Primordial Magnetogenesis and Gravitational Waves from ALP-assisted Phase Transition

Based on: JCAP 09 (2026) 118

in collaboration with
P. S. Bhupal Dev and A. Ghoshal

by

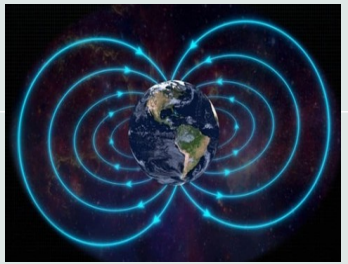
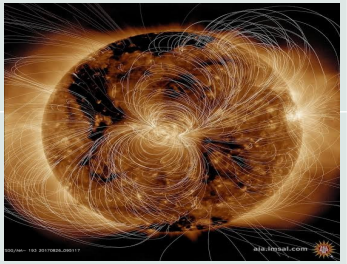
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IITD

Cosmic Magnetic Fields

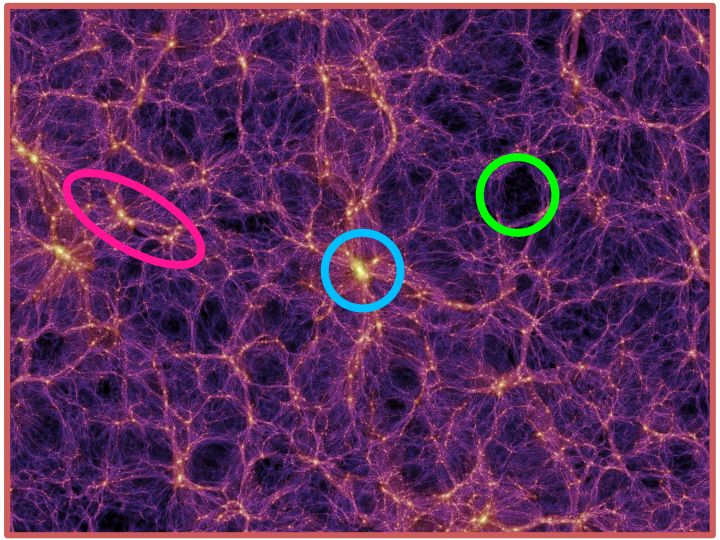
Source: nasa.gov

Planets	Star	Galaxies
		
$B \sim \mathbf{G}$	$B \sim \mathbf{kG}$	$B \sim \mathbf{1-10}\mu\mathbf{G}$

- Magnetic fields play crucial role on many different scales in the Universe
- Growing evidence of magnetic fields on the largest scales of the **cosmic web** of matter

What is the origin of "cosmic magnetic fields" ?

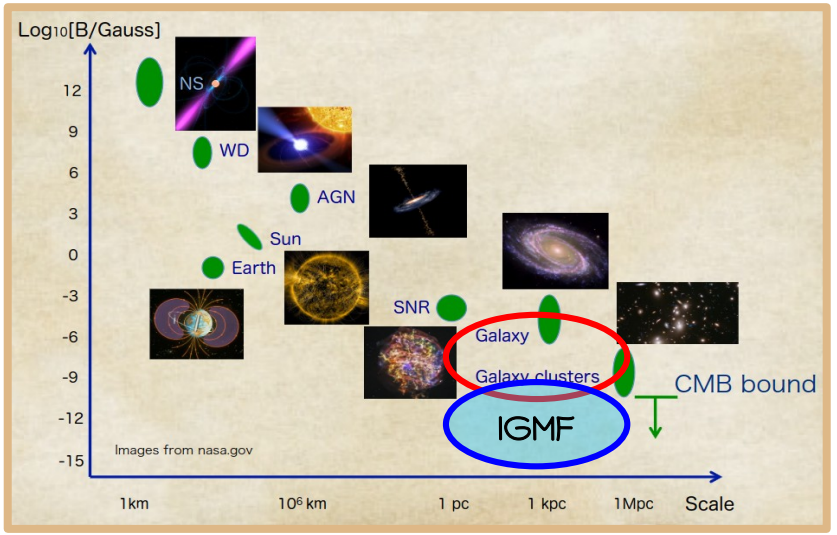
Large Scale Structure (LSS)



Source: nasa.gov

Galaxy clusters	$B \sim \mu\mathbf{G}$
Filaments	$B \sim \mathbf{nG}$
Voids	$B \gtrsim \mathbf{fG}$

Origin of Magnetic Fields (MFs)

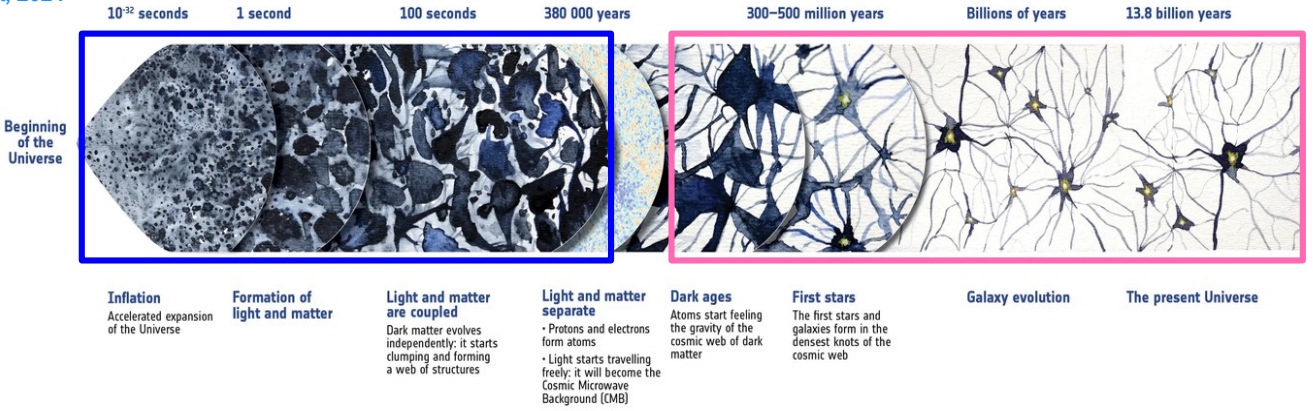


Source: Kohei Kamada, 2024

- Various **astrophysical** origin of cosmic MFs are well known (e.g., Battery/dynamo mechanism, instabilities, etc.)
  - Seed for galaxy/galaxy culster magnetic fields (old problem)
- **Evidence for strong extragalactic magnetic fields from Fermi observation**

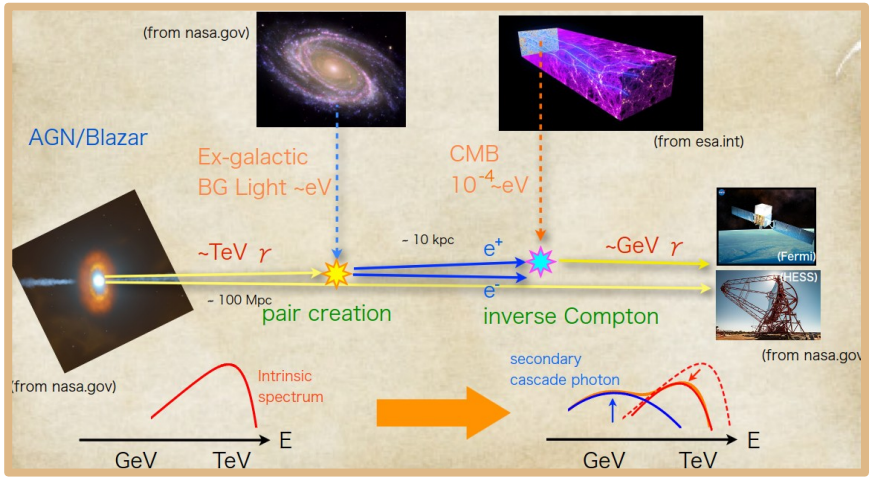
Intergalactic Magnetic Field (IGMF)

Primordial



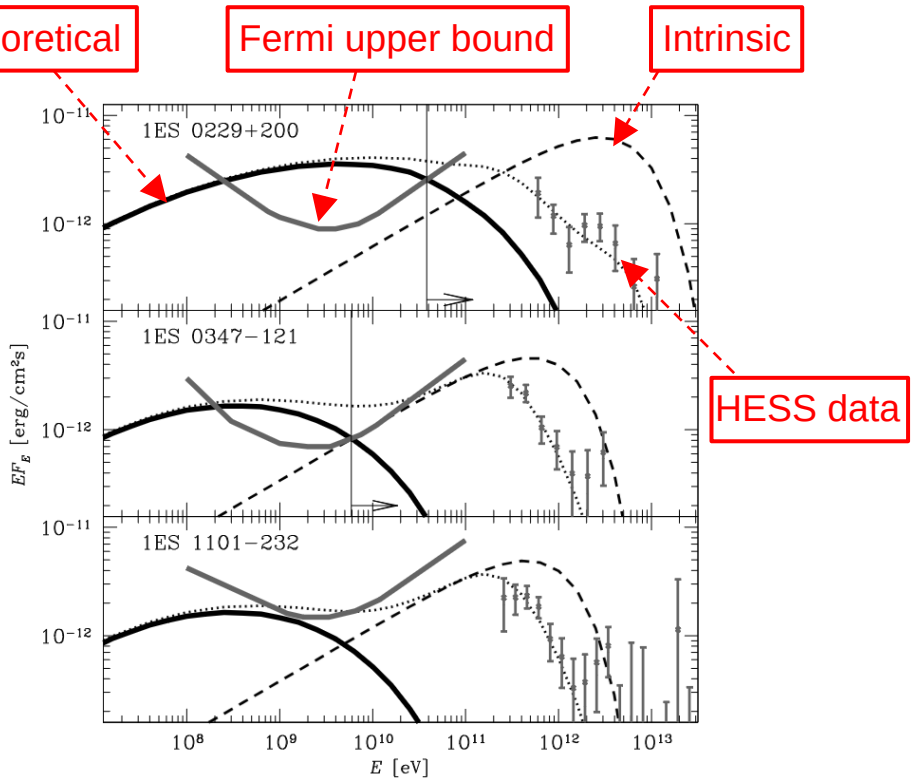
Astrophysical

IGMFs: Astrophysical? Primordial?



Source: Kohei Kamada, 2024

- The observed IGMFs could have a primordial or an astrophysical origin
- However, astrophysical origin of the existent of IGMFs in **voids** is less plausibe
  - MFs are nearly space filling ($f > 0.67$) to explain observations (f - fraction of space filled by a strong IGMF)
  - For astrophysical origin, f is too small and are **excluded** *F. Vazza et al., Astrophys.J. 963 (2024) 2, 135*

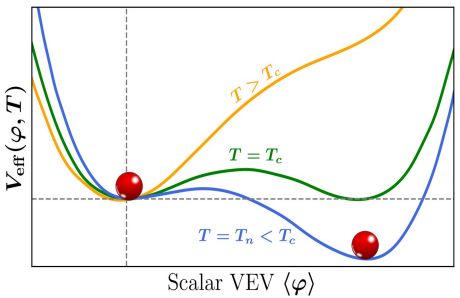


A. Neronov, I. Vovk, Science 328, 73-75 (2010)

Non-observation of secondary photon cascades suggests the existence of IGMFs

Origin of Primordial MFs

- Primordial magnetic fields (PMFs): Origin in the early universe
  - Inflationary origin
  - Chiral magnetic field instability
  - **Cosmic phase transitions** (e.g., EWPT, QCD, etc.,)



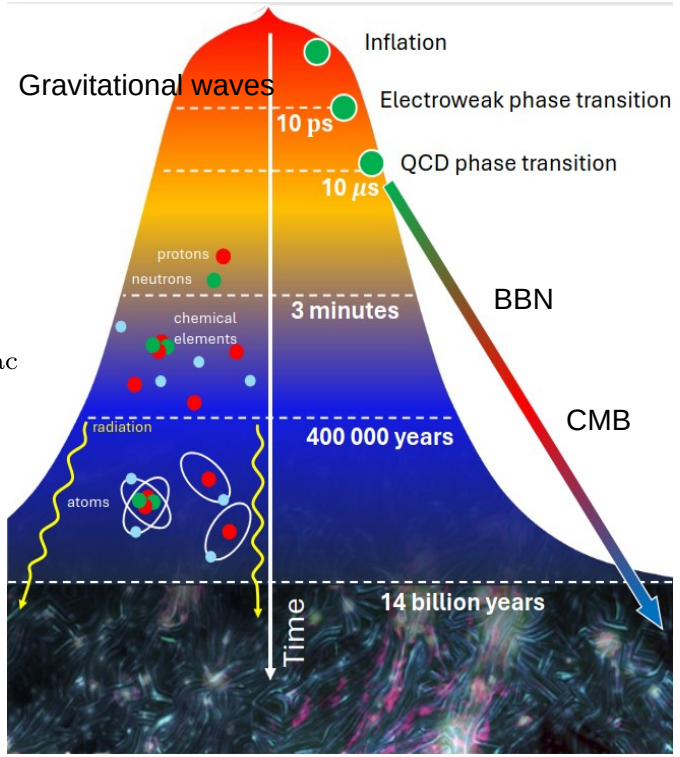
Production

$$\rho_{B,*} = 0.1\frac{\kappa_{\rm col}\alpha}{1+\alpha}\rho_* \approx \frac{\pi^2}{3}T_{\rm reh}^4 \approx 0.1\,\rho_{\rm vac}$$

$$\rho_* = \frac{3M_{\rm Pl}^2}{8\pi}H_*^2 = \frac{g_r(T_{\rm reh})\pi^2}{30}T_{\rm reh}^4 \approx \rho_{\rm vac}$$

$$B_* = \sqrt{2\rho_{B,*}}$$

- $F_{\mu\nu}^{em} \equiv \sin\theta_W n^a F_{\mu\nu}^a + \cos\theta_W F_{\mu\nu}^Y - i4/(gv^2)\sin\theta_W \times [(D_\mu\phi)^\dagger D_\nu\phi - (D_\nu\phi)^\dagger D_\mu\phi]$

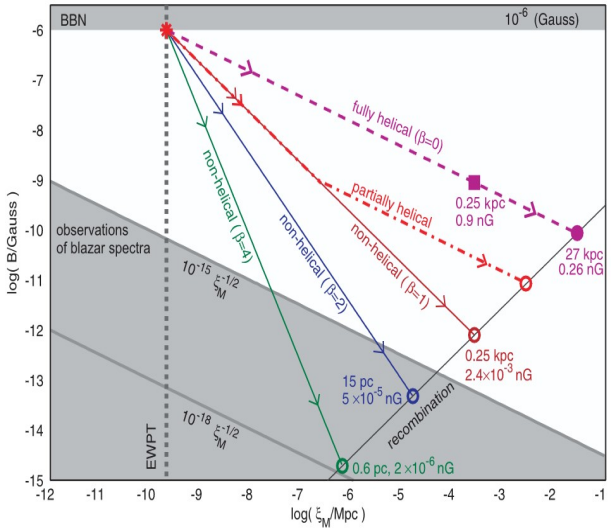


Source: nasa.gov

PMF Evolution and Limits

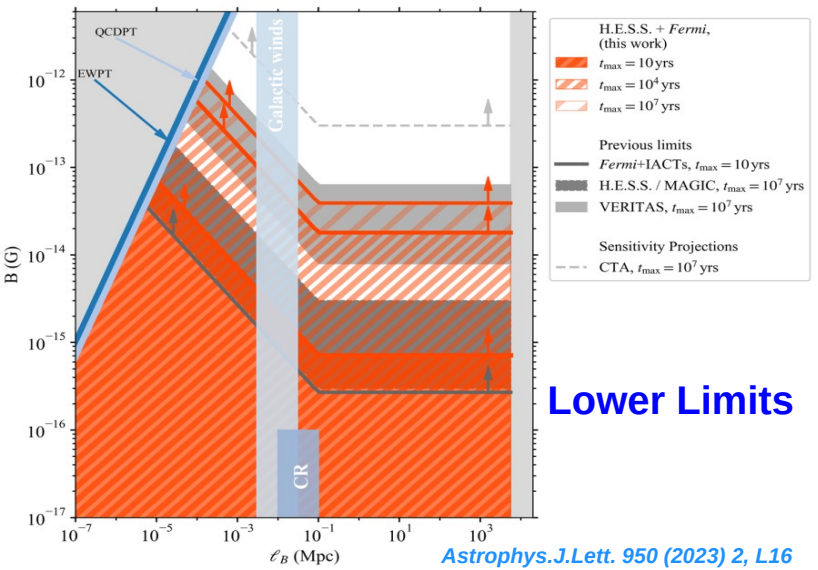
Evolution → Magnetohydrodynamic simulation (MHD) → Present day relic MF parameters are related to **initial field characterization** **(magnetic helicity is important)**

A. Brandenburg, Phys.Rev.D 96 (2017) 12



- $q_b = \frac{2}{b+3}$, and, $p_b = \frac{2}{b+3}(b+1)$
- $B \sim a^{-p_b/2}$, and $\lambda(\equiv \xi_M) \sim a^{q_b}$
- $b = 0$, maximally helical, $b = 1$ non-helical, $1 + \beta = \frac{p_b}{q_b}$

Limits

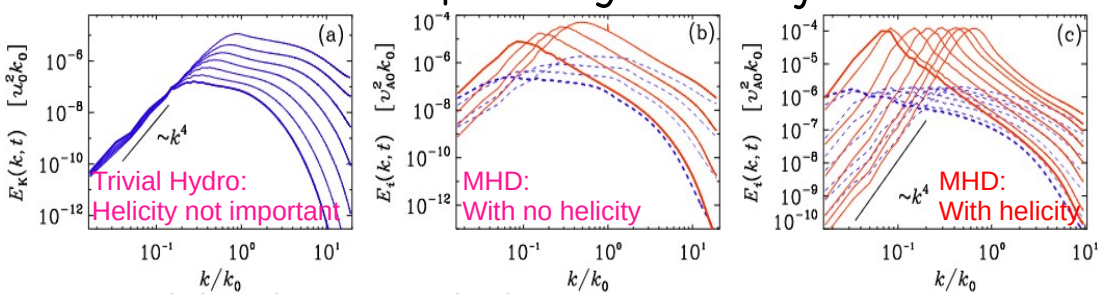


Lower Limits

Astrophys.J.Lett. 950 (2023) 2, L16

- $10^{-9}\ \mathrm{G} \gtrsim B \gtrsim 10^{-16}\ \mathrm{G}$

Inverse cascade: unique to magnetic decay

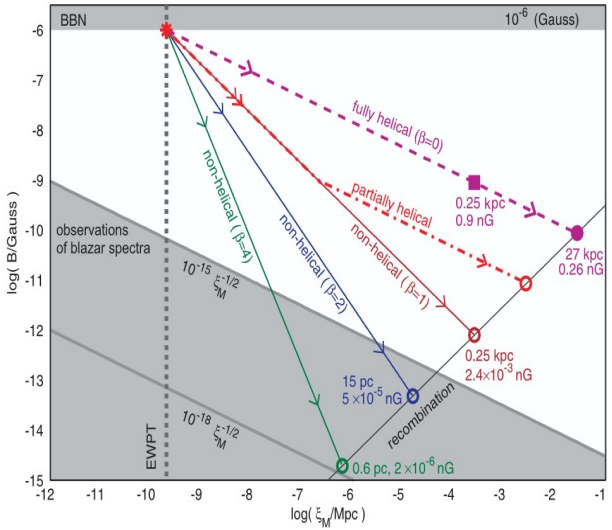


A. Brandenburg, Phys.Rev.Lett. 118 (2017) 5, 055102

PMF Evolution and Limits

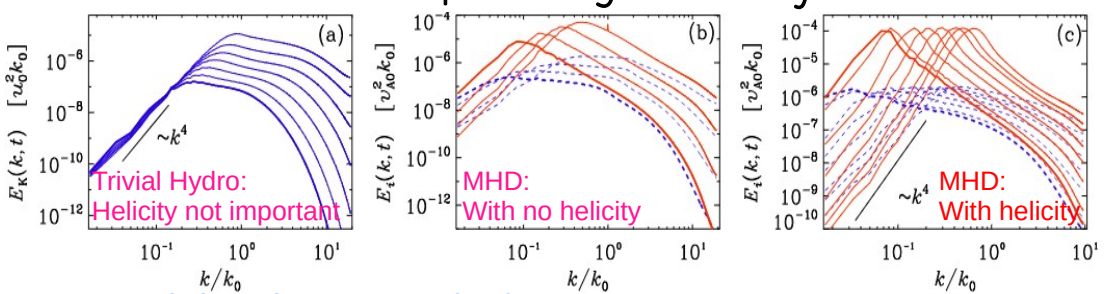
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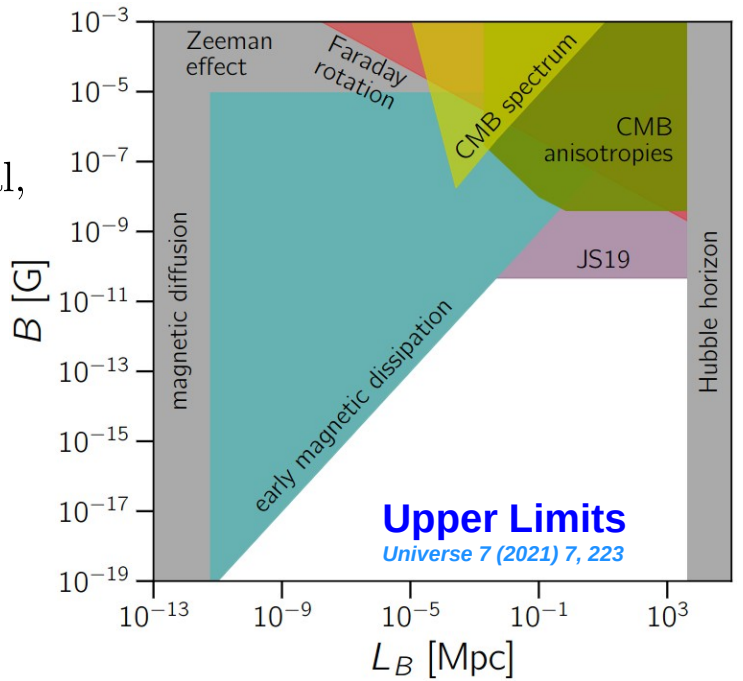
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Inverse cascade: unique to magnetic decay



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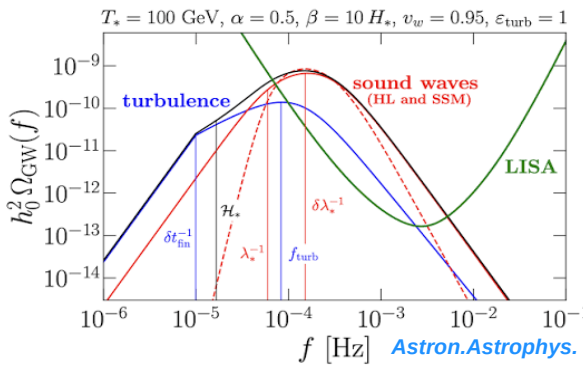
Limits



A multi-messenger opportunity

- Strong first-order PT sources sthocastic **Gravitational wave** backgrounds (SGWB)
- The MFs are strongly coupled to primordial plasma and leads to MHD turbulance

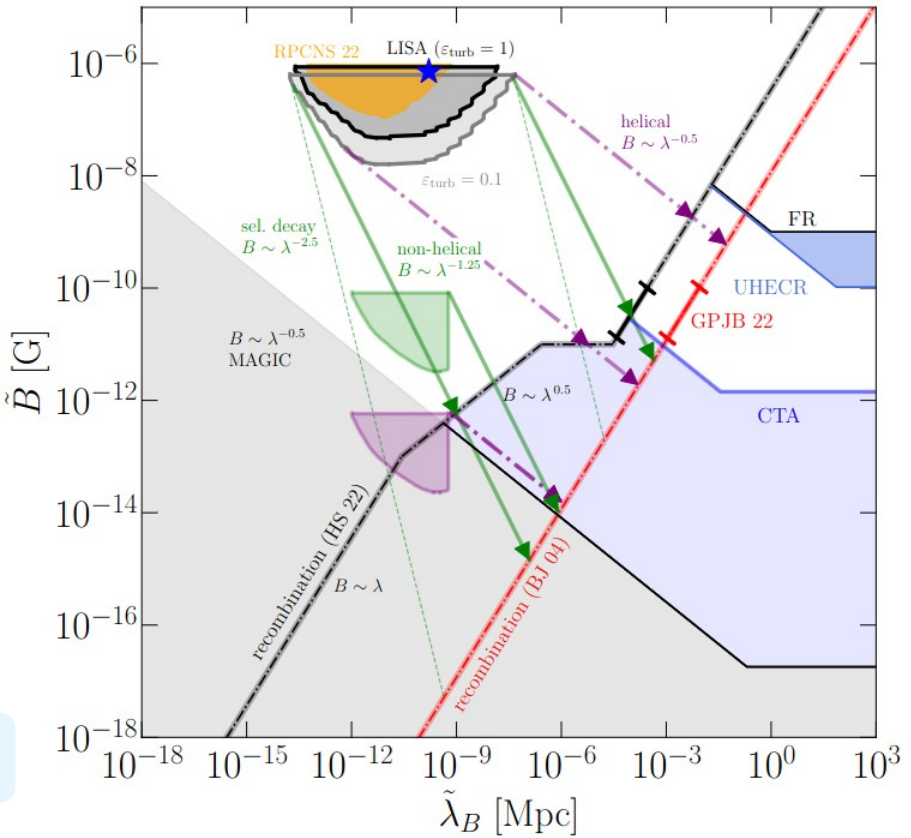
$$\Omega_{\rm GW}h^2 \simeq \Omega_b h^2 + \Omega_{sw}h^2 + \Omega_t h^2$$



Astron.Astrophys. 708 (2026) A337

- **GWs are another probe of the origin of PMFs**

Astron.Astrophys. 708 (2026) A337



A minimal framework for PMFs and GWs

- The Standard Model (SM) ?
  - Electroweak Phase Transition (EWPT) is cross-over
  - **Not sufficient** for producing GWs and MFs generated is too weak for LSS
- A minimal Axion-like Particle (ALP) framework with a coupling to the SM Higgs sector

$$\mathcal{L} = -\frac{F'^2}{4g^2} + |D'_\mu \phi_1|^2 + |D_\mu H|^2 + |\partial_\mu \phi_2|^2 + \bar{\psi} i\gamma^\mu \partial_\mu \psi + \bar{\psi}^c i\gamma^\mu \partial_\mu \psi^c$$
$$- \lambda_H |H|^4 - \lambda_1 |\phi_1|^4 - \lambda_2 |\phi_2|^4 - \lambda_{12} |\phi_1|^2 |\phi_2|^2 - \lambda_{h2} |H|^2 |\phi_2|^2 + (y \phi_2 \psi \psi^c + \text{H.c.})$$

Field	$U(1)_S$	$U(1)_{\rm PQ}$
ϕ_1	1	0
ϕ_2	0	1
ψ	0	$-1/2$
ψ^c	0	$-1/2$

$D'^\mu \phi_1 = (\partial^\mu - i\boldsymbol{g} A'^\mu)\phi_1$

- For FOPT analysis, we follow Gildener-Weinberg approach
  - For simplicity, we assume SM Higgs *H=0* along the flat direction
  - Two-field flat direction in (ϕ_1, ϕ_2), and parametrize them as,

$$|\phi_1| = \frac{\sigma}{\sqrt{2}} \cos\theta, \qquad \hat{f} = \langle \sigma \rangle \quad \text{PQ-breaking scale}$$
$$|\phi_2| = \frac{\sigma}{\sqrt{2}} \sin\theta \qquad f_a = \hat{f} \sin\theta \quad \text{ALP decay const.}$$

$\lambda_1 \simeq \lambda_2 \ll g^2$ and $y \simeq 0$

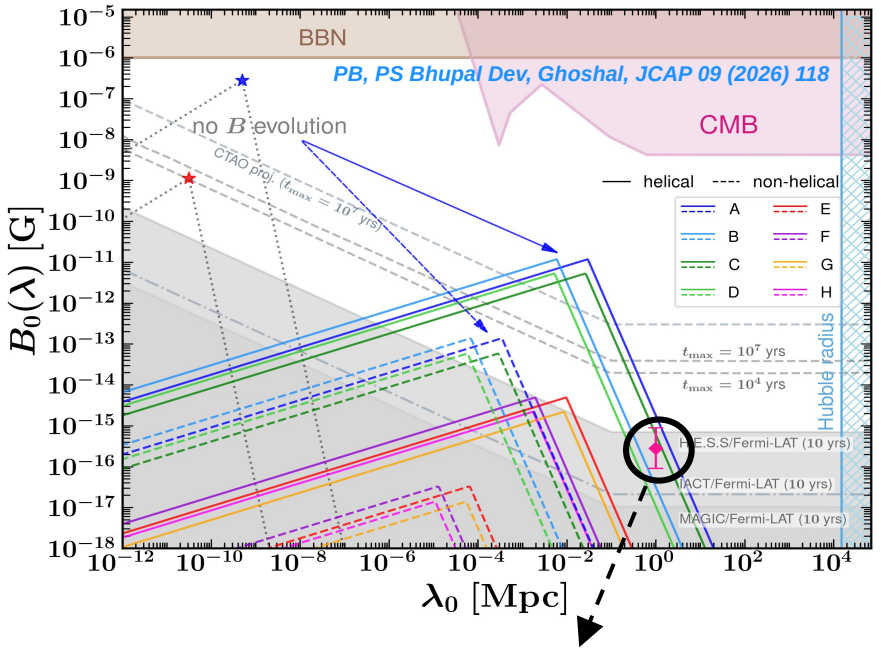
PT is driven by hidden-gauge sector

$\boldsymbol{g}, \boldsymbol{f_a}$

Free parameter of the model

Results – FOPT & PMFs

$g = \{0.85, 1.2\}, f_a = \{10^3, 10^{4.5}\}, \beta/H = \{10, 50\}$



Recent 3.8σ evidence for an IGMF from anisotropic pair-halo searches in Fermi-LAT data

- Inverse duration β shifts the location of the peak along the coherence-length axis, while leaving the peak amplitude B_0 nearly unchanged
- **Increasing f_a leads to a pronounced suppression of the peak field strength**

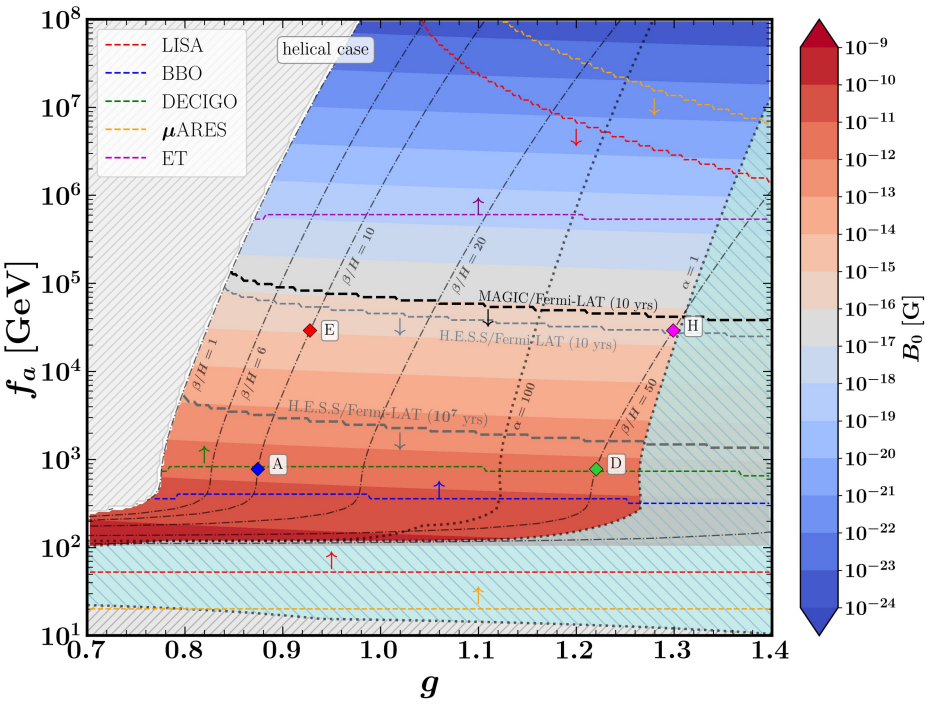
  Vacuum energy is initially released in the ALP sector, then tranferred to the visible plasma:

$$B_0 \sim \sqrt{\kappa_h \rho_B}, \quad \kappa_h = 1 - \frac{V_{\rm eff}(\varphi, v)}{V_{\rm eff}(\varphi, 0)}$$

$$\kappa_h \simeq \frac{\lambda_{h2}^2 \sin^4\theta}{6g^4 \cos^4\theta + \lambda_{h2}^2 \sin^4\theta}$$

- Increasing g suppresses the final magnetic amplitude, however the dependence is less steep than for f_a

Results – PMFs & GWs



PB, PS Bhupal Dev, Ghoshal, JCAP 09 (2026) 118

- Combining the GW forecasts with the magnetic field predictions allows us to delineate the viable parameter space of the model
- Our model produces blazar allowed magnetic fields with strengths up to

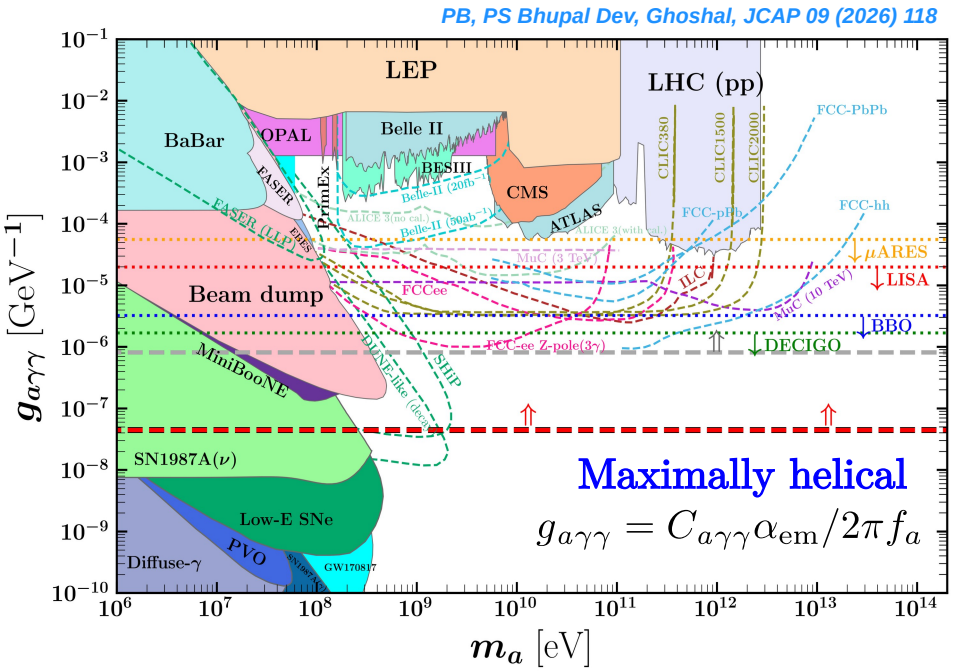
  $B_0 \sim 10^{-9}(10^{-11})$ G helical (non-helical)

  $\lambda_0 \sim 10^{-3}(10^{-5}) - 10^{-1}(10^{-2})$ Mpc
- Sufficient PMFs + detectable GW signals

  $10^3(10^3) \lesssim f_a[\mathrm{GeV}] \lesssim 10^5(10^4)$ helical (non-helical)
- GW signals with SNR > 10 fall within LISA, BBO, DECIGO and μARES.

LISA and μARES can probe entire blazar allowed region

Complementarity: PMFs, GWs & ALP searches



$$\mathcal{L}_a \supset -C_{a\gamma\gamma}\frac{\alpha_{\rm em}}{8\pi}\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$-C_{agg}\frac{\alpha_s}{8\pi}\frac{a}{f_a}G^a_{\mu\nu}\tilde{G}^{\mu\nu,a} + \frac{\partial^\mu a}{2f_a}\sum_f C_{aff}\left(\bar{f}\gamma_\mu\gamma_5 f\right)$$

- Existing ALP searches put constraints on the ALP mass that accomodates PMFs + GWs
- Considering **maximally helical** MF configuration, parameter space favouring observable PMFs and GWs provide a complementary probe of the relatively heavier ALP ($m_a \gtrsim 10^8$ eV) that remain unconstrained by ALP **laboratory** and **astrophysical** searches
- Future sensitivities can further probe part of the parameter space

SUMMARY

- The Universe is magnatized. The evidence of magnetic fields in the voids preferes to have a primordial origin.
- Understanding primordial field origin and evolution provides insights into the mystries of the early Universe and they leave signatures in SGWB, γ-rays, etc.
- We investigated slow first-order phase transitions as a source of PMFs, GWs in a minimal ALP framework.
- A multi-messenger probe: GWs (LISA, μARES), γ-ray telecopes, and collider and astrophysical ALP searches.



Back Up Slides

The present-day magnetic field spectrum can be computed as [52, 55, 60]

$$B_0(\lambda) \equiv B(\lambda, t_0) = \left(\frac{a_{\rm reh}}{a_{\rm rec}}\right)^{p_b/2} \left(\frac{a_{\rm reh}}{a_0}\right)^2 \sqrt{\frac{10}{17}\rho_{B,*}} \begin{cases} \left(\frac{\lambda}{\lambda_0}\right)^{-5/2} & \text{for} \quad \lambda \geq \lambda_0 \\ \left(\frac{\lambda}{\lambda_0}\right)^{1/3} & \text{for} \quad \lambda < \lambda_0 \,, \end{cases} \tag{4.6}$$

which assumes a power-law spectrum for the magnetic field strength. The coherence length scale of the magnetic field λ_0 redshifted to today is [52]

$$\lambda_0 \equiv \lambda_B(t_0) = \left(\frac{a_{\rm rec}}{a_{\rm reh}}\right)^{q_b} \left(\frac{a_0}{a_{\rm reh}}\right) \lambda_*, \tag{4.7}$$

where the initial correlation length λ_* is determined by the bubble size R_* at percolation [158],

$$\lambda_* = R_* = \frac{(8\pi)^{1/3}}{H_*} \left(\frac{\beta}{H}\right)^{-1}, \tag{4.8}$$

where a bubble wall velocity of $v_w = 1$ is assumed. The peak value of the magnetic field spectrum is denoted as $B_0 = B_0(\lambda_0)$. The redshift factors are given by

$$\begin{aligned} \frac{a_{\rm reh}}{a_0} &= 8 \times 10^{-14} \left(\frac{100}{g_*(T_{\rm reh})}\right)^{1/3} \left(\frac{1\,\text{GeV}}{T_{\rm reh}}\right), \\ \frac{a_{\rm reh}}{a_{\rm rec}} &= 8 \times 10^{-11} \left(\frac{100}{g_*(T_{\rm reh})}\right)^{1/3} \left(\frac{1\,\text{GeV}}{T_{\rm reh}}\right), \end{aligned} \tag{4.9}$$

