# Spin-2 mediated Dark Matter in Warped Extra-Dimensions

**Arturo de Giorgi**

**arXiv:** 2105.06794

**In collaboration with:** Stefan Vogl (Freiburg University)

**Contact:** arturo dot degiorgi at uam dot es

- Measured DM density parameter:

$$\Omega_{DM} h^2 = 0.120 \pm 0.001$$

Planck 2018 results. VI. Cosmological parameters

- Relic abundance via *freeze-out* mechanism;

$\implies$ controlled by Boltzmann equation:

$$\dot{n} + 3Hn = -\langle \sigma v \rangle \left[ n^2 - n_{eq}^2 \right]$$
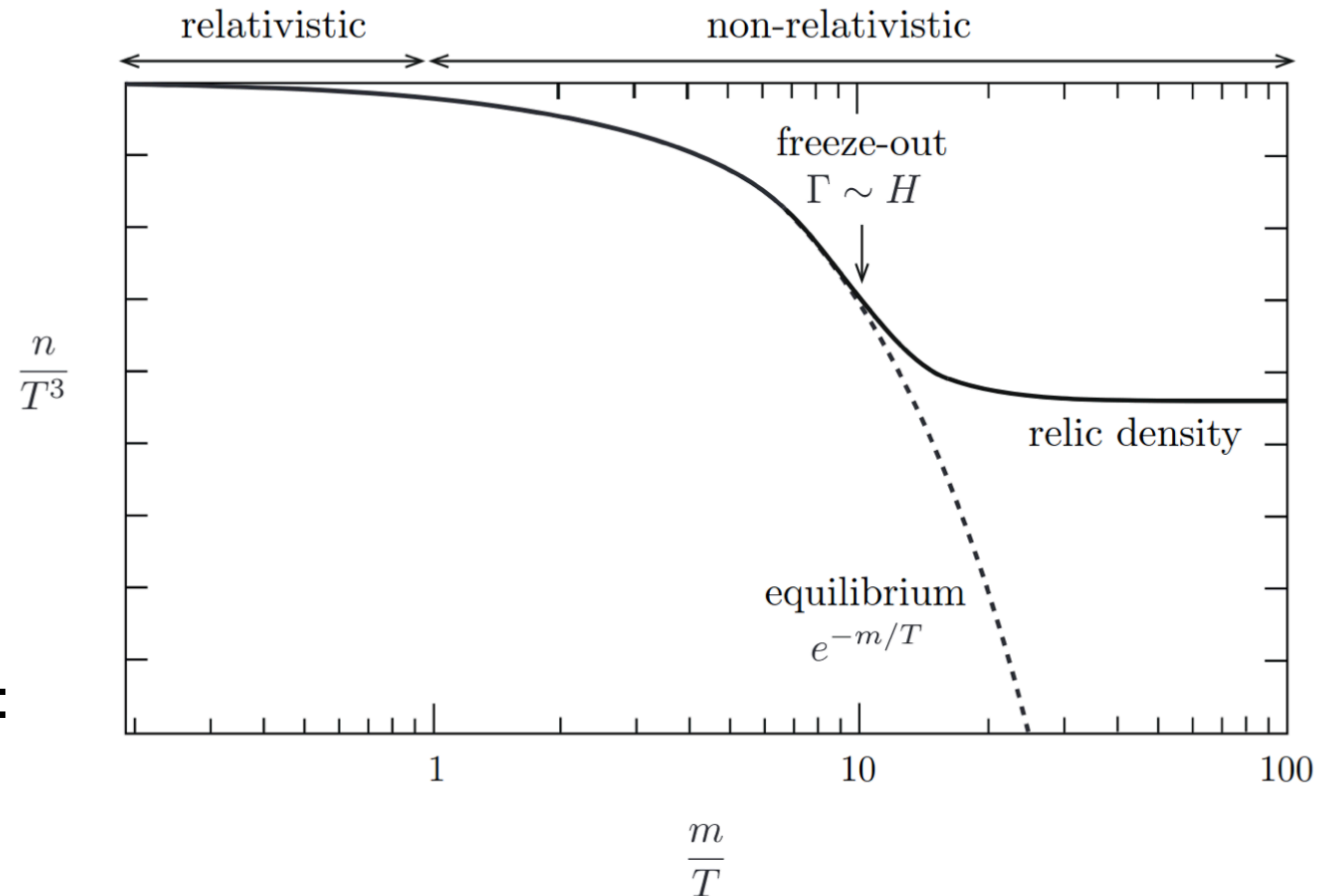


Image credit: Daniel Baumann, "Lectures Notes on Cosmology"

| **Dark Matter** | | **Gravity** |
|---|---|---|
| Real Massive Scalar Field | + | Randall-Sundrum Model (Warped Extra-Dimensional gravity) |
| Interaction with SM only via gravity | | • If used to alleviate Hierarchy Problem |
| Relic Abundance via *freeze-out* mechanism | | $\implies$ Coupling Matter-Gravity $\Lambda^{-1} \sim$ TeV$^{-1}$ |

## Focus on:

- **DM annihilation into massive spin-2 final states**

- Perturbative Unitarity of the Theory;

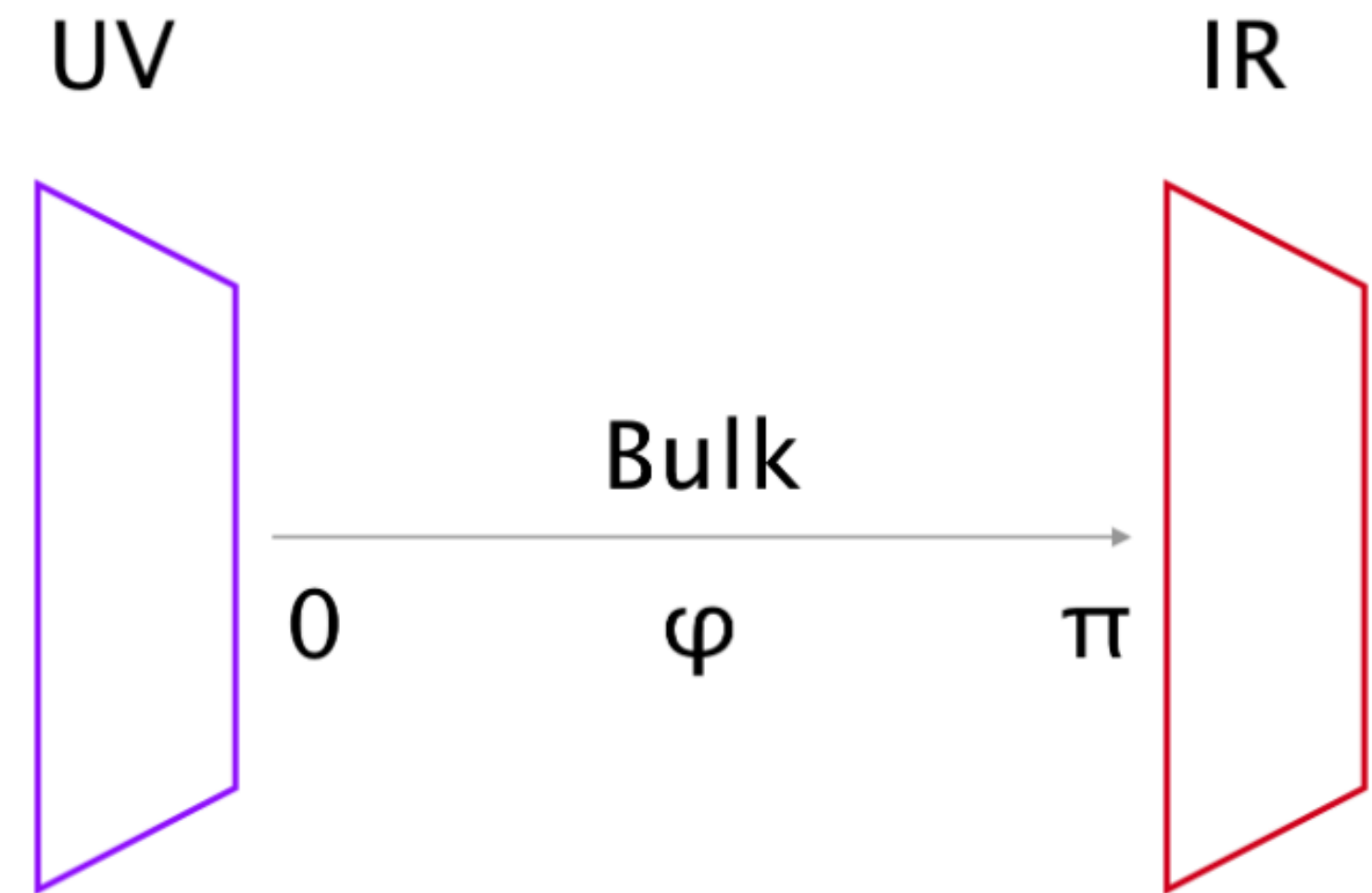- LHC Bounds on RS-parameters;

- Constraints on DM.

**Key points:**

- A 5th dimension compactified on $S^1/\mathbb{Z}^2$;
- 4D Poincaré invariance;
- All dimensionful parameters are of the order of $M_{Pl}$;
- Only gravity is 5D.

**Metric:**

$$\mathrm{ds}^2 = e^{-2\mu|\varphi|}\eta_{\mu\nu}\mathrm{d}x^\mu\mathrm{d}x^\nu - r_c^2\mathrm{d}\varphi^2$$

'warp factor'

UV          IR

**Bulk**

0          φ          π

$$\mathcal{L}_{\mathrm{UV}} = 0 \quad , \quad \mathcal{L}_{\mathrm{IR}} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{DM}}$$

$$\mathcal{L}_{\mathrm{DM}} = \tfrac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - \tfrac{1}{2}m_\phi^2\phi^2$$

- Weak field expansion of the metric:

$$\boxed{\text{5D massless graviton}} \ \hat{h}_{\mu\nu}(x,\varphi) \ \xrightarrow{\text{KK-decomposition}} \ \hat{h}_{\mu\nu}(x,\varphi) = \sum_{n=0}^{\infty} \frac{1}{\sqrt{r_c}} h_{\mu\nu}^{(n)}(x) \ \psi_n(\varphi) \ \xrightarrow{\text{4D-EFT}} \ \left\{ h_{\mu\nu}^{(n)}, m_n \right\}_n$$

- 5D wave-functions set by:

$$-\frac{1}{r_c^2} \frac{d}{d\varphi} \left[ e^{-4\mu|\varphi|} \frac{d\psi_n}{d\varphi} \right] = m_n^2 e^{-2\mu|\varphi|} \psi_n \qquad \text{with} \qquad m_n \sim n m_1$$
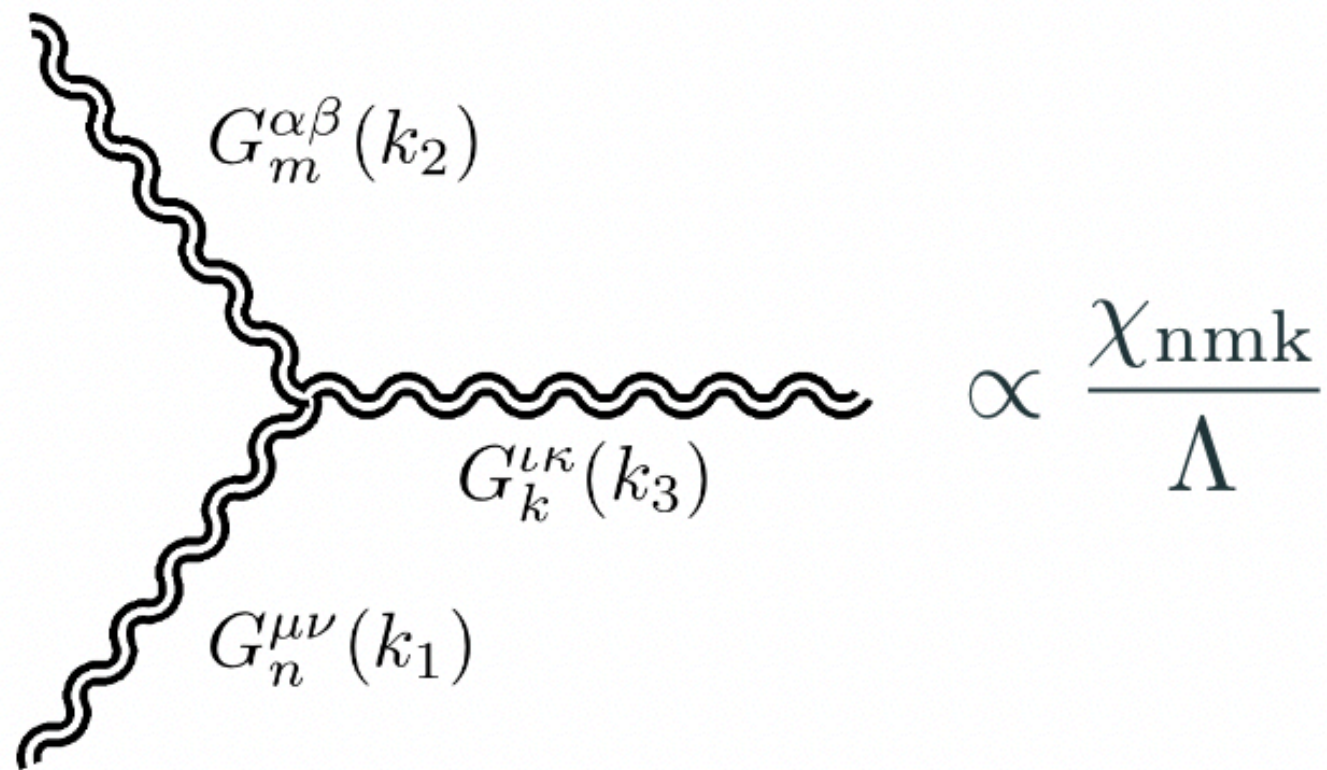
RS-spectrum $\begin{cases} \text{massless spin-2 field} & \{G_0 \ , m_0 = 0\} & \equiv \text{'GR-graviton'} \\ \text{massive spin-2 fields} & \{G_n \ , m_n\}_{n=1}^{\infty} & \equiv \text{'KK-gravitons'} \\ \text{massless}^{*} \text{ spin-0 field} & \{r \ , m_r = 0\} & \equiv \text{'radion'} \end{cases}$

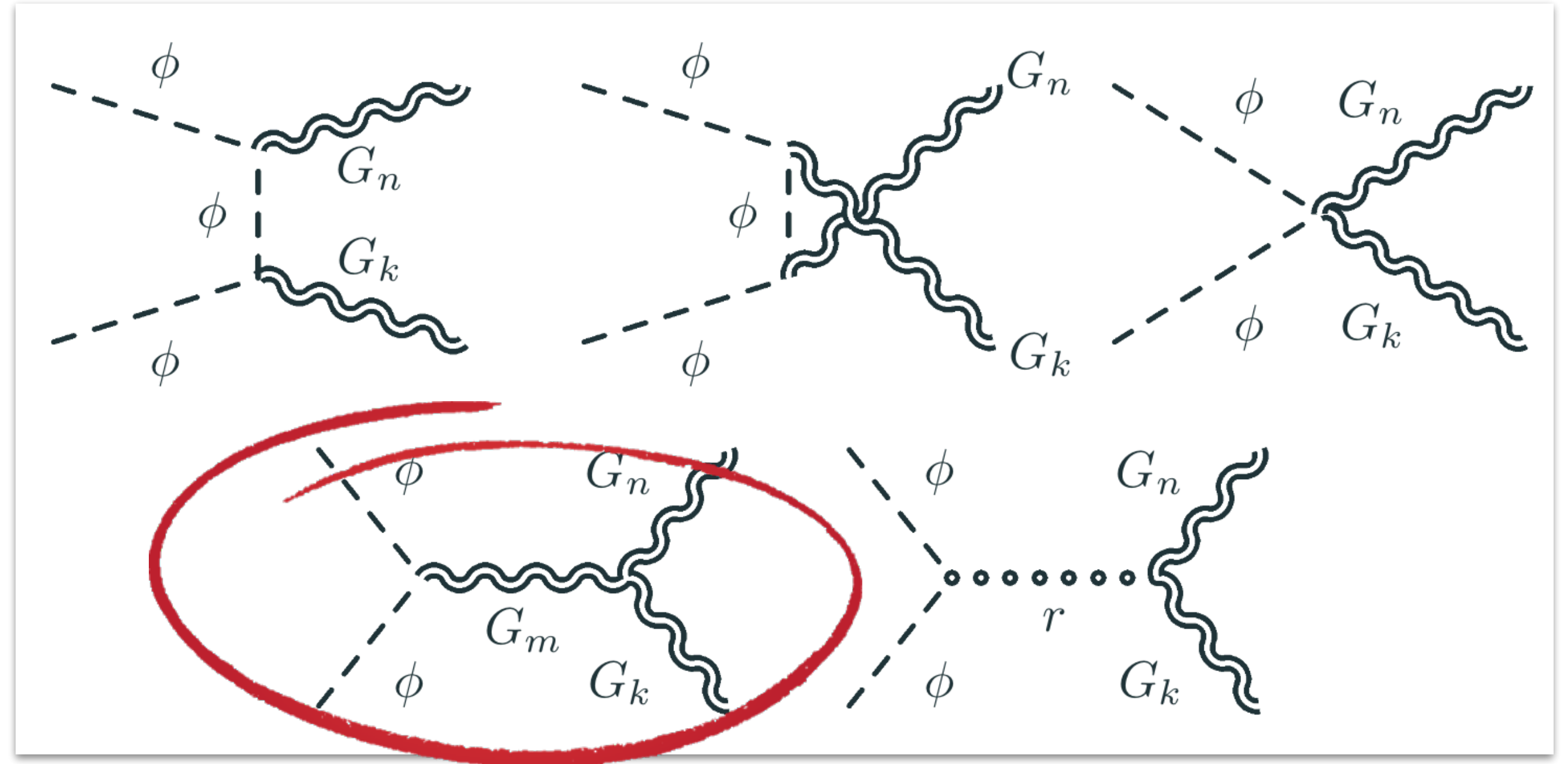*mass term added by hand; it can be generated via an extra mechanism, e.g. *Goldberger–Wise mechanism*

- 3rd order gravity sector:

$$\mathcal{L} \propto \left[ \int_{-\pi}^{\pi} \mathrm{d}\varphi\, e^{-2\mu|\varphi|} \psi_n(\varphi) \psi_m(\varphi) \psi_k(\varphi) \right] \mathcal{L}_{4D}$$
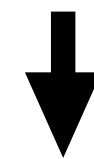


$$\propto \frac{\chi_{\mathrm{nmk}}}{\Lambda}$$

$G_m^{\alpha\beta}(k_2)$
$G_k^{\iota\kappa}(k_3)$
$G_n^{\mu\nu}(k_1)$

$$\Lambda \equiv M_{Pl}\, e^{-\mu\pi} \sim \mathrm{TeV}$$

Truncate KK-tower

**How many?**

$$\mathcal{M}_{\mathrm{trunc.}}\, (\phi\phi \longrightarrow G_n G_k) \sim s^3/\Lambda^2$$

**Huge impact on DM annihilation at high temperature!**

$$\sigma_{\mathrm{trunc.}} \sim s^5/\Lambda^4$$

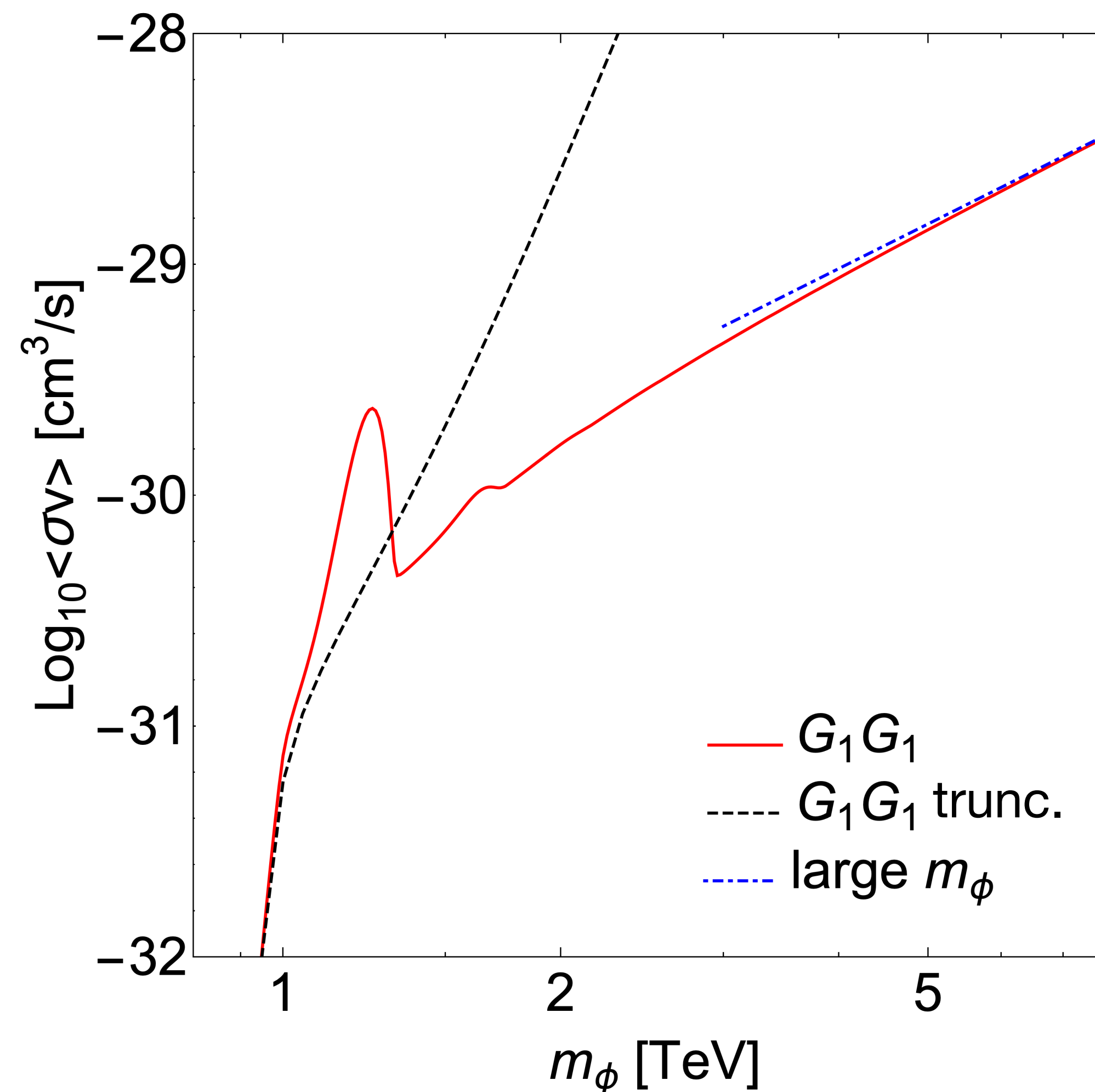$$\langle \sigma v \rangle_{\mathrm{trunc.}} \sim T^{10}/\Lambda^4$$

- 4D EFT single-diagram amplitudes are plagued by unitarity issues due to energy growth of *longitudinal modes* of KK-gravitons

- Include full KK-tower:

$$\mathcal{M}_{00} = -\frac{is^3 \sin^2(\theta) \left( \sum_{m}^{\infty} \chi_{\mathrm{nkm}} - 1 \right)}{24\Lambda^2 m_k^2 m_n^2} + \mathcal{O}(s^2)$$

$\Longrightarrow$ if **all** RS-spectrum is summed, subtle **sum-rules** involving couplings **cancel high energy growth**

$$\Longrightarrow \quad \mathcal{M} \sim s/\Lambda^2$$

A. d. G. and S. V. - 2012.09672
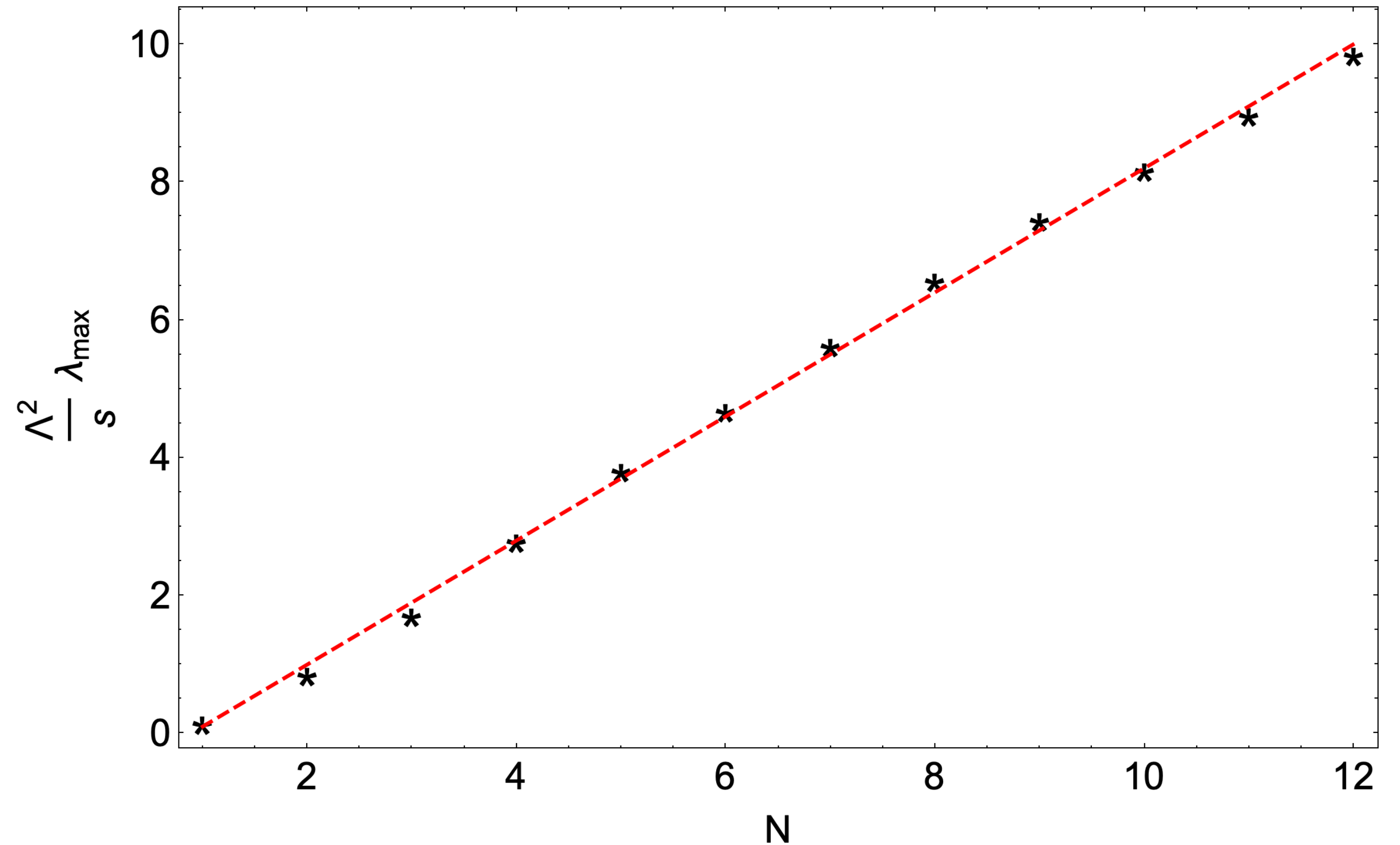
R. S. C. et al. - 2002.12458

- As the energy grows more channels available in the final states;

$\implies$ identify **breakdown scale** performing **coupled channel analysis** on scattering of KK-gravitons

$\implies$ study **eigenvalues** $\{\lambda_i\}$ of S-Matrix as a function of $N$ (i.e. if $G_N G_N$ can be produced)

- Actual breakdown scale:

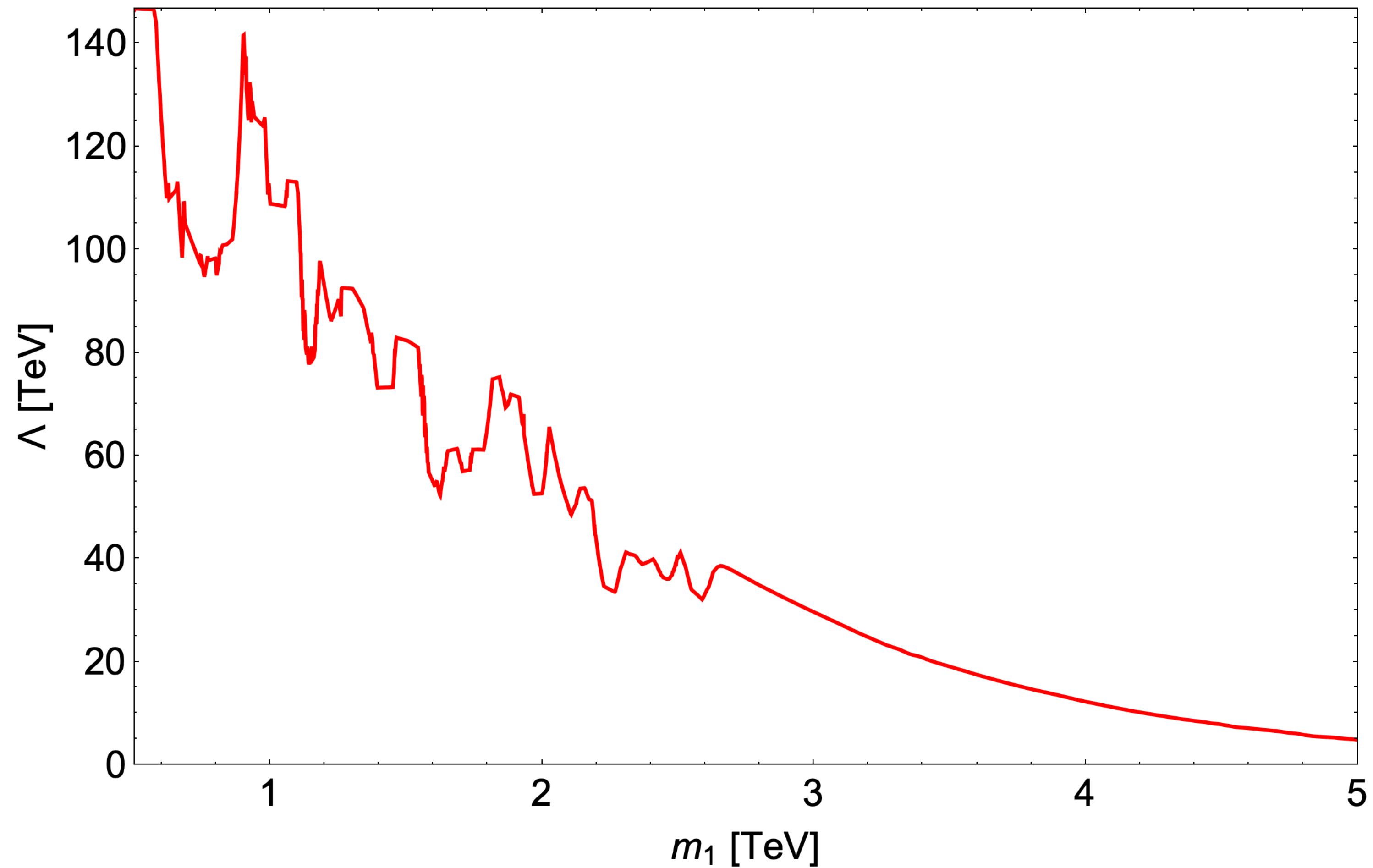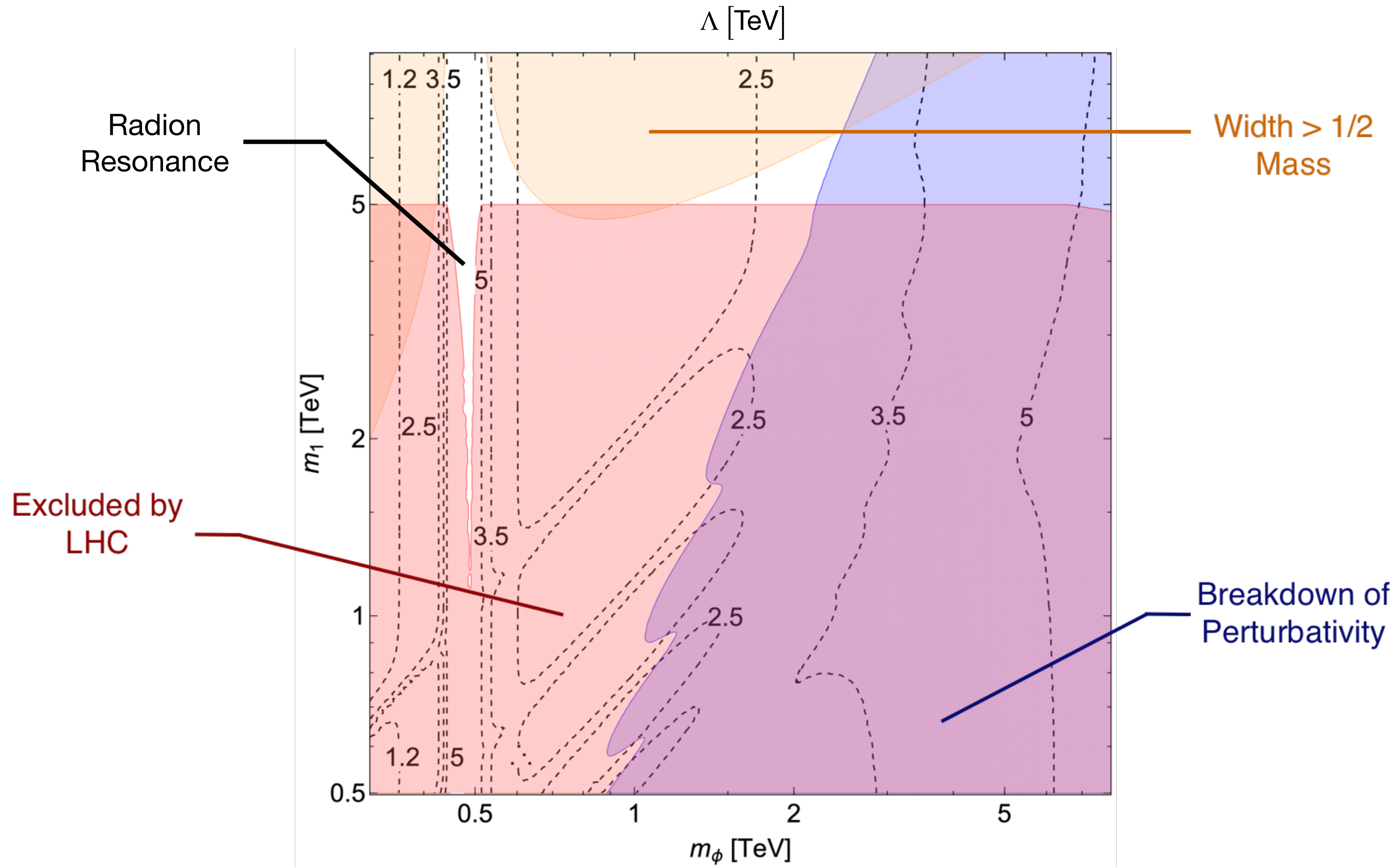$$\bar{M}_5 \equiv M_5 e^{-\mu\pi} \sim \left(m_1 \Lambda^2\right)^{\frac{1}{3}}$$

# LHC Bounds

- Upper bounds on cross-section studying $PP \longrightarrow G_1 \longrightarrow \gamma\gamma$ from ATLAS.

  $\Longrightarrow$ Compare them with theoretical calculated cross-section

# Conclusions

- Amplitudes' huge energy growths of higher dimensional theories can be reduced once the **full particle content** is included.

  ⚠️ $\implies$ a general **EFT field approach** with a **finite** number of fields **cannot** capture such behaviour!

- <u>Within perturbative region</u> this set up is *more under pressure* than previously thought.

## What's next?

- avoid LHC bounds with much smaller coupling $\Lambda^{-1}$

$\implies$ DM via *freeze-in* mechanism

Thank you.

# Backup Slides

# The RS metric & its effects

- RS metric: $ds^2 = e^{-2\mu|\varphi|}\eta_{\mu\nu}dx^\mu dx^\nu - r_c^2 d\varphi^2$

  warp-factor                    size of the 5th dimension

- The 4D and 5D Higgs vacuum expectation values are related as:

$$v_4 = v_5\, e^{-\mu\pi} \quad \Longrightarrow \quad \text{if } v_5 \sim M_{Pl} \text{ and } v_4 \sim \text{TeV} \implies \mu \sim \mathcal{O}(10)$$

- Matter-gravity coupling:

$$\Lambda^{-1} = M_{Pl}^{-1}e^{\mu\pi} \quad \overset{\mu\sim\mathcal{O}(10)}{\Longrightarrow} \quad \Lambda^{-1} \sim \text{TeV}^{-1}$$

- Couplings:

$$\chi_{ijk} \equiv \frac{-2}{J_0(\gamma_i)J_0(\gamma_j)J_0(\gamma_k)} \int\limits_0^1 du \ u^3 J_2(\gamma_i u)J_2(\gamma_j u)J_2(\gamma_k u) \ ,$$

$$\tilde{\chi}_{ijr} \equiv 2\frac{\gamma_i\gamma_j}{J_0(\gamma_i)J_0(\gamma_j)} \int\limits_0^1 du \ u^3 J_1(\gamma_i u) J_1(\gamma_j u) \ ,$$
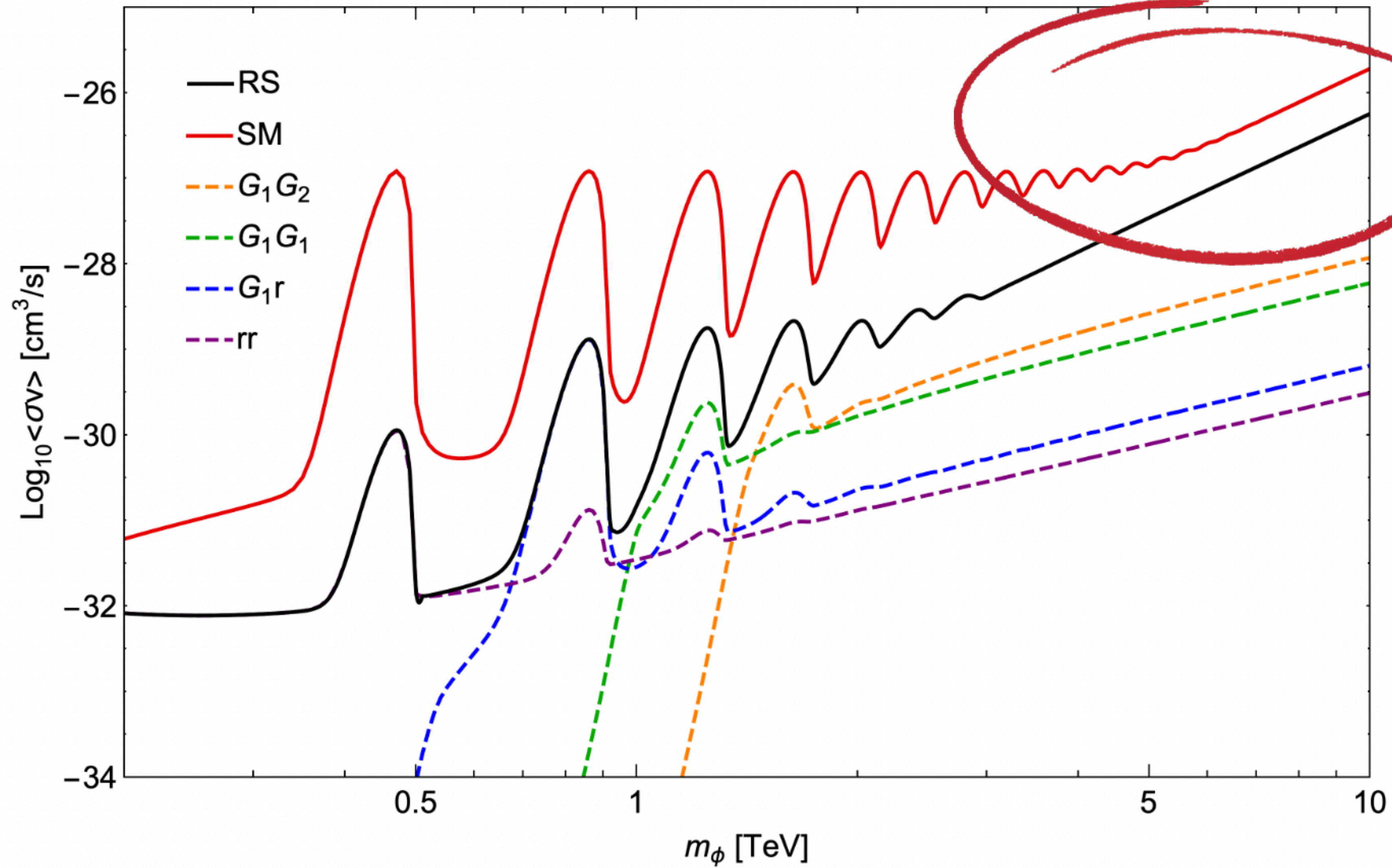
$$\chi_{irr} \equiv \frac{-2}{J_0(\gamma_i)} \int\limits_0^1 du \ u^3 J_2(\gamma_i u) = \frac{8}{\gamma_i^2} \ .$$

$$\chi_{rrr} = 1/2.$$

$$\left(\gamma_n \equiv \text{nth-zero of } J_1(z)\right)$$

| | |
|---|---|
| Sum rule 1: | $\sum\limits_{m=1}^{\infty} \chi_{nkm} = 1$ |
| Sum rule 2: | $\sum\limits_{m=1}^{\infty} \chi_{nkm} \ \gamma_m^2 = \gamma_n^2 + \gamma_k^2$ |
| Sum rule 3: | $\sum\limits_{m=1}^{\infty} \frac{\chi_{nkm}}{\gamma_m^2}(\gamma_n^2 - \gamma_k^2)^2 = (\gamma_n^2 + \gamma_k^2) - 6\tilde{\chi}_{nkr} \quad \overset{k=n}{\Longrightarrow} \quad \tilde{\chi}_{nnr} = \frac{1}{3}\gamma_n^2$ |
| Sum rule 4: | $\sum\limits_{m=1}^{\infty} \frac{\tilde{\chi}_{nmr}}{\gamma_m^2} = 1 - \chi_{nrr}$ |

# DM Annihilation



Breakdown of
Pertubativity!

$$\mathcal{M} \propto s^{3/2}$$

$\Lambda = 20$ TeV , $m_1 = 1$ TeV , $\bar{M}_5 \sim 5$ TeV