Gravity-mediated dark matter confronts astrophysics data

Hyun Min Lee
(Chung-Ang University)

Ref. H. M. Lee, M. Park, V. Sanz, 1306.4107 [hep-ph], to appear in EPJC; 1401.5301 [hep-ph], submitted to JHEP.

KIAS-NCTS workshop on Particle Physics,
String theory and Cosmology
High-1 Resort, Feb. 13, 2014

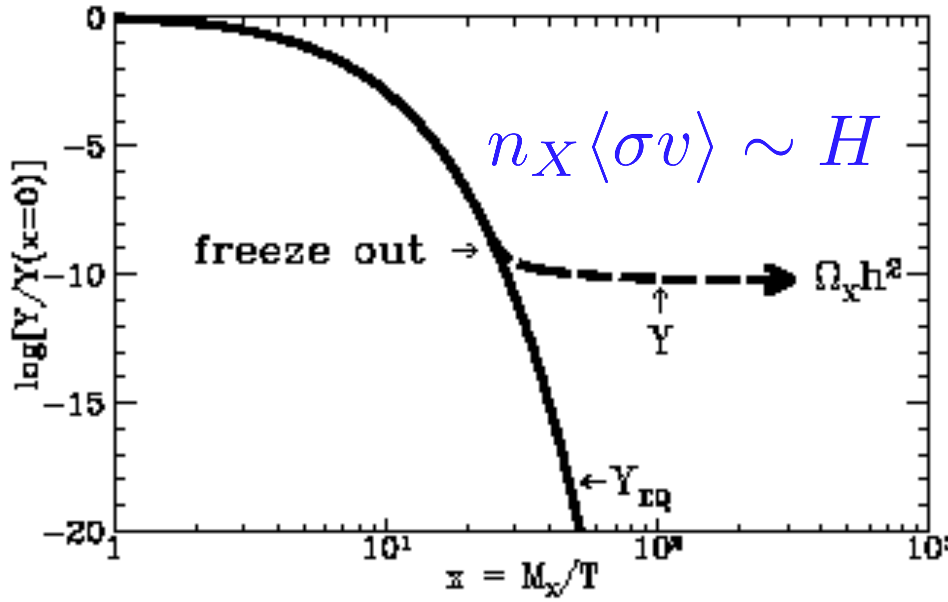
Outline

- Introduction
- Gravity-mediated dark matter
- Bounds on KK graviton
- GMDM & astrophysical bounds
- Conclusions

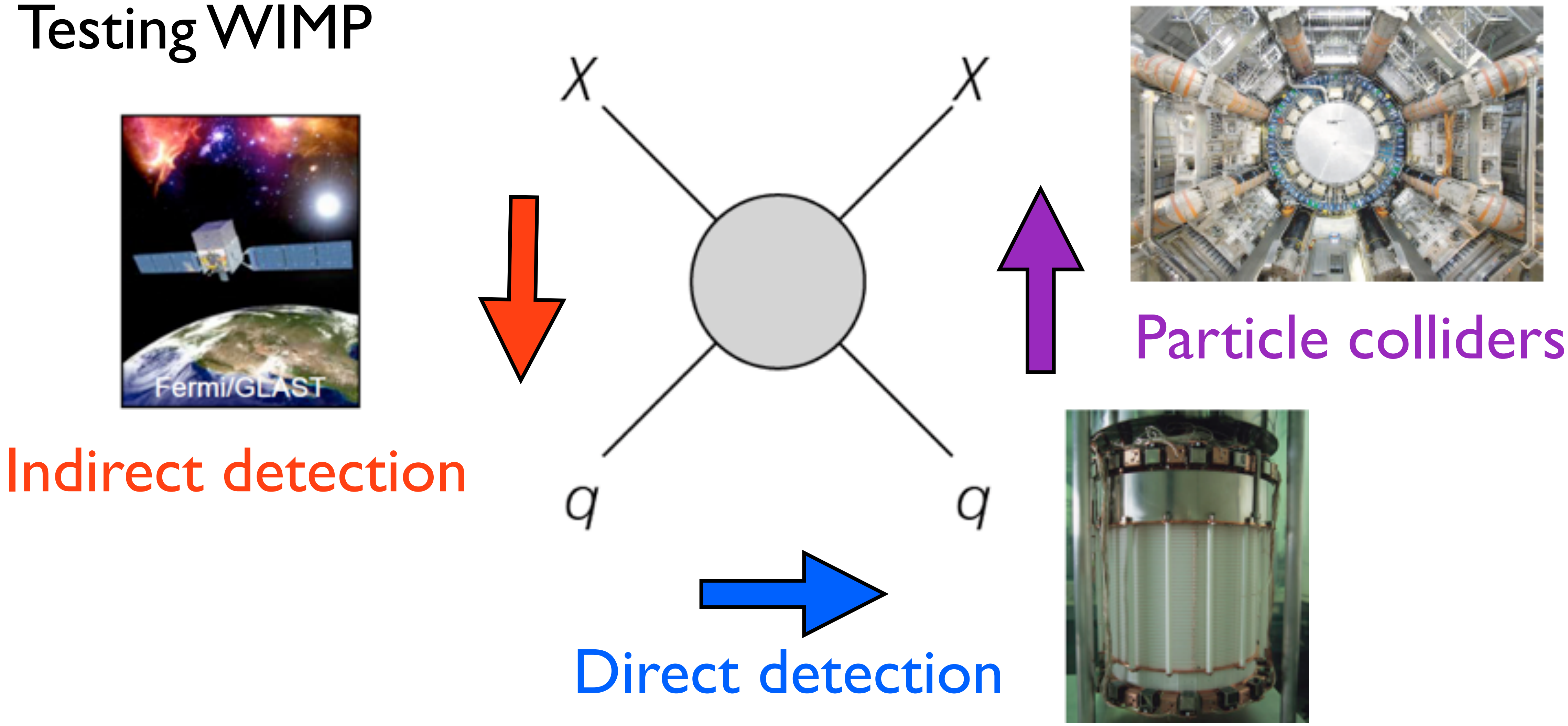
WIMP dark matter

- WIMP(Weakly Interacting Massive Particle) explains matter energy density by "thermal freezeout":

$$\Omega_X h^2 = 0.1 \cdot (3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1} / \langle \sigma v \rangle)$$

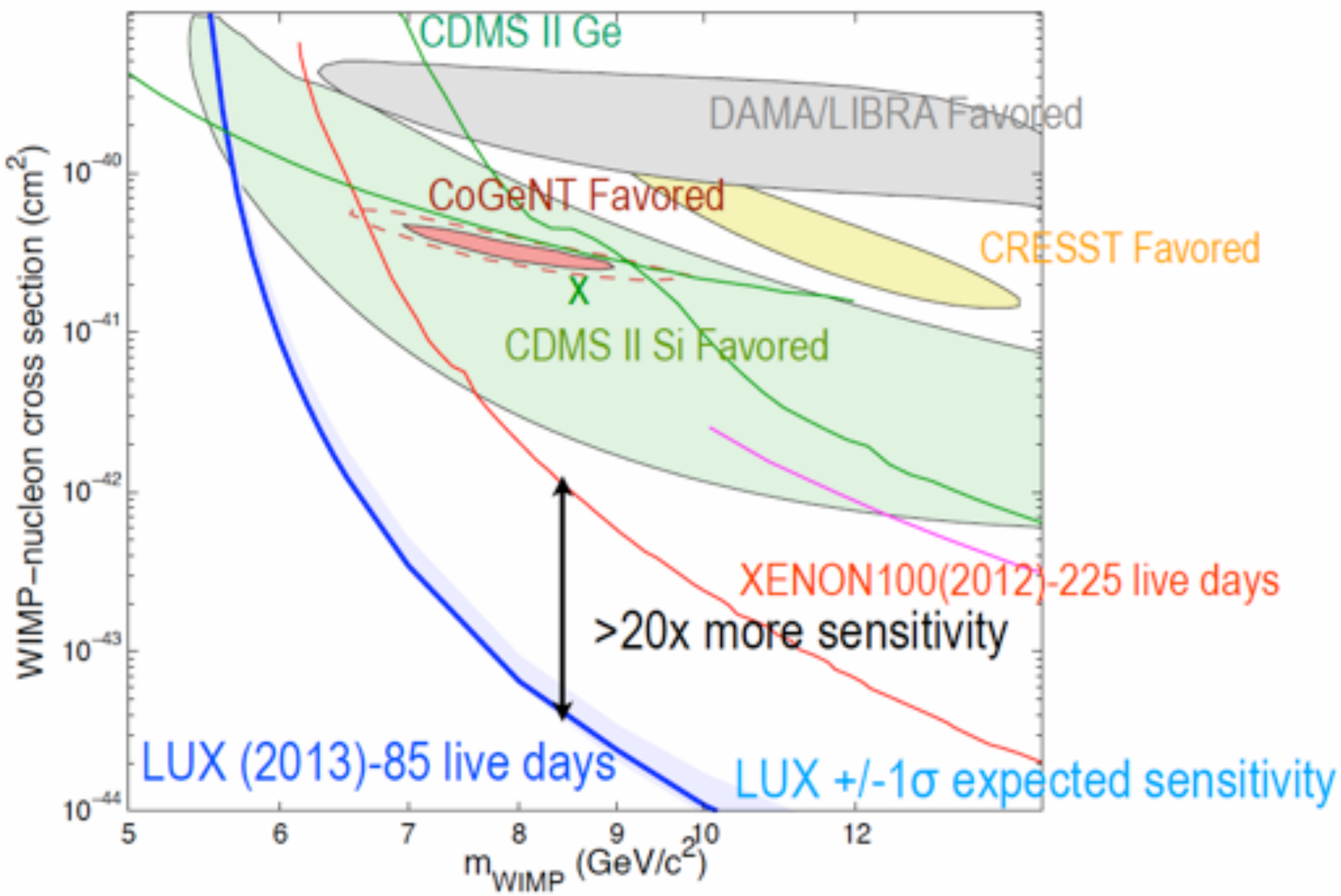


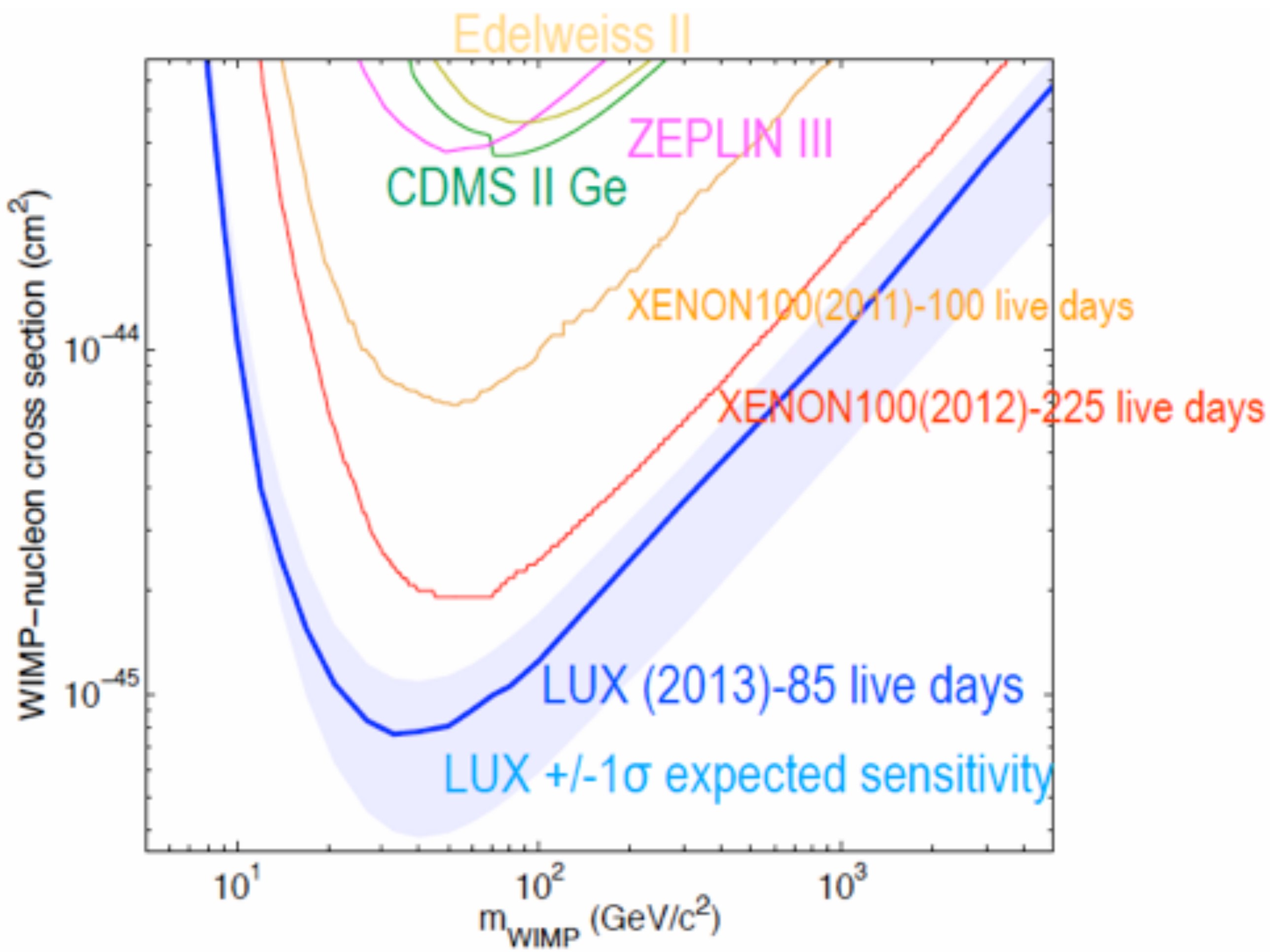
- Testing WIMP



Direct detection

- Light dark matter signals @~10GeV: DAMA/LIBRA, CoGeNT, CRESST-II, CDMSII-Si.
- Strong limits from XENON-10, XENON-100, LUX.

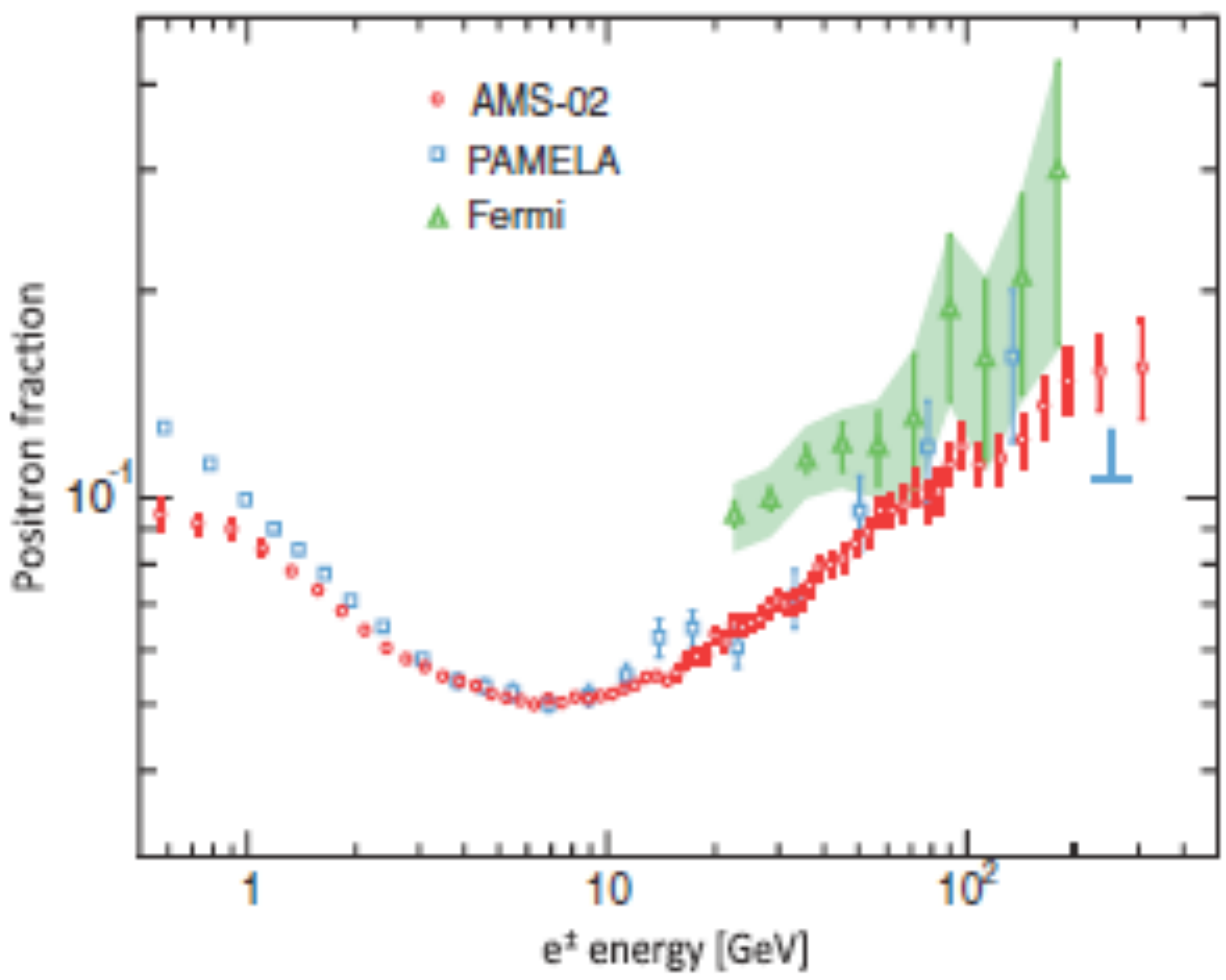


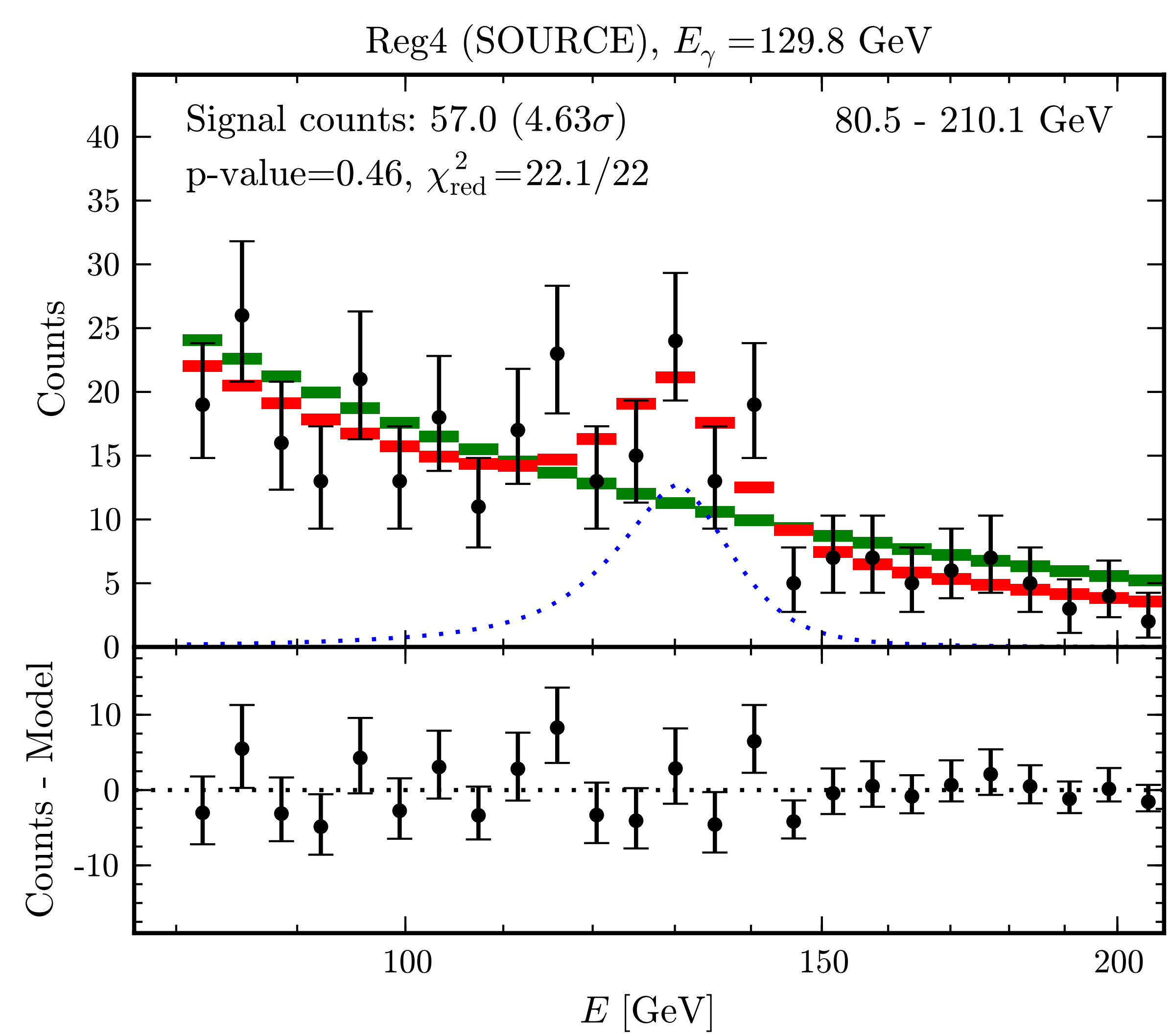


Best: $\sigma_{X-N} < 7.6 \times 10^{-46}\,\mathrm{cm}^2$ @ $33\,\mathrm{GeV}$.

Indirect detection

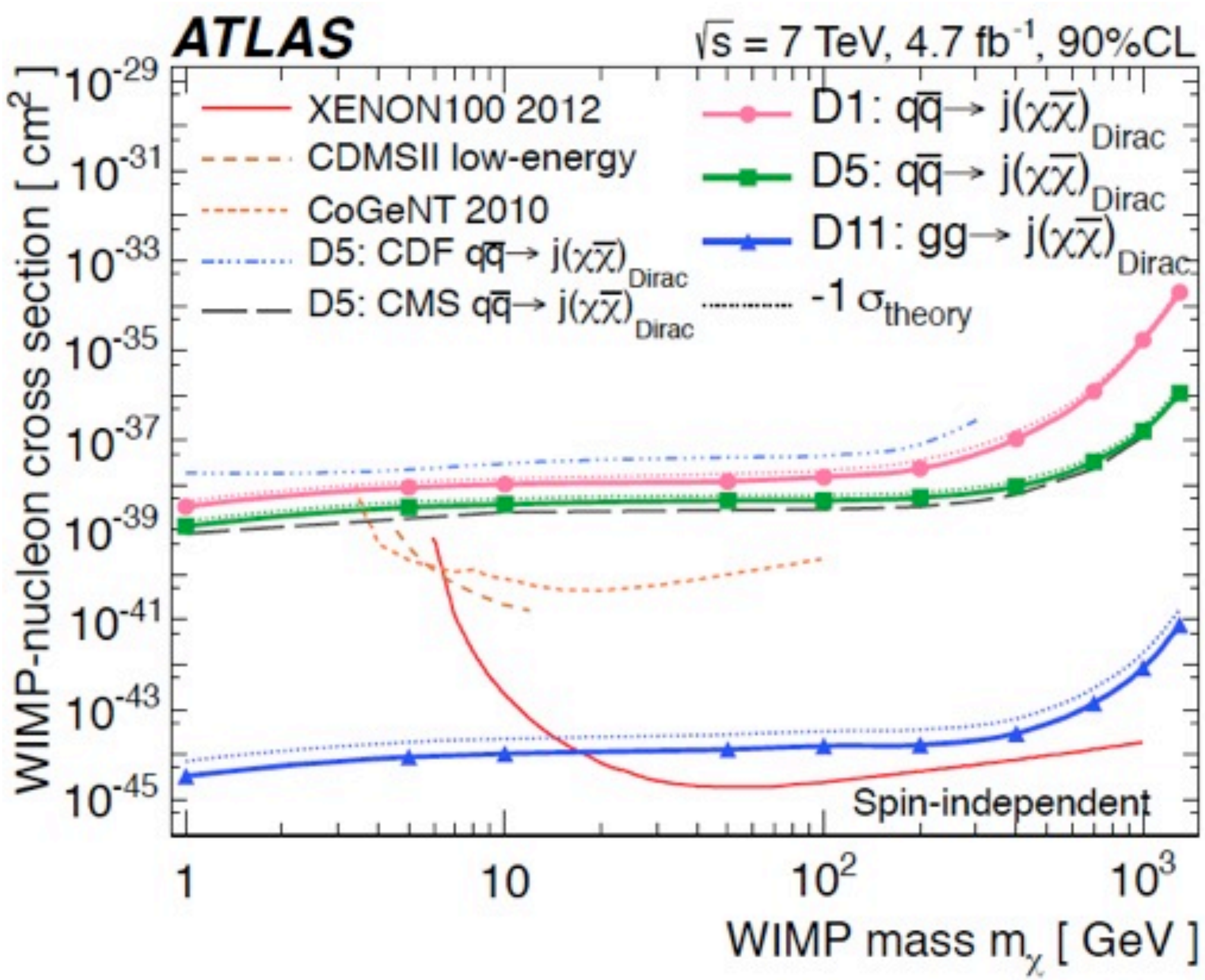
- Excesses in cosmic rays from AMS-02, PAMELA, Fermi-LAT, etc. may be due to DM annihilation or decay.
- But, there are also strong bounds from Fermi-LAT, HESS.

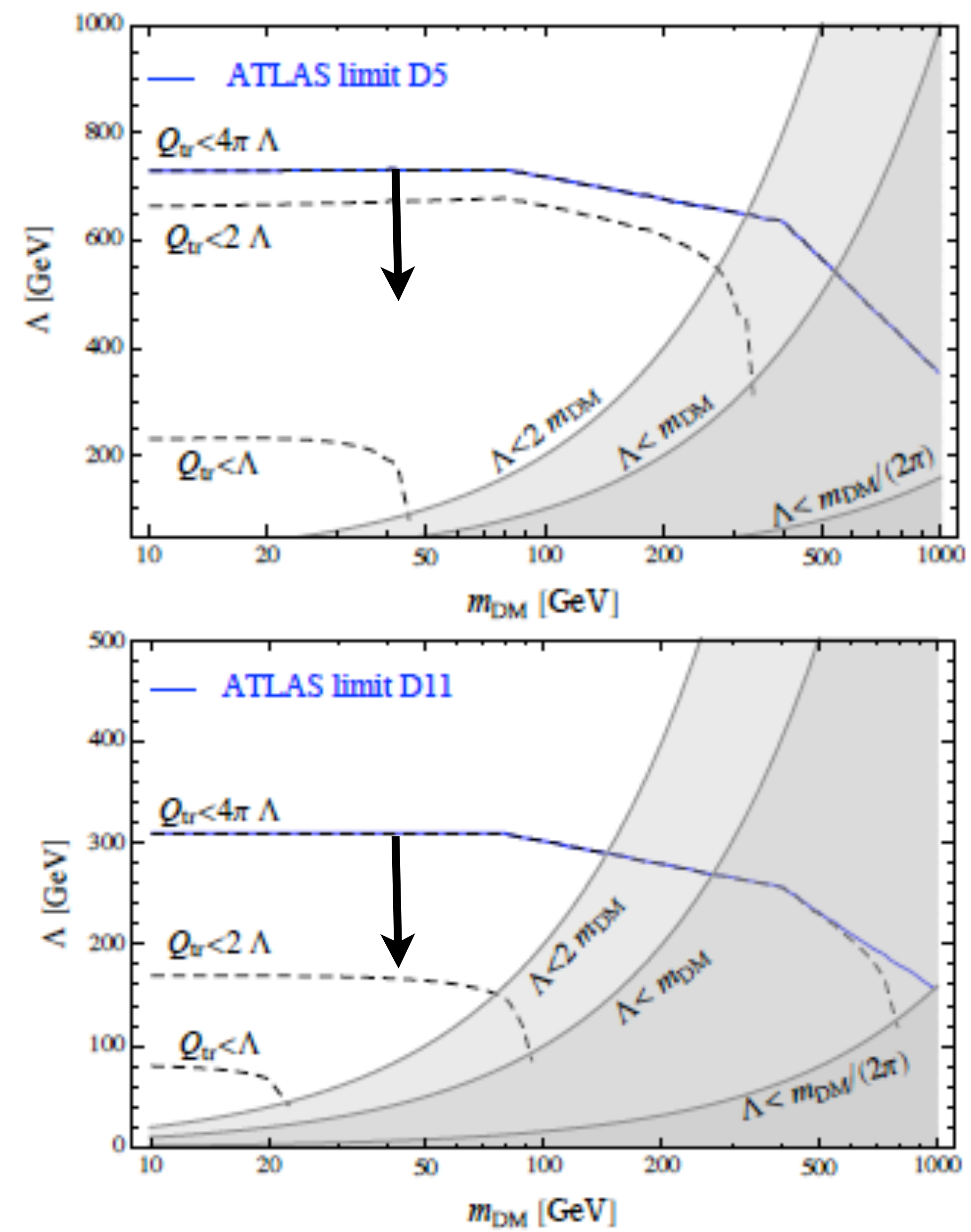




EFT for DM at colliders

- Dark mater produced in pair: monojet + MET





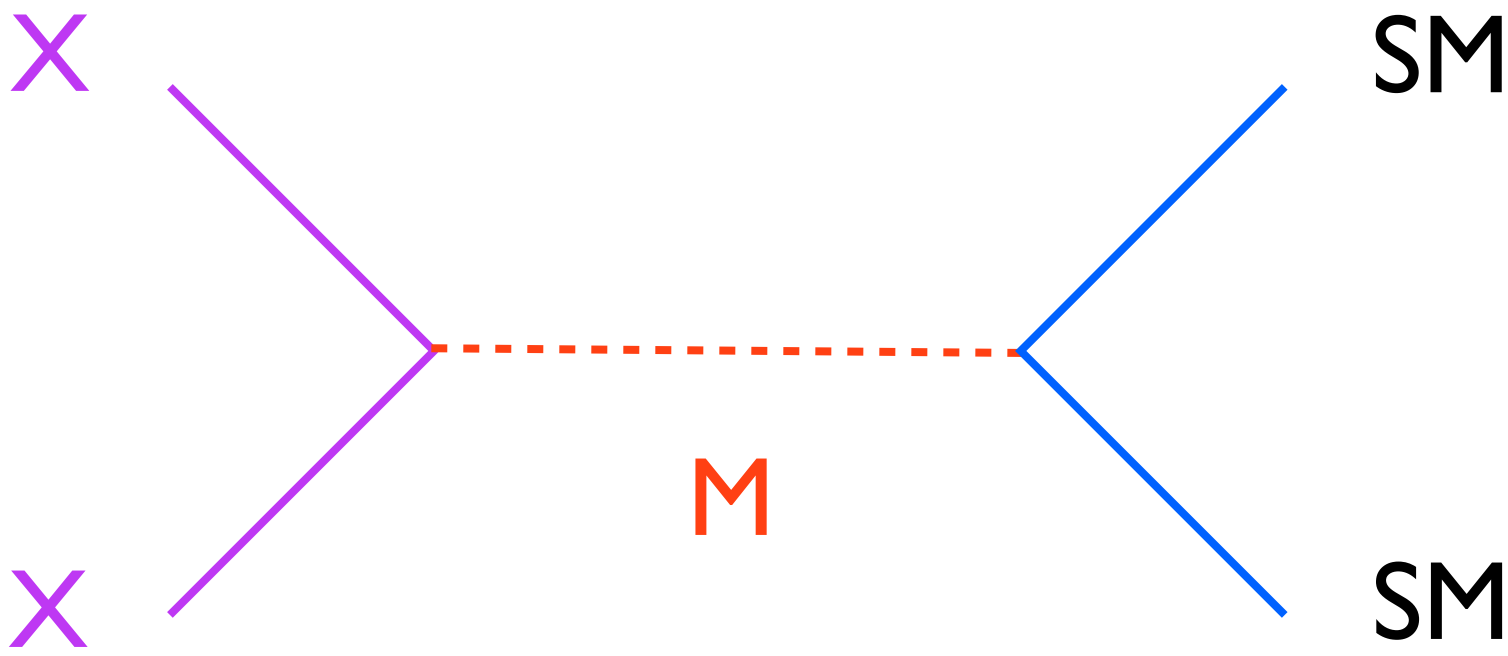
Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_*^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_*^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_*^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

EFT can break down at colliders.

[Busoni et al, 1402.1275]

Beyond EFT-DM

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



- Neutral mediator couples to SM particles, e.g. through Higgs, axion, and/or Z'portals.

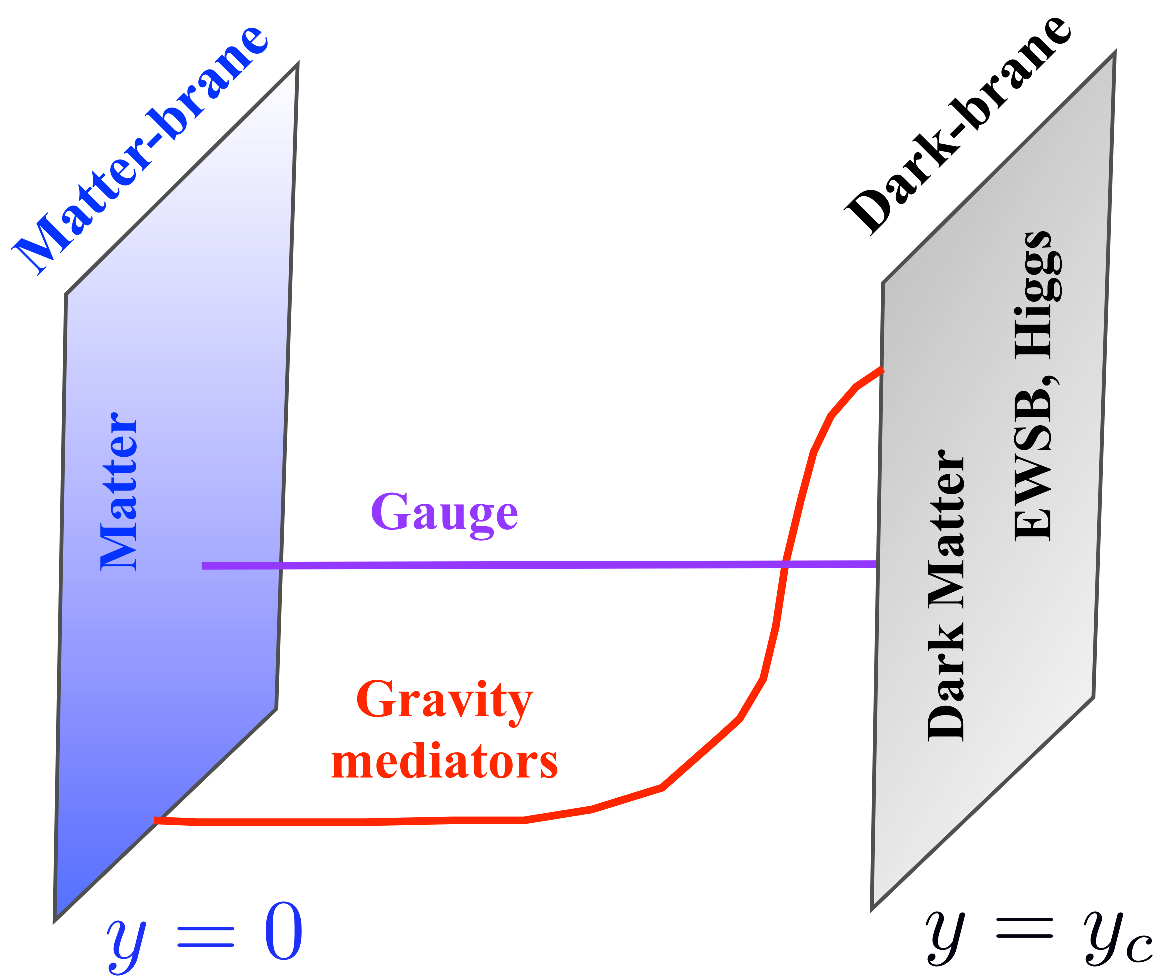
[HML, M.Park, W. Park(2012); HML, M.Park, V. Sanz (2012,2013)]

cf. mediator can be charged, e.g. sleptons, squarks.

Gravity-mediated DM

Bulk-RS model (A)

- Warp factor explains electroweak scale of Higgs sector.
- Flavor problem and proton stability requires SM fermions localized on UV brane. ⟶ Flavor hierarchy
- Dark matter is localized on the IR brane too.



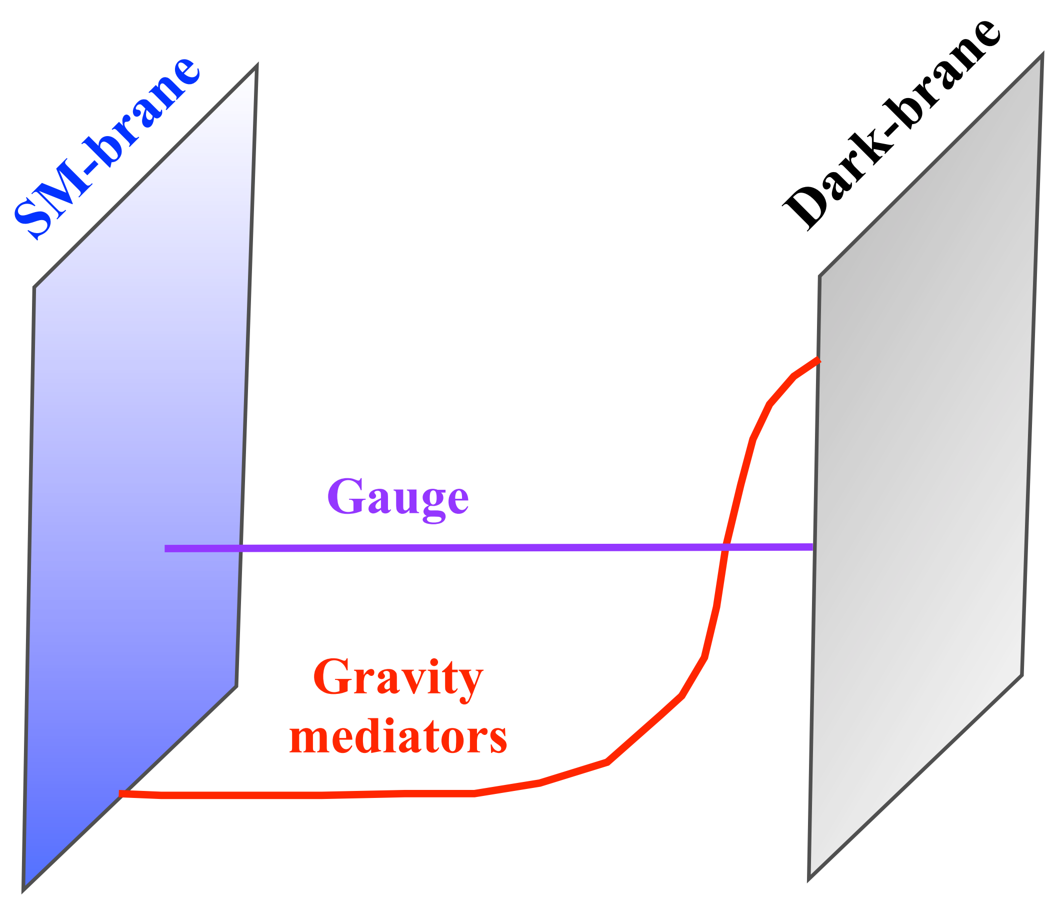
$$ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$

$$M_P^2 = \frac{M^3}{k}(1 - e^{-2ky_c}),$$

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

Dark-brane model (B)

- Warp factor explains WIMP dark matter only; SM Higgs/fermions are localized on the UV brane.
- Gauge bosons live in bulk so couple to the KK graviton with sizable strength.

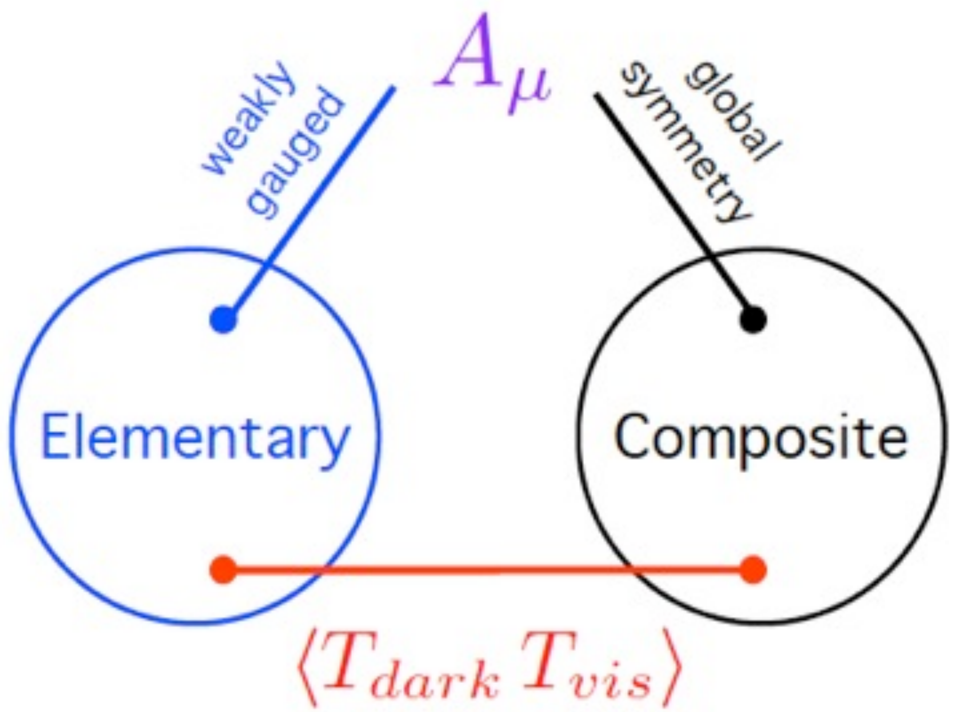


$$\frac{m_X}{M_P} \sim e^{-ky_c} \ll 1.$$

Higgs/fermions to KK graviton vanishes.

→ DM annihilates into transverse gauge bosons.

Holographic dual



AdS

- radion
- KK-graviton
- Matter-brane
- Dark-brane

↔

CFT

- dilaton — dilatation symmetry
- spin-2 resonance — CFT diffeomorphism
- "elementary"
- "composite"

DM: composite state, Z_2 from global symmetry.

KK graviton mediator

- KK graviton and/or radion is the DM mediator.

mass: $m_G = \frac{k}{M_P} x_G \Lambda$ $\quad (\Lambda = e^{-k y_c} M_P,$

$x_G = 3.83$: first zero of $J_1(x_G)$.)

$k \lesssim M_P \;\Rightarrow\; m_G \lesssim 3.83\,\Lambda.$

- KK graviton couplings depend on localization.

$$\mathcal{L}_{\rm KK} = -\frac{c_i^G}{\Lambda} G_{\mu\nu} T_i^{\mu\nu} + \frac{c_i^r}{\sqrt{6}\Lambda} r\, T_i$$

Dark-brane fields : $c_X^G \simeq c_H^G \simeq O(1)$,

Bulk fields : $c_A^G \simeq \frac{1}{\int_{\rm Dark}^{\rm Matter} w(z)\, dz} = (\ln(M_P/{\rm TeV}))^{-1} \simeq 0.03.$

Matter-brane fields : $c_\psi^G = \left(\frac{z_{\rm Matter}}{z_{\rm Dark}}\right)^\alpha$, $\quad \alpha > 1.$ $\quad (z = e^{-ky})$

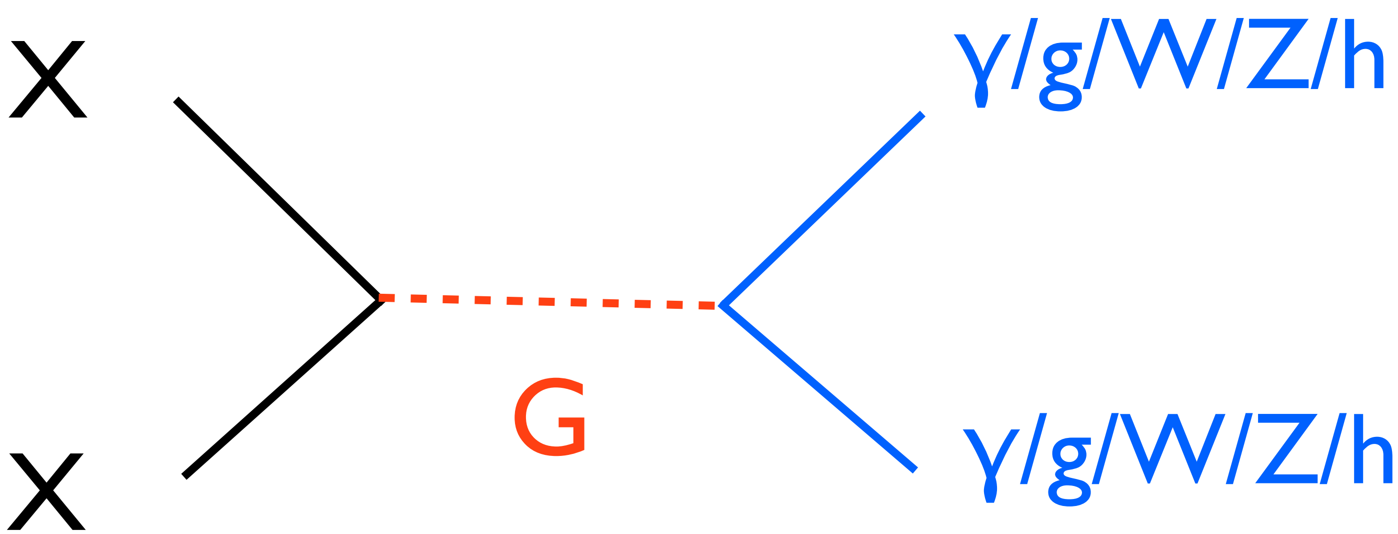
KK graviton couplings

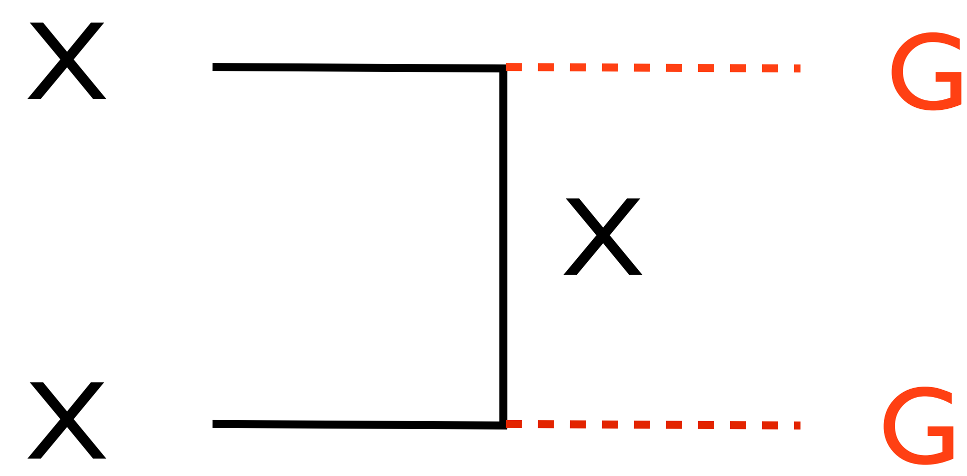
$$\begin{aligned}
\mathcal{L}_{\rm KK} \;=\; & -\frac{1}{\Lambda}G^{\mu\nu}\Big[T^{\rm DM}_{\mu\nu} + c^G_\psi\Big(\frac{i}{4}\bar\psi(\gamma_\mu D_\nu + \gamma_\nu D_\mu)\psi - \frac{i}{4}(D_\mu\bar\psi\gamma_\nu + D_\nu\bar\psi\gamma_\nu)\psi \\
& -g_{\mu\nu}(\bar\psi\gamma^\mu D_\mu\psi - m_\psi\bar\psi\psi) + \frac{i}{2}g_{\mu\nu}\partial^\rho(\bar\psi\gamma_\rho\psi)\Big) \\
& +c^G_V\left(\frac{1}{4}g_{\mu\nu}F^{\lambda\rho}F_{\lambda\rho} - F_{\mu\lambda}F^\lambda{}_\nu\right) \\
& +c^G_H\Big(-g_{\mu\nu}D^\rho H^\dagger D_\rho H + g_{\mu\nu}V(H) + D_\mu H^\dagger D_\nu H + D_\nu H^\dagger D_\mu H\Big)\Big]
\end{aligned}$$

$$\begin{aligned}
T^{(\rm Vector\ DM)}_{\mu\nu} &= \frac{1}{4}g_{\mu\nu}X^{\lambda\rho}X_{\lambda\rho} - X_{\mu\lambda}X^\lambda{}_\nu + m_X^2\Big(X_\mu X_\nu - \frac{1}{2}g_{\mu\nu}X^\lambda X_\lambda\Big), \\
T^{(\rm Fermion\ DM)}_{\mu\nu} &= \frac{i}{4}\bar\chi(\gamma_\mu\partial_\nu + \gamma_\nu\partial_\mu)\chi - \frac{i}{4}(\partial_\mu\bar\chi\gamma_\nu + \partial_\nu\bar\chi\gamma_\nu)\chi - g_{\mu\nu}(i\bar\chi\gamma^\mu\partial_\mu\chi - m_\chi\bar\chi\chi) \\
&\quad + \frac{i}{2}g_{\mu\nu}\partial^\rho(\bar\chi\gamma_\rho\chi), \\
T^{(\rm Scalar\ DM)}_{\mu\nu} &= \partial_\mu S\partial_\nu S - \frac{1}{2}g_{\mu\nu}\partial^\rho S\partial_\rho S + \frac{1}{2}g_{\mu\nu}m_S^2S^2.
\end{aligned}$$

Gravity-mediation

- KK graviton / radion exchanges lead to annihilations of dark matter into the SM particles.





- Spin-dependent suppression of DM annihilation cross sections.

Mediator	X (s=0)	X (s=1/2)	X (s=1)
Graviton	s-wave	p-wave	s-wave
Radion	s-wave	p-wave	s-wave

$m_X \gg m_\phi, m_G$, and $c_H \gg c_V$

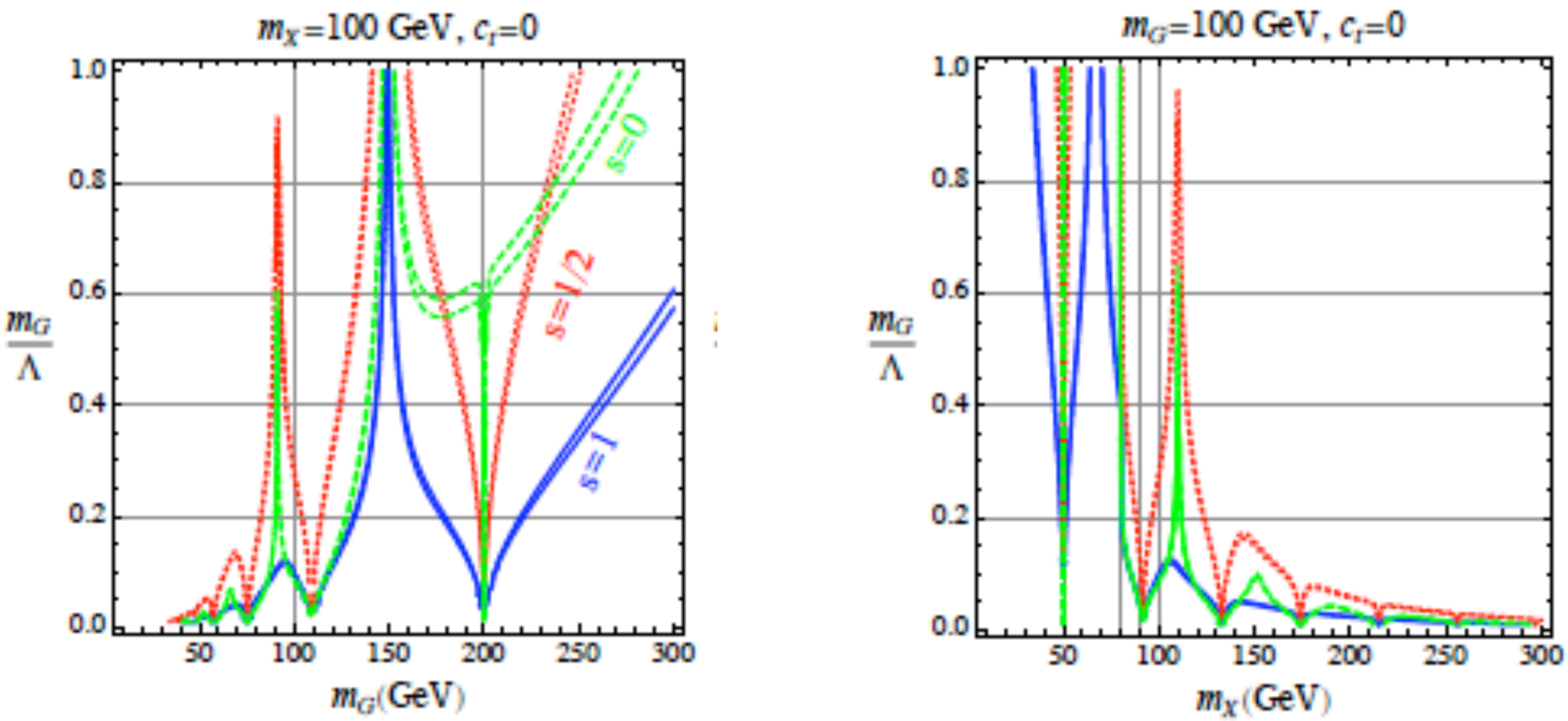
$$(\sigma v)_{SS\to\phi\phi} \simeq \frac{3(c_S^G c_H^G)^2}{16\pi}\frac{m_S^2}{\Lambda^4}\left(\frac{m_Z^4}{m_G^4} + 2\frac{m_W^4}{m_G^4}\right),$$

$$(\sigma v)_{\chi\bar{\chi}\to\phi\phi} \simeq \frac{(c_\chi^G c_H^G)^2 v^2}{576\pi}\frac{m_\chi^2}{\Lambda^4},$$

$$(\sigma v)_{XX\to\phi\phi} \simeq \frac{(c_X^G c_H^G)^2}{54\pi}\frac{m_X^2}{\Lambda^4}.$$

DM relic density

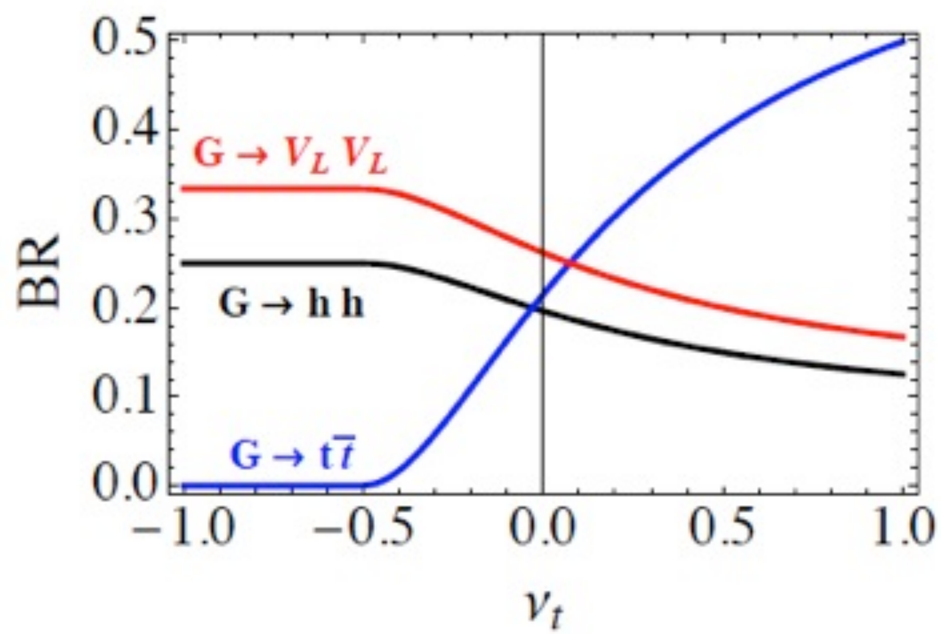
- s-channel dominance: KK graviton couplings should be large, except "vector DM".
- t-channel dominance: KK graviton couplings can be small for all spins of DM.



$$c_X = 1,\ c_H = 1,\ c_V = 0.03 \text{ and } c_f = 0$$

Effects of top localization

- Graviton BR depends on top localization.

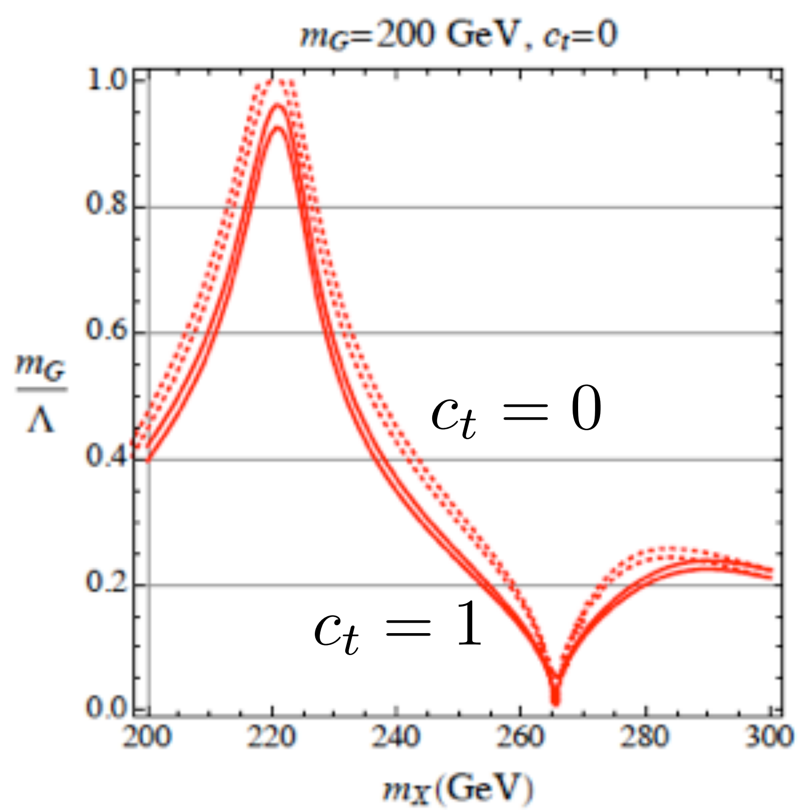


$$\mathcal{L}_{5D} \supset M_t\,\mathrm{sgn}(y)\bar{t}t, \quad M_t = k\nu_t$$

$$f_t(y) \sim e^{-(\nu_t - \frac{1}{2})ky};$$

$$c_t^G \sim f_t(y_c).$$

- Effect of tt channel is sizable only for large DM masses.



$$(\sigma v)_{SS\to t\bar{t}} \simeq \frac{(c_S^G c_t^G)^2 v^4}{1920\pi\Lambda^4} m_S^2,$$

$$(\sigma v)_{X\bar{X}\to t\bar{t}} \simeq \frac{(c_X^G c_t^G)^2 v^2}{384\pi\Lambda^4} m_X^2, \qquad m_X \gg m_t, m_G.$$

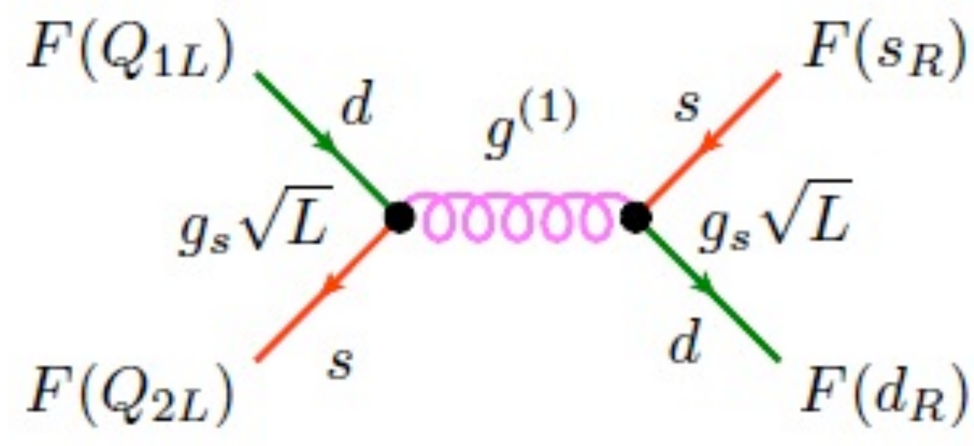
$$(\sigma v)_{XX\to t\bar{t}} \simeq \frac{(c_X^G c_t^G)^2}{36\pi\Lambda^4} m_X^2,$$

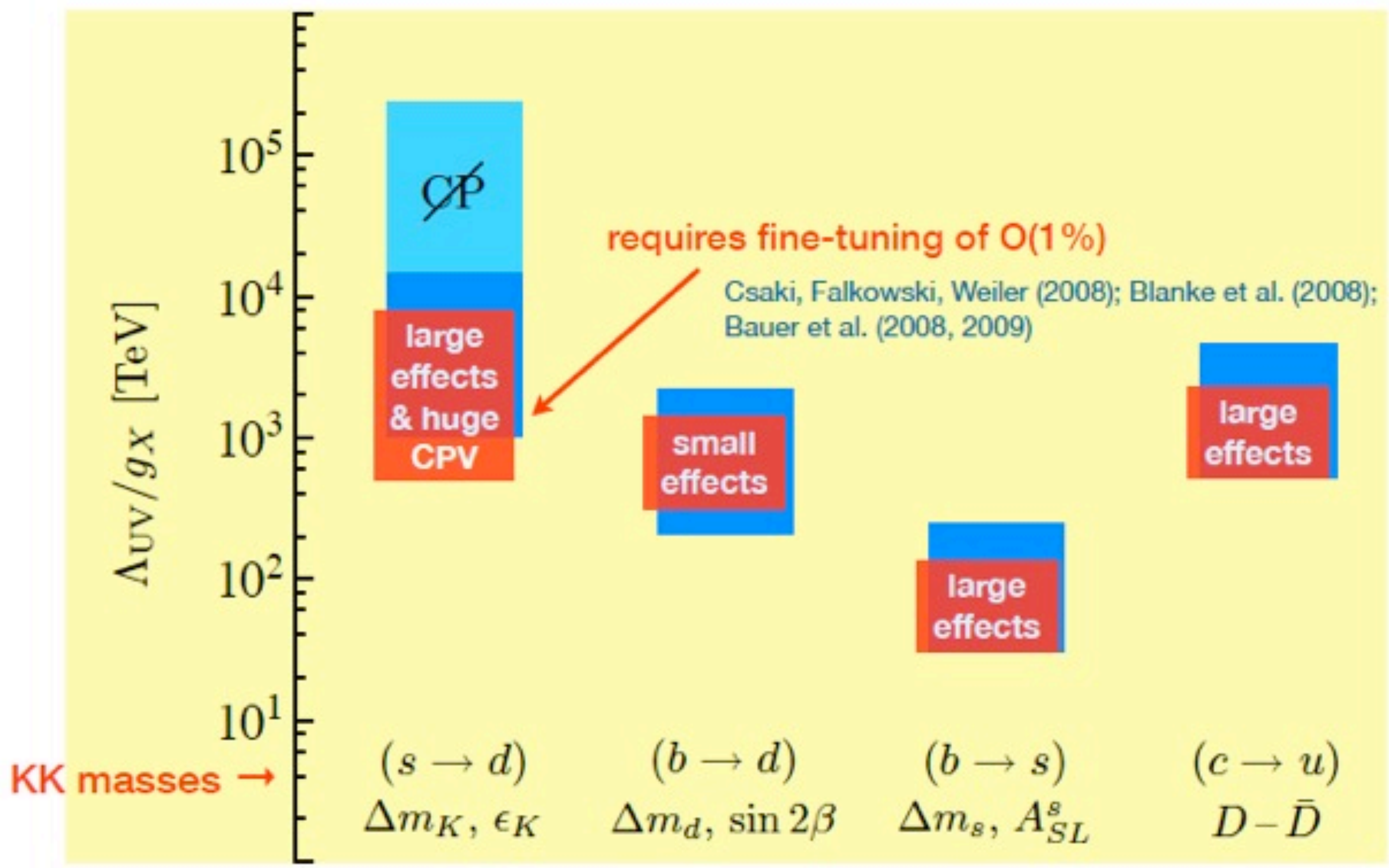
tt channel is sizable
for fermion/vector DM.

Bounds on KK graviton

Flavor bounds

- RS-GIM protects FCNCs caused by KK gauge bosons.





[M. Neubert, plenary talk @SUSY 2012]

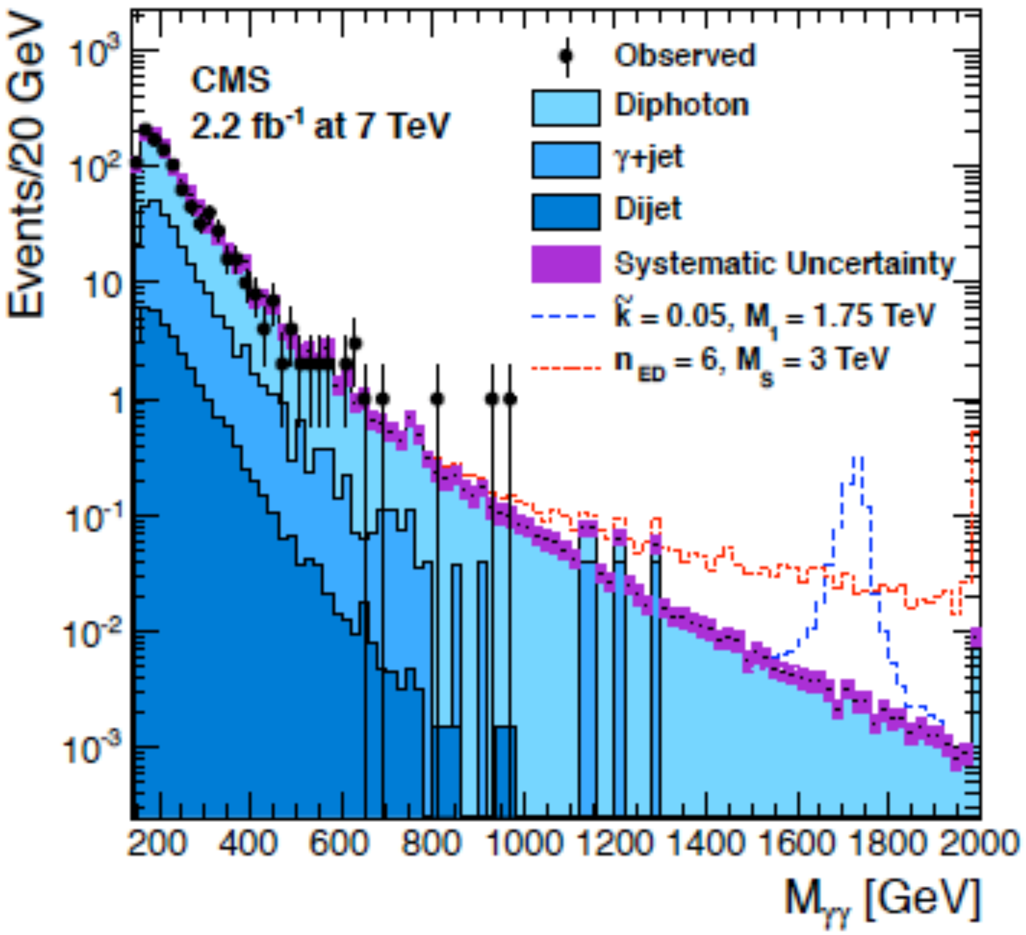
$$m_{g^{(1)}} = \frac{x_g}{x_G} m_G \gtrsim 1\,\text{TeV}$$

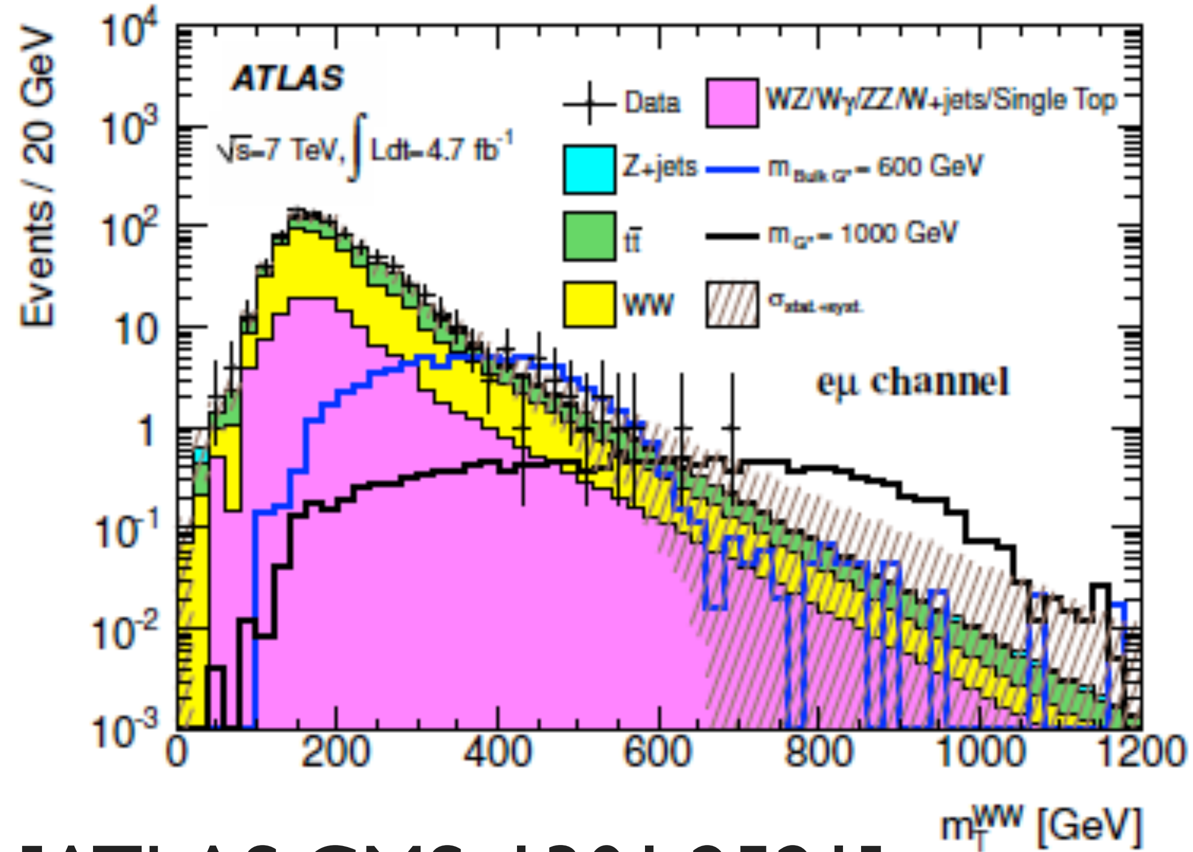
$$x_G = 3.83,\ \ x_g = 2.45.$$

cf. Similar bounds from EWPT.

But, FCNC and EWPT bounds are model-dependent.

LHC bounds





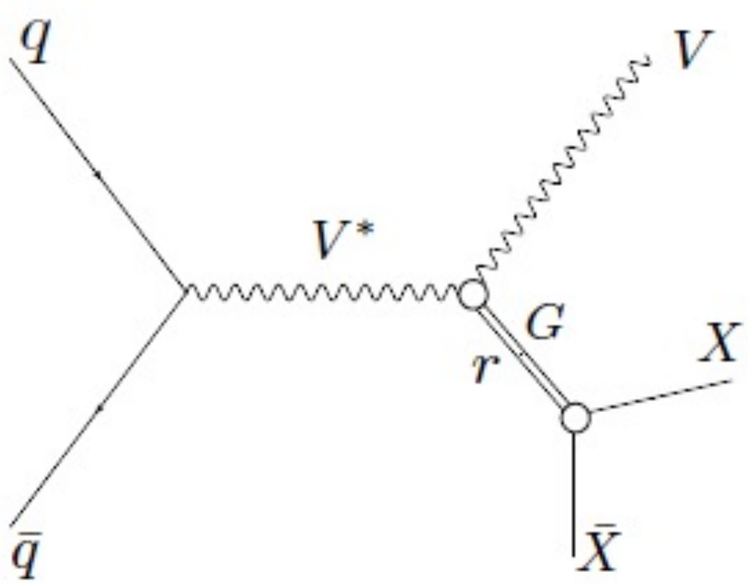
[ATLAS,CMS, 1301.2521]

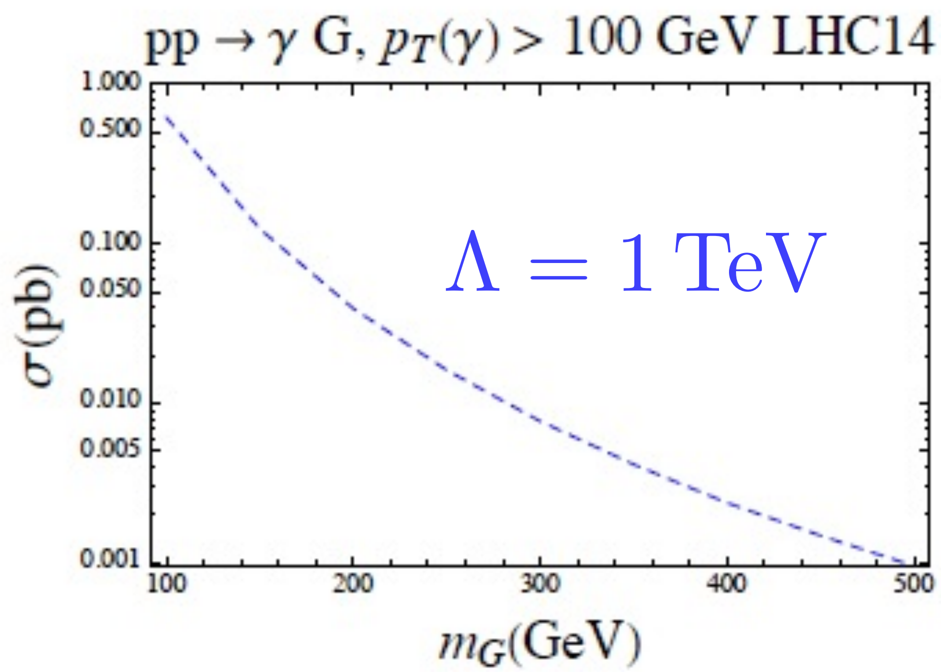
- di-electron, di-muon: $m_G > 0.92(2.16)$ TeV
- di-photon: $m_G > 1(2.06)$ TeV for $\frac{k}{M_P} = 0.01(0.1)$.
- boosted particle from $gg \to G \to WW/ZZ$.
  $m_G > 0.84(1.23)$ TeV for $\frac{k}{M_P} = 0.1(1)$.
- But, such LHC limits can be evaded when SM fermions are localised toward UV brane.

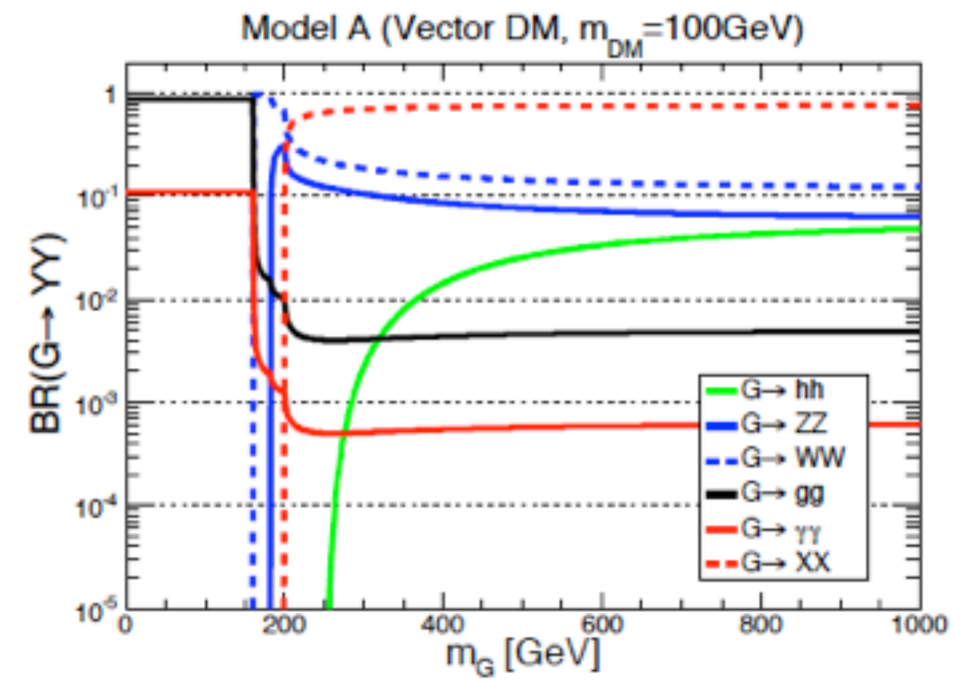
KK graviton production

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

- Associated KK graviton with a gauge boson.







- Missing energy + mono-photon, mono-Z, mono-lepton, etc. [HML, M.Park, V. Sanz (2012)]

- Diphoton resonance for KK graviton produced by gluon fusion is strongest for 110-150 GeV at LHC.

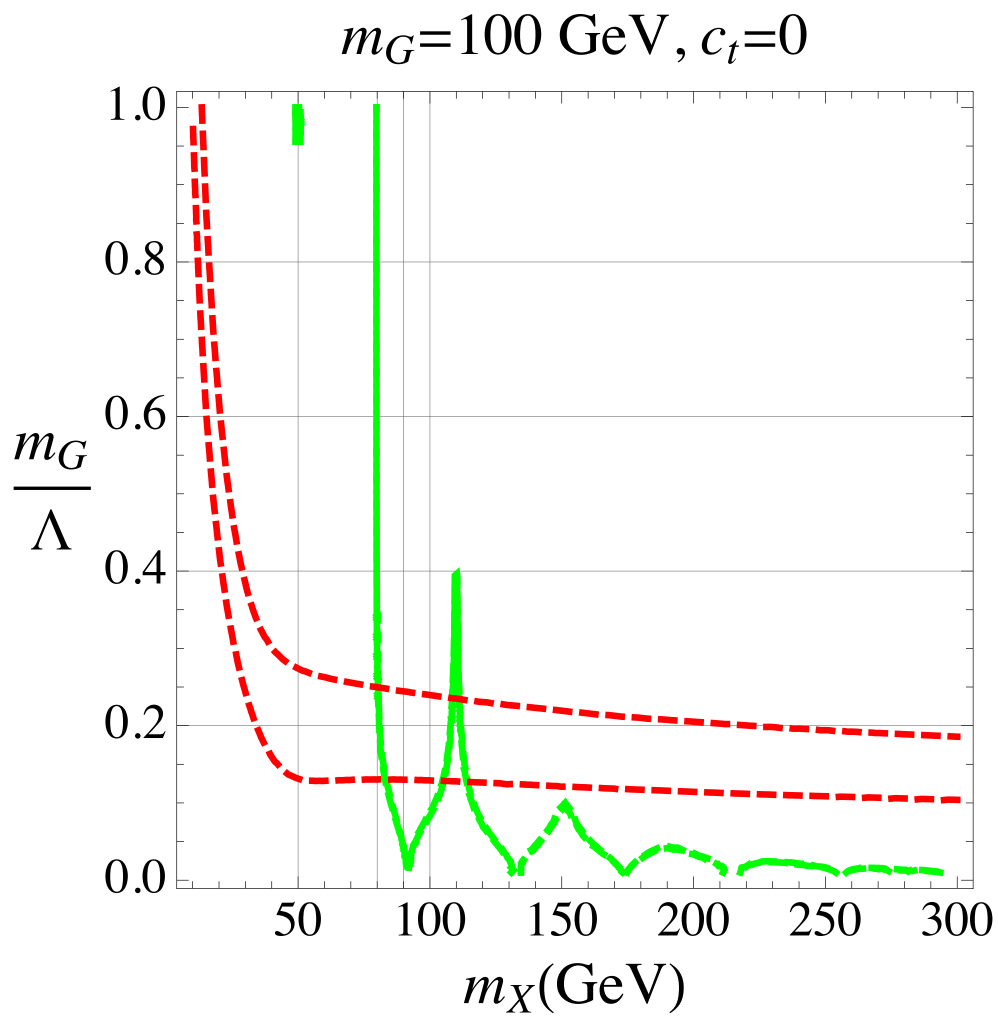
[Jaeckel, Jankowiak, Spannowsky (2012); CMS PAS HIG-13-001]

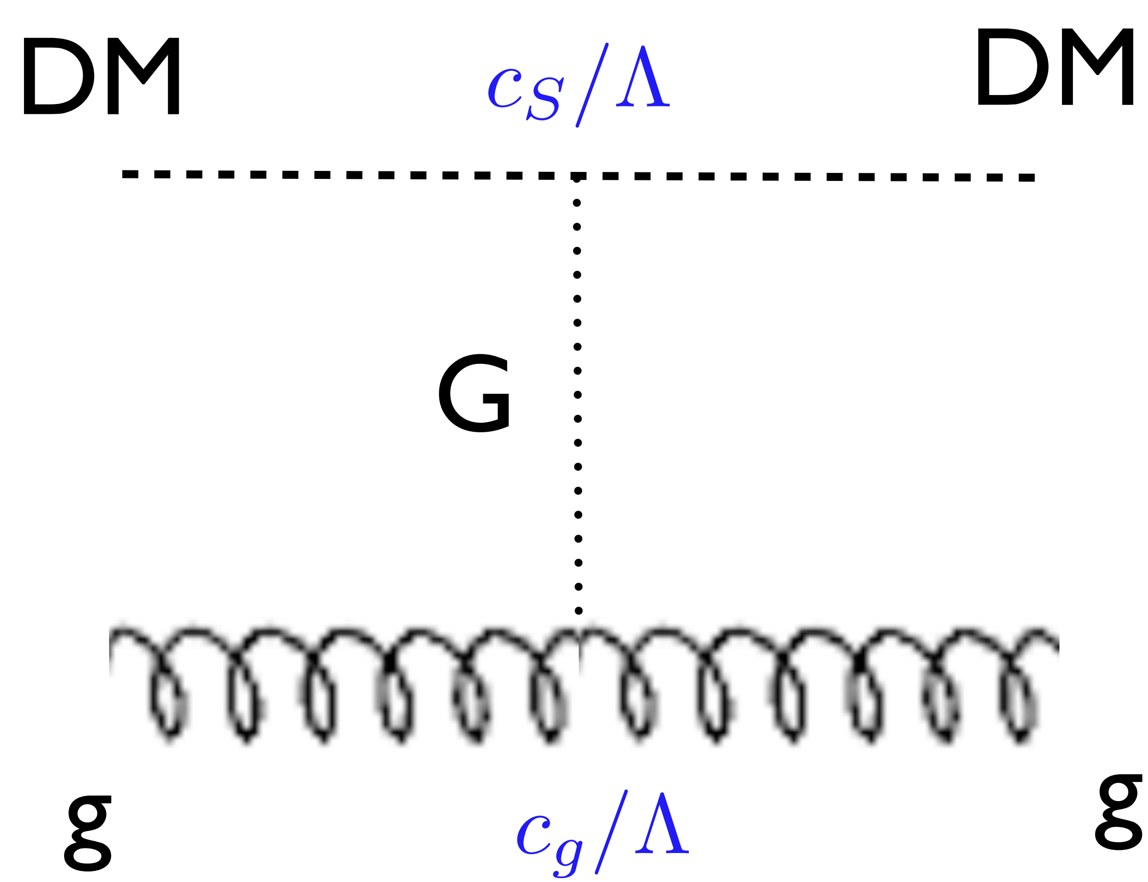
Direct detection

- Graviton coupling to gluons is constrained by LUX.

$$\mathcal{L}_{S-N} = \xi_g S^2 G_{\mu\nu} G^{\mu\nu}, \ \xi_g = \frac{c_S c_g}{6\Lambda^2} \frac{m_S^2}{m_G^2}, \qquad c_S = 1, \quad c_g = 0.03.$$

$$\sigma_{S-N} = \frac{\mu^2}{\pi m_S^2}\left(\frac{8\pi}{9\alpha_S}\right)^2 m_N^2 \xi_g^2 f_{TG}^2, \quad f_{TG} = \frac{1}{m_N}\langle N|\frac{-9\alpha_S}{8\pi} G_{\mu\nu}G^{\mu\nu}|N\rangle$$
$$= 0.472 - 0.952(\text{MILC}).$$

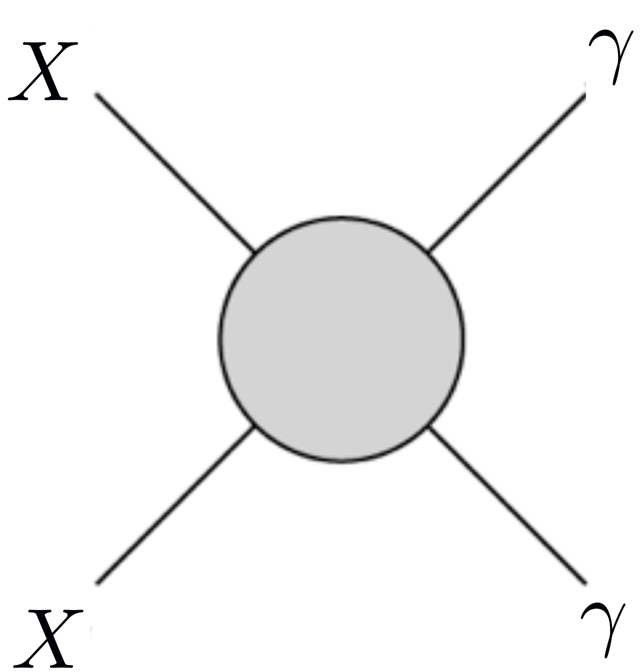


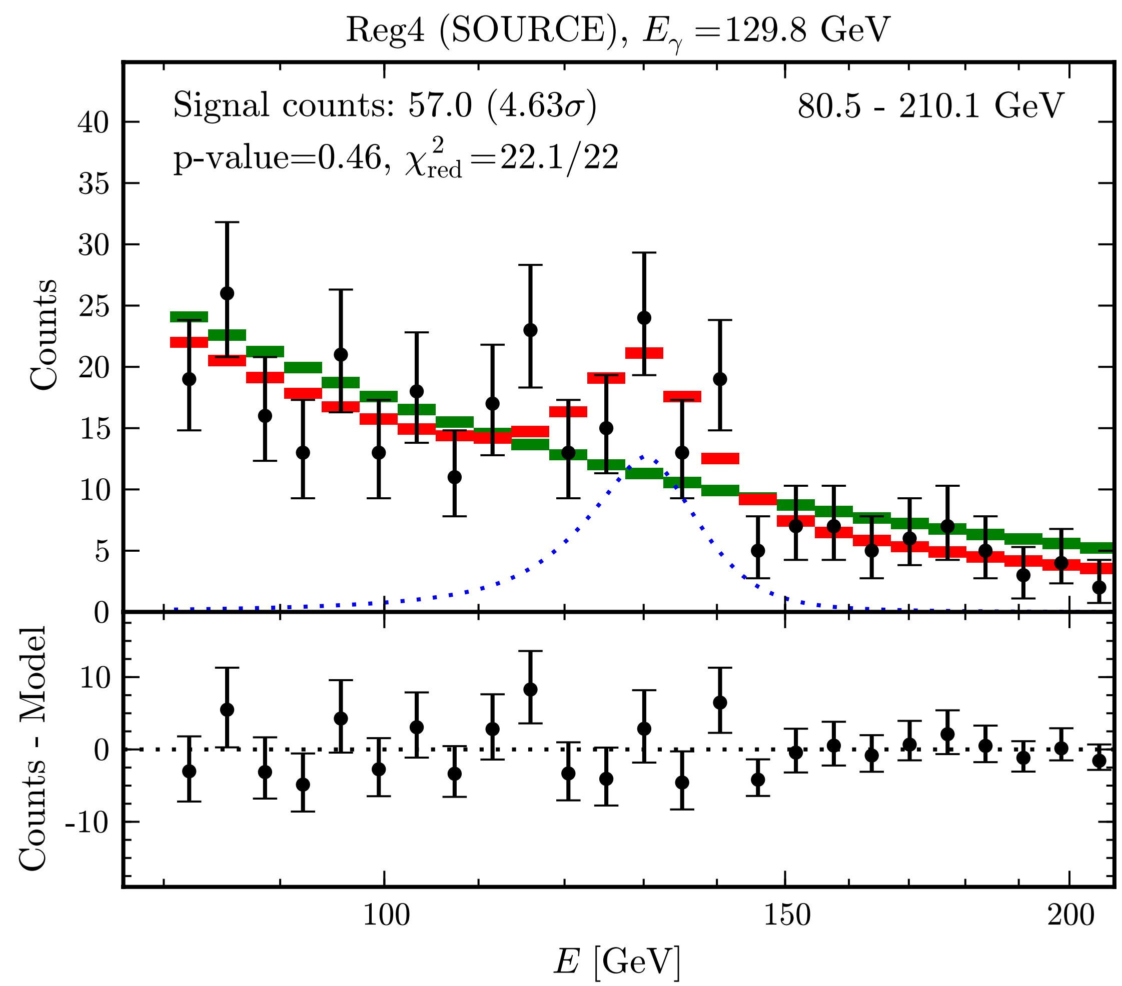


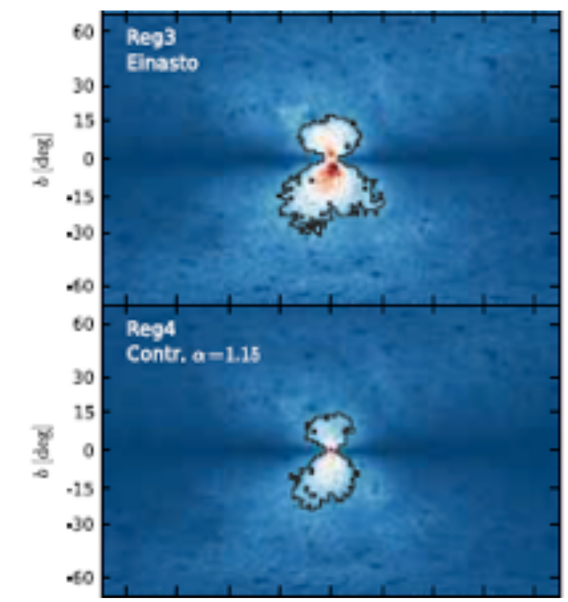
GMDM & gamma-rays

Fermi gamma-ray line

- Gamma-ray line observed from galactic center (3°x3°) in Fermi LAT data. [C. Weniger (2012); Fermi-LAT(2013)]







If the line comes from dark matter annihilation,

$$m_X \approx 130\,\mathrm{GeV},\ \langle\sigma v\rangle_{\gamma\gamma} = 1.3 - 2.3\times 10^{-27}\mathrm{cm}^3/\mathrm{s}\,(4.6\sigma).$$

→ About 10% of thermal cross section.

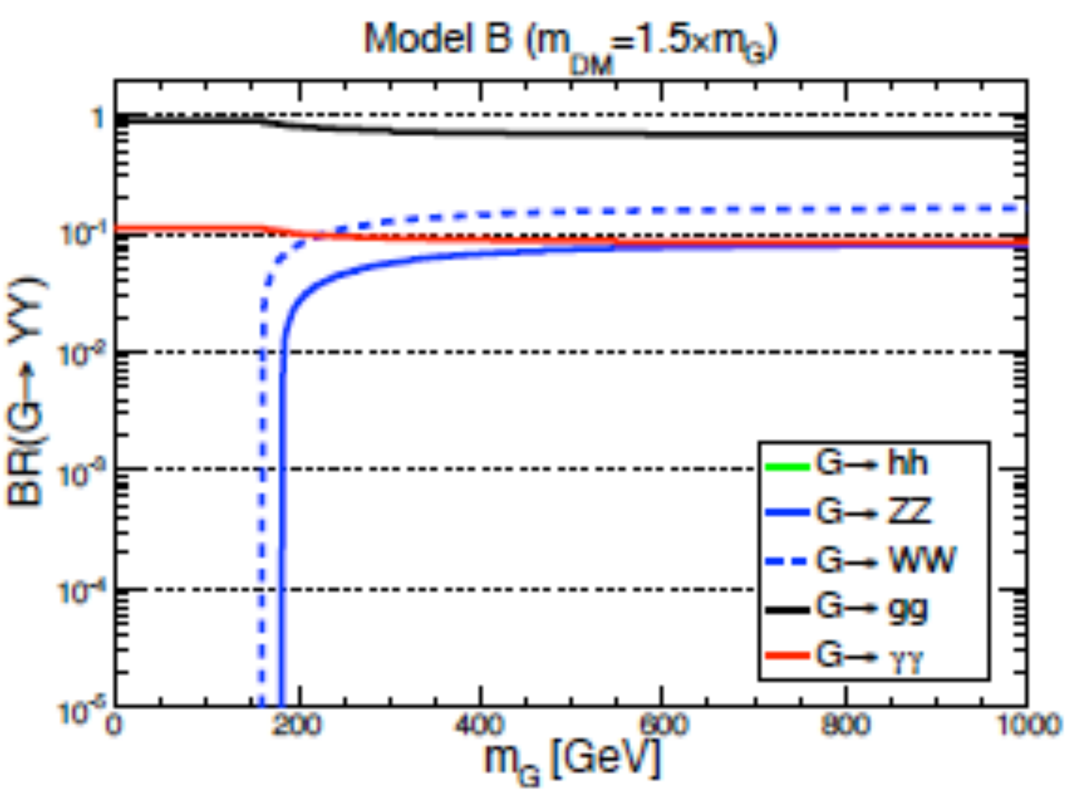
Fermi line from GMDM

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

- For dark brane model, DM annihilates dominantly into a pair of gluons or photons due to

$$\frac{\Gamma_G(\gamma\gamma)}{\Gamma_G(\text{total})} = \frac{(c_B^G)^2}{8(c_g^G)^2 + (c_B^G)^2} = \frac{1}{9} \simeq 0.11.$$

→ **Large DM annihilation into a photon pair.**

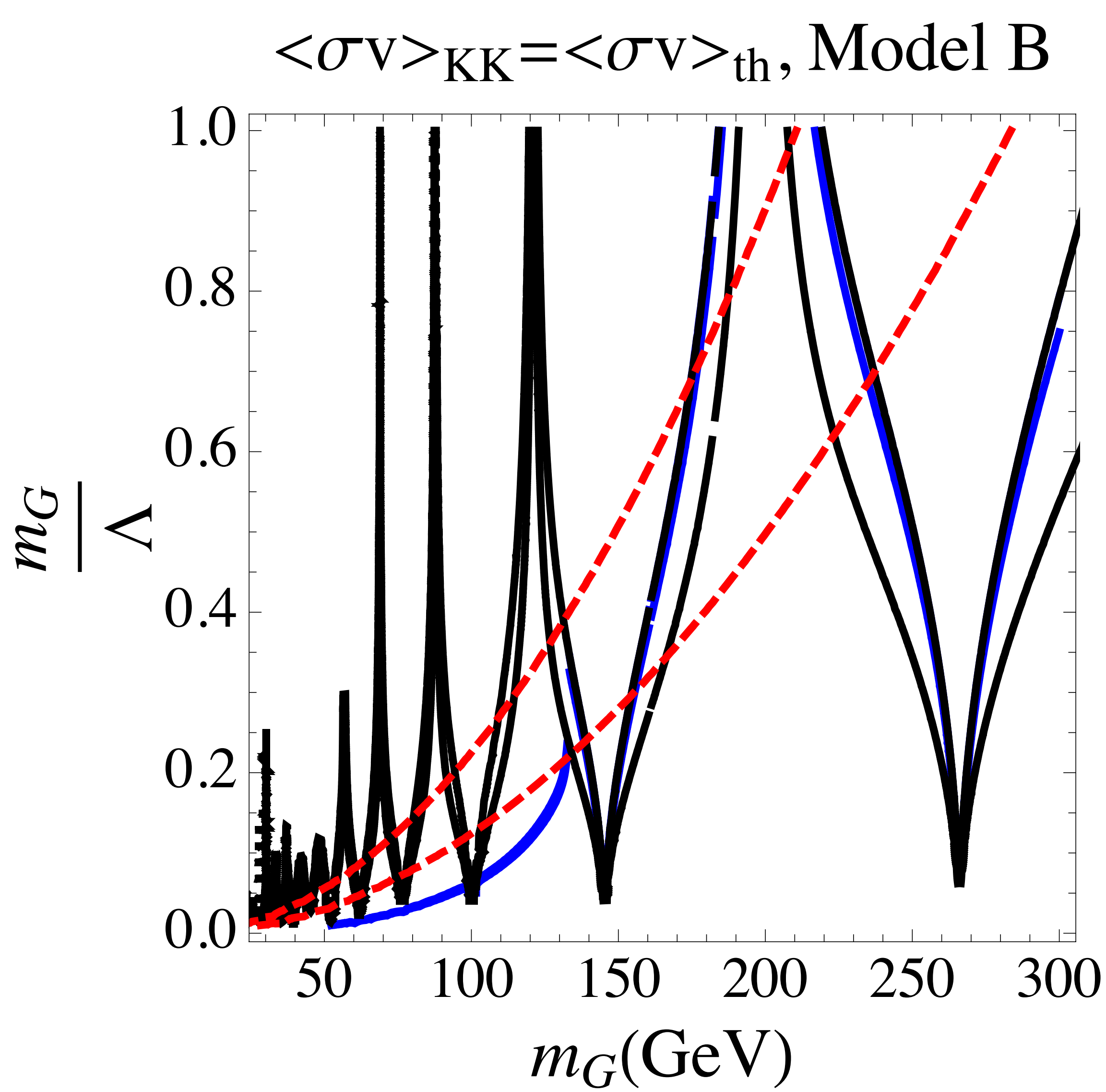


cf. non-gravity mediator:

$$\frac{\Gamma_M(\gamma\gamma)}{\Gamma_M(gg)} \sim (\alpha/\alpha_s)^2 \sim 0.01$$

Fermi line + Planck + LUX

- Vector dark matter only can explain Fermi line.
- Parameter space explaining Fermi line as well as relic density is constrained by direct detection.



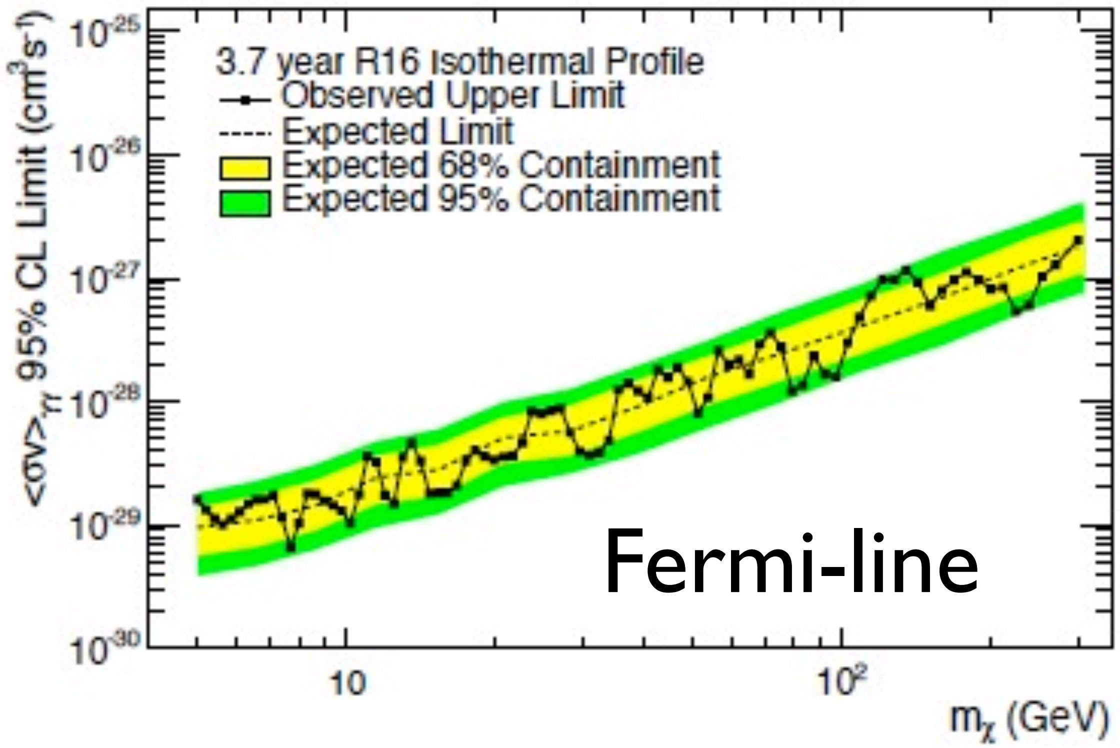
DM mass: $m_S = 133\,\mathrm{GeV}$

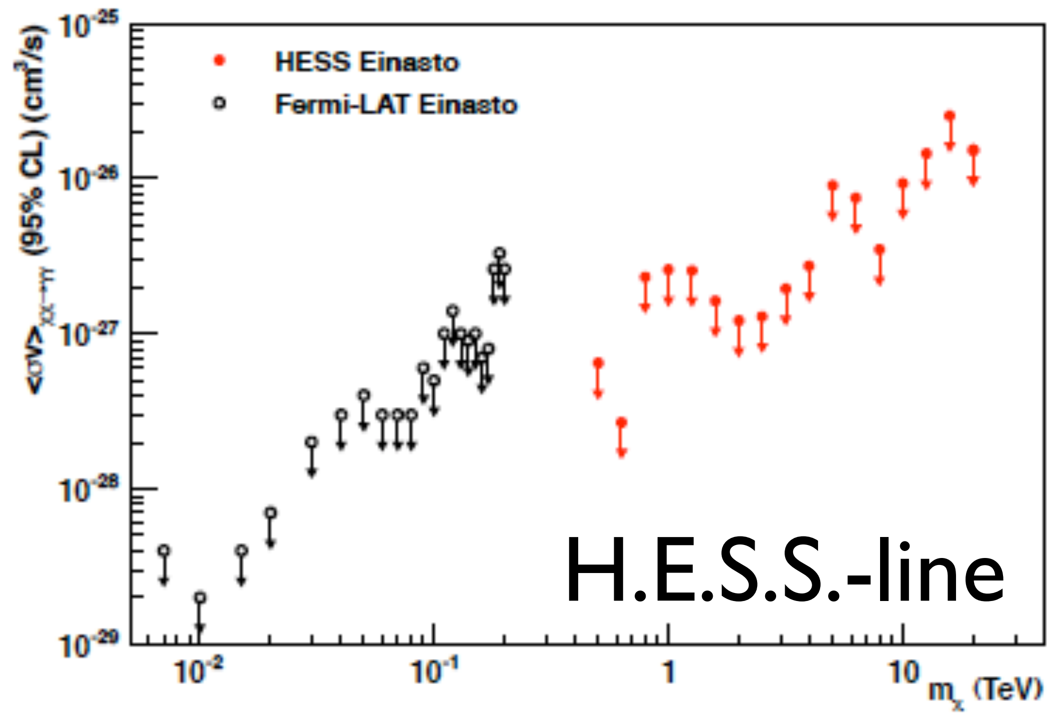
Black: Fermi line

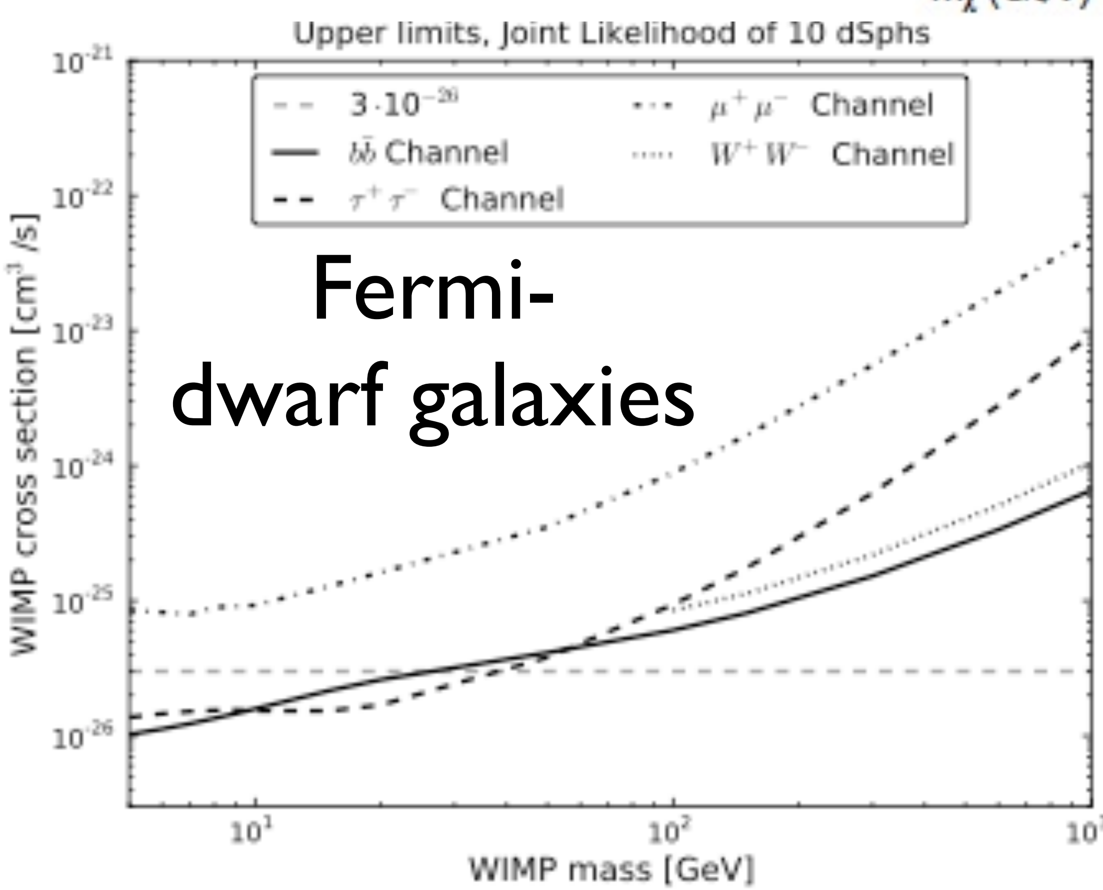
Blue: Planck relic density

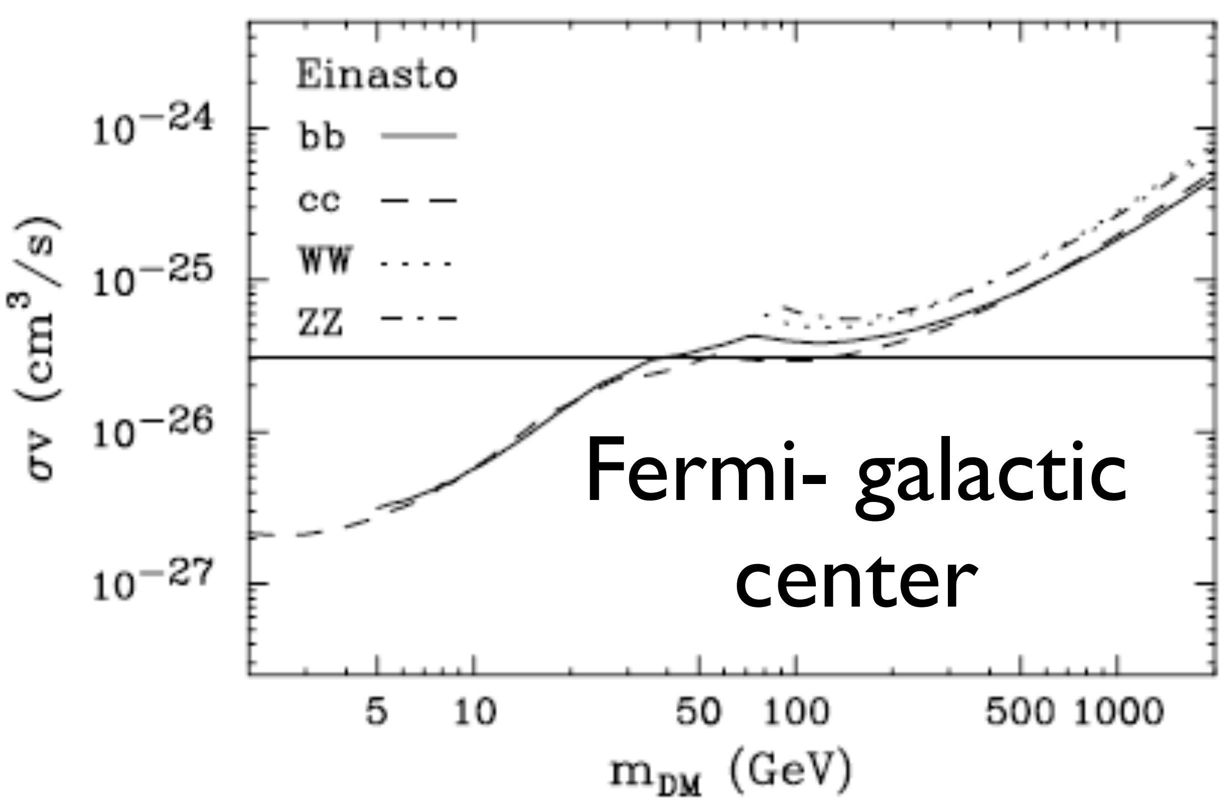
Red: LUX bound

Astrophysical bounds





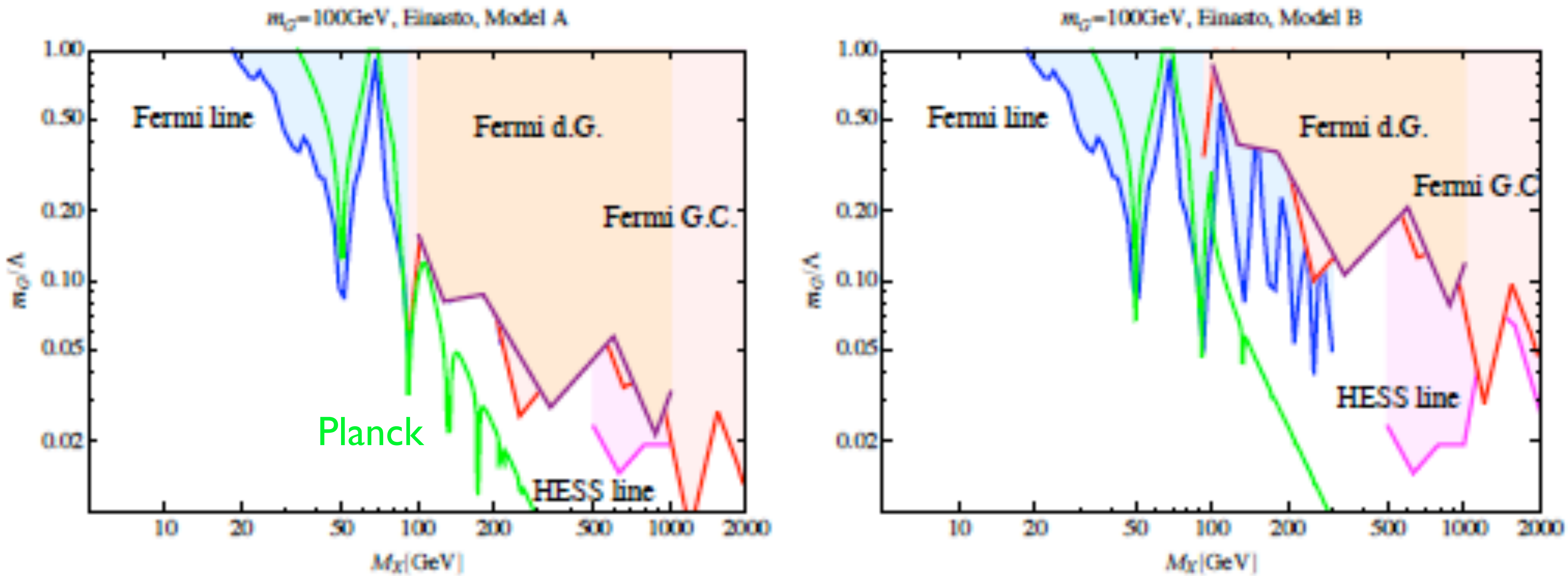




[Hooper et al, 1209.3015]

Bounds on s-channels

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



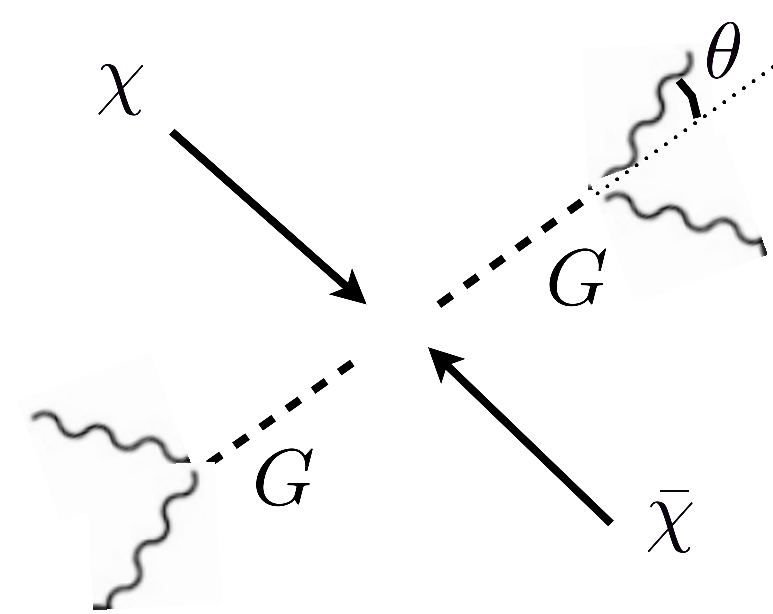
- Gamma-ray line and continuum bounds are strong for vector DM, while those are negligible from scalar and fermion DM.

- Anti-proton bounds gg/WW/ZZ channels similarly.

Bounds on t-channels

- Photons are box-shaped due to diphoton decay of a boosted graviton wrt galactic frame, $v_G = \frac{p_G}{E_G} = \sqrt{1 - \frac{m_G^2}{m_\chi^2}}.$

$$E_\gamma = \frac{1}{\gamma} E_{\rm r.f.} (1 - v_G \cos\theta)^{-1}$$
$$= \frac{m_G^2}{2m_\chi} \left(1 - \cos\theta \sqrt{1 - \frac{m_G^2}{m_\chi^2}} \right)^{-1}$$



- GG annihilations

$$(\sigma v)_{SS\to GG} \simeq \frac{4c_S^4 m_S^2}{9\pi\Lambda^4} \frac{(1-r_S)^{\frac{9}{2}}}{r_S^4(2-r_S)^2}$$

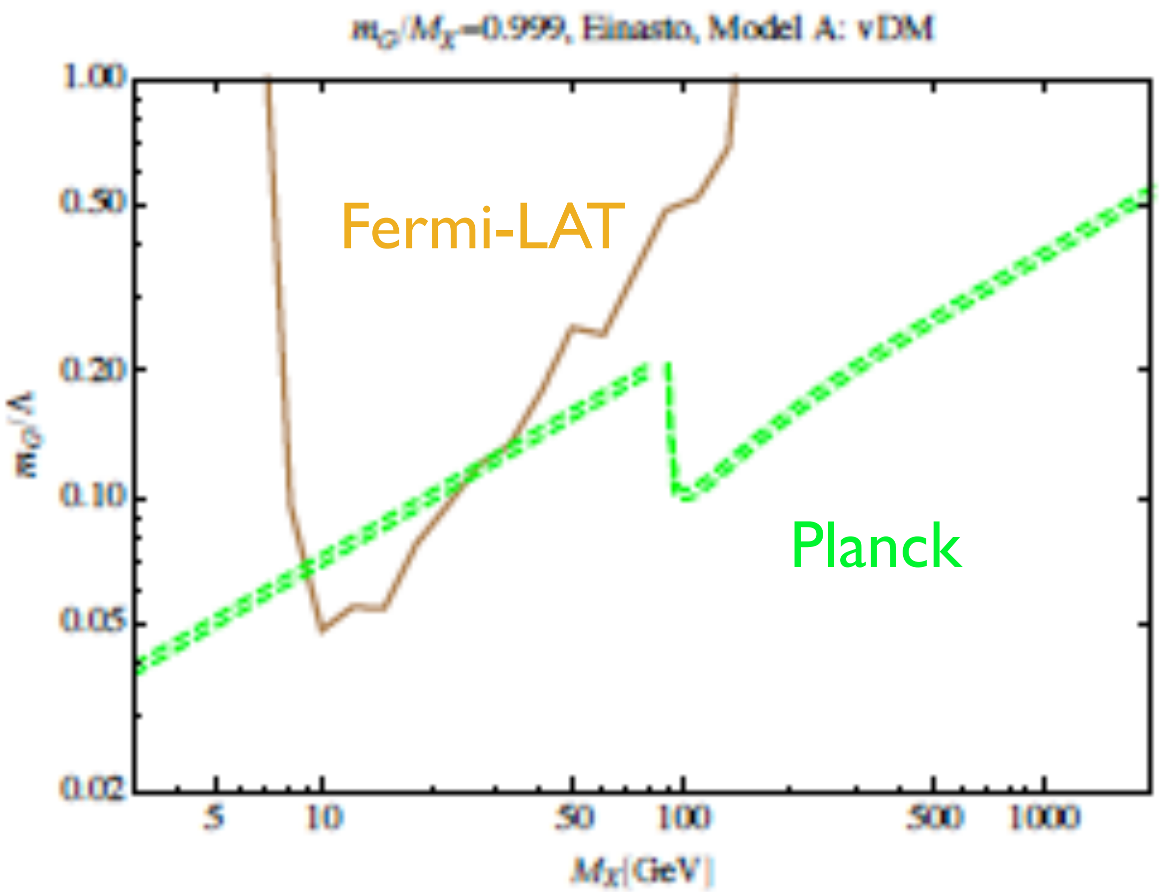
$$(\sigma v)_{\chi\bar\chi\to GG} \simeq \frac{c_\chi^4 m_\chi^2}{16\pi\Lambda^4} \frac{(1-r_\chi)^{\frac{7}{2}}}{r_\chi^4(2-r_\chi)^2}$$

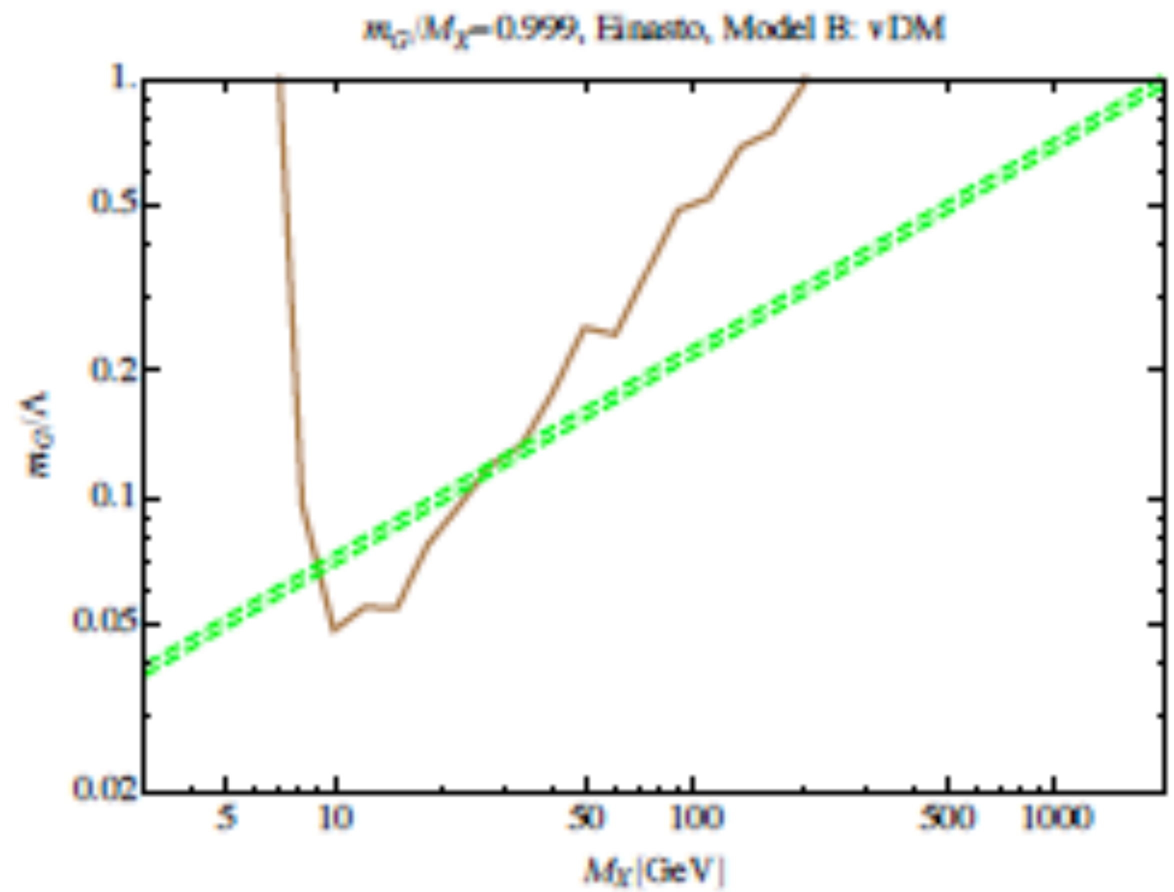
$$(\sigma v)_{XX\to GG} \simeq \frac{c_X^4 m_X^2}{324\pi\Lambda^4} \frac{\sqrt{1-r_X}}{r_X^4(2-r_X)^2} \Big(176 + 192 r_X + 1404 r_X^2 - 3108 r_X^3 + 1105 r_X^4 + 362 r_X^5 + 34 r_X^6\Big)$$

$$r_i = \left(\frac{m_G}{m_i}\right)^2$$

Results - narrow box

- Narrow boxes: $r_i \simeq 1$ → Only vector DM is relevant.



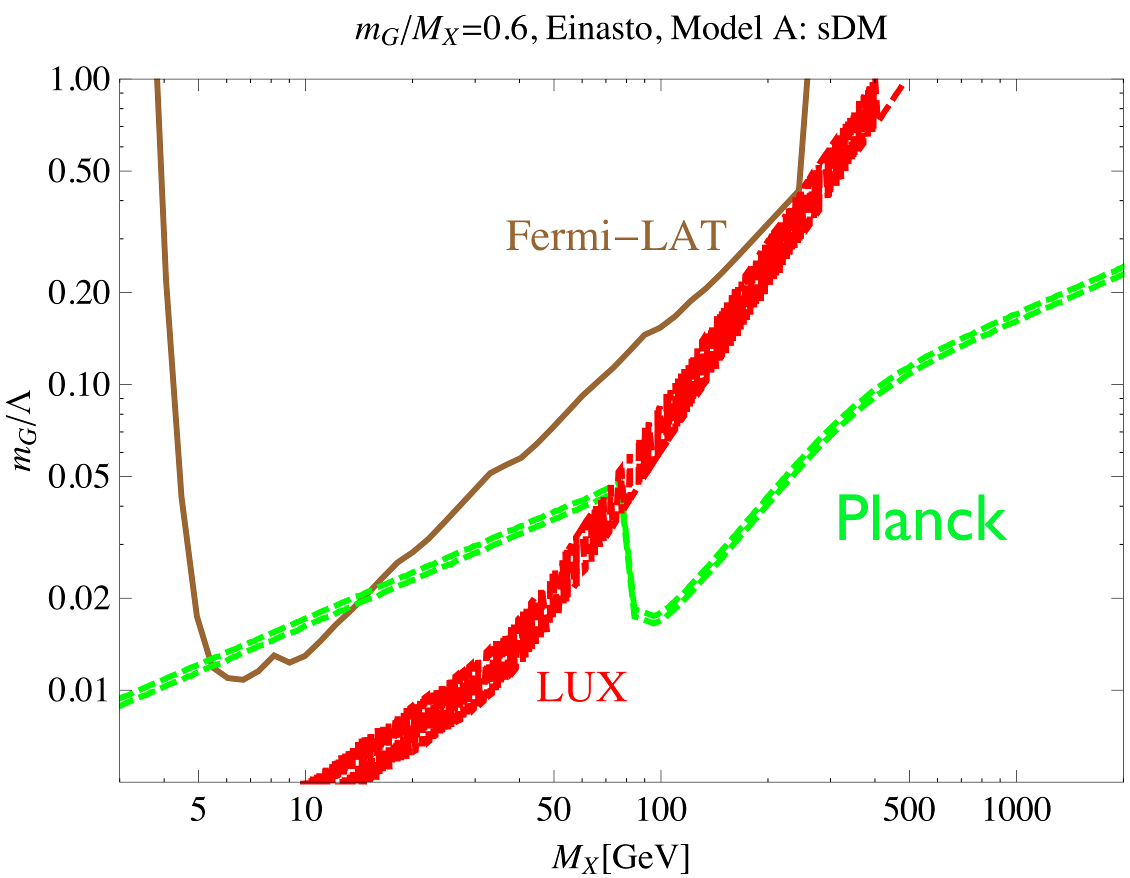


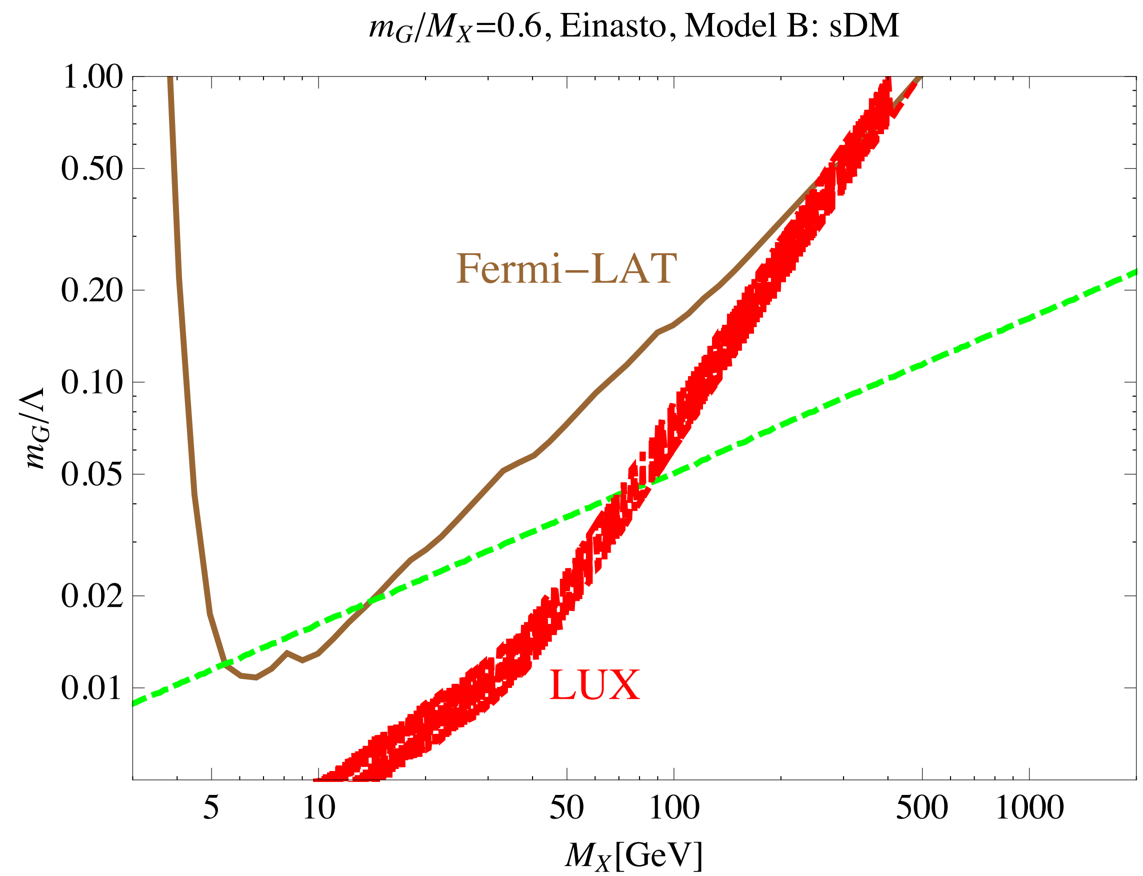
- Vector DM masses of 9-30 GeV, that are consistent with relic density, are excluded in both Model A and B.

Results - wide box

- Wide boxes: $r_i \ll 1$

All spins contribute sizably.





- DM of any spin with 6-15GeV masses are excluded by Fermi-LAT.
- LUX bound excludes the region below DM masses of 70-80 GeV.

Conclusions

- “Warped space” explains natural EWSB and/or WIMP dark matter.
- DM interactions are “purely gravitational” due to KK gravitons, suppressed by TeV-scale in warped extra dimension.
- Fermi gamma-ray line can be explained by vector dark matter without large coupling or resonace.
- Spins of DM can be distinguished by the velocity dependence of DM annihilations and constrained differently by astrophysical data.