Asymmetries in Extended Dark Sectors

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Light Dark World 2023

Based on: JHEP 05 (2023) 049
[Juan Herrero-García, Giacomo Landini, DV]

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Why Dark Sector + Asymmetries?

Visible Sector

Several stable components
- stabilising symmetries

Electrons	Electric charge
Protons	Baryon number
Neutrinos	Spin
Photons	Poincare

Abundance set by the baryon asymmetry of the universe $\eta_B \sim 10^{-10}$

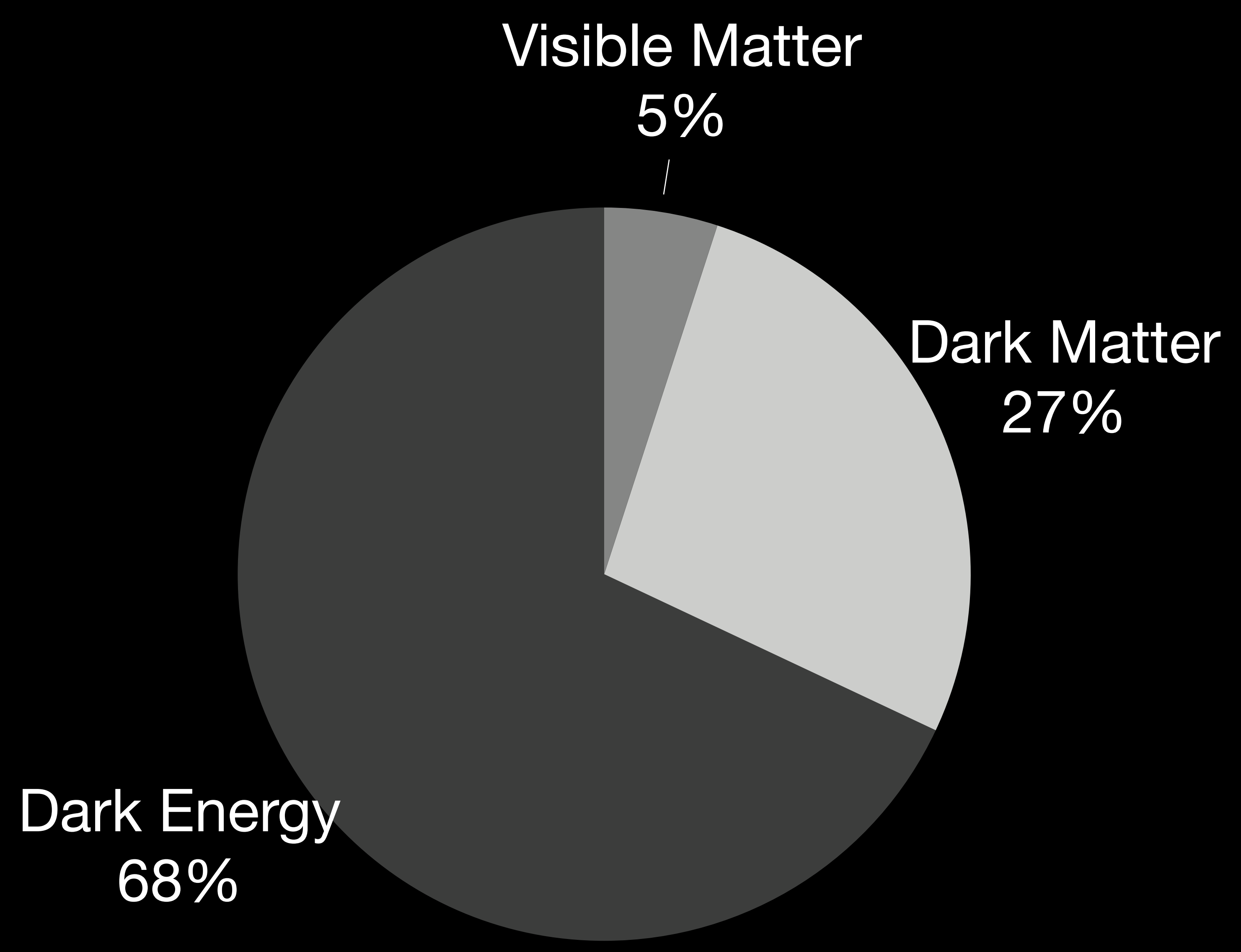
Particle DM

Only **one** DM state makes up the entire dark sector

Freeze-out $\Omega_{\rm DM} \propto 1/\langle \sigma v \rangle$

Freeze-in $\Omega_{\rm DM} \propto \langle \sigma v \rangle$

DM states are **symmetric** in nature $\rightarrow \Omega_\chi = \Omega_{\bar{\chi}}$



$$\rho_{DM} = 5\rho_B$$

Dark Sector

+ Asymmetries

Multi-component DM:

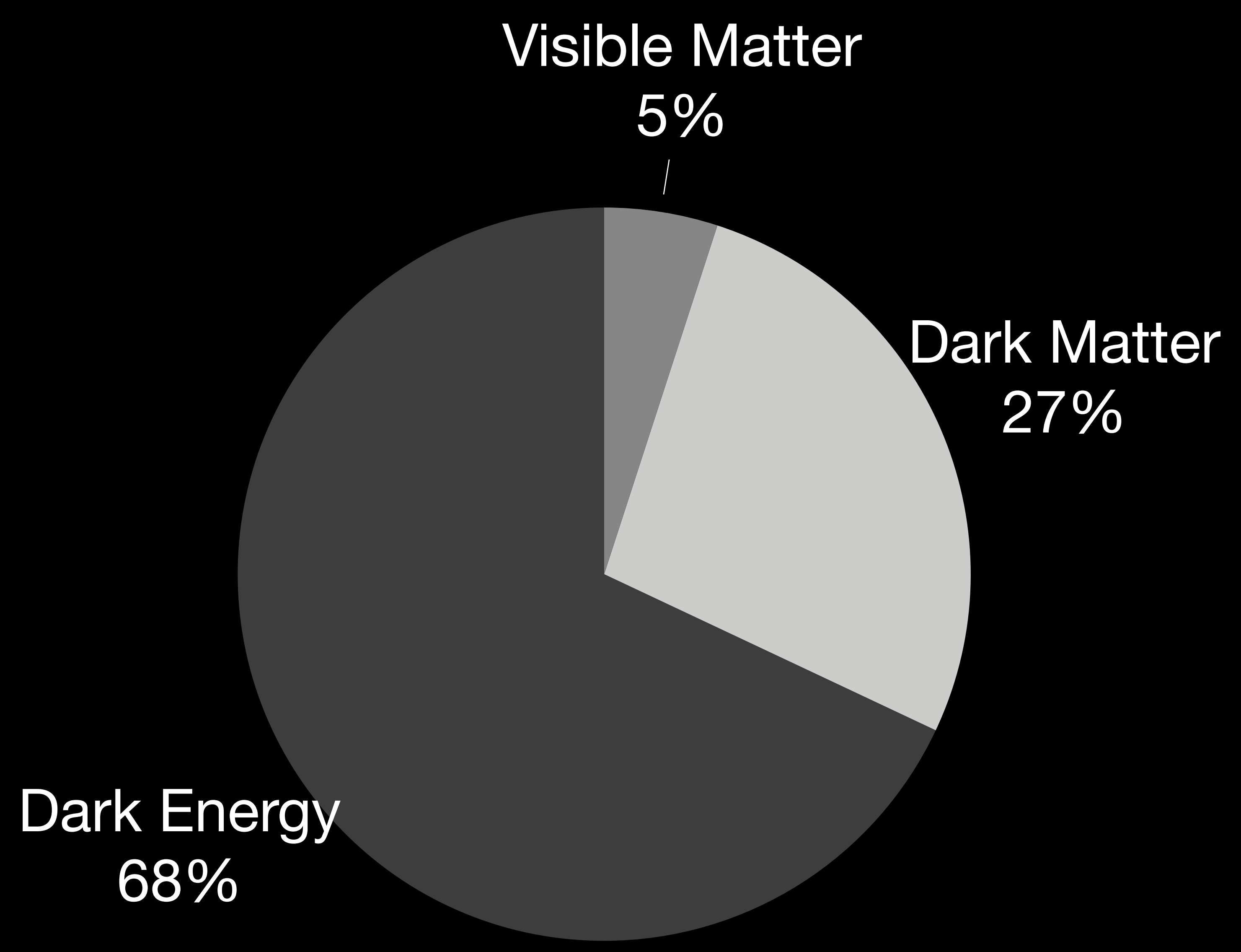
Several stable particles make up the DM relic abundance → Richer phenomenology, relaxation of existing bounds

Bas i Beneito, Herrero-García, DV: JHEP 10 (2022) 075

Asymmetric DM:

DM abundance set by an initial asymmetry in the dark sector $\eta_D \equiv n_\chi - n_{\bar{\chi}}$

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm B}} \sim 5 \simeq \frac{\sum_i \eta_i m_i}{\eta_B m_p}$$

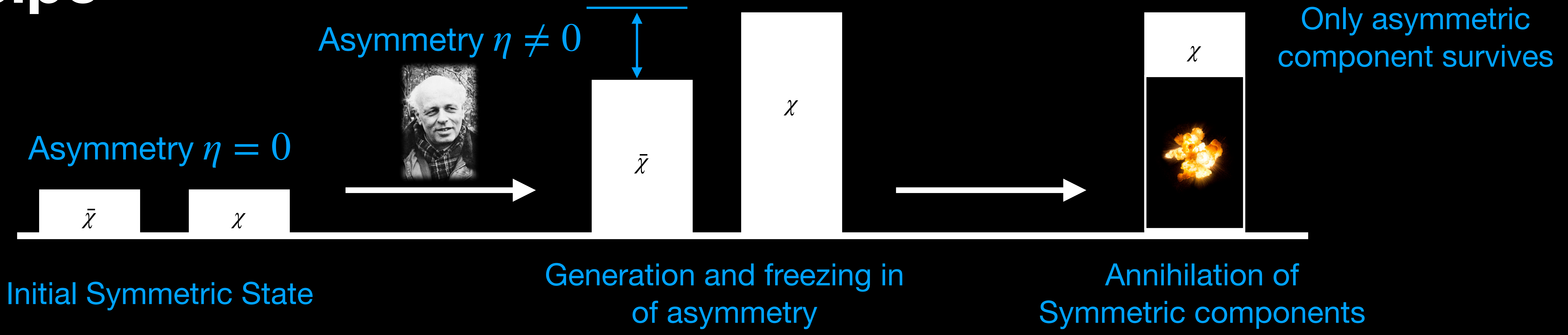


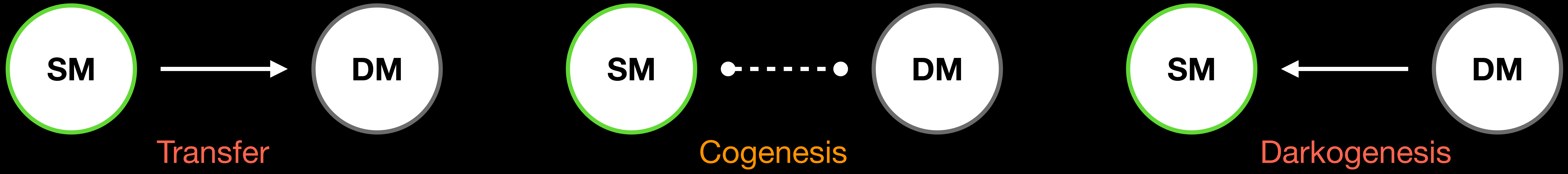
$$\rho_{DM} = 5\rho_B$$

'Cosmic Coincidence'

Asymmetric Dark Matter

The Recipe





Processes communicating this asymmetry (e.g. higher dimensional operators, sphalerons, etc.) should decouple → asymmetry freezes in both sectors

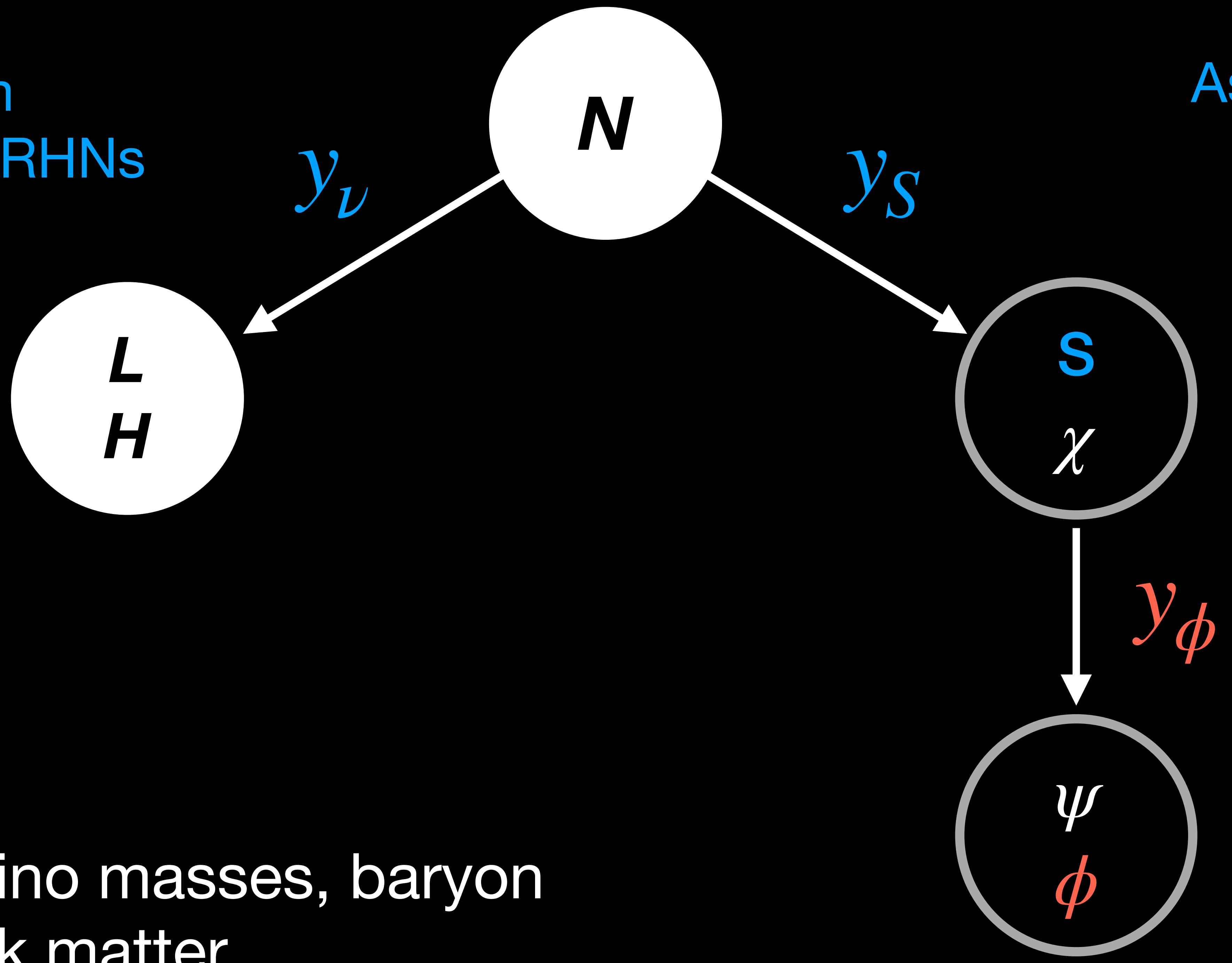
A Cogenesis Scenario

Two-sector Thermal Leptogenesis

Falkowski, Ruderman, Volansky: 1101.4936

Out-of-equilibrium CP violating decays of RHNs

Asymmetries set in both sectors once the temperature < M_N



Lepton asymmetry → baryon asymmetry by sphalerons

Dark asymmetry carried by dark fermion χ and dark scalar *S*

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

The asymmetry can be transferred from χ to ψ via decays

The framework connects neutrino masses, baryon asymmetry and dark matter

Asymmetric Freeze-out

How it works?

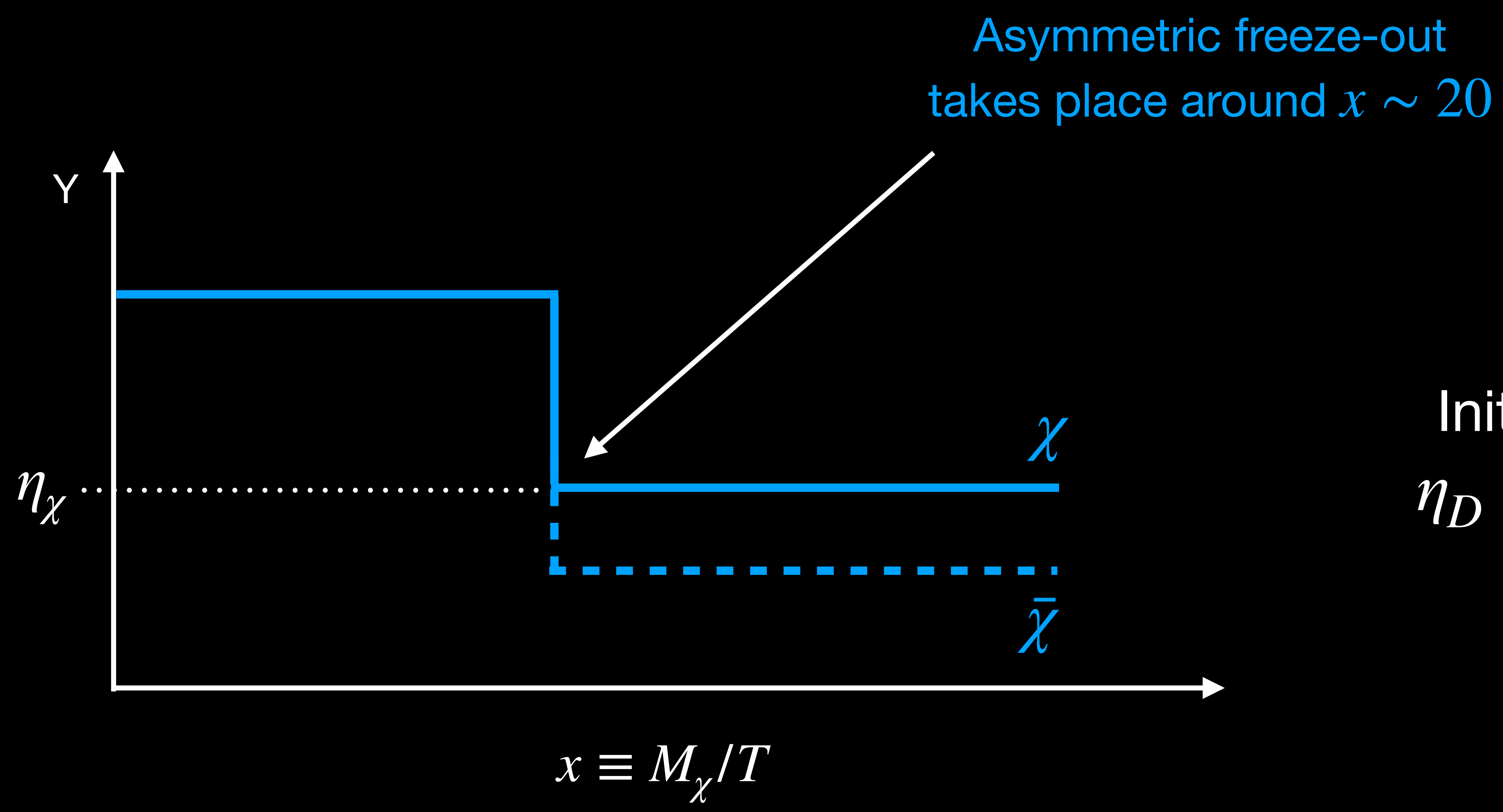
Asymmetric ratio:

$$r_\chi \equiv Y_{\bar{\chi}}/Y_\chi$$

$r_i < 10^{-2}$
Highly asymmetric

$10^{-2} < r_i < 0.9$
Partially asymmetric

$r_i > 0.9$
Highly symmetric



Initial asymmetry:

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

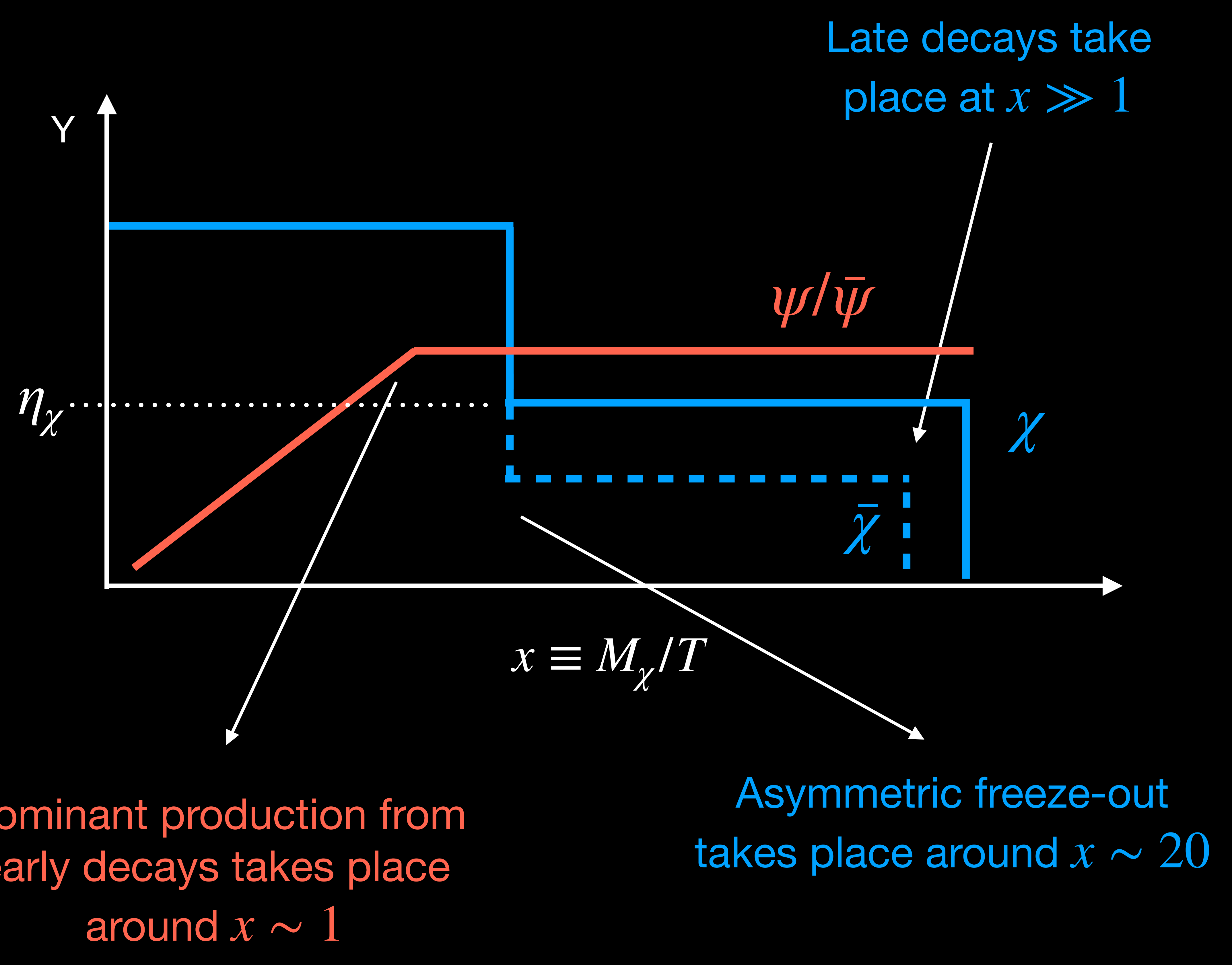
$$r_i^{(\infty)} \simeq \exp\left[-\sqrt{\frac{\pi g_*}{45 x_f}} M_{\rm Pl} \langle \sigma v \rangle_i \eta_D m_i\right]$$

Graesser, Shoemaker, Vecchi: 1103.2771

Asymmetric Freeze-in

From decays

Production from early decays: $Y_\psi = Y_{\bar{\psi}} > Y_\chi \sim \eta_\chi$ $\rightarrow \psi$ population is symmetric as χ and $\bar{\chi}$ are in equilibrium

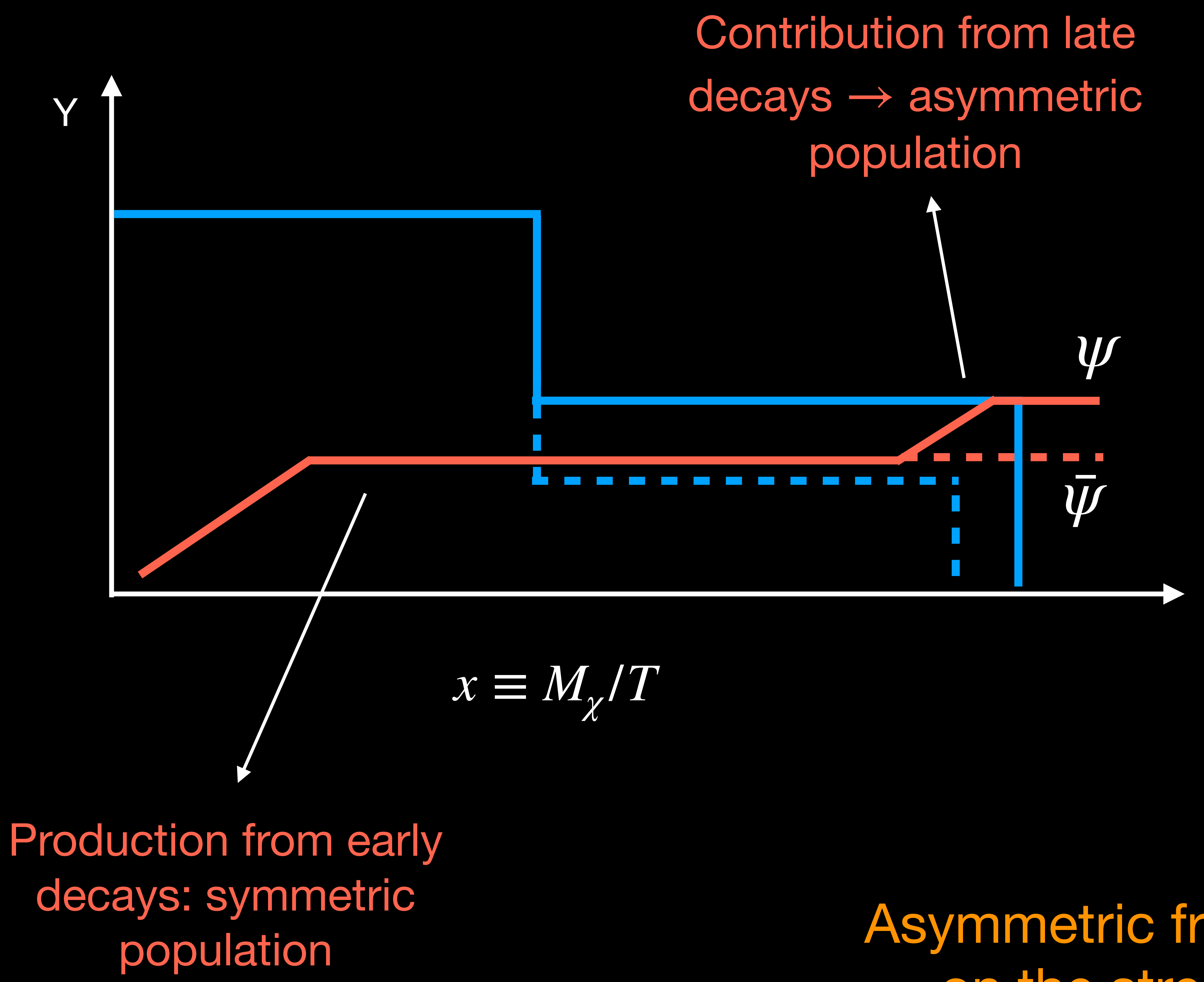


Production from late decays$\rightarrow$ sub-dominant/ negligible

Asymmetric Freeze-in

From decays

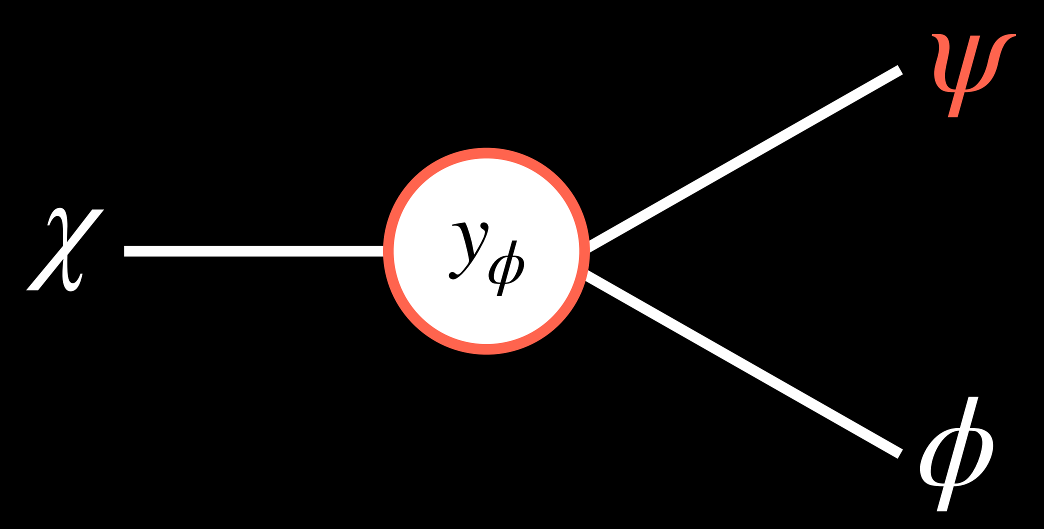
Production from early decays: $Y_\psi < Y_\chi \sim \eta_\chi$ $\rightarrow \psi$ population can become asymmetric



Late decays (active once the asymmetry has already frozen) will produce more ψ than $\bar{\psi}$

Asymmetric freeze-in via decays depends on the strength of feeble interaction

DM Components

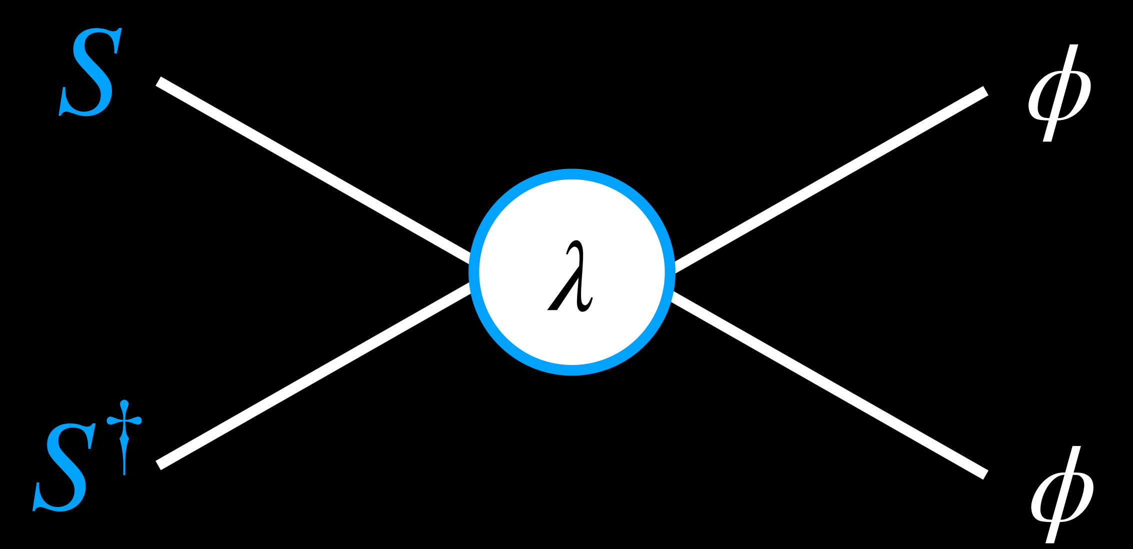


$$Y_\psi^+ \simeq \frac{Y_{\rm FI}}{2} + \eta_D$$

$$Y_\psi^- \simeq \frac{Y_{\rm FI}}{2} + \eta_D\, r_\chi$$

Asymmetric Freeze-in:

$$Y_{\rm FI} \ll \eta_D$$

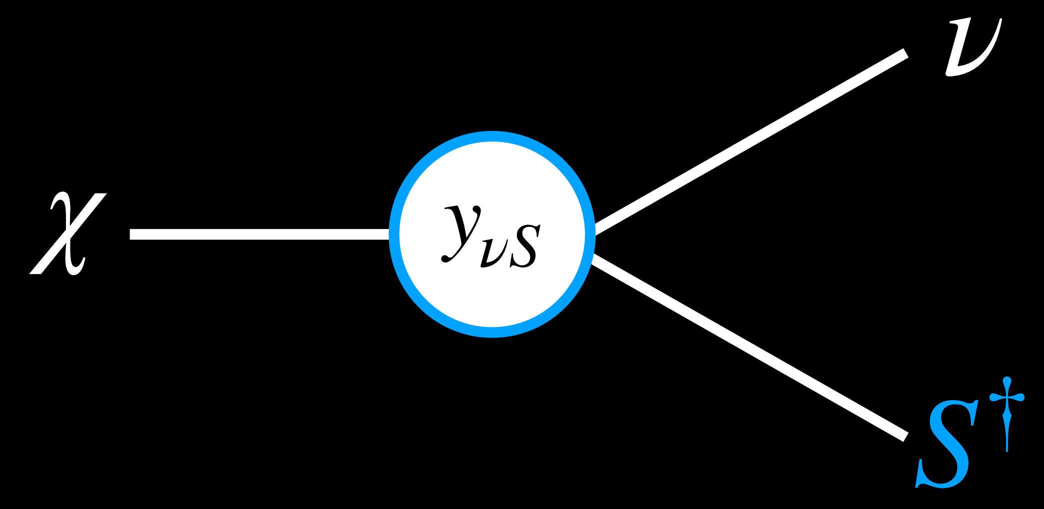


Asymmetric Freeze-out:

$$Y_S^+ = \eta_D\,, \quad Y_S^- = r_S\, \eta_D$$

$$R \equiv \frac{{\rm Br}(\chi \to S^\dagger \nu)}{{\rm Br}(\chi \to \psi\varphi)} \sim \frac{|y_S|^2}{y_\phi^2}\, \frac{m_\nu}{M_{N_1}}$$

$$y_\nu\, y_S\, \bar{L}\tilde{H}S\chi / M_{N_1}$$



After AFO → Populate symmetric component, no annihilations

$$Y_S^+ = \eta_D, \quad Y_S^- = \frac{R}{1+R}\,\eta_D$$

Before AFO → Annihilations active, partial washout

$$Y_S^+ = \frac{1}{1+R}\,\eta_D, \quad Y_S^- \ll Y_S^+$$

S population by late decays may be warm + early population from FO is cold → mix of cold/warm DM

Possible Scenarios

ψ

Asymmetric:
$y_\phi \lesssim 6\times 10^{-12}$
Early FI - Negligible
LD- Dominant
$Y_\psi^+ = \eta_D \gg Y_{FI}$

Symmetric:
$y_\phi \gtrsim 2\times 10^{-10}$
Early FI - Dominant
LD- Negligible
$Y_{FI} \gg \eta_D$

S

Asymmetric:
$R \ll 1$
AFO
χ Decays - Negligible
$Y_S^+ = \eta_D$

Symmetric:
$R > \mathcal{O}(10)$
AFO+
χ Decays produce $S^\dagger$
$Y_S + Y_S^\dagger \sim 2\eta_D$

$m_S = 2.5\,\mathrm{GeV}\left(\frac{\eta_B}{\eta_D}\right)$

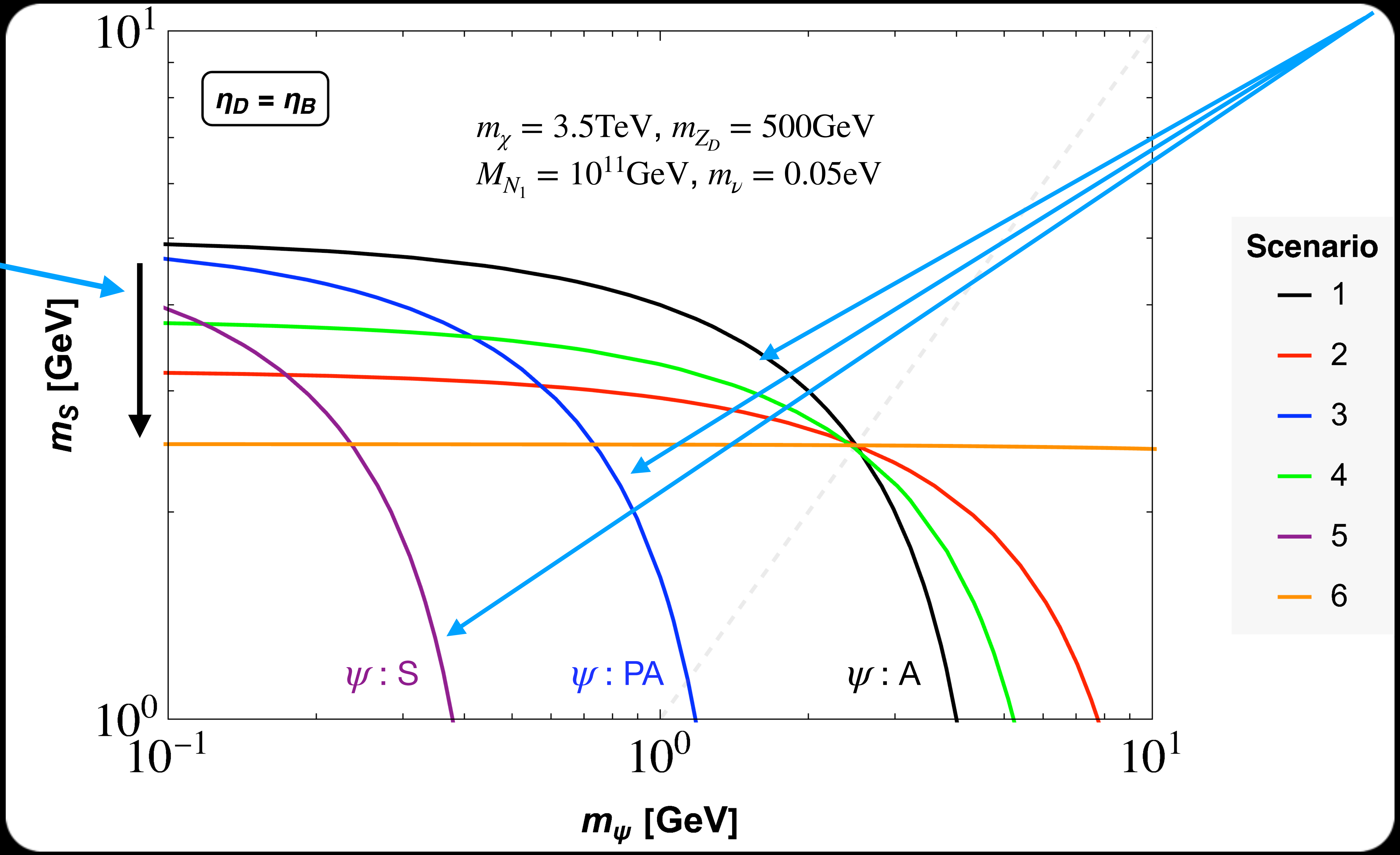
Sc.	ψ population	S population	$10^{-10}y_\phi/\sqrt{\eta_D/\eta_B}$	R	$T_D^{(S)}/T_*^{(S)}$
1	Asymmetric	Asymmetric	≤ 0.06	$\ll 1$	Any
2	Asymmetric	Partially Asymmetric	≤ 0.06	$\mathcal{O}(1)$	< 1
1-2	Asymmetric	Asymmetric	≤ 0.06	$\mathcal{O}(1)$	> 1
3	Partially Asymmetric	Asymmetric	$0.06 - 2$	$\ll 1$	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

Practically 1-component DM

DM Relic Abundance

Scenarios with $R \ll 1$
ψ is lighter when symmetric and heavier when asymmetric

As R grows
S becomes lighter



$$\frac{\Omega_\psi}{\Omega_S} = \frac{m_\psi(\eta_D + Y_{\rm FI})}{\eta_D m_S f(R)}$$

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

$f(R) \to 1 + 2R$ If $T_D^{(S)} < T_*^{(S)}$

$f(R) \to 1$ If $T_D^{(S)} > T_*^{(S)}$

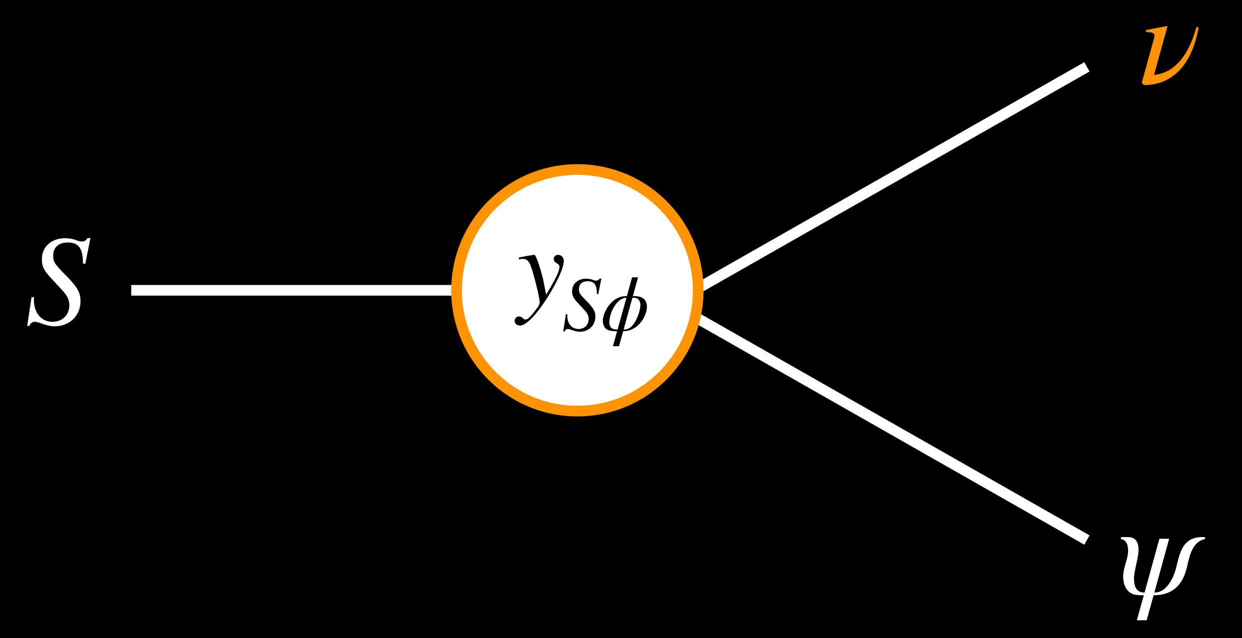
Phenomenology

Neutrino Line from DM Decay

Generated at low energies

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

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



Cosmologically stable:

$\tau_S > t_U > 4 \times 10^{17}\, s$

If decay contains ν_L: $\tau_S > 10^{23}\, s$

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

Garcia-Cely, Heeck: 1701.07209

Coy, Gupta, Hambye: 2104.00042

S decays at late times → neutrino line peaked at $m_s/2 \sim \mathcal{O}\,(\mathrm{GeV})$

Conclusions

Dark sector may be very rich

DM relic abundance $\rightarrow$ Asymmetry + FO + Ealry/Late decays

Late decays $\rightarrow$ Enhanced ID signals + mixture of warm/cold DM

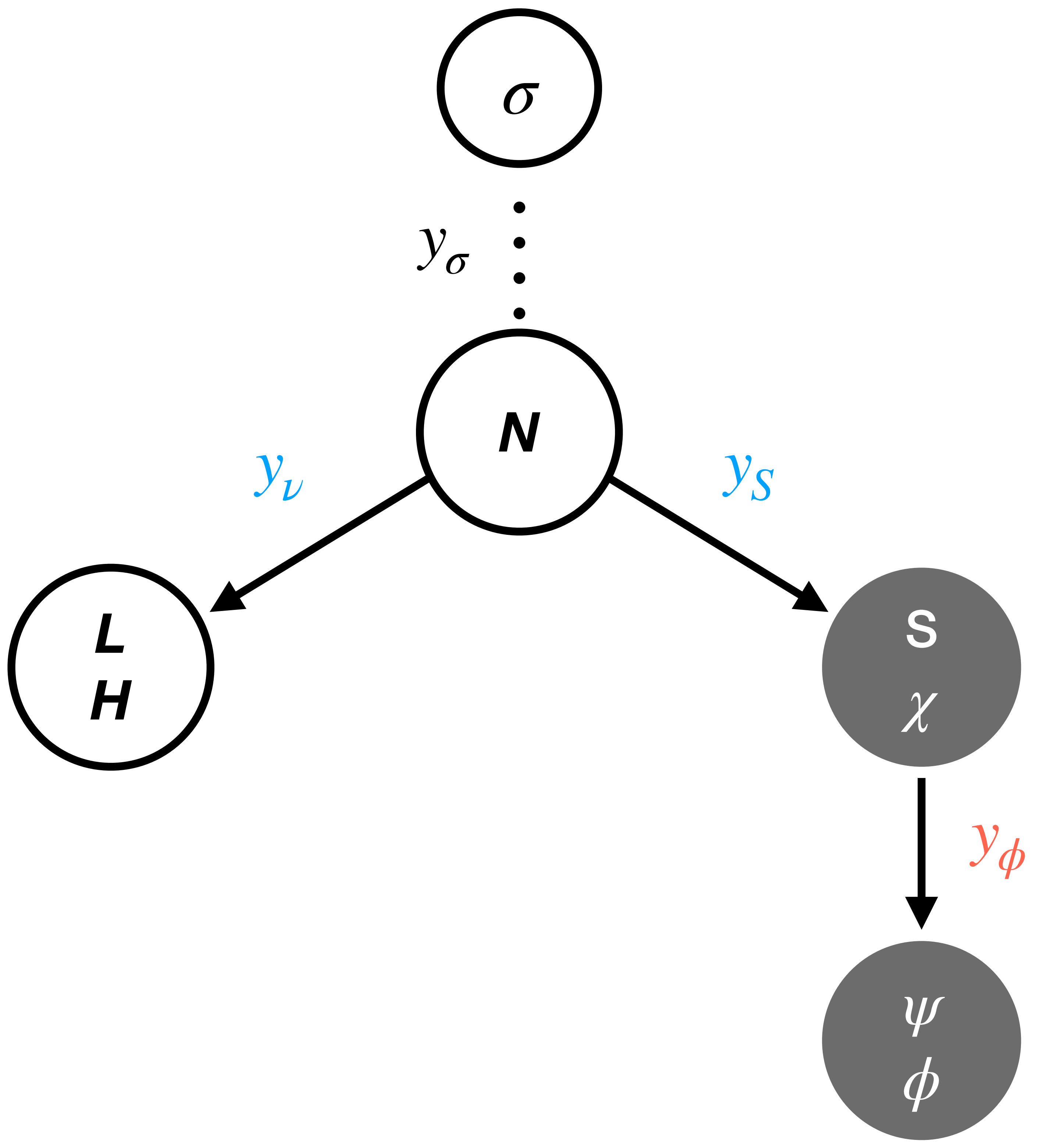
Abundance $\propto$ Asymmetry for symmetric DM state

Lighter (heavier) DM from larger (smaller) η_D

Backup

The Model

3 new gauge $U(1)$ symmetries: $U(1)_{B-L}$ and dark product $U(1)_D \otimes U(1)_X$



3 New gauge bosons: Z^0_{B-L}, Z^0_D, A'^0 with couplings g_{B-L}, g_D and g_X

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

The Model

Lagrangian

$$\mathscr{L}_{\text{new}} = \mathscr{L}^0_{\chi\psi} + \mathscr{L}^0_{\text{kin}} + \mathscr{L}_{\text{int}} - V(\sigma, S, \phi, H)$$

$$\mathscr{L}^0_{\chi\psi} = \bar{\chi}_0(i\not{D} - m^0_\chi)\chi_0 + \bar{\psi}_0(i\not{D} - m^0_\psi)\psi_0$$

$$\mathscr{L}_{\text{int}} = -y^{\alpha i}_\nu \bar{L}^\alpha \tilde{H} N^i_R - y^{ij}_\sigma \sigma \overline{N^{ic}_R} N^j_R - y^i_S S \bar{N}^i_R \chi - y_\phi \phi \bar{\psi}\chi + \text{H.c.}$$

$$\epsilon_f \equiv \frac{y_\phi v_\phi}{m^0_\chi - m^0_\psi} \qquad \phi(x) = v_\phi + \varphi(x)/\sqrt{2}$$

Field	Spin	$U(1)_{B-L}$	$U(1)_D$	$U(1)_X$
N^i_R	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

The Model

Symmetry Breaking and Masses

$v_{B-L} > 10^{11}\,\mathrm{GeV}$ $\qquad\qquad$ $v_\phi \ll v_{B-L}$

$$U(1)_{B-L} \otimes U(1)_D \otimes U(1)_X \xrightarrow{\langle\sigma\rangle} U(1)_D \otimes U(1)_X \xrightarrow{\langle\phi\rangle} U(1)_{X+D}$$

$$m^2_{Z_{B-L}} = 8 g^2_{B-L} v^2_{B-L} \qquad m^2_{Z_D} = 2 g^2_D v^2_\phi \qquad m^2_{A'} = 0$$

Mass hierarchies

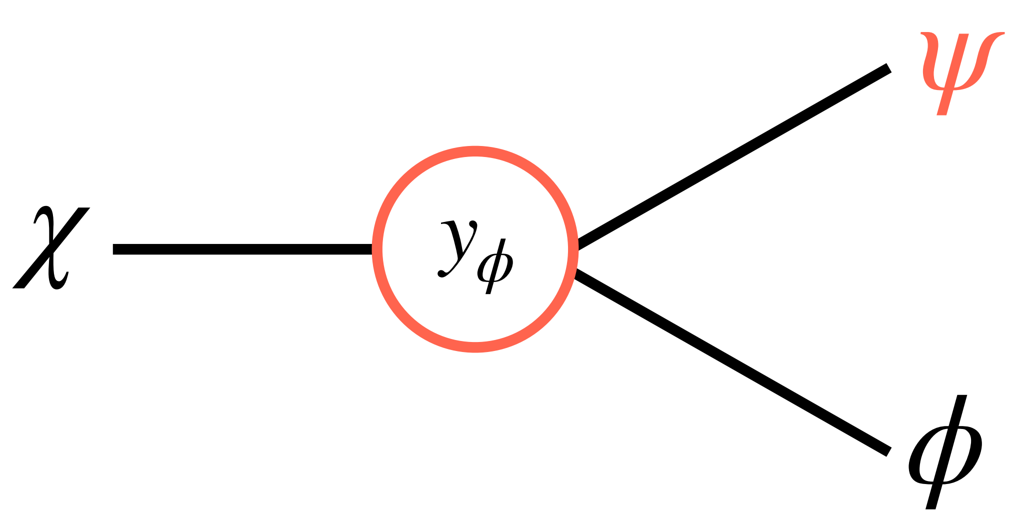
$$M_{Z_{B-L}}, M_\sigma > M_{N_1}$$

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

$$2m_S < m_{Z_D} < 2m_\chi$$

Mixing between gauge bosons and fermions suppressed due to tiny values of g_X and v_ϕ/v_{B-L} and y_ϕ

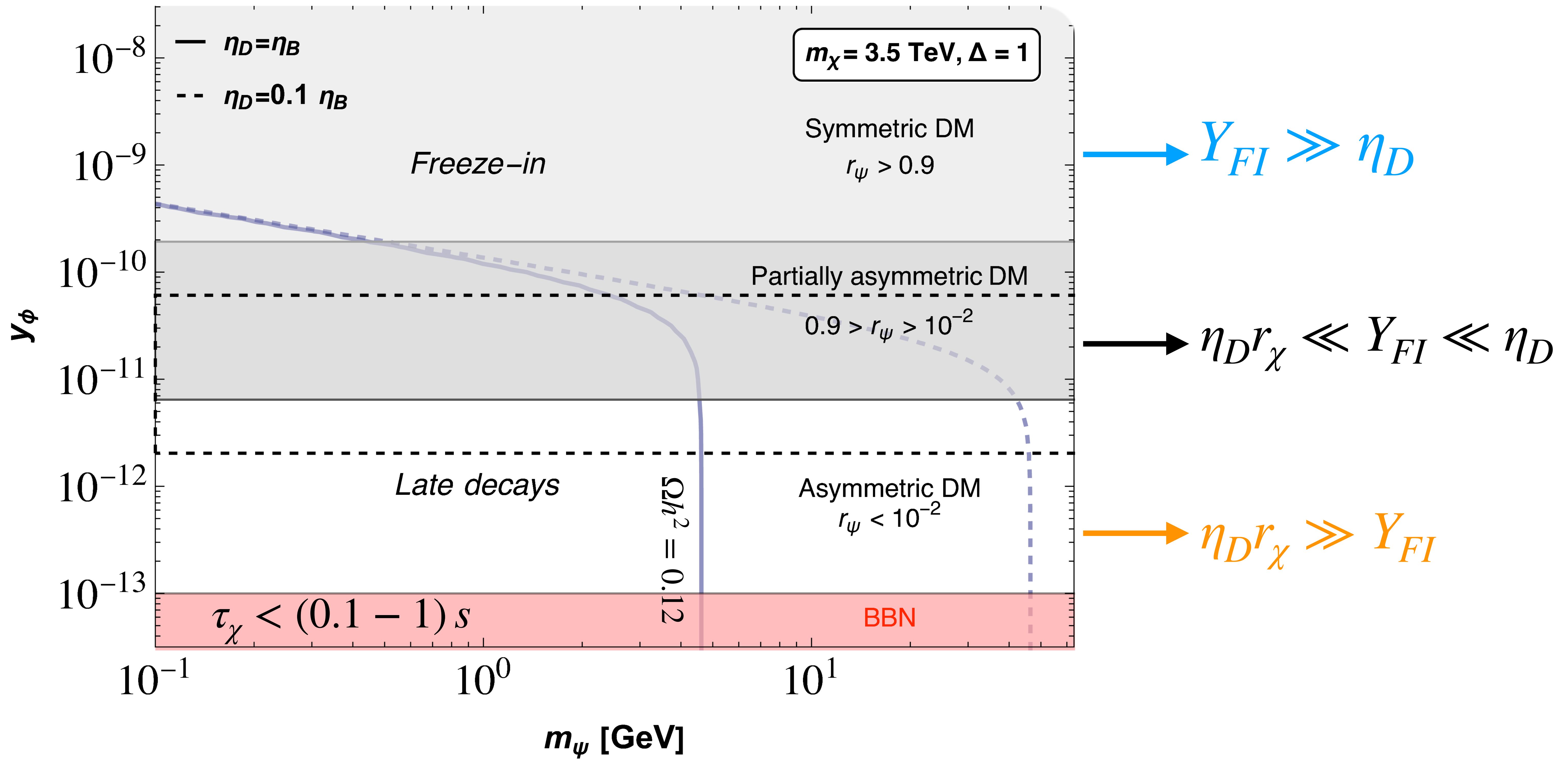
DM ψ



$$Y_\psi^+ \simeq \frac{Y_{\rm FI}}{2} + \eta_D$$

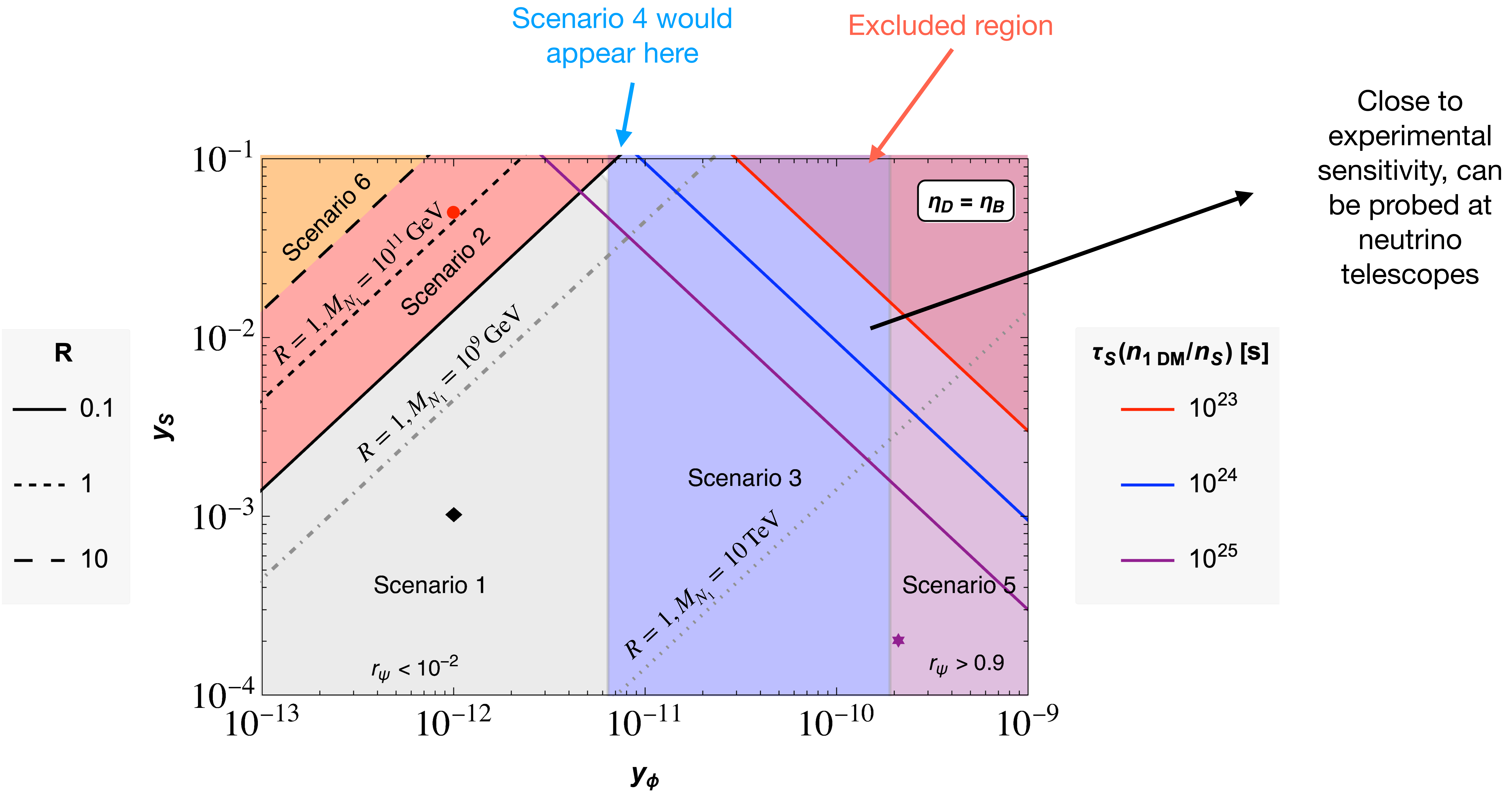
$$Y_\psi^- \simeq \frac{Y_{\rm FI}}{2} + \eta_D\, r_\chi$$

$10^{-13} \lesssim y_\phi \lesssim 10^{-7}$



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	$\frac{\eta_D}{\eta_B}\frac{2m_S}{m_p}$

The Scenarios



Low-energy variant

Inverse Seesaw

$R \ll 1$

$$|y_S| \ll \left(\frac{y_\phi}{2\times 10^{-11}}\right)\left(\frac{M_{N_1}}{10^{11}\text{GeV}}\right)^{1/2}\left(\frac{0.05\text{eV}}{m_\nu}\right)^{1/2}$$

Scale of $B-L$ breaking can be lowered, mass of $M_{Z_{B-L}} \sim \mathcal{O}(10)\,\text{TeV}$

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

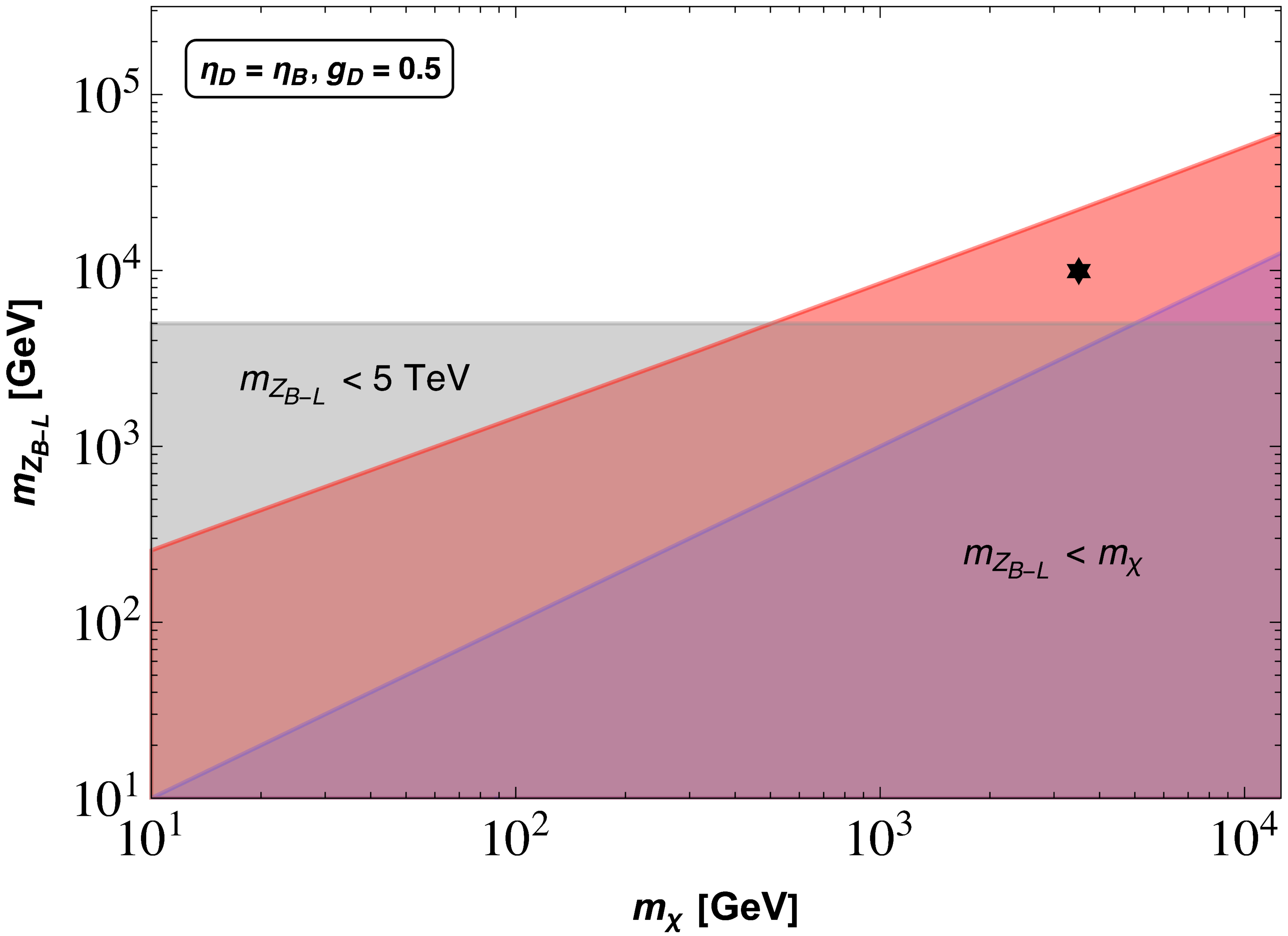
Field	Spin	$U(1)_{B-L}$	$U(1)_D$	$U(1)_X$
S_L	$1/2$	0	0	0
σ'	0	$+1$	0	0

χ Can be produced at colliders:

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

Low $M_{Z_{B-L}}$ can lead to annihilation into SM fermions that erases the symmetric component of χ

No gauged $U(1)_D$ required



Asymmetries in DS

- A DM asymmetry can be generated from an asymmetry in visible sector or vice versa
- Higher dimensional operator active at high energies:

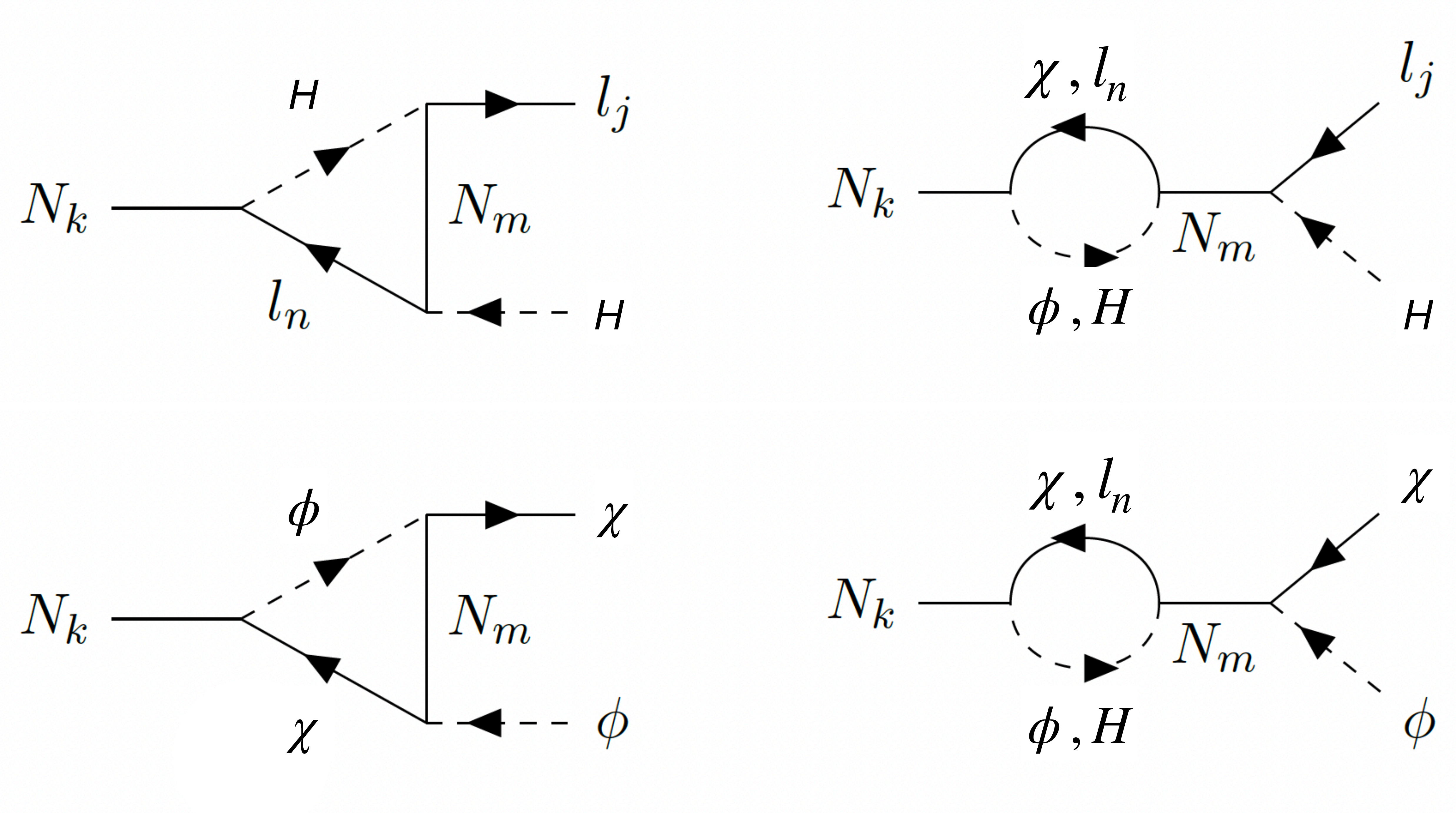
$$\mathscr{L}_{B-L=0} = \sum_i \frac{1}{\Lambda_i^n} \underbrace{\mathcal{O}_i}_{-Q_{B-L}} \underbrace{\mathcal{O}_{\rm SM}}_{Q_{B-L}}$$

- Large annihilation cross sections → symmetric component significantly erased
- Reproducing the correct relic abundance → prediction for combination of DM masses:

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm B}} \simeq 5 = \frac{\sum_i \epsilon_i m_i}{m_b}, \qquad \epsilon_i = \frac{\eta_i}{\eta_B}$$

Two Sector Leptogenesis

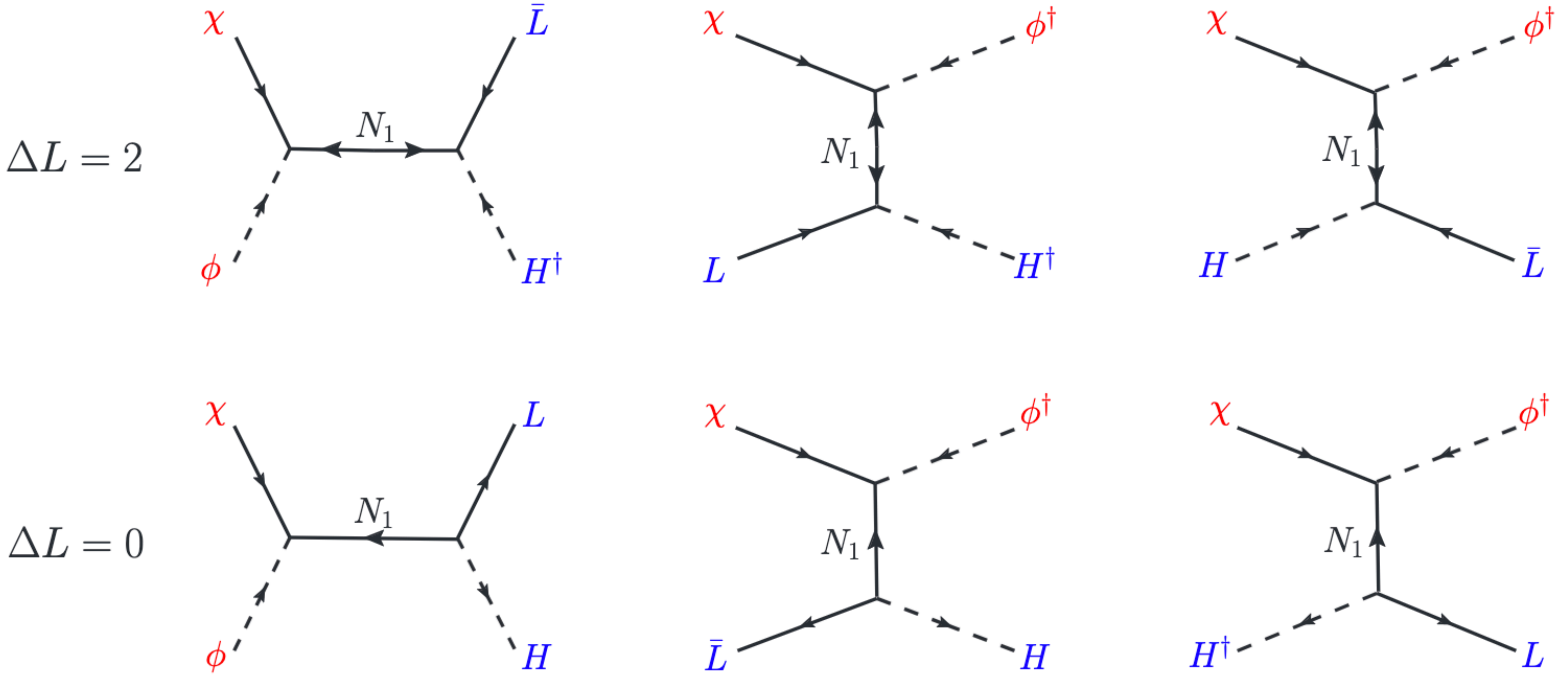
Generation of CP Asymmetry



Falkowski, Ruderman, Volansky: 1101.4936

Two Sector Leptogenesis

Washout and Transfer



Falkowski, Ruderman, Volansky: 1101.4936

Asymmetric Freeze-in

Solution of Boltzmann equations