Baryon Asymmetry from Dark Matter Decay

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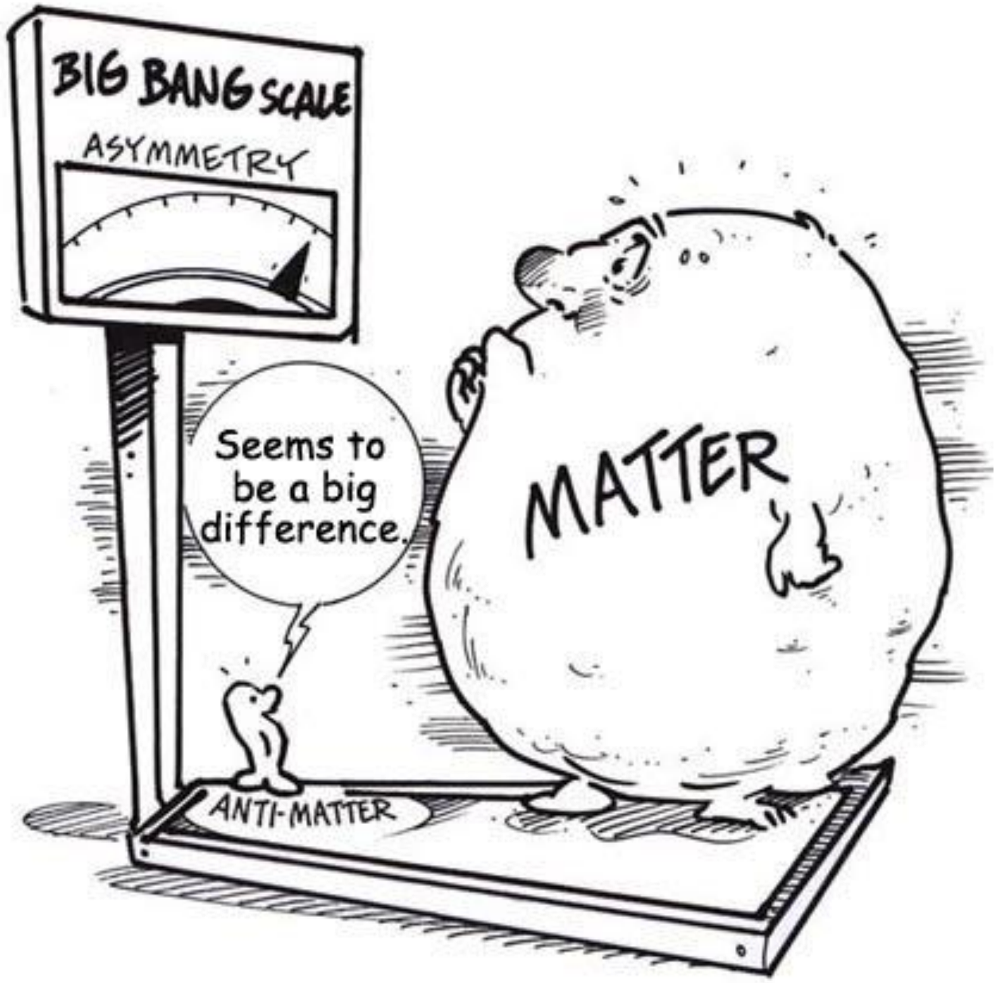
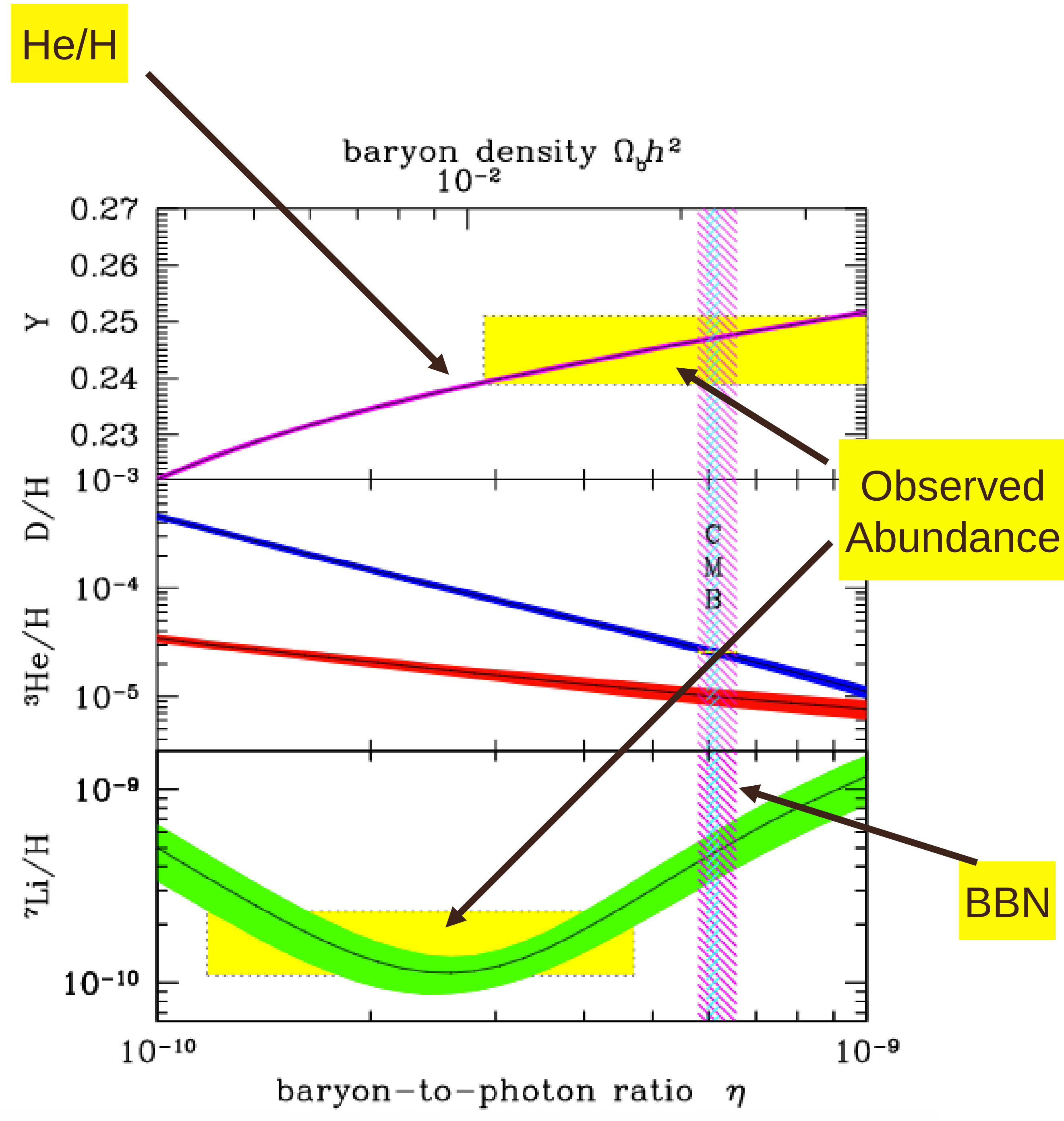
Matter-antimatter (baryon) asymmetry



- 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).



Particle Data Group

Sakharov's Conditions

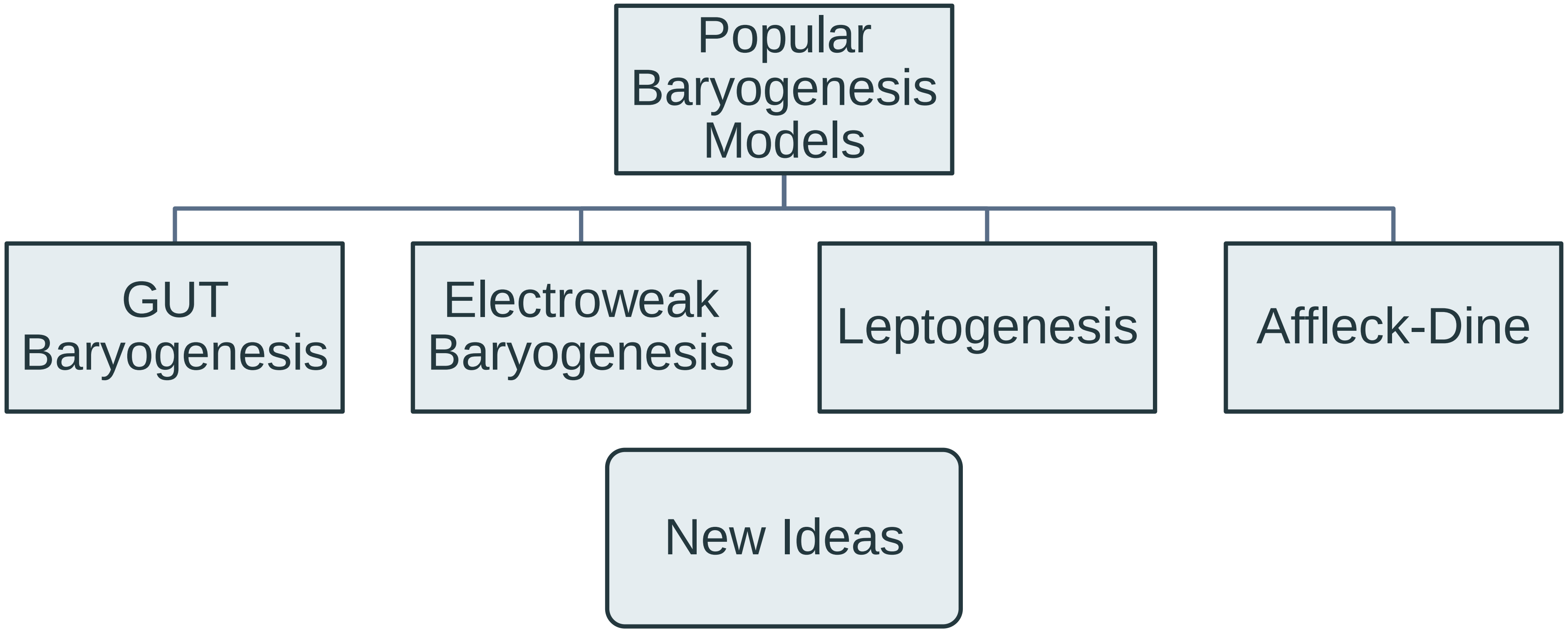
Three basic ingredients necessary to generate a net baryon asymmetry from an initially baryon symmetric Universe (Sakharov 1967):

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

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

- Departure from thermal equilibrium.

Standard Model fails to satisfy these conditions in required amount



Snowmass 2021
arXiv:2203.05010

2 New Ideas in Baryogenesis Models

Baryogenesis via Leptogenesis

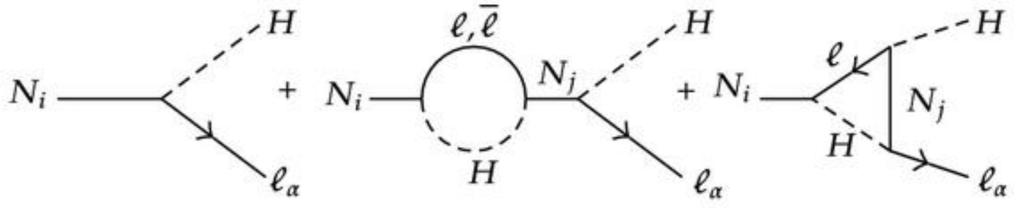
arXiv: hep-ph/0401240, 0802.2962, 1301.3062 for reviews

- 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

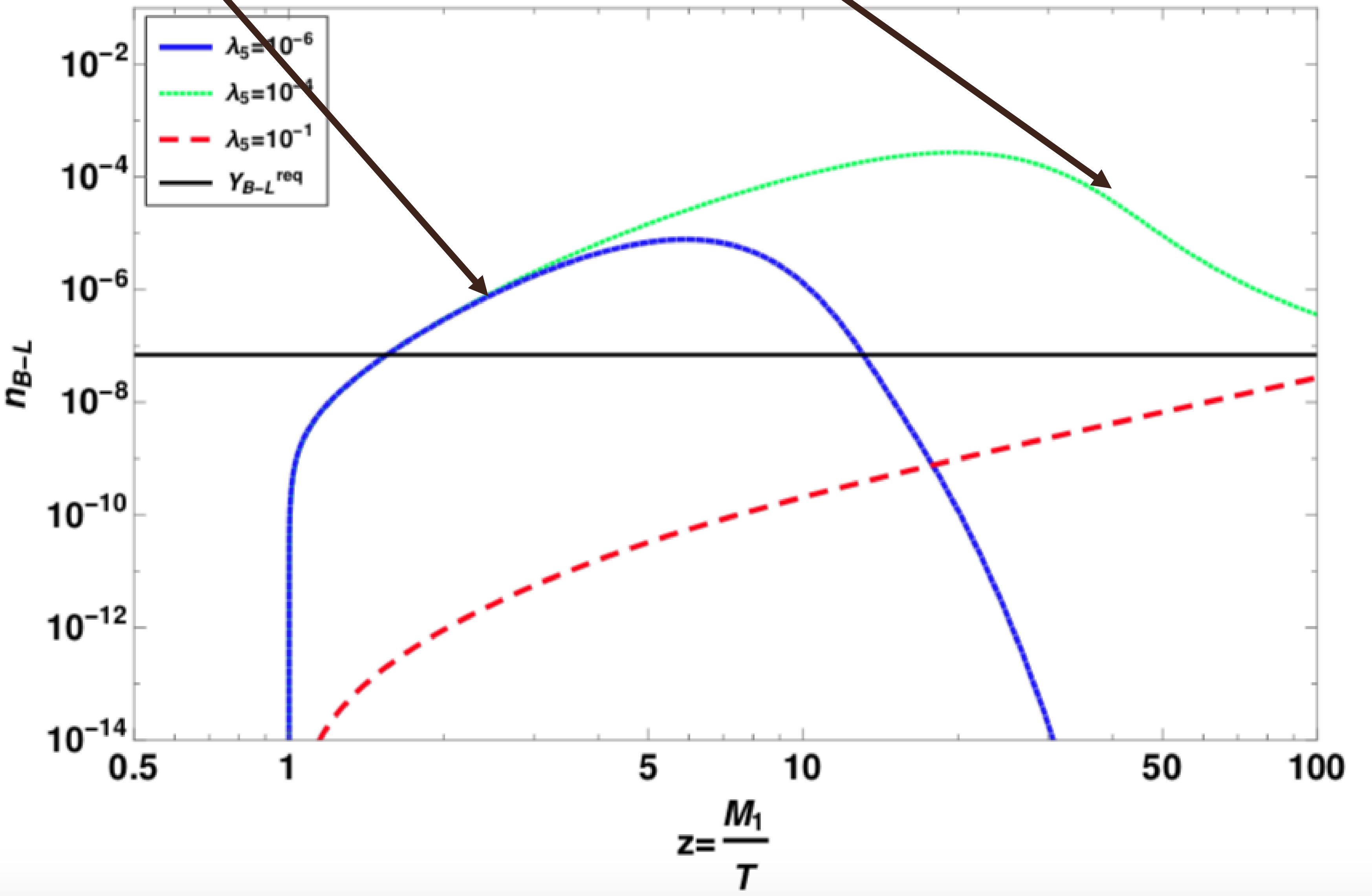
- Low scale leptogenesis possibilities: Resonant leptogenesis (Pilaftsis 1998), ARS leptogenesis (Akhmedov, Rubakov & Smirnov 1998), Radiative seesaw leptogenesis (Racker 2014, Hugle, Platscher & Schmitz 2018, DB, P S B Dev & Kumar 2019).

Talks by C. Hagedorn, A. Sil, Y. Georis

Boltzmann Equations

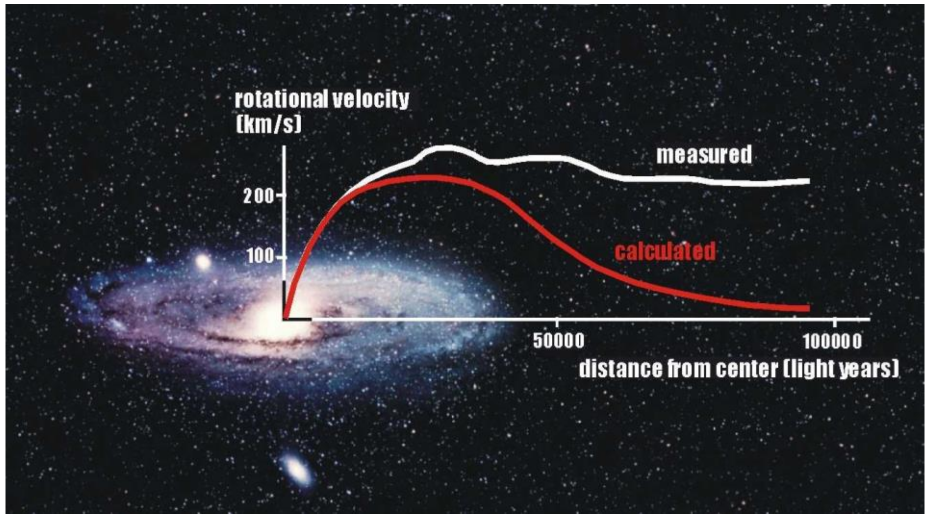
$$\frac{dn_{N_1}}{dz} = -D_1(n_{N_1} - n_{N_1}^{\rm eq})\,,$$
$$\frac{dn_{B-L}}{dz} = -\epsilon_1 D_1(n_{N_1} - n_{N_1}^{\rm eq}) - W^{\rm Total} n_{B-L}\,,$$

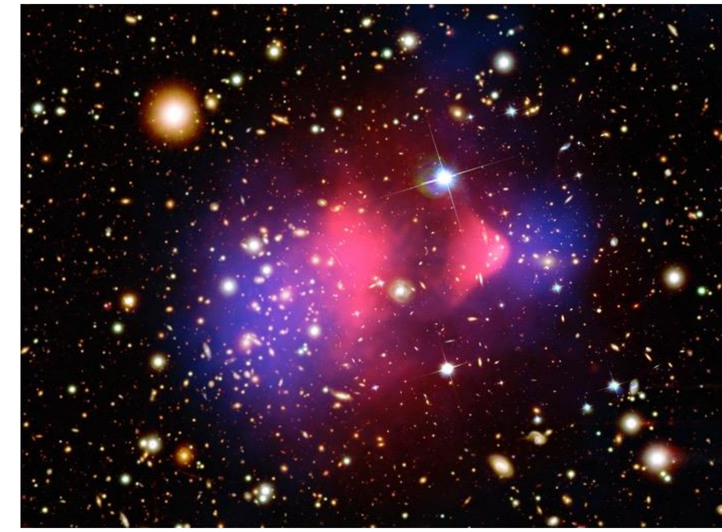
$$D_1 \equiv \frac{\Gamma_1}{Hz} = K_{N_1} z \frac{K_1(z)}{K_2(z)}$$

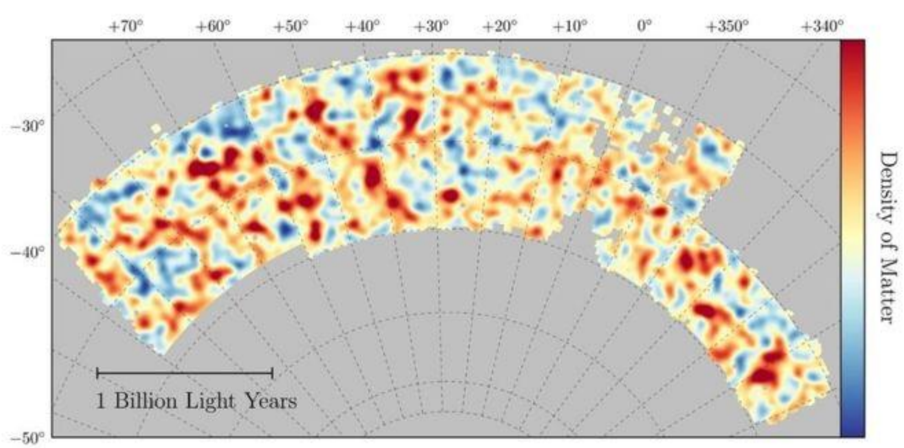


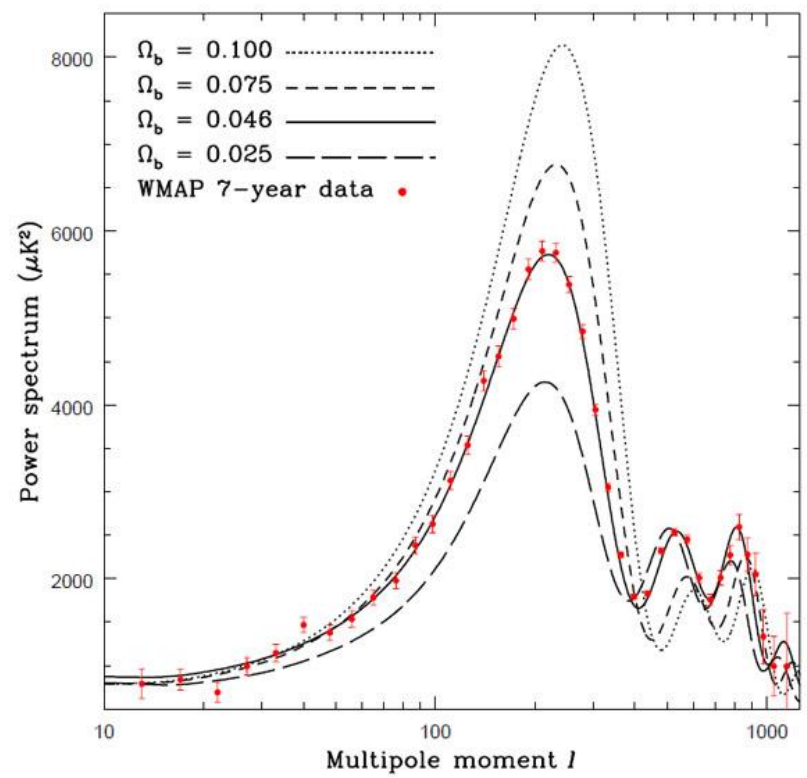
DB, D. Mahanta, arXiv:1912.09726

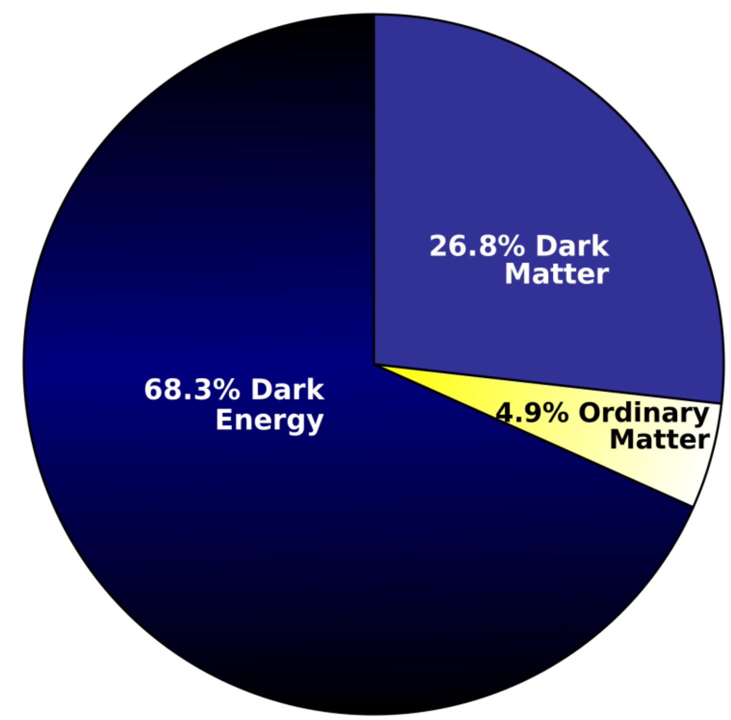
Dark Matter: Evidences

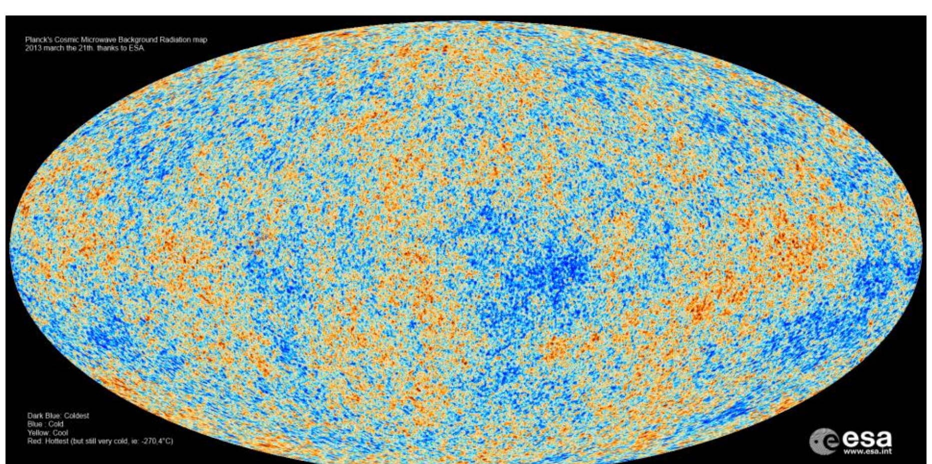












Credits: HST, Chandra, DES, WMAP, Planck

Standard Model does not have any DM candidate

Bertone & Tait
arXiv:1810.01668

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.

$$\frac{dn_{\rm DM}}{dt} + 3Hn_{\rm DM} = -\langle \sigma v \rangle (n_{\rm DM}^2 - (n_{\rm DM}^{\rm eq})^2)$$

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

- In terms of comoving density

$$Y \equiv \frac{n}{T^3} \sim \frac{n}{s} \qquad x = \frac{m}{T}.$$

$$\frac{dY}{dx} = -\frac{\lambda}{x^2}\left(Y^2 - Y_{\rm EQ}^2\right), \qquad \lambda = \frac{m^3 \langle \sigma v \rangle}{H(m)}.$$

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

$$H(T)^2 = \frac{8\pi}{3} G\rho(T)$$

$$\rho_R(T) = \frac{\pi^2}{30} g_* T^4,$$

$$s = \frac{2\pi^2}{45} g_{*s} T^3.$$

Dark Matter: WIMP Miracle

Approximate analytical solution:

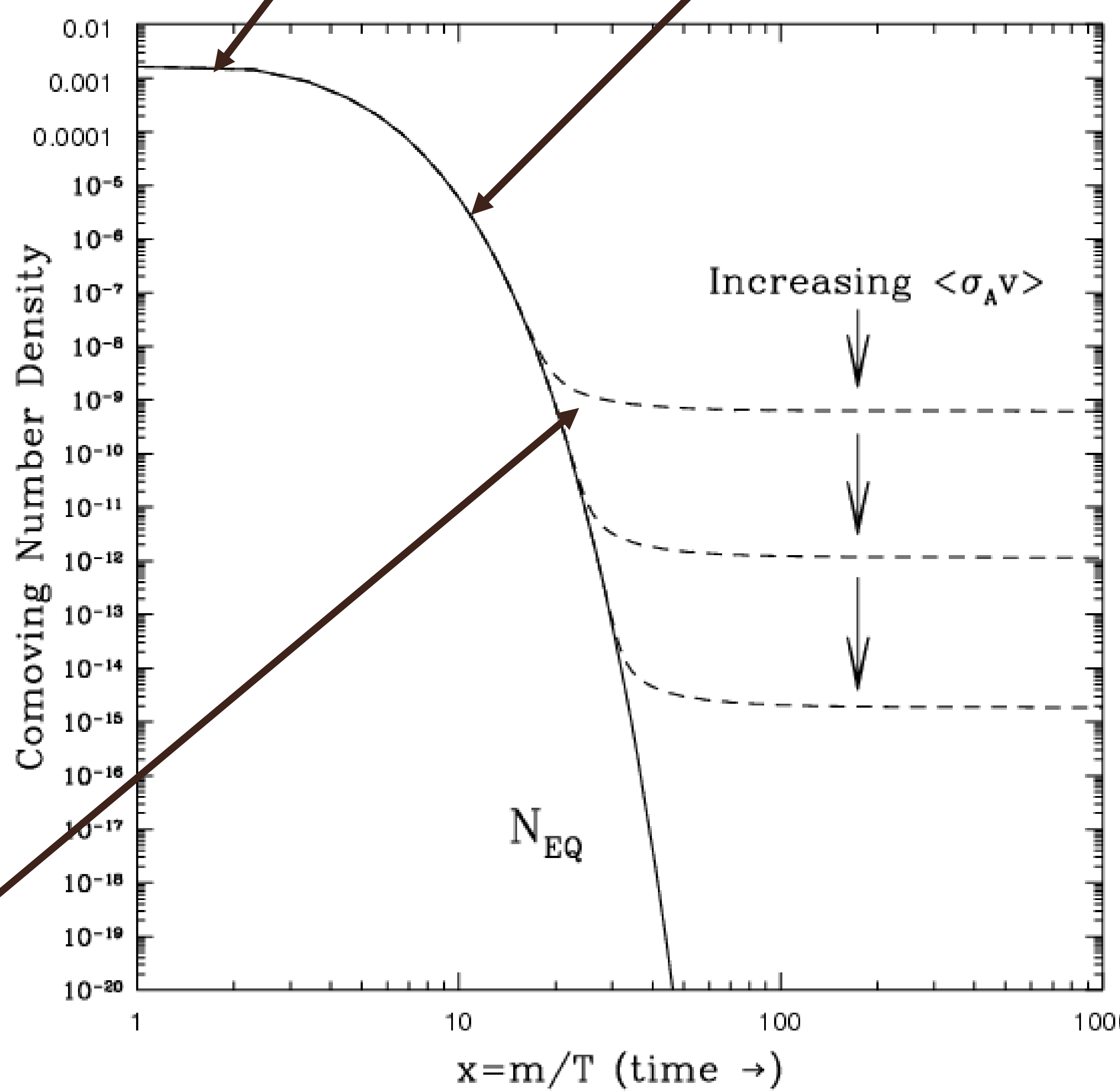
$$\Omega_{\rm DM} h^2 \approx \frac{3 \times 10^{-27} cm^3 s^{-1}}{\langle \sigma v \rangle}$$

Planck 2018, Astron. Astrophys. 2020

$$\Omega_{\rm DM} h^2 = 0.120 \pm 0.001$$

Relativistic & in eqb at high T

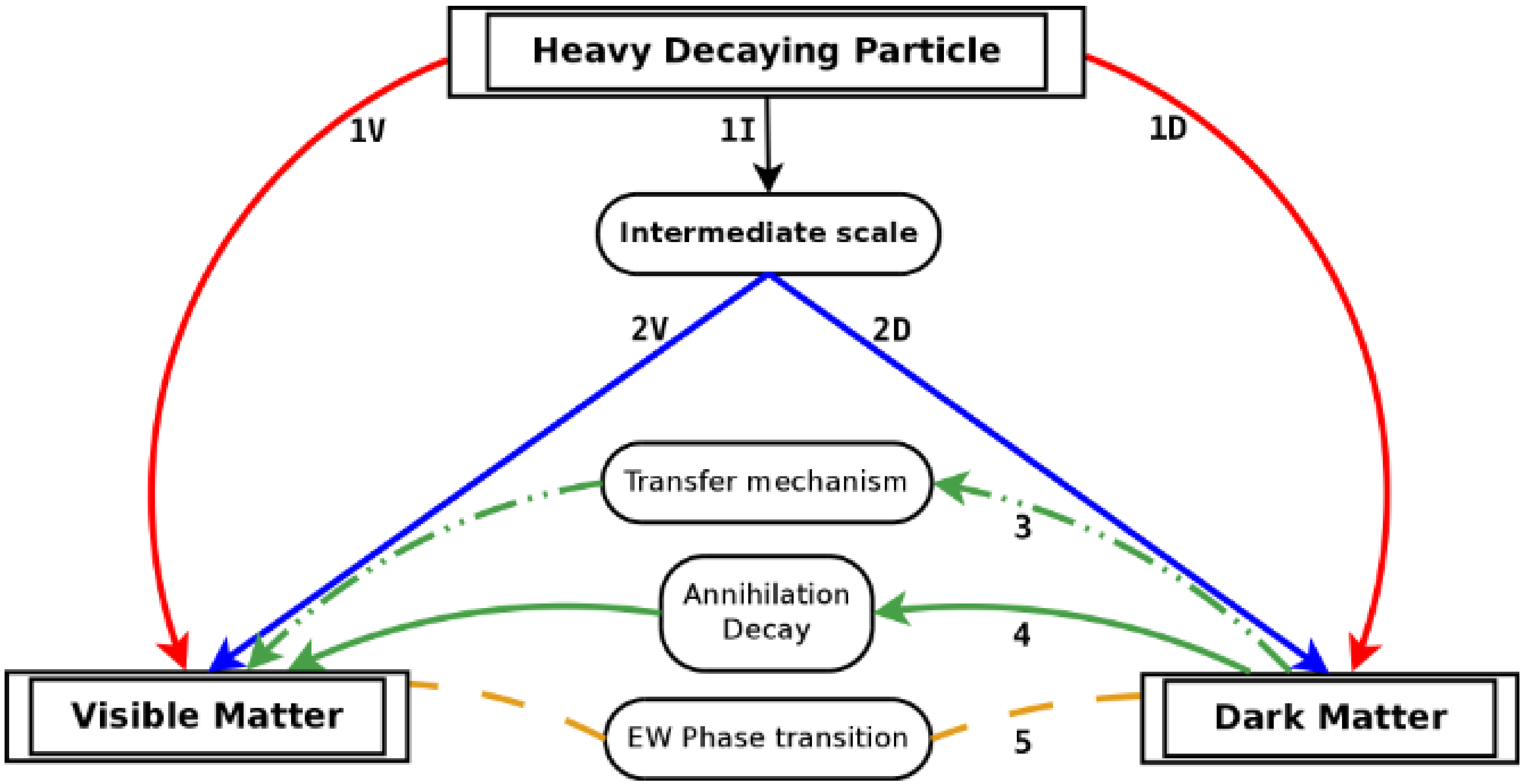
Non-relativistic & in eqb.



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

arXiv: 0901.4090

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



Schematic of popular ideas; arXiv:1310.1904

Popular cogenesis scenarios:

- Asymmetric DM (Nussinov'87; Petraki & Volkas'13; Zurek'14; Barman, DB, Das, Roshan'22++)
- WIMPy baryogenesis (Yoshimura'78; Barr'79; Baldes et al'14; Cui, Randall & Shuve'12; Mahanta & DB'23++)
- Affleck-Dine cogenesis (Cheung & Zurek'11; DB, Das & Okada'23++)

Baryon Asymmetry from Dark Matter Decay

- A particle DM, cosmologically stable at low temperature, can decay at high temperatures due to finite temperature corrections to its mass: forbidden decay!

- If DM has an in-built asymmetry, it can transfer part of its symmetry into the standard model baryon/leptons (arXiv:2305:16637; DB, Suruj Jyoti Das, Rishav Roshan).

- If the DM decay can satisfy the Sakharov's conditions, baryon/lepton asymmetry can be generated in the vicinity of a first-order phase transition (arXiv:2306.05459; DB, Arnab Dasgupta, Matthew Knauss, Indrajit Saha).

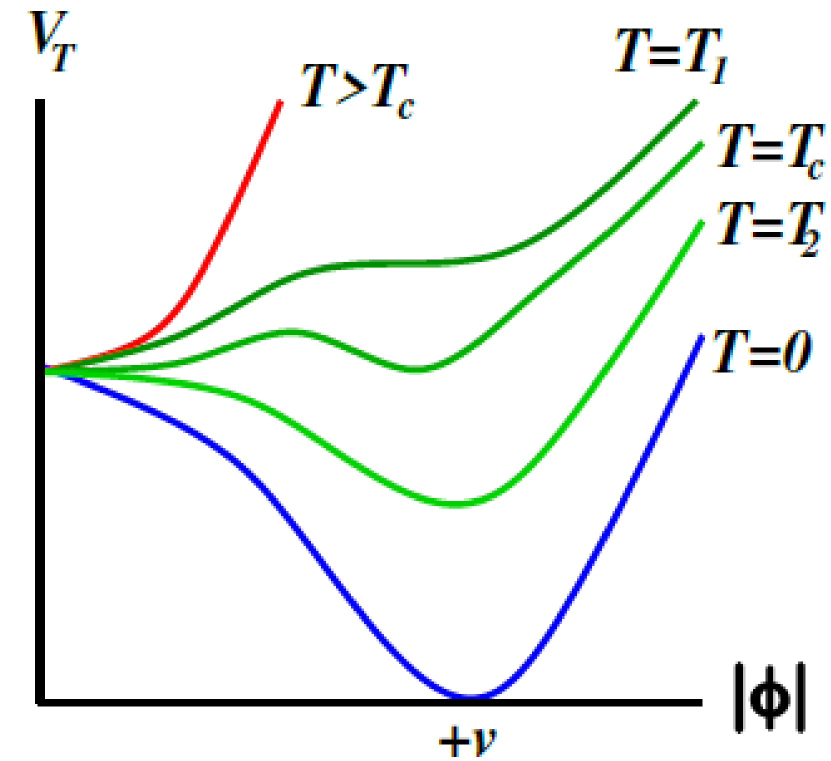
First order phase transition (FOPT)

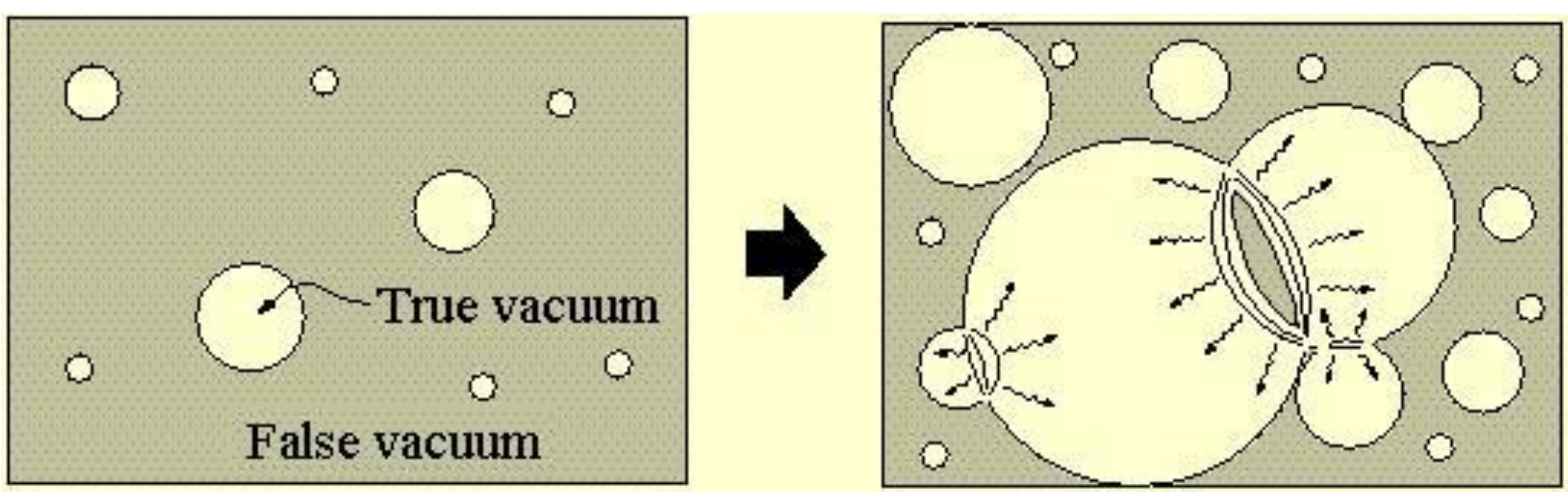
- Depending upon the model parameters, the transition from symmetric to broken phase can be a first or second order phase transition.

$$V_{eff}(\varphi, T) \approx \frac{\mu^2 + cT^2}{2}\varphi^2 - (ET + A)\varphi^3 + \frac{\lambda}{4}\varphi^4$$

- Larger the order parameter: $\frac{\varphi_c}{T_c}$, stronger will be the phase transition.

- In a FOPT, bubbles form and subsequently stochastic gravitational waves can be generated from bubble collisions, sound waves and turbulence in the plasma.





Courtesy: http://www.ctc.cam.ac.uk

Hindmarsh et al
arXiv: 2008.09136

DM decay in the vicinity of a FOPT

- Electroweak phase transition (EWPT) can not be of first order in the SM (Kajantie, Laine, Rummukainen, Shaposhnikov 1996++).
- Need additional scalars to have first order EWPT.
- Need DM, additional fields to generate non-zero CP asymmetry, stabilizing symmetry etc.
- Could possibly solve the neutrino mass puzzle?

arXiv:2306.05459

Scotogenic model: an illustrative example

Z. Tao'96
E. Ma'06

- Two types of BSM fields: 3 copies of singlet right handed neutrinos N_i and one $SU(2)_L$ scalar doublet η, all odd under an unbroken Z_2 symmetry.
- New Yukawa Lagrangian: $-\mathcal{L} \supset Y_{\alpha i}\overline{L_\alpha}\tilde{\eta}N_i + \mathrm{h.c.}$
- Tree level scalar potential:

$$V_0 = \mu_\Phi^2|\Phi|^2 + \mu_\eta^2|\eta|^2 + \lambda_1|\Phi|^4 + \lambda_2|\eta|^4 + \lambda_3|\Phi|^2|\eta|^2 + \lambda_4|\eta^\dagger\Phi|^2 + \frac{\lambda_5}{2}\left[\left(\eta^\dagger\Phi\right)^2 + \mathrm{h.c.}\right]$$

- Denoting SM Higgs Φ and new scalar doublet as

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \phi + v \end{pmatrix}, \eta = \begin{pmatrix} \eta^\pm \\ \frac{(H+iA)}{\sqrt{2}} \end{pmatrix}$$

leads to physical scalars H, A, η^+ in addition to the SM Higgs *h*.

- Light neutrino masses arise at one-loop level.

Finite-temperature masses

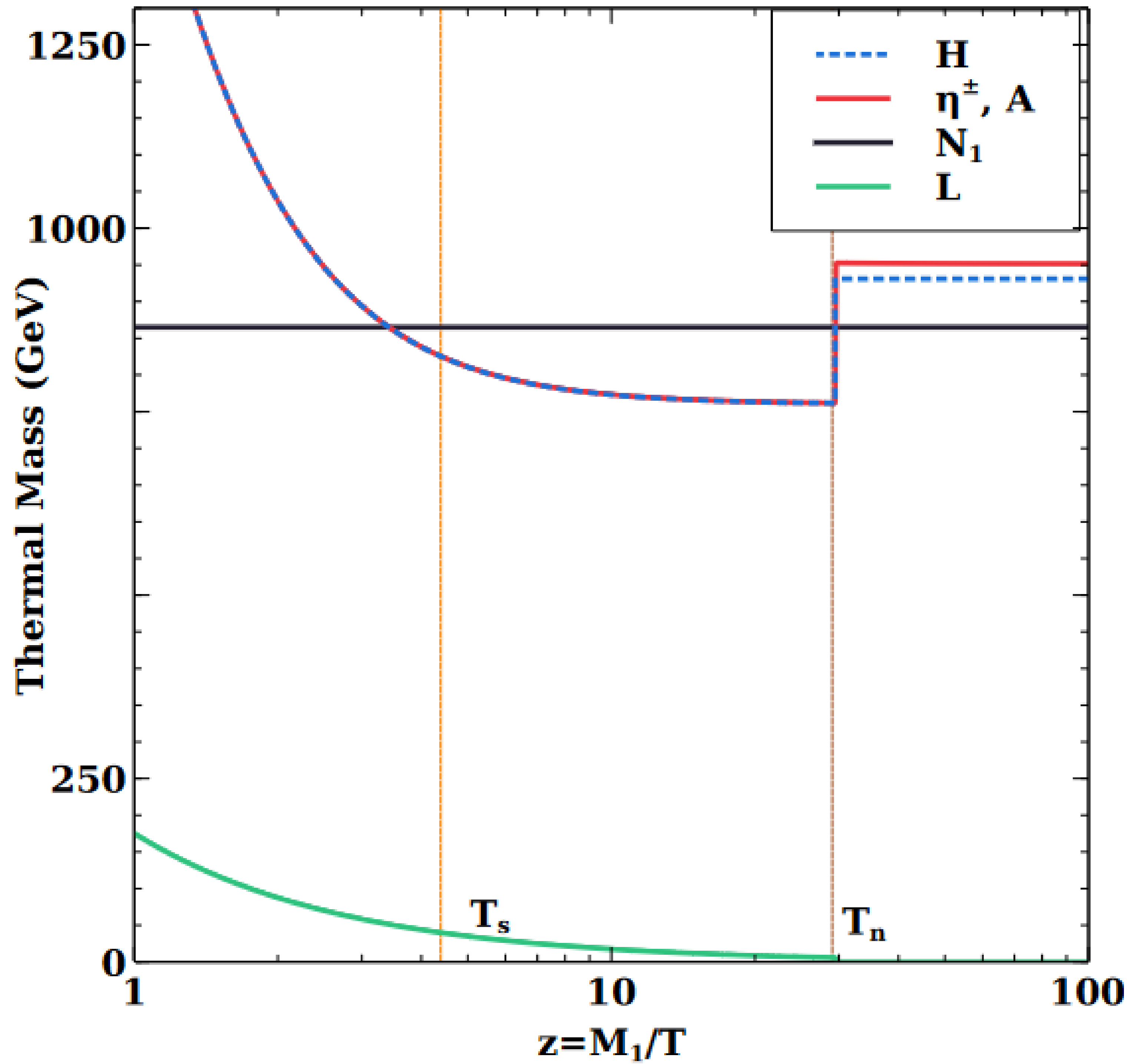
$$m_i^2(\phi, T) = m_i^2(\phi) + \Pi_S(T)$$

$$M_L(T) = \sqrt{m_L^2 + \frac{1}{2}\Pi^2_{\rm gauge}(T)}$$

During $T_n < T < T_s$:

$$M_N > m_\eta + M_L$$

Allowing DM decay!



1st order EWPT with inert scalar doublet (DB, Cline'12; Gil, Chankowski, Krawczyk'12; DB, Dasgupta, Fujikura, Kang, Mahanta'20; Shibuya, Toma'22++)

Boltzmann Equations

$$\frac{dY_N}{dz} = \frac{g_\eta \langle \Gamma_\eta \rangle}{z\tilde{\mathcal{H}}} \left[Y_\eta - \frac{Y_\eta^{eq} Y_N}{Y_N^{\rm eq}} \right] - \frac{g_\eta \langle \Gamma_{N_1} \rangle}{z\tilde{\mathcal{H}}} \left[Y_N - \frac{Y_N^{\rm eq} Y_\eta}{Y_\eta^{\rm eq}} \right],$$

$$\frac{dY_\eta}{dz} = -\frac{g_\eta \langle \sigma_{\eta\eta} v_{\rm rel} \rangle s}{z\tilde{\mathcal{H}}} \left[Y_\eta^2 - Y_\eta^{\rm eq\,2} \right] - \frac{g_\eta \langle \Gamma_\eta \rangle}{z\tilde{\mathcal{H}}} \left[Y_\eta - \frac{Y_\eta^{\rm eq} Y_N}{Y_N^{\rm eq}} \right] + \frac{g_\eta \langle \Gamma_{N_1} \rangle}{z\tilde{\mathcal{H}}} \left[Y_N - \frac{Y_N^{\rm eq} Y_\eta}{Y_\eta^{\rm eq}} \right],$$

$$\frac{dY_{B-L}}{dz} = -\epsilon_1 \frac{g_\eta \langle \Gamma_{N_1} \rangle}{z\tilde{\mathcal{H}}} \left[Y_N - \frac{Y_N^{\rm eq} Y_\eta}{Y_\eta^{\rm eq}} \right] - \epsilon_\eta \frac{g_\eta \langle \Gamma_\eta \rangle}{z\tilde{\mathcal{H}}} \left[Y_\eta - \frac{Y_\eta^{\rm eq} Y_N}{Y_N^{\rm eq}} \right] - (W_1 + \Delta W)\, Y_{B-L}.$$

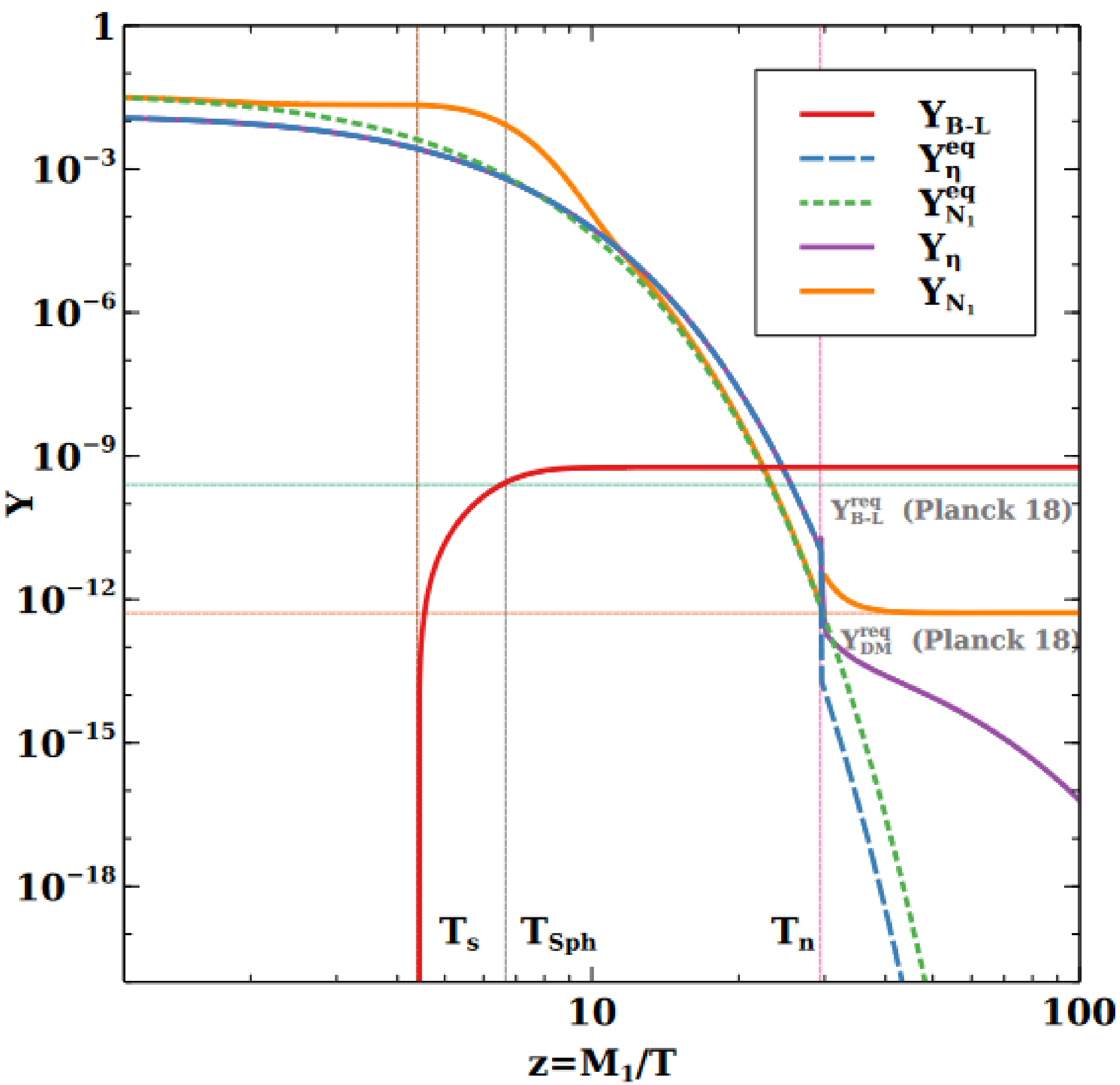
$$\tilde{\mathcal{H}} \sim \mathcal{H} = \sqrt{\frac{4\pi^3 g_*(T)}{45}}\, \frac{T^2}{M_{\rm Pl}} \qquad z = M_1/T$$

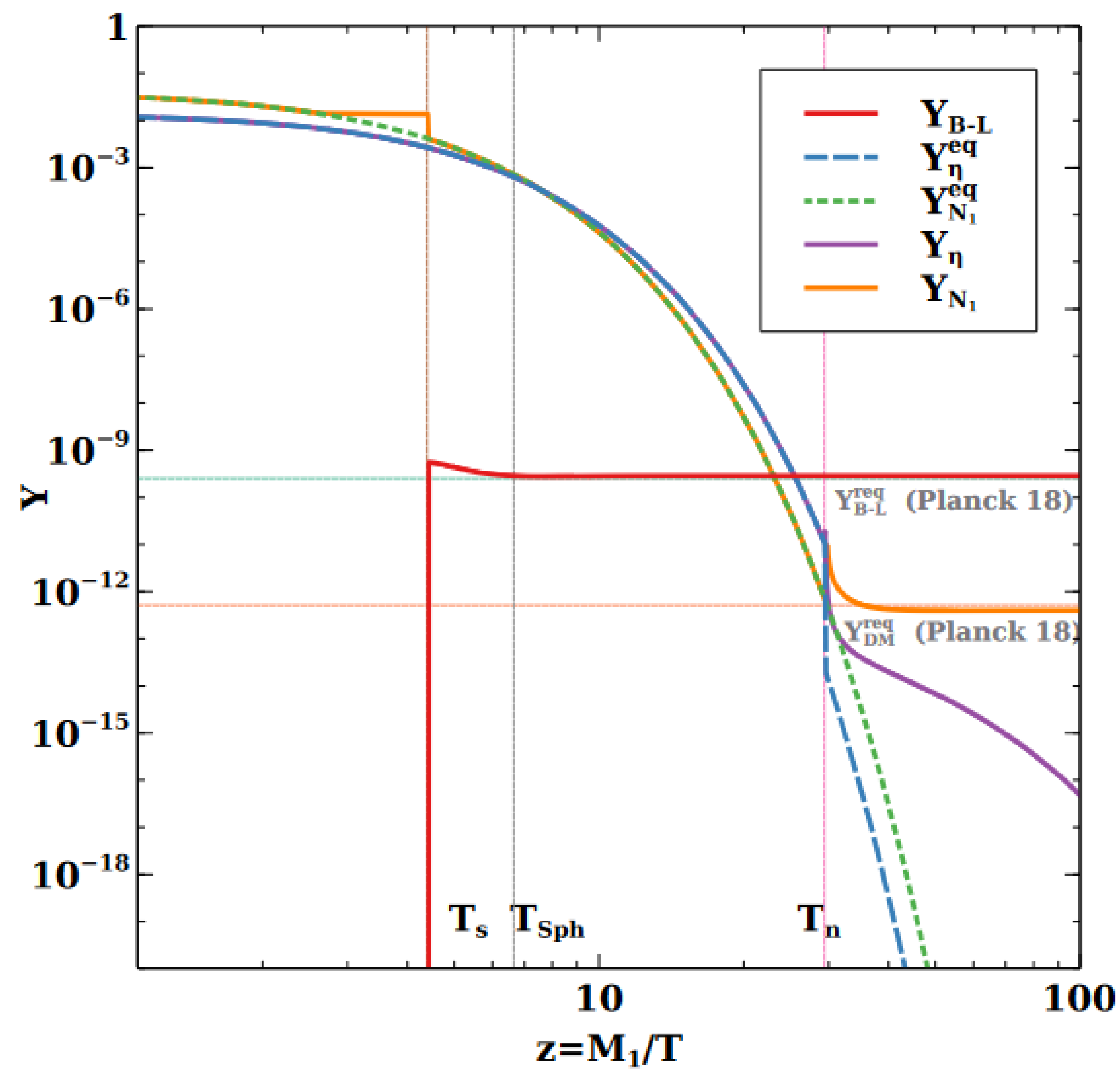
Wash-out

$$\epsilon_i = \left[\left(M_i^2 + M_L^2 - m_\eta^2\right) \lambda^{1/2}\left(M_i^2, M_L^2, m_\eta^2\right) \Theta\left(M_i^2 - (m_\eta + M_L)^2\right) \right] \frac{1}{(Y^\dagger Y)_{ii}} \sum_{j \neq i} \frac{{\rm Im}[((Y^\dagger Y)_{ij})^2]}{16\pi M_i^3} \frac{M_j \Delta_{ij}}{\Delta_{ij}^2 + \left(M_j \Gamma_{N_j}\right)^2}$$

arXiv:2306.05459

Evolution of commoving densities: BP1 (NO)



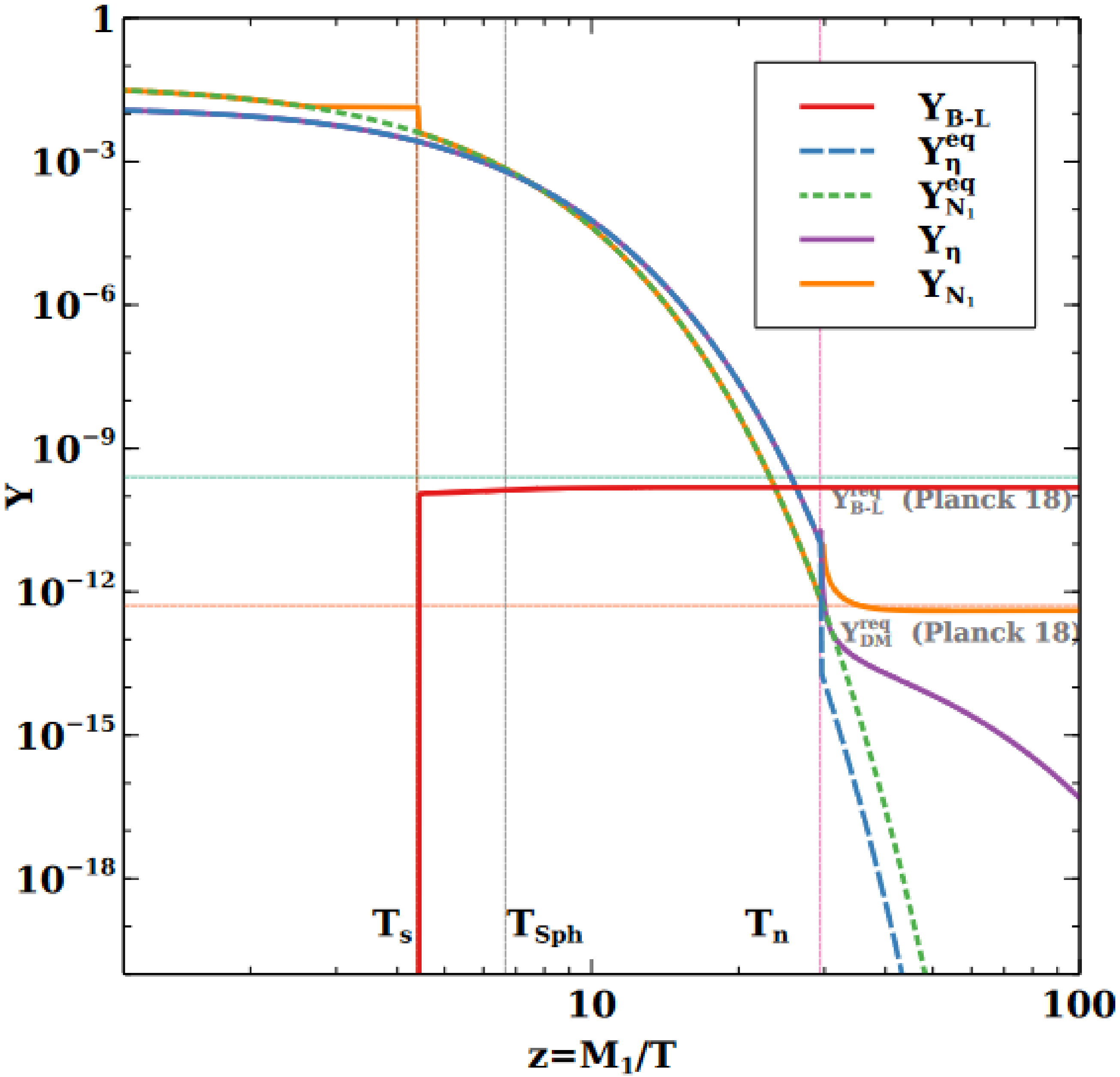


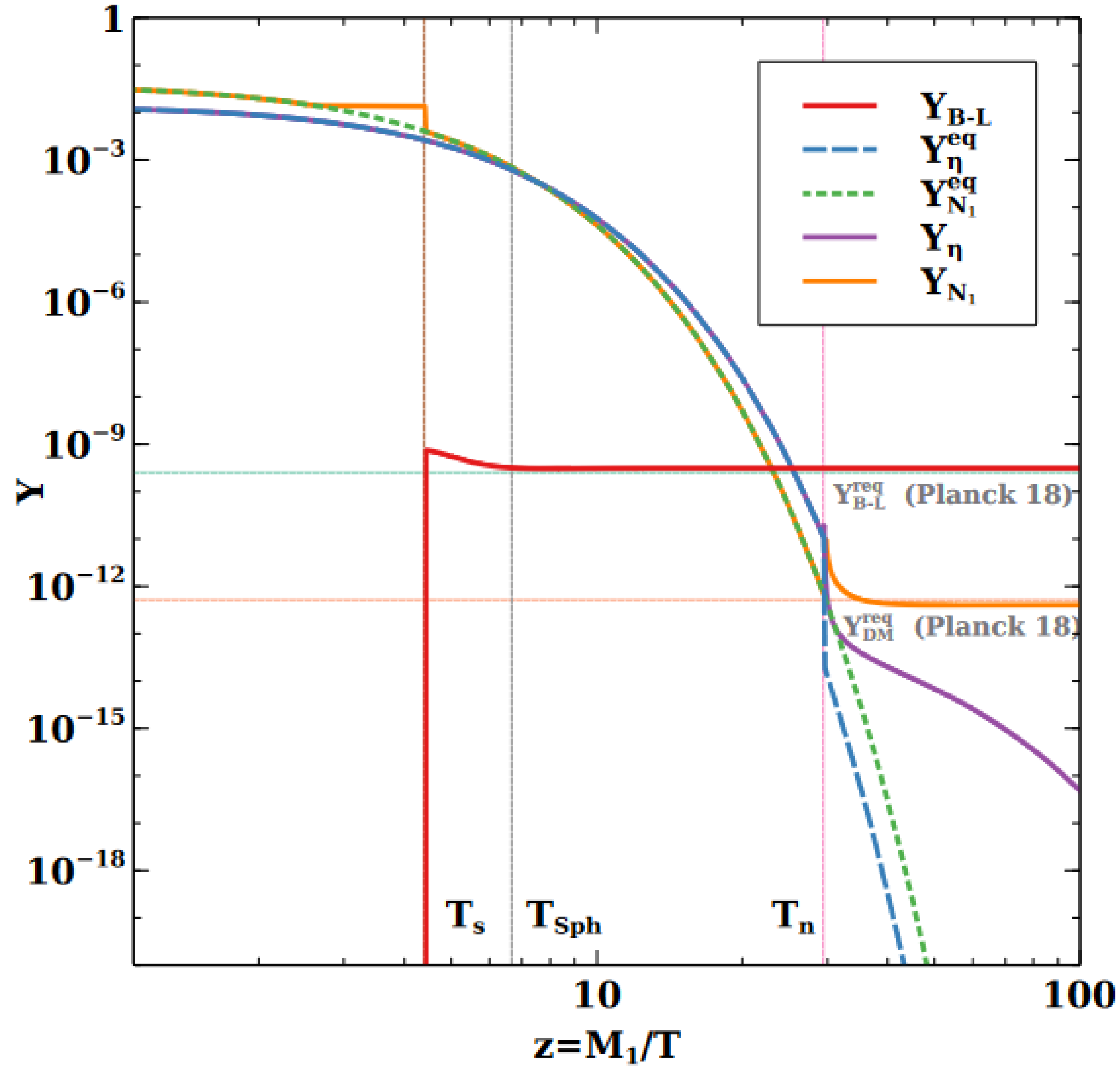
Weak washout $m_1 = 10^{-5}$eV

Strong washout $m_1 = 10^{-1}$eV

arXiv:2306.05459

Evolution of commoving densities: BP1 (IO)





Weak washout $m_3 = 10^{-5}$eV

Strong washout $m_3 = 10^{-1}$eV

arXiv:2306.05459

GW Aspects

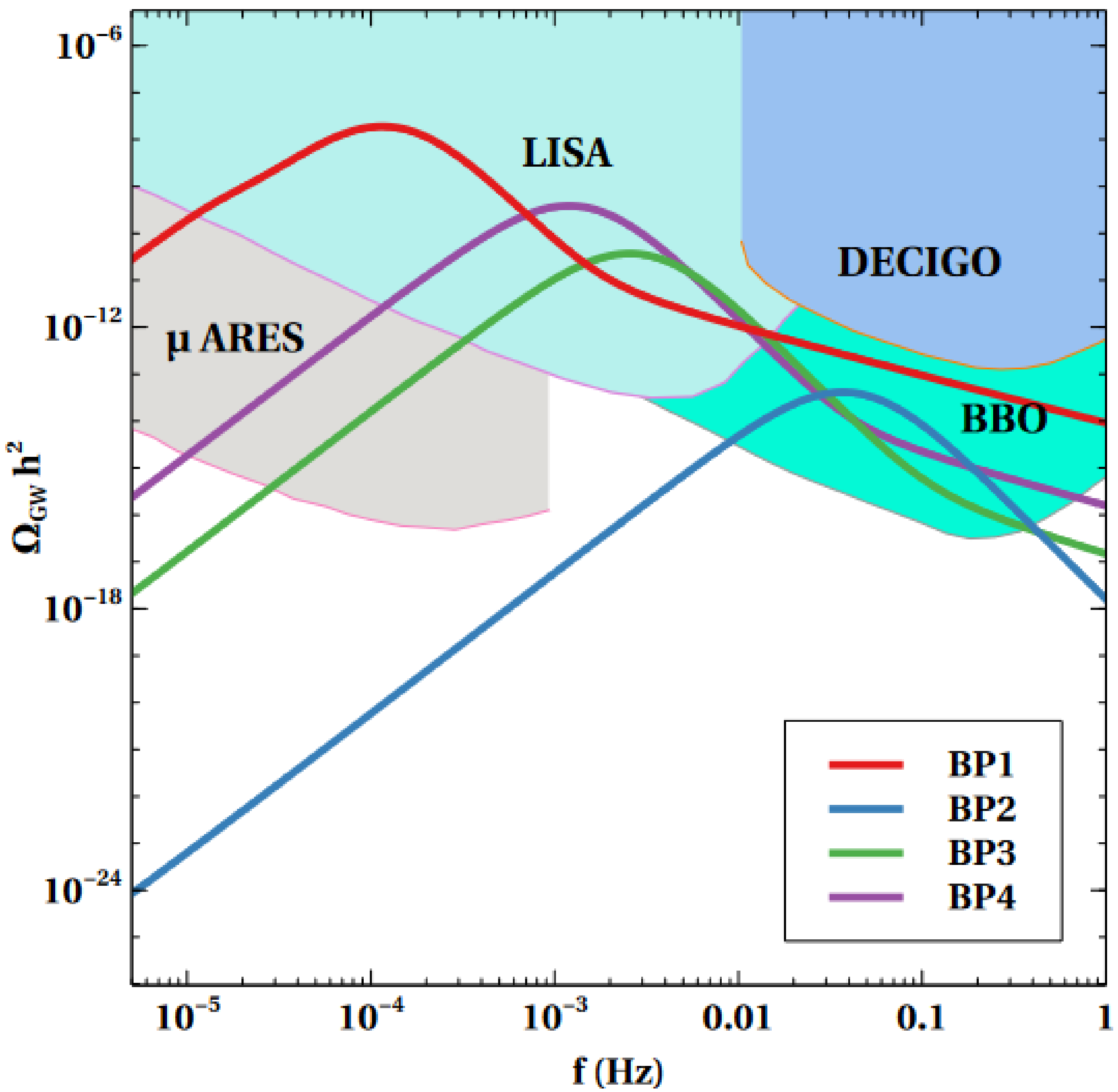
Key GW parameters:

- Duration of FOPT $\frac{\beta}{\mathcal{H}(T)} \simeq T\frac{d}{dT}\left(\frac{S_3}{T}\right)$
- Latent heat $\alpha_* = \frac{1}{\rho_{\rm rad}}\left[\Delta V_{\rm tot} - \frac{T}{4}\frac{\partial \Delta V_{\rm tot}}{\partial T}\right]_{T=T_n}$
- Bubble velocity

$$\Omega_{\rm GW}(f) = \Omega_\phi(f) + \Omega_{\rm sw}(f) + \Omega_{\rm turb}(f)$$

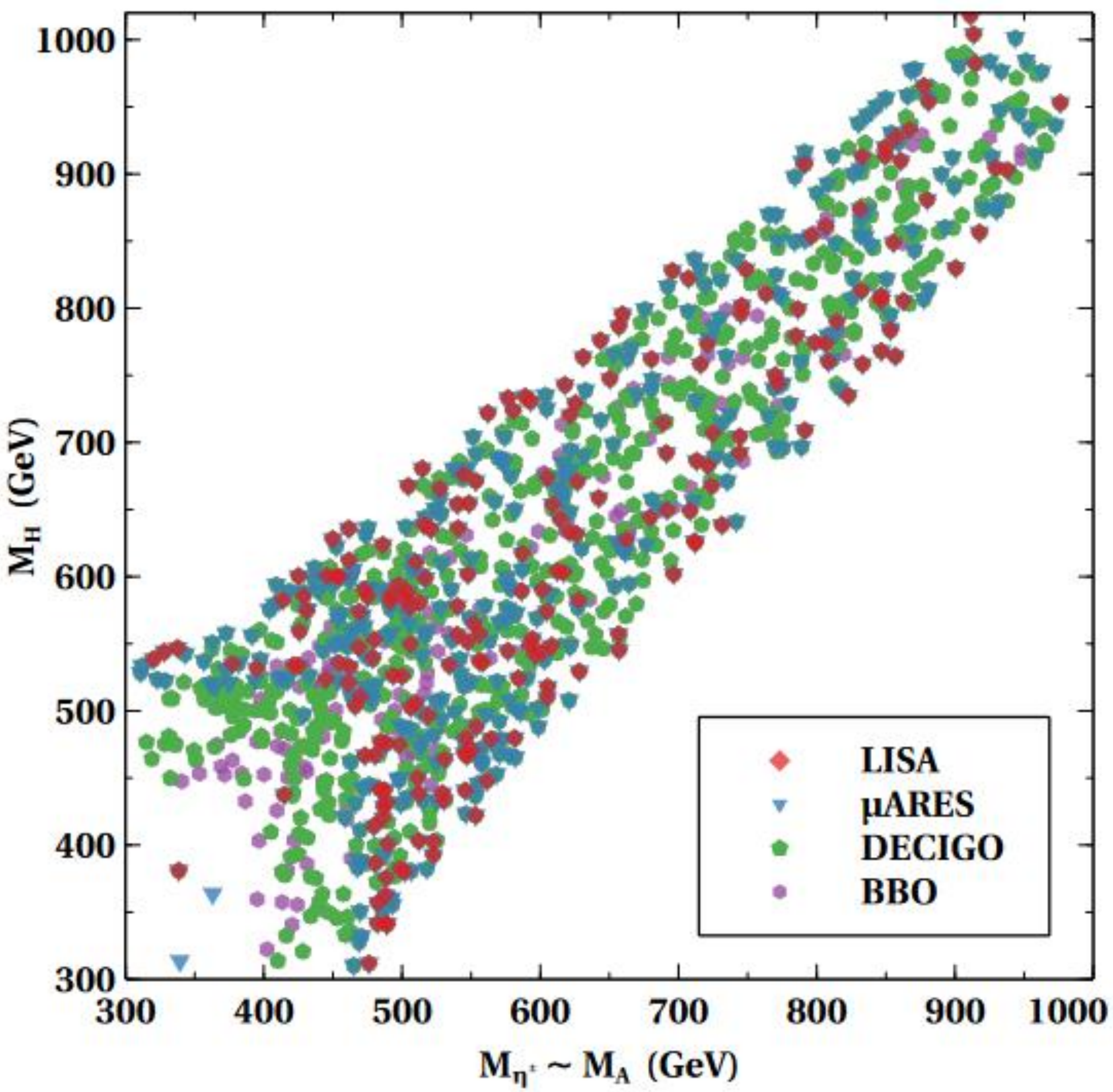
$$h^2\Omega(f) = \mathcal{R}\Delta(v_w)\left(\frac{\kappa\alpha_*}{1+\alpha_*}\right)^p\left(\frac{\mathrm{H}_*}{\beta}\right)^q \mathcal{S}(f/f_{\rm peak})$$

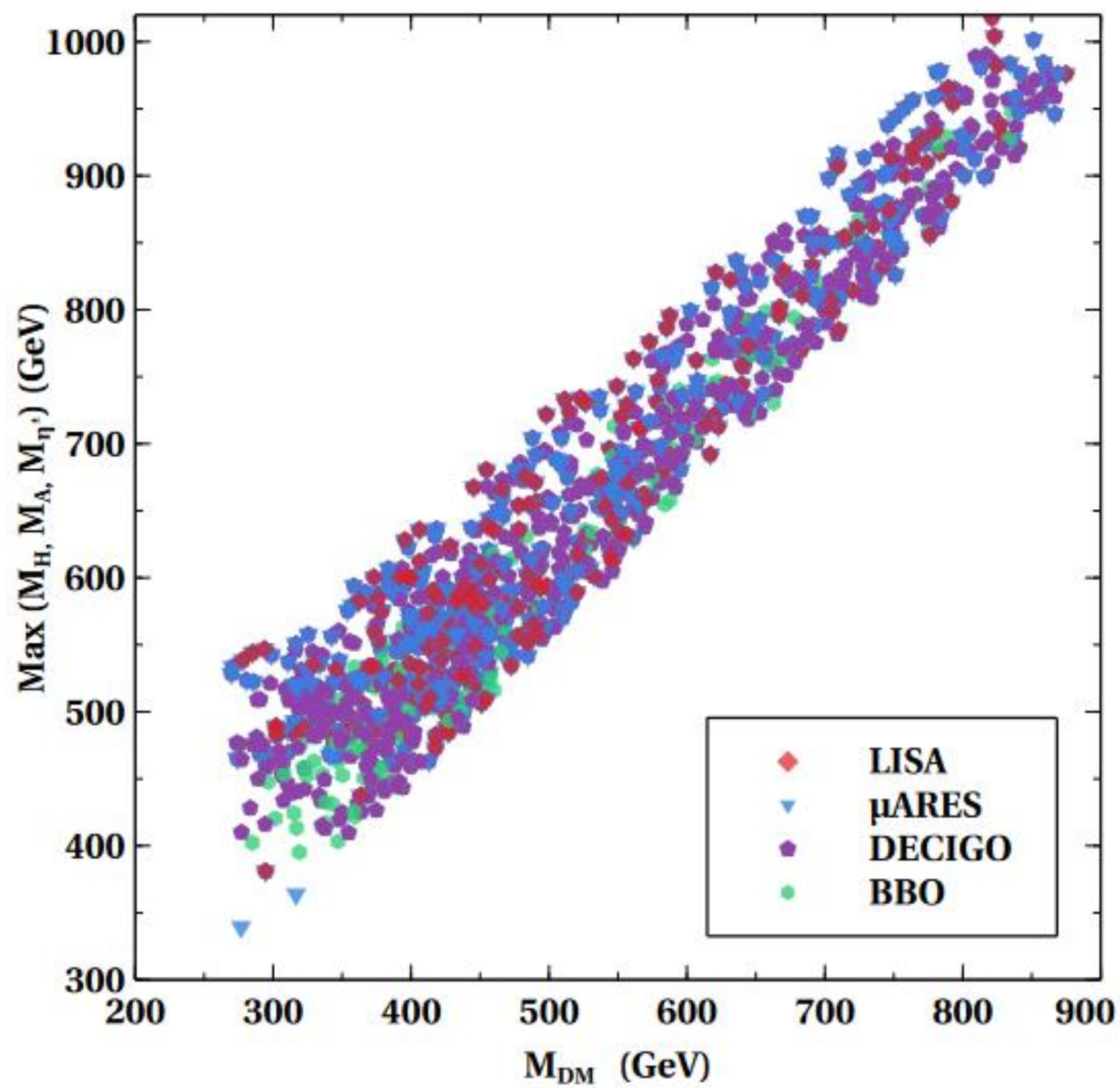
Caprini et al, arXiv:1512.06239



	T_c (GeV)	v_c (GeV)	T_n(GeV)	M_1 (GeV)	μ_η (GeV)	$M_{\eta^\pm} \sim M_A$(GeV)	M_H (GeV)	α_*	$\beta/\mathcal{H}$	v_J	$T_{\rm RH}$ (GeV)
BP1	60.05	217.22	29.27	859.50	760.25	951.51	931.26	1.29	20.21	0.94	30.37
BP2	73.55	187.62	68.54	866.70	787.07	958.89	944.72	0.04	2862.35	0.71	68.54
BP3	71.30	199.28	64.33	676.64	579.36	774.96	743.73	0.06	1829.84	0.74	64.33
BP4	63.35	216.65	38.49	493.74	368.04	608.38	548.60	0.45	159.33	0.88	38.49

Parameter space within reach of GW experiments





arXiv:2306.05459

Other detection prospects

- The second Higgs doublet can have collider signatures like dilepton/dijet + MET, displaced vertex etc.
- Observable charged lepton flavour violation like $\mu \to e\,\gamma$.

Conclusion

- Explaining baryon asymmetry from dark matter decay addresses the baryon-DM coincidence problem $\Omega_{DM} \simeq 5\Omega_B$, providing a new cogenesis possibility.
- Realising this around a first order EWPT in scotogenic model leads to observable GW in future experiments like LISA.
- Realising it in low scale baryogenesis or two-step FOPT can open up new detection prospects.

Thank You