

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



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

Phenomenology
Symposium 2022

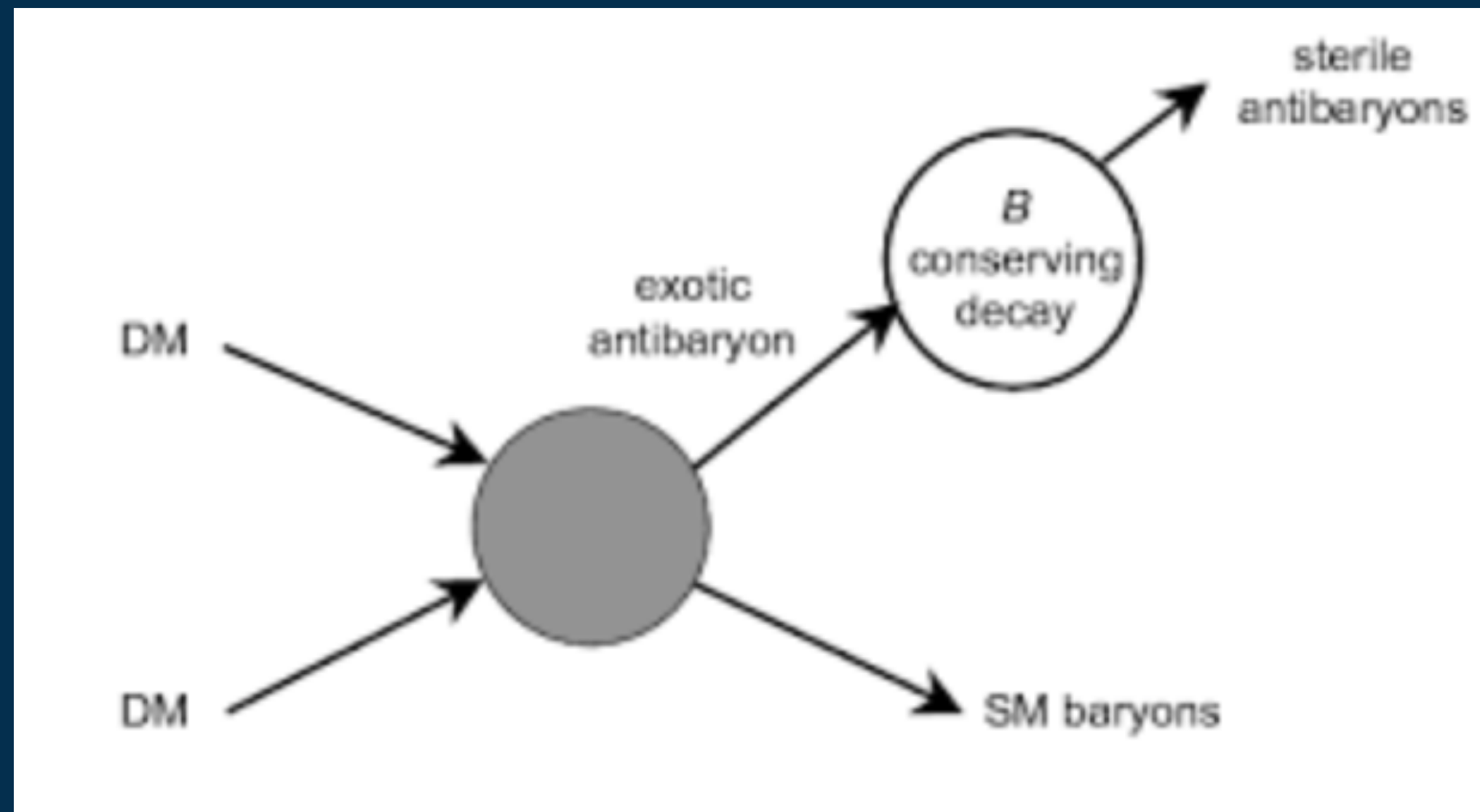
DM and the BAU

DM and the BAU

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

DM and the BAU

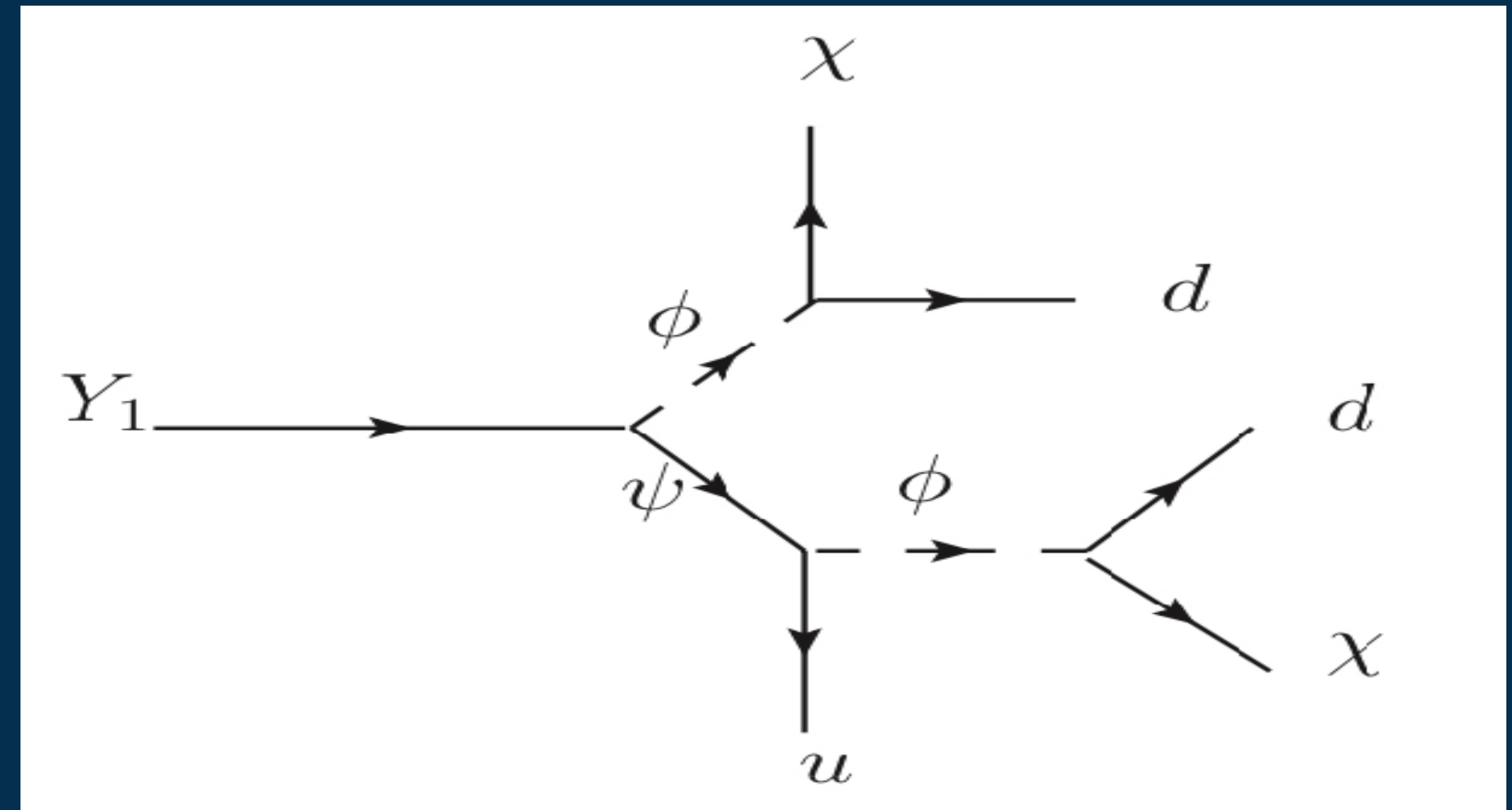
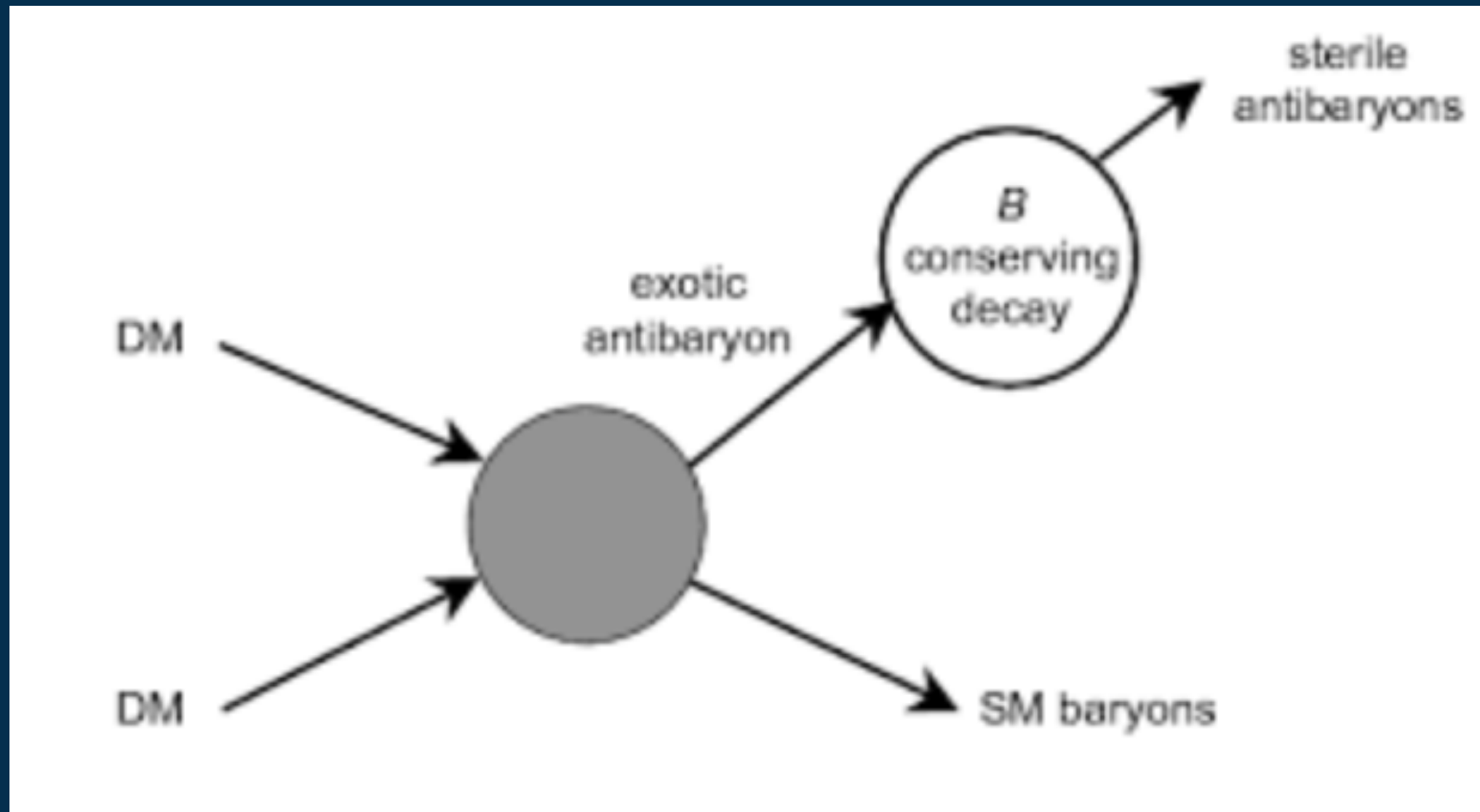
$$\Omega_{DM} \approx 5\Omega_B \quad [\text{Planck Collab}]$$



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

DM and the BAO

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

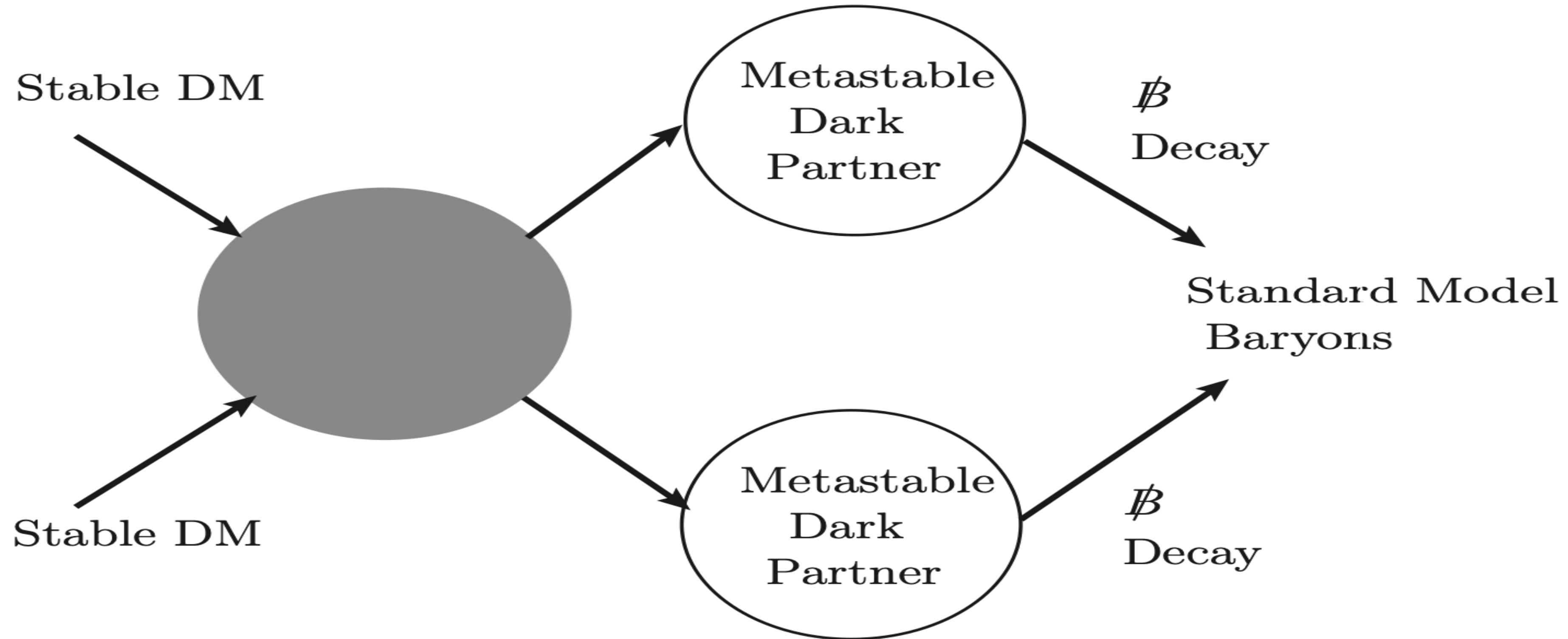


$$\Omega_B \sim \Omega_{WIMP} \propto m_{ew}^2 / g_{ew}^4 \quad [\text{Cui, Sundrum}]$$

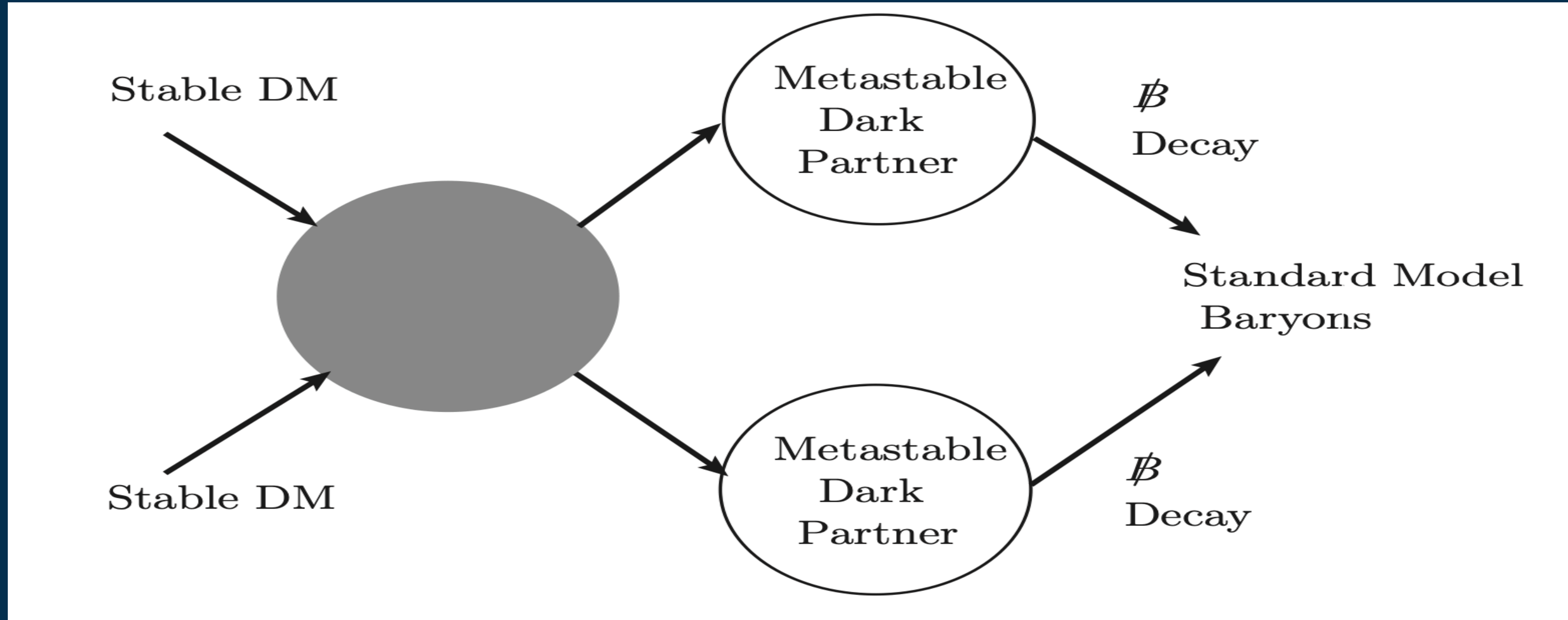
$$\Omega_{ADM} / \Omega_B \simeq (n_{ADM} / n_B) (m_{ADM} / m_n)$$

Dark Freeze-out Cogenesis

Dark Freeze-out Cogenesis

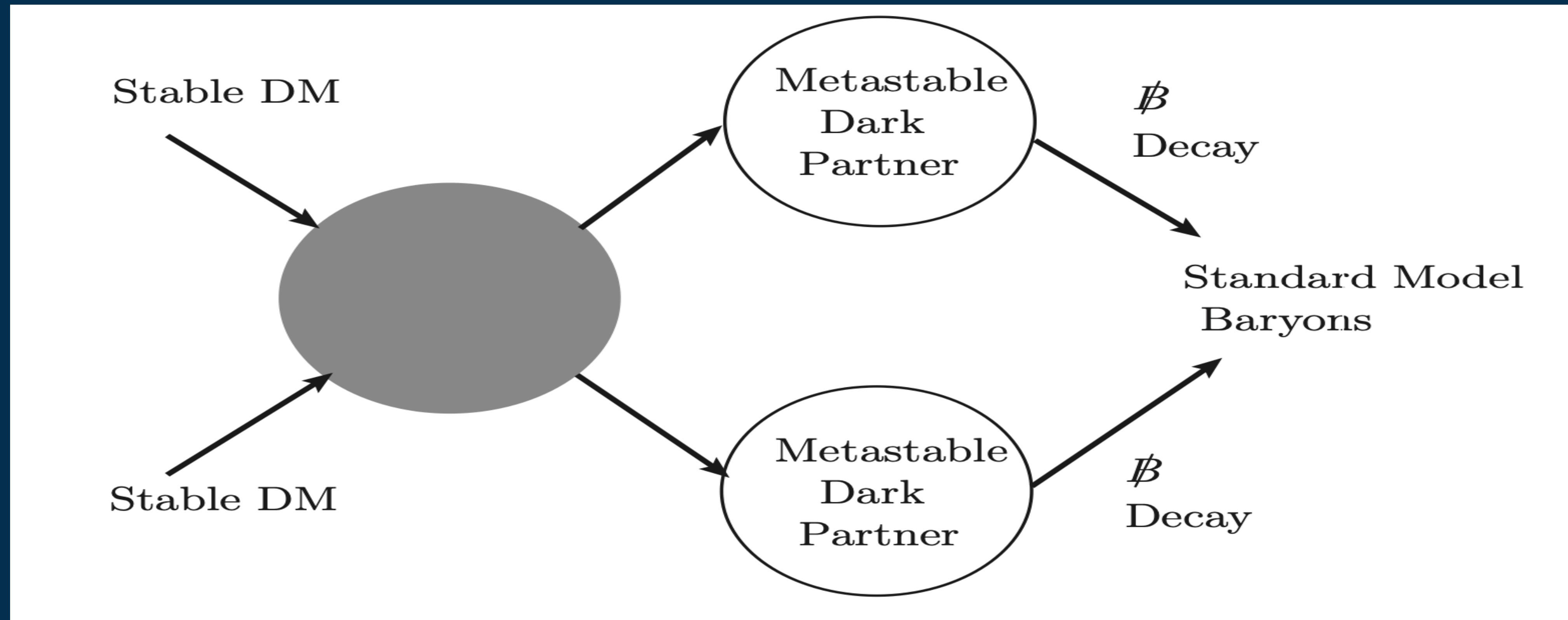


Dark Freeze-out Cogeneration



$$Y_{\chi_{1,f}} + Y_{\chi_{2,f}} = Y_{\chi_{1,i}} + Y_{\chi_{2,i}} = C$$

Dark Freeze-out Cogeneration



$$Y_{\chi_{1,f}} + Y_{\chi_{2,f}} = Y_{\chi_{1,i}} + Y_{\chi_{2,i}} = C$$

$$Y_B \simeq \epsilon_{CP}(C - Y_{\chi_{1,f}})$$

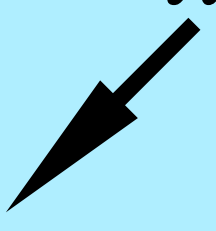
Near Degenerate Freeze-out

Near Degenerate Freeze-out

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

Near Degenerate Freeze-out

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

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

Near Degenerate Freeze-out

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

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

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

Near Degenerate Freeze-out

$$\frac{dY_{\chi_1}}{dx} = - \frac{\frac{s(m_{\chi_1})}{H(m_{\chi_1})} \langle \sigma_{\chi_1} v \rangle}{x^{2+n}} \left[Y_{\chi_1}^2 - (1 - \delta)^{-3} e^{-\frac{2\delta x}{\xi}} Y_{\chi_2}^2 \right]$$

Near Degenerate Freeze-out

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

Annotations in the diagram:

- An arrow points from $\frac{\lambda \xi^n}{x^{2+n}}$ to $\frac{s(m_{\chi_1})}{H(m_{\chi_1})} \langle \sigma_{\chi_1} v \rangle$.
- An arrow points from $\frac{\lambda \xi^n}{x^{2+n}}$ to $\frac{T'}{T}$.
- An arrow points from $\frac{\lambda \xi^n}{x^{2+n}}$ to $\frac{m_{\chi_1}}{T}$.
- An arrow points from $(1 - \delta)^{-3} e^{-\frac{2\delta x}{\xi}}$ to $\frac{m_{\chi_1} - m_{\chi_2}}{m_{\chi_1}}$.

Near Degenerate Freeze-out

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

Annotations in the diagram:

- $\frac{s(m_{\chi_1})}{H(m_{\chi_1})} \langle \sigma_{\chi_1} v \rangle$ points to $\lambda \xi^n$.
- $\frac{T'}{T}$ points to $(1 - \delta)^{-3}$.
- $\frac{m_{\chi_1} - m_{\chi_2}}{m_{\chi_1}}$ points to $e^{-\frac{2\delta x}{\xi}}$.
- $\frac{m_{\chi_1}}{T}$ points to x^{2+n} .
- $C - Y_{\chi_1}$ points to $Y_{\chi_2}^2$.

Near Degenerate Freeze-out

$$\frac{dY_{\chi_1}}{dx} = - \frac{\frac{s(m_{\chi_1})}{H(m_{\chi_1})} \langle \sigma_{\chi_1 \nu} \rangle}{x^{2+n}} \left[Y_{\chi_1}^2 - (1 - \delta)^{-3} e^{-\frac{2\delta x}{\xi}} Y_{\chi_2}^2 \right]$$

$\frac{m_{\chi_1}}{T}$ (pointing to x^{2+n})
 $\frac{T'}{T}$ (pointing to $\frac{s(m_{\chi_1})}{H(m_{\chi_1})} \langle \sigma_{\chi_1 \nu} \rangle$)
 $\frac{m_{\chi_1} - m_{\chi_2}}{m_{\chi_1}}$ (pointing to $(1 - \delta)^{-3}$)
 $C - Y_{\chi_1}$ (pointing to $Y_{\chi_2}^2$)

Quasi-Static Equilibrium

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

Near Degenerate Freeze-out

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

$\frac{s(m_{\chi_1})}{H(m_{\chi_1})} \langle \sigma_{\chi_1 \nu} \rangle$ (pointing to $\lambda \xi^n$)
 $\frac{T'}{T}$ (pointing to $\lambda \xi^n$)
 $\frac{m_{\chi_1} - m_{\chi_2}}{m_{\chi_1}}$ (pointing to $(1 - \delta)^{-3}$)
 $\frac{m_{\chi_1}}{T}$ (pointing to x^{2+n})
 $C - Y_{\chi_1}$ (pointing to $Y_{\chi_2}^2$)
 Quasi-Static Equilibrium

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

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

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

Near Degenerate Freeze-out

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

$\frac{s(m_{\chi_1})}{H(m_{\chi_1})} \langle \sigma_{\chi_1 \nu} \rangle$ (pointing to $\lambda \xi^n$)
 $\frac{T'}{T}$ (pointing to $\lambda \xi^n$)
 $\frac{m_{\chi_1} - m_{\chi_2}}{m_{\chi_1}}$ (pointing to $(1 - \delta)^{-3}$)
 $\frac{m_{\chi_1}}{T}$ (pointing to x^{2+n})
 $C - Y_{\chi_1}$ (pointing to $Y_{\chi_2}^2$)
 Quasi-Static Equilibrium

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

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

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

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

Near Degenerate Freeze-out

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

$\frac{s(m_{\chi_1})}{H(m_{\chi_1})} \langle \sigma_{\chi_1 \nu} \rangle$ (pointing to $\lambda \xi^n$)
 $\frac{T'}{T}$ (pointing to $\lambda \xi^n$)
 $\frac{m_{\chi_1} - m_{\chi_2}}{m_{\chi_1}}$ (pointing to $(1 - \delta)^{-3}$)
 $\frac{m_{\chi_1}}{T}$ (pointing to x^{2+n})
 $C - Y_{\chi_1}$ (pointing to $Y_{\chi_2}^2$)
 Quasi-Static Equilibrium

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

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

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

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

Number conservation

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

Near Degenerate Freeze-out

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

$\frac{s(m_{\chi_1})}{H(m_{\chi_1})} \langle \sigma_{\chi_1 \nu} \rangle$ (pointing to $\lambda \xi^n$)
 $\frac{T'}{T}$ (pointing to $\lambda \xi^n$)
 $\frac{m_{\chi_1} - m_{\chi_2}}{m_{\chi_1}}$ (pointing to $(1 - \delta)^{-3}$)
 $\frac{m_{\chi_1}}{T}$ (pointing to x^{2+n})
 $C - Y_{\chi_1}$ (pointing to $Y_{\chi_2}^2$)
 Quasi-Static Equilibrium

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

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

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

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

Number conservation

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

χ_2 Decays

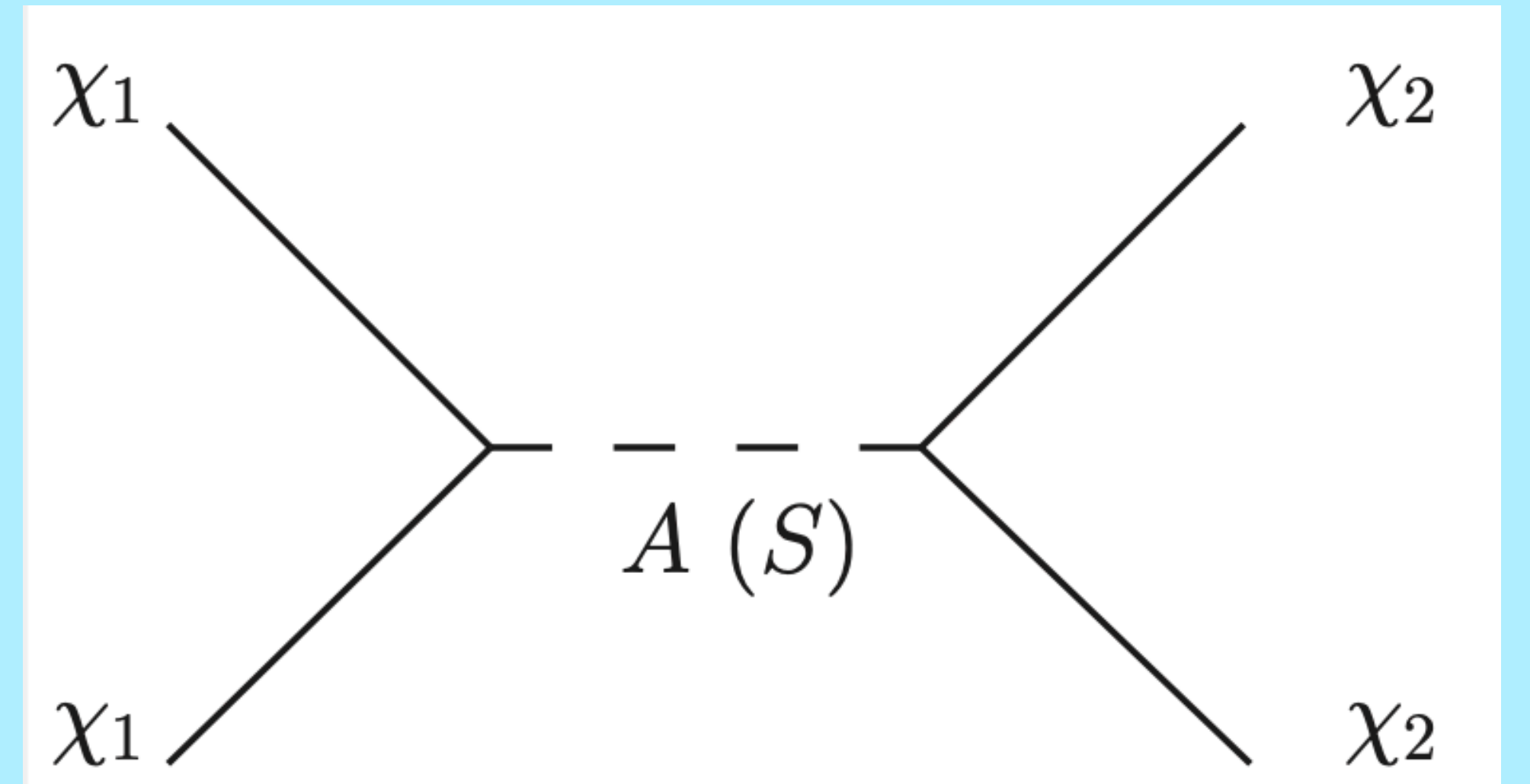
$$Y_{B,0} = \epsilon_{CP} Y_{\chi_2, f} = \epsilon_{CP} [(0.42 g_\chi \xi_i^3 / g_*) - Y_{\chi_1, f}]$$

Model

Model

Freeze-out

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

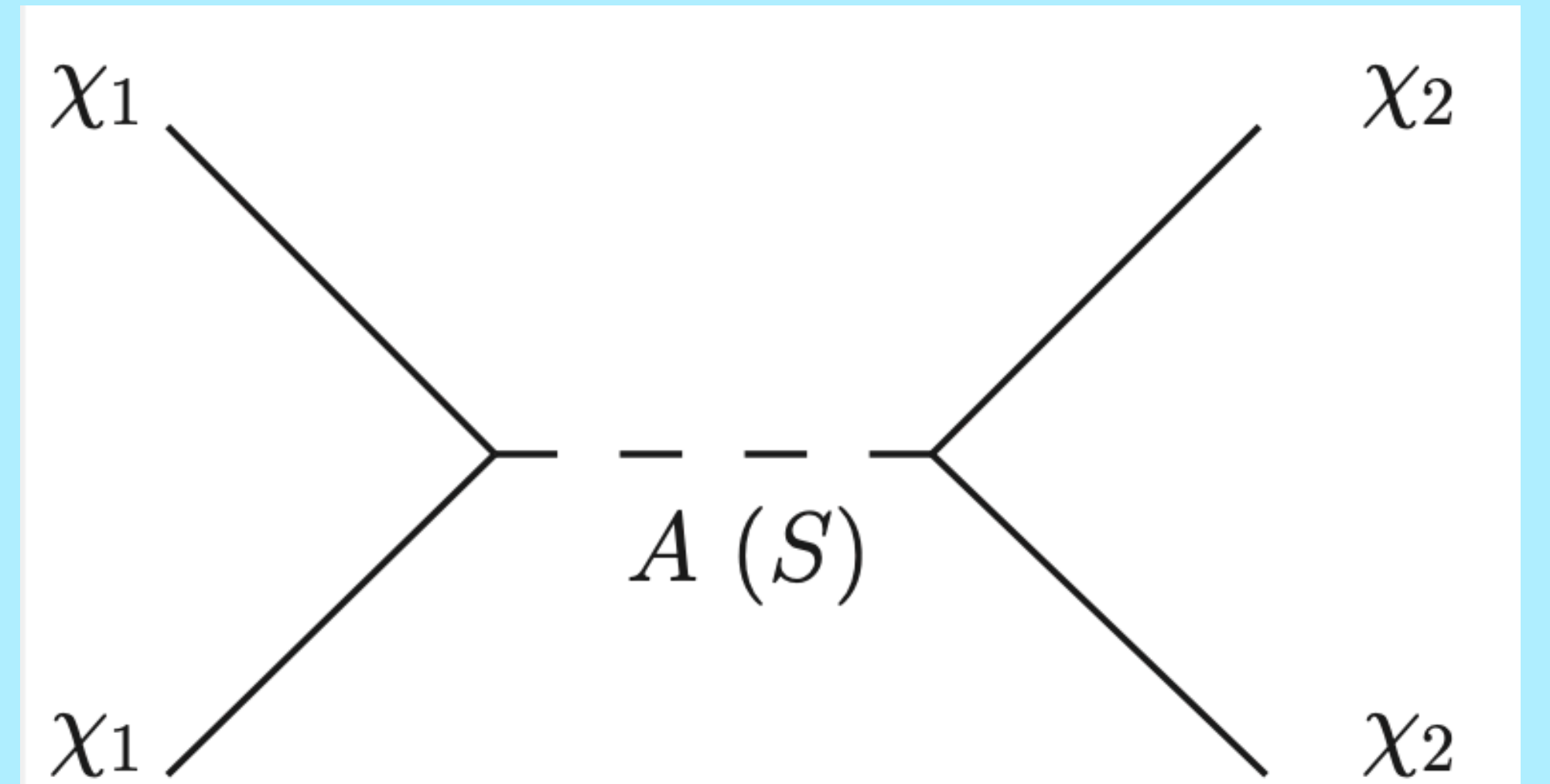


Model

Freeze-out

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

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

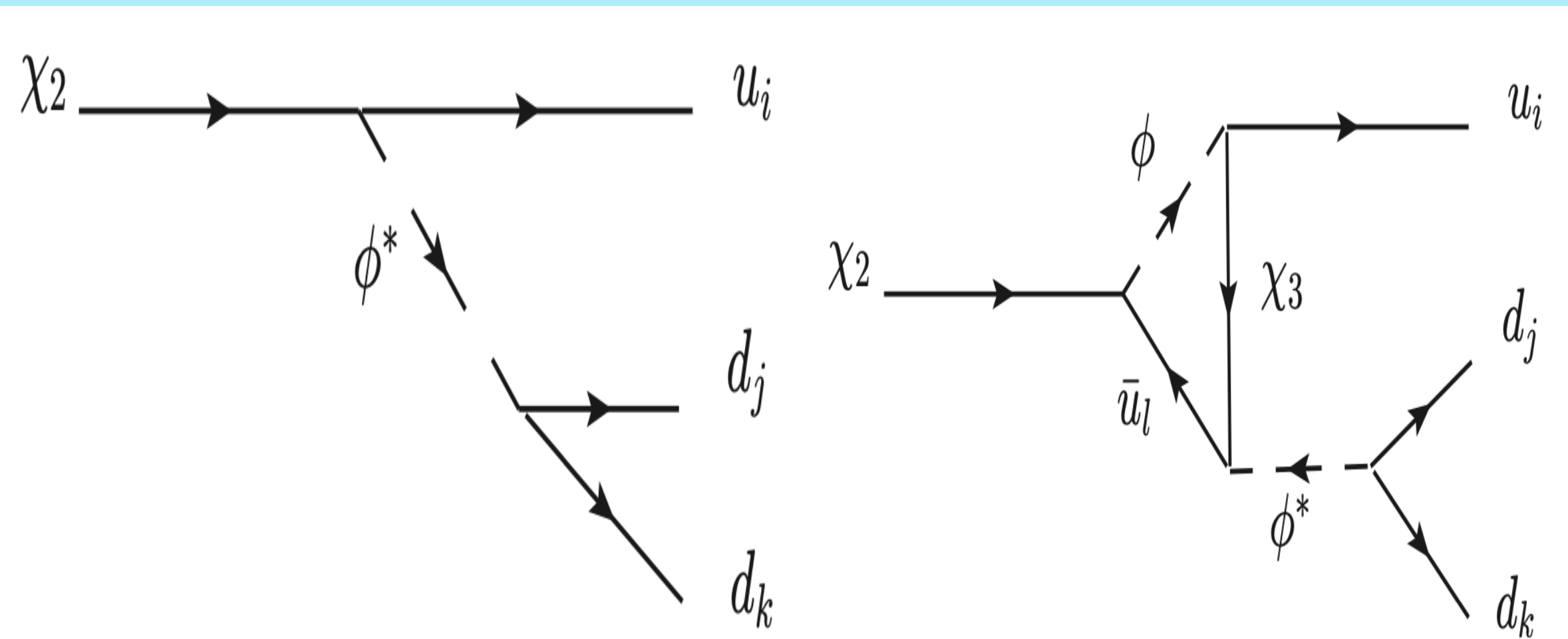
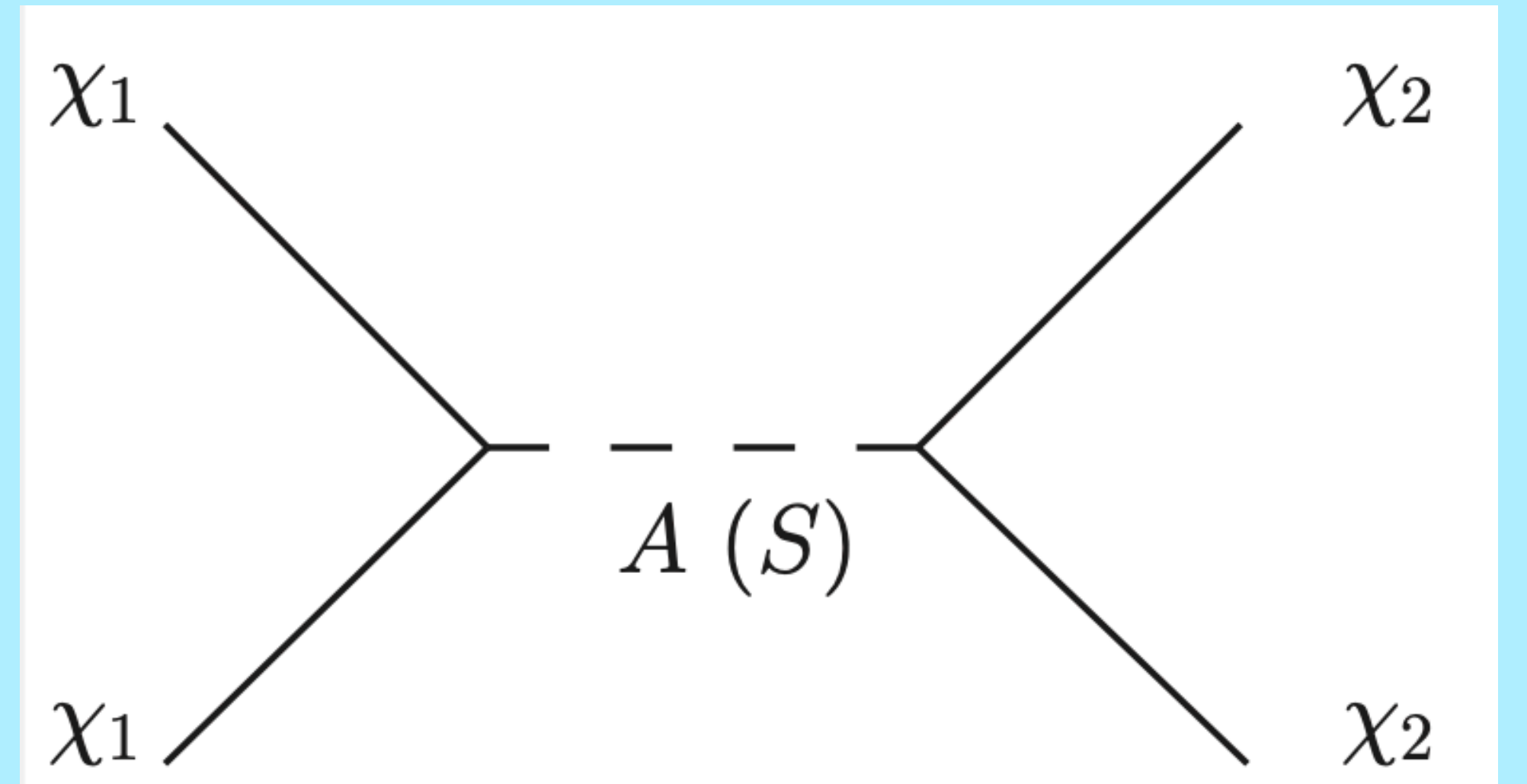


Model

Freeze-out

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

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



Asymmetry Generation

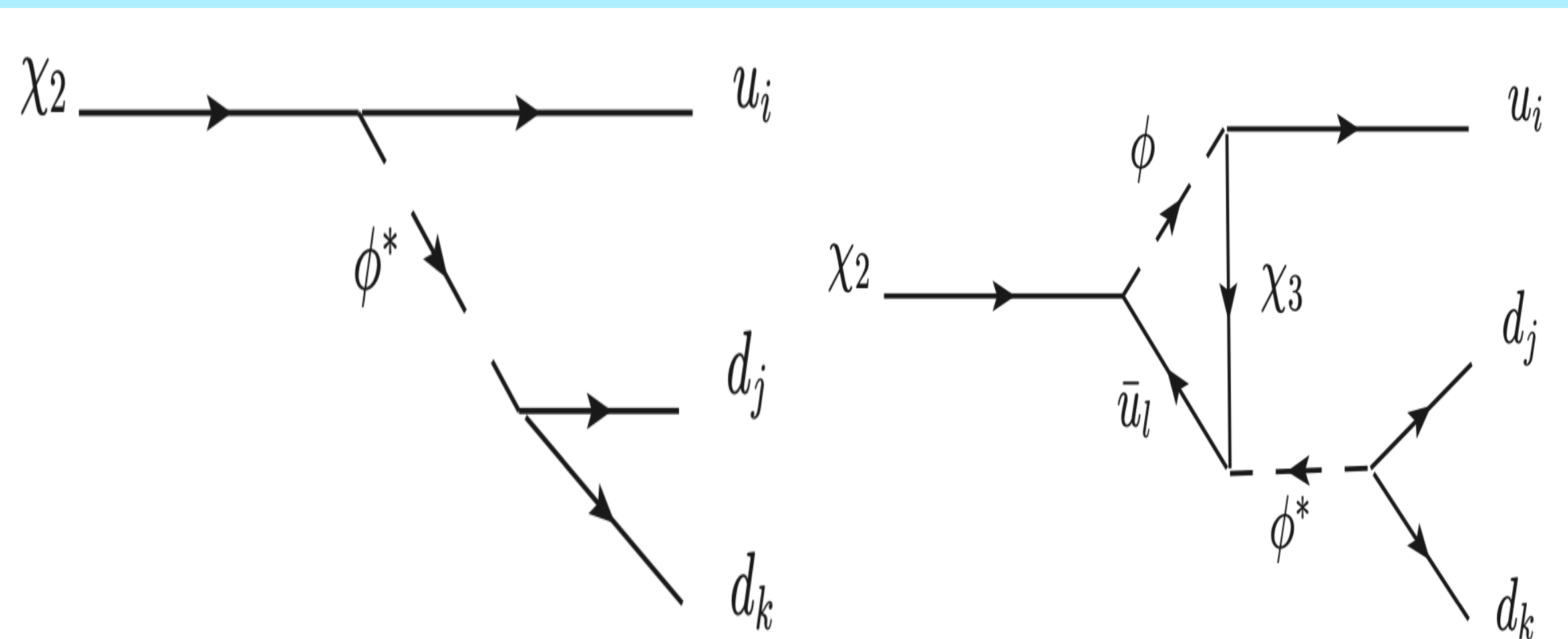
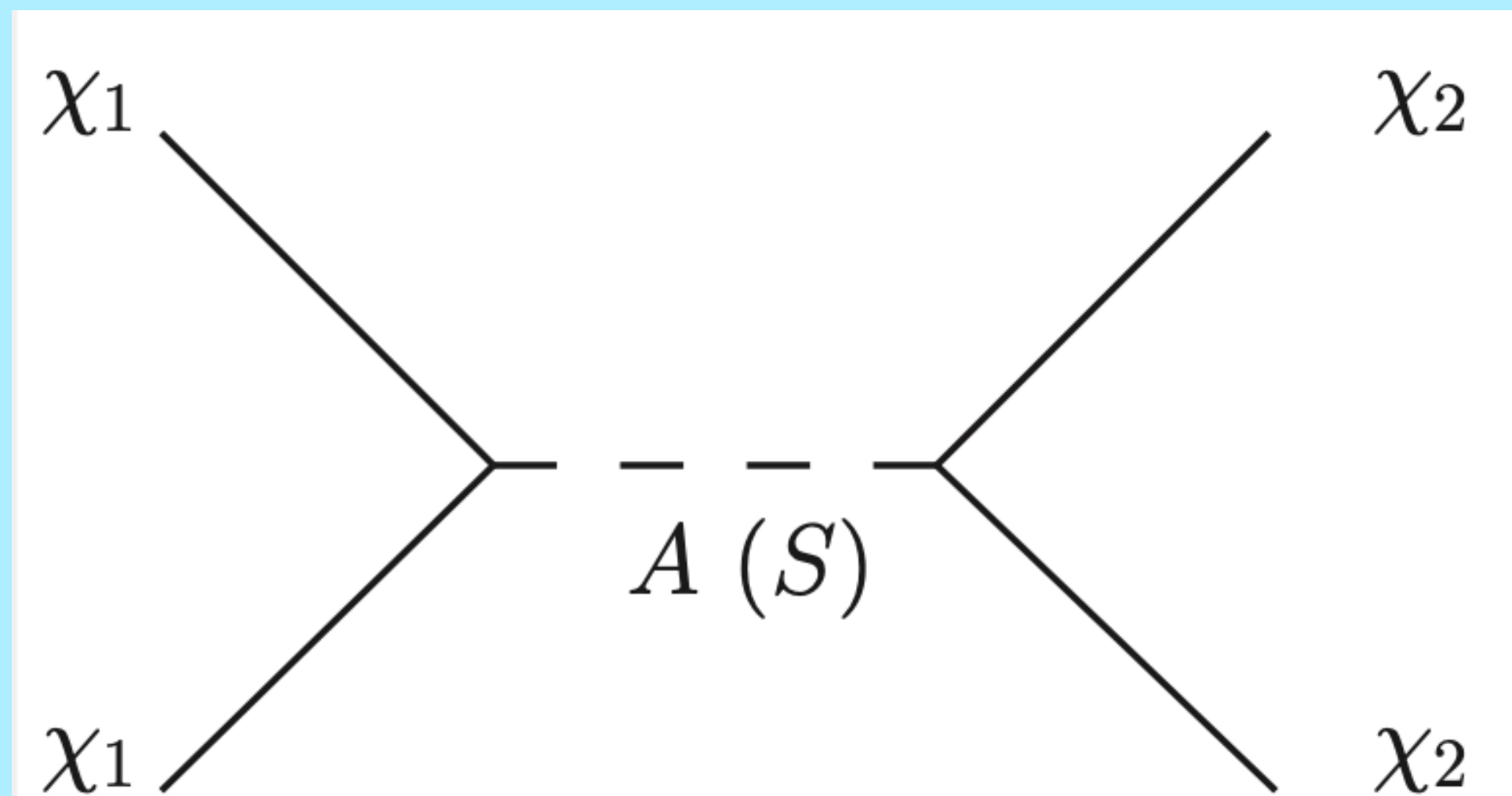
$$\mathcal{L}_{\text{baryog.}} = -\alpha_j \bar{u}_j P_L \chi_2 \phi - \beta_j \bar{u}_j P_L \chi_3 \phi - \eta_{kl} \epsilon_{kl} \phi^* \bar{d}_k P_L d_l^c + \text{h.c.}$$

Model

Freeze-out

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

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



Asymmetry Generation

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

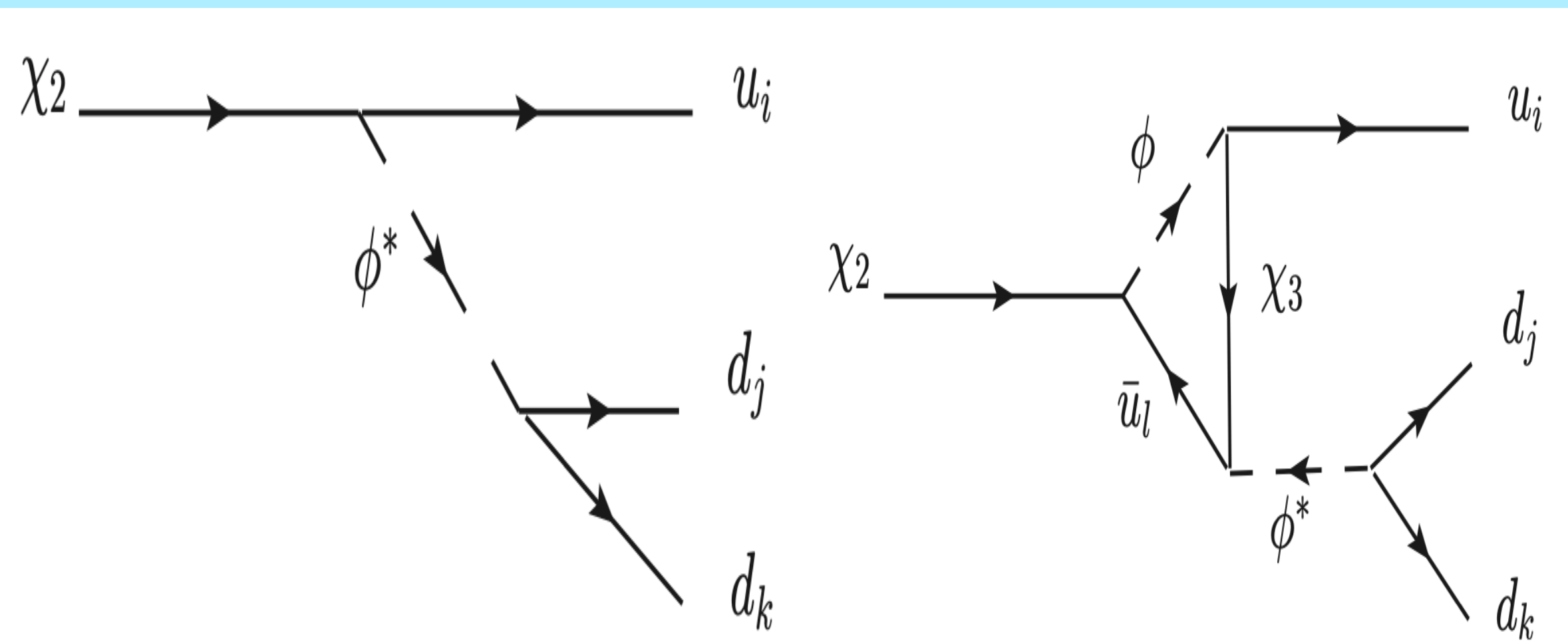
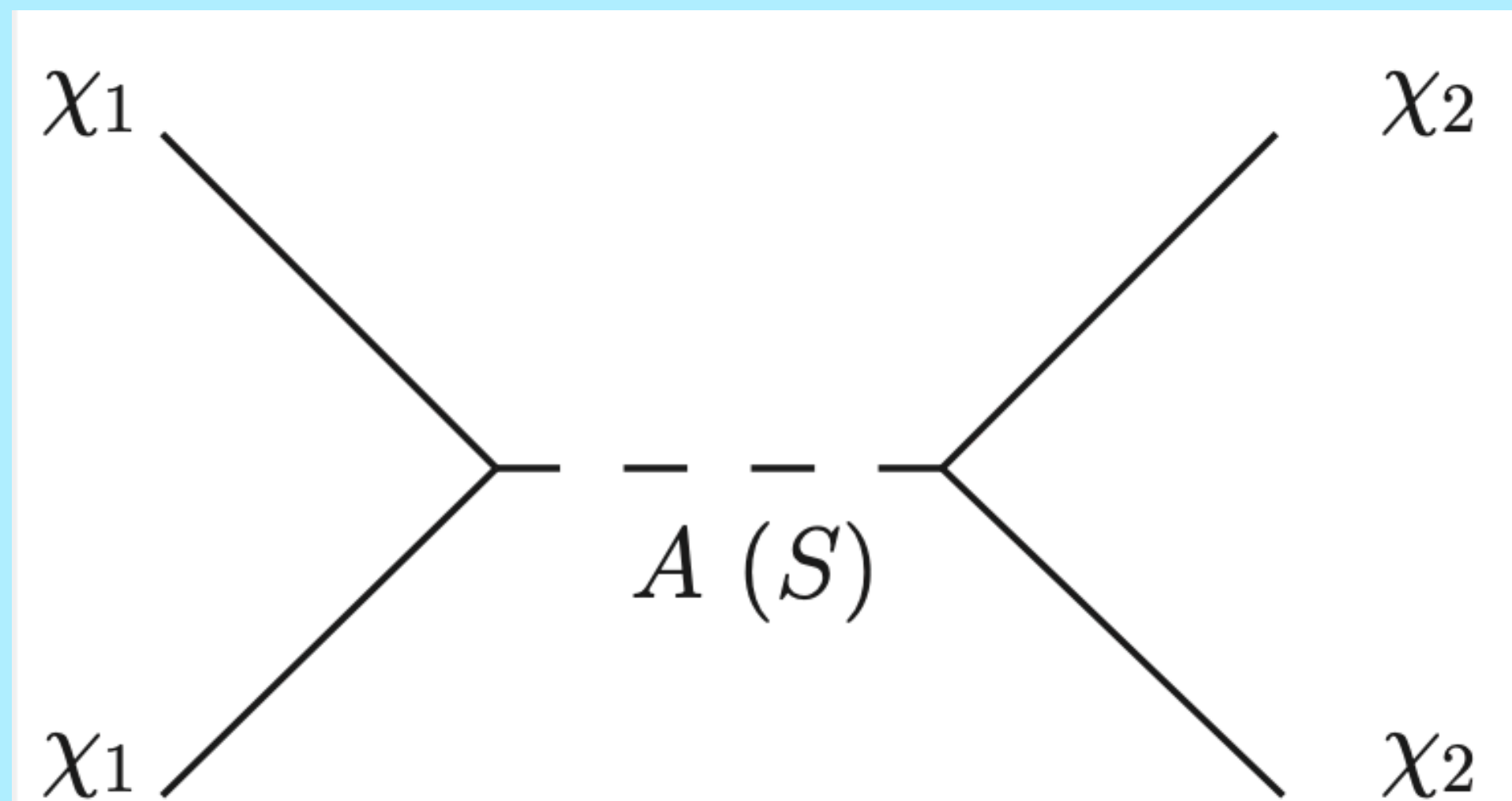
$$\epsilon_{CP} = \text{Im} [\beta_l^* \beta_i^* \alpha_l \alpha_i] m_{\chi_2}^2 / 20\pi |\alpha_i|^2 |\eta_{jk}|^2 m_\phi^2$$

Model

Freeze-out

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

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



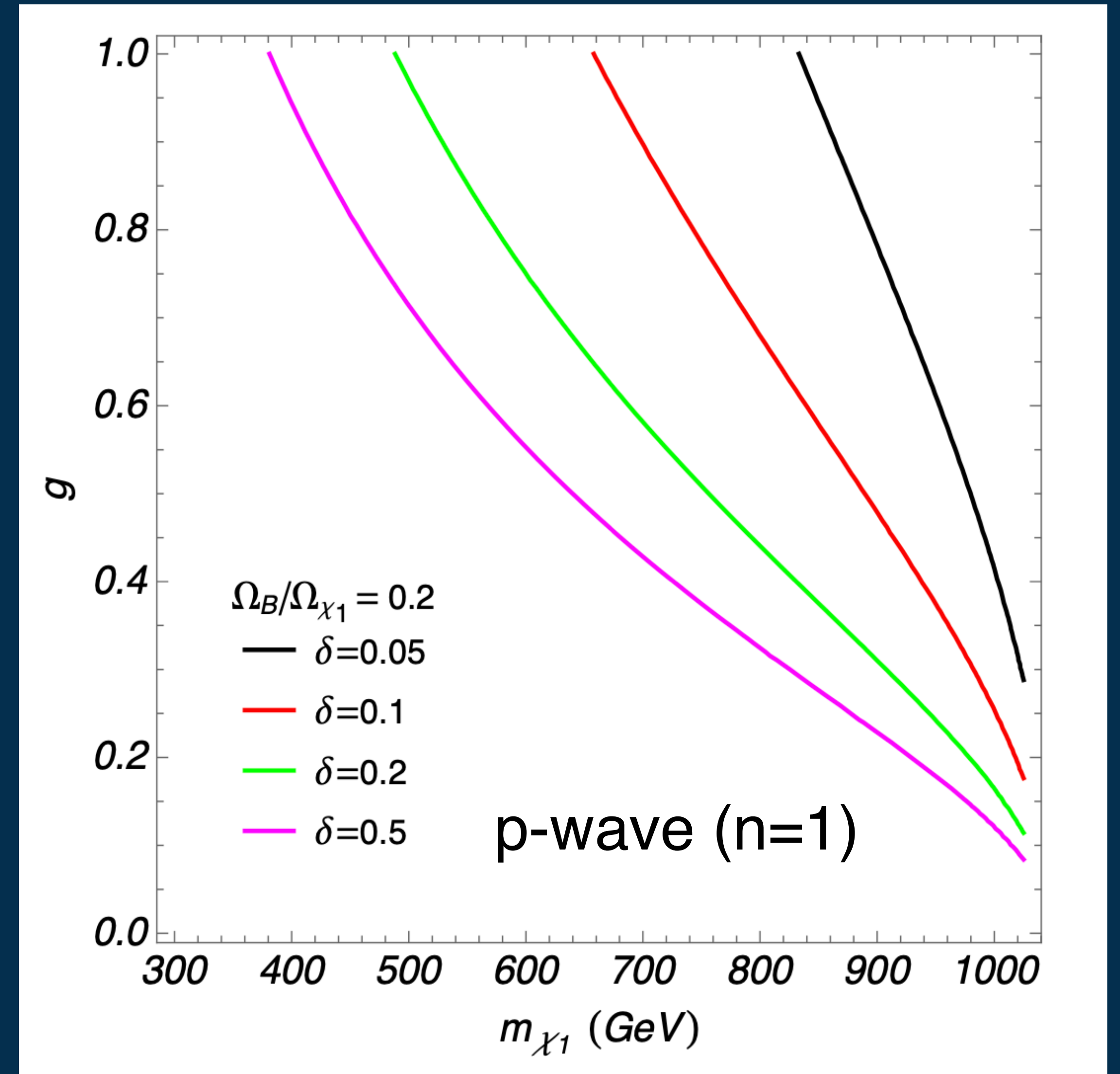
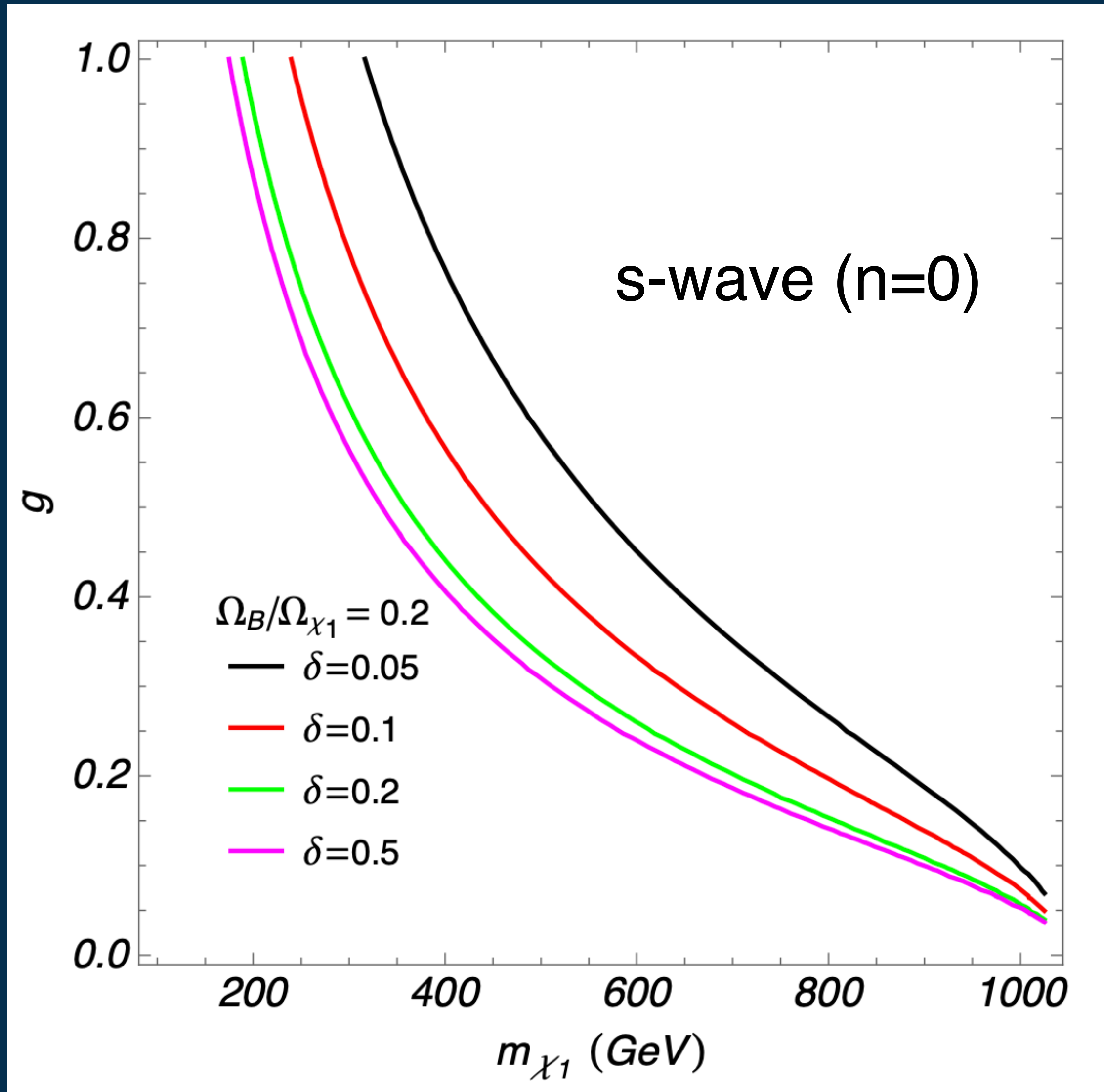
Asymmetry Generation

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

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

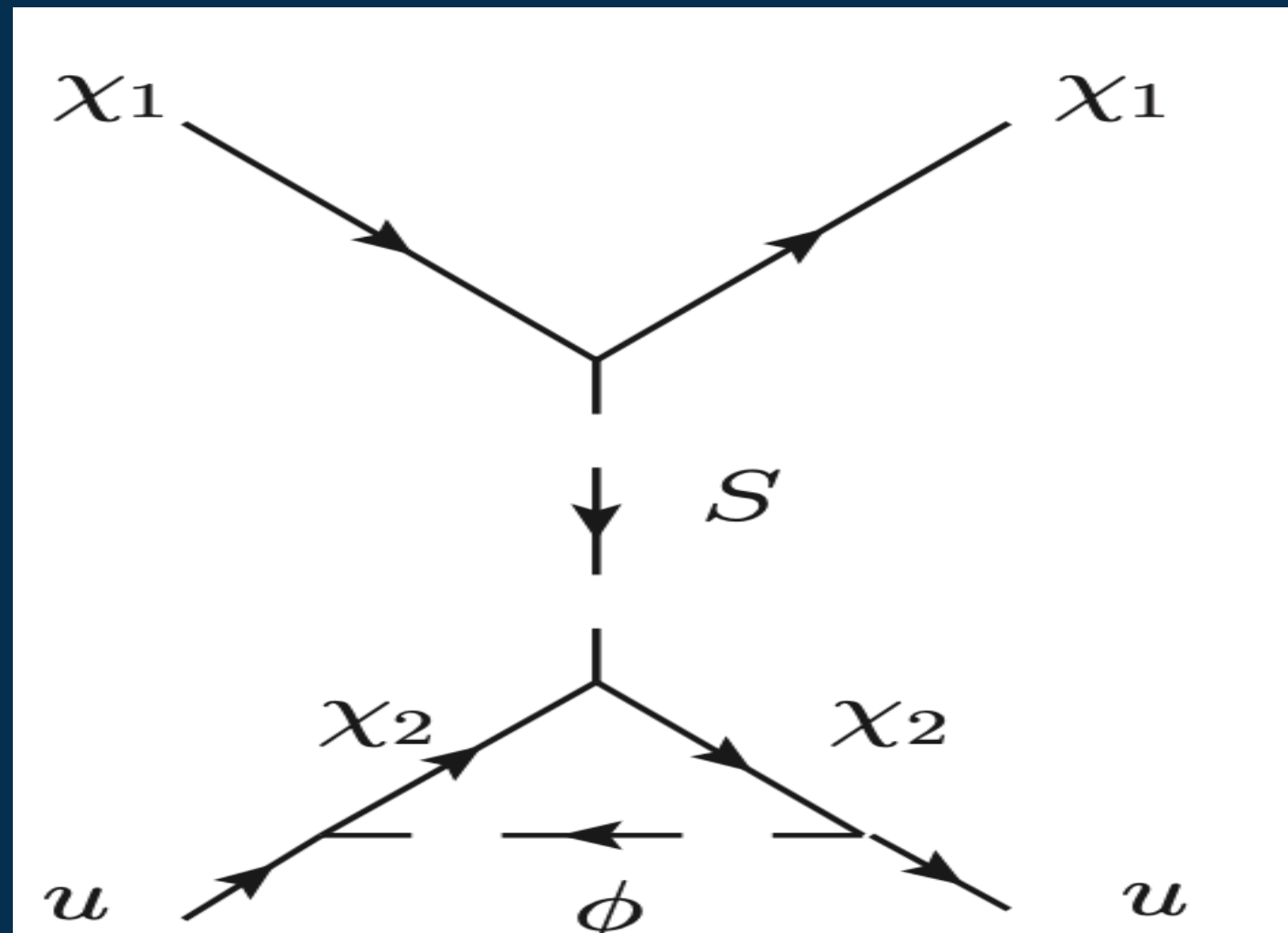
$$\frac{\Omega_B}{\Omega_{\chi_1}} = \epsilon_{CP} \frac{m_p}{m_{\chi_1}} \left[0.42 \frac{g_\chi}{g_*} \frac{\xi_i^3 \lambda}{(2n+1)\beta^n} \frac{1}{x_{\text{f.o.}}^{2n+1}} - 1 \right]$$

Results

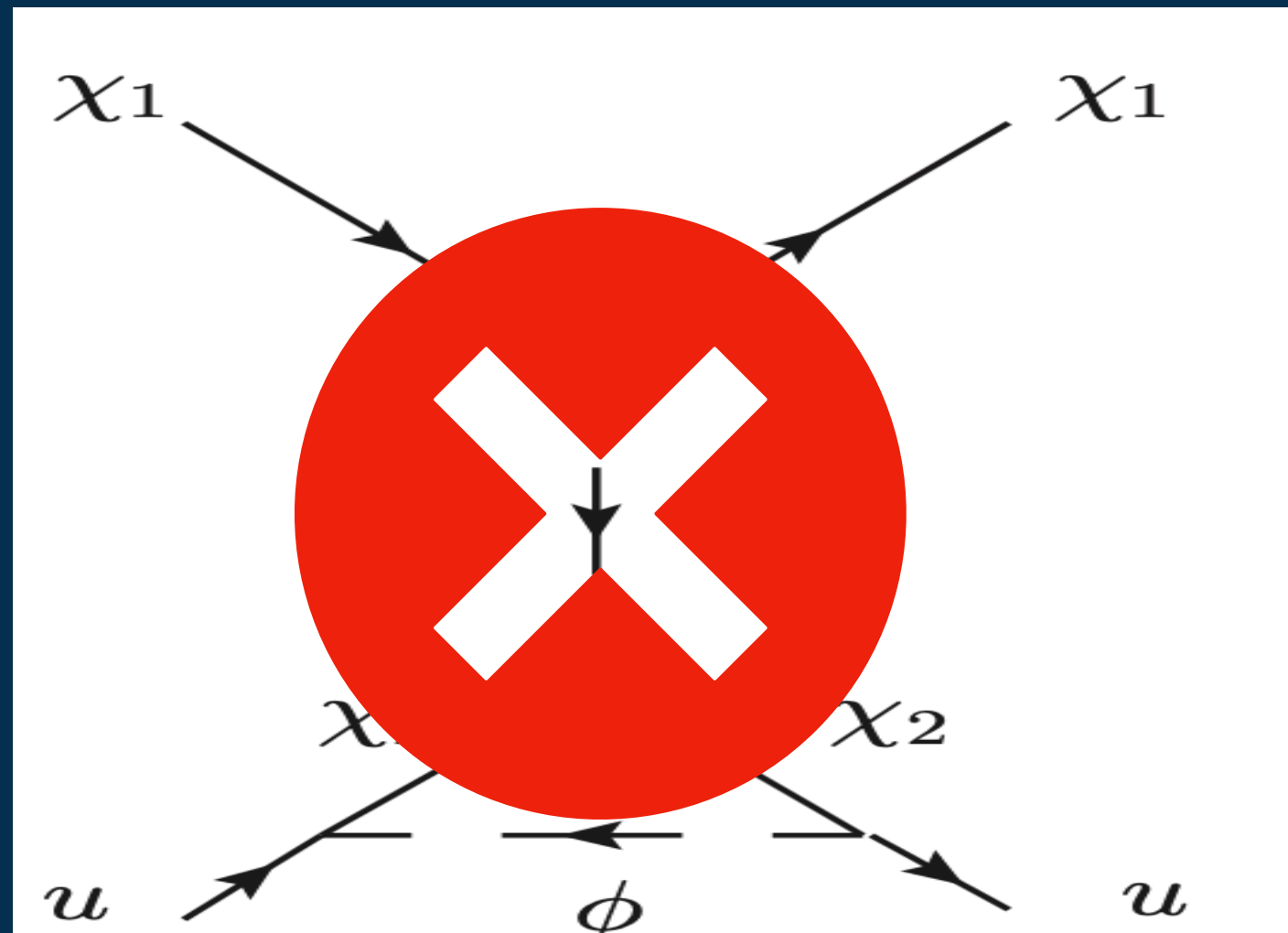


Pheno and Future Directions

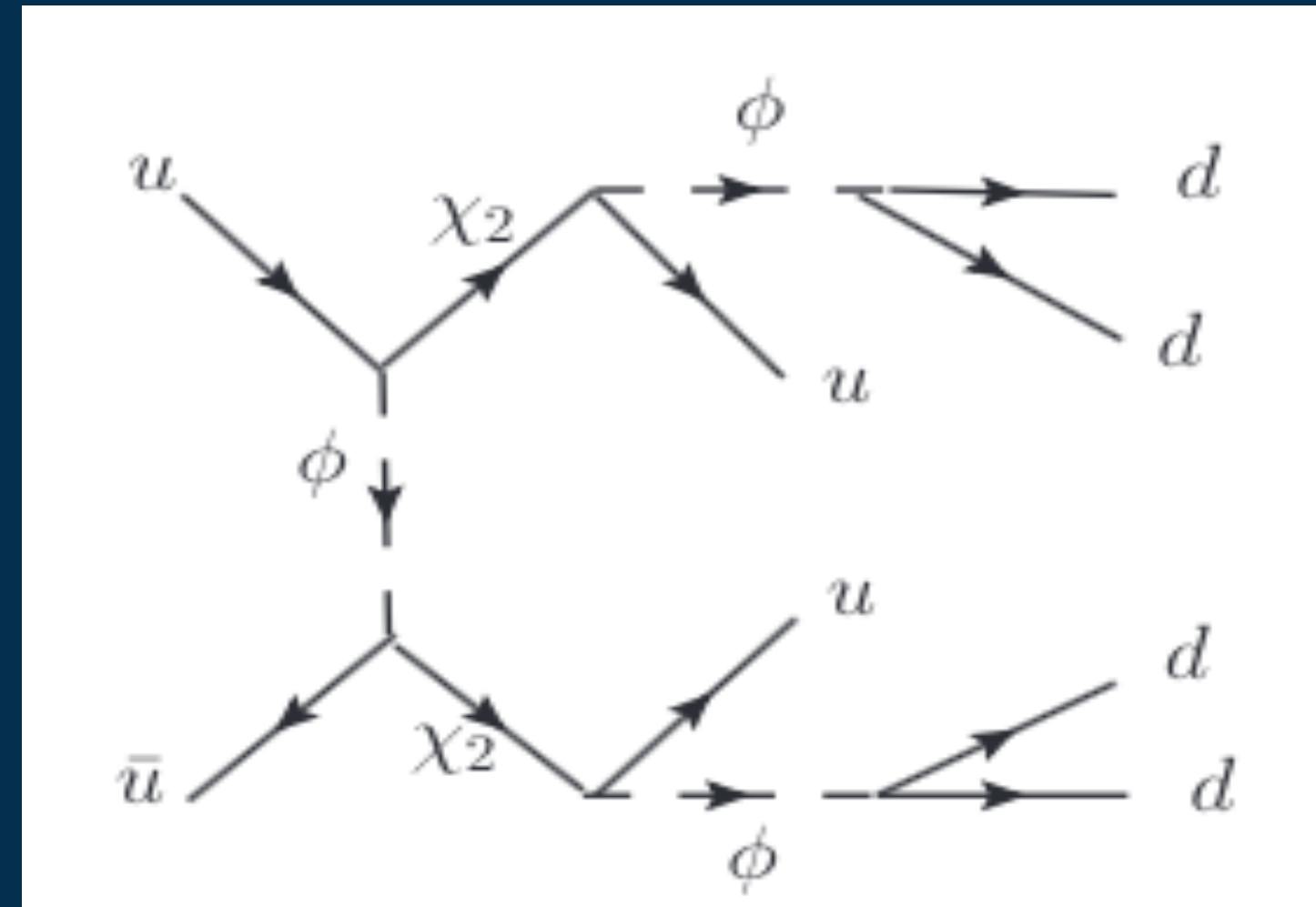
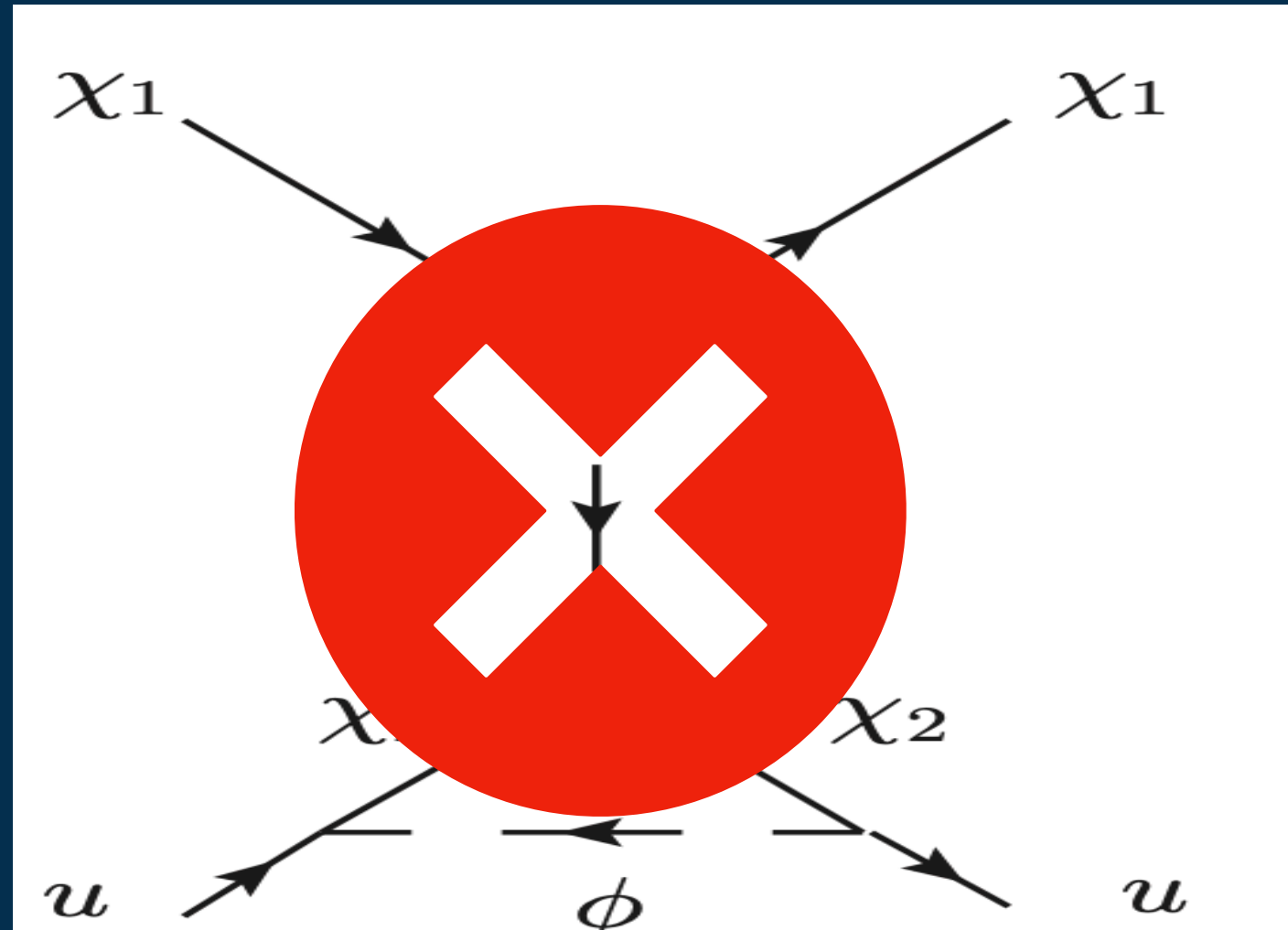
Pheno and Future Directions



Pheno and Future Directions

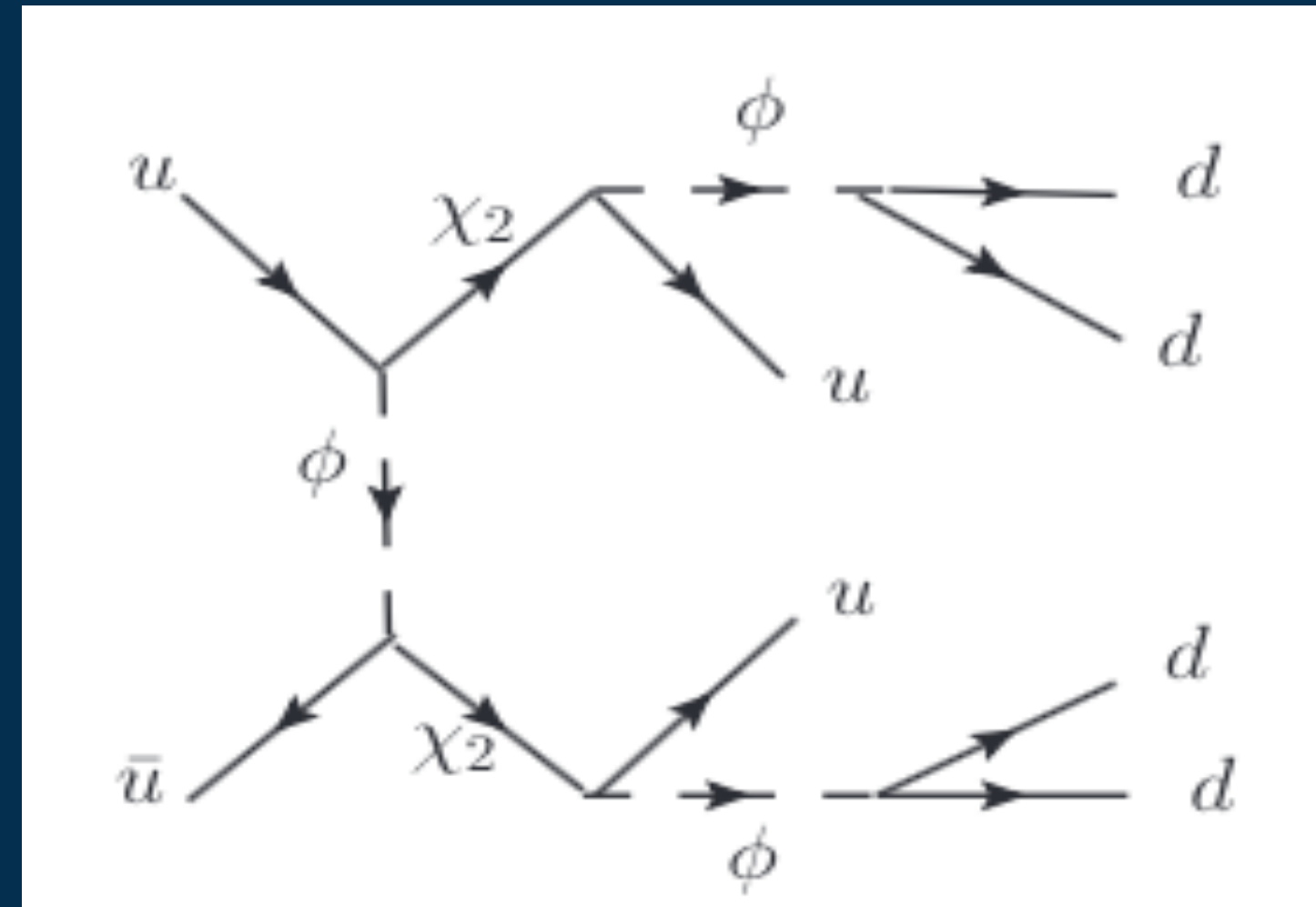
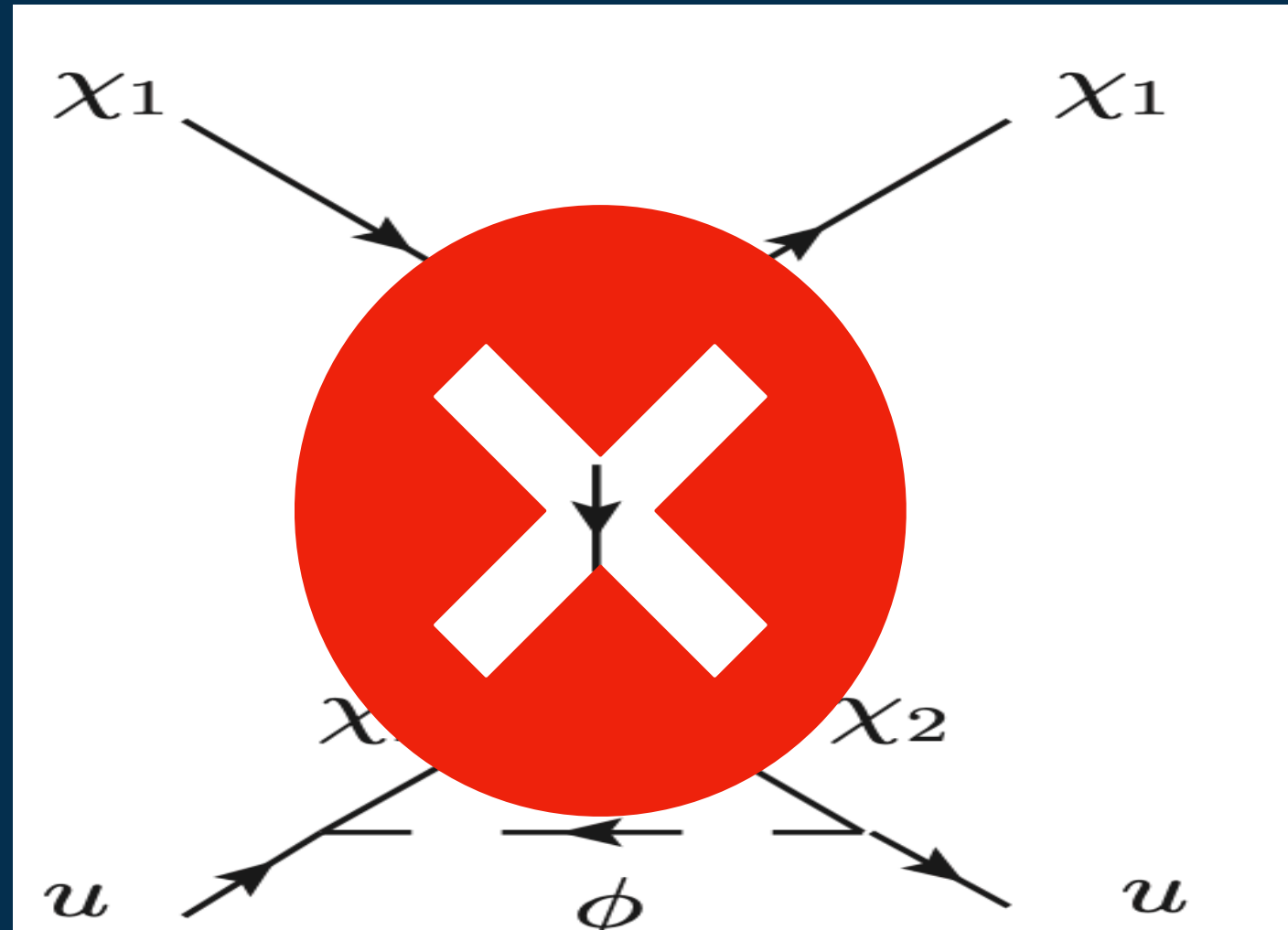


Pheno and Future Directions



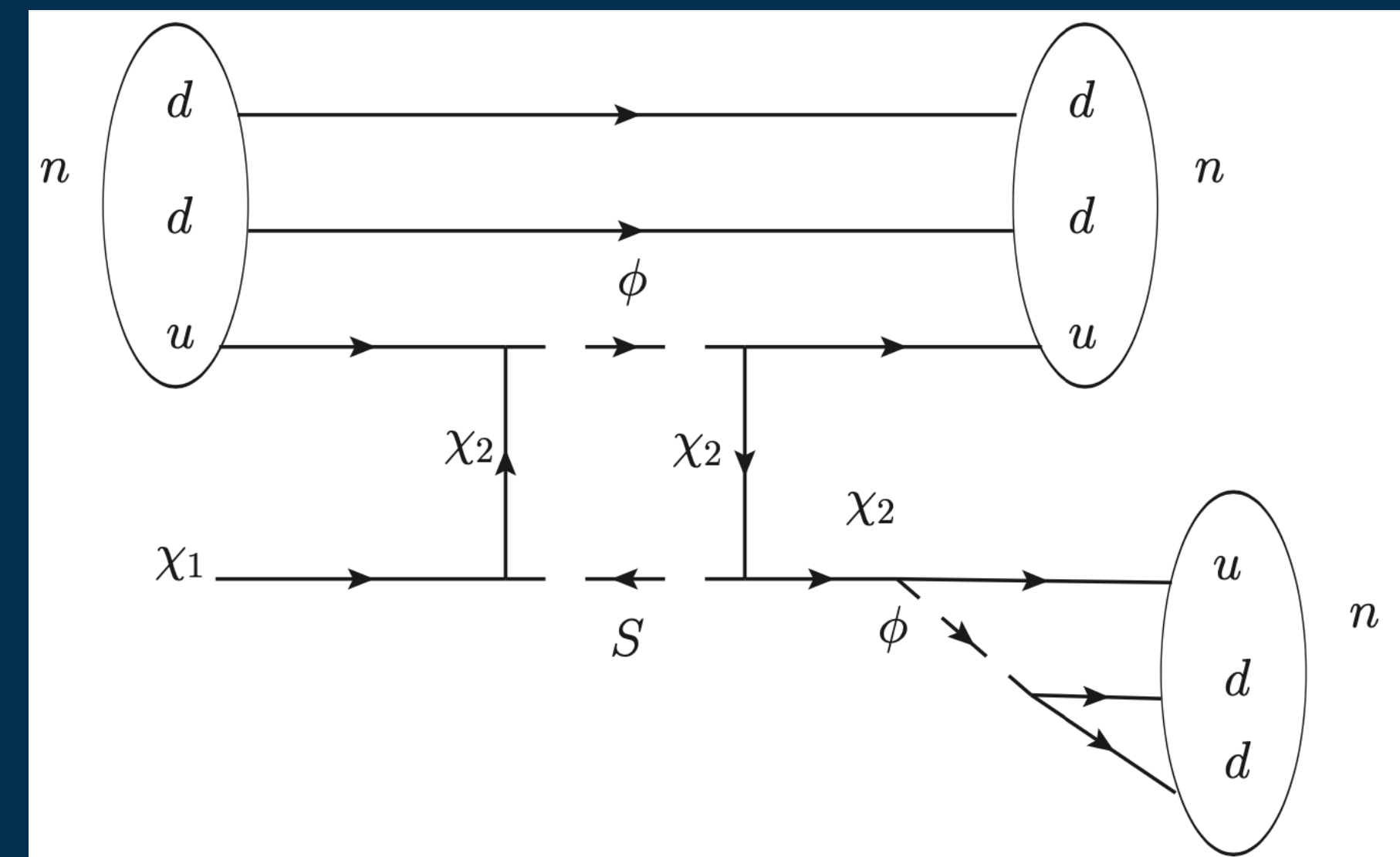
$$c\gamma\tau_{\chi_3} = 4 \text{ cm} \left(\frac{\gamma}{10} \right) \left(\frac{10^{-4}}{\beta\eta} \right)^2 \left(\frac{1 \text{ TeV}}{m_{\chi_3}} \right)^5 \left(\frac{m_\phi}{10 \text{ TeV}} \right)^4$$

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



PHENO 2022
indico.cern.ch/e/pheno22

May 9 to 11
Latest topics in particle physics and related issues in astrophysics and cosmology

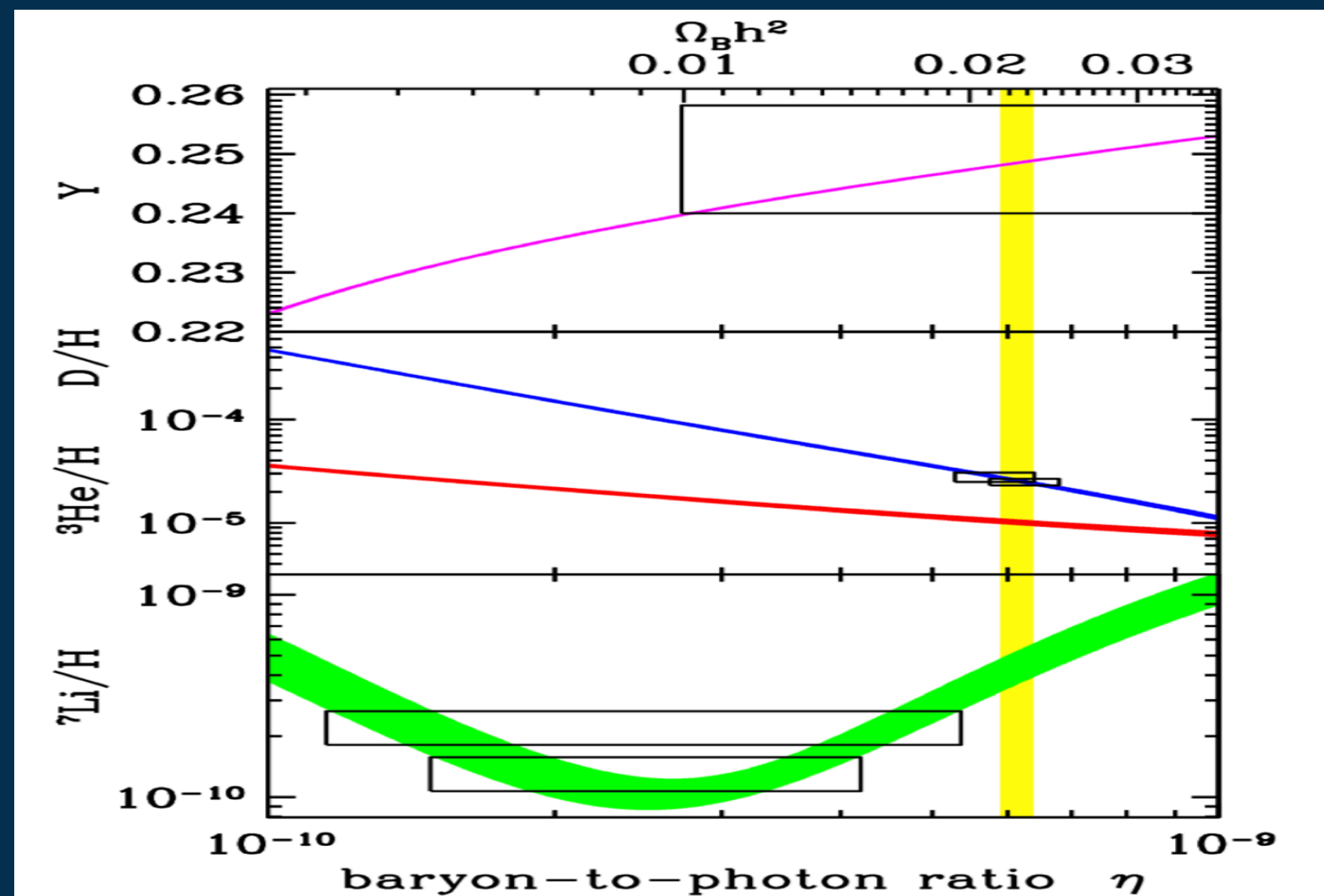
Organizers
Brian Batell
Arnab Dasgupta
Ayres Freitas
Joni George
Akshay Ghalsasi
Gracie Gollinger
Tao Han (Chair)
Adam Leibovich
Matthew Low
Keping Xie

Program Advisors
Vernon Barger
Lisa Everett
Kaoru Hagiwara
JoAnne Hewett
Tae Min Hong
Arthur Kosowsky
James Mueller
Vittorio Paolone
Tilman Plehn
Vladimir Savinov
Xerxes Tata
Andrew Zentner
Dieter Zeppenfeld

Pheno Symposia are supported by the US DOE, NSF and PITT PACC

Baryogenesis

Baryogenesis

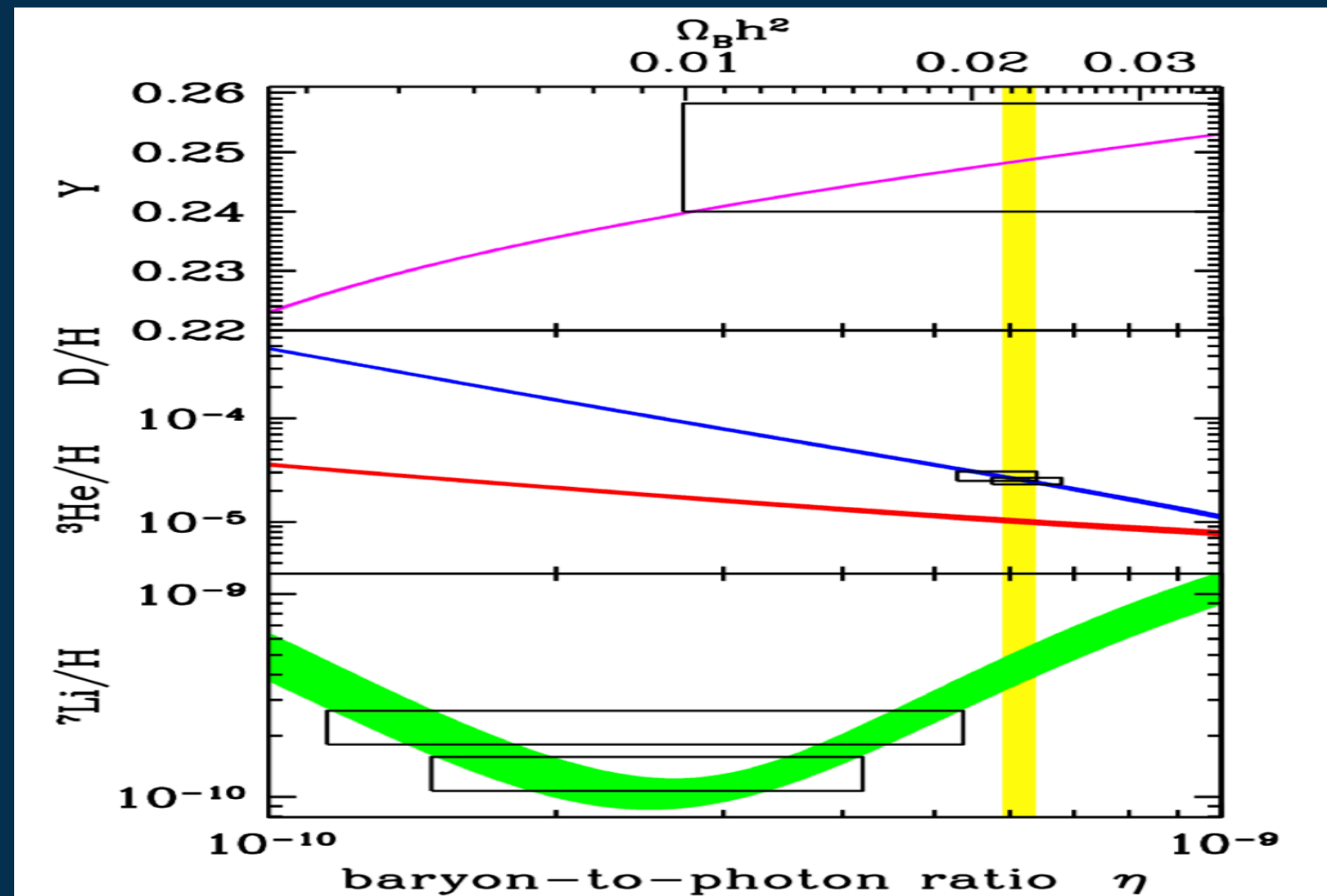


$$\text{BBN} \implies \eta_B \sim 10^{-10}$$

Baryogenesis:

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

Baryogenesis

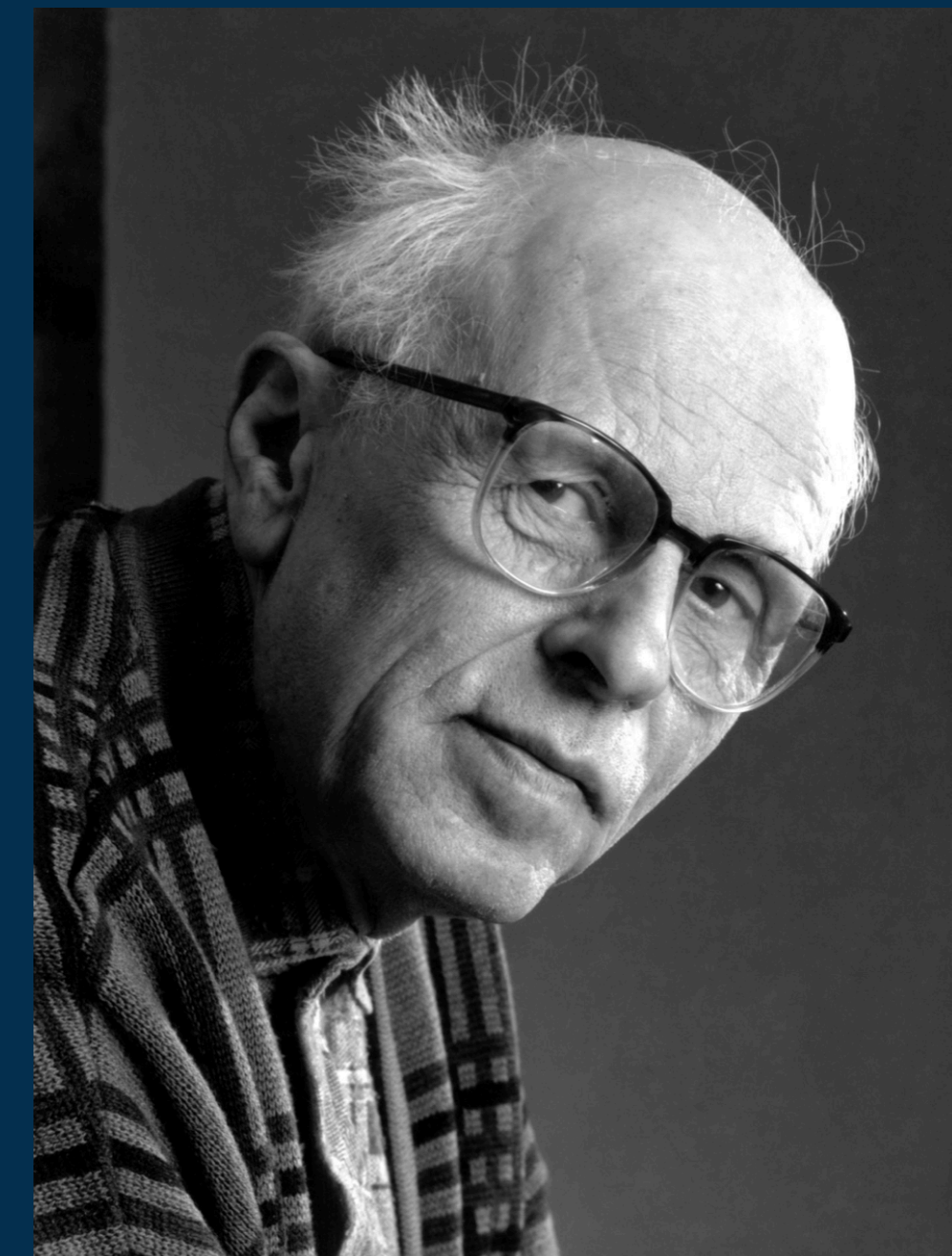


$$\text{BBN} \implies \eta_B \sim 10^{-10}$$

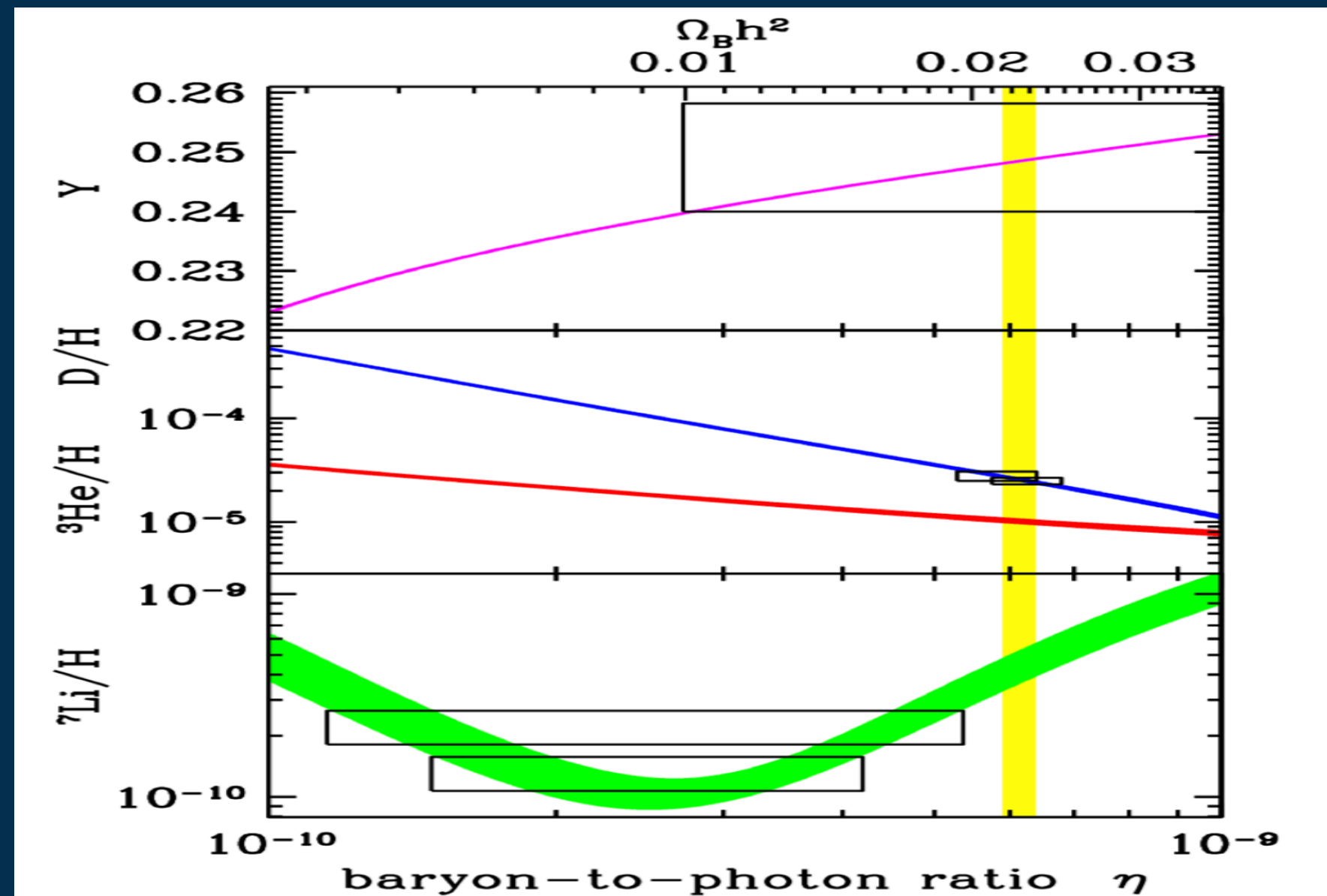
Baryogenesis:

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

Sakharov conditions [Sakharov, 1967]



Baryogenesis



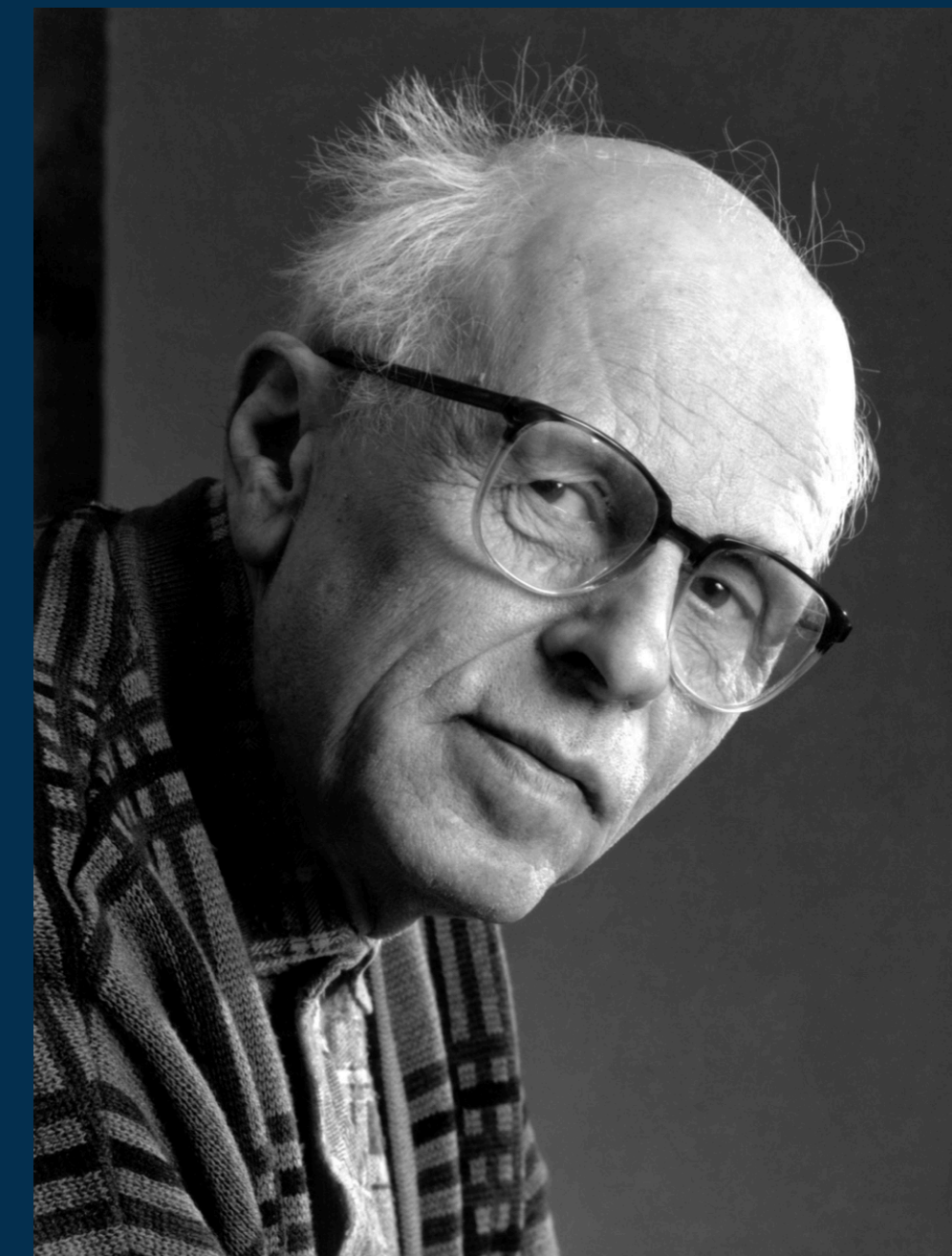
$$\text{BBN} \implies \eta_B \sim 10^{-10}$$

Baryogenesis:

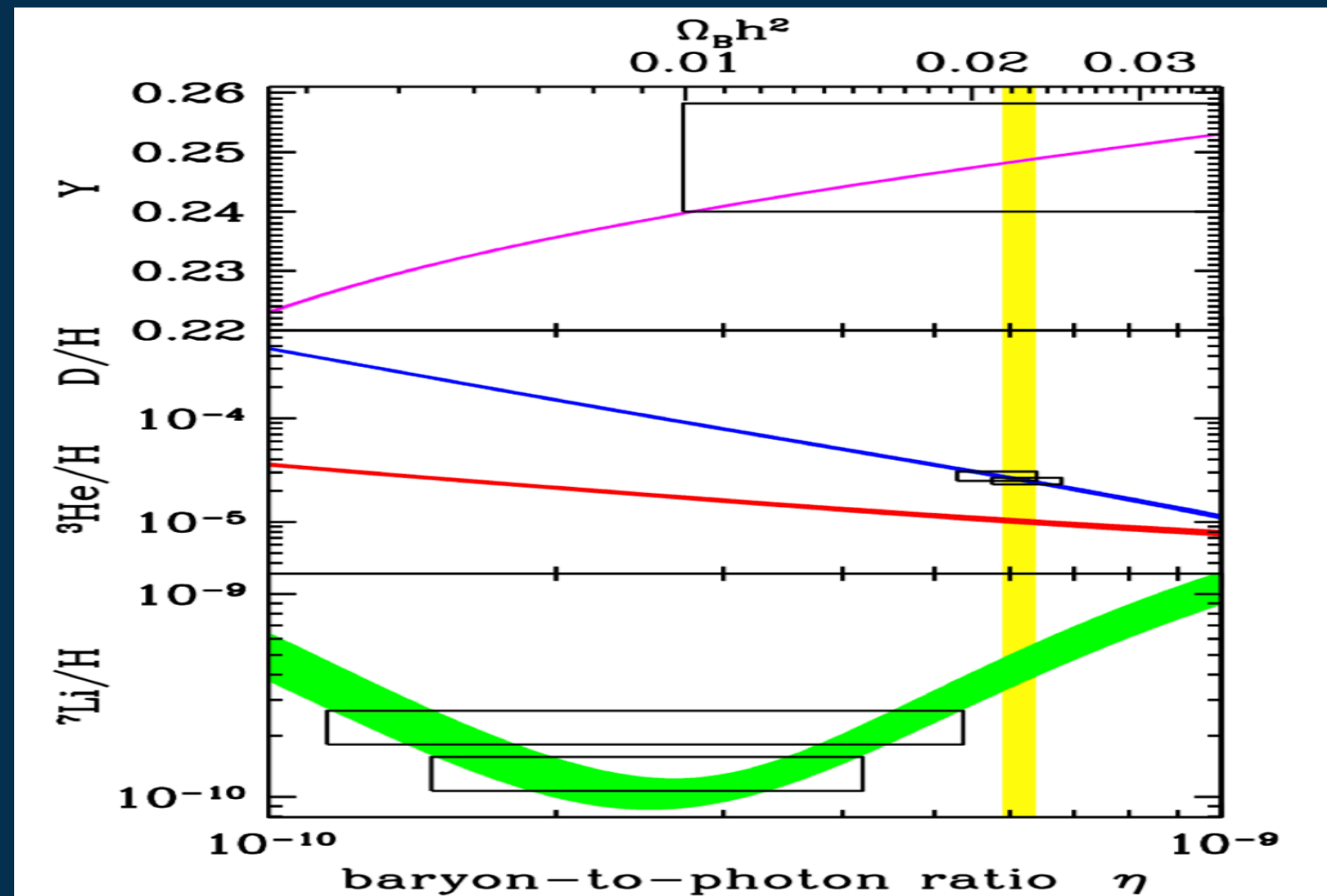
$$\eta_B(t = 0) = 0 \rightarrow \eta_B(t = t_{\text{BBN}}) \neq 0$$

Sakharov conditions [Sakharov, 1967]

1. $\Delta B \neq 0$



Baryogenesis



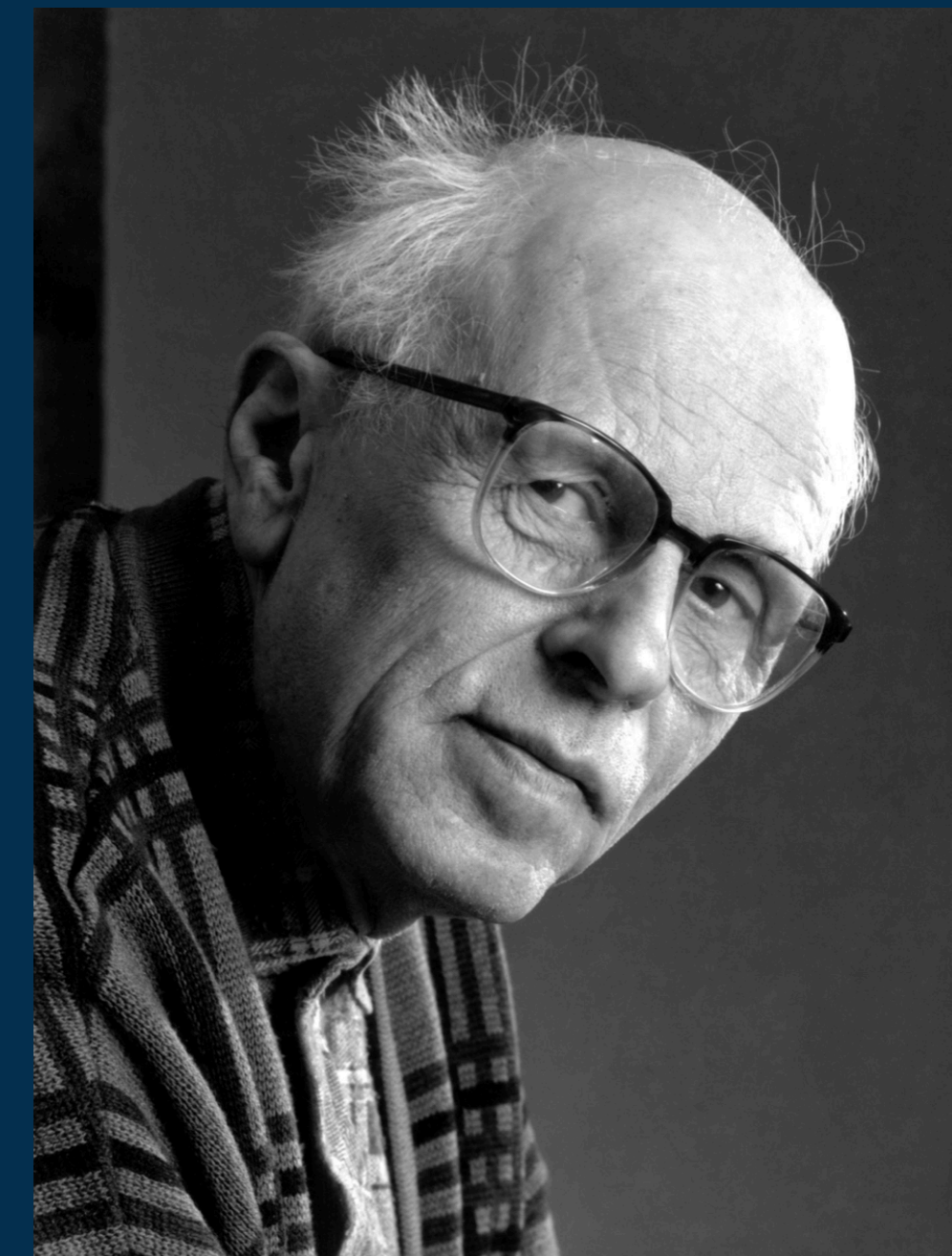
$$\text{BBN} \implies \eta_B \sim 10^{-10}$$

Baryogenesis:

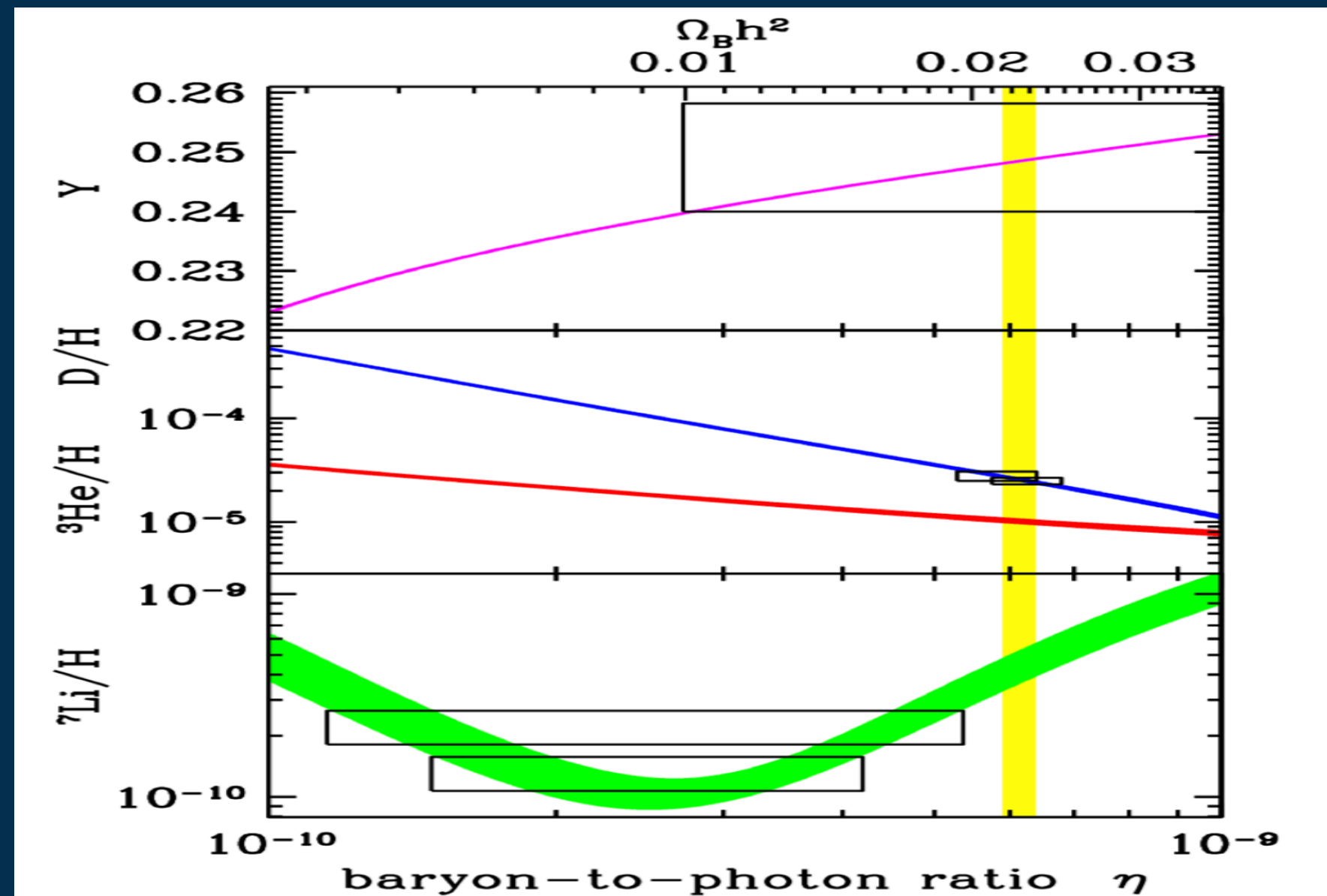
$$\eta_B(t = 0) = 0 \rightarrow \eta_B(t = t_{\text{BBN}}) \neq 0$$

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



$$\text{BBN} \implies \eta_B \sim 10^{-10}$$

Baryogenesis:

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

Sakharov conditions [Sakharov, 1967]

$$1. \Delta B \neq 0 \quad 2. \Gamma(F_L^+ \rightarrow f_L^+ + s) + \Gamma(F_R^+ \rightarrow f_R^+ + s) \neq \Gamma(F_R^- \rightarrow f_R^- + s) + \Gamma(F_L^- \rightarrow f_L^- + s)$$

$$3. \langle B \rangle_T$$

