Freeze-in production of dark matter through spin-1 and spin-2 portals

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Carleton UNIVERSITY
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Canadian Astroparticle Physics Research Institute

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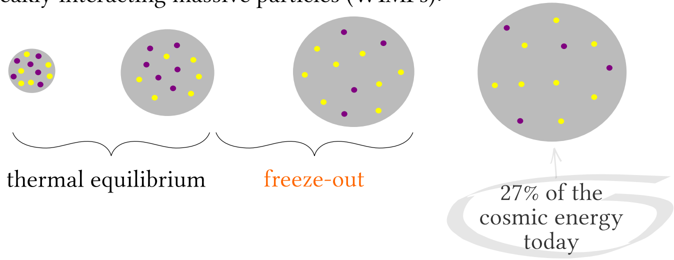
Introduction

Dark matter genesis: two possibilities

time (t), scale factor (a) → ● visible particles (SM) ● dark matter particles (DM)

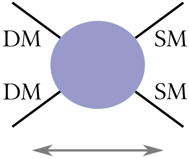
Weakly interacting massive particles (WIMPs):



thermal equilibrium

freeze-out

27% of the cosmic energy today



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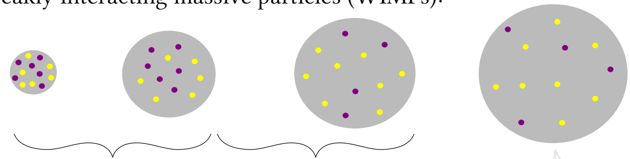
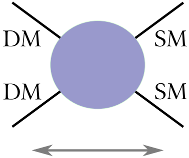


thermal equilibrium freeze-out



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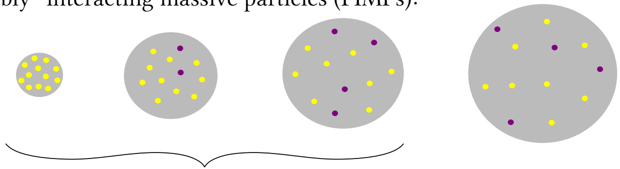
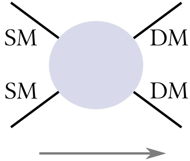
Feebly* interacting massive particles (FIMPs):

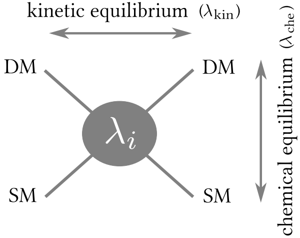


(out-of-equilibrium) freeze-in



* Weaker than "weak"!

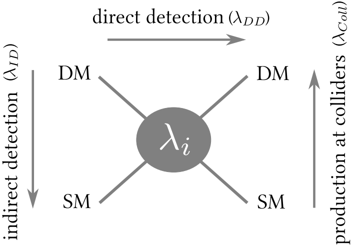
Production of DM particles



kinetic equilibrium $(\lambda_{\rm kin})$

chemical equilibrium $(\lambda_{\rm che})$

Searches for DM particles

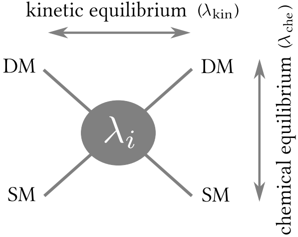


direct detection (λ_{DD})

indirect detection (λ_{ID})

production at colliders (λ_{Coll})

Production of DM particles



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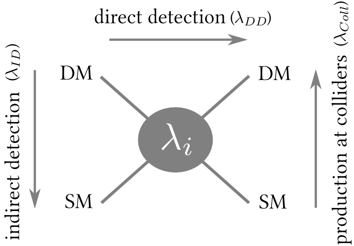

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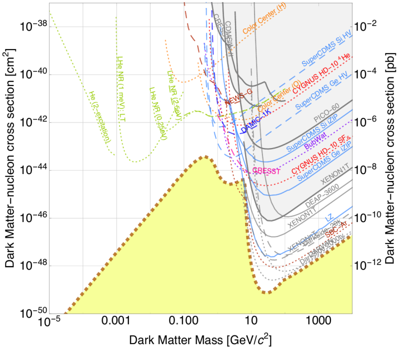
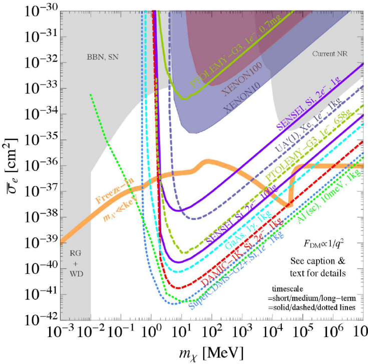
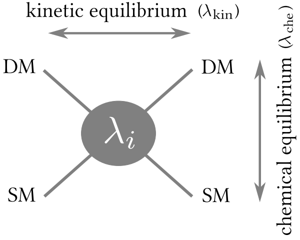




[arXiv:1707.04591]

Production of DM particles



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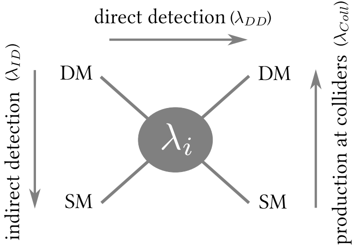
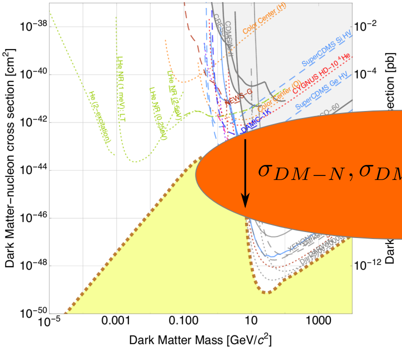
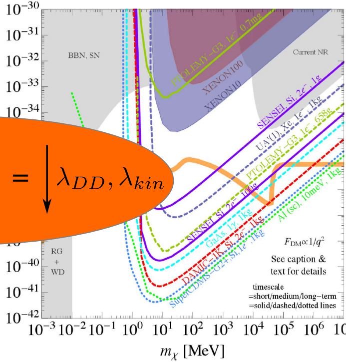


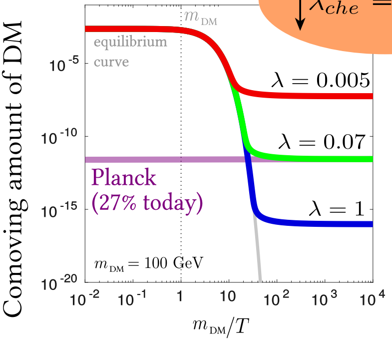


$$\downarrow \sigma_{DM-N}, \sigma_{DM-e} = \downarrow \lambda_{DD}, \lambda_{kin}$$



[arXiv:1707.04591]

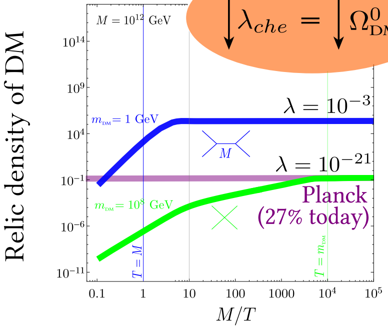
$$\downarrow \lambda_{che} = \uparrow \Omega^0_{\rm DM} h^2$$



- Thermal relics forget about their "dark past"
- Sizable DM-SM couplings: rich DM phenomenology
- Stronger DD bounds easily lead to overproduced DM

$$\frac{\Omega^0_{DM} h^2}{0.12} \sim \left(\frac{x_f}{23.8}\right) \left(\frac{86.3}{g_*(x_f)}\right)^{1/2} \left(\frac{2 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma v \rangle}\right)$$

$$\langle \sigma v \rangle \sim 2 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1} \times \begin{cases} \left(\frac{\lambda}{0.07}\right)^4 \left(\frac{m_{DM}}{100\mathrm{GeV}}\right)^{-2} \\ \left(\frac{\lambda}{0.2}\right)^4 \left(\frac{m_{DM}}{1000\mathrm{GeV}}\right)^{-2} \end{cases}$$



$$\downarrow \lambda_{che} = \downarrow \Omega^0_{\rm DM} h^2$$

- Out-of-equilibrium origin: final relic density might depend on initial conditions
- Feeble DM-SM couplings: challenging DM phenomenology
- Stronger DD bounds easily lead to underproduced DM, allowing for complex dark sector

$$\frac{\Omega^0_{DM} h^2}{0.12} \sim \frac{\lambda}{10^{-20}} \frac{m_{DM}}{T_{FI}}$$

$$\frac{\Omega^0_{DM} h^2}{0.12} \sim \frac{\epsilon_{RH}}{44\%} \frac{\lambda}{0.1} \left(\frac{m_{DM}}{100\text{GeV}}\right) \left(\frac{T_{RH}}{10^{10}\text{GeV}}\right)^3 \left(\frac{M}{10^{12}\text{GeV}}\right)^{-4}$$

Possible solutions for the DD *vs* thermal production "tension"

weakening the bounds/channels:

- pseudoscalar couplings
- most of DM annihilation into leptons or EW bosons
- coannihilation

changing early universe:

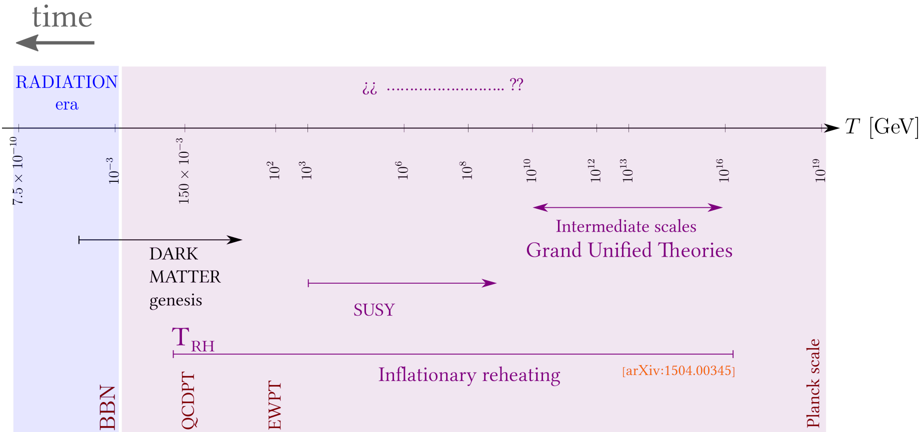
- non-standard cosmologies: change Hubble rate during DM production

changing assumptions:

- dark freeze-out production (from hidden thermal bath)
- non-thermal production (from decoupled sector)
- freeze-in production (from visible thermal bath)

Freeze-in during reheating

Landscape of dark matter genesis



RADIATION
era

¿¿ .... ??

Intermediate scales
Grand Unified Theories

DARK
MATTER
genesis

SUSY

T_{RH}

Inflationary reheating

[arXiv:1504.00345]

BBN

QCDPT

EWPT

Planck scale

- Generation of neutrino masses
- Generation of matter/antimatter asymmetry
- Structural extensions of the standard model (SUSY, GUT, string)
- Seeds of structure formation (inflationary theories)

$$\boxed{\frac{dN_\chi}{dt} = \underbrace{R_\chi(t)a^3}_{\substack{\text{interaction rate} \\ \text{(gain - loss)}}}} \qquad \frac{d\ln a}{dt} = \underbrace{H(t)}_{\substack{\text{expansion rate} \\ \text{(Hubble rate)}}} \propto \sqrt{\rho(t)}$$

total entropy:

evolution over temperature (T)

$$S = sa^3 \propto T^3 a^3 \xrightarrow[\substack{\dot{S} = 0 \\ Y_\chi \equiv N_\chi / S}]{} \boxed{\frac{dY_\chi}{dT} \propto -\frac{R_\chi}{HsT}}$$

$N = na^3$: total number of matter content

t, a, T : time, scale factor, temperature

$$\boxed{\frac{dN_\chi}{dt} = \underbrace{R_\chi(t)a^3}_{\text{interaction rate}}}$$

interaction rate

(gain - loss)

$$\frac{d\ln a}{dt} = \underbrace{H(t)}_{\text{expansion rate}} \propto \sqrt{\rho(t)}$$

expansion rate

(Hubble rate)

total entropy:

$$S = sa^3 \propto T^3a^3$$

$$\xrightarrow[\substack{\dot{S}=0 \\ Y_\chi \equiv N_\chi/S}]{}$$

evolution over temperature (T)

$$\boxed{\frac{dY_\chi}{dT} \propto -\frac{R_\chi}{HsT}}$$

$\dot{S} \neq 0$

$$\Delta \equiv \frac{S_{\text{after}}}{S_{\text{before}}}$$

dilution by entropy production:

$$Y_\chi^{\text{after}} = \frac{N_\chi}{S_{\text{after}}} = \frac{N_\chi}{\Delta S_{\text{before}}} = \frac{Y_\chi^{\text{before}}}{\Delta}$$

unstable matter (ϕ)
decaying into radiation (γ)

("reheating")

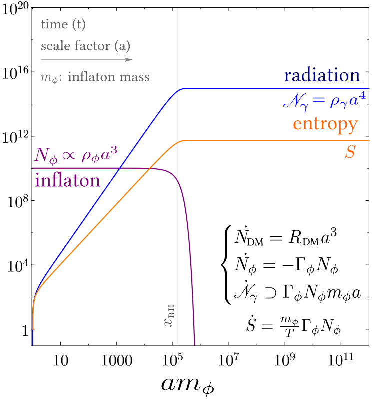
$$\begin{cases} \dot{N}_\chi = R_\chi a^3 \\ \dot{N}_\phi = -\Gamma_\phi N_\phi \\ \dot{\mathcal{N}}_\gamma \supset \Gamma_\phi N_\phi m_\phi a \end{cases}$$

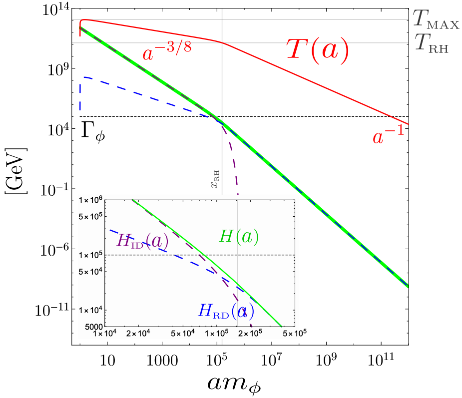
$$\dot{S} = \frac{m_\phi}{T}\Gamma_\phi N_\phi \qquad \Delta \propto \frac{Y_\phi^{\text{before}} m_\phi}{\sqrt{\Gamma_\phi}}$$

$N = na^3$: total number of matter content
$\mathcal{N} = \rho a^4$: total number of radiation content

n, ρ : number and energy densities
t, a, T : time, scale factor, temperature

DM genesis during post-inflationary reheating





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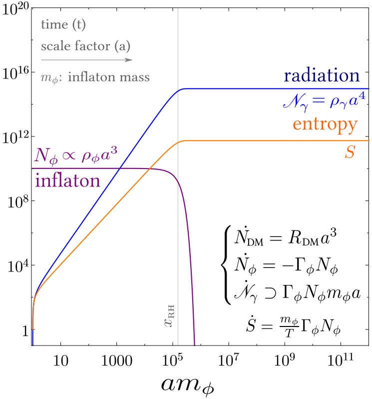
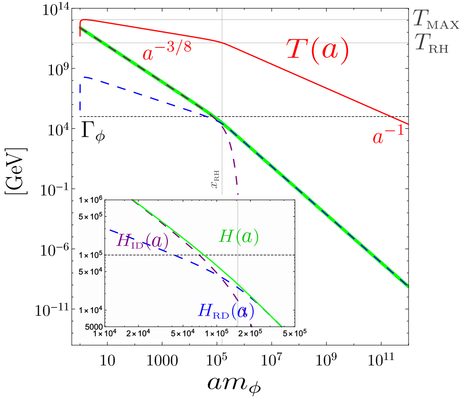
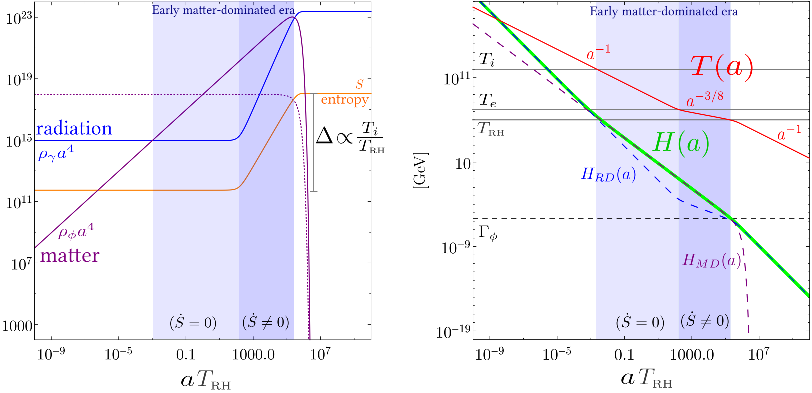




$$\Omega^0_{DM} h^2 \sim \frac{m_{DM}}{10^{-28}} \left(T_{RH}^7 \int_{T_{RH}}^{T_{MAX}} dT \frac{R_{DM}(T)}{T^{13}} + \int_{T_0}^{T_{RH}} dT \frac{R_{DM}(T)}{T^6} \right)$$

Reading suggestion: "Largest temperature of the radiation era and its cosmological implications", by G. F. Giudice, E. W. Kolb, A. Riotto 2000

DM genesis during early matter era



$$H_{RD}(T) \propto \frac{T^2}{M_P}$$

$$H_{MD}(T)|_{\dot{S}=0} \propto H_{RD}(T_{RH})\sqrt{\Delta}\left(\frac{T}{T_{RH}}\right)^{3/2}$$

$$H_{MD}(T)|_{\dot{S}\neq 0} \propto H_{RD}(T_{RH})\left(\frac{T}{T_{RH}}\right)^{4}$$

Temperature-dependence of the rate density

The temperature dependence of the rate density can tell us if **most of the production** would happen at the smallest (IR) or at the highest (UV) scale available.

When $R(T) \propto T^n$:

$$\Omega^0_{DM} h^2|_{radiation} \propto \int_{T_{IR}}^{T_{UV}} dT \frac{T^n}{T^6} = \begin{cases} \frac{T_{IR}^{-(5-n)}}{5-n}\left(1-\frac{T_{IR}^{5-n}}{T_{UV}^{5-n}}\right), & n < 5 \text{ (IR)} \\ \ln\left(\frac{T_{IR}}{T_{UV}}\right), & n = 5 \text{ (IR/UV)} \\ \frac{T_{UV}^{n-5}}{n-5}\left(1-\frac{T_{IR}^{n-5}}{T_{UV}^{n-5}}\right), & n > 5 \text{ (UV)} \end{cases}$$

$$\Omega^0_{DM} h^2|_{inflaton} \propto \int_{T_{IR}}^{T_{UV}} dT \frac{T^n}{T^{13}} = \begin{cases} \frac{T_{IR}^{-(12-n)}}{12-n}\left(1-\frac{T_{IR}^{12-n}}{T_{UV}^{12-n}}\right), & n < 12 \text{ (IR)} \\ \ln\left(\frac{T_{IR}}{T_{UV}}\right), & n = 12 \text{ (IR/UV)} \\ \frac{T_{UV}^{n-12}}{n-12}\left(1-\frac{T_{IR}^{n-12}}{T_{UV}^{n-12}}\right), & n > 12 \text{ (UV)} \end{cases}$$

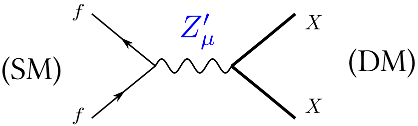
The spin-1 portal

Freezing-in dark matter through a heavy invisible Z′

Gautam Bhattacharyya, MD, Yann Mambrini, Mathias Pierre

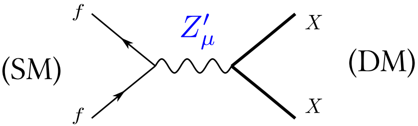
Phys. Rev. D 98, 035038 (2018) - arXiv:1806.00016

SM fermions **charged** under $U(1)'$



- Good relic density for WIMPs and Z' in the 10 GeV - 10 TeV mass range
- Pole regions ($m_X \sim M_{Z'}/2$) and Majorana WIMPs evade DD bounds in simplified models [arXiv:1703.07364]

SM fermions **charged** under $U(1)'$



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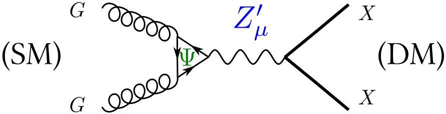
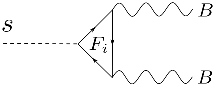
SM fermions **neutral** under $U(1)'$



- Good relic density for FIMPs in wide mass range, even for Z' in the $10^8 - 10^{15}$ GeV mass range
- No kinetic mixing in this model

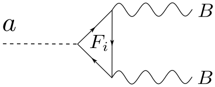
Scalar giving mass to the heavy fermions: $\Phi = s + ia; \;\; \langle \Phi \rangle = V$

Higgs-like



$$\mathscr{L}^{\text{eff}}_{\text{scalar}} = \frac{1}{V}\left[\sum_{ij}(Q^i_L + Q^j_R)\right] s\, B_{\mu\nu}B^{\mu\nu}$$

Peccei–Quinn



$$\mathscr{L}^{\text{eff}}_{\text{axion}} = \frac{1}{V}\left[\sum_{ij}(Q^i_L + Q^j_R)\right] a\, \epsilon_{\mu\nu\sigma\rho}B^{\mu\nu}B^{\sigma\rho}$$

$$\delta\mathscr{L}^{\text{eff}}_{\text{scalar}} \Rightarrow 0 \qquad\qquad \delta\mathscr{L}^{\text{eff}}_{\text{axion}} \Rightarrow 0$$

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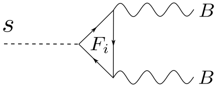

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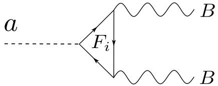
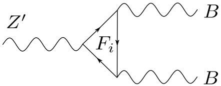


$$\mathscr{L}^{\text{eff}}_{\text{axion}} = \frac{1}{V}\left[\sum\nolimits_{ij} (Q^i_L + Q^j_R)\right] a\, \epsilon_{\mu\nu\sigma\rho} B^{\mu\nu} B^{\sigma\rho}$$

$$\delta \mathscr{L}^{\text{eff}}_{\text{scalar}} \Rightarrow 0 \qquad \delta \mathscr{L}^{\text{eff}}_{\text{axion}} \Rightarrow 0$$

Generalized Chern-Simons



$$\mathscr{L}^{\text{eff}}_{\text{GCS}} = \left[\sum\nolimits_{ij} (Q^i_L - Q^j_R)\right] \epsilon_{\mu\nu\sigma\rho} Z'^{\mu} B^{\nu} B^{\sigma\rho}$$

[Z′ portal to Chern-Simons Dark Matter arXiv:1706.04198]

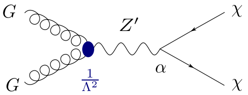
$$a \to a + \frac{\tilde{g}V}{2}\alpha$$
$$Z'_\mu \to Z'_\mu + \partial_\mu \alpha$$

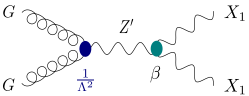
$$\delta(\mathscr{L}^{\text{eff}}_{\text{axion}} + \mathscr{L}^{\text{eff}}_{\text{GCS}}) \Rightarrow 0$$

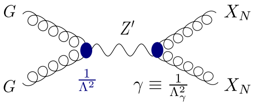
Heavy secluded Z' portal

Beyond the standard model sector [arXiv:1806.00016]

- local $U(1)_{\boldsymbol{x}}$, with gauge boson Z'
- heavy fermions charged under $U(1)_{\boldsymbol{x}}$ and $SU(3)_c$ – Generalized Chern-Simons (GCS) effective terms
- fermionic DM χ charged under $U(1)_{\boldsymbol{x}}$; GCS for Abelian DM vector X_1 and non-Abelian DM vector X_N







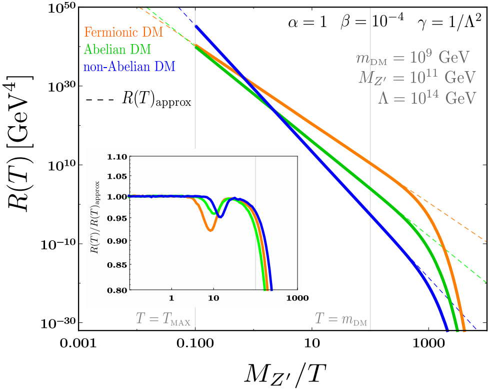
$$\mathscr{L}_{\rm eff} \supset \frac{1}{\Lambda^2}\partial^\alpha Z'_\alpha \epsilon^{\mu\nu\rho\sigma}\,\mathrm{Tr}[G^a_{\mu\nu}G^a_{\rho\sigma}] + \begin{cases} \alpha\, \bar{\chi}\gamma^\mu\gamma_5\chi Z'_\mu \\ \beta\, \epsilon_{\mu\nu\rho\sigma} Z'^\mu X_1^\nu X_1^{\rho\sigma} \\ \gamma\, \partial^\alpha Z'_\alpha \epsilon_{\mu\nu\rho\sigma}\,\mathrm{Tr}[X_N^{\mu\nu} X_N^{\rho\sigma}] \end{cases}$$

Production rate densities

$$\int d\Omega|\mathscr{M}|^2 \propto \frac{m_\chi^2 s^3}{\Lambda^4 M_{Z'}^4}$$

$$\int d\Omega|\mathscr{M}|^2 \propto \frac{s^4}{\Lambda^4 M_{Z'}^4}$$

$$\int d\Omega|\mathscr{M}|^2 \propto \frac{s^6}{\Lambda_\gamma^4 \Lambda^4 M_{Z'}^4}$$



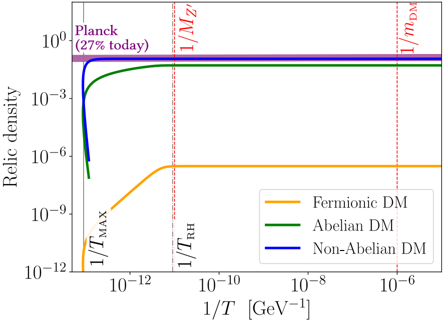
- non-resonant exchange of Z'
- strong temperature dependence: T^{10}, T^{12}, T^{16}

- the higher the temperature, the more DM is produced;
- Boltzmann suppression $(T \ll m_{\mathbf{DM}})$

$\Gamma_{Z'}^2 \ll M_{Z'}^2$

Heavy secluded Z' portal: results

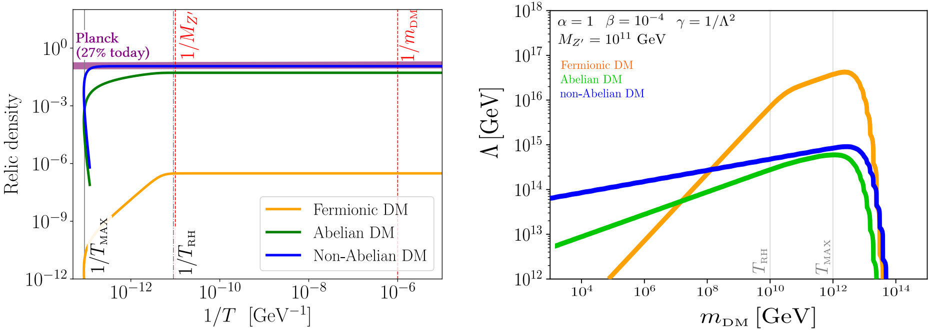
Evolution of DM relic density...



- non-resonant exchange of Z'
- all UV w.r.t. radiation (n>5); IR (n=10), IR/UV (n=12), UV (n=16) w.r.t. reheating

Heavy secluded Z' portal: results

Evolution of DM relic density... ... and agreement with Planck 2018



- non-resonant exchange of Z'
- all UV w.r.t. radiation (n>5); IR (n=10), IR/UV (n=12), UV (n=16) w.r.t. reheating

- Good relic density for Z' mass and new physics scale at intermediate scales, for a wide range of FIMP mass

The spin-2 portal

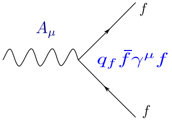
Spin-2 portal dark matter

Nicolás Bernal, MD, Yann Mambrini, Keith A. Olive, Marco Peloso, Mathias Pierre

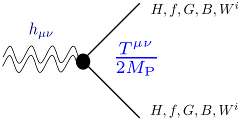
Phys. Rev. D 97, 115020 (2018) - arXiv:1803.01866

Heavy spin-2 portal

Electromagnetism

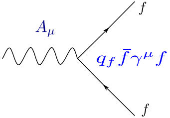


Gravity

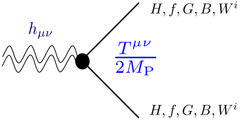


Heavy spin-2 portal

Electromagnetism

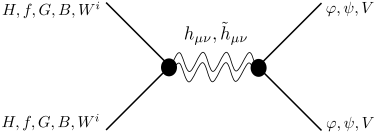


Gravity



Beyond the standard model sector [arXiv:1803.01866]

- massless spin-2 field (graviton) $h_{\mu\nu}$;
- massive spin-2 field, $\tilde{h}_{\mu\nu}$;
- **DM**: scalar φ, fermion ψ and vector V.



$$\mathscr{L} \supset \frac{1}{2M_\mathrm{P}} h_{\mu\nu}\left(\sum_{i=SM} T_i^{\mu\nu} + T_{DM}^{\mu\nu}\right) + \frac{1}{\Lambda}\tilde{h}_{\mu\nu}\left(g_{SM}\sum_{i=SM} T_i^{\mu\nu} + g_{DM} T_{DM}^{\mu\nu}\right)$$

Production rate densities

Massive spin-2 contribution:

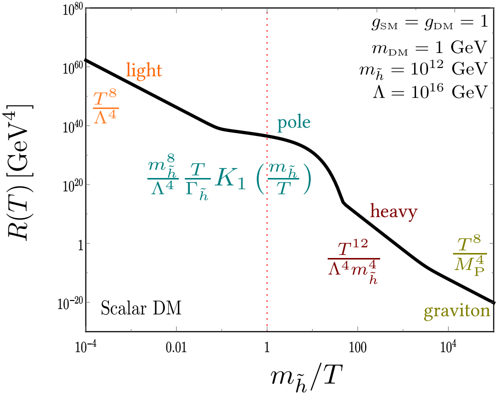
$$\int d\Omega |\mathscr{M}|^2 \propto \frac{s^4/\Lambda^4}{(s-m_{\tilde{h}}^2)^2 + m_{\tilde{h}}^2\Gamma_{\tilde{h}}^2}$$

$$\rightarrow \begin{cases} s^2/\Lambda^4 & \text{(light)} \\ \delta(s-m_{\tilde{h}}^2)\frac{s^4}{\Lambda^4 m_{\tilde{h}}\Gamma_{\tilde{h}}} & \text{(pole)} \\ s^4/(m_{\tilde{h}}^4\Lambda^4) & \text{(heavy)} \end{cases}$$

Graviton contribution:

$$\int d\Omega |\mathscr{M}|^2 \propto \frac{s^2}{M_P^4} \quad \text{(graviton)}$$

- universal gravity couplings
- resonant exchange of $\tilde{h}$

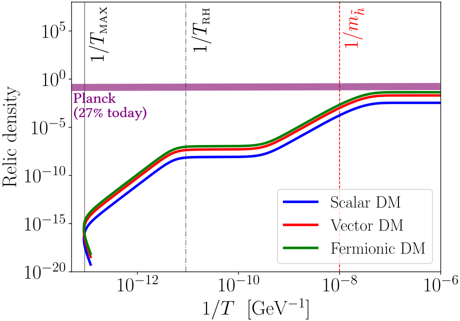


- temperature dependence according to mediator regime (independent of DM spin)

$s \gg m^2_{\rm DM}$

Heavy spin-2 portal: results

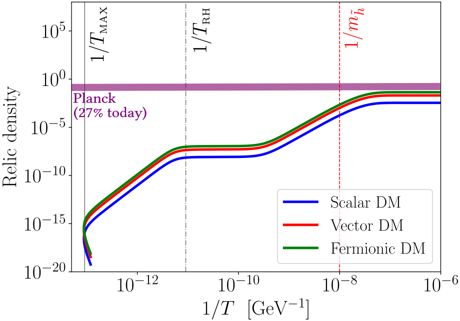
Evolution of DM relic density...



- universal gravity couplings
- The freeze-in happens either close to T_{RH} or $m_{\tilde{h}}$

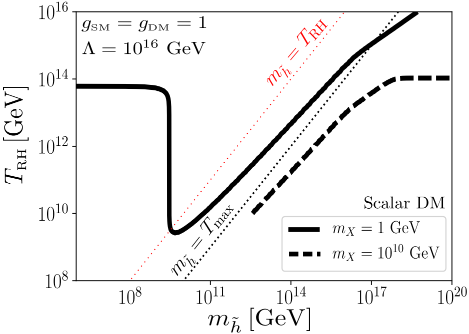
Heavy spin-2 portal: results

Evolution of DM relic density...



- universal gravity couplings
- The freeze-in happens either close to T_{RH} or $m_{\tilde h}$

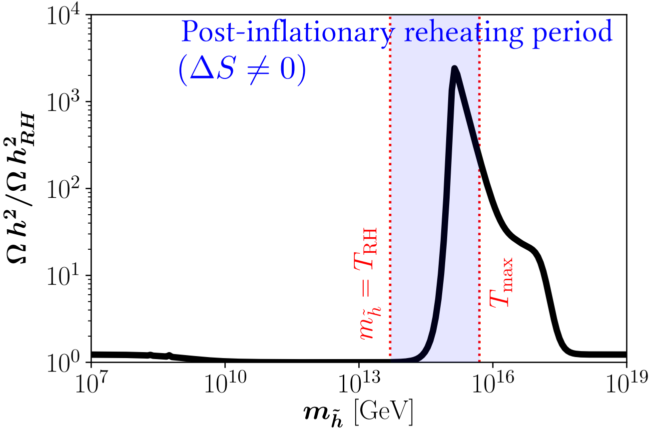
... and agreement with Planck 2018



- Good relic density for $m_{\tilde h}$ and Λ at intermediate scales, for a wide range of FIMP mass

Dark matter production during reheating & resonant portals

If the mediator mass lies between the reheating and maximal temperature, the production rate of dark matter contains a "wild" pole due to resonant production of mediators



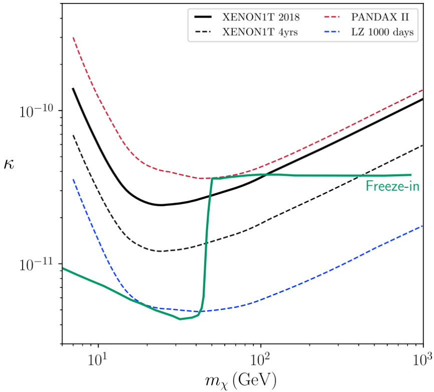
Conclusions and perspectives

Conclusions

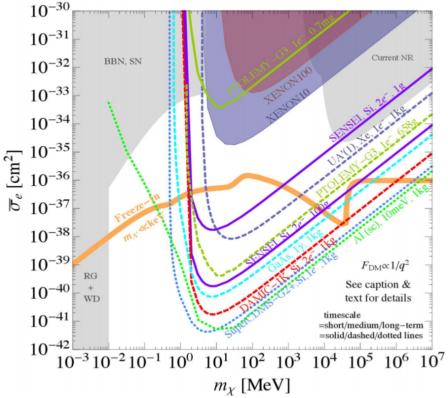
- Usual direct detection *vs* thermalization condition tension: frozen-out relics easily overproduced;
- Freeze-in & structural extensions of the SM: heavy feebly interacting fields (Z', fermions, spin-2, moduli) easily mediate the freeze-in production of dark matter;
- Resonant production of mediators during reheating needs to be carefully taken into account, as the resulting relic density of dark matter would be orders of magnitude underestimated otherwise.

Perspectives for FIMP pheno: direct detection

- Direct detection is testing freeze-in and there is a concrete phenomenological future



Hambye, Tytgat, Vandecasteele, Vanderheyden
arXiv: 1807.05022

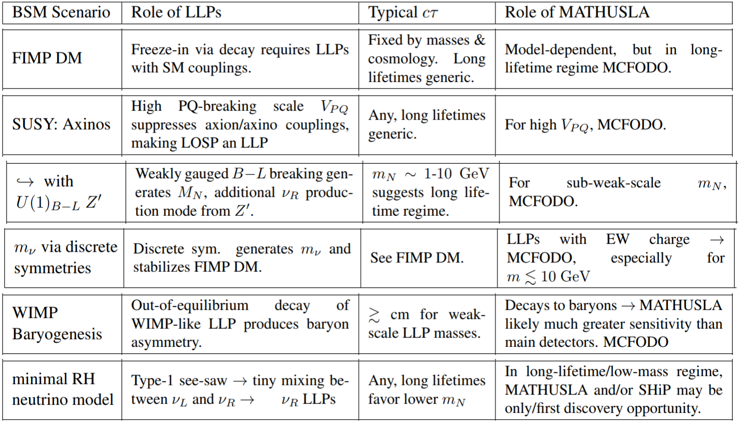


US Cosmic Visions - Community Report
arXiv: 1707.04591

Perspectives for FIMP pheno: LLPs @ MATHUSLA

MAssive Timing Hodoscope for Ultra-Stable neutraL PArticles: proposed detector at the life-time frontier

MATHUSLA Could be First or Only Discovery Opportunity (MCFODO) [Theory White Paper - arXiV:1806.07396]



BSM Scenario	Role of LLPs	Typical $c\tau$	Role of MATHUSLA
FIMP DM	Freeze-in via decay requires LLPs with SM couplings.	Fixed by masses & cosmology. Long lifetimes generic.	Model-dependent, but in long-lifetime regime MCFODO.
SUSY: Axinos	High PQ-breaking scale V_{PQ} suppresses axion/axino couplings, making LOSP an LLP	Any, long lifetimes generic.	For high V_{PQ}, MCFODO.
$\hookrightarrow$ with $U(1)_{B-L}$ Z'	Weakly gauged $B-L$ breaking generates M_N, additional ν_R production mode from Z'.	$m_N \sim$ 1-10 GeV suggests long lifetime regime.	For sub-weak-scale m_N, MCFODO.
m_ν via discrete symmetries	Discrete sym. generates m_ν and stabilizes FIMP DM.	See FIMP DM.	LLPs with EW charge $\rightarrow$ MCFODO, especially for $m \lesssim 10$ GeV
WIMP Baryogenesis	Out-of-equilibrium decay of WIMP-like LLP produces baryon asymmetry.	$\gtrsim$ cm for weak-scale LLP masses.	Decays to baryons $\rightarrow$ MATHUSLA likely much greater sensitivity than main detectors. MCFODO
minimal RH neutrino model	Type-1 see-saw $\rightarrow$ tiny mixing between ν_L and ν_R $\rightarrow$ ν_R LLPs	Any, long lifetimes favor lower m_N	In long-lifetime/low-mass regime, MATHUSLA and/or SHiP may be only/first discovery opportunity.

Muito Obrigada!

Maíra Dutra @ DARKWINS 2019