Dark matter in Extra-Dimensions

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Based on:

Folgado, Donini and Rius, *JHEP* 01 (2020) 161
Folgado, Donini and Rius, *JHEP* 04 (2020) 036
Folgado, Donini and Rius, *Eur.Phys.J.C* 81 (2021) 3, 197
Bernal, Donini, Folgado and Rius, *JHEP* 09 (2020) 142
Bernal, Donini, Folgado and Rius, *JHEP* 04 (2021) 061
Bernal, Cosme, Donini and Rius, in preparation

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…

If the SM is an effective (low-energy) theory

HIERARCHY PROBLEM

Solving the HP?

Many proposals have been advanced
to solve the Hierarchy Problem. To name a few:

SUPERSYMMETRY (MSSM, mSUGRA, split, NMSSM, etc)
TECHNICOLOR (walking, running, extended, etc)
COMPOSITE HIGGS
EXTRA-DIMENSIONS (flat, RS, CW/LD, …)
Other ideas I forgot (but maybe you don't)…

No hints of any of the implications of these
solutions to the HP
have been discovered at the LHC,
after Run I and Run II.
We have many bounds, though….

Solving the HP?

Many proposals have been advanced
to solve the Hierarchy Problem. To name a few:

SUPERSYMMETRY (MSSM, mSUGRA, split, NMSSM, etc)

What then?

have been discovered at the LHC,
after Run I and Run II.
We have many bounds, though….

(F-word) the HP!

**Maybe, we could salvage some of these ideas,
and use them to solve one (or more) of the observational
open problems of the SM. Choose from the previous list:
Dark Matter, Dark Energy, Neutrino Masses, Baryogenesis,
Quantum Gravity,…**

Why?

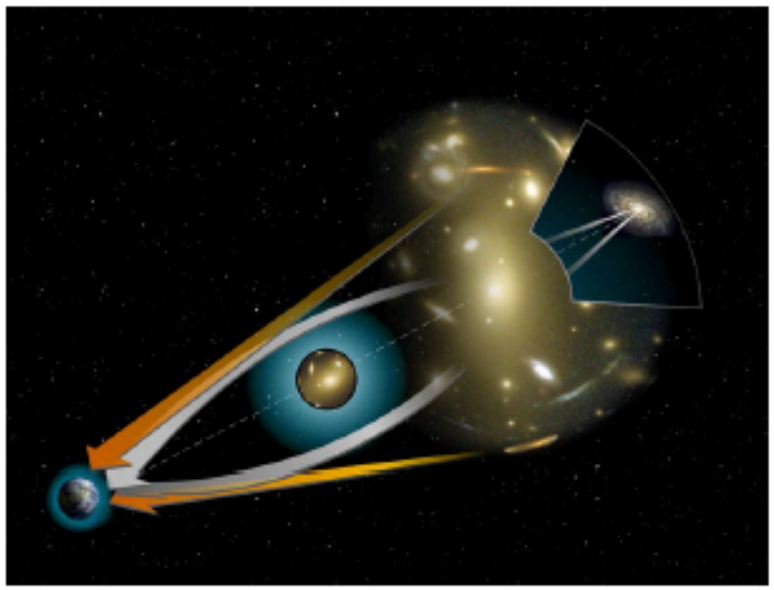
**Because they are very clever ideas, with huge parameter space,
with the drawback that they do not work to solve the HP**

(F-word) the HP!

Maybe, we could salvage some of these ideas.

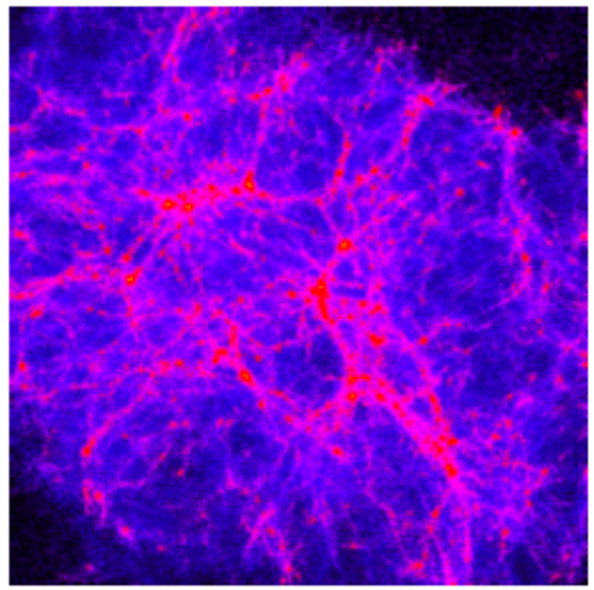
I will review our attempt to explain
the observed
DARK MATTER RELIC ABUNDANCE Ω_{DM}
using
EXTRA-DIMENSIONAL MODELS

Evidence for Dark Matter

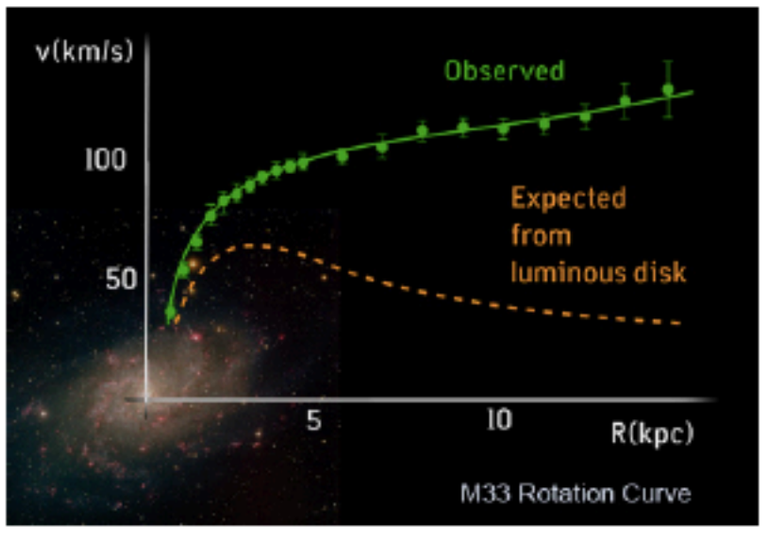


Gravitational lensing

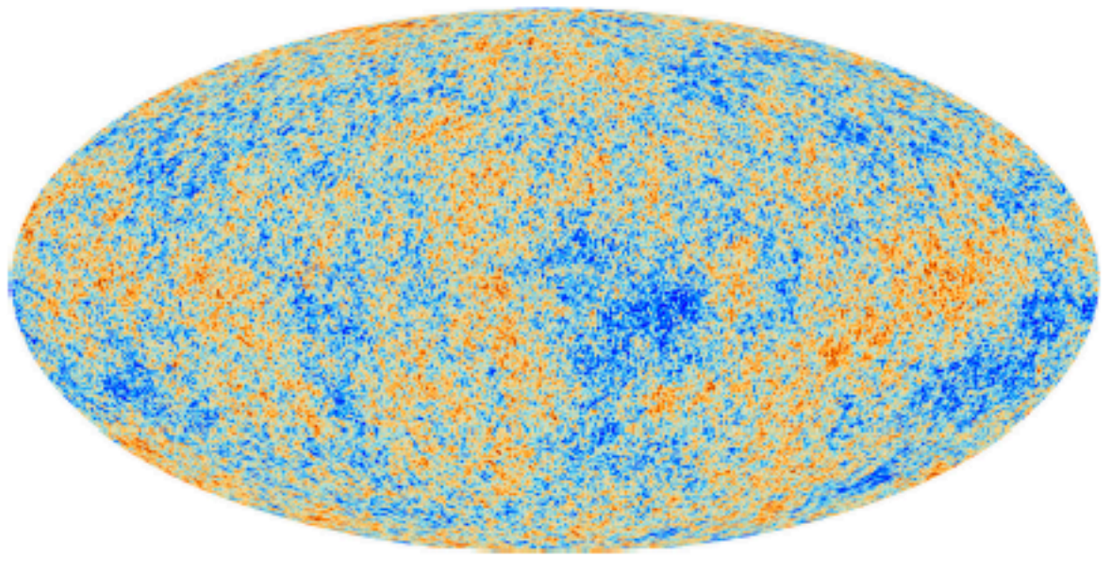
Galaxy clusters



Structure formation



Rotation Curves of Galaxies



Cosmic microwave background

Why Extra-Dimensions?

The only evidence for Dark Matter is that it GRAVITATES

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

In extra-dimensional frameworks, gravity is stronger than in 4-dimensions: GRAVITATIONAL PORTAL

Extra-dimensions

1. Add one or more spatial dimensions to your space-time
2. Choose some geometry
3. Compactify extra spatial dimensions
4. Add SM fields at some defects in your manifold (branes)

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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Features of RS and CW/LD

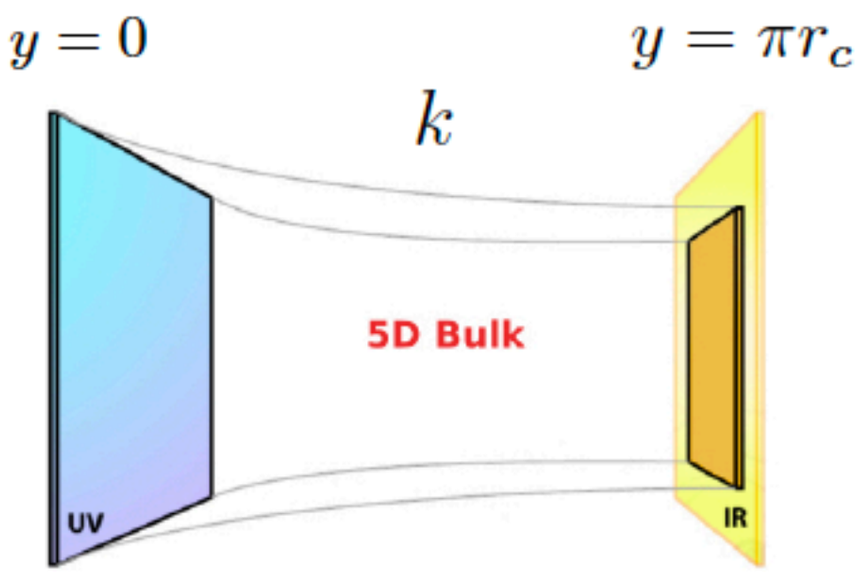
D = 4 + 1

$\mathcal{M}_5 = \mathcal{M}_4 \times \mathcal{Z}_2$

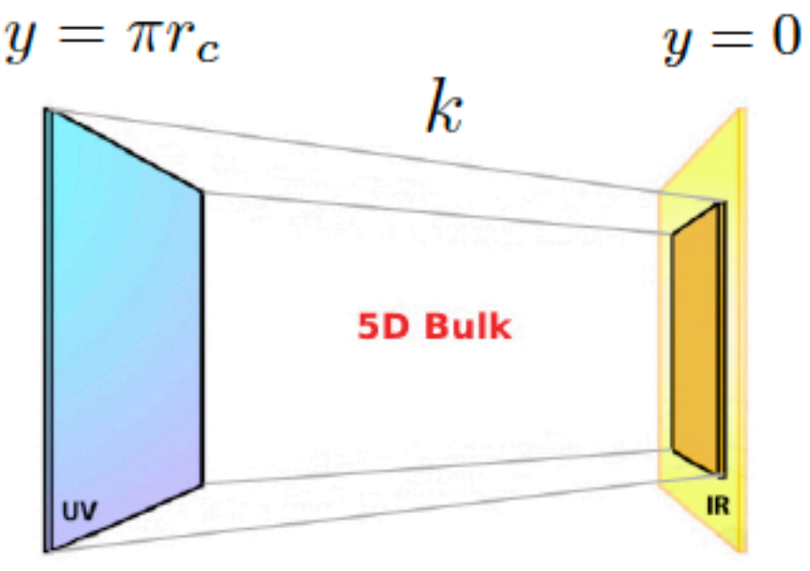
$$ds^2 = e^{2\sigma(y)}(\eta_{\mu\nu}dx^\mu dx^\nu - e^{-2l\sigma(y)}r_c^2 dy^2)$$

Large Extra-Dimensions	Randall-Sundrum	Clockwork/Linear Dilaton
• $\sigma(y) = 0$	• $\sigma(y) = -kr_c\lvert y\rvert$	• $\sigma(y) = \frac{2}{3}kr_c\lvert y\rvert$
$\bar{M}_{pl}^2 = M_5^3 2\pi r_c$	• $l = 1$	• $l = 0$
Volume factor	$\bar{M}_{pl}^2 = \frac{M_5^3}{k}(1 - e^{-2k\pi r_c})$	$\bar{M}_{pl}^2 = \frac{M_5^3}{k}(e^{2k\pi r_c} - 1)$
$M_5 \ll \bar{M}_{pl}$	$k, M_5 \sim \bar{M}_{pl}$	Warping factor $k, M_5 \ll \bar{M}_{pl}$

Geometry of RS and CW/LD



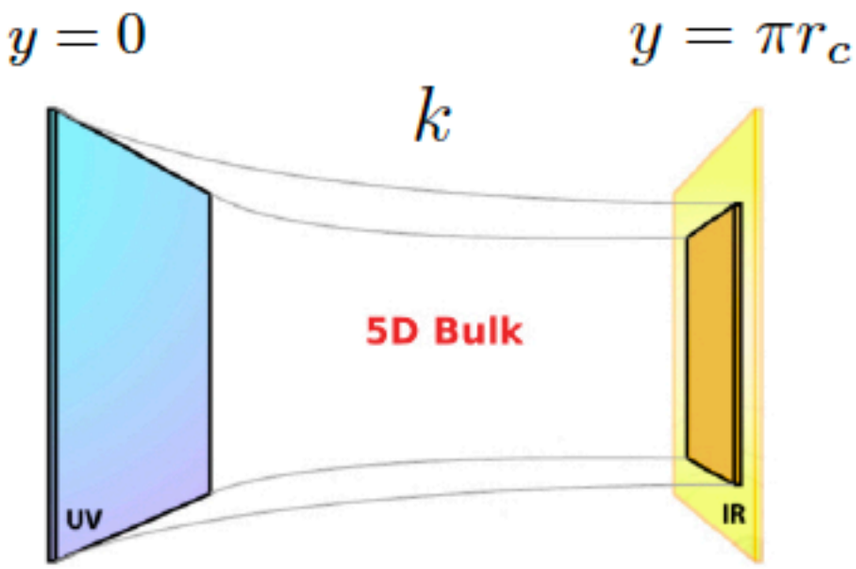
$$ds^2 = e^{-2kr_c|y|}\eta_{\mu\nu}dx^\mu dx^\nu - r_c^2 dy^2$$



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

5D massless graviton ⟷ 4-D tower massive gravitons (KK Theory)

KK-Spectra of RS and CW/LD



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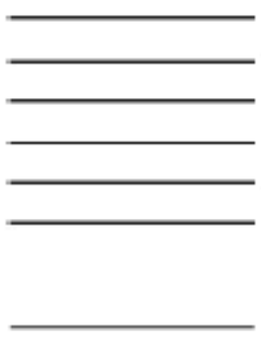
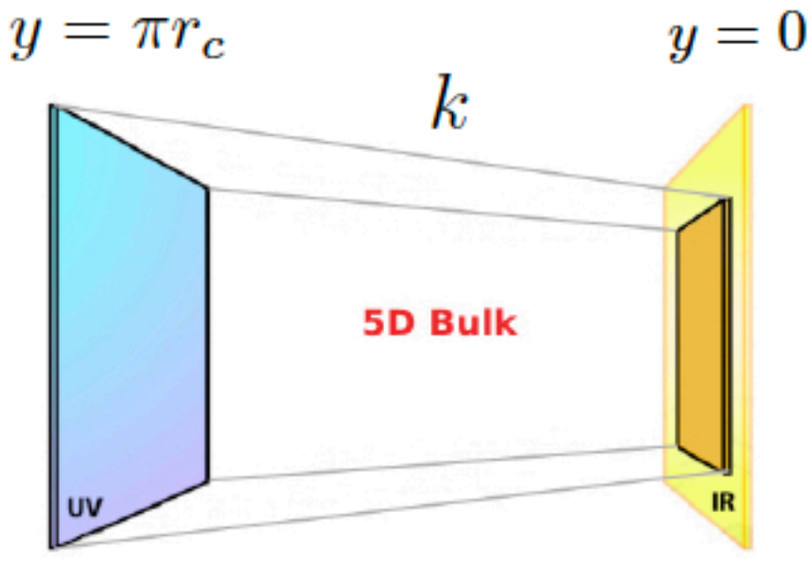


$$\Lambda = \bar{M}_{pl}e^{-\pi r_c k} \ll \bar{M}_{pl}$$

Mass spectra

$$m_n = kx_n e^{-k\pi r_c} \longleftrightarrow J_1(x_n) = 0$$
$$m_0 = 0$$



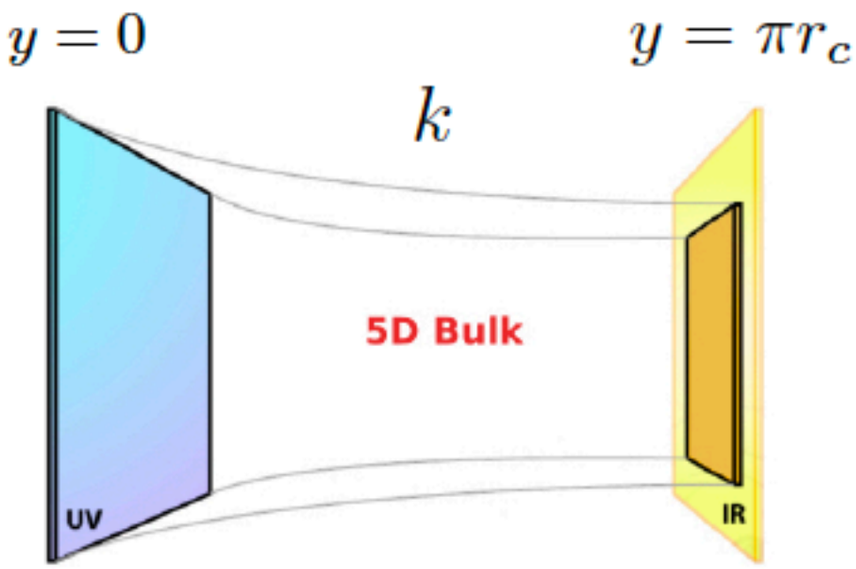
$$ds^2 = e^{\frac{4}{3}kr_c|y|}(\eta_{\mu\nu}dx^\mu dx^\nu - r_c^2 dy^2)$$

$$\Lambda_n \propto \sqrt{M_5^3 \pi r_c} \sim k, M_5$$

Mass spectra

$$m_n^2 = k^2 + \frac{n^2}{r_c^2}$$
$$m_0 = 0$$

KK-Spectra of RS and CW/LD



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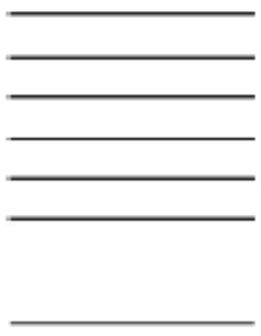

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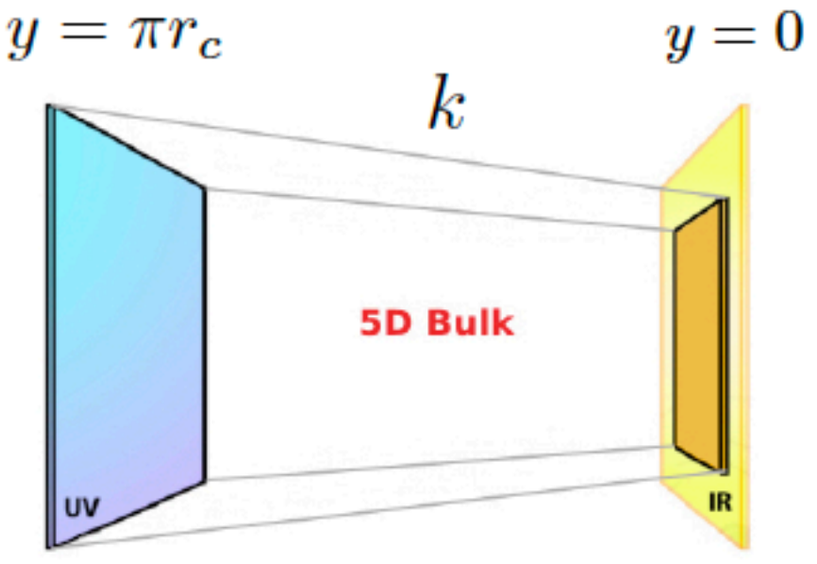

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Mass spectra

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$$m_0 = 0$$

$k = 0$

LED

DM on the IR-brane

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

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

RS

$$\mathcal{S} = \int d^4x \int_0^{\pi} r_c dy \sqrt{G^{(5)}} \left\{ \frac{M_{5,\rm CW}^3}{2} \left[-R^{(5)} + \frac{1}{3} G^{MN}_{(5)} \partial_M S \partial_N S + 4 e^{-\frac{2}{3}S} k^2 \right] \right\}$$

CW/LD

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

$$S_{\rm UV} = \int d^4x \sqrt{-g}\, \{ -f_{\rm UV}^4 + \dots \}$$

Branes Actions (depending on the model, they can be at 0 or π)

Parameter space

- The interaction between the particles located in the IR brane and the gravitons is given by:

$$\mathcal{L} = -\frac{1}{M_5^{3/2}} T^{\mu\nu}(x) h_{\mu\nu}(x, y = 0) = -\sum_{n=1} \frac{1}{\Lambda_n} T^{\mu\nu}(x) h_{\mu\nu}^{(n)}(x),$$

Free Parameters

Randall-Sundrum	Clockwork/Linear Dilaton
Λ, m_{G_1}, m_{DM}	M_5, k, m_{DM}
	$k \backsimeq m_{G_1}$

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Free P

Enhancement of gravitational coupling with respect to 4D

Randall-Sundrum

$$\Lambda, m_{G_1}, m_{DM}$$

Clockwork/Linear Dilaton

$$M_5, k, m_{DM}$$

$$k \backsimeq m_{G_1}$$

Stabilization of the ED

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

Randall-Sundrum

- It is necessary to introduce a new field.
- This field mixes with the component $G_{55}^{(5)}$ resulting in the radion field r.

m_r → New Free parameter!

Goldberger-Wise mechanism

Clockwork/Linear Dilaton

- We can use the already present bulk dilaton field (Φ_n).
- The 5D dilaton field can be written as a KK tower

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

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

Radion interactions

$$\mathcal{L}_r = \frac{1}{2}(\partial_\mu r)(\partial^\mu r) - \frac{1}{2}m_r^2 r^2 + \frac{1}{\sqrt{6}\Lambda} r T + \frac{\alpha_{EM}\, C_{EM}}{8\pi\sqrt{6}\Lambda} r F_{\mu\nu}F^{\mu\nu} + \frac{\alpha_S C_3}{8\pi\sqrt{6}\Lambda} r \sum_a F^a_{\mu\nu}F^{a\mu\nu} + \mathcal{O}(r^2) + \mathcal{O}(r^3)$$

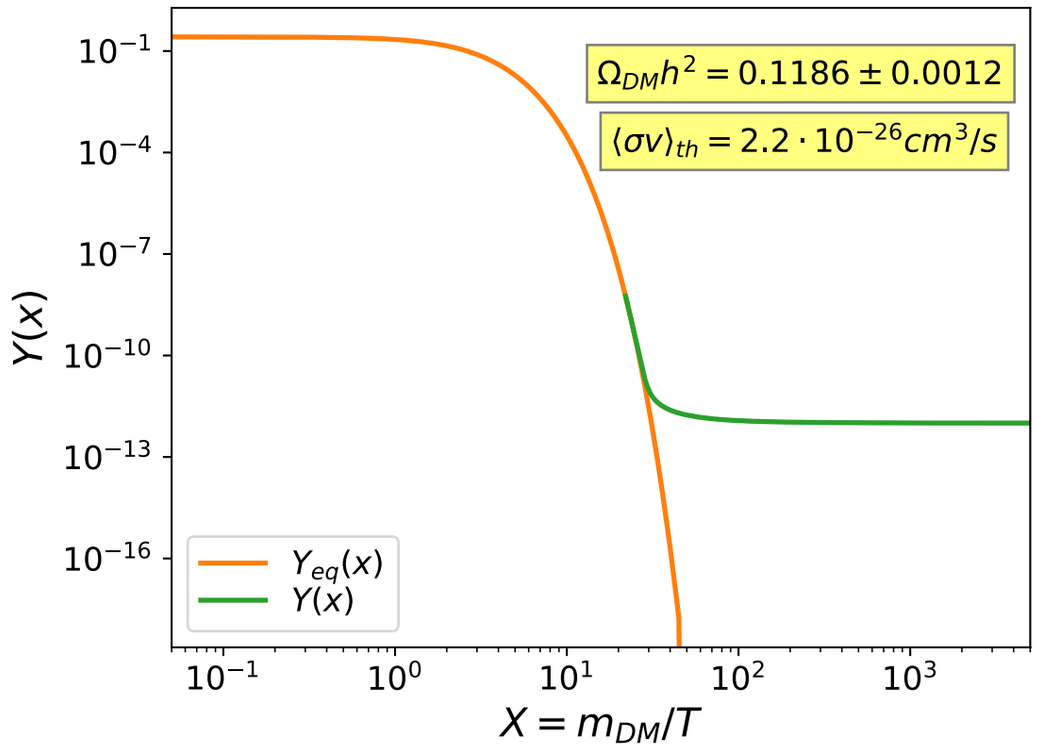
Previously neglected when computing DM annihilation

Folgado, Donini and Rius,
JHEP 01 (2020) 161
JHEP 04 (2020) 036
Eur. Phys.J.C 81 (2021) 3, 197

Relevant to enforce unitarity

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

1) Freeze-out (WIMPs)



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

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

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

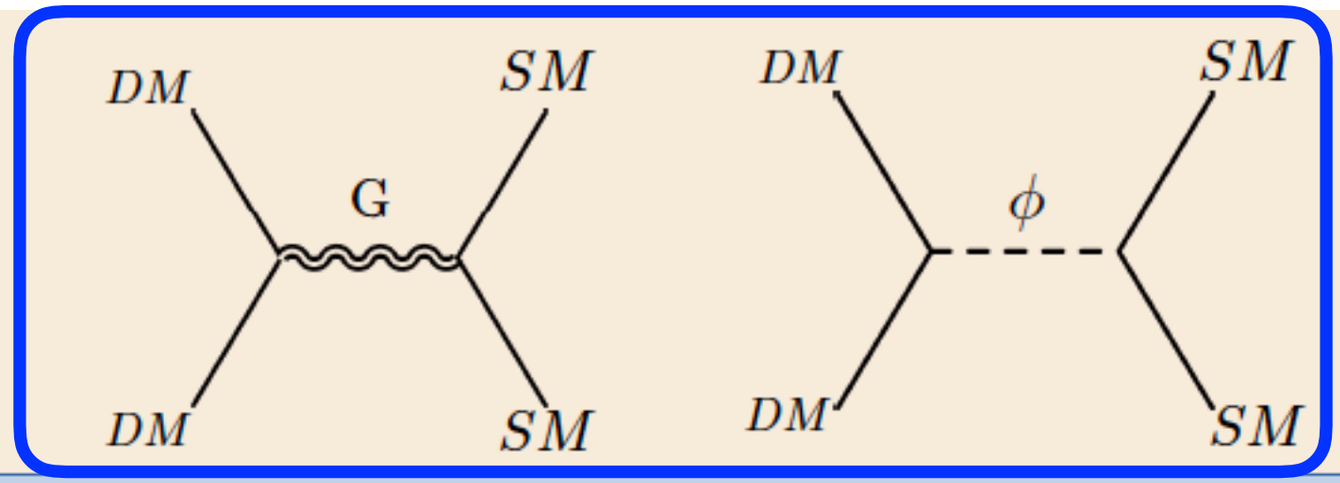
$$\frac{dY}{dx} = \frac{-x\langle\sigma v\rangle\mathfrak{s}}{H(m_{DM})}(Y^2(x) - Y_{eq}^2(x))$$

Evolution of the DM density with the temperature

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

DM annihilation

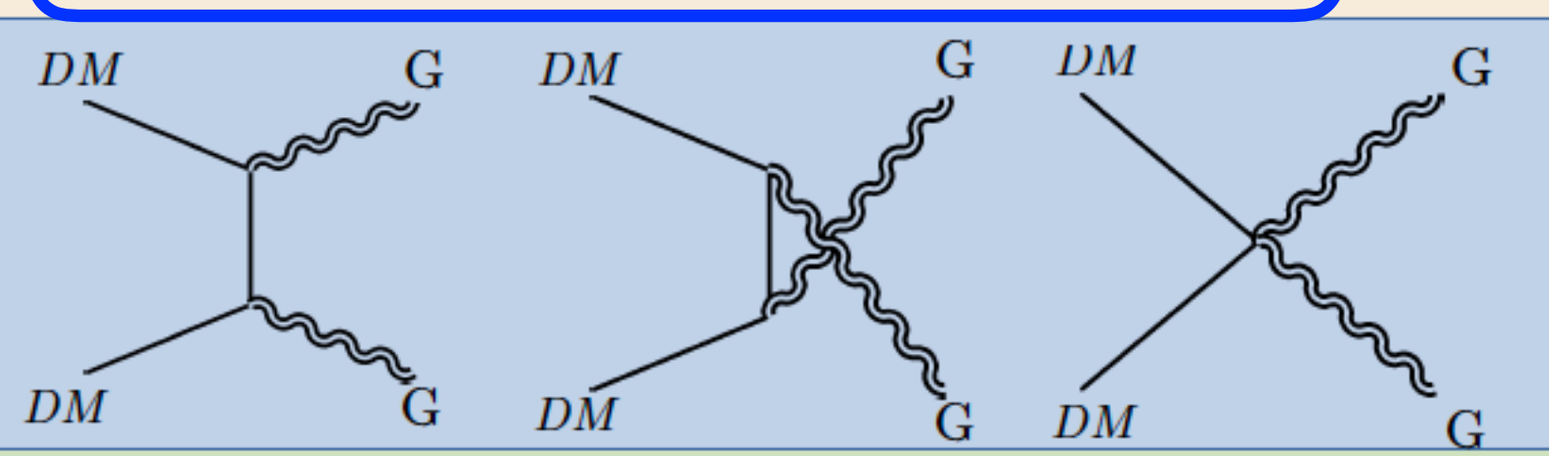
$|\mathrm{DM}, \mathrm{DM}\rangle$



$\langle SM, SM|$

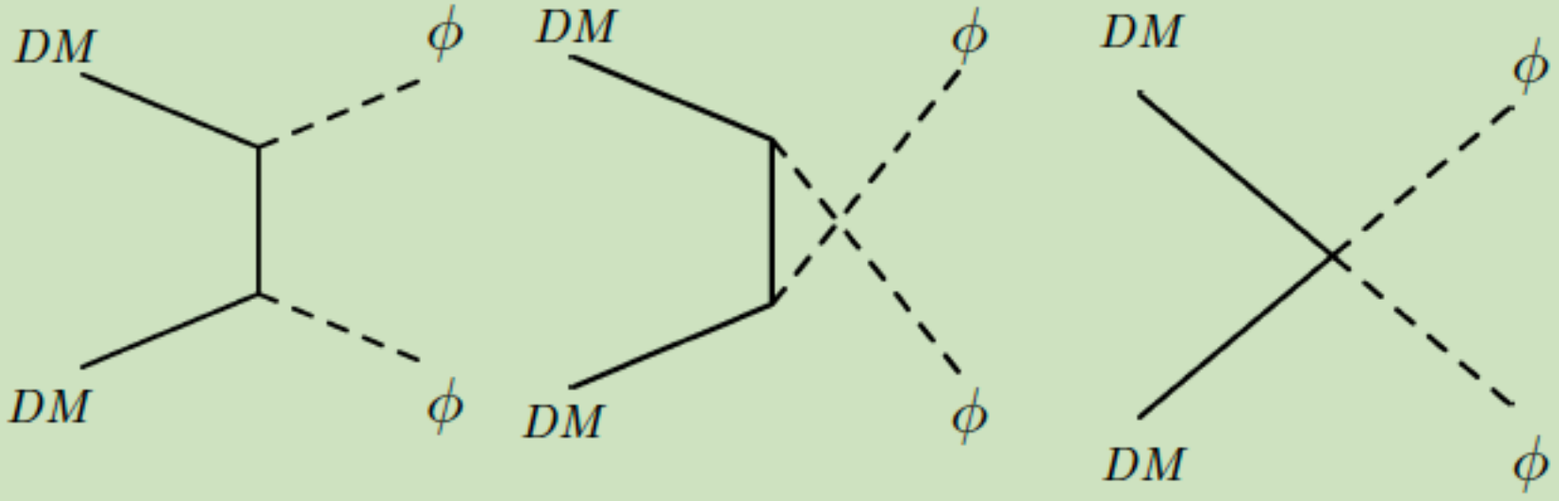
Rueter, Rizzo and Hewett, JHEP 10 (2017) 094

$|\mathrm{DM}, \mathrm{DM}\rangle$



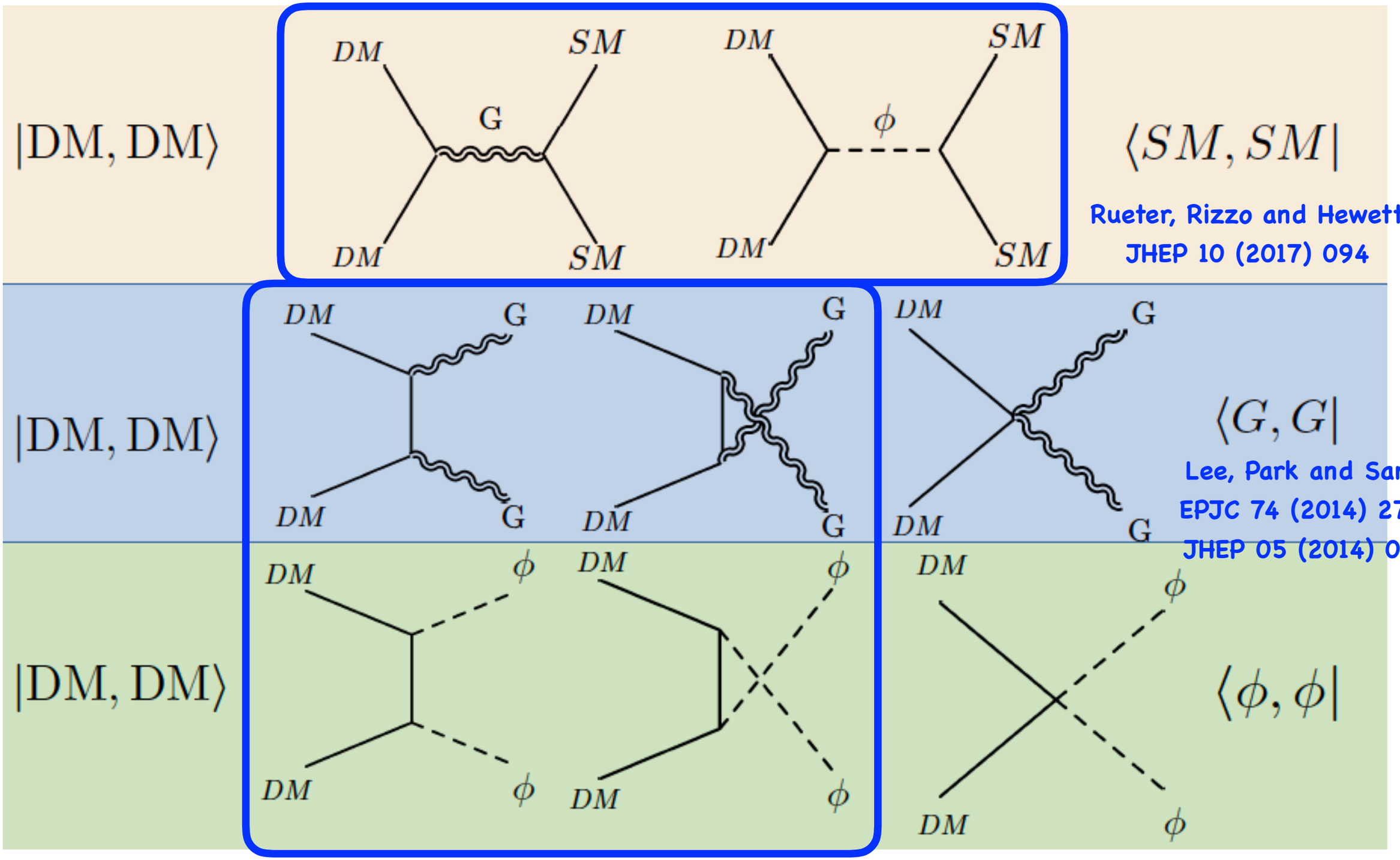
$\langle G, G|$

$|\mathrm{DM}, \mathrm{DM}\rangle$



$\langle \phi, \phi|$

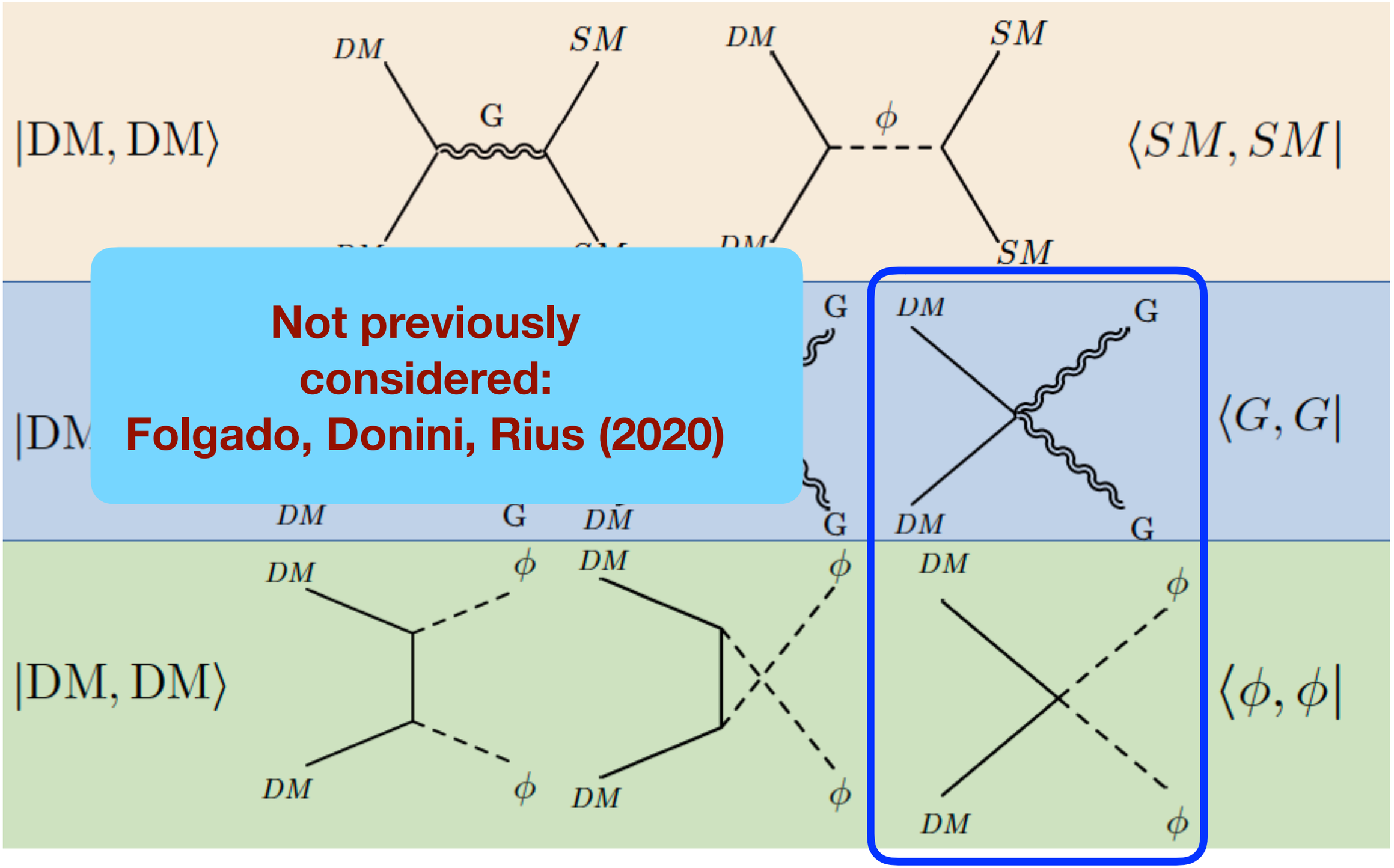
DM annihilation



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

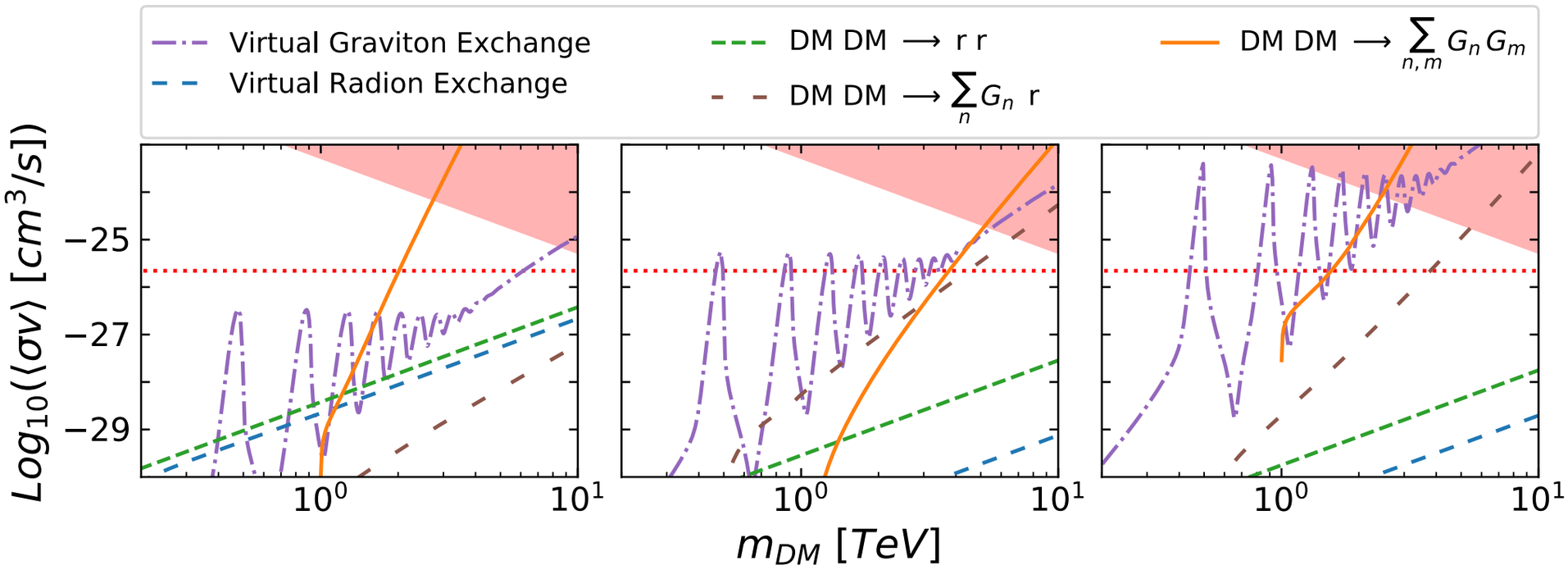
Lee, Park and Sanz, EPJC 74 (2014) 2715
JHEP 05 (2014) 063

DM annihilation



Annihilation into gravitons

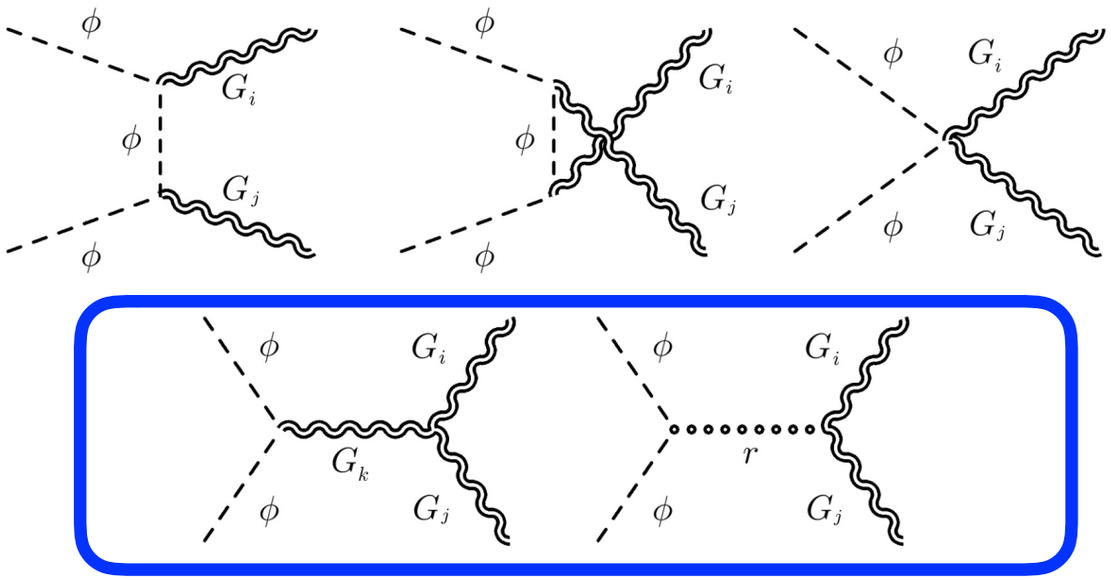
$$m_r = 100\,\mathrm{GeV}, M_{G_1} = 1\,\mathrm{TeV}, \Lambda = 10\,\mathrm{TeV}$$

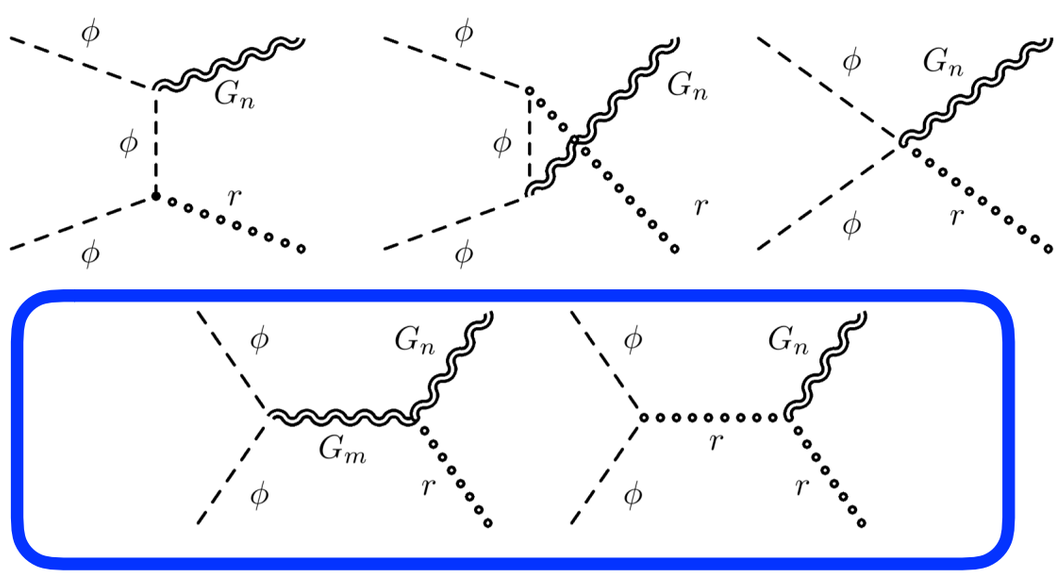


$\langle \sigma_{\mathrm{FO}}\, v \rangle$

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

However…Enforcing unitarity





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

Annihilation into gravitons

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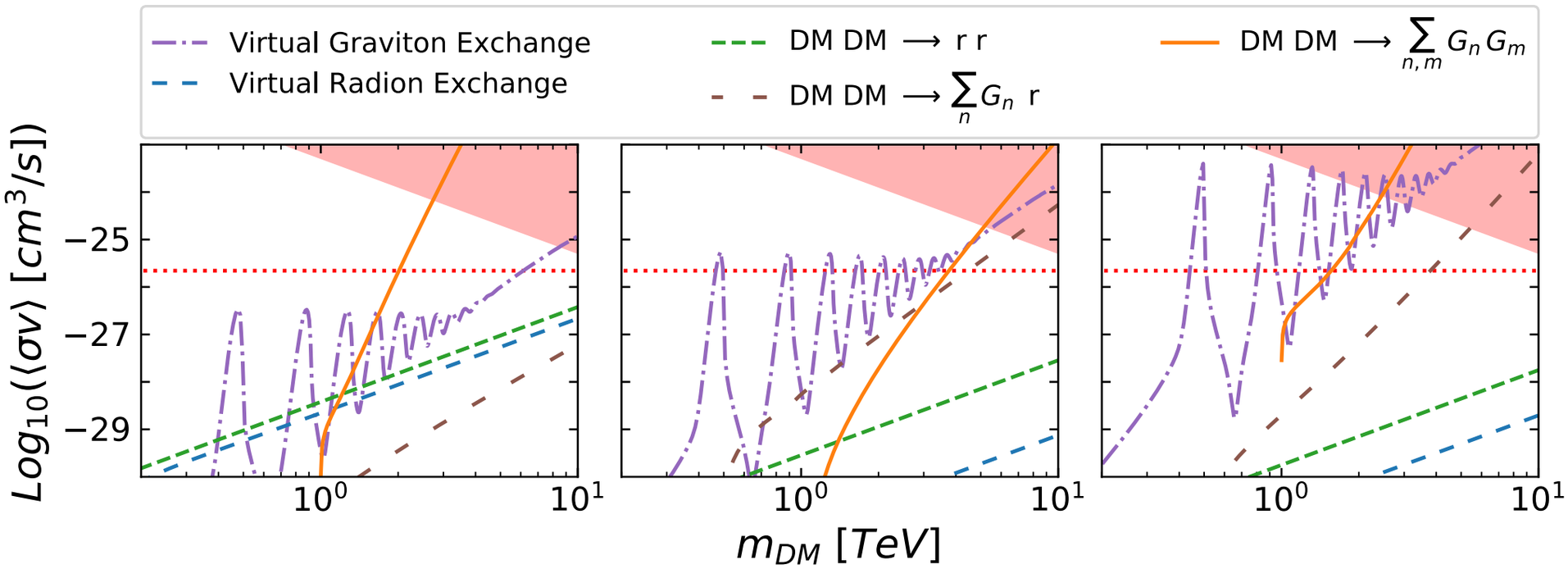
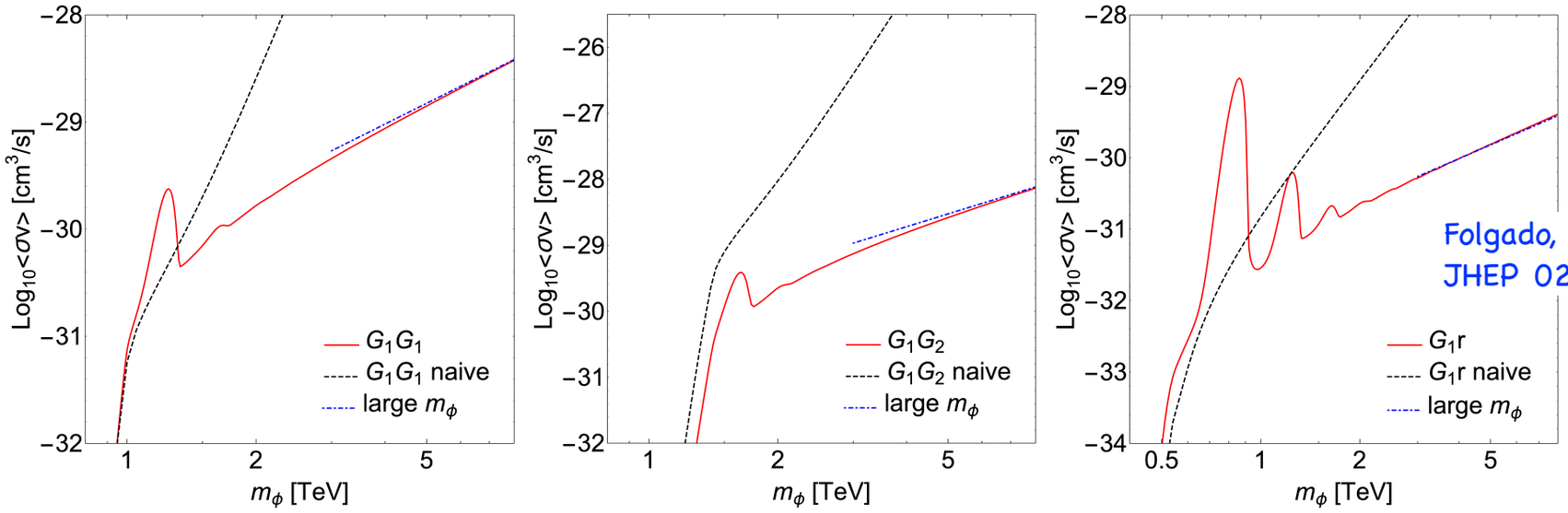


$\langle \sigma_{\mathrm{FO}}\, v \rangle$

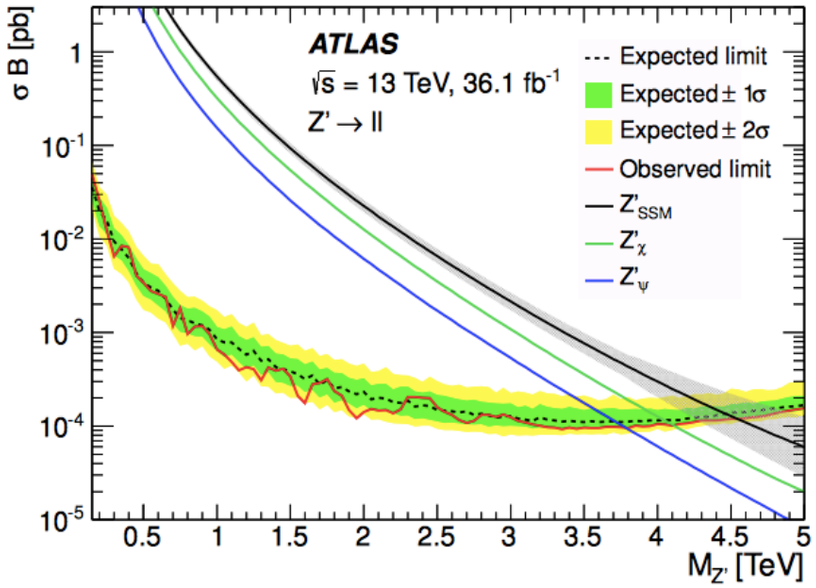
Scalar DM Dirac Fermion DM Vector DM

Λ = 20 TeV



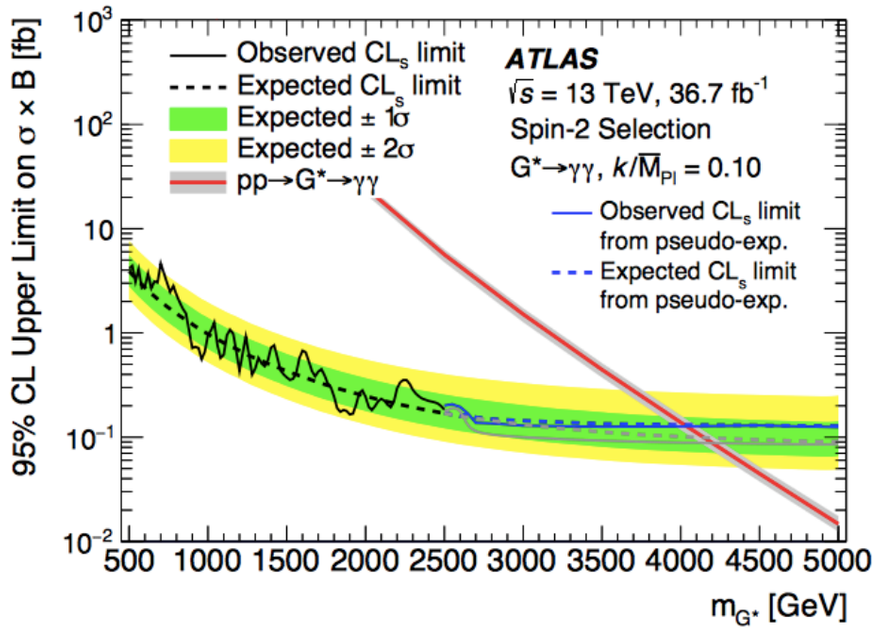
Folgado, Donini and Rius, JHEP 02 (2022) 129 (erratum)

LHC bounds: RS



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

(1707.02424)

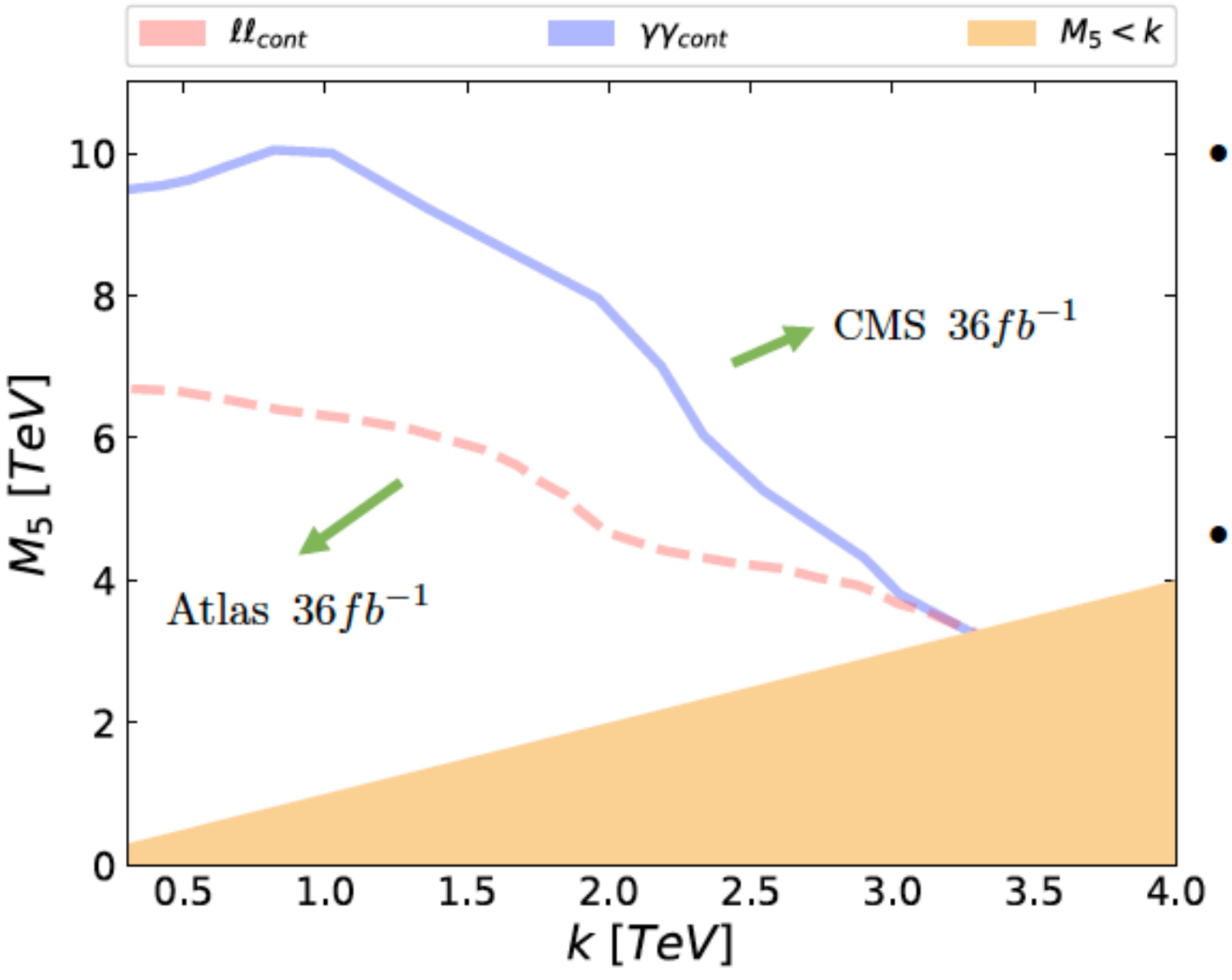


ATLAS: Search for new phenomena in high-mass diphoton final states using 37

(1707.04147)

Resonant searches at Run II

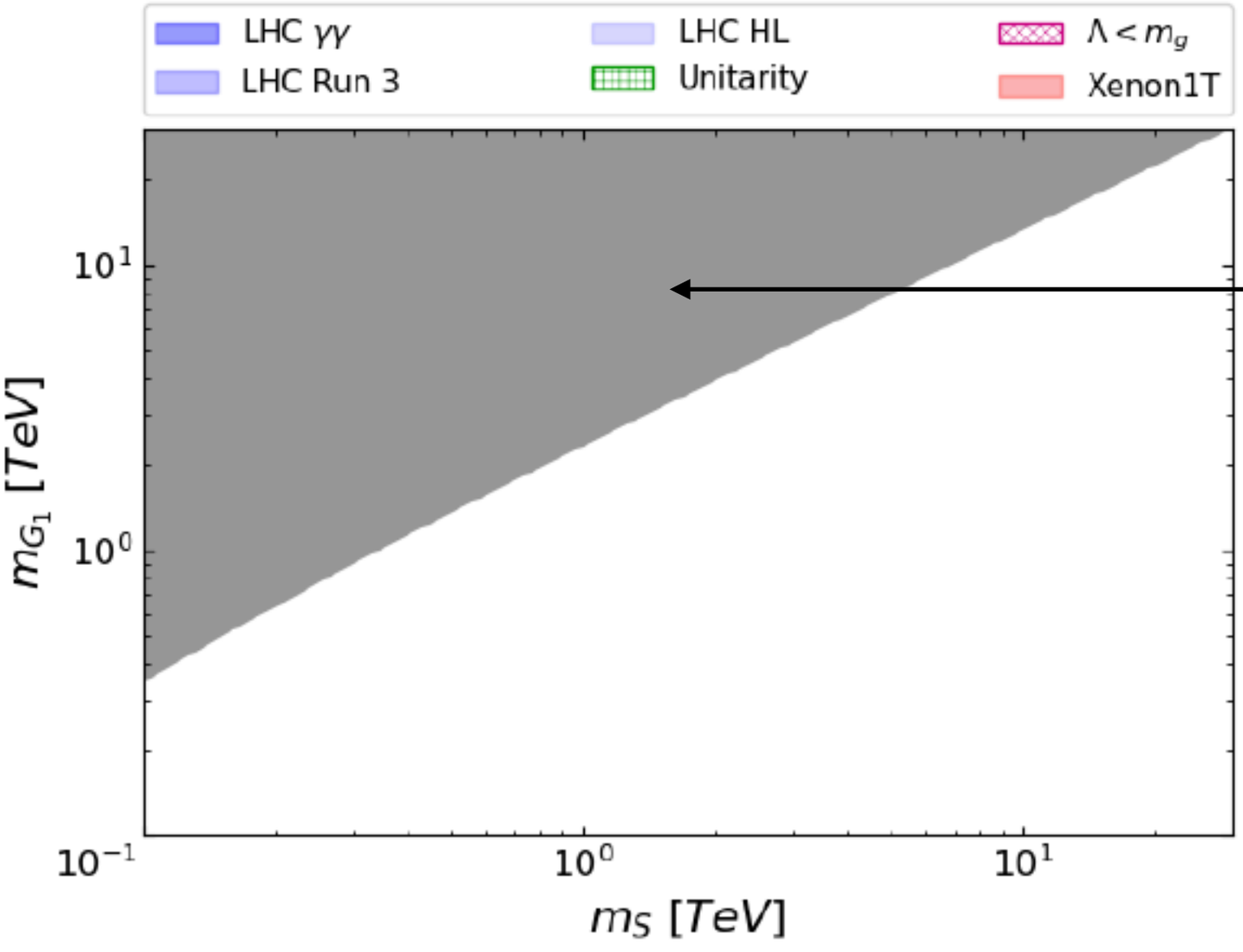
LHC bounds: CW/LD



- 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.

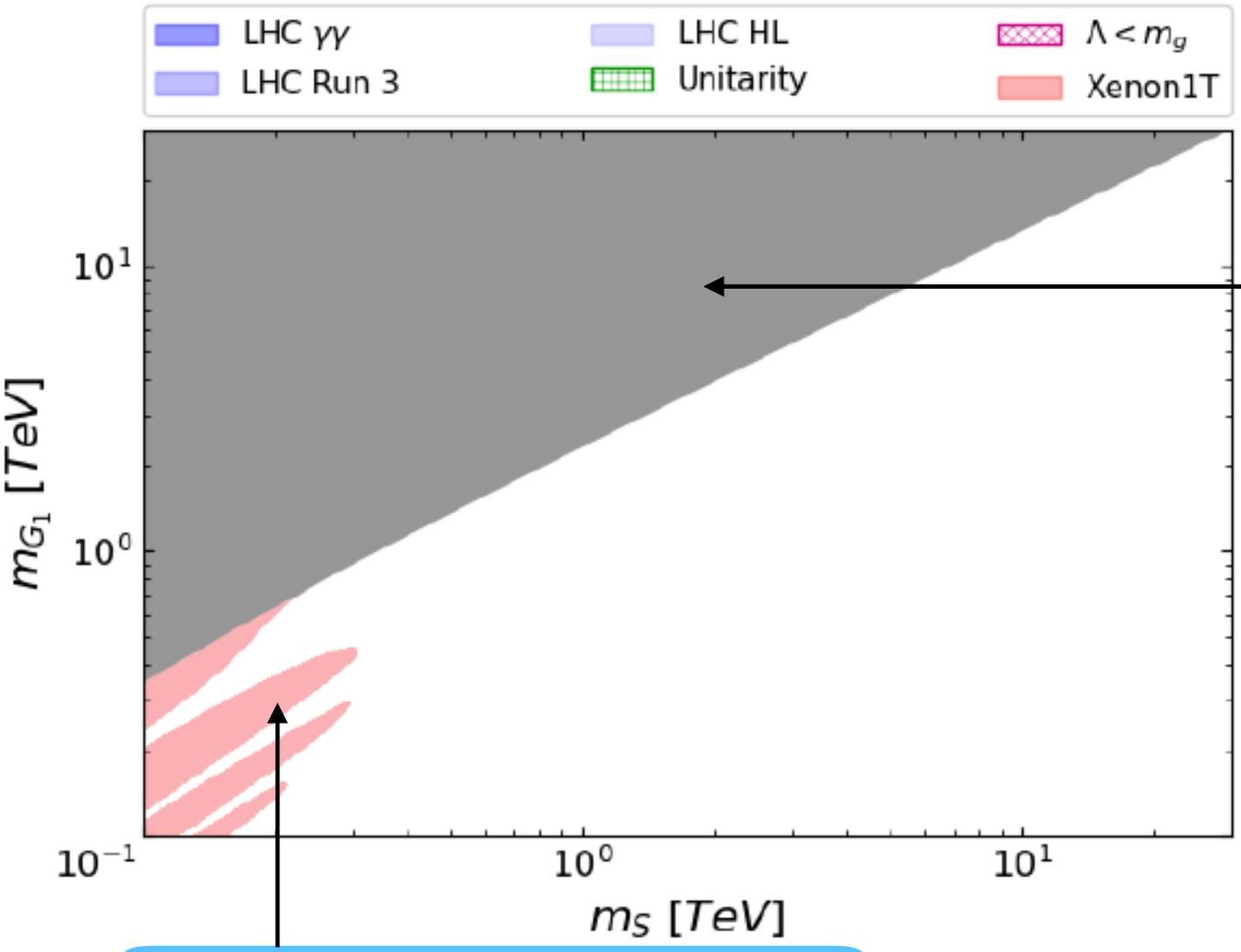
Non-Resonant searches at Run II

Adding constraints: RS



Allowed with a fine-tuned radion mass, excluded otherwise

Adding constraints: RS



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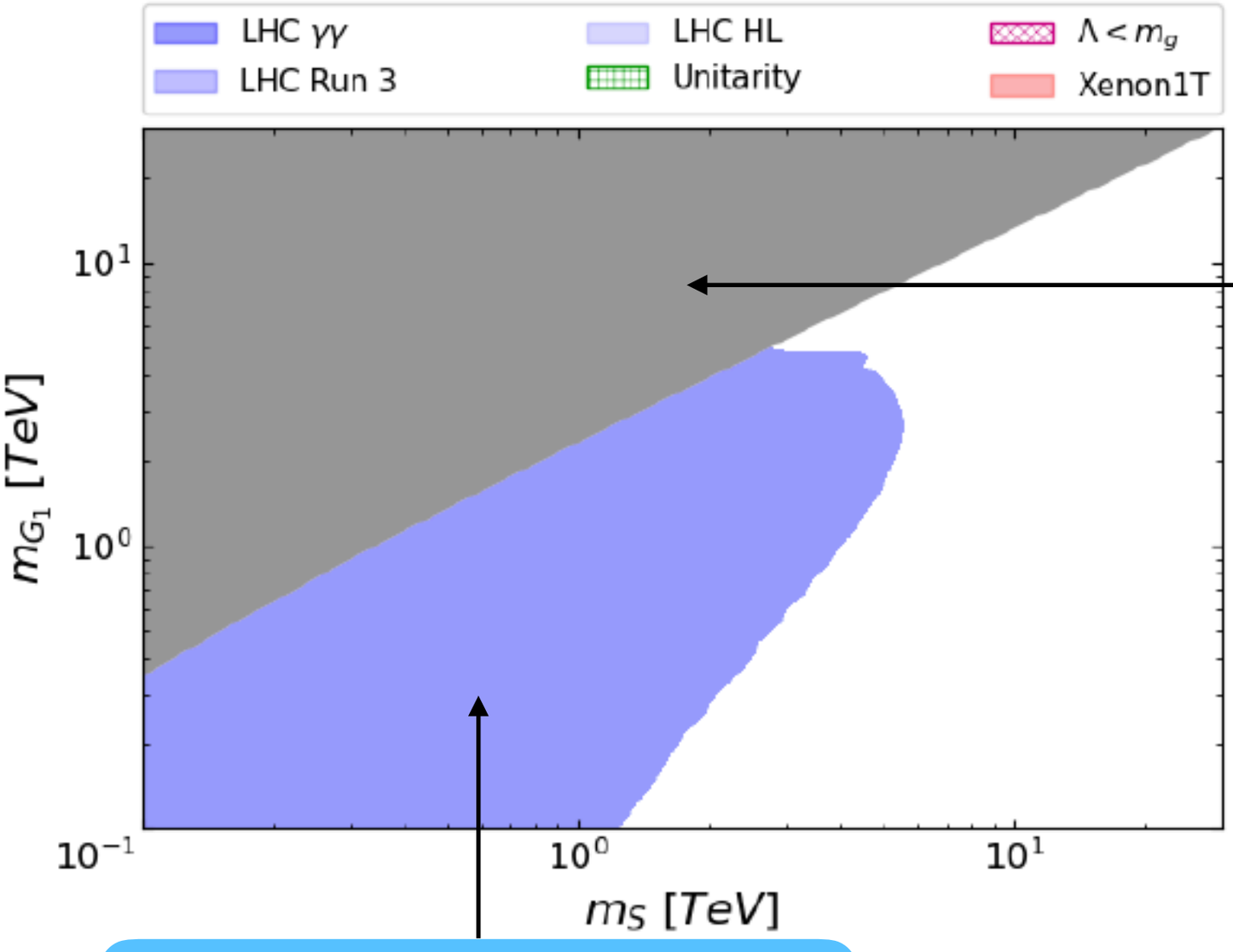
Xenon 1T Direct Detection bound

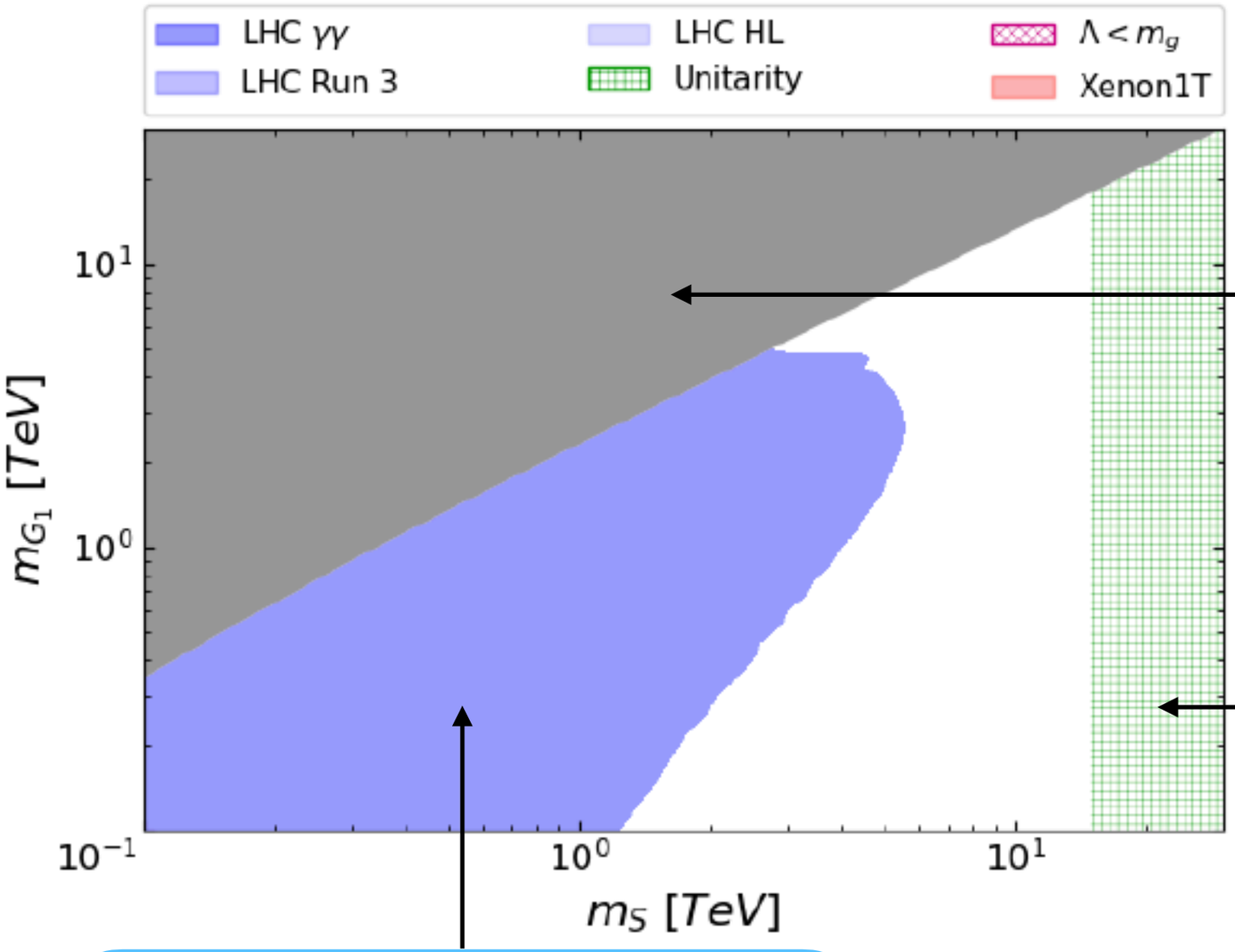
Adding constraints: RS



Allowed with a fine-tuned radion mass, excluded otherwise

36 fb^{-1} LHC Bound

Adding constraints: RS



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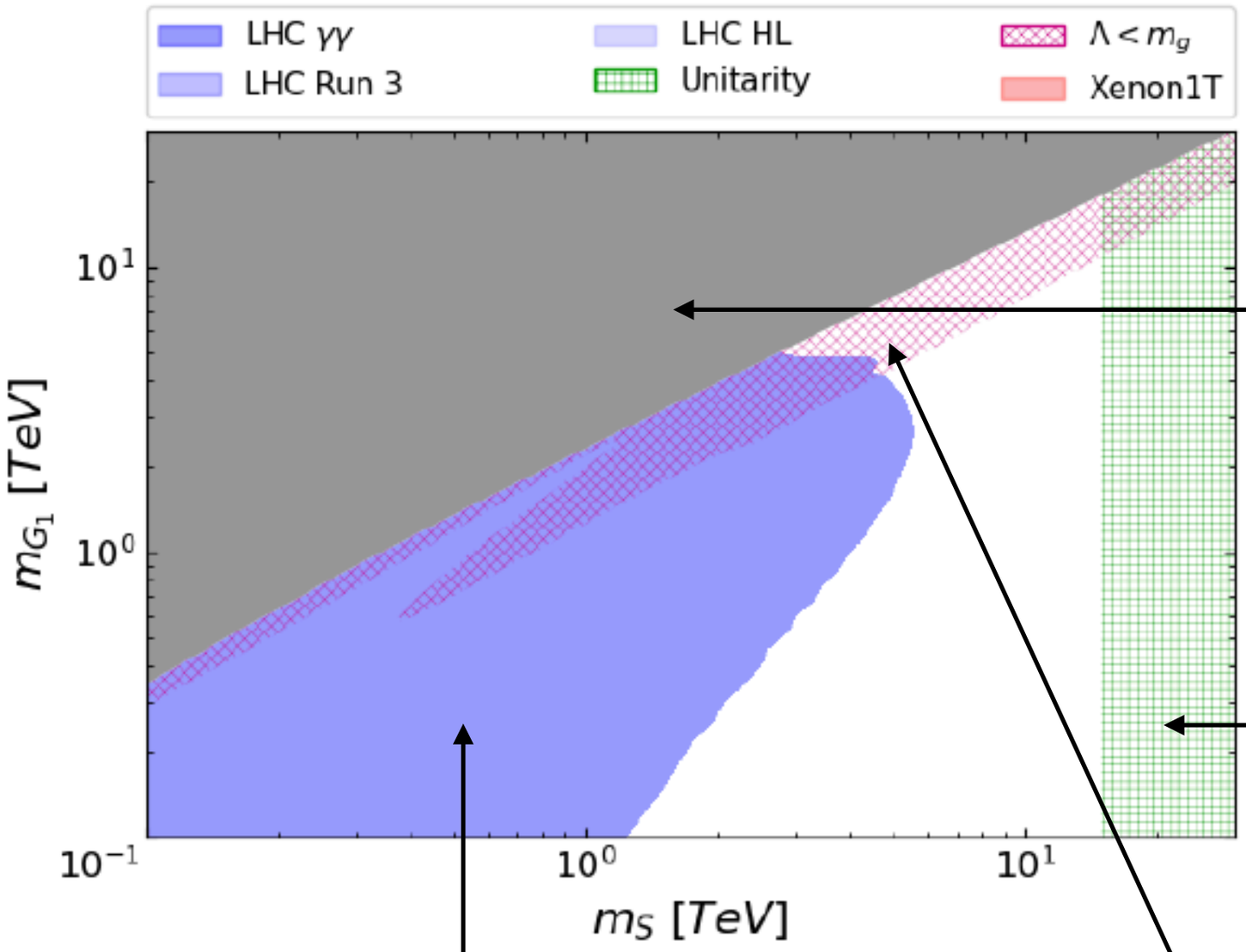
Unitarity

36 fb^{-1} LHC Bound

Adding constraints: RS



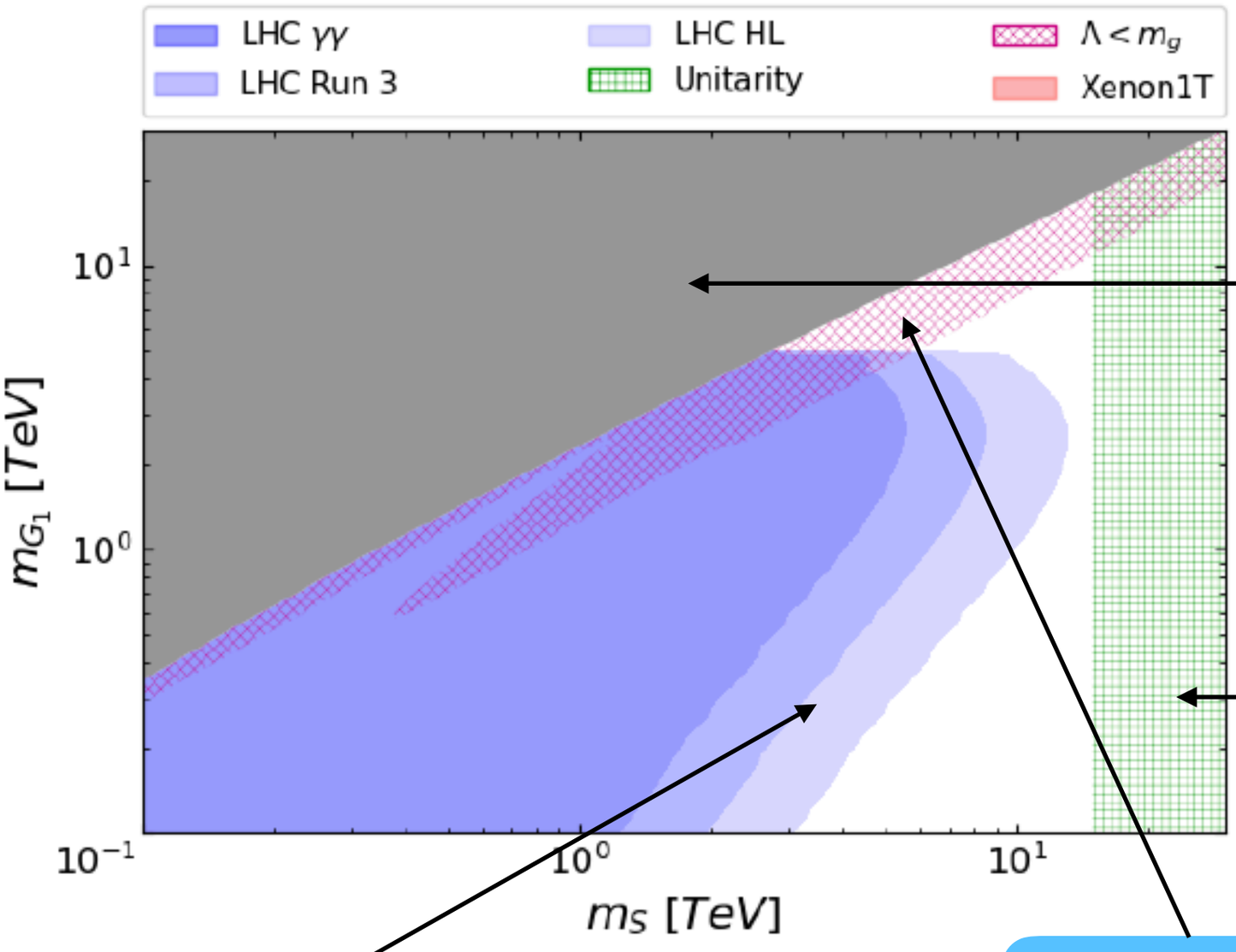
Allowed with a fine-tuned radion mass, excluded otherwise

Unitarity

36 fb^{-1} LHC Bound

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

Adding constraints: RS



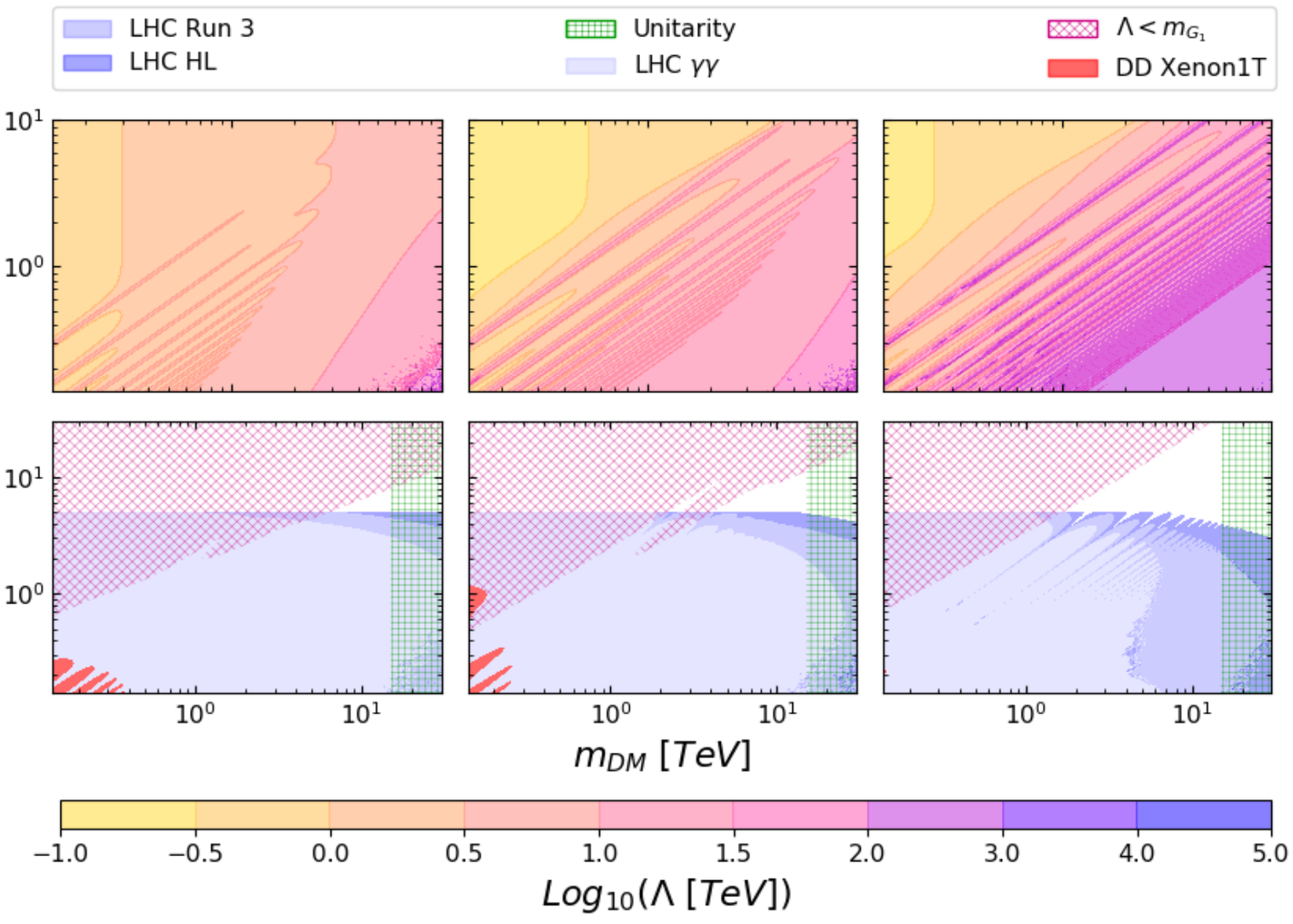
Allowed with a fine-tuned radion mass, excluded otherwise

Unitarity

Foreseen Bounds at LHC Run III and HL-LHC

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

Final results: RS



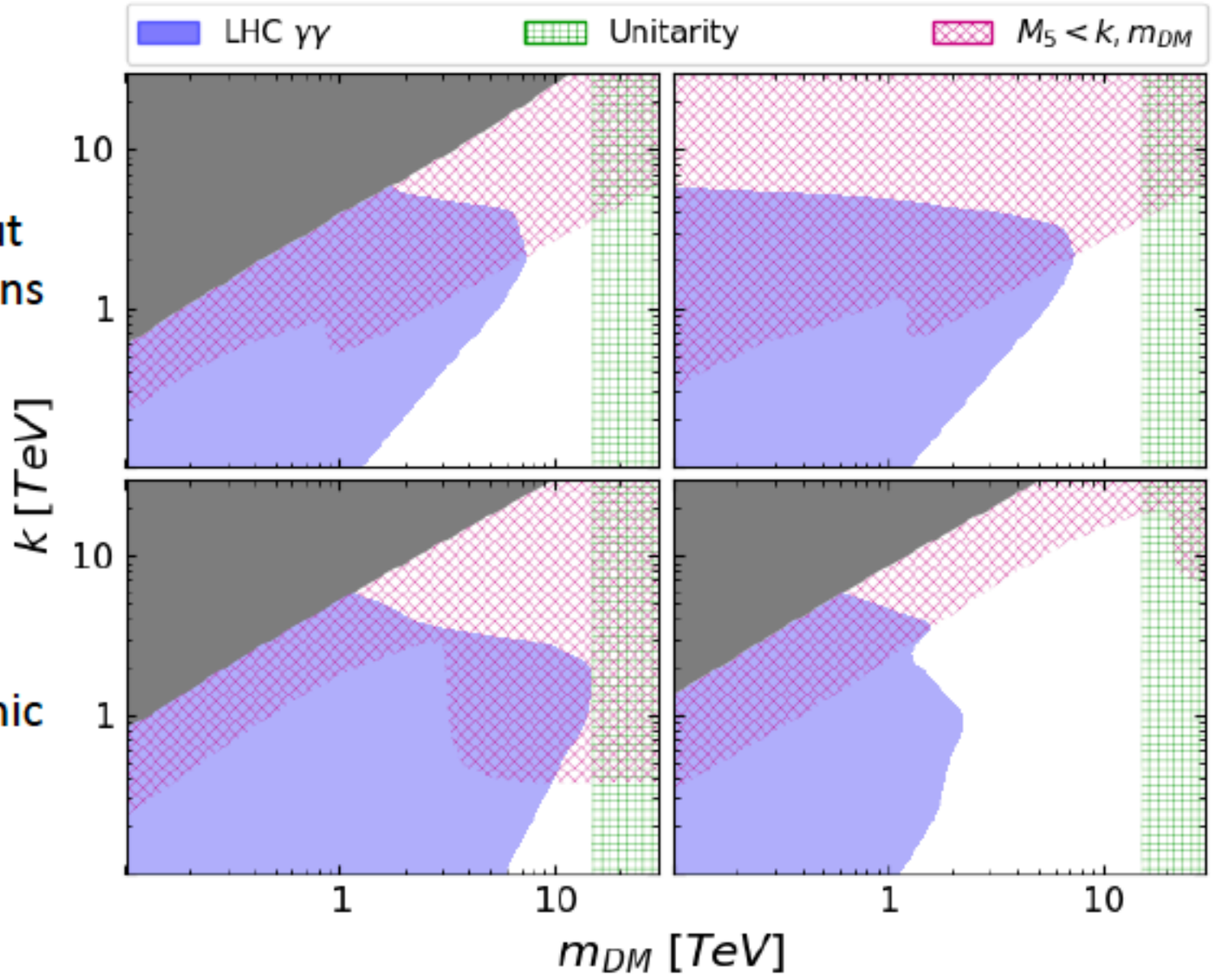
Values of Λ needed to achieve Ω_{DM}

Allowed regions (after adding triple vertices)

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

Final results: CW/LD

Scalar without radion/dilatons



Scalar with radion/dilatons

Fermionic

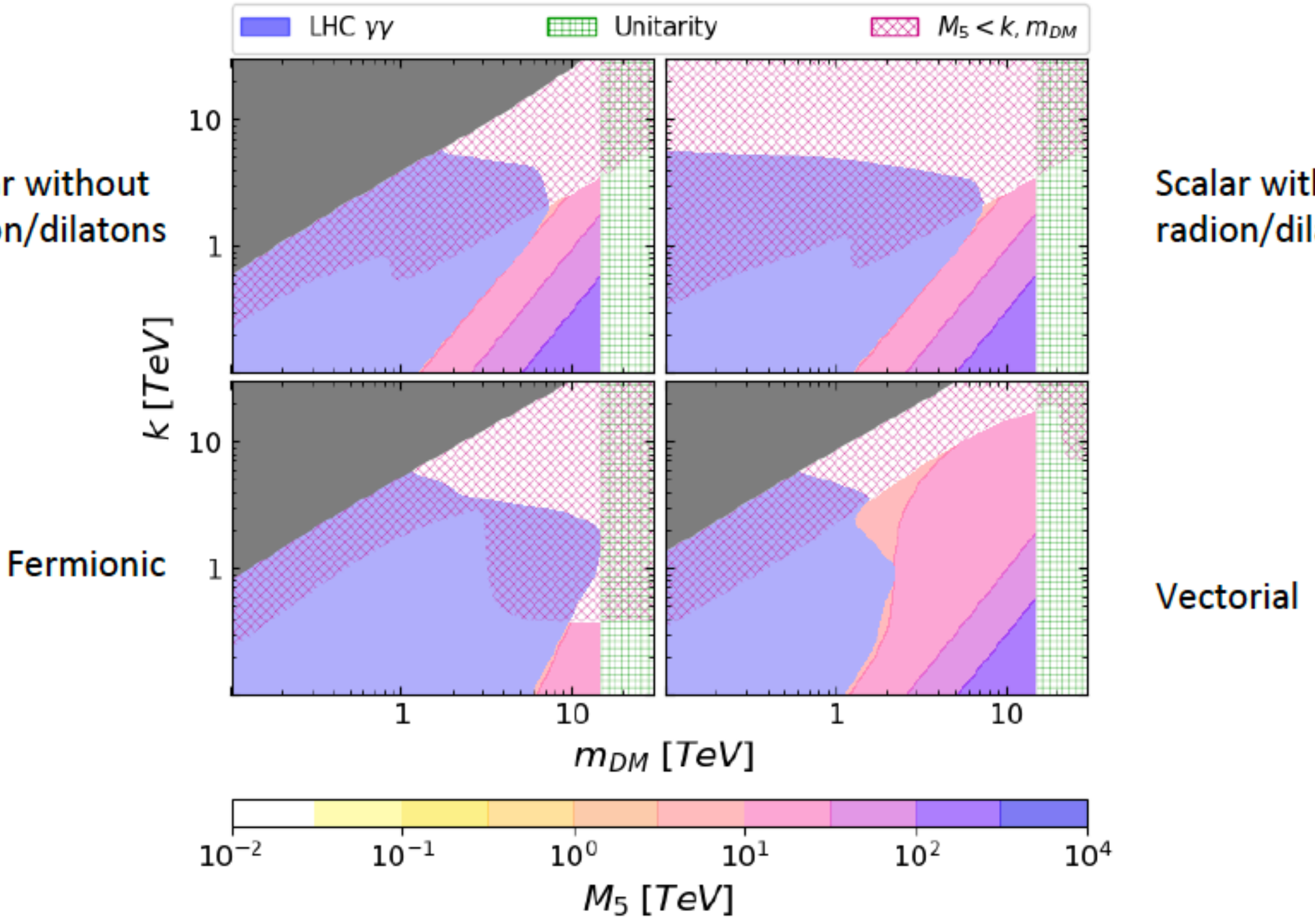
Vectorial

Work in progress to include triple vertices and recompute LHC bounds (Donini, Landini, Muñoz, Rius)

Final results: CW/LD

Scalar without radion/dilatons

Scalar with radion/dilatons



Fermionic

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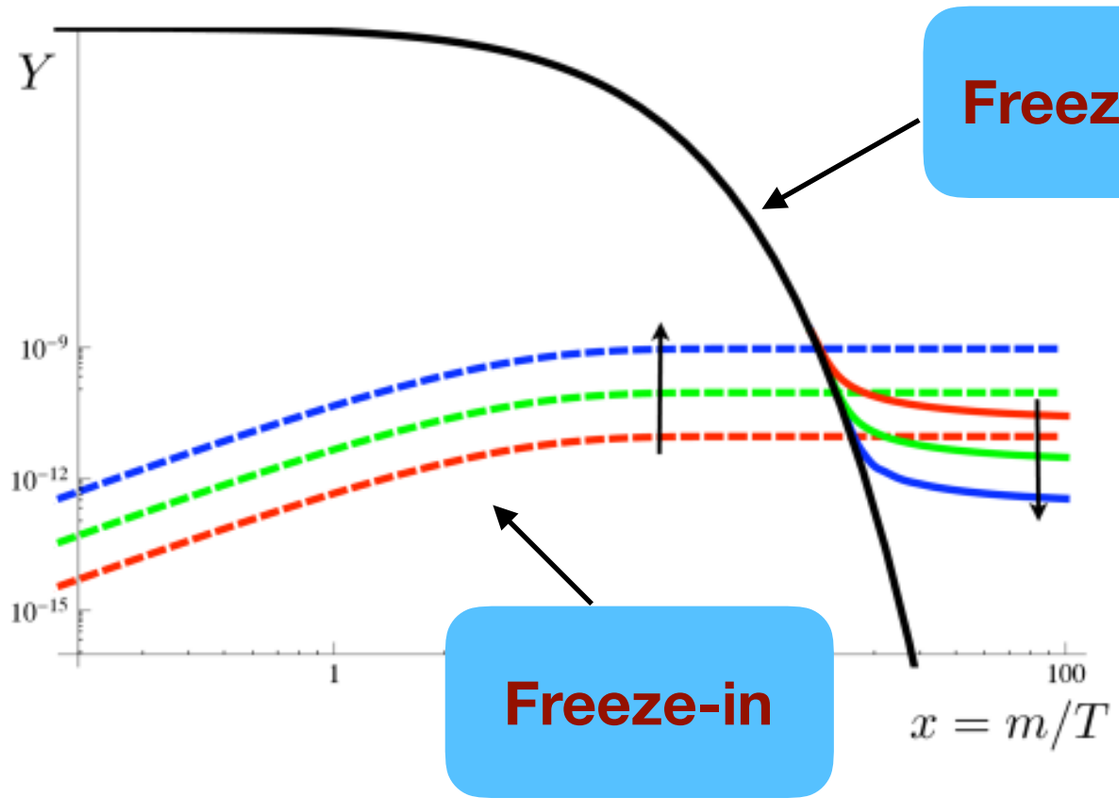
Remarks for WIMPs

We may achieve the observed DM relic abundance in an extra-dimensional framework within the freeze-out paradigm, both in RS and CW/LD geometries

Typically, SMALL regions in the parameter space are allowed

However, the effective interaction scale is $\mathcal{O}$(10-1000) TeV for RS and $\mathcal{O}$(10-100) TeV for CW/LD (maybe a Little Hierarchy Problem?)

2) Freeze-in (FIMPs)



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

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

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

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

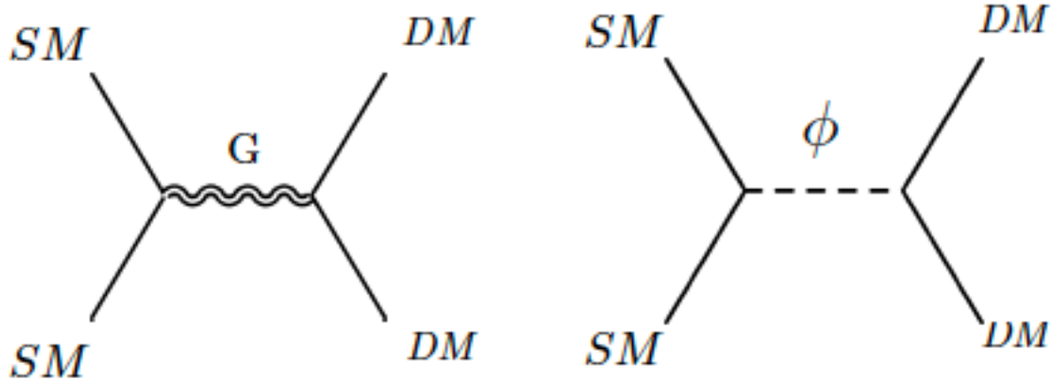
Evolution of the DM density with the temperature (only valid for Direct Freeze-in)

$$\langle\sigma v\rangle \sim \int_{4m_{DM}}^{\infty} ds(s - 4m_{DM}^2)\sqrt{s}\sigma_{an}(s)K_1(\sqrt{s}/T) \quad = ?$$

Relevant processes

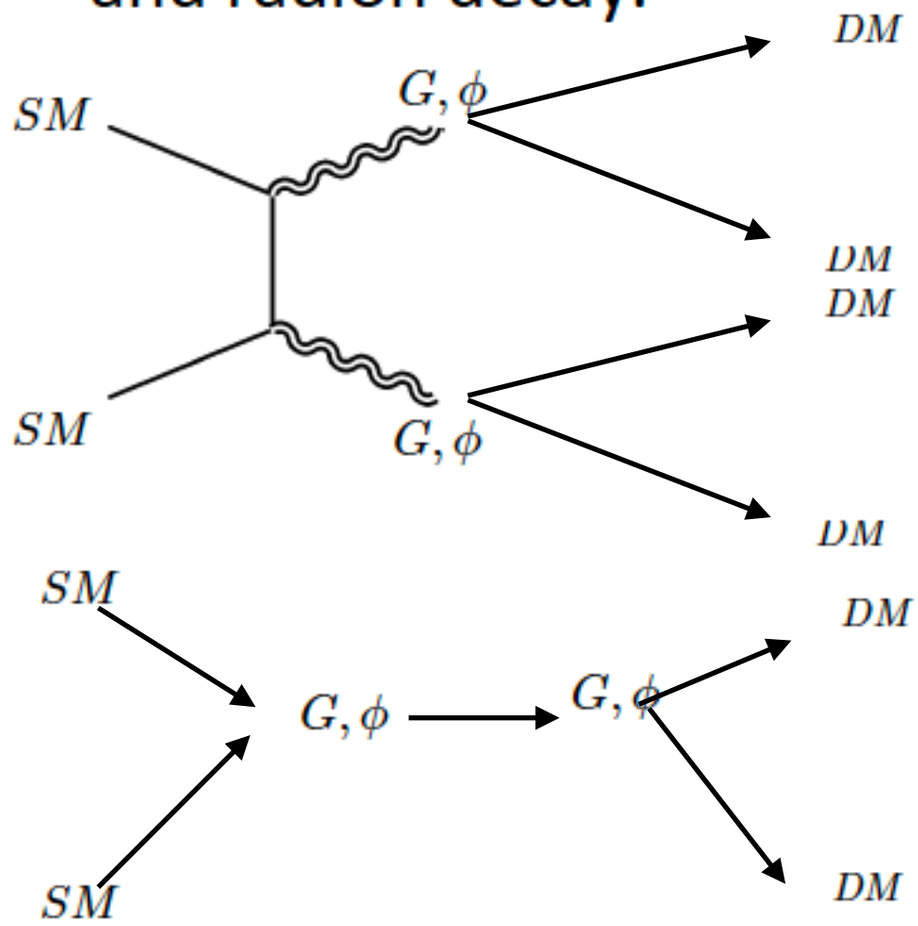
Direct Freeze In

- DM production via virtual graviton and radion exchange



Sequential Freeze In

- DM production via graviton and radion decay.



Careful to avoid double counting here

The Boltzmann equations

$$\frac{dY}{dT} = -\frac{\gamma_{\rm DM\to SM}}{H\,s\,T}\left[\left(\frac{Y}{Y^{\rm eq}}\right)^2 - 1\right] + \frac{\gamma^d_{\rm KK\to DM}}{H\,s\,T}\left[\frac{Y_K}{Y_K^{\rm eq}} - \left(\frac{Y}{Y^{\rm eq}}\right)^2\right],$$

$$\frac{dY_r}{dT} = -\frac{\gamma_{\rm r\to SM}}{H\,s\,T}\left[\left(\frac{Y_r}{Y_r^{\rm eq}}\right)^2 - 1\right] - \frac{\gamma^d_{\rm r\to DM}}{H\,s\,T}\left[\frac{Y_r}{Y_r^{\rm eq}} - \left(\frac{Y}{Y^{\rm eq}}\right)^2\right] - \frac{\gamma^d_{\rm r\to SM}}{H\,s\,T}\left[\frac{Y_r}{Y_r^{\rm eq}} - 1\right]$$

$$\frac{dY_K}{dT} = -\frac{\gamma_{\rm KK\to SM}}{H\,s\,T}\left[\left(\frac{Y_K}{Y_K^{\rm eq}}\right)^2 - 1\right] - \frac{\gamma^d_{\rm KK\to DM}}{H\,s\,T}\left[\frac{Y_K}{Y_K^{\rm eq}} - \left(\frac{Y}{Y^{\rm eq}}\right)^2\right] - \frac{\gamma^d_{\rm KK\to SM}}{H\,s\,T}\left[\frac{Y_K}{Y_K^{\rm eq}} - 1\right].$$

Taking into account
both Direct and Sequential Freeze-in

Approximate solution

- The Boltzmann equation solution in the Freeze in case can be approximated by:

$$Y(T) \simeq \frac{135}{2\pi^3 g_{\star s}} \sqrt{\frac{10}{g_\star}} M_P \int_{T_{\rm rh}}^{T} \frac{\gamma_{\rm DM\to SM}(T)}{T^6} dT$$

- The relevant value is the abundance today

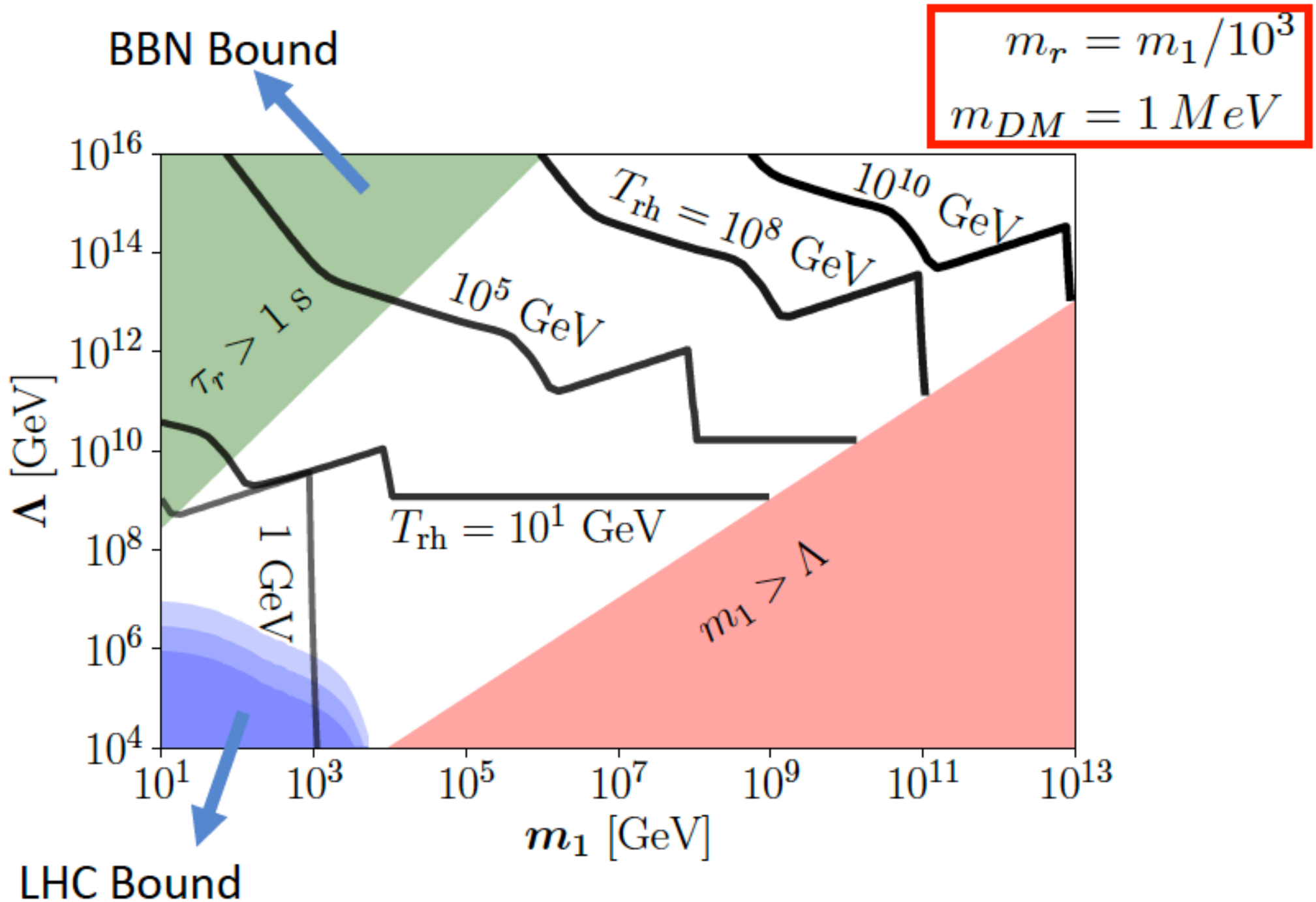
$$Y_0 \longrightarrow T \ll T_{rh}$$

- The value of the reheating temperature is fixed in order to obtain the measured DM abundance.

$$T_{rh} = f(m_{DM}, m_1, \Lambda, m_r)$$

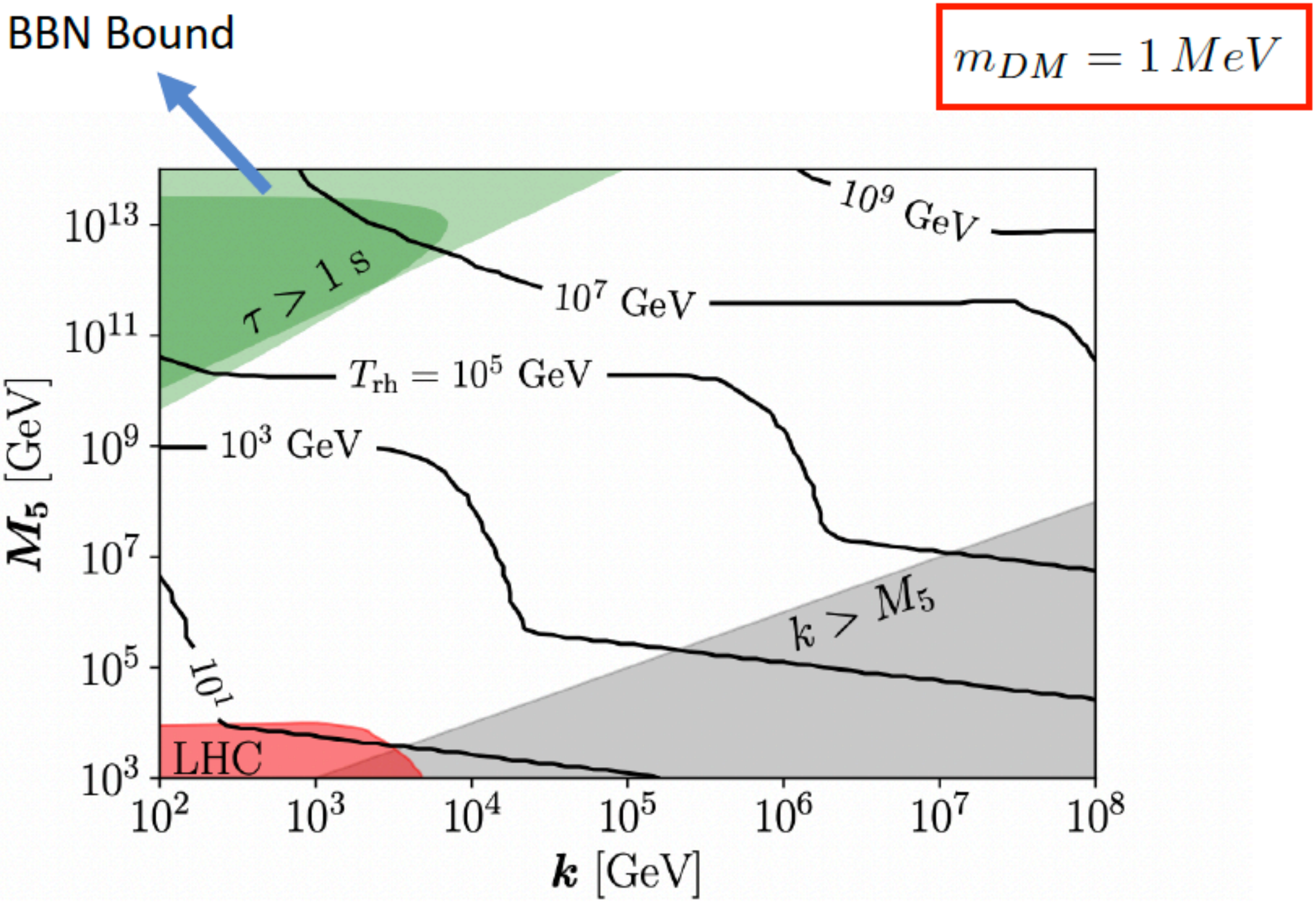
Maximal temperature reached by the SM thermal bath

Final results: RS



Final results: CW/LD

$m_{DM} = 1\,MeV$



Remarks for FIMPs

We may achieve the observed DM relic abundance in an extra-dimensional framework within the freeze-in paradigm, both in RS and CW/LD geometries

Typically, HUGE regions in the parameter space are allowed

However, the effective interaction scale is $\Lambda > 10$ TeV for RS and $M_5 > 10$ TeV for CW/LD (maybe a Little Hierarchy Problem?)

Very low values of T_{rh} are allowed. Does this make sense?

Outlook

We are looking for INFLATIONARY MODELS in extra-dimensional frameworks with low reheating temperature: not there yet…

However, we have found that a common feature of RS and CW/LD is to have a modified Friedmann Equation

$$H^2 = \frac{\rho}{3\,M_P^2}\left(1+\frac{\rho}{2\sigma}\right)$$

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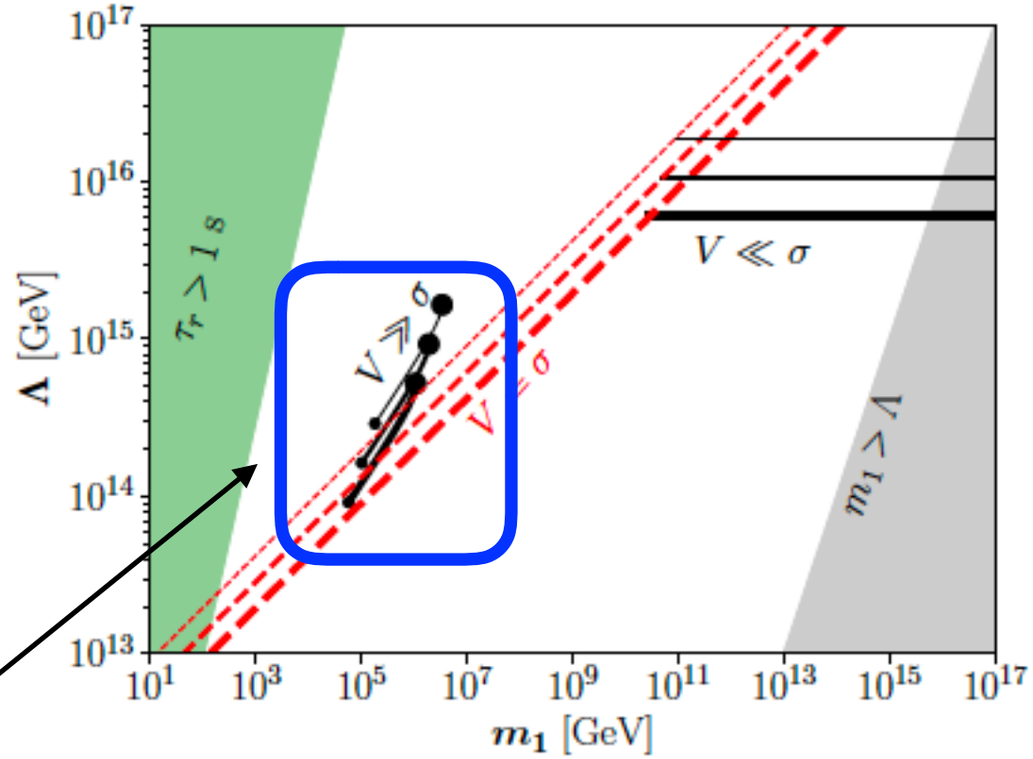


New viable inflationary models

Bernal, Cosme, Donini and Rius, in preparation

Overall conclusions

Extra-dimensional extensions of the Standard Model seem to give possible solutions to some of its open problems, although they do not solve the original problem they were proposed for, the HIERARCHY PROBLEM

...

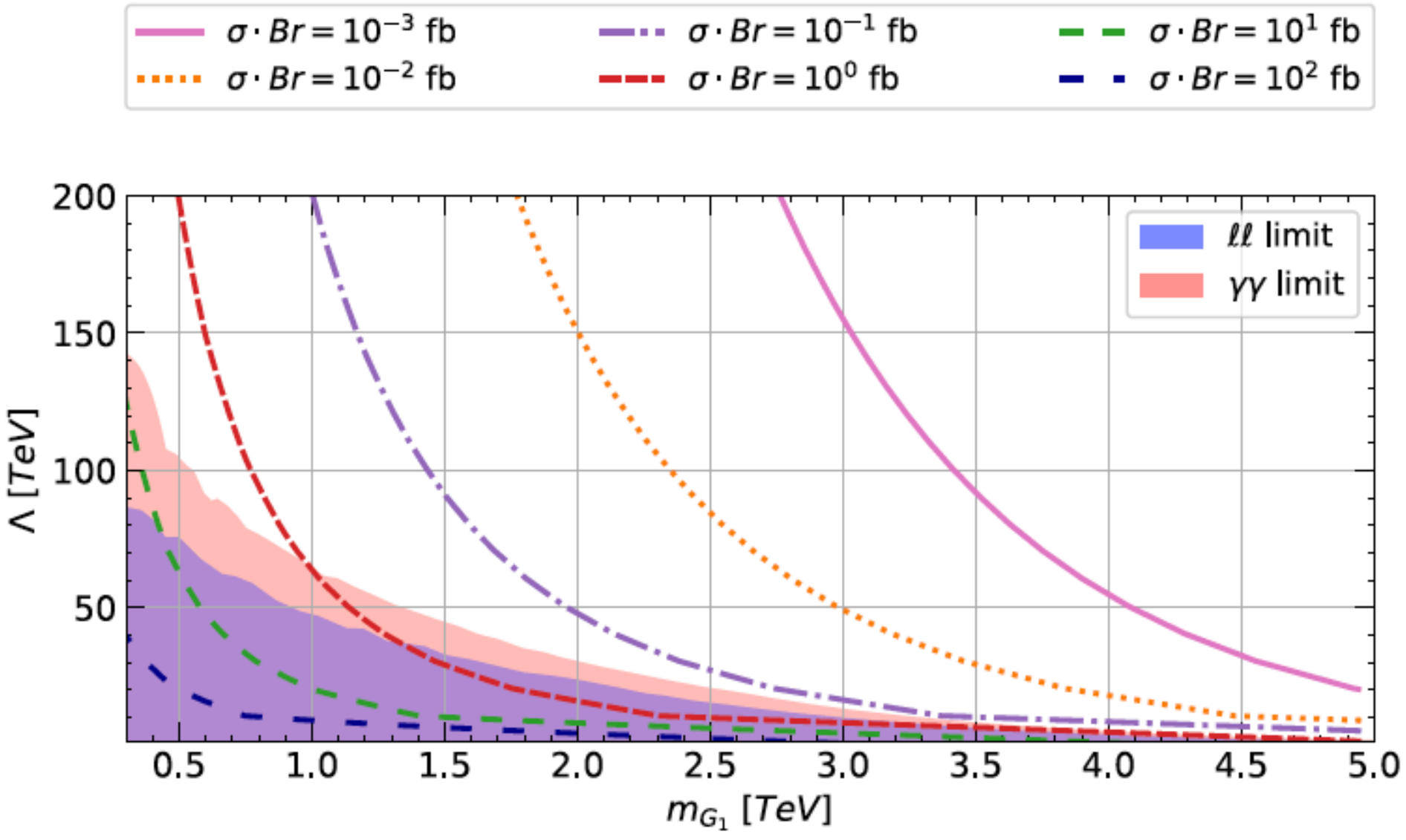
...

Who does it, anyway?

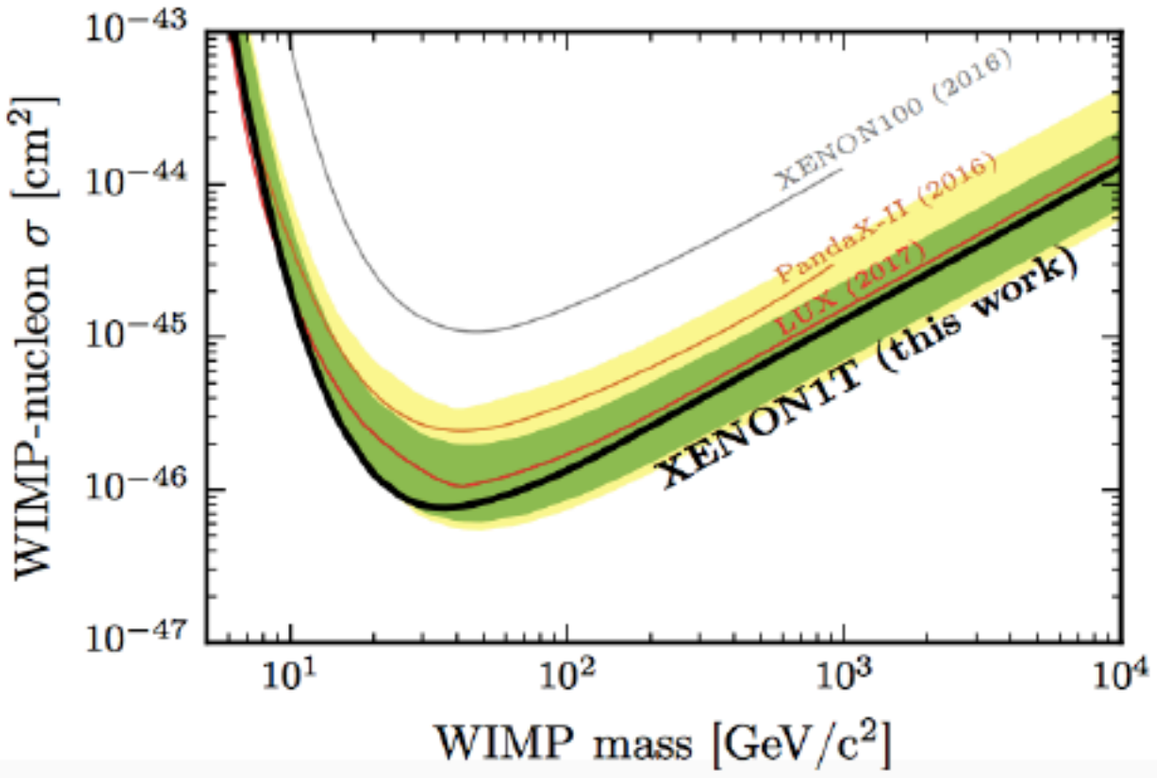
It seems to me fruitful to explore further this framework, keeping in the back of my mind that Extra-dimensions may be a step Towards understanding Quantum Gravity

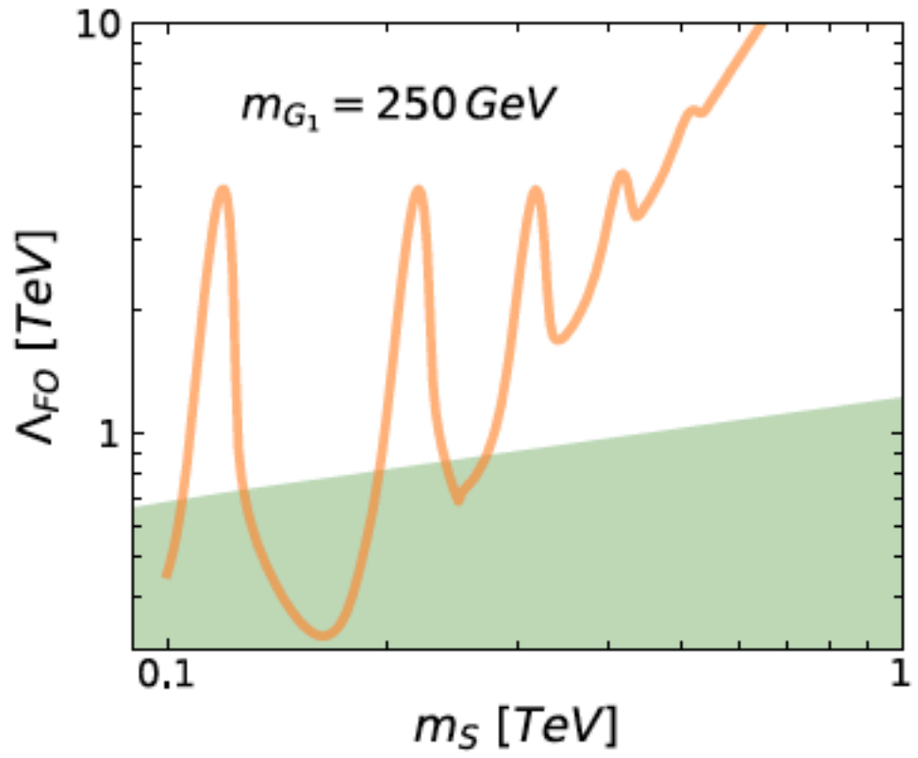
Backup slides

Bounds from resonance searches at LHC



Bounds from Direct Detection experiments

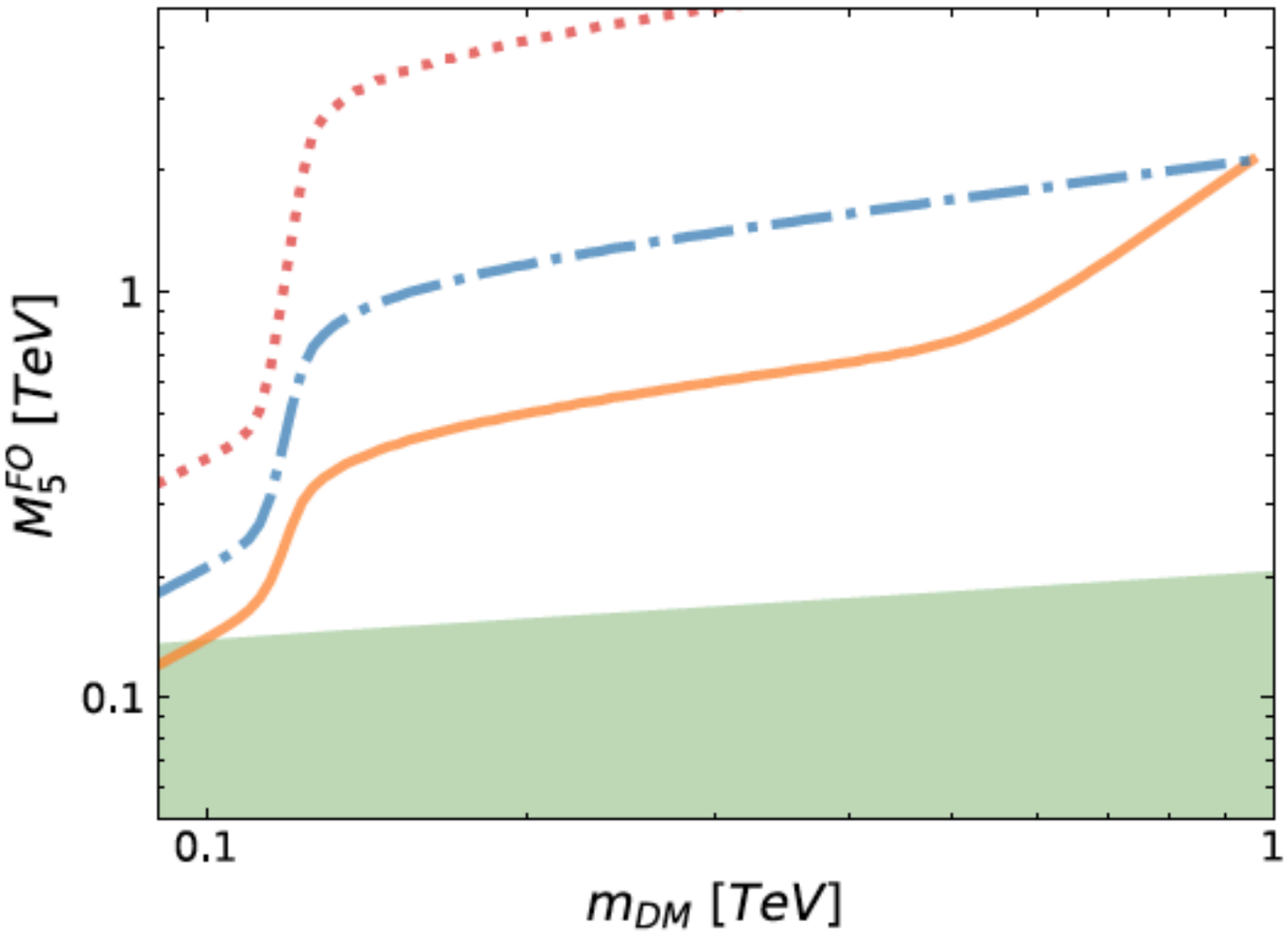




In our analysis we have fixed the scale using the restriction

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

Bounds from Direct Detection experiments



$$k = 250\,GeV$$

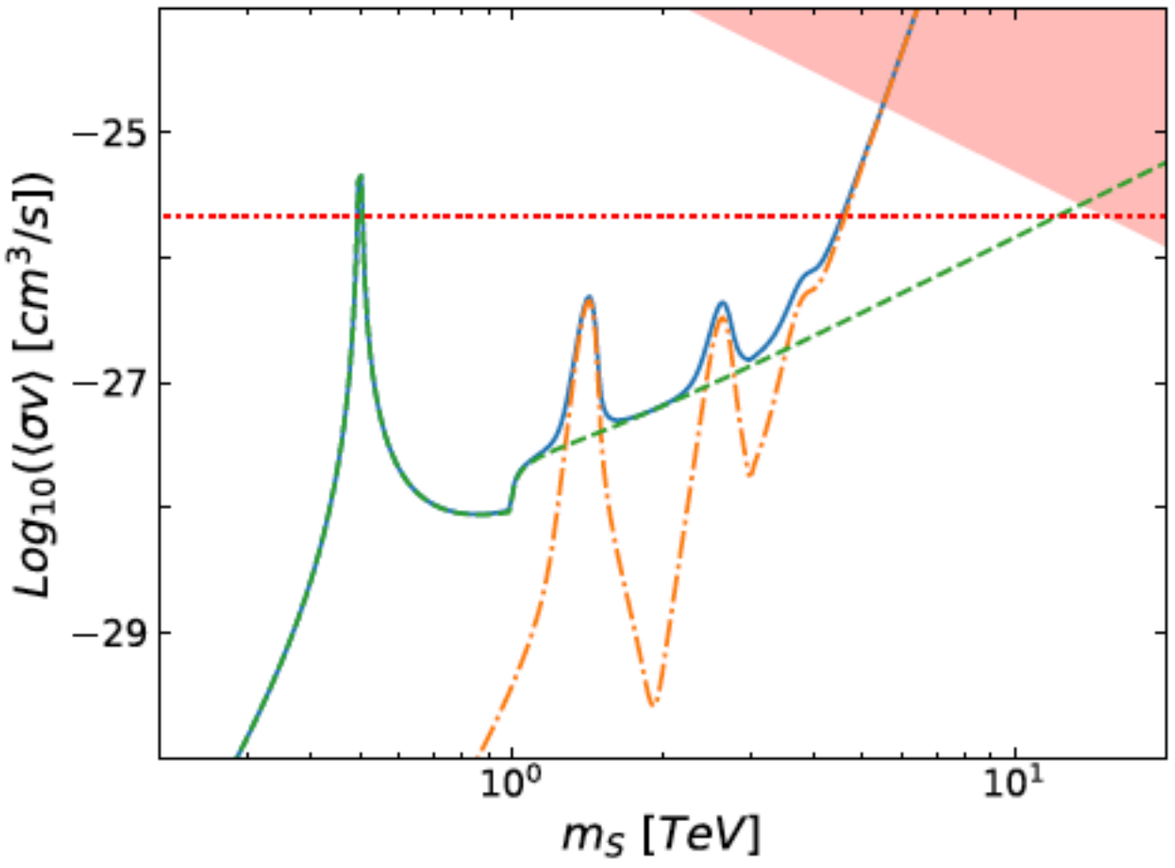
The DM-nucleon scattering cross section is too weak to constrain the model in any point of the analysed region.

Vectorial

Fermionic

Scalar

Radion impact in the phenomenology (scalar DM)



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

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

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

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