Dark matter in Extra-Dimensional Scenarios

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Based on:

Folgado, Donini and Rius, *JHEP* 01 (2020) 161
Folgado, Donini and Rius, *Eur. Phys. J. C* 81 (2021) 3, 197
Donini, Folgado, Herrero, Landini, Muñoz-Ovalle, Rius, arXiv:2505.13601
Donini, Folgado, Muñoz-Ovalle; arXiv:2509.04580

Motivations

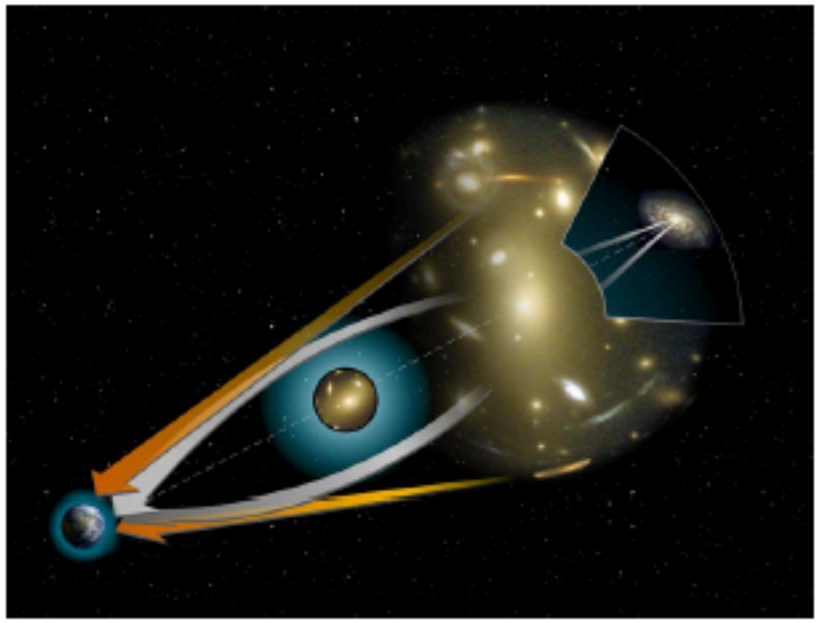
The Standard Model works extremely well,
but....
it is not the End of (high-energy physics) History

Neutrino masses....
Dark Matter....
Baryogenesis....
Dark Energy....
Quantum Gravity...
Hierarchy Problem...

1. CHOOSE YOUR FAVOURITE PROBLEM

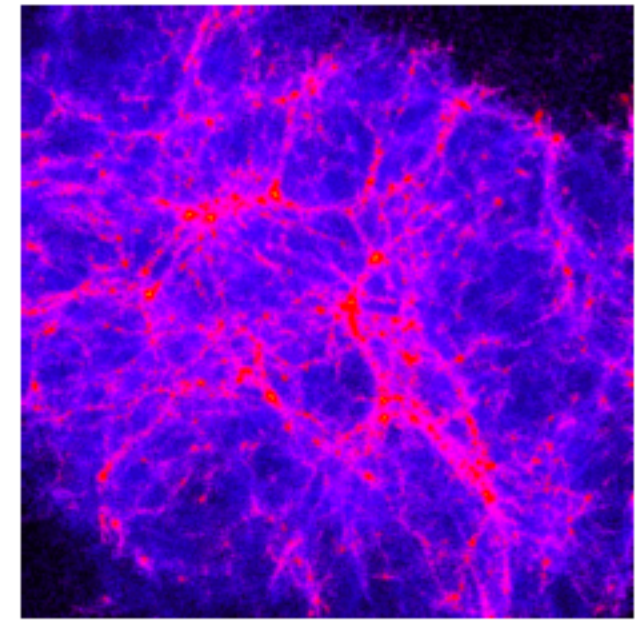
2. CHOOSE YOUR FAVOURITE SOLUTION

My problem: Dark Matter

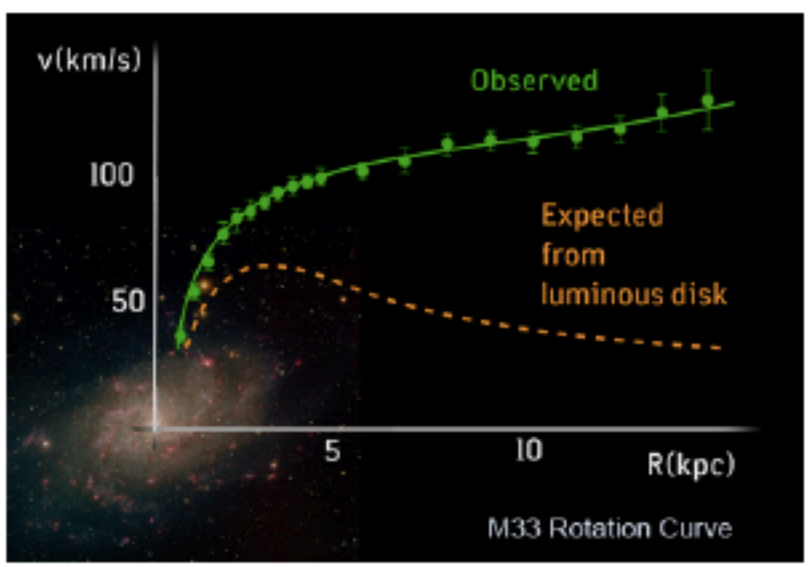


Gravitational lensing

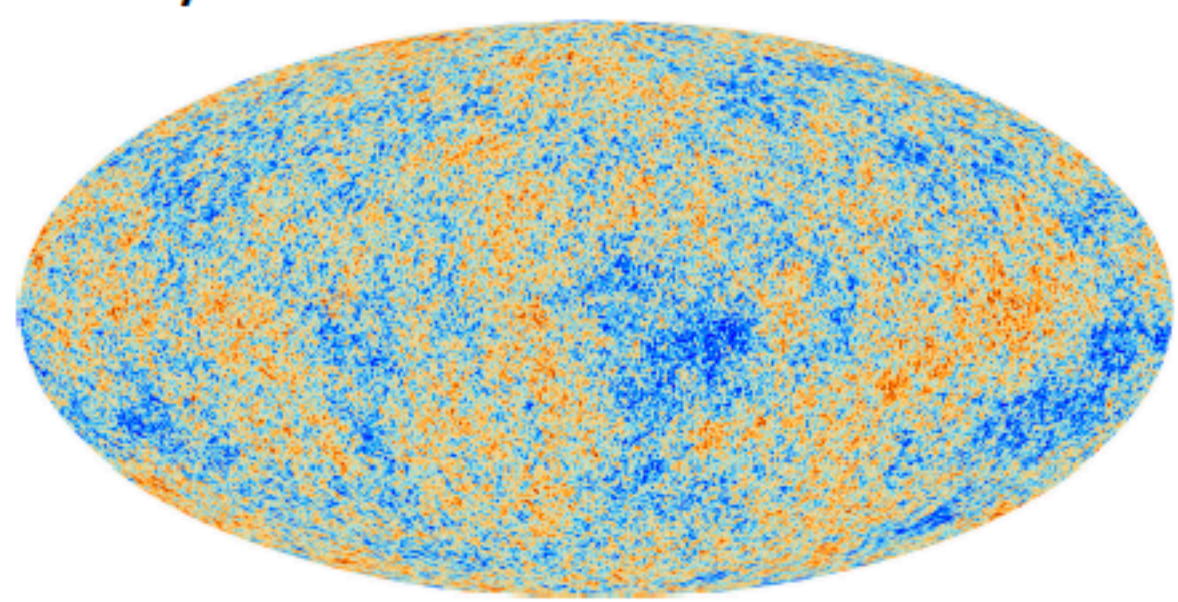
Galaxy clusters



Structure formation



Rotation Curves of Galaxies



Cosmic microwave background

My solution: Extra-Dimensions

The only evidence for Dark Matter is that IT GRAVITATES

Extra Spatial Dimensions are a key ingredient in attempts to QUANTISE GRAVITY

Gravity is stronger in D > 4:

GRAVITATIONAL PORTAL

The Recipe

1. Add one or more spatial dimensions to your space-time
2. Choose some geometry
3. Compactify the extra spatial dimensions
4. Add SM fields at some brane (a defect in your manifold)
5. Add a candidate DM particle either in the bulk or on a brane

Popular Extra-dimensional models in the literature

A. Large Extra-Dimensions (Antoniadis et al., Phys. Lett. B436 (1998) 257)
B. Warped (Randall and Sundrum, Phys. Rev. Lett. 83 (1999) 3370)
C. Clockwork/Linear Dilaton (Giudice and McCullough, JHEP02 (2017) 036)

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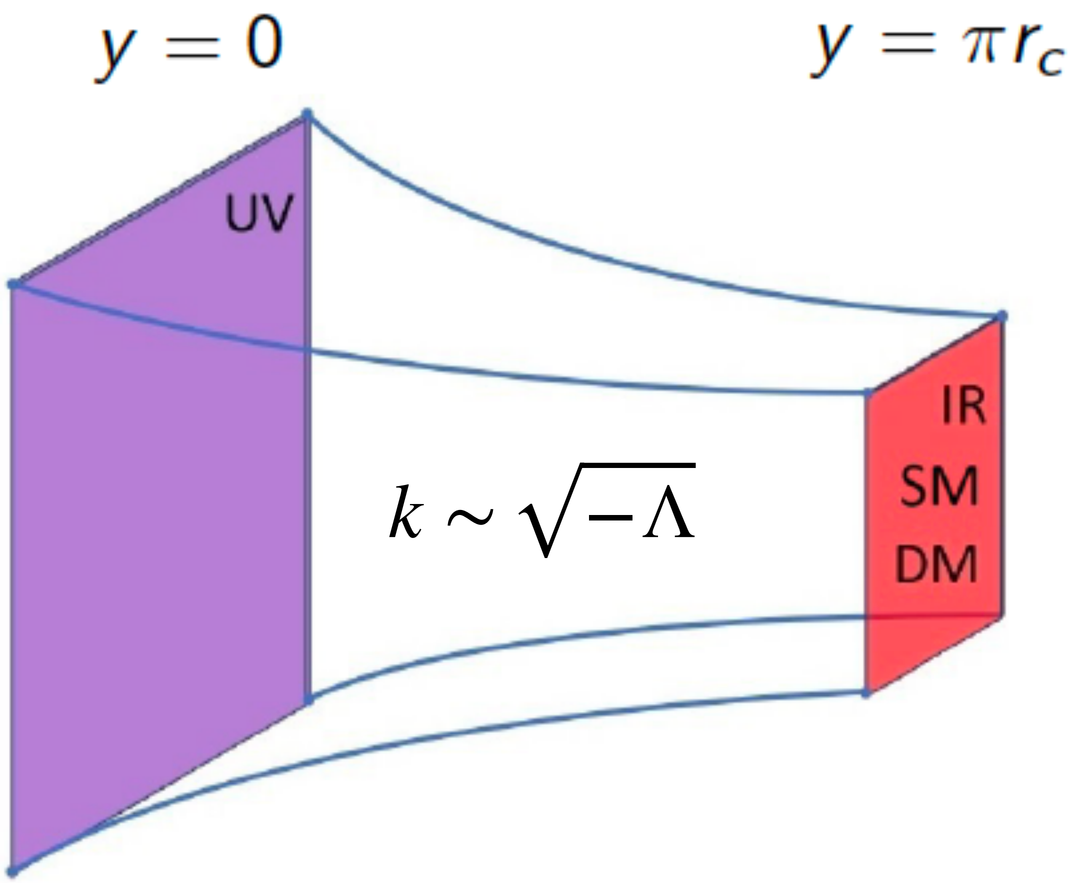
The Randall-Sundrum setup

ONE EXTRA-DIMENSION



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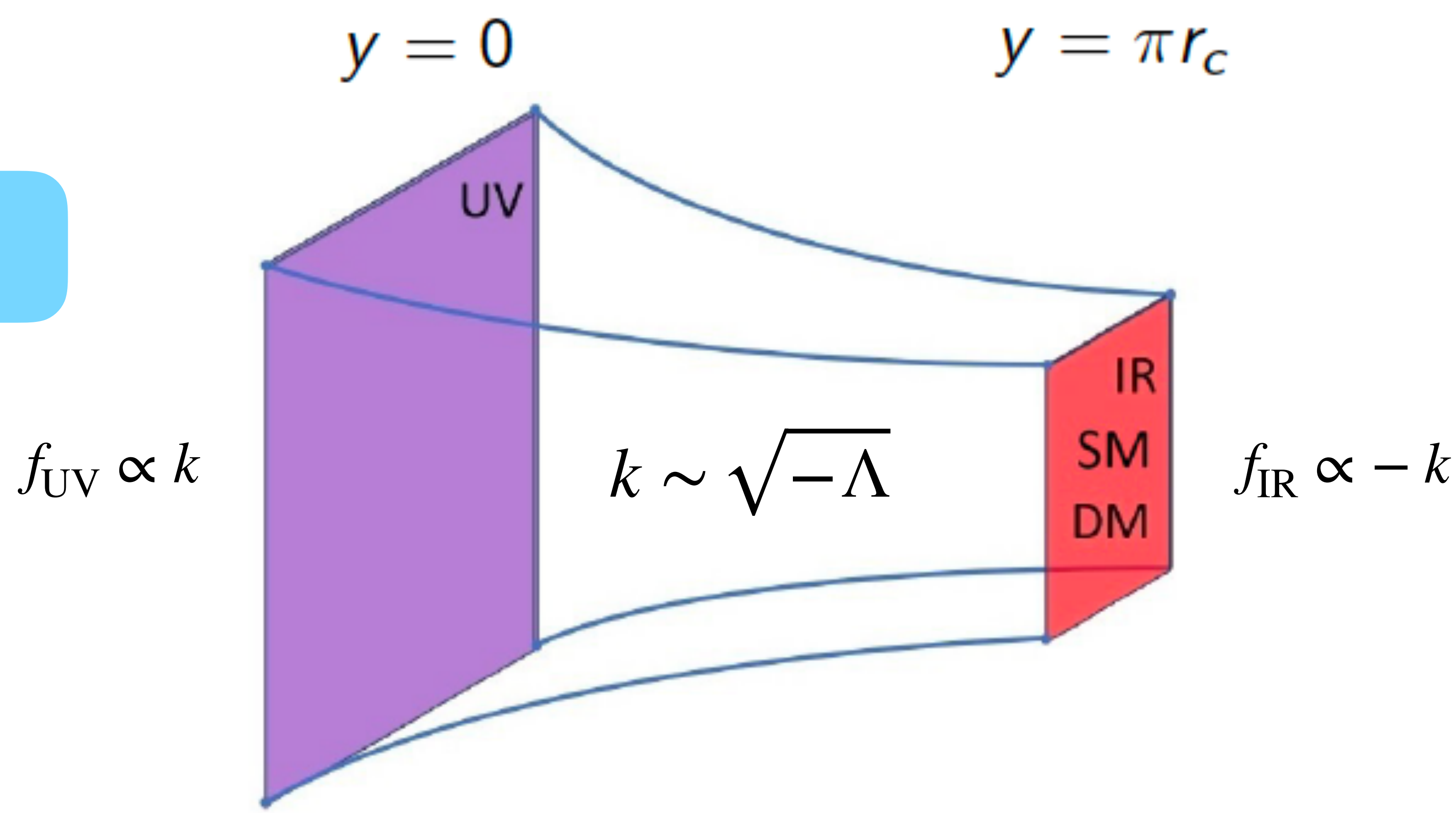

THE METRIC: $ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$

The Randall-Sundrum setup

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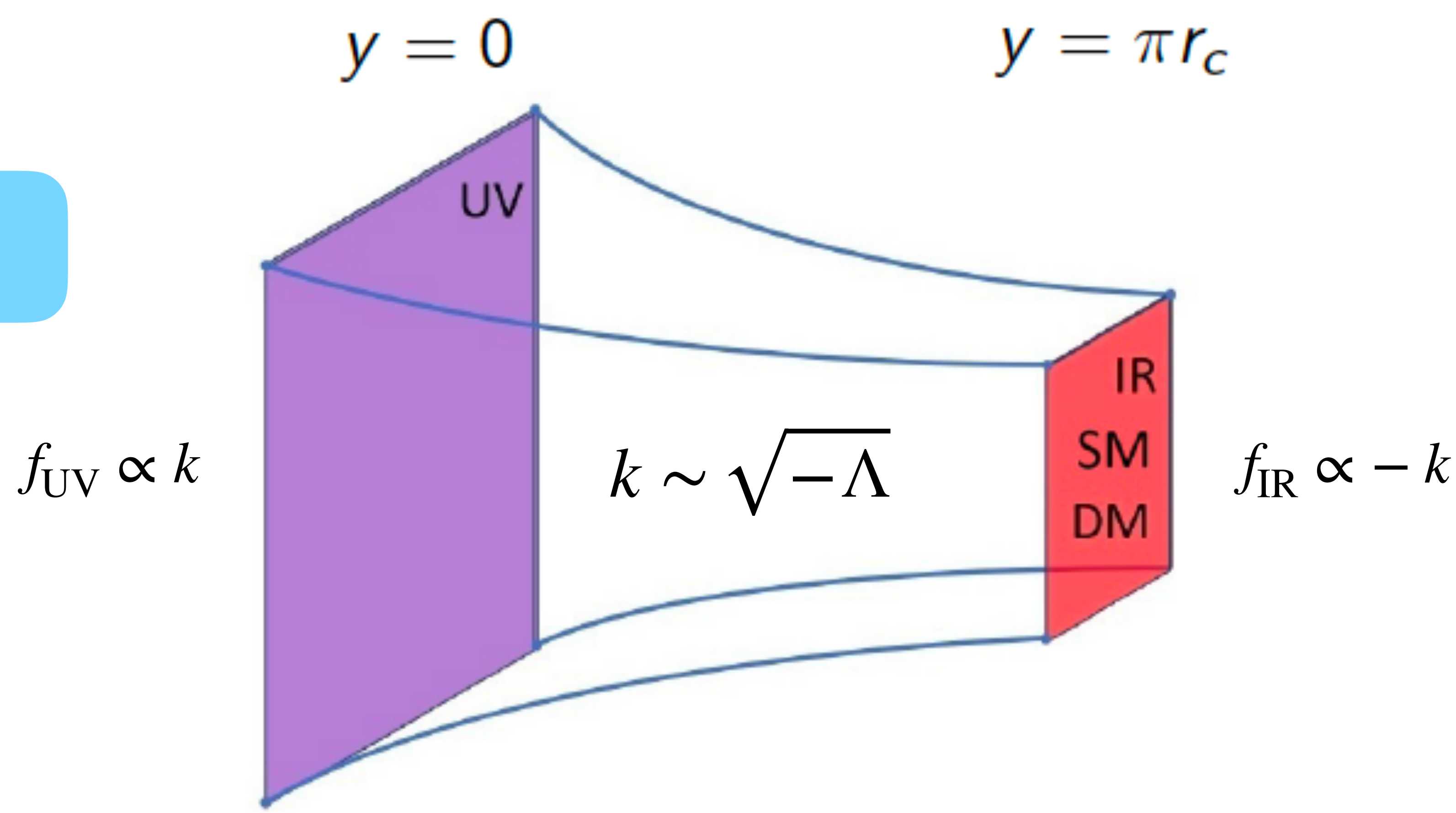

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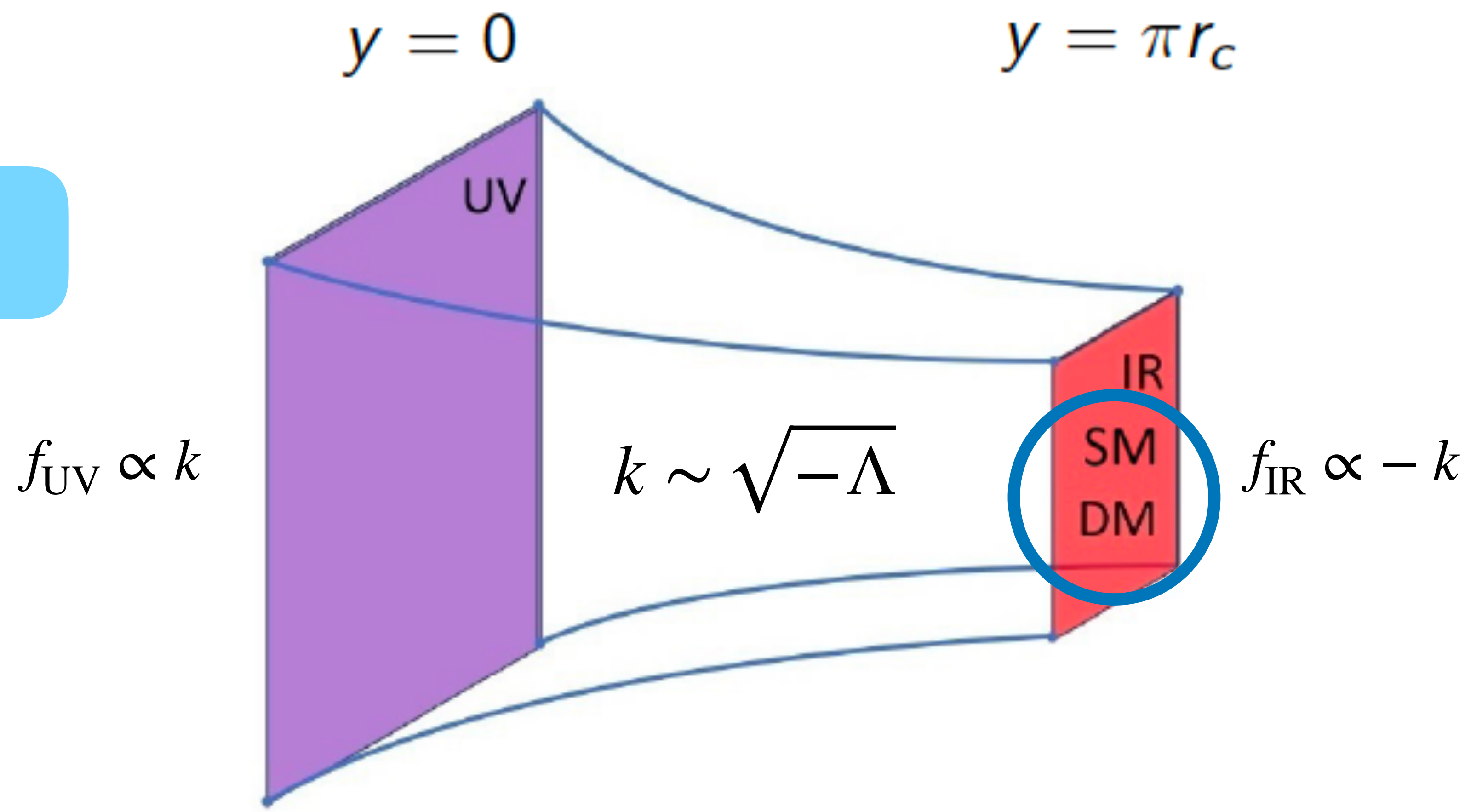

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THE COMPACTIFICATION: S^1/Z_2

DM on the IR-brane

$$S_{\text{RS}} = -4\, M_{5,\text{RS}}^3 \int d^4x \int_0^{\pi r_c} dy\, \sqrt{G^{(5)}} \left[R^{(5)} + 2\, \Lambda_5^{RS} \right]$$

Gravitational Action in the Einstein frame (+,-,-,-,-)

$$S_{\text{IR}} = \int d^4x \sqrt{-g}\, \left\{ -f_{\text{IR}}^4 + \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DM}} \right\}$$

$$S_{\text{UV}} = \int d^4x \sqrt{-g}\, \left\{ -f_{\text{UV}}^4 + \ldots \right\}$$

Branes Actions

Gravity d.o.f.'s and interactions

1. The massless graviton zero-mode: $h_{\mu\nu}^{(0)}$
2. A tower of massive KK gravitons: $h_{\mu\nu}^{(n)}$
3. The graviscalar zero-mode (aka the "radion"): r
4. One heavy Goldberger-Wise scalar: $\Phi^{(0)}$

$$\mathcal{L} = -\frac{1}{\bar{M}_P} T^{\mu\nu}(x) h^0_{\mu\nu}(x) - \frac{1}{\Lambda_{IR}} \sum_{n=1} T^{\mu\nu}(x) h^n_{\mu\nu}(x) + \frac{1}{\sqrt{6}\Lambda_{IR}} rT$$

$$\Lambda_{IR} = M_P\, e^{-\pi k r_c} \ll M_P$$

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Enhancement of gravitational couplings with respect to 4D

Gravity d.o.f.'s and interactions

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$m_n \sim x_n \Lambda_{\text{IR}}$

$m_r \sim \left(\frac{m}{k}\right)^2 \Lambda_{\text{IR}}$

$m_\Phi \sim \left(\frac{m}{k}\right)^2 M_{\text{P}}$

$$\mathcal{L} = -\frac{1}{M_{\text{P}}} T^{\mu\nu}(x) h^0_{\mu\nu}(x) - \frac{1}{\Lambda_{\text{IR}}} \sum_{n=1} T^{\mu\nu}(x) h^n_{\mu\nu}(x) + \frac{1}{\sqrt{6}\Lambda_{\text{IR}}} r T$$

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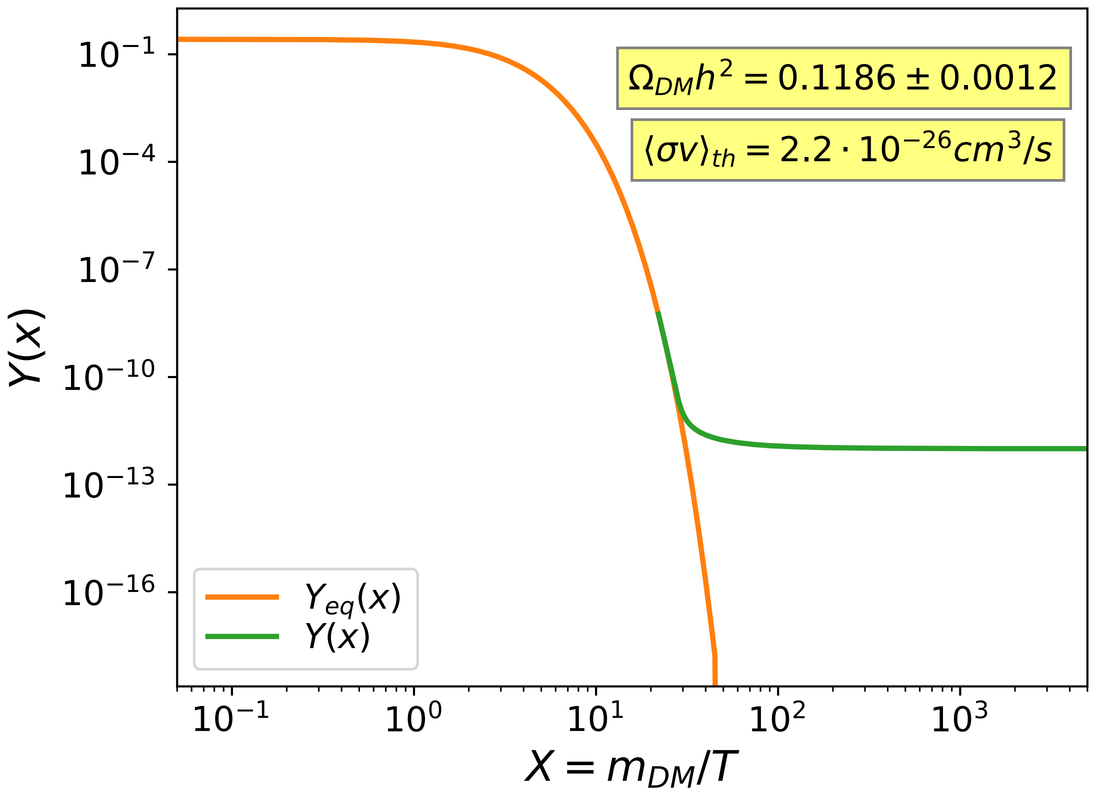
Enhancement of gravitational couplings with respect to 4D

Scalar DM on the IR brane



The Freeze-out of a WIMP

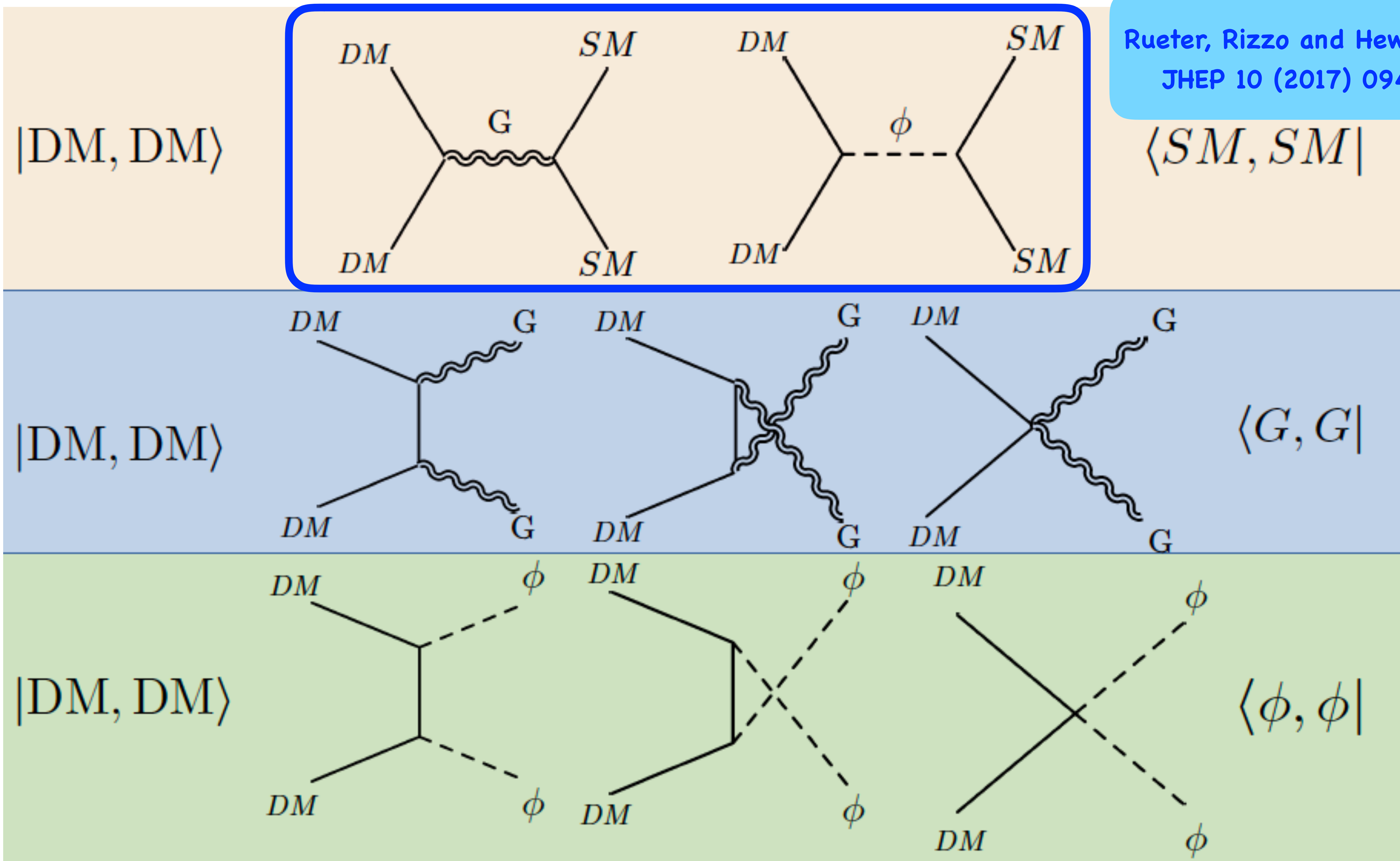
$$\frac{dY}{dx} = \frac{-x\langle\sigma v\rangle\mathfrak{s}}{H(m_{DM})}\left(Y^2(x) - Y_{eq}^2(x)\right)$$

Evolution of the DM density with the temperature

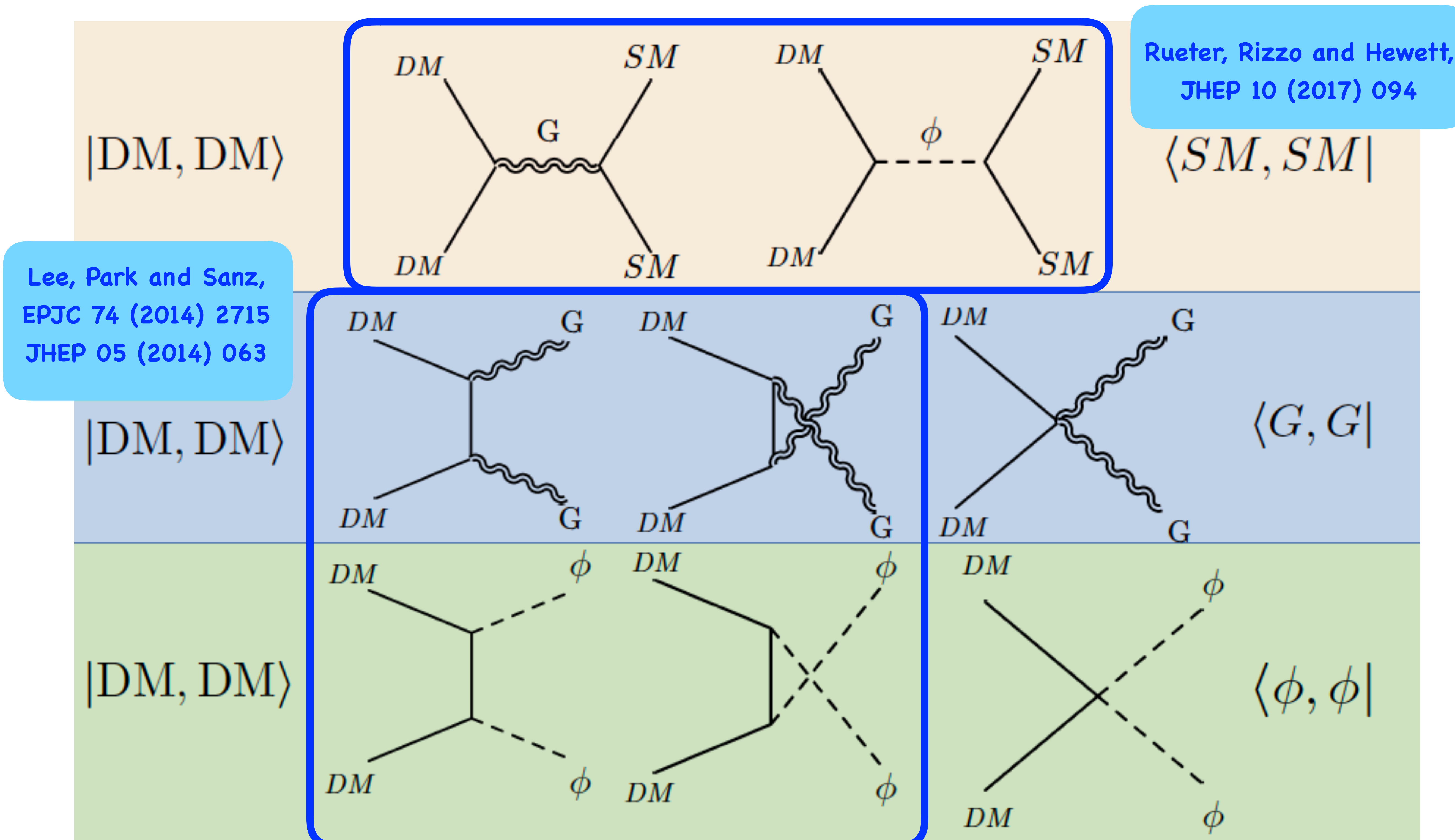
$$\langle\sigma v\rangle \sim \int_{4m_{DM}}^{\infty} ds(s-4m_{DM}^2)\sqrt{s}\sigma_{an}(s)K_1(\sqrt{s}/T) \;\; = 2.2\times 10^{-26}\mathrm{cm}^3/\mathrm{s}$$

DM annihilation

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



DM annihilation



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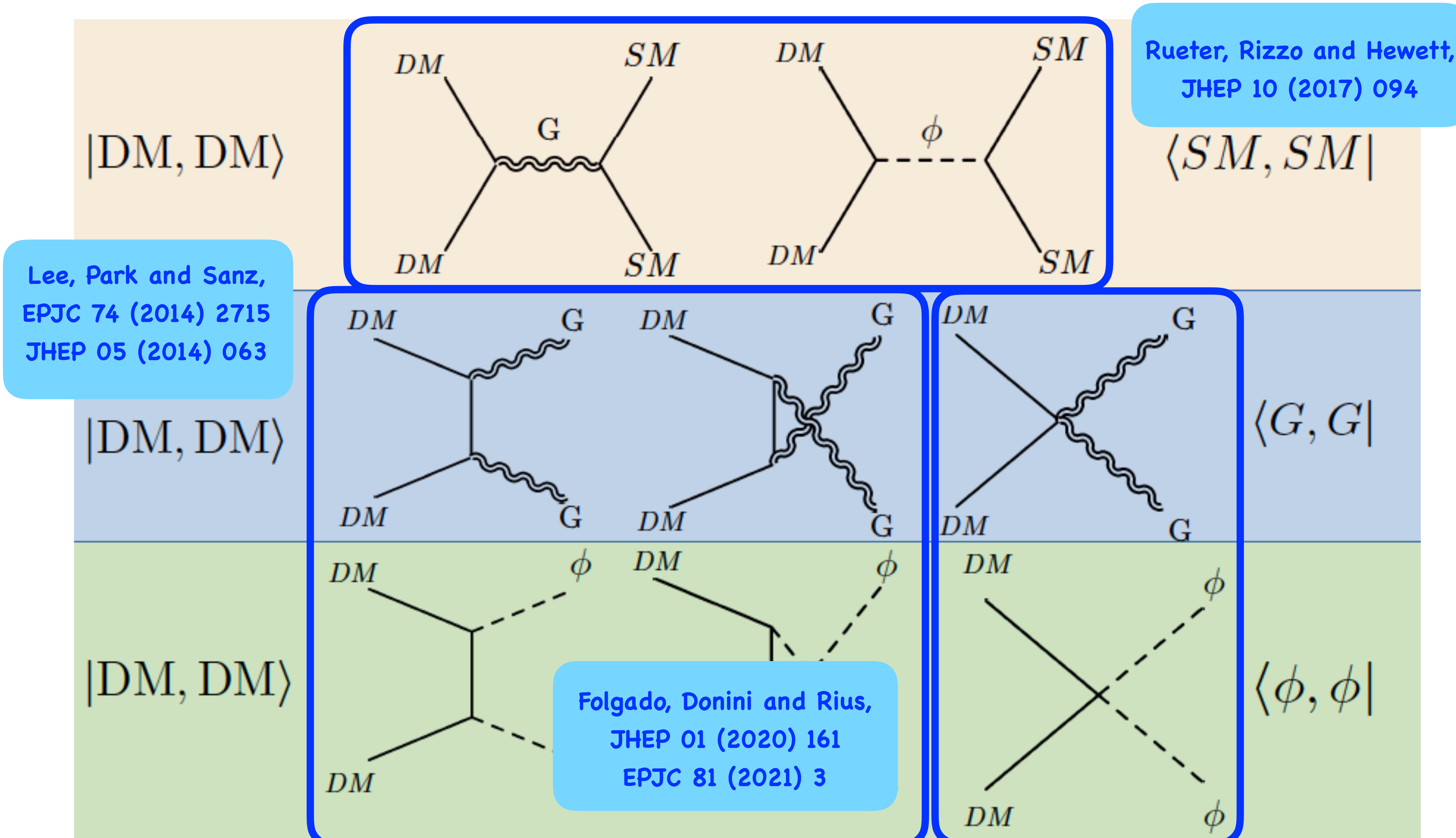
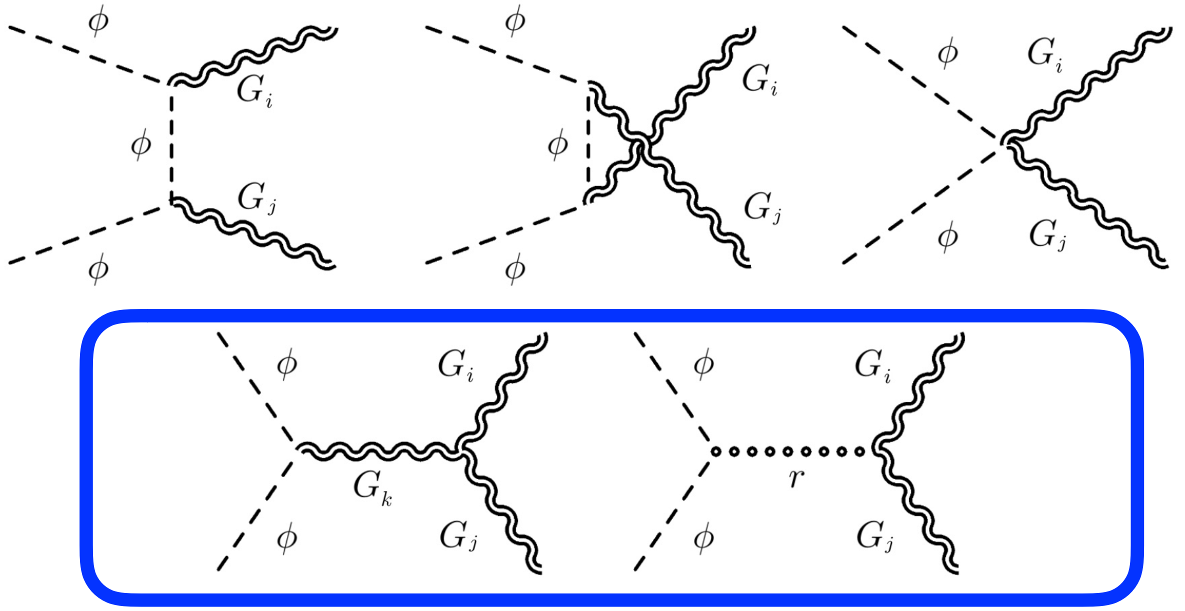
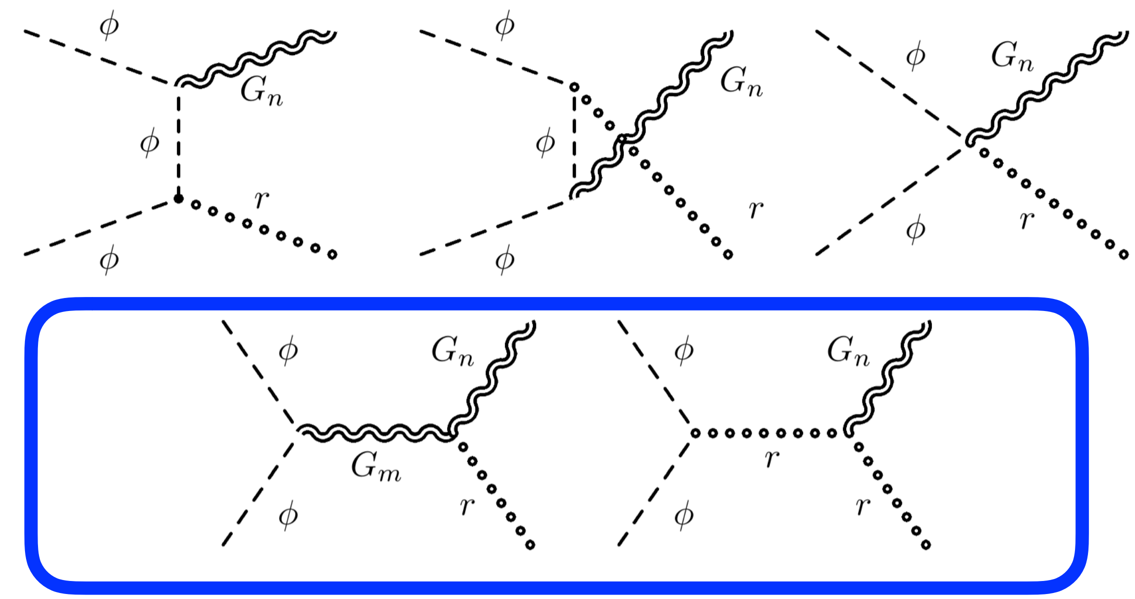


However… softening unitarity violation: $\mathcal{O}(s^3) \longrightarrow \mathcal{O}(s)$



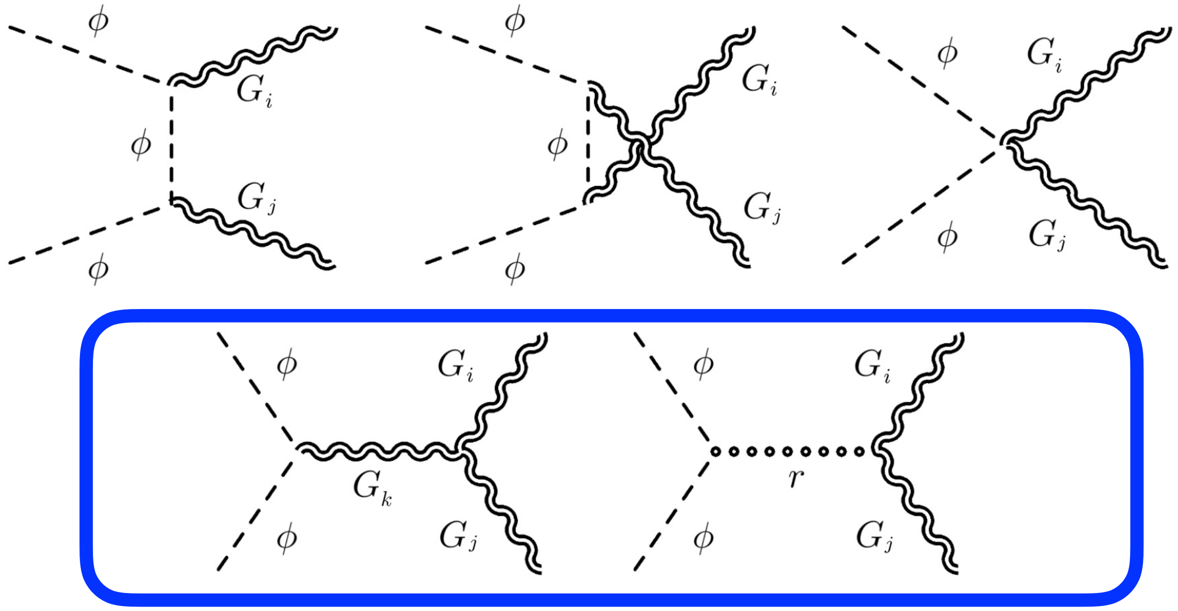


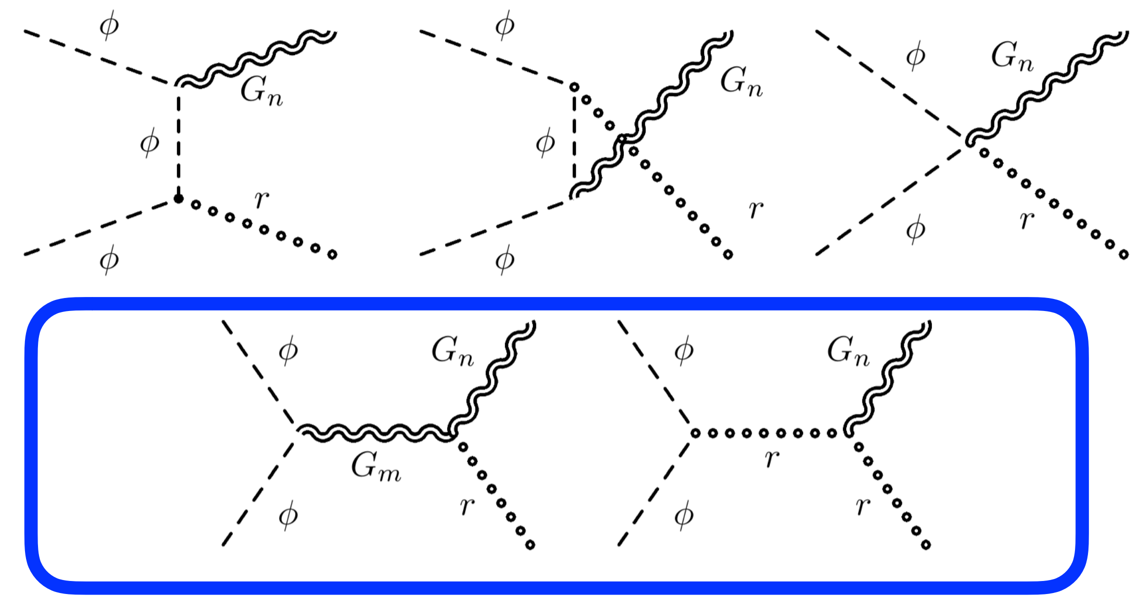
Triple graviton and radion vertices (and combinations) are

$\mathcal{O}(1/M_p)$

and not $\mathcal{O}(1/M_p^3)$ as one would naively think

However… softening unitarity violation: $\mathcal{O}(s^3) \longrightarrow \mathcal{O}(s)$





Triple graviton and radion vertices

Very constrained parameter space

ons) are

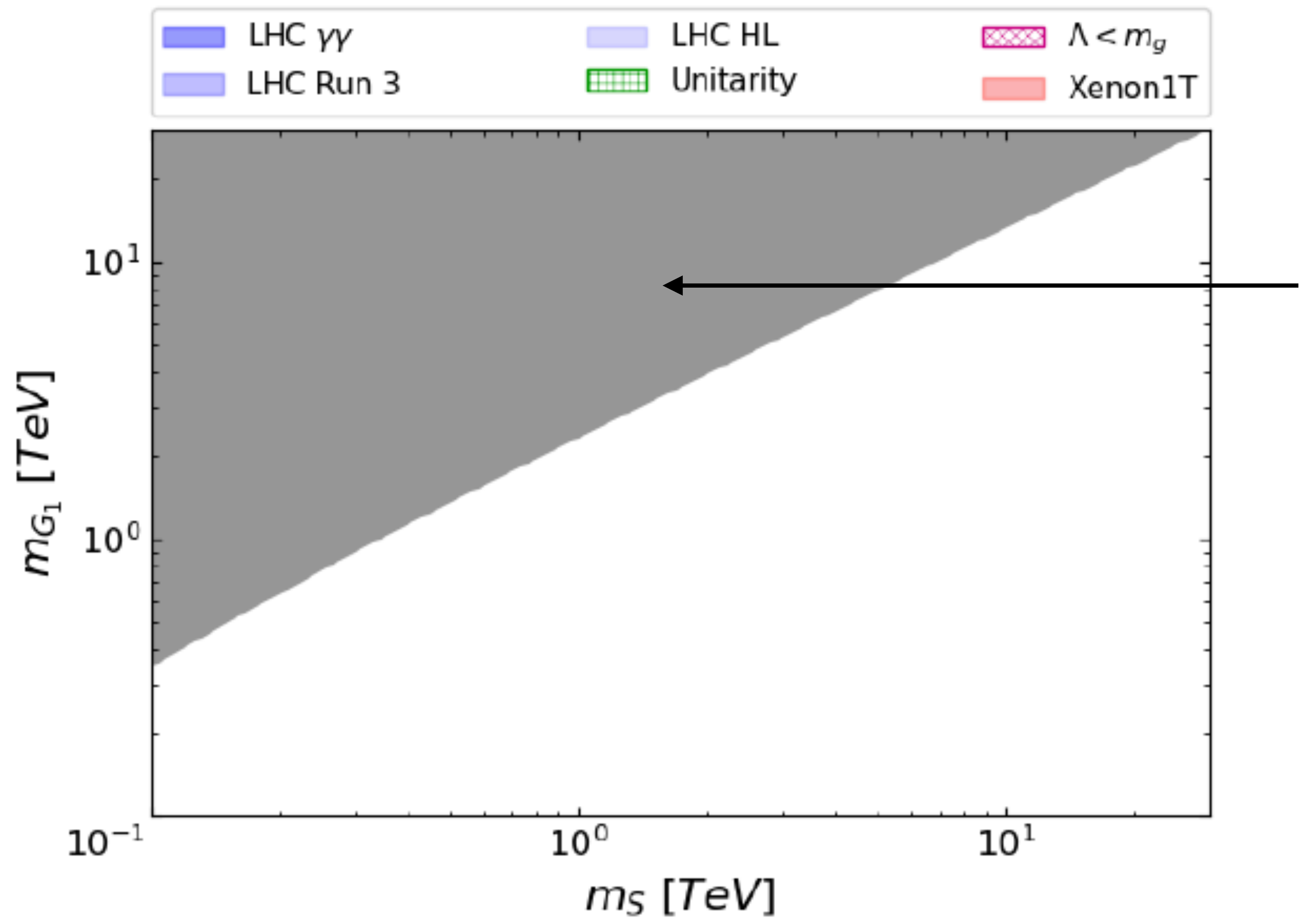
$\mathcal{O}$**(1/M$_p$)**

Chivukula et al. (2020,...), de Giorgi and Vogl (2021,...)...

and not $\mathcal{O}$(1/M$_p^3$) as one wo

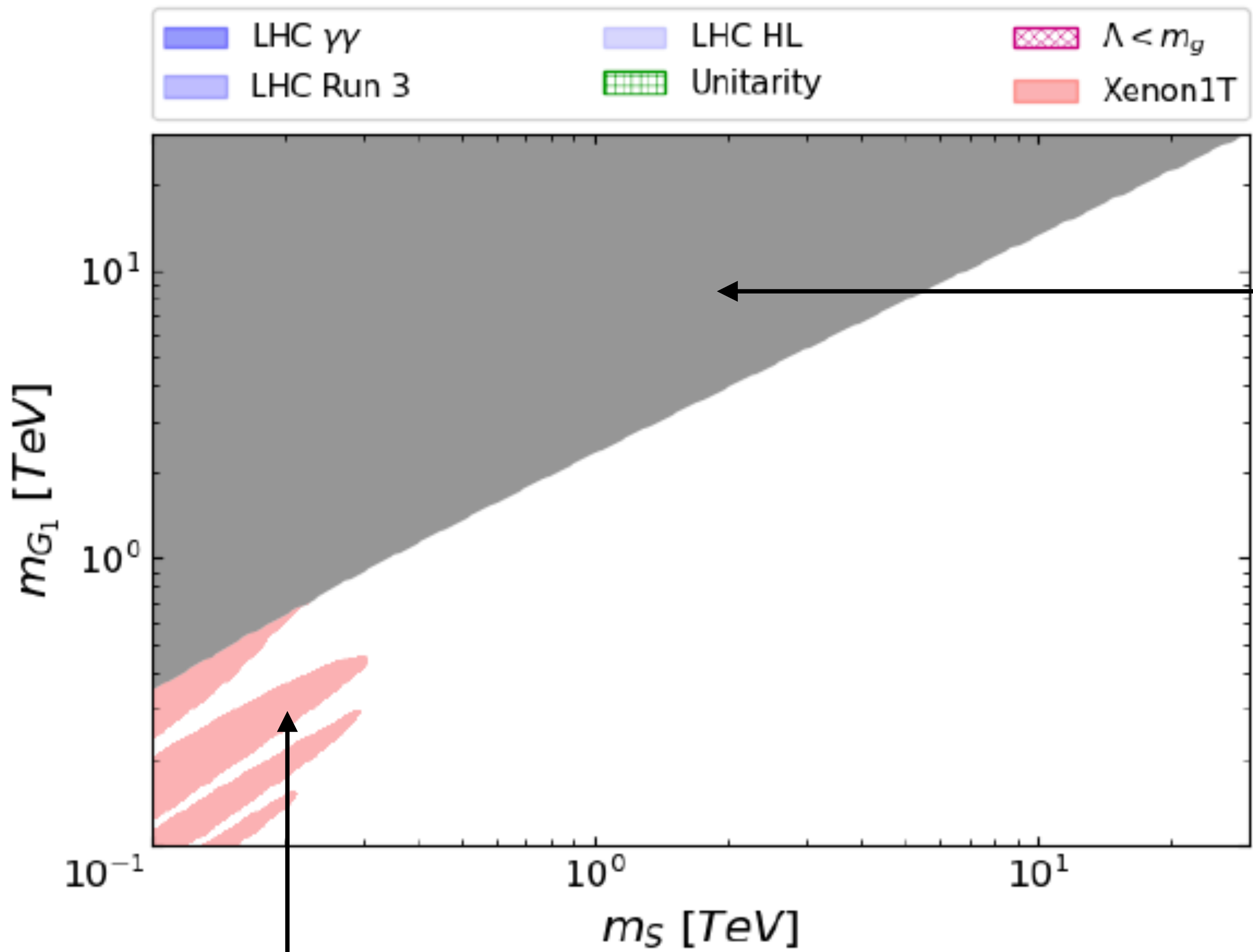
k

Adding constraints: RS



Allowed with a fine-tuned radion mass, excluded otherwise

Adding constraints: RS



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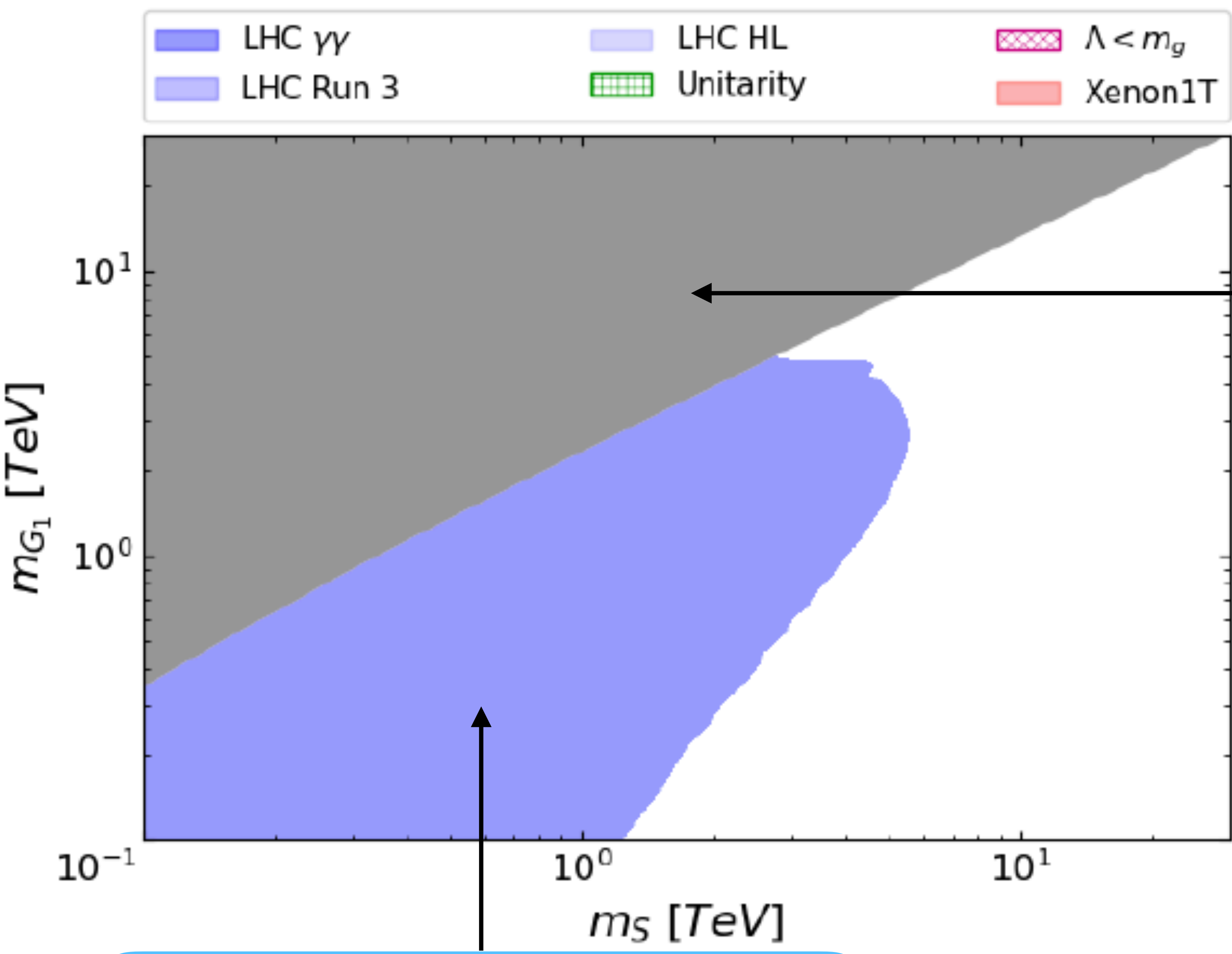
Xenon 1T Direct Detection bound

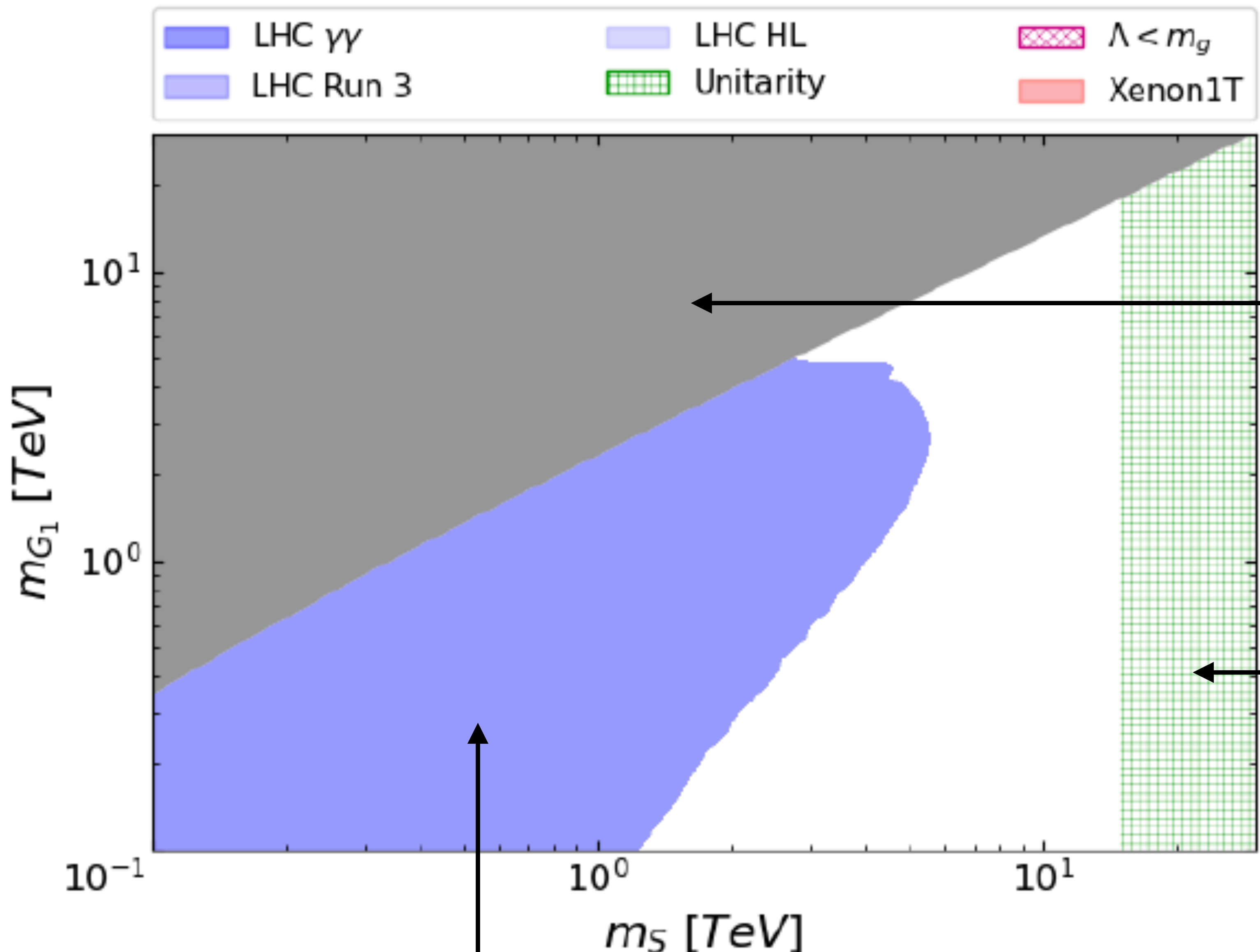
Adding constraints: RS



Allowed with a fine-tuned radion mass, excluded otherwise

36 fb^{-1} LHC Bound

Adding constraints: RS



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Unitarity

$$m_{\rm DM} < \frac{1}{\langle \sigma v \rangle}$$

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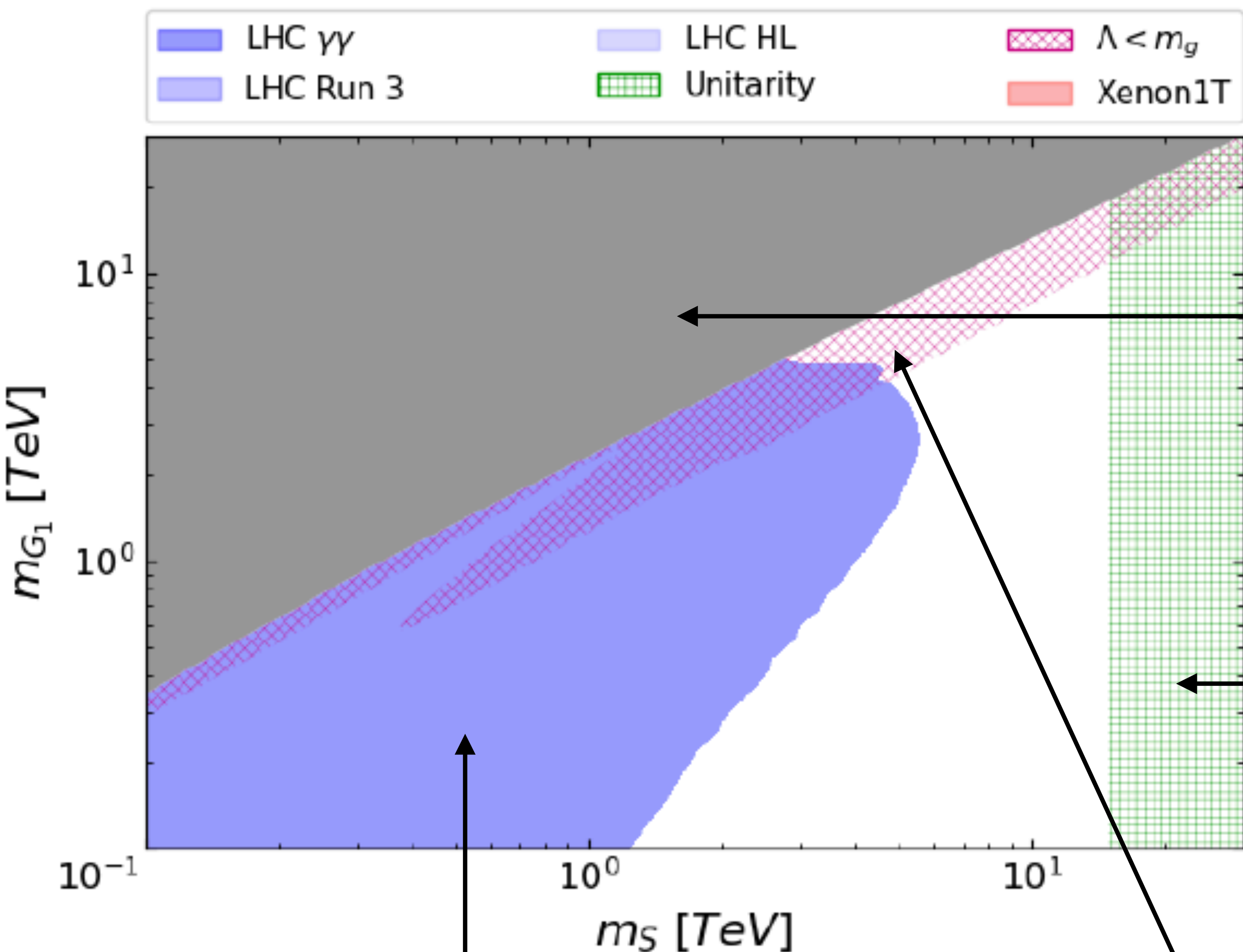

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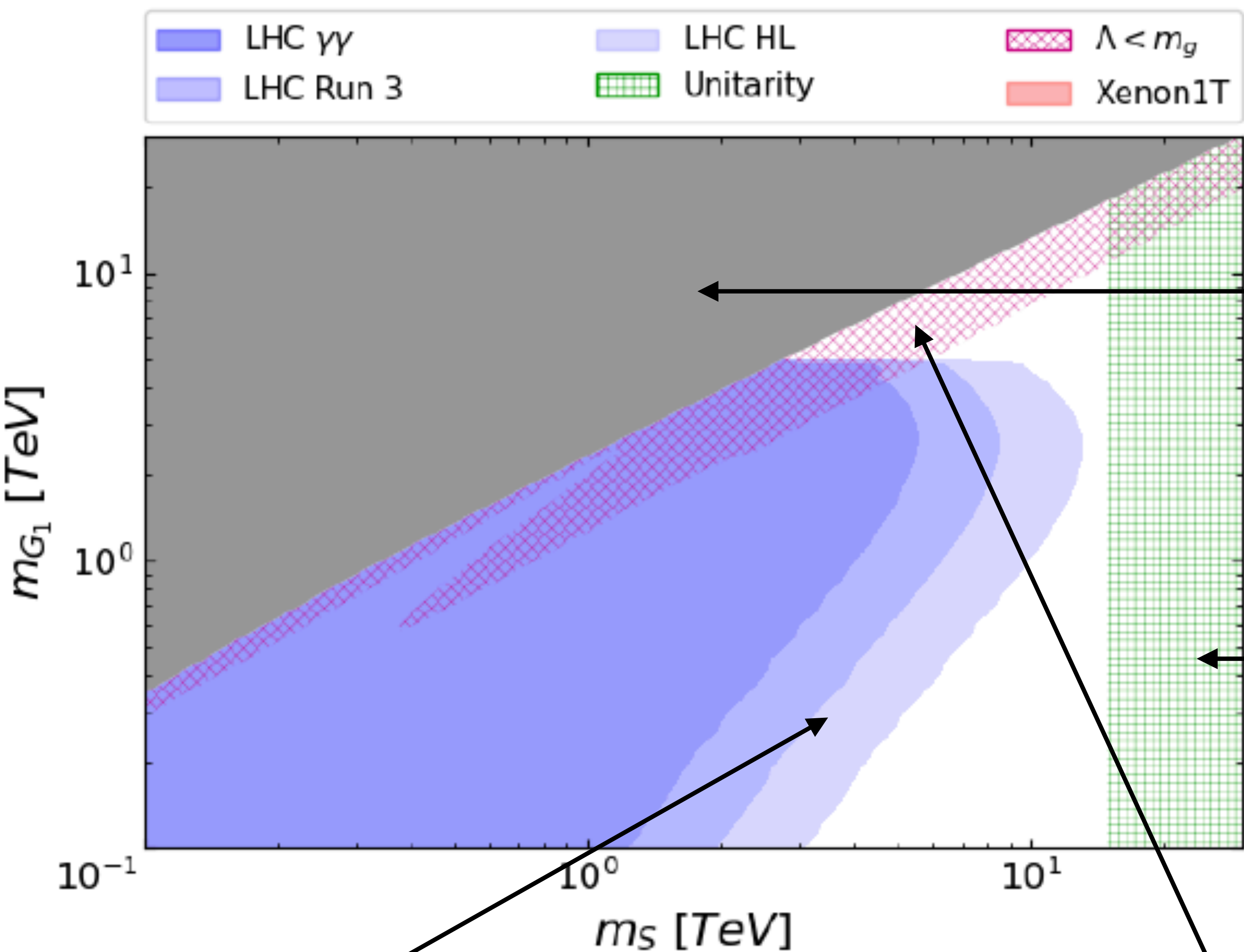
36 fb^{-1} LHC Bound

Consistency of the effective theory:
$\Lambda < m_{G1}, m_{DM}$

Adding constraints: RS



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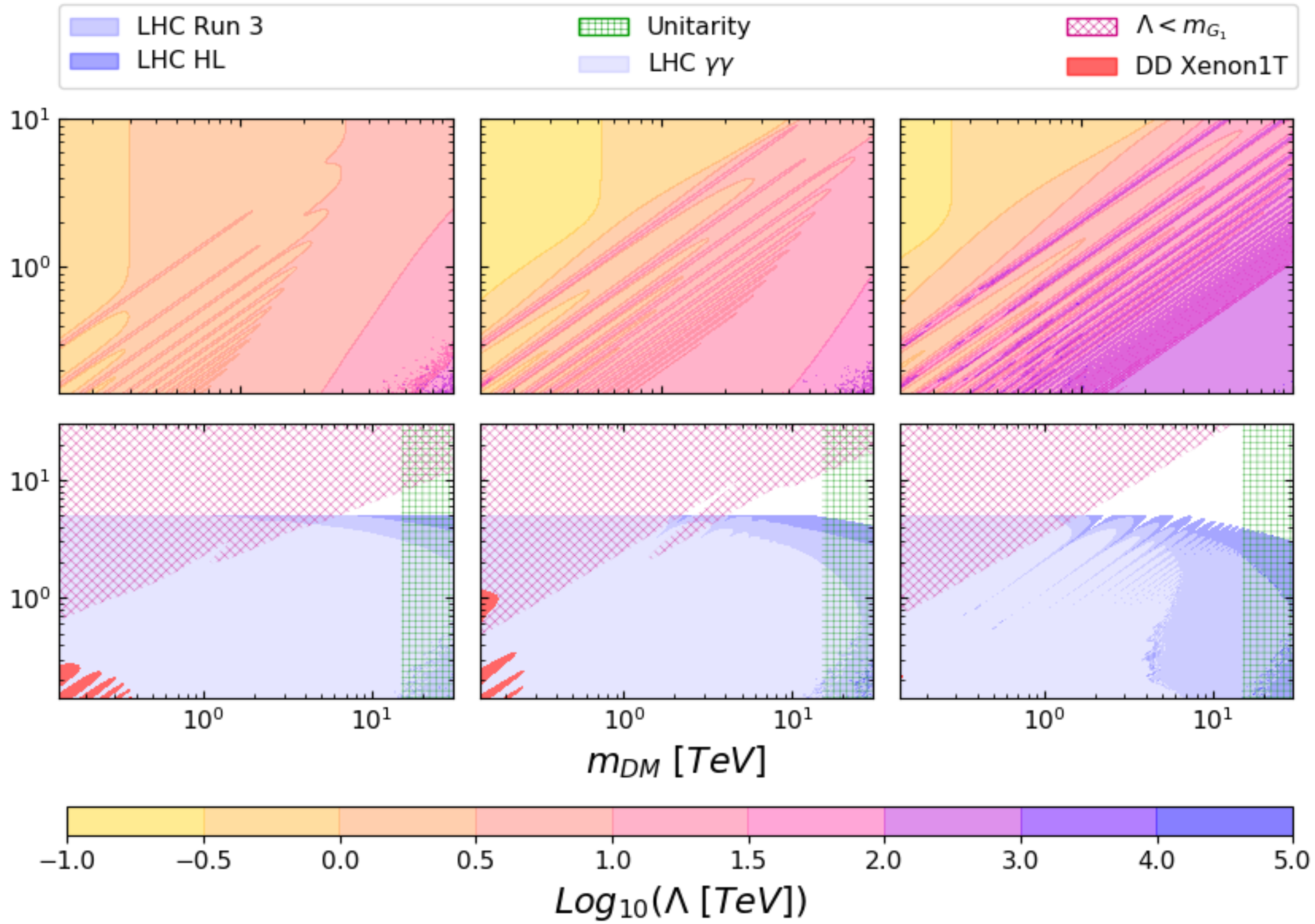
Foreseen Bounds at LHC Run III and HL-LHC

Final results: RS



Scalar DM **Dirac Fermion DM** **Vector DM**

Values of Λ needed to achieve Ω_{DM}

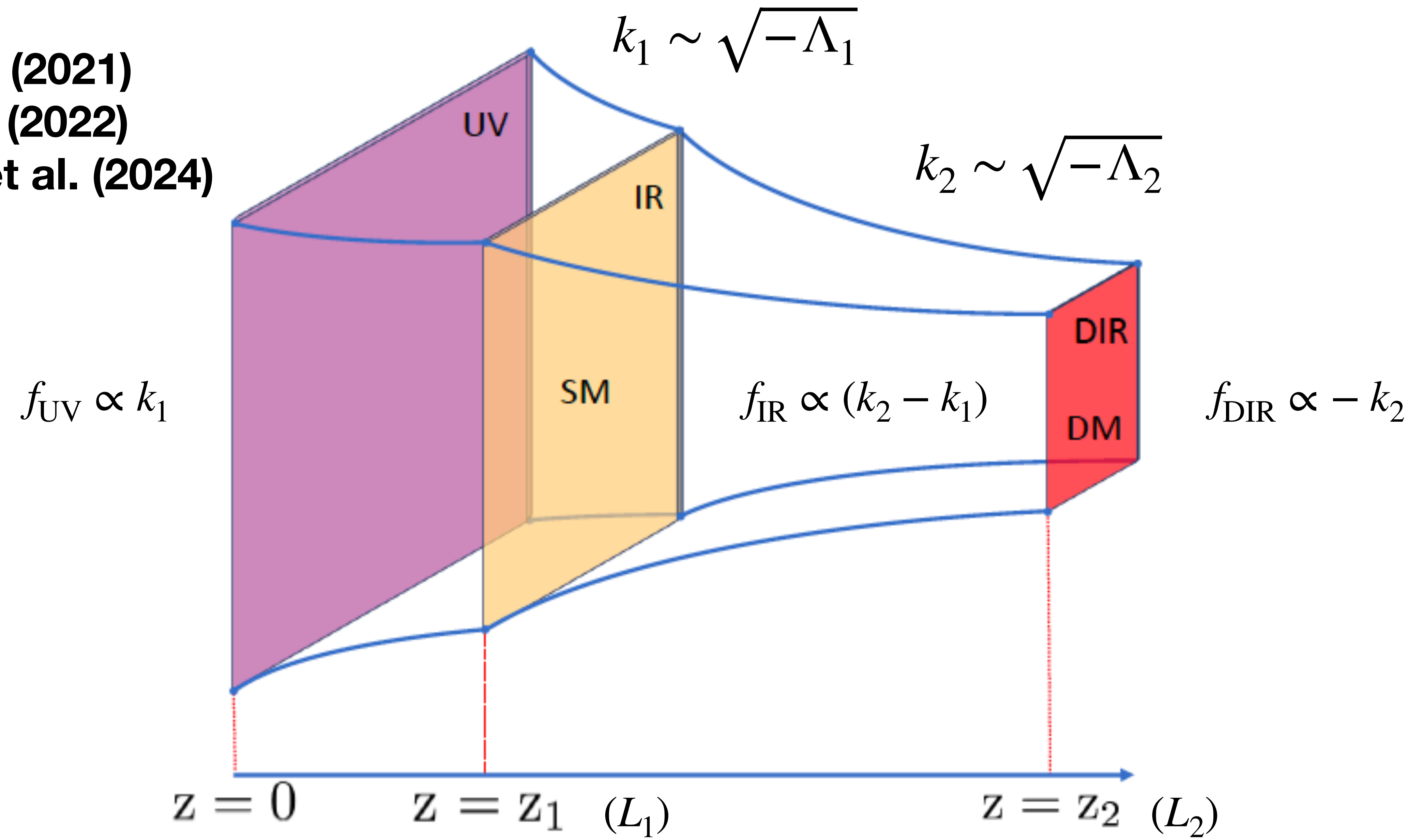
Allowed regions (after adding triple vertices)

Folgado Donini and Rius, Erratum: JHEP 02 (2022) 192

The three-brane Randall-Sundrum setup

Kogan et al. (2000)

Lee et al. (2021)
Cai et al. (2022)
Koustroulis et al. (2024)



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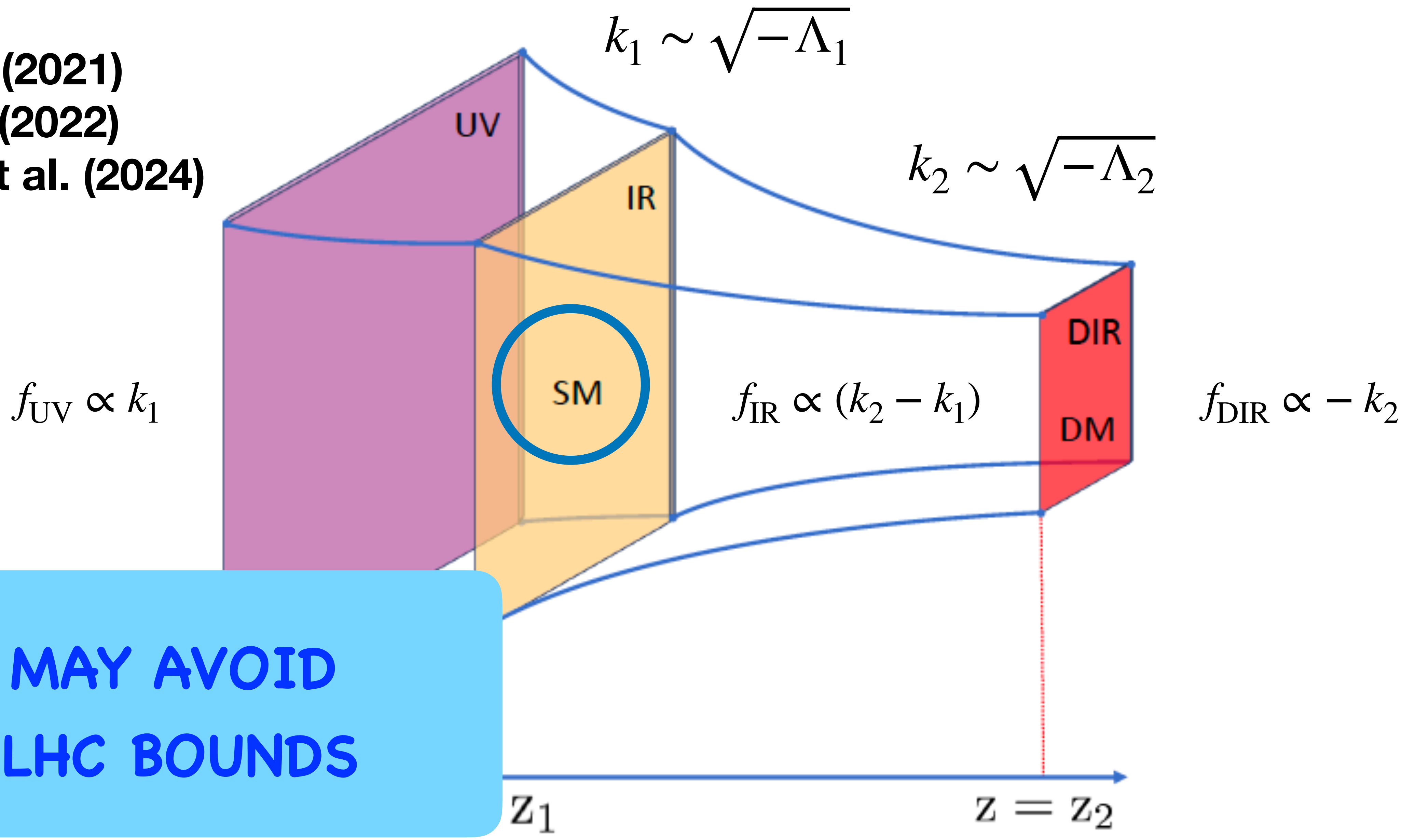

WE MAY AVOID THE LHC BOUNDS

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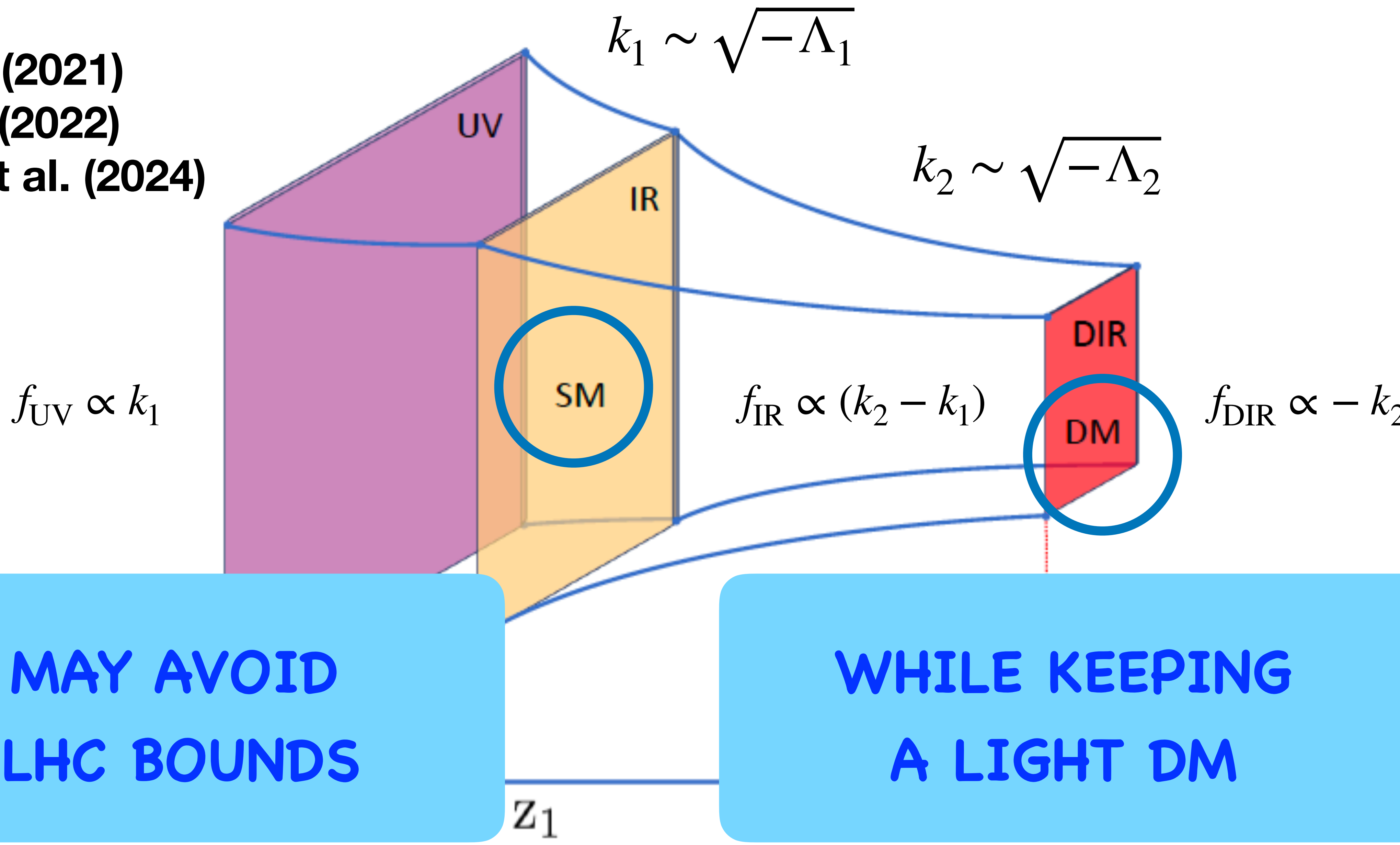

WE MAY AVOID THE LHC BOUNDS

WHILE KEEPING A LIGHT DM

Gravity d.o.f.'s and interactions

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3. A light graviscalar zero-mode (the "radion"): r_2
4. A heavy graviscalar zero-mode (a second radion?) r_1
5. Two heavy Goldberger-Wise scalars: $\Phi_1^{(0)}, \Phi_2^{(0)}$

$$\mathcal{L}_h = \frac{1}{\bar{M}_P} h_{\mu\nu}^{(0)}(x)\, T^{\mu\nu}(x) + \sum_{n=1}^{\infty} \frac{1}{\Lambda_{IR}^{n}} h_{\mu\nu}^{(n)}(x)\, T_{IR}^{\mu\nu}(x) + \sum_{n=1}^{\infty} \frac{1}{\Lambda_{DIR}} h_{\mu\nu}^{(n)}(x)\, T_{DIR}^{\mu\nu}(x) + \frac{1}{\sqrt{6}\Lambda_{IR}} r T_{IR} + \frac{1}{\sqrt{6}\Lambda_{DIR}} r T_{DIR}$$

$$\Lambda_{IR} = M_P\, e^{-\pi k_1 L_1} \ll M_P$$

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$$\Lambda_{IR} = M_P\, e^{-\pi k_1 L_1} \ll M_P \qquad \Lambda_{DIR} = M_P\, e^{-k_1 L_1}\, e^{-k_2(L_2 - L_1)} < \Lambda_{IR}$$

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$m_n \sim x_n \Lambda_{\rm DIR}$

$m_{r_2} \sim \left(\frac{m_2}{k_2}\right)^2 \Lambda_{\rm DIR}$

$m_{r_1} \sim \left(\frac{m_1}{k_2 - k_1}\right)^2 \Lambda_{\rm DIR}$

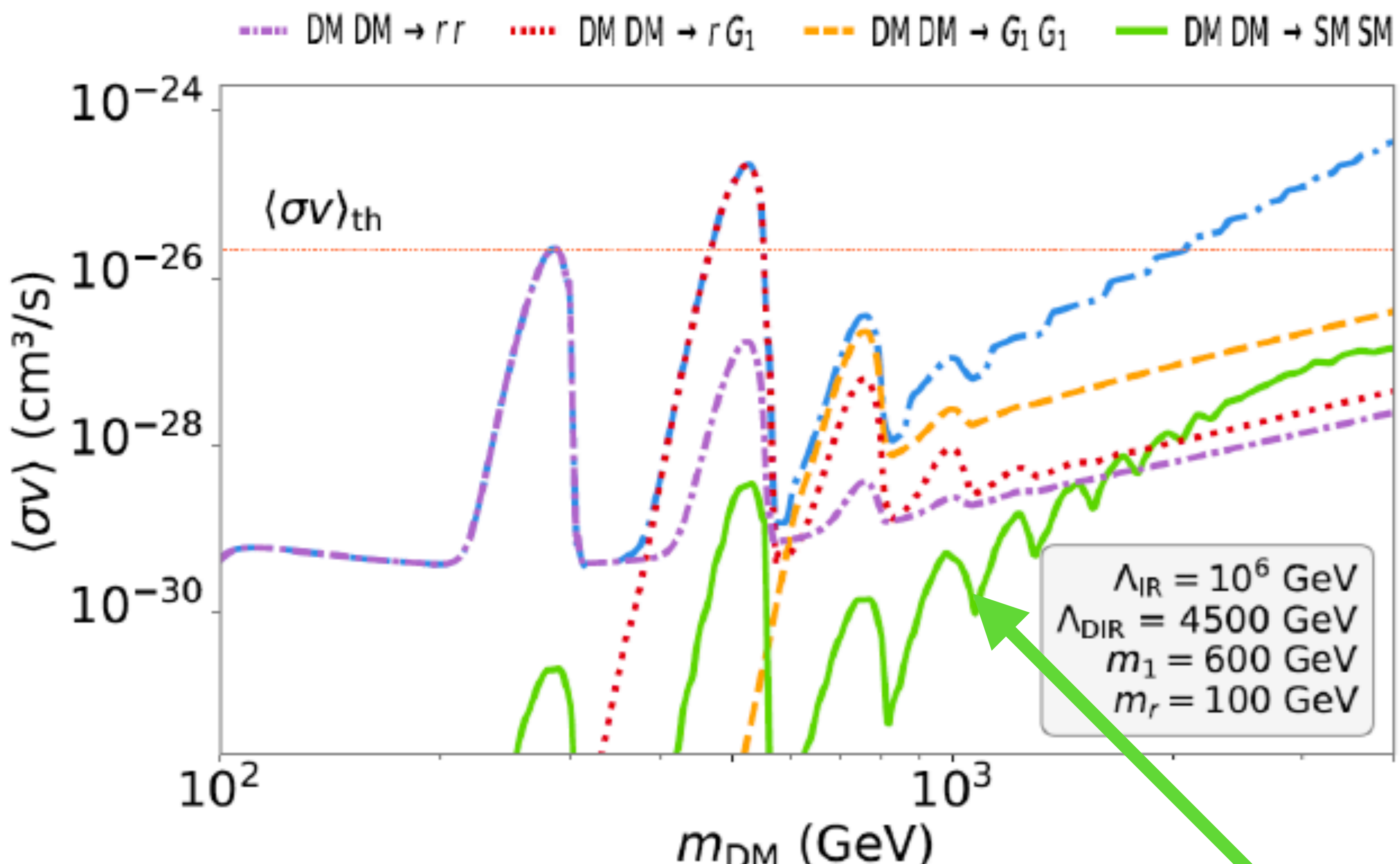
$m_{\Phi_1,\Phi_2} \sim \left(\frac{m_i}{k_i}\right)^2 M_{\rm P}$

$$\mathcal{L}_h = \frac{1}{M_{\rm P}}\, h_{\mu\nu}^{(0)}(x)\, T^{\mu\nu}(x) + \sum_{n=1}^{\infty} \frac{1}{\Lambda_{\rm IR}^n}\, h_{\mu\nu}^{(n)}(x)\, T_{\rm IR}^{\mu\nu}(x) + \sum_{n=1}^{\infty} \frac{1}{\Lambda_{\rm DIR}}\, h_{\mu\nu}^{(n)}(x)\, T_{\rm DIR}^{\mu\nu}(x) + \frac{1}{\sqrt{6}\Lambda_{\rm IR}}\, r T_{\rm IR} + \frac{1}{\sqrt{6}\Lambda_{\rm DIR}}\, r T_{\rm DIR}$$

$\Lambda_{\rm IR} = M_{\rm P}\, e^{-\pi k_1 L_1} \ll M_{\rm P}$

$\Lambda_{\rm DIR} = M_{\rm P}\, e^{-k_1 L_1}\, e^{-k_2 (L_2 - L_1)} < \Lambda_{\rm IR}$

DM Annihilation Channels

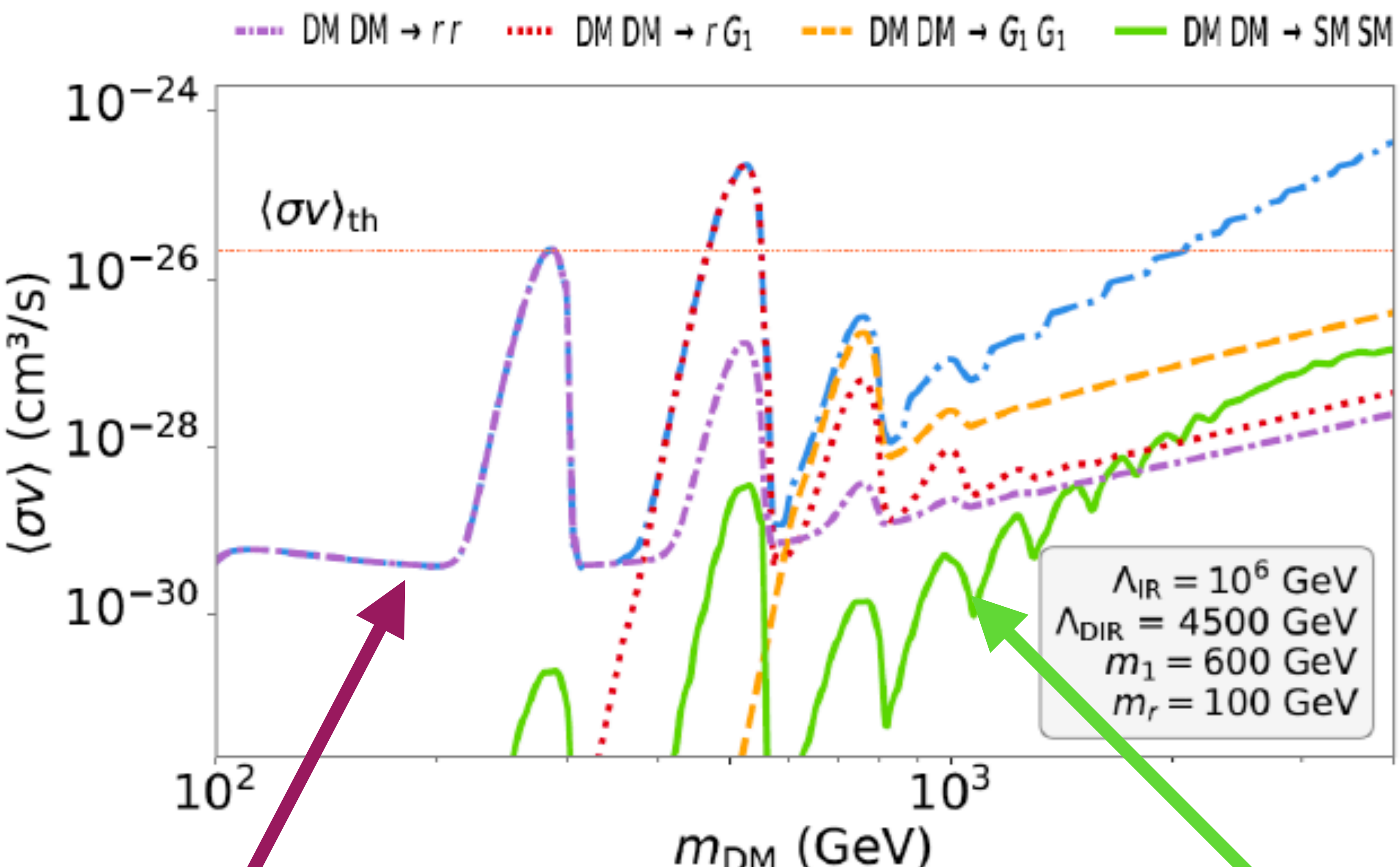


$\langle \sigma_{\rm FO}\, v \rangle$

DM DM -> SM SM

$$\propto \frac{1}{\Lambda_{\rm DIR}^2}\,\frac{1}{\Lambda_{\rm IR}^2}$$

DM Annihilation Channels



$\langle \sigma_{\mathrm{FO}}\, v \rangle$

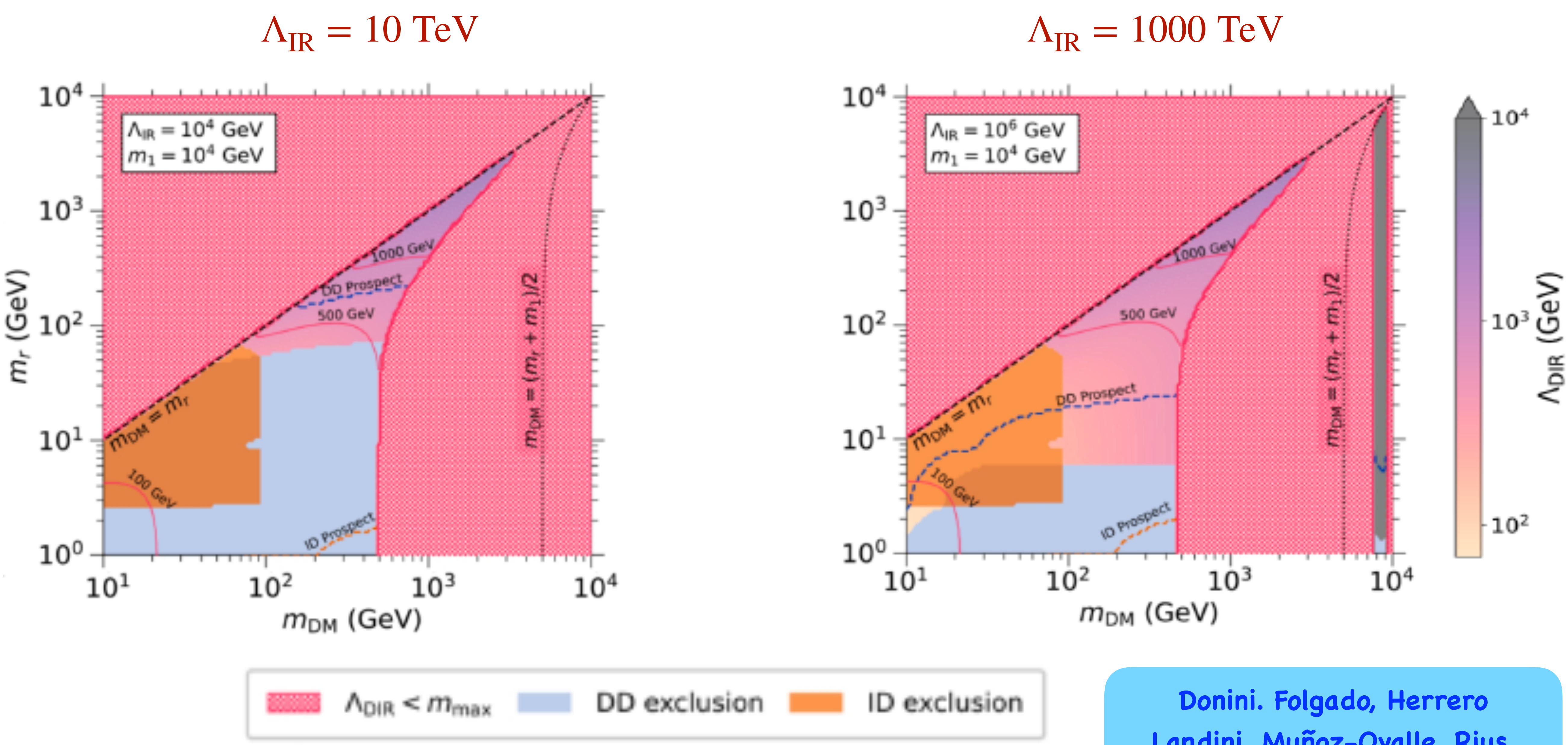
DM DM -> G_m G_n; G_m r; r r

DM DM -> SM SM

$\propto \frac{1}{\Lambda_{\mathrm{DIR}}^4}$

$\propto \frac{1}{\Lambda_{\mathrm{DIR}}^2} \frac{1}{\Lambda_{\mathrm{IR}}^2}$

The evanescent limit: $k_2 = k_1$



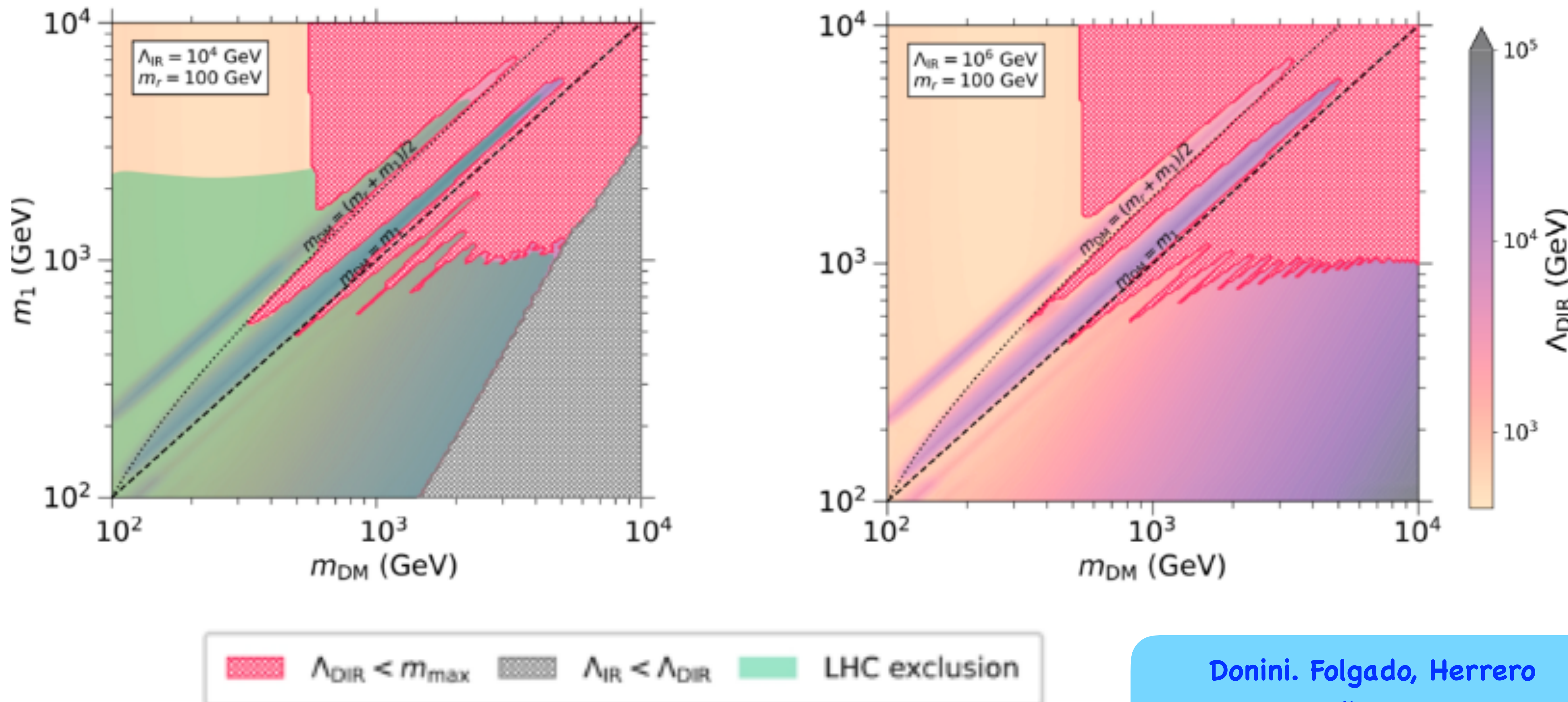
remind that $f_{IR} \propto (k_2 - k_1)$

Donini. Folgado, Herrero Landini, Muñoz-Ovalle, Rius, 2505.13601

The evanescent limit: $k_2 = k_1$

$\Lambda_{\rm IR} = 10$ TeV

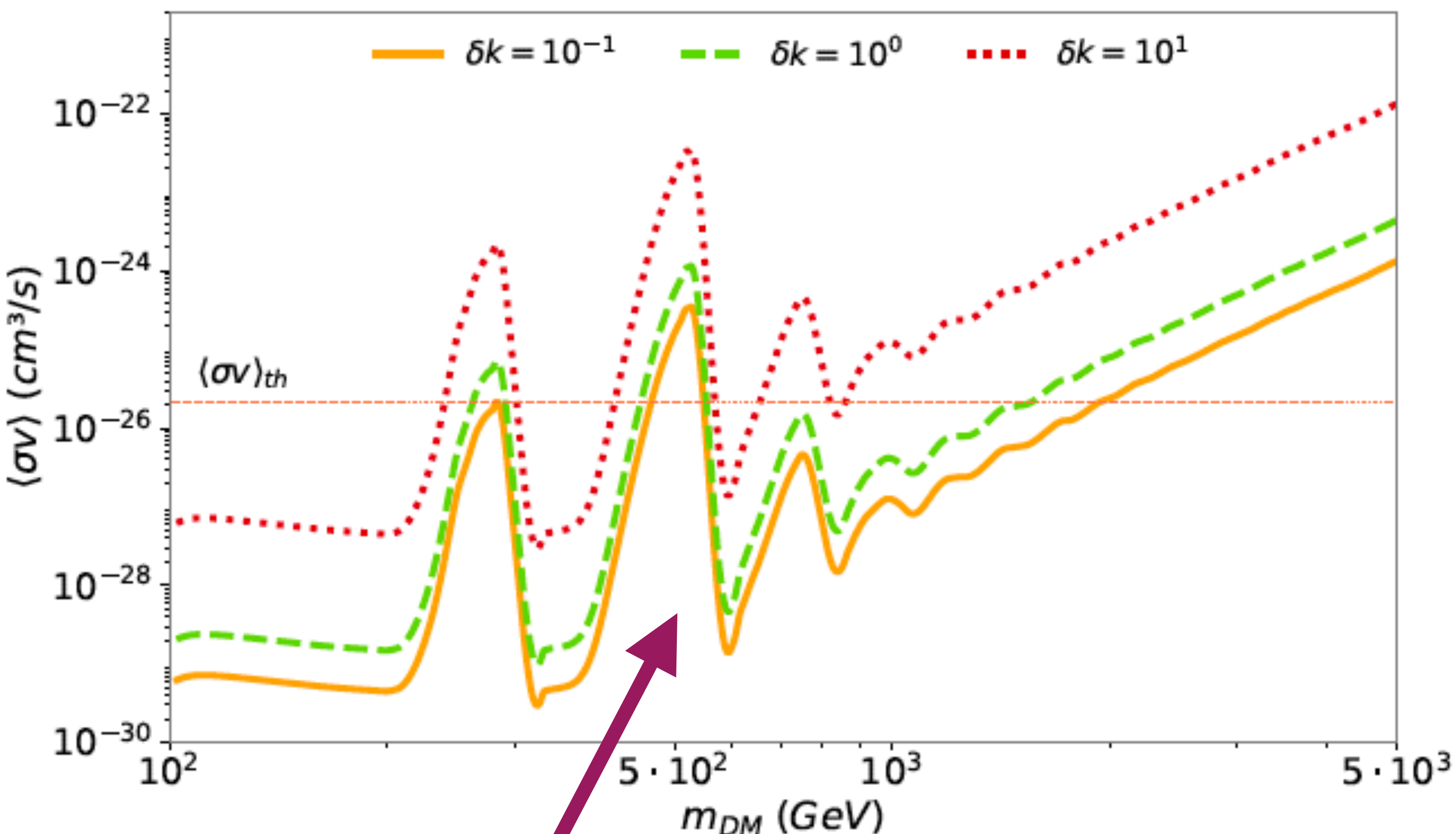
$\Lambda_{\rm IR} = 1000$ TeV



Donini. Folgado, Herrero Landini, Muñoz-Ovalle, Rius, 2505.13601

remind that $f_{\rm IR} \propto (k_2 - k_1)$

Out of the evanescent limit: $k_2 > k_1$



DM DM -> G_m G_n; G_m r; r r

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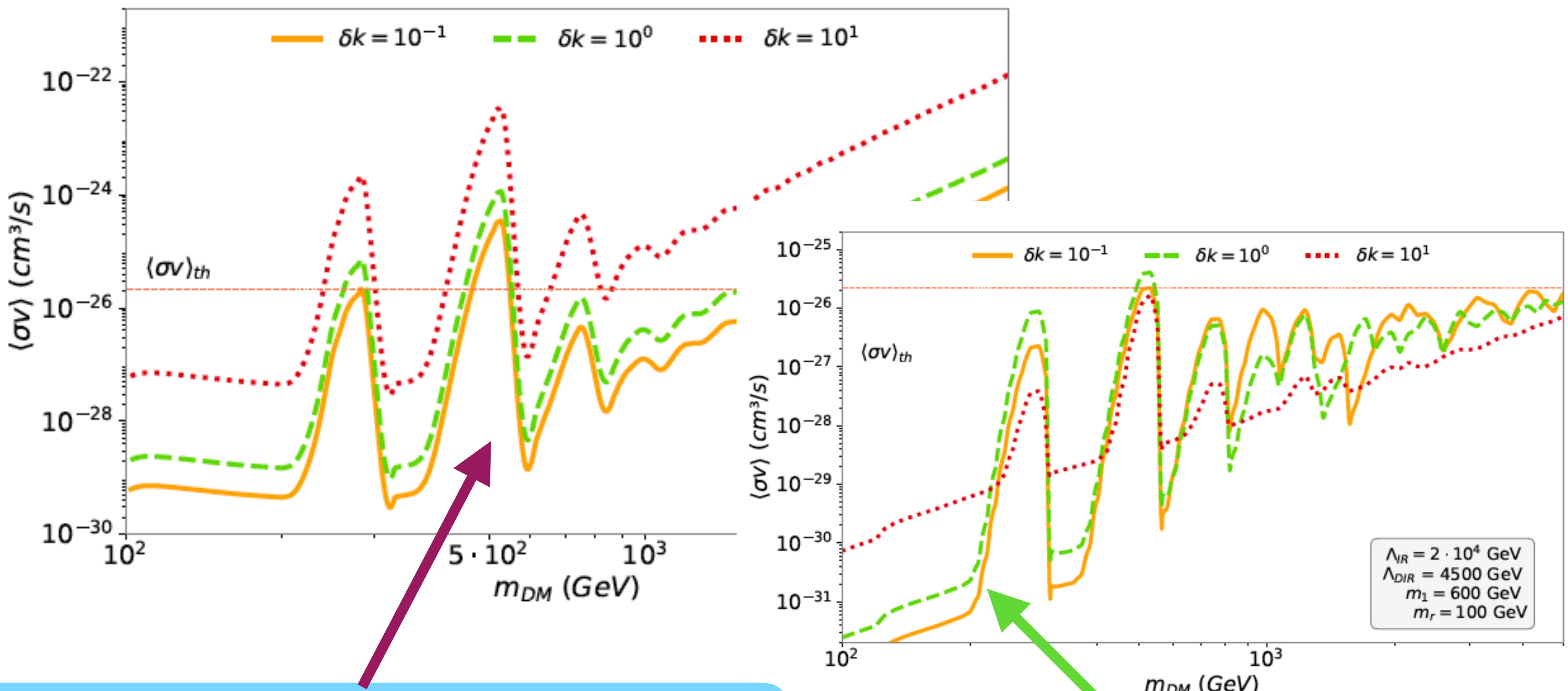


DM DM -> G_m G_n; G_m r; r r

DM DM -> SM SM

Conclusions

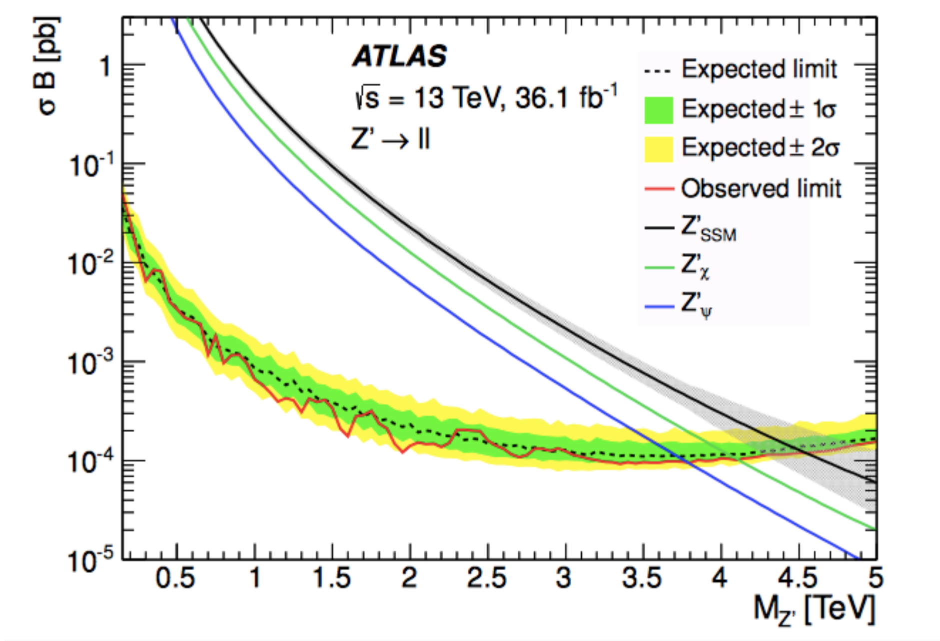
WITHIN THE FREEZE-OUT PARADIGM:

We may achieve the observed DM relic abundance in the two-brane RS model in a very small region of the parameter space

We may achieve the observed DM relic abundance in the three-brane RS model, in and out of the evanescent limit, in a rather large region of the parameter space

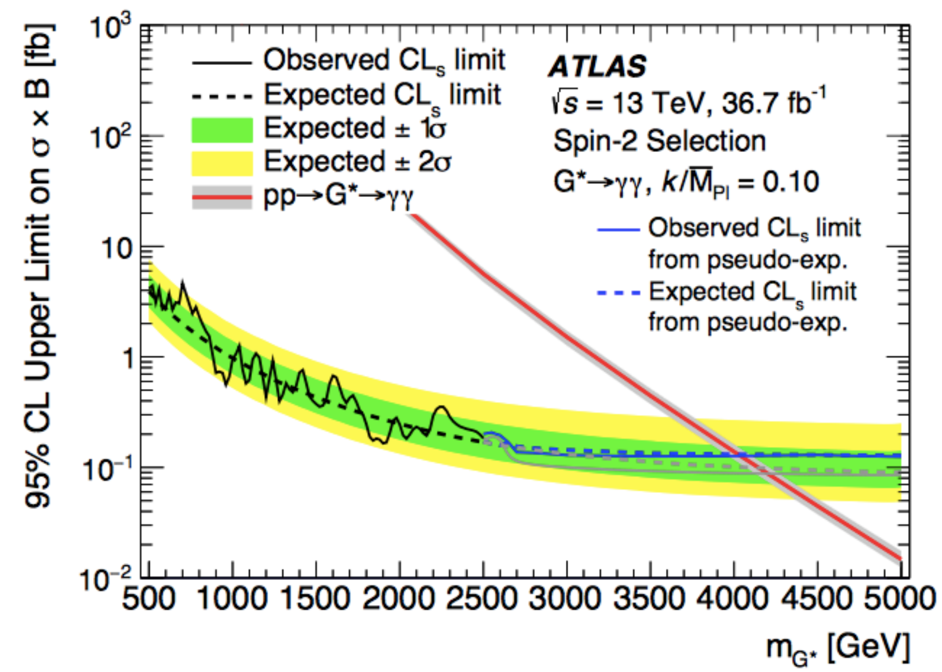
Backup slides

LHC bounds: RS



ATLAS: Search for new phenomena in high-mass dilepton final states using 37

(1707.02424)

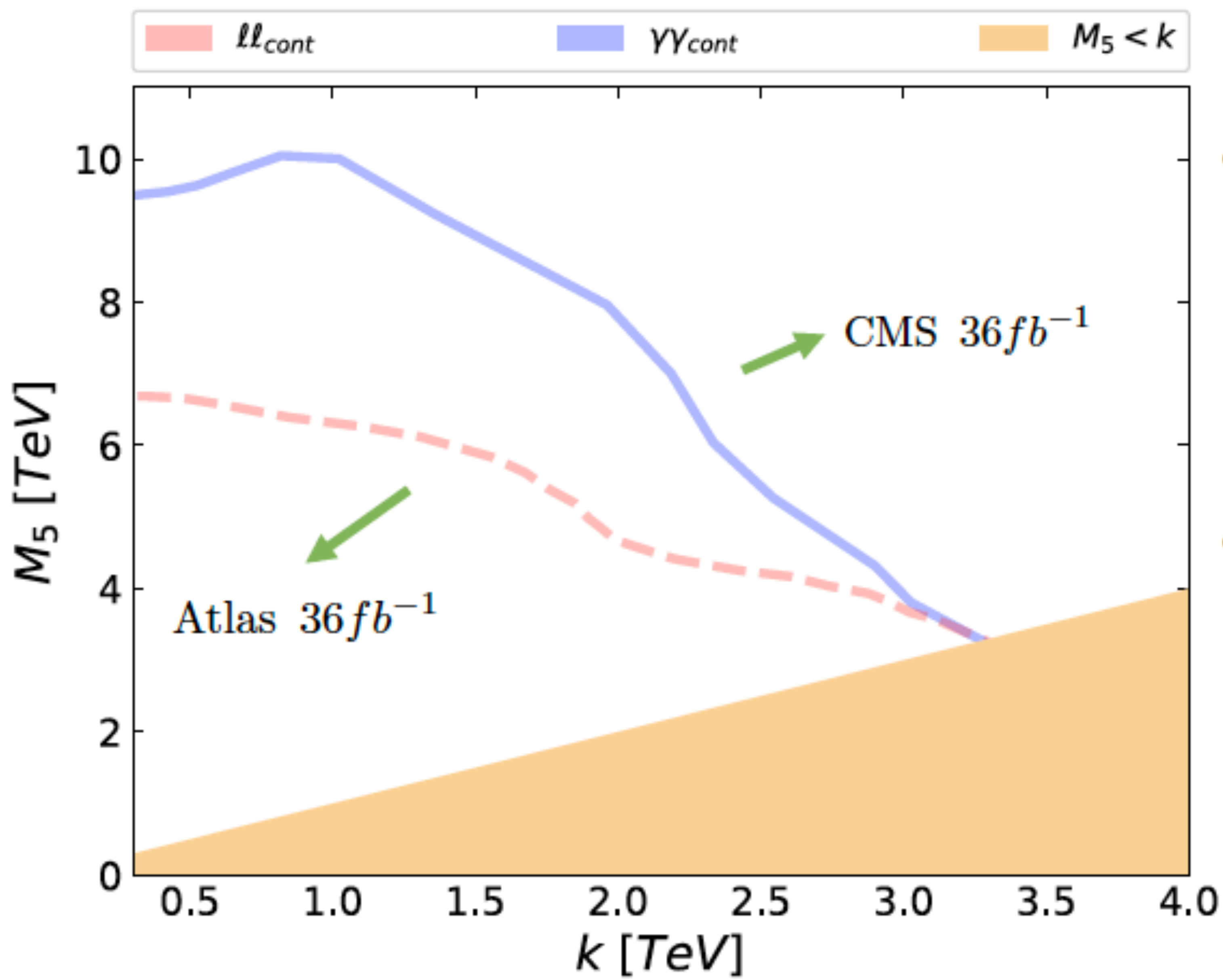


ATLAS: Search for new phenomena in high-mass diphoton final states using 37

(1707.04147)

Resonant searches at Run II

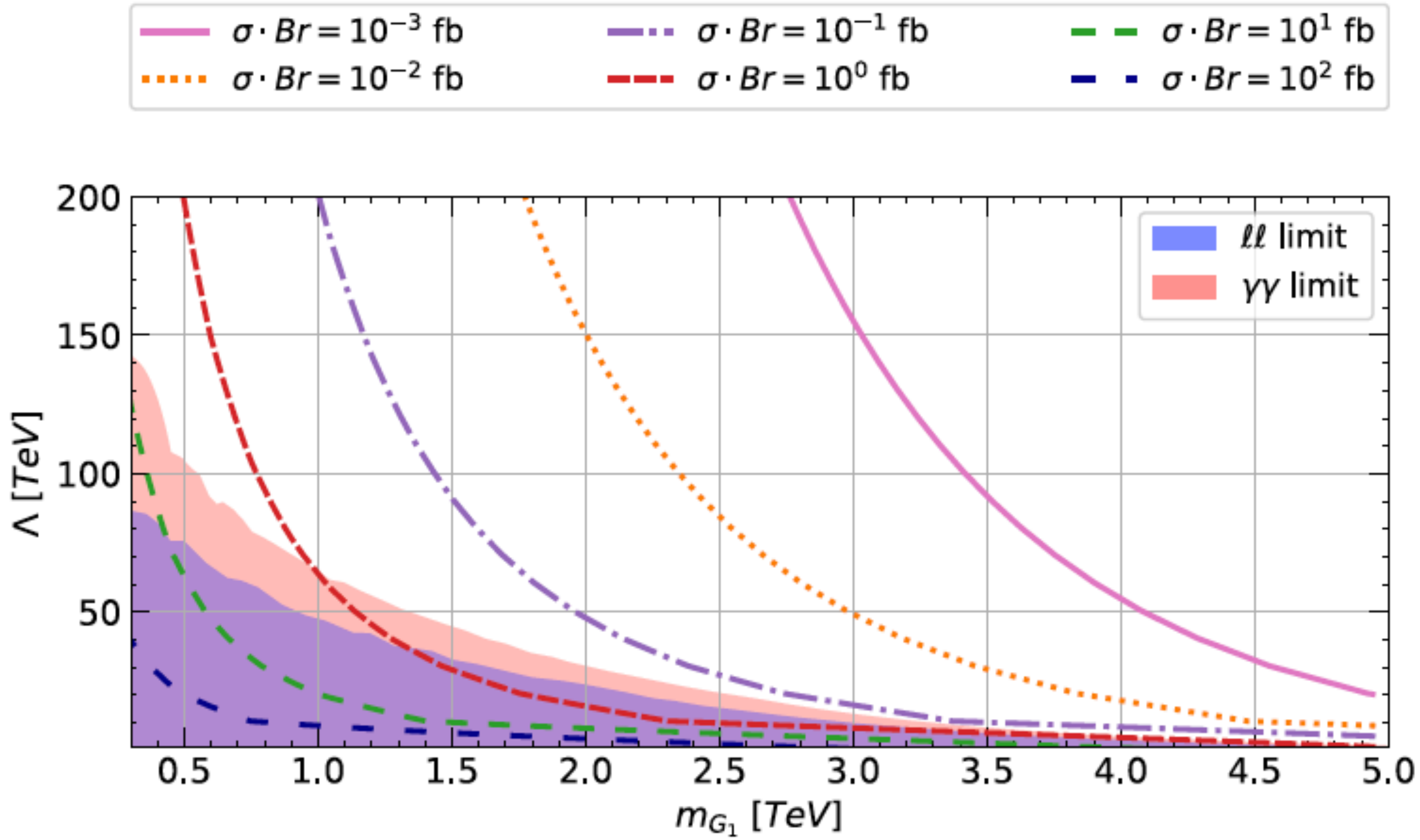
LHC bounds: CW/LD



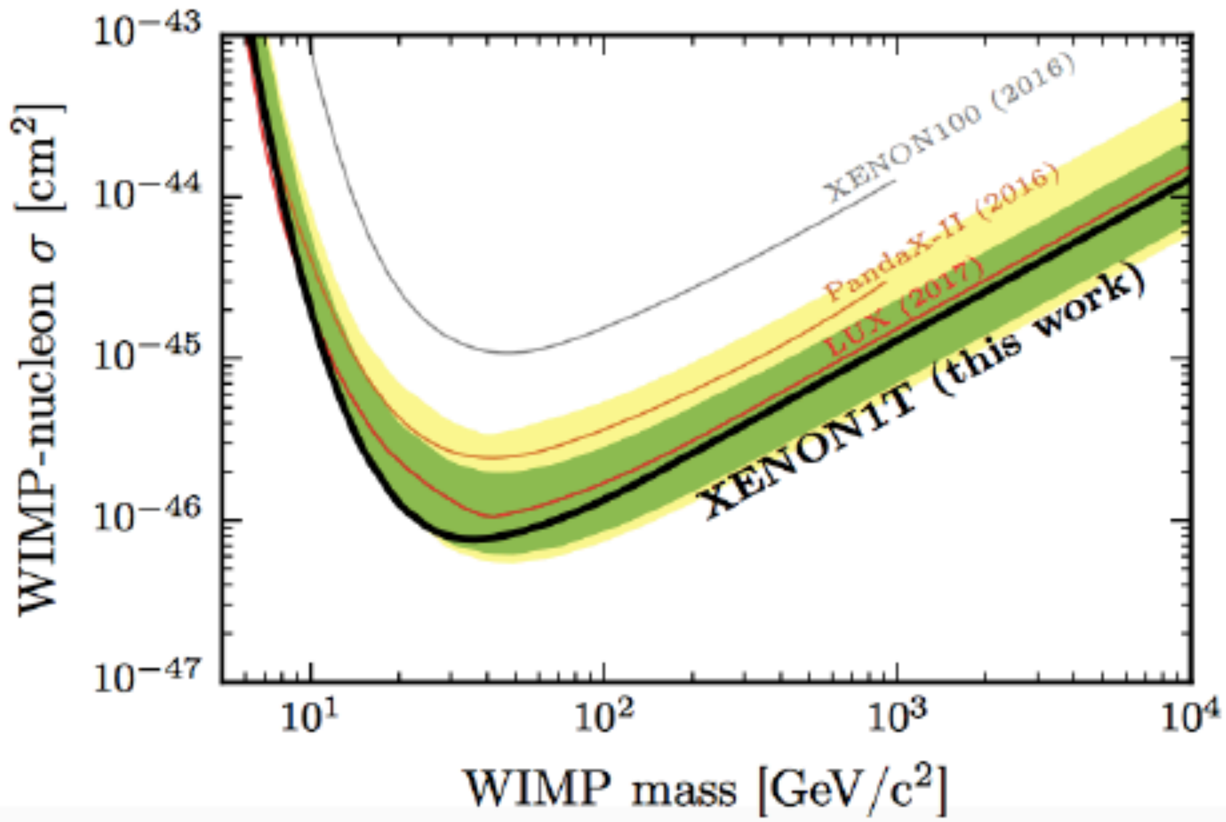
- The strongest constraints are given by the non-resonant searches at LHC.
- The orange area is the region of the parameter space in which the effective theory is not consistent.

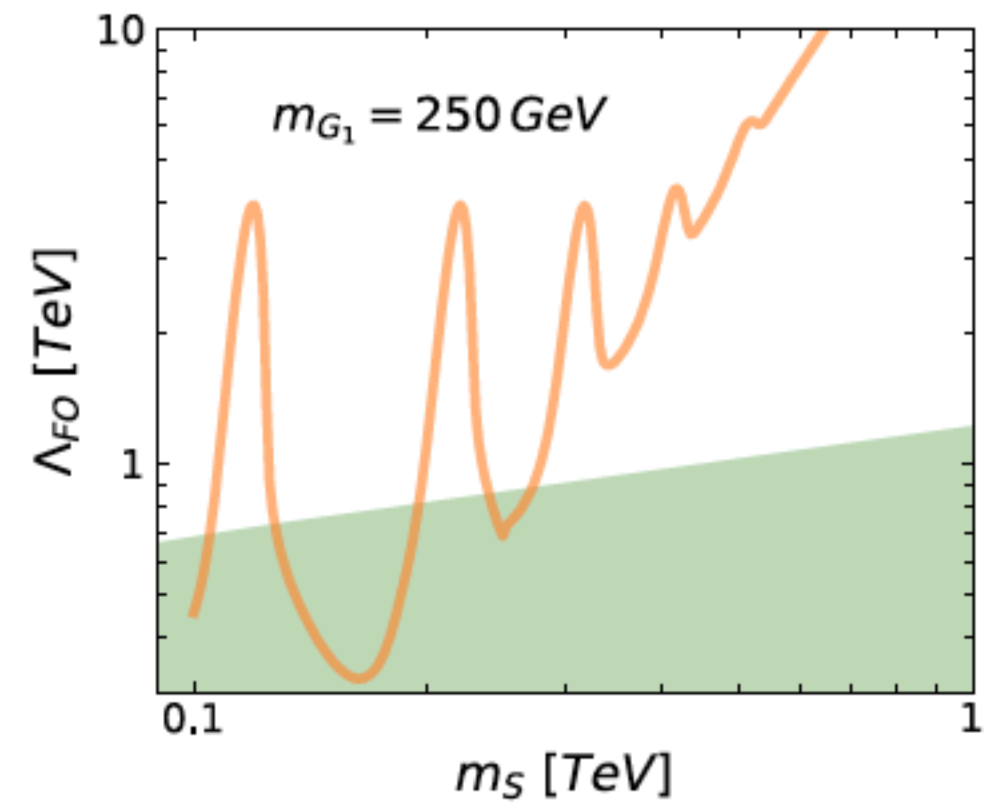
Non-Resonant searches at Run II

Bounds from resonance searches at LHC



Bounds from Direct Detection experiments

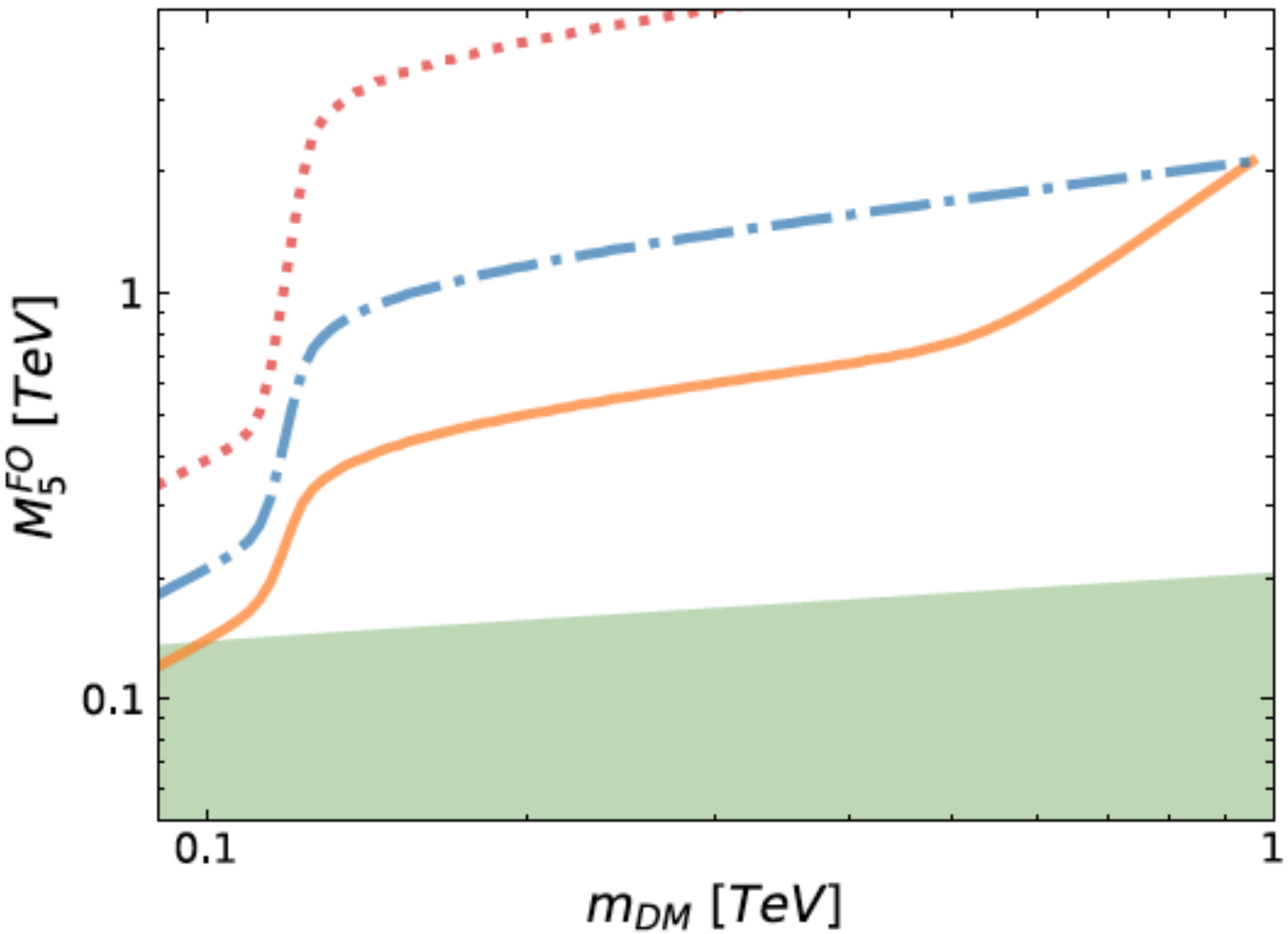




In our analysis we have fixed the scale using the restriction

$$\langle \sigma v \rangle = f(m_{DM}, \Lambda, m_{G_1} = 250\,GeV) \equiv 2.2 \times 10^{-26} cm^3/s$$

Bounds from Direct Detection experiments

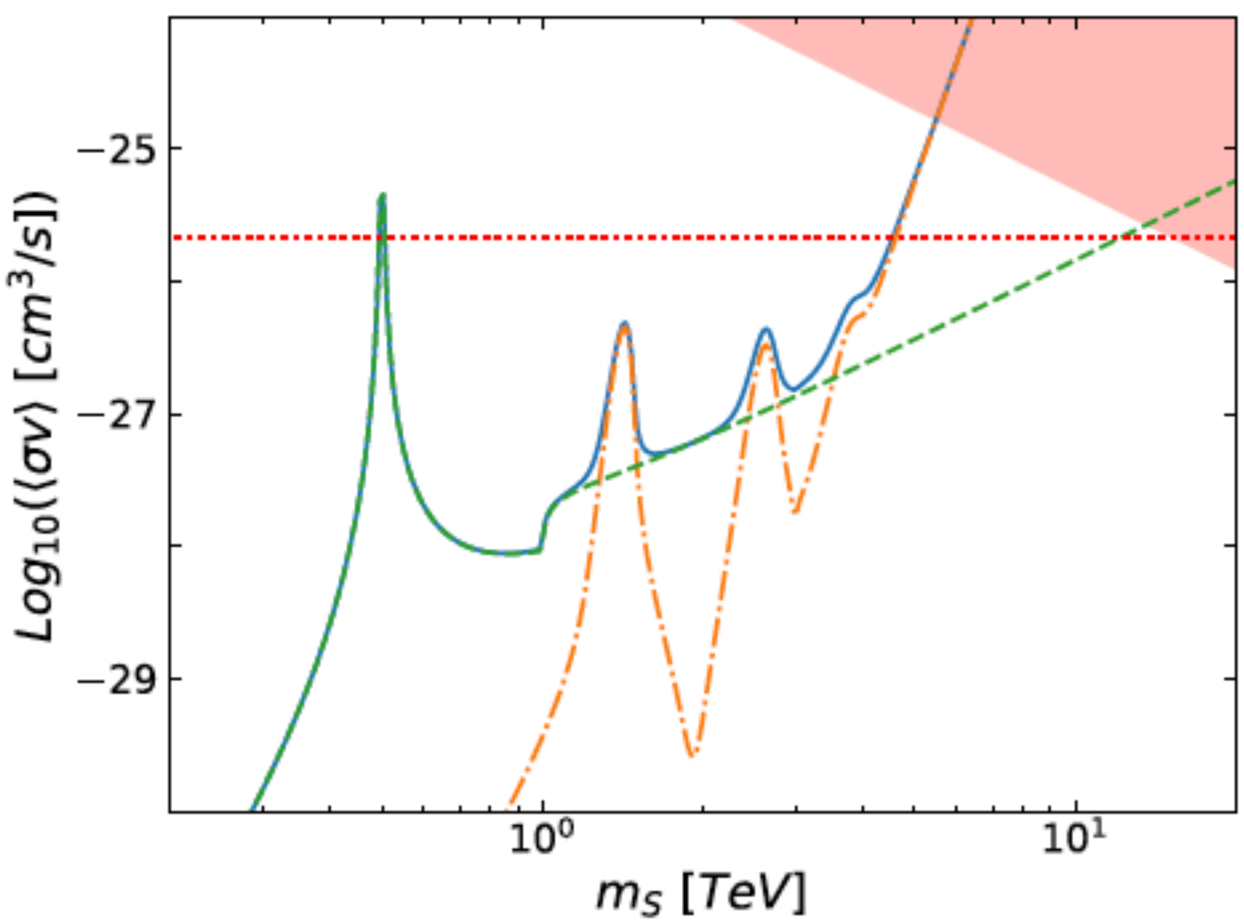


$$k = 250\, GeV$$

The DM-nucleon scattering cross section is too weak to constrain the model in any point of the analysed region.

Vectorial | Fermionic | Scalar

Radion impact in the phenomenology (scalar DM)



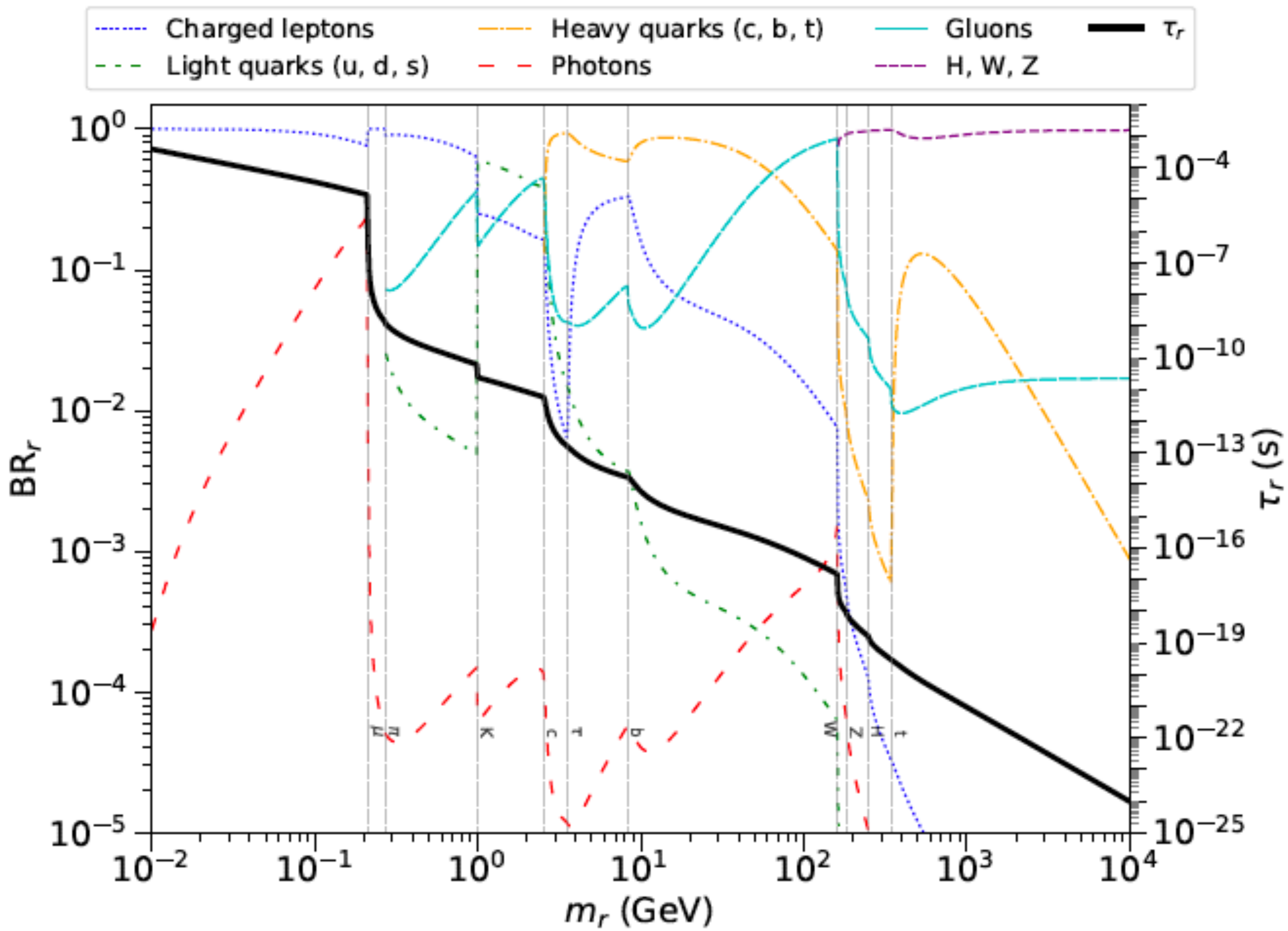
The correct relic abundance is only achieved with the radion when:

$$m_{\text{DM}} \sim m_r/2$$

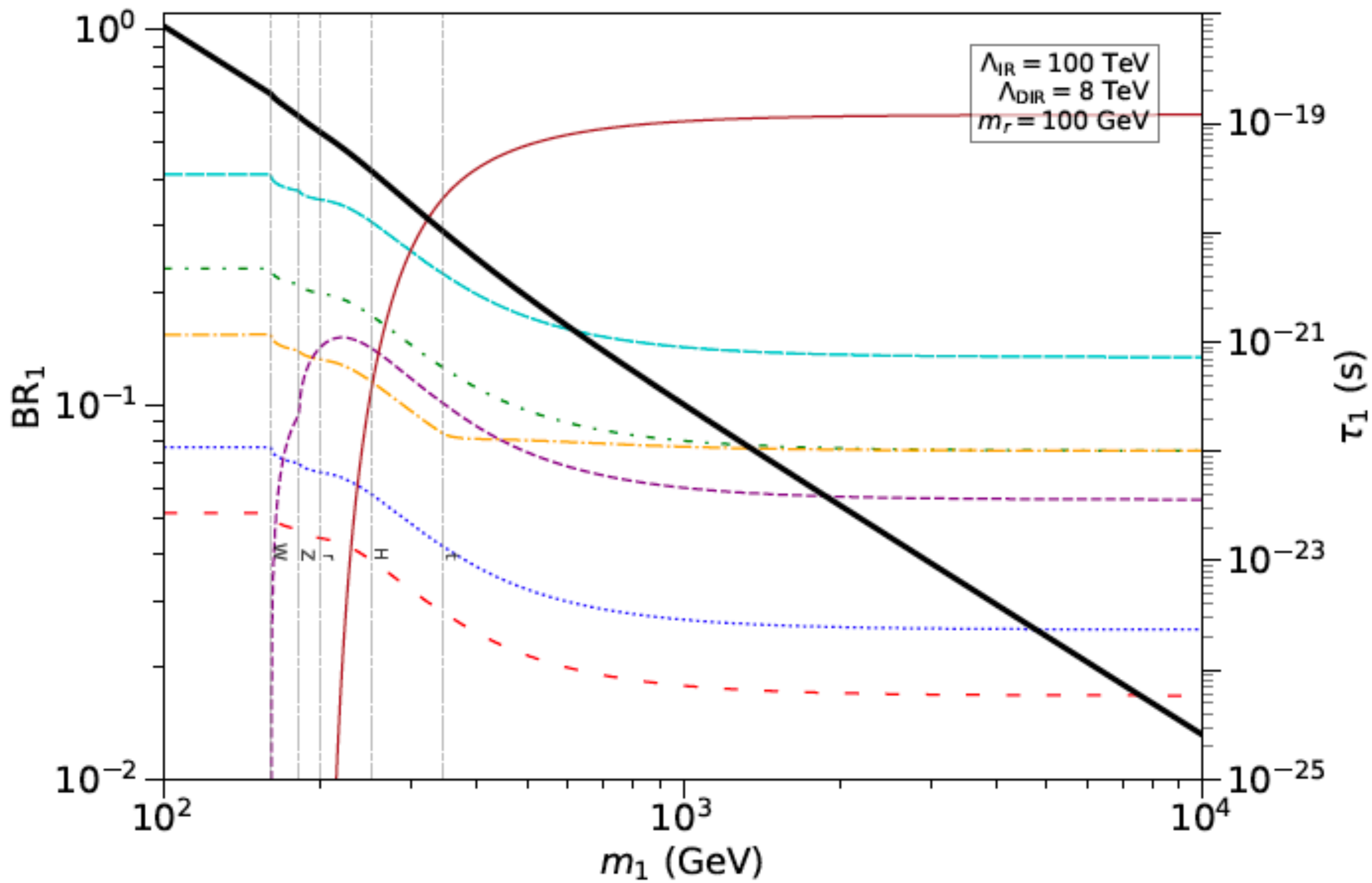
$$\Lambda = 8\,\text{TeV}$$
$$m_{G_1} = 3\,\text{TeV}$$
$$m_r = 1\,\text{TeV}$$

The total annihilation cross section is weakly dependent of the radion mass out of the radion mass resonance.

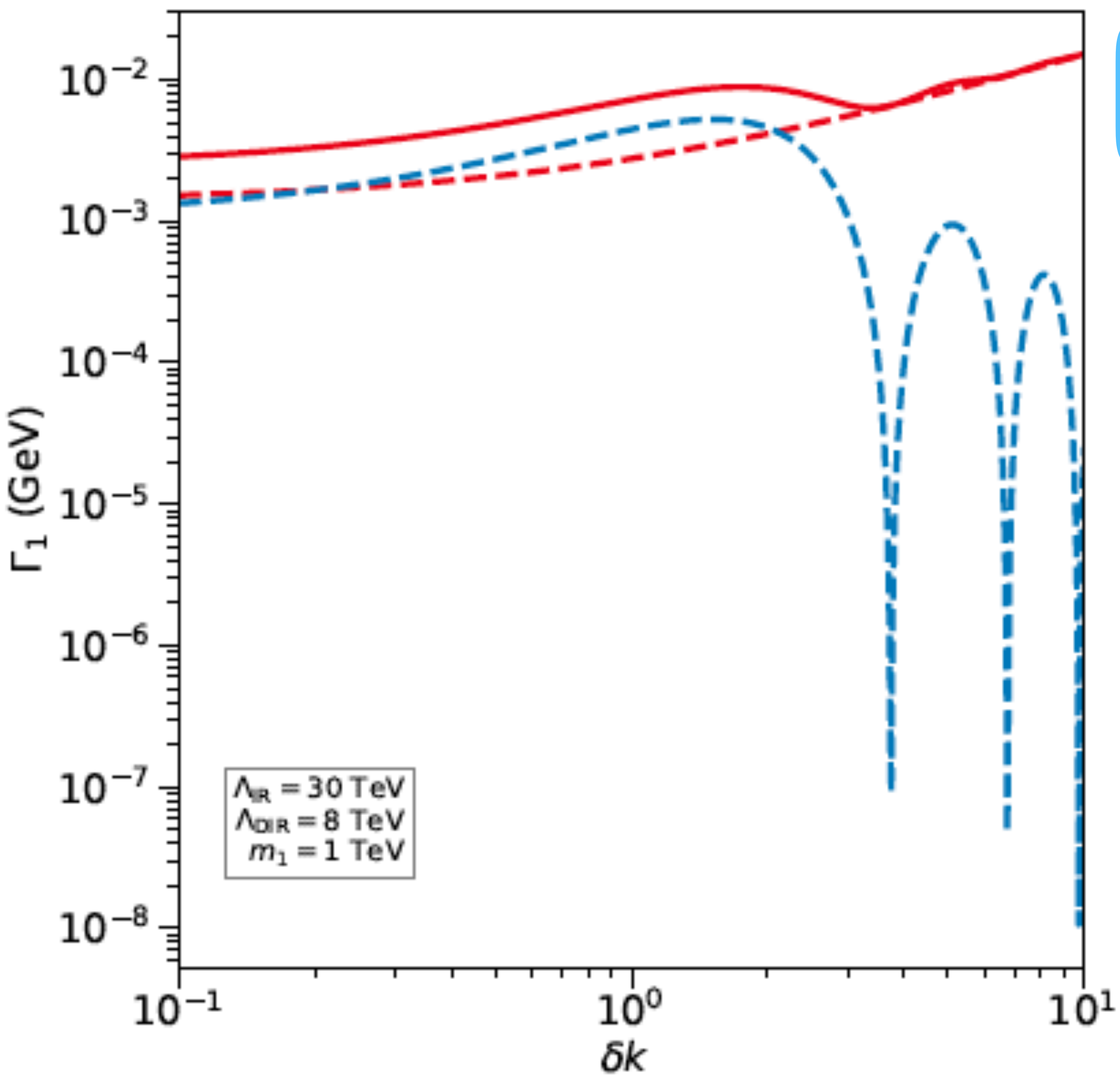
Branching Ratios: radion



Branching Ratios: KK graviton



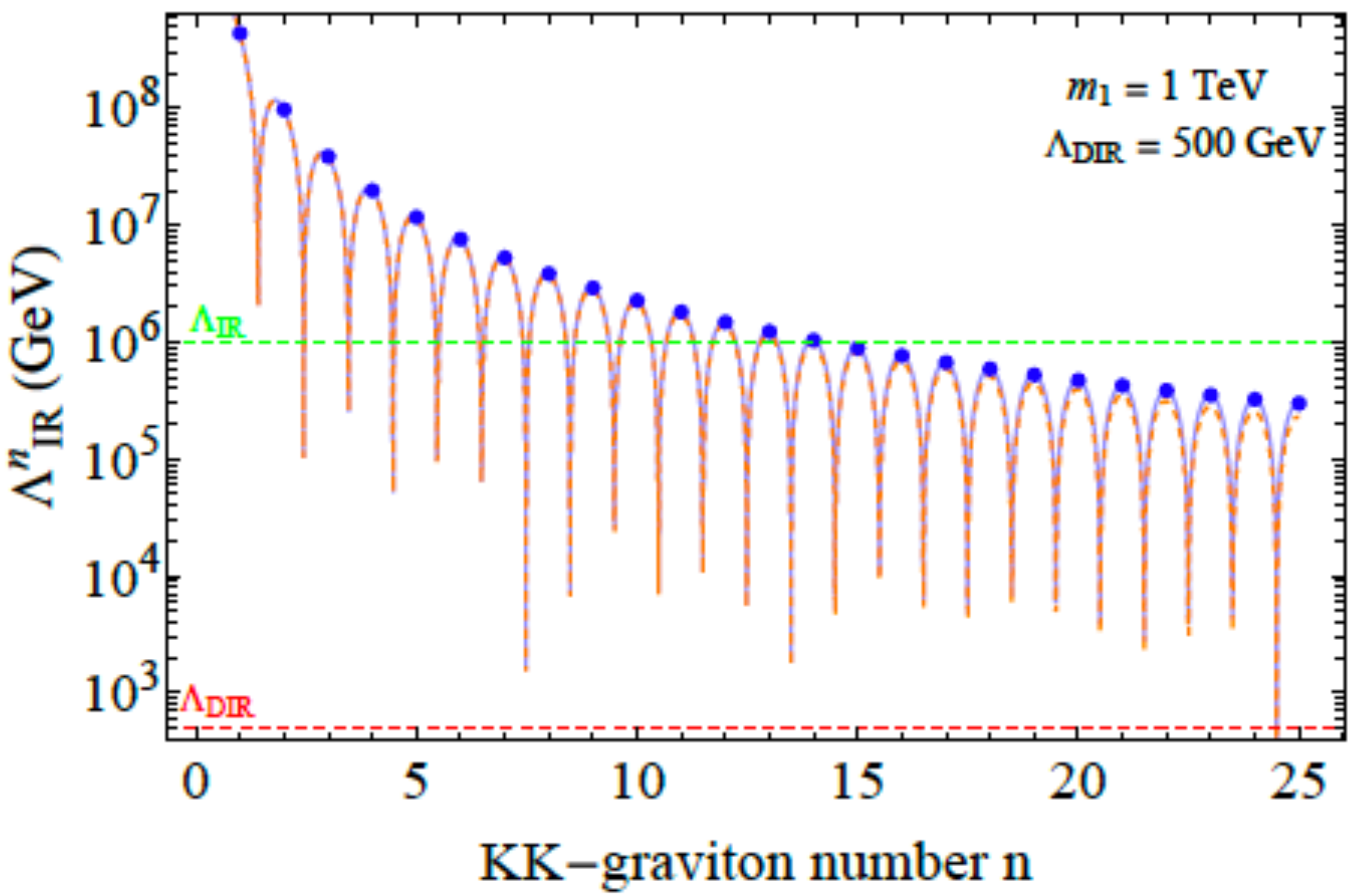
Branching Ratios: KK graviton out of the evanescent limit



$\Gamma(G_1 \to r\, r)$

$\Gamma(G_1 \to \mathrm{SM\,SM})$

KK graviton couplings



Underabundance of DM