Baryogenesis from Primordial Hypermagnetic Helicity at Electroweak Symmetry Breaking

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(IBS-CTPU)

COSPA 2017

14/12/2017 @ Kyoto U

Magnetic Fields in the Universe

Log$_{10}$[B/Gauss]

Scale

1km   10^6 km   1 pc   1 kpc   1Mpc

NS
WD
AGN
Sun
Earth
SNR
Galaxy
Galaxy clusters
CMB bound
Intergalactic MFs?

Images from nasa.gov

Courtesy H.Oide
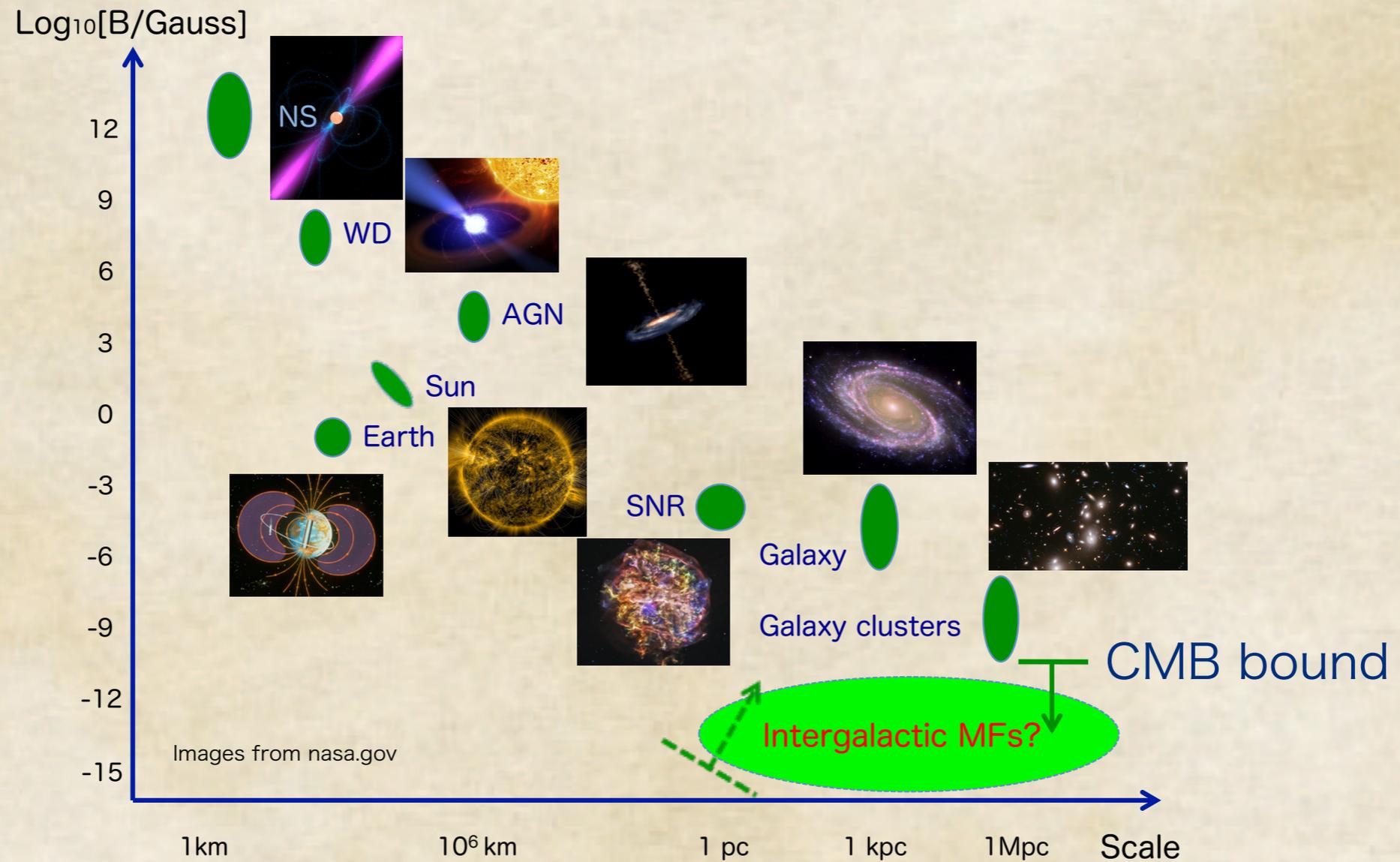
Has intergalactic magnetic fields been detected?

'10 Neronov and Vovk

MF strength

MF correlation length
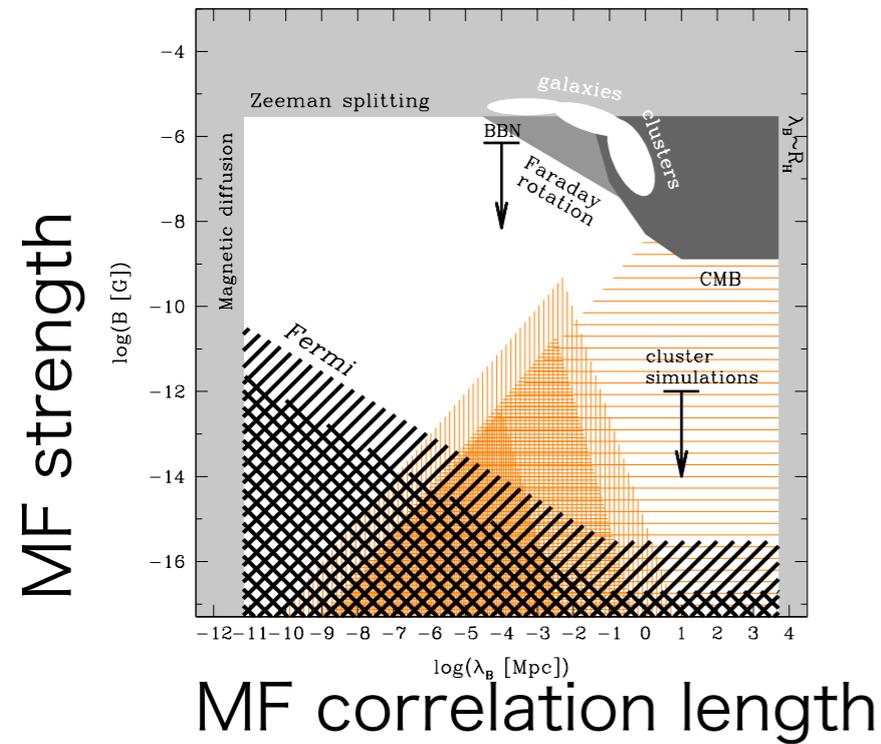
'15 Finke+
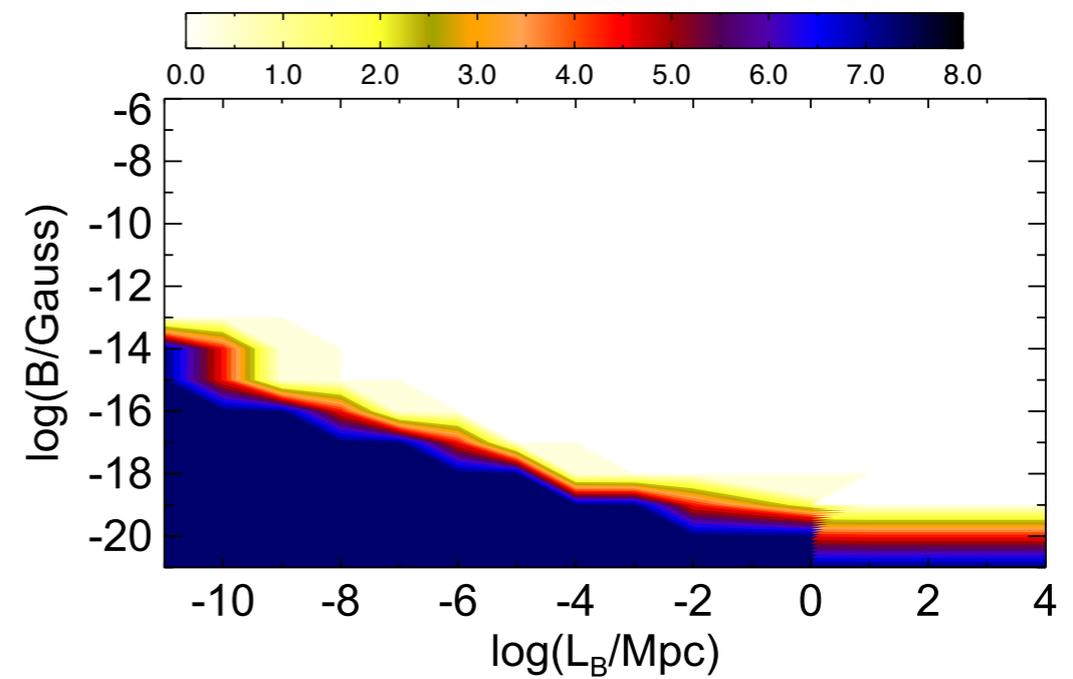
'17 Wood+ (Fermi-LAT Col.)

Courtesy H.Oide
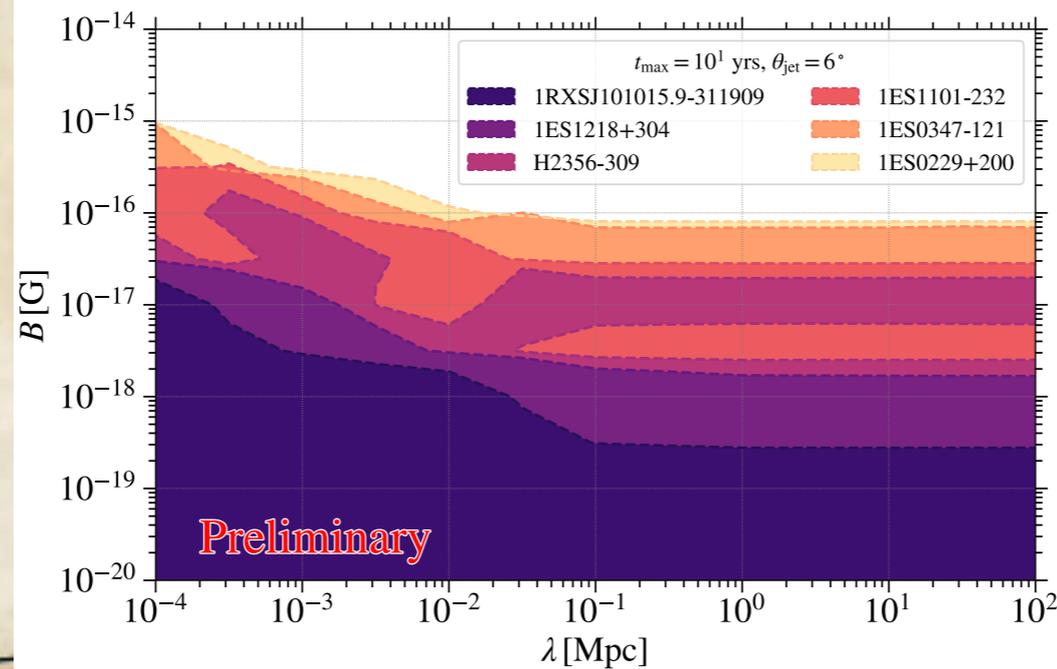
Evidence (?) of large scale magnetic fields
: ϒ-ray from Blazars (theory)

AGN/Blazar

~TeV ϒ

~ 100 Mpc

(from nasa.gov)

Intrinsic
spectrum

E
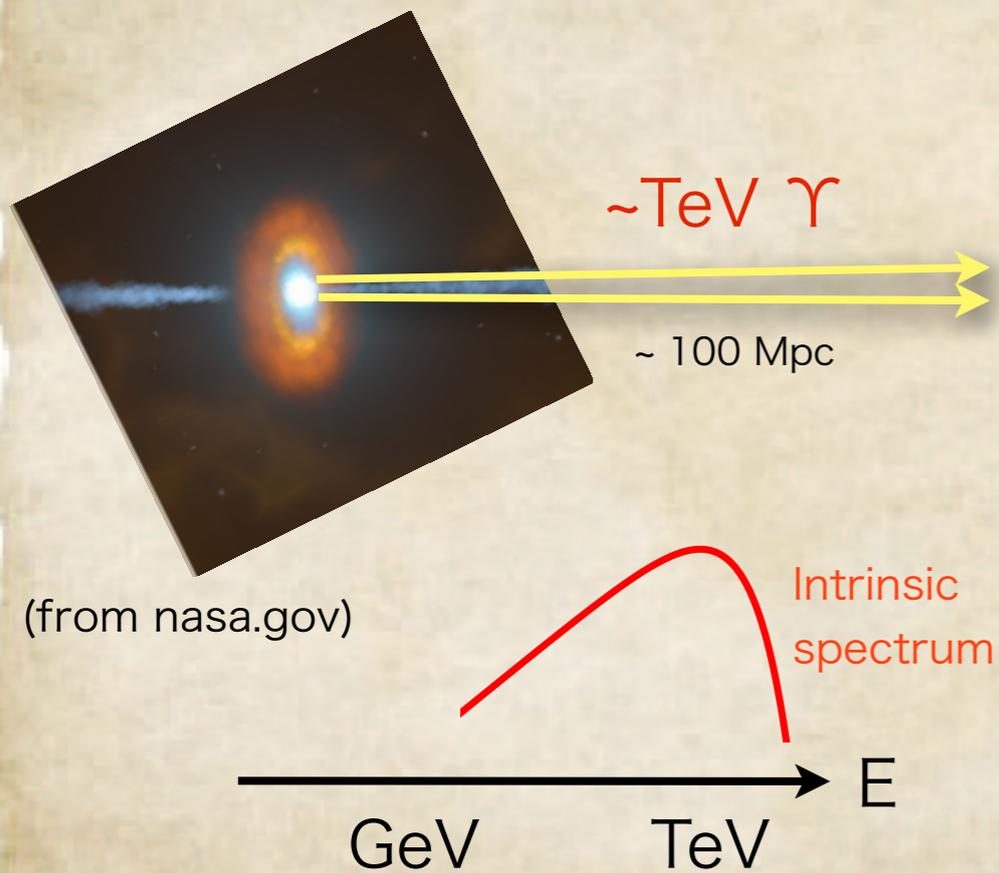
GeV   TeV

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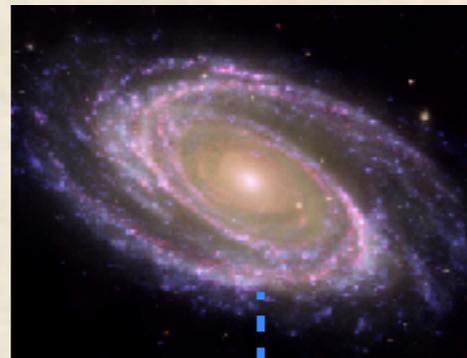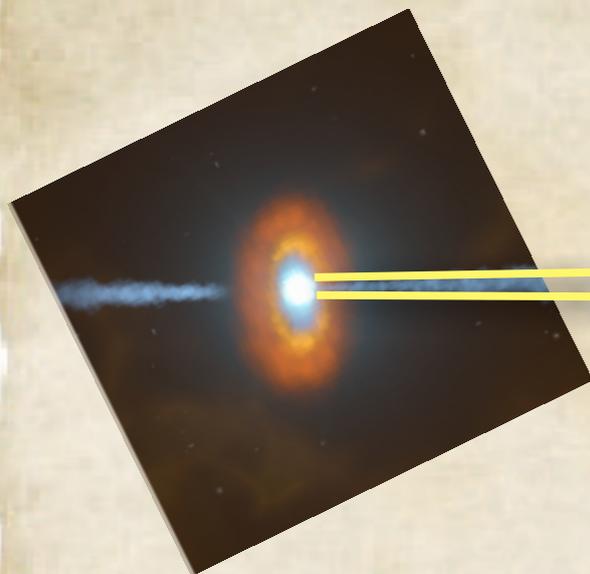
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(from nasa.gov)

(from esa.int)

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CMB
10^{-4}~eV

~ 10 kpc

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~GeV Υ

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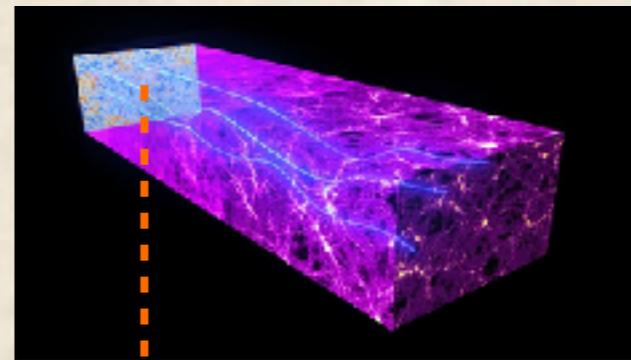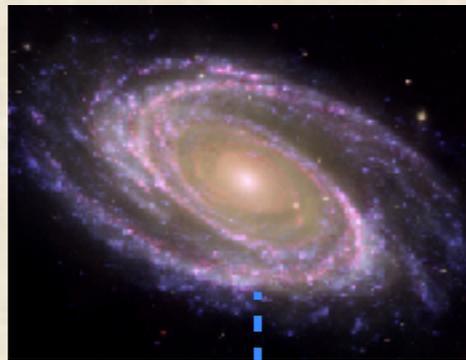
(Fermi)

(HESS)

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pair creation

inverse Compton

(from nasa.gov)

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secondary
cascade photon

E

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GeV   TeV

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Intrinsic

Fermi upper bound

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HESS data
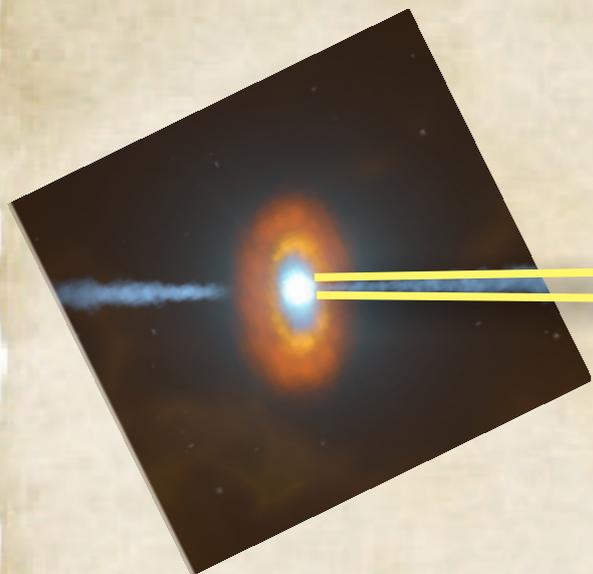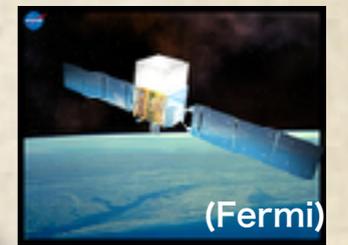
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1ES 0229+200

1ES 0347−121

1ES 1101−232

EF_E [erg/cm²s]

E [eV]

10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13}

GeV

TeV

E

'10 Neronov and Vovk

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Non-detection of GeV ϒ !!!

(from nasa.gov)

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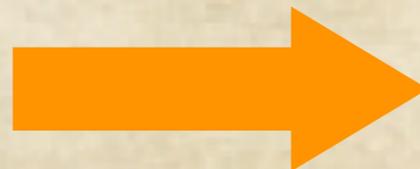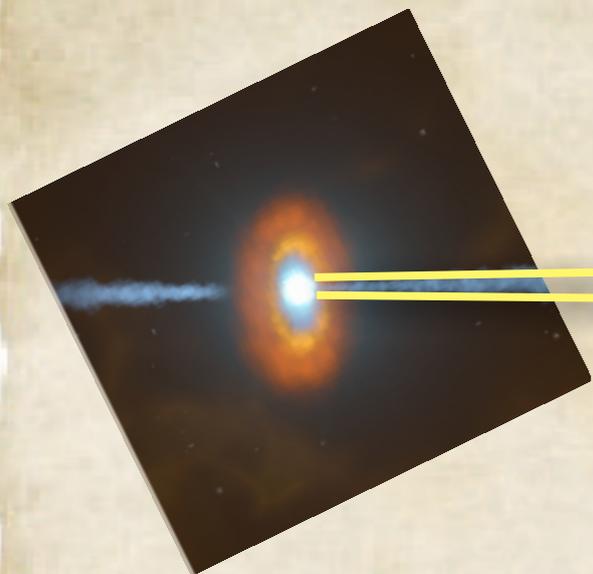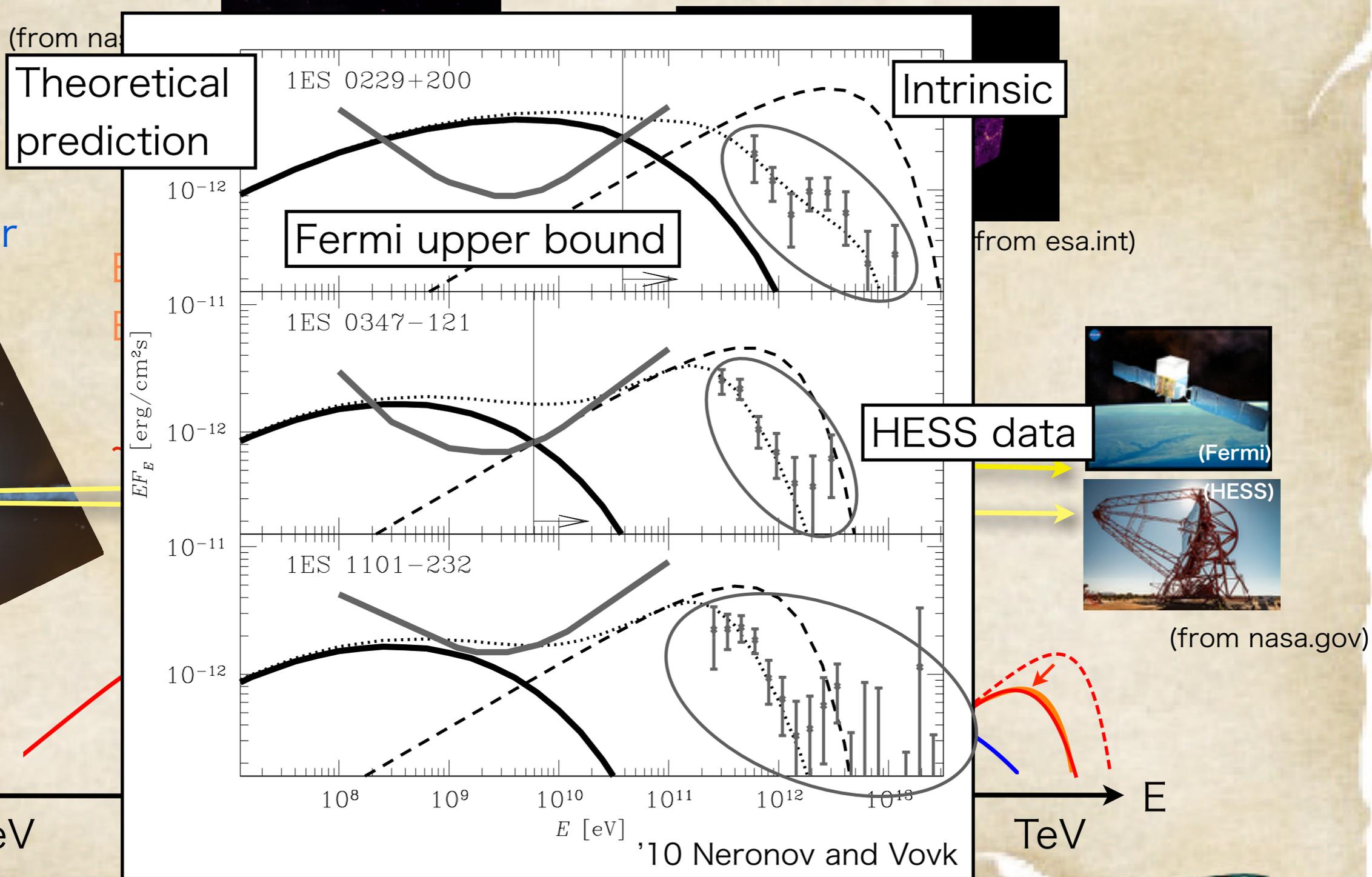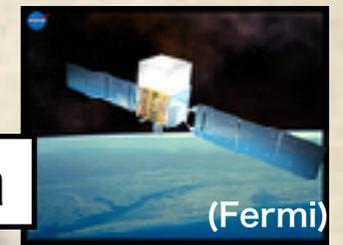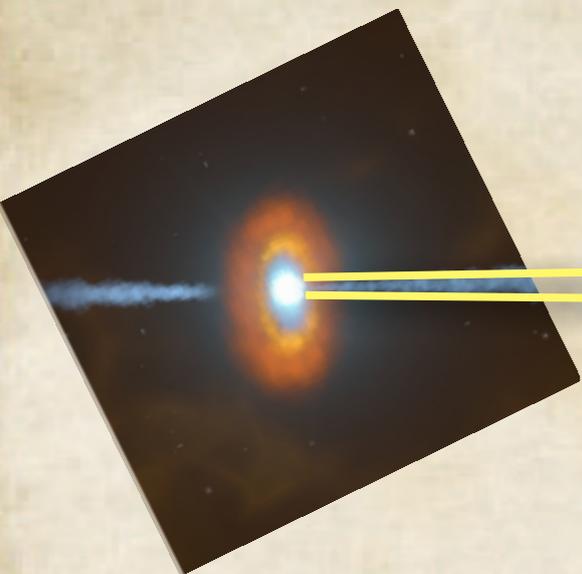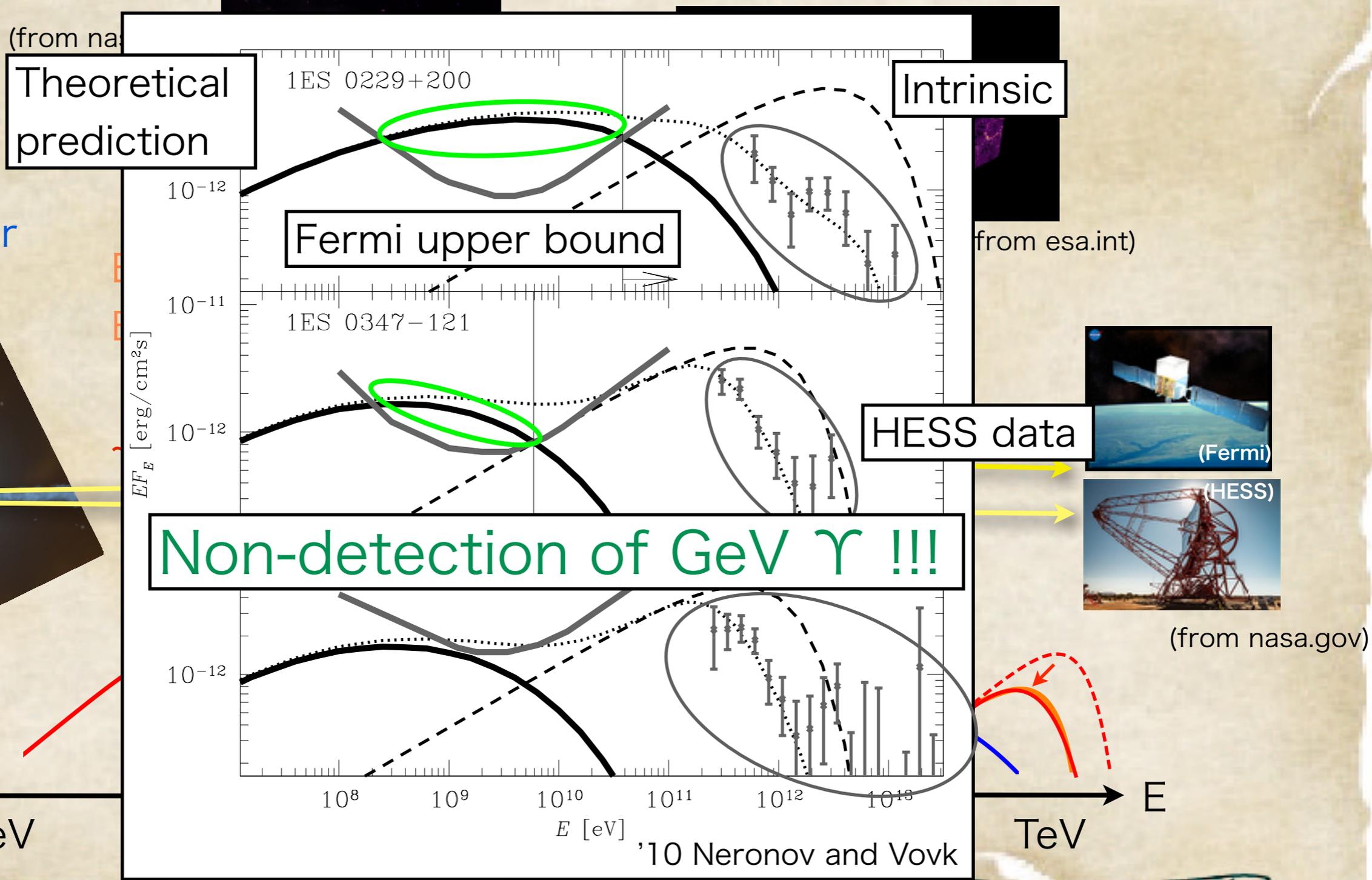
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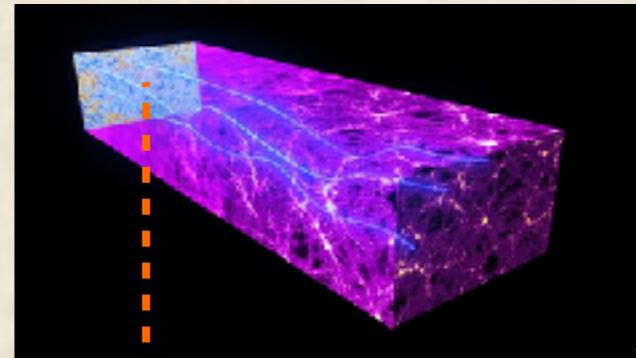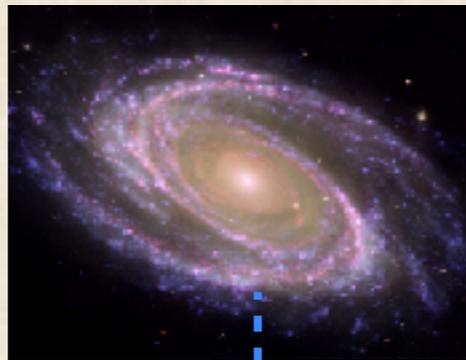
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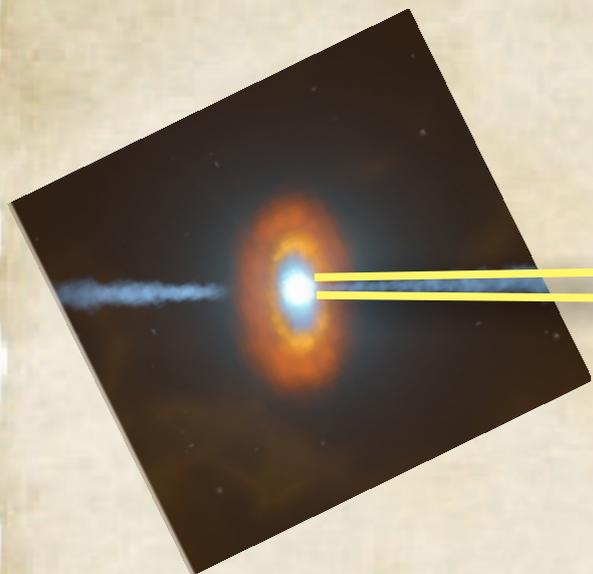
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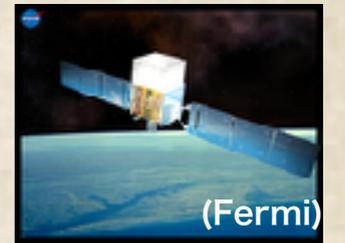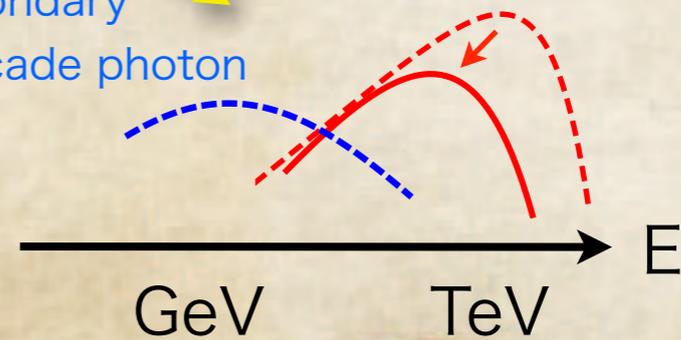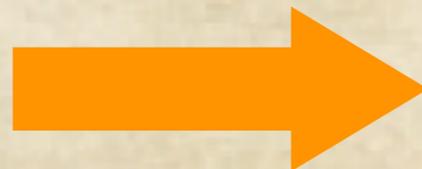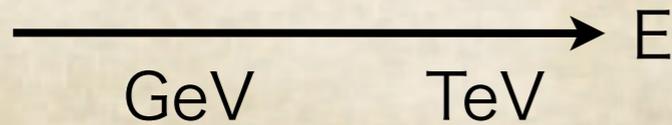
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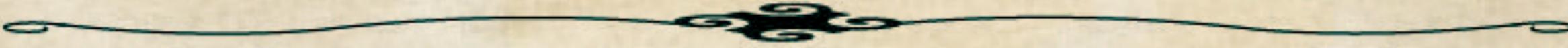
What happens if they originated from very early Universe?

One interesting possibility ('98 Givannini&Shaposhnikov, '16 KK&Fujita, KK&Long)

If the MFs existed before the EWSB (as hyperMFs) and they have non-zero helicity, baryon asymmetry of the Universe is generated through the chiral anomaly of the SM.

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

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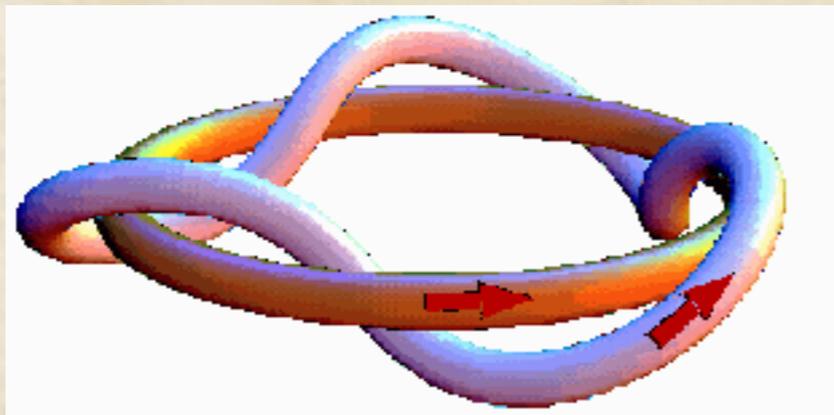
solar.physics.montana.edu

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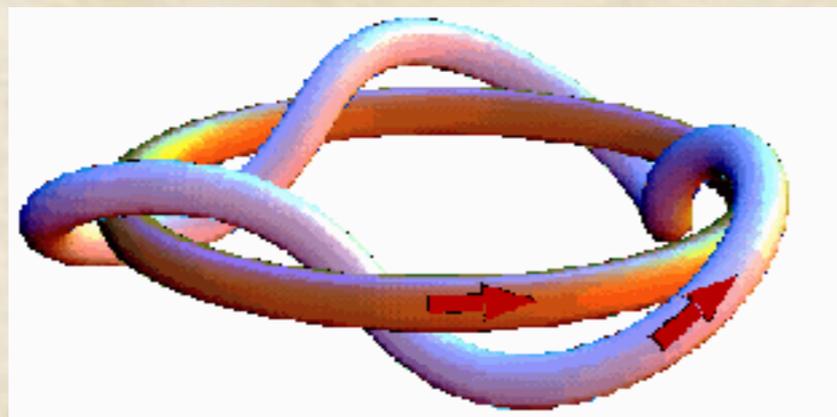
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Chiral anomaly in the SM ('76 't Hooft)

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

SU(2) part:"EW sphaleron"

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BG hypermagnetic helicity can be the source of B-asymmetry

How can the hypermagnetc helicity decay?

- "Free" decay due to MHD ('98 Givannini&Shaposhnikov)

$$\dot{h} = -a^2 \frac{2}{\sigma} \langle \mathbf{B} \cdot \nabla \times \mathbf{B} \rangle \simeq -a^3 \frac{4\pi}{\sigma} \frac{B_p^2}{\lambda_B} \qquad \sigma \simeq 100T$$

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- Conversion from hyper to electromagnetic field at EWSB

('16 KK&Long)

Lattice results

Analytic (1-loop)

$\cos^2\theta_W$
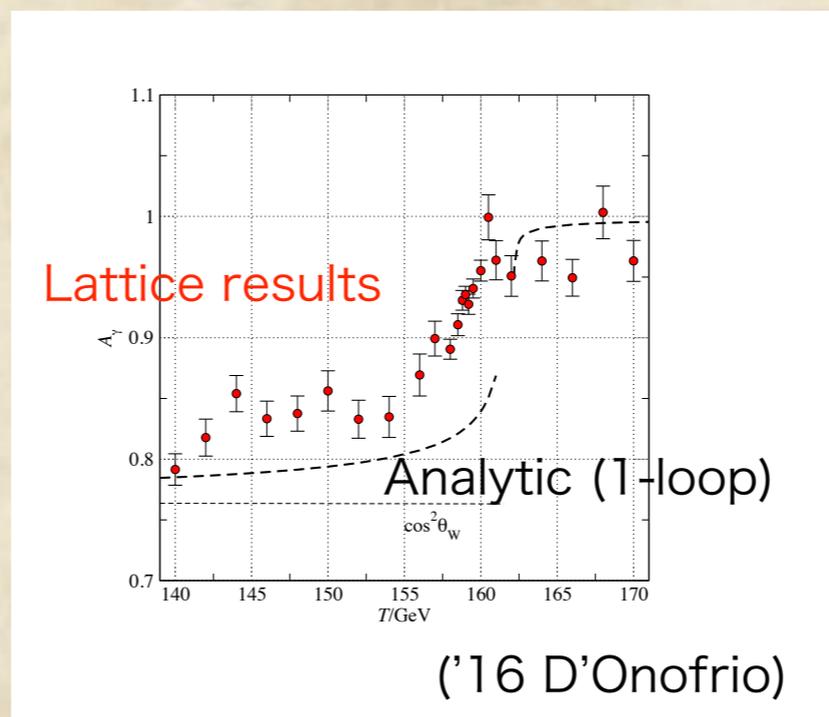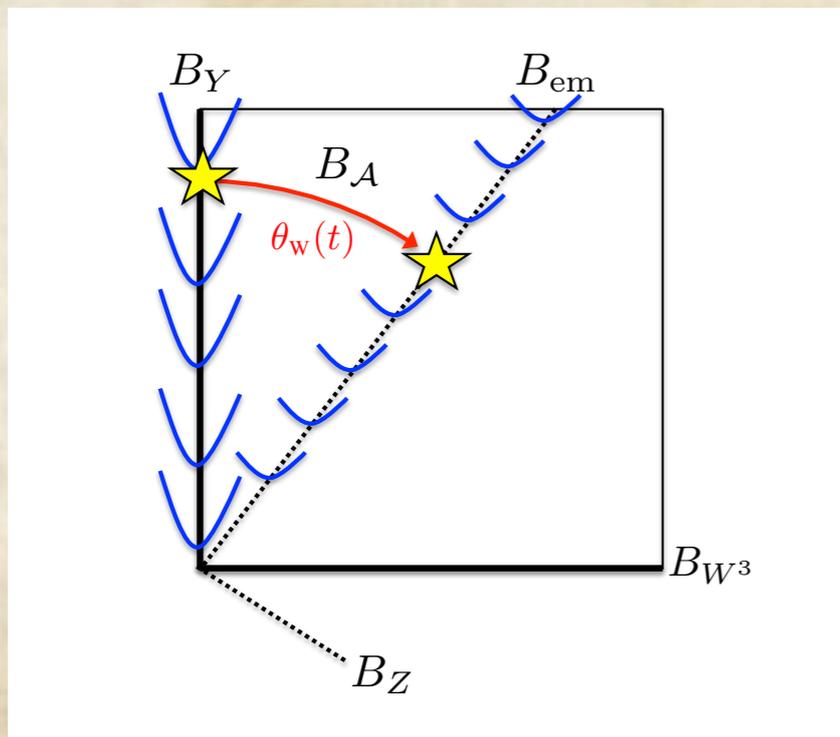
('16 D'Onofrio)

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

$$(d\mathcal{H}/dt)/V \sim \dot{\theta}_W \lambda_B B_p^2 / 2\pi$$

Courtesy H.Oide

Doesn't EW sphaleron washout the asymmetry?

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No. EW sphaleron gets out of equilibrium before the completion of EWSB.

$$\Gamma_W \simeq \exp[-145 + 0.8(T/\text{GeV})]T$$
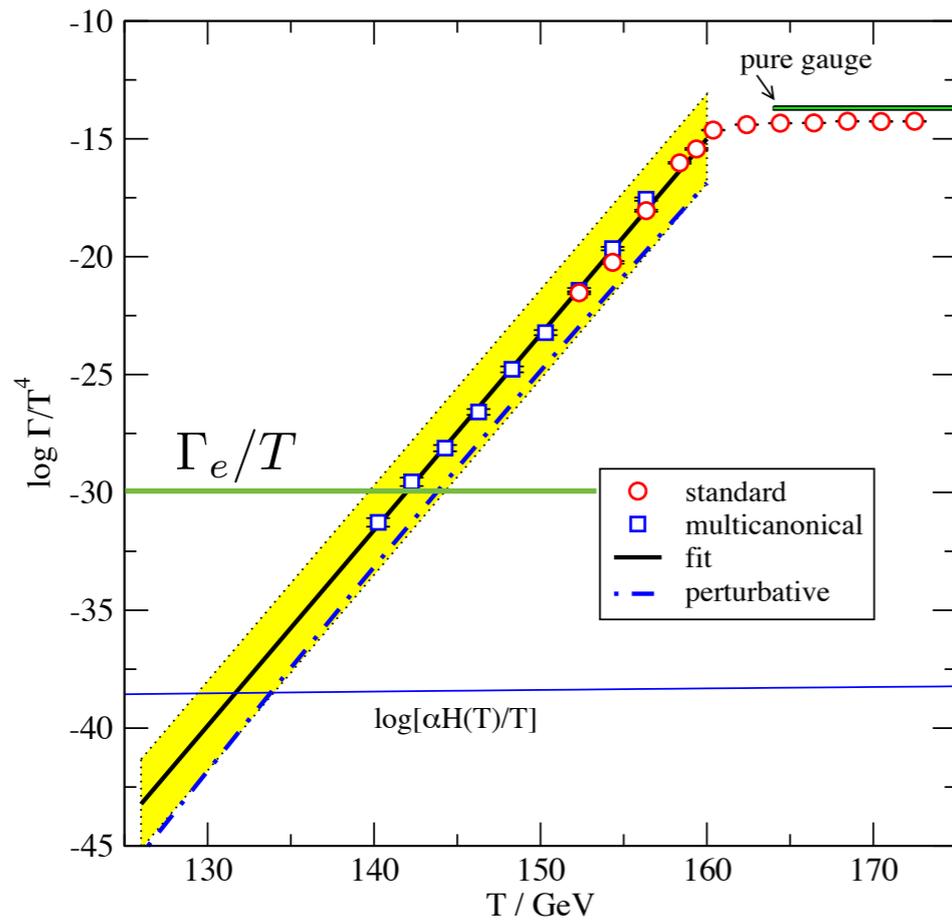
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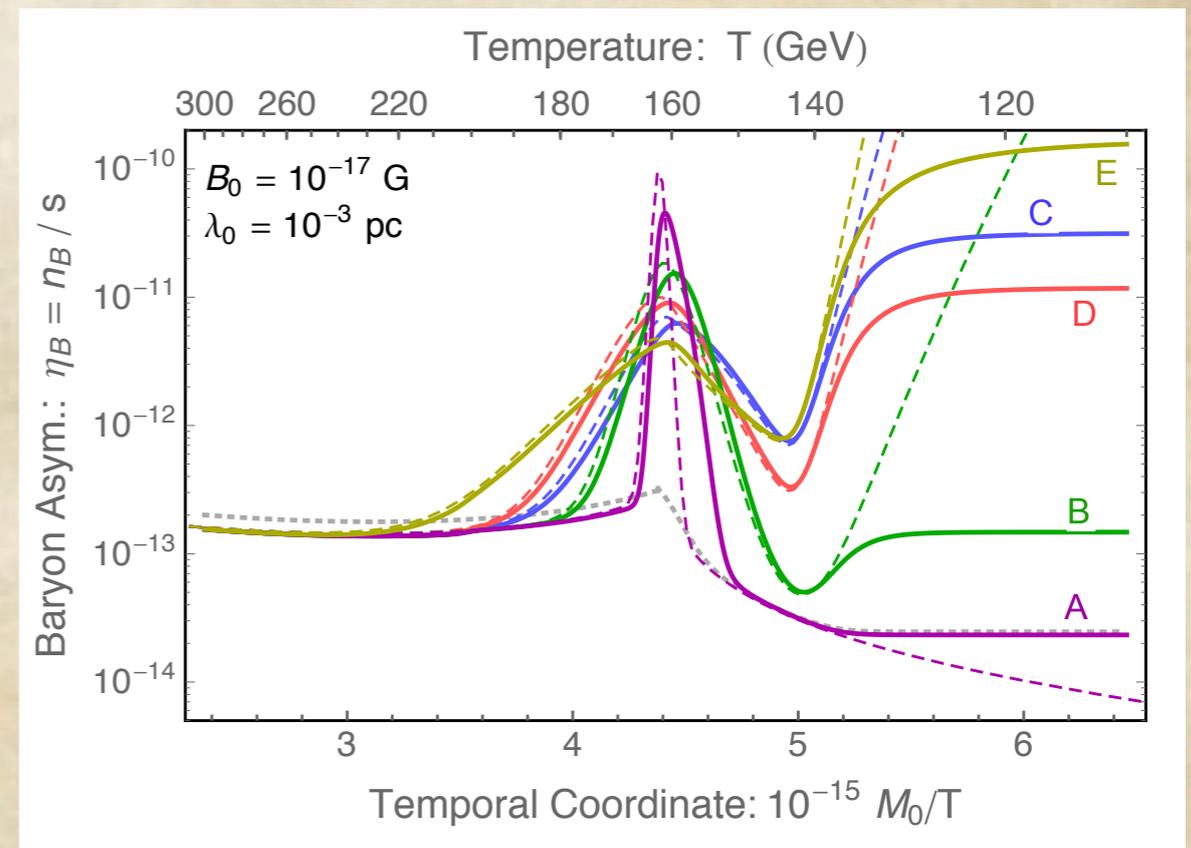
Evolution of B-asymmetry

('16 KK&Long)

$$\frac{n_B}{s}\bigg|_{\text{today}} \simeq \frac{\text{Hyperhelicity decay}}{\text{Washout effect}}\bigg|_{T \simeq 135\text{GeV}} = \frac{17}{37}\left[(g^2 + g'^2)\frac{f(T)S(T)}{\gamma_{\text{sph}}}\right]_{T \sim 135\text{GeV}}$$

$$f(T) \equiv -T\frac{d\theta_{\text{W}}}{dT}\sin(2\theta_W(T)) \qquad S(T) \equiv \frac{H}{sT}\frac{\lambda_p(T)B_p(T)}{16\pi^3}$$

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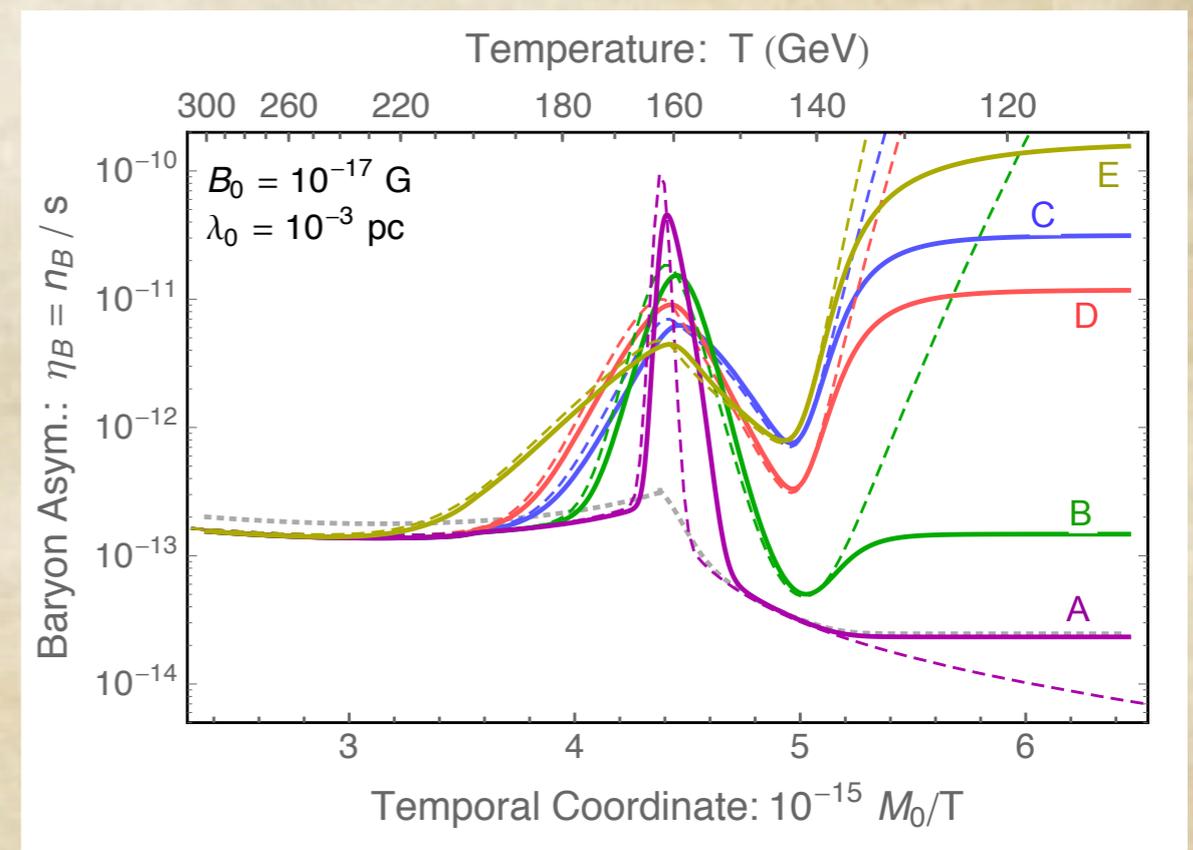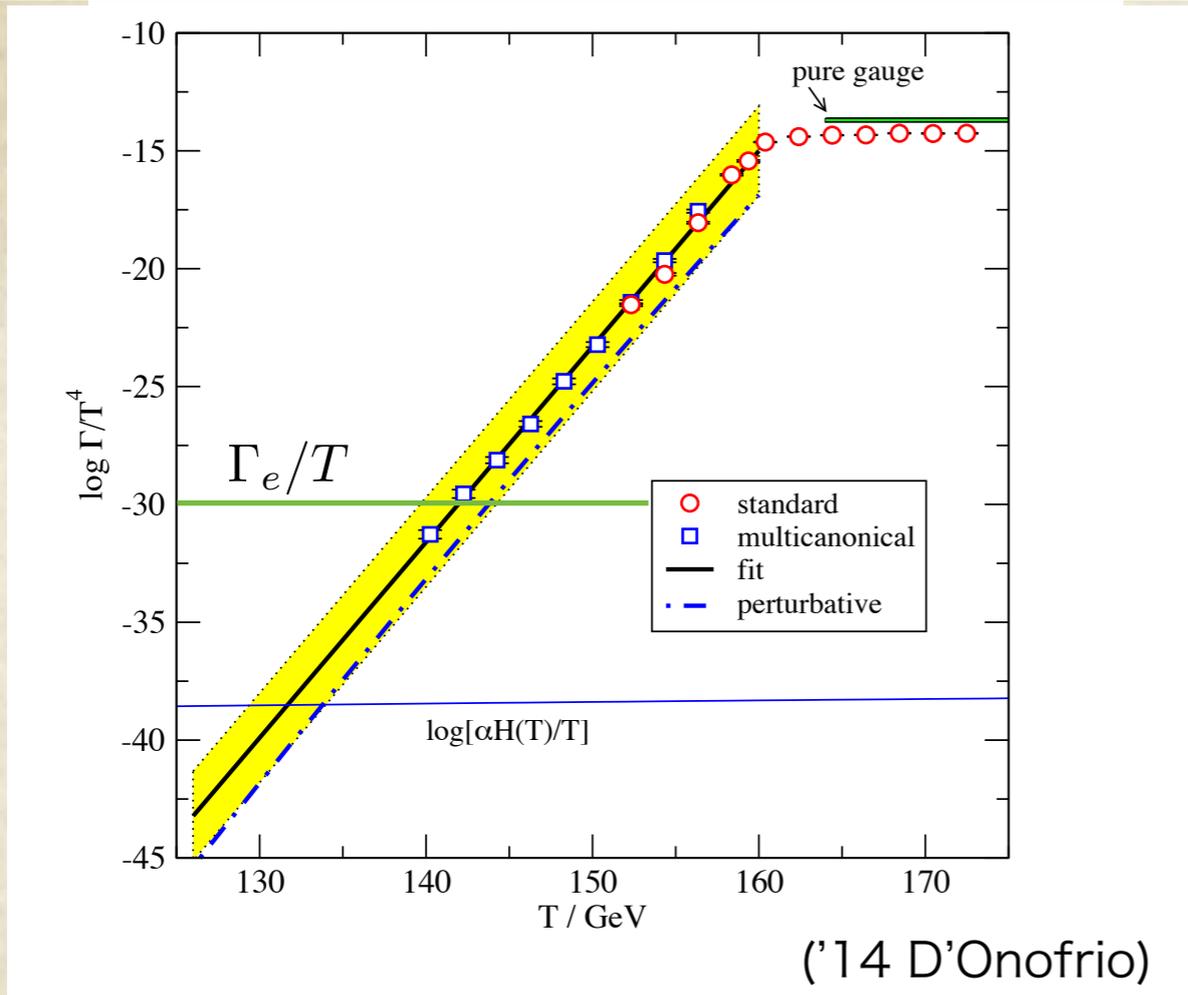
('16 KK&Long)

If we use a simple scaling law for the evolution of magnetic fields (inverse cascade), suggested by the MHD simulations, we can relate the B-asymmetry and the properties of the intergalactic MFs. ('16 Fujita&KK)

('16 KK&Long)

Coherence length, today: λ_0 (pc)

E: T_{step} = 155 GeV , ΔT = 20 GeV
D: T_{step} = 155 GeV , ΔT = 10 GeV
C: T_{step} = 160 GeV , ΔT = 10 GeV
B: T_{step} = 160 GeV , ΔT = 5 GeV
A: T_{step} = 162 GeV , ΔT = 1 GeV

observed BAU: $\eta_B \simeq 10^{-10}$

Baryon Asym., today: $\eta_B = n_B / s$

Field strength, today: B_0 (Gauss)

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

by H.Oide
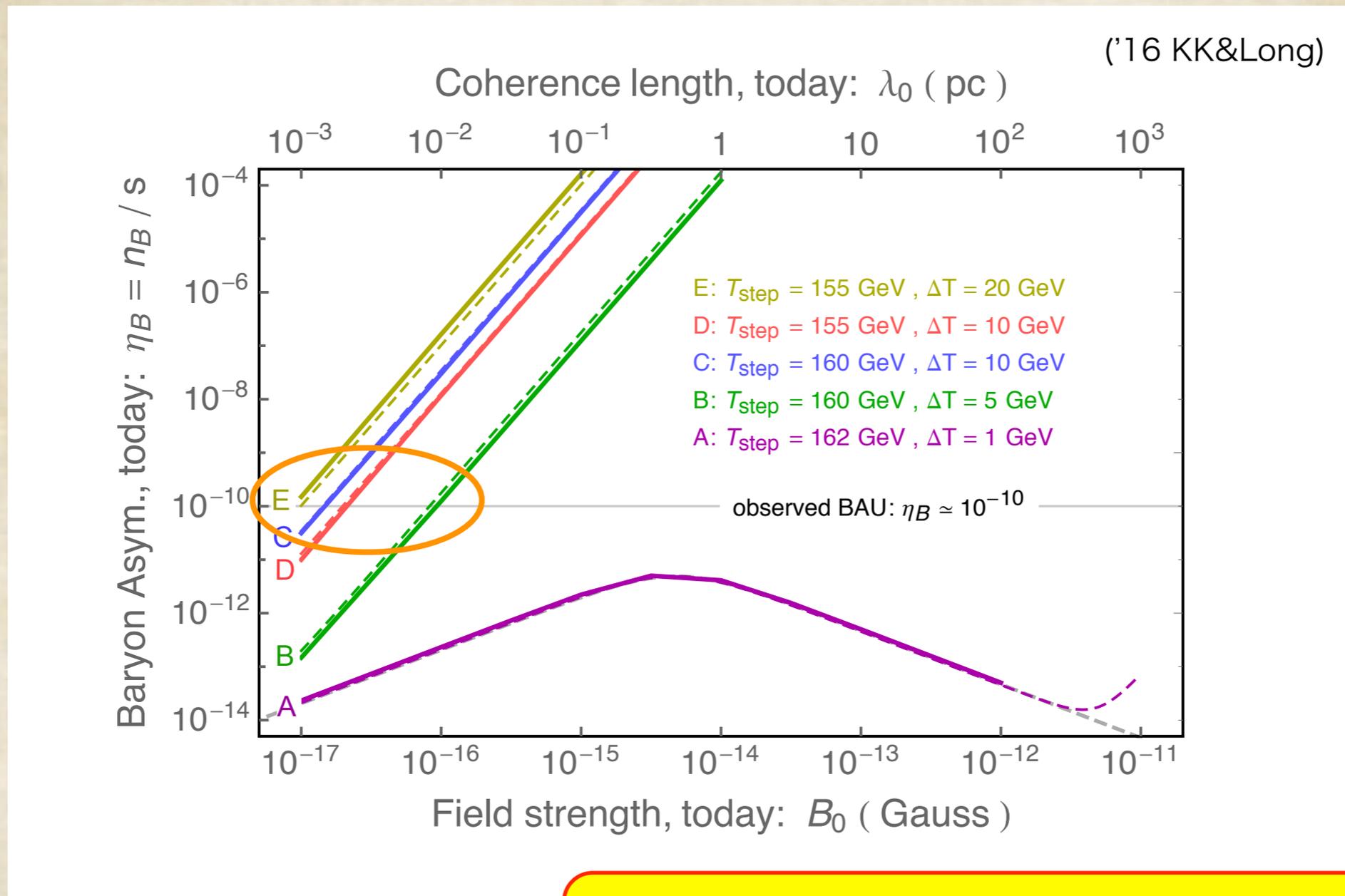
Compare to suggestion from blazar observations...

MF strength log(B/Gauss)

Too short corr. length.

CMB constraint

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

Baryons are overproduced!!

Blazar observations

log(L_B/Mpc)

MF coherent length

('15 Finke+)

Courtesy H.Oide
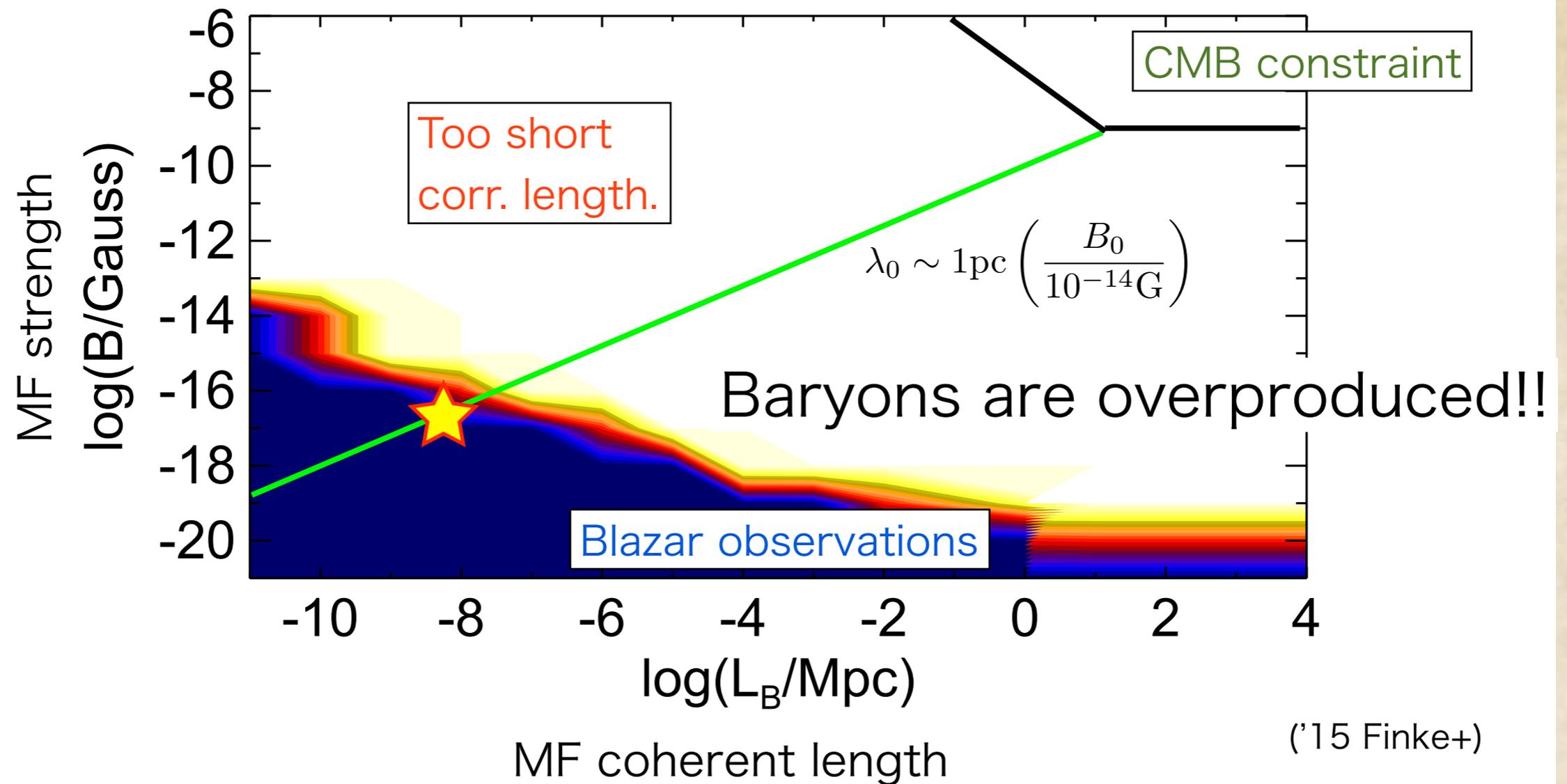
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One example is pseudoscalar inflation ('06 Anber+)

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

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

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With several simplifications and approximations, we can relate the inflation parameters and present B-asymmetry

('17 Jimenez, KK+)
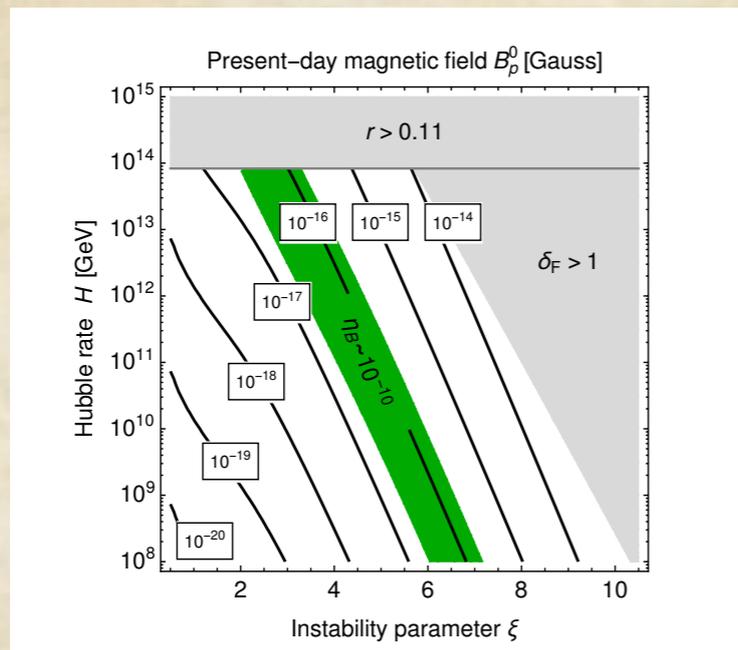
Present–day magnetic field B_ρ^0 [Gauss]

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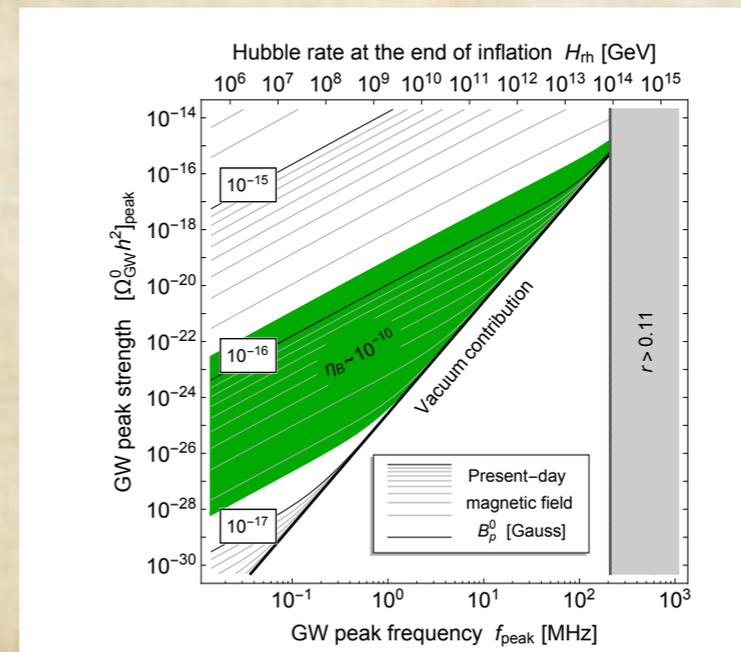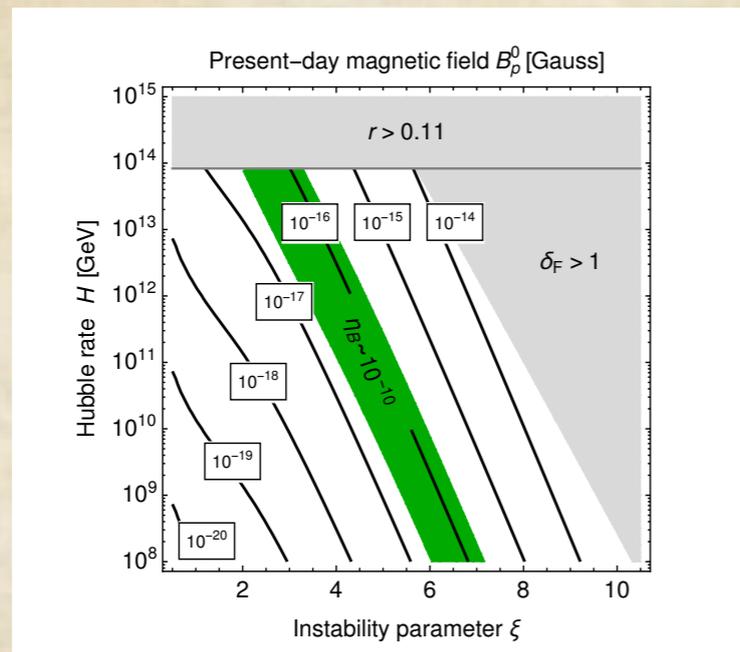
Conclusion

- 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 $B_0 \simeq 10^{-16 \sim 17} \mathrm{G}$ $\lambda_0 \simeq 10^{-2 \sim 3} \mathrm{pc}$.
- Larger MFs (that explain blazars) predict baryon overproduction.

Future directions

- Evolution of MFs around EWSB (crossover); precise $\theta_{\mathrm{W}}(T)$
- Further study on magnetogenesis from pseudoscalar inflation
- Other magnetogenesis mechanism? (e.g. 1st order PT)
- Is the inverse cascade true? or evolution of MFs in MHD.
- Determine the properties of intergalactic MFs.
  Detect the helicity! CTA might be able to.

Appendix

Scaling relation during the radiation dominated era

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

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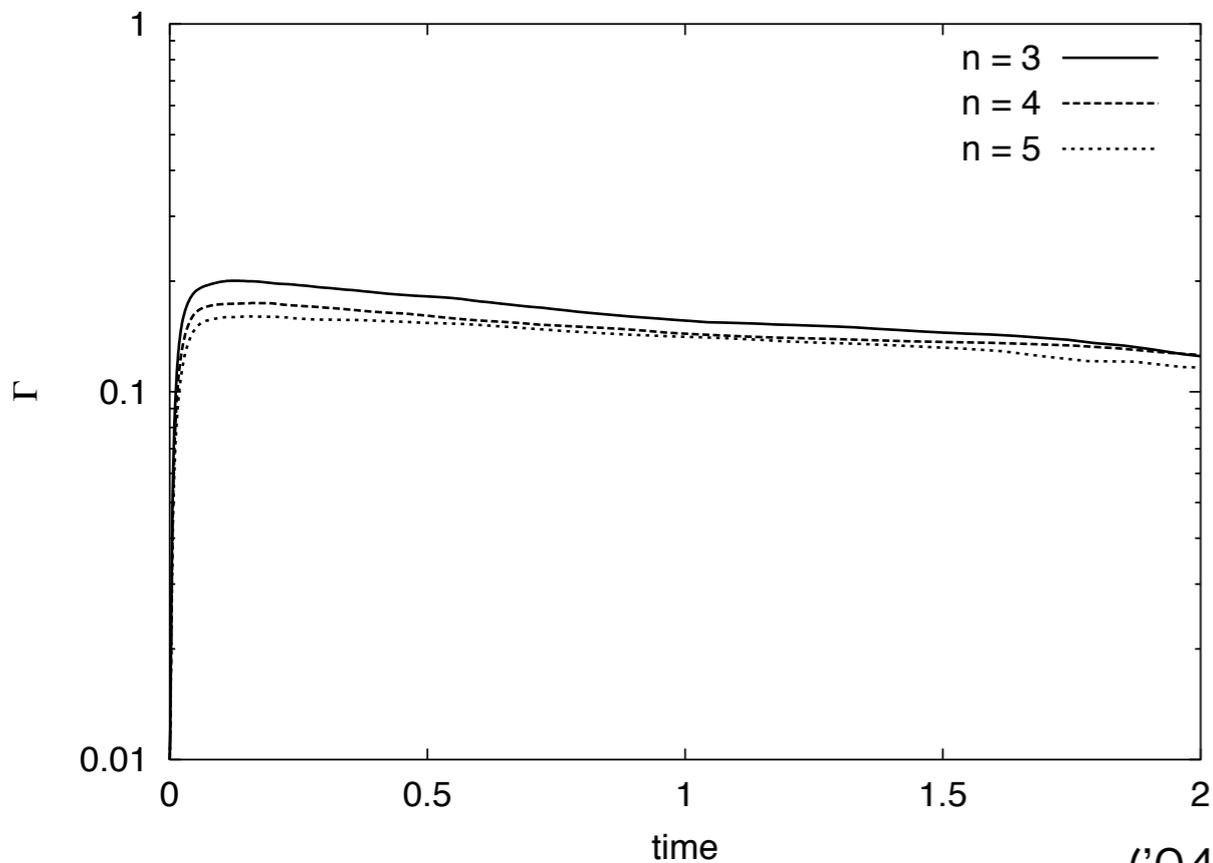
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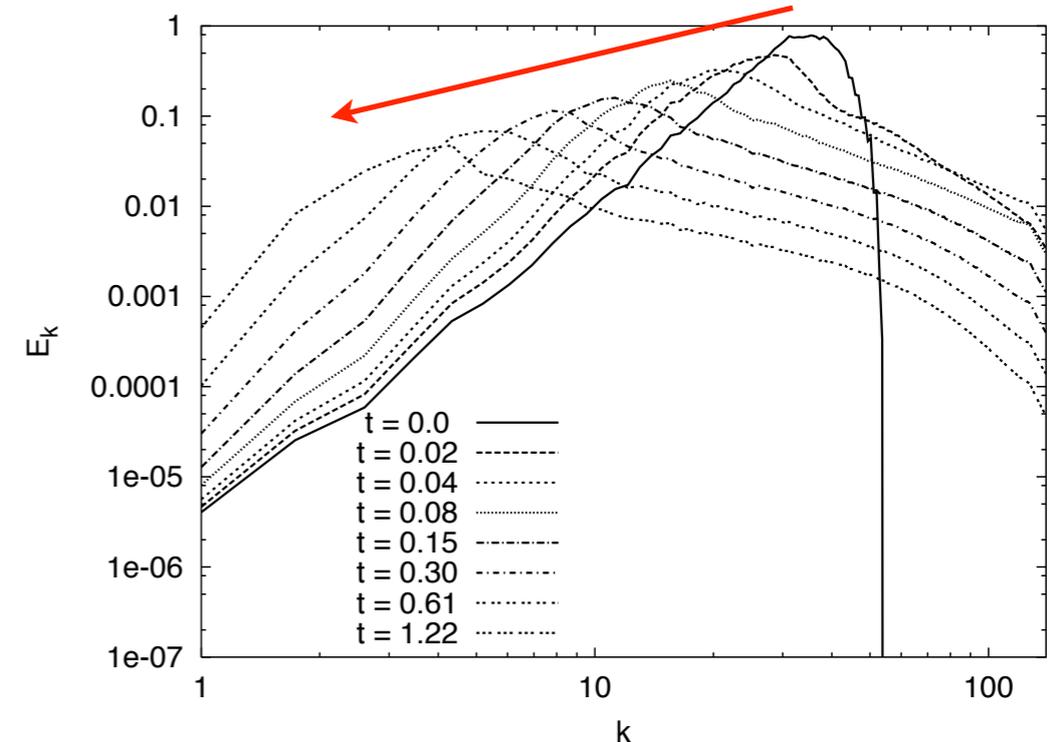
Helicity conservation leads to an enhancement of large-scale correlation of MFs: Inverse Cascade (IC)

MHD simulations tells that coherent length (or peak scale) of MFs is determined by the eddy scale (at recombination).

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

('04 Banerjee+)

CMB constraint

Inconsistent with MHD evolution

Blazar observations

log(B/Gauss)

log(L_B/Mpc)

MF coherent length

- Wash   oshnikov)

s_L

s_L

c_L arried

Baryon as

$$\eta_B \equiv$$

re)

d_L

Temperature: T (GeV)
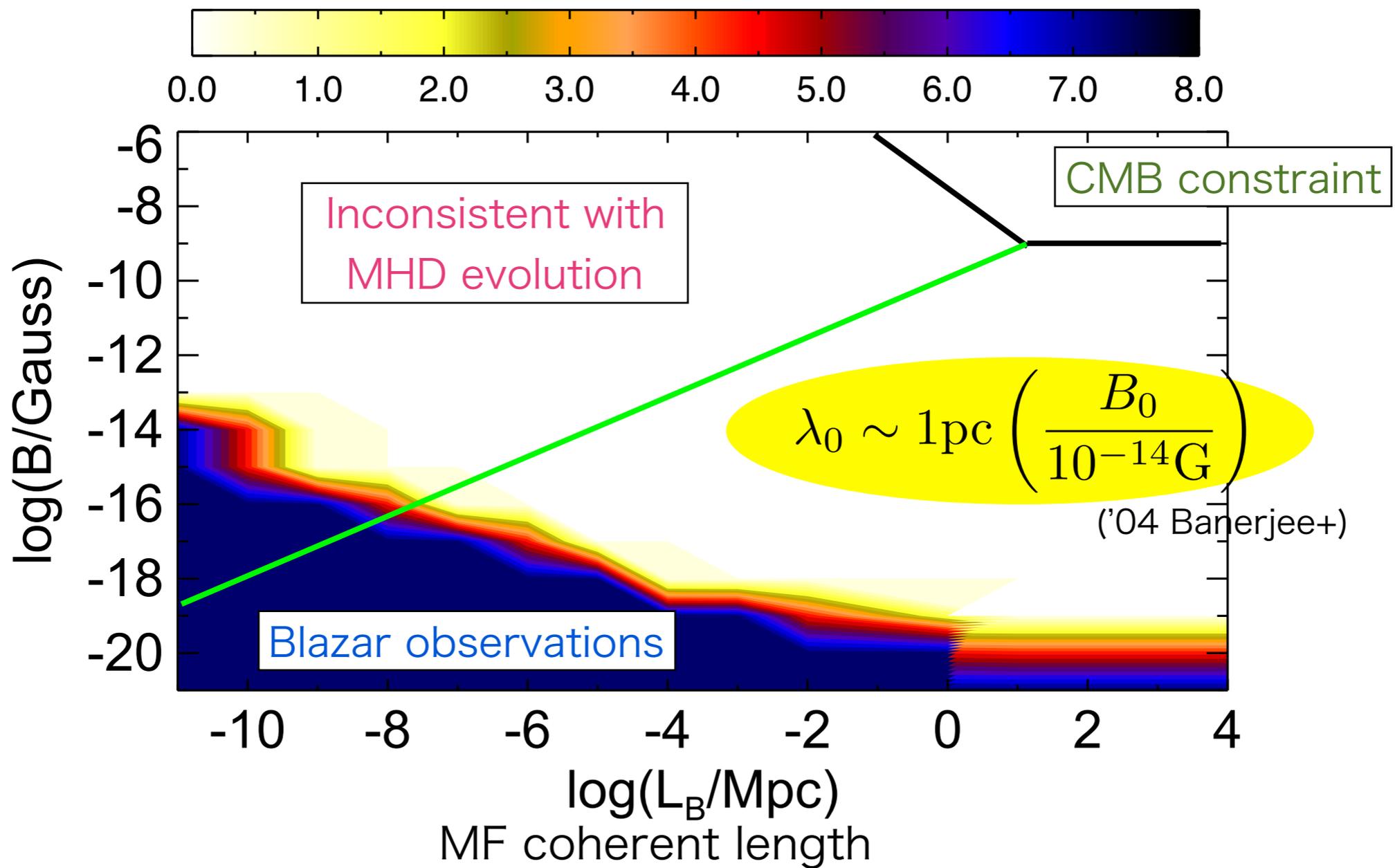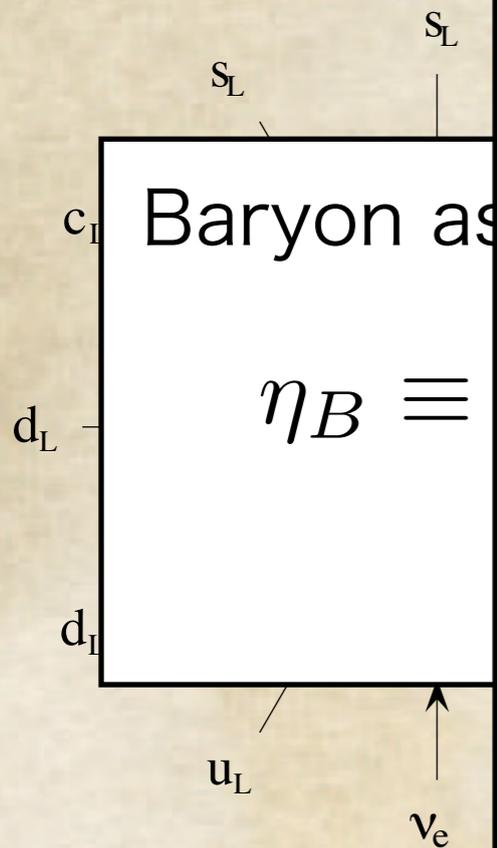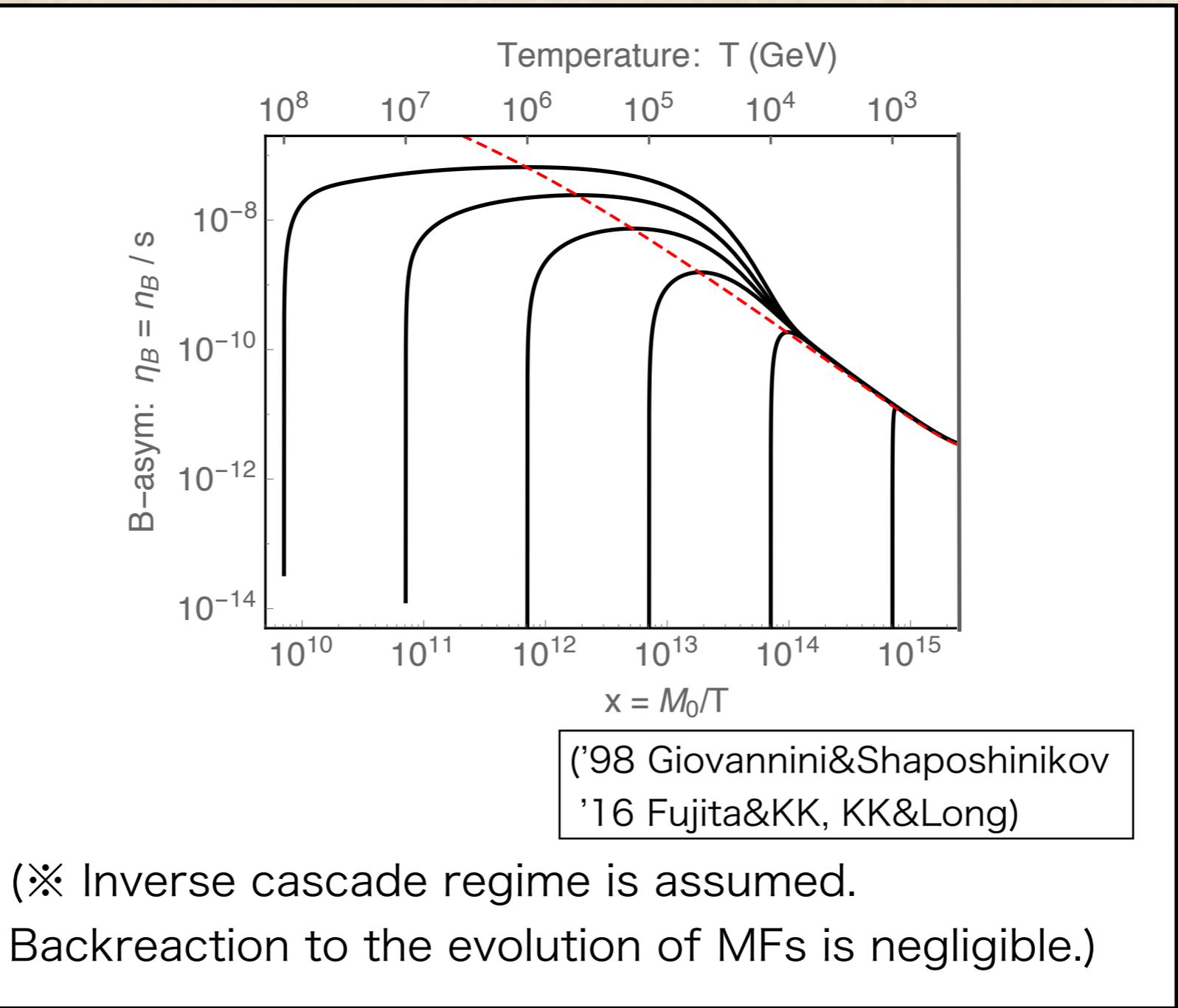
($'$98 Giovannini&Shaposhinikov
$'$16 Fujita&KK, KK&Long)

d_L shout term.)

u_L

ν_e

e_R^+

W. Buchmüller, 1212.355 y_e^{ij}

(※ Inverse cascade regime is assumed.
Backreaction to the evolution of MFs is negligible.)

At th

Washout is determined by spin-flip interactions

Parameterization of the evolution of weak mixing angle