KK graviton as mediator for dark matter and cascade decays

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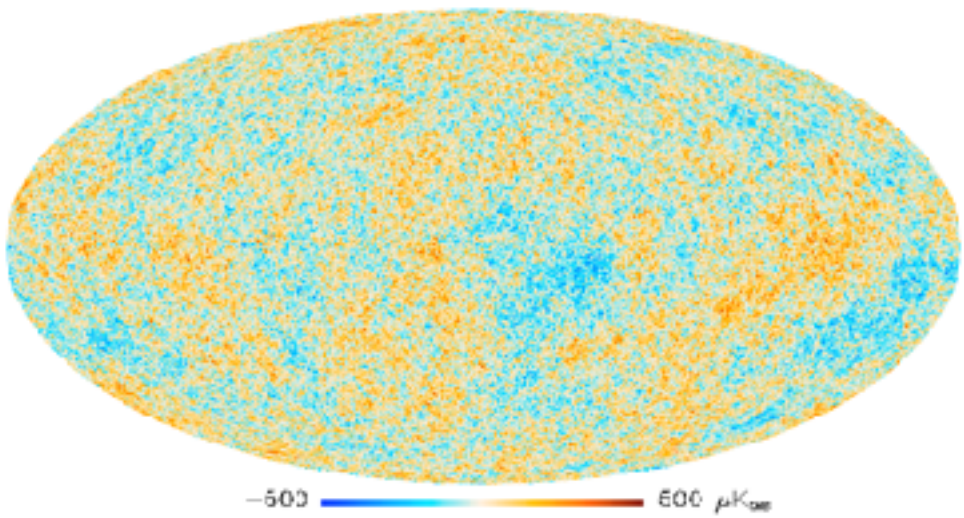
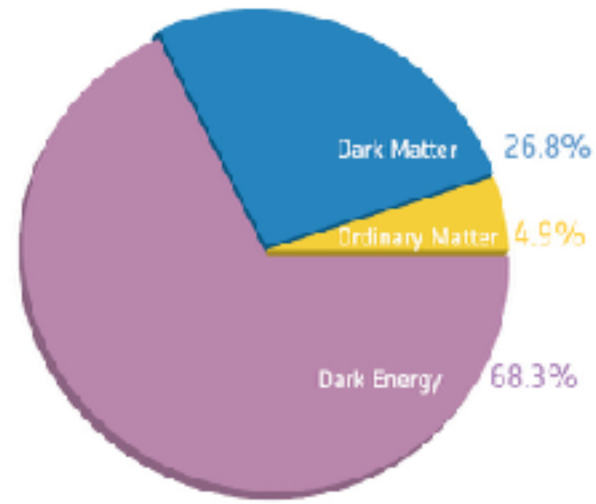
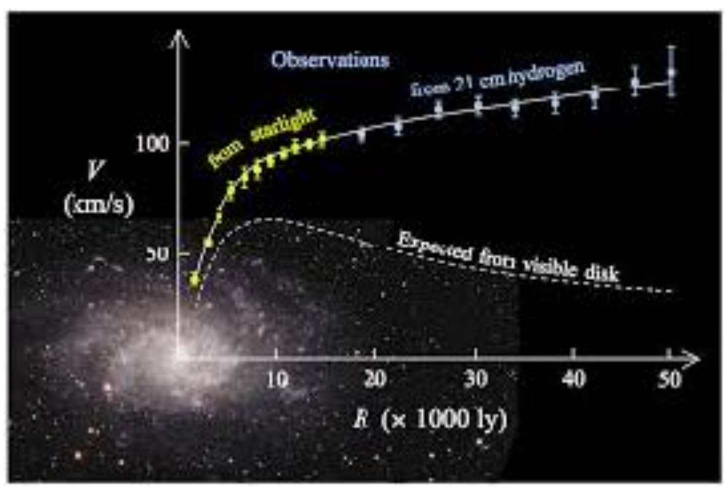
Outline

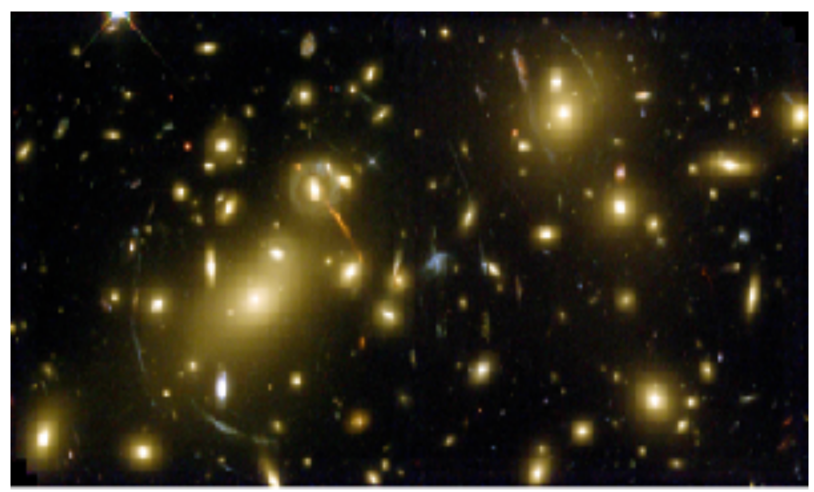
- Introduction
- Gravity-mediated dark matter
- KK graviton at LHC
- Graviton-radion interplay
- Conclusions

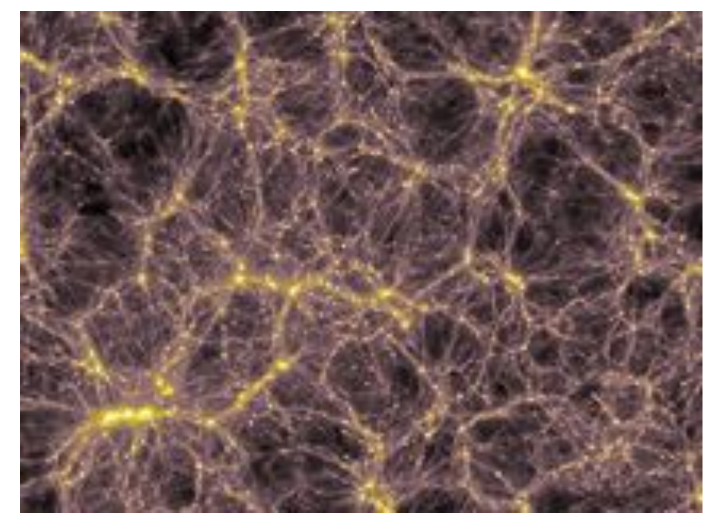
Dark matter from sky











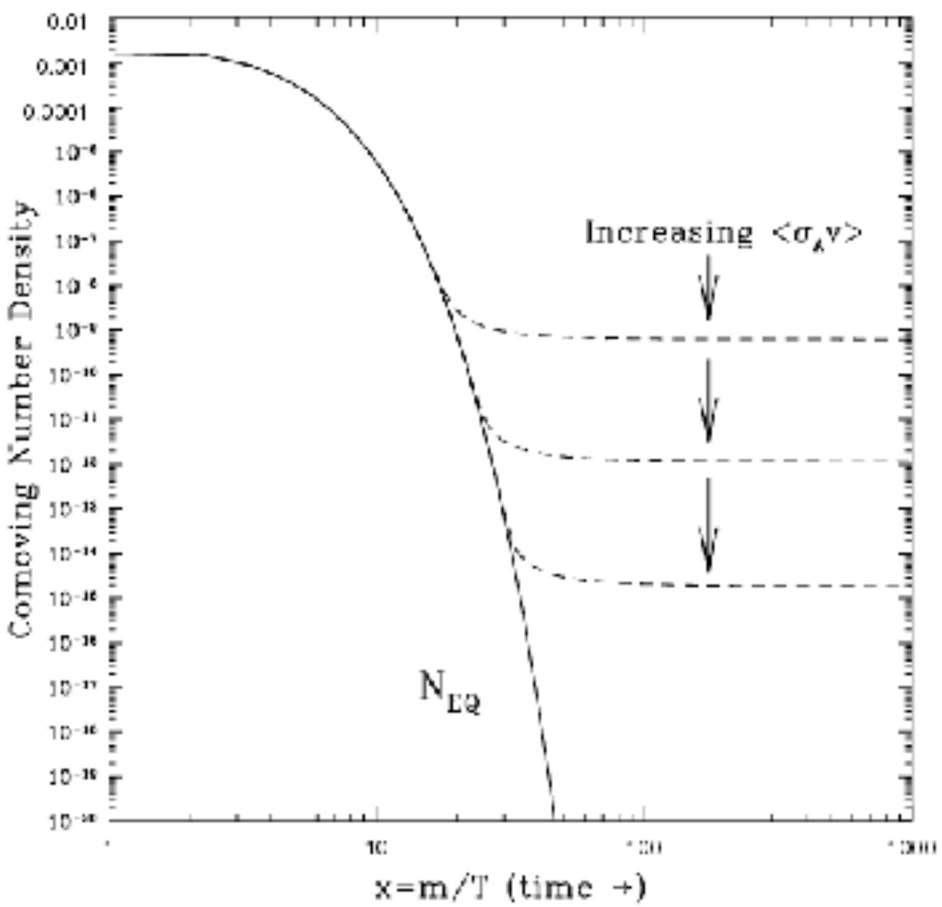
- Various evidences for dark matter from galaxy rotation curves, CMB, gravitational lensing, and large scale structure.

The origin of dark matter is a compelling question.

WIMP Paradigm

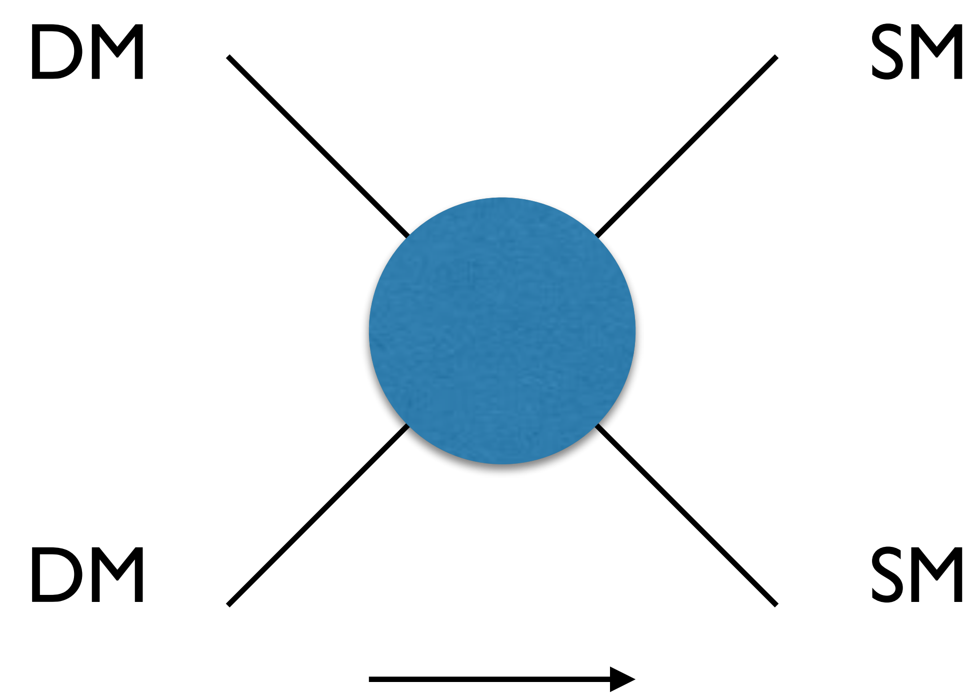
[Lee, Weinberg(1977)]

DM number



time

Dark matter once in thermal equilibrium with SM particles

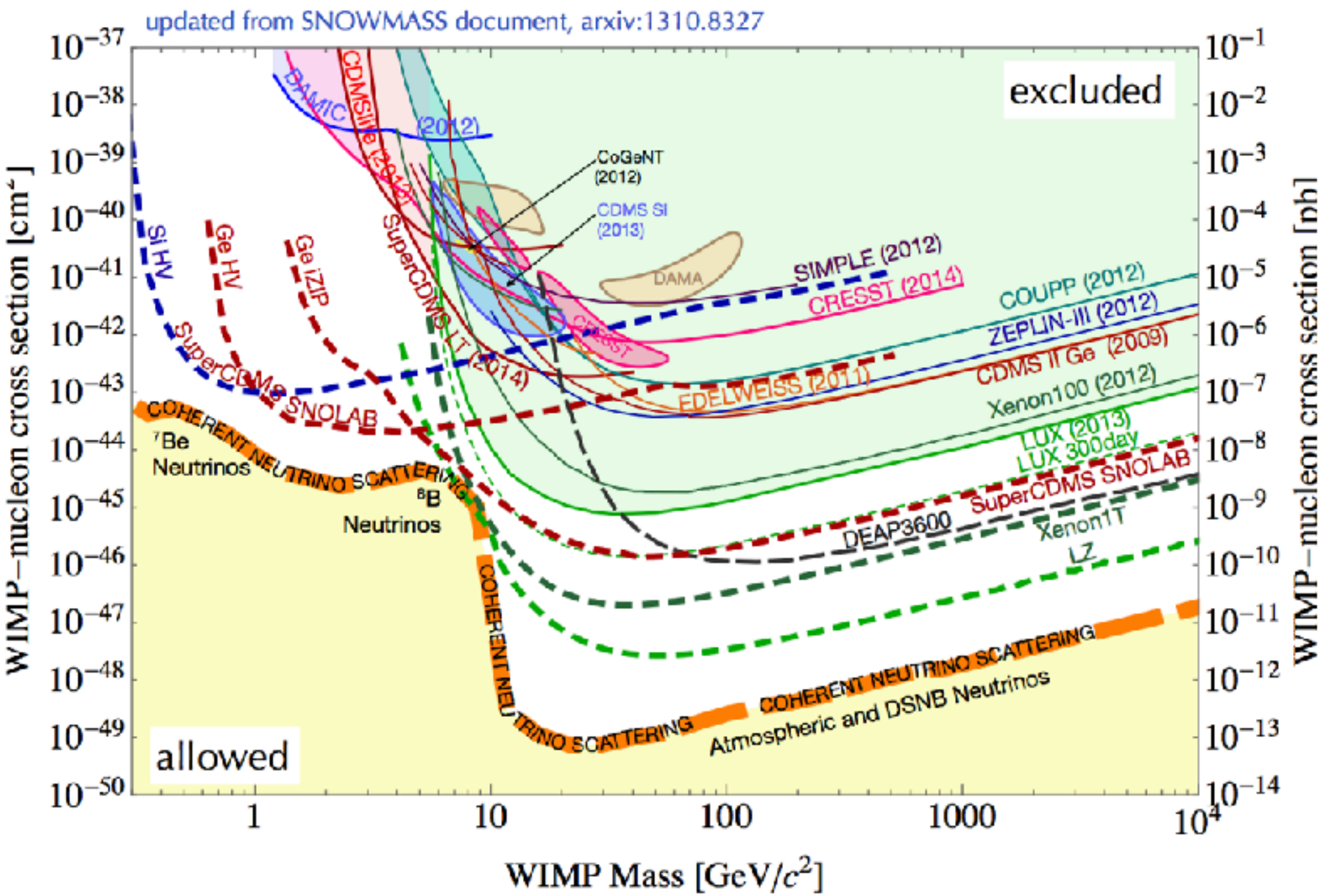


Weak interaction with 100GeV-1TeV mass:

$$\Omega_{\rm DM} h^2 = 0.1 \left(\frac{1\,{\rm pb}\cdot c}{\langle \sigma_A v \rangle} \right)$$

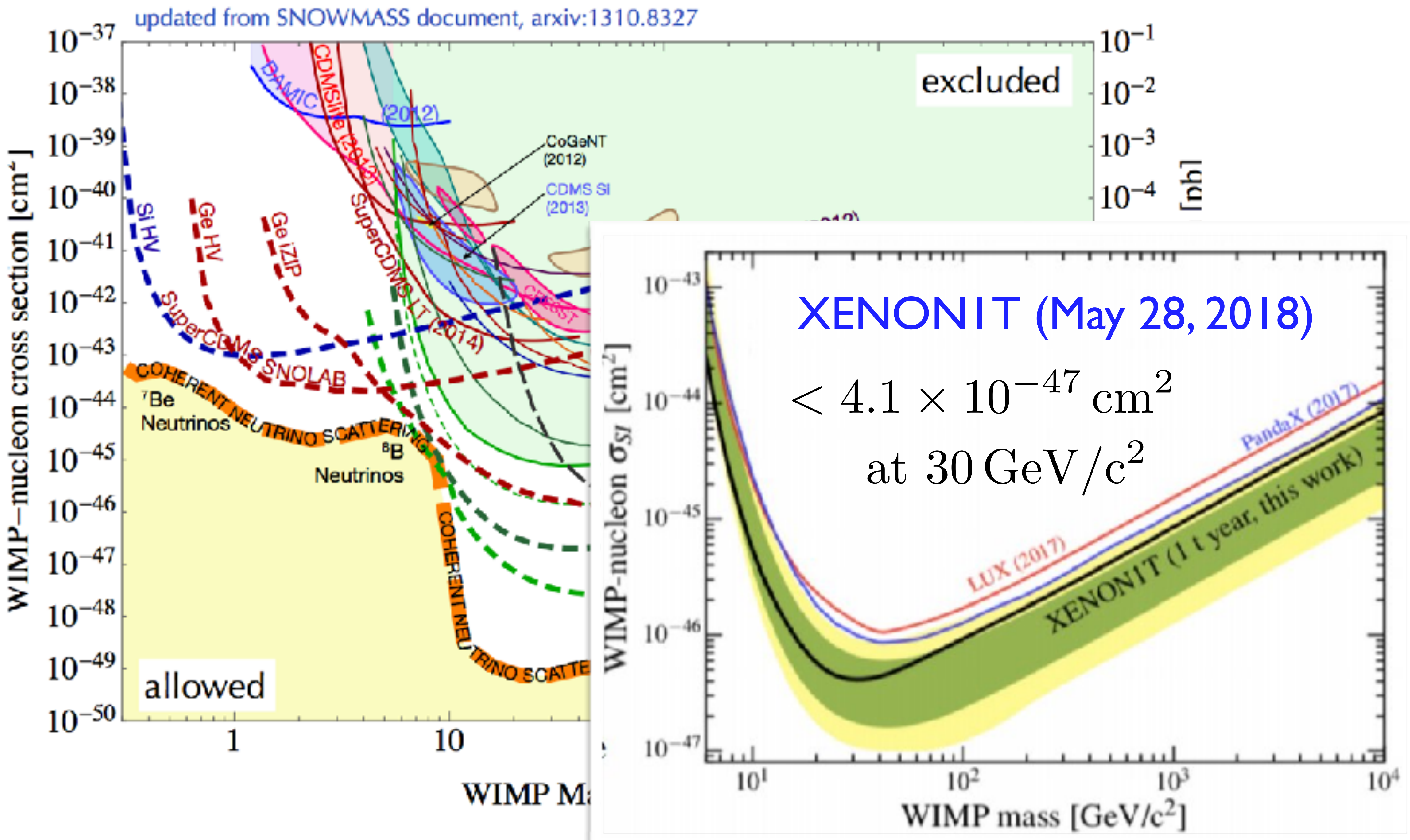
Interplay of direct, indirect and collider detections!

Direct detection



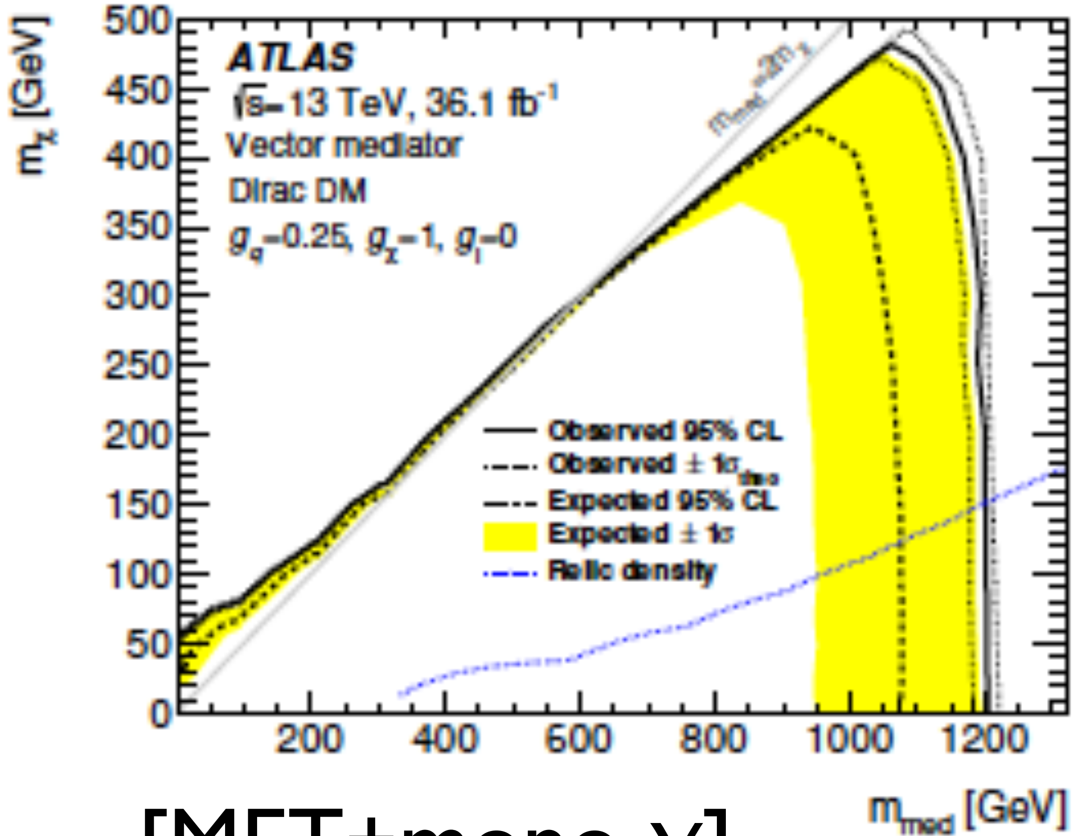
No direct evidence for WIMP yet

Direct detection

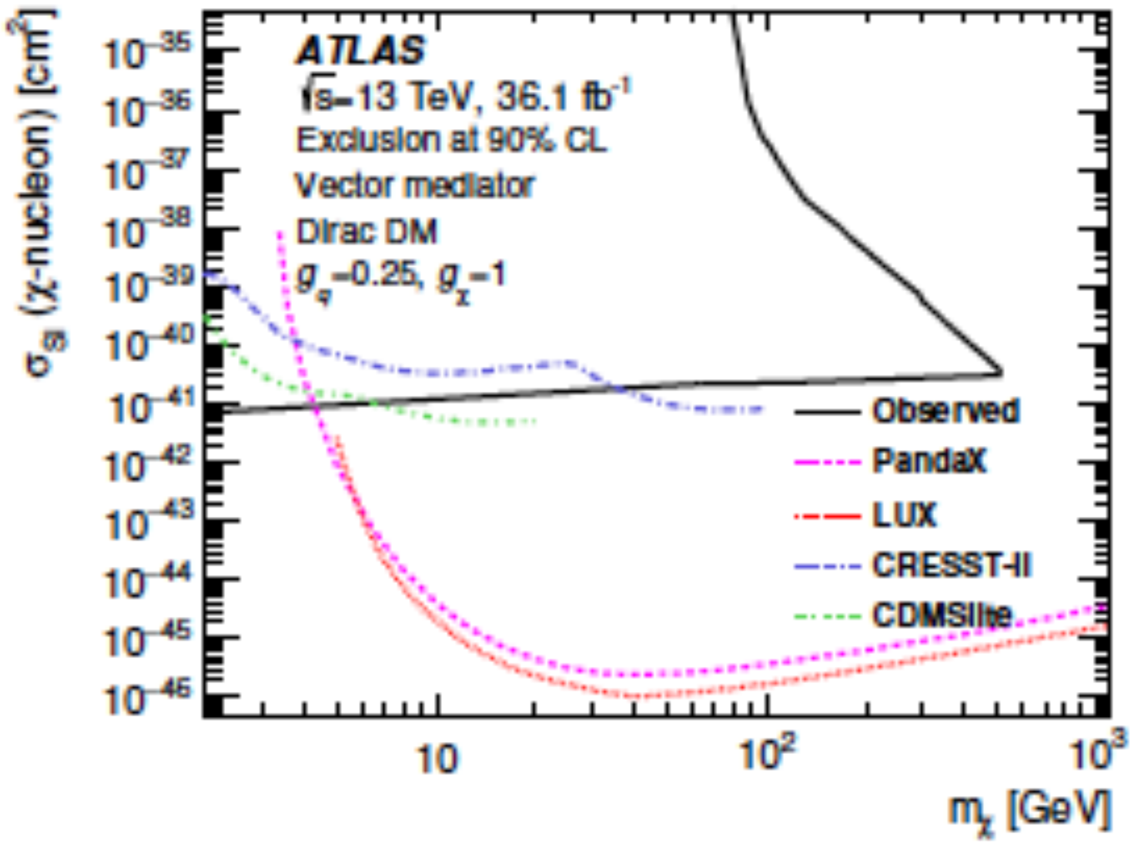


- Mass and interaction of WIMP have been strongly constrained.

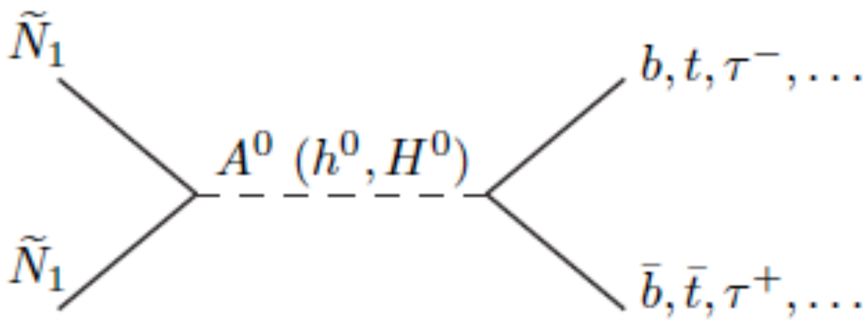
DM mediators at LHC

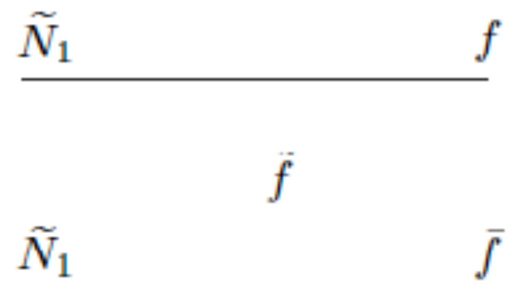


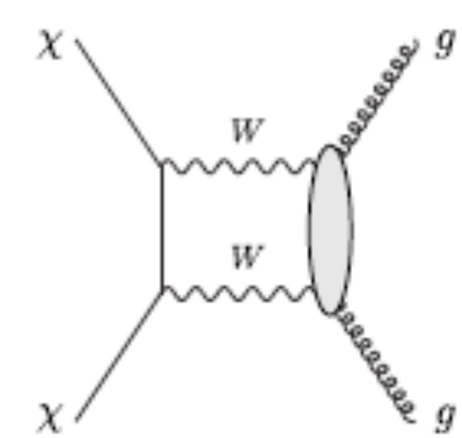
[MET+mono-γ]



- Mediators & effective interactions for DM







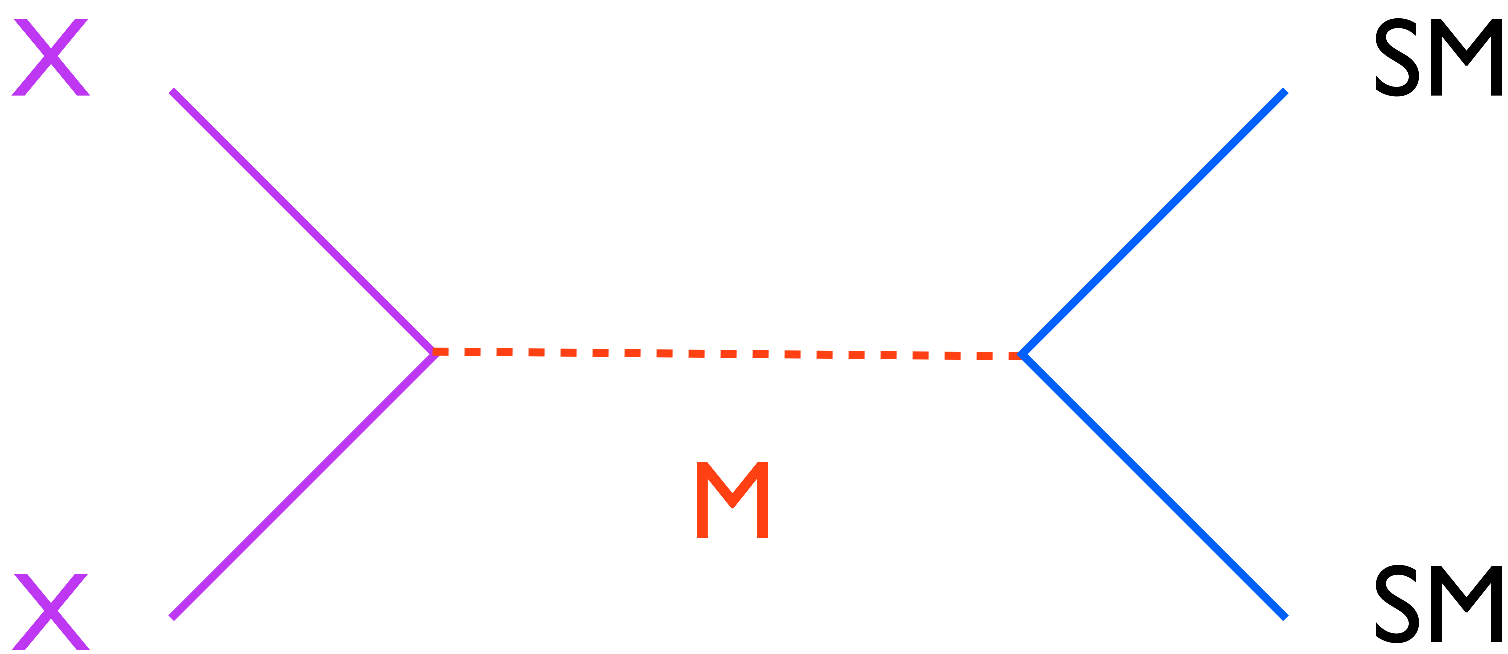
D1	$[\bar\chi\chi][\bar f f]$
D4	$[\bar\chi\gamma^5\chi][\bar f\gamma^5 f]$

D8	$[\bar\chi\gamma^\mu\gamma^5\chi][\bar f\gamma_\mu\gamma^5 f]$
D5	$[\bar\chi\gamma^\mu\chi][\bar f\gamma_\mu f]$

D11	$[\bar\chi\chi][G_{\mu\nu}G^{\mu\nu}]$

Beyond EFT operators

- Dark matter (DM) X is a singlet with spin (0, 1/2, or 1).
- Mediator particle M of spin (0,1,2) couples to DM.



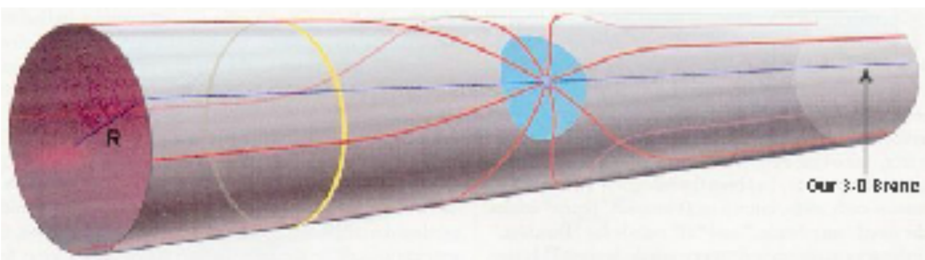
- Mediator particles have been discussed mainly from Higgs, axion(spin-0), and/or Z'(spin-1) portals.

[HML, M.Park, W. Park(2012); HML, M.Park, V. Sanz (2012,2013)]

What about spin-2 mediator for dark matter ?

Extra dimensions and branes

Arkani-Hamed et al, 1998 | Large extra dimensions



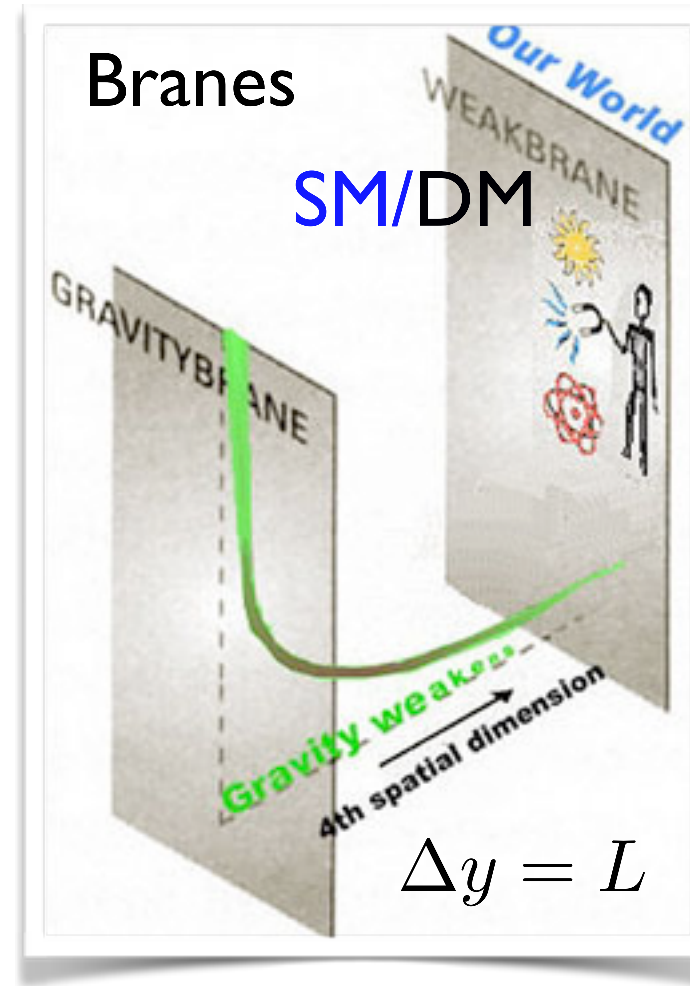
Gauss-law: gravity permeates into bulk.

$$G_N = \frac{G_{4+d}}{R^d}$$

Randall, Sundrum, 1999 | Warped extra dimension

$$ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2; \;\; -\Lambda_0 = \Lambda_\pi = 4kM_5^3.$$

$$\rightarrow \quad m_H^2 = e^{-2kL}\, M_P^2, \;\; kL \sim 40.$$



- Higgs field is localized on IR brane, with its mass kept small by the warped factor.
- Gravity becomes weak as graviton is localized on UV brane.

KK graviton

- Higher dimensional graviton is expanded as

$$h_{\alpha\beta}(x,\phi) = \sum_{n=0}^{\infty} h_{\alpha\beta}^{(n)}(x) \frac{\chi^{(n)}(\phi)}{\sqrt{r_c}}$$

$h_{\alpha\beta}^{(0)}(x)$: massless graviton → **4D gravity**

$h_{\alpha\beta}^{(n\neq 0)}(x)$: Kaluza-Klein gravitons → **Massive spin-2 messenger**

$$\mathcal{L} = -\frac{1}{\overline{M}_{Pl}} T^{\alpha\beta}(x) h_{\alpha\beta}^{(0)}(x) - \frac{1}{\Lambda_\pi} T^{\alpha\beta}(x) \sum_{n=1}^{\infty} h_{\alpha\beta}^{(n)}(x) \, .$$

- KK graviton is localized on IR brane in RS model.

KK masses: "discrete" $m_G = \frac{k}{M_P} x_G \Lambda$ $\quad m_G \lesssim 3.83\,\Lambda$

$x_G = 3.83$, first zero of $J_1(x_G)$

KK couplings depend on localization of matter fields.

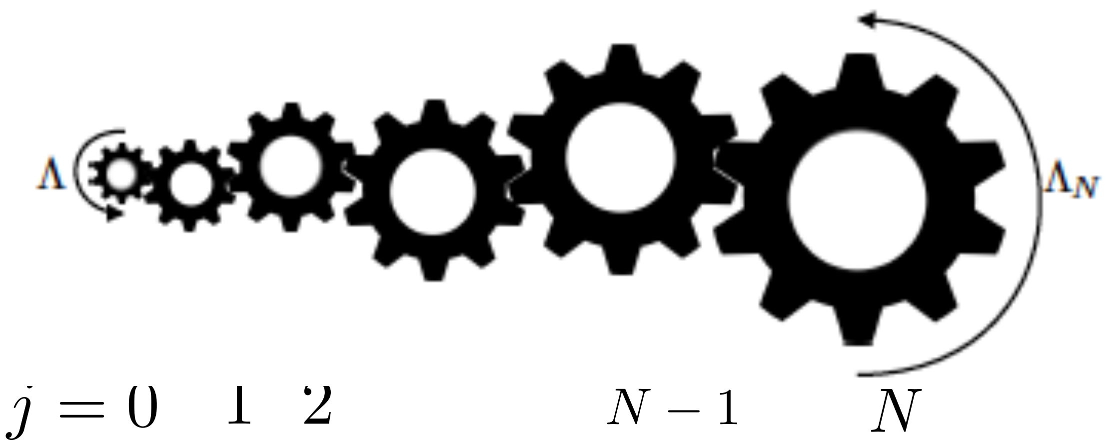
Clockwork theory

- Clockwork theory: nearest-neighbor interactions.

$$\mathcal{L} = \frac{1}{2}\sum_{j=0}^{N} \partial_\mu \phi_j \partial^\mu \phi_j - \frac{m^2}{2}\sum_{j=0}^{N-1} (\phi_j - q\phi_{j+1})^2,$$

Choi, Im, 2015; Kaplan, Rattazzi, 2015
Giudice et al, 2016; HML, 2017

$$M_\phi^2 = m^2 \begin{pmatrix} 1 & -q & 0 & \cdots & & 0 \\ -q & 1+q^2 & -q & \cdots & & 0 \\ 0 & -q & 1+q^2 & \cdots & & 0 \\ \vdots & \vdots & \vdots & \ddots & & \vdots \\ & & & & 1+q^2 & -q \\ 0 & 0 & 0 & \cdots & -q & q^2 \end{pmatrix}.$$



$$\Rightarrow \quad \phi_N = \frac{1}{q}\phi_{N-1} = \cdots = \frac{1}{q^N}\phi_0$$: ground state of clock gears

Nth clock gear moves least, most weakly coupled:

$\phi_i =$ graviton: weak gravity

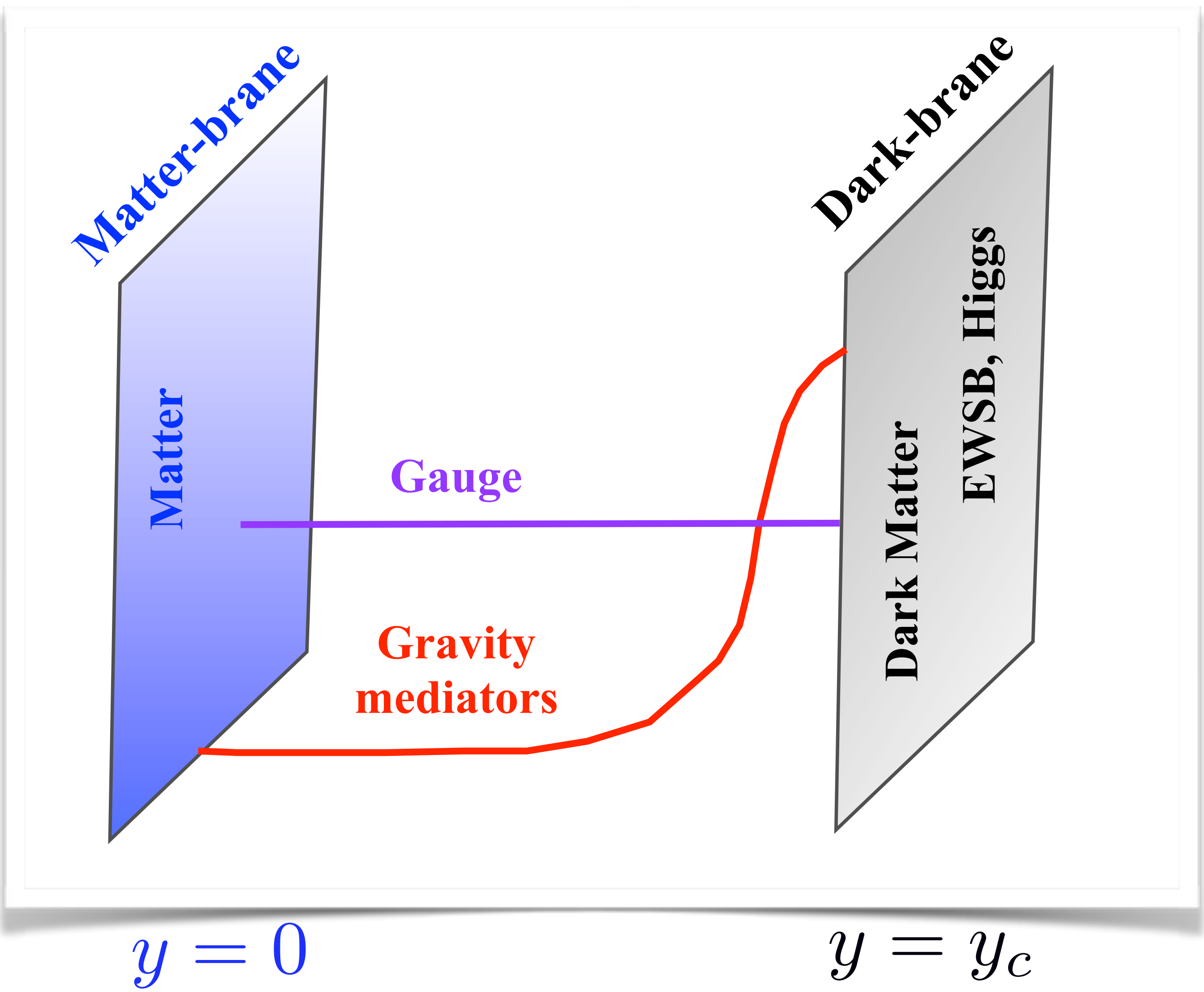
Matter couplings depend on localization.

$\Leftrightarrow$ Bulk force + brane fields in warped extra dimension

Gravity-mediated dark matter

Higgs mass and KK graviton

- Bulk RS model (Model A): Higgs & top quark on IR brane; light fermions on UV brane; gauge fields in bulk.



Higgs/WIMP hierarchy:

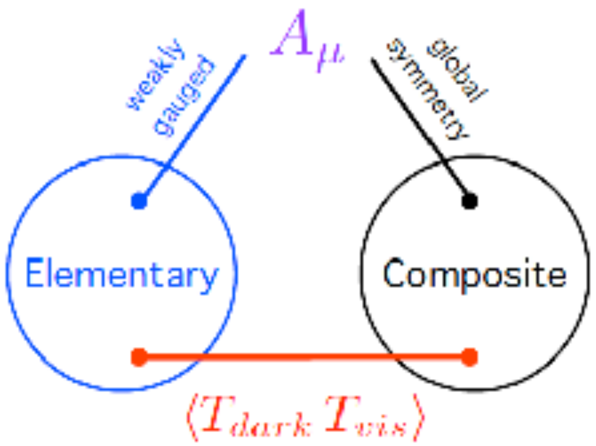
$$\frac{m_H}{M_P}, \frac{m_X}{M_P} \sim e^{-ky_c} \ll 1.$$

Flavors and strong bounds from dileptons favor bulk RS model.

KK graviton decays into hh, tt, WW, ZZ

[A. Falkowski & J. Kamenik, 1603.06980; J. Hewett, T. Rizzo, 1603.08250]

Holography dual



AdS		CFT
• radion	⟷	• dilaton (dilatation symmetry)
• KK-graviton		• spin-2 resonance (CFT diffeomorphism)
• Matter-brane		• “elementary”
• Dark-brane		• “composite”

DM: composite state, Z_2 from global symmetry.

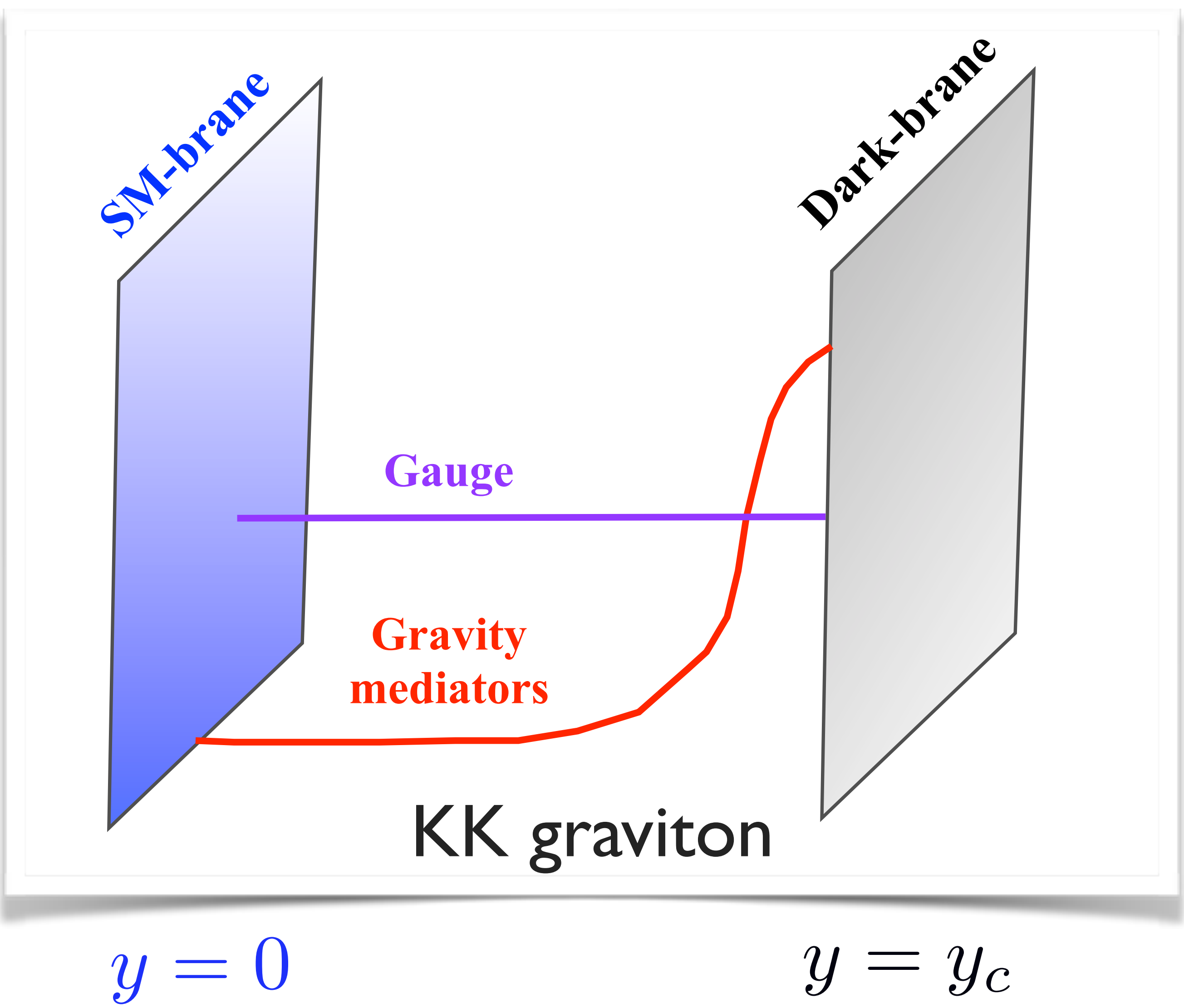
Pure dark QCD (SU(2)): spin-0(broad)& spin-2 are the lowest.

[V. Sanz, 2016]

WIMP and KK graviton

- Gauge bulk model (Model B): dark matter on IR brane; gauge fields in bulk; others on UV brane.

[HML, M.Park, V. Sanz, 2013, 2014]



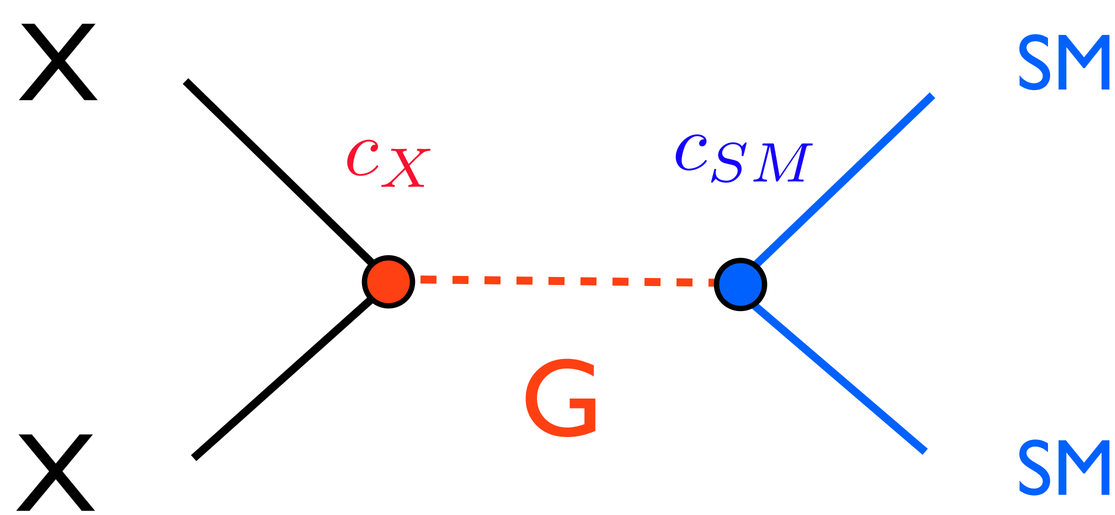
WIMP hierarchy:

$$\frac{m_X}{M_P} \sim e^{-ky_c} \ll 1.$$

KK graviton has universal couplings to gauge fields and larger couplings to WIMP dark matter.

Direct annihilations

- Dark matter annihilates mainly into a pair of SM particles through KK graviton.



Model A: SM=γ,g,W_L,Z_L,h(t,b)

Model B: SM=γ, g,W_T,Z_T

- DM annihilates sizably into a photon pair.

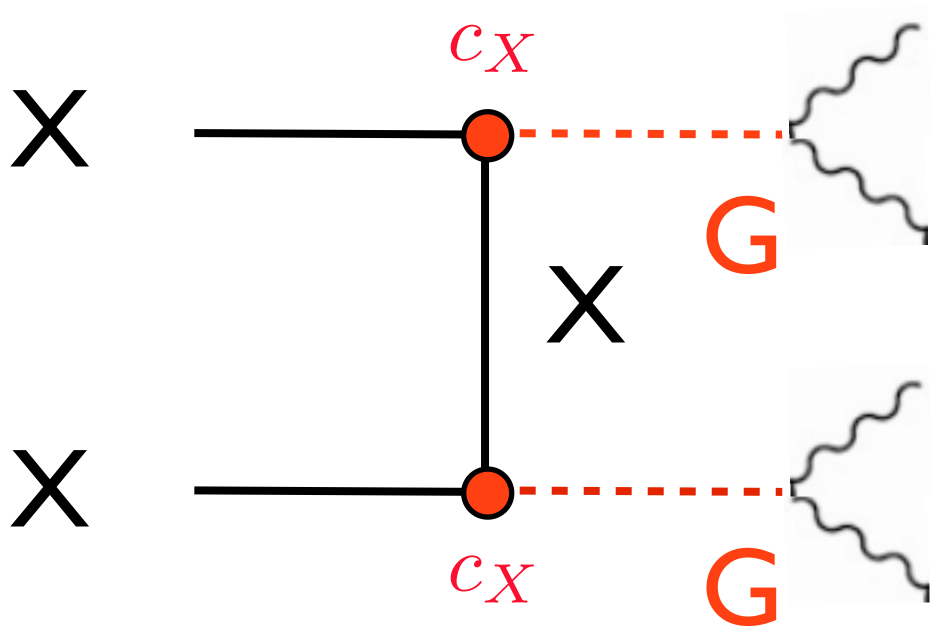
Model B: $$\frac{\Gamma_G(\gamma\gamma)}{\Gamma_G(\text{total})} = \frac{(c_B^G)^2}{8(c_g^G)^2 + (c_B^G)^2} \simeq 0.11.$$

cf. scalar mediator $\mathrm{Br}_{\gamma\gamma} \sim \frac{\alpha^2}{\alpha_s^2} \sim 0.01$

⇒ Fermi-LAT or HESS line searches.

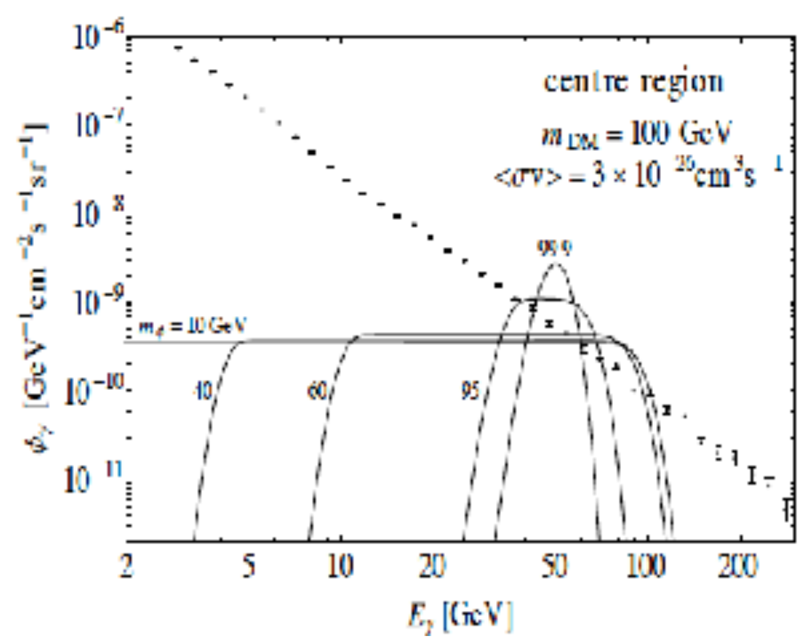
Cascade annihilations

- Dark matter can annihilate into a pair of KK gravitons, each of which decays into SM particles.



$$(\sigma v)_t \sim \frac{c_X^4 m_X^2}{\Lambda^4}\left(\frac{m_X}{m_G}\right)^8$$

- Light SM particles are boosted and "box-shaped".

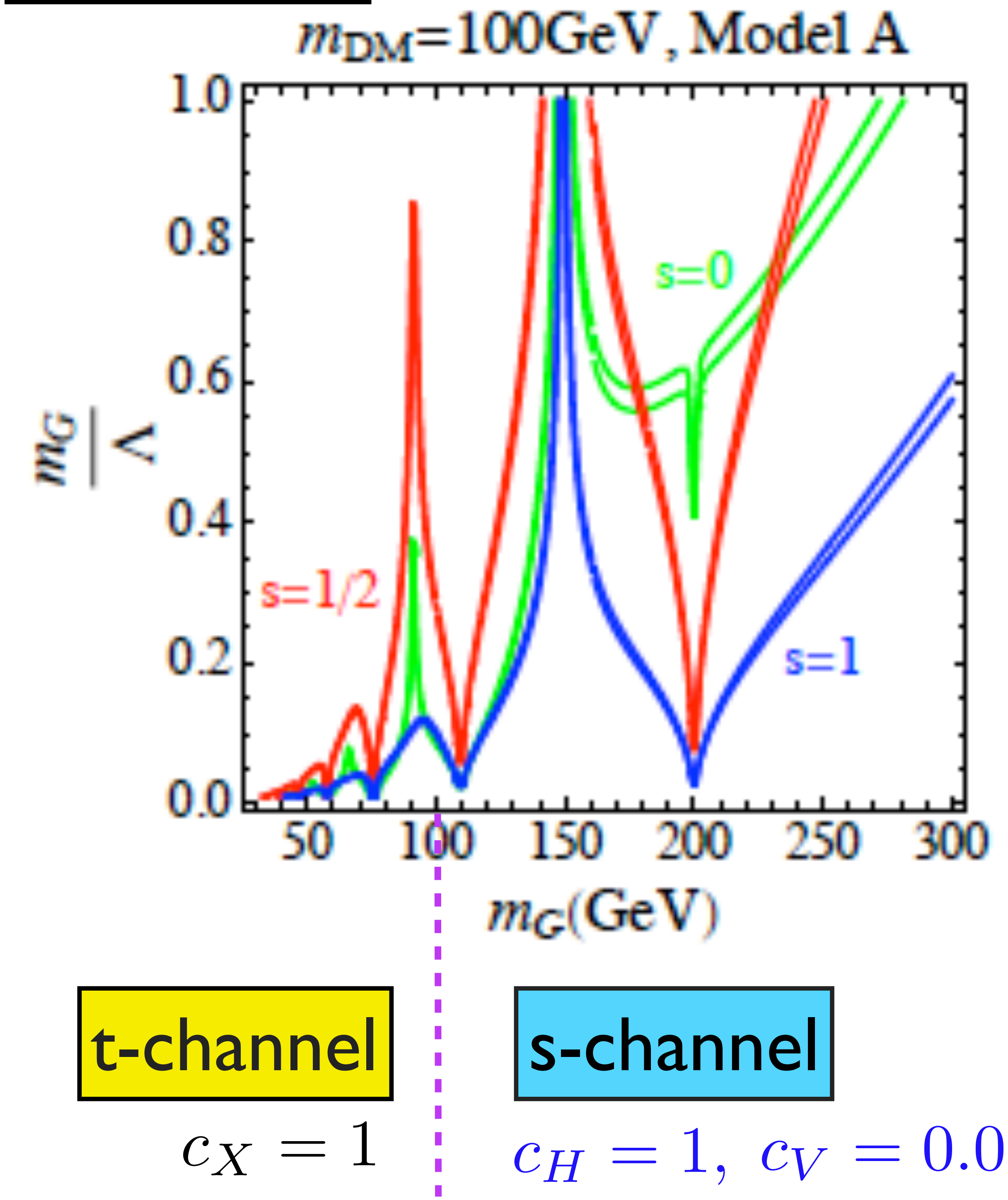


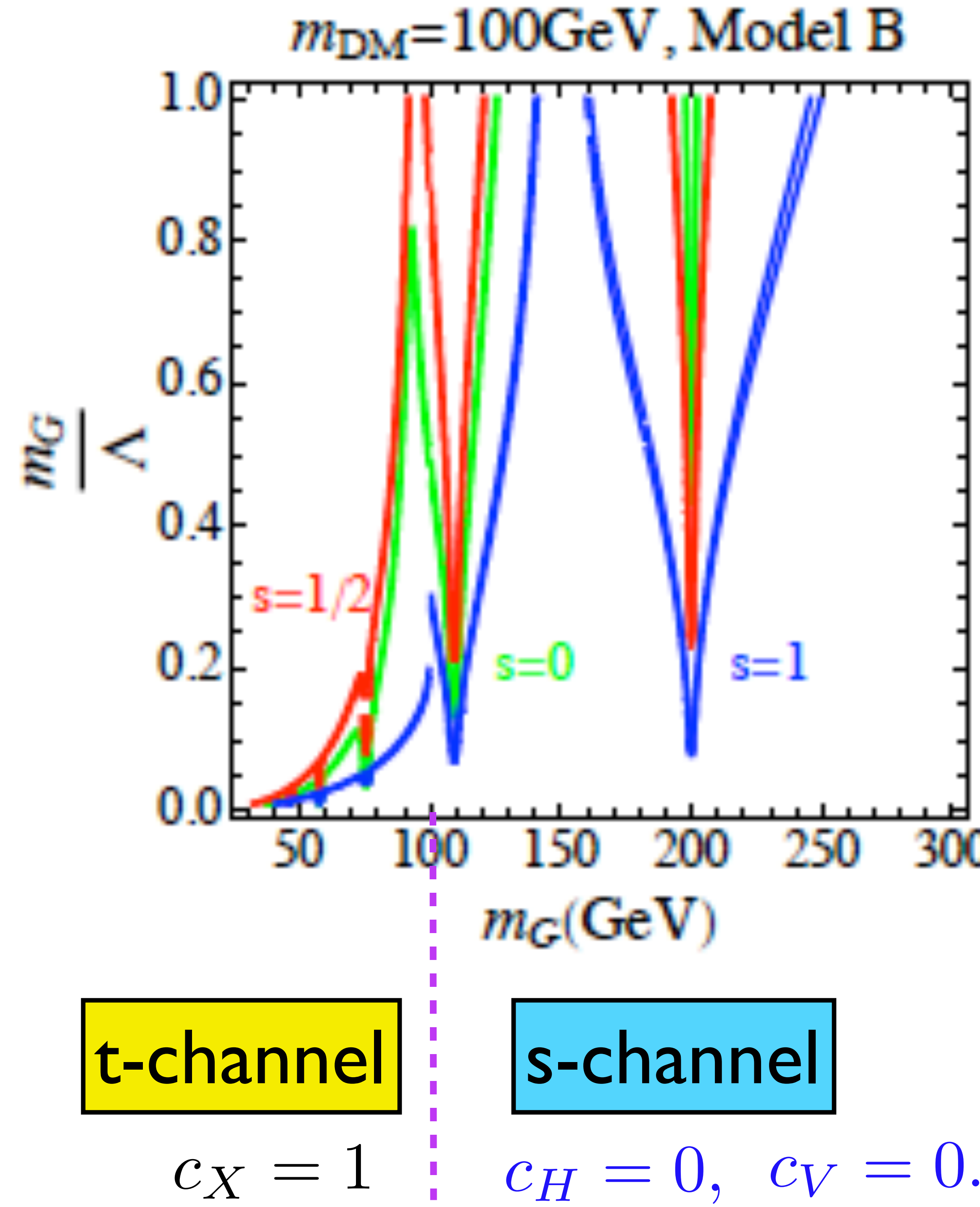
$$r = \left(\frac{m_G}{m_{\rm DM}}\right)^2 \sim 1: \quad \text{narrow}$$

$$r = \left(\frac{m_G}{m_{\rm DM}}\right)^2 \ll 1: \quad \text{wide}$$

DM relic density

$$\frac{m_G}{\Lambda} = 3.83\,\frac{k}{M_P}$$





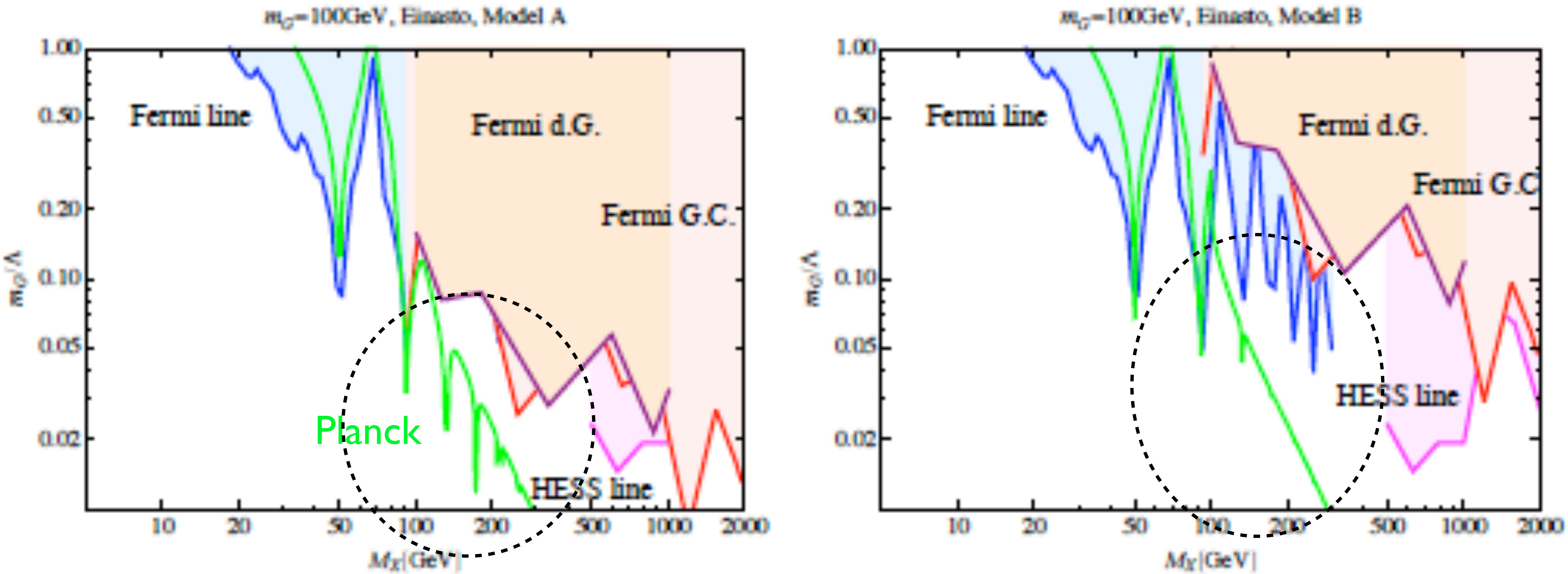
t-channel $c_X = 1$ | **s-channel** $c_H = 1,\ c_V = 0.03$

t-channel $c_X = 1$ | **s-channel** $c_H = 0,\ c_V = 0.03$

S-channels (or Model B) need a larger KK graviton coupling.

Bounds from gamma-rays

[HML, M.Park, V. Sanz (2014)]



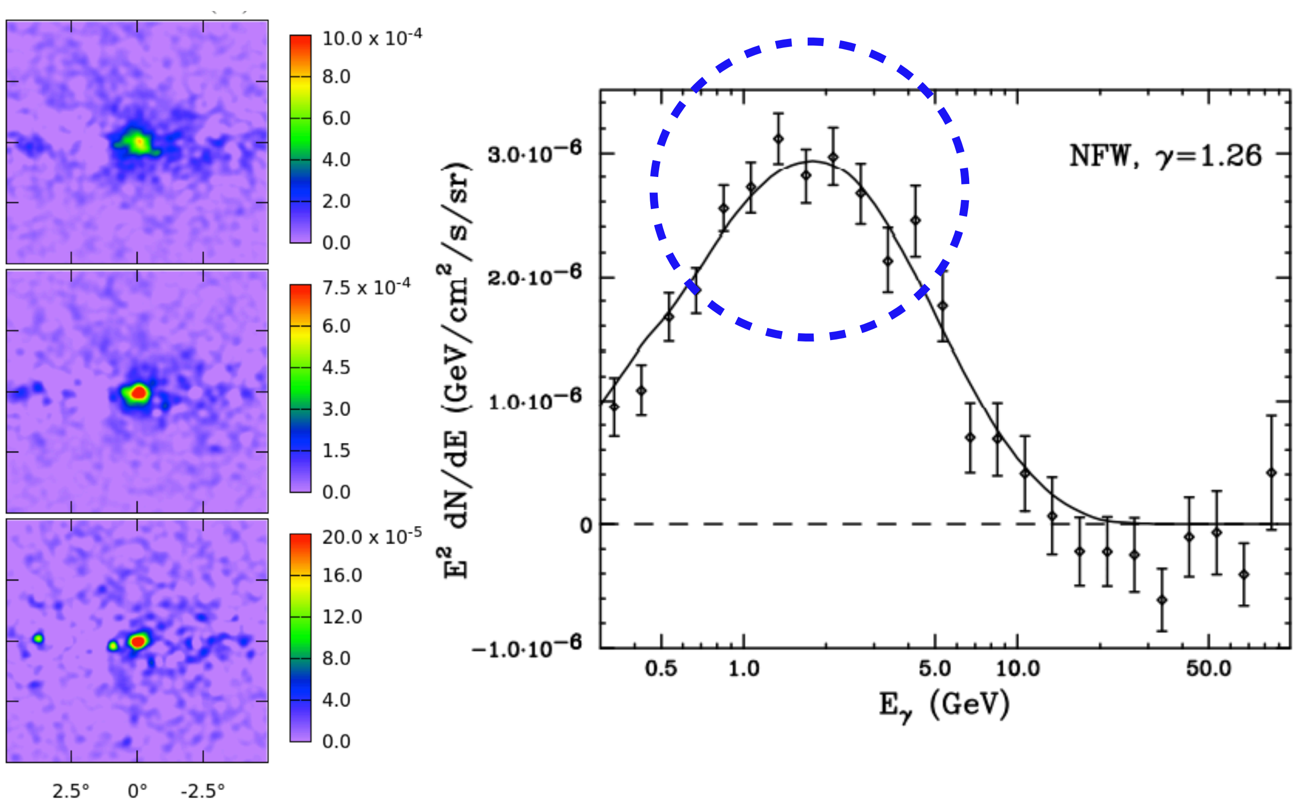
channels	DM mass	X (s=0)	X (s=1/2)	X (s=1)
s-channel	$m_{DM} < m_W$	d-wave	p-wave	s-wave
s-channel	$m_{DM} > m_W$	s-wave	p-wave	s-wave

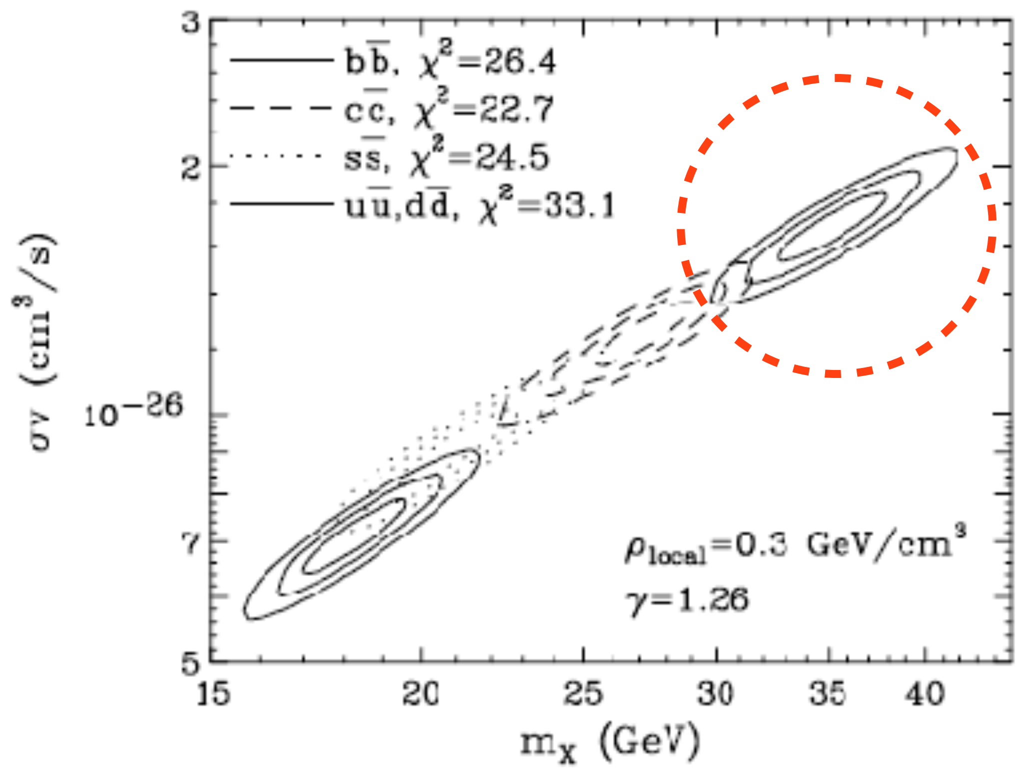
$gg, \gamma\gamma$

$+WW, ZZ, hh$

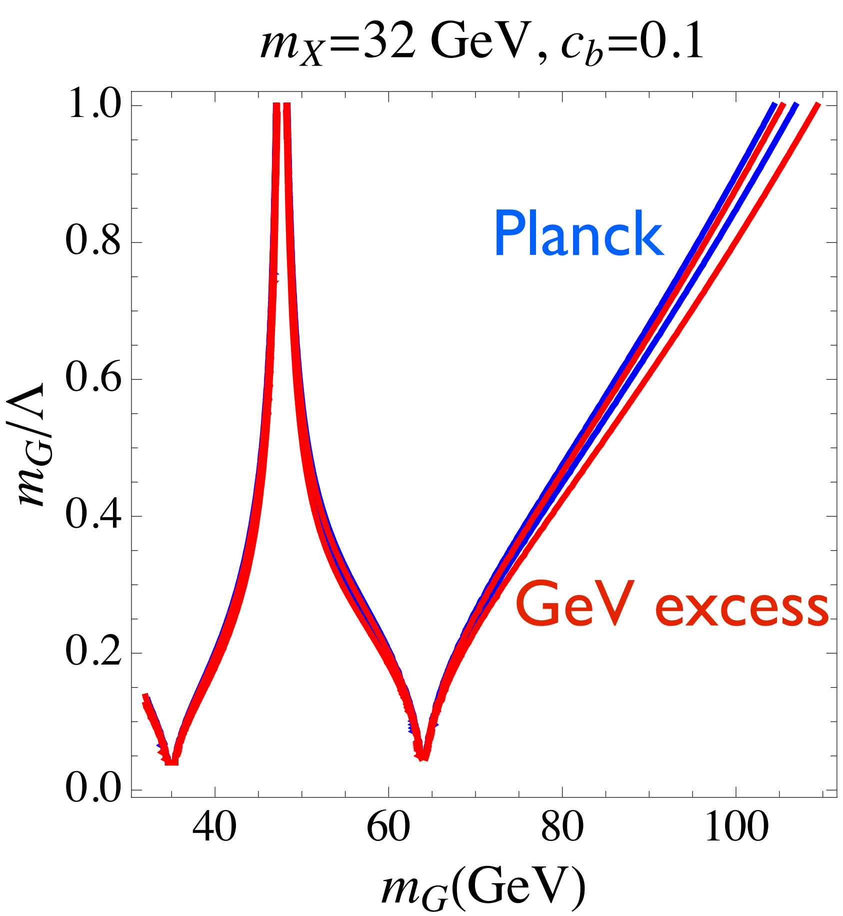
- s-channel depends on DM spins: vector DM is strongly constrained by gamma-rays and anti-protons.

Fermi GeV-excess





[Daylan et al (2014)]

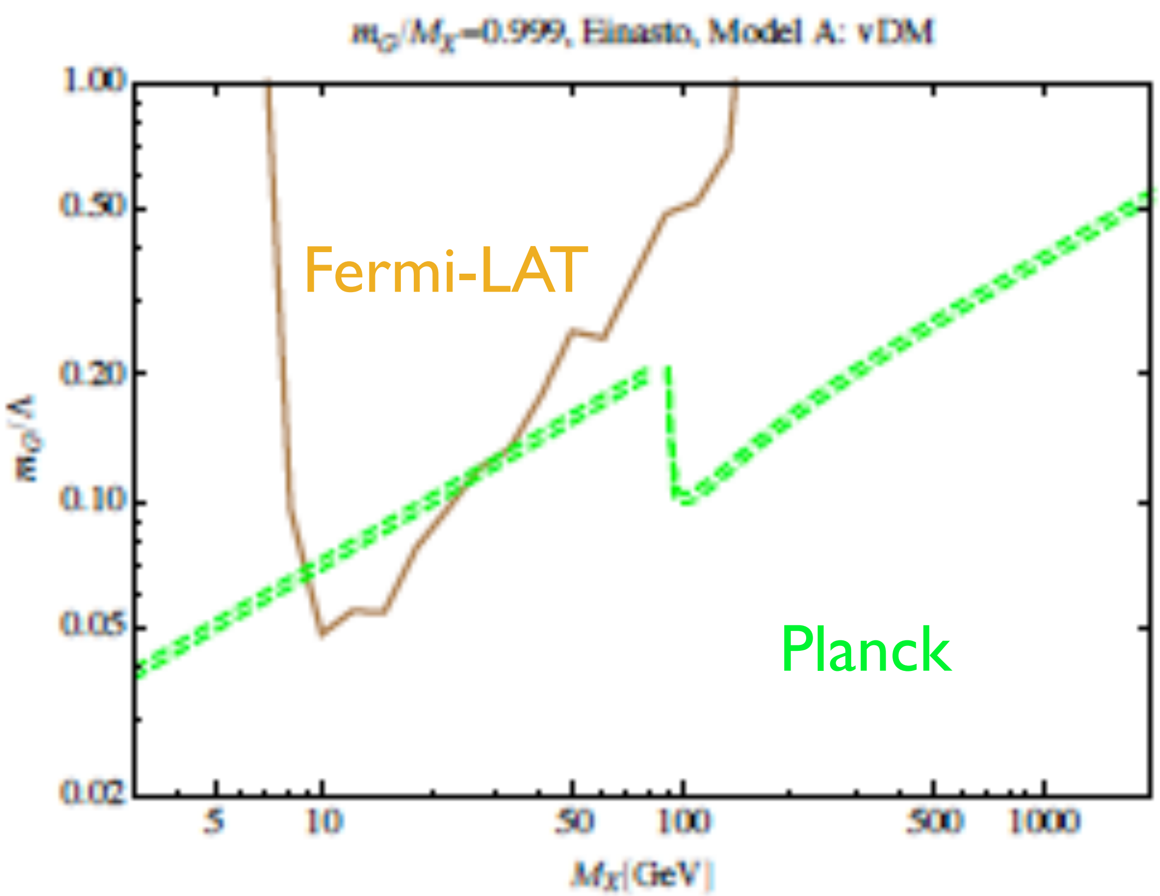


- Gamma-ray excess from galactic center at 1-2GeV
- VDM annihilations, XX→bb or XX→GG→bbbb in cascade, could account for GeV excesses.

[HML, Park, Sanz, unpublished]

Bounds on boxes

- Narrow boxes: $r_i \sim 1$ Vector DM is most constrained.



$$(\sigma v)_{SS\to GG} \sim (1-r_S)^{\frac{9}{2}}$$

$$(\sigma v)_{\chi\bar{\chi}\to GG} \sim (1-r_S)^{\frac{7}{2}}$$

$$(\sigma v)_{XX\to GG} \sim (1-r_S)^{\frac{1}{2}}$$

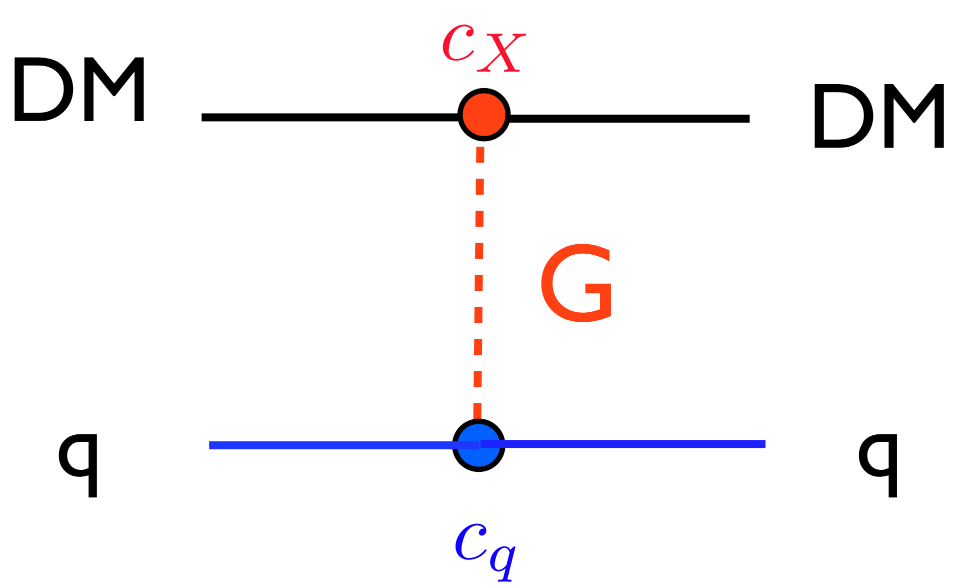
- Narrow boxes from vector DM with masses of 9-30 GeV are excluded in both Model A and B.

- Wide boxes: $r_i \ll 1$ Similar bounds for all spins of DM.

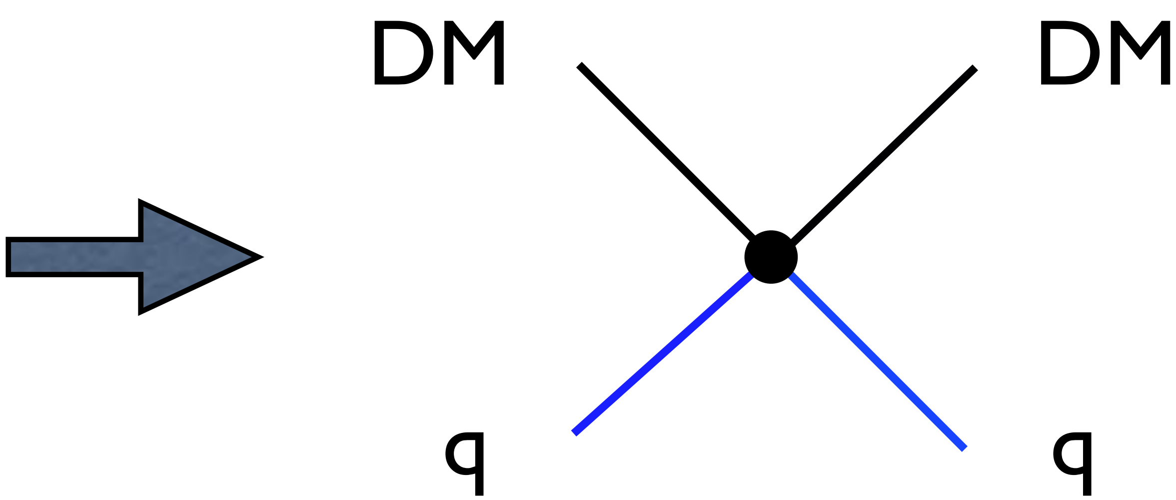
Direct detection

[A. Carrillo-Monteverde, Y. Kang, HML, M.Park, V. Sanz, 2018]

- Effective DM-quarks interactions



$$\mathcal{L}_{KK} = -\frac{1}{\Lambda} G_{\mu\nu}(c_q T^{q,\mu\nu} + c_X T^{X,\mu\nu})$$



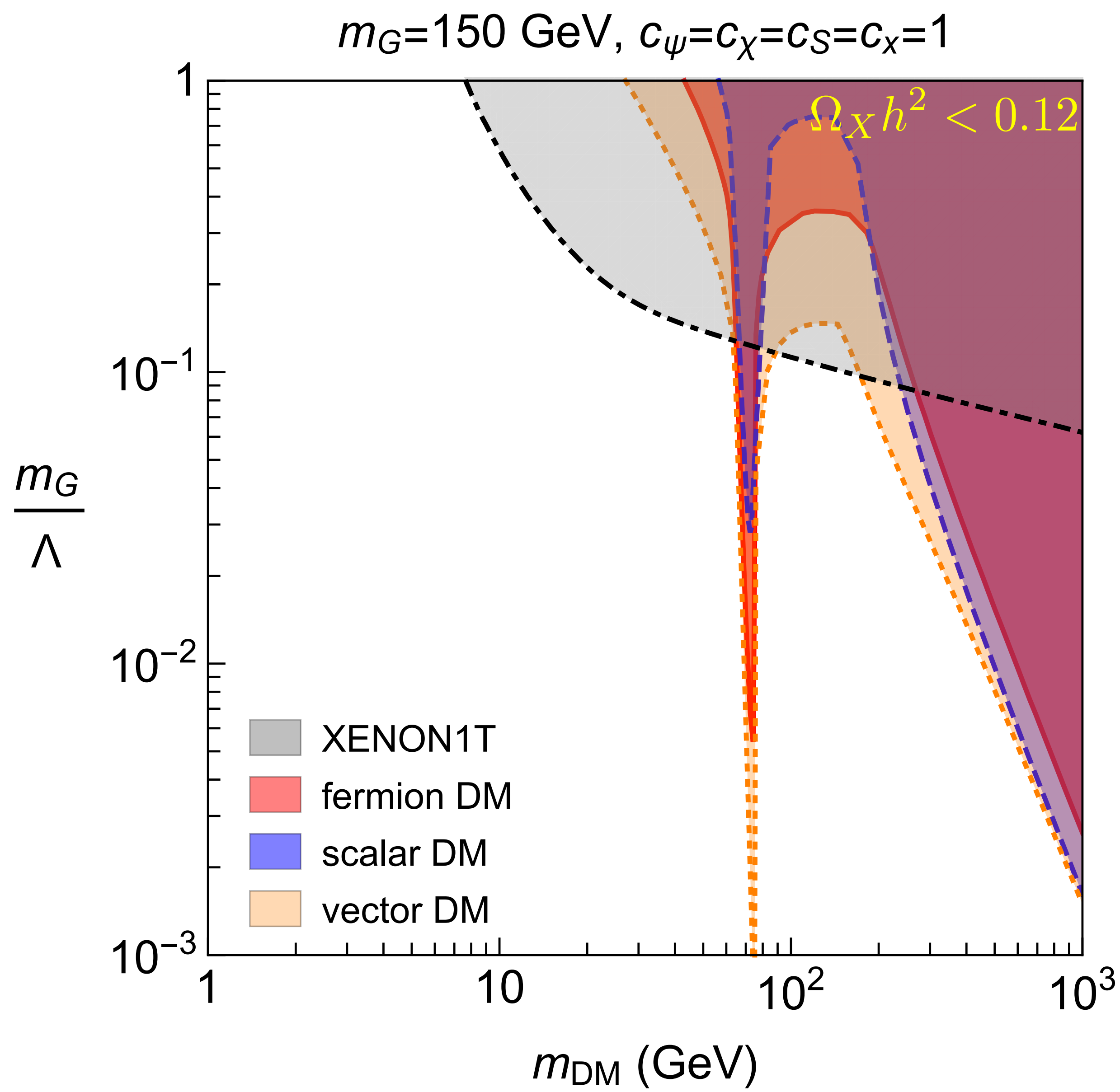
$$\mathcal{L}_{\rm eff} = -\frac{c_X c_q}{m_G^2 \Lambda^2}\left(T^{q,\mu\nu}T^X_{\mu\nu} - \frac{1}{3}T^q T^X\right)$$

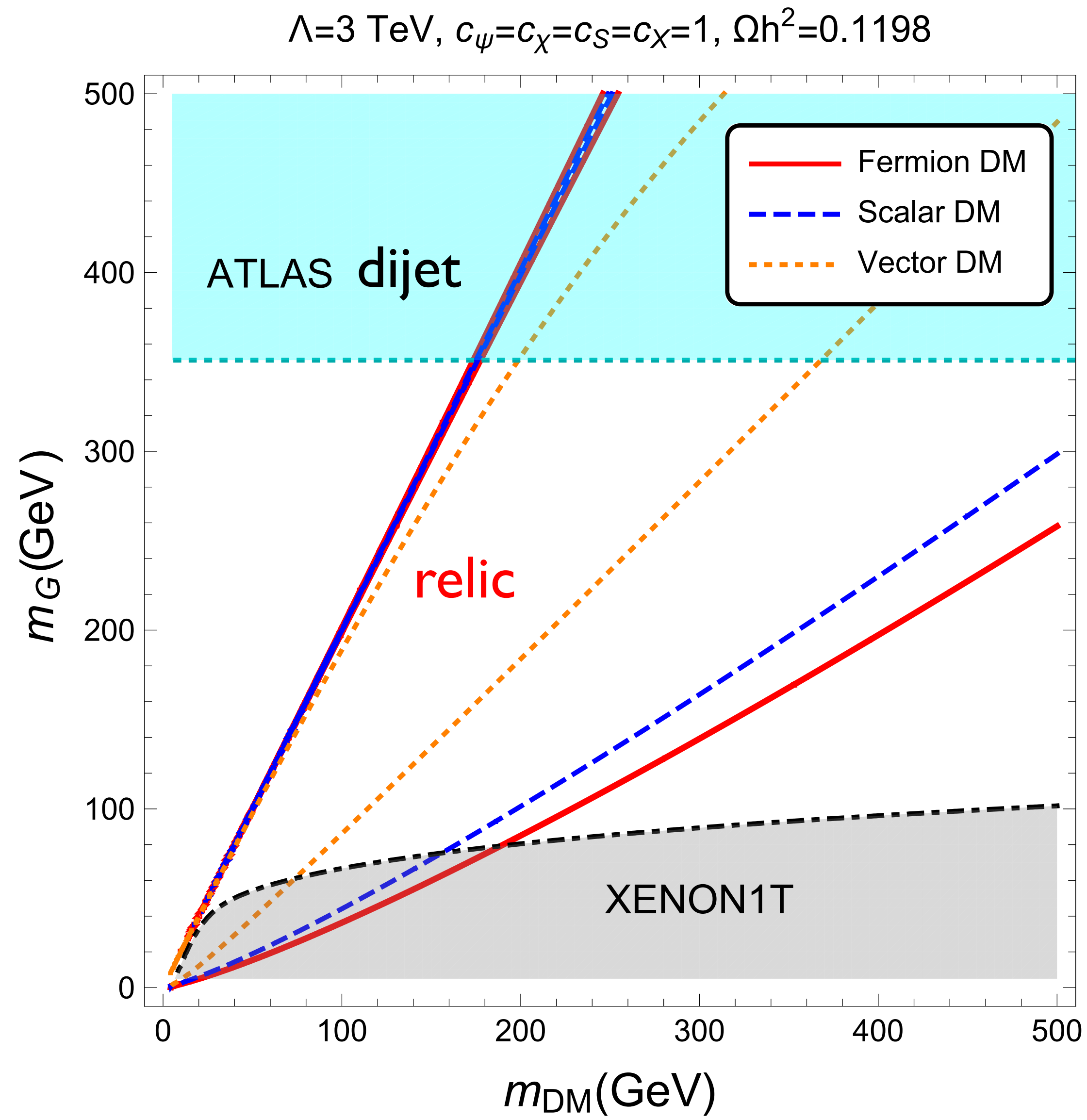
Nuclear matrix elements: $\langle N(p_2)|i\mathcal{L}_{\rm eff}|N(p_1)\rangle$

$$\Rightarrow \quad \mathcal{L}_{X-N} = \frac{3c_X c_q m_X^2 m_N^2}{m_G^2\Lambda^2}\left(F_{qT} - \frac{2}{9}F_{qS}\right)(X^+X^-)(N^+N^-),$$

$$F_{qS} = \langle N|m_q\bar{q}q|N\rangle/m_N, \qquad F_{qT} = \int_0^1 dx\, x(q(x)+\bar{q}(x)).$$

XENON1T + LHC





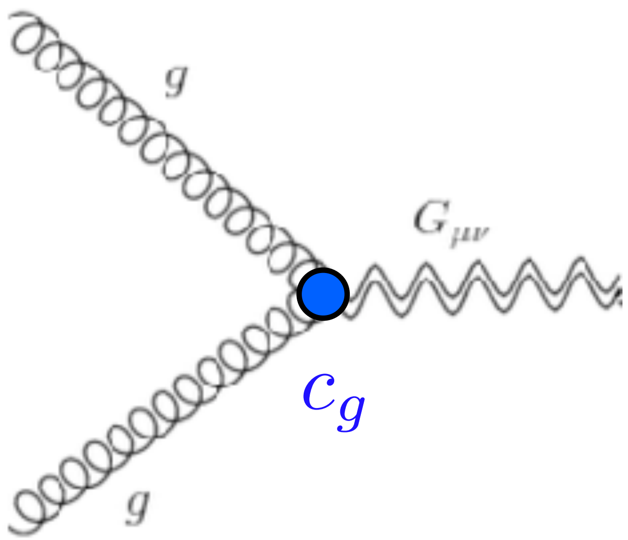
$$\sigma^{SI}_{DM-N} = \frac{\mu_N^2}{\pi}\, f_p^2, \qquad \mu_N = \frac{m_X m_N}{m_X + m_N},$$

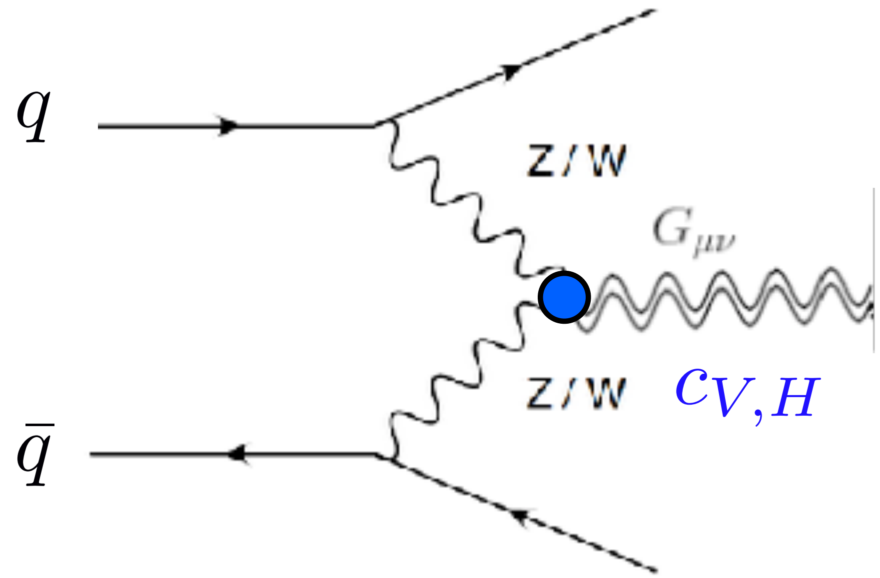
$$f_p = \frac{3 c_X m_N m_X}{4 m_G^2 \Lambda^2}\Big(\sum_{q=u,d,s,c,b} c_q F_{qT} + \frac{1}{9}\sum_{u,d,s} c_q F_{qS}\Big).$$

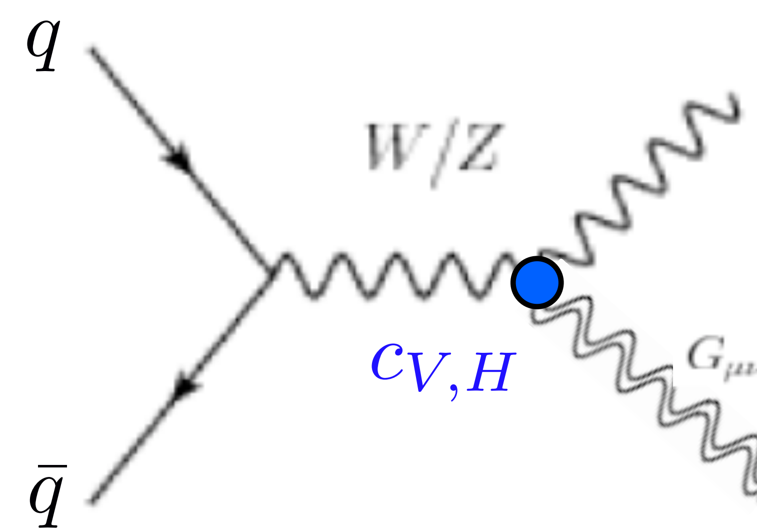
KK graviton at LHC

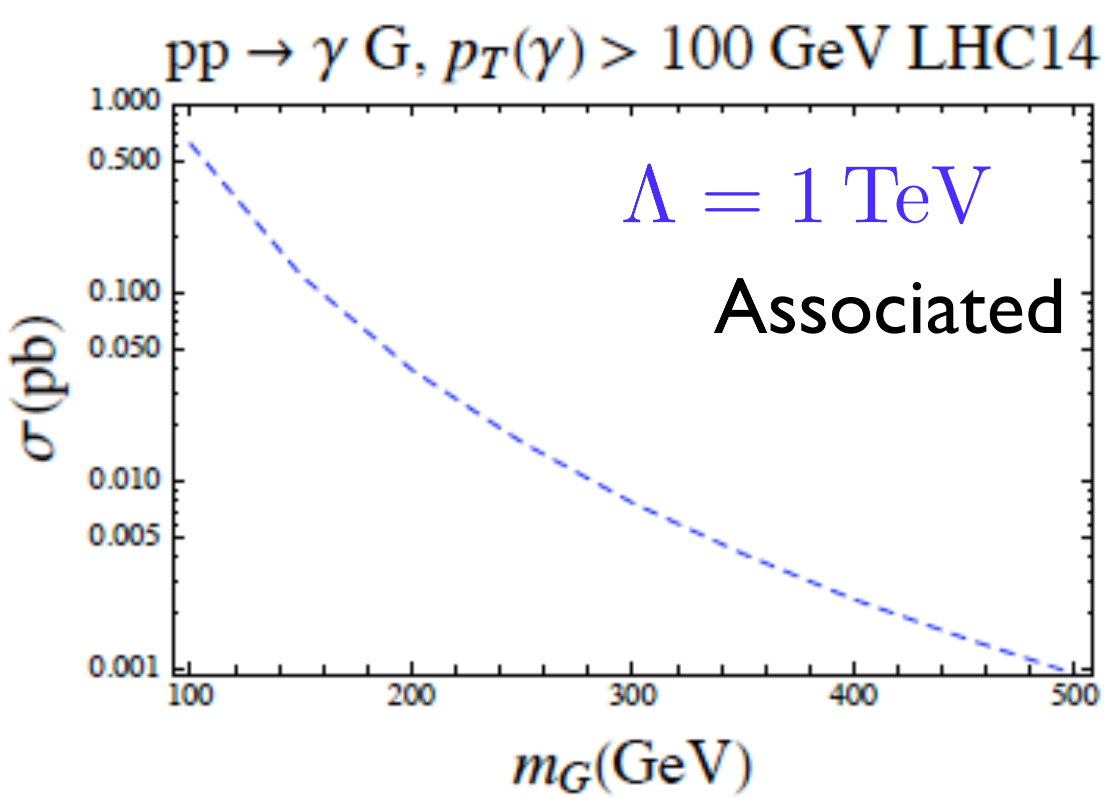
KK gravitons at LHC

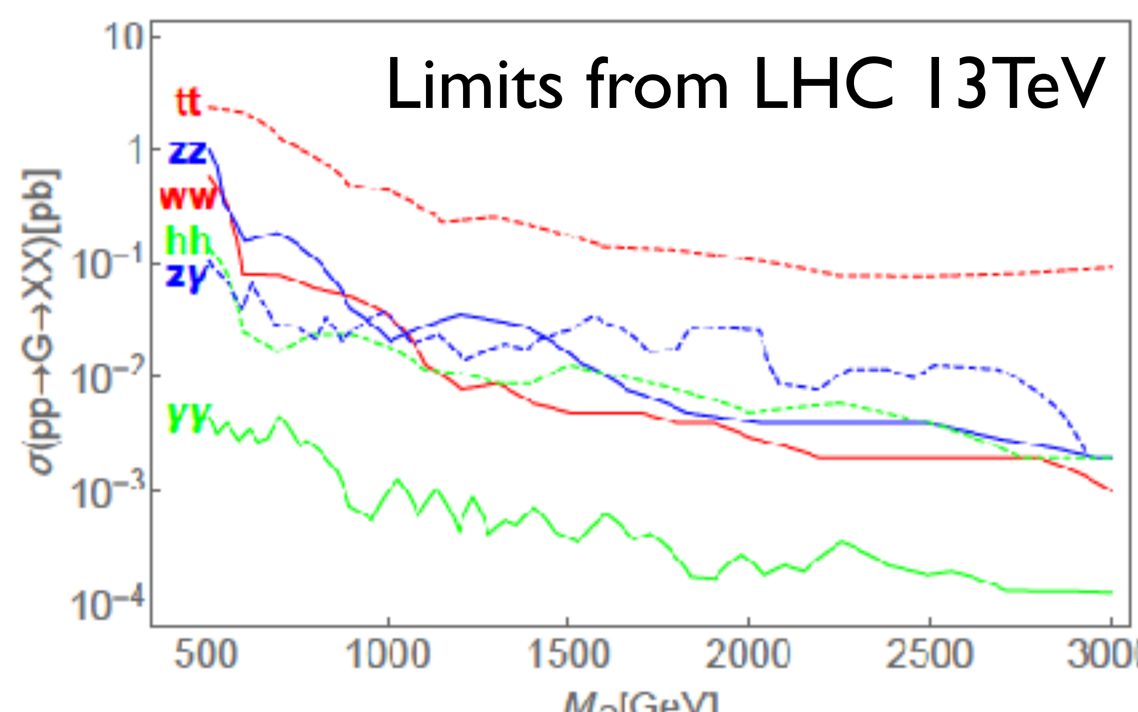
- Gluon fusion
  [Model B: all comparable]
- VBF(Model A)
- Associated (Model A)



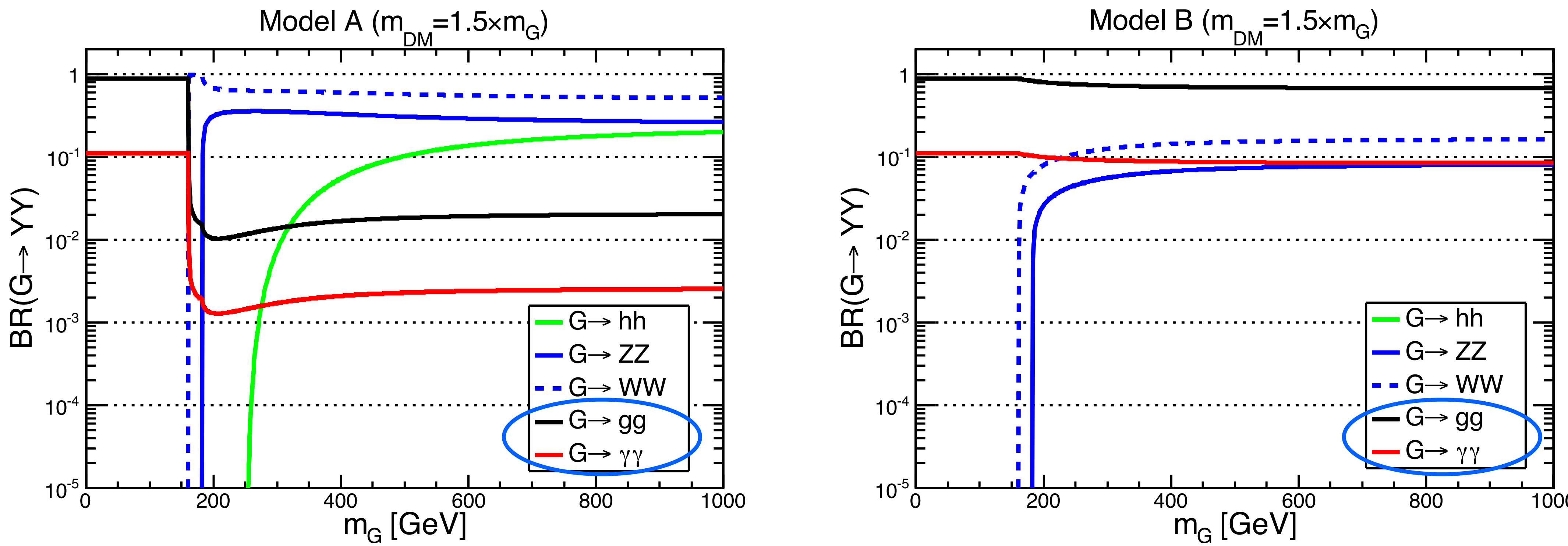








Light KK graviton: $m_G < 2m_X$



Cascade DM ann. → KK graviton coupling can be small, evading LHC limits easily.

- Model A: gg, γγ (WW, ZZ, hh, gg, γγ) below(above) WW threshold.

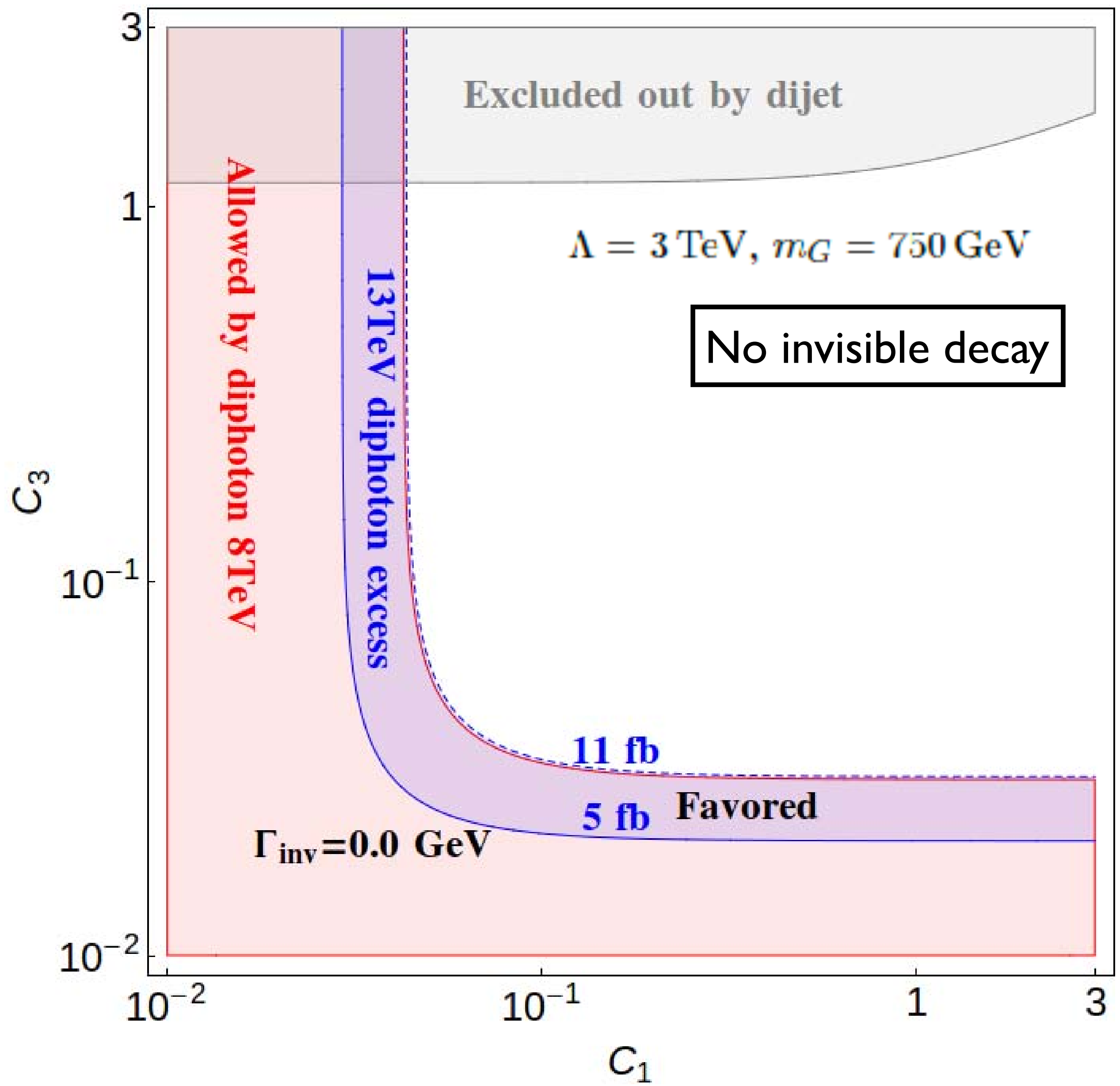
di-jet, di-photon

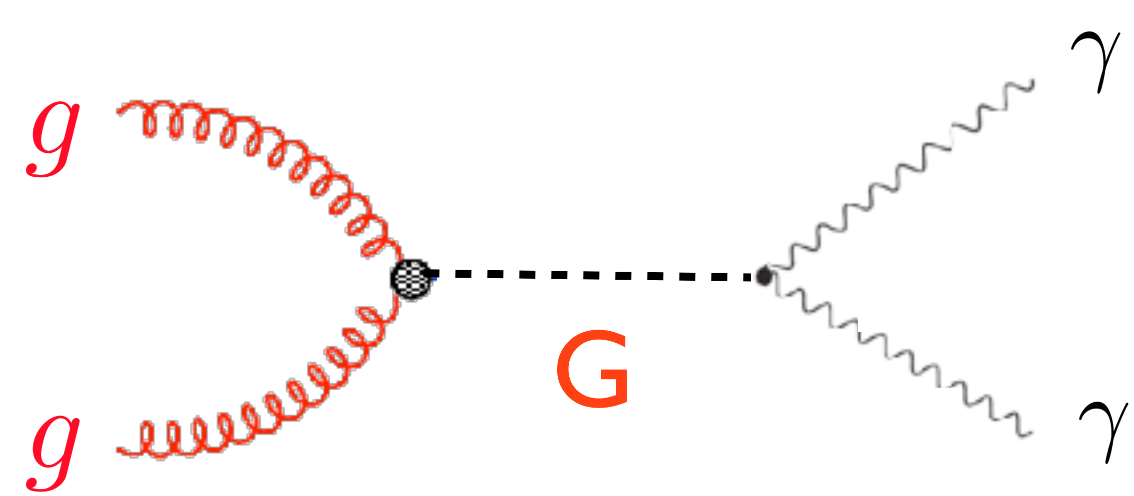
- Model B: gg, γγ (gg, WW, ZZ, γγ) below(above) WW threshold.

Visible decays: diphoton

C. Han et al, 2015

- Consider the production of KK graviton via gluon fusion,decaying into a pair of photons.



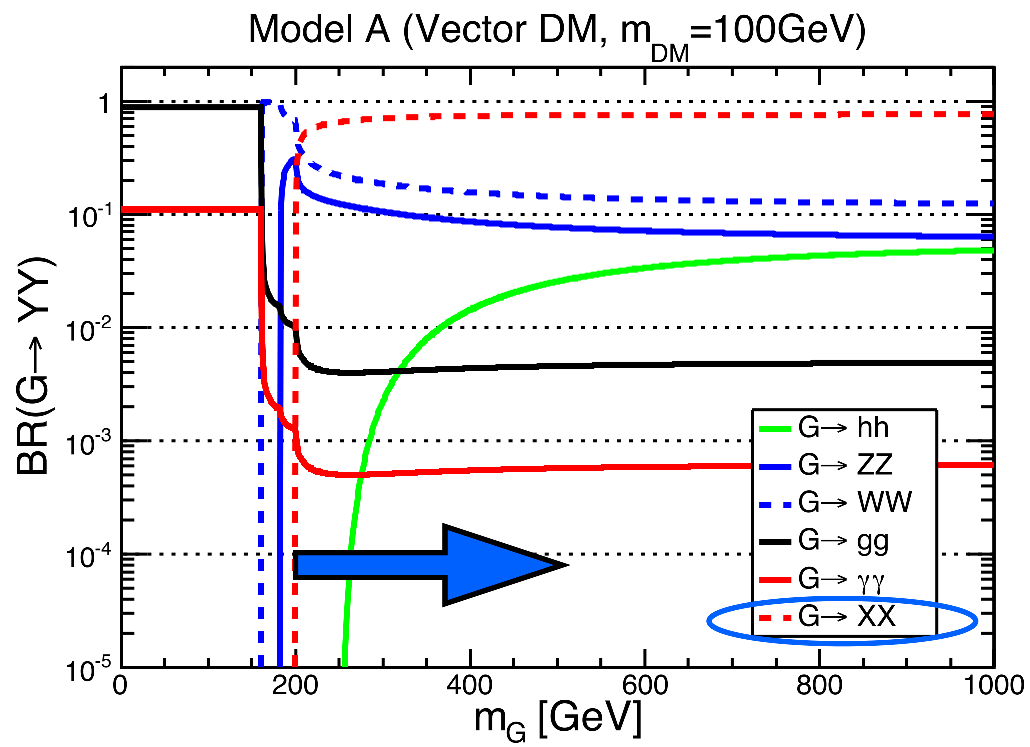


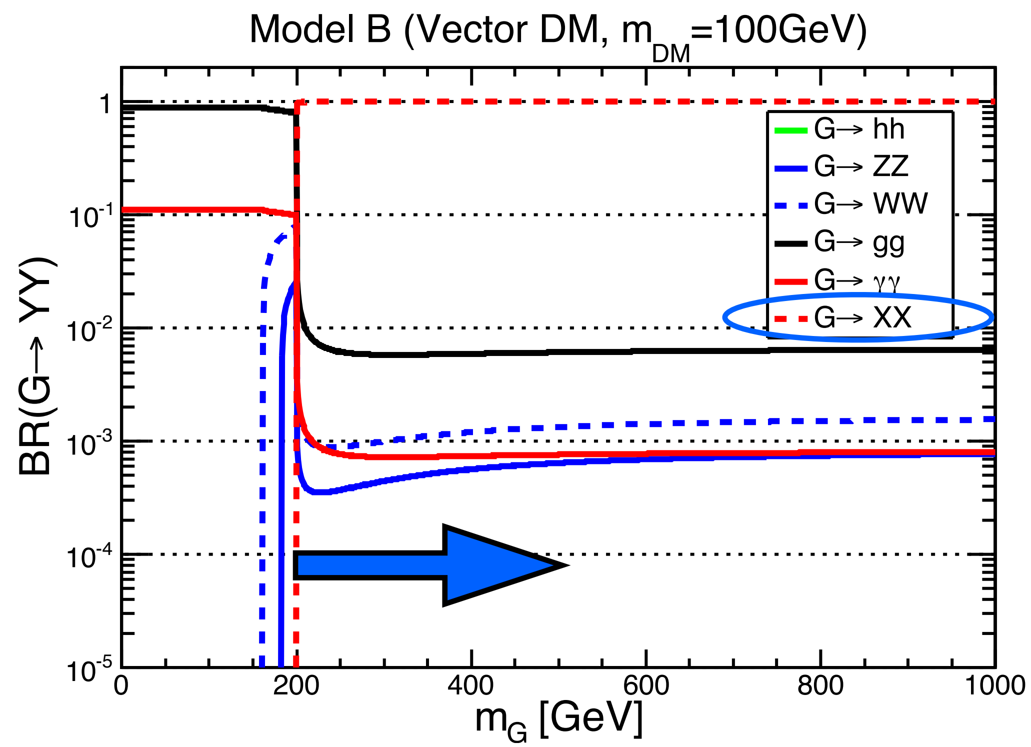
KK couplings & diphoton production:

$$c_3 \times c_1 = 0.16 \left(\frac{\sigma_{pp\to\gamma\gamma}}{8\,\mathrm{fb}}\right)^{1/2} \left(\frac{\Lambda}{3\,\mathrm{TeV}}\right)^2 \left(\frac{\Gamma_G}{45\,\mathrm{GeV}}\right)^{1/2}.$$

Dijet bound: $|c_3| \lesssim 1.5$

Heavy KK graviton: $m_G > 2m_X$





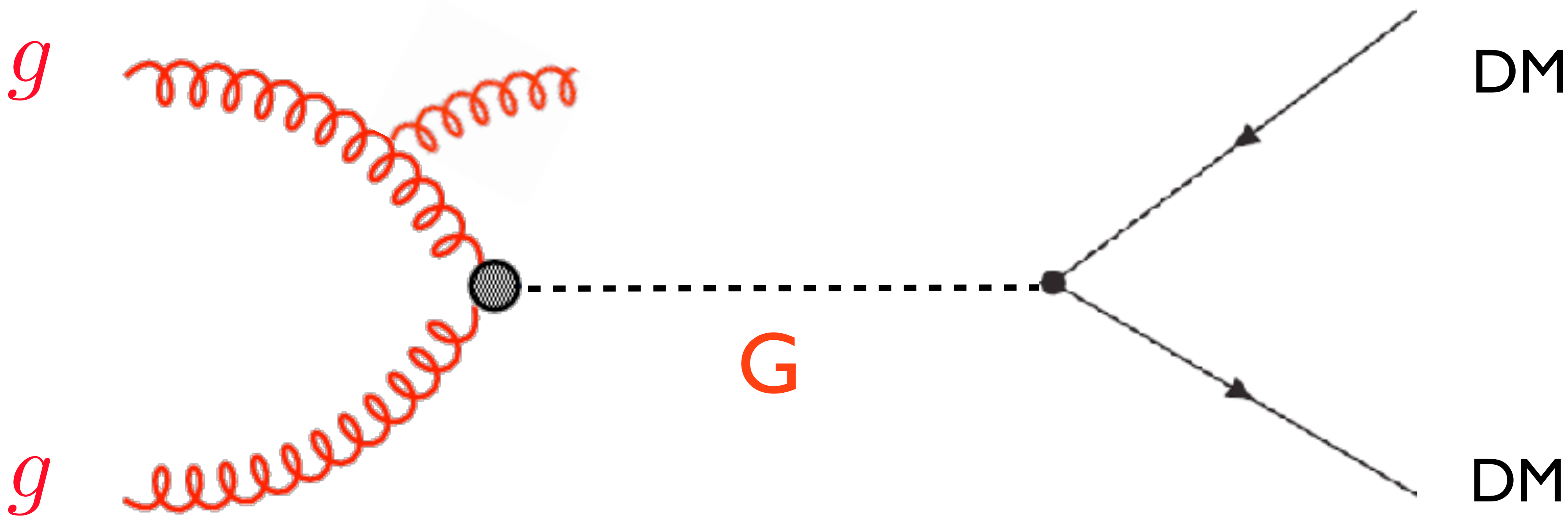
Direct DM ann. → Sizable KK graviton coupling; invisible decays open

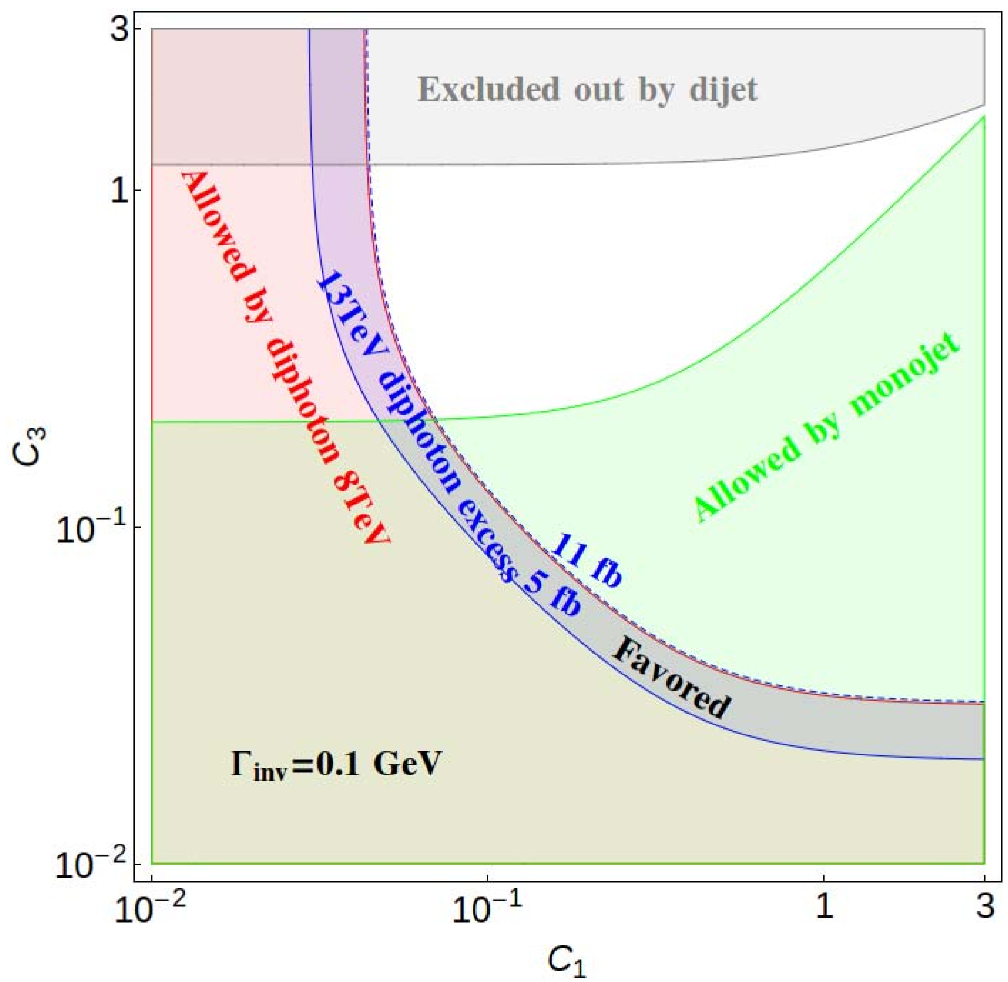
- Model A: gg, γγ (XX, WW, ZZ, hh, gg) below(above) XX threshold.

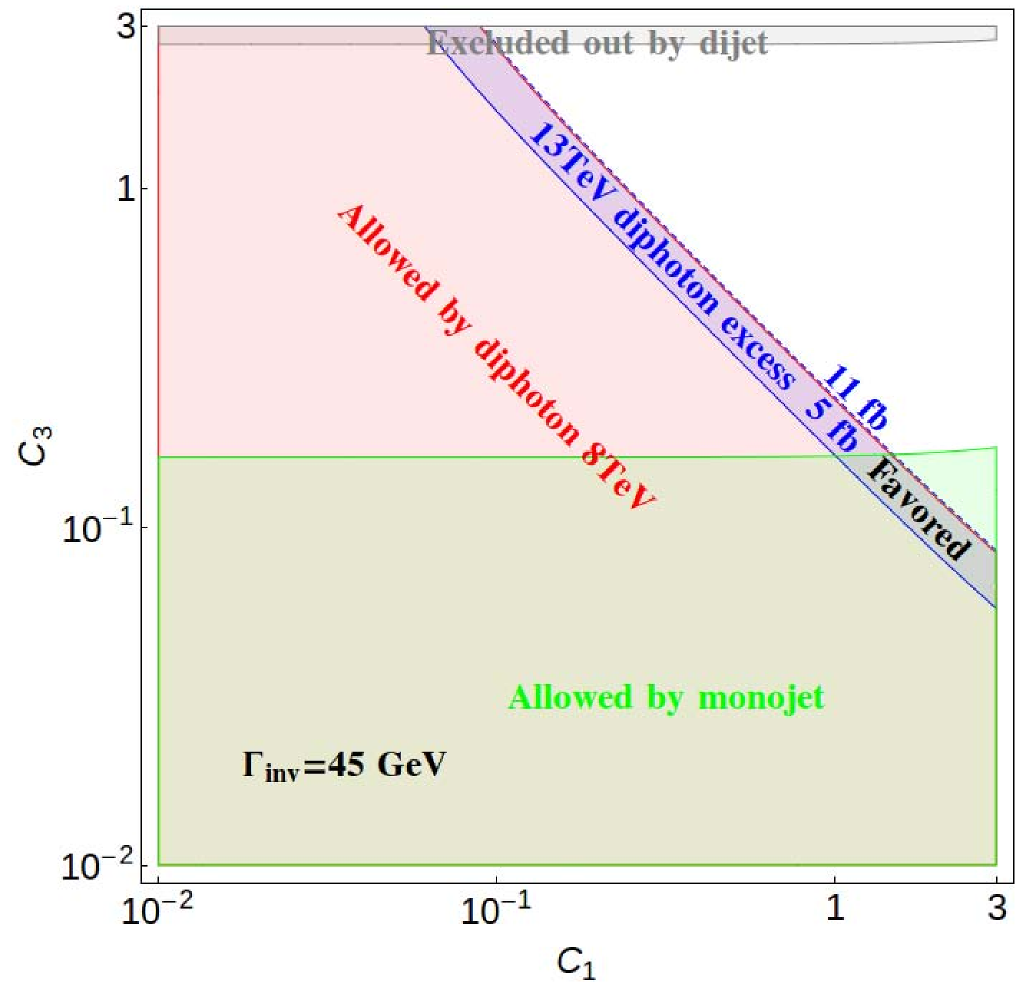
- Model B: gg, γγ (XX) below(above) XX threshold.

Mono-γ/jet/Z/W + MET

Invisible decays: mono-jet

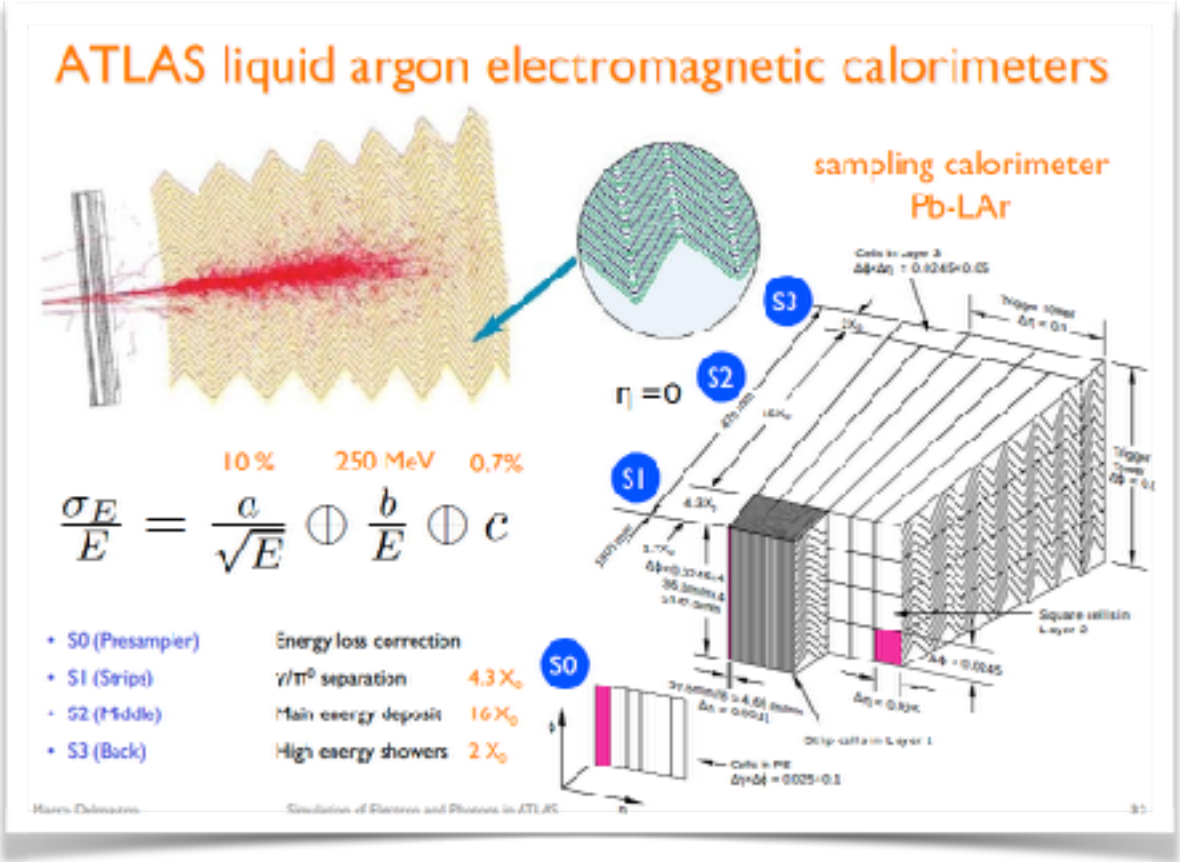






Graviton-radion interplay

Photon-jets

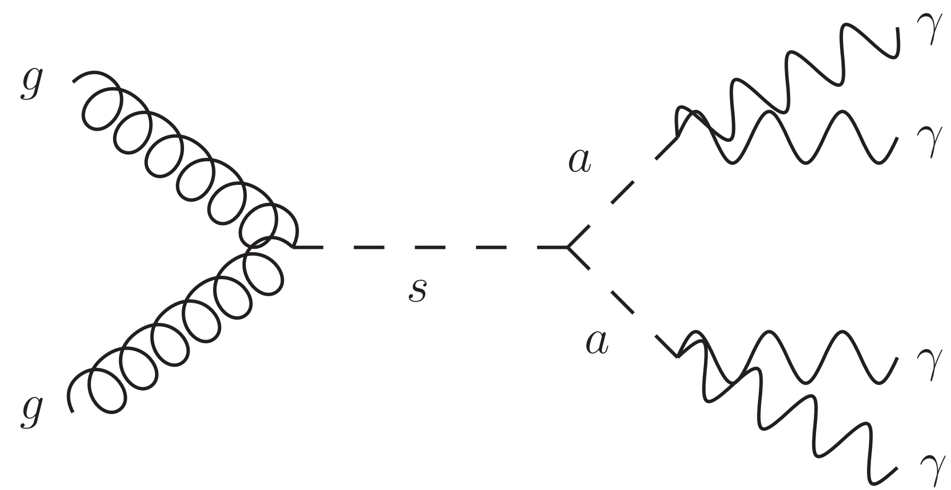


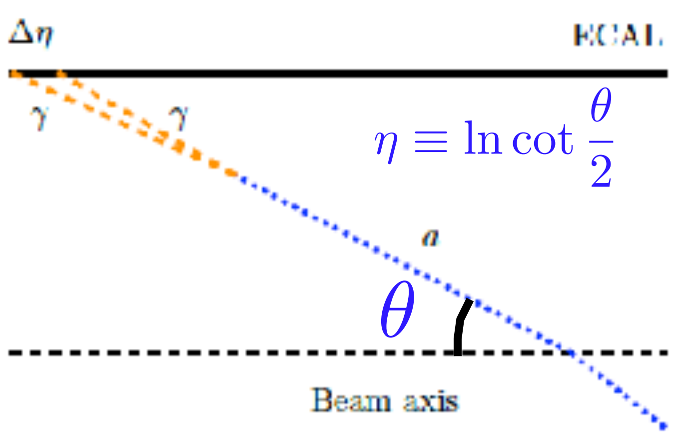
ATLAS EM calorimeter:

$\Delta\eta = 0.025\,, \quad r = 1.5\mathrm{m}$

cf. CMS: $\Delta\eta = 0.0174\,, \quad r = 1.3\mathrm{m}$

(first layer: $\Delta\eta = 0.003 - 0.006$)





$$|\Delta\eta| \approx \frac{2m_a}{E_a}\left(1 - \frac{d}{r}\right), \quad d = (c\tau_a)\gamma \approx \frac{1}{\Gamma_a}\frac{E_a}{m_a}.$$

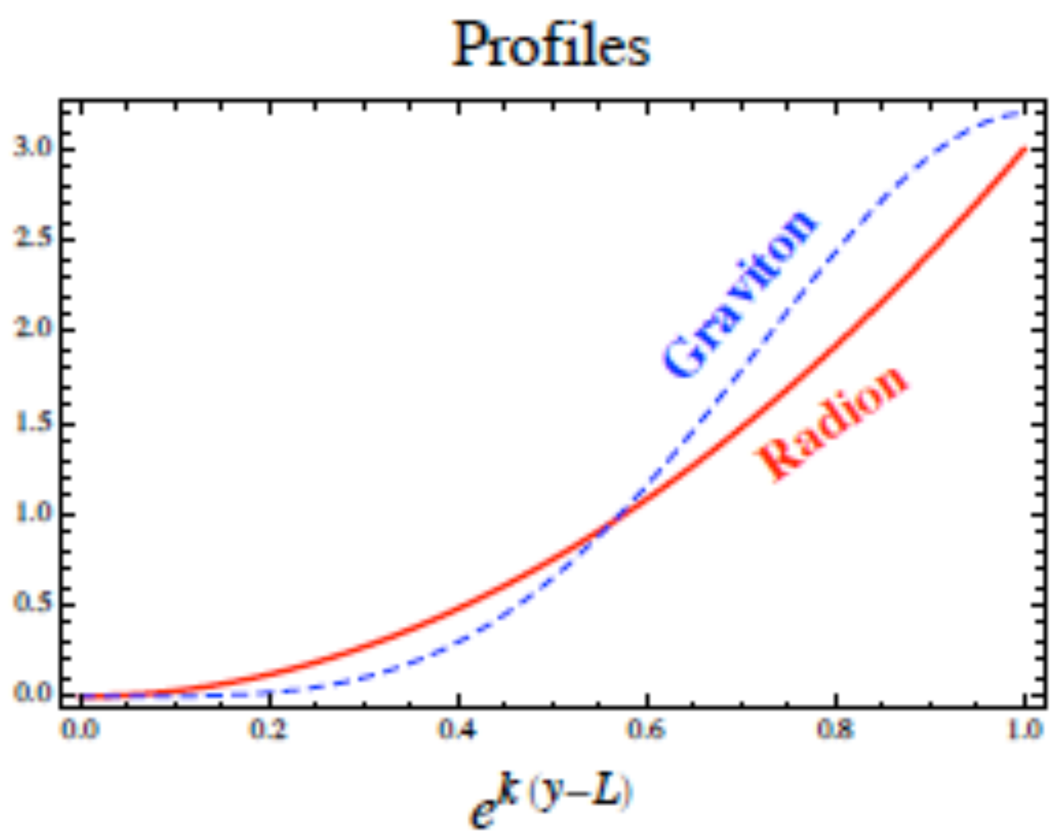
$$\Rightarrow \quad m_s = 750\,\mathrm{GeV}, \quad m_a \lesssim 0.5\,\mathrm{GeV}.$$

If intermediate particle decays into two photons within ECAL, photons are collimated and could mimic one photon.

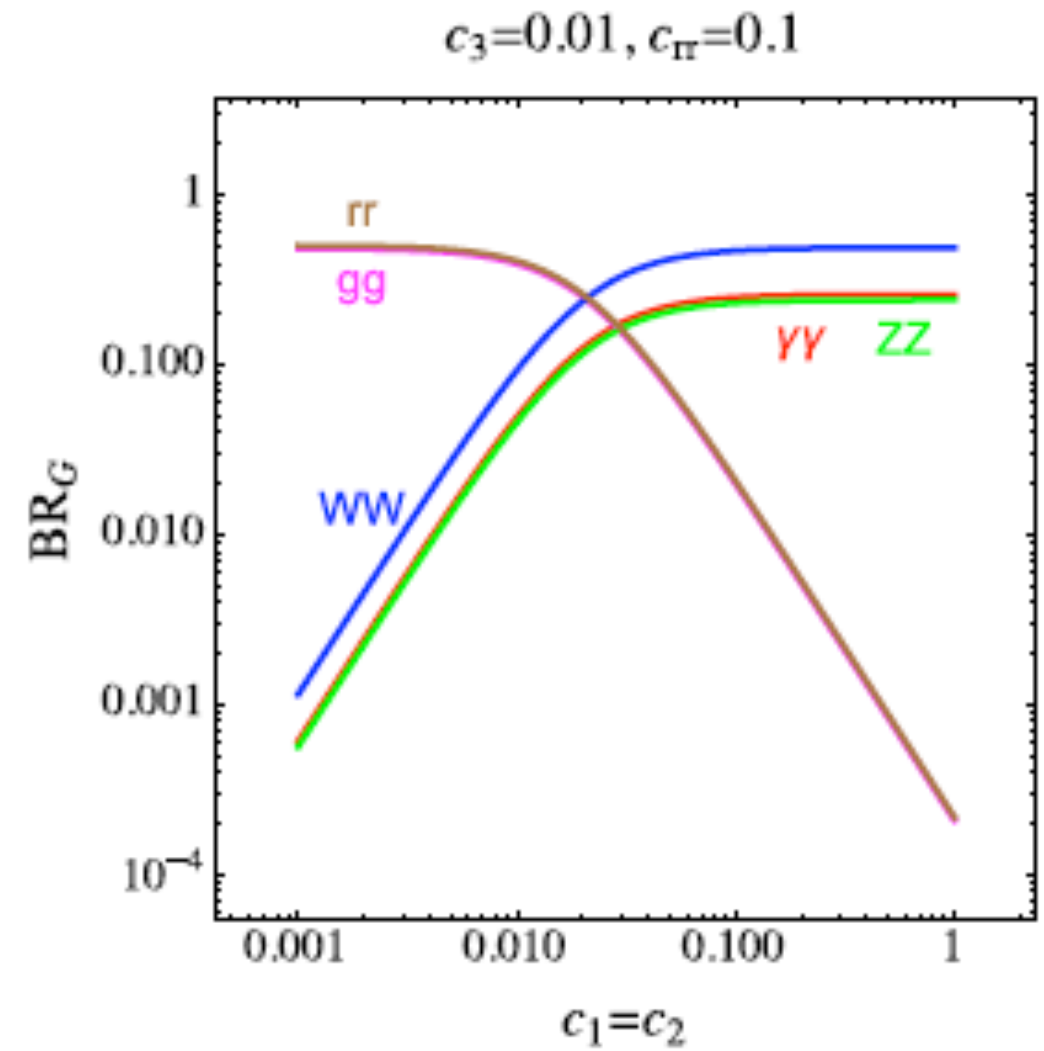
KK graviton and light radion

- Radion is localized toward the IR brane, so it couples strongly to KK graviton.

Dillon et al, 2016



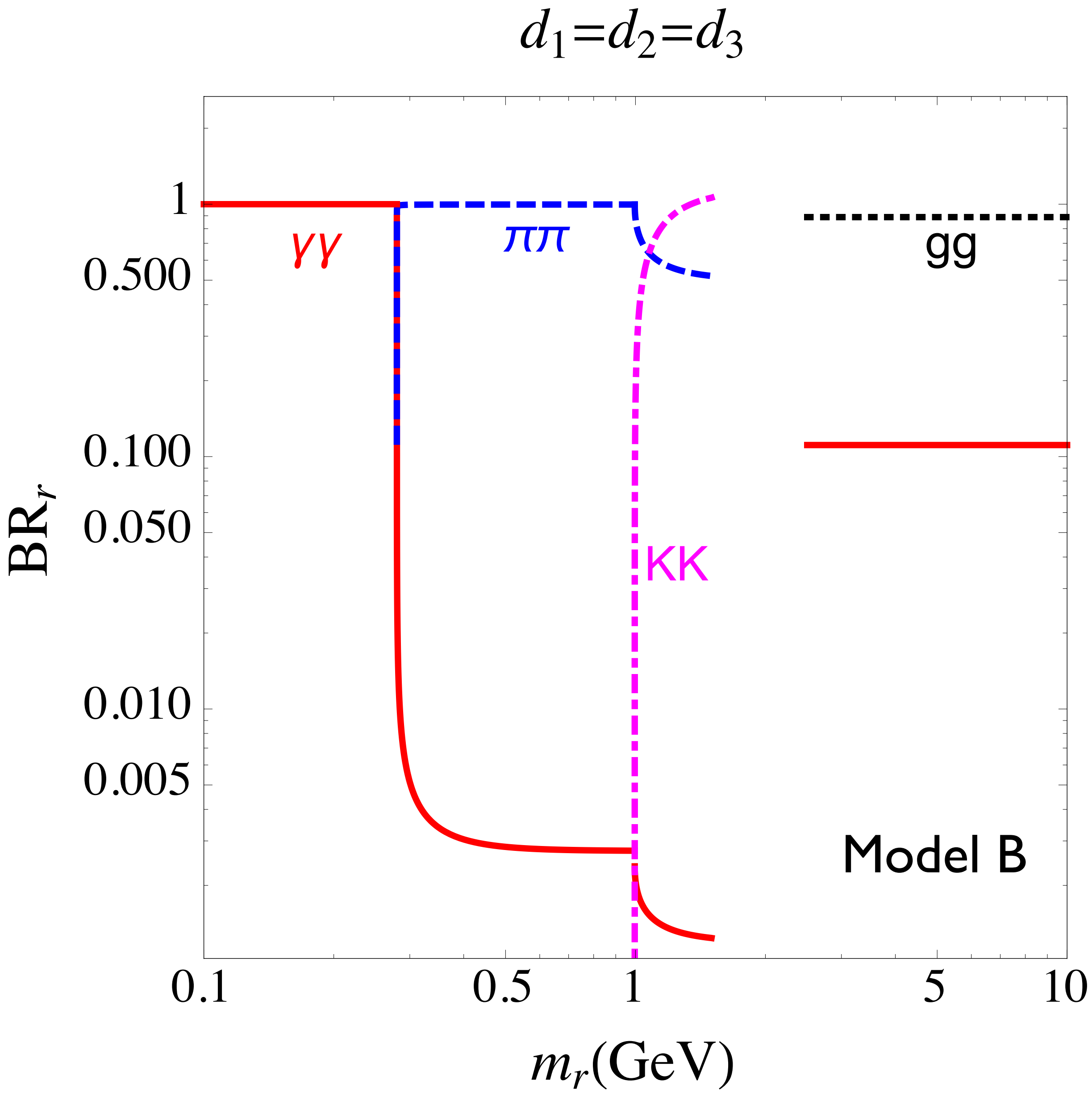
Gouzevitch et al, 2013

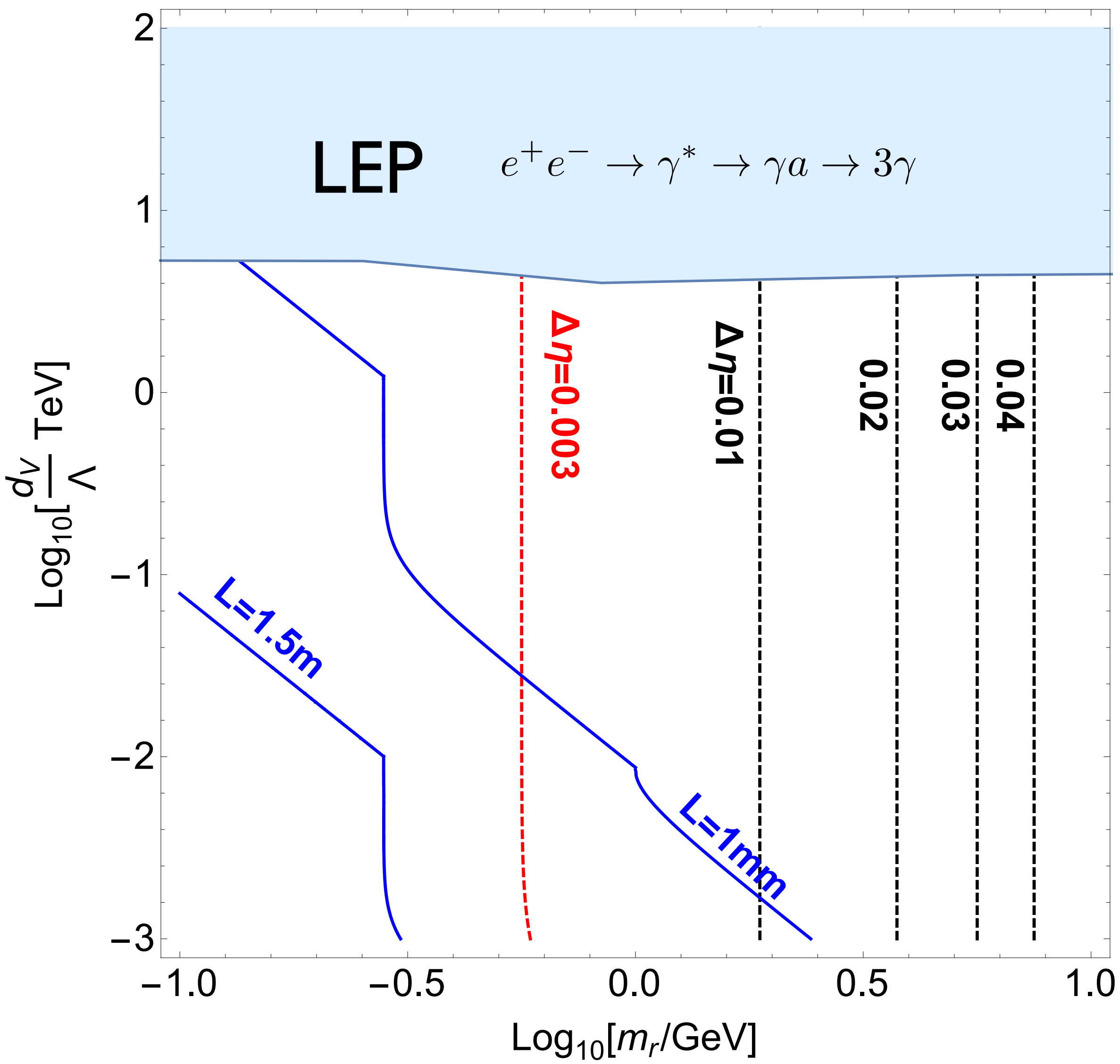


$$\mathcal{L}_r = \frac{1}{\sqrt{6}\Lambda}\, r\, T^\mu_\mu \sim \quad -\frac{r}{\Lambda}\left(d_1 B_{\lambda\rho}B^{\lambda\rho} + d_2 W_{\lambda\rho}W^{\lambda\rho} + d_3 g_{\lambda\rho}g^{\lambda\rho}\right) + \frac{d_f}{\Lambda} m_f r \bar{f} f + \frac{4 d_H}{\Lambda} m_H^2 r |H|^2 - \frac{d_V}{\Lambda} r (m_Z^2 Z_\mu Z^\mu + 2 m_W^2 W_\mu W^\mu) - \frac{c_{rr}}{\Lambda}\left[G^{\mu\nu}\partial_\mu r \partial_\nu r + \frac{3}{2} G (\partial r)^2 + r^2 (\partial_\mu \partial_\nu G^{\mu\nu} - \Box G)\right]$$

Radion decays

Dillon et al, 2016

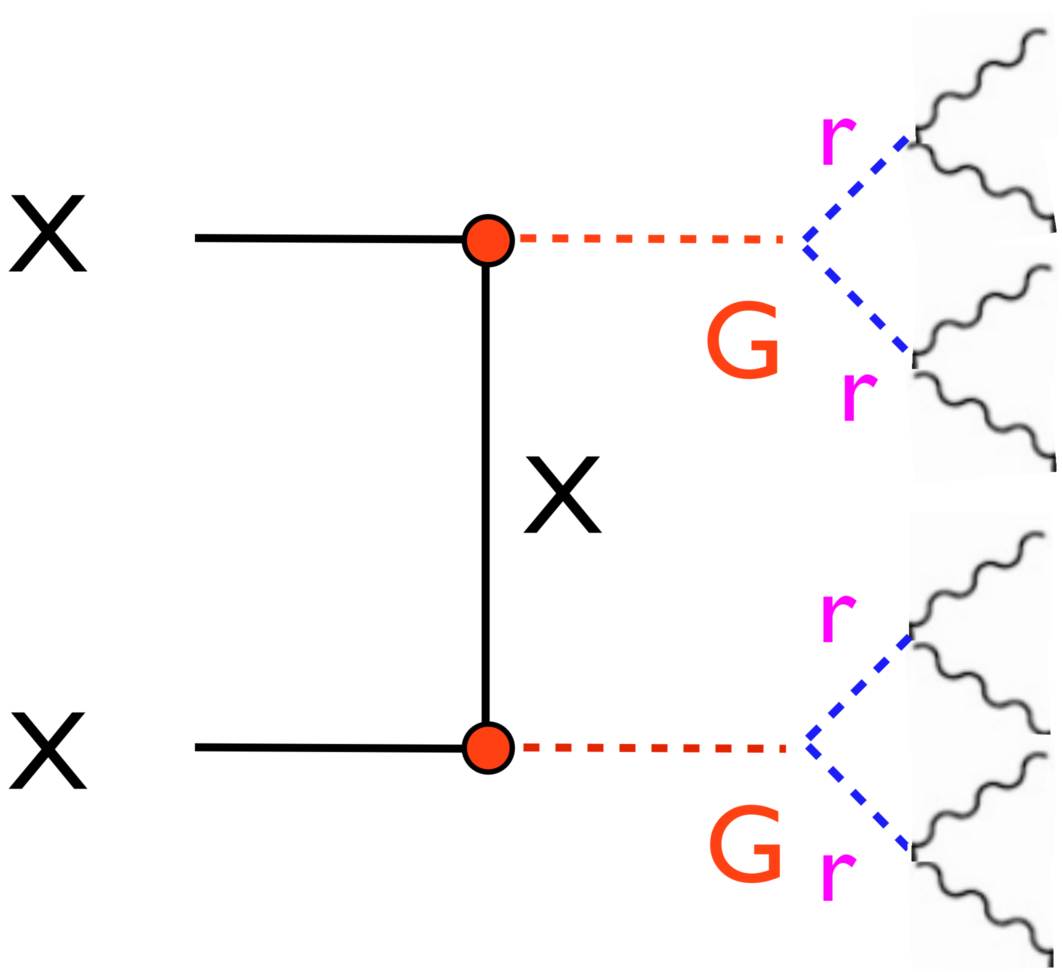


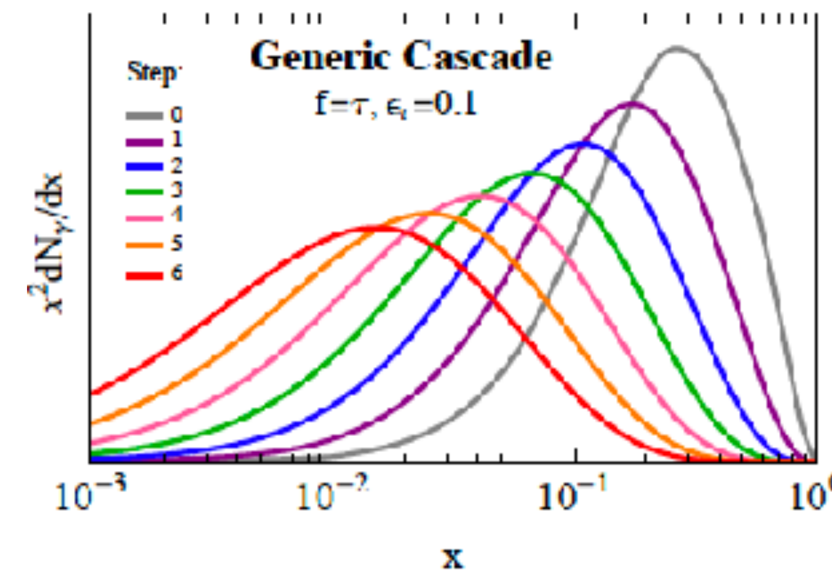


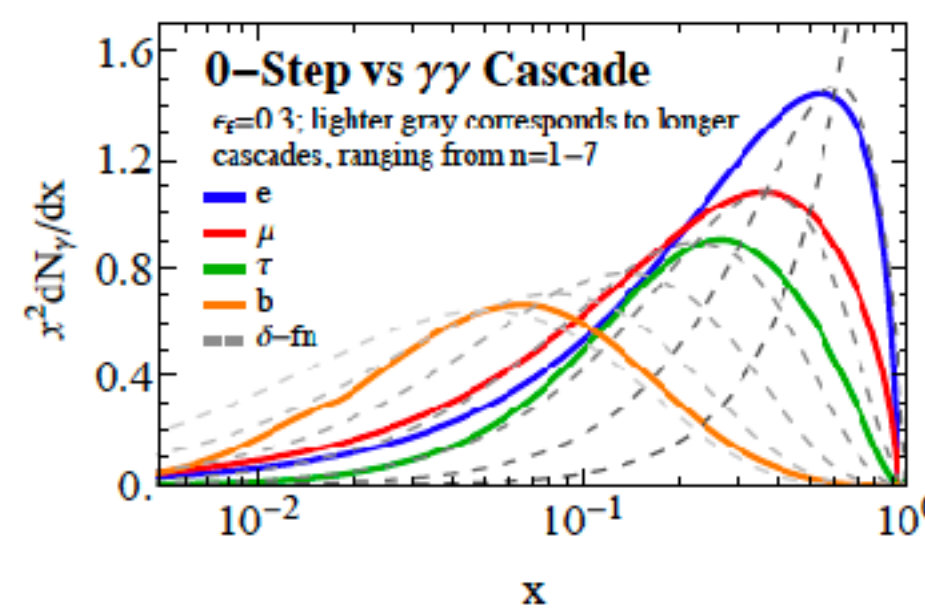
- Radion decays into multiple photons (2γ or 2π→4γ).
- Decay length L is displaced in tracker or within ECAL.

Multi-step annihilations

- Dark matter can annihilate into a pair of KK gravitons, with cascade decays, G→rr and r→SM SM.







See, for instance, Elor et al, 2015.

- Photons from 2-step cascade annihilations are shifted to low energies, mimicking muons or taus.

The origin of photons

C. Han et al, 2015; Dillon et al, 2016

- Angular correlations between photons can be used to test (1) spin and CP; (2) direct or cascade decays.

Parton-level cross-section at resonance rest-frame:

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\cos\theta^*} \propto \begin{cases} 1 + 6\cos^2\theta^* + \cos^4\theta^* & \text{in } (gg \to G \to \gamma\gamma), \\ 1 - 2\cos^2\theta^* + \cos^4\theta^* & \text{in } (gg \to G \to r\,r \to 2\gamma_{\text{jet}}), \\ 1 & \text{in } (gg \to S \to \gamma\gamma), \end{cases}$$

cascade decays

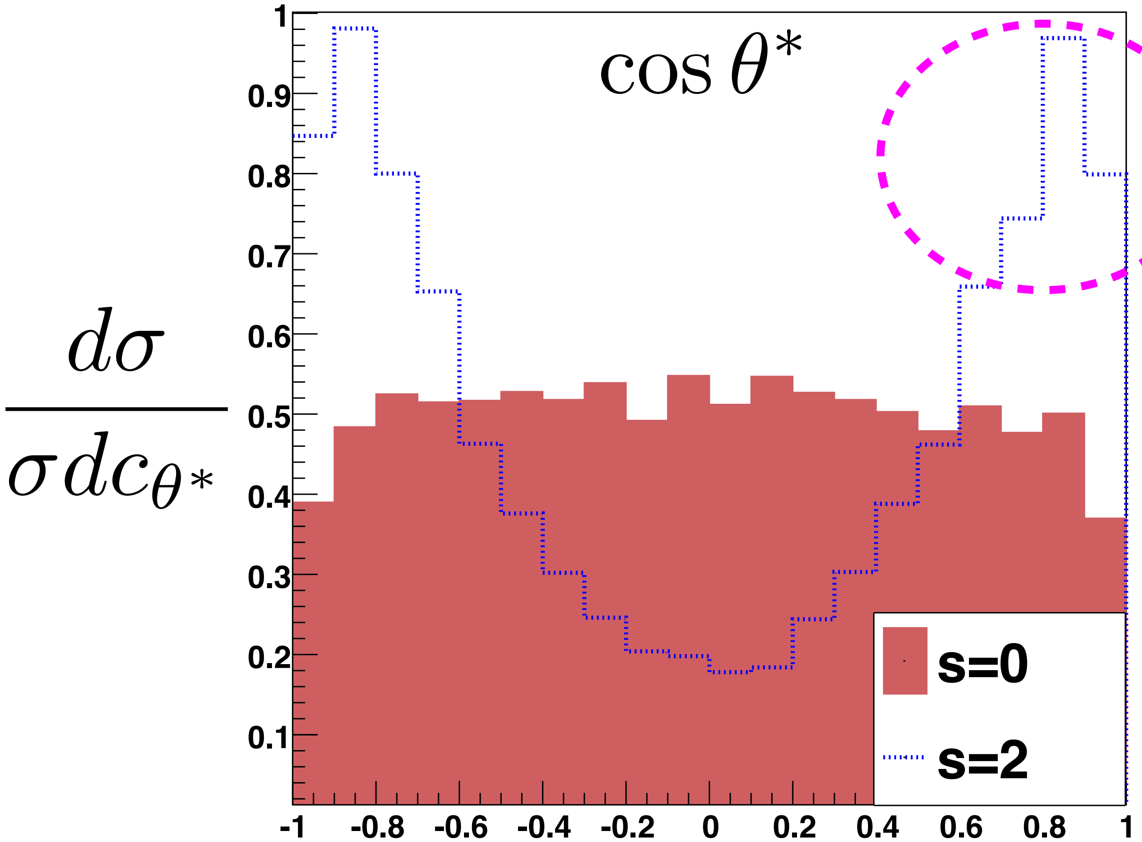
direct decays

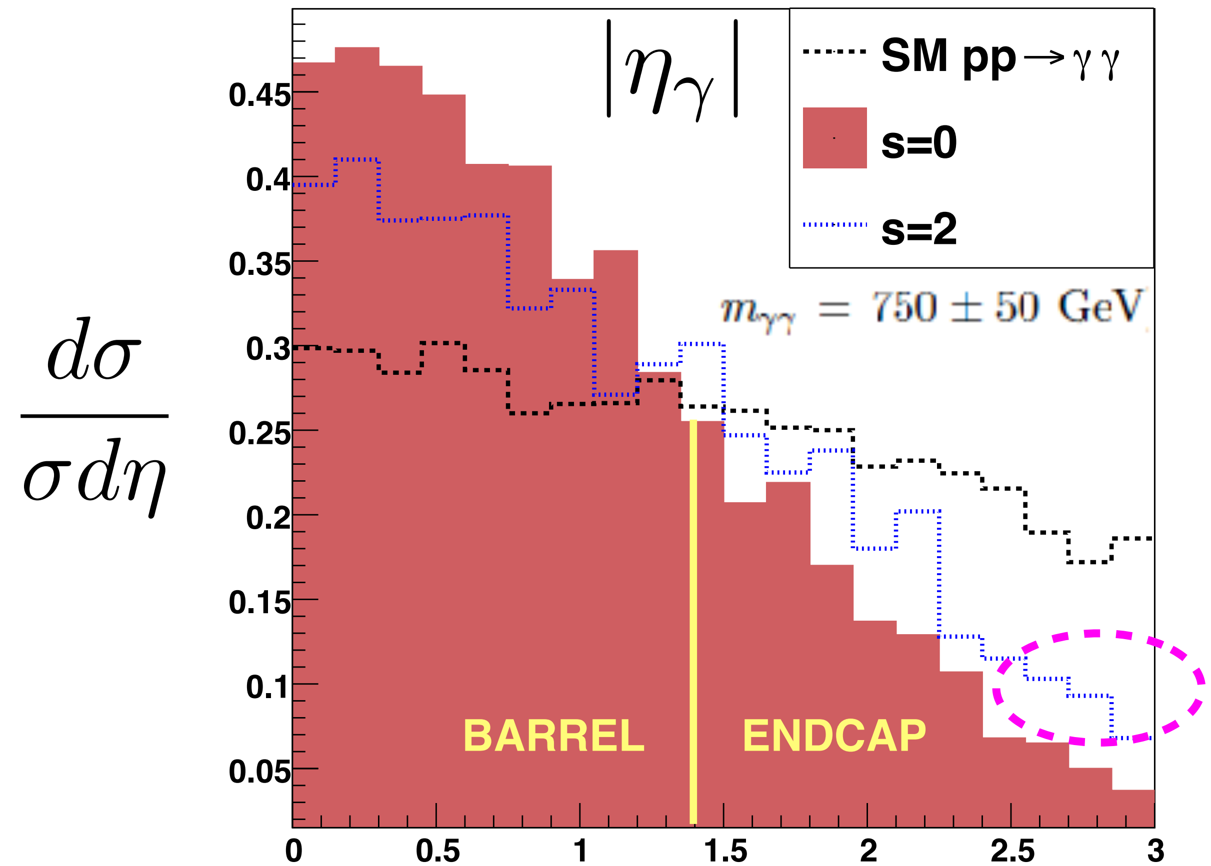
G: spin-2 vs S: spin-0

G: Direct vs Cascade decays

Spin-2 vs Spin-0

C. Han et al, 2015





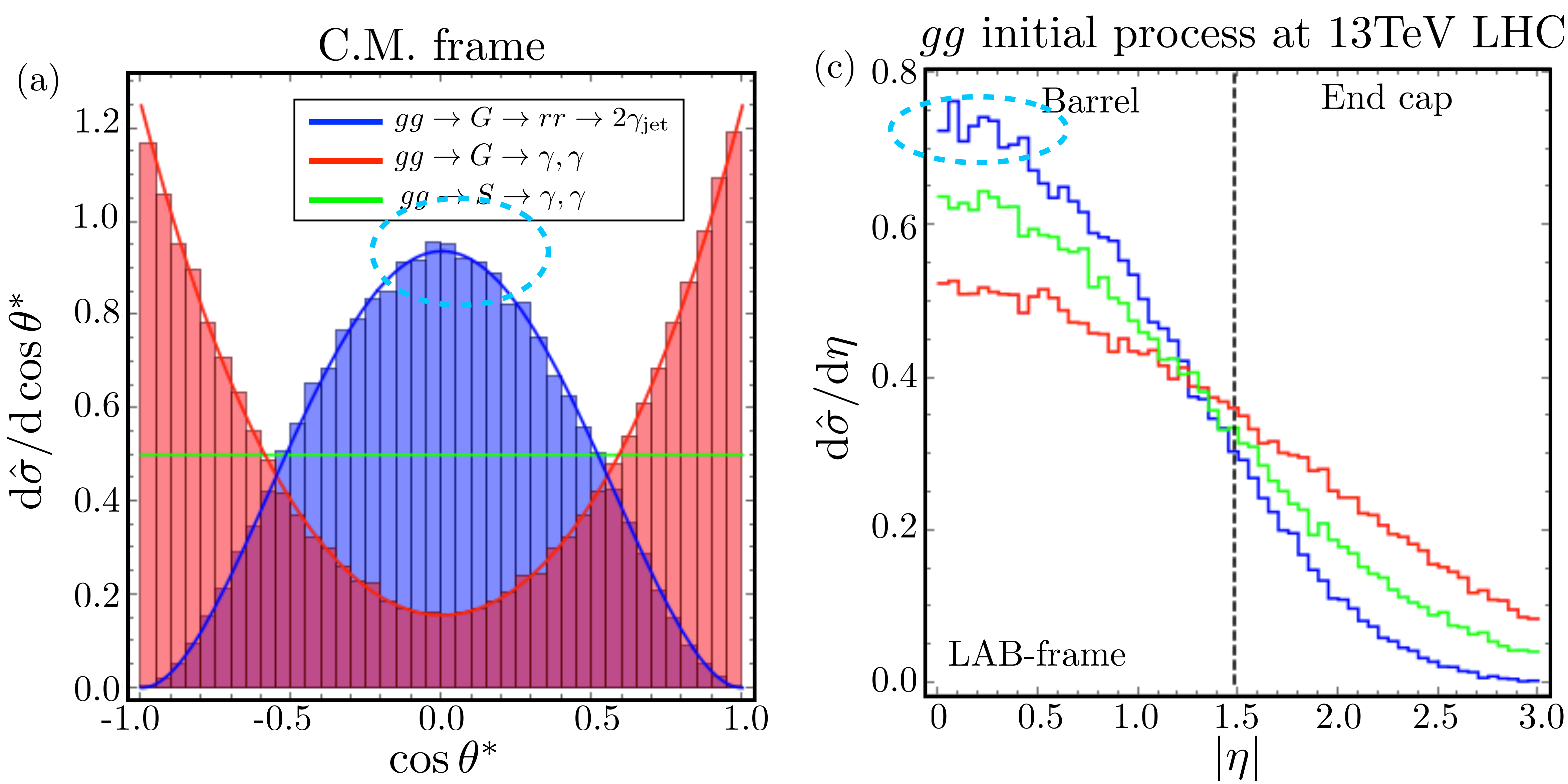
θ^* : photon angle from beam in rest frame of the resonance

$|\eta_{\gamma\gamma}|$: pseudo-rapidity separation

- Direct photons from the decay of KK graviton are "more forward (30%)" (ENDCAP) and are more separated.
- Useful information from $N_{\rm jet}$, $p_T^{\gamma\gamma}$, $E_T^{\rm miss}$, $\cos\theta^*$, etc.

Direct vs Cascade decays

Dillon et al, 2016



- Photon-jets coming from cascade decays are "more central" (BARREL), closer to scalar resonance (cf. photon-jets: 15% in ENDCAP).

Conclusions

- KK graviton can be portals to dark matter and new physics.
- KK graviton couplings depend on localization of SM particles in extra dimension. Large couplings to dark matter and/or universal couplings to gauge fields in RS-like models lead to distinct signals for DM and colliders.
- Cascade decays of KK graviton could lead to more smooth gamma-ray spectrum for dark matter signals and displaced signatures such as photon-jets at LHC.
- It would be worthwhile to study the couplings and spectrum of KK graviton in general warped geometry, such as linear dilaton background.

Backup

Light KK graviton

- In bulk RS: $m_G = x_G \tilde{\kappa} \Lambda$, $\tilde{\kappa} \equiv \frac{k}{M_P}$, $\Lambda = e^{-kL} M_P$, $(x_G = 3.83)$.
  $m_A = x_A \tilde{\kappa} \Lambda = 0.64 m_G$, $(x_A = 2.45)$.

- Brane Einstein term: $\Delta \mathcal{L}_{\rm RS} = -\frac{1}{2} M_*^3 \sqrt{-g_4} R_4 \left[r_0 \delta(y) + r_L \delta(y-L) \right]$

$$\Rightarrow \quad m_G \approx \frac{2k e^{-kL}}{\sqrt{kL}} = \frac{0.8 m_A}{\sqrt{kL}}$$

[H. Davoudiasl et al, 2003]

[Falkowski et al & Hewett et al, 2016]

$kr_L = 10 - 20$: KK graviton can be light for 3-4TeV KK gauge bosons, being consistent with direct searches and EWPD.

Wrong-sign kinetic term needs new physics.

[Dillon et al, 2016]

$$\mathcal{L}_r = -\frac{1}{2} N_r^2 (\partial_\mu r)^2, \ \ N_r^2 = \Big(1 - 2kr_L\Big)\Big(1 + 2kr_0\Big) > 0,$$

$$M_P^2 = \frac{M_*^3}{2k} \left(1 + 2kr_0 - e^{-2kL}(1 - 2kr_L)\right) > 0.$$

Clockwork at LHC

- General warped geometry with dilaton:

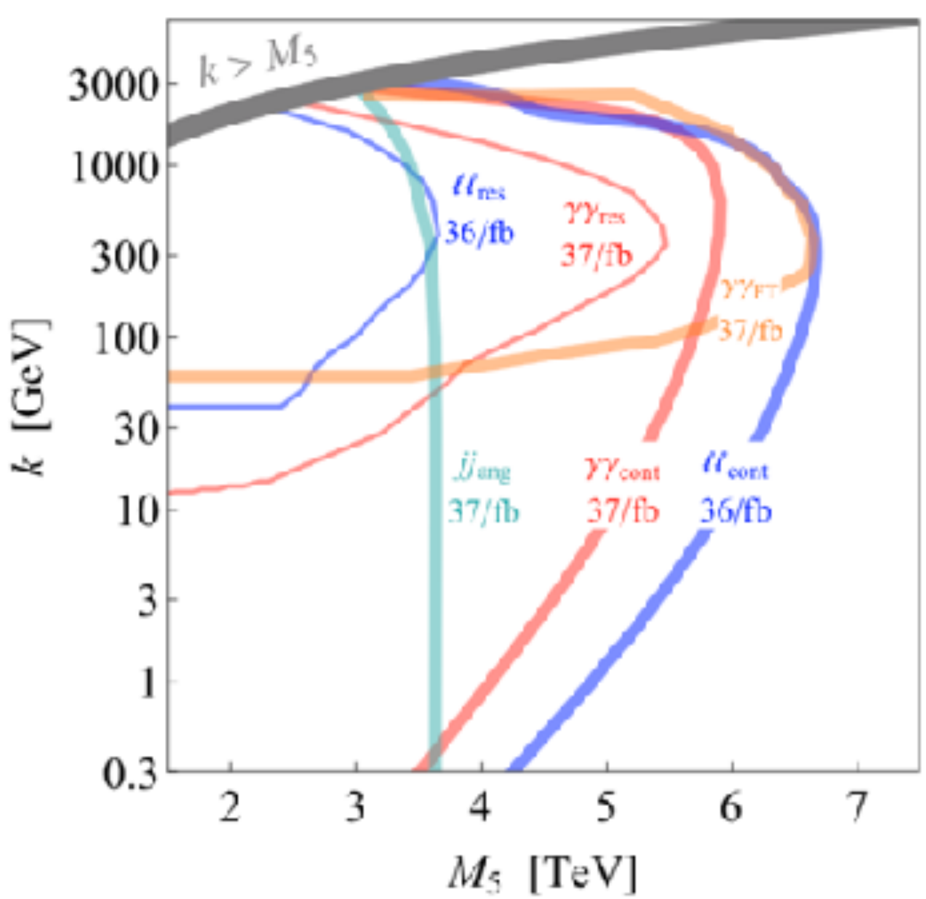
$$S = \int d^5x \sqrt{-g}\, \frac{M_5^3}{2}\, e^S \left(R + (\partial_M S)^2 + 4k^2 \right)$$

$$ds^2 = e^{\frac{4}{3}k|y|}(\eta_{\mu\nu}dx^\mu dx^\nu + dy^2); \;\; S = 2k|y|. \qquad -\Lambda_0 = \Lambda_\pi = 4kM_5^3.$$

$$M_P^2 = \frac{M_5^3}{3}\, L_5\, e^{\frac{1}{3}k\pi R}.$$

kR>>1: Squeezed KK spectrum

$$m_0 = 0\,, \qquad m_n^2 = k^2 + \frac{n^2}{R^2}\,, \qquad n = 1, 2, 3, \ldots$$



Giudice et al, 2017

Almost continuous diphoton resonances.