Intergalactic Magnetic Fields as the Origin of Baryon Asymmetry of the Universe

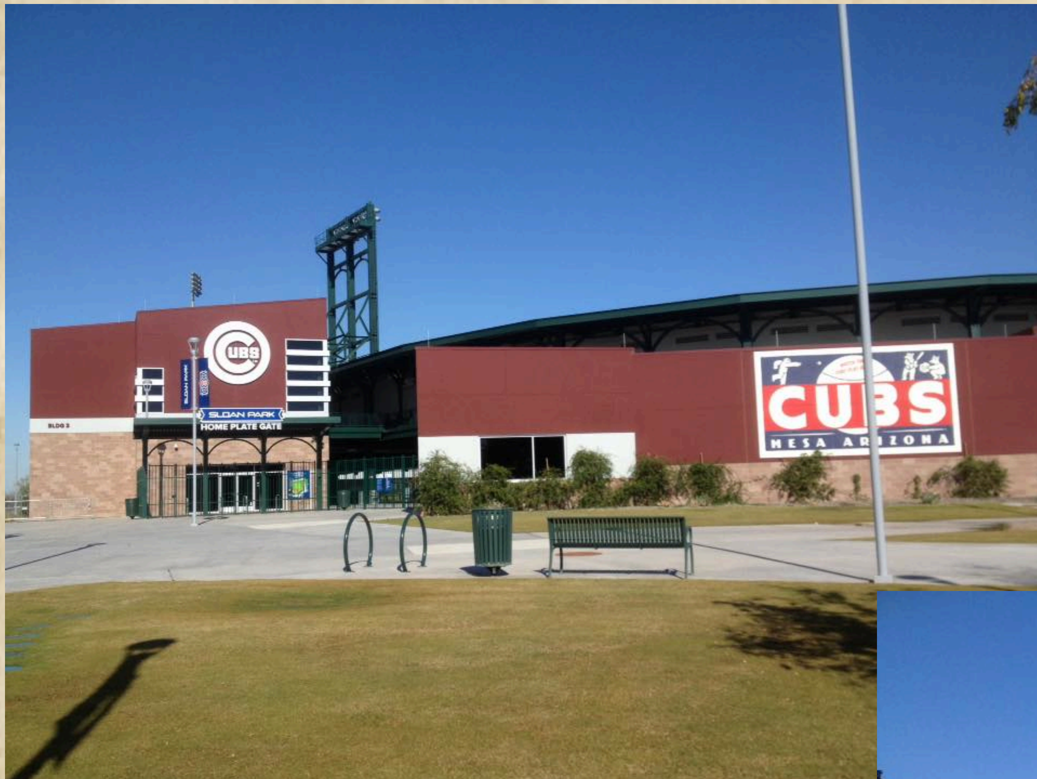
based on: T. Fujita (Stanford) & KK, PRD93 (2016) 083520 [arXiv:1602.02109 (hep-ph)].
KK & A.J.Long (Chicago), PRD94 (2016) 063501 [arXiv:1606.08891(astro-ph.CO)],
arXiv: 1610.03074[hep-ph].

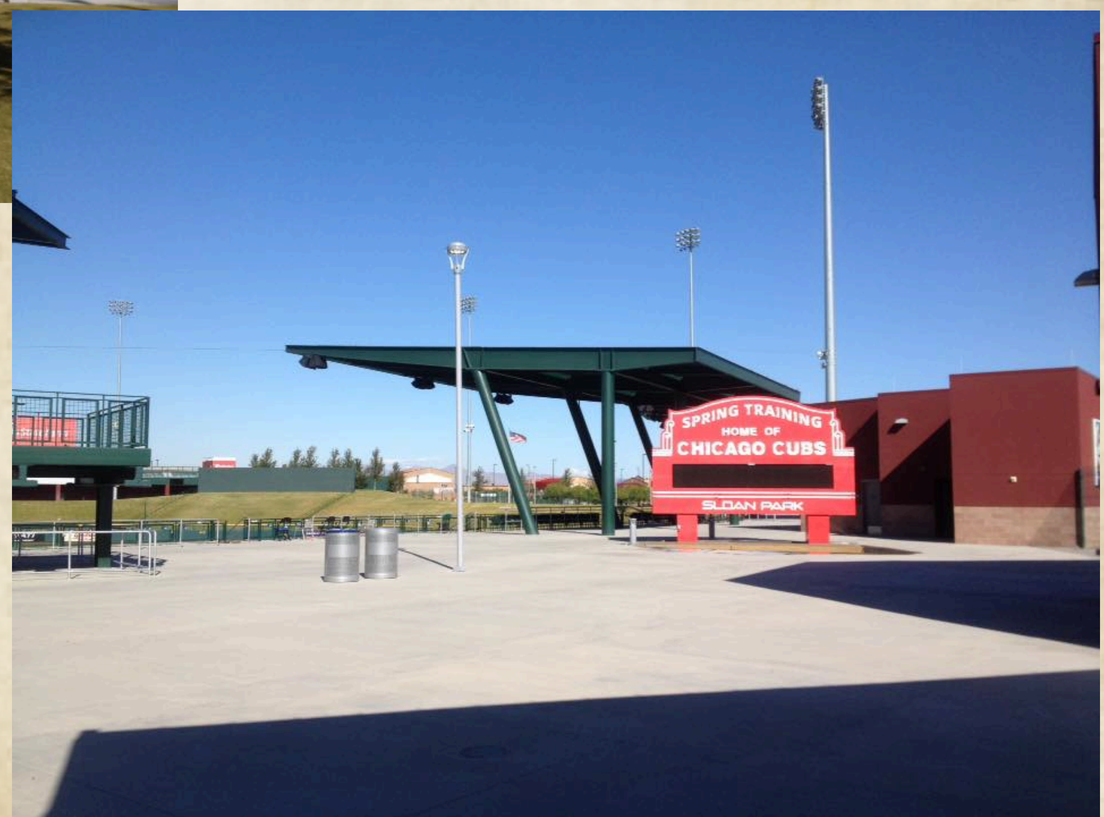
SCHOOL OF EARTH & SPACE EXPLORATION
ARIZONA STATE UNIVERSITY

Kohei Kamada
(Arizona State University)

KICP Workshop: Theoretical Advances in Particle Cosmology
10/15/2016 @ University of Chicago

Courtesy H.Oide





Courtesy H.Oide

Today's message is...

- Baryon asymmetry of the Universe (BAU) is one of the mysteries in cosmology and particle physics; B-violation is needed; BSM??

- However, B-violation is implemented in the SM through chiral anomaly.

- A baryogenesis model can be formulated by using helical primordial (hyper)magnetic fields (PMFs).

- The PMFs can remain until today as the intergalactic MFs (IGMFs).

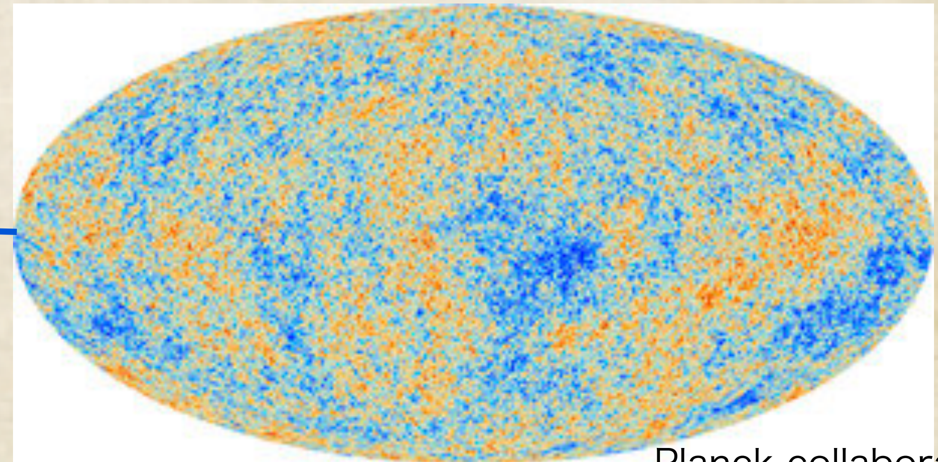
(cf. T. Kobayashi's talk)

- BSM might not be needed for baryogenesis but for magnetogenesis!

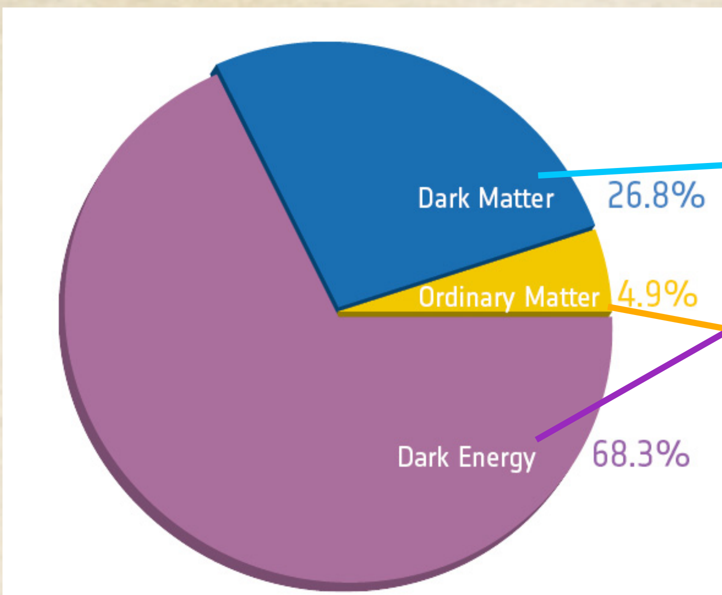
Courtesy H.Oide

Mysteries in modern cosmology

Origin of primordial density perturbation; Inflation?



Planck collaboration



Planck collaboration

Dark Matter

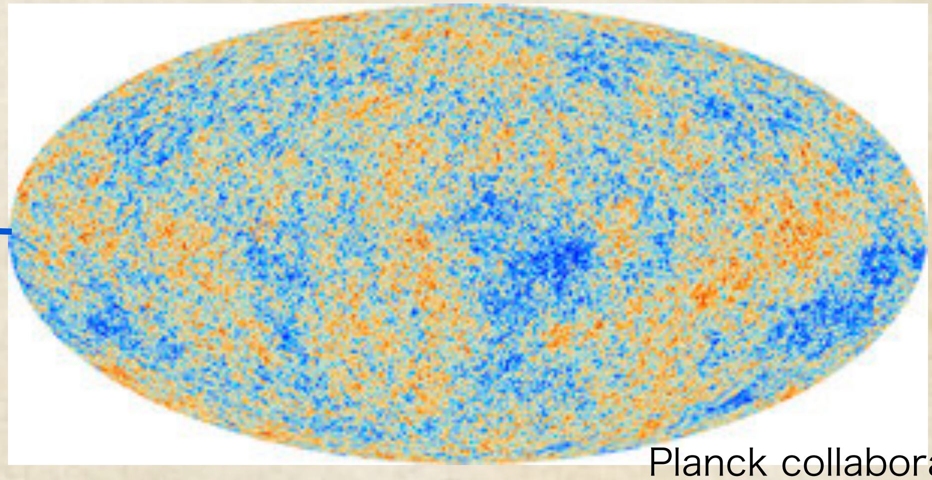
Dark Energy

Baryon Asymmetry

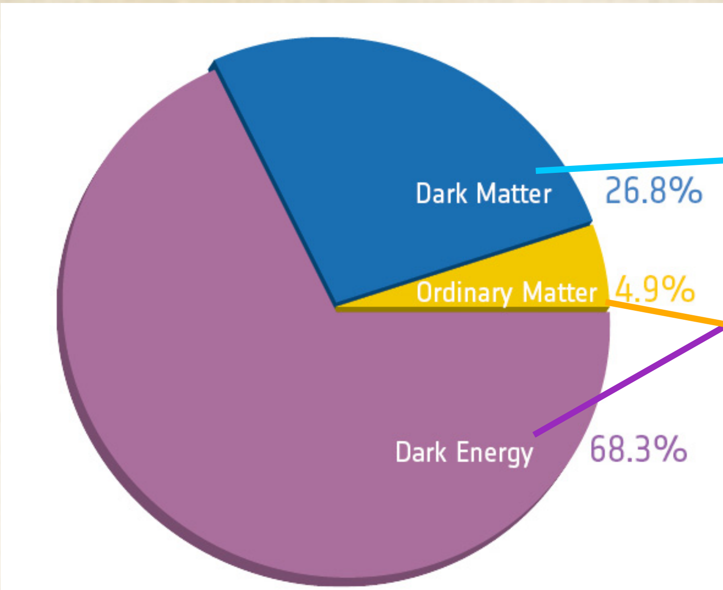
Courtesy H.Oide

Mysteries in modern cosmology

Origin of primordial density perturbation; Inflation?



Planck collaboration



Planck collaboration

Dark Matter

Dark Energy

Baryon Asymmetry

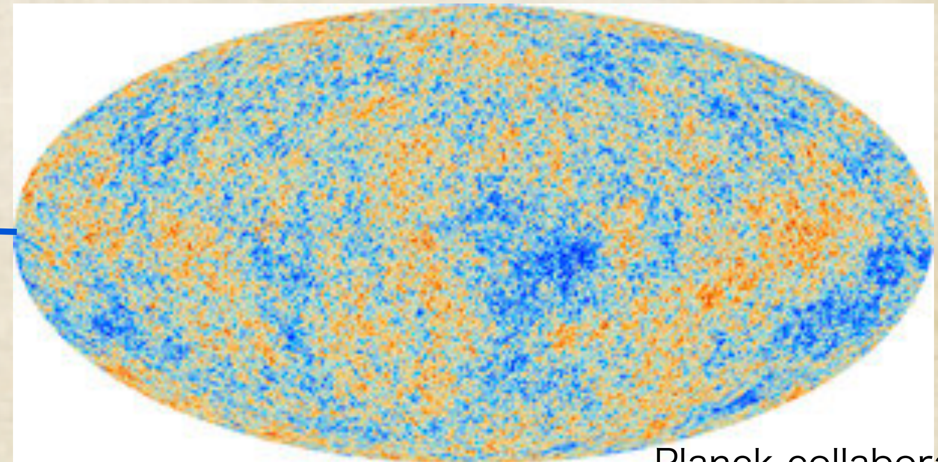
Few observational prospects

- Relation to BSM models?
- Relation to other relics?

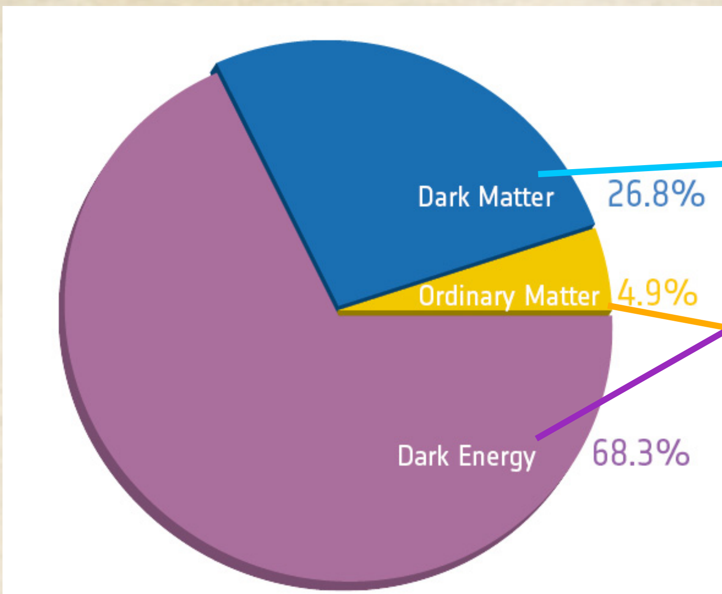
Courtesy H.Oide

Mysteries in modern cosmology

Origin of primordial density perturbation; Inflation?



Planck collaboration



Planck collaboration

Dark Matter

Dark Energy

Baryon Asymmetry

Few observational prospects

- Relation to BSM models?
- Relation to other relics?

IGMF?

Courtesy H.Oide

The task for theoretical cosmologists and particle physicists:

Courtesy H.Oide

The task for theoretical cosmologists and particle physicists:

Construct a model of baryogenesis

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

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

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.

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

BSM is really 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.

Courtesy H.Oide

1. B-violation in the SM

2. Baryogenesis from helical MFs in thermal environment

3. Realization in the early Universe and the fossil : intergalactic MFs

Courtesy H.Oide

B-violation in the SM

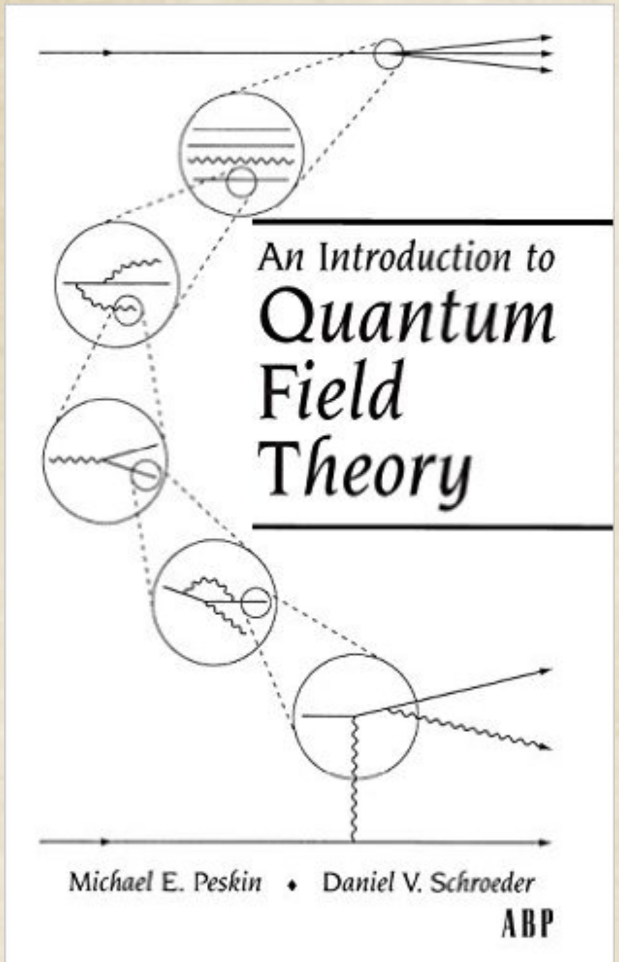
Courtesy H.Oide

Chiral anomaly

('69 Adler; Bell&Jackiw)

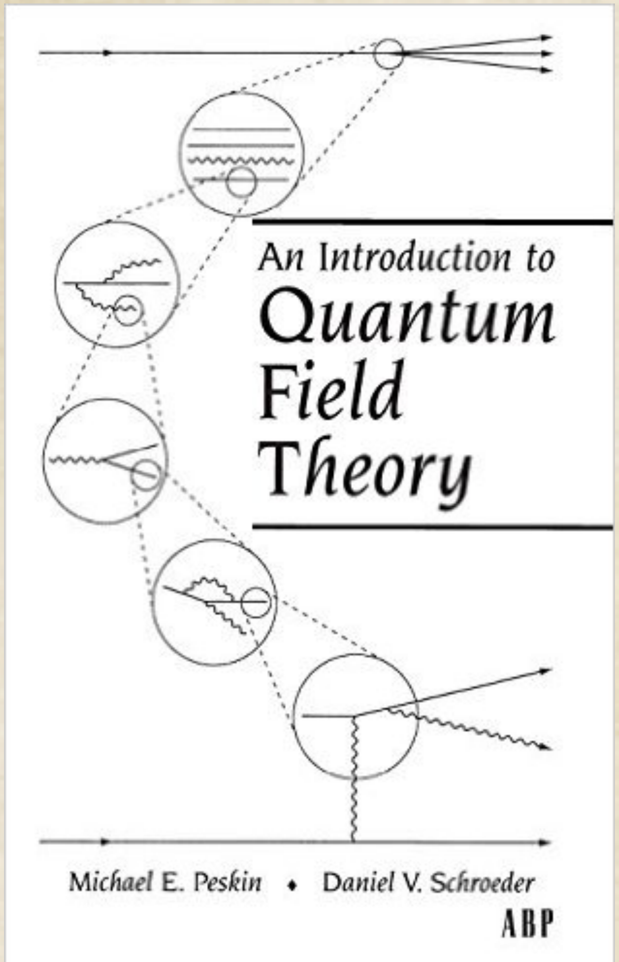
... Read a QFT textbook!

(e.g. Peskin&Chroeder Chap.19)



Chiral anomaly

('69 Adler; Bell&Jackiw)



Chiral symmetry in a gauge theory

$$\mathcal{L} = i\bar{\psi}\not{D}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

Invariant under chiral rotation

$$\psi \rightarrow e^{i\theta\gamma^5}\psi$$

Axial vector current is conserved

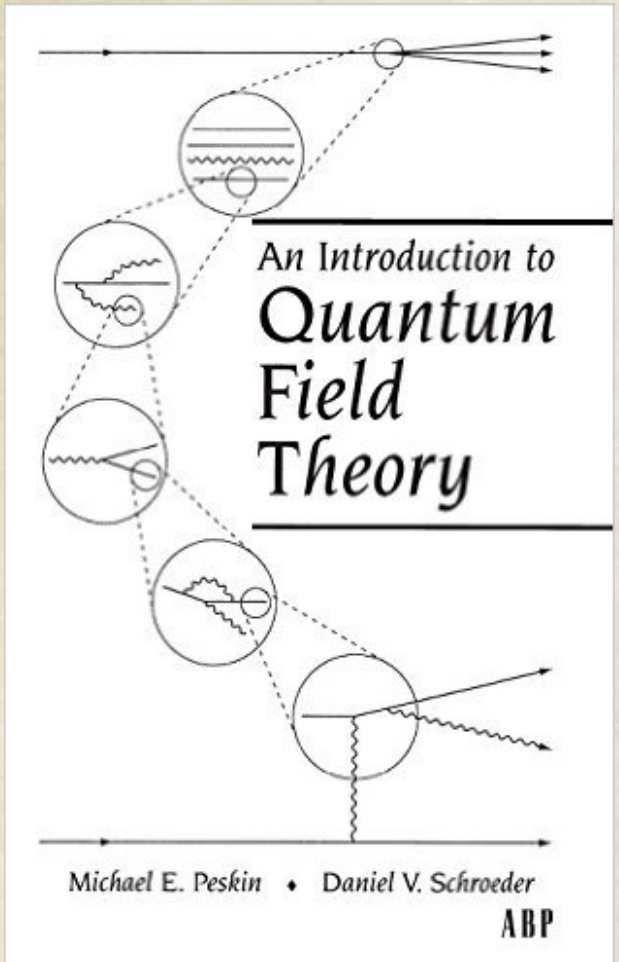
$$\partial_\mu j^{\mu 5} = 0$$

$(j^{\mu 5} \equiv \bar{\psi}\gamma^\mu\gamma^5\psi)$

Courtesy H.Oide

Chiral anomaly

('69 Adler; Bell&Jackiw)



Chiral symmetry in a gauge theory

$$\mathcal{L} = i\bar{\psi}\not{D}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

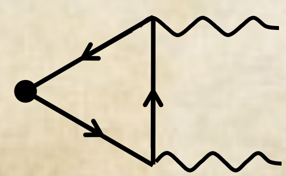
Invariant under chiral rotation

$$\psi \to e^{i\theta\gamma^5}\psi$$

Axial vector current is NOT conserved due to quantum effect

$$\partial_\mu j^{\mu 5} = -\frac{g^2}{8\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$(j^{\mu 5} \equiv \bar{\psi}\gamma^\mu\gamma^5\psi)$



Courtesy H.Oide

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

Each left- and right-handed fermion in the SM receives chiral anomaly from SU(3)xSU(2)xU(1) gauge fields.

$$\partial_\mu j_f^\mu = \pm\Bigg(c_1^f y_f^2 \frac{g'^2}{8\pi^2} Y_{\mu\nu}\tilde{Y}^{\mu\nu} + c_2^f \frac{g^2}{16\pi^2}\mathrm{tr}[W_{\mu\nu}\tilde{W}^{\mu\nu}] + c_{12}^f y_f \frac{gg'}{16\pi^2}(Y_{\mu\nu}\tilde{W}^{3\mu\nu} + W^3_{\mu\nu}\tilde{Y}^{\mu\nu}) + c_3^f \frac{g_s^2}{16\pi^2}\mathrm{tr}[G_{\mu\nu}\tilde{G}^{\mu\nu}]\Bigg)$$

+: right-handed fermion, -: left-handed fermion

Courtesy H.Oide

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

Each left- and right-handed fermion in the SM receives chiral anomaly from SU(3)xSU(2)xU(1) gauge fields.

$$\partial_\mu j_f^\mu = \pm \Big(c_1^f y_f^2 \frac{g'^2}{8\pi^2} Y_{\mu\nu}\tilde{Y}^{\mu\nu} + c_2^f \frac{g^2}{16\pi^2} \mathrm{tr}[W_{\mu\nu}\tilde{W}^{\mu\nu}] + c_{12}^f y_f \frac{g g'}{16\pi^2} (Y_{\mu\nu}\tilde{W}^{3\mu\nu} + W^3_{\mu\nu}\tilde{Y}^{\mu\nu}) + c_3^f \frac{g_s^2}{16\pi^2} \mathrm{tr}[G_{\mu\nu}\tilde{G}^{\mu\nu}] \Big)$$

+: right-handed fermion, -: left-handed fermion

Div. of B(L)-current is obtained by summing up them:

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

B and L are violated, but B-L is conserved.

Courtesy H.Oide

Integrate over a finite time interval and space:

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

$$Q_B = \int d^3x j_B^0$$

Chern-Simons number: $N_{\rm CS} \equiv \frac{g^2}{32\pi^2} \int d^3x \epsilon^{ijk} {\rm tr} \left[W_{ij}^a W_k^a - \frac{g}{3} \epsilon^{abc} W_i^a W_j^b W_k^c \right]$

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

Courtesy H.Oide

Integrate over a finite time interval and space:

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

$$Q_B = \int d^3x j_B^0$$

☆ Chern-Simons number: $N_{\rm CS} \equiv \frac{g^2}{32\pi^2} \int d^3x \epsilon^{ijk} {\rm tr} \left[W_{ij}^a W_k^a - \frac{g}{3} \epsilon^{abc} W_i^a W_j^b W_k^c \right]$

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

☆ Diffusion due to thermal fluctuation = EW sphaleron

=> Used in Electroweak baryogenesis and leptogenesis

Courtesy H.Oide

Integrate over a finite time interval and space:

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

$$Q_B = \int d^3x j_B^0$$

☆ Chern-Simons number: $N_{\rm CS} \equiv \frac{g^2}{32\pi^2} \int d^3x \epsilon^{ijk} {\rm tr} \left[W_{ij}^a W_k^a - \frac{g}{3} \epsilon^{abc} W_i^a W_j^b W_k^c \right]$

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

☆ Diffusion due to thermal fluctuation = EW sphaleron

=> Used in Electroweak baryogenesis and leptogenesis

※ No CP-violation -> tend to washout B asymmetry

('85 Kuzmin, Rubakov&Shaposhnikov)

Courtesy H.Oide

Integrate over a finite time interval and space:

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

$$Q_B = \int d^3x j_B^0$$

Chern-Simons number: $N_{\rm CS} \equiv \frac{g^2}{32\pi^2} \int d^3x \epsilon^{ijk} {\rm tr} \left[W_{ij}^a W_k^a - \frac{g}{3} \epsilon^{abc} W_i^a W_j^b W_k^c \right]$

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

☆ ... difference between right- and left- circular polarization modes

Courtesy H.Oide

Integrate over a finite time interval and space:

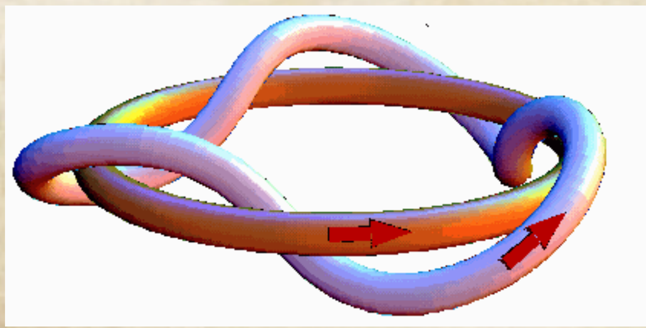
$$\Delta Q_B = \Delta Q_L = N_g \left(\Delta N_{\rm CS} - \frac{g'^2}{16\pi^2} \Delta \mathcal{H}_Y \right)$$

$$Q_B = \int d^3x j_B^0$$

Chern-Simons number: $N_{\rm CS} \equiv \frac{g^2}{32\pi^2} \int d^3x \epsilon^{ijk} {\rm tr} \left[W_{ij}^a W_k^a - \frac{g}{3} \epsilon^{abc} W_i^a W_j^b W_k^c \right]$

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

☆ ... difference between right- and left- circular polarization modes



solar.physics.montana.edu

describes twist and linkage of magnetic field lines

is not screened by thermal environment
and can develop in the early Universe

Courtesy H.Oide

Integrate over a finite time interval and space:

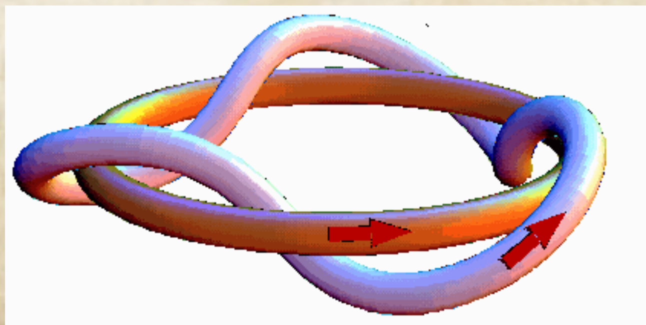
$$\Delta Q_B = \Delta Q_L = N_g \left(\Delta N_{\rm CS} - \frac{g'^2}{16\pi^2} \Delta \mathcal{H}_Y \right)$$

$$Q_B = \int d^3x j_B^0$$

Chern-Simons number: $N_{\rm CS} \equiv \frac{g^2}{32\pi^2} \int d^3x \epsilon^{ijk} {\rm tr} \left[W_{ij}^a W_k^a - \frac{g}{3} \epsilon^{abc} W_i^a W_j^b W_k^c \right]$

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

☆ ... difference between right- and left- circular polarization modes



solar.physics.montana.edu

describes twist and linkage of magnetic field lines

is not screened by thermal environment
and can develop in the early Universe

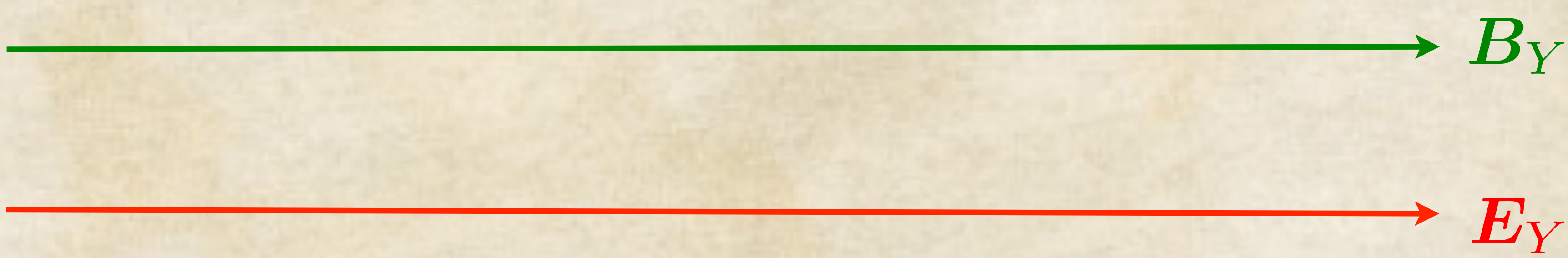
Often discarded!

Courtesy H.Oide

Decay of (hyper)magnetic helicity:

$$\frac{1}{V}\partial_t \mathcal{H} = -2\langle \boldsymbol{E}_Y \cdot \boldsymbol{B}_Y \rangle$$

In the thermal media, E-field can run parallel to B-field.



(Hyper)magnetic helicity automatically decays and can cause baryon number injection.

Courtesy H.Oide

Short summary

- B-number violation is implemented in the SM through chiral anomaly.

- It corresponds to decay of hypermagnetic helicity.

- Helical hypermagnetic fields can exist in the hot early Universe.

(cf. T. Kobayashi's talk)

- CP-violation and deviation from thermal equilibrium is implemented.

(cf. A.Hook's talk)

Courtesy H.Oide

Baryogenesis from helical MFs in thermal environment

(in the symmetric phase)

Courtesy H.Oide

How does the B-violation mechanism act in the hot early Universe?

Courtesy H.Oide

How does the B-violation mechanism act in the hot early Universe?

Toy model: simple QED with $(e_L^-, \bar{e}_L^+, e_R^-, \bar{e}_R^+)$

$$\mathcal{L} = \bar{\psi}\left(i\not{D} - m_e\right)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

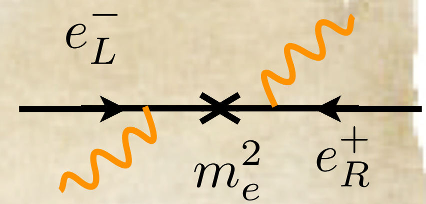
Courtesy H.Oide

How does the B-violation mechanism act in the hot early Universe?

Toy model: simple QED with $(e_L^-, \bar{e}_L^+, e_R^-, \bar{e}_R^+)$

$$\mathcal{L} = \bar{\psi}\left(i\not{D} - m_e\right)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$\Gamma_e =$



Evolution of left-right asymmetry w/o MFs

$$\frac{\partial n_L}{\partial t} + 3Hn_L = -\Gamma_e(n_L - n_R)$$

$$\frac{\partial n_R}{\partial t} + 3Hn_R = -\Gamma_e(n_R - n_L)$$

$$\Gamma_e \simeq g'^2 \frac{m_e^2}{8\pi T}$$

$$(n_L - n_R) = \exp\left[-2\int_{t_i}^{t} \Gamma_e dt'\right]\left(\frac{a}{a_i}\right)^{-3}(n_L - n_R)|_{t=t_i}$$

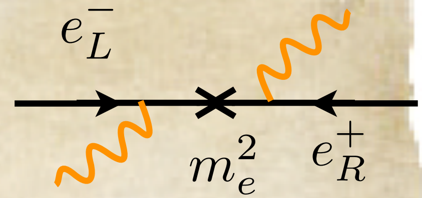
exponentially damped.

Courtesy H.Oide

How does the B-violation mechanism act in the hot early Universe?

Toy model: simple QED with $(e_L^-, \bar{e}_L^+, e_R^-, \bar{e}_R^+)$

$$\mathcal{L} = \bar{\psi}\left(i\not{D} - m_e\right)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$\Gamma_e =$ 

Evolution of left-right asymmetry w/ MFs,

$$\frac{\partial n_L}{\partial t} + 3Hn_L = -\Gamma_e(n_L - n_R) - \mathcal{S}_{\text{anomaly}} \qquad \Gamma_e \simeq g'^2 \frac{m_e^2}{8\pi T}$$

$$\frac{\partial n_R}{\partial t} + 3Hn_R = -\Gamma_e(n_R - n_L) + \mathcal{S}_{\text{anomaly}} \qquad \mathcal{S}_{\text{anomaly}} = \frac{g'^2}{2\pi^2}\langle \boldsymbol{E}_Y \cdot \boldsymbol{B}_Y \rangle$$

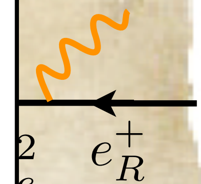
$$(n_L - n_R) \simeq -\frac{\mathcal{S}_{\text{anomaly}}}{\Gamma_e} \qquad \leftarrow \frac{\partial}{\partial t}(a^3(n_L - n_R)) = 0$$

for $\Gamma_e > H$

Courtesy H.Oide

How does the B-violation mechanism act in the hot early Universe?

Toy model: simple QED with $(e_L^-, \bar{e}_L^+, e_R^-, \bar{e}_R^+)$



Left-right asymmetry has the form

$$\frac{n_{\text{asymmetry}}}{s} \simeq \frac{\text{(Source term from chiral anomaly)}}{\text{(Washout term from spin-flip interaction)} \times s}$$

$$(n_L - n_R) \simeq -\frac{\mathcal{S}_{\text{anomaly}}}{\Gamma_e} \quad \leftarrow \frac{\partial}{\partial t}(a^3(n_L - n_R)) = 0$$

for $\Gamma_e > H$

Courtesy H.Oide

How does the B-violation mechanism act in the hot early Universe?

Same analogy works for B-asymmetry.

Courtesy H.Oide

How does the B-violation mechanism act in the hot early Universe?

Same analogy works for B-asymmetry.

- Source term from chiral anomaly … exists if $\langle \boldsymbol{E}_Y \cdot \boldsymbol{B}_Y \rangle \neq 0$

Courtesy H.Oide

How does the B-violation mechanism act in the hot early Universe?

Same analogy works for B-asymmetry.

- Source term from chiral anomaly ... exists if $\langle \boldsymbol{E}_Y \cdot \boldsymbol{B}_Y \rangle \neq 0$

It is nonzero in thermal environment and if maximally helical!

$|Y_k^R|^2 \gg |Y_k^L|^2$

Ampere's law: $\boldsymbol{\nabla} \times \boldsymbol{B}_Y = \sigma(\boldsymbol{E}_Y + \boldsymbol{v} \times \boldsymbol{B}_Y) + \dot{\boldsymbol{E}}_Y + \cdots$

Electric conductivity: $\sigma \simeq 10^2 T$ ('97 Baym+) ('00 Arnold+)

$$\Rightarrow \quad \langle \boldsymbol{E}_Y \cdot \boldsymbol{B}_Y \rangle \simeq \frac{1}{\sigma} \langle \boldsymbol{B}_Y \cdot \boldsymbol{\nabla} \times \boldsymbol{B}_Y \rangle + \cdots$$

Courtesy H.Oide

How does the B-violation mechanism act in the hot early Universe?

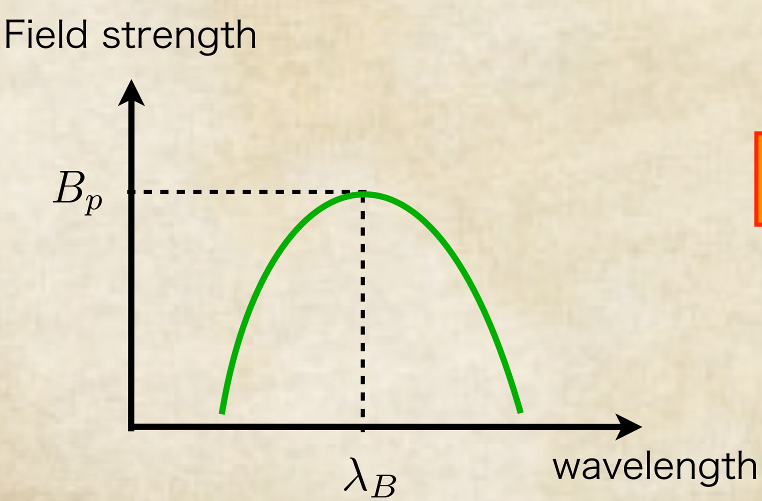
Same analogy works for B-asymmetry.

- Source term from chiral anomaly ... exists if $\langle \boldsymbol{E}_Y \cdot \boldsymbol{B}_Y \rangle \neq 0$

It is nonzero in thermal environment and if maximally helical!

$|Y_k^R|^2 \gg |Y_k^L|^2$

Ampere's law: $\boldsymbol{\nabla} \times \boldsymbol{B}_Y = \sigma(\boldsymbol{E}_Y + \boldsymbol{v} \times \boldsymbol{B}_Y) + \dot{\boldsymbol{E}}_Y + \cdots$



Electric conductivity: $\sigma \simeq 10^2 T$ ('97 Baym+) ('00 Arnold+)

$$\langle \boldsymbol{E}_Y \cdot \boldsymbol{B}_Y \rangle \simeq \frac{1}{\sigma} \langle \boldsymbol{B}_Y \cdot \boldsymbol{\nabla} \times \boldsymbol{B}_Y \rangle + \cdots$$

$\simeq 2\pi B_p^2 / \lambda_B$

(If maximally helical $\boldsymbol{B}_Y \parallel \boldsymbol{\nabla} \times \boldsymbol{B}_Y$)

('98 Giovannini&Shaposhnikov)

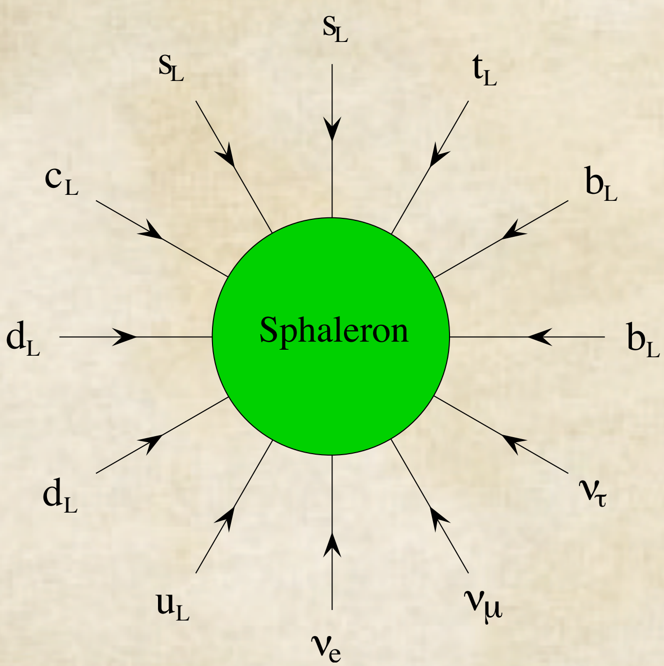
Courtesy H.Oide

How does the B-violation mechanism act in the hot early Universe?

Same analogy works for B-asymmetry.

- Source term from chiral anomaly $\mathcal{S}_1 \simeq \frac{g'^2}{8\pi\sigma}\frac{2\pi B_p^2}{\lambda_B}$

- Washout term: EW sphaleron (?) ('85 Kuzmin, Rubakov&Shaposhnikov)



W. Buchmüller, 1212.3554

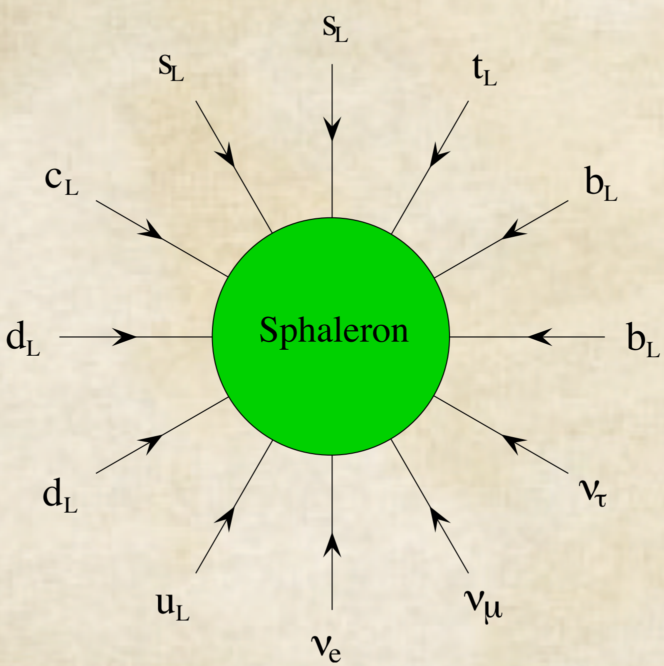
Courtesy H.Oide

How does the B-violation mechanism act in the hot early Universe?

Same analogy works for B-asymmetry.

- Source term from chiral anomaly $$\mathcal{S}_1 \simeq \frac{g'^2}{8\pi\sigma}\frac{2\pi B_p^2}{\lambda_B}$$

- Washout term: EW sphaleron (?) ('85 Kuzmin, Rubakov&Shaposhnikov)



W. Buchmüller, 1212.3554

Washes out B(+L) asymmetry carried by left-handed fermions: $\Gamma_W \simeq 20\alpha_W^5 T$
('97 Moore)

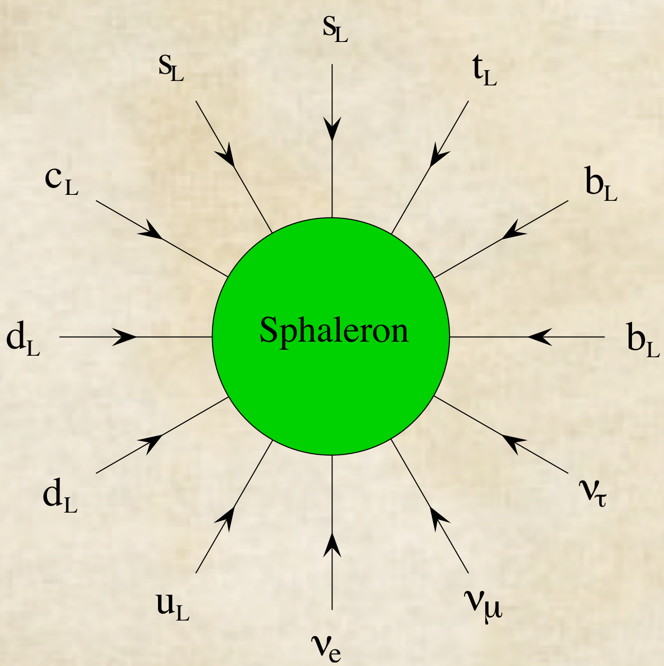
Courtesy H.Oide

How does the B-violation mechanism act in the hot early Universe?

Same analogy works for B-asymmetry.

- Source term from chiral anomaly $\mathcal{S}_1 \simeq \frac{g'^2}{8\pi\sigma}\frac{2\pi B_p^2}{\lambda_B}$

- Washout term: EW sphaleron (?) ('85 Kuzmin, Rubakov&Shaposhnikov)

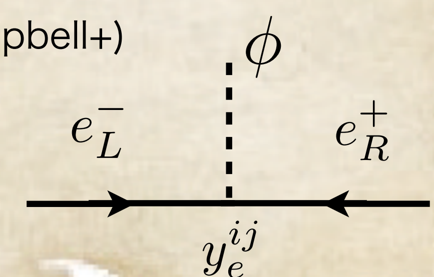


W. Buchmüller, 1212.3554

Washes out B(+L) asymmetry carried by left-handed fermions: $\Gamma_W \simeq 20\alpha_W^5 T$ ('97 Moore)

Spin-flip interactions are needed to remove asymmetry carried by right-handed fermions ('92 Campbell+)

$$\Gamma_e \sim \frac{|y_e|^2}{8\pi}T$$



Courtesy H.Oide

How does the B-violation mechanism act in the hot early Universe?

Same analogy works for B-asymmetry.

- Source term from chiral anomaly

$$\mathcal{S}_1 \simeq \frac{g'^2}{8\pi\sigma}\frac{2\pi B_p^2}{\lambda_B}$$

- Washout term: EW sphaleron (?) ('85 Kuzmin, Rubakov&Shaposhnikov)

At the symmetric phase, $\Gamma_W \gg \Gamma_e$

⟶ Washout is determined by spin-flip interactions

Courtesy H.Oide

How does the B-violation mechanism act in the hot early Universe?

Same analogy works for B-asymmetry.

- Source term from chiral anomaly $\mathcal{S}_1 \simeq \frac{g'^2}{8\pi\sigma}\frac{2\pi B_p^2}{\lambda_B}$

- Washout term: EW sphaleron (?) ('85 Kuzmin, Rubakov&Shaposhnikov)

At the symmetric phase, $\Gamma_W \gg \Gamma_e$

⟶ Washout is determined by spin-flip interactions

Baryon asymmetry has the form

$$\eta_B \equiv \frac{n_B}{s} \simeq \frac{\text{(Source term from chiral anomaly)}}{\text{(Washout term from spin-flip interaction)x}\, s}$$

Courtesy H.Oide

How does the B-violation mechanism act in the hot early Universe?

Same analogy works for B-asymmetry.

- Source term from chiral anomaly $\mathcal{S}_1 \simeq \frac{g'^2}{8\pi\sigma}\frac{2\pi B_p^2}{\lambda_B}$

- Washout term: EW sphaleron (?) ('85 Kuzmin, Rubakov&Shaposhnikov)

At the symmetric phase, $\Gamma_W \gg \Gamma_e$

⟶ Washout is determined by spin-flip interactions

Baryon asymmetry has the form

$$\eta_B \equiv \frac{n_B}{s} \simeq \frac{\mathcal{S}_1}{s\Gamma_e} \simeq \frac{(g'^2/4\sigma)B_p^2/\lambda_B}{(|y_e|^2/8\pi)sT}$$

(※ Chiral magnetic effect can change the washout term.)

Courtesy H.Oide

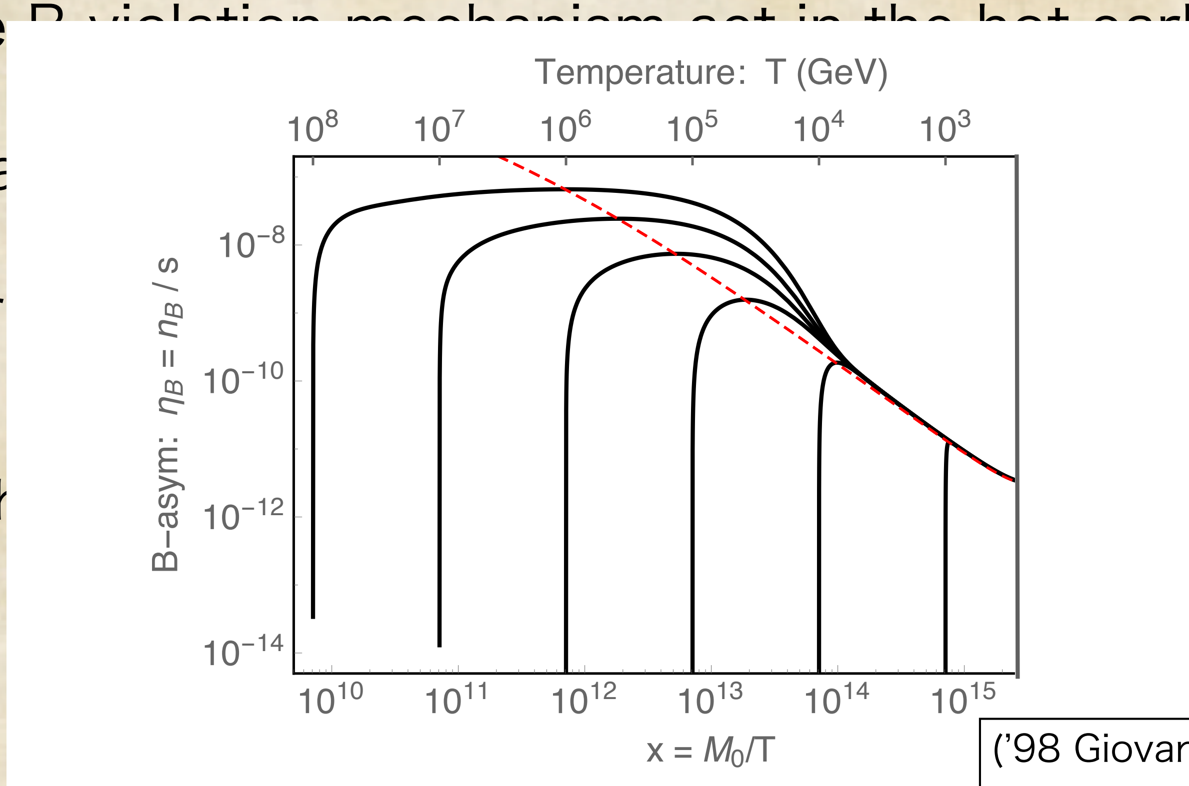
How does the B-violation mechanism act in the hot early Universe?

Same ana

- Sour

- Wash

Shaposhnikov)



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

Baryon asymmetry has the form

$$\eta_B \equiv \frac{n_B}{s} \simeq \frac{\mathcal{S}_1}{s\Gamma_e} \simeq \frac{(g'^2/4\sigma) B_p^2/\lambda_B}{(|y_e|^2/8\pi) sT}$$

(※ Chiral magnetic effect can change the washout term.)

Courtesy H.Oide

Short summary

- The source term for B-asymmetry from hypermagnetic helicity decay is nonzero in thermal environment: $\propto B_p^2/\lambda_B$

- Baryon asymmetry is determined by the balance between the source term and washout effect from the spin-flip interaction in the symmetric phase.

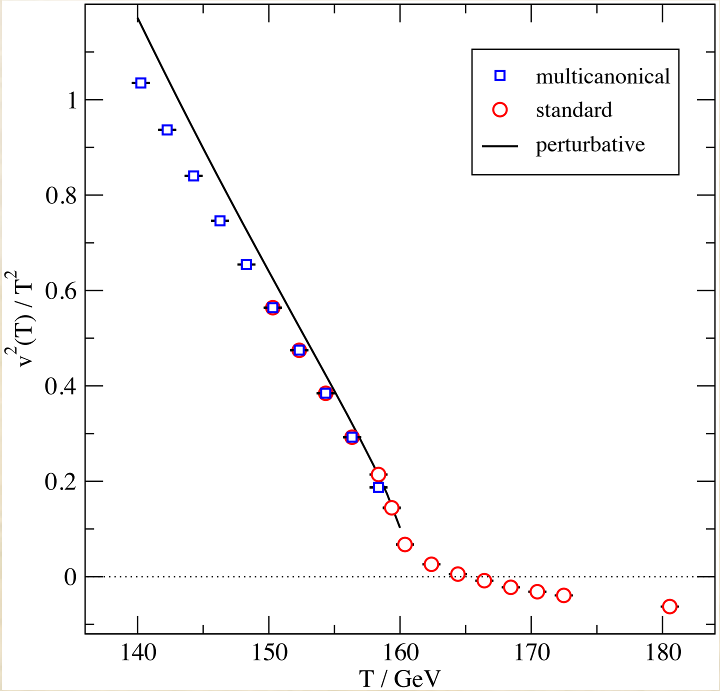
Courtesy H.Oide

Realization in the early Universe and IGMF as the fossil

Courtesy H.Oide

Realization in the early Universe

We must take care of the effect of EW crossover.



('14 D'Onofrio)

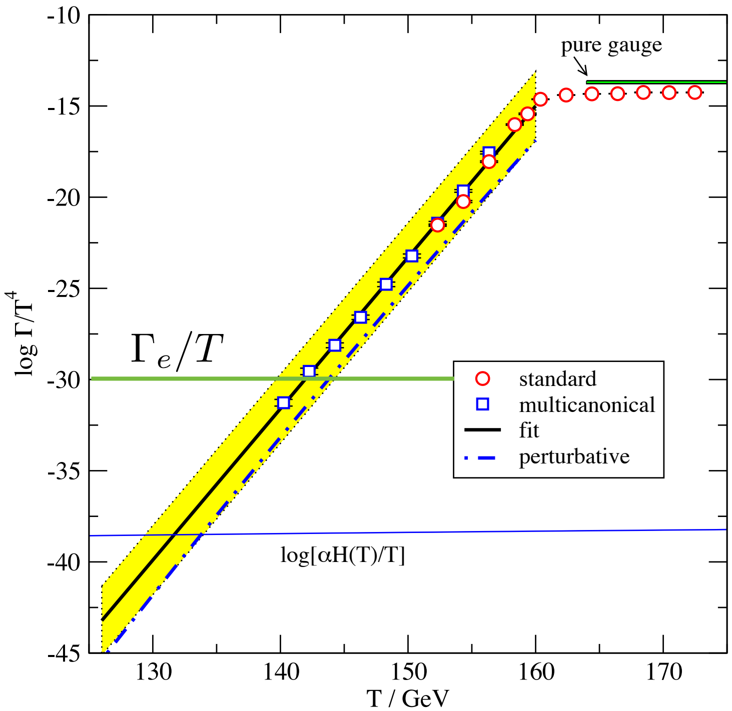
Higgs VEV develops -> Weak bosons get massive

- Source term vanishes due to hypermagnetic to electromagnetic field conversion. (EM theory does not violate B)
- Washout term gets ineffective due to EW sphaleron shut off.

Courtesy H.Oide

EW sphaleron shutoff at EW crossover

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



('14 D'Onofrio)

- $\Gamma_W \ll \Gamma_e$ at $T \lesssim 140\mathrm{GeV}$

  washout is determined by EW sphaleron

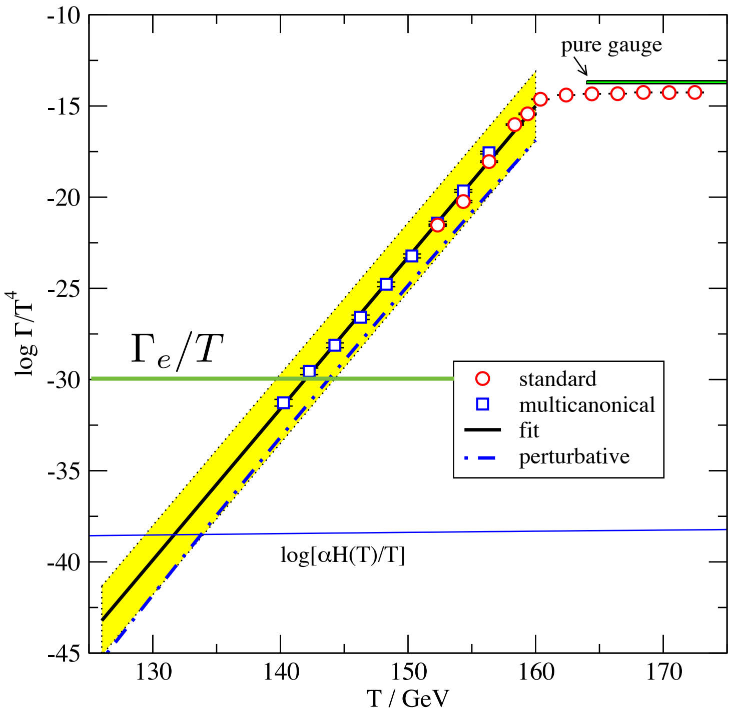
$$\eta_B \simeq \frac{(g'^2/8\pi)\langle \boldsymbol{E} \cdot \boldsymbol{B} \rangle}{\Gamma_W}$$

exponential growth?

Courtesy H.Oide

EW sphaleron shutoff at EW crossover

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



('14 D'Onofrio)

- $\Gamma_W \ll \Gamma_e$ at $T \lesssim 140\mathrm{GeV}$

  washout is determined by EW sphaleron

$$\eta_B \simeq \frac{(g'^2/8\pi)\langle \boldsymbol{E}\cdot\boldsymbol{B}\rangle}{\Gamma_W}$$

exponential growth?

- In equilibrium until $T \simeq 130 \sim 135\mathrm{GeV}$

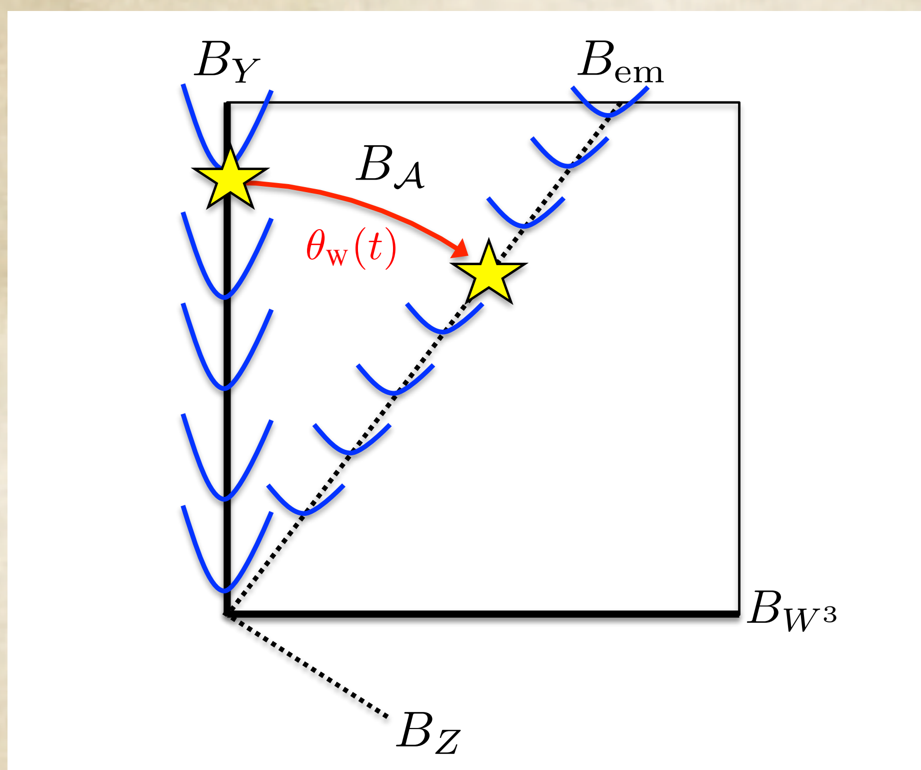
- If the hypermagnetic to electromagnetic field conversion completes earlier, no B-asymmetry will be left.

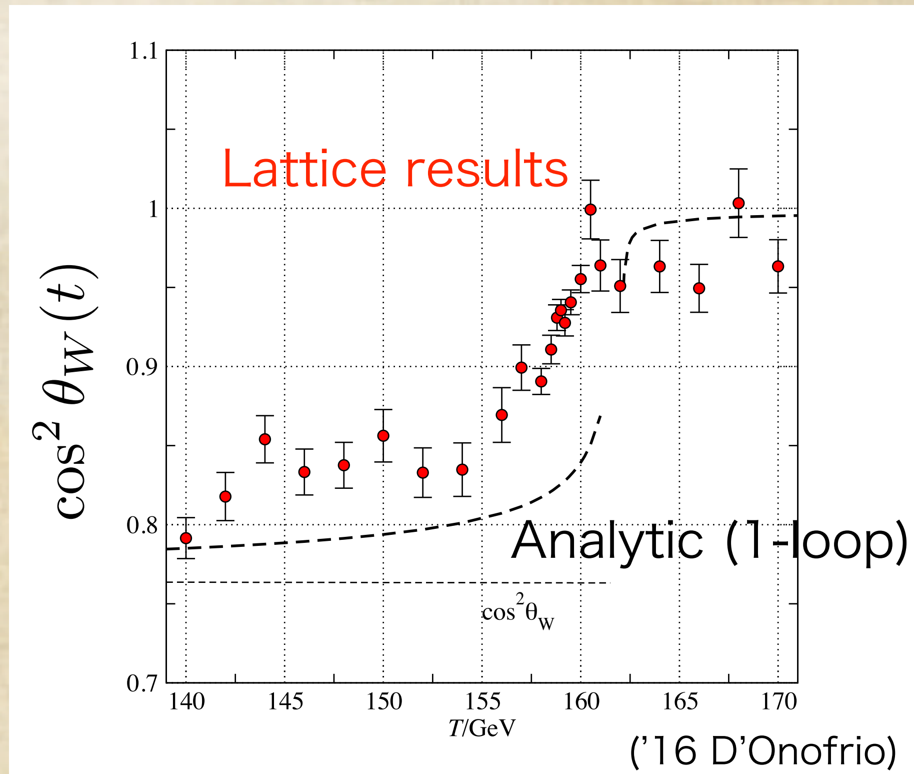
('98 Giovannini&Shaposhnikov)

Courtesy H.Oide

Conversion from $U(1)_Y$ to $U(1)_{em}$ at EW crossover

Due to thermal mass, the conversion does not take place abruptly at $T \sim 160\mathrm{GeV}$ but proceeds relatively slow.





Courtesy H.Oide

Effect on the source term

Courtesy H.Oide

Effect on the source term

- Does not reach the vacuum state $\tan\theta_W = \frac{g'}{g}$ at $T \sim 140\mathrm{GeV}$

⟶ The source term $\mathcal{S}_1 \propto B_p^2/\lambda_B$ persists after EW sphaleron shutoff.

Courtesy H.Oide

Effect on the source term

- Does not reach the vacuum state $\tan\theta_W = \frac{g'}{g}$ at $T \sim 140\mathrm{GeV}$

⟶ The source term $\mathcal{S}_1 \propto B_p^2/\lambda_B$ persists after EW sphaleron shutoff.

- Another contribution to the source term $\mathcal{S}_2 \propto \dot{\theta}_W \lambda_B B_p^2$ appears.

Note that $\boldsymbol{E}_Y \equiv \dot{\boldsymbol{Y}} \ni \dot{\theta}_W \sin\theta_W \boldsymbol{Y}$

⟶ $\langle \boldsymbol{E}_Y \cdot \boldsymbol{B}_Y \rangle \sim \dot{\theta}_W \langle \boldsymbol{Y} \cdot \boldsymbol{B}_Y \rangle \sim \dot{\theta}_W \mathcal{H}/V \sim \dot{\theta}_W \lambda_B B_p^2 / 2\pi$

Courtesy H.Oide

Effect on the source term

- Does not reach the vacuum state $\tan\theta_W = \dfrac{g'}{g}$ at $T \sim 140\mathrm{GeV}$

⟶ The source term $\mathcal{S}_1 \propto B_p^2/\lambda_B$ persists after EW sphaleron shutoff.

- Another contribution to the source term $\mathcal{S}_2 \propto \dot{\theta}_W \lambda_B B_p^2$ appears.

Note that $\boldsymbol{E}_Y \equiv \dot{\boldsymbol{Y}} \ni \dot{\theta}_W \sin\theta_W \boldsymbol{Y}$

⟶ $\langle \boldsymbol{E}_Y \cdot \boldsymbol{B}_Y \rangle \sim \dot{\theta}_W \langle \boldsymbol{Y} \cdot \boldsymbol{B}_Y \rangle \sim \dot{\theta}_W \mathcal{H}/V \sim \dot{\theta}_W \lambda_B B_p^2/2\pi$

This is not surprising!

$$\Delta Q_B = \#\Delta N_{\mathrm{cs}} - \#\Delta \mathcal{H}_Y$$

at the conversion: $\mathcal{H}_Y \to \mathcal{H}_{\mathrm{em}} = \mathcal{H}_Y + N_{\mathrm{cs}}$

⟶ $\Delta \mathcal{H}_Y = -\Delta N_{\mathrm{cs}} < 0$

Courtesy H.Oide

Effect on the source term

- Does not reach the vacuum state $\tan\theta_W = \dfrac{g'}{g}$ at $T \sim 140\mathrm{GeV}$

→ The source term $\mathcal{S}_1 \propto B_p^2/\lambda_B$ persists after EW sphaleron shutoff.

- Another contribution to the source term $\mathcal{S}_2 \propto \dot{\theta}_W \lambda_B B_p^2$ appears.

Note that $\boldsymbol{E}_Y \equiv \dot{\boldsymbol{Y}} \ni \dot{\theta}_W \sin\theta_W \boldsymbol{Y}$

→ $\langle \boldsymbol{E}_Y \cdot \boldsymbol{B}_Y \rangle \sim \dot{\theta}_W \langle \boldsymbol{Y} \cdot \boldsymbol{B}_Y \rangle \sim \dot{\theta}_W \mathcal{H}/V \sim \dot{\theta}_W \lambda_B B_p^2/2\pi$

This is not surprising!

$$\Delta Q_B = \#\Delta N_{\mathrm{cs}} - \#\Delta\mathcal{H}_Y = -\#\cos\theta_{\mathrm{w0}}\Delta\mathcal{H}_Y (> 0)$$

at the conversion: $\mathcal{H}_Y \to \mathcal{H}_{\mathrm{em}} = \mathcal{H}_Y + N_{\mathrm{cs}}$

→ $\Delta\mathcal{H}_Y = -\Delta N_{\mathrm{cs}} < 0$

Courtesy H.Oide

Resultant baryon asymmetry

$$\eta_B \equiv \frac{n_B}{s} \simeq \frac{\text{(Source term from chiral anomaly)}}{\text{(Washout term from spin-flip interaction)x } s}$$

Courtesy H.Oide

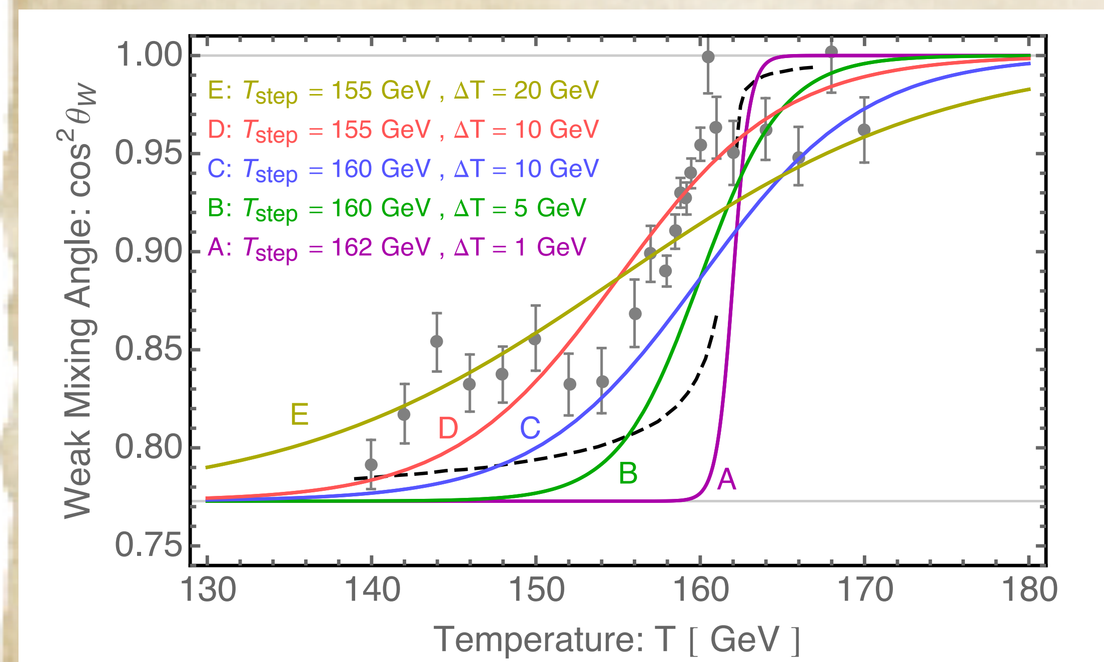
Resultant baryon asymmetry

$$\eta_B \equiv \frac{n_B}{s} \simeq \frac{\mathcal{S}_1 + \mathcal{S}_2}{s \times \min(\Gamma_e, \Gamma_W)} \simeq \frac{\# B_p^2/(\sigma \lambda_B) + \# \dot{\theta}_W \lambda_B B_p^2}{s \times \min(\Gamma_e, \Gamma_W)}$$

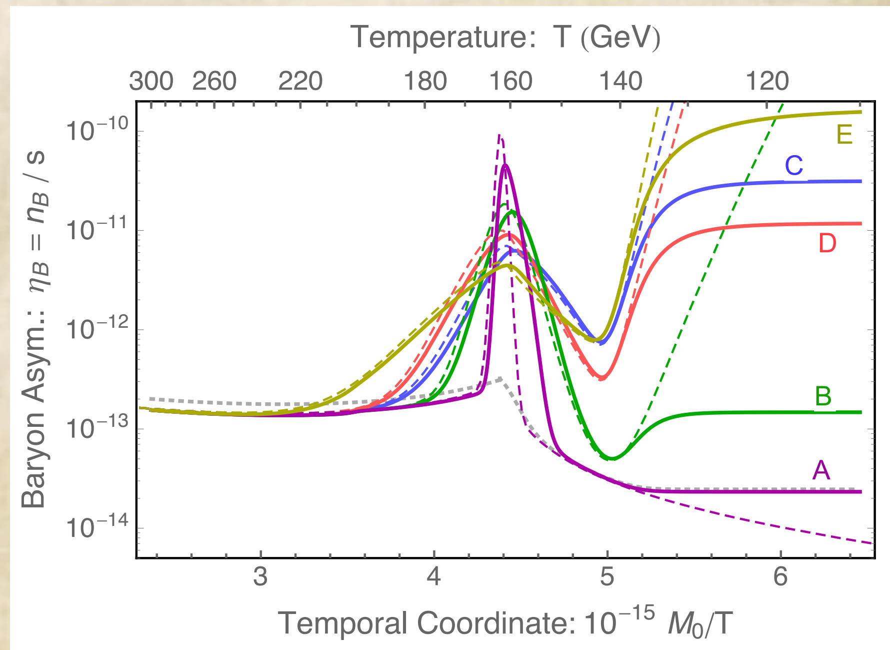
Courtesy H.Oide

Resultant baryon asymmetry

$$\eta_B \equiv \frac{n_B}{s} \simeq \frac{\mathcal{S}_1 + \mathcal{S}_2}{s \times \min(\Gamma_e, \Gamma_W)} \simeq \frac{\# B_p^2/(\sigma \lambda_B) + \# \dot{\theta}_W \lambda_B B_p^2}{s \times \min(\Gamma_e, \Gamma_W)}$$



Parameterization of the evolution of weak angle



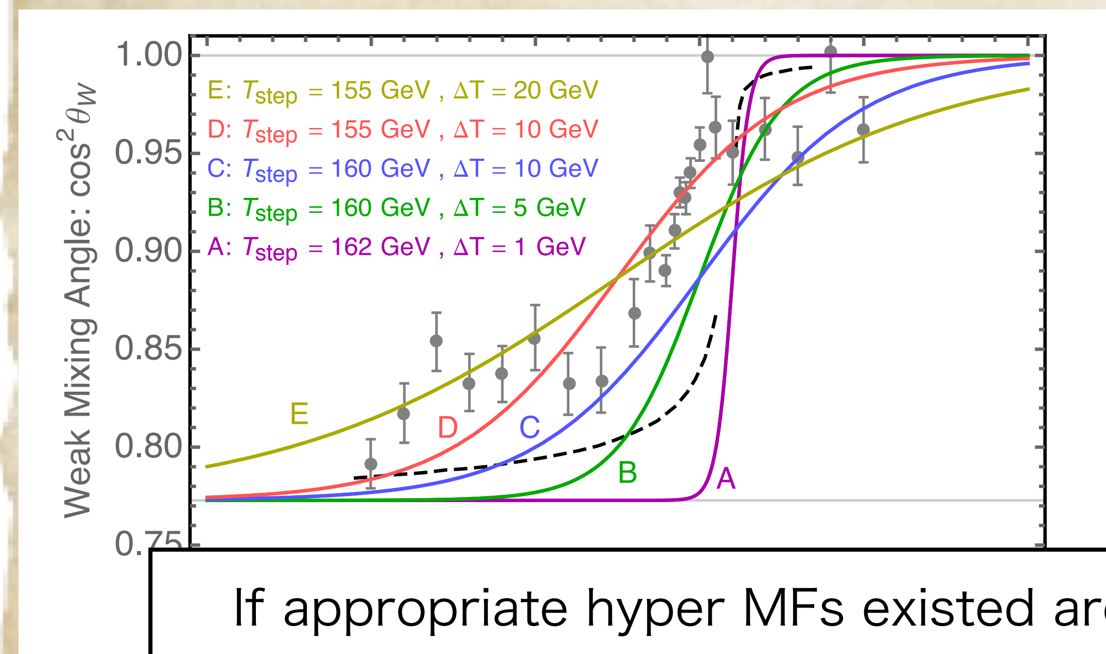
Evolution of B-asymmetry

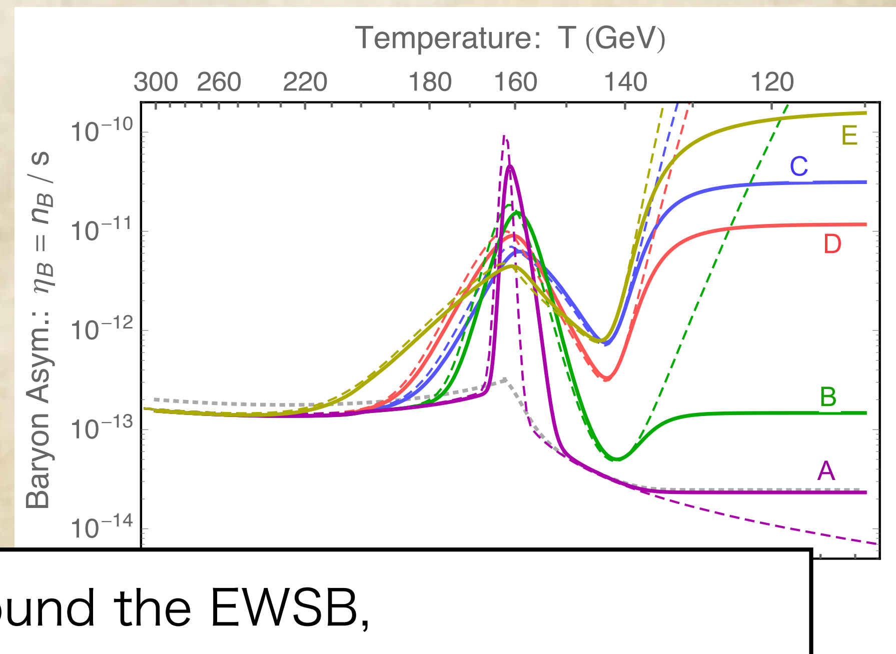
('16 KK&Long)

Courtesy H.Oide

Resultant baryon asymmetry

$$\eta_B \equiv \frac{n_B}{s} \simeq \frac{\mathcal{S}_1 + \mathcal{S}_2}{s \times \min(\Gamma_e, \Gamma_W)} \simeq \frac{\# B_p^2/(\sigma \lambda_B) + \# \dot{\theta}_W \lambda_B B_p^2}{s \times \min(\Gamma_e, \Gamma_W)}$$





Param

If appropriate hyper MFs existed around the EWSB,
B-asymmetry of the present Universe can be explained w/o BSM (?)

ong)

Courtesy H.Oide

...but what are these magnetic fields...???

Courtesy H.Oide

...but what are these magnetic fields...???

How are they generated? Inflation? (cf. M. Peloso's talk;
Recent study: '16 Adshead+)
But model model-dependent.

Anyway BSM will be needed. (cf. T. Kobayashi's talk)

Courtesy H.Oide

...but what are these magnetic fields...???

How are they generated? Inflation? (cf. M. Peloso's talk;
But model model-dependent. Recent study: '16 Adshead+)
Anyway BSM will be needed. (cf. T. Kobayashi's talk)

The hyperMFs responsible for baryogenesis
will remain until today as intergalactic MFs!

Courtesy H.Oide

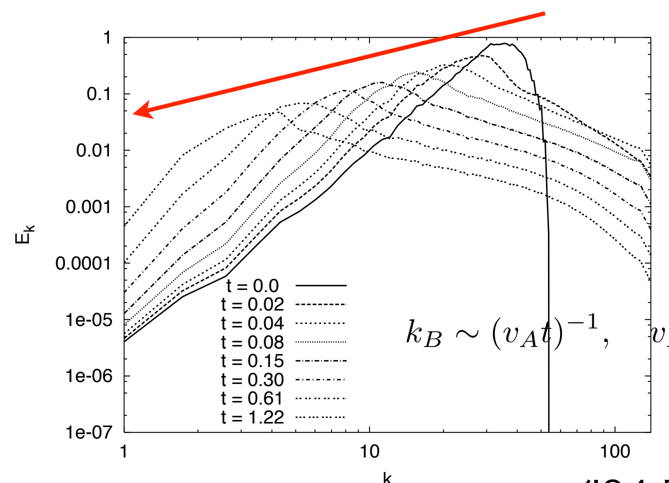
...but what are these magnetic fields...???

How are they generated? Inflation? (cf. M. Peloso's talk; Recent study: '16 Adshead+)

But model model-dependent.

Anyway BSM will be needed. (cf. T. Kobayashi's talk)

The hyperMFs responsible for baryogenesis will remain until today as intergalactic MFs!



$$k_B \sim (v_A t)^{-1}, \quad v_A = \frac{B_p}{\sqrt{\rho_{\rm ch} + p_{\rm ch}}}$$

('04 Banerjee+)

Maximally helical MFs experiences inverse cascade.

$$B_p \propto a^{-7/3}, \quad \lambda_B \propto a^{5/3}$$

('12. Kahniashvili+)

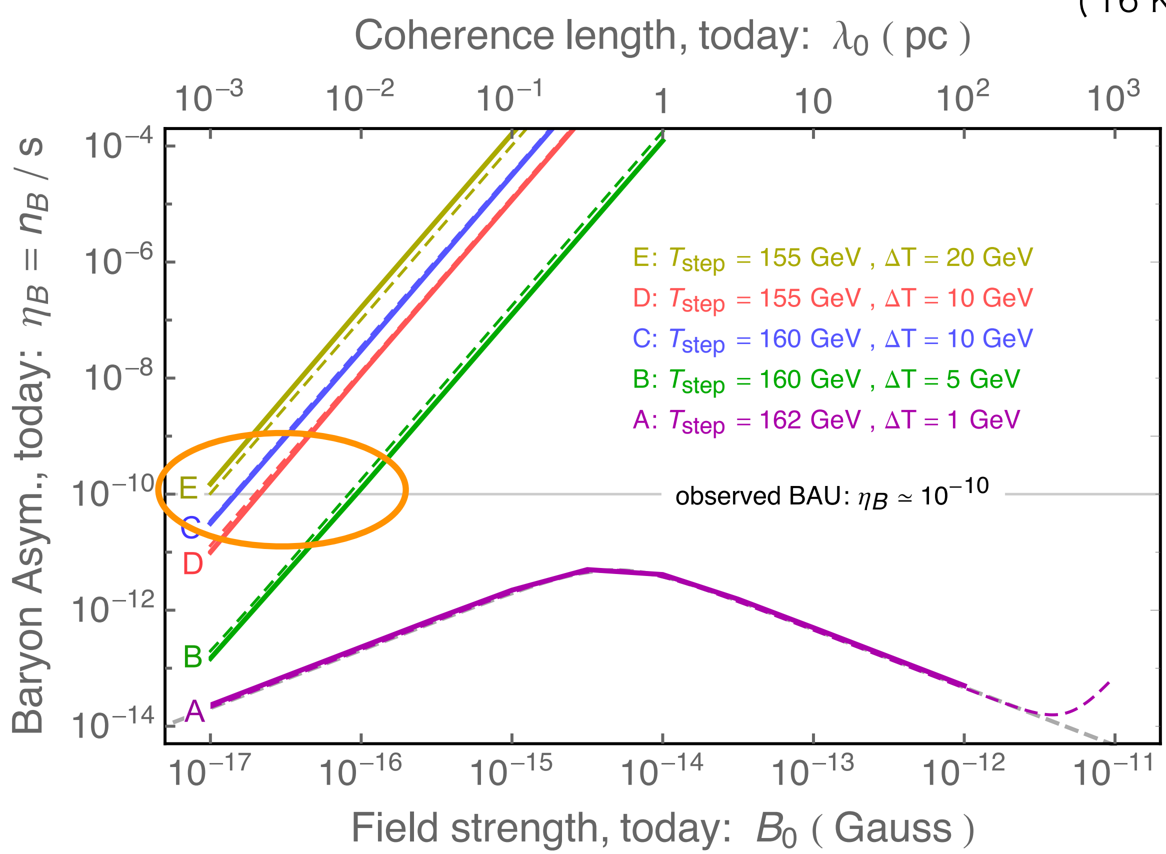
$$\lambda_0 \sim 1{\rm pc}\left(\frac{B_0}{10^{-14}{\rm G}}\right)$$

('04 Banerjee+)

Courtesy H.Oide

BAU can be written in terms of present IGMFs

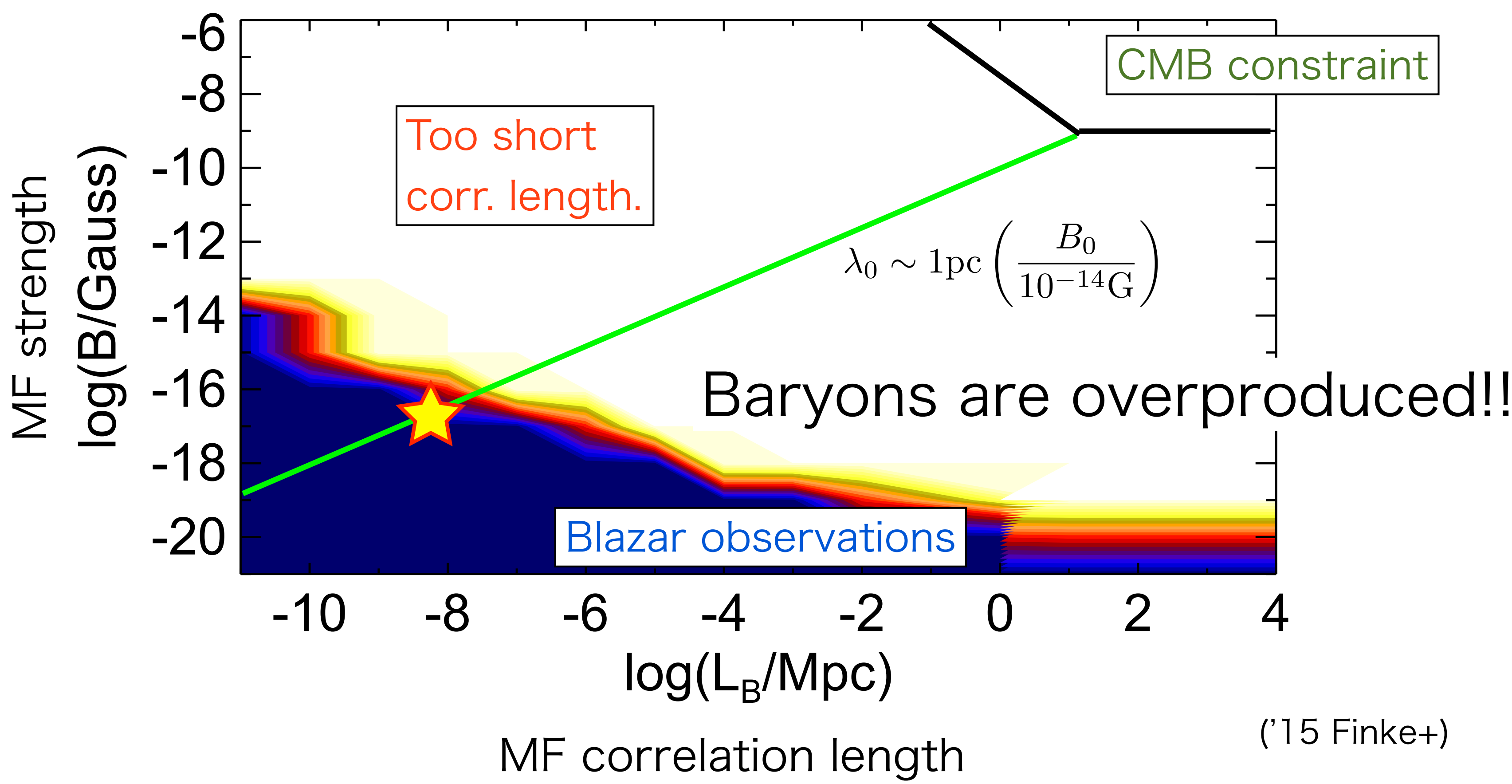
('16 KK&Long)



$$B_0 \simeq 10^{-16\sim17}\mathrm{G} \quad \lambda_0 \simeq 10^{-2\sim3}\mathrm{pc}$$

Courtesy H.Oide

Compare to suggestion from blazar observations...



Courtesy H.Oide

Summary & Conclusion

- B-asymmetry can be generated by helical hyper MFs within the SM.

- EW sphaleron do not completely washout the asymmetry generated by this mechanism even at the EW crossover.

- The MFs responsible for this mechanism can persist until today.

- Present B-asymmetry is explained for $B_0 \simeq 10^{-16\sim17}\mathrm{G} \quad \lambda_0 \simeq 10^{-2\sim3}\mathrm{pc}$.

- There might be baryon overproduction problem.

Courtesy H.Oide

Possible way-outs

- Blazar observation is explained by other mechanism or late-generated MFs: the PMFs responsible for BAU is still hidden.

- Blazar observation is explained by PMFs, but it is not maximally but partially helical. BAU is generated by this PMFs.

Future directions

- Model building of magnetogenesis.

- Determine the IGMF properties. Especially helicity.

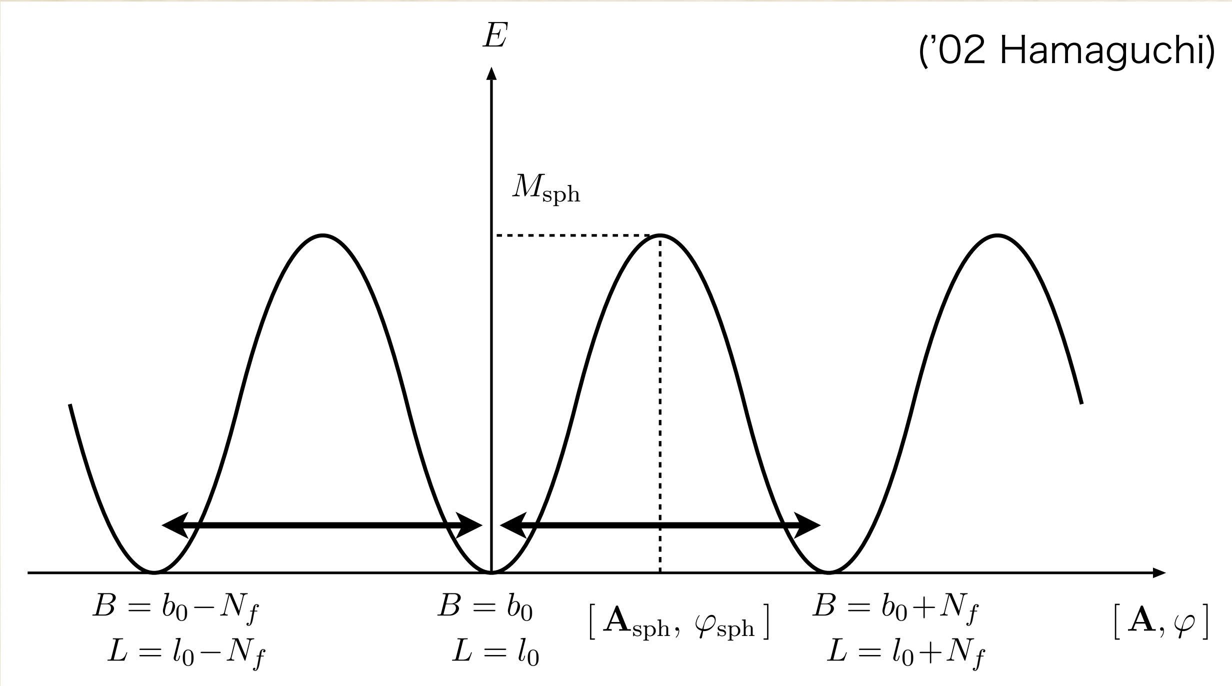
- More accurate description of EW crossover.

Courtesy H.Oide

Appendix

Courtesy H.Oide

Light and shadow of Sphalerons: ('76 't Hooft)



Chiral anomaly in SM $\nabla_\mu j_f^\mu \propto \frac{\alpha}{8\pi} {\rm Tr} W_{\mu\nu} \tilde{W}^{\mu\nu}$ breaks B and L

- Nontrivial vacuum structure of SU(2)
- Sphaleron (B-L preserved; ~~B+L~~) => EW baryogenesis

  Leptogenesis

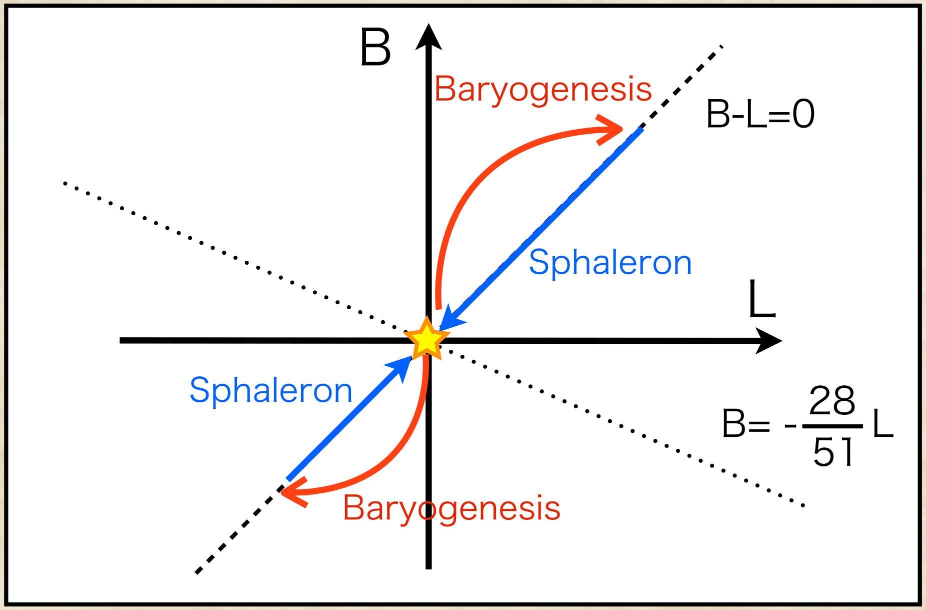
Courtesy H.Oide

Light and shadow of Sphalerons: ('76 't Hooft)

Sphaleron (+charge conservation & Yukawa)

washes out preexisting B+L asymmetry before EWPT.

('85 Kuzmin, Rubakov & Shaposhnikov)



Non-BAU if B-L=0

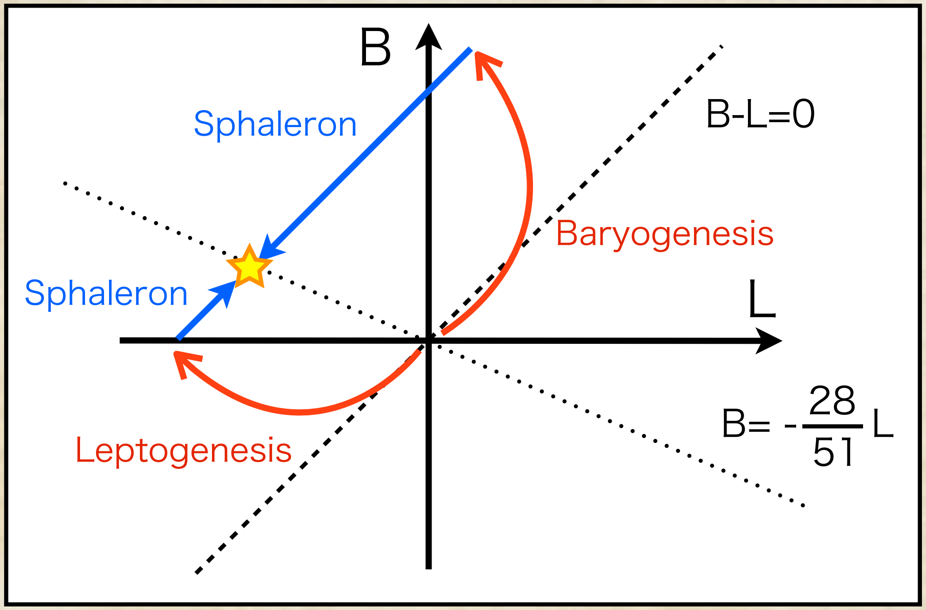
Courtesy H.Oide

Light and shadow of Sphalerons: ('76 't Hooft)

Sphaleron (+charge conservation & Yukawa)

washes out preexisting B+L asymmetry before EWPT.

('85 Kuzmin, Rubakov & Shaposhnikov)



Successful BAU
<-> B-L genesis.

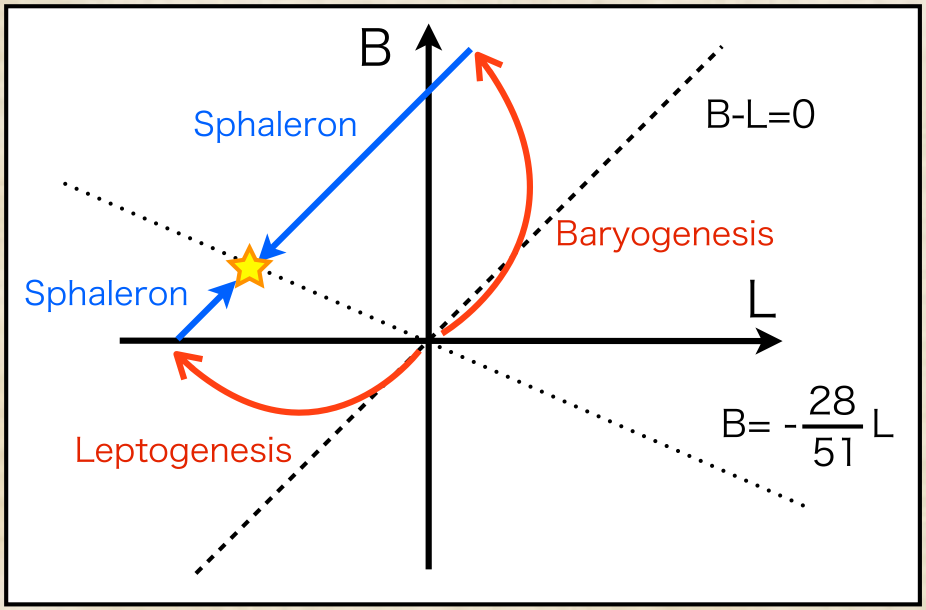
Courtesy H.Oide

Light and shadow of Sphalerons: ('76 't Hooft)

Sphaleron (+charge conservation & Yukawa)

washes out preexisting B+L asymmetry before EWPT.

('85 Kuzmin, Rubakov & Shaposhnikov)



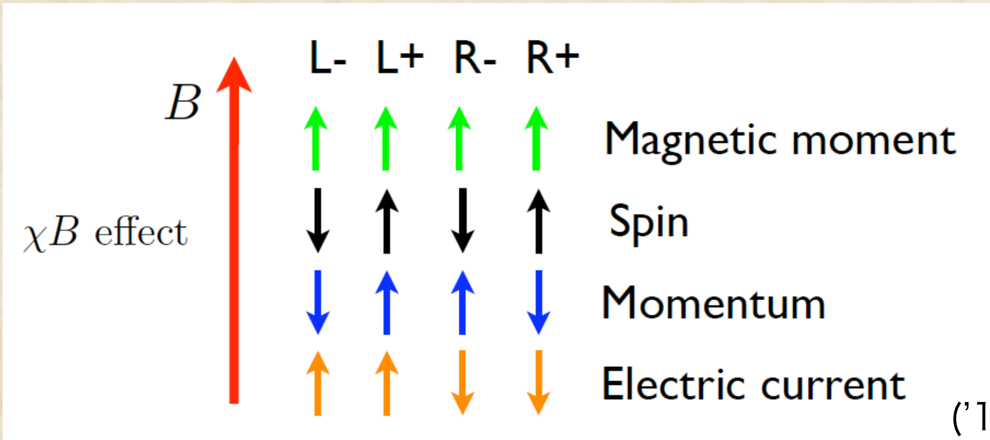
Successful BAU
<-> B-L genesis.

It is often considered that...

"For the present BAU, not ~~B~~ but ~~B-L~~ is needed."

Courtesy H.Oide

Chiral Magnetic Effect (CME) ('80 Vilenkin)



('12 Tashro+)

In the presence of MFs, magnetic moments of fermions aligned along MFs. This generates electric current oppositely for left and right-handed fermions.

Electric current proportional to the chiral asymmetry is induced: $$\boldsymbol{j}_{\rm CME} = \frac{2}{\pi}\alpha\mu_5 \boldsymbol{B}$$

$\mu_5 = \sum_i q_i^2 \mu_{R,i} - \sum_j q_j^2 \mu_{L,j}$:charge weighted chiral chemical potential

(See also '14 Long, Sabancilar and Vachaspati)

The structure differs, but this effect exists both before and after EWPT.

Courtesy H.Oide

Modified Ampere's law

$$\nabla \times \mathbf{B} = \mathbf{j}_{\rm Ohm} + \mathbf{j}_{\rm CME} + \dot{\mathbf{E}} = \sigma(\mathbf{E} + \mathbf{v} \times \mathbf{B}) + \frac{2}{\pi}\alpha\mu_5\mathbf{B} + \dot{\mathbf{E}}$$

$$\Rightarrow \mathbf{E} = \frac{1}{\sigma}\left(\nabla \times \mathbf{B} - \frac{2}{\pi}\alpha\mu_5\mathbf{B} + \dot{\mathbf{E}}\right) - \mathbf{v} \times \mathbf{B}$$

$$\Rightarrow \langle \mathbf{E} \cdot \mathbf{B} \rangle \simeq \frac{1}{\sigma}\langle \mathbf{B} \cdot \nabla \times \mathbf{B} \rangle - \frac{2\alpha}{\pi\sigma}\mu_5 \langle \mathbf{B}^2 \rangle$$

$$\simeq \frac{2\pi}{\sigma}\frac{B_p^2(T)}{\lambda_B(T)} - \frac{2\alpha}{\pi\sigma}\mu_5 B_p^2(T)$$

Courtesy H.Oide

Kinetic equations

$$x \equiv T/H$$

$$\eta_f = n_f/s$$

$$\frac{d\eta_{u_L^i}}{dx} = N_c y_{Q_L}^2 \mathcal{S}_Y - \gamma_W(\eta_{u_L^i} - \cdots) - \cdots$$

$$\vdots$$

$$\mathcal{S}_Y = -\frac{2\alpha}{\sigma s T}\frac{B_p^2(T)}{\lambda_B(T)} + \frac{12\alpha^2}{\pi^2 \sigma T^3} B_p^2(T)\eta_5$$

$$\equiv -\gamma_Y(x) + \gamma_Y^{\mathrm{CME}}(x)\eta_5$$

Courtesy H.Oide

Kinetic equations

$x \equiv T/H$

$\eta_f = n_f/s$

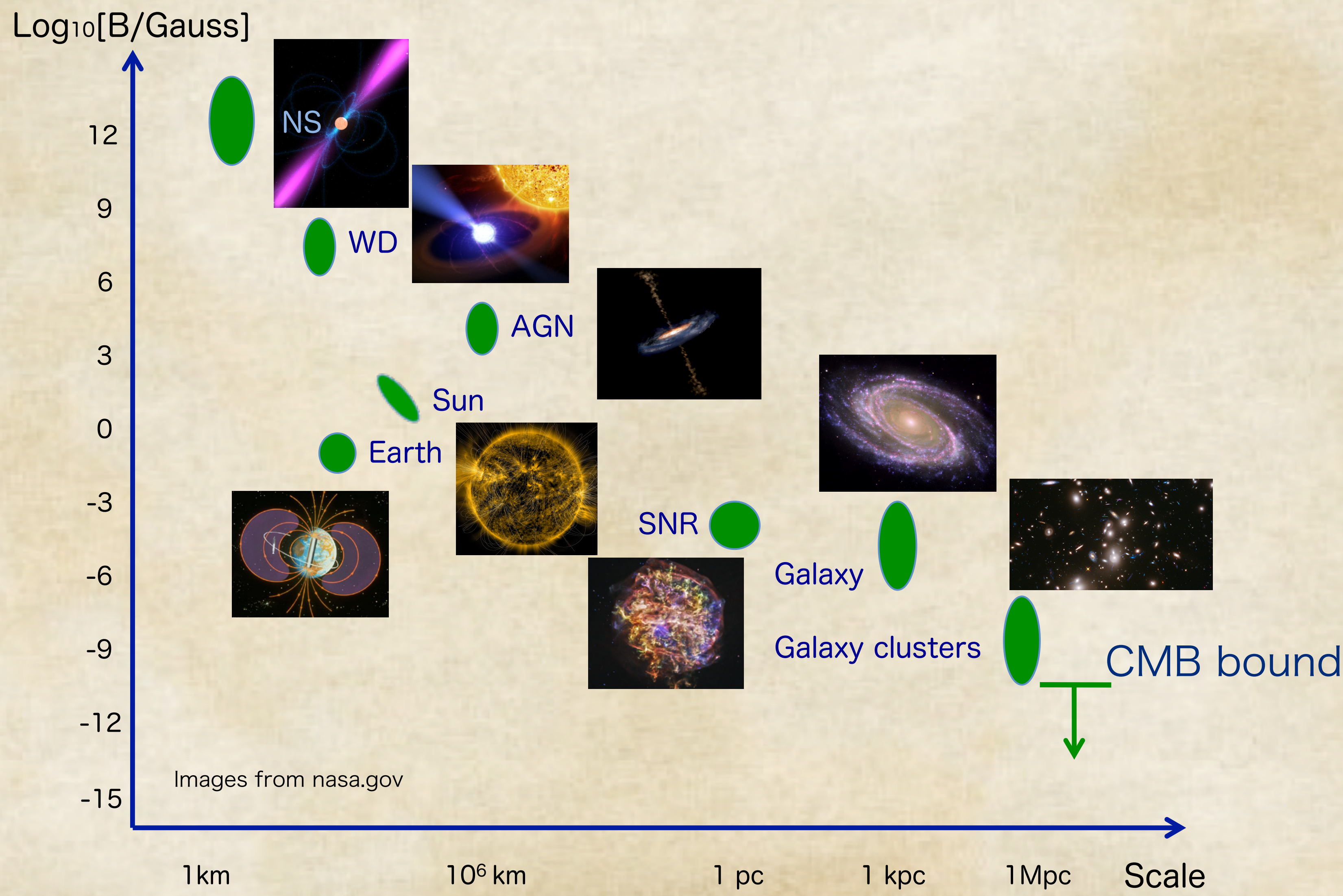
$$\frac{\partial \eta_{u_L^i}}{\partial x} = -N_c q_Q^2(\gamma_y - \gamma_y^{\rm CME}\mu_5^Y) - N_c\frac{\gamma_w}{2}\sum_j(\eta_{u_L^j}+\eta_{d_L^j}+\eta_{e_L^j}+\eta_{\nu_L^j}) - \frac{\gamma_s}{2}\sum_j(\eta_{u_L^j}+\eta_{d_L^j}-\eta_{u^j}-\eta_{d^j})$$
$$-\sum_j\frac{\gamma_{u^{ij}}}{2}\left(\frac{\eta_{u_L^i}}{3}+\frac{\eta_{\varphi^0}}{2}-\frac{\eta_{u_R^j}}{3}\right)-\sum_j\frac{\gamma_{d^{ij}}}{2}\left(\frac{\eta_{u_L^i}}{3}-\frac{\eta_{\varphi^+}}{2}-\frac{\eta_{d_R^j}}{3}\right)$$
$$-\sum_j\gamma^M_{u^{ij}}\left(\frac{\eta_{u_L^i}}{3}-\frac{\eta_{u_R^j}}{3}\right)-\gamma_2(\eta_{u_L^i}-\eta_{d_L^i}),$$

$$\frac{\partial \eta_{d_L^i}}{\partial x} = -N_c q_Q^2(\gamma_y - \gamma_y^{\rm CME}\mu_5^Y) - N_c\frac{\gamma_w}{2}\sum_j(\eta_{u_L^j}+\eta_{d_L^j}+\eta_{e_L^j}+\eta_{\nu_L^j}) - \frac{\gamma_s}{2}\sum_j(\eta_{u_L^j}+\eta_{d_L^j}-\eta_{u^j}-\eta_{d^j})$$
$$-\sum_j\frac{\gamma_{u^{ij}}}{2}\left(\frac{\eta_{d_L^i}}{3}+\frac{\eta_{\varphi^+}}{2}-\frac{\eta_{u_R^j}}{3}\right)-\sum_j\frac{\gamma_{d^{ij}}}{2}\left(\frac{\eta_{d_L^i}}{3}-\frac{\eta_{\varphi^0}}{2}-\frac{\eta_{d_R^j}}{3}\right)$$
$$-\sum_j\gamma^M_{d^{ij}}\left(\frac{\eta_{d_L^i}}{3}-\frac{\eta_{d_R^j}}{3}\right)-\gamma_2(\eta_{d_L^i}-\eta_{u_L^i}),$$

$$\frac{\partial \eta_{\nu_L^i}}{\partial x} = -q_L^2(\gamma_y - \gamma_y^{\rm CME}\mu_5^Y) - \frac{\gamma_w}{2}\sum_j(\eta_{u_L^j}+\eta_{d_L^j}+\eta_{e_L^j}+\eta_{\nu_L^j}) - \sum_j\frac{\gamma_{e^{ij}}}{2}\left(\eta_{\nu_L^i}-\frac{\eta_{\varphi^+}}{2}-\eta_{e_R^j}\right)-\gamma_2(\eta_{\nu_L^i}-$$

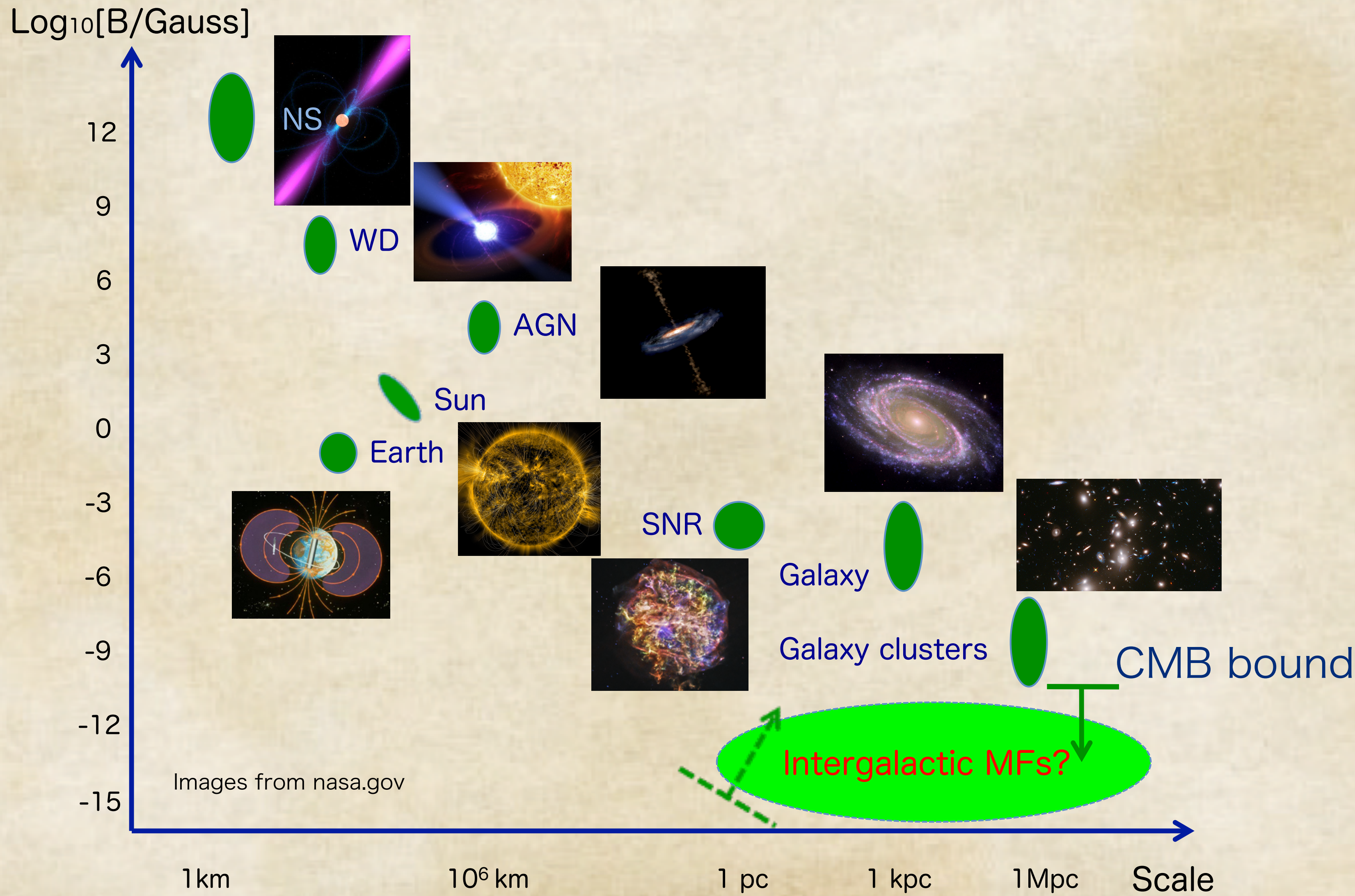
$$\frac{\partial \eta_{e_L^i}}{\partial x} = -q_L^2(\gamma_y - \gamma_y^{\rm CME}\mu_5^Y) - \frac{\gamma_w}{2}\sum_j(\eta_{u_L^j}+\eta_{d_L^j}+\eta_{e_L^j}+\eta_{\nu_L^j}) - \sum_j\frac{\gamma_{e^{ij}}}{2}\left(\eta_{e_L^i}-\frac{\eta_{\varphi^0}}{2}-\eta_{e_R^j}\right)$$

Magnetic fields in the Universe



Courtesy H.Oide

Magnetic fields in the Universe



Courtesy H.Oide

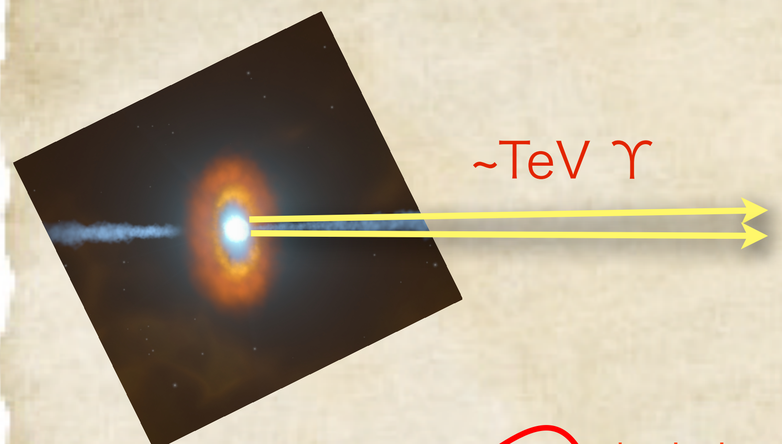
Evidence (?) of large scale magnetic fields

Courtesy H.Oide

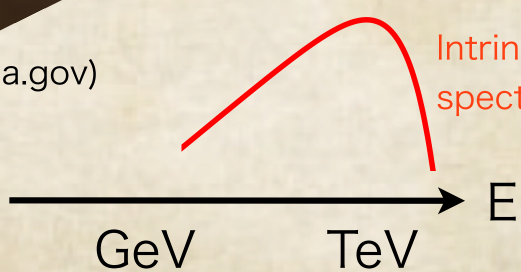
Evidence (?) of large scale magnetic fields

: ϒ-ray from Blazars (theory)

AGN/Blazar



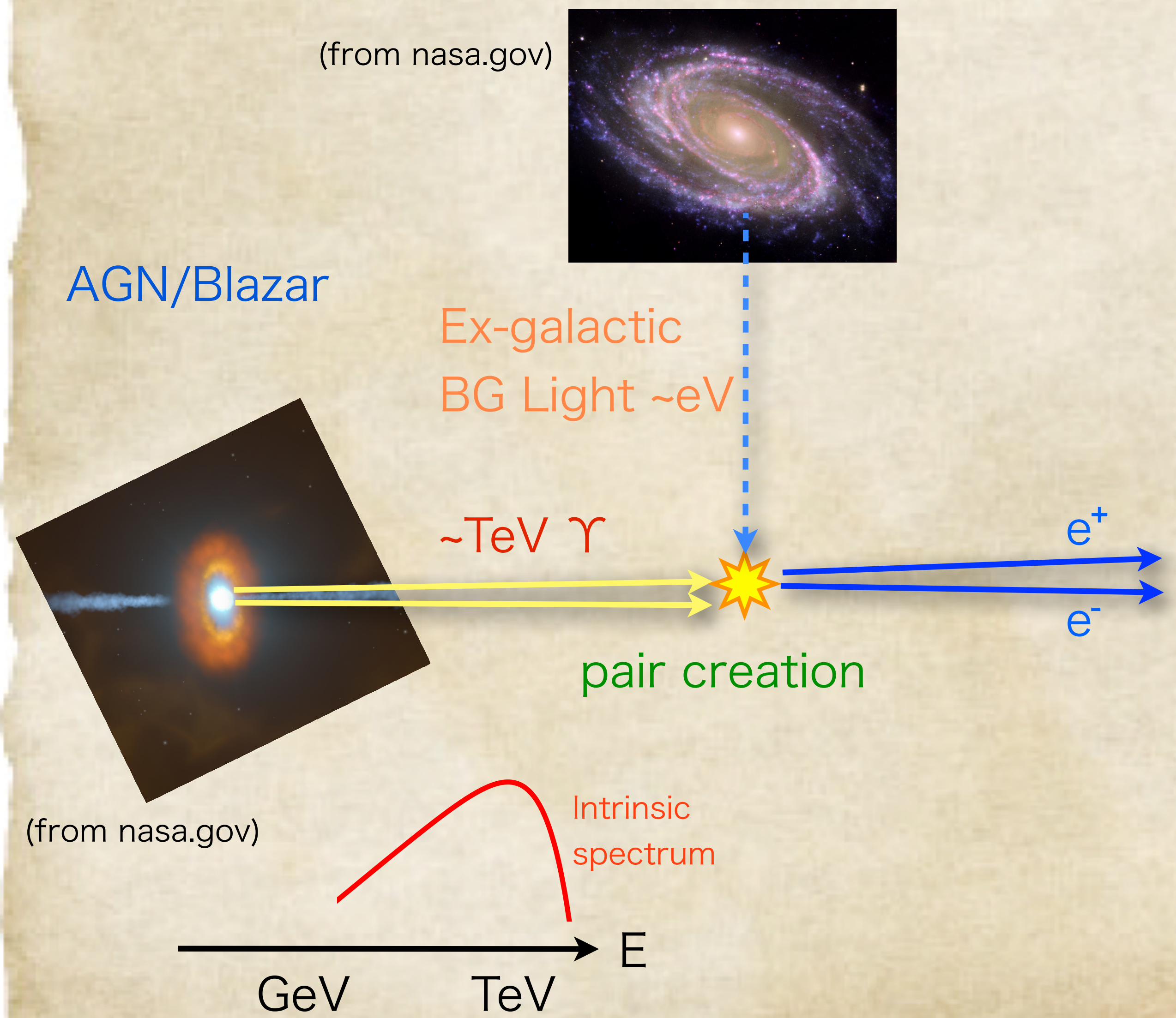
(from nasa.gov)



Courtesy H.Oide

Evidence (?) of large scale magnetic fields

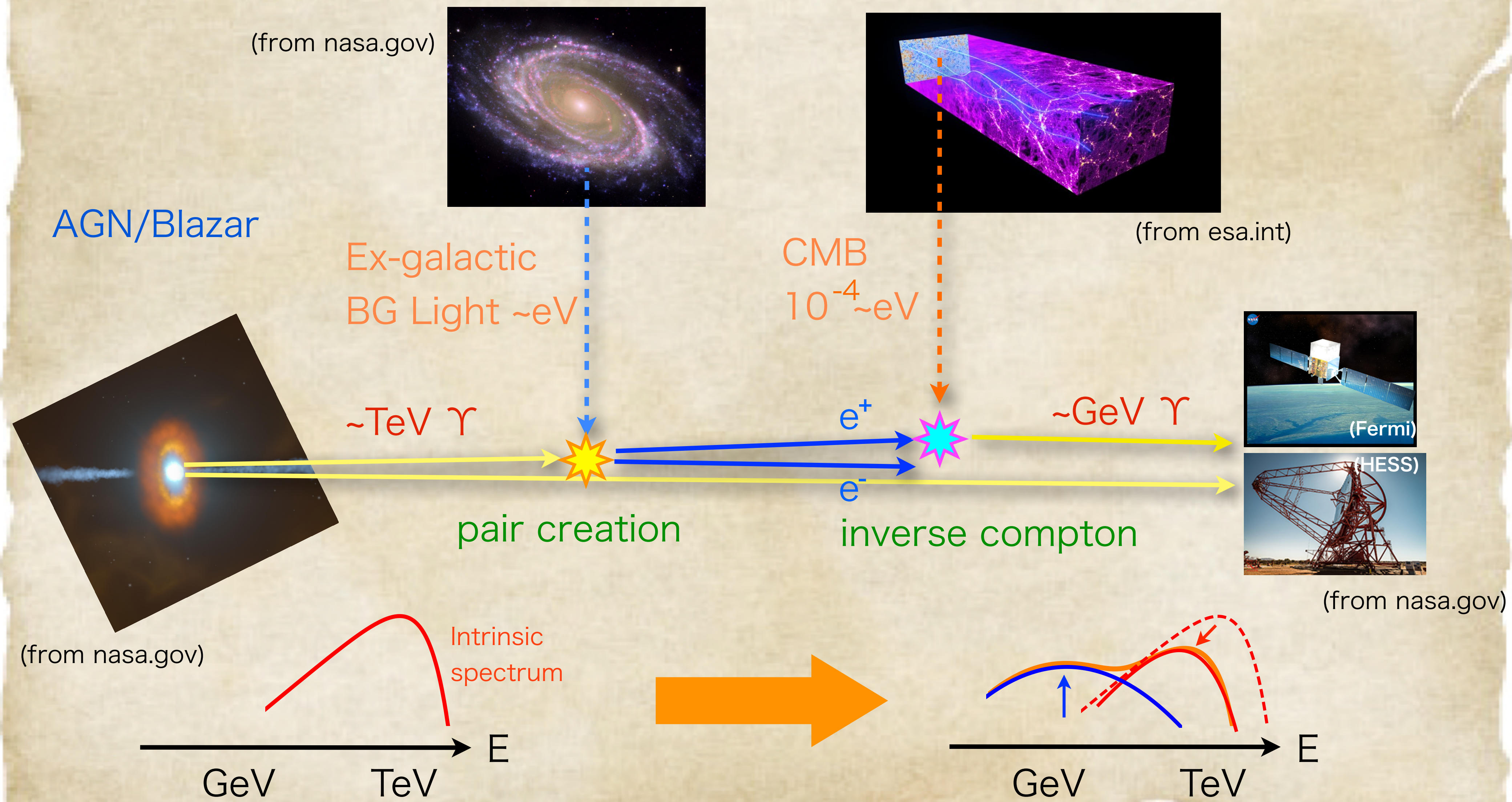
: ϒ-ray from Blazars (theory)



Courtesy H.Oide

Evidence (?) of large scale magnetic fields

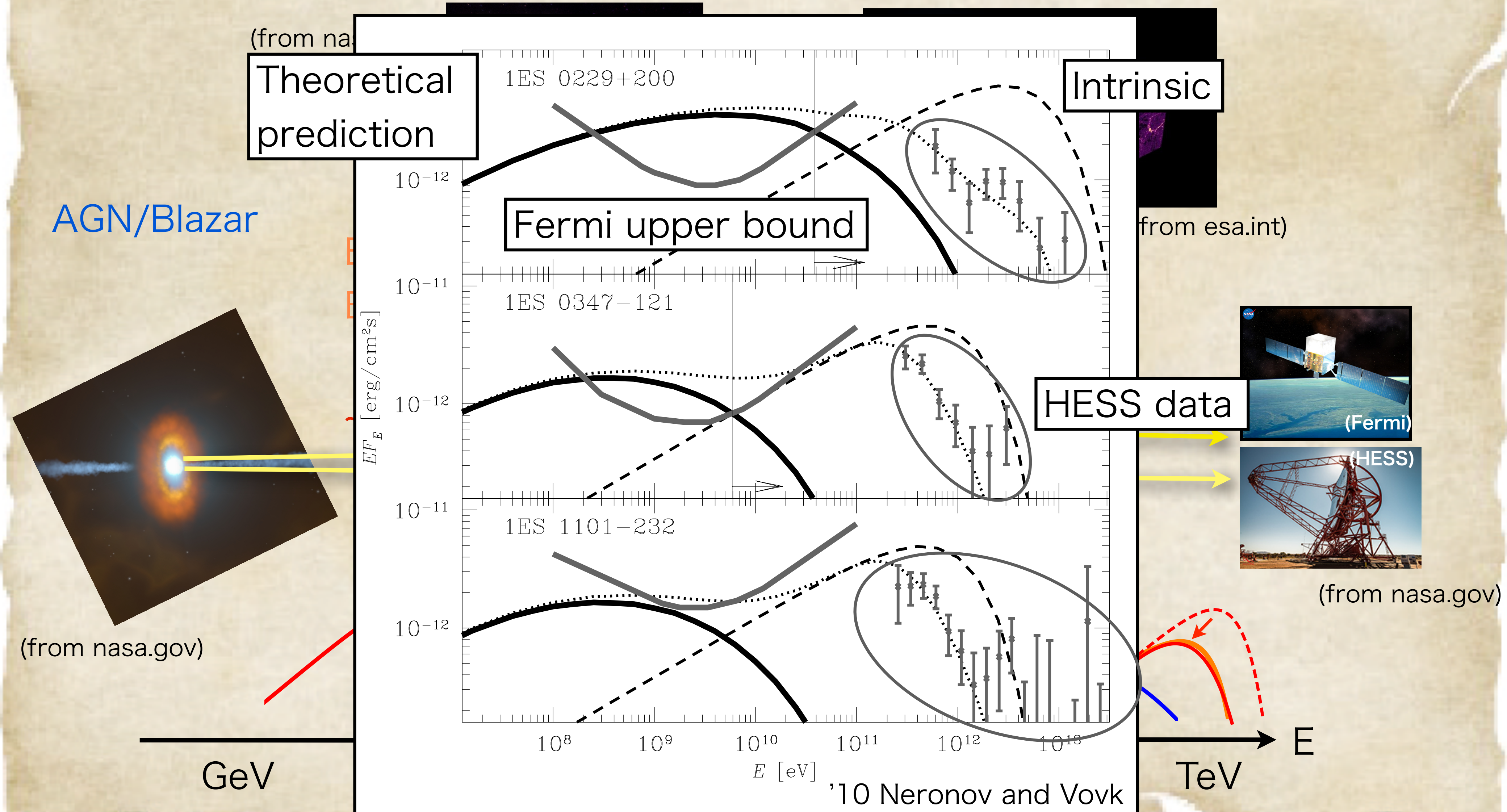
: ϒ-ray from Blazars (theory)



Courtesy H.Oide

Evidence (?) of large scale magnetic fields

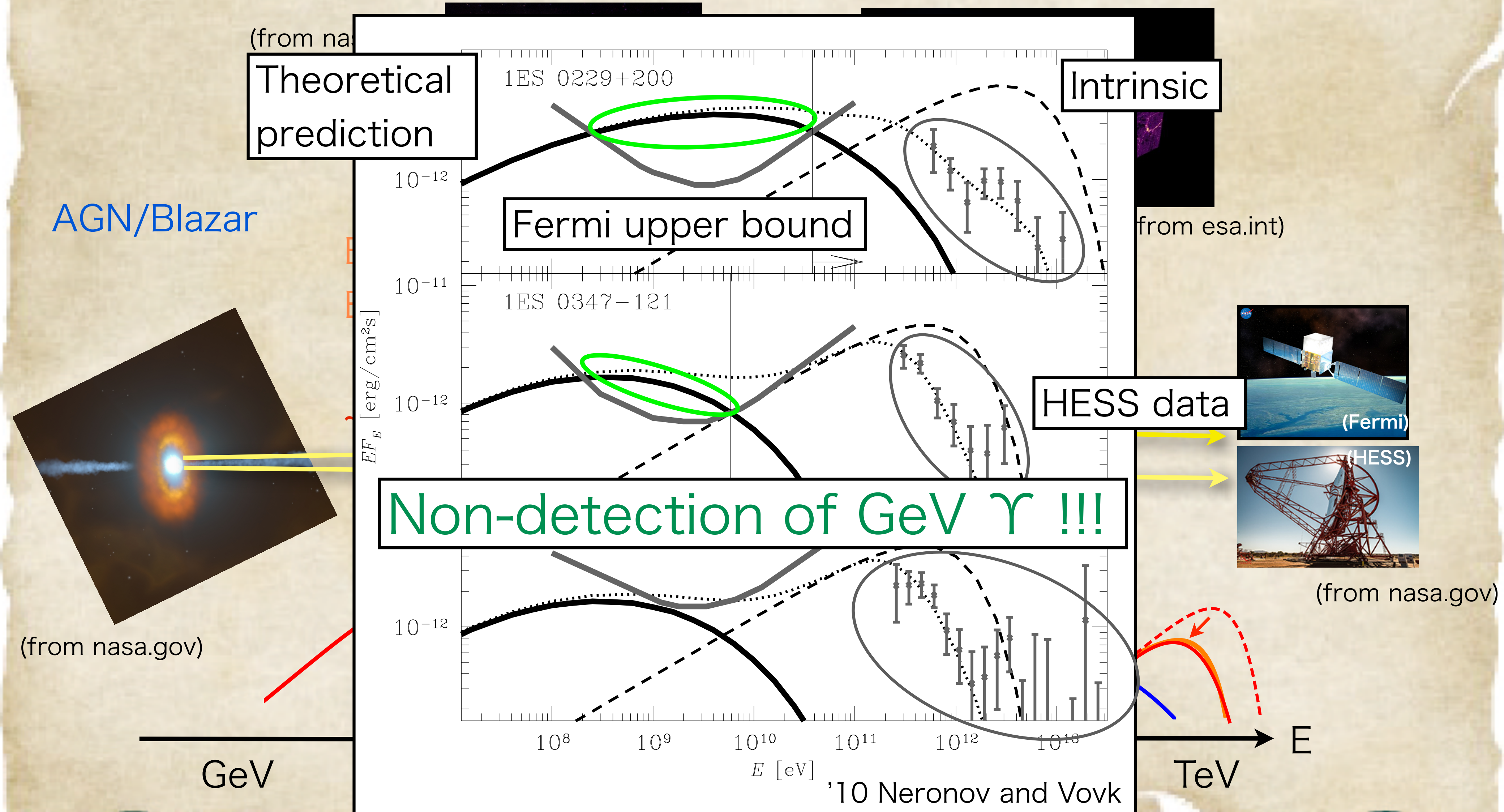
: ϒ-ray from Blazars (observation)



Courtesy H.Oide

Evidence (?) of large scale magnetic fields

: ϒ-ray from Blazars (observation)



Courtesy H.Oide

Evidence (?) of large scale magnetic fields

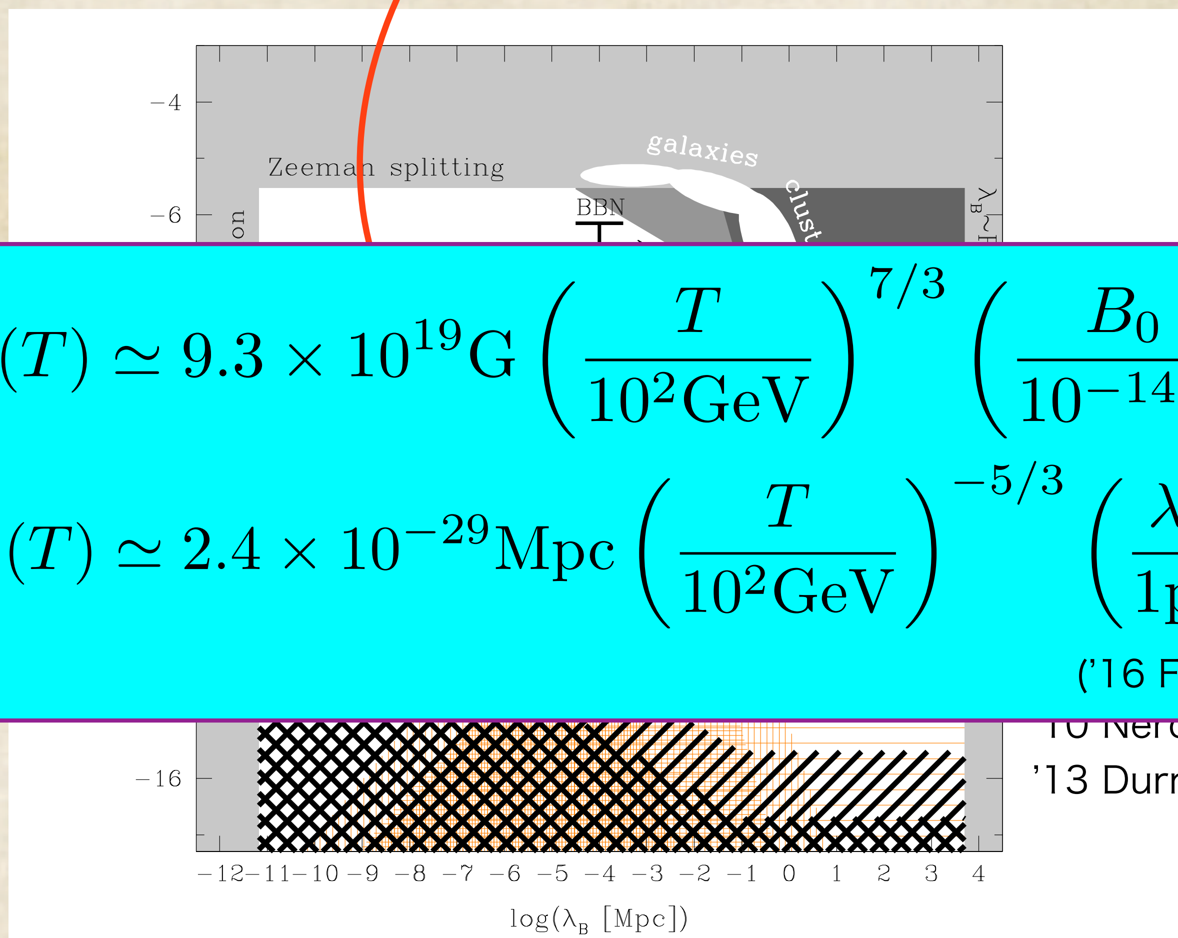
Most convincing explanation: Extragalactic MFs

Courtesy H.Oide

MFs produced by a causal process will stay at:

$$\lambda_0 \sim 1\text{pc}\left(\frac{B_0}{10^{-14}\text{G}}\right)$$

('04 Banerjee+)



$$B_p(T) \simeq 9.3\times10^{19}\text{G}\left(\frac{T}{10^2\text{GeV}}\right)^{7/3}\left(\frac{B_0}{10^{-14}\text{G}}\right)$$

$$\lambda_B(T) \simeq 2.4\times10^{-29}\text{Mpc}\left(\frac{T}{10^2\text{GeV}}\right)^{-5/3}\left(\frac{\lambda_0}{1\text{pc}}\right)$$

('16 Fujita+)

'10 Neronov and Vovk

'13 Durrer and Neronov

Courtesy H.Oide

Backreaction to the B-field dynamics from CME

We evaluate the B-field evolution as

$$\dot{B}_p \simeq H B_p$$

through Inverse Cacade

CME w/o IC leads

$$\dot{B}_p \simeq \frac{2\alpha}{\pi\sigma}\mu_5 \nabla \times B_p \sim \frac{2\alpha}{\pi\sigma}\mu_5 \frac{B_p}{\lambda_B}$$

For

$$H > \frac{\alpha}{\sigma}\frac{\mu_5}{\lambda_B}$$

CME is negligible.

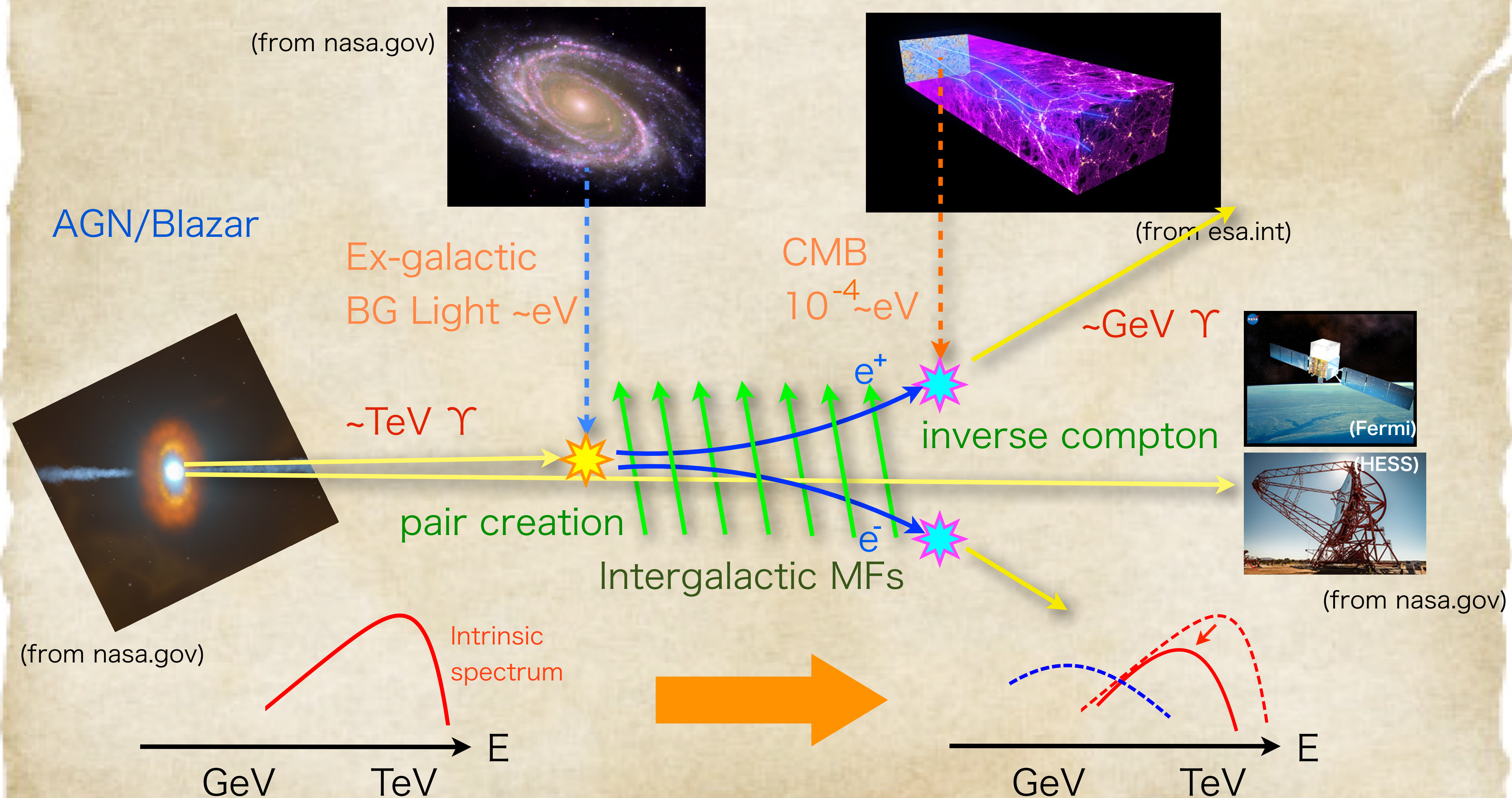
$$10^{-14}\left(\frac{T}{10^2\mathrm{GeV}}\right)^2 \mathrm{GeV}$$

$$10^{-24}\left(\frac{\mu_5/T}{10^{-10}}\right)\left(\frac{T}{10^2\mathrm{GeV}}\right)^{5/3}\left(\frac{\lambda_0}{1\mathrm{pc}}\right)^{-1} \mathrm{GeV}$$

Courtesy H.Oide

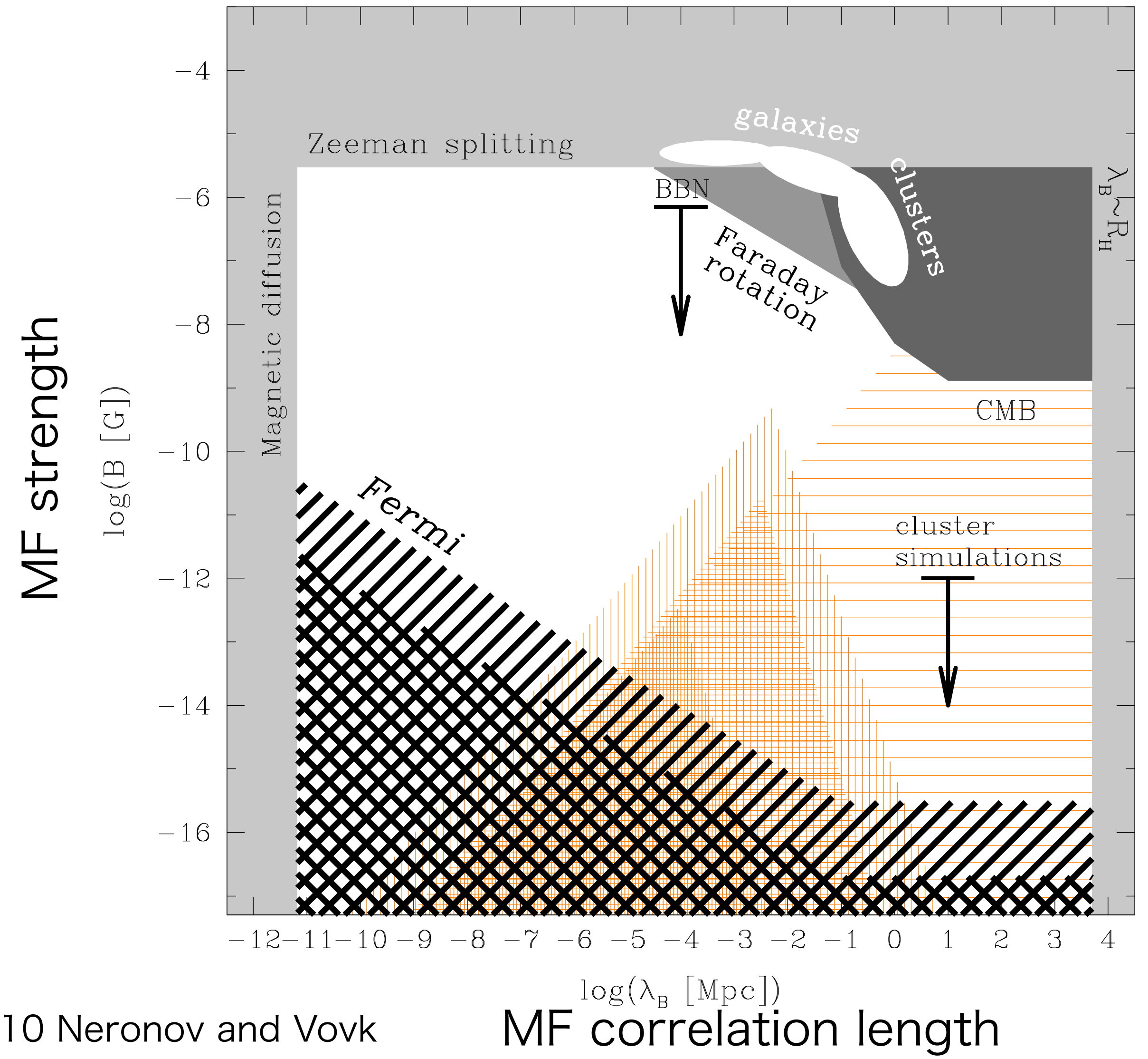
Evidence (?) of large scale magnetic fields

Most convincing explanation: Extragalactic MFs



Courtesy H.Oide

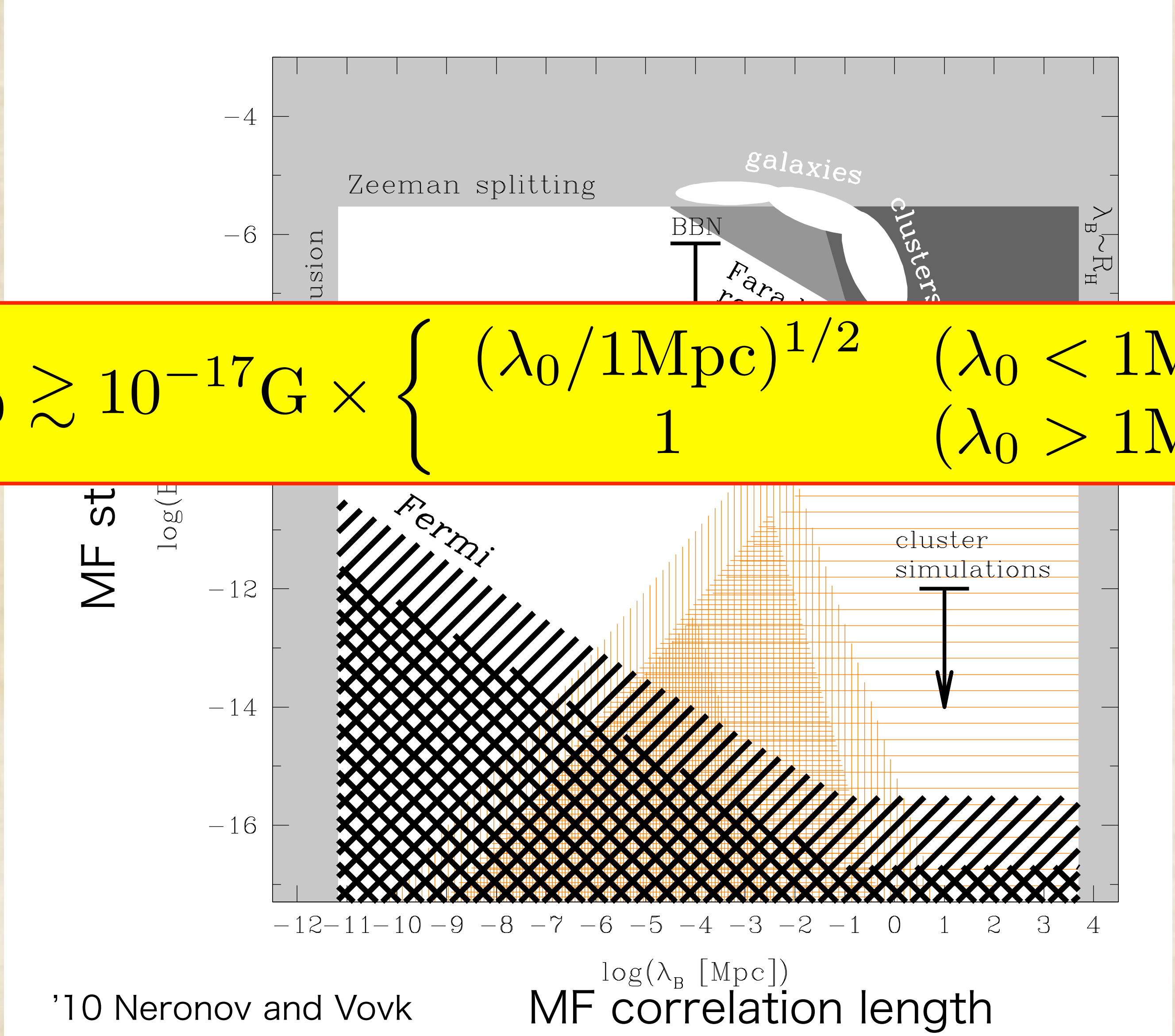
Constraints on the magnetic fields



'10 Neronov and Vovk

Courtesy H.Oide

Constraints on the magnetic fields



$$B_0 \gtrsim 10^{-17}\mathrm{G} \times \begin{cases} (\lambda_0/1\mathrm{Mpc})^{1/2} & (\lambda_0 < 1\mathrm{Mpc}) \\ 1 & (\lambda_0 > 1\mathrm{Mpc}) \end{cases}$$

'10 Neronov and Vovk

Courtesy H.Oide