# Magnetogenesis for Baryogenesis from Axion Inflation

based on: T. Fujita (Geneva) & KK, PRD93 (2016) 083520 [arXiv:1602.02109 (hep-ph)],
KK & A.J.Long (Michigan), PRD94 (2016) 063501 [arXiv:1606.08891 (astro-ph.CO)],
PRD94 (2016) 123509 [arXiv:1610.03074 (hep-ph)],
D. Jiménez (MPIK), KK, K. Schmitz (Padova) & X.J. Xu (MPIK),
JCAP12 (2017) 011[arXiv:1707.07943[hep-ph]].

Kohei Kamada
(RESCEU, U Tokyo)

mini-workshop: Axion Cosmology
14/05/2019 @ Yukawa Institute for Theoretical Physics, Kyoto University

Courtesy H.Oide

1. Baryogenesis from decaying hypermagnetic helicity
2. Axion inflation can be the source of magnetic fields for baryogenesis
3. Summary

Courtesy H.Oide

# Baryogenesis from helical hypermagnetic fields

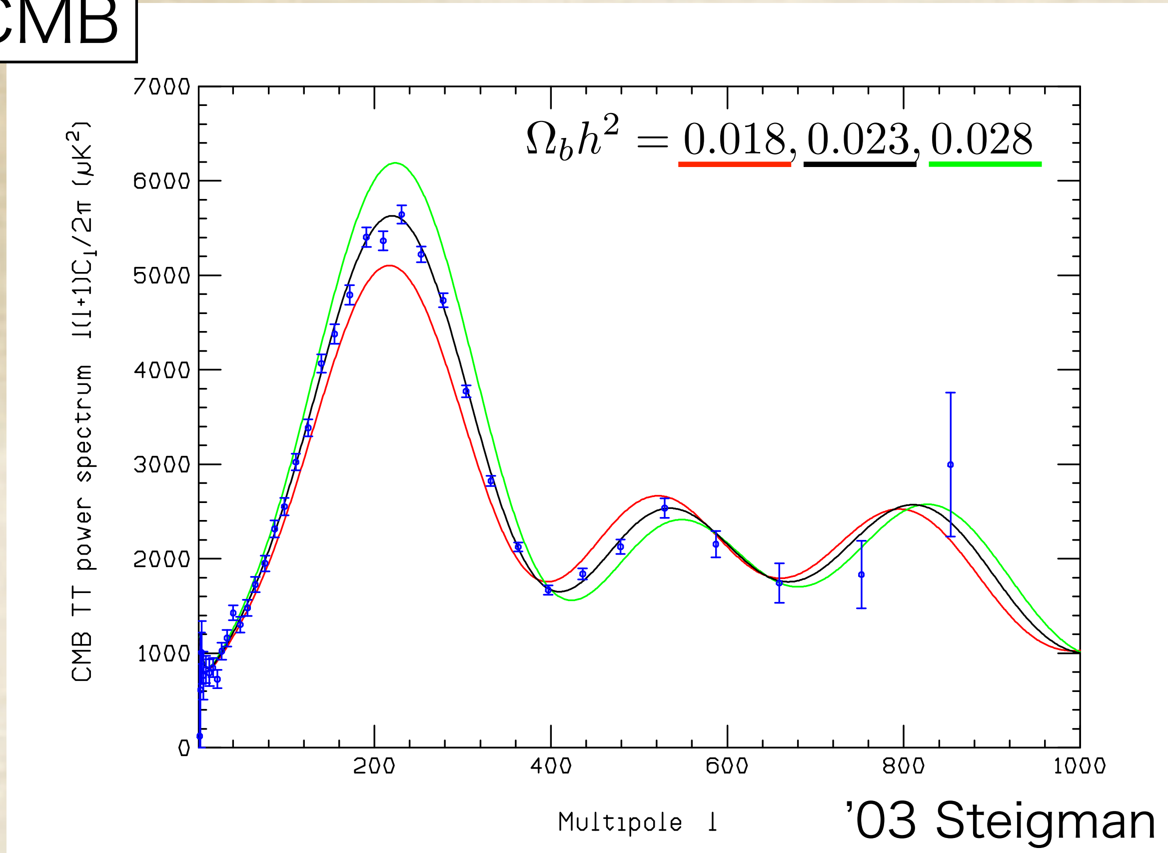
T. Fujita (Kyoto) & KK, PRD93 (2016) 083520 [arXiv:1602.02109 (hep-ph)],
KK & A.J.Long (Chicago), PRD94 (2016) 063501 [arXiv:1606.08891 (astro-ph.CO)],
PRD94 (2016) 123509 [arXiv:1610.03074 (hep-ph)]

Courtesy H.Oide

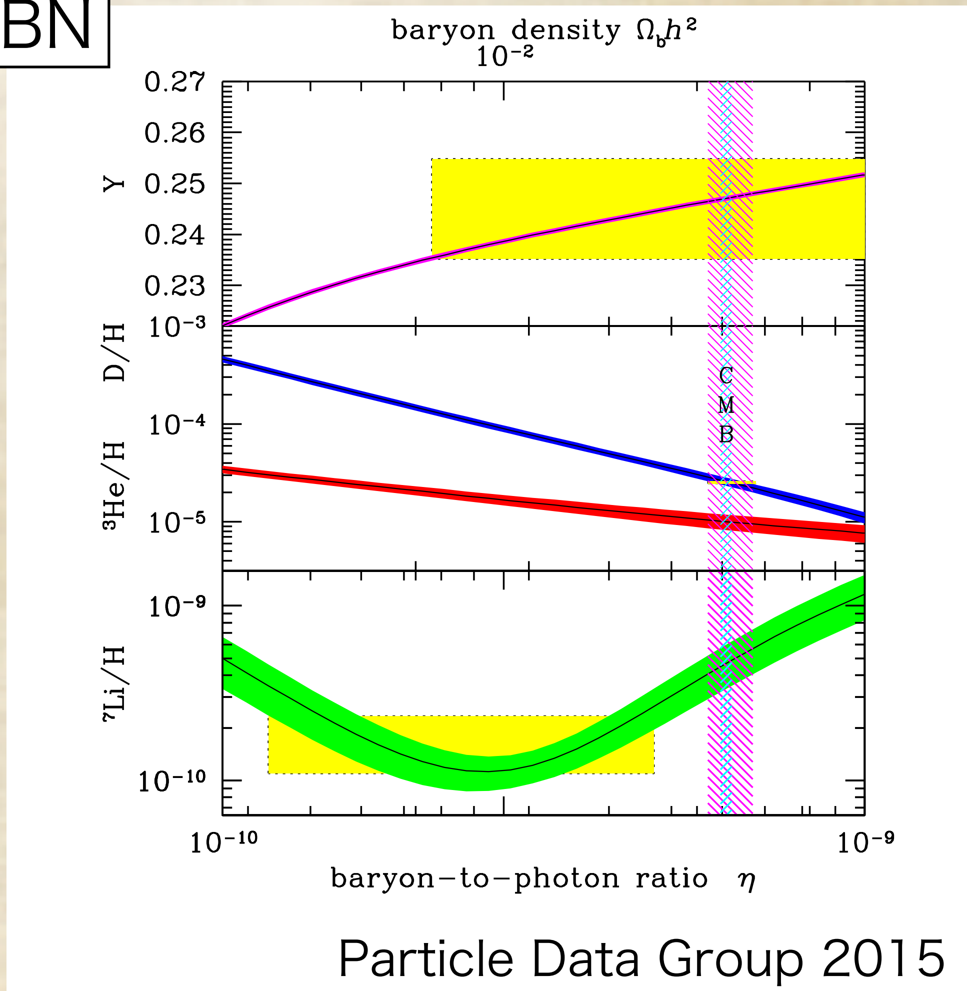
# Baryon Asymmetry of the Universe

- We live in a matter-antimatter asymmetric Universe.
- BBN and CMB can evaluate it quantitatively.

CMB




BBN




$$\eta \equiv \frac{n_B}{n_\gamma} = (6.09 \pm 0.06) \times 10^{-10}$$

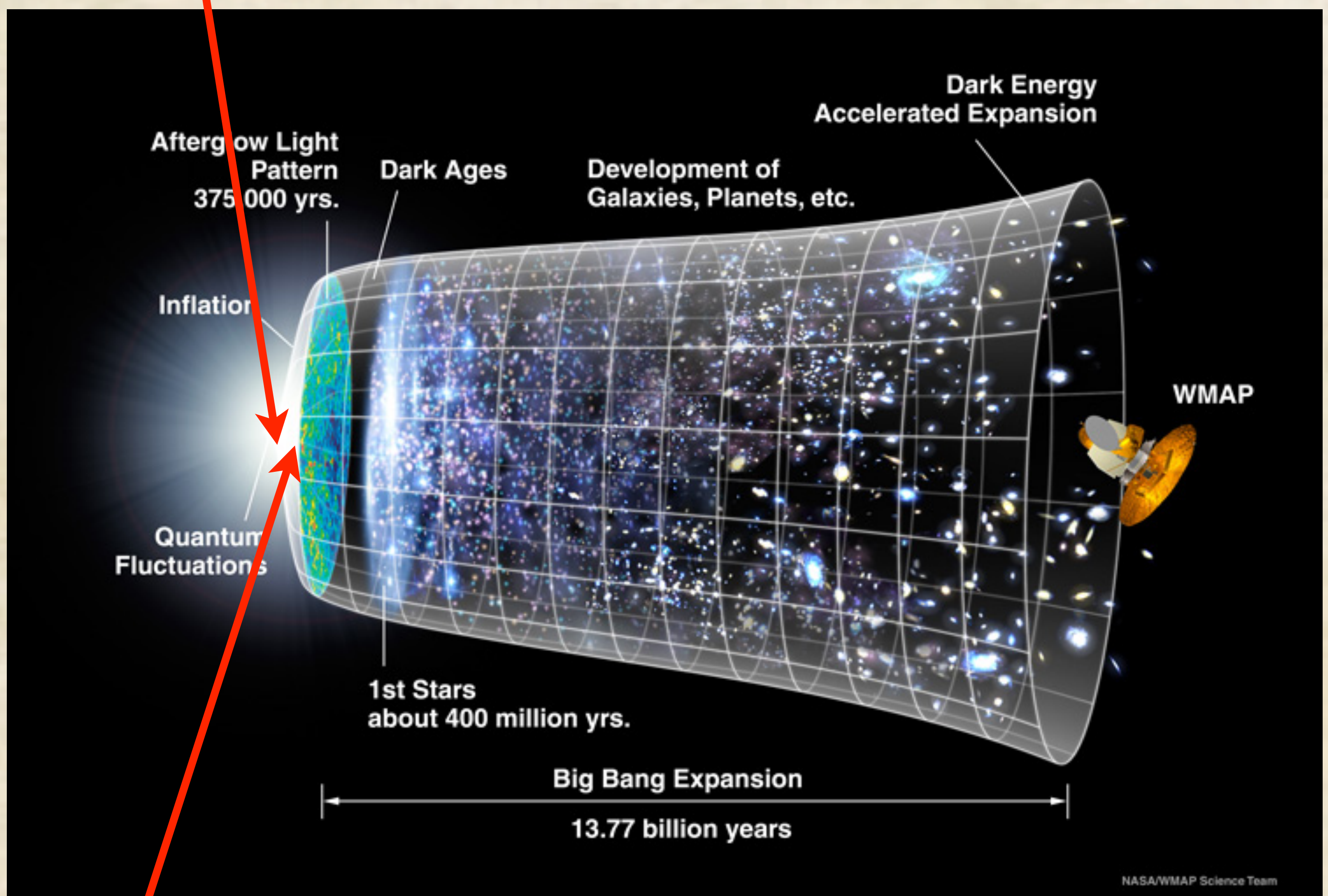
(Planck 2015)

$$\eta = (6.180 \pm 0.195) \times 10^{-10}$$

BBN+D ; '15 Cyburt+

Courtesy H.Oide

## Inflation dilutes the preexisting asymmetry.




WMAP team

## After inflation before BBN, asymmetry must be generated.

| | | | | |
|---|---|---|---|---|
| matter : | ~10000000000+1 | annihilation → $T \sim 100\,\mathrm{MeV}$ | matter : | ~1 |
| anti matter : | ~10000000000 | | anti matter : | ~0 |
| photon : | ~10000000000 | | photon : | ~10000000000 |

Courtesy H.Oide

In order to generate baryon asymmetry...

Sakharov's condition is required. ('67 Sakharov)

1. B-violation
2. C & CP-violation
3. Deviation from thermal equilibrium

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BSM is required!?

- Leptogenesis ('85 Fukigita&Yanagida) : RH neutrinos
- Affleck-Dine ('85 Affleck&Dine, '95 Dine,Randall&Thomas) : SUSY with $\not B$ and $\not{CP}$ op.
- EW baryogenesis ('85 Kuzmin, Rubakov&Shaposhnikov) : 1st order EWPT + $\not{CP}$ op.

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If magnetic fields existed in the early Universe,

a new story can be imagined !!

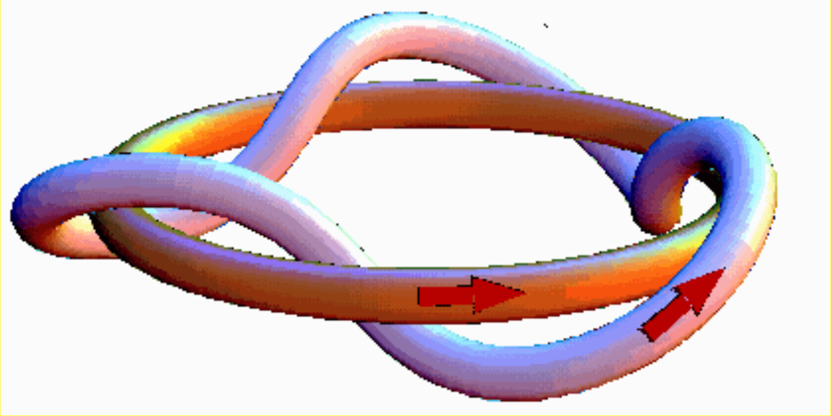
Giovannini&Shaposhnikov ('98), KK& Fujita, KK&Long ('16)

Courtesy H.Oide

# Key elements

Hypermagnetic helicity

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



solar.physics.montana.edu

(The gauge field is the one of $U(1)_Y$ in the SM. )

Courtesy H.Oide

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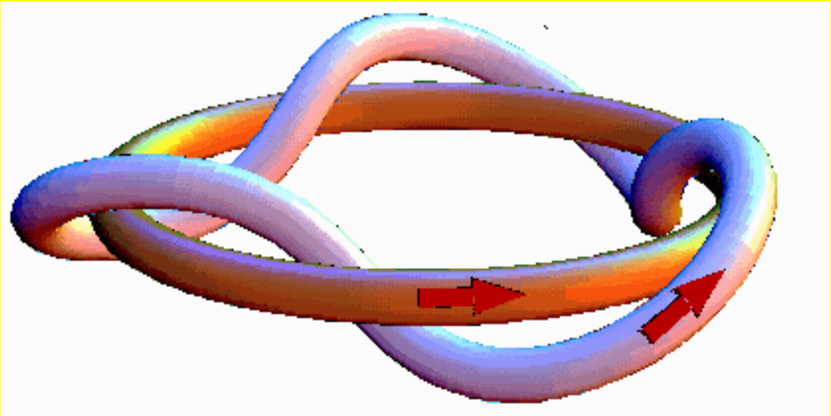

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## Chiral anomaly in the SM ('76 't Hooft)

$$\partial_\mu j_B^\mu = \partial_\mu j_L^\mu = N_g \left( \frac{g^2}{16\pi^2} \mathrm{tr}\left[W_{\mu\nu}\tilde{W}^{\mu\nu}\right] - \frac{g'^2}{32\pi^2} Y_{\mu\nu}\tilde{Y}^{\mu\nu} \right)$$

SU(2) part:"EW sphaleron"

U(1) part: often neglected

Courtesy H.Oide

# Key elements

Hypermagnetic helicity

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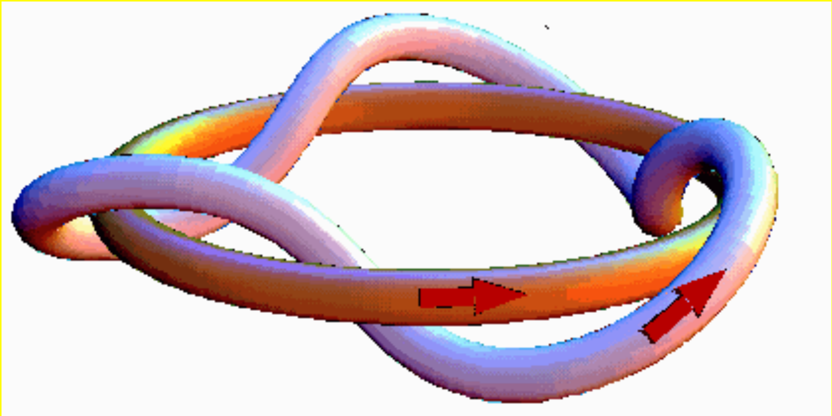

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Chiral anomaly in the SM ('76 't Hooft)

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

SU(2) part:"EW sphaleron"

U(1) part: often neglected

Change of BG hypermagnetic helicity can be the source of BAU

Courtesy H.Oide

# Key elements

Hypermagnetic helicity

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lected

AU

If there were 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!

Courtesy H.Oide

Once there are large-scale helical hyperMFs before EWSB, decay of hypermagnetic helicity occurs automatically.

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

$$\frac{1}{V}\partial_t \mathcal{H} = -2\langle \boldsymbol{E}_Y \cdot \boldsymbol{B}_Y \rangle = -\frac{2}{\sigma}\langle \boldsymbol{B}_Y \cdot \boldsymbol{\nabla} \times \boldsymbol{B}_Y \rangle \simeq -\frac{2}{\sigma}\frac{B_p^2}{\lambda_B}$$

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

Courtesy H.Oide

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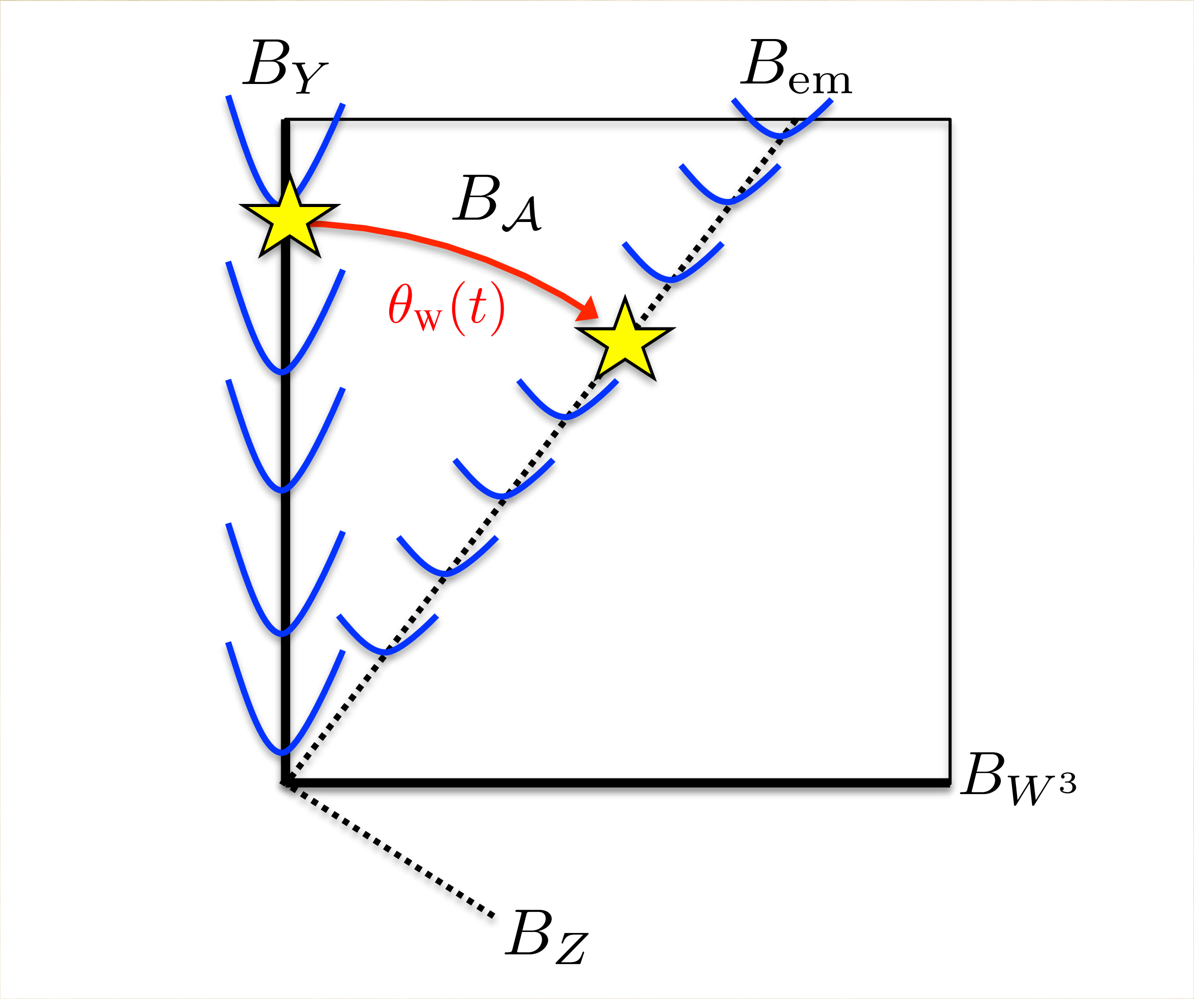
2. Electroweak symmetry breaking ('98 Giovannini&Shaposhnikov,'16 KK&Long)

Courtesy H.Oide

# Electroweak symmetry breaking




## Gauge group

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

## Large-scale (massless) MFs

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

## Magnetic helicity

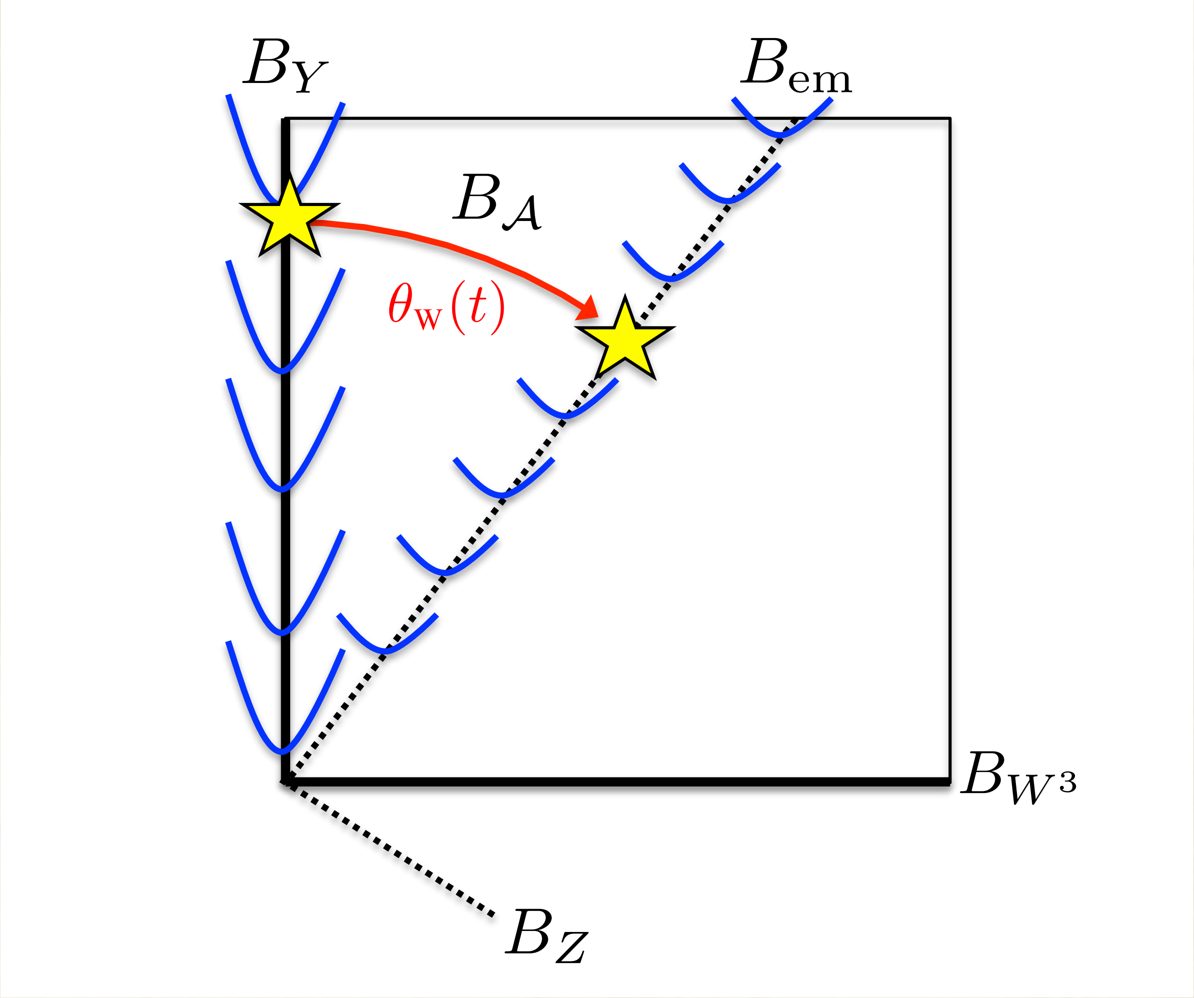
$$H_Y^{\rm before} \to H_{em}^{\rm after} = H_Y^{\rm before}$$

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

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

Courtesy H.Oide

# Electroweak symmetry breaking

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BAU induction

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

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

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

Courtesy H.Oide

# Back reactions/washout effects?

EW sphalerons+chirality flip by electron Yukawa

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

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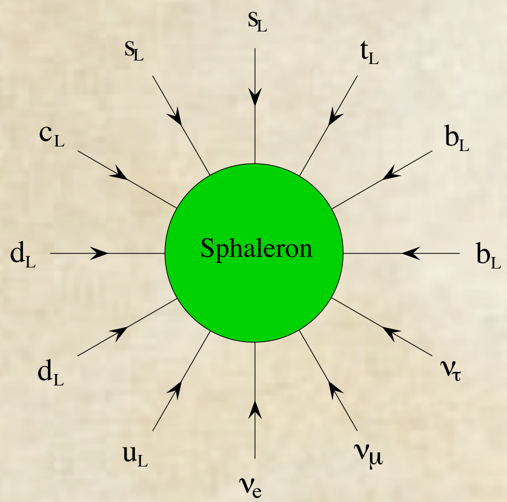


W. Buchmüller, 1212.3554

Thermal fluctuations of W-boson induces $\Delta N_{\rm CS}$

Together with Yukawa int., try to washout $Q_B$

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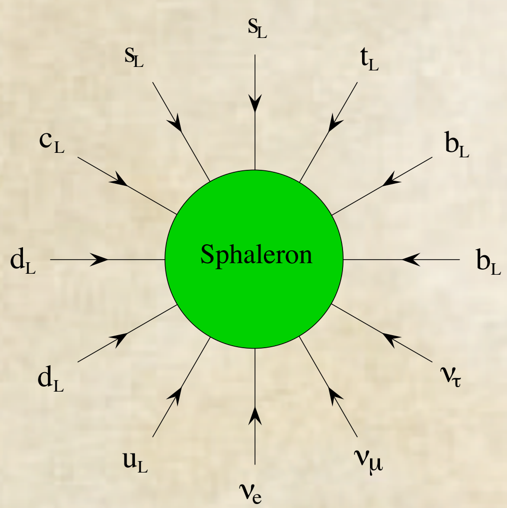


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Ampere's law

$$\boldsymbol{\nabla} \times \boldsymbol{B}_Y = \boldsymbol{J} = \sigma(\boldsymbol{E}_Y + \boldsymbol{v} \times \boldsymbol{B}_Y) + \frac{2\alpha_Y}{\pi}\mu_5 \boldsymbol{B}_Y$$

Ohm's current — Chiral magnetic current

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

Courtesy H.Oide

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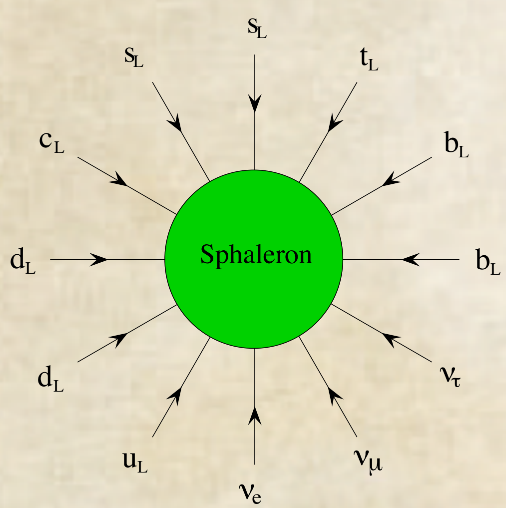


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$$\frac{d}{dt}n_f \ni \#\langle Y_{\mu\nu}\tilde{Y}^{\mu\nu}\rangle \; (= -4\langle \boldsymbol{E}_Y \cdot \boldsymbol{B}_Y\rangle)$$

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

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

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

Courtesy H.Oide

Schematically evolution equation is given by

Source term　　washout term

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

MHD decay　　EWSB　　EW sphaleron chirality-flip CME

Courtesy H.Oide

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Source term — washout term

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MHD decay — EWSB — EW sphaleron chirality-flip CME

Reaches at "terminal" asymmetry…

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

Courtesy H.Oide

# We really solved…

$$\frac{d\eta_{u_L^i}}{dx} = -\mathcal{S}^i_{\rm UDW} - \sum_{j=1}^{N_{\rm g}}\left(\mathcal{S}^{ij}_{\rm Uhu} + \mathcal{S}^{ij}_{\rm Uu} + \mathcal{S}^{ij}_{\rm Uhd}\right) - \mathcal{S}_{\rm s,sph} - \frac{N_{\rm c}}{2}\mathcal{S}_{\rm w,sph} + \left(N_{\rm c} y_{Q_L}^2 \mathcal{S}_{\rm y}^{\rm bkg} + \frac{N_{\rm c}}{2}\mathcal{S}_{\rm w}^{\rm bkg} + N_{\rm c}\frac{y_{Q_L}}{2}\mathcal{S}_{\rm yw}^{\rm bkg}\right)$$

$$\frac{d\eta_{d_L^i}}{dx} = \mathcal{S}^i_{\rm UDW} - \sum_{j=1}^{N_{\rm g}}\left(\mathcal{S}^{ij}_{\rm Dhd} + \mathcal{S}^{ij}_{\rm Dd} + \mathcal{S}^{ij}_{\rm Dhu}\right) - \mathcal{S}_{\rm s,sph} - \frac{N_{\rm c}}{2}\mathcal{S}_{\rm w,sph} + \left(N_{\rm c} y_{Q_L}^2 \mathcal{S}_{\rm y}^{\rm bkg} + \frac{N_{\rm c}}{2}\mathcal{S}_{\rm w}^{\rm bkg} - N_{\rm c}\frac{y_{Q_L}}{2}\mathcal{S}_{\rm yw}^{\rm bkg}\right)$$

$$\frac{d\eta_{\nu_L^i}}{dx} = -\mathcal{S}^i_{\nu\rm EW} - \sum_{j=1}^{N_{\rm g}}\mathcal{S}^{ij}_{\nu\rm he} - \frac{1}{2}\mathcal{S}_{\rm w,sph} + \left(y_{L_L}^2 \mathcal{S}_{\rm y}^{\rm bkg} + \frac{1}{2}\mathcal{S}_{\rm w}^{\rm bkg} + \frac{y_{L_L}}{2}\mathcal{S}_{\rm yw}^{\rm bkg}\right)$$

$$\frac{d\eta_{e_L^i}}{dx} = \mathcal{S}^i_{\nu\rm EW} - \sum_{j=1}^{N_{\rm g}}\left(\mathcal{S}^{ij}_{\rm Ehe} + \mathcal{S}^{ij}_{\rm Ee}\right) - \frac{1}{2}\mathcal{S}_{\rm w,sph} + \left(y_{L_L}^2 \mathcal{S}_{\rm y}^{\rm bkg} + \frac{1}{2}\mathcal{S}_{\rm w}^{\rm bkg} - \frac{y_{L_L}}{2}\mathcal{S}_{\rm yw}^{\rm bkg}\right)$$

$$\frac{d\eta_{u_R^i}}{dx} = \sum_{j=1}^{N_{\rm g}}\left(\mathcal{S}^{ji}_{\rm Uhu} + \mathcal{S}^{ji}_{\rm Uu} + \mathcal{S}^{ji}_{\rm Dhu}\right) + \mathcal{S}_{\rm s,sph} - N_{\rm c} y_{u_R}^2 \mathcal{S}_{\rm y}^{\rm bkg}$$

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$$\frac{d\eta_{e_R^i}}{dx} = \sum_{j=1}^{N_{\rm g}}\left(\mathcal{S}^{ji}_{\rm Ehe} + \mathcal{S}^{ji}_{\rm Ee} + \mathcal{S}^{ji}_{\nu\rm he}\right) - y_{e_R}^2 \mathcal{S}_{\rm y}^{\rm bkg}$$

$$\frac{d\eta_{\phi^+}}{dx} = -\left(\mathcal{S}_{\rm hhw} + \mathcal{S}_{\rm hw}\right) + \sum_{i,j=1}^{N_{\rm g}}\left(-\mathcal{S}^{ij}_{\rm Dhu} + \mathcal{S}^{ij}_{\rm Uhd} + \mathcal{S}^{ij}_{\nu\rm he}\right)$$

$$\frac{d\eta_{\phi^0}}{dx} = \mathcal{S}_{\rm hhw} - \mathcal{S}_{\rm h} + \sum_{i,j=1}^{N_{\rm g}}\left(-\mathcal{S}^{ij}_{\rm Uhu} + \mathcal{S}^{ij}_{\rm Dhd} + \mathcal{S}^{ij}_{\rm Ehe}\right)$$

$$\frac{d\eta_{W^+}}{dx} = \left(\mathcal{S}_{\rm hhw} + \mathcal{S}_{\rm hw}\right) + \sum_{i=1}^{N_{\rm g}}\left(\mathcal{S}^i_{\rm UDW} + \mathcal{S}^i_{\nu\rm EW}\right) .$$

$$\mathcal{S}^{ij}_{\rm Dhu} \equiv \frac{\gamma^{ij}_{\rm Dhu}}{2}\left(\frac{\eta_{d_L^i}}{k_{d_L^i}} + \frac{\eta_{\phi^+}}{k_{\phi^+}} - \frac{\eta_{u_R^j}}{k_{u_R^j}}\right) , \quad \mathcal{S}^{ij}_{\rm Uhu} \equiv \frac{\gamma^{ij}_{\rm Uhu}}{2}\left(\frac{\eta_{u_L^i}}{k_{u_L^i}} + \frac{\eta_{\phi^0}}{k_{\phi^0}} - \frac{\eta_{u_R^j}}{k_{u_R^j}}\right) ,$$

$$\mathcal{S}^{ij}_{\rm Uhd} \equiv \frac{\gamma^{ij}_{\rm Uhd}}{2}\left(\frac{\eta_{u_L^i}}{k_{u_L^i}} - \frac{\eta_{\phi^+}}{k_{\phi^+}} - \frac{\eta_{d_R^j}}{k_{d_R^j}}\right) , \quad \mathcal{S}^{ij}_{\rm Dhd} \equiv \frac{\gamma^{ij}_{\rm Dhd}}{2}\left(\frac{\eta_{d_L^i}}{k_{d_L^i}} - \frac{\eta_{\phi^0}}{k_{\phi^0}} - \frac{\eta_{d_R^j}}{k_{d_R^j}}\right) ,$$

$$\mathcal{S}^{ij}_{\nu\rm he} \equiv \frac{\gamma^{ij}_{\nu\rm he}}{2}\left(\frac{\eta_{\nu_L^i}}{k_{\nu_L^i}} - \frac{\eta_{\phi^+}}{k_{\phi^+}} - \frac{\eta_{e_R^j}}{k_{e_R^j}}\right) , \quad \mathcal{S}^{ij}_{\rm Ehe} \equiv \frac{\gamma^{ij}_{\rm Ehe}}{2}\left(\frac{\eta_{e_L^i}}{k_{e_L^i}} - \frac{\eta_{\phi^0}}{k_{\phi^0}} - \frac{\eta_{e_R^j}}{k_{e_R^j}}\right) ,$$

$$\mathcal{S}^i_{\rm UDW} \equiv \gamma^i_{\rm UDW}\left(\frac{\eta_{u_L^i}}{k_{u_L^i}} - \frac{\eta_{d_L^i}}{k_{d_L^i}} - \frac{\eta_{W^+}}{k_{W^+}}\right)$$

$$\mathcal{S}^i_{\nu\rm EW} \equiv \gamma^i_{\nu\rm EW}\left(\frac{\eta_{\nu_L^i}}{k_{\nu_L^i}} - \frac{\eta_{e_L^i}}{k_{e_L^i}} - \frac{\eta_{W^+}}{k_{W^+}}\right)$$

$$\mathcal{S}_{\rm hhw} \equiv \gamma_{\rm hhw}\left(\frac{\eta_{\phi^+}}{k_{\phi^+}} - \frac{\eta_{\phi^0}}{k_{\phi^0}} - \frac{\eta_{W^+}}{k_{W^+}}\right)$$

$$\mathcal{S}_{\rm s,sph} \equiv \gamma_{\rm s,sph}\sum_{i=1}^{N_{\rm g}}\left(\frac{\eta_{u_L^i}}{k_{u_L^i}} + \frac{\eta_{d_L^i}}{k_{d_L^i}} - \frac{\eta_{u_R^i}}{k_{u_R^i}} - \frac{\eta_{d_R^i}}{k_{d_R^i}}\right) ,$$

$$\mathcal{S}_{\rm w,sph} \equiv \gamma_{\rm w,sph}\sum_{i=1}^{N_{\rm g}}\left(\frac{N_{\rm c}}{2}\frac{\eta_{u_L^i}}{k_{u_L^i}} + \frac{N_{\rm c}}{2}\frac{\eta_{d_L^i}}{k_{d_L^i}} + \frac{1}{2}\frac{\eta_{\nu_L^i}}{k_{\nu_L^i}} + \frac{1}{2}\frac{\eta_{e_L^i}}{k_{e_L^i}}\right)$$

$$\mathcal{S}^{ij}_{\rm Uu} \equiv \gamma^{ij}_{\rm Uu}\left(\frac{\eta_{u_L^i}}{k_{u_L^i}} - \frac{\eta_{u_R^j}}{k_{u_R^j}}\right) ,$$

$$\mathcal{S}^{ij}_{\rm Dd} \equiv \gamma^{ij}_{\rm Dd}\left(\frac{\eta_{d_L^i}}{k_{d_L^i}} - \frac{\eta_{d_R^j}}{k_{d_R^j}}\right) ,$$

$$\mathcal{S}^{ij}_{\rm Ee} \equiv \gamma^{ij}_{\rm Ee}\left(\frac{\eta_{e_L^i}}{k_{e_L^i}} - \frac{\eta_{e_R^j}}{k_{e_R^j}}\right) ,$$

$$\mathcal{S}_{\rm hw} \equiv \gamma_{\rm hw}\left(\frac{\eta_{\phi^+}}{k_{\phi^+}} - \frac{\eta_{W^+}}{k_{W^+}}\right)$$

$$\mathcal{S}_{\rm h} \equiv \gamma_{\rm h}\frac{\eta_{\phi^0}}{k_{\phi^0}} .$$

$$\eta = n/s$$
$$x = T/H \sim M_{\rm pl}/T$$
$$k = \#\ \text{degree of freedom}$$

$$\mathcal{S}_{\rm y}^{\rm bkg} = \frac{1}{sT}\frac{\alpha_{\rm y}}{4\pi}\frac{1}{2}\epsilon^{\mu\nu\rho\sigma}\overline{\langle Y_{\mu\nu}\rangle\langle Y_{\rho\sigma}\rangle}$$

$$\mathcal{S}_{\rm w}^{\rm bkg} = \frac{1}{sT}\frac{1}{2}\frac{\alpha_{\rm w}}{4\pi}\frac{1}{2}\epsilon^{\mu\nu\rho\sigma}\overline{\langle W^a_{\mu\nu}\rangle\langle W^a_{\rho\sigma}\rangle}$$

$$\mathcal{S}_{\rm yw}^{\rm bkg} = \frac{1}{sT}\frac{gg'/4\pi}{4\pi}\epsilon^{\mu\nu\rho\sigma}\overline{\langle Y_{\mu\nu}\rangle\langle W^3_{\rho\sigma}\rangle} .$$

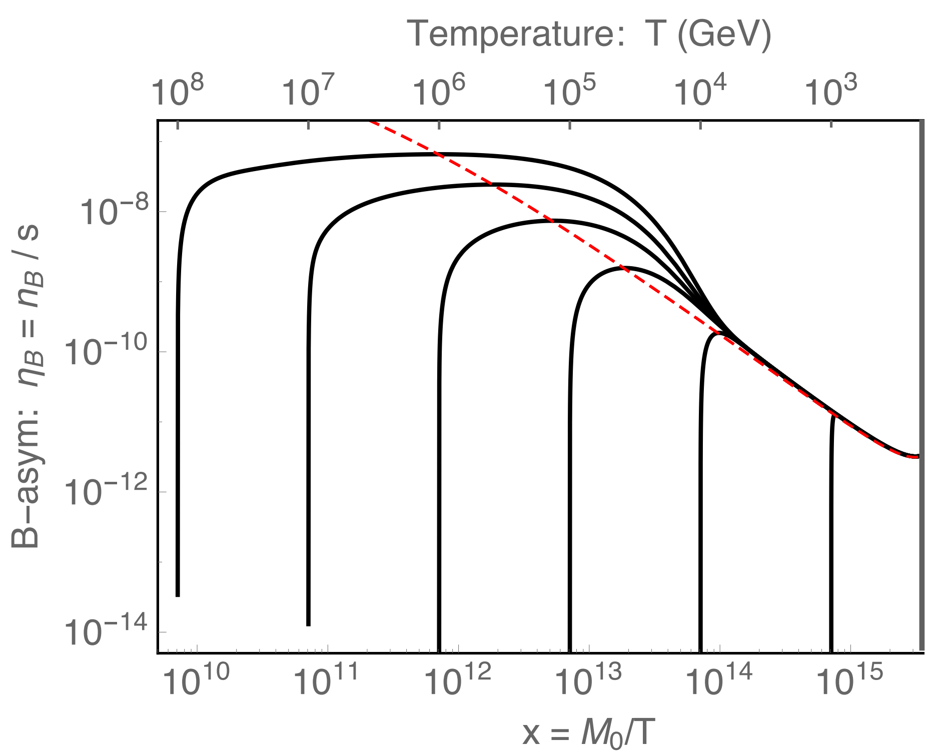
Related work: Giovannini & Shaposhnikov; Fujita & Kamada; AL, Sabancilar, & Vachaspati; Semikoz, Dvornikov, Smirnov, Sokoloff, Valle

Courtesy: A. J. Long

Courtesy H.Oide

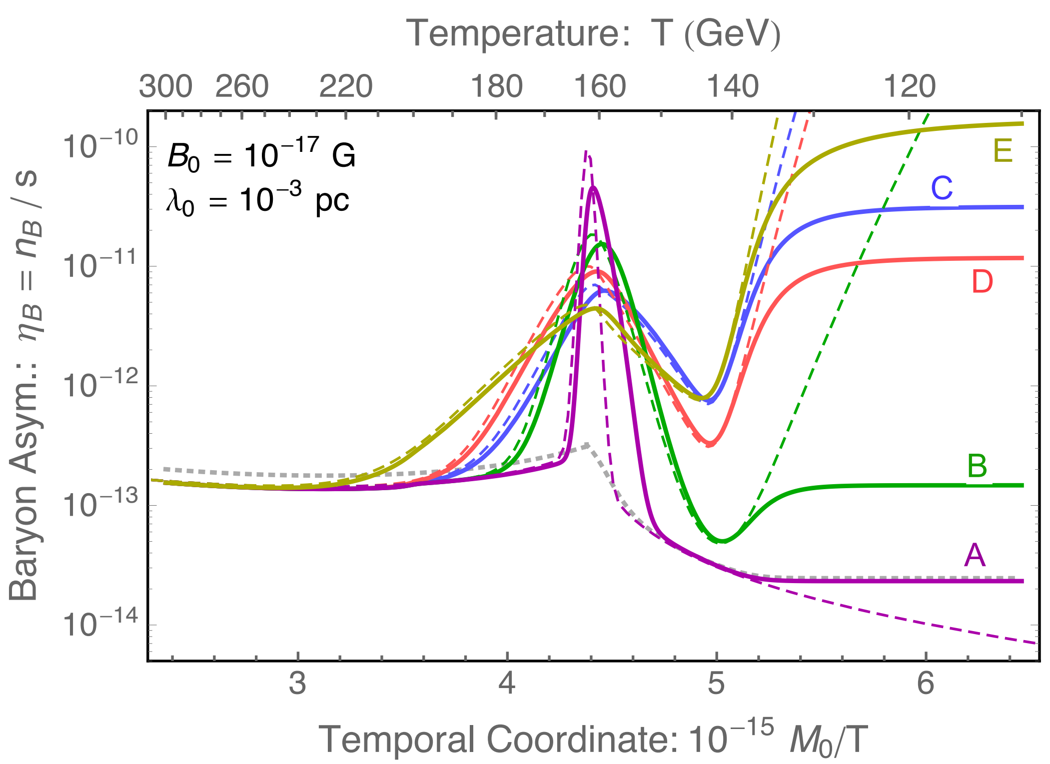
# Evolution of baryon asymmetry

$T \gg T_{\mathrm{EWSB}}$




('16 KK&Long)

$T \sim T_{\mathrm{EWSB}}$




('16 KK&Long)

Courtesy H.Oide

# What determines final BAU?

Early EWSB (crossover) completion, late sphaleron freeze out

=> Net BAU is suppressed

('98 Giovannini&Shaposhnikov)

Early sphaleron freeze out, late EWSB (crossover) completion

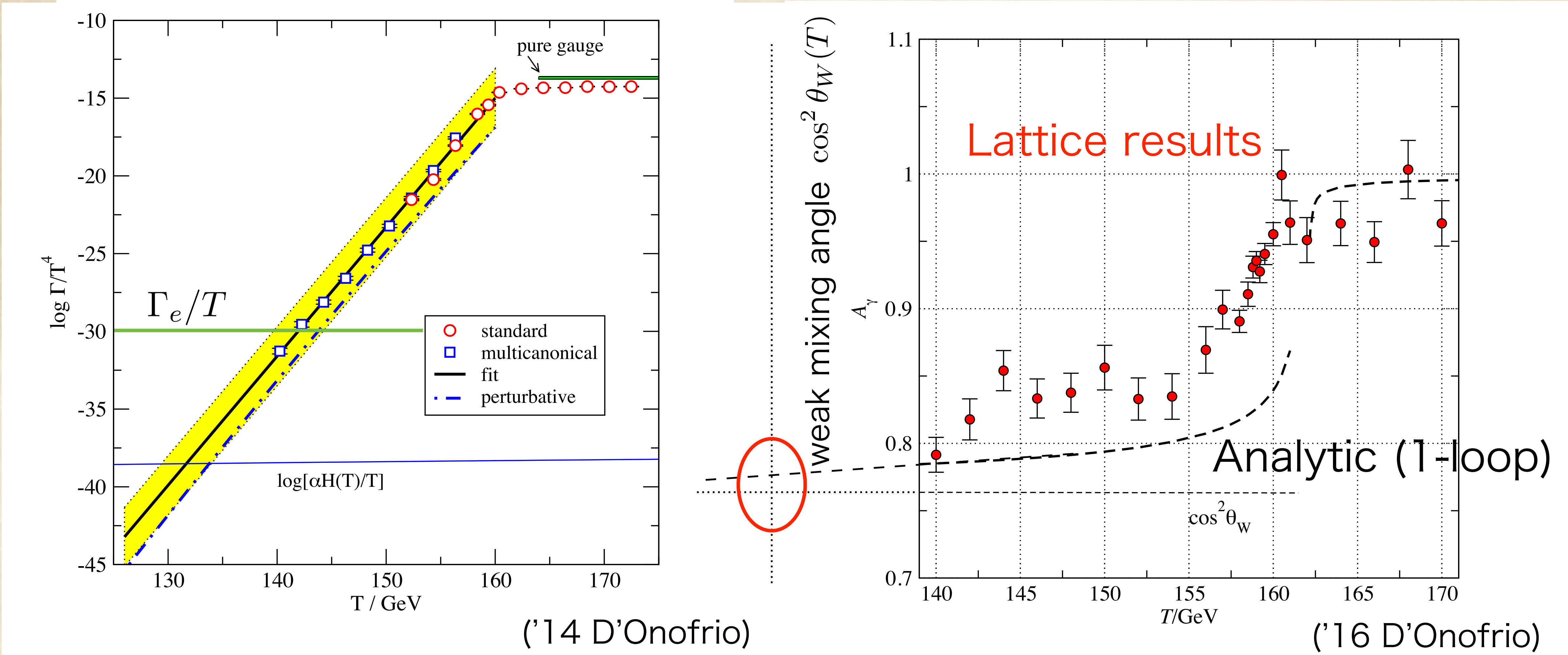
=> Net BAU is efficiently remained

Courtesy H.Oide

# What determines final BAU?

Freezeout of EW sphalerons vs Completion of EWSB

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

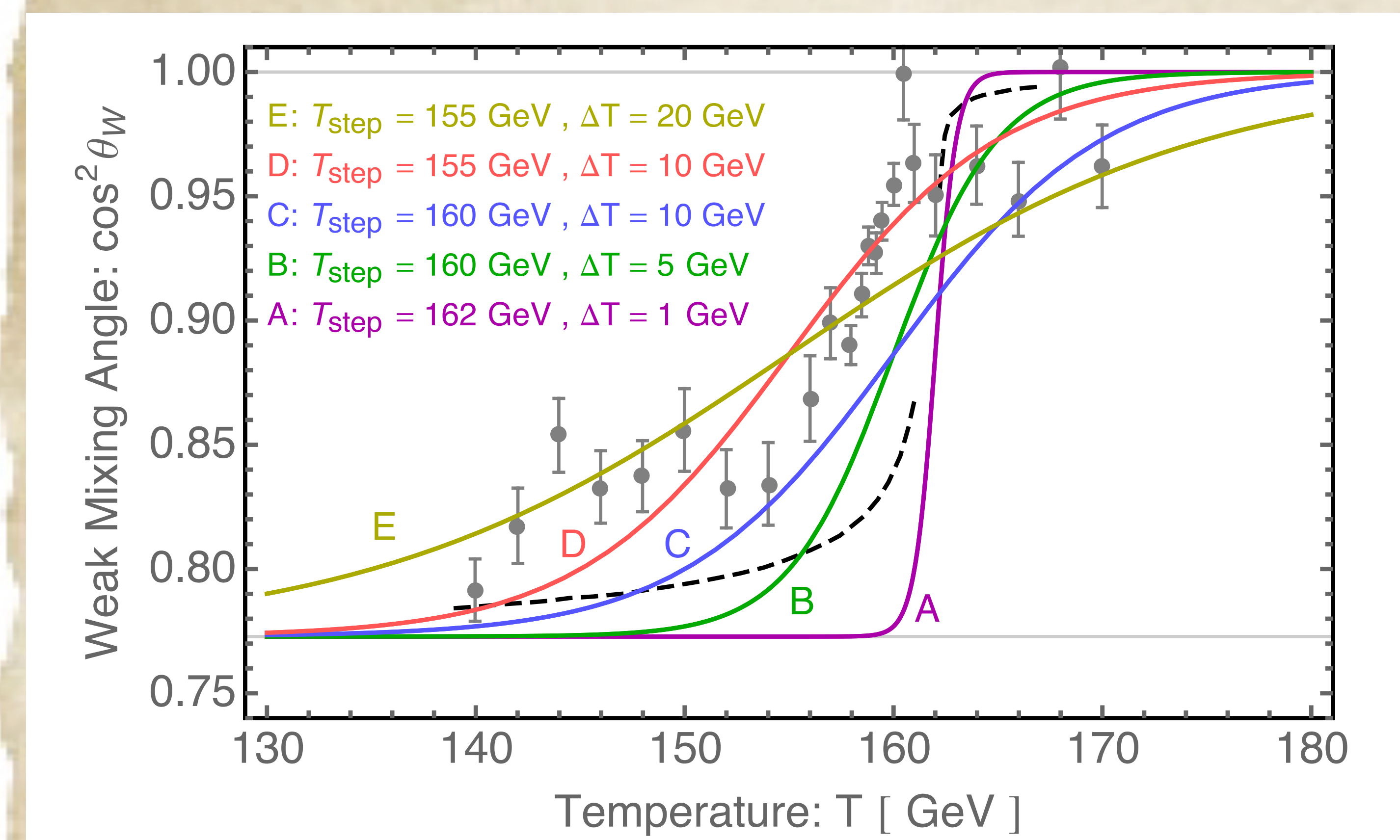



lattice simulations for the EW crossover with 125 GeV Higgs

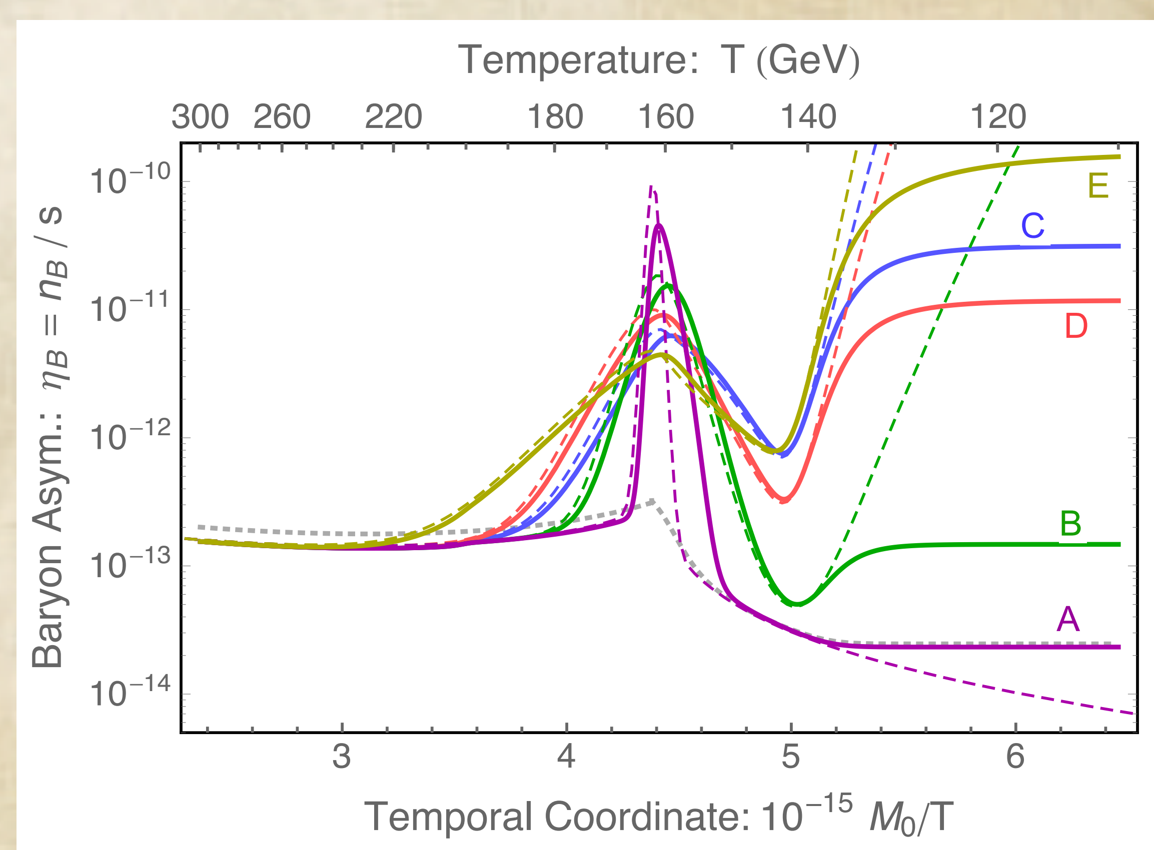
BAU remains! Quantitative results are sensitive to $\theta_W(t)$

Courtesy H.Oide

Since the lattice results and one-loop calculation for the SM EW crossover differ each other significantly for this purpose, we choose several fitting functions of temperature dependence of the weak mixing angle.




Parameterization of the evolution of weak angle




Evolution of B-asymmetry

('16 KK&Long)

From B to E, uncertainty is $\mathcal{O}(10^3)$

Courtesy H.Oide

# What determines final BAU?

$$\eta_B \simeq 10^{-10} f(\theta_W, T \sim 135\mathrm{GeV}) \left(\frac{\lambda_{\mathrm{EW}}}{10^6\mathrm{GeV}^{-1}}\right) \left(\frac{B_{\mathrm{EW}}}{10^{-3}\mathrm{GeV}^2}\right)^2$$

$$f(\theta_W, T) \equiv -\sin(2\theta_W) T \frac{d\theta_W}{dT} \quad (\lesssim 1 \quad @T \sim 135\mathrm{GeV})$$

('16 KK&Long)

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.

Courtesy H.Oide

# Helical magnetic field generation from Axion inflation

D. Jiménez, KK, K. Schmitz & X.J. Xu (MPIK), JCAP12 (2017) 011[arXiv:1707.07943[hep-ph]].

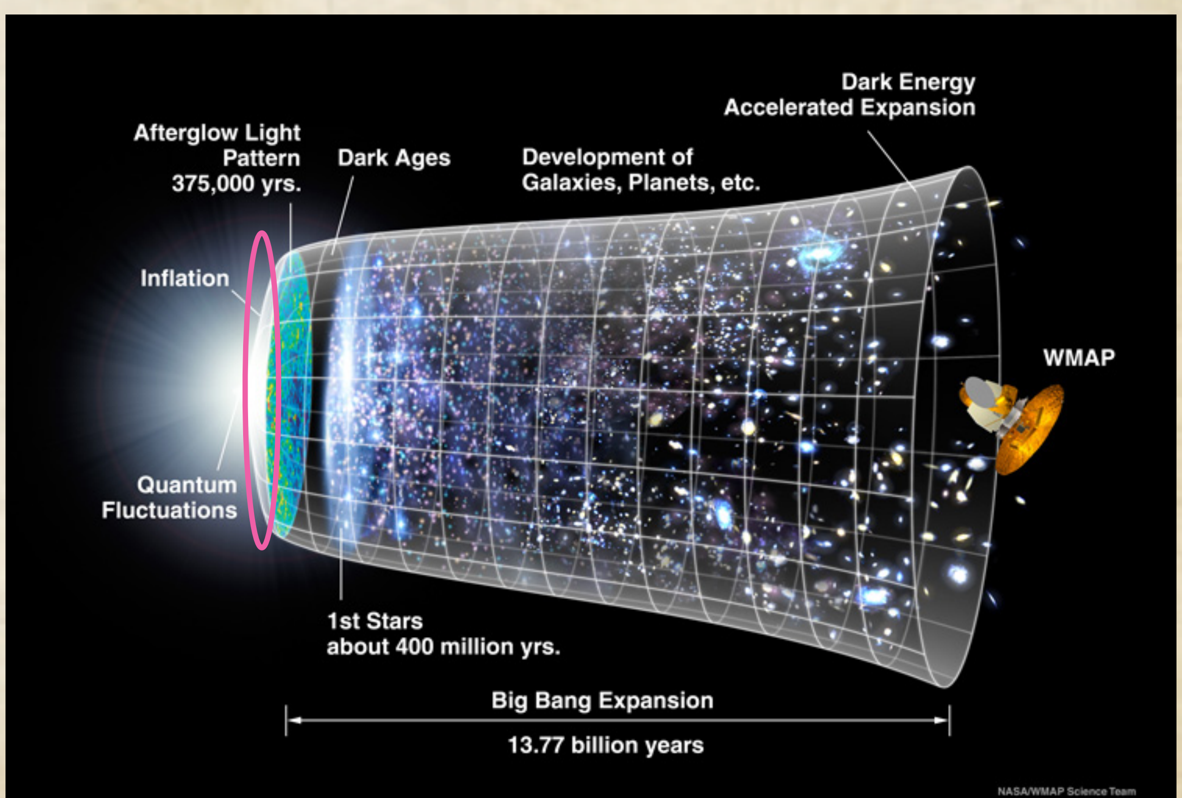
Courtesy H.Oide

# Pseudoscalar inflation ('90 Freese+, '93 Adams, ⋯ )

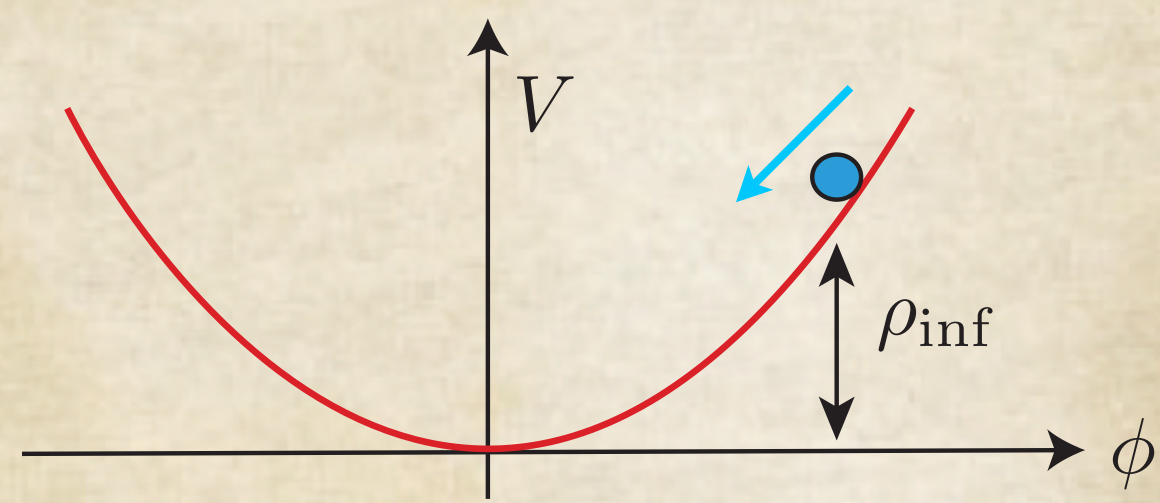
Inflation ('80 Starobinsky, '81 Sato, '81 Guth, '82 Linde, '82 Albrecht & Steinhardt)

⋯ an era with accelerated cosmic expansion before the Big Bang.

- often driven by the potential energy of a scalar field (inflaton)
- solution to the flatness/horizon/monopole problems and seed for the CMB fluctuation and large scale structures.




(from WMAP team)




Courtesy H.Oide

# Pseudoscalar inflation ('90 Freese+, '93 Adams, ⋯ )

If inflaton is a pseudoscalar, e.g. axions,
it can have an anomalous coupling to hypergauge fields:

$$\frac{\phi}{f} Y_{\mu\nu} \tilde{Y}^{\mu\nu}$$

During inflation, inflaton slow-rolls homogeneously.

$$\dot{\phi} \neq 0, \quad |\partial_i \phi| \ll |\dot{\phi}| \ll \sqrt{V(\phi)}$$

⇒

The dynamics of the gauge fields is affected by inflaton motion.

$$\left[\frac{\partial^2}{\partial \tau^2} + k^2 \left(1 \pm \frac{4\dot{\phi}/(Hf)}{k\tau}\right)\right] Y_\pm = 0.$$

One polarization mode feels instability, especially around the end of inflation ('06 Anber+)

Generation of maximally helical hypermagnetic (and electric) Fields!

Courtesy H.Oide

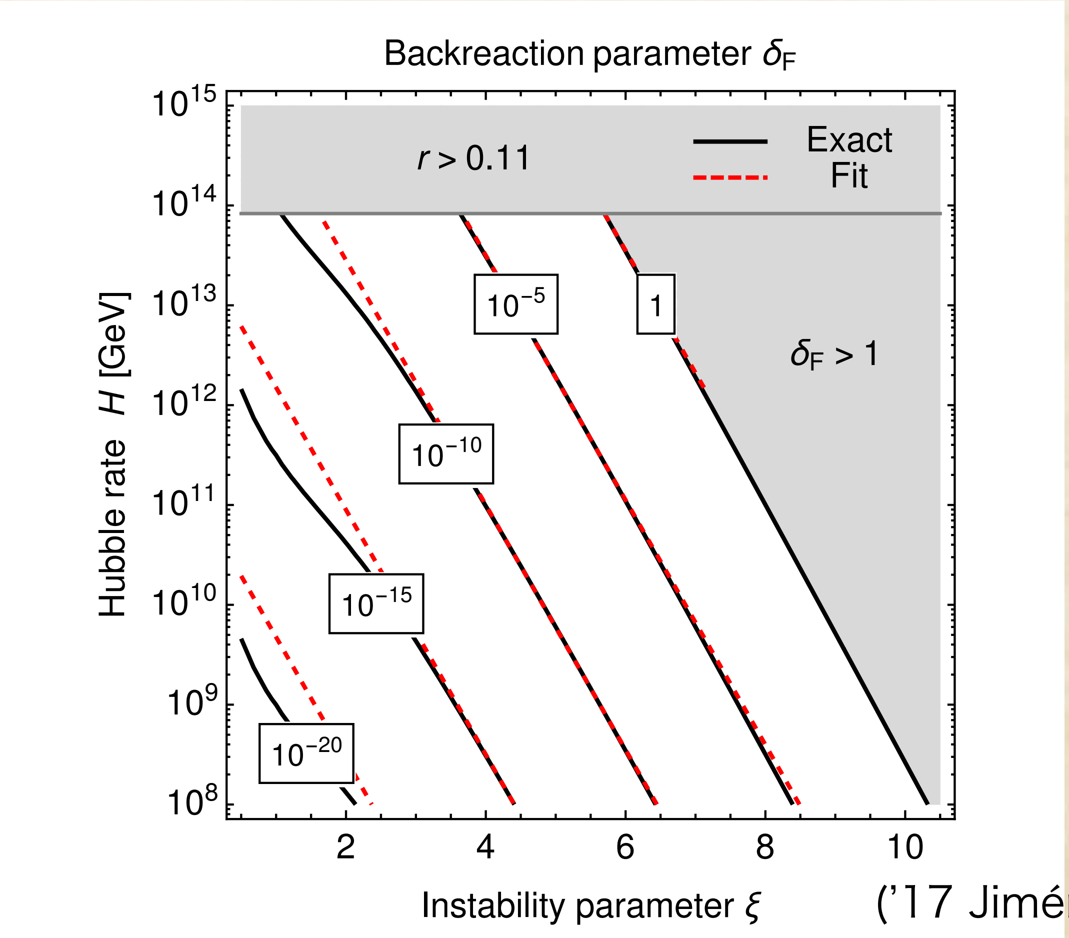
## Estimated magnetic field properties just after inflation

$$B \sim 10^{-2} \frac{e^{\pi\xi}}{\xi^{5/2}} H^2 \qquad \lambda \sim \frac{\xi}{H} \qquad \text{with} \qquad \xi \equiv \frac{\dot{\phi}}{2fH}$$

('06 Anber+)

$H_{\rm inf}$ & $\xi$: parameters that characterizes magnetogenesis

## Conditions to avoid too much backreaction; $\rho_B + \rho_E \ll \rho_{\rm inf}$

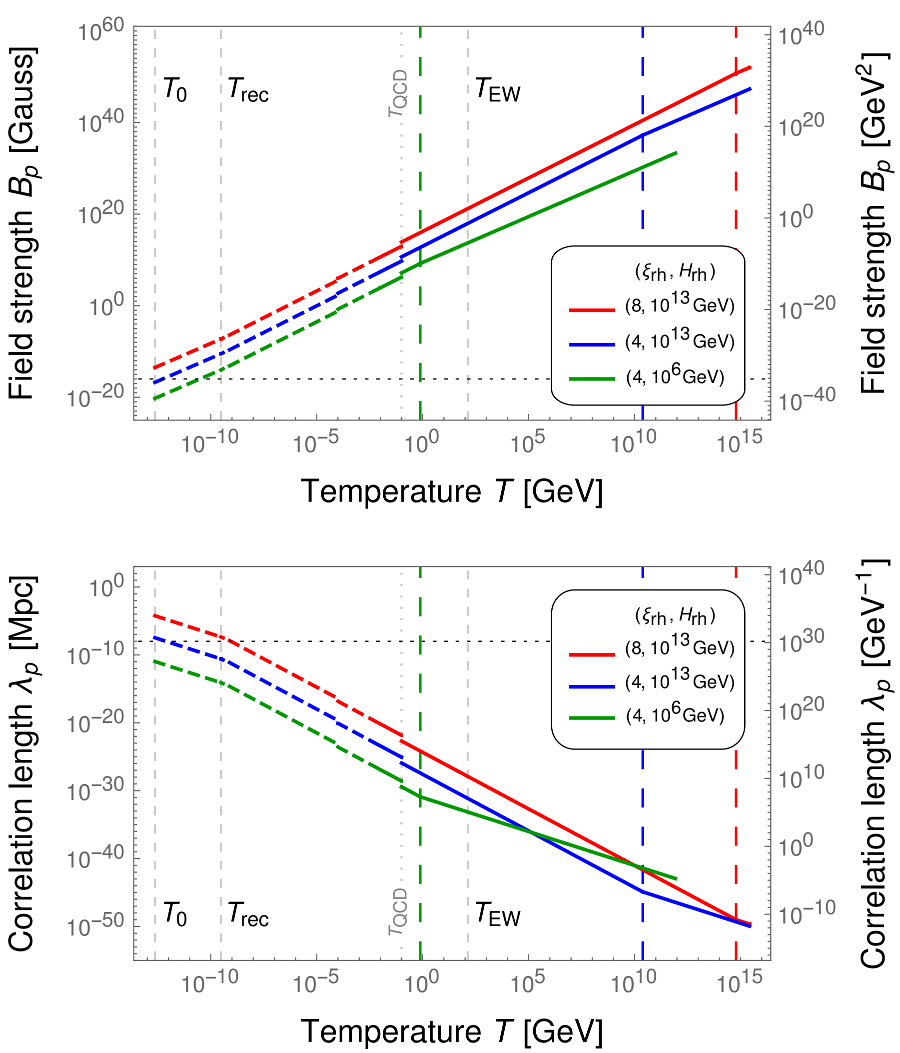



('17 Jiménez+)

Courtesy H.Oide

# Magnetic field evolution after inflation

# instant reheating is assumed




('17 Jiménez+)

Eddy turn-over scale

$$\lambda_{\rm ed} = vt \simeq \frac{B}{\sqrt{\rho}H}$$

initially $\lambda > \lambda_{\rm ed}$

adiabatic evolution

$$B \propto a^{-2}, \quad \lambda \propto a$$

eventually $\lambda \simeq \lambda_{\rm ed}$

MHD evolution; "inverse cascade"

$$B \propto a^{-7/3}, \quad \lambda \propto a^{5/3}$$

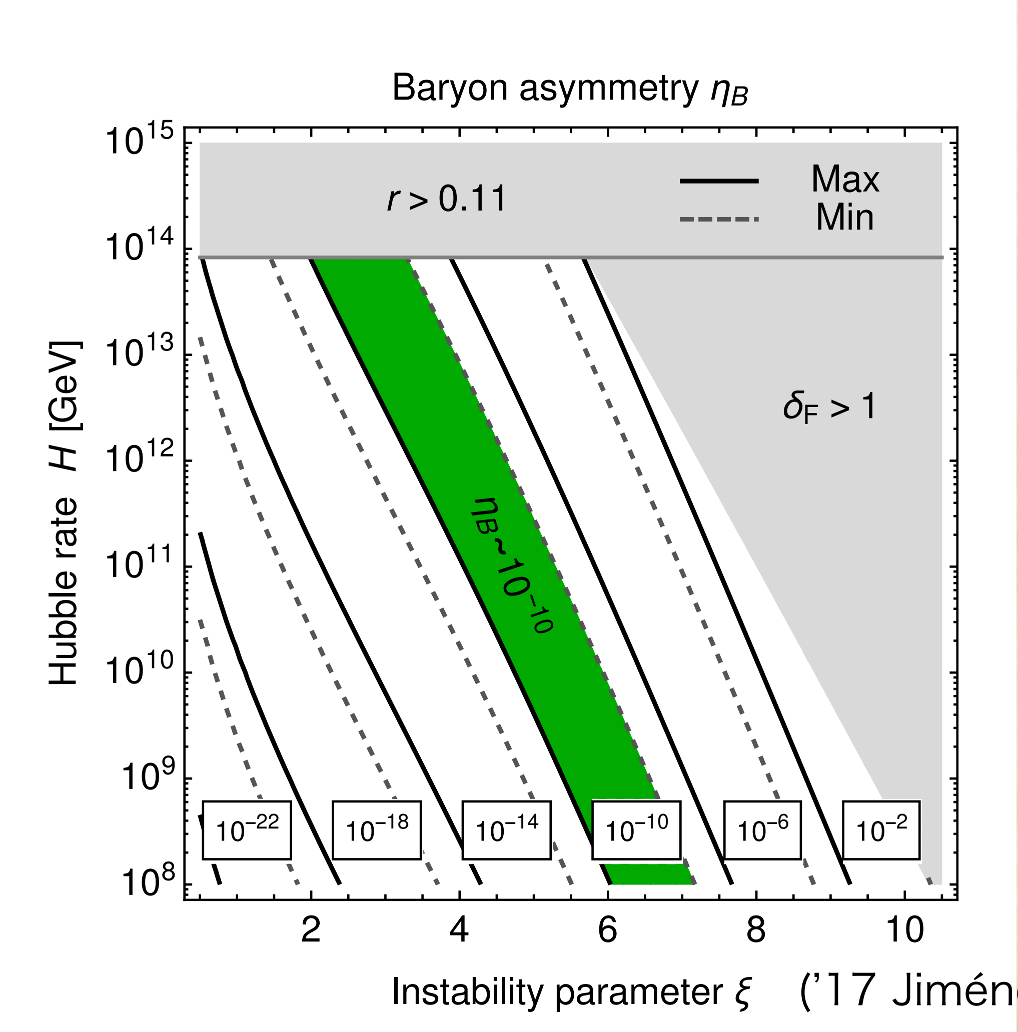
('04 banerjee&Jedamzik)

(approximate) helicity conservation prevents MFs from complete decay.

Courtesy H.Oide

# Resultant baryon asymmetry

$$\eta_B \simeq (10^{-3} - 1) \times 10^{-16} \left( \frac{e^{2\pi\xi_{\rm rh}}}{\xi_{\rm rh}^4} \right) \left( \frac{H_{\rm rh}}{10^{13}{\rm GeV}} \right)^{3/2}$$




('17 Jiménez+)

MFs that predict $\eta_B \sim 10^{-10}$ remains until today at intergalactic void with

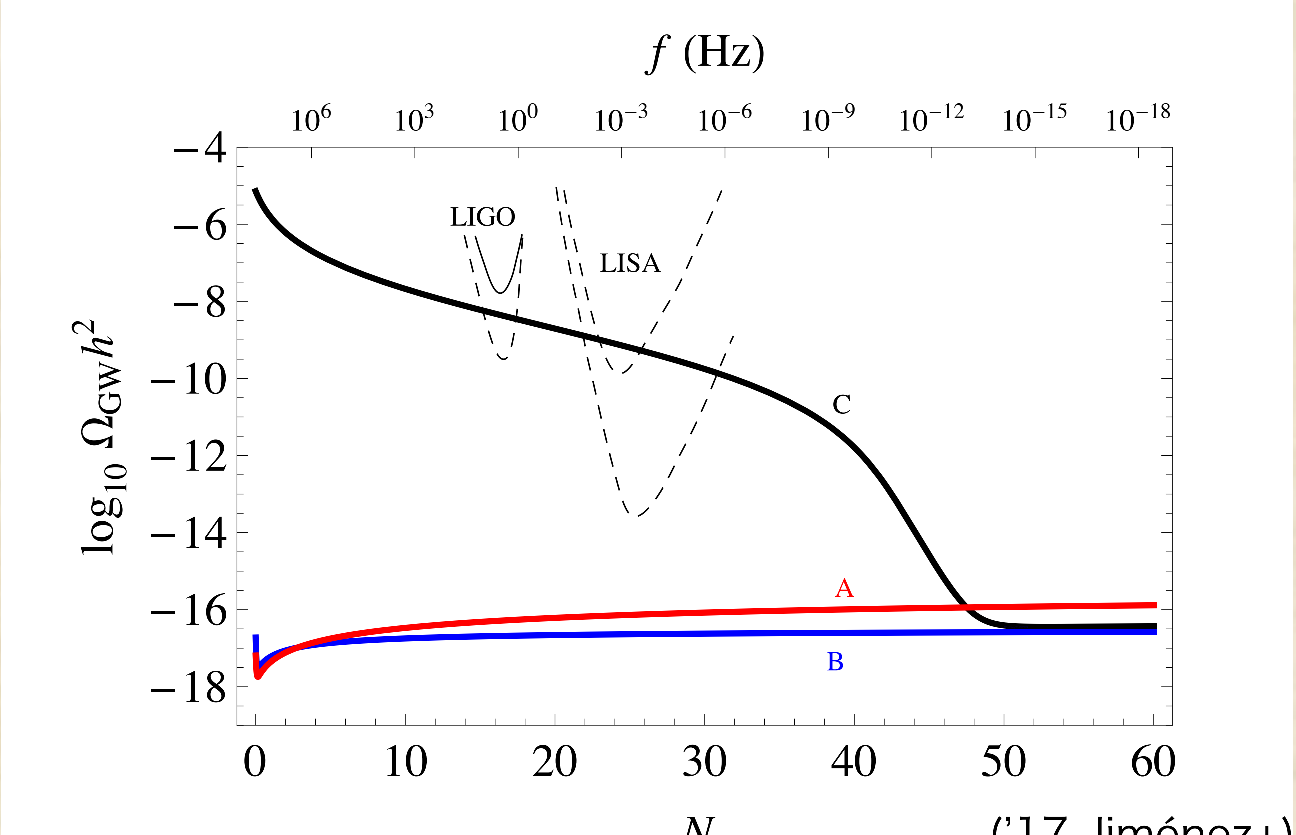
$$B \sim 10^{-17}{\rm G}, \quad \lambda \sim 10^{-2}{\rm pc}$$

Courtesy H.Oide

# One benefit: Generation of stochastic GWs

$$\Omega_{\rm GW}h^2 \simeq (\Omega_{\rm GW}h^2)_{\rm inf} \times \left(\frac{H}{M_{\rm pl}}\right)^2 (f_L(\xi)+f_R(\xi))e^{4\pi\xi}$$
$$\simeq 2.3\times 10^{-22}\exp[0.91\times 4\pi(\xi-4.61)]\left(\frac{H}{10^{11}\mathrm{GeV}}\right)^4$$

('12 Cook+)




('17 Jiménez+)

But appropriate parameter choice gives the GW signature at small amplitude $\Omega_{\rm GW}h^2 \sim 10^{-17}$ and high frequency $f \sim 1-10^2\mathrm{MHz}$

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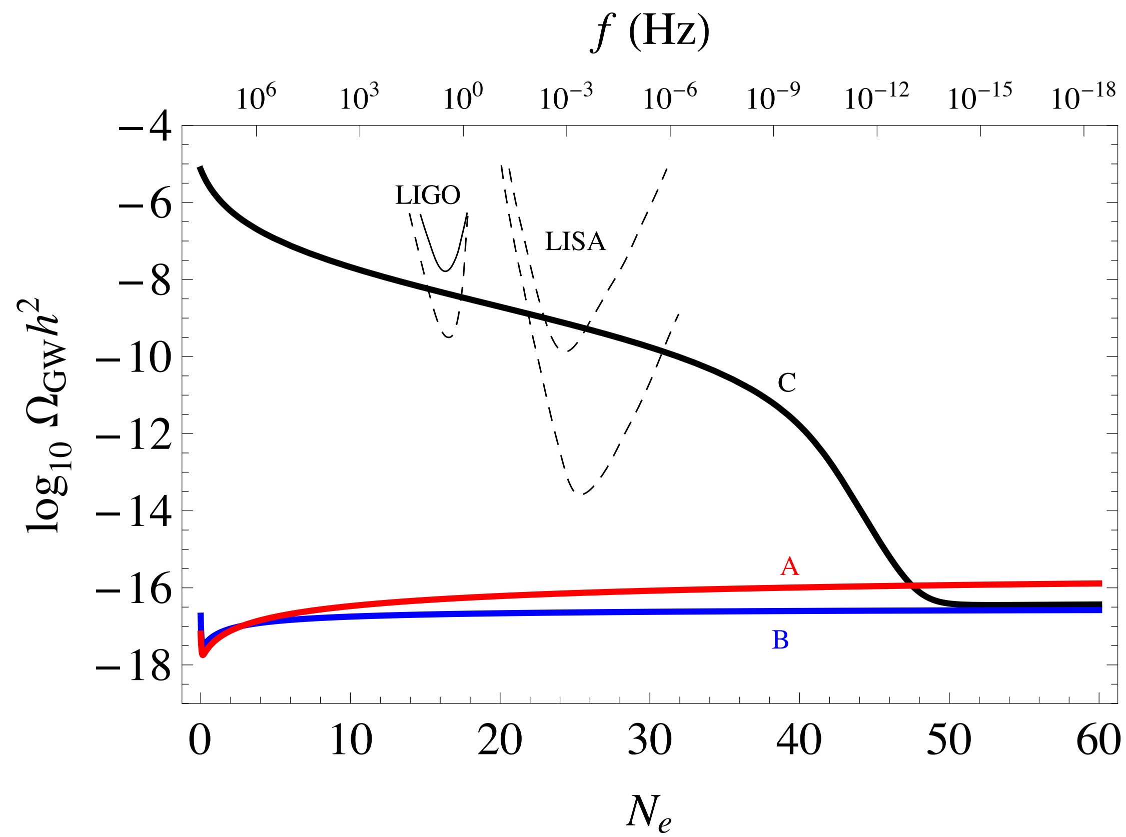


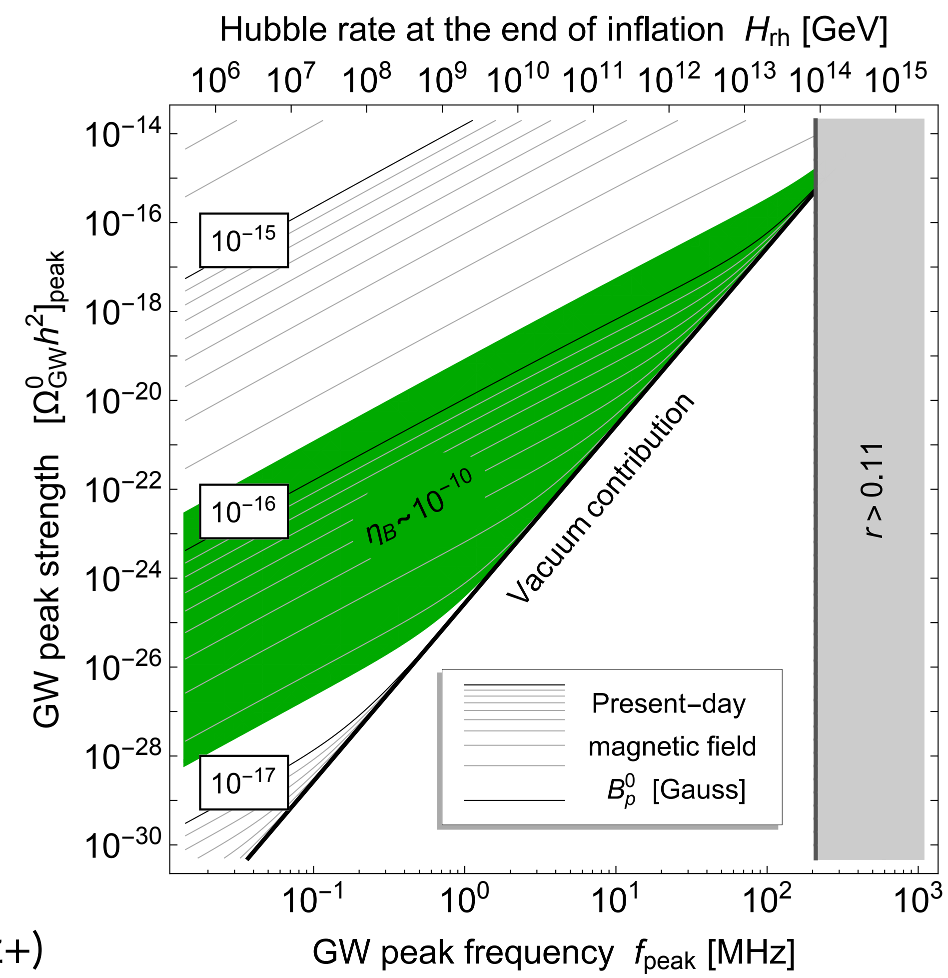


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But appropriate parameter choice gives the GW signature at small amplitude $\Omega_{\rm GW}h^2 \sim 10^{-17}$ and high frequency $f \sim 1 - 10^2 {\rm MHz}$

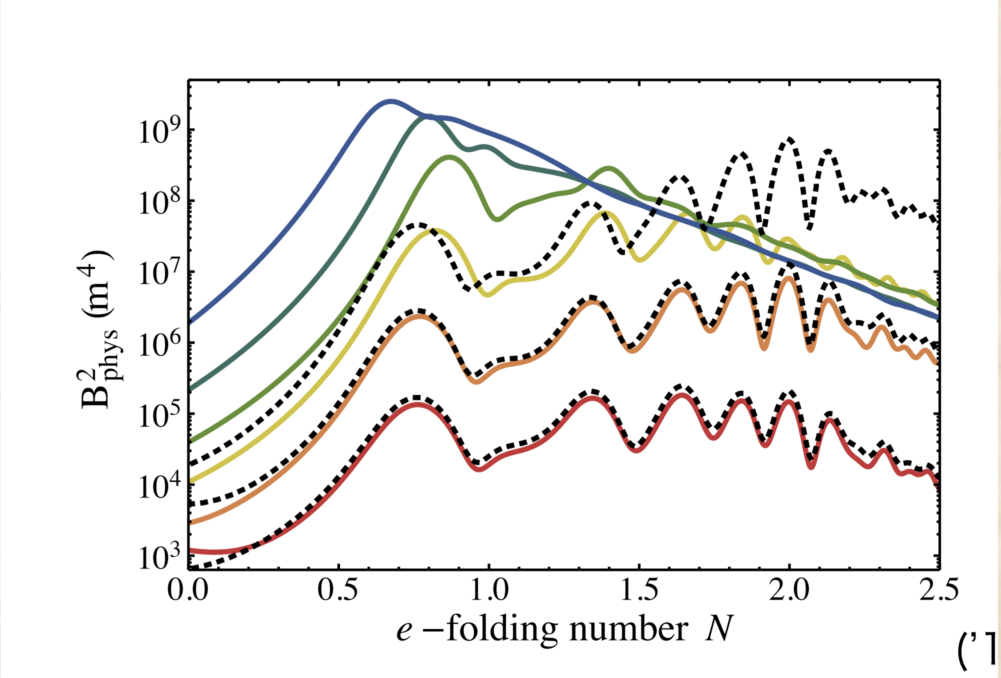
Especially, detectable GWs predicts baryon overproduction.

=> New U(1) gauge interaction is needed.

# Remaining issues

1. Reheating…at oscillating stage, $|\dot{\phi}|$ is larger.

Larger MFs can be generated?




('16 Adshead+)

(See also '18 Canivete Cuissa+)

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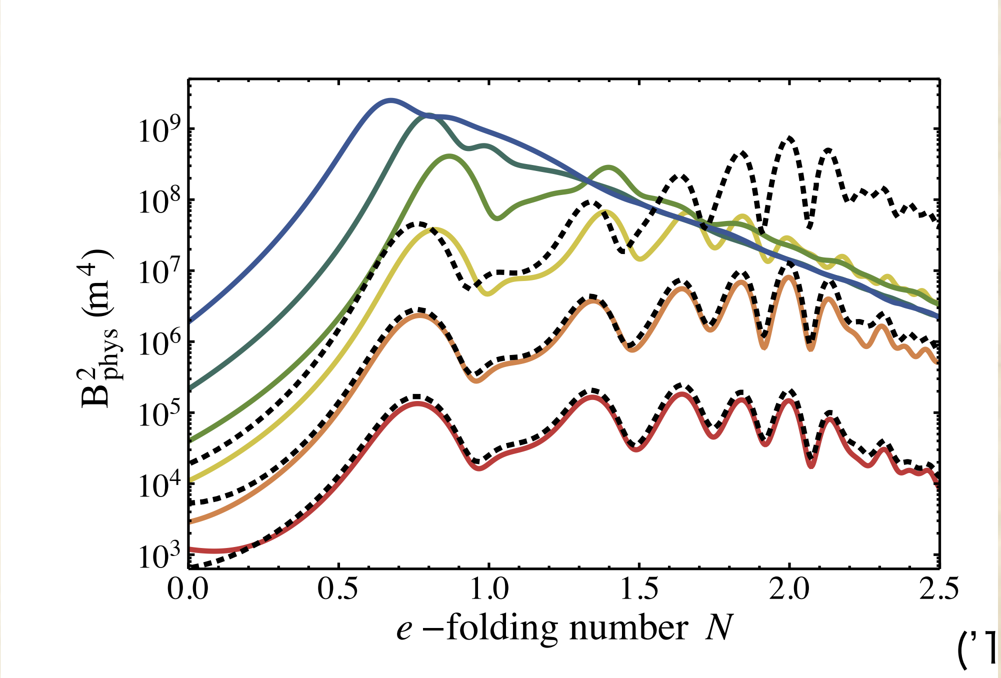


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1. Reheating$\cdots$at oscillating stage, $|\dot{\phi}|$ is larger.
Larger MFs can be generated? ('16 Adshead+,'18 Canivete Cuissa+)

But charged high energy particles produced at that time might prevent MFs to be amplified. ('15 Fujita+)

2. Larger $\xi(\gtrsim 3)$ might be problematic
for the breakdown of perturbativity ('16 Ferreira+, '16 Peloso+)
and possible thermalization. ('17 Ferreira+)

3. Other backreaction problem? Schwinger effect?
('18 Domcke&Mukaida)

# Summary

Courtesy H.Oide

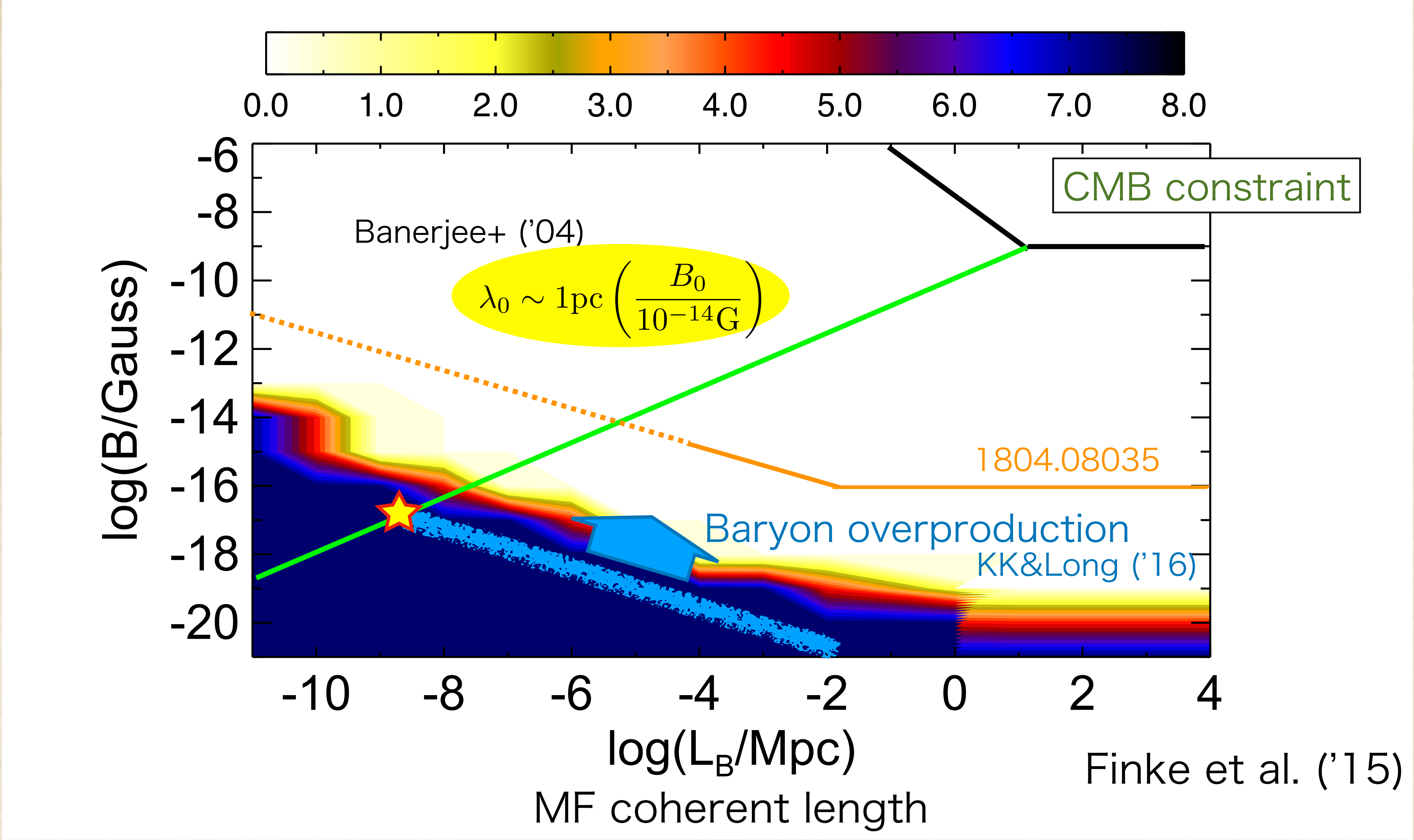
1. Helical hypermagnetic fields, if existed before the EWSB, can be the source of BAU through the SM chiral anomaly. No BSM physics is involved in this mechanism.
2. Axion inflation is one of the well-motivated models for the source of helical hypermagnetic fields (but not limited to). In the point of view of axion inflation, this mechanism is complimentary to the one in Peter’s talk.
3. GWs from the gauge fields from axionic inflation is also of interest, but detectable ones predict baryon overproduction, if they are the SM gauge fields.
4. In other words, detection of such GWs at LIGO/Virgo/KAGRA shows the existence of hidden gauge interaction.

Courtesy H.Oide

# Appendix

Courtesy H.Oide

# Present properties of MFs in the $B_0$-$\lambda_0$ plane…




in the case magnetic fields are maximally helical.

MFs that explain BAU cannot explain the blazar observation simultaneously.

Courtesy H.Oide