Cosmological Magnetic Fields Meet Chiral Anomaly

based on: T. Fujita (Kyoto) & 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.Jimenéz (MPIK), KK, K.Schmitz(CERN), X.Xu (MPIK),
JCAP12 (2017) 011 [arXiv:1707.07943 (hep-ph)]
KK, PRD97 (2018) 103506 [arXiv:1802.03055 (hep-ph)]
KK, Chang Sub Shin (IBS-CTPU), arXiv:1905.06966 [hep-ph]

Kohei Kamada
(RESCEU, U Tokyo)

E-lab Seminar
16/10/2019 @Nagoya Univ.

Courtesy H.Oide

The message of this talk

1. Recently there are several claims that suggest the existence of tiny intergalactic magnetic fields.

2. You might think it is too tiny to think seriously, but I will convince you that it is extremely large for the baryon asymmetry of the Universe (BAU).

3. Pseudoscalar dynamics (including axion inflation) as well as the chiral plasma instability can be the origin of such magnetic fields responsible for BAU.

Courtesy H.Oide

1. Introduction: intergalactic magnetic fields
2. Baryogenesis from decaying hypermagnetic helicity
3. Magnetogenesis models
   ~ pseudoscalar dynamics
   / chiral plasma instability ~
4. Summary

Courtesy H.Oide

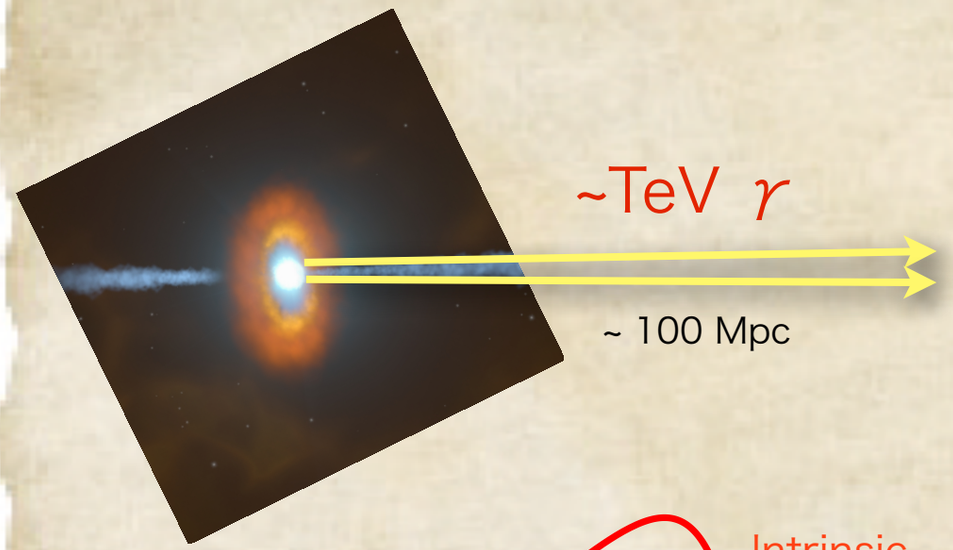
Introduction

Courtesy H.Oide

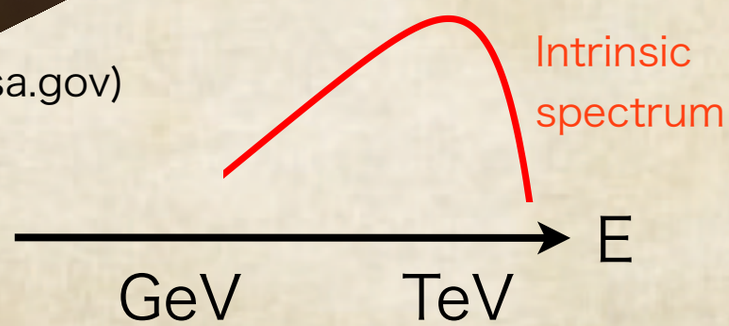
Evidence (?) of large scale magnetic fields

: γ-ray from Blazars (theory)

AGN/Blazar



(from nasa.gov)



Courtesy H.Oide

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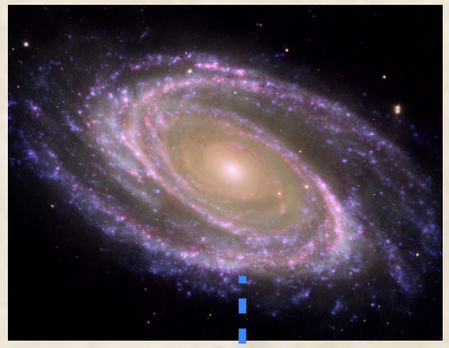
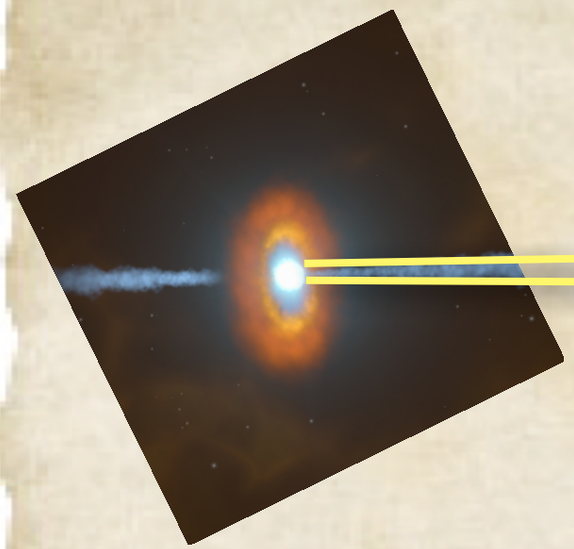


AGN/Blazar

Ex-galactic

BG Light ~eV



(from nasa.gov)

~TeV γ

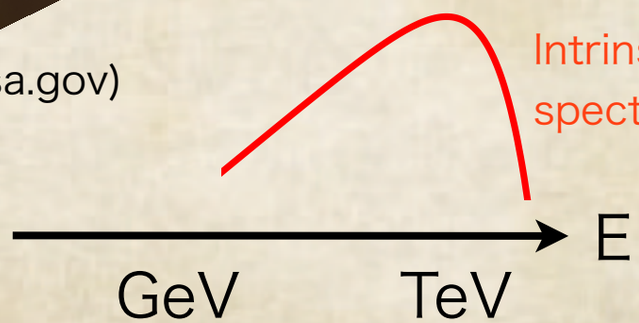
~ 10 kpc

e^+

e^-

~ 100 Mpc

pair creation



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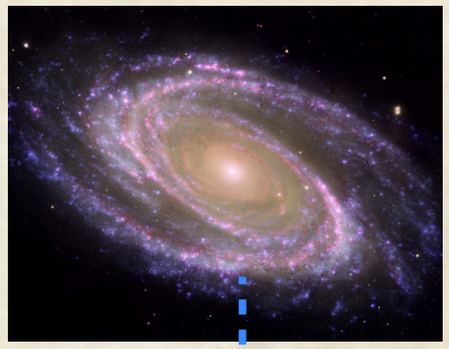
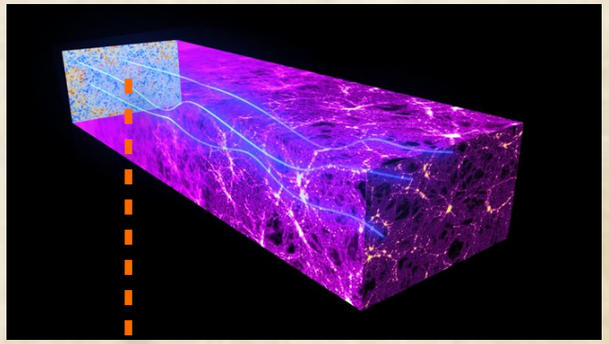


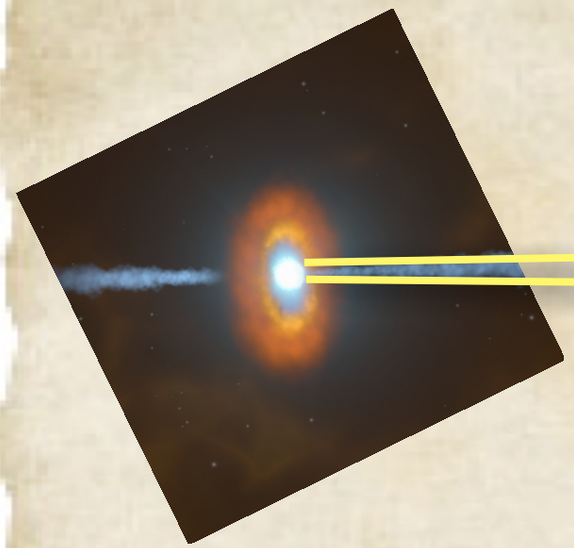


(from esa.int)

AGN/Blazar

Ex-galactic
BG Light ~eV

CMB
10^{-4}~eV



(from nasa.gov)

~TeV γ

~ 10 kpc

e^+

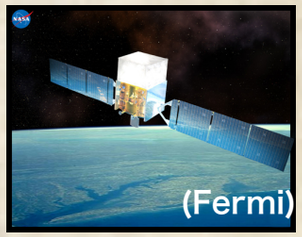
e^-

~GeV γ

~ 100 Mpc

pair creation

inverse Compton



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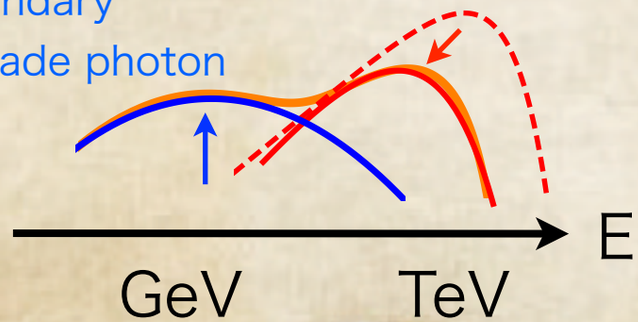


Courtesy H.Oide

Evidence (?) of large scale magnetic fields

: γ-ray from Blazars (observation)

(from na

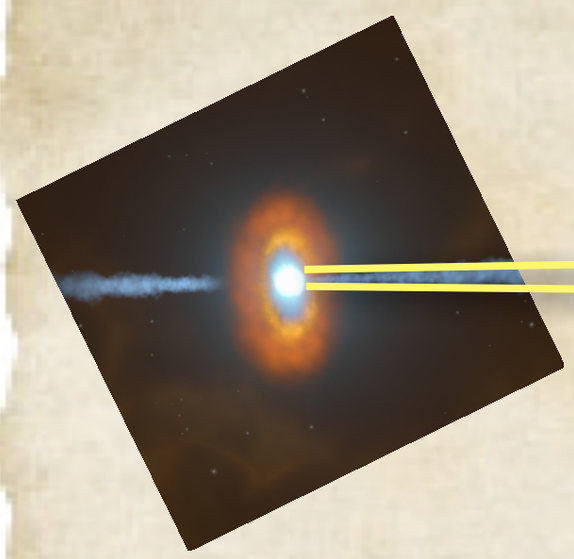
Theoretical prediction

Intrinsic

AGN/Blazar

Fermi upper bound

(from esa.int)



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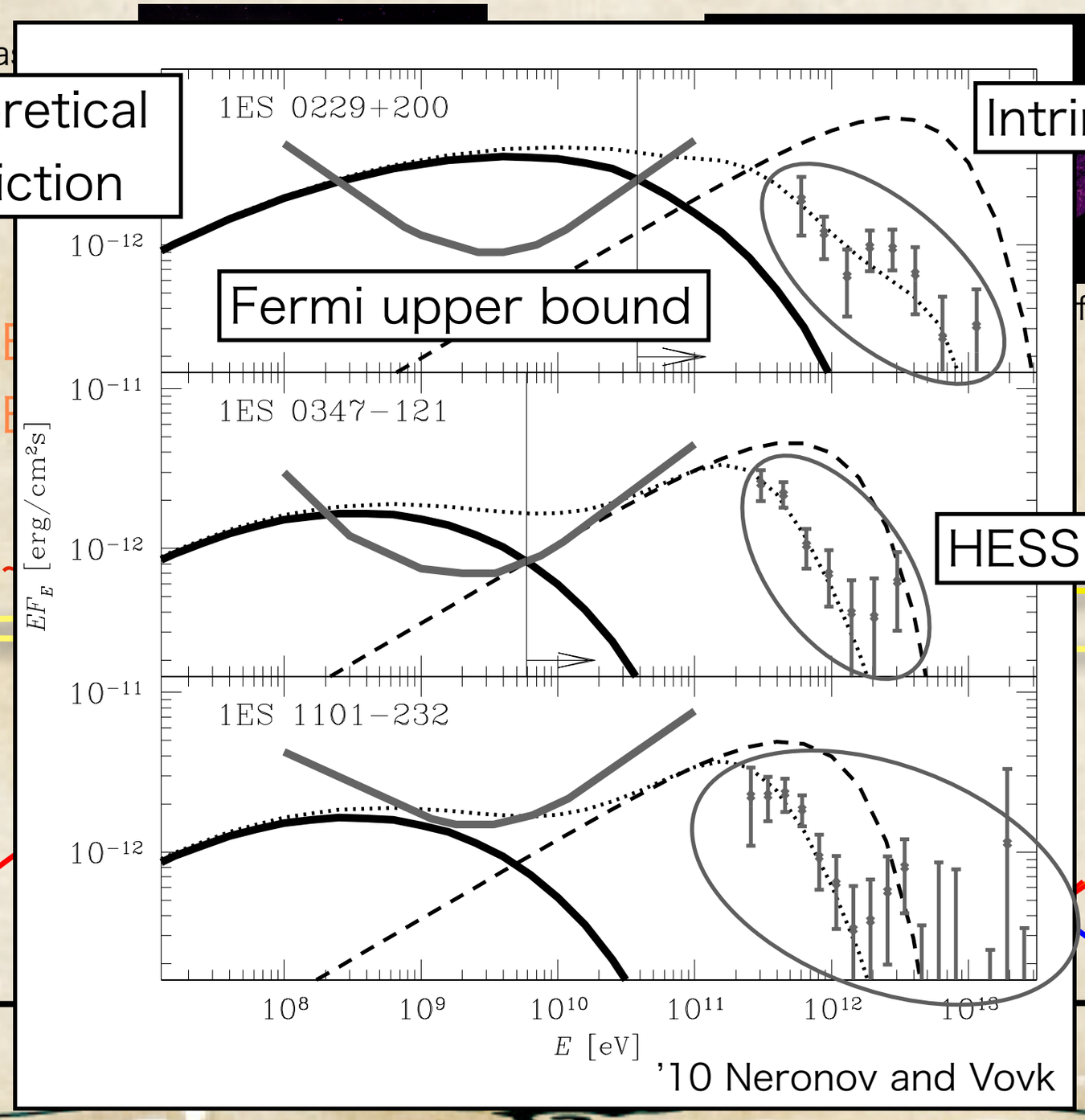
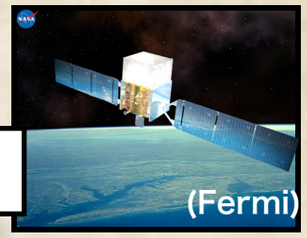


HESS data



(from nasa.gov)

'10 Neronov and Vovk

GeV

TeV

E

Courtesy H.Oide

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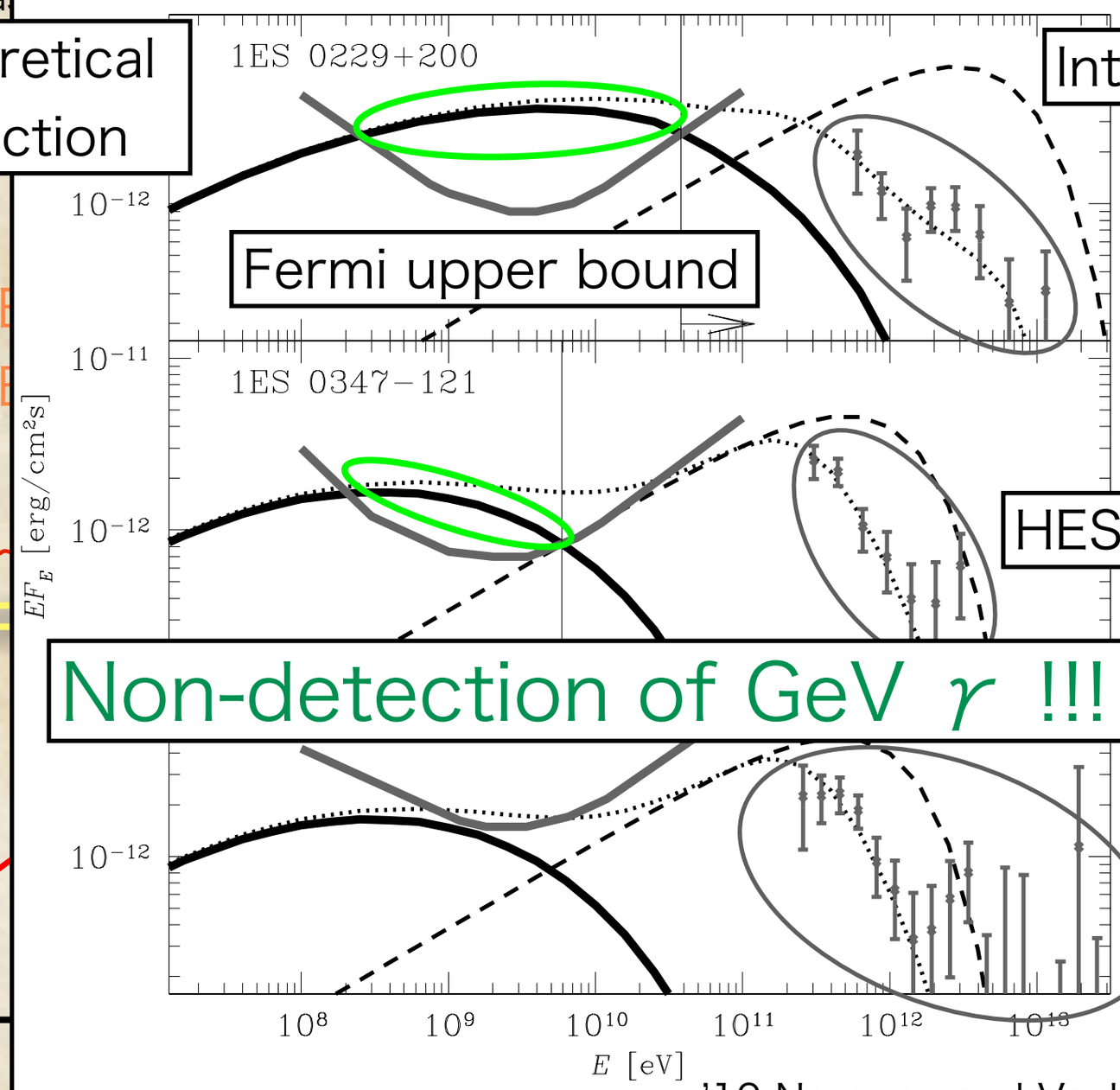
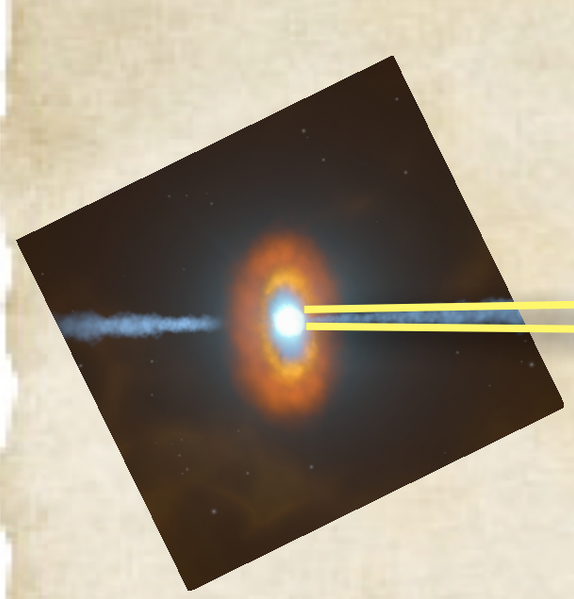


Fermi upper bound

HESS data

Non-detection of GeV γ !!!

'10 Neronov and Vovk



(from nasa.gov)

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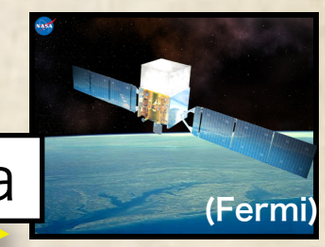


(from nasa.gov)

GeV

TeV

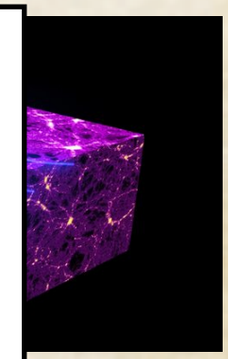
E

Courtesy H.Oide

Evidence (?) of intergalactic magnetic fields

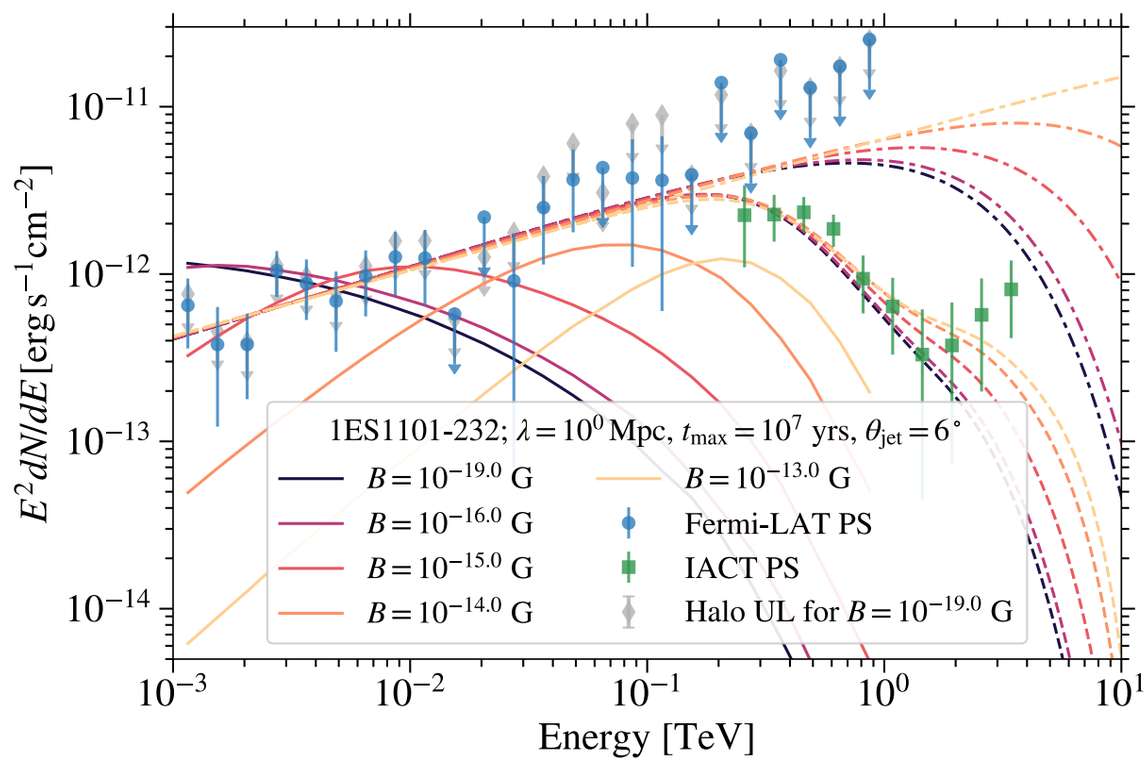
: γ-ray from Blazars (observation)

(from nasa



(from esa.int)

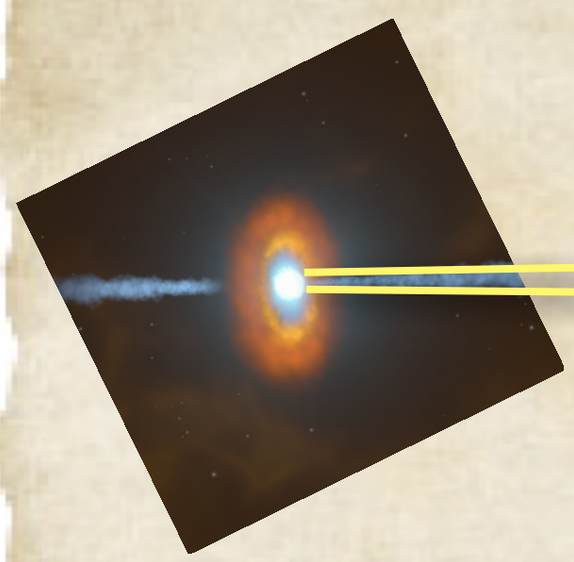
Furthermore, recent paper by Fermi collaboration gives…



1804.08035 (Fermi-LAT collaboration)

GeV spectrum is consistent with intrinsic one.

AGN/Blazar



(from nasa.gov)

E

B

~

eV γ

on

(from nasa.gov)

GeV

TeV

E

Courtesy H.Oide

Evidence (?) of large scale magnetic fields

Most convincing explanation: Extragalactic MFs

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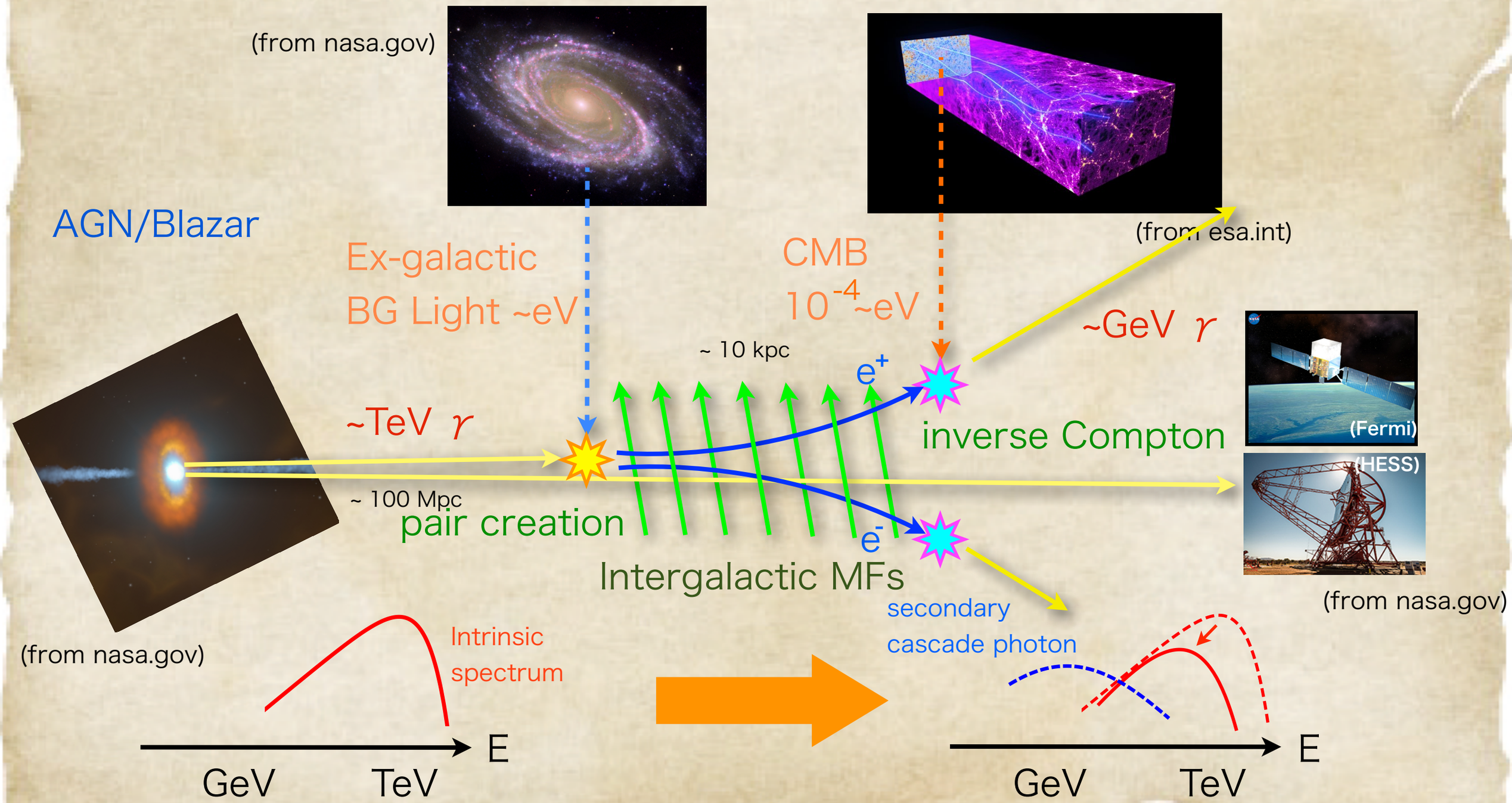
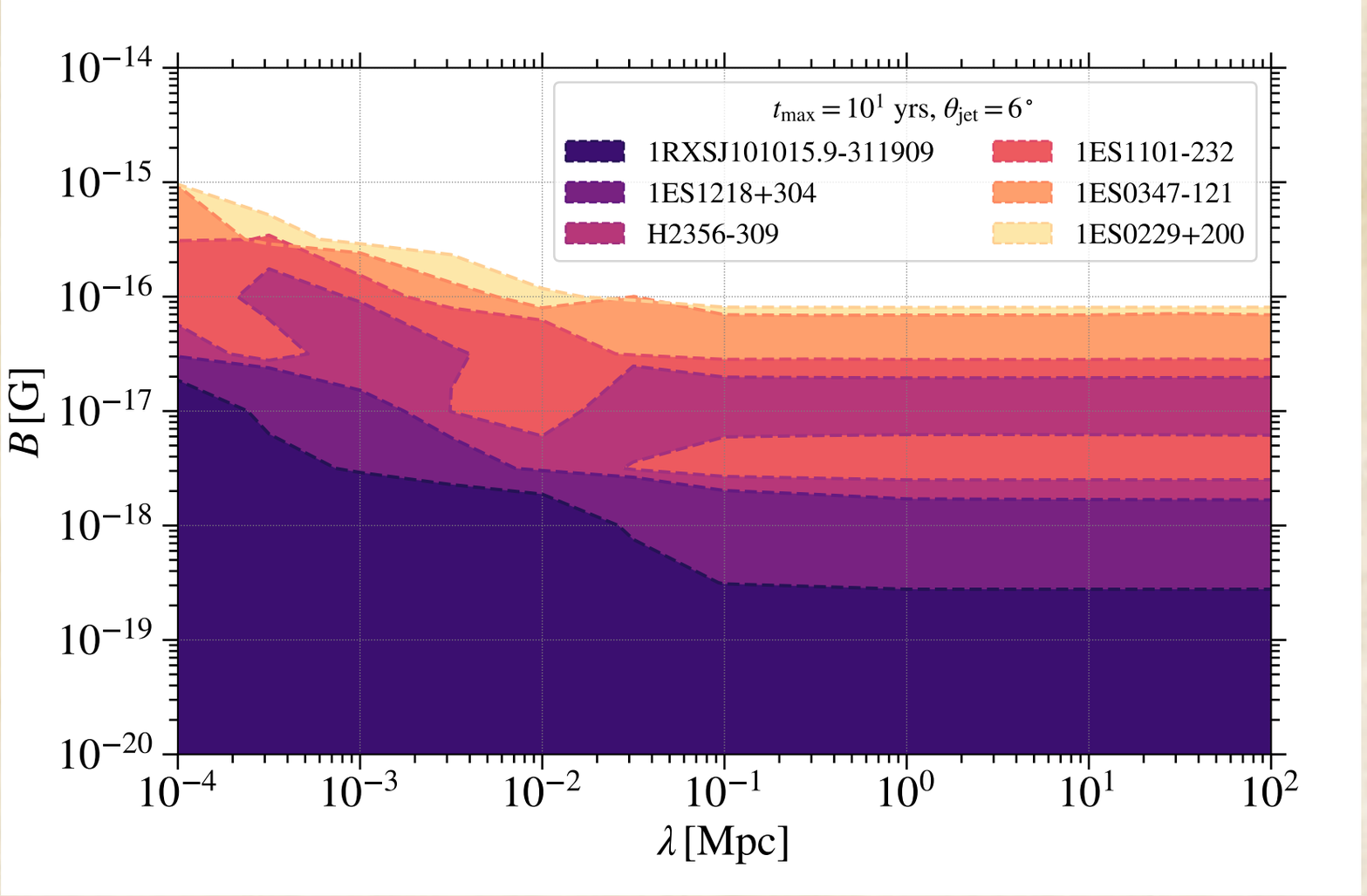


Courtesy H.Oide

Latest constraints from Fermi 1804.08035 (Fermi-LAT collaboration)

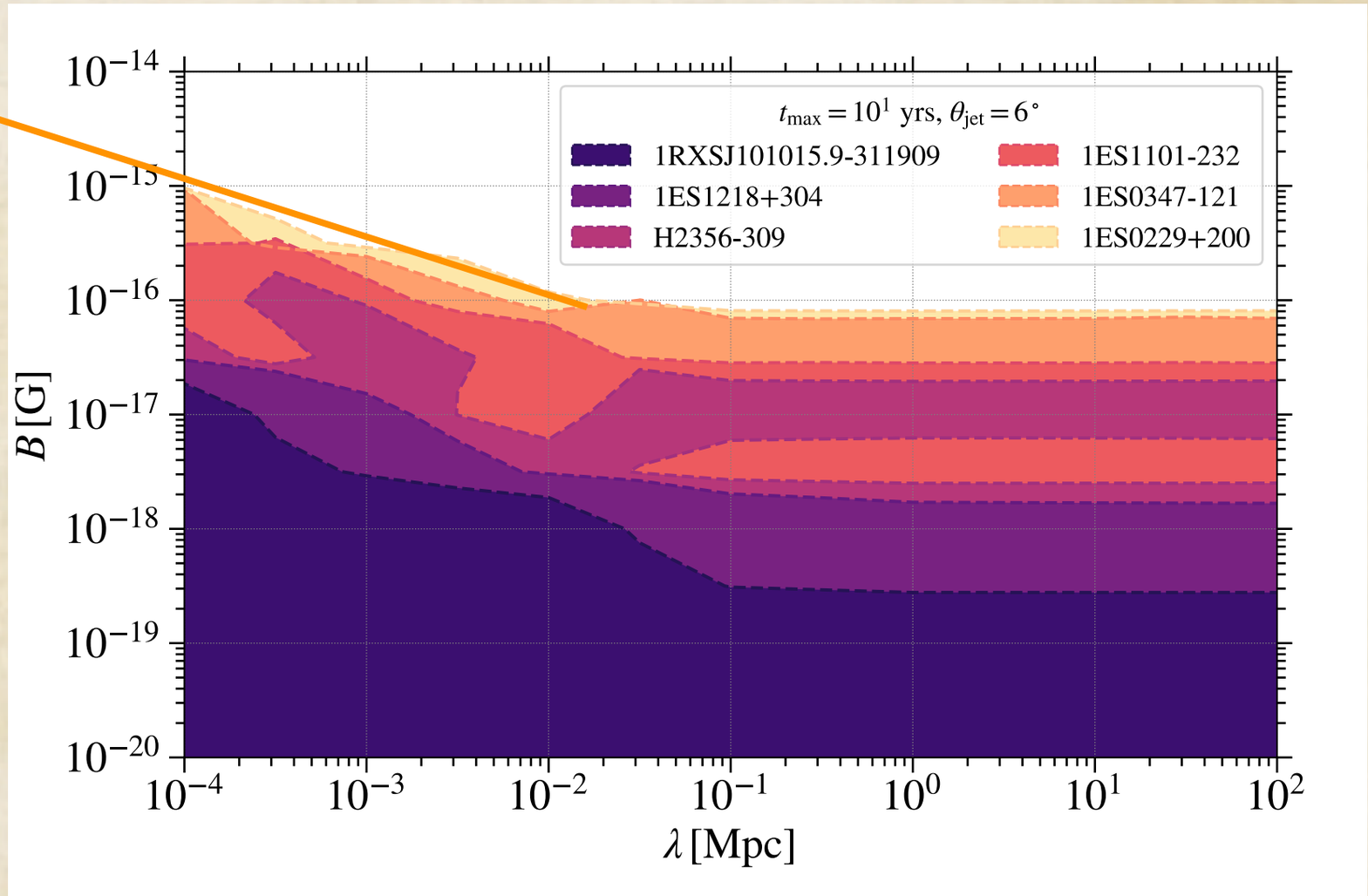


Courtesy H.Oide

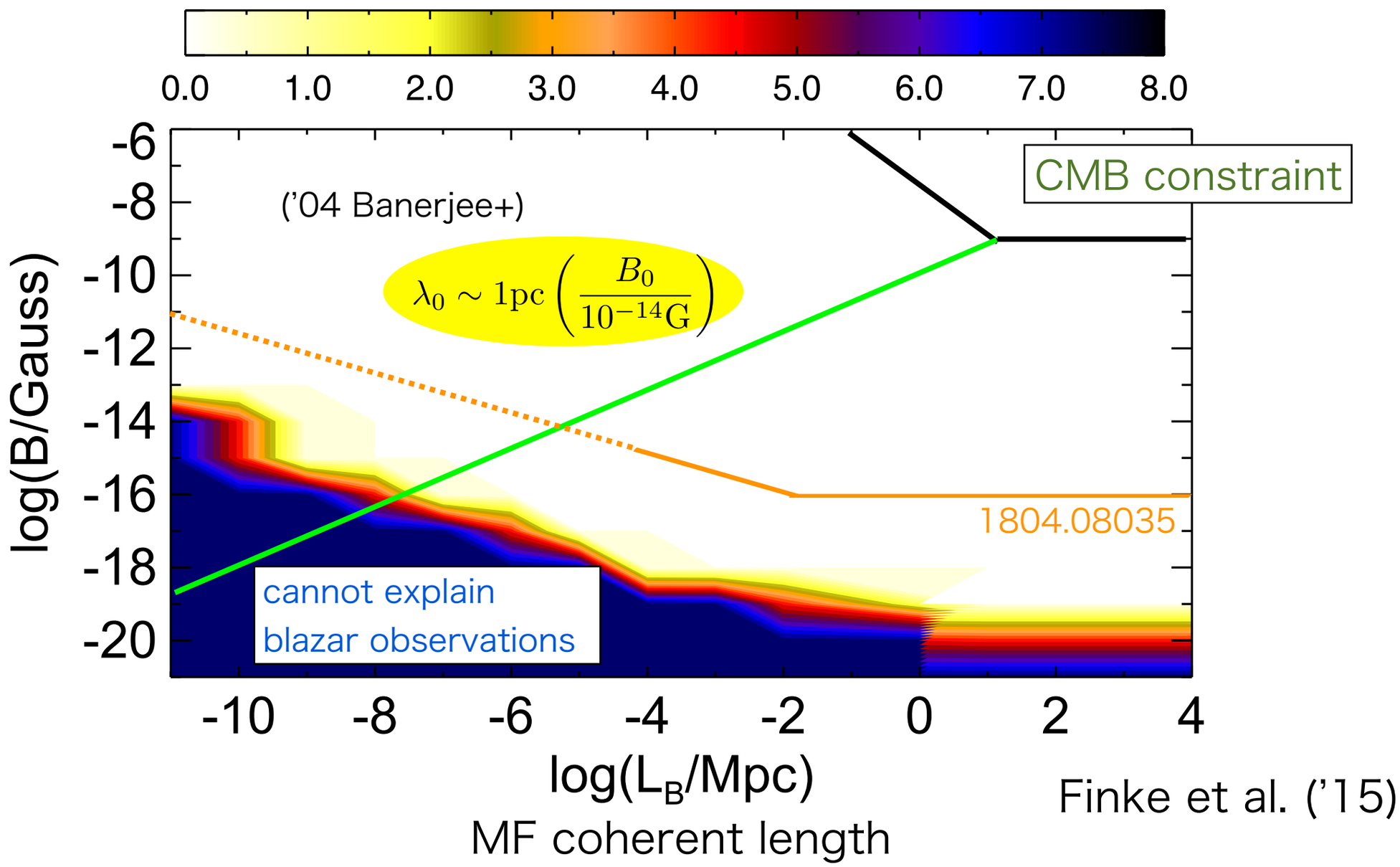
Latest constraints from Fermi 1804.08035 (Fermi-LAT collaboration)

Expected to continue to smaller scales with $B_0 \gtrsim 10^{-16}\mathrm{G}\left(\frac{\lambda_0}{10^{-2}\mathrm{Mpc}}\right)^{-1/2}$

Excluded.

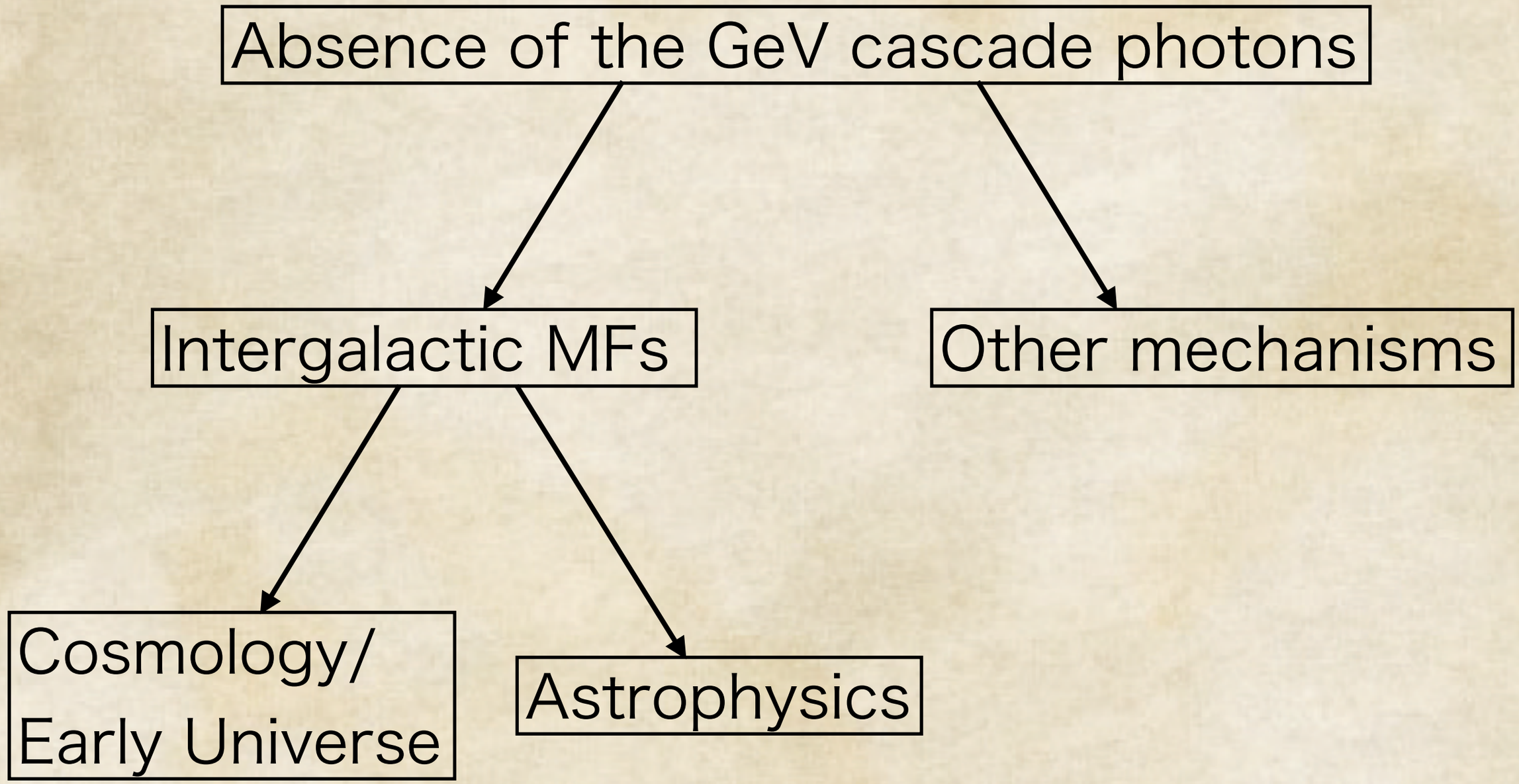


Courtesy H.Oide



Finke et al. ('15)

Courtesy H.Oide



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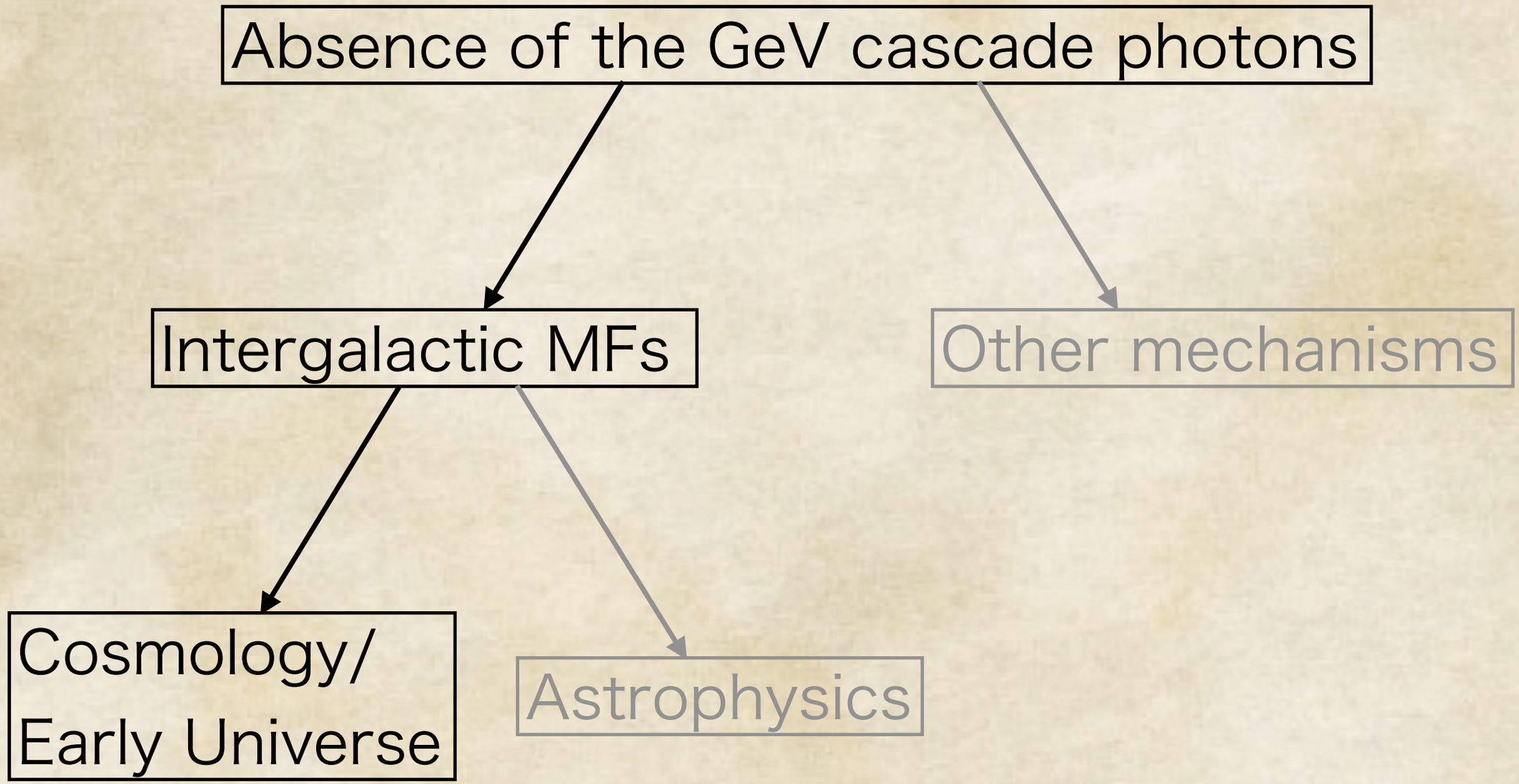

It is not so strange to imagine that (relatively) long-range (hyper)magnetic fields existed in the early Universe.

Courtesy H.Oide

Can there be any interesting phenomena
in the early Universe
caused by the primordial magnetic fields?

How to generate magnetic fields in the early Universe?

Courtesy H.Oide

Can there be any interesting phenomena
in the early Universe
caused by the primordial magnetic fields?

=> Baryogenesis

How to generate magnetic fields in the early Universe?

=> (Pseudo)scalar dynamics

Chiral Plasma Instability

Courtesy H.Oide

Baryogenesis from helical hypermagnetic fields

T. Fujita (Kyoto) & KK, PRD93 (2016) 083520 [arXiv:1602.02109 (hep-ph)],
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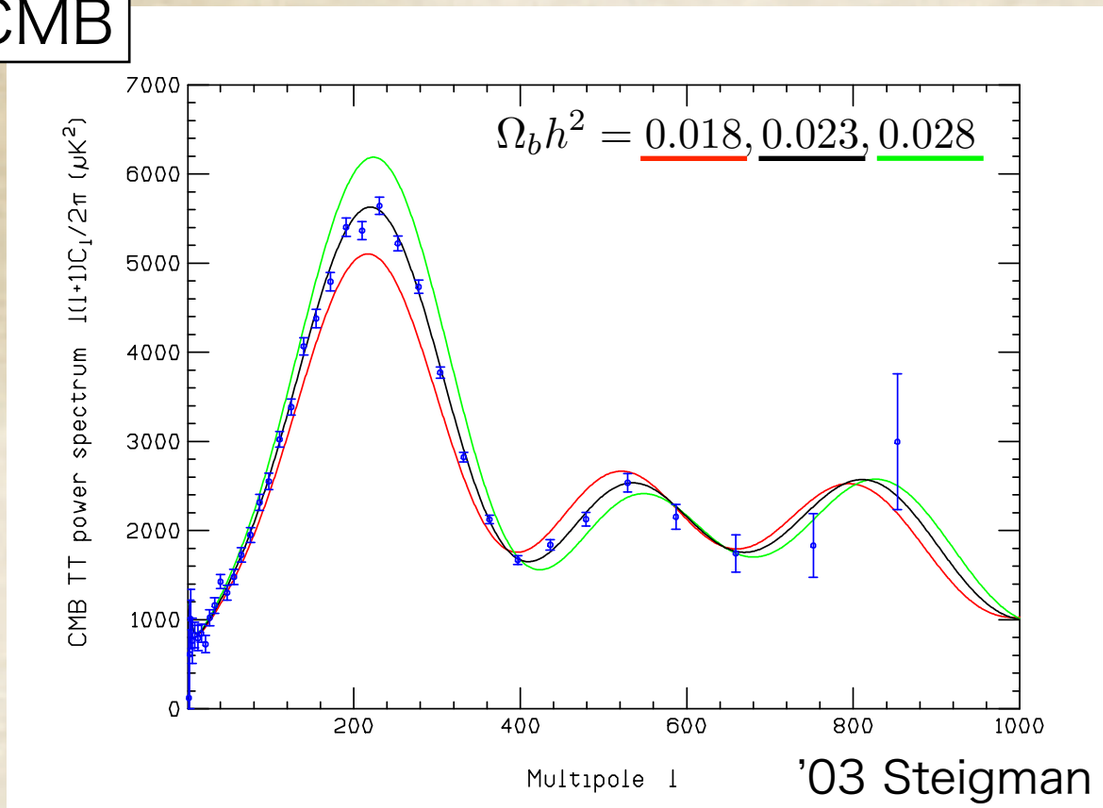
Courtesy H.Oide

Baryon Asymmetry of the Universe

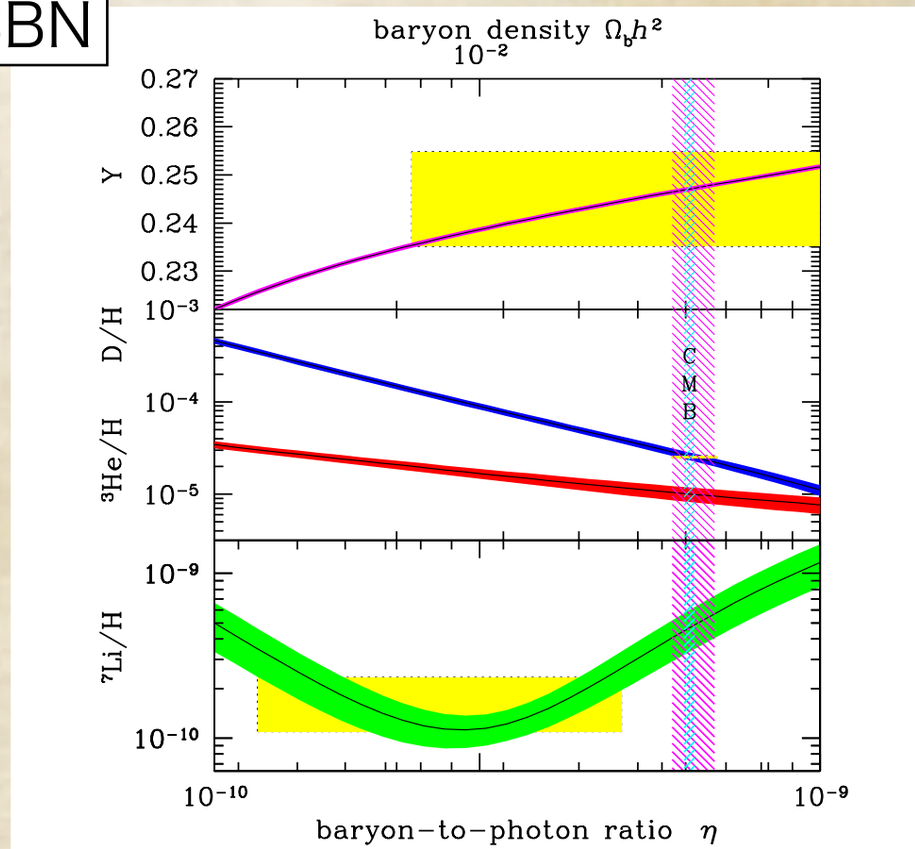
- We live in a matter-antimatter asymmetric Universe.
- BBN and CMB can evaluate it quantitatively.

CMB



'03 Steigman

BBN



Particle Data Group 2015

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

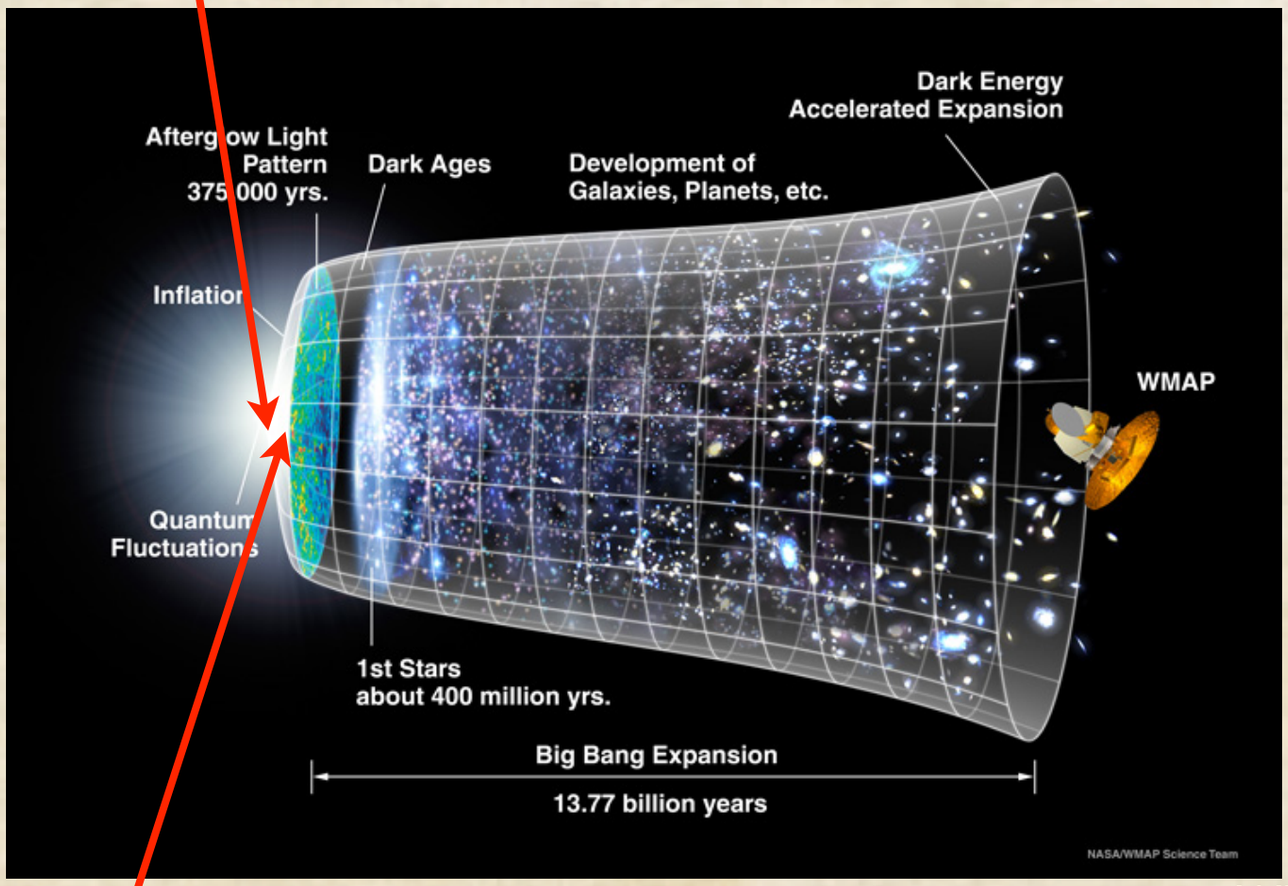
(Planck 2015)

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

BBN+D ; '15 Cyburt+

Courtesy H.Oide

Inflation dilutes the preexisting asymmetry.



WMAP team

After inflation before BBN, asymmetry must be generated.

$$\left\{\begin{array}{ll} \text{matter :} & \sim 10000000000+1 \\ \text{anti matter :} & \sim 10000000000 \\ \text{photon :} & \sim 10000000000 \end{array}\right. \xrightarrow[T \sim 100\,\text{MeV}]{\text{annihilation}} \left\{\begin{array}{ll} \text{matter :} & \sim 1 \\ \text{anti matter :} & \sim 0 \\ \text{photon :} & \sim 10000000000 \end{array}\right.$$

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

Courtesy H.Oide

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BSM is required!?

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

Courtesy H.Oide

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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)

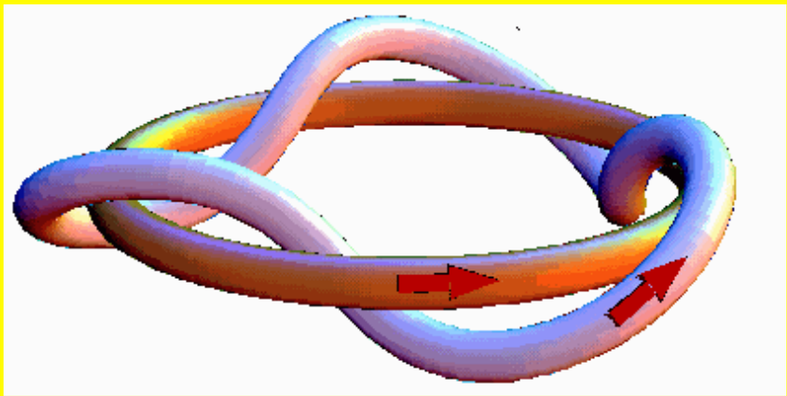
Courtesy H.Oide

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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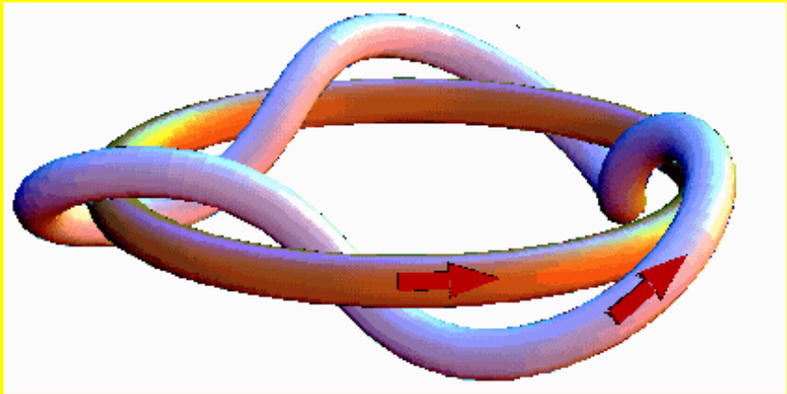

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Chiral anomaly in the SM ('76 't Hooft)

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

SU(2) part:"EW sphaleron"

U(1) part: often neglected

Courtesy H.Oide

Key elements

Hypermagnetic helicity

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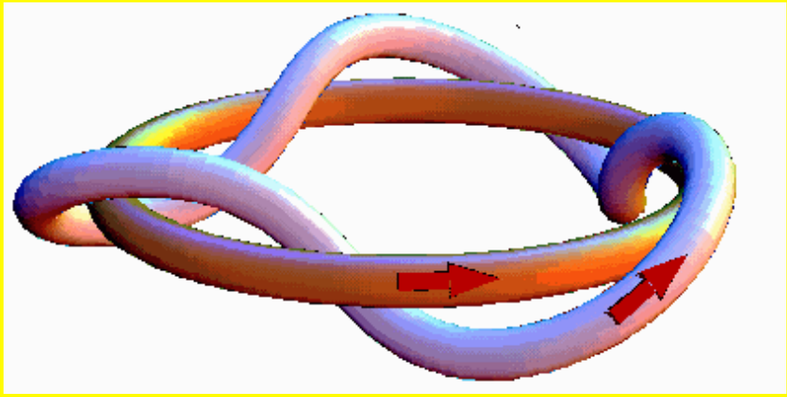

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Chiral anomaly in the SM ('76 't Hooft)

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

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

$$\mathcal{H} = \int d^3x \epsilon^{ijk} Y_i \partial_j Y_k$$

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

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

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!

lected

AU

Courtesy H.Oide

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

Courtesy H.Oide

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

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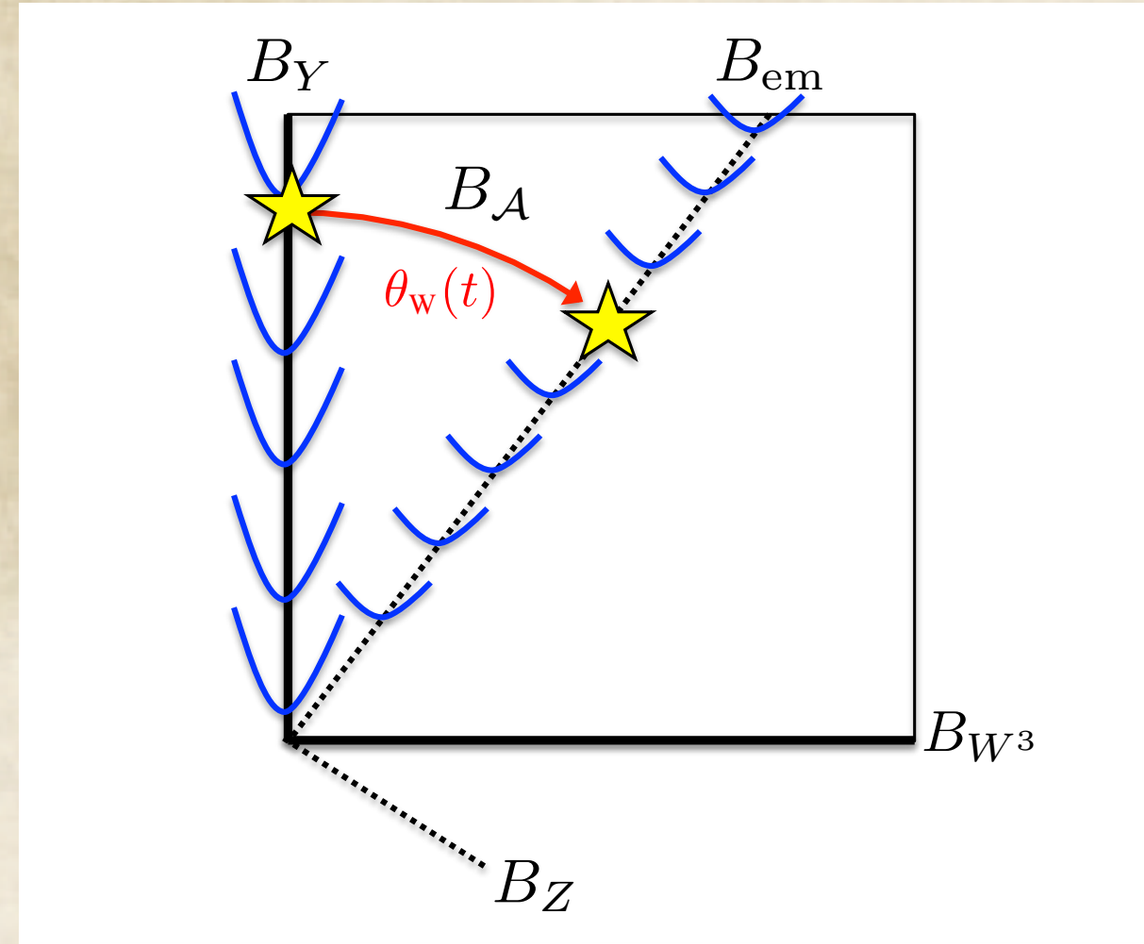
$\sigma \simeq 100T$ ('97 Baym+, '00 Arnold+)

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

Courtesy H.Oide

Electroweak symmetry breaking



Gauge group

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

Large-scale (massless) MFs

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

Magnetic helicity

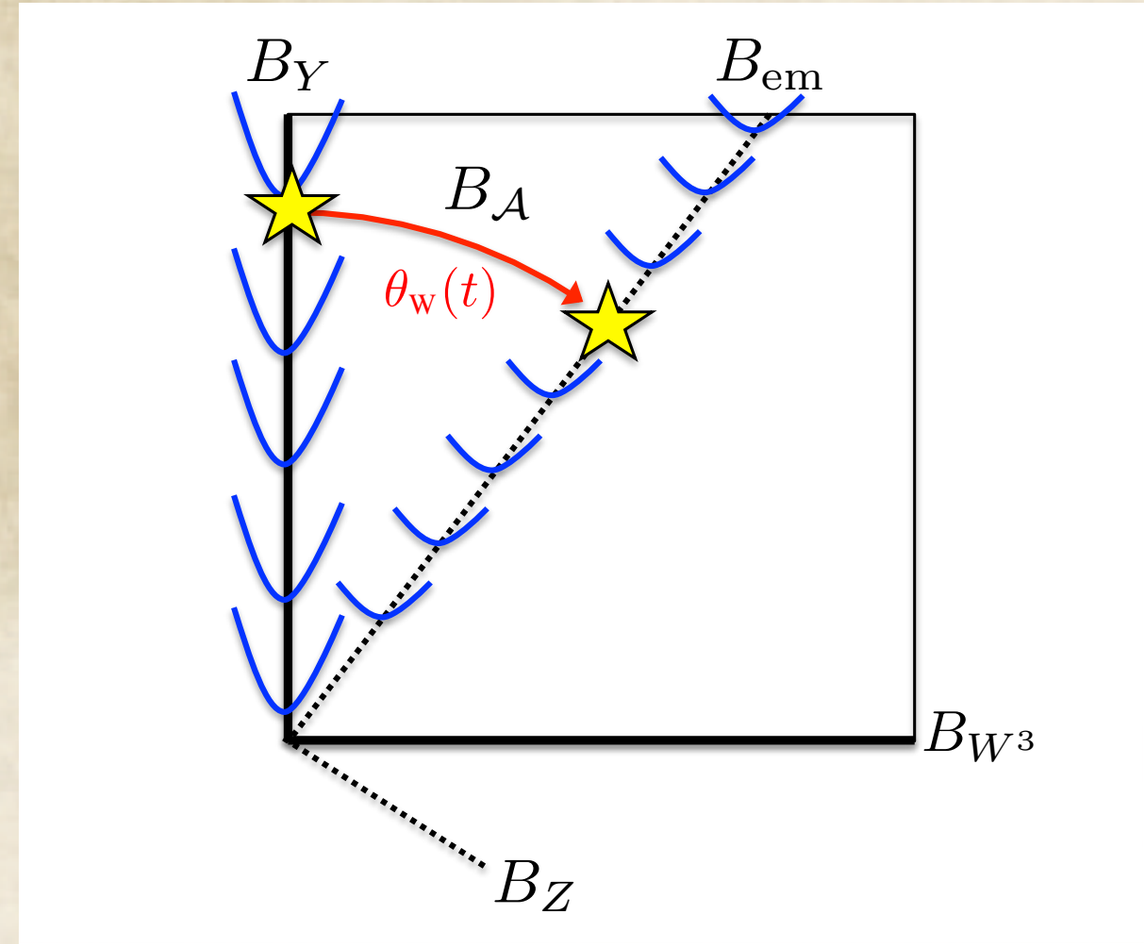
$$H_Y^{\rm before} \to H_{\rm em}^{\rm after} = H_Y^{\rm before}$$

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

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

Courtesy H.Oide

Electroweak symmetry breaking



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 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?

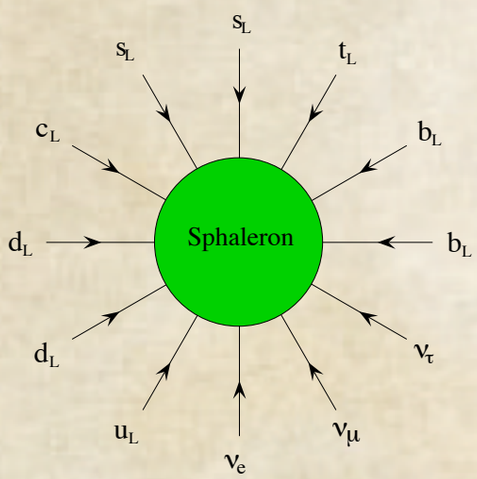
EW sphalerons+chirality flip by electron Yukawa

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

Courtesy H.Oide

Back reactions/washout effects?

EW sphalerons+chirality flip by electron Yukawa



W. Buchmüller, 1212.3554

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

Together with Yukawa int., try to washout Q_B

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

Courtesy H.Oide

Back reactions/washout effects?

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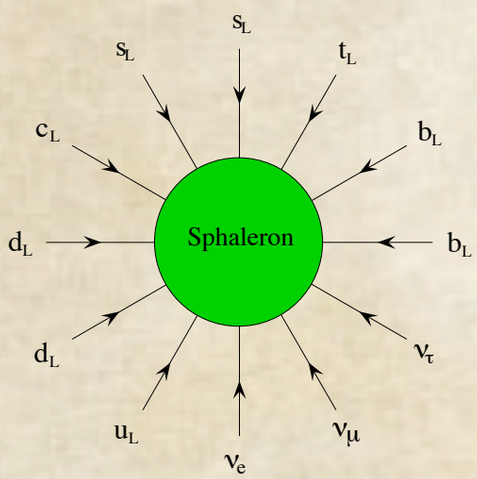

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Ampere's law

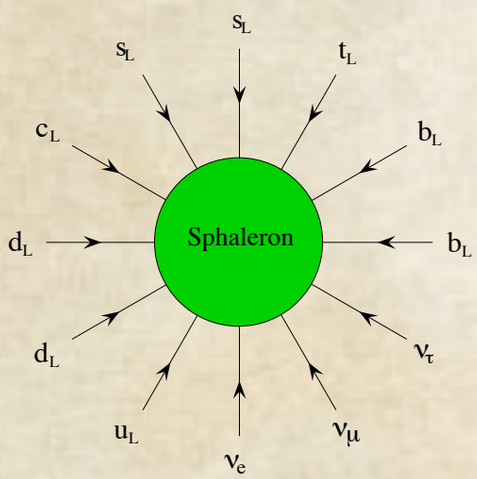
$$\boldsymbol{\nabla} \times \boldsymbol{B}_Y = \boldsymbol{J} = \underbrace{\sigma(\boldsymbol{E}_Y + \boldsymbol{v} \times \boldsymbol{B}_Y)}_{\text{Ohm's current}} + \underbrace{\frac{2\alpha_Y}{\pi}\mu_5 \boldsymbol{B}_Y}_{\text{Chiral magnetic current}}$$

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

Courtesy H.Oide

Back reactions/washout effects?

EW sphalerons+chirality flip by electron Yukawa



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

Together with Yukawa int., try to washout Q_B

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

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

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

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

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

Courtesy H.Oide

Schematically evolution equation is given by

Source term washout term

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

MHD decay EWSB EW sphaleron chirality-flip CME

Courtesy H.Oide

Schematically evolution equation is given by

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MHD decay EWSB EW sphaleron chirality-flip CME

Reaches at “terminal” asymmetry…

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

Courtesy H.Oide

We really solved…

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$\eta = n/s$$

$$x = T/H \sim M_{\rm pl}/T$$

$$k = \#\ \text{degree of freedom}$$

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

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

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

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

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

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

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

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

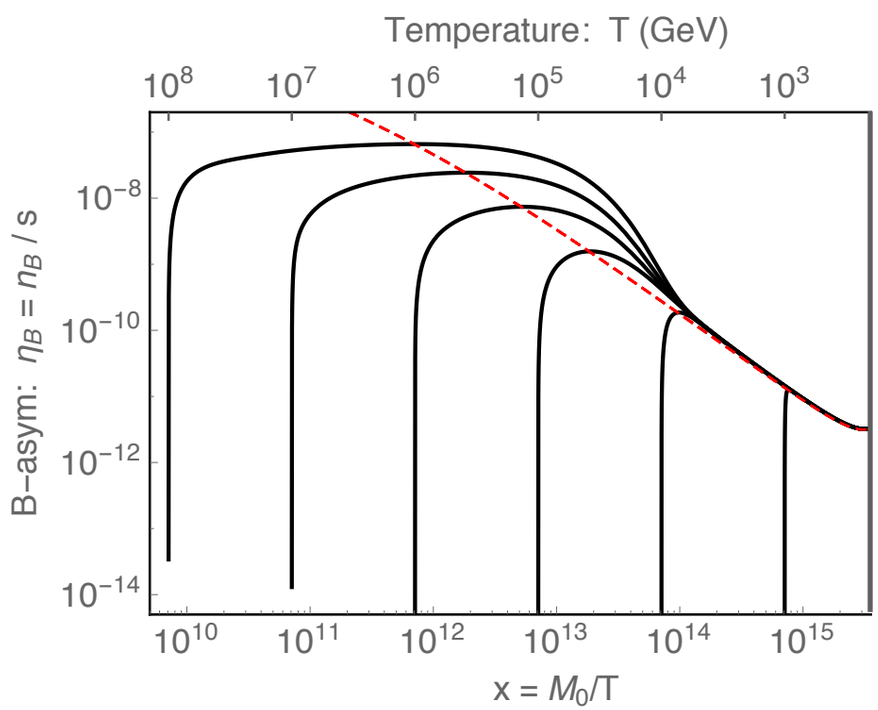
Related work: Giovannini & Shaposhnikov; Fujita & Kamada; AL, Sabancilar, & Vachaspati; Semikoz, Dvornikov, Smirnov, Sokoloff, Valle

Courtesy: A. J. Long

Courtesy H.Oide

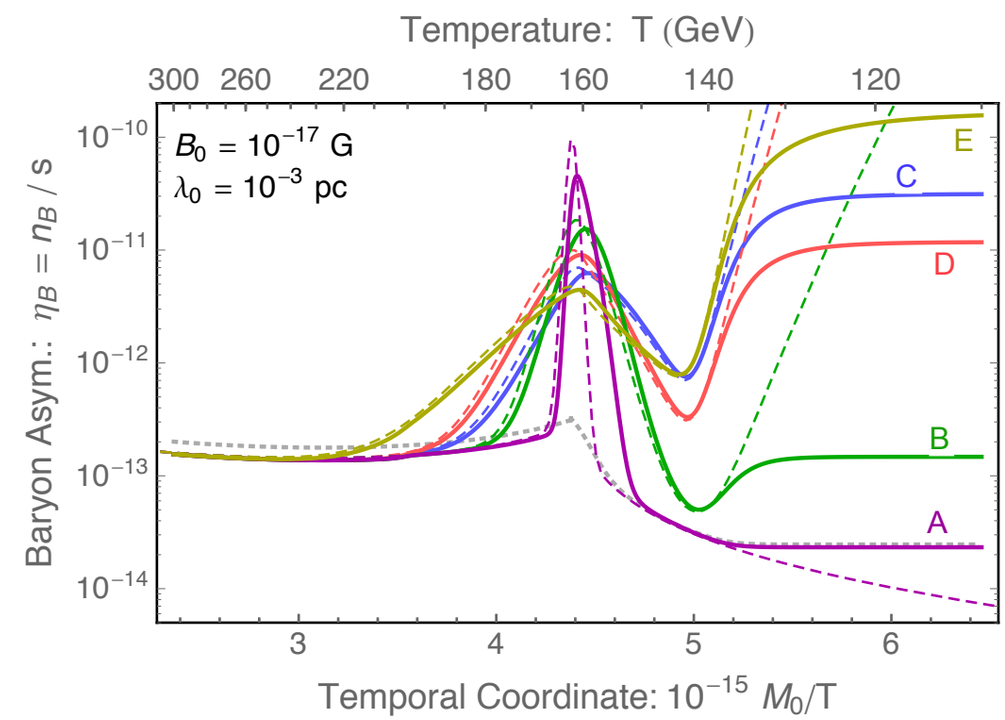
Evolution of baryon asymmetry

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



('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

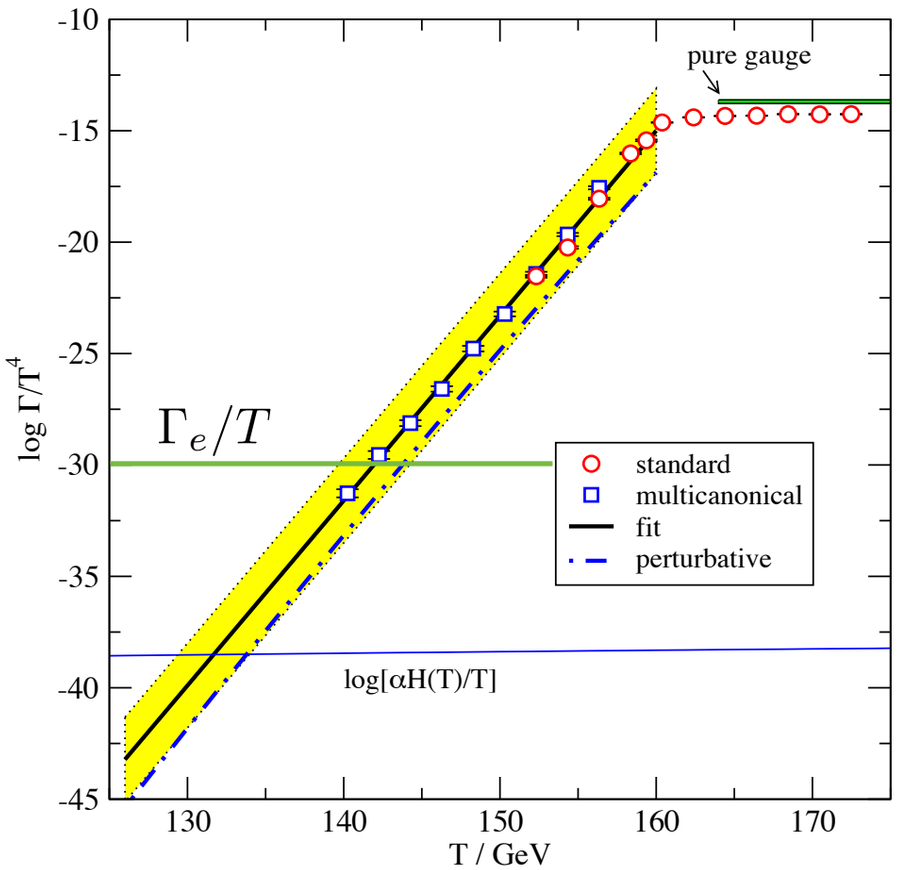
=> Net BAU is efficiently remained

Courtesy H.Oide

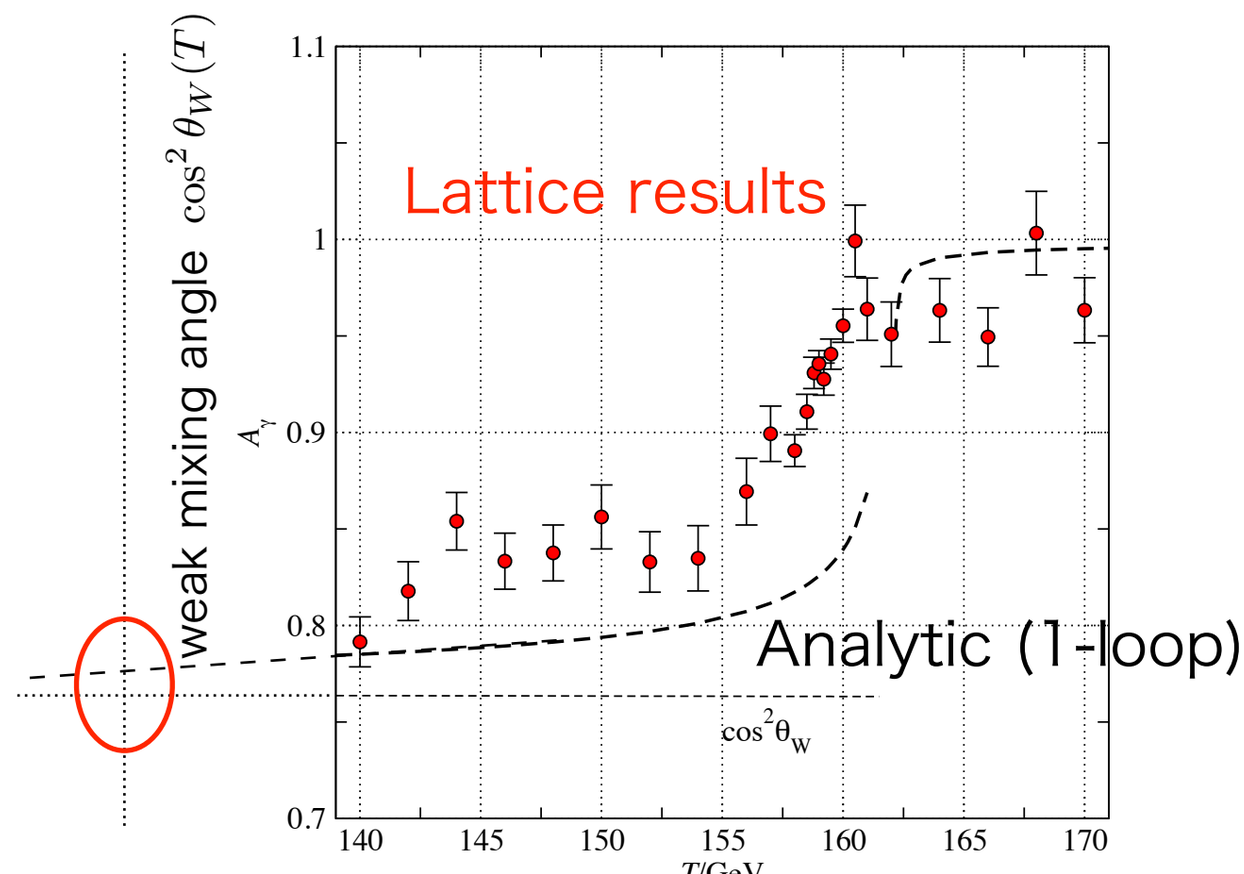
What determines final BAU?

Freezeout of EW sphalerons vs Completion of EWSB

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



('14 D'Onofrio)



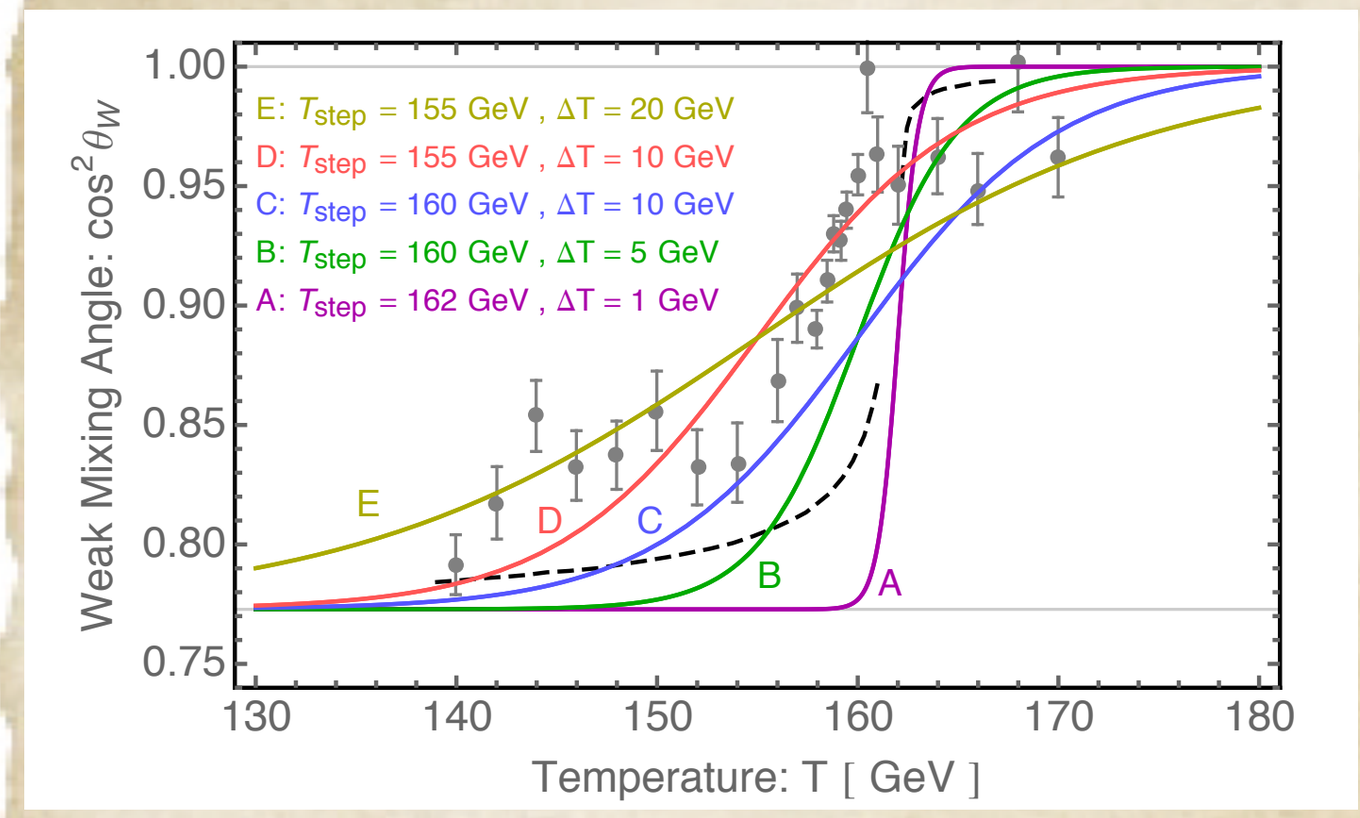
('16 D'Onofrio)

lattice simulations for the EW crossover with 125 GeV Higgs

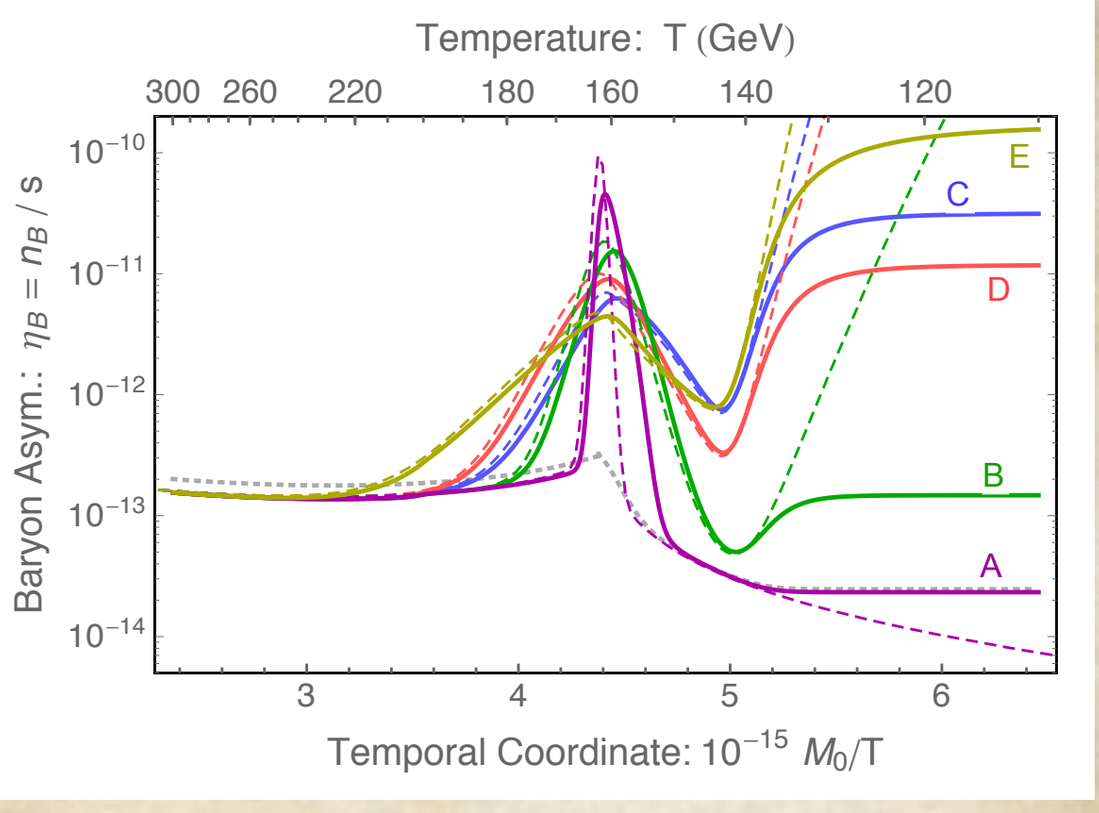
BAU remains! Quantitative results are sensitive to $\theta_W(t)$

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?

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

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

Magnetogenesis with positive helicity before EWSB.

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

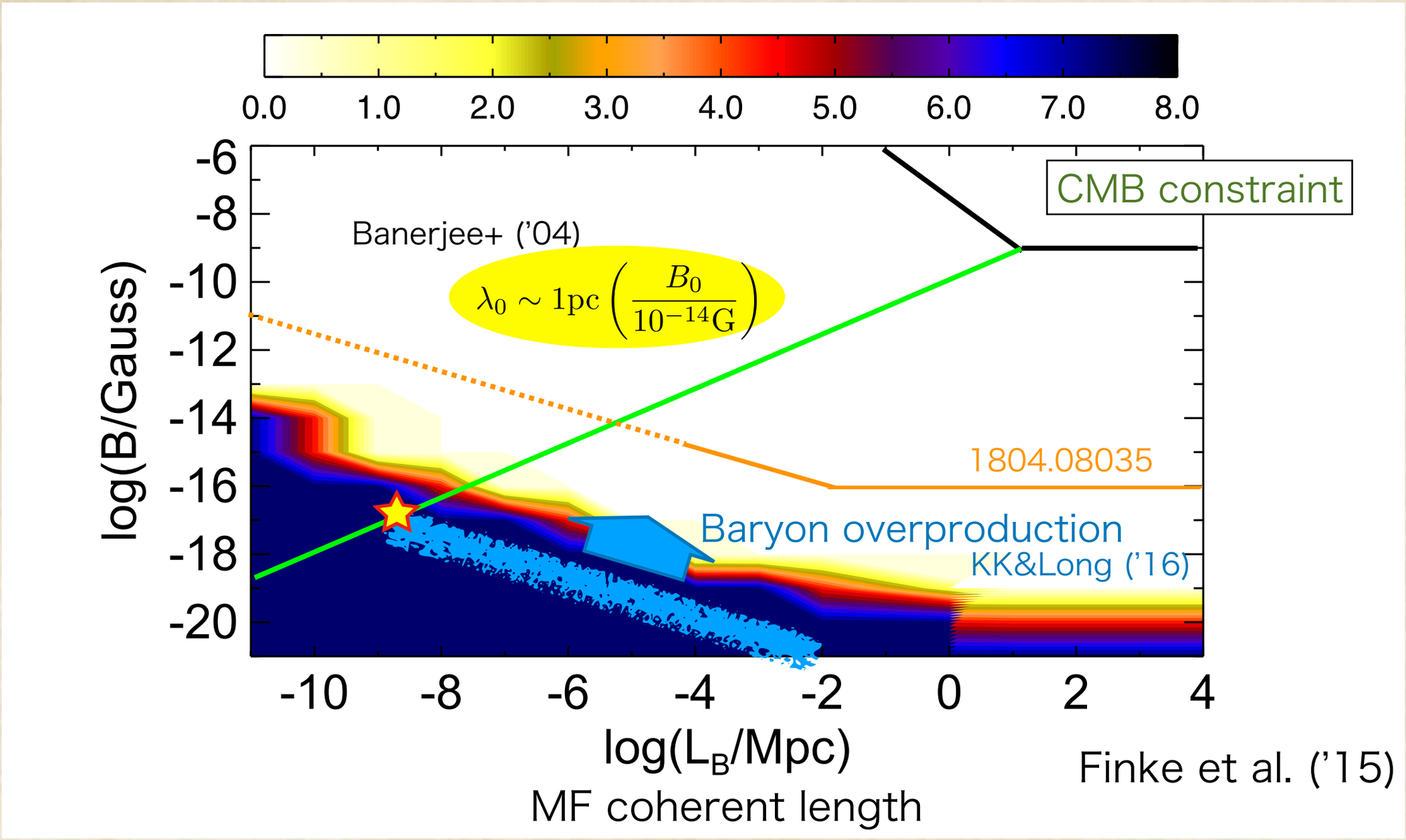
※Since helicity is just the difference between the right and left helicity modes, the sign of helicity can be the same beyond the coherence length of MFs.

Courtesy H.Oide

Unfortunately, not everything can be explained at once.

Courtesy H.Oide

In the B_0-λ_0 plane…



in the case magnetic fields are maximally helical.

Courtesy H.Oide

Interpretations

1. Intergalactic MFs are not maximally helical.
   - If they carry tiny helicity, blazar observations and baryon asymmetry can be explained simultaneously.
2. Intergalactic MFs are maximally helical and they are generated after EWSB. No relation to BAU.
3. Two magnetogenesis scenario. One occurred before EWSB and is responsible for BAU, the other occurred after EWSB and is responsible for blazars.
4. Something is wrong in the blazar observations or evolution of MFs.

e.g. Broderick+, 1808.02959

Courtesy H.Oide

Short summary

- Baryon asymmetry is generated from decaying hypermagnetic helicity through the chiral anomaly. No BSM ingredient!
- B-violation: chiral anomaly/ C&CP-violation: hypermagnetic helicity
  Out of equilibrium: Decay of hypermagnetic helicity/EWSB
- Present B-asymmetry is explained for $B_0 \simeq 10^{-16\sim17}\mathrm{G} \quad \lambda_0 \simeq 10^{-2\sim3}\mathrm{pc}$.
- Larger MFs (that explain blazars) predict baryon overproduction.
- Way outs?
- How to generate (hyper) MFs?

Courtesy H.Oide

Magnetogenesis models

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

KK, PRD97 (2018) 103506 [arXiv:1802.03055 (hep-ph)]

KK, Chang Sub Shin (IBS-CTPU), arXiv:1905.06966 [hep-ph]

Courtesy H.Oide

Known magnetogenesis mechanism

… though non of them are satisfactory yet.

1) (Pseudo)scalar dynamics (includes axion inflation)

e.g., Tuner&Widrow ('88), Ratra('92), Garretson+('92), Anber&Sorbo ('06), Fujita&Namba ('16), …

$$f(\phi)F_{\mu\nu}F^{\mu\nu} \qquad g(\phi)F_{\mu\nu}\tilde{F}^{\mu\nu}$$

2) First order phase transition

e.g., Quashnock+('89), Vachaspati ('91), Baym+ ('96), Grasso&Riotto('98),…

3) Chiral plasma instability

e.g., Joyce&Shaposhnikov ('97), KK ('18),

Courtesy H.Oide

Magnetogenesis with helicity is particularly interesting.

Courtesy H.Oide

Known magnetogenesis mechanism

… though non of them are satisfactory yet.

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e.g., Joyce&Shaposhnikov ('97), KK ('18)

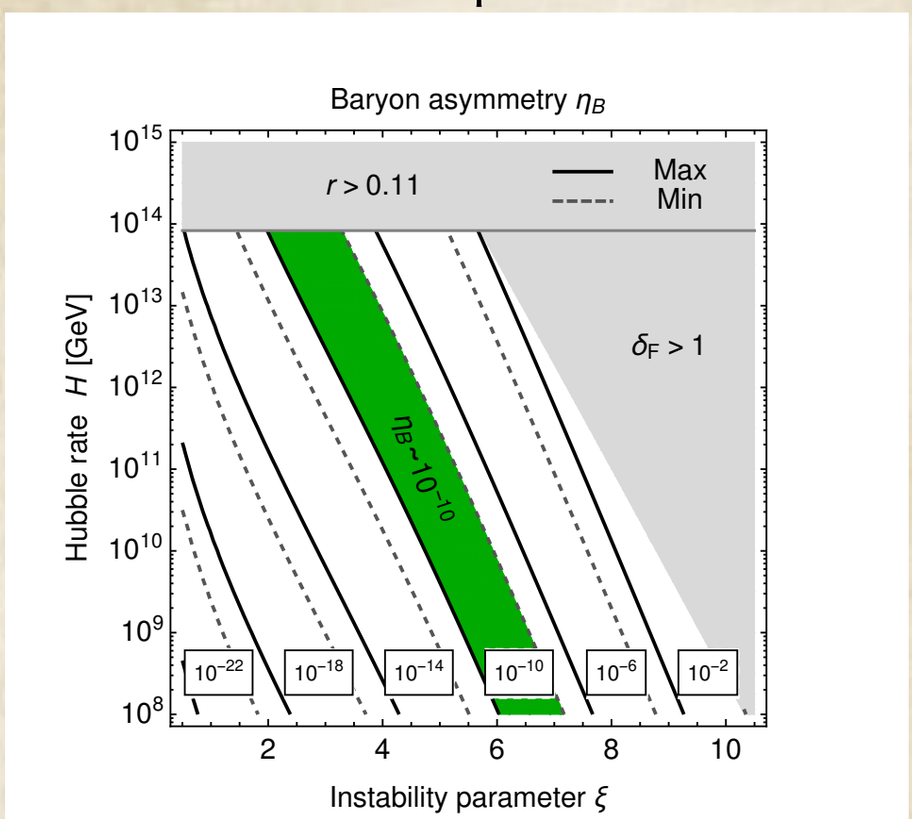
Courtesy H.Oide

Magnetogenesis models

1. pseudoscalar inflation ('06 Anber+, and many others including '17 Jimenez, KK, Schmitz, Xu)

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

One polarization mode feels instability => maximally helical MFs



('17 Jiménez+)

Courtesy H.Oide

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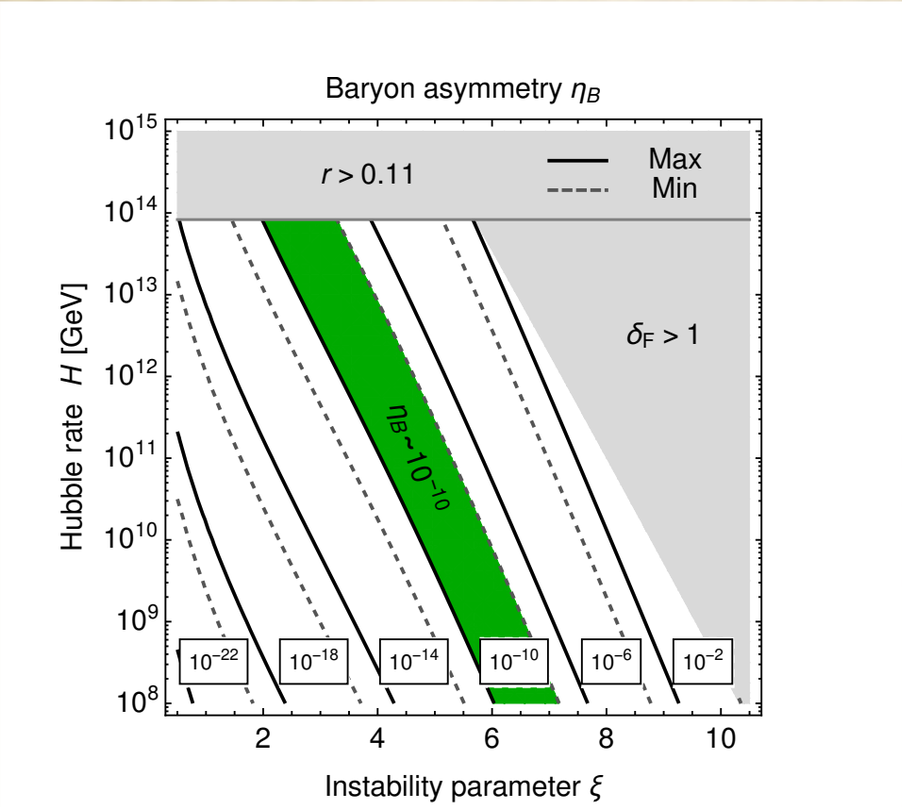
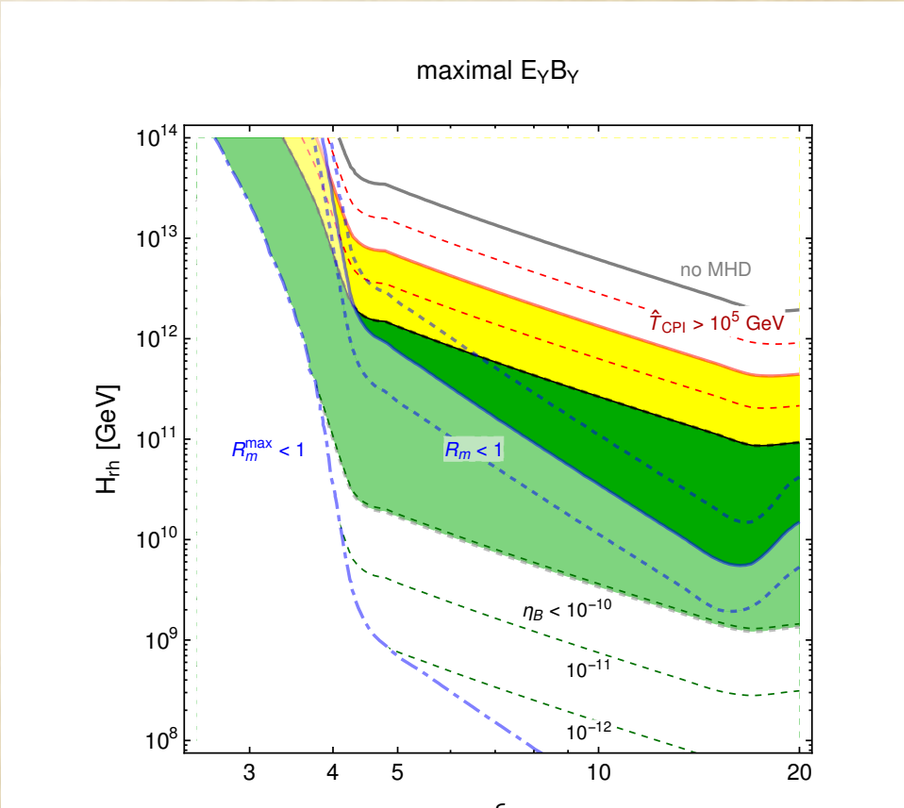
One polarization mode feels instability => maximally helical MFs



('17 Jiménez+)



('19 Domcke+)

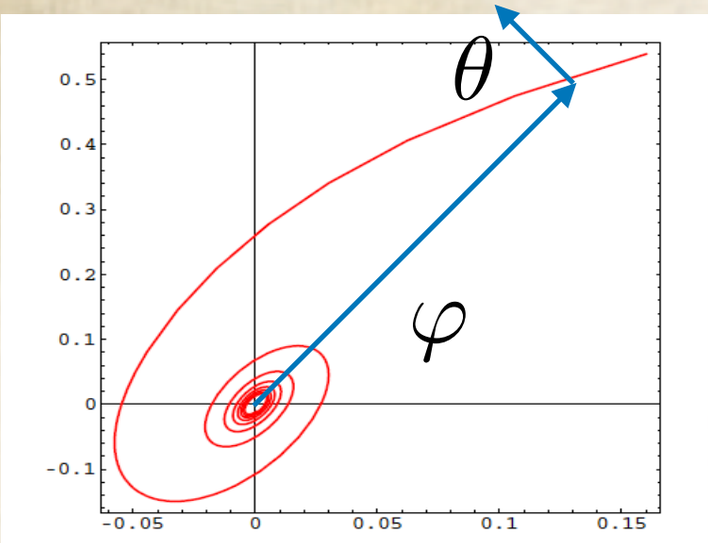
Courtesy H.Oide

Magnetogenesis models

1. pseudoscalar inflation ('06 Anber+, and many others including '17 Jimenez, KK, Schmitz, Xu)

$$\frac{c\alpha}{\pi}\theta F_{\mu\nu}\tilde{F}^{\mu\nu} \Rightarrow \left[\frac{\partial^2}{\partial\tau^2} + k^2\left(1 \mp \frac{c\alpha}{\pi k}\theta'\right)\right] A_k^{\pm} = 0$$

One polarization mode feels instability => maximally helical MFs

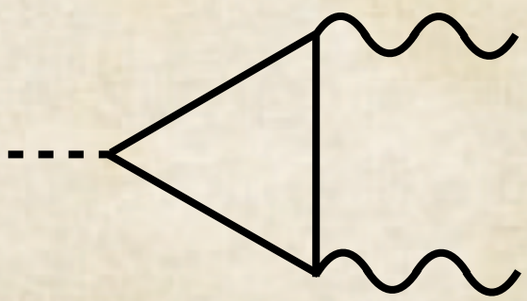


In the Affleck-Dine mechanism by integrating out heavy fields around the flat direction (AD field), the phase direction of the AD field obtain the anomalous coupling to unbroken U(1) gauge fields, if any.

('19 KK & Shin)

$$\frac{c\alpha}{\pi}\theta F_{\mu\nu}\tilde{F}^{\mu\nu}$$

e.g. HuHd or LHu flat direction.



It is indeed obvious noting that the phase direction of HuHd flat direction is nothing but the PQWW axion.

Courtesy H.Oide

Magnetogenesis models

1. pseudoscalar inflation ('06 Anber+, and many others including '17 Jimenez, KK, Schmitz, Xu)

$$\frac{c\alpha}{\pi}\theta F_{\mu\nu}\tilde{F}^{\mu\nu} \Rightarrow \left[\frac{\partial^2}{\partial\tau^2} + k^2\left(1 \mp \frac{c\alpha}{\pi k}\theta'\right)\right] A_k^{\pm} = 0$$

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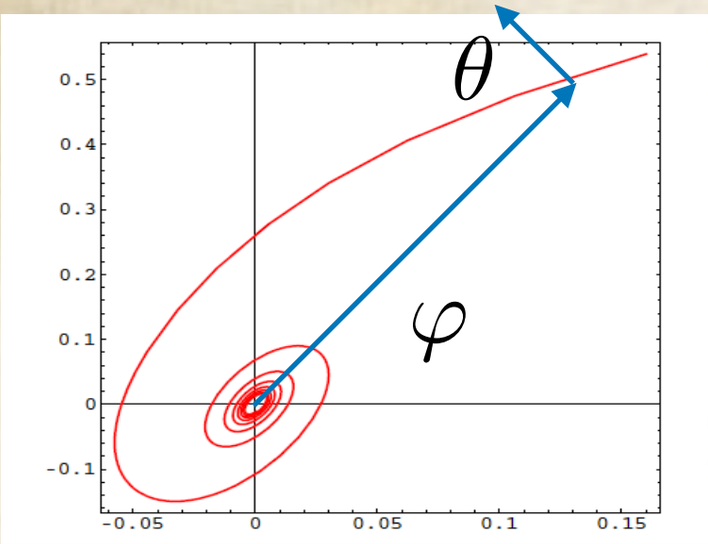

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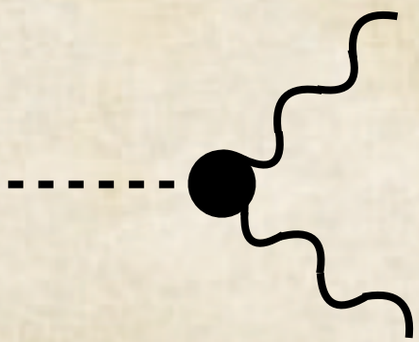

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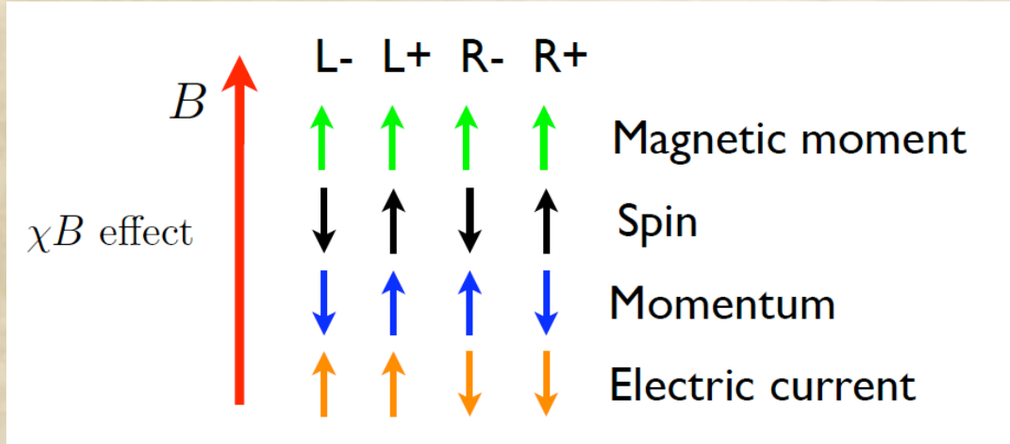
Courtesy H.Oide

2. Chiral plasma instability ('97 Joyce&Schaposhnikov, '17 Schober+, '18 KK)

Chiral Magnetic Effect ('80 Vilenkin, '08 Fukushima, Kharzéev&Warringa, and more…)



('12 Tashro+)

$$\boldsymbol{J}_{\rm CME} = \frac{g'^2}{2\pi^2}\mu_5^Y \boldsymbol{B}_Y$$

$$\mu_5^Y = \sum_i y_i^2 \mu_i^{(R)} - \sum_j y_j^2 \mu_j^{(L)}$$

$$\mu_5 \leftrightarrow \frac{\dot{\theta}}{f}$$

$$\frac{d\boldsymbol{B}}{d\tau} = -\boldsymbol{\nabla}\times\boldsymbol{E}, \quad \boldsymbol{\nabla}\times\boldsymbol{B} = \boldsymbol{J}, \quad \boldsymbol{J} = \sigma(\boldsymbol{E}+\boldsymbol{v}\times\boldsymbol{B}) + \frac{2\alpha}{\pi}\mu_5\boldsymbol{B}$$

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

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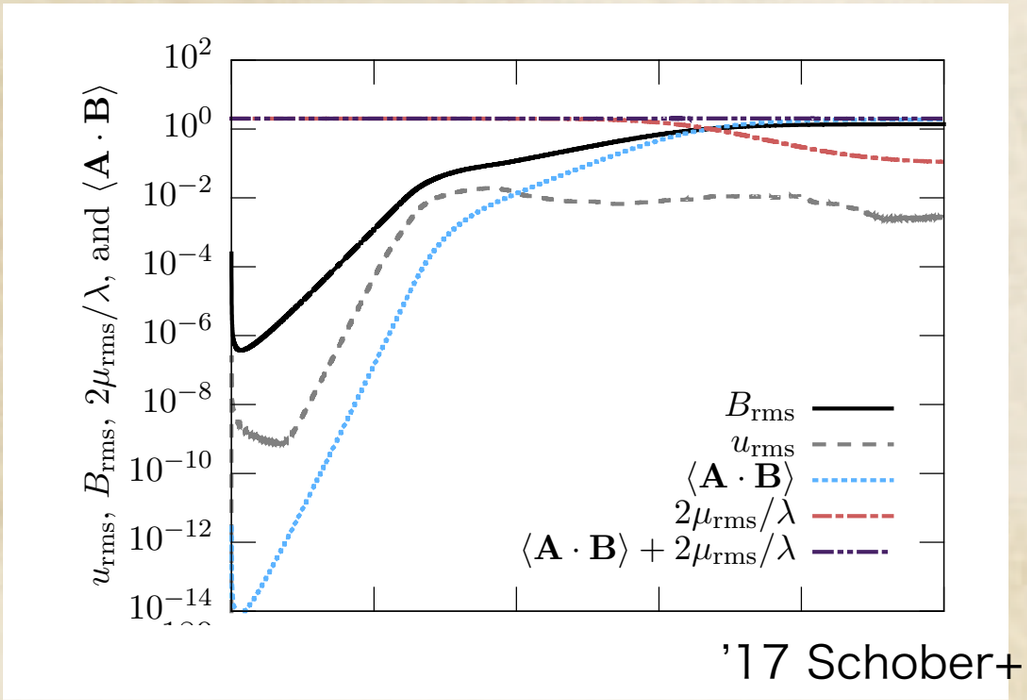

'17 Schober+

Numerical MHD now suggests complete transfer from the chiral asymmetry to magnetic helicity is realized.

$$\frac{d}{dt}\left[n_5 + \frac{c\alpha}{2\pi}H\right] = 0$$

SU(5) GUT baryogengesis-like scenario may give rise to large initial chiral asymmetry.

('18 KK)

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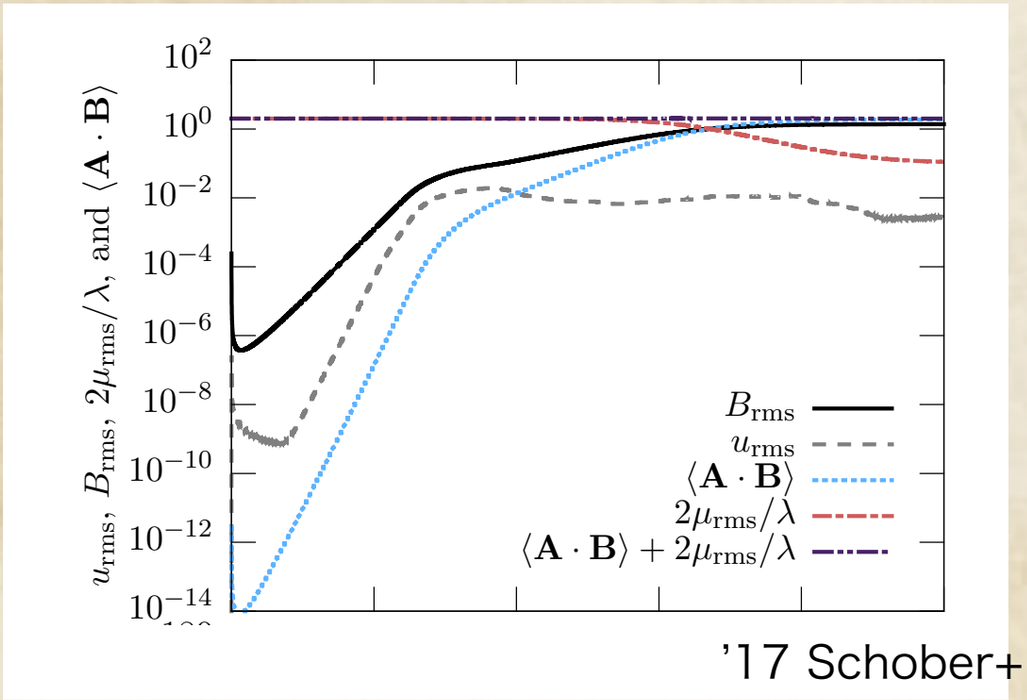

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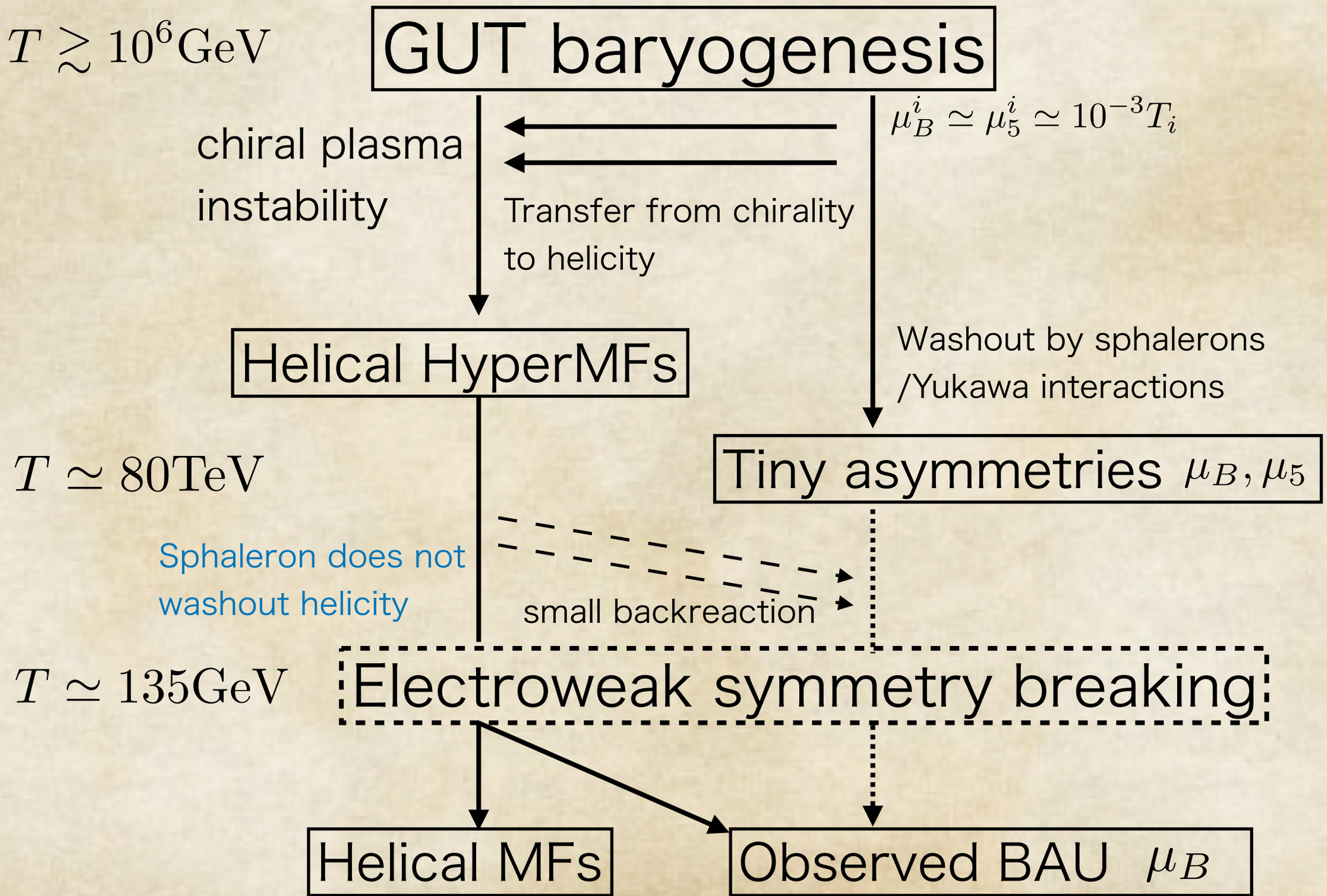
('18 KK)

For $\frac{n_5}{s} \simeq \frac{n_B}{s} \simeq 10^{-5}$, while initial BAU is washed out by the sphalerons, with the transferred hyper magnetic fields, present BAU can be explained.

Courtesy H.Oide

Revival of the GUT baryogenesis



Courtesy H.Oide

Summary

Courtesy H.Oide

1. Absence of GeV cascade photon from blazars as well as the new mechanism of baryogenesis from helical hypermagnetic fields give a strong motivation to study cosmological magnetic fields.
2. Unfortunately at present there are no concrete models that can explain everything at once.
3. Nevertheless the seeking for the magnetogenesis mechanism is an interesting field of study. Blazars and baryogenesis are the good guiding principles.
4. Inflationary magnetogenesis is one of the popular and interesting options, which needs more investigations.
5. Chiral plasma instability is an physically interesting process, which can have nontrivial implications on GUT.

Courtesy H.Oide

Appendix

Courtesy H.Oide

Chiral anomaly ('69 Adler; Bell&Jackiw)

$$\partial_\mu j_5^\mu = -\frac{g^2}{8\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

-> B+L violation in SM ('76 't Hooft)

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

Courtesy H.Oide

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Example in particle physics:

$\pi^0 \to 2\gamma$ decay

EW sphaleron => EW baryogenesis, Leptogenesis

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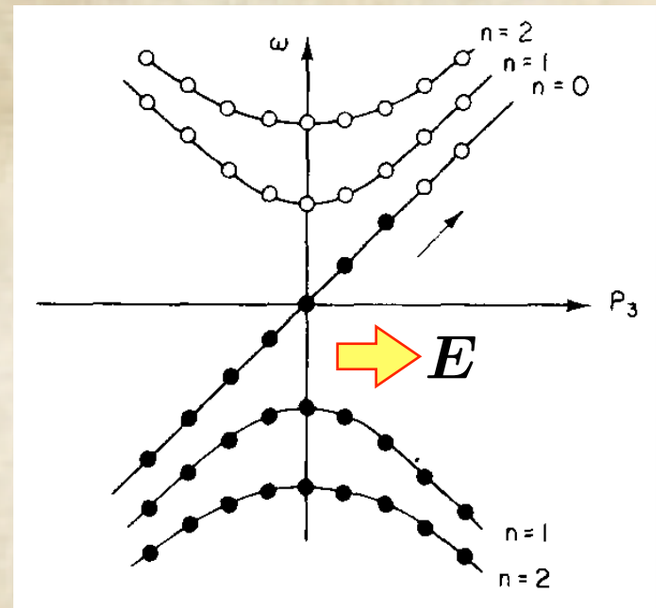
Effect of gauge bosons as particle

Courtesy H.Oide

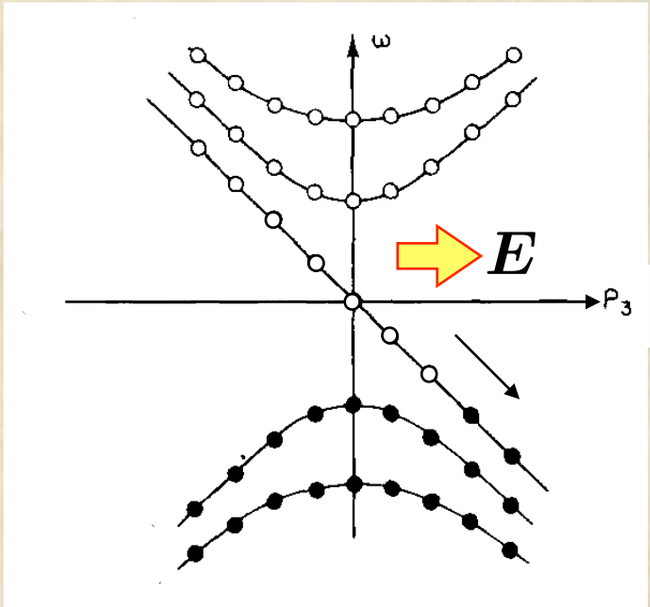
Chiral anomaly ('69 Adler; Bell&Jackiw)

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

If there are coherent and parallel electric & magnetic fields in the background, $j_5^0 = n_5$ is induced in the system



R-handed fermion



L-handed fermion

('83 Ninomiya&Nielsen)

Landau level appears by adding MFs in z-direction

Further adding EFs in z-direction, the levels are occupied along the gapless modes

Difference in particle number of L-and R-handed mode.

=> $j_5^0 = n_5$ is induced

Courtesy H.Oide

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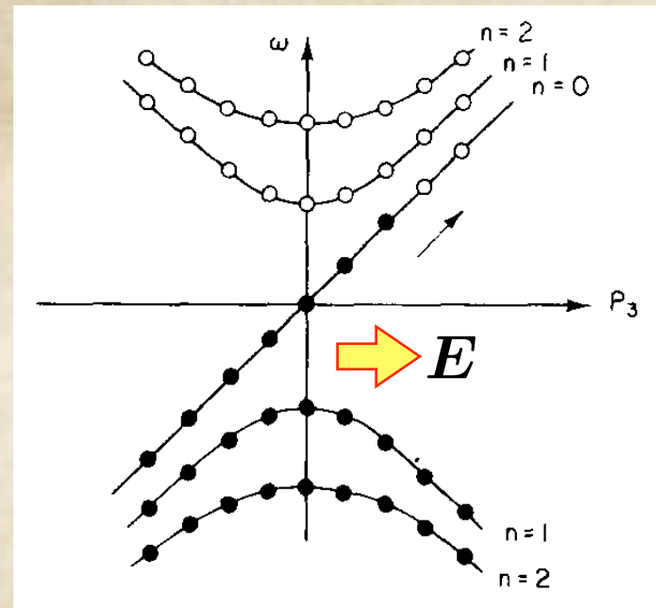

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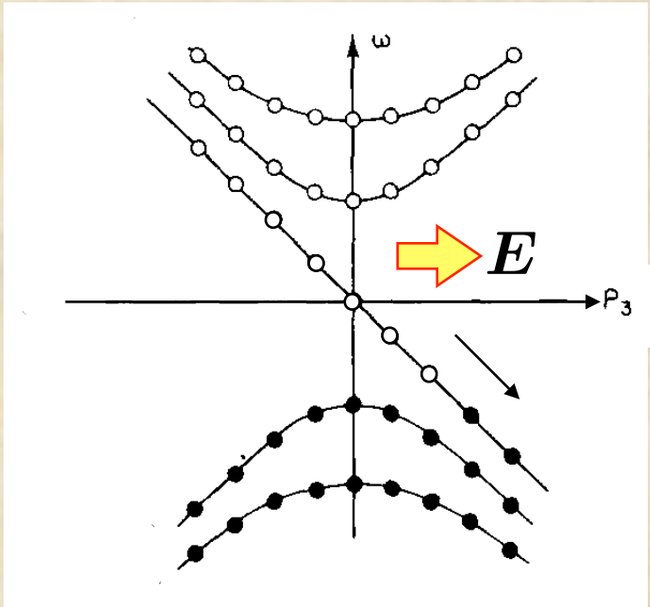

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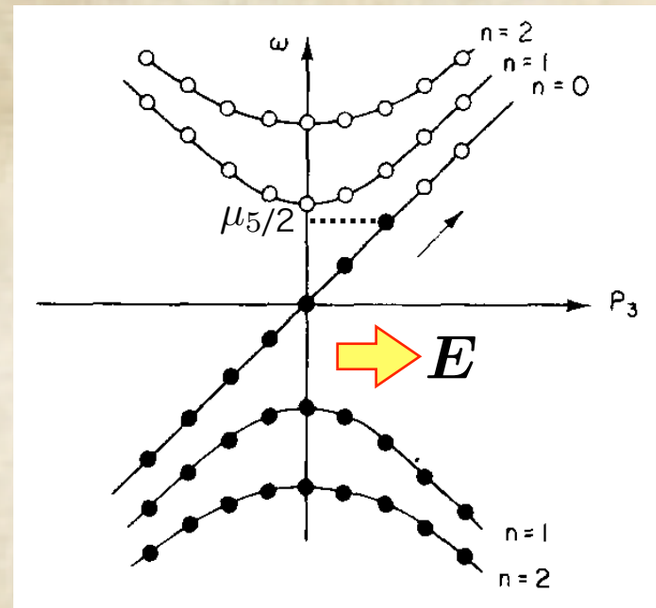
Courtesy H.Oide

Chiral magnetic effect (CME)

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

In the system with MFs and chiral asymmetry (μ_5 or n_5) electric current is induced by the CME.

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



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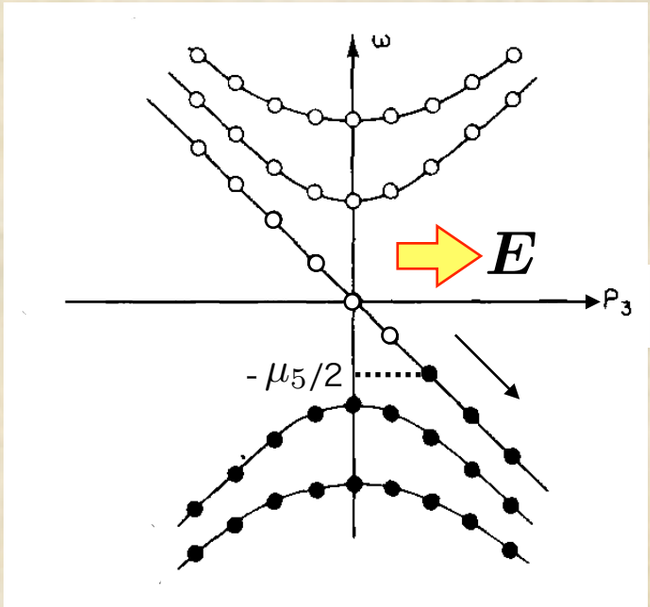


L-handed fermion

('83 Ninomiya&Nielsen)

EFs in z-dir. => positive momentum modes in z-dir. of R/L-handed fermions are in/decreased

= E-current is induced.

$\boldsymbol{E} \to 0$ limit, we still have this effect

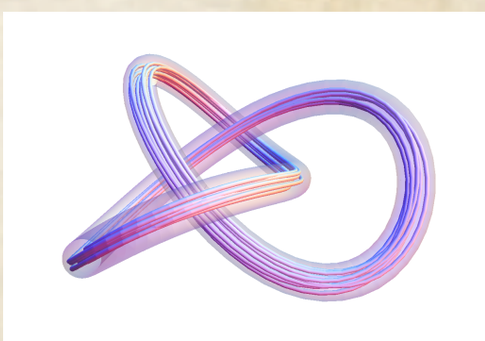
Courtesy H.Oide

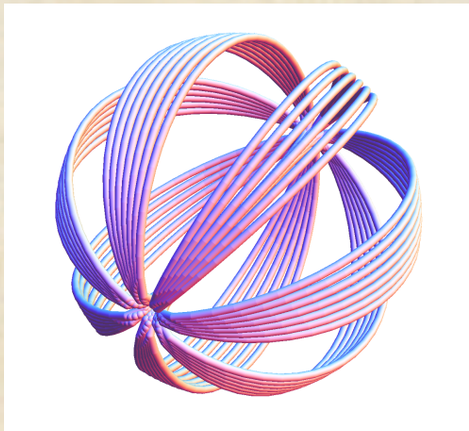
Chiral anomaly ('69 Adler; Bell&Jackiw)

=Chirality (N_5) + Helicity ($\mathcal{H}$) の保存則

$$\partial_\mu j_5^\mu = -\frac{g^2}{8\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu} \quad \Rightarrow \quad \partial_\mu \left(j_5^\mu + \frac{g^2}{8\pi^2} K^\mu \right) = 0$$

$$\frac{d}{dt}\left(N_5 + \frac{g^2}{8\pi^2}\mathcal{H} \right) = 0$$





('15 Hirono, Kharzeev & Yin)

Helicity:

1. Winding number of MF line
2. Difference between R and L modes

$$\mathcal{H} \equiv \int d^3x K^0 = \int d^3x \boldsymbol{A}\cdot\boldsymbol{B} = \int d^3x \epsilon^{ijk} A_i \partial_j A_k$$

$$= V \int \frac{d^3k}{(2\pi)^3} k \left[|A_k^R|^2 - |A_k^L|^2 \right]$$

Courtesy H.Oide

CME can be understood as the backreaction of generation of chiral asymmetry by the background EM fields.

In terms of the magnetohydrodynamics

$$\frac{d\boldsymbol{B}}{d\tau} = -\boldsymbol{\nabla}\times\boldsymbol{E}, \quad \boldsymbol{\nabla}\times\boldsymbol{B} = \boldsymbol{J}, \quad \boldsymbol{J} = \sigma(\boldsymbol{E}+\boldsymbol{v}\times\boldsymbol{B}) + \frac{2\alpha}{\pi}\mu_5\boldsymbol{B}$$

CME

$$\Rightarrow \quad \frac{d\boldsymbol{B}}{d\tau} = \frac{1}{\sigma}\left(\boldsymbol{\nabla}^2\boldsymbol{B} + \frac{2\alpha}{\pi}\mu_5\boldsymbol{\nabla}\times\boldsymbol{B}\right) + \boldsymbol{\nabla}\times(\boldsymbol{v}\times\boldsymbol{B})$$

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CME

$$\frac{d\boldsymbol{B}_k^{\pm}}{d\tau} = \frac{1}{\sigma}\left(-k^2\boldsymbol{B}_k^{\pm} \pm \frac{2\alpha}{\pi}\mu_5 k\boldsymbol{B}_k^{\pm}\right) + \left(\boldsymbol{\nabla}\times(\boldsymbol{v}\times\boldsymbol{B}^{\pm})\right)_k$$

non-zero $\boldsymbol{E}\cdot\boldsymbol{B} = -\frac{1}{2V}\frac{d}{dt}\mathcal{H}$ induces chiral asymmetry

non-zero μ_5 induces instability in the helical gauge fields

<Chiral plasma instability>

conservation law for $N_5 + \frac{g^2}{8\pi^2}\mathcal{H}$ is satisfied.

Courtesy H.Oide