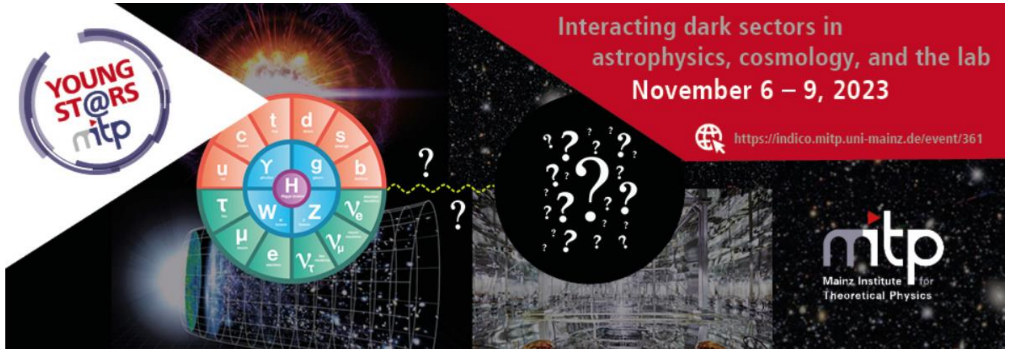
HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Asymmetries in Extended Dark Sectors: A Cogenesis Scenario

Juan Herrero-García, GL, Drona Vatsyayan

[2301.13238]

Giacomo Landini



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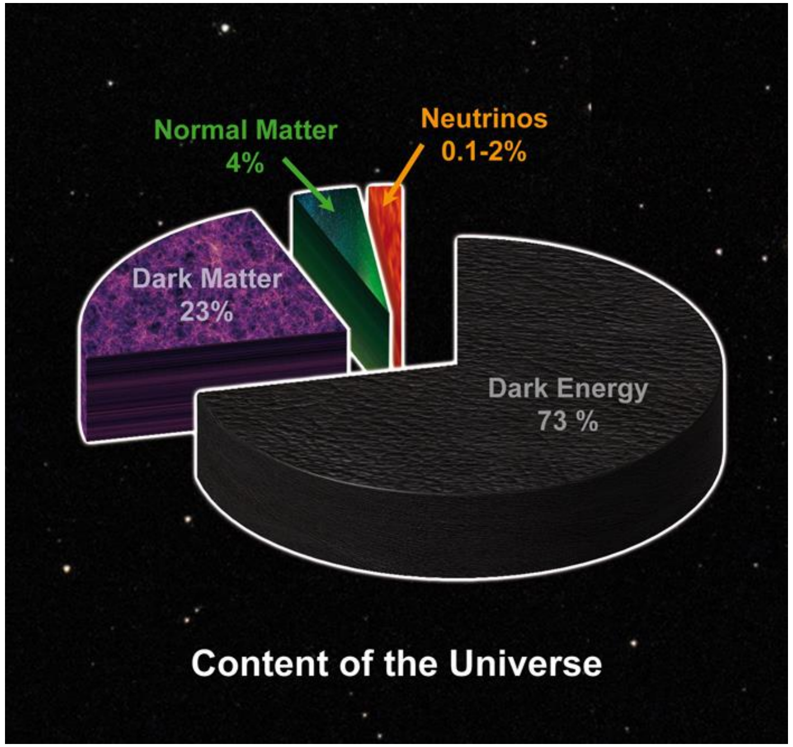
06/11/2023

Dark Matter

Dark Matter is five times more abundant than baryonic matter



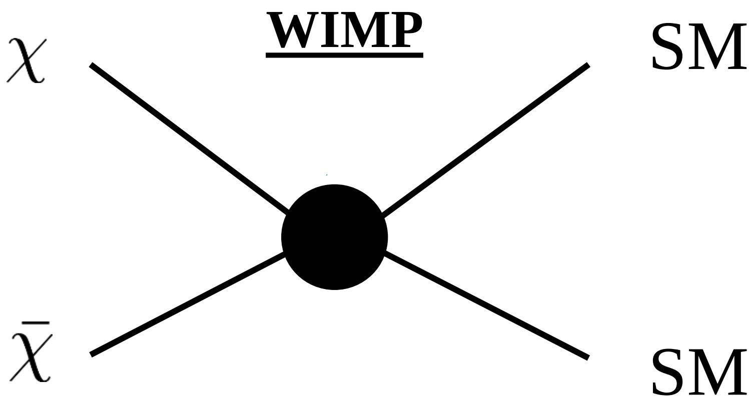
$$\rho_{\rm DM} \simeq 5\rho_B$$

Cosmic coincidence

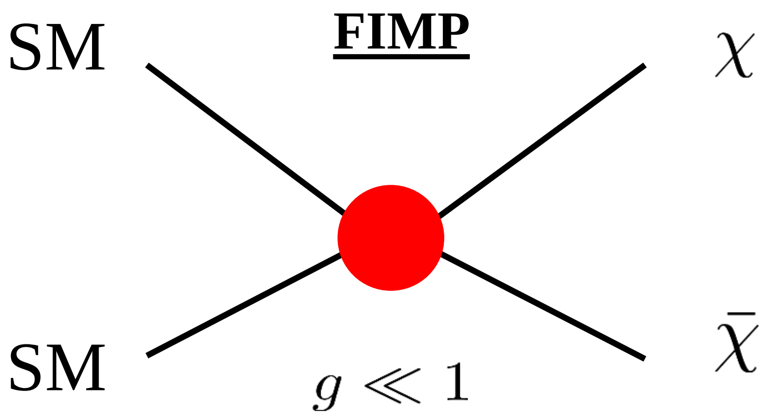
→ A common origin for baryons and DM?

Standard (symmetric) production

Freeze-out: DM is in thermal equilibrium with the SM



Freeze-in: DM is **not** in thermal equilibrium with the SM



$g \ll 1$

Tiny couplings evade experimental bounds!

Dark Matter is **symmetric (?)**

$$Y_\chi = Y_{\bar{\chi}}$$

Asymmetric Dark Matter

The Baryon abundance is set by an asymmetry

$$\eta_B = Y_b - Y_{\bar{b}} = 0.88 \times 10^{-11}$$

,

The nature of DM could also be asymmetric!

$$\eta_D = Y_\chi - Y_{\bar{\chi}}$$

$$\frac{\rho_{\rm DM}}{\rho_B} = \frac{m_{\rm DM}\eta_D}{m_p \eta_B} \simeq 5$$

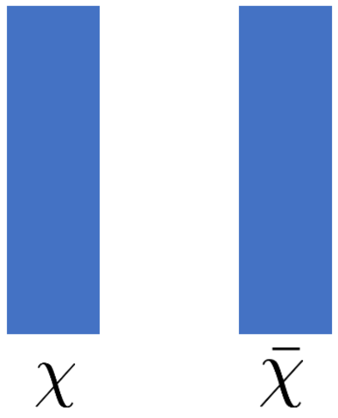
Attractive scenario: $\eta_D \simeq \eta_B \longrightarrow m_{\rm DM} \simeq 5 m_p \simeq 5\ {\rm GeV}$

Asymmetric Dark Matter

$$\eta_D = Y_\chi - Y_{\bar{\chi}} \qquad r = Y_{\bar{\chi}}/Y_\chi$$

Symmetric

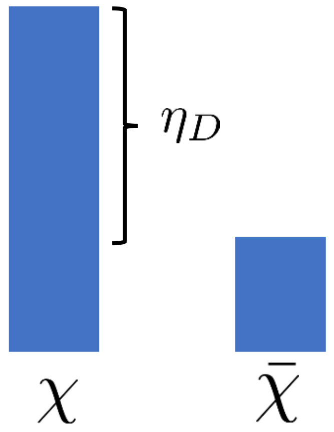
$$r > 0.9$$



$$\rho_{\rm DM} \propto 1/\sigma v$$

Asymmetric

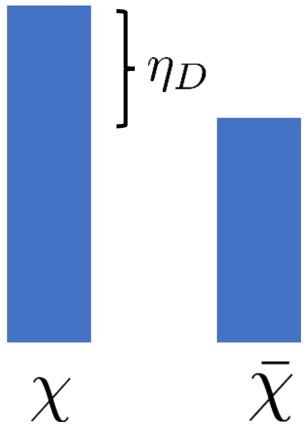
$$r < 10^{-2}$$



$$\rho_{\rm DM} \propto m\eta_D$$

Partially Asymmetric

$$10^{-2} < r < 0.9$$

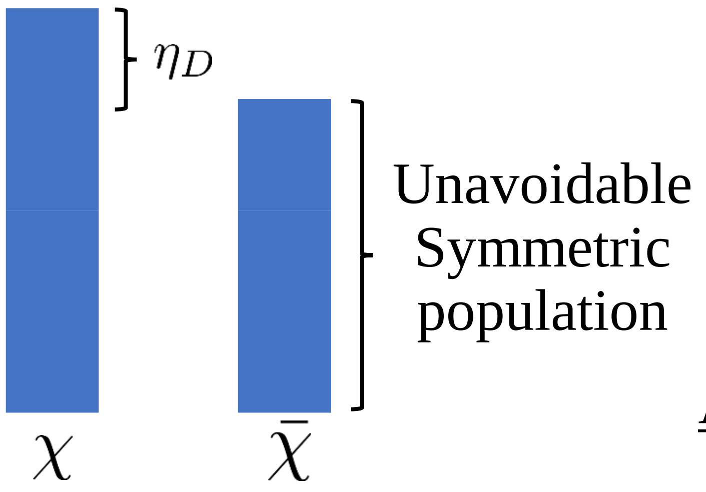


$$\rho_{\rm DM} = f(m, \sigma v, \eta_D)$$

Asymmetric freeze-out

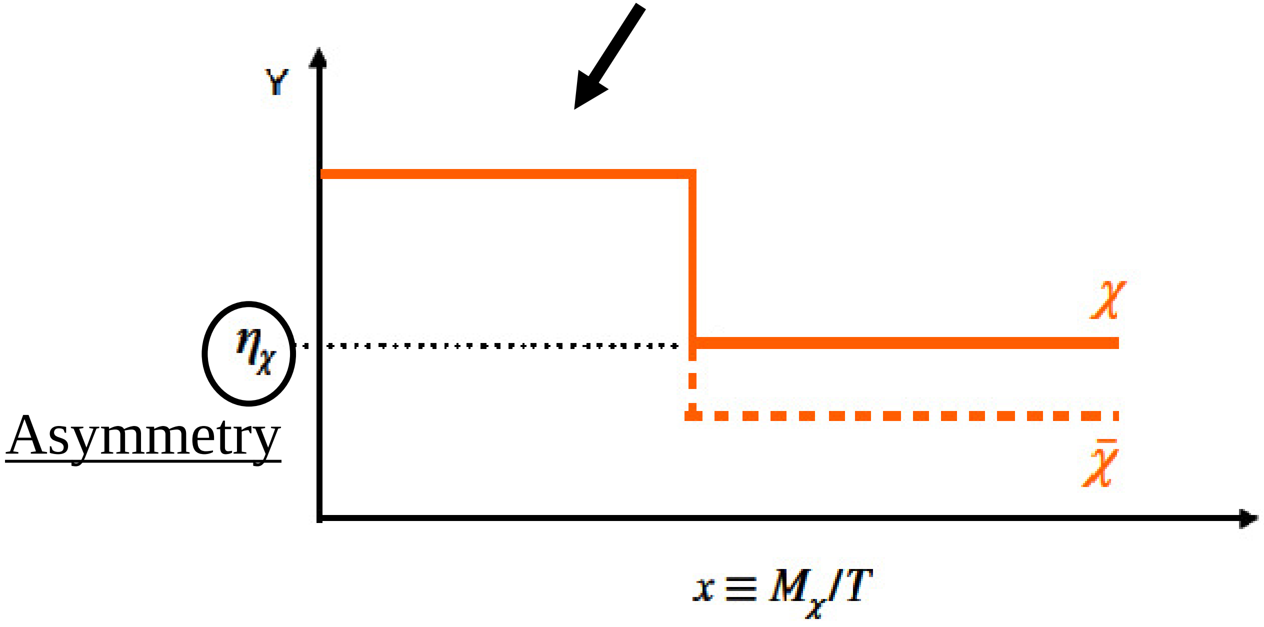
$$\eta_D = Y_\chi - Y_{\bar{\chi}} \qquad r = Y_{\bar{\chi}}/Y_\chi$$

Asymmetry generation



$$r \simeq 1$$

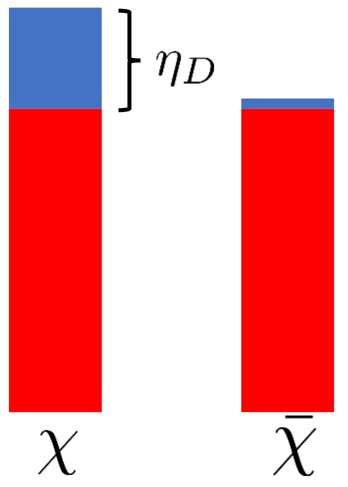
Symmetric (thermal) population



Asymmetric freeze-out

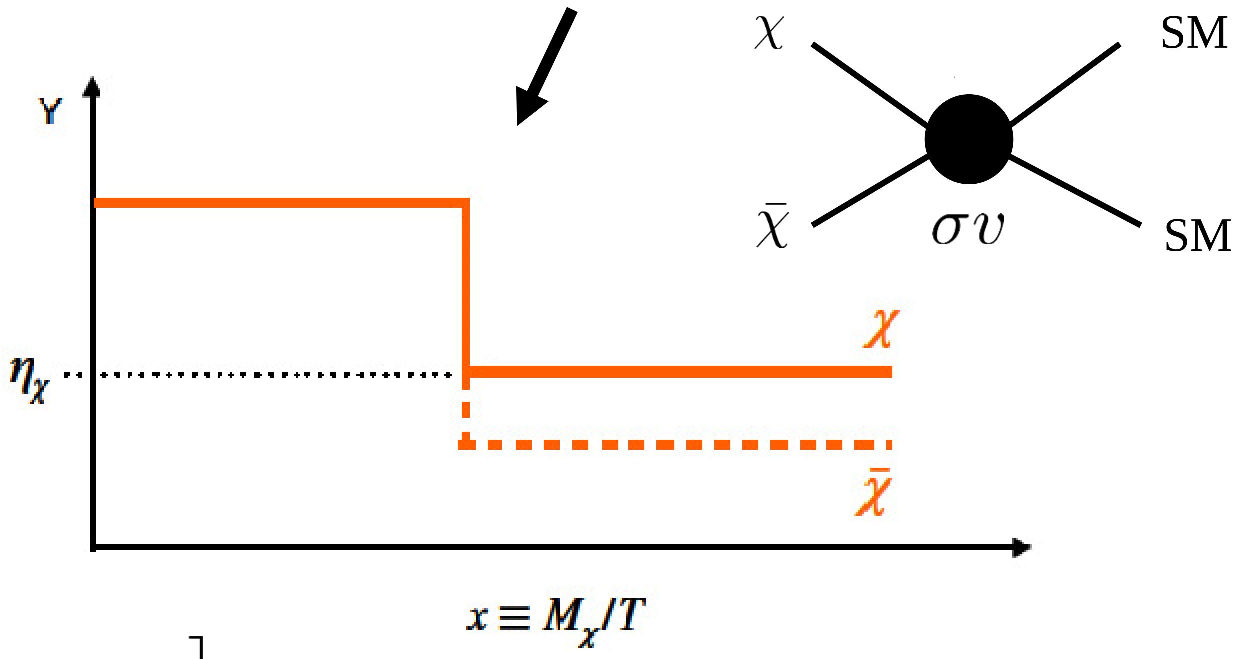
$$\eta_D = Y_\chi - Y_{\bar{\chi}} \qquad r = Y_{\bar{\chi}}/Y_\chi$$

Annihilation of the symmetric component



$$r < 1$$

Annihilations (thermal equilibrium)

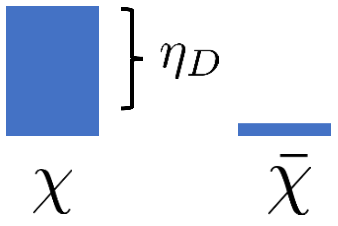


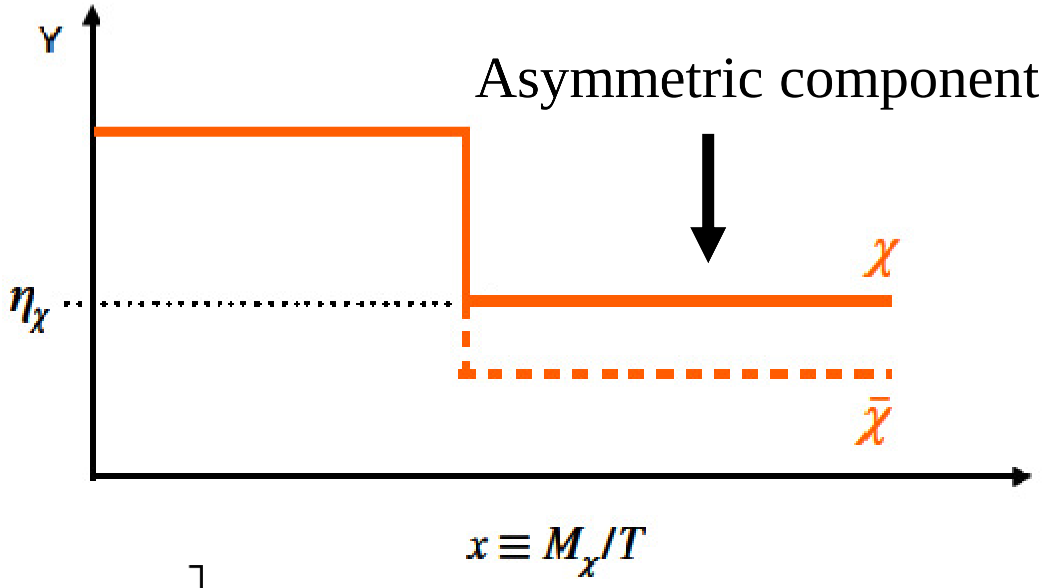
$$r_\infty \propto \exp\left[-\frac{\pi g_*}{45 x_f} M_{\rm Pl} \sigma v \eta_D m\right]$$

Graesser, Shoemaker, Vecchi
[1103.2771]

Asymmetric freeze-out

$$\eta_D = Y_\chi - Y_{\bar{\chi}} \qquad r = Y_{\bar{\chi}}/Y_\chi$$





$$r \ll 1$$

$$r_\infty \propto \exp\left[-\frac{\pi g_*}{45 x_f} M_{\rm Pl} \sigma v \eta_D m\right]$$

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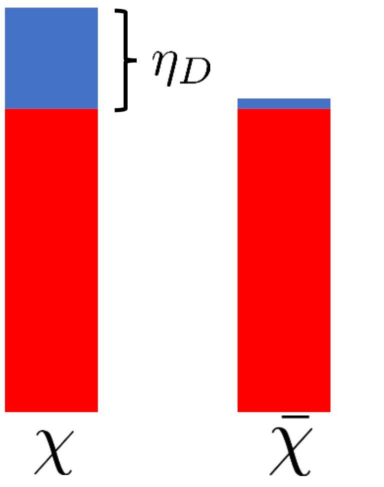
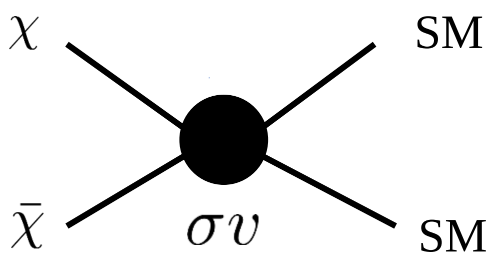
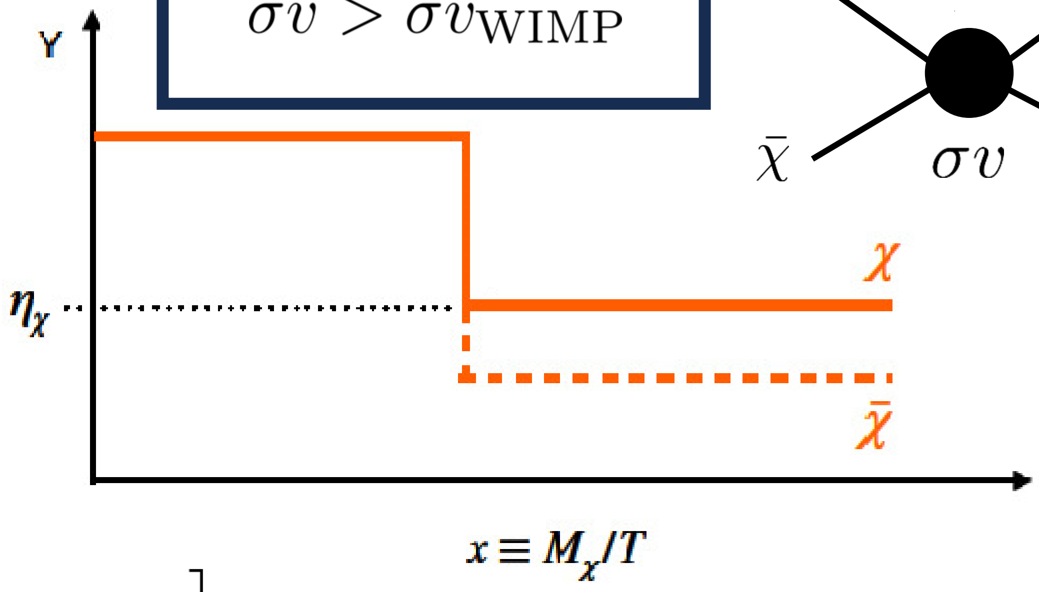


Large cross sections are needed!

$$\sigma v > \sigma v_{\rm WIMP}$$





$$r_\infty \propto \exp\left[-\frac{\pi g_*}{45 x_f} M_{\rm Pl} \sigma v \eta_D m\right]$$

Graesser, Shoemaker, Vecchi
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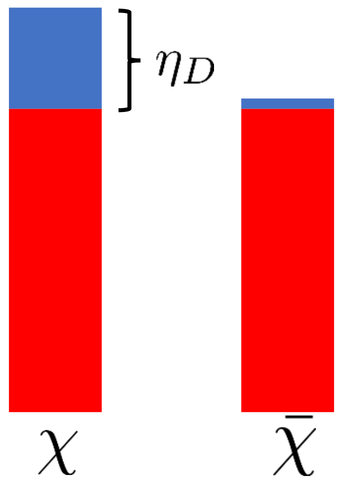
Asymmetric freeze-in?

$$\eta_D = Y_\chi - Y_{\bar{\chi}} \qquad r = Y_{\bar{\chi}}/Y_\chi$$

Annihilation of the symmetric component



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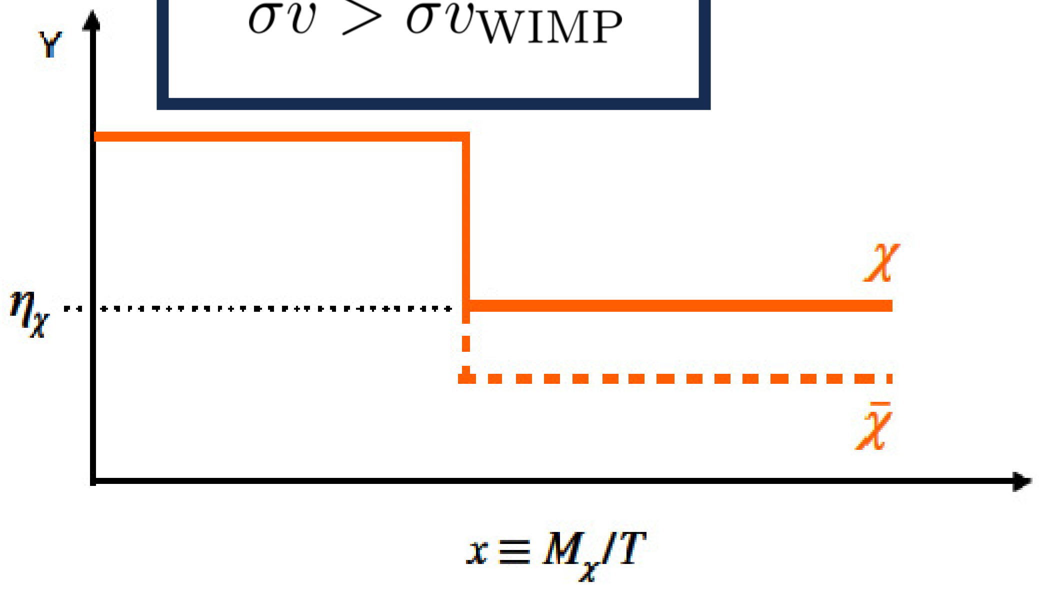


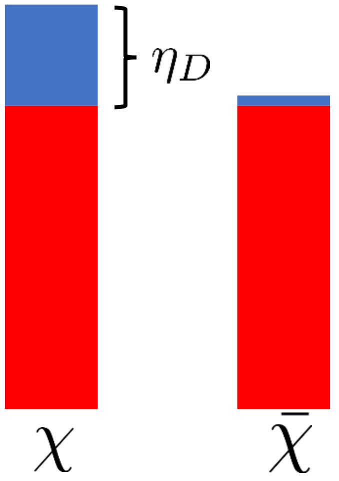
Asymmetric DM out of equilibrium (tiny couplings, freeze-in) ?

(How to erase the symmetric component?)

Asymmetric freeze-in?

$$\eta_D = Y_\chi - Y_{\bar{\chi}} \qquad r = Y_{\bar{\chi}}/Y_\chi$$

Annihilation of the symmetric component



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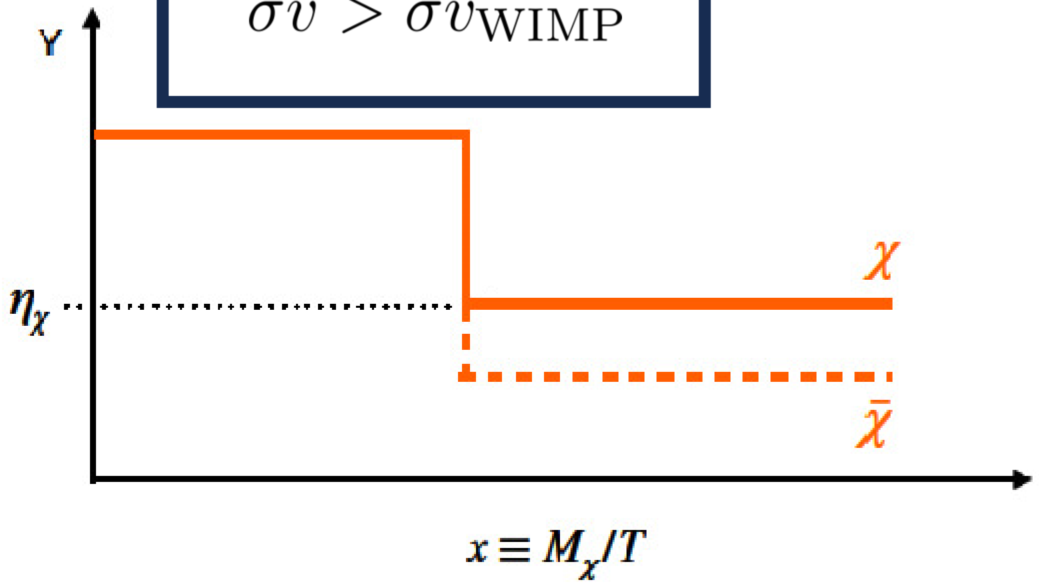
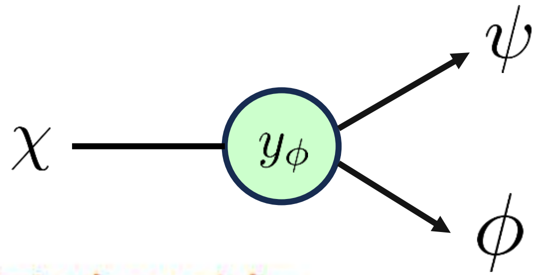
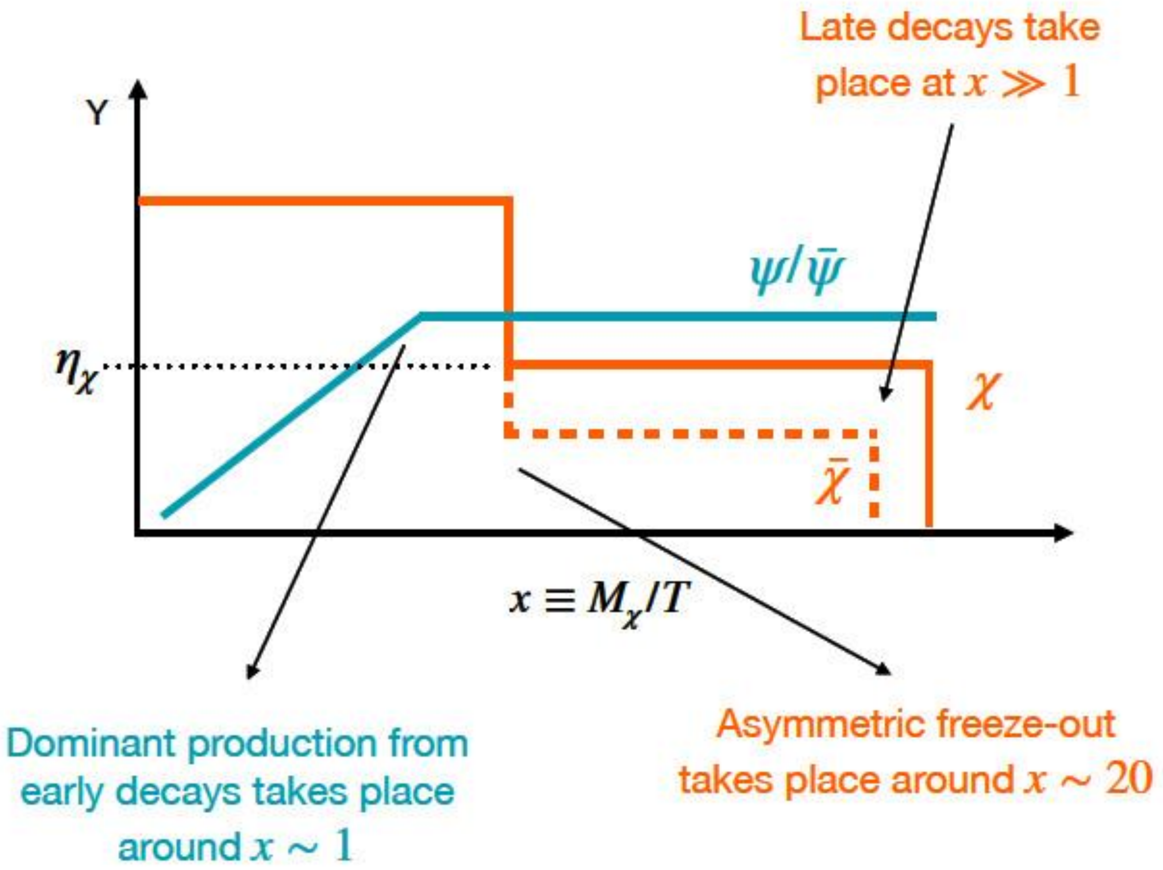
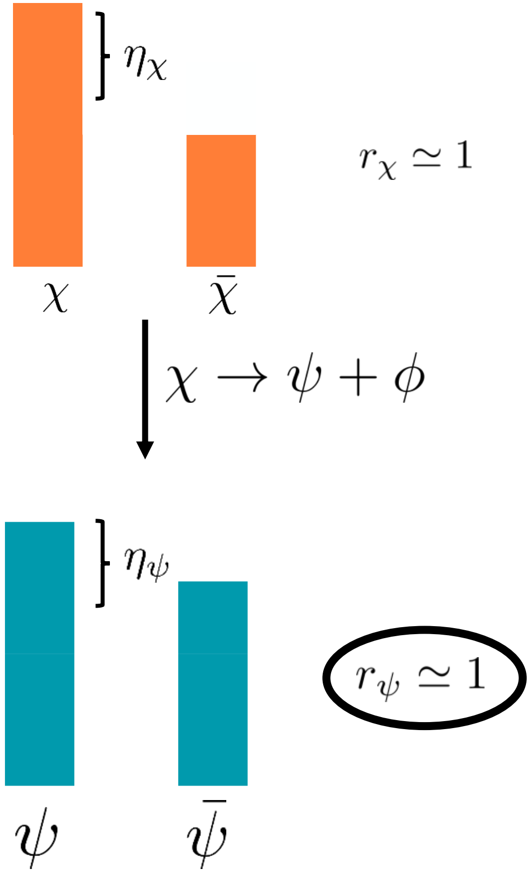


Idea: late decays of an asymmetric species

Early vs Late decays

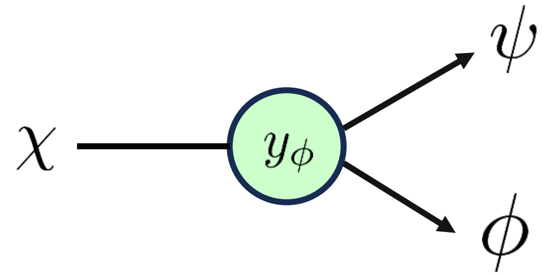


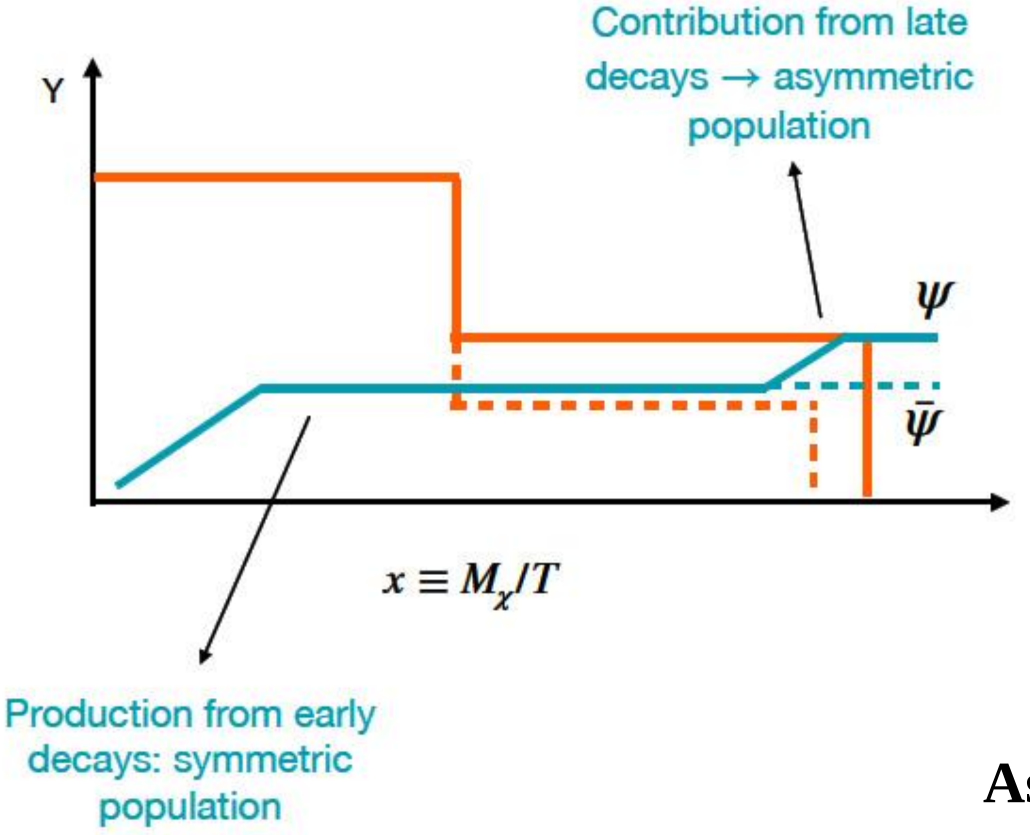


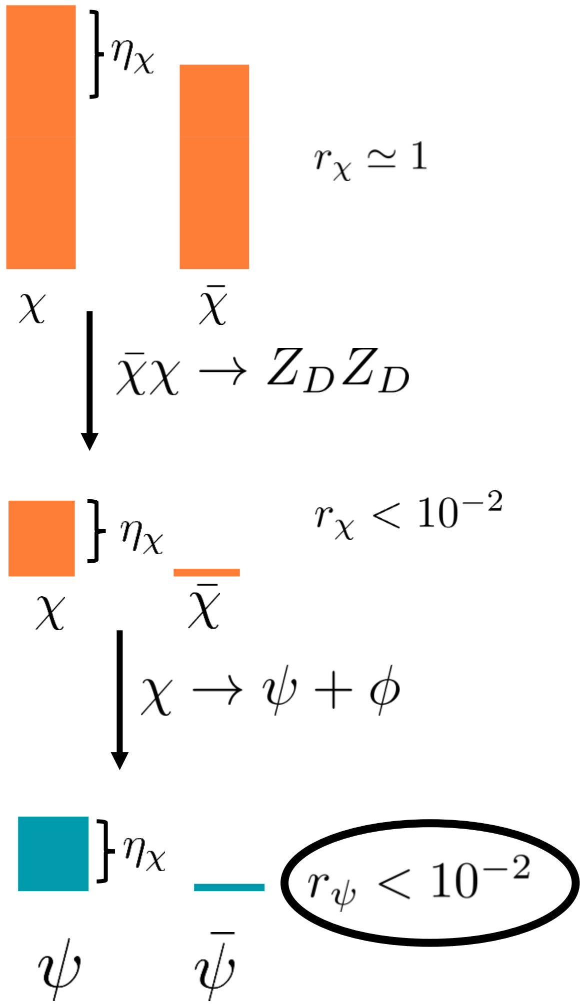


No annihilations

Early vs Late decays







Asymmetric FIMP DM!

A Cogenesis scenario

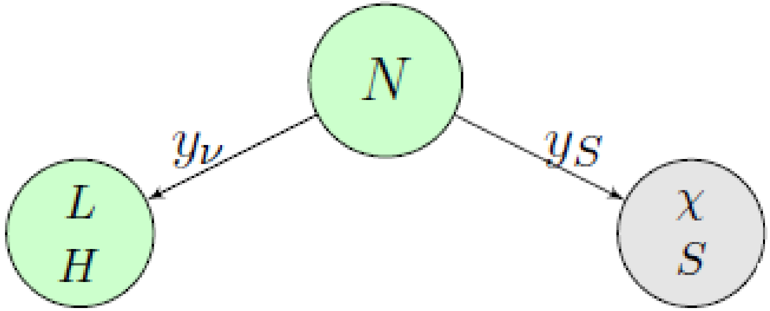
Falkowski, Ruderman, Volansky [1101.4936]

CP-violating decays of **RHNs**
out of equilibrium

Lepton asymmetry

Sphalerons

Baryon asymmetry η_B



In thermal equilibrium

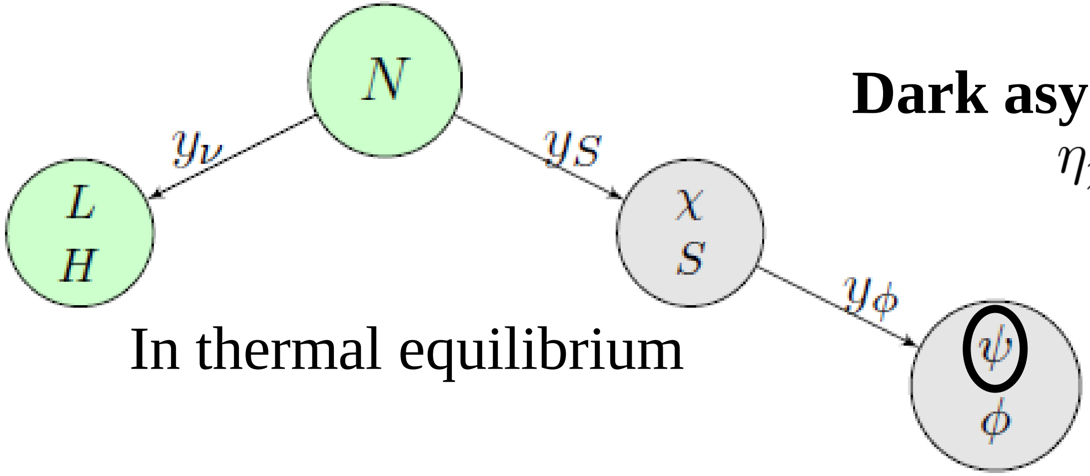
Dark asymmetry generation

$\eta_\chi = \eta_S \sim \eta_B$

$\bar{\chi}\chi$, $S^\dagger S$
annihilations erase
symmetric components

A Cogenesis scenario

CP-violating decays of **RHNs**
out of equilibrium



Lepton asymmetry

Sphalerons

Baryon asymmetry η_B

In thermal equilibrium

Dark asymmetry generation

$$\eta_\chi = \eta_S \sim \eta_B$$

FIMP DM particle
(out of equilibrium)

$$\chi \to \psi + \phi$$
$$\eta_\psi = \eta_\chi$$

The asymmetry is transferred to ψ
via **late** decays after χ symmetric
population has been erased

A Cogenesis scenario

CP-violating decays of **RHNs**
out of equilibrium

Lepton asymmetry

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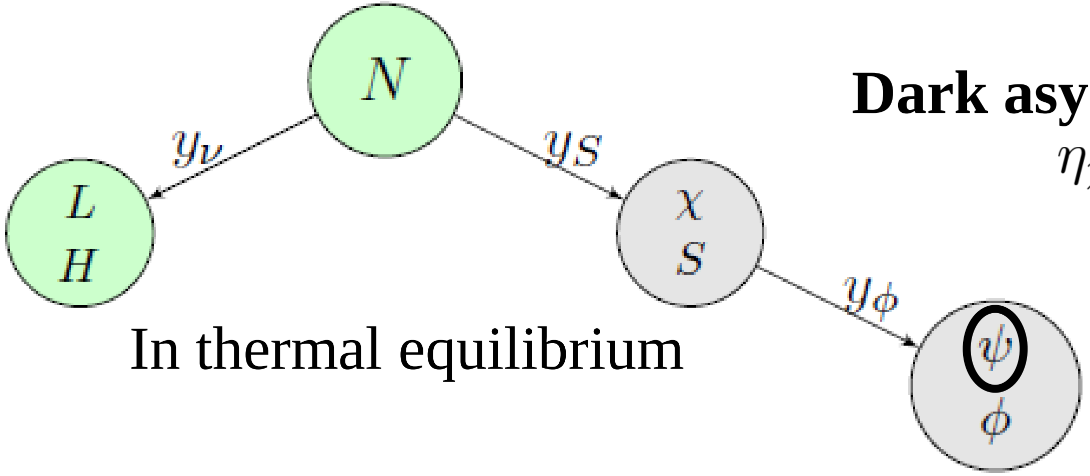
Baryon asymmetry η_B



In thermal equilibrium

Dark asymmetry generation

$$\eta_\chi = \eta_S \sim \eta_B$$

FIMP DM particle
(out of equilibrium)

Neutrino masses

$$m_\nu = -m_D M_N^{-1} m_D^T$$

$$\chi \to \psi + \phi$$

$$\eta_\psi = \eta_\chi$$

The asymmetry is transferred to ψ
via **late** decays after χ symmetric
population has been erased

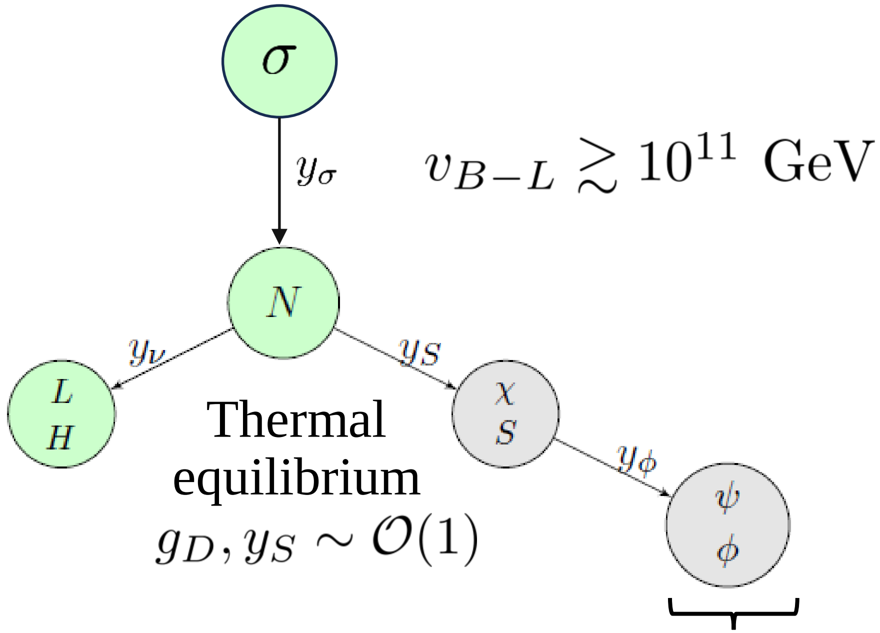
This scenario can explain neutrino masses, baryon asymmetry and (FIMP) Dark Matter!

The model

Field	Spin	$U(1)_{B-L}$	$U(1)_D$	$U(1)_X$
N_R^i	1/2	-1	0	0
σ	0	+2	0	0
χ_0	1/2	-1	1	0
ψ_0	1/2	0	0	+1
S	0	0	-1	0
ϕ	0	+1	-1	+1

$$M_{N_3}, M_{N_2} \gg M_{N_1} \gg m_\chi^0 \gg m_\psi^0, m_S > m_\phi$$

DM stability + Dirac Nature



$y_\phi \ll 1$, $g_X \ll 1$

ψ is **not** in thermal equilibrium

$$\mathcal{L}_{\rm int} = -y_\nu^{\alpha i}\bar{L}^\alpha \tilde{H} N_R^i - y_\sigma^{ij}\sigma \overline{N_R^{ic}} N_R^j - y_S^i S \bar{N}_R^i \chi_0 - y_\phi \phi \bar{\psi}_0 \chi_0 + {\rm H.c.}\,.$$

Neutrino masses

$$M_{N_1} \propto \langle \sigma \rangle = v_{B-L} \longrightarrow m_\nu = -m_D M_N^{-1} m_D^T$$

The model

$$U(1)_{B-L} \otimes U(1)_D \otimes U(1)_X \;\rightarrow\; U(1)_D \otimes U(1)_X \;\rightarrow\; U(1)_{X+D}$$

$$\langle \sigma \rangle = v_{B-L} > 10^{11}\ \text{GeV} \qquad \langle \phi \rangle = v_\phi \ll v_{B-L}$$

Particle	$U(1)_{X+D}$
χ	$+1$
ψ	$+1$
S	-1

DM candidates: ψ, S

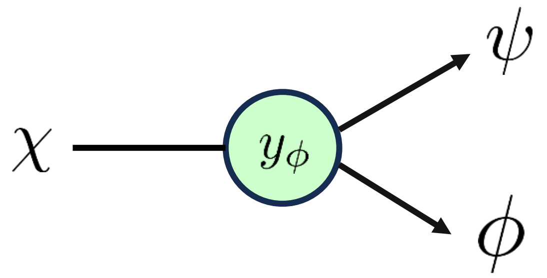
$S \to \bar{\psi} + \bar{\nu}$ or $\psi \to S^\dagger + \nu$ are allowed but suppressed

Both cosmologically stable

Multicomponent DM

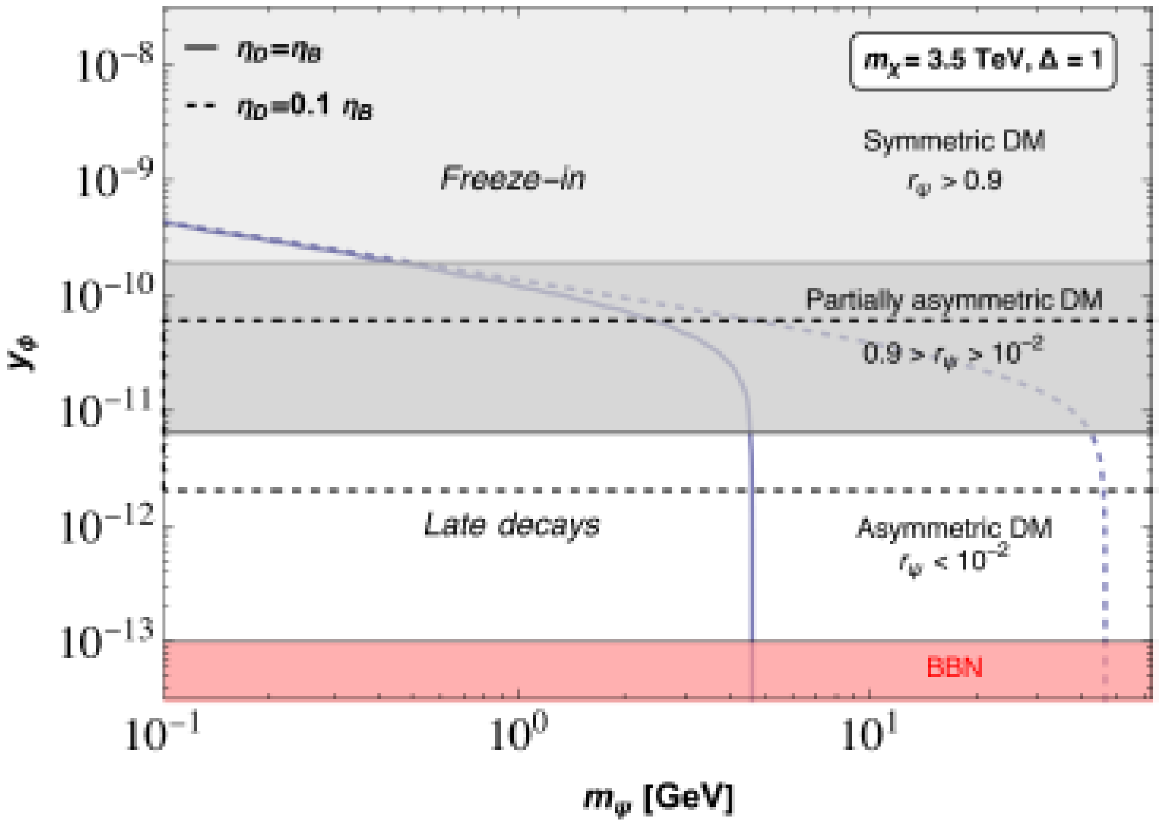
DM production (Fermion)

$$T_D \simeq 10 \text{ MeV} \left(\frac{y_\phi}{10^{-12}}\right)$$



$\psi \longrightarrow$ No thermalization, stable DM (freeze-in)

$\phi \longrightarrow$ decays through Higgs portal



Early decays are dominant

$$Y_\psi = Y_{\bar{\psi}}$$

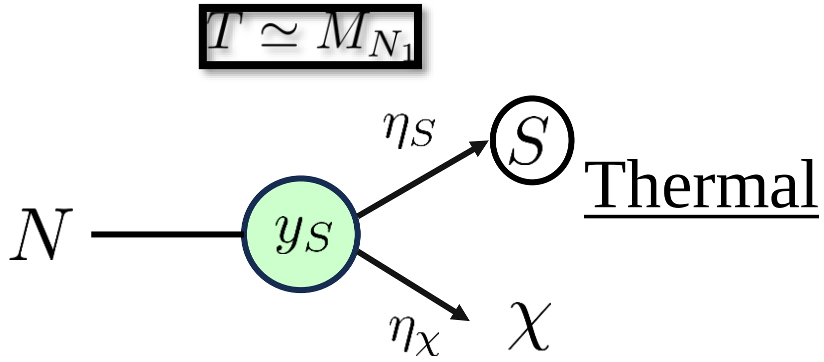
Symmetric DM

Late decays are dominant

$$Y_\psi = \eta_\psi \gg Y_{\bar{\psi}}$$

Asymmetric DM

DM production (Scalar)

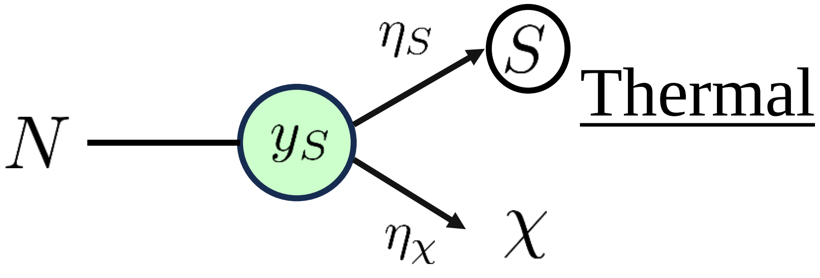


Asymmetric freeze-out $S^\dagger S \to \phi\phi$

$$Y_S = \eta_S$$

DM production (Scalar)

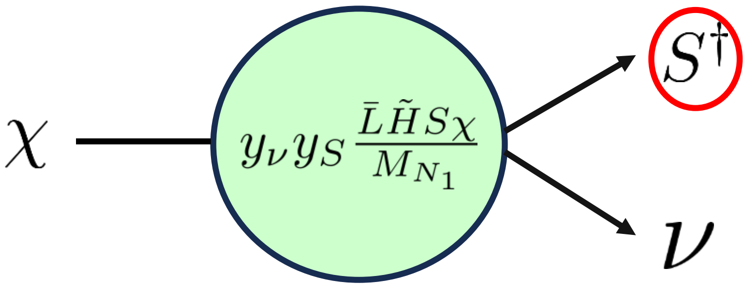
$T \simeq M_{N_1}$



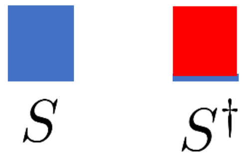
Asymmetric freeze-out $S^\dagger S \to \phi\phi$

$$Y_S = \eta_S$$

$T_D^S \simeq \text{MeV}\left(\frac{|y_S|}{10^{-3}}\right)$



$$Y_{S^\dagger} = \frac{R}{1+R}\eta_S$$



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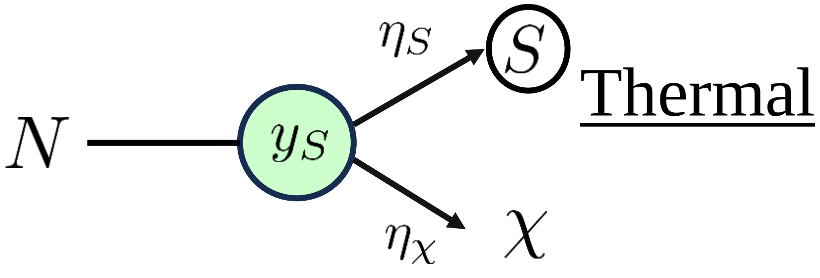

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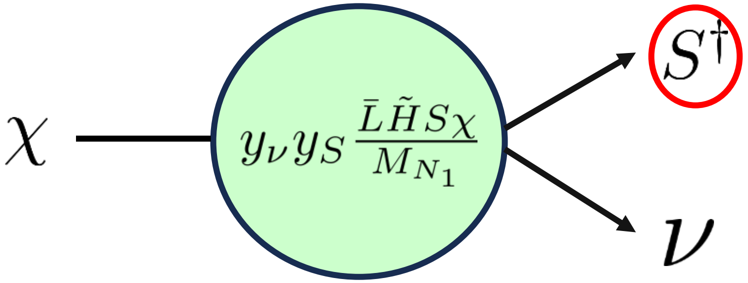
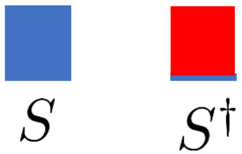


Asymmetric freeze-out $S^\dagger S \to \phi\phi$

$$Y_S = \eta_S$$

$$Y_{S^\dagger} = \frac{R}{1+R}\eta_S$$



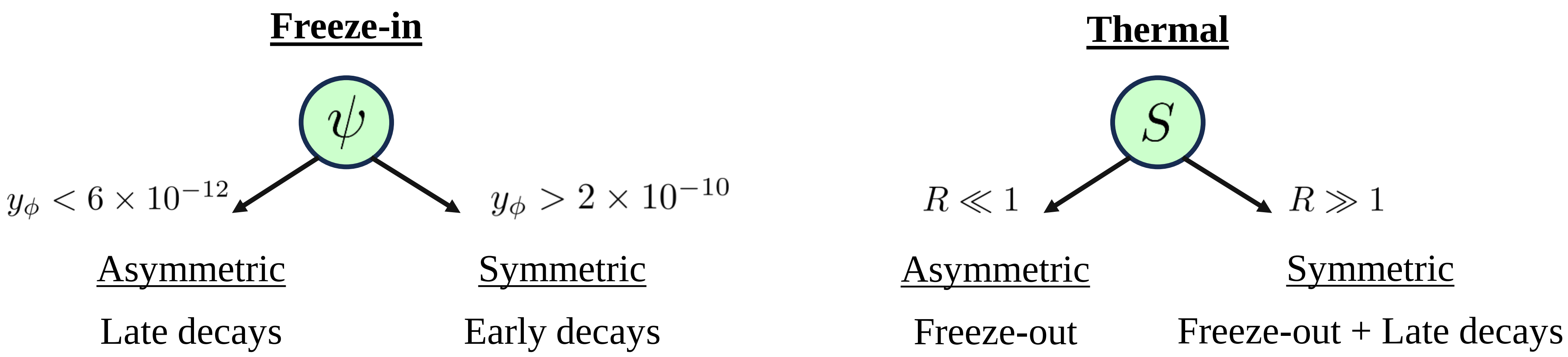
$$R = \frac{\Gamma(\chi \to S^\dagger \nu)}{\Gamma(\chi \to \psi\phi)} \sim \frac{|y_S|^2}{y_\phi^2}\frac{m_\nu}{M_{N_1}}$$

$R \ll 1$ No extra decays, asymmetric DM (freeze-out)

$$Y_S = \eta_S \ , \quad Y_{S^\dagger} = \frac{R}{1+R}\eta_S$$

$R \gg 1$ Cancellation of the asymmetry, symmetric DM (freeze-out)

Scenarios



Sc.	ψ population	S population	$10^{-10} y_\phi/\sqrt{\eta_D/\eta_B}$	R	$T_D^{(S)}/T_*^{(S)}$
1	Asymmetric	Asymmetric	$\lesssim 0.06$	$\ll 1$	Any
2	Asymmetric	Partially Asymmetric	$\lesssim 0.06$	$\mathcal{O}(1)$	< 1
1-2	Asymmetric	Asymmetric	$\lesssim 0.06$	$\mathcal{O}(1)$	> 1
3	Partially Asymmetric	Asymmetric	$0.06 - 2$	$\ll 1$	Any
4	Partially Asymmetric	Partially Asymmetric	$0.06 - 2$	$\mathcal{O}(1)$	< 1
3-4	Partially Asymmetric	Asymmetric	$0.06 - 2$	$\mathcal{O}(1)$	> 1
5	Symmetric	Asymmetric	$\gtrsim 2$	$\ll 1$	Any
6	Negligible	Symmetric	$y_\phi \lesssim 5 \times 10^{-7}$	$\gtrsim \mathcal{O}(10)$	< 1

Scenarios

Freeze-in

ψ

$y_\phi < 6 \times 10^{-12}$ → Asymmetric: Late decays

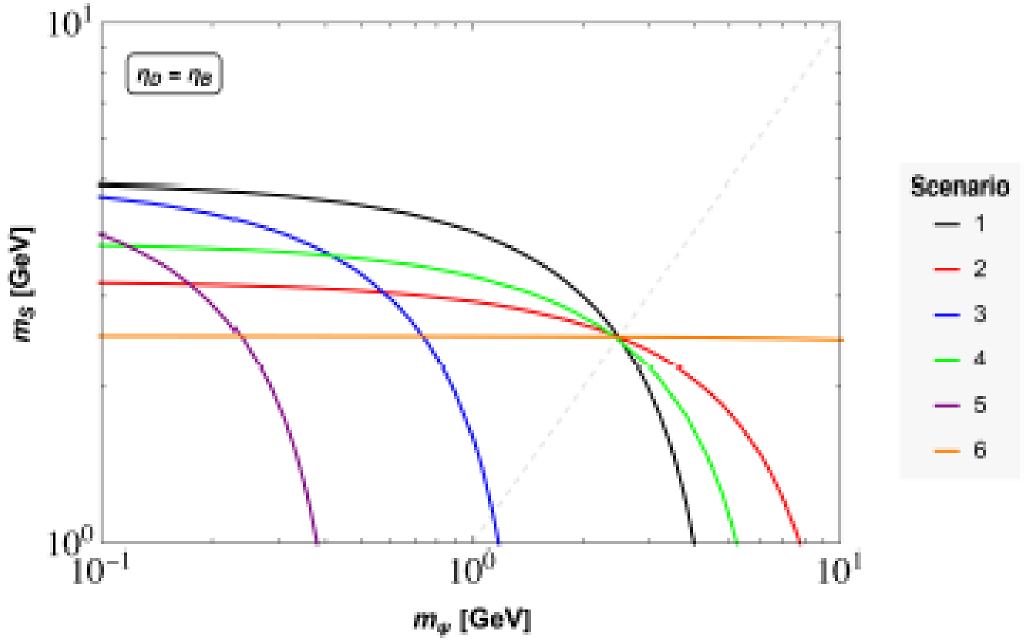
$y_\phi > 2 \times 10^{-10}$ → Symmetric: Early decays

Thermal

S

$R \ll 1$ → Asymmetric: Freeze-out

$R \gg 1$ → Symmetric: Freeze-out + Late decays



$$\frac{\Omega_\psi}{\Omega_S} = \frac{m_\psi(\eta_D + Y_{\rm FI})}{\eta_D m_S f(R)}\,, \qquad \frac{\Omega_{\rm DM}}{\Omega_B} = \frac{m_\psi(\eta_D + Y_{\rm FI}) + \eta_D m_S f(R)}{\eta_B (1+R) m_p}\,,$$

$$f(R) \equiv \begin{cases} 1 + 2R & \text{if } T_D^{(S)} < T_*^{(S)} \\ 1 & \text{if } T_D^{(S)} > T_*^{(S)}\,. \end{cases}$$

The DM abundance is reproduced for

$$m_\psi, m_S \sim \text{GeV}$$

Phenomenology

Freeze-in: small couplings, suppressed DD

$$y_\phi \ll 1 \qquad g_X \ll 1$$

ADM: suppressed ID + annihilations in dark sectors

Large $B-L$ scale: no collider searches

$$v_{B-L} \gtrsim 10^{11}\ \text{GeV}$$

DD of scalar DM through Higgs portal

$$\lambda_{HS}(H^\dagger H)(S^\dagger S)$$

ID of scalar DM when S is symmetric

Enhanced ID signal for **Scenario 6**

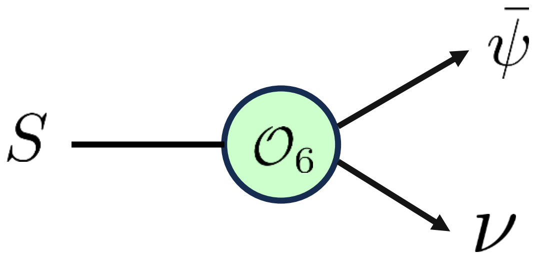
$$Y_S = Y_{S^\dagger} = \eta_S \qquad m_S = 2.5\ \text{GeV} \quad \sigma v > \sigma v_{\text{WIMP}}$$

+ neutrino line!

Smoking gun: neutrino line

$$\mathcal{O}_6 = \bar{L}\tilde{H}S\phi^\dagger\psi$$

generated at $E \ll m_\chi \ll M_{N_1}$



$m_S > m_\psi$
(analogous if $m_\psi > m_S$)

$$\Gamma(S \to \bar{\psi} + \nu) = \frac{|y_S|^2 y_\phi^2 m_S}{32\pi}\left(\frac{v_\phi}{m_\chi}\right)^2\left(\frac{m_\nu}{M_{N_1}}\right)\left(1 - \frac{m_\psi^2}{m_S^2}\right)$$

Neutrino line peaked at $E_\nu \simeq m_S/2 \longrightarrow \mathcal{O}(\text{GeV})$

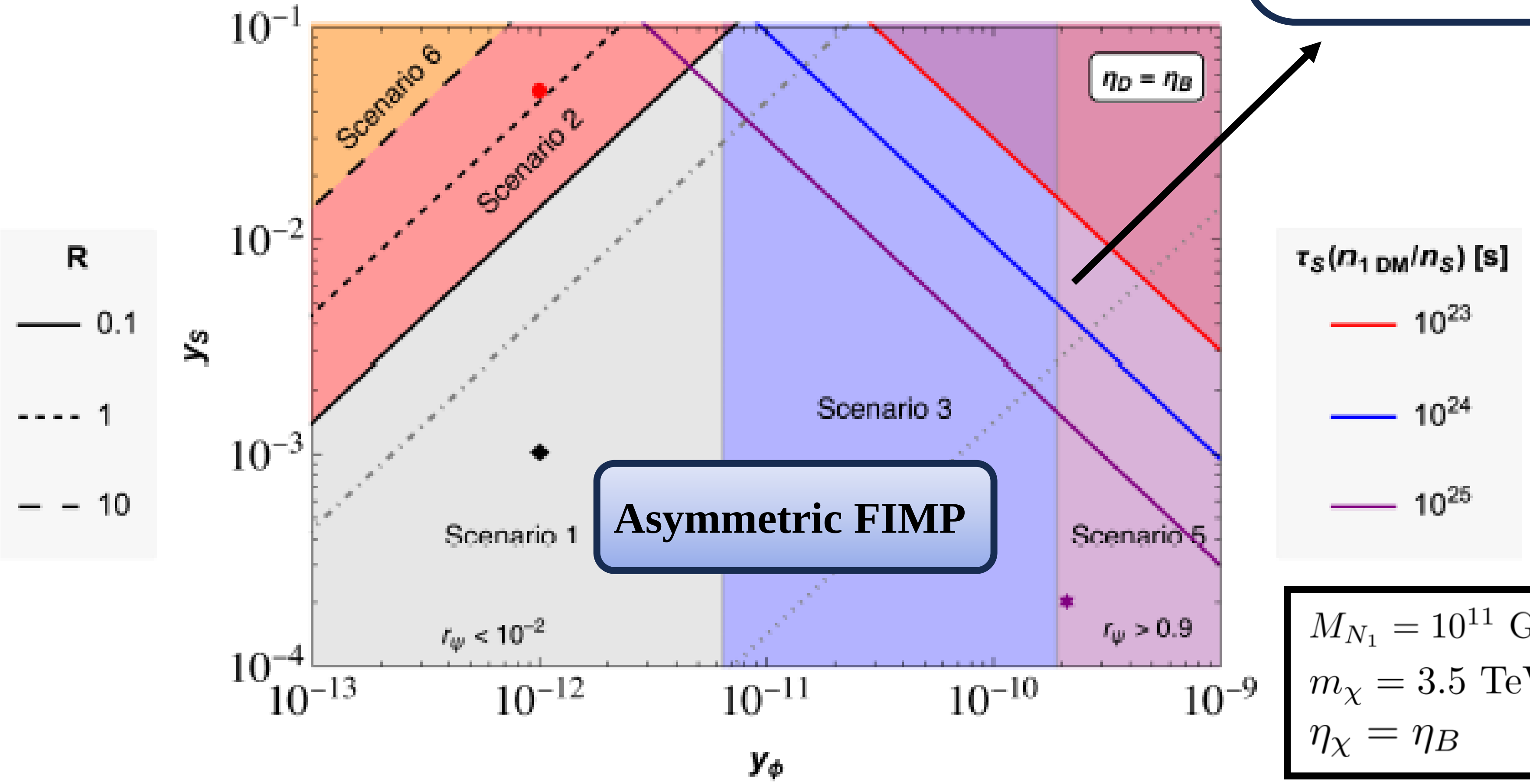
Experimental bound $\tau > 10^{23}$ sec

Future neutrino telescopes? $\tau \sim 10^{24-25}$ sec

[Palomares-Ruiz *2008*, Garcia-Cely *et al. 2017*, Coy *et al. 2021*]

Summary

Smoking Gun **neutrino line**: close to experimental sensitivity (neutrino experiments)

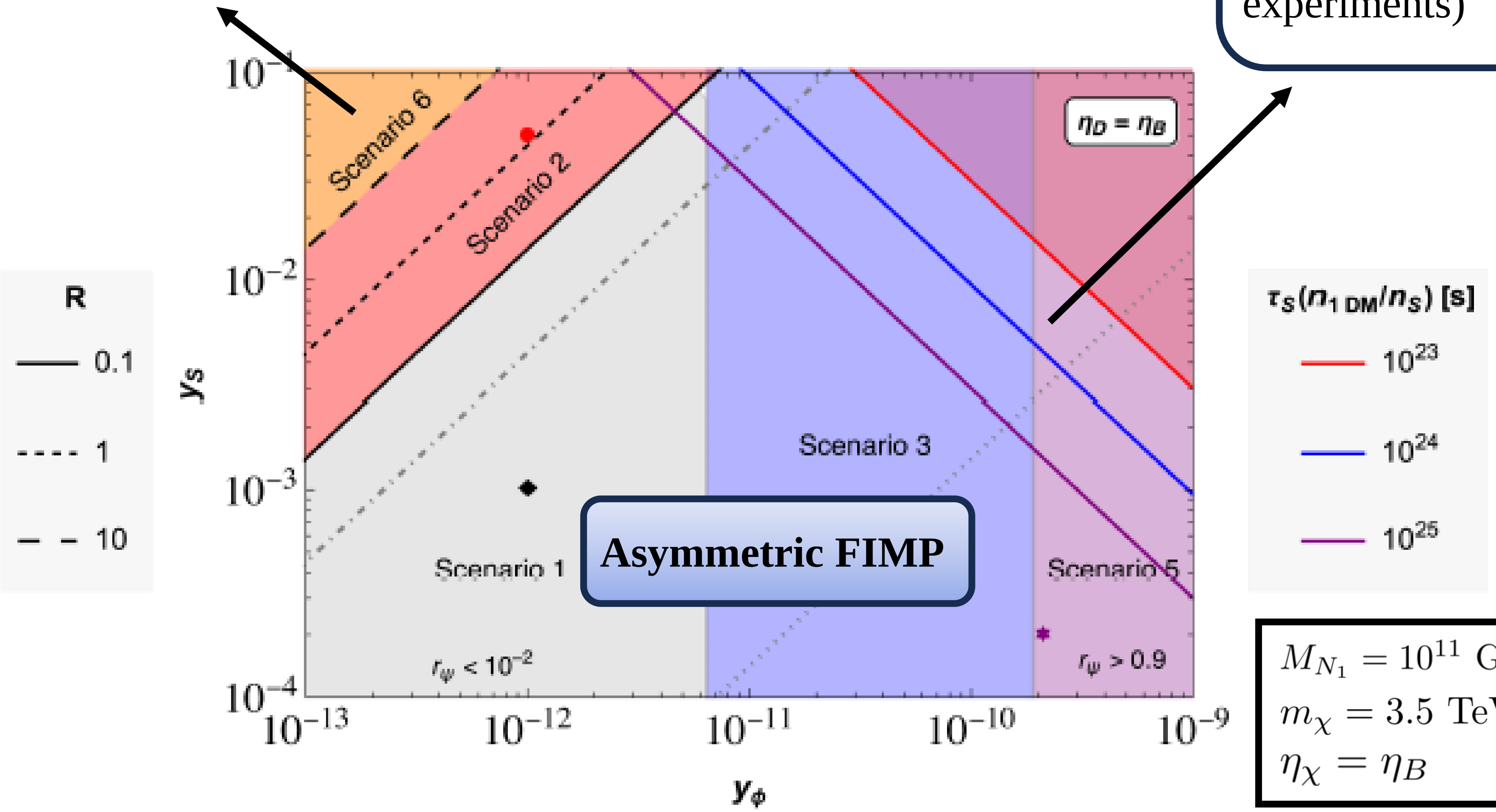


$M_{N_1} = 10^{11}$ GeV
$m_\chi = 3.5$ TeV
$\eta_\chi = \eta_B$

Summary

Symmetric 1DM with interesting features (mix Cold/Warm DM, enhanced ID signals,...)

Smoking Gun **neutrino line**: close to experimental sensitivity (neutrino experiments)



$M_{N_1} = 10^{11}$ GeV
$m_\chi = 3.5$ TeV
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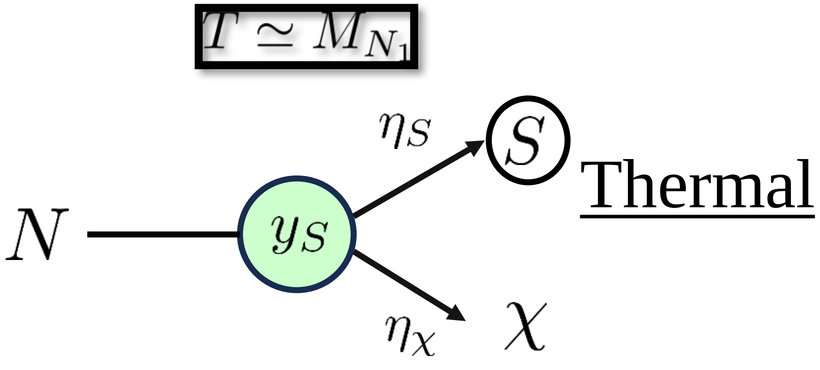
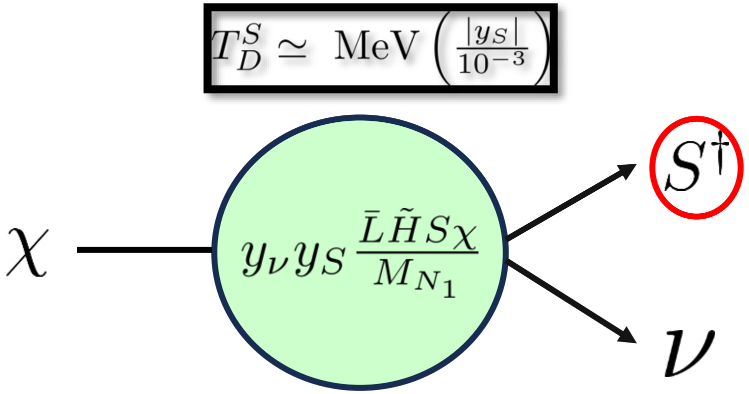
DM production (Scalar)



Cold DM



Warm DM

$$R = \frac{\Gamma(\chi \to S^\dagger \nu)}{\Gamma(\chi \to \psi\phi)} \sim \frac{|y_S|^2}{y_\phi^2} \frac{m_\nu}{M_{N_1}} \gg 1 \longrightarrow Y_S = Y_{S^\dagger} = \eta_S$$

No decays to ψ

1 DM

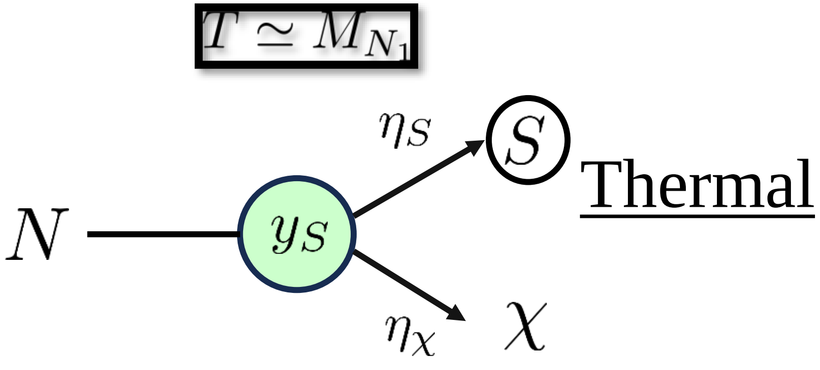
Symmetric population

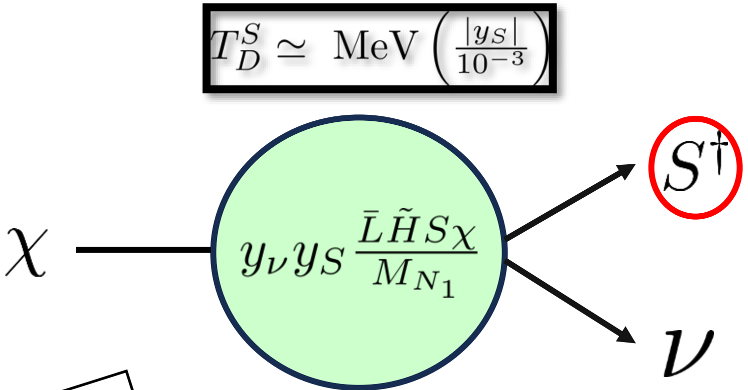
$m_S = 2.5$ GeV

Asymmetry sets the abundance

Enhanced Indirect Detection signals may be present $\sigma v > \sigma v_{\text{WIMP}}$

DM production (Scalar)





Cold DM

Warm DM

Work in progress for more details!

$R = \Gamma($

η_S

Symmetric population

$m_S = 2.5$ GeV

Asymmetry sets the abundance

to ψ

1 DM

ed Indirect Detection signals may be present $\sigma v > \sigma v_{\text{WIMP}}$

Summary

- Asymmetric DM models needs large annihilations cross section: thermalization

- Asymmetric FIMP DM can be realized through late decays of asymmetric particle

- The framework naturally needs an extended dark sector: multicomponent DM, baryogenesis, neutrino masses

- Late DM decays can be constrained by neutrino experiments

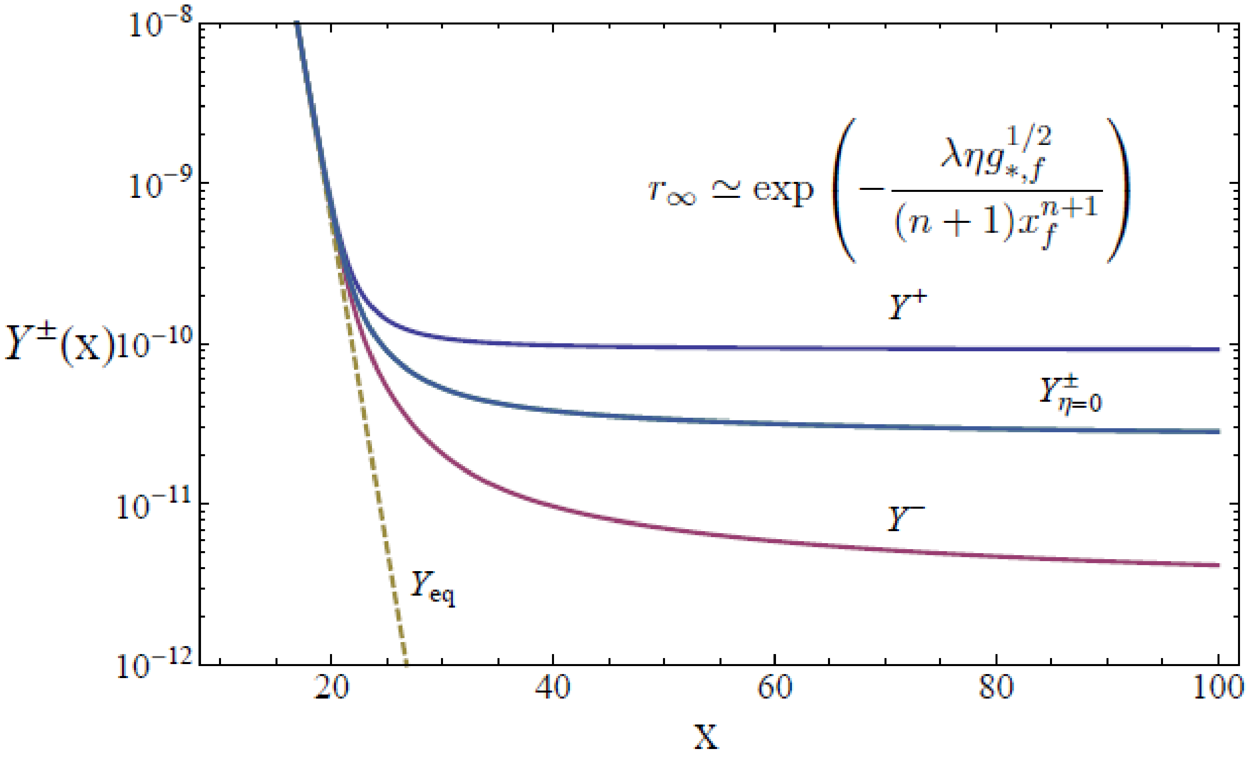
Backup

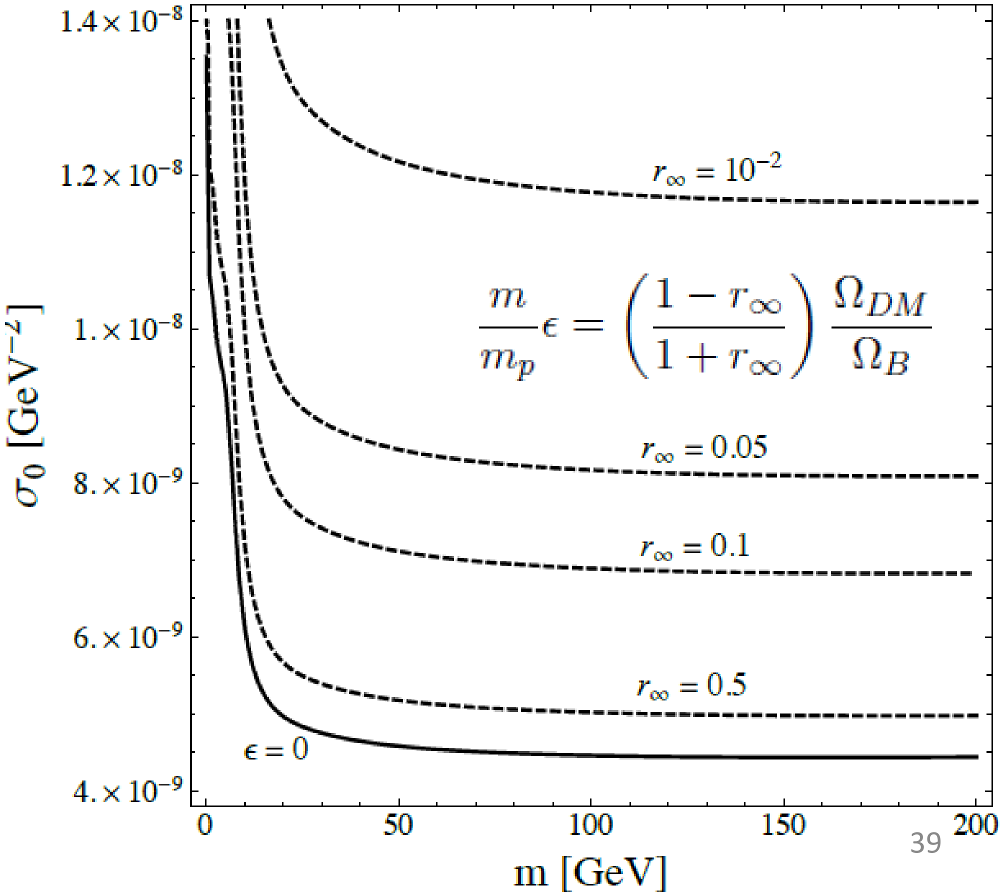
Asymmetric WIMP

Graesser, Shoemaker, Vecchi
[1103.2771]

$$\frac{dr}{dx} = -\lambda \eta g_*^{1/2} x^{-n-2} \left[r - \frac{Y_{eq}^2}{\eta^2}(1-r)^2 \right]$$

$$r = Y^-/Y^+$$
$$\eta = Y^+ - Y^- = \epsilon \eta_B$$
$$\lambda = \left(\frac{\pi}{45}\right)^{1/2} M_{Pl} m \sigma_0$$





Partially asymmetric DM

$$\rho_{\mathrm{DM}} = s \sum_i m_i \eta_i \left(1 + 2\frac{r_i}{1-r_i}\right)$$

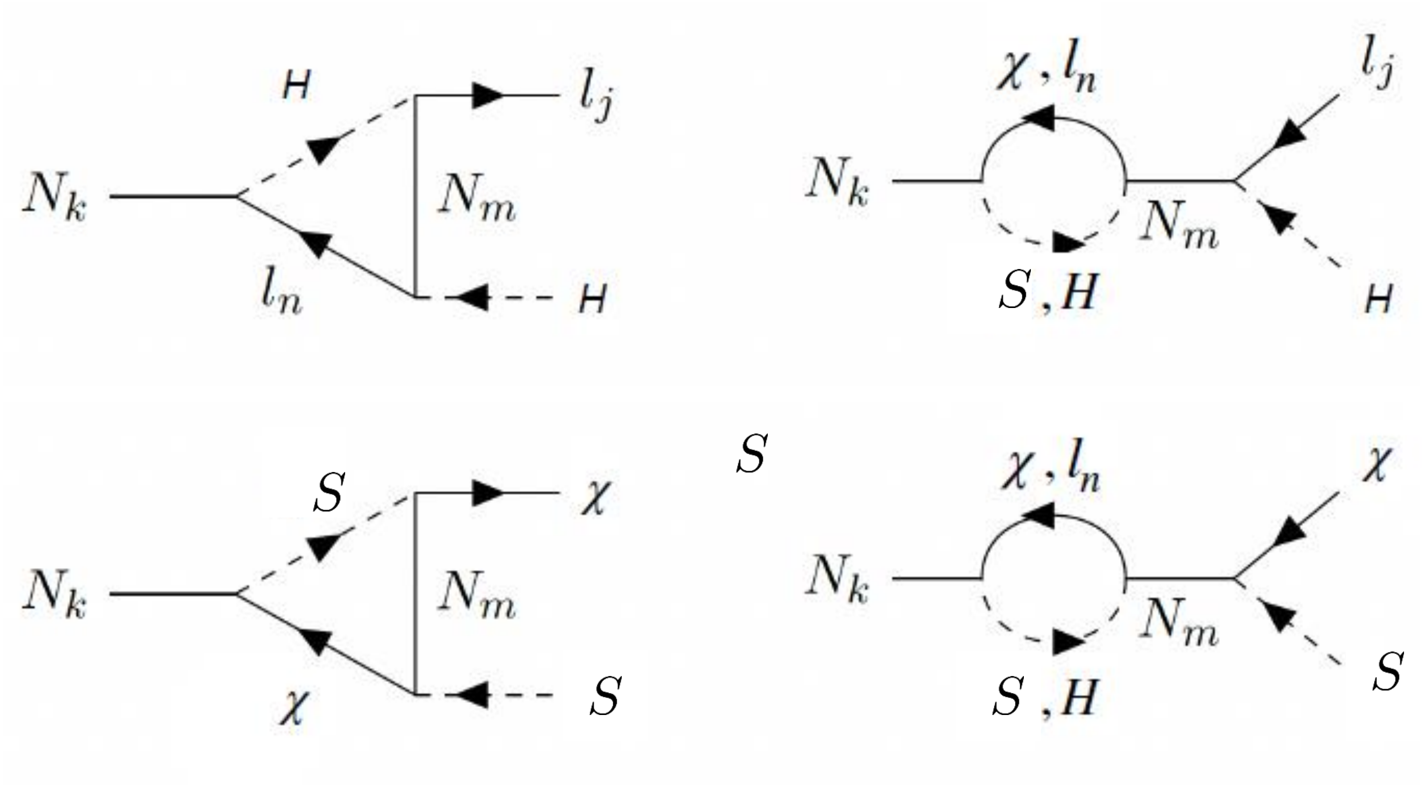
Asymmetric

Symmetric

Cogenesis

Generation of the asymmetries through out-of-equilibrium decays

Falkowski, Ruderman, Volansky [1101.4936]

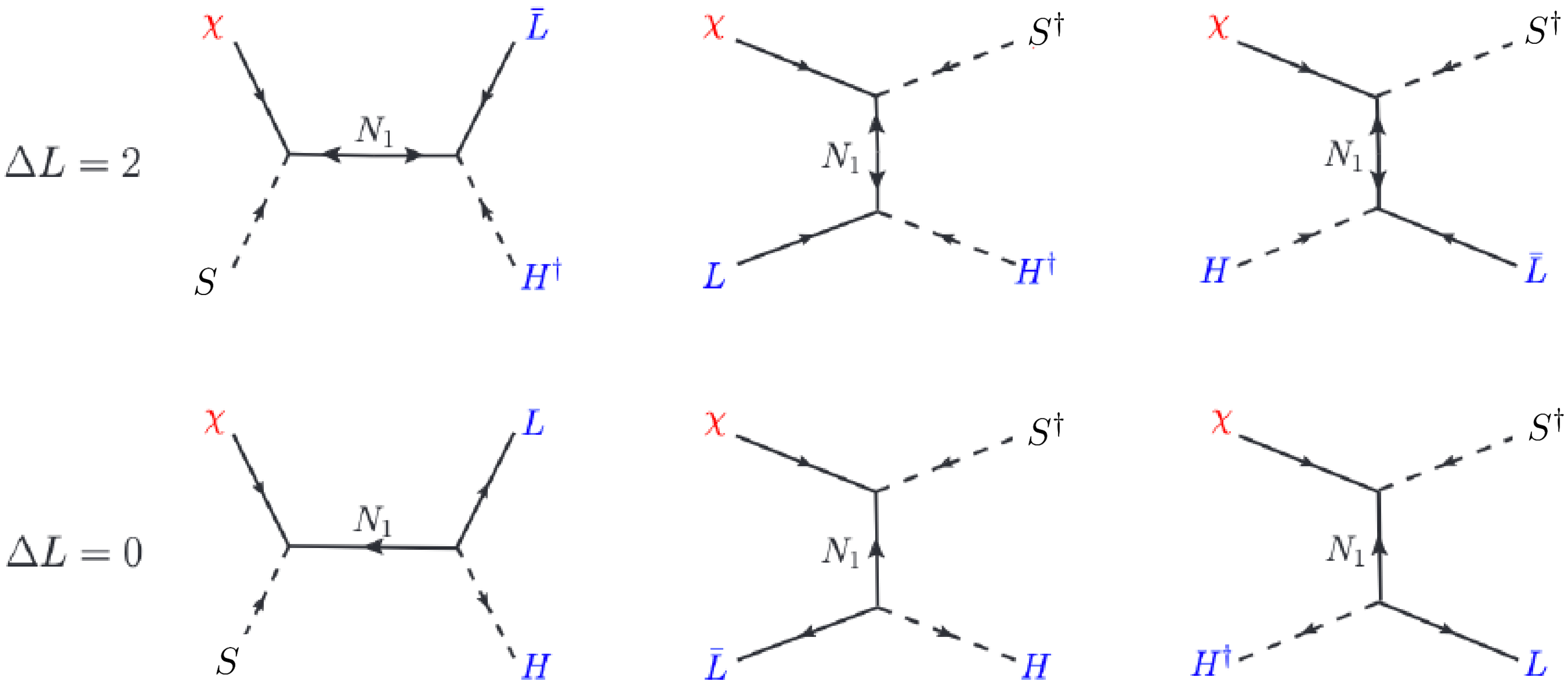


$$\varepsilon_L = \sum_\alpha \frac{\Gamma_{N_1 \to L_\alpha H} - \Gamma_{N_1 \to \bar{L}_\alpha H^\dagger}}{\Gamma_{N_1}}, \quad \varepsilon_\chi = \frac{\Gamma_{N_1 \to \chi S} - \Gamma_{N_1 \to \bar{\chi} S^\dagger}}{\Gamma_{N_1}}$$

Cogenesis

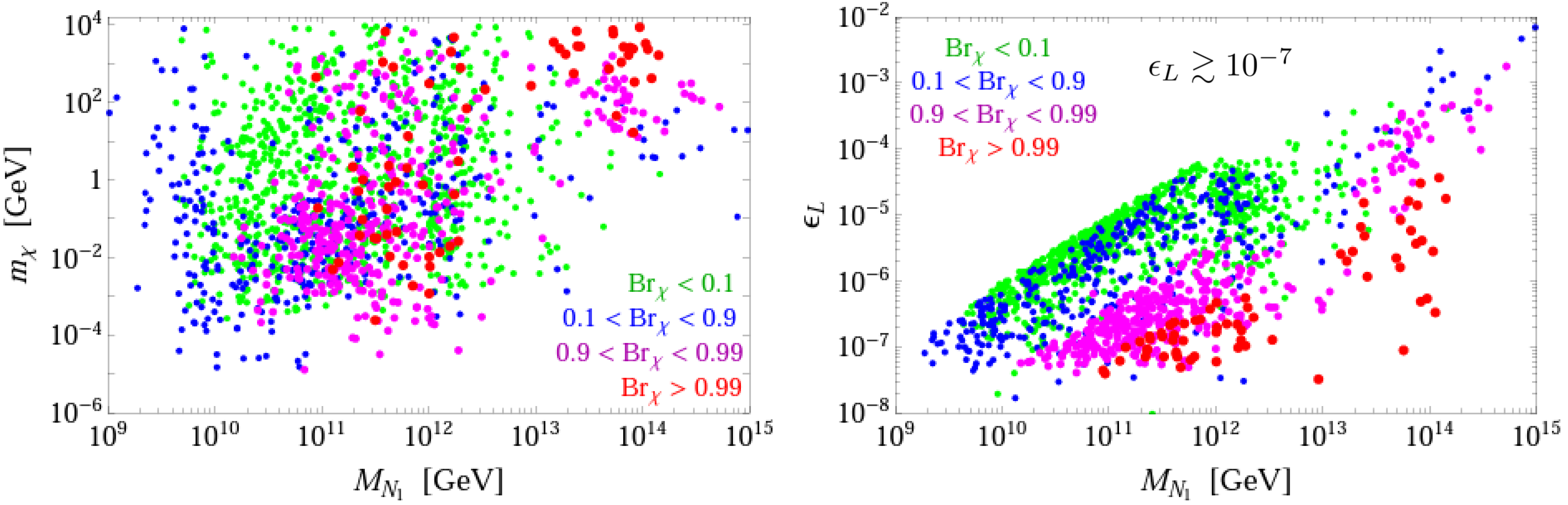
Washout and transfer of the asymmetries

Falkowski, Ruderman, Volansky [1101.4936]



Cogenesis

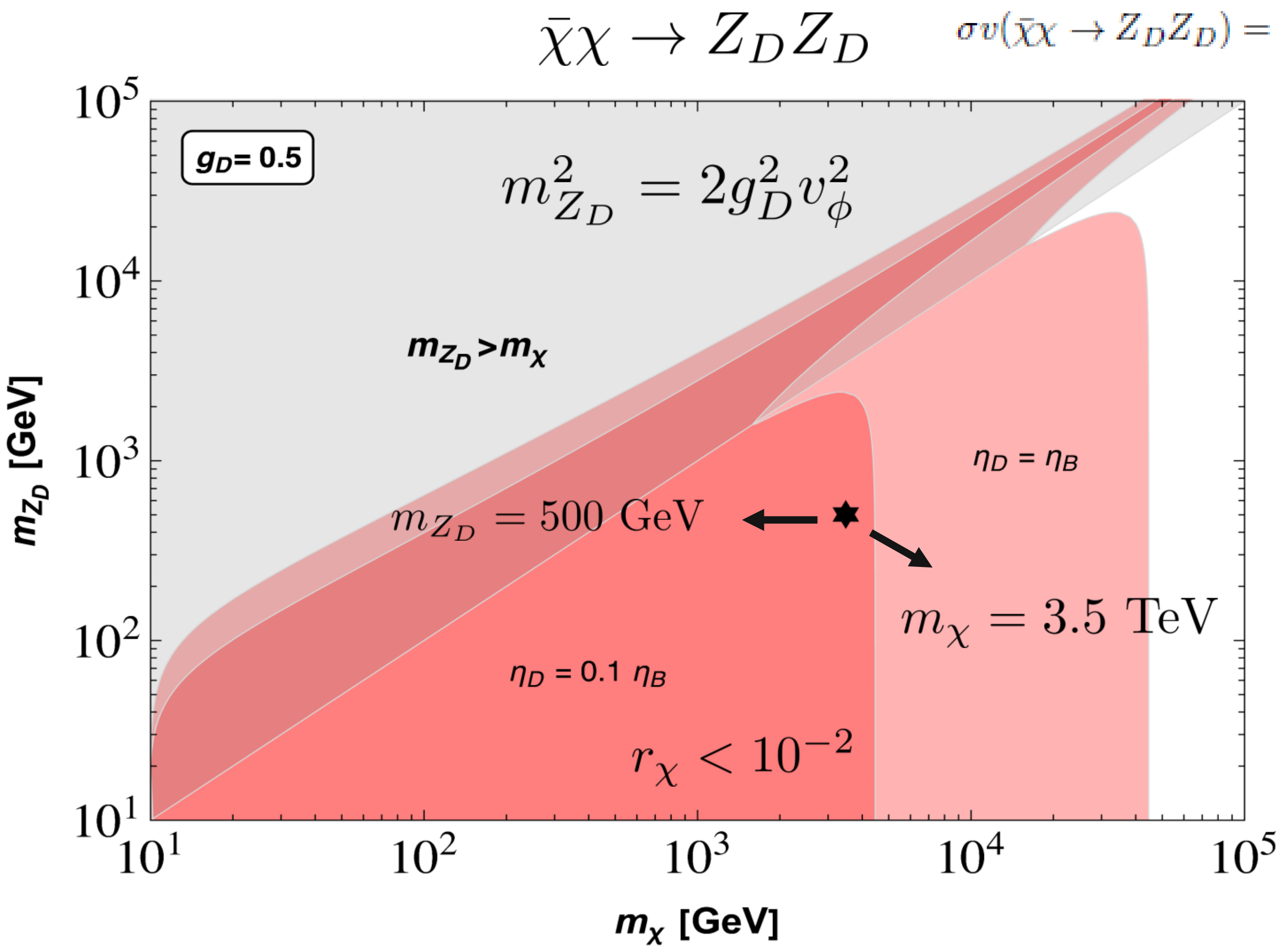
Falkowski, Ruderman, Volansky [1101.4936]



SM lepton asymmetry, neutrino spectrum and mixing angles are correctly reproduced

Fermion annihilations

$$\sigma v(\bar{\chi}\chi \to Z_D Z_D) = \frac{g_D^4}{16\pi m_\chi^2}\left(1-\frac{m_{Z_D}^2}{m_\chi^2}\right)^{3/2}\left(1-\frac{m_{Z_D}^2}{2m_\chi^2}\right)^{-2}$$

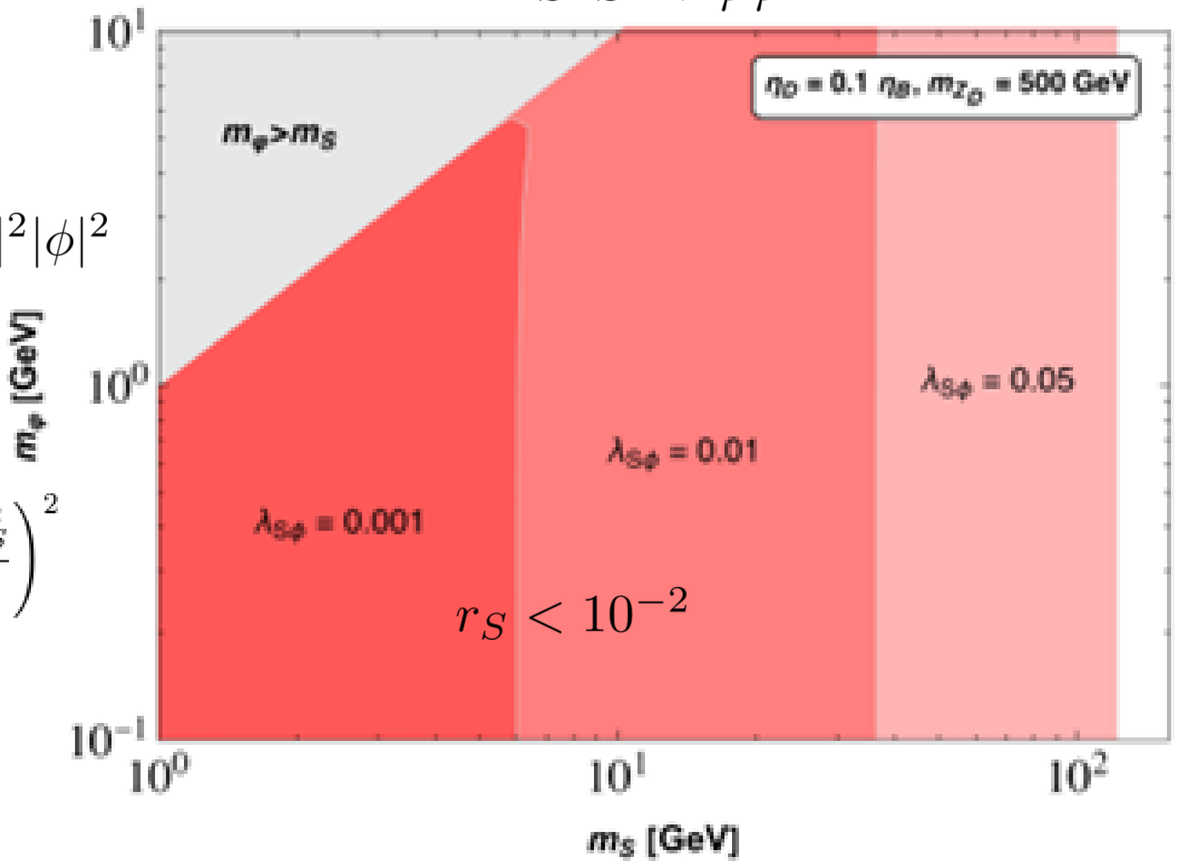


Scalar annihilations

Field	Spin	$U(1)_{B-L}$	$U(1)_D$	$U(1)_X$
N_R^i	1/2	-1	0	0
σ	0	+2	0	0
χ_0	1/2	-1	1	0
ψ_0	1/2	0	0	+1
S	0	0	-1	0
ϕ	0	+1	-1	+1

$$\phi(x) = v_\phi + \varphi(x)/\sqrt{2}$$

$S^\dagger S \to \varphi\varphi$

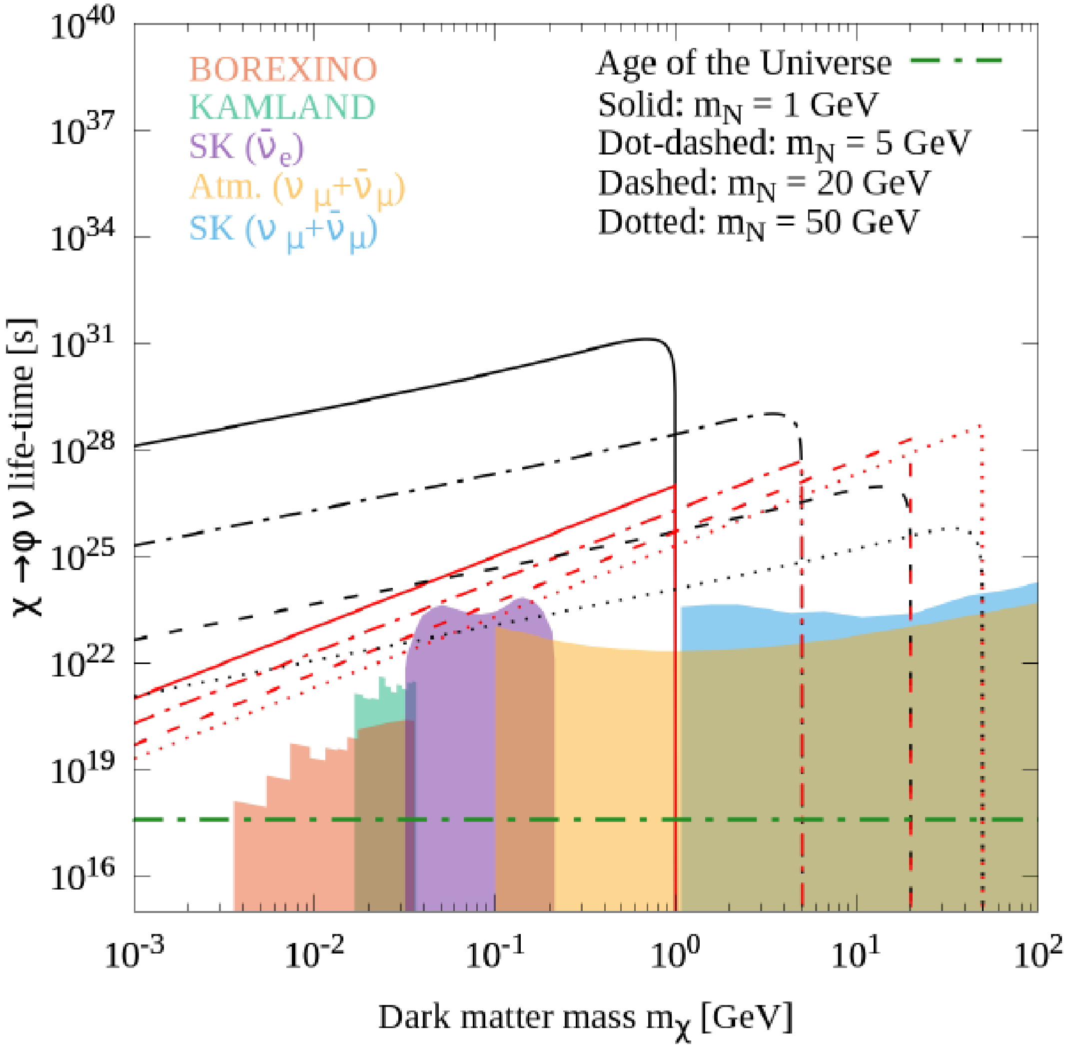


Various terms in the scalar potential such as $\lambda_{S\phi}|S|^2|\phi|^2$

$$\sigma v(S^\dagger S \to \varphi\varphi) \simeq \frac{\lambda_{S\phi}^2}{32\pi m_S^2}\left(1-\frac{m_\varphi^2}{m_S^2}\right)^{1/2}\left(\frac{1-m_\varphi^2/2m_S^2-2\lambda_{S\phi}v_\phi^2/m_S^2}{1-m_\varphi^2/2m_S^2}\right)^2$$

Sc.	ψ	S	$\Omega_{\rm DM}/\Omega_B$	Ω_S/Ω_ψ
1	Asymmetric LD $\chi \to \psi\varphi$ $Y_\psi^+ = \eta_D$ $Y_\psi^- \ll Y_\psi^+$	Asymmetric FO $S^\dagger S \to \varphi\varphi$ $Y_S^+ = \eta_D$ $Y_S^- \ll Y_S^+$	$\frac{\eta_D}{\eta_B}\frac{m_\psi+m_S}{m_p}$	$\frac{m_\psi}{m_S}$
2	Asymmetric LD $\chi \to \psi\varphi$ $Y_\psi^+ = \eta_D/(1+R)$ $Y_\psi^- \ll Y_\psi^+$	Partially asymmetric FO $S^\dagger S \to \varphi\varphi$ + LD $\chi \to S^\dagger \nu_L$ $Y_S^+ = \eta_D$ $Y_S^- = \eta_D R/(1+R)$	$\frac{\eta_D}{\eta_B}\frac{m_\psi+(1+2R)m_S}{(1+R)m_p}$	$\frac{m_\psi}{m_S(1+2R)}$
1-2	Asymmetric LD $\chi \to \psi\varphi$ $Y_\psi^+ = \eta_D/(1+R)$ $Y_\psi^- \ll Y_\psi^+$	Asymmetric FO $S^\dagger S \to \varphi\varphi$ + LD $\chi \to S^\dagger \nu_L$ $Y_S^+ = \eta_D/(1+R)$ $Y_S^- \ll Y_S^+$	$\frac{\eta_D}{\eta_B}\frac{m_\psi+m_S}{(1+R)m_p}$	$\frac{m_\psi}{m_S}$
3	Partially asymmetric FI + LD $\chi \to \psi\varphi$ $Y_\psi^+ = Y_{\rm FI}/2 + \eta_D$ $Y_\psi^- = Y_{\rm FI}/2$	Asymmetric FO $S^\dagger S \to \varphi\varphi$ $Y_S^+ = \eta_D$ $Y_S^- \ll Y_S^+$	$\frac{m_\psi(\eta_D+Y_{\rm FI})+\eta_D m_S}{\eta_B m_p}$	$\frac{m_\psi(\eta_D+Y_{\rm FI})}{m_S\eta_D}$
4	Partially Asymmetric FI +LD $\chi \to \psi\varphi$ $Y_\psi^+ = (Y_{\rm FI}/2 + \eta_D)/(1+R)$ $Y_\psi^- = Y_{\rm FI}/(2(1+R))$	Partially Asymmetric FO $S^\dagger S \to \varphi\varphi$ + LD $\chi \to S^\dagger \nu_L$ $Y_S^+ = \eta_D$ $Y_S^- = \eta_D R/(1+R)$	$\frac{m_\psi(\eta_D+Y_{\rm FI})+\eta_D(1+2R)m_S}{\eta_B(1+R)m_p}$	$\frac{m_\psi(\eta_D+Y_{\rm FI})}{m_S\eta_D(1+2R)}$
3-4	Partially Asymmetric FI +LD $\chi \to \psi\varphi$ $Y_\psi^+ = (Y_{\rm FI}/2 + \eta_D)/(1+R)$ $Y_\psi^- = Y_{\rm FI}/(2(1+R))$	Asymmetric FO $S^\dagger S \to \varphi\varphi$ + LD $\chi \to S^\dagger \nu_L$ $Y_S^+ = \eta_D/(1+R)$ $Y_S^- \ll Y_S^+$	$\frac{m_\psi(\eta_D+Y_{\rm FI})+\eta_D m_S}{\eta_B(1+R)m_p}$	$\frac{m_\psi(\eta_D+Y_{\rm FI})}{m_S\eta_D}$
5	Symmetric FI $\chi \to \psi\varphi$ $Y_\psi^+ = Y_{\rm FI}/2 + \eta_D \simeq Y_{\rm FI}/2$ $Y_\psi^- = Y_{\rm FI}/2$	Asymmetric FO $S^\dagger S \to \varphi\varphi$ $Y_S^+ = \eta_D$ $Y_S^- \ll Y_S^+$	$\frac{\eta_D}{\eta_B}\frac{m_\psi(Y_{\rm FI}/\eta_D)+m_S}{m_p}$	$\frac{m_\psi Y_{\rm FI}}{m_S\eta_D}$
6	Negligible production	Symmetric FO $S^\dagger S \to \varphi\varphi$ + LD $\chi \to S^\dagger \nu_L$ $Y_S^+ = \eta_D$ $Y_S^- = \eta_D$	< 1	$\frac{\eta_D}{\eta_B}\frac{2m_S}{m_p}$

Smoking gun: neutrino line



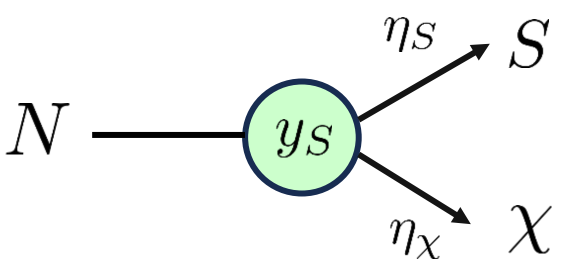
Coi, Gupta, Hambye [2104.00042]

Cold vs Warm

Small-scale structure constraint

$$m_S \gtrsim \underbrace{3.5\ \text{KeV}\langle p/T\rangle_{\text{prod}}}_{\mathcal{O}(\text{KeV})} \left(\frac{10}{g_s(T_D^S)}\right)^{1/3}$$

$m_S \rightarrow \mathcal{O}(\text{ GeV})$



$S \longrightarrow$ Thermalization with SM bath

↓

Asymmetric freeze-out

$S^\dagger S \to \phi\phi$

Decoupling at $T_*^S \simeq m_S/20$

$\langle p/T\rangle_{\text{prod}} \sim 3$

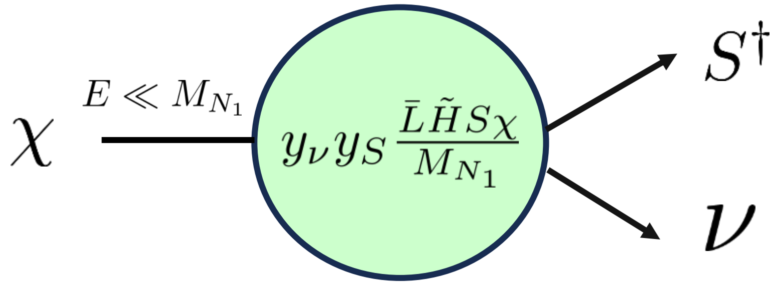
Cold

Cold vs Warm

Small-scale structure constraint

$$m_S \gtrsim 3.5\ \text{KeV} \langle p/T \rangle_{\text{prod}} \left(\frac{10}{g_s(T_D^S)} \right)^{1/3}$$

m_S → $\mathcal{O}(\text{ GeV})$; $\langle p/T \rangle_{\text{prod}}$ → $\mathcal{O}(\text{ GeV})$



→ Decay peaked around

$$T_D^S = \text{MeV} \left(\frac{|y_S|}{10^{-3}} \right) \left(\frac{m_\nu}{0.05\text{eV}} \frac{m_\chi}{3.5\text{TeV}} \frac{10^{11}\text{GeV}}{M_{N_1}} \right)^{1/2}$$

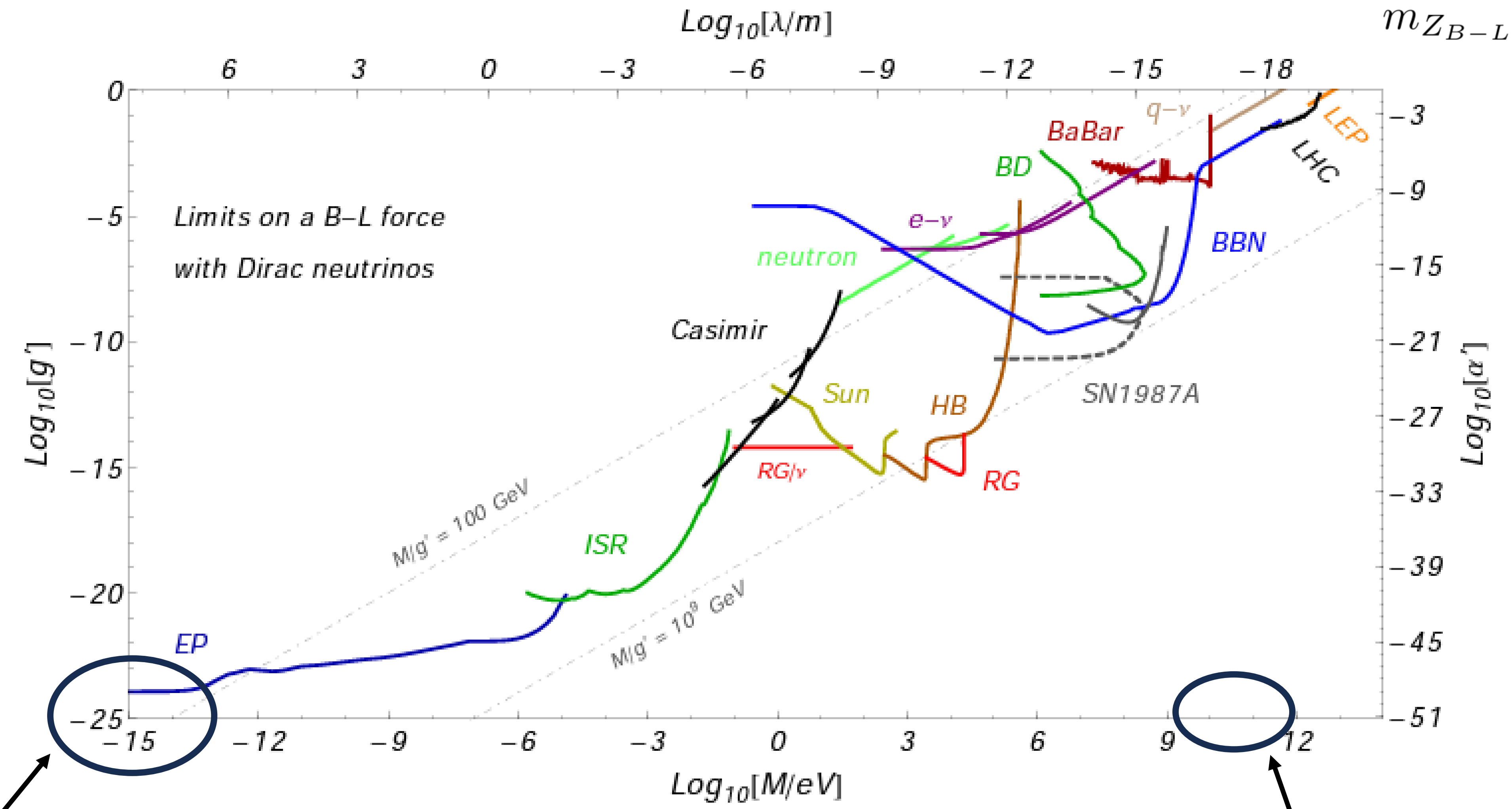
$$\langle p/T \rangle_{\text{prod}} \simeq m_\chi / T_D^S \gg 1$$

Warm

m_χ → $\mathcal{O}(\text{TeV})$

Gauge boson bounds

$m_{Z_{B-L}} \geq 10^{11}$ GeV



[Heeck, *2014*]

$g_X^{\text{eff}} A'_\mu J^\mu_{B-L}$

$\longrightarrow \; g_X \leq 10^{-8}$

$$g_i^{\text{eff}} \sim g_i \left(\frac{v_\phi}{v_{B-L}}\right)^2 \sim 10^{-16} g_i$$

$g_D^{\text{eff}} Z_{D,\mu} J^\mu_{B-L}$

$\longrightarrow \; g_D \leq 10^{13}$

A low-energy variant

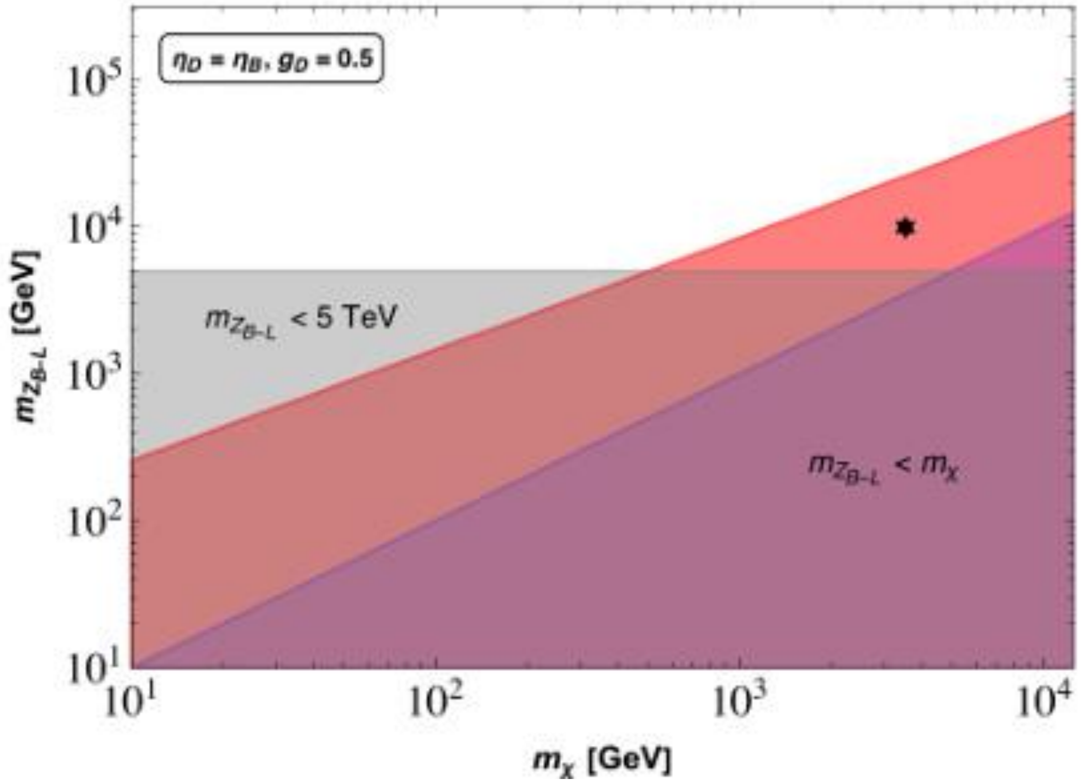
Lowering the $B-L$ scale → Resonant leptogenesis
→ **Inverse see-saw**

Field	Spin	$U(1)_{B-L}$	$U(1)_D$	$U(1)_X$
S_L	$1/2$	0	0	0
σ'	0	$+1$	0	0

$$\langle \sigma' \rangle = v_{B-L} \sim \mathcal{O}(\text{TeV})$$

$$\mathcal{L}_{\text{ISS}} = \overline{S_L} i \not{\partial} S_L - \sigma' \overline{S_L} y_{\sigma'} N_R - \frac{1}{2} \overline{S_L} \mu S_L^c + \text{H.c.}$$

Neutrino masses $m_\nu \simeq m_D M_D^{-1} \mu (M_D^{-1})^T m_D^T$



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S_L	1/2	0	0	0
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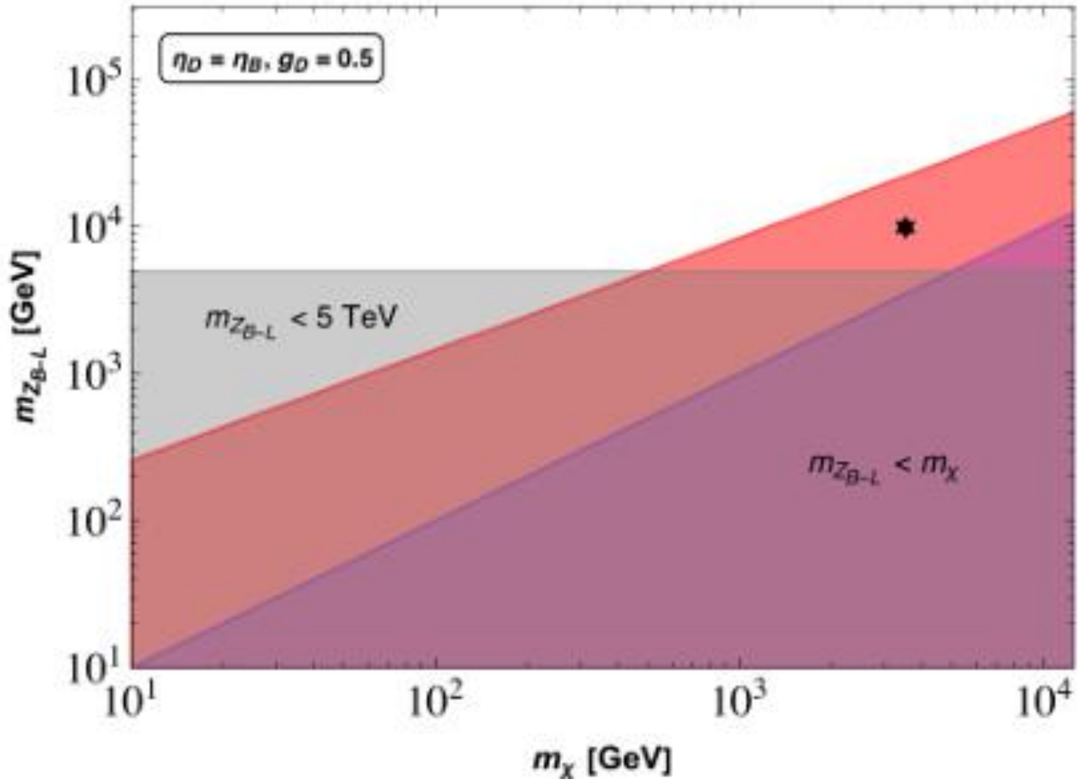
$$\langle \sigma' \rangle = v_{B-L} \sim \mathcal{O}(\text{TeV})$$

$$\mathcal{L}_{\text{ISS}} = \overline{S_L} i \partial\!\!\!/ S_L - \sigma' \overline{S_L} y_{\sigma'} N_R - \frac{1}{2} \overline{S}_L \mu S_L^c + \text{H.c.}$$

Low-scale $m_{Z_{B-L}}$ allows for annihilations to SM fermions to erase the symmetric component

$$\bar{\chi}\chi \to Z_{B-L} \to \bar{q}q(\bar{l}l)$$

(highly suppressed in the high-scale scenario)



A low-energy variant

Lowering the $B-L$ scale → Resonant leptogenesis; **Inverse see-saw**

Field	Spin	$U(1)_{B-L}$	$U(1)_D$	$U(1)_X$
S_L	$1/2$	0	0	0
σ'	0	$+1$	0	0

$$\langle\sigma'\rangle = v_{B-L} \sim \mathcal{O}(\text{TeV})$$

↑

$$\mathcal{L}_{\text{ISS}} = \overline{S_L} i\partial\!\!\!/ S_L - \sigma' \overline{S_L} y_{\sigma'} N_R - \frac{1}{2}\overline{S}_L \mu S_L^c + \text{H.c.}$$

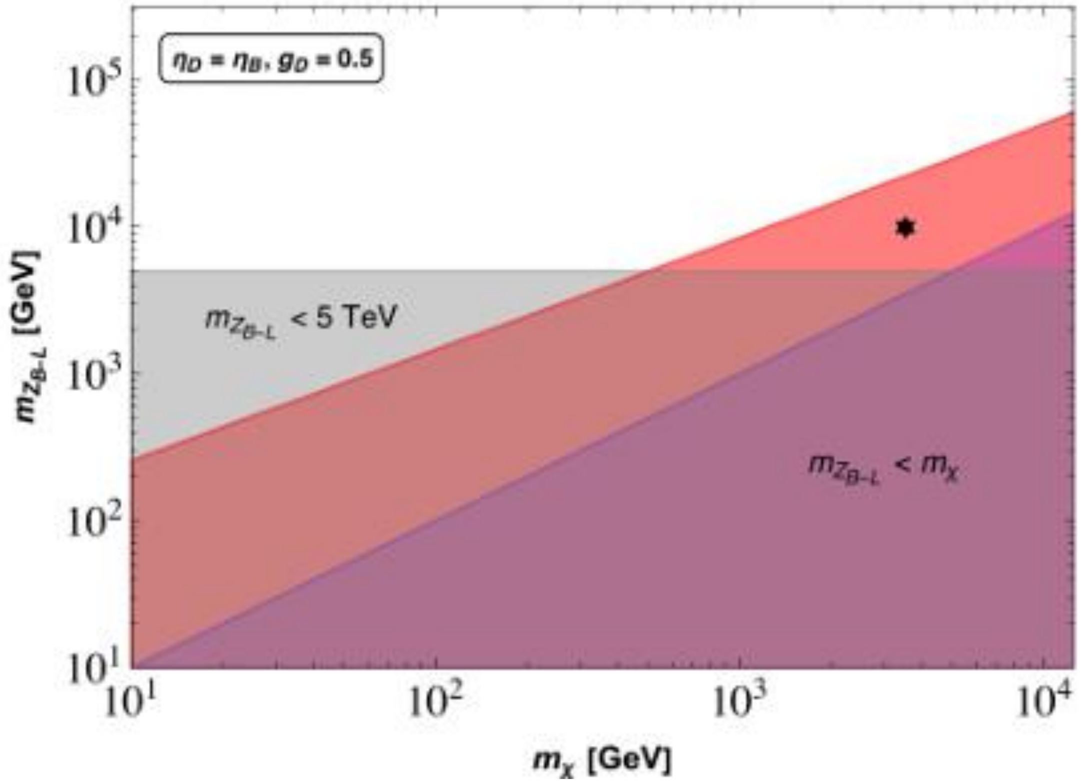
The ratio m_ν/M_{N_1} is enhanced

↓

Scenarios with $R \gg 1$ are preferred

↓

S is the dominant DM candidate



A low-energy variant

Lowering the $B-L$ scale → Resonant leptogenesis
→ **Inverse see-saw**

Field	Spin	$U(1)_{B-L}$	$U(1)_D$	$U(1)_X$
S_L	1/2	0	0	0
σ'	0	+1	0	0

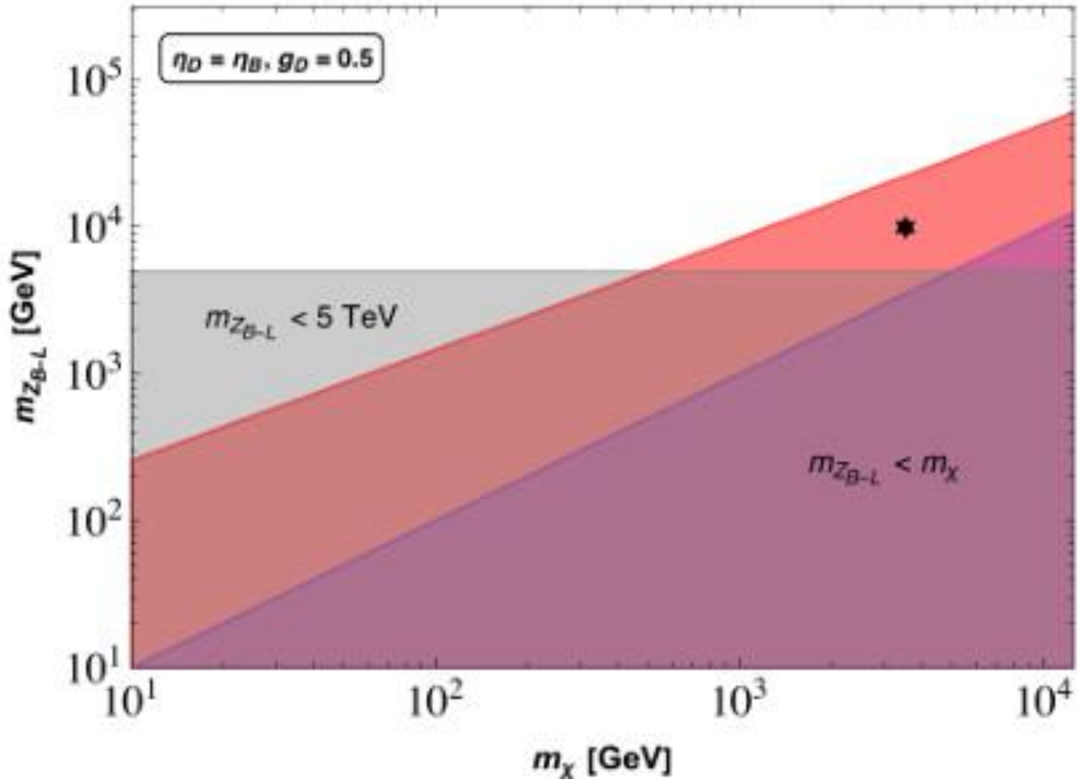
$$\langle\sigma'\rangle = v_{B-L} \sim \mathcal{O}(\text{TeV})$$

$$\mathcal{L}_{\text{ISS}} = \overline{S_L} i\partial\!\!\!/ S_L - \sigma' \overline{S_L} y_{\sigma'} N_R - \frac{1}{2}\overline{S_L}\mu S_L^c + \text{H.c.}$$

Collider searches

$$\bar{q}q \to Z_{B-L} \to \bar{\chi}\chi$$

Looking for missing energy from χ decays



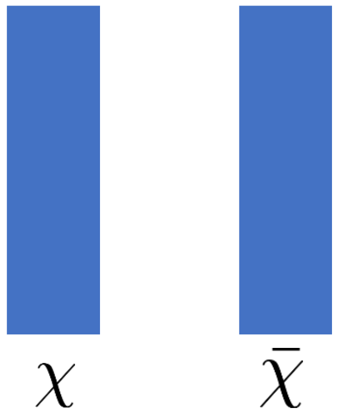
Dark Matter nature

Asymmetry and Fractional asymmetry

$$\eta_D = Y_\chi - Y_{\bar{\chi}} \qquad r = Y_{\bar{\chi}}/Y_\chi$$

Symmetric

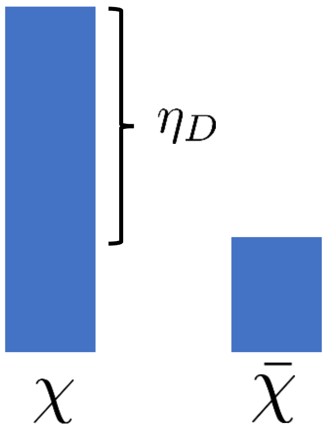
$r_\infty > 0.9$



$\rho_{\rm DM} \propto 1/\sigma v$

Asymmetric

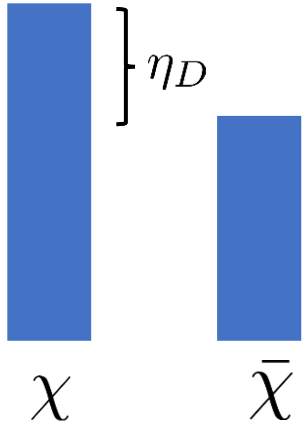
$r_\infty < 10^{-2}$



$\rho_{\rm DM} \propto m\eta_D$

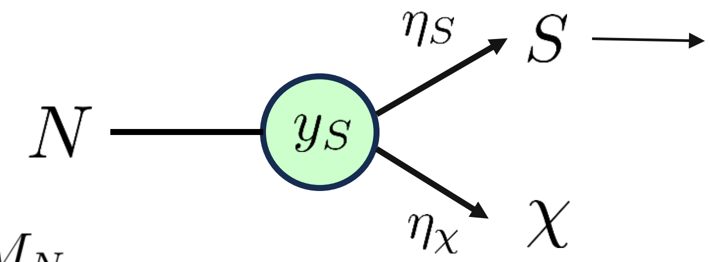
Partially Asymmetric

$10^{-2} < r_\infty < 0.9$



$\rho_{\rm DM} = f(m, \sigma v, \eta_D)$

DM production (Scalar)



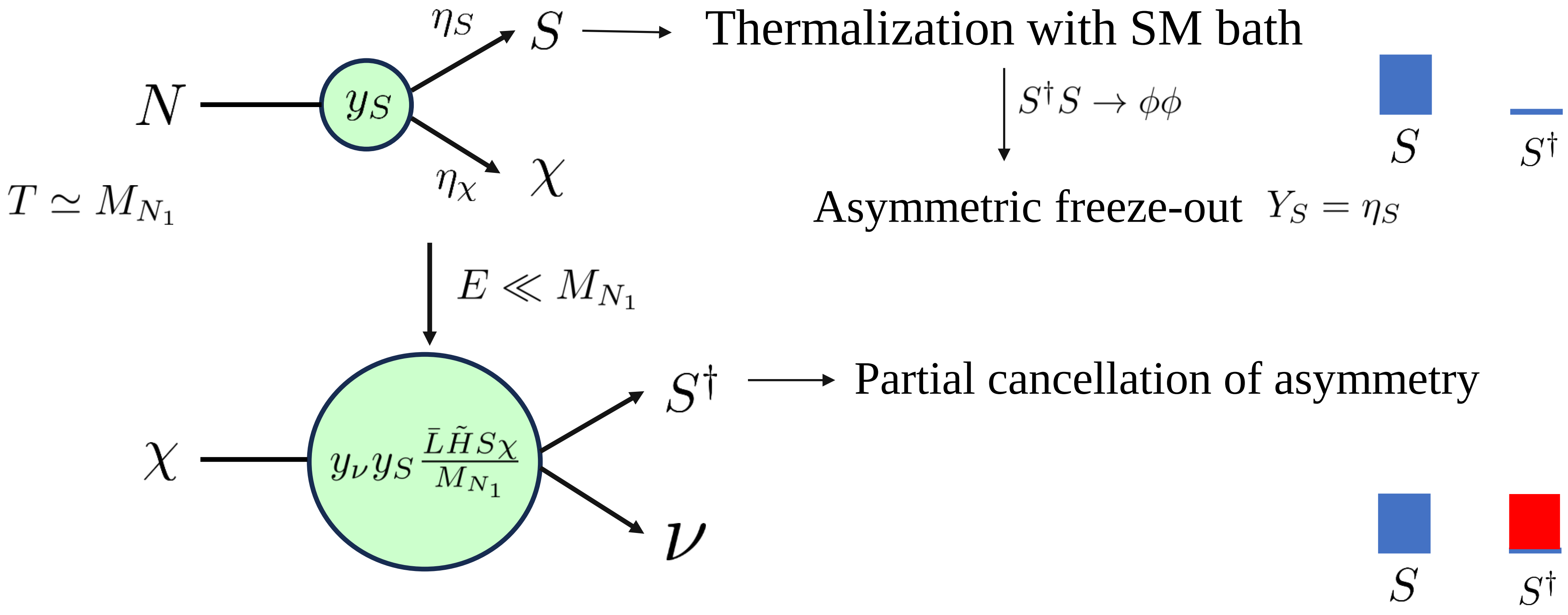
$T \simeq M_{N_1}$

Thermalization with SM bath

$S^\dagger S \to \phi\phi$

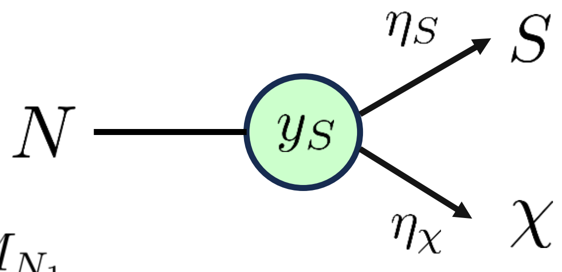
Asymmetric freeze-out $Y_S = \eta_S$

DM production (Scalar)



$$T_D^S \simeq \text{ MeV} \left(\frac{|y_S|}{10^{-3}}\right)$$

DM production (Scalar)



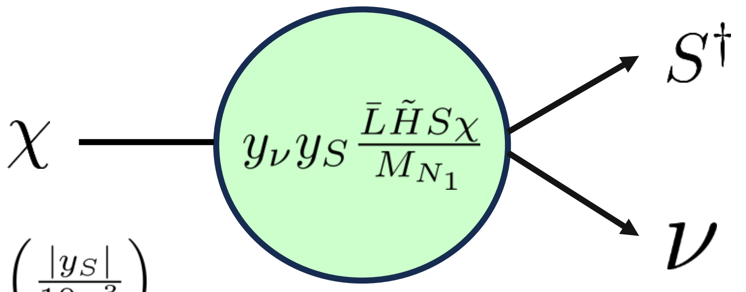
$T \simeq M_{N_1}$

$S \longrightarrow$ Thermalization with SM bath

$S^\dagger S \to \phi\phi$

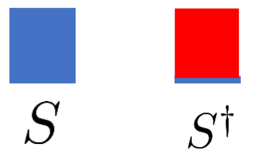
Asymmetric freeze-out $Y_S = \eta_S$

$E \ll M_{N_1}$



$T_D^S \simeq \text{ MeV} \left(\frac{|y_S|}{10^{-3}}\right)$

$S^\dagger \longrightarrow$ Partial cancellation of asymmetry



$$R = \frac{\Gamma(\chi \to S^\dagger \nu)}{\Gamma(\chi \to \psi\phi)} \sim \frac{|y_S|^2}{y_\phi^2} \frac{m_\nu}{M_{N_1}}$$

$R \ll 1$ No extra decays, asymmetric DM (freeze-out)

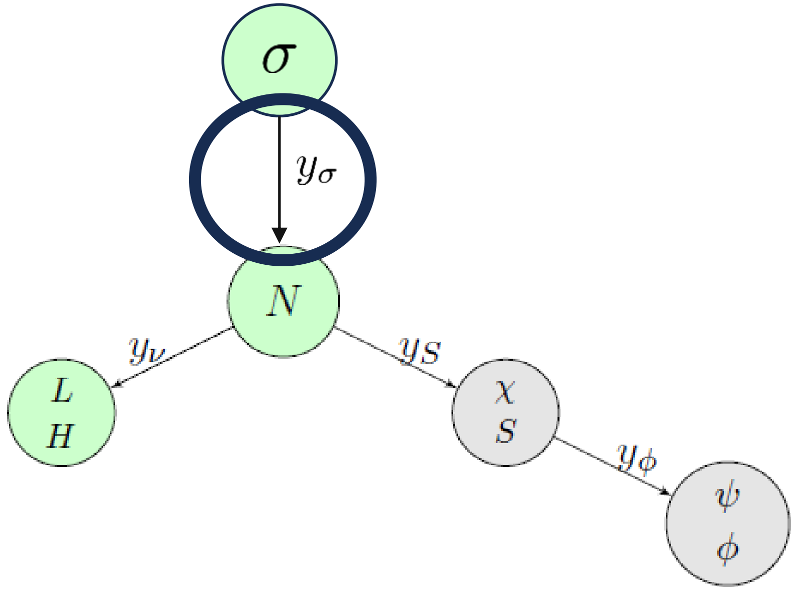
$$Y_S = \eta_S \ , \quad Y_{S^\dagger} = \frac{R}{1+R}\eta_S$$

$R \gg 1$ Cancellation of the asymmetry, symmetric DM (freeze-out)

The model

Field	Spin	$U(1)_{B-L}$	$U(1)_D$	$U(1)_X$
N_R^i	1/2	-1	0	0
σ	0	+2	0	0
χ_0	1/2	-1	1	0
ψ_0	1/2	0	0	+1
S	0	0	-1	0
ϕ	0	+1	-1	+1

$$M_{N_3}, M_{N_2} \gg M_{N_1} \gg m_\chi^0 \gg m_\psi^0, m_S > m_\phi$$



$$\mathcal{L}_{\rm int} = -y_\nu^{\alpha i}\bar{L}^\alpha \tilde{H} N_R^i - y_\sigma^{ij}\sigma \overline{N_R^{ic}} N_R^j - y_S^i S \bar{N}_R^i \chi_0 - y_\phi \phi \bar{\psi}_0 \chi_0 + \text{H.c.}\,.$$

Majorana masses for RHNs from $U(1)_{B-L}$ breaking $v_{B-L} \gtrsim 10^{11}$ GeV

neutrino masses (Type- I see-saw) $m_\nu = -m_D M_N^{-1} m_D^T$

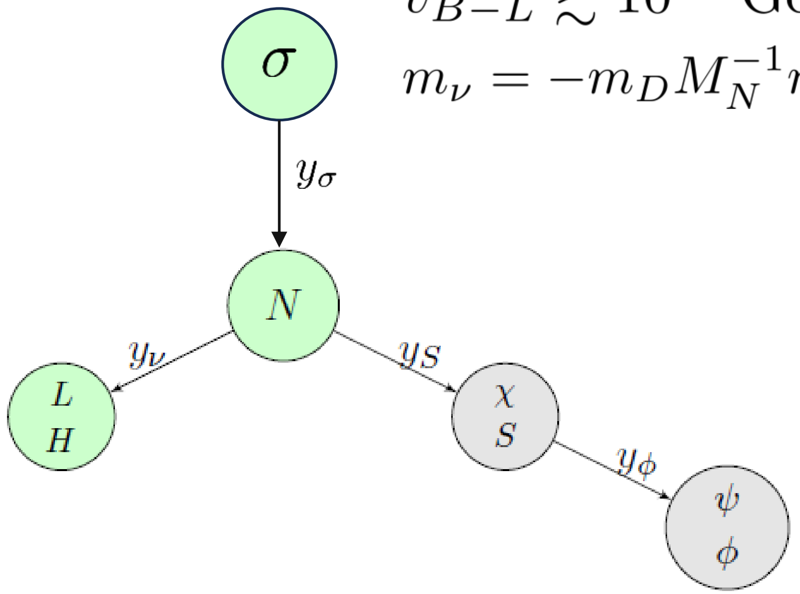
The model

Field	Spin	$U(1)_{B-L}$	$U(1)_D$	$U(1)_X$
N_R^i	1/2	-1	0	0
σ	0	+2	0	0
χ_0	1/2	-1	1	0
ψ_0	1/2	0	0	+1
S	0	0	-1	0
ϕ	0	+1	-1	+1

$$M_{N_3}, M_{N_2} \gg M_{N_1} \gg m_\chi^0 \gg m_\psi^0, m_S > m_\phi$$

$$v_{B-L} \gtrsim 10^{11}\ \text{GeV}$$

$$m_\nu = -m_D M_N^{-1} m_D^T$$



$$\mathcal{L}_{\text{int}} = -y_\nu^{\alpha i} \bar{L}^\alpha \tilde{H} N_R^i - y_\sigma^{ij} \sigma \overline{N_R^{ic}} N_R^j - y_S^i S \bar{N}_R^i \chi_0 - y_\phi \phi \bar{\psi}_0 \chi_0 + \text{H.c.}\,.$$

Dark gauge group $U(1)_D \otimes U(1)_X$

Assure DM stability and Dirac nature of dark fermions (necessary to have an asymmetry)

The model

Field	Spin	$U(1)_{B-L}$	$U(1)_D$	$U(1)_X$
N_R^i	1/2	-1	0	0
σ	0	+2	0	0
χ_0	1/2	-1	1	0
ψ_0	1/2	0	0	+1
S	0	0	-1	0
ϕ	0	+1	-1	+1

$$M_{N_3}, M_{N_2} \gg M_{N_1} \gg m_\chi^0 \gg m_\psi^0, m_S > m_\phi$$

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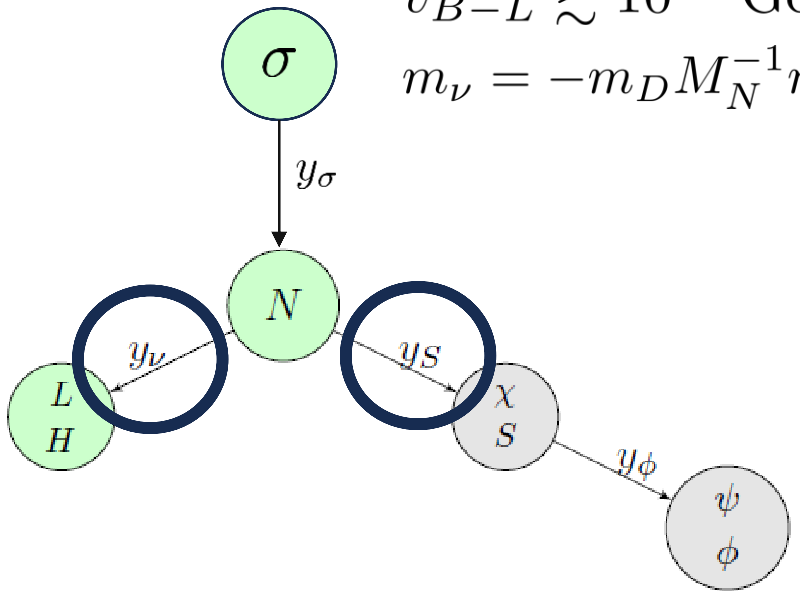

$$\mathcal{L}_{\text{int}} = -y_\nu^{\alpha i} \bar{L}^\alpha \tilde{H} N_R^i - y_\sigma^{ij} \sigma \overline{N_R^{ic}} N_R^j - y_S^i S \bar{N}_R^i \chi_0 - y_\phi \phi \bar{\psi}_0 \chi_0 + \text{H.c.}\,.$$

Gauge invariance allows for Yukawa operators

→ Generation baryon and dark asymmetries $\quad \eta_\chi = \eta_S \sim \eta_B$

The model

Field	Spin	$U(1)_{B-L}$	$U(1)_D$	$U(1)_X$
N_R^i	1/2	-1	0	0
σ	0	+2	0	0
χ_0	1/2	-1	1	0
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S	0	0	-1	0
ϕ	0	+1	-1	+1

$$M_{N_3}, M_{N_2} \gg M_{N_1} \gg m_\chi^0 \gg m_\psi^0, m_S > m_\phi$$

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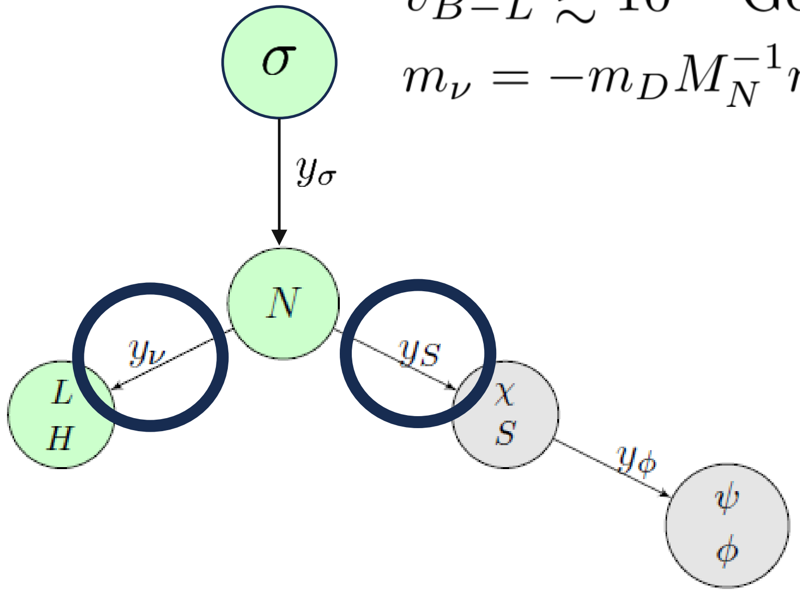

$$\mathcal{L}_{\rm int} = -y_\nu^{\alpha i} \bar{L}^\alpha \tilde{H} N_R^i - y_\sigma^{ij} \sigma \overline{N_R^{ic}} N_R^j - y_S^i S \bar{N}_R^i \chi_0 - y_\phi \phi \bar{\psi}_0 \chi_0 + \text{H.c.}\,.$$

χ and S get in thermal equilibrium with the SM through gauge and scalar interactions

$$Y_\chi = Y_\chi^{\rm eq} + \eta_\chi \qquad Y_{\bar{\chi}} = Y_\chi^{\rm eq} \qquad \eta_\chi = \eta_S \sim \eta_B$$

The model

Field	Spin	$U(1)_{B-L}$	$U(1)_D$	$U(1)_X$
N_R^i	1/2	-1	0	0
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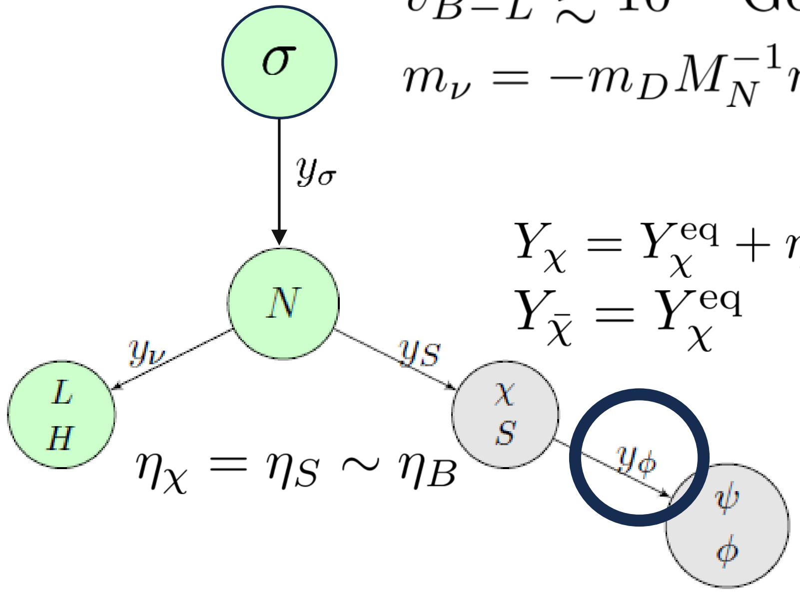
$$M_{N_3}, M_{N_2} \gg M_{N_1} \gg m_\chi^0 \gg m_\psi^0, m_S > m_\phi$$

$$v_{B-L} \gtrsim 10^{11}\ \text{GeV}$$

$$m_\nu = -m_D M_N^{-1} m_D^T$$



$$Y_\chi = Y_\chi^{\text{eq}} + \eta_\chi$$

$$Y_{\bar{\chi}} = Y_\chi^{\text{eq}}$$

$$\eta_\chi = \eta_S \sim \eta_B$$

$$\mathcal{L}_{\text{int}} = -y_\nu^{\alpha i} \bar{L}^\alpha \tilde{H} N_R^i - y_\sigma^{ij} \sigma \overline{N_R^{ic}} N_R^j - y_S^i S \bar{N}_R^i \chi_0 - \underline{y_\phi \phi \bar{\psi}_0 \chi_0} + \text{H.c.}\,.$$

We assume $\begin{cases} y_\phi \ll 1 \\ g_X \ll 1 \end{cases}$ so that ψ is never in thermal equilibrium

The model

Field	Spin	$U(1)_{B-L}$	$U(1)_D$	$U(1)_X$
N_R^i	1/2	-1	0	0
σ	0	+2	0	0
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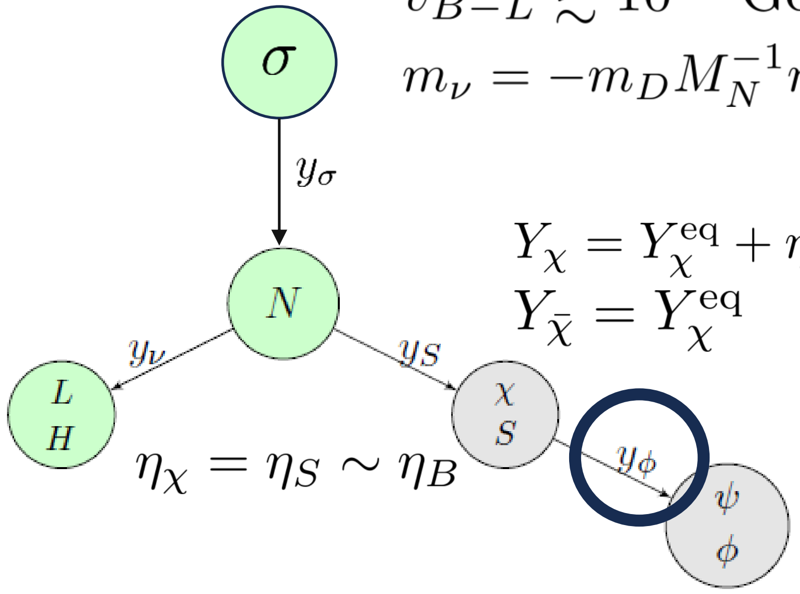


$$Y_\chi = Y_\chi^{\mathrm{eq}} + \eta_\chi$$

$$Y_{\bar\chi} = Y_\chi^{\mathrm{eq}}$$

$$\mathcal{L}_{\mathrm{int}} = -y_\nu^{\alpha i} \bar{L}^\alpha \tilde{H} N_R^i - y_\sigma^{ij} \sigma \overline{N_R^{ic}} N_R^j - y_S^i S \bar{N}_R^i \chi_0 - y_\phi \phi \bar{\psi}_0 \chi_0 + \mathrm{H.c.}\,.$$

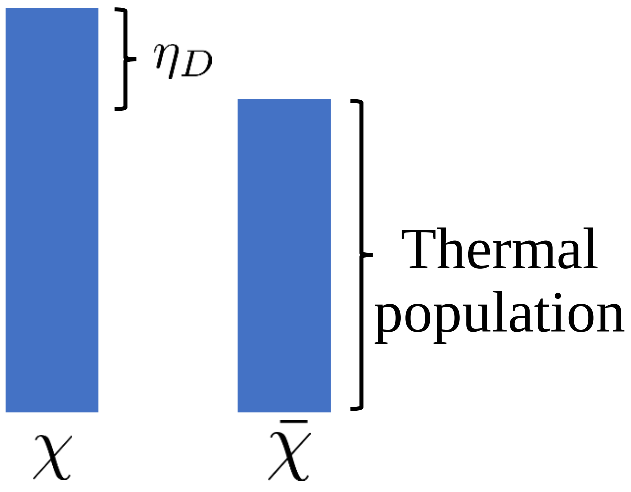
The χ asymmetry is transferred to ψ through late decays $\chi \to \psi + \phi$

Asymmetric freeze-out

Asymmetry and Fractional asymmetry

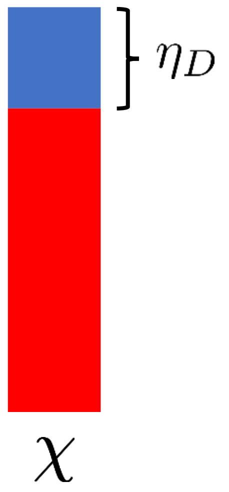
$$\eta_D = Y_\chi - Y_{\bar{\chi}} \qquad\qquad r = Y_{\bar{\chi}}/Y_\chi$$

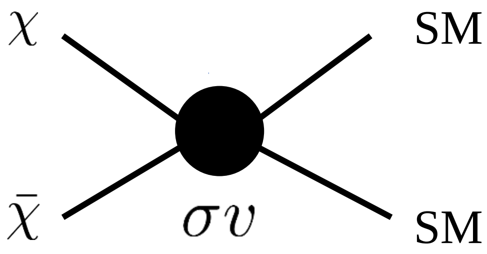
Asymmetry generation



$$r \simeq 1$$

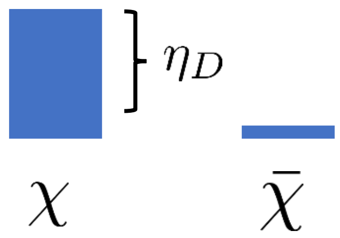
Annihilation of the symmetric component





$$r_\infty \propto \exp\left[-\frac{\pi g_*}{45 x_f} M_{\rm Pl}\sigma v \eta_D m\right]$$

Only asymmetric component survives



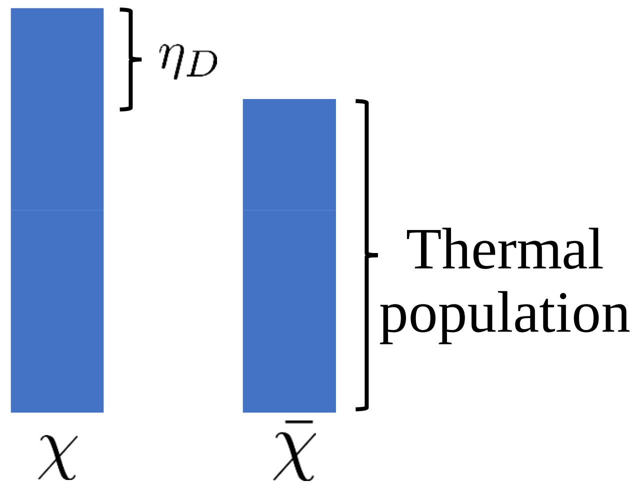
Graesser, Shoemaker, Vecchi
[1103.2771]

Asymmetric freeze-out

Asymmetry and Fractional asymmetry

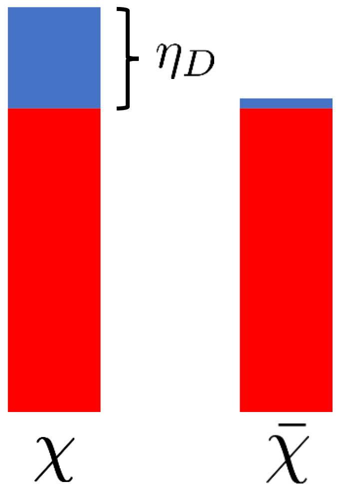
$$\eta_D = Y_\chi - Y_{\bar{\chi}} \qquad r = Y_{\bar{\chi}}/Y_\chi$$

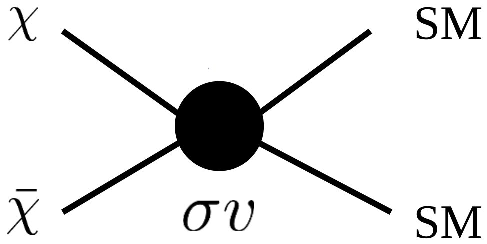
Asymmetry generation



$r \simeq 1$

Annihilation of the symmetric component

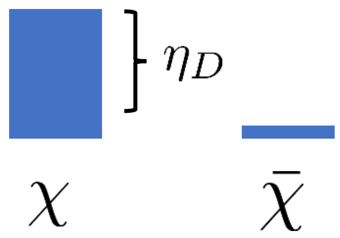




Large cross sections are needed!

$$\sigma v > \sigma v_{\rm WIMP}$$

Only asymmetric component survives



$$r_\infty \propto \exp\left[-\frac{\pi g_*}{45 x_f} M_{\rm Pl} \sigma v \eta_D m\right]$$

Graesser, Shoemaker, Vecchi
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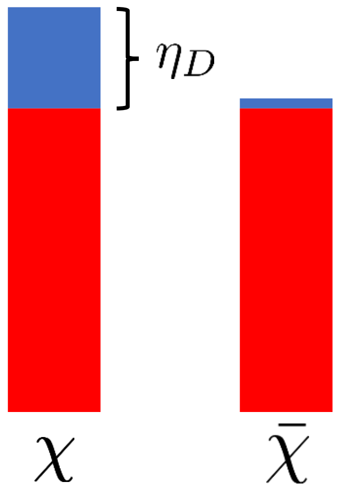
Asymmetric freeze-out

Asymmetry and Fractional asymmetry

$$\eta_D = Y_\chi - Y_{\bar{\chi}} \qquad r = Y_{\bar{\chi}}/Y_\chi$$

Annihilation of the symmetric component



Large cross sections are needed!

$$\sigma v > \sigma v_{\mathrm{WIMP}}$$

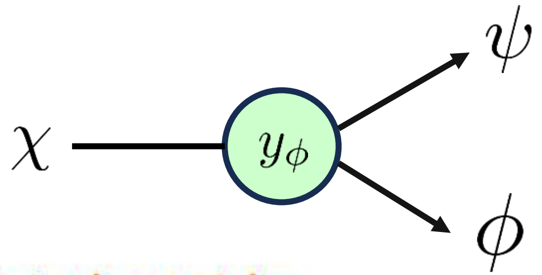
Asymmetric DM out of equilibrium (tiny couplings, freeze-in) ?

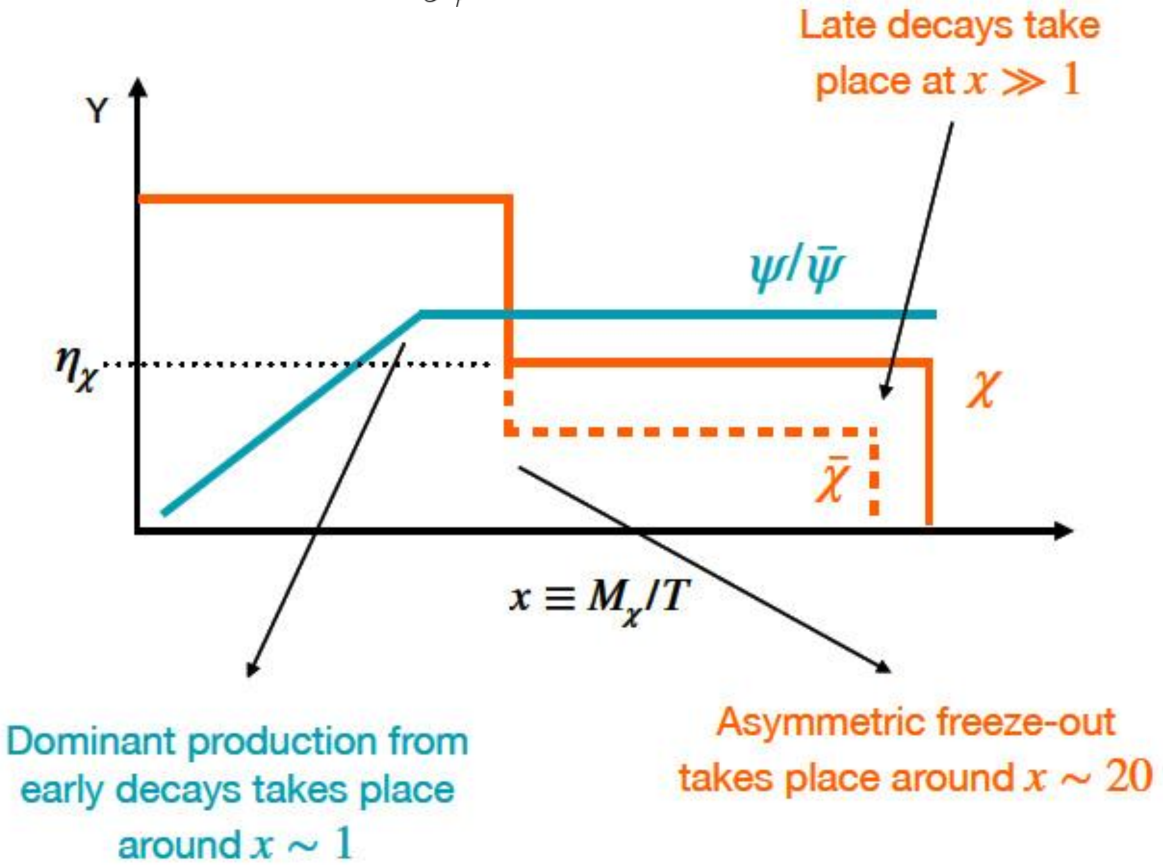
(How to erase the symmetric component?)

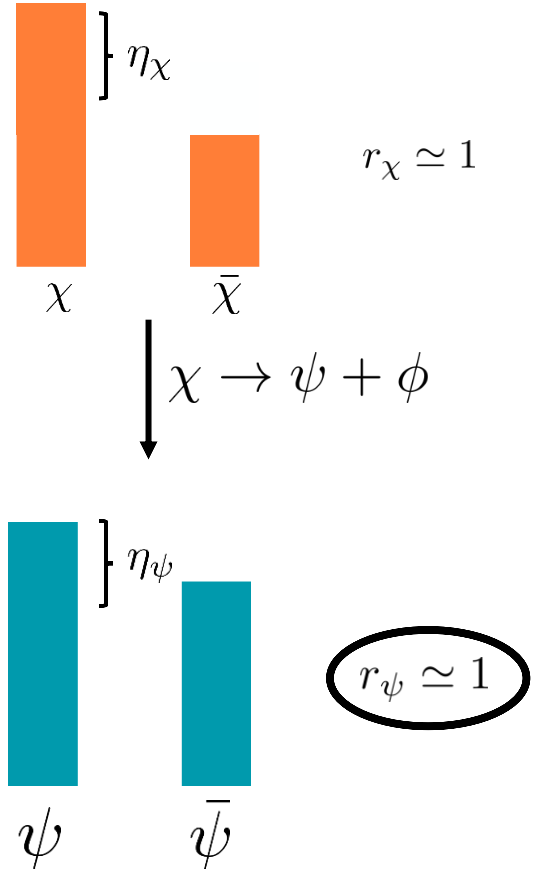
Early vs Late decays

$$T_D \simeq 10\ \text{MeV}\left(\frac{y_\phi}{10^{-12}}\right)$$

$$2 \times 10^{-10} < y_\phi < 5 \times 10^{-7}$$







No annihilations

Early vs Late decays

$$T_D \simeq 10 \text{ MeV} \left(\frac{y_\phi}{10^{-12}}\right)$$

$$y_\phi < 6 \times 10^{-12}$$