GRAVITATIONAL DARK MATTER PORTAL IN EXTRA DIMENSIONS

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With **N. Bernal, A. Donini, M.G. Folgado,**

JHEP 01 (2020) 161, *JHEP* 09 (2020) 142, *Eur.Phys.J.C* 81 (2021) 3, 197

Workshop on Standard Model and Beyond, Corfu, 29/08/2024

Outline

1) Introduction

2) Freeze-out DM

3) Freeze-in DM

4) Summary and outlook

1) Introduction

- Only gravitational evidence of DM ...

... but maybe in extra dimensions there are possible observational signatures

- Extra Dimension theories were proposed at the end of the XX century in order to solve the hierarchy problem

- Large Extra-Dimensions (LED) → flat extra dimensions

Arkani-Hamed, Dimopoulos, Dvali, PLB429 (1998) 263

- Randall-Sundrum (RS)

PRL 83 (1999) 4690

warped extra dimensions

- Clockwork/Linear Dilaton (CW/LD)

Giudice, McCullough, JHEP 02(2017)036

Mini-review of extra dimensional scenarios

5-Dimensional Metric

$$ds^2 = e^{2\sigma(y)}(\eta_{\mu\nu}dx^\mu dx^\nu - e^{-2l\sigma(y)}r_c^2 dy^2)$$

Large Extra-Dimensions

- $\sigma(y) = 0$

$$\bar{M}_{pl}^2 = M_5^3 2\pi r_c$$

Volume factor

Randall-Sundrum

- $\sigma(y) = -kr_c|y|$
- $l = 1$

$$\bar{M}_{pl}^2 = \frac{M_5^3}{k}(1 - e^{-2k\pi r_c})$$

$$k, M_5 \sim \bar{M}_{pl}$$

Clockwork/Linear Dilaton

- $\sigma(y) = \frac{2}{3}kr_c|y|$
- $l = 0$

$$\bar{M}_{pl}^2 = \frac{M_5^3}{k}(e^{2k\pi r_c} - 1)$$

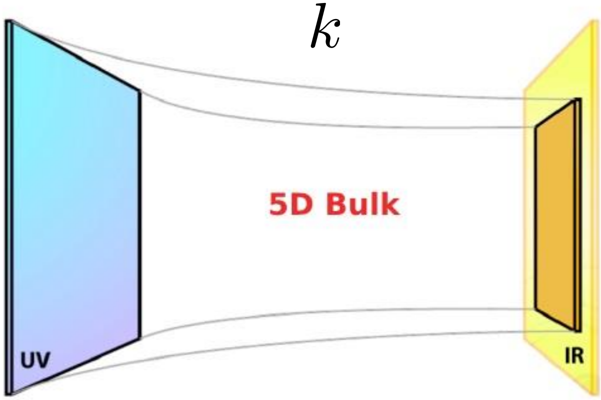
Warping factor

$$k, M_5 \ll \bar{M}_{pl}$$

Randall-Sundrum

$y = 0$ $\qquad$ $y = \pi r_c$

k

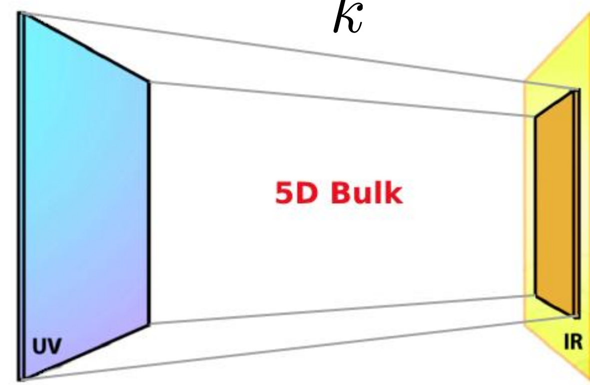


$$ds^2 = e^{-2kr_c|y|}\eta_{\mu\nu}dx^\mu dx^\nu - r_c^2 dy^2$$

Clockwork/LD

$y = \pi r_c$ $\qquad$ $y = 0$

k



$$ds^2 = e^{\frac{4}{3}kr_c|y|}(\eta_{\mu\nu}dx^\mu dx^\nu - r_c^2 dy^2)$$

R-S:

$$S = S_{\rm Bulk} + S_{\rm IR} + S_{\rm UV} \qquad y = r_c\phi$$

$$S_{\rm Bulk} = \frac{M_5^3}{2}\int d^4x \int_0^\pi r_c d\phi \sqrt{G}\,(\mathcal{R} - 2\Lambda_5)$$

$$S_{\rm IR} = \int d^4x \int_0^\pi r_c d\phi \sqrt{-g_{\rm IR}}\,(-V_{\rm IR} + \mathcal{L}_{\rm IR})\,\delta(\phi - \pi)$$

$$S_{\rm UV} = \int d^4x \int_0^\pi r_c d\phi \sqrt{-g_{\rm UV}}\,(-V_{\rm UV} + \mathcal{L}_{\rm UV})\,\delta(\phi)$$

- 5D Graviton field $g_{\mu\nu} = \eta_{\mu\nu} + \hat{h}_{\mu\nu}$
- KK decomposition: $\hat{h}_{\mu\nu}(x,y) = \sum_{n=0}^{\infty} h^n_{\mu\nu}(x) \frac{\chi_n(y)}{\sqrt{r_c}}$

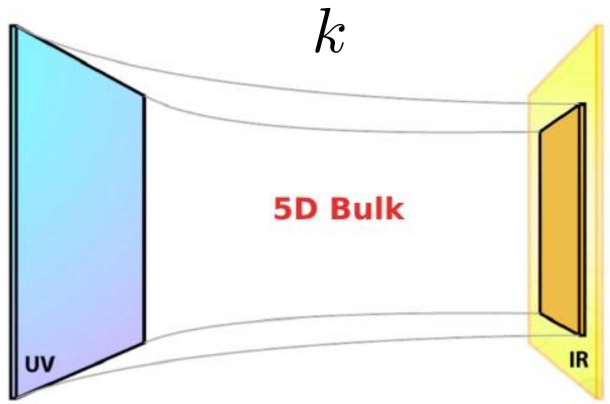
$$(\eta^{\mu\nu}\partial_\mu\partial_\nu + m_n^2) h^n_{\mu\nu}(x) = 0$$

- In R-S: $\chi^n(y) = \frac{e^{2\sigma(y)}}{N_n}\left[J_2(z_n) + \alpha_n Y_2(z_n)\right]$ $\quad z_n(y) = m_n/ke^{\sigma(y)}$
- In CW/LD: $\chi_n(y) = N_n e^{-ky}[\sin(\beta_n y) + \omega_n \cos(\beta_n y)]$

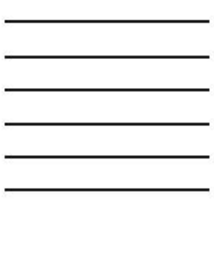
5D massless graviton ↔ 4D tower massive KK gravitons

Randall-Sundrum

$y = 0$ $\qquad$ $y = \pi r_c$



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



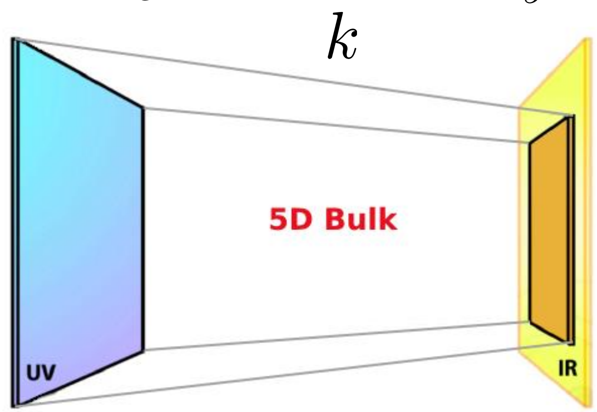
Mass spectra

$m_n = k x_n e^{-k\pi r_c}$ $\longleftrightarrow$ $J_1(x_n) = 0$

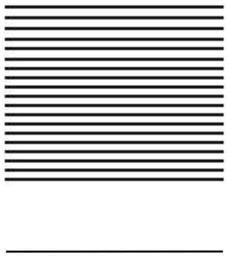
$m_0 = 0$

Clockwork/LD

$y = \pi r_c$ $\qquad$ $y = 0$



$$ds^2 = e^{\frac{4}{3}kr_c|y|}(\eta_{\mu\nu}dx^\mu dx^\nu - r_c^2 dy^2)$$



Mass spectra

$m_n^2 = k^2 + \frac{n^2}{r_c^2}$

$m_0 = 0$

$k = 0$

LED

Brane distance stabilization mechanism

The distance between the two 4D-branes is determined by r_c, to stabilise dynamically this distance a scalar field in the 5D-bulk is introduced (Radion).

Randall-Sundrum

m_r → New Free parameter

Goldberger-Wise mechanism:

typically $m_r < m_1$

Clockwork/Linear Dilaton

- Already present bulk dilaton field (Φ_n)
- The 5D dilaton field can be written as a KK tower:

$$m_r^2 = m_{\Phi_0}^2 = \frac{8}{9}k^2$$

$$m_{\Phi_n}^2 = k^2 + \frac{n^2}{r_c^2}$$

- **Here, I focus on Randall-Sundrum scenario (dual to a 4D strongly interacting model)**
- **SM and DM in the IR brane**
- **CW/LD studied in A. Donini, M.G. Folgado, N. Rius,** *JHEP* 04 (2020) 036, **N. Bernal et al.,** *JHEP* 04 (2021) 061
- From the weak field expansion of the metric:

$$ds^2 = e^{-2kr_c y} e^{-2r} (\eta_{\mu\nu} + \hat{h}_{\mu\nu}) dx^\mu dx^\nu - (1+2r)^2 dy^2$$

- Graviton-matter interaction:

$$\mathcal{L} = -\frac{1}{M_5^{3/2}} T^{\mu\nu}(x) h_{\mu\nu}(x, y=\pi) = -\frac{1}{M_P} T^{\mu\nu}(x) h^0_{\mu\nu}(x) - \frac{1}{\Lambda} \sum_{n=1} T^{\mu\nu}(x) h^n_{\mu\nu}(x)$$

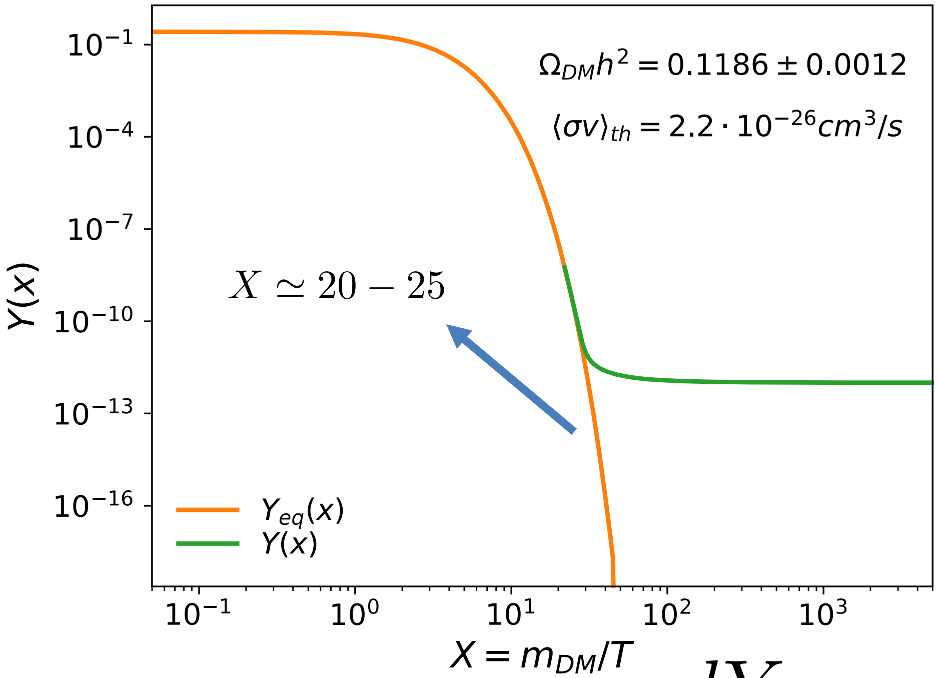
$$\Lambda = \bar{M}_{pl} e^{-\pi k r_c}$$

- Radion-matter interaction:

$$\mathcal{L}_r = \frac{1}{\sqrt{6}\Lambda} r T + \frac{\alpha_{\rm EM}\, C_{\rm EM}}{8\pi\sqrt{6}\Lambda} r F_{\mu\nu} F^{\mu\nu} + \frac{\alpha_S C_3}{8\pi\sqrt{6}\Lambda} r \sum_a F^a_{\mu\nu} F^{a\mu\nu}$$

- Gravitational field interactions (3rd order expansion)

2) Freeze-out DM



$$Y \equiv n(T)/\mathfrak{s}(T)$$

$$\mathfrak{s}(T) = \frac{2\pi^2}{45} g_{*s}(T) T^3$$

$$x \equiv m_{DM}/T$$

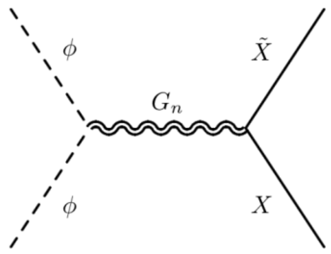
$$\frac{dY}{dx} = \frac{-x\langle\sigma v\rangle\mathfrak{s}}{H(m_{DM})}(Y^2(x) - Y^2_{eq}(x))$$

$$\langle\sigma v\rangle \sim \int_{4m_{DM}}^{\infty} ds(s - 4m_{DM})\sqrt{s}\sigma_{an}(s)K_1(\sqrt{s}/T)$$

$$= 2.2 \times 10^{-26} cm^3/s$$

- Only DM-SM scattering (mediated by KK gravitons)

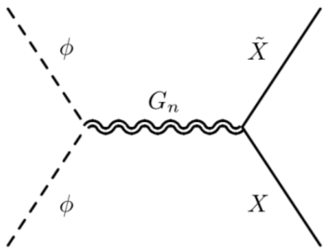
Rueter, Rizzo, Hewett, *JHEP* 10 (2017) 094

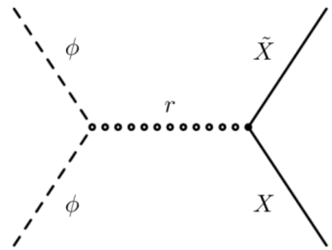


- SM + DM in the IR brane
- 3rd generation quarks in the IR brane, fermions near the UV brane, gauge fields in the bulk (avoid strong LHC bounds)
- All SM in the bulk, with different BLKTs (to explain fermion massses and CKM mixing matrix)

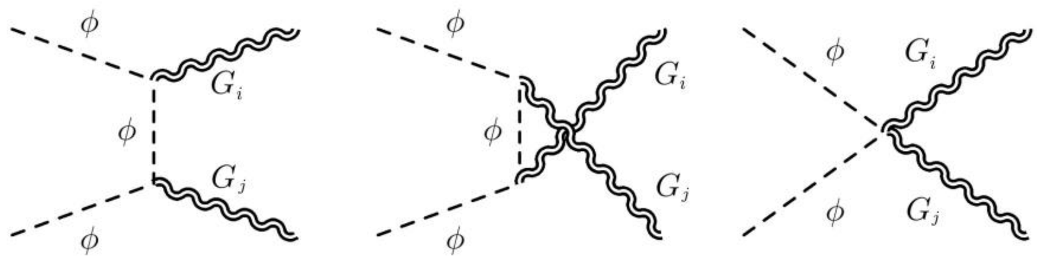
- DM annihilation into KK gravitons Min Lee, Park, Sanz *Eur.Phys.J.C* 74 (2014) 2715, *JHEP* 05 (2014) 063

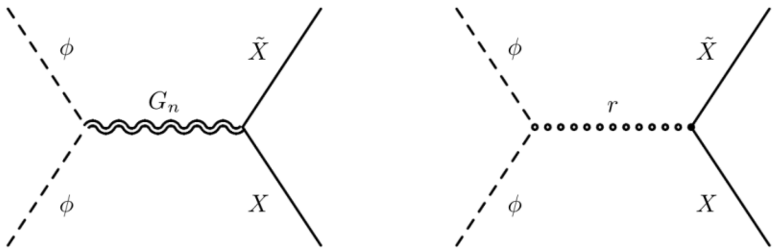
- DM and Higgs in the IR brane, SM in the UV brane
- Only DM in the IR brane





	Scalar	Fermion	Vector
Graviton Virtual Exchange	v^4 (d)	v^2 (p)	v^0 (s)
Radion Virtual Exchange	v^0 (s)	v^2 (p)	v^0 (s)
Annihilation into Gravitons	v^0 (s)	v^0 (s)	v^0 (s)
Annihilation into Radions	v^0 (s)	v^2 (p)	v^0 (s)
Annihilation into Radion + Graviton	v^0 (s)	v^0 (s)	v^0 (s)





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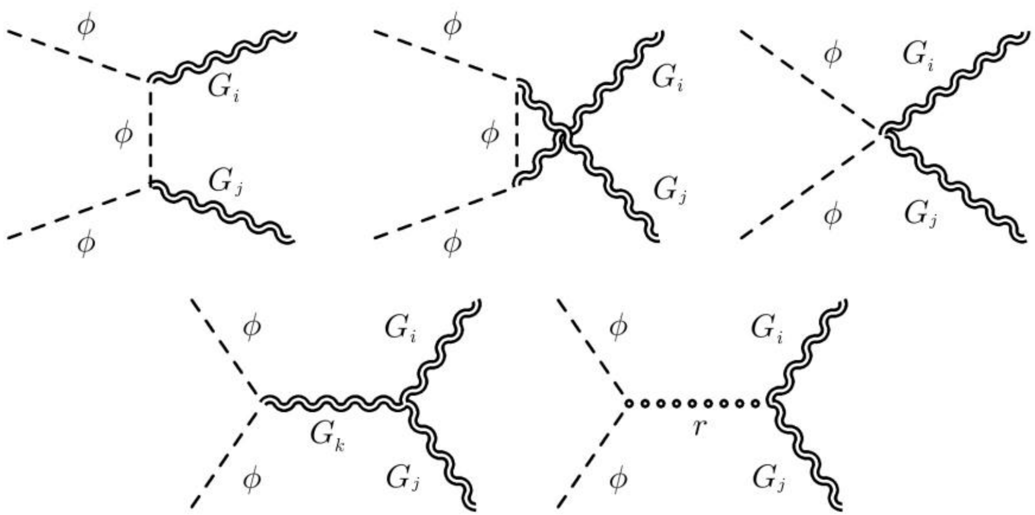

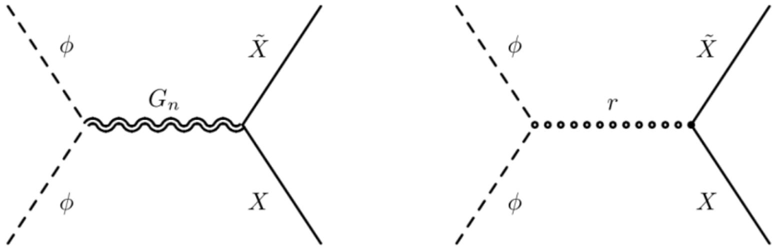

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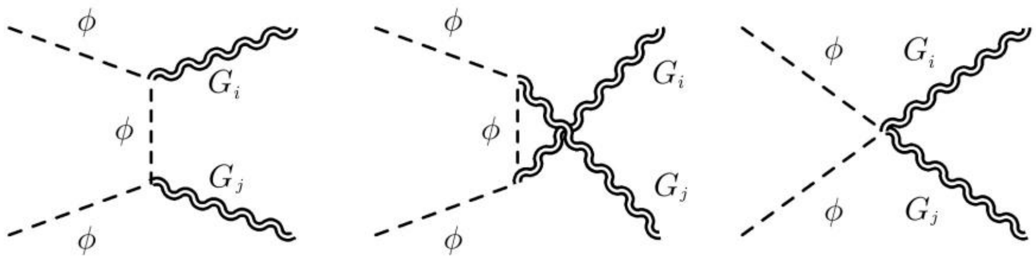
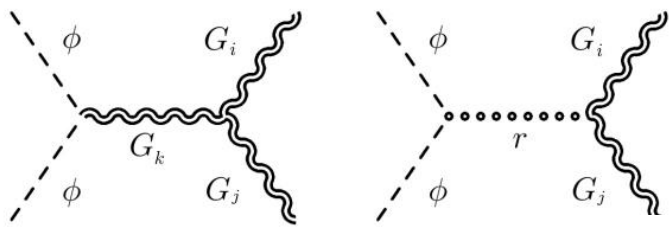
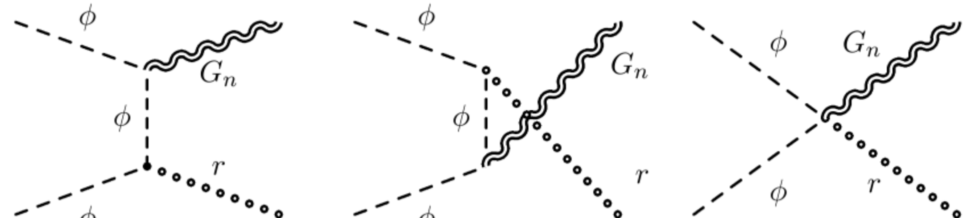
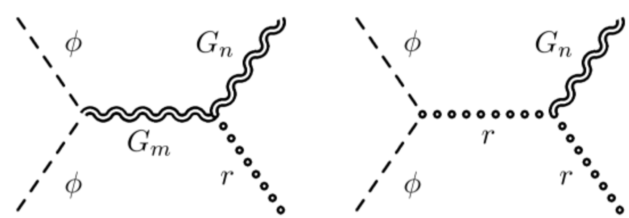


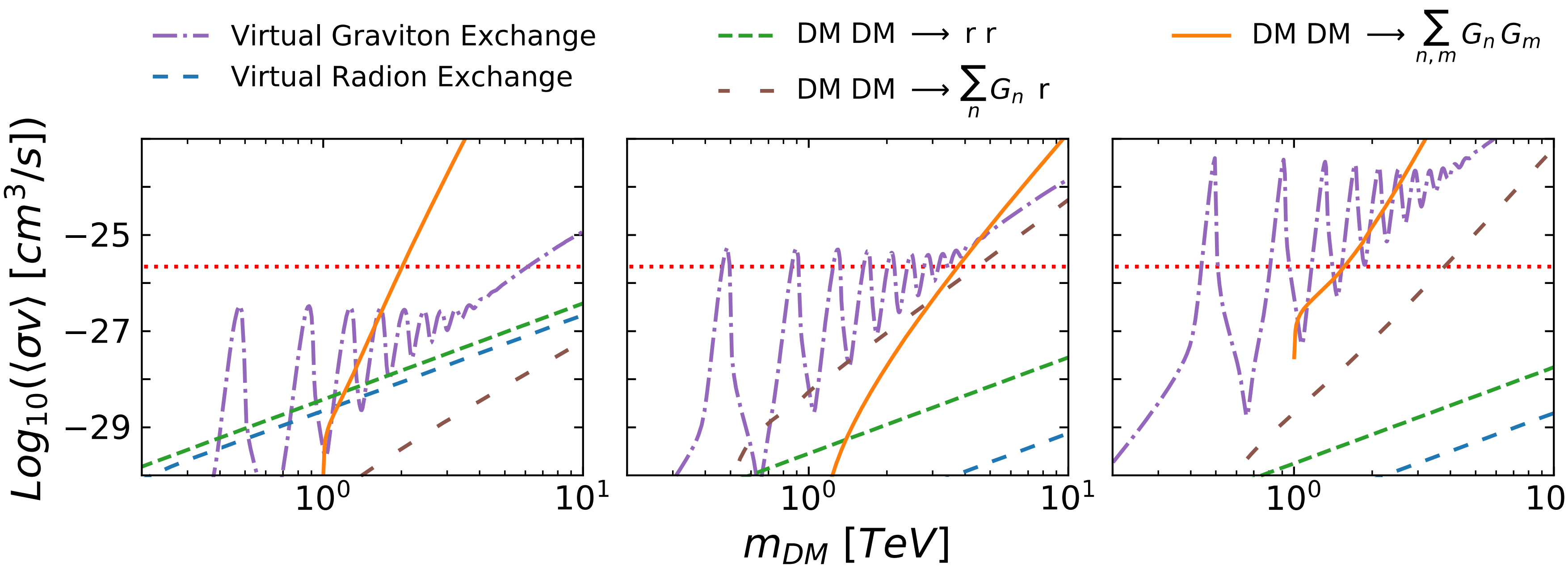






Gravitational portal to DM in Xdims

Anomalous enhancement due to the sum over massive KK graviton polarizations



Scalar Fermion Vector

$$m_r = 100\,\mathrm{GeV},\, M_{G_1} = 1\,\mathrm{TeV},\, \Lambda = 10\,\mathrm{TeV}$$

$$\sigma(\mathrm{DM},\mathrm{DM} \to G_n G_n) \propto \frac{s}{\Lambda^2}\left(\frac{s}{m_n^2}\right)^k$$

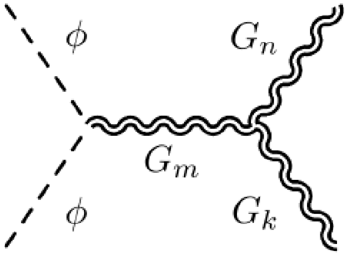
fermion: $k = 2$

scalar, vector: $k = 4$

Scalar DM

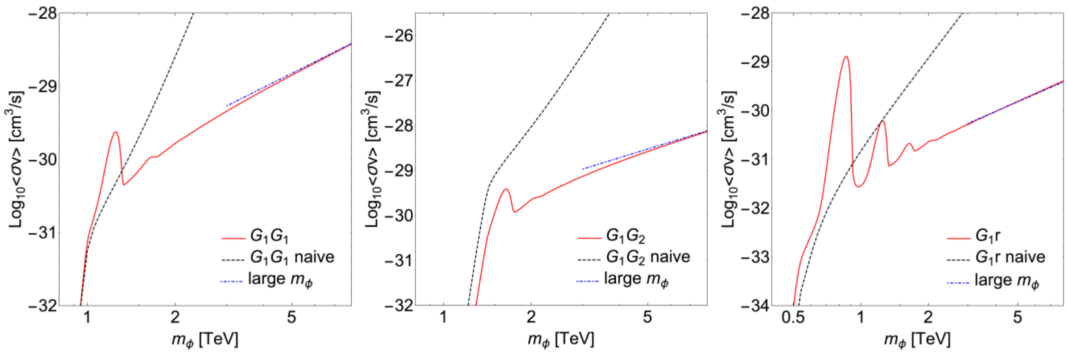
- It is needed to sum over the infinite tower of KK gravitons in the s channel

Giorgi, Vogl, *JHEP* 04 (2021) 143;
JHEP 11 (2021) 036



Subtle cancellations due to sum rules of Bessel functions (wave funtions of KK gravitons)

Radion contribution is also essential



(a) (b) (c)

$$m_r = 100\,\mathrm{GeV}\,,\, M_{G_1} = 1\,\mathrm{TeV}\,,\, \Lambda = 20\,\mathrm{TeV}$$

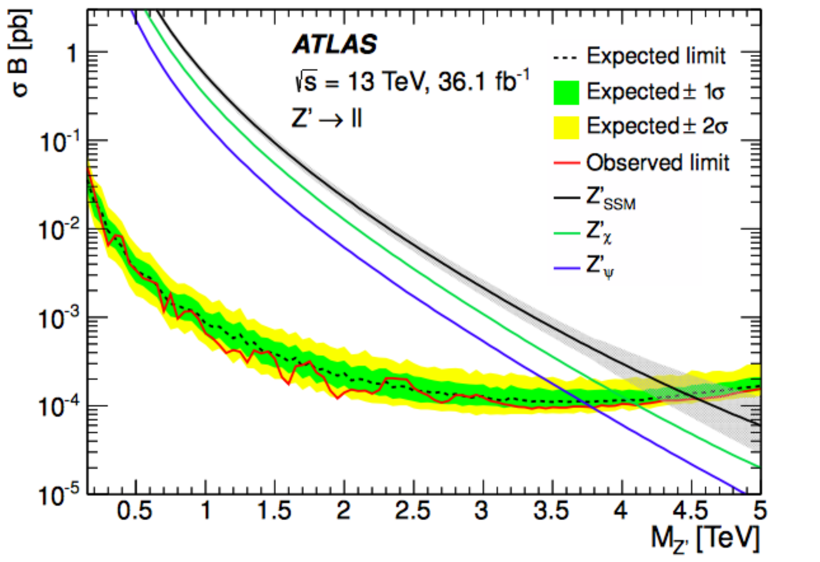
Final result, as expected :

$$\sigma(\mathrm{DM},\mathrm{DM}\to G_n G_n) \propto \frac{s}{\Lambda^2}$$

Analogous result for

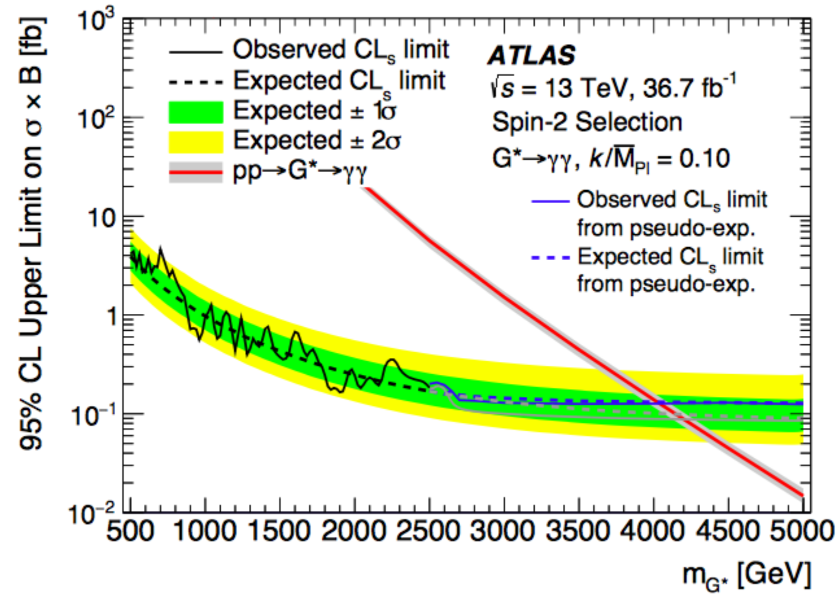
$$\sigma(\mathrm{DM},\mathrm{DM}\to G_n r) \propto \frac{s}{\Lambda^2}\left(\frac{s}{m_n^2}\right)^2$$

Bounds from resonance searches at LHC



ATLAS: Search for new phenomena in high-mass dilepton final states using 37 fb^{-1}

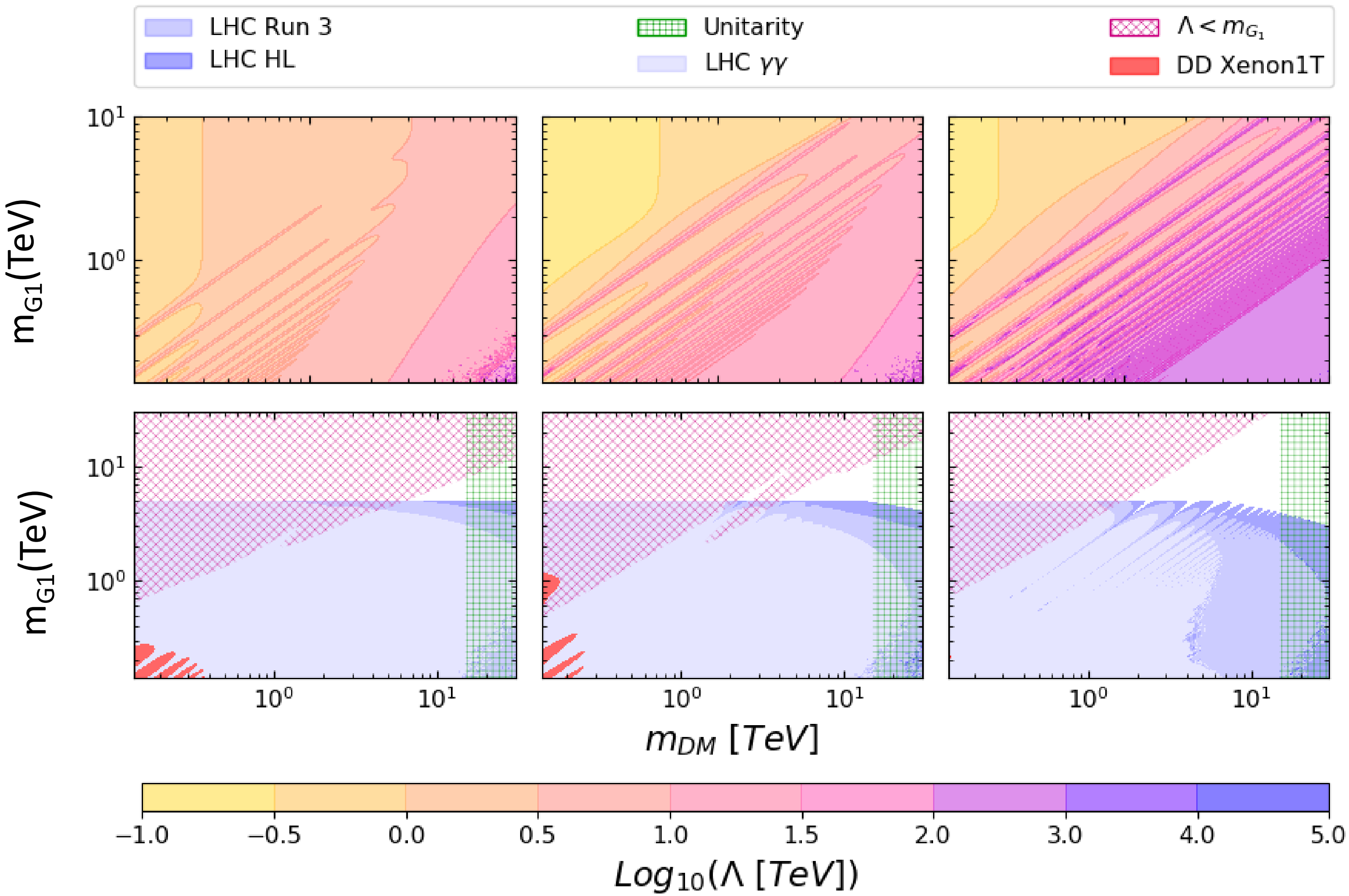
(1707.02424)



ATLAS: Search for new phenomena in high-mass diphoton final states using 37 fb^{-1}

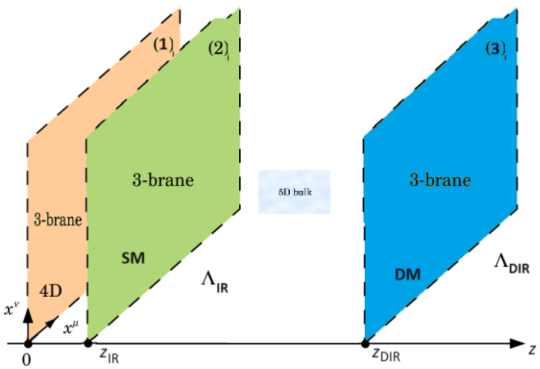
(1707.04147)

Scalar fermion vector



Dark branes

- Warped three brane scenario: UV, IR and Deep IR (DIR) or Dark brane
- SM lives in the IR brane ($\Lambda_{IR} \sim 1 - 100$ TeV), DM in the DIR one ($\Lambda_{DIR} \sim$ GeV – TeV)



$\Lambda_{DIR} < \Lambda_{IR}$

l annihilation into gravity

diators : G_n , r

- Dark brane pase transition compatible with PTA gravitational signal for:

  - Dirac fermion DM, talk by Fotis Koutroulis in this workshop

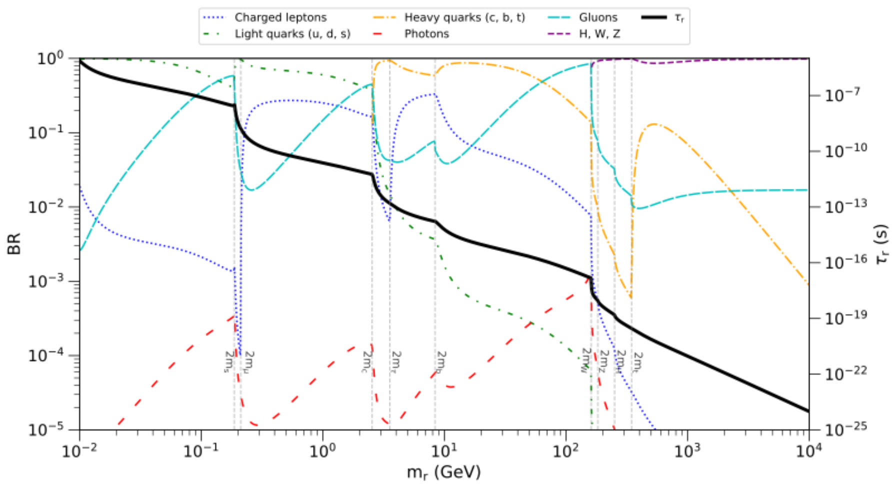
  F. Koutroulis, E. Megías, S. Pokorski and M. Quirós, arXiv:2403.06276

  - Forbidden scalar DM ($m_{DM} < m_r$), Ferrante et al., *JHEP* 11 (2023) 186

- Full analysis of scalar DM, in preparation

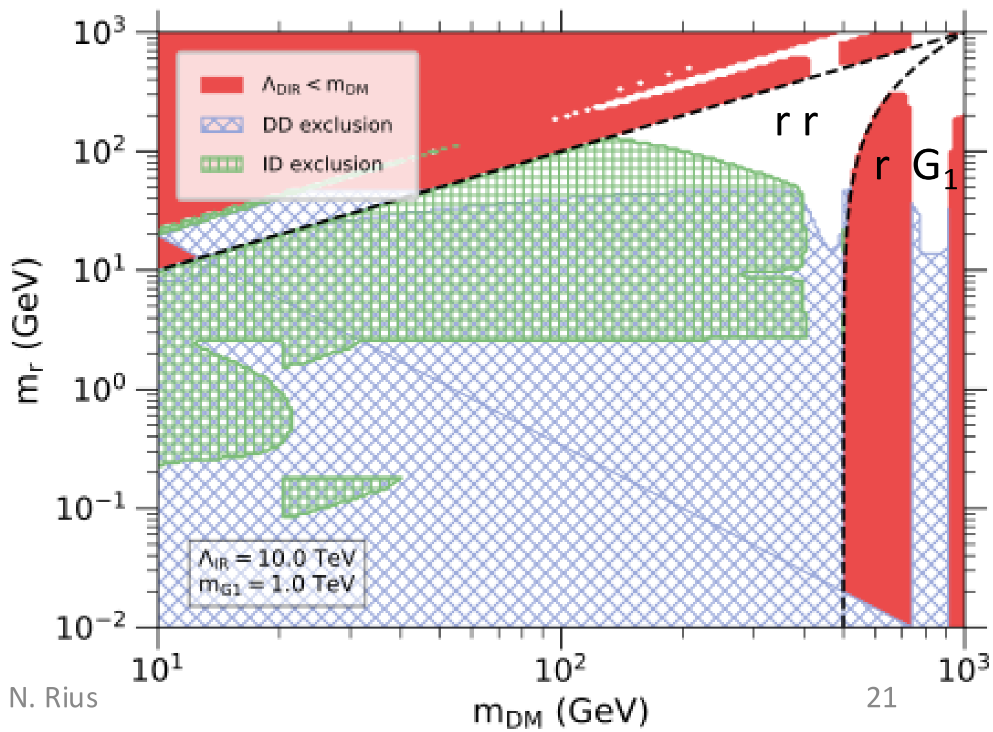
A. Donini, M.G. Folgado, J. Herrero-García, G. Landini, A. Muñoz, and N.R.

- LHC limits evaded, but we need to consider
  - DM direct detection: suppressed by Λ_{IR}
  - DM indirect detection: depends on r and G_n decay modes into SM

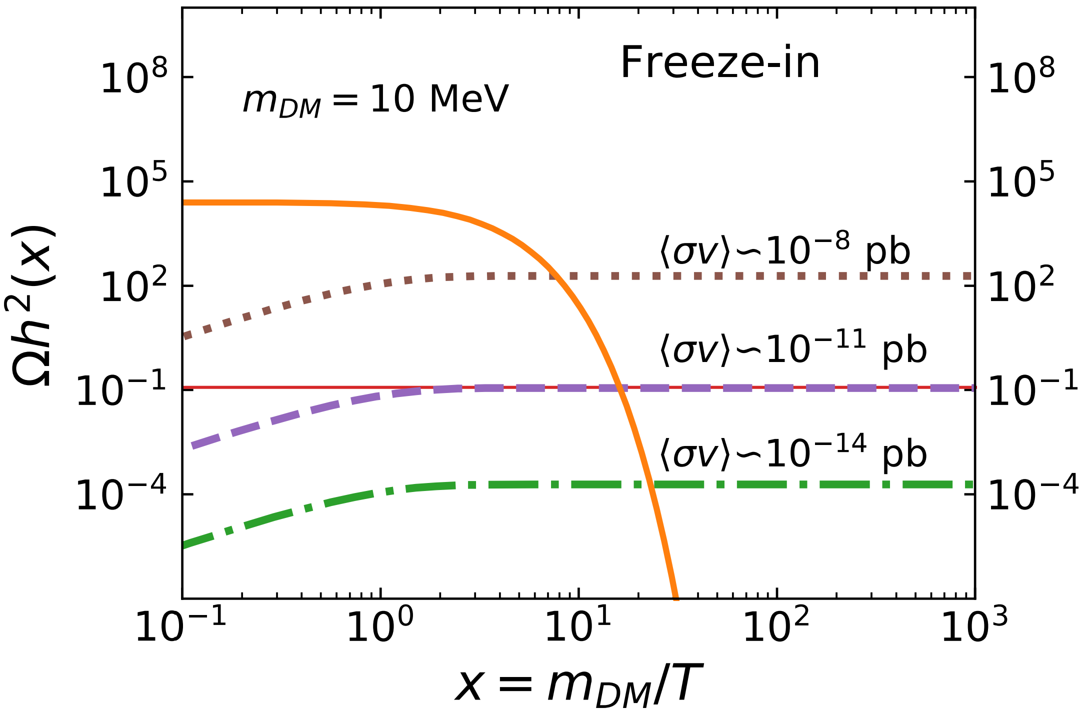


Preliminary :

Λ_{DIR} determined by requiring correct DM relic abundance



3) Freeze-in DM

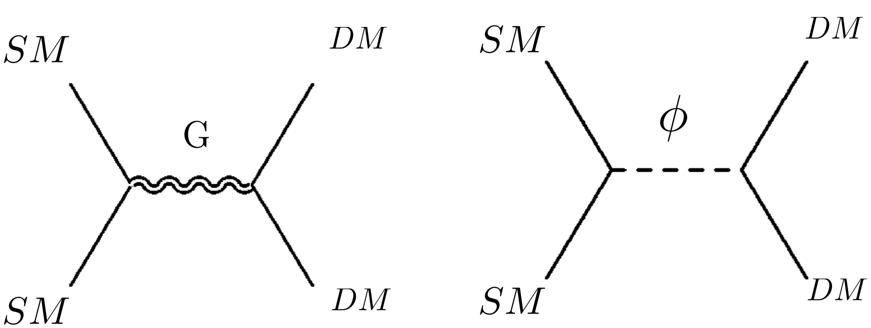


DM is a Feebly Interacting Massive Particle (FIMP)
It never reaches thermal equilibrium

Scalar DM

Direct Freeze In

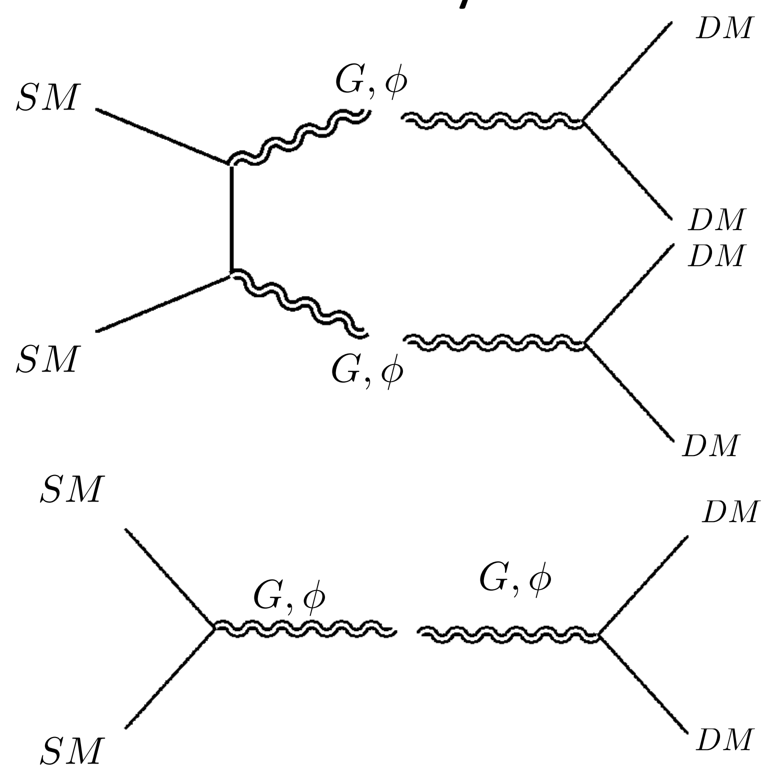
- DM production via virtual graviton and radion exchange



Relevant when G,$\boldsymbol{\phi}$ are in thermal equilibrium
or $T < m_r$, m_1

Sequential Freeze In

- DM production via graviton and radion decay.



- Sequential freeze-in: Boltzmann equations for DM, G and $\boldsymbol{\phi}$

- SM - G_n G_m scattering suffers from unphysical divergences when $m_1 << s \sim T^2$ (work in progress)

- Approx. solutions:

1) Direct freeze-in: $T < m_r$

$$\frac{dY}{dT} \simeq \frac{\gamma_{\mathrm{DM}\to\mathrm{SM}}}{H\,\mathfrak{s}\,T}\left[\left(\frac{Y}{Y^{\mathrm{eq}}}\right)^2 - 1\right] \simeq -\frac{\gamma_{\mathrm{DM}\to\mathrm{SM}}}{H\,\mathfrak{s}\,T}$$

$$\sigma_{\mathrm{DM}\to\mathrm{SM}}(s) \simeq \frac{49}{1440\pi}\frac{s^3}{\Lambda^4}\left|\sum_{n=1}^{\infty}\frac{1}{s-m_n^2+i\,m_n\,\Gamma_n}\right|^2 + \frac{s^3}{288\pi\Lambda^4}\frac{1}{(s-m_r^2)^2+m_r^2\,\Gamma_r^2}$$

$$Y_0 \simeq \frac{3\times 10^{-1}}{g_{*s}}\sqrt{\frac{10}{g_*}}\left(\frac{M_P}{m_r^4\,\Lambda^4}\right)$$

2) Sequential freeze in via inverse decays:

$$\frac{dY}{dT} \simeq \frac{\gamma^d_{\mathrm{KK}\to\mathrm{SM}}}{H\,\mathfrak{s}\,T}\left[\frac{Y_K}{Y_K^{\mathrm{eq}}}-1\right]\mathrm{BR}(\mathrm{KK}\to\mathrm{DM}) + \frac{\gamma^d_{\mathrm{r}\to\mathrm{SM}}}{H\,\mathfrak{s}\,T}\left[\frac{Y_r}{Y_r^{\mathrm{eq}}}-1\right]\mathrm{BR}(\mathrm{r}\to\mathrm{DM})$$

$$\simeq -\frac{1}{H\,\mathfrak{s}\,T}\left[\gamma^d_{\mathrm{KK}\to\mathrm{SM}}\,\mathrm{BR}(\mathrm{KK}\to\mathrm{DM}) + \gamma^d_{\mathrm{r}\to\mathrm{SM}}\,\mathrm{BR}(\mathrm{r}\to\mathrm{DM})\right]$$

Summing over G_n with $m_n < T_{rh}$:

$$Y_0 \simeq \frac{2.2\times10^{-4}}{g_{*s}}\sqrt{\frac{10}{g_s}}\frac{M_P\,T_{rh}^2}{m_1\,\Lambda^2} + \frac{3.5\times10^{-2}}{g_{*s}}\sqrt{\frac{10}{g_s}}\frac{M_P\,m_r}{\Lambda^2}\left(\frac{z}{z+37}\right)$$

$$z_n \equiv \left(1-4\frac{m_\chi^2}{m_n^2}\right)^{5/2},$$

$$z \equiv \sqrt{1-4\frac{m_\chi^2}{m_r^2}}\left(1+2\frac{m_\chi^2}{m_r^2}\right)^2$$

3) Sequential freeze in via annihilations

$$\frac{dY}{dT} \simeq -\frac{1}{H\,\mathfrak{s}\,T}\left[\gamma_{\mathrm{KK}\to\mathrm{SM}}\,\mathrm{BR}(\mathrm{KK}\to\mathrm{DM}) + \gamma_{\mathrm{r}\to\mathrm{SM}}\,\mathrm{BR}(\mathrm{r}\to\mathrm{DM})\right]$$

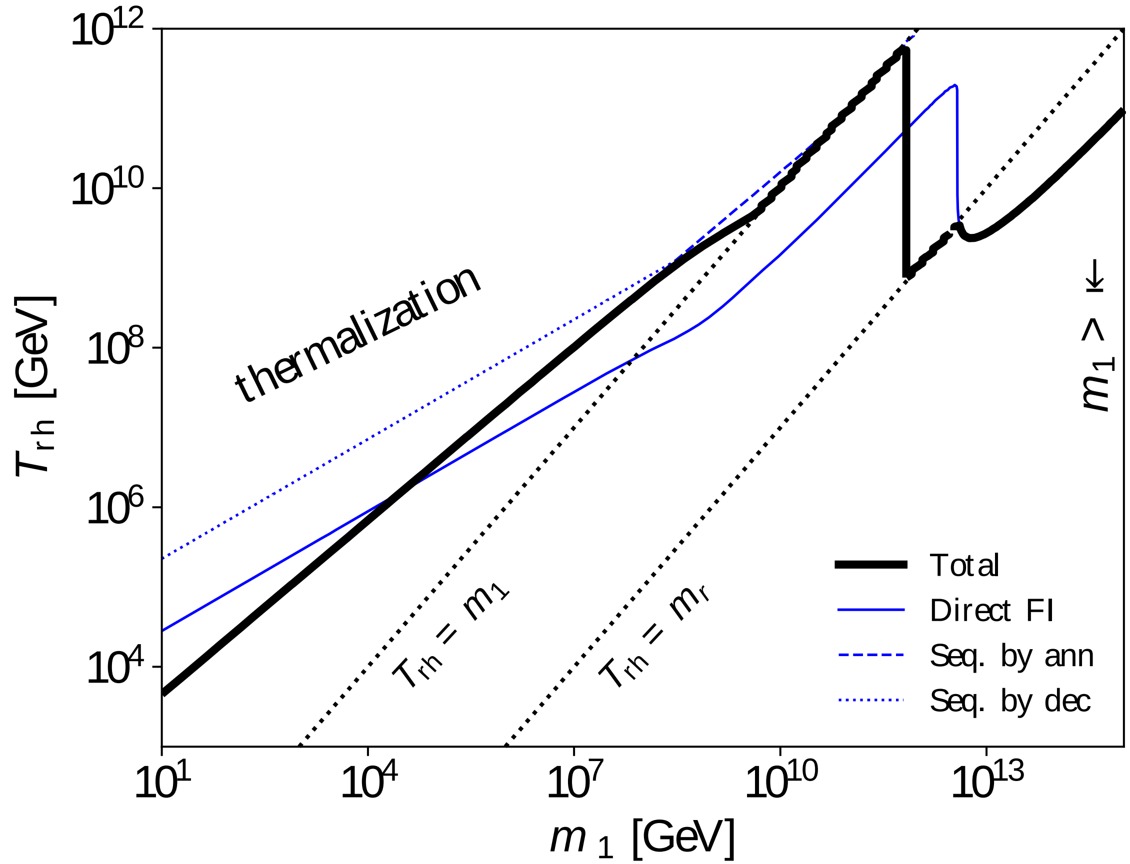
$$\gamma_{\mathrm{KK}\to\mathrm{SM}}(T) \simeq 4.8\times 10^{4}\,\frac{T^{16}}{\Lambda^4 m_n^8}$$

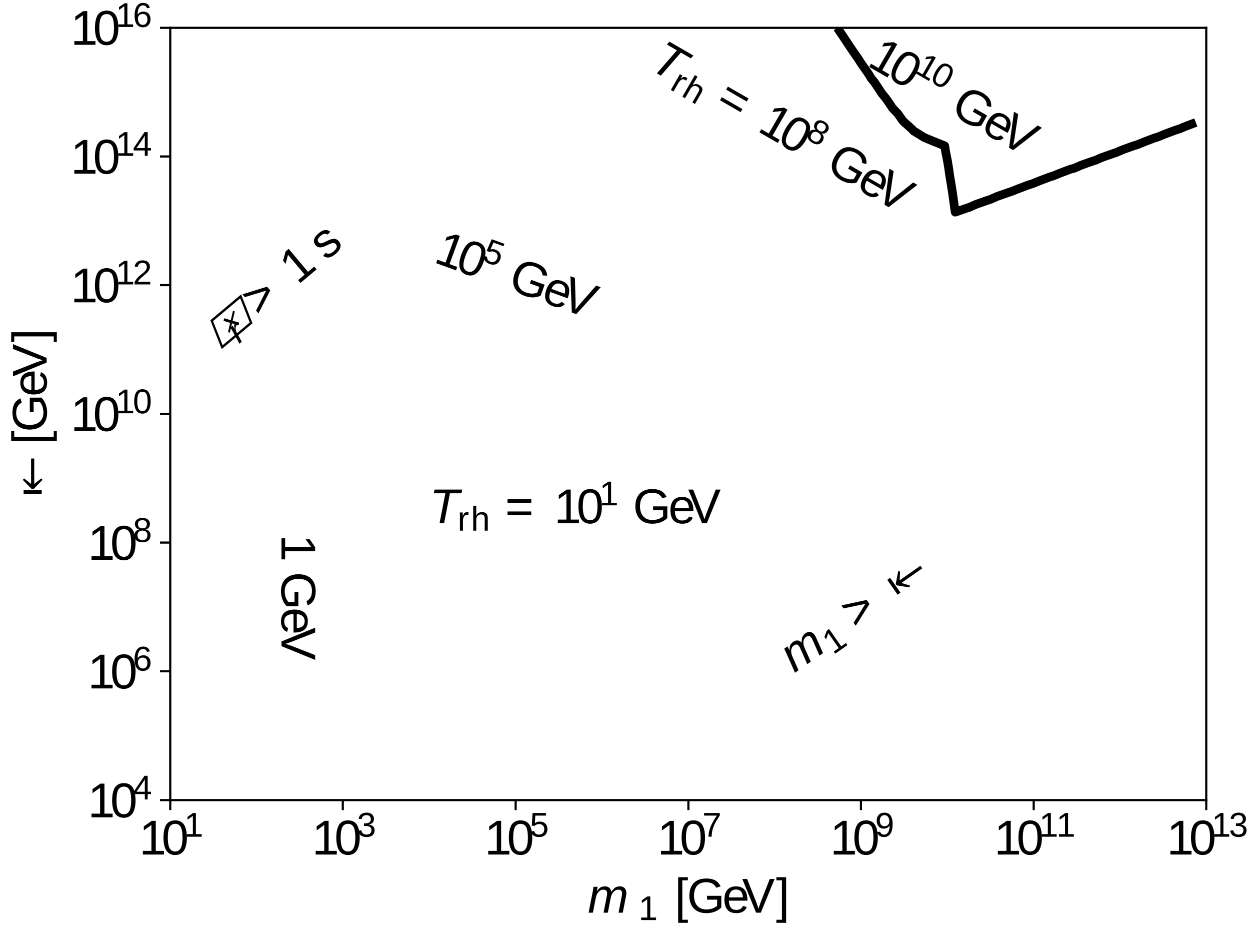
(to be corrected)

$$\gamma_{\mathrm{r}\to\mathrm{SM}}(T) \simeq 2.2\times 10^{-4}\,\frac{T^8}{\Lambda^4}$$

$m_r = 10^{-3}\, m_1$

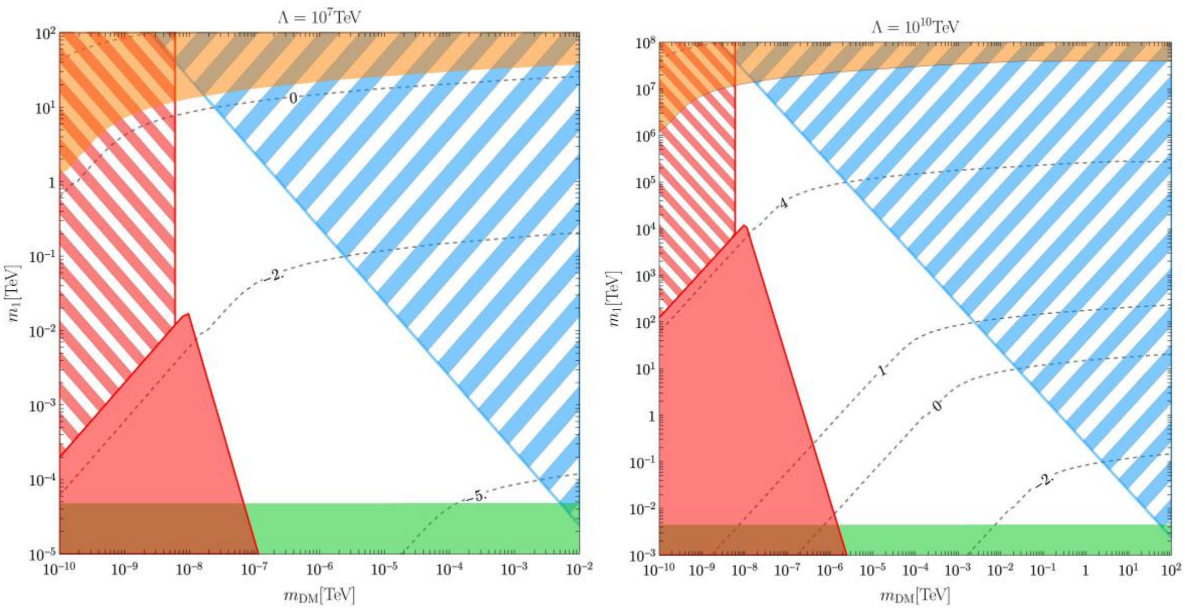
$m_{DM} = 1$ MeV




T_{rh} = 10^8 GeV
10^{10} GeV
10^5 GeV
> 1 s
T_{rh} = 10^1 GeV
1 GeV
m_1 >
[GeV]
m_1 [GeV]
10^{16}
10^{14}
10^{12}
10^{10}
10^8
10^6
10^4
10^1
10^3
10^5
10^7
10^9
10^{11}
10^{13}

Fermionic DM

- Only sequential freeze-in via inverse decays
- Radion contribution suppressed, since ∝ m^2_{DM}
- Constraints from velocity distribution of DM: too fast due to KK graviton late decays



Giorgi, Vogl, *JHEP 04 (2023)*

4) Summary and outlook

- Importance of summing over all KK graviton modes to recover unitarity

- WIMP DM freeze-out strongly constrained by LHC. Ways out: - SM not confined on the IR brane

  - Dark brane scenarios: full analysis of scalar DM in progress

- Giving up the hierarchy problem, plenty of room for FIMP DM freeze-in

- To do:

➢ Sum rules for fermion and vector scattering to G_n G_m, and G_n r

➢ Construct full inflationary models (Bernal, Cosme, Donini)

Thanks for your attention !