Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

Collaborative Research Center TRR 257

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Particle Physics Phenomenology after the Higgs Discovery

Phenomenological Aspects of Flavoured Majorana Dark Matter

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Young Scientists Meeting

Siegen

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Outline

Dark Matter model

- Flavoured Majorana Dark Matter
- Previous analysis and results

Freeze-out scenarios

- Freeze-out with coannihilations
- Conversion driven freeze-out

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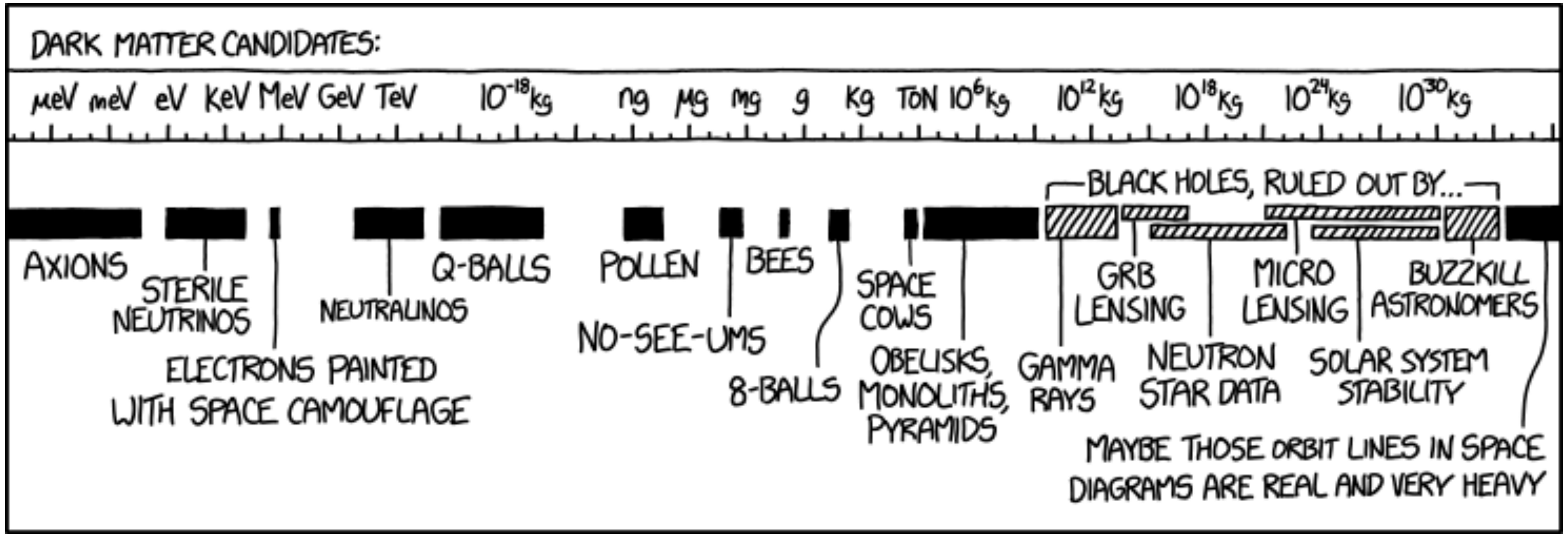
Why Flavoured Dark Matter?

- Simple weakly interacting massive particle (WIMP) models under severe pressure

  → Assume Dark Matter (DM) is charged under non-trivial flavour symmetry

- New source of flavour and CP violation → different phenomenology

- More degrees of freedom → opens up parameter space



https://xkcd.com/2035/

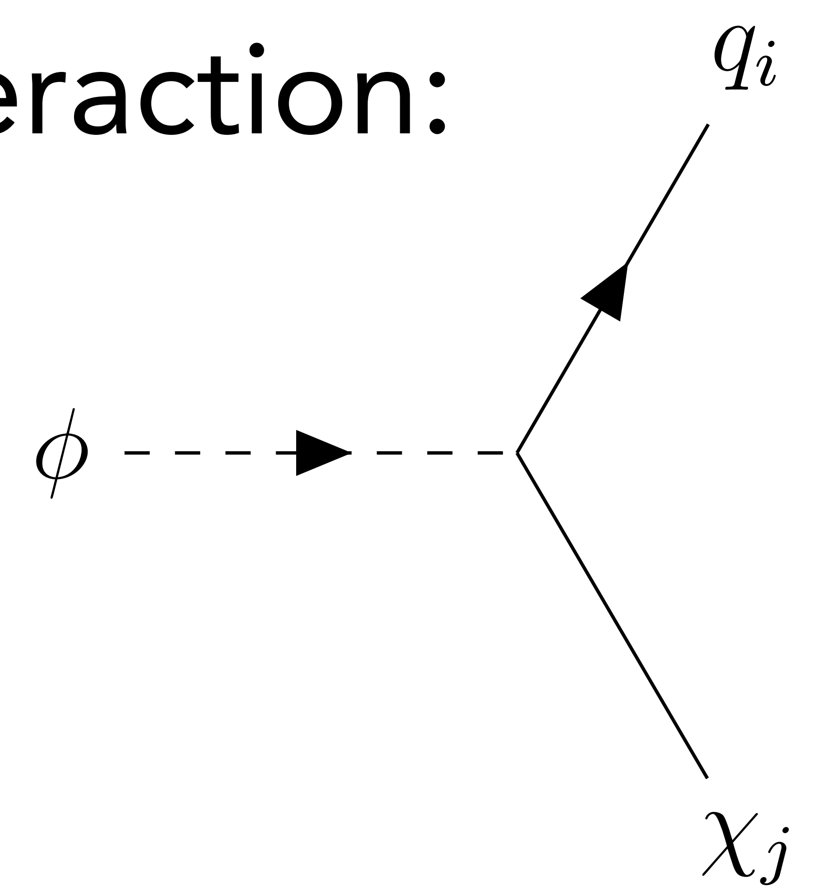
Dark Minimal Flavour Violation

- Dark Minimal Flavour Violation (DMFV) framework: Extend SM by new flavour symmetry and new fields (DM flavour triplet χ_i and mediator ϕ)
- Dirac DMFV models have been studied for DM coupling to
  - right-handed down-type quarks — Agrawal, Blanke, Gemmler [1405.6709]
  - right-handed up-type quarks — Blanke, Kast [1702.08457]
  - left-handed quarks — Blanke, Das, Kast [1711.10493]
- Here: Consider flavoured Majorana DM which couples to right-handed up-type quarks via a scalar mediator — Acaroglu, Blanke [2109.10357]

Flavoured Majorana DM

- New physics contribution with flavour and CP violating interaction:

$$\mathcal{L}_{\mathrm{NP}} \supset \frac{1}{2}(i\bar{\chi}\partial\!\!\!/\chi - M_\chi \bar{\chi}\chi) - (\lambda_{ij}\bar{u}_{R_i}\chi_j\phi + \mathrm{h.c.})$$
$$+(D_\mu\phi)^\dagger(D^\mu\phi) - m_\phi^2\phi^\dagger\phi$$



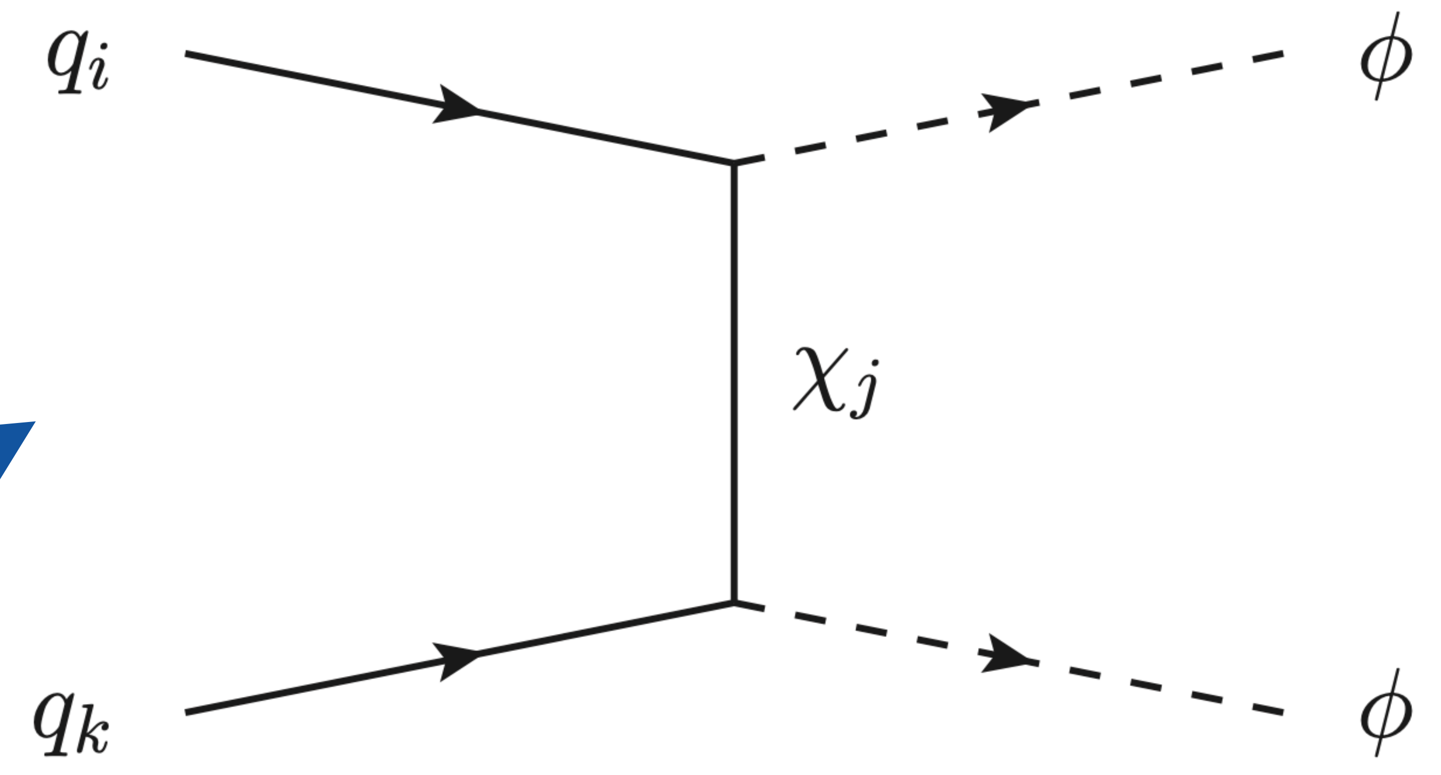
- Mass matrix cannot be generic → expand mass matrix in powers of λ:

$$M_\chi = m_\chi\left(\mathbf{1} + \frac{\eta}{2}(\lambda^\dagger\lambda + \lambda^T\lambda^*)\right) \xrightarrow{\text{Diagonalize}} M_\chi^D = \mathrm{diag}(m_{\chi_1}, m_{\chi_2}, m_{\chi_3})$$

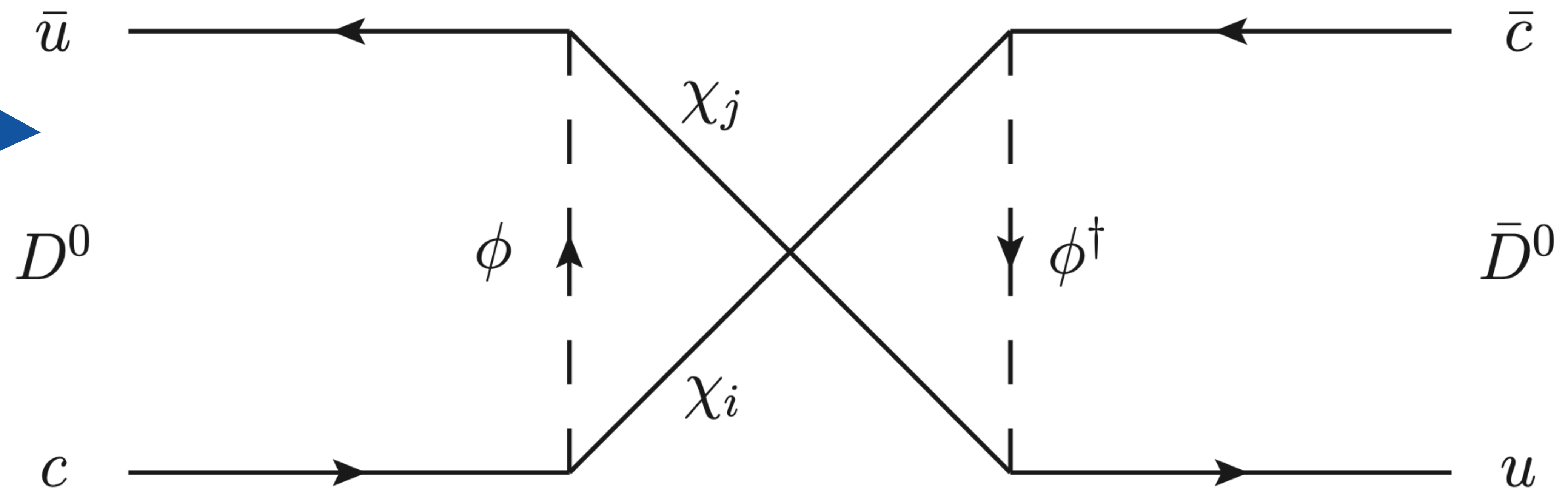
with $m_{\chi_1} > m_{\chi_2} > m_{\chi_3}$ and $m_\phi > m_{\chi_3}$

Previous Analysis

- Phenomenology studied in Acaroglu, Blanke [2109.10357]
- Collider: Relevant signatures tops + $\not{E}$ and jets + $\not{E}$, Majorana-specific same-sign signature $tt + \not{E}$

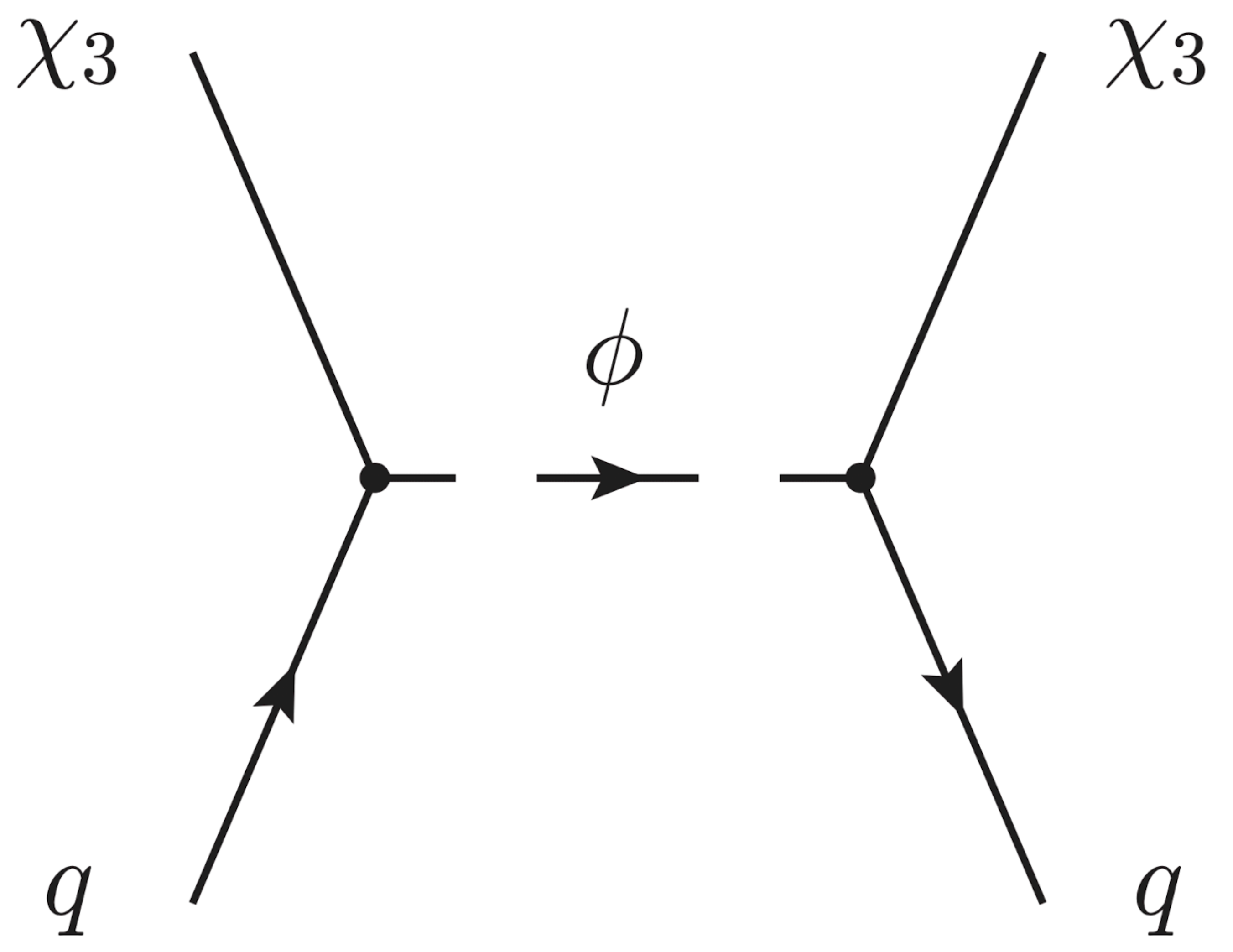


- Flavour Physics: Limits from $D^0 - \bar{D}^0$ mixing, additional crossed diagram extends allowed parameter space

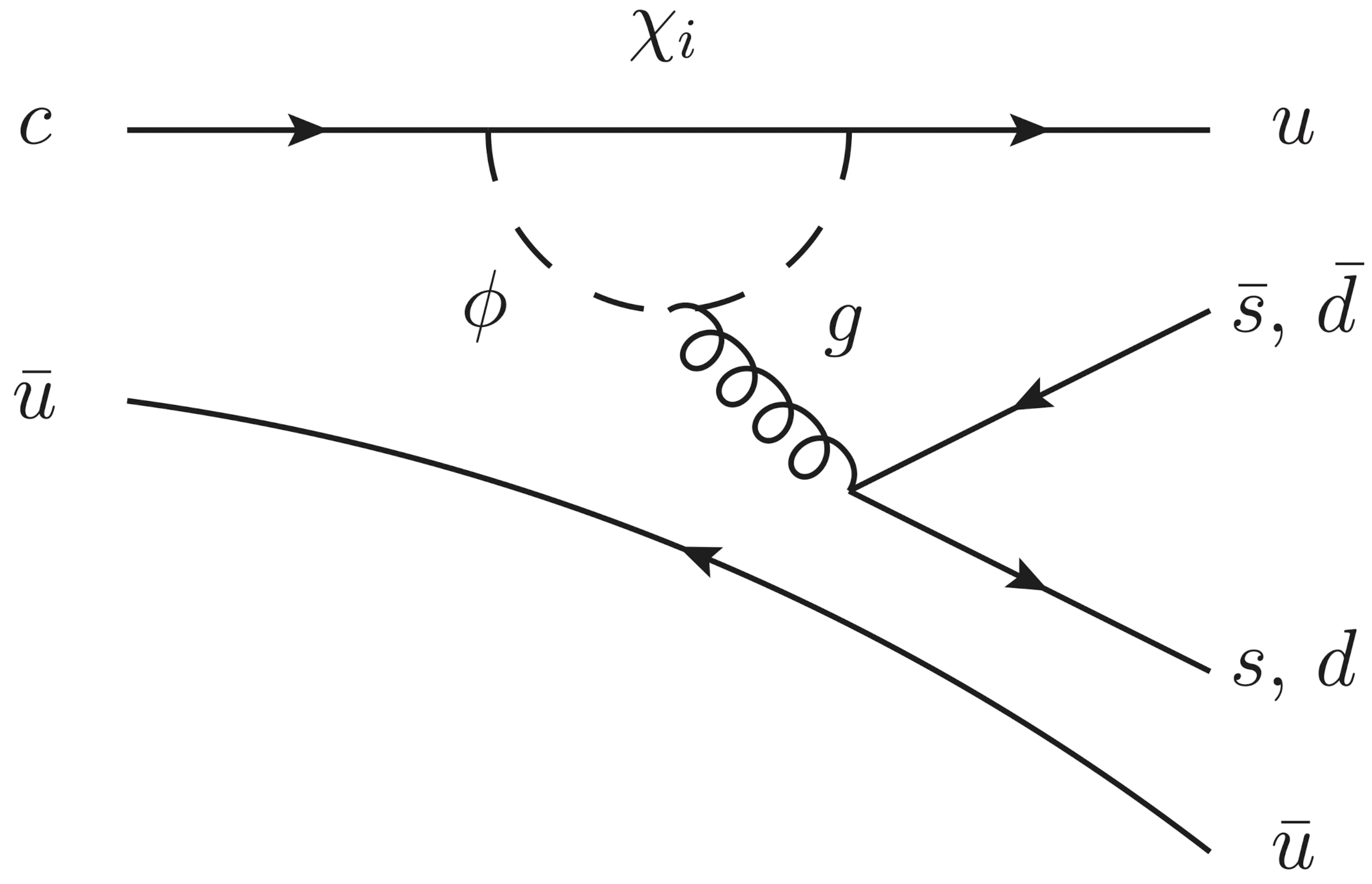


Previous Analysis

- Direct detection: Limits from spin-dependent and spin-independent WIMP-nucleon scattering



- CP violation in charm decays: Model is able to explain large measured value of CP asymmetry $\Delta A_{CP}^{dir} = A_{CP}(D \to K^+K^-) - A_{CP}(D \to \pi^+\pi^-)$



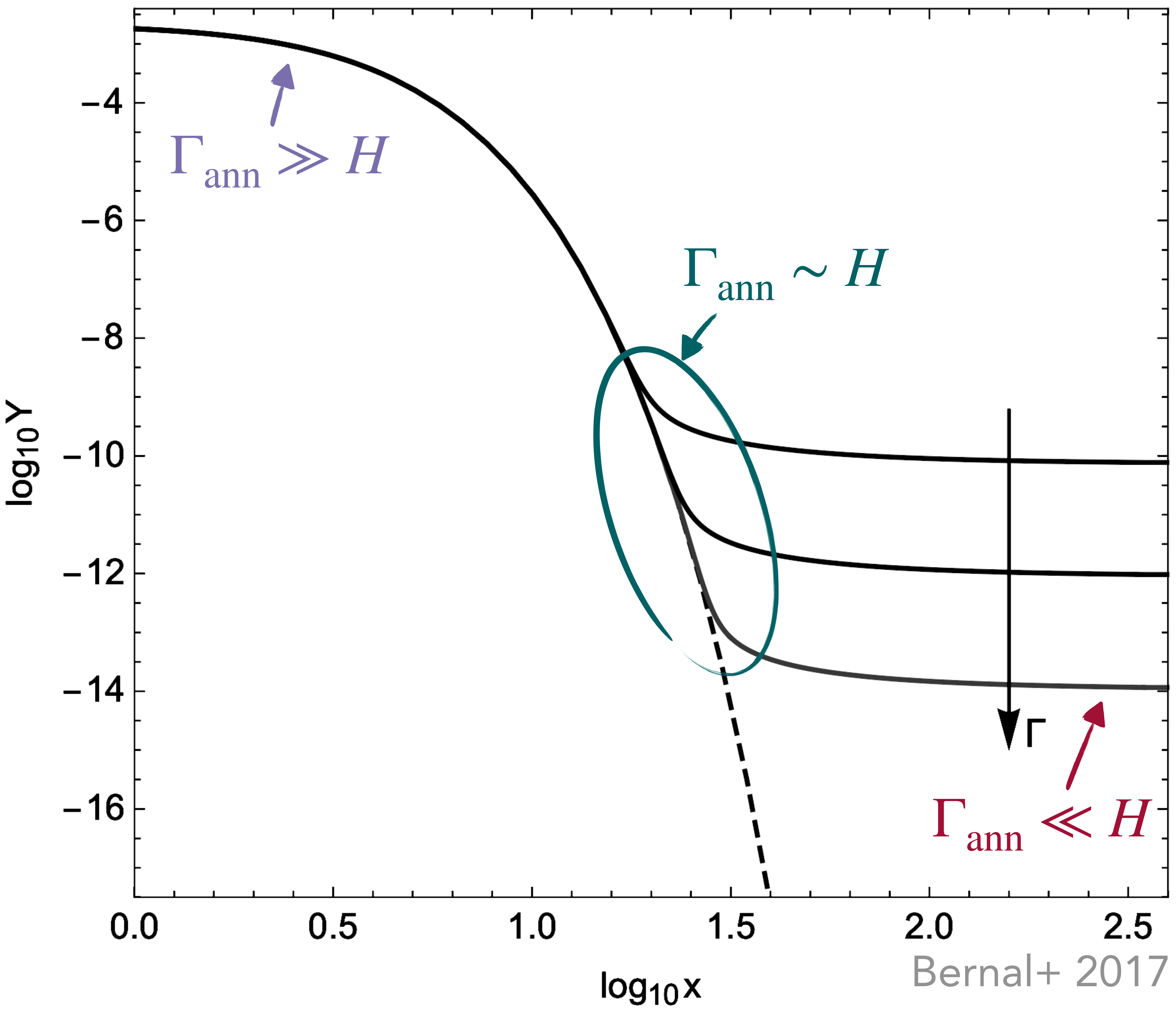
Cosmological Constraints

- Freeze-out mechanism: solve Boltzmann equation for $Y = n/s$ and $x = m_\chi/T$

$$\frac{dY}{dx} = -\frac{1}{3H}\frac{ds}{dx}\langle\sigma_{\chi\chi}v\rangle(Y^2 - Y_{eq}^2)$$

Expansion of Universe — Number-changing interactions

- Three regions for $\Gamma_{ann} = n_\chi\langle\sigma_{\chi\chi}v\rangle$:
  - $\Gamma_{ann} \gg H$: DM in thermal equilibrium
  - $\Gamma_{ann} \sim H$: Freeze-out
  - $\Gamma_{ann} \ll H$: Constant abundance Y

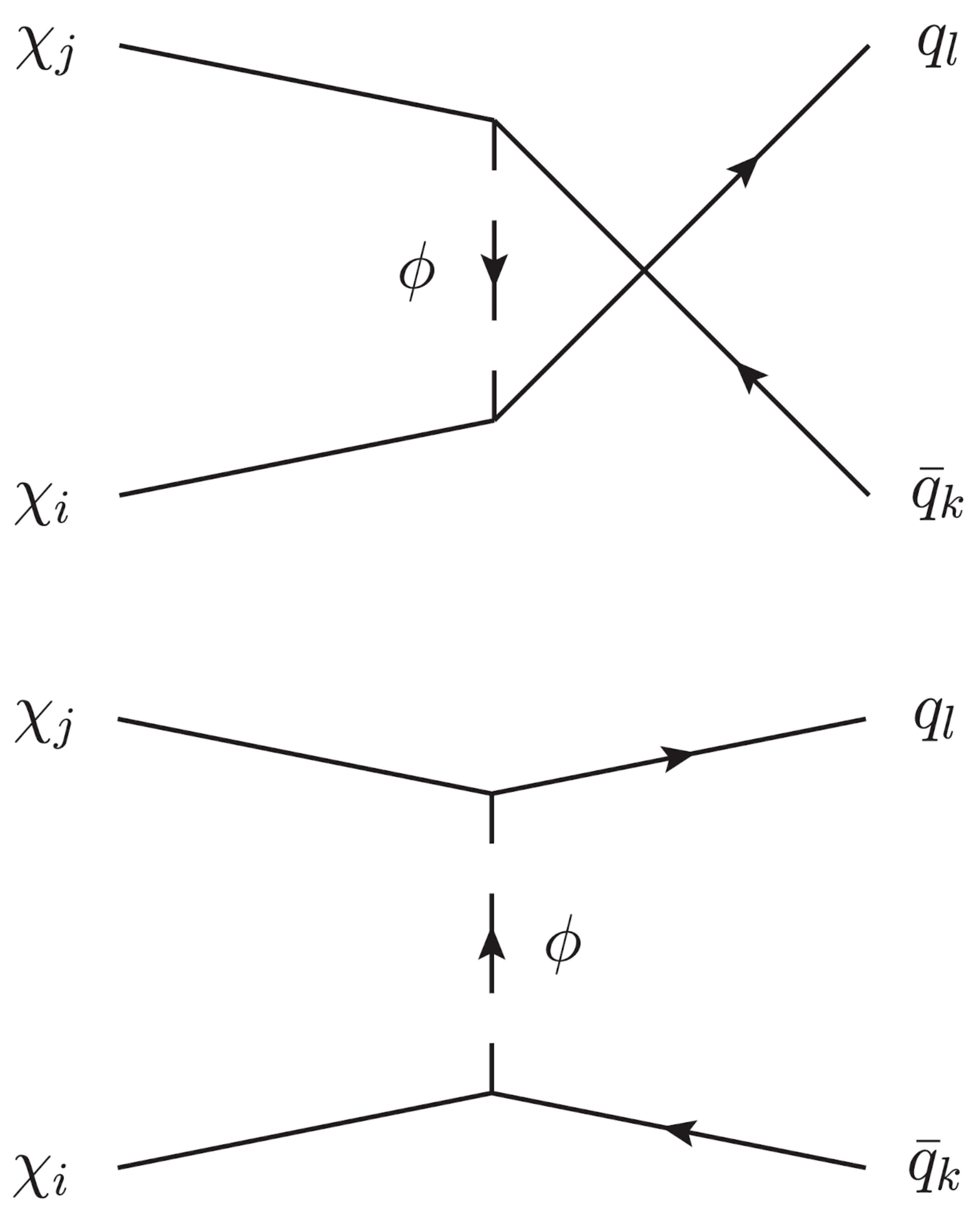


Bernal+ 2017

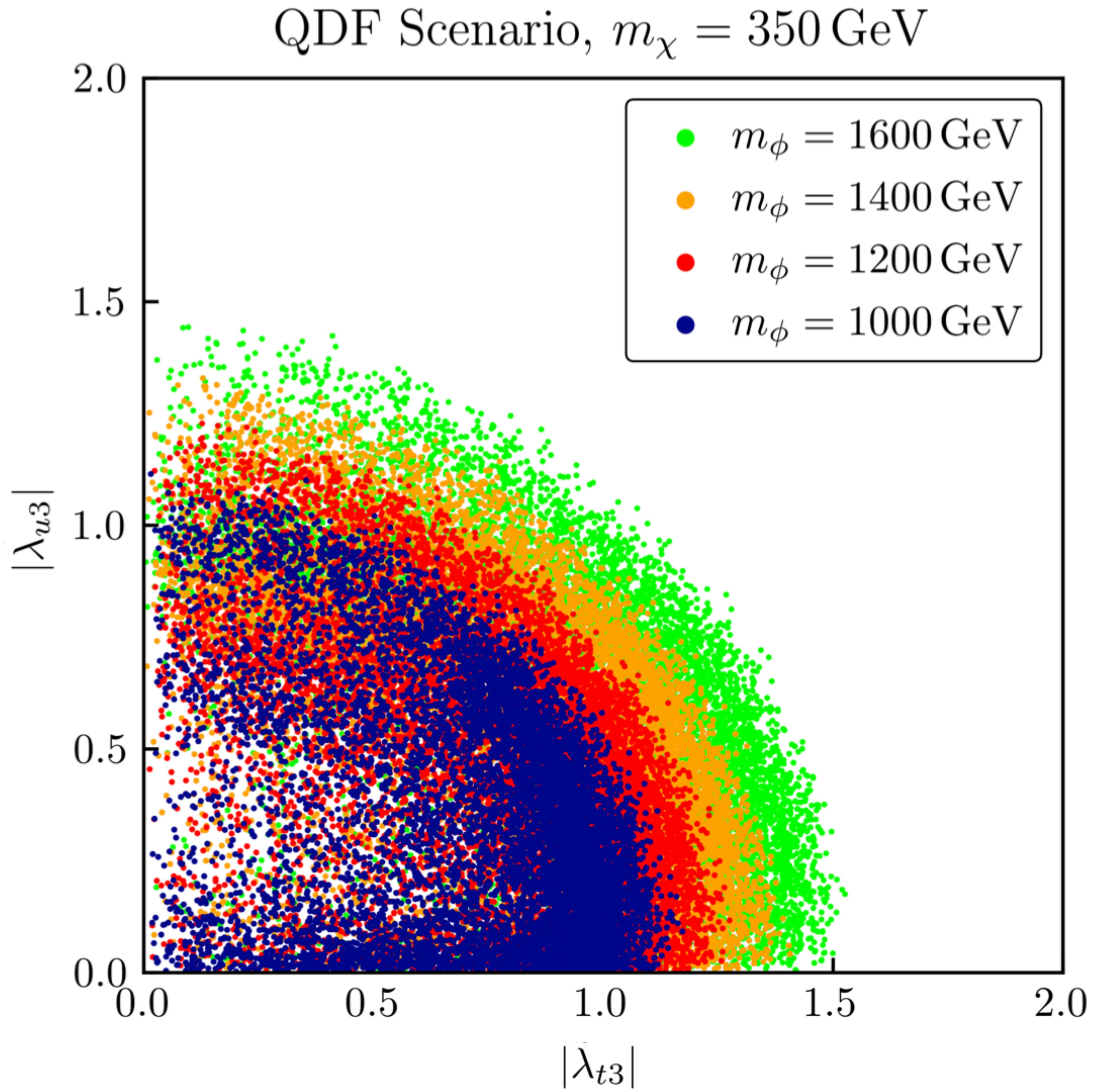
Cosmological Constraints

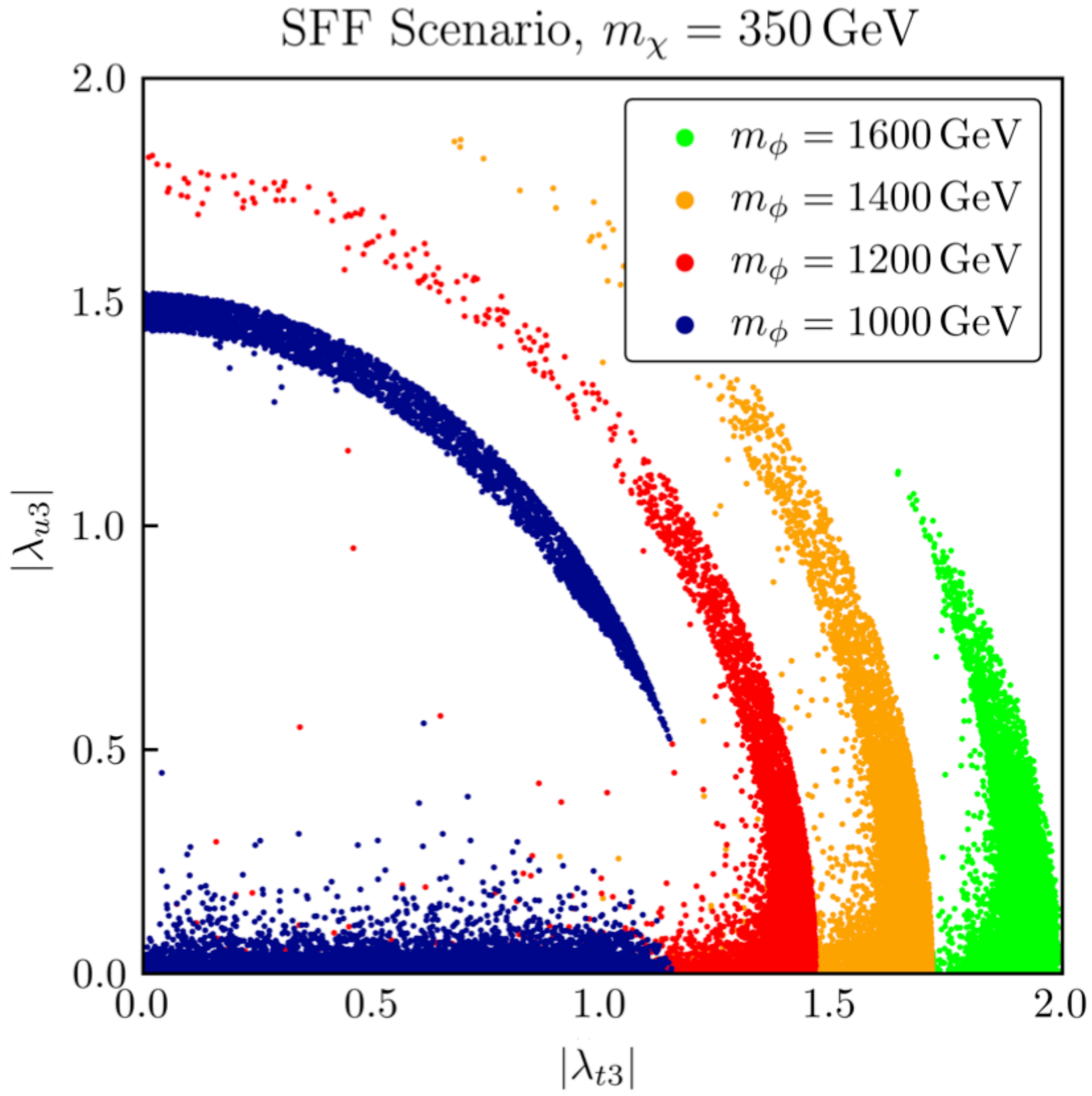
- Two benchmark freeze-out scenarios:
  - <u>Quasi-Degenerate Freeze-Out (QDF):</u> mass splitting below 1%
  - <u>Single-Flavour Freeze-Out (SFF):</u> mass splitting above 10%
- ϕ does not contribute to freeze-out
- Low-velocity expansion $\langle \sigma v \rangle = a + b \langle v^2 \rangle$

  with $\langle v^2 \rangle = 6T_f/m_\chi \approx 0.3$
- Compare to $\langle \sigma v \rangle \approx 2.2 \cdot 10^{-26} \mathrm{cm}^3/\mathrm{s}$



Combined Analysis





→ DM mostly top-flavoured with larger coupling, flavour and relic abundance constraints dominant

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Freeze-Out with Coannihilations

- Include coannihilations of all χ_i and ϕ — Edsjö, Gondolo [hep-ph/9704361]
- All particles decay into lightest → abundance can be described with $n = \sum_i n_i$
- Assuming efficient conversion rates → dark sector in thermal equilibrium
  $\frac{n_i}{n} \approx \frac{n_i^{\text{eq}}}{n^{\text{eq}}}$ → approximation
- One Boltzmann equation (BME) for $Y = n/s$ and $x = m_{\chi_3}/T$:

$$\frac{dY}{dx} = -\frac{1}{3H}\frac{ds}{dx}\langle\sigma_{\text{eff}}v\rangle(Y^2 - Y_{\text{eq}}^2)$$

where

$$\langle\sigma_{\text{eff}}v\rangle = \sum_{ij}\langle\sigma_{ij}v_{ij}\rangle\frac{n_i^{\text{eq}}}{n^{\text{eq}}}\frac{n_j^{\text{eq}}}{n^{\text{eq}}}$$

Freeze-Out with Coannihilations

- Example:

  $m_\chi = 800$ GeV, $m_\phi = 816$ GeV,

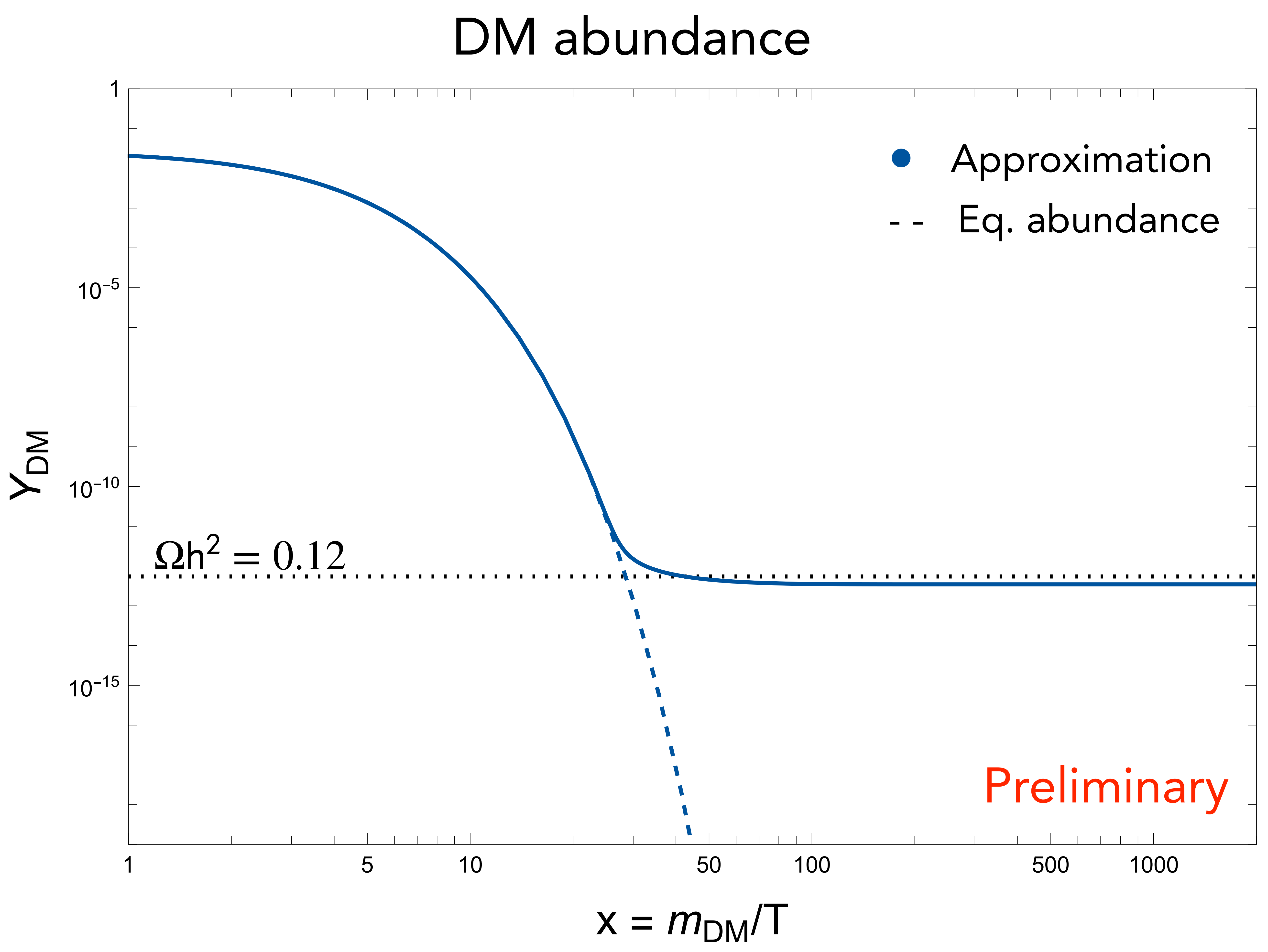
  $$\lambda = \begin{pmatrix} 0 & 0 & 1.9 \cdot 10^{-7} \\ 0 & 0.5 & 0 \\ 0.55 & 0 & 0 \end{pmatrix}$$

  ↓

  $m_{\chi_1} = 969$ GeV, $m_{\chi_2} = 940$ GeV, $m_{\chi_3} = 800$ GeV

- Can be solved by micrOMEGAs (code for calculation of DM properties)

  [Bélanger, Boudjema, Pukhov, Semenov]



Conversion Driven Freeze-Out

- Conversions $\chi_i \leftrightarrow \chi_j$ or $\chi_i \leftrightarrow \phi$ can become inefficient during freeze-out when conversion rate $\Gamma \sim H$
- Chemical equilibrium breaks down $\rightarrow$ coupled BME of all particles need to be solved

$$\frac{dY_{\chi_i}}{dx} = \frac{1}{3H}\frac{ds}{dx}\left(\langle\sigma_{\chi_i\chi_j}v\rangle(Y_{\chi_i}Y_{\chi_j} - Y_{\chi_i}^{\mathrm{eq}}Y_{\chi_j}^{\mathrm{eq}}) + \frac{\Gamma_{\chi_i\to\chi_j}}{s}\left(Y_{\chi_i} - Y_{\chi_j}\frac{Y_{\chi_i}^{\mathrm{eq}}}{Y_{\chi_j}^{\mathrm{eq}}}\right) + \langle\sigma_{\phi\chi_i}v\rangle(Y_{\chi_i}Y_{\phi} - Y_{\chi_i}^{\mathrm{eq}}Y_{\phi}^{\mathrm{eq}}) - \frac{\Gamma_{\phi\to\chi_i}}{s}\left(Y_{\phi} - Y_{\chi_i}\frac{Y_{\phi}^{\mathrm{eq}}}{Y_{\chi_i}^{\mathrm{eq}}}\right)\right)$$

$$\frac{dY_{\phi}}{dx} = \frac{1}{3H}\frac{ds}{dx}\left(\frac{1}{2}\langle\sigma_{\phi\phi}v\rangle(Y_{\phi}^2 - (Y_{\phi}^{\mathrm{eq}})^2) + \langle\sigma_{\phi\chi_i}v\rangle(Y_{\chi_i}Y_{\phi} - Y_{\chi_i}^{\mathrm{eq}}Y_{\phi}^{\mathrm{eq}}) + \frac{\Gamma_{\phi\to\chi_i}}{s}\left(Y_{\phi} - Y_{\chi_i}\frac{Y_{\phi}^{\mathrm{eq}}}{Y_{\chi_i}^{\mathrm{eq}}}\right)\right)$$

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$$\frac{dY_\phi}{dx} = \frac{1}{3H}\frac{ds}{dx}\left(\frac{1}{2}\langle\sigma_{\phi\phi}v\rangle(Y_\phi^2 - (Y^{\text{eq}}_\phi)^2) + \langle\sigma_{\phi\chi_i}v\rangle(Y_{\chi_i}Y_\phi - Y^{\text{eq}}_{\chi_i}Y^{\text{eq}}_\phi) + \frac{\Gamma_{\phi\to\chi_i}}{s}\left(Y_\phi - Y_{\chi_i}\frac{Y^{\text{eq}}_\phi}{Y^{\text{eq}}_{\chi_i}}\right)\right)$$

All coannihilations

Conversion Driven Freeze-Out

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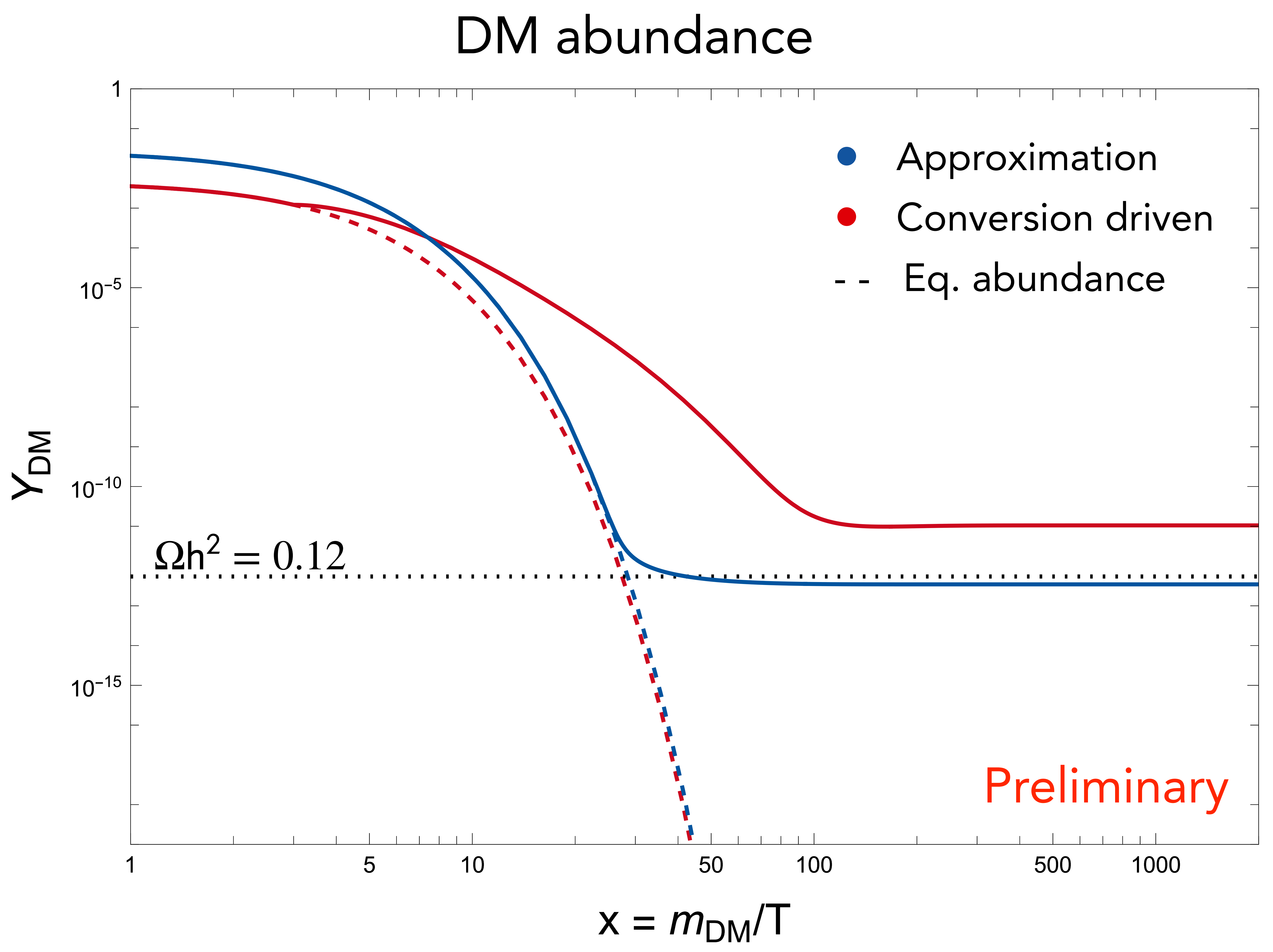
$$\frac{dY_\phi}{dx} = \frac{1}{3H}\frac{ds}{dx}\left(\frac{1}{2}\langle\sigma_{\phi\phi}v\rangle(Y_\phi^2 - (Y^{\rm eq}_\phi)^2) + \langle\sigma_{\phi\chi_i}v\rangle(Y_{\chi_i}Y_\phi - Y^{\rm eq}_{\chi_i}Y^{\rm eq}_\phi) + \frac{\Gamma_{\phi\to\chi_i}}{s}\left(Y_\phi - Y_{\chi_i}\frac{Y^{\rm eq}_\phi}{Y^{\rm eq}_{\chi_i}}\right)\right)$$

All conversions including decays

Conversion Driven Freeze-Out

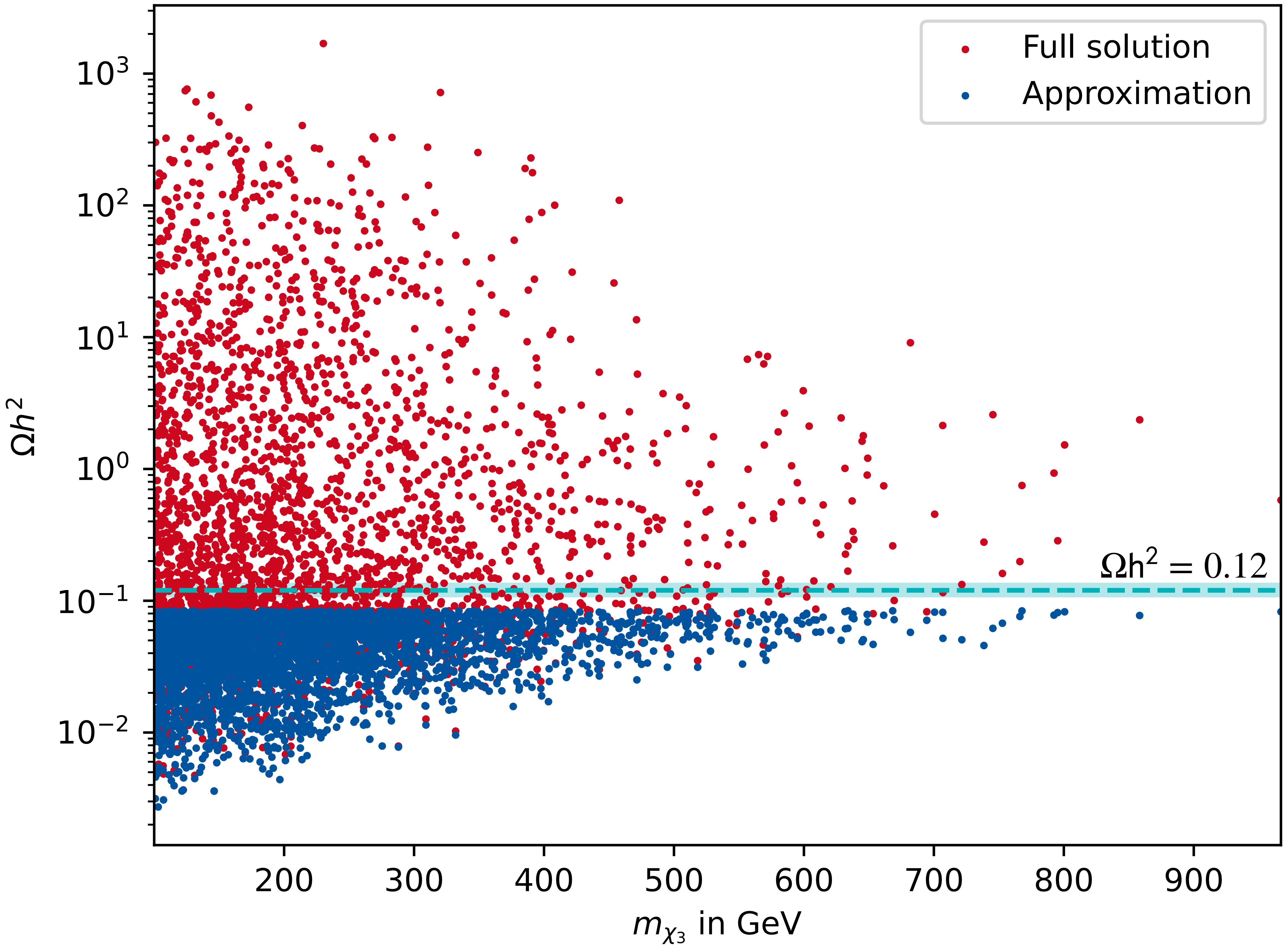
- Using same parameter values, relic abundance is enhanced significantly as $\chi_3 \leftrightarrow \phi$ conversions become inefficient
- Requires very small couplings $\lambda_{t3} = 1.9 \cdot 10^{-7}$
- Cannot be solved by micrOMEGAs out of the box
- Studied in Garny et al. [1705.09292] for one generation χ with conversions $\chi \leftrightarrow \phi$



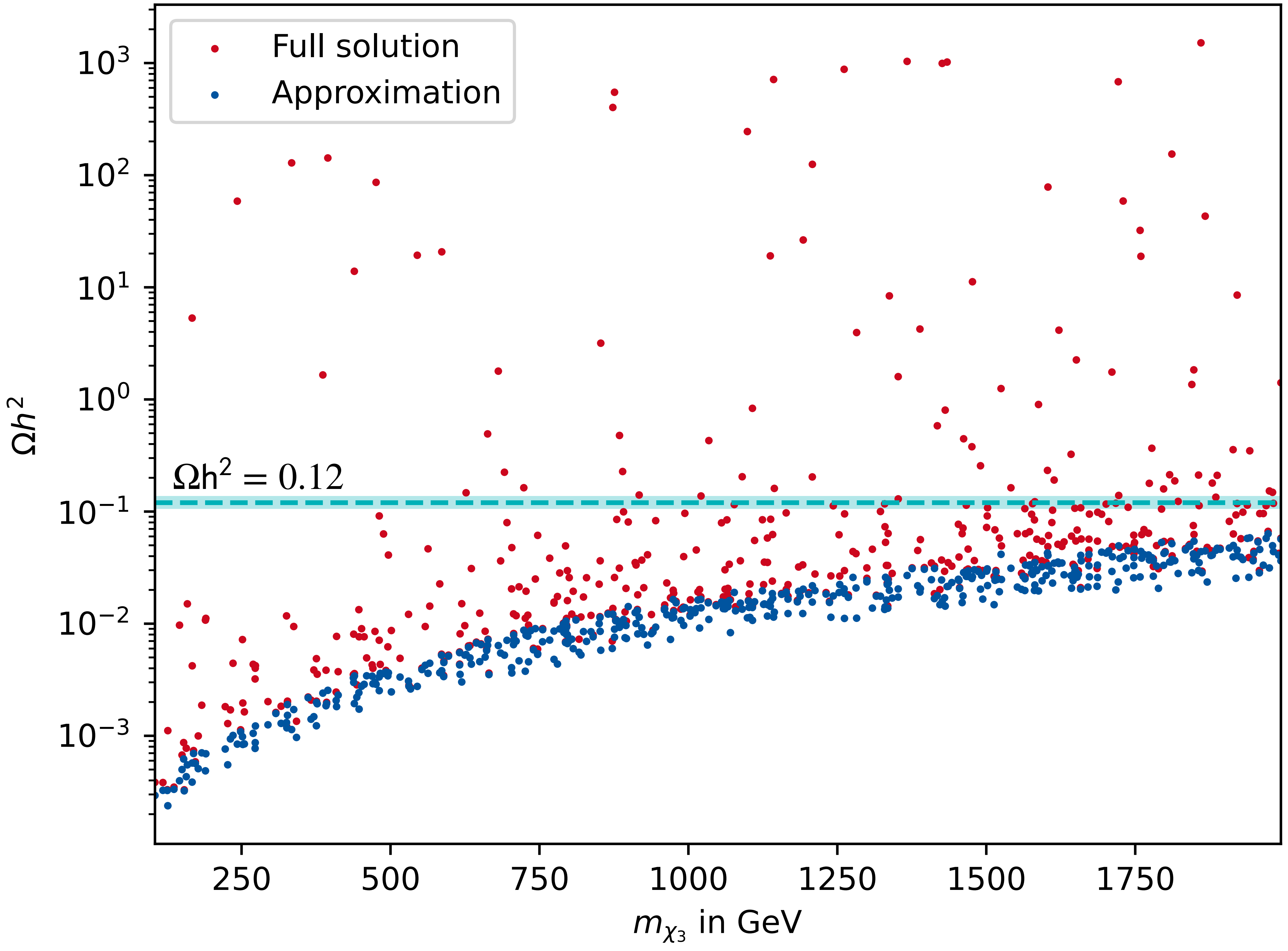
Parameter Scans

Preliminary

$\chi_2 \leftrightarrow \chi_3$ conversions inefficient, χ_3 couples to up

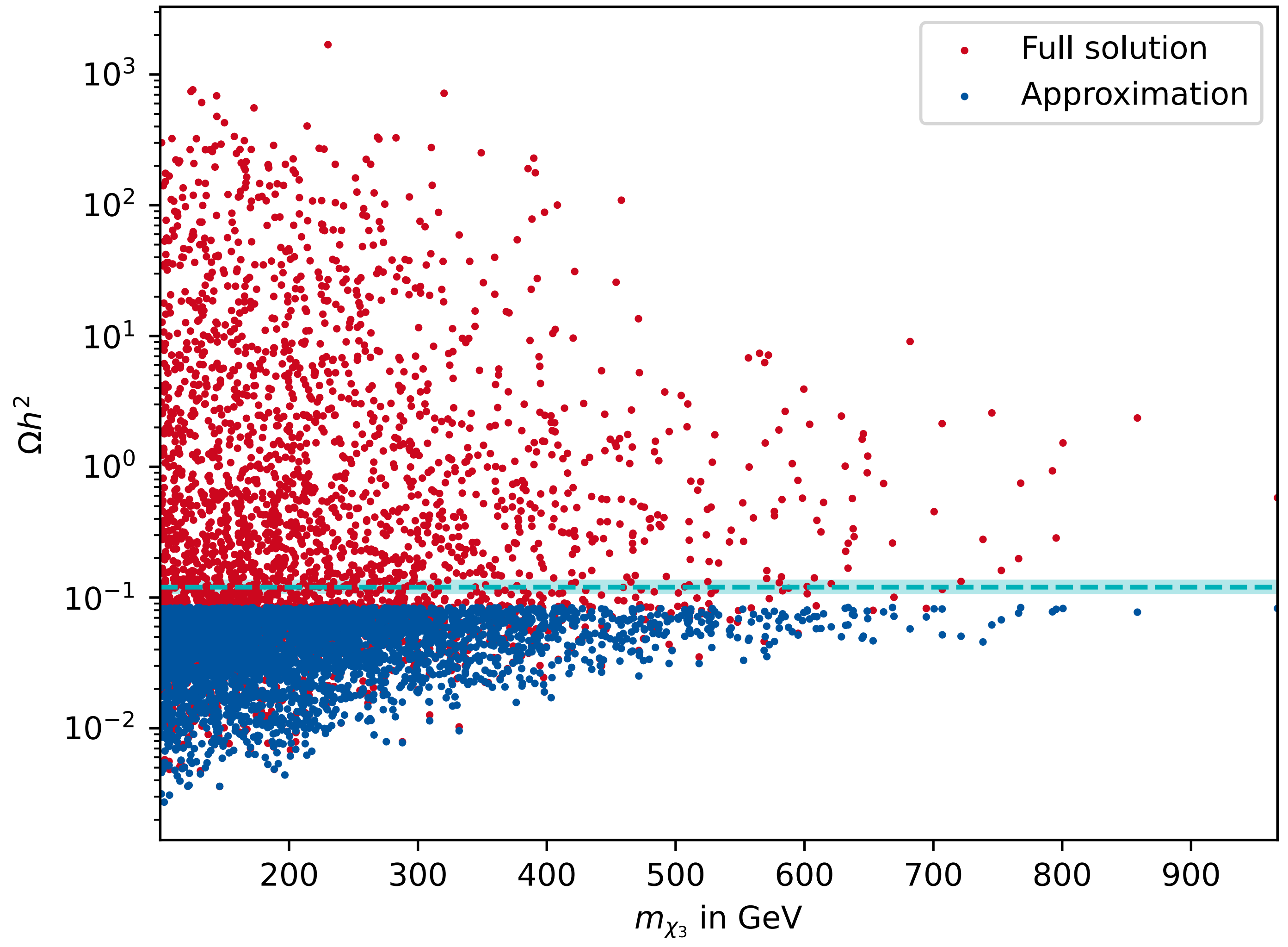


$\phi \leftrightarrow \chi_3$ conversions inefficient, χ_3 couples to up



Obtaining the Correct Relic Abundance

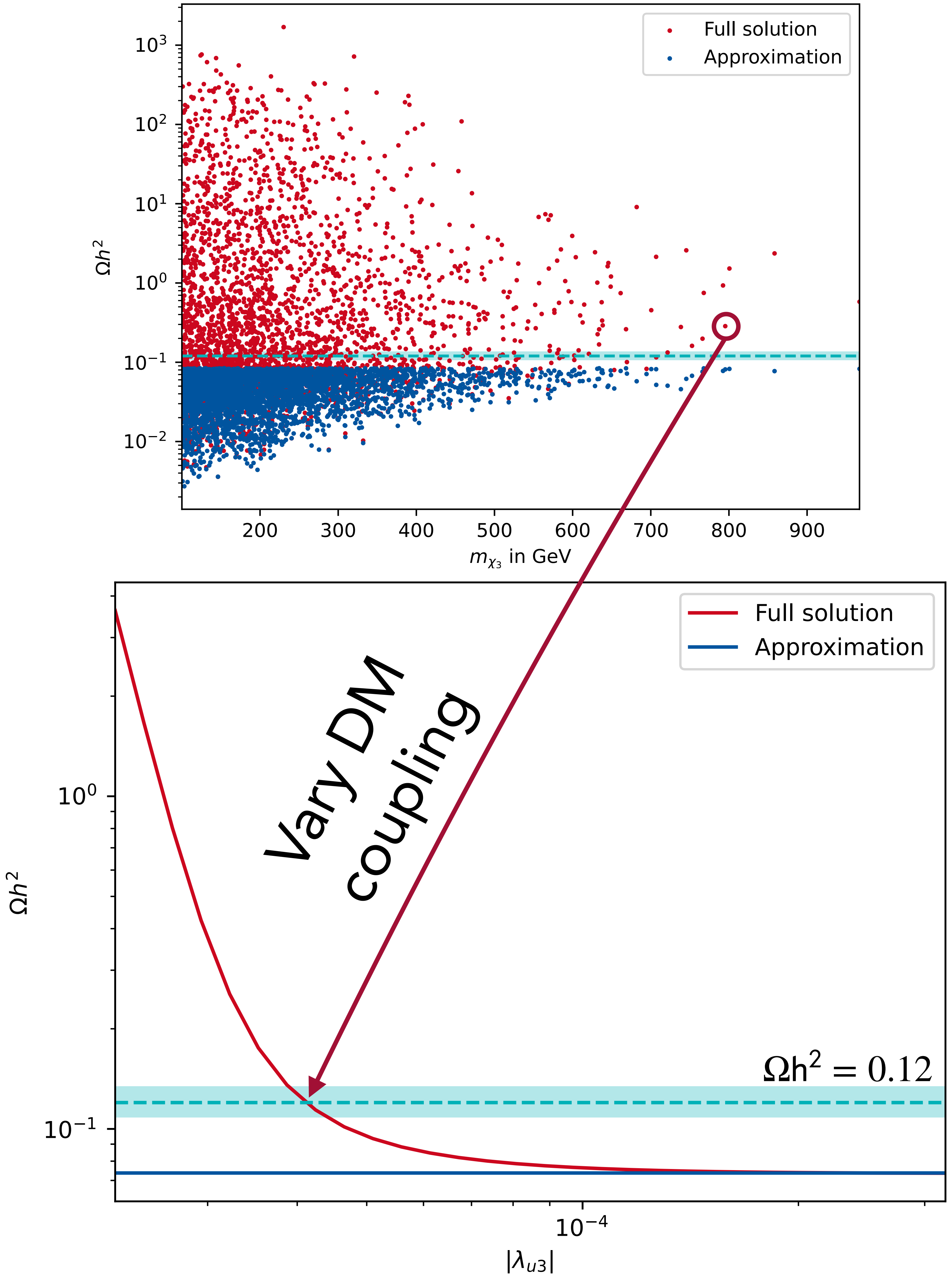
Preliminary



$\Omega h^2 = 0.12$

Obtaining the Correct Relic Abundance

Preliminary



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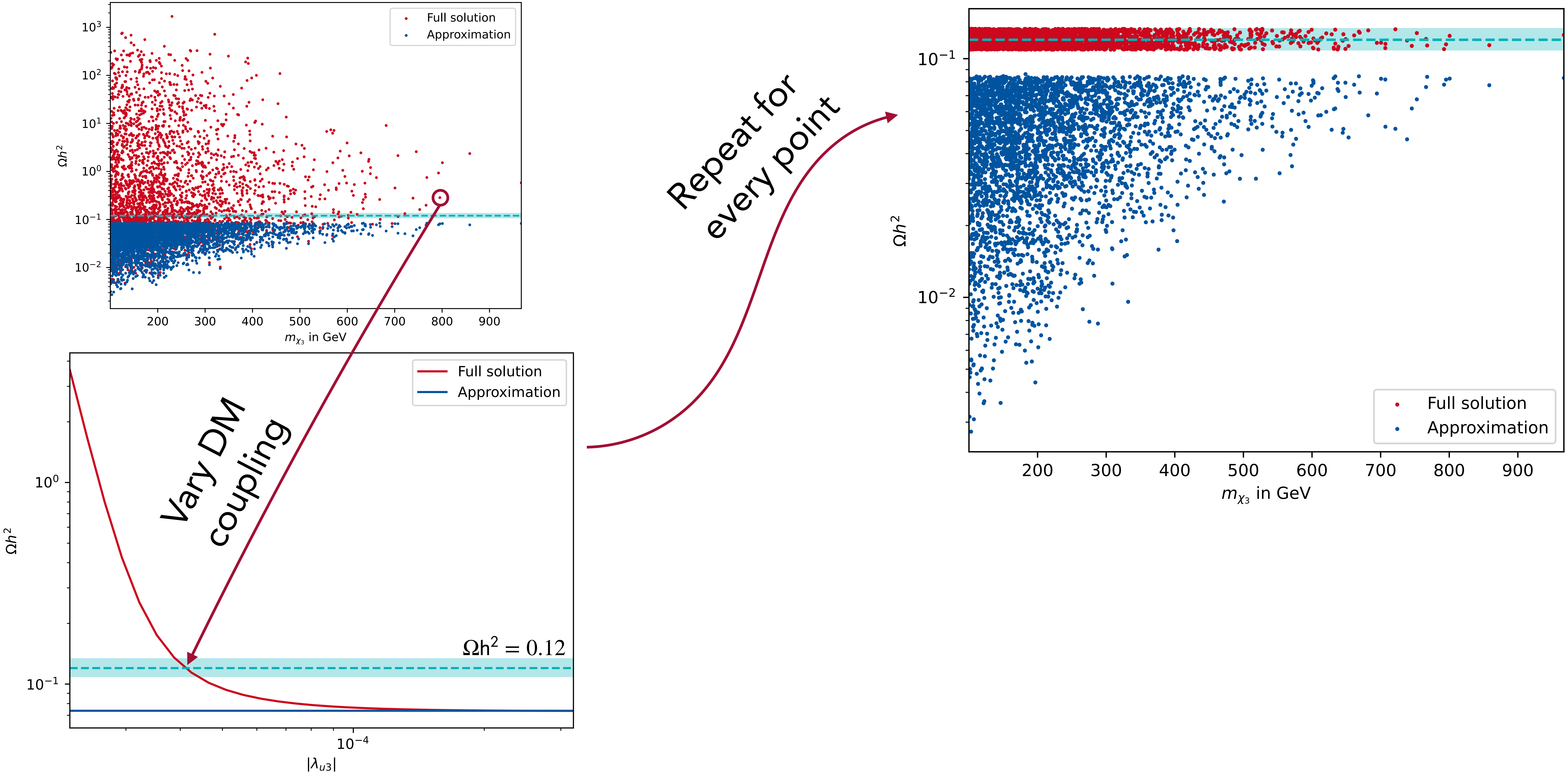

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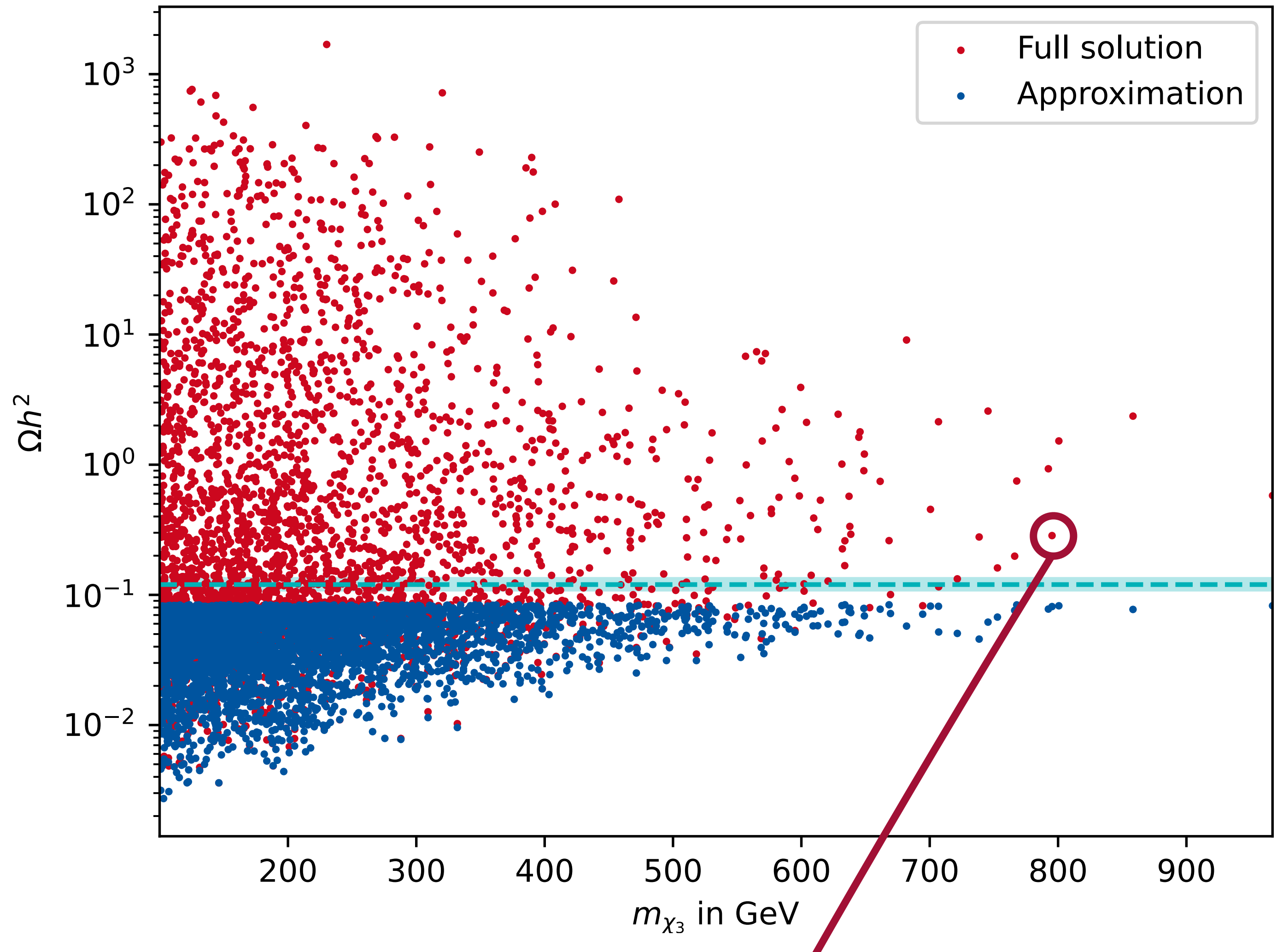
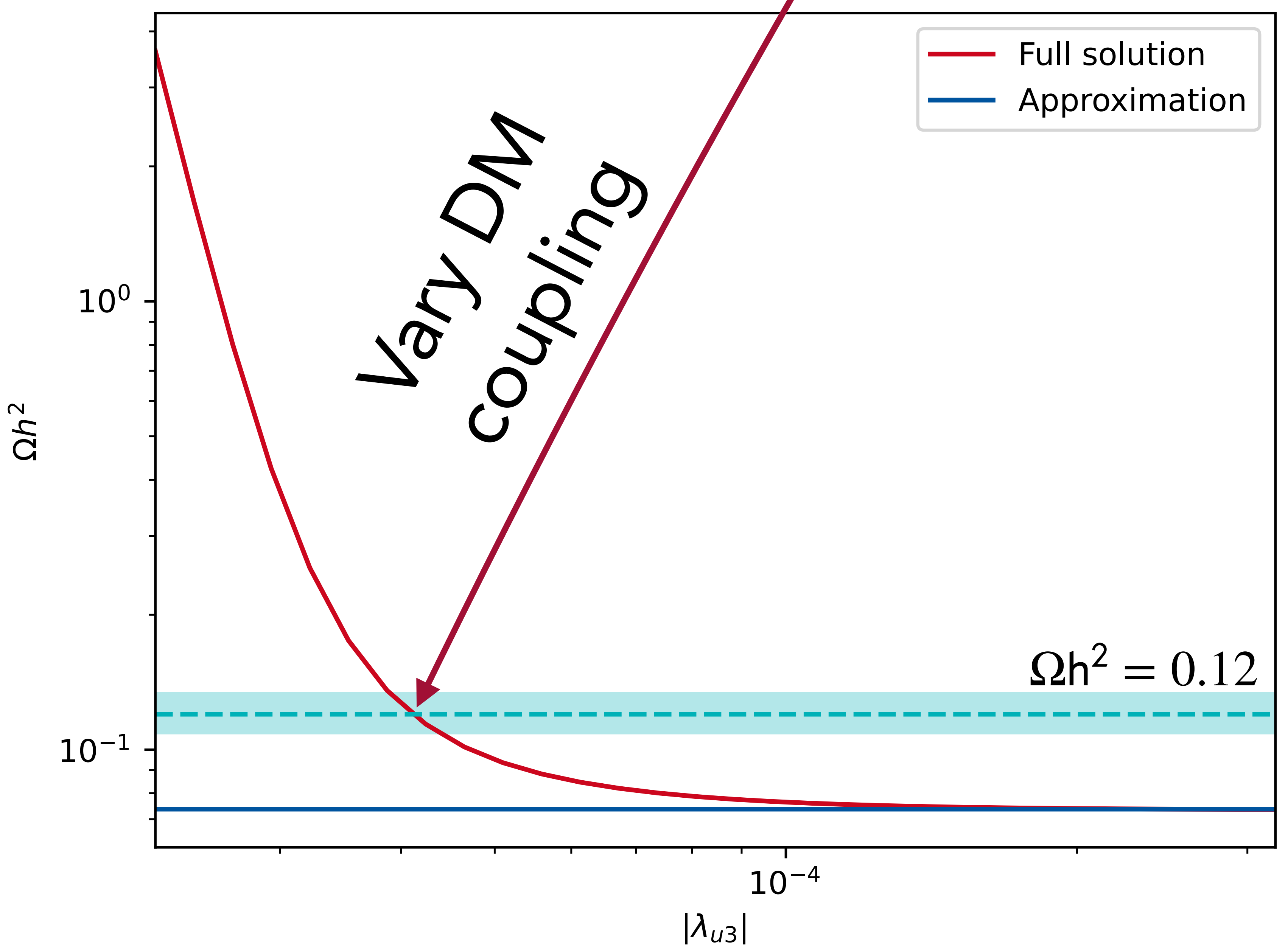
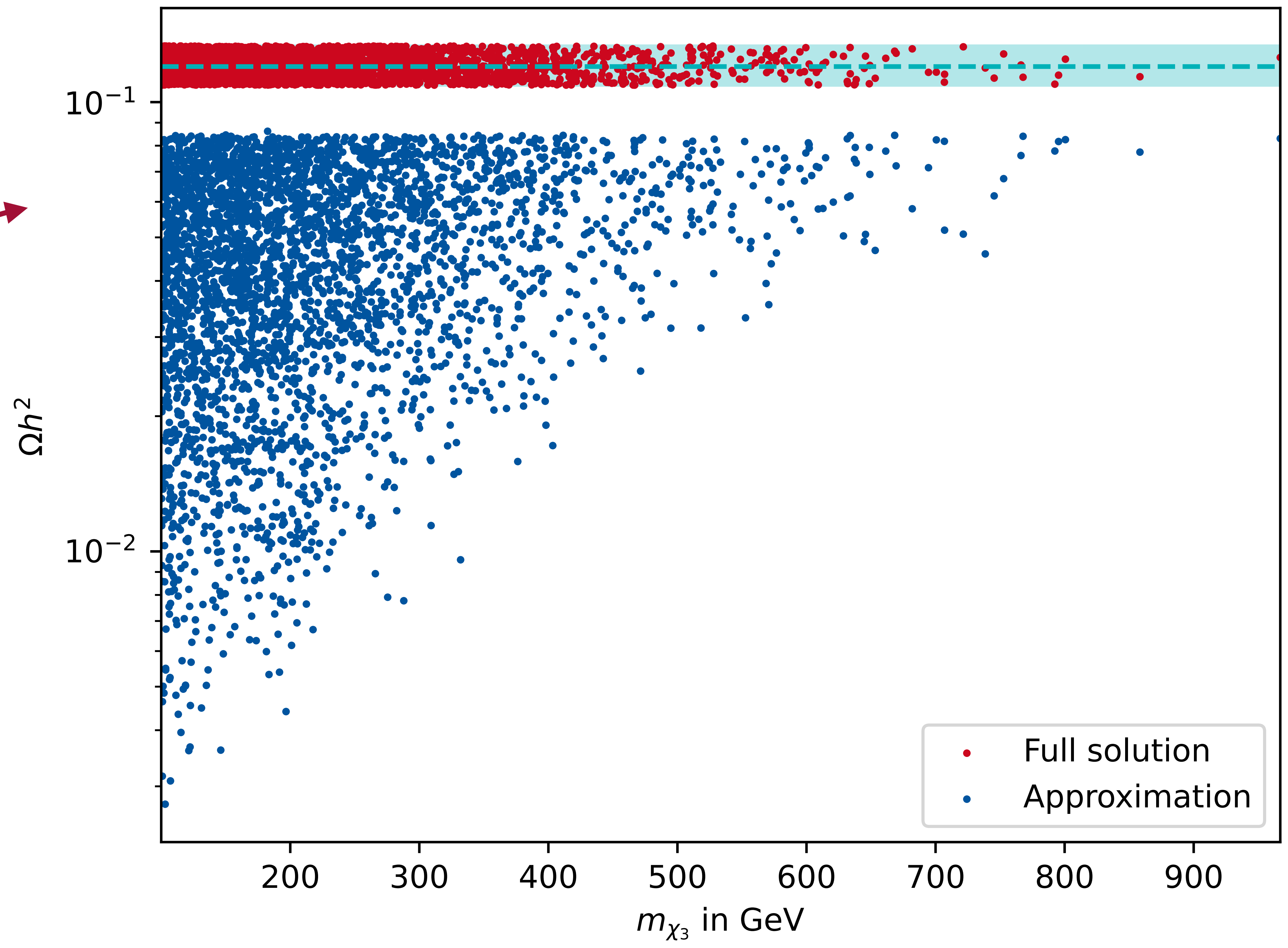
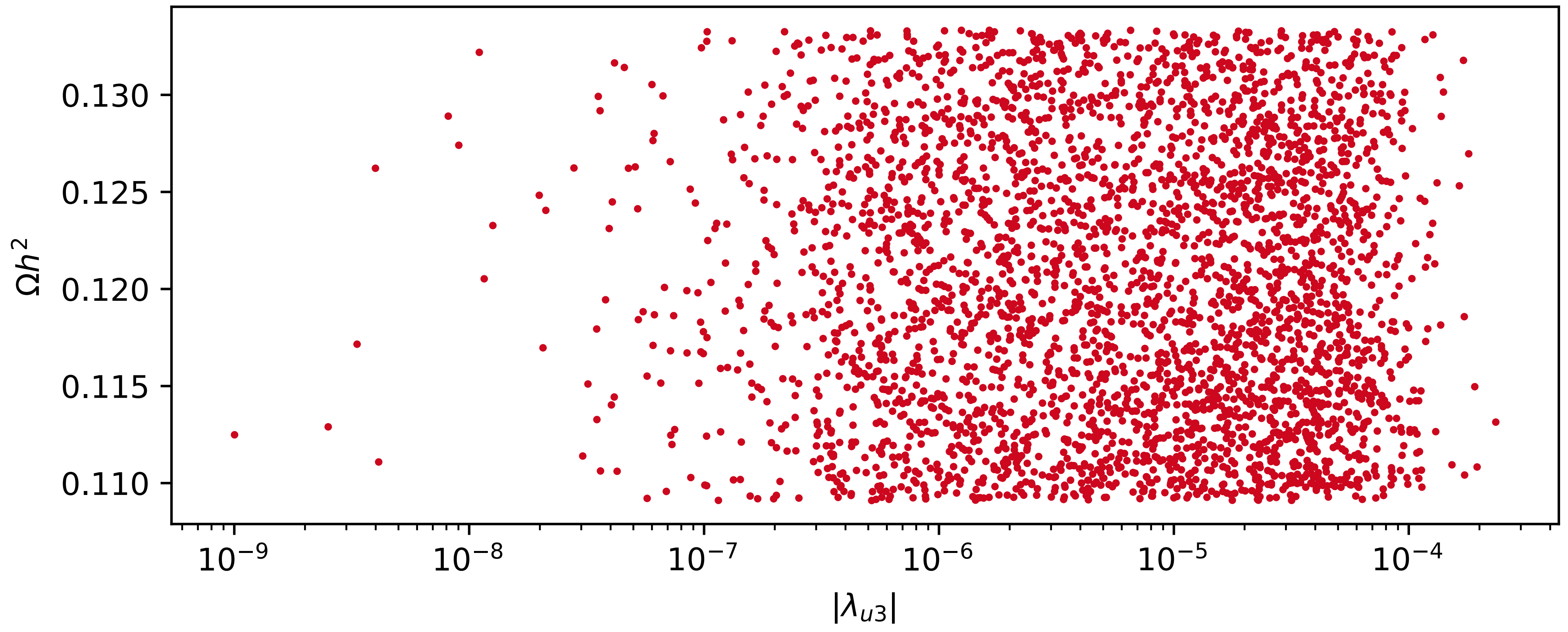


Vary DM coupling



Repeat for every point





→ Very small couplings allowed

Summary and Outlook

- Flavoured DM models have rich phenomenology
- Combined analysis of QDF and SFF scenario generally compatible with larger DM coupling to tops
- Considering coannihilations and conversion driven freeze-out opens up parameter space

  → very small couplings and up-flavoured DM also allowed
- Outlook: New signatures at LHC

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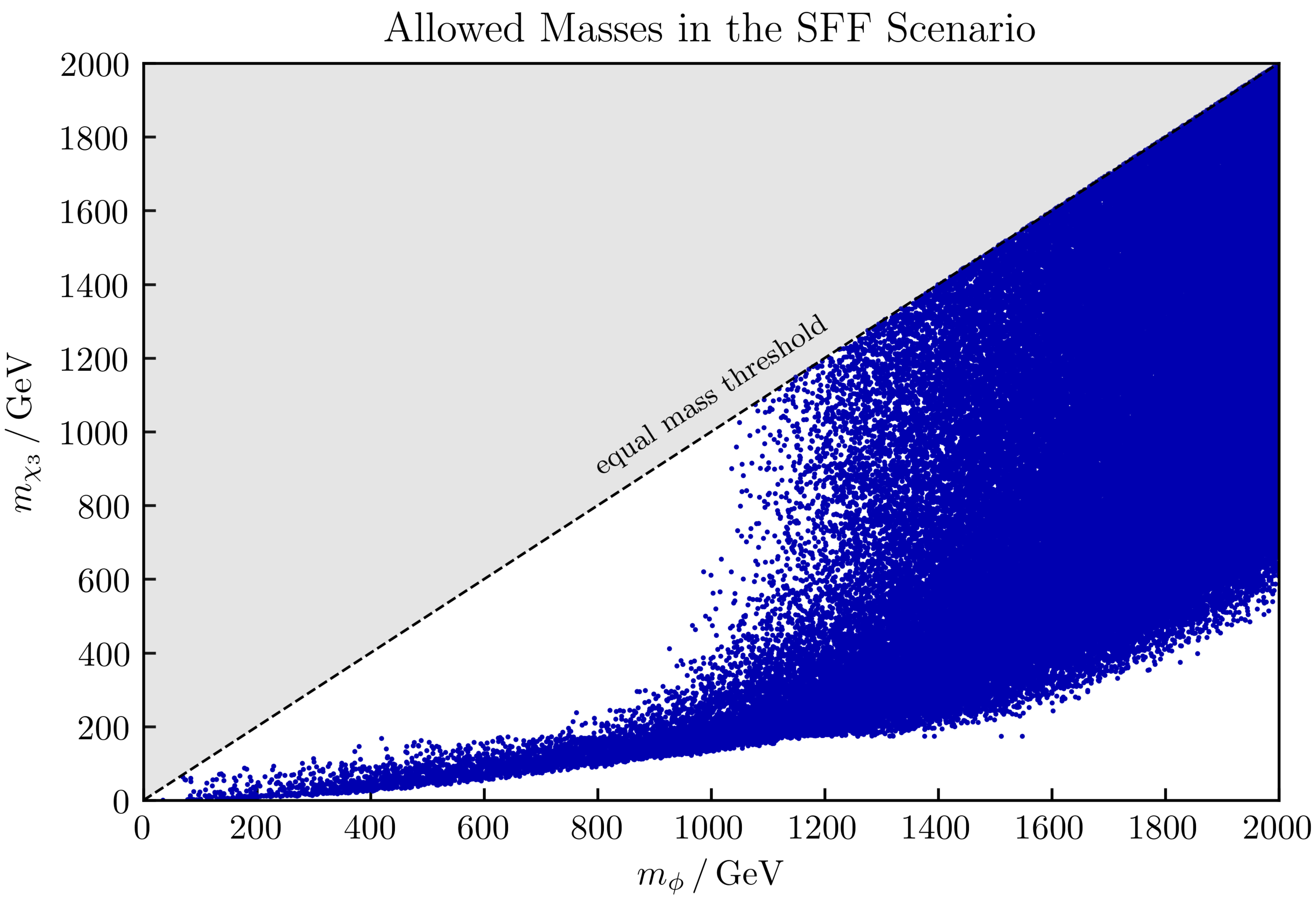
- Outlook: New signatures at LHC

Thank you!

Backup

Combined Analysis



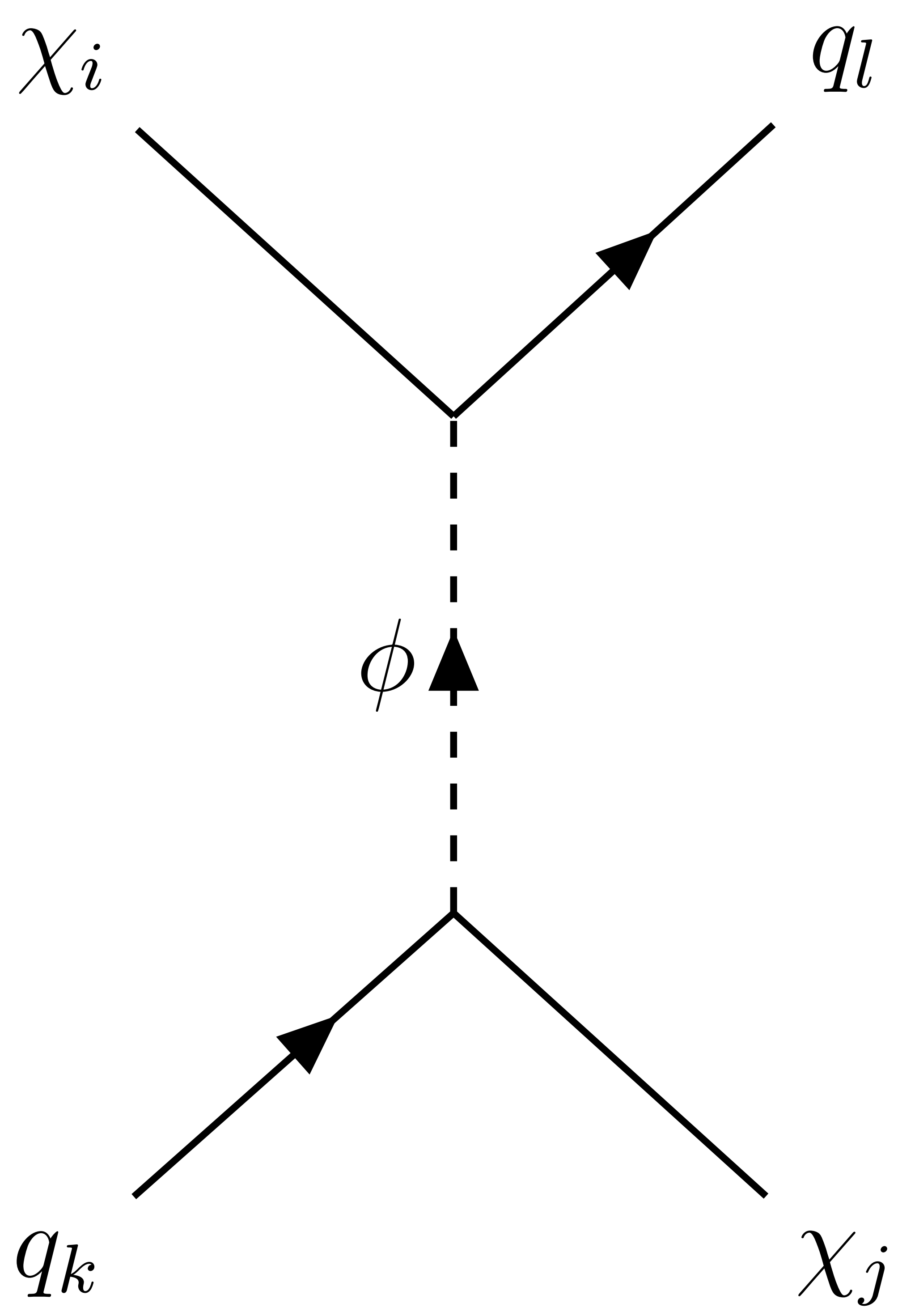
- Upper bound on m_{χ_3} in SFF scenario because of large mass splitting vs. small couplings

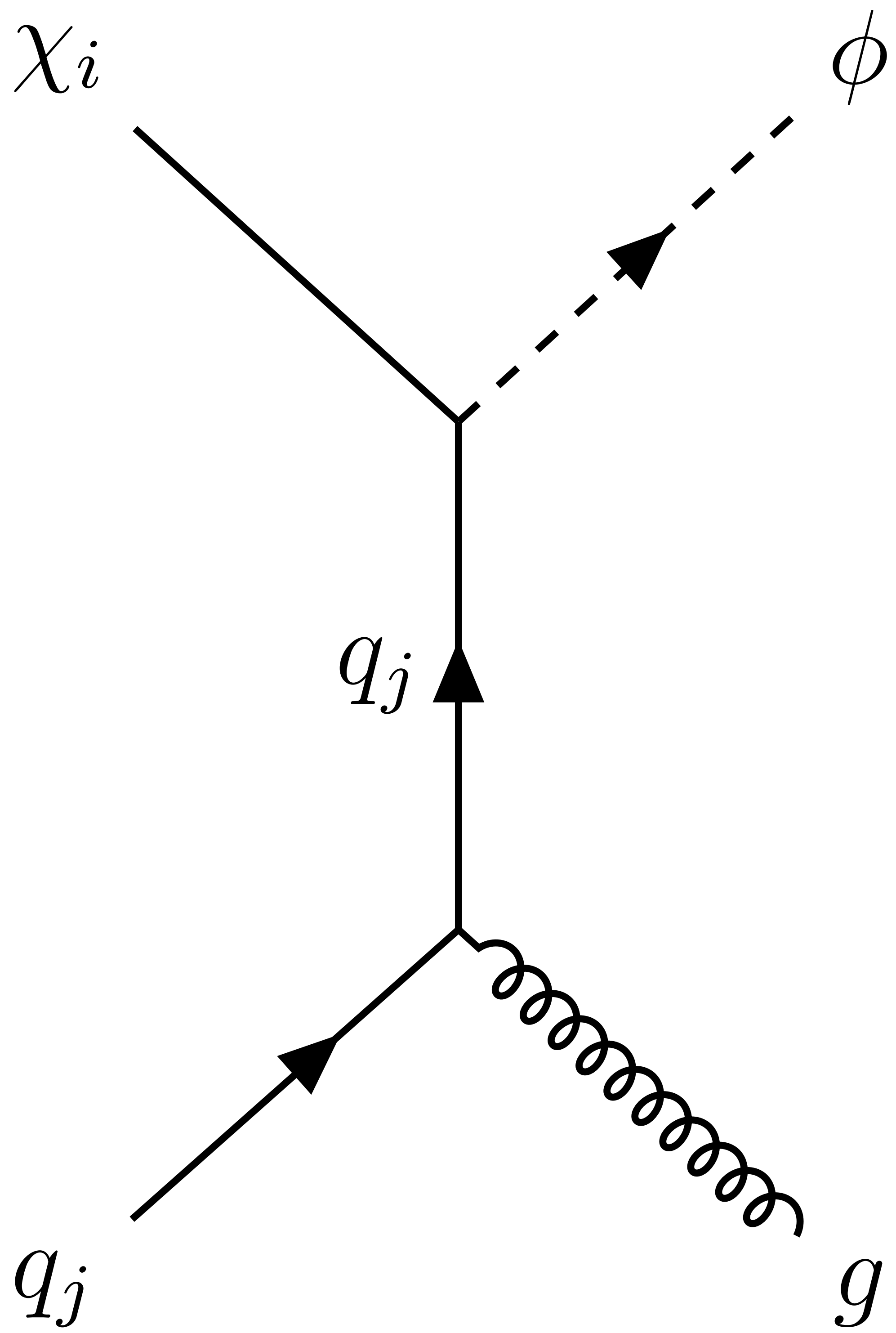
$$M_\chi = m_\chi \left(\mathbf{1} + \frac{\eta}{2}(\lambda^\dagger \lambda + \lambda^T \lambda^*) \right)$$

- Lower bound on m_{χ_3} in SFF and QDF scenario due to upper limit on couplings

Conversions

- Examples for conversions $\chi_i \leftrightarrow \chi_j$ and $\chi_i \leftrightarrow \phi$

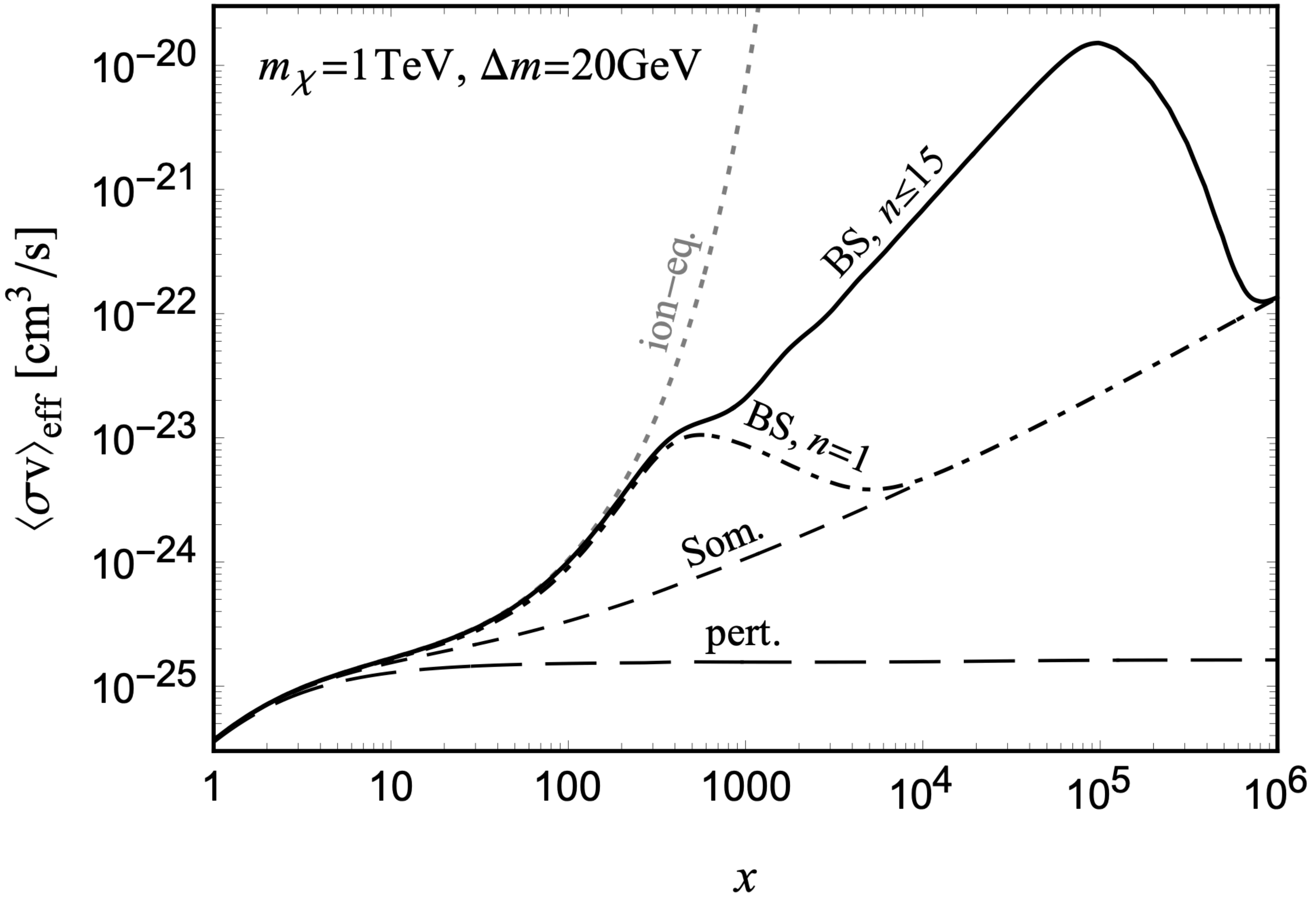




Sommerfeld Enhancement & Bound State Effects

- Sommerfeld enhancement and bound state effects for Majorana singlet χ and scalar mediator

Garny, Heisig [2112.01499]



Experiments used for analysis

- LHC: ATLAS and CMS
- Flavour Physics: LHCb
- Direct detection: Limits from spin-dependent scattering from PICO-60 and spin-independent scattering from XENON1T
- CP violation in charm decays: LHCb