Magnetogenesis and Baryogenesis in Pseudoscalar Inflation

T. Fujita (Waseda) & KK, PRD93 (2016) 083520 [arXiv:1602.02109 (hep-ph)],
KK & A.J.Long (Rice), PRD94 (2016) 063501 [arXiv:1606.08891 (astro-ph.CO)],
KK & A.J.Long (Rice), PRD94 (2016) 123509 [arXiv:1610.03074 (hep-ph)],
D. Jimenez (MPIK), KK, K. Schmitz (Münster), X. Xu (IHEP), JCAP12 (2017) 011 [arXiv:1707.07943 (hep-ph)],
KK, F. Uchida, J. Yokoyama (Tokyo), JCAP 04 (2021) 034 [arXiv: 2012.14435 (astro-ph.CO)]
V. Domcke (CERN), KK, K. Mukaida (KEK), K. Schmitz (Münster), M. Yamada (Tohoku),
Phys. Rev. Lett 126 (2021) 201802 (arXiv: 2011.09347[hep-ph]); JHEP01 (2023)053 (arXiv: 2210.06412[hep-ph]),
A. Brandenburg (Nordita), KK, J. Schober (EPFL), PRR 5 (2023) 2, L022028 (arXiv: 2302.00512 [physics.plasma-ph]);
A. Brandenburg (Nordita), KK, K. Mukaida (KEK), K. Schmitz (Münster), J. Schober (EPFL),
Phys Rev. D108 (2023) 063529 (arXiv: 2304.06612 [hep-ph]).

(See also Valerie, Kyohei, Axel's talk)

國科大杭州高等研究院
Hangzhou Institute for Advanced Study,UCAS

Kohei Kamada

(Hangzhou Institute for Advanced Study, UCAS)

Workshop: Generation, evolution, and observations of cosmological magnetic fields

Bernoulli Center, EPFL, 1/5/2024

Introduction

— Magnetic Fields and Baryon Asymmetry Just after Pseudoscalar Inflation —

Chiral Anomaly

$$\partial_\mu J_5^\mu = -\frac{\alpha}{2\pi} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

leads to baryon and lepton number violation in the SM

$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = \frac{3\alpha}{4\pi}\mathrm{Tr}(W_{\mu\nu}\tilde{W}^{\mu\nu}) - \frac{3\alpha'}{8\pi} Y_{\mu\nu}\tilde{Y}^{\mu\nu}$$

or

$$\Delta Q_B = \Delta Q_L = 3\Delta N_{\mathrm{CS}} - \frac{3\alpha'}{4\pi}\Delta\mathcal{H}_Y$$

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$$\Delta Q_B = \Delta Q_L = 3\Delta N_{\rm CS} - \frac{3\alpha'}{4\pi}\Delta\mathcal{H}_Y$$

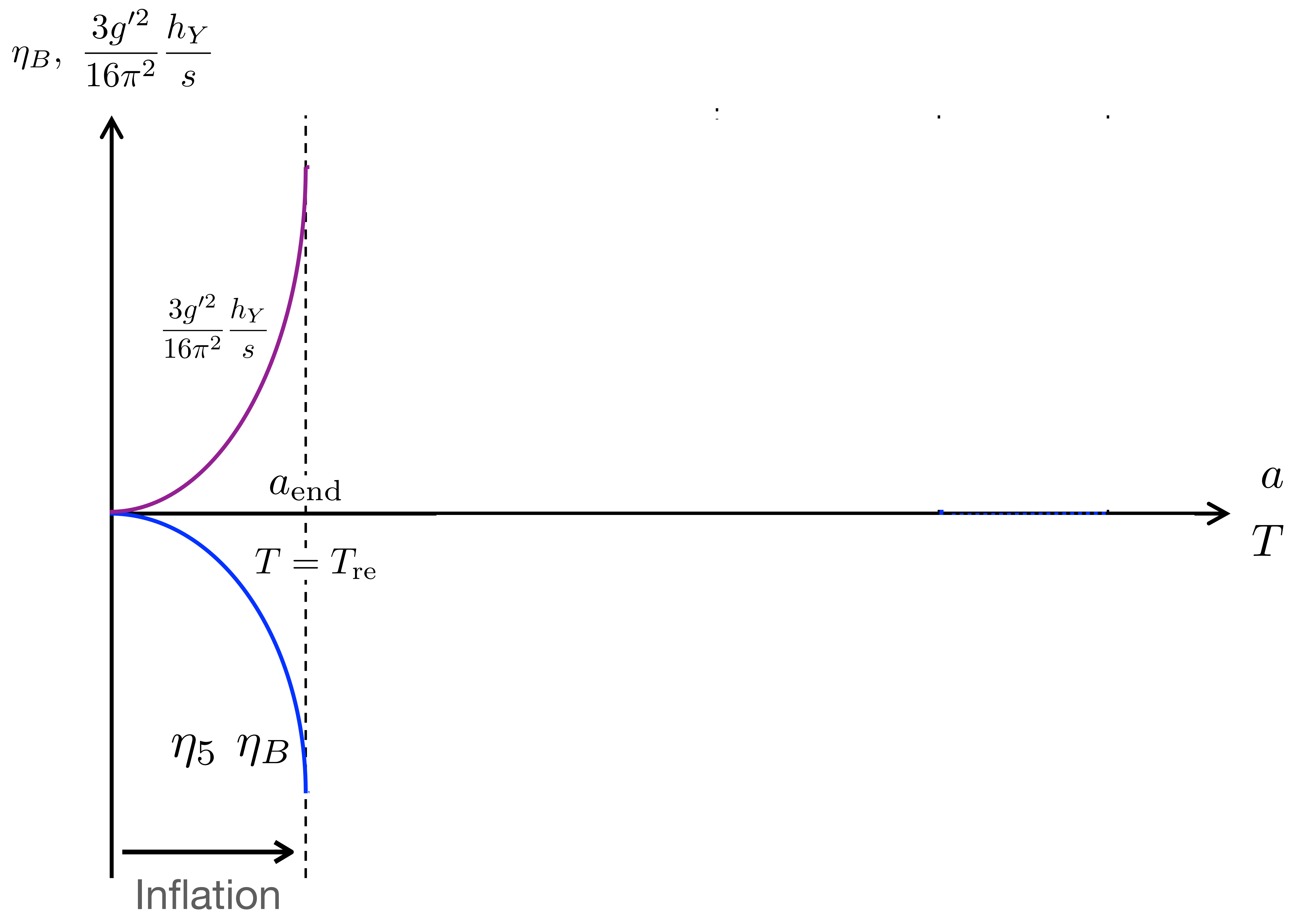
Axion inflation generates anyway maximally helical MFs.

(Valerie's talk)

=> Baryon asymmetry has been already generated as

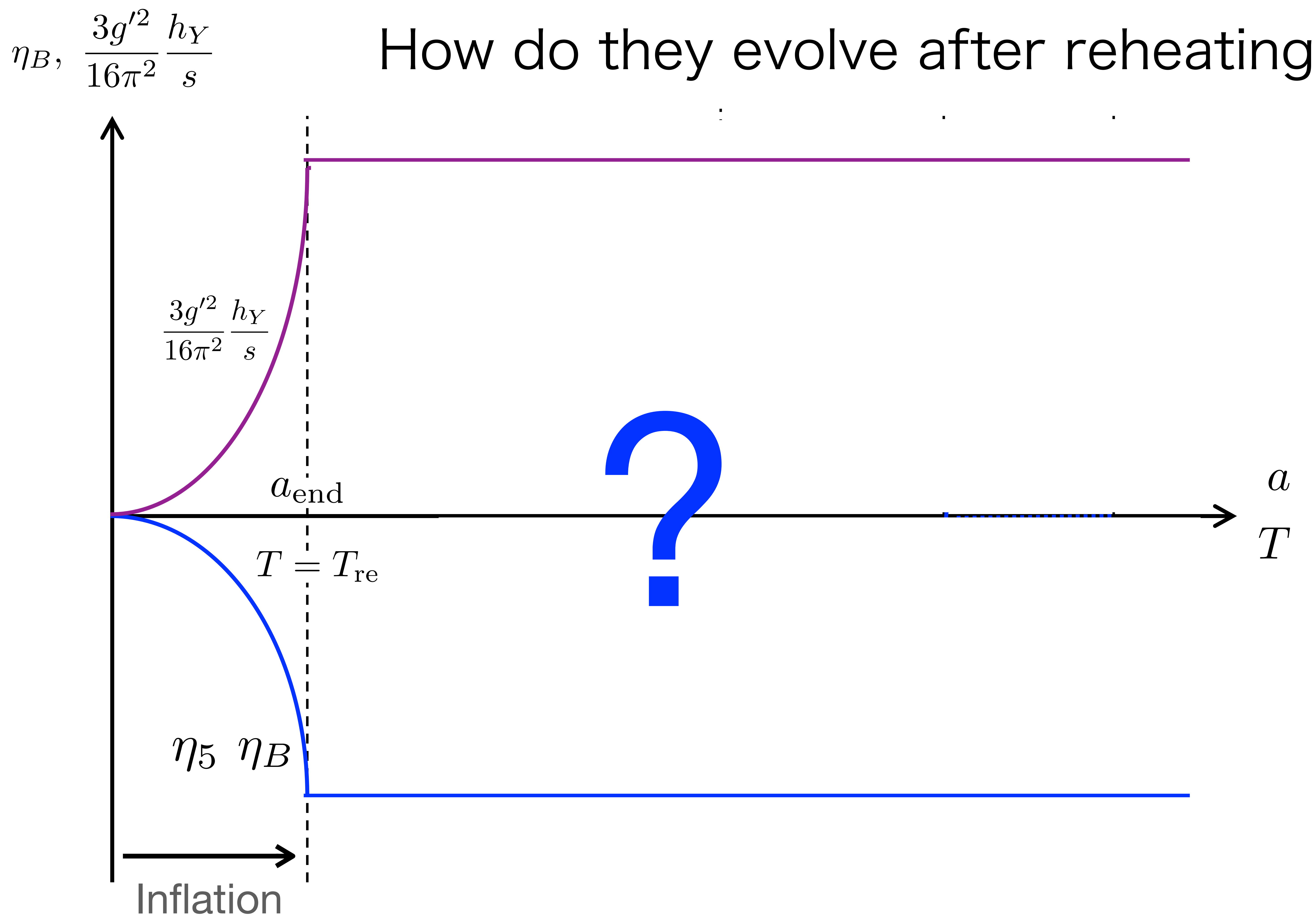
$$Q_B = Q_L = -\frac{3\alpha'}{4\pi}\left.\mathcal{H}_Y\right|_{\rm axion\ \ inflation}$$

$$\eta_X \equiv \frac{q_X}{s}$$



How do they evolve after reheating?

$$\eta_X \equiv \frac{q_X}{s}$$



Naive guess

— Baryogenesis from Hypermagnetic Helicity Decay —

Naive guess:

Generated asymmetry is B+L, which is washed out by electroweak sphalerons.

’83 Manton, ’84 Klinkhamer & Manton, ’85 Kuzmin, Rubakov, Shaposhnikov

Magnetic helicity is a relatively good conserved quantity.

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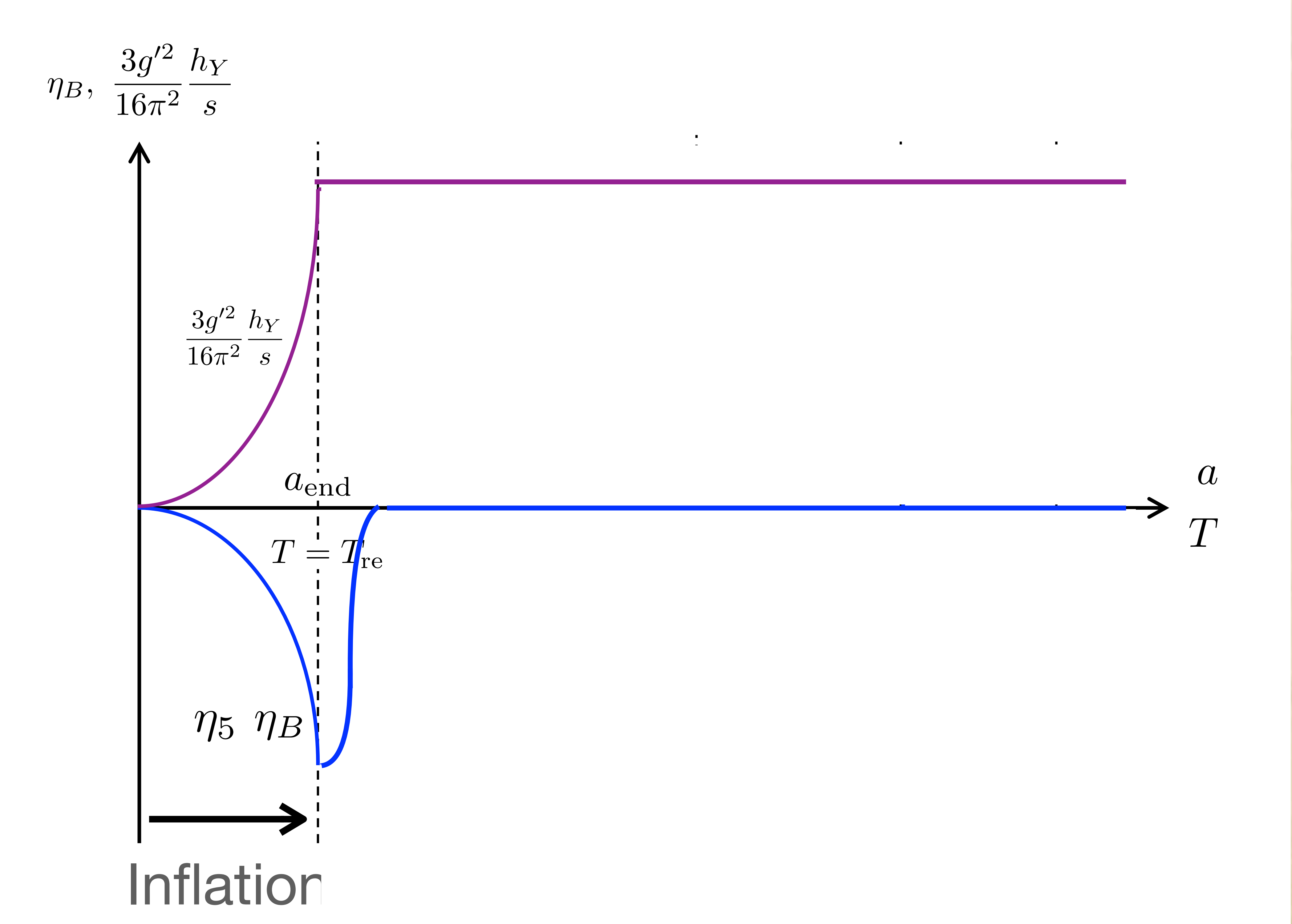

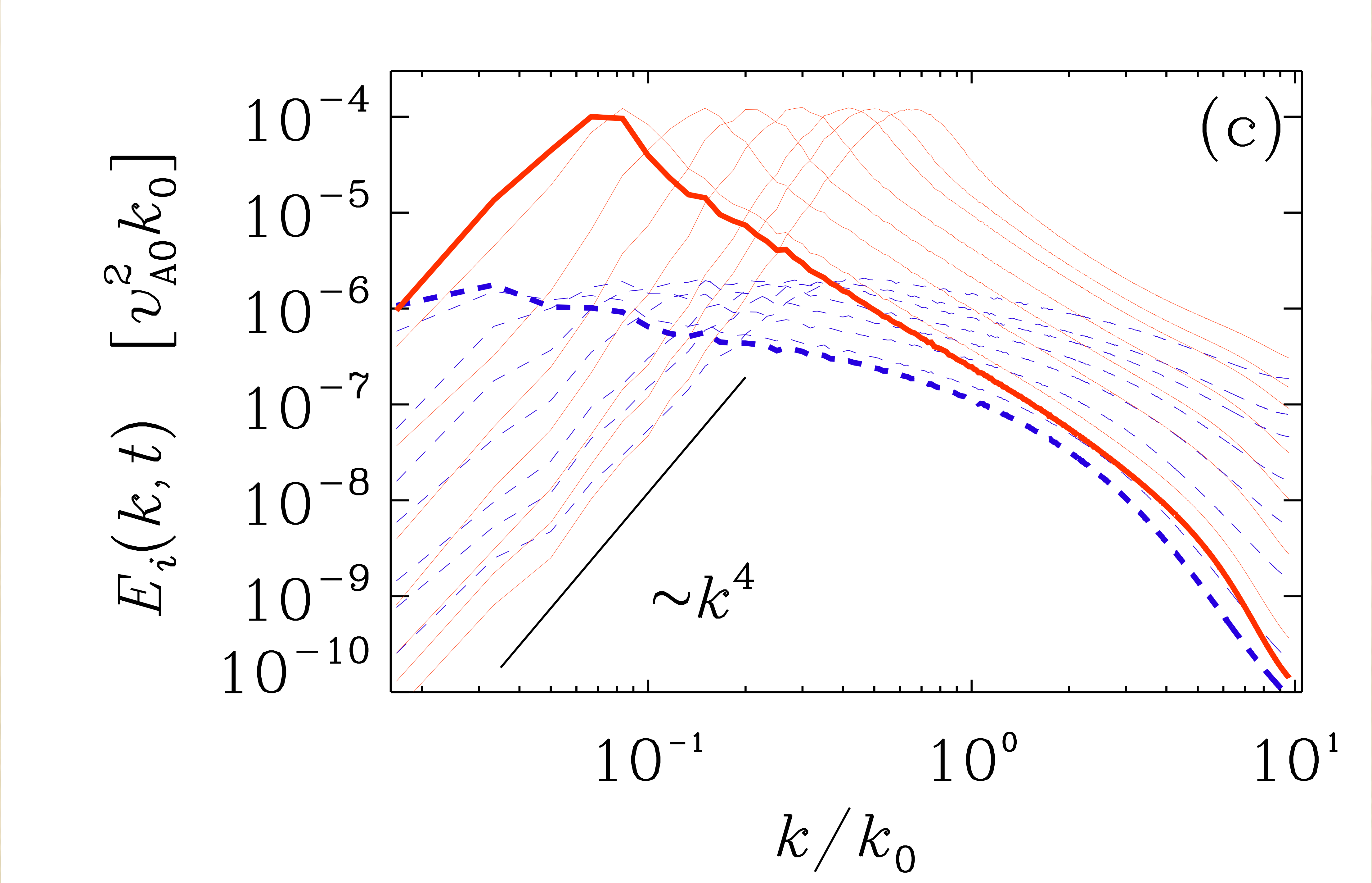

'17 Brandenburg & Kahniashvili

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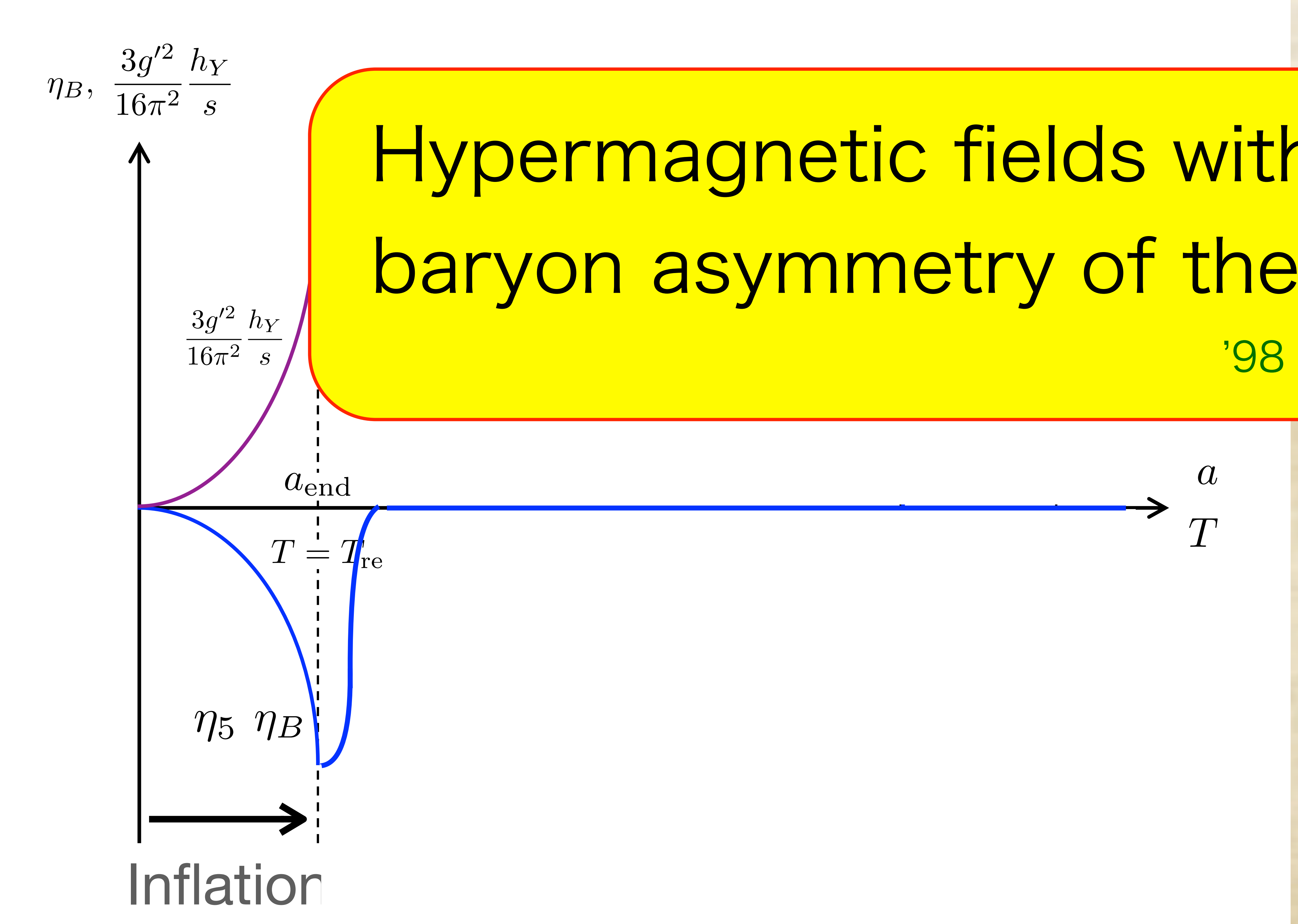

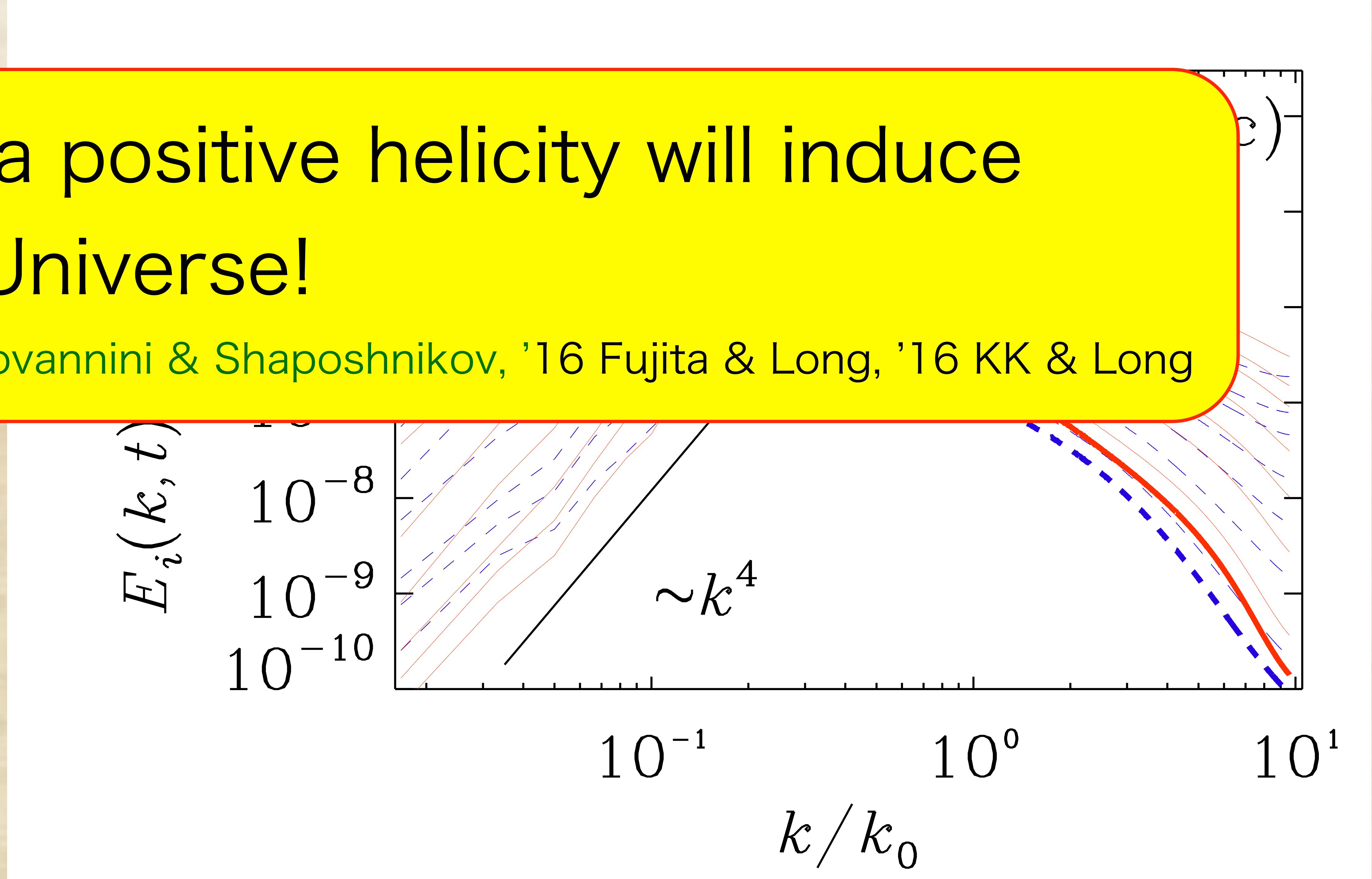

Hypermagnetic fields with a positive helicity will induce baryon asymmetry of the Universe!

’98 Giovannini & Shaposhnikov, ’16 Fujita & Long, ’16 KK & Long

’17 Brandenburg & Kahniashvili

The helical hypermagnetic fields are not screened but evolve according to MHD, which are described as Gaussian stochastic fields,

$$\langle B_i(\boldsymbol{k})\rangle = 0 \qquad \langle B_i(\boldsymbol{k})B_j(\boldsymbol{k}')\rangle = (2\pi)^3 \left((\delta_{ij} - \hat{k}_i\hat{k}_j)\underline{S(k)} + i\epsilon_{ijk}\hat{k}_k\underline{A(k)}\right)\delta(\boldsymbol{k}-\boldsymbol{k}')$$

$$(S(k) \geq A(k))$$

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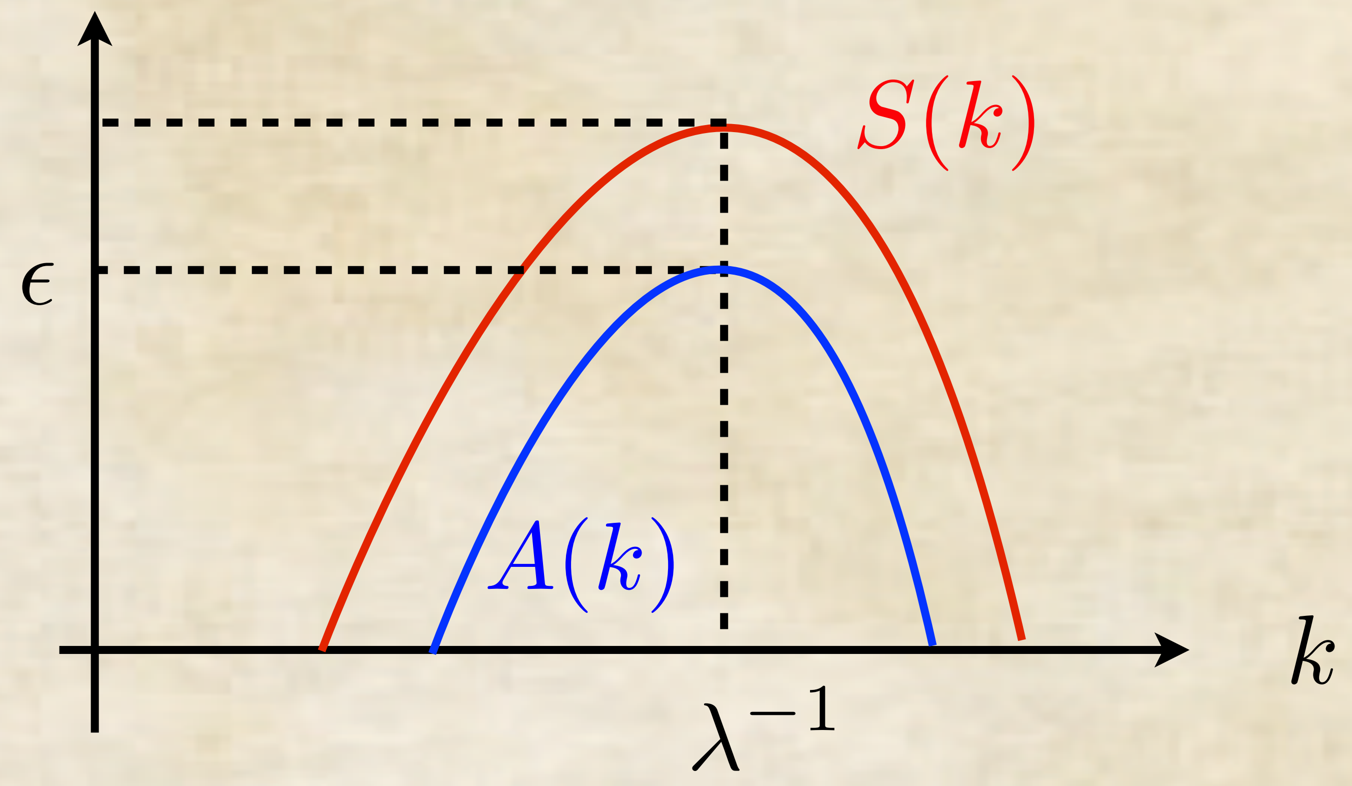
From these notations, characteristics of the magnetic fields are given by

$$\rho_B = \int \frac{d^3k}{(2\pi)^3}k^2 S(k) \quad \Rightarrow \overline{B} = \sqrt{2\rho_B} \qquad \mathcal{H} = 2\int \frac{d^3k}{(2\pi)^3}kA(k) \qquad \lambda = \frac{\int dk k^3 S(k)}{\int dk k^4 S(k)}$$



Hypermagnetic fields generated by axion inflation is localized at the horizon scale at the end of inflation.

$$\mathcal{H} \simeq \lambda \overline{B}^2$$

If the average of helicity density $\mathcal{H}$ decays, B+L asymmetry is generated in the Universe?

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

The helical hypermagnetic fields are not screened but evolve according to MHD, which are described as Gaussian stochastic fields,

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$$(S(k)\geq A(k))$$

From these no

$$\rho_B = \int \frac{d}{(2} \cdots \frac{{}^3 S(k)}{{}^4 S(k)}$$

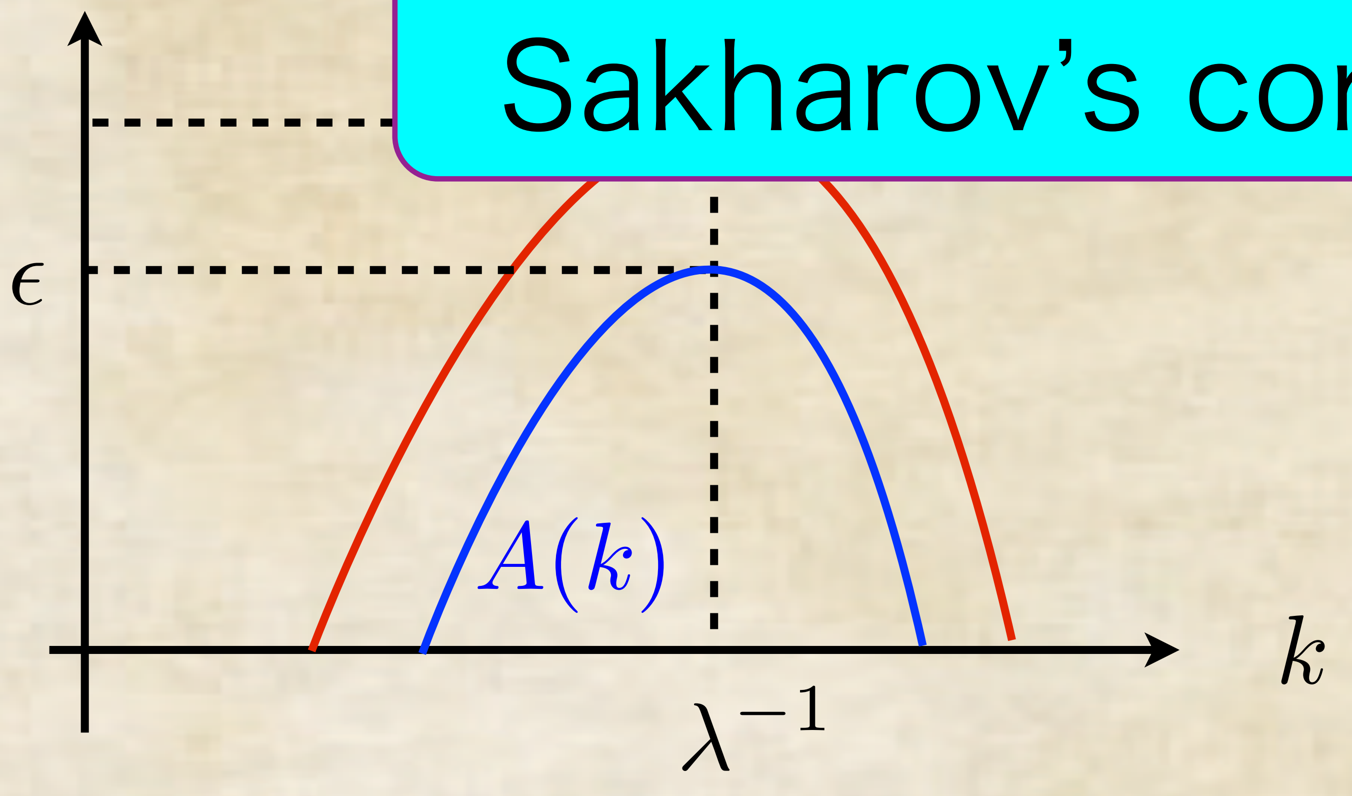
Now we have BG large-scale helical hyperMFs,

B-violation: SM chiral anomaly

C&CP-violation/non-equilibrium

:existence of large-scale magnetic helicity

Sakharov's conditions are satisfied!



axion inflation

the end of inflation.

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B+L asymmetry is generated in the Universe?

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

How to realize helicity decay?

1. Decay due to MHD with finite conductivity ('98 Giovannini&Shaposhnikov)

The characteristic MF strength obeys the Maxwell eq. with the MHD approximation.

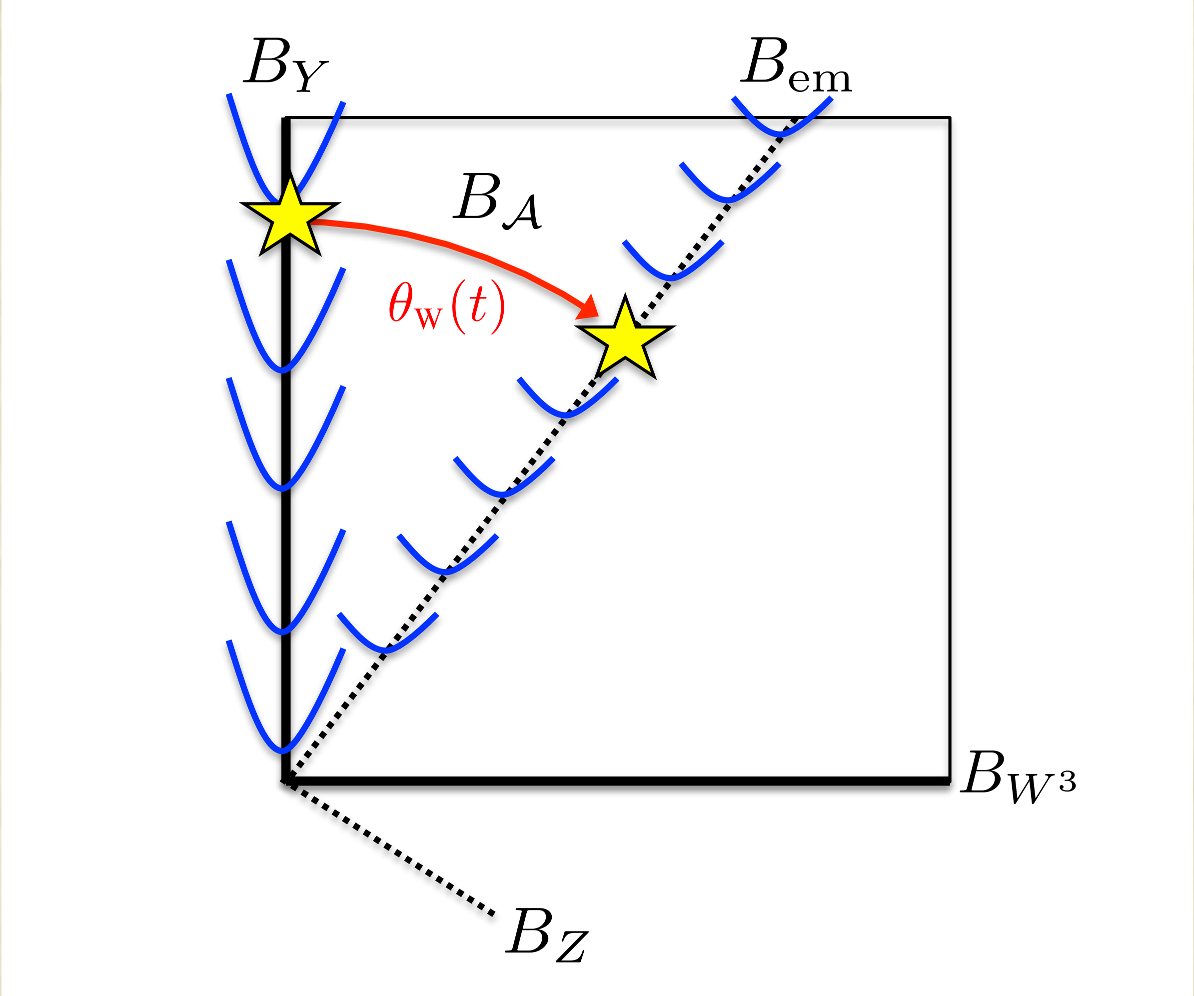
$$\boldsymbol{\nabla} \times \overline{\boldsymbol{B}} = \boldsymbol{J} = \sigma \overline{\boldsymbol{E}} \qquad \Rightarrow \overline{\boldsymbol{E}} = \frac{1}{\sigma} \boldsymbol{\nabla} \times \overline{\boldsymbol{B}}$$

$$\partial_t \mathcal{H} = -2\overline{\boldsymbol{E} \cdot \boldsymbol{B}} = -\frac{2}{\sigma} \overline{(\boldsymbol{\nabla} \times \boldsymbol{B}) \cdot \boldsymbol{B}} \simeq -\frac{2}{\sigma} \epsilon \frac{\overline{B}^2}{\lambda}$$

$\sigma \simeq 100T$ ('97 Baym+, '00 Arnold+)

Hypermagnetic helicity is almost constant but slightly decays

2. Electroweak symmetry breaking (16 KK&Long)



Gauge group

$$SU(2)_W \times U(1)_Y \to U(1)_{\rm em}$$

Large-scale (massless) MFs

$$B_Y \to B_{\rm em} = \cos\theta_W B_Y + \sin\theta_w B_{W^3}$$

Magnetic helicity

$$H_Y^{\rm before} \to H_{\rm em}^{\rm after} = H_Y^{\rm before}$$

$$H_Y^{\rm after} = \cos^2\theta_W H_{\rm em}^{\rm after} = \cos^2\theta_W H_Y^{\rm before}$$

$$N_{\rm CS, W^3}^{\rm after} \sim \sin^2\theta_W H_{\rm em}^{\rm after} = \sin^2\theta_W H_Y^{\rm before}$$

BAU:

$$\Delta H_Y = -\sin^2\theta_W H_Y^{\rm before}$$

$$\Delta N_{\rm CS} \sim \sin^2\theta_W H_Y^{\rm before}$$

$$\Rightarrow \Delta Q_B = \#\Delta N_{\rm CS} - \#\Delta H_Y \sim \sin^2\theta_W H_Y^{\rm before}$$

How to characterize the electroweak symmetry breaking/crossover?

(Misha's question.)

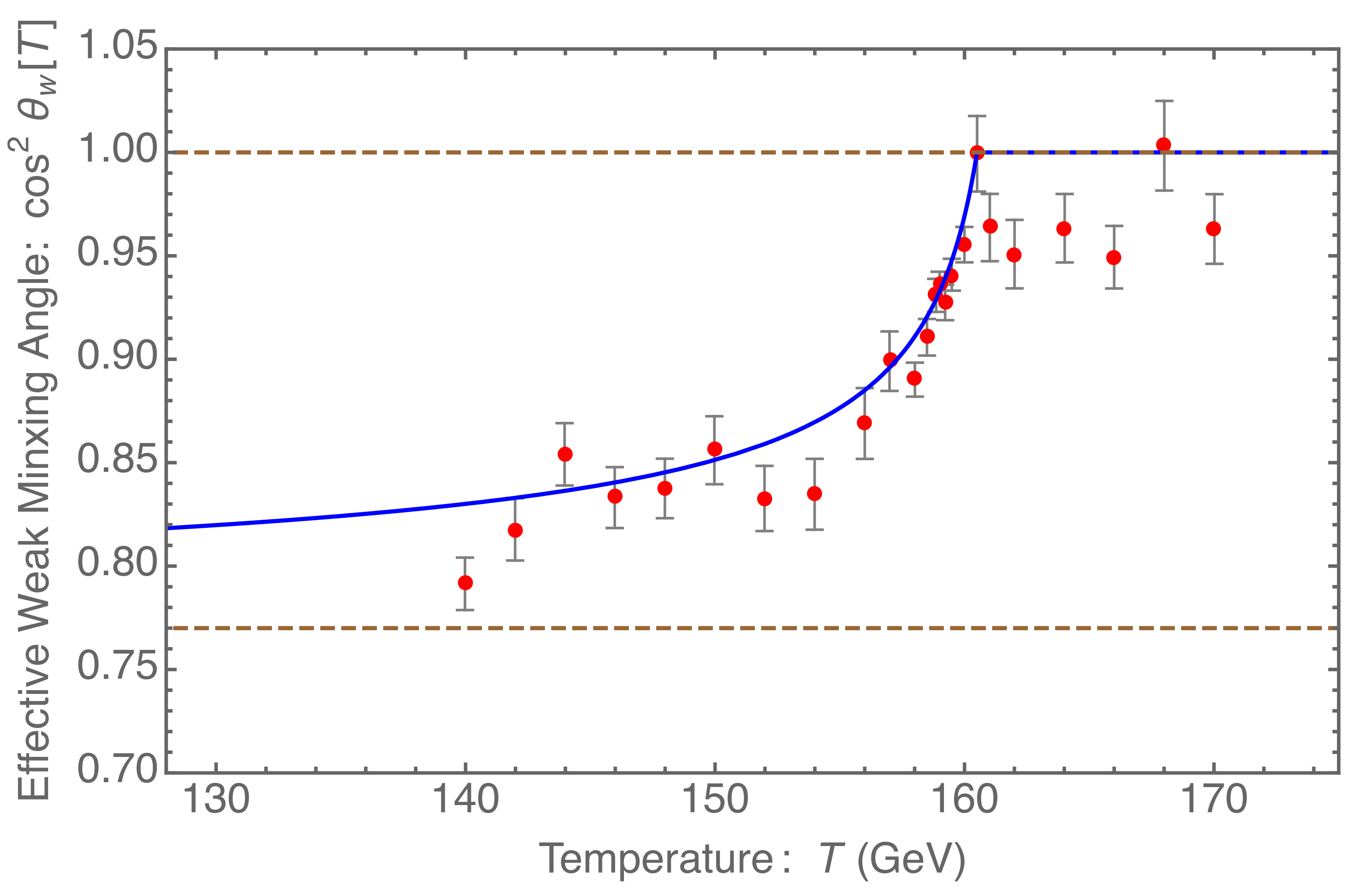
$$G(z) = \frac{1}{N^3} \sum_t \langle O_{\mathbf{p}}(t) O^*_{\mathbf{p}}(z+t) \rangle$$

$$O_{\mathbf{p}}(z) = \sum_{x_1, x_2} \alpha_{12}(x_1, x_2, z) e^{i\mathbf{p}\cdot\mathbf{x}},$$

$$\alpha_{ij}(x) = \alpha_i(x) + \alpha_j(x+\hat{i}) - \alpha_i(x+\hat{j}) - \alpha_j(x).$$

: U(1) plaquette

$$G(z) \to \frac{A_\gamma z}{2\beta_G} \frac{ap^2}{\sqrt{p^2+m_\gamma^2}} e^{-z\sqrt{p^2+m_\gamma^2}}$$



('16 D'Onofrio)

A well-motivated guess: $A_\gamma(T) = \cos^2 \theta_{\mathrm{W}}^{\mathrm{eff}}(T)$

To evaluate the baryon asymmetry from the hypermagnetic helicity decay, we need to evaluate the washout effect.

EW sphalerons+chirality flip by electron Yukawa

The rate determining process does not have to be electroweak sphaleron.

Chiral Magnetic Effect ('80 Vilenkin, '08 Fukushima, Kharzeev, &Warringa)

Ampere's law

$$\nabla \times \boldsymbol{B}_Y = \boldsymbol{J} = \underbrace{\sigma(\boldsymbol{E}_Y + \boldsymbol{v} \times \boldsymbol{B}_Y)}_{\text{Ohm's current}} + \underbrace{\frac{2\alpha_Y}{\pi}\mu_5 \boldsymbol{B}_Y}_{\text{Chiral magnetic current}}$$

=> $$\boldsymbol{E}_Y = -\boldsymbol{v} \times \boldsymbol{B}_Y + \frac{1}{\sigma}\left(\nabla \times \boldsymbol{B}_Y - \frac{2\alpha_Y}{\pi}\mu_5 \boldsymbol{B}_Y\right)$$

$$\frac{d}{dt} n_f \ni \#\langle Y_{\mu\nu}\tilde{Y}^{\mu\nu}\rangle \,(= -4\langle \boldsymbol{E}_Y \cdot \boldsymbol{B}_Y\rangle)$$

$$= \#\frac{1}{\sigma}\left(\langle \boldsymbol{B}_Y \cdot (\nabla \times \boldsymbol{B}_Y)\rangle - \frac{2\alpha}{\pi}\boxed{\mu_5}\langle|\boldsymbol{B}_Y|^2\rangle\right)$$

$$= \#\frac{1}{\sigma}\left(\frac{B_p^2}{\lambda_B} - \frac{2\alpha}{\pi}\boxed{\mu_5} B_p^2\right)$$

$$\boxed{\mu_5 = \sum_{f'} (-)^{q_{R/L}} 6 y_{f'}^2 n_{f'}/T^2}$$

Schematically evolution equation is given by

Source term — washout term

$$\frac{dn_B}{dt} = \left(\# \frac{B^2}{\sigma\lambda} + \#\dot{\theta}_W \lambda B^2\right) - \Gamma_{\mathrm{w.o.}} n_B$$

MHD decay — EWSB — EW sphaleron — chirality-flip — CME

Reaches at "terminal" asymmetry…

$$n_B \simeq \frac{\# B^2/\sigma\lambda + \#\dot{\theta}_W \lambda B^2}{\Gamma_{\mathrm{w.o.}}} \quad (\sim \mathcal{H}_Y)$$

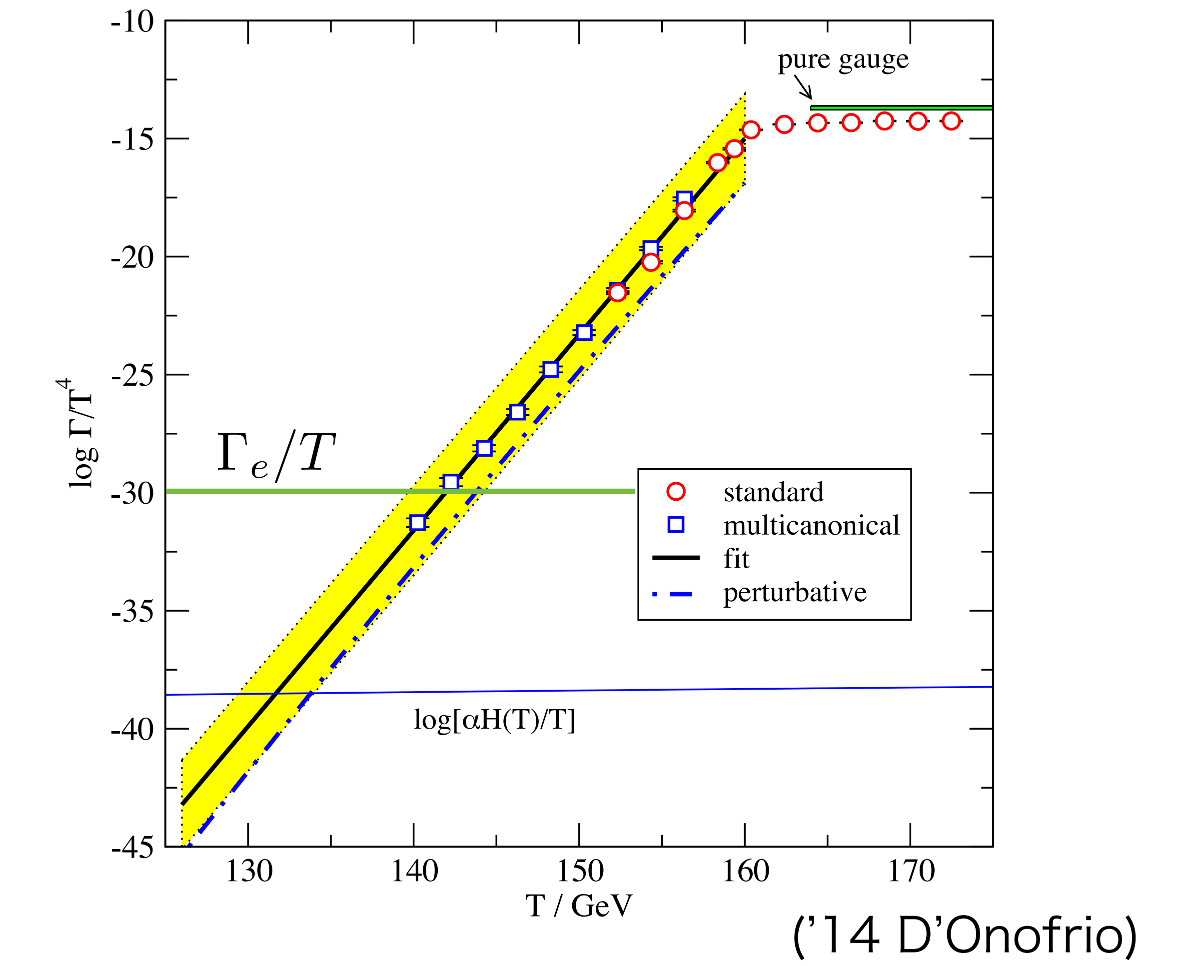
Washout term $\Gamma_{\mathrm{w.o}}$

High temperature (T>140 GeV): electron Yukawa or CME

Low temperature (T<140 GeV): EW sphaleron

Sphaleron rate

$\Gamma_W \simeq \exp[-145 + 0.8(T/\mathrm{GeV})]T$



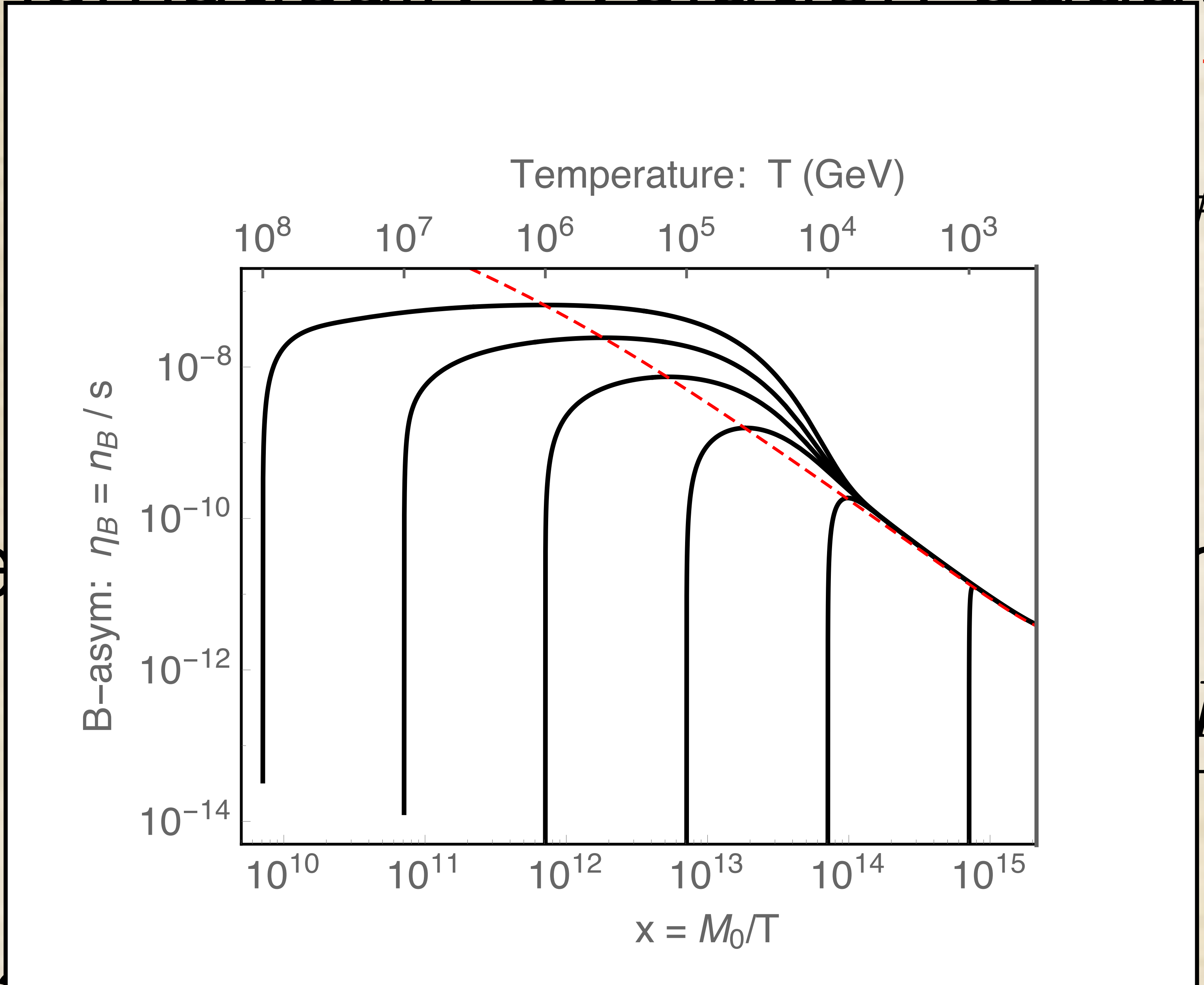
('14 D'Onofrio)

Schematically evolution equation is given by

term washout

$$\#\dot{\theta}_W \lambda B^2\Big) - \Gamma_{\rm w.o.} n$$

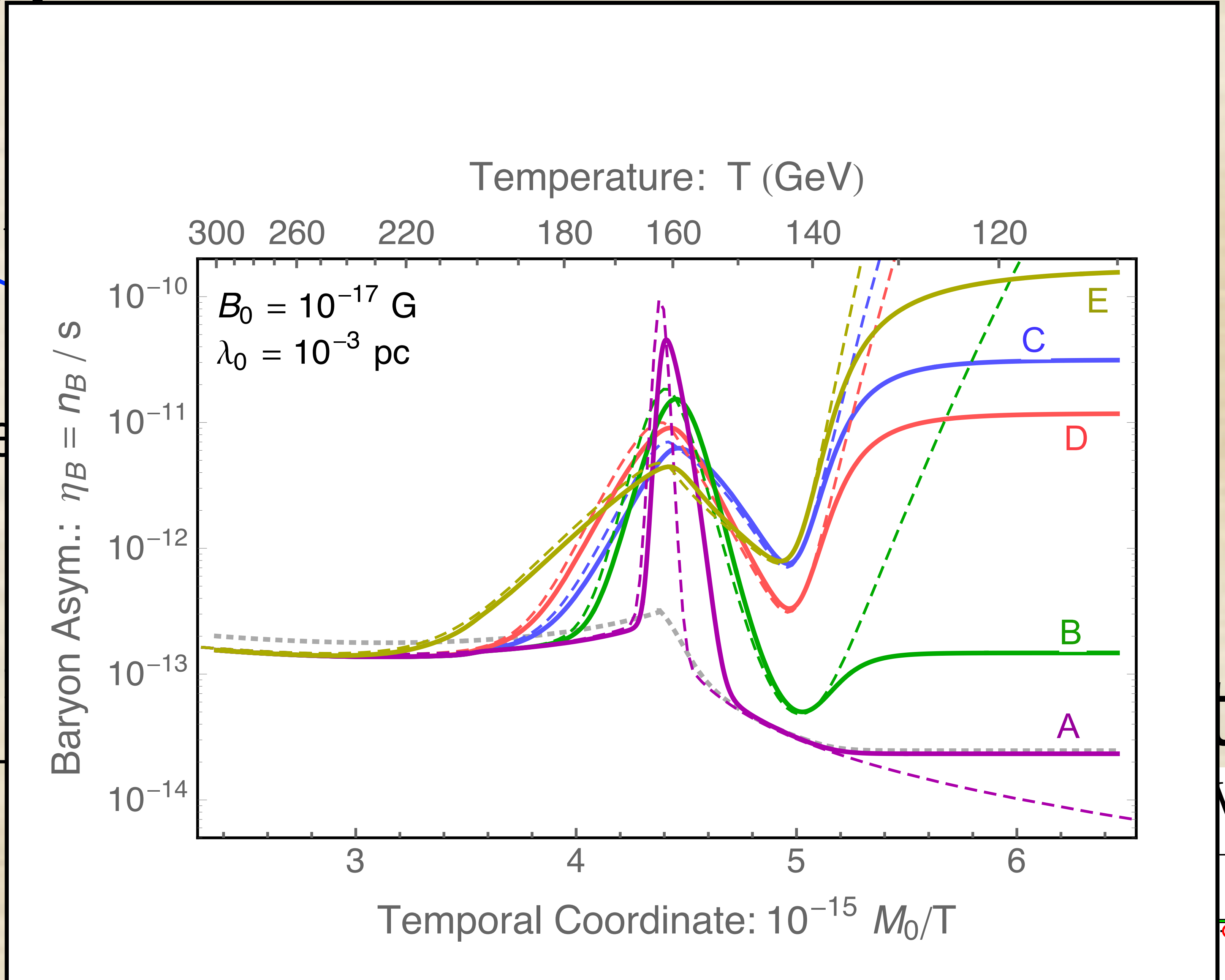
EWSB EW sphale



('16 KK&Long)

Re… …etry⋯

$$\frac{B^2/\sigma\lambda + \#\dot{\theta}_W \lambda B}{\Gamma_{\rm w.o.}}$$



('16 KK&Long)

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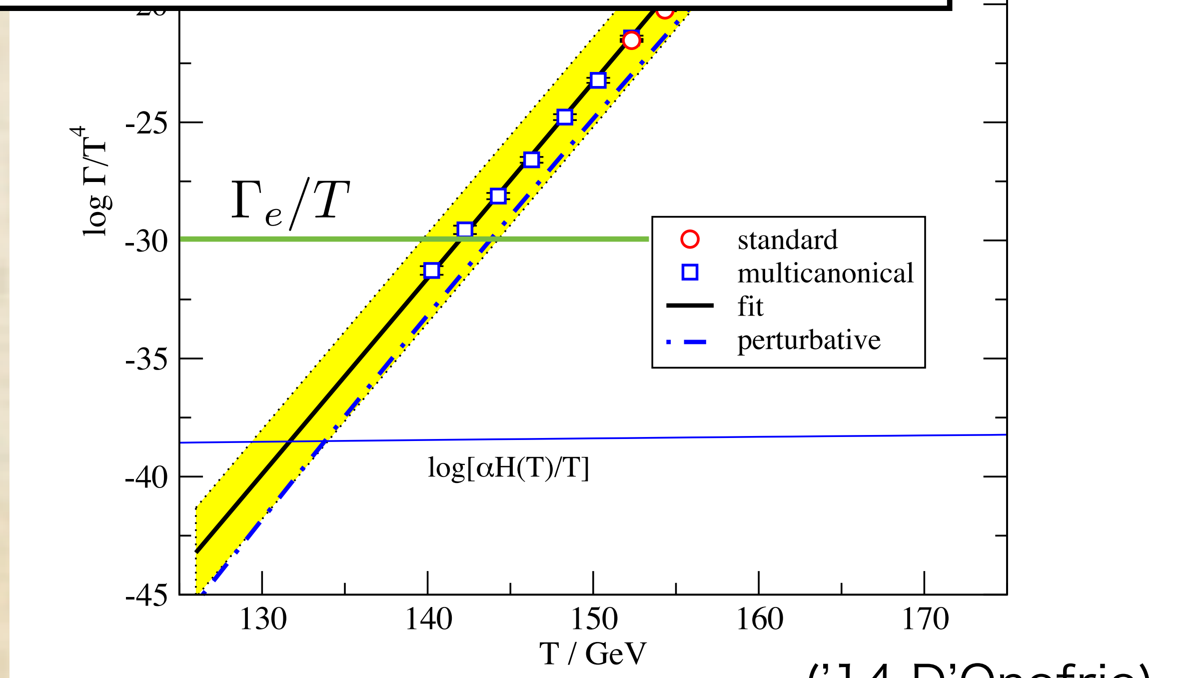
W…



('14 D'Onofrio)

High temperature (T>140 GeV): electron Yukawa or CME

Low temperature (T<140 GeV): EW sphaleron

Subtle issue behind that…

Early EWSB (crossover) completion, late sphaleron freeze out

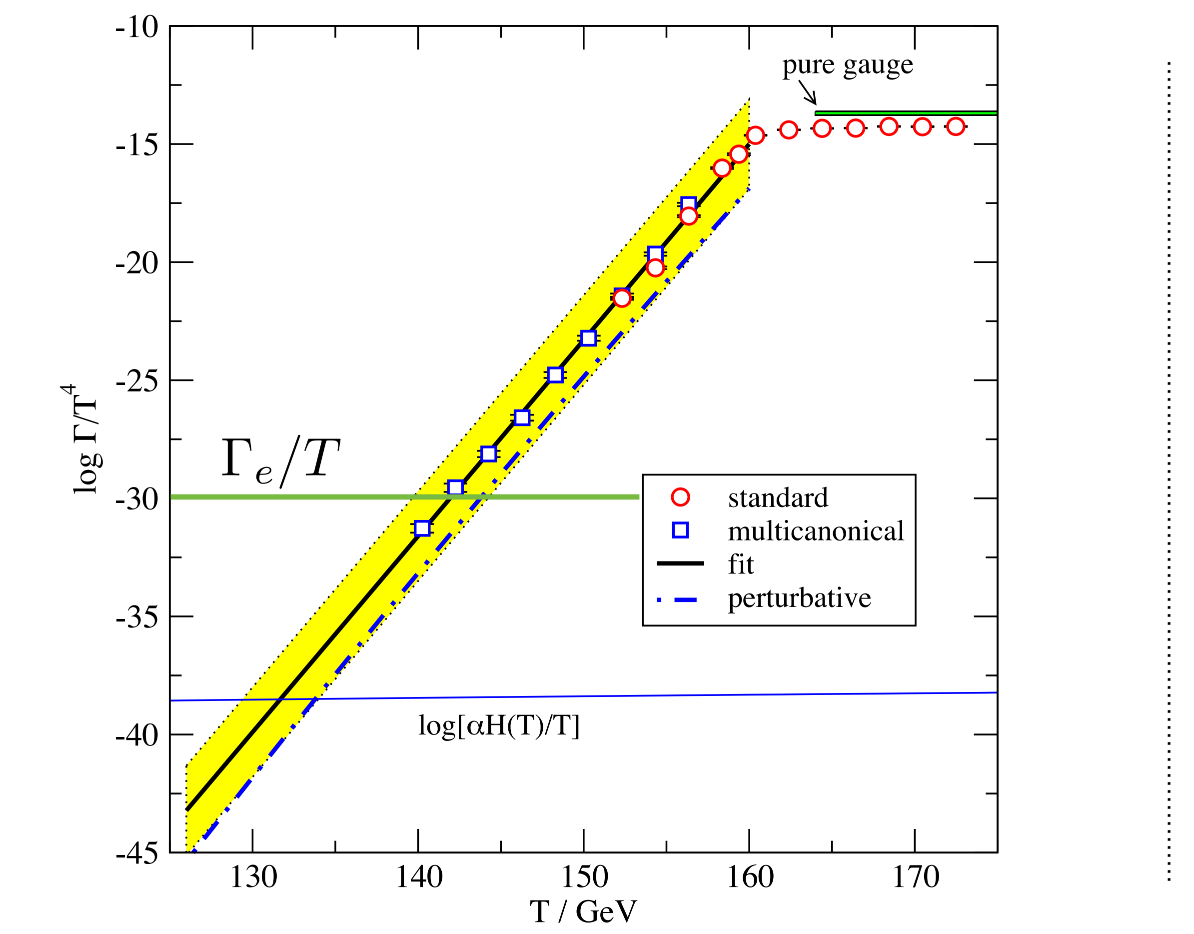
=> Net BAU is suppressed ('98 Giovannini&Shaposhnikov)

Early sphaleron freeze out, late EWSB (crossover) completion

=> Net BAU is efficiently remained

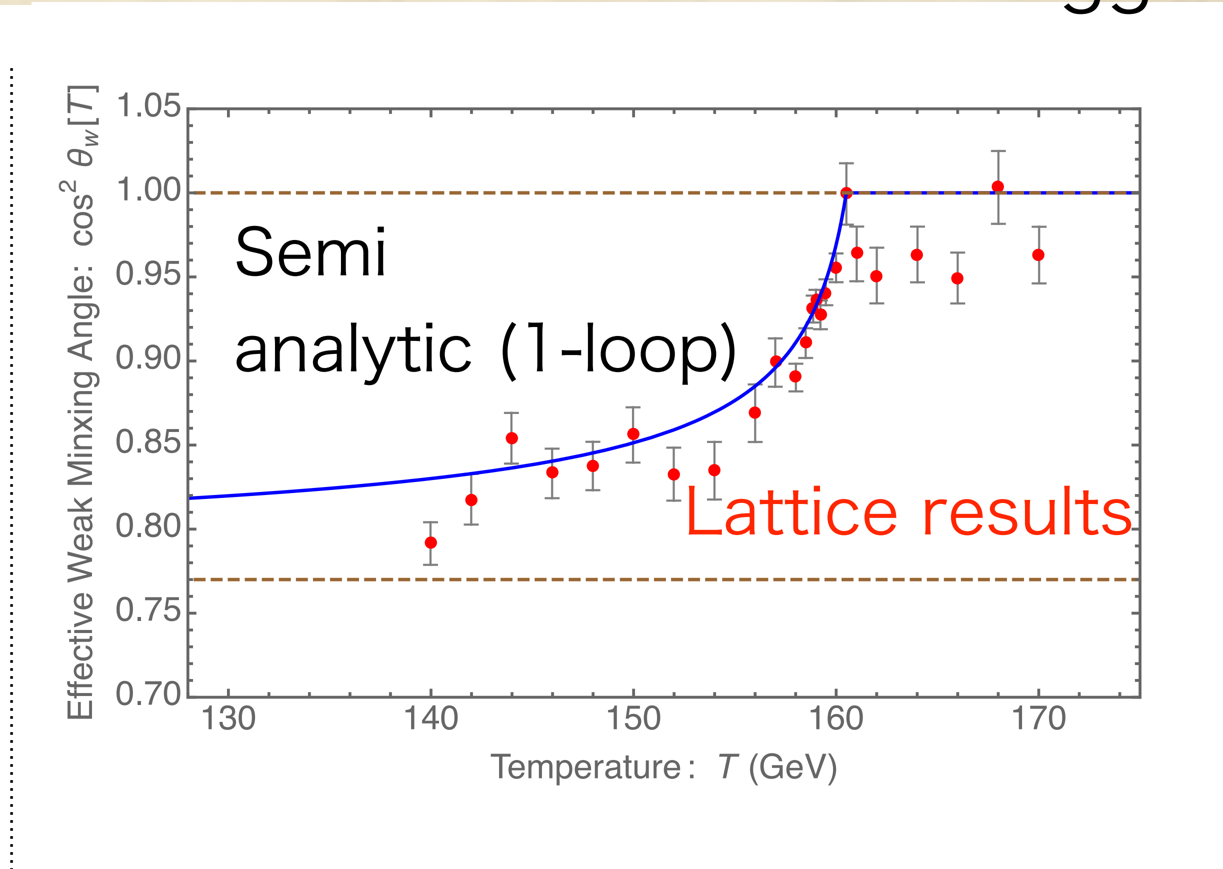
Sphaleron rate

$\Gamma_W \simeq \exp[-145 + 0.8(T/\mathrm{GeV})]T$



('14 D'Onofrio)

lattice simulations for the EW crossover with 125 GeV Higgs



('16 D'Onofrio)

BAU is very likely to remain!

Quantitative results are sensitive to $\theta_W(t)$

Finally analytic formula for the generated average baryon asymmetry is given.

$$\Delta\overline{\eta_B} \simeq 10^{-10}\,\epsilon f(T,\theta_{\rm w})\left(\frac{\lambda}{10^6{\rm GeV}^{-1}}\right)\left(\frac{\overline{B}}{10^{-3}{\rm GeV}^2}\right)^2\Bigg|_{T=135{\rm GeV}}$$

$$f(T,\theta_{\rm w}) \equiv -\sin 2\theta_{\rm w} T\frac{d\theta_{\rm w}}{dT}(\simeq 0.1) \quad \text{at} \quad T\simeq 135{\rm GeV}$$

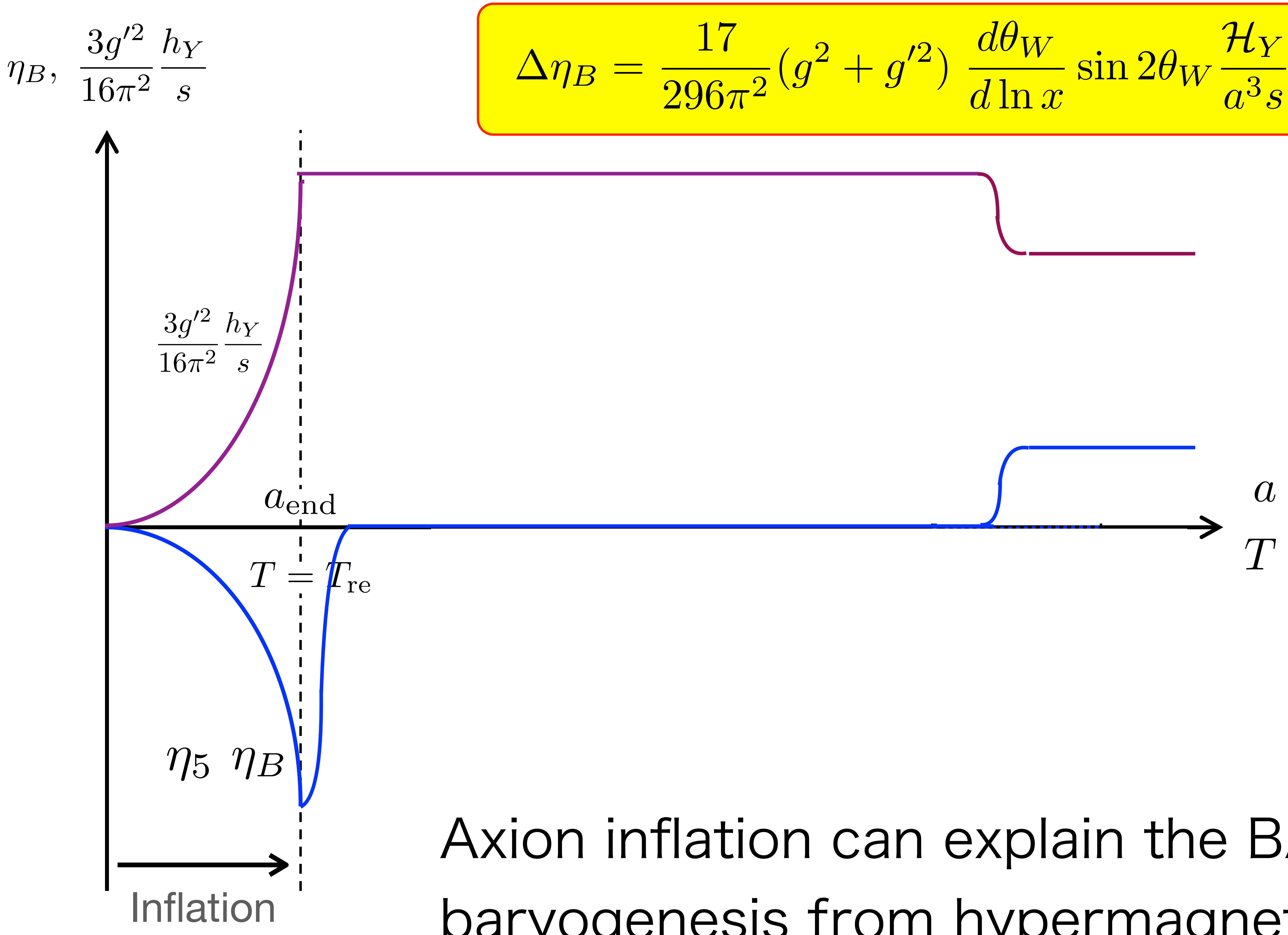
perturbative/Fitting C-E

Magnetogenesis with positive helicity before EWSB.

→ With appropriate properties of hyper MFs, present BAU can be explained.

※Since helicity is just the difference between the right and left helicity modes, the sign of helicity can be the same beyond the coherence length of MFs.

$$\Delta\eta_B = \frac{17}{296\pi^2}(g^2 + g'^2)\,\frac{d\theta_W}{d\ln x}\,\sin 2\theta_W\,\frac{\mathcal{H}_Y}{a^3 s}\bigg|_{T\simeq 135\mathrm{GeV}}$$



Axion inflation can explain the BAU through baryogenesis from hypermagnetic helicity decay!

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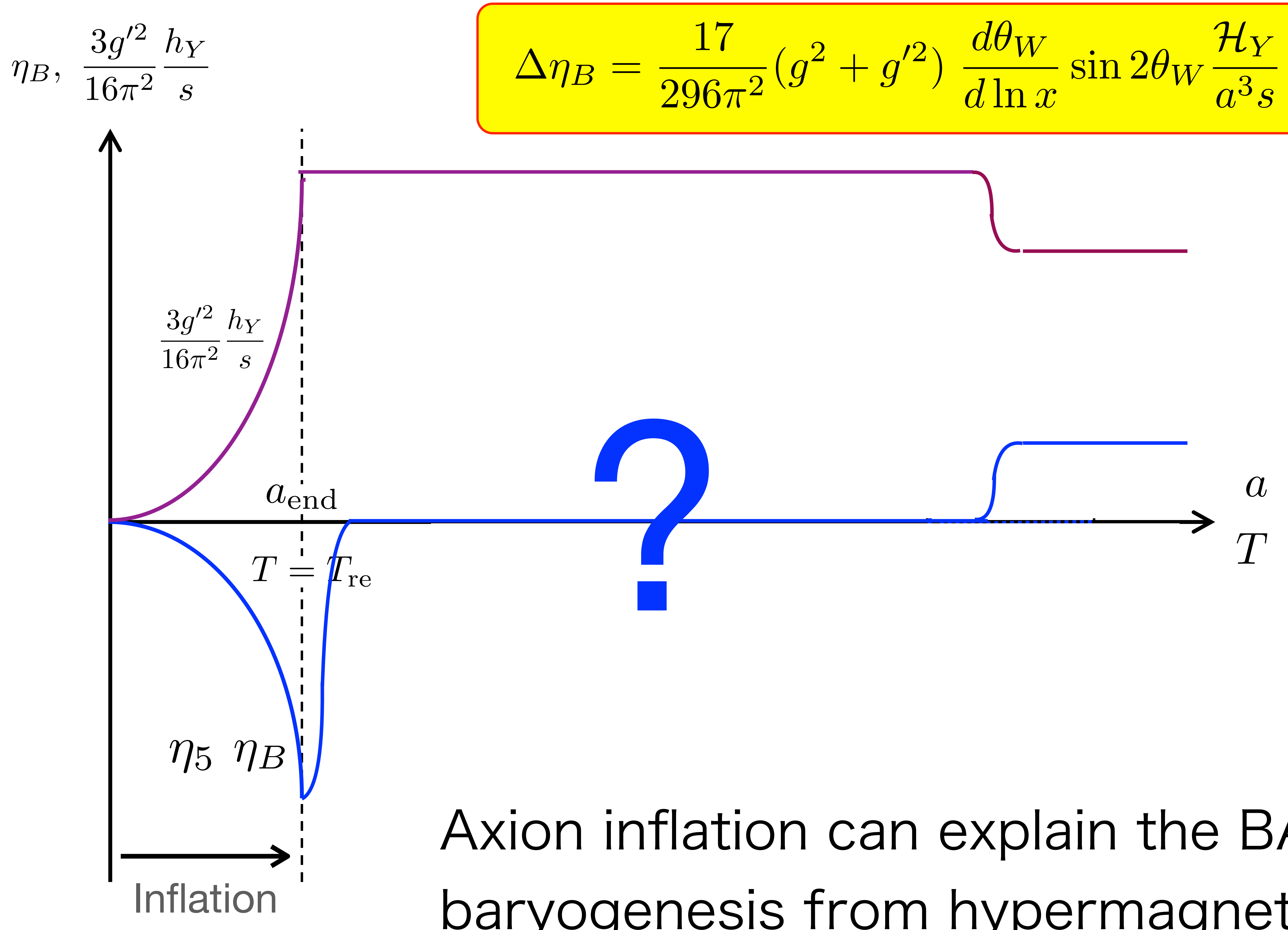
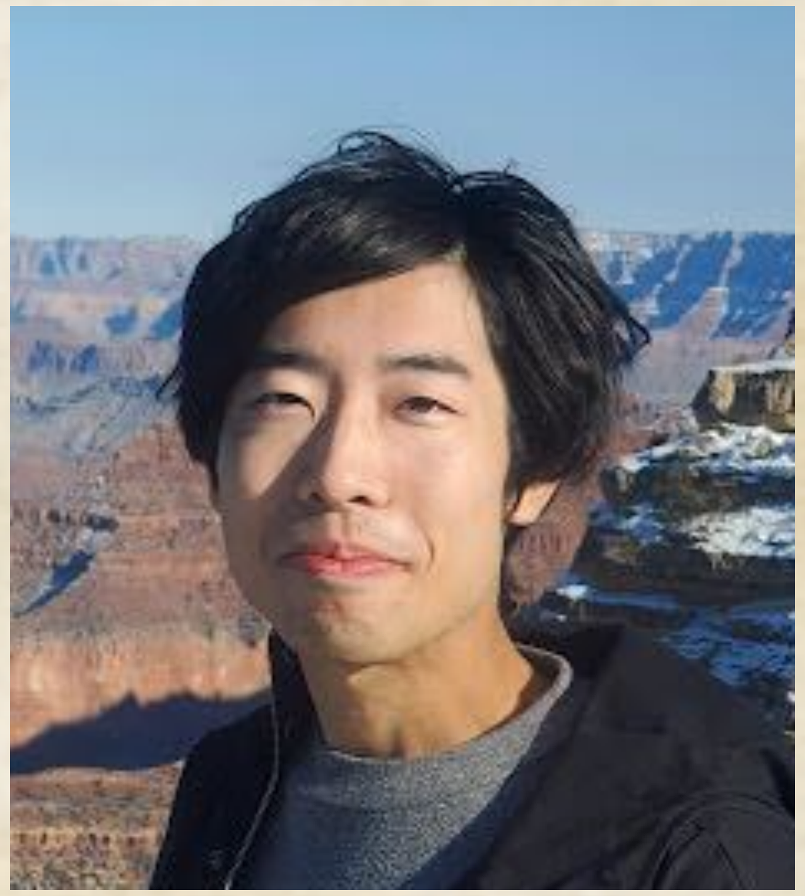


Axion inflation can explain the BAU through baryogenesis from hypermagnetic helicity decay?



Baryon isocurvature constraints

a.k.a. Uchida bound

KK, F. Uchida, J. Yokoyama (Tokyo), JCAP 04 (2021) 034 [arXiv: 2012.14435 (astro-ph.CO)]

Baryon asymmetry is generated
in response to magnetic fields with a certain correlation length,
regardless of its generation mechanism.

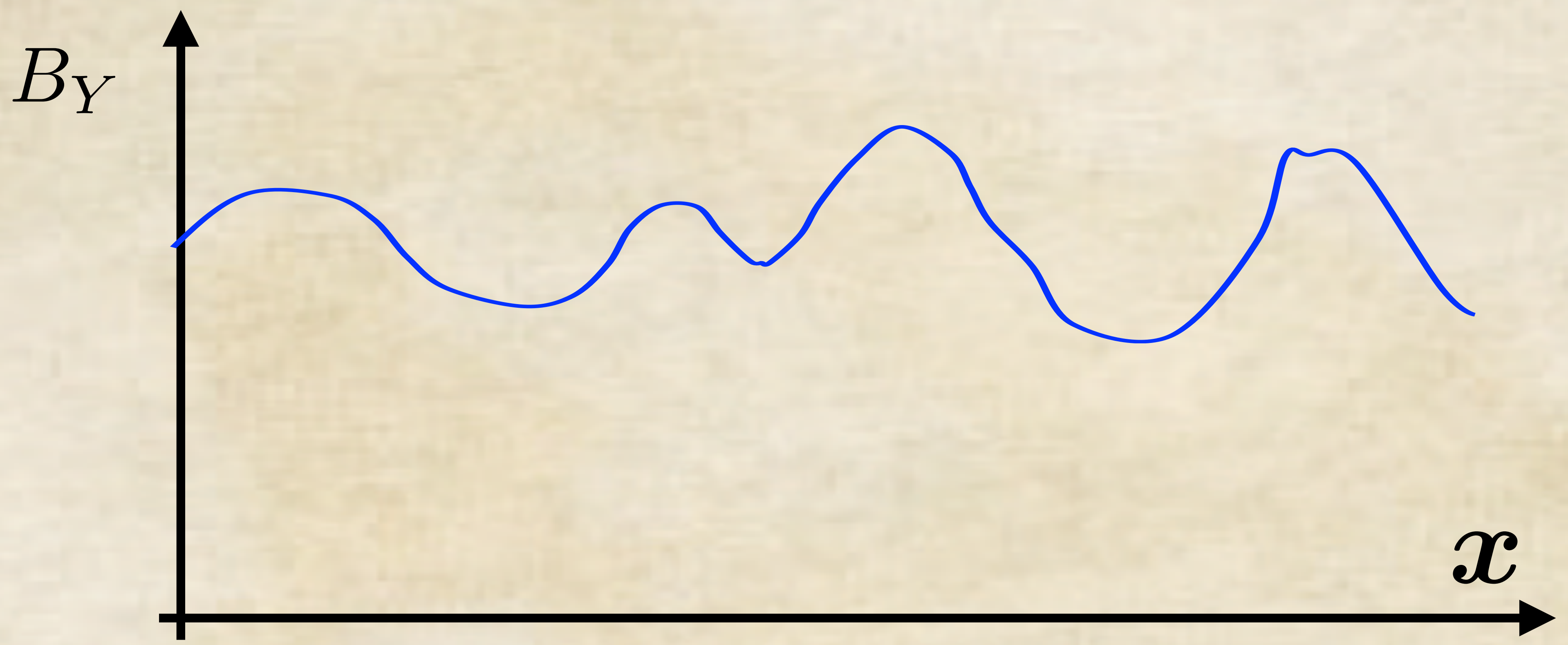
=> We can give a generic constraints on magnetic fields
from the baryon isocurvature perturbation.

Indeed, it gives a constraint even for non-helical magnetic fields.

Basic idea

Baryon asymmetry evaluated thus far is the spatially-averaged one

=> We expect that it has spatial dependence (“baryon isocurvature perturbation”) according to the spatial distributions of hypermagnetic fields.



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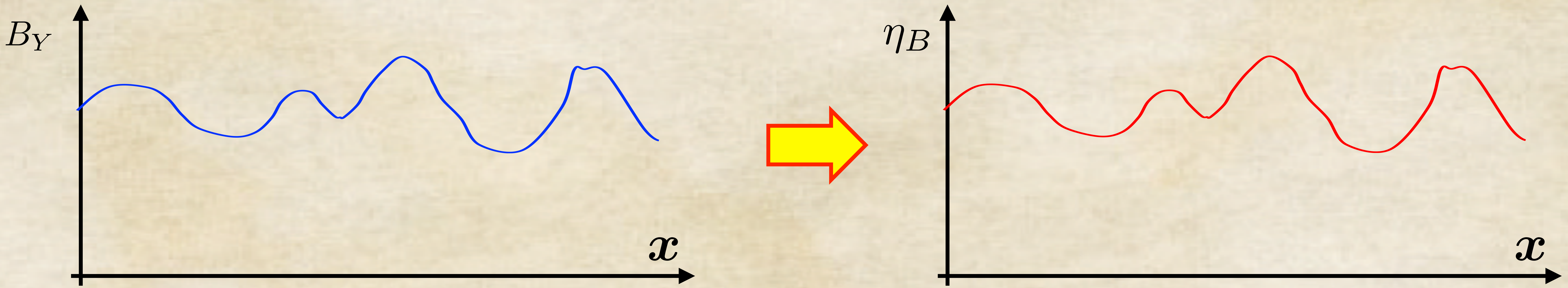
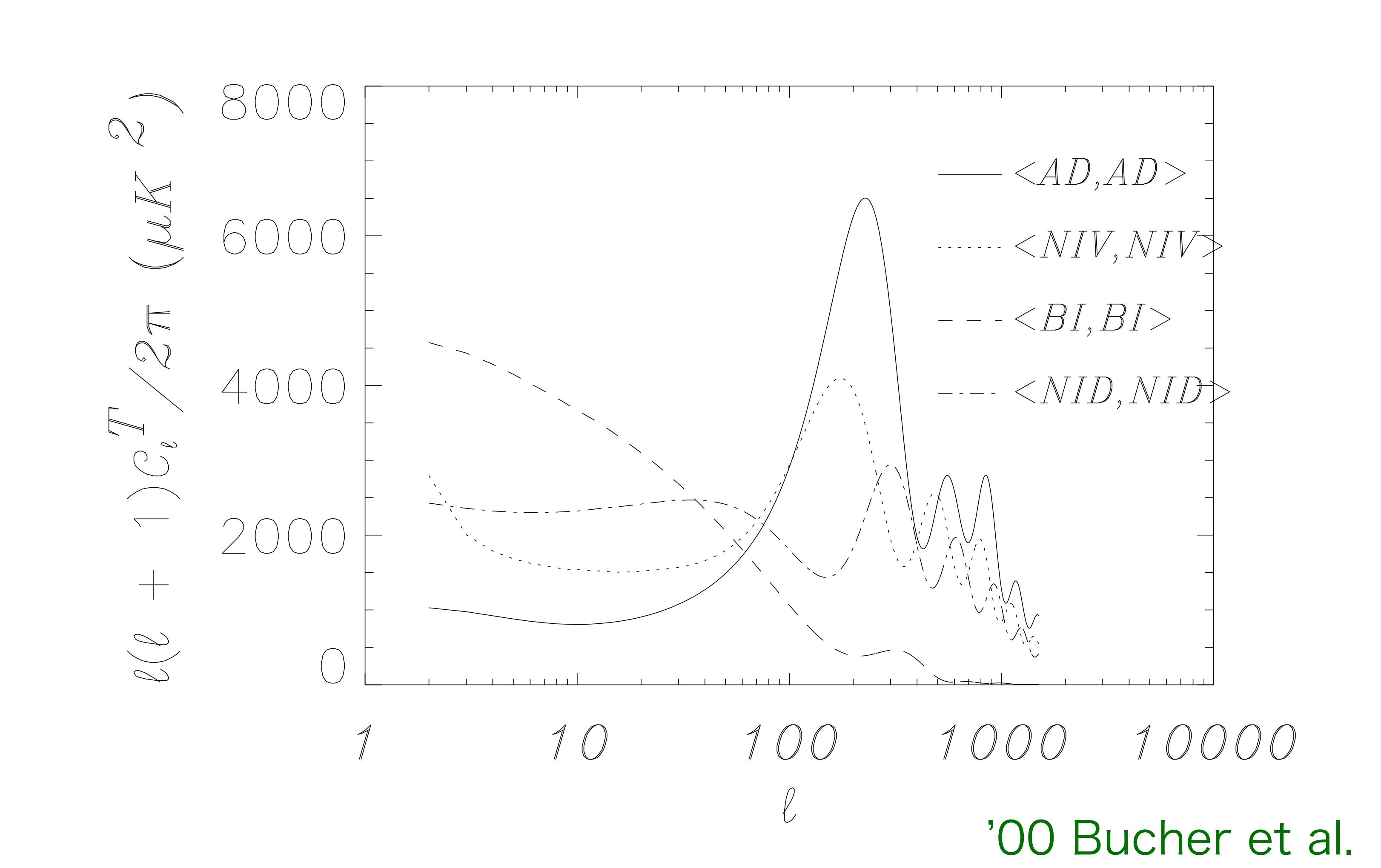


constrained by observations?

Observational constraints on the baryon isocurvature perturbations

Mpc scales: CMB gives constraints.



$$\beta_{\rm iso} \equiv \frac{\mathcal{P}_{II}}{\mathcal{P}_{\mathcal{R}\mathcal{R}} + \mathcal{P}_{II}} \lesssim 0.49 \quad @k = 0.1{\rm Mpc}^{-1}$$

'18 Planck

Observational constraints on the baryon isocurvature perturbations

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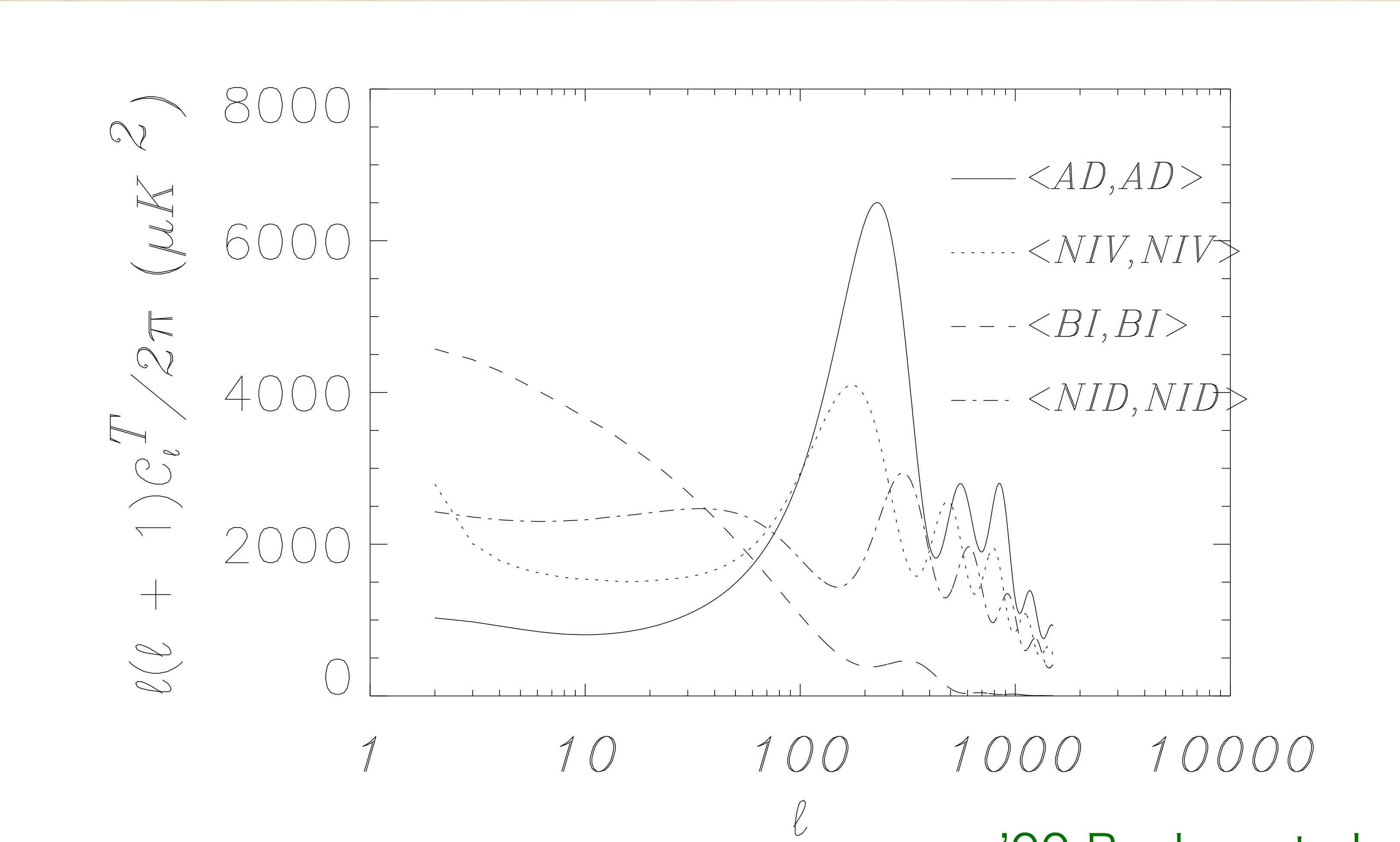


'00 Bucher et al.

$$\beta_{\rm iso} \equiv \frac{\mathcal{P}_{II}}{\mathcal{P}_{\mathcal{RR}} + \mathcal{P}_{II}} \lesssim 0.49 \quad @k = 0.1{\rm Mpc}^{-1}$$

'18 Planck

Much smaller scales: Inhomogeneous BBN

'87 Applegate+, Alock+

Baryon fluctuation with the scale larger than the neutron diffusion scale remains at BBN epoch and changes the prediction of light elements.

'08 Pisanti+, '15 Planck

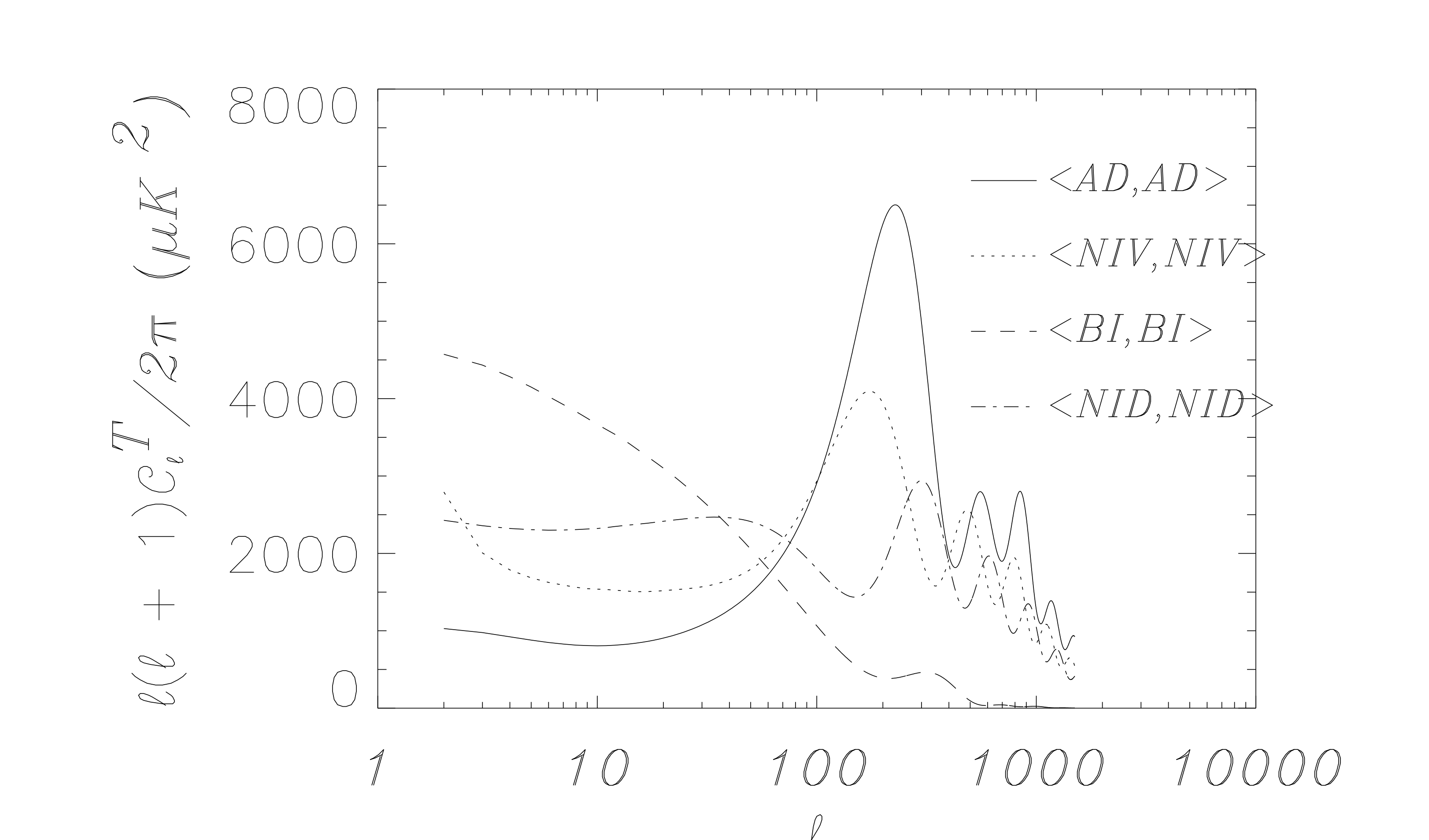
$$10^5 ({\rm D/H})_p = 18.754 - 1534.4\,\omega_B + 48656\,\omega_B^2 - 552670\,\omega_B^3,$$

$$\omega_B = \Omega_B h^2$$

$$\overline{\omega}_B{}^2 + \langle \delta\omega_B^2 \rangle$$

Observational constraints on the baryon isocurvature perturbations

Mpc scales: CMB gives constraints.



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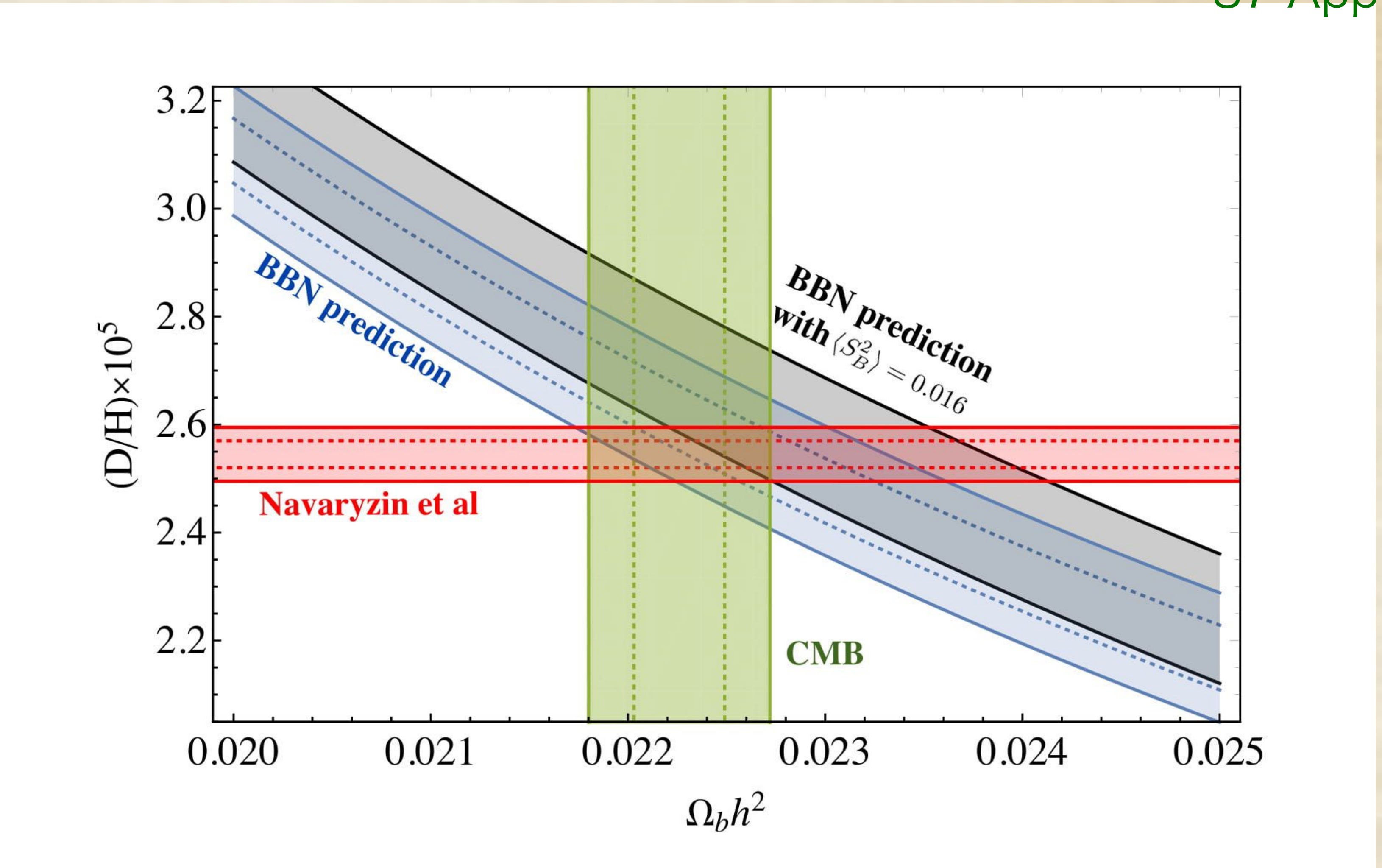

$$\langle S^2_{B,\rm BBN}\rangle = \frac{\langle \delta\eta^2_{B,\rm BBN}(\boldsymbol{x})\rangle}{\overline{\eta_B}^2} = \frac{1}{V}\int \frac{d^3k}{(2\pi)^3}\mathcal{P}^{\rm BBN}_{\delta B} < 0.016$$

'18 Inomata +

Baryon isocurvature perturbations from hypermagnetic fields at EWSB

$$\eta_{B,\mathrm{EW}}(\boldsymbol{x}) = \mathcal{C}\boldsymbol{Y}(\boldsymbol{x})\cdot\boldsymbol{B}_Y(\boldsymbol{x})(=\mathcal{C}\mathcal{H}_Y(\boldsymbol{x})) \Rightarrow \langle\delta\eta_{B,\mathrm{EW}}(\boldsymbol{x})\delta\eta_{B,\mathrm{EW}}(\boldsymbol{x}+\boldsymbol{r})\rangle = \mathcal{C}^2\langle\boldsymbol{Y}(\boldsymbol{x})\cdot\boldsymbol{B}_Y(\boldsymbol{x})\boldsymbol{Y}(\boldsymbol{x}+\boldsymbol{r})\cdot\boldsymbol{B}_Y(\boldsymbol{x}+\boldsymbol{r})\rangle - \overline{\eta_{B,\mathrm{EW}}}^2$$

Fourier transform

$$\mathcal{G}(\boldsymbol{k}) = \frac{\mathcal{C}^2}{\overline{\eta}_B^2}\int\frac{d^3p}{(2\pi)^3}\left[p^2 S(|\boldsymbol{k}-\boldsymbol{p}|)S(p) + |\boldsymbol{k}-\boldsymbol{p}|pA(|\boldsymbol{k}-\boldsymbol{p}|)A(p)\right]\times\left[1-\frac{2(\boldsymbol{k}-\boldsymbol{p})\cdot\boldsymbol{p}}{p^2}+\frac{((\boldsymbol{k}-\boldsymbol{p})\cdot\boldsymbol{p})^2}{|\boldsymbol{k}-\boldsymbol{p}|^2p^2}\right].$$

Two-point function has nonzero value even for non-helical magnetic fields!

'98 Giovannini & Shaposhnikov

Baryon isocurvature perturbations from hypermagnetic fields at EWSB

$$\eta_{B,\mathrm{EW}}(\boldsymbol{x}) = \mathcal{C}\boldsymbol{Y}(\boldsymbol{x})\cdot\boldsymbol{B}_Y(\boldsymbol{x})(=\mathcal{C}\mathcal{H}_Y(\boldsymbol{x})) \Rightarrow \langle\delta\eta_{B,\mathrm{EW}}(\boldsymbol{x})\delta\eta_{B,\mathrm{EW}}(\boldsymbol{x}+\boldsymbol{r})\rangle = \mathcal{C}^2\langle\boldsymbol{Y}(\boldsymbol{x})\cdot\boldsymbol{B}_Y(\boldsymbol{x})\boldsymbol{Y}(\boldsymbol{x}+\boldsymbol{r})\cdot\boldsymbol{B}_Y(\boldsymbol{x}+\boldsymbol{r})\rangle - \overline{\eta_{B,\mathrm{EW}}}^2$$

Fourier transform

$$\mathcal{G}(\boldsymbol{k}) = \frac{\mathcal{C}^2}{\overline{\eta}_B^2}\int\frac{d^3p}{(2\pi)^3}\left[p^2 S(|\boldsymbol{k}-\boldsymbol{p}|)S(p) + |\boldsymbol{k}-\boldsymbol{p}|p A(|\boldsymbol{k}-\boldsymbol{p}|)A(p)\right]\times\left[1 - \frac{2(\boldsymbol{k}-\boldsymbol{p})\cdot\boldsymbol{p}}{p^2} + \frac{((\boldsymbol{k}-\boldsymbol{p})\cdot\boldsymbol{p})^2}{|\boldsymbol{k}-\boldsymbol{p}|^2p^2}\right].$$

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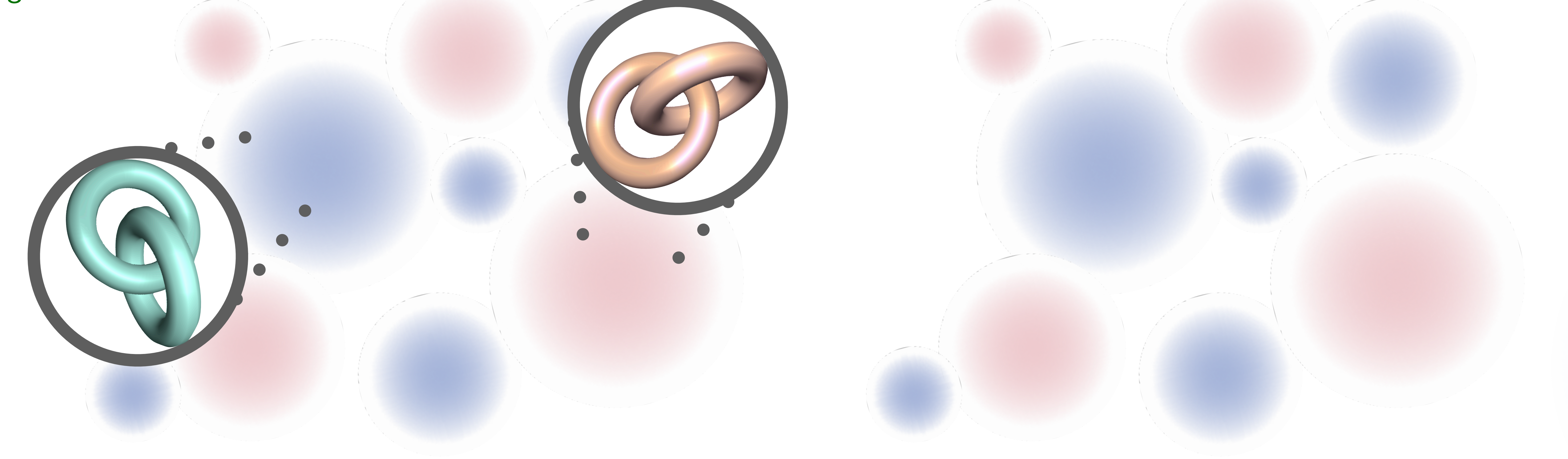
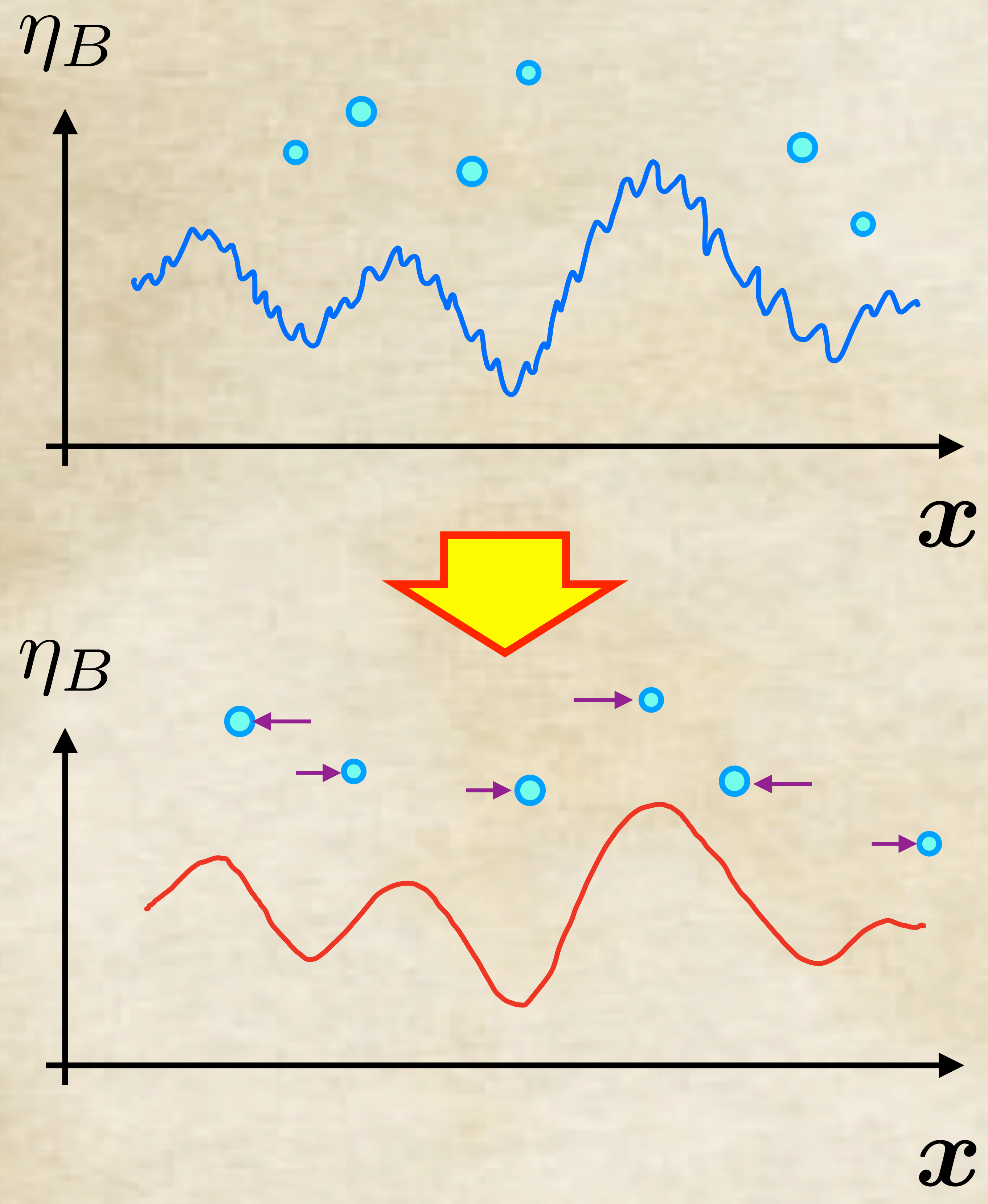
Figure from F. Uchida Ph. D thesis



magnetic helicity density baryon number density at EWSB

Baryon isocurvature perturbations at BBN

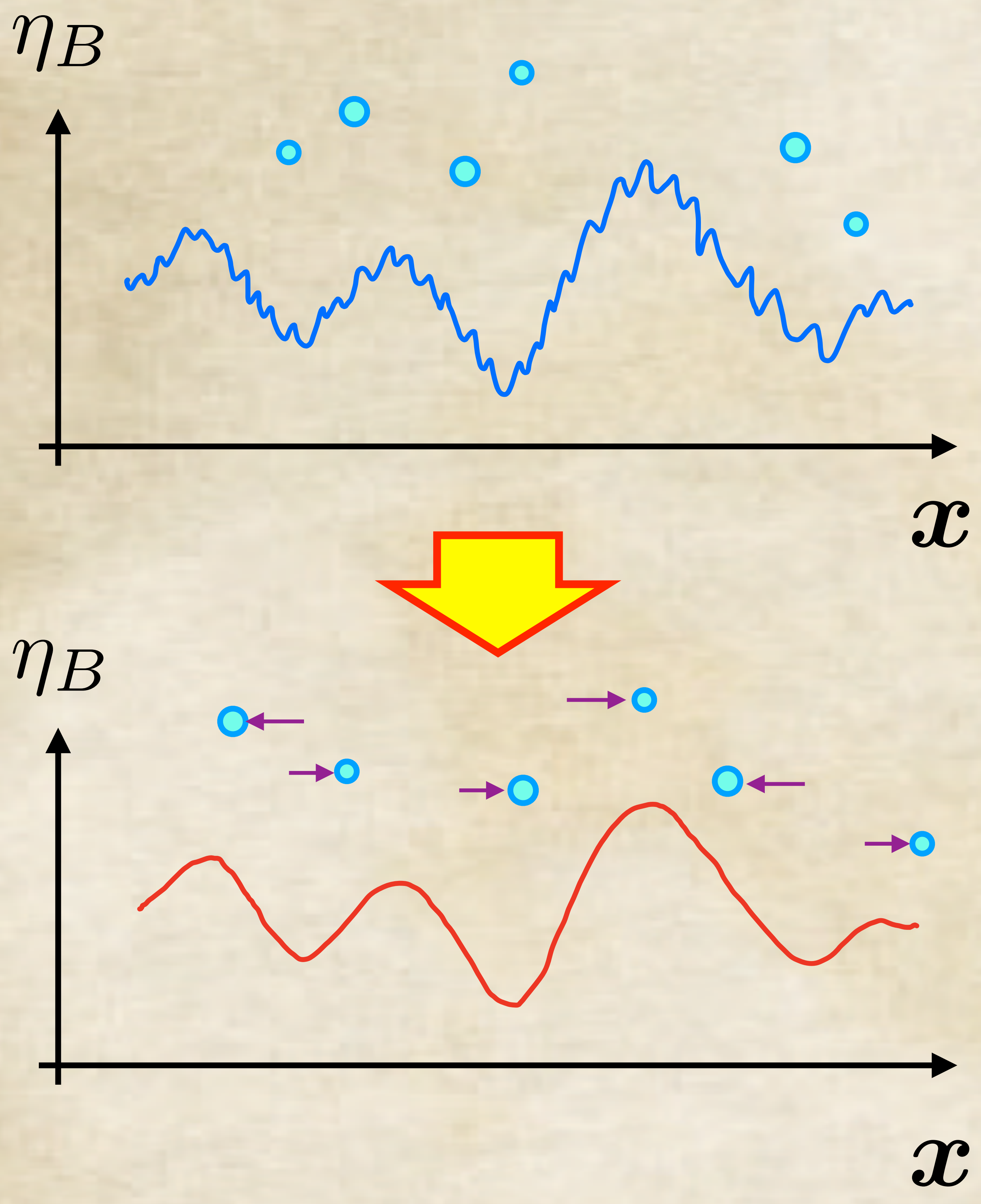
… Neutron diffusion erases the small scale inhomogeneities.



Baryon isocurvature perturbations at BBN

⋯ Neutron diffusion erases the small scale inhomogeneities.

=> Corresponds to the treatment that the baryon asymmetry is convoluted with the Gaussian window function.



$$\langle S^2_{B,\mathrm{BBN}} \rangle = \int \frac{d^3 k}{(2\pi)^3} e^{-\frac{k^2}{3k_\mathrm{d}^2}} \mathcal{G}(\boldsymbol{k})$$

neutron diffusion scale: $k_\mathrm{d}^{-1} = 0.0025\mathrm{pc}$

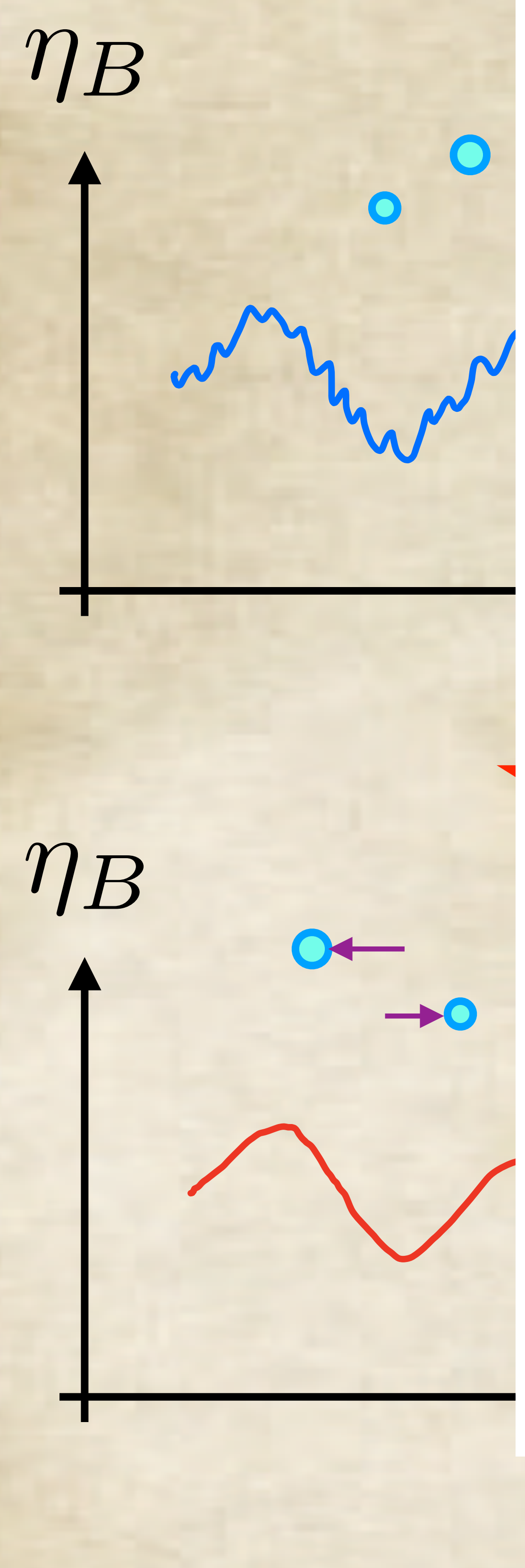
$$= \frac{\mathcal{C}^2}{4\pi^4 \bar{\eta}_B^2} \int dk_1 dk_2 k_1^2 k_2^2 \sum_\pm \left(\pm \left\{ \frac{(k_1 \pm k_2)^2}{2} [S(k_1)S(k_2) \pm A(k_1)A(k_2)] \frac{3k_\mathrm{d}^2}{3k_1 k_2} \left(1 \mp \frac{3k_\mathrm{d}^2}{2k_1 k_2}\right) + \left[\frac{k_1^2 + k_2^2}{2} S(k_1)S(k_2) + k_1 k_2 A(k_1)A(k_2)\right] \left(\frac{3k_\mathrm{d}^2}{2k_1 k_2}\right)^3 \right\} \exp\left[-\frac{2(k_1 \mp k_2)^2}{3k_\mathrm{d}^2}\right] \right).$$

For given the MF spectra ($S(k)$, $A(k)$), we can evaluate the baryon isocurvature perturbation at BBN.

=> BBN constraint $\langle S^2_{B,\mathrm{BBN}} \rangle < 0.016$ can be given with respect to any MF spectra :)

Baryon isc… …try

… Ne…



$_{\mathrm{d}}^{-1} = 0.0025\mathrm{pc}$

$\left(1 \mp \frac{3k_{\mathrm{d}}^2}{2k_1k_2}\right)$

$\Big\} \exp\left[-\frac{2(k_1 \mp k_2)^2}{3k_{\mathrm{d}}^2}\right]\Big) .$

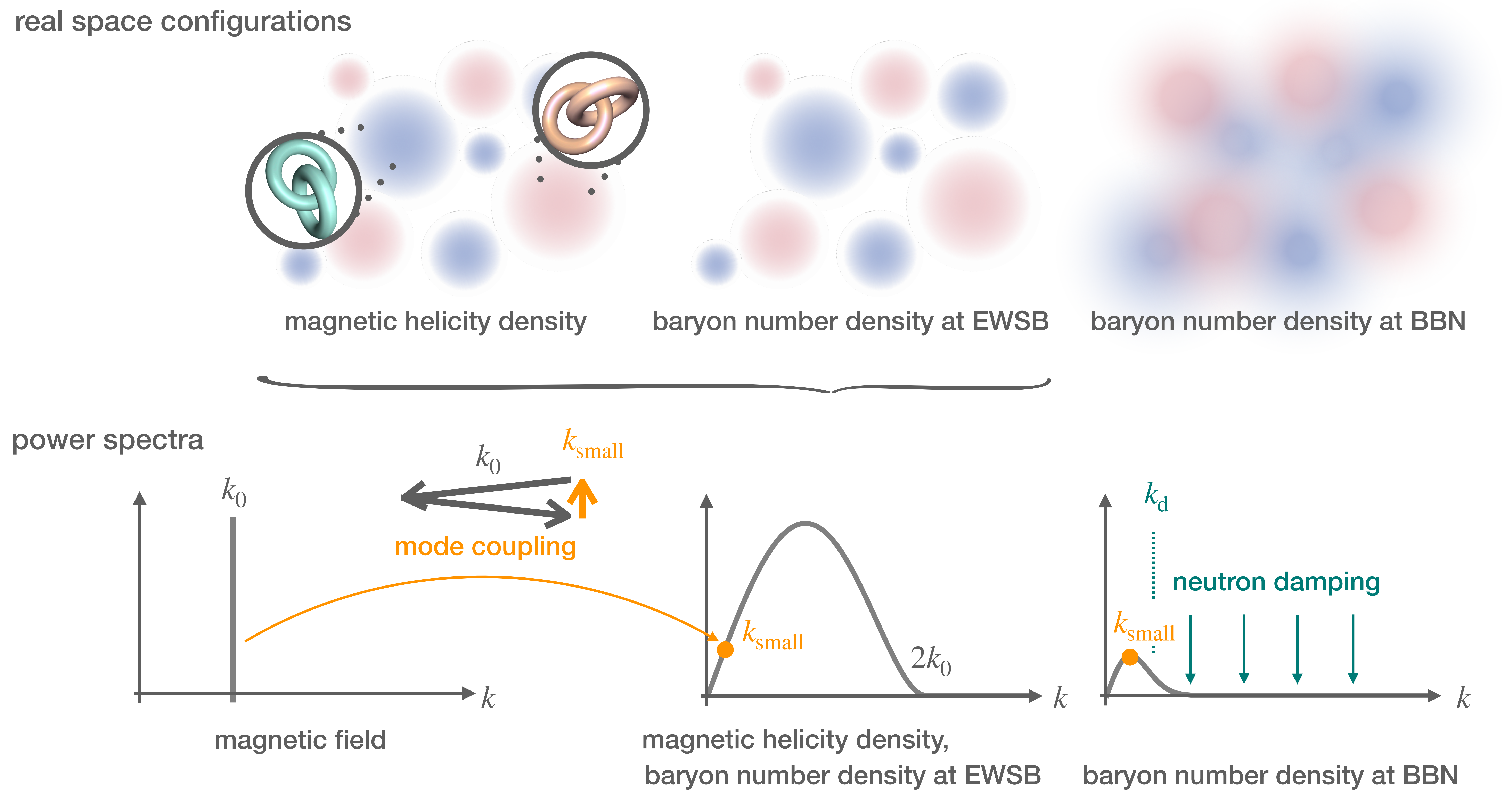


Figure from F. Uchida Ph. D thesis

=> BBN constraint $\langle S_{B,\mathrm{BBN}}^2 \rangle < 0.016$ can be given with respect to any MF spectra :)

Some general features:

- BBN constrains the ensemble average of baryon isocurvature perturbations

$$\langle S^2_{B,\mathrm{BBN}} \rangle < 0.016$$

=> perturbations at all the scales up to the present Hubble scale matters.

- Baryon isocurvature perturbation at small scale, $k > k_{\mathrm{d}}$, at the EWSB becomes smaller by the neutron diffusion until BBN, but is not completely washed out.

Constraints on peaky MF spectra

$$\rho_{B,\mathrm{c}} \simeq \frac{1}{2} B_{\mathrm{c,fo}}^2, \quad \lambda_{\mathrm{c,fo}} \simeq k_\sigma^{-1}, \quad \mathcal{H}_Y = \epsilon_{\mathrm{fo}} \lambda_{\mathrm{c,fo}} B_{\mathrm{c,fo}}$$

- delta-function model: $S(k) = \pi^2 \frac{B_{\mathrm{c,fo}}^2}{k_\sigma^4} \delta(k - k_\sigma), \quad A(k) = \epsilon_{\mathrm{fo}} S(k),$

- power-law with exponential UV cutoff: $S(k) = \frac{2\pi^2}{\Gamma(\frac{5+\alpha}{2})} \frac{B_{\mathrm{c,fo}}^2}{k_\sigma^5} \left(\frac{k}{k_\sigma}\right)^\alpha \exp\left[-\left(\frac{k}{k_\sigma}\right)^2\right], \quad A(k) = \epsilon_{\mathrm{fo}} S(k).$ $(\alpha > -5/2)$

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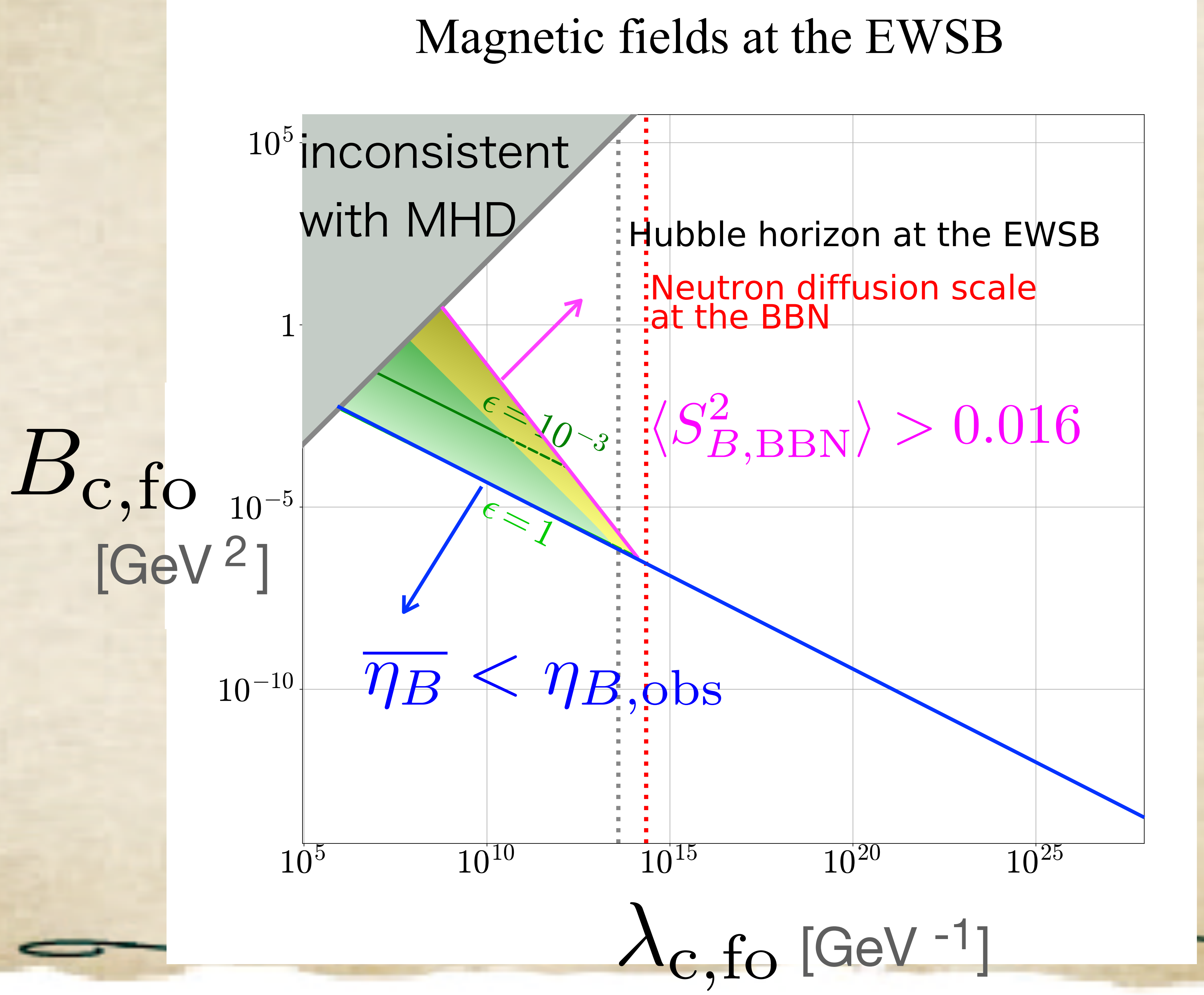
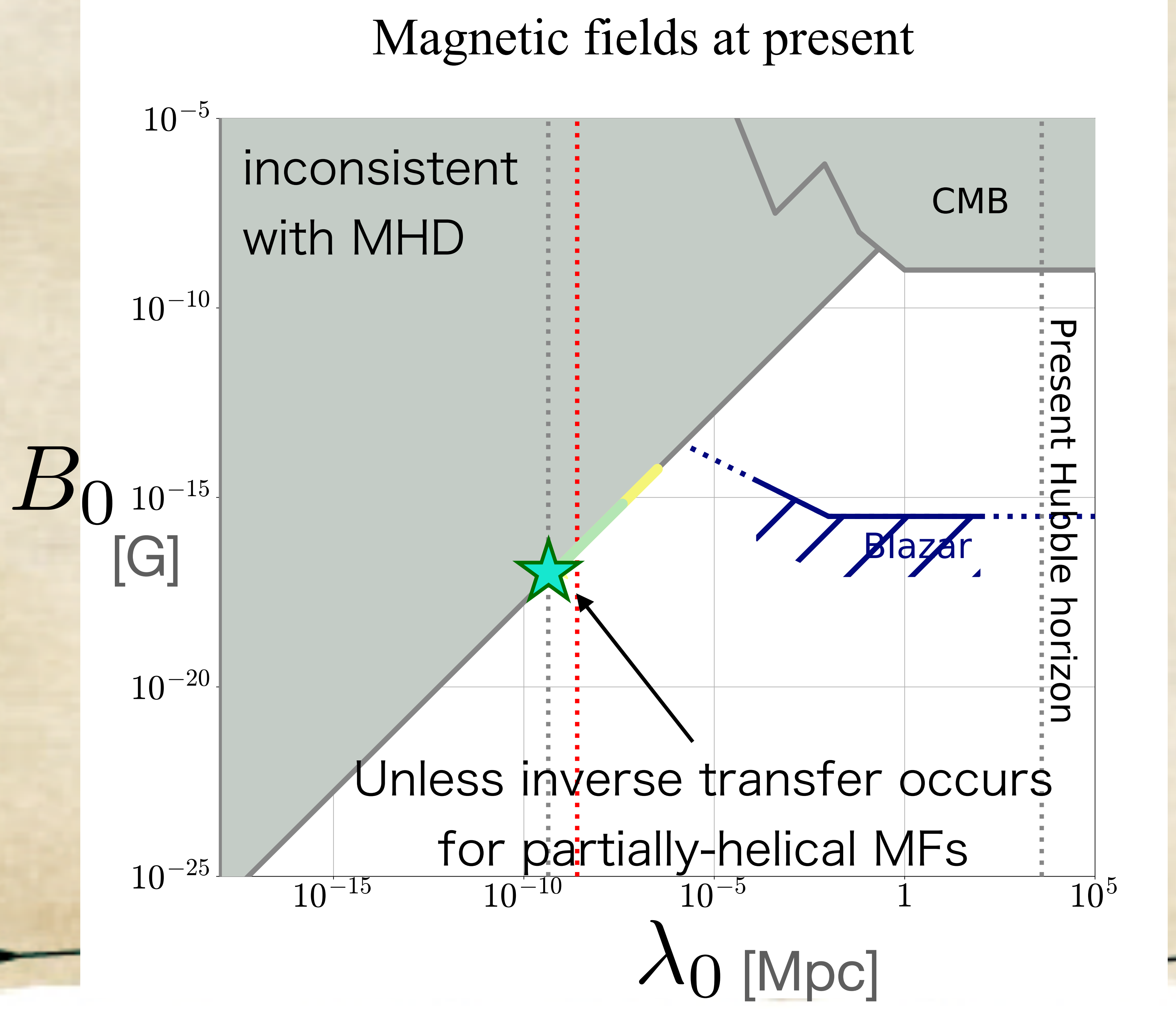
If you would like to explain the BAU···



MF evolution with cascade being taken into account



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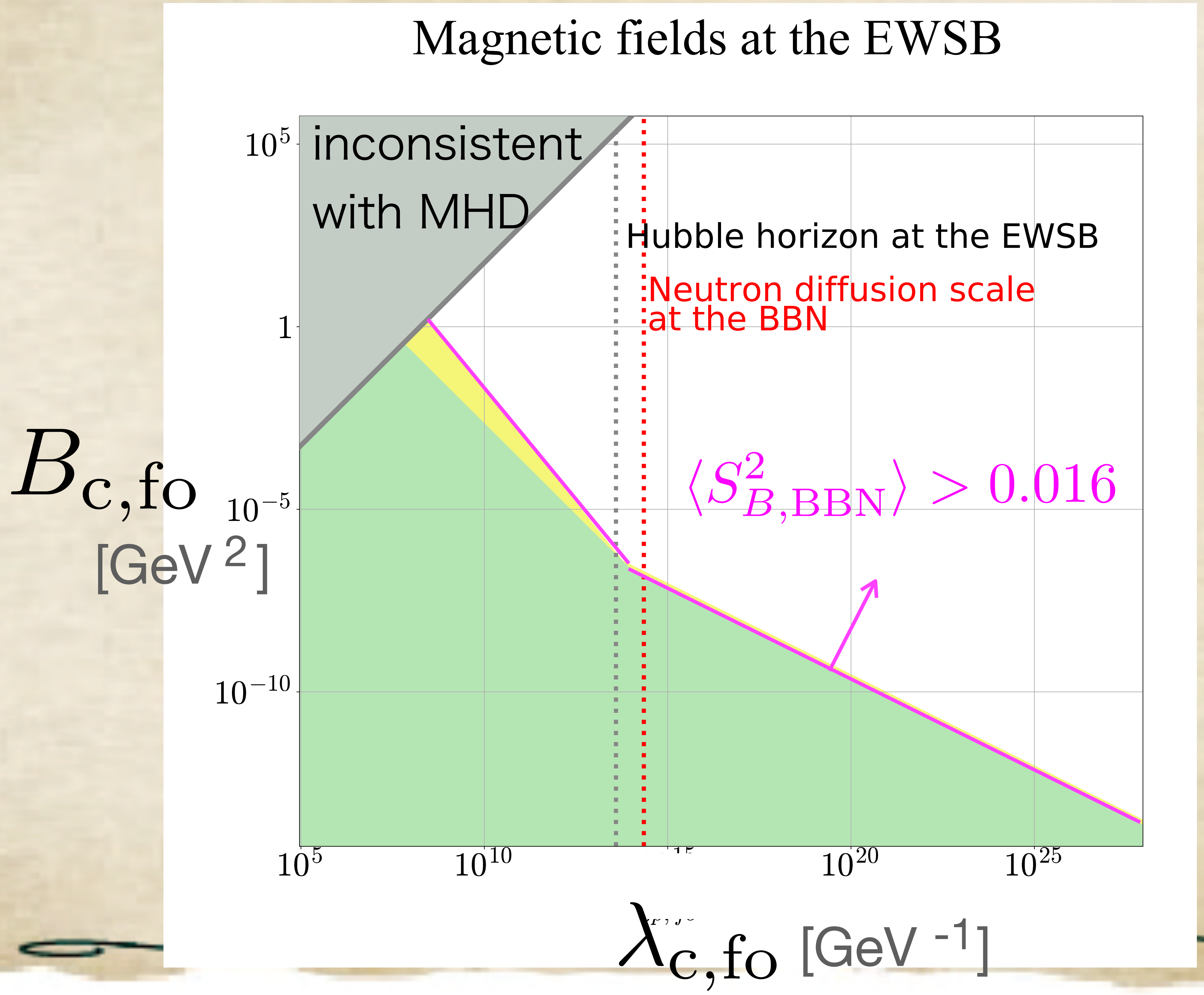
$(\alpha > -5/2)$

For non-helical MFs, forgetting about BAU



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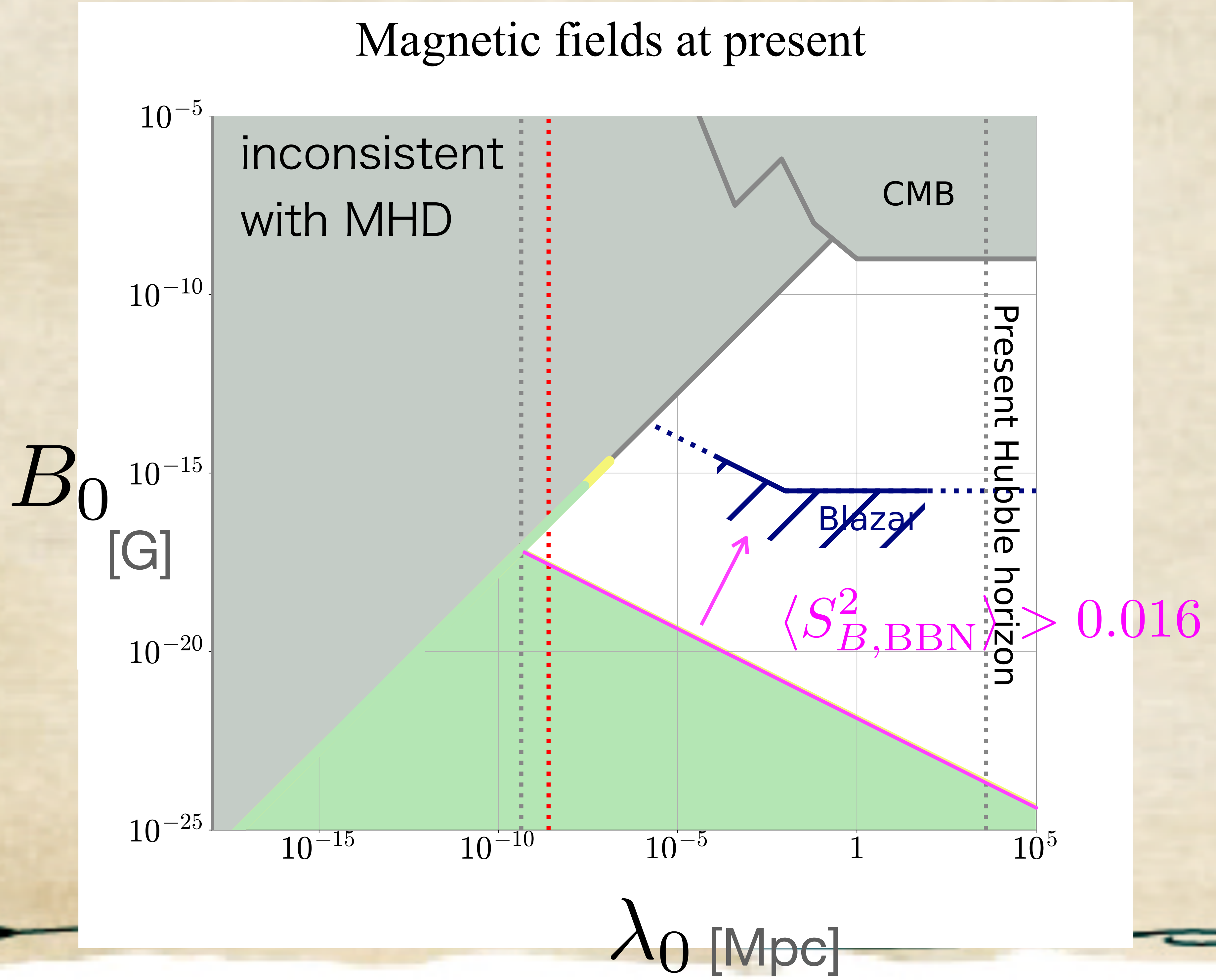


For more flat spectrum such as those from inflationary magnetogenesis?

Just taking

$$S(k) = \frac{2\pi^2}{\Gamma(\frac{5+\alpha}{2})} \frac{B^2_{\rm c,fo}}{k^5_\sigma} \left(\frac{k}{k_\sigma}\right)^\alpha \exp\left[-\left(\frac{k}{k_\sigma}\right)^2\right]$$ with $\alpha \simeq -5$ ⇨ $\langle S^2_{B,\rm BBN}\rangle$: IR divergent?

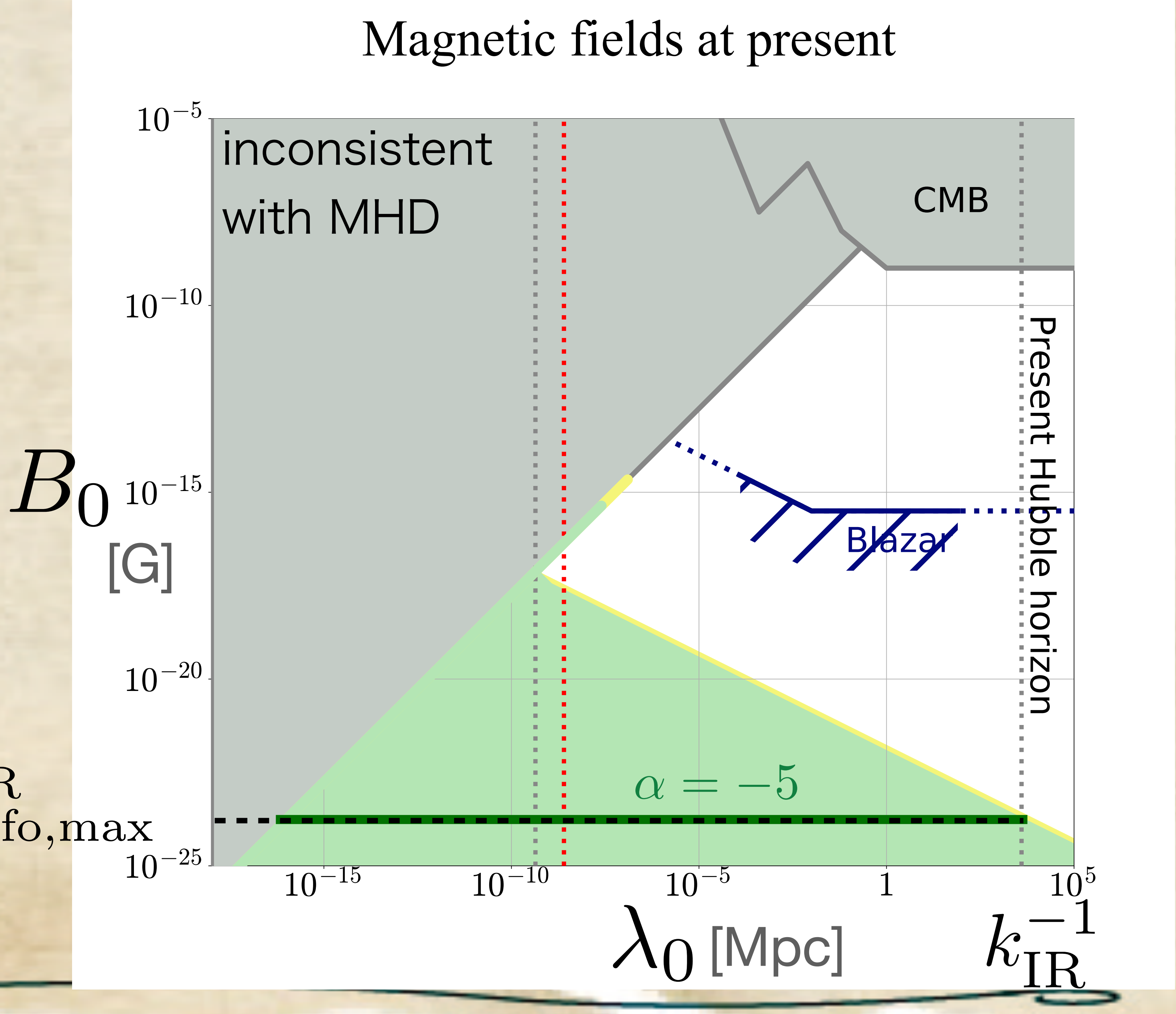
Reparameterize as

$$S(k) = \frac{(B^{\rm IR}_{\rm c,fo})^2}{k^5_{\rm IR}} \left(\frac{k}{k_{\rm IR}}\right)^\alpha$$ with IR cutoff $k_{\rm IR}$

For long enough magnetogenesis during inflation, the IR cutoff $k_{\rm IR}$ should be taken as H_0

⇨ $$\langle S^2_{B,\rm BBN}\rangle \sim \frac{\mathcal{C}^2 (B^{\rm IR}_{\rm c,fo})^4}{\overline{\eta}^2_{B,\rm obs} k^2_{\rm IR}} < 0.016$$ → $B^{\rm IR}_{\rm c,fo,max}$

Constraint on flat MF spectrum

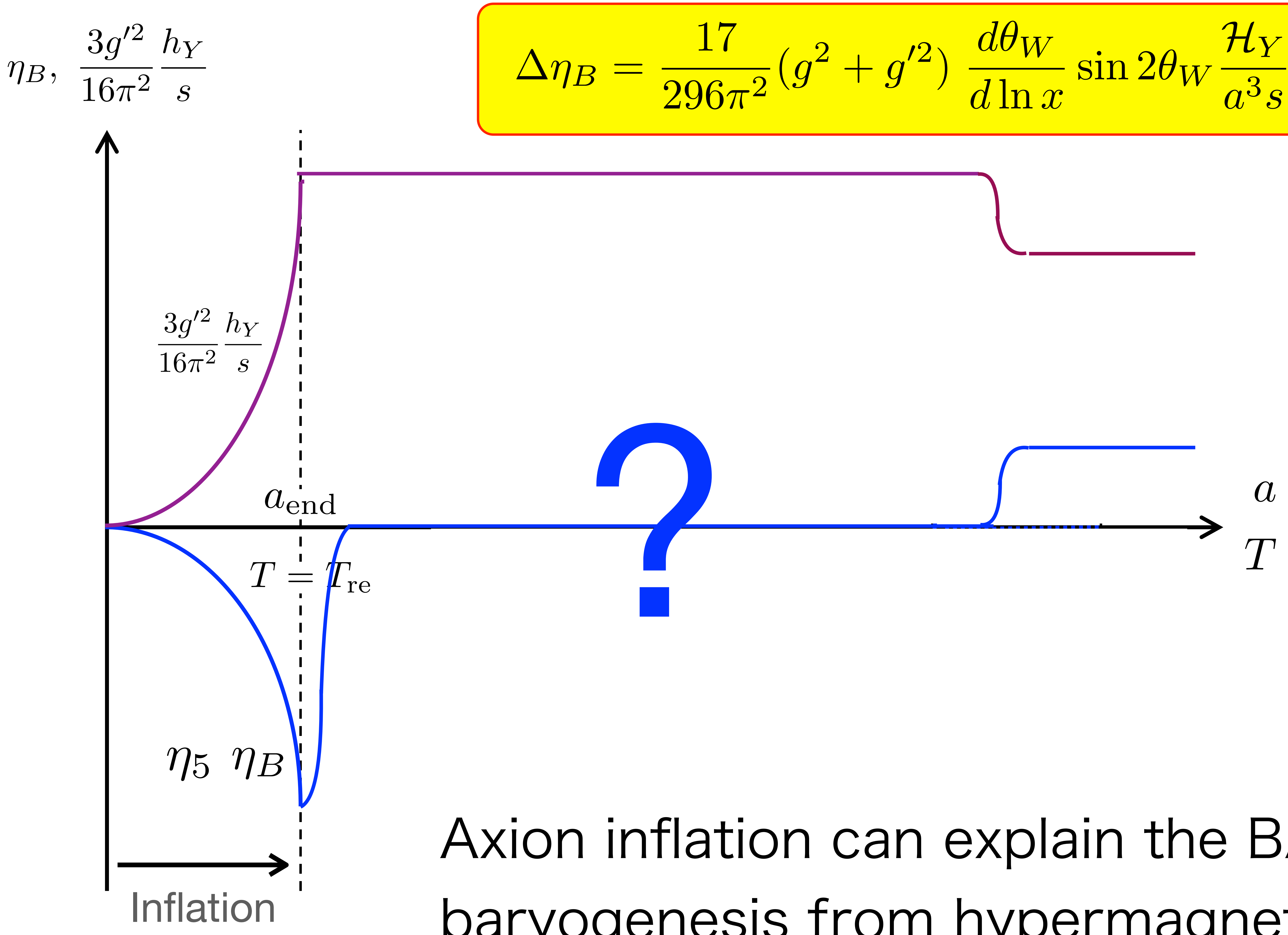


Cancellation by Chiral Anomaly?

Let’s go back to pseudoscalar inflation.

閑話休題

$$\Delta\eta_B = \frac{17}{296\pi^2}(g^2 + g'^2)\,\frac{d\theta_W}{d\ln x}\,\sin 2\theta_W\,\frac{\mathcal{H}_Y}{a^3 s}\bigg|_{T\simeq 135\mathrm{GeV}}$$



Axion inflation can explain the BAU through baryogenesis from hypermagnetic helicity decay?

The assumption in the previous arguments:

The asymmetry generated during axion inflation is B+L
is washed out by electroweak sphaleron just after reheating.

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It is not correct.

When the sphaleron washout completes?

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⋯ Electron Yukawa is small $y^e \sim 10^{-6}$ and hence right-handed electron number is a conserved quantity, which prevents washout from being completed at $T \gtrsim 10^5\mathrm{GeV}$. ('92 Campbell+)

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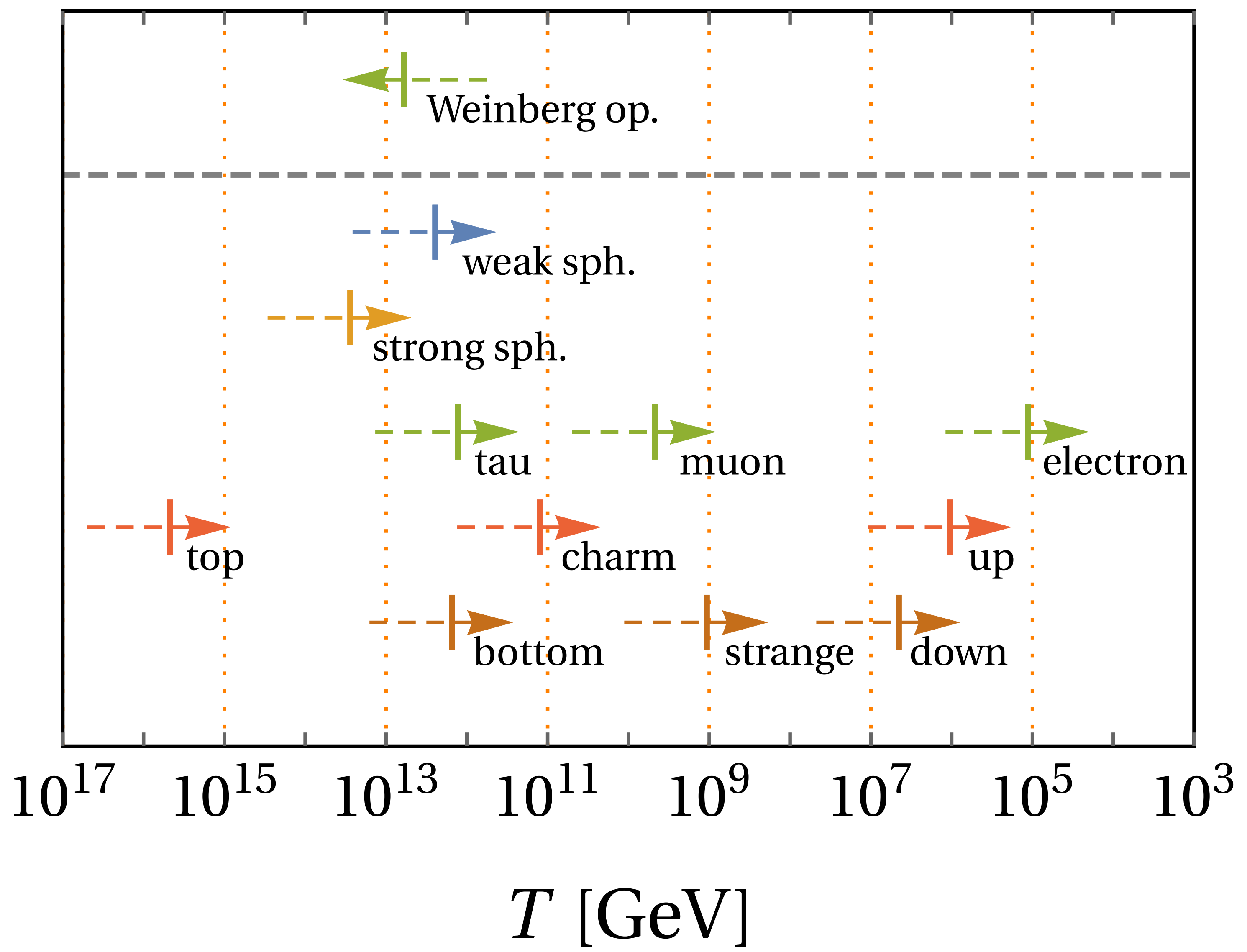
Depending on temperature, there are several approximate conserved charges.



Equilibrium temperature of Yukawa/sphalerons
(Figure from '20 Domcke+)

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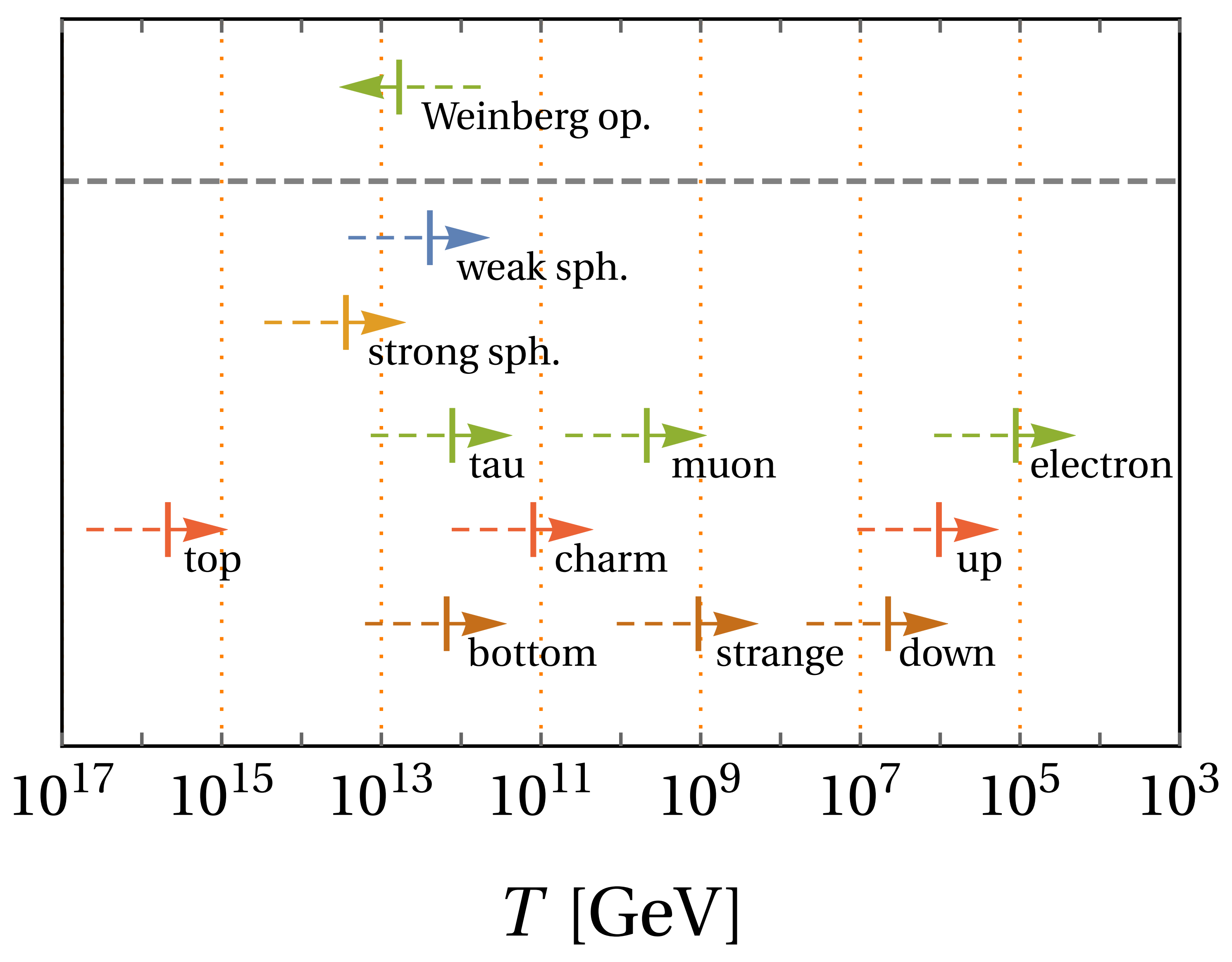

Equilibrium temperature of Yukawa/sphalerons
(Figure from '20 Domcke+)

	T[GeV]	y_e	y_{ds}	y_d	y_s	y_{sb}	y_μ	y_c	y_τ	y_b	WS	SS	y_t
(v)	$(10^5, 10^6)$	q_e	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
(iv)	$(10^6, 10^9)$	q_e	$q_{2B_1-B_2-B_3}$	q_{u-d}	✓	✓	✓	✓	✓	✓	✓	✓	✓
(iii)	$(10^9, 10^{11-12})$	q_e	$q_{2B_1-B_2-B_3}$	q_{u-d}	q_{d-s}	$q_{B_1-B_2}$	q_μ	✓	✓	✓	✓	✓	✓
(ii)	$(10^{11-12}, 10^{13})$	q_e	$q_{2B_1-B_2-B_3}$	q_{u-d}	q_{d-s}	$q_{B_1-B_2}$	q_μ	q_{u-c}	q_τ	q_{d-b}	q_B	✓	✓
(i)	$(10^{13}, 10^{15})$	q_e	$q_{2B_1-B_2-B_3}$	q_{u-d}	q_{d-s}	$q_{B_1-B_2}$	q_μ	q_{u-c}	q_τ	q_{d-b}	q_B	q_u	✓

List of conserved charges at several temperature regime
('21 Domcke, KK+)

When the sphaleron washout completes?

… on

being completed at $T \lesssim 10^5\,\mathrm{GeV}$. ('92 Campbell+)

We often say, "the SM has only three conserved global charges, B/3-Li", but it is practically true only for $T \lesssim 10^5\mathrm{GeV}$

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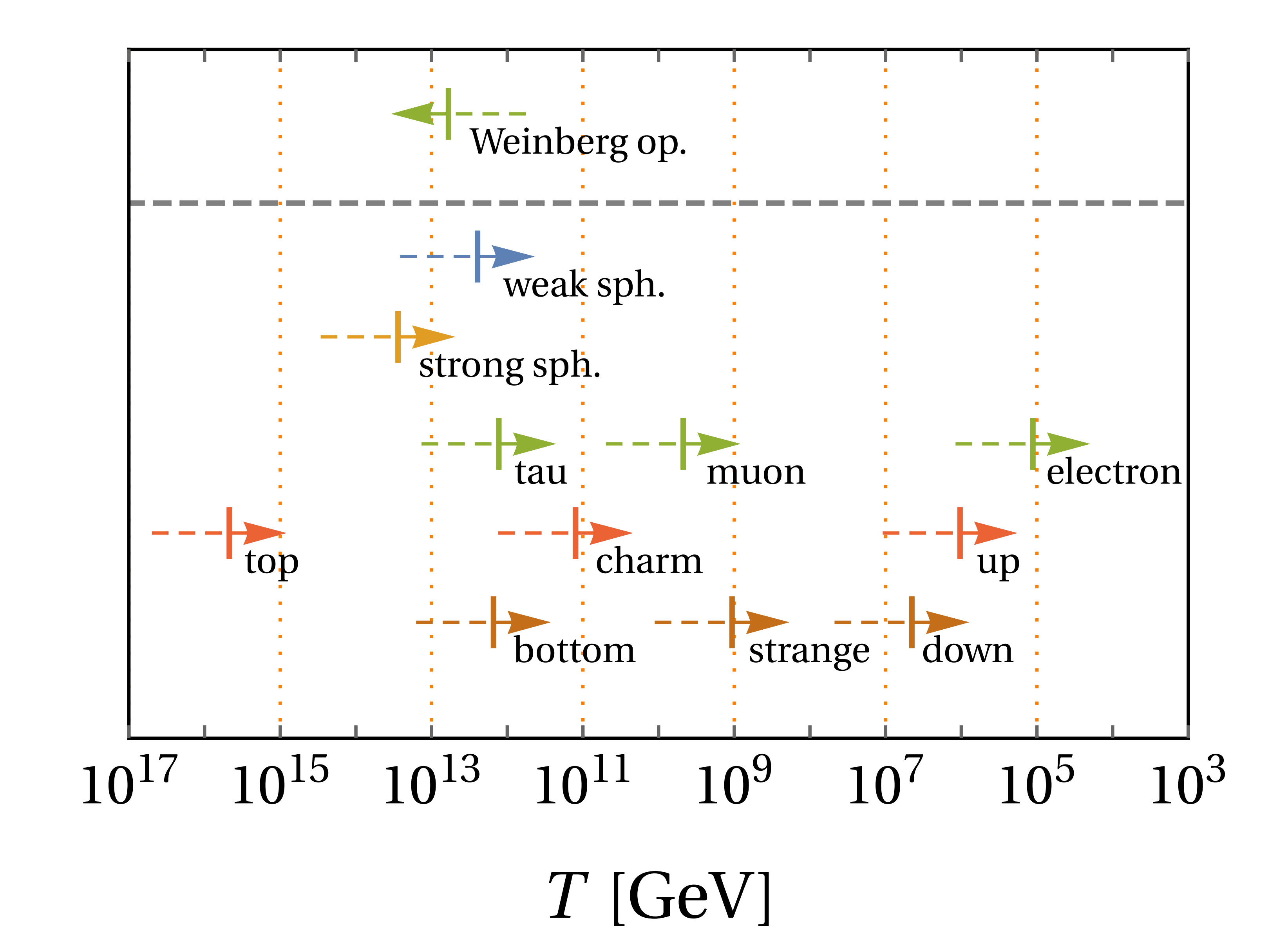

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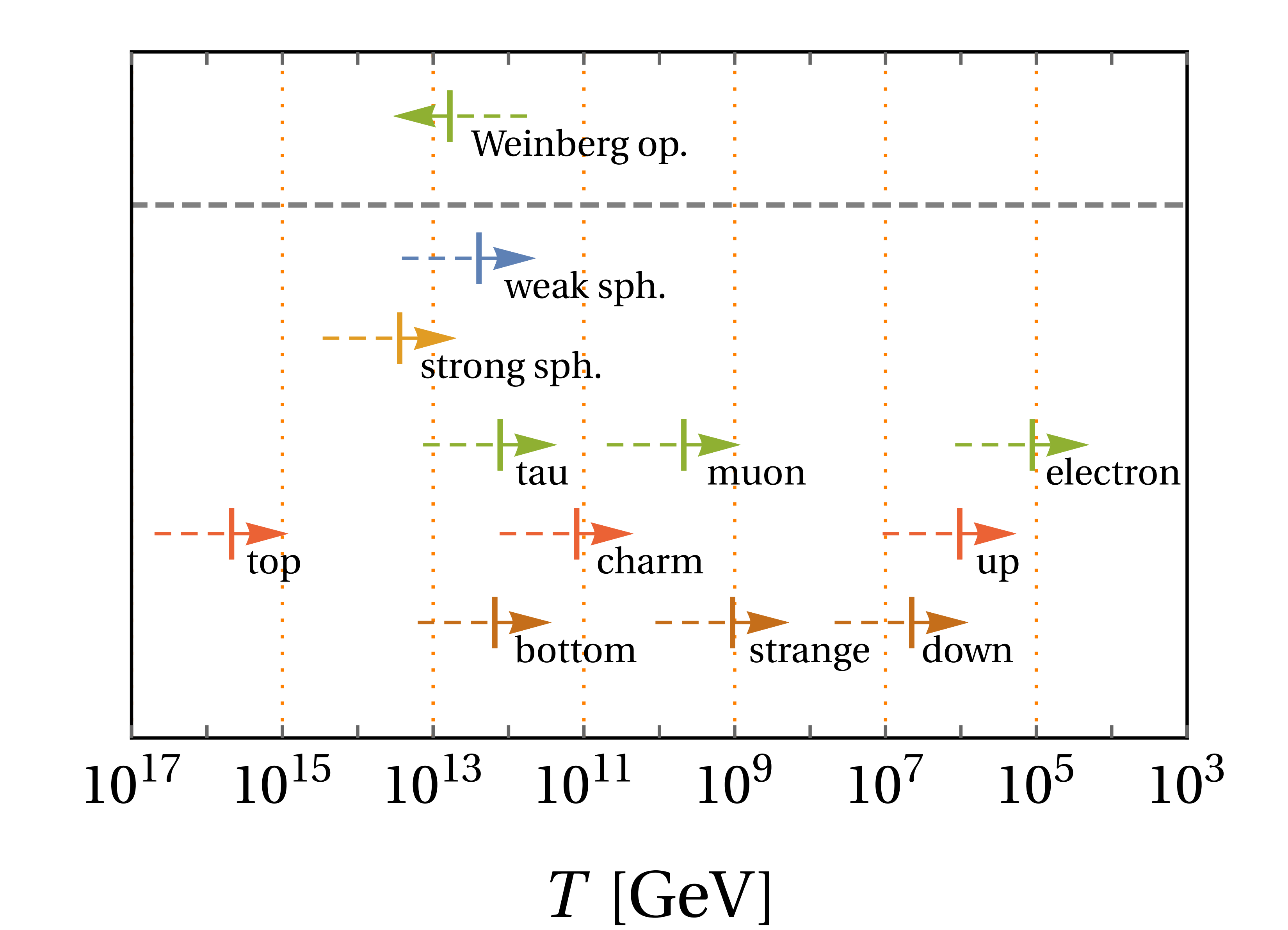

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List of conserved charges at several temperature regime
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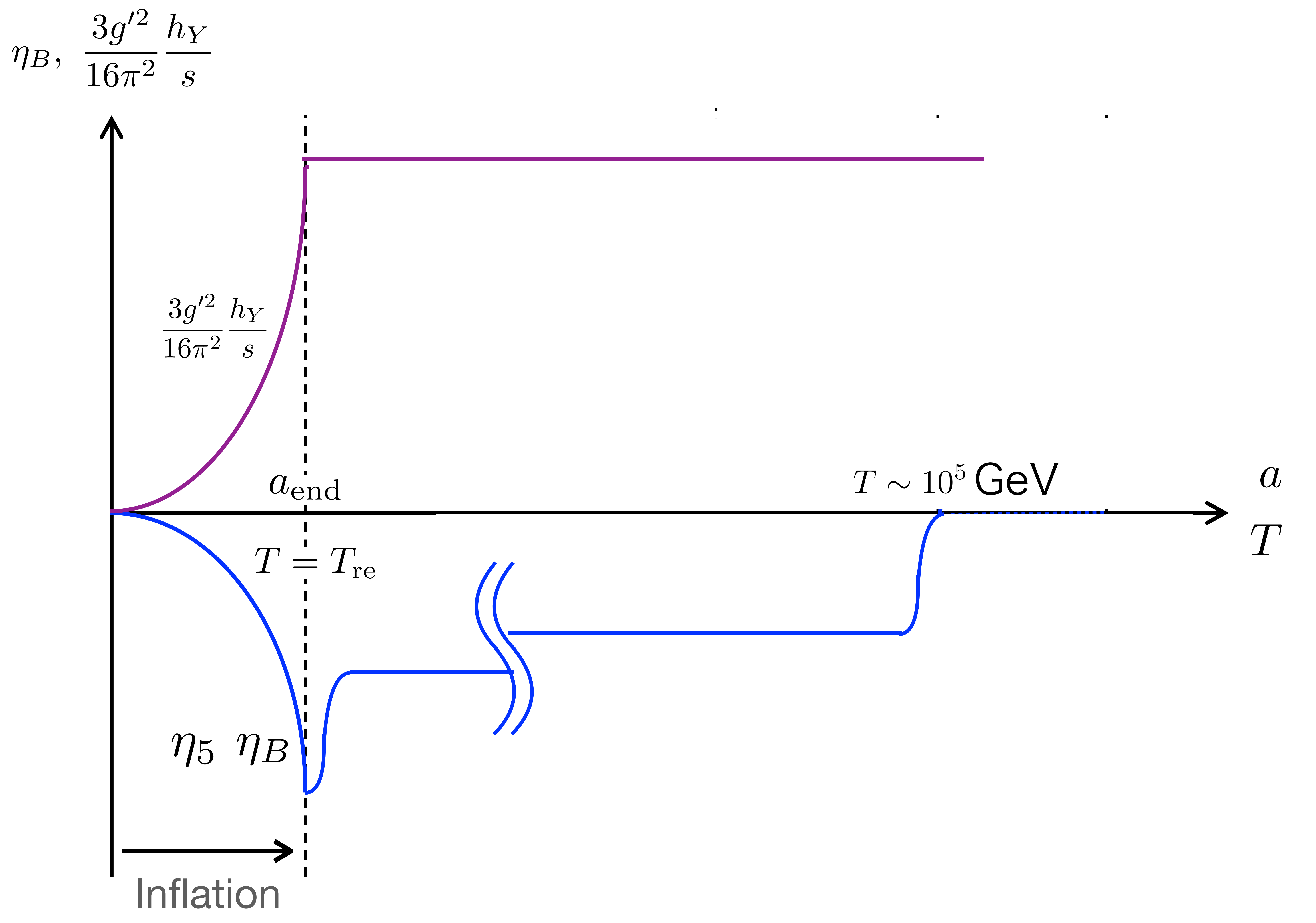
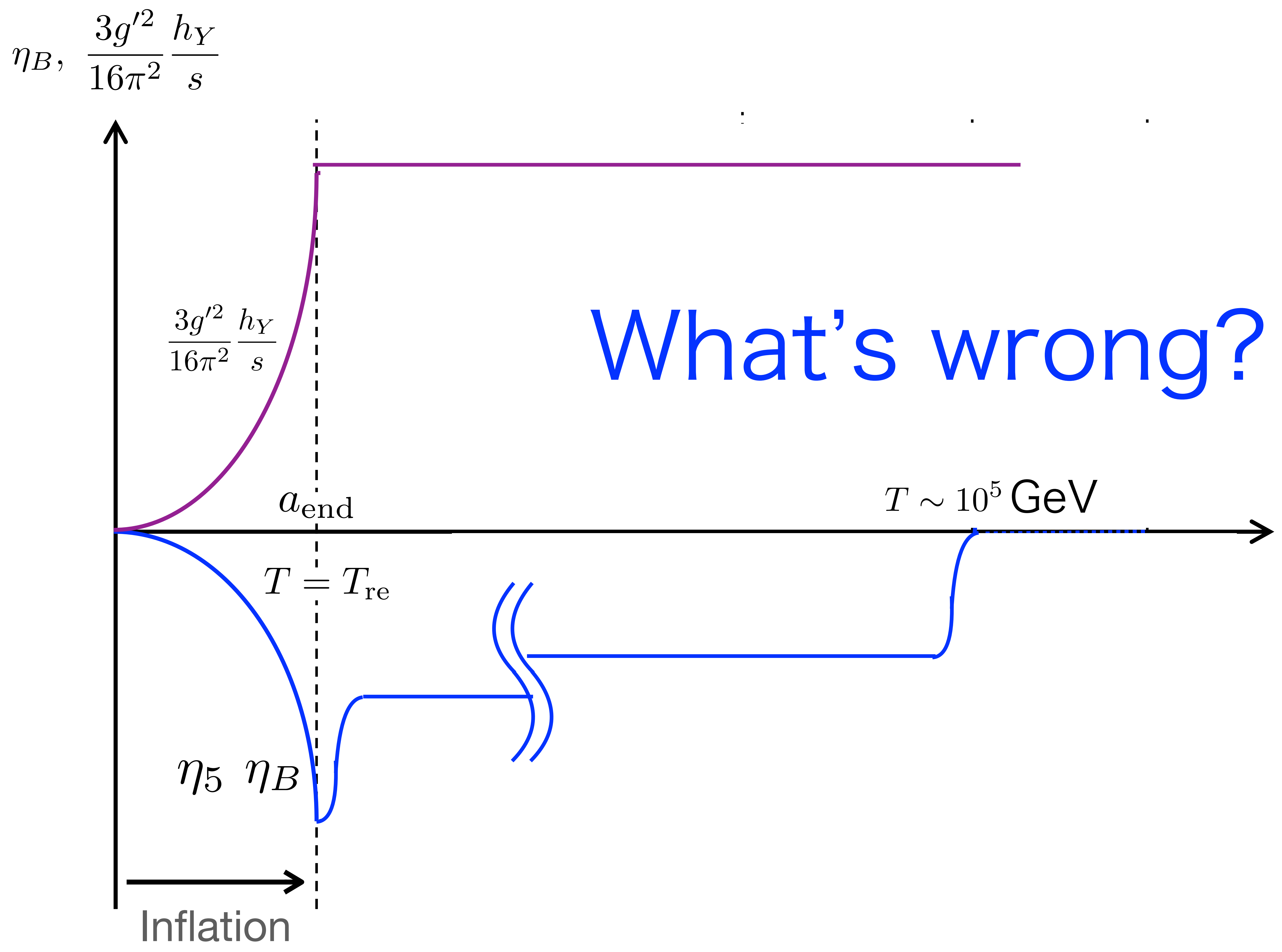
(See also Kyohei's talk)



Baryon number changes, but is not washed away until $T \sim 10^5$ GeV.



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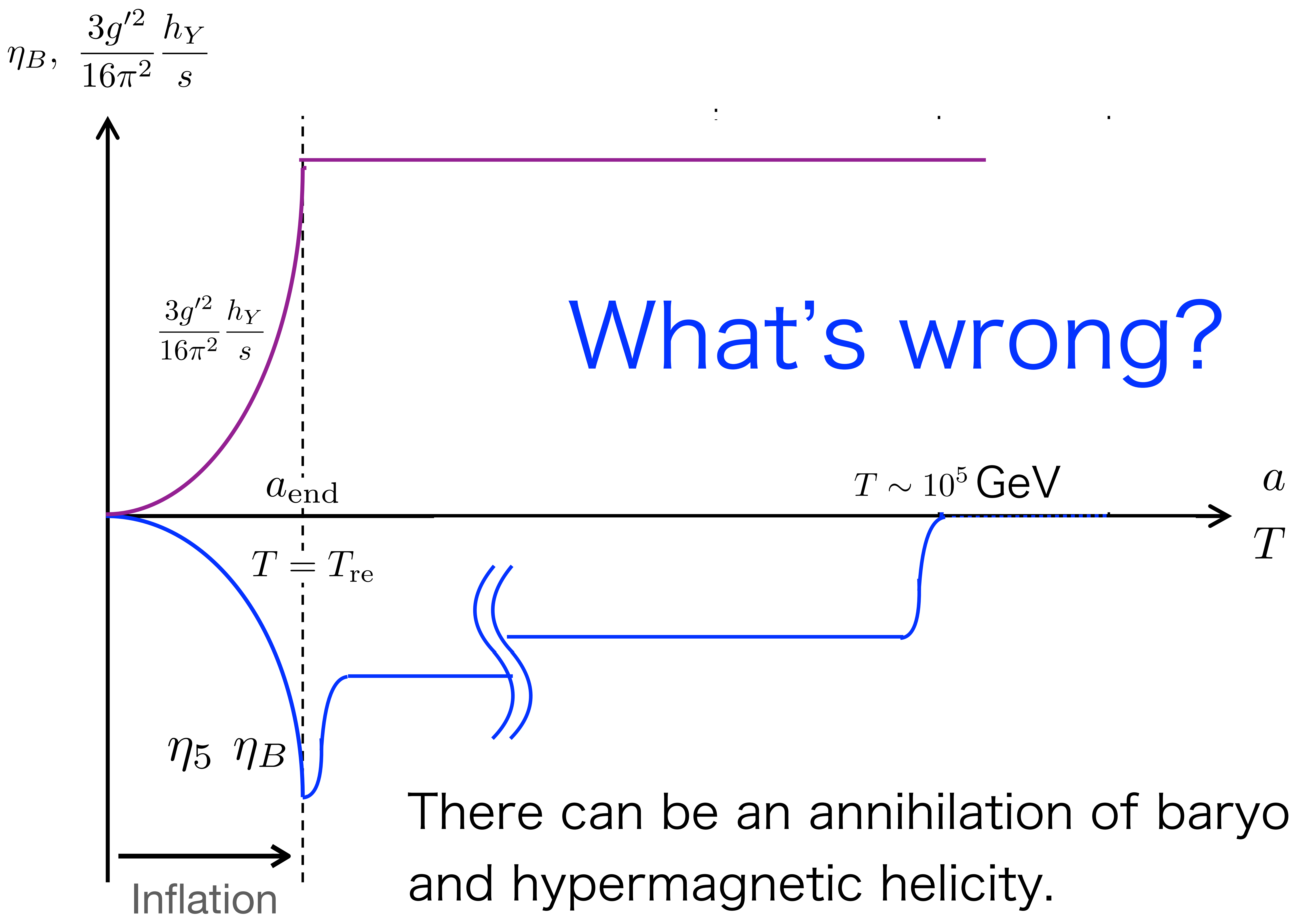

What's wrong?

There can be an annihilation of baryon/chiral asymmetry and hypermagnetic helicity.

Baryon number changes, but is not washed away until $T \sim 10^5$ GeV.

Anomaly equation = conservation of total chirality $\frac{\alpha}{2\pi}h + q_5$

Even after baryon number is redistributed by the sphaleron and Yukawa interactions, cancellation always holds until $T \sim 10^5$ GeV.

('18, '19 Domcke+, '24 Domcke, KK+)

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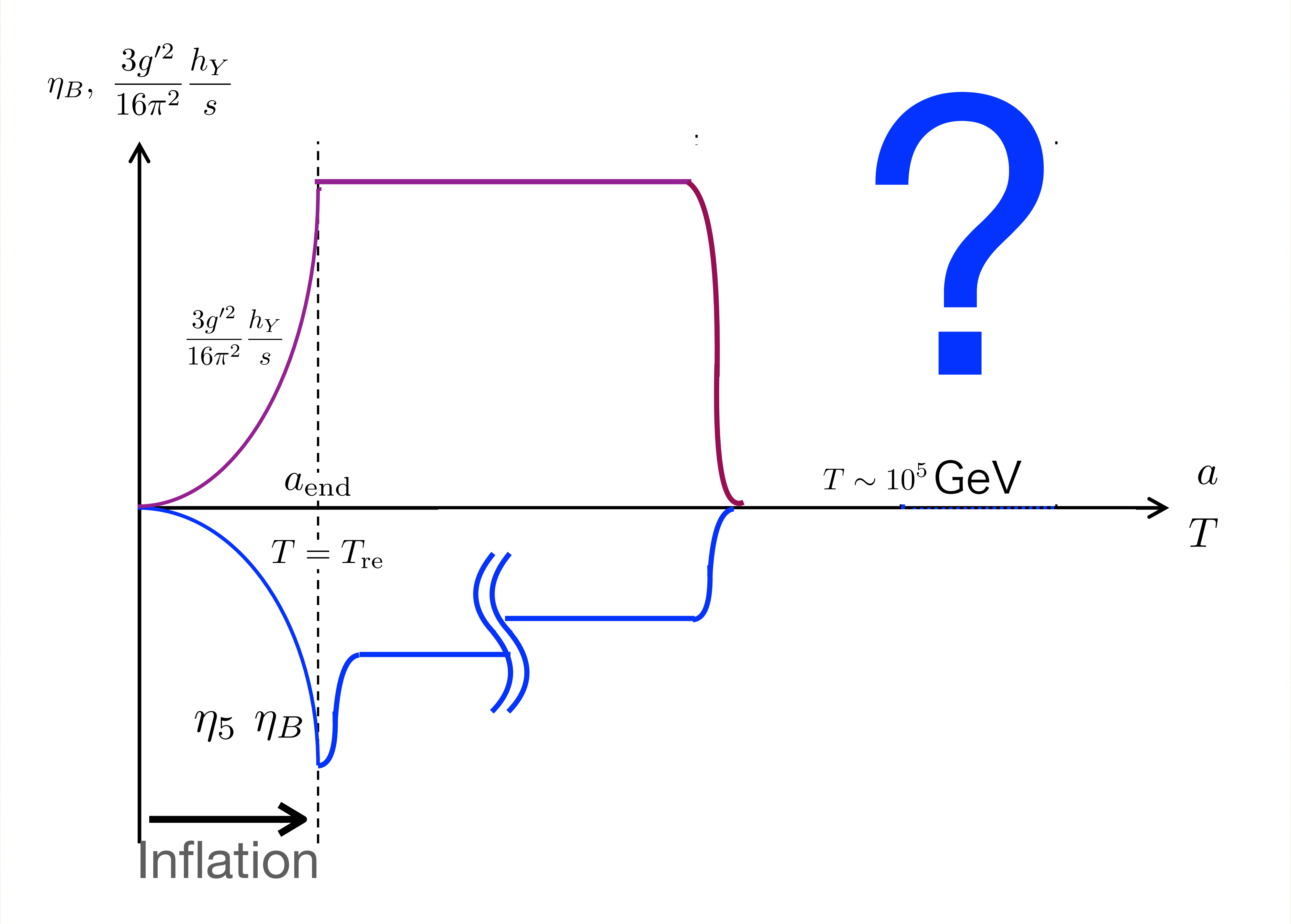

How can such a process be investigated?

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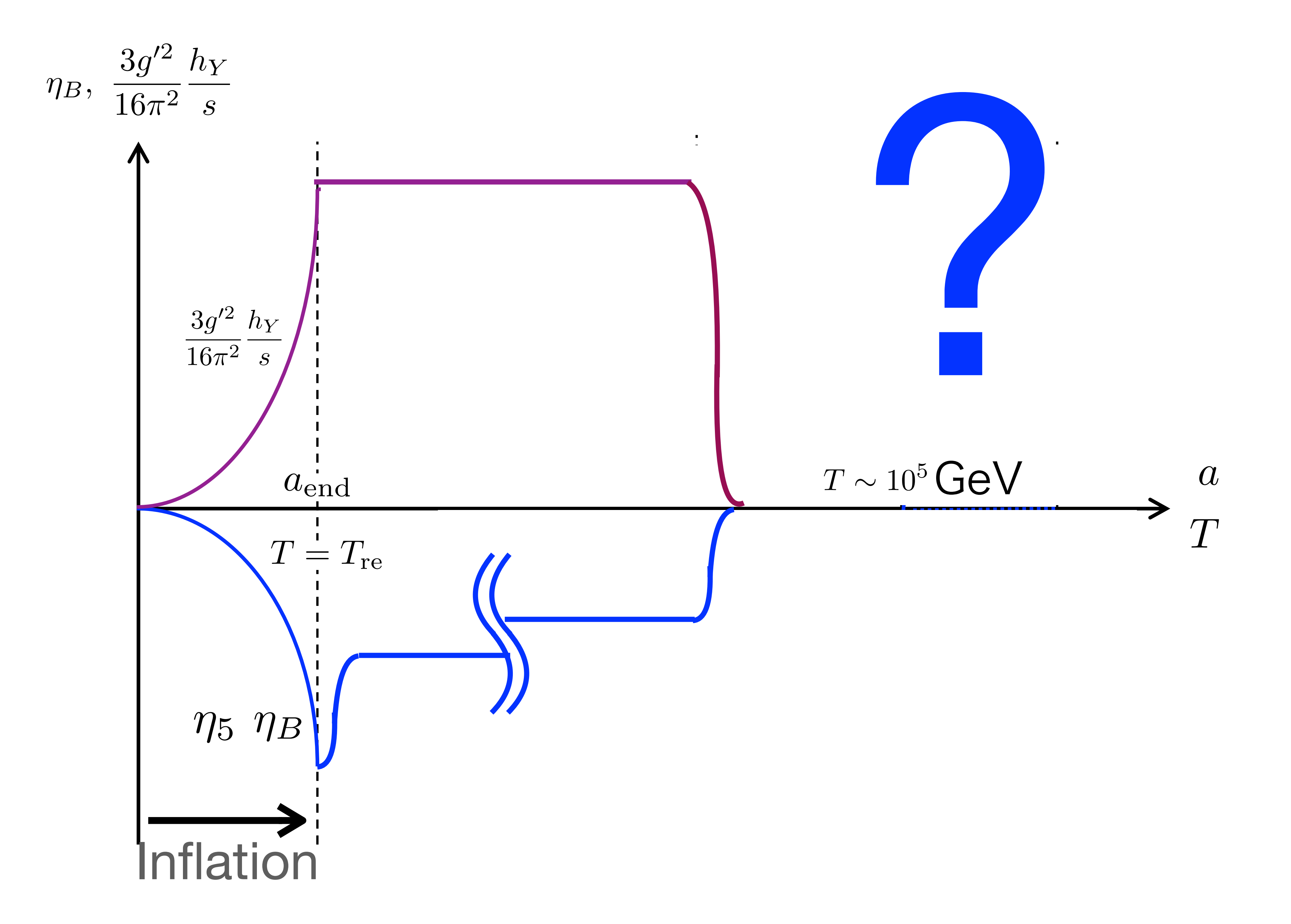

How can such a process be investigated?

Write down the evolution eq. of the system with chiral anomaly.

= chiral MHD

Q: Isn't electric current induced by magnetic field?

No, for usual media. Parity doesn't allow it.

$$\text{P:}\quad \boldsymbol{j} \to -\boldsymbol{j}, \quad \boldsymbol{E} \to -\boldsymbol{E}, \quad \boldsymbol{B} \to \boldsymbol{B}$$

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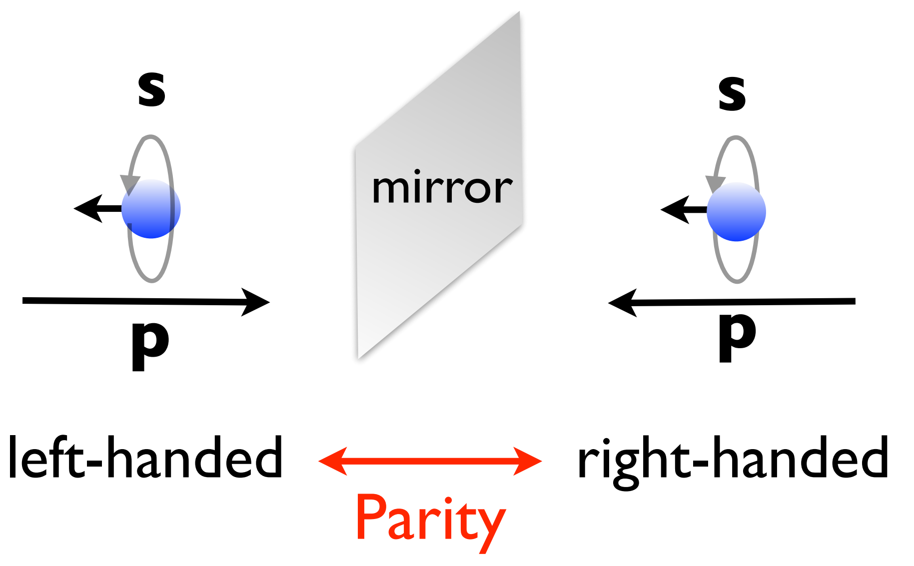
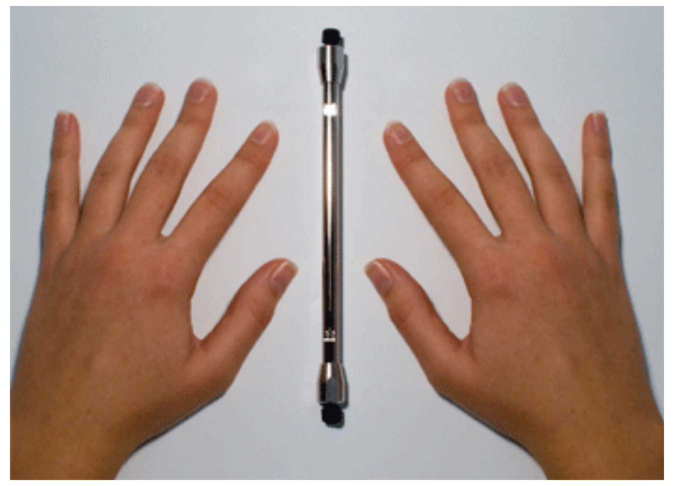
Chirality of fermions





$$\mu_5 \equiv \mu_{\rm R} - \mu_{\rm L}$$

from the slide of N. Yamamoto

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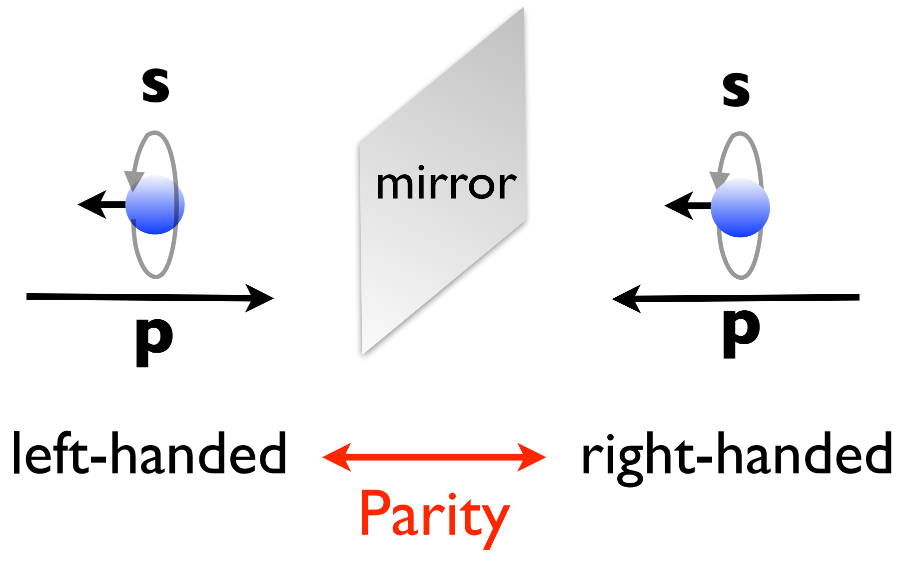
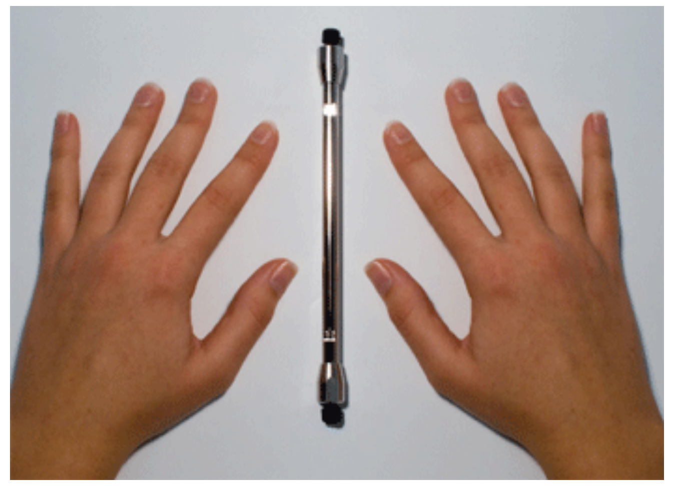
Chiral magnetic effect: $\boldsymbol{j} = \dfrac{2\alpha}{\pi}\mu_5 \boldsymbol{B}$

Chirality of fermions





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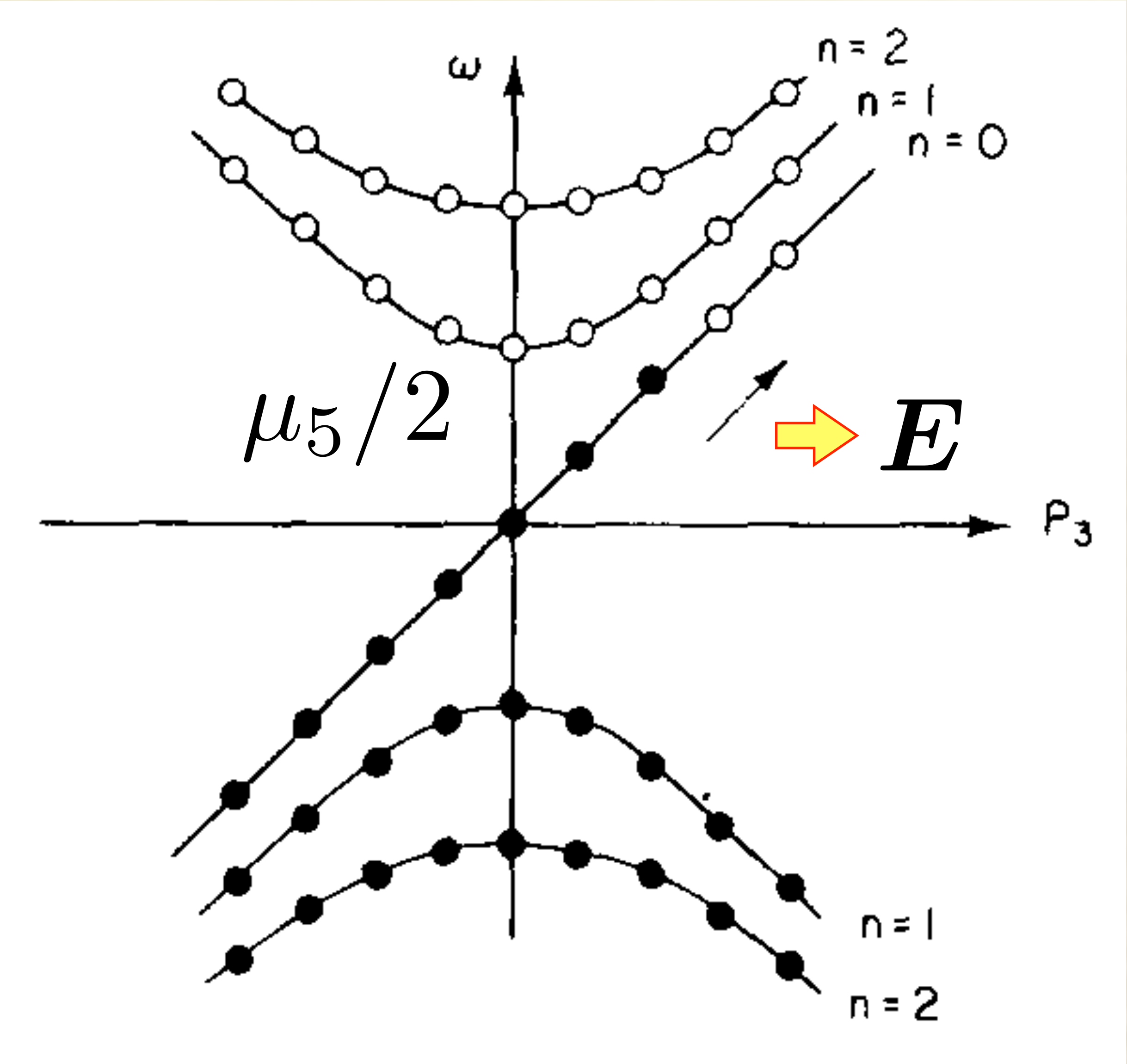
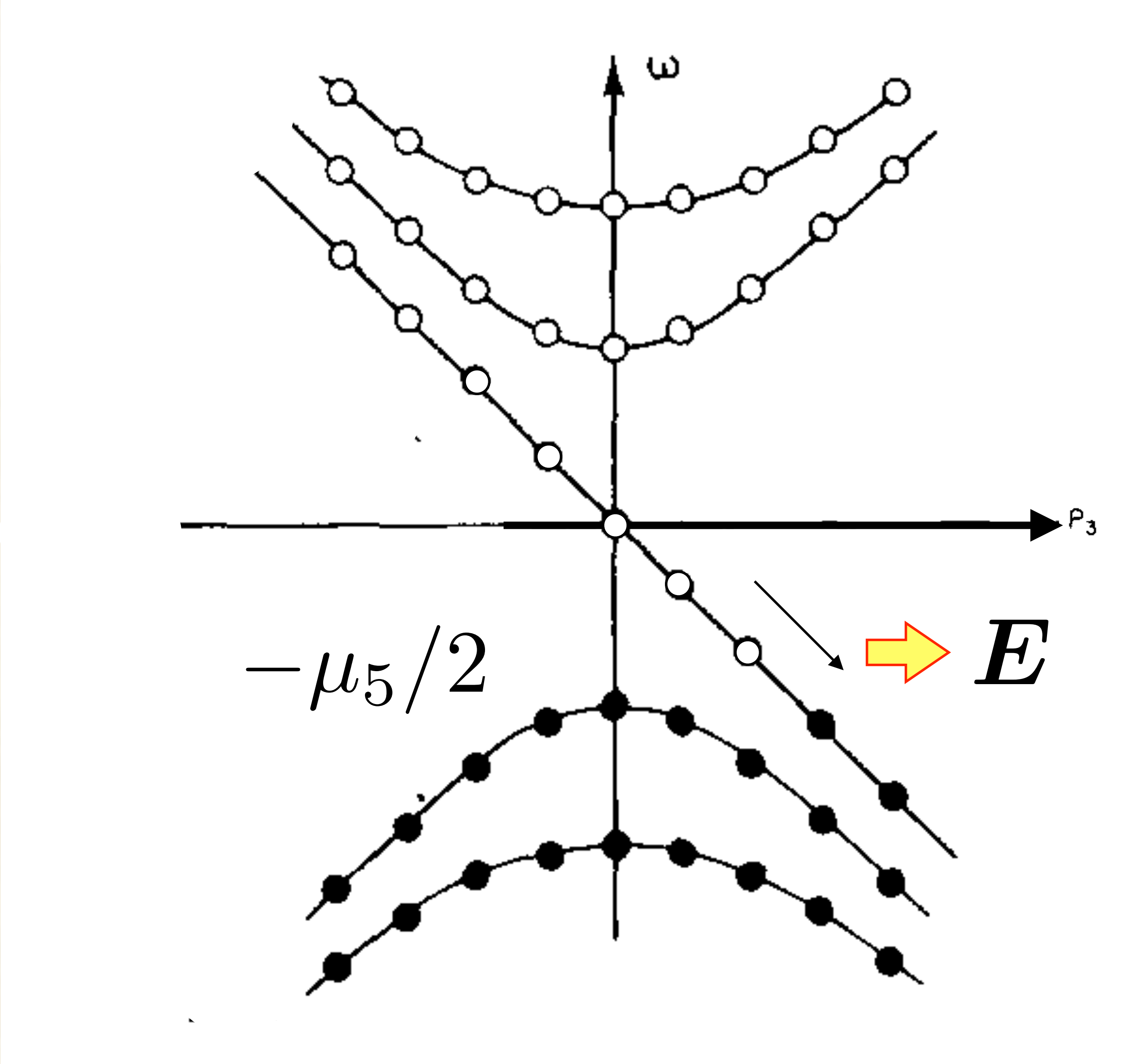
from the slide of N. Yamamoto

The relevance of the CME and chiral anomaly

can be seen by looking at the Landau level



Right-handed fermion



Left-handed fermion

('83 Nielsen&Ninomiya)

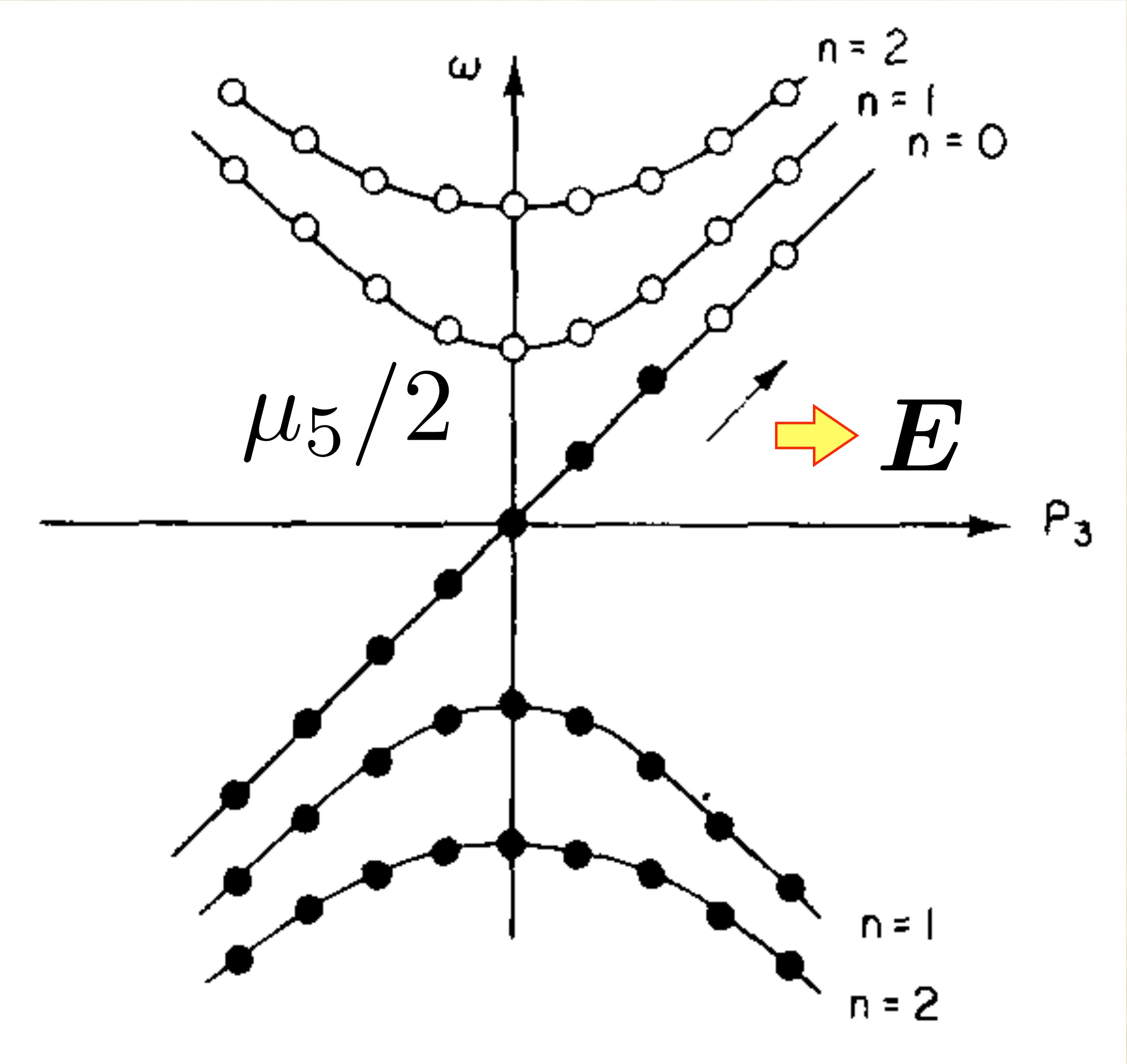
Landau degeneracy factoer: $n_i = \dfrac{eB}{2\pi}$

The number of states with $p_z > 0$ is large for right-handed fermions with charge +e and vice versa

➡ positive current in z-direction

The relevance of the CME and chiral anomaly

can be seen by looking at the Landau level



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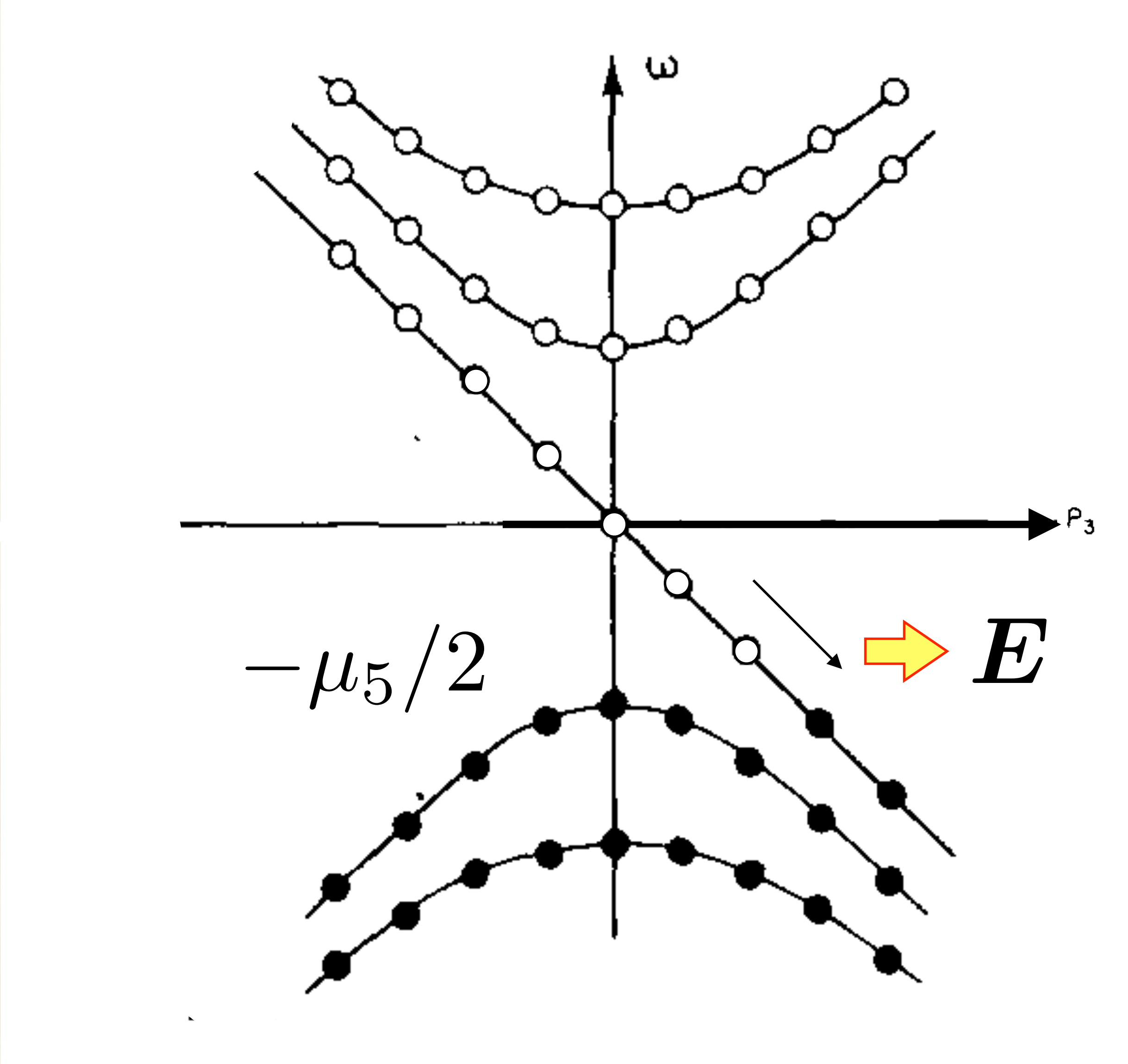

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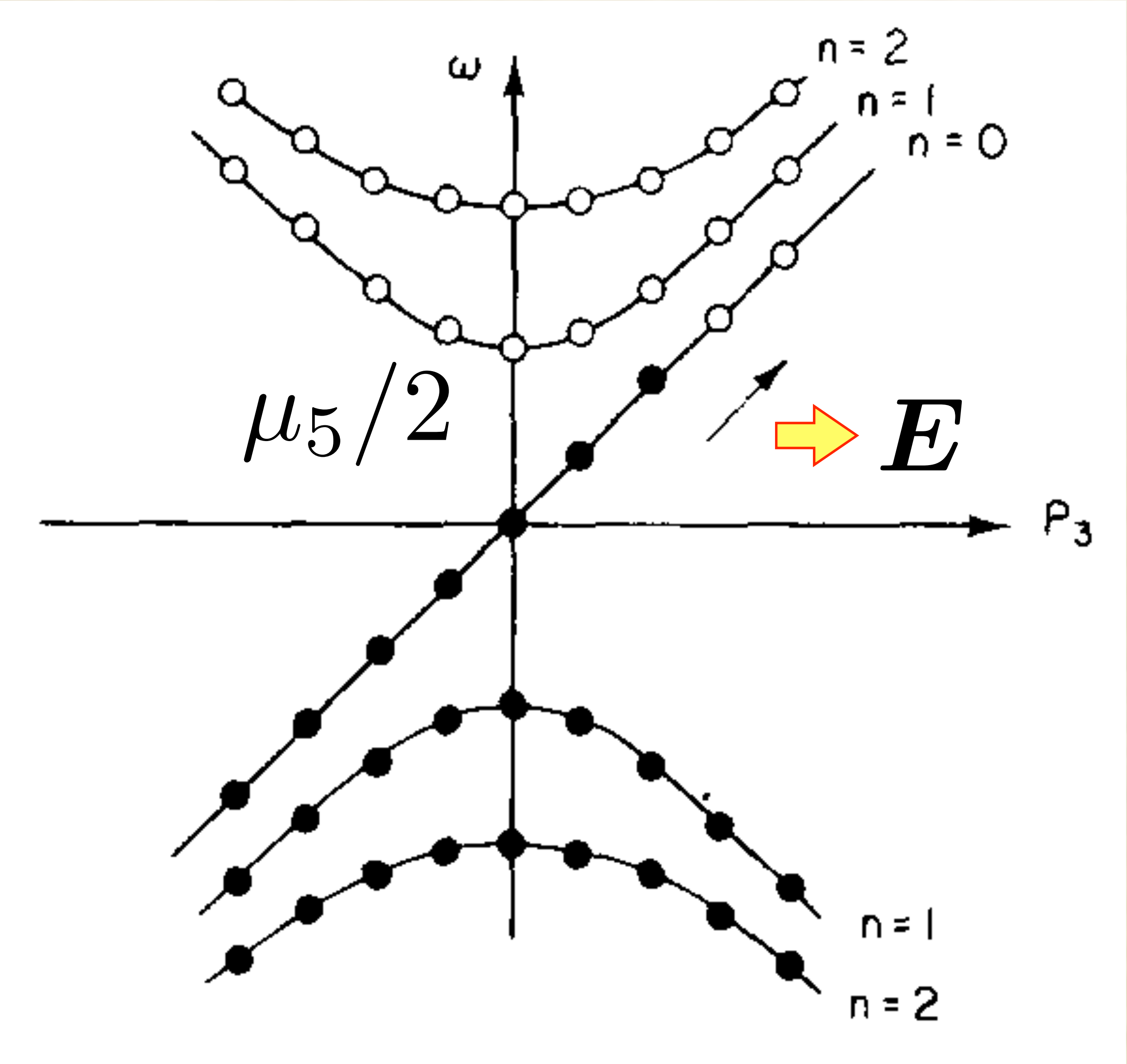

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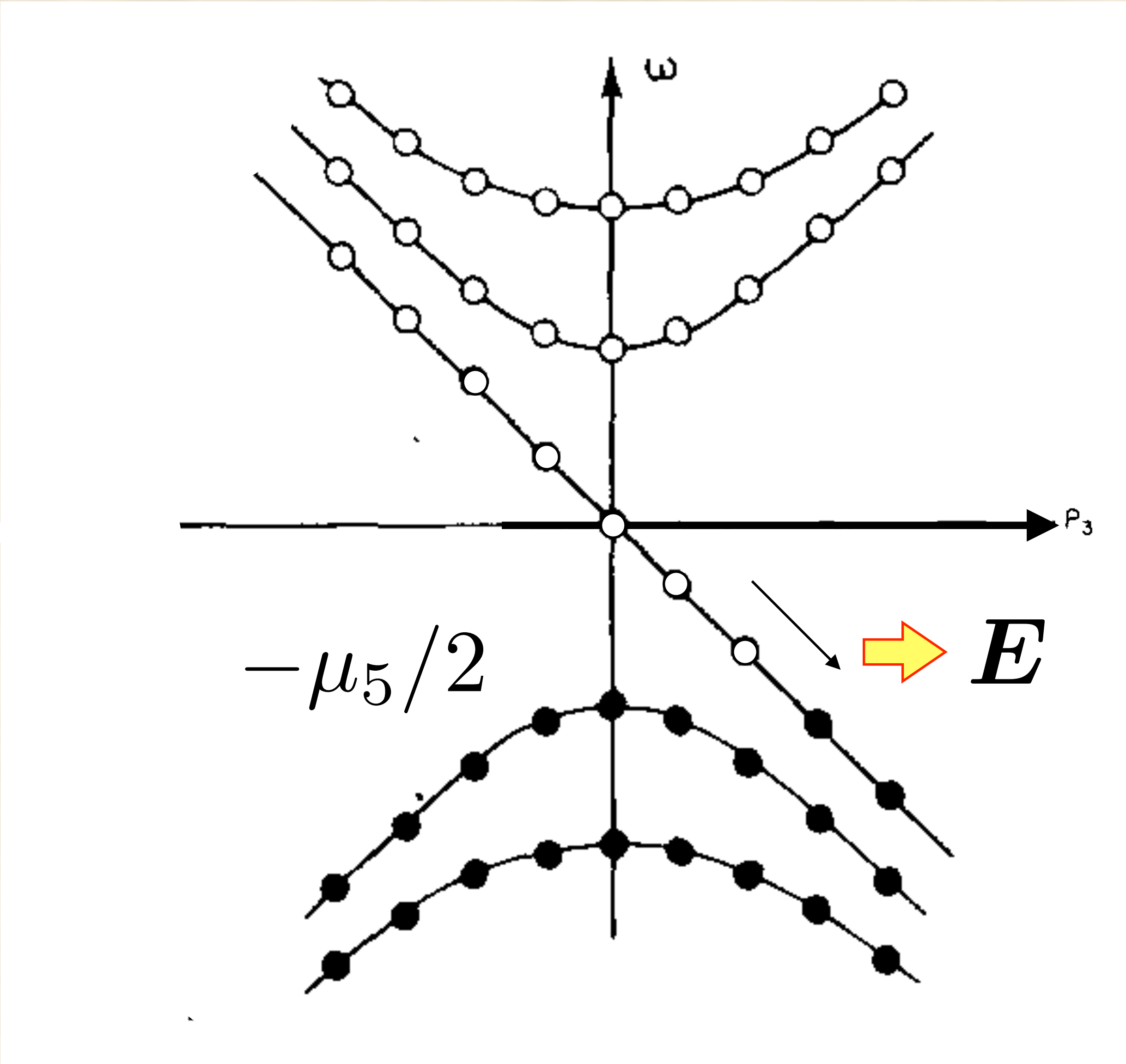

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$$\frac{dn_5}{dt} = \frac{e^2}{2\pi^2}\boldsymbol{E}\cdot\boldsymbol{B} \qquad \partial_\mu j_5^\mu = -\frac{e^2}{8\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

MHD equations with chiral magnetic effect = chiral MHD

The dynamical degrees of freedom:

Magnetic field: $\boldsymbol{B}$, Plasma velocity: $\boldsymbol{u}$, Energy density: ρ , Chirality: μ_5

Maxwell eq. : $$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla} \times [\boldsymbol{u} \times \boldsymbol{B} - \eta(\boldsymbol{J} - C\mu_5 \boldsymbol{B})], \quad \boldsymbol{J} = \boldsymbol{\nabla} \times \boldsymbol{B},$$

Navier-Stokes eq. : $$\rho \frac{D\boldsymbol{u}}{Dt} = (\boldsymbol{\nabla} \times \boldsymbol{B}) \times \boldsymbol{B} - \boldsymbol{\nabla} p + \boldsymbol{\nabla} \cdot (2\nu\rho \boldsymbol{S}) + \rho \boldsymbol{f}$$

Continuity eq. : $$\frac{D\rho}{Dt} = -\rho \boldsymbol{\nabla} \cdot \boldsymbol{u}$$

Anomaly eq.: $$\frac{D\mu_5}{Dt} = D_5 \boldsymbol{\nabla}^2 \mu_5 + \lambda\eta[\boldsymbol{B} \cdot (\boldsymbol{\nabla} \times \boldsymbol{B}) - C\mu_5 \boldsymbol{B}^2]$$

$$\boldsymbol{S}_{ij} \equiv \frac{1}{2}(\partial_j u_i + \partial_i u_j) - \frac{1}{3}\delta_{ij} \boldsymbol{\nabla} \cdot \boldsymbol{u}$$

$$\boldsymbol{f} = \boldsymbol{J} \times \boldsymbol{B}$$

$$C \sim \frac{g^2}{2\pi}, \quad \lambda \sim \frac{6C}{T^2}, \quad \left(n_5 \simeq \frac{\mu_5 T^2}{3}\right)$$

η, ν : resistivity/viscosity

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Solve them in the initial condition,

- Magnetic fields ⋯ Maximally helical, peaked at a relatively large scale.
- chiral asymmetry ⋯ opposite sign to the magnetic helicity to cancel. uniformly distributed.

Anomaly eq.: $\frac{D\mu_5}{Dt} = D_5\boldsymbol{\nabla}^2\mu_5 + \lambda\eta[\boldsymbol{B}\cdot(\boldsymbol{\nabla}\times\boldsymbol{B}) - C\mu_5\boldsymbol{B}^2]$

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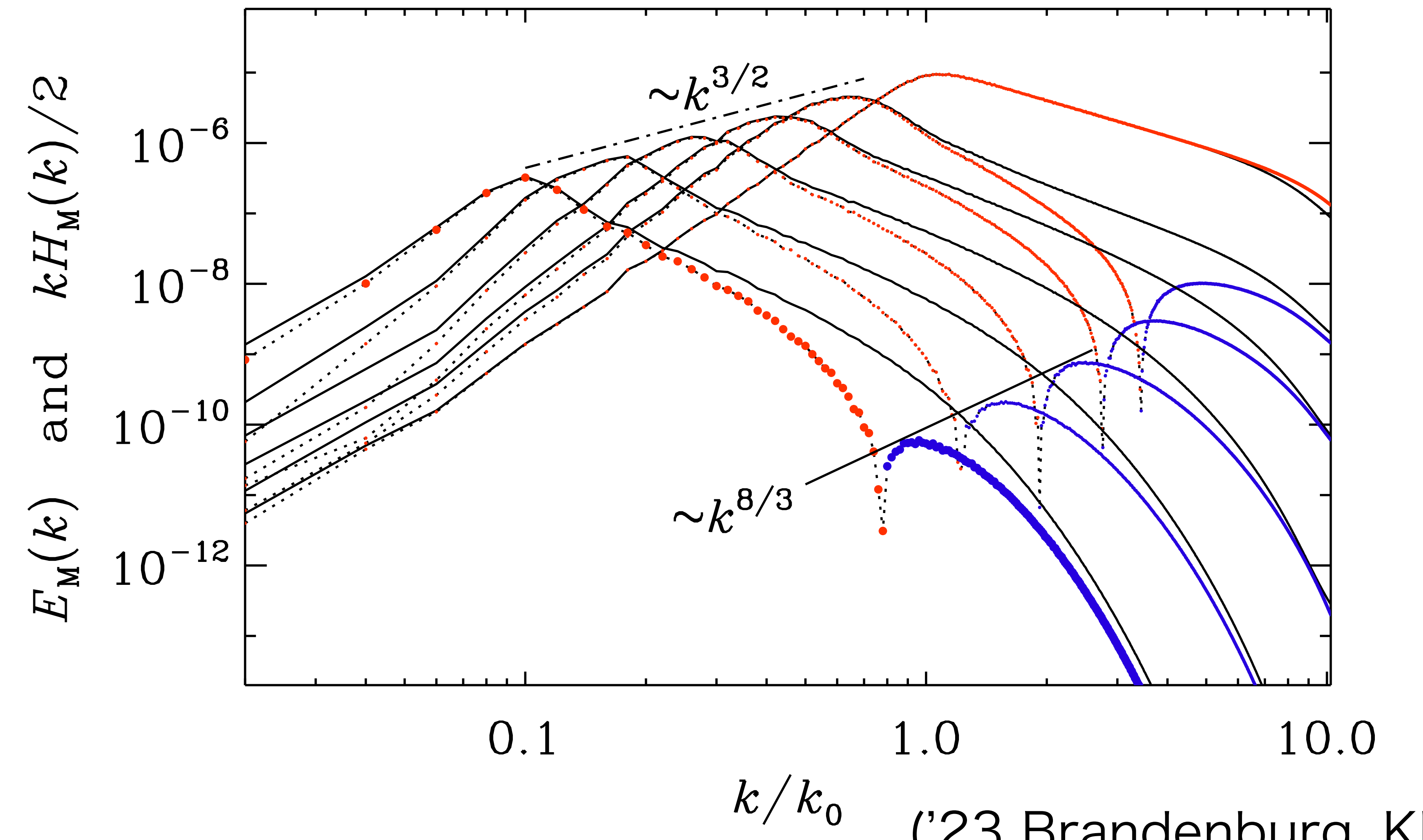
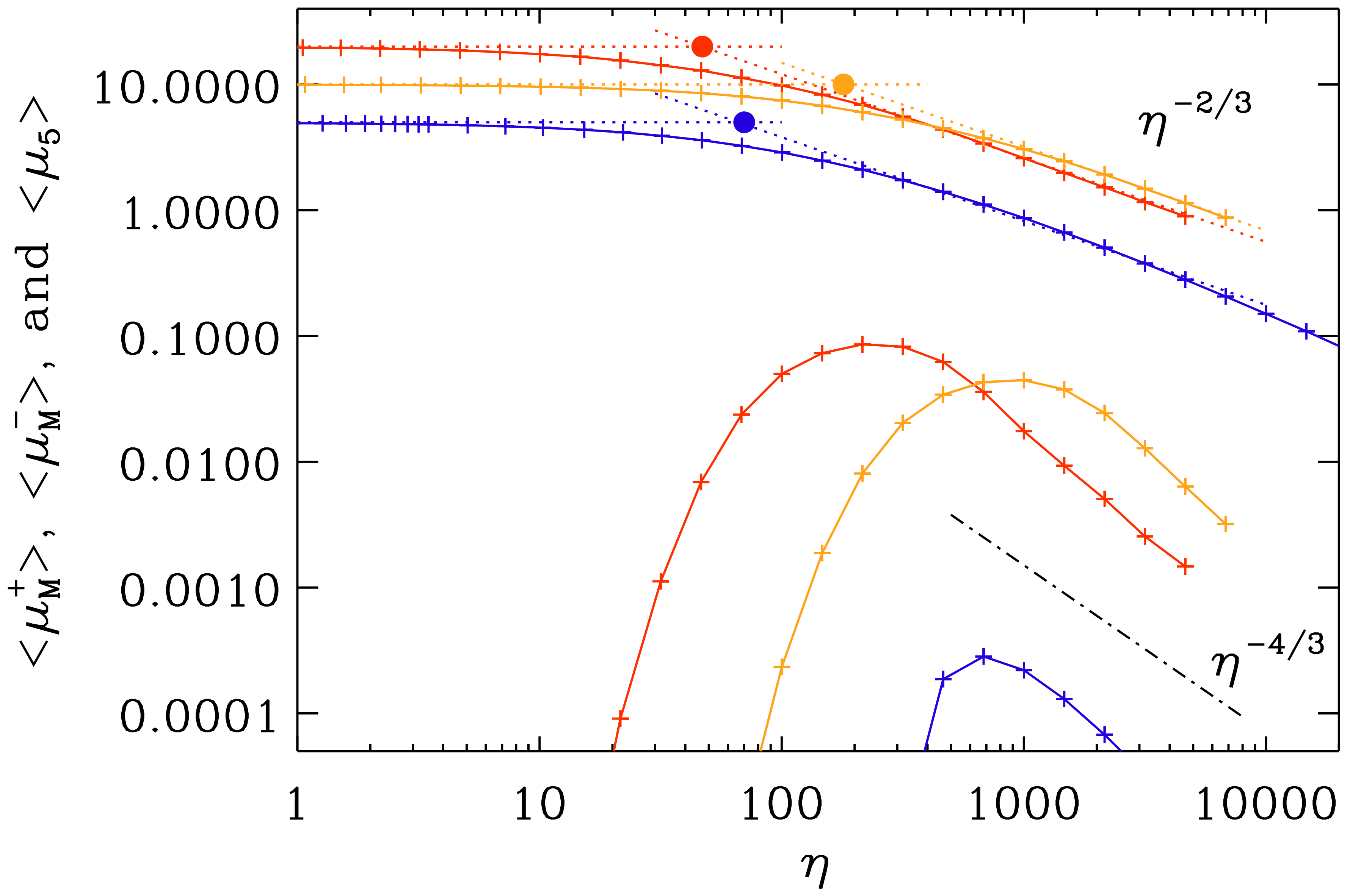
A typical evolution we obtained.



('23 Brandenburg, KK+)



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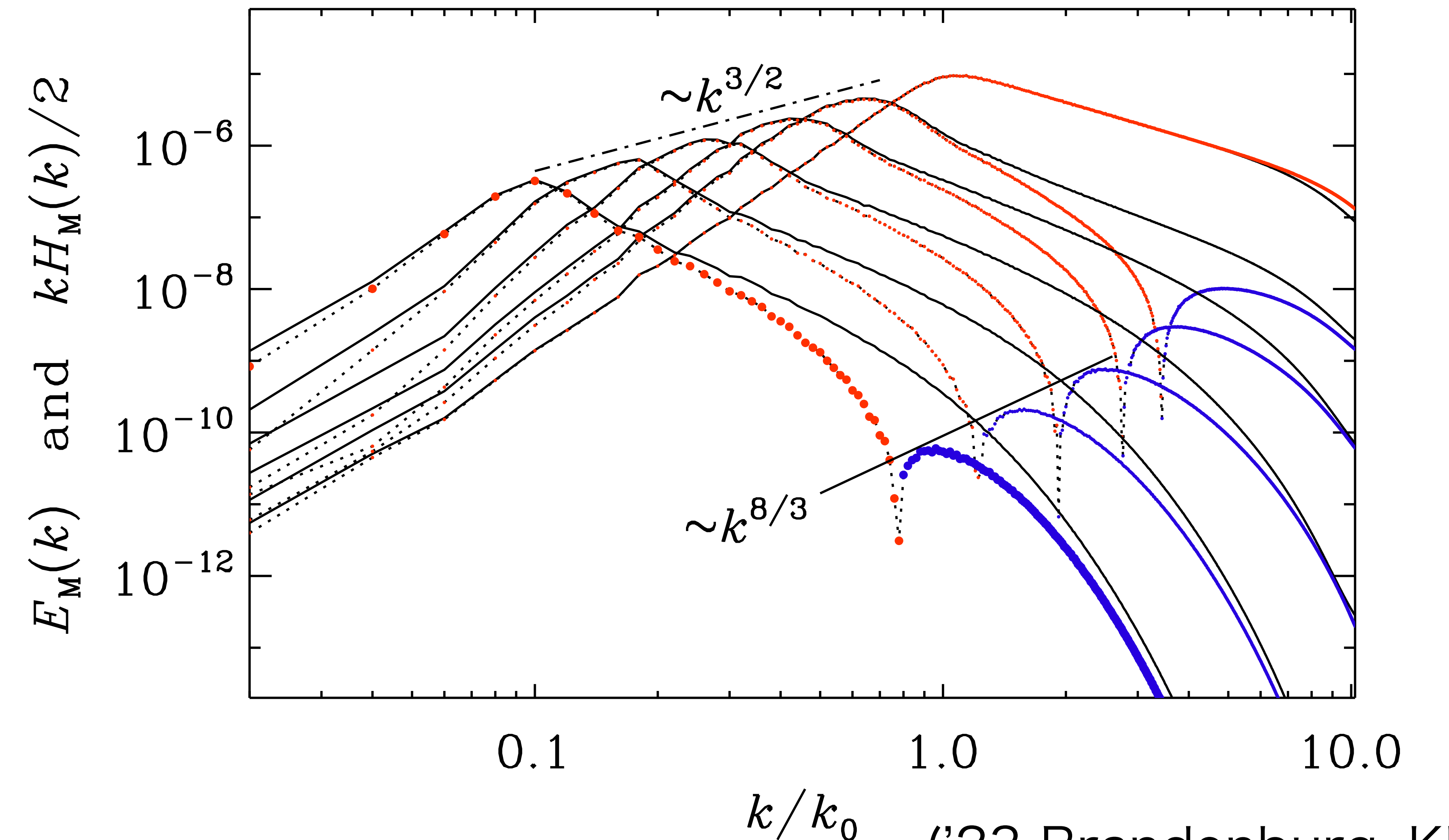

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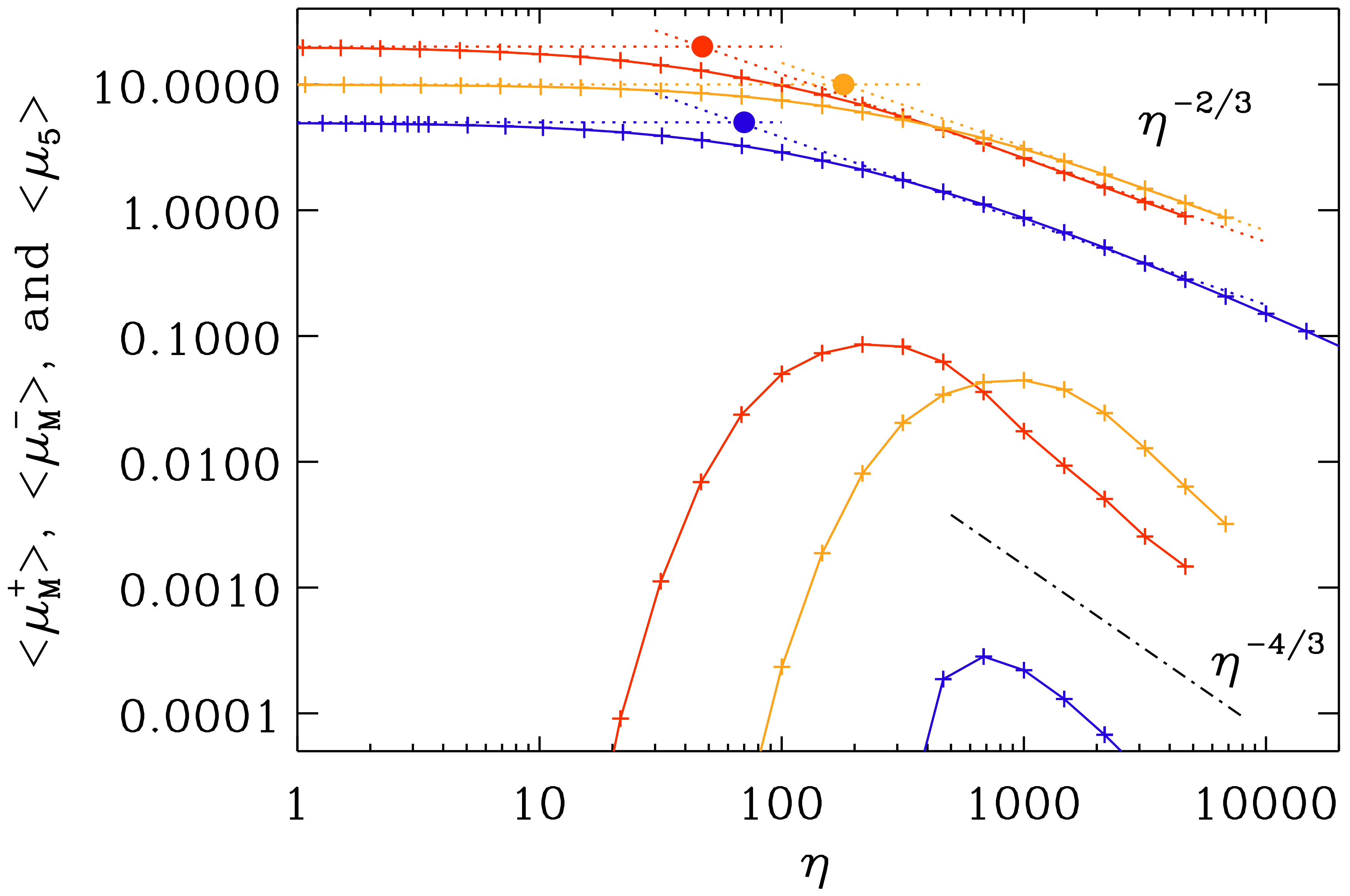


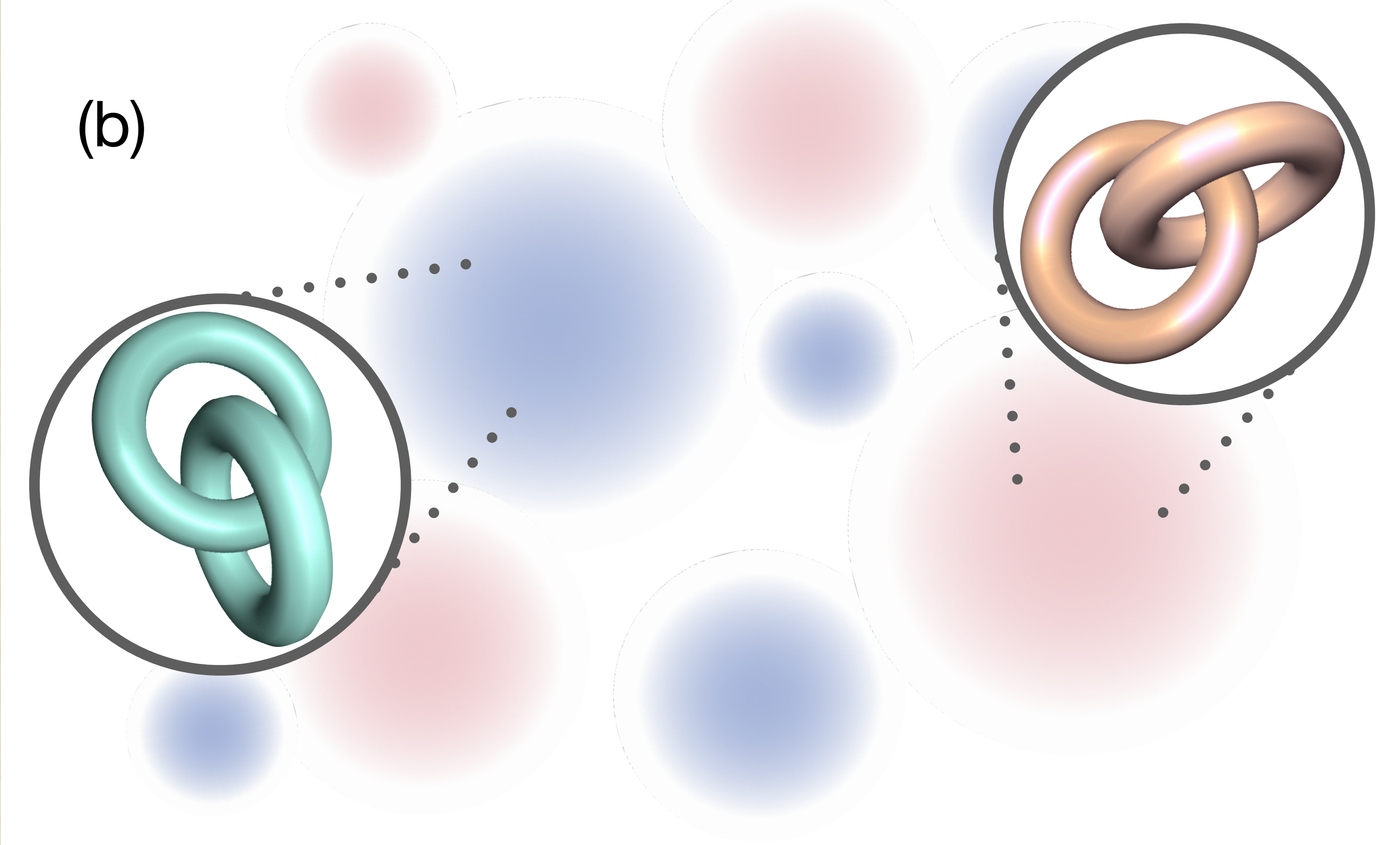
('23 Brandenburg, KK+)

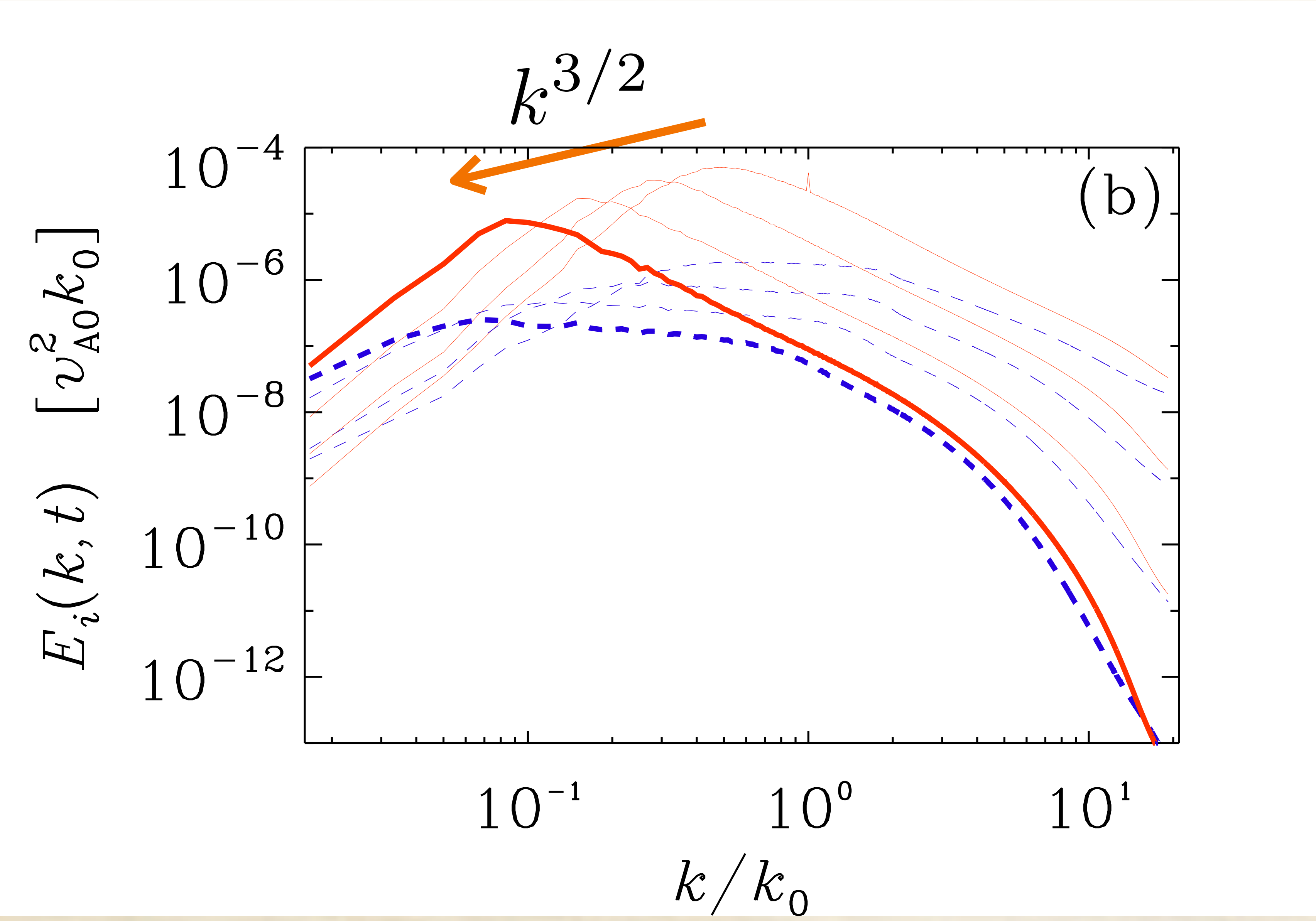
- Negative helicity modes are amplified similar to the chiral plasma instability, but weak.
- Inverse cascade for long-wave length positive helicity mode with the conservation of (adapted) Hosking integral

Hosking integral

'21, '22 Hosking & Schekochihin

~ Two-point function of helicity $\int \mathrm{d}^3 r \langle h(\boldsymbol{x}) h(\boldsymbol{x}+\boldsymbol{r}) \rangle \sim (E(k_{\mathrm{peak}}))^2 k_{\mathrm{peak}}^{-3} = \mathrm{const.}$





'17 Brandenburg & Kahniashvili

Its conservation explains the inverse cascade for the non-helical MFs

Hosking integral '21, '22 Hosking & Schekochihin

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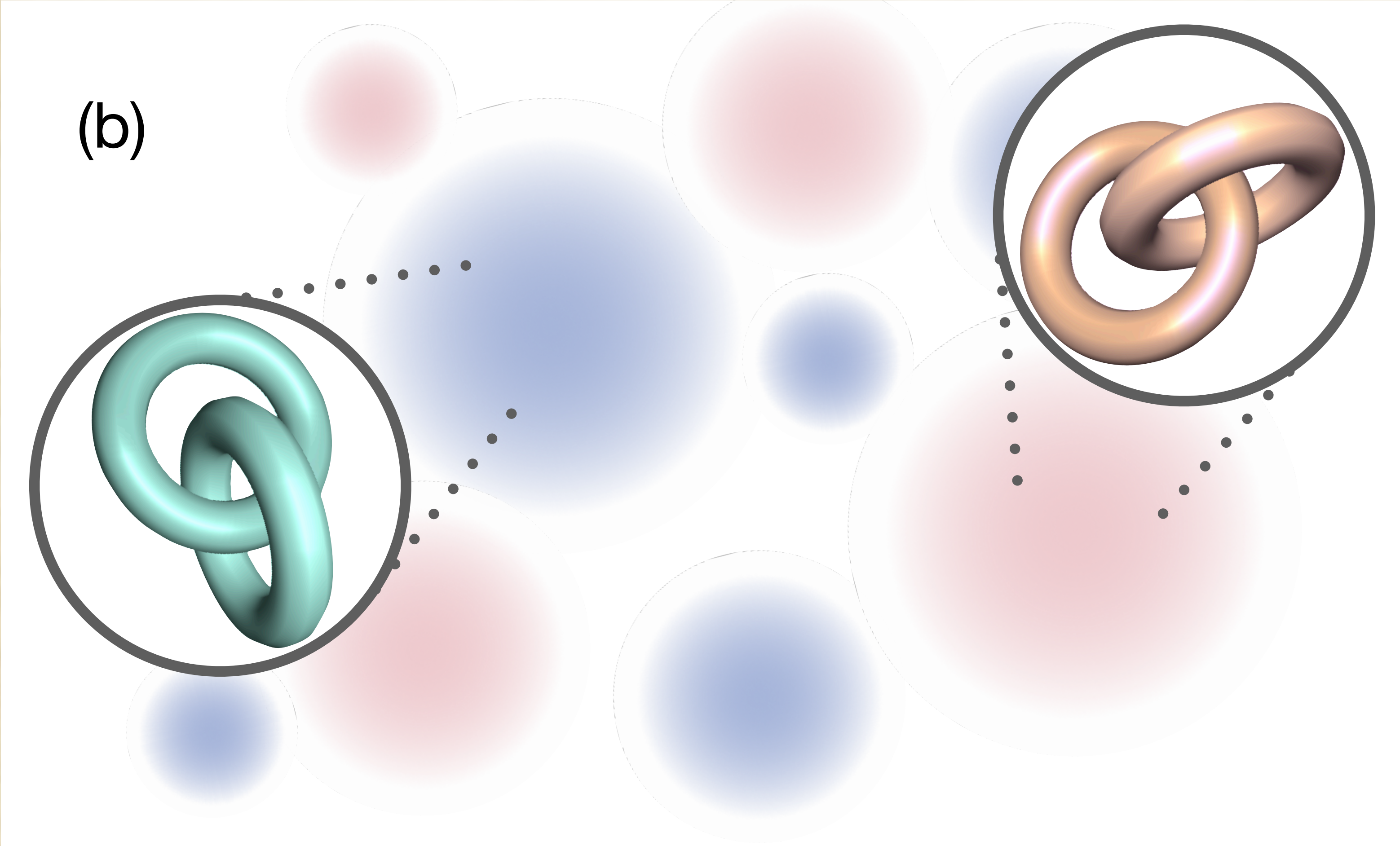
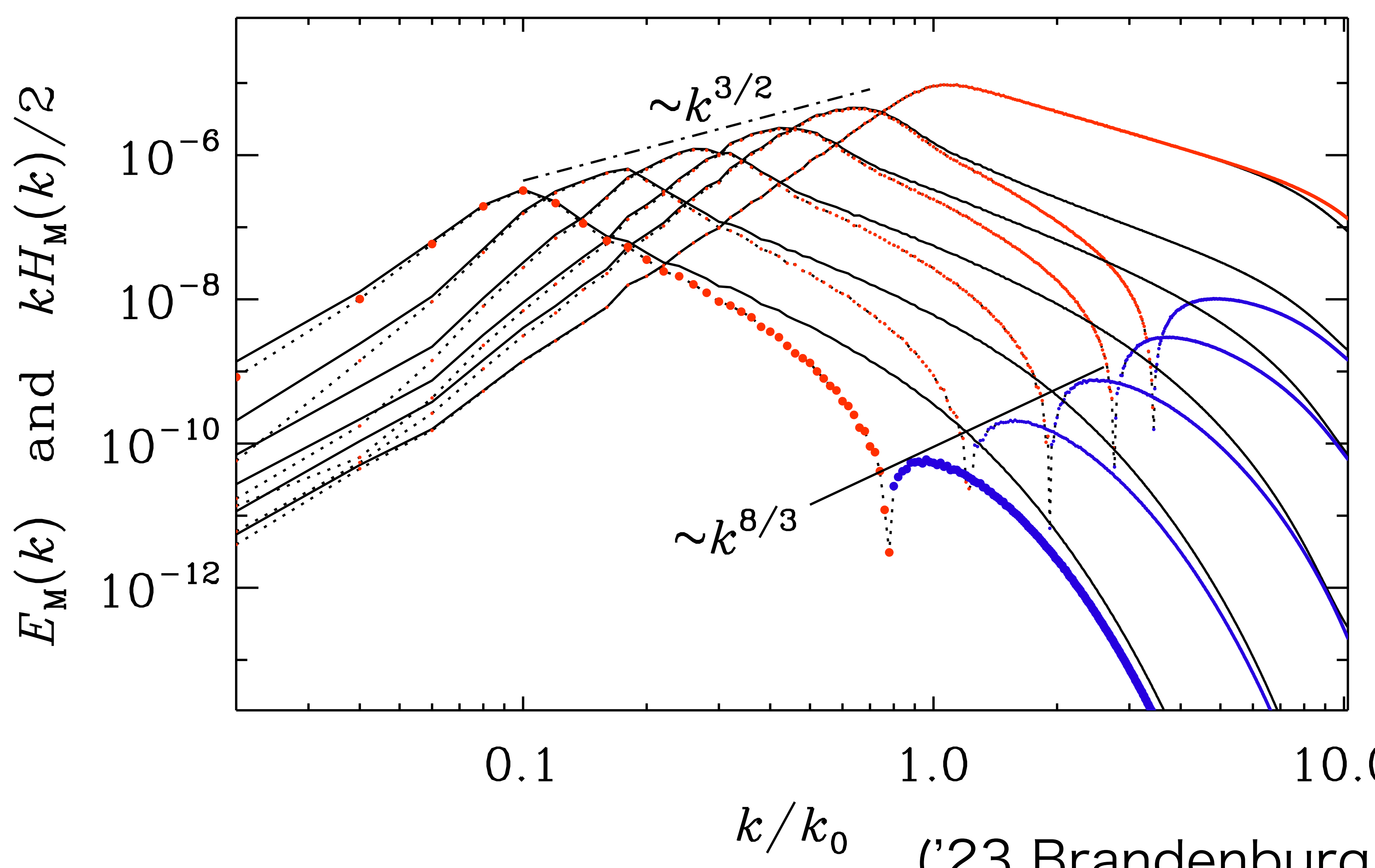




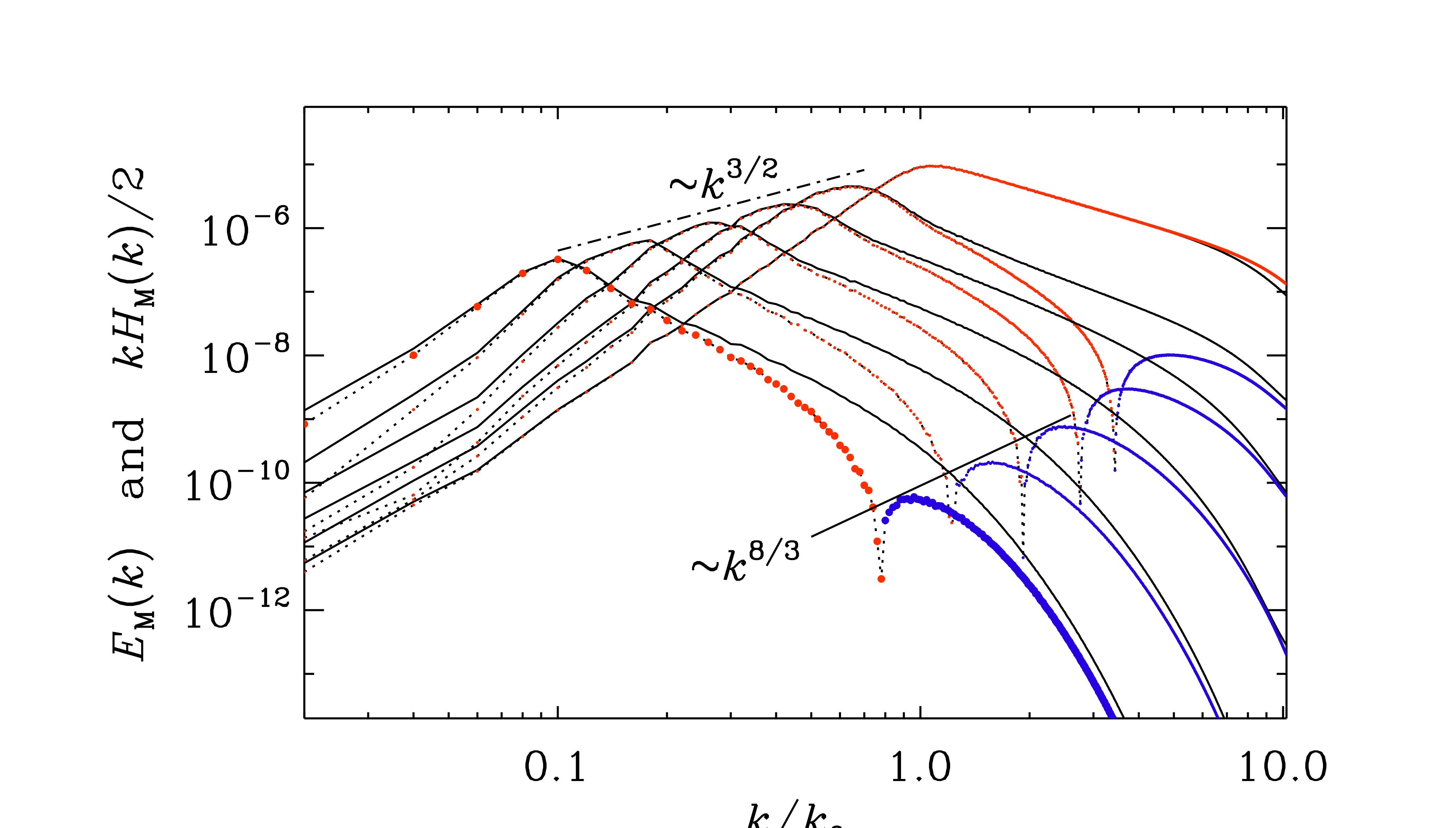
('23 Brandenburg, KK+)

Its conservation explains the inverse cascade for the non-helical MFs

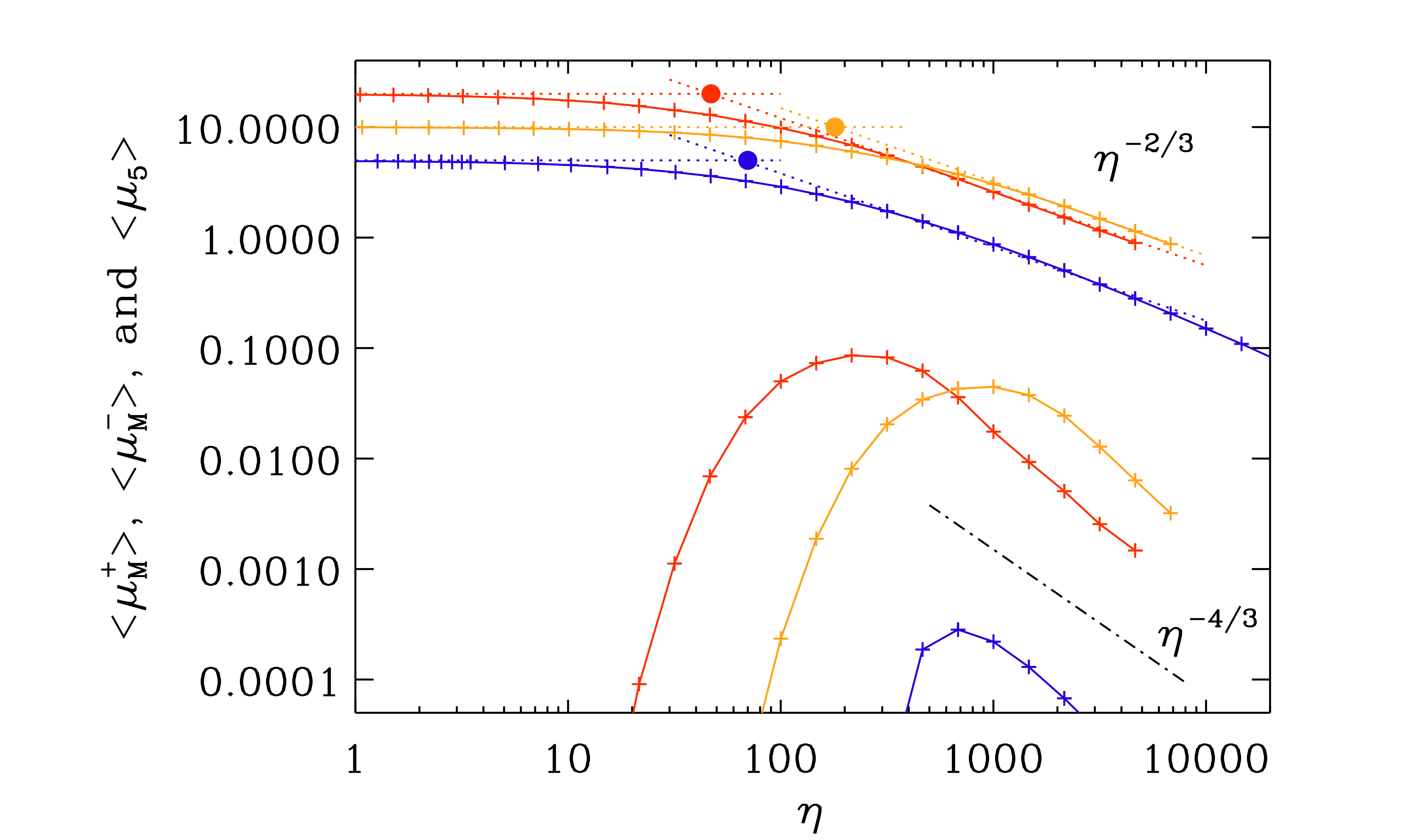
At large scale, magnetic helicity is not conserved,

but Hosking integral for the total chirality $\frac{\alpha}{2\pi}h + q_5$ is conserved.

A typical evolution we obtained.



('23 Brandenburg, KK+)

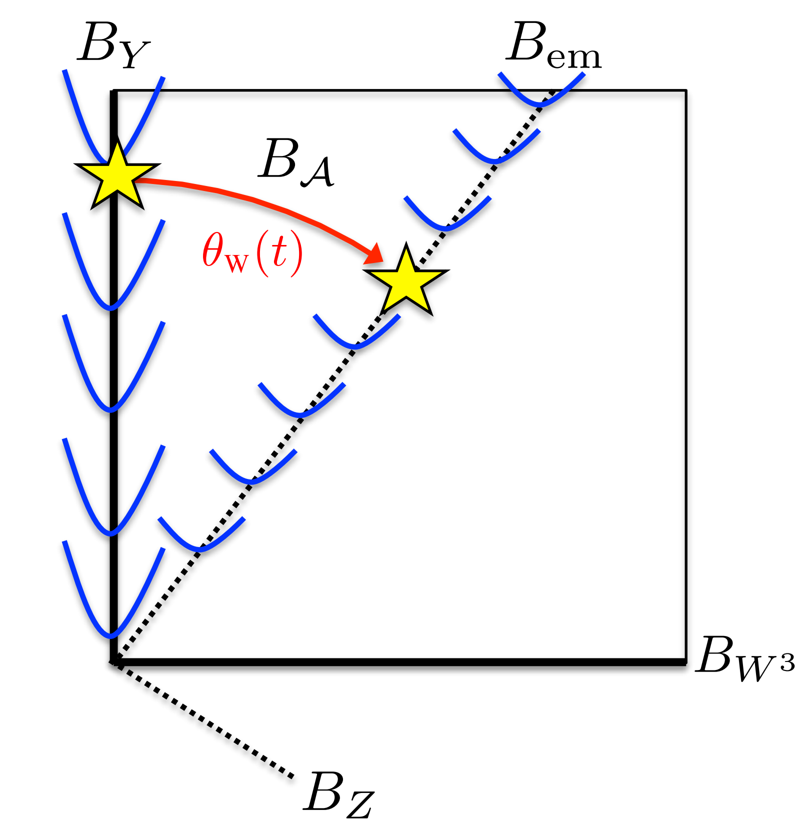


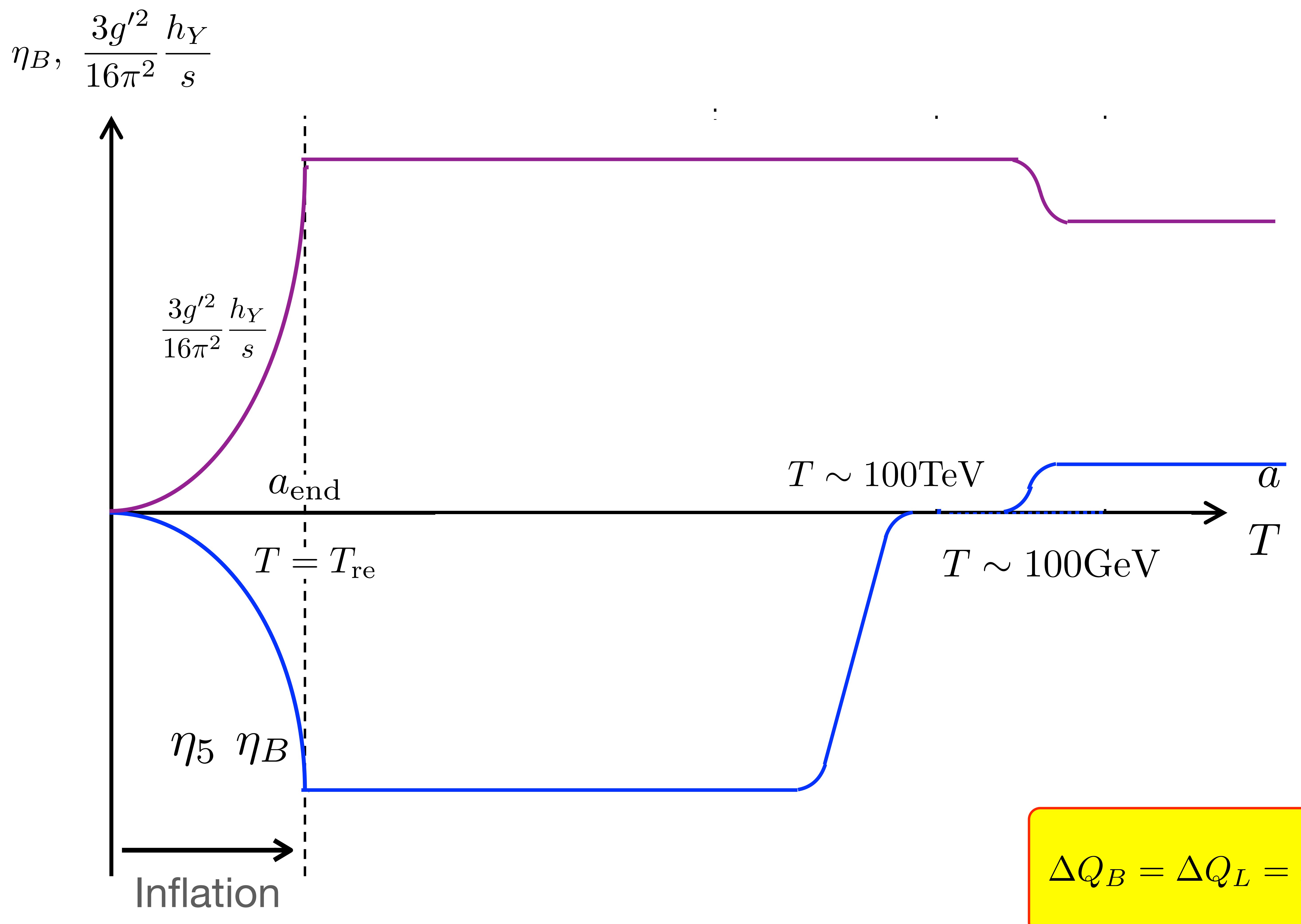
('23 Brandenburg, KK+)

In the parameters we have studied,

- The magnetic helicity and chirality shows a power-law decay $h, \mu_5 \propto \eta^{-2/3}$
- The power-law decay starts at $\eta \simeq \frac{\sigma}{|\mu_{50}|k_0}$ when the CME part for the initial spectrum becomes important in Maxwell eq.

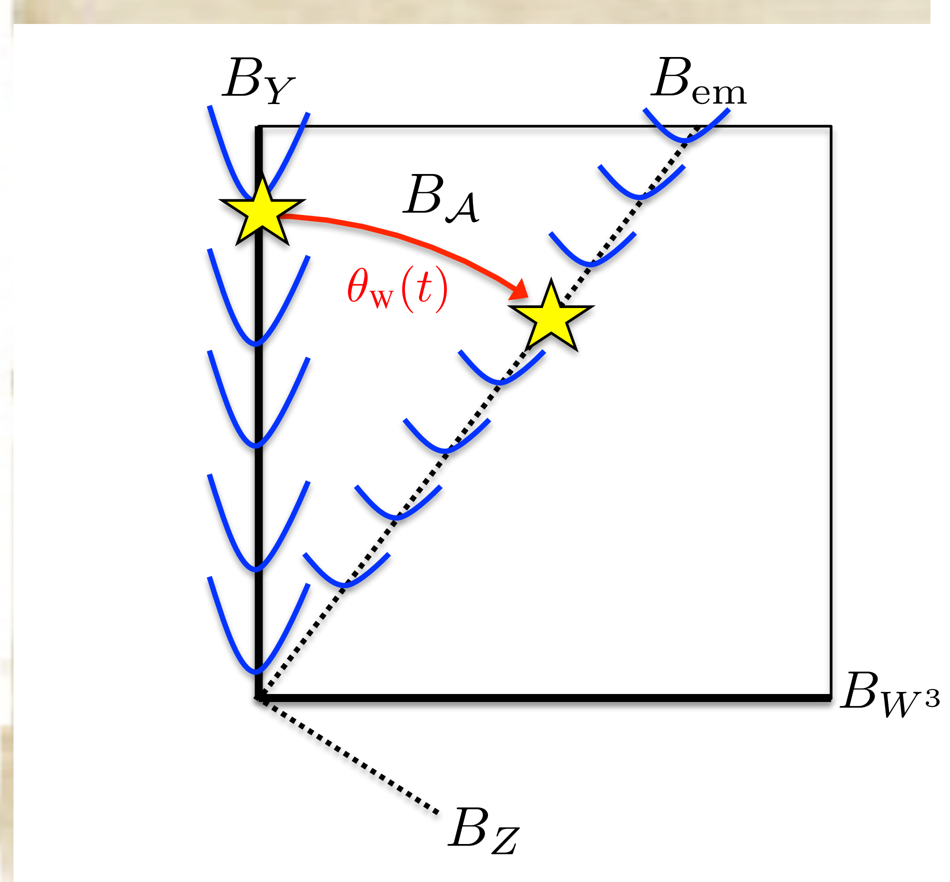
For the typical parameter BAU is solely explained by helicity decay

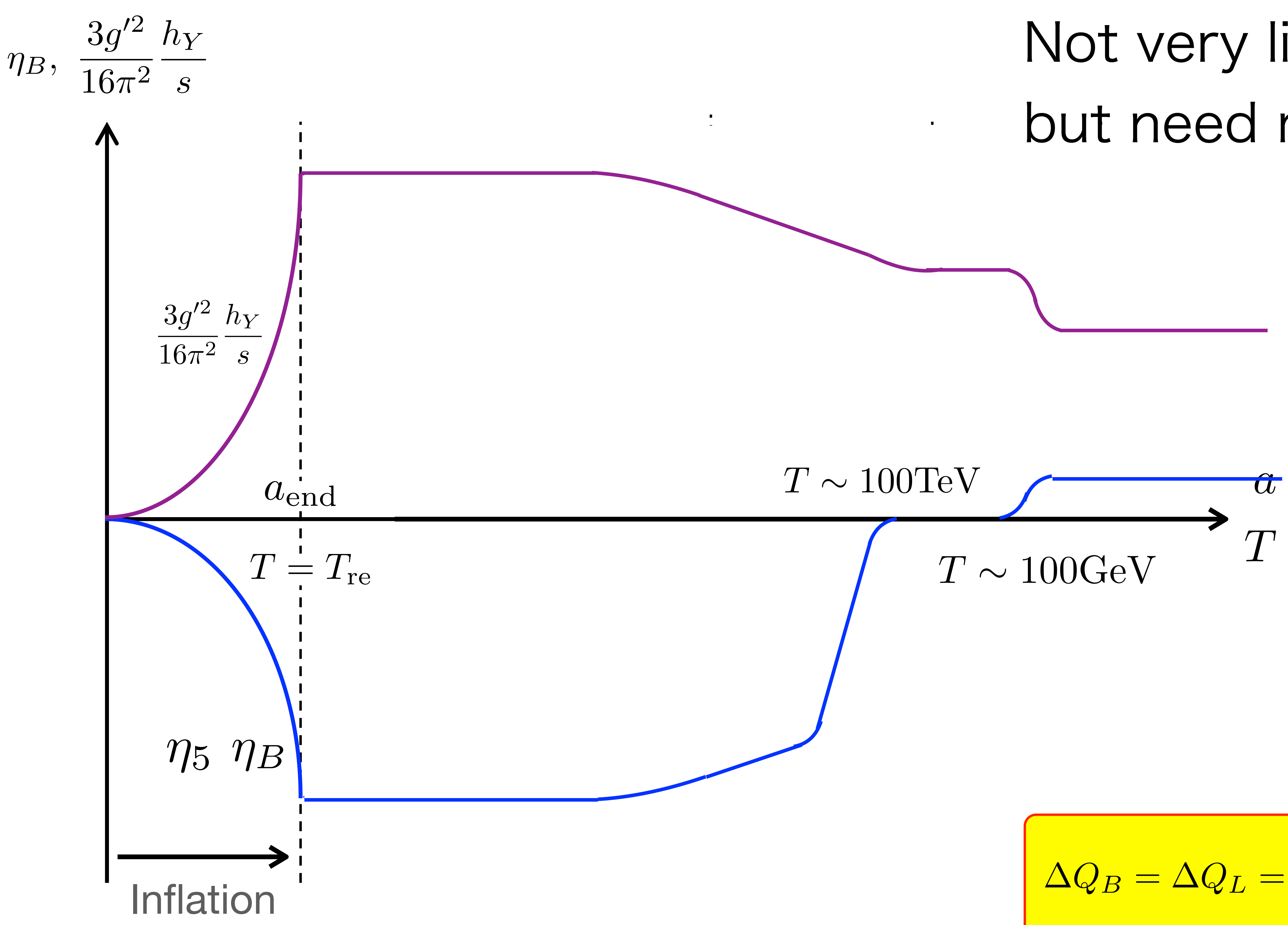




$$\Delta Q_B = \Delta Q_L = N_g \left(\Delta N_{CS} - \frac{g'^2}{16\pi^2} \Delta \mathcal{H}_Y \right)$$

Overproduction is avoided by partial cancellation?



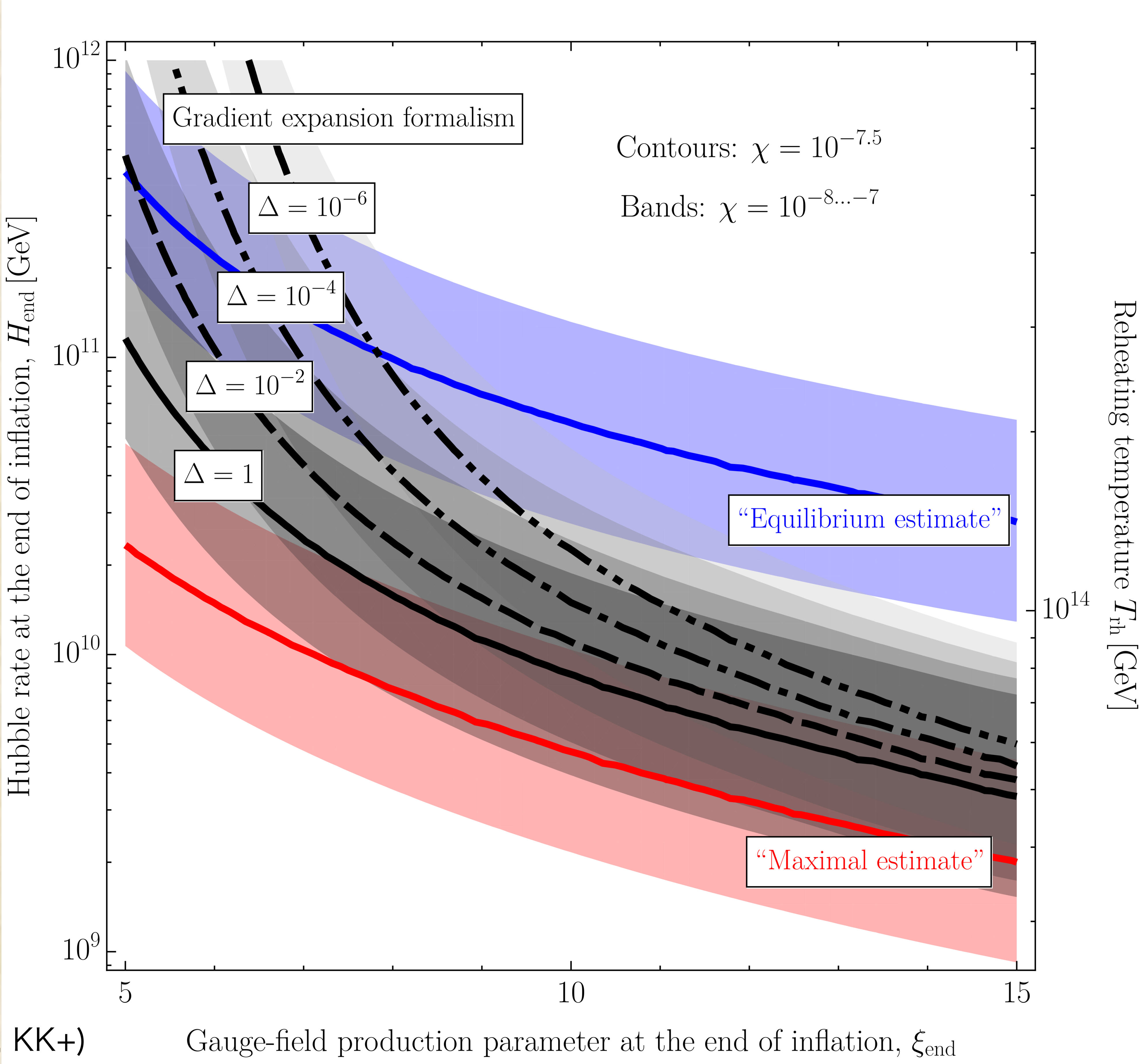


Not very likely,

but need more simulation.

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

Good parameters to explain BAU by axion inflation

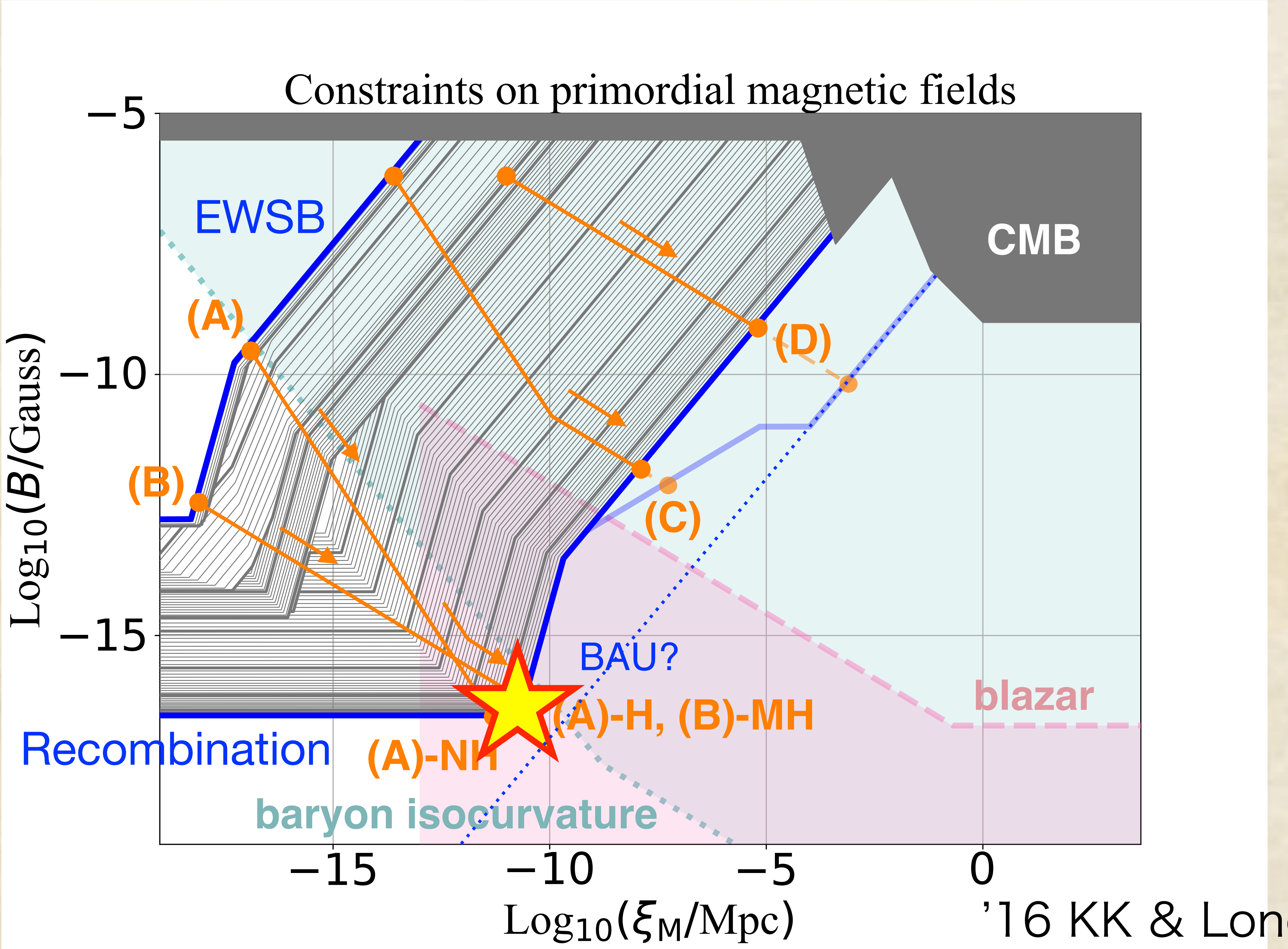


('23 Domcke, KK+)

But needs more study with lattice?

Courtesy: H. Oide

Still difficult to reconcile the BAU and intergalactic MFs…



'16 KK & Long, '24 Uchida, KK+ to appear

But primordial MFs are interesting as the origin of BAU.

Summary

- B+L genesis has been thought not to be a viable baryogenesis model due to the sphaleron washout.
- Pseudoscalar inflation with helical hyper magnetogenesis generates B+L asymmetry. But it is irrelevant for the present BAU?
- No. BAU can be generated by the hypermagnetic helicity decay.

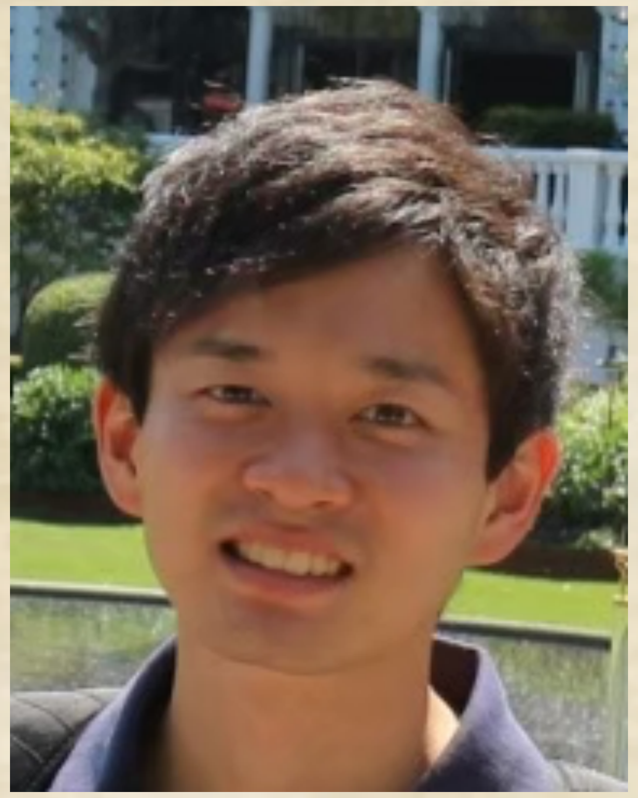
(- Baryogenesis from hypermagnetic helicity decay also predicts the baryon isocurvature perturbation, which constrains even non-helical magnetogenesis.)

- BAU-helicity annihilation is a possible night-mare in this scenario, but it seems to be so worrisome.
- Definite prediction to the IGMFs, but lower than the blazar lower bound.

Courtesy: H. Oide

- Baryogenesis/Leptogenesis from helical GWs?

See, however, my new paper with Jun’ya Kume @Padua



arXiv > hep-ph > arXiv:2404.19726

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High Energy Physics – Phenomenology

[Submitted on 30 Apr 2024]

On the inefficiency of fermion level-crossing under the parity-violating spin-2 gravitational field

Kohei Kamada, Jun'ya Kume

Gravitational chiral anomaly connects the topological charge of spacetime and the chirality of fermions. It has been known that the chirality is carried by the particles (or the excited states) and also by vacuum. While the gravitational anomaly equation has been applied to cosmology, distinction between these two contributions has been rarely discussed. In the study of gravitational leptogenesis, for example, lepton asymmetry associated with the chiral gravitational waves sourced during inflation is evaluated only by integrating the anomaly equation. How these two contributions are distributed has not been seriously investigated. Meanwhile, a dominance of vacuum contribution is observed in some specific types of Bianchi spacetime with parity-violating gravitational fields, whose application to cosmology is not straightforward. One may wonder whether such a vacuum dominance takes place also in the system with chiral gravitational waves around the flat background, which is more suitable for application to realistic cosmology. In this work, we apply an analogy between U(1) electromagnetism and the weak gravity to the spacetime that resembles the one considered in the gravitational leptogenesis scenario. This approach allows us to obtain intuitive understanding of the fermion chirality generation under the parity-violating spin-2 gravitational field. By assuming the emergence of Landau level-like dispersion relation in our setup, we conjecture that level-crossing does not seem to be efficient while the charge accumulation in the vacuum likely takes place. Phenomenological implication is also discussed in the context of gravitational leptogenesis.