Baryon Asymmetry, Chiral Asymmetry, and the Magnetic Fields in the Universe

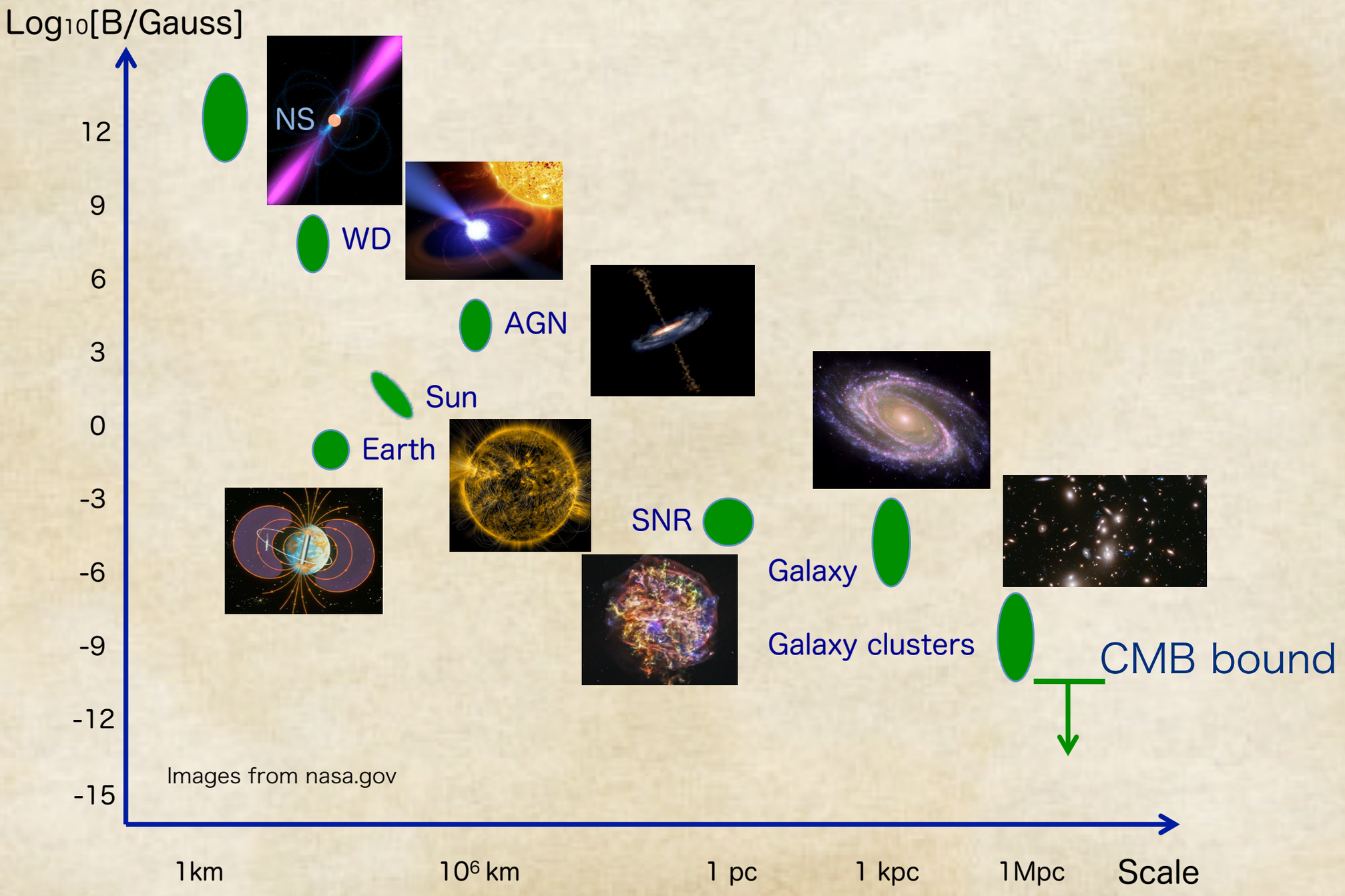
based on: T. Fujita (Kyoto) & KK, PRD93 (2016) 083520 [arXiv:1602.02109 (hep-ph)]
KK & A.J.Long (Michigan), PRD94 (2016) 063501 [arXiv:1606.08891 (astro-ph.CO)]
KK & A.J.Long (Michigan), PRD94 (2016) 123509 [arXiv:1610.03074 (hep-ph)]
D.Jimenéz (MPIK), KK, K.Schmitz(Padova), X.Xu (MPIK),
JCAP12 (2017) 011 [arXiv:1707.07943 (hep-ph)]
KK, PRD97 (2018) 103506 [arXiv:1802.03055 (hep-ph)]
KK, Chang Sub Shin (IBS-CTPU), arXiv:1905.06966 [hep-ph]

Kohei Kamada
(RESCEU, U Tokyo)

43rd John Hopkins Workshop
03/06/2019 @ Kavli IPMU, U Tokyo

Courtesy H.Oide

Magnetic fields (MFs) in the Universe



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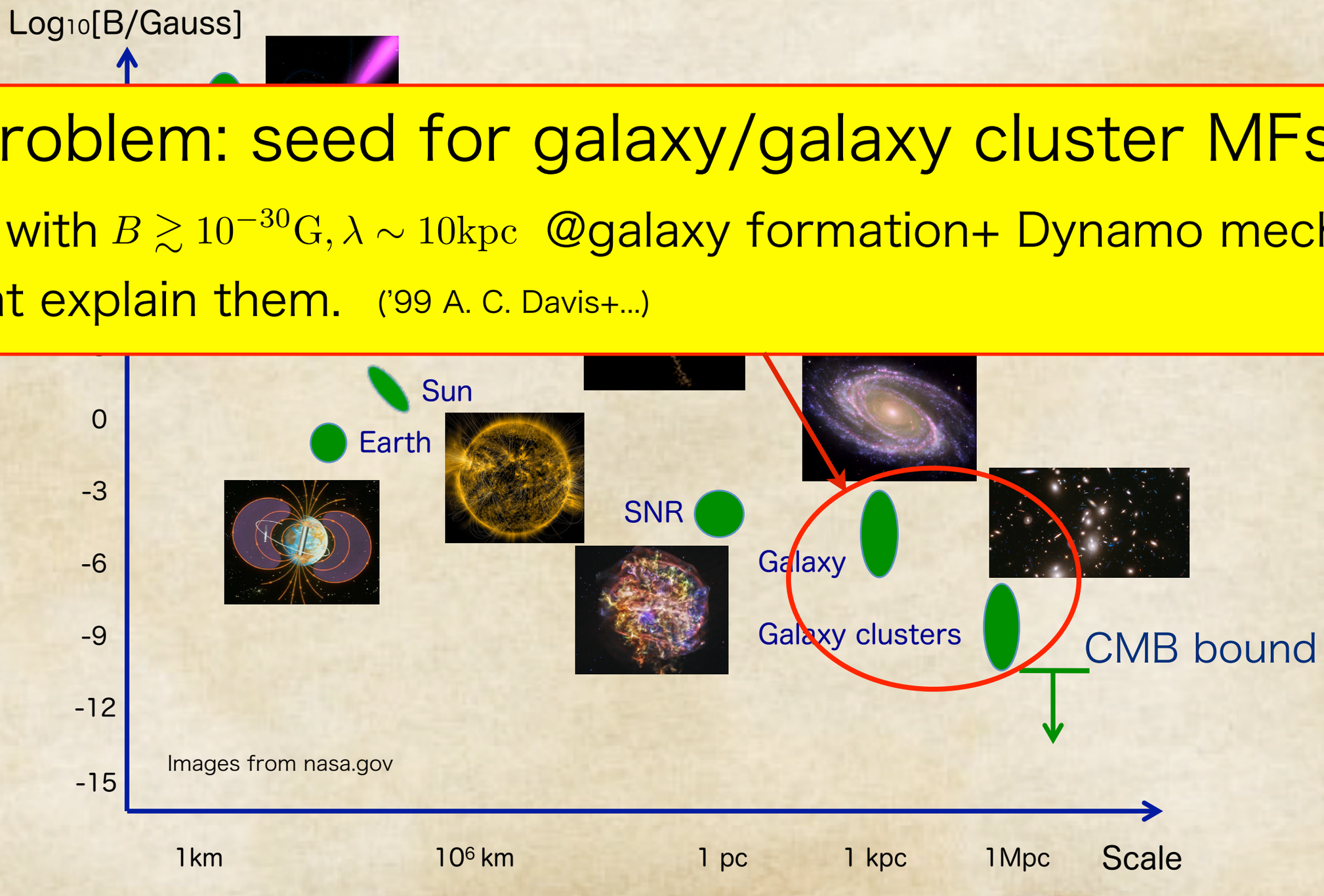
Magnetic fields (MFs) in the Universe

Old problem: seed for galaxy/galaxy cluster MFs.

MFs with $B \gtrsim 10^{-30}\mathrm{G}, \lambda \sim 10\mathrm{kpc}$ @galaxy formation+ Dynamo mech. might explain them. ('99 A. C. Davis+...)



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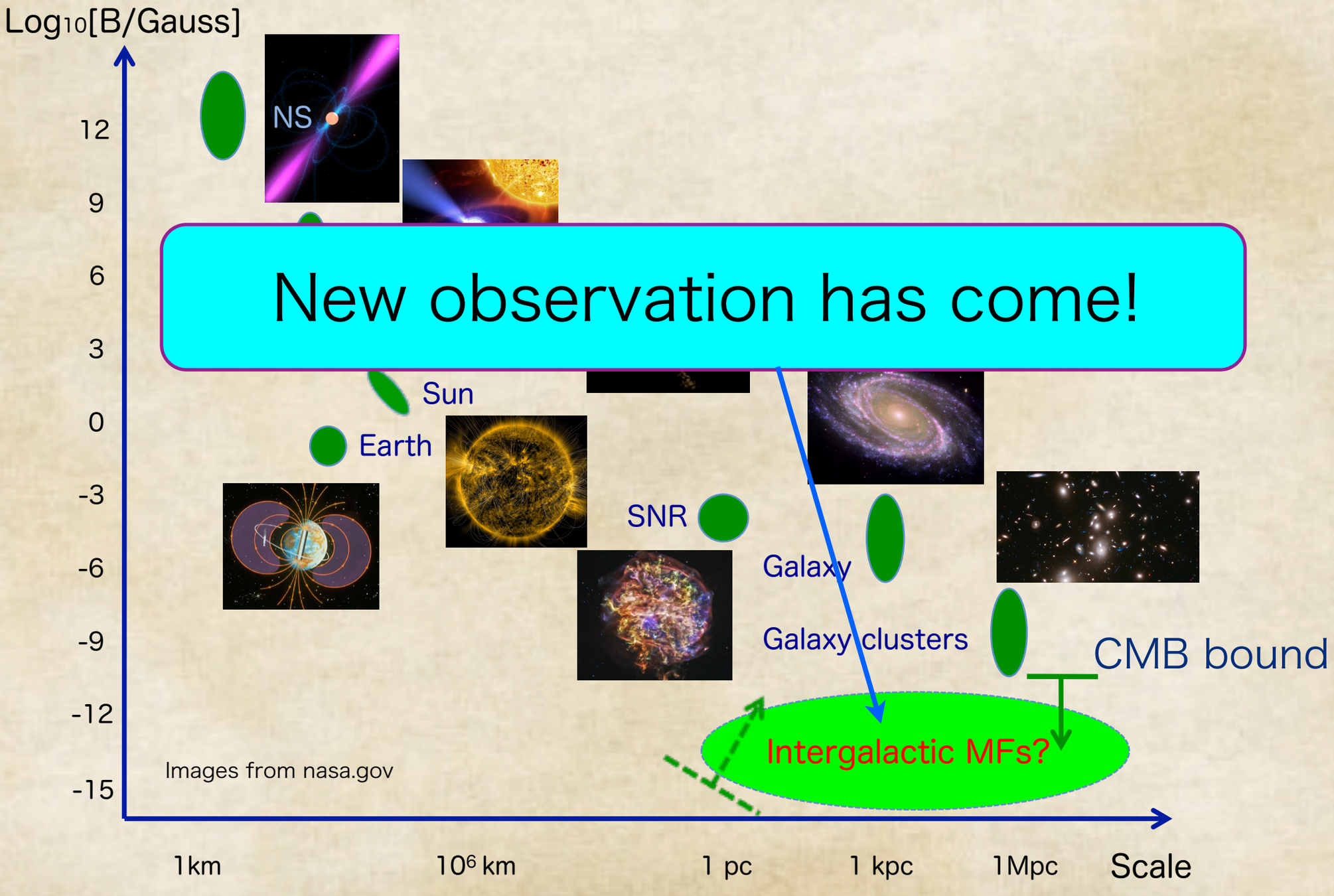
Magnetic fields (MFs) in the Universe



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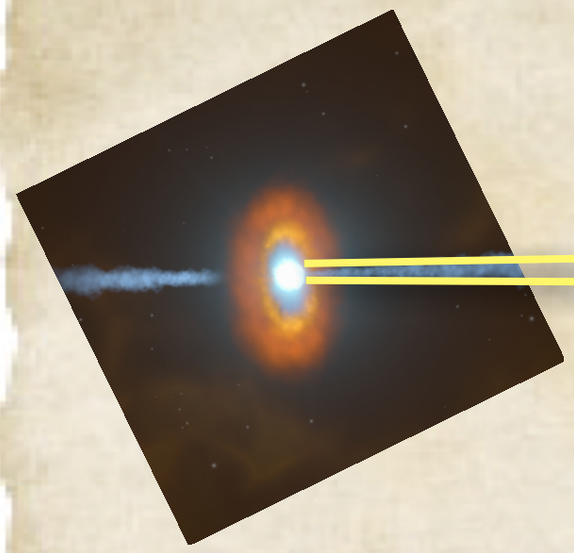
Evidence (?) of large scale magnetic fields

: γ-ray from Blazars (theory)

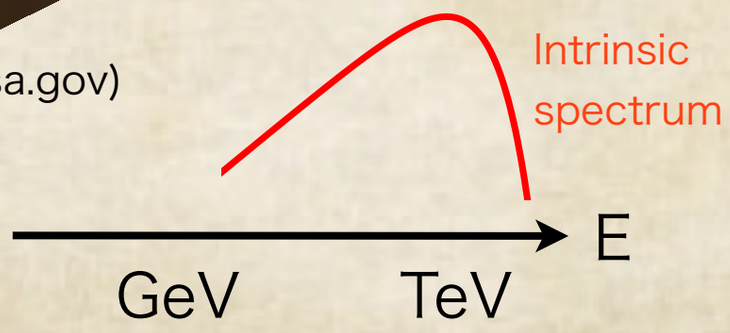
AGN/Blazar



~TeV γ

~ 100 Mpc

(from nasa.gov)



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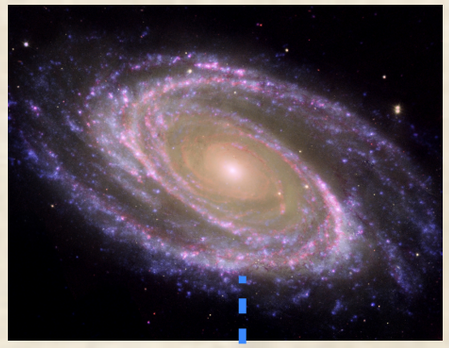
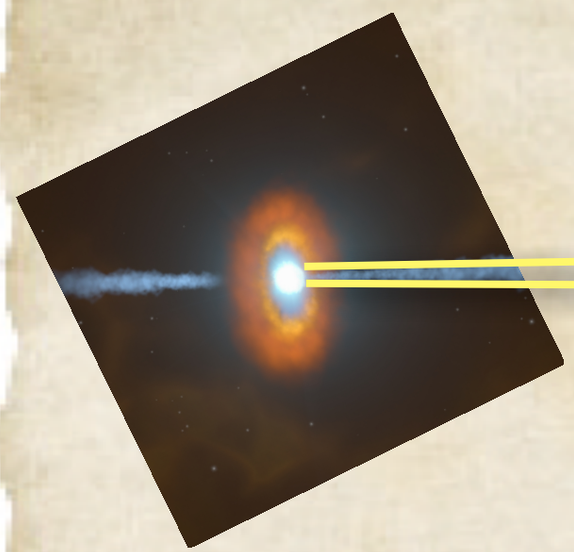


AGN/Blazar

Ex-galactic

BG Light ~eV



~TeV γ

~ 10 kpc

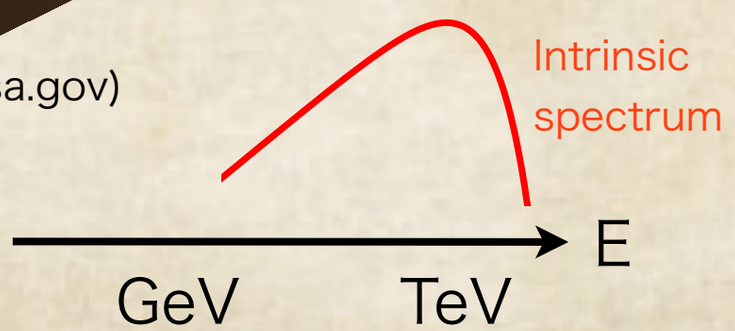
e^+

e^-

~ 100 Mpc

pair creation

(from nasa.gov)



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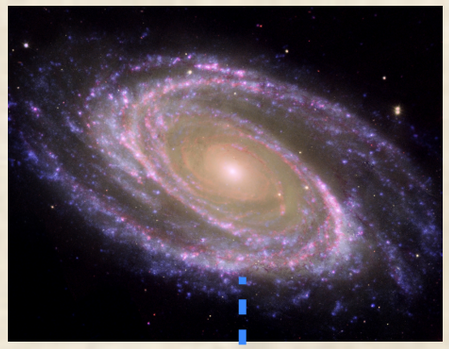
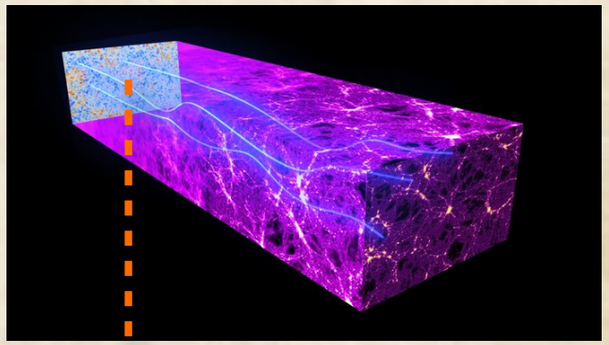


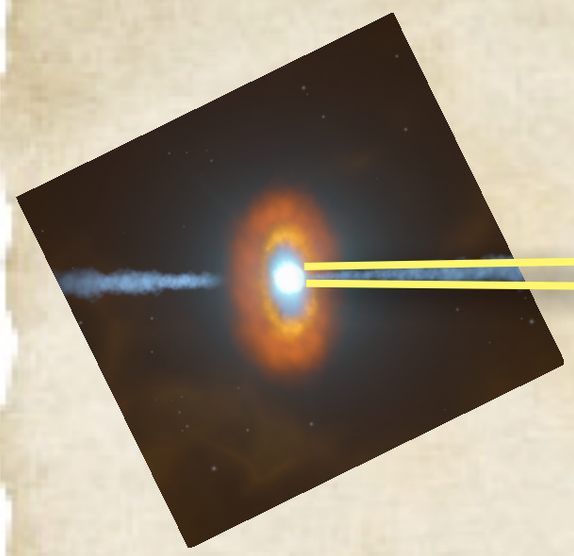


(from esa.int)

AGN/Blazar

Ex-galactic
BG Light ~eV

CMB
10^{-4}~eV



(from nasa.gov)

~TeV γ

~ 100 Mpc

pair creation

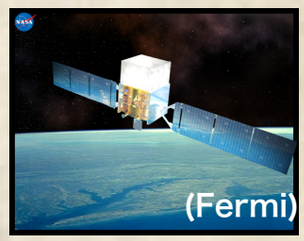
~ 10 kpc

e^+

e^-

inverse Compton

~GeV γ



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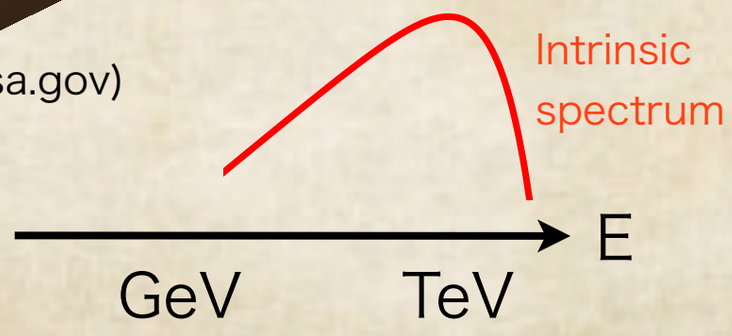
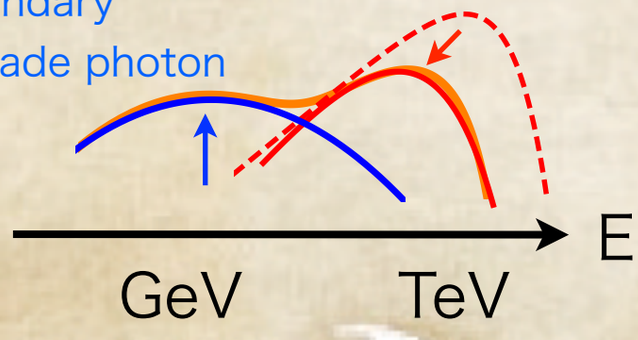




Courtesy H.Oide

Evidence (?) of large scale magnetic fields

: γ-ray from Blazars (observation)

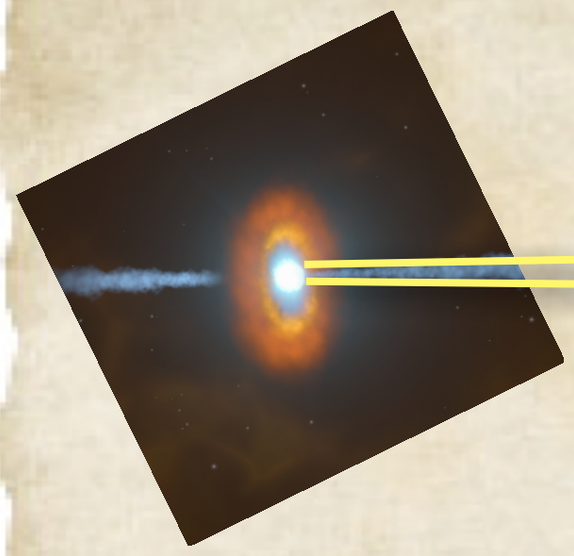
(from na

Theoretical prediction

Intrinsic

from esa.int)

AGN/Blazar



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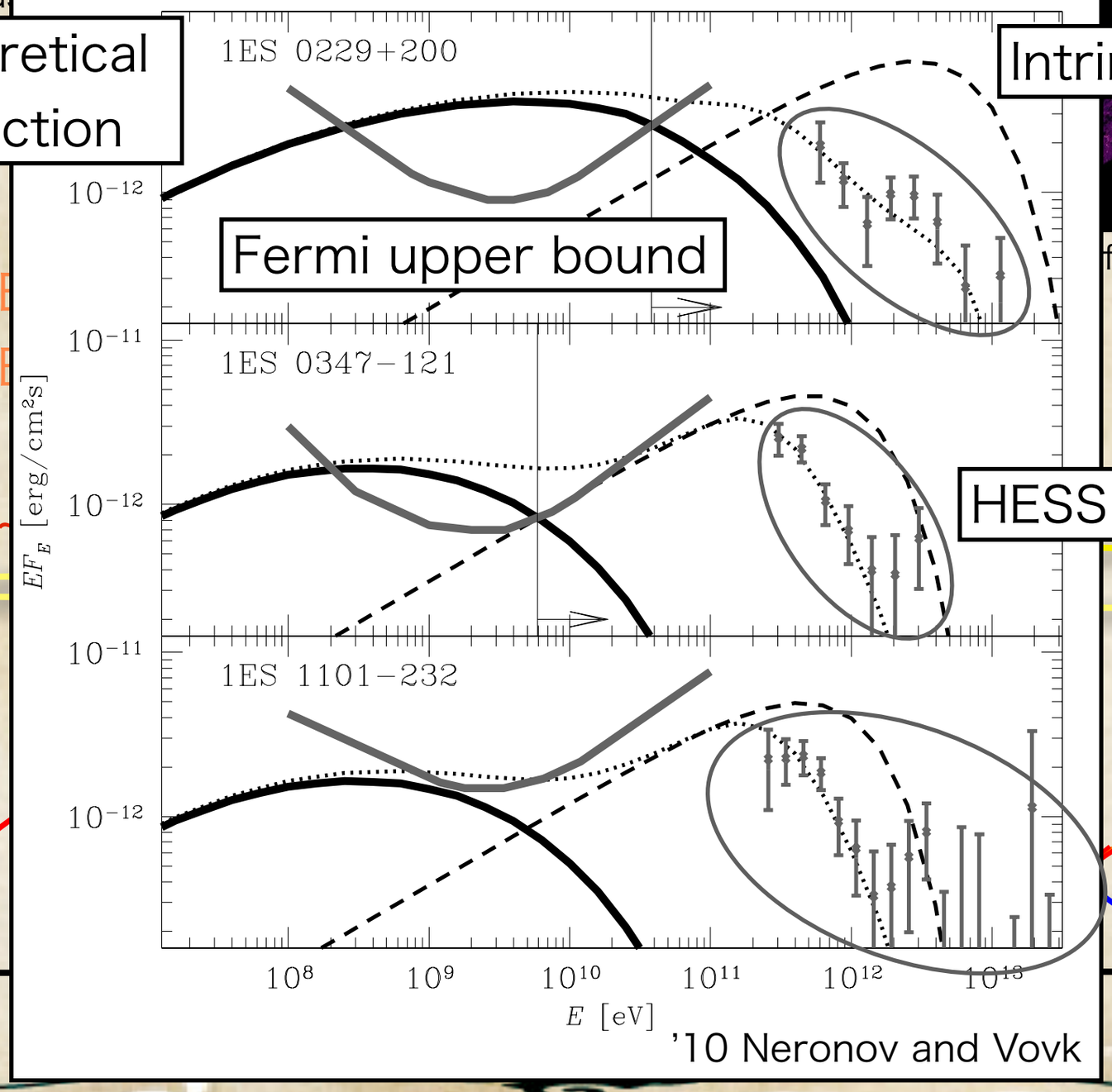
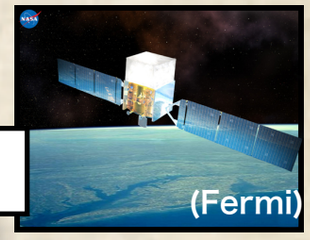


Fermi upper bound

HESS data



(from nasa.gov)

GeV

TeV

E

'10 Neronov and Vovk

Courtesy H.Oide

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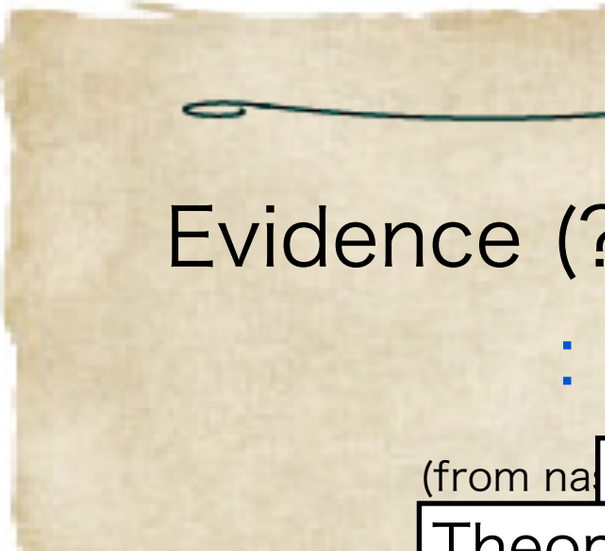
Theoretical prediction

AGN/Blazar



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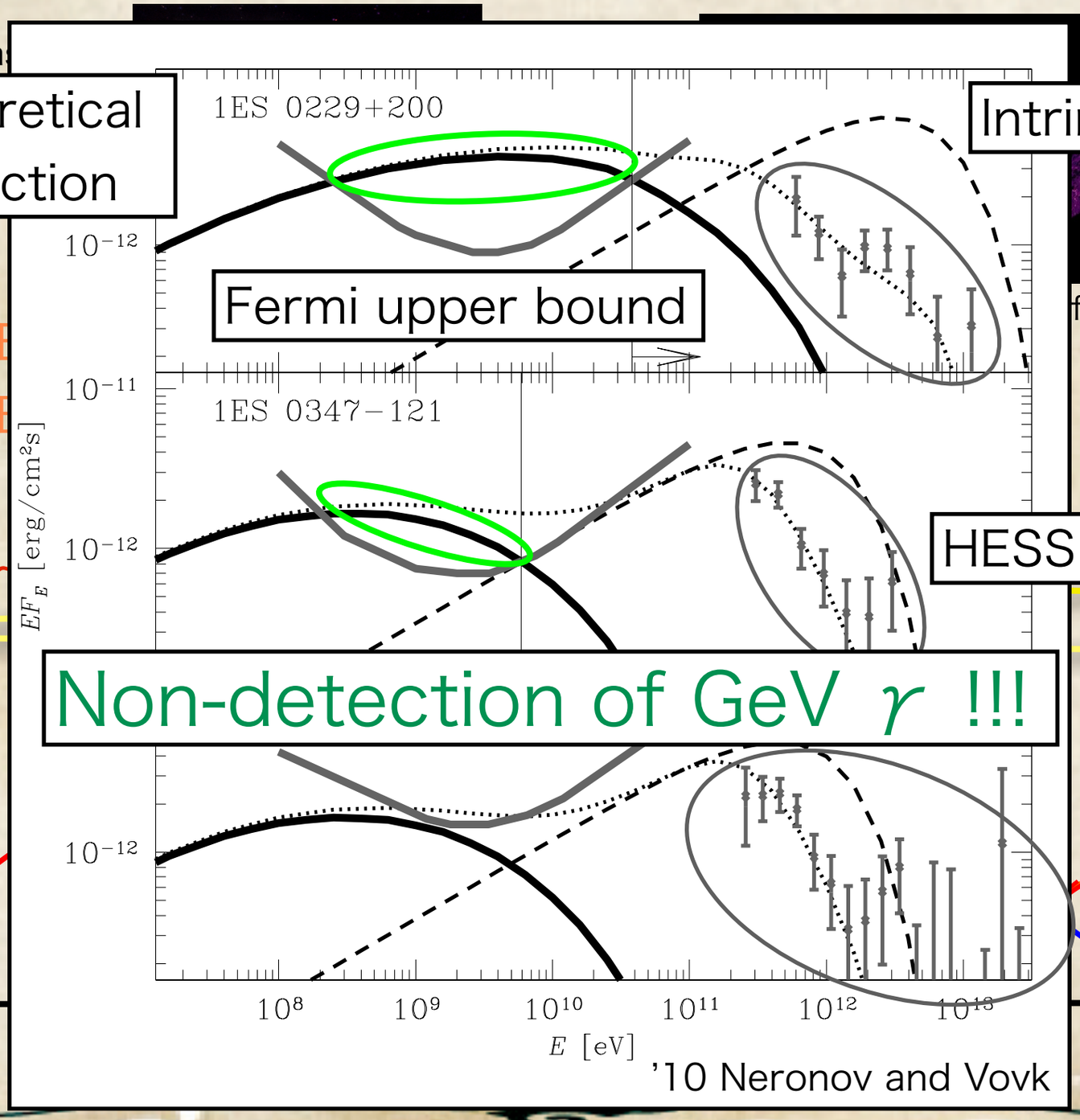
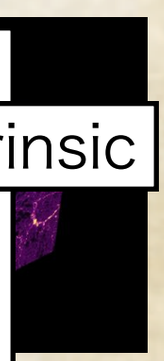
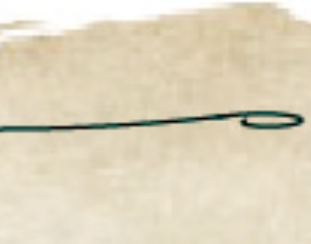




(from esa.int)

HESS data



(from nasa.gov)

GeV

TeV

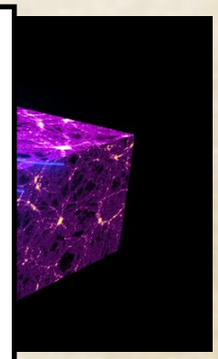
E

Courtesy H.Oide

Evidence (?) of intergalactic magnetic fields

: γ-ray from Blazars (observation)

(from nasa



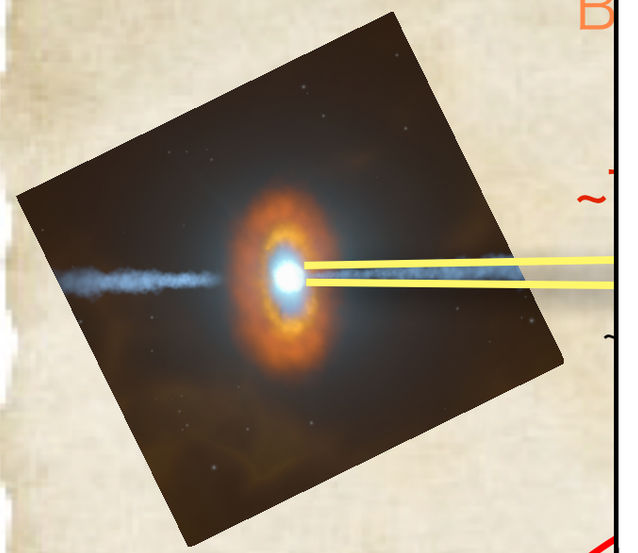
(from esa.int)

AGN/Blazar

E

B

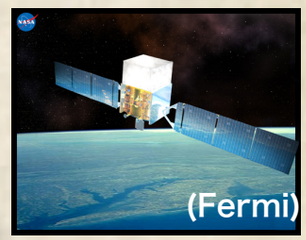
~



(from nasa.gov)

V γ

on



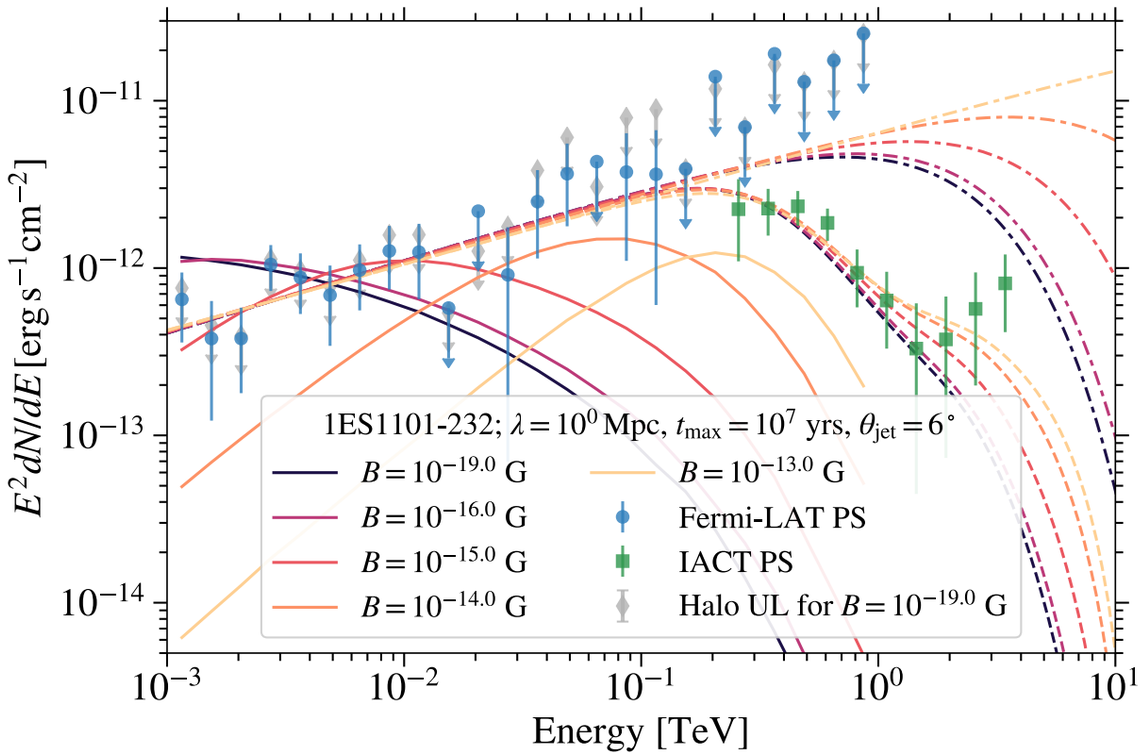
(from nasa.gov)

GeV

TeV

E

Furthermore, recent paper by
Fermi collaboration gives…



1804.08035 (Fermi-LAT collaboration)

GeV spectrum is consistent with intrinsic one.

Courtesy H.Oide

Evidence (?) of large scale magnetic fields

Most convincing explanation: Extragalactic MFs

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Evidence (?) of large scale magnetic fields

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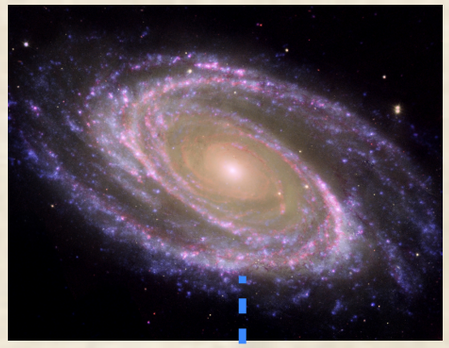

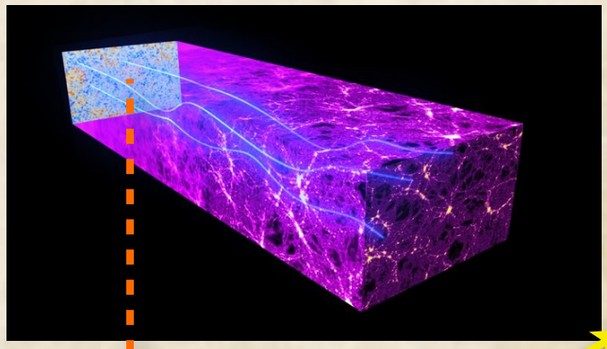

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AGN/Blazar

Ex-galactic
BG Light ~eV

CMB
10^{-4}~eV

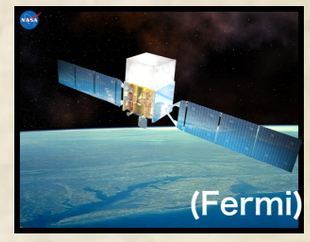
~GeV γ

~ 10 kpc

e^+

~TeV γ

inverse Compton



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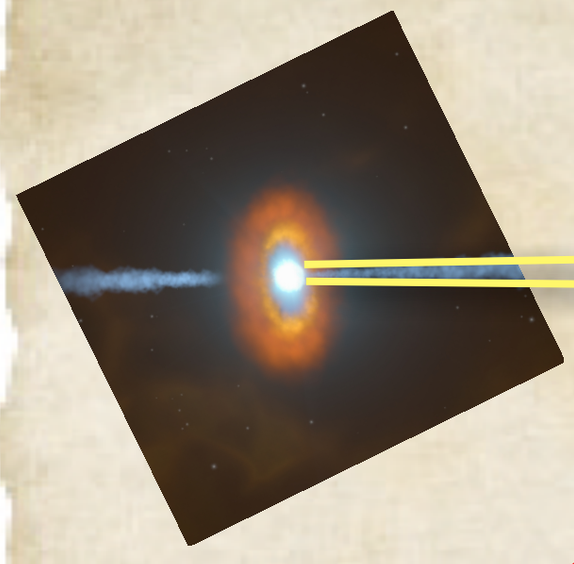


(from nasa.gov)

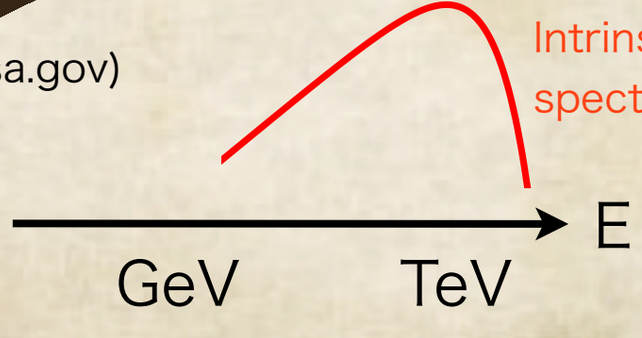
~ 100 Mpc

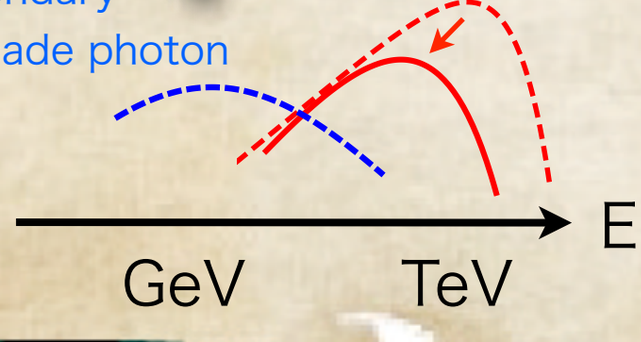
pair creation

e^-

Intergalactic MFs

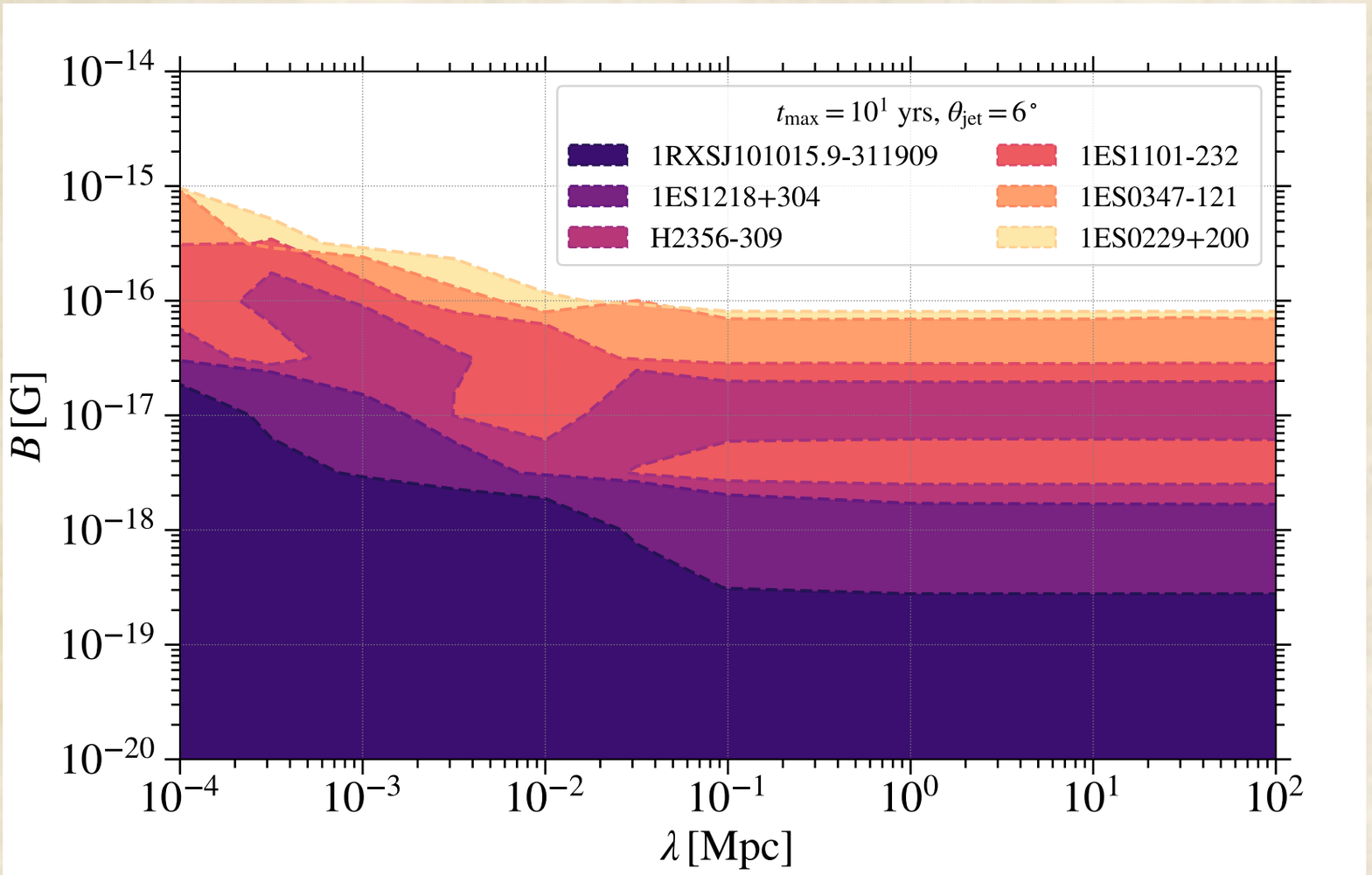
secondary
cascade photon





Courtesy H.Oide

Latest constraints from Fermi 1804.08035 (Fermi-LAT collaboration)



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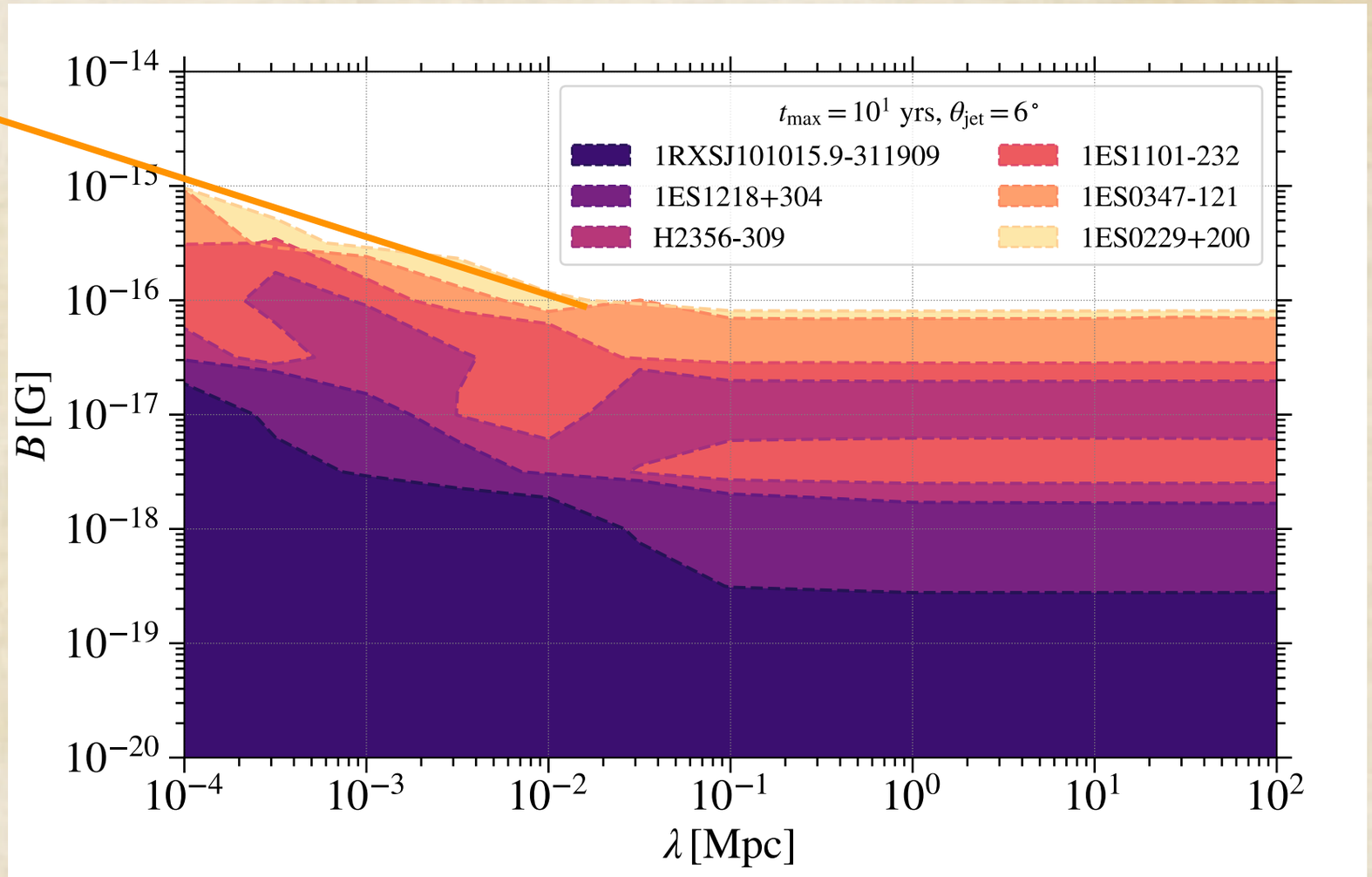
Latest constraints from Fermi 1804.08035 (Fermi-LAT collaboration)

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

Excluded.



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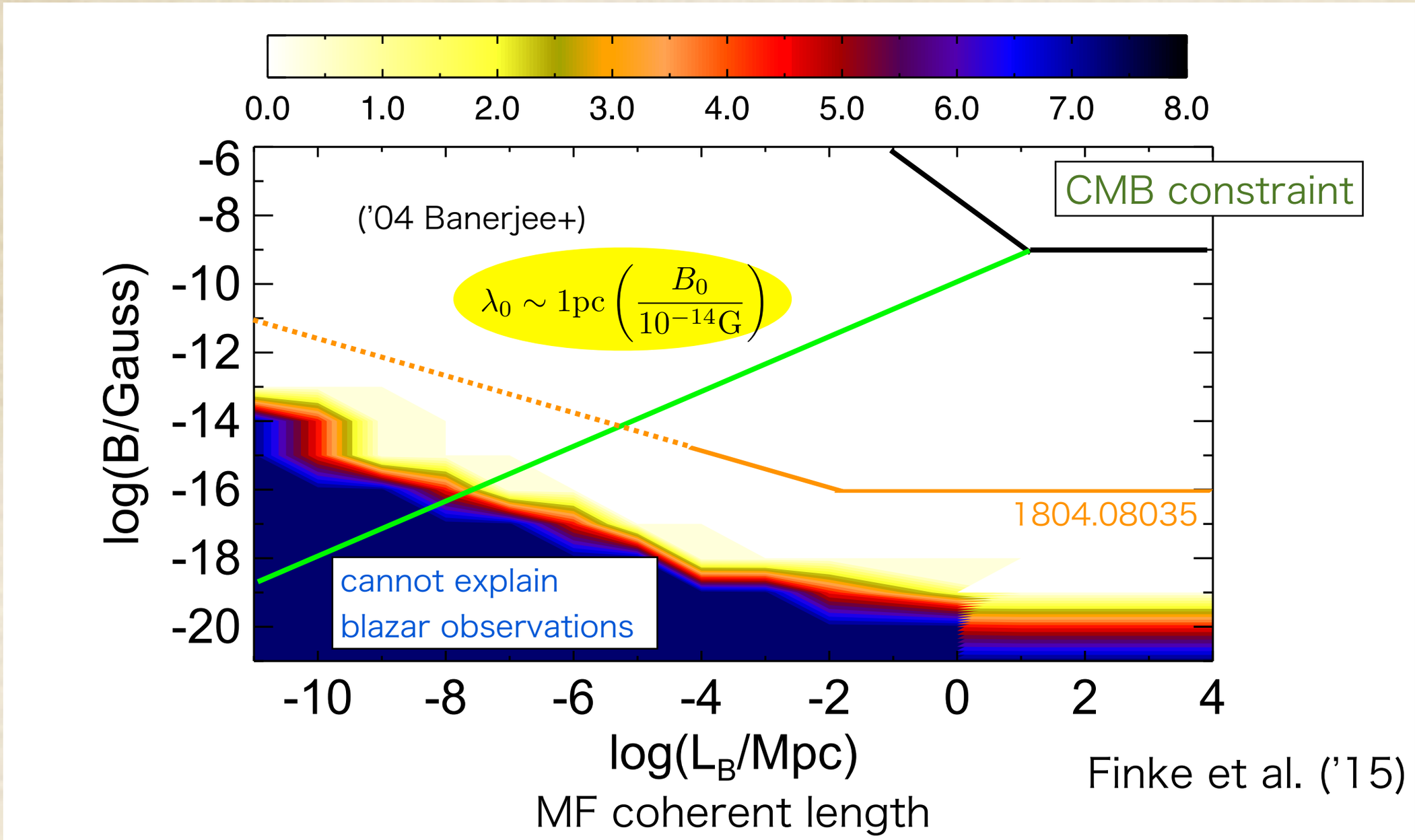

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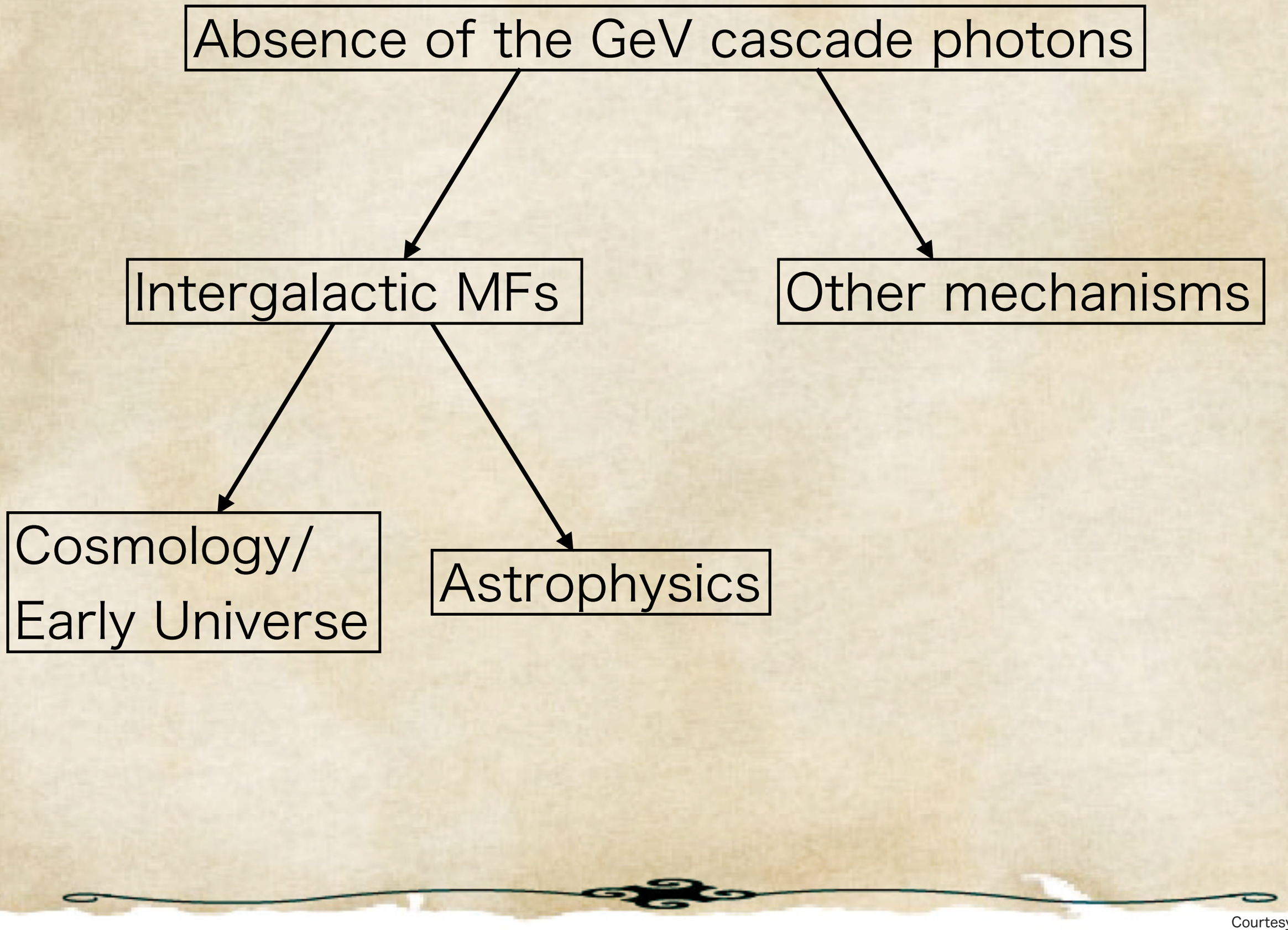


Courtesy H.Oide

Absence of the GeV cascade photons

Intergalactic MFs

Other mechanisms

Cosmology/
Early Universe

Astrophysics

Especially focus on the generation before the EWSB
- Relation to other mysteries (inflation, DM).
- Compatible with the Standard Cosmology.

Courtesy H.Oide

The message of this talk

1. If helical hyper MFs existed in the early Universe before the Electroweak symmetry breaking, Baryon asymmetry is generated automatically.

2. Pseudo scalar dynamics as well as the CME is a good mechanism to produce helical hyper MFs.

Courtesy H.Oide

Chiral anomaly in the SM breaks B+L

('76 't Hooft)

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

$$\frac{d}{dt} n_B = \frac{d}{dt} n_L \ni - \frac{g'^2}{16\pi^2} N_g \frac{d}{dt} \left(\frac{H_Y}{V} \right) = \frac{g'^2}{4\pi^2} N_g \boldsymbol{E} \cdot \boldsymbol{B}$$

Hypermagnetic helicity decay = baryon & lepton number induction

Courtesy H.Oide

Hypermagnetic helicity decay in the early Universe

(BG hyperMFs with large coherence length)

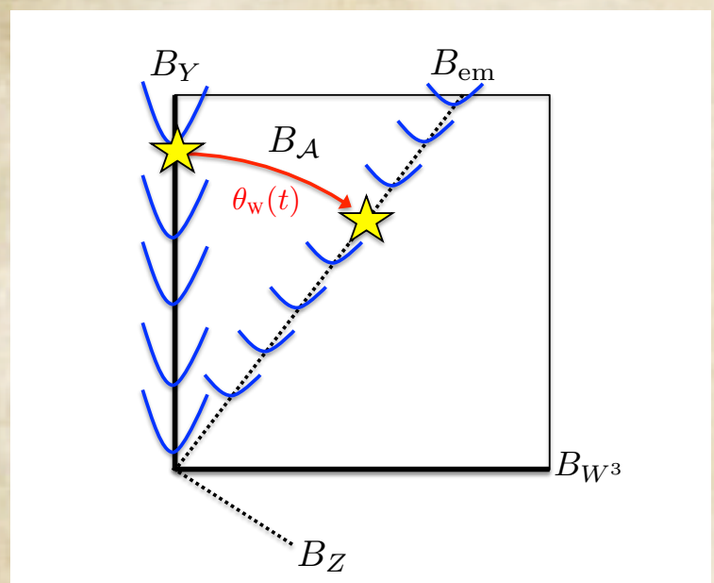
1. MHD diffusion ('98 Givannini&Shaposhnikov, '16 Fujita&KK)

$$\frac{dn_B}{dt} \ni \langle \boldsymbol{E}\cdot\boldsymbol{B}\rangle = \frac{\langle \boldsymbol{B}\cdot(\boldsymbol{\nabla}\times\boldsymbol{B})\rangle}{\sigma} \simeq \frac{B^2}{\lambda\sigma} \quad \sigma \simeq 100T$$

('97 Baym+, '00 Arnold+)

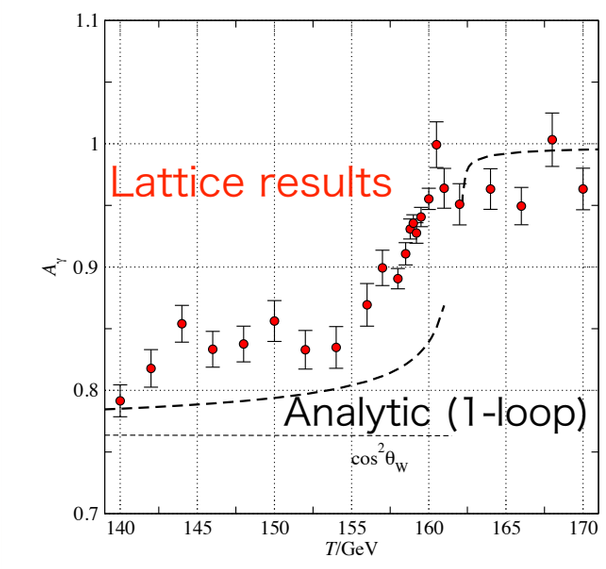
$$\left(\boldsymbol{\nabla}\times\boldsymbol{B} = \cancel{\dot{\boldsymbol{E}}} + \boldsymbol{J}, \quad \boldsymbol{J} = \sigma(\boldsymbol{E}+\boldsymbol{v}\times\boldsymbol{B})\right)$$

2. EWSB ('16 KK&Long)



$$\Delta N_{CS} - \frac{g'^2}{16\pi^2}\Delta H_Y \sim \sin^2\theta_W H_Y$$

$$\frac{dn_B}{dt} \ni \dot{\theta}_W \sin 2\theta_W \frac{H_Y}{V} \simeq \dot{\theta}_W \sin 2\theta_W \lambda B^2$$



('16 D'Onofrio)

Courtesy H.Oide

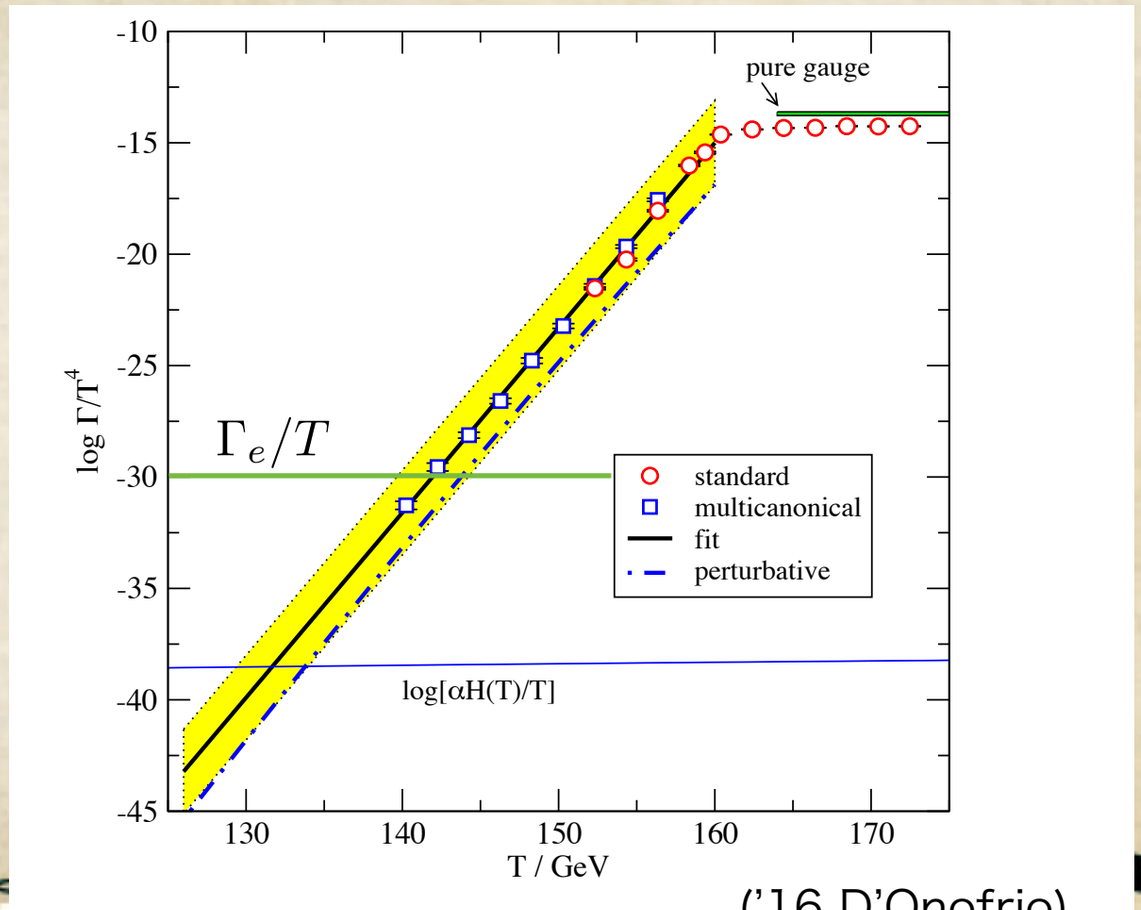
Worry about washout by sphaleron?

Source term　　washout term

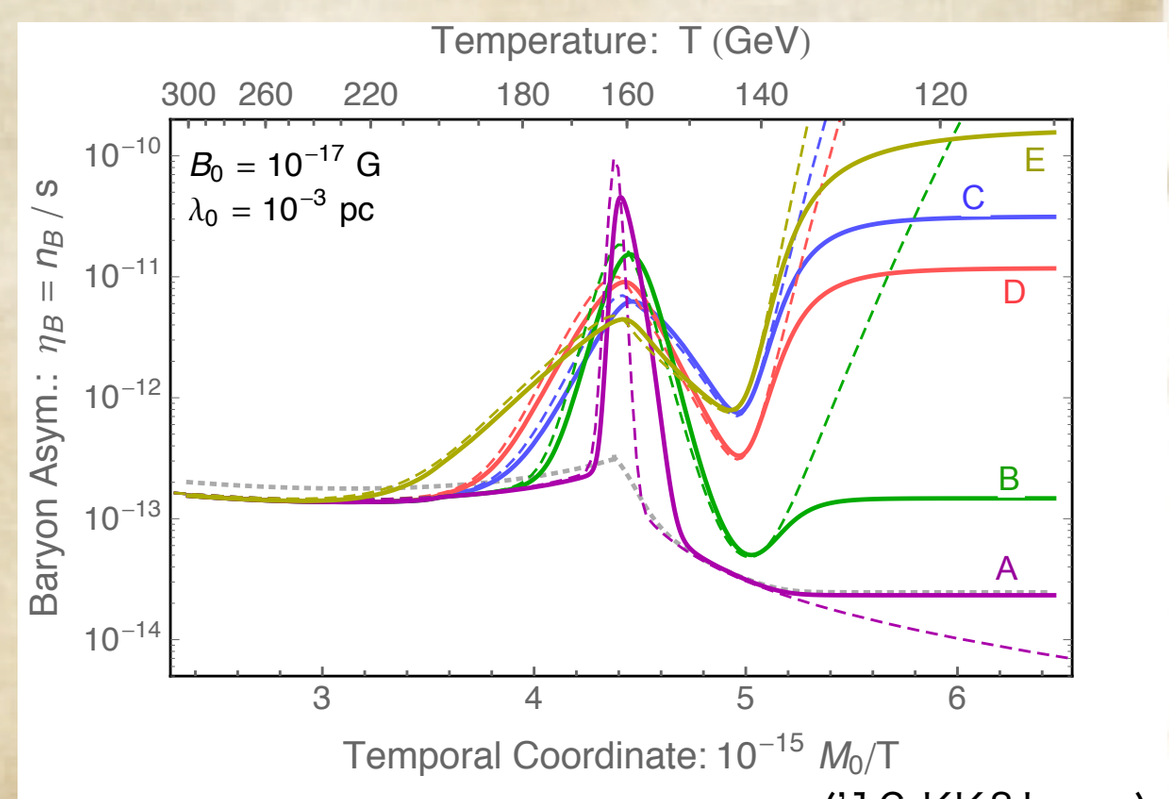
$$\frac{dn_B}{dt} = \left(\#\frac{B^2}{\sigma\lambda} + \#\dot{\theta}_W \lambda B^2 \right) - \Gamma_{\rm w.o.} n_B$$

MHD decay　　EWSB　　EW sphaleron chirality-flip CME

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



('16 D'Onofrio)



('16 KK&Long)

Courtesy H.Oide

Resultant final baryon asymmetry

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

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

$$\gamma_{\rm sph} = \exp\left[-145 + 0.8\left(\frac{T}{\rm GeV}\right)\right]$$

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

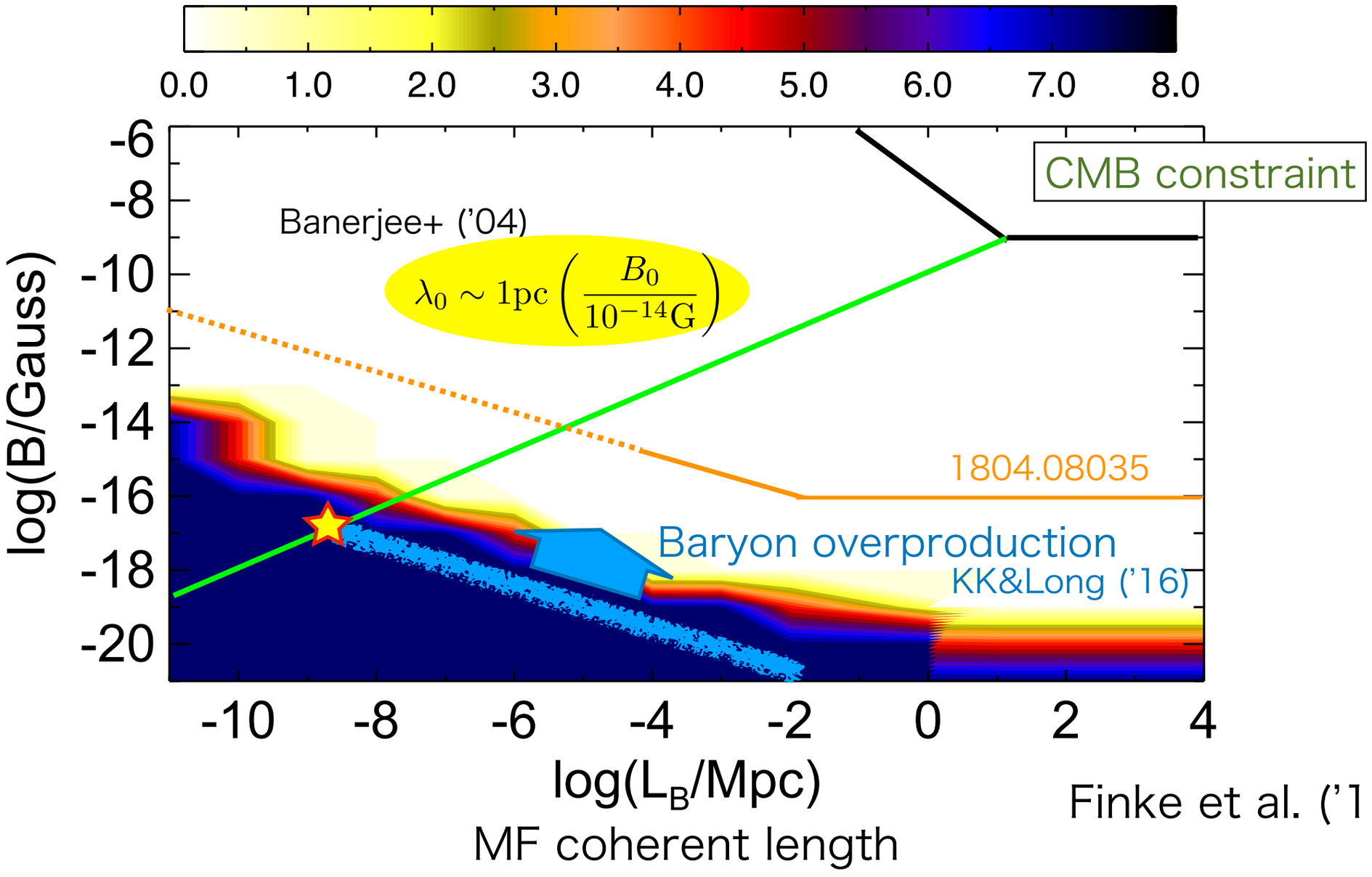
('16 KK&Long)

Corresponds to the intergalactic magnetic field properties:

$$\lambda_0 = 10^{-3\sim 2}{\rm pc}, \quad B_0 \simeq 10^{-16\sim 17}{\rm G}$$

Courtesy H.Oide

In the B_0-λ_0 plane…



in the case magnetic fields are maximally helical.

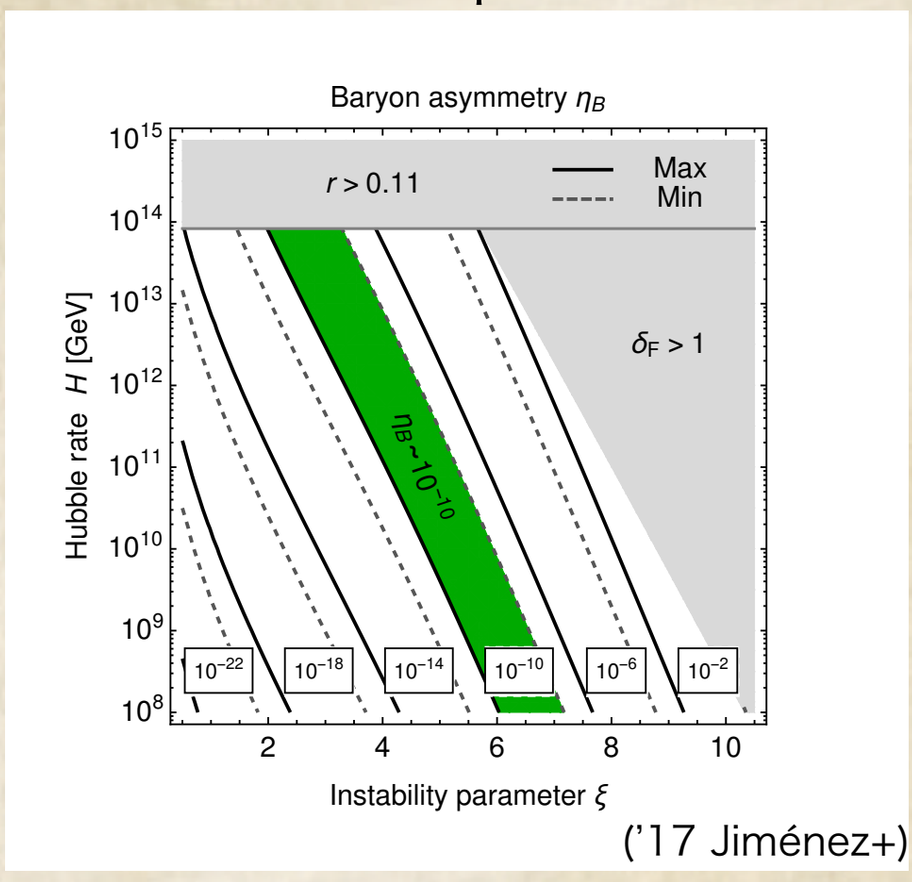
Courtesy H.Oide

Magnetogenesis models

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

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

One polarization mode feels instability => maximally helical MFs



('17 Jiménez+)

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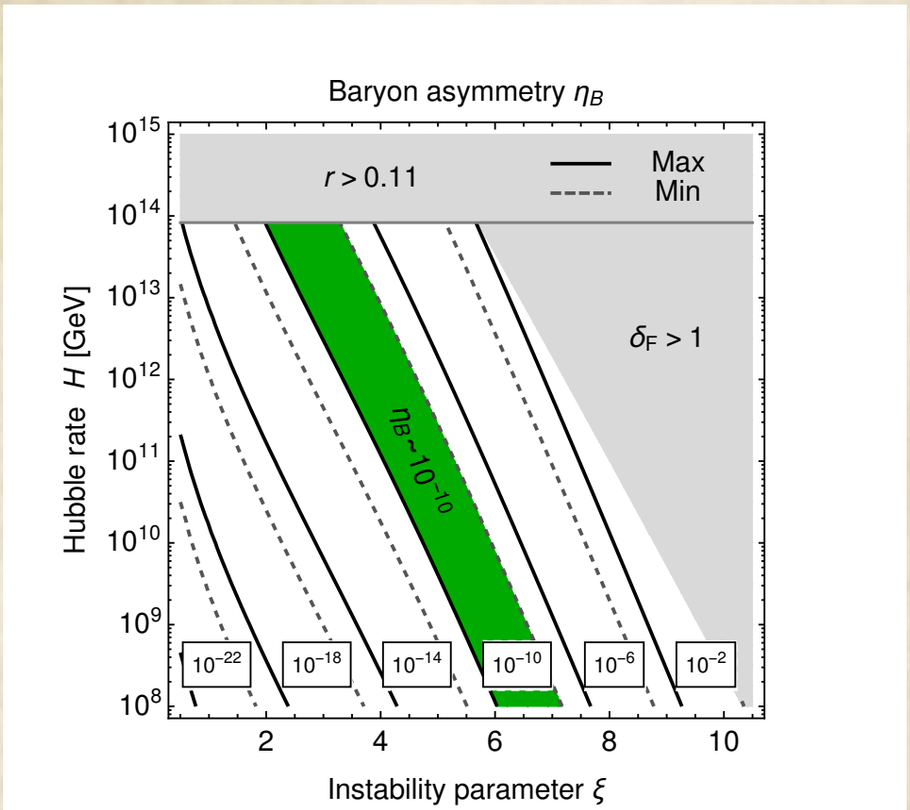
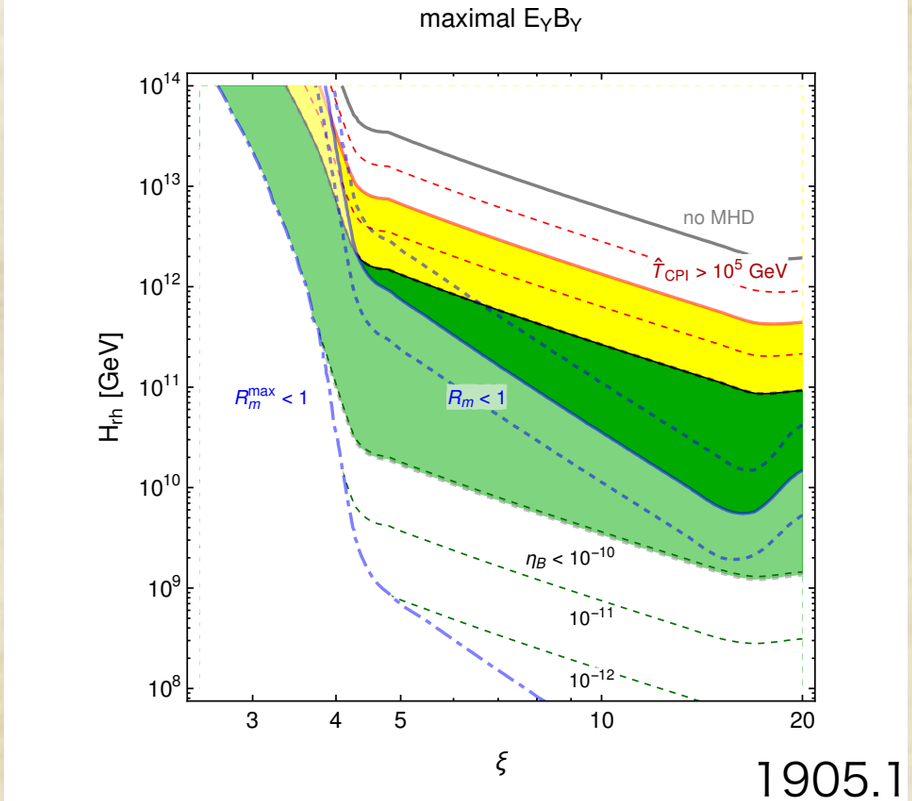
One polarization mode feels instability => maximally helical MFs



('17 Jiménez+)



1905.13318

(Today's paper by Domcke, Harling, Morgante, &Mukaida)

Courtesy H.Oide

Magnetogenesis models

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

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

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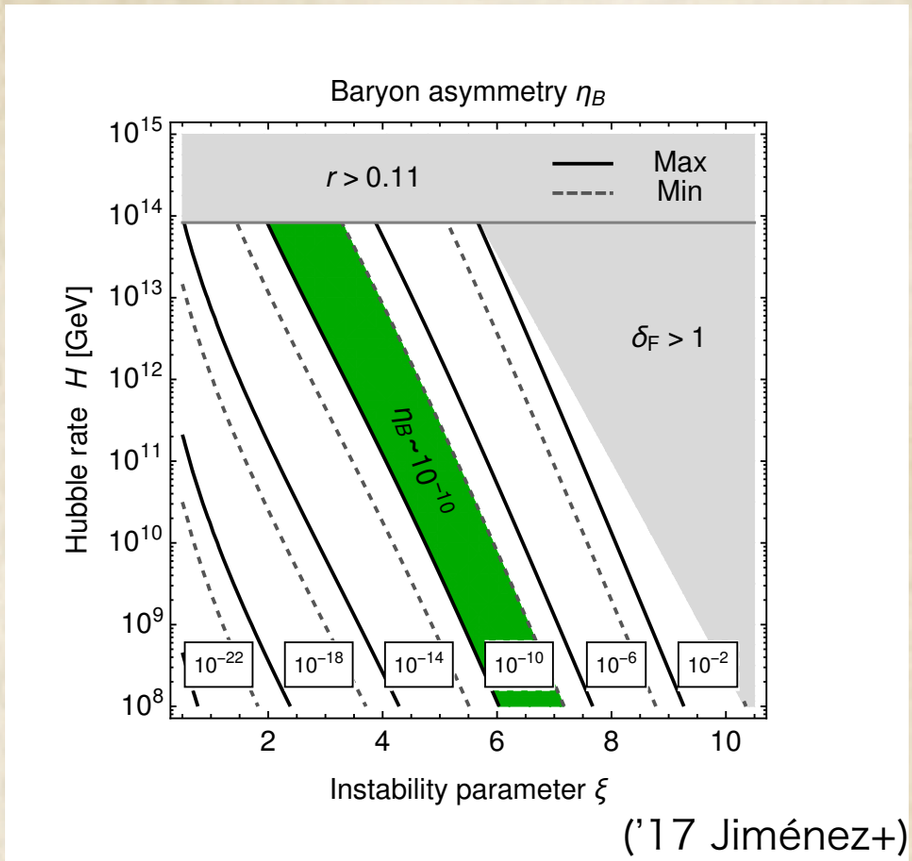
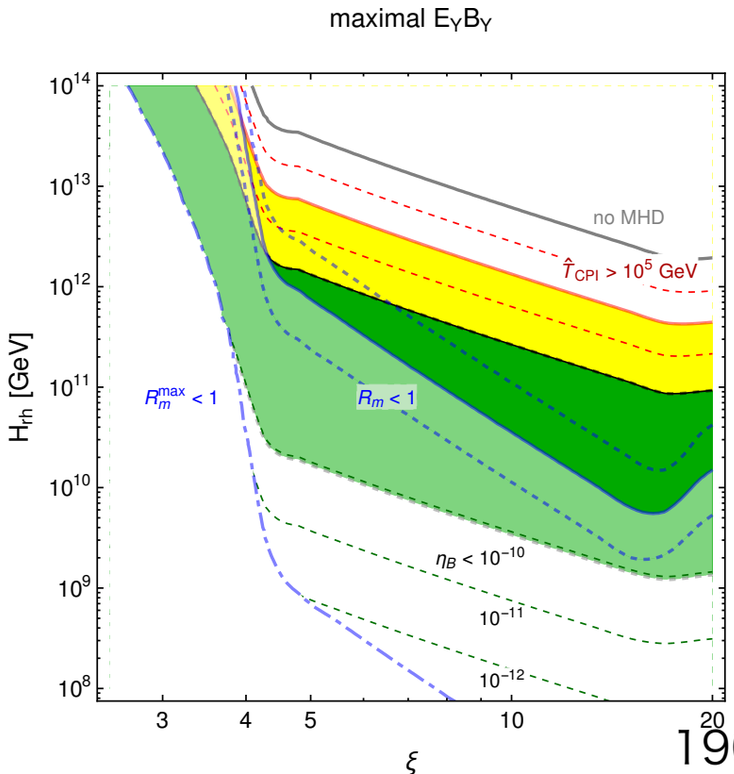


('17 Jiménez+)



1905.13318

(Today's paper by Domcke, Harling, Morgante, &Mukaida)

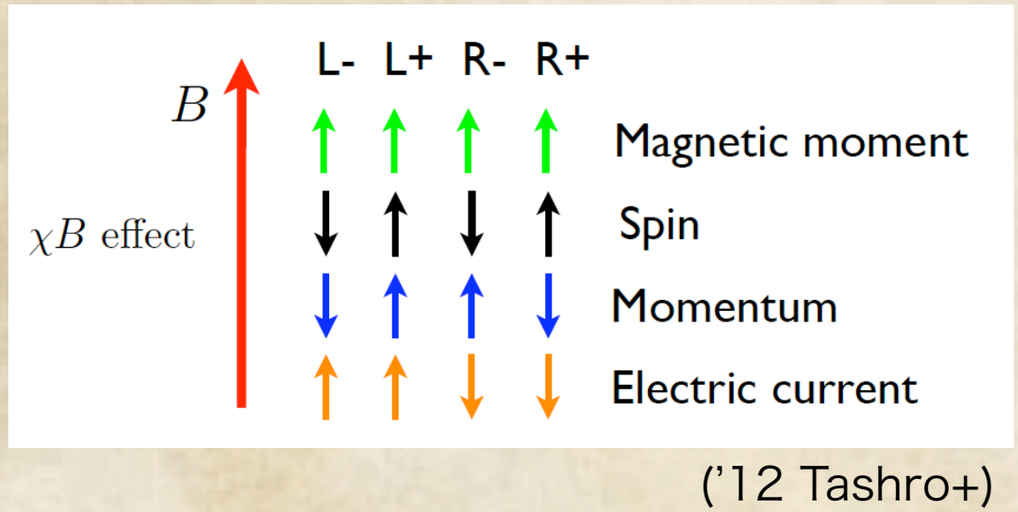
Phase of the Affleck Dine field can also have such an anomalous coupling

('19 KK & Shin)

Courtesy H.Oide

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

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



('12 Tashro+)

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

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

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

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

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

One polarization mode feels instability => maximally helical MFs

Courtesy H.Oide

Summary

- Baryon asymmetry is generated from decaying hypermagnetic helicity through the chiral anomaly. No BSM ingredient!
- B-violation: chiral anomaly/ C&CP-violation: hypermagnetic helicity
  Out of equilibrium: Decay of hypermagnetic helicity/EWSB
- Present B-asymmetry is explained for $B_0 \simeq 10^{-16\sim17}\mathrm{G} \quad \lambda_0 \simeq 10^{-2\sim3}\mathrm{pc}$ with positive maximally helical MFs.
- Anomalous coupling of the pseudo scalar including inflaton and AD field as well as the chiral magnetic effect can generate helical magnetic fields.
- It will be interesting to explore other magnetogenesis mechanisms.

Courtesy H.Oide