Dark Matter via the Neutrino Portal

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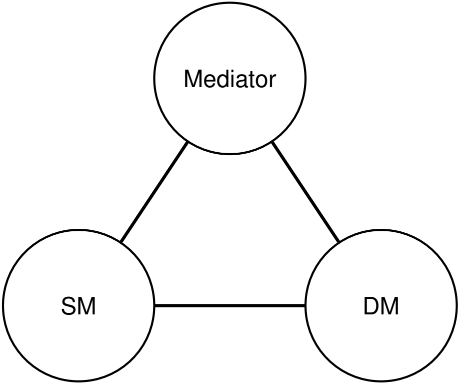
May 2020

Overview

- Dark Matter Production
- Experimental Constraints
- Neutrino Portal
- Consistency Condition of the Neutrino Portal to Dark Matter

Dark Matter Production [Hambye et. al (2019)]



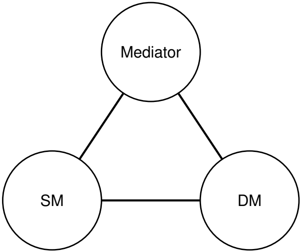
Boltzmann Equations

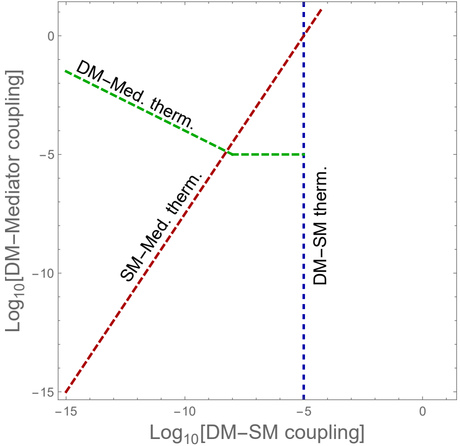
Boltzmann-Equations

$$\frac{dY}{dt} \sim -\frac{\Gamma}{H}\left(\prod_{i\in I}\frac{Y_i}{Y_i^{\mathrm{eq}}} - \prod_{f\in F}\frac{Y_f}{Y_f^{\mathrm{eq}}}\right)$$

- Process Efficiency? $\rightarrow$ Compare Γ to $H \sim T^2 M_{\mathrm{Pl}}^{-1}$
  $\rightarrow$ If $\Gamma \ll H$ process decouples; If $\Gamma \gg H$ process is in equilibrium

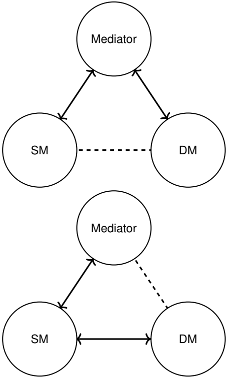
Dark Matter Production [Chu,Hambye,Tytgat (2011)]





Do not forget: We assume (SM-DM) = (SM-Mediator) · (Mediator-DM)

Dark Matter Production – Freeze-Out



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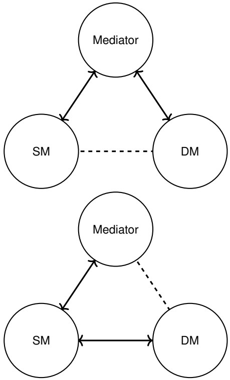
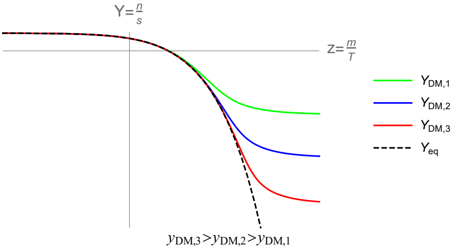
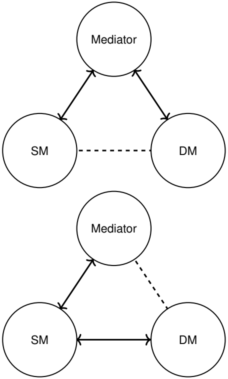
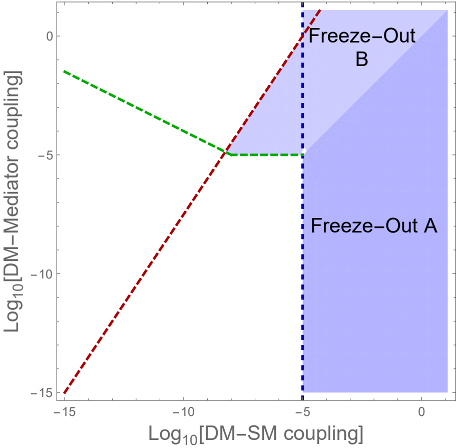




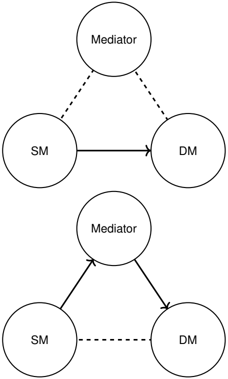
- DM density *decreases* with an *increasing* coupling
- $\Omega_{DM} \sim <\sigma v>^{-1}$
- Typically bounds DM mass from above

Dark Matter Production – Freeze-Out





Dark Matter Production – Freeze-In [Hall et. al(2009)]



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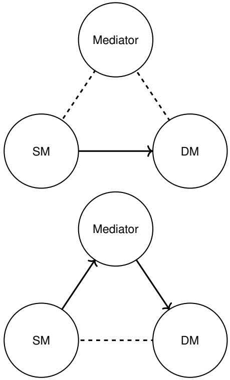
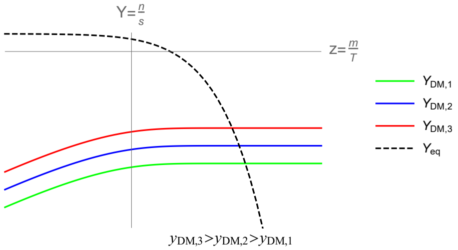
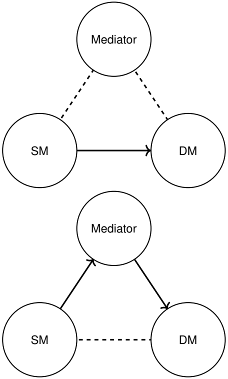
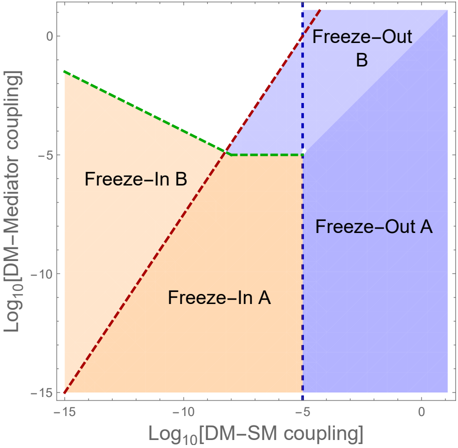




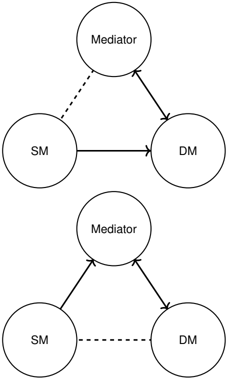
- DM density *increases* with an *increasing* coupling
- $\Omega_{DM} \sim M_{\max}^{-1} M_{DM}$

Dark Matter Production – Freeze-In





Dark Matter Production – Dark Freeze-Out



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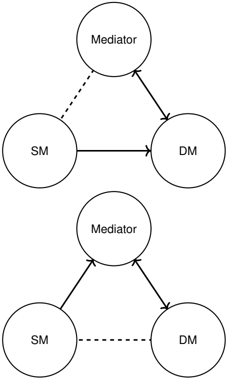
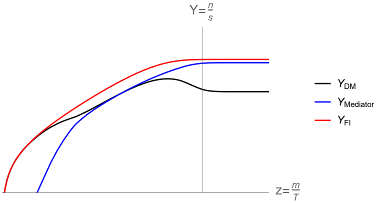
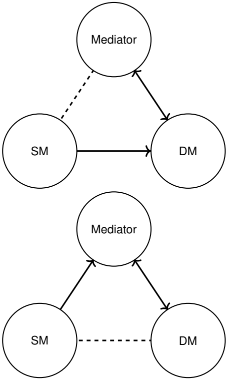




Dark Freeze−Out

- Energy transfer into the dark sector (DS) stops before the DS self-interactions decouple.
- A larger SM-DS coupling *increases* Ω_{DM}
- A larger DS self-interaction *decreases* Ω_{DM}.

Dark Matter Production – Reannihilation



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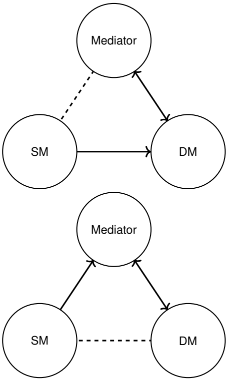

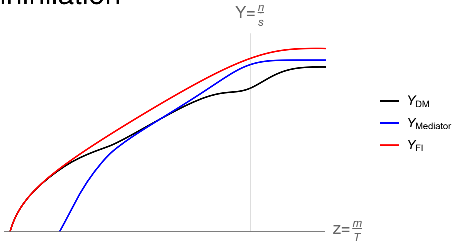

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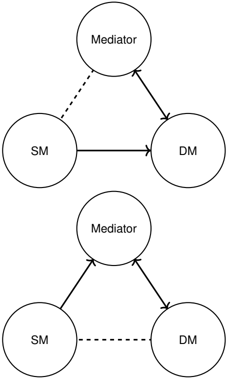
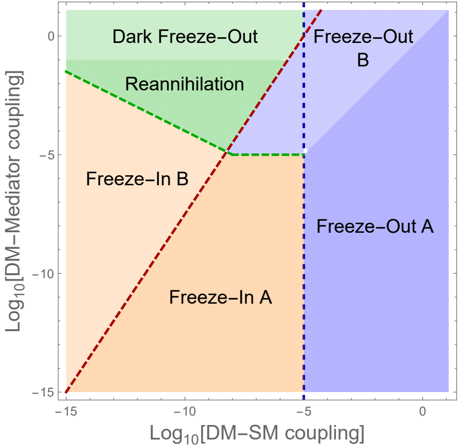
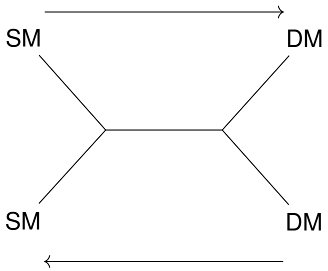
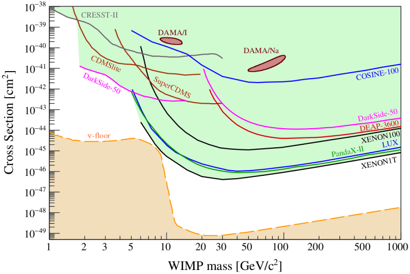




Experimental Constraints



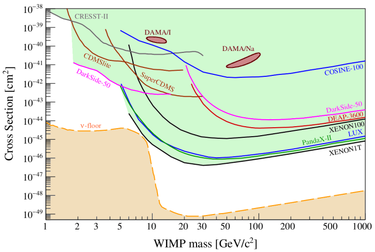
Direct Detection



[1903.03026]

- Search for DM scattering with nucleons on earth.
- Looses sensitivity for $M_{DM} \lesssim 10\,\mathrm{GeV}$.
- Constrains the DM-SM coupling.
- Light Mediators: Even Freeze-In can be tested [Hambye et. al (2018)]

Direct Detection



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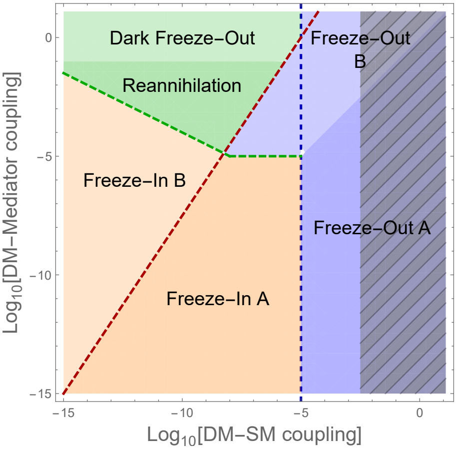
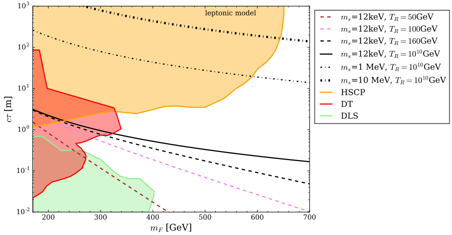
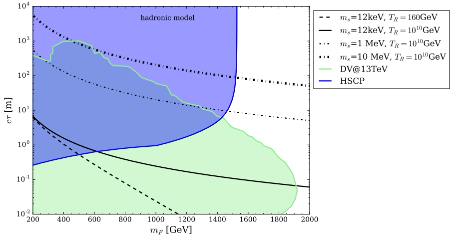


Collider Constraints

- Requires a sizeable SM-DM or SM-Mediator coupling.
- Large SM-DM : DM production and its signatures, e.g. missing energy.
- Large SM-Mediator can test feeble SM-DM interaction via long-lived particle searches.

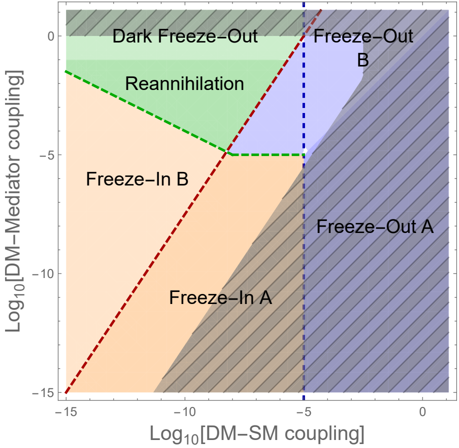
LHC friendly Freeze-In [Belanger et al (2018)]





- Lines indicate correct relic density
- Hadronic model: $m_F \geq 1.5\,\mathrm{TeV}$
- A measurement of the leptonic model might rule out certain leptogenesis scenarios

Collider Constraints and Self-Interactions



- DM self-interaction is constrained to $\frac{\sigma_{DM}}{M_{DM}} \lesssim 1 \frac{cm^2}{g}$ from Bullet Cluster.
- Astrophysical constraints (BBN,CMB,Lyman-α) constrain small DM masses.

Portals to Dark Matter

Higgs Portal

$$\left(\phi^\dagger \phi\right) \eta^2$$

[Arcadi,Djouadi,Raidal (2019)]

Vector Portal

$$B^{\mu\nu} B'_{\mu\nu}$$

[Hambye et. al (2019)]

Neutrino Portal

$$\bar{L}\phi N$$

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$$\left(\phi^\dagger \phi\right) \eta^2$$

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Neutrino Portal

$$\bar{L} \phi N$$

- N itself can be a DM candidate

  $\rightarrow$ simplest scenario tightly constrained from Lyman-α and $N \rightarrow \nu\gamma$

The Neutrino Portal to Dark Matter

- Dark sector: Fermion χ and scalar η, stabilized by $U(1)$ or $\mathcal{Z}_2$.

Lagrangian (Type-I Seesaw)

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{kin,DS}} - V_{\text{sc.}} - \left(\bar{N}\left[(y_\nu \tilde{\phi} L + y_\chi \eta \chi_L\right] + h.c.\right)$$

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Type-I seesaw Freeze-Out	Inverse seesaw Freeze-Out	Type-I seesaw Freeze-In
[Escudero,Rius,Sanz (2016)]	[Batell et. al (2017)]	[MB (2018)]
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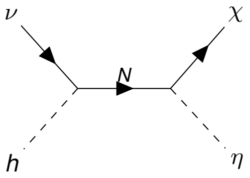
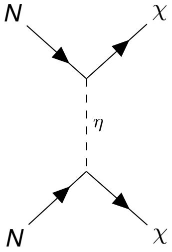
Freeze-In, based on [MB,2018]

SM Particle Scattering $\sigma \sim y_\nu^2 y_\chi^2$



Heavy Neutrino Scattering $\sigma \sim y_\chi^4$

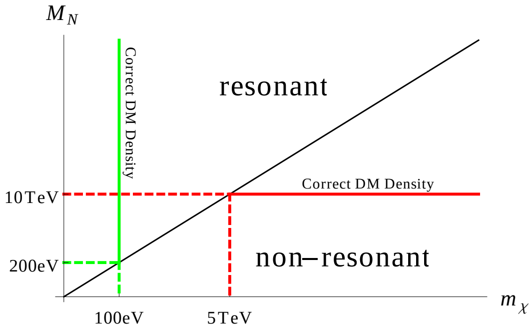


Analytic Approximation with $M_N \ll m_\chi$ (non-resonant)

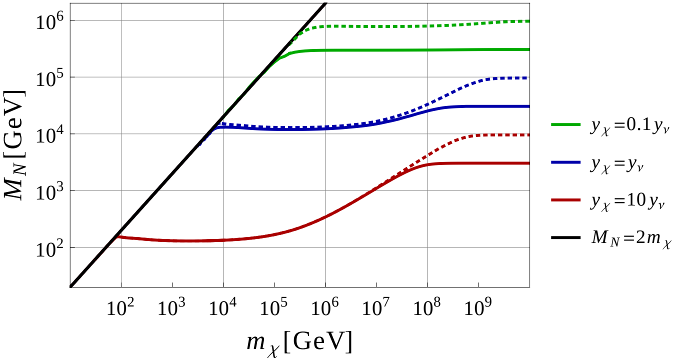
$$Y_\chi \sim \frac{M_{\mathrm{Pl}}}{m_\chi}\left(6 y_\nu^2 y_\chi^2 + 35 y_\chi^4\right)$$

Results I

Same suppression mechanism for y_χ and y_ν can lead to $y_\chi \sim y_\nu$, e.g. extra dimensional model. [MB,Päs 2017],[Bhattacharyya et. al 2002]



Results II



- Heavy neutrino scattering suppressed for $m_\chi \gtrsim 10^3 M_N$.
- Lower Bound: $m_\chi \gtrsim \left(\frac{y_\nu}{y_\chi}\right)^{\frac{4}{3}}\ \mathrm{MeV}$

Constraints

- Non-resonant case hard to constrain.
- Resonant case is mainly constrained from the Lyman-α measurement.

$y_\chi \gtrsim y_\nu$: **Freeze-Out**

- Thermal DM spectrum
- $z_{\text{prod}} = z\left(T = T_{\text{Freeze-Out}}\right)$
- $m_{\text{DM}} \gtrsim 10\,\mathrm{keV}$

$\rightarrow$ This case is *ruled out*.

$y_\chi \ll y_\nu$: **Freeze-In**

- Non-thermal DM spectrum
- $z_{\text{prod}} \approx z\left(T = M_N\right)$
- $m_{\text{DM}} \gtrsim 3\,\mathrm{keV}$

$\rightarrow$ This case is *constrained*.

Consistency Conditions, ongoing work with C. Hormigos-Feliu

Scalar Potential

$$\mathcal{L} \supset -m_\eta^2 \eta^\dagger \eta - \frac{\lambda_2}{2}\left(\eta^\dagger \eta\right)^2 - \lambda_3 \left(\phi^\dagger \phi\right)\left(\eta^\dagger \eta\right) - y_\chi \bar{\chi} \nu_R \eta$$

Consistency Conditions

$$0 \leq \lambda_2 \leq 2\,(4\pi)^2\,; \quad 0 \leq \lambda_1 \leq 2\,(4\pi)^2\,; \quad -\sqrt{\lambda_1 \lambda_2} \leq \lambda_3 \leq (4\pi)^2$$

Strategy :

- Randomly generate data points that fit DM phenomenology (Ω_{DM}, DD, Colliders).
- Take these values at the DM mass sclae μ_{DM} and run them up to higher sclaes.
- Determine scale Λ_{max}, where the model becomes inconsistent.

RGEs

RGEs

$$\beta_{\lambda_2} \sim 10\lambda_2^2 + 4\lambda_3^2 - 36 y_\chi^4 + 12\lambda_2 y_\chi^2 \,,$$

$$\beta_{y_\chi} \sim y_\nu^2 y_\chi + y_\chi^3$$

RGEs

- Type I Seesaw: $y_\nu \sim 10^{-7}\sqrt{M_N[\mathrm{GeV}]}$

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Analytic Estimate

$$y_\chi\left(\mu_{DM}\right) \leq \sqrt{\frac{16+\sqrt{31}}{3\left(1+\sqrt{31}\right)}}\frac{4\pi}{\sqrt{1+\log\left(\frac{M_{\mathrm{Pl}}}{\mu_{DM}}\right)}}$$

Numerical Study I

RGEs

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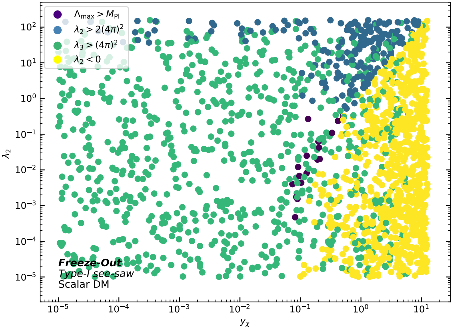

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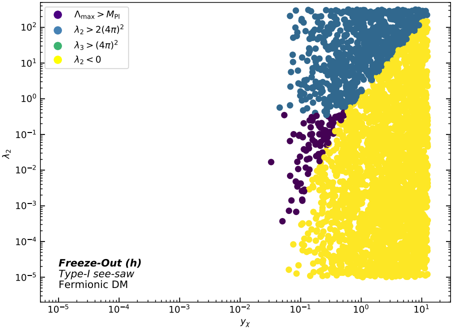
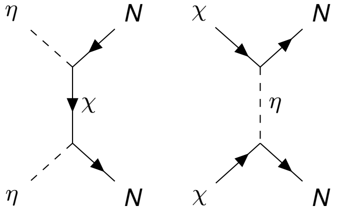


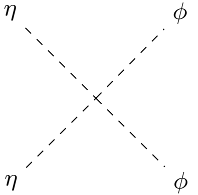
Freeze-Out Contributions

Neutrino Portal Contributions $\sigma \sim y_\chi^4$ Higgs Portal Contributions $\sigma \sim \lambda_3^2$



contributes via coannihilations

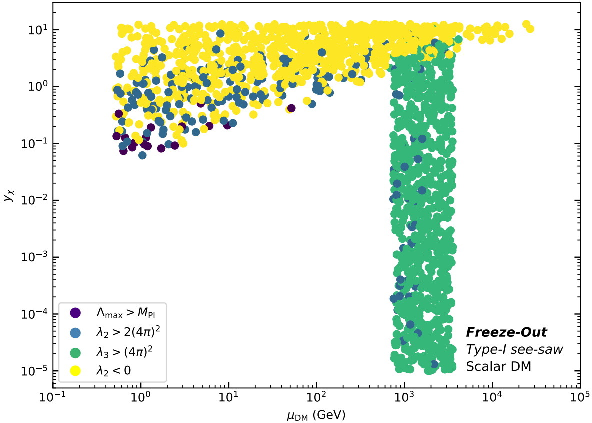
$$\Omega_{DM} \sim \frac{m_{DM}^2}{y_\chi^4} \to y_\chi \sim \sqrt{m_{DM}}$$



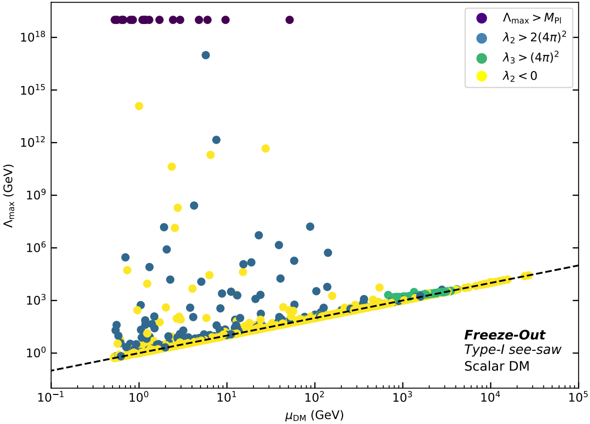
contributes only for $m_\eta \gtrsim 10\,\mathrm{TeV}$

$$\Omega_{DM} \sim \frac{m_{DM}^2}{\lambda_3^2}\ ;\ \sigma_{DD} \sim \frac{\lambda_3^2}{m_{DM}^2}$$

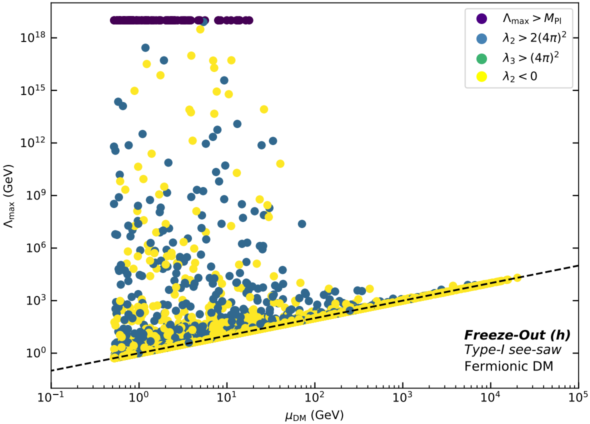
Numerical Study II



Numerical Study III



Numerical Study III

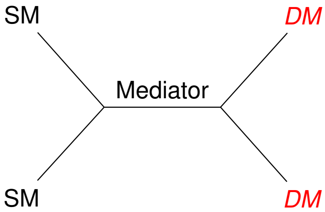


Conclusions

- Successful DM production is possible in a very large coupling range.
- The neutrino portal relies on Yukawa interactions to produce DM
  $\rightarrow$ Potentially unstable vacuum
- Consistency conditions might constrain the *DM* mass in the neutrino portal to $m_{DM} \lesssim \mathrm{TeV}$ and improve limits on the mediator-DM coupling (y_χ) significantly.
- Small SM-mediator interaction (y_ν) in the type-I seesaw motivates Freeze-In scenarios, which, in the non-resonant scenario, remain unconstrained.

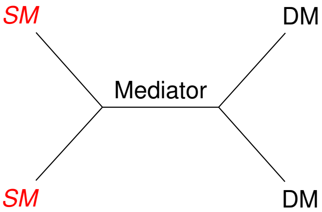
Freeze-In Parametrics

- Dark Matter production stops at $T_{\mathrm{FI}} \approx M_{\mathrm{MAX}}$.
- $M_{\mathrm{MAX}} = m_{\mathrm{DM}}$
- $T < m_{\mathrm{DM}} \rightarrow$ SM particles dont have enough energy



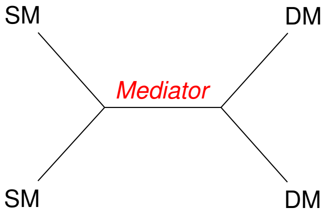
Freeze-In Parametrics

- Dark Matter production stops at $T_{\mathrm{FI}} \approx M_{\mathrm{MAX}}$.
- $M_{\mathrm{MAX}} = m_{\mathrm{SM}}$
- $T < m_{\mathrm{SM}} \rightarrow$ SM too diluted due to Boltzmann suppression



Freeze-In Parametrics

- Dark Matter production stops at $T_{\mathrm{FI}} \approx M_{\mathrm{MAX}}$.
- $M_{\mathrm{MAX}} = m_{\mathrm{Mediator}}$
- $T < m_{\mathrm{Mediator}} \rightarrow$ Resonance is not accessible



Freeze-In Parametrics

- Dark Matter production stops at $T_{\mathrm{FI}} \approx M_{\mathrm{MAX}}$.
- Production Time: $t = H^{-1}\left(T_{\mathrm{FI}}\right) \sim T_{\mathrm{FI}}^{-2} M_{\mathrm{pl}} = M_{\mathrm{MAX}}^{-2} M_{\mathrm{pl}}$.
- Production Rate: $\Gamma\left(T_{\mathrm{FI}}\right) \sim T_{\mathrm{FI}}^{x} M_{\mathrm{MAX}}^{-x+1} = M_{\mathrm{MAX}}$.

Freeze-In Yield

$$Y \sim \Gamma t|_{T=T_{\mathrm{FI}}} \sim \frac{M_{\mathrm{pl}}}{M_{\mathrm{MAX}}}$$

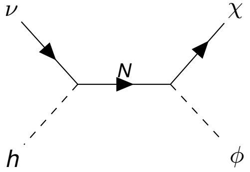
3 Generation Setup

Casas-Ibarra Parametrization (heavy Neutrinos mass-degenerate)

$$Y_\nu = \underbrace{\frac{\sqrt{M_N \Delta m_\nu}}{v}}_{\equiv y_\nu} \underbrace{R \frac{1}{\sqrt{\Delta m_\nu}} \sqrt{m_\nu}}_{\equiv R'} U^\dagger_{\mathrm{PMNS}} \,,$$

y_ν : Coupling Strength

R' : Flavor Stucture



$\times f_1\,(R)$