Freeze-in Complements Freeze-out

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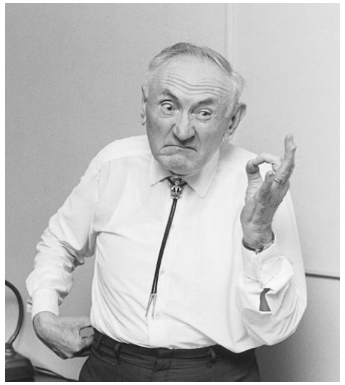
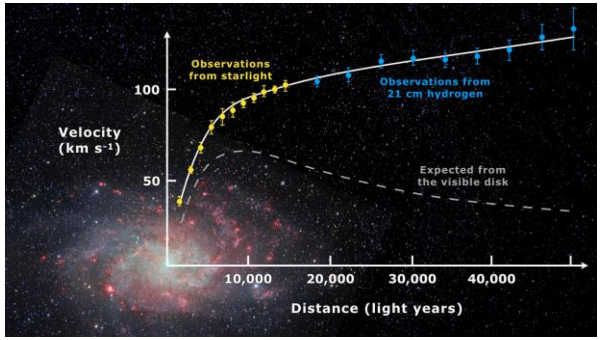
A (very) brief introduction to Dark Matter

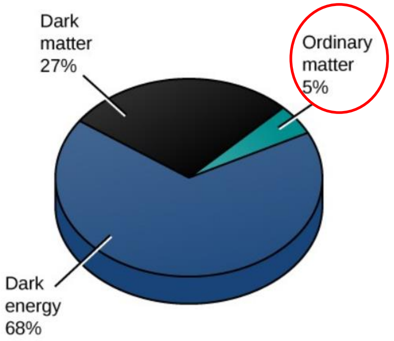
In 1933, **Fritz Zwicky**, while studying the **Coma Cluster**, estimated its mass based on the motion of galaxies near its edge. He concluded the cluster had about **400 times more mass than what was visually observable**. He called this unseen mass **dark matter** (more accurate estimations show that the **discrepancy is actually by a factor of 5**).



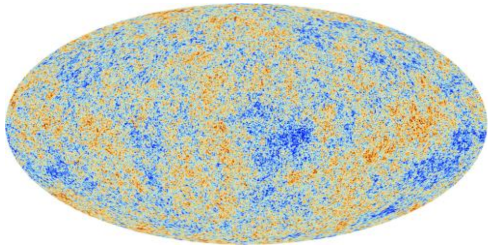


Vera Rubin's work in the 1960s and 1970s provided further evidence, using **galaxy rotation curves**. She showed that several galaxies contain about **six times as much dark as visible mass**.

Since then, many other observations with increasing precision confirmed these results: **gravitational lensing, cosmic microwave background (CMB), structure formation, bullet cluster**. The existence of dark matter (DM) is now widely accepted.

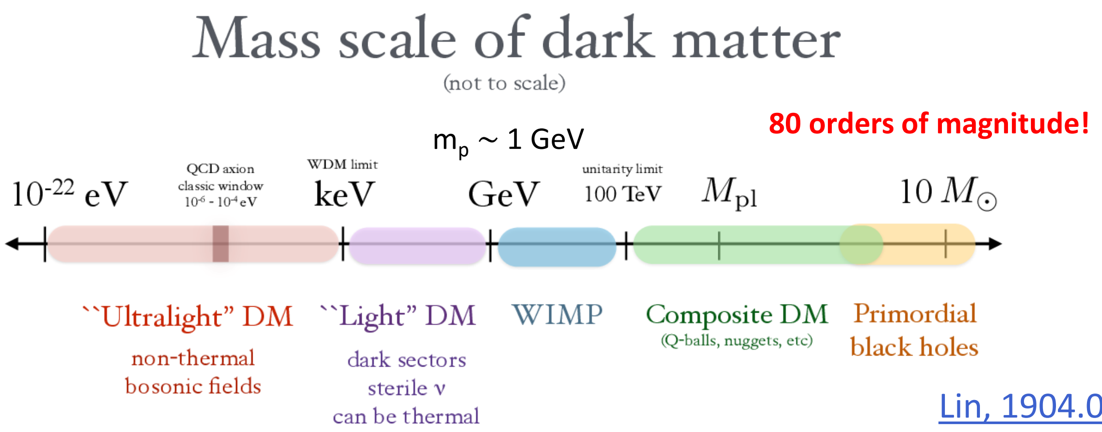


This is what we know!



A (very) brief introduction to Dark Matter

- There are **no viable DM candidates in the SM**. **New Particle?** Something else?
- What are its properties (spin, mass)? How is it produced?



Lin, 1904.07915

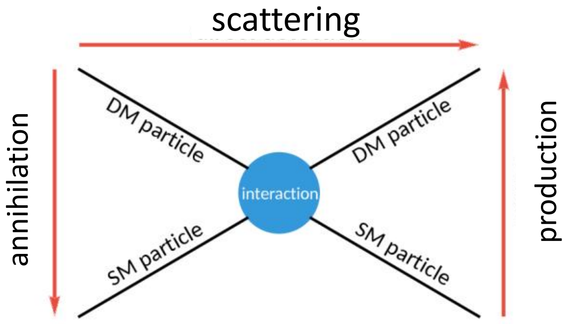
Bertone and Tait, 1810.01668

- **WIMPs (Weakly Interacting Massive Particles)** are by far the **most studied and searched DM candidate**. However, experimental efforts to detect WIMPs via **direct detection (DD)**, **indirect detection (ID)** and **collider searches** have been **unsuccessful so far**. Other candidates like **FIMPs (Feebly Interacting Massive Particles)** have gained a new life in recent years because no WIMPS were found.

- There are **two main mechanisms of DM production** in agreement with all observations and in particular with the observed relic density measured by PLANCK: **freeze-out (FO)** and **freeze-in (FI)**, which can describe the evolution of WIMPs and FIMPs, respectively.

Mechanisms of thermal DM generation - Freeze-out

- Let us assume the existence of a **WIMP** which at some point in the early Universe is at **thermal equilibrium with the thermal bath,** interacting with it via scattering and annihilation/production processes, responsible for keeping this equilibrium.



How does **n(t), the number density of DM**, evolve over time? This is described by the **Boltzmann equation for freeze-out:**

$$\boxed{\dot{n}(t) + 3H(t)n(t) = -\langle\sigma v\rangle(n(t)^2 - n_{eq}^2)}$$

- Further simplifications can be made to the Boltzmann equation, by defining **Y = n/$\hat{s}$** and **x = m_{DM}/T**. Assuming absence of entropy production, and that freeze-out occurs during the radiation-dominated era, we have:

$$\boxed{\frac{dY}{dx} = -\sqrt{\frac{\pi}{45G}}\frac{g_*^{1/2} m_{DM}}{x^2}\langle\sigma v\rangle\left(Y^2 - Y_{\rm eq}^2\right)}$$

- Integrate Boltzmann equation between x = 0 and $x_0 = m_{DM}/T_0$, $T_0 = T_{CMB}$, to get $Y_0 = Y(T_0)$, and the relic density of DM:

$$\Omega_{DM} = \rho_{DM,0}/\rho_{\rm crit} = m_{DM}\hat{s}_0 Y_0/\rho_{\rm crit}$$

$$\boxed{\Omega_{DM}h^2 \approx 2.742 \cdot 10^8 \frac{m_{DM}}{\rm GeV} Y_0}$$

$$\rho_{\rm crit} = \frac{3H^2}{8\pi G} = 1.8788 \times 10^{-26} h^2 \,{\rm kg\,m^{-3}}$$

$$h \equiv \frac{H_0}{100\,{\rm km\,s^{-1}Mpc^{-1}}}$$

Mechanisms of thermal DM generation - Freeze-out

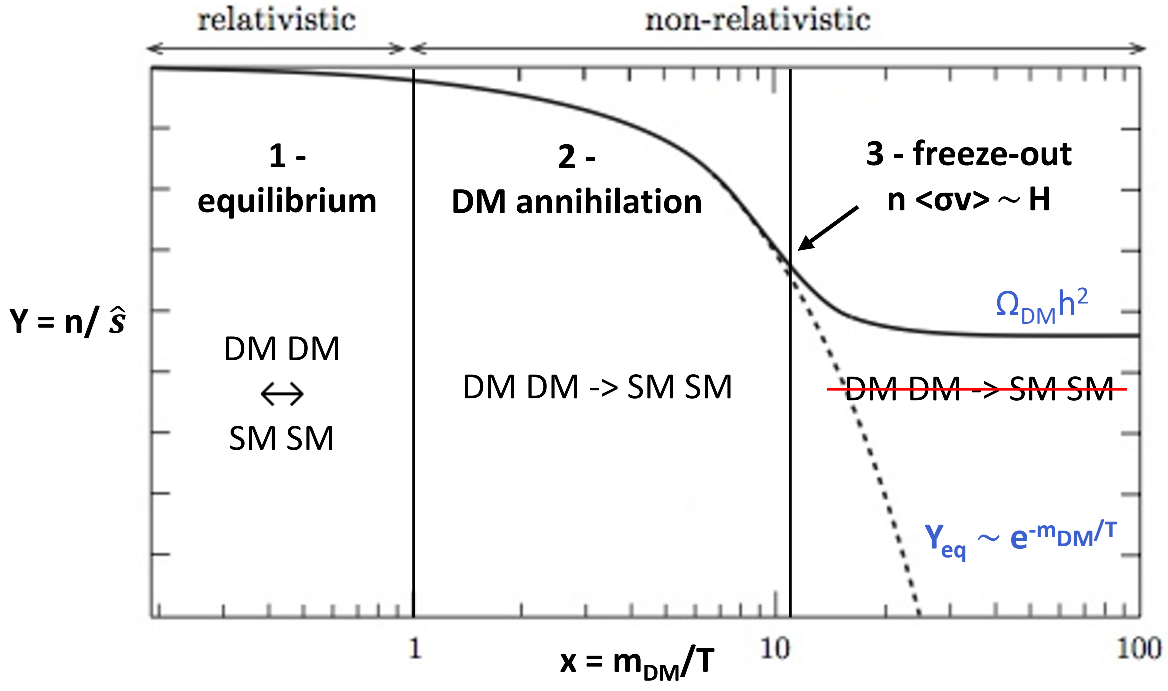
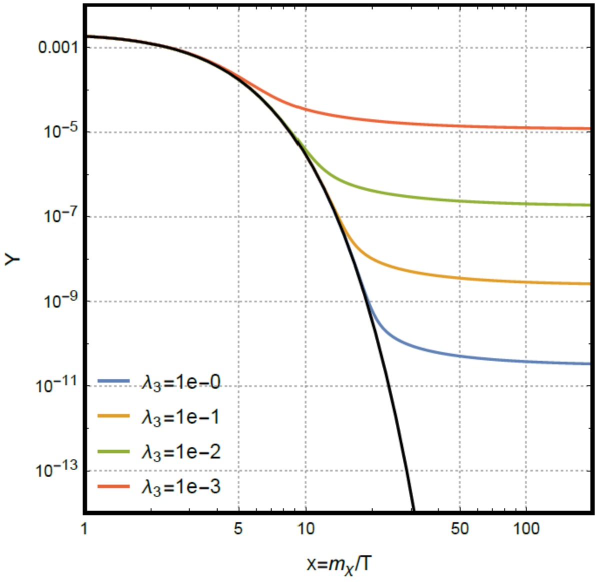


Image source: Daniel D. Baumann, Lecture notes on Cosmology

1 - T > m_{DM}, **equilibrium** between DM and SM particles.

2 - Universe cools off, DM production is disfavoured (T ~ m_{DM}). **DM annihilation dominates**.

3 - **freeze-out:** DM annihilation rate ~ Universe expansion rate. Annihilation heavily suppressed, DM number density "freezes-out" (typical x_{FO} = 20-30).



DM annihilation into a final state with b-quarks, for the **real singlet model**. A **larger portal coupling** is equivalent to a larger thermal averaged cross section (TAC) and a **more efficient annihilation rate**. Hence, this leads to a **smaller Yield/relic density**. Yield is inversely proportional to the TAC in the freeze-out.

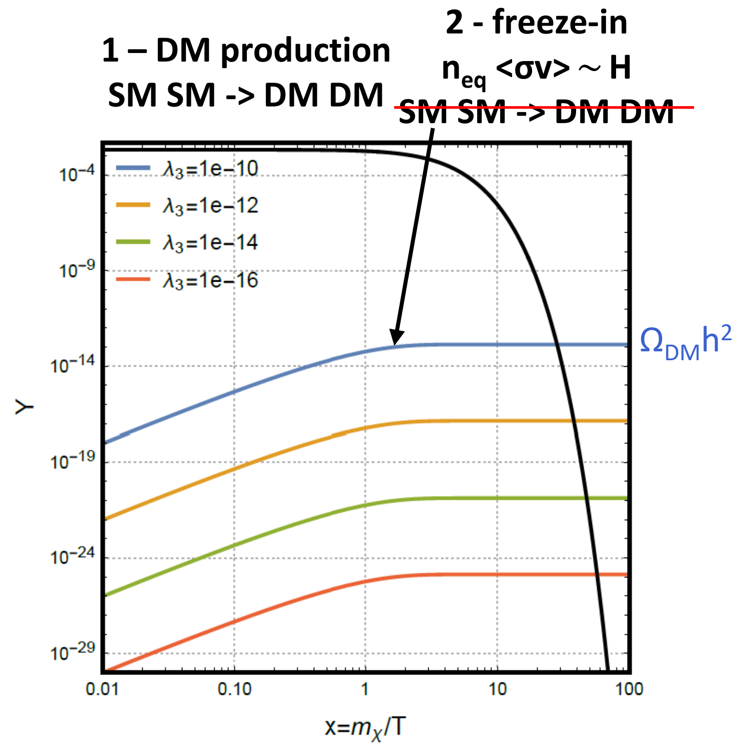
Mechanisms of thermal DM generation - Freeze-in

- Let us assume the existence of a **FIMP** which interacts so weakly with the thermal bath (**portal coupling ~ 10^{-10} or smaller**) that it **never reaches thermal equilibrium.**
- Furthermore, we start with a **null initial DM abundance** (Y(0) = 0). Then, DM annihilation processes are extremely suppressed and can be neglected. **Only DM production from SM particles** is responsible for changing n(t).

$$\boxed{\frac{dY}{dx} = -\sqrt{\frac{\pi}{45G}}\frac{g_*^{1/2} m_{DM}}{x^2}\langle\sigma v\rangle\left(\cancel{Y^2} - Y_{\rm eq}^2\right)}$$

At the reheating temperature, DM starts being produced from SM particles. Once the **DM production rate ~ Universe expansion rate**, production is heavily suppressed, and **DM "freezes-in"**. Usually **freeze-in happens earlier than freeze-out** (typical x_{FI} = 2-5).

DM production from an initial state with b-quarks, for the **real singlet model**. Opposite to the freeze-out, a **larger portal coupling** leads to a **larger Yield/relic density**, since now the Yield is proportional to the production rate.

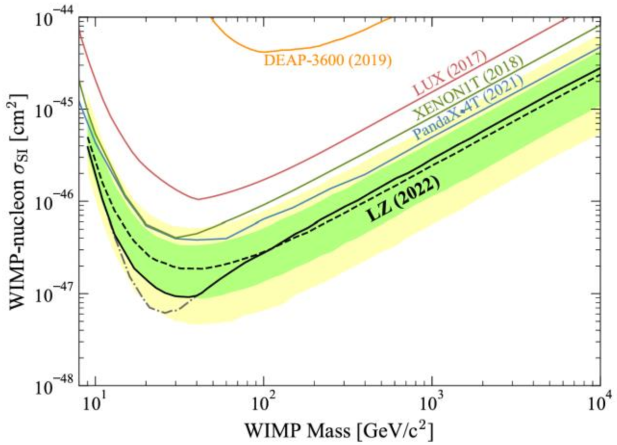


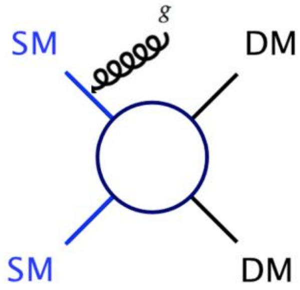
Dark Matter Constraints

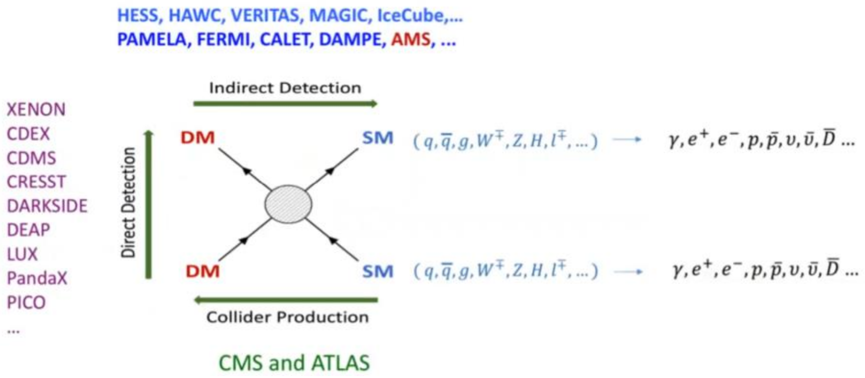
[Planck Collaboration et al., A&A 641, A6 (2020)](#)

The most important constraints are provided by **PLANCK** which measures the DM relic density to be **$\Omega_{DM}h^2 = 0.120 \pm 0.001$**, and **direct detection experiments**. The best experimental upper bounds on the spin-independent DM-nucleon cross section are from the **LUX-ZEPLIN (LZ)** experiment.

[Image source: LZ collaboration, 2207.03764](#)







There are also constraints from **indirect detection experiments** (usually weaker than DD), and **collider searches** which look for an excess of events in final state objects recoiling against large amounts of missing transverse energy, or **Higgs to invisible decays.**

If there is only one portal coupling we can look at these constraints in very simple terms: we need a **large portal coupling to agree with PLANCK**, and a **small portal coupling to avoid DD** bounds. **For FO only, this interplay can result in the exclusion of most of the parameter space**. For **FI only**, the bounds of DD do not apply, the **model is usually sound but not easy to probe experimentally**.

Freeze-in + Freeze-out complementarity

- **Combining FO with FI can alleviate the constraints on the model while still being able to test it**, as we have a DM particle generated via FO. This could be achieved by **adding a FIMP to the model**, which would contribute to the total relic density. Due to its small portal couplings, this **FIMP will evade most experimental constraints**.

- DM particle is found in a DD experiment, and collider searches point to a given model, allowing to determine couplings and masses. **If the model can explain all observables apart from the relic density, this could hint to a FIMP being present**.

- **DM hint at a collider, having no correspondence in DD/ID experiments** in models with DM being produced via freeze-out, could signal the existence of a FIMP. This can happen if the freeze-out DM particle has a very low density.

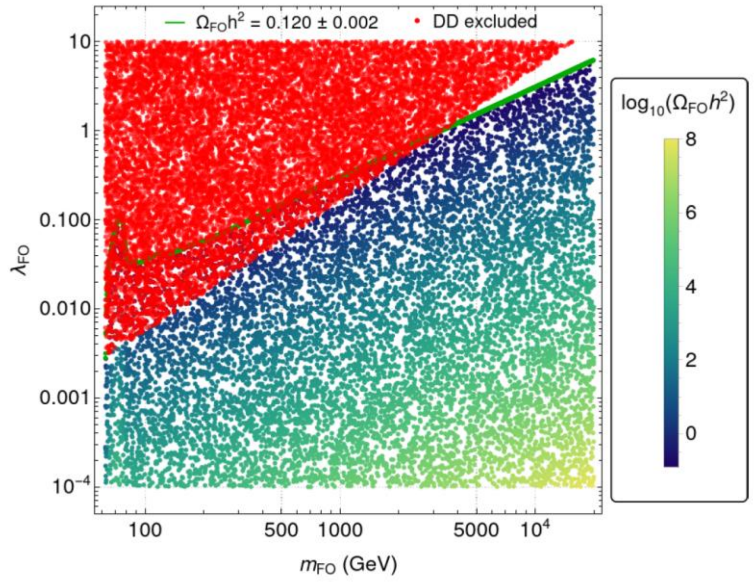
- We study the **complementarity between FO and FI** in models which can have two DM candidates, produced via FO and FI. This complementarity will be shown using the **two real singlets SM extension with two independent Z_2 symmetries**. We will also show the difference in having one or two DM candidates, and then move to more elaborated SM extensions.

Two Real Singlets Extension of the SM

- The simplest extension of the SM that shows the **freeze-out and freeze-in complementarity** is the addition of **two real singlets** to the SM. Two DM candidates emerge by imposing two discrete symmetries, $\mathbf{Z_2^{FO}}$ **(ϕ_{FO} -> - ϕ_{FO})** and $\mathbf{Z_2^{FI}}$ **(ϕ_{FI} -> - ϕ_{FI})**. The two DM quantum numbers are independent and the corresponding DM candidates cannot decay to each other.

$$V_{\rm Scalar} = + \; \mu_h^2|H|^2 + \lambda_h|H|^4 + \frac{1}{2}\mu_{\rm FO}^2\,\phi_{\rm FO}^2 + \frac{\lambda_1}{4!}\,\phi_{\rm FO}^4 + \frac{1}{2}\mu_{\rm FI}^2\,\phi_{\rm FI}^2 + \frac{\lambda_2}{4!}\,\phi_{\rm FI}^4 \; + \frac{\lambda_{\rm FO}}{2}\,\phi_{\rm FO}^2|H|^2 + \frac{\lambda_{\rm FI}}{2}\,\phi_{\rm FI}^2|H|^2 + \frac{\lambda_{\rm IO}}{4}\,\phi_{\rm FI}^2\phi_{\rm FO}^2$$

For the **real singlet model**, if the DM candidate is generated via FO, the **model is excluded in a vast region of the parameter space**. The tension between DD and relic density constraints leads to a small region of allowed couplings for **masses above $\sim$ 4 TeV**. **Future DD constraints will further reduce this region** and make the searches at the LHC harder.

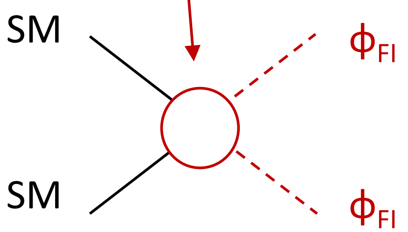


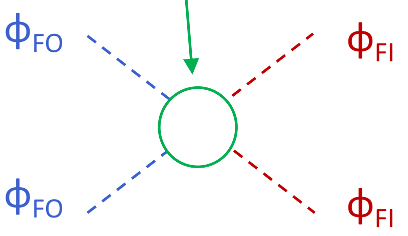
Relic Density via Freeze-in and Freeze-out

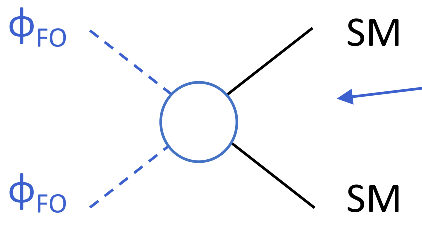
- **Coupled Boltzmann equations to determine the FI and FO yields:**

$$\frac{dY_{\rm FI}}{dx} = \sqrt{\frac{\pi}{45G}}\frac{g_*^{1/2}m}{x^2}\left[\boxed{\langle\sigma v\rangle_{\phi_{\rm FI}\phi_{\rm FI}{\rm SMSM}}(Y_{\rm FI,eq}^2 - Y_{\rm FI}^2)} + \boxed{\langle\sigma v\rangle_{\phi_{\rm FI}\phi_{\rm FI}\phi_{\rm FO}\phi_{\rm FO}}\left(\frac{Y_{\rm FO}^2}{Y_{\rm FO,eq}^2}Y_{\rm FI,eq}^2 - Y_{\rm FI}^2\right)}\right]$$

$$\frac{dY_{\rm FO}}{dx} = \sqrt{\frac{\pi}{45G}}\frac{g_*^{1/2}m}{x^2}\left[\boxed{\langle\sigma v\rangle_{\phi_{\rm FO}\phi_{\rm FO}{\rm SMSM}}(Y_{\rm FO,eq}^2 - Y_{\rm FO}^2)}\right. \left.\boxed{-\langle\sigma v\rangle_{\phi_{\rm FI}\phi_{\rm FI}\phi_{\rm FO}\phi_{\rm FO}}\left(\frac{Y_{\rm FO}^2}{Y_{\rm FO,eq}^2}Y_{\rm FI,eq}^2 - Y_{\rm FI}^2\right)}\right],$$







- The **enhancement factor $Y_{FO}/Y_{FO,eq}$** measures how much bigger the FO particle's density is compared to its equilibrium value. Since the SM is always in thermal equilibrium during FO/FI, the corresponding terms do not have enhancement factors.

- **The Boltzmann equations can be simplified and decoupled**, by considering a **null initial ϕ_{FI} abundance**, setting the **enhancement factors to one**, and **neglecting $\langle\sigma v\rangle_{\phi_{FI}\phi_{FI}\phi_{FO}\phi_{FO}}$ in the FO equation** ($\langle\sigma v\rangle_{\phi_{FI}\phi_{FI}\phi_{FO}\phi_{FO}} \ll \langle\sigma v\rangle_{\phi_{FO}\phi_{FO}SMSM}$):

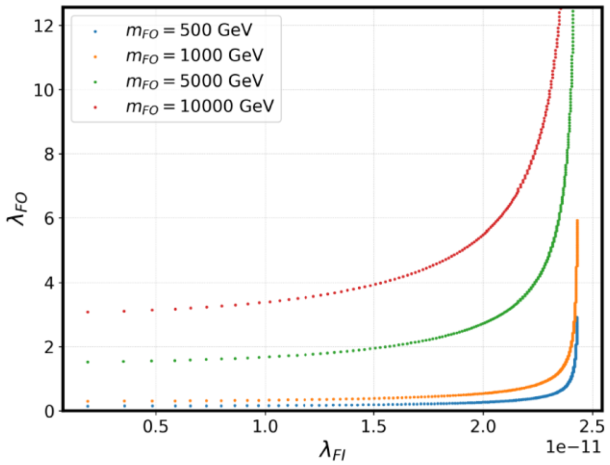
$$\frac{dY_{\rm FI}}{dx} = \sqrt{\frac{\pi}{45G}}\frac{g_*^{1/2}m_{\rm FI}}{x^2}\left[\langle\sigma v\rangle_{\phi_{\rm FI}\phi_{\rm FI}{\rm SMSM}} + \langle\sigma v\rangle_{\phi_{\rm FI}\phi_{\rm FI}\phi_{\rm FO}\phi_{\rm FO}}\right]Y_{\rm FI,eq}^2 \qquad \frac{dY_{\rm FO}}{dx} = -\sqrt{\frac{\pi}{45G}}\frac{g_*^{1/2}m_{\rm FI}}{x^2}\langle\sigma v\rangle_{\phi_{\rm FO}\phi_{\rm FO}{\rm SMSM}}\left(Y_{\rm FO} - Y_{\rm FO,eq}^2\right)$$

Relic Density via Freeze-in and Freeze-out

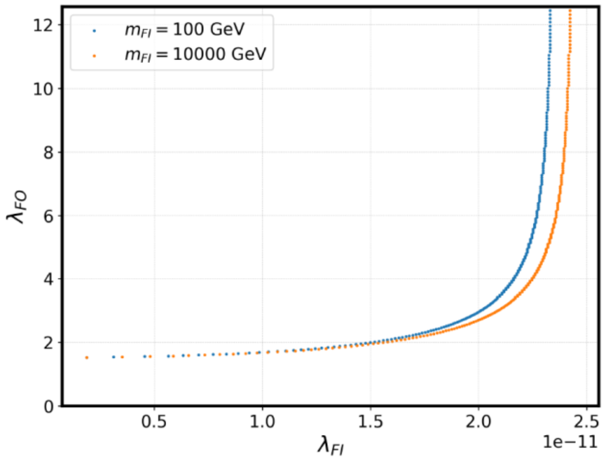
$$(\Omega h^2)_{\text{Planck}} = (\Omega_{\text{FI}} + \Omega_{\text{FO}})h^2 = 0.120 \pm 0.002$$

- **FO relic density is proportional to $(m_{FO}/\lambda_{FO})^2$. FI relic density is proportional to λ_{FI}^2 with a negligible mass dependence**. Both portal couplings need to simultaneously increase (or decrease) so that we obtain the correct relic density.
- **If FO or FI are underabundant, we can always find a combination between the couplings which reproduces the observed relic density. Large FO portal couplings** which were previously excluded for FO only are no longer excluded, which will make **collider searches more interesting**. **Valid for any model with FO+FI!**

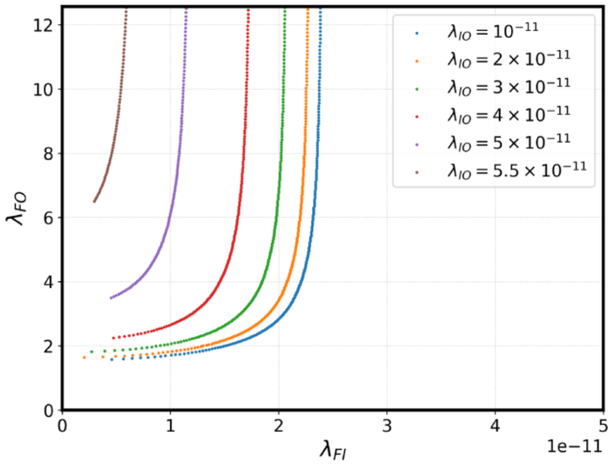
$\lambda_{IO} = 0$, $m_{FI} = 700$ GeV



$\lambda_{IO} = 0$, $m_{FO} = 5000$ GeV



$m_{FO} = 4000$ GeV, $m_{FI} = 5000$ GeV



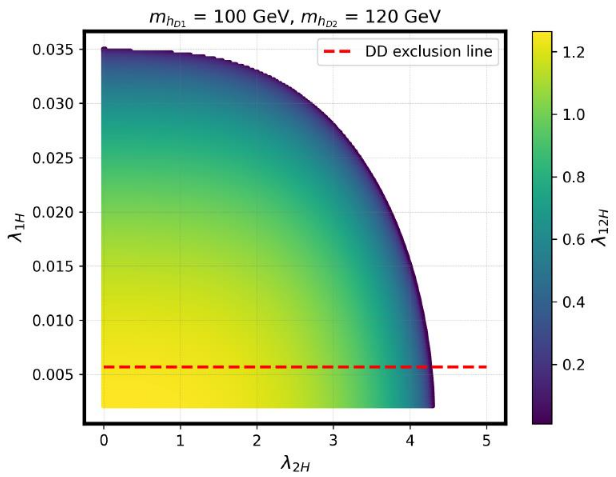
Consequences of having only one Z_2 symmetry

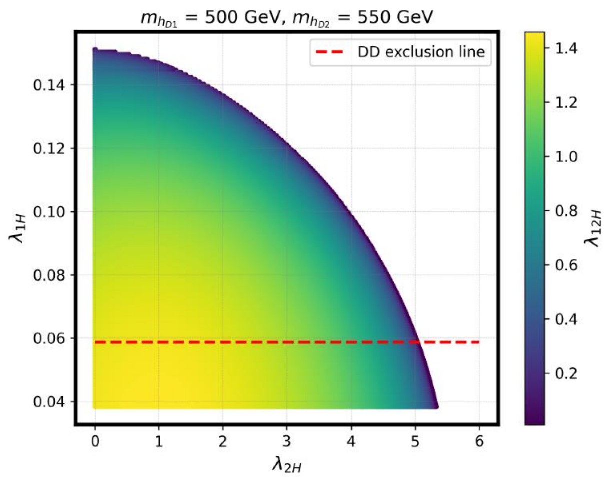
$$V_{\text{Scalar}} = + \ \mu_h^2 |H|^2 + \lambda_h |H|^4 + m_1^2\, \phi_1^2 + \frac{\lambda_1}{4!}\, \phi_1^4 + m_2^2\, \phi_2^2 + \frac{\lambda_2}{4!}\, \phi_2^4 \ + \frac{\lambda_{1H}}{2}\, \phi_1^2 |H|^2 + \frac{\lambda_{2H}}{2}\, \phi_2^2 |H|^2 + \frac{\lambda_{12}}{4}\, \phi_1^2 \phi_2^2 \boxed{+ m_{12}^2 \phi_1 \phi_2 + \frac{\lambda_{112}}{4}\, \phi_1^3 \phi_2 + \frac{\lambda_{122}}{4}\, \phi_1 \phi_2^3 + \frac{\lambda_{12H}}{2}\, \phi_1 \phi_2 |H|^2}$$

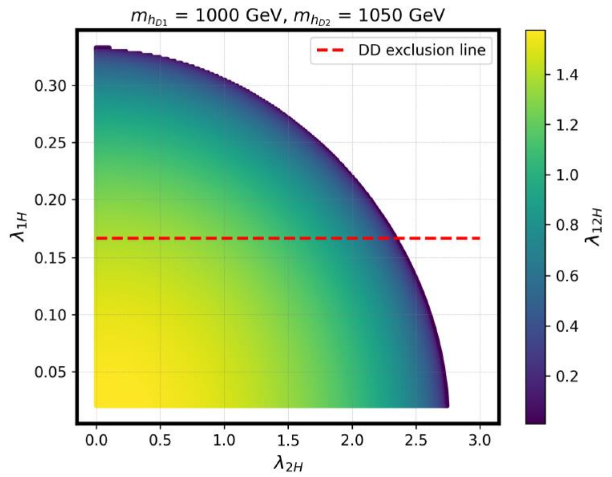
- With the symmetry $\phi_1 \to -\phi_1$, $\phi_2 \to -\phi_2$, **we will now only have one DM candidate,** corresponding to the lighter of the two dark sector (DS) particles. **Several DM generation mechanisms can be considered**, depending on the values given to the portal couplings. For **typical FO couplings**, the scalar fields are forced into thermal equilibrium, and **DM is generated via FO**.

$$\frac{dY}{dx} = -\sqrt{\frac{\pi}{45G}}\frac{g_*^{1/2} m_{h_{D1}}}{x^2} \langle \sigma v \rangle_{\text{eff}} \left(Y^2 - Y_{\text{eq}}^2 \right)$$

- Three relevant processes: $h_{D1}h_{D1} \to SMSM$, $h_{D2}h_{D2} \to SMSM$ and $h_{D1}h_{D2} \to SMSM$. **Only the portal couplings λ_{1H}, λ_{2H}, λ_{12H} contribute to FO**. Masses must be close to ensure that co-annihilations are relevant. **There is a large parameter space which allows to obtain the experimental relic density via FO alone**, because now co-annihilation processes play a role. **DD constraints only impose an upper bound on λ_{1H}**.



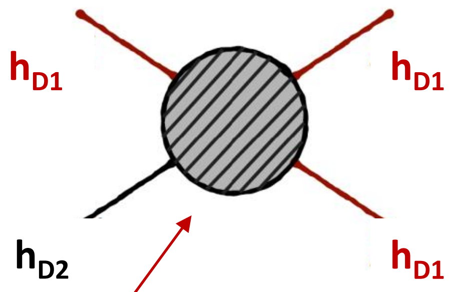




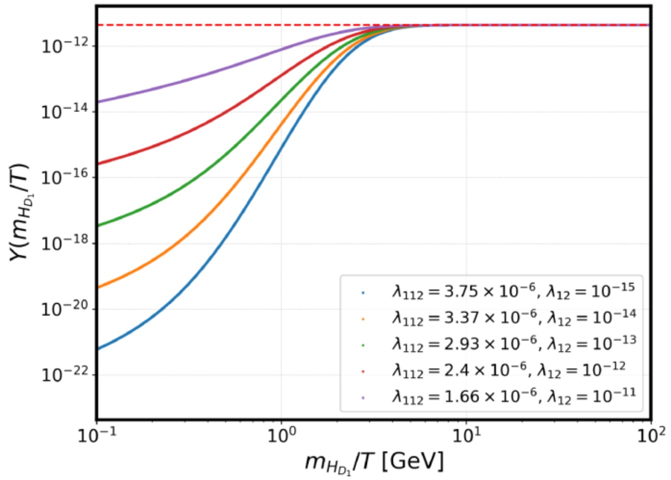
Consequences of having only one Z_2 symmetry

Bringmann et al., 2103.16572

- This model also allows for another mechanism to take place: **DM from exponential growth**. At least two DS particles are necessary. The heavier one is in thermal equilibrium with the SM bath and the lighter one (DM candidate) starts with zero initial abundance and then obtains a small abundance through FI. **With the right choice of couplings this small abundance grows exponentially through the process $h_{D1}h_{D2} \rightarrow h_{D1}h_{D1}$** until it reaches a plateau.



$$\frac{\mathrm{d}Y_{h_{D_1}}}{\mathrm{d}x} = \sqrt{\frac{\pi}{45G}}\frac{g_*^{1/2} m_{h_{D_2}}}{x^2}\left(\langle\sigma v\rangle_{\exp} Y^{\mathrm{eq}}_{h_{D_2}} Y_{h_{D_1}} + \langle\sigma v\rangle_{\mathrm{DS}}(Y^{\mathrm{eq}}_{h_{D_2}})^2 + \langle\sigma v\rangle_{\mathrm{SM}}(Y^{\mathrm{eq}}_{h_{D_1}})^2\right)$$



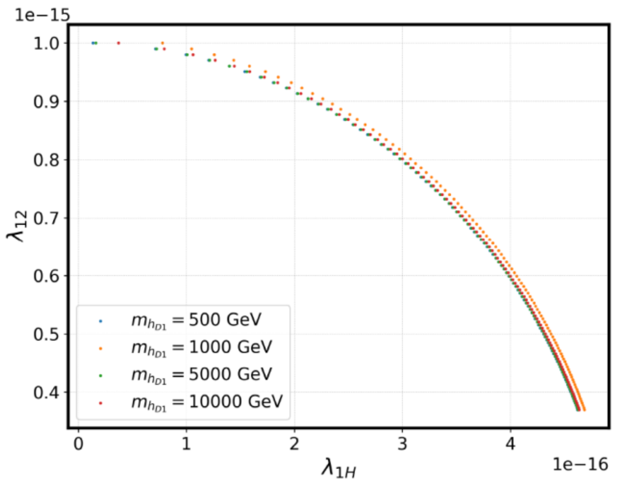
- **The exponential growth mechanism allows smaller FI couplings which are otherwise not able to reach the observed relic density**. If FI alone does not result in an overabundance, we can choose any value for the FI coupling and then adjust λ_{112}.

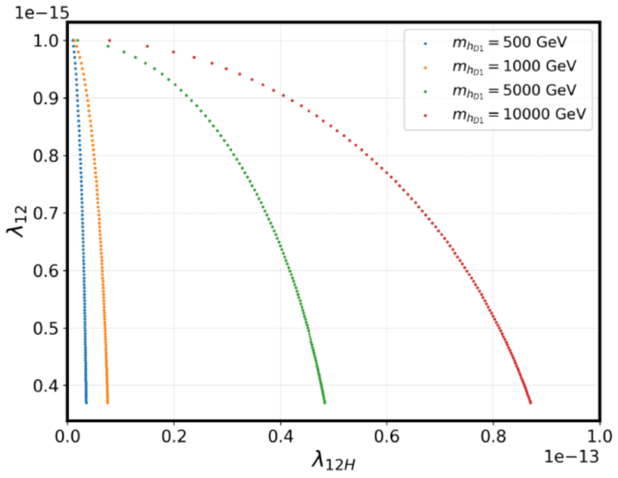
- The coupling associated to exponential growth changes very little. For instance, **while λ_{12} varies between four orders of magnitude, λ_{112} only changes by a factor of ≈ 2.26**, meaning that this parameter is very well constrained.

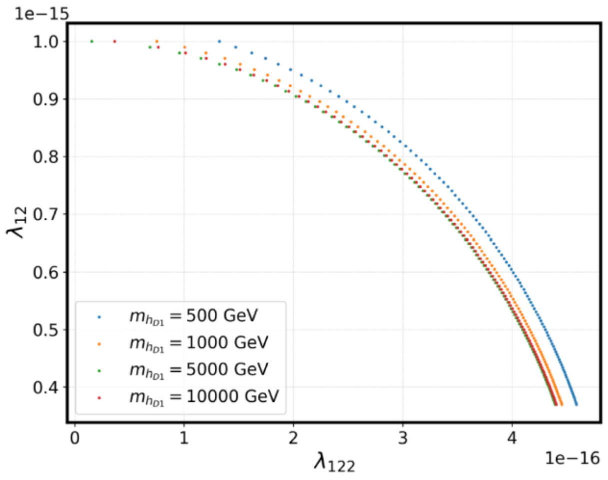
Consequences of having only one Z_2 symmetry

- **We can easily obtain a parameter region which is able to generate the observed DM relic density**. The FI couplings are too small to be affected by other constraints.

- By considering **different symmetries** for a given Lagrangian and by moving into **different parameter space regions**, we are able to obtain **different DM generation scenarios** which can reproduce the observed relic density.







The Full Dark Phase of the N2HDM

- **Full Dark Phase (FDP) of the N2HDM** - two doublets + one real singlet. Two Z_2 discrete symmetries are introduced, from which two DM candidates will emerge.

Engeln et al., 2004.05382

$$\mathbb{Z}_2^{(1)}: \quad \Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_2, \quad \Phi_S \to \Phi_S\,,$$
$$\mathbb{Z}_2^{(2)}: \quad \Phi_1 \to \Phi_1, \quad \Phi_2 \to \Phi_2, \quad \Phi_S \to -\Phi_S\,,$$

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\,\eta_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(\rho_2 + i\,\eta_2) \end{pmatrix}, \quad \Phi_S = \rho_s$$

$$\begin{aligned} V_{\rm Scalar} =\ & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + \frac{\lambda_1}{2}\left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger \Phi_2\right)^2 \\ +\ & \lambda_3 \Phi_1^\dagger \Phi_1 \Phi_2^\dagger \Phi_2 + \lambda_4 \Phi_1^\dagger \Phi_2 \Phi_2^\dagger \Phi_1 + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger \Phi_2\right)^2 + \text{h.c.}\right] \\ +\ & \frac{1}{2} m_s^2 \Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}\Phi_1^\dagger \Phi_1 \Phi_S^2 + \frac{\lambda_8}{2}\Phi_2^\dagger \Phi_2 \Phi_S^2\,, \end{aligned}$$

- There is no mixing in the scalar sector, and the SM-like Higgs couplings to the other SM particles do not change relative to the SM. **The DS fields couplings to the SM are via the SM-like Higgs but also the SU(2) gauge bosons in the dark doublet case**. Input values:

$$m_{H_{\rm SM}}, \quad m_{H_{\rm DD}}, \quad m_{A_{\rm D}}, \quad m_{H_{\rm DS}}, \quad m_{H_{\rm D}^\pm}, \quad m_{22}^2, \quad \lambda_2, \quad \lambda_6, \quad \lambda_7, \quad \lambda_8$$

- Since the dark doublet particles couple to the SU(2) gauge bosons, these interactions have a fixed value. **Neither H_{DD} nor A_D can be produced via FI**. The condition for FI requires that the portal couplings between the singlet and the SM/doublet particles must be small (λ_7 and λ_8). **The dark sector from the doublet will be responsible for FO and the dark sector from the singlet for FI.**

Constraints

Mühlleitner et al., 2007.02985

- **Several theoretical and experimental constraints imposed via the tool *ScannerS***: boundedness from below, perturbative unitarity, vacuum stability, electroweak precision, flavour, Higgs searches and measurements, and DM constraints.

- DM particle from the singlet has no other restrictions besides the relic density measurement. The one from the doublet must also agree with DD/ID bounds. **The DD exclusion limit assumes the observed relic density**. Since in our case the FO relic density is below the measured value, the **cross section must be normalized by the corresponding reduced fraction** such that the comparison with the experimental results can be made.

$$\sigma_{\text{SI-DD-N}} = \hat{\sigma}_{\text{SI-DD-N}} \frac{\Omega_{\text{FO}} h^2}{\Omega_{\text{exp}} h^2}$$

- Indirect constraint on the FO dark sector: the **charged scalars will change the decay width of the SM-like Higgs into photons** relative to the SM. The **signal strength $\mu_{\gamma\gamma}$** is constrained by the latest measurement of the ATLAS experiment. Scanned points signal strengths must lie in their 2σ bound.

ATLAS Collaboration, 2207.00348

$$\mu_{\gamma\gamma} = \frac{\sigma(pp \to H_{\text{SM}} \to \gamma\gamma)_{\text{FDP}}}{\sigma(pp \to H_{\text{SM}} \to \gamma\gamma)_{\text{SM}}} = \frac{\sigma_{\text{prod,FDP}} \mathcal{B}(H_{\text{SM}} \to \gamma\gamma)_{\text{FDP}}}{\sigma_{\text{prod,SM}} \mathcal{B}(H_{\text{SM}} \to \gamma\gamma)_{\text{SM}}} = \frac{\mathcal{B}(H_{\text{SM}} \to \gamma\gamma)_{\text{FDP}}}{\mathcal{B}(H_{\text{SM}} \to \gamma\gamma)_{\text{SM}}}$$

$$\mu_{\gamma\gamma} = 1.04^{+0.10}_{-0.09}$$

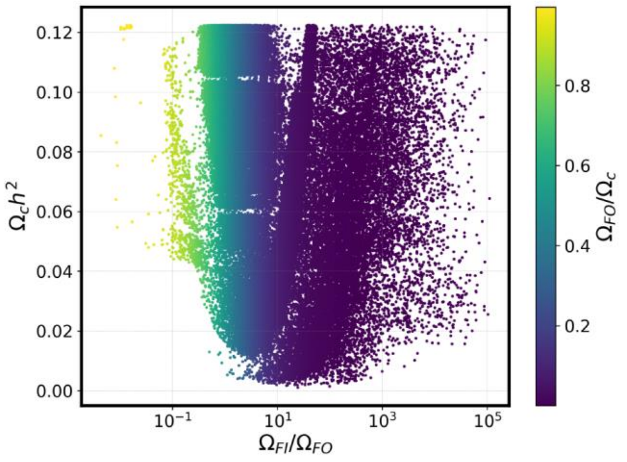
Results

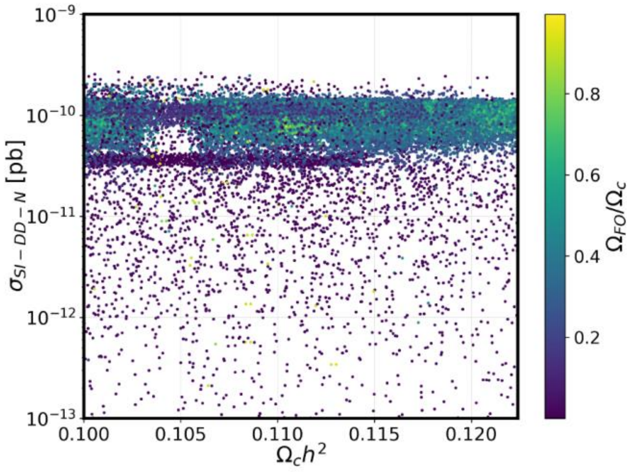
[Bélanger et al., 1801.03509](https://arxiv.org/abs/1801.03509)

- The parameter scans are performed using ***ScannerS***. The relic density and DD cross section are calculated with ***micrOMEGAs***.

$$60\,\mathrm{GeV} \le m_{H_{DD}}, m_{A_D}, m_{H_D^\pm} \le 1\,\mathrm{TeV} \qquad 1\,\mathrm{GeV} \le m_{H_{\mathrm{DS}}} \le 1\mathrm{TeV} \qquad 10^{-14} \le \lambda_7, \lambda_8 \le 10^{-9} \qquad 0 \le \lambda_2, \lambda_6 \le 20 \qquad 0 \le m_{22}^2 \le 10^6\,\mathrm{GeV}^2$$

- **Most points in the scanned parameter region are dominated by FI**. Even when FO starts to dominate, FI still plays a crucial role in accounting for the total relic density. Without FI most of the parameter space would be excluded.
- **Even when FI is the dominant process, the SI DD cross section for FO can be quite large**, and it remains possible to detect the FO DM particle in DD experiments.

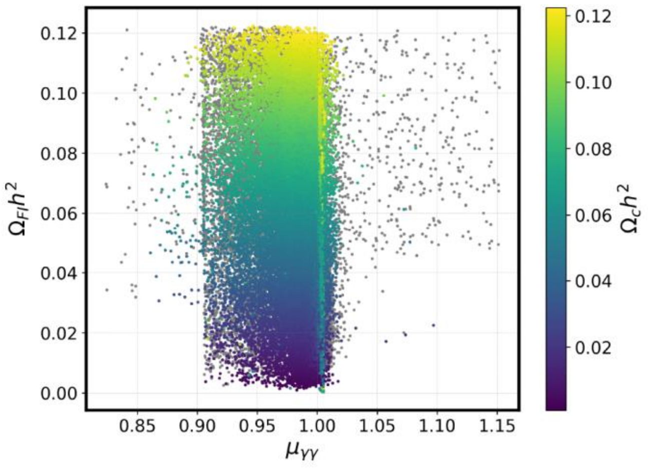


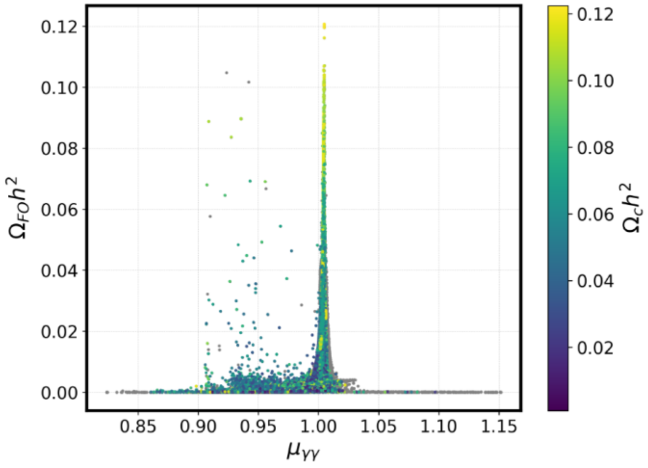


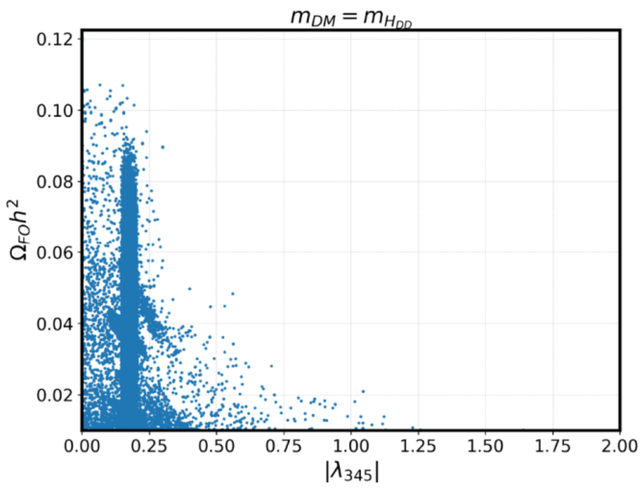
Results

- **The signal strength $\mu_{\gamma\gamma}$ will depend on λ_3, which affects FO, but is independent of λ_7 and λ_8, responsible for FI.**

- For all $\mu_{\gamma\gamma}$ values below one, the observed relic density can only be achieved when FI dominates. For FO, $\mu_{\gamma\gamma}$ must be close to one. **A measurement of $\mu_{\gamma\gamma}$ clearly below one could hint to the existence of FI in this model**.







- **For FO to be the dominant process in this model, the coupling combinations $\lambda_3 + \lambda_4 \pm \lambda_5$ must be small** (which usually implies that λ_3 is small). Otherwise, the FI mechanism is needed to obtain the observed relic density.

CP-violation in the FI+FO framework

- Consider a new model where we start with the FDP of the N2HDM potential, but we impose a different symmetry. Dubbed **CP in the dark (CPD), it allows for CP-violation in the dark scalar sector**. FO was shown to be possible in a substantial region of the parameter space. **Can FO+FI occur simultaneously?**

Azevedo et al., 1807.10322

$$\mathbb{Z}_2^{(3)}: \quad \Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_2, \quad \Phi_S \to -\Phi_S \qquad\qquad V_{\text{CPD}} = V_{\text{N2HDM}}^{\text{FDP}} + (A\Phi_1^\dagger \Phi_2 \Phi_S + \text{h.c.})$$

- The three mass eigenstates of the neutral dark sector, h_i, can be obtained from the gauge eigenstates via the rotation matrix

$$R = \begin{pmatrix} c_{\alpha_1} c_{\alpha_2} & s_{\alpha_1} c_{\alpha_2} & s_{\alpha_2} \\ -(c_{\alpha_1} s_{\alpha_2} s_{\alpha_3} + s_{\alpha_1} c_{\alpha_3}) & c_{\alpha_1} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & c_{\alpha_2} s_{\alpha_3} \\ -c_{\alpha_1} s_{\alpha_2} c_{\alpha_3} + s_{\alpha_1} s_{\alpha_3} & -(c_{\alpha_1} s_{\alpha_3} + s_{\alpha_1} s_{\alpha_2} c_{\alpha_3}) & c_{\alpha_2} c_{\alpha_3} \end{pmatrix}$$

- Since all dark neutral states can couple to gauge bosons, the **only way to have FI is to force one of the h_i to decouple from the Z and W bosons**. This can be done by choosing $\alpha_2 = \pi/2$: h_1 becomes a singlet like field and can be the FI DM candidate.

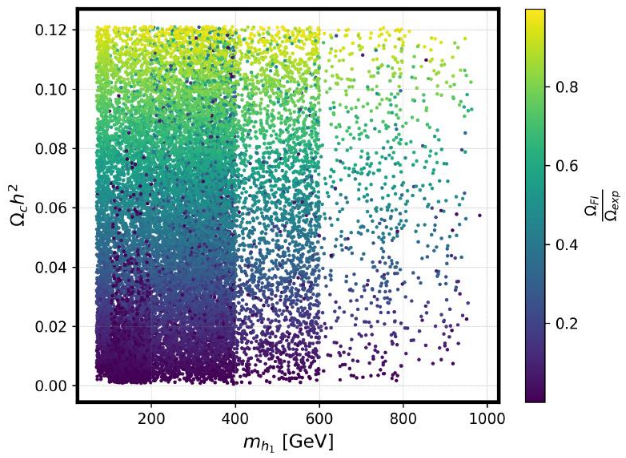
$$R = \begin{pmatrix} 0 & 0 & 1 \\ -s_{\alpha_1+\alpha_3} & c_{\alpha_1+\alpha_3} & 0 \\ -c_{\alpha_1+\alpha_3} & -s_{\alpha_1+\alpha_3} & 0 \end{pmatrix}$$

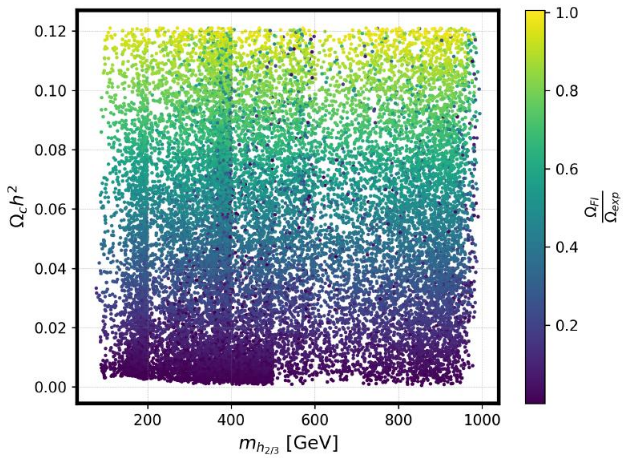
$$\begin{aligned} h_1 &= \rho_s\,, \\ h_2 &= -\, s_{\alpha_1+\alpha_3}\rho_2 + c_{\alpha_1+\alpha_3}\eta_2 \\ h_3 &= -\, c_{\alpha_1+\alpha_3}\rho_2 - s_{\alpha_1+\alpha_3}\eta_2 \end{aligned}$$

CP-violation in the FI+FO framework

- **When we decouple one of the scalars we lose CP-violation** because we need to set $A = \lambda_5 = 0$. This can be achieved by imposing an additional U(1) symmetry $\phi_1 \to \phi_1$, $\phi_2 \to e^{i\theta}\phi_2$, $\phi_S \to \phi_S$. **This restricted version of the model** where we have FI for h_1 and FO for $h_{2,3}$ (same mass) **is very similar to the FDP of the N2HDM.**

- **The entire region for the DM FO masses in the scan is allowed**. Without FI, which again is the dominant process, most of the points would be excluded.





- CP in the Dark gives the observed relic density via FO+FI. This is achieved at the cost of losing the CP-violation feature in the dark scalar sector. However, **it would be enough to add an extra singlet to allow FO+FI while preserving CP-violation**.

Conclusions

- We discussed the possibility of having **two DM candidates, produced via FI and FO**. Even a simple extension with only two extra singlets can implement the idea. **More elaborate extensions can have this FI+FO complementarity** such as the FDP of the N2HDM and CPD **if the correct symmetries are imposed**.

- **Any model that does not fulfil the relic density can be easily extended with a new field and a new symmetry** that stabilises it such that **FI solves the DM density issue**. This new particle will evade most experimental constraints, due to its small portal couplings.

- **Combining FI and FO can alleviate the constraints on the FO portal couplings**, allowing for larger values of those couplings. This will make **collider searches more interesting**, allowing to probe the FO DM candidate at colliders when it cannot be detected via DD/ID. However, **both collider and DD/ID experiments can be sensitive to the FO particle when FI is the dominant process**.

- **If a DM particle is found this complementarity should always be considered**, especially if a proposed model does not match the measured relic density and/or an unexpected result at a collider is found. **DD must be used carefully to exclude searches** in regions of the parameter space of a given model. **Collider searches have to disregard DD bounds in particular scenarios**.

THE END.
THANK YOU!