Exploring the Dark Sector: Self Interactions, Baryon Asymmetry and Gravitational Waves

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7th CUBES Workshop

"CHIRALITY IN THE UNIVERSE BEYOND THE ELECTROWEAK SCALE"

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Presentation Outline

Triplet Fermion Cogenesis & Long lived DM

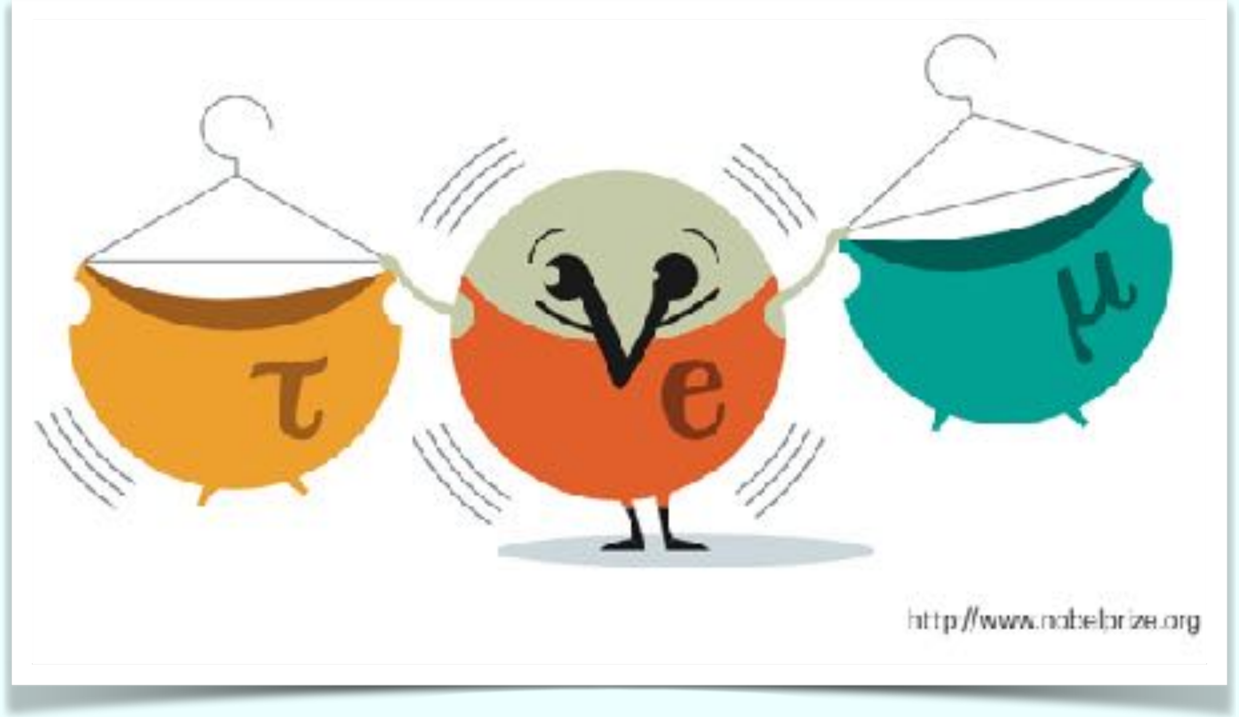
Asymmetric SIDM with Canonical Seesaw

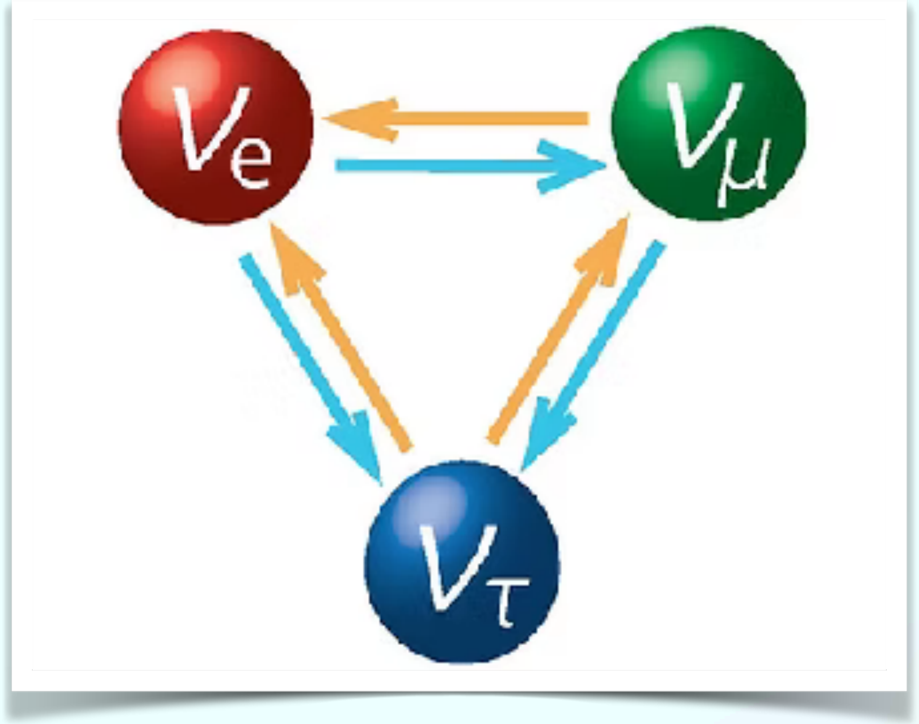
Rescuing Thermal under-abundant DM with FOPT

Unsolved Mysteries..

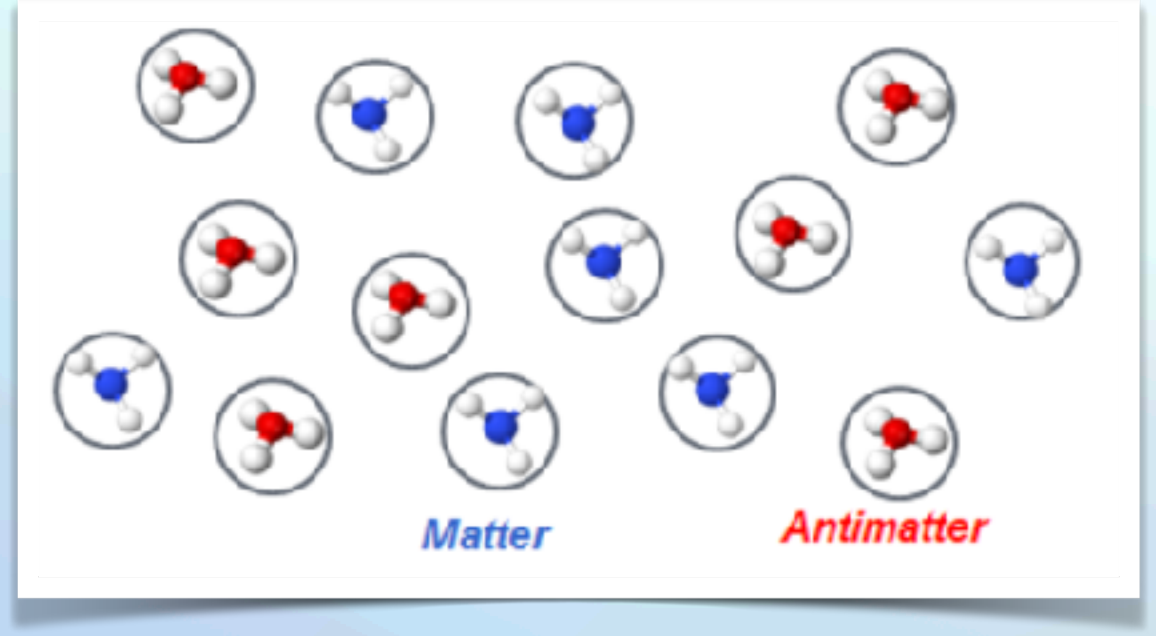
Dark Matter

Neutrino Mass

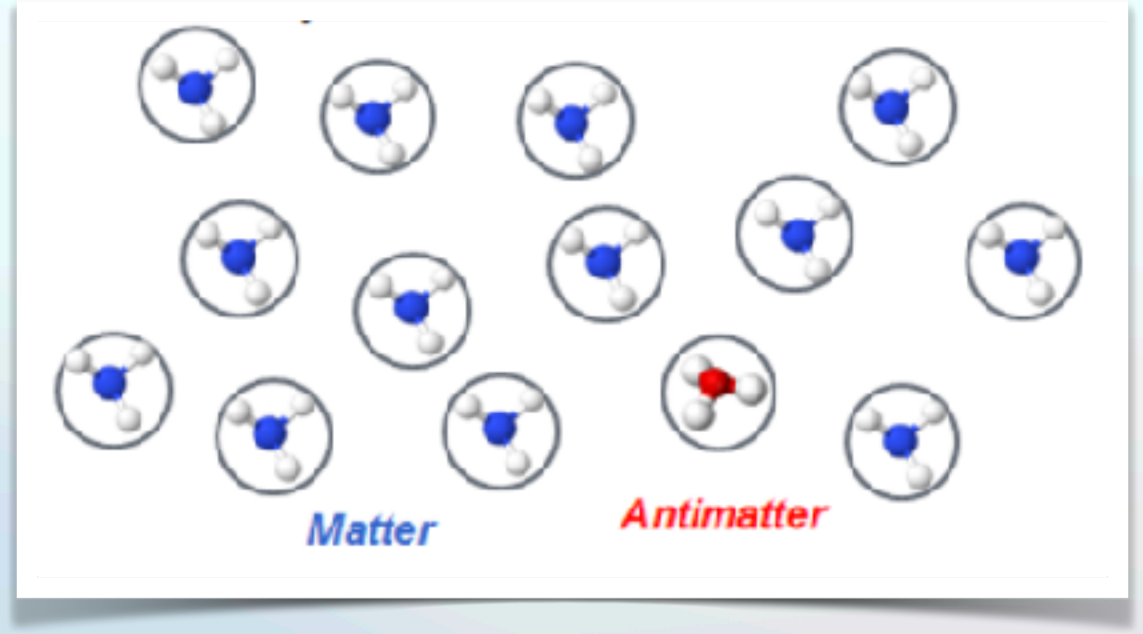




Matter-Antimatter asymmetry



What we should see



What we see

And some more...

Hint towards
Physics
Beyond the Standard Model (BSM)

Ultimate Goal...

$$\mathscr{L}_{BSM} \supset \mathscr{L}_{SM} + \mathscr{L}_{\nu-mass} + \mathscr{L}_{DM} + \mathscr{L}_{BAU} + \mathscr{L}_{Other\ Anomalies..}$$

New Particles, New symmetries...

?

Neutrino Mass

Baryon Asymmetry

(g-2) Anomaly

Dark Matter

Hubble Tension

95 GeV Di-photon Excess

KM3-230213A Events

W-Mass Anomaly

GRB221009A Events

Cogenesis from fermion triplet seesaw

PHYSICAL REVIEW D **111,** 015043 (2025)

Asymmetric long-lived dark matter and leptogenesis from the type-III seesaw framework

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We propose a simple model in the type-III seesaw framework to explain the neutrino mass, asymmetric dark matter (DM), and baryon asymmetry of the Universe. We extend the Standard Model with a vectorlike singlet lepton (χ) and a hypercharge zero scalar triplet (Δ) in addition to three hypercharge zero triplet fermions ($\Sigma_i, i = 1, 2, 3$). A Z_2 symmetry is imposed under which χ and Δ are odd, while all other particles are even. As a result, the lightest Z_2 odd particle χ behaves as a candidate of DM. In the early Universe, the CP-violating out-of-equilibrium decay of heavy triplet fermions to the Standard Model lepton (L) and Higgs (H) generate a net lepton asymmetry, while that of triplet fermions to χ and Δ generate a net asymmetric DM. The lepton asymmetry is converted to the required baryon asymmetry of the Universe via the electroweak sphalerons, while the asymmetry in χ remains as a DM relic that we observe today. We introduce a singlet scalar Φ, with mass $M_\Phi < M_\chi$, which not only assists to deplete the symmetric component of χ through the annihilation process $\bar{\chi}\chi \to \Phi\Phi$, but also paves a path to detect DM χ at direct search experiments through $\Phi - H$ mixing. The electroweak symmetry breaking induces a nonzero vacuum expectation value to Δ, which leads to an unstable asymmetric DM ranging from a few MeV to hundreds of GeV. We then explore the displaced vertex signatures of the charged components of the scalar triplet Δ at colliders.

DOI: 10.1103/PhysRevD.111.015043

PHYSICAL REVIEW D **110,** 035033 (2024)

Asymmetric self-interacting dark matter with a canonical seesaw model

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[2]*Department of Physics and Institute of Basic Science, Sungkyunkwan University, Suwon 16419, Korea*
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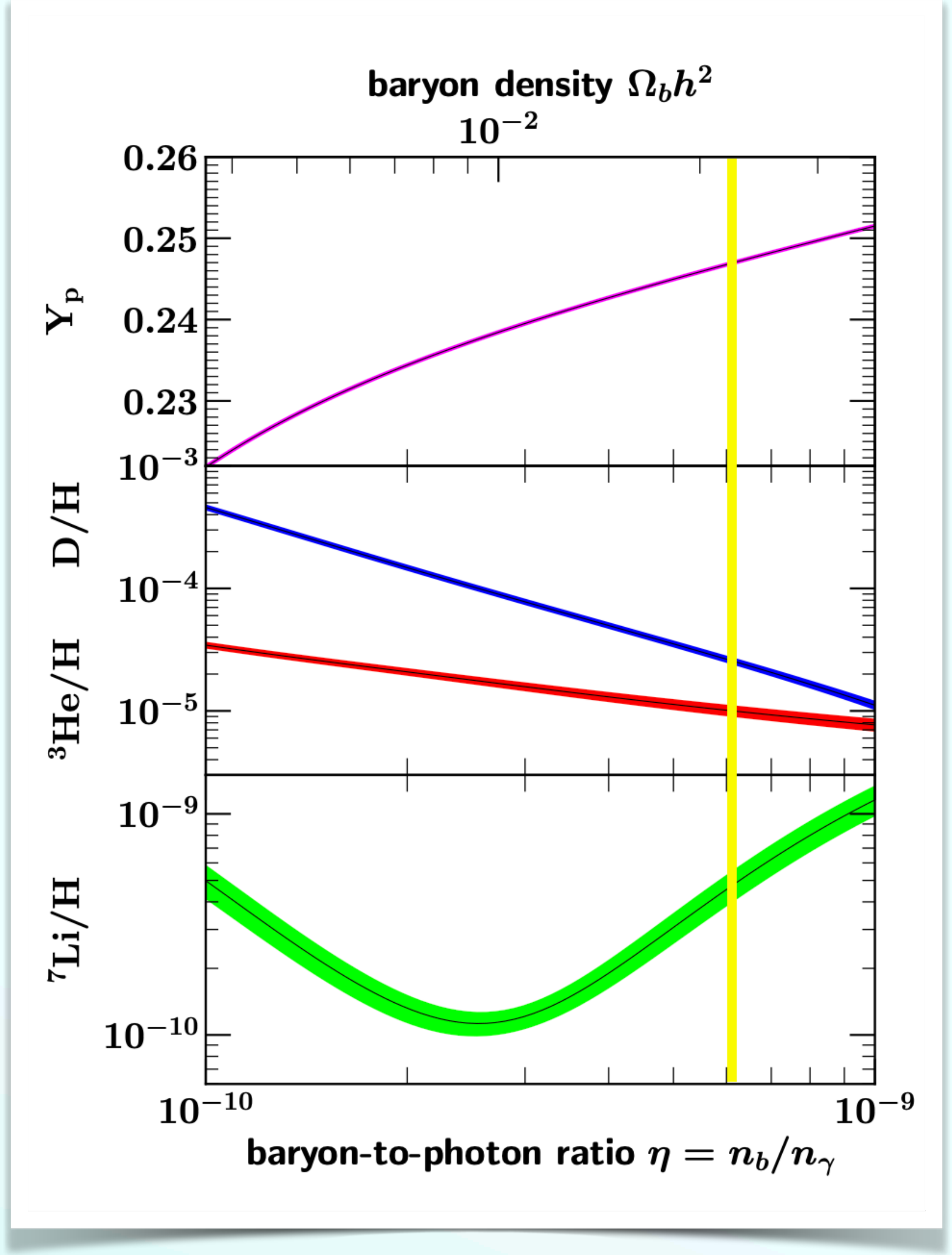
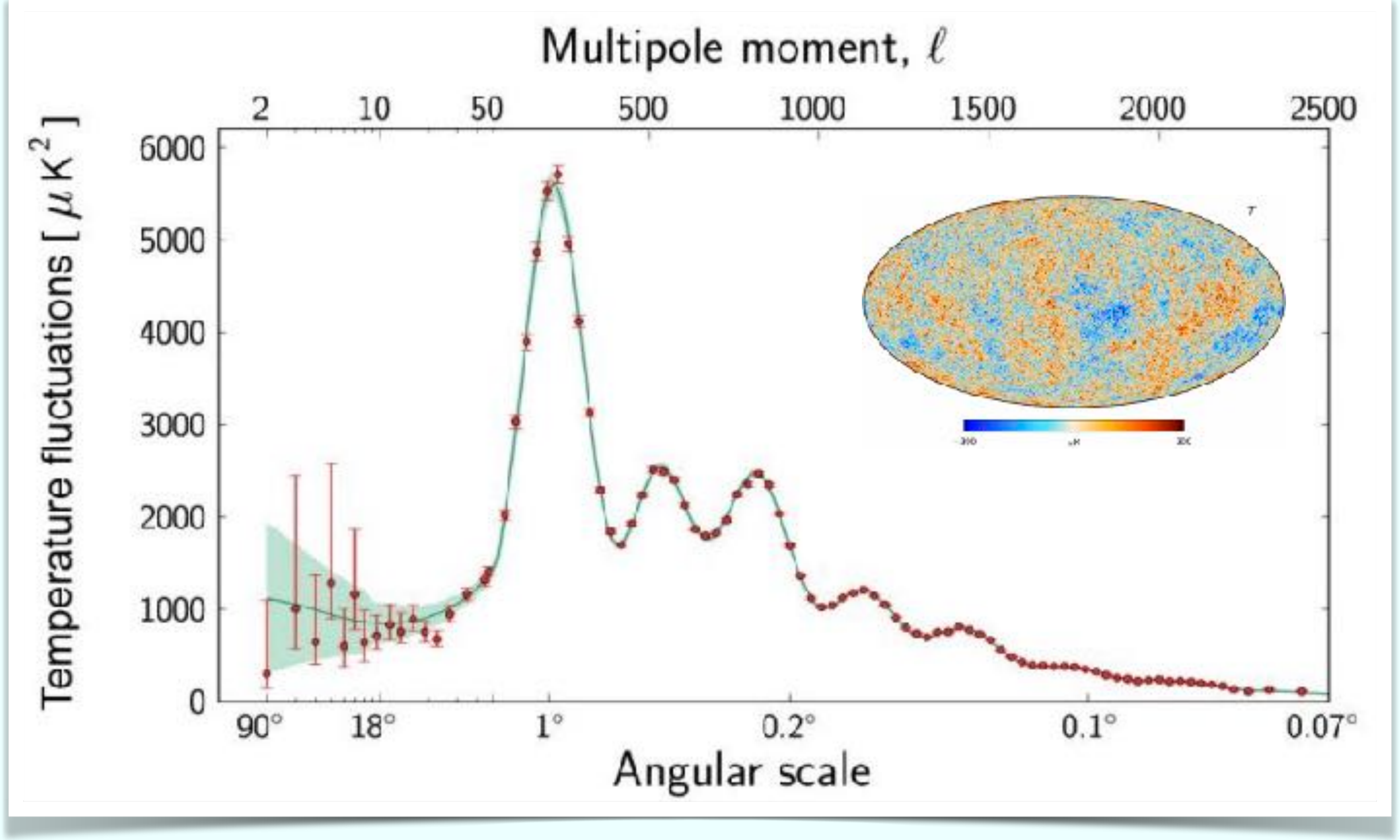
(Received 3 May 2024; accepted 3 August 2024; published 28 August 2024)

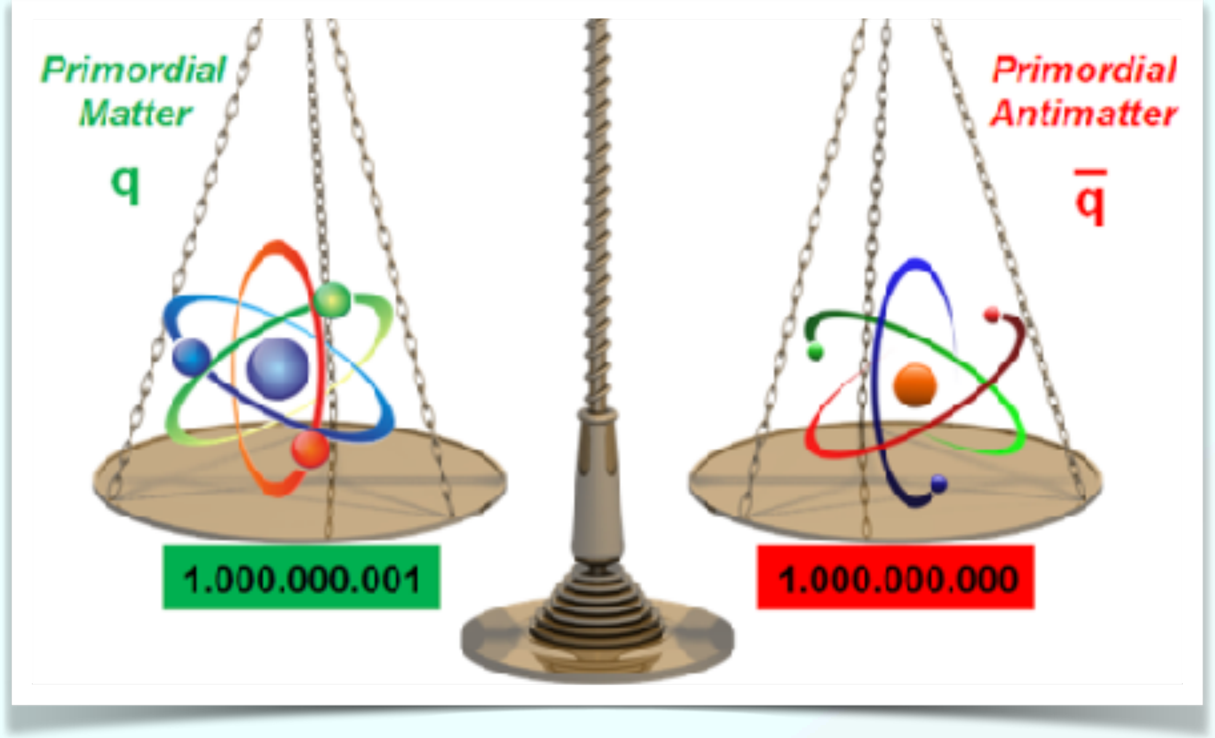
We study the possibility of generating dark matter (DM) and baryon asymmetry of the Universe (BAU) simultaneously in an asymmetric DM framework, which also alleviates the small-scale structure issues of cold DM. While the thermal relic of such self-interacting DM remains underabundant due to efficient annihilation into light mediators, a nonzero asymmetry in the dark sector can lead to the survival of the required DM in the Universe. The existence of a light mediator leads to the required self-interactions of DM at small scales while keeping DM properties similar to cold DM at large scales. It also ensures that the symmetric DM component annihilates away, leaving the asymmetric part in the spirit of cogenesis. The particle physics implementation is done in canonical seesaw models of light neutrino mass, connecting it to the origin of DM and BAU. In particular, we consider type-I and type-III seesaw origin of neutrino mass for simplicity and minimality of the field content. We show that the desired self-interactions and relic of DM together with BAU while satisfying relevant constraints lead to strict limits on DM mass $\mathcal{O}(\mathrm{GeV}) \lesssim M_{\mathrm{DM}} \lesssim 460$ GeV. In spite of being a high-scale seesaw, the models remain verifiable in different experiments, including direct and indirect DM searches as well as colliders.

DOI: 10.1103/PhysRevD.110.035033

Baryon Asymmetry of the Universe







$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

$$\boxed{\eta \sim 6 \times 10^{-10}}$$

Sakharov's Conditions

- **Baryon Number Violation: To evolve from $Y_{\Delta B} = 0$ to $Y_{\Delta B} \neq 0$**
- **C & CP violation : Interactions has to treat matter and antimatter differently**
- **Out of equilibrium dynamics: Else Asymmetries will be washed out.**

Cosmic Coincidence

$\boxed{\Omega_{DM}h^2 \sim 0.12}$ $\boxed{\Omega_B h^2 \sim 0.0224}$ $\boxed{\Omega_{DM}h^2/\Omega_B h^2 \sim 5}$

Cogenesis from fermion triplet seesaw

$\Omega_{DM}h^2 \sim 0.12$

$\Omega_B h^2 \sim 0.0224$

$\Omega_{DM}h^2/\Omega_B h^2 \sim 5$

Z_2 Even

Fermion Triplet Σ

Singlet Scalar Φ

Standard Model

Z_2 Odd

Scalar Triplet Δ

Singlet Lepton χ

Cogenesis from fermion triplet seesaw

$\Omega_{DM}h^2 \sim 0.12$

$\Omega_B h^2 \sim 0.0224$

$\Omega_{DM}h^2/\Omega_B h^2 \sim 5$

$$\mathscr{L} = \sqrt{2}\, y_{\Sigma}\bar{L}\tilde{H}\Sigma + y_{\chi}Tr[\bar{\Sigma}\ \Delta\ \chi] + -\lambda_{DM}\phi\bar{\chi}\chi - V(H,\Delta,\phi)$$

Z_2 Even

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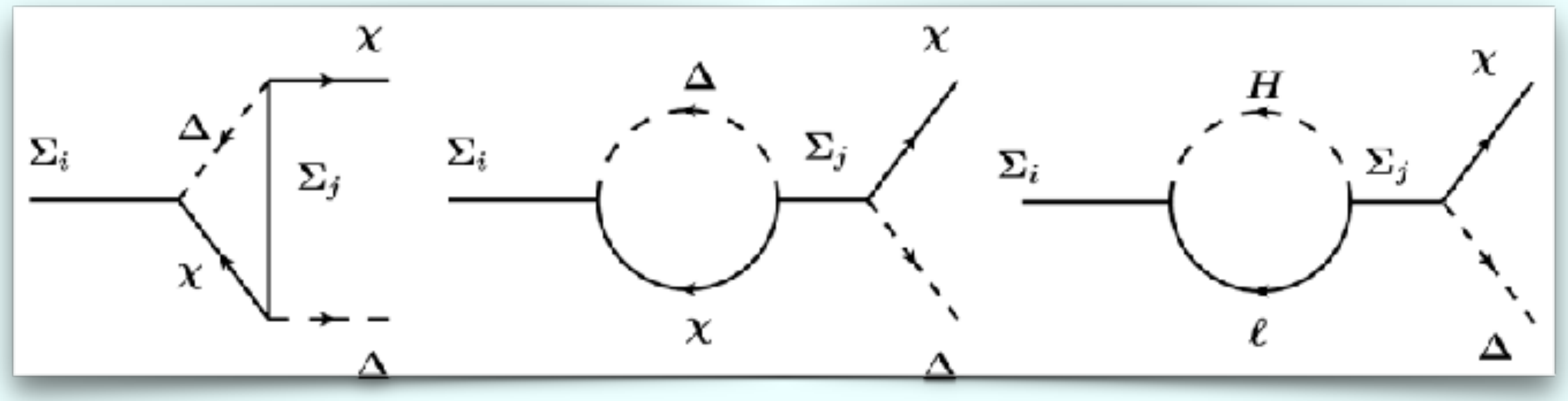
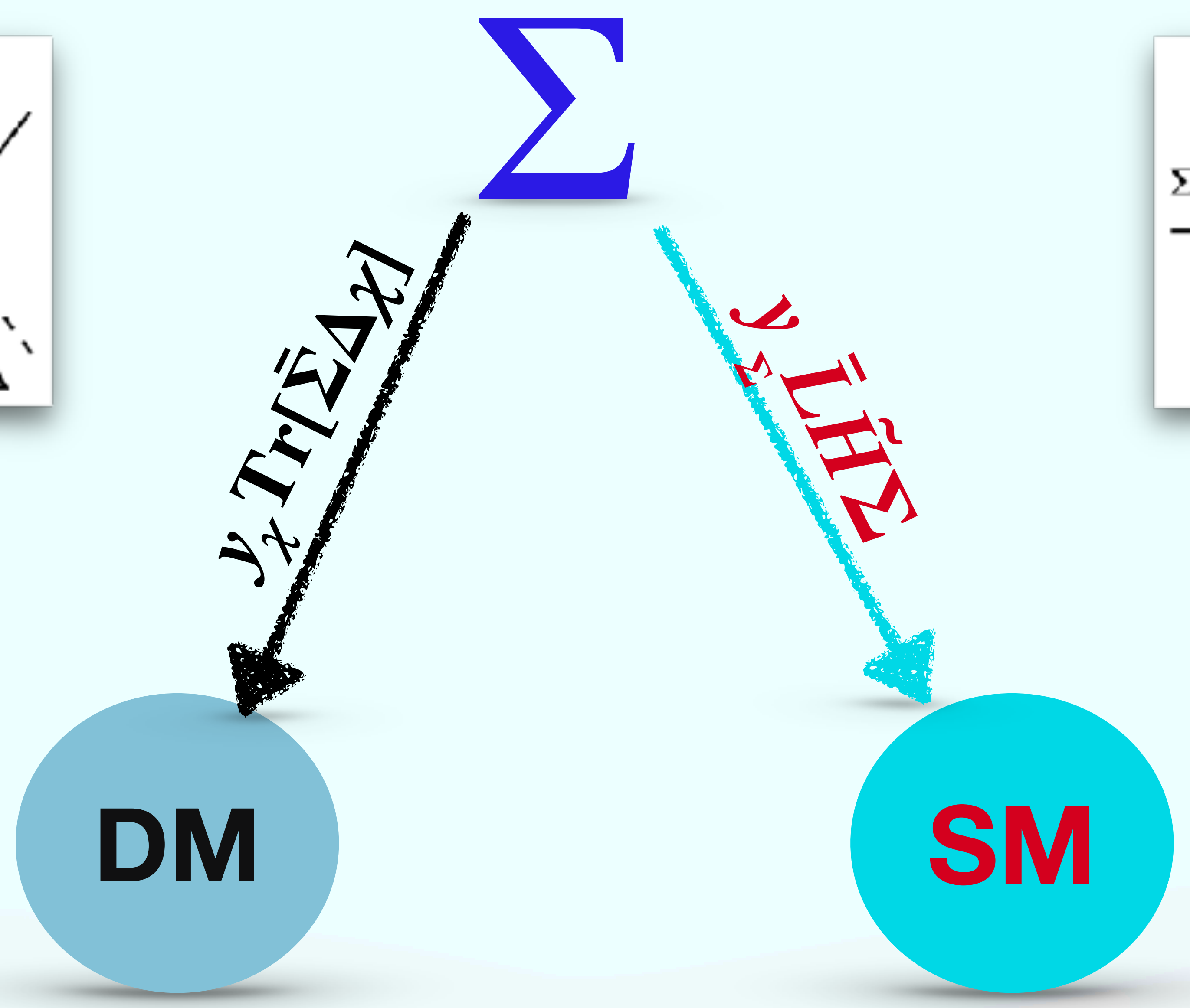
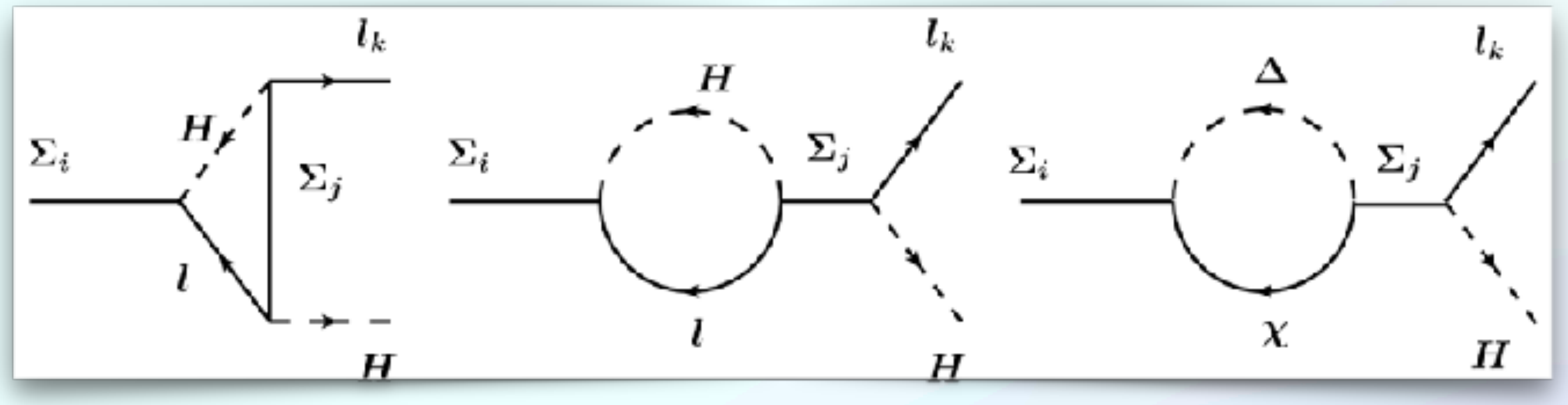
Dark-o-Leptogenesis







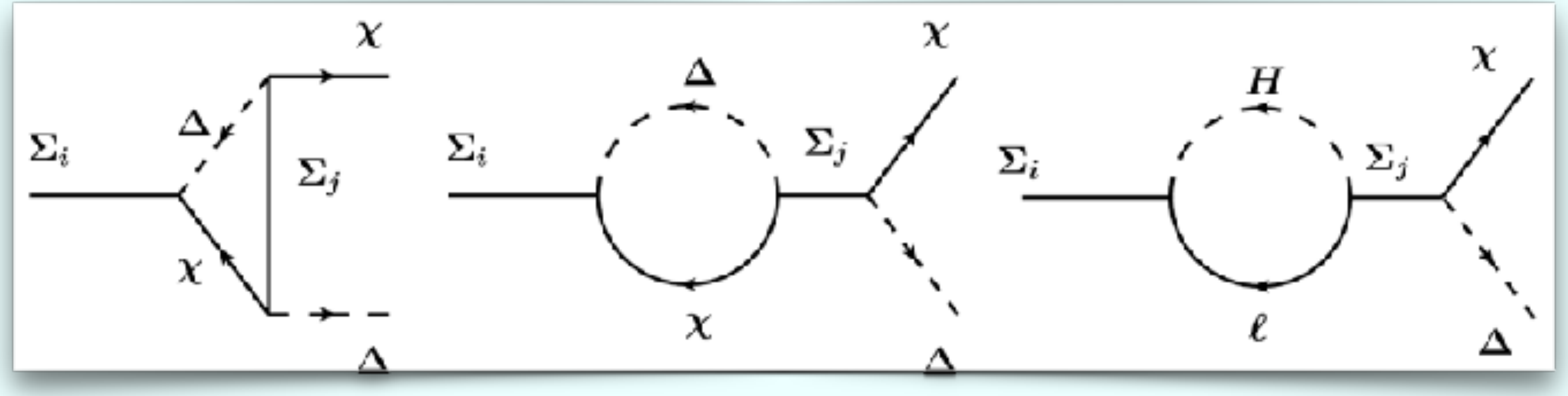
$$R \equiv \frac{\Omega_{\chi}h^2}{\Omega_B h^2} = \frac{f}{3C}\frac{M_{\chi}}{M_p}\frac{\epsilon_{\chi}}{\epsilon_L}\frac{\eta_{\chi}}{\eta_L} = \frac{f}{3S}\frac{M_{\chi}}{M_p}\frac{Y_{\Delta\chi}}{Y_{\Delta L}}$$

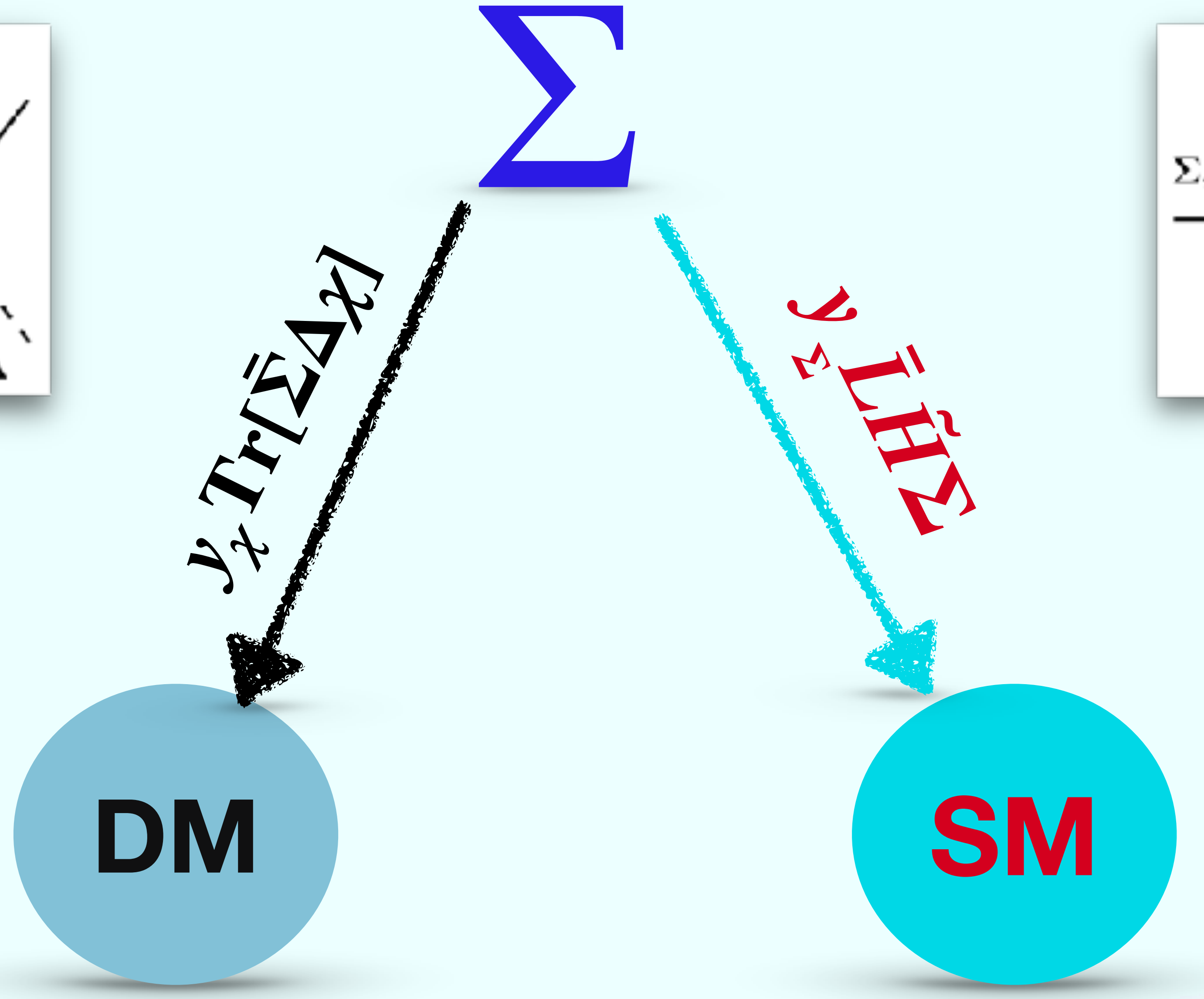
Cogenesis from fermion triplet seesaw

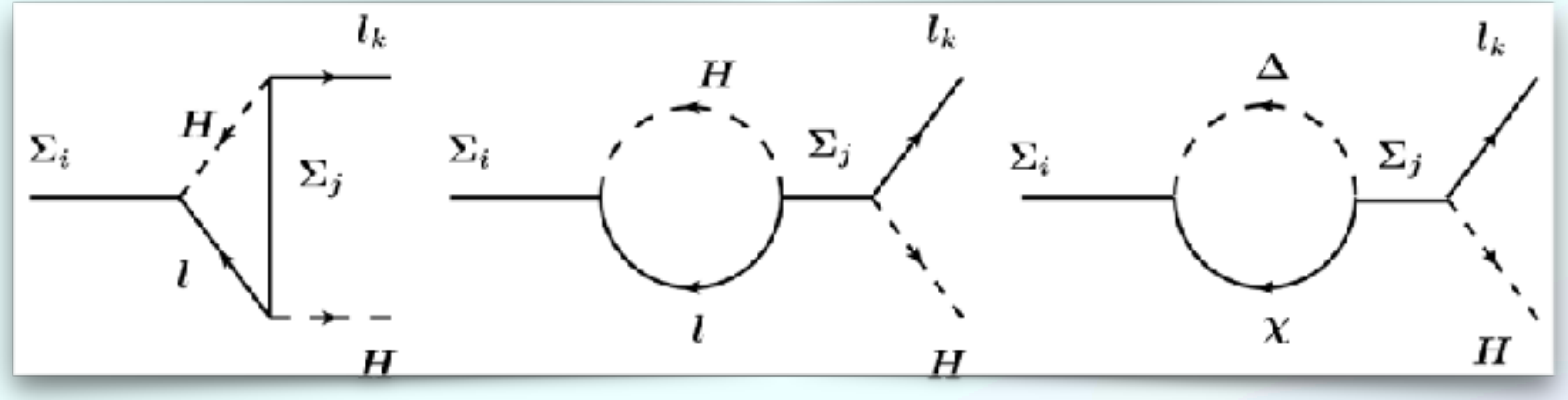
$$\mathscr{L} = \sqrt{2}\, y_{\Sigma} \bar{L}\tilde{H}\Sigma + y_{\chi} Tr[\bar{\Sigma}\ \Delta\ \chi] + -\lambda_{DM}\phi\bar{\chi}\chi - V(H,\Delta,\phi)$$

Gauge Interactions ⟷ **Thermal Initial Abundance**

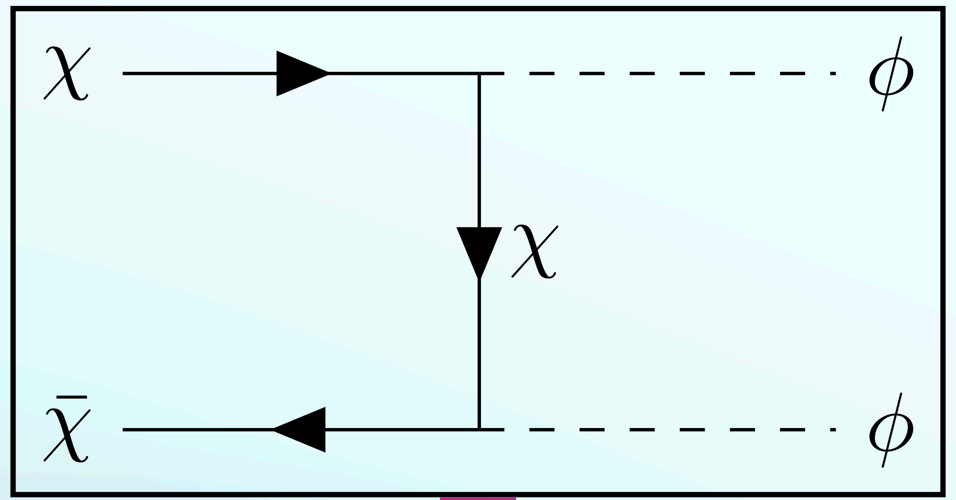
Dark-o-Leptogenesis





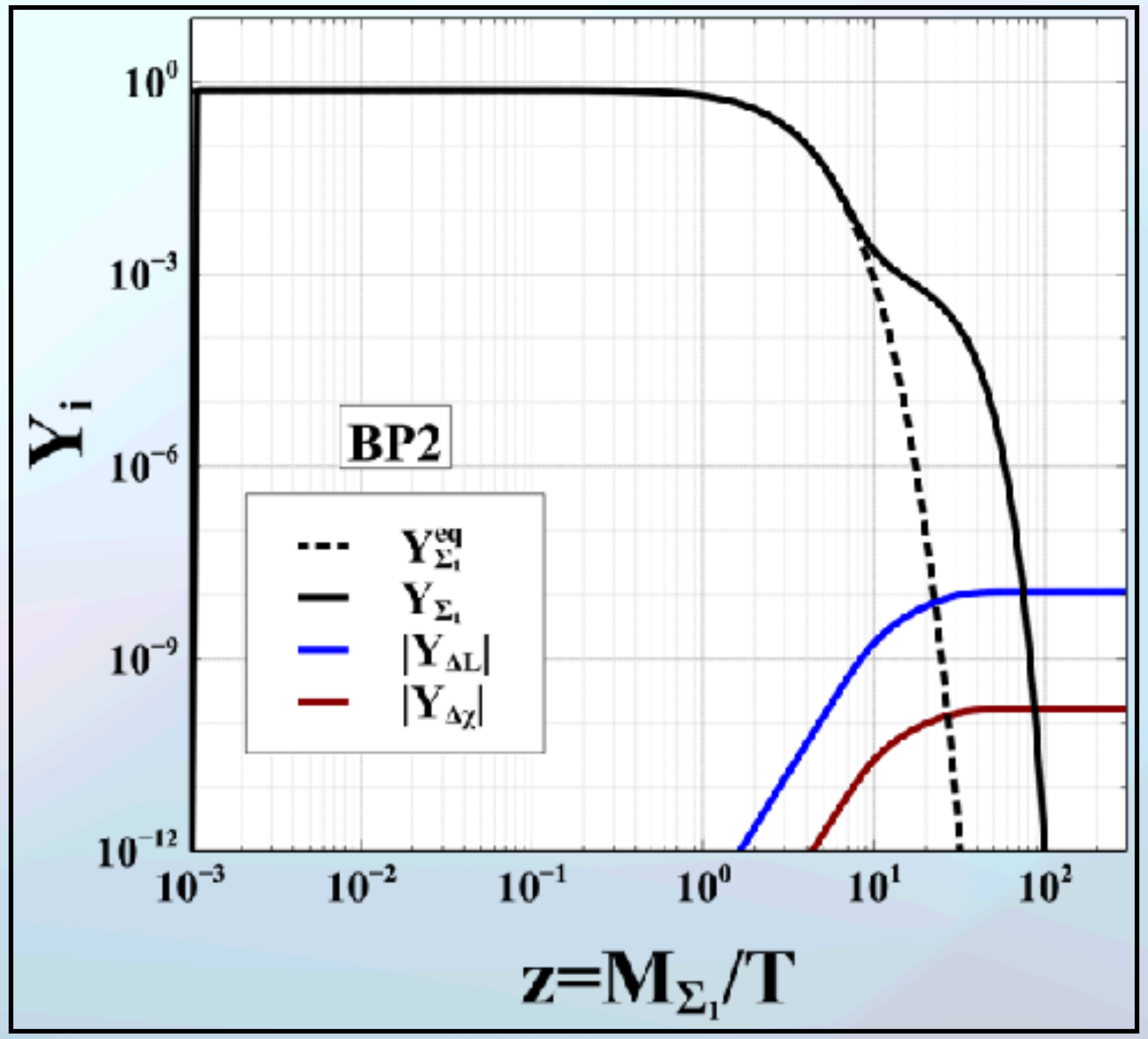


Depletion of symmetric component



$$R \equiv \frac{\Omega_\chi h^2}{\Omega_B h^2} = \frac{f}{3C}\frac{M_\chi}{M_p}\frac{\epsilon_\chi}{\epsilon_L}\frac{\eta_\chi}{\eta_L} = \frac{f}{3S}\frac{M_\chi}{M_p}\frac{Y_{\Delta\chi}}{Y_{\Delta L}}$$

$f = 30.56\ \&\ C = -0.52$



✓ **Motivates Asymmetric SIDM**

PHYSICAL REVIEW D 110, 035033 (2024)

✓ **Scale of Leptogenesis can be lowered**

Scale of Leptogenesis can be lowered

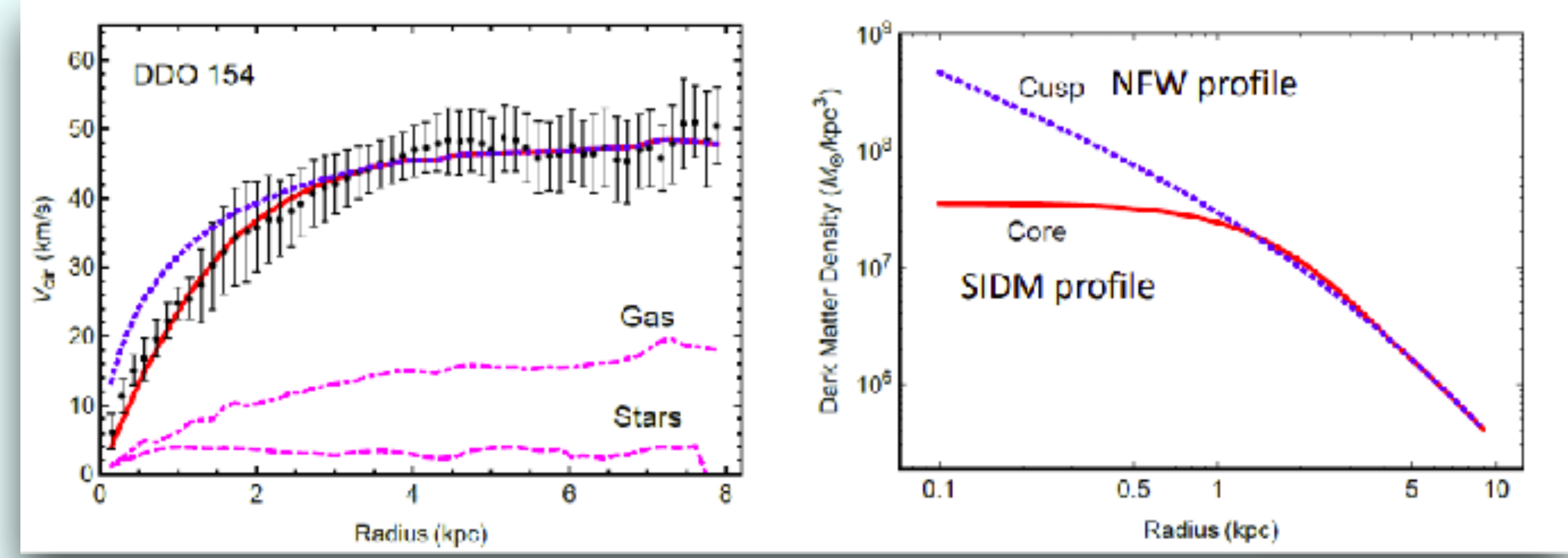
$$\begin{aligned}
\epsilon_L &= \frac{\Gamma(\Sigma_1 \to LH) - \Gamma(\Sigma_1 \to \overline{L}H^\dagger)}{\Gamma_{\Sigma_1}} \\
&= -\frac{1}{16\pi} \frac{M_1}{((y^\dagger y)_{11} + y_{\chi_1} y^*_{\chi_1})} \sum_j \frac{1}{M_j} \{\mathrm{Im}[(y^\dagger y)^2_{1j}] + 2\mathrm{Im}[(y^\dagger y)_{1j} y_{\chi_1} y^*_{\chi_j}]\} \\
\epsilon_\chi &= \frac{\Gamma(\Sigma_1 \to \chi\Delta) - \Gamma(\Sigma_1 \to \overline{\chi}\Delta^\dagger)}{\Gamma_{\Sigma_1}} \\
&= -\frac{1}{16\pi} \frac{M_1}{((y^\dagger y)_{11} + y_{\chi_1} y^*_{\chi_1})} \sum_j \frac{1}{M_j} \{\mathrm{Im}[(y_{\chi_1} y^*_{\chi_j})^2] + 2\mathrm{Im}[(y^\dagger y)_{1j} y_{\chi_1} y^*_{\chi_j}]\}.
\end{aligned}$$

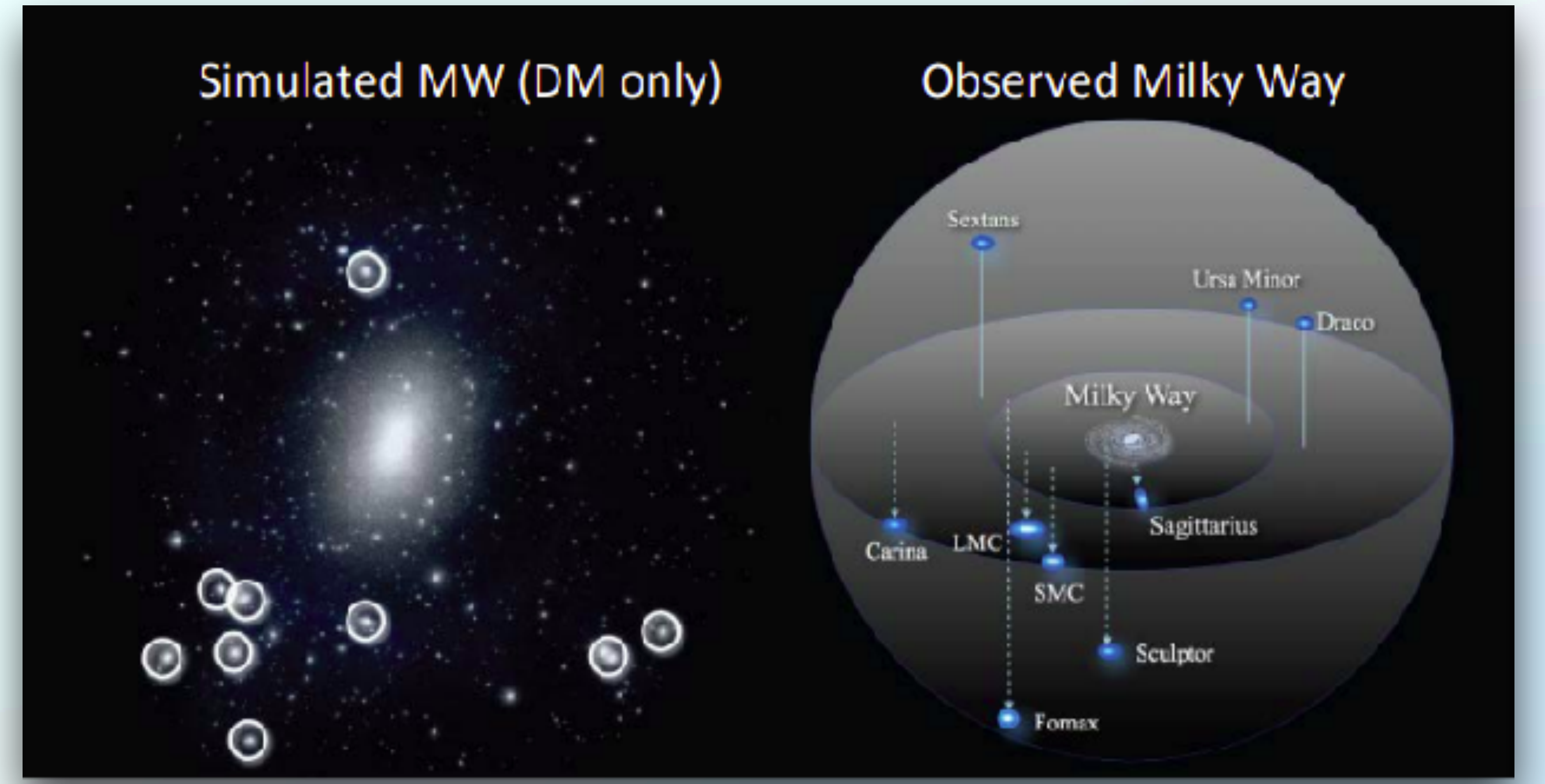
$$|\epsilon_L| \lesssim \frac{1}{8\pi} \frac{M_{\Sigma_1}(m_3 - m_1)}{v_0^2} \mathcal{C},$$

$$\mathcal{C} \simeq \begin{cases} 1 & , \quad Br_L \gg Br_\chi \\ \sqrt{\dfrac{y^2_{\chi_2} M_{\Sigma_1}}{y^2_{\chi_1} M_{\Sigma_2}}} & , \quad Br_L \ll Br_\chi \end{cases}$$

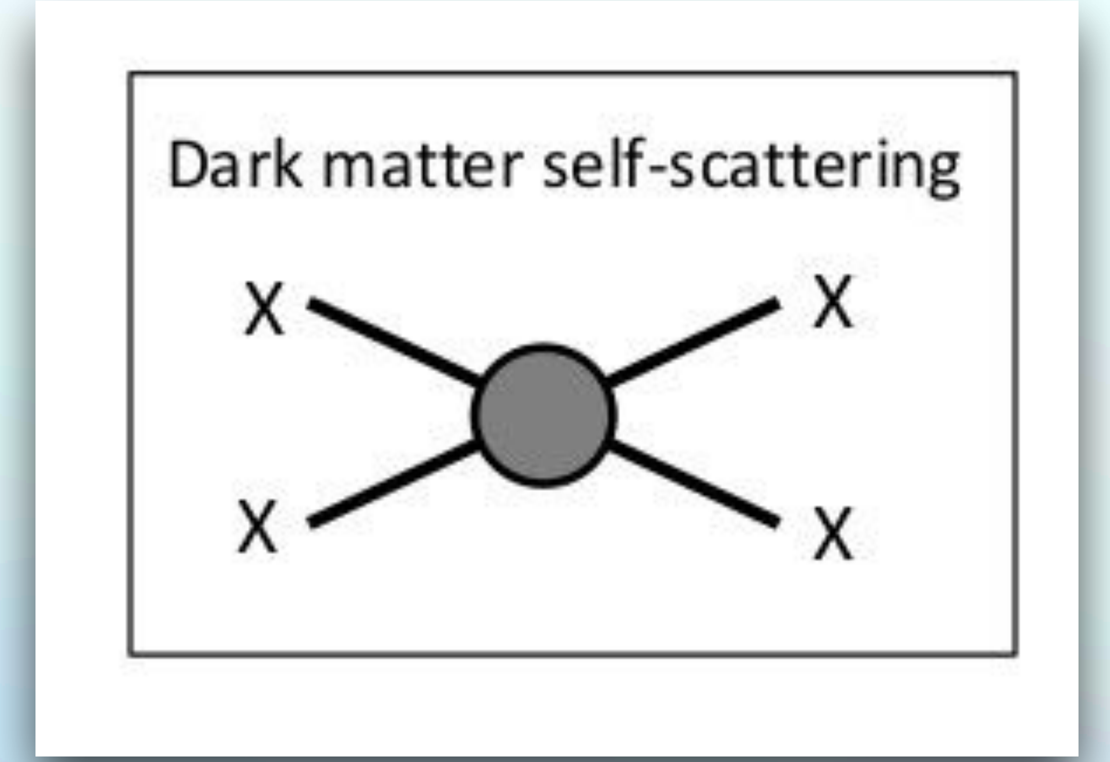
Small Scale Issues of CDM

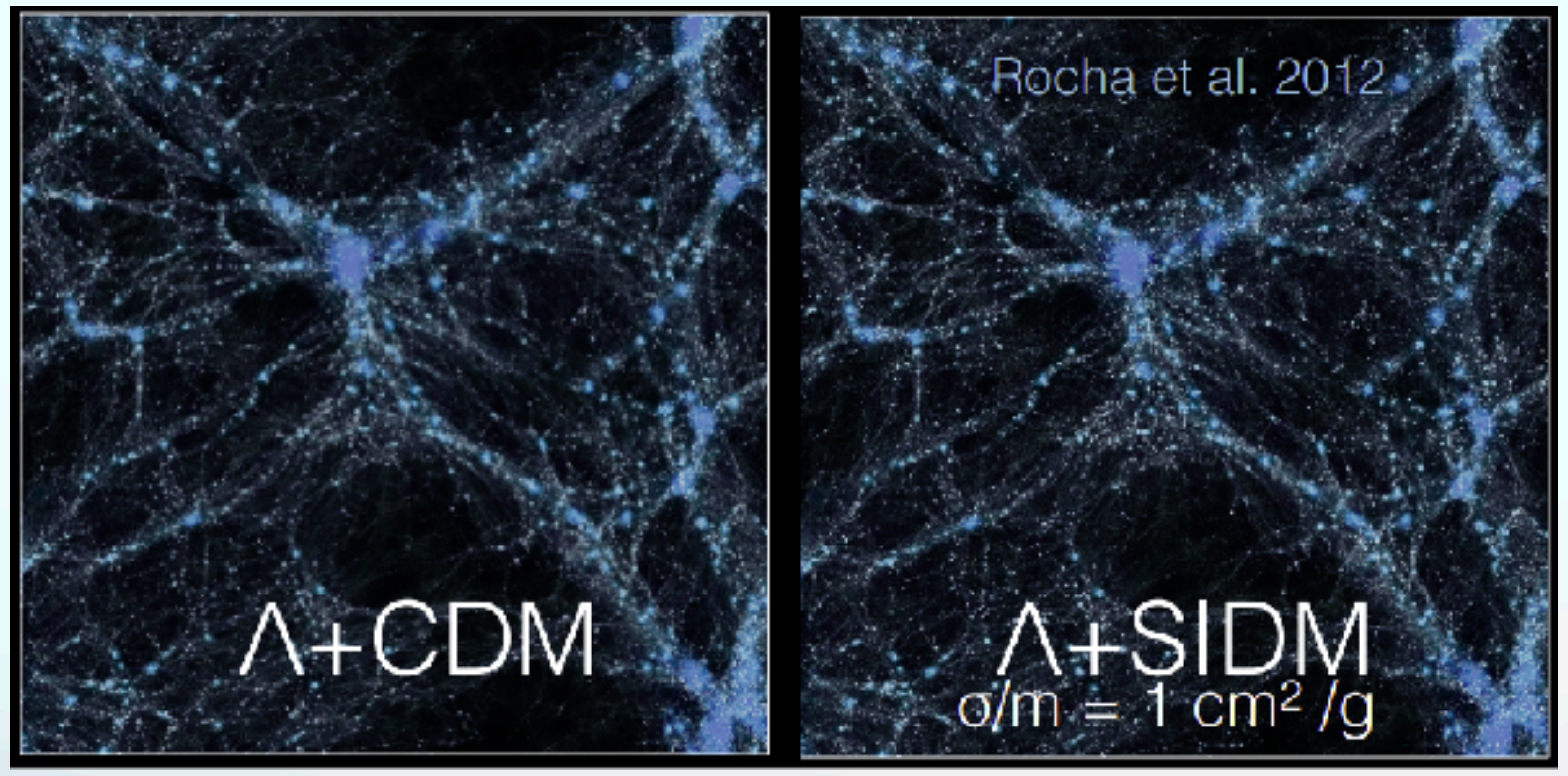
- ◉ **Cusp Core Problem**
- ◉ **Missing Satellite Problem**
- ◉ **Too Big to Fail Problem**





Solution : Self Interacting Dark Matter





Velocity dependent self interaction of DM is needed.

Small Scale Issues of CDM

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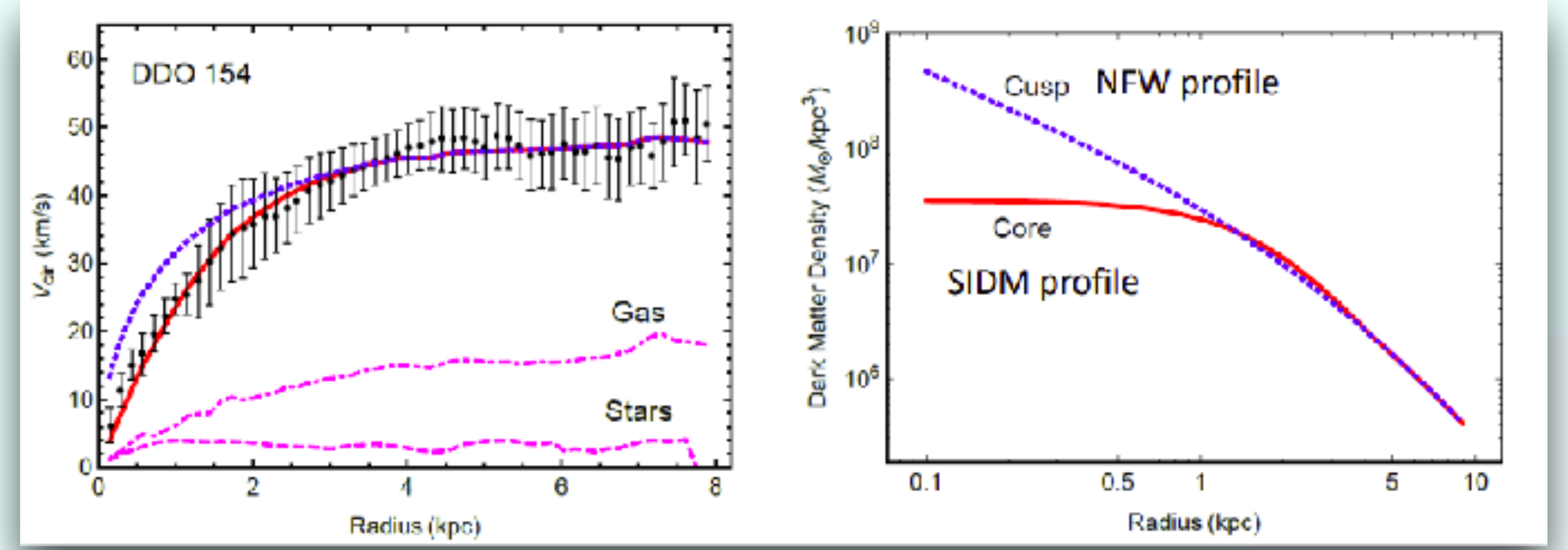
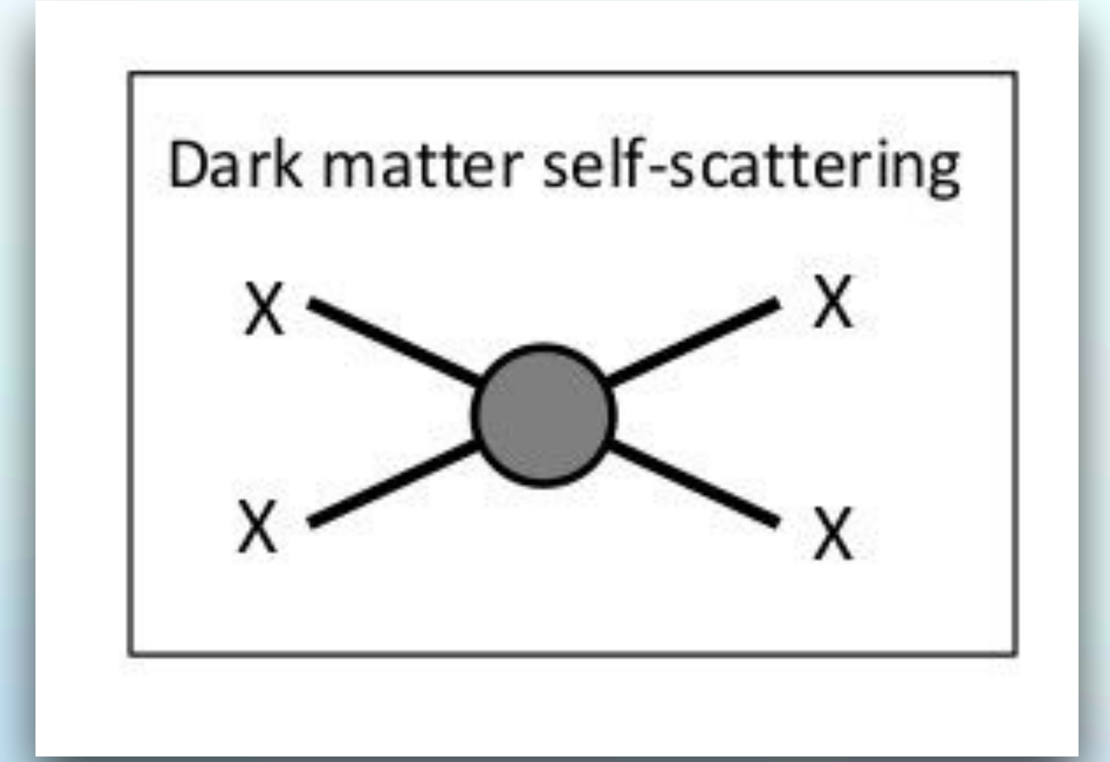
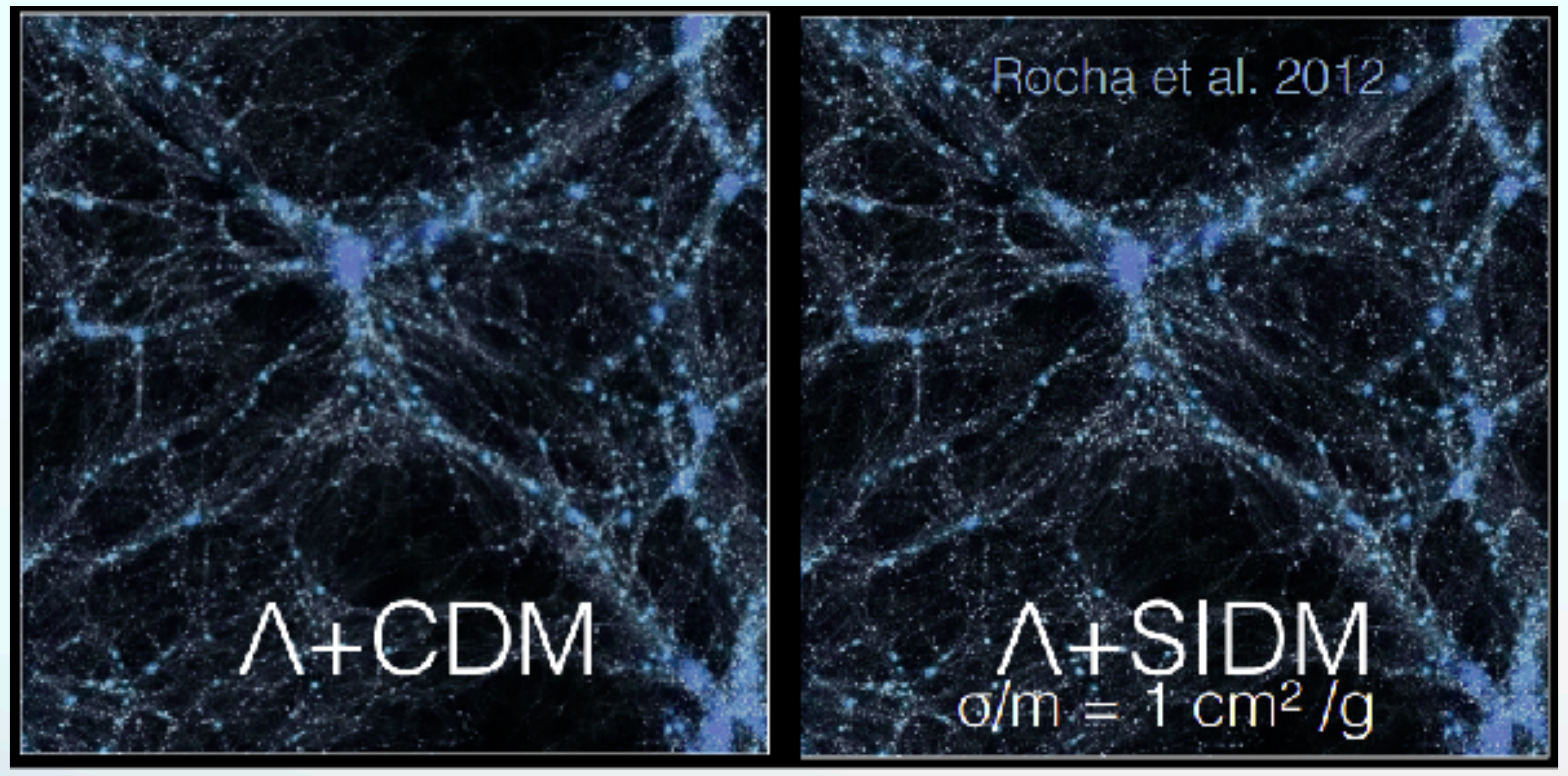
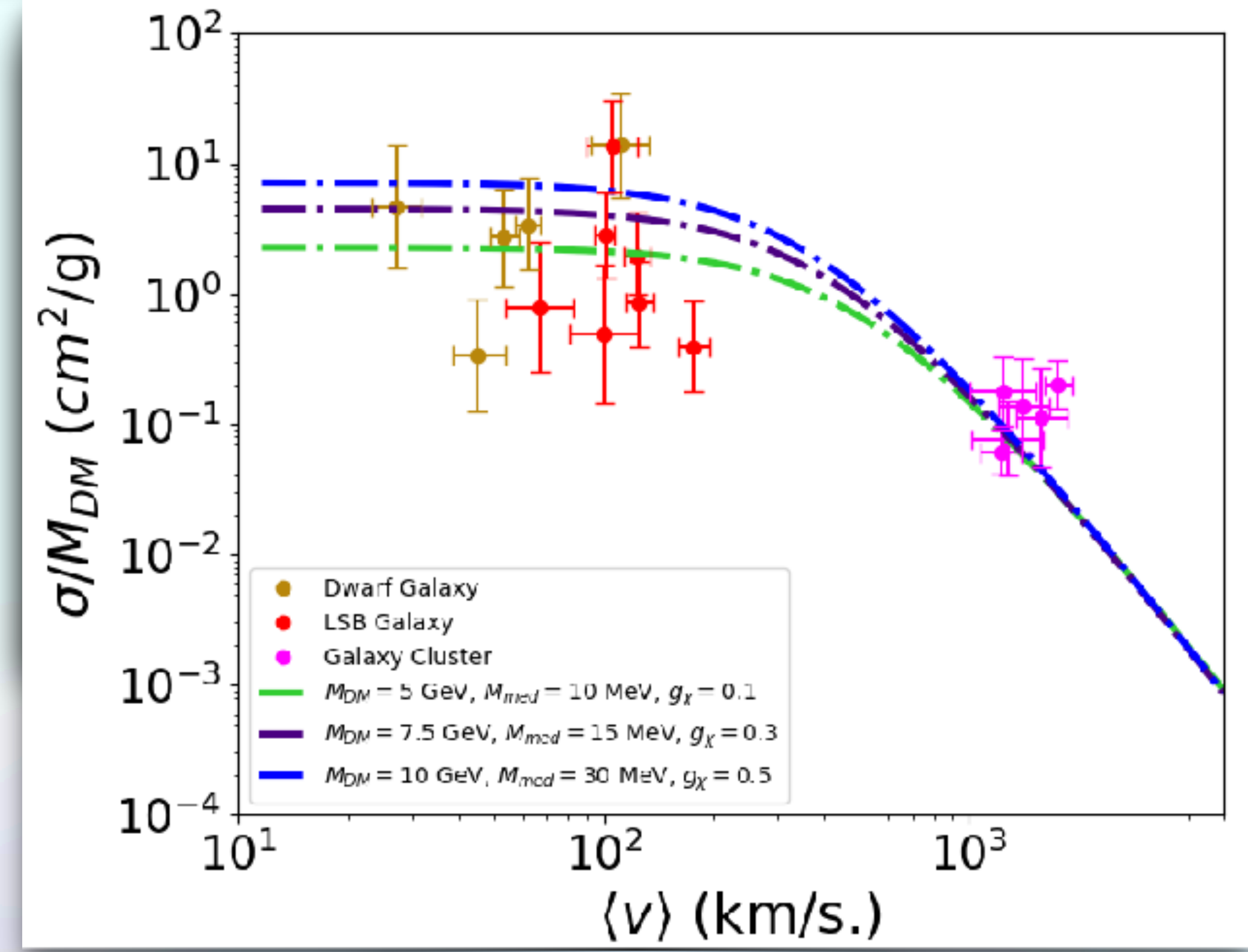


Solution : Self Interacting Dark Matter





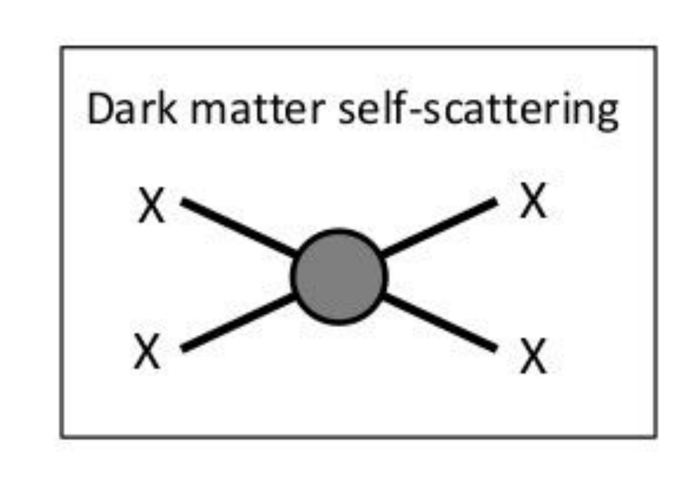


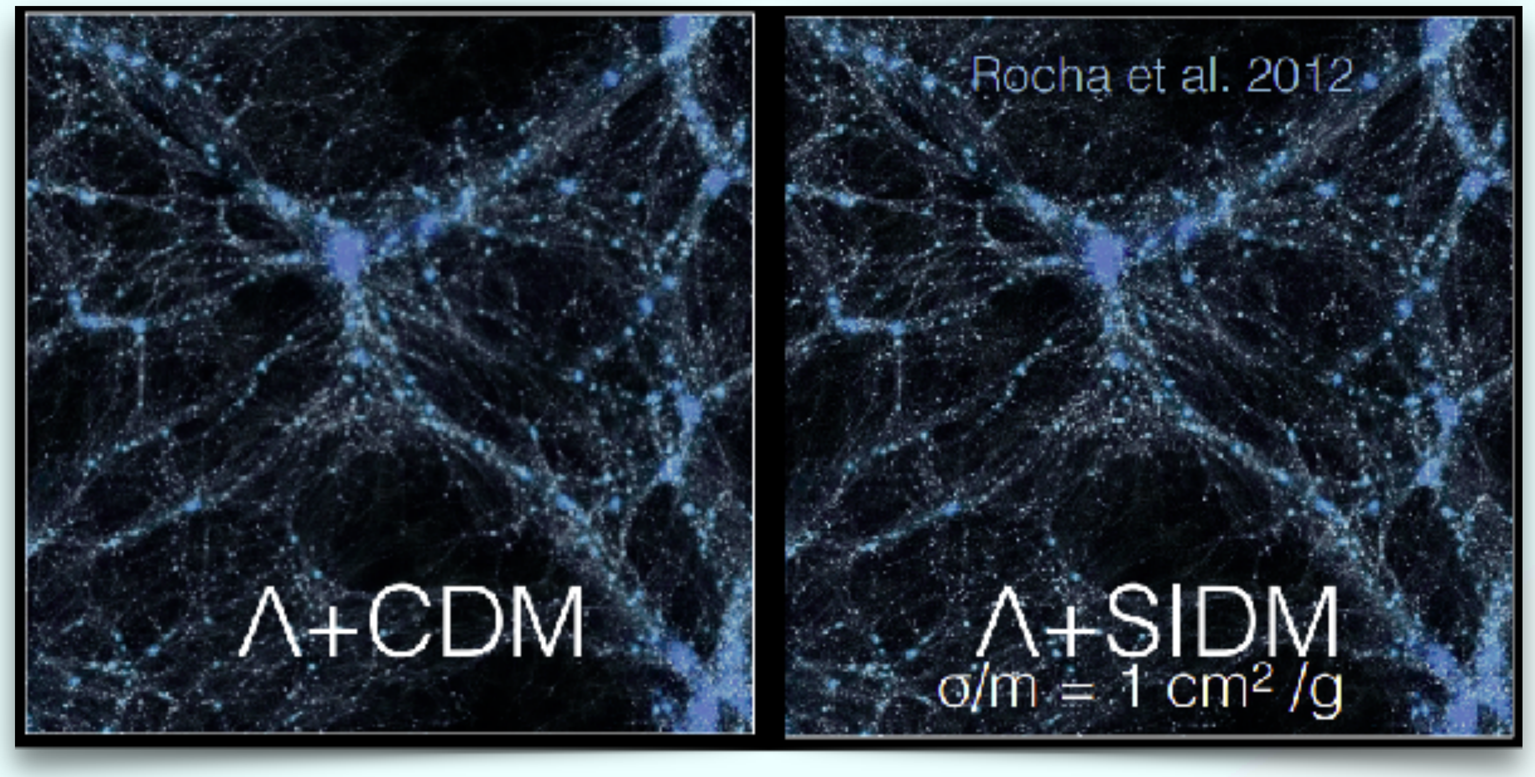
Velocity dependent self interaction of DM is needed.

Self-interacting Dark Matter

Motivation: To solve small scale issues

(Cusp-core, Missing satellite, TBTF)





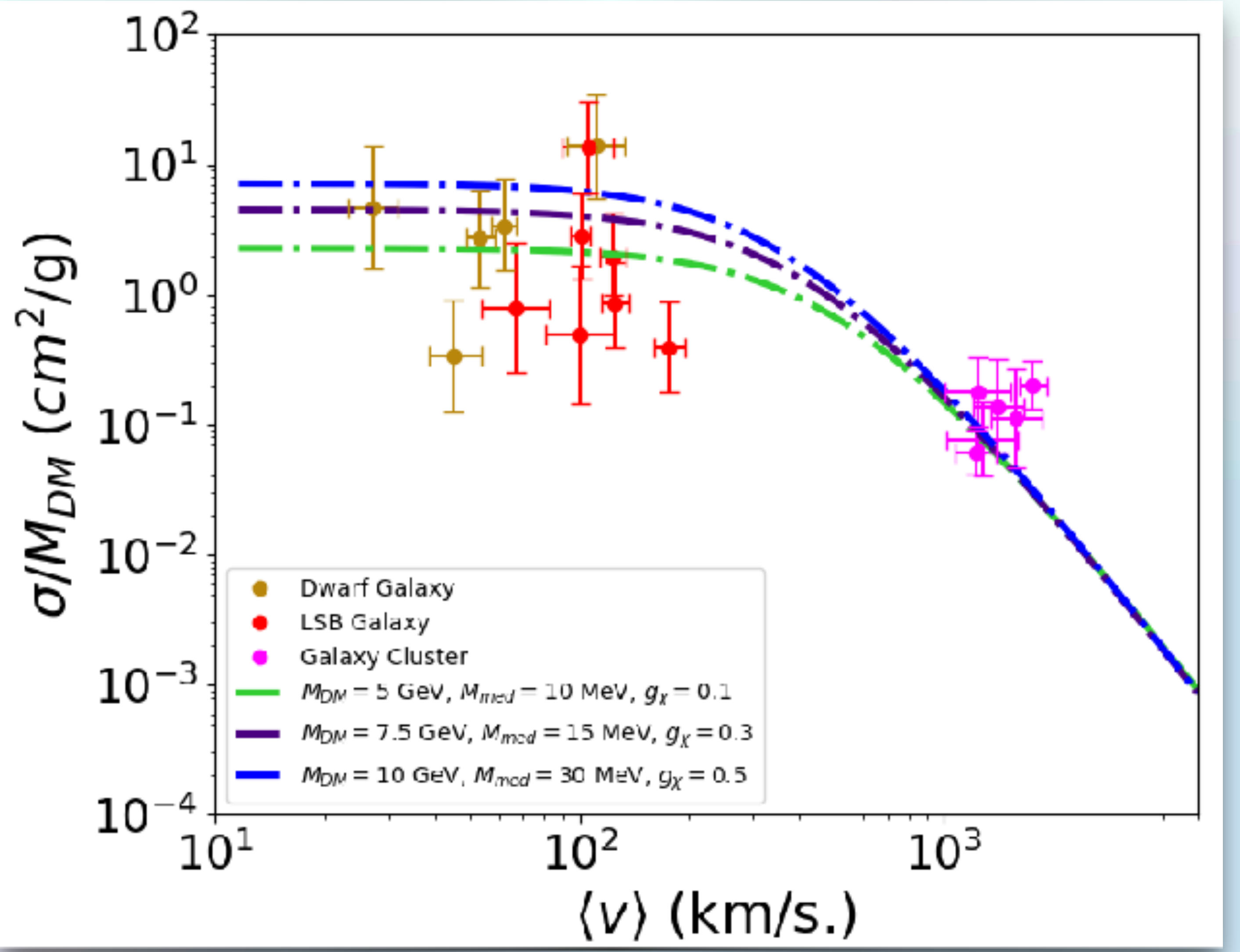
What value of scattering cross-section is needed?

Collision rate:

$$R_{\rm Scatt.} = \frac{\sigma v_{rel}\,\rho_{DM}}{m} = 0.1\ {\rm Gyr}^{-1}\left(\frac{\rho_{DM}}{0.1M_\odot/pc^3}\right)\left(\frac{v_{rel.}}{50{\rm km/s}}\right)\left(\frac{\sigma/m}{1{\rm cm}^2/{\rm g}}\right)$$

Thus

$$\frac{\sigma}{m_{\rm DM}} \sim 1{\rm cm}^2/g \sim 2\ {\rm barns/GeV}$$



$$\mathcal{L}_{\rm int} = \begin{cases} g_\chi \bar{\chi}\gamma^\mu\chi\phi_\mu & \text{(vector mediator)} \\ g_\chi\bar{\chi}\chi\phi & \text{(scalar mediator)} \end{cases}$$

$$V(r) = \pm\frac{\alpha_\chi}{r}e^{-m_\phi r}$$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha_\chi^2 m_\chi^2}{\left[m_\chi^2 v_{\rm rel}^2(1-\cos\theta)/2 + m_\phi^2\right]^2}.$$

A small but finite mediator mass can provide required velocity dependence

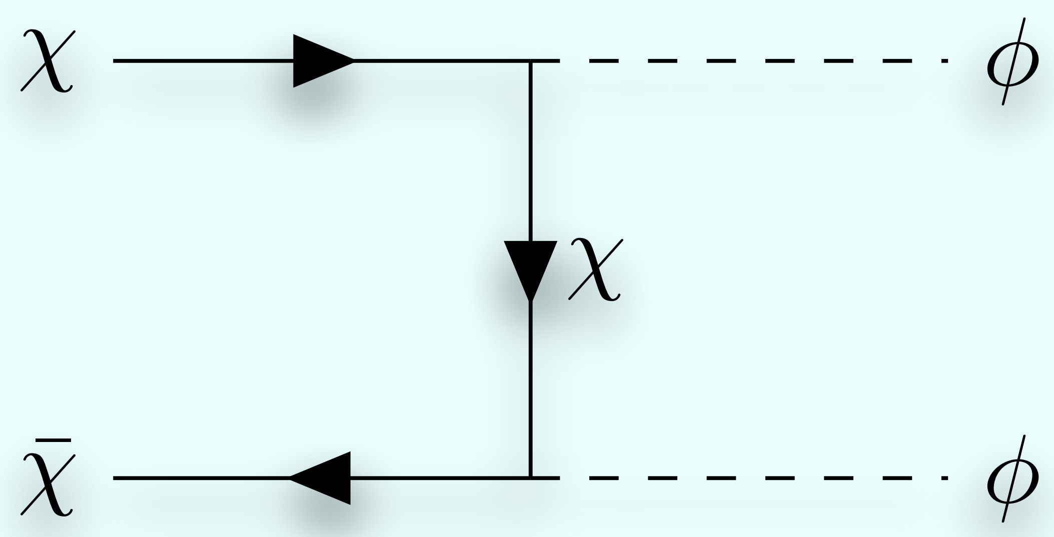
Asymmetric SIDM with Canonical Seesaw

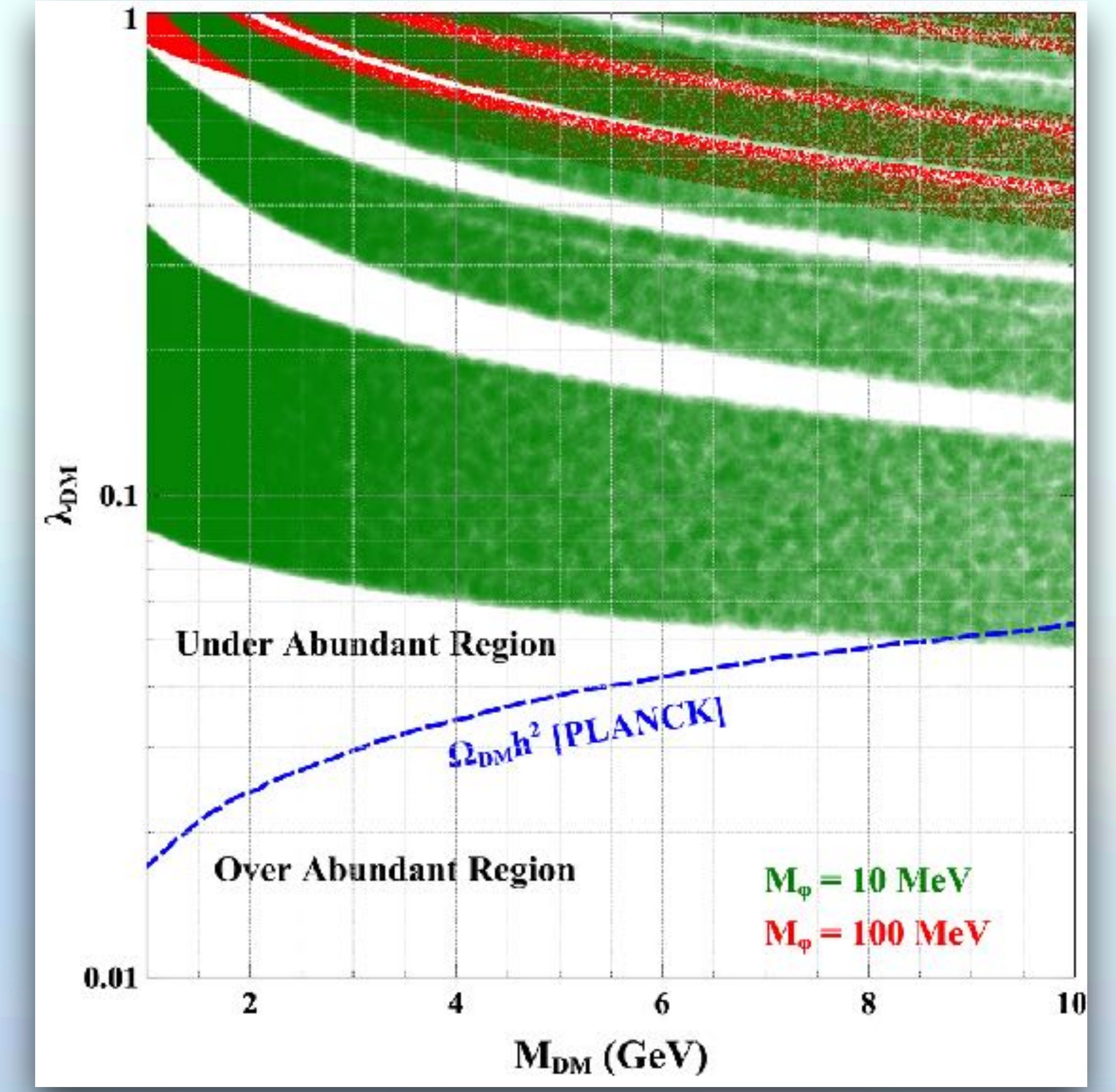
$M_{\mathrm{DM}} < \mathcal{O}(10)$ GeV+

Light Mediator +

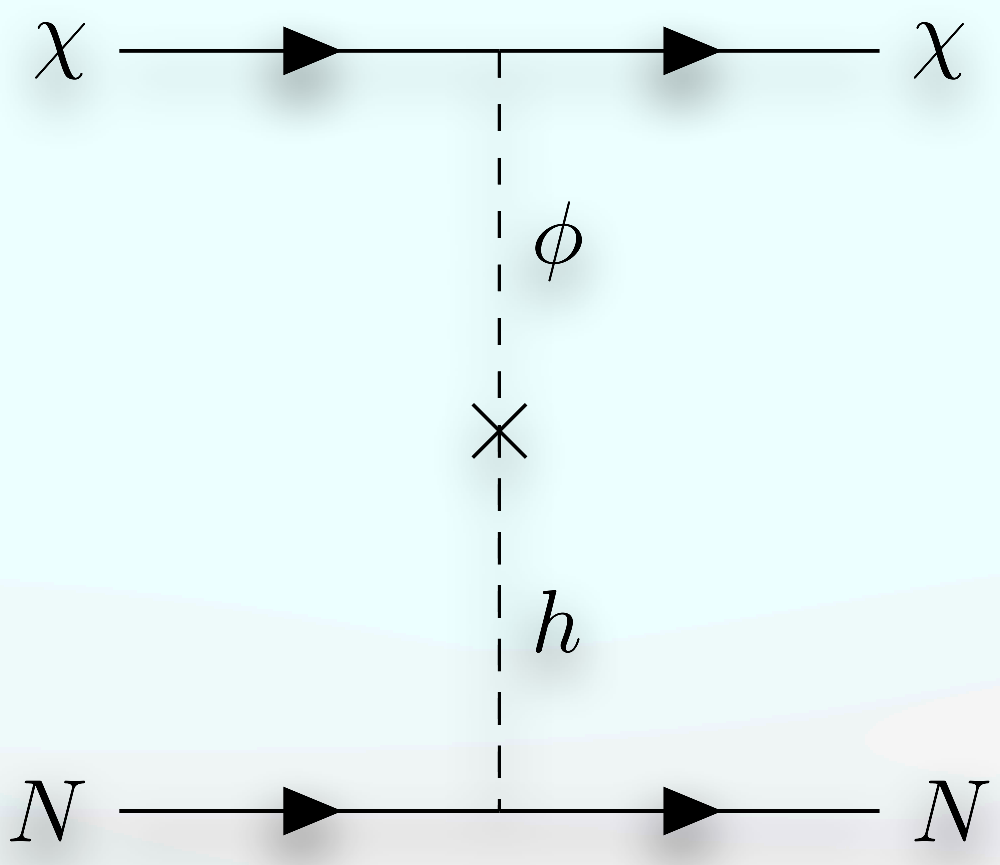
Sizable Coupling

Under-abundant relic

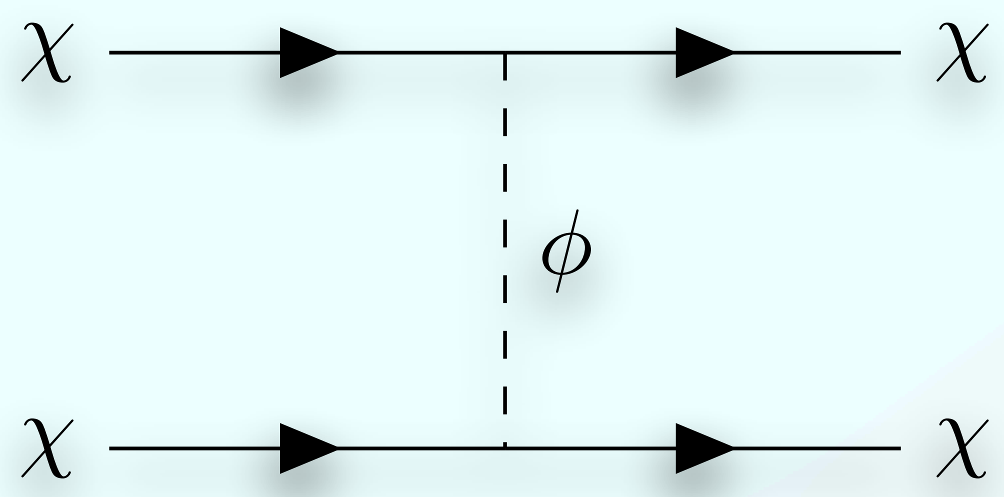


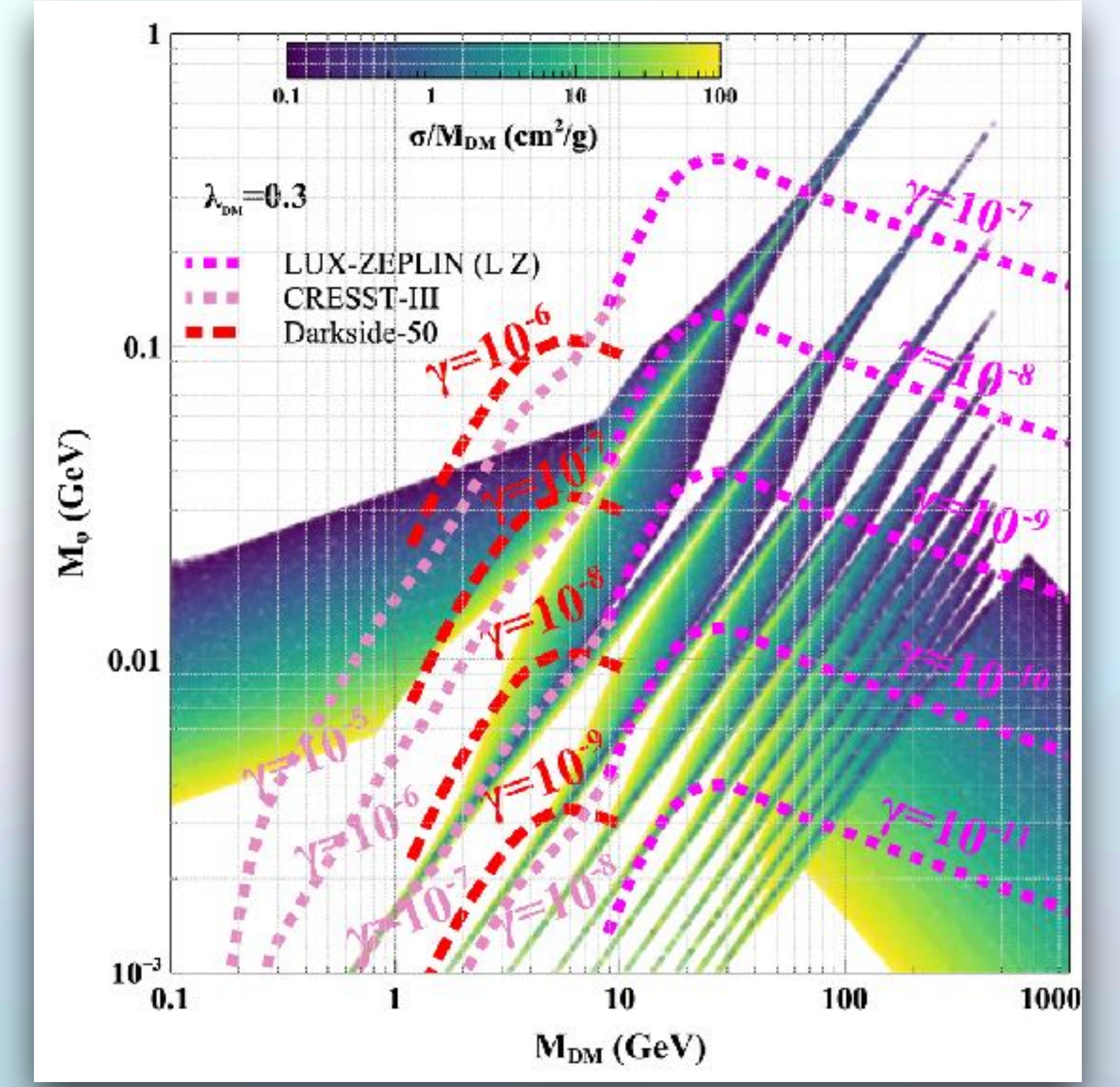


Observable DD



Self Interaction





Cogenesis from fermion triplet seesaw

Boltzmann Equations

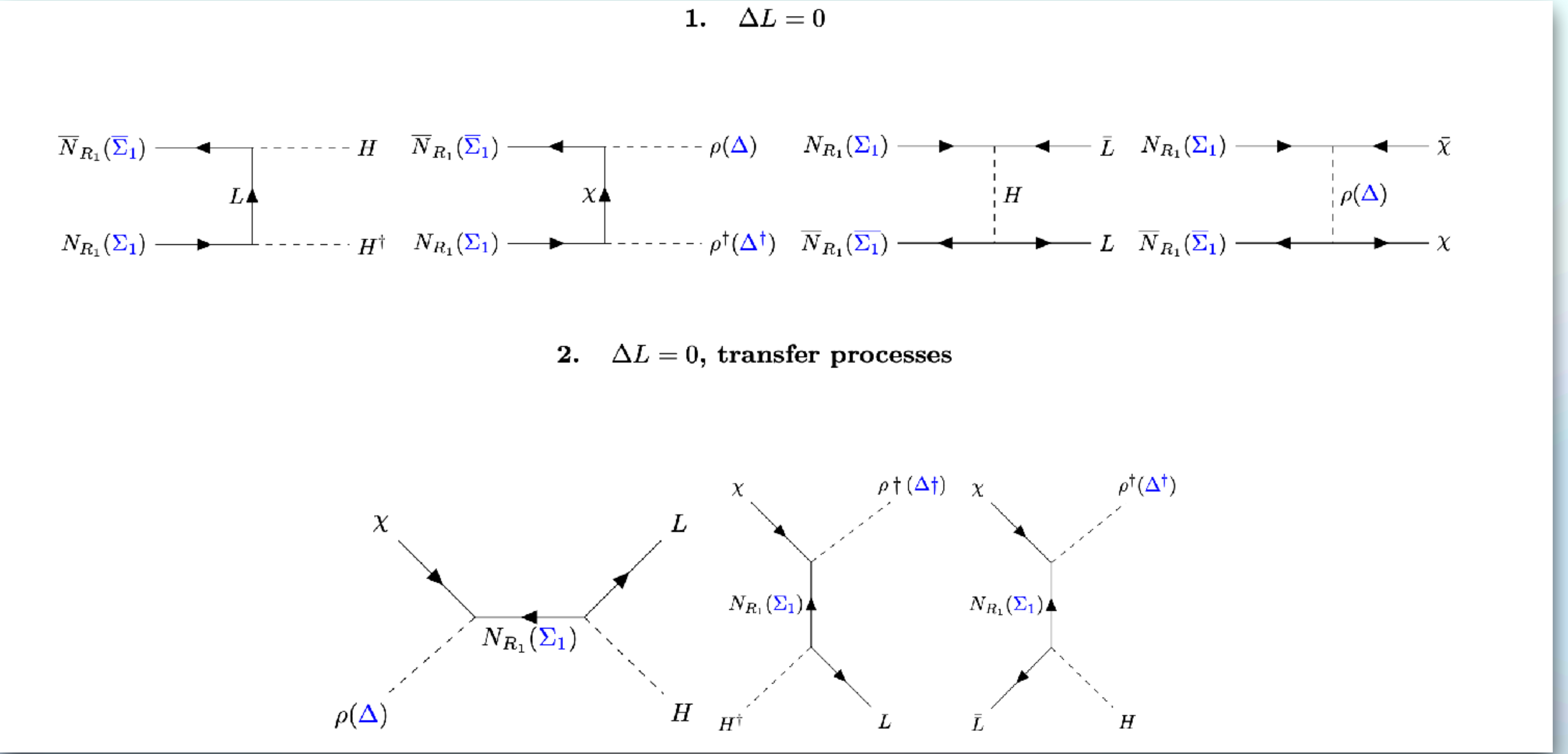
$$\frac{dY_{\Sigma_1}}{dz} = -\frac{\Gamma_D}{\mathrm{H}z}(Y_{\Sigma_1} - Y^{eq}_{\Sigma_1}) - \frac{\Gamma_1}{\mathrm{H}z}(Y_{\Sigma_1} - Y^{eq}_{\Sigma_1}) - \frac{(\Gamma_0 + \Gamma_A)}{\mathrm{H}z}\frac{\left(Y^2_{\Sigma_1} - (Y^{eq}_{\Sigma_1})^2\right)}{Y^{eq}_{\Sigma_1}} \quad \text{..........(1)}$$

$$\frac{dY_{\Delta L}}{dz} = \epsilon_L \frac{\Gamma_D}{\mathrm{H}z}(Y_{\Sigma_1} - Y^{eq}_{\Sigma_1}) - \left(\frac{1}{2}\frac{\Gamma_D}{\mathrm{H}z}\frac{Y^{eq}_{\Sigma_1}}{Y^{eq}_l} Br_l + \frac{(\Gamma^W_{1L} + \Gamma^W_{2L} + \Gamma_{2W})}{\mathrm{H}z}\right) Y_{\Delta L}$$
$$-\frac{\Gamma_{\Sigma_1}}{\mathrm{H}_1} Br_l Br_\chi \left(I_{T_+}(z)(Y_{\Delta L} + Y_{\Delta\chi}) + I_{T\_}(z)(Y_{\Delta L} - Y_{\Delta\chi})\right) \quad \text{..........(2)}$$

$$\frac{dY_{\Delta\chi}}{dz} = \epsilon_\chi \frac{\Gamma_D}{\mathrm{H}z}(Y_{\Sigma_1} - Y^{eq}_{\Sigma_1}) - \left(\frac{1}{2}\frac{\Gamma_D}{\mathrm{H}z}\frac{Y^{eq}_{\Sigma_1}}{Y^{eq}_\chi} Br_\chi + \frac{\Gamma^W_{1\chi} + \Gamma^W_{2\chi} + \Gamma_{2W}}{\mathrm{H}z}\right) Y_{\Delta\chi}$$
$$-\frac{\Gamma_{\Sigma_1}}{\mathrm{H}_1} Br_l Br_\chi \left(I_{T_+}(z)(Y_{\Delta\chi} + Y_{\Delta L}) + I_{T\_}(z)(Y_{\Delta\chi} - Y_{\Delta L})\right) \quad \text{..........(3)}$$

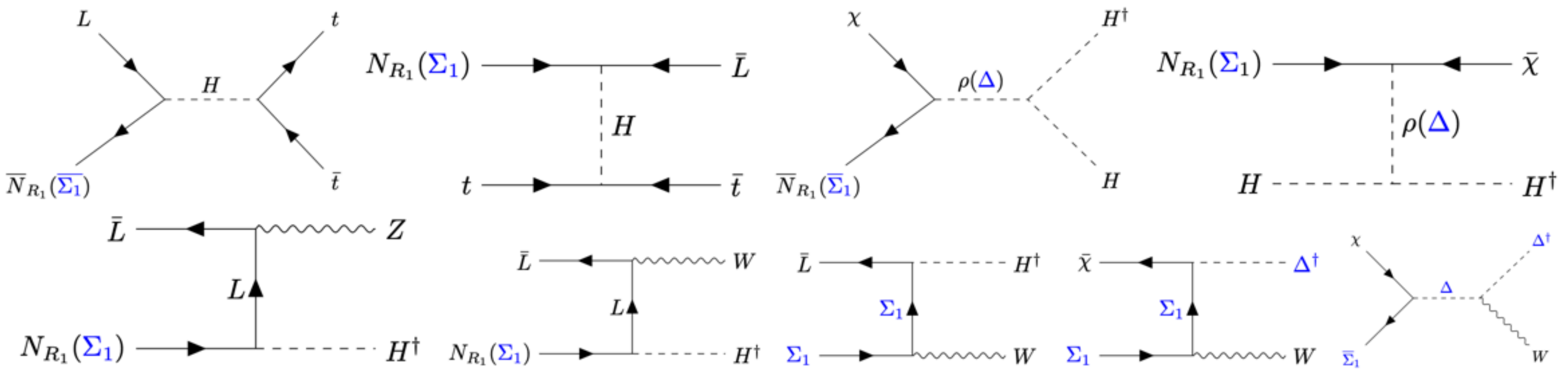
$z = M_{\Sigma_1}/T \qquad Y_x = n_x/n_\gamma$

Relevant Processes

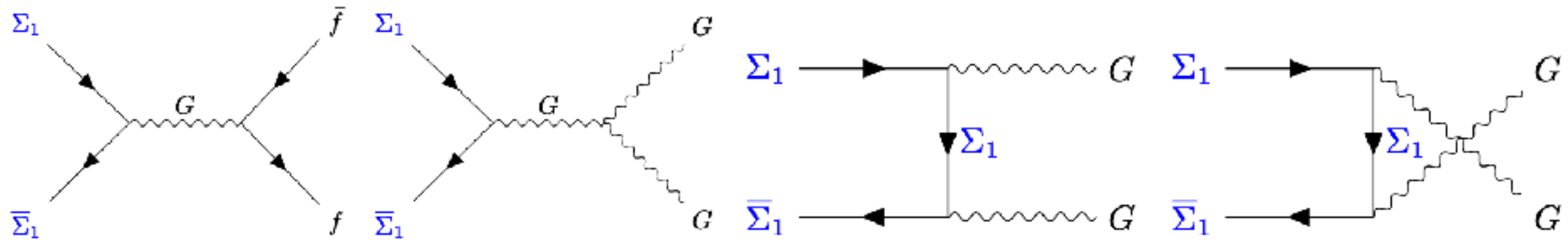


Relevant Processes

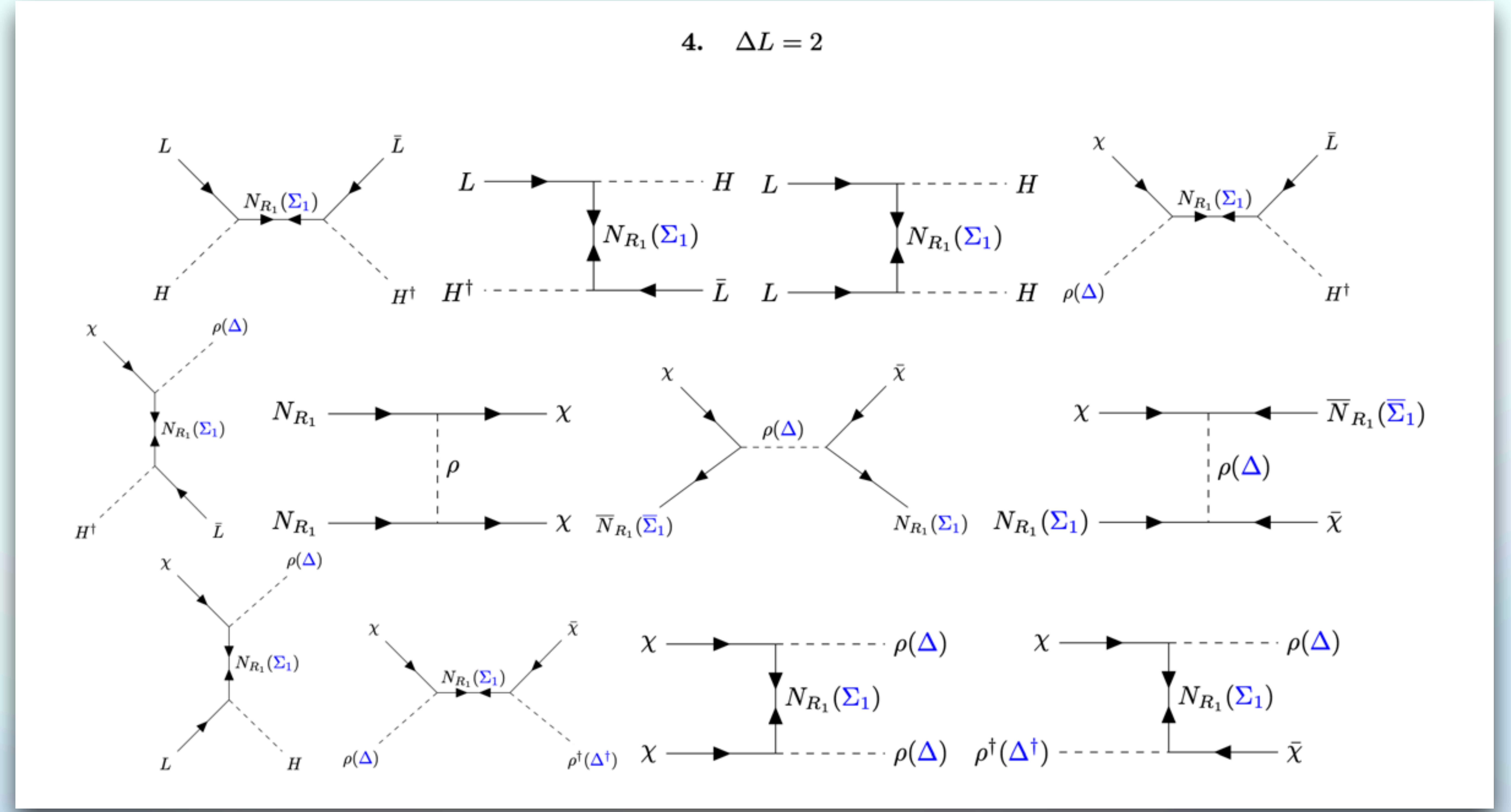
3. $\Delta L = 1$



5. Gauge processes

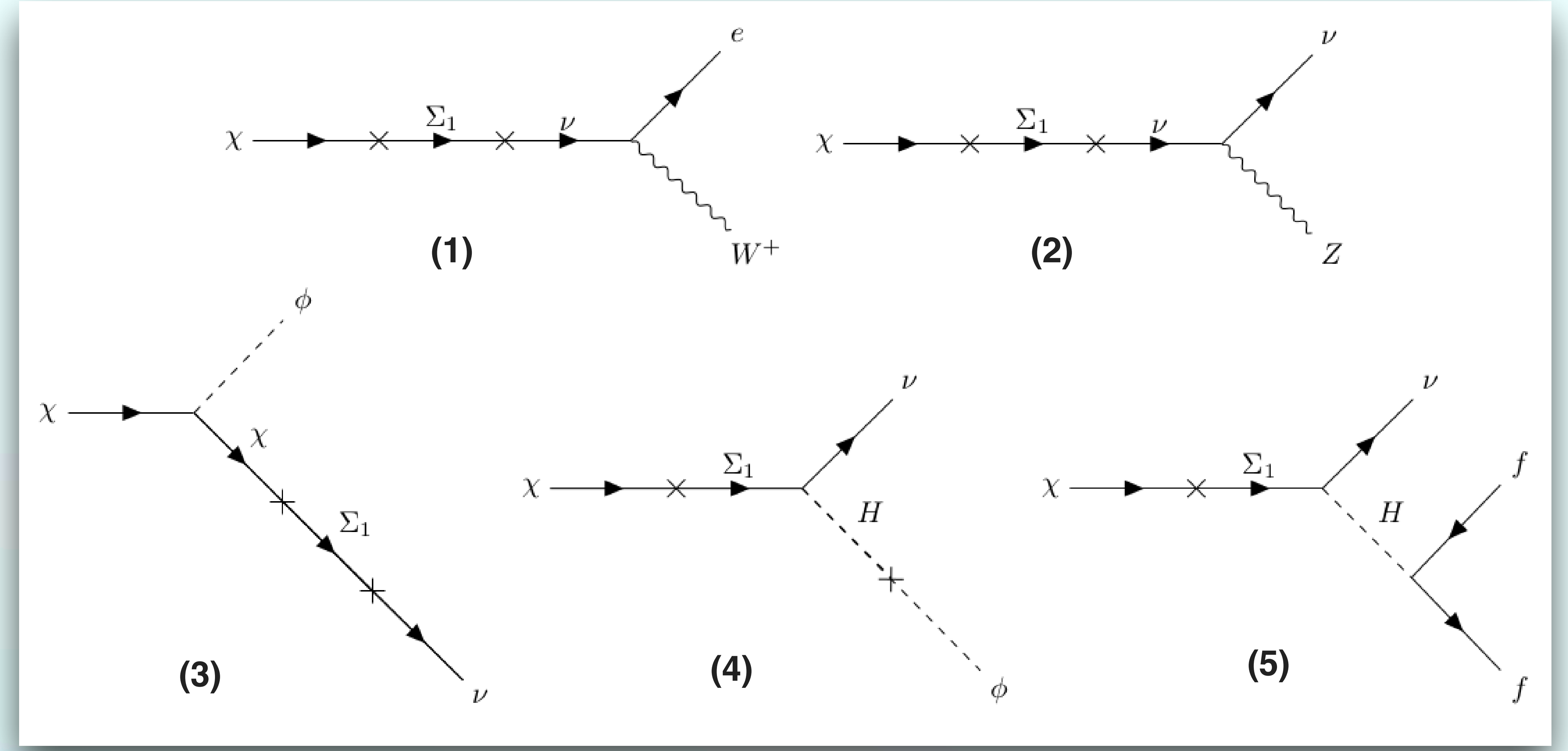


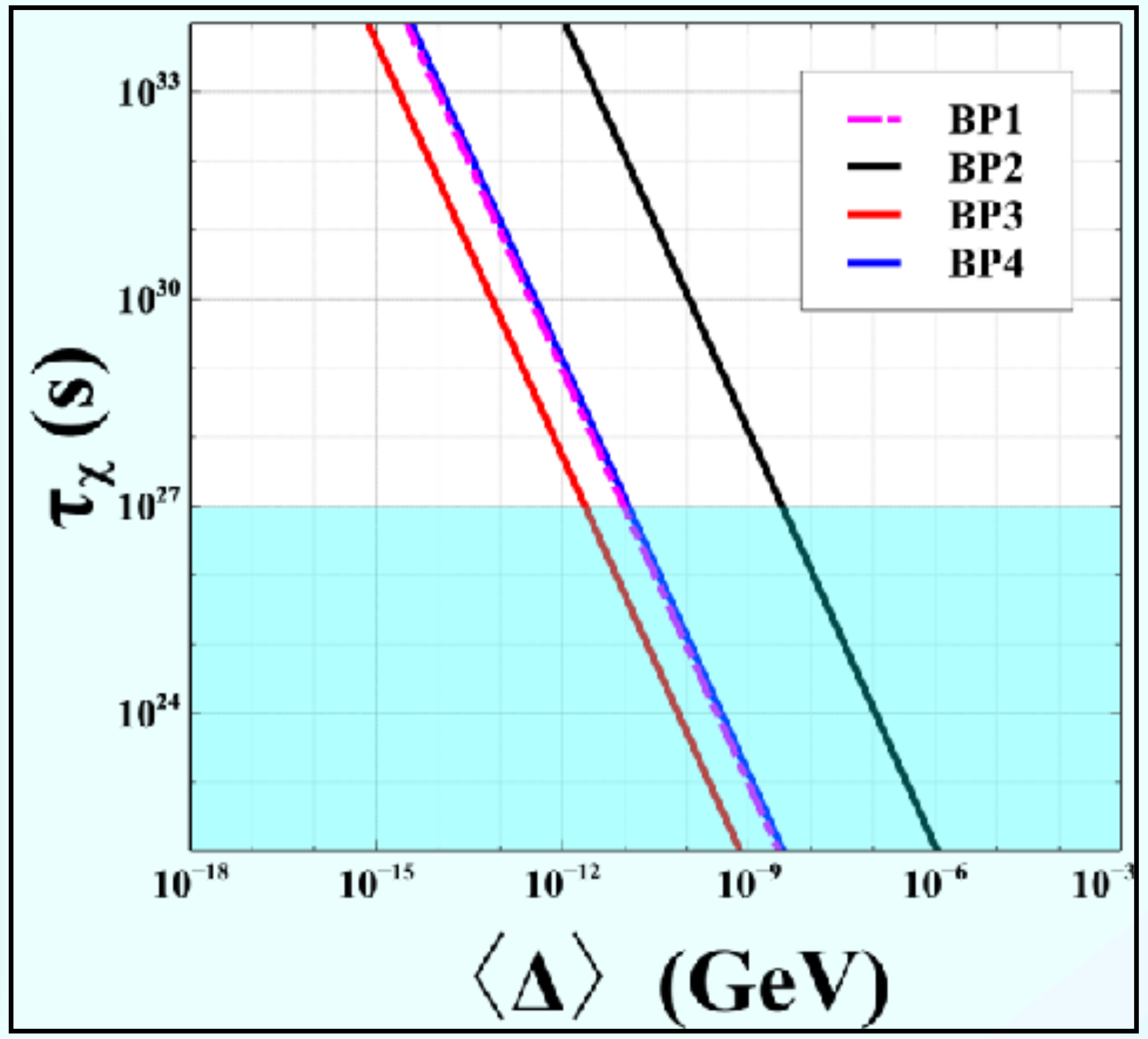
Relevant Processes

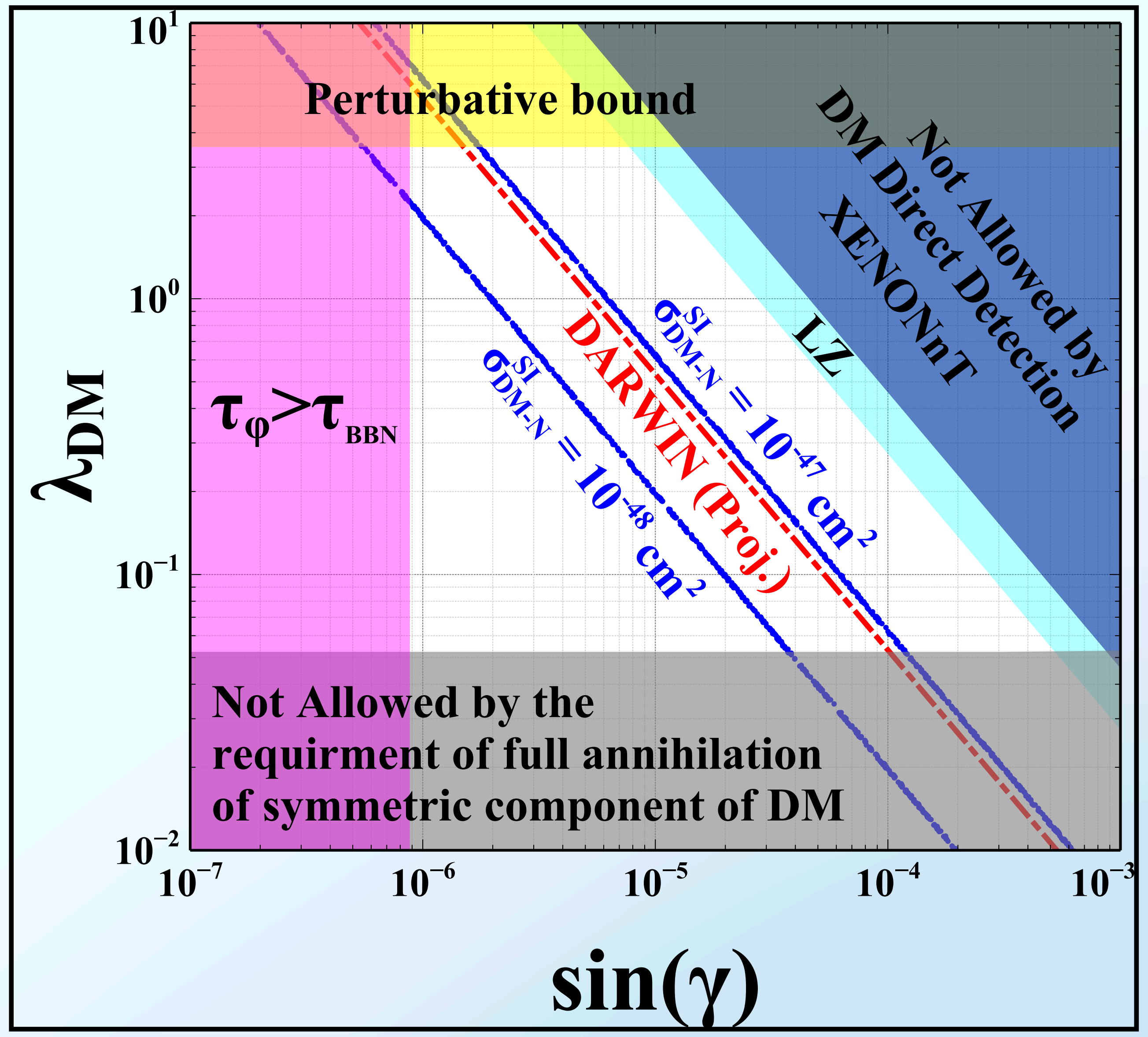


Cogenesis from fermion triplet seesaw

$$\boxed{V(H,\Delta,\Phi) \supset \sqrt{2}\mu H^\dagger(\vec{\sigma}\cdot\vec{\Delta})H} \qquad v_\Delta \neq 0 \implies \textbf{Unstable DM} \,(\chi \,\&\, \Sigma \text{ mix})$$



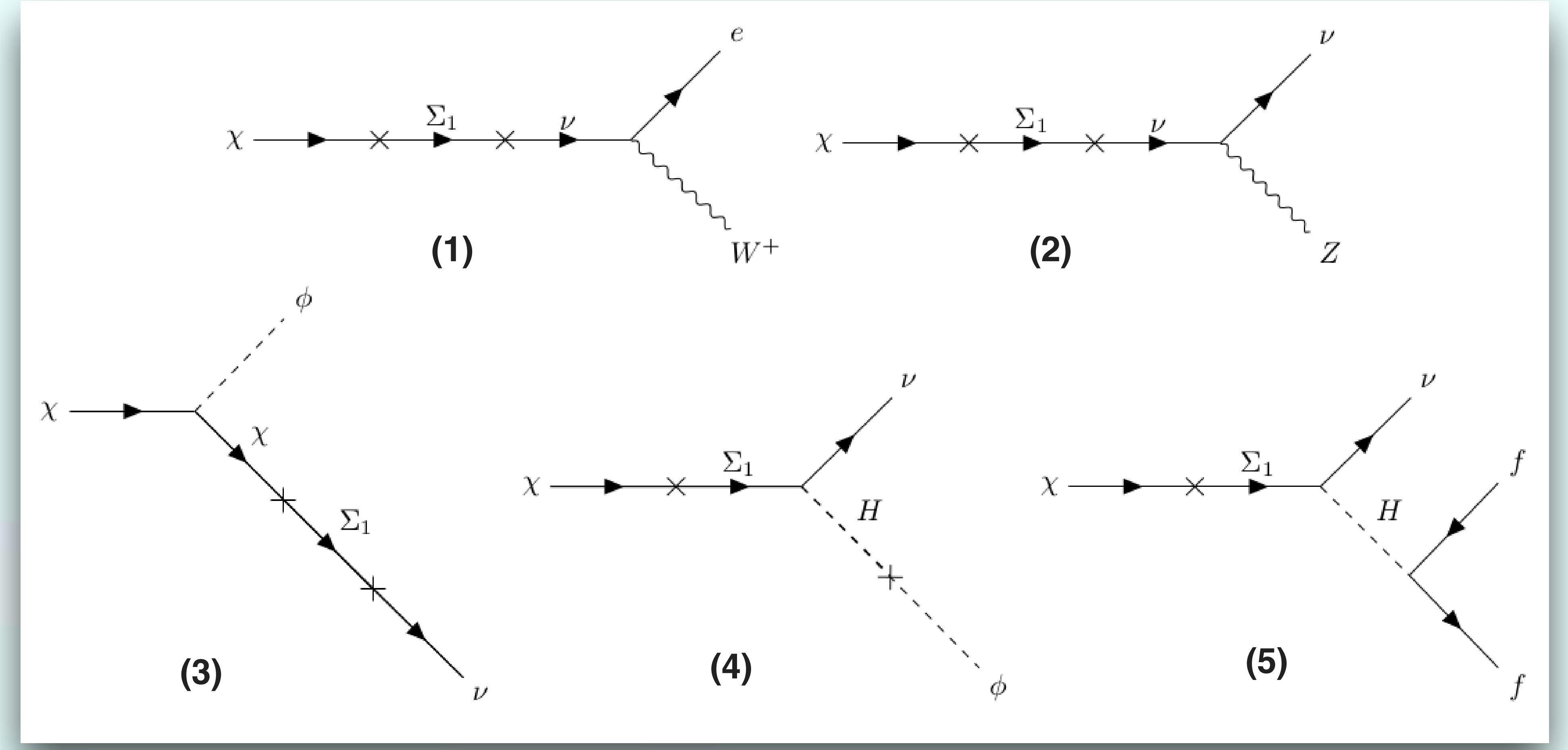


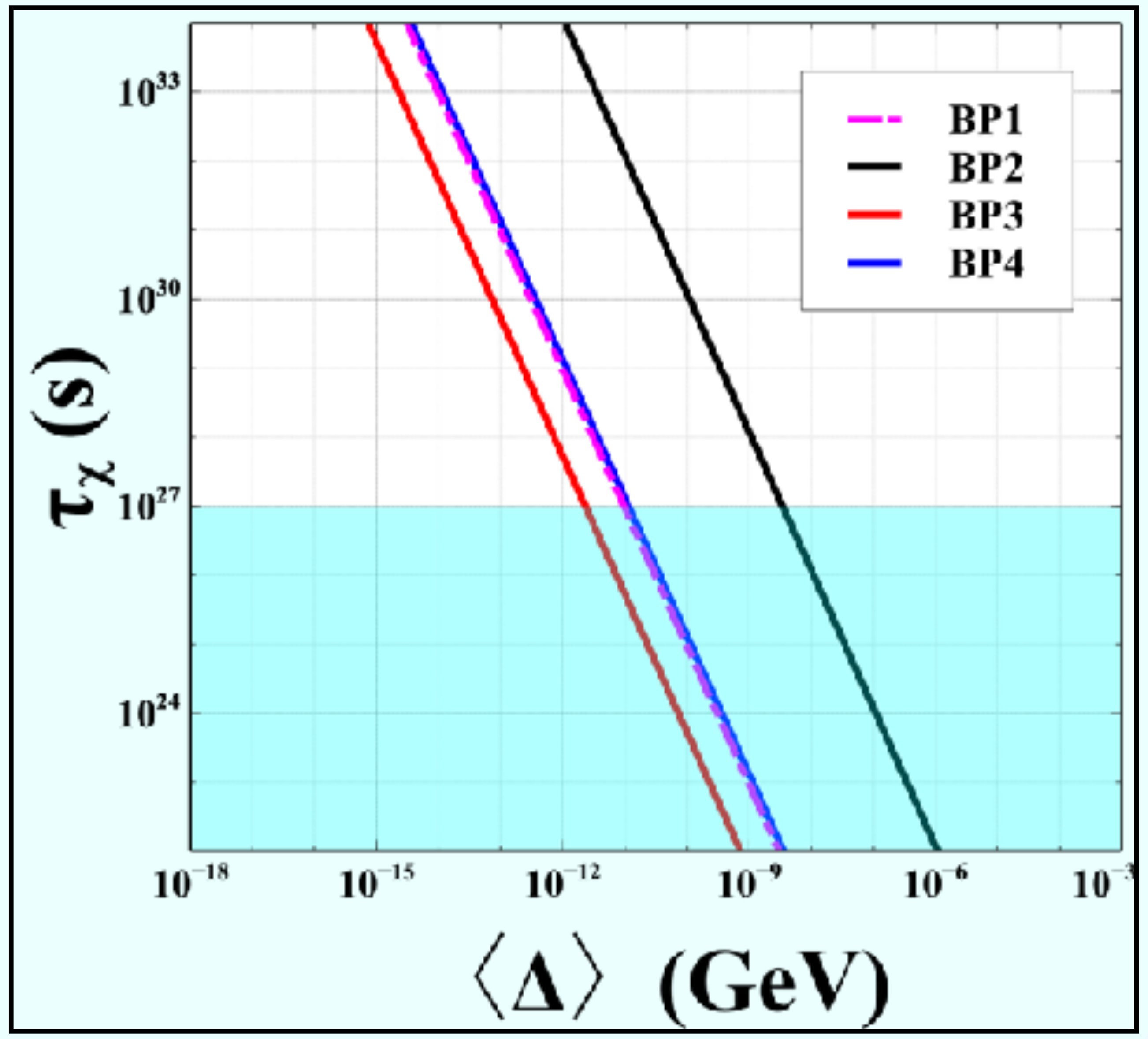


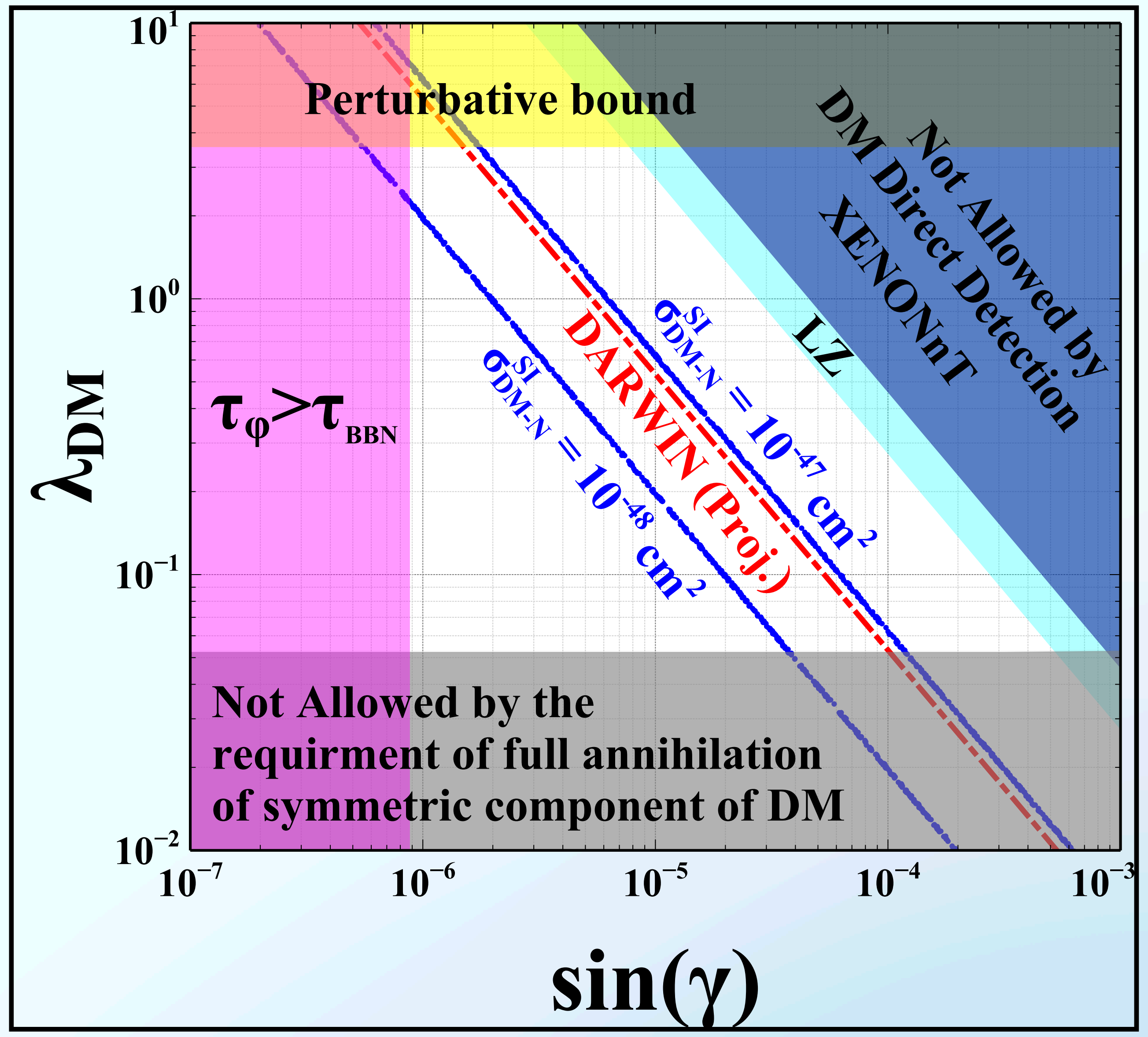
Cogenesis from fermion triplet seesaw

$$\boxed{V(H, \Delta, \Phi) \supset \sqrt{2}\mu H^\dagger(\vec{\sigma} \cdot \vec{\Delta})H}$$

$v_\Delta \neq 0 \implies$ **Unstable DM**







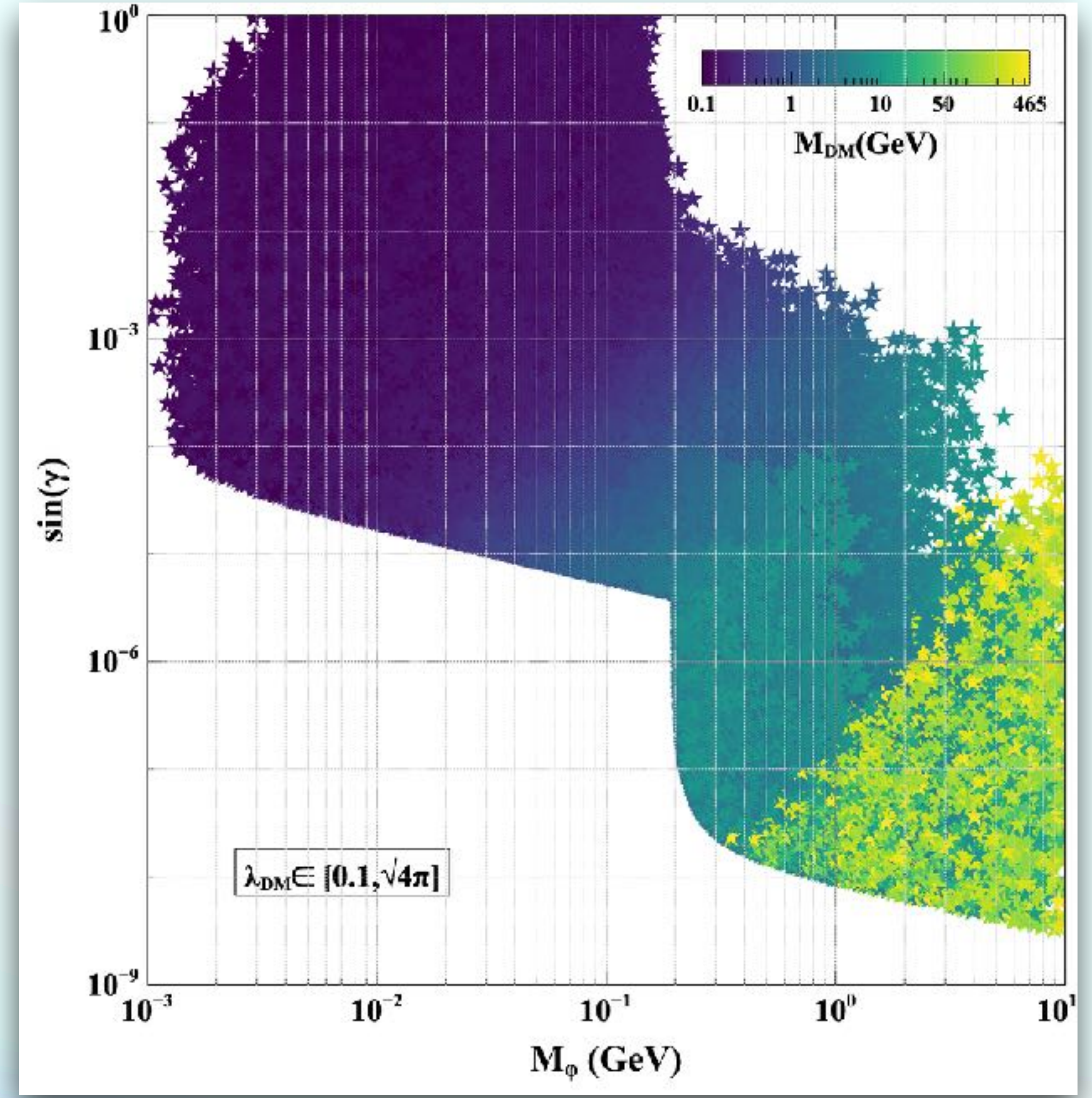
$M_{\rm DM} = 10$ GeV

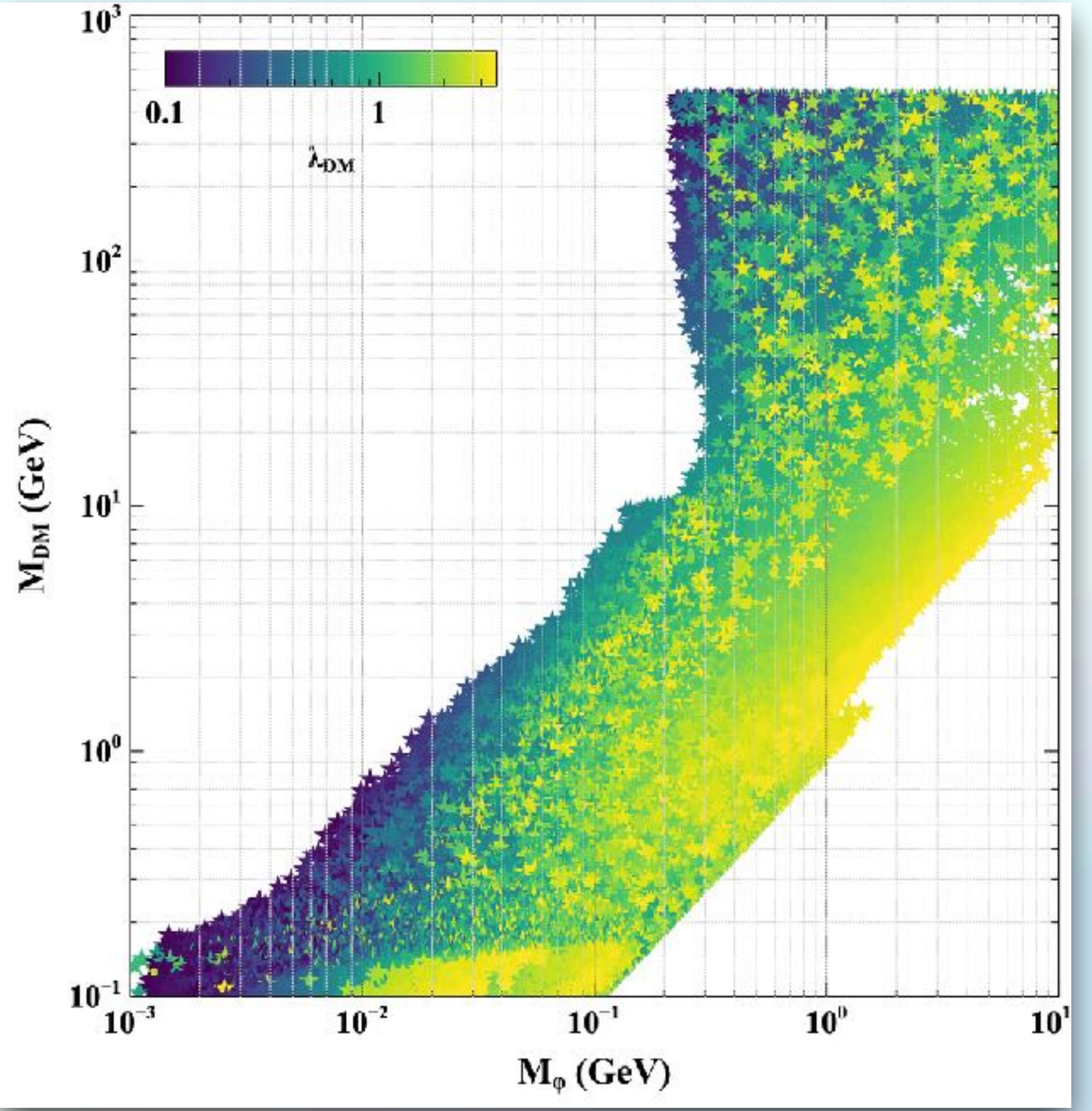
$M_{\rm h_2} = 5$ GeV

Monochromatic gamma-ray line and neutrino lines signatures

Additional constraints on $\theta_{\chi\Sigma}$ and $\theta_{\Sigma\nu}$

Asymmetric SIDM





Limit on DM Mass : $\mathcal{O}(\text{GeV}) \leq M_{DM} \leq 460$ GeV

Combined constraint from SIDM + DD + BBN

How to achieve correct relic density for such under-abundant DM thermally?

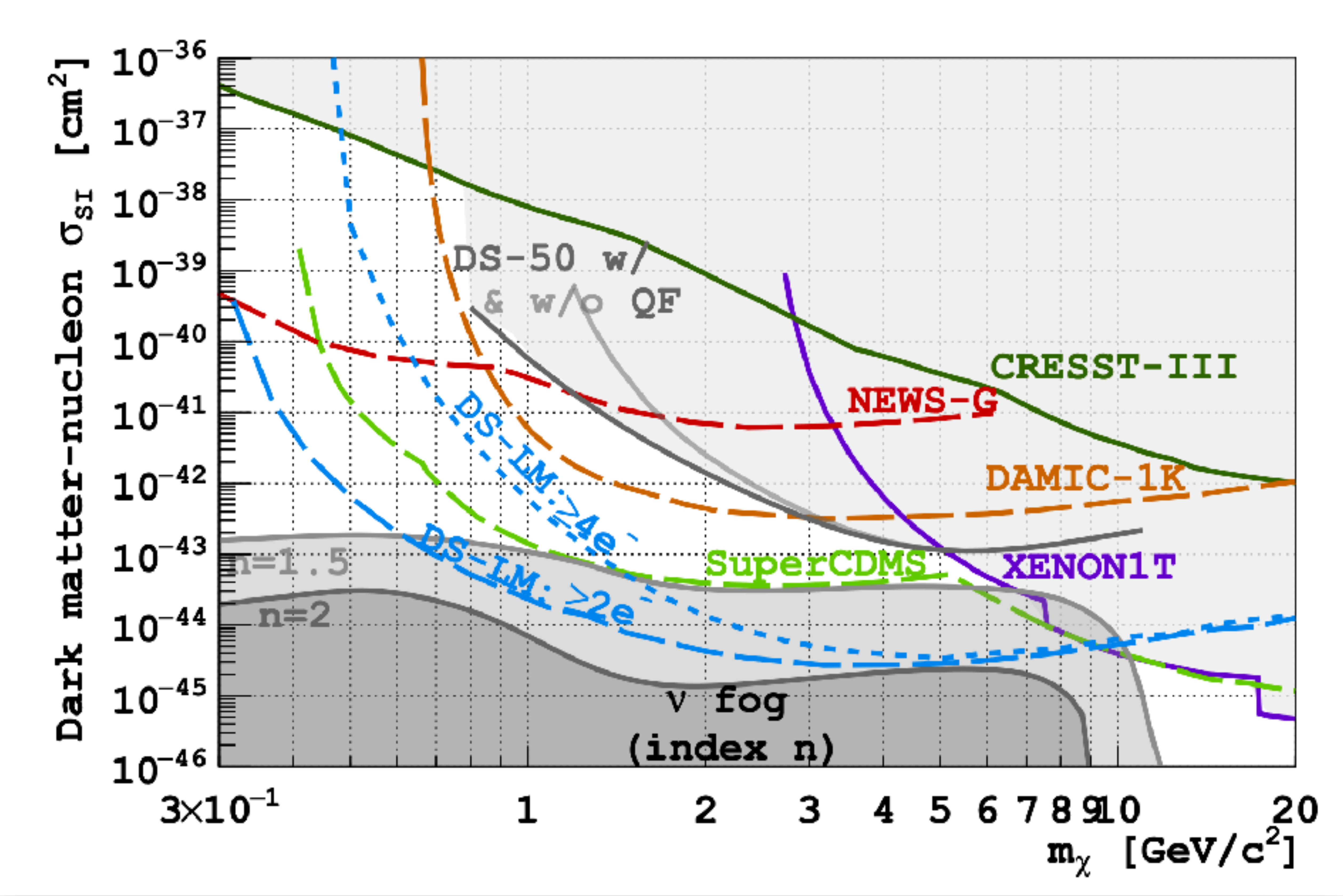
Rescuing Thermally under-abundant DM with First Order Phase Transition

$M_{DM} < \mathcal{O}(10)$ GeV+
Light Mediator +
Sizable Coupling

Observable DD $\Longleftarrow$

$\Downarrow$

Under-abundant relic



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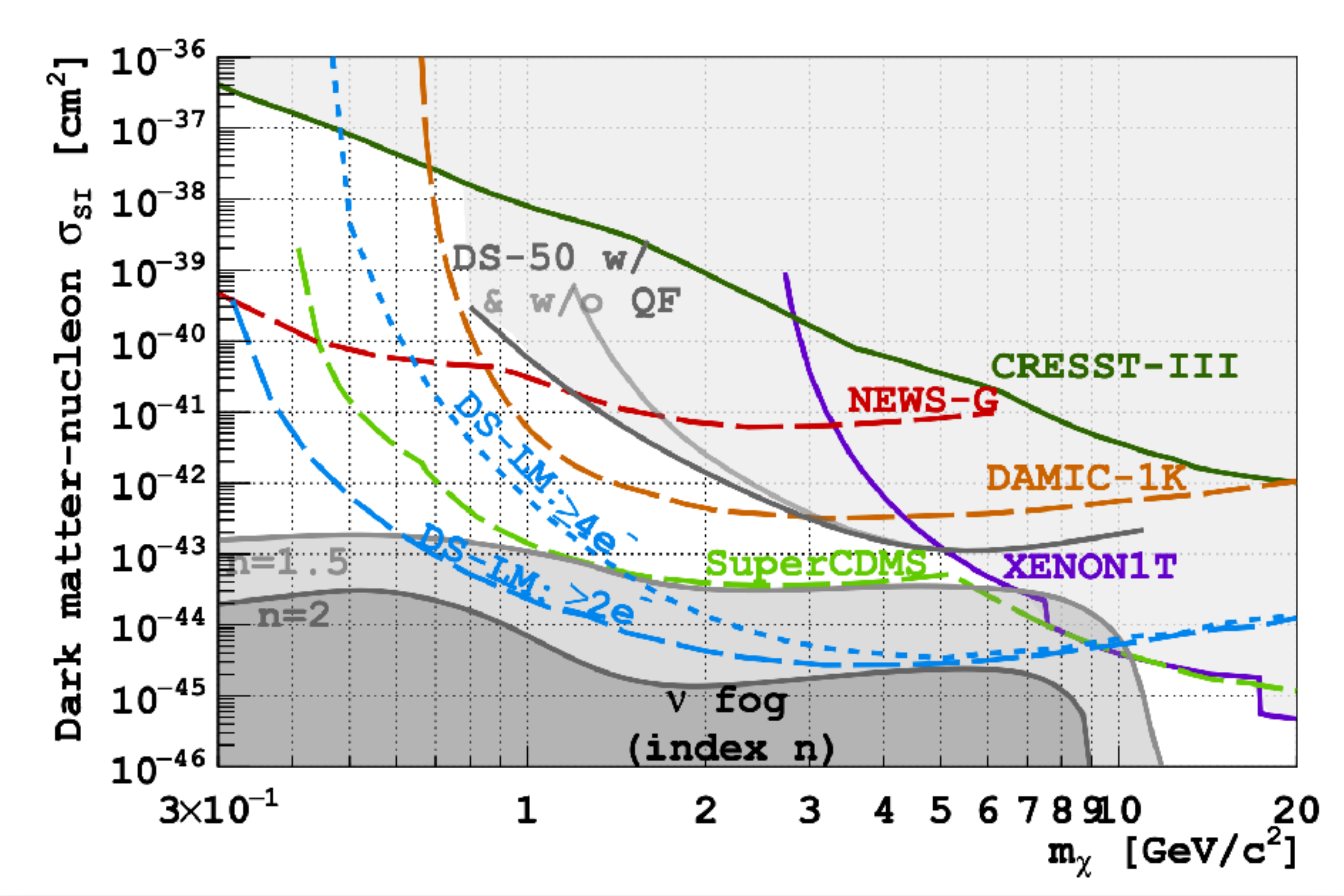
Rescuing Thermally under-abundant DM with First Order Phase Transition

Observable DD ⟸ $M_{\text{DM}} < \mathcal{O}(10)$ GeV+ Light Mediator + Sizable Coupling ⟹ Self Interaction

⇓

Under-abundant relic



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Rescuing Thermally under-abundant DM with First Order Phase Transition

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New realisation of light thermal dark matter with enhanced detection prospects

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Abstract: Light dark matter (DM) with mass around the GeV scale faces weaker bounds from direct detection experiments. If DM couples strongly to a light mediator, it is possible to have observable direct detection rate. However, this also leads to a thermally under-abundant DM relic due to efficient annihilation into light mediators. We propose a novel scenario where a first-order phase transition (FOPT) occurring at MeV scale can restore GeV scale DM relic by changing the mediator mass sharply at the nucleation temperature. The MeV scale FOPT predicts stochastic gravitational waves with nano-Hz frequencies within reach of pulsar timing array (PTA) based experiments like NANOGrav. In addition to enhancing direct detection rate, the light mediator can also give rise to the required DM self-interactions necessary to solve the small scale structure issues of cold dark matter. The existence of light scalar mediator and its mixing with the Higgs keep the scenario verifiable at different particle physics experiments.

JCAP12(2024)043

Rescuing Thermally under-abundant DM with First Order Phase Transition

$M_{\mathrm{DM}} < \mathcal{O}(10)$ GeV+

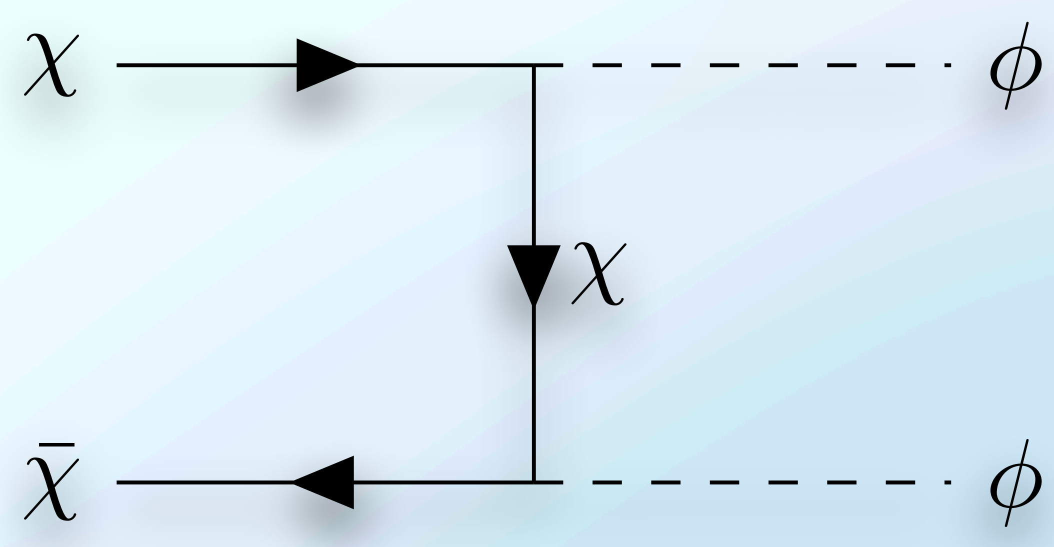
Light Mediator +

Sizable Coupling

Observable DD $\Longleftarrow$ (box above) $\Longrightarrow$ Self Interaction

$\Downarrow$

Under-abundant relic



Correct Relic density

$M_S^f = M_S \ll M_S^i$

$\Uparrow$

FOPT

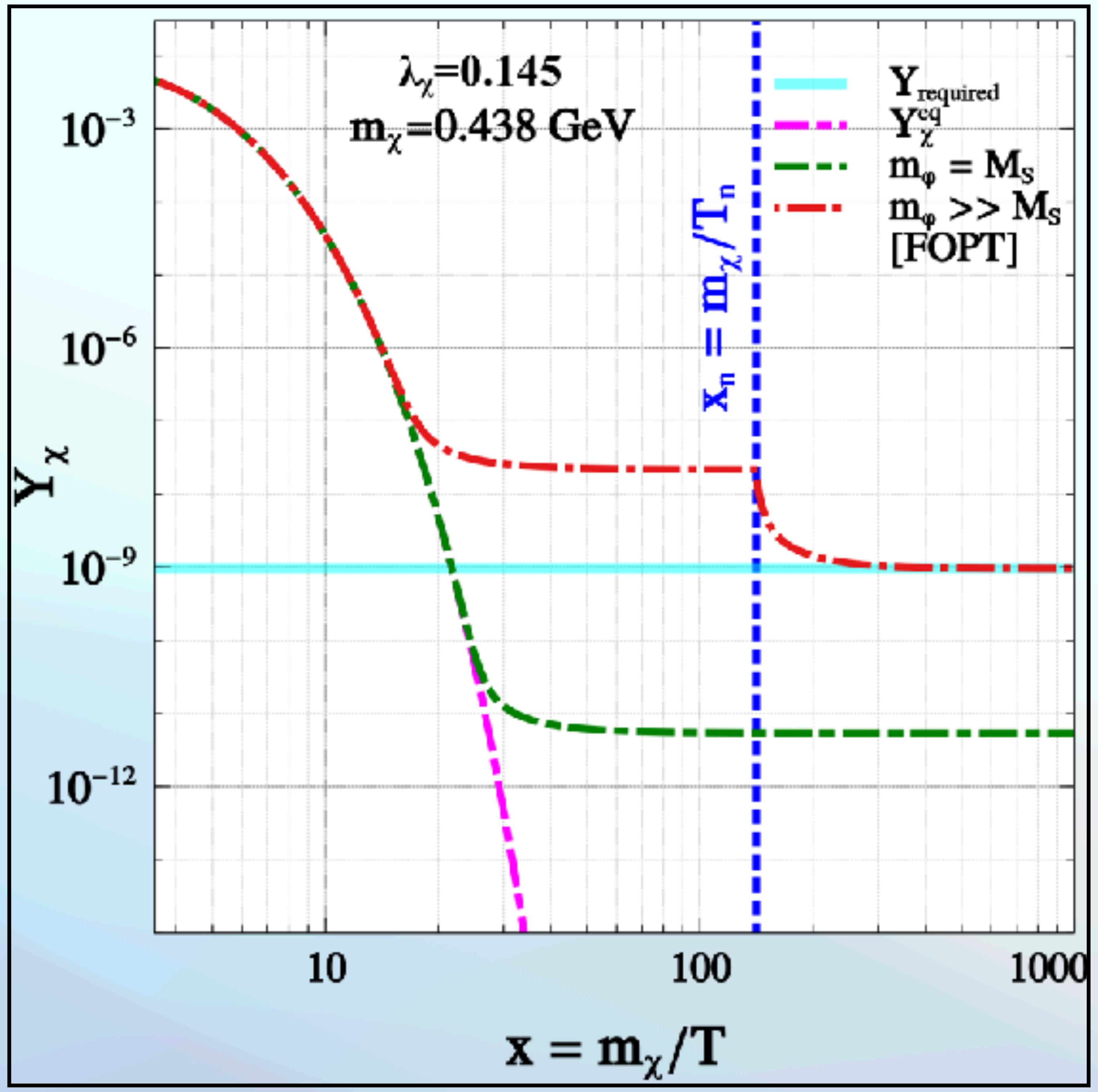
Rescuing Thermally under-abundant DM with First Order Phase Transition

$M_{\rm DM} < \mathcal{O}(10)$ GeV+
Light Mediator +
Sizable Coupling

Observable DD ⟸ ⟹ Self Interaction

⇓

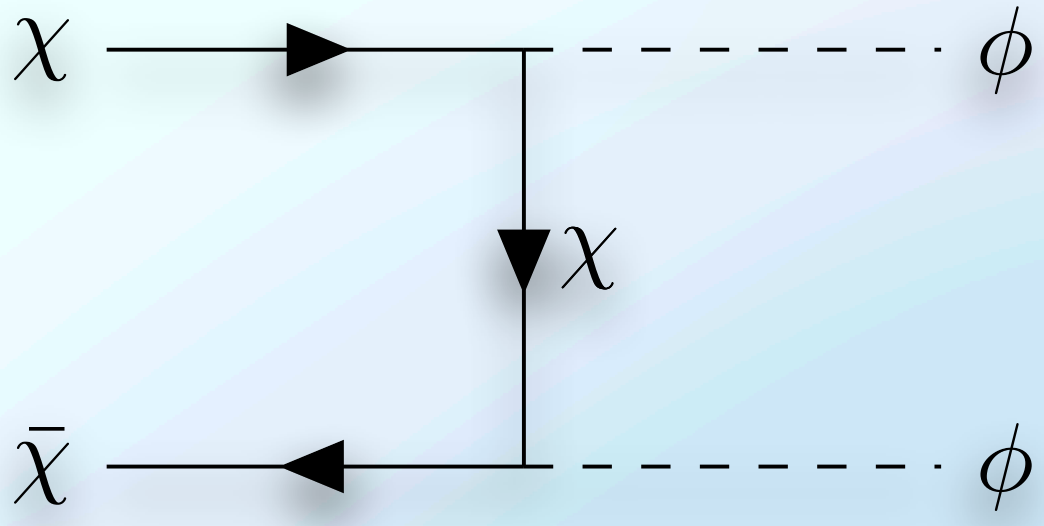
Under-abundant relic



Correct Relic density

$M_S^f = M_S \ll M_S^i$

FOPT

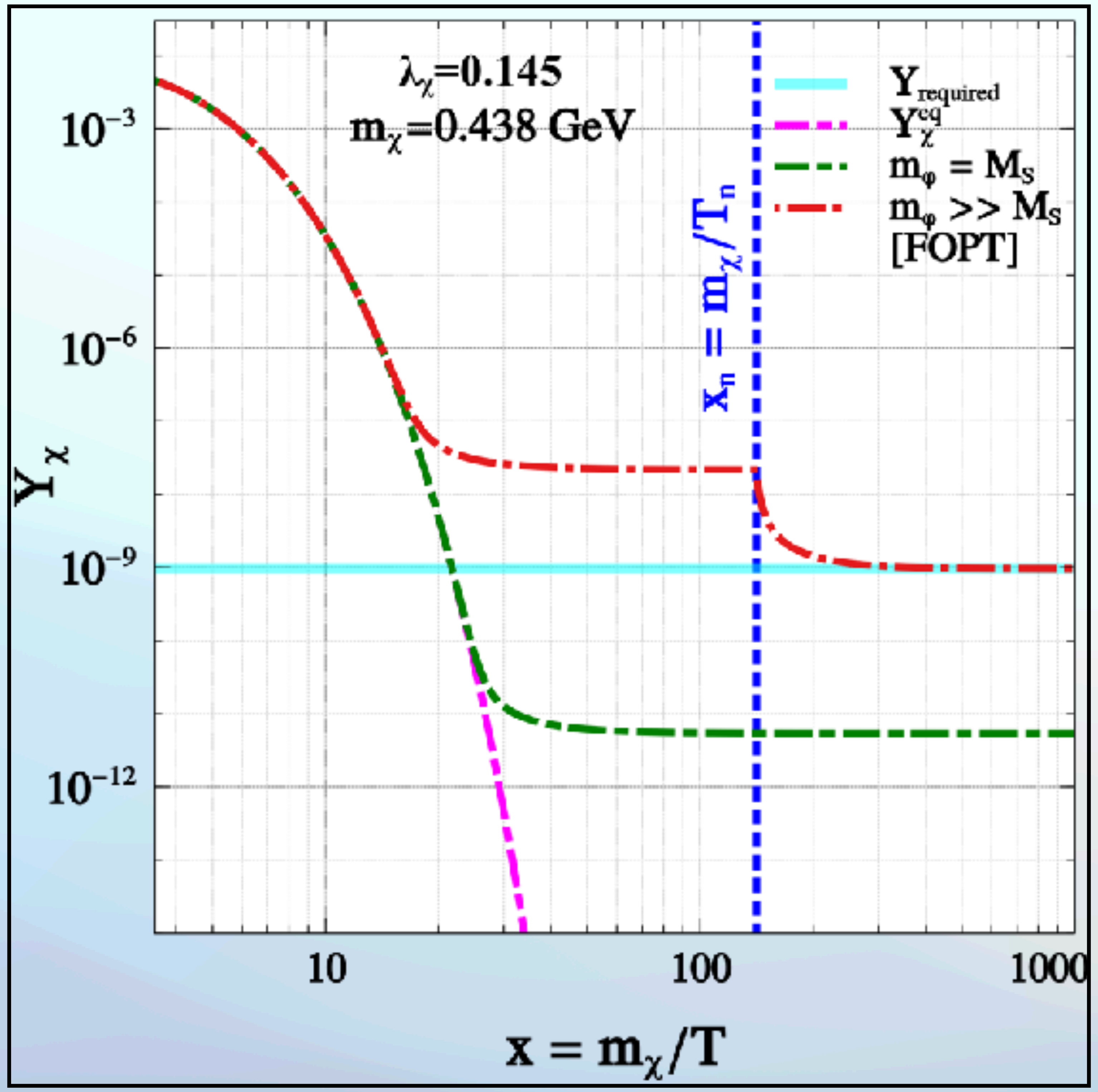


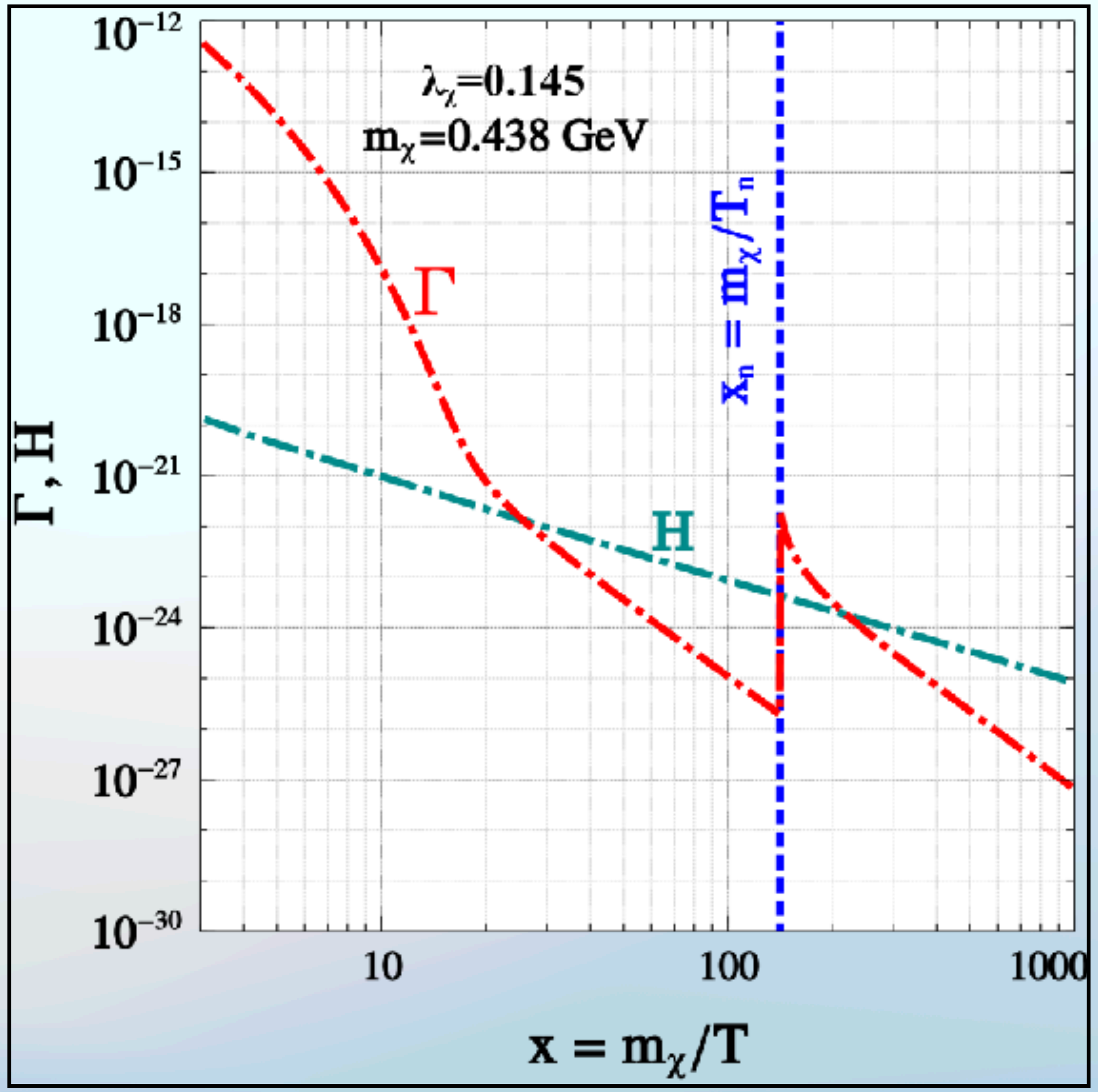
Rescuing Thermally under-abundant DM with First Order Phase Transition

$$-\mathscr{L} = \lambda_\chi \phi \bar{\chi}\chi + \boxed{\frac{1}{2}\mu_\phi^2\phi^2 + \mu_{\phi'\phi}\phi'\phi^2 + \frac{1}{4}\lambda_{\phi'\phi}\phi'^2\phi^2} + \frac{1}{2}\lambda_{\phi_1\phi'}\phi'^2|\phi_1|^2 + \frac{1}{4}\lambda'\phi'^4$$

$$\boxed{m_\phi^2 = \mu_\phi^2 + 2\mu_{\phi'\phi}v_{\phi'} + \frac{\lambda_{\phi'\phi}}{2}v_{\phi'}^2}$$

FOPT changes the mass of the mediator



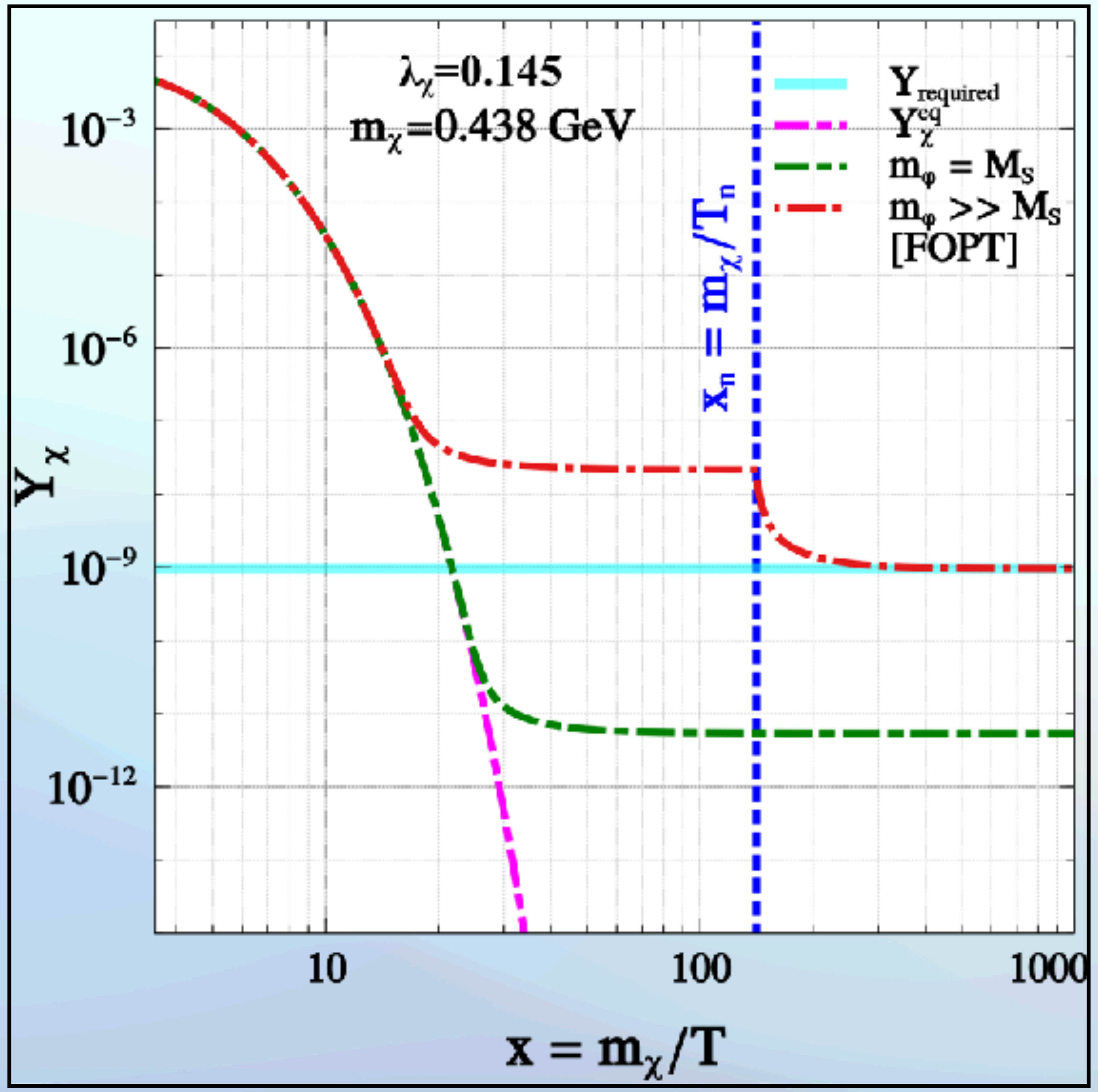


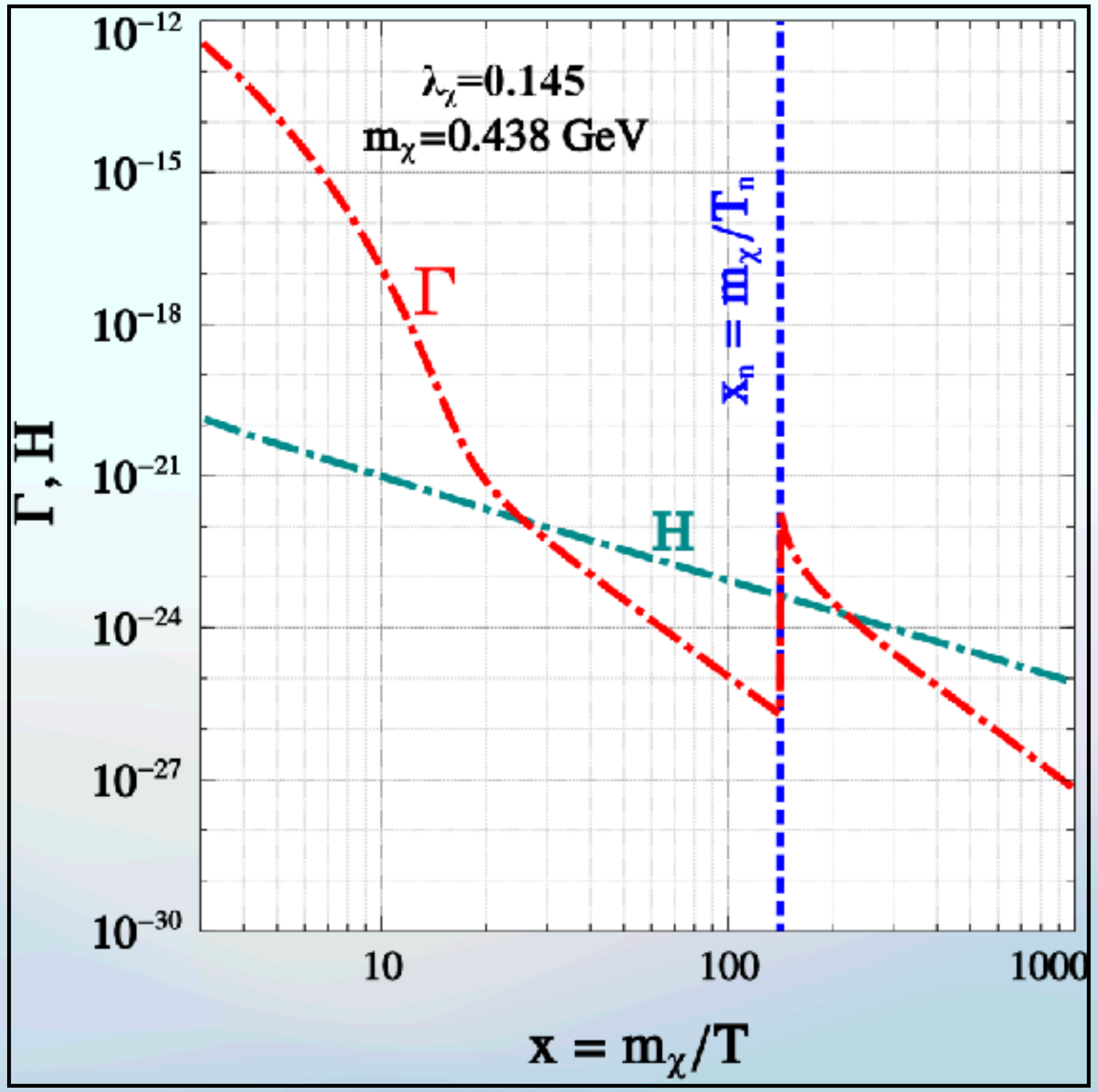
Rescuing Thermally under-abundant DM with First Order Phase Transition

$$-\mathscr{L} = \lambda_\chi \phi \bar{\chi}\chi + \frac{1}{2}\mu_\phi^2 \phi^2 + \mu_{\phi'\phi}\phi'\phi^2 + \frac{1}{4}\lambda_{\phi'\phi}\phi'^2\phi^2 + \frac{1}{2}\lambda_{\phi_1\phi'}\phi'^2|\phi_1|^2 + \frac{1}{4}\lambda'\phi'^4$$

$$m_\phi^2 = \mu_\phi^2 + 2\mu_{\phi'\phi}v_{\phi'} + \frac{\lambda_{\phi'\phi}}{2}v_{\phi'}^2$$

FOPT changes the mass of the mediator





Requirement:

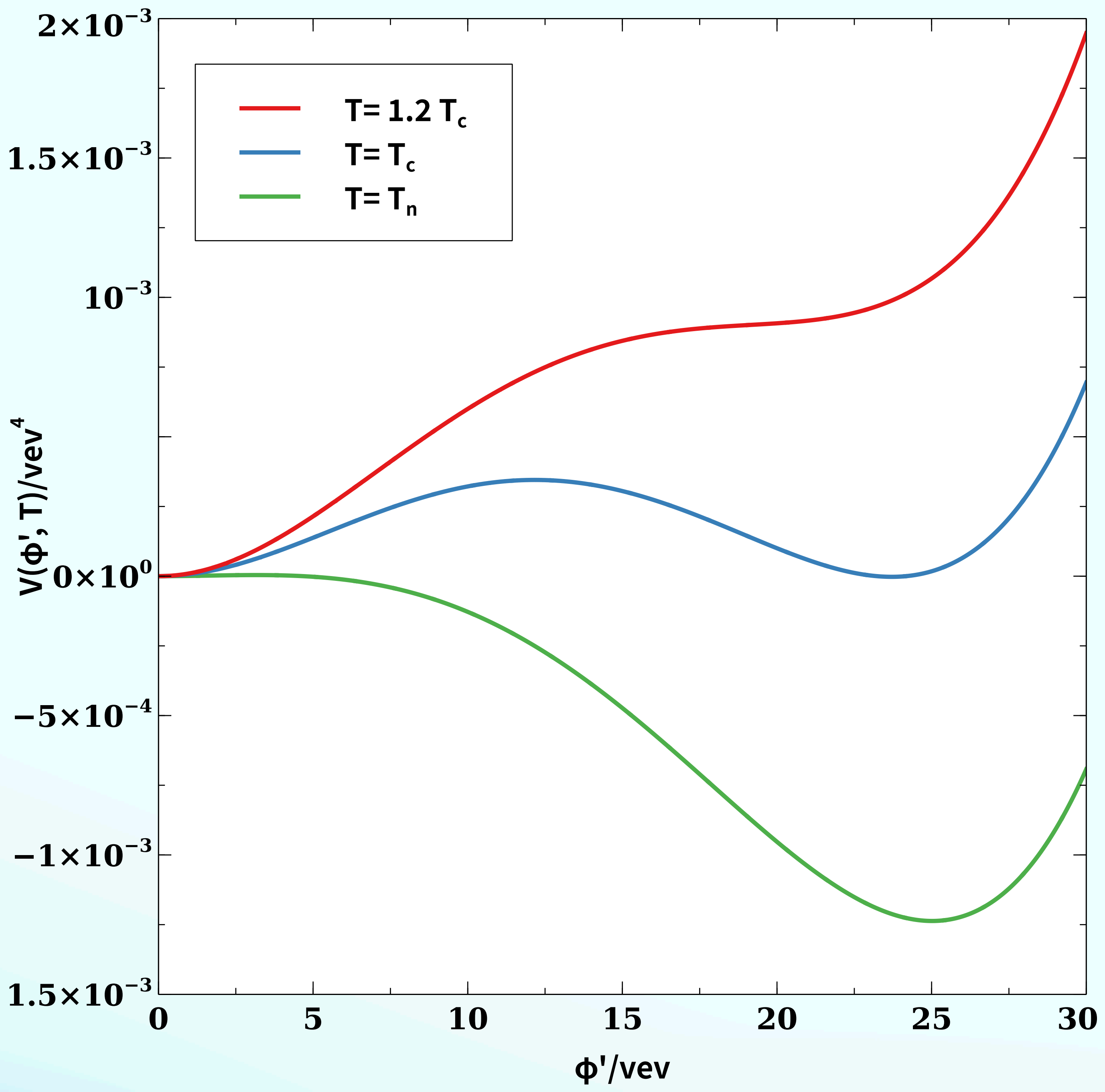
$$T_{F.O.1} > T_n$$

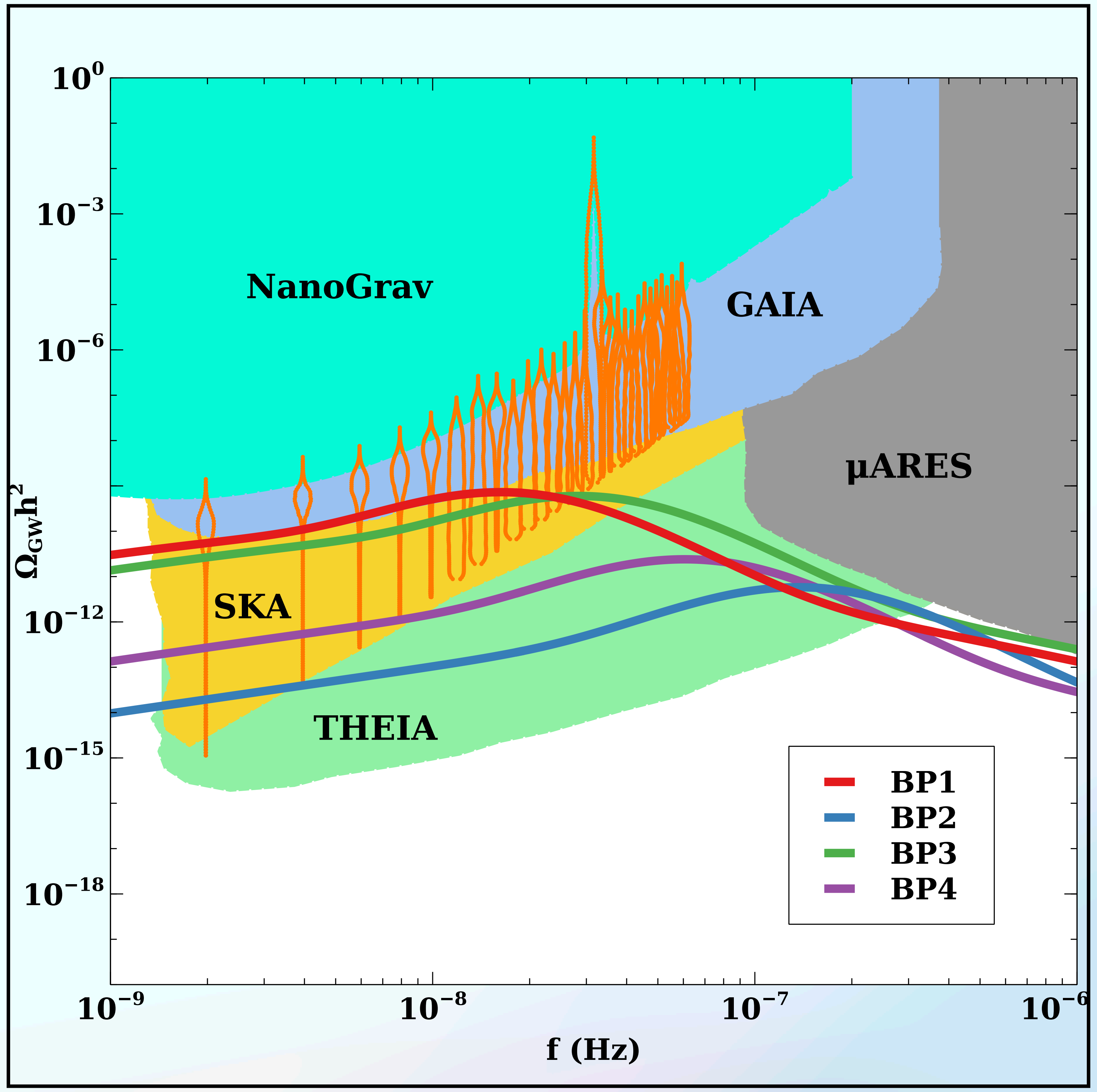
$$m_\chi > 40\ T_n$$

DM mass fixes the scale of FOPT

Rescuing Thermally under-abundant DM with First Order Phase Transition

FOPT origin of PTA results

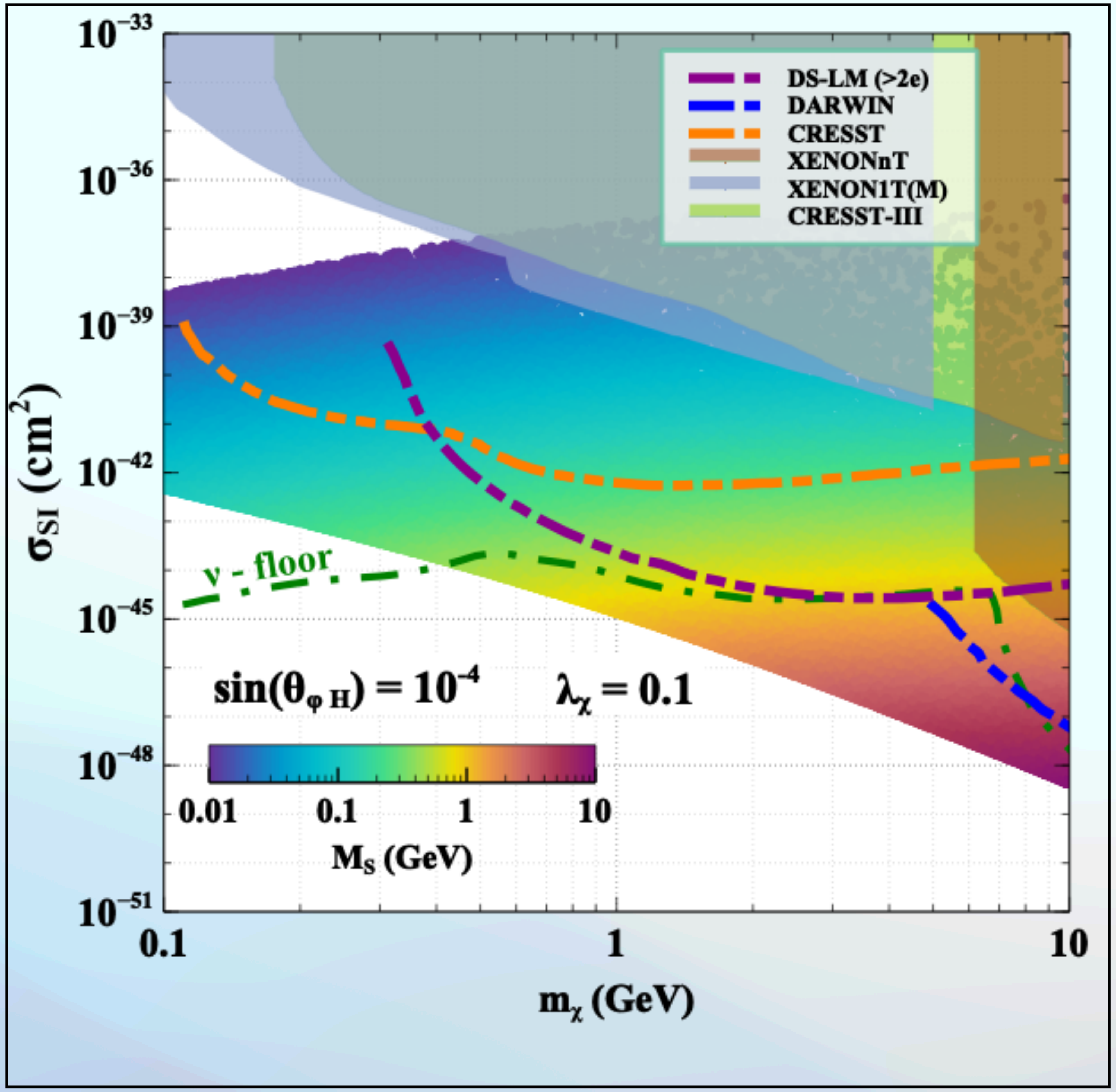


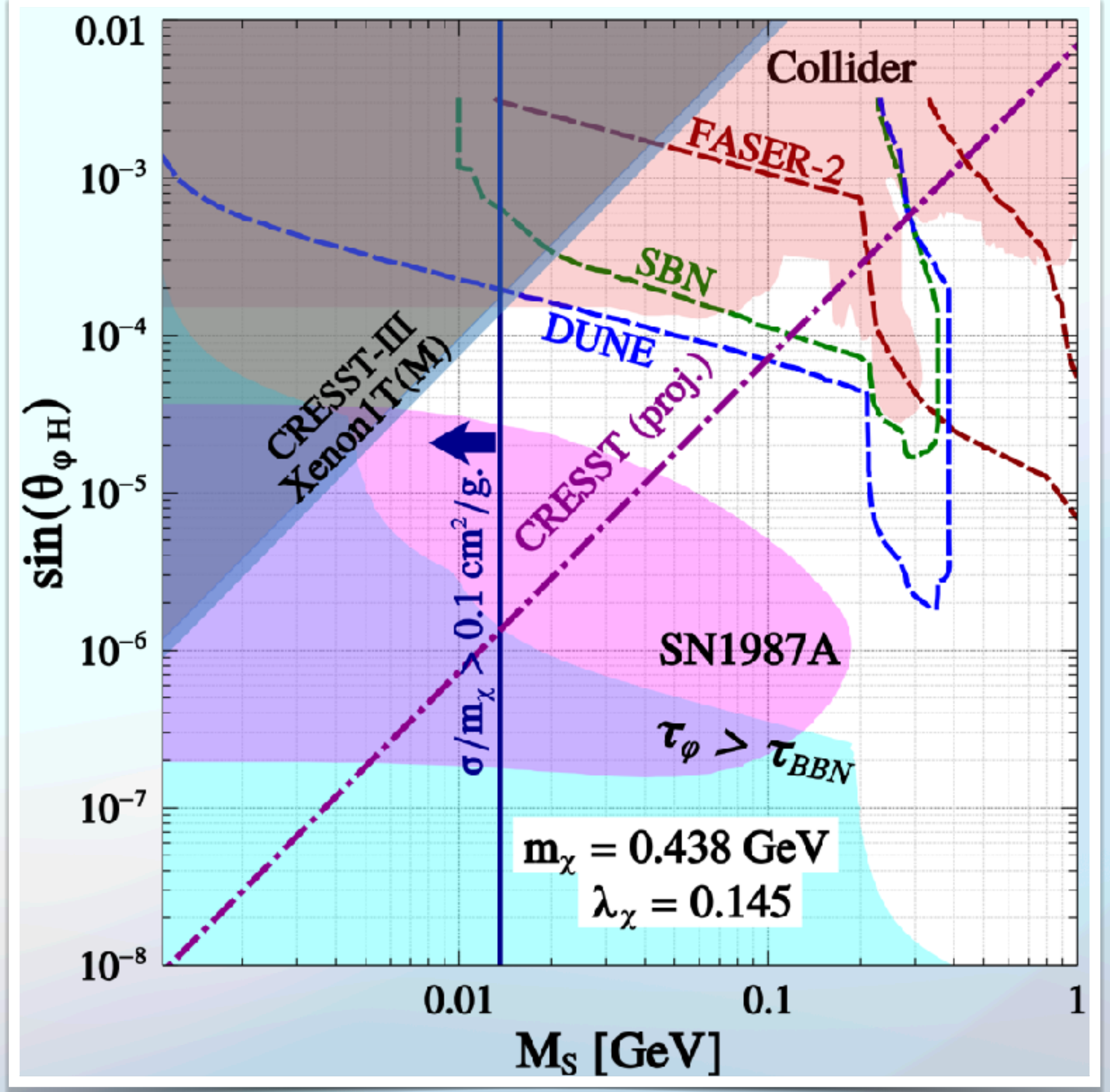


	$v_{\phi'}$ (MeV)	T_c (MeV)	v_c (MeV)	T_n (MeV)	μ_ϕ (MeV)	M_S (MeV)	$\mu_{\phi'\phi}$ (GeV)	$\lambda_{\phi'\phi}$	$\lambda_{\phi'\phi_1}$	λ_{ϕ_1}	λ'	α_*	$\beta/\mathcal{H}_*$	v_w	$T_{\rm RH}$ (MeV)
BP1	25	7.91	23.75	3.10	438	10	-3.839	0.4	1.76	0.1	0.01	1.61	82.15	0.94	3.14
BP2	30	9.69	28.20	5.38	750	15	-9.377	0.3	1.70	0.1	0.01	0.39	363.32	1	5.38
BP3	40	12.86	38.00	5.10	990	20	-12.253	0.2	1.76	0.2	0.01	1.46	86.34	0.94	5.46
BP4	22	7.03	20.68	3.51	1200	25	-32.727	0.1	1.73	0.1	0.01	0.61	255.67	1	3.51

Rescuing Thermally under-abundant DM with First Order Phase Transition

Detection Prospects





Thank You.

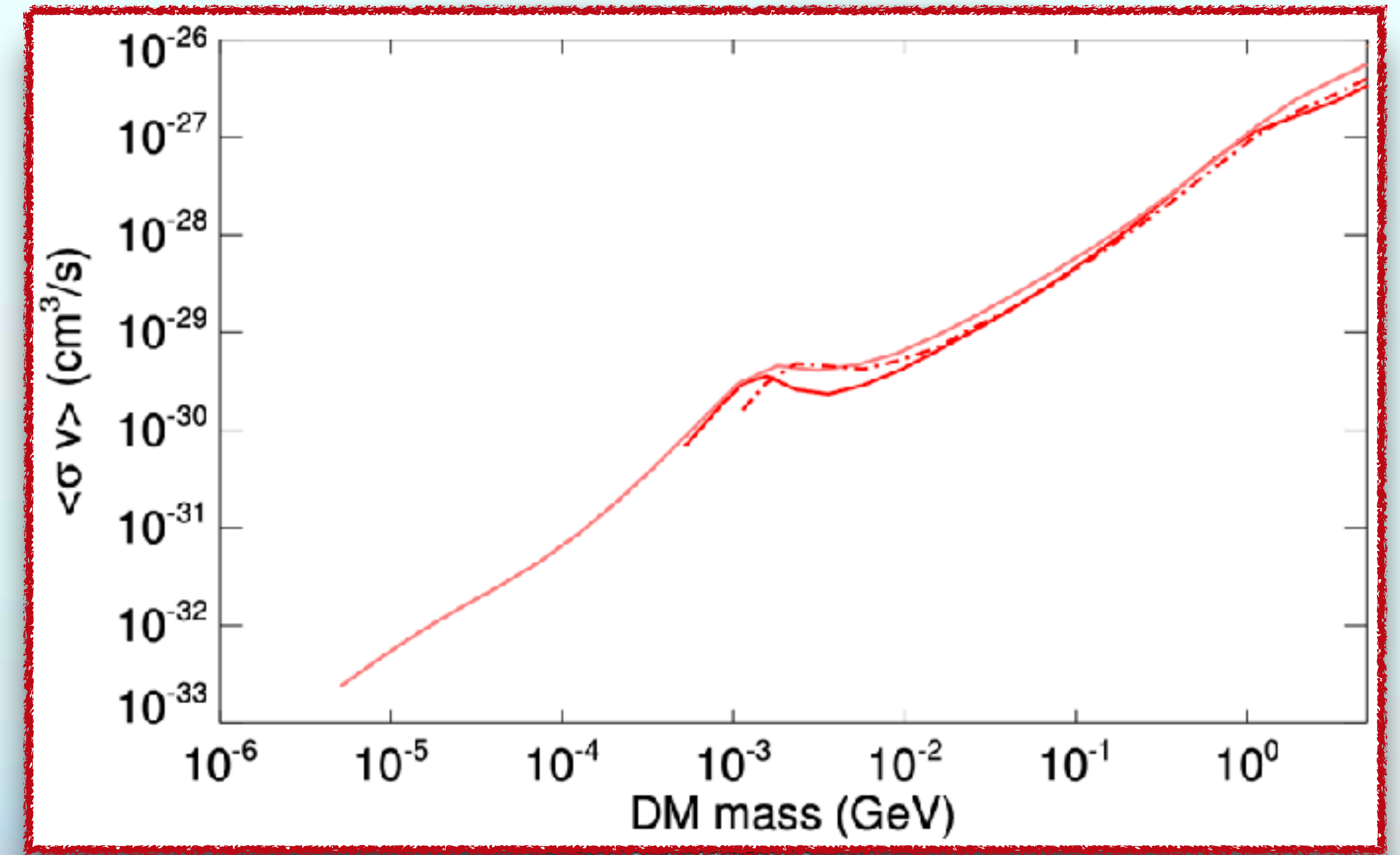
satyabrata.mahapatra02@gmail.com

Indirect Search and CMB Constrainrs

Focus on: $M_{\rm DM} \lesssim \mathcal{O}(10\,\mathrm{GeV})$

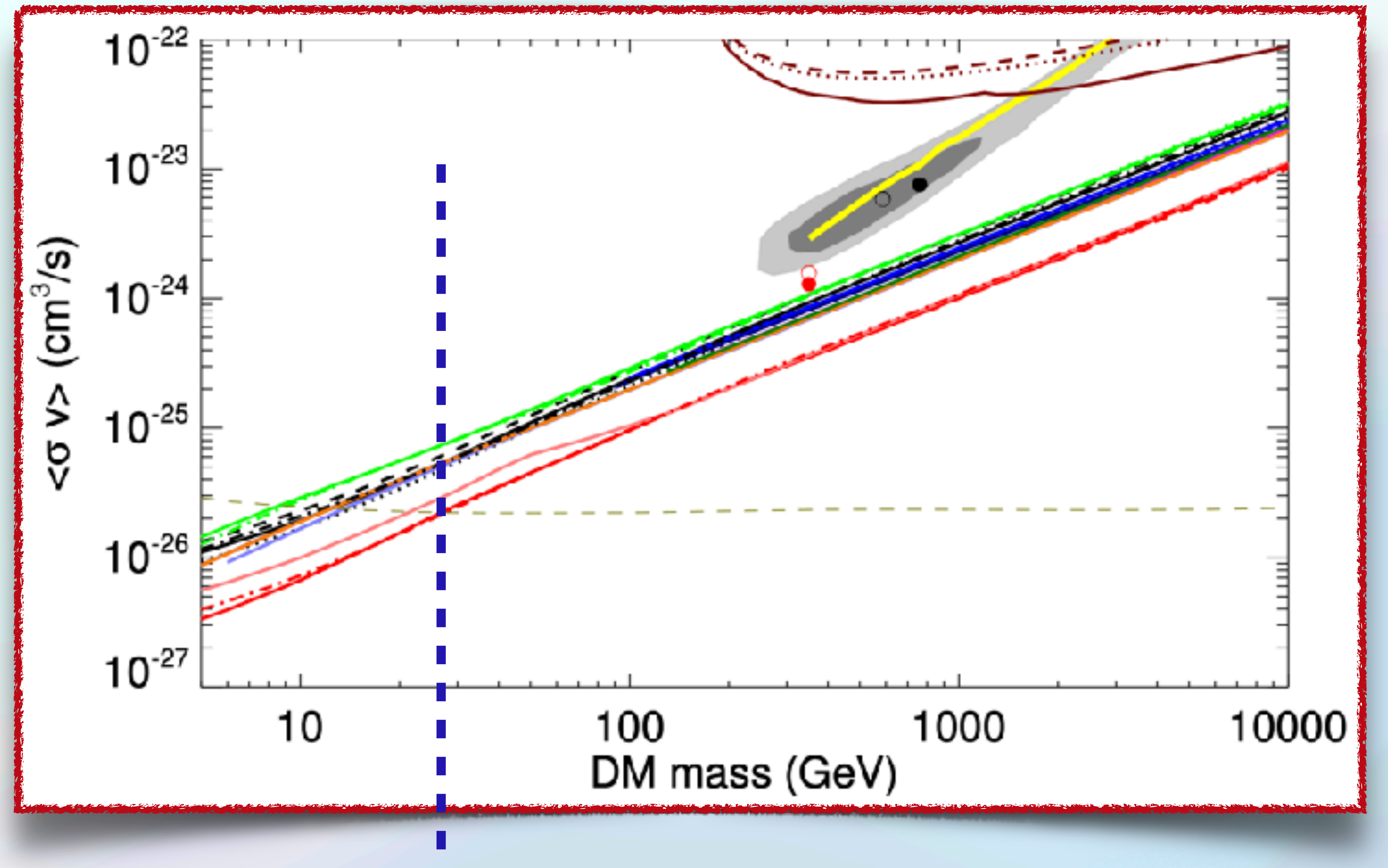
Difficult to achieve WIMP miracle. ⟵ **Insufficient** $\langle \sigma v \rangle_{ann.}$

Solution: Invoke light mediators



Severe constraints from CMB observations.

1506.03811



Injection of Ionizing particles increases the residual ionization fraction, broadening the last scattering surface and thus modifies the CMB anisotropy.

Cogenesis

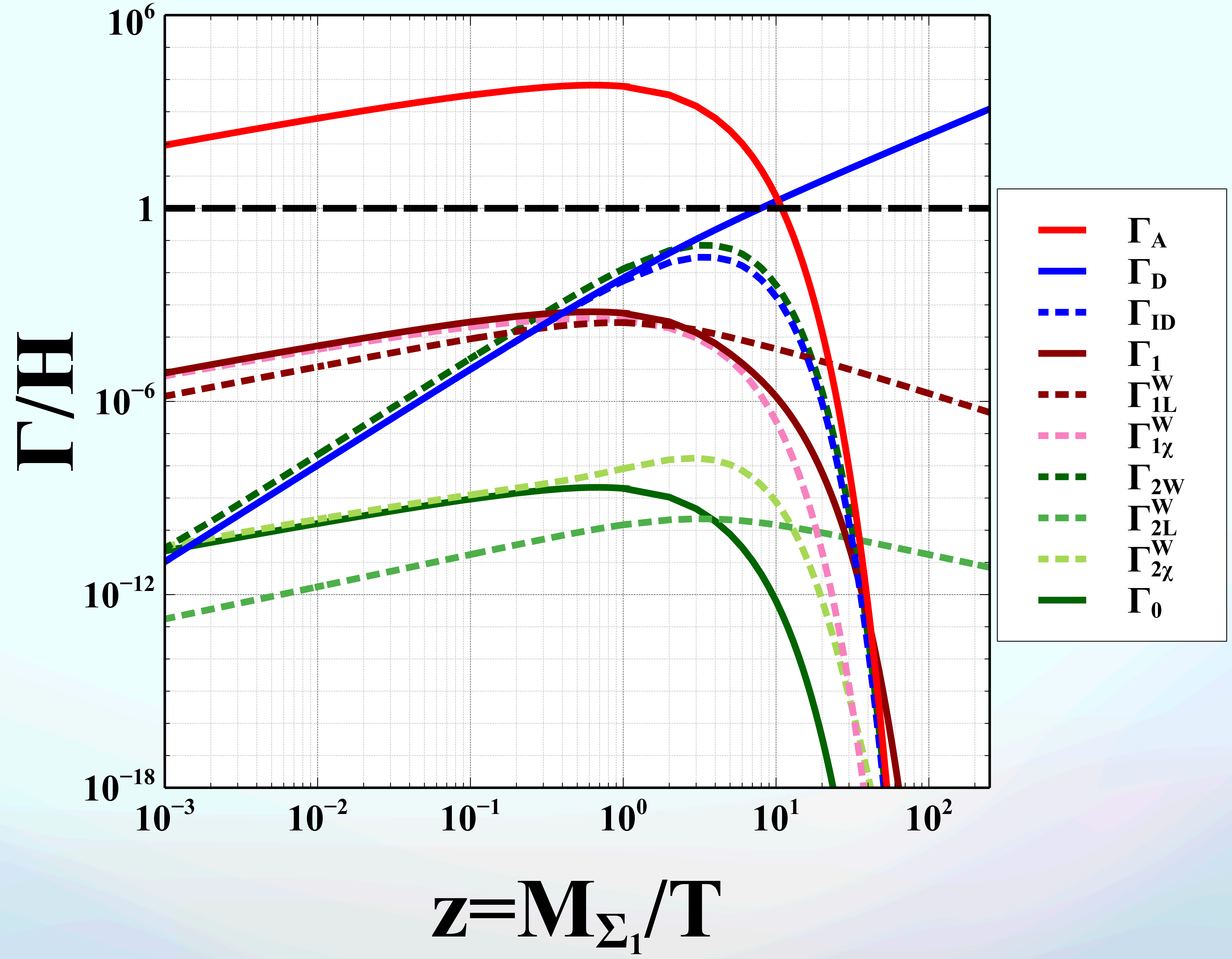
$$
\begin{aligned}
\mathcal{L} \;=\; & \mathrm{Tr}[\overline{\Sigma} i\gamma_\mu D^\mu \Sigma] + \mathrm{Tr}[(D_\mu \Delta)^\dagger (D_\mu \Delta)] + (D_\mu H)^\dagger (D_\mu H) + \frac{1}{2}\, \partial_\mu \Phi\, \partial^\mu \Phi - [\frac{1}{2}\mathrm{Tr}[m_\Sigma \overline{\Sigma^c} \Sigma] \\
& + \sqrt{2}\, y_\Sigma \overline{L} \tilde{H} \Sigma + y_\chi \mathrm{Tr}[\overline{\Sigma}\ \Delta\ \chi] + \mathrm{h.c.}] + \ \overline{\chi} i \gamma_\mu \partial^\mu \chi - M_\chi \overline{\chi}\chi - \lambda_{\mathrm{DM}} \Phi \bar{\chi}\chi - V(H, \Delta, \Phi),
\end{aligned}
$$

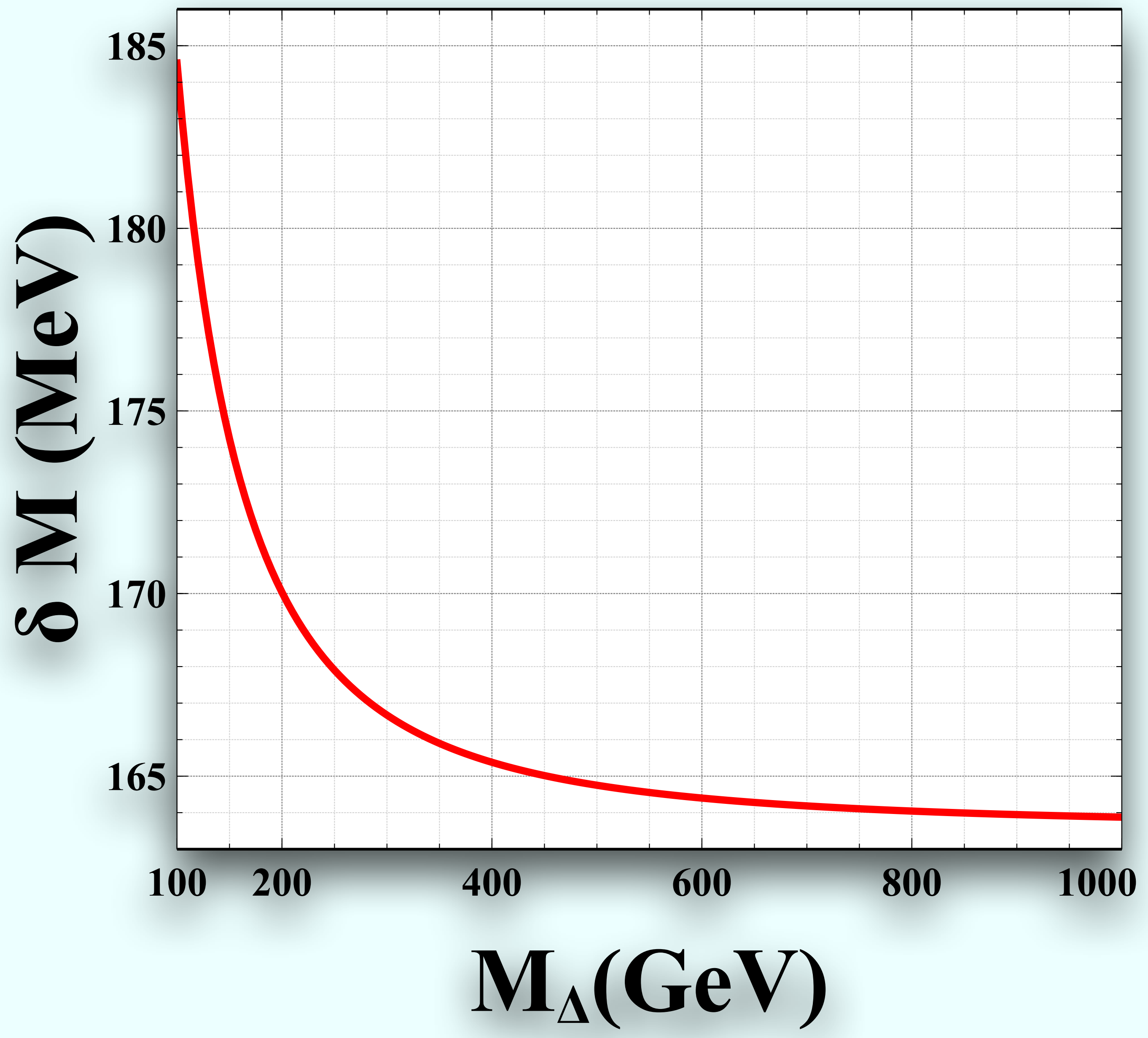
$$
\begin{aligned}
V(H,\Delta,\Phi) \;=\; & \frac{1}{2}\mu_\Phi^2 \Phi^2 - \mu_H^2 (H^\dagger H) + \mu_\Delta^2 \mathrm{Tr}[\Delta^\dagger \Delta] + \lambda_H (H^\dagger H)^2 + \lambda_\Delta \mathrm{Tr}[(\Delta^\dagger \Delta)^2] + \lambda_{H\Delta}(H^\dagger H)\mathrm{Tr}[\Delta^\dagger \Delta] \\
& + \sqrt{2}\mu H^\dagger (\vec{\sigma}\cdot\vec{\Delta}) H + \frac{\lambda_\Phi}{4}\Phi^4 + \frac{\rho_1}{\sqrt{2}}\Phi(H^\dagger H) + \frac{\rho_2}{\sqrt{2}}\Phi \mathrm{Tr}[(\Delta^\dagger \Delta)] + \frac{\lambda_{H\Phi}}{2}(H^\dagger H)\Phi^2,
\end{aligned}
$$

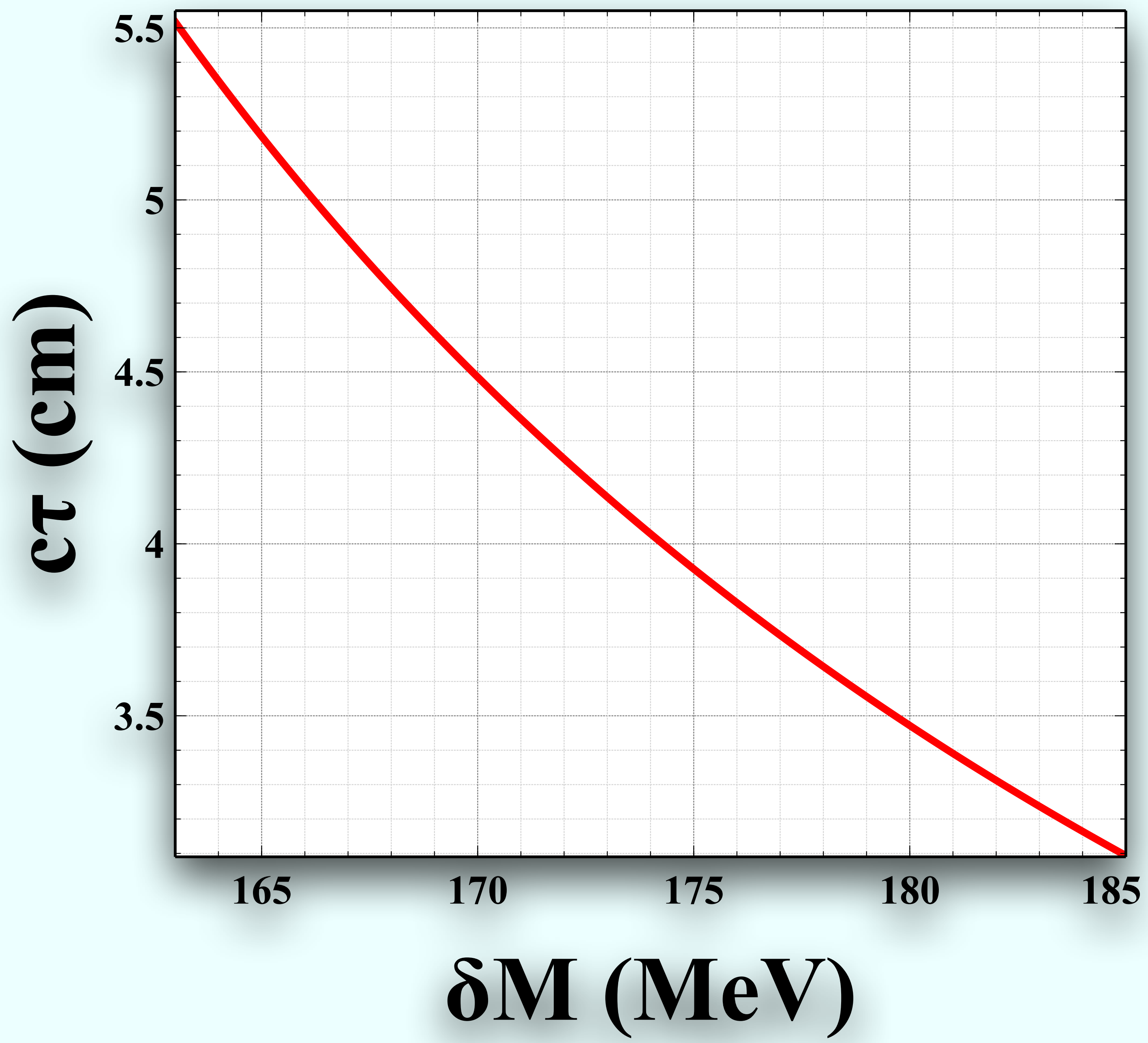
BPs	M_1(GeV)	M_χ(GeV)	y_{χ_1}	y_{χ_2}	y_{χ_3}	θ	ϵ_L	ϵ_χ
$BP1$	6.04×10^{13}	0.85	3.01×10^{-2}	$(2.39 + i0.19) \times 10^{-2}$	$(2.65 + i0.96) \times 10^{-1}$	$6.27 + i5.49 \times 10^{-3}$	3.61×10^{-5}	1.07×10^{-5}
$BP2$	1.98×10^{12}	17	6.78×10^{-5}	$(1.92 + i0.39)$	$(0.56 + i3.63) \times 10^{-1}$	$(0.36 + i1.19) \times 10^{-2}$	9.32×10^{-6}	1.38×10^{-7}
$BP3$	3.92×10^{9}	1.48	1.35×10^{-3}	$(0.036 + i2.06) \times 10^{-1}$	$1.11 \times 10^{-2} + i1.54$	$3.57 + i2.86 \times 10^{-2}$	9.05×10^{-6}	1.32×10^{-6}
$BP4$	4.44×10^{11}	920	9.78×10^{-3}	$0.19 + i2.82 \times 10^{-4}$	$2.52 + i0.54$	$1.40 \times 10^{-4} + i0.52$	1.92×10^{-4}	5.09×10^{-8}

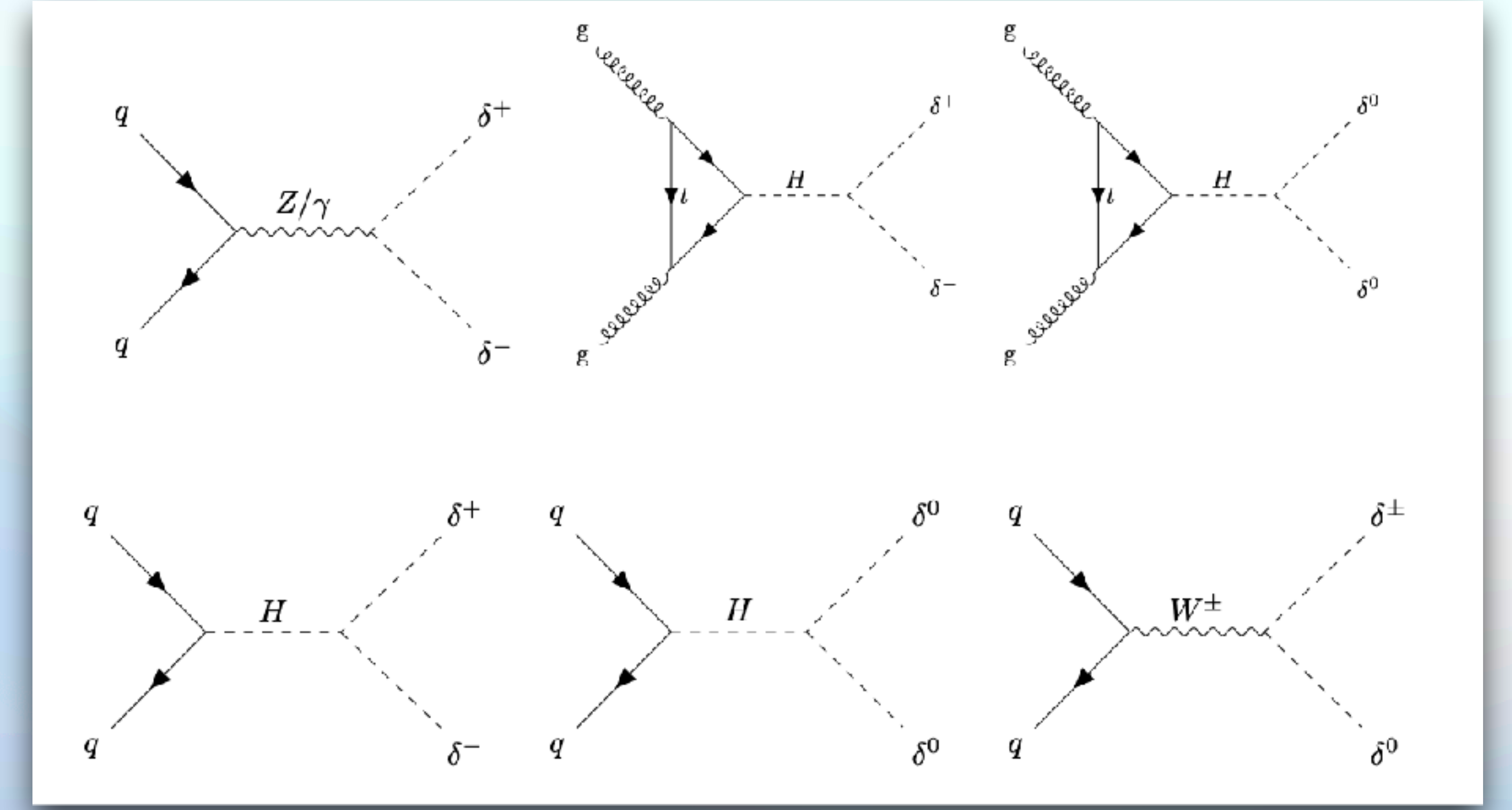
TABLE III. Benchmark points chosen for showcasing the evolution of visible sector and dark sector asymmetries.

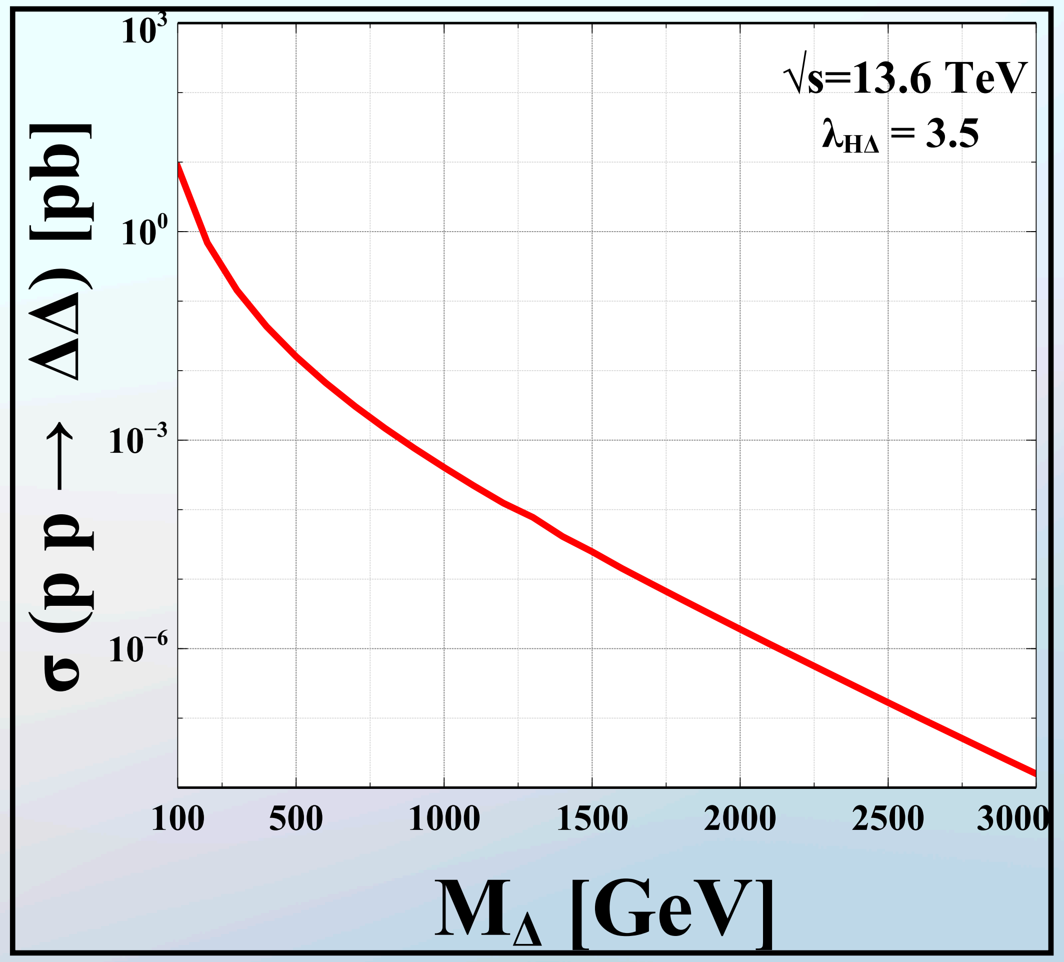
Relevant Processes in Cogenesis

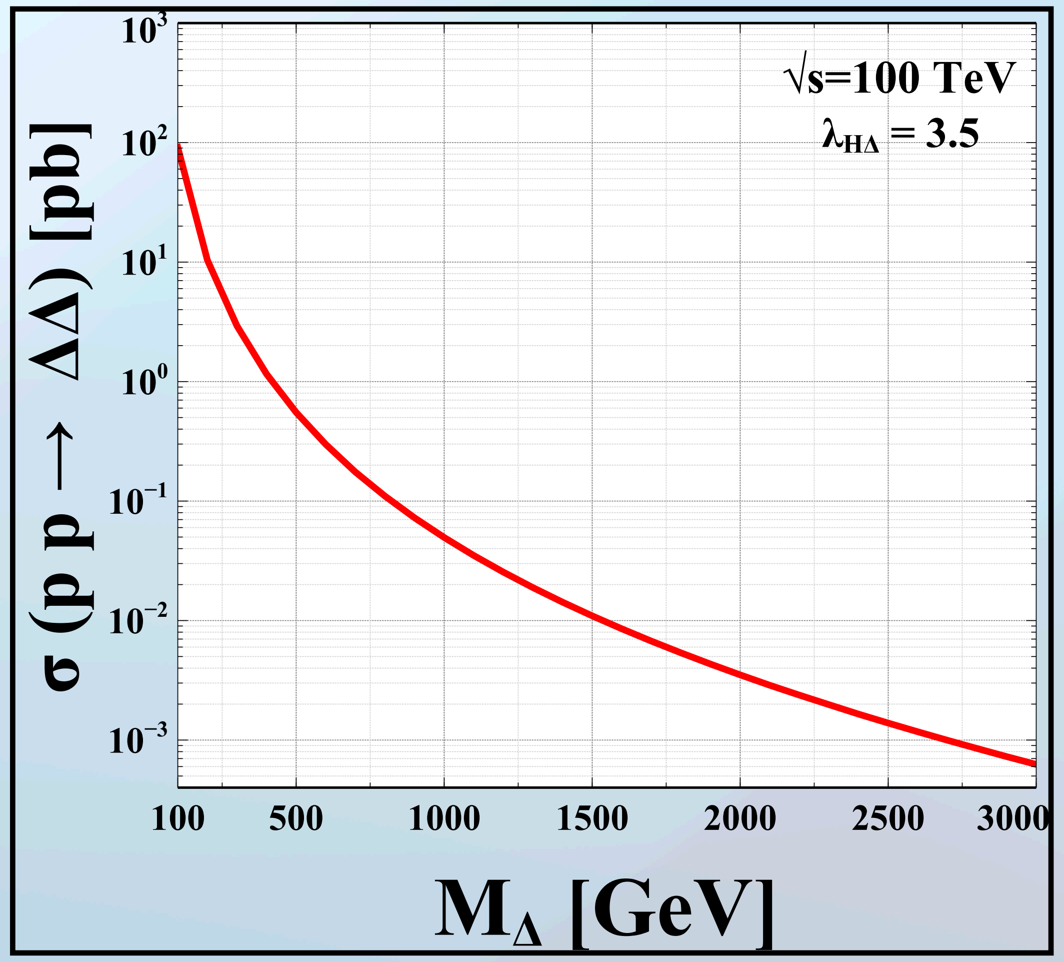



δ M (MeV)
185
180
175
170
165
100
200
400
600
800
1000
M_Δ(GeV)

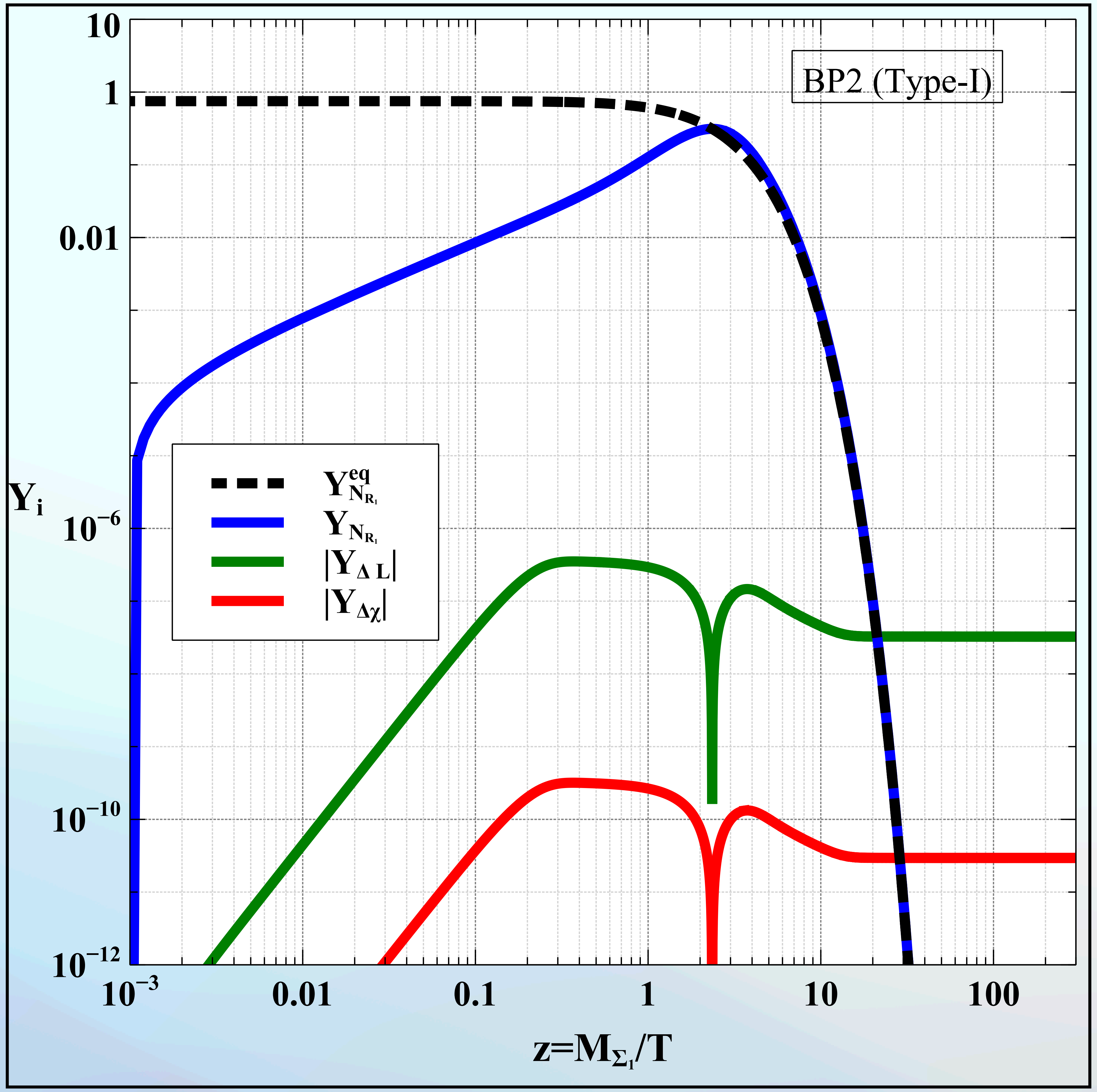

cτ (cm)
5.5
5
4.5
4
3.5
165
170
175
180
185
δM (MeV)

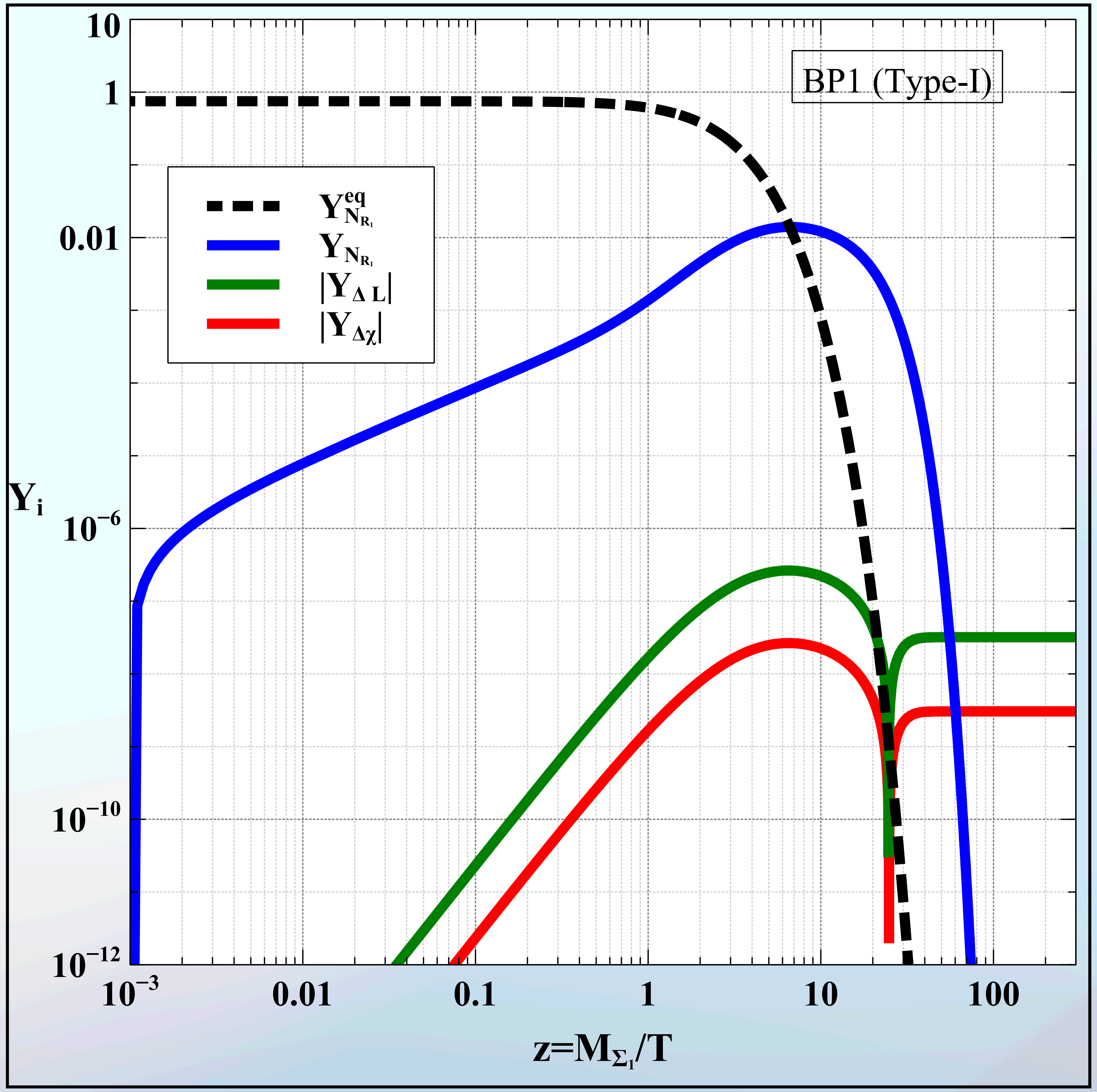

q
q
Z/γ
δ+
δ−
g
g
H
δ0
H
W±
δ±


√s=13.6 TeV
$\lambda_{H\Delta}$ = 3.5
σ (p p → ΔΔ) [pb]
10^3
10^0
10^{-3}
10^{-6}
100
500
1000
1500
2000
2500
3000
M_Δ [GeV]

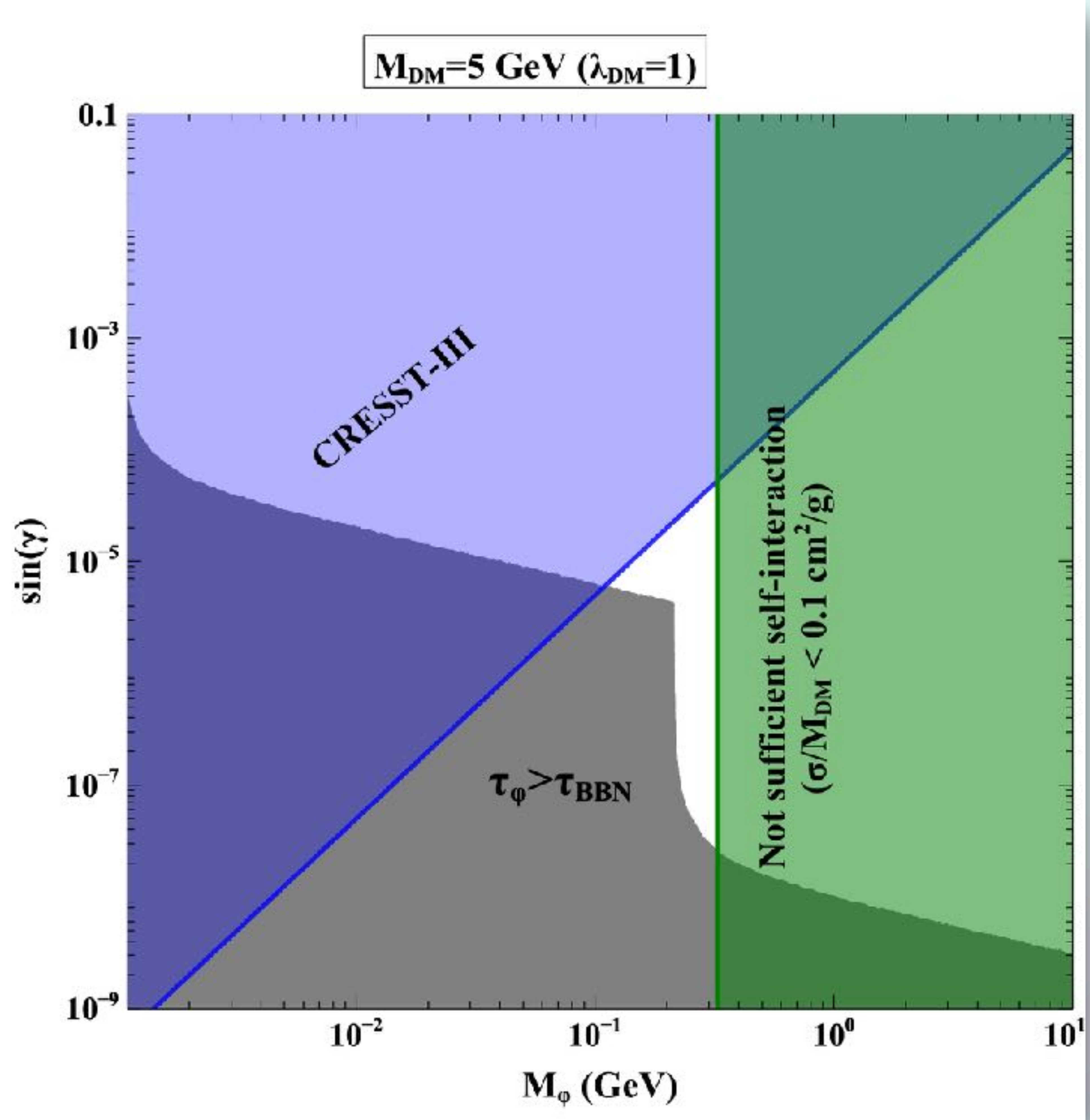

√s=100 TeV
$\lambda_{H\Delta}$ = 3.5
σ (p p → ΔΔ) [pb]
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
100
500
1000
1500
2000
2500
3000
M_Δ [GeV]

Type-I seesaw Cogenesis





Parameter space for a fixed DM mass

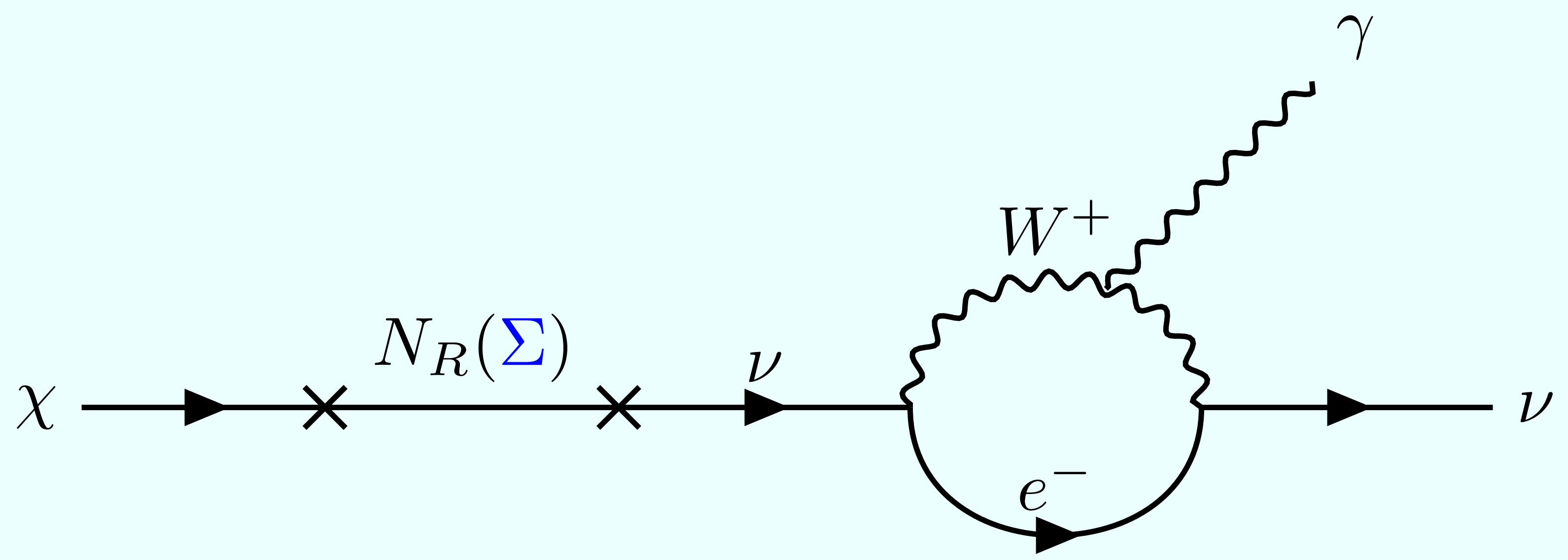


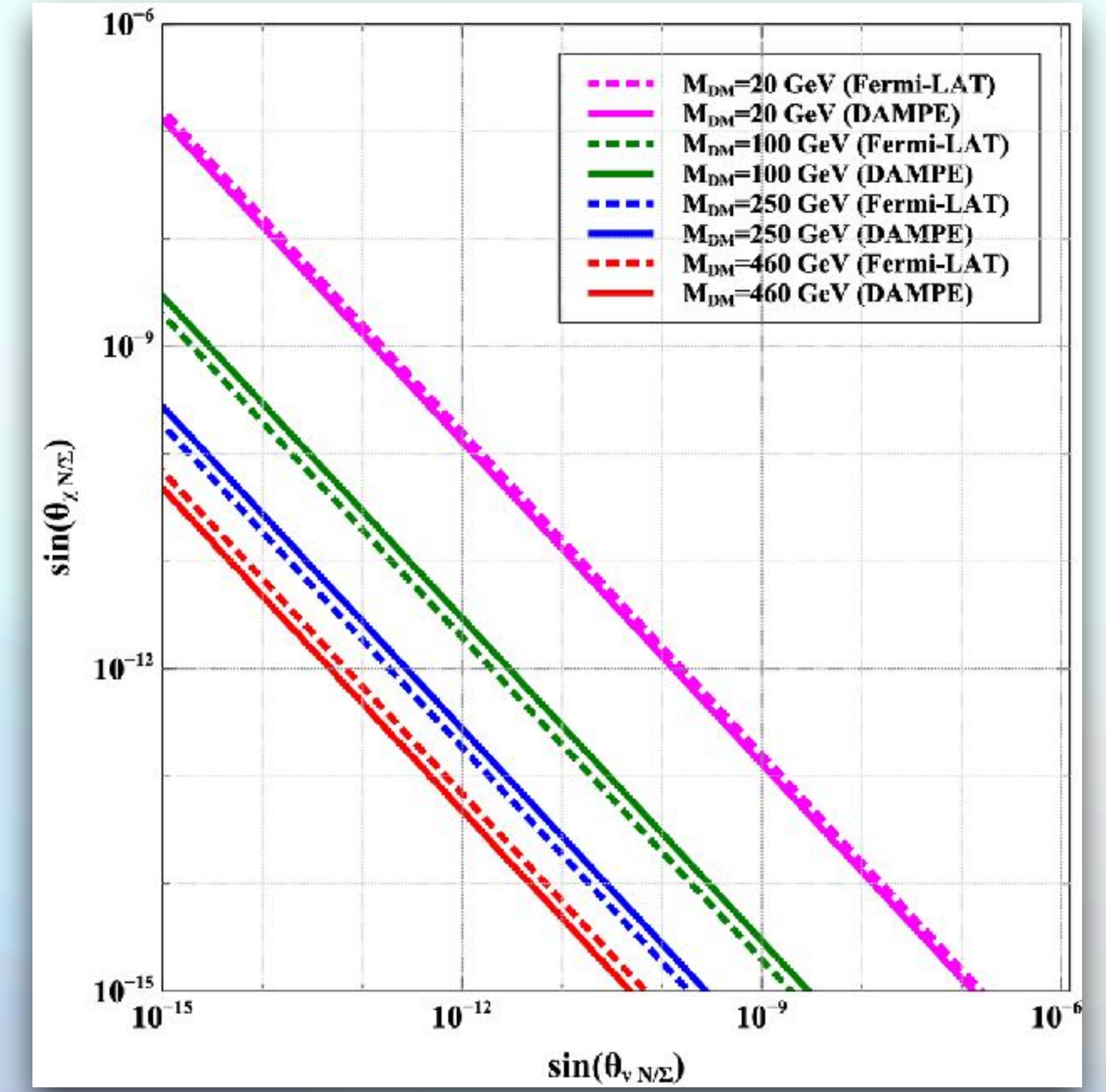
Benchmark Points ASIDM

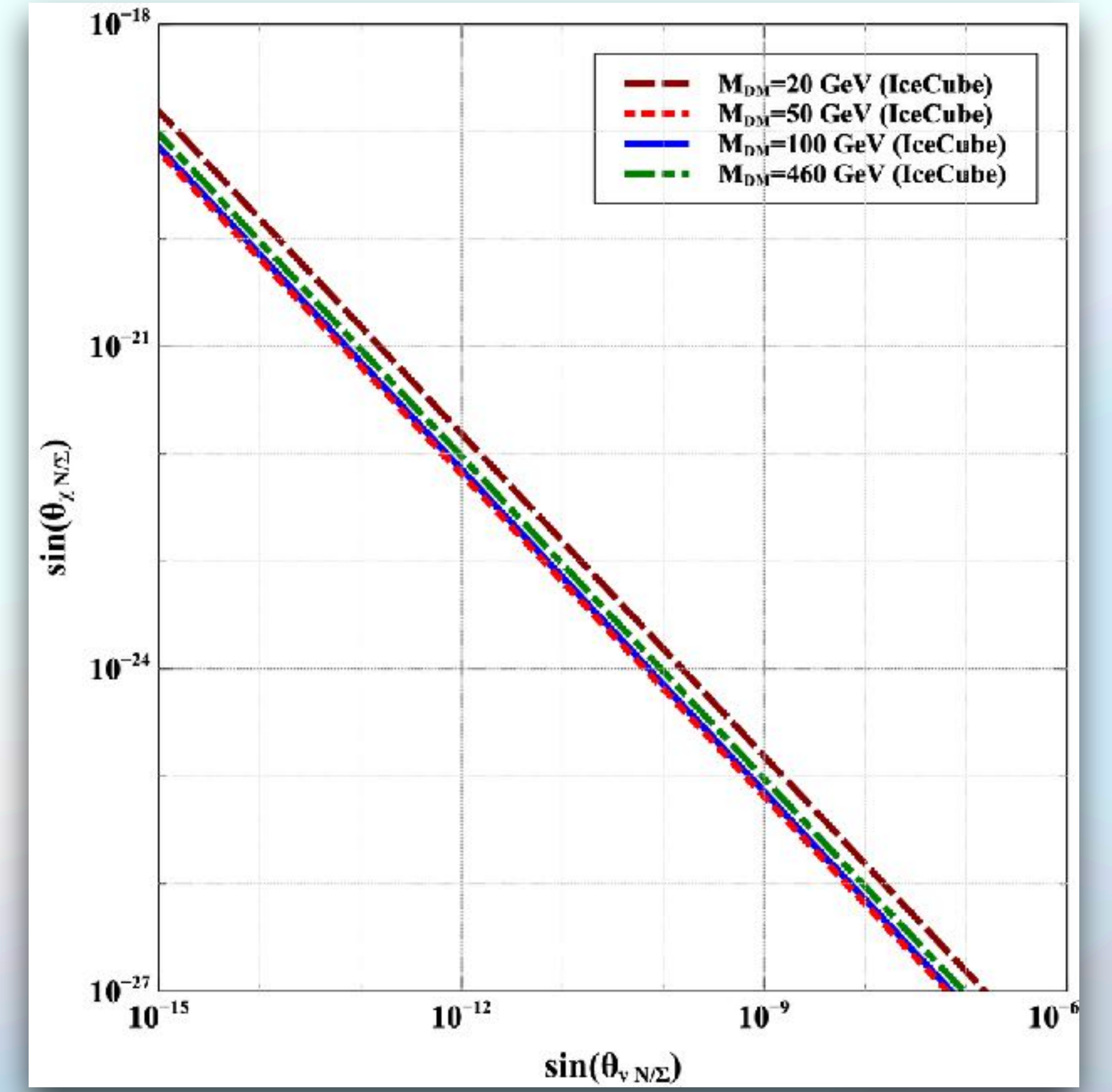
TABLE II. Benchmark points that simultaneously satisfy DM self-interaction, direct detection, and BBN constraints.

BPs	$M_{\rm DM}$(GeV)	M_ϕ(MeV)	$\lambda_{\rm DM}$	$\sin\gamma$	$\sigma^{\rm SI}_{\rm DM-N}$ (cm^2)	τ_ϕ(s)
BP1	0.1	67.54	1.26	2.02×10^{-3}	5.71×10^{-37}	1.39×10^{-5}
BP2	1	223.00	2.89	8.67×10^{-5}	1.33×10^{-39}	1.64×10^{-6}
BP3	10	586.27	1.11	1.88×10^{-8}	6.11×10^{-49}	5.31×10^{-1}
BP4	100	2531.10	0.72	2.64×10^{-7}	1.69×10^{-49}	5.12×10^{-4}

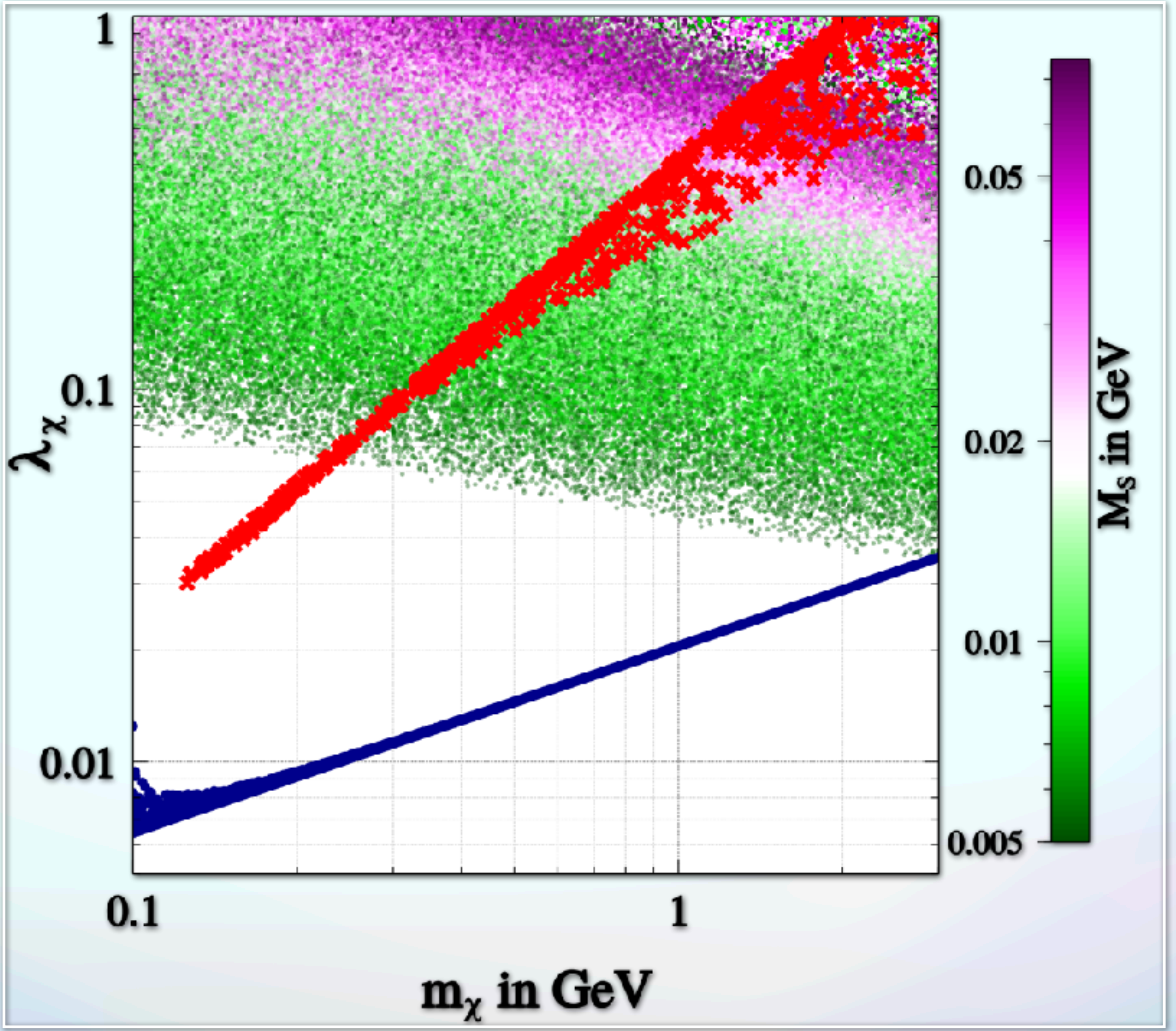
Monochromatic gamma-ray line and neutrino lines signatures







SIDM and Relic consistent parameter space with FOPT



SIDM Cross-section

The non-relativistic DM self-scattering can be effectively described using the attractive Yukawa potential:

$$V(r) = -\frac{\lambda_\chi^2}{4\pi r} e^{-M_S r}$$

To capture the relevant physics of forward scattering, the transfer cross-section is defined as

$$\sigma_T = \int d\Omega (1 - cos\theta) \frac{d\sigma}{d\Omega}$$

In the Born limit, where ${\lambda_\chi}^2 m_\chi/(4\pi M_S) \ll 1$, the transfer cross-section is given by:

$$\sigma_T^{\mathrm{Born}} = \frac{{\lambda_\chi}^4}{2\pi m_\chi^2 v^4} \left[\log\left(1 + \frac{m_\chi^2 v^2}{M_S^2}\right) - \frac{m_\chi^2 v^2}{M_S^2 + m_\chi^2 v^2} \right]$$

SIDM Cross-section

Outside the Born limit, where $\lambda_\chi^2 m_\chi/(4\pi M_S) \geq 1$, there are two different regimes: the classical regime and the resonance regime. In the classical regime ($m_\chi/M_S \geq 1$), solution for an attractive potential is given by

$$\sigma_T^{\text{classical}} = \begin{cases} \frac{4\pi}{M_S^2}\beta^2 \ln(1+\beta^{-1}) & \beta > 1 \\ \frac{8\pi}{M_S^2}\left[\beta^2/(1+1.5\beta^{1.65})\right] & 10^{-1} < \beta \leq 10^3 \\ \frac{\pi}{M_S^2}\left[\ln\beta + 1 - 1/2\ln^{-1}\beta\right]^2 & \beta \geq 10^3 \end{cases}$$

where $\beta = \frac{2\lambda_\chi^2 M_S}{4\pi m_\chi v^2}$.

SIDM Cross-section

Finally in the resonance regime ($m_\chi v/M_S \leq 1$), there is no analytical formula for σ_T. So approximating the Yukawa potential by Hulthen potential $\left(V(r) = -\frac{{\lambda_\chi}^2}{4\pi}\frac{\delta e^{-\delta r}}{1-e^{-\delta r}}\right)$, the transfer cross-section is obtained as:

$$\sigma_T^{\text{Hulthen}} = \frac{16\pi \sin^2 \delta_0}{m_\chi^2 v^2}$$

where $l = 0$ phase shift δ_0 is given by:

$$\delta_0 = \text{Arg}\left[\frac{i\Gamma(im_\chi v/kM_S)}{\Gamma(\lambda_+)\Gamma(\lambda_-)}\right]$$

with

$$\lambda_\pm = 1 + \frac{im_\chi v}{2kM_S} \pm \sqrt{\frac{{\lambda_\chi}^2 m_\chi}{4\pi k M_S} - \frac{m_\chi^2 v^2}{4k^2 M_S^2}}$$

and $k \approx 1.6$ is a dimensionless number.