Cosmological Helical Hypermagnetic Fields and Baryogenesis

based on: T. Fujita (Stanford->Kyoto) & KK, PRD93 (2016) 083520 [arXiv:1602.02109 (hep-ph)],
KK & A.J.Long (Chicago), PRD94 (2016) 063501 [arXiv:1606.08891 (astro-ph.CO)],
PRD94 (2016) 123509 [arXiv:1610.03074 (hep-ph)],
KK, PRD97 (2018) 103506 [arXiv:1802.03055 (hep-ph)].

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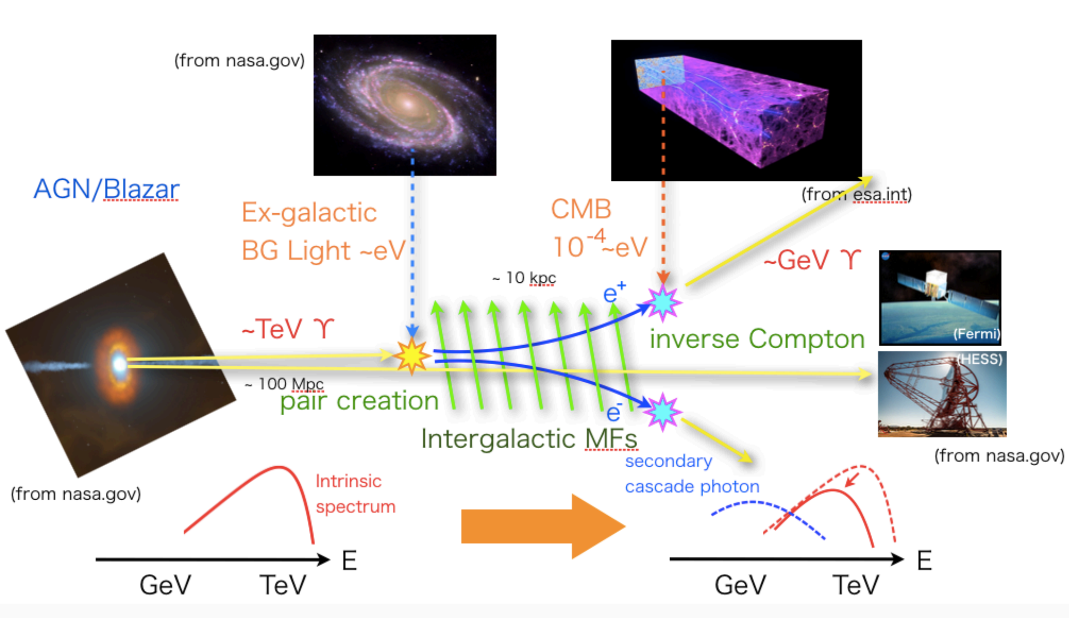
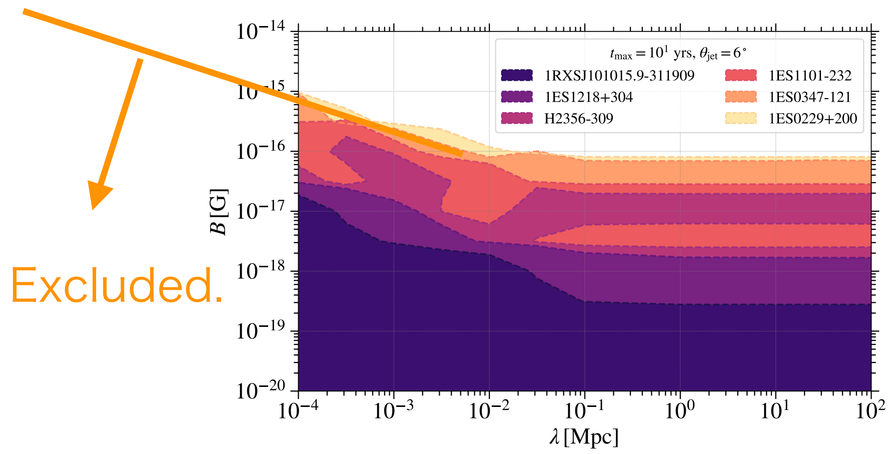
Courtesy H.Oide

Introduction

Intergalactic Magnetic Fields suggested by the gamma-ray observations from TeV blazars





1804.08035 (Fermi-LAT collaboration)

Courtesy H.Oide

Introduction

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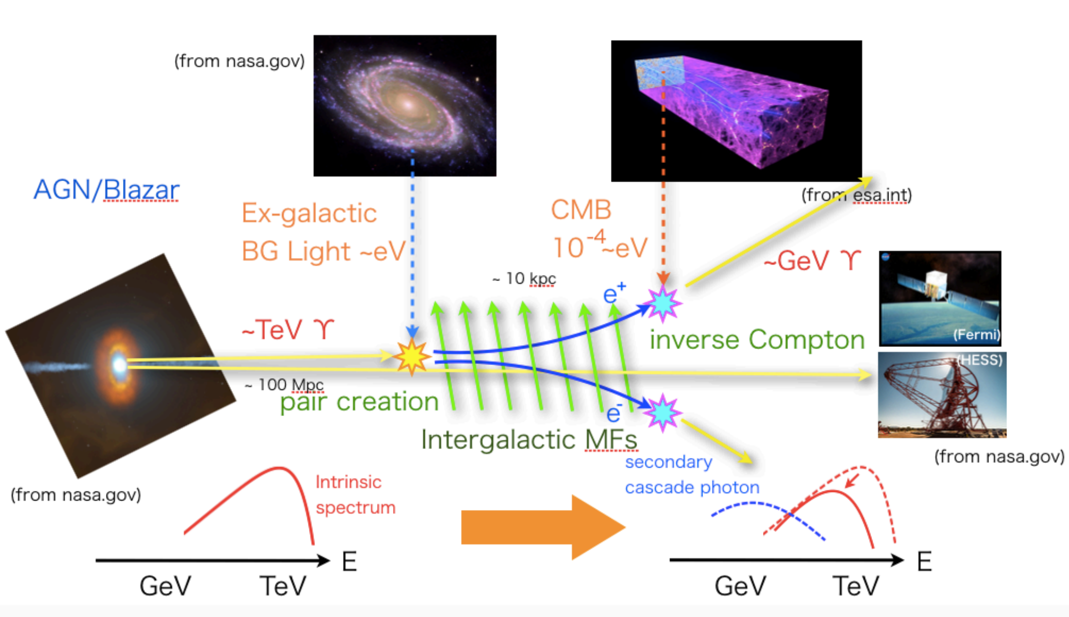

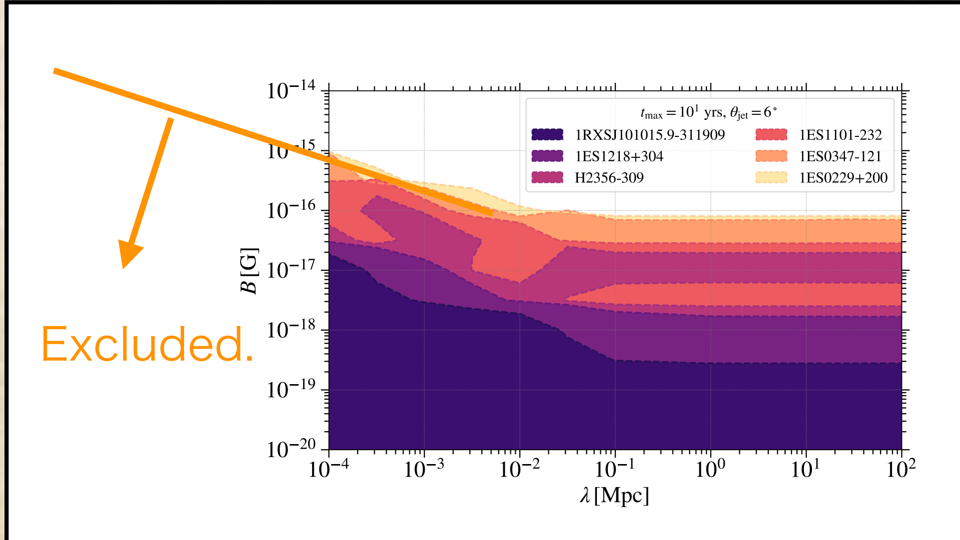

1804.08035 (Fermi-LAT collaboration)

- What is their origin? Early Universe?
- If primordial origin, are there any implications?

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Magnetogenesis in the Early Universe

Inflation?

e.g., Tuner&Widrow ('88), Ratra('92), …

Phase transition?

e.g., Quashnock+('89), Vachaspati ('91), Baym+ ('96),…

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Chiral Plasma Instability?

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Magnetogenesis in the Early Universe

Chiral Plasma Instability e.g. Joyce & Shaposhnikov ('97)

… Instability of magnetic fields in the presence of chiral asymmetric plasma through the chiral magnetic effect/chiral anomaly

('80 Vilenkin, '08 Fukushima, Kharzéev&Warringa,…)

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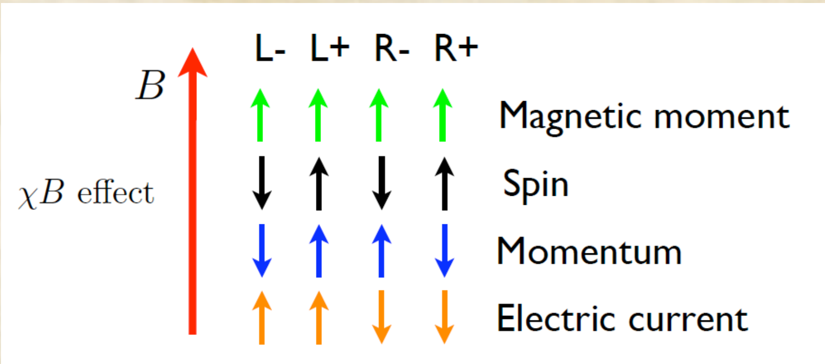
Magnetogenesis in the Early Universe

Chiral Plasma Instability e.g. Joyce & Shaposhnikov ('97)

⋯ Instability of magnetic fields in the presence of chiral asymmetric plasma through the chiral magnetic effect/chiral anomaly

('80 Vilenkin, '08 Fukushima, Kharzéev&Warringa,⋯)

In the presence of chiral asymmetry, (hyper)electric currents are induced parallel to the (hyper)magnetic fields.



('12 Tashro+)

$$\boldsymbol{J}_{\rm CME} = \frac{g'^2}{2\pi^2}\mu_5^Y \boldsymbol{B}_Y \qquad \mu_5^Y = \sum_i y_i^2 \mu_i^{(R)} - \sum_j y_j^2 \mu_j^{(L)}$$

(The magnetic fields are the one of U(1)$_Y$ in the SM.)

Courtesy H.Oide

(Hyper)MFs feel instability

if there are nonzero chiral chemical potential.

Modified Maxwell equation:

$$\frac{d\boldsymbol{B}_Y}{d\tau} = -\boldsymbol{\nabla} \times \boldsymbol{E}_Y, \quad \boldsymbol{\nabla} \times \boldsymbol{B}_Y = \boldsymbol{J}_Y = \sigma_Y(\boldsymbol{E}_Y + \boldsymbol{v} \times \boldsymbol{B}_Y) + \frac{\alpha_Y}{\pi}\mu_5^Y \boldsymbol{B}_Y$$

(Displacement current $d\boldsymbol{E}_Y/d\tau$ is omitted since it is tiny in the MHD description)

$$\Rightarrow \frac{d\boldsymbol{B}_Y}{d\tau} = \frac{1}{\sigma_Y}\left(\boldsymbol{\nabla}^2 \boldsymbol{B}_Y + \frac{2\alpha_Y}{\pi}\mu_5^Y \boldsymbol{\nabla} \times \boldsymbol{B}_Y\right) + \boldsymbol{\nabla} \times (\boldsymbol{v} \times \boldsymbol{B}_Y)$$

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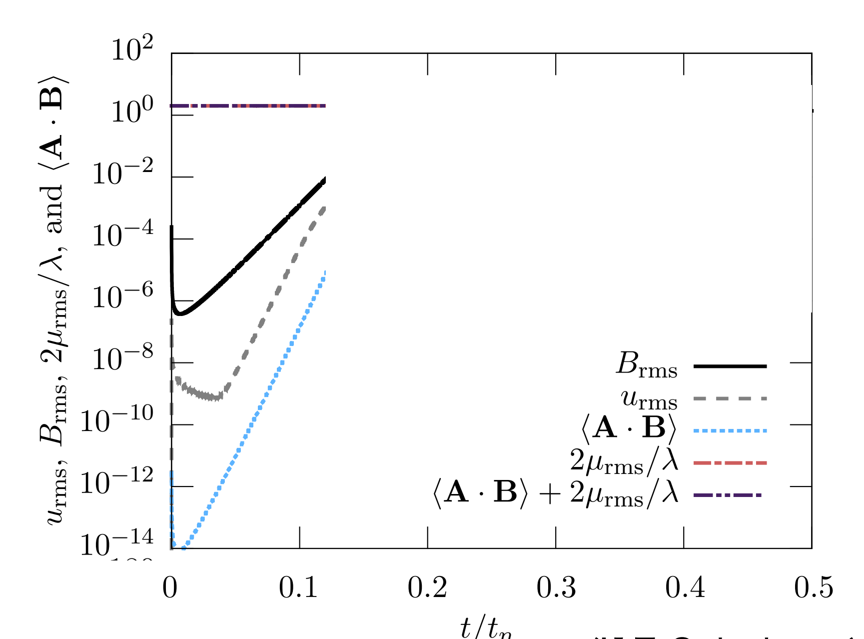
If $\boldsymbol{v}$ is negligibly small and μ_5^Y is kept constant, one helicity mode of (hyper)MF (depending on the sign of μ_5^Y) feels instability at $k \simeq k_c \equiv \frac{\alpha_Y\mu_5^Y}{\pi}$ as $B_Y^+ \propto \exp\left[\frac{k_c^2}{\sigma_Y}\tau\right]$. (for $\mu_5^Y > 0$) ('97 Joyce&Shaposhnikov)

⇒ Maximally helical (hyper)MFs will be generated!

Courtesy H.Oide

The evolution of MFs involve the velocity fields, which requires full MHD study. This has been done recently and whole picture has been established.

('17 Schober+)



('17 Schober+)

1. Amplification with negligible v-field and constant μ_5^Y

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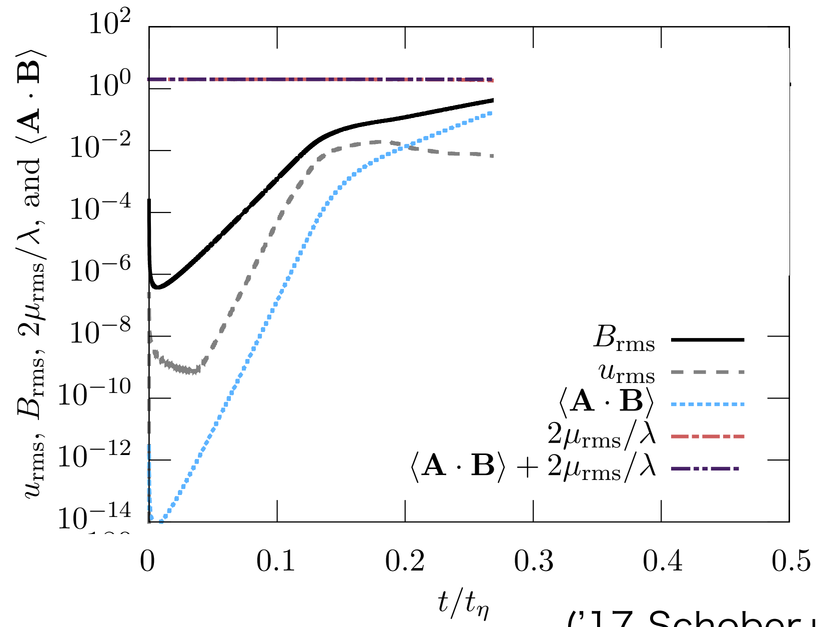

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1. Amplification with negligible v-field and constant μ_5^Y
2. v-field develops and amplification gets milder.

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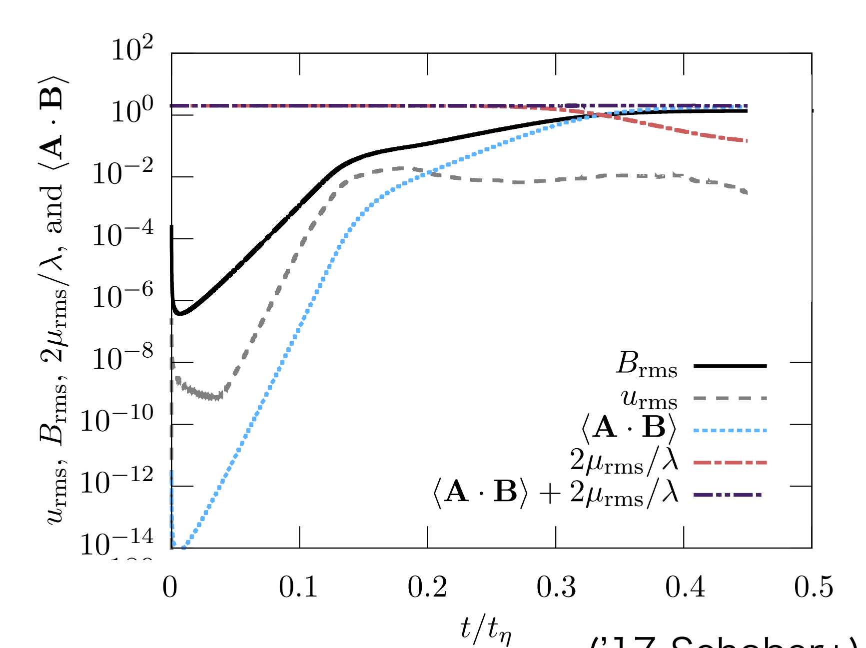

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1. Amplification with negligible v-field and constant μ_5^Y
2. v-field develops and amplification gets milder.
3. Magnetic helicity fully developed and saturated. μ_5^Y starts to decay.

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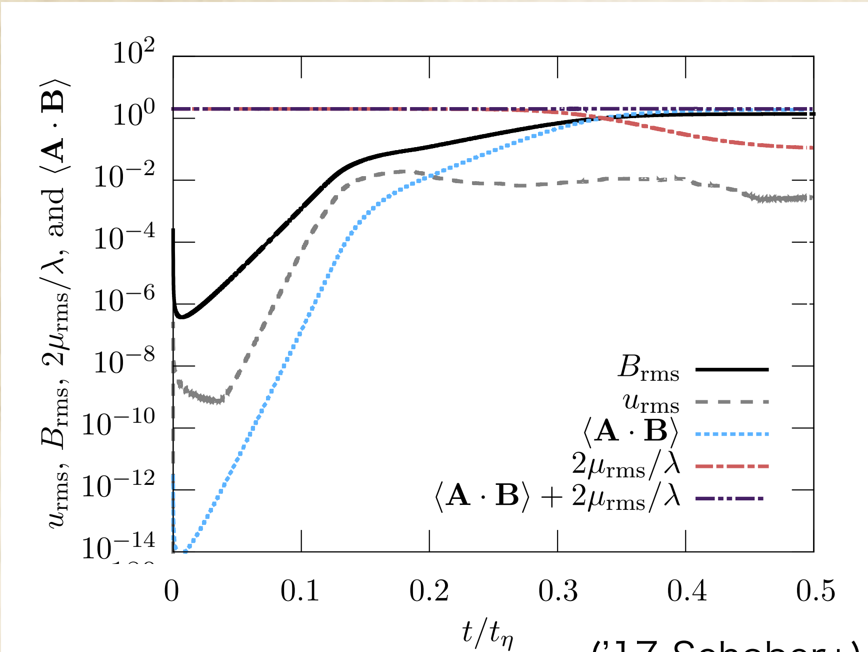

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1. Amplification with negligible v-field and constant μ_5^Y

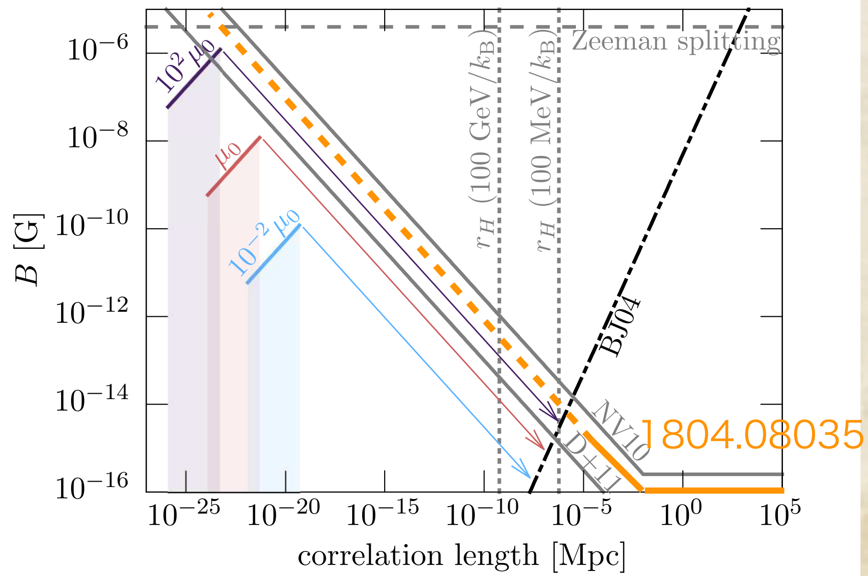
2. v-field develops and amplification gets milder.

3. Magnetic helicity fully developed and saturated. μ_5^Y starts to decay.

4. MFs are now driven by velocity fields and evolve with inverse cascade, $B_p \propto a^{-7/3}, \quad \lambda_B \propto a^{5/3}$
μ_5^Y becomes smaller and smaller.

Courtesy H.Oide

Predictions of the MF generation in this scenario:



('17 Schober+)

$$B_Y^{\rm phys}(T) \simeq 0.82{\rm GeV}^2 \left(\frac{g_{*s}(T)}{g_{*s}(T_{\rm s})}\right)^{7/9} c_1^{-1/3} \left(\frac{\gamma}{10^{-2}}\right)^{-1/3}$$
$$\times \left(\frac{\alpha_Y}{10^{-2}}\right)^{-1/3} \left(\frac{\mu^i_{5,Y}/T_i}{10^{-2}}\right)^{1/3} \left(\frac{g_*}{106.75}\right)^{1/3} \left(\frac{T}{10^2{\rm GeV}}\right)^{7/3},$$
$$\lambda_Y^{\rm phys}(T) \simeq 9.8\times 10^6{\rm GeV}^{-1} \left(\frac{g_{*s}(T_{\rm s})}{g_{*s}(T)}\right)^{5/9} c_1^{-1/3} \left(\frac{\gamma}{10^{-2}}\right)^{2/3}$$
$$\times \left(\frac{\alpha_Y}{10^{-2}}\right)^{-1/3} \left(\frac{\mu^i_{5,Y}/T_i}{10^{-2}}\right)^{1/3} \left(\frac{g_*}{106.75}\right)^{-2/3} \left(\frac{T}{10^2{\rm GeV}}\right)^{-5/3}.$$

$$B^0_{\rm phys} \simeq 9.9\times 10^{-16}{\rm G}\ c_1^{-1/3} \left(\frac{\gamma}{10^{-2}}\right)^{-1/3} \left(\frac{\alpha_Y}{10^{-2}}\right)^{-1/3}$$
$$\times \left(\frac{\mu^i_{5,Y}/T_i}{10^{-2}}\right)^{1/3} \left(\frac{g_*}{106.75}\right)^{1/3},$$
$$\lambda^0_{\rm phys} \simeq 6.9\times 10^{-3}{\rm pc}\ c_1^{-1/3} \left(\frac{\gamma}{10^{-2}}\right)^{2/3} \left(\frac{\alpha_Y}{10^{-2}}\right)^{-1/3}$$
$$\times \left(\frac{\mu^i_{5,Y}/T_i}{10^{-2}}\right)^{1/3} \left(\frac{g_*}{106.75}\right)^{-2/3}.$$

('18 KK)

$\dfrac{\mu^i_{5,Y}}{T_i} \simeq 1$ can explain the blazar observation.

Courtesy H.Oide

Can it be realized in the SM or well-motivated BSM?

Courtesy H.Oide

Can it be realized in the SM or well-motivated BSM?

- Approximated conservation of chirality
- Large initial chiral asymmetry

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Can it be realized in the SM or well-motivated BSM?

- Approximated conservation of chirality => Yes. Even in the SM.
- Large initial chiral asymmetry

➡ Chirality carried by R-handed electrons is conserved when its Yukawa interaction is weak $T \gtrsim 80\mathrm{TeV}$

('92 Campbell+)

For $\mu^i_{5,Y}/T_i \gtrsim 10^{-3}$ instability grows earlier.

Other interactions (Yukawa, Sphalerons) redistribute the chemical potentials to (partial) equilibrium as

(a lá '90 Harvey&Turner)

e.g.) Yukawa interaction: $\mu_{Q^i_L} + \mu_H - \mu_{u^i_R} = 0, \cdots$

Sphalerons: $\sum_i \mu_{Q^i_L} + \mu_{L^i_L} = 0, \cdots$

Charge conservation: $\frac{1}{3}\mu_B - \mu_{L^1} = -\frac{2}{3}\mu_{e_R}, \ \sum_i y_i \mu_i = 0, \cdots$

If SU(5) 5 Higgs decay only into the first generation, at the time of decay we have

$$\mu_{u^1_L} = \mu_{d^1_L} = \mu_{u^1_R} = \frac{1}{3}\mu_{e^1_R}$$

$$\mu_5^Y = c\mu_{e^1_R}, \quad c = \frac{553}{481}.$$

('18 KK)

Courtesy H.Oide

Can it be realized in the SM or well-motivated BSM?

- Approximated conservation of chirality
- Large initial chiral asymmetry => Well, BSM might be.

SU(5) **5** Higgs decay, one of the process in the GUT baryogenesis, can generate e_R asymmetry.

But simple GUT baryogenesis does not work well. e.g. Yoshimura ('78)

- Need to avoid the monopole problem.
- Usually SU(5) **5** Higgs couples strongly to 2nd & 3rd generation.

Large chiral asymmetry is generated if⋯

- SU(5) **5** scalar is produced through a specific effect such as instant preheating.
- SU(5) **5** scalar then dominates the Universe.
- SU(5) **5** scalar mainly decay into 1st generation fermions.

which can give large e_R asymmetry
$$\frac{\mu^Y_{e_R,\mathrm{ini}}}{T_{\mathrm{ini}}} = \frac{\pi^2 g_*}{5}\epsilon\frac{T_{\mathrm{dec}}}{m_X}$$

Realistic model building is a remaining task.

Courtesy H.Oide

Baryogenesis from hypermagnetic helicity

Interesting consequence of helical hypermagnetic fields

… baryogenesis from SM chiral anomaly

('98 Giovannini&Shaposhnikov, '16 KK&Long)

Courtesy H.Oide

Baryogenesis from hypermagnetic helicity

Interesting consequence of helical hypermagnetic fields

$\cdots$ baryogenesis from SM chiral anomaly

('98 Giovannini&Shaposhnikov, '16 KK&Long)

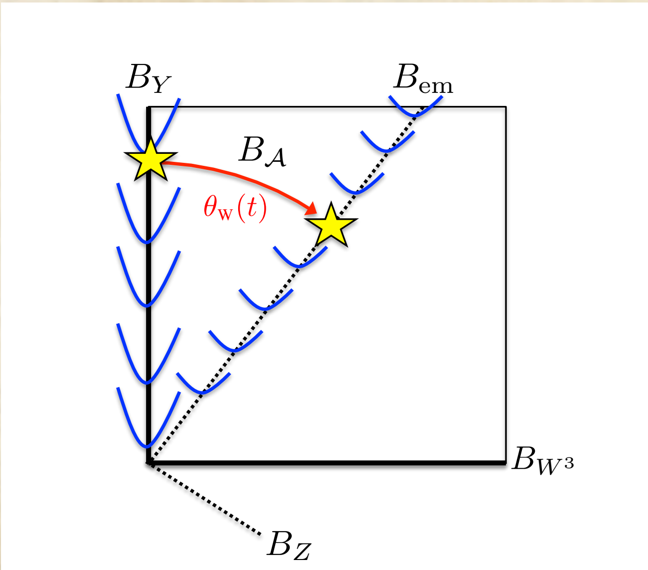
Hypermagnetic helicity

$$\mathcal{H} = \int d^3x \epsilon^{ijk} Y_i \partial_j Y_k$$
$$= V \int \frac{d^3k}{(2\pi)^3} k \left[|Y_k^{\mathrm{R}}|^2 - |Y_k^{\mathrm{L}}|^2 \right]$$

Chiral anomaly

$$\Delta Q_B = \Delta Q_L = N_g \left(\underline{\Delta N_{\mathrm{CS}}} - \underline{\frac{g'^2}{16\pi^2} \Delta \mathcal{H}_Y} \right)$$

SU(2) part:"EW sphaleron" U(1) part: often neglected

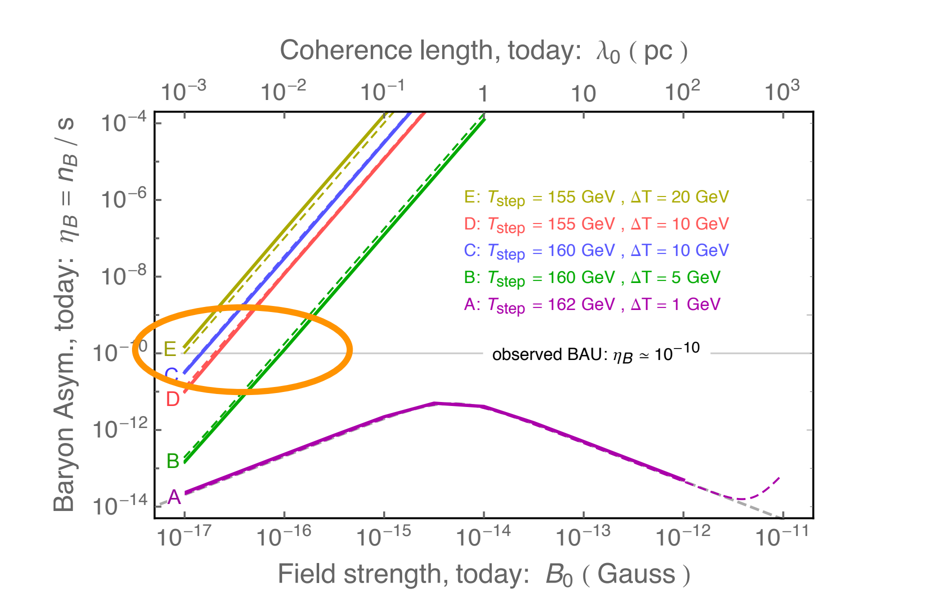


- Most efficient around EWSB
- Baryon asymmetry remains against the EW sphaleron washout

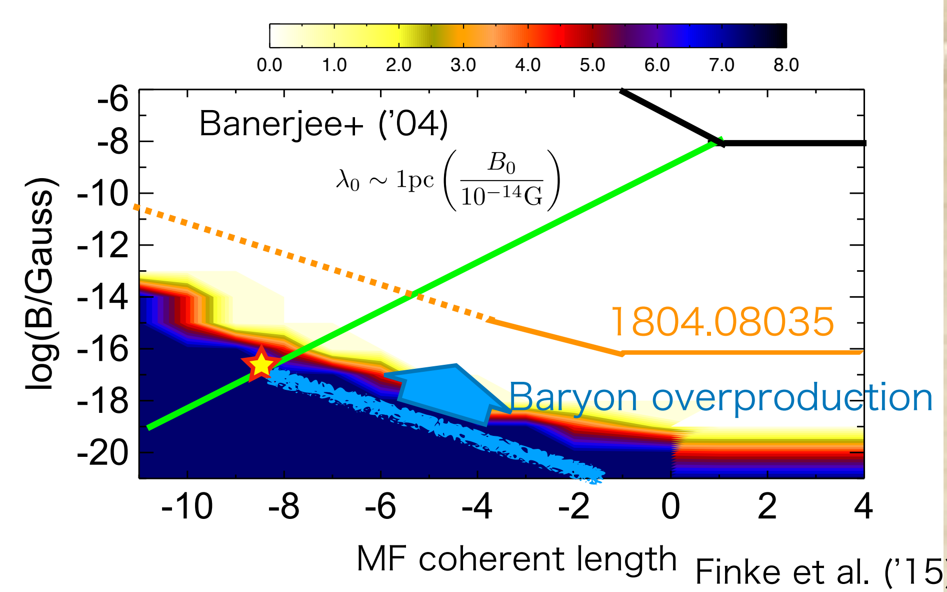
('16 KK&Long)

Courtesy H.Oide

We suffer from baryon “over”production.



Assuming the inverse cascade ('16 KK&Long)



Finke et al. ('15)

in the case magnetic fields are maximally helical, including the case of chiral plasma instability.

Courtesy H.Oide

Implications for the magnetogenesis from chiral plasma instability

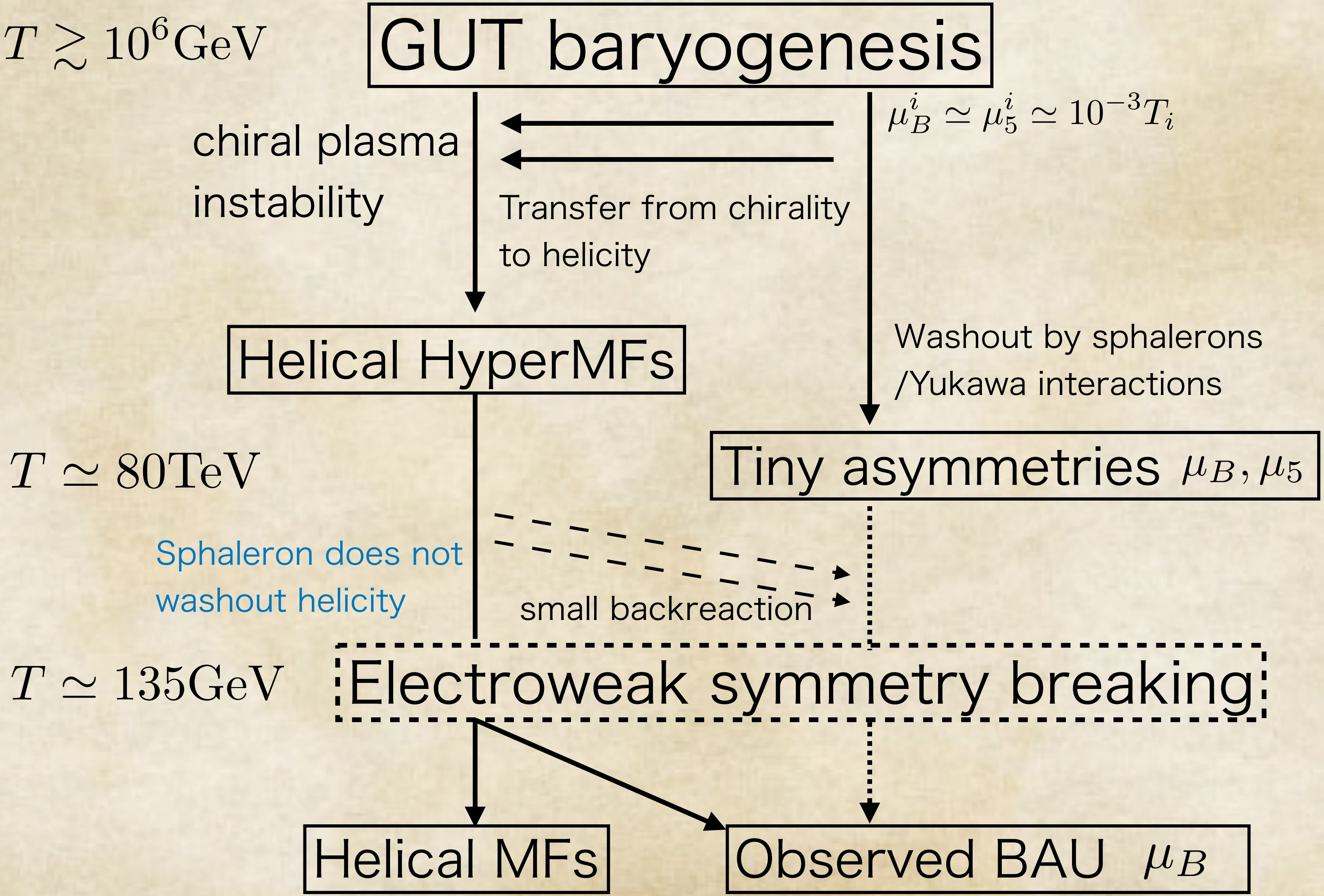
Courtesy H.Oide

Implications for the magnetogenesis from chiral plasma instability

- Chiral plasma instability cannot explain the blazar observations solely due to baryon overproduction.
- If we forget about the blazar observation, we can say that the GUT baryogenesis is revived as an indirect origin of BAU, avoiding the sphaleron washout, if it can produce initially $\mu_B^i/T_i \simeq 10^{-3}$.

Courtesy H.Oide

Revival of the GUT baryogenesis



Courtesy H.Oide

Summary

1. Magnetic helicity is important information to explore the origin of intergalactic MFs.
2. If intergalactic MFs are not maximally helical…
   - If they carry tiny helicity, blazar observations and baryon asymmetry can be explained simultaneously.
3. If intergalactic MFs are maximally helical, they should have been generated after EWSB. No relation to BAU.
4. One can imagine two magnetogenesis scenario. One occurred before EWSB and is responsible for BAU, perhaps chiral plasma instability (GUT baryogenesis?). The other occurred after EWSB and is responsible for blazars.
5. Note that it is still possible that blazar observations are explained by other mechanism than the intergalactic MFs.

Courtesy H.Oide