Spin-2 mediated Dark Matter in Warped Extra-Dimensions

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Dark Matter

- 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;

$\Longrightarrow$ controlled by Boltzmann equation:

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

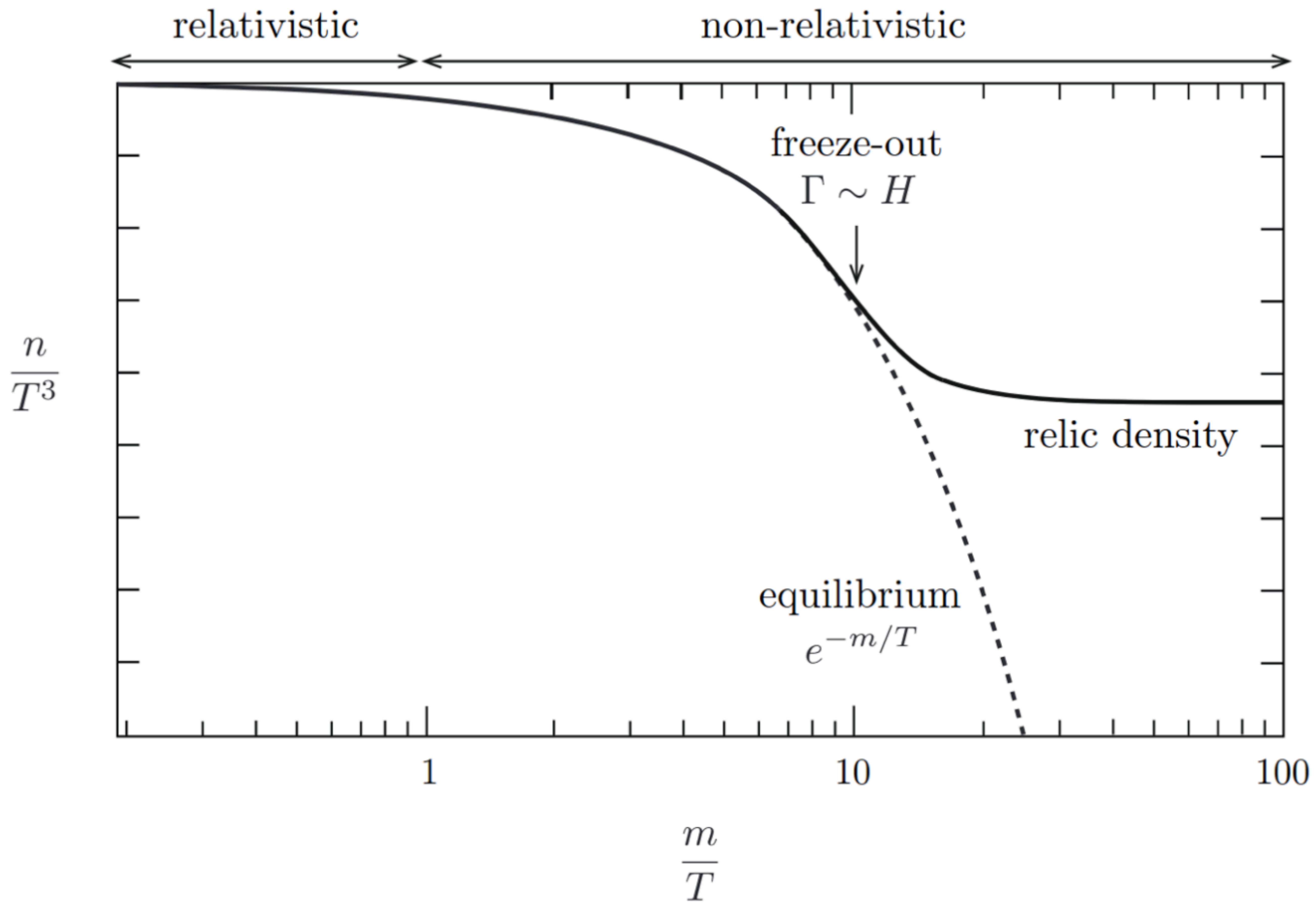


Image credit: Daniel Baumann, "Lectures Notes on Cosmology"

Set Up

Dark Matter

Real Massive Scalar Field

Interaction with SM only via gravity

Relic Abundance via *freeze-out* mechanism

+

Gravity

Randall-Sundrum Model
(Warped Extra-Dimensional gravity)

- If used to alleviate Hierarchy Problem

$\Longrightarrow$ 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.

The RS-Model

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:

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

'warp factor'

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

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

The 4D-EFT

- Weak field expansion of the metric:

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

- 5D wave-functions set by:

$$-\frac{1}{r_c^2}\frac{d}{d\varphi}\left[e^{-4\mu|\varphi|}\frac{d\psi_n}{d\varphi}\right] = m_n^2 e^{-2\mu|\varphi|}\psi_n$$

with $m_n \sim n m_1$

RS-spectrum:
- massless spin-2 field $\{G_0\ , m_0 = 0\}$ ≡ 'GR-graviton'
- massive spin-2 fields $\{G_n\ , m_n\}_{n=1}^{\infty}$ ≡ 'KK-gravitons'
- massless* spin-0 field $\{r\ , m_r = 0\}$ ≡ 'radion'

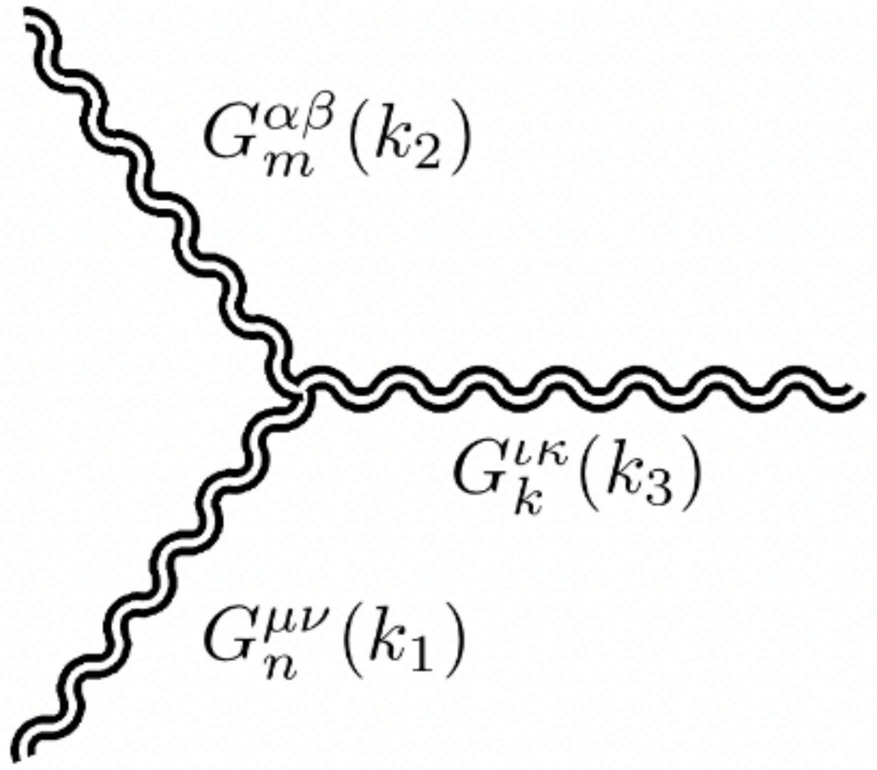
*mass term added by hand; it can be generated via an extra mechanism, e.g. *Goldberger–Wise mechanism*

Annihilation of DM into RS-spin-2 states

- 3rd order gravity sector:

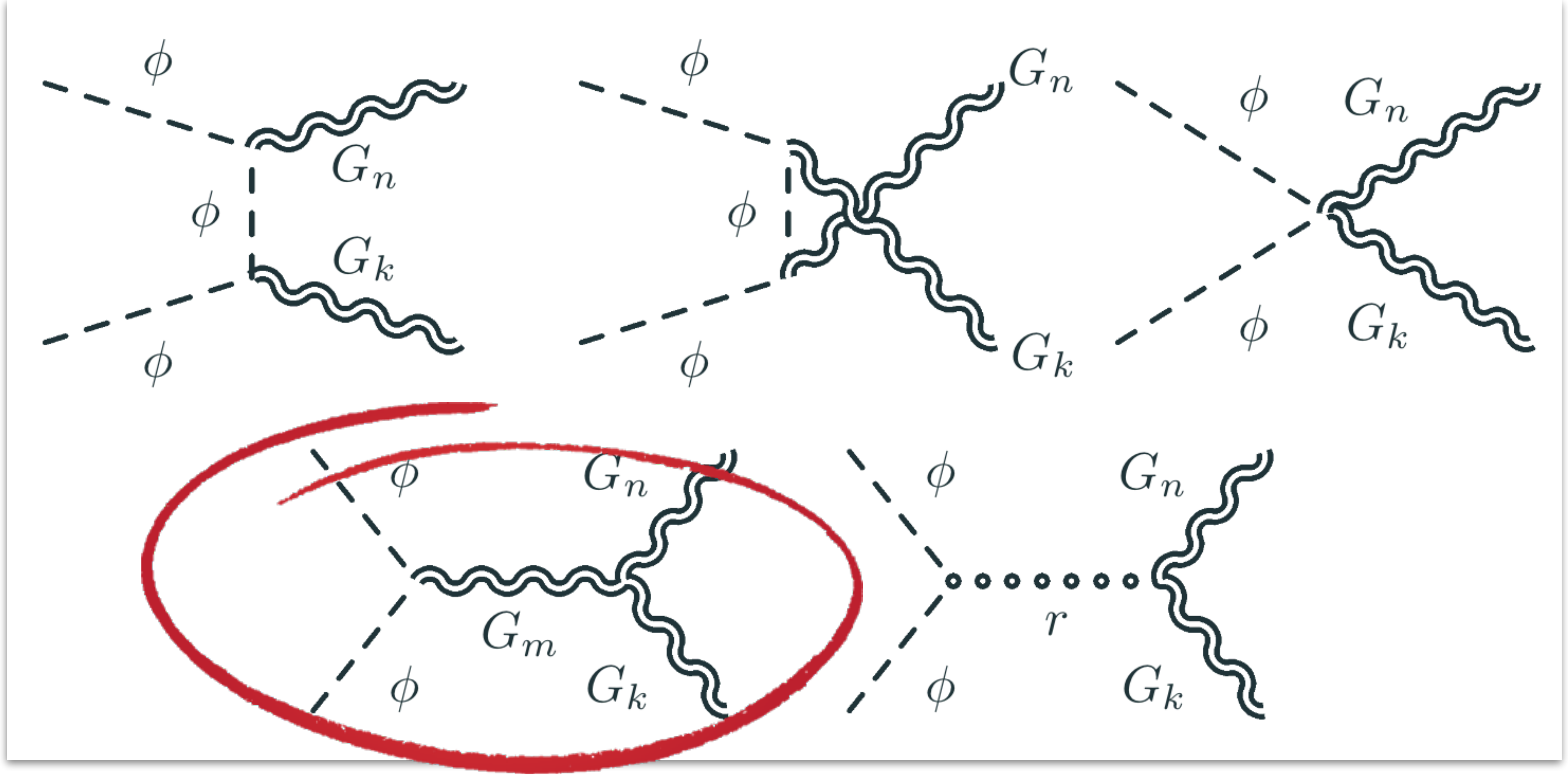
$$\mathcal{L} \propto \left[\int_{-\pi}^{\pi} d\varphi \; e^{-2\mu|\varphi|}\psi_n(\varphi)\psi_m(\varphi)\psi_k(\varphi)\right]\mathcal{L}_{4D}$$

↓



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

$$\Lambda \equiv M_{Pl}\; e^{-\mu\pi} \;\sim\; \text{TeV}$$



Truncate KK-tower

~~How many~~?

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

↓

Huge impact on DM annihilation at high temperature!

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

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

Full VS Truncated Spectrum

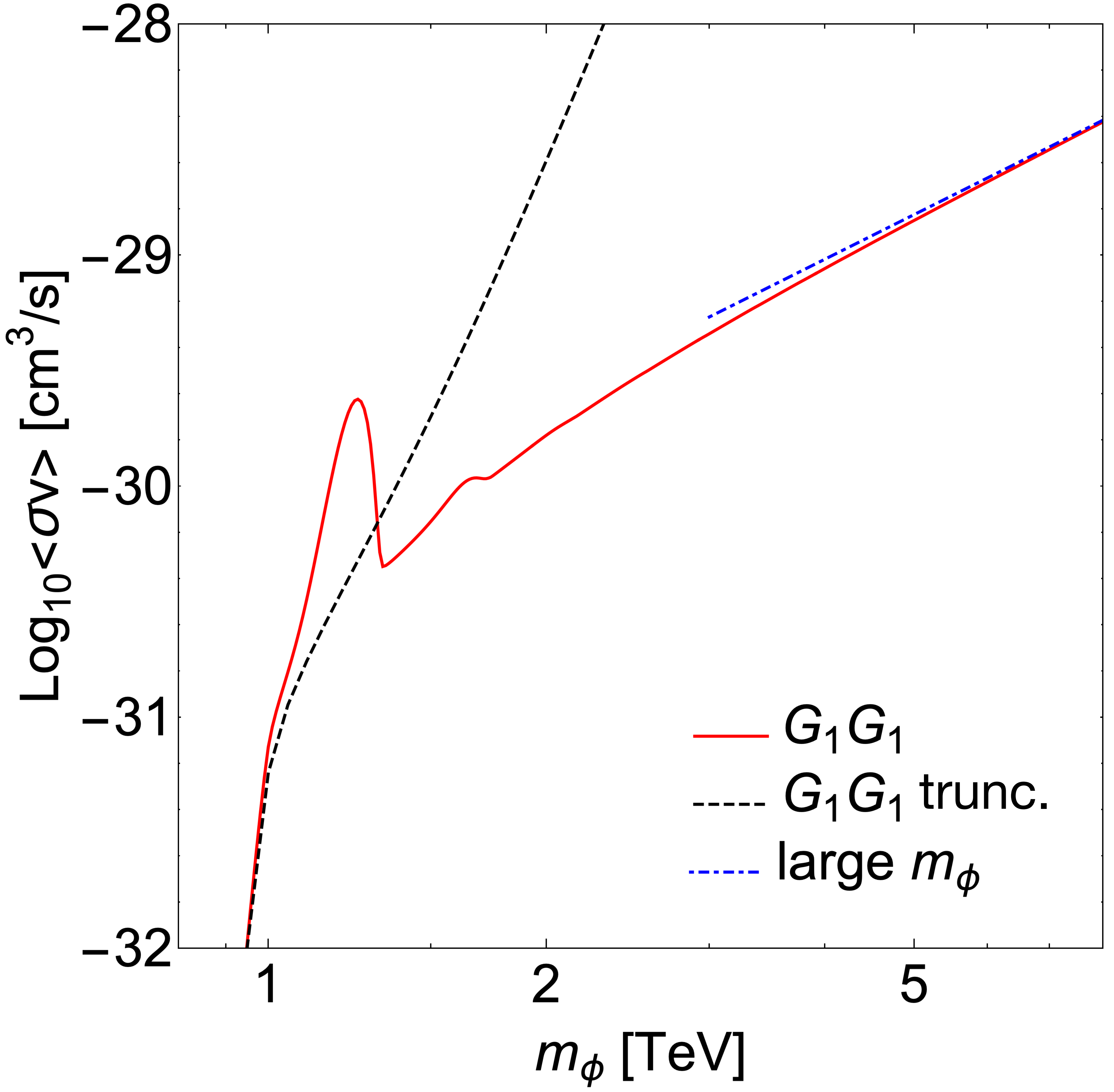
- 4D EFT single-diagram amplitudes are plagued by unitarity issues due to energy growth of *longitudinal modes* of KK-gravitons

- Include full KK-tower:

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

$\Longrightarrow$ 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

Perturbative Unitarity

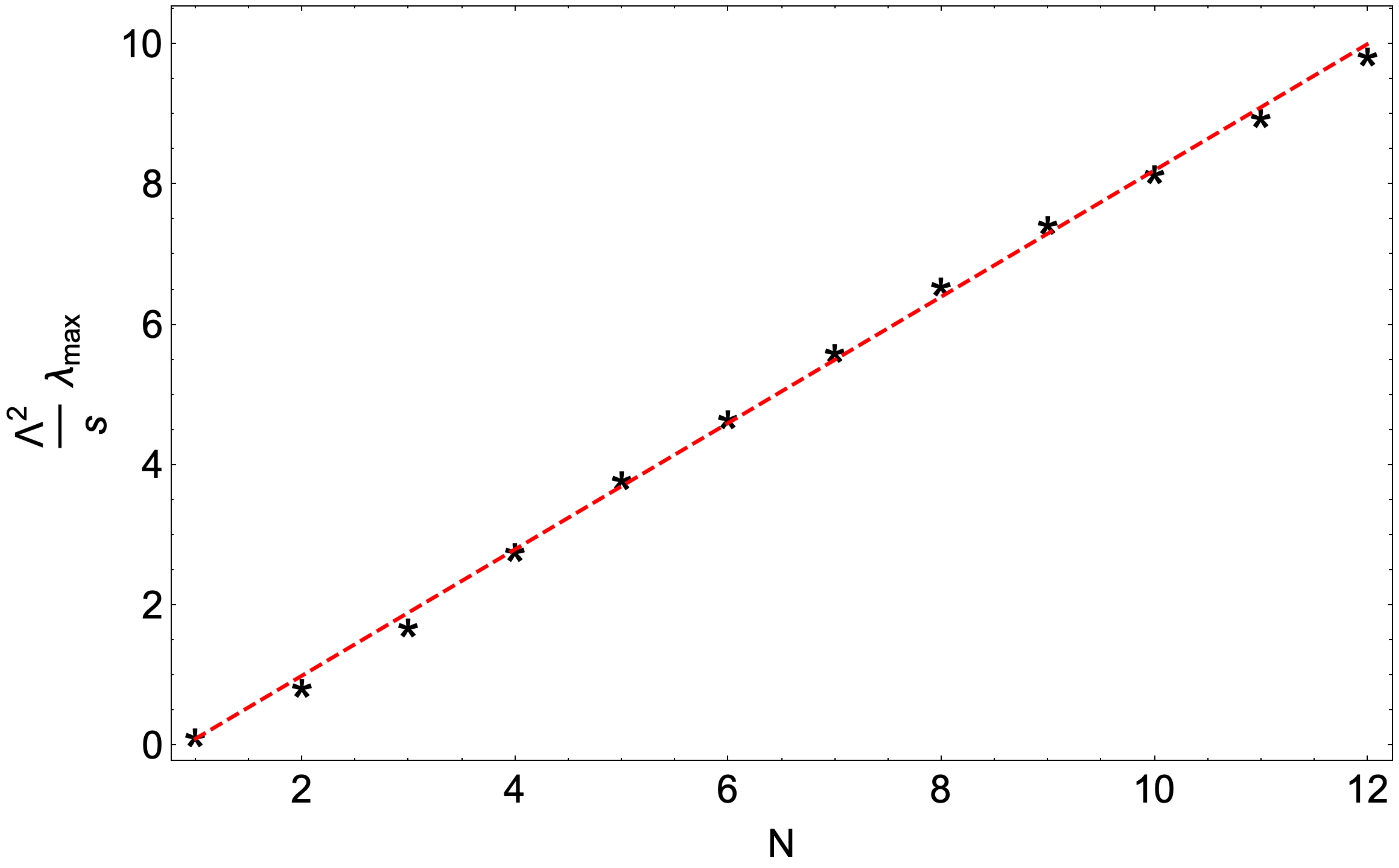
- As the energy grows more channels available in the final states;

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

$\Longrightarrow$ 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:

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

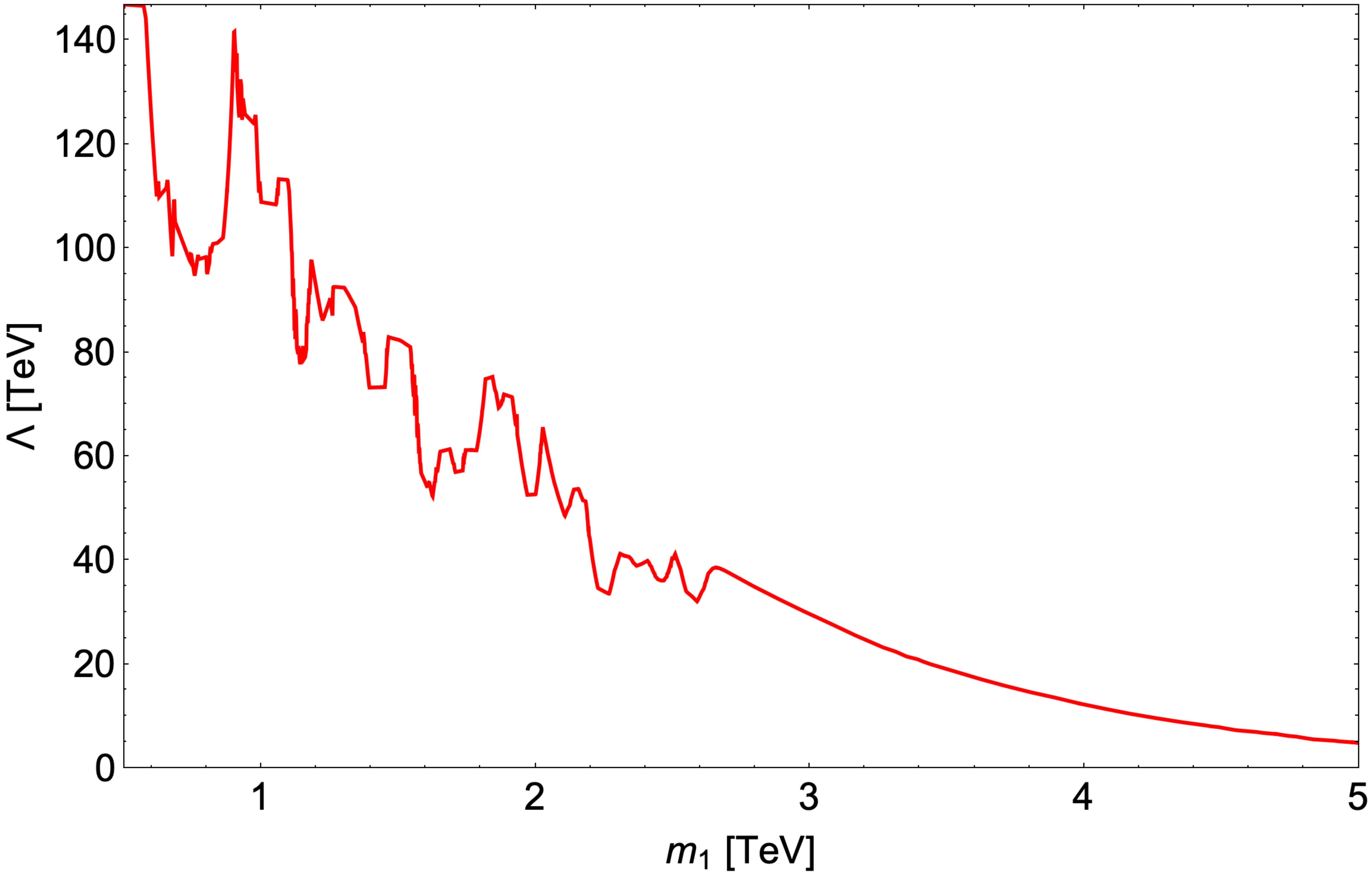


LHC Bounds

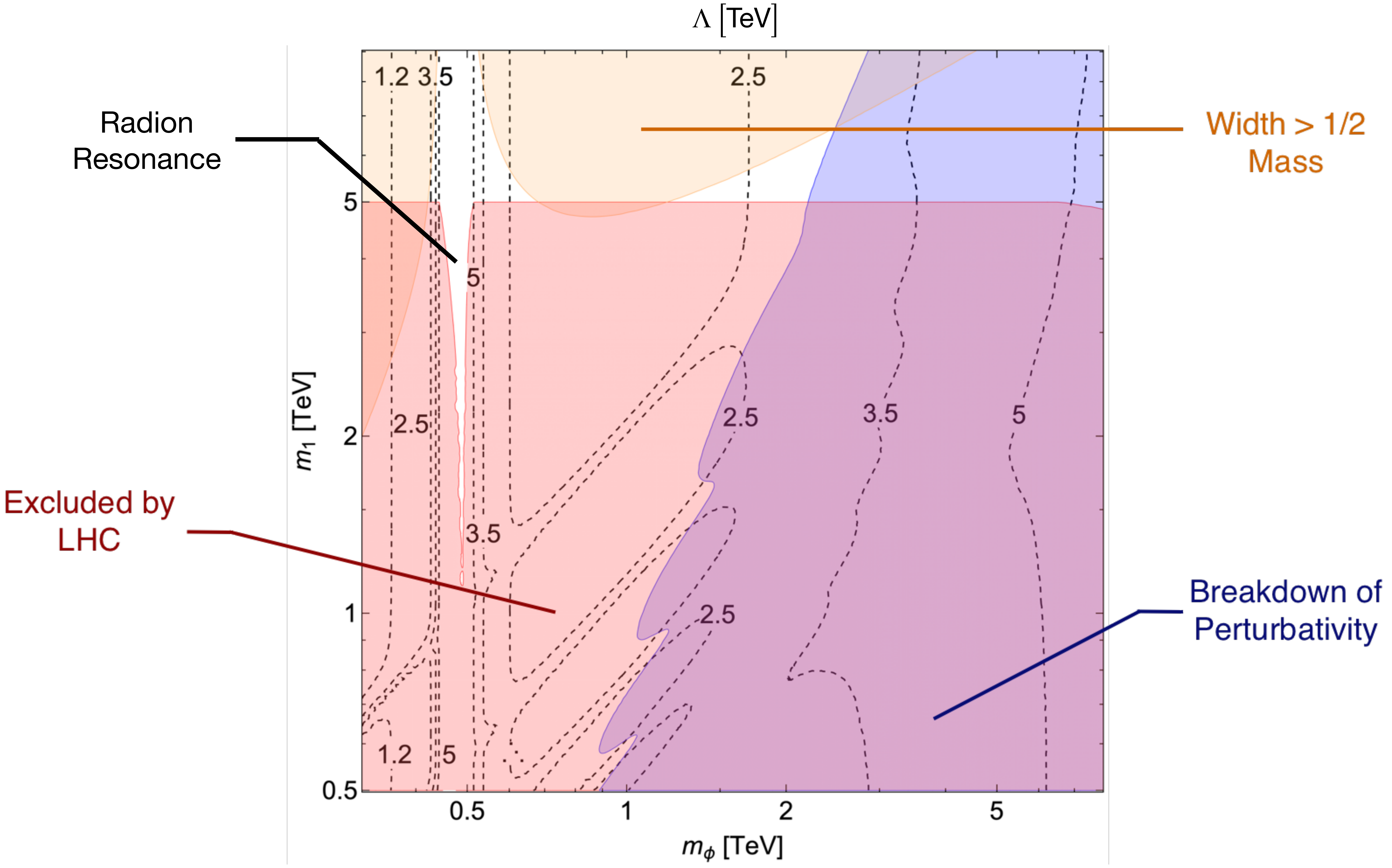
- Upper bounds on cross-section studying $PP \longrightarrow G_1 \longrightarrow \gamma\gamma$ from ATLAS.

arXiv: 1707.04147

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



DM Constraints



Conclusions

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

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

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

What's next?

- avoid LHC bounds with much smaller coupling Λ^{-1}

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

Thank you.

Backup Slides

The RS metric & its effects

- RS metric: $$\mathrm{d}s^2 = e^{-2\mu|\varphi|}\eta_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu - r_c^2 \mathrm{d}\varphi^2$$

  warp-factor ($e^{-2\mu|\varphi|}$); size of the 5th dimension (r_c)

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

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

- Matter-gravity coupling:

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