


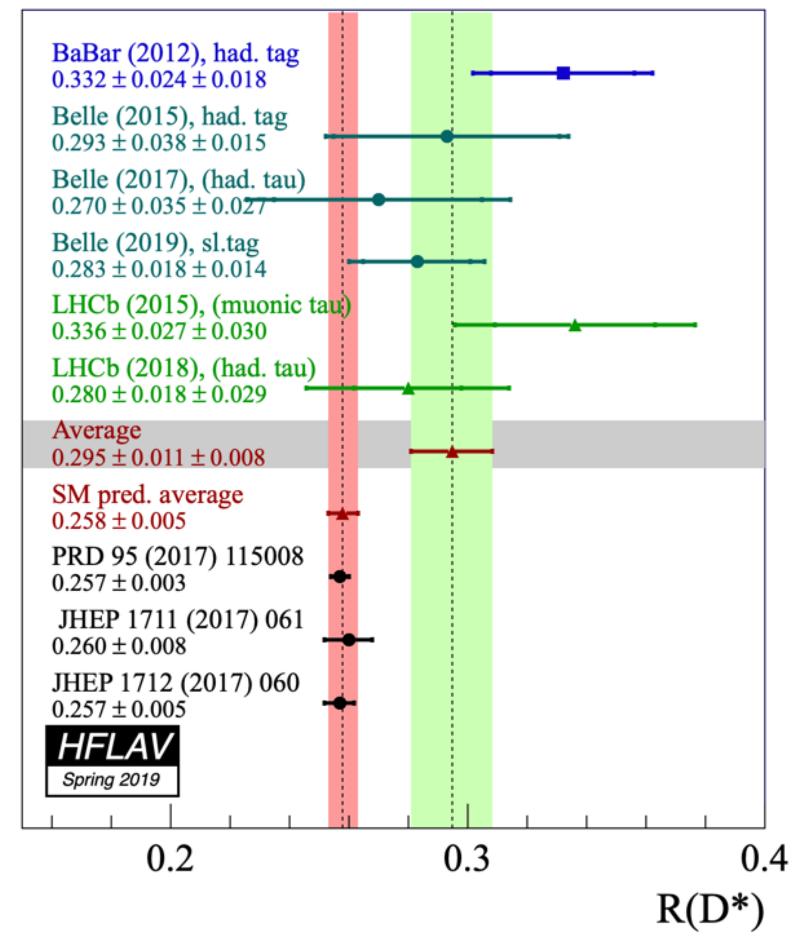


  - ~ *Δ* couples to S and the Higgs via the potential
  - ~ Models well constrained by LHC direct searches: $m_\Delta > 1.5$ TeV

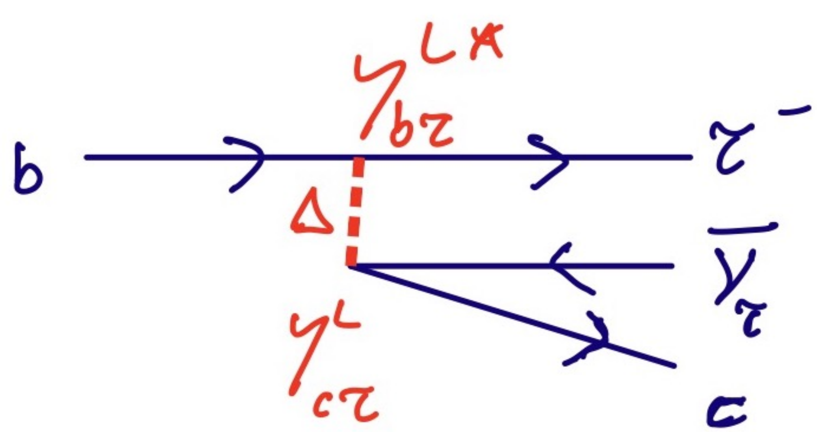
SCALAR LEPTOQUARK

- Lepton universality violation in charged current B decays





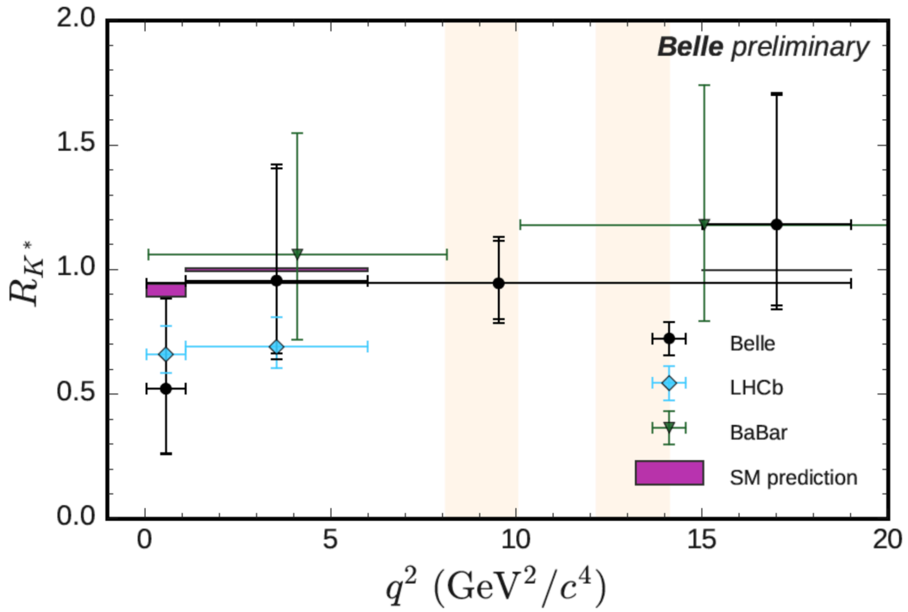
3-4σ

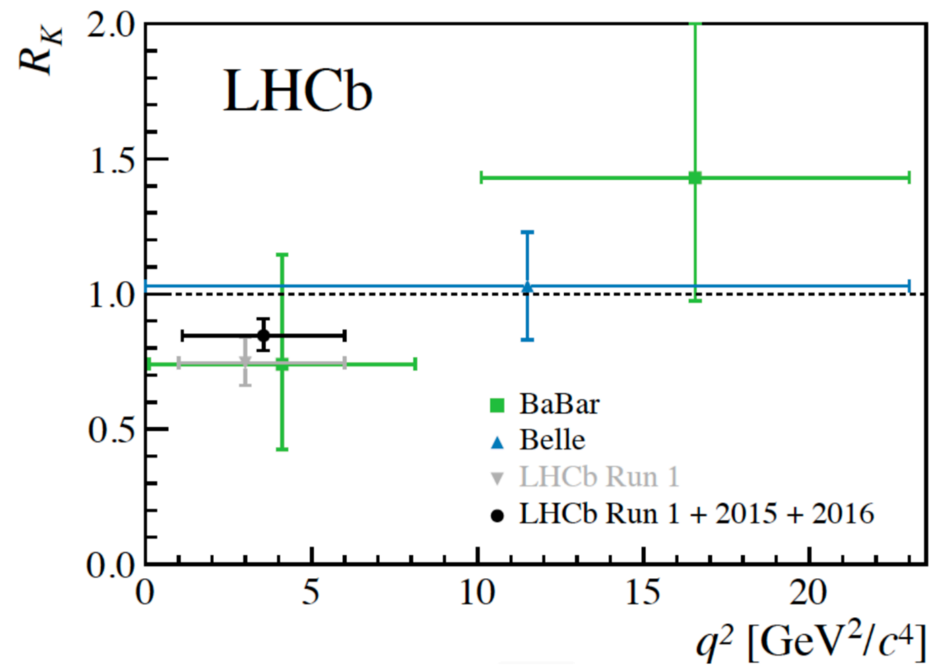


$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathcal{B}(B \to D^{(*)}\mu\bar{\nu}_\mu)}$$

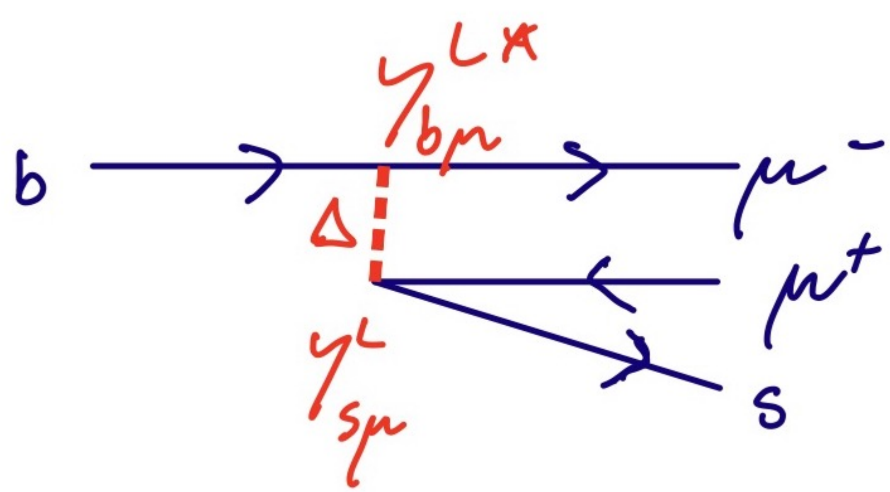
SCALAR LEPTOQUARK

- Lepton universality violation in neutral current decays





4-6σ



$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}$$

EFFECTIVE PICTURE

- If New Physics is heavy $m_{NP} > v$, at scale Λ

Grzadkowski et al, '10

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{c_W}{\Lambda} LLHH + \frac{1}{\Lambda^2}\sum_i c_i \mathcal{O}_i^{(d=6)}$$

- 2499 dimension-6 operators, many of them violate flavor:

$$\mathcal{O}_{\substack{eq\\prst}} = (\bar{e}_p \gamma_\mu e_r)(\bar{q}_s \gamma^\mu q_t)$$ }right-handed leptons, left handed quarks

$$\mathcal{O}^{(1)}_{\substack{lq\\prst}} = (\bar{l}_p \gamma^\mu l_r)(\bar{q}_s \gamma_\mu q_t)$$

$$\mathcal{O}^{(3)}_{\substack{lq\\prst}} = (\bar{l}_p \gamma^\mu \sigma^I l_r)(\bar{q}_s \gamma_\mu \sigma^I q_t)$$

} Left-handed currents

- Naive scale information

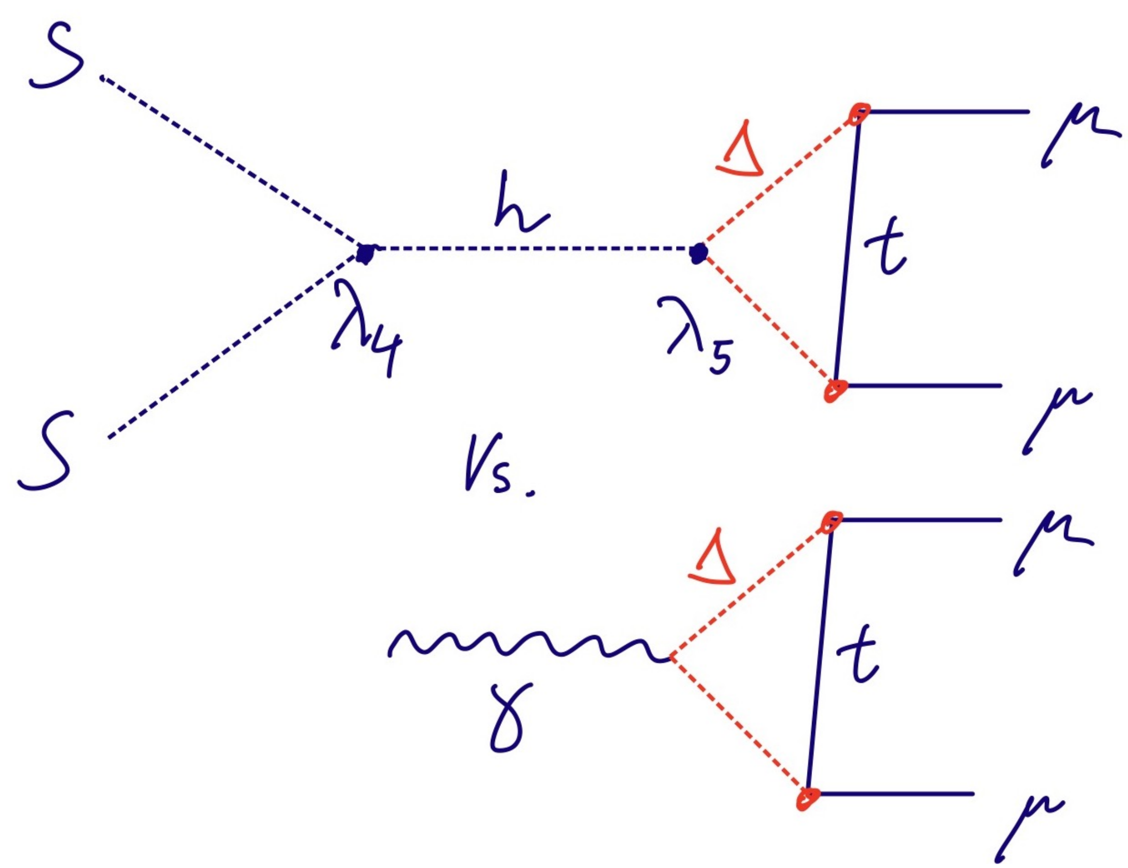
✳ $b \to s\mu\mu$ $$\frac{c_i}{\Lambda^2} \approx 10\% \times \frac{4G_F V_{tb}^* V_{ts}}{\sqrt{2}} C_{9,10}^{\rm SM} \quad \Rightarrow \quad \Lambda \approx 30\,{\rm TeV}\sqrt{c_i}$$

✳ $b \to c\tau\nu$ $$\frac{c_i^{R_D}}{\Lambda^2} \approx 10\% \times \frac{4G_F V_{cb}}{\sqrt{2}} \quad \Rightarrow \quad \Lambda \approx 3\,{\rm TeV}\sqrt{c_i^{R_D}}$$

$$\Lambda \sim m_\Delta \gtrsim 1\,{\rm TeV}$$

MOTIVATION

- Leptoquark of few TeV affects indirectly the DM phenomenology
- Can we further constrain the LQ properties via DM pheno?



See also S. M. Choi, Y. J. Kang, H. M. Lee[arXiv:1807.06547 [hep-ph]]

S + A MODELS

LEPTOQUARK STATES *Δ*

- F = 3B+L = 0 (B = 1/3, L = -1)

$$R_2 = (\mathbf{3}, \mathbf{2}, 7/6): \qquad \mathcal{L}_{R_2} = -\left(y^L_{R_2}\right)_{ij} \bar{u}_{R_i} R_2^T i\tau_2 L_j + \left(y^R_{R_2}\right)_{ij} \bar{Q}_i R_2 \ell_{R_j} + \text{h.c.}\,,$$

$$\widetilde{R}_2 = (\mathbf{3}, \mathbf{2}, 1/6): \qquad \mathcal{L}_{\widetilde{R}_2} = -\left(y^L_{\widetilde{R}_2}\right)_{ij} \bar{d}_{R_i} \widetilde{R}_2^T i\tau_2 L_j + \text{h.c.}\,.$$

- F = 3B+L = -2 (QQ*Δ* violates B and L)

$$S_1 = (\overline{\mathbf{3}}, \mathbf{1}, 1/3): \qquad \mathcal{L}_{S_1} = \left(y^L_{S_1}\right)_{ij} \overline{Q^C_i} i\tau_2 S_1 L_j + \left(y^R_{S_1}\right)_{ij} \overline{u^C_{R_i}} S_1 \ell_{R_j} + \text{h.c.}\,,$$

$$S_3 = (\overline{\mathbf{3}}, \mathbf{3}, 1/3): \qquad \mathcal{L}_{S_3} = \left(y^L_{S_3}\right)_{ij} \overline{Q^C_i} i\tau_2 (\vec{\tau}\cdot\vec{S}_3) L_j + \text{h.c.}\,,$$

$$\widetilde{S}_1 = (\overline{\mathbf{3}}, \mathbf{1}, 4/3): \qquad \mathcal{L}_{\widetilde{S}_1} = \left(y^R_{\widetilde{S}_1}\right)_{ij} \overline{d^C_{R_i}} \widetilde{S}_1 \ell_{R_j} + \text{h.c.}\,,$$

- Interactions fixed by gauge numbers

$$D_\mu = \partial_\mu + i\frac{g_2}{\sqrt{2}}\,(T^+ W^+_\mu + T^- W^-_\mu) + i\frac{g_2}{c_W}\,(T_3 - Q s^2_W) Z_\mu + ie\,QA^\mu + ig_3\,T^A G^A_\mu$$

- Consider one *Δ* at a time

SCALAR POTENTIAL

- The three scalars: Higgs, Δ, S

$$\mathcal{L}_{\text{scalars}} = (D_\mu H)^\dagger (D^\mu H) + (D_\mu \Delta)^\dagger (D^\mu \Delta) + \frac{1}{2} (\partial_\mu S)(\partial^\mu S) - V(H, \Delta, S)$$

- Z_2-symmetric scalar potential. S → -S under Z_2

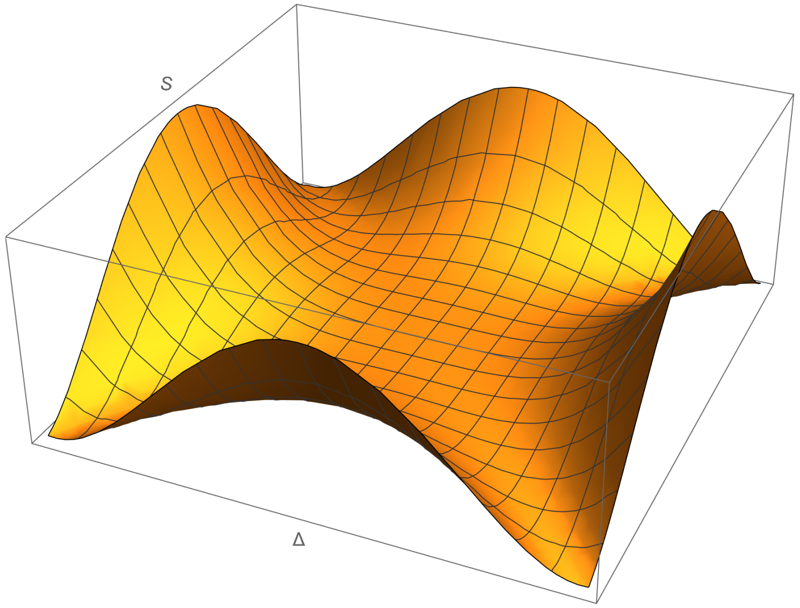
$$V_{\text{BSM}}(H, \Delta, S) = \underbrace{m_1^2 |\Delta|^2 + \frac{m_2^2}{2} S^2}_{\text{mass}} + \underbrace{\frac{\lambda_1}{4} S^4 + \frac{\lambda_2}{4} |\Delta|^4}_{\text{self-interaction}} + \underbrace{\frac{\lambda_3}{2} S^2 |\Delta|^2 + \frac{\lambda_4}{2} S^2 |H|^2 + \frac{\lambda_5}{2} |\Delta|^2 |H|^2}_{\text{portals}}$$

- Stability determined by the quartic terms

$$V_\lambda(H, \Delta, S) = \begin{pmatrix} |H|^2 & S^2 & |\Delta|^2 \end{pmatrix} \begin{pmatrix} \lambda & \lambda_4/4 & \lambda_5/4 \\ \lambda_4/4 & \lambda_1/4 & \lambda_3/4 \\ \lambda_5/4 & \lambda_3/4 & \lambda_2/4 \end{pmatrix} \begin{pmatrix} |H|^2 \\ S^2 \\ |\Delta|^2 \end{pmatrix}$$

V has to remain positive for large fields

$\lambda, \lambda_1, \lambda_2 > 0$ is necessary



SCALAR POTENTIAL

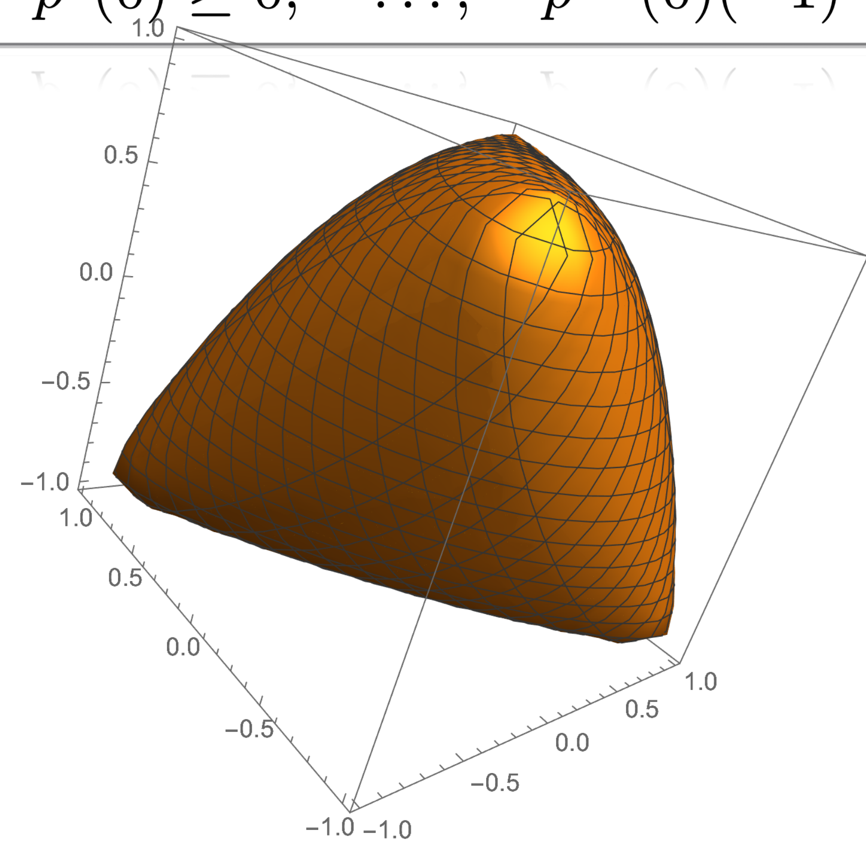
- Stability is guaranteed if the potential matrix is positive definite:

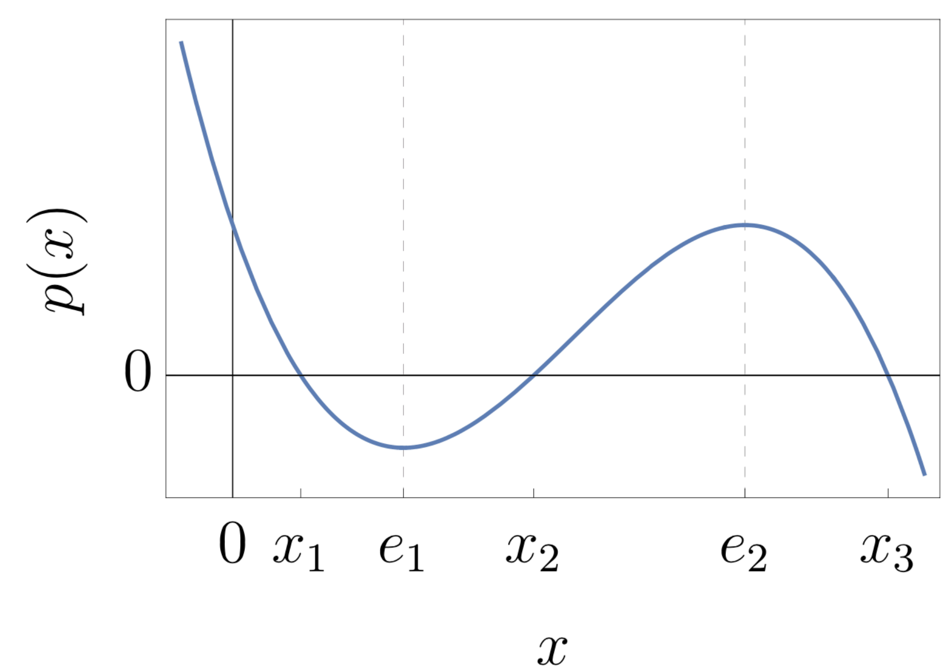
$$V = \begin{pmatrix} \lambda & \lambda_4/4 & \lambda_5/4 \\ \lambda_4/4 & \lambda_1/4 & \lambda_3/4 \\ \lambda_5/4 & \lambda_3/4 & \lambda_2/4 \end{pmatrix} \qquad p(x) = \det(V - xI) = -x^3 + \cdots$$

- $x_1 > 0 : \quad p(0) > 0 \text{ and } e_1 > 0$
- $e_1 > 0 : \quad p'(0) < 0 \text{ and } p''(x) \text{ should vanish at } x > 0$
- $\vdots$

➡ $p(0) \geq 0, \quad p'(0) \leq 0, \quad p''(0) \geq 0, \quad \ldots, \quad p^{(n)}(0)(-1)^n \geq 0$

$$|x|, |y|, |z| < 1$$
$$x^2 + y^2 + z^2 - 2xyz < 1$$





$x \equiv \frac{\lambda_4}{2\sqrt{\lambda\lambda_1}}, \qquad y \equiv \frac{\lambda_5}{2\sqrt{\lambda\lambda_2}}, \qquad z \equiv \frac{\lambda_3}{\sqrt{\lambda_1\lambda_2}}$

SCALAR POTENTIAL

- Is positive definiteness necessary? V matrix acts on positive vectors, not on $\mathbf{R}^3$
- Broader class: copositive definite matrices

K. Kannike, 1205.3781

$$\Leftrightarrow \; a^T V a > 0 \text{ for } a > 0$$

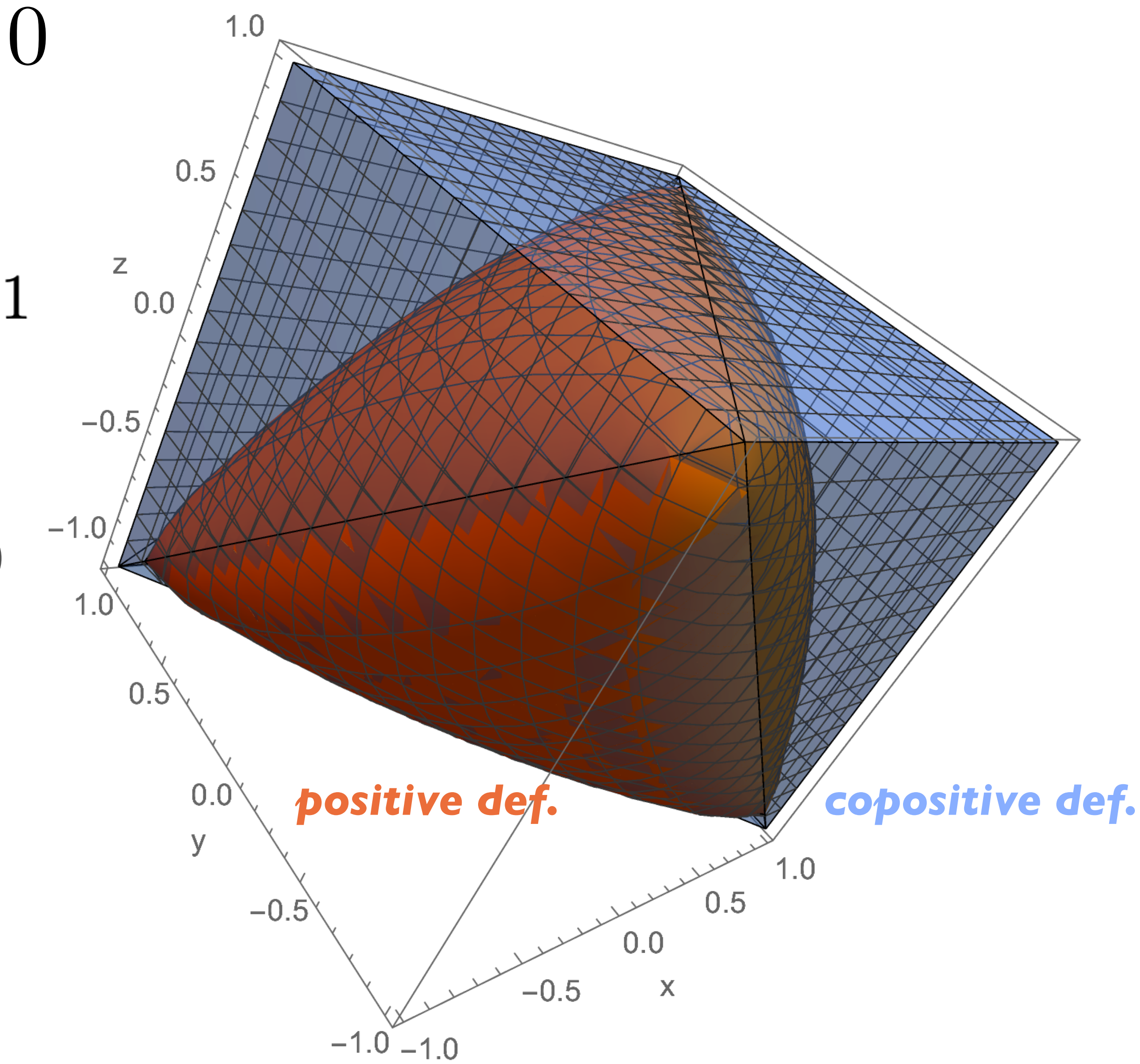
➡

$$x, y, z > -1$$

$$x^2 + y^2 + z^2 - 2xyz < 1 \quad \text{for} \quad x + y + z < -1$$

$$-3.5 \lesssim \lambda_3 \lesssim 3.5$$
$$-1.4 \lesssim \lambda_4 \lesssim 3.5$$
$$-1.4 \lesssim \lambda_5 \lesssim 3.5$$

(stability + perturbativity)



$$x \equiv \frac{\lambda_4}{2\sqrt{\lambda\lambda_1}}, \qquad y \equiv \frac{\lambda_5}{2\sqrt{\lambda\lambda_2}}, \qquad z \equiv \frac{\lambda_3}{\sqrt{\lambda_1\lambda_2}}$$

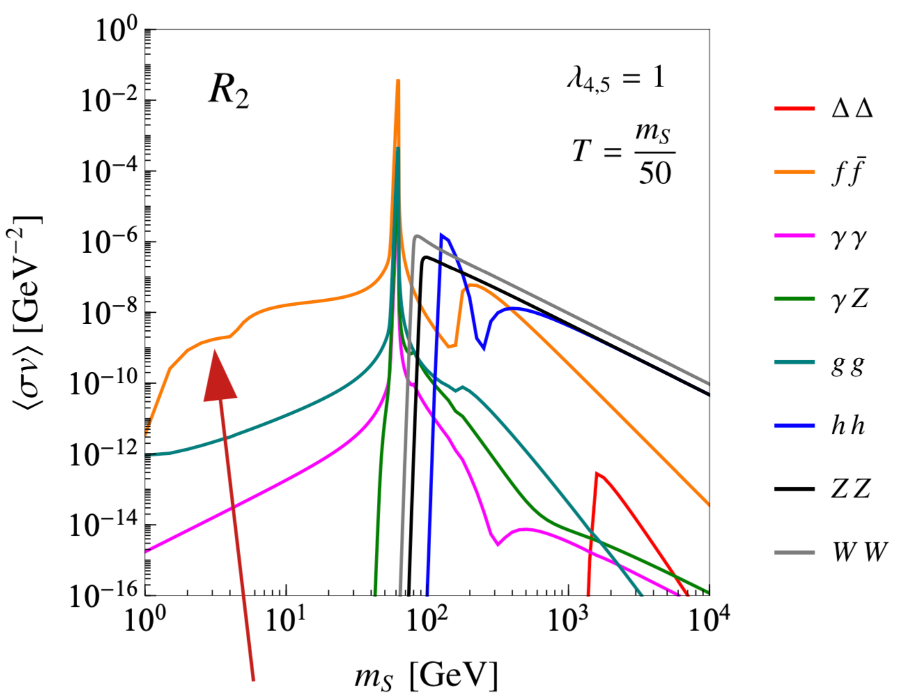
DM PHENOMENOLOGY

ANNIHILATION CROSS SECTIONS

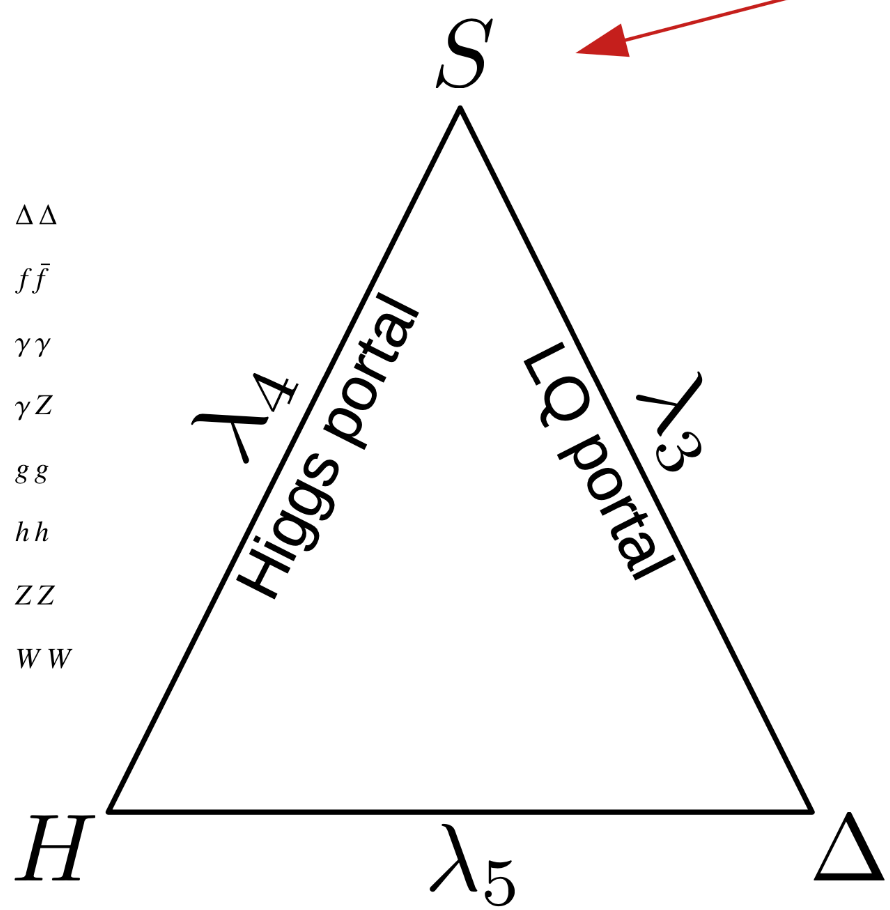
The Scalar Potential

$$V_{\rm BSM}(H,\Delta,S) = \underbrace{m_1^2\,|\Delta|^2 + \frac{m_2^2}{2}S^2}_{\text{mass}} + \underbrace{\frac{\lambda_1}{4}S^4 + \frac{\lambda_2}{4}|\Delta|^4}_{\text{self-interaction}} + \underbrace{\frac{\lambda_3}{2}S^2\,|\Delta|^2 + \frac{\lambda_4}{2}S^2\,|H|^2 + \frac{\lambda_5}{2}|\Delta|^2\,|H|^2}_{\text{portals}}$$

Annihilation channels:

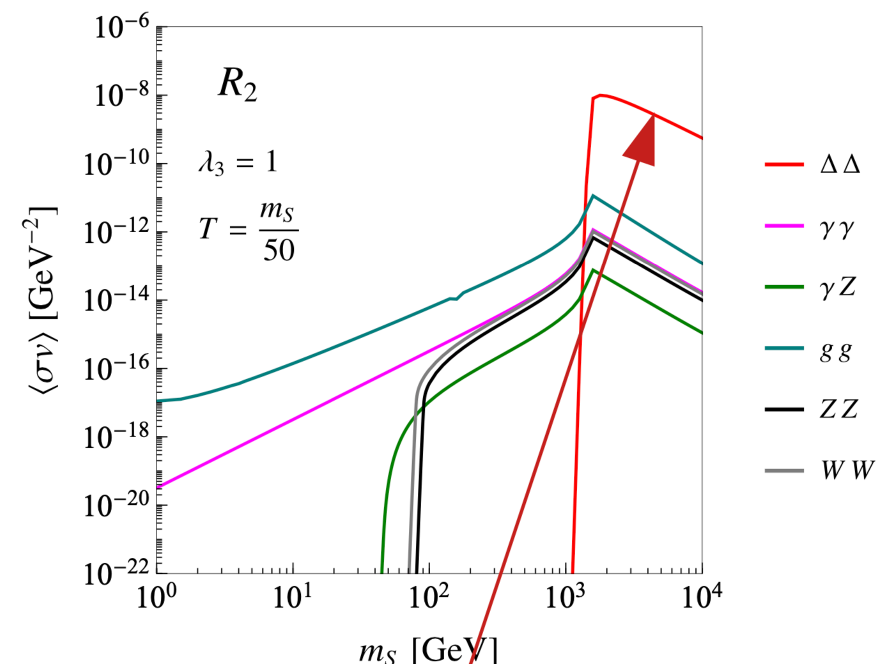


Light DM, connection with LQ Yukawas?



(not relevant for DM pheno)

Annihilation channels:



Heavy DM?

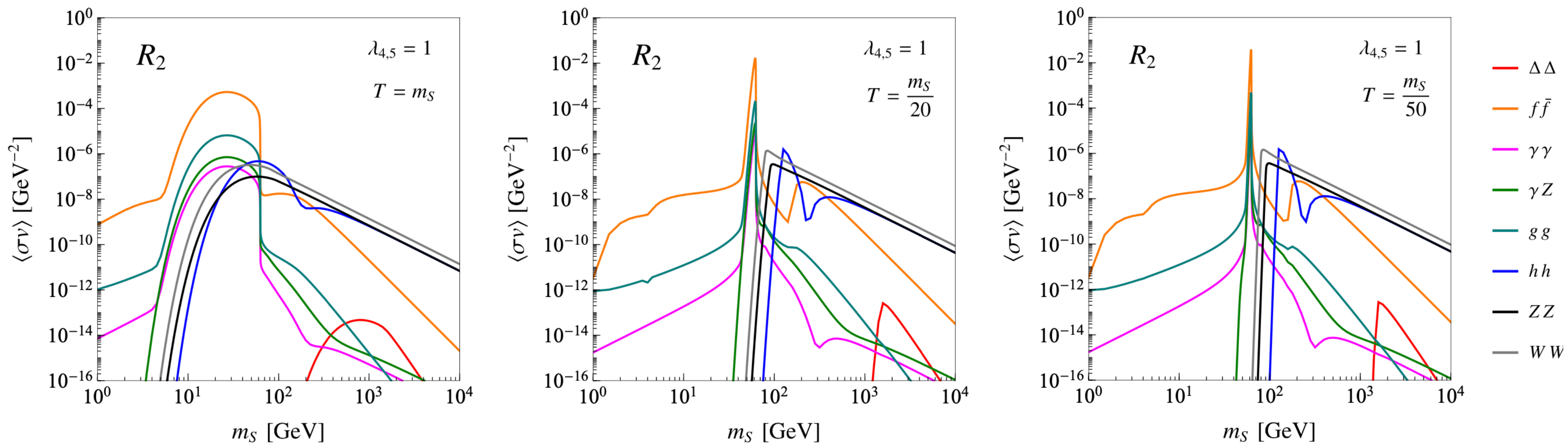
"Scalar triangle"© (by A. Smolkovič)

RELIC DENSITY

- Boltzmann equation solution, tested the effects of T-averaging

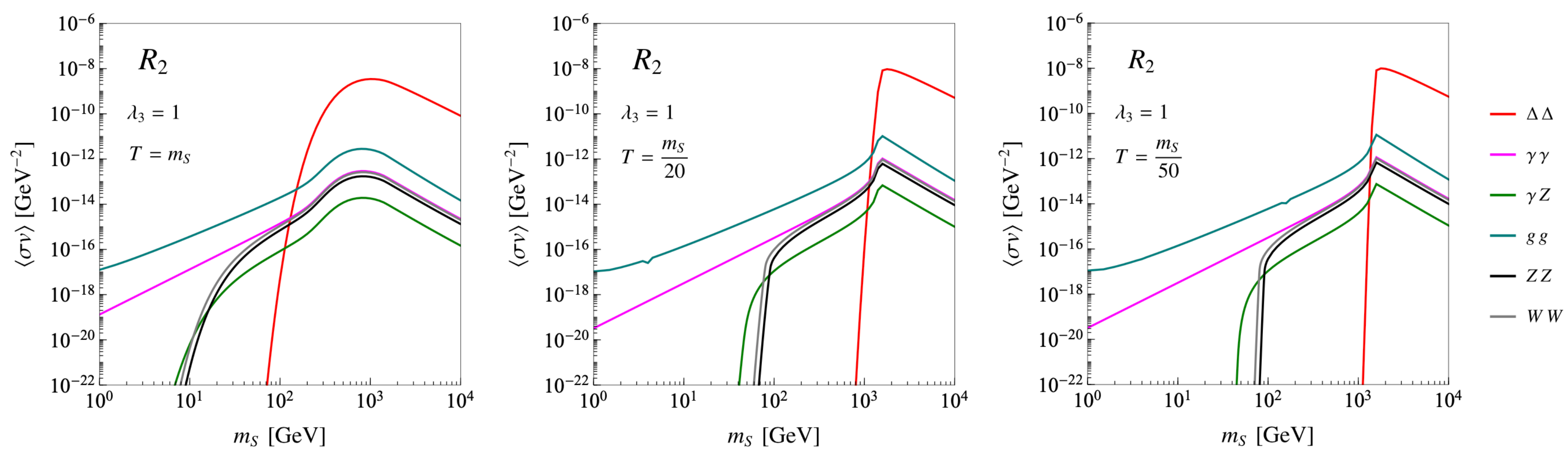
$$\frac{\mathrm{d}n_S}{\mathrm{d}t} + 3Hn_S = -\langle\sigma v\rangle\left(n_S^2 - n_S^{\mathrm{eq}\,2}\right) \qquad n_S^{\mathrm{eq}} = \left(\frac{m_S T}{2\pi}\right)^{3/2} \exp(-m_S/T)$$

Higgs portal



$$\langle\sigma v\rangle_{SS\to ij} = \frac{1}{8\, m_S^4\, T\, K_2^2[m_S/T]} \int_{4m_S^2}^{\infty} ds\,(s-4m_S^2)\,\sqrt{s}\,\sigma_{SS\to ij}(s)\, K_1\left(\frac{\sqrt{s}}{T}\right)$$

LQ portal



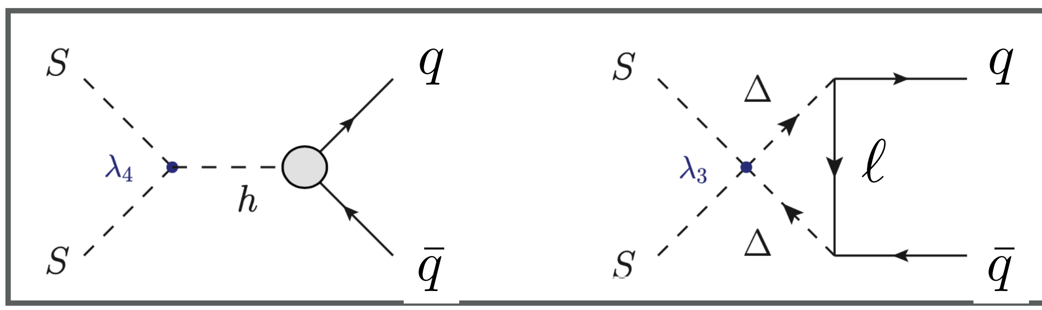
- Choose $m_{S,\Delta}$, λ_i, Yukawas such to reproduce present $\Omega_c h^2 = 0.120 \pm 0.001$

DIRECT DETECTION

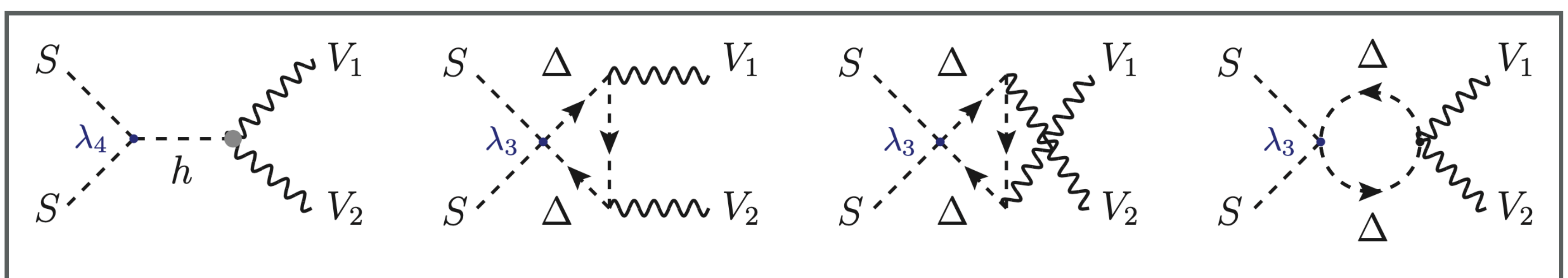
- Direct detection on nucleons (SN → SN)

$$\mathcal{L}_N^{\rm eff} = C_N\, S^2 \bar{N} N$$

$$C_N = \sum_{q=u,d,s} \frac{C_q}{m_q}\, m_N\, f_{Tq}^N - C_g\, \frac{2}{27}\, m_N\, f_{TG}^N$$



$$C_q = \frac{\lambda_4 m_q}{2 m_h^2}$$



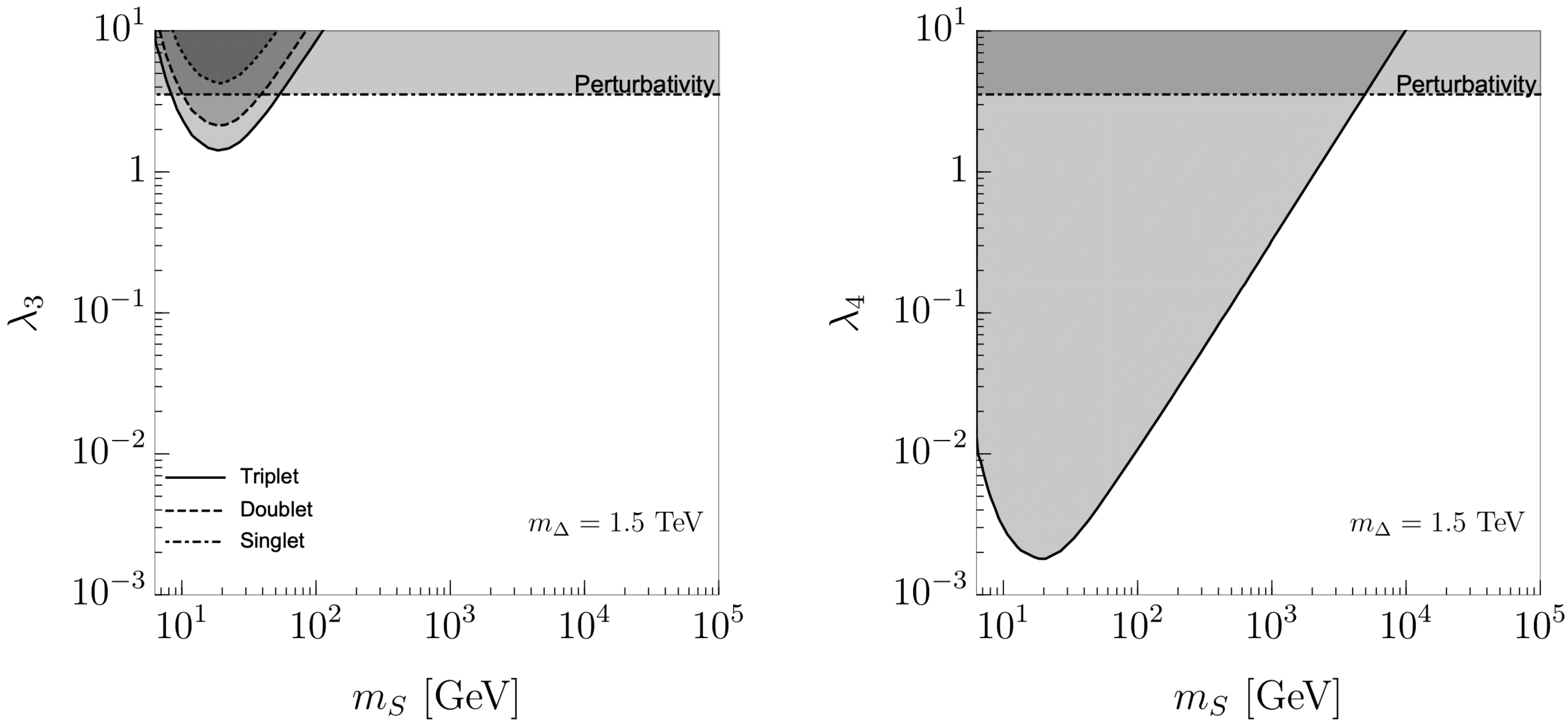
$$C_g = \frac{\lambda_3}{8 m_\Delta^2}(2T+1) - \frac{\lambda_4}{2 m_h^2}\left[n_H + \frac{\lambda_5 (2T+1) v^2}{16 m_\Delta^2} \right]$$

- Consider spin independent scattering on Xe nucleus

$$\sigma_{\rm SI} = \frac{\mu_p^2}{\pi m_S^2}\left[\frac{Z\, C_p + (A-Z)\, C_n}{A}\right]$$

DIRECT DETECTION

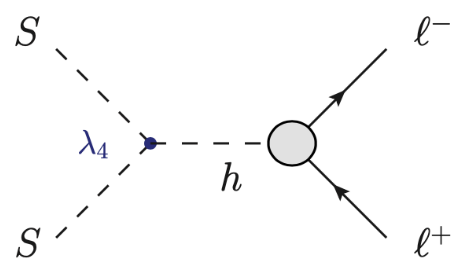
Xenon1T constraints



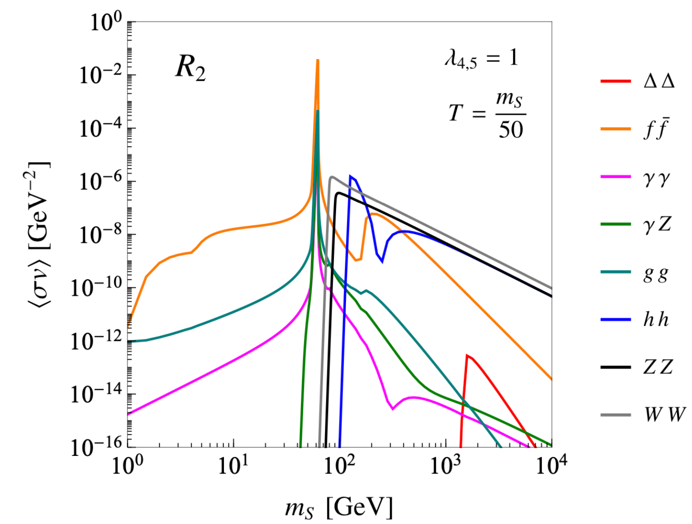
HIGGS PORTAL

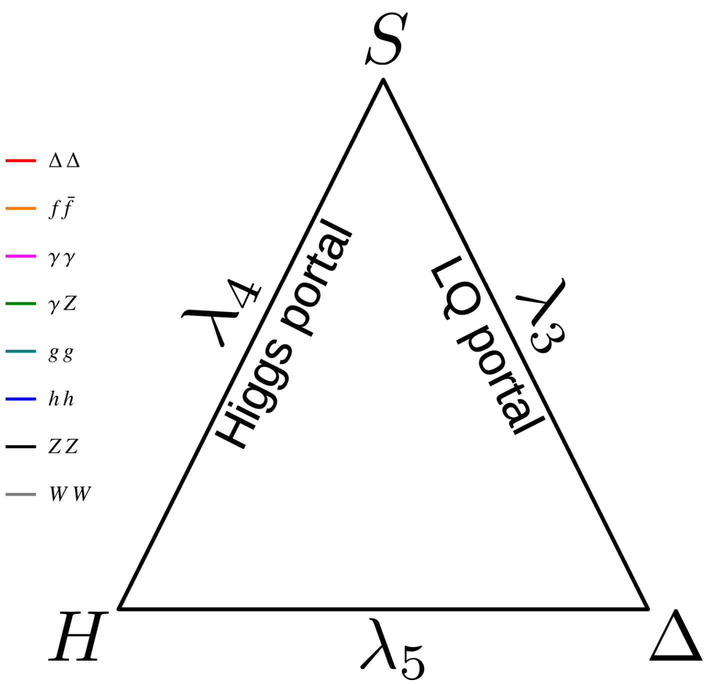
- Leptoquark ***Δ*** enters strictly via loops

$$\lambda_4 > 0, \quad \lambda_3 = 0$$



Annihilation channels:

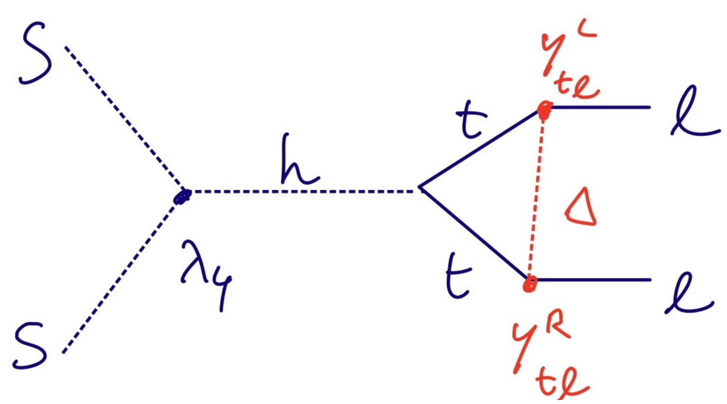




(not relevant for DM pheno)

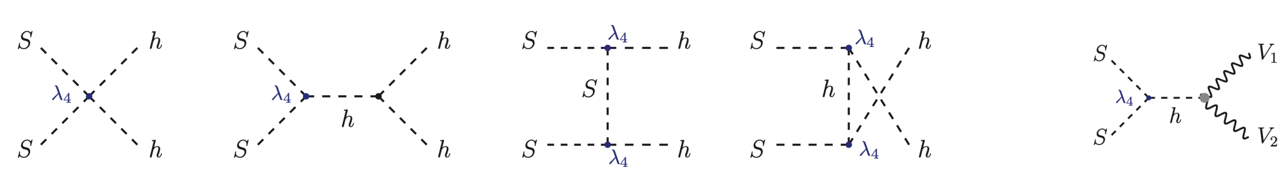
- At m_S ~ 1-10 GeV cross section

dominated by ff, opportunity for the LQ Yukawas to drive the relic abundance



Direct relation to $(g-2)_l$ and b-quark semileptonic decays

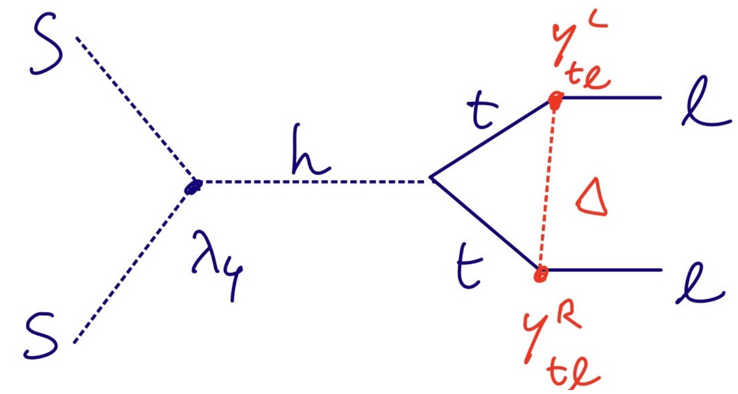
Also:



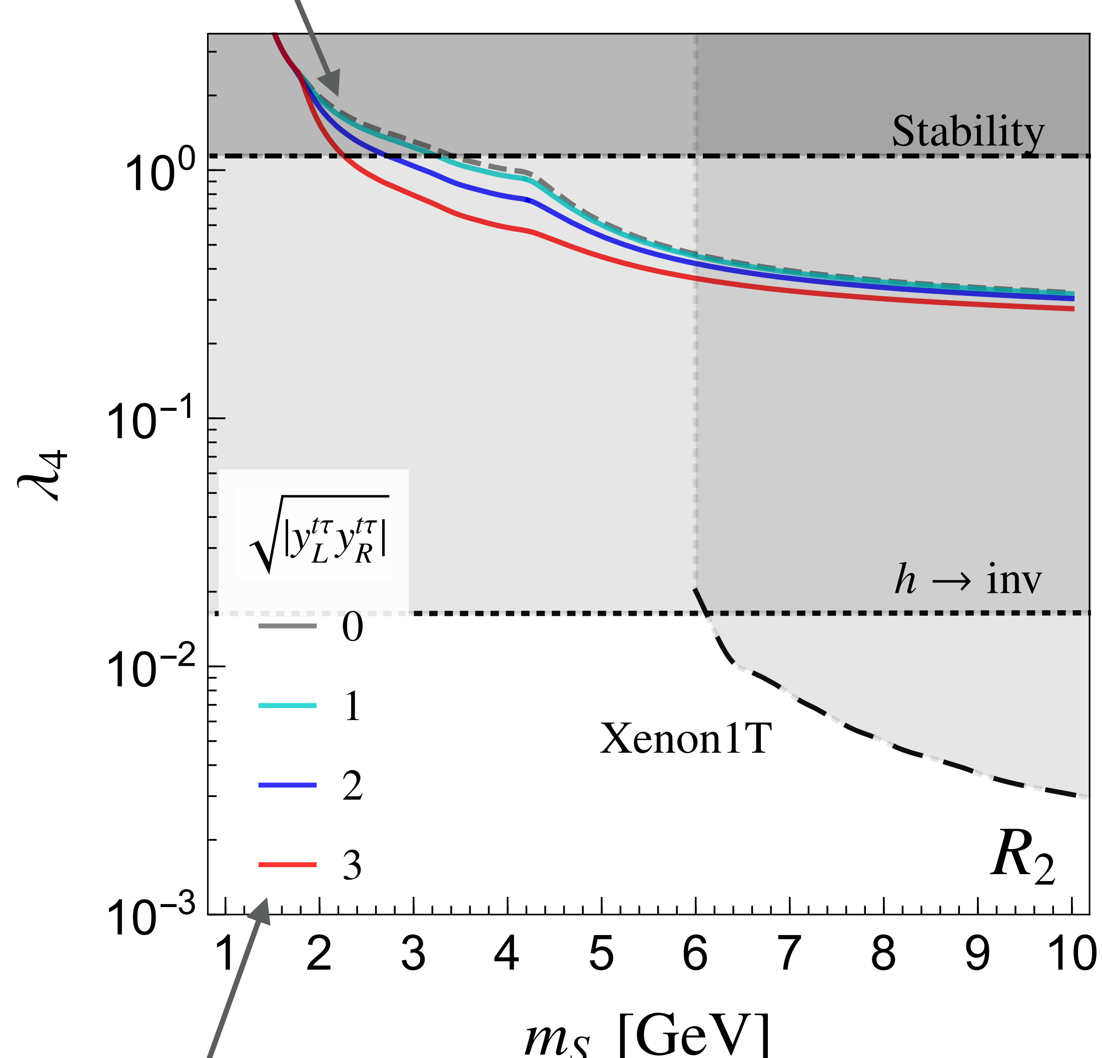
HIGGS PORTAL REGIME

- Leptoquark Δ enters strictly via loops

$$\lambda_4 > 0, \quad \lambda_3 = 0$$



$\Omega_c h^2 = 0.120 \pm 0.001$



(Allowed by current LHC h→ττ searches)

Despite significant effect of the LQ Yukawas, h → inv. constraint rules out this region

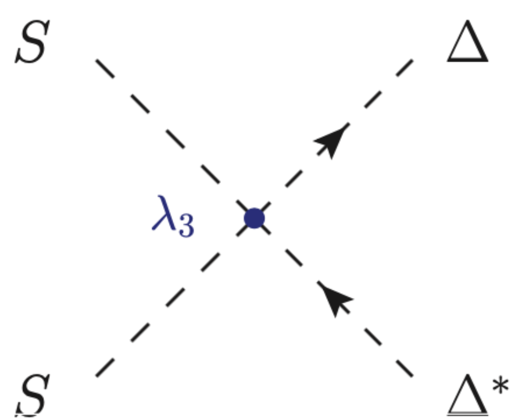
$$\frac{\Gamma_{h\to SS}}{\Gamma_h^{\rm SM} + \Gamma_{h\to SS}} < {\rm Br}(h \to {\rm inv.})$$

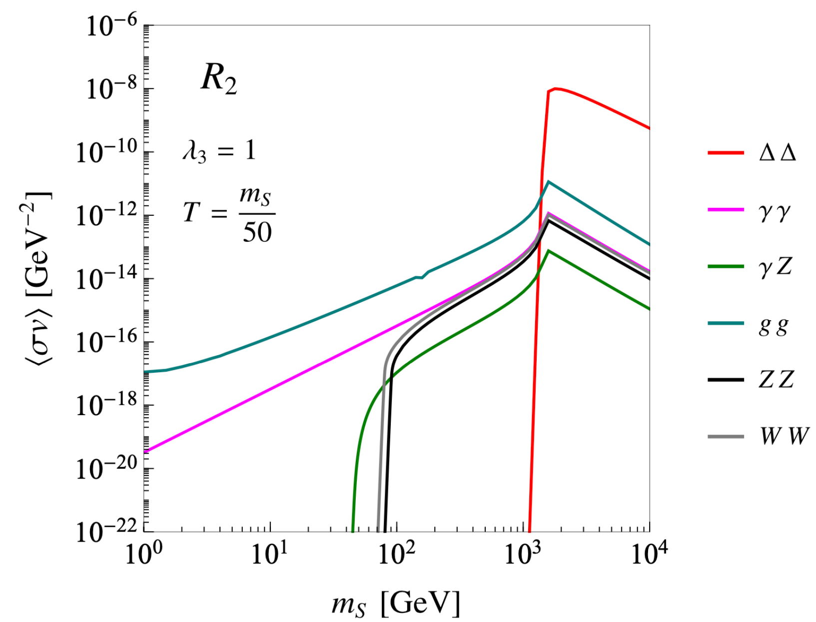
$$\Gamma_{h\to SS} = \frac{\lambda_4^2 v^2}{32\pi m_h}\sqrt{1 - \frac{4m_S^2}{m_h^2}}$$

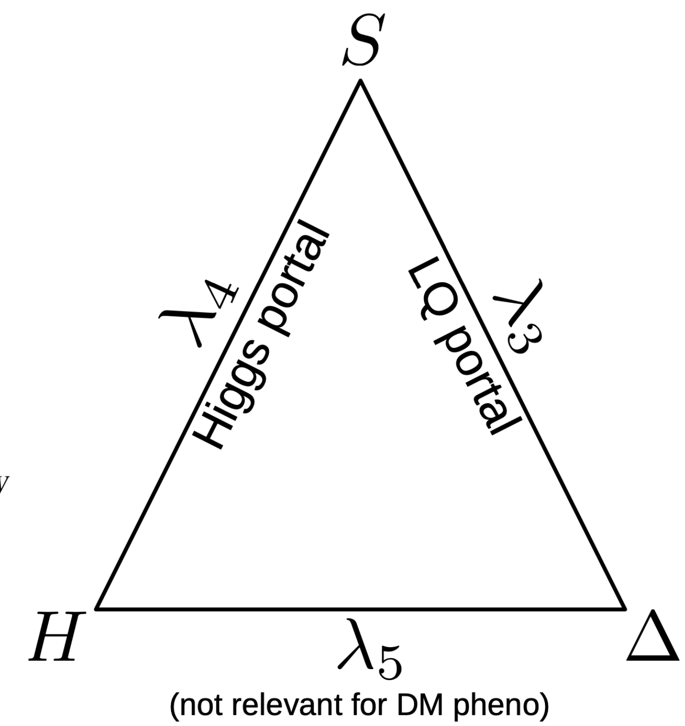
LQ PORTAL

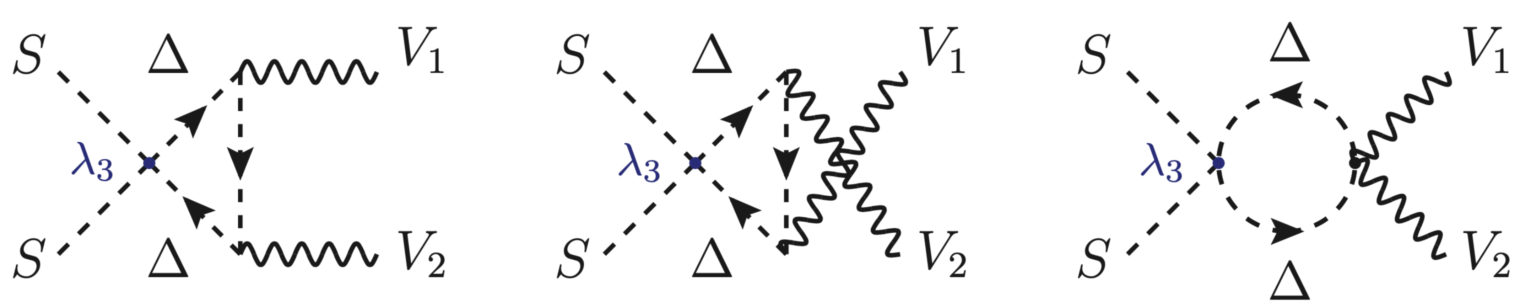
- Leptoquark Δ is allowed as final state
- Δ mediates SS → VV

$$\lambda_3 \neq 0, \quad \lambda_{4,5} = 0$$





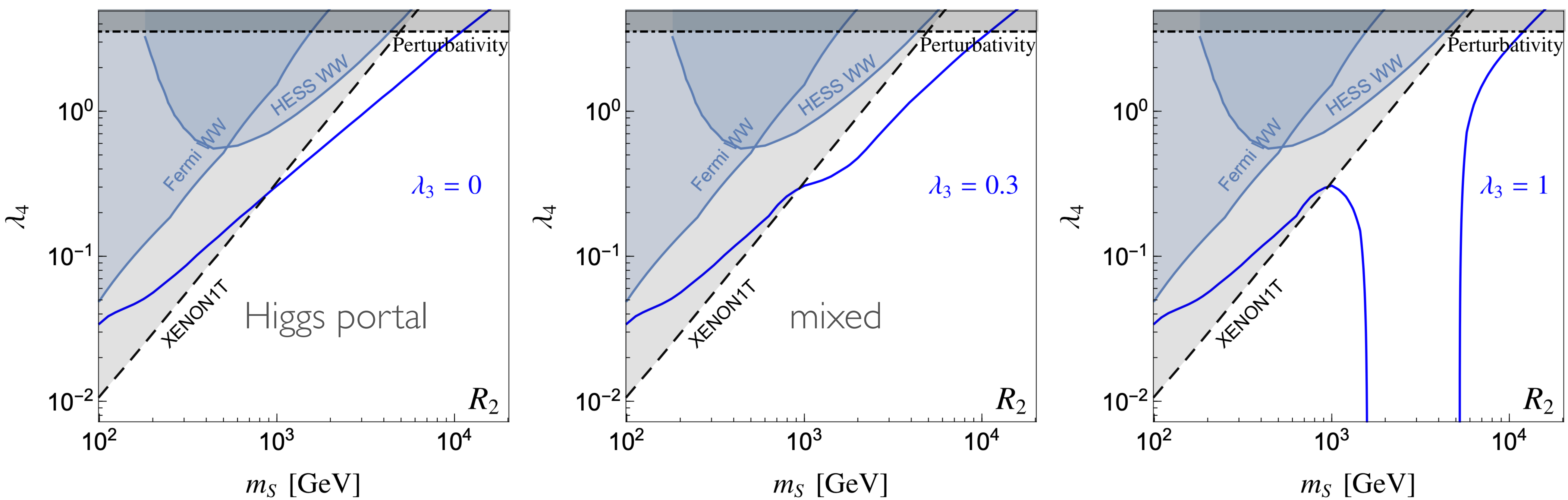




- Fermionic final states not allowed - scenario insensitive to LQ Yukawas

LQ VS. HIGGS PORTAL

$\Delta = R_2$ and $m_{R_2} = 1.5\,\mathrm{TeV}$

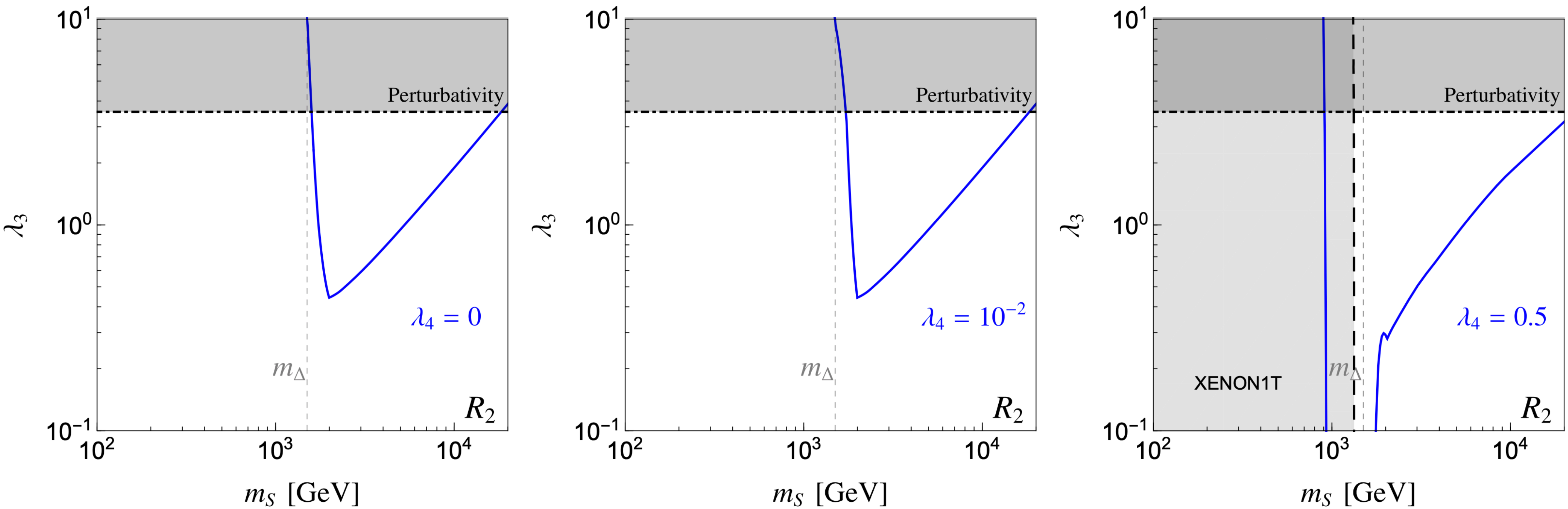


Higgs portal

LQ portal

LQ VS. HIGGS PORTAL

$\Delta = R_2$ and $m_{R_2} = 1.5\,\text{TeV}$



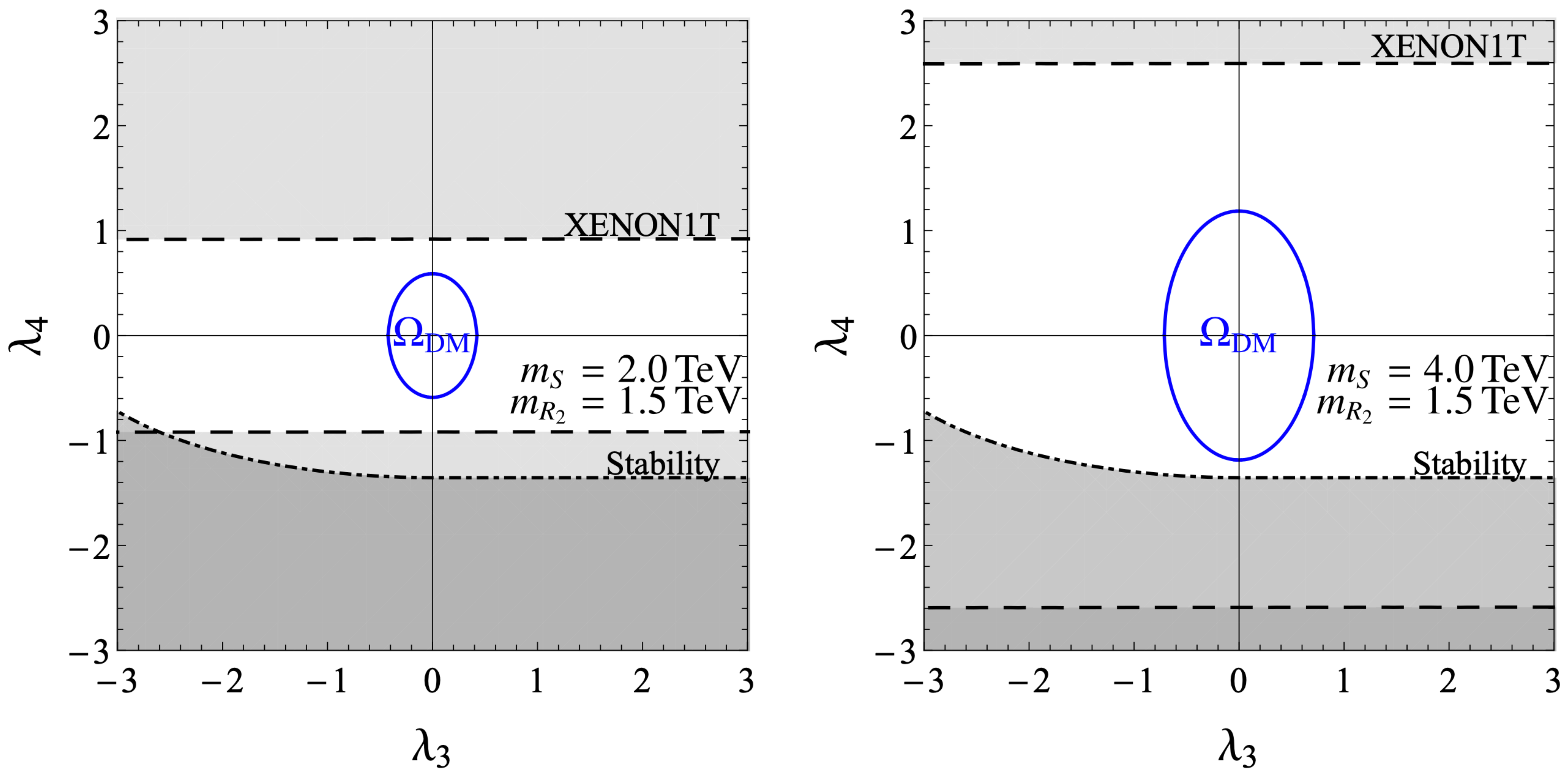
LQ portal

Higgs portal

LQ VS. HIGGS PORTAL

$m_S > m_\Delta$, fixed masses

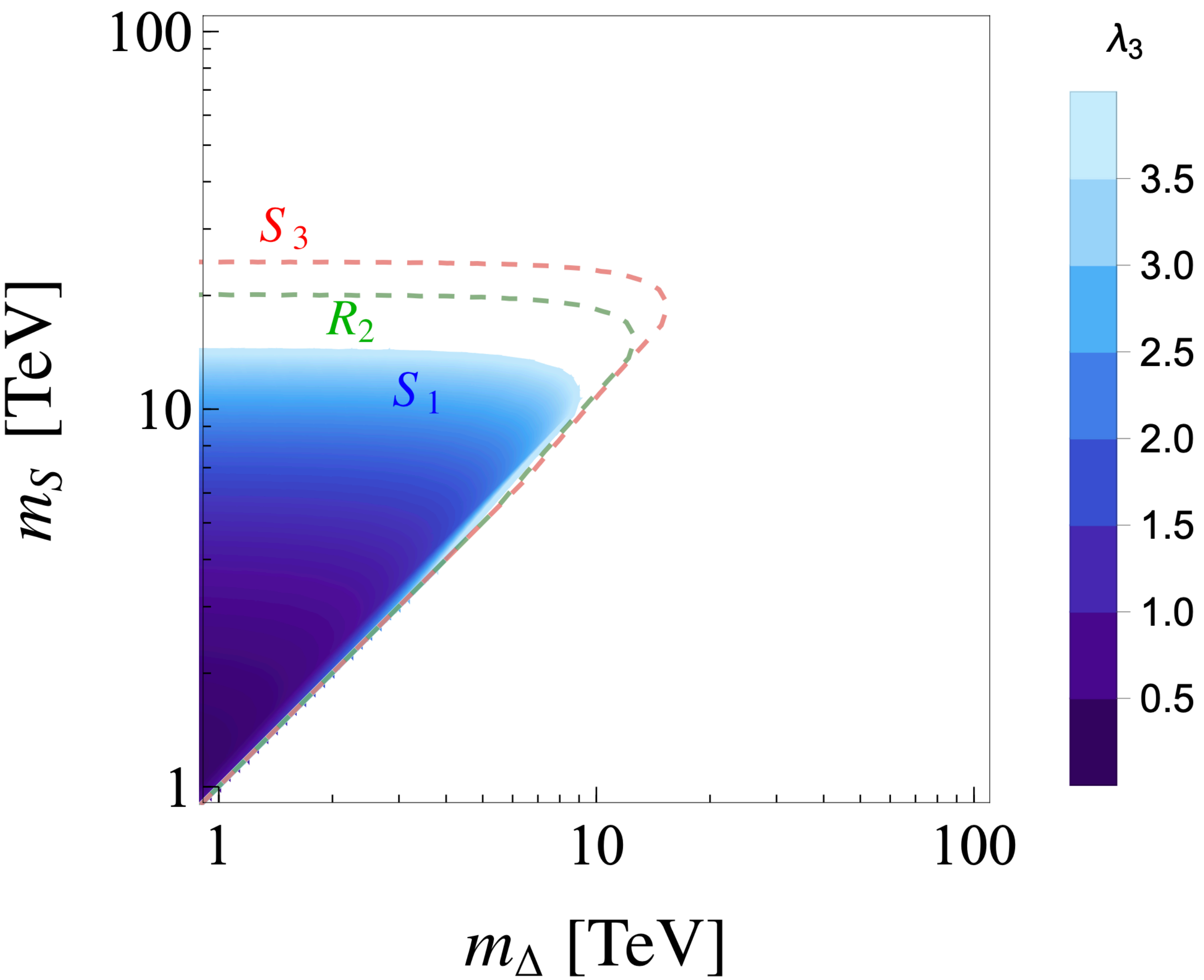
Testable by direct detection experiments.



LQ portal constrained only by relic density.

EXCLUSIVE LQ PORTAL

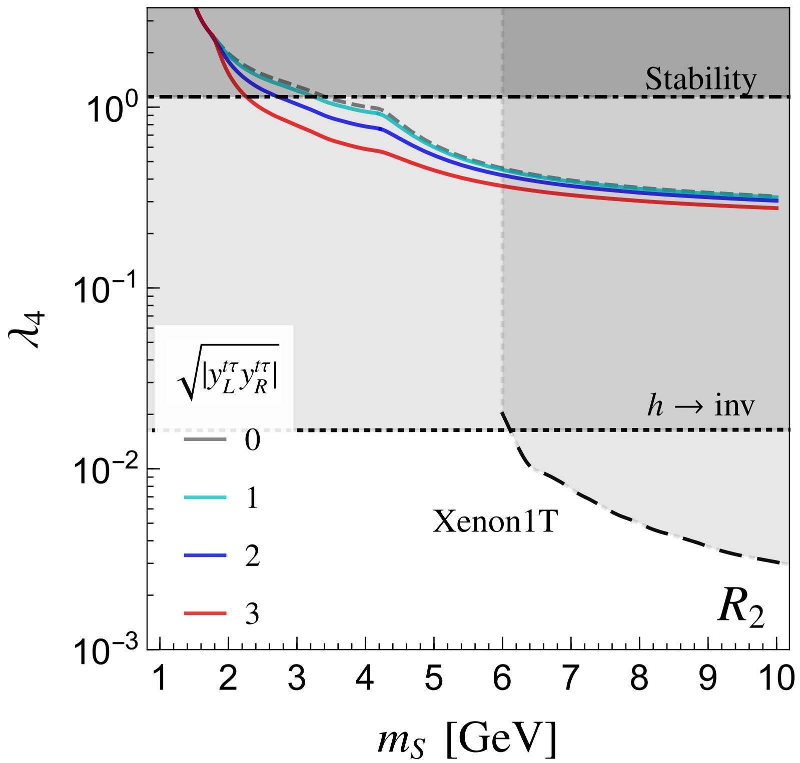
$m_S > m_\Delta$, $\lambda_4=0$, tune λ_3 to reproduce relic density

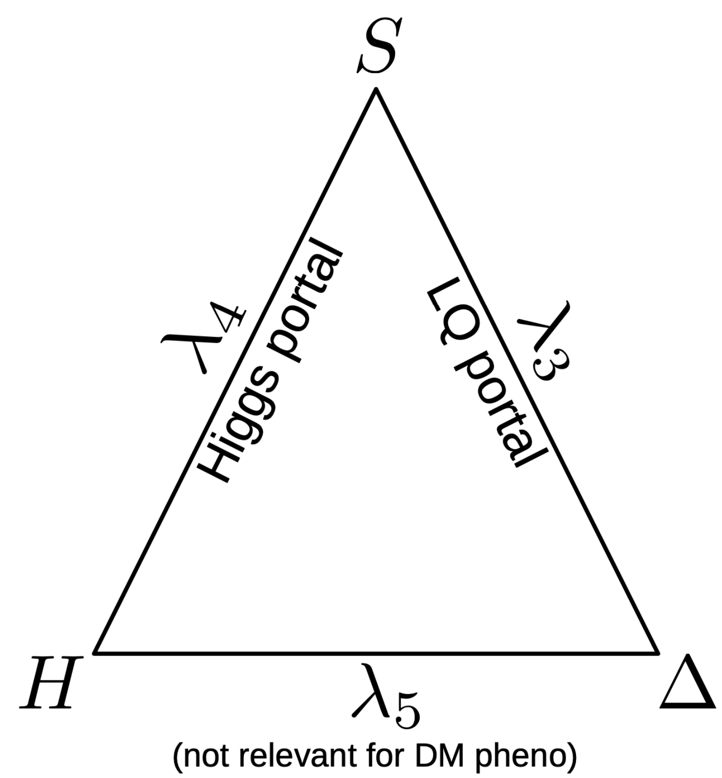


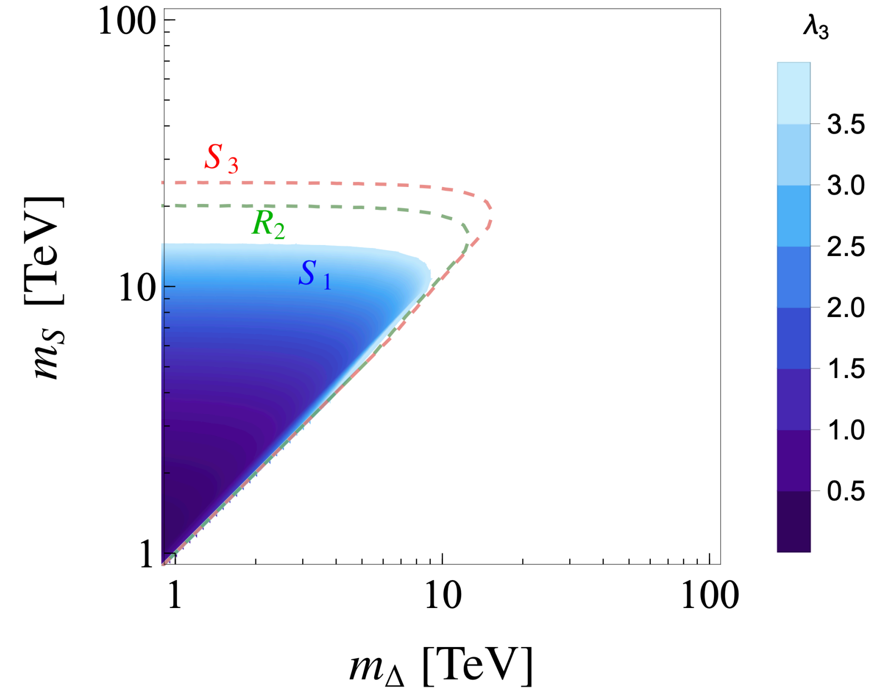
Stop at perturbativity bound!

10 TeV > m_S > m_Δ

SUMMARY & CONCLUSION







- Light S allows for tuning of relic density by Yukawa couplings
- Excluded by direct detection and Higgs physics

- Heavy S regime
- Upper bounds on S and Δ masses
- Upper bound on Δ mass implies upper bound on LQ flavour Yukawas

- Further testability ensured by flavor measurements, (in)direct searches for S, LHC searches for leptoquarks