Large scale magnetic fields as the origin of baryon asymmetry

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

SCHOOL OF EARTH & SPACE EXPLORATION
ARIZONA STATE UNIVERSITY

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(Arizona State University)

DESY theory seminar
25/7/2016 @ DESY, Hamburg

Courtesy H.Oide

Today's message is…

- The existence of intergalactic magnetic fields (MFs) are indicated recently.
- If they have originated from a mechanism before or around EWPT, they might be related to baryon asymmetry of the Universe (BAU).
- The parameter space that can explain the present BAU is on the edge of the constraints, in other words, the sweet spot is indicated.
- BSM (BGR?) might not be needed for baryogenesis but for magnetogenesis!

Courtesy H.Oide

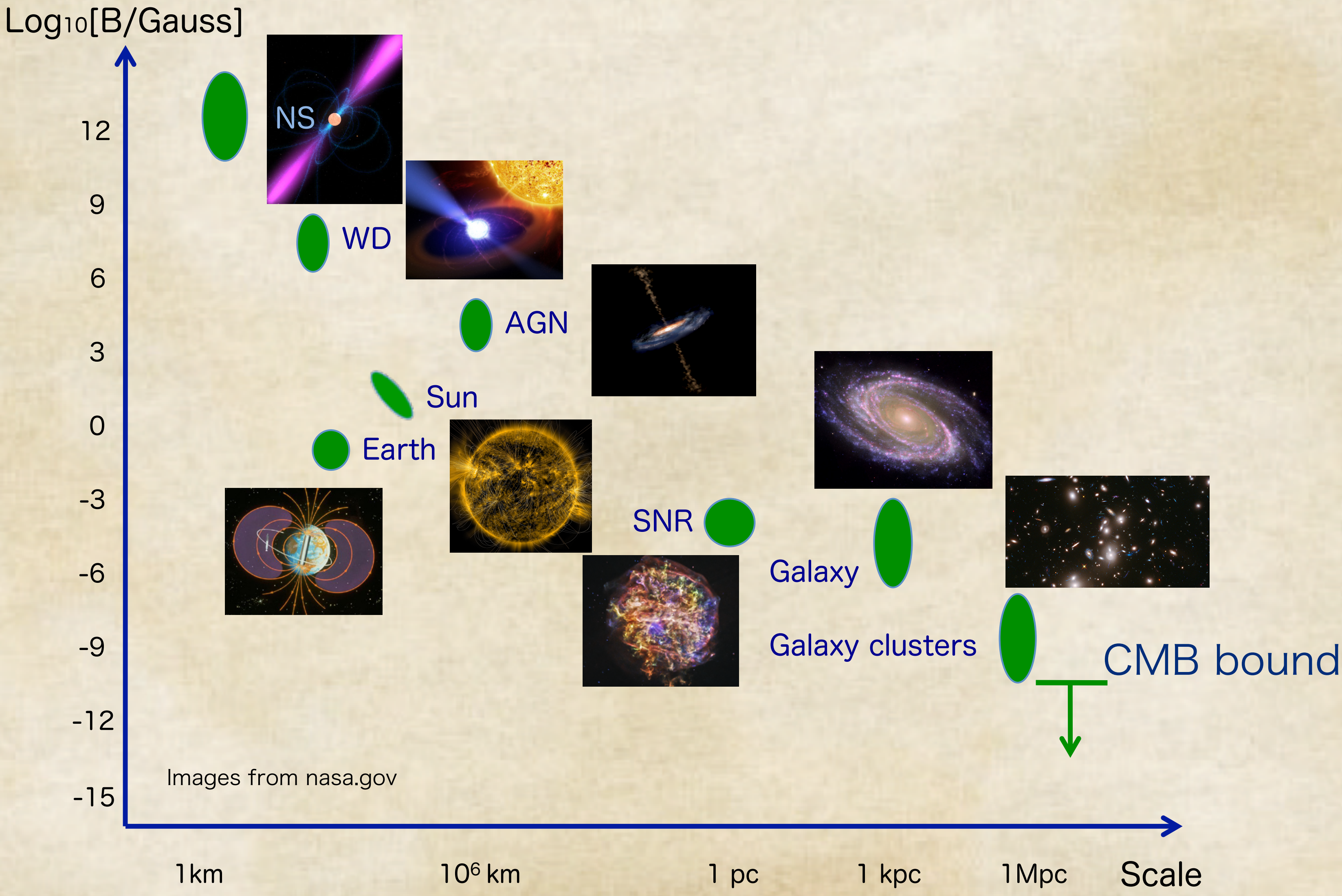
1. Magnetic fields in the Universe

2. Baryon asymmetry of the Universe

3. Baryogenesis from helical MFs

Courtesy H.Oide

Magnetic fields in the Universe



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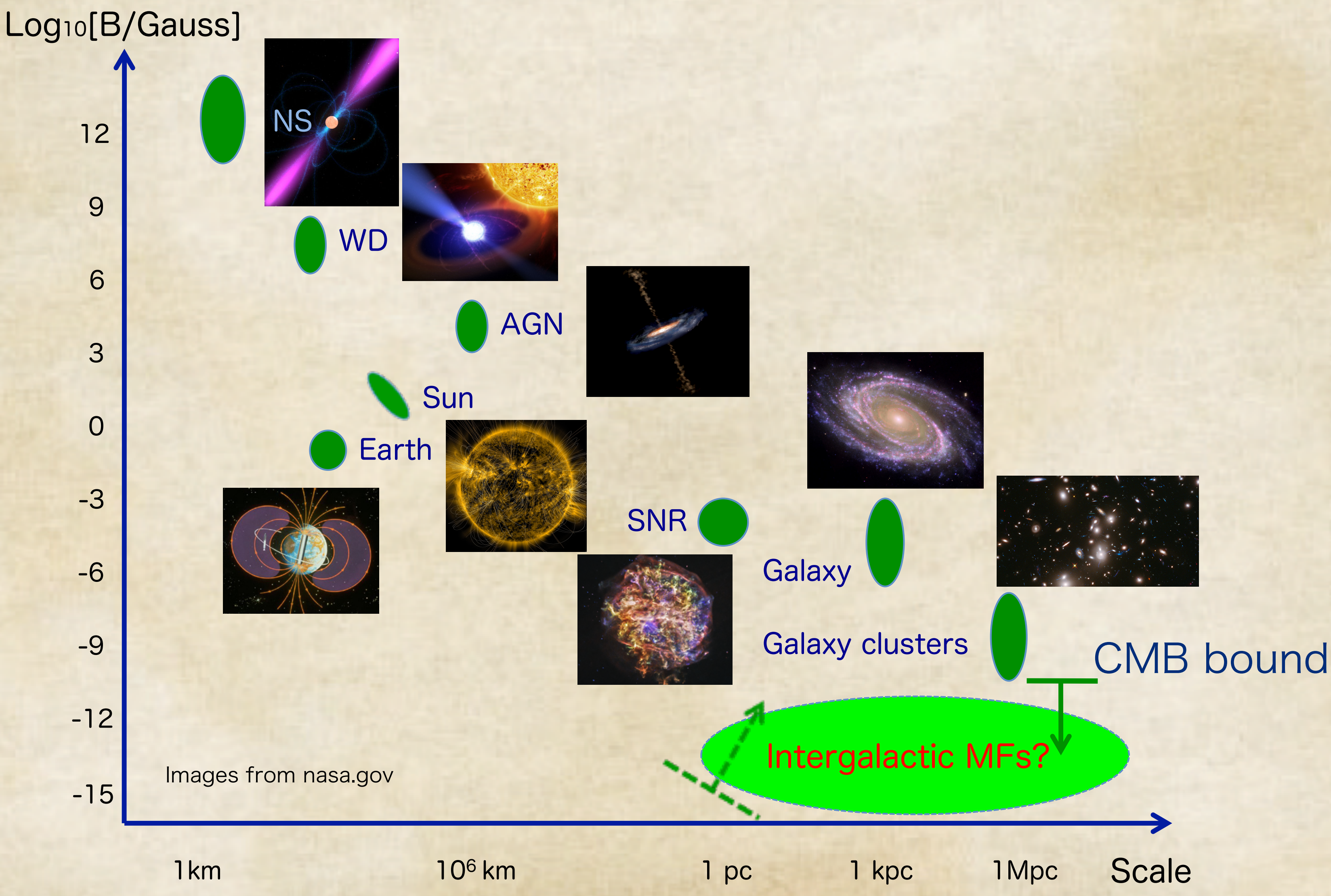

Courtesy H.Oide

Evidence (?) of large scale magnetic fields

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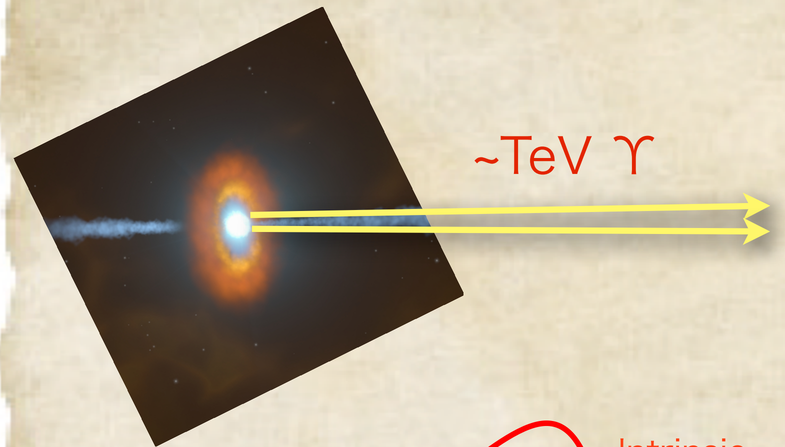
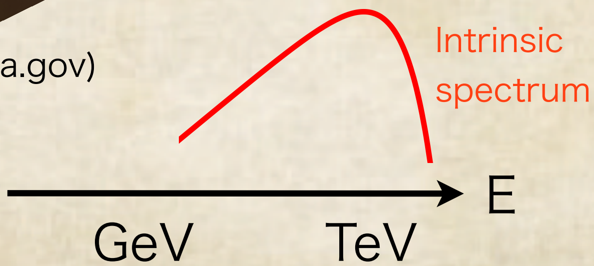
: ϒ-ray from Blazars (theory)

AGN/Blazar



(from nasa.gov)



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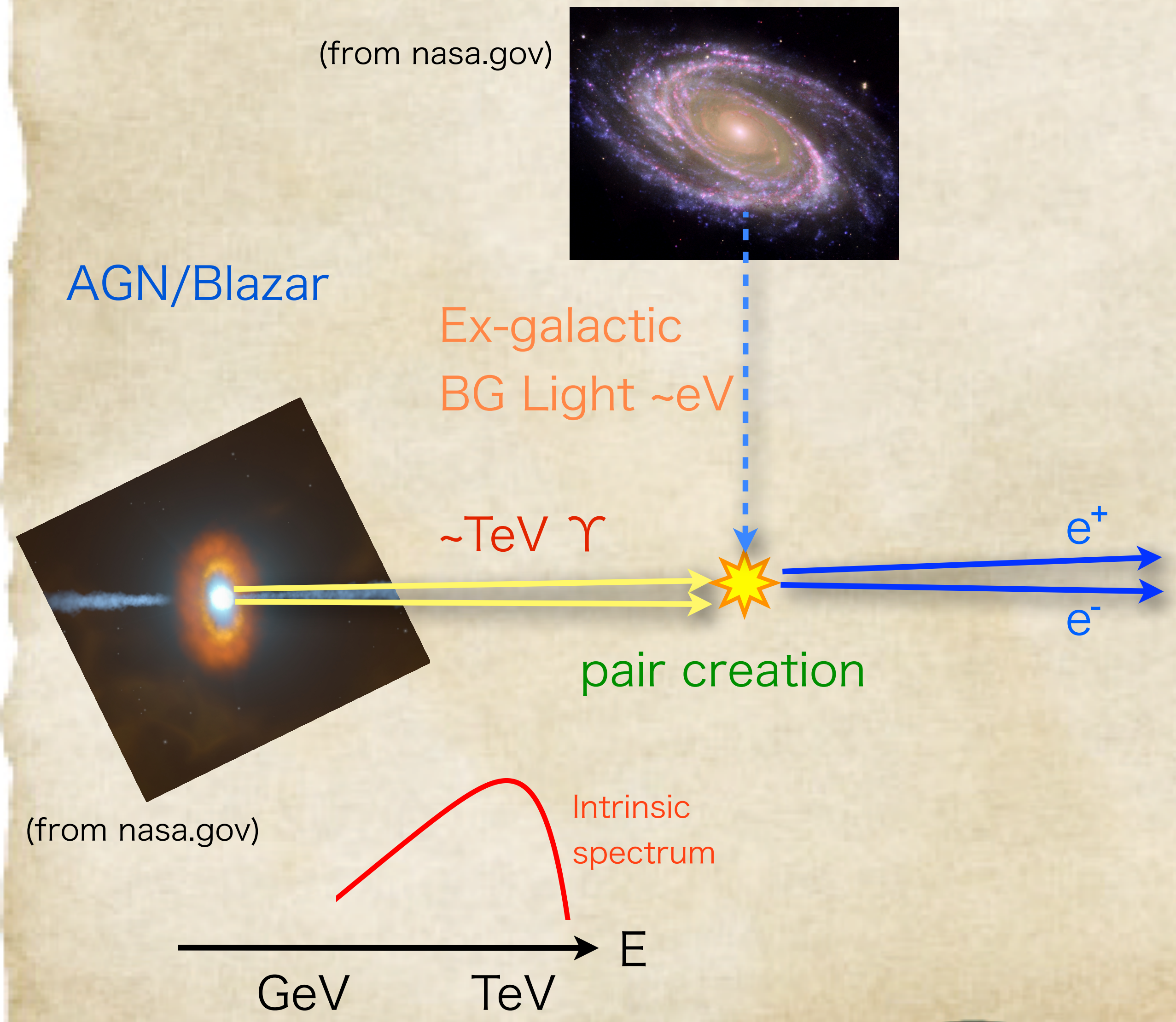

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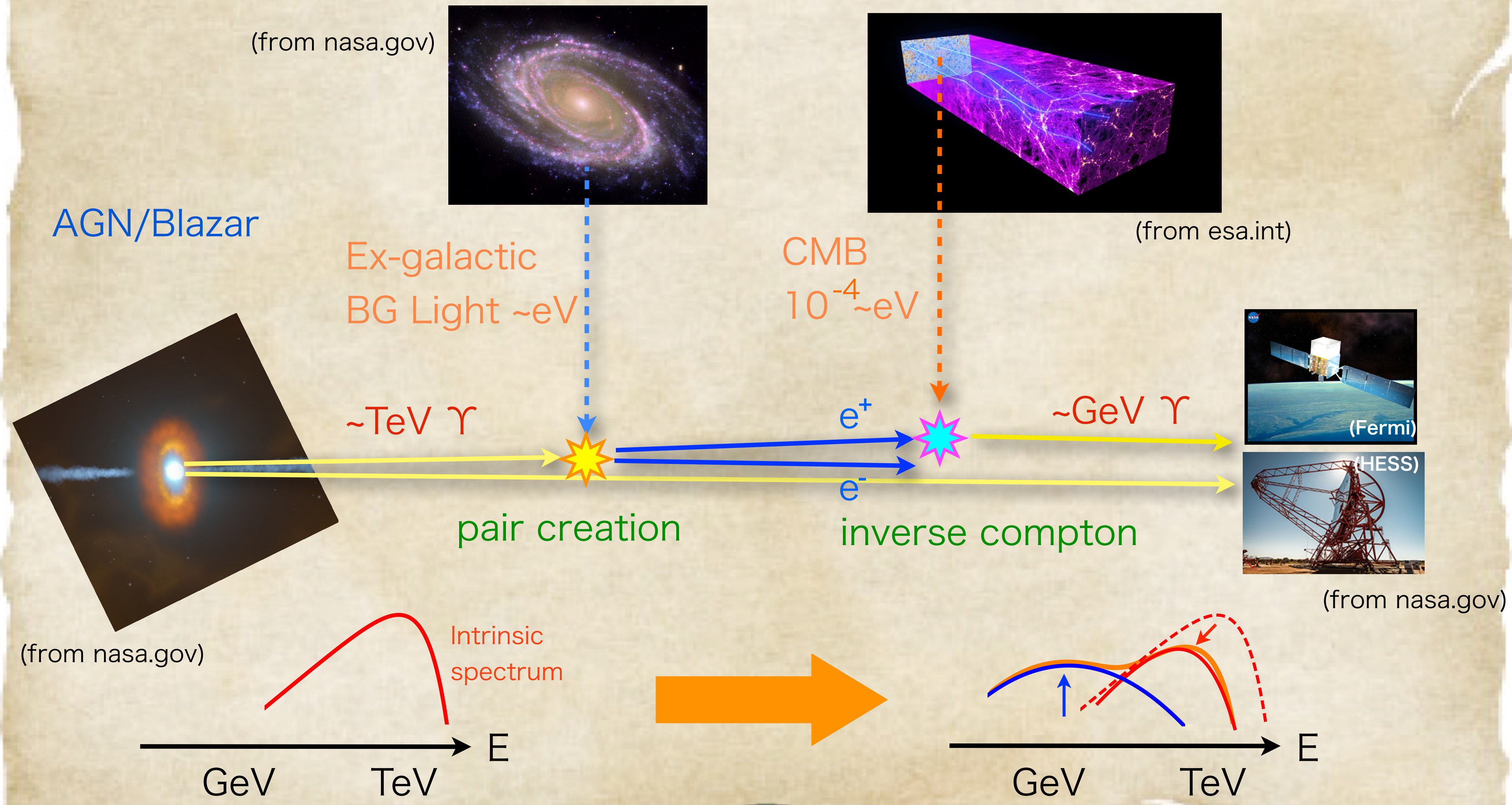

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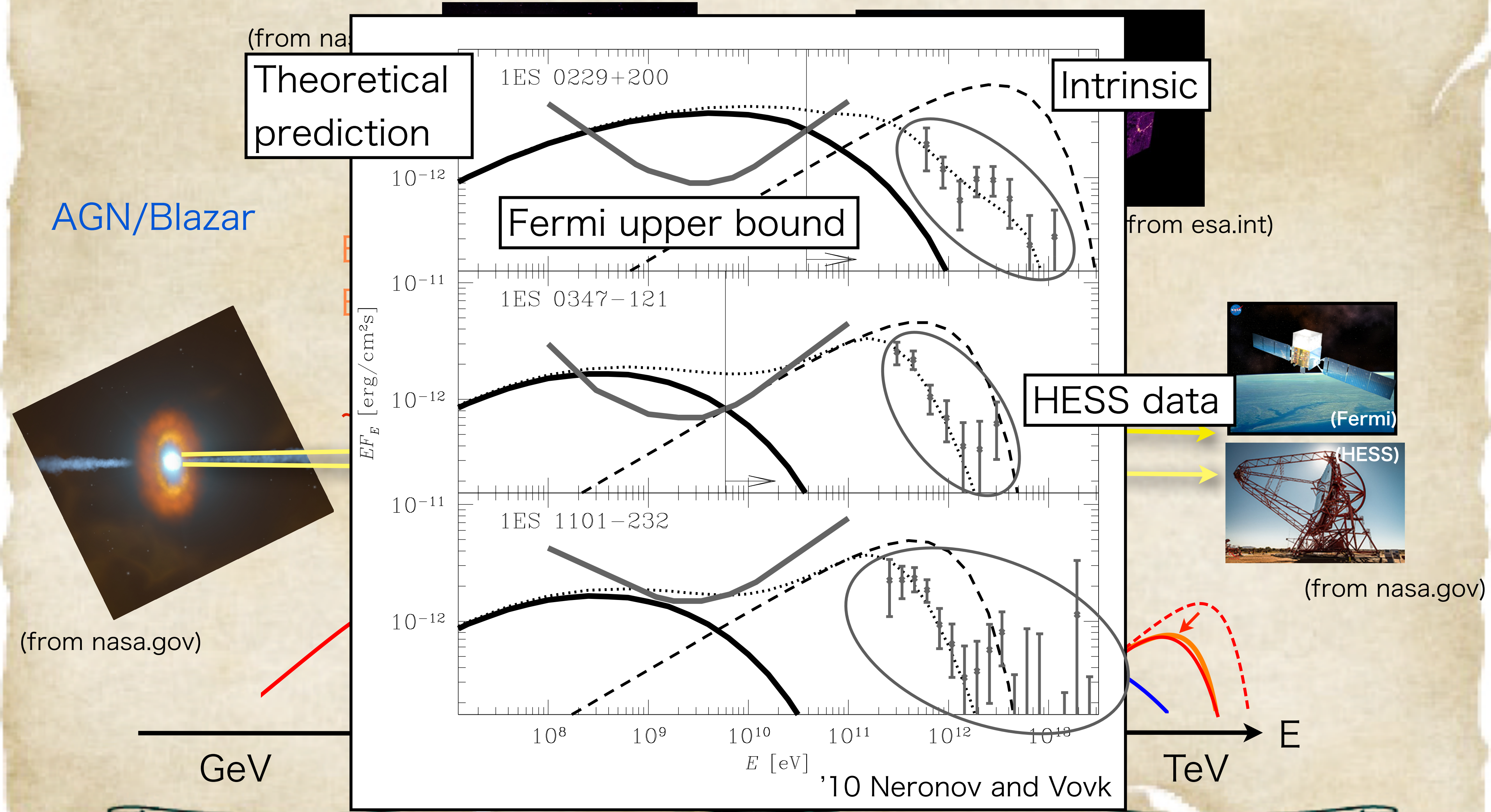

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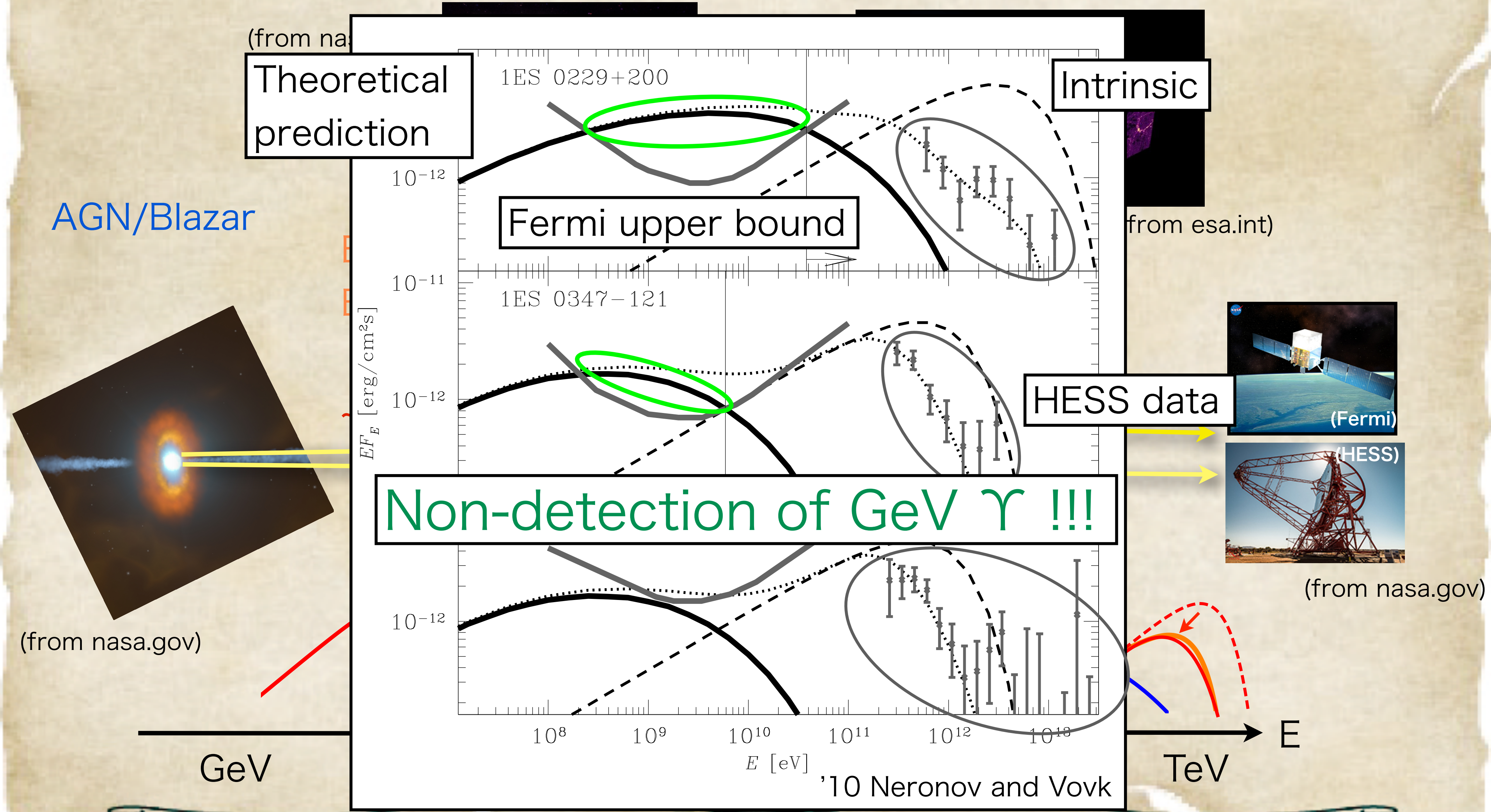

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Most convincing explanation: Extragalactic MFs

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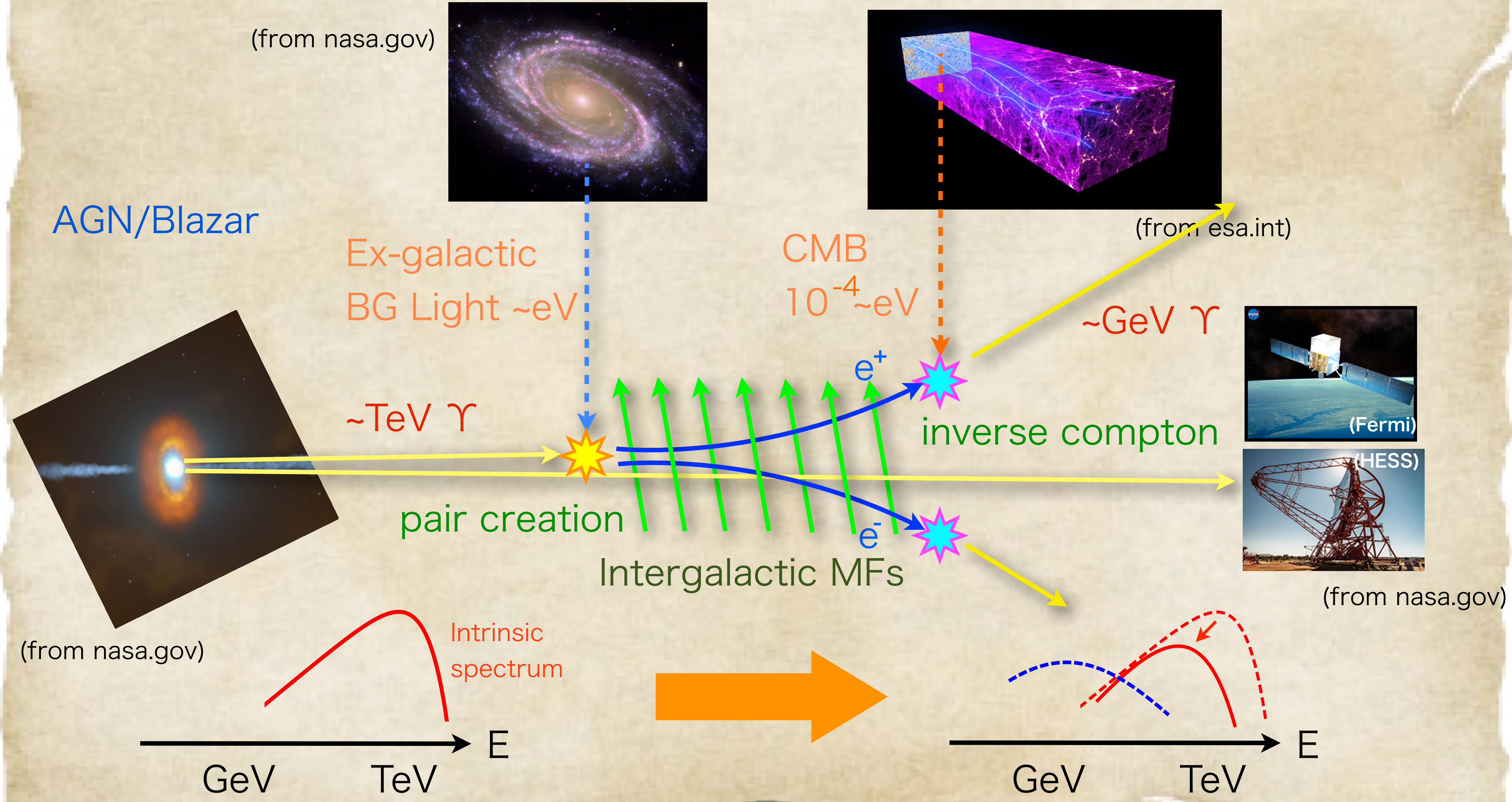

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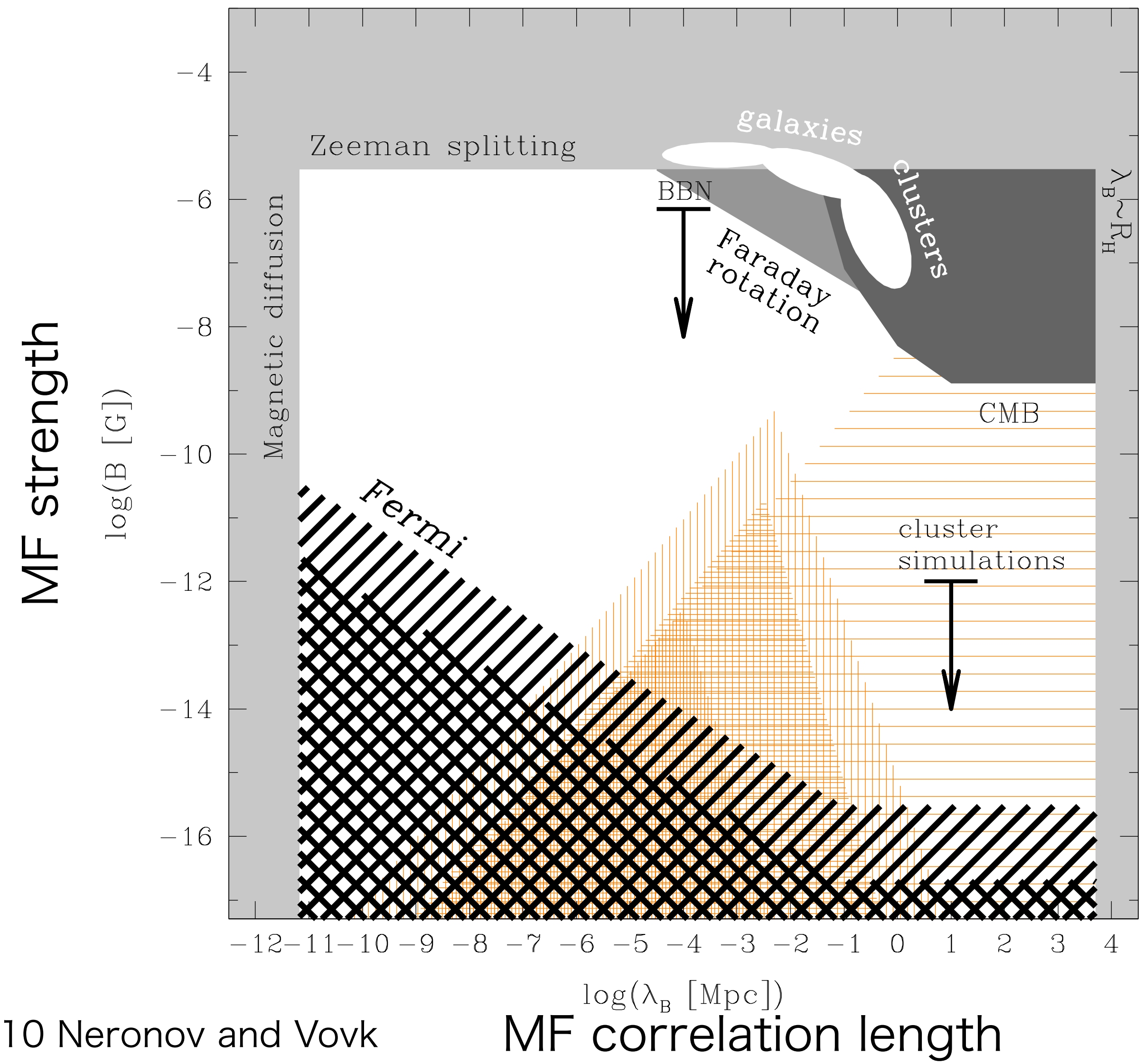
Constraints on the magnetic fields



'10 Neronov and Vovk

Courtesy H.Oide

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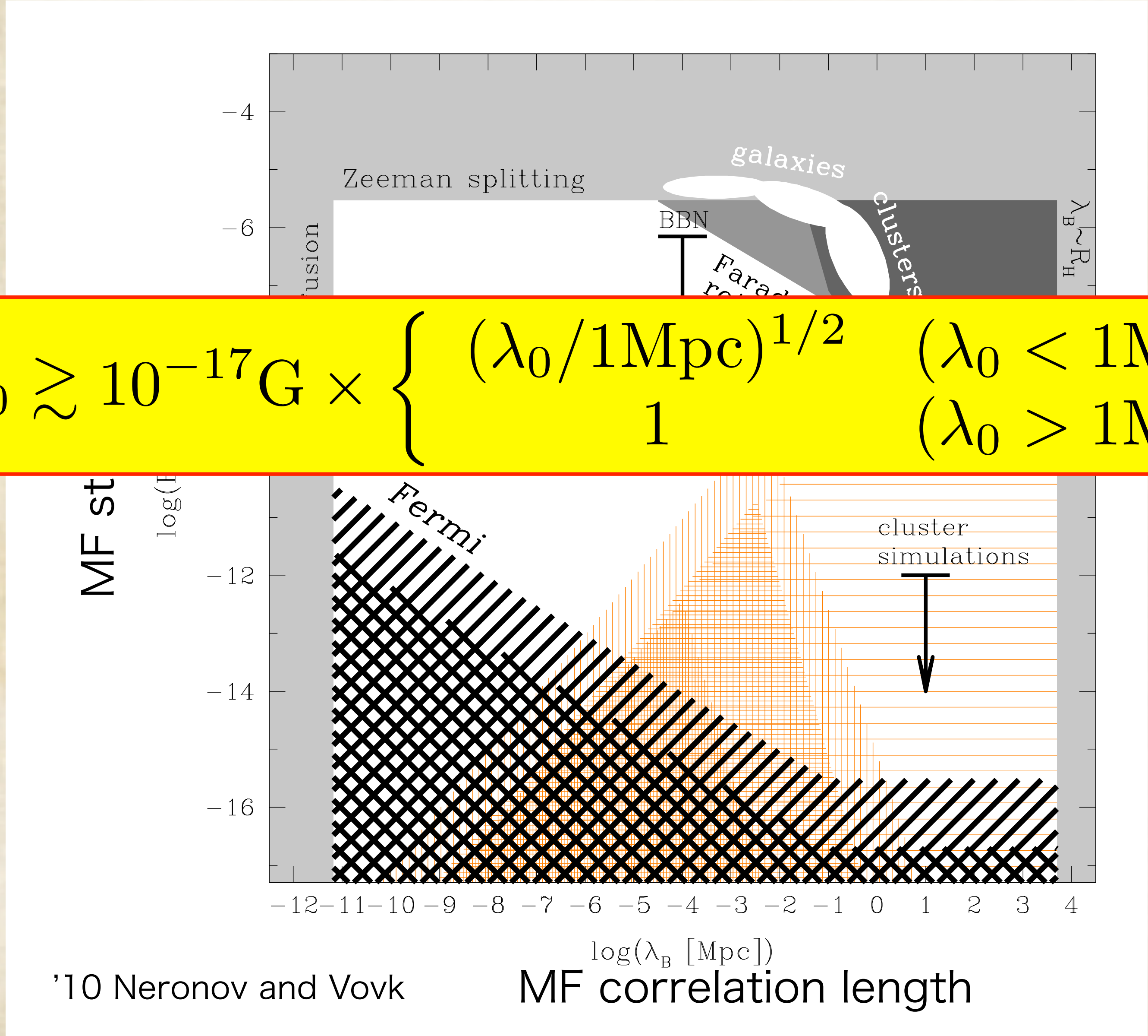

$$B_0 \gtrsim 10^{-17}\mathrm{G} \times \begin{cases} (\lambda_0/1\mathrm{Mpc})^{1/2} & (\lambda_0 < 1\mathrm{Mpc}) \\ 1 & (\lambda_0 > 1\mathrm{Mpc}) \end{cases}$$

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If we believe the existence of such MFs,
they are likely originated from very early Universe.

What kind of feature do they have in the Early Universe?
Especially before the electroweak phase transition (EWPT)?

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If we believe the existence of such MFs,
they are likely originated from very early Universe.

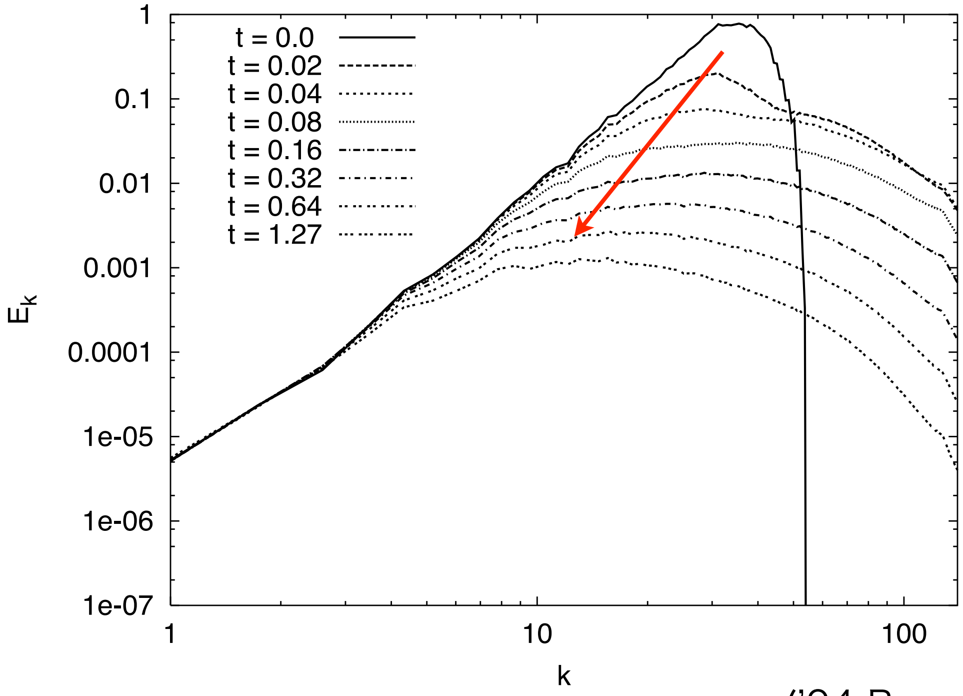
What kind of feature do they have in the Early Universe?
Especially before the electroweak phase transition (EWPT)?

They interact with turbulent plasma nontrivially and evolve following complicated magnetohydro dynamics (MHD) equations.

→ need MHD simulations

Courtesy H.Oide

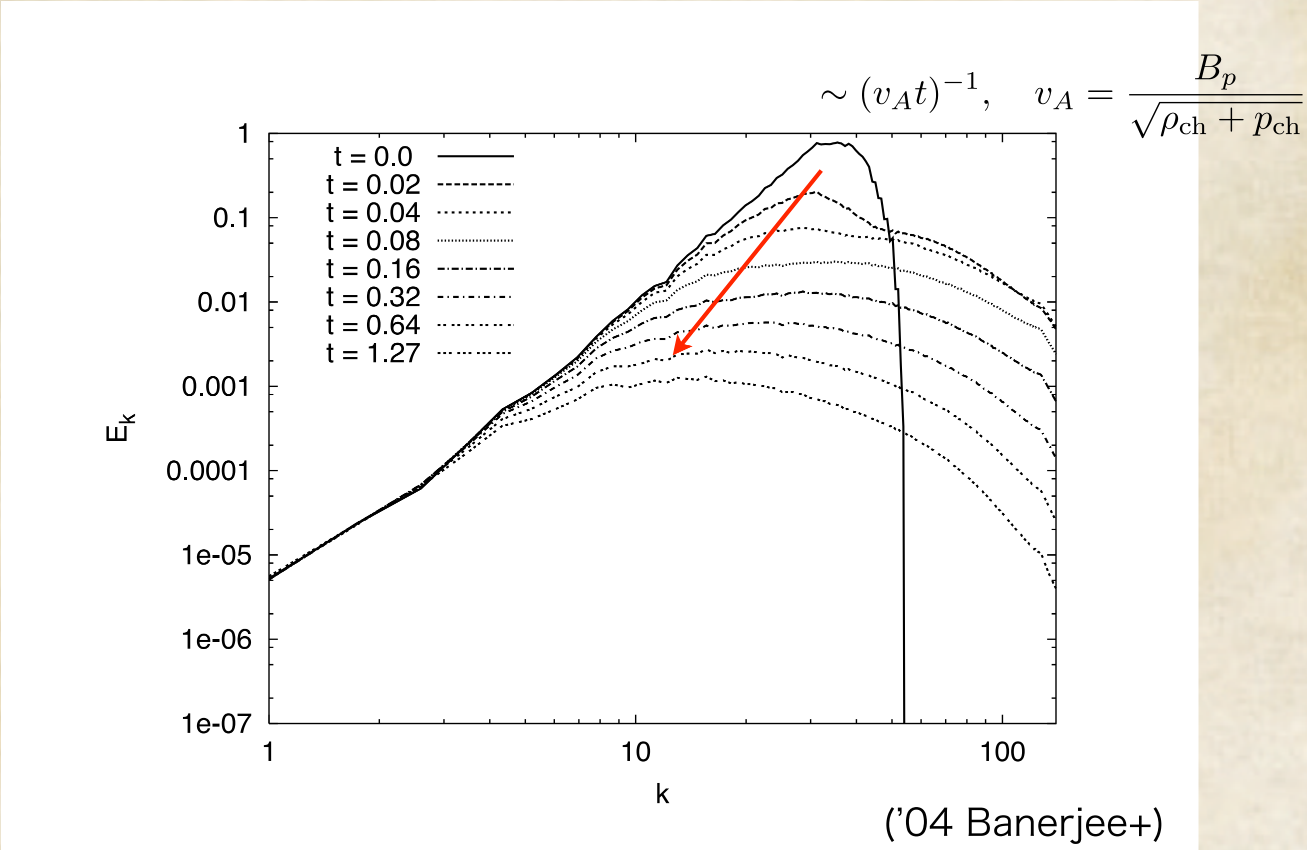
MHD simulation tells...



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

('04 Banerjee+)

MHD simulation tells...



small scale structure is erased by charged plasma and energy of MFs is easily deprived.

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MFs produced by a causal process will stay at:

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

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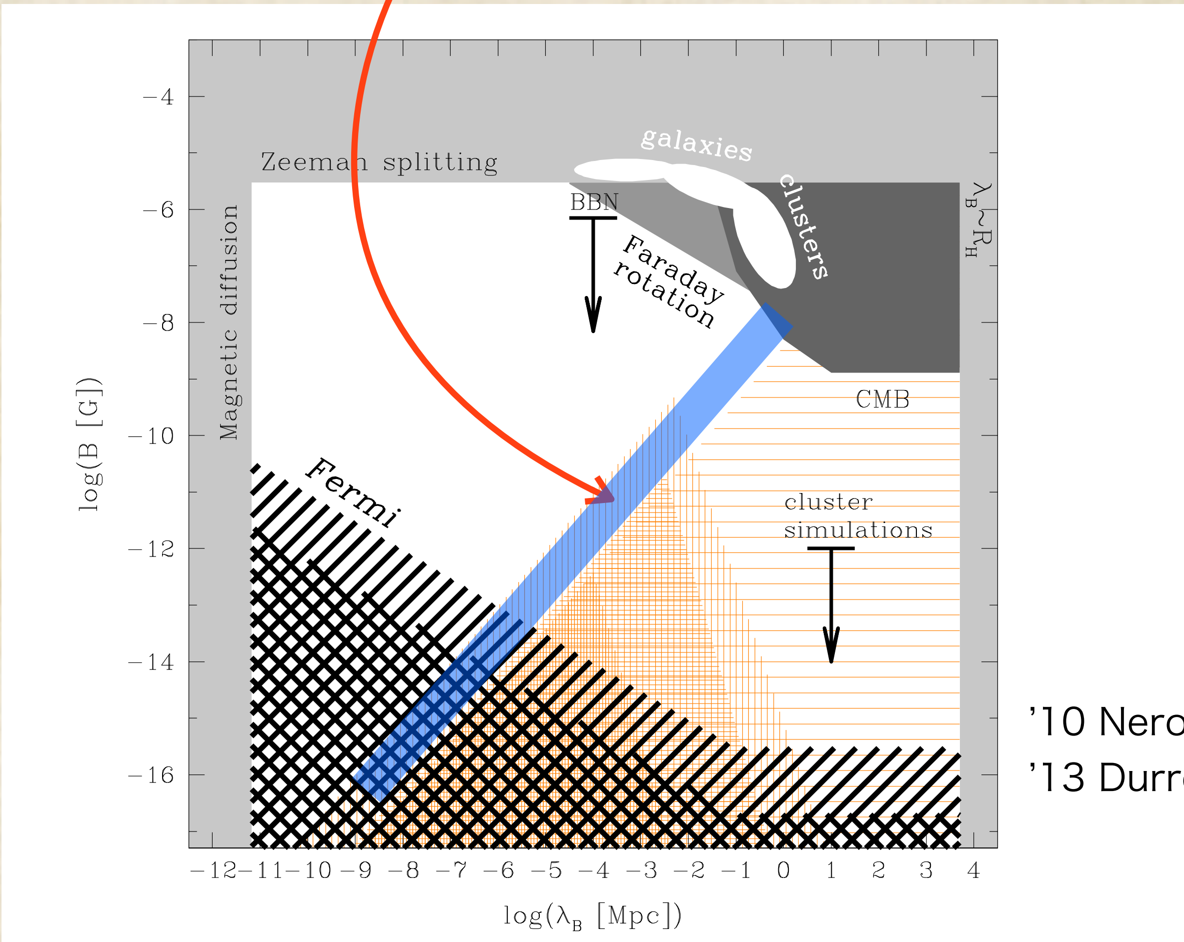

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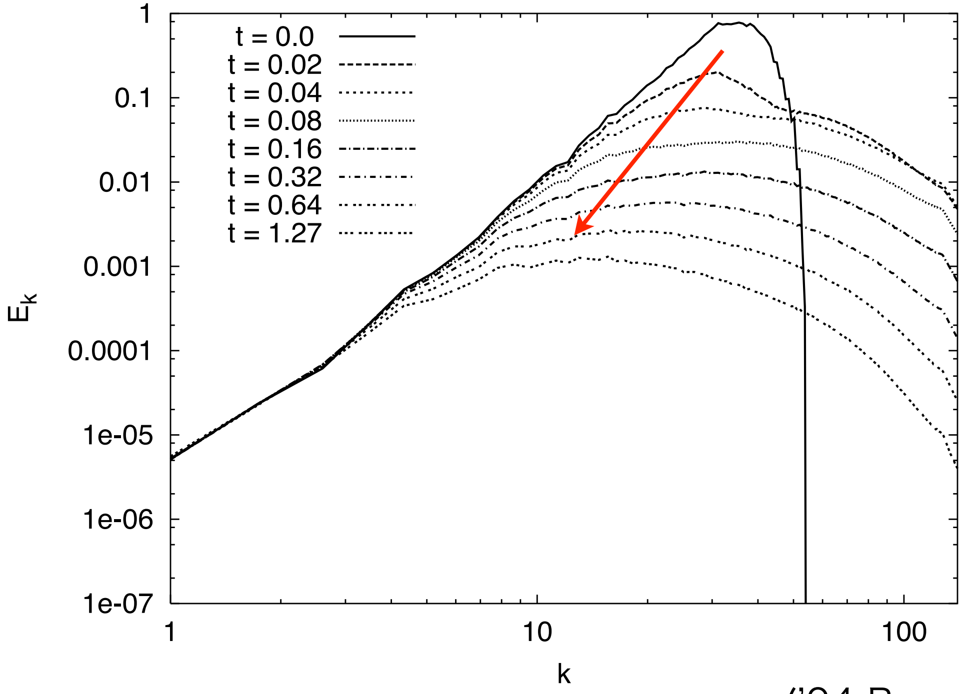

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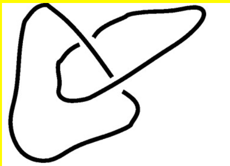
small scale structure is erased by charged plasma and energy of MFs is easily deprived.

This is the case with non-helical MFs.

Courtesy H.Oide

Helicity of MFs

$$\mathcal{H} \equiv \int_V d^3x \mathbf{A}\cdot\mathbf{B} \quad \text{or} \quad h \equiv \frac{1}{V}\int_V d^3x \mathbf{A}\cdot\mathbf{B}$$



Expanding A_i w.r.t. helicity eigenstate,

$$A_i(t,\mathbf{x}) = \sum_{\pm}\int \frac{\mathrm{d}^3k}{(2\pi)^3} e^{i\mathbf{k}\cdot\mathbf{x}} e_i^{(\pm)}(\hat{\mathbf{k}}) \left[a_{\mathbf{k}}^{(\pm)}\mathcal{A}_{(\pm)}(k,t) + a_{-\mathbf{k}}^{(\pm)\dagger}\mathcal{A}_{(\pm)}^*(k,t)\right]$$

$$\Rightarrow \quad h = \int \frac{\mathrm{d}^3k}{(2\pi)^3} k\left(|\mathcal{A}_+|^2 - |\mathcal{A}_-|^2\right).$$

$$\simeq \pm a^3 \lambda_B B_p^2$$

Courtesy H.Oide

Helicity (density) is a good conserved quantity for large electric conductivity.

$$\dot{h} = -a^2 \frac{2}{\sigma} \langle \mathbf{B} \cdot \nabla \times \mathbf{B} \rangle \simeq -a^3 \frac{4\pi}{\sigma} \frac{B_p^2}{\lambda_B}$$

(Assumed $h > 0$)

For thermal plasma with charged particles:

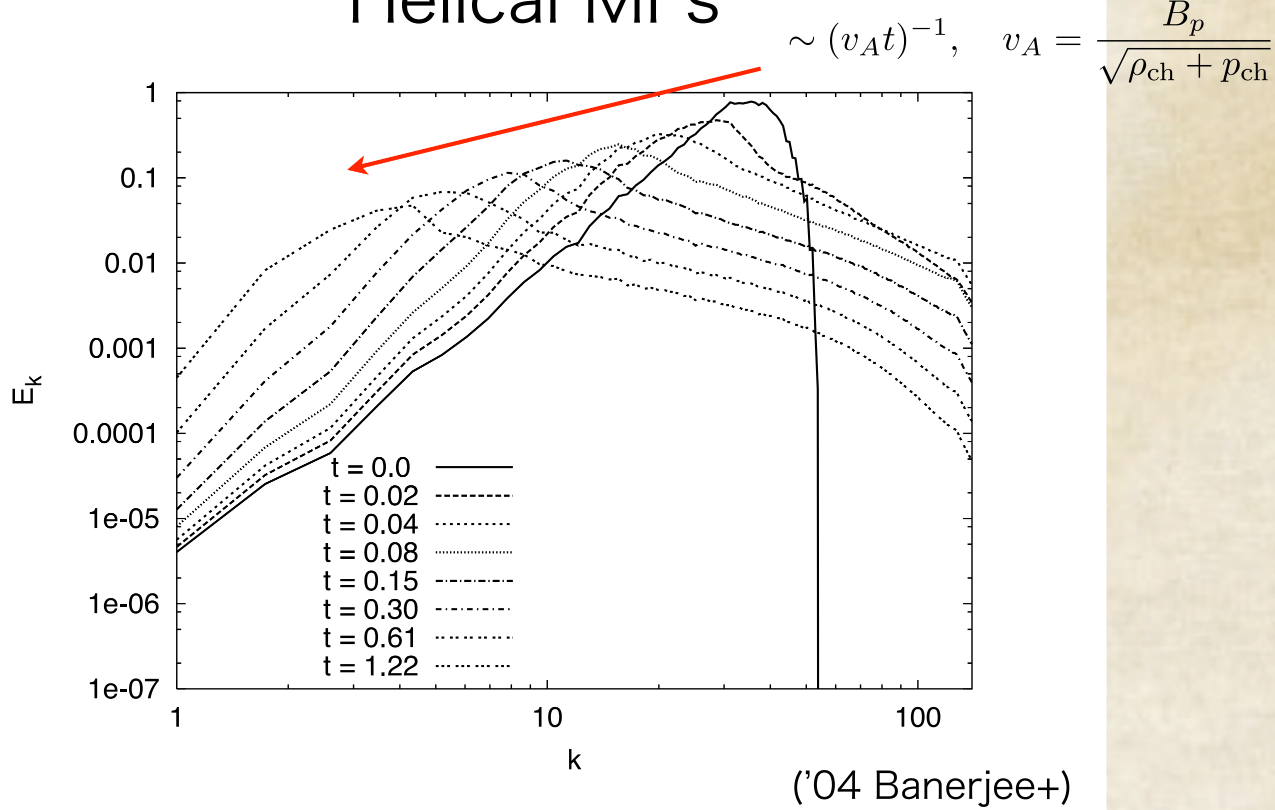
$$\sigma \simeq 100T$$ ('97 Baym+)

Large electric conductivity prevents MFs' helicity from decaying.

$h \simeq \pm a^3 \lambda_B B_p^2$ can be treated as an approximate conserved quantity.

Courtesy H.Oide

Helical MFs



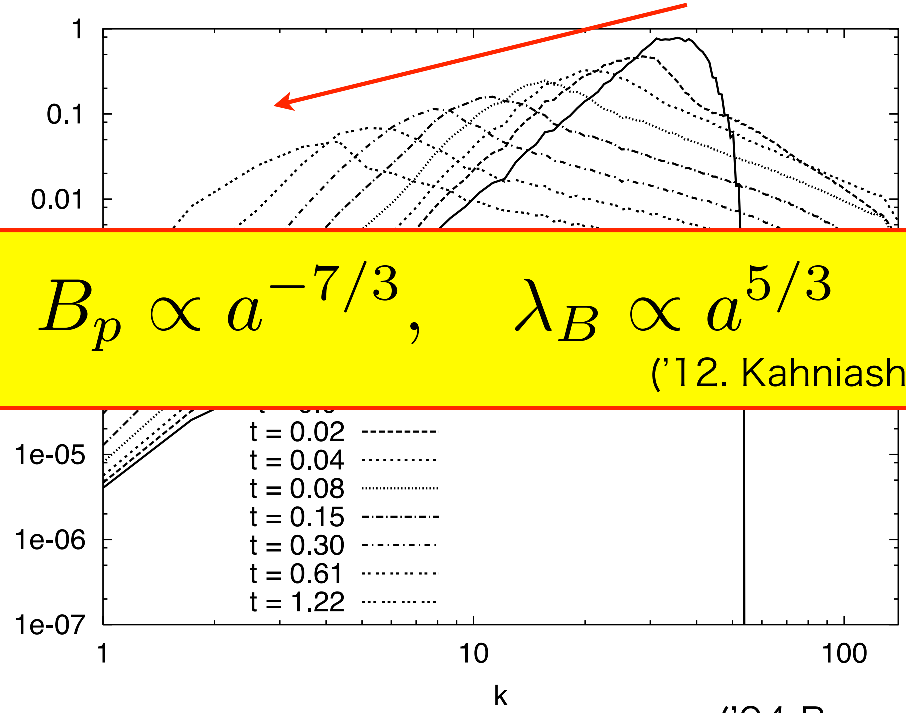
Helicity conservation leads to an enhancement of large-scale correlation of MFs: Inverse Cascade (IC)

MF decay is slower.

Courtesy H.Oide

Helical MFs

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



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

('12. Kahniashvili+)

('04 Banerjee+)

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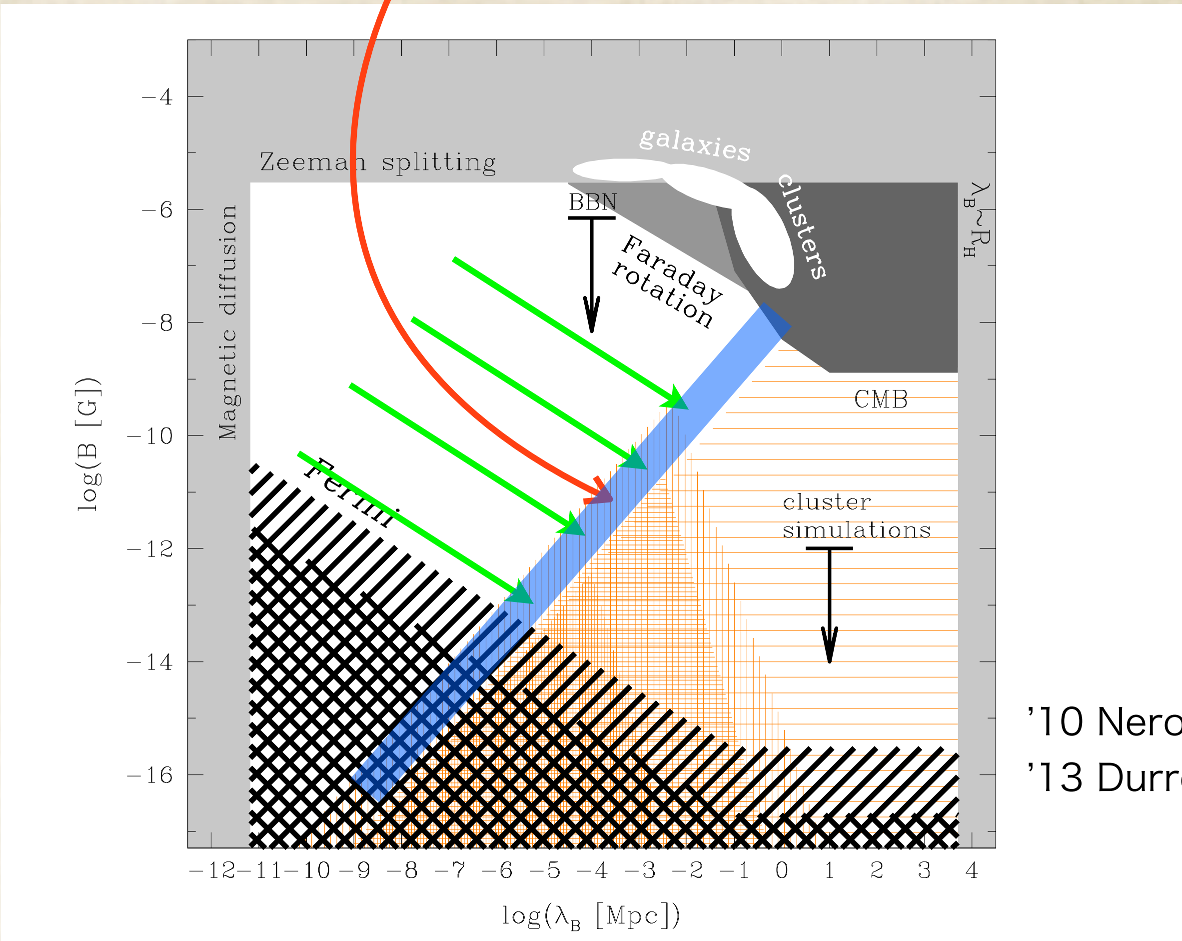

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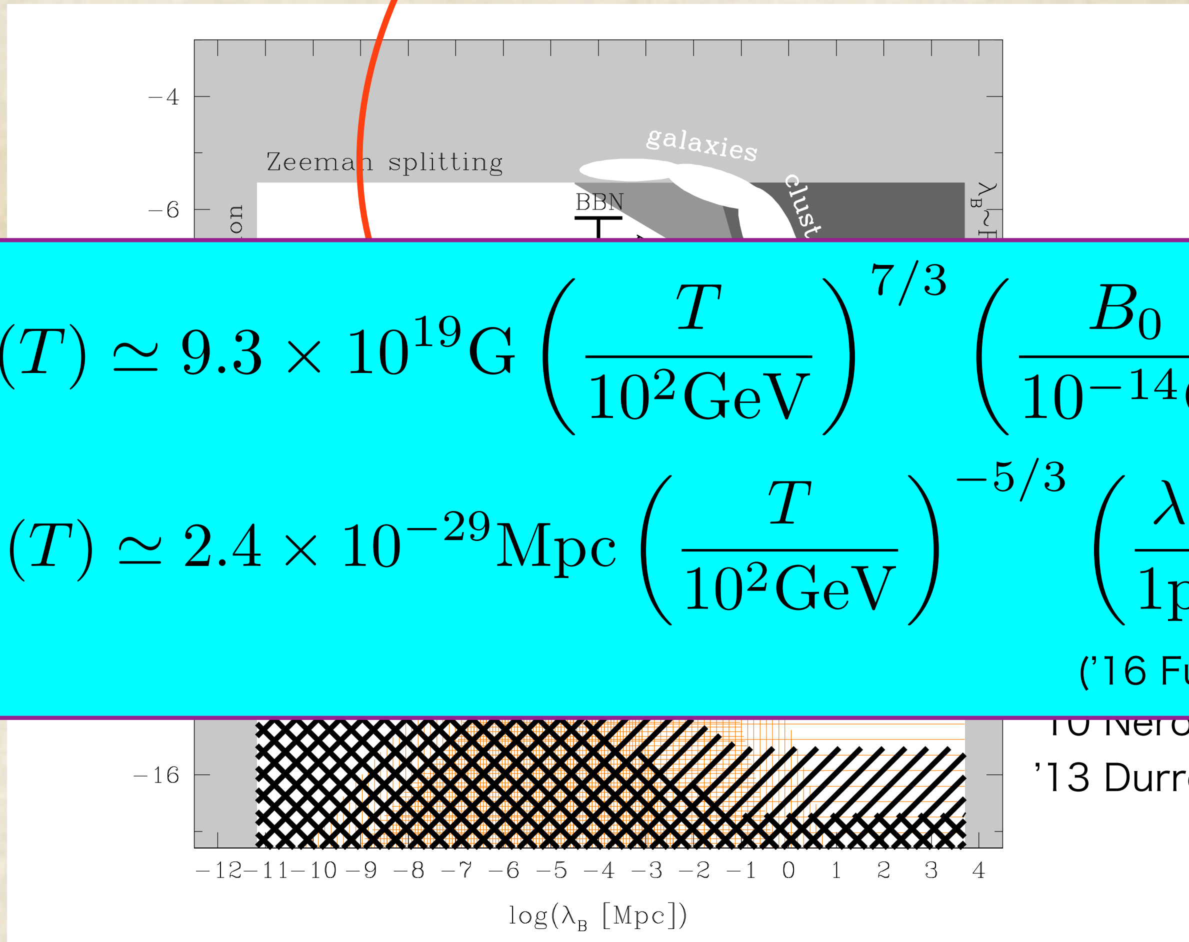

$$B_p(T) \simeq 9.3 \times 10^{19}\mathrm{G}\left(\frac{T}{10^2\mathrm{GeV}}\right)^{7/3}\left(\frac{B_0}{10^{-14}\mathrm{G}}\right)$$

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

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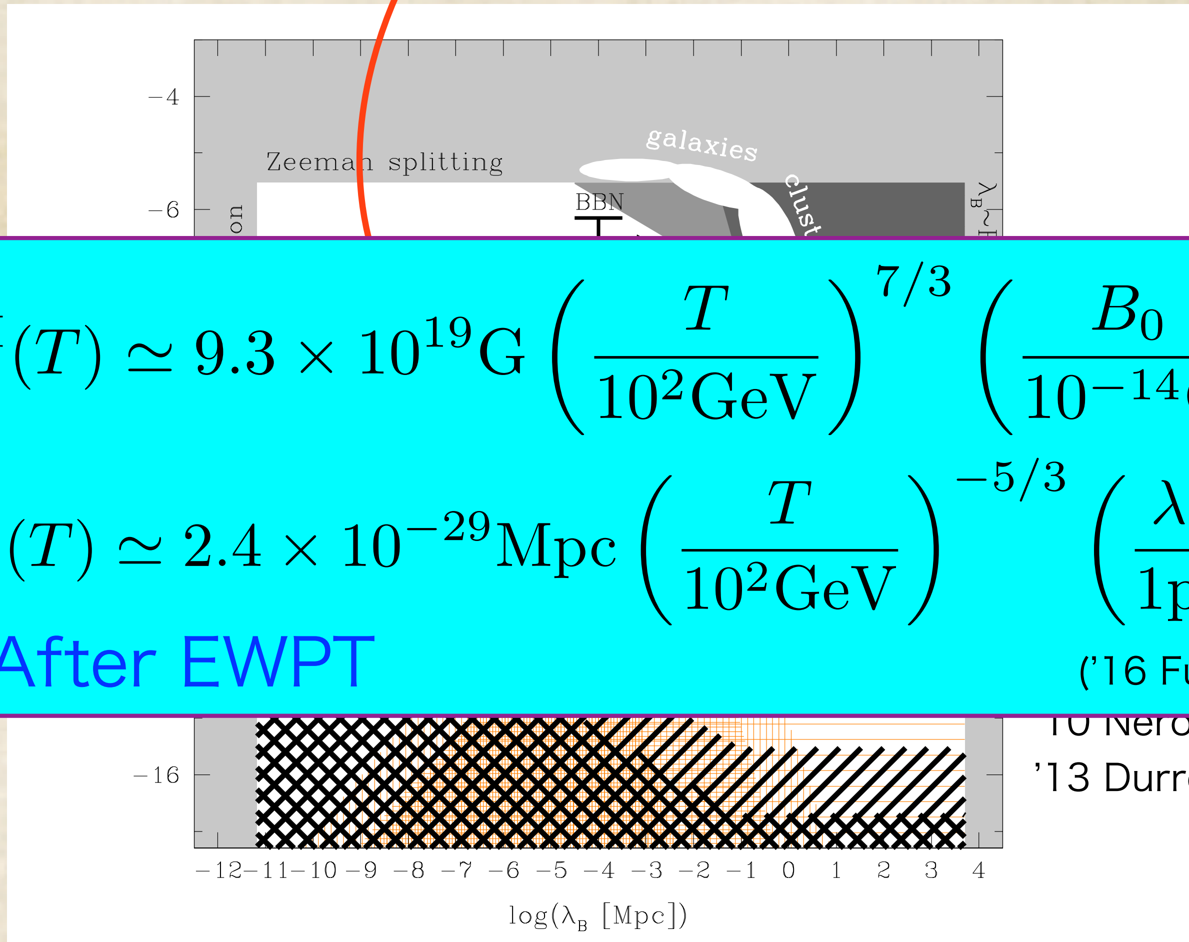

$$B_p^{\mathrm{EM}}(T) \simeq 9.3 \times 10^{19}\mathrm{G}\left(\frac{T}{10^2\mathrm{GeV}}\right)^{7/3}\left(\frac{B_0}{10^{-14}\mathrm{G}}\right)$$

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After EWPT

('16 Fujita+)

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Before and after EWPT

…originally hypermagnetic fields turn to magnetic fields associated with Z-boson part decay

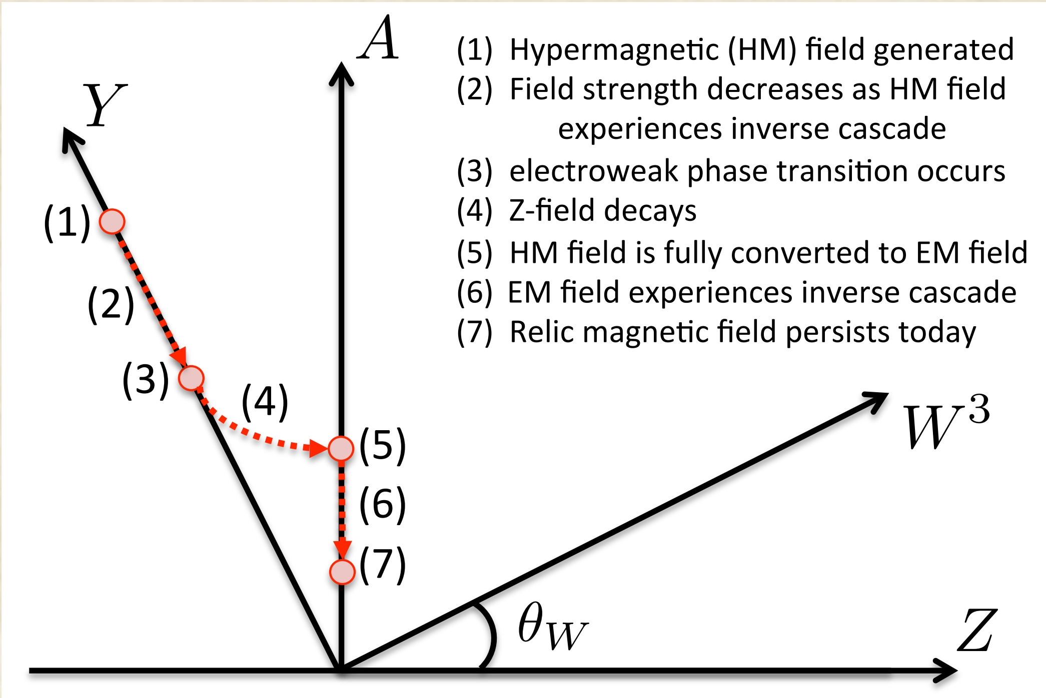

Figure 1: A cartoon of the Z-decay, which is modeled in this section.

Courtesy H.Oide

Before and after EWPT

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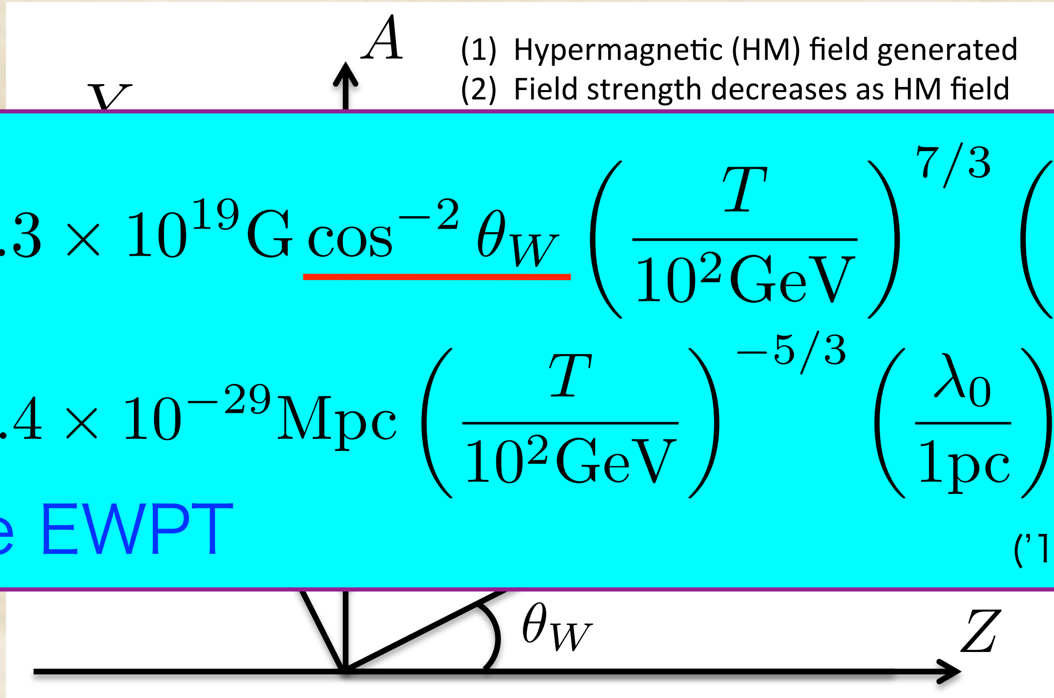

$$B_p^Y(T) \simeq 9.3 \times 10^{19}\mathrm{G}\,\underline{\cos^{-2}\theta_W} \left(\frac{T}{10^2\mathrm{GeV}}\right)^{7/3} \left(\frac{B_0}{10^{-14}\mathrm{G}}\right)$$

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

Before EWPT

('16 Fujita+, KK+)

Figure 1: A cartoon of the Z-decay, which is modeled in this section.

Courtesy H.Oide

What is the origin of such MFs (magnetogenesis)?

Related to inflation?

e.g. '88 Turner+, '06 Anber+, '09 Demozzi+, '12 Bernaby+, '14 Ferreira+,'15 Fujita+,...

Phase transition? e.g. '89 Vachaspati, '89 Quashnock+, '97 Sigl+,...

at present there are no satisfactory models.

But see '16 Fujita+
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Axionic coupling of pseudoscalar?

$$\frac{\alpha}{8\pi} C_{\alpha\gamma} \frac{a}{f_a} F^{\mu\nu} \tilde{F}_{\mu\nu}$$

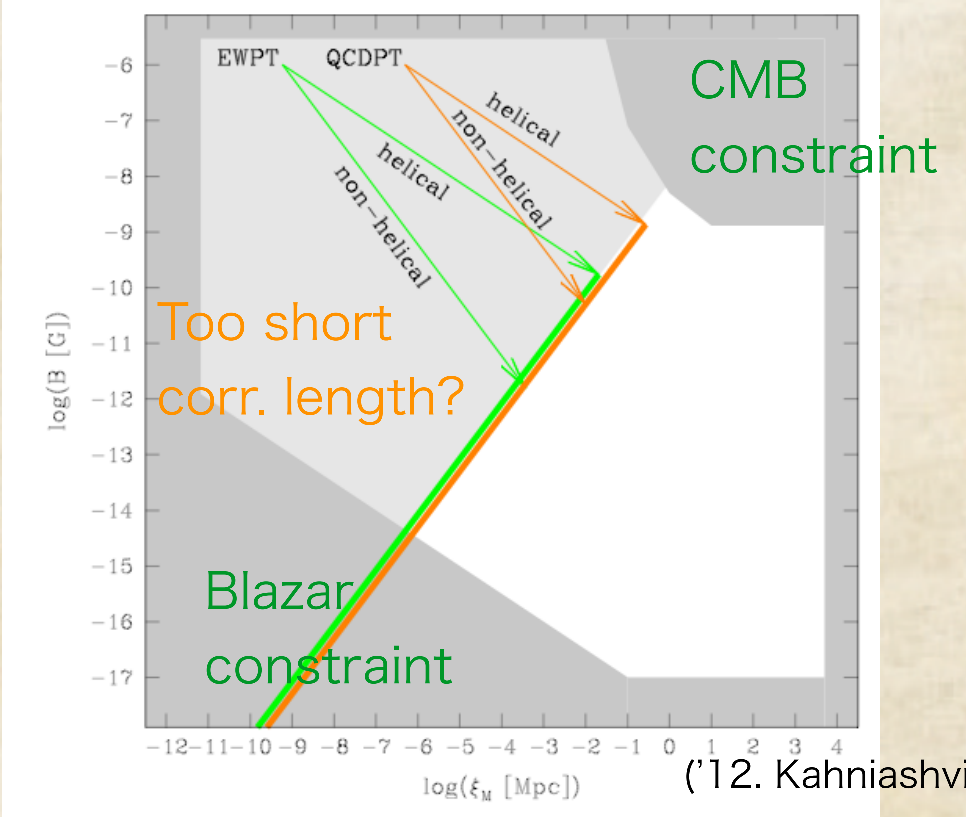
Chiral asymmetry induced by bubbles from 1st order PT?

$$\Delta n_5 = \# \Delta \mathcal{H} + \# \Delta \mathcal{N}_{\rm CS}$$

Or other mechanism???

Courtesy H.Oide

Here I do NOT pursue model buildings.
But give a “sweet spot” of the parameter space,
not specifying their origin.



('12. Kahniashvili+)

The hint is baryogenesis.

Courtesy H.Oide

Baryon asymmetry of the Universe (BAU)

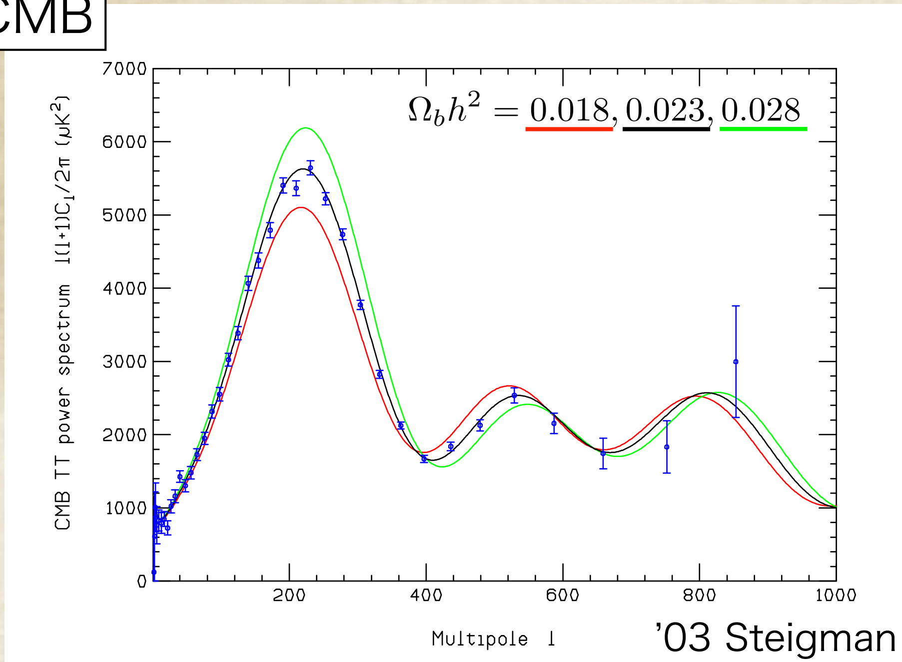
Courtesy H.Oide

- We live in a matter-antimatter asymmetric Universe.

Courtesy H.Oide

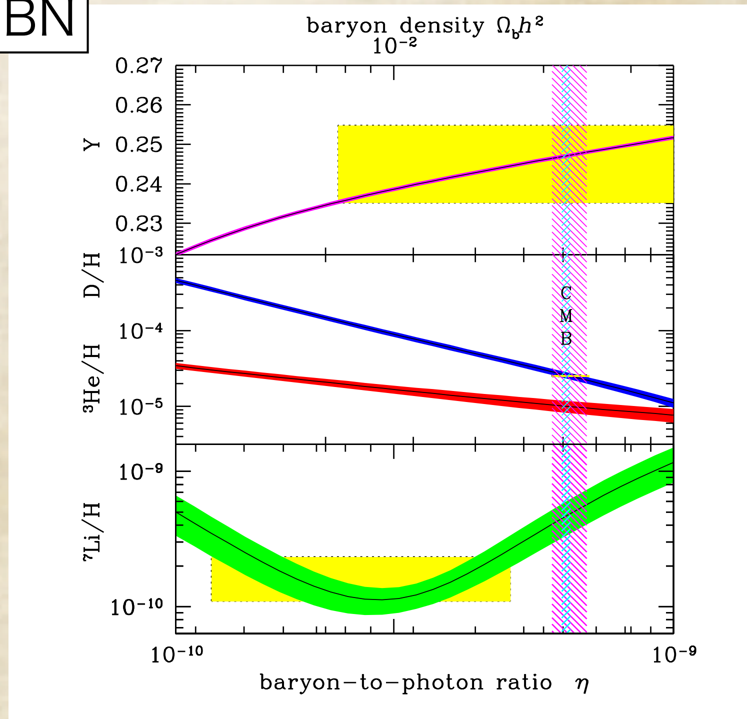
- We live in a matter-antimatter asymmetric Universe.
- BBN and CMB can evaluate it quantitatively.

CMB



'03 Steigman

BBN



Particle Data Group 2015

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

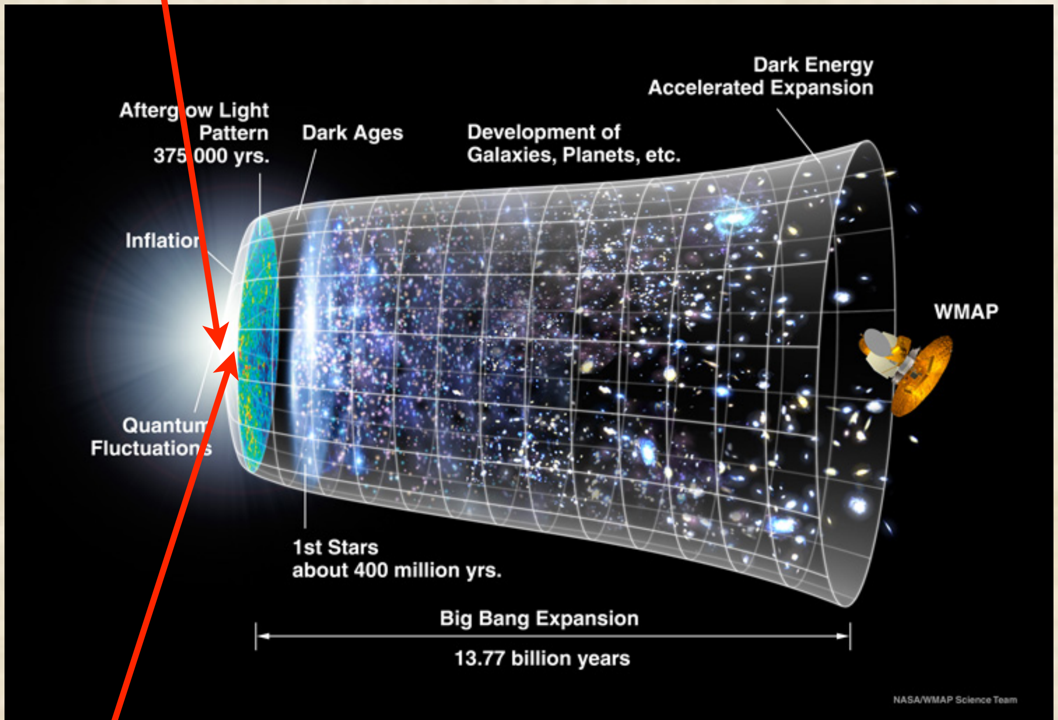
(Planck 2015)

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

BBN+D ; '15 Cyburt+

Courtesy H.Oide

Inflation dilutes the preexisting asymmetry.



WMAP team

After inflation before BBN, asymmetry must be generated.

matter :	~10000000000+1	annihilation	matter :	~1
anti matter :	~10000000000	$\longrightarrow$	anti matter :	~0
photon :	~10000000000	$T \sim 100$MeV	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

Courtesy H.Oide

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1. B-violation
2. C & CP-violation
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BSM is required!?

- Leptogenesis ('85 Fukigita&Yanagida) : RH neutrinos
- Affleck-Dine ('85 Affleck&Dine) : SUSY with $\cancel{B}$ and $\cancel{CP}$ op.
- EW baryogenesis ('85 Kuzmin, Rubakov&Shaposhnikov) : 1st order EWPT + $\cancel{CP}$ op.

Courtesy H.Oide

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

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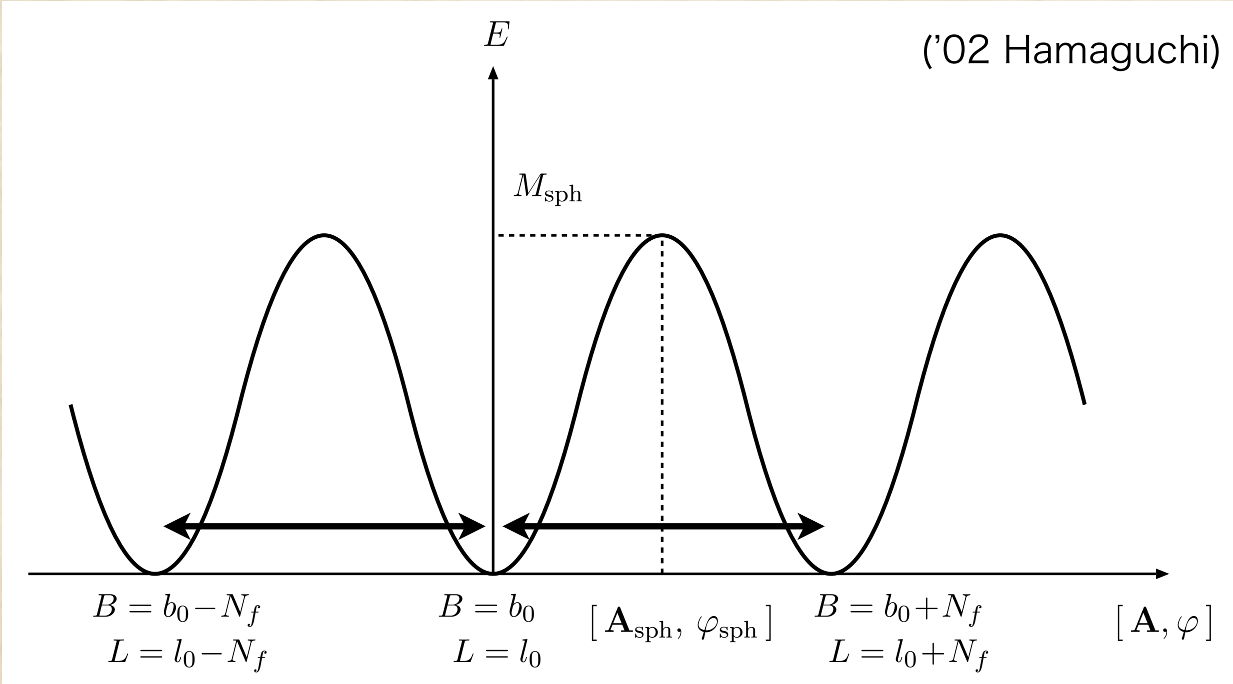


Chiral anomaly in SM $\boxed{\nabla_\mu j^\mu_f \propto \frac{\alpha}{8\pi} \mathrm{Tr} W_{\mu\nu} \tilde{W}^{\mu\nu}}$ breaks B and L

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

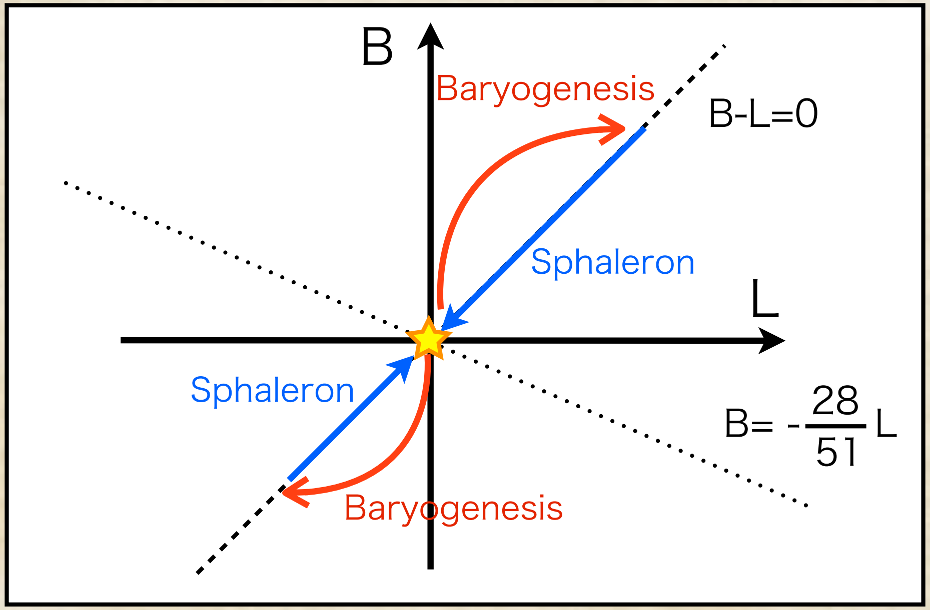
Courtesy H.Oide

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

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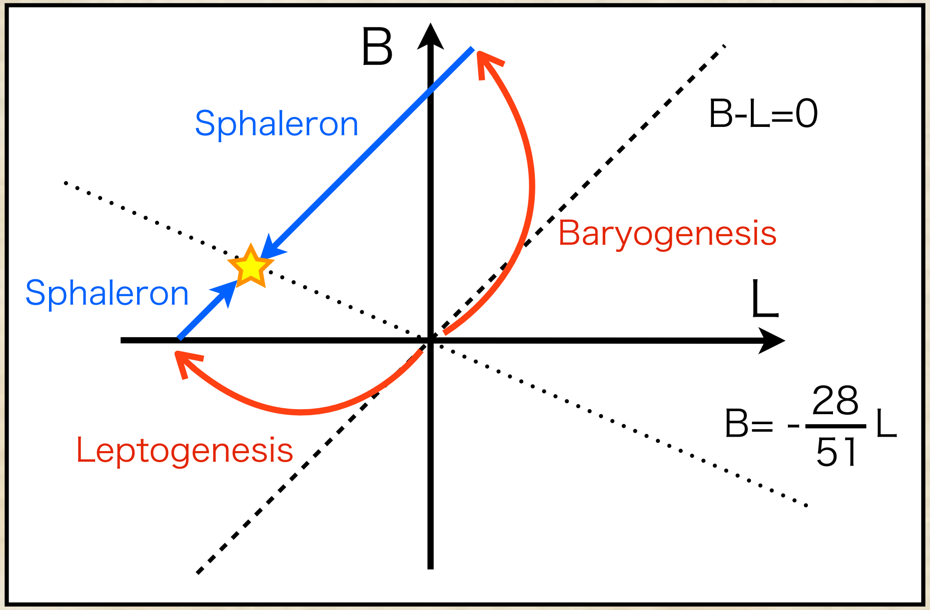

Successful BAU
<-> B-L genesis.

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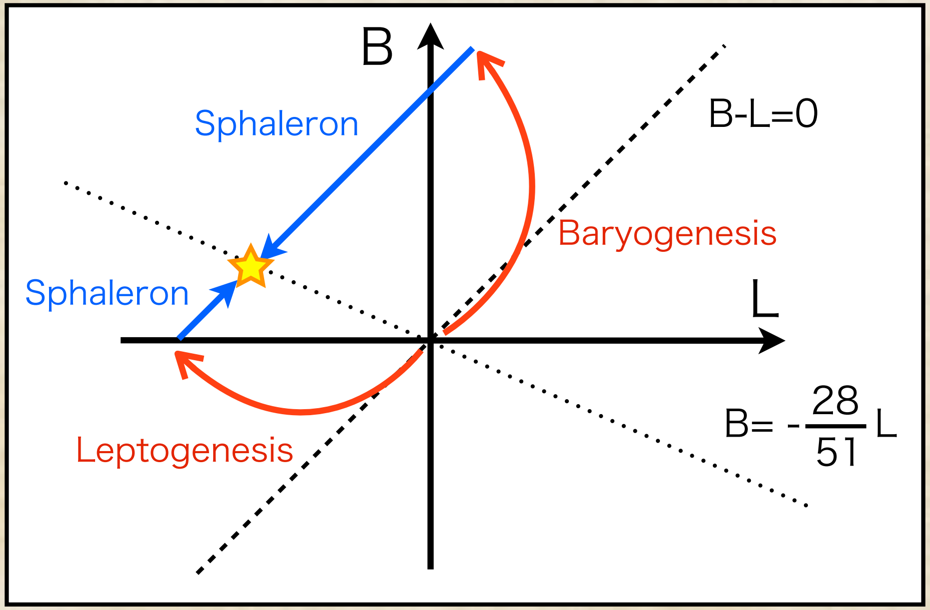

Successful BAU <-> B-L genesis.

It is often considered that...

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

Courtesy H.Oide

Baryogenesis from helical MFs

Courtesy H.Oide

(hyper)MFs and $U(1)_{Y/EM}$ charged chiral fermions interact in two ways.

Courtesy H.Oide

(hyper)MFs and $U(1)_{Y/EM}$ charged chiral fermions interact in two ways.

- chiral anomaly ('76 't Hooft)
- chiral magnetic effect (CME) ('80 Vilenkin)

Courtesy H.Oide

Full chiral anomaly in SM

U(1)Y SU(2)L SU(3)C

$$\nabla_\mu j_f^\mu = C_{\rm y}^f \frac{\alpha_{\rm y}}{4\pi} Y_{\mu\nu}\tilde{Y}^{\mu\nu} + C_{\rm w}^f \frac{\alpha_{\rm w}}{8\pi} {\rm Tr} W_{\mu\nu}\tilde{W}^{\mu\nu} + C_{\rm s}^f \frac{\alpha_{\rm s}}{8\pi} {\rm Tr} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

Courtesy H.Oide

Full chiral anomaly in SM

$$\nabla_\mu j_f^\mu = \overbrace{C_{\mathrm{y}}^f \frac{\alpha_{\mathrm{y}}}{4\pi} Y_{\mu\nu}\tilde{Y}^{\mu\nu}}^{\boxed{\mathrm{U(1)_Y}}} + \overbrace{C_{\mathrm{w}}^f \frac{\alpha_{\mathrm{w}}}{8\pi} \mathrm{Tr} W_{\mu\nu}\tilde{W}^{\mu\nu}}^{\boxed{\mathrm{SU(2)_L}}} + \overbrace{C_{\mathrm{s}}^f \frac{\alpha_{\mathrm{s}}}{8\pi} \mathrm{Tr} G_{\mu\nu}\tilde{G}^{\mu\nu}}^{\boxed{\mathrm{SU(3)_C}}}$$

EW sphaleron (~~B+L~~)

Courtesy H.Oide

Full chiral anomaly in SM

$$\nabla_\mu j^\mu_f = \overbrace{C^f_{\rm y}\frac{\alpha_{\rm y}}{4\pi}Y_{\mu\nu}\tilde{Y}^{\mu\nu}}^{\boxed{\mathrm{U(1)_Y}}} + \overbrace{C^f_{\rm w}\frac{\alpha_{\rm w}}{8\pi}{\rm Tr}W_{\mu\nu}\tilde{W}^{\mu\nu}}^{\boxed{\mathrm{SU(2)_L}}} + \overbrace{C^f_{\rm s}\frac{\alpha_{\rm s}}{8\pi}{\rm Tr}G_{\mu\nu}\tilde{G}^{\mu\nu}}^{\boxed{\mathrm{SU(3)_C}}}$$

EW sphaleron (~~B+L~~)

Strong sphaleron (B, L)

Courtesy H.Oide

Full chiral anomaly in SM

U(1)$_{\mathrm{Y}}$ SU(2)$_{\mathrm{L}}$ SU(3)$_{\mathrm{C}}$

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? EW sphaleron (~~B+L~~) Strong sphaleron (B, L)

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$\mathrm{U(1)}_{\mathrm{Y}}$ $\mathrm{SU(2)}_{\mathrm{L}}$ $\mathrm{SU(3)}_{\mathrm{C}}$

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Trivial vacuum structure: EW sphaleron (~~B+L~~) Strong sphaleron (B, L)

Courtesy H.Oide

Full chiral anomaly in SM

$$\nabla_\mu j_f^\mu = C_{\rm y}^f \frac{\alpha_{\rm y}}{4\pi} \underbrace{Y_{\mu\nu}\tilde{Y}^{\mu\nu}}_{\text{U(1)}_{\rm Y}} + C_{\rm w}^f \frac{\alpha_{\rm w}}{8\pi} \underbrace{{\rm Tr} W_{\mu\nu}\tilde{W}^{\mu\nu}}_{\text{SU(2)}_{\rm L}} + C_{\rm s}^f \frac{\alpha_{\rm s}}{8\pi} \underbrace{{\rm Tr} G_{\mu\nu}\tilde{G}^{\mu\nu}}_{\text{SU(3)}_{\rm C}}$$

Trivial vacuum structure: EW sphaleron ($\cancel{\text{B+L}}$) Strong sphaleron (B, L)

Nothing special happens in the vacuum

See also '16 Long&Sabancilar

Courtesy H.Oide

Full chiral anomaly in SM

U(1)$_Y$ SU(2)$_L$ SU(3)$_C$

$$\nabla_\mu j^\mu_f = C^f_{\mathrm{y}} \frac{\alpha_{\mathrm{y}}}{4\pi} Y_{\mu\nu}\tilde{Y}^{\mu\nu} + C^f_{\mathrm{w}} \frac{\alpha_{\mathrm{w}}}{8\pi} \mathrm{Tr} W_{\mu\nu}\tilde{W}^{\mu\nu} + C^f_{\mathrm{s}} \frac{\alpha_{\mathrm{s}}}{8\pi} \mathrm{Tr} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

Trivial vacuum structure: EW sphaleron (~~B+L~~) Strong sphaleron (B, L)

Situation will change
for nonvanishing BG hyperfield

Courtesy H.Oide

Full chiral anomaly in SM

U(1)Y SU(2)L SU(3)c

$$\nabla_\mu j_f^\mu = C_{\rm y}^f \frac{\alpha_{\rm y}}{4\pi} Y_{\mu\nu}\tilde{Y}^{\mu\nu} + C_{\rm w}^f \frac{\alpha_{\rm w}}{8\pi} {\rm Tr} W_{\mu\nu}\tilde{W}^{\mu\nu} + C_{\rm s}^f \frac{\alpha_{\rm s}}{8\pi} {\rm Tr} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

Trivial vacuum structure: EW sphaleron (~~B+L~~) Strong sphaleron (B, L)

Situation will change
for nonvanishing BG hyperfield

Note that: $$\int_V d^3x Y_{\mu\nu}\tilde{Y}^{\mu\nu} = -4\int_V d^3x \mathbf{E}\cdot\mathbf{B} = -2\frac{d}{dt}\mathcal{H}$$

- If there are time-dependent helical hypermagnetic fields,
it will affect the fermion number density.

Courtesy H.Oide

Full chiral anomaly in SM

U(1)Y SU(2)L SU(3)C

$$\nabla_\mu j_f^\mu = C_{\rm y}^f \frac{\alpha_{\rm y}}{4\pi} Y_{\mu\nu}\tilde{Y}^{\mu\nu} + C_{\rm w}^f \frac{\alpha_{\rm w}}{8\pi} {\rm Tr} W_{\mu\nu}\tilde{W}^{\mu\nu} + C_{\rm s}^f \frac{\alpha_{\rm s}}{8\pi} {\rm Tr} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

Trivial vacuum structure: EW sphaleron (~~B+L~~) Strong sphaleron (B, L)

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- This is another source of ~~B+L~~!!!

'98 Giovanninni & Shaposhnikov

Courtesy H.Oide

Full chiral anomaly in SM

U(1)Y SU(2)L SU(3)C

$$\nabla_\mu j^\mu_f = C^f_{\mathrm{y}} \frac{\alpha_{\mathrm{y}}}{4\pi} Y_{\mu\nu}\tilde{Y}^{\mu\nu} + C^f_{\mathrm{w}} \frac{\alpha_{\mathrm{w}}}{8\pi}\mathrm{Tr} W_{\mu\nu}\tilde{W}^{\mu\nu} + C^f_{\mathrm{s}}\frac{\alpha_{\mathrm{s}}}{8\pi}\mathrm{Tr}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

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- If there are time-dependent helical hypermagnetic fields, it will affect the fermion number density.
- This is another source of ~~B+L~~!!!

'98 Giovanninni & Shaposhnikov

\# Both ~~B+L~~ processes (sphalerons and U(1)Y anomaly) are active until EWPT.

Courtesy H.Oide

Full chiral anomaly in SM

U(1)$_\mathrm{Y}$ SU(2)$_\mathrm{L}$ SU(3)$_\mathrm{C}$

$$\nabla_\mu j_f^\mu = C_\mathrm{y}^f \frac{\alpha_\mathrm{y}}{4\pi} Y_{\mu\nu}\tilde{Y}^{\mu\nu} + C_\mathrm{w}^f \frac{\alpha_\mathrm{w}}{8\pi} \mathrm{Tr} W_{\mu\nu}\tilde{W}^{\mu\nu} + C_\mathrm{s}^f \frac{\alpha_\mathrm{s}}{8\pi} \mathrm{Tr} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

Trivial vacuum structure: EW sphaleron (~~B+L~~) Strong sphaleron (B, L)

Situation will change
for nonvanishing BG hyperfield

Note that: $$\int_V d^3x Y_{\mu\nu}\tilde{Y}^{\mu\nu} = -4 \int_V d^3x \mathbf{E}\cdot\mathbf{B} = -2\frac{d}{dt}\mathcal{H}$$

- If there are time-dependent helical hypermagnetic fields,

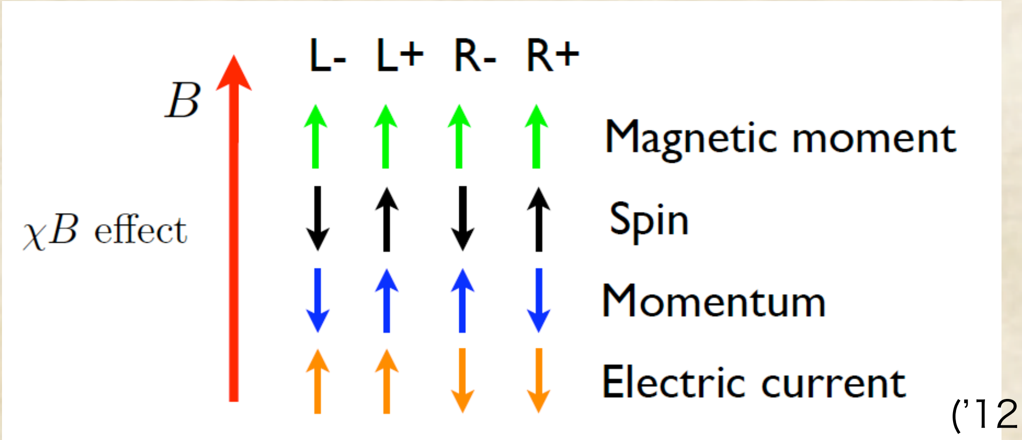
$$\frac{dn_f}{dt} = -C_\mathrm{y}^f \frac{\alpha_\mathrm{y}}{\pi}\langle \mathbf{E}^Y \cdot \mathbf{B}^Y \rangle \Rightarrow \frac{dn_B}{dt} \propto \frac{\alpha_\mathrm{y}}{4\pi}\langle \mathbf{E}^Y \cdot \mathbf{B}^Y \rangle$$

nikov

are active until EWPT.

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.

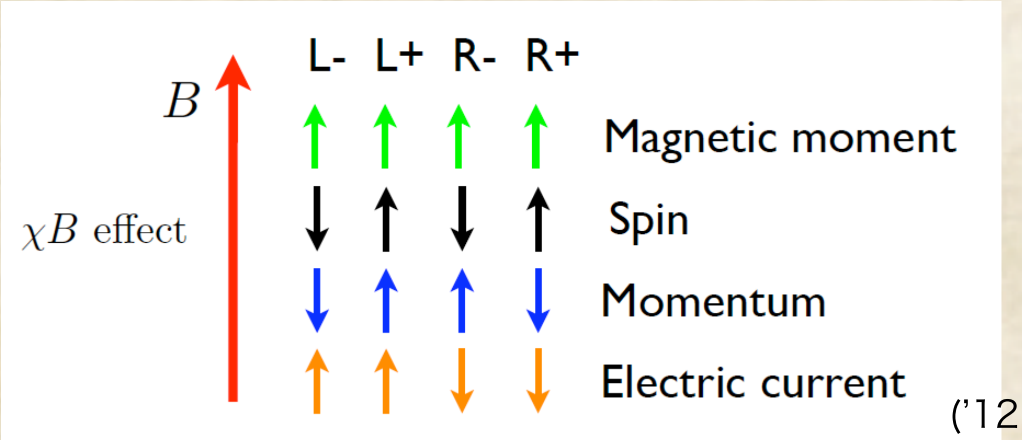
Electric current proportional to the chiral asymmetry is induced: $$\boldsymbol{j}_{\mathrm{CME}} = \frac{2}{\pi}\alpha\mu_5 \boldsymbol{B}$$

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

(See also '14 Long, Sabancilar and Vachaspati)

Courtesy H.Oide

Chiral Magnetic Effect (CME) ('80 Vilenkin)



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(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

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

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

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

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

Courtesy H.Oide

Kinetic equations

$$x \equiv T/H$$

$$\eta_f = n_f/s$$

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

$$\vdots$$

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

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

Kinetic equations

$$x \equiv T/H$$

$$\eta_f = n_f/s$$

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

$$\vdots$$

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

Kinetic equations

$$x \equiv T/H$$

$$\eta_f = n_f/s$$

$$\begin{aligned}
\frac{\partial \eta_{u_L^i}}{\partial x} =& - N_\mathrm{c} q_Q^2 (\gamma_\mathrm{y} - \gamma_\mathrm{y}^\mathrm{CME} \mu_5^Y) - N_\mathrm{c} \frac{\gamma_\mathrm{w}}{2} \sum_j (\eta_{u_L^j} + \eta_{d_L^j} + \eta_{e_L^j} + \eta_{\nu_L^j}) - \frac{\gamma_\mathrm{s}}{2} \sum_j (\eta_{u_L^j} + \eta_{d_L^j} - \eta_{u^j} - \eta_{d^j}) \\
& - \sum_j \frac{\gamma_{u^{ij}}}{2} \left(\frac{\eta_{u_L^i}}{3} + \frac{\eta_{\varphi^0}}{2} - \frac{\eta_{u_R^j}}{3} \right) - \sum_j \frac{\gamma_{d^{ij}}}{2} \left(\frac{\eta_{u_L^i}}{3} - \frac{\eta_{\varphi^+}}{2} - \frac{\eta_{d_R^j}}{3} \right) \\
& - \sum_j \gamma_{u^{ij}}^M \left(\frac{\eta_{u_L^i}}{3} - \frac{\eta_{u_R^j}}{3} \right) - \gamma_2 (\eta_{u_L^i} - \eta_{d_L^i}),
\end{aligned}$$

$$\begin{aligned}
\frac{\partial \eta_{d_L^i}}{\partial x} =& - N_\mathrm{c} q_Q^2 (\gamma_\mathrm{y} - \gamma_\mathrm{y}^\mathrm{CME} \mu_5^Y) - N_\mathrm{c} \frac{\gamma_\mathrm{w}}{2} \sum_j (\eta_{u_L^j} + \eta_{d_L^j} + \eta_{e_L^j} + \eta_{\nu_L^j}) - \frac{\gamma_\mathrm{s}}{2} \sum_j (\eta_{u_L^j} + \eta_{d_L^j} - \eta_{u^j} - \eta_{d^j}) \\
& - \sum_j \frac{\gamma_{u^{ij}}}{2} \left(\frac{\eta_{d_L^i}}{3} + \frac{\eta_{\varphi^+}}{2} - \frac{\eta_{u_R^j}}{3} \right) - \sum_j \frac{\gamma_{d^{ij}}}{2} \left(\frac{\eta_{d_L^i}}{3} - \frac{\eta_{\varphi^0}}{2} - \frac{\eta_{d_R^j}}{3} \right) \\
& - \sum_j \gamma_{d^{ij}}^M \left(\frac{\eta_{d_L^i}}{3} - \frac{\eta_{d_R^j}}{3} \right) - \gamma_2 (\eta_{d_L^i} - \eta_{u_L^i}),
\end{aligned}$$

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

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

Kinetic equations

$x \equiv T/H$

$\eta_f = n_f/s$

$$\frac{\partial \eta_{u_L^i}}{\partial x} = -N_c q_Q^2(\gamma_y - \gamma_y^{\rm CME}\mu_5^Y) - N_c \frac{\gamma_w}{2}\sum_j(\eta_{u_L^j} + \eta_{d_L^j} + \eta_{e_L^j} + \eta_{\nu_L^j}) - \frac{\gamma_s}{2}\sum_j(\eta_{u_L^j} + \eta_{d_L^j} - \eta_{u^j} - \eta_{d^j})$$

$$-\sum_j \frac{\gamma_{u^{ij}}}{2} \cdots$$

$$-\sum_j \gamma^M_{u^{ij}} \cdots$$

$\gamma_Y(x)$:Source term ⇒ BAU ↗

$\gamma_Y^{\rm CME}(x), \gamma_W(x), \gamma_u \cdots$

:Washout term ⇒ BAU ↘

$$\frac{\partial \eta_{d_L^i}}{\partial x} = -N_c q_Q^2(\gamma \cdots - \eta_{u^j} - \eta_{d^j})$$

$$-\sum_j \frac{\gamma_{u^{ij}}}{2} \cdots$$

$$-\sum_j \gamma^M_{d^{ij}}\left(\frac{\eta_{d_L^i}}{3} - \frac{\eta_{d_R^j}}{3}\right) - \gamma_2(\eta_{d_L^i} - \eta_{u_L^i}),$$

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

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

Kinetic equations

$x \equiv T/H$

$\eta_f = n_f/s$

$$\frac{\partial \eta_{u_L^i}}{\partial x} = -N \cdots - \eta_{u^j} - \eta_{d^j})$$

$$-\sum_j \cdots$$

$$-\sum_j \cdots$$

$$\frac{\partial \eta_{d_L^i}}{\partial x} = -N \cdots - \eta_{u^j} - \eta_{d^j})$$

$$-\sum_j \cdots$$

$$-\sum_j \cdots$$

Analytic solution

requiring the equilibrium of sphalerons and Yukawa interactions except for 1st gen. e_R

$\Rightarrow$ η_B, η_5^Y are expressed in terms of $\eta_{e^1_{R,L}}$

$$\frac{\partial \eta_{e_R^1}}{\partial x} \simeq 0 \Rightarrow \eta_B(x) \simeq \frac{22}{79}\frac{\gamma_Y(x)}{\gamma_Y^{\mathrm{CME}}(x) + \gamma_{e^{11}}(x)}$$

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

$$\frac{\partial \eta_{\nu_L^i}}{\partial x} = -q_L^2(\gamma_{\mathrm{y}} - \gamma_{\mathrm{y}}^{\mathrm{CME}}\mu_5^{\cdots}) - \frac{\cdots}{2}\sum_j(\eta_{u_L^j} + \eta_{d_L^j} + \eta_{e_L^j} + \eta_{\nu_L^j}) - \sum_j \frac{\cdots}{2}\left(\eta_{\nu_L^i} - \frac{\eta_{\varphi^+}}{2} - \eta_{e_R^j}\right) - \gamma_2(\eta_{\nu_L^i} - \cdots$$

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

$$\sum \cdots$$

Kinetic equations

$x \equiv T/H$

※ Sphaleron can washout asymmetries of SU(2) charged fermions only.
※ Washout is completed by CME term or electron Yukawa interaction.

$$\gamma_{e^{11}} \sim 10^{-2} h_{e^{11}}^2 \frac{m_H^2(T)}{T^2}$$

('92 Campbell+, '06 Cirigliano+)

Analytic s

requiring

Yukawa in

η_B, η_5^Y are expressed in terms of $\eta_{e^1_{R,L}}$

$$\frac{\partial \eta_{e^1_R}}{\partial x} \simeq 0 \Rightarrow \eta_B(x) \simeq \frac{22}{79} \frac{\gamma_Y(x)}{\gamma_Y^{\rm CME}(x) + \gamma_{e^{11}}(x)}$$

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

$$\frac{\partial \eta_{u^i_L}}{\partial x} = - N \cdots$$

$$\frac{\partial \eta_{d^i_L}}{\partial x} = - N \cdots - \eta_{u^j} - \eta_{d^j})$$

$$\frac{\partial \eta_{\nu^i_L}}{\partial x} = - q_L^2(\gamma_{\rm y} - \gamma_{\rm y}^{\rm CME}\mu_5^Y) - \frac{\gamma_{\rm w}}{2}\sum_j (\eta_{u^j_L} + \eta_{d^j_L} + \eta_{e^j_L} + \eta_{\nu^j_L}) - \sum_j \frac{\gamma}{2}\left(\eta_{\nu^i_L} - \frac{\eta_{\varphi^+}}{2} - \eta_{e^j_R}\right) - \gamma_2(\eta_{\nu^i_L} - \cdots$$

$$\frac{\partial \eta_{e^i_L}}{\partial x} = - q_L^2(\gamma_{\rm y} - \gamma_{\rm y}^{\rm CME}\mu_5^Y) - \frac{\gamma_{\rm w}}{2}\sum_j (\eta_{u^j_L} + \eta_{d^j_L} + \eta_{e^j_L} + \eta_{\nu^j_L}) - \sum_j \frac{\gamma_{e^{ij}}}{2}\left(\eta_{e^i_L} - \frac{\eta_{\varphi^0}}{2} - \eta_{e^j_R}\right)$$

Kinetic equations

$x \equiv T/H$

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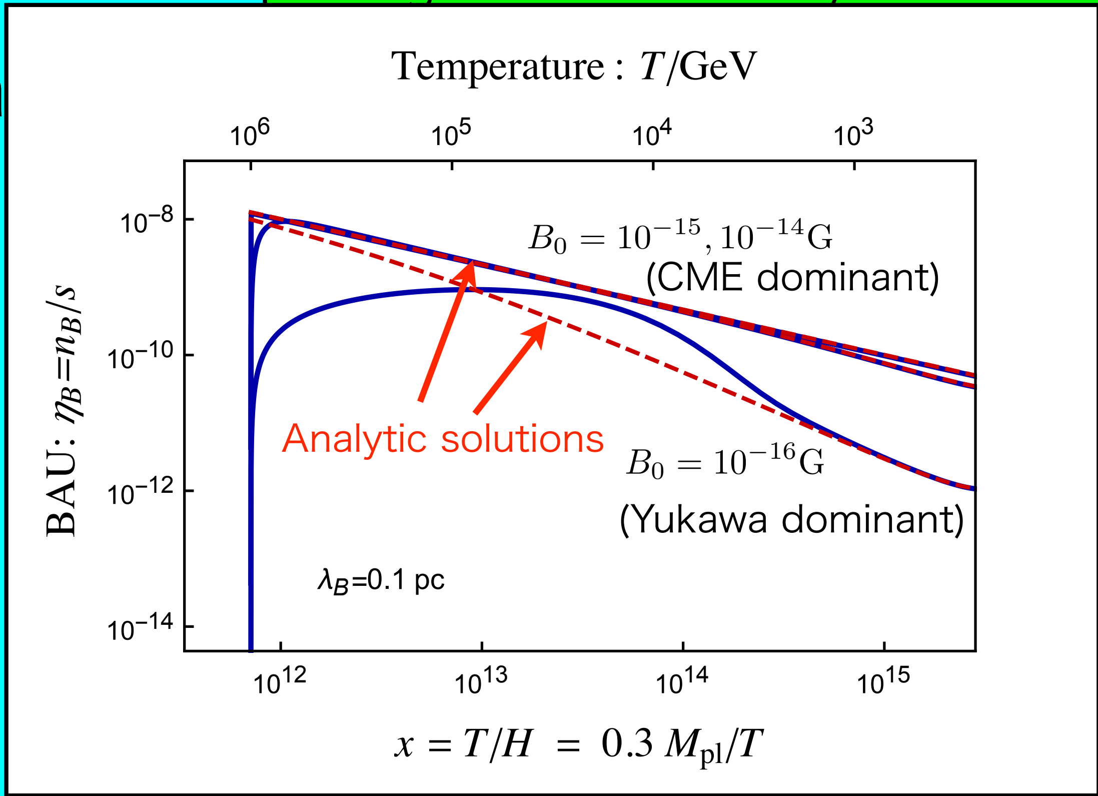
E term or

bell+, '06 Cirigliano+)

An



nikov)

$$\frac{\partial \eta_{u_L^i}}{\partial x} = -N \cdots$$

$$- \sum_j \cdots$$

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$$\sum \gamma^M \left(\cdots\right) \ \gamma (\cdots)$$

Kinetic equations

$x \equiv T/H$

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pbell+, '06 Cirigliano+)

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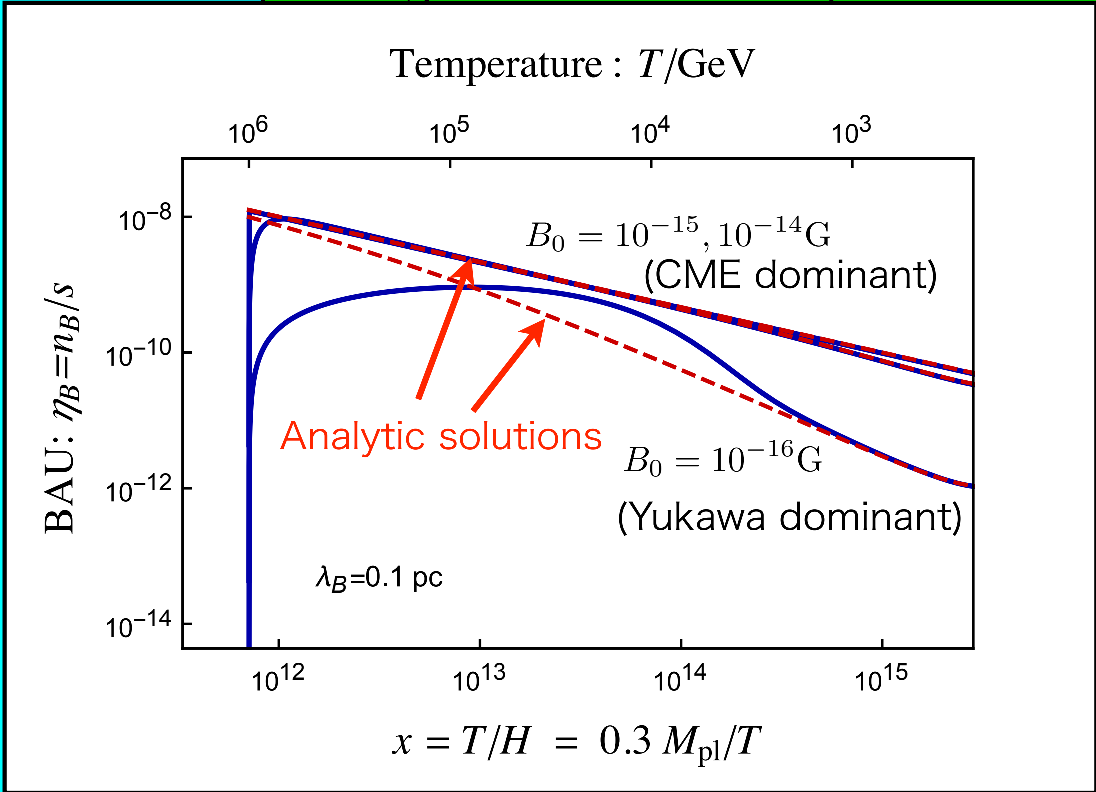

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Time-varying helical MFs ⇒~~B~~, ~~C&CP~~, Out of Equilibrium

After EWPT (T~160 GeV)...

The structure of kinetic equations are similar:

Just $U(1)_Y$ -> $U(1)_{EM}$

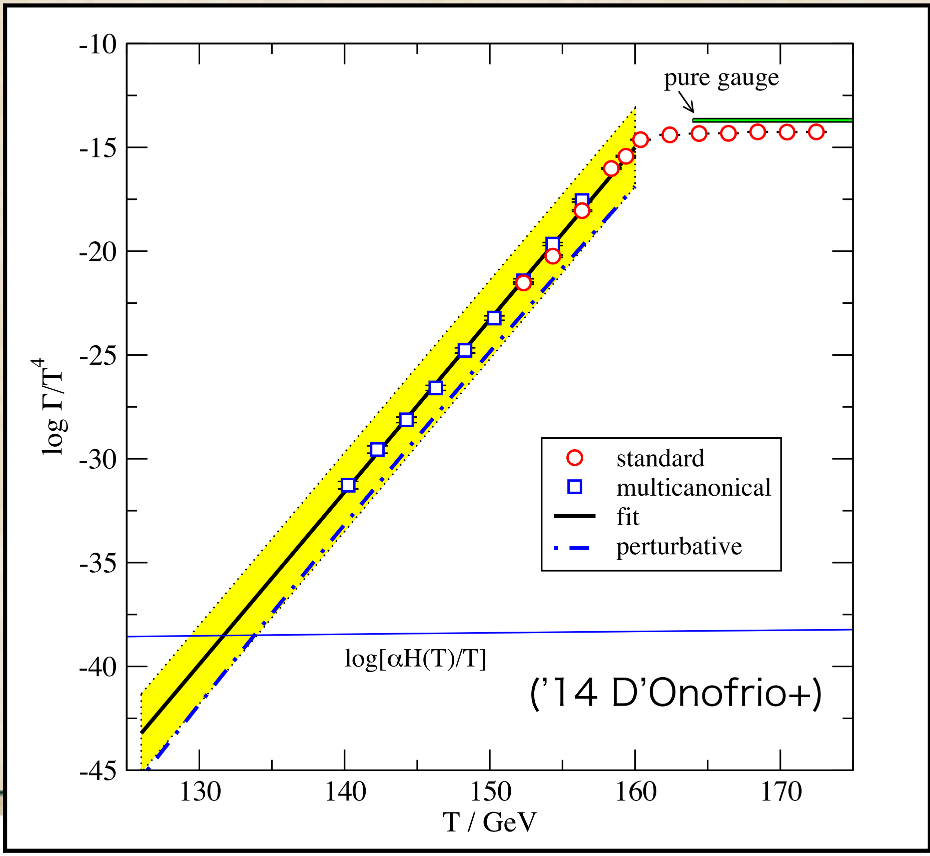
Courtesy H.Oide

After EWPT (T~160 GeV)...

The structure of kinetic equations are similar:

Just $U(1)_{Y}$ -> $U(1)_{EM}$

- Chiral anomaly of $U(1)_{EM}$ does not break baryon #
- Sphaleron still lasts until T~135 GeV



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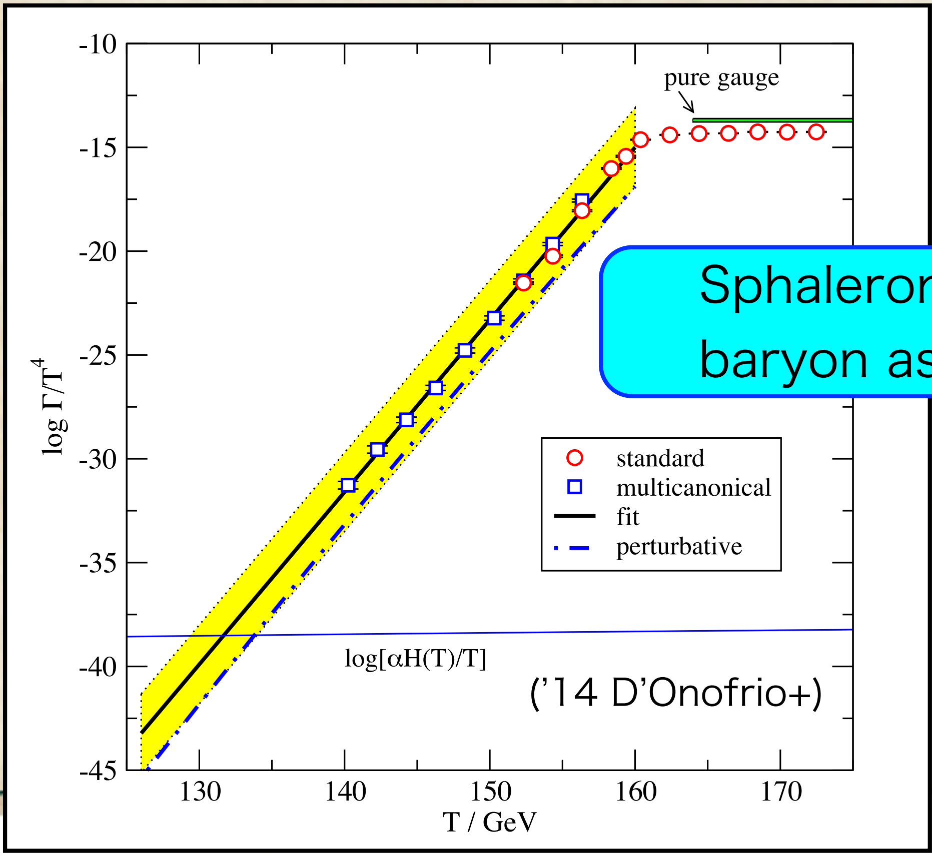

Sphaleron washes out baryon asymmetry??

'98 Givanninni & Shaposhnikov

Courtesy H.Oide

After EWPT (T~160 GeV)...

The structure of kinetic equations are similar:

Just $U(1)_Y$ -> $U(1)_{EM}$

- Chi ... aryon #
- Sph

- Source term $\mathcal{S}_{\rm EM}$ still exists.
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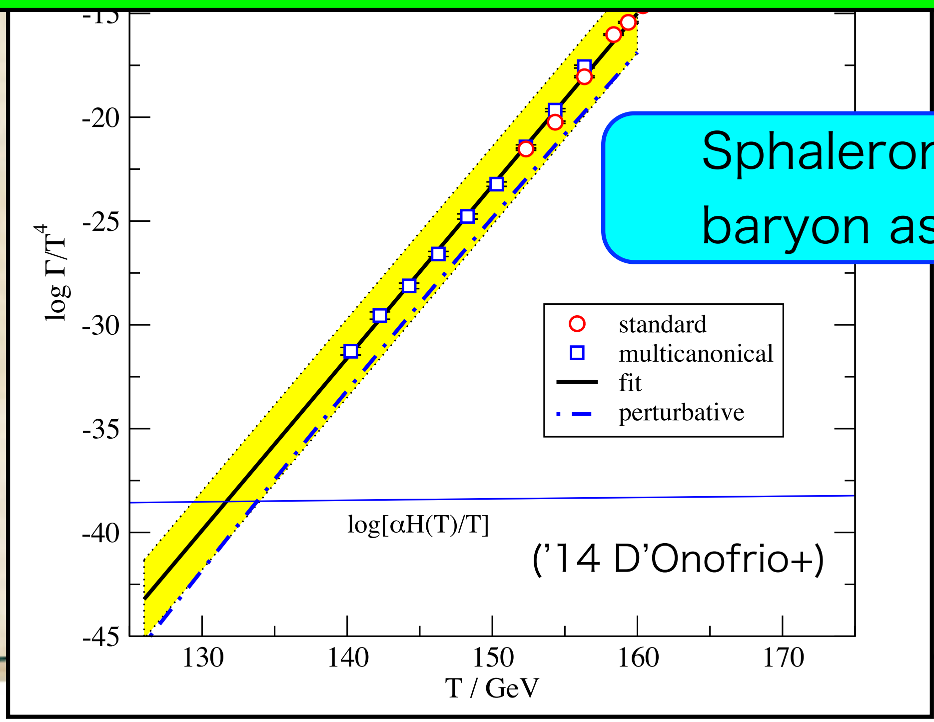

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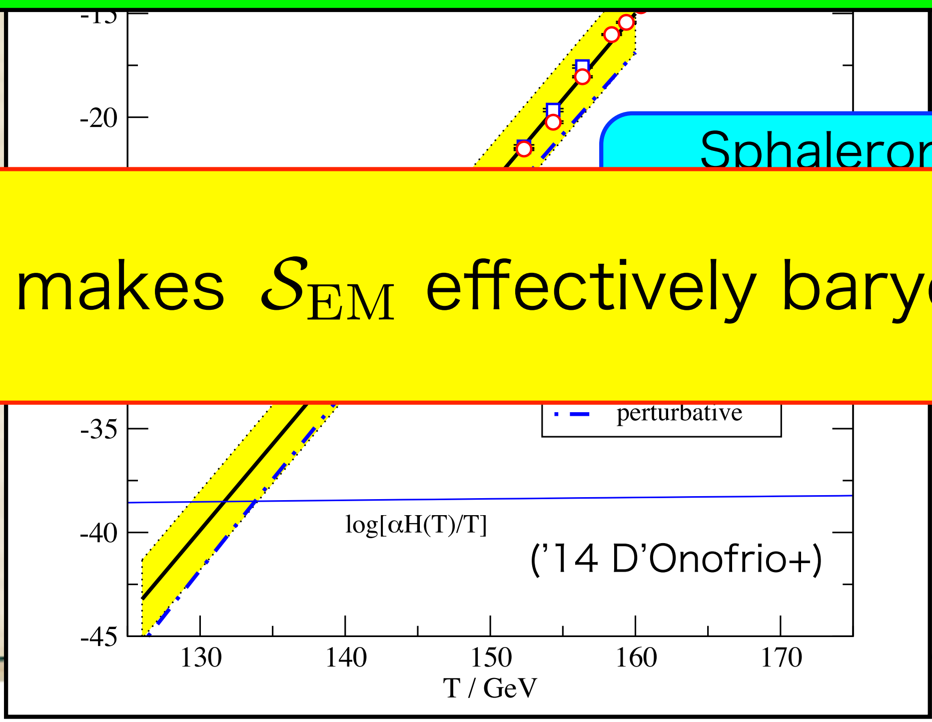


Sphaleron washes out

Sphaleron makes $\mathcal{S}_{\rm EM}$ effectively baryon-violating!!

...ikov

Courtesy H.Oide

After EWPT (T~160 GeV)...

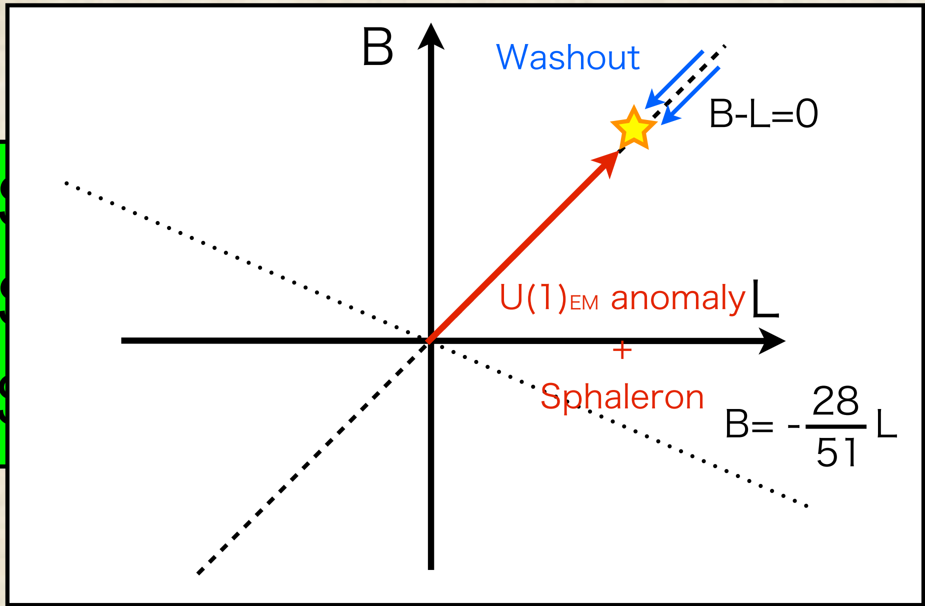
The structure of kinetic equations are similar:

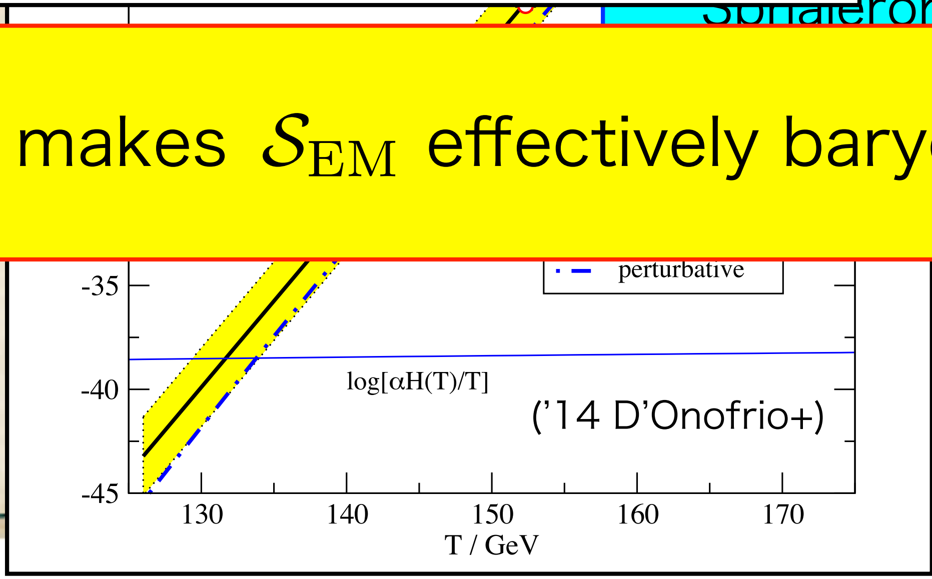
- Chi
- Sph

aryon #

s.

y.





Sphaleron washes out

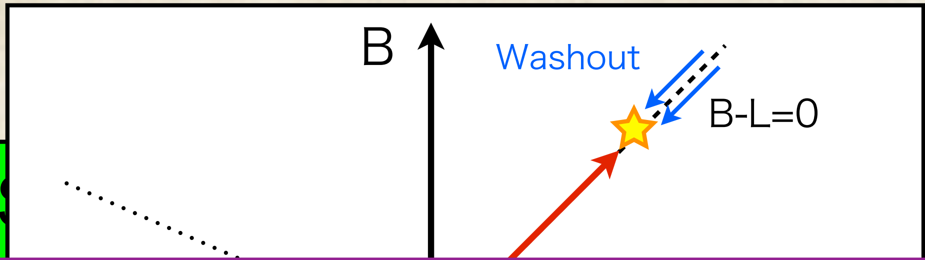
Sphaleron makes $\mathcal{S}_{\mathrm{EM}}$ effectively baryon-violating!!

nikov

Courtesy H.Oide

After EWPT (T~160 GeV)…

The structure of kinetic equations are similar:



- Chi
- S
s.
aryon #
- S

Analytic solution

$$\frac{\partial \eta_{e^1_R}}{\partial x} \simeq 0 \Rightarrow \eta_B(x) \simeq \frac{11}{37}\frac{\gamma_{\rm EM}(x)}{\gamma^{\rm CME}_{\rm EM}(x)+\gamma_{e^{11}}(x)+\gamma^M_{e^{11}}(x)}$$

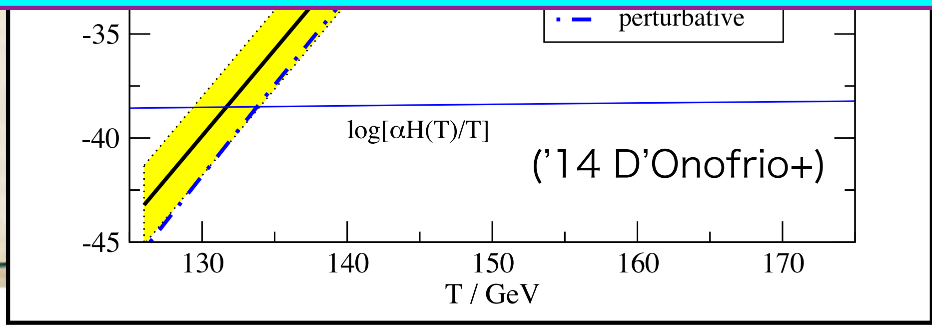
$$\gamma^M_{e^{11}} \sim 10^{-2} h^2_{e^{11}} \frac{\phi^2(T)}{T^2}$$ ('05 Lee+)

out

Sp

ating!!

nikov



Courtesy H.Oide

After EWPT (T~160 GeV)...

The structure of kinetic equations are similar:

- Chi … aryon #
- S

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Sp … ating!!

out

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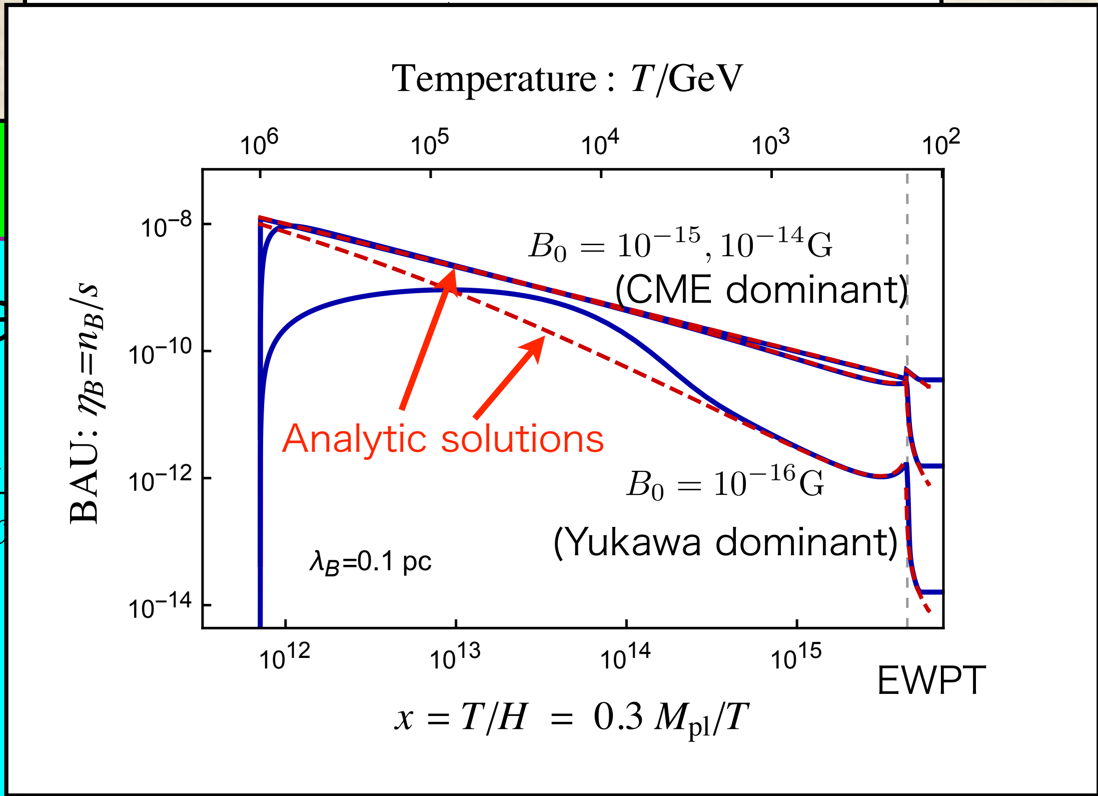

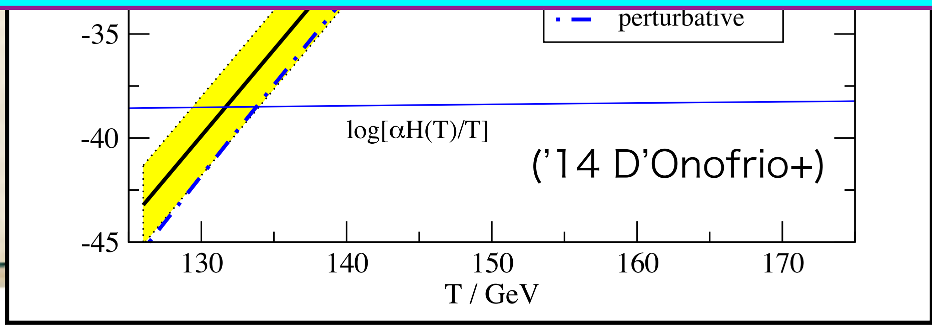

Courtesy H.Oide

After EWPT (T~160 GeV)...

The str milar:

- Chi aryon #
- S

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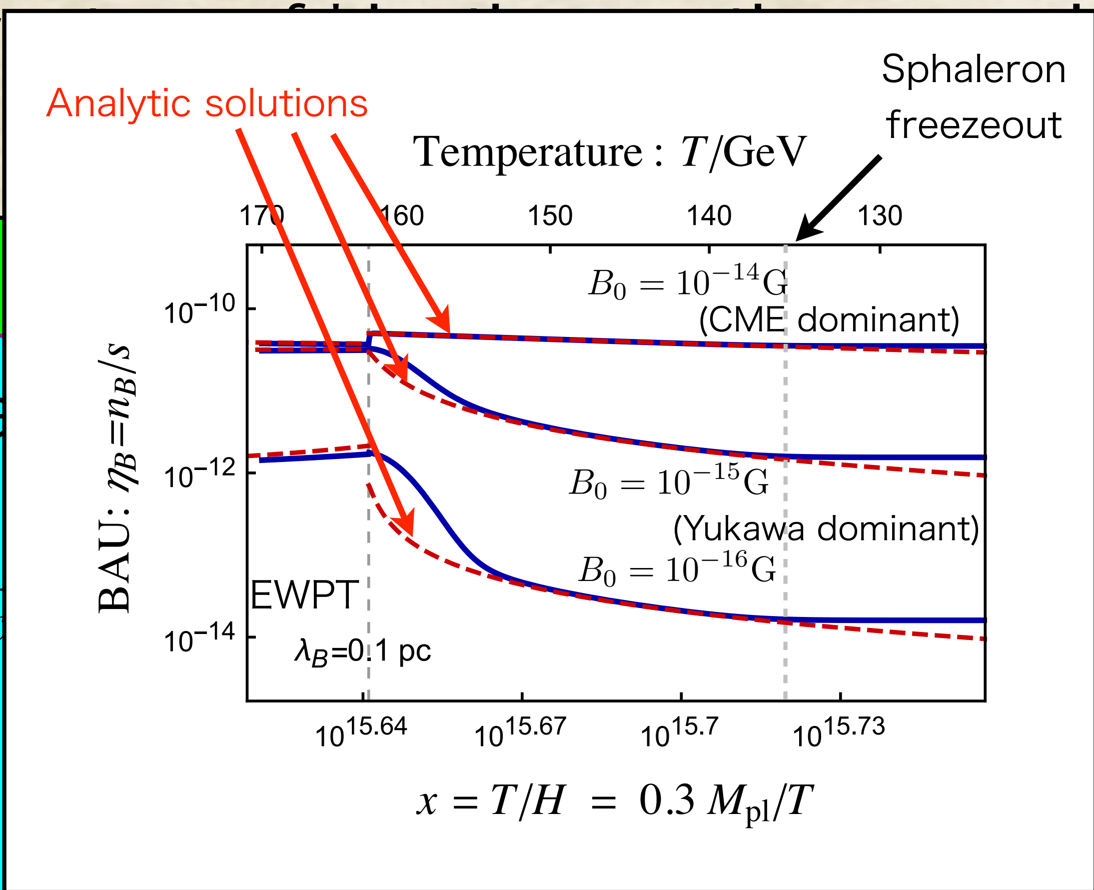


out

Sp ating!!

ikov

Baryon asymmetry is fixed at sphaleron freeze out T~135GeV

Sphaleron ⇒ ~~B~~

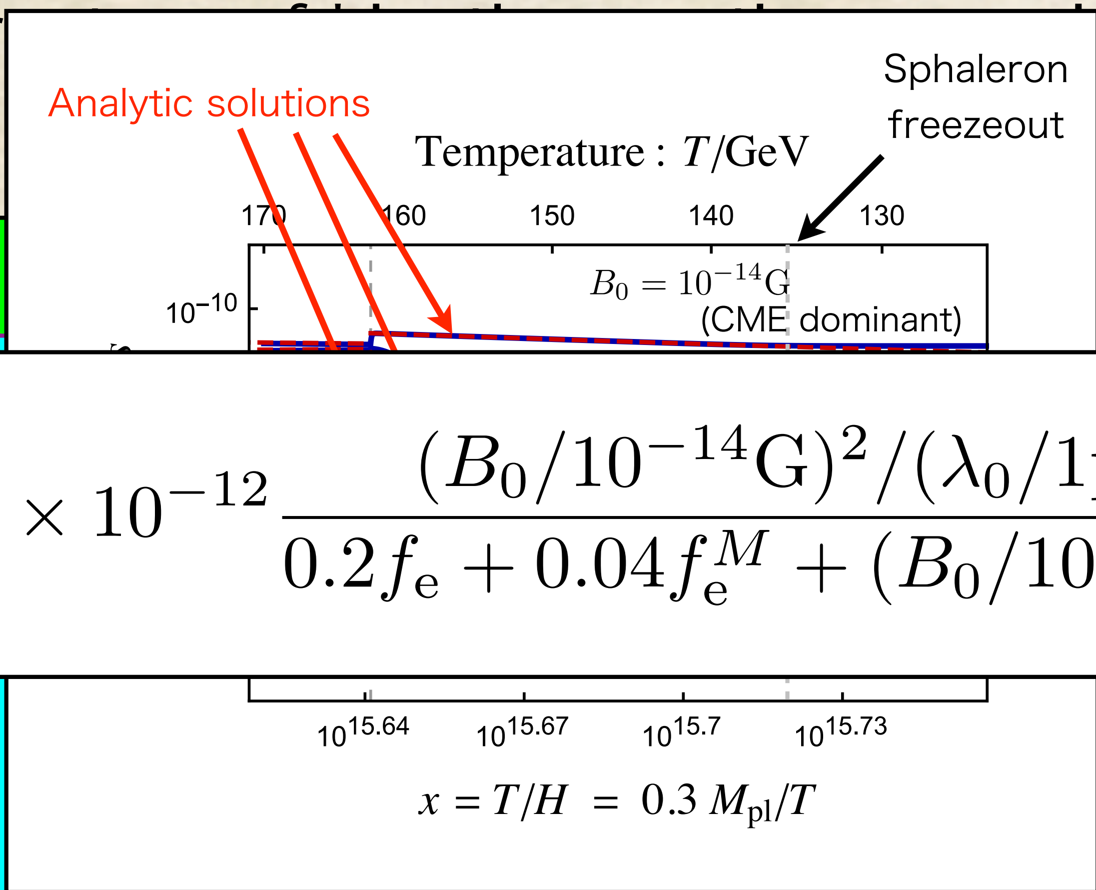
Time-varying helical MFs ⇒ ~~C&CP~~, Out of Equilibrium

Courtesy H.Oide

After EWPT (T~160 GeV)...

The str… …milar:

- Chi… …aryon #



$$\eta_B \simeq 4 \times 10^{-12} \frac{(B_0/10^{-14}\mathrm{G})^2/(\lambda_0/1\mathrm{pc})}{0.2 f_{\rm e} + 0.04 f_{\rm e}^M + (B_0/10^{-14}\mathrm{G})^2}$$

Sp… …ating!! …nikov

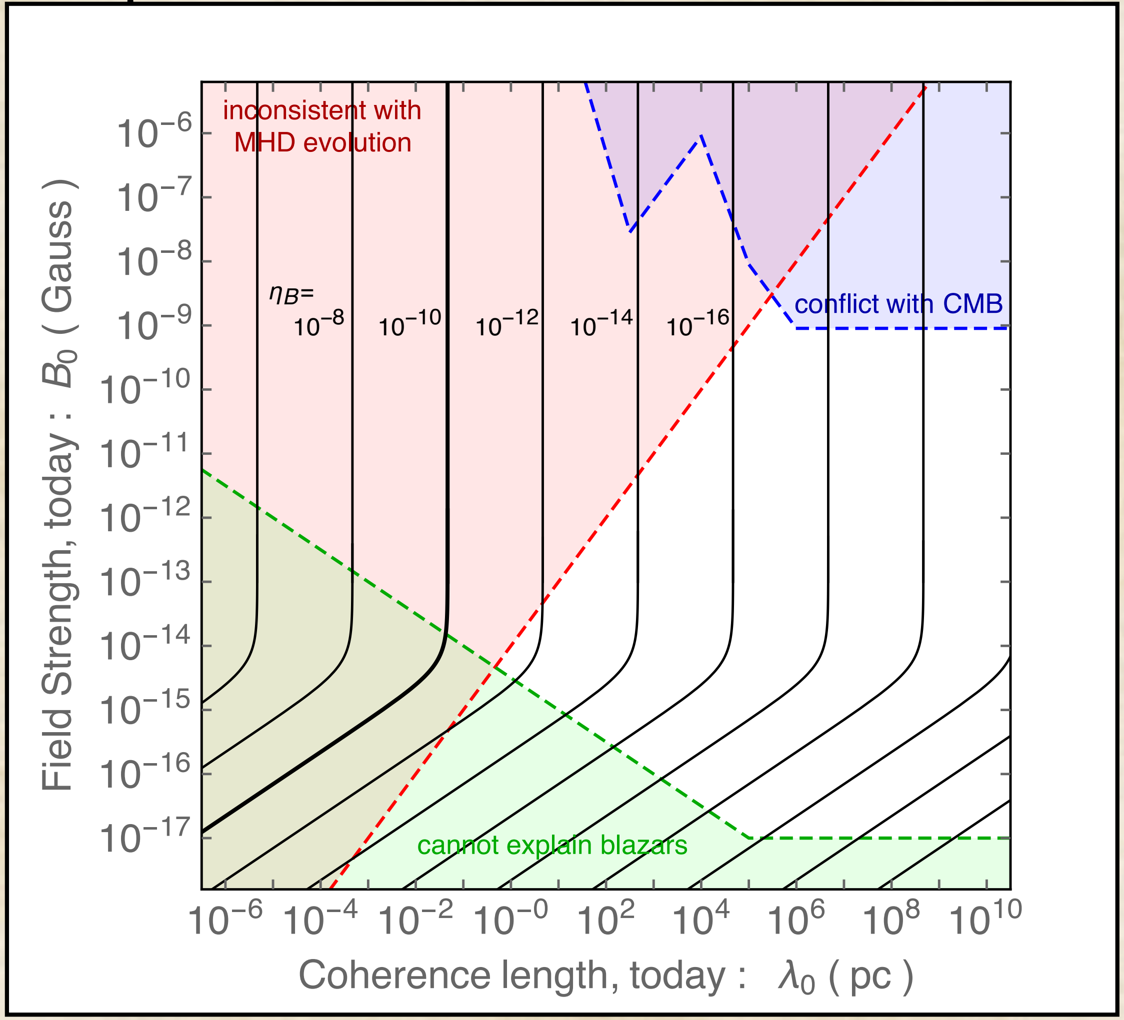
Baryon asymmetry is fixed at sphaleron freeze out T~135GeV

Sphaleron ⇒ $\cancel{B}$

Time-varying helical MFs ⇒ ~~C&CP~~, Out of Equilibrium

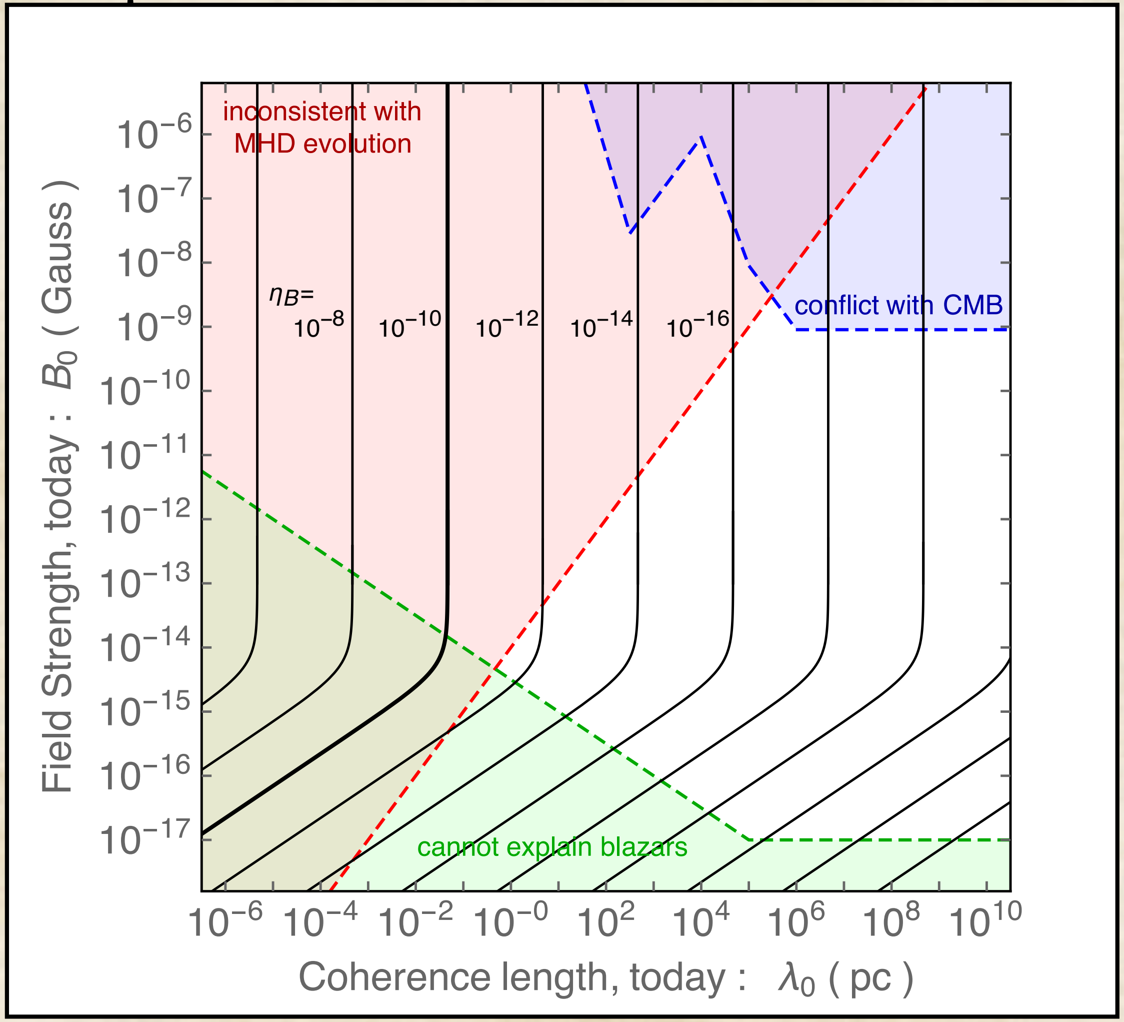
Courtesy H.Oide

Parameter spaces...



Courtesy H.Oide

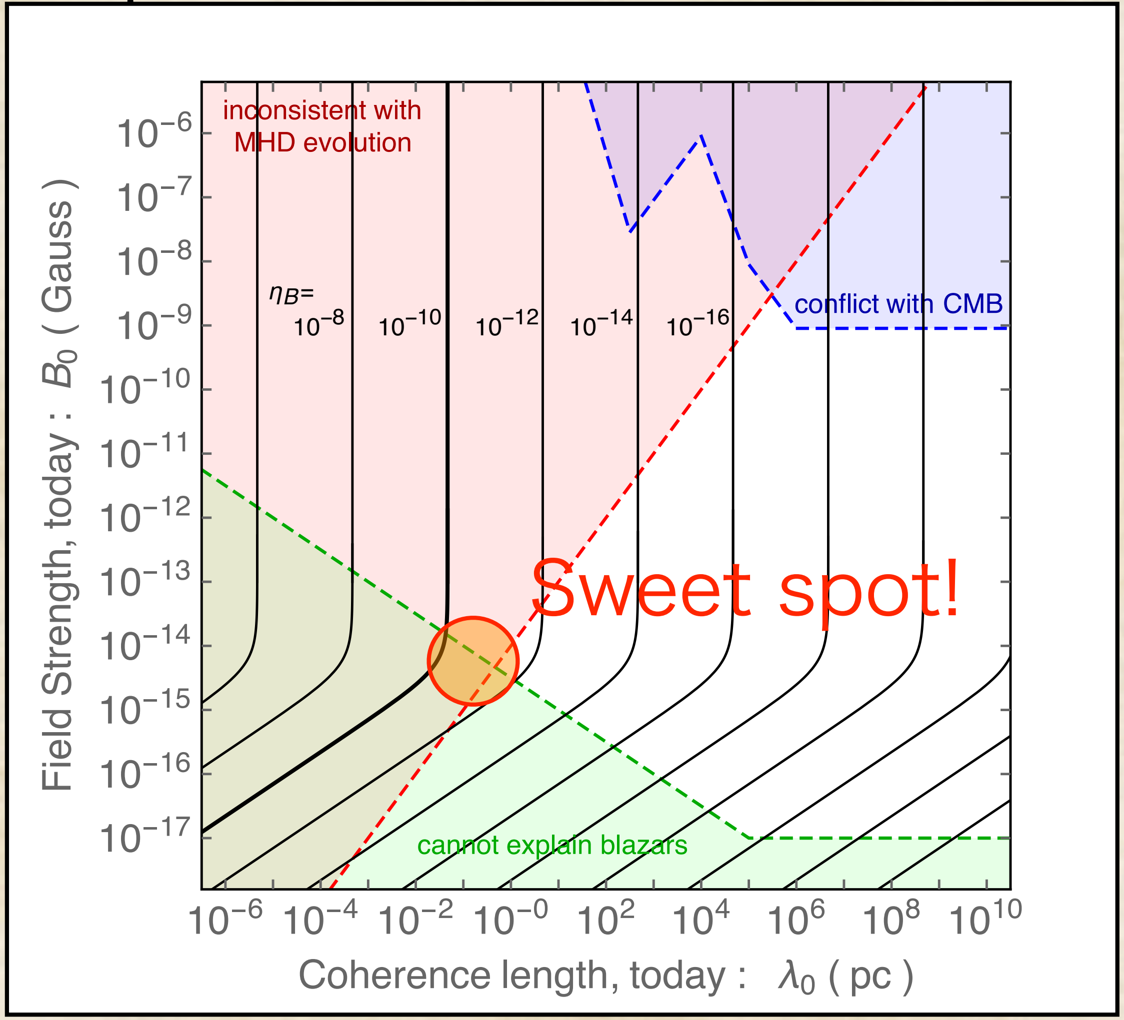
Parameter spaces...



Ruled out? But constraints are not so precise.

Courtesy H.Oide

Parameter spaces...



Ruled out? But constraints are not so precise.

Courtesy H.Oide

Summary

Courtesy H.Oide

- The existence of intergalactic magnetic fields (MFs) are indicated recently.

- If they have originated from a mechanism before EWPT, they might be related to baryon asymmetry of the Universe (BAU).

- The parameter space that can explain the present BAU is on the edge of the constraints, in other words, the sweet spot is indicated.

$$B_0 \sim 10^{-14\sim15}\mathrm{G}, \quad \lambda_0 \sim 0.1 - 1\mathrm{pc}$$

- Precise determination of constraint as well as transport coefficients $\gamma_{\mathrm{CME}}^{\mathrm{EM}}, \gamma_{e^{11}}, \gamma_{e^{11}}^{M}$ at T~135 GeV are needed.

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

Courtesy H.Oide

Appendix

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.

$$10^{-14}\left(\frac{T}{10^2\mathrm{GeV}}\right)^2 \mathrm{GeV} \qquad 10^{-24}\left(\frac{\mu_5/T}{10^{-10}}\right)\left(\frac{T}{10^2\mathrm{GeV}}\right)^{5/3}\left(\frac{\lambda_0}{1\mathrm{pc}}\right)^{-1} \mathrm{GeV}$$

Courtesy H.Oide