Variations in the dark matter interpretation of the diphoton excess

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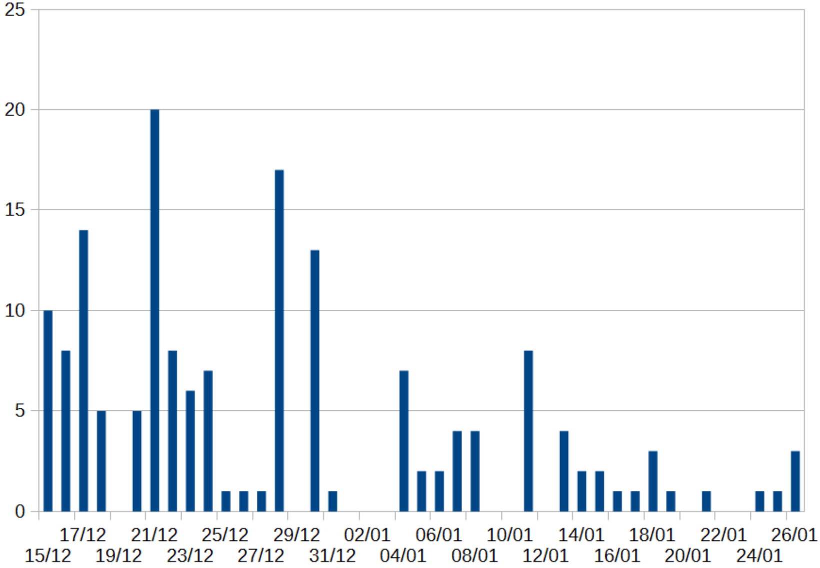
ON THE DIPHOTON EXCESS, VUB, 28/01/2016

The diphoton rush



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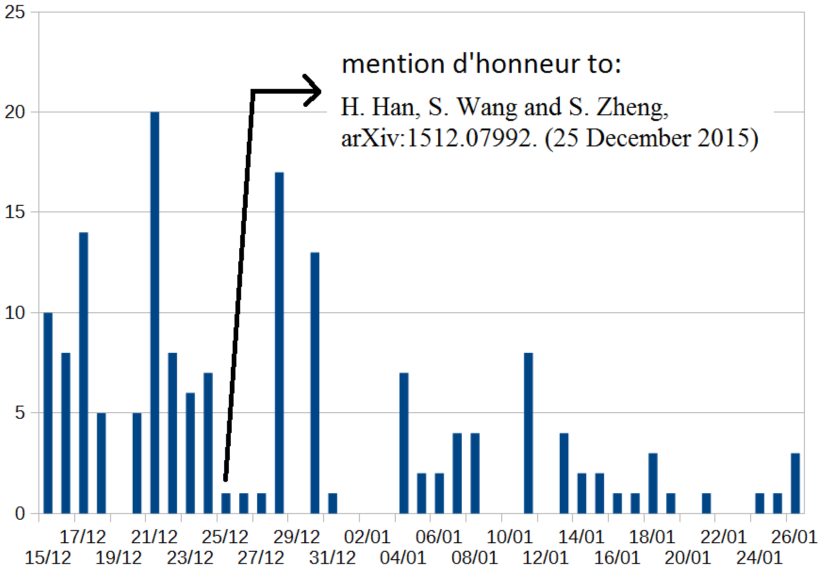


The early hours (from A. Strumia website)

December 2015: the Gold Rush			
0	ATLAS and CMS	seminar	15 Dec 2015 14-16
1	K. Harigaya, Y. Nomura, 7 pages	1512.04850	v1: 15 Dec 2015 16:47:58 v2: 16 Dec 2015 08:19:11
2	Y. Mambrini, G. Arcadi, A. Djouadi, 9 pages	1512.04913	15 Dec 2015 20:05:04
3	M. Backovic, A. Mariotti, D. Redigolo, 17 pages	1512.04917	15 Dec 2015 20:26:16
4	A. Angelescu, A. Djouadi, G. Moreau, 15 pages	1512.04921	15 Dec 2015 20:32:58
5	Y. Nakai, R. Sato, K. Tobioka, 6 pages	1512.04924	15 Dec 2015 20:39:32
6	S. Knapen, T. Melia, M. Papucci, K. Zurek, 20 pages	1512.04928	15 Dec 2015 20:44:08
7	D. Buttazzo, A. Greljo, D. Marzocca, 16 pages	1512.04929	15 Dec 2015 20:49:36
8	A. Pilaftsis, 6 pages	1512.04931	15 Dec 2015 20:50:27
9	R. Franceschini, G. Giudice, J.F. Kamenik, M. McCullough, A. Pomarol, R Rattazzi, M. Redi, F. Riva, A. Strumia, R. Torre, 32 pages	1512.04933	15 Dec 2015 20:53:14
10	S. Di Chiara, L. Marzola, M. Raidal, 5 pages	1512.04939	15 Dec 2015 20:59:17
11	T. Higaki, K.S. Jeong, N. Kitajima, F. Takahashi, 8 pages	1512.05295	16 Dec 2015 19:36:36
12	S.D. McDermott, P. Meade, H. Ramani, 6 pages	1512.05295	16 Dec 2015 20:48:16
13	J. Ellis, S.A.R. Ellis, J. Quevillon, V. Sanz, T. You, 36 pages	1512.05327	16 Dec 2015 20:49:44
14	M. Low, A. Tesi, L.T. Wang, 23 pages	1512.05328	16 Dec 2015 20:50:26

[http://astrumia.web.cern.ch/astrumia/]

Outline

- C. Han, H. M. Lee, M. Park and V. Sanz,
  The diphoton resonance as a gravity mediator of dark matter, arXiv:1512.06376.
- A. Berlin,
  The Diphoton and Diboson Excesses in a Left-Right Symmetric Theory of Dark Matter, arXiv:1601.01381.
- P. S. B. Dev and D. Teresi,
  Asymmetric Dark Matter in the Sun and the Diphoton Excess at the LHC, arXiv:1512.07243.
- Conclusions

Part 1

C. Han, H. M. Lee, M. Park and V. Sanz,
The diphoton resonance as a gravity mediator of dark matter, arXiv:1512.06376.

Location of the fields in the warped extra dimension

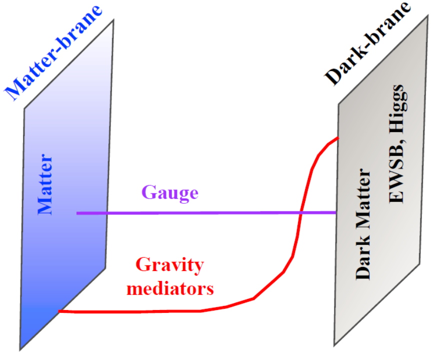


FIG. 1. *The set-up in extra-dimensions. Electroweak symmetry breaking, and the origin of Dark Matter stability and mass are related, hence their location on the same brane (IR brane, or Dark Brane). Gauge fields live in the bulk, and matter fields are located on the opposite brane (UV brane). EWSB is transmitted to fermions trough gauge and gravitational interactions.*

[Lee, Park, Sanz, 1306.4107]

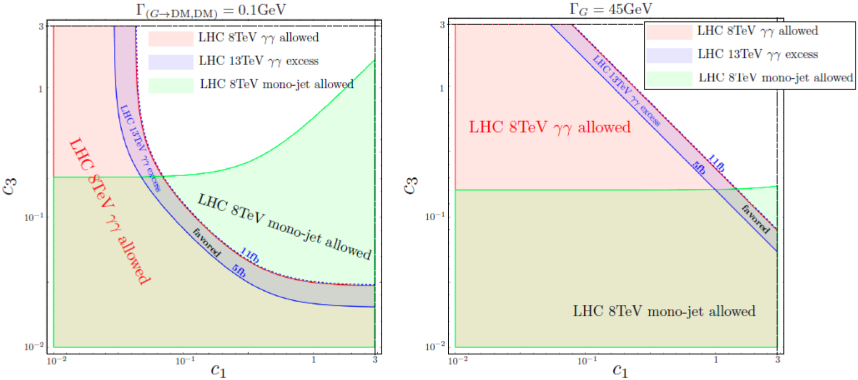
Effective 4D Lagrangian

- Kaluza-Klein graviton $G_{\mu\nu}$ as spin-2 750 GeV resonance
- $$\mathcal{L}_{\rm KK} = -\frac{1}{\Lambda} G^{\mu\nu}\left[T^{\rm DM}_{\mu\nu} + \sum_{a=1}^{3} c_a \left(\frac{1}{4} g_{\mu\nu} F^{\lambda\rho}_a F_{\lambda\rho,a} - F_{\mu\lambda,a} F^{\lambda}{}_{\nu,a}\right)\right]$$
- $\Lambda \sim 3\,\text{TeV}$ is the compactification scale
- couplings to the vector-boson mass eigenstates:

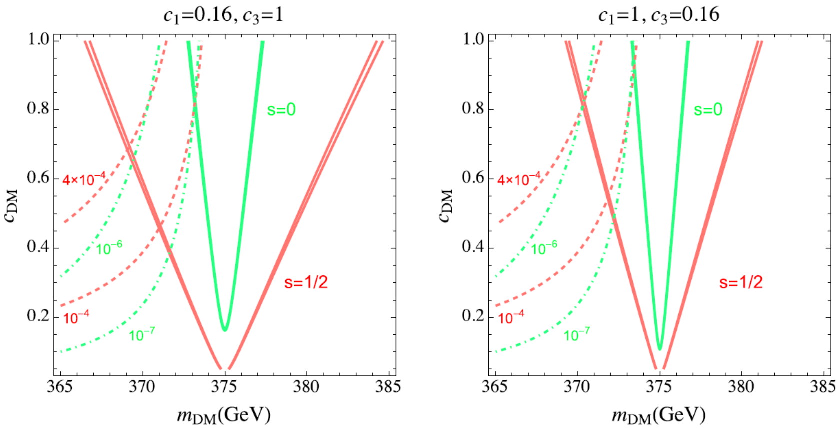
$$\begin{aligned}
c_{\gamma\gamma} &= c_1 \cos^2\theta_W + c_2 \sin^2\theta_W, \\
c_{Z\gamma} &= (c_2 - c_1)\sin(2\theta_W), \\
c_{ZZ} &= c_1 \sin^2\theta_W + c_2 \cos^2\theta_W, \\
c_{WW} &= 2c_2, \\
c_{gg} &= c_3.
\end{aligned}$$

- take $c_2 = c_1$ to suppress $Z\gamma$ signal

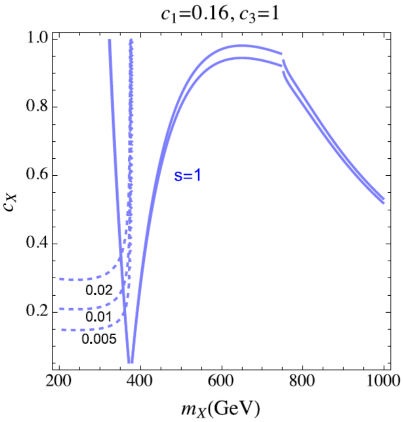
The diphoton signal

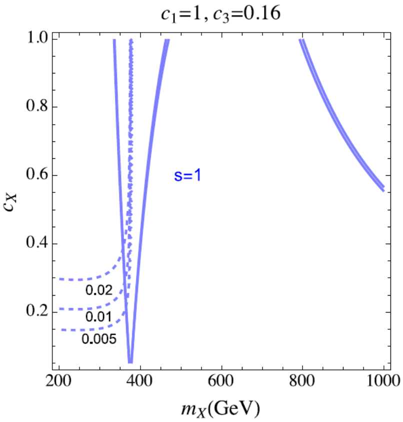


Dark Matter relic density (spin 0, 1/2)



Dark Matter relic density (spin 1)





The spin of the 750 GeV resonance

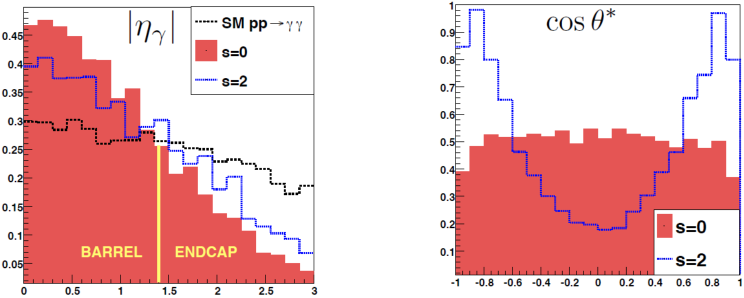


Figure 6: *Angular distributions:* (Left) Comparison of the photon rapidity distribution for the SM, and new heavy spin-zero and -two resonances. (Right) Angle of the photon respect to the beam axis, in the CM frame of the decaying particle.

Part 2

A. Berlin,

The Diphoton and Diboson Excesses in a Left-Right Symmetric Theory of Dark Matter, arXiv:1601.01381.

Production of a 750 GeV Δ_R^0 in L-R symmetric theories

- by mixing with SM scalar h: doesn't work ($\Delta_R^0 \to t\bar{t}$, unless very large $\Gamma_{\gamma\gamma}$)
- $pp \to W' \to W\Delta_R^0$, suggested in the early hours... [Knapen, Melia, Papucci, Zurek, 1512.04928]

  suppressed by L-R mixing $\mathcal{L} \supset \frac{\sqrt{2}\, g_R^2 s_{2\beta}}{g_L} \frac{m_W^2}{m_{W'}} \Delta^0\, W^{+\mu} W_\mu'^- + \text{h.c.}$:

  doesn't work ($BR(W' \to W\Delta_R^0) \sim 10^{-5}$)

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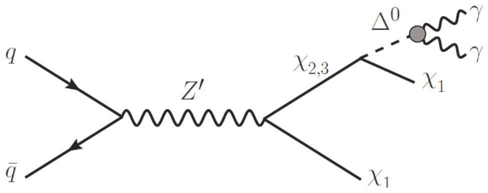
  doesn't work ($BR(W' \to W\Delta_R^0) \sim 10^{-5}$)
- Introduce a dark sector!



also gives charged states for the decay loop

L-R symmetric model with a dark sector

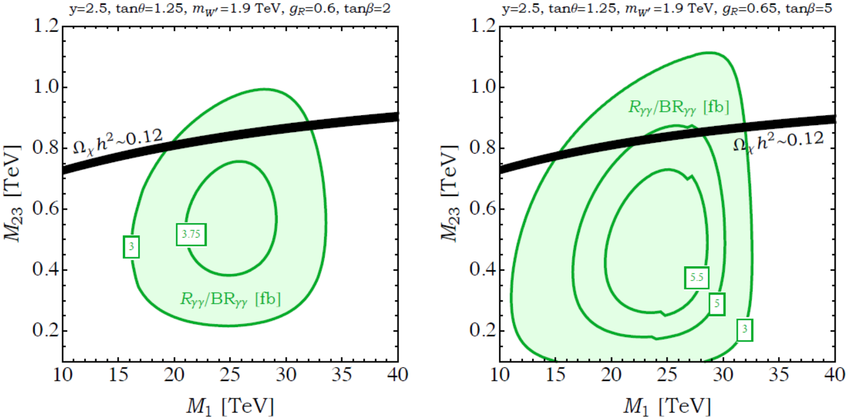
- L-R symmetric model with bidoublet $\phi = (\mathbf{2}, \mathbf{2}, 0)$ and triplet $\Delta_R = (\mathbf{1}, \mathbf{3}, 2)$
- take $v_R \sim 3 - 4\,\text{TeV}, \quad g_R \sim 0.45 - 0.6, \quad \tan\beta \sim 0.5 - 2$
  to reproduce the diboson anomaly in run-I
- introduce 3 dark fermion triplets $T_1 = (\mathbf{1}, \mathbf{3}, 0)$, $T_2 = (\mathbf{1}, \mathbf{3}, 2)$, $T_3 = (\mathbf{1}, \mathbf{3}, -2)$
- $$-\mathcal{L} \supset \frac{1}{2} M_1 \ \mathrm{tr}(T_1^2) + M_{23} \ \mathrm{tr}(T_2 T_3) + \lambda_1 \ \mathrm{tr}(T_3 T_1 \Delta_R) + \lambda_2 \ \mathrm{tr}(T_2 T_1 \Delta_R^\dagger) + \text{h.c.}$$
- mixings:

$$-\mathcal{L} \supset \frac{1}{2} \begin{pmatrix} t_1^0 & t_2^0 & t_3^0 \end{pmatrix} \begin{pmatrix} M_1 & \lambda_2 v_R/\sqrt{2} & -\lambda_1 v_R/\sqrt{2} \\ \lambda_2 v_R/\sqrt{2} & 0 & M_{23} \\ -\lambda_1 v_R/\sqrt{2} & M_{23} & 0 \end{pmatrix} \begin{pmatrix} t_1^0 \\ t_2^0 \\ t_3^0 \end{pmatrix}$$

$$+ \begin{pmatrix} t_1^+ & t_2^+ \end{pmatrix} \begin{pmatrix} M_1 & \lambda_1 v_R/\sqrt{2} \\ -\lambda_2 v_R \sqrt{2} & M_{23} \end{pmatrix} \begin{pmatrix} t_1^- \\ t_3^- \end{pmatrix} + M_{23} \ t_2^{++} t_3^{--} + \text{h.c.}$$

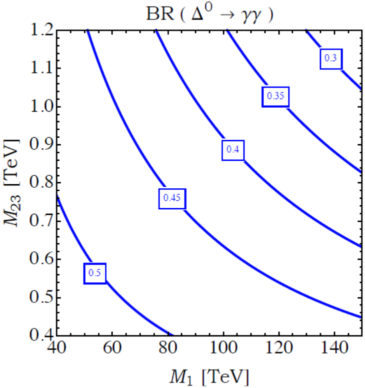
- mass eigenstates $\chi_{1,2,3}$, $\chi_{1,2}^+$, χ_1^{++}

Production cross-section of Δ_R^0 and relic density of χ_1



Decay of Δ_R^0

- suppress mixing and tree-level trilinear couplings to SM h
- take $m_{\chi_1} > 375\,\mathrm{GeV}$ (cannot reproduce 45 GeV width)
- only tree-level decay: $\Delta_R^0 \to W^+W^-$, suppressed by L-R mixing^2
- loop-level decay channels $\gamma\gamma$, γZ, ZZ through loops of $\chi_{1,2}^+$



Part 3

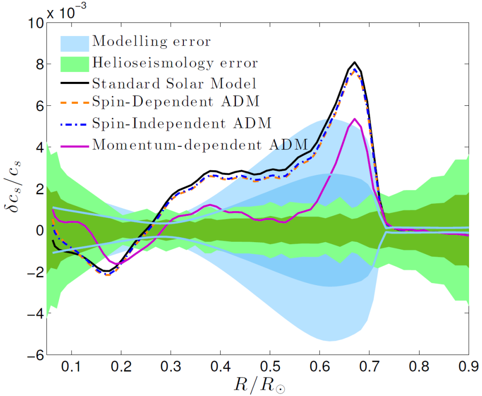
P. S. B. Dev and D. Teresi,
Asymmetric Dark Matter in the Sun and the Diphoton Excess at the LHC, arXiv:1512.07243.

Asymmetric Dark Matter

- in the WIMP freeze-out scenario n_{DM} from $n_{DM}(T_f)\langle\sigma_{ann}v\rangle \simeq H(T_f)$
- in baryo/leptogenesis n_B from $n_B \sim \frac{\epsilon}{\mathrm{K}}$
- but $\rho_{DM} \approx \rho_B$ (just a coincidence or more behind?)
- asymmetric Dark Matter paradigm: $n_{DM} \approx n_B$ from a common mechanism
- light Dark Matter: $\rho_{DM} \simeq 5\rho_B \implies m_{DM} \approx 5\,\mathrm{GeV}$
- basically no annihilation today, since $n_{\overline{DM}} \ll n_{DM}$ (if asymmetry survives)
- asymmetric Dark Matter can accumulate inside the Sun

Momentum-dependent ADM and the solar anomaly

- asymmetric DM with $m_\chi = 3\,\mathrm{GeV}$, $\sigma_{DD} = (|\vec{q}|/40\,\mathrm{MeV})^2\, 10^{-37}\mathrm{cm}^2$
- it can explain the anomaly of solar models in predicting heliseismological observables (6σ evidence, taken at face value) [Vincent, Scott, Serenelli, 1411.6626]



- compatible with collider and direct detection constraints

Minimal simplified model for momentum-dependent ADM

- $\sigma_{DD} \propto |\vec{q}|^2$ from operators $i\,\overline{\chi}\gamma_5\chi\overline{q}q$ or $i\,\overline{\chi}\sigma_{\mu\nu}\gamma_5\chi\overline{q}\sigma^{\mu\nu}q$ (we focus on 1st one)
- minimal simplified model [Dev, DT, 1512.07243]:

$$-\mathcal{L} \supset \frac{m_\phi^2}{2}\,\phi^2 + \frac{m_P^2}{2}\,\phi_P^2 + \mu^2\,\phi_P\phi + m_\chi\overline{\chi}\chi$$
$$+ g_\phi\,\phi\,\overline{q}q + i\,g_P\,\phi_P\,\overline{q}\gamma_5 q + i\,h\,\phi_P\,\overline{\chi}\gamma_5\chi$$

- ϕ, ϕ_P mix into mass eigenstates ϕ_S, ϕ_A:

$$-\mathcal{L} \supset g_\phi\,c_\alpha\,\phi_S\,\overline{q}q + g_\phi\,s_\alpha\,\phi_A\,\overline{q}q - i\,g_P\,s_\alpha\,\phi_S\,\overline{q}\gamma_5 q$$
$$+ i\,g_P\,c_\alpha\,\phi_A\,\overline{q}\gamma_5 q - i\,h\,s_\alpha\,\phi_S\,\overline{\chi}\gamma_5\chi + i\,h\,c_\alpha\,\phi_A\,\overline{\chi}\gamma_5\chi$$

- flavour-blind couplings for simplicity
- in a full model, the scalar and pseudoscalar may originate from suitable $SU(2)_L$ multiplets

Matching the $\chi N \to \chi N$ cross section

- at the quark level, $\chi q \to \chi q$ via t-channel ϕ_S, ϕ_A
- for $q^2 \ll m^2_{S,A}$ the effective local term is generated

$$\frac{\sin 2\alpha}{2}\, h\, g_\phi \left(\frac{1}{m_S^2} - \frac{1}{m_A^2} \right) i\, \overline{\chi}\gamma_5\chi\, \overline{q}q$$

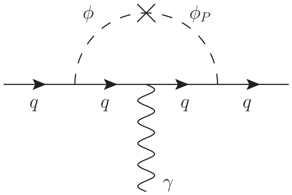
- by matching with the best-fit values of [Vincent, Scott, Serenelli, 1411.6626]:

$$\frac{\sin 2\alpha}{2}\, h\, g_\phi \left| \frac{\mathrm{GeV}^2}{m_S^2} - \frac{\mathrm{GeV}^2}{m_A^2} \right| \simeq 1.7 \times 10^{-2}$$

- at least one mediator in the GeV range (compatible with fixed-target experiments and colliders, only interacts with quarks, no flavour changing)
- ϕ_A can be taken at 750 GeV, large coupling to DM $\to$ large width, needs additional physics for $\phi_A \to \gamma\gamma$ (general fact [Knapen, Melia, Papucci, Zurek, 1512.04928])

Nuclear EDM constraint

- scalar/pseudoscalar mixing generates the EDM diagram:



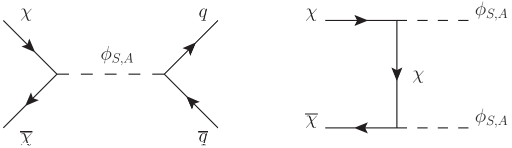
- which gives

$$d_d \approx 0.5 \times 8.3 \times 10^{-19}\, e\,\text{cm} \times \left(4.55 + \ln \frac{\widetilde{m}}{\text{GeV}}\right) \times \frac{\sin 2\alpha}{2}\, g_P\, g_\phi \left(\frac{\text{GeV}^2}{m_S^2} - \frac{\text{GeV}^2}{m_A^2}\right)$$

- imposing the "observed" $\chi N \to \chi N$ cross-section: $\frac{g_P}{g_\phi} \lesssim 10^{-6} \to 0$

CMB constraints

- for ADM the relic density depends on the primordial asymmetry
- necessary to have sufficient annihilation of the symmetric component



- at the recombination epoch, CMB requires [Lin, Yu, Zurek, 1111.0293]

$$\langle \sigma v \rangle_{\rm CMB} \; < \; 1.2 \, \times \, 10^{-27} \, \frac{\rm cm^3}{\rm s} \, \times \, \frac{m_\chi}{\rm GeV} \, \frac{1}{r_\infty}$$

- relic density [Graesser, Shoemaker, Vecchi, 1103.2771]

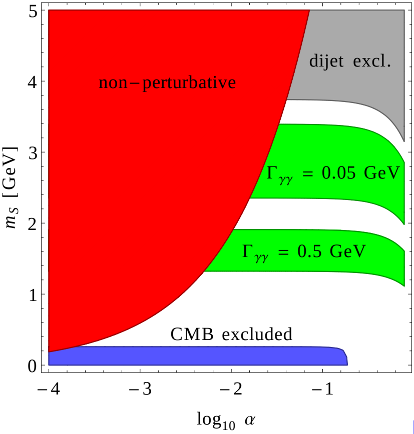
$$\langle \sigma v \rangle_{\rm f} \; \simeq \; 5 \, \times \, 10^{-26} \, \frac{\rm cm^3}{\rm s} \, \times \, \ln \frac{1}{r_\infty} \, .$$

- combining, we find the bound

$$\langle \sigma_{qq} v \rangle_{\rm f} \; < \; 3.6 \, \times \, 10^{-27} \, \frac{\rm cm^3}{\rm s} \, \times \, \exp \frac{\langle \sigma_{qq} v \rangle_{\rm f} + \langle \sigma_{\phi\phi} v \rangle_{\rm f}}{5 \, \times \, 10^{-26} \, \frac{\rm cm^3}{\rm s}}$$

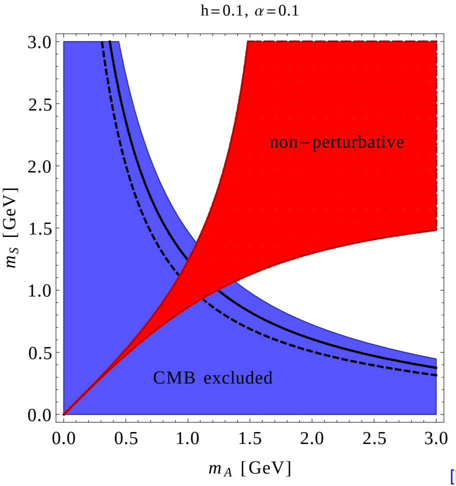
Diphoton excess

- assume additional new physics in $\phi_A \to \gamma\gamma$, parametrized by $\Gamma_{\gamma\gamma}$
- impose 45 GeV width $\to$ $h = 1.2$
- strongest limits from non-observation of dijet signal



[Dev, DT, 1512.07243]

Not identifying ϕ_A with the diphoton resonance



[Dev, DT, 1512.07243]

Conclusions

Wait for more data, have fun meanwhile.