Gravitational Wave Probes of Dark Matter and Leptogenesis

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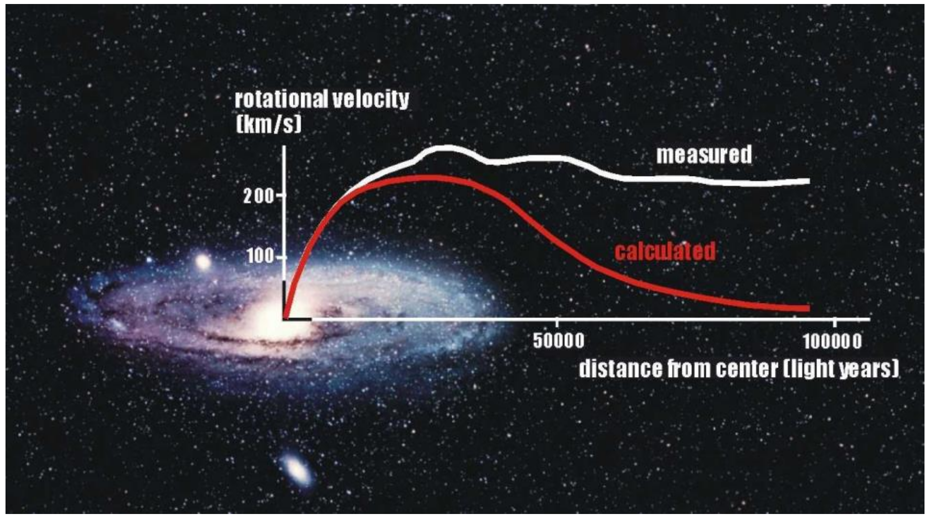
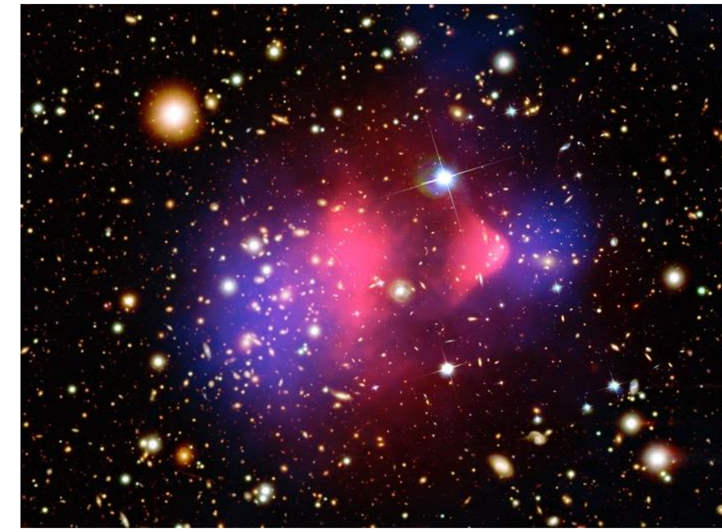
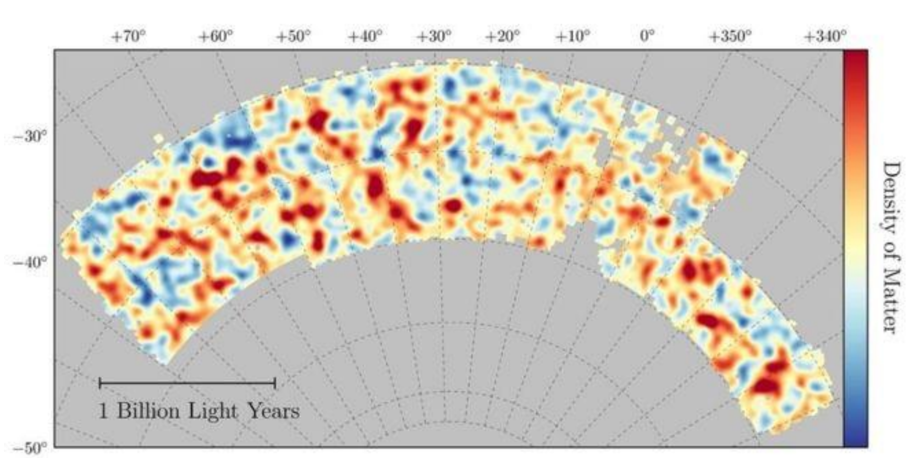
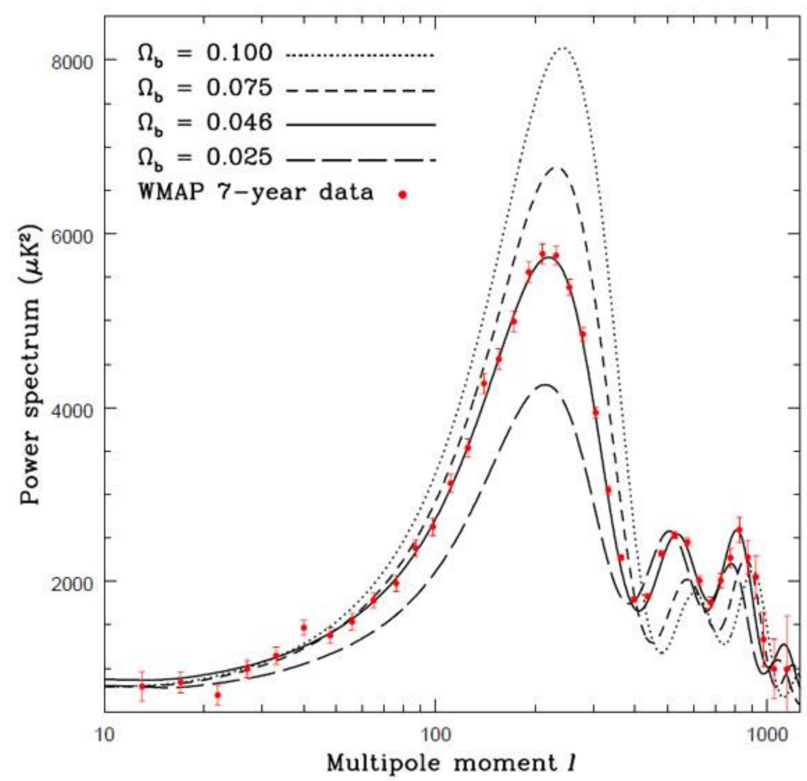
At PPC 2022, Washington University in St. Louis

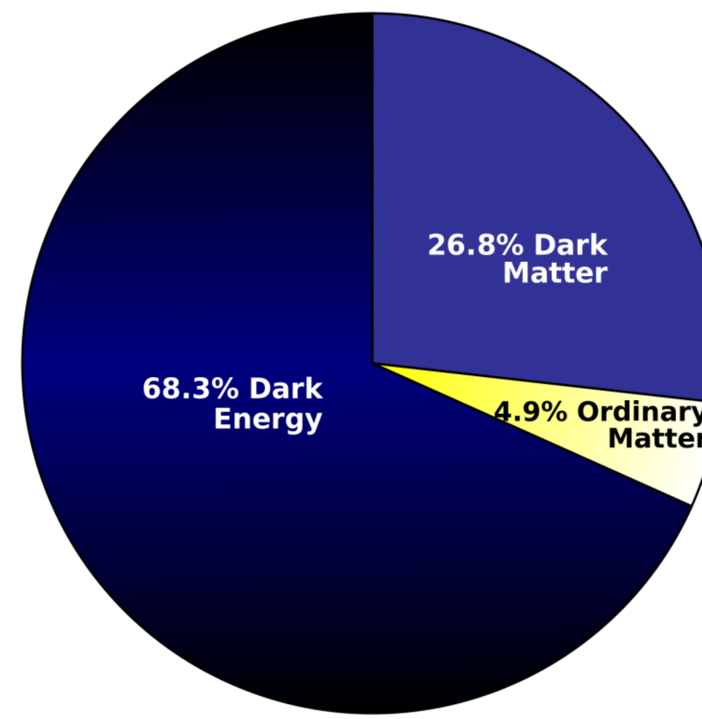
Dark Matter: Evidences

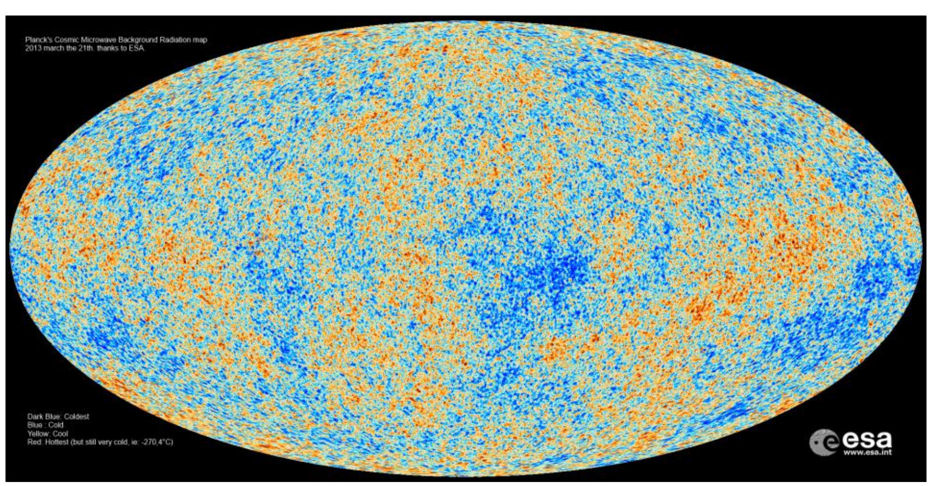








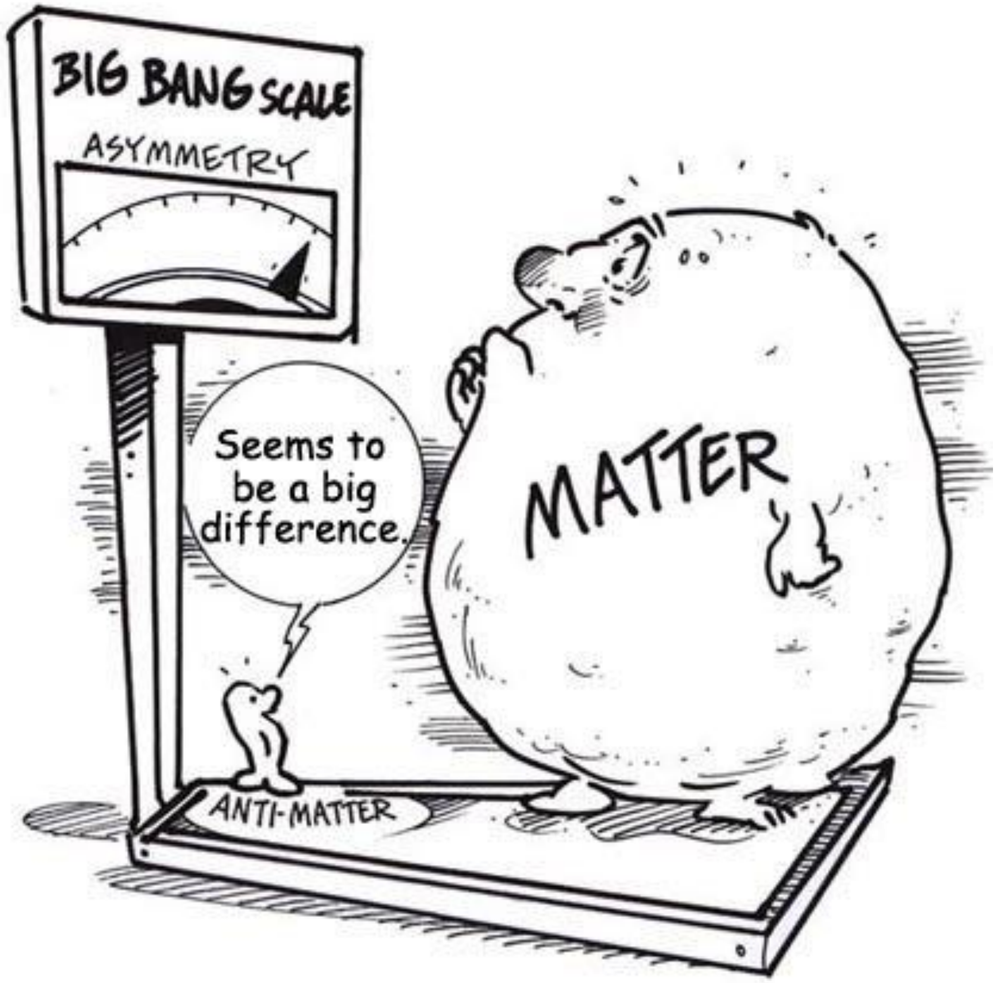




Credits: HST, Chandra, DES, WMAP, Planck

Standard Model does not have any DM candidate

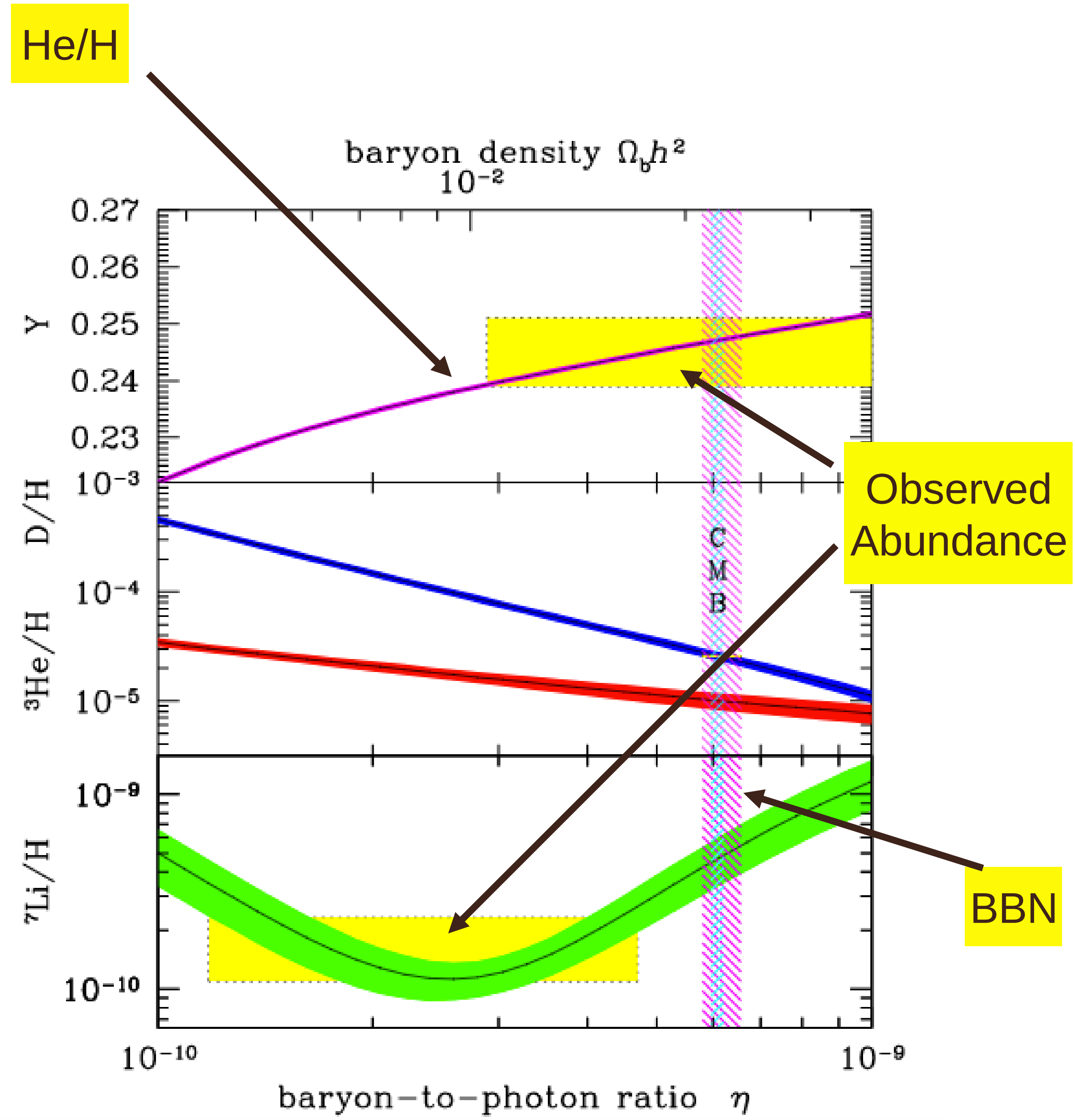
Matter-antimatter (baryon) asymmetry



- 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 the BBN agrees well with the observed value inferred from the CMB measurements (Planck 2018).



Particle Data Group

Sakharov's Conditions

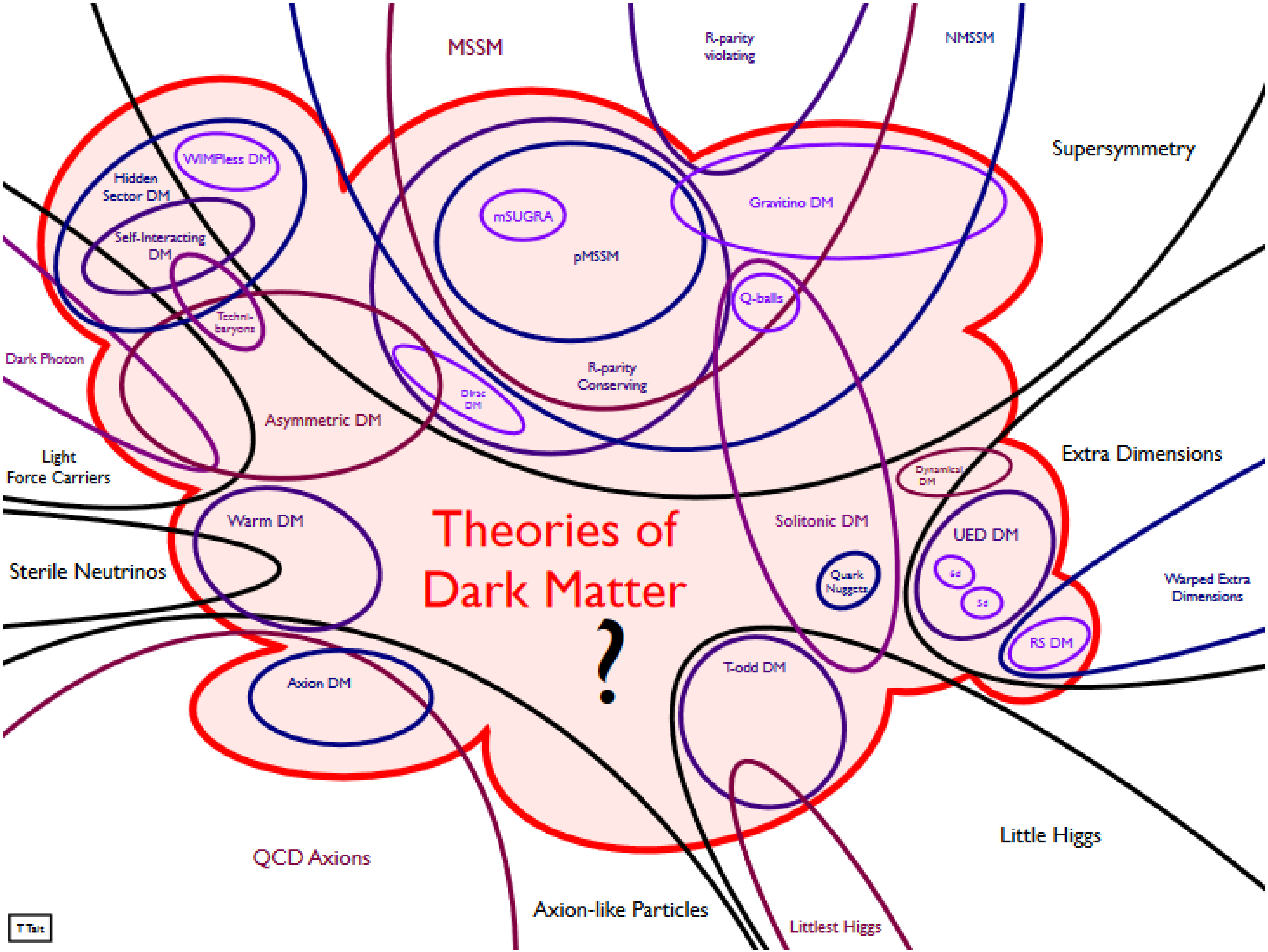
Three basic ingredients necessary to generate a net baryon asymmetry from an initially baryon symmetric Universe (Sakharov 1967):

- 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


MSSM
R-parity
violating
NMSSM
Supersymmetry
WIMPless DM
Hidden
Sector DM
Self-Interacting
DM
Techni-
baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
Dark Photon
Dirac
DM
R-parity
Conserving
Asymmetric DM
Light
Force Carriers
Extra Dimensions
Dynamical
DM
Warm DM
Theories of
Dark Matter
?
Solitonic DM
UED DM
Sterile Neutrinos
Quark
Nuggets
Warped Extra
Dimensions
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
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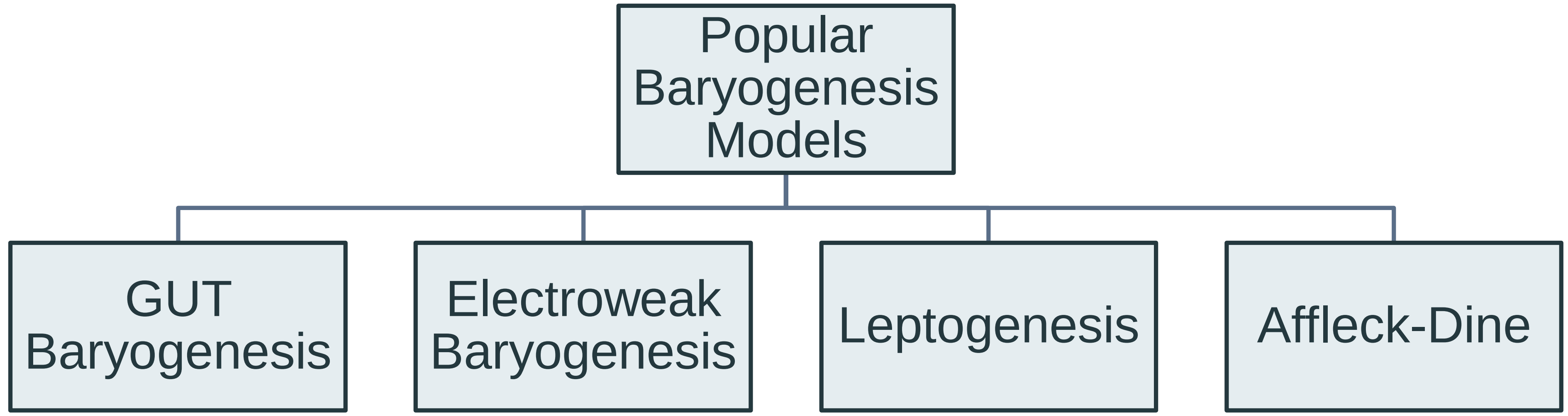


New Ideas

Snowmass 2021
Arxiv:2203.05010

2 New Ideas in Baryogenesis Models

Related Parallel Session talks:

Freeze-in leptogenesis by Brian Shuve

LRSUSY by Urjit Yajnik

Freeze-in baryogenesis by David Tucker-Smith

GW pathways for testable leptogenesis by Arnab Dasgupta

Baryogenesis via Leptogenesis

Plenary by K S Babu

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

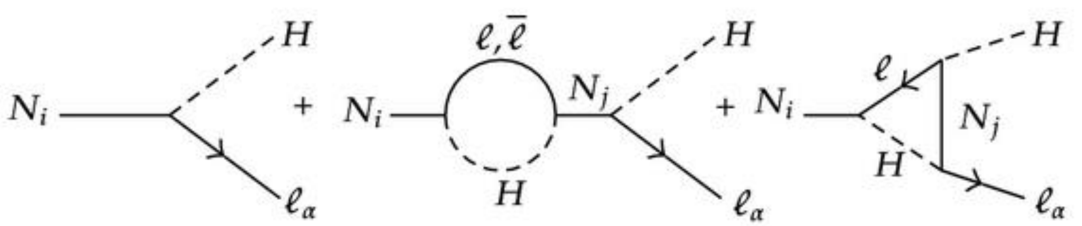
- Right handed neutrino decays out of equilibrium (Fukugita & Yanagida 1986)

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

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

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

- At least two N are required to generate an asymmetry. The Boltzmann equations can be written as



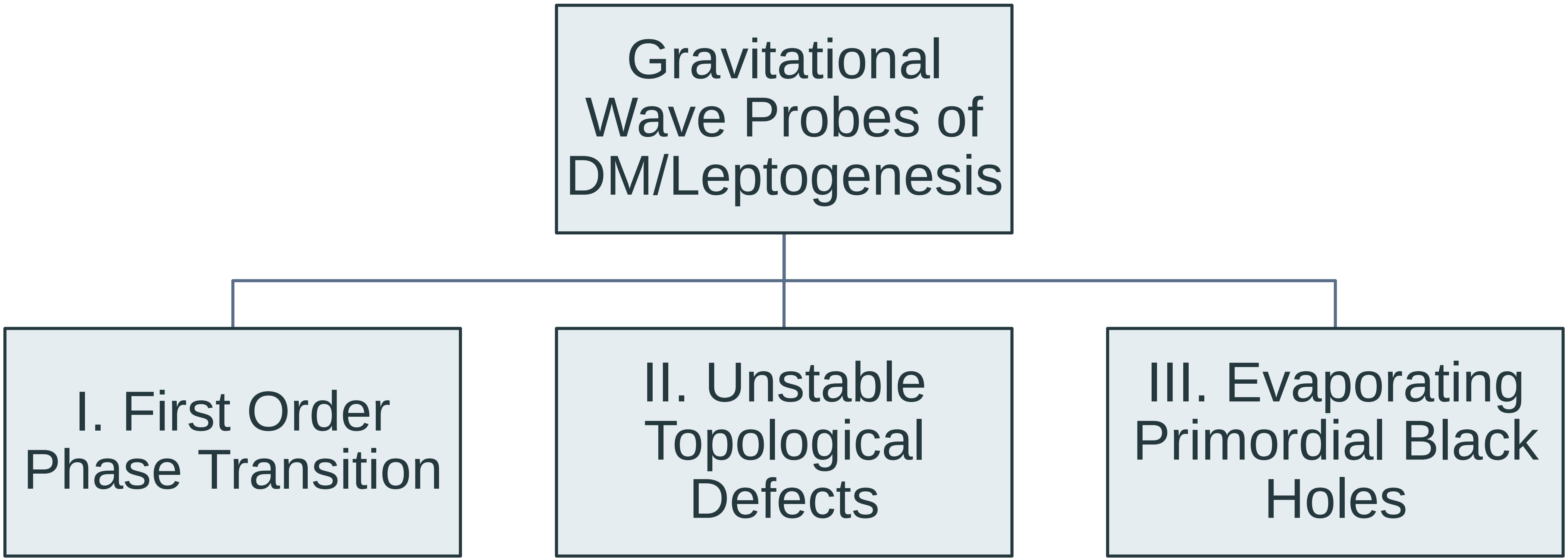
$$\frac{dY_N}{dz} = -\frac{\Gamma_1}{\mathbf{H}z}\left(Y_N - Y_N^{eq}\right), \frac{dY_{B-L}}{dz} = -\epsilon_1\frac{\Gamma_1}{\mathbf{H}z}\left(Y_N - Y_N^{eq}\right) - WY_{B-L}$$

- 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'88

Davidson-Ibarra Bound: M > 10^9GeV ⟹ Typically a high scale phenomena with limited direct search scope!



+ other possibilities

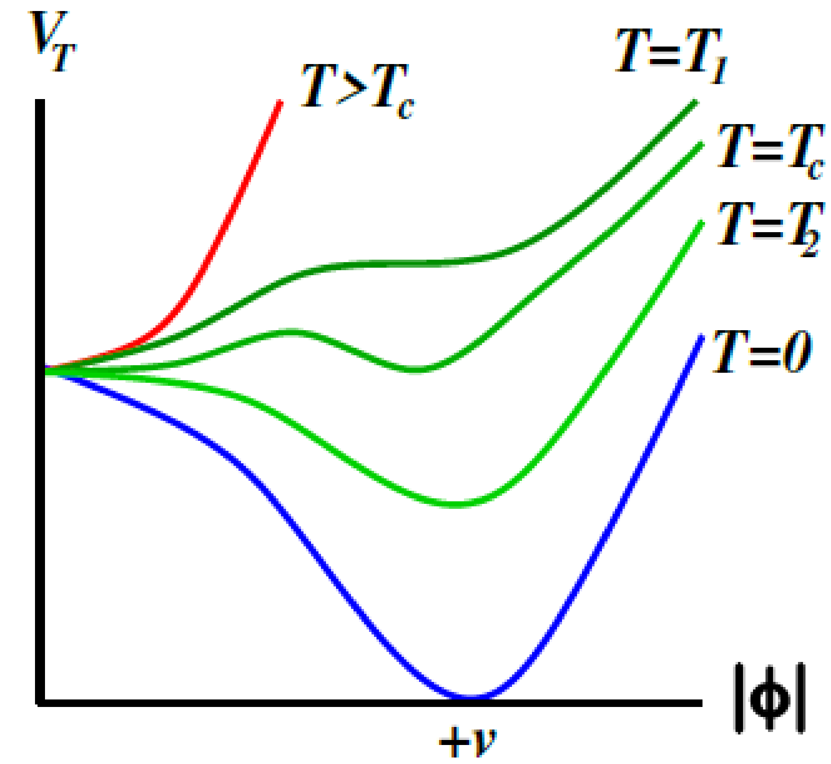
Part I: First order phase transition (FOPT)

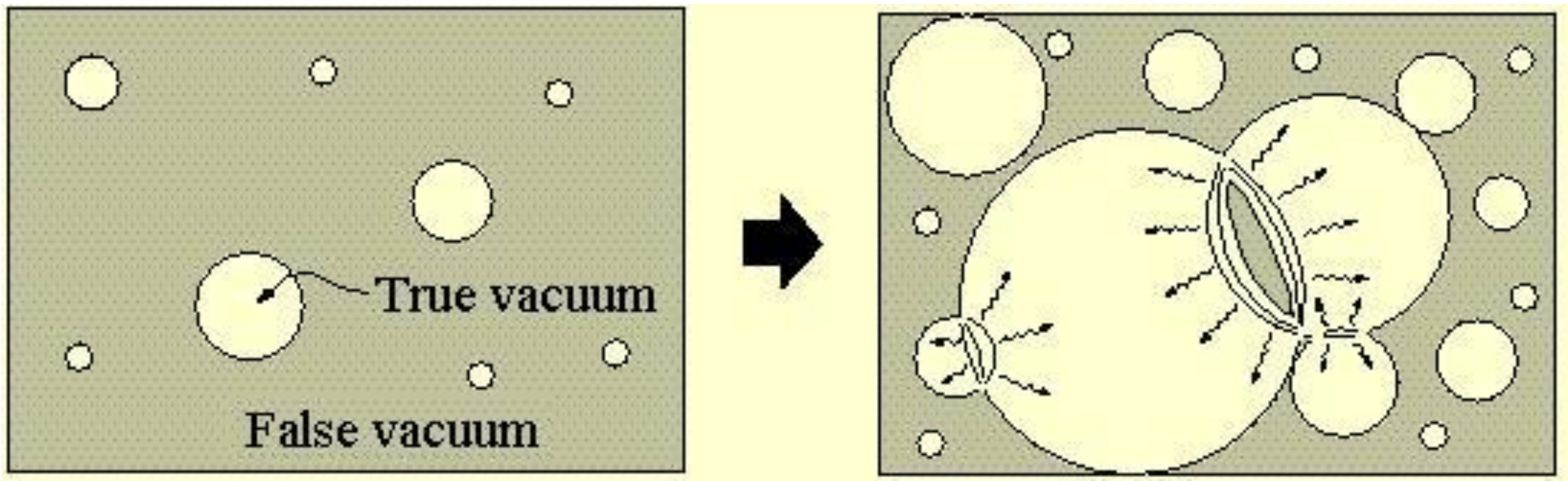
- Depending upon the model parameters, the transition from symmetric to broken phase can be a first or second order phase transition.

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

- 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

Plenary by James Dent

Hindmarsh et al Arxiv: 2008.09136

Snowmass 2021
Arxiv:2203.07972

DM ?⟷ FOPT

DM induced EWPT

- SM+scalar singlet (Espinosa, Quiros'93; Benson'93; Choi, Volkas'93; Vergara'96; Cline, Kainulainen, Tucker-Smith'17++)
- SM+scalar doublet (Turok, Zadrozny'92; Cline, Lemieux'97; DB, Cline'12, DB, Dasgupta, Fujikura, Kang, Mahanta'20++)
- SM+scalar triplet (Patel, Ramsey-Musolf'12++)
- Dark sector (Ghosh, Guo, Han, Liu'20++)

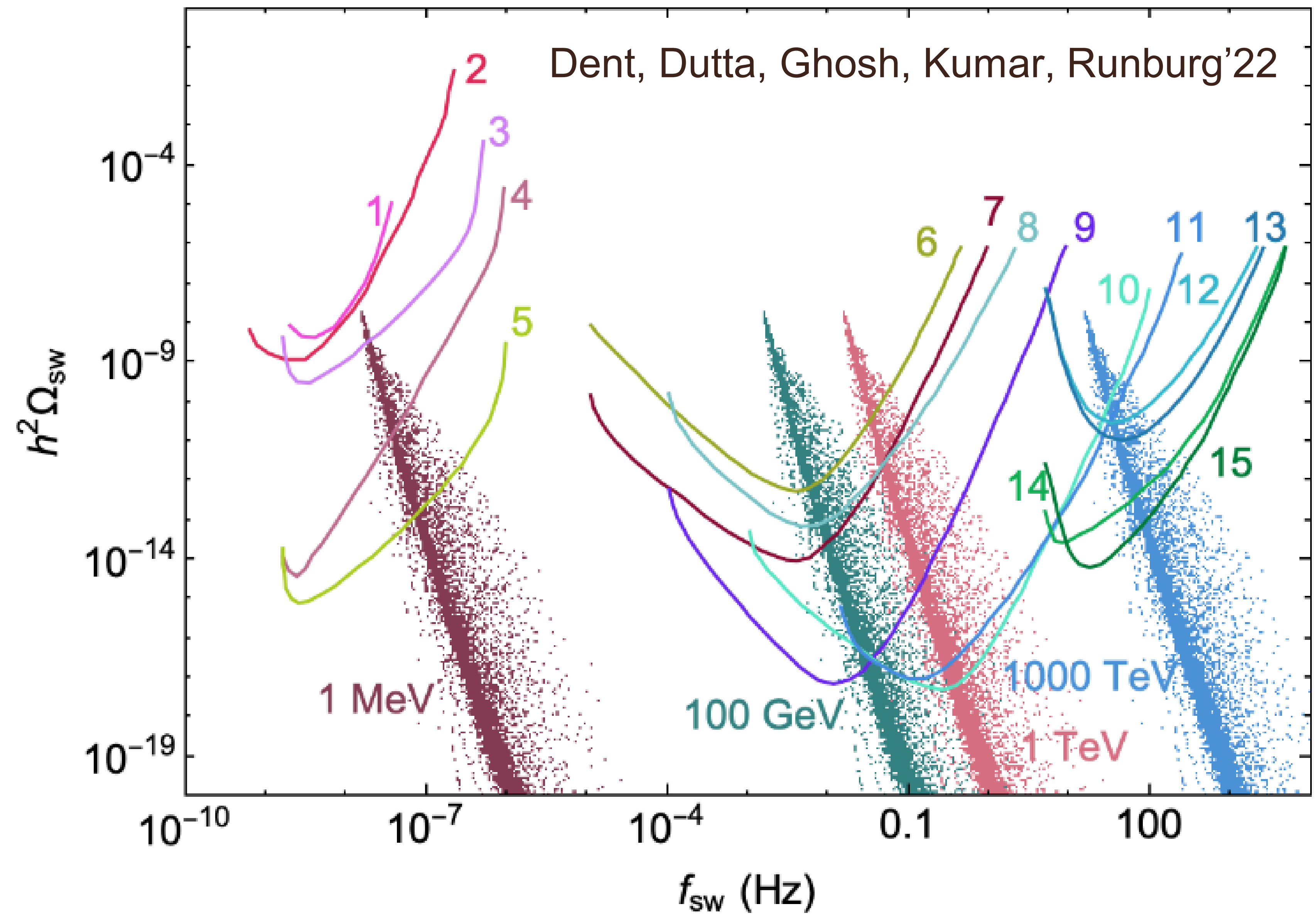
BSM scenarios with > TeV scale symmetry

- B-L gauge extension (Jinno, Takimoto'17; Okada, Seto'18; Hasegawa, Okada, Seto'19++)
- B/L gauge extension (Fornal, Haghi'20)
- Flavour symmetry (Greljo, Opferkuch, Stefanek'20; Fornal'21)
- Left-right extension (Brdar, Graf, Helmboldt, Xu'19, Graf, Jana, Kaladharan, Saad'22++).....

Dark Sector PT

- Dark U(1) (Schwaller'15; Chiang, Senaha'17; DB, Dasgupta, Kang'21++)
- Dark SU(N) (Baldes, Garcia-Cely'19; Prokopek, Rezacek, Swiezewska'19; DB, Dasgupta, Kang'21++)
- DM production from FOPT: via bubble collisions (Falkowski, No'13), via bubble wall filtering (Baker, Kopp, Long'20), via relativistic bubble walls (Azatov, Vanvlasselaer, Yin'21)++.

1. EPTA
2. NANOGrav
3. GAIA
4. SKA
5. THEIA
6. LISA
7. TAIJI
8. TIANQIN
9. ALIA
10. BBO
11. DECIGO
12. aLIGO
13. A+
14. Et
15. CE



- Typically, DM induced FO EWPT leads to smaller GW amplitude as couplings/masses are tightly constrained by direct search bounds. Multi-step FOPT can enhance it.
- High scale PT can give a large GW amplitude if it can be made a supercooled one.
- Dark sector PT can occur all the way from MeV to very high scale and can be supercooled: can be probed in most of the GW experiments.

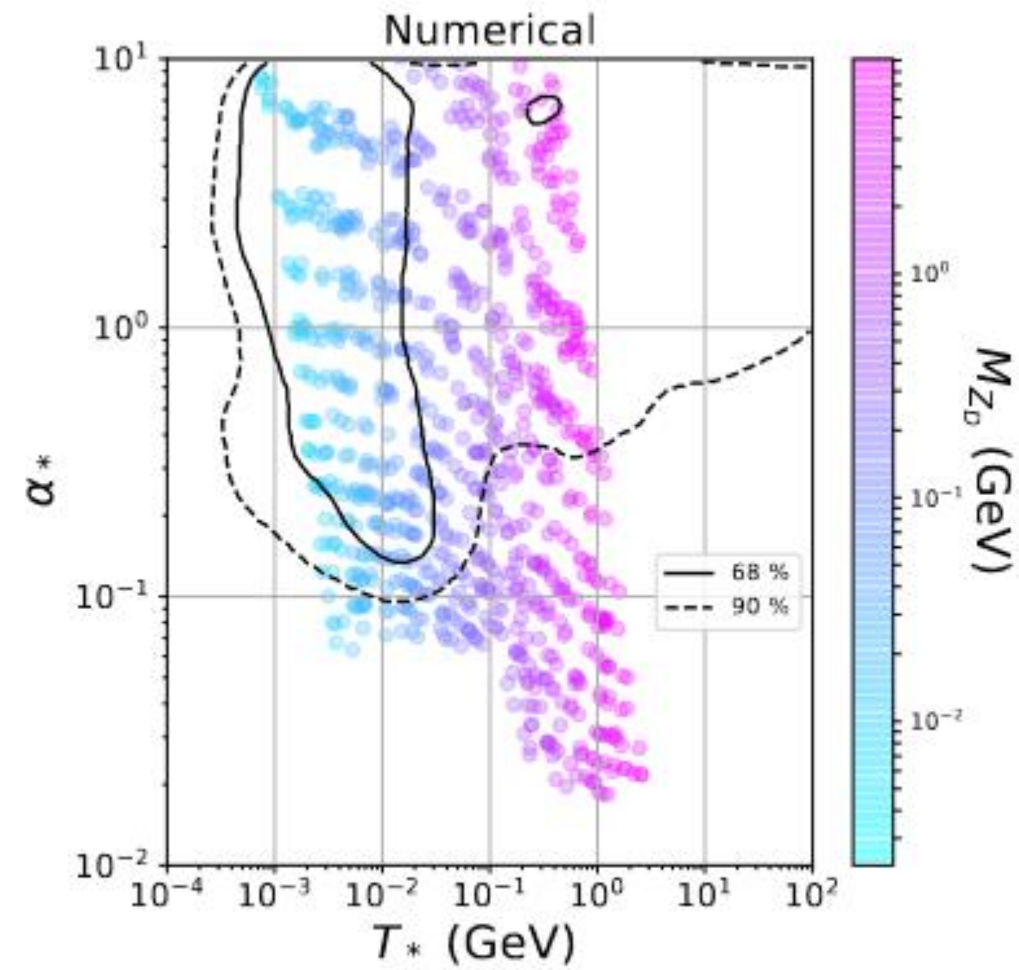
Dark FOPT@NANOGrav

- NANOGrav: Strong evidence of a stochastic process, modeled as a power-law, with common amplitude and spectral slope across pulsars." (ApJ Lett. 905, 2 (2020)). Similar results reported by the PPTA collaboration (ApJ Lett. 917, 2 (2021)).

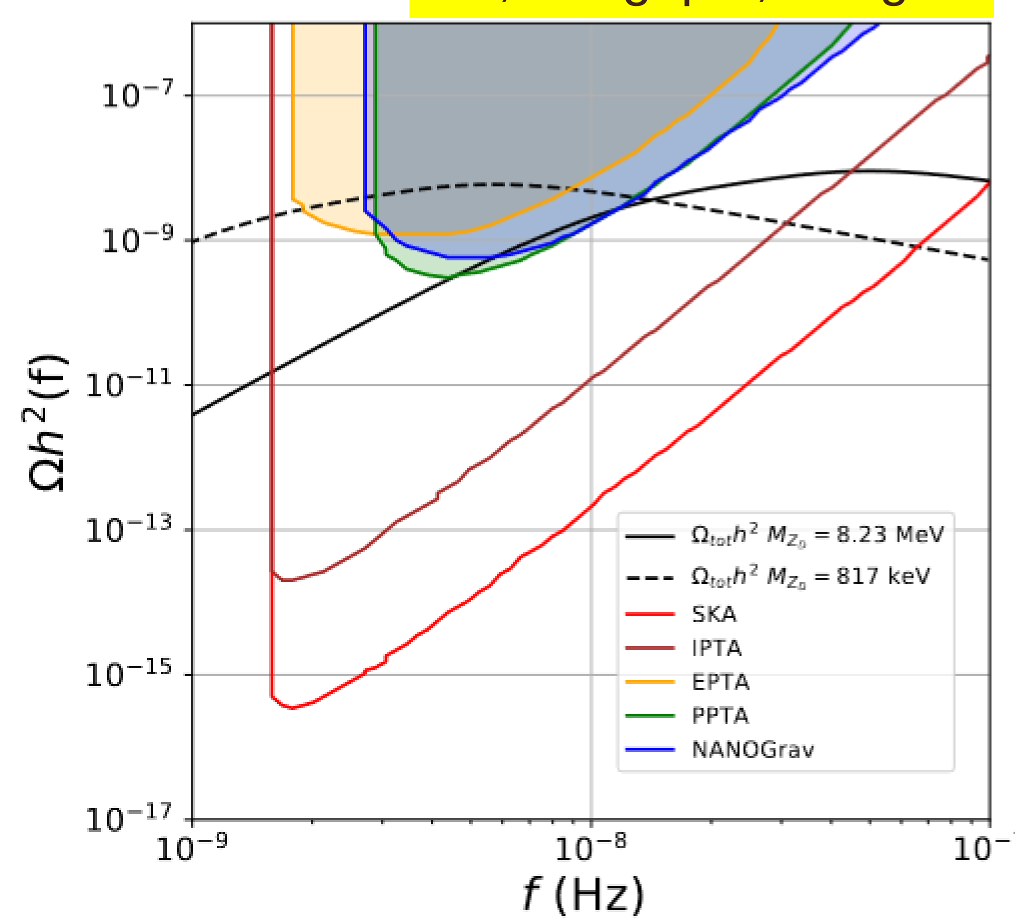
- Consistent with a strong FOPT taking place at sub-electroweak scale temperatures T < 100 GeV (PRL 127, 251302 (2021)). Similar results obtained for the PPTA data (PRL 127, 251303 (2021)).

- Such low scale FOPT can be realized in dark U(1) or SU(N) sectors. A classical conformal symmetry can lead to a supercooled FOPT bringing the GW amplitude within experimental range.

- The dark gauge boson which acquires mass in the FOPT can be DM.



DB, Dasgupta, Kang'22



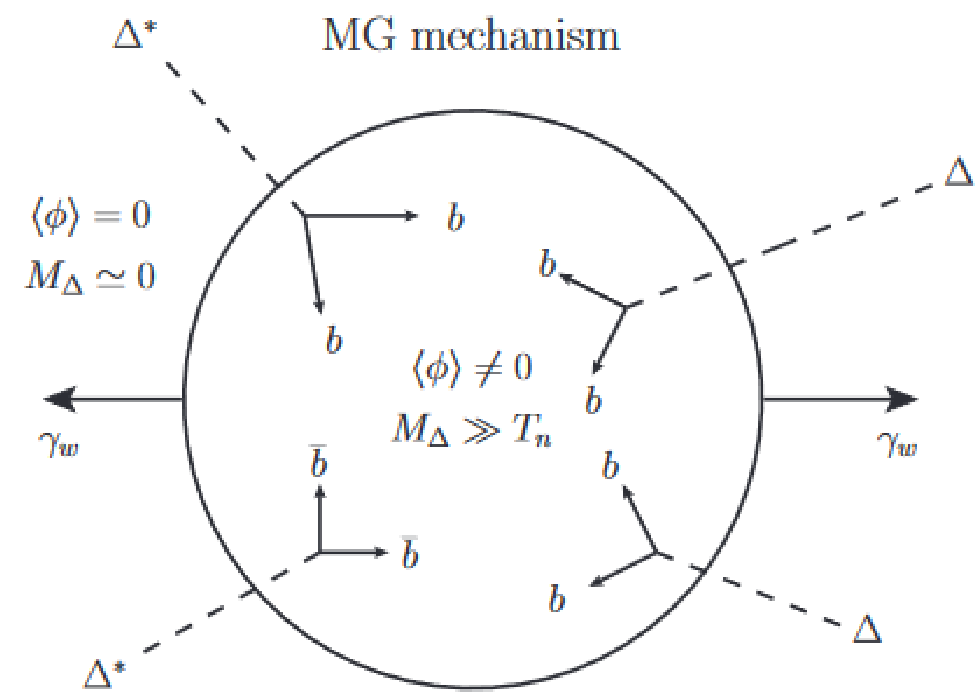
Possible connection to

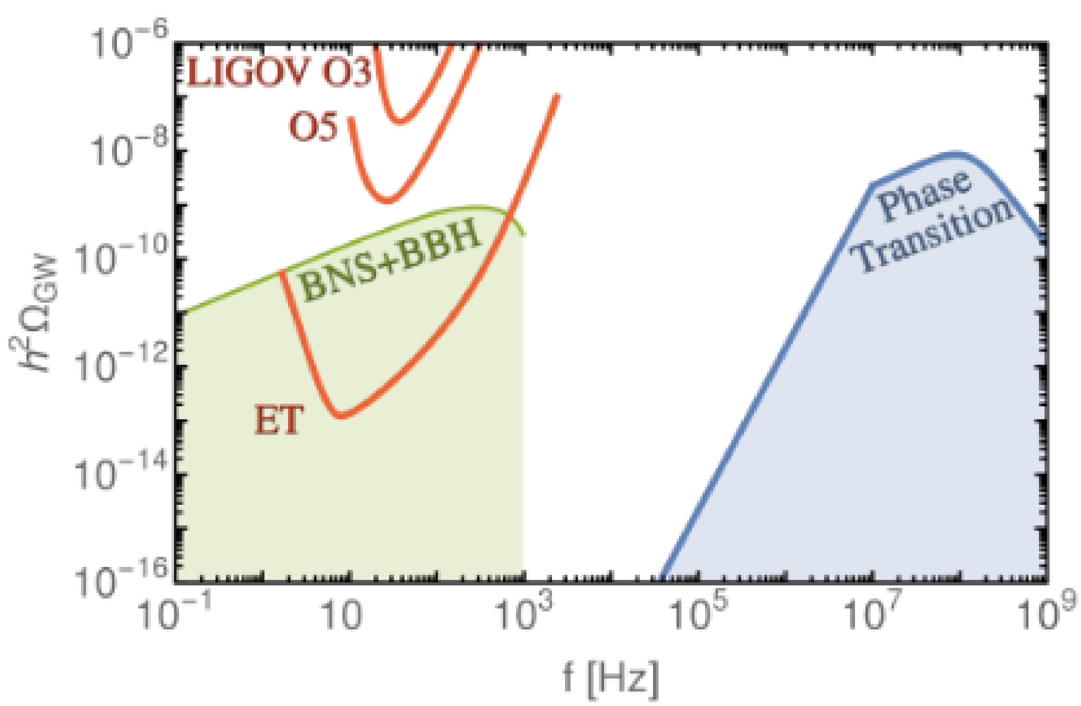
GW from Axion DW: Plenary by F. Rompineve
QCD scale: Parallel session talk by Emma Clarke

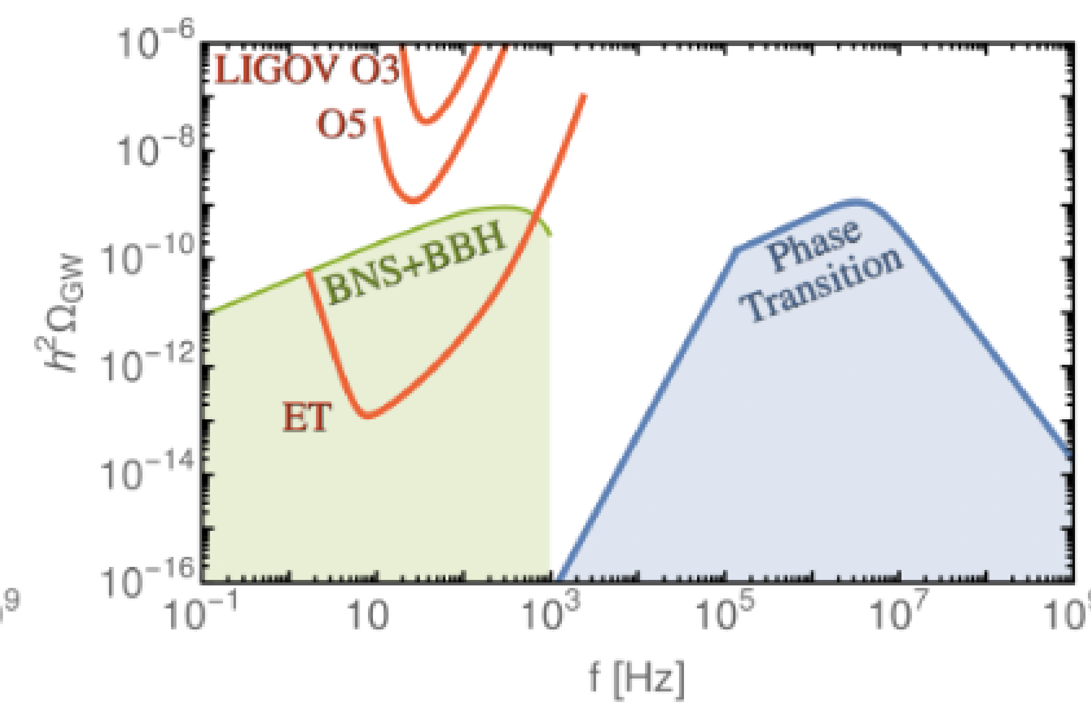
Leptogenesis via FOPT I

- The heavy state N can gain mass in the FOPT itself.
- For ultra-relativistic bubble walls with Lorentz index $\gamma > M_N/T_n$ can lead to a large abundance of N in true vacuum.
- Out-of-equilibrium decay of Heavy N can lead to leptogenesis.

Baldes, Blasi, Mariotti, Sevrin, Turbang'21







Parallel session talk by Arnab Dasgupta

Leptogenesis via FOPT II

N is produced during relativistic bubble expansion

↓

Asymmetry in N, χ generated

↓

χ asymmetry is washed out after the FOPT

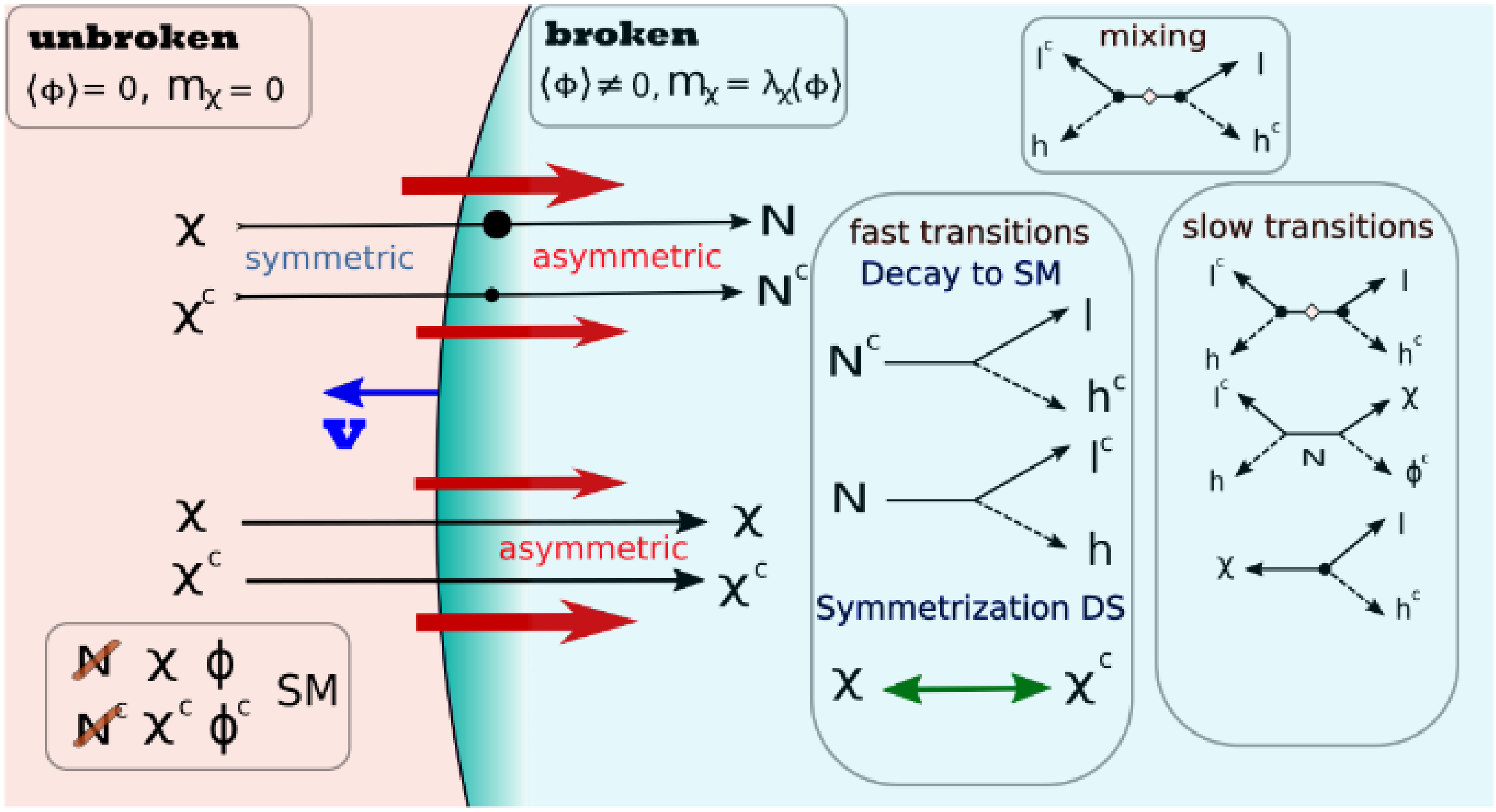
↓

Asymmetry in N is transferred to leptons

↓

Lepton asymmetry is converted to baryon asymmetry by sphaleron

Azatov, Vanvlasselaer, Yin’21



$$\mathcal{L}_{\rm int} = \underbrace{\sum_I \Big(Y_I(\phi^\dagger \bar{\chi})P_L N_I + Y_I^\star \bar{N}_I P_R(\phi\chi)\Big) - V(\phi) + \frac{1}{2}\lambda_\chi \phi \bar{\chi}^c \chi + \sum_I M_I \bar{N}_I N_I}_{\text{Toy model of Dark Sector}}$$

$$+ \underbrace{\sum_{\alpha I} y_{\alpha I}(h\bar{l}_{\alpha,SM})P_R N_I + h.c.,}_{\text{Connection to SM}}$$

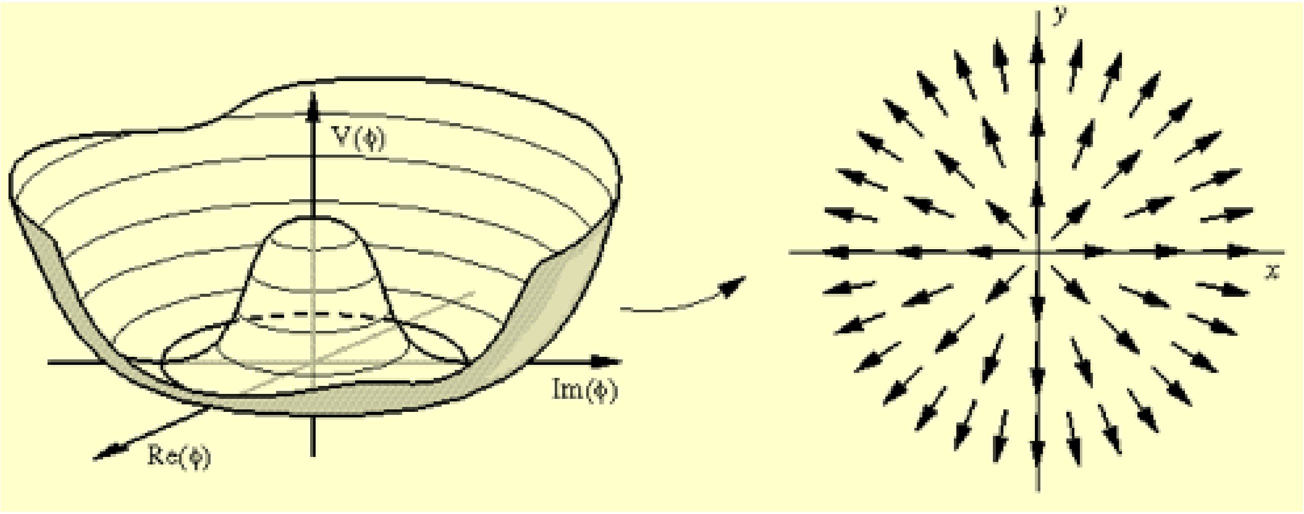
$$\frac{n_l - n_{l^c}}{s} \simeq \frac{1}{s(T_{reh})}\sum_{iI}\epsilon_{Ii}\frac{3\zeta(3)|Y_{iI}|^2 T_{\rm nuc}^3 \langle\phi\rangle^2}{4\pi^2 M_I^2} \times \frac{Br(N_I \to hl)}{Br(N_I \to hl) + Br(N_I \to \chi\phi)}$$

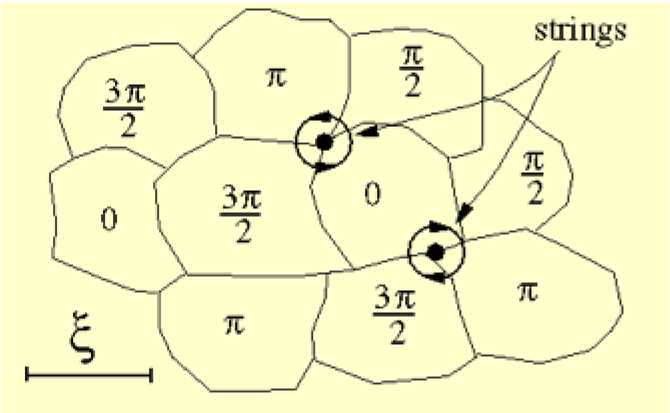
$$\simeq \frac{135\zeta(3) g_\chi}{8\pi^4 g_\star}\sum_I \theta_I^2 \frac{2\sum_{\alpha,J}{\rm Im}(Y_I Y_J^\star y_{\alpha J} y_{\alpha I}^\star){\rm Im} f_{IJ}^{(hl)}}{|Y_I|^2}\left(\frac{T_{nuc}}{T_{reh}}\right)^3 \times \frac{\sum_\alpha |y_{\alpha I}|^2}{\sum_\alpha |y_{\alpha I}|^2 + |Y_I|^2}$$

Heavy states from Bubble collisions: Katz & Riotto’16

Part II: Cosmic Strings, Domain Walls

- Spontaneous breaking of U(1) symmetry (or any other symmetry group containing a vacuum manifold which is not simply connected) at a scale $\mathbf{v}$ can produce cosmic strings (Nielsen, Olesen'73; Kibble'76), characterised by their tension $\mu \approx \mathbf{v}^2$.





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

- Cosmic strings emit GW (Vilenkin'81; Vachaspati, Vilenkin'85; Burden'85++) which are detectable in future experiments if $\mathbf{v} > 10^9$ GeV.

- It is a perfect probe of high-scale physics like

  - U(1) symmetry (Buchmuller, Domcke, Kamada, Schmitz'13; Fornal, Haghi'20; Buchmuller, Domcke, Schmitz'21; Masoud, Rehman, Shafi'21).

  - GUT (Buchmuller, Domcke, Murayama, Schmitz'20; King, Pascoli, Turner, Zhou'21).

  - Non-standard epoch in pre-BBN Universe (Cui, Lewicki, Morrissey, Wells'19).

  - Leptogenesis with U(1) (Dror, Hiramatsu, Kohri, Murayama, White'20; Blasi, Brdar, Schmitz'20; Samanta, Datta'21).

  - Superheavy DM with U(1) (Bian, Liu, Xi'21), sub-TeV DM with U(1) (DB, Das, Saha, Samanta'22).

Leptogenesis with GW from Cosmic Strings

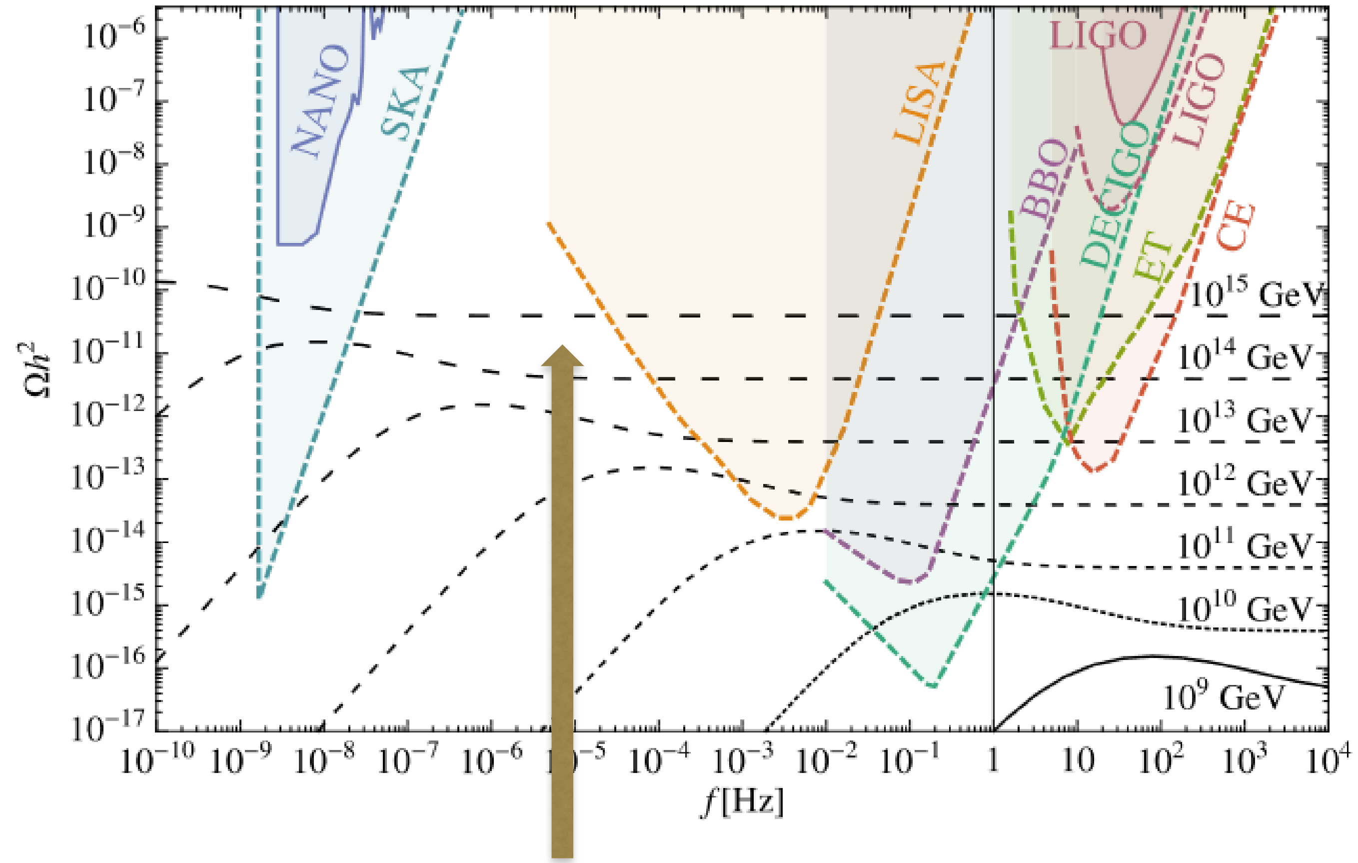
- Cosmic string loops radiate energy as GW leading to shrinking of its length:

$$\frac{dE}{dt} = -\Gamma G\mu^2, \quad l(t) = \alpha t_i - \Gamma G\mu(t - t_i)$$

- GW spectrum (Cui et al'19):

$$\Omega_{\rm GW} = \frac{f}{\rho_c}\frac{d\rho_{\rm GW}}{df}, \quad \Omega_{\rm GW}(f) = \sum_k \Omega_{\rm GW}^{(k)}(f)$$

$$\Omega_{\rm GW}^{(k)}(t_0, f) = \frac{2kG\mu^2\Gamma_k}{f\rho_c}\int_{t_{osc}}^{t_0} dt \left[\frac{a(t)}{a(t_0)}\right]^5 n(t, l_k)$$



$$\Omega_{GW}^{(k=1)}(f) = \frac{128\pi G\mu}{9\zeta(\delta)}\frac{A_r}{\epsilon_r}\Omega_r\left[(1+\epsilon_r)^{3/2} - 1\right]$$

$$\epsilon_r = \frac{\alpha}{\Gamma G\mu} \gg 1, \Omega_{GW}^{k=1}(f) \propto \Lambda_{CS}$$

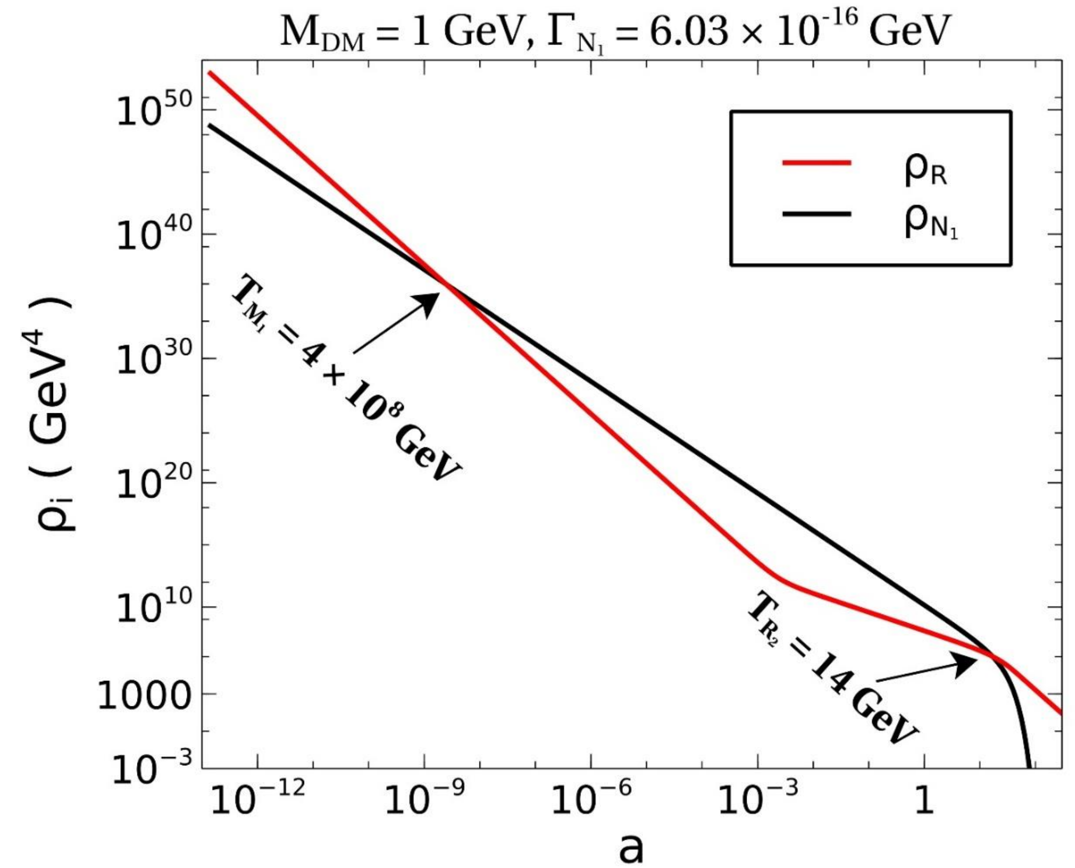
- Consider a gauged B-L setup with three right handed neutrinos (RHN)+ Type-I Seesaw. RHNs make the model anomaly free!
- High scale B-L breaking by ϕ also generates RHN mass enabling thermal leptogenesis.
- Observation of GW with scale-invariant spectrum can probe high scale seesaw/leptogenesis.

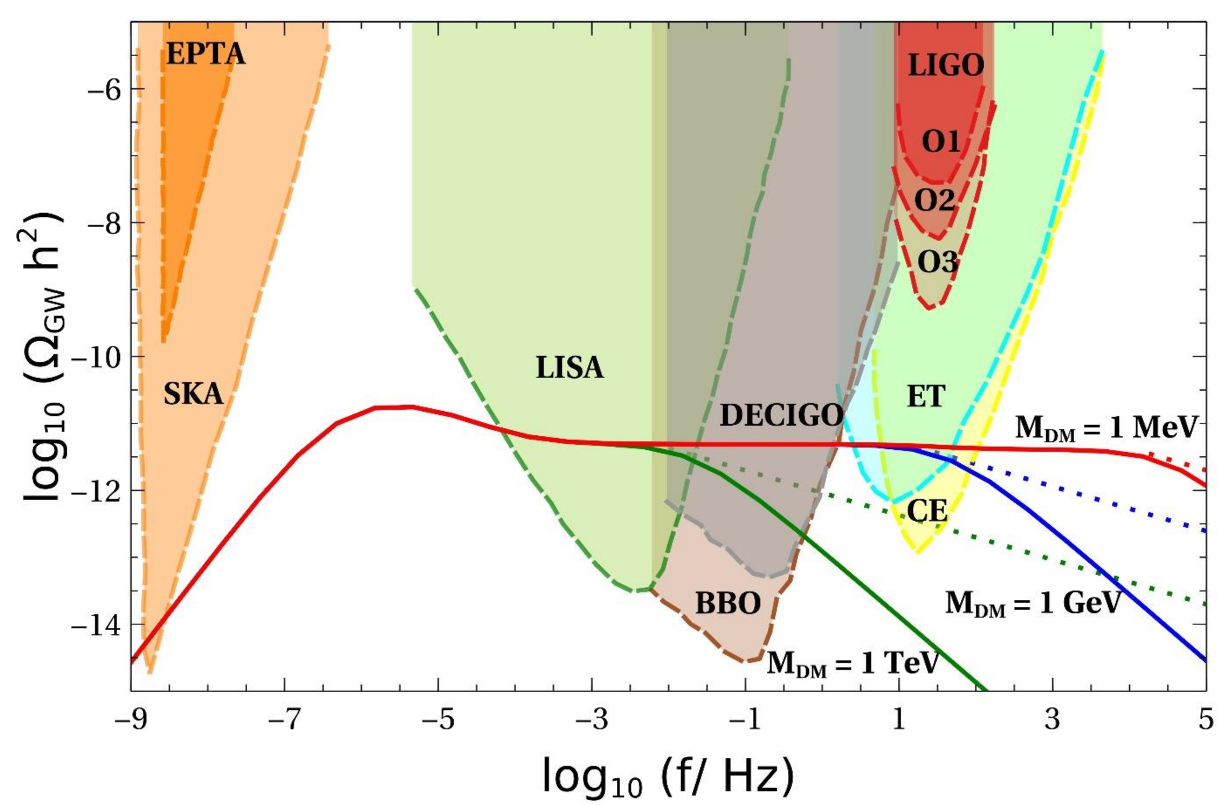
Dror, Hiramatsu, Kohri, Murayama, White'20

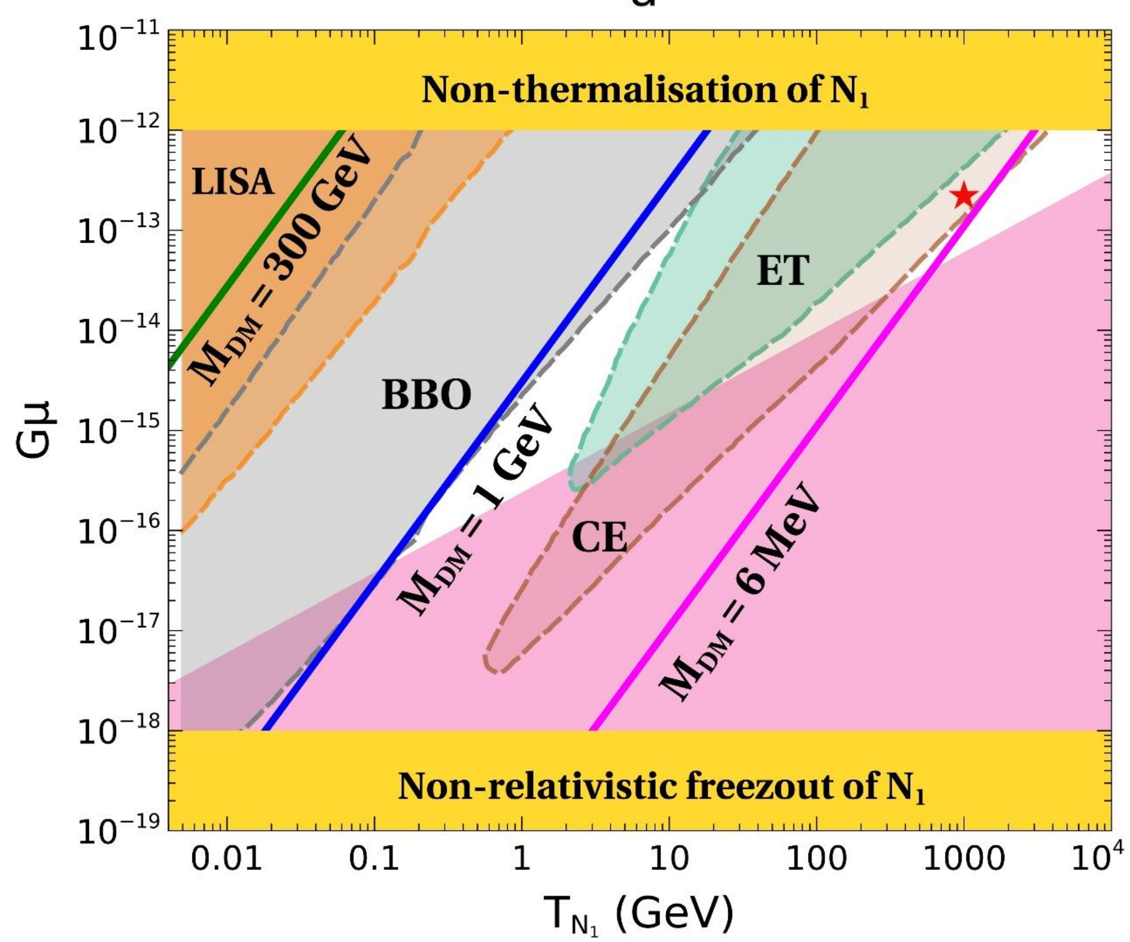
DM with GW from Cosmic Strings

DB, Das, Saha, Samanta'22

- A singlet fermion DM with B-L interactions is thermally overproduced if Z' is superheavy.
- Its abundance can be brought within limits by entropy dilution (Scherrer, Turner'85) from late decay of one of the RHNs.
- RHN domination and subsequent entropy release leads to distortion in scale-invariant GW spectrum: **one-to-one correspondence between DM mass and turning frequency**!
- The other two RHN's can generate light neutrino mass and also lead to successful leptogenesis

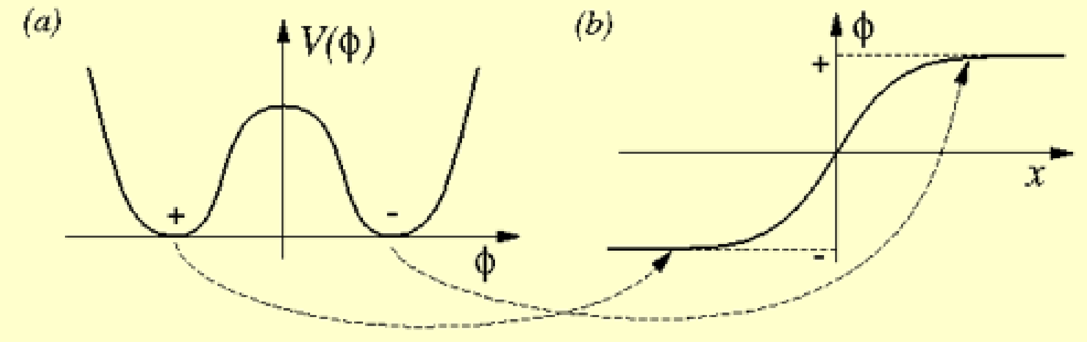






Domain Walls

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



- Spontaneous breaking of discrete symmetries lead to domain wall (DW) formation (Zeldovich, Kobzarev, Okun'74; Kibble'76; Vilenkin'81).

- For example, Z_2-odd scalar with potential

$$V(\phi) = \frac{\lambda_\phi}{4}(\phi^2 - u^2)^2$$

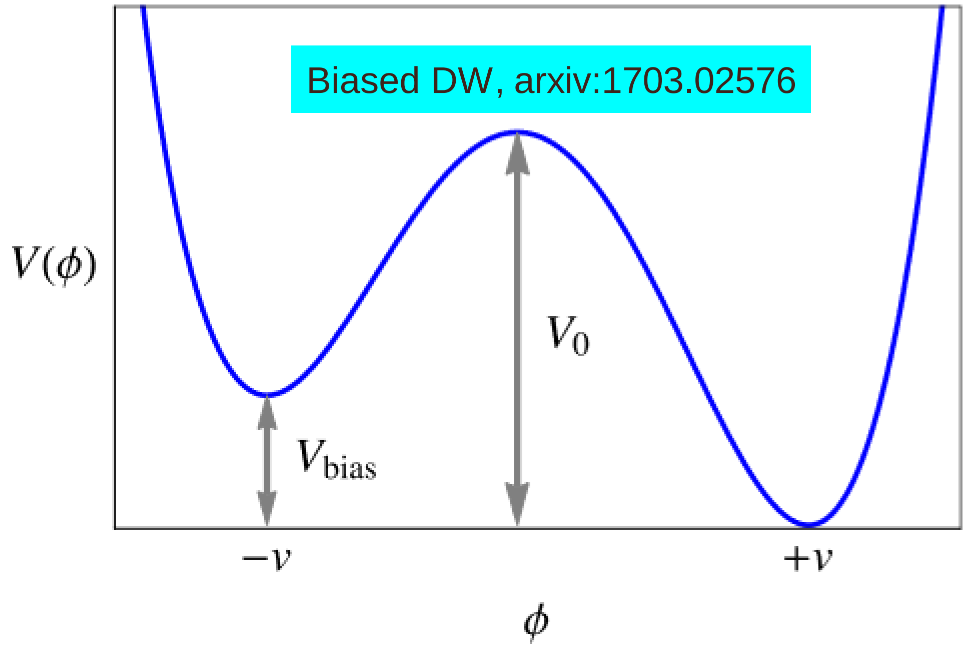
leads to the formation of DW

$$\phi(\mathbf{x}) = u \tanh\left(\sqrt{\frac{\lambda_\phi}{2}} u x\right)$$ characterised by

I. Width: $\delta = m_\varphi^{-1} = 1/\sqrt{2\lambda_\varphi} u$

II. Tension: $\sigma = \int_{-\infty}^{\infty} dx\, \rho_\phi = \frac{2\sqrt{2}}{3}\sqrt{\lambda_\phi} u^3 = \frac{2}{3} m_\phi u^2$

- DW can start dominating the universe soon after formation (scaling regime): $\rho_{DW} \propto t^{-1}$, $a(t) \propto t^2$ (Press, Ryden, Spergel'89; Hindmarsh'96, '03++).



- DW can be made unstable and disappear before dominating, by introducing a bias term (Vilenkin'81; Gelmini, Gleiser, Kolb'89; Larsson, Sarkar, White'97++).

- Such unstable DW can emit stochastic GW (Vilenkin'81; Preskill, Trivedi, Wilczek, Wise'91; Chang, Hagmann, Sikivie'99; Gleiser, Roberts'98; Hiramatsu, Kawasaki, Saikawa'10,'14++).

Axion DW & GW: Plenary by F. Rompineve

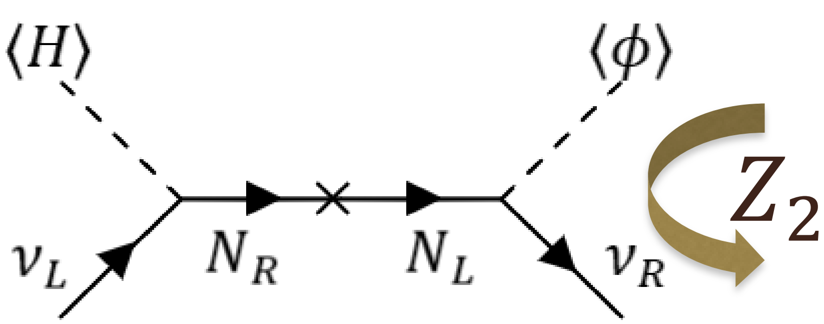
Leptogenesis with GW from DW

- Minimal Dirac neutrino mass models typically have discrete symmetries, which gets broken spontaneously (hence form DW).

- Lepton asymmetry can be generated by incorporating the idea of Dirac leptogenesis, even with total lepton number conservation (Dick, Lindner, Ratz, Wright'00; Murayama, Pierce'02).

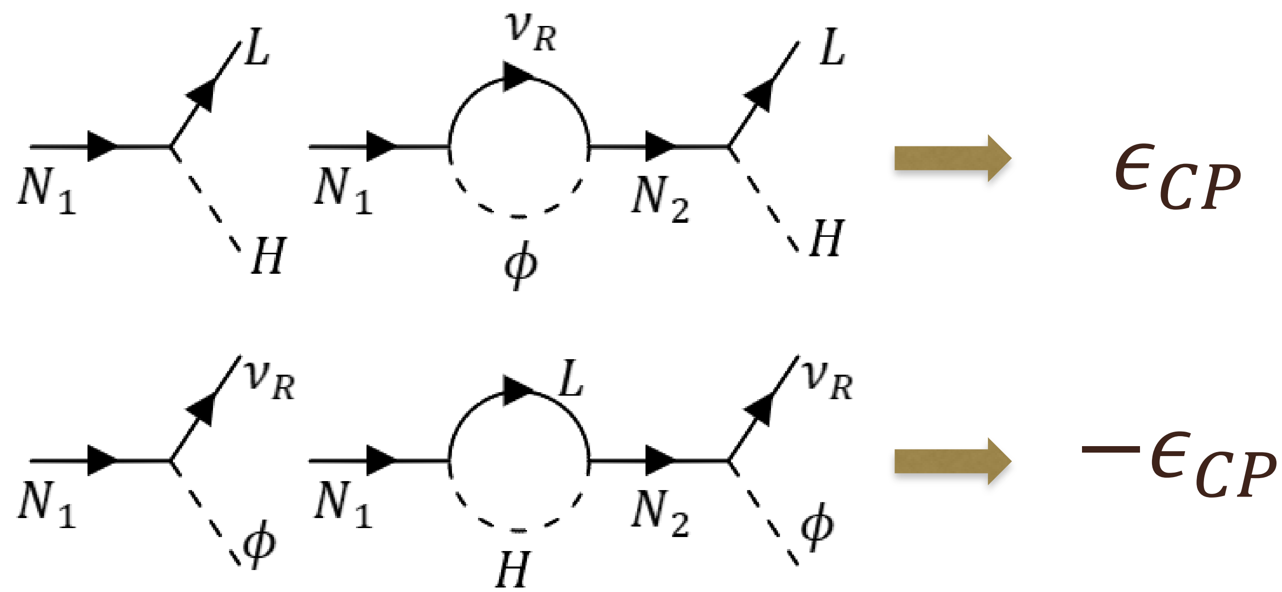
- Z_2 symmetry forbids direct coupling of the type $\bar{L}\widetilde{H}\nu_R$ to validate seesaw origin of Dirac neutrino mass.

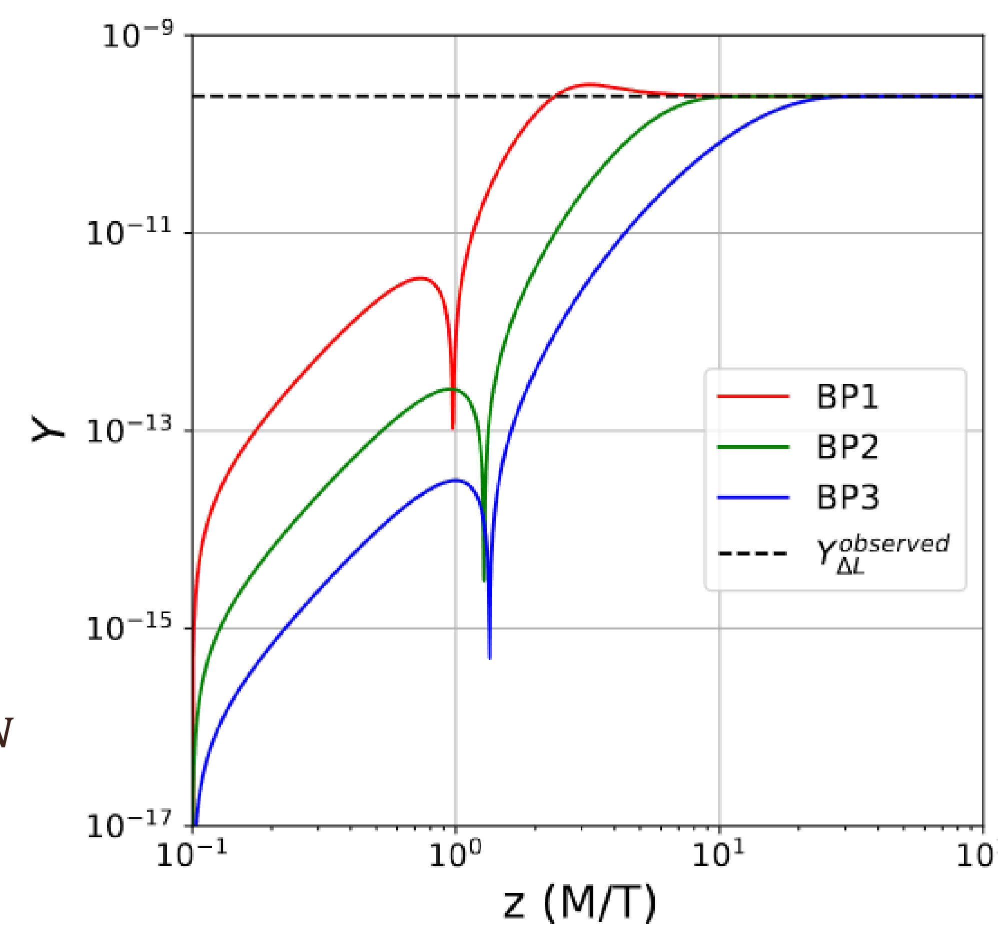
$$-\mathcal{L}_Y \supset Y_L\,\overline{L}\,\tilde{H}\,N_R + M_N\,\overline{N}\,N + Y_R\,\overline{N_L}\,\phi\,\nu_R + \text{h.c.}$$



$$m_\nu = Y_L Y_R v_{\rm EW} u / M_N$$

Barman, DB, Dasgupta, Ghoshal'22

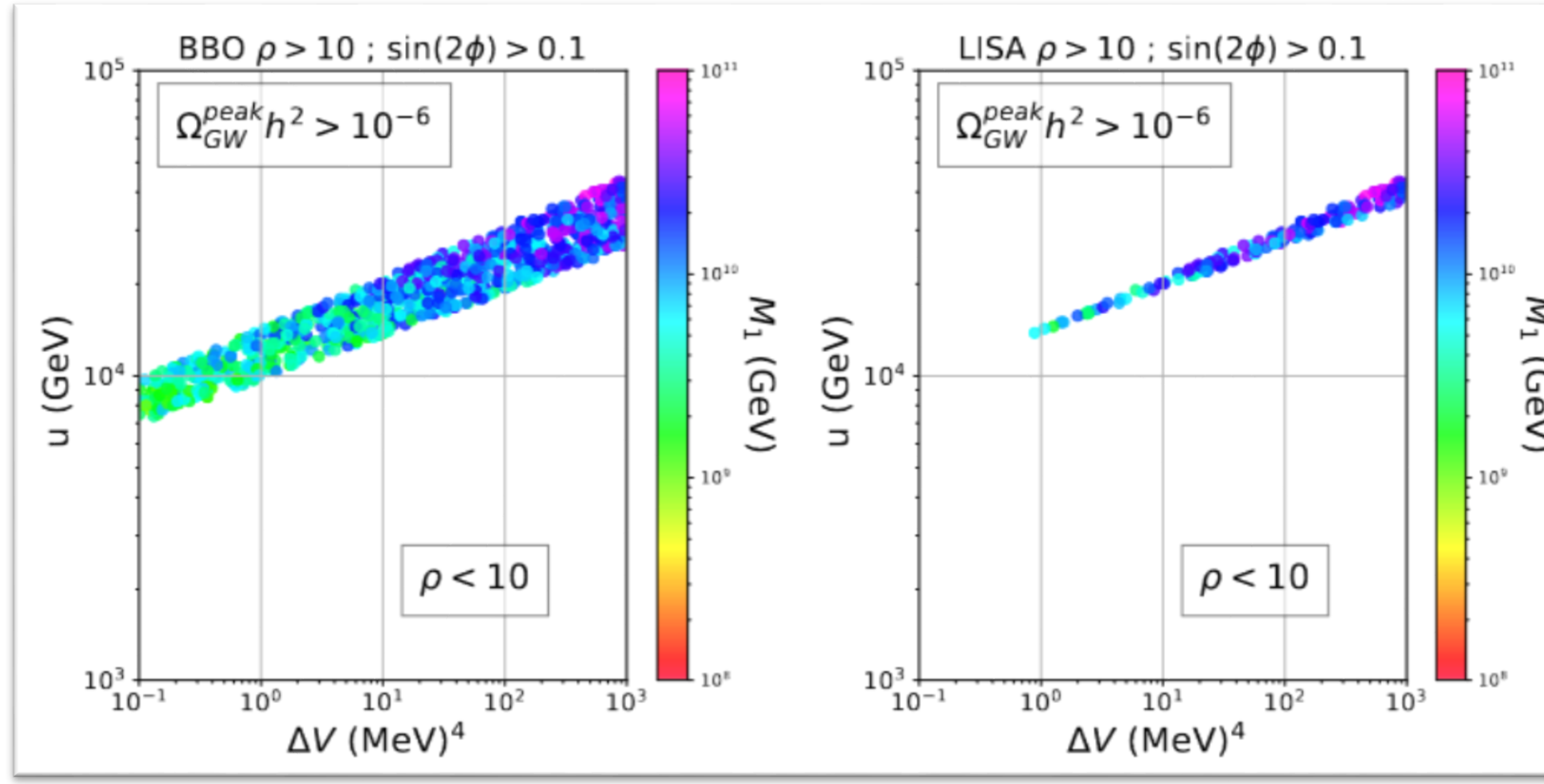


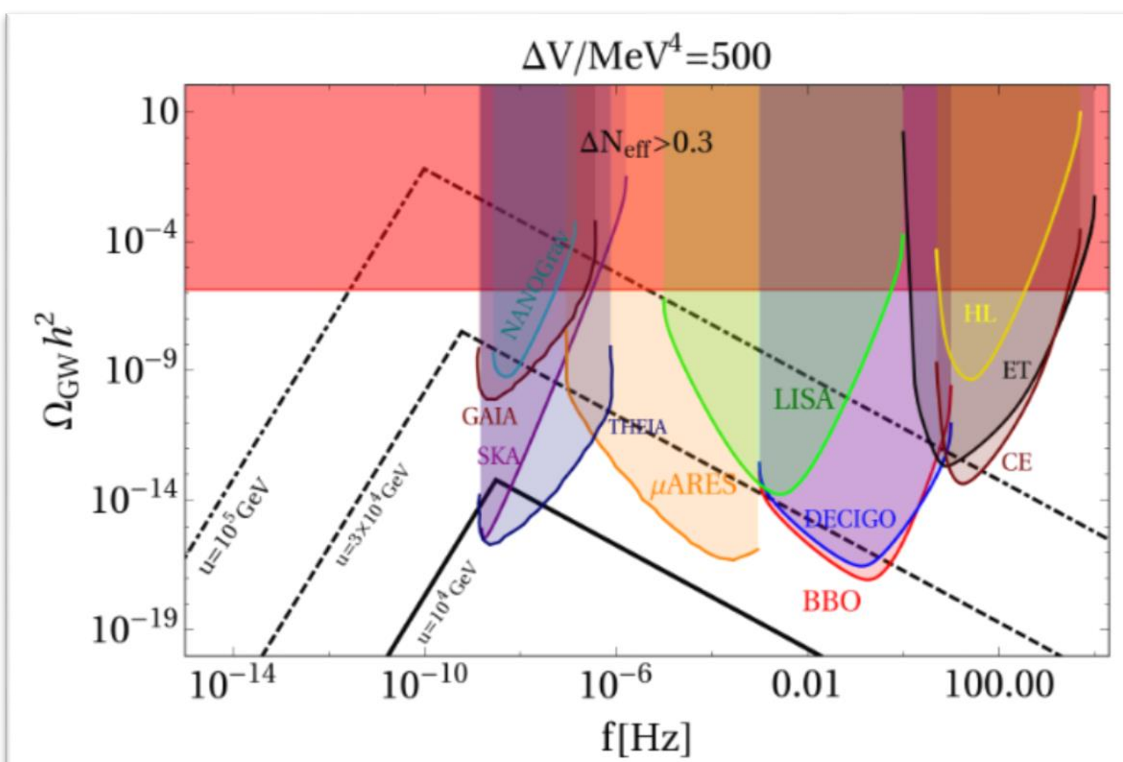


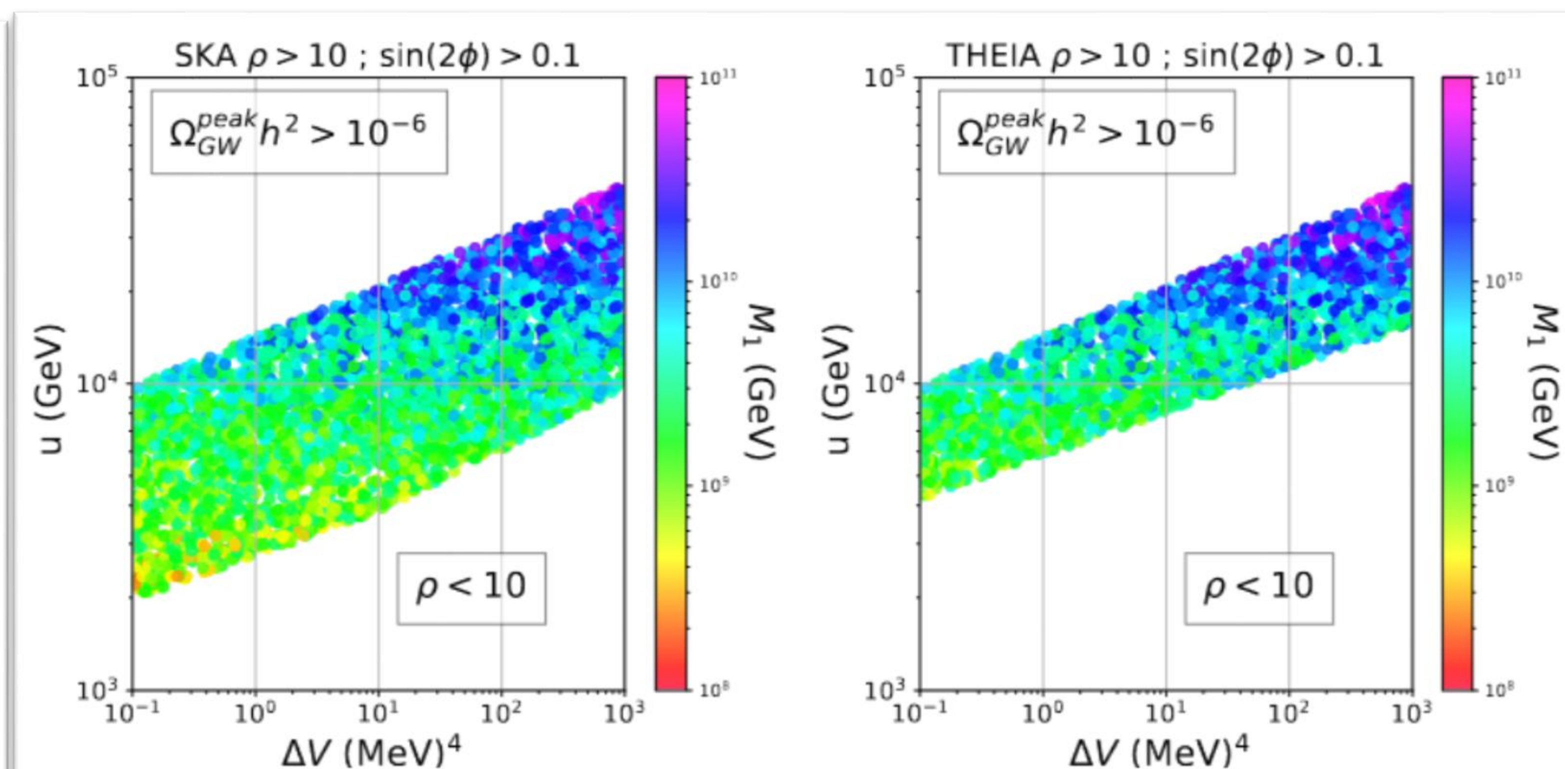
Leptogenesis with GW from DW

Barman, DB, Dasgupta, Ghoshal'22

- A bias term ΔV is introduced to make the DW unstable.
- GW amplitude can be calculated and correlated with scale of Dirac leptogenesis as Z_2 breaking is related to Yukawa's via neutrino mass constraints.
- SNR > 10 can be obtained in most of the GW experiments operating from nano-Hz to Hz regime.

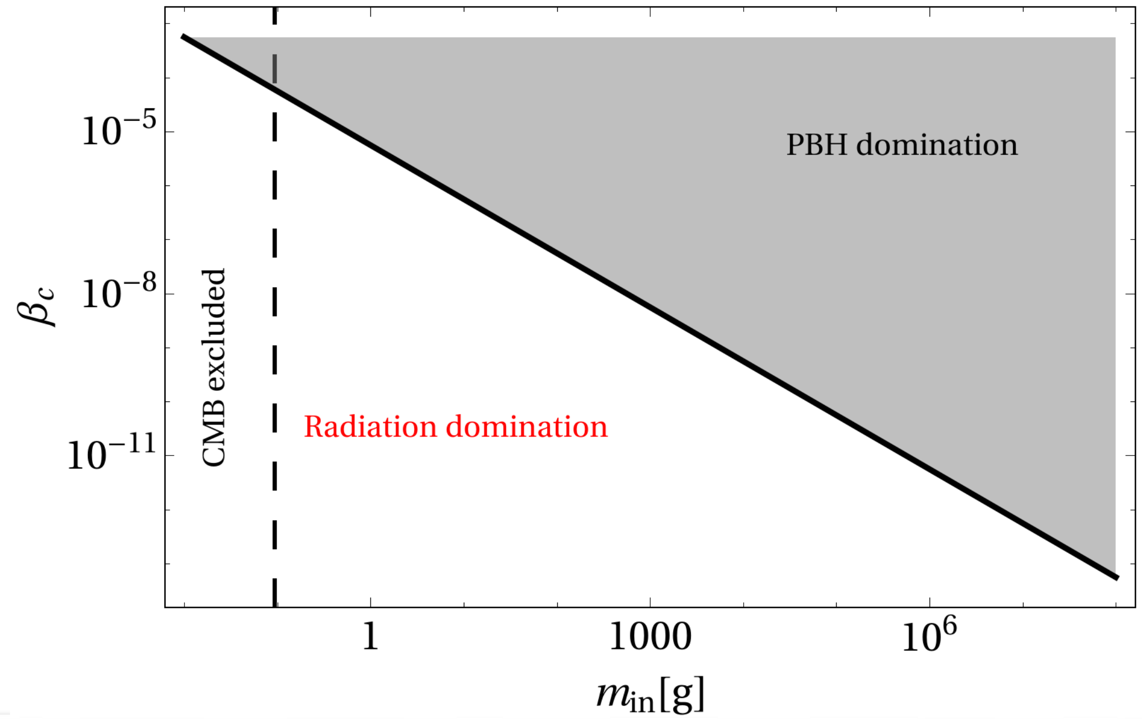






Part III: Ultra-light PBH Evaporation

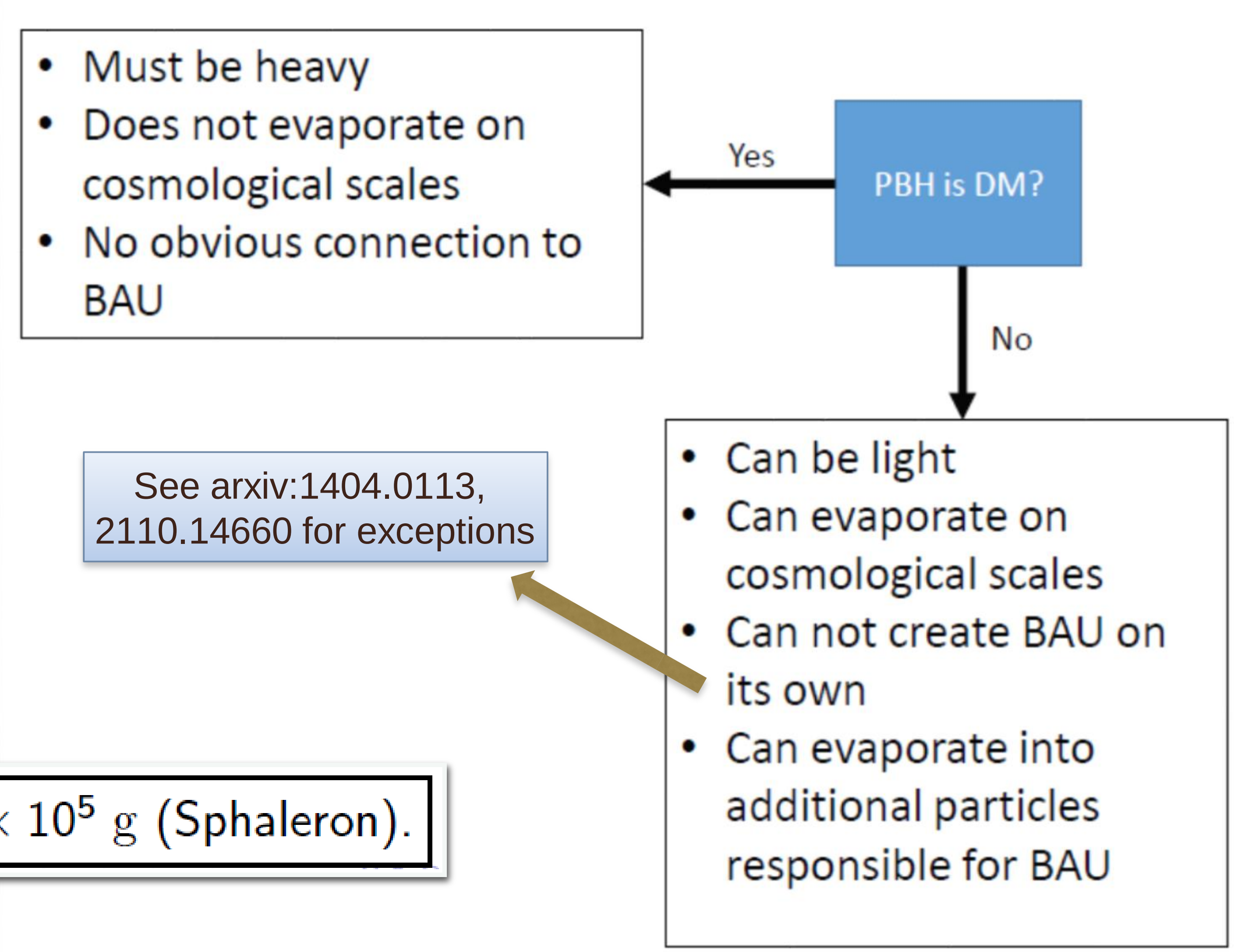
For PBH review, see arXiv:2002.12778



- PBH of a wide mass range can form in the early Universe due to collapse of over-densities (Hawking'71). Typically characterised by initial fraction (β) and initial mass.
- Ultra-light PBH evaporation can play non-trivial role in Baryogenesis or Leptogenesis:

  Hawking'74; Carr'76; Baumann, Steinhardt, Turok'07; Hook'14; Fujita, Kawasaki, Harigaya, Matsuda'14; Hamada, Iso'16; Morrison, Profumo, Yu'18; Hooper, Krnjaic'20; Perez-Gonzalez, Turner'20; Datta, Ghoshal, Samanta'20; Das, Mahanta, DB'21; Barman, DB, Das, Roshan'21, '22; Bernal, Fong, Perez-Gonzalez, Turner'22++

- For Leptogenesis, the desired PBH mass range is:



Upper bound : $M_{\rm in} \lesssim 2 \times 10^8$ g (BBN) $\quad M_{\rm in} \lesssim 2 \times 10^5$ g (Sphaleron).

Leptogenesis from PBH

Thermal + Non-thermal: Need to solve Boltzmann equations. Can either enhance or dilute the asymmetry in pure thermal leptogenesis (Perez-Gonzalez, Turner'20; Das, Mahanta, DB'21; Barman, DB, Das, Roshan'21, '22).

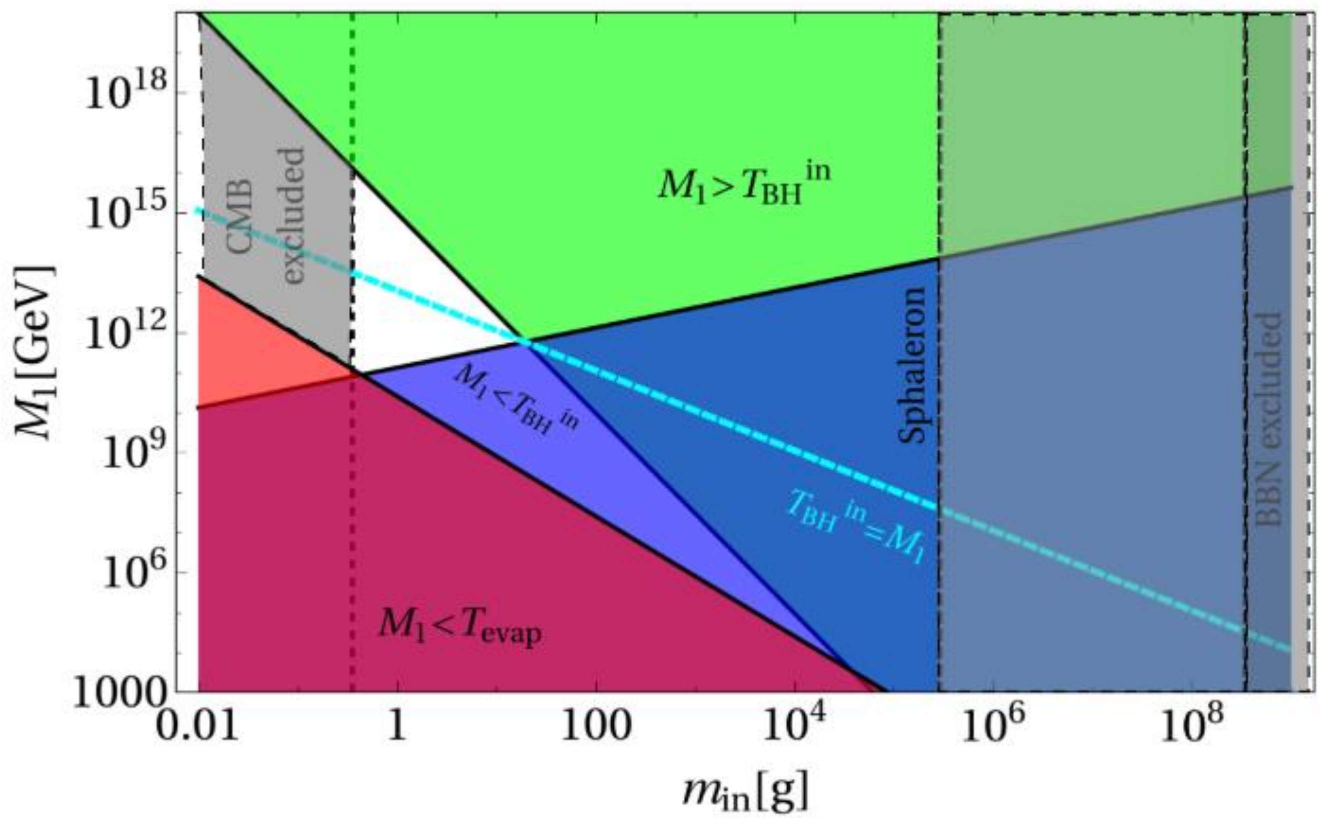
Non-thermal (Fujita, Kawasaki, Harigaya, Matsuda'14):

$$(\text{PBH}) \xrightarrow[\times N_\nu]{\text{evaporation}} \begin{pmatrix}\text{right handed}\\ \text{neutrino}\end{pmatrix} \xrightarrow[\times \epsilon]{\text{decay}} \begin{pmatrix}\text{lepton}\\ \text{number}\end{pmatrix} \xrightarrow[\times \kappa]{\text{sphaleron}} \begin{pmatrix}\text{baryon}\\ \text{number}\end{pmatrix}$$

$$\frac{n_B}{s}(T_0) = \mathcal{N}\,\epsilon_1\, a_{\rm sph}\, \frac{n_{\rm PBH}}{s}\Big|_{T_{\rm evap}}$$

For Type-I seesaw $\quad \epsilon \lesssim \frac{3}{16\,\pi}\frac{M_1\, m_{\nu,\max}}{v^2}$

$$M_1 \begin{cases} > \frac{2\,g_\star(T_{\rm BH})}{a_{\rm sph}\, g_N}\frac{M_{\rm pl}^2\, v^2}{m_{\nu,\max}\, m_{\rm in}^2}\, Y_B(T_0)\, \frac{n_{\rm PBH}}{s}\Big|_{T_{\rm evap}} & \text{for } M_1 < T_{\rm BH}^{\rm in}\,; \\ < \frac{a_{\rm sph}\, g_N}{128\,\pi\, g_\star(T_{\rm BH})}\frac{M_{\rm pl}^2\, m_{\nu,\max}}{v^2}\frac{1}{Y_B(T_0)}\frac{n_{\rm PBH}}{s}\Big|_{T_{\rm evap}} & \text{for } M_1 > T_{\rm BH}^{\rm in}\,, \end{cases}$$

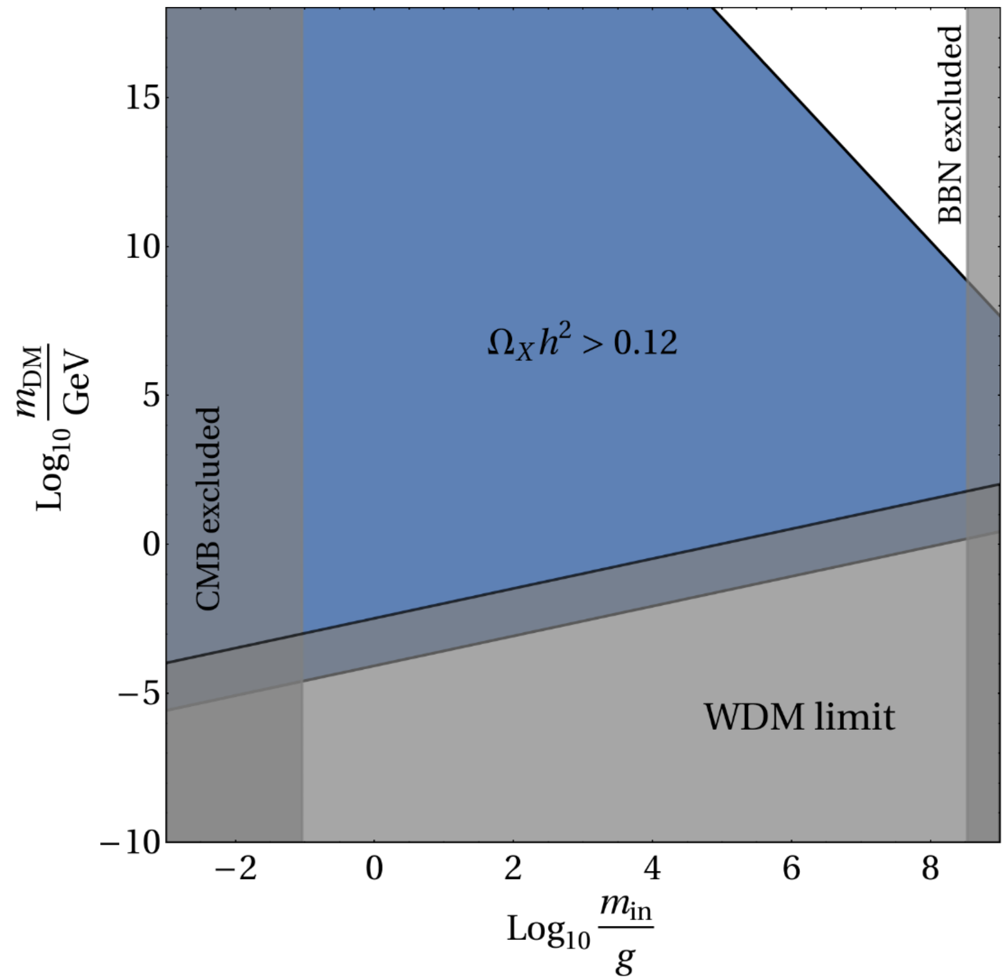


Analogous to Davidson-Ibarra bound in thermal leptogenesis.

DM & Leptogenesis from PBH

PBH evaporation can also produce DM along with lepton asymmetry: typically leads to overproduction (unless DM is superheavy):

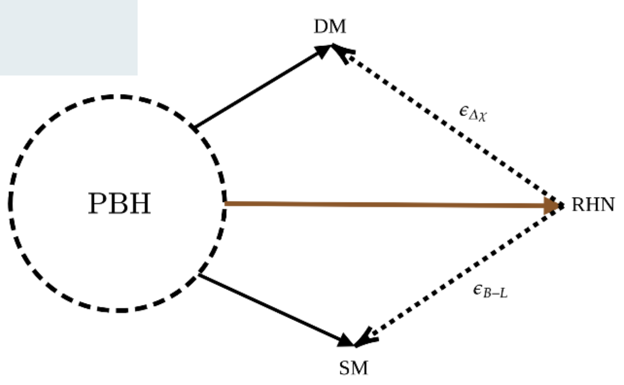
Green'99; Dai, Freese, Stojkovic'09; Allahverdi, Dent, Osinski'17; Lennon, March-Russel, Petrossian-Byrne, Tillim'17; Hooper, Krnjaic, McDermott'19; Gondolo, Sandick, Haghi'20; Bernal, Zapata'20; Cheek, Heurtier, Perez-Gonzalez, Turner'21++



Possible remedies:

1. Ensure DM freeze-out after PBH evaporation: $M_{\mathrm{DM}} \lesssim 20\, T_{\mathrm{evap}}$

2. Introduce dark sector asymmetry



3. Late entropy dilution from a long-lived particle produced from PBH

Barman, DB, Das, Roshan'21-22

GW Signatures (PBH)

- GW can originate from the large primordial curvature perturbations which preceded and given rise to the PBHs (Saito, Yokoyama’08; Bugaev, Klimai’09; Nakama, Suyama’15, ‘16; Cai, Pi, Sasaki’18++)
- GW from the Hawking radiated gravitons (Dong, Kinney, Stojkovic’15++)
- GW from PBH mergers (Hooper, Krnjaic, March-Russel, McDermott, Petrossian-Byrne’20++).
- GW from large scale density perturbations seeded by PBH (Papanikolaou, Vennin, Langlois’20++).
- Doubly peaked induced stochastic GW background in PBH generated baryogenesis models (Bhaumik, Ghoshal, Lewicki’22).

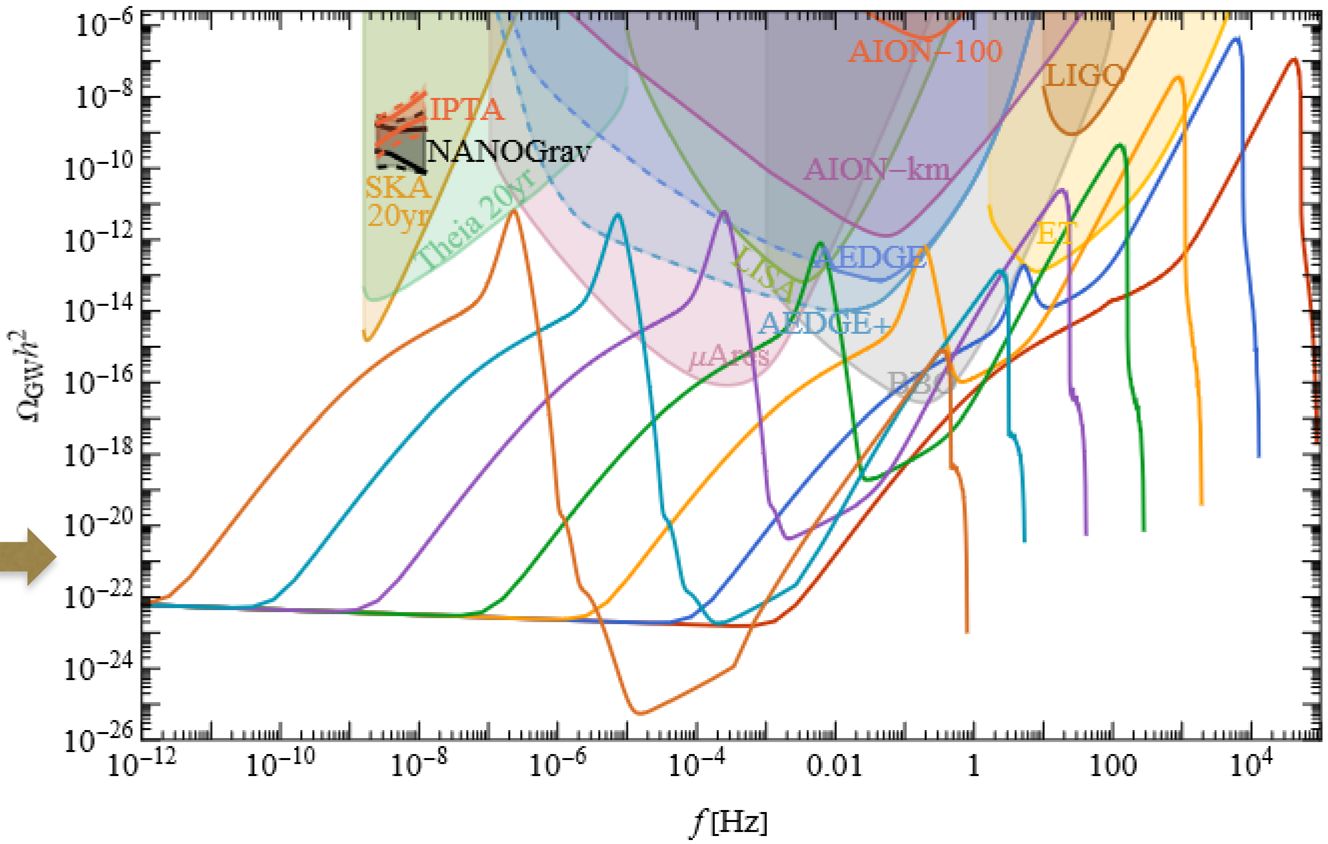
Plenary by James Dent

Related Parallel session talks:

GW & Multi-messenger Astronomy of PBH by Volodymyr Takhistov

Detection of high frequency GW by Jan Schütte-Engel

GW background from PBH by Heling Deng



Conclusion

- GW offers a complementary probe to different DM and Leptogenesis scenarios. This can be the only probe for high scale leptogenesis and some DM scenarios with superheavy DM or mediator mass, which are difficult to probe at directly.
- Depending upon the particular implementation of leptogenesis, the GW signatures (spectral shape/peak frequency) can vary and remain sensitive at different types of experiments: from PTA based experiments to interferometric ones.
- In addition to FOPT, Cosmic strings, Domain walls and PBH, there exist other interesting frameworks where DM or leptogenesis can have indirect GW signatures. For example,

I. The Axiogenesis mechanism can lead to an early matter dominated epoch having the potential to change primordial GW spectrum (Co, Dunsky, Fernandez, Ghalsasi, Hall, Harigaya, Shelton'21)

II. Affleck-Dine Leptogenesis (Barrie, Han, Murayama'21) can lead to the formation of Q-balls which, if sufficiently long-lived, can lead to an early matter domination epoch enhancing the primordial GW signal (White, Pearce, Vagie, Kusenko'21).

Thank You

Parallel Session Talk on DM Spikes and GW by Niklas Becker