Dark Freeze-out Cogenesis

Based on JHEP03(2022)031 arXiv:2112.10784 [hep-ph]
with X. Chu, Y. Cui, J. Pradler

Michael Shamma
mshamma@triumf.ca

TRIUMF Canada's particle accelerator centre
Centre canadien d'accélération des particules

Phenomenology Symposium 2022

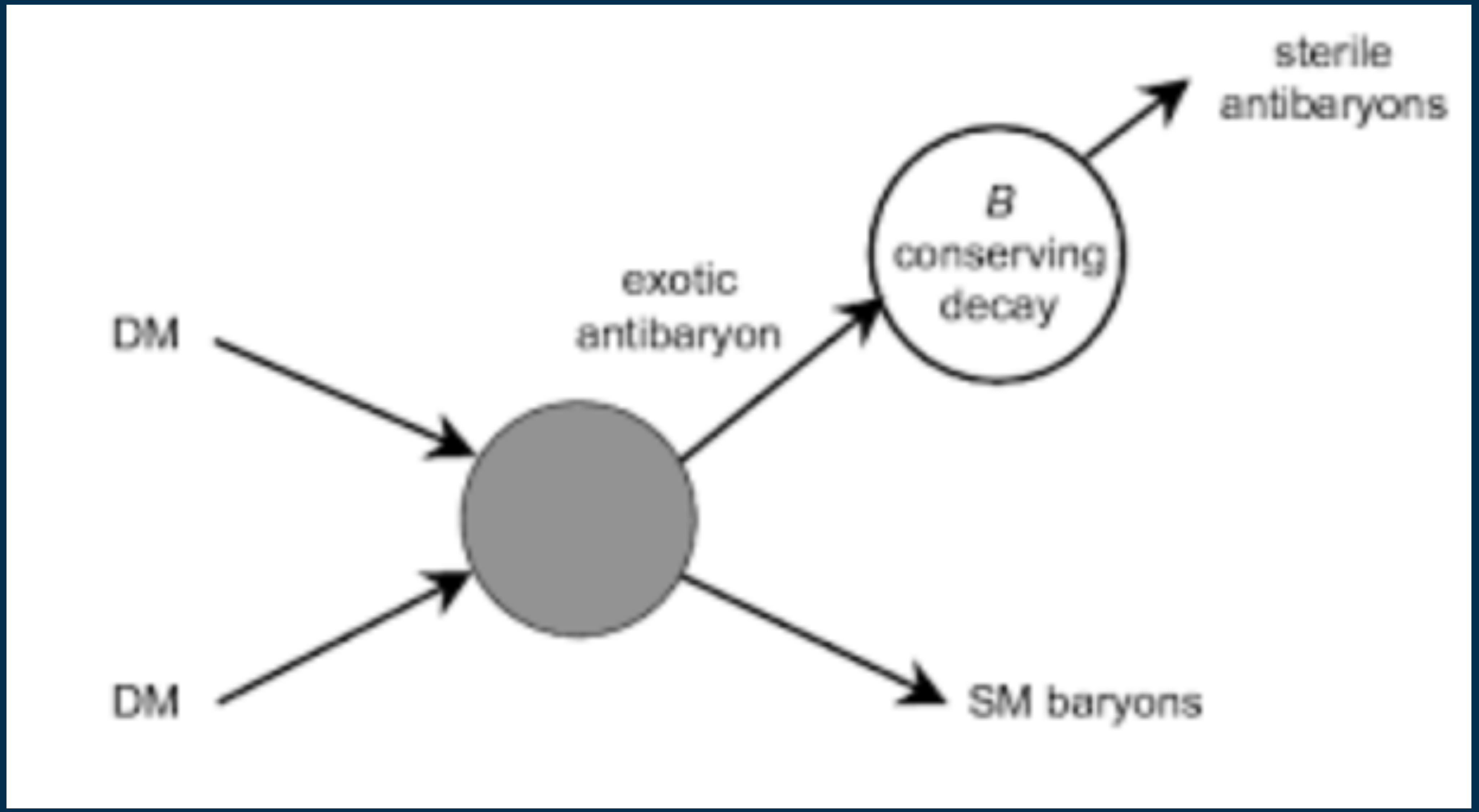
DM and the BAU

DM and the BAU

$$\Omega_{DM} \approx 5\Omega_B$$ [Planck Collab]

DM and the BAU

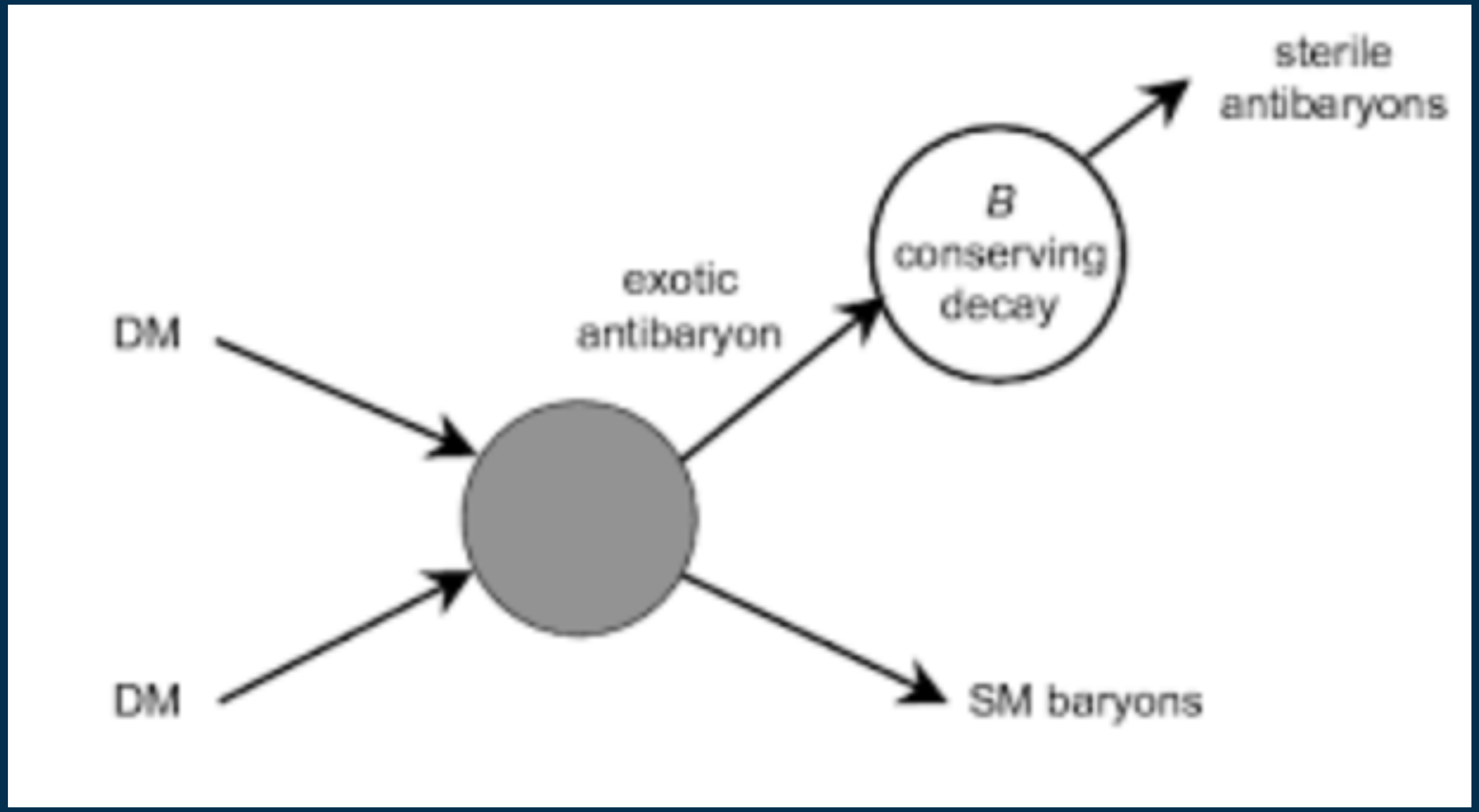
$$\Omega_{DM} \approx 5\Omega_B$$ [Planck Collab]



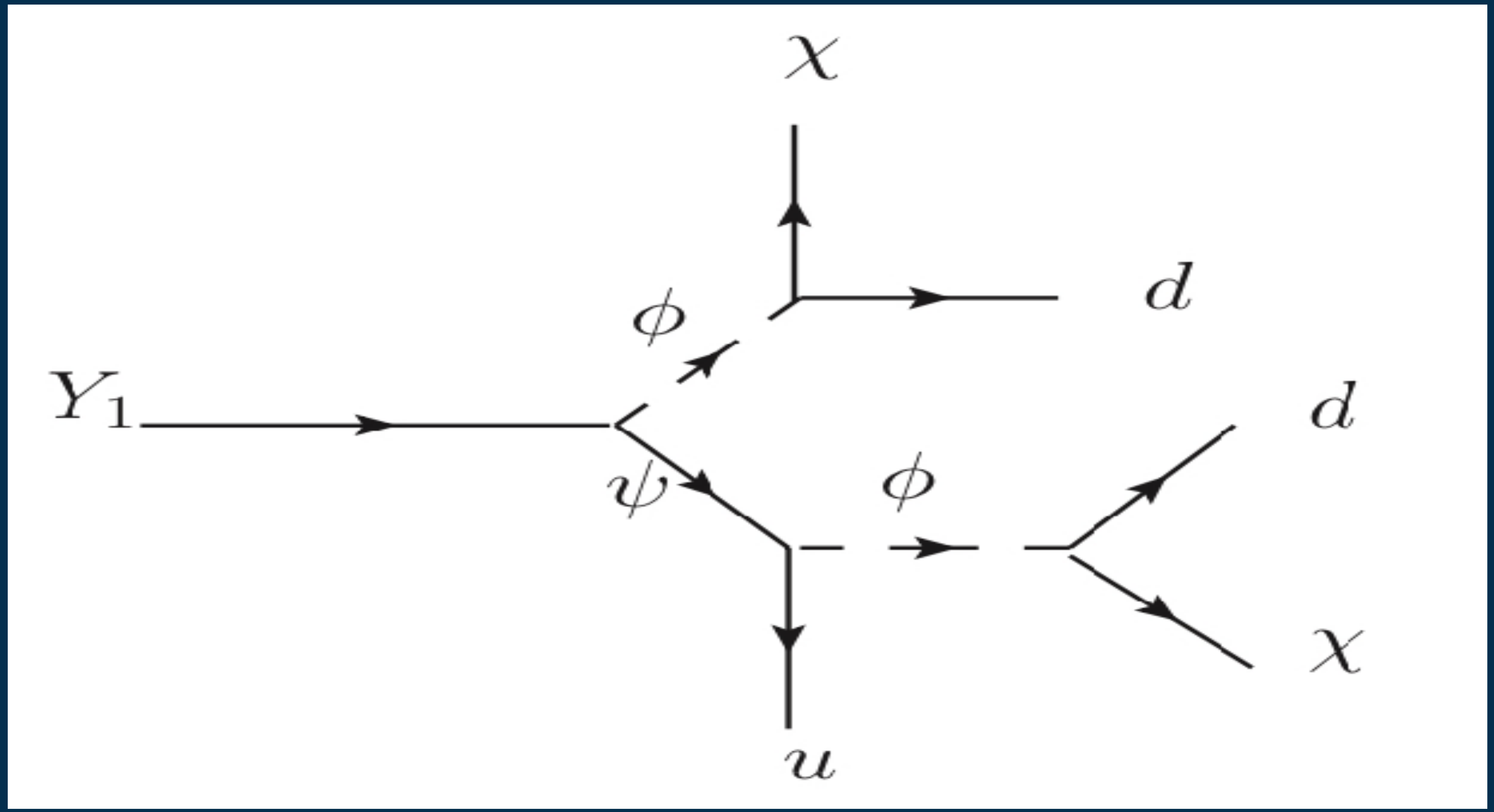
$$\Omega_B \sim \Omega_{WIMP} \propto m_{ew}^2 / g_{ew}^4$$ [Cui, Sundrum]

DM and the BAU

$\Omega_{DM} \approx 5\Omega_B$ [Planck Collab]



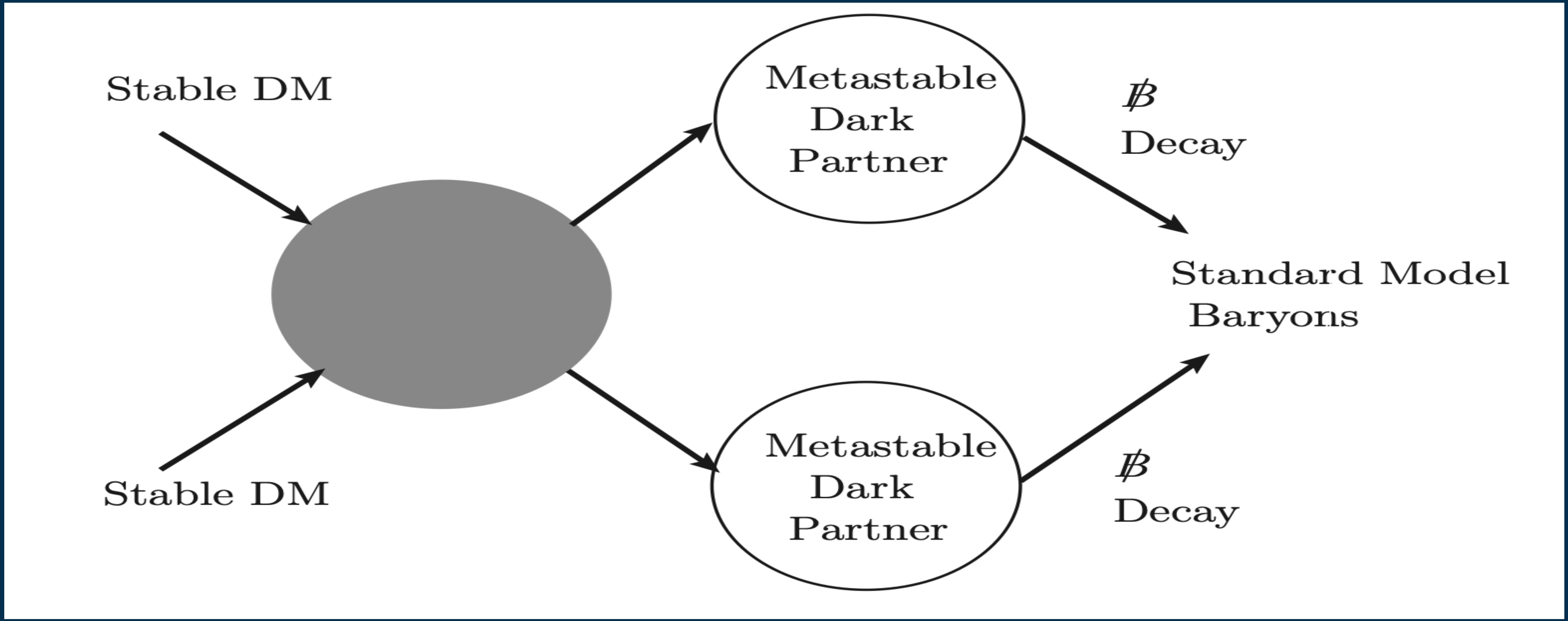
$\Omega_B \sim \Omega_{WIMP} \propto m_{ew}^2/g_{ew}^4$ [Cui, Sundrum]



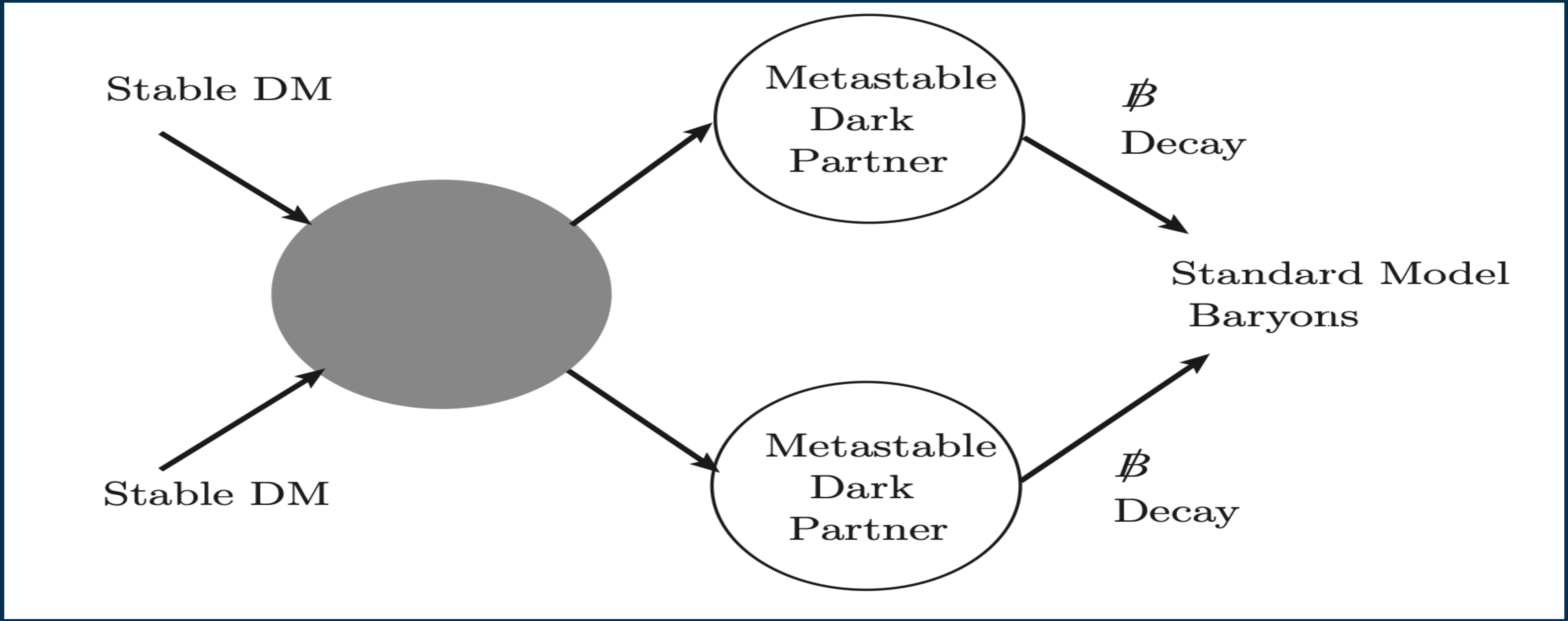
$\Omega_{ADM}/\Omega_B \simeq (n_{ADM}/n_B)(m_{ADM}/m_n)$

Dark Freeze-out Cogenesis

Dark Freeze-out Cogenesis

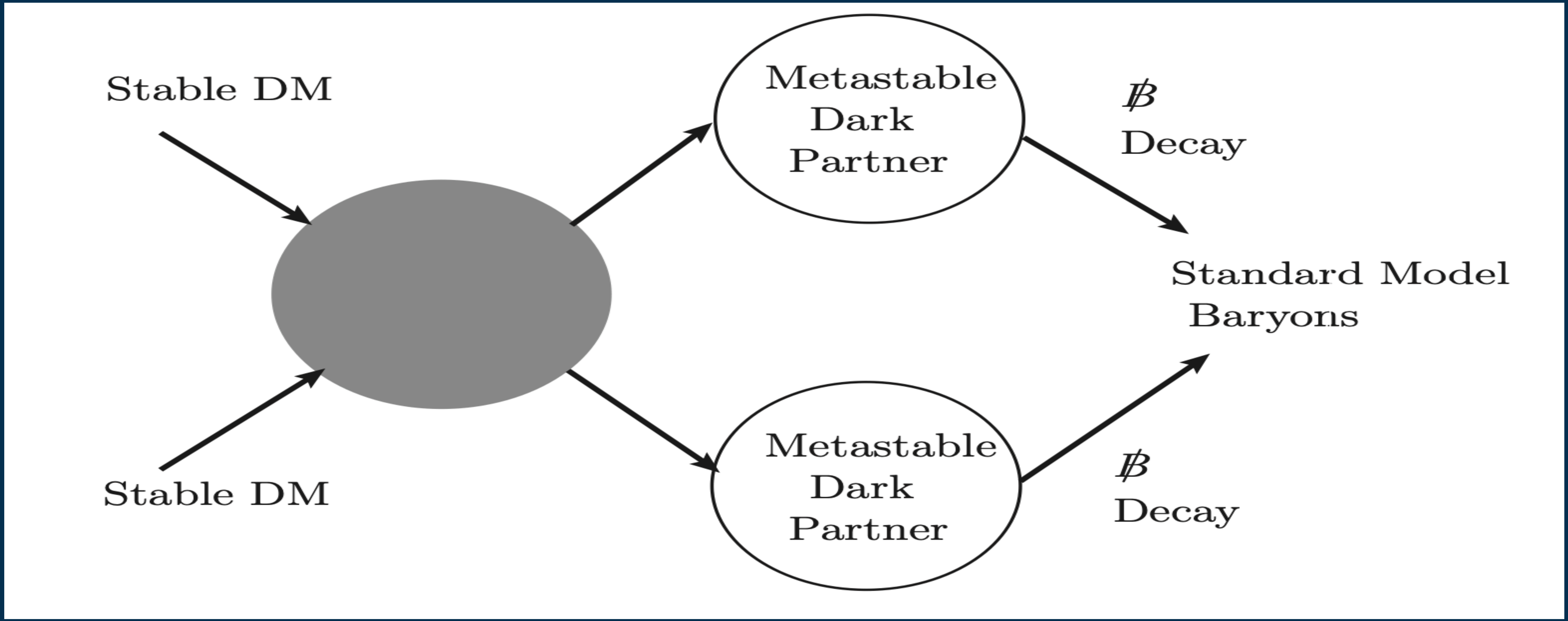


Dark Freeze-out Cogenesis



$$Y_{\chi_1,f} + Y_{\chi_2,f} = Y_{\chi_1,i} + Y_{\chi_2,i} = C$$

Dark Freeze-out Cogenesis



$$Y_{\chi_1,f} + Y_{\chi_2,f} = Y_{\chi_1,i} + Y_{\chi_2,i} = C$$

$$Y_B \simeq \epsilon_{CP}(C - Y_{\chi_1,f})$$

Near Degenerate Freeze-out

Near Degenerate Freeze-out

$$\frac{dY_{\chi_1}}{dx} = -\frac{\lambda \xi^n}{x^{2+n}}\left[Y_{\chi_1}^2 - \left(1-\delta\right)^{-3} e^{-\frac{2\delta x}{\xi}} Y_{\chi_2}^2\right]$$

Near Degenerate Freeze-out

$$\frac{dY_{\chi_1}}{dx} = -\frac{\lambda \xi^n}{x^{2+n}}\left[Y_{\chi_1}^2 - \left(1-\delta\right)^{-3} e^{-\frac{2\delta x}{\xi}} Y_{\chi_2}^2\right]$$

$$x \to \frac{m_{\chi_1}}{T}$$

Near Degenerate Freeze-out

$$\frac{s(m_{\chi_1})}{H(m_{\chi_1})}\langle\sigma_{\chi_1} v\rangle$$

$$\frac{dY_{\chi_1}}{dx} = -\frac{\lambda\xi^n}{x^{2+n}}\left[Y_{\chi_1}^2 - \left(1-\delta\right)^{-3} e^{-\frac{2\delta x}{\xi}} Y_{\chi_2}^2\right]$$

$$\frac{m_{\chi_1}}{T}$$

Near Degenerate Freeze-out

$$\frac{s(m_{\chi_1})}{H(m_{\chi_1})}\langle\sigma_{\chi_1}v\rangle$$

$$\frac{T'}{T}$$

$$\frac{dY_{\chi_1}}{dx} = -\frac{\lambda\xi^n}{x^{2+n}}\left[Y_{\chi_1}^2 - \left(1-\delta\right)^{-3} e^{-\frac{2\delta x}{\xi}} Y_{\chi_2}^2\right]$$

$$\frac{m_{\chi_1}}{T}$$

Near Degenerate Freeze-out

$$\frac{s(m_{\chi_1})}{H(m_{\chi_1})}\langle\sigma_{\chi_1} v\rangle$$

$$\frac{T'}{T}$$

$$\frac{m_{\chi_1} - m_{\chi_2}}{m_{\chi_1}}$$

$$\frac{dY_{\chi_1}}{dx} = -\frac{\lambda\xi^n}{x^{2+n}}\left[Y_{\chi_1}^2 - \left(1-\delta\right)^{-3} e^{-\frac{2\delta x}{\xi}} Y_{\chi_2}^2\right]$$

$$\frac{m_{\chi_1}}{T}$$

Near Degenerate Freeze-out

$$\frac{s(m_{\chi_1})}{H(m_{\chi_1})}\langle\sigma_{\chi_1}v\rangle$$

$$\frac{T'}{T}$$

$$\frac{m_{\chi_1}-m_{\chi_2}}{m_{\chi_1}}$$

$$\frac{dY_{\chi_1}}{dx} = -\frac{\lambda\xi^n}{x^{2+n}}\left[Y_{\chi_1}^2 - \left(1-\delta\right)^{-3} e^{-\frac{2\delta x}{\xi}} Y_{\chi_2}^2\right]$$

$$\frac{m_{\chi_1}}{T}$$

$$C - Y_{\chi_1}$$

Near Degenerate Freeze-out

$$\frac{s(m_{\chi_1})}{H(m_{\chi_1})}\langle \sigma_{\chi_1} v \rangle \qquad \frac{T'}{T} \qquad \frac{m_{\chi_1} - m_{\chi_2}}{m_{\chi_1}}$$

$$\frac{dY_{\chi_1}}{dx} = -\frac{\lambda \xi^n}{x^{2+n}}\left[Y_{\chi_1}^2 - \left(1-\delta\right)^{-3} e^{-\frac{2\delta x}{\xi}} Y_{\chi_2}^2\right]$$

$$\frac{m_{\chi_1}}{T} \qquad C - Y_{\chi_1}$$

Quasi-Static Equlibrium

$$\implies Y_{\chi_1}^{QSE} = \frac{(1-\delta)^{-3/2} e^{-\frac{2\delta x}{\xi}}}{1 + (1-\delta)^{-3/2} e^{-\frac{2\delta x}{\xi}}} C$$

Near Degenerate Freeze-out

$$\frac{dY_{\chi_1}}{dx} = -\frac{\lambda \xi^n}{x^{2+n}}\left[Y_{\chi_1}^2 - \left(1-\delta\right)^{-3} e^{-\frac{2\delta x}{\xi}} Y_{\chi_2}^2\right]$$

$\lambda \rightarrow \frac{s(m_{\chi_1})}{H(m_{\chi_1})}\langle \sigma_{\chi_1} v\rangle$

$\xi \rightarrow \frac{T'}{T}$

$\delta \rightarrow \frac{m_{\chi_1} - m_{\chi_2}}{m_{\chi_1}}$

$x \rightarrow \frac{m_{\chi_1}}{T}$

$Y_{\chi_2} \rightarrow C - Y_{\chi_1}$

Quasi-Static Equlibrium

$$\Longrightarrow \quad Y_{\chi_1}^{QSE} = \frac{(1-\delta)^{-3/2} e^{-\frac{2\delta x}{\xi}}}{1 + (1-\delta)^{-3/2} e^{-\frac{2\delta x}{\xi}}} C$$

ξ not a constant since $T' \propto T^2$

$$\Longrightarrow \quad \xi = \frac{1}{\beta x}, \beta = \frac{1-\delta}{4 \times 2^{2/3} \xi_i^2}$$

Near Degenerate Freeze-out

$$\frac{s(m_{\chi_1})}{H(m_{\chi_1})}\langle \sigma_{\chi_1} v\rangle \qquad \frac{T'}{T} \qquad \frac{m_{\chi_1} - m_{\chi_2}}{m_{\chi_1}}$$

$$\frac{dY_{\chi_1}}{dx} = -\frac{\lambda \xi^n}{x^{2+n}}\left[Y_{\chi_1}^2 - \left(1-\delta\right)^{-3} e^{-\frac{2\delta x}{\xi}} Y_{\chi_2}^2\right]$$

$$\frac{m_{\chi_1}}{T} \qquad C - Y_{\chi_1}$$

Quasi-Static Equlibrium

$$\implies Y_{\chi_1}^{QSE} = \frac{(1-\delta)^{-3/2} e^{-\frac{2\delta x}{\xi}}}{1 + (1-\delta)^{-3/2} e^{-\frac{2\delta x}{\xi}}} C$$

ξ not a constant since $T' \propto T^2$

$$\implies \xi = \frac{1}{\beta x}, \beta = \frac{1-\delta}{4 \times 2^{2/3}\xi_i^2}$$

$$Y_{\chi_1,f} \approx [(2n+1)\beta^n/\lambda] x_f^{2n+1}$$

Near Degenerate Freeze-out

$$\frac{dY_{\chi_1}}{dx} = -\frac{\lambda \xi^n}{x^{2+n}}\left[Y_{\chi_1}^2 - \left(1-\delta\right)^{-3} e^{-\frac{2\delta x}{\xi}} Y_{\chi_2}^2\right]$$

$\lambda \to \frac{s(m_{\chi_1})}{H(m_{\chi_1})}\langle \sigma_{\chi_1} v\rangle$

$\xi \to \frac{T'}{T}$

$\delta \to \frac{m_{\chi_1} - m_{\chi_2}}{m_{\chi_1}}$

$x \to \frac{m_{\chi_1}}{T}$

$Y_{\chi_2} \to C - Y_{\chi_1}$

Quasi-Static Equlibrium

$$\implies Y_{\chi_1}^{QSE} = \frac{(1-\delta)^{-3/2} e^{-\frac{2\delta x}{\xi}}}{1 + (1-\delta)^{-3/2} e^{-\frac{2\delta x}{\xi}}} C$$

ξ not a constant since $T' \propto T^2$

$$\implies \xi = \frac{1}{\beta x}, \beta = \frac{1-\delta}{4 \times 2^{2/3} \xi_i^2}$$

$$Y_{\chi_1, f} \approx [(2n+1)\beta^n/\lambda] x_f^{2n+1}$$

Number conservation

$$\implies Y_{\chi_2, f} \approx (0.42 g_\chi \xi_i^3 / g_*) - Y_{\chi_1, f}$$

Near Degenerate Freeze-out

$$\frac{dY_{\chi_1}}{dx} = -\frac{\lambda \xi^n}{x^{2+n}}\left[Y_{\chi_1}^2 - \left(1-\delta\right)^{-3} e^{-\frac{2\delta x}{\xi}} Y_{\chi_2}^2\right]$$

$$\lambda = \frac{s(m_{\chi_1})}{H(m_{\chi_1})}\langle \sigma_{\chi_1} v\rangle, \quad \xi = \frac{T'}{T}, \quad \delta = \frac{m_{\chi_1} - m_{\chi_2}}{m_{\chi_1}}, \quad x = \frac{m_{\chi_1}}{T}, \quad Y_{\chi_2} = C - Y_{\chi_1}$$

Quasi-Static Equlibrium

$$\implies Y_{\chi_1}^{QSE} = \frac{(1-\delta)^{-3/2} e^{-\frac{2\delta x}{\xi}}}{1 + (1-\delta)^{-3/2} e^{-\frac{2\delta x}{\xi}}} C$$

ξ not a constant since $T' \propto T^2$

$$\implies \xi = \frac{1}{\beta x}, \beta = \frac{1-\delta}{4 \times 2^{2/3} \xi_i^2}$$

$$Y_{\chi_1,f} \approx [(2n+1)\beta^n/\lambda] x_f^{2n+1}$$

Number conservation

$$\implies Y_{\chi_2,f} \approx (0.42 g_\chi \xi_i^3 / g_*) - Y_{\chi_1,f}$$

χ_2 Decays

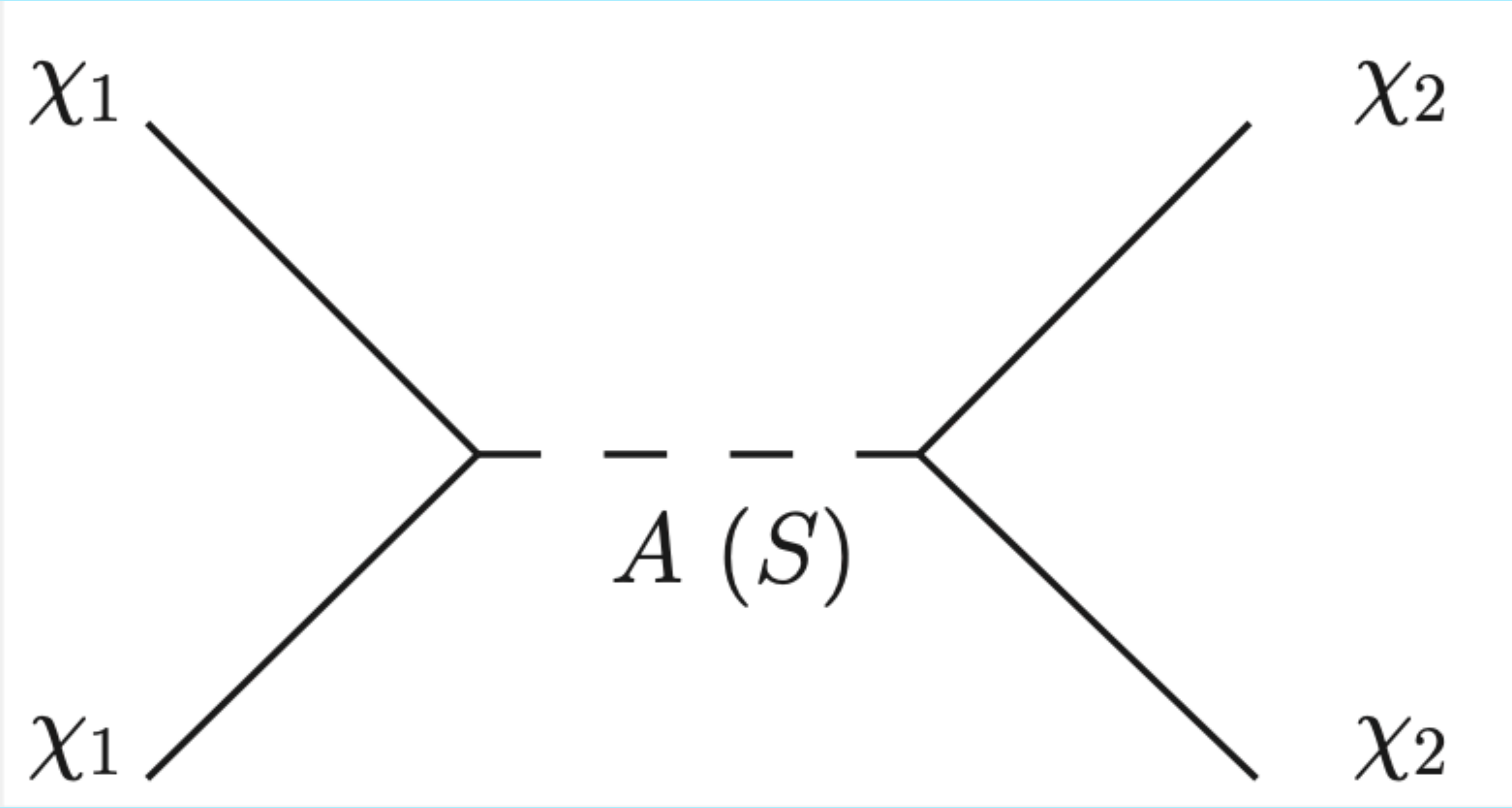
$$Y_{B,0} = \epsilon_{CP} Y_{\chi_2,f} = \epsilon_{CP}\left[(0.42 g_\chi \xi_i^3/g_*) - Y_{\chi_1,f}\right]$$

Model

Model

Freeze-out

$$\mathscr{L}_{\text{f.o.}} = -g_j\bar{\chi}_j i\gamma^5\chi_j A - g_j'\bar{\chi}_j\chi_j S \qquad j = 1,2,3$$

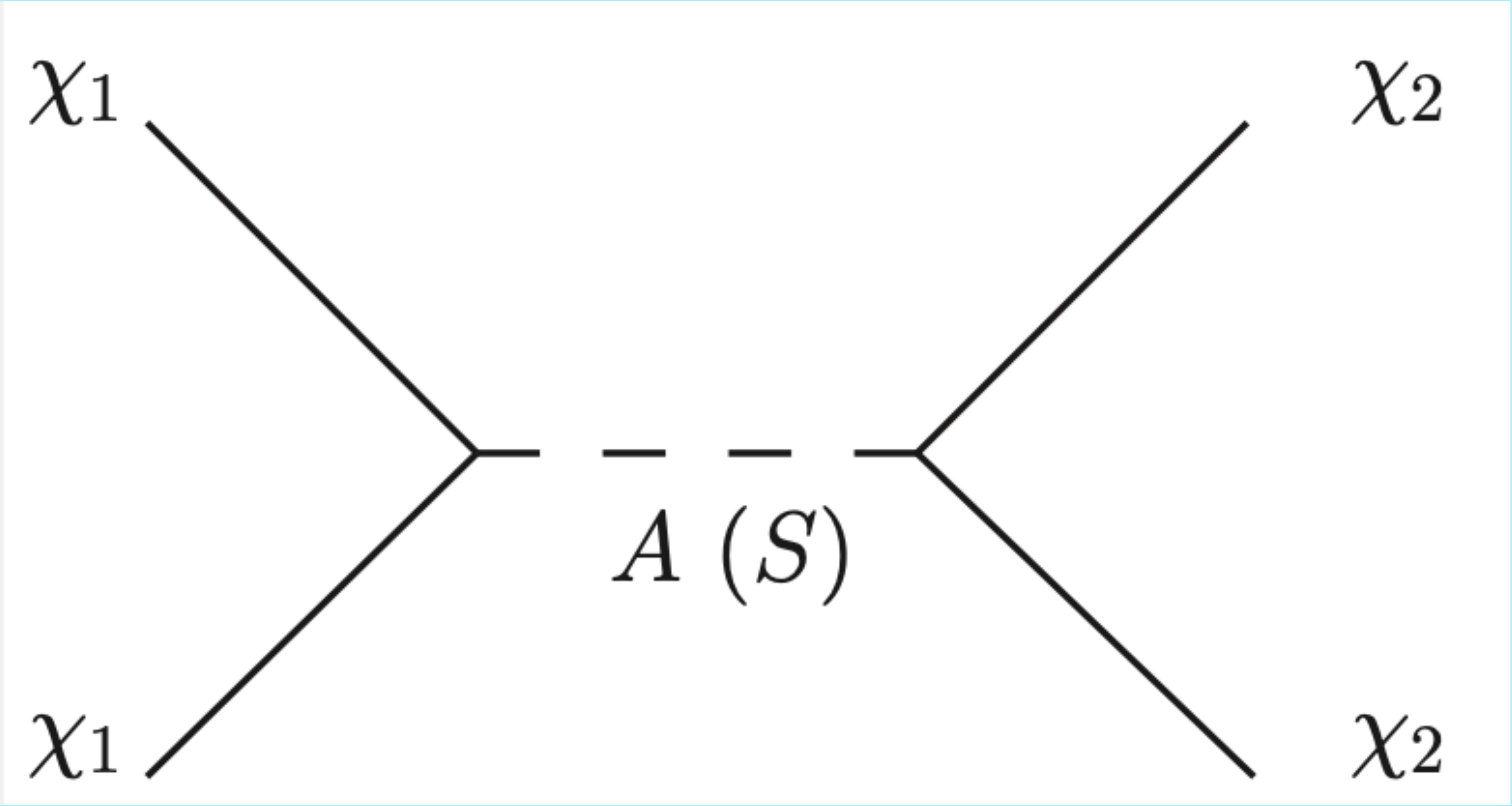


Model

Freeze-out

$$\mathscr{L}_{\text{f.o.}} = -g_j \bar{\chi}_j i\gamma^5 \chi_j A - g_j' \bar{\chi}_j \chi_j S \qquad j = 1,2,3$$

$m_S \geq 2m_{\chi_1}$ $\qquad g_3, g_3' \ll 1$ $\qquad \lambda S|H|^2$ suppressed

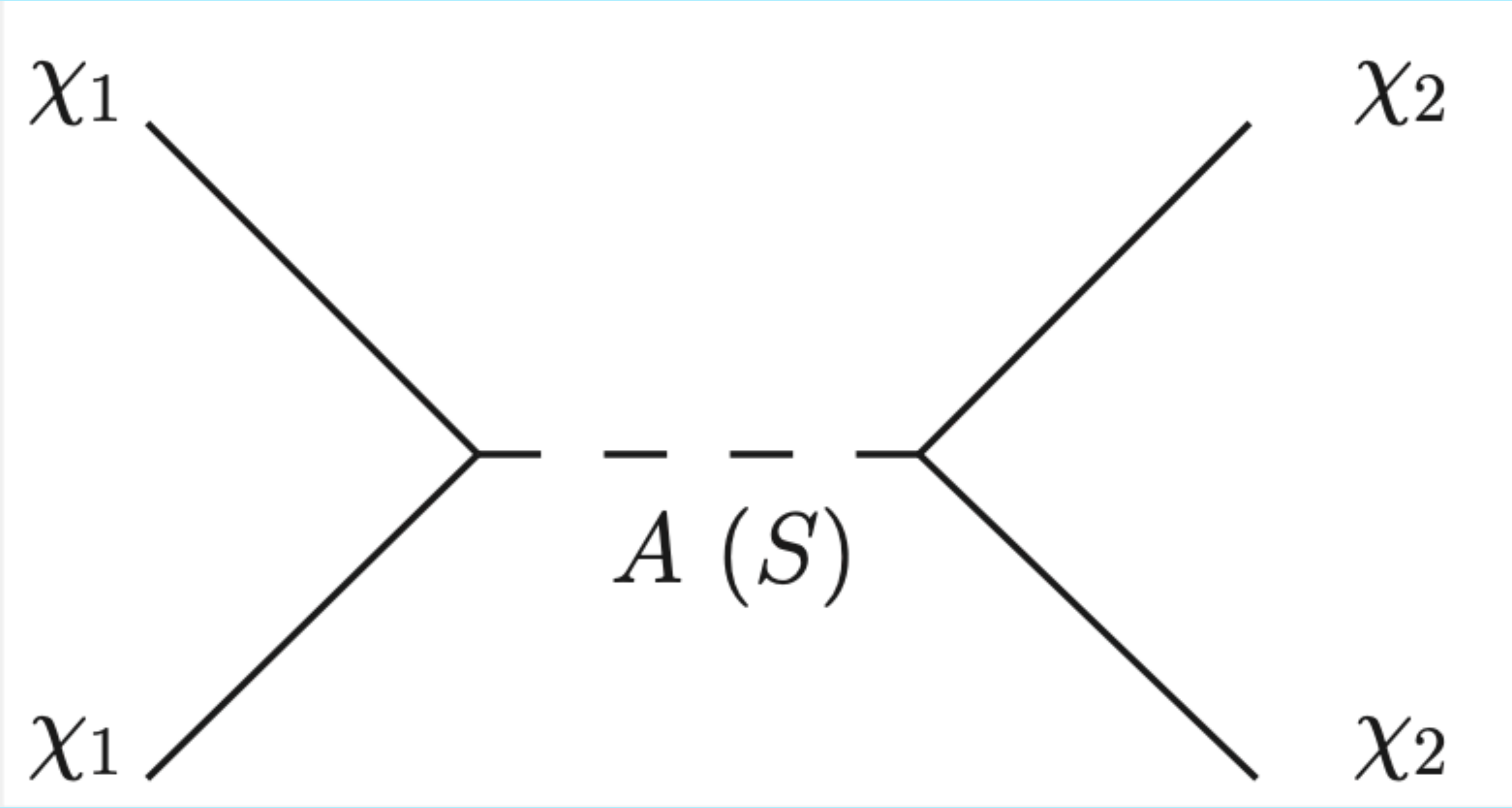


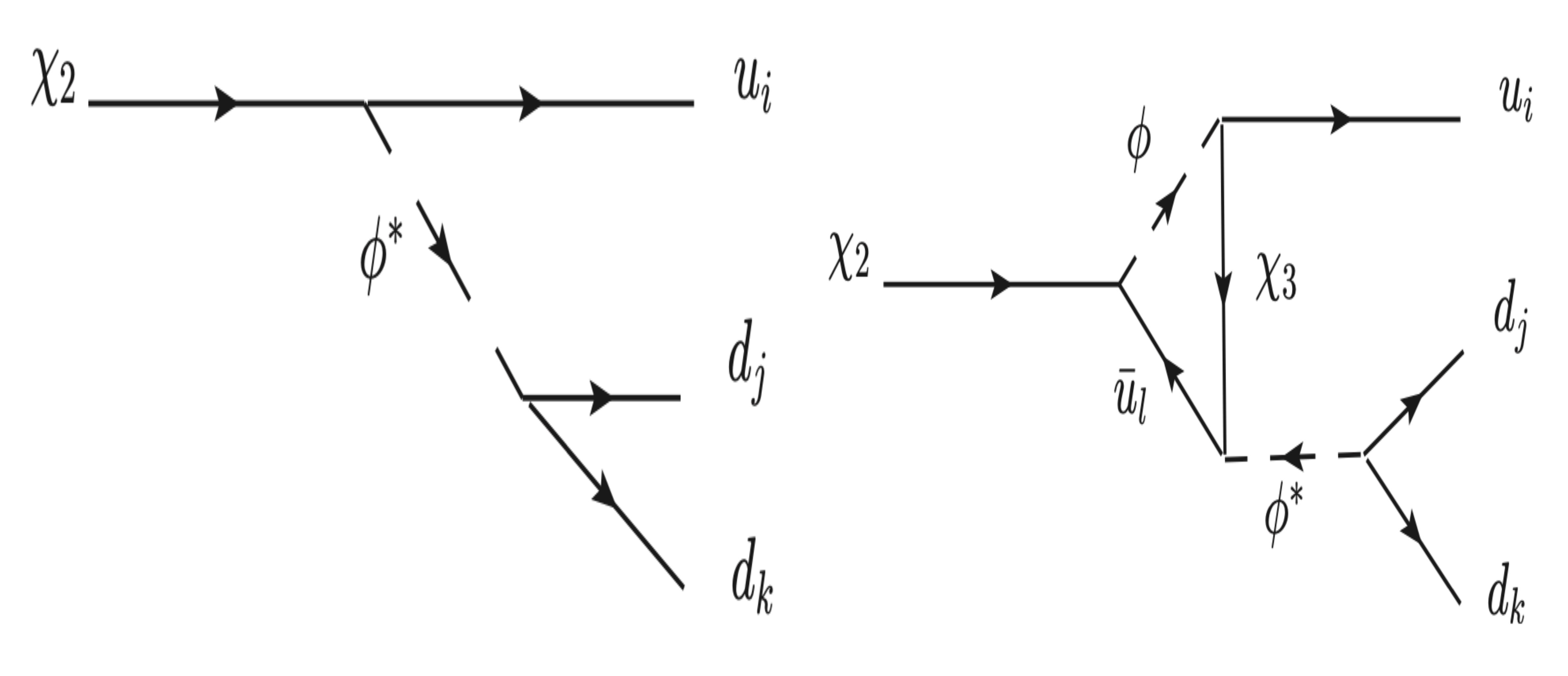
Model

Freeze-out

$$\mathscr{L}_{\text{f.o.}} = -g_j \bar{\chi}_j i\gamma^5 \chi_j A - g'_j \bar{\chi}_j \chi_j S \qquad j = 1,2,3$$

$m_S \geq 2m_{\chi_1}$ $\qquad g_3, g'_3 \ll 1$ $\qquad \lambda S|H|^2$ suppressed





Asymmetry Generation

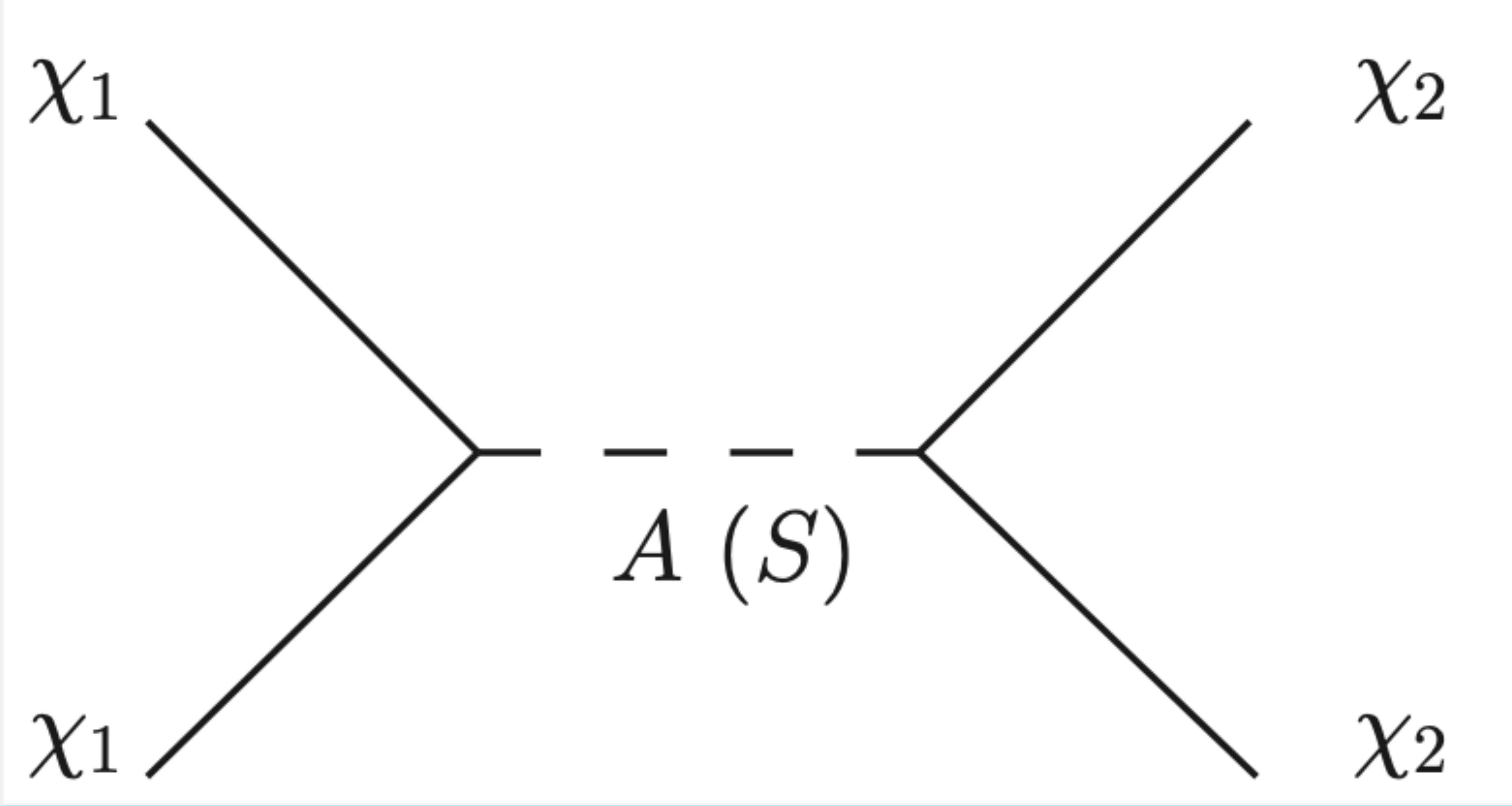
$$\mathscr{L}_{\text{baryog.}} = -\alpha_j \bar{u}_j P_L \chi_2 \phi - \beta_j \bar{u}_j P_L \chi_3 \phi - \eta_{kl} \epsilon_{kl} \phi^* \bar{d}_k P_L d_l^c + \text{h.c.}$$

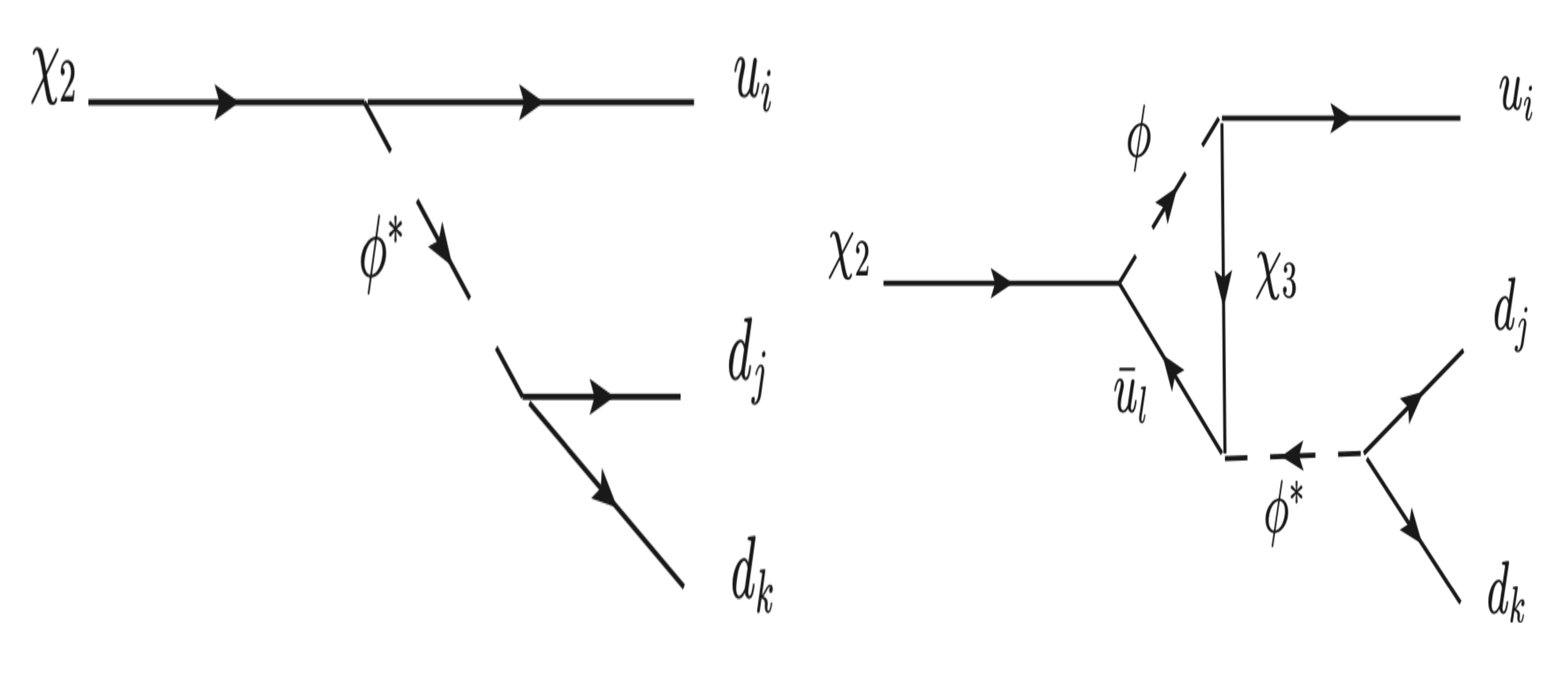
Model

Freeze-out

$$\mathscr{L}_{\text{f.o.}} = -g_j \bar{\chi}_j i\gamma^5 \chi_j A - g_j' \bar{\chi}_j \chi_j S \qquad j = 1,2,3$$

$m_S \geq 2m_{\chi_1}$ $\qquad g_3, g_3' \ll 1$ $\qquad \lambda S|H|^2$ suppressed





Asymmetry Generation

$$\mathscr{L}_{\text{baryog.}} = -\alpha_j \bar{u}_j P_L \chi_2 \phi - \beta_j \bar{u}_j P_L \chi_3 \phi - \eta_{kl} \epsilon_{kl} \phi^* \bar{d}_k P_L d_l^c + \text{h.c.}$$

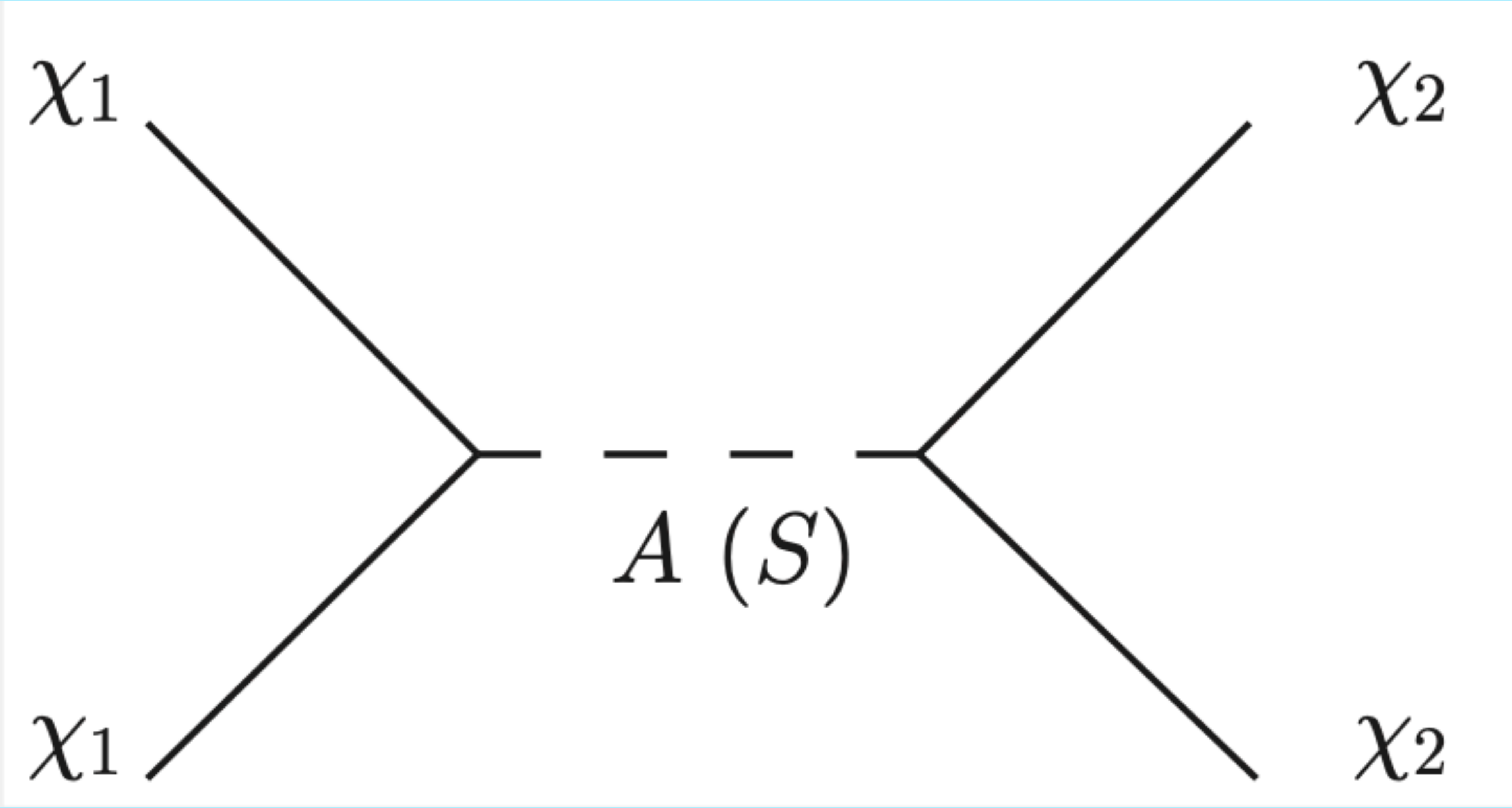
$$\epsilon_{CP} = \text{Im}\left[\beta_l^* \beta_i^* \alpha_l \alpha_i\right] m_{\chi_2}^2 / 20\pi |\alpha_i|^2 |\eta_{jk}|^2 m_\phi^2$$

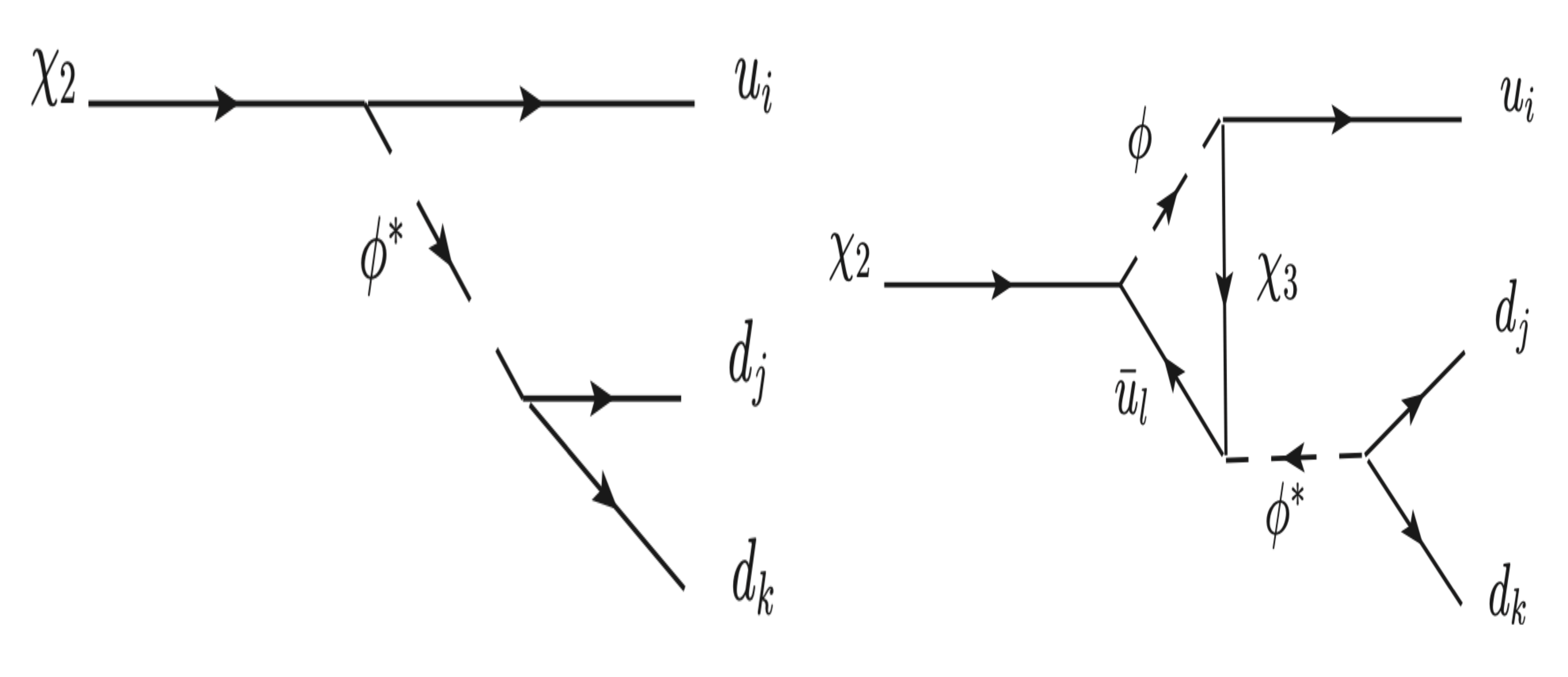
Model

Freeze-out

$$\mathscr{L}_{\text{f.o.}} = -g_j\bar{\chi}_j i\gamma^5\chi_j A - g_j'\bar{\chi}_j\chi_j S \qquad j = 1,2,3$$

$$m_S \geq 2m_{\chi_1} \qquad g_3, g_3' \ll 1 \qquad \lambda S|H|^2 \text{ suppressed}$$





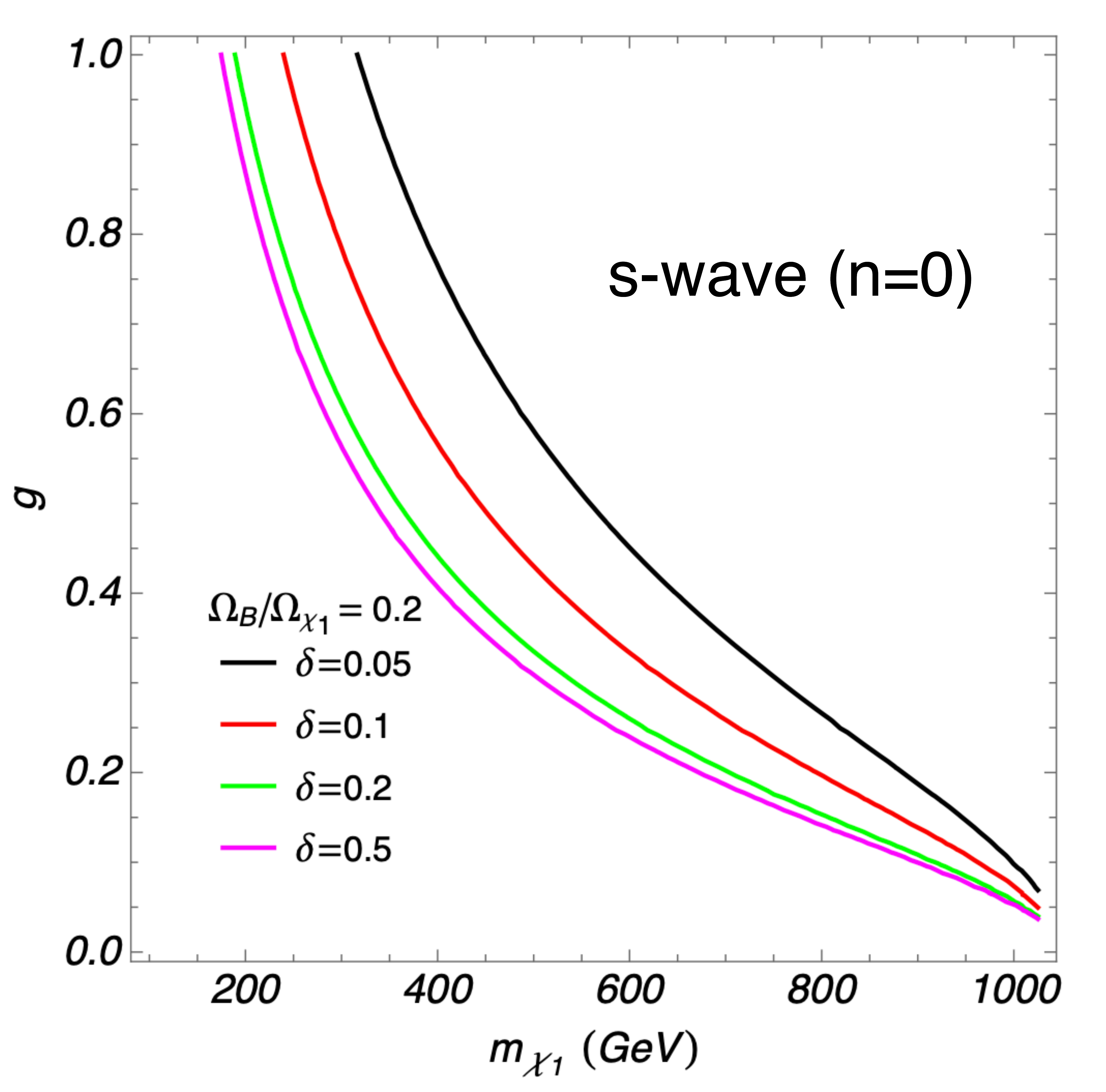
Asymmetry Generation

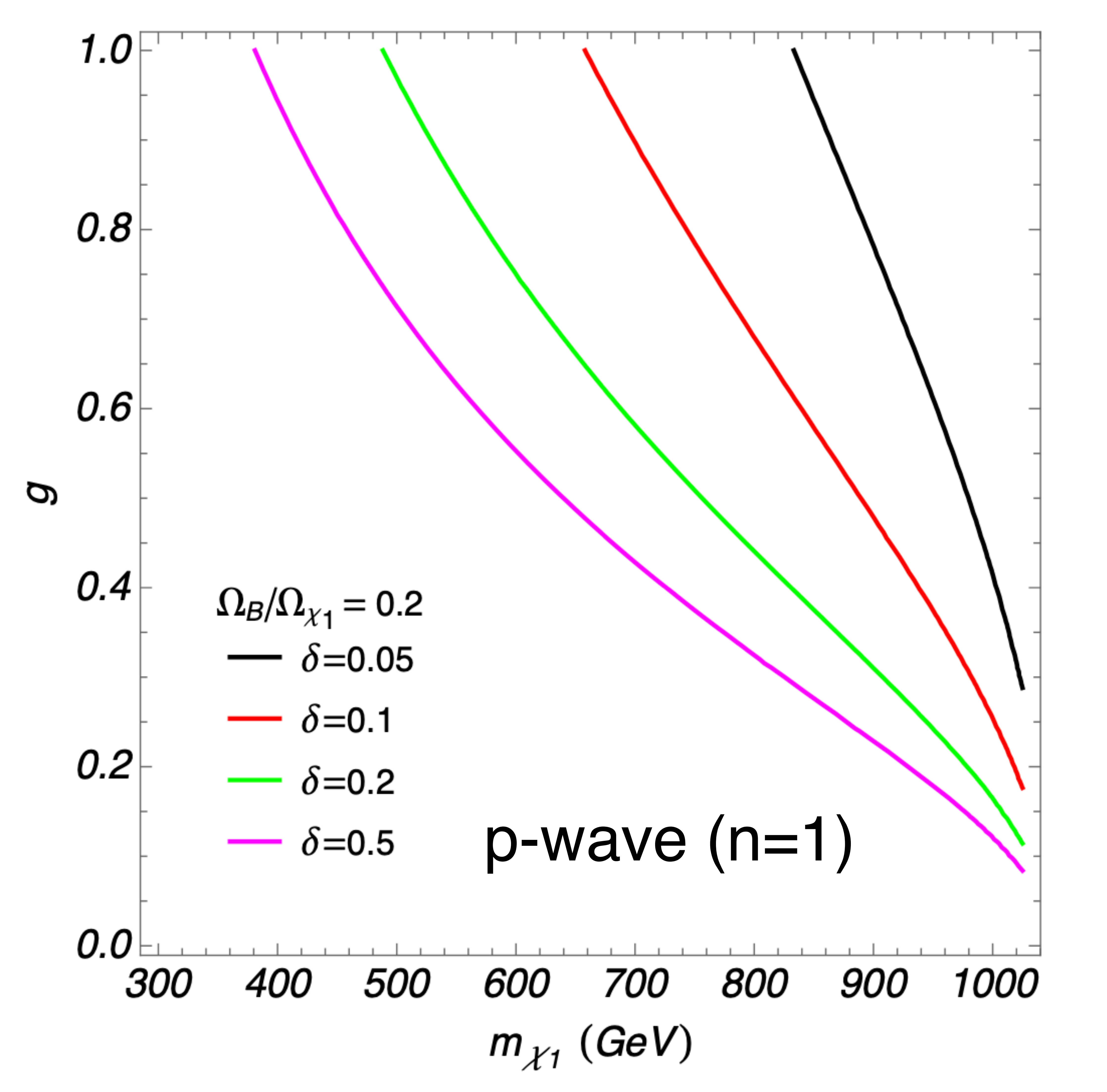
$$\mathscr{L}_{\text{baryog.}} = -\alpha_j\bar{u}_jP_L\chi_2\phi - \beta_j\bar{u}_jP_L\chi_3\phi - \eta_{kl}\epsilon_{kl}\phi^*\bar{d}_kP_Ld_l^c + \text{h.c.}$$

$$\epsilon_{CP} = \text{Im}\left[\beta_l^*\beta_i^*\alpha_l\alpha_i\right]m_{\chi_2}^2/20\pi|\alpha_i|^2|\eta_{jk}|^2m_\phi^2$$

$$\frac{\Omega_B}{\Omega_{\chi_1}} = \epsilon_{CP}\frac{m_p}{m_{\chi_1}}\left[0.42\frac{g_\chi}{g_*}\frac{\xi_i^3\lambda}{(2n+1)\beta^n}\frac{1}{x_{\text{f.o.}}^{2n+1}} - 1\right]$$

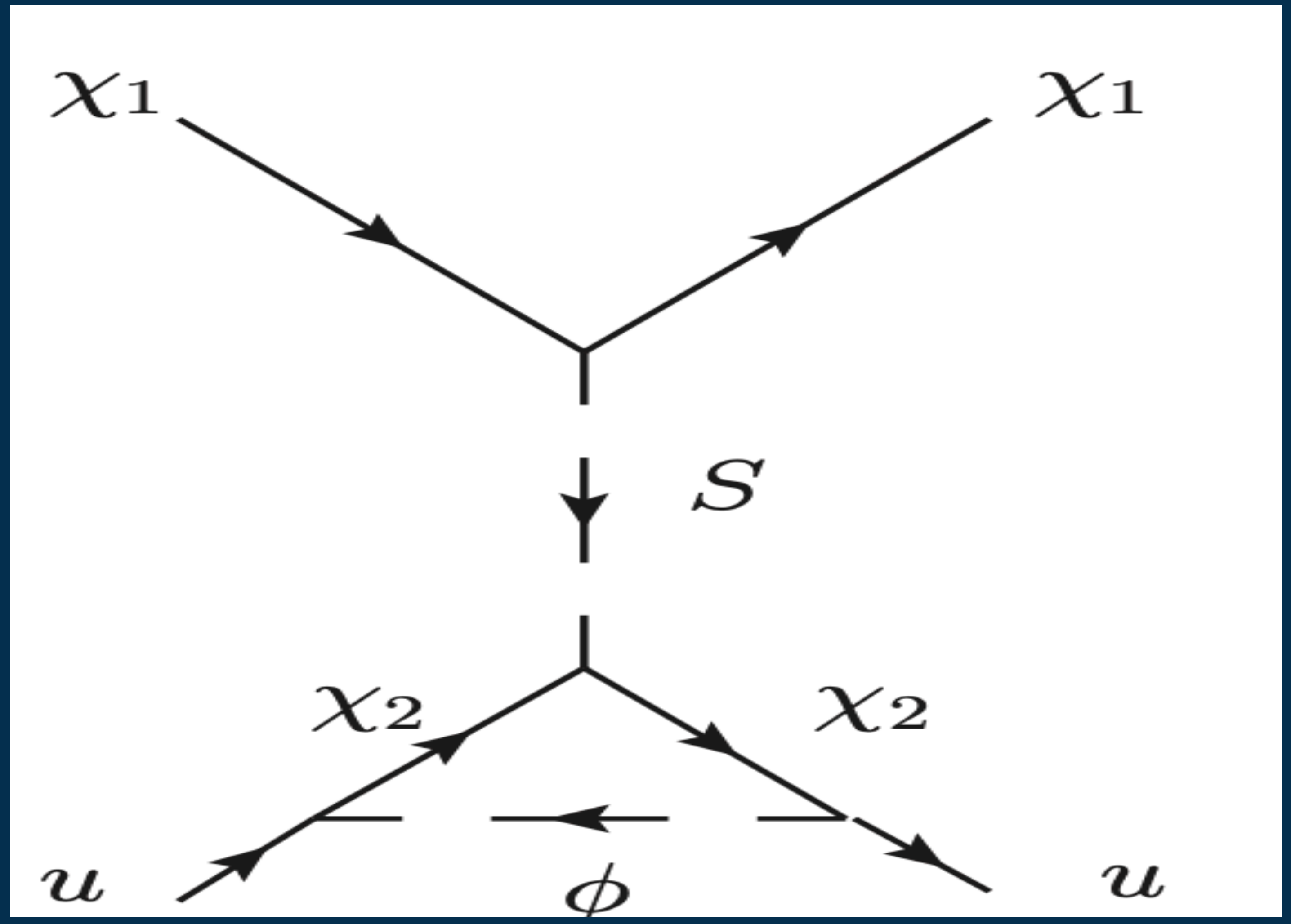
Results


1.0
0.8
0.6
0.4
0.2
0.0
g
200
400
600
800
1000
m_{χ_1} (GeV)
s-wave (n=0)
$\Omega_B/\Omega_{\chi_1} = 0.2$
δ=0.05
δ=0.1
δ=0.2
δ=0.5

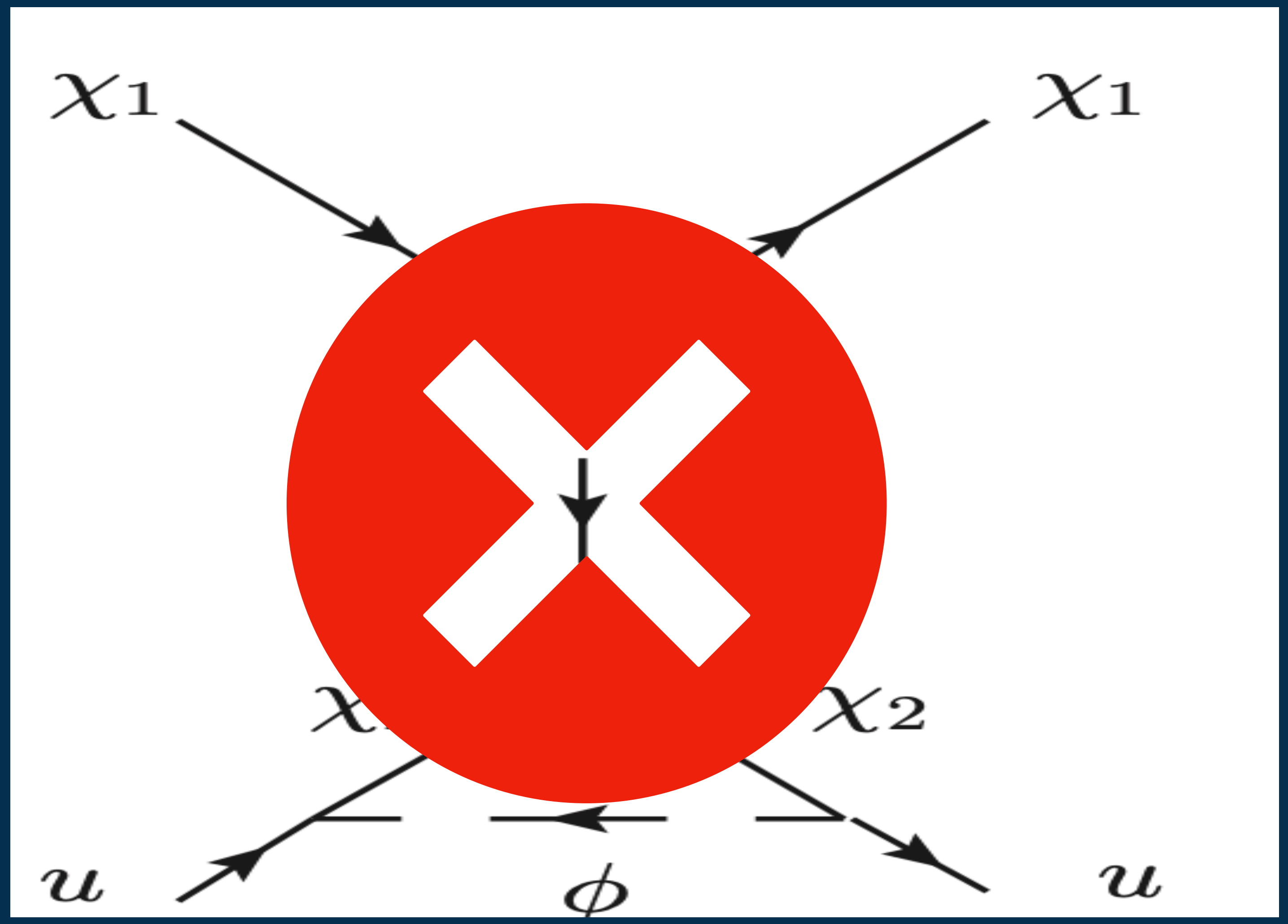

1.0
0.8
0.6
0.4
0.2
0.0
g
300
400
500
600
700
800
900
1000
m_{χ_1} (GeV)
$\Omega_B/\Omega_{\chi_1} = 0.2$
δ=0.05
δ=0.1
δ=0.2
δ=0.5
p-wave (n=1)

Pheno and Future Directions

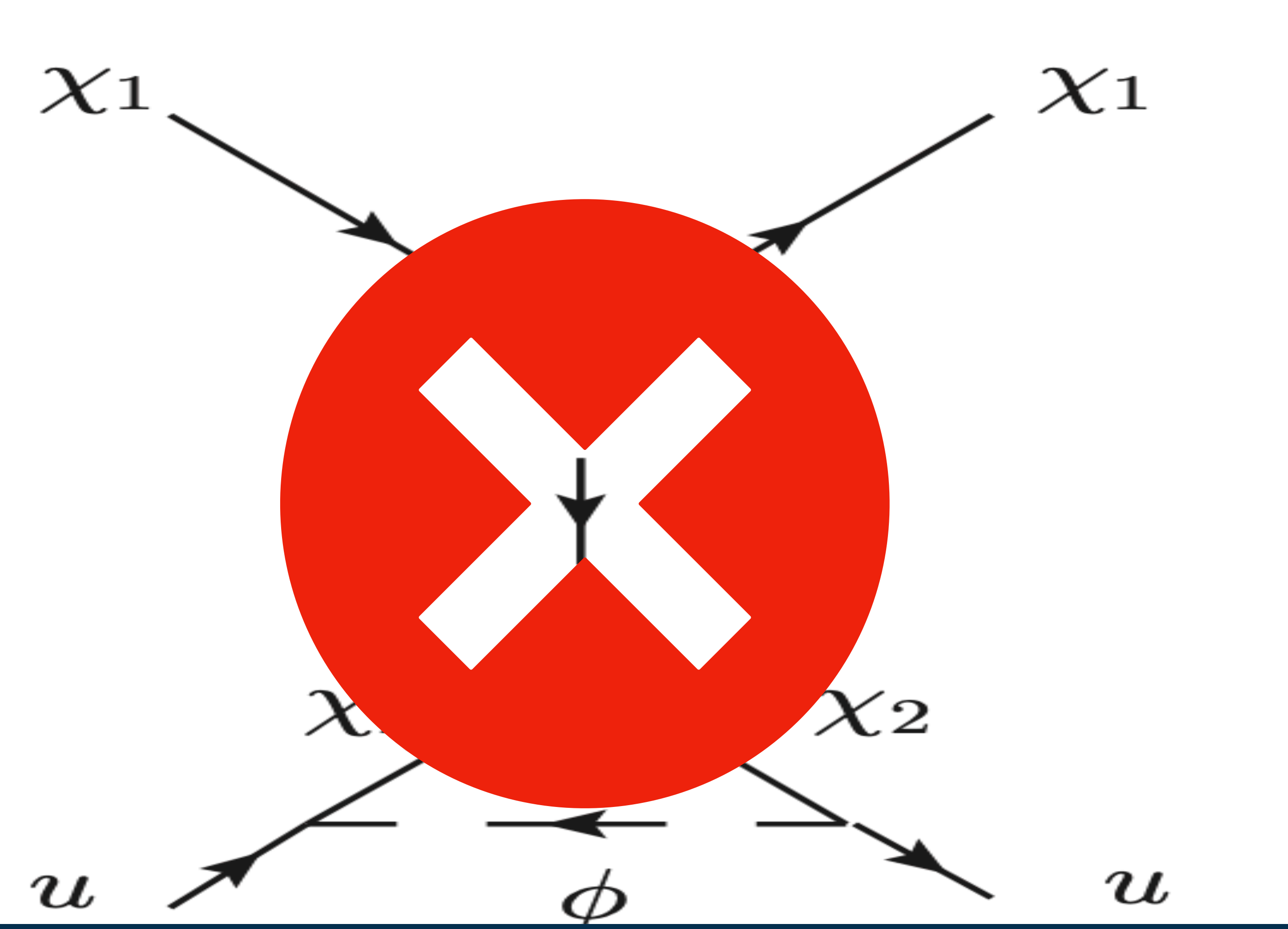
Pheno and Future Directions

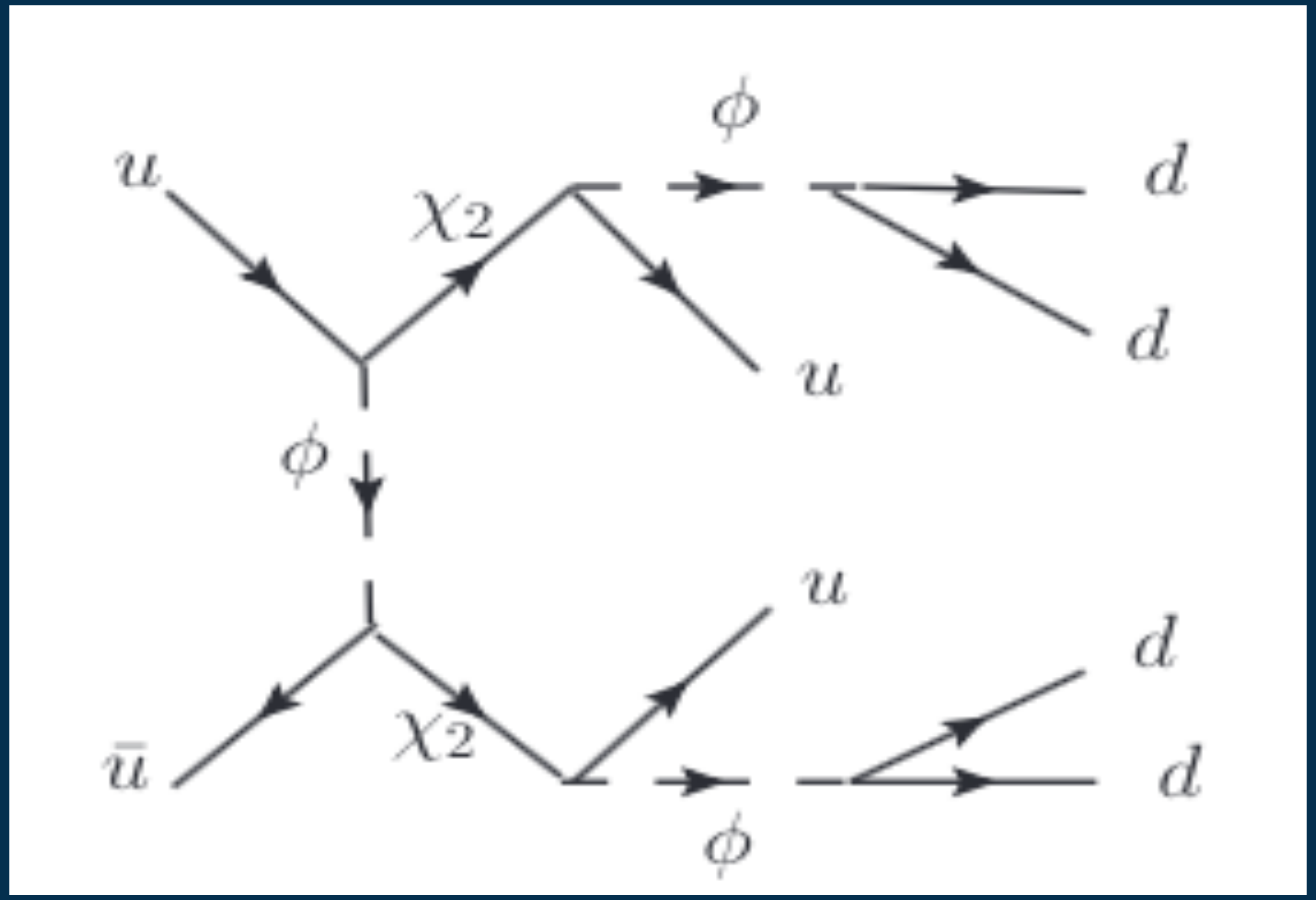


Pheno and Future Directions



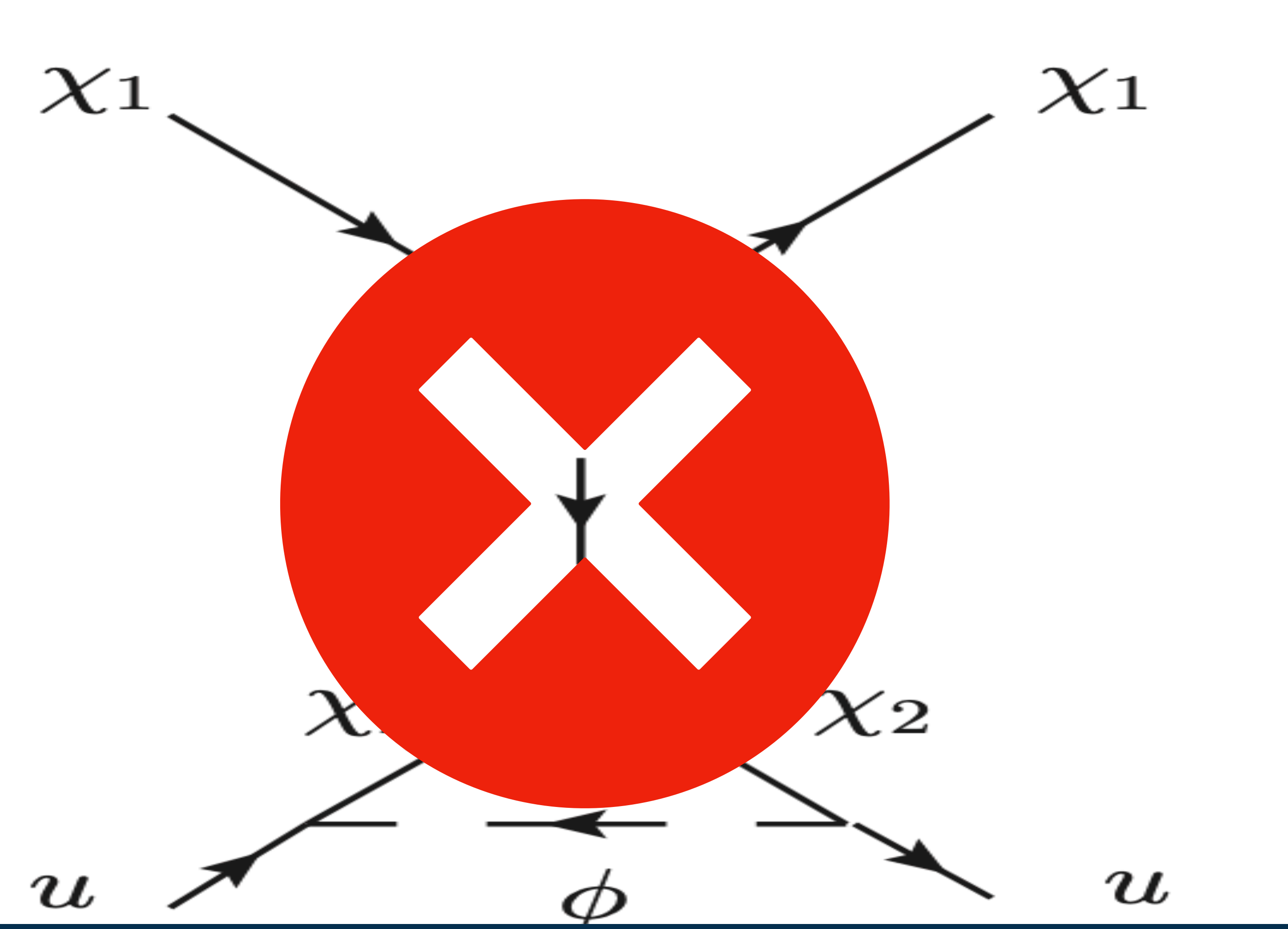
Pheno and Future Directions

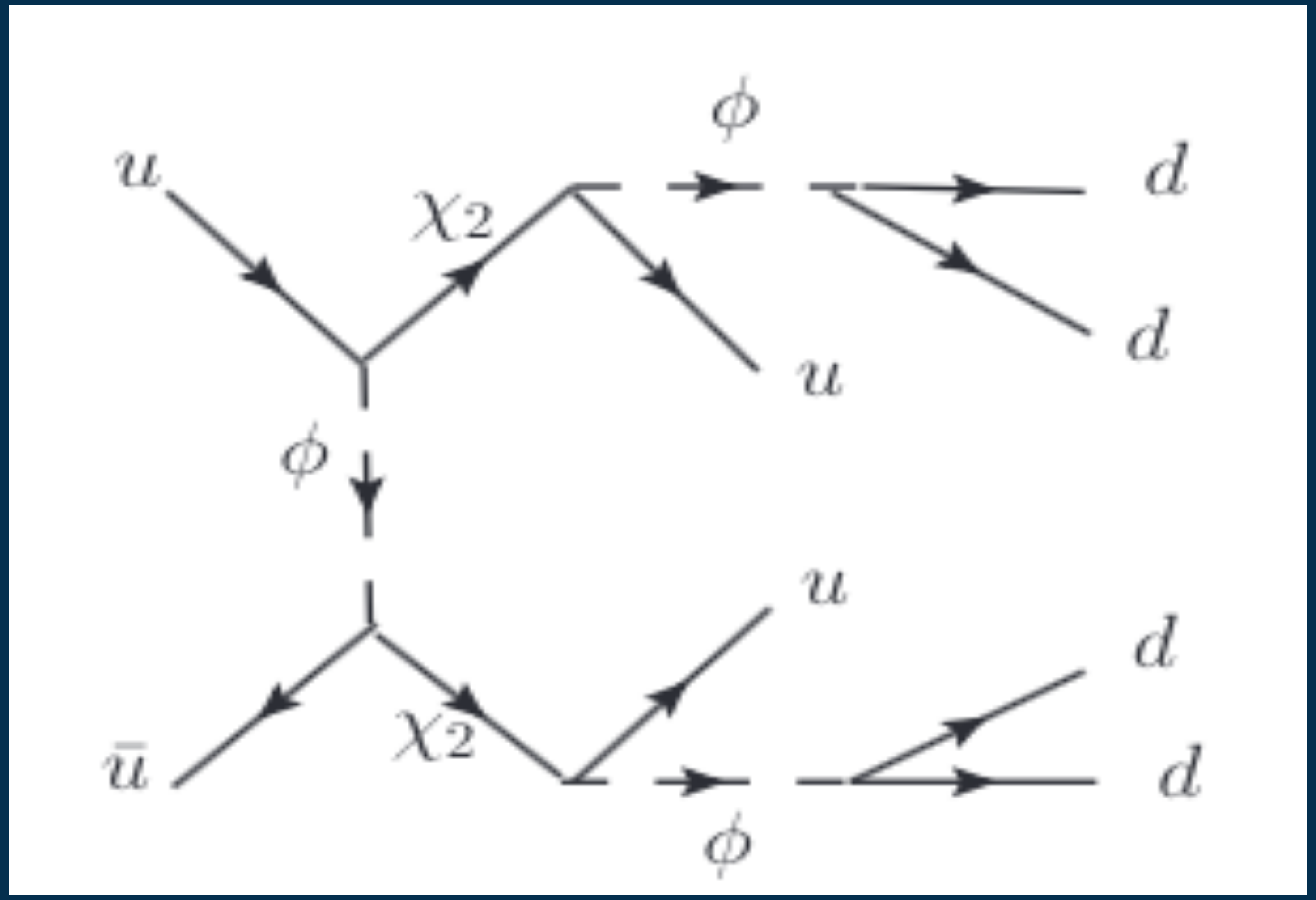




$$c\gamma\tau_{\chi_3} = 4\text{ cm}\left(\frac{\gamma}{10}\right)\left(\frac{10^{-4}}{\beta\eta}\right)^2\left(\frac{1\text{ TeV}}{m_{\chi_3}}\right)^5\left(\frac{m_\phi}{10\text{ TeV}}\right)^4$$

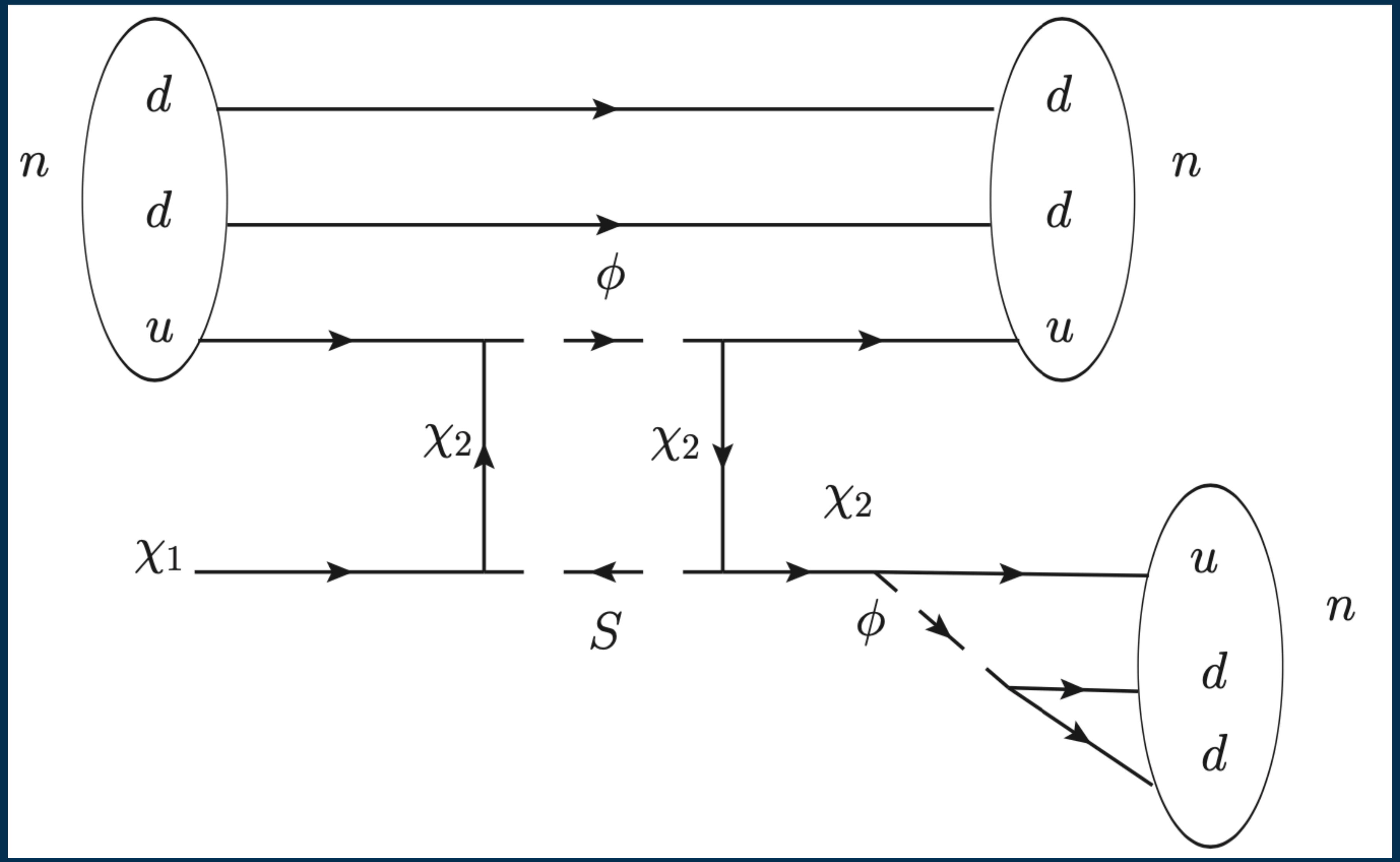
Pheno and Future Directions





$$c\gamma\tau_{\chi_3} = 4\text{ cm}\left(\frac{\gamma}{10}\right)\left(\frac{10^{-4}}{\beta\eta}\right)^2\left(\frac{1\text{ TeV}}{m_{\chi_3}}\right)^5\left(\frac{m_\phi}{10\text{ TeV}}\right)^4$$

$\Delta B = 1$ processes in astrophysical objects/Earth?



Summary

Summary

Unique framework relating symmetric DM to BAU

Summary

Unique framework relating symmetric DM to BAU

Novel analytic treatment for dark sector freeze-out

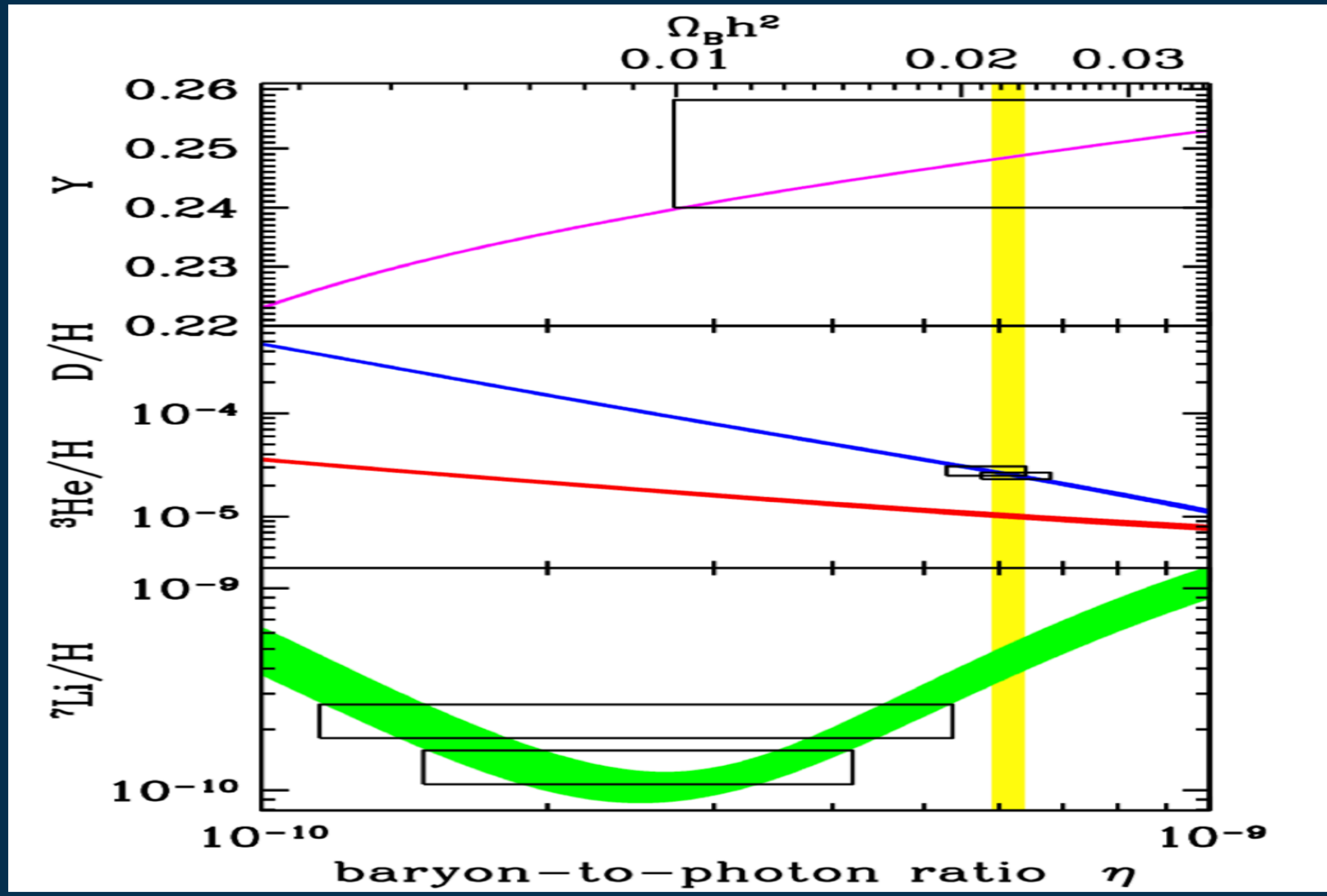
Summary

Unique framework relating symmetric DM to BAU

Novel analytic treatment for dark sector freeze-out

Baryogenesis

Baryogenesis

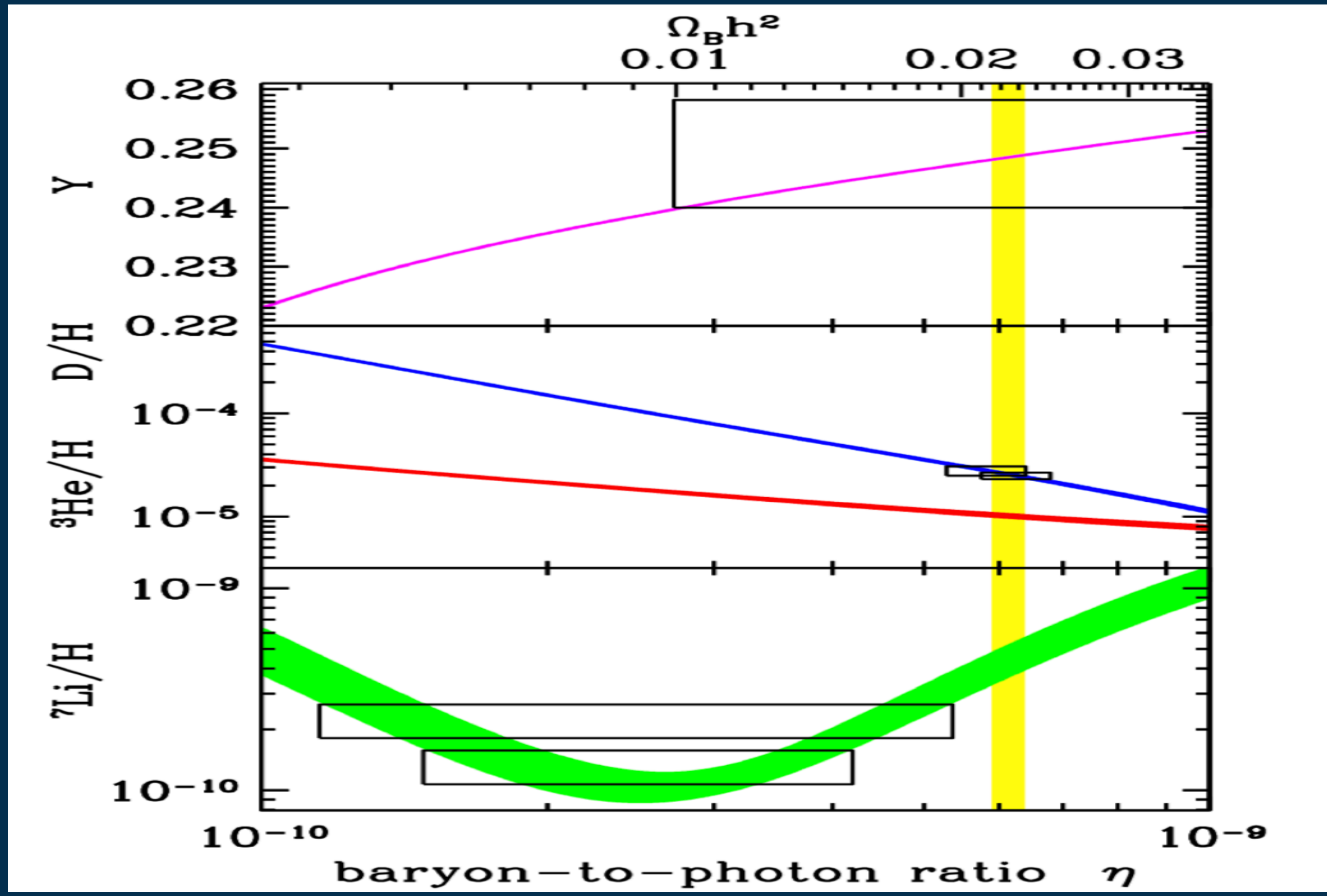


BBN $\Longrightarrow\ \eta_B \sim 10^{-10}$

Baryogenesis:

$\eta_B(t=0) = 0 \rightarrow \eta_B(t = t_{BBN}) \neq 0$

Baryogenesis

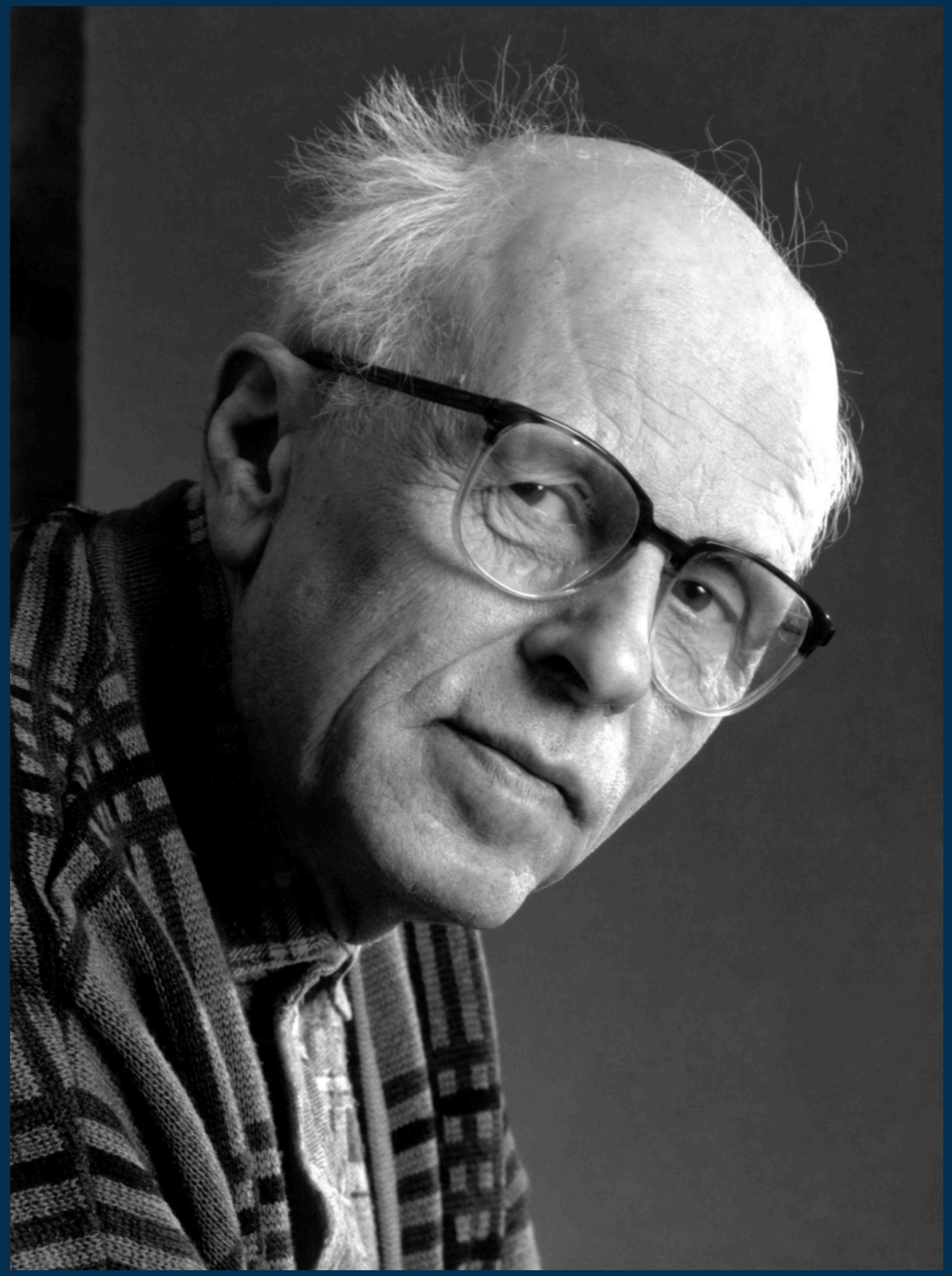


BBN $\Longrightarrow \ \eta_B \sim 10^{-10}$

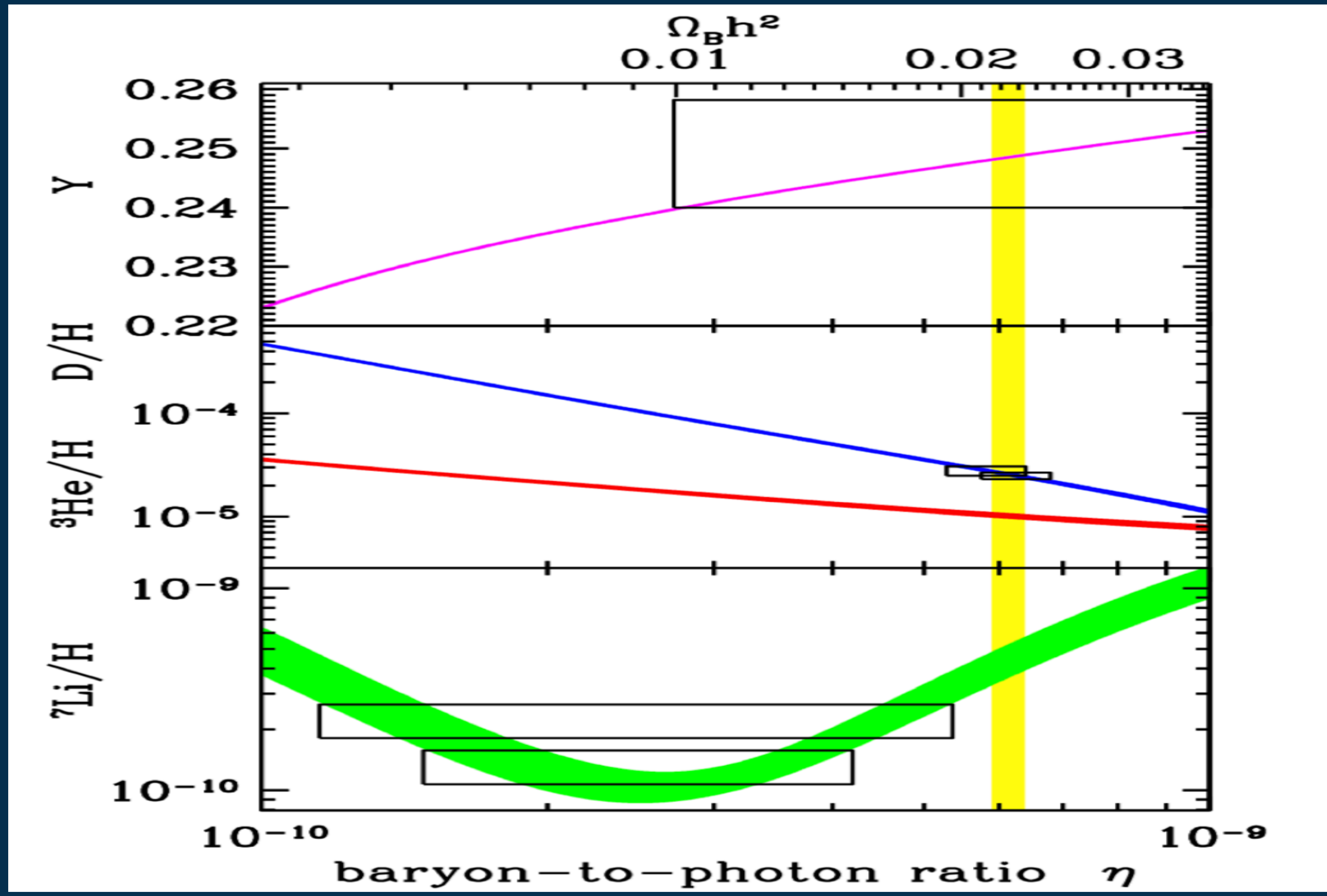
Baryogenesis:

$\eta_B(t=0) = 0 \rightarrow \eta_B(t = t_{BBN}) \neq 0$

Sakharov conditions [Sakharov, 1967]



Baryogenesis



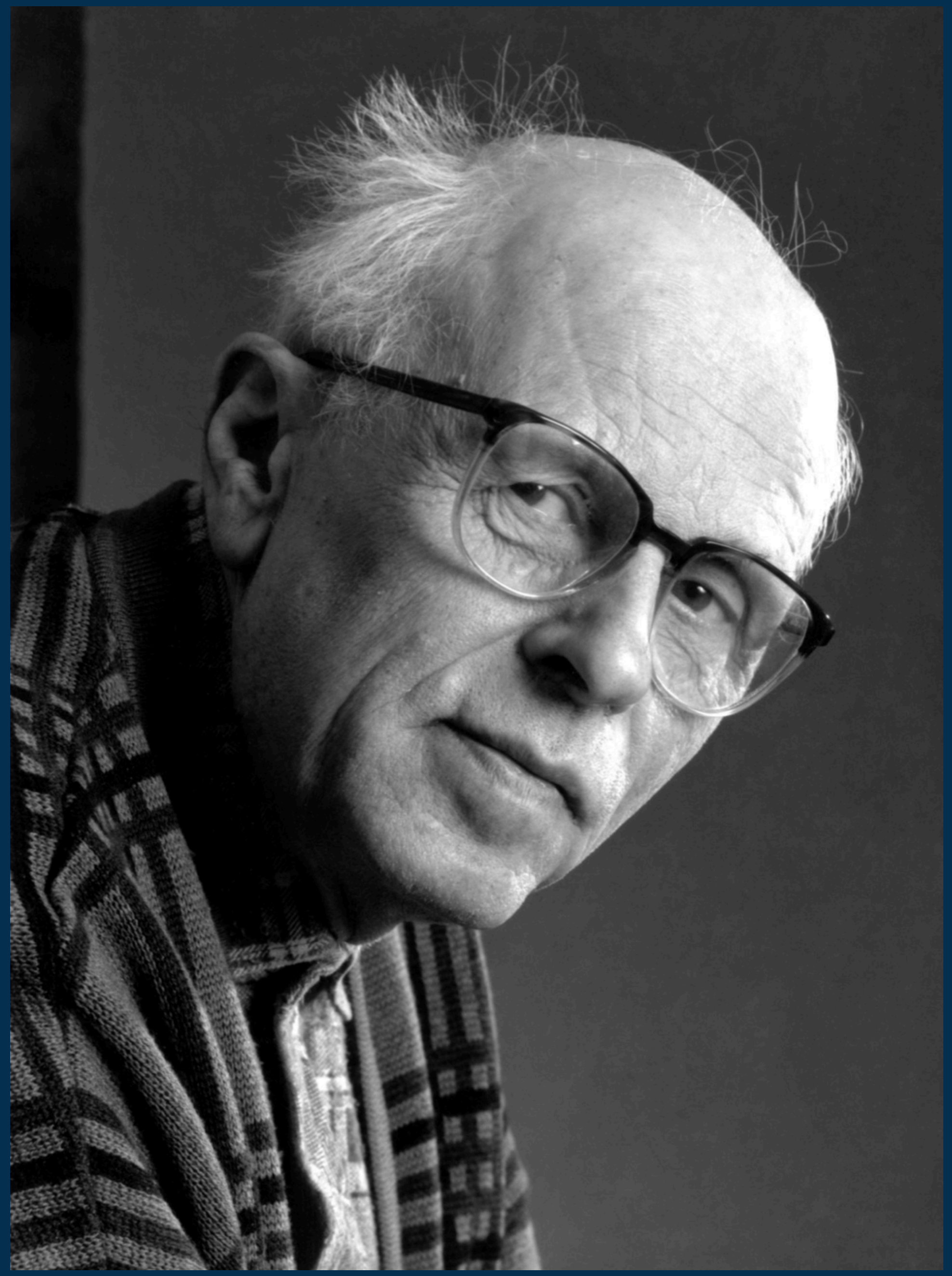
BBN $\Longrightarrow$ $\eta_B \sim 10^{-10}$

Baryogenesis:

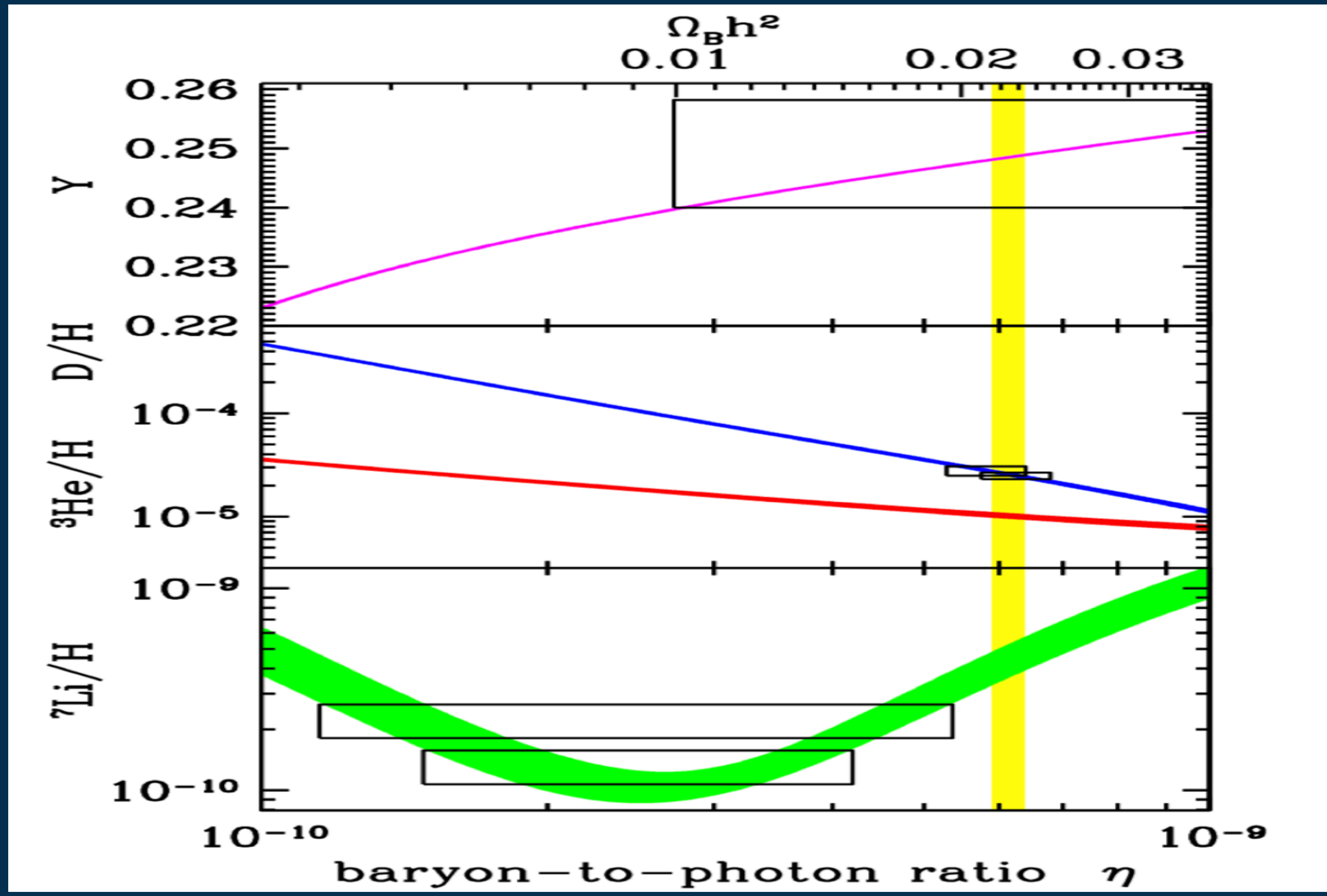
$\eta_B(t=0) = 0 \rightarrow \eta_B(t = t_{BBN}) \neq 0$

Sakharov conditions [Sakharov, 1967]

1. $\Delta B \neq 0$



Baryogenesis



BBN $\Longrightarrow$ $\eta_B \sim 10^{-10}$

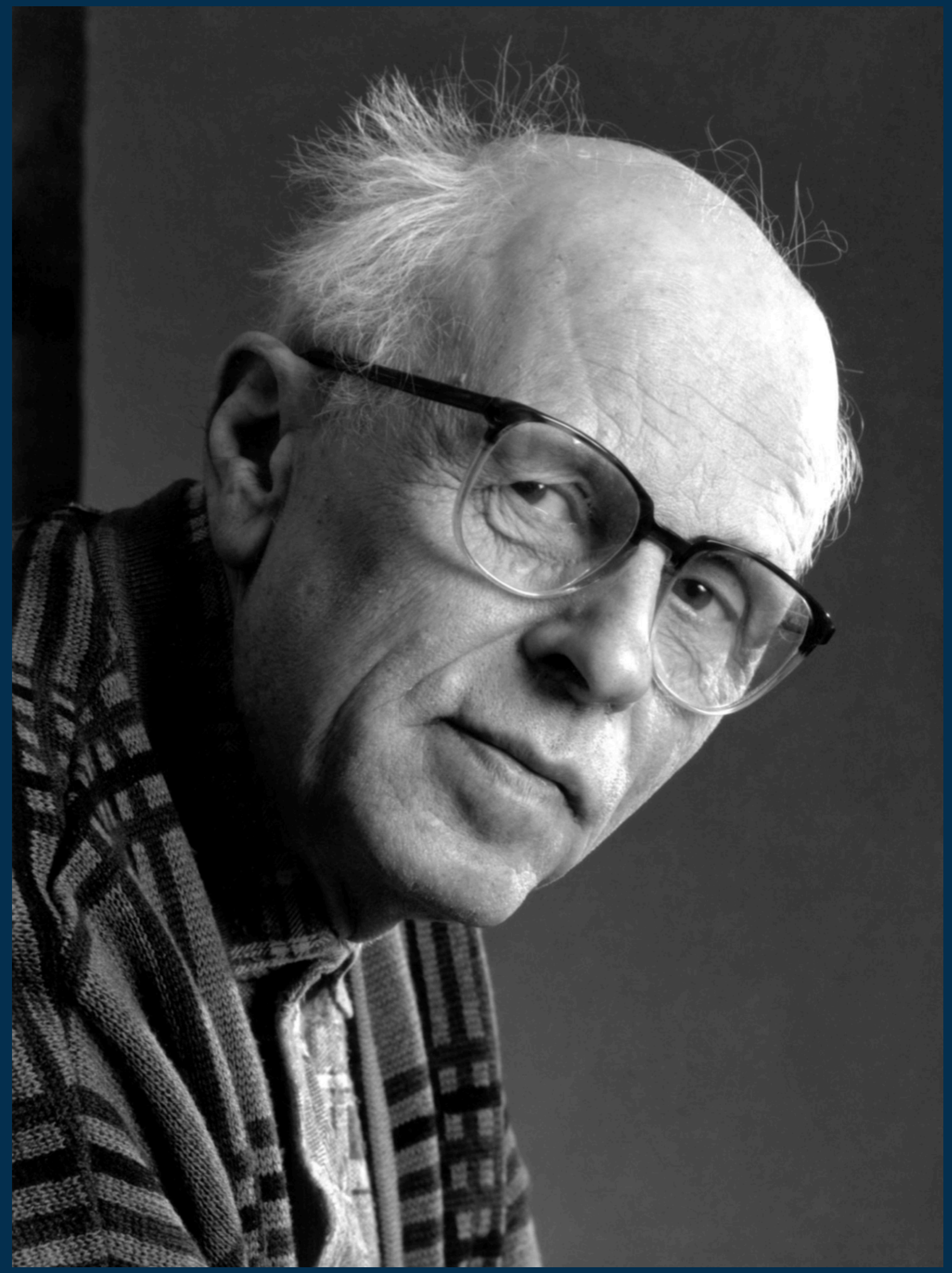
Baryogenesis:

$\eta_B(t=0) = 0 \rightarrow \eta_B(t = t_{BBN}) \neq 0$

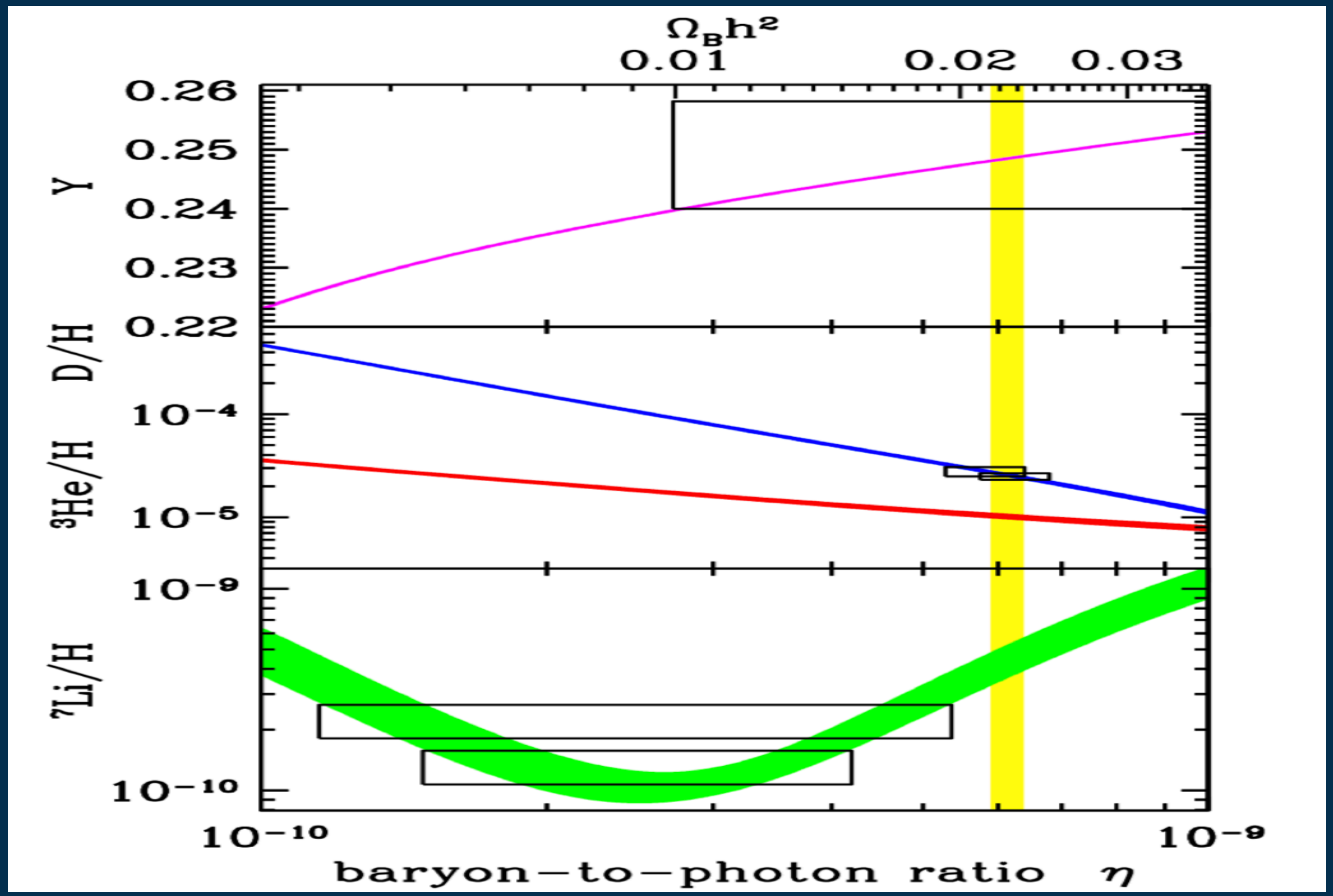
Sakharov conditions [Sakharov, 1967]

1. $\Delta B \neq 0$

2. $\Gamma(F_L^+ \rightarrow f_L^+ + s) + \Gamma(F_R^+ \rightarrow f_R^- + s)$
$\neq \Gamma(F_R^- \rightarrow f_R^- + s) + \Gamma(F_L^- \rightarrow f_L^- + s)$



Baryogenesis



BBN $\Longrightarrow$ $\eta_B \sim 10^{-10}$

Baryogenesis:

$$\eta_B(t=0) = 0 \rightarrow \eta_B(t = t_{BBN}) \neq 0$$

Sakharov conditions [Sakharov, 1967]

1. $\Delta B \neq 0$

2. $$\Gamma(F_L^+ \rightarrow f_L^+ + s) + \Gamma(F_R^+ \rightarrow f_R^- + s) \neq \Gamma(F_R^- \rightarrow f_R^- + s) + \Gamma(F_L^- \rightarrow f_L^- + s)$$

~~3. $\langle B \rangle_T$~~