Asymmetric Dark Matter

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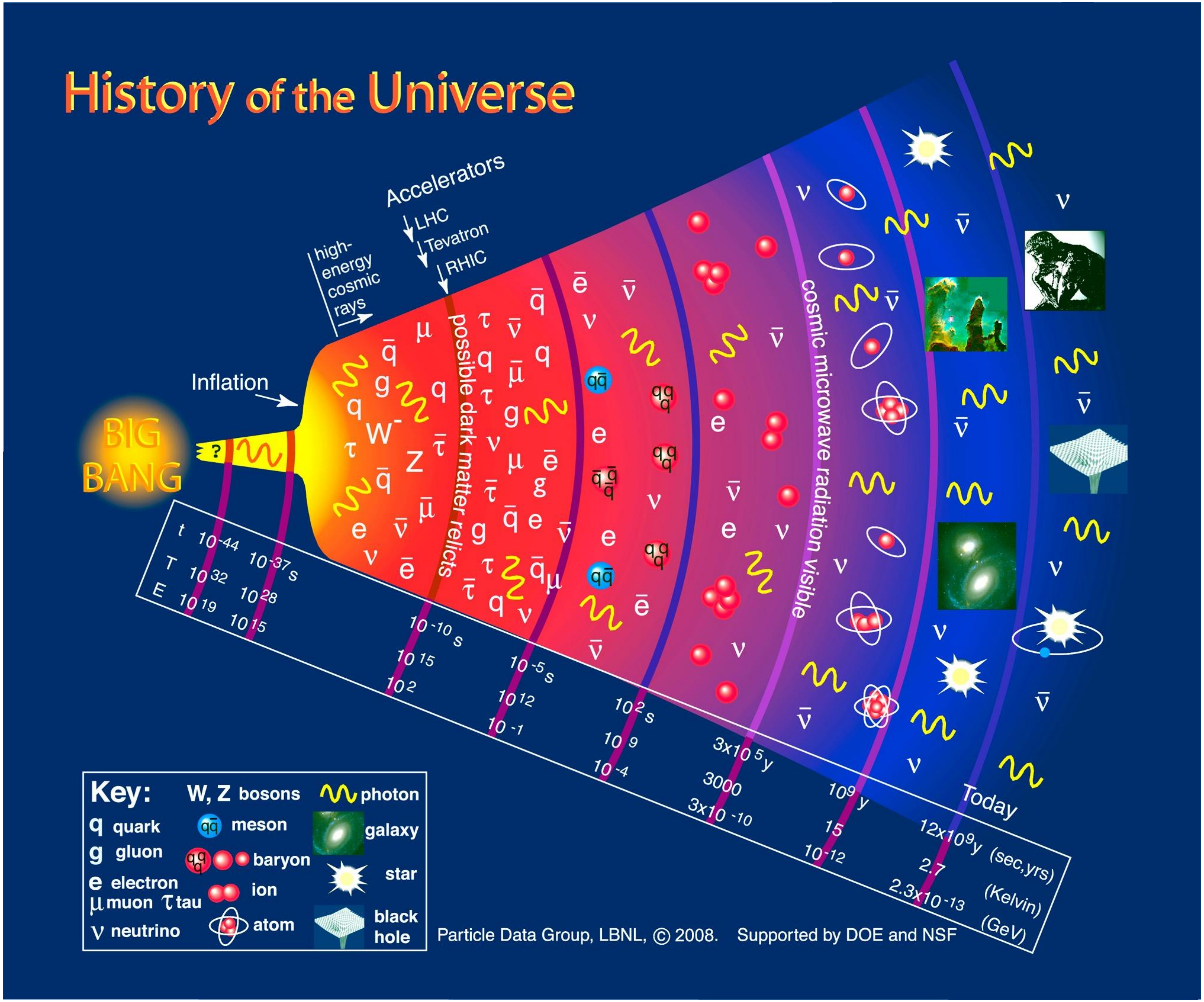
Outline

- Introduction
- Generic features of Asymmetric Dark Matter (ADM)
  - Relic Abundance
  - Detection Prospects
- Model building aspects
- Conclusion



History of the Universe

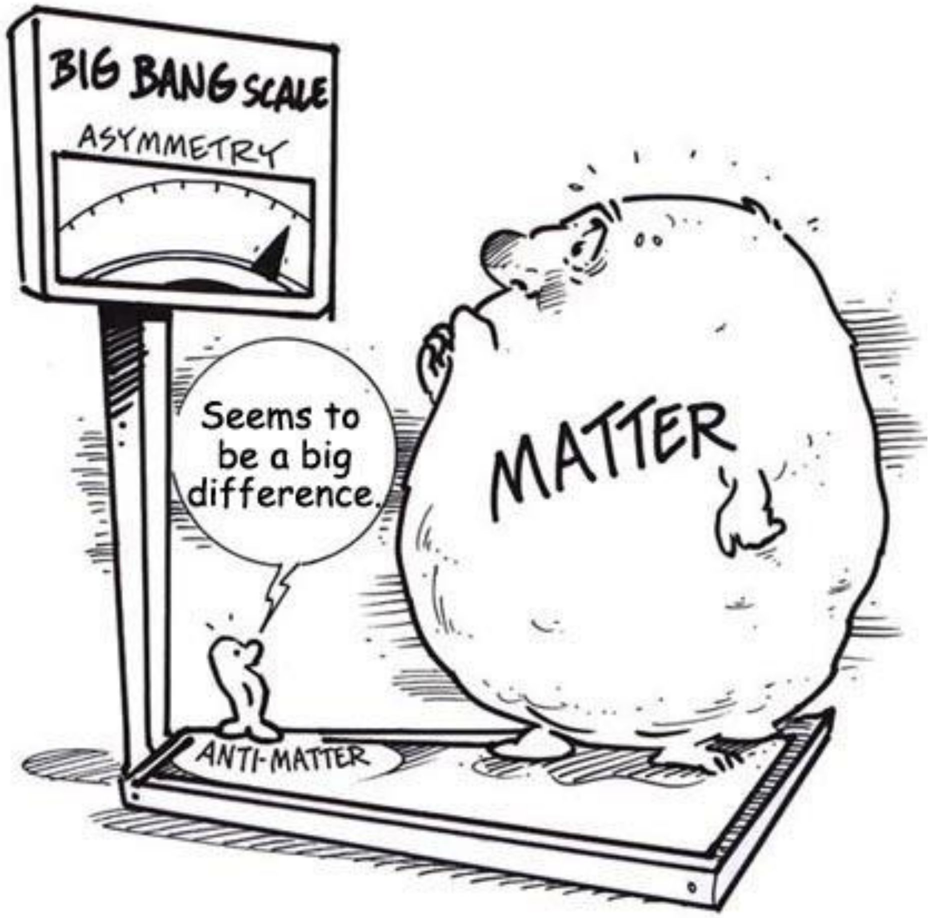
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Matter-Antimatter Asymmetry

- Dirac predicted the existence of anti-particle in 1928; later it was confirmed in observations: positron (1933), antiproton (1955), antineutron (1956) and so on.
- However, we observe mostly matter around us in the Universe without any trace of anti-matter leading to the longstanding puzzle of baryon asymmetry of Universe (BAU).
- Cosmic rays contain negligible trace of anti-matter.

Matter-Antimatter Asymmetry

- Absence of characteristic gamma-rays from matter-antimatter annihilation suggests asymmetry or separation of their respective patches beyond horizon distances.
- No known causal mechanism can separate these patches in the Universe.
- Equal baryon and antibaryon will lead to efficient annihilations for a long epoch leaving a small baryon to photon ratio: inconsistent with light nuclei abundance (BBN).

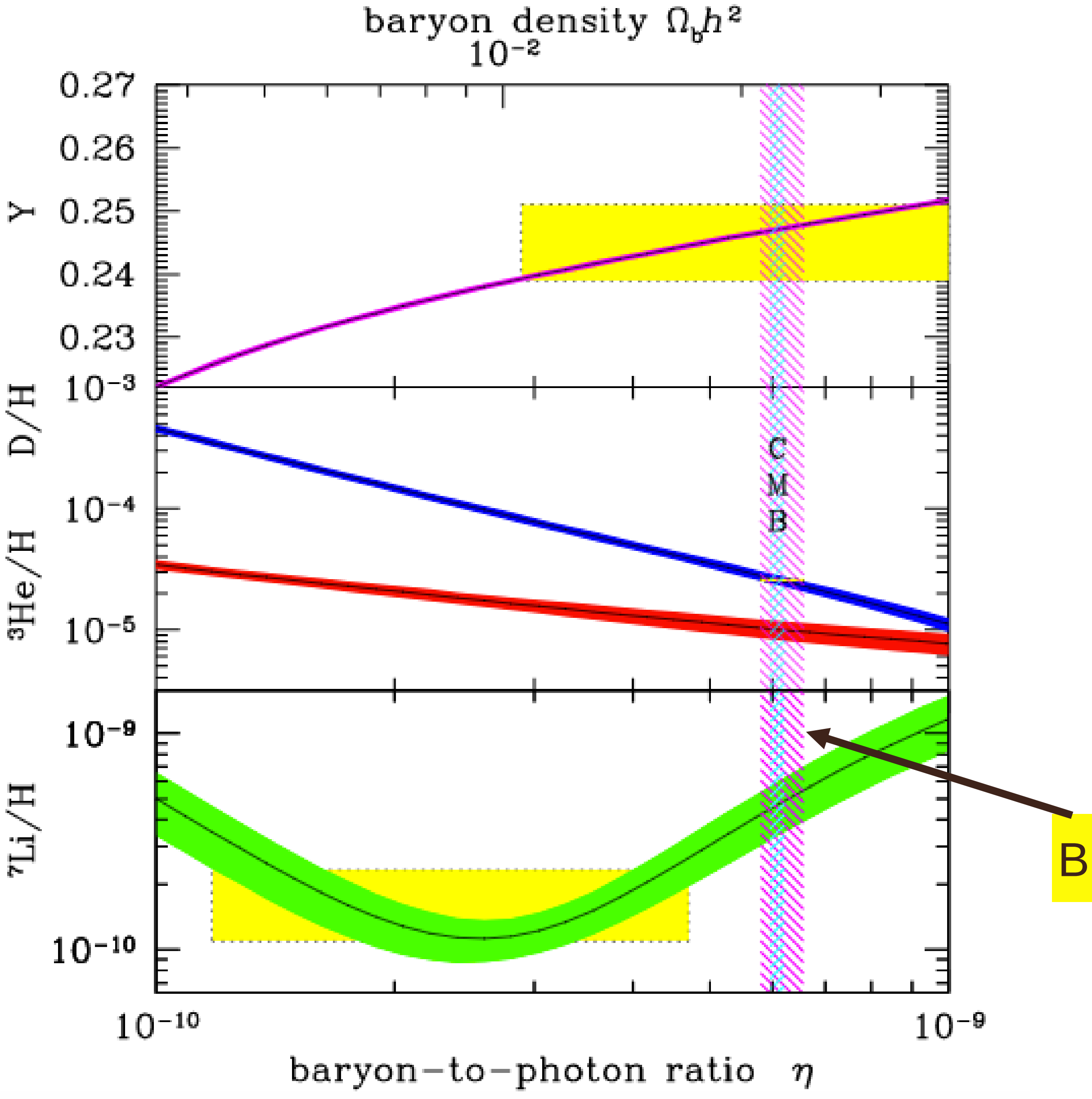


Matter-Antimatter asymmetry

- The observed BAU is often quoted in terms of baryon to photon ratio

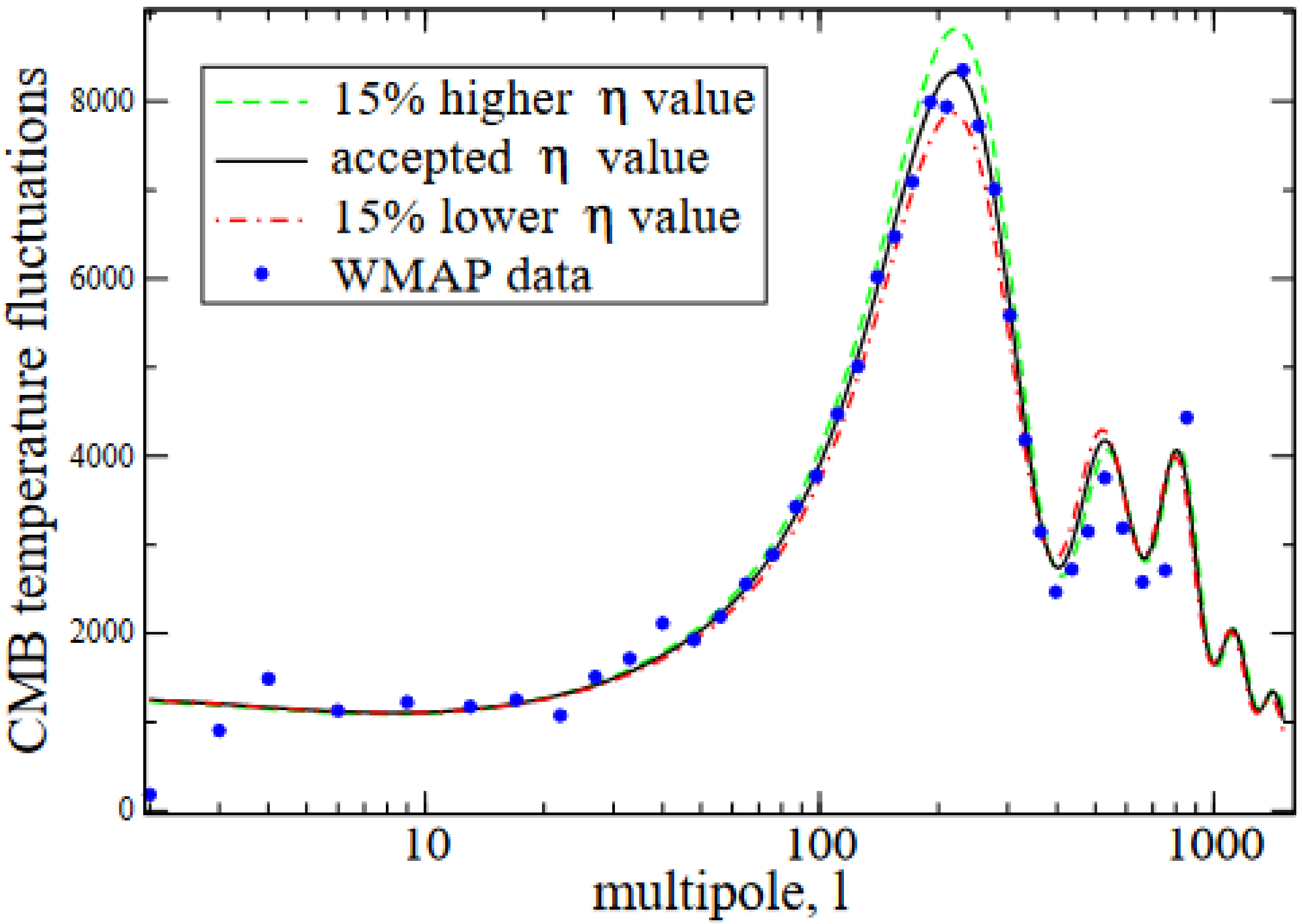
$$\eta_B = \frac{n_B - n_{\overline{B}}}{n_\gamma} = 6.04 \pm 0.08 \times 10^{-10}$$

- The prediction for this ratio from the BBN agrees well with the observed value inferred from the CMB measurements (Planck 2018, arXiv:1807.06209).



BBN

Particle Data Group



- CMB gives stricter constraint on baryon to photon ratio compared to BBN.

Source: hep-ph/0609145

How to create baryon asymmetry?

- Start with an asymmetric initial condition? “*Unnatural*” and likely to be diluted by inflationary expansion phase.
- Early freeze-out?
- Dynamically generate an asymmetry.

Sakharov’s Conditions

Three basic ingredients necessary to generate a net baryon asymmetry from an initially baryon symmetric Universe (Sakharov 1967):

- Baryon Number (B) violation $X \rightarrow Y + B$
- C & CP violation. $\Gamma(X \rightarrow Y + B) \neq \Gamma(\overline{X} \rightarrow \overline{Y} + \overline{B})$

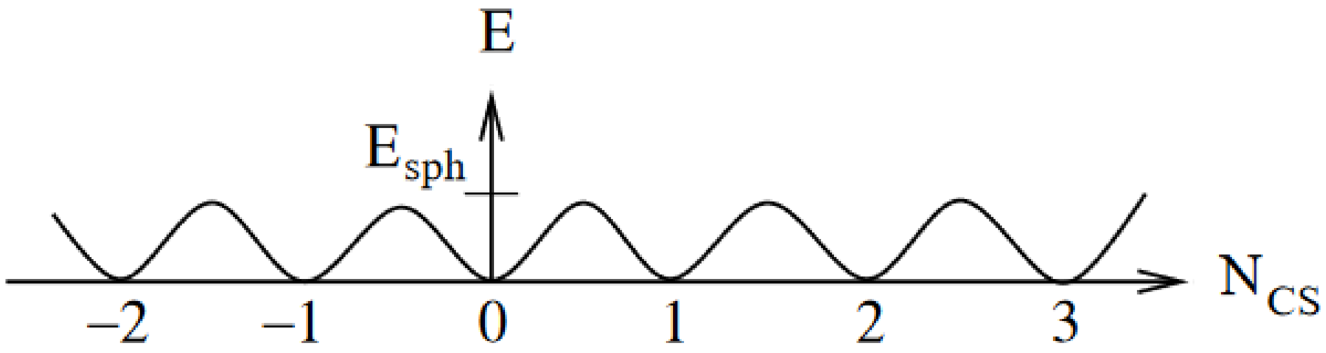
$$\Gamma(X \rightarrow q_L q_L) + \Gamma(X \rightarrow q_R q_R) \neq \Gamma(\overline{X} \rightarrow \overline{q_L} + \overline{q_L}) + \Gamma(\overline{X} \rightarrow \overline{q_R} + \overline{q_R})$$

- Departure from thermal equilibrium.

Standard Model (SM) fails to satisfy these conditions in required amount

B violation

- While B is conserved in the SM at perturbative level, it is broken by non-perturbative instanton like transitions, known as sphalerons ('t Hooft 1976).



- The tunnelling amplitude is suppressed at zero temperature: $A \approx e^{-8\pi^2/g^2} \approx 10^{-173}$.

- Finite temperature effects can make these transitions efficient (Kuzmin, Rubakov, Shaposhnikov 1985).

- Sphalerons remain in equilibrium for $10^2\mathrm{GeV} < T < 10^{13}\mathrm{GeV}$

CP Violation

- CKM is the only known source of CP violation in the SM, can be parametrised as

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

- A parametrisation-independent measure of CP violation is the Jarlskog invariant J (Jarlskog 1985):

$$\begin{aligned} \mathrm{Im}\,\det\left([M^u M^{u\dagger}, M^d M^{d\dagger}]\right) &= 2\,J\,(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2) \\ &\quad \times (m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2) \end{aligned}$$

$J = c_{12}c_{23}c_{13}^2 s_{12}s_{23}s_{13}\sin\delta \approx 3 \times 10^{-5}$ Too small to give observed $\eta \sim 10^{-10}$

Baryogenesis in SM

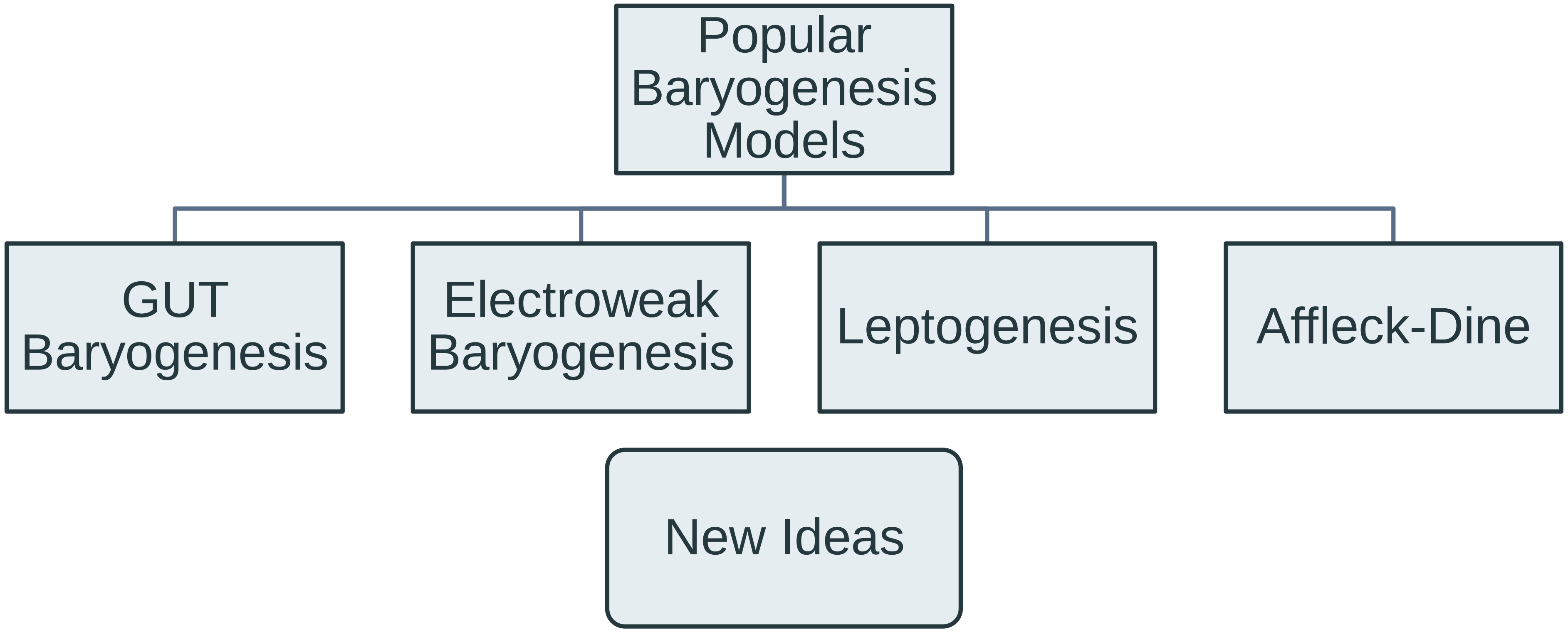
Requires

- Sufficient B violation
- Sufficient C and CP violation
- Departure from equilibrium which can be provided by a strong first order electroweak phase transition creating necessary barriers.

However,

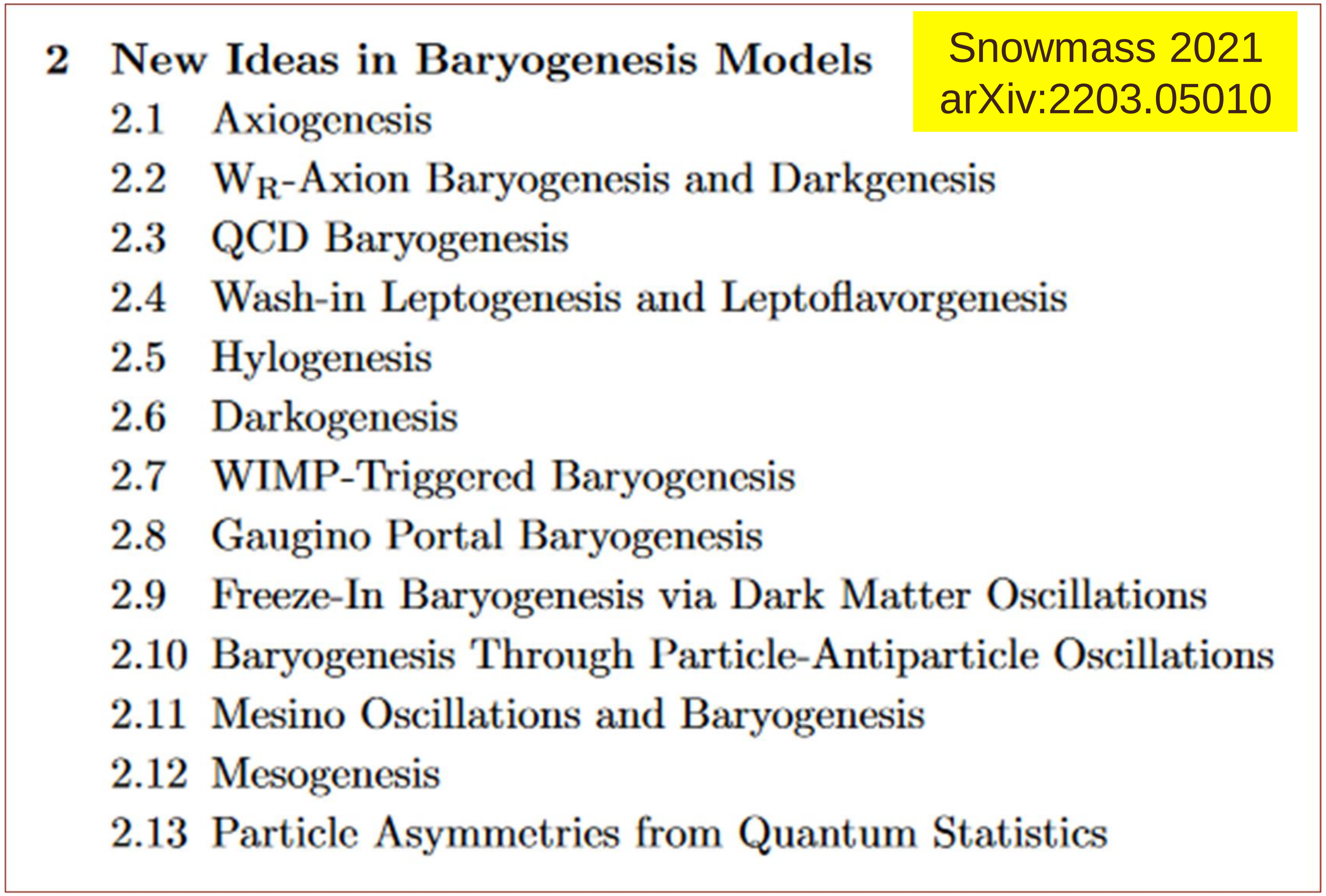
SM has insufficient CP violation in the quark sector.

Electroweak phase transition is not a first order transition.



- Popular Baryogenesis Models
  - GUT Baryogenesis
  - Electroweak Baryogenesis
  - Leptogenesis
  - Affleck-Dine

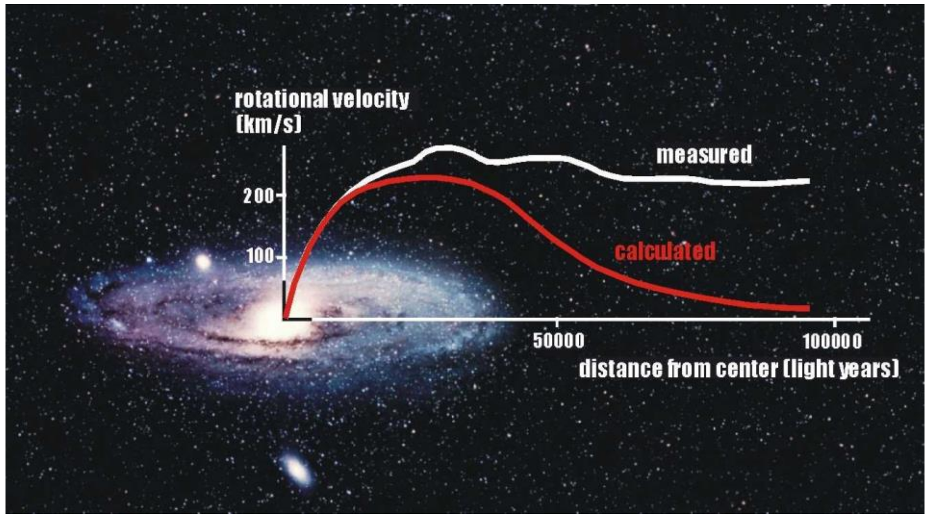
New Ideas

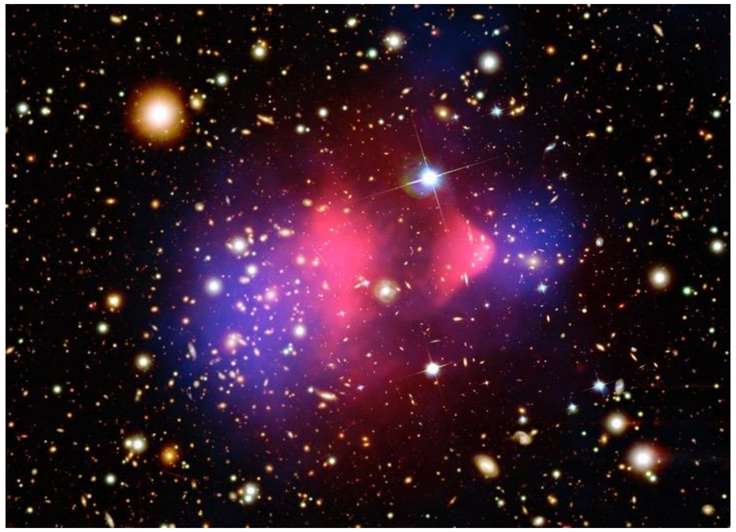


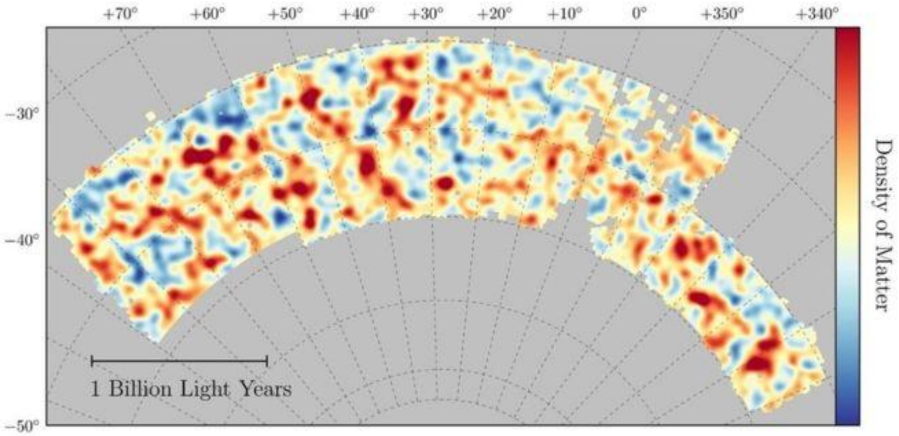
Snowmass 2021
arXiv:2203.05010

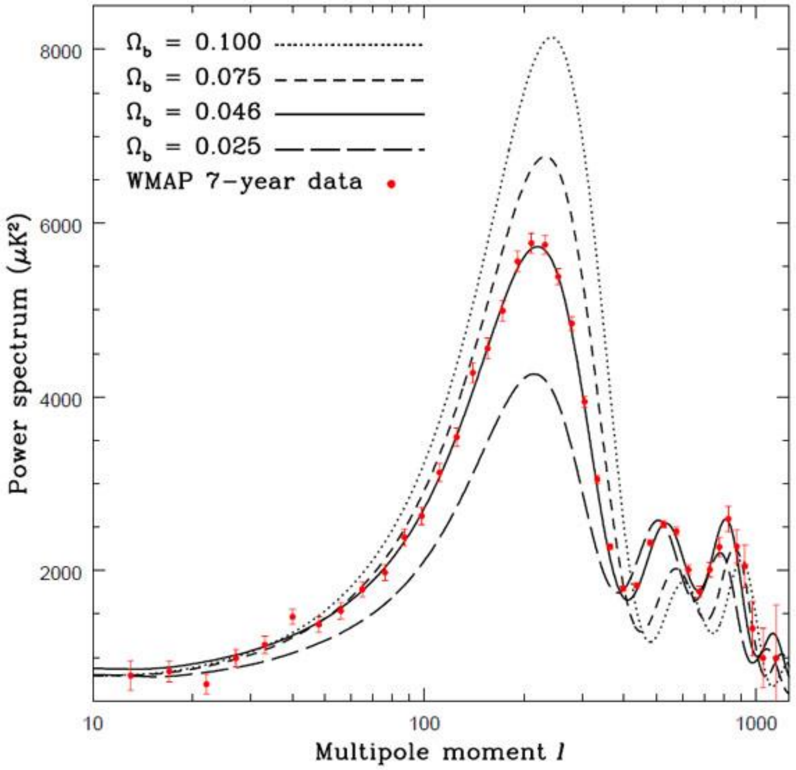
Could dark matter play any role in antimatter disappearance?

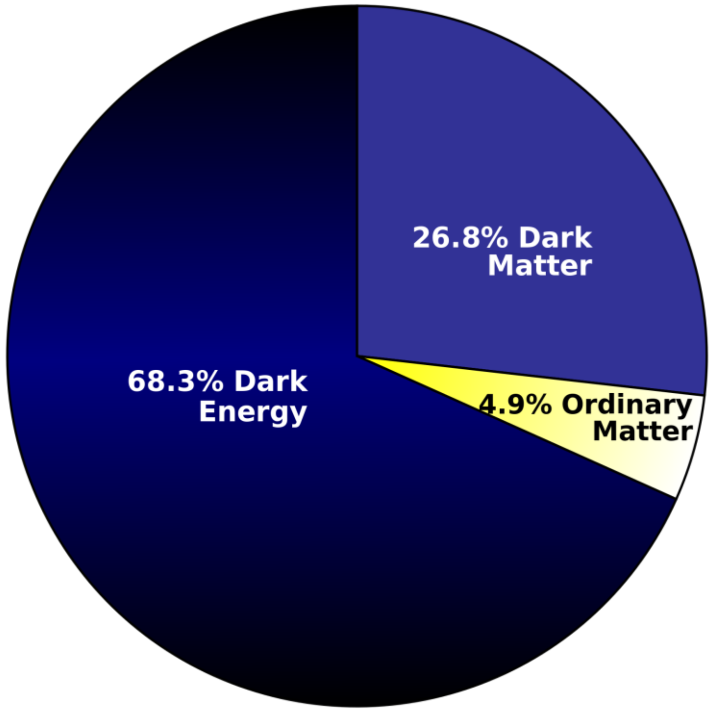
Dark Matter: Evidences

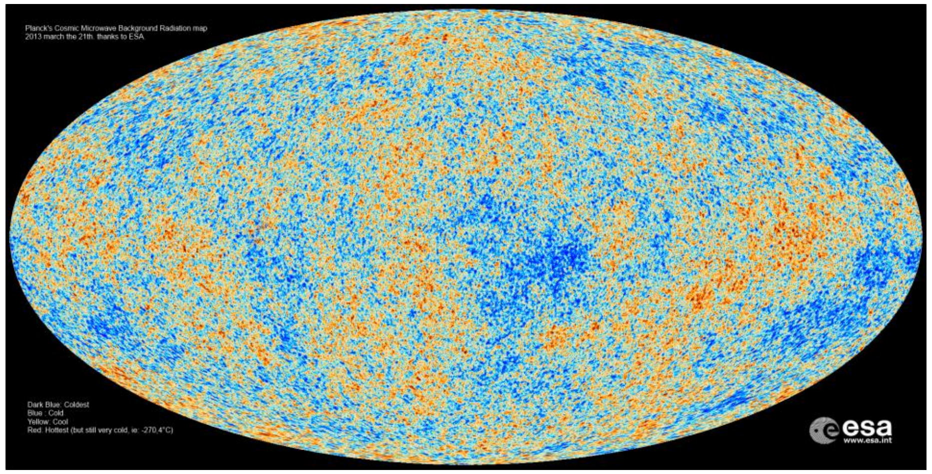








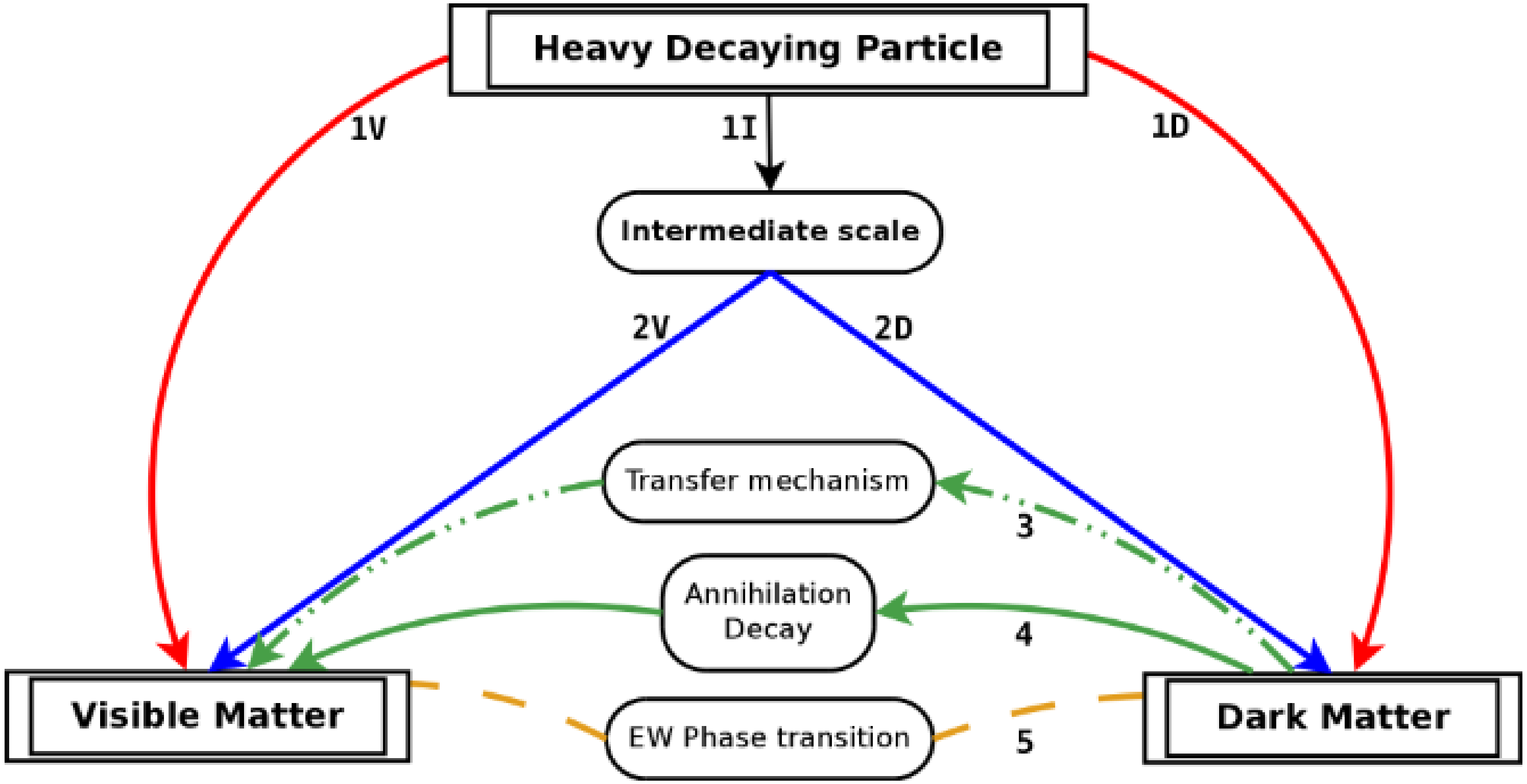




Credits: HST, Chandra, DES, WMAP, Planck

Standard Model does not have any DM candidate

- Baryon-DM coincidence: $\Omega_{DM} \simeq 5\Omega_B$
- They could possibly have a common origin?



Schematic of popular ideas; arXiv:1310.1904

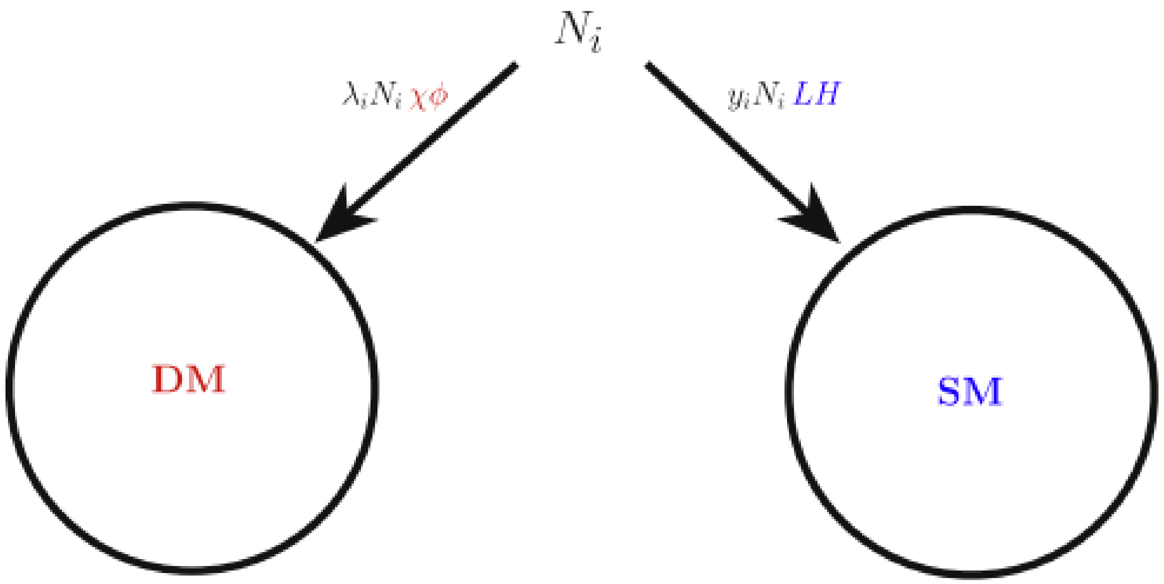
Nussinov'87; Yoshimura'78, Barr'79, arXiv:1112.2714, 1203.1247, 1305.4939, 1308.0338, 1407.4566, 2002.05170, 2112.10784++

Popular scenarios:

- Asymmetric Dark Matter
- WIMPy baryogenesis/leptogenesis

Asymmetric DM

- Baryon/lepton asymmetry and DM asymmetry have a common origin.
- Requires a large annihilation rate of DM to get rid of symmetric part: can give large direct detection rate.
- No DM annihilation in present epoch: suppressed indirect detection.
- Non-annihilating nature of DM at present epoch can lead to other detection prospects due to DM capture in compact objects (see e.g., arXiv:2302.07898)



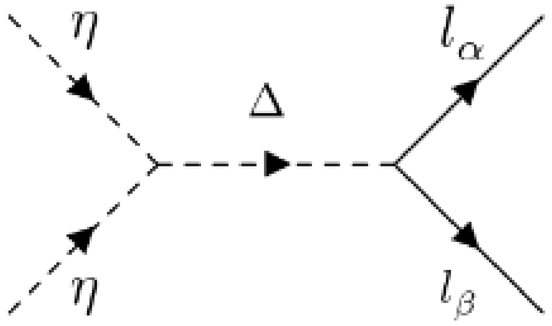
Nussinov 1985
Kaplan, Luty, Zurek 2009
Falkowski, Ruderman, Volanksy 2011
Arina, Sahu 2011
Petraki, Volkas 2013, Zurek 2014 (Reviews)
Barman, DB, Das, Roshan 2022, 2023
DB, Das, Okada 2023
++

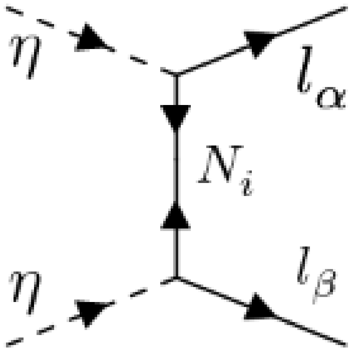
WIMPy Leptogenesis

- DM annihilations can also generate a non-zero lepton or baryon asymmetry. DM annihilations also decide WIMP DM abundance (thermal freeze-out).

- Wash-out processes should freeze-out before DM freeze-out.

- Can have both direct and indirect signatures like WIMP.





Yoshimura 1978;
Cui, Randall, Shuve 2012;
Bernal, Josse-Michaux, Ubaldi 2013;
Bernal, Colucci, Josse-Michaux, Racker, Ubaldi 2013;
Racker, Nius 2014;
Baldes, Bell, Petraki, Volkas 2014;
DB, Dasgupta, Kang 2019, 2020;
Dasgupta, Bhupal Dev, Kang, Zhang 2020;
Mahanta, DB 2023
++

Generic Features of ADM

- Dark sector has a conserved or approximately conserved quantum number (a global symmetry).
- Dark matter has some sizeable interactions to annihilate away the symmetric part efficiently.

Relic abundance: Boltzmann Equation

Liouville operator [f] $\hat{L}[f] = C[f]$ Collision operator [f]

$$\hat{L} = p^{\alpha}\frac{\partial}{\partial x^{\alpha}} - \Gamma^{\alpha}_{\beta\gamma}p^{\beta}p^{\gamma}\frac{\partial}{\partial p^{\alpha}}$$

$$\hat{L}[f] = E\frac{\partial f}{\partial t} - H(t)\,p^{2}\frac{\partial f}{\partial E}$$

$$\frac{g}{(2\pi)^3}\int \hat{L}[f]\,\frac{d^3p}{E} = \frac{\partial n}{\partial t} + 3Hn$$

$$\frac{\partial n}{\partial t} + 3Hn = \frac{g}{(2\pi)^3}\int C[f]\,\frac{d^3p}{E}$$

$$\boxed{\begin{aligned}\frac{g_\chi}{(2\pi)^3}\int C[f]\,\frac{d^3p_\chi}{E_\chi} &= -\int d\Pi_\chi d\Pi_a d\Pi_i d\Pi_j \times (2\pi)^4 \times \delta^4(p_\chi + p_a - p_i - p_j) \\ &\times \Big(|\mathcal{M}|^2_{\chi+a\to i+j} f_\chi f_a (1\pm f_i)(1\pm f_j) - |\mathcal{M}|^2_{i+j\to\chi+a} f_i f_j (1\pm f_\chi)(1\pm f_a)\Big)\end{aligned}}$$

$$\sigma_{\chi+a\to i+j} = \frac{1}{E_\chi E_a g_\chi g_a v}\sum_{\text{spin}}\int d\Pi_i d\Pi_j (2\pi)^4\delta^4(p_\chi + p_a - p_i - p_j)|\mathcal{M}|^2_{\chi+a\to i+j},$$

$$\frac{\partial n_\chi}{\partial t} + 3Hn_\chi = -\langle\sigma_{\chi+a\to i+j}v\rangle\left(n_\chi n_a - n_\chi^{\text{eq}} n_a^{\text{eq}}\right)$$

Assumptions:

- FLRW Metric
- CP invariance
- 2->2 process $1 \pm f \simeq 1$
- Classical statistics
- Bath follows MB distribution

Reference:

1. The Early Universe by Kolb & Turner
2. Modern Cosmology by Dodelson

Dark Matter: WIMP Miracle

The abundance of DM which was in thermal equilibrium in the early Universe can be calculated by solving the Boltzmann equation.

$$\frac{\partial n_\chi}{\partial t} + 3Hn_\chi = -\langle \sigma_{\rm tot}\, v\rangle \left(n_\chi^2 - (n_\chi^{\rm eq})^2\right)$$

In terms of comoving density

$$\frac{dY_\chi}{dx} = -\frac{x\,\langle \sigma_{\rm tot}\, v\rangle\, s}{H(m_\chi)} \left(Y_\chi^2 - (Y_\chi^{\rm eq})^2\right)$$

$$Y_\chi \equiv \frac{n_\chi}{s} \qquad x \equiv \frac{m_\chi}{T}$$

$$\Omega_\chi h^2(x=\infty) = 2.755 \times 10^8 \left(\frac{m_\chi}{\rm GeV}\right) Y_\chi(x=\infty)$$

A particle having mass and interactions around the electroweak scale, can satisfy the correct relic criteria: WIMP Miracle!

$$H(T)^2 = \frac{8\pi}{3} G\rho(T) \qquad s = \frac{2\pi^2}{45} g_{*s} T^3.$$

$$\rho_R(T) = \frac{\pi^2}{30} g_* T^4, \qquad sR^3 = {\rm constant}$$

Dark Matter: WIMP Miracle

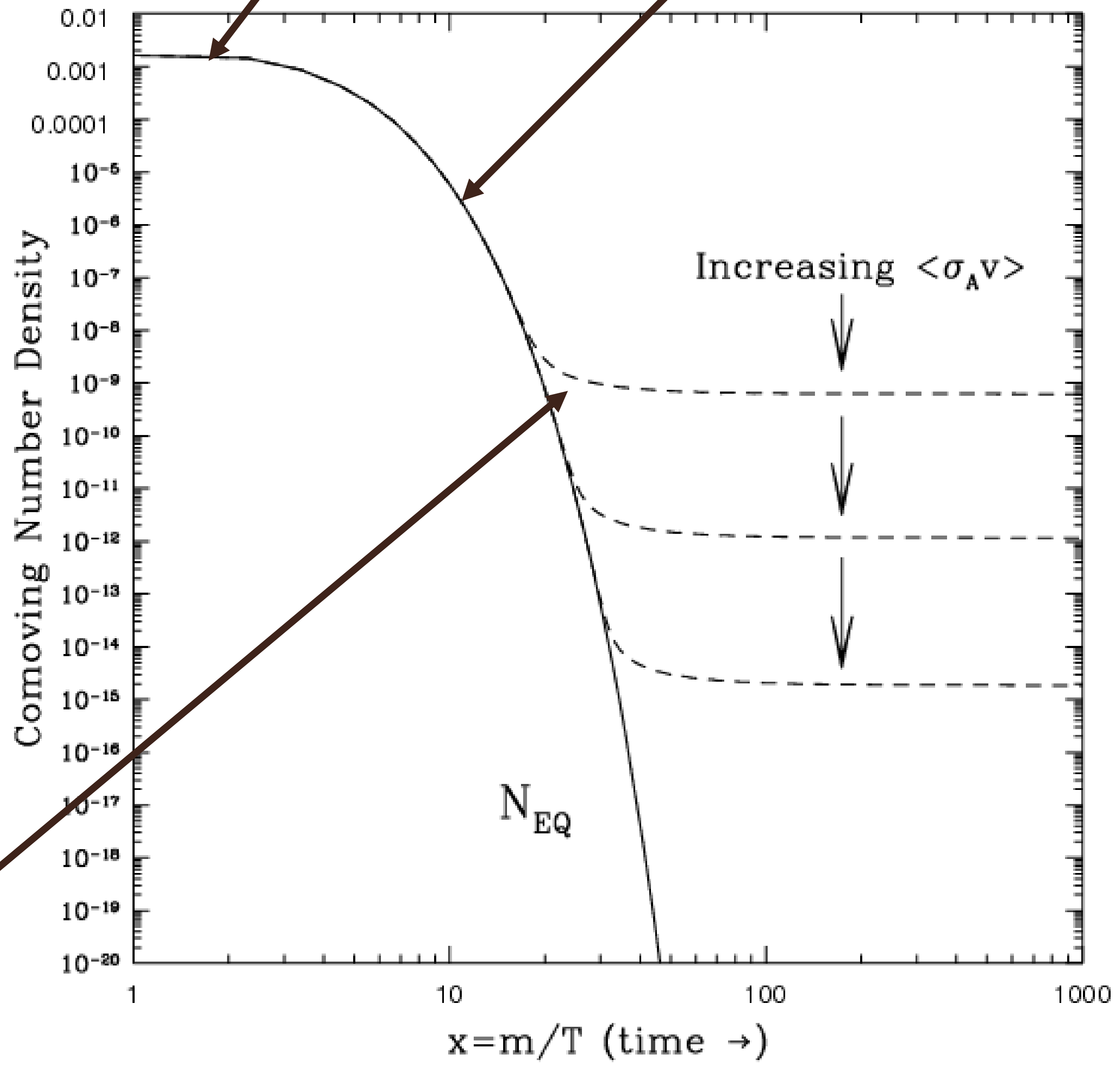
Approximate analytical solution:

$$\Omega_{\mathrm{DM}} h^2 \approx \frac{3 \times 10^{-27} cm^3 s^{-1}}{\langle \sigma v \rangle}$$

Planck 2015, Astron. Astrophys. 2016

$$\Omega_{\mathrm{DM}} h^2 = \frac{\rho_{\mathrm{DM}}}{\rho_{\mathrm{c}}} h^2 = 0.1186 \pm 0.0020$$

Decouples from the thermal bath when rate of interaction falls below Hubble rate of expansion: freeze-out



Relativistic & in eqb at high T

Non-relativistic & in eqb.

arXiv:0901.4090

Relic of ADM

- Only DM & $\overline{\mathrm{DM}}$ can annihilate. No self-annihilation due to conserved charge.
- $Y_\chi - Y_{\bar\chi}$ = Constant (C).

$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + 3Hn_\chi = -\langle\sigma v\rangle(n_\chi n_{\bar\chi} - n_{\chi,\mathrm{eq}} n_{\bar\chi,\mathrm{eq}})$$

$$\frac{\mathrm{d}n_{\bar\chi}}{\mathrm{d}t} + 3Hn_{\bar\chi} = -\langle\sigma v\rangle(n_\chi n_{\bar\chi} - n_{\chi,\mathrm{eq}} n_{\bar\chi,\mathrm{eq}})$$

$$\frac{dY_\chi}{dx} = -\frac{\lambda\langle\sigma v\rangle}{x^2}\,(Y_\chi\,Y_{\bar\chi} - Y_{\chi,\mathrm{eq}}\,Y_{\bar\chi,\mathrm{eq}})$$

$$\frac{dY_{\bar\chi}}{dx} = -\frac{\lambda\langle\sigma v\rangle}{x^2}\,(Y_\chi\,Y_{\bar\chi} - Y_{\chi,\mathrm{eq}}\,Y_{\bar\chi,\mathrm{eq}})$$

$$\lambda = \frac{4\pi}{\sqrt{90}}\,m_\chi M_{\mathrm{Pl}}\,\sqrt{g_*}$$

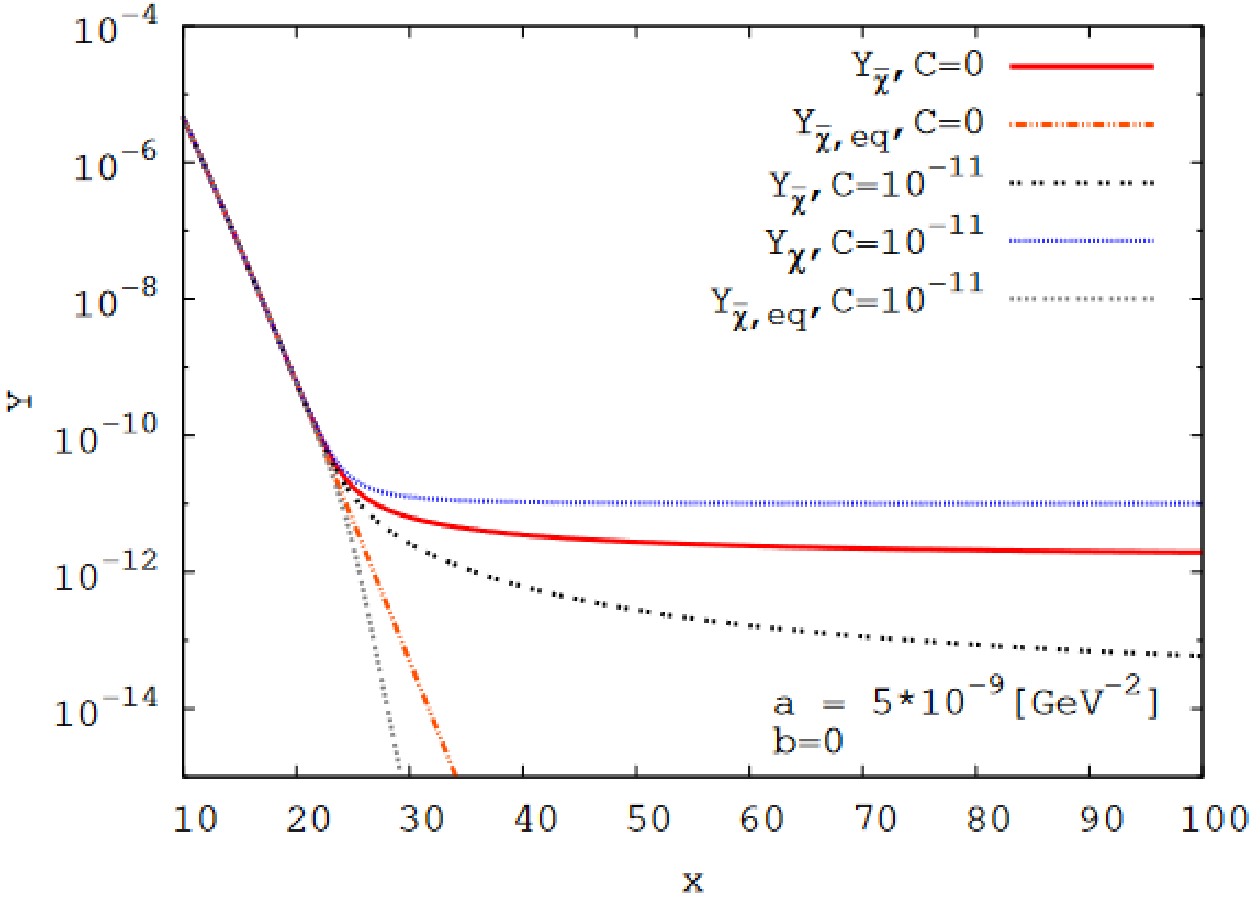
$$\frac{dY_\chi}{dx} = -\frac{\lambda\langle\sigma v\rangle}{x^2}\,(Y_\chi^2 - CY_\chi - P)$$

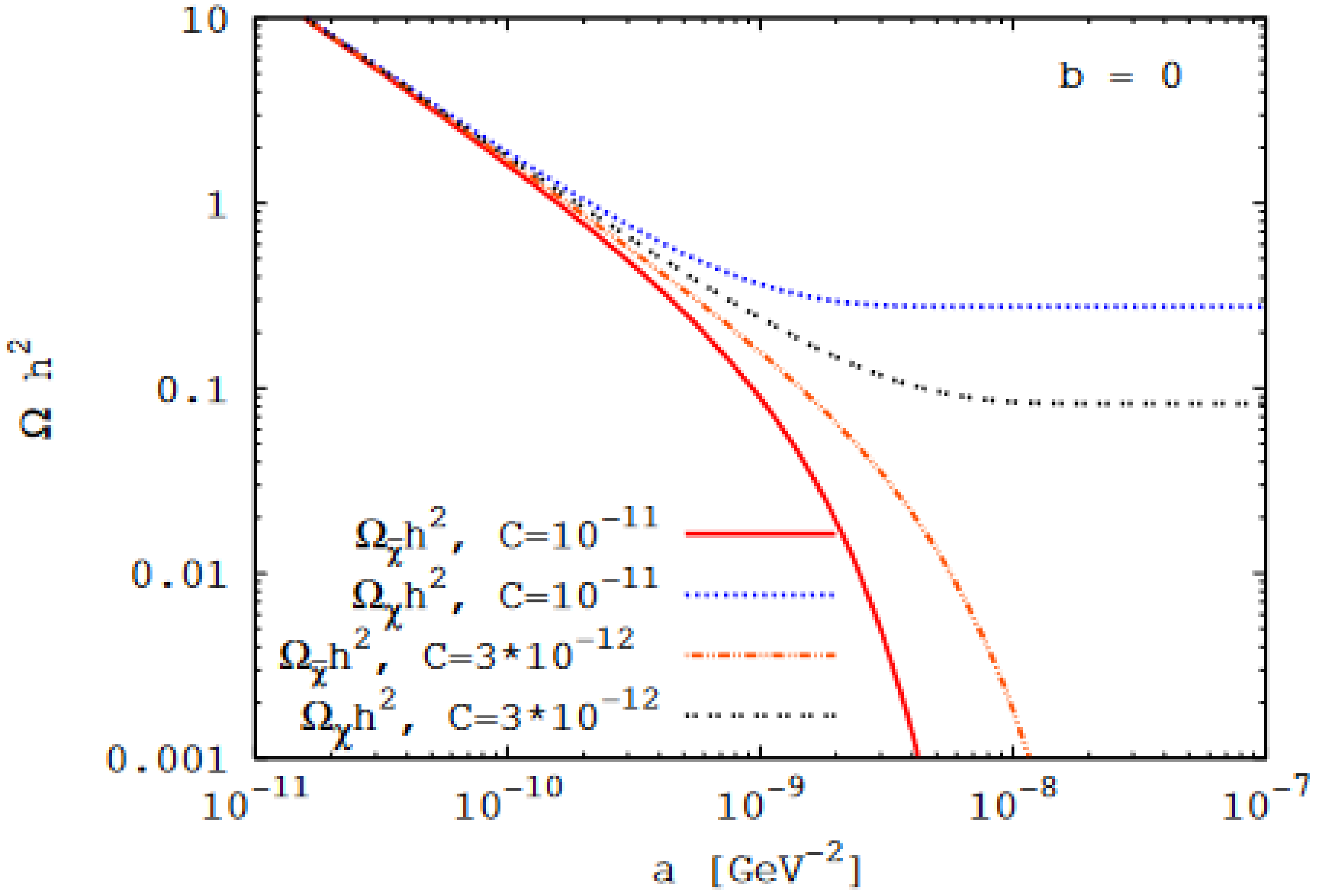
$$\frac{dY_{\bar\chi}}{dx} = -\frac{\lambda\langle\sigma v\rangle}{x^2}\,(Y_{\bar\chi}^2 + CY_{\bar\chi} - P)$$

$$P = Y_{\chi,\mathrm{eq}} Y_{\bar\chi,\mathrm{eq}} = (0.145 g_\chi/g_*)^2\,x^3\,\mathrm{e}^{-2x}$$

arXiv:1104.5548

$\sigma v = a + bv^2$





- Y_χ cannot decrease arbitrarily, being bounded from below by C>0.
- For small σv, relic is independent of C, asymmetry.
- For large σv, $Y_\chi \rightarrow C$ while $Y_{\bar{\chi}} \rightarrow 0$. Total DM relic is independent of σv.

arXiv:1104.5548

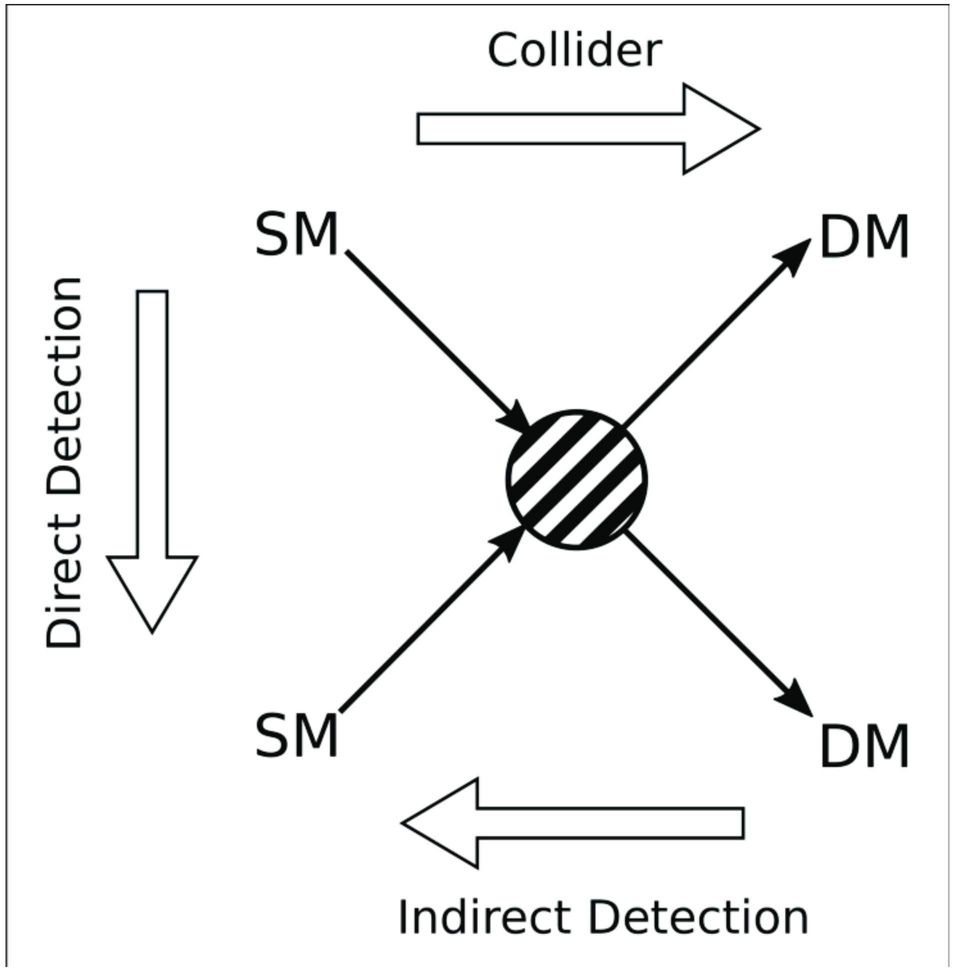
- In purely asymmetric DM scenario, total DM relic is set by the asymmetry only $\Omega_{\mathrm{DM}}\mathrm{h}^2 = 2.76 \times 10^8 \left(\frac{m_\chi}{\mathrm{GeV}}\right)(Y_\chi - Y_{\overline{\chi}})$.

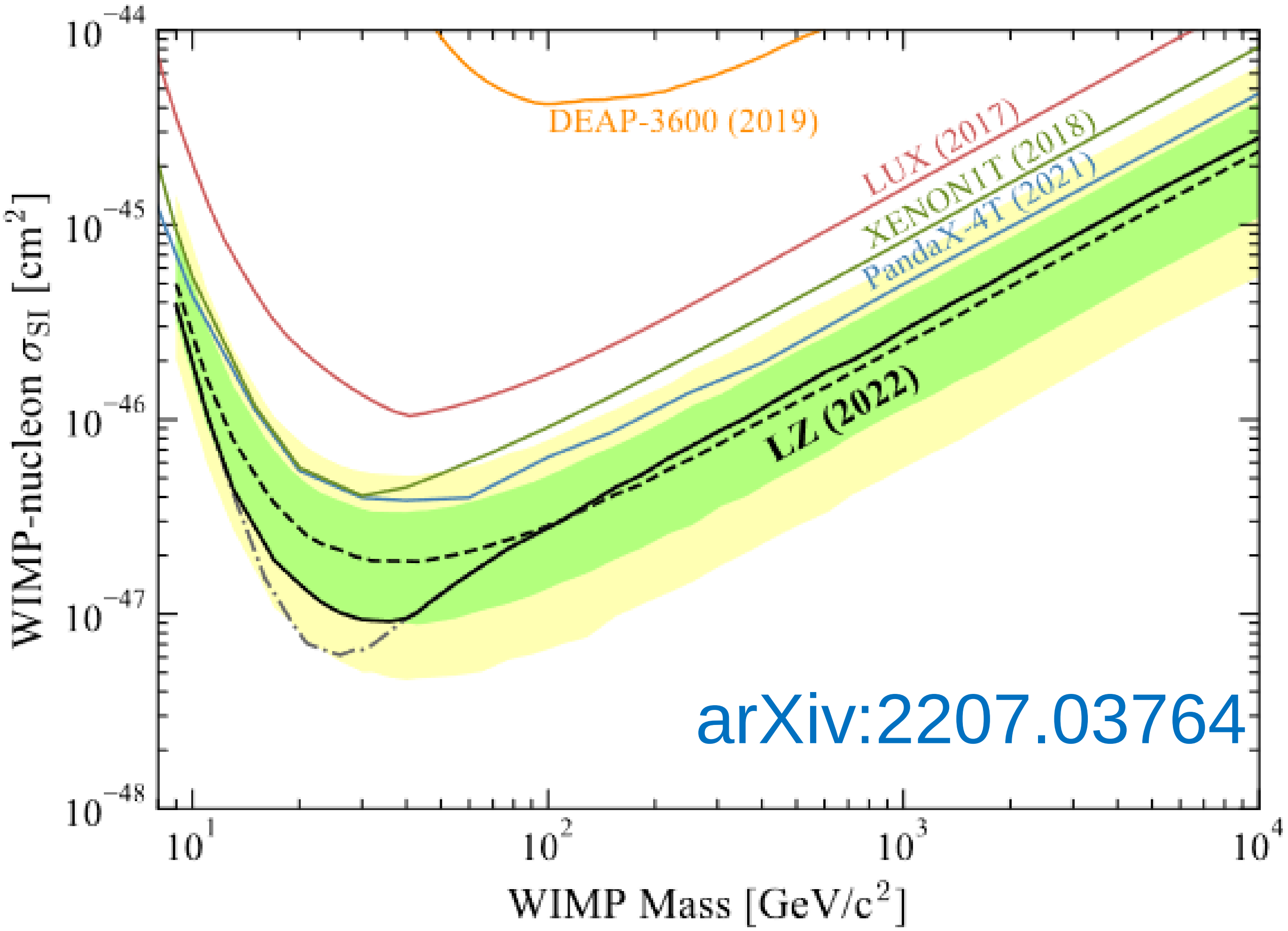
- For $Y_\chi - Y_{\overline{\chi}} \sim Y_B - Y_{\overline{B}}$, we have $m_\chi \sim 5 m_p \sim 5$ GeV as $\Omega_{\mathrm{DM}} \sim 5\Omega_B$.

- Depending upon the model implementation, it is possible to generate different asymmetries in dark and visible sectors leading to deviations from $m_\chi \sim 5 m_p \sim 5$ GeV limit.

Detection of ADM

- The requirement of large σv can also enhance DM direct detection prospects either via
  I. Direct DM-SM interactions
  II. Dark photon or Higgs portal

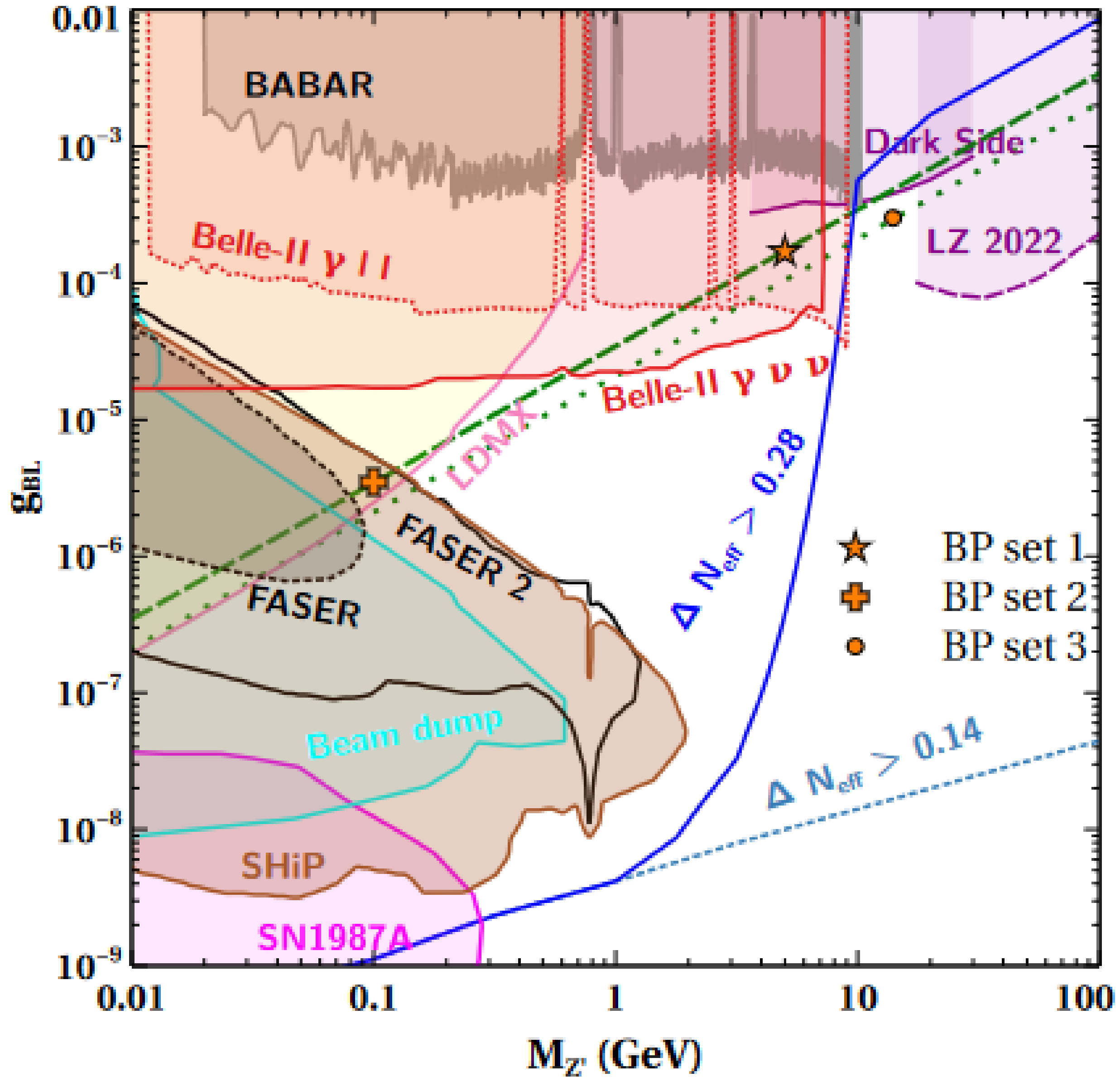




arXiv:2207.03764

Direct DM-SM portal

- DM-SM interactions can be mediated by a mediator say B-L gauge boson.
- Large σv requirement leads to the resonant regime.
- Low DM mass is preferred due to weaker constraints.

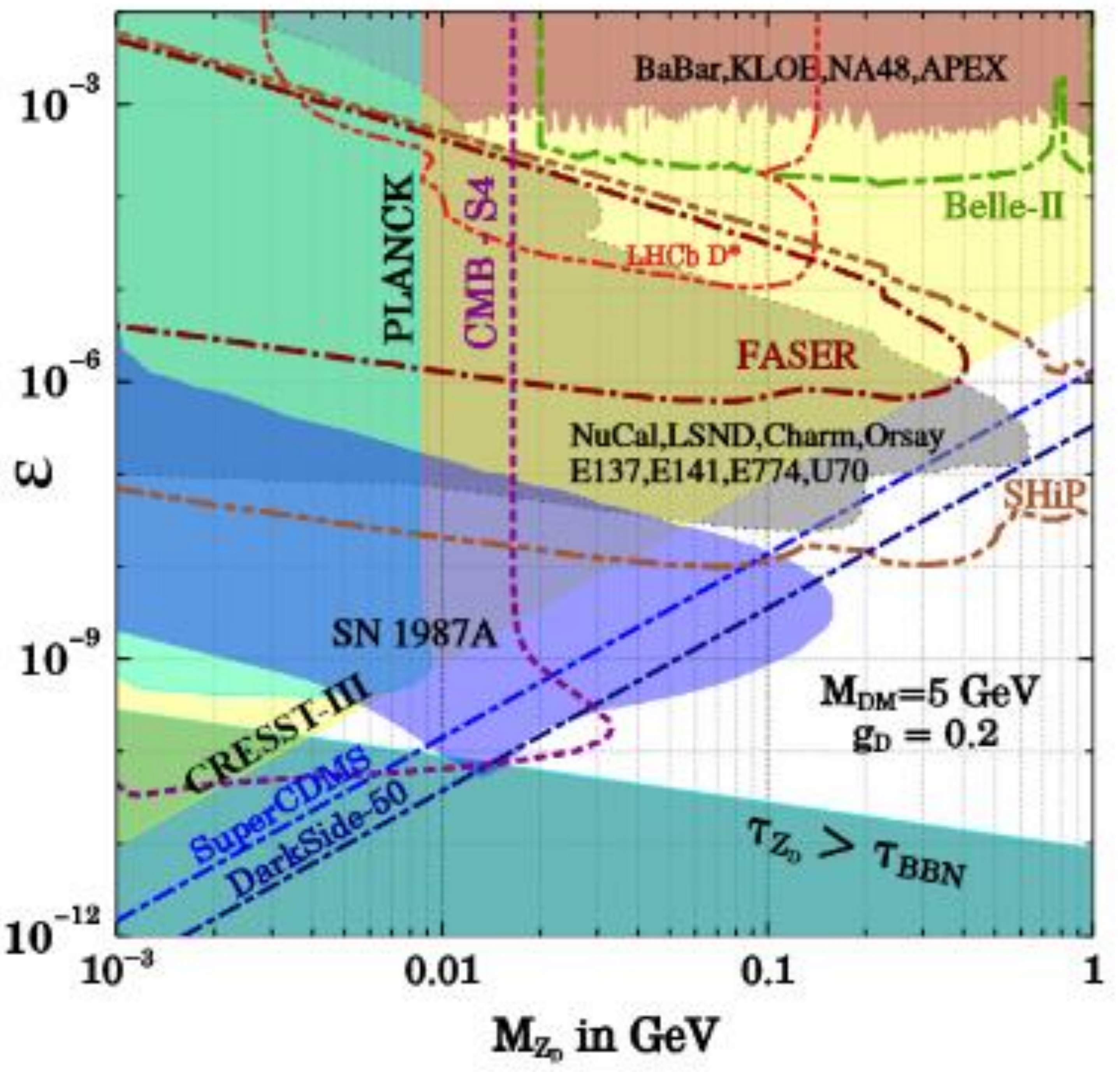


$$\sigma^{\rm SI}_{B-L} \approx (10^{-46}\,{\rm cm}^2)\, q^2_{\rm DM} \left(\frac{g_{B-L}}{0.1}\right)^4 \left(\frac{3\ {\rm TeV}}{M_{B-L}}\right)^4$$

arXiv:2212.04516

Dark photon/Higgs portal

- DM-$\overline{\mathrm{DM}}$ annihilates efficiently into light bosons.
- Direct detection rate can be kept under control by tuning the mixing.
- Constraints on dark bosons apply.



$$\sigma_D^{\mathrm{SI}} \approx (10^{-40}\,\mathrm{cm}^2)\left(\frac{\epsilon}{10^{-4}}\right)^2\left(\frac{g_D}{0.1}\right)^2\left(\frac{1\,\mathrm{GeV}}{M_D}\right)^4$$

arXiv:2211.15703

Model building aspects

- Asymmetric dark matter models broadly fall into two categories:

  I. Simultaneous generation of baryon and dark sector asymmetries: *cogenesis*

  II. Visible sector asymmetry is generated first, which then gets transferred to the dark sector.

  III. Dark sector asymmetry is generated first, which then gets transferred into the visible sector.

Cogenesis

- Cogenesis can occur simply by implementing one of the known baryogenesis mechanisms to dark sector.
- Let us consider such possibility via the leptogenesis route

Baryogenesis via Leptogenesis

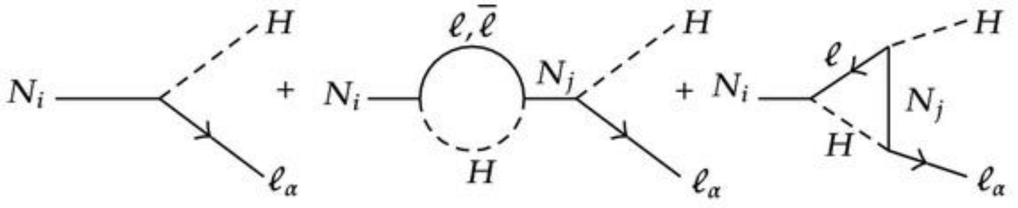
arXiv: hep-ph/0401240, 0802.2962, 1301.3062 for reviews

- Right handed neutrino decays out of equilibrium (Fukugita & Yanagida 1986)

$$Y_{ij}\bar{L}_i\tilde{H}N_j + \frac{1}{2}M_{ij}N_iN_j$$

- CP violation due to phases in Yukawa couplings Y, leads to a lepton asymmetry.

$$\epsilon_{N_k} = -\sum_i \frac{\Gamma(N_k \to L_i + H^*) - \Gamma(N_k \to L_i + H)}{\Gamma(N_k \to L_i + H^*) + \Gamma(N_k \to L_i + H)}$$



- The frozen out lepton asymmetry at $T \ll M_i$ is converted into baryon asymmetry by electroweak sphalerons:

$$\frac{n_{\Delta B}}{s} = -\frac{28}{79}\frac{n_{\Delta L}}{s}$$

Khlebnikov & Shaposhnikov 1988

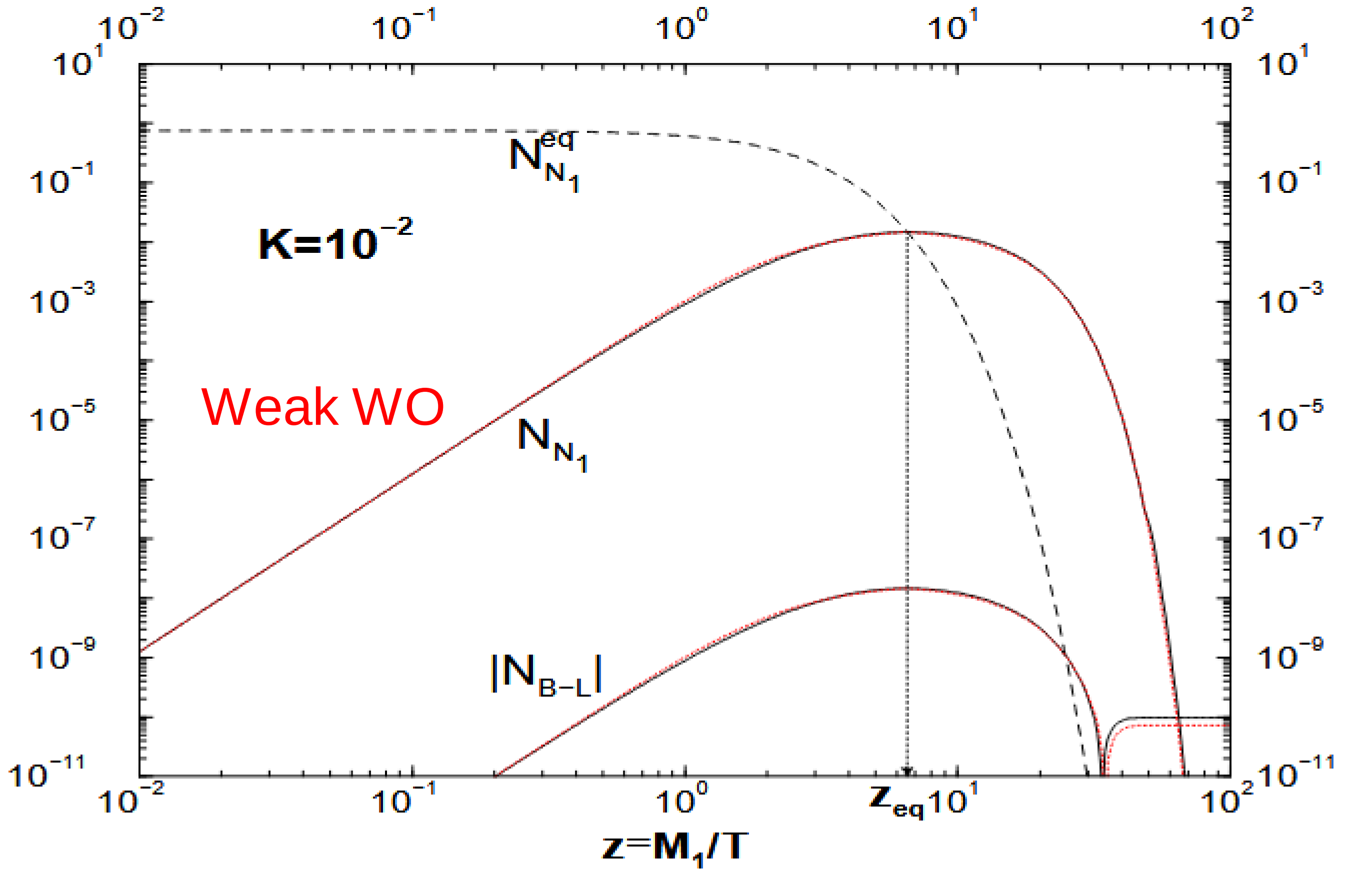
- For hierarchical RHN, there exists a lower bound on scale of leptogenesis M > 10^9GeV.

Davidson & Ibarra 2002

- Low scale leptogenesis possibilities: Resonant leptogenesis (Pilaftsis 1998), ARS leptogenesis (Akhmedov, Rubakov & Smirnov 1998), Radiative seesaw leptogenesis (Racker 2014, Hugle, Platscher & Schmitz 2018, DB, P S B Dev & Kumar 2019).

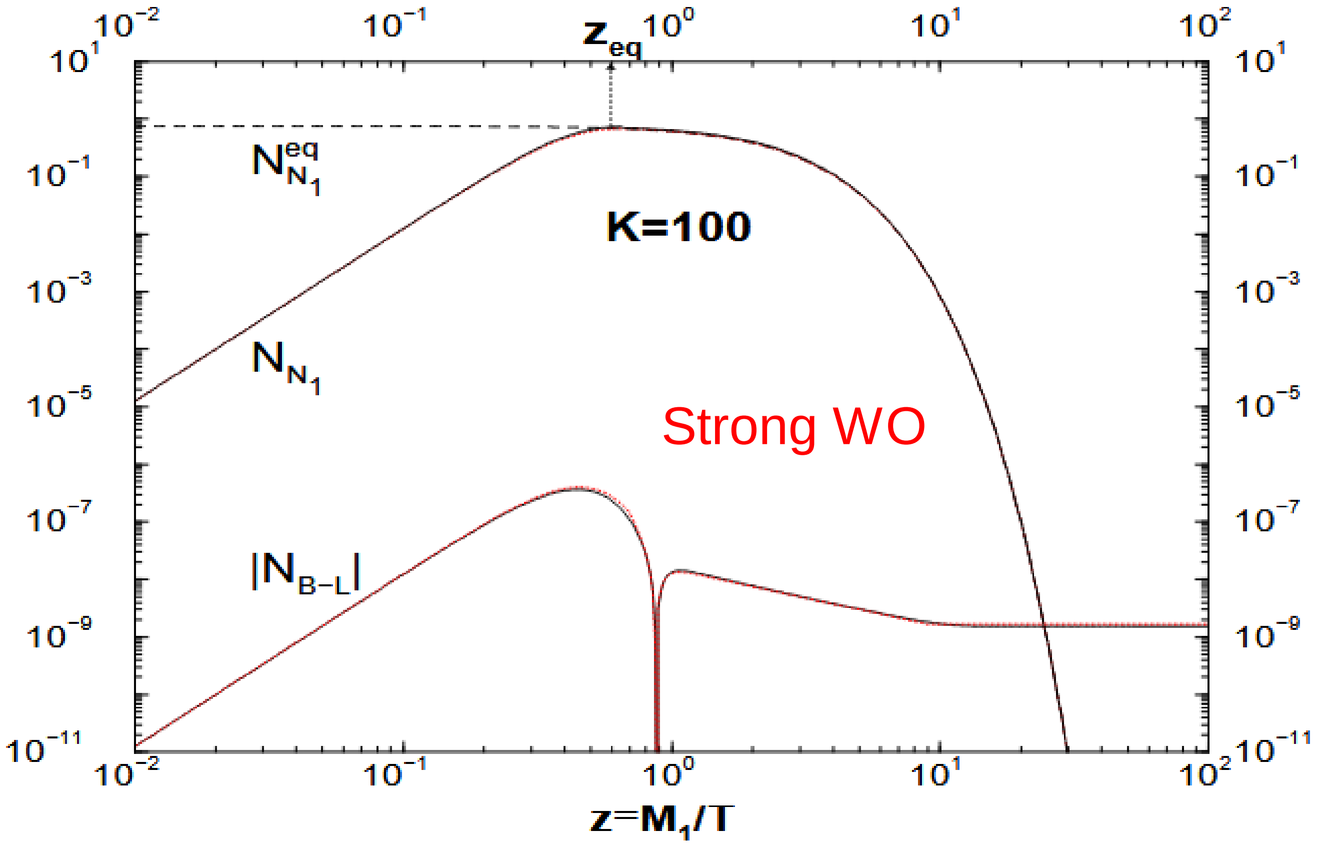
Boltzmann Equations

$$\frac{dN_{N_1}}{dz} = -(D+S)\,(N_{N_1} - N_{N_1}^{\rm eq})\,,$$
$$\frac{dN_{B-L}}{dz} = -\varepsilon_1\, D\,(N_{N_1} - N_{N_1}^{\rm eq}) - W\, N_{B-L}\,,$$



For decay/inverse decays only

$$\frac{dN_{N_1}}{dz} = -D\,(N_{N_1} - N_{N_1}^{\rm eq})\,,$$
$$\frac{dN_{B-L}}{dz} = -\varepsilon_1\, D\,(N_{N_1} - N_{N_1}^{\rm eq}) - W_{ID}\, N_{B-L}\,,$$



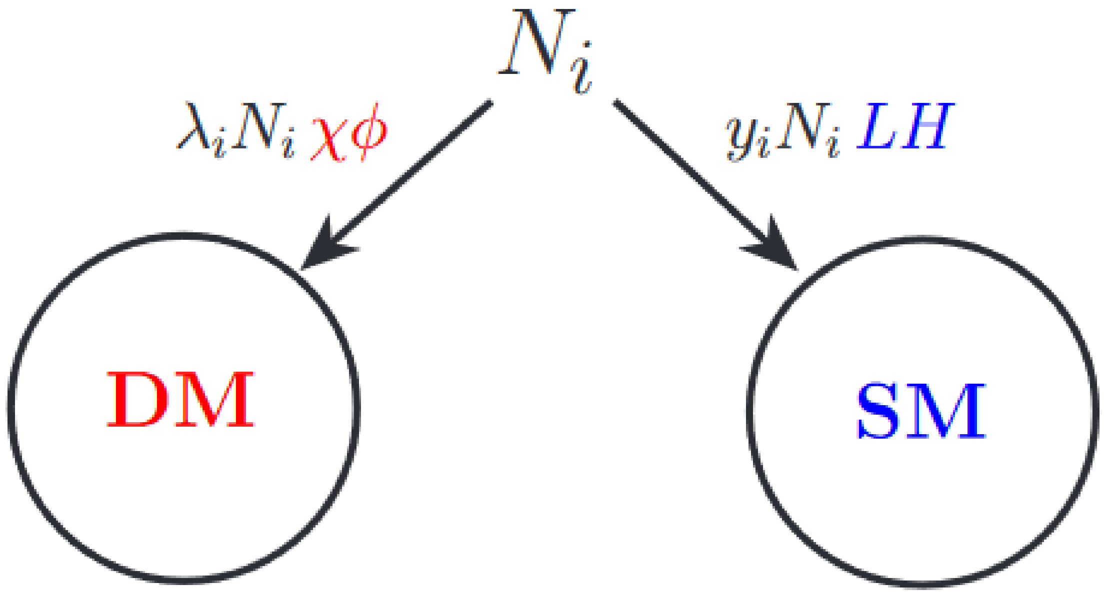
hep-ph/0401240, Buchmuller, Di Bari, Plumacher

Lectures by A Sil

ADM from Type-I Leptogenesis

- Consider a type-I seesaw model extended with two dark sector particles.
- The lightest right handed neutrino (RHN) decay can create asymmetry in lepton and dark sectors simultaneously.
- RHNs also generate light neutrino masses, providing an origin of neutrino mass, mixing.

$$-\mathcal{L} \supset \frac{1}{2} M_i N_i^2 + y_i N_i l h + \lambda_i N_i \chi \phi + h.c.$$



N_i

$\lambda_i N_i \, \chi\phi$

$y_i N_i \, LH$

DM

SM

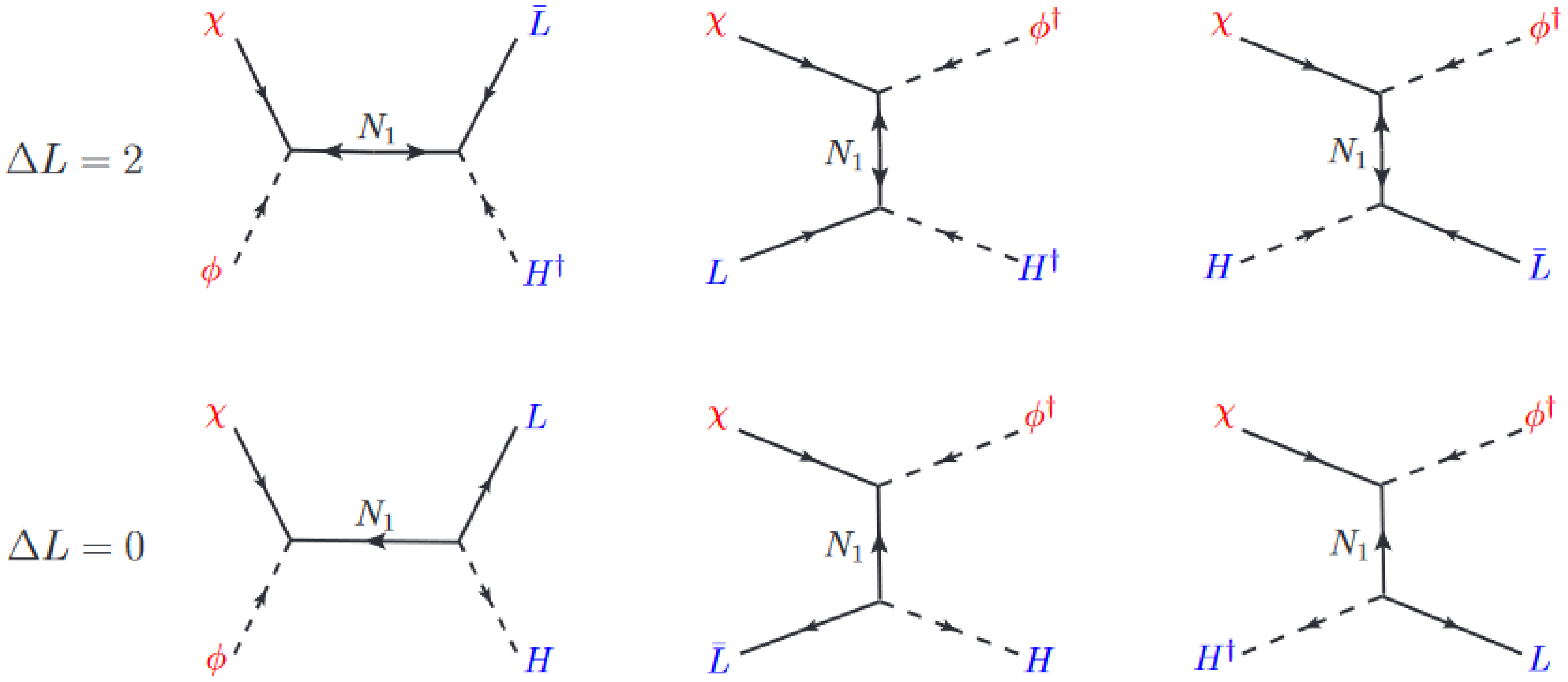
$$\begin{aligned}
\epsilon_\chi &\simeq \frac{M_1}{M_2} \frac{1}{16\pi (y_1^2 + \lambda_1^2)} \left(2\lambda_1^2 |\lambda_2|^2 \sin\left(2\phi_\chi\right) + y_1 y_2 \lambda_1 |\lambda_2| \sin\left(\phi_l + \phi_\chi\right) \right) \ , \\
\epsilon_l &\simeq \frac{M_1}{M_2} \frac{1}{16\pi (y_1^2 + \lambda_1^2)} \left(2 y_1^2 |y_2|^2 \sin\left(2\phi_l\right) + y_1 y_2 \lambda_1 |\lambda_2| \sin\left(\phi_l + \phi_\chi\right) \right) \ .
\end{aligned}$$

(Asymmetric DM from Leptogenesis by Falkowski, Ruderman & Volansky; arXiv:1101.4936)

$$\frac{sH_1}{z}Y'_{N_1} = -\gamma_D\left(\frac{Y_{N_1}}{Y_N^{\rm eq}}-1\right) + (2\leftrightarrow 2)\,, \qquad \gamma_D = \frac{m_{N_1}^3 K_1(z)}{\pi^2 z}\Gamma_{N_1}$$

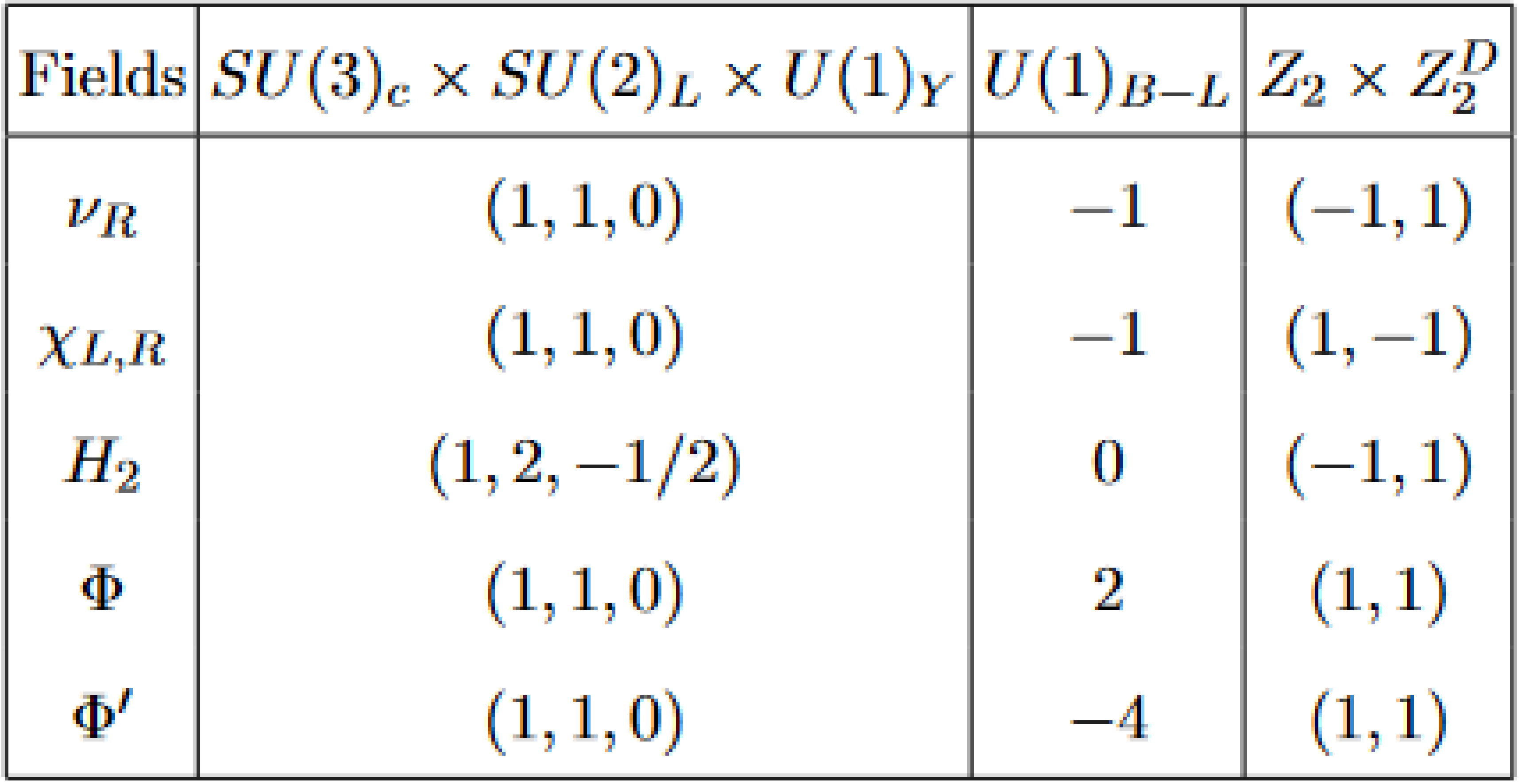
$$\frac{sH_1}{z}Y'_{\Delta\chi} = \gamma_D\left[\epsilon_\chi\left(\frac{Y_{N_1}}{Y_{N_1}^{\rm eq}}-1\right) - \frac{Y_{\Delta\chi}}{2Y_\chi^{\rm eq}}\,{\rm Br}_\chi\right] + (2\leftrightarrow 2\ \text{washout} + \text{transfer})\,,$$

$$\frac{sH_1}{z}Y'_{\Delta l} = \gamma_D\left[\epsilon_l\left(\frac{Y_{N_1}}{Y_{N_1}^{\rm eq}}-1\right) - \frac{Y_{\Delta l}}{2Y_l^{\rm eq}}\,{\rm Br}_l\right] + (2\leftrightarrow 2\ \text{washout} + \text{transfer})\,.$$



Similar model building is possible in type-II, type-III seesaw as well

Cogenesis via Affleck-Dine Mechanism



Fields	$SU(3)_c \times SU(2)_L \times U(1)_Y$	$U(1)_{B-L}$	$Z_2 \times Z_2^D$
ν_R	$(1,1,0)$	-1	$(-1,1)$
$\chi_{L,R}$	$(1,1,0)$	-1	$(1,-1)$
H_2	$(1,2,-1/2)$	0	$(-1,1)$
Φ	$(1,1,0)$	2	$(1,1)$
Φ'	$(1,1,0)$	-4	$(1,1)$

$$\mathcal{L} \supset \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm inf}(\Phi, R) - Y_\nu \overline{L}\tilde{H}_2\nu_R - M_\chi \overline{\chi}\chi - Y_R \overline{\nu_R^c}\nu_R\Phi - Y_D\overline{\chi^c}\chi\Phi - V(\Phi,\Phi') + {\rm h.c.},$$

$$\frac{n_L}{s} \simeq Q_\Phi {\rm Br}_{\rm vis}\frac{T_R^3}{\epsilon m_\Phi^2 M_P} \simeq 10^{-10},$$

$$\frac{n_{\rm DM}}{s} \simeq Q_\Phi {\rm Br}_{\rm dark}\frac{T_R^3}{\epsilon m_\Phi^2 M_P} \simeq \frac{0.12}{2.75\times 10^8}\left(\frac{M_{\rm DM}}{\rm GeV}\right)^{-1}$$

arXiv:2212.04516

Affleck & Dine 1985

Asymmetry transfer to dark sector

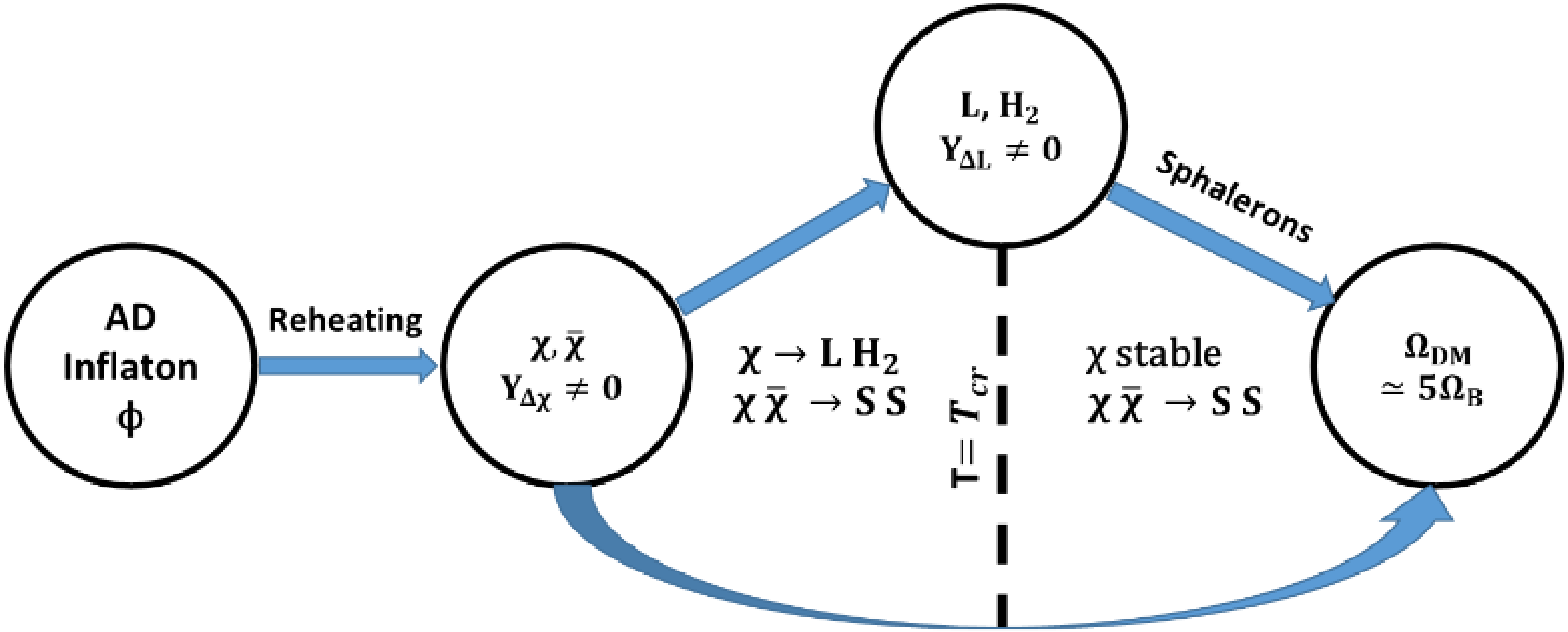
- B-L asymmetry generated at high scale. Transfer via effective interactions like $XX\bar{L}\tilde{H}$ are in equilibrium.
- Transfer interactions decouple while other DM-SM interactions may continue.
- At $T < M_{\rm DM}$, symmetric component annihilates out.

arXiv:0901.4117

Transfer of DM asymmetry to leptons

Fields	$SU(3)_c \times SU(2)_L \times U(1)_Y$	$U(1)_L$	Z_2
χ	$(1,1,0)$	1	-1
H_2	$(1,2,-1/2)$	0	-1
Φ	$(1,1,0)$	2	1
S	$(1,1,0)$	0	1

$$-\mathcal{L} \supset M_\chi \overline{\chi}\chi + Y_\nu \overline{L}\tilde{H}_2 \chi_R + Y_D \overline{\chi^c}\chi\Phi^\dagger + Y_S \overline{\chi_L}\chi_R S + \text{h.c.}$$



Dark asymmetry from AD field

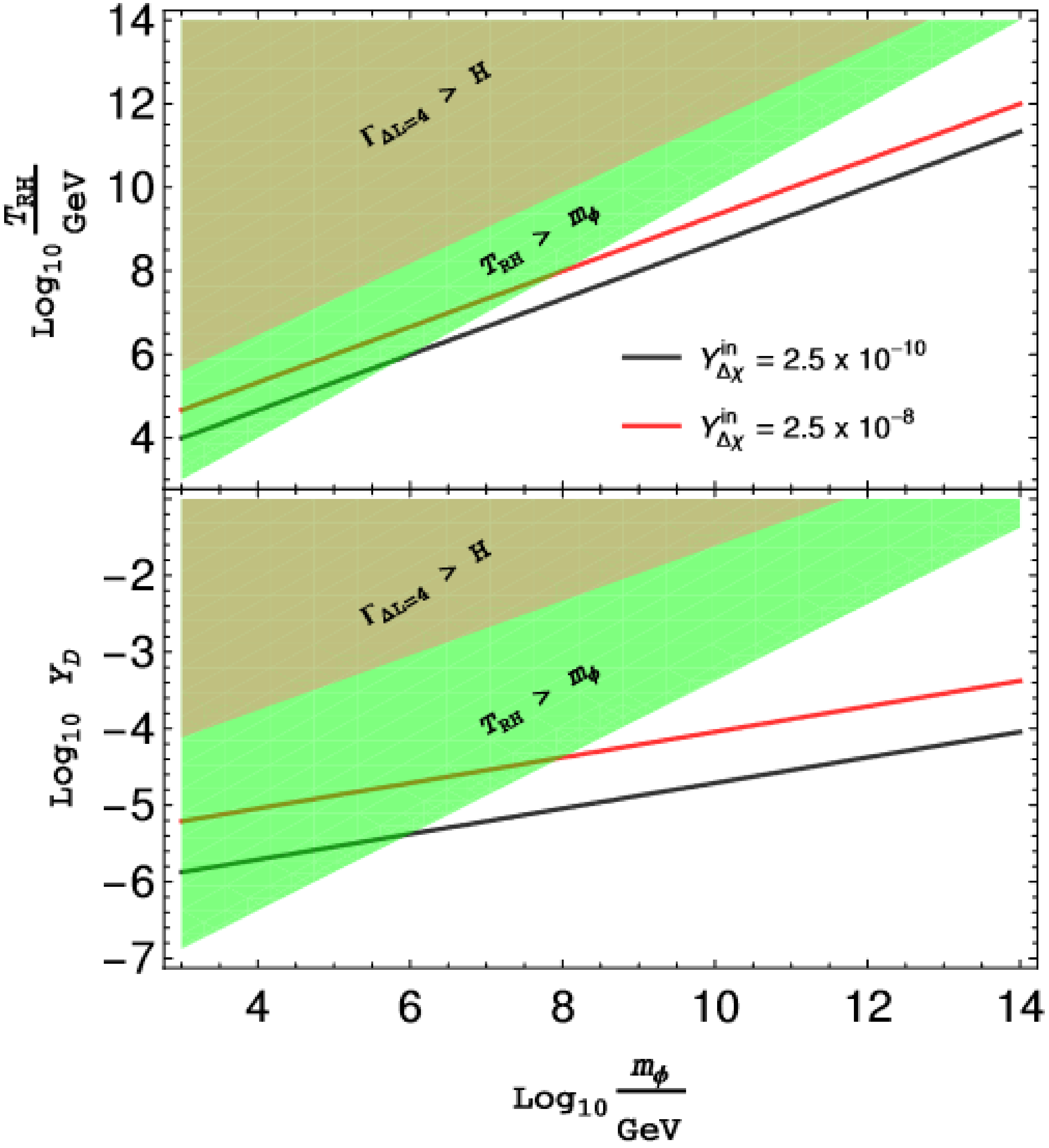
- The Affleck-Dine (AD) field plays the role of inflaton via $\phi^2 R$ coupling and reheats the Universe by decaying into DM χ.

- The AD field breaks L number explicitly due to the $\epsilon m_\phi^2 \phi^2$ term in the potential.

- Cosmic evolution of the AD field leads to the dark sector asymmetry given by

$$Y^{\rm in}_{\Delta\chi} = \frac{(n_\chi - n_{\bar{\chi}})^{\rm in}}{s} \simeq \frac{T^3_{\rm RH}}{\epsilon m^2_\Phi M_P}.$$

- Dark asymmetry is partially transferred into leptons via *forbidden decay*.



Affleck and Dine 1985; also see arXiv:0802.1328, 1105.4612, 1201.2200, 1309.0007, 1309.0010, 1405.1959, 1909.12300, 2001.11505, 2008.04339 2107.01514, 2106.03381, 2201.06151, 2212.04516 ++

Thermal masses

$$\begin{aligned} M_\chi(T) &= \sqrt{m_\chi^2 + \Pi_{S\chi}^2(T)}, \\ M_{H_2}(T) &= \sqrt{m_{H_2}^2 + \Pi_{\rm gauge}^2(T)}, \\ M_L(T) &= \sqrt{m_L^2 + \frac{1}{2}\Pi_{\rm gauge}^2(T)}, \end{aligned}$$

$$\begin{aligned} \Pi_{S\chi}^2(T) &= \frac{Y_S^2}{16}T^2, \\ \Pi_{\rm gauge}^2(T) &= \left(\frac{1}{16}g'^2 + \frac{3}{16}g^2\right)T^2. \end{aligned}$$

Boltzmann Equations

$$\frac{dY_\chi}{dz} = -\frac{s}{\mathbf{H}z}\left[\langle\sigma v_{\chi\bar\chi\to{\rm SM}}\rangle(Y_\chi Y_{\bar\chi} - Y_\chi^{\rm eq}Y_{\bar\chi}^{\rm eq})\right] - \frac{1}{s\mathbf{H}z}\gamma(\chi\to LH_2)\left(\frac{Y_\chi}{Y_\chi^{\rm eq}} - 1\right) + \frac{1}{s\mathbf{H}z}\gamma(H_2\to\chi\bar L),$$

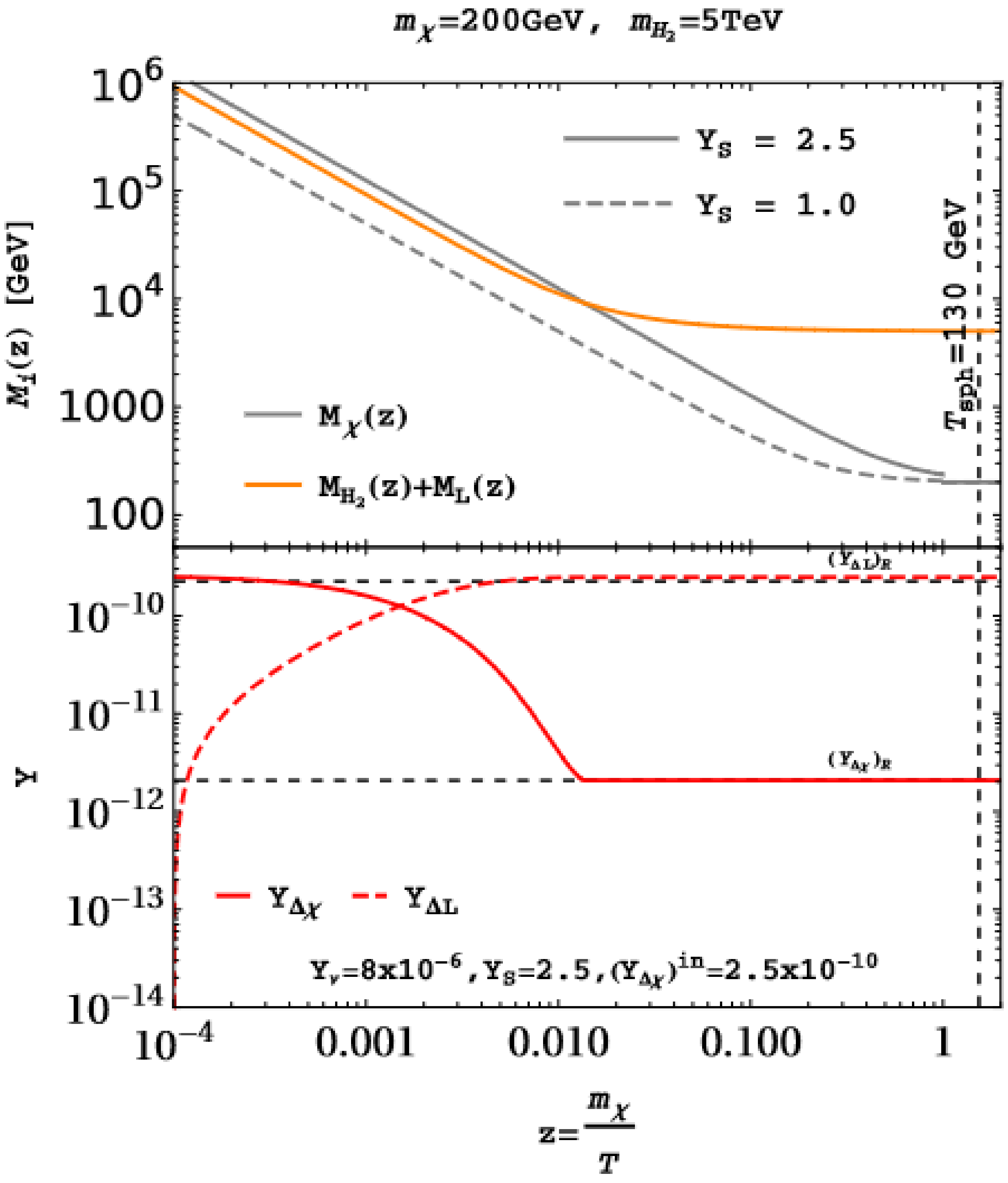
$$\frac{dY_{\bar\chi}}{dz} = -\frac{s}{\mathbf{H}z}\left[\langle\sigma v_{\chi\bar\chi\to{\rm SM}}\rangle(Y_\chi Y_{\bar\chi} - Y_\chi^{\rm eq}Y_{\bar\chi}^{\rm eq})\right] - \frac{1}{s\mathbf{H}z}\gamma(\bar\chi\to \bar LH_2)\left(\frac{Y_{\bar\chi}}{Y_{\bar\chi}^{\rm eq}} - 1\right) + \frac{1}{s\mathbf{H}z}\gamma(H_2\to\bar\chi L),$$

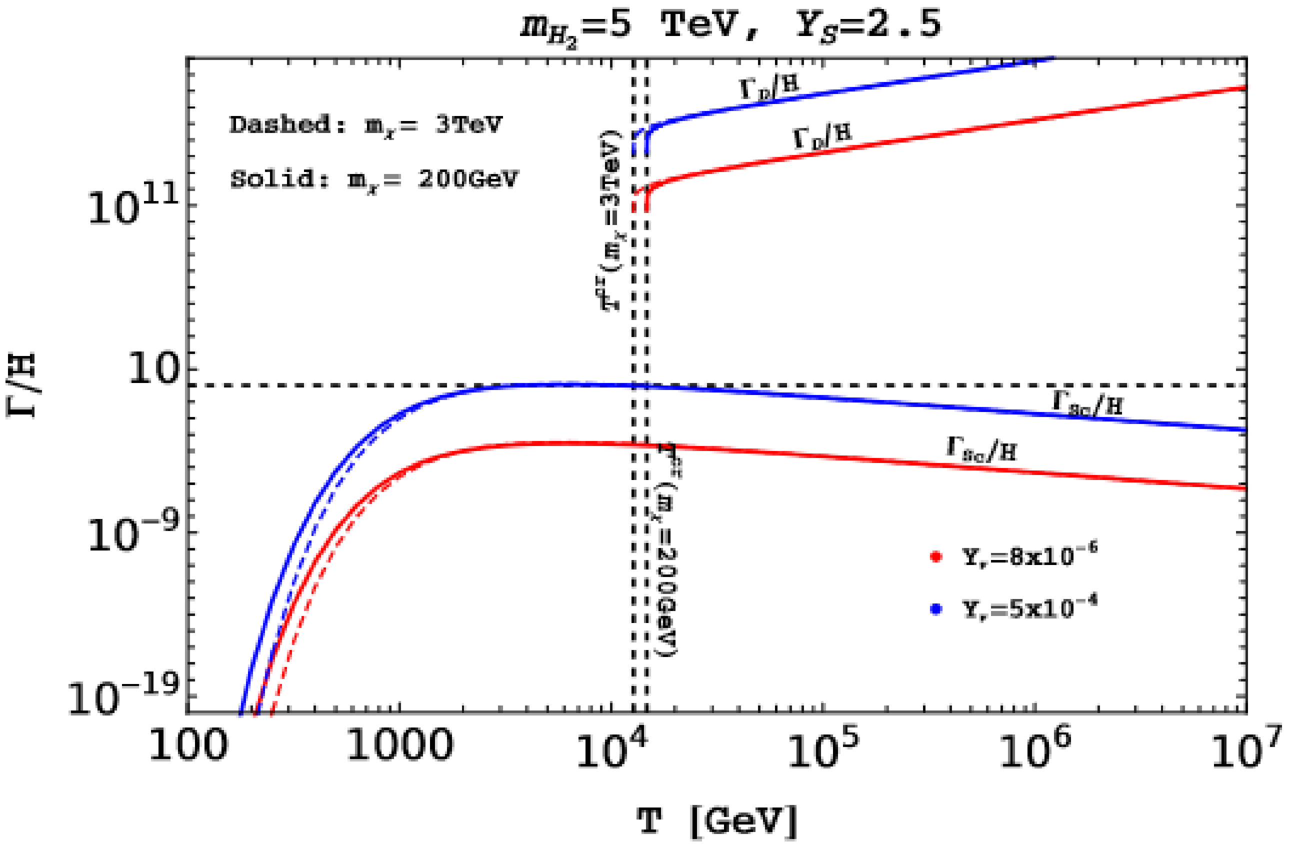
$$\frac{dY_L}{dz} = \frac{1}{s\mathbf{H}z}\gamma(\chi\to LH_2)\left(\frac{Y_\chi}{Y_\chi^{\rm eq}} - 1\right) + \frac{1}{s\mathbf{H}z}\gamma(H_2\to\bar\chi L),$$

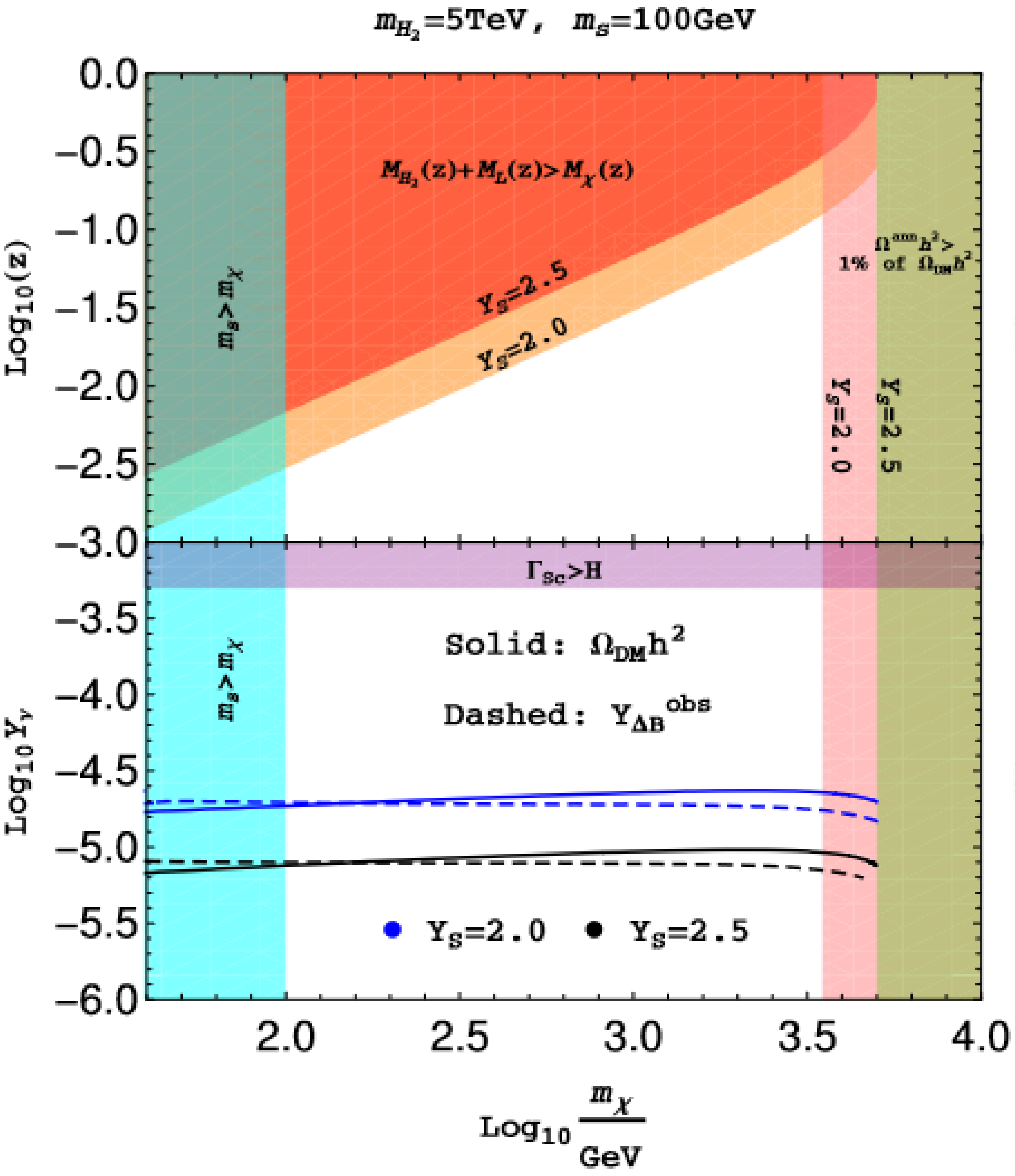
$$\frac{dY_{\bar L}}{dz} = \frac{1}{s\mathbf{H}z}\gamma(\bar\chi\to \bar LH_2)\left(\frac{Y_{\bar\chi}}{Y_{\bar\chi}^{\rm eq}} - 1\right) + \frac{1}{s\mathbf{H}z}\gamma(H_2\to\chi\bar L),$$

$$Y_\chi(0) = Y_\chi^{\mathrm{eq}},\ Y_{\bar{\chi}}(0) = Y_\chi^{\mathrm{eq}} - Y_{\Delta\chi}^{\mathrm{in}}$$
$$Y_L(0) = Y_L^{\mathrm{eq}},\ Y_{\bar{L}}(0) = Y_L^{\mathrm{eq}}$$

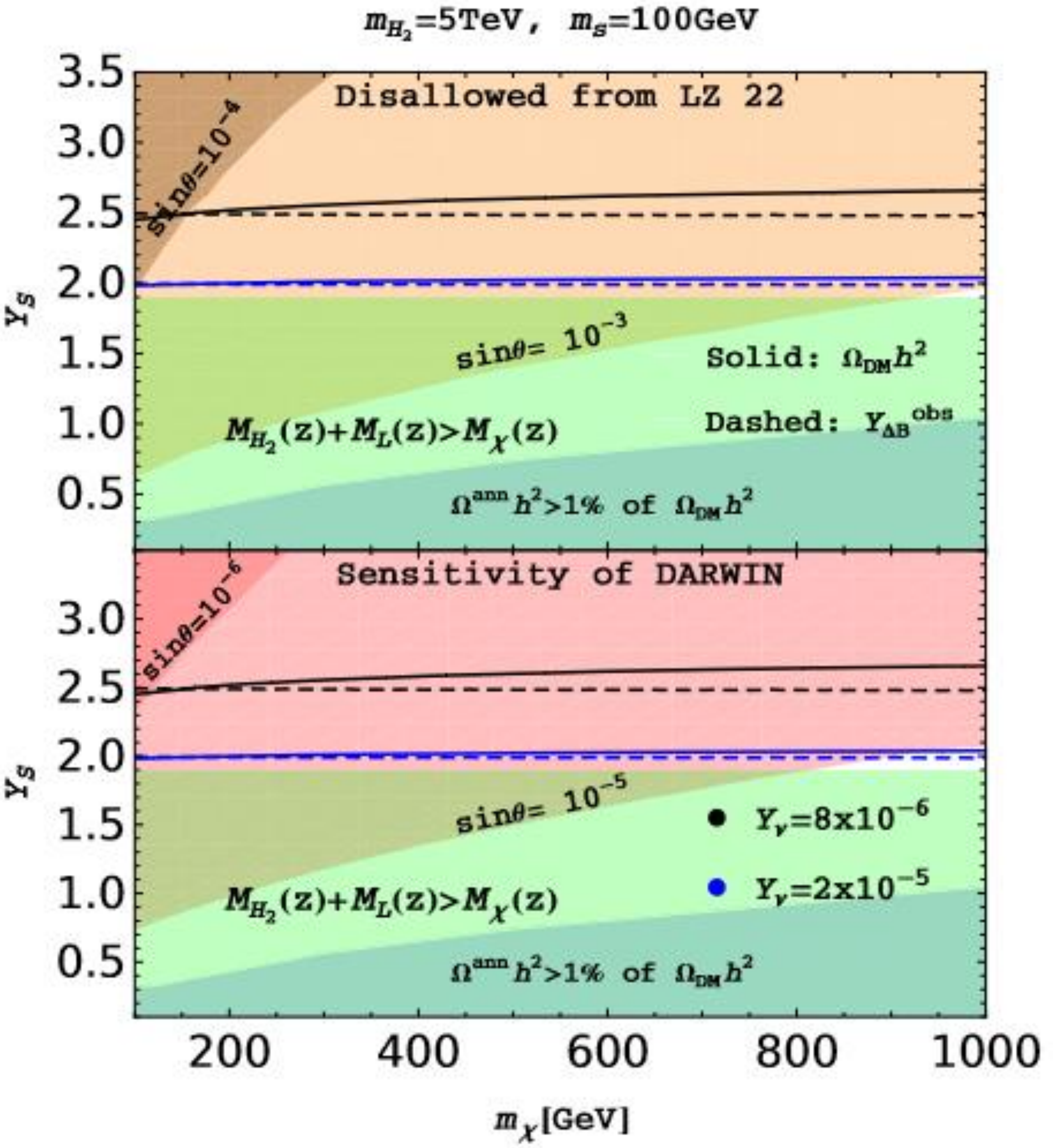
- The DM-lepton coupling is small such that asymmetry is transferred dominantly via decay.
- The decay $H_2 \to \chi L$ at low T can not alter asymmetries if $H_2 \leftrightarrow H_2^\dagger$ process remains efficient.







m_{H_2}=5TeV, m_s=100GeV
$M_{H_2}(z)+M_L(z)>M_\chi(z)$
Y_S=2.5
Y_S=2.0
$m_s>m_\chi$
$\Omega^{ann}h^2>$ 1% of $\Omega_{DM}h^2$
Y_S=2.0
Y_S=2.5
$\Gamma_{Sc}>H$
$m_s>m_\chi$
Solid: $\Omega_{DM}h^2$
Dashed: $Y_{\Delta B}^{obs}$
● Y_S=2.0 ● Y_S=2.5
$\mathrm{Log}_{10}(z)$
$\mathrm{Log}_{10}Y_\nu$
$\mathrm{Log}_{10}\frac{m_\chi}{\mathrm{GeV}}$
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
−3.5
−4.0
−4.5
−5.0
−5.5
−6.0
2.0
2.5
3.0
3.5
4.0



m_{H_2}=5TeV, m_s=100GeV
Disallowed from LZ 22
$\sin\theta=10^{-4}$
$\sin\theta=10^{-3}$
Solid: $\Omega_{DM}h^2$
Dashed: $Y_{\Delta B}^{obs}$
$M_{H_2}(z)+M_L(z)>M_\chi(z)$
$\Omega^{ann}h^2>$1% of $\Omega_{DM}h^2$
Sensitivity of DARWIN
$\sin\theta=10^{-6}$
$\sin\theta=10^{-5}$
● $Y_\nu=8\mathrm{x}10^{-6}$
● $Y_\nu=2\mathrm{x}10^{-5}$
$M_{H_2}(z)+M_L(z)>M_\chi(z)$
$\Omega^{ann}h^2>$1% of $\Omega_{DM}h^2$
Y_S
Y_S
m_χ[GeV]
3.5
3.0
2.5
2.0
1.5
1.0
0.5
200
400
600
800
1000

Other avenues of ADM

- Capture in stars
- Collider signatures
- Bound state formation
- Dark matter self-interactions
- More production mechanisms: first order phase transitions, dark sphalerons, primordial black holes etc.