Testing Super-WIMPs and the Reheating Temperature at Collider Experiments

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Encuentro CosmoConce y Partículas
Concepción, November 2025

Plan for Today

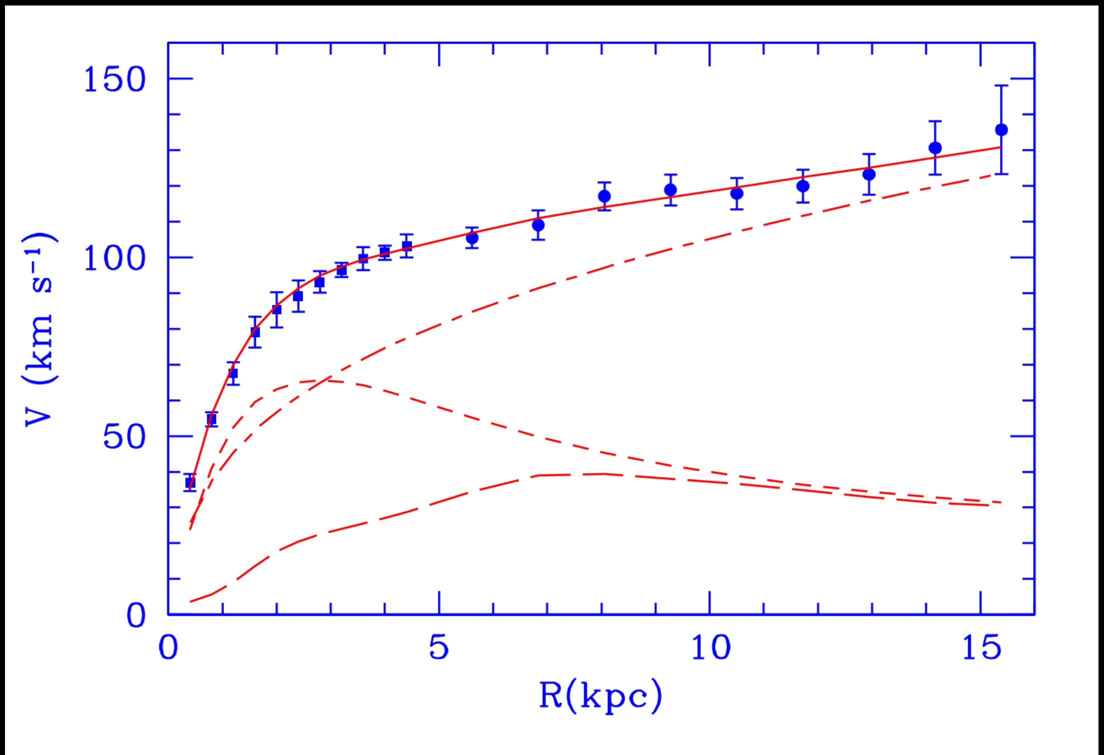
- A review of Dark Matter and production Mechanisms
- Our Model and the Super-WIMP
- Can we constrain The reheating Temperature at Colliders?
    - LLP Detectors
    - ATLAS DV+MET Searches

Dark Matter

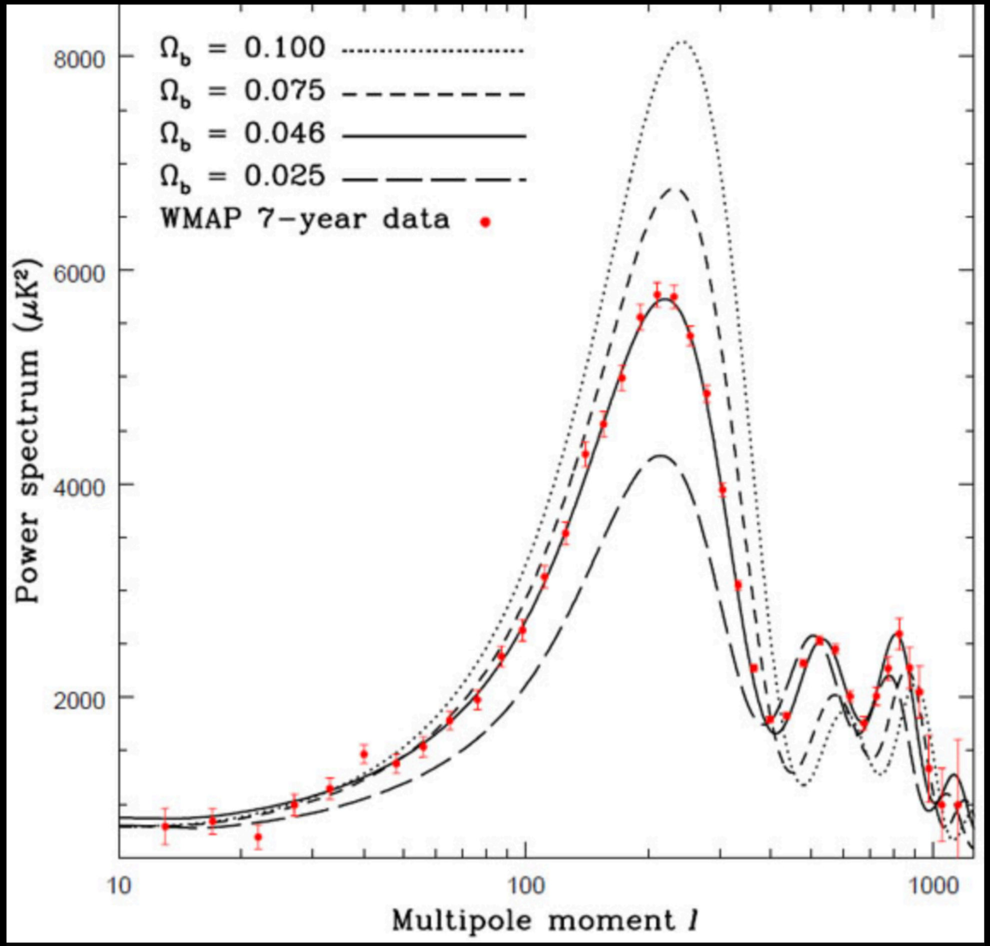
In a nutshell: We know something is out there, but don't know what it is.
Plenty of evidence, great motivation for BSM Model Building

CMB anisotropies

Galaxy rotation curves

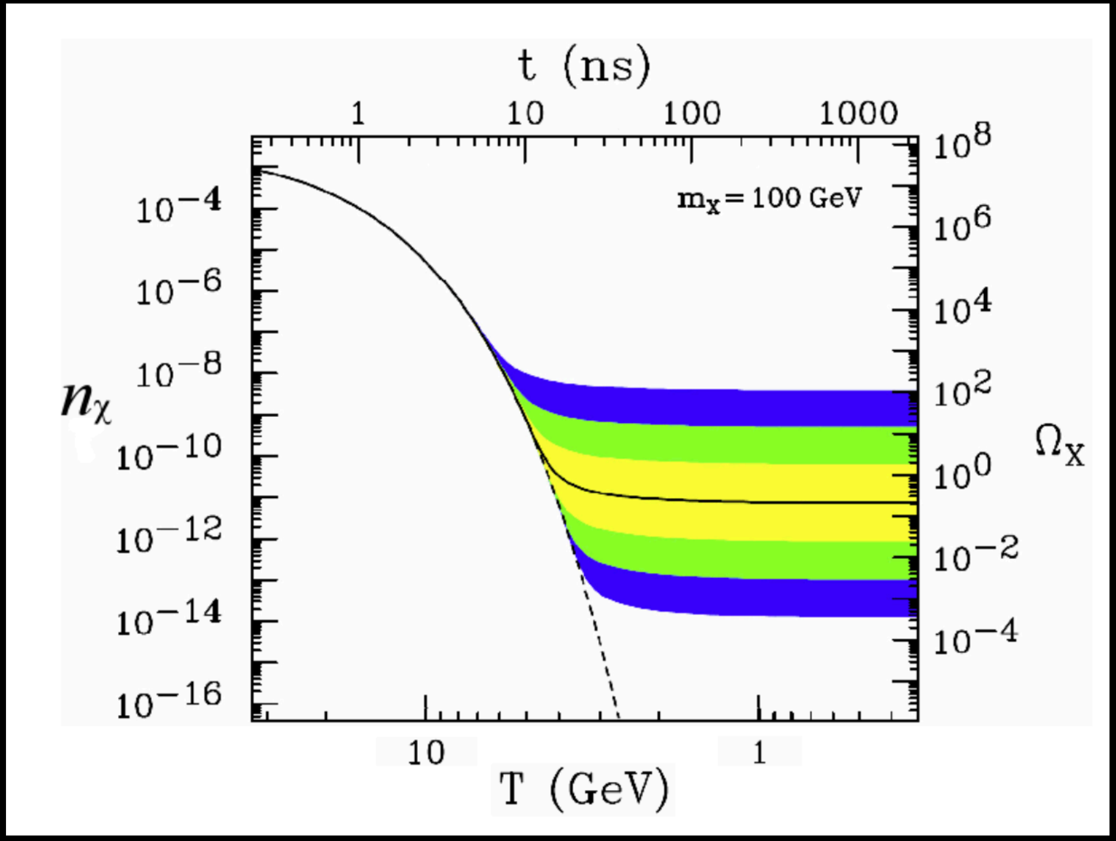


Corbelli & Salucci: arXiv:9909252

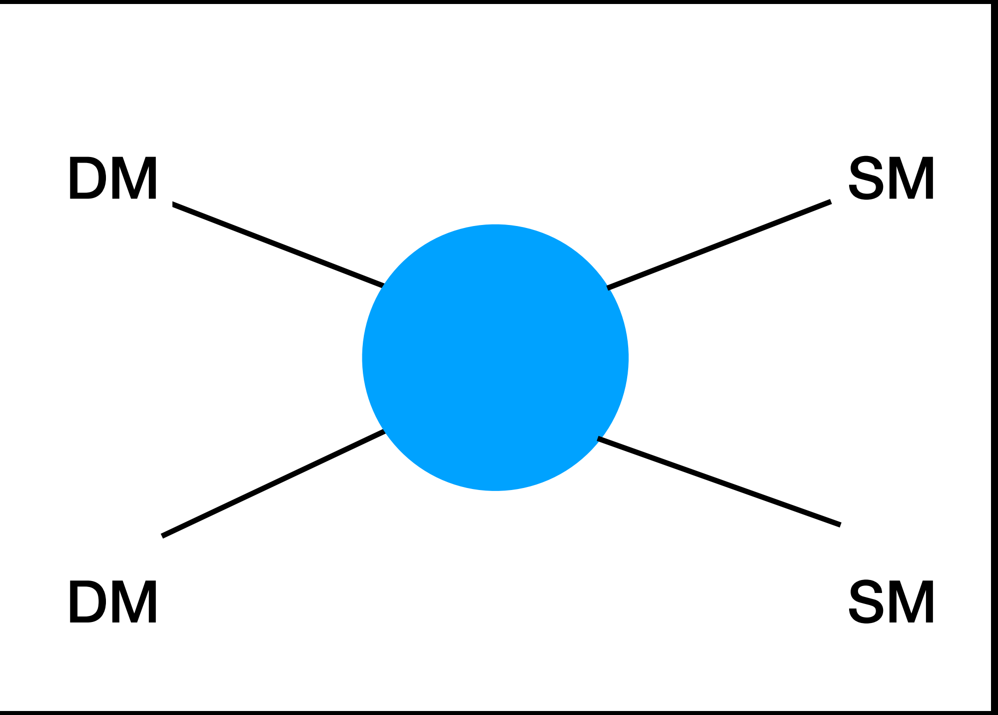


Garrett & Duda: arXiv:1006.2483

Freeze-Out and WIMPs

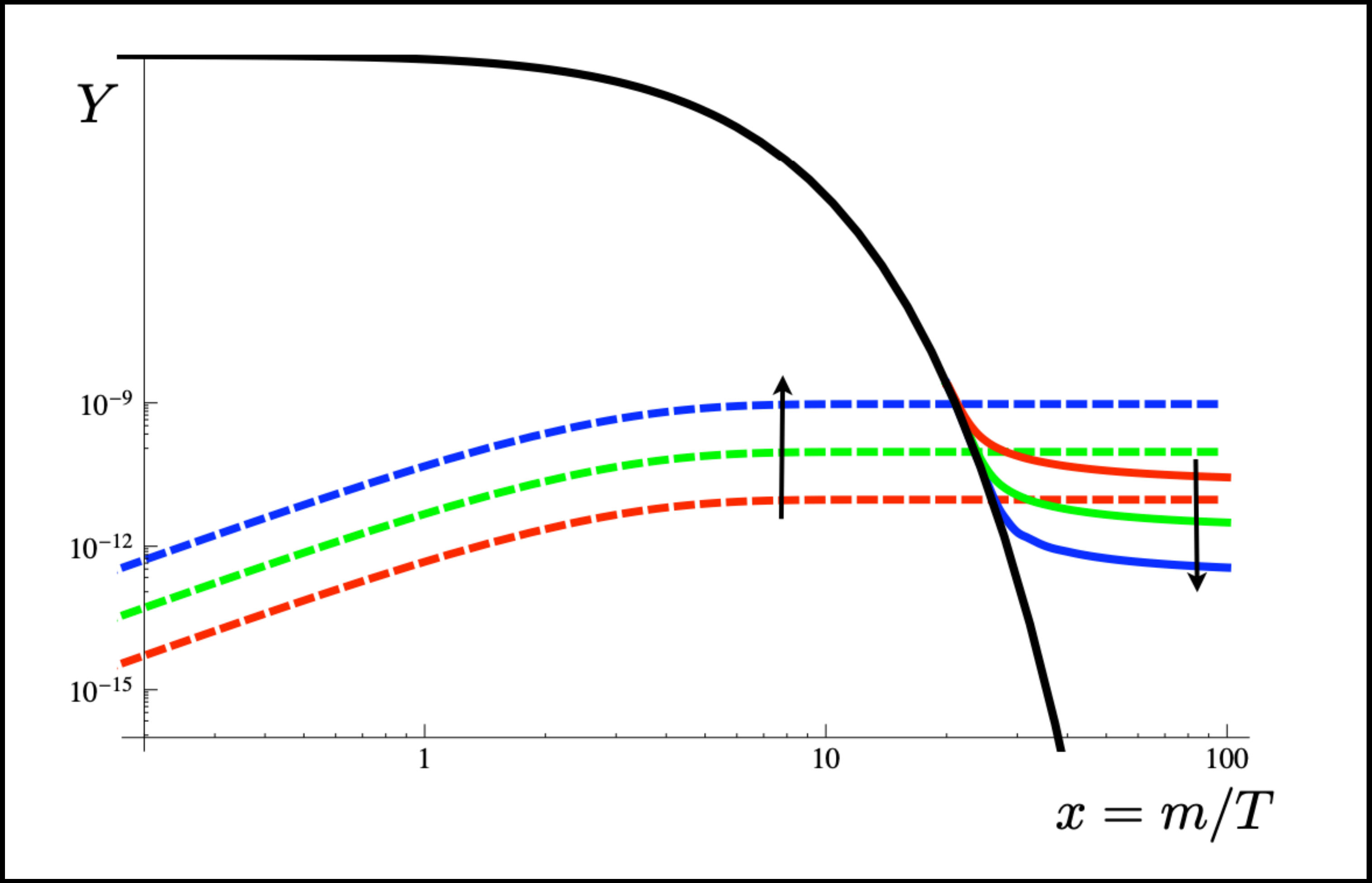


Credits to "La Ciencia de la Mula Francis"



Key details: assumes Dark Matter in thermal equilibrium with primordial plasma

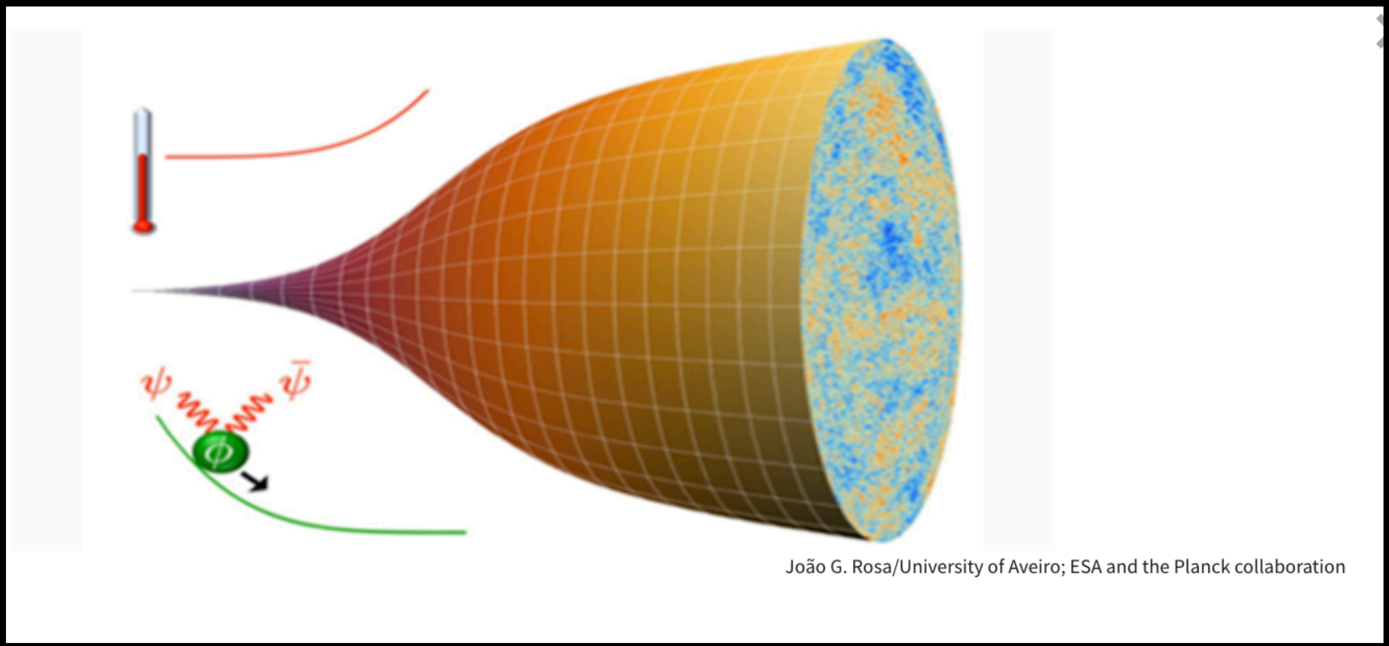
Freeze-In and FIMPs

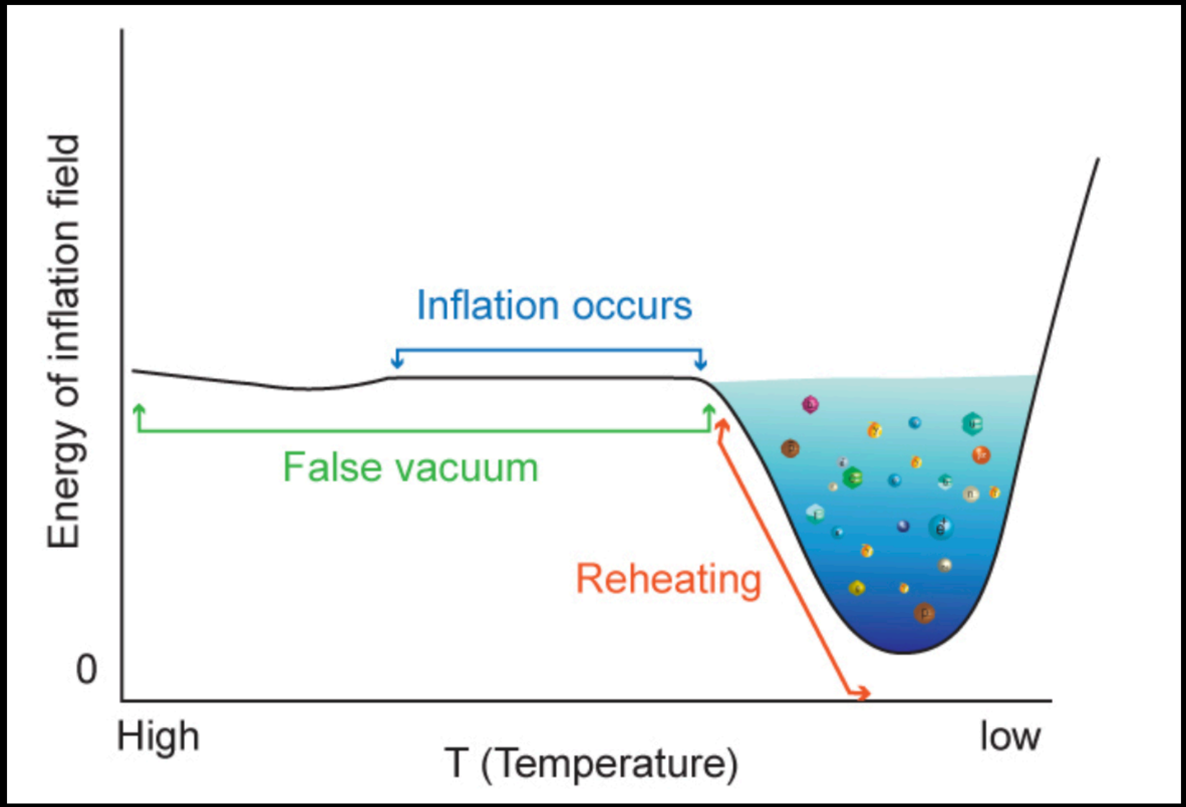


Key details: DM decoupled from Visible Sector.
Relic density depends strongly on Reheating Temperature

Taken from Hall et al: arXiv:0911.1120

(Very) Basics of Inflation





Taken from Physics LibreTexts

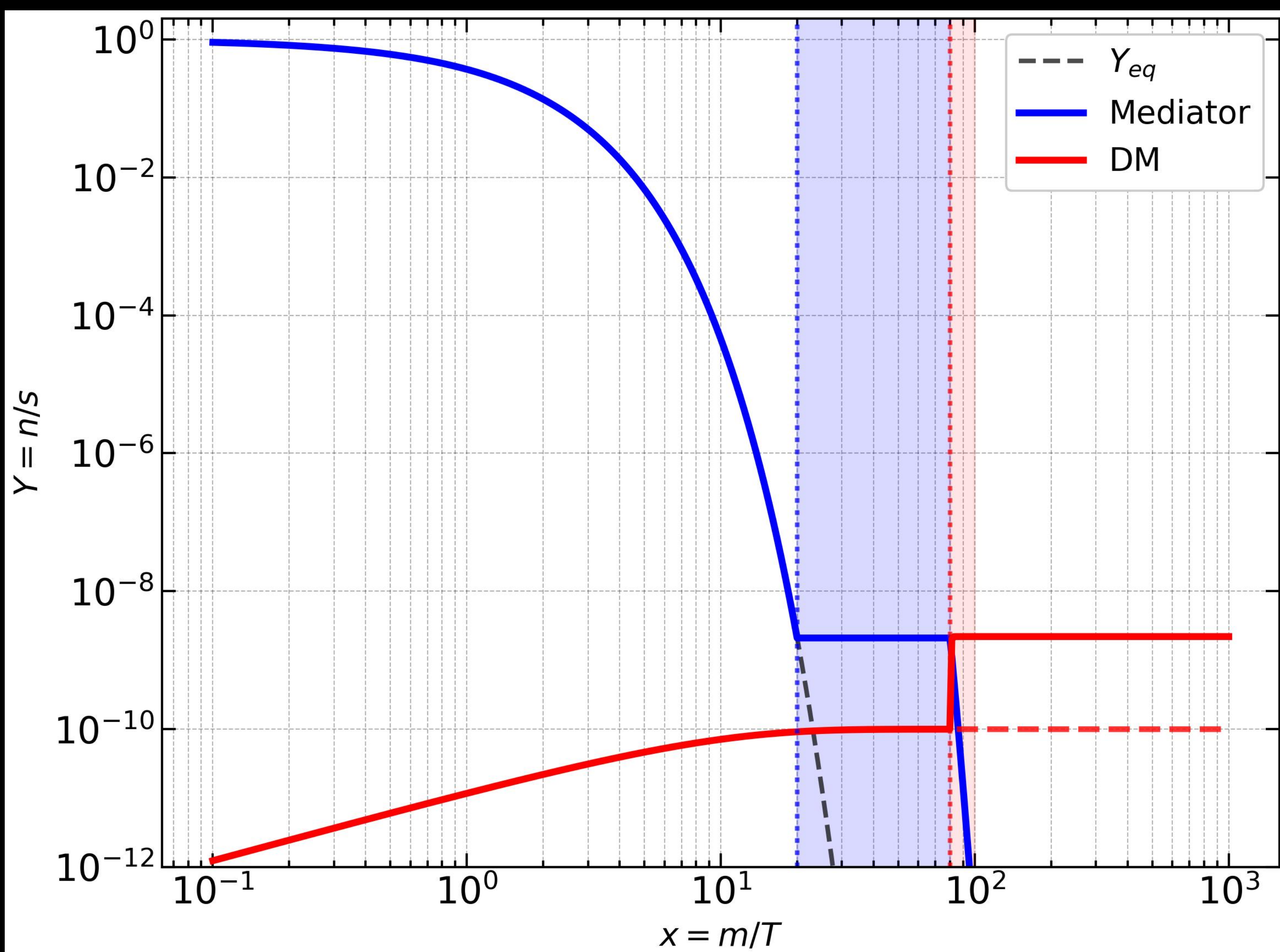
We assume instantaneous reheating

T_{RH}: **maximum temperature of the primordial plasma**

Can both mechanisms coexist?

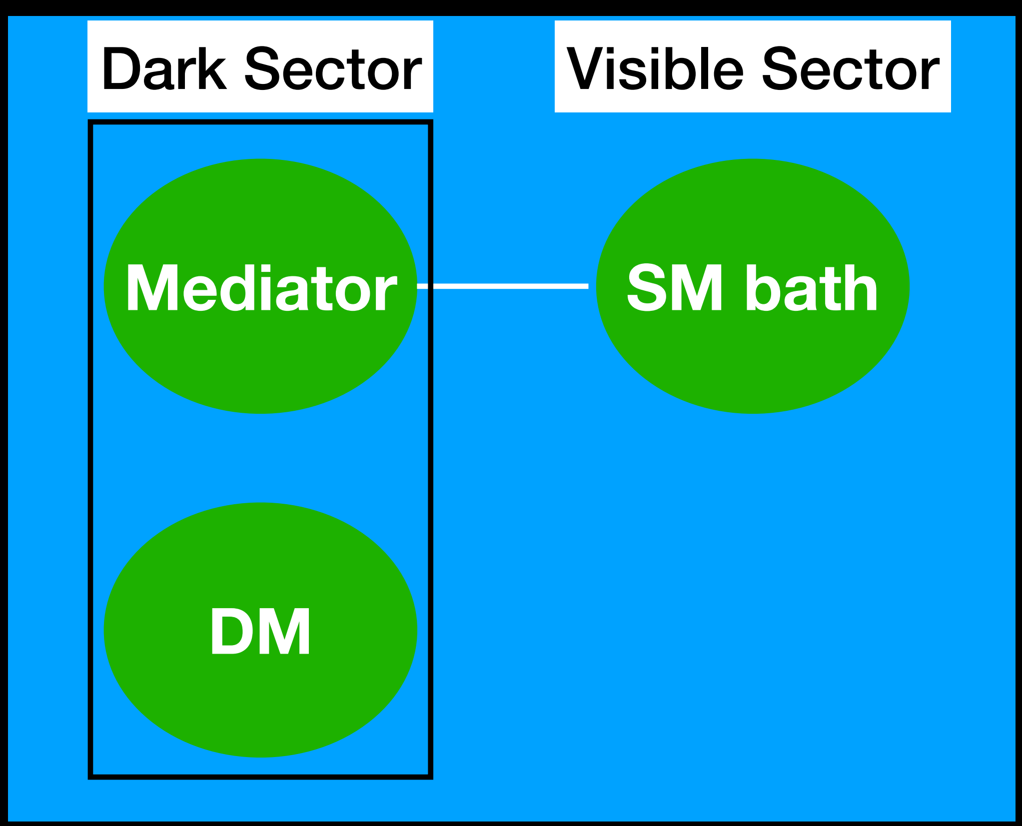
Short Answer: Yes! Typically called Super-WIMP mechanism.

Covi, Kim & Roszkowski (1999) arXiv:9905212



Please don't look at the scale, just schematics

Dark Sector: Mediator follows typical freeze-out, later decaying to the DM candidate



A concrete realisation

Add a scalar singlet and a new gauge U(1) symmetry
Accidental Z_2 allows DM stability

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu + \frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 - \lambda_\phi\,\phi^4 - \lambda_{HS}\,\phi^2|H|^2 + \frac{c}{\Lambda}\phi\,V_{\mu\nu}\,\hat{B}^{\mu\nu}, \quad \hat{B}^{\mu\nu} \equiv \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}B_{\alpha\beta}.$$

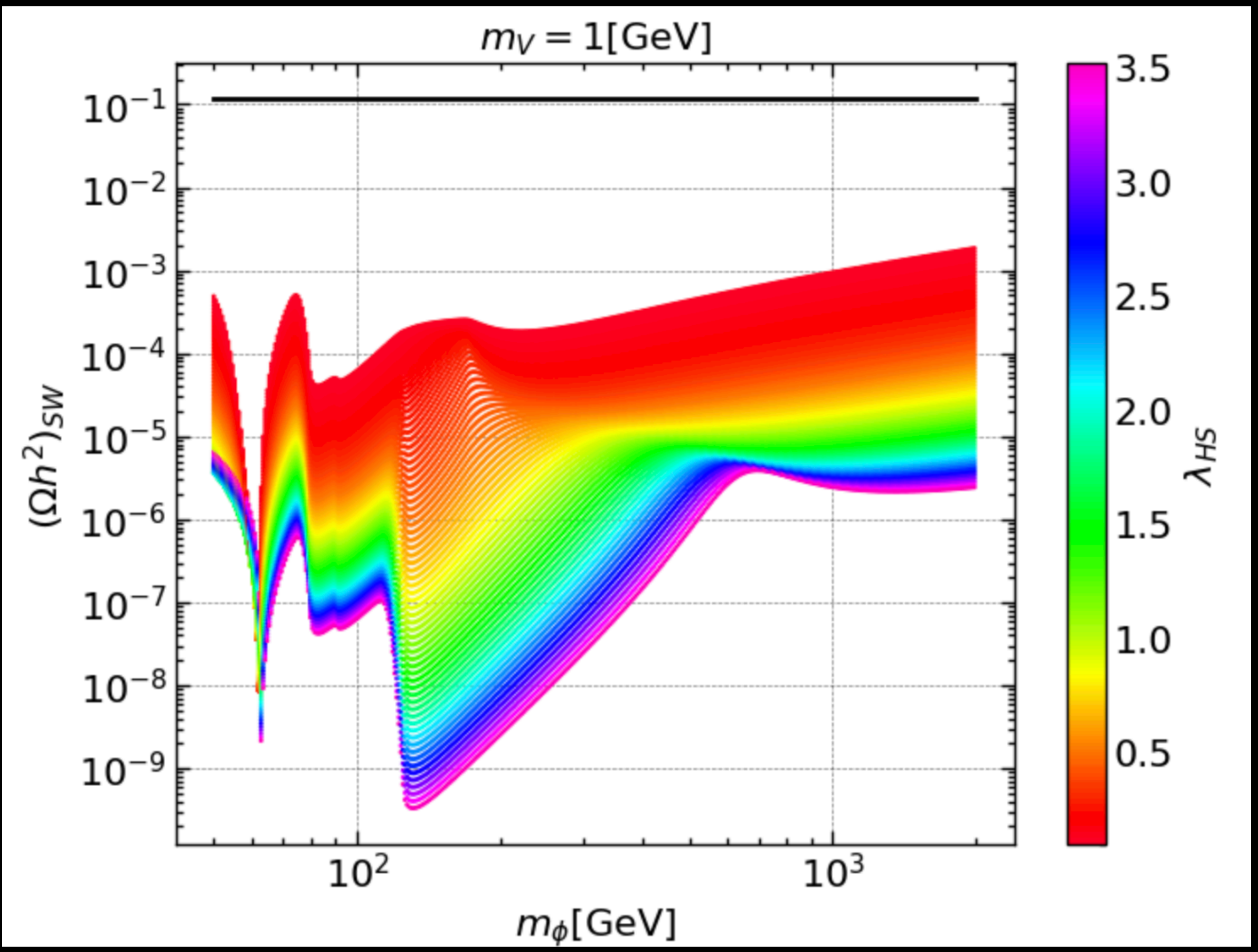
Vector interact only via non-renormalizable operator

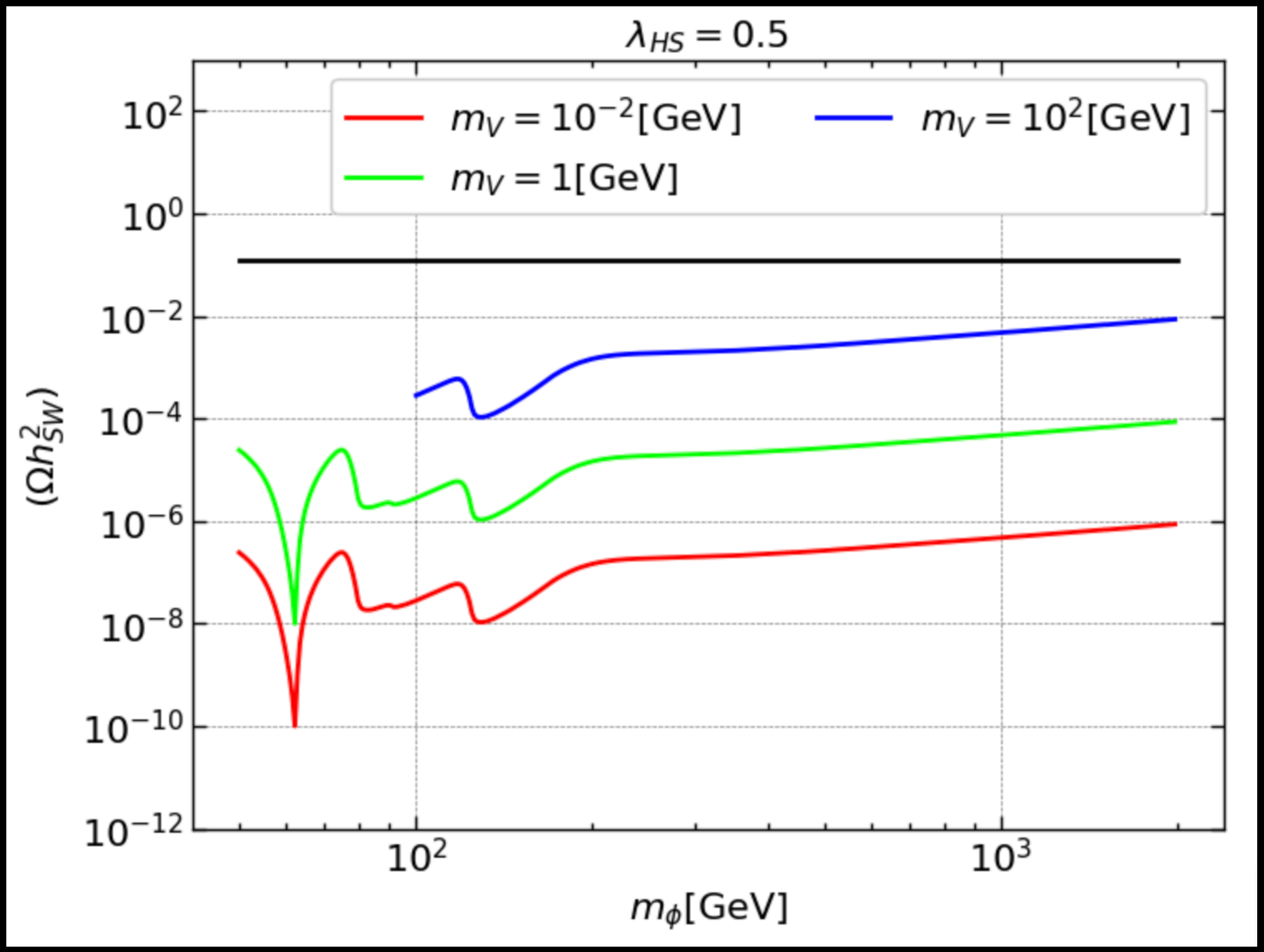
If $\lambda_{HS} \sim 1$ the scalar thermalizes
If $\frac{c}{\Lambda} << 1$ the vector interacts feebly

If $m_V < m_\phi$ we have all conditions for a super-WIMP DM production

There are 2 contributions to the DM relic density

$$\Omega h^2 = \Omega h^{2(FI)} + \frac{m_V}{m_\phi}\Omega h^{2(FO)}$$





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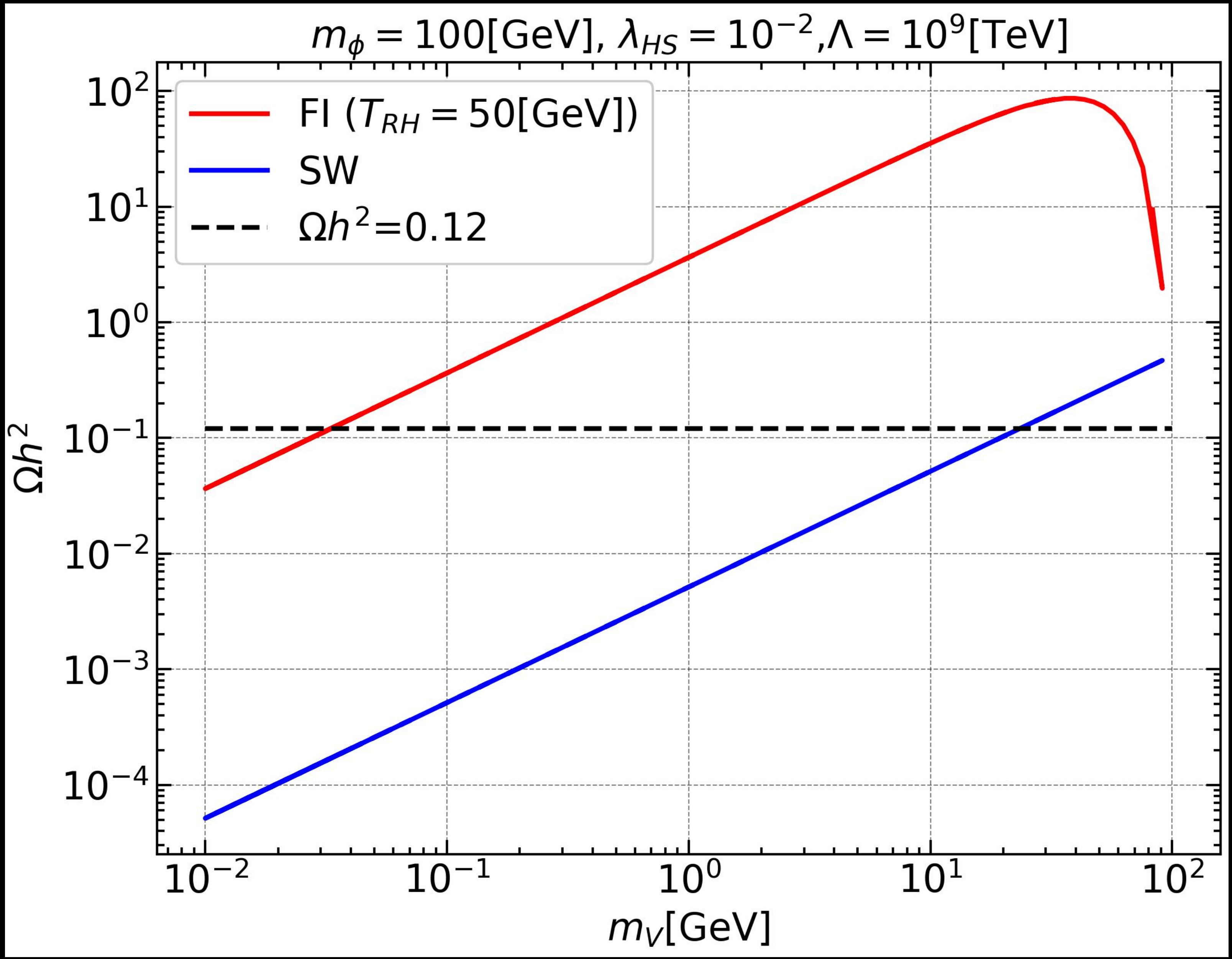
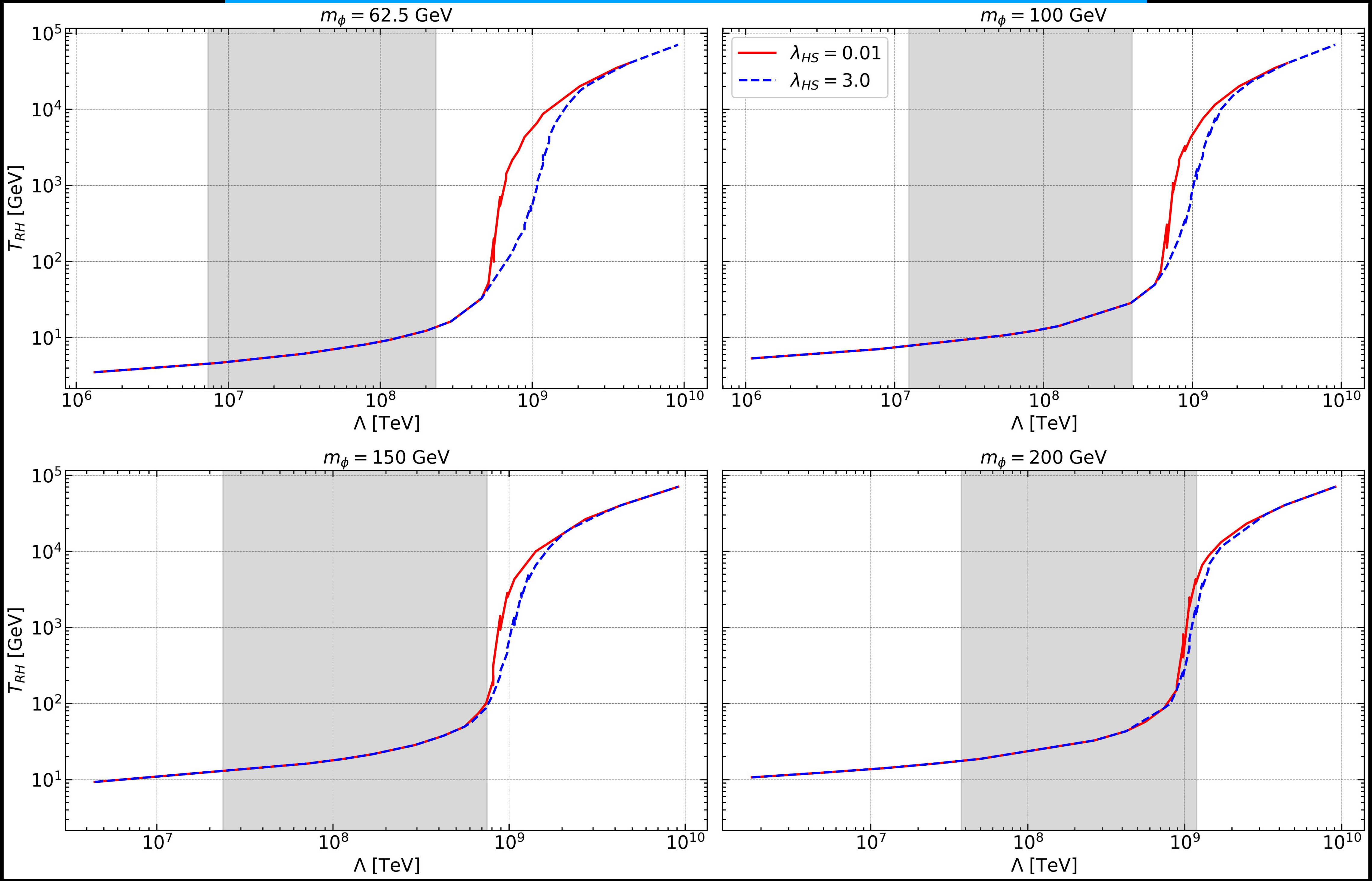
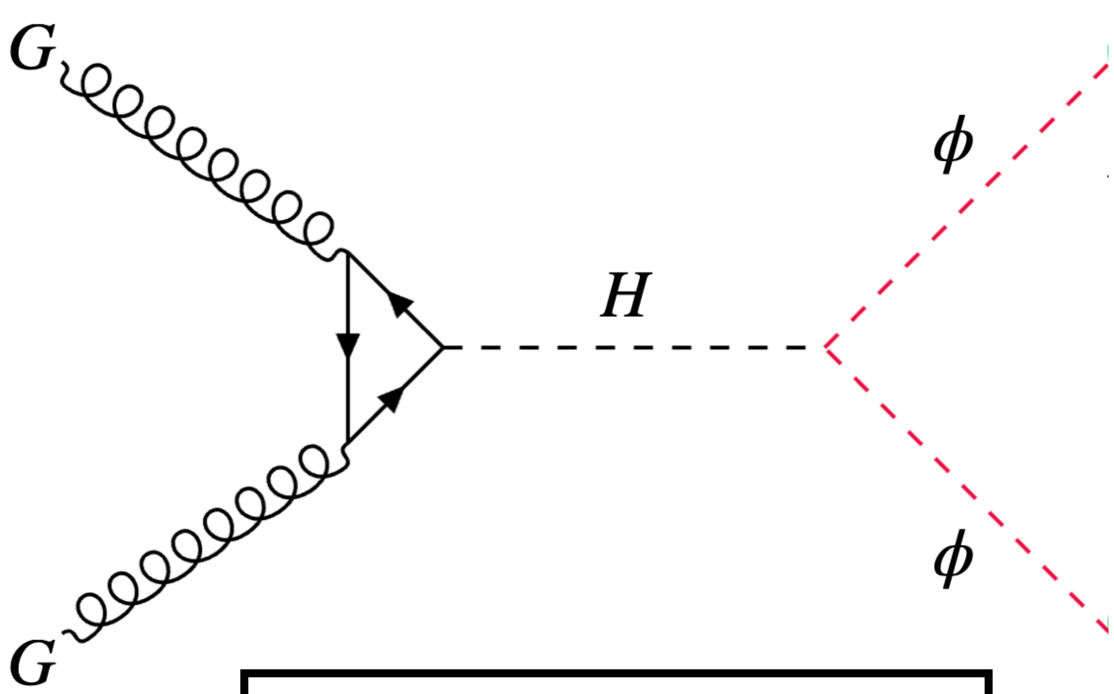


The latter is subleading and we should focus on sub-GeV DM

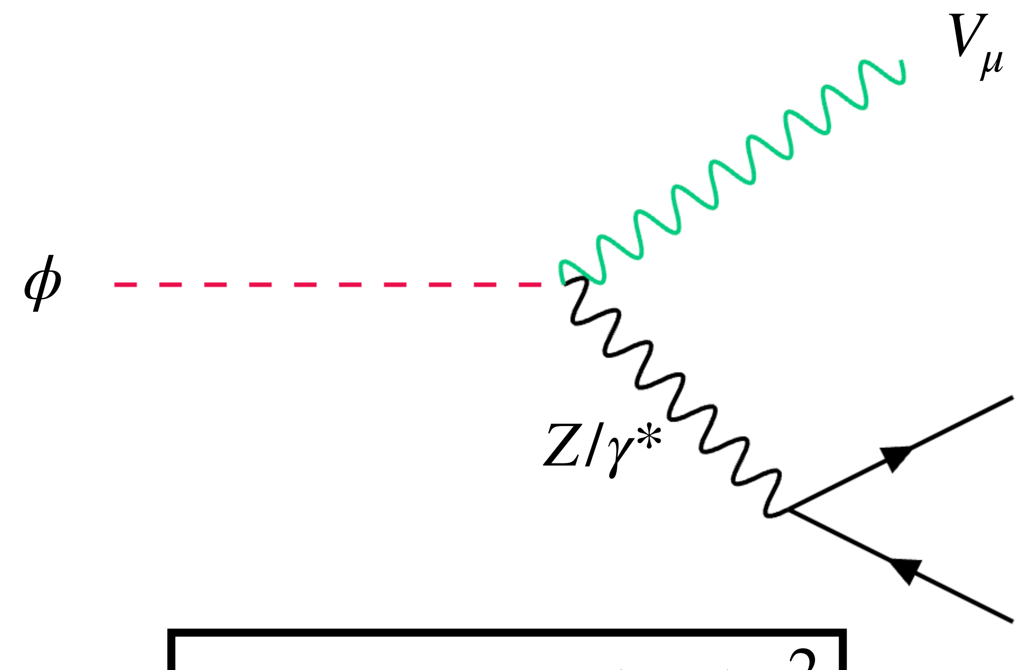
Relic density depends on two very important quantities:
-The energy scale where the model breaks
-The reheating Temperature



Connection with HEP



$$\sigma(pp \to \phi\phi) \sim \lambda_{HS}^2$$



$$\frac{1}{\tau} \sim \Gamma \sim \left(\frac{c}{\Lambda}\right)^2$$

$\lambda_{HS} \sim 1$ **Increases cross section**

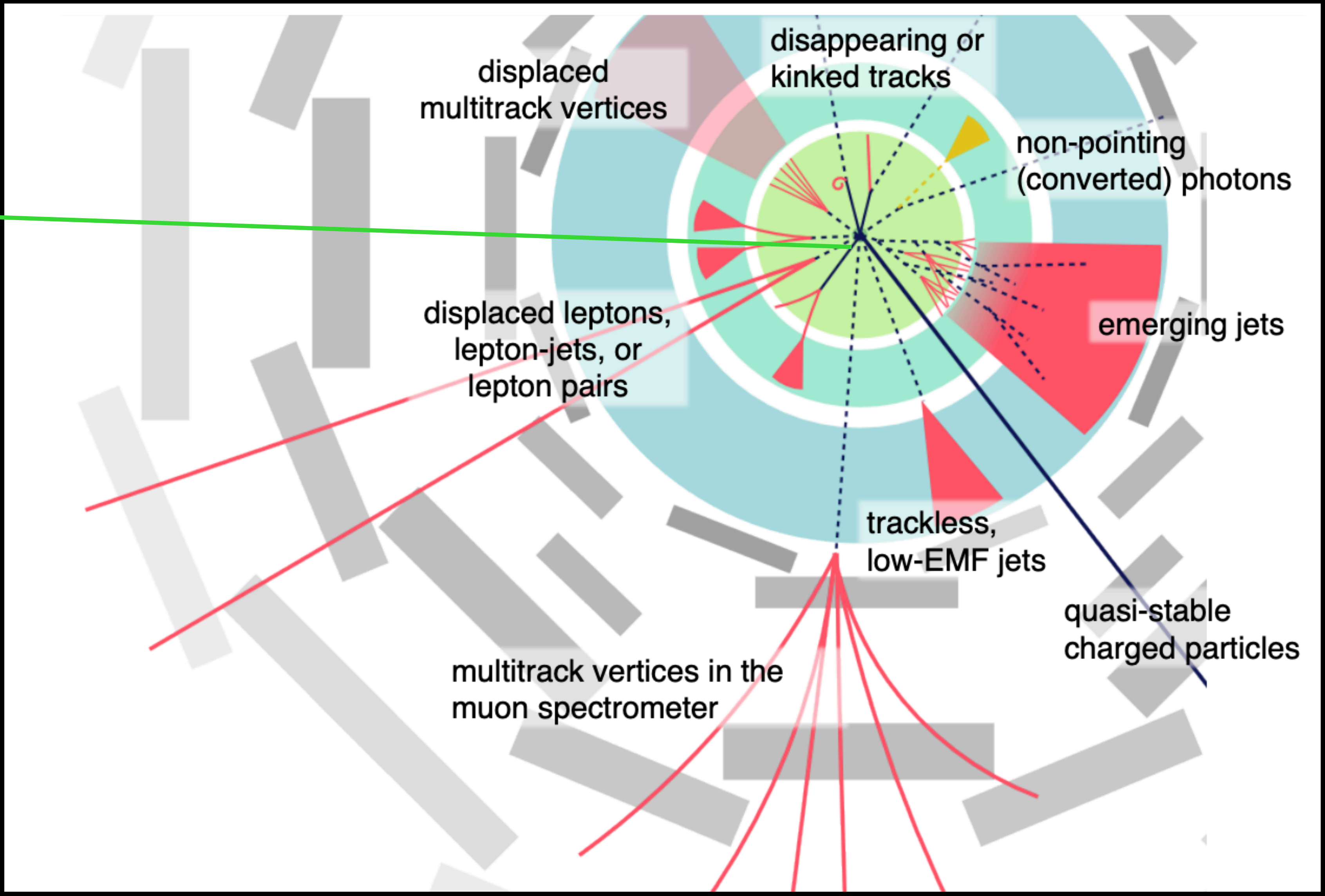
$\frac{c}{\Lambda} << 1$ **increases lifetime**

Expect LLP Signature

Ok, but what are LLPs?

Metastable particles that live enough to travel inside detectors before decaying
Different strategies depending on Lifetime

LLP Detectors!



Russell, 2017

The crucial observable is the particle lifetime

LLP detectors: Put a detector very far away from Interaction point
low background
Sensitive to the largest lifetimes (meters)

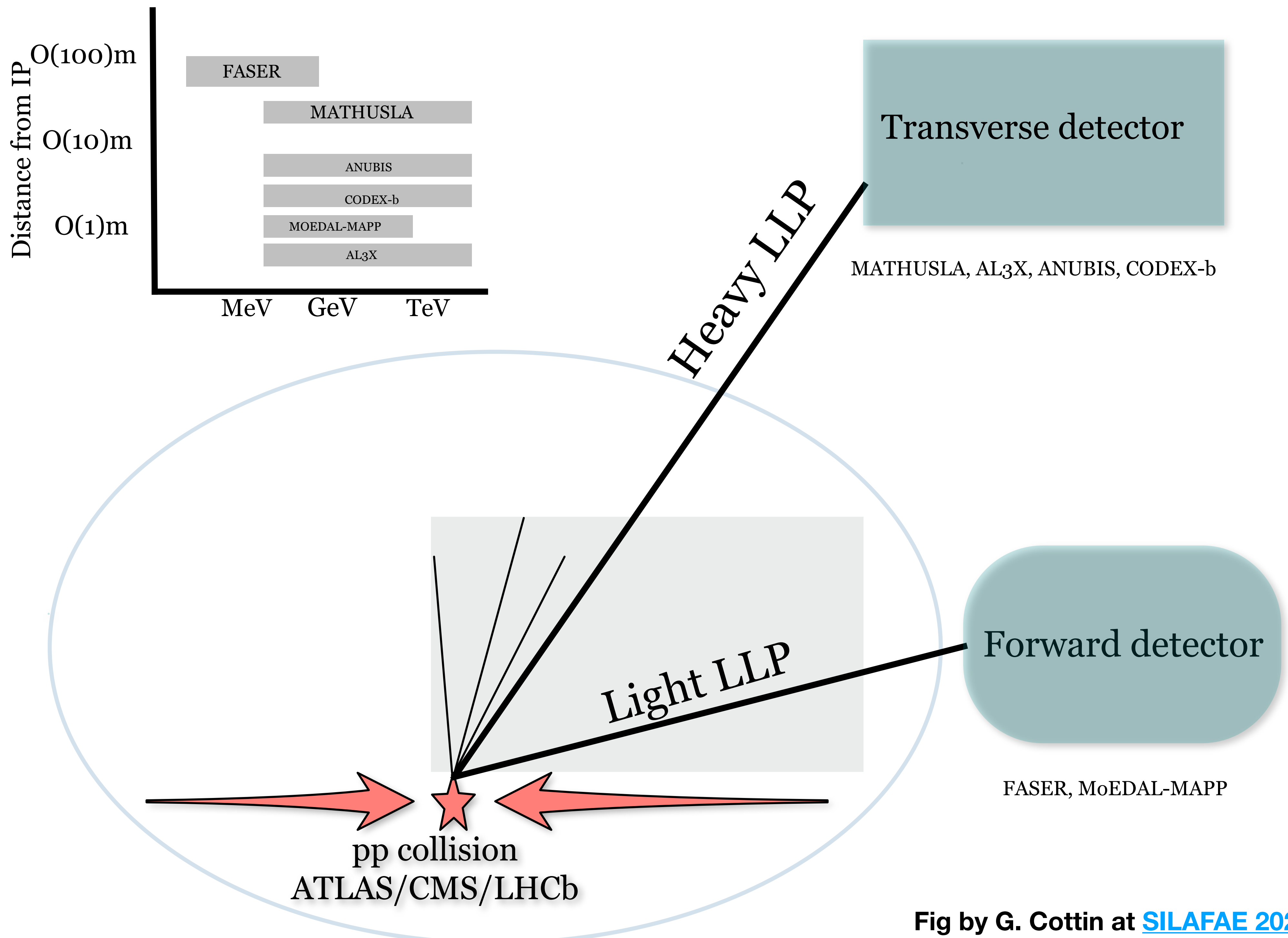
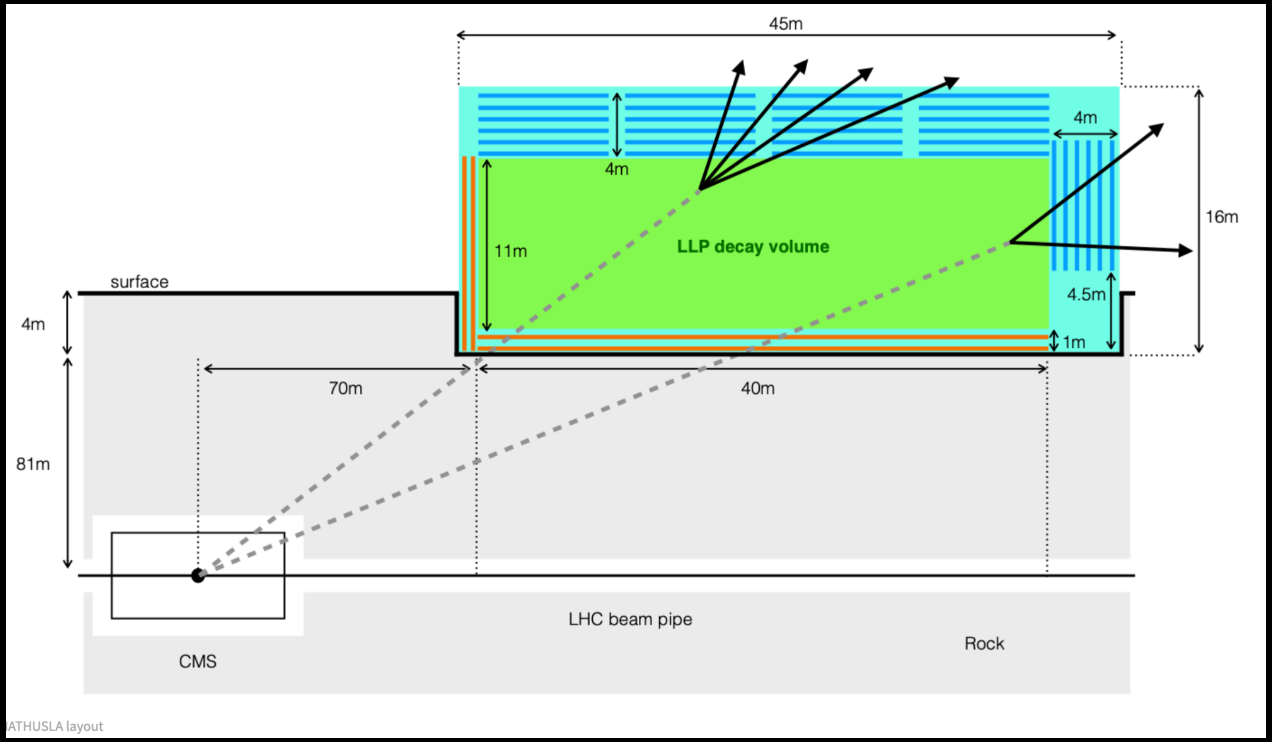


Fig by G. Cottin at SILAFAE 2024

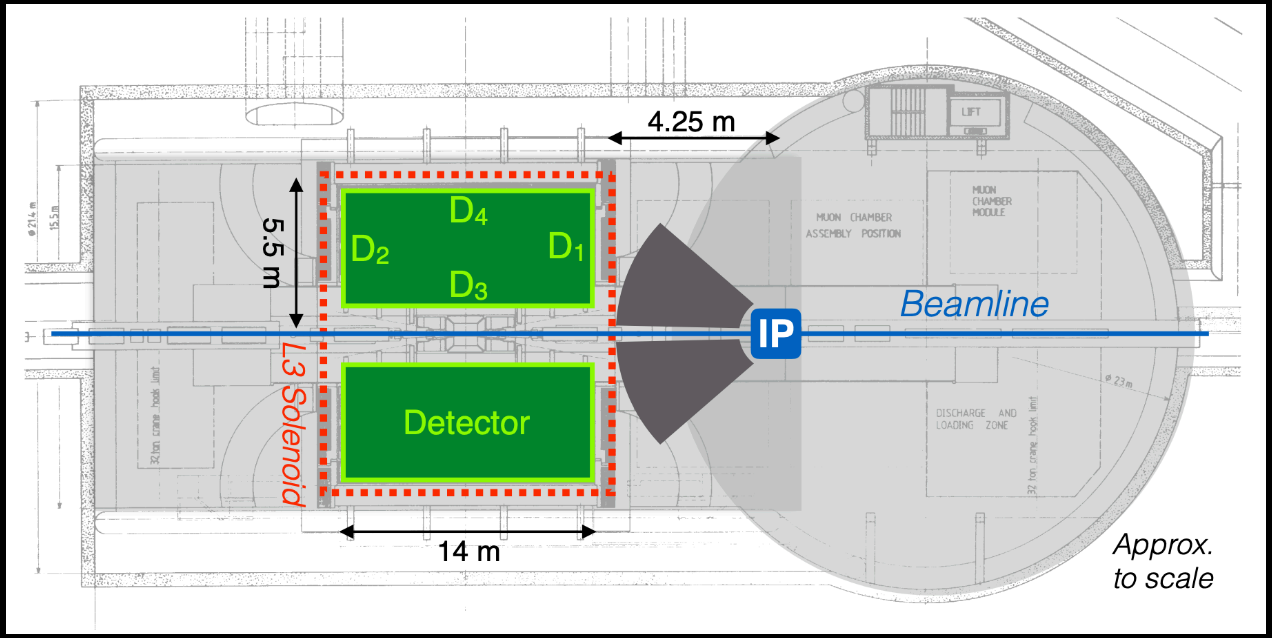
A few examples

MATHUSLA



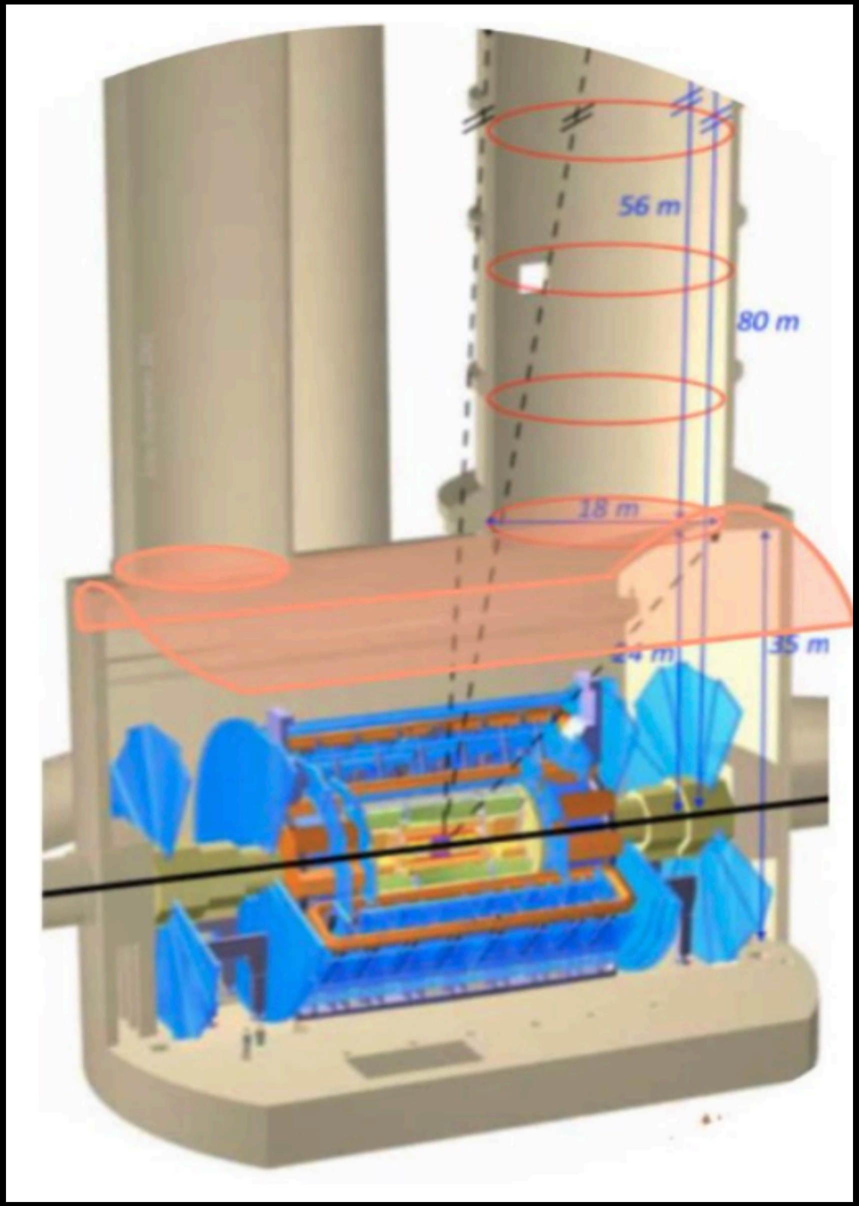
https://mathusla-experiment.web.cern.ch/

AL3X



arXiv:1810.03636

ANUBIS

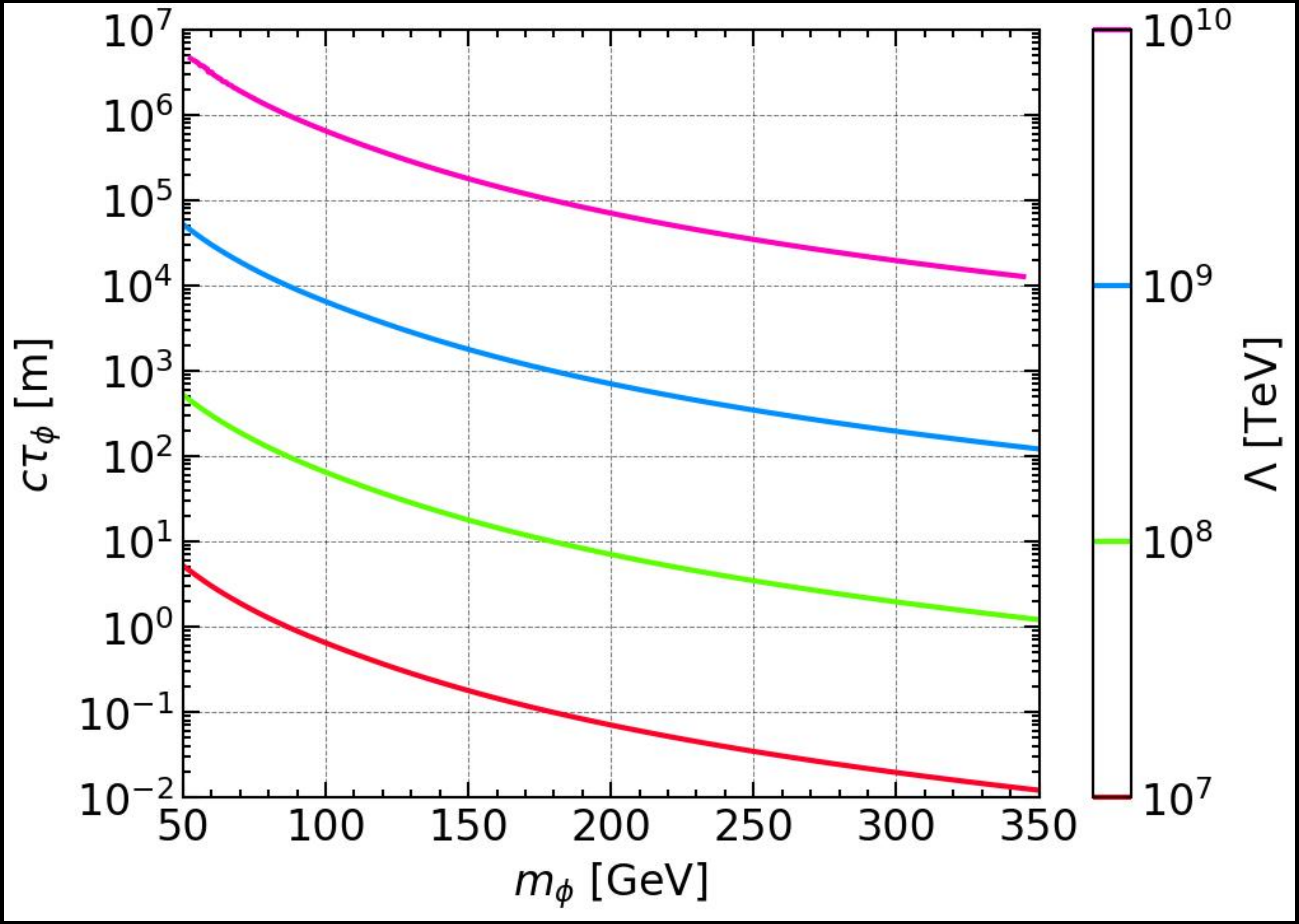


https://twiki.cern.ch/twiki/bin/view/ANUBIS/

For this model, $c\tau_\phi \sim \Lambda^2$

LLP signatures can shine light on the Energy Scale where New Physics appear

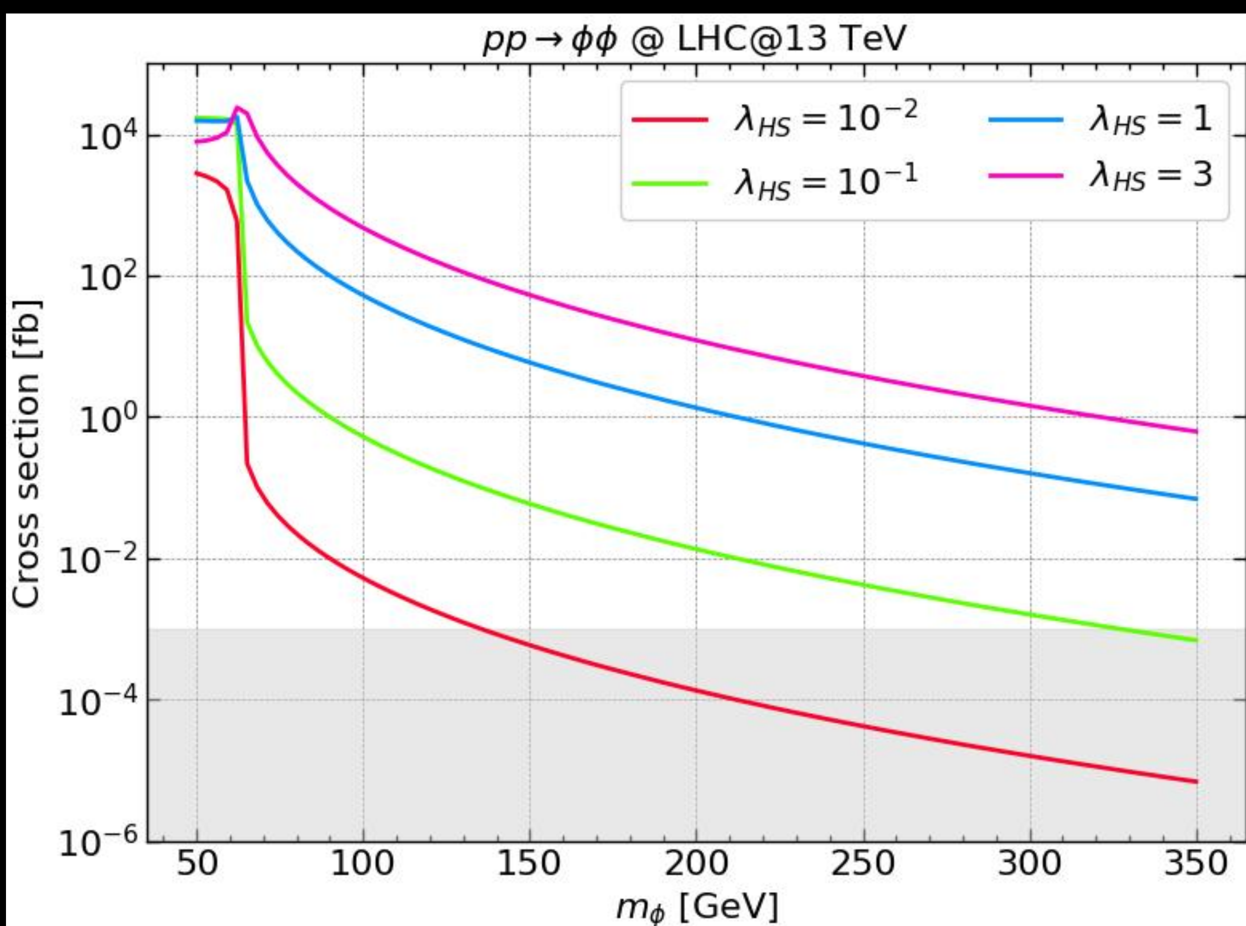
What would be the largest Energy Scale that we can probe at the LHC?

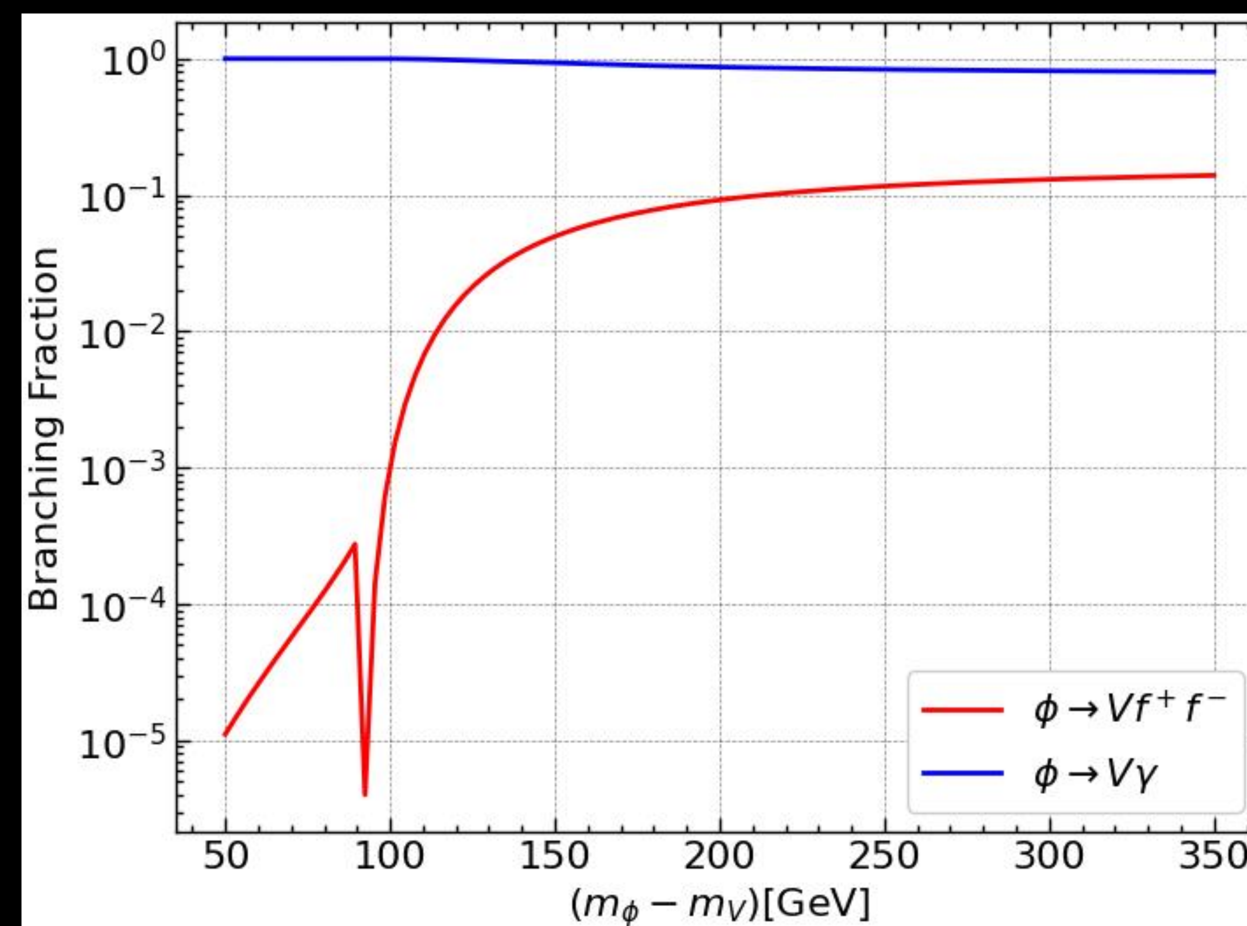


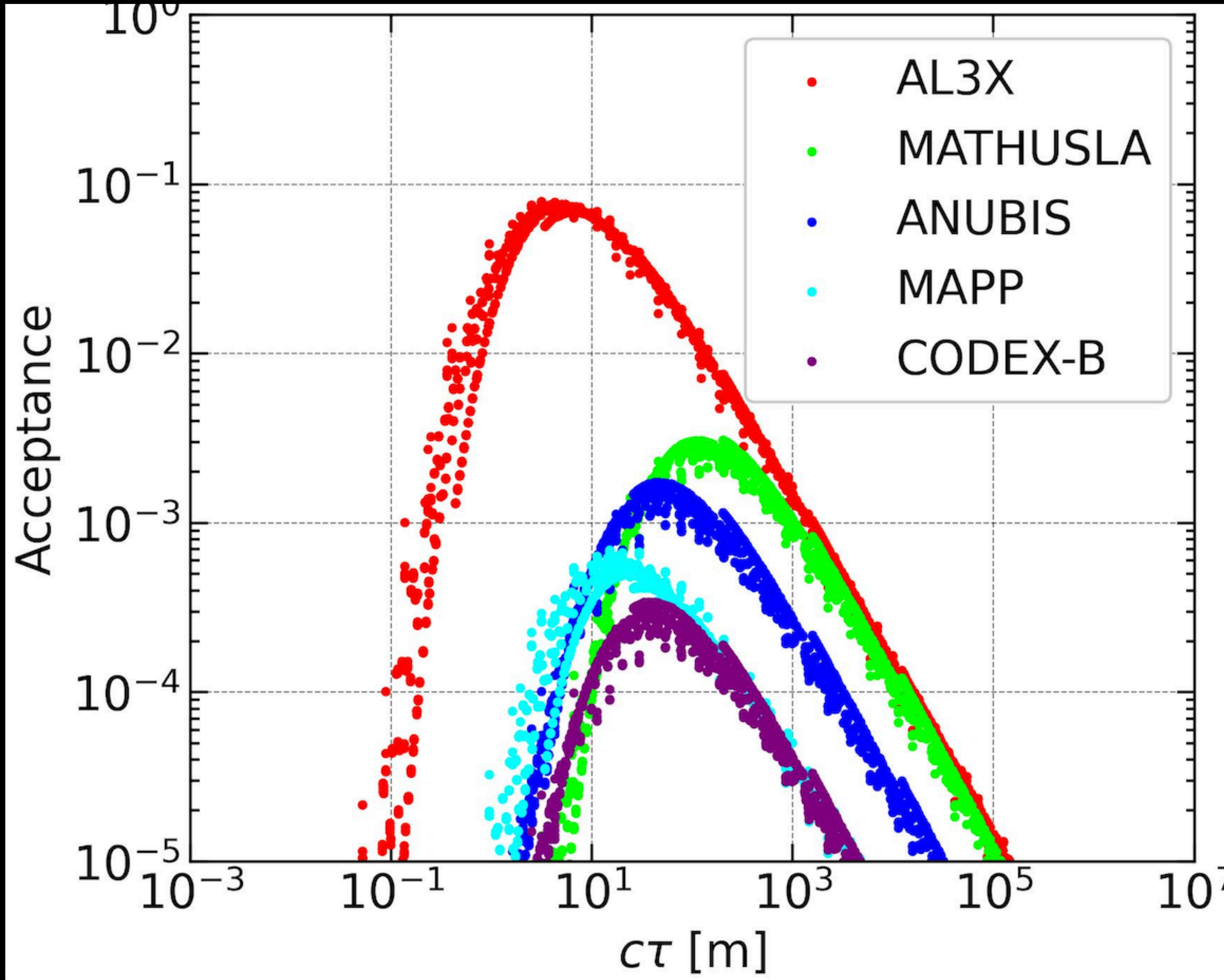
The Master Formula for Particle Pheno:

$$\mathcal{N} = Acceptance \times \sigma(pp \to \phi\phi) \times [Br(\phi \to Vf\bar{f})]^2 \times Luminosity$$

Cross section and branching fraction: theoretical quantities, "easy" to calculate
Acceptance: depends on detector, need to perform simulations





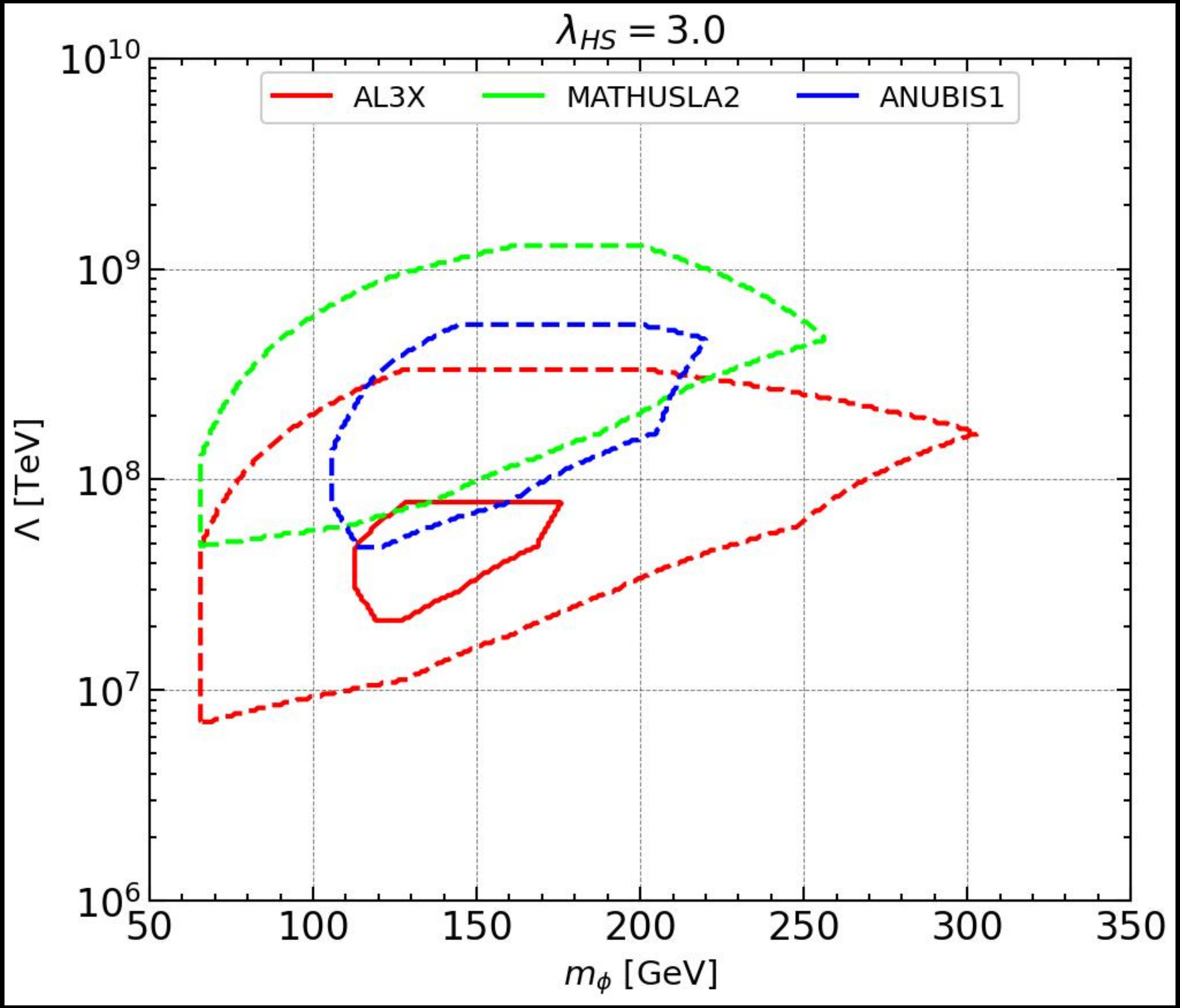


A C++ program for estimating detector sensitivities to long-lived particles: Displaced Decay Counter

Florian Domingo, Julian Günther, Jong Soo Kim, Zeren Simon Wang

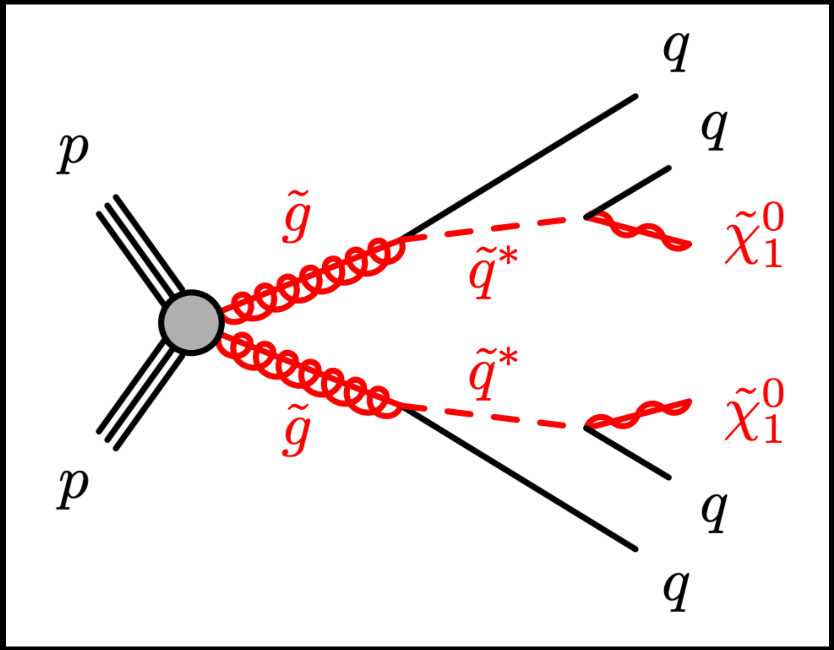
2308.07371

With the master formula, we can highlight the region of the parameter space that can be probed in these experiments

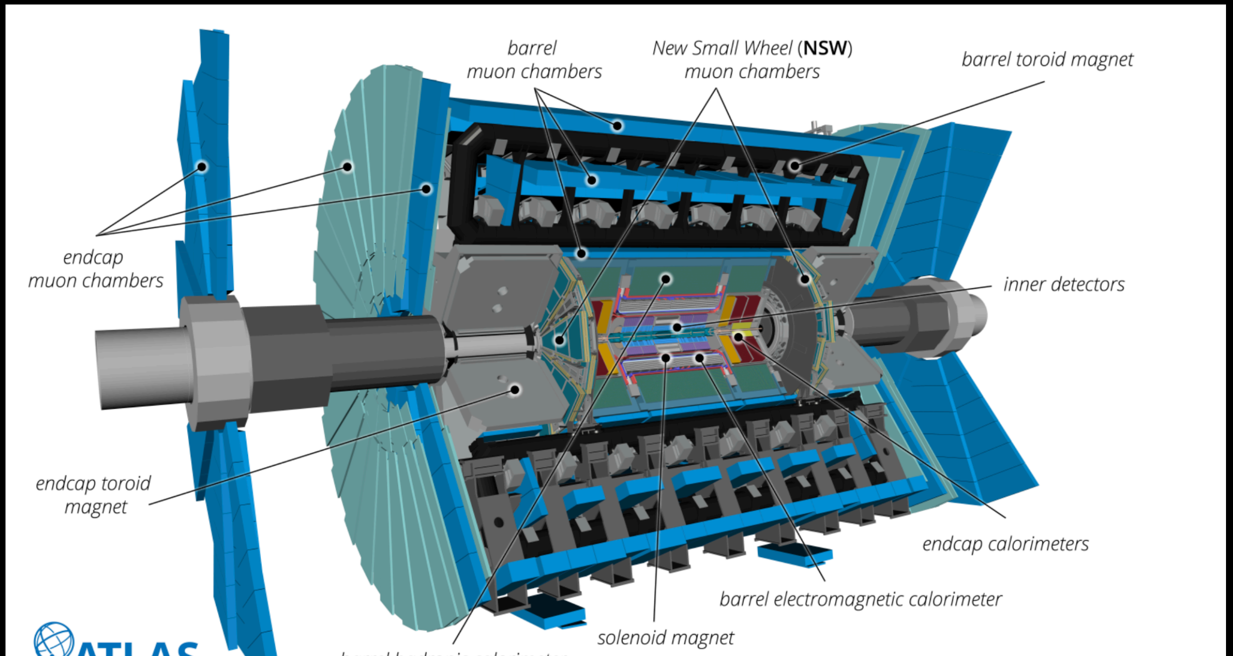


Dashed lines: 3 or more events
Solid lines: 30 or more events

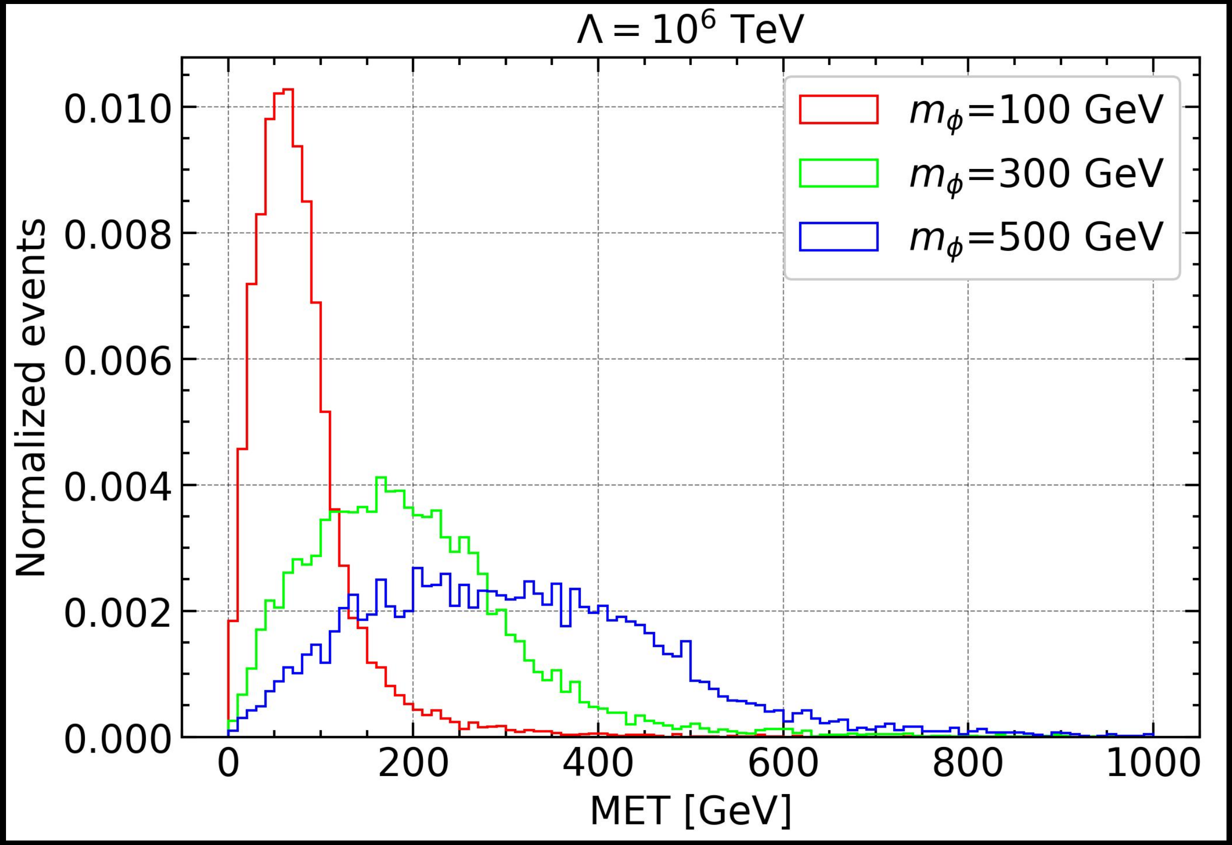
Searches Displaced vertex + Missing Energy Recast



ATLAS Collaboration **arXiv:1710.04901**

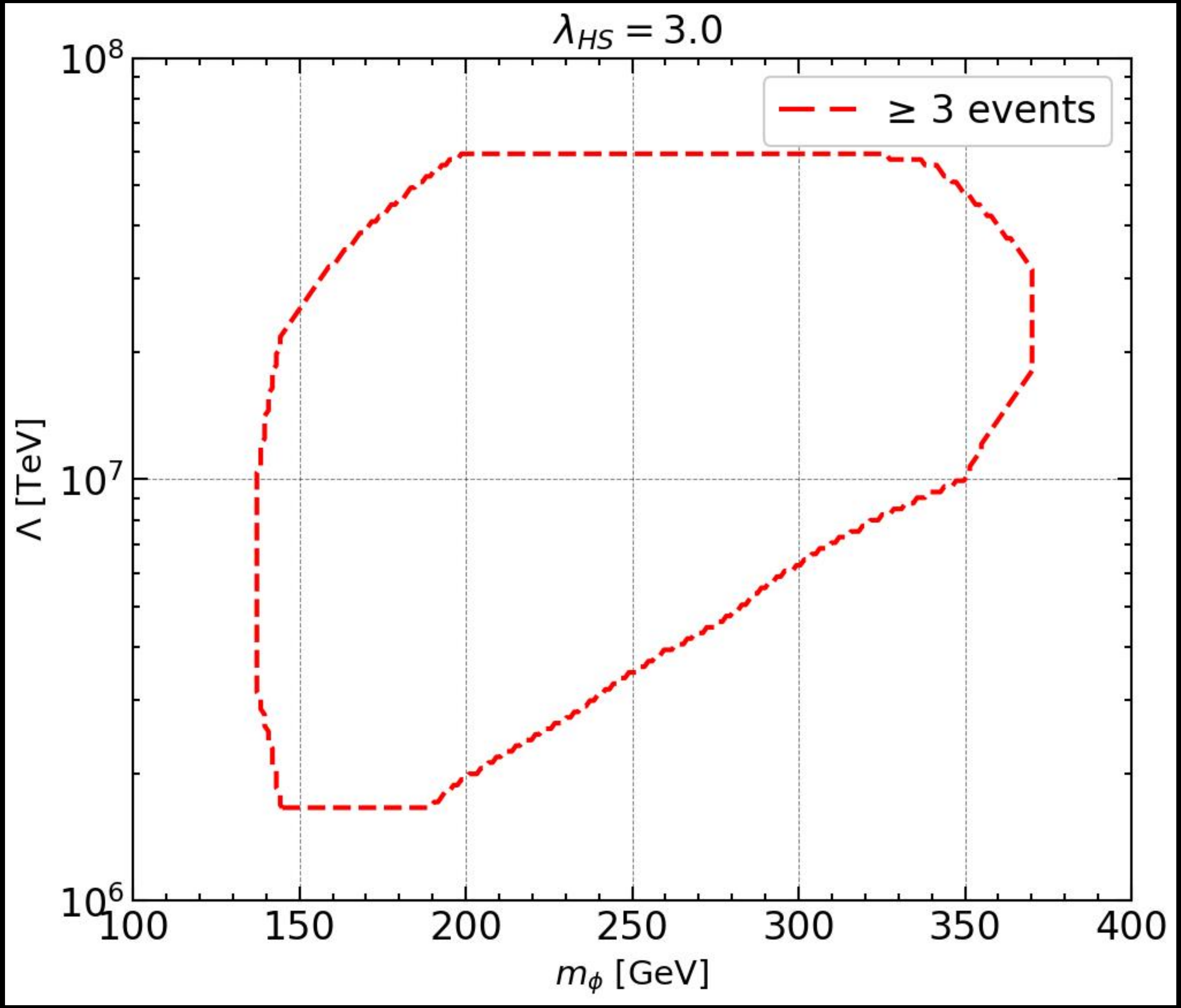


ATLAS Collaboration



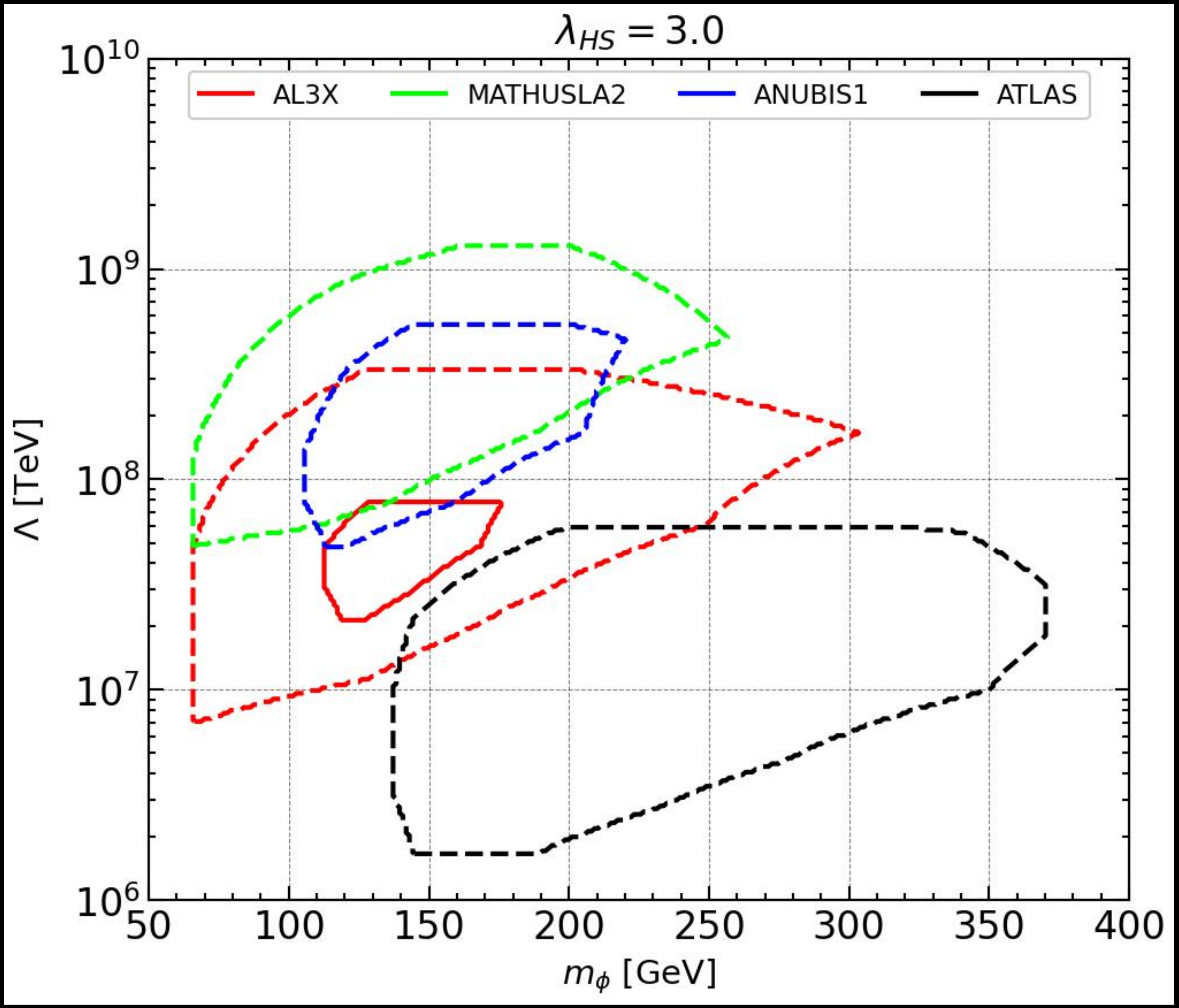
Typical cuts consider MET> 200[GeV], but kills a lot of signal, need to relax MET> 50[GeV]

ATLAS DV+MET



$\lambda_{HS} = 3.0$
≥ 3 events
10^8
10^7
10^6
Λ [TeV]
100
150
200
250
300
350
400
m_ϕ [GeV]

We can compare ATLAS+LLP-dedicated detectors



Dashed lines: 3 or more events
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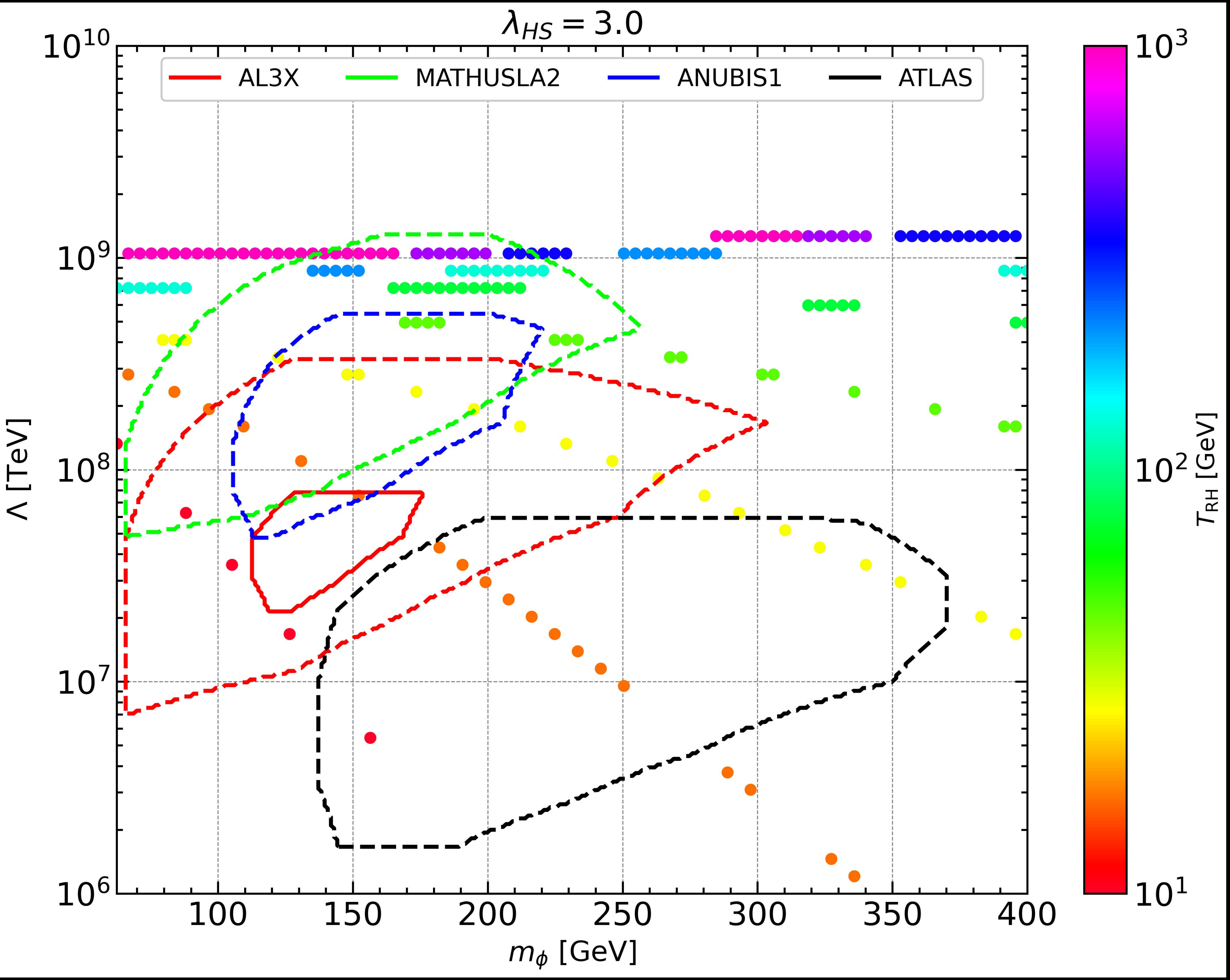
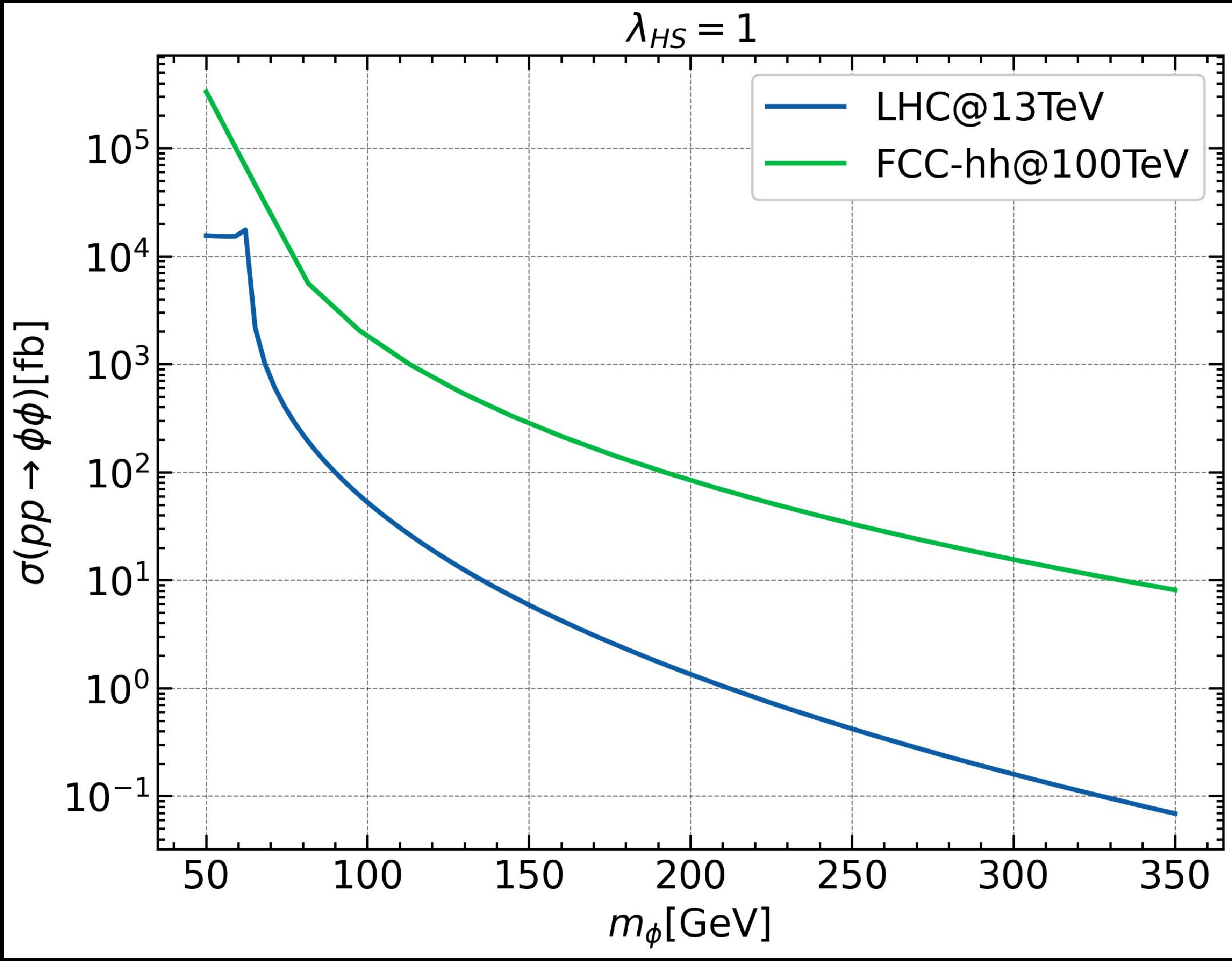
Potential signatures at this facilities could probe $10 < T_{RH} < 10^3$ [GeV]



We need high values for λ_{HS}, due to small acceptance and branching fraction

Can we probe smaller values for this parameter?
Not yet!



Next steps: going to FCC
Advantages: Room for optimization

Conclusions

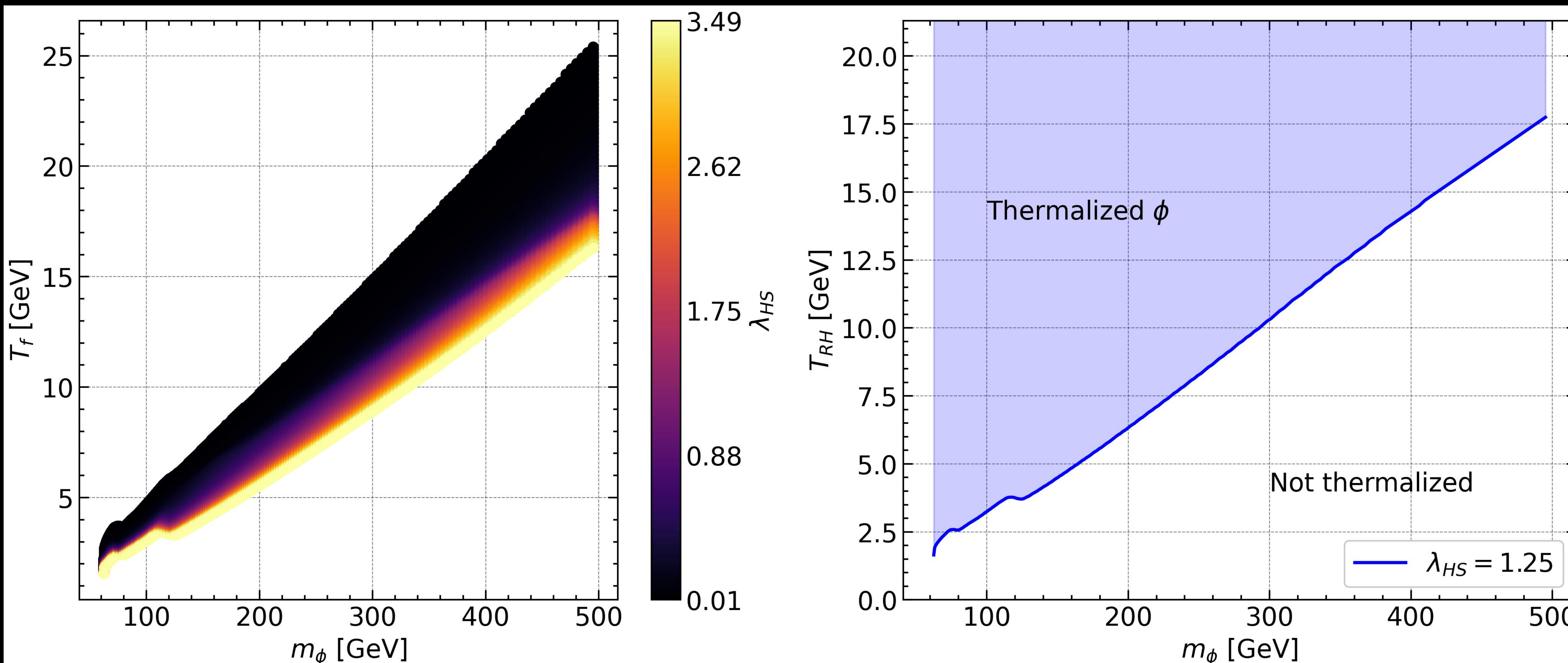
- We revisited the super-WIMP mechanism in a concrete realization
- This mechanism opens interesting phenomenology at colliders, especially at far detectors/LLPs
- Nice interplay between collider signatures and cosmological observables (relic density and reheating temperature)
- Work on this line can motivate LLP-Detector proposals at the LHC and the FCC

Project partially founded by ANID dirección de Capital Humano Avanzado

BACK UP

Important: For Super-WIMP mechanism to work we need ϕ to be thermalized after the reheating

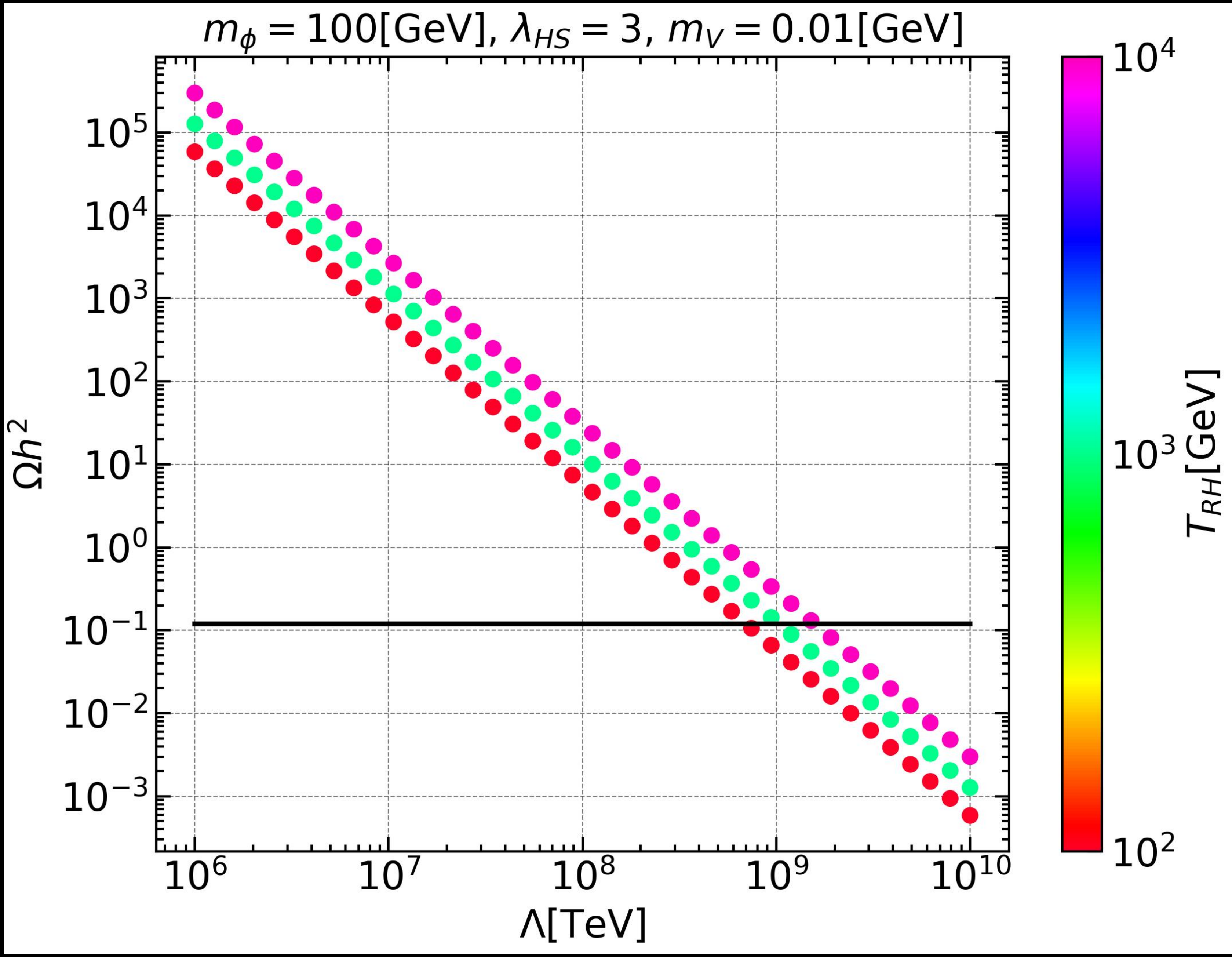
$$T_{RH} > T_f$$



Puts a bound on how low we can take the reheating temperature for our model

$$\Omega h^2 = \Omega h^{2(FI)} + \frac{m_V}{m_\phi}\Omega h^{2(FO)}$$

Freeze-in



Seems that higher masses increase acceptance, but is misleading! Also reduces cross section