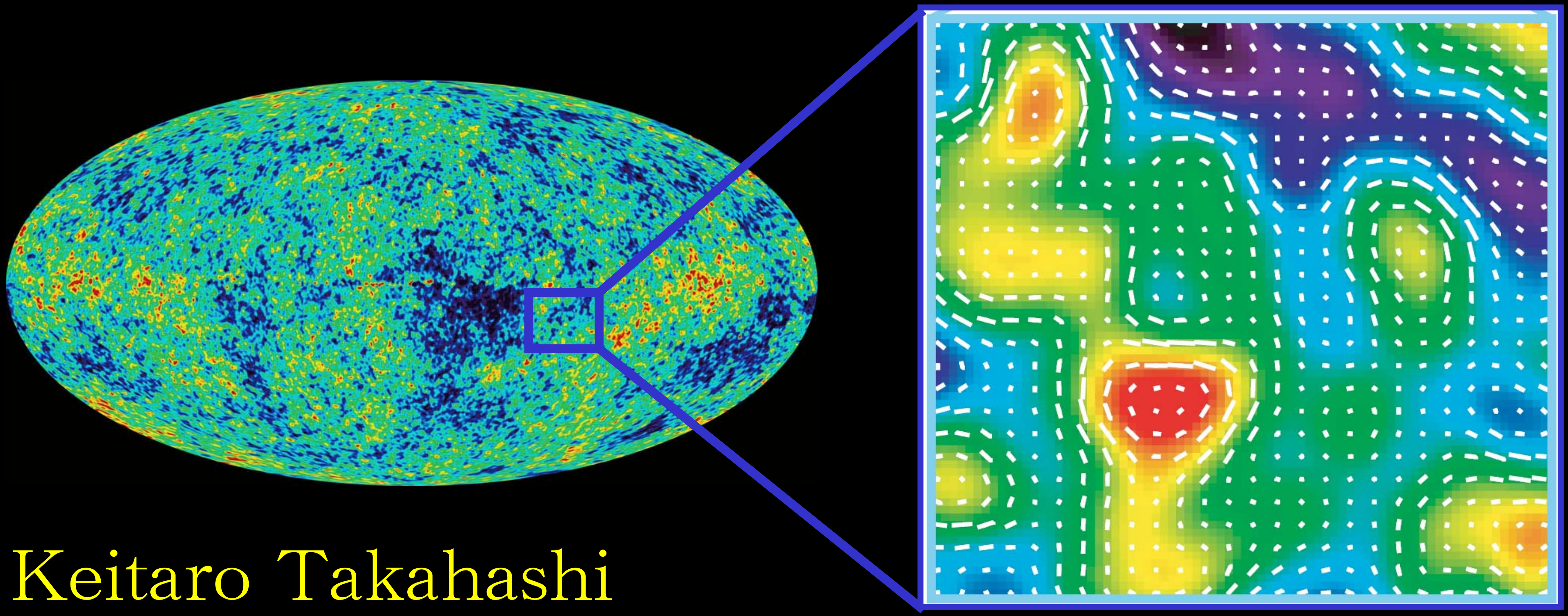
Origin of cosmic magnetic fields



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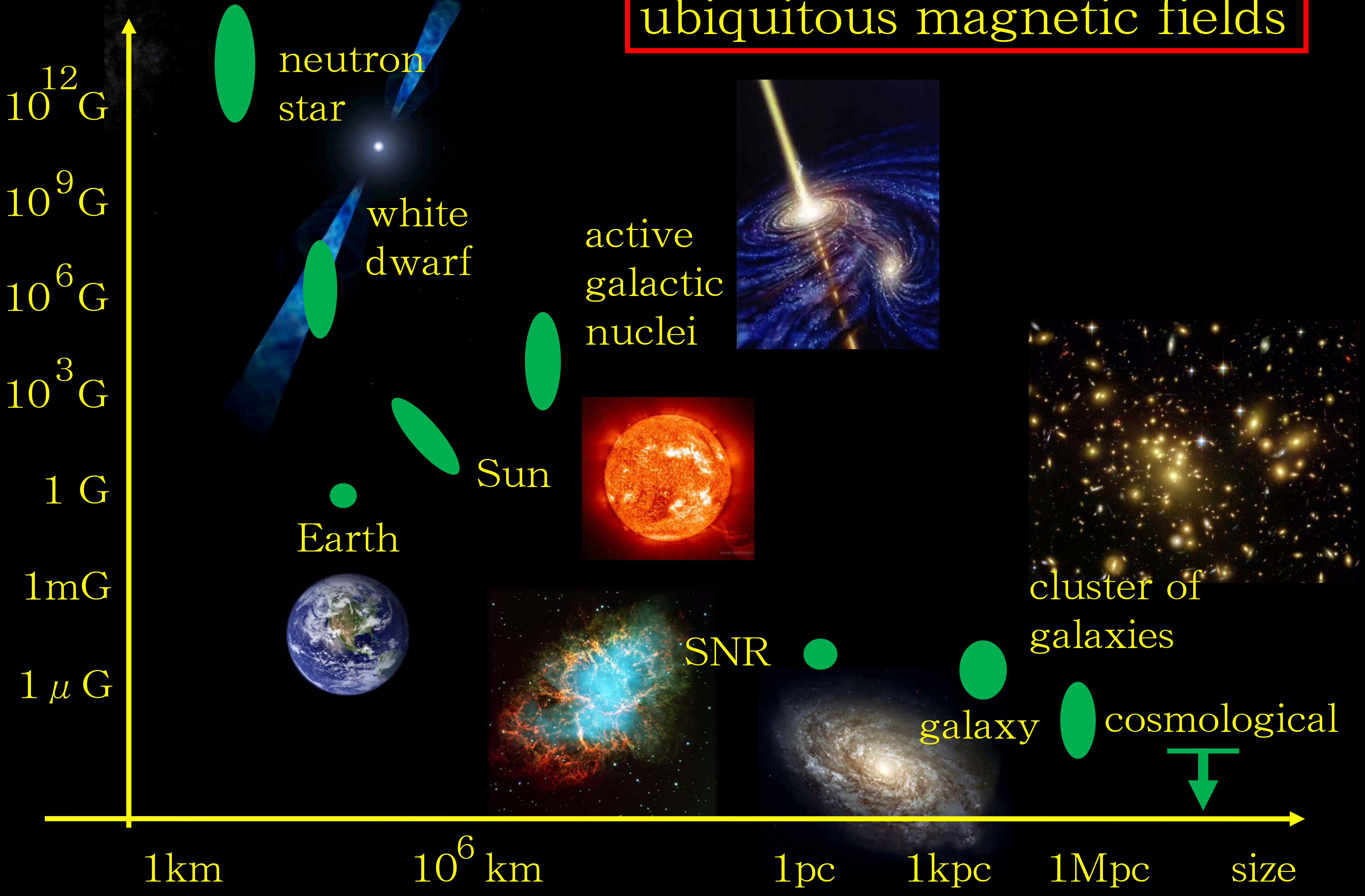
1. Introduction

ubiquitous magnetic fields



cosmological magnetic field

big bang nucleosynthesis

$B < 1\,\mu\mathrm{G}$ (Cheng et al. 96)

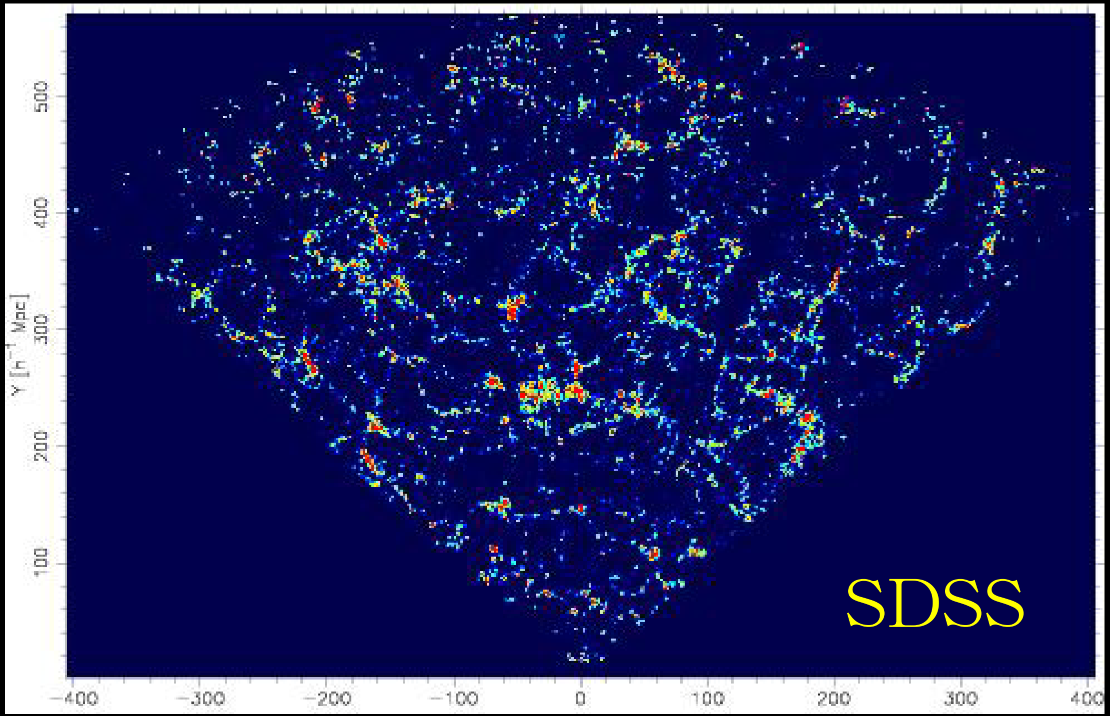
CMB anisotropy

$B < 10\,\mathrm{nG}$ (Giovannini, Yamazaki et al.)

Faraday rotation of distant radio sources

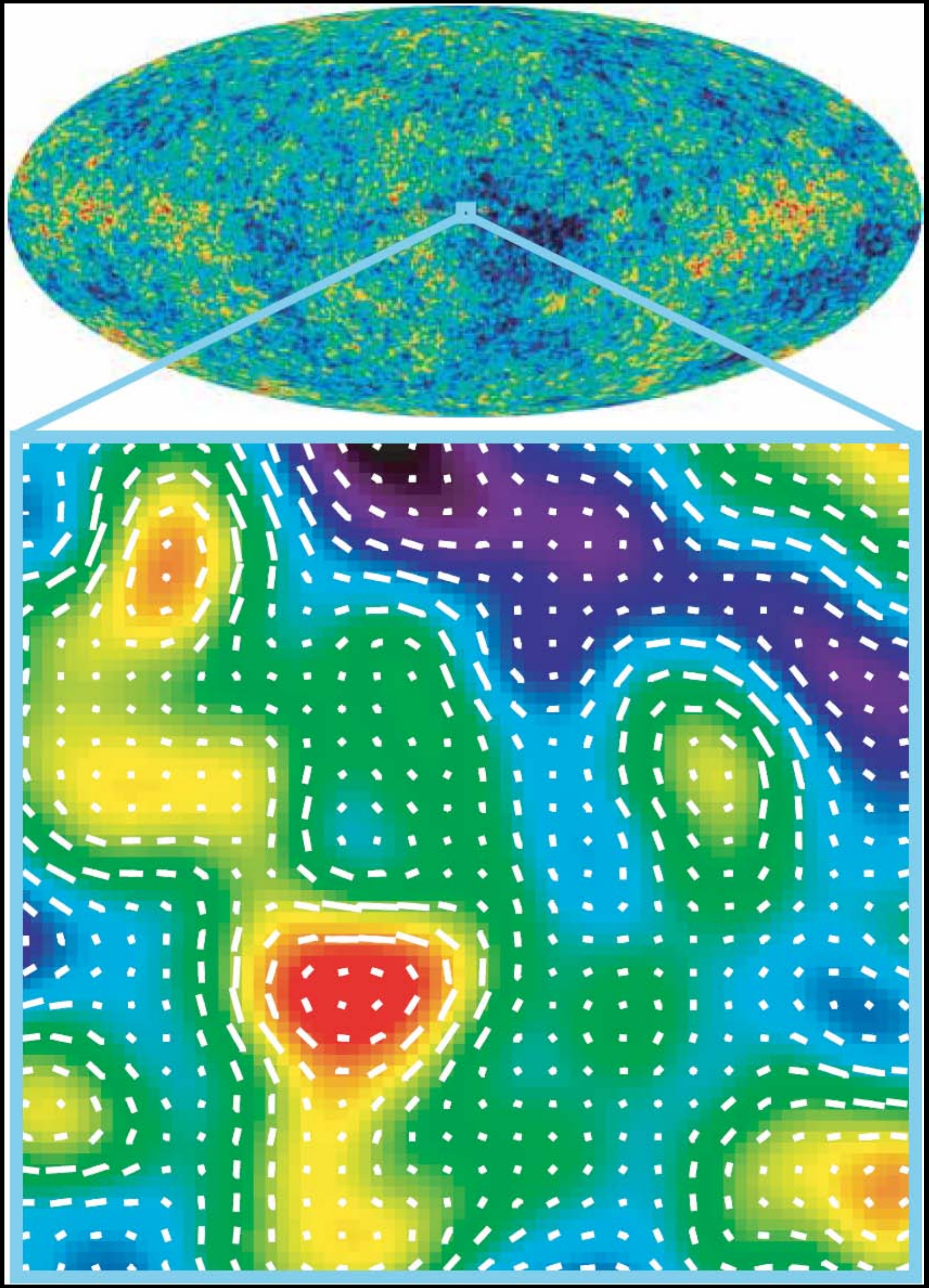
$B_c < 0.1\,\mathrm{nG}$ (Vallee 90)

Do cosmological magnetic fields exist?



magnetogenesis

- mechanisms
  - cosmological perturbation
    - KT et al. 05, 06, 07, 08
  - inflation
    - Turner & Widrow 88
    - Demozzi et al. 09
  - phase transition
    - Hogan 83
  - reionization
    - Langer et al. 03, 05



motivation

origin of magnetic fields

  especially galaxies and clusters of galaxies

  dynamo amplify tiny "seed" fields

  where did the seed come from?

probe early universe

  B fields may be preserved as a remnant of various phenomenon such as, inflation, density fluctuations, reionization.

influence on structure formation

this talk

generation and observation

- magnetogenesis from cosmological perturbations before recombination

- observation of tiny cosmological magnetic fields with pair echo from high-energy γ-ray sources

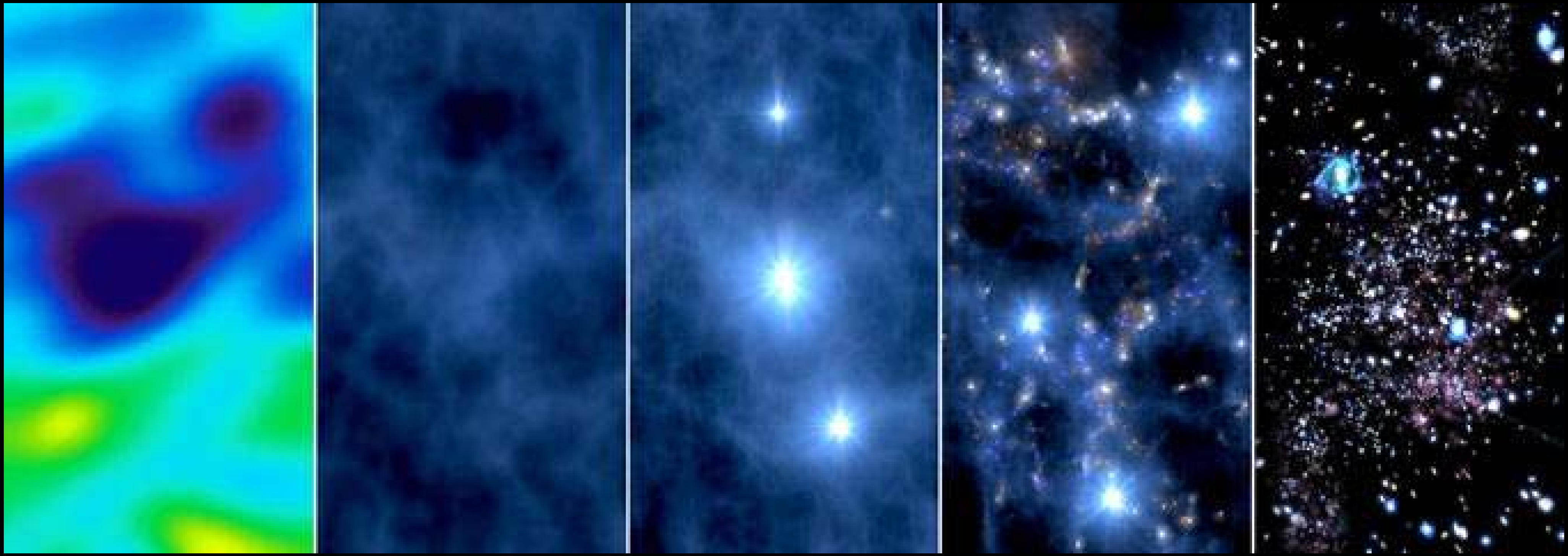
2. Magnetogenesis from cosmological perturbations

KT, K. Ichiki, N. Sugiyama 05, 06, 07, 08
KT, T. Kobayashi, R. Maartens, T. Shiromizu, 07

cosmological perturbations

perturbation
= deviation from homogeneous isotropic universe

- generated during inflation quantum mechanically
  → density fluctuation, gravitational waves
- evolve linearly after inflation
  → CMB anisotropy, structure formation



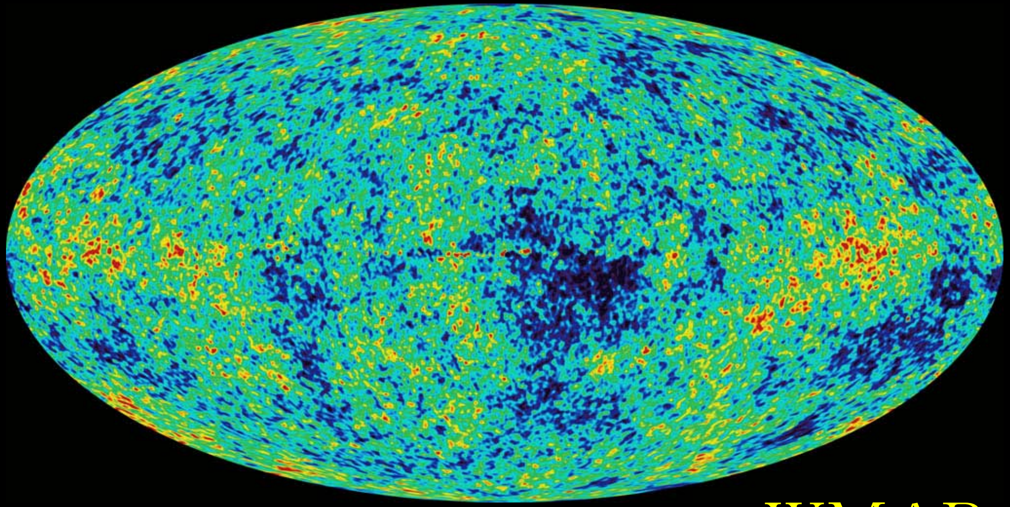
primordial fluctuations

observation

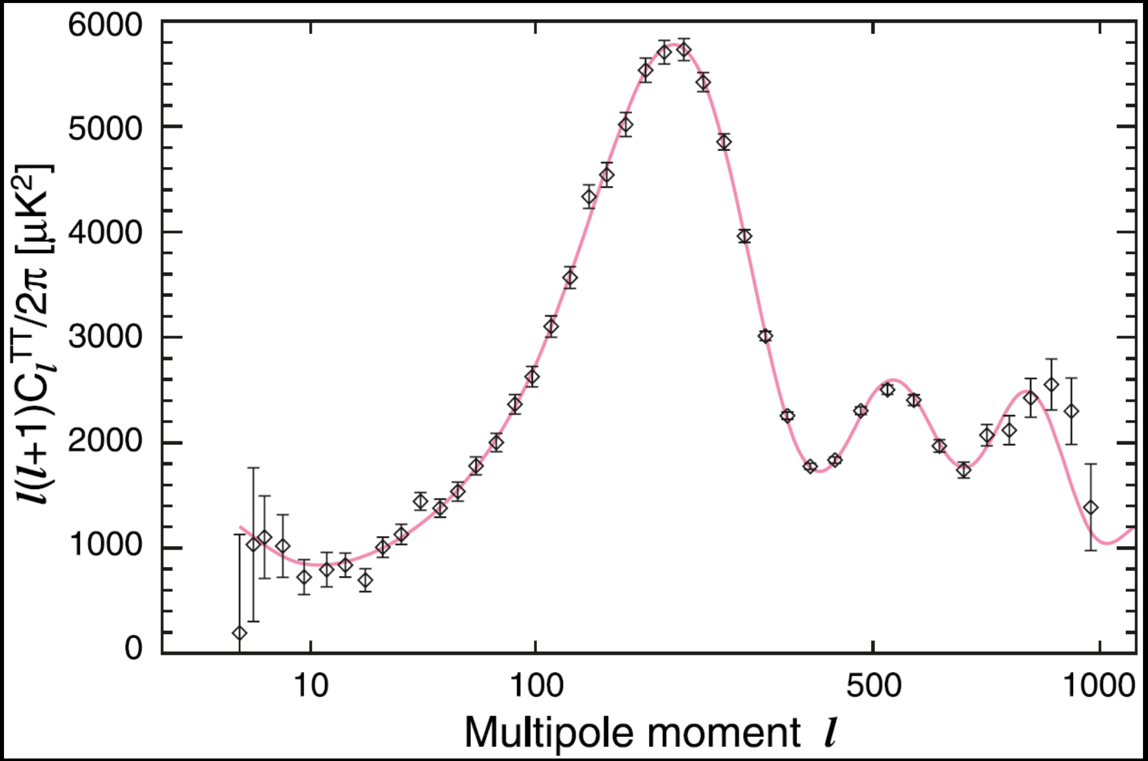
- CMB
- galaxy distribution

theory

- inflation
  (initial condition)
- cosmological
  perturbation theory
  (linear)



WMAP



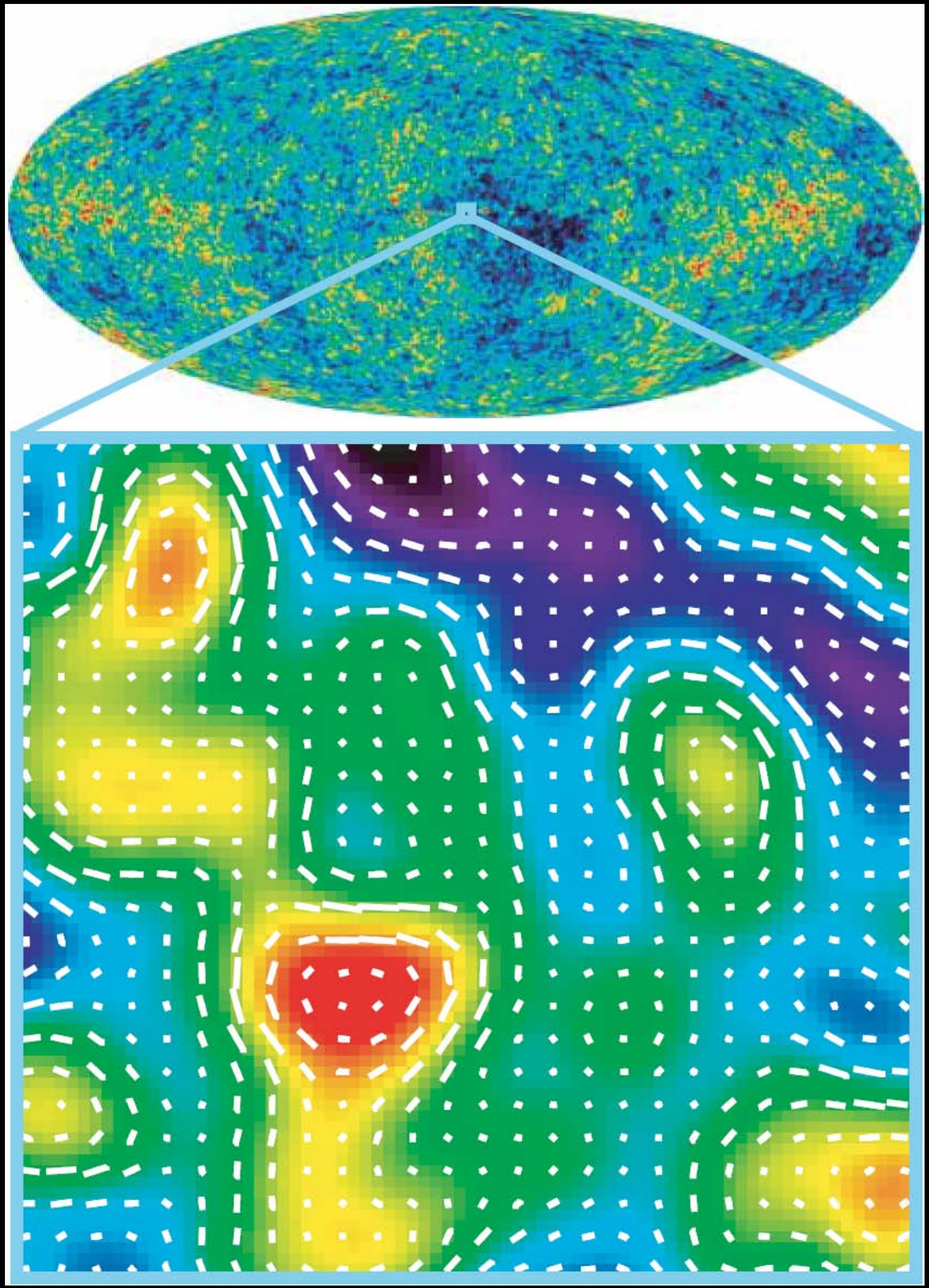
magnetogenesis

magnetogenesis from cosmological perturbations before recombination

Hogan (2000)
Berezhiani & Dolgov (2004)
Matarrese et al. (2005)
Gopal & Sethi (2005)
KT et al. (2005, 2006, 2007, 2008)
Siegel & Fry (2006)
Hollenstein et al. (2008)
Maeda et al. (2009)

based on

- cosmological perturbation theory (nonlinear)
- observational facts
- no physical assumption



basic idea

Thomson scattering

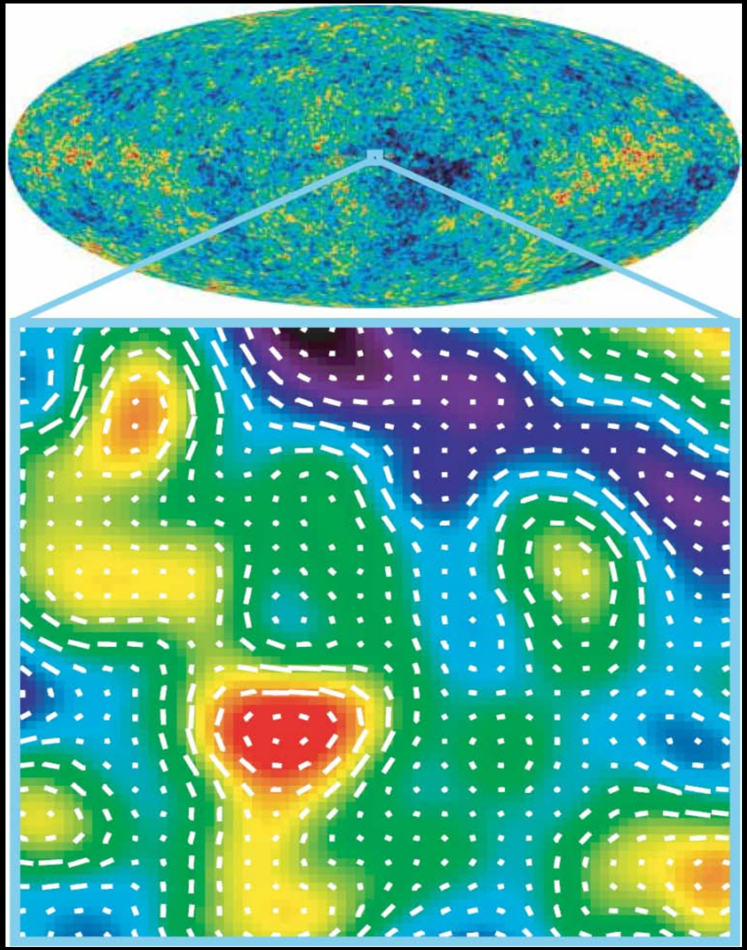
photons
→ CMB

baryon

protons

electrons

Coulomb interaction



Thomson scattering
→ deviation in motion
due to mass difference
→ net electric charge density
and electric current
→ magnetic fields

extensions to the conventional formalism

What do we need for magnetogenesis?

$$\partial_t \vec{B} = -\nabla \times \vec{E}$$

electric field and its rotation

electric field
- Conventionally, baryons
- Separate treatment of p and e is necessary.

rotational part
- No rotational part at the linear order
- generated by nonlinear effect
  Linear order is sufficient for CMB
  but insufficient for B.

Two extensions are needed for magnetogenesis.

generalized Ohm’s law

(special relativistic) EOMs for protons and electrons

$$\begin{aligned} m_p n_p \left[\partial_t \vec{v}_p + (\vec{v}_p \cdot \nabla)\,\vec{v}_p\right] \\ = e n_p(\vec{E} + \vec{v}_p \times \vec{B}) - \underline{e^2 n_p n_e \eta(\vec{v}_p - \vec{v}_e)} + \underline{\frac{m_e^2}{m_p^2}\sigma_T n_p \rho_\gamma(\vec{v}_\gamma - \vec{v}_p)} - m_p n_p \nabla\Phi, \end{aligned}$$

Coulomb

Thomson

$$\begin{aligned} m_e n_e \left[\partial_t \vec{v}_e + (\vec{v}_e \cdot \nabla)\,\vec{v}_e\right] \\ = -e n_e(\vec{E} + \vec{v}_e \times \vec{B}) + \underline{e^2 n_p n_e \eta(\vec{v}_p - \vec{v}_e)} + \underline{\sigma_T n_e \rho_\gamma(\vec{v}_\gamma - \vec{v}_e)} - m_e n_e \nabla\Phi, \end{aligned}$$

generalized Ohm’s law

$$\frac{1}{\omega_p^2}\partial_t \vec{j} = \vec{E} - \eta_{\mathrm{eff}}\vec{j} + \vec{C}$$

“wind” of photons

$$\vec{C} \equiv \frac{1-\beta^3}{1+\beta}\frac{\sigma_T \rho_\gamma}{e}\left(\delta\vec{v}_{\gamma b} - \frac{1}{4}\vec{v}_b \cdot \Pi_\gamma\right)$$

behaviour of charge density

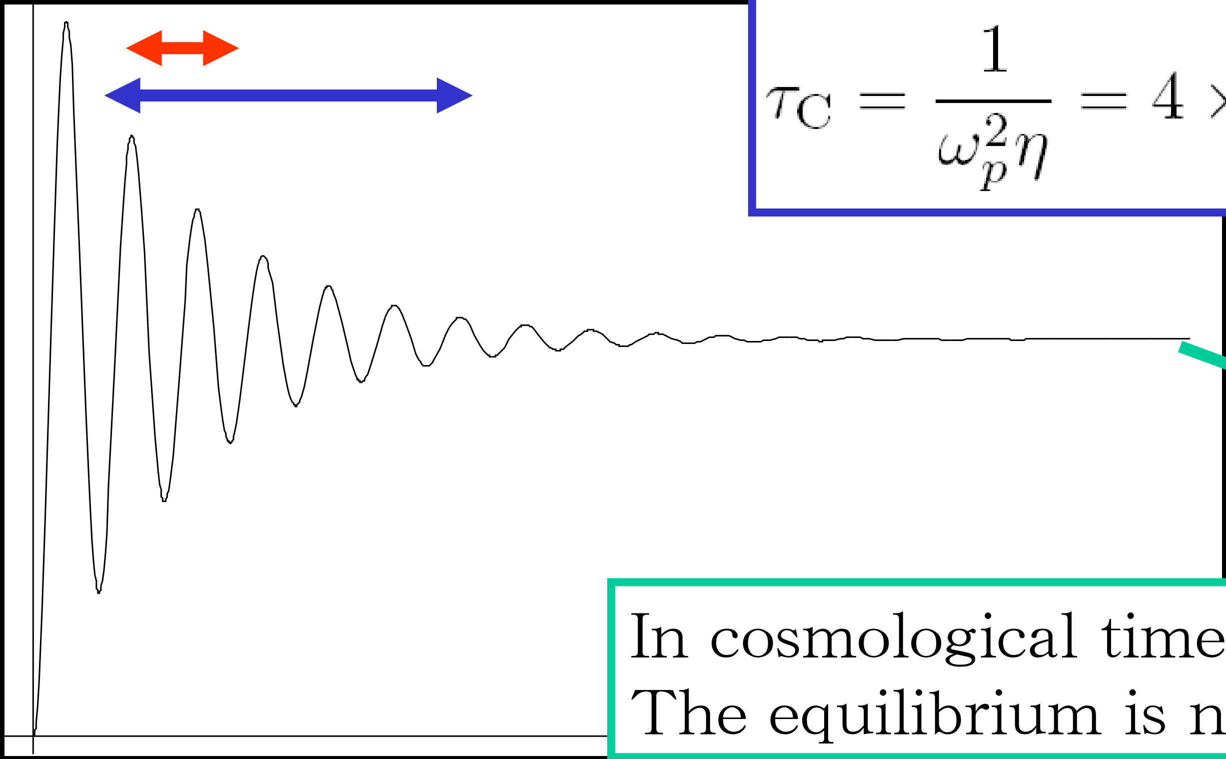
divergence of the generalized Ohm's law

$$\frac{1}{\omega_p^2}\partial_t^2\rho + \eta_{\rm eff}\partial_t\rho + \rho = \nabla\cdot\vec{C}$$

damped oscillation
with an external source

$$\omega_p^{-1} \equiv \sqrt{\frac{m_e}{e^2 n^{(0)}}} = 2\times 10^{-9}\ \mathrm{sec}\left(\frac{1+z}{10^5}\right)^{-3/2}$$

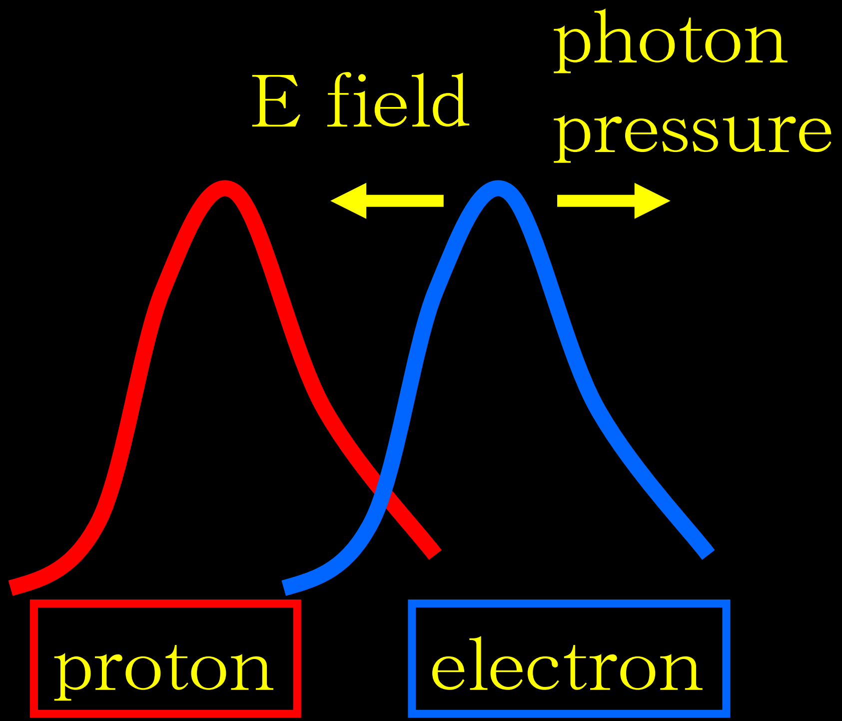
$$\tau_{\rm C} = \frac{1}{\omega_p^2\eta} = 4\times 10^{-3}\ \mathrm{sec}\left(\frac{1+z}{10^5}\right)^{-3/2}$$



$$\rho \approx \nabla\cdot\vec{C}$$

In cosmological timescale, plasma oscillation damps.
The equilibrium is nonzero due to the source.

electromagnetic properties of the early universe



$$\rho = \nabla \cdot \vec{C},$$

$$\vec{j} = -\partial_t \vec{C} - \int dt\, \nabla \times \nabla \times \vec{C},$$

$$\vec{E} = \vec{C},$$

$$\vec{B} = -\int dt\, \nabla \times \vec{C},$$

- electric current term is not important in Ohm’s law
  → photon pressure balances with E field
- current → (displacement current) + (B field)
- E and charge vanish when Thomson term disappear.
  B and current do not because they are integral.

relative motion of baryons and photons

source for B field (neglect anisotropic stress)

$$\nabla \times \vec{C}^{(2)} = \frac{\sigma_T \rho_\gamma^{(0)}}{e} \left[\frac{\nabla \rho_\gamma^{(1)}}{\rho_\gamma^{(0)}} \times \delta \vec{v}_{\gamma b}^{(1)} + \nabla \times \delta \vec{v}_{\gamma b}^{(2)} \right]$$

equation for velocity difference

$$\partial_t \delta \vec{v}_{\gamma b} + (\vec{v} \cdot \nabla)\, \delta \vec{v}_{\gamma b} + (\delta \vec{v}_{\gamma b} \cdot \nabla)\, \vec{v} - (\delta \vec{v}_{\gamma b} \cdot \nabla)\, \delta \vec{v}_{\gamma b}$$
$$= -\frac{1}{4} \frac{\nabla \rho_\gamma}{\rho_\gamma} - (1+R) \frac{\sigma_T \rho_\gamma}{m_p} \delta \vec{v}_{\gamma b}.$$

tight coupling approximation $k\tau_T \ll 1$

$$\delta \vec{v}_{\gamma b} = k\tau_T \delta \vec{v}_{\gamma b}^{(I)} + (k\tau_T)^2 \delta \vec{v}_{\gamma b}^{(II)} + \cdots$$

results

$$\nabla \times \vec{C}^{(2)} = \frac{\sigma_T \rho_\gamma^{(0)}}{e}\left[\frac{\nabla \rho_\gamma^{(1)}}{\rho_\gamma^{(0)}} \times \delta\vec{v}_{\gamma b}^{(1)} + \nabla \times \delta\vec{v}_{\gamma b}^{(2)}\right]$$

The source vanishes at the lowest order in tight coupling approximation.
So B is second order in both tight coupling and cosmological perturbation.

All electromagnetic quantities are expressed in terms of familiar quantities like first-order □□.

$$\vec{B}^{(2)} = -\frac{1}{16}\frac{\bar{R}^{(0)}}{(1+\bar{R}^{(0)})^3}\frac{m_p^2}{e\sigma_T\bar{\rho}_\gamma^{(0)}}\int dt\,\frac{\nabla\bar{\rho}_\gamma^{(1)}}{\bar{\rho}_\gamma^{(0)}} \times \left[\frac{\partial_t\nabla\bar{\rho}_\gamma^{(1)}}{\bar{\rho}_\gamma^{(0)}} + \int dt\,\frac{\nabla(\nabla^2\bar{\rho}_\gamma^{(1)})}{\bar{\rho}_\gamma^{(0)}}\right]$$

quantitative study

KT et al. (2006)

- derive the source term relativistically

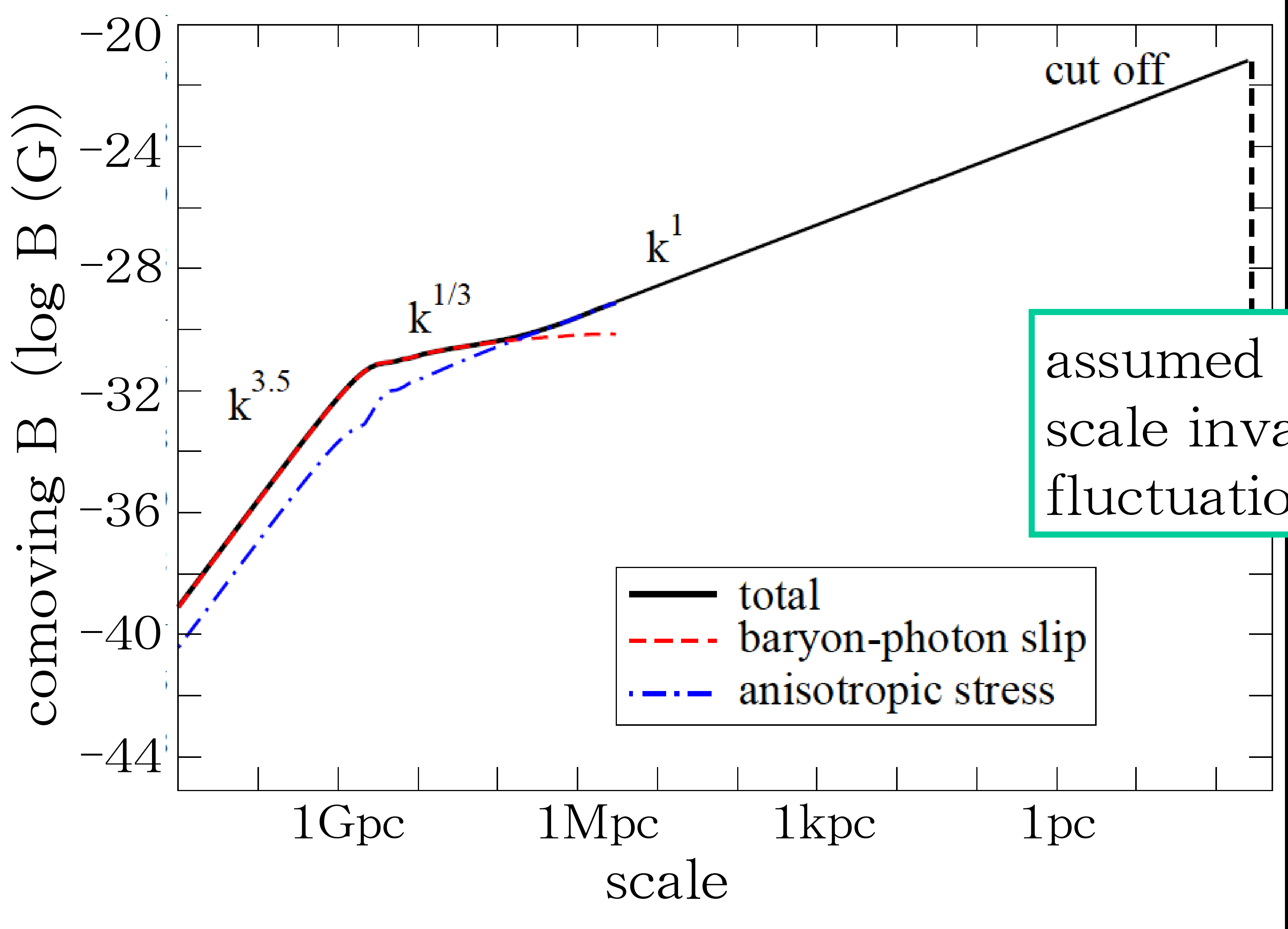
$$\partial_t B^i = \frac{8\sigma_T \rho_\gamma^{(0)}}{3e}\epsilon^{ijk}\left[\underline{\frac{\rho^{(1)}_{\gamma,k}}{\rho^{(0)}_\gamma}\delta v^{(1)}_{b\gamma\ j}} + \underline{\delta v^{(2)}_{b\gamma\ j,k}} + \underline{\frac{1}{8}\left(v^{(1)}_{b\ l}\Pi^{(1)l}_{\gamma\ j}\right)_{,k}}\right]$$

- numerically calculate the spectrum contributed from (1st order) × (1st order), neglecting the vorticity (purely 2nd order)

(The products of 1st-order quantities are easily calculated with CMBFAST or CAMB. But the vorticity needs 2nd-order Boltzmann solver.)

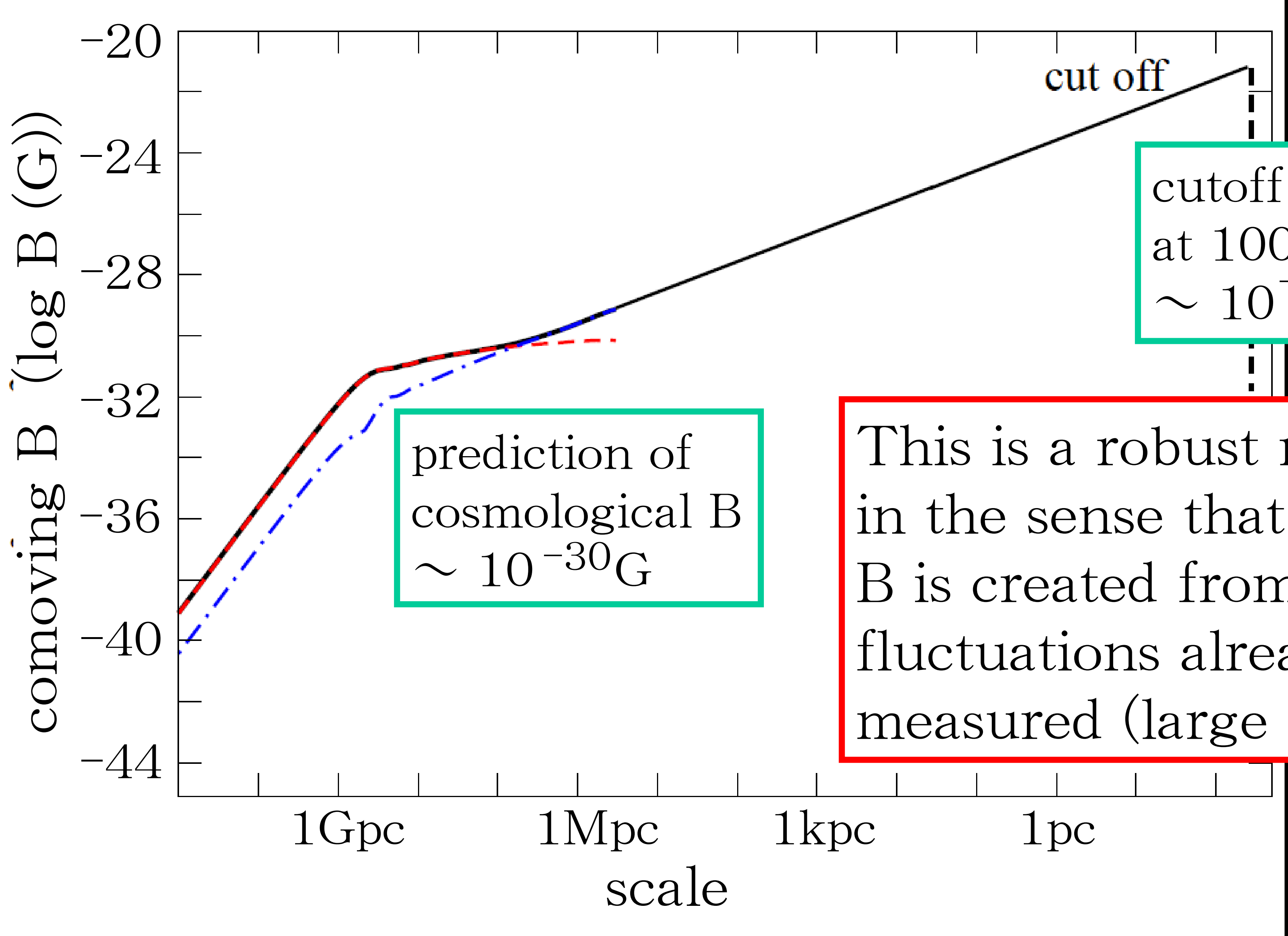
spectrum

$$\partial_t B^i = \frac{8\sigma_T \rho_\gamma^{(0)}}{3e}\epsilon^{ijk}\left[\frac{\rho^{(1)}_{\gamma,k}}{\rho^{(0)}_\gamma}\delta v^{(1)}_{b\gamma\ j} + \delta v^{(2)}_{b\gamma\ j,k} + \frac{1}{8}\left(v^{(1)}_{b\ l}\Pi^{(1)l}_{\gamma\ j}\right)_{,k}\right]$$



assumed scale invariant fluctuations

implication



cutoff
at 100AU
$\sim 10^{-21}$G

prediction of
cosmological B
$\sim 10^{-30}$G

This is a robust result in the sense that B is created from fluctuations already measured (large scale).

toward the complete spectrum

analytic approach

- based on tight coupling approximation
- understand the physics of magnetogenesis and confirm the results of numerical calculation
- needs relativistic formalism including anisotropic stress (KT. Maartens, Pitrou)

numerical approach

- evaluate the spectrum
- confirm the validity of tight coupling approximation
- include vorticity (purely 2nd order)

These two approaches are necessary
to cross check and evaluate the complete spectrum.

summary of magnetogenesis

magnetogenesis from cosmological perturbations

- difference of motion of p and e due to Thomson scattering

- two extensions: p–e system and nonlinear effect

- B field is generated at 2nd order in both tight coupling and cosmological perturbation

- B $\sim 10^{-21}$ Gauss (preliminary)

- prediction of cosmological magnetic fields

3. Observation of tiny cosmic magnetic fields

KT, K. Ichiki, S. Inoue, K. Murase et al. 07, 08, 09

cosmological magnetic fields

mechanisms

- cosmological perturbation (KT et al. 05, 06, 07, 08)
- inflation (Turner & Widrow 88, Demozzi et al. 09)
- phase transition (Hogan 83)
- reionization (Langer et al. 03, 05)
- quasar outflow (Furlanetto & Loeb 2001)

How can they be verified?

- galaxy, cluster of galaxies
- → amplification, no information on initial condition
- void region
- → Initial condition is preserved?

method

How can we probe tiny B fields in void region?

CMB・Faraday rotation

→ current limit: B < 1nG

→ hard to reach 10^{-20} G

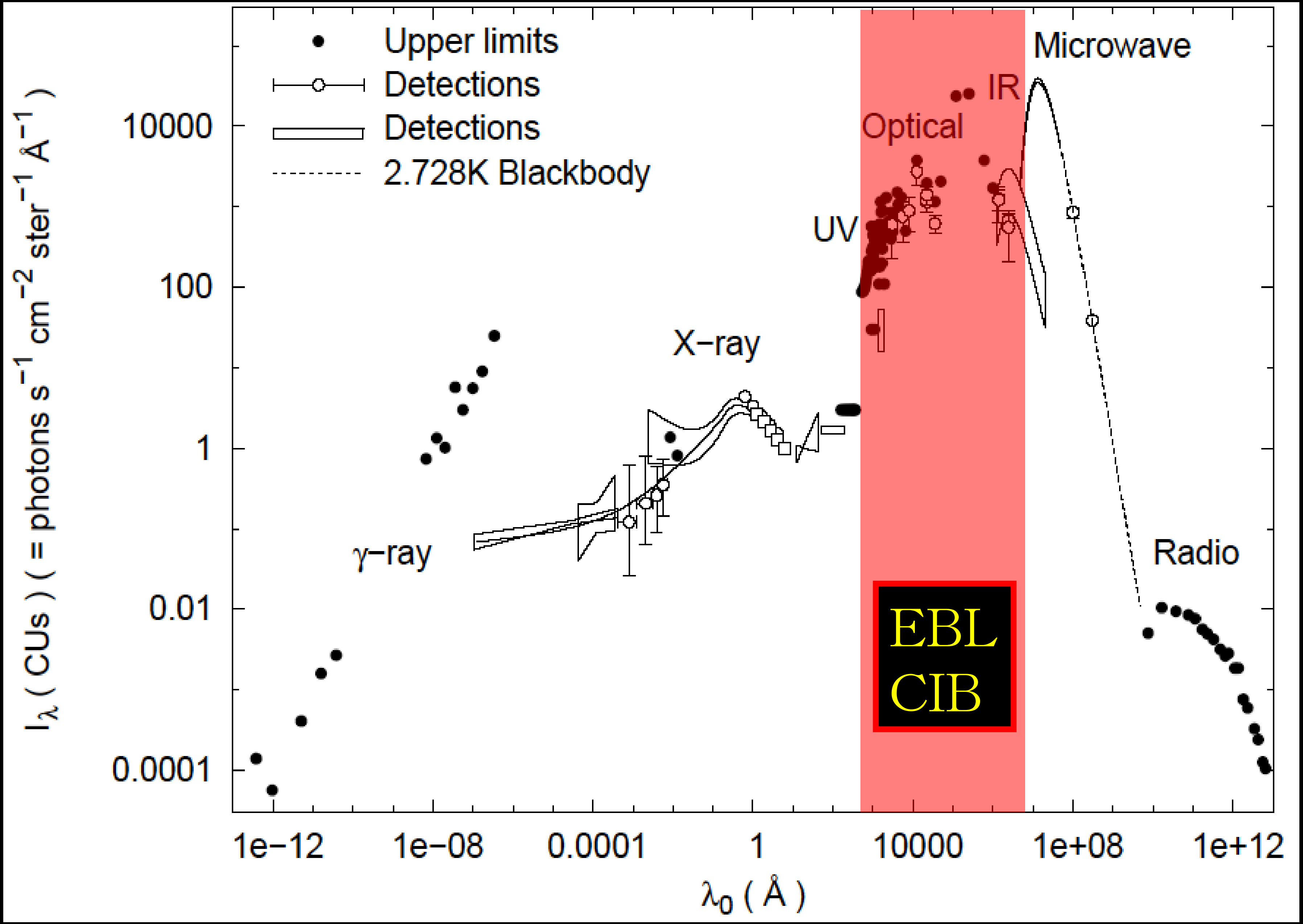
Plaga’s method (Plaga, 1994)

probe tiny B fields by delayed emission from high-energy sources like GRB and blazar

→ $B = 10^{-15} \sim 10^{-20}$ G

→ currently the most effective method

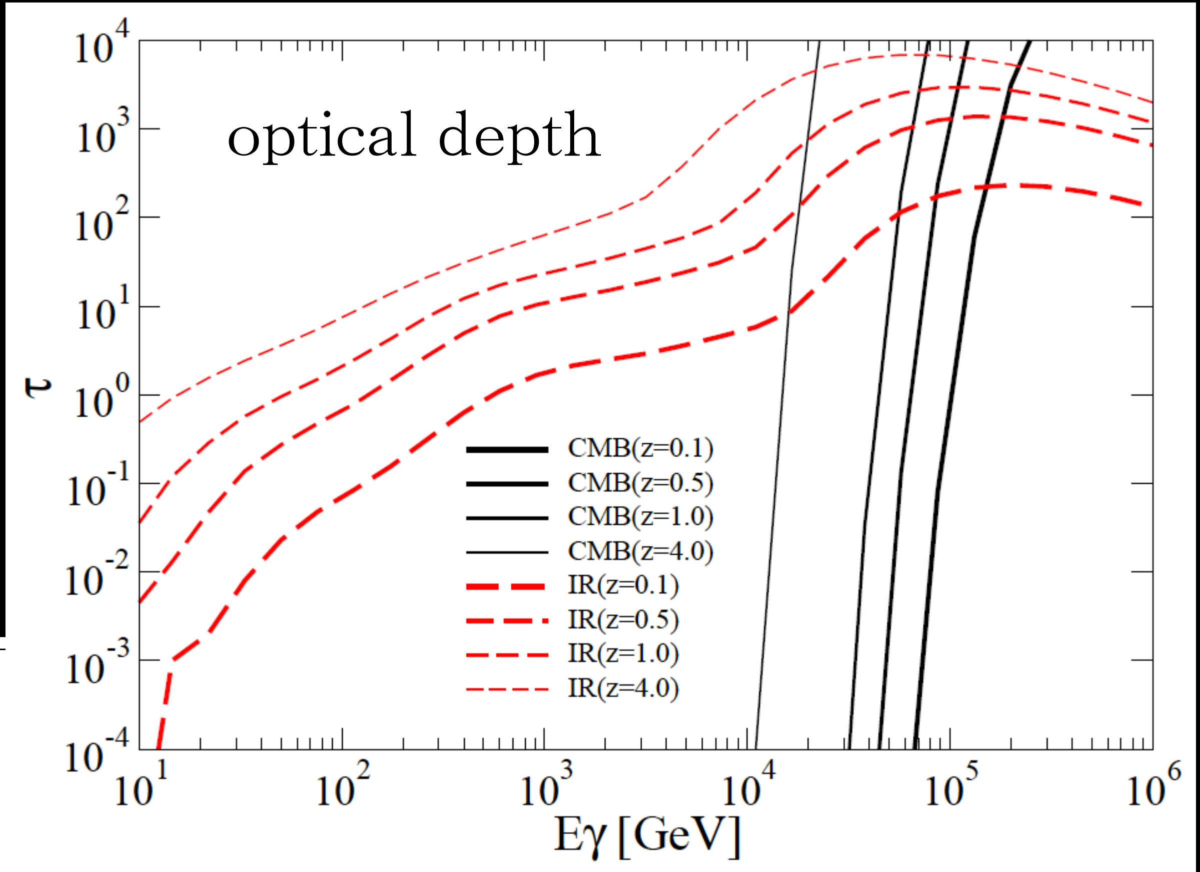
extragalactic background light

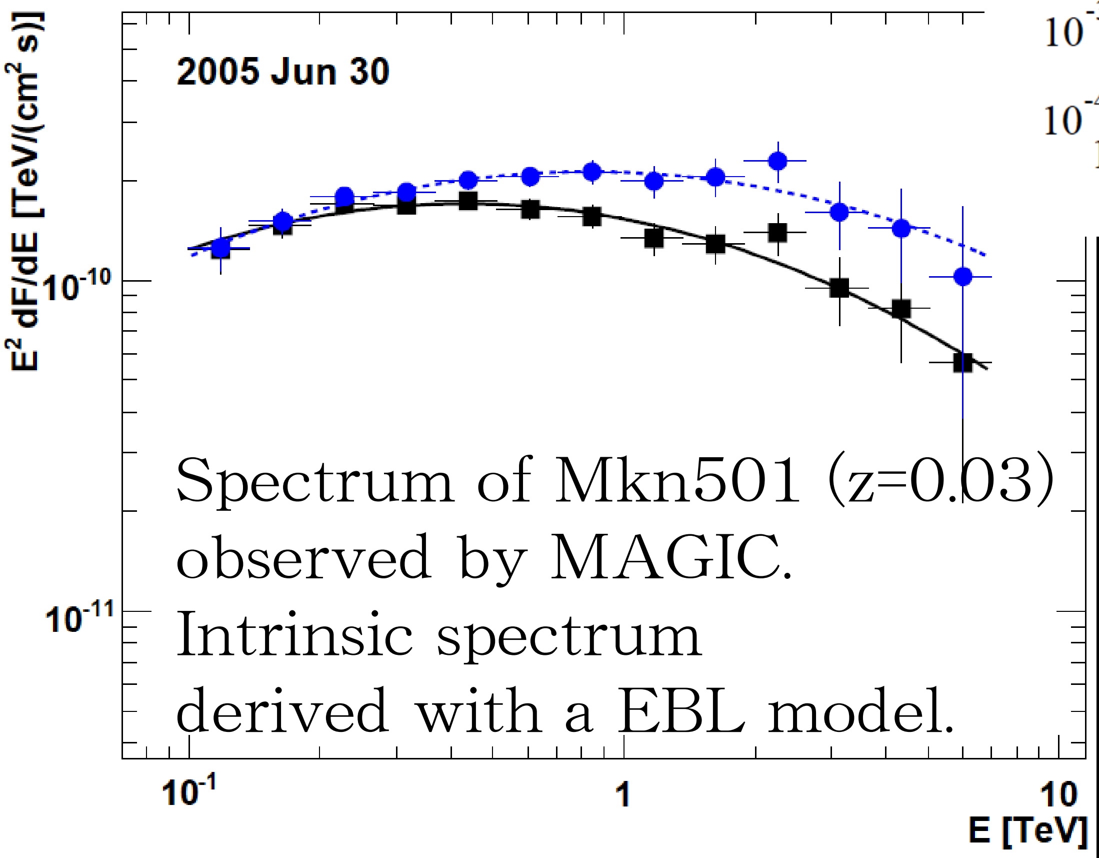


γ-ray absorption

γ-rays with energy > TeV from cosmological sources are absorbed.

$$E_\gamma E_{\rm bg} = m_e^2$$



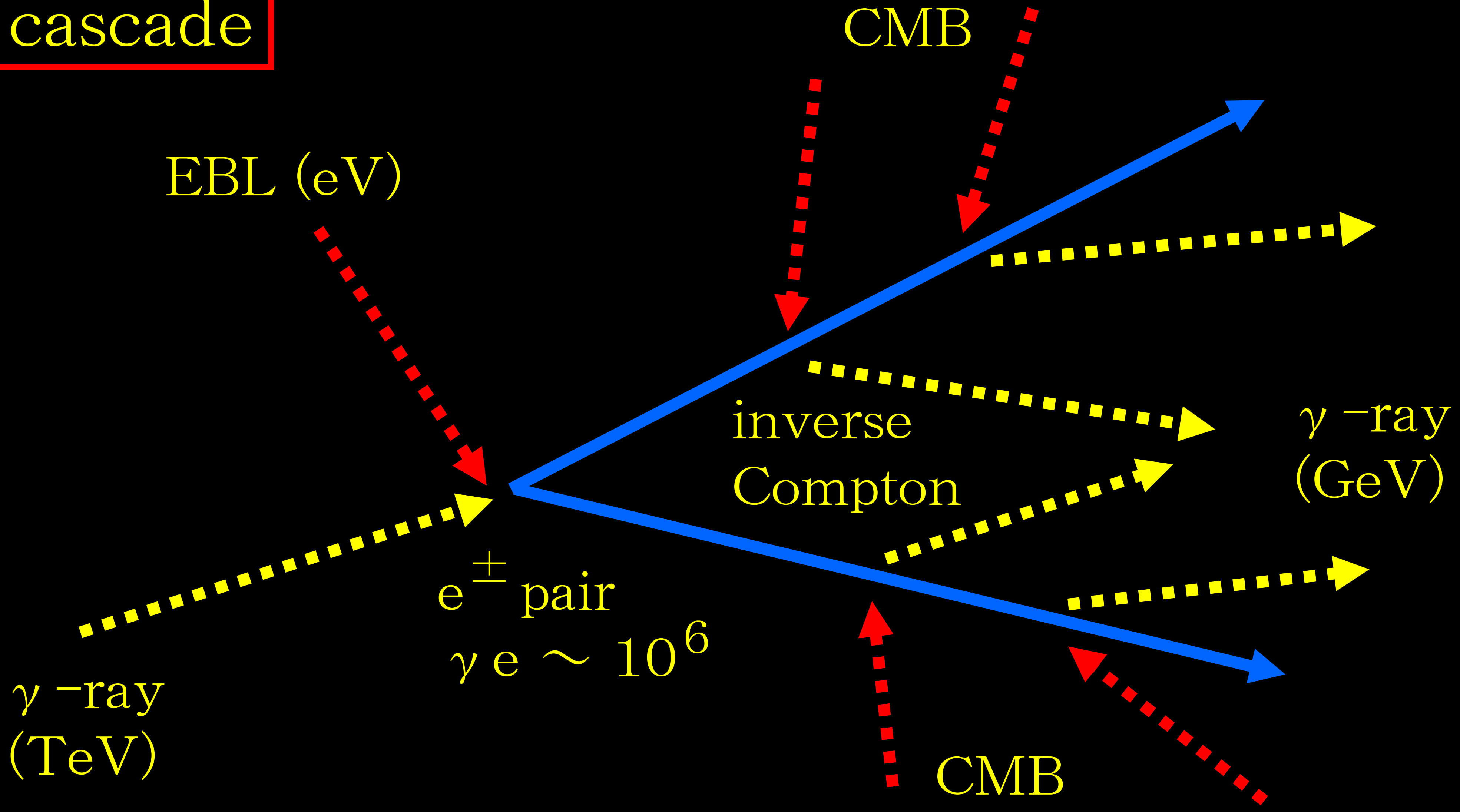


Spectrum of Mkn501 (z=0.03) observed by MAGIC.

Intrinsic spectrum derived with a EBL model.

What happened to the absorbed energy?

cascade



CMB

EBL (eV)

inverse Compton

γ -ray (GeV)

$e^{\pm}$ pair

$\gamma_e \sim 10^6$

γ -ray (TeV)

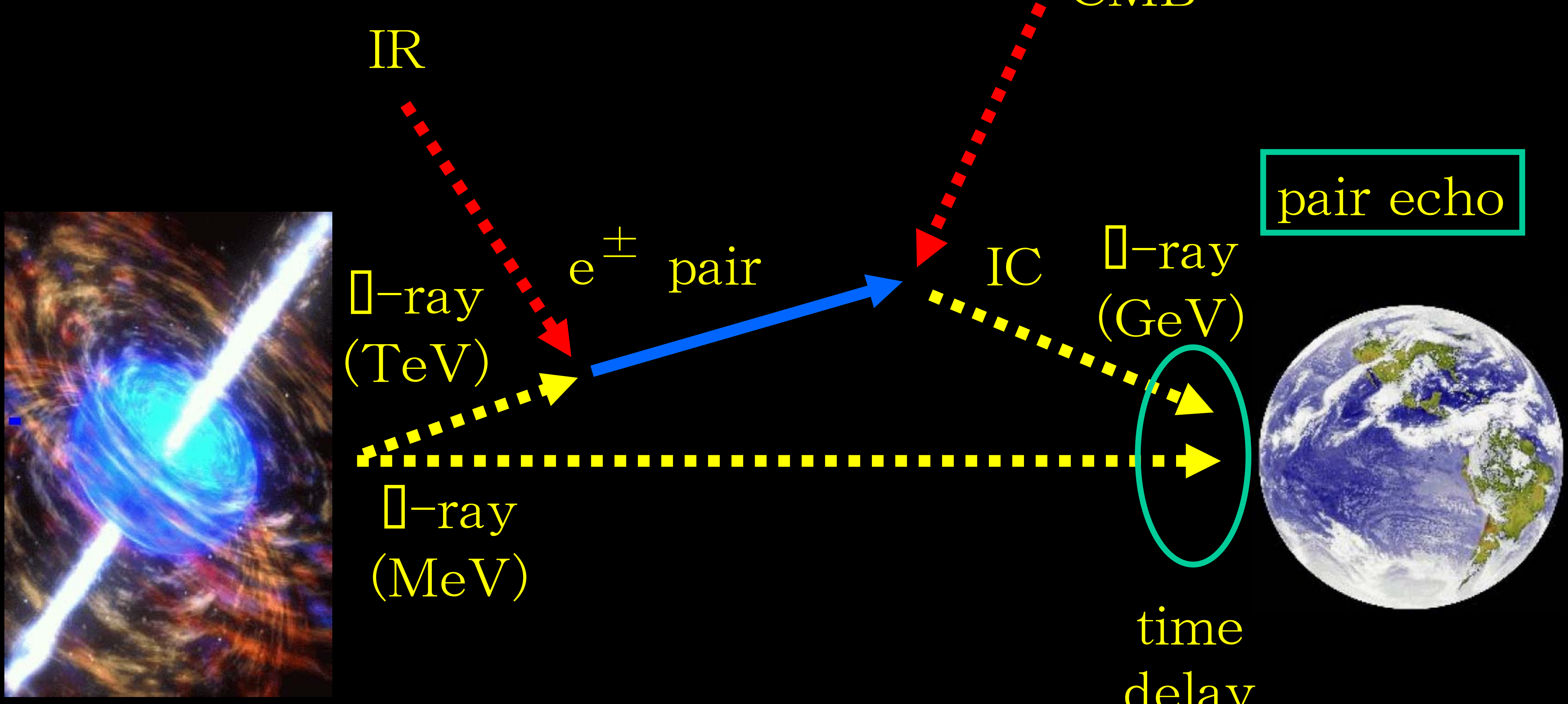
CMB

TeV γ -ray is transformed to many GeV γ -rays.

＊The direction changes by $1/\gamma_e$ in each interaction.

pair echo

Plaga 95
Cheng & Cheng 96
Dai & Lu 02
KT et al. 07, 08, 09



CMB

IR

$e^{\pm}$ pair

IC

γ-ray
(TeV)

γ-ray
(GeV)

pair echo

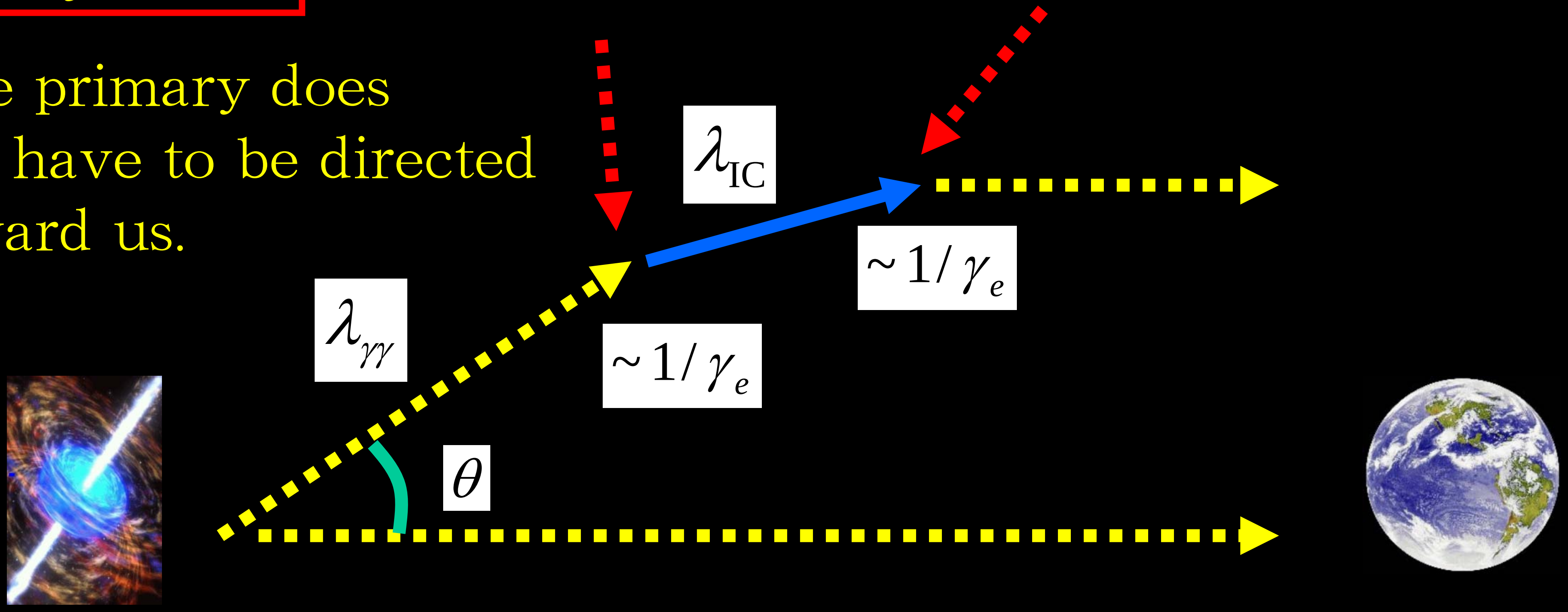
γ-ray
(MeV)

time
delay

GRB, AGN

delay time

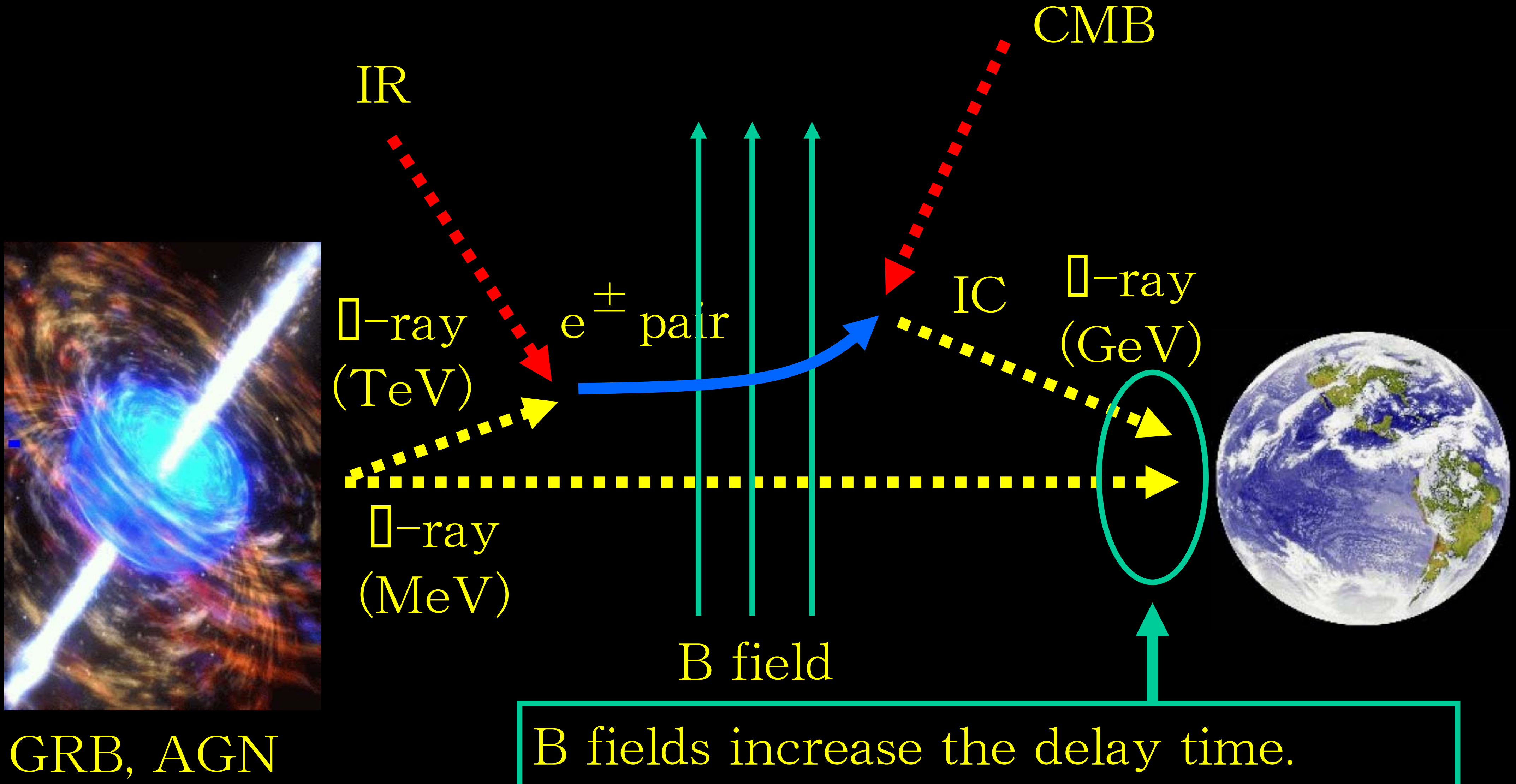
The primary does
not have to be directed
toward us.



$$\Delta t_{\rm delay} = (1 - \cos(1/\gamma_e))(\lambda_{\gamma\gamma} + \lambda_{\rm IC}) \approx \frac{1}{2\gamma_e^2}(\lambda_{\gamma\gamma} + \lambda_{\rm IC})$$

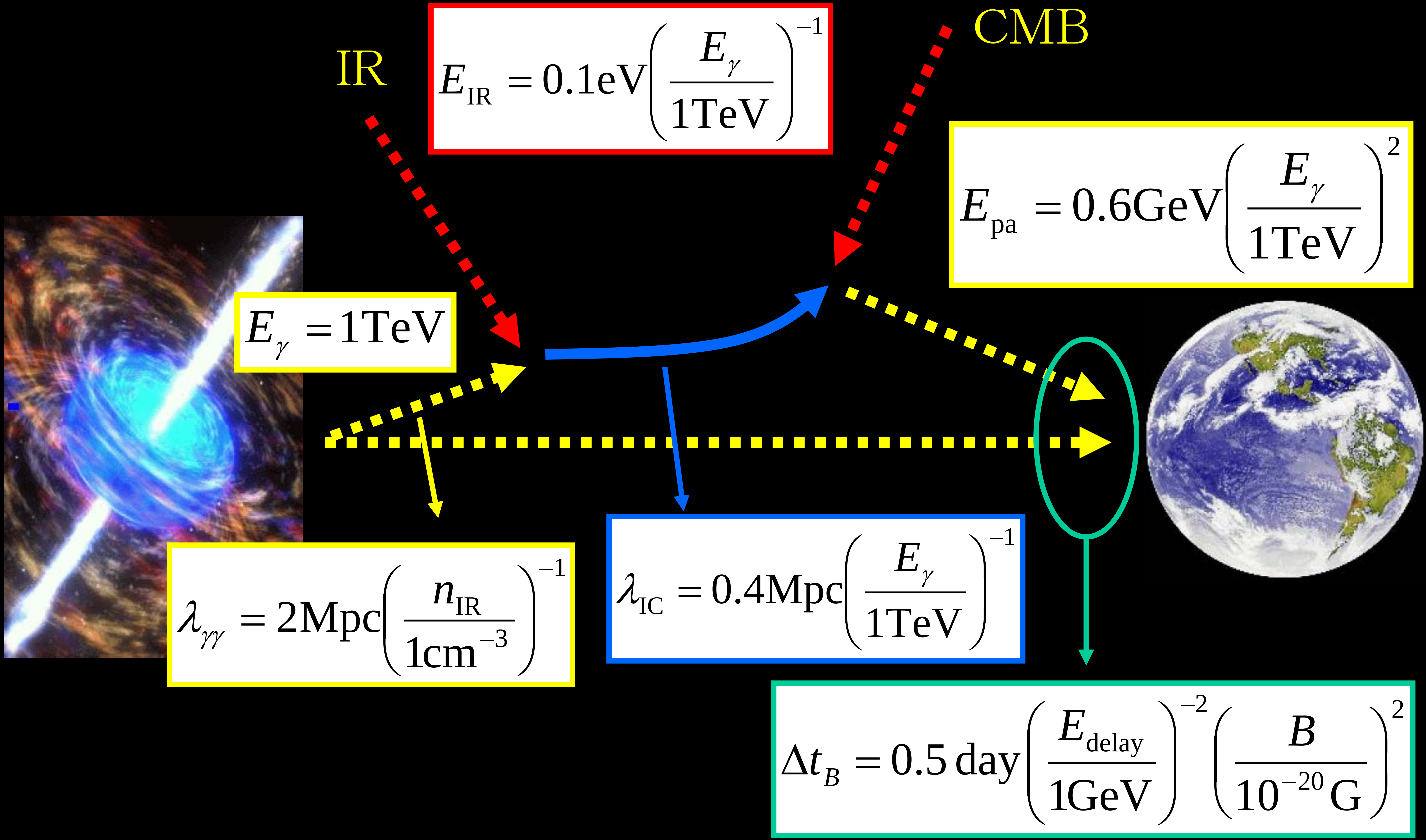
Delay time is determined by the mean free path
and the deflection angle, which depend on the energy.

pair echo with magnetic field



B fields increase the delay time.
The delay time has information on B.

characteristic numbers ①



$$E_{\mathrm{IR}} = 0.1\,\mathrm{eV}\left(\frac{E_\gamma}{1\,\mathrm{TeV}}\right)^{-1}$$

$$E_{\mathrm{pa}} = 0.6\,\mathrm{GeV}\left(\frac{E_\gamma}{1\,\mathrm{TeV}}\right)^{2}$$

$$E_\gamma = 1\,\mathrm{TeV}$$

$$\lambda_{\gamma\gamma} = 2\,\mathrm{Mpc}\left(\frac{n_{\mathrm{IR}}}{1\,\mathrm{cm}^{-3}}\right)^{-1}$$

$$\lambda_{\mathrm{IC}} = 0.4\,\mathrm{Mpc}\left(\frac{E_\gamma}{1\,\mathrm{TeV}}\right)^{-1}$$

$$\Delta t_B = 0.5\,\mathrm{day}\left(\frac{E_{\mathrm{delay}}}{1\,\mathrm{GeV}}\right)^{-2}\left(\frac{B}{10^{-20}\,\mathrm{G}}\right)^{2}$$

characteristic numbers ②

$$E_\gamma = 1\,\mathrm{TeV}$$

- TeV blazar
- no observation from GRB, but theoretically likely

$$E_{\mathrm{pa}} = 0.6\,\mathrm{GeV}\left(\frac{E_\gamma}{1\,\mathrm{TeV}}\right)^2$$

- energy range for Fermi
- terrestrial Cherenkov telescopes are also useful

$$\Delta t_B = 0.5\,\mathrm{day}\left(\frac{E_{\mathrm{pa}}}{1\,\mathrm{GeV}}\right)^{-2}\left(\frac{B}{10^{-20}\,\mathrm{G}}\right)^2$$

- high-energy (low-energy) □-rays for large (small) B

characteristic numbers ③

$$\lambda_{\gamma\gamma} = 2\mathrm{Mpc}\left(\frac{n_{\mathrm{IR}}}{1\mathrm{cm}^{-3}}\right)^{-1}$$

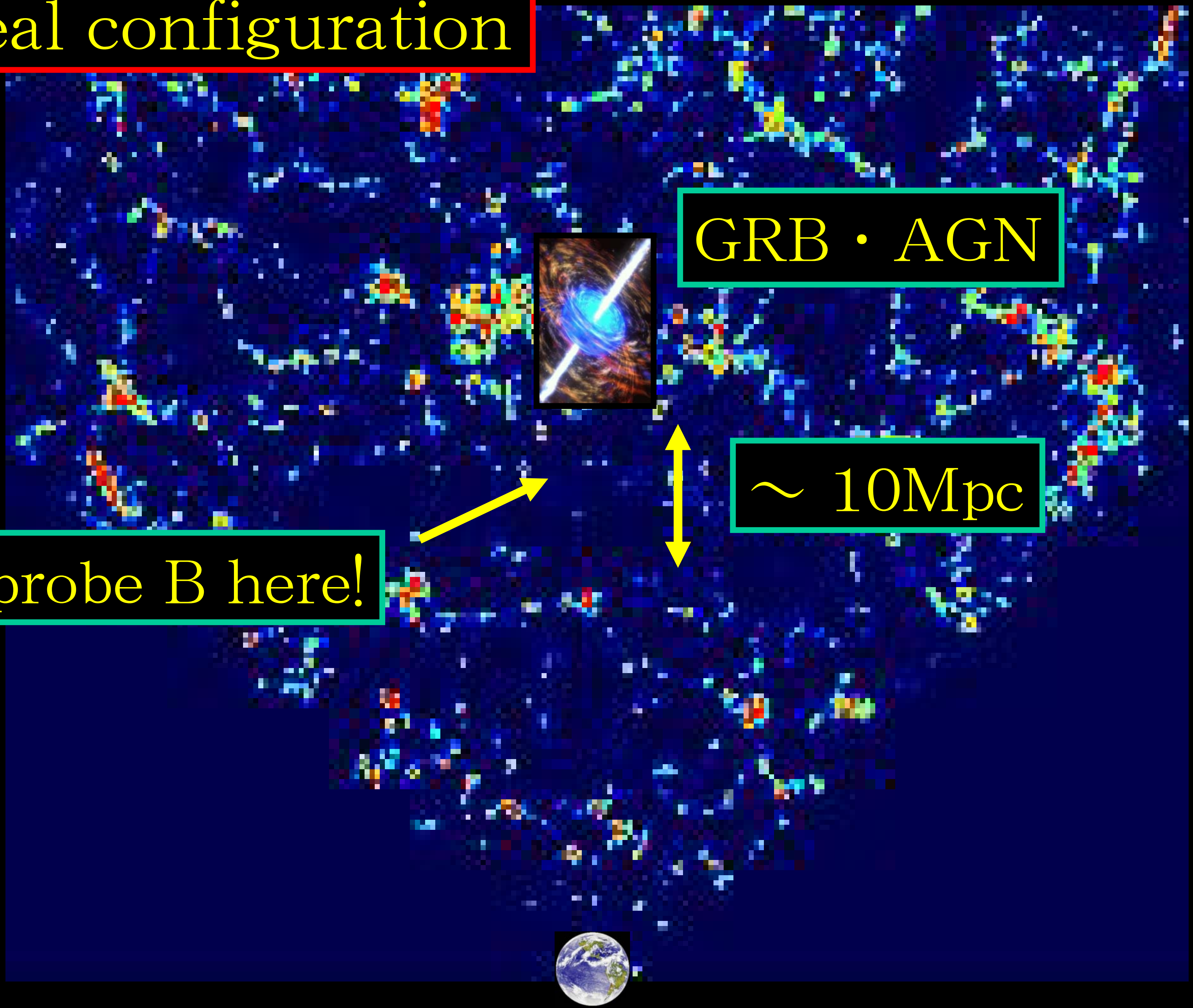
- enough large for the primary to escape the host

$$\lambda_{\mathrm{IC}} = 0.4\mathrm{Mpc}\left(\frac{E_{\gamma}}{1\mathrm{TeV}}\right)^{-1}$$

- interaction is local even combined with the above

We can probe B fields in void region in many cases. (Of course it depends on the configuration.)
→ It is useful to probe cosmic magnetic fields.

ideal configuration

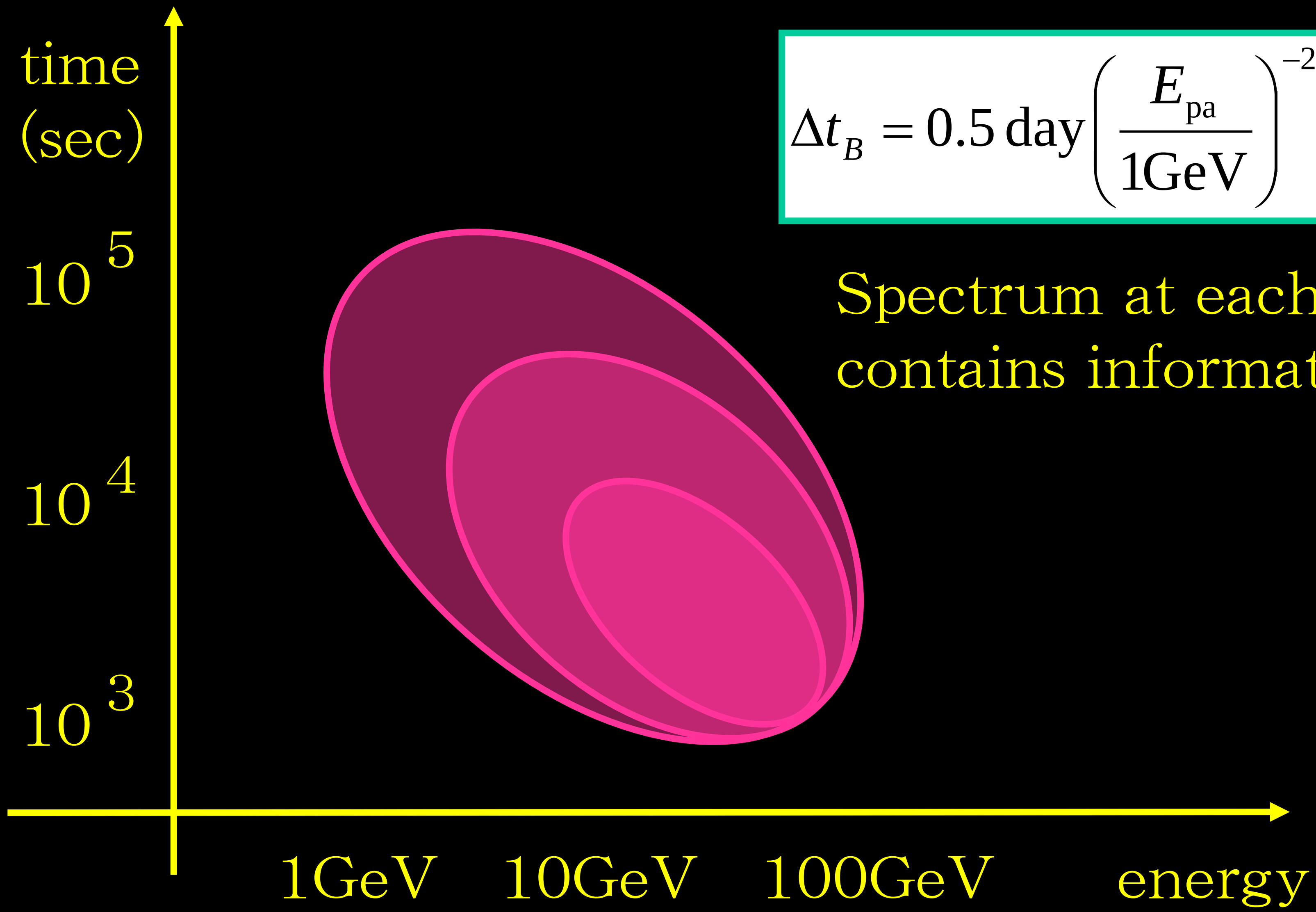


GRB・AGN

$\sim$ 10Mpc

probe B here!

expected flux contour



$$\Delta t_B = 0.5\,\mathrm{day}\left(\frac{E_{\mathrm{pa}}}{1\mathrm{GeV}}\right)^{-2}\left(\frac{B}{10^{-20}\,\mathrm{G}}\right)^{2}$$

Spectrum at each time contains information on B.

setup

primary GRB

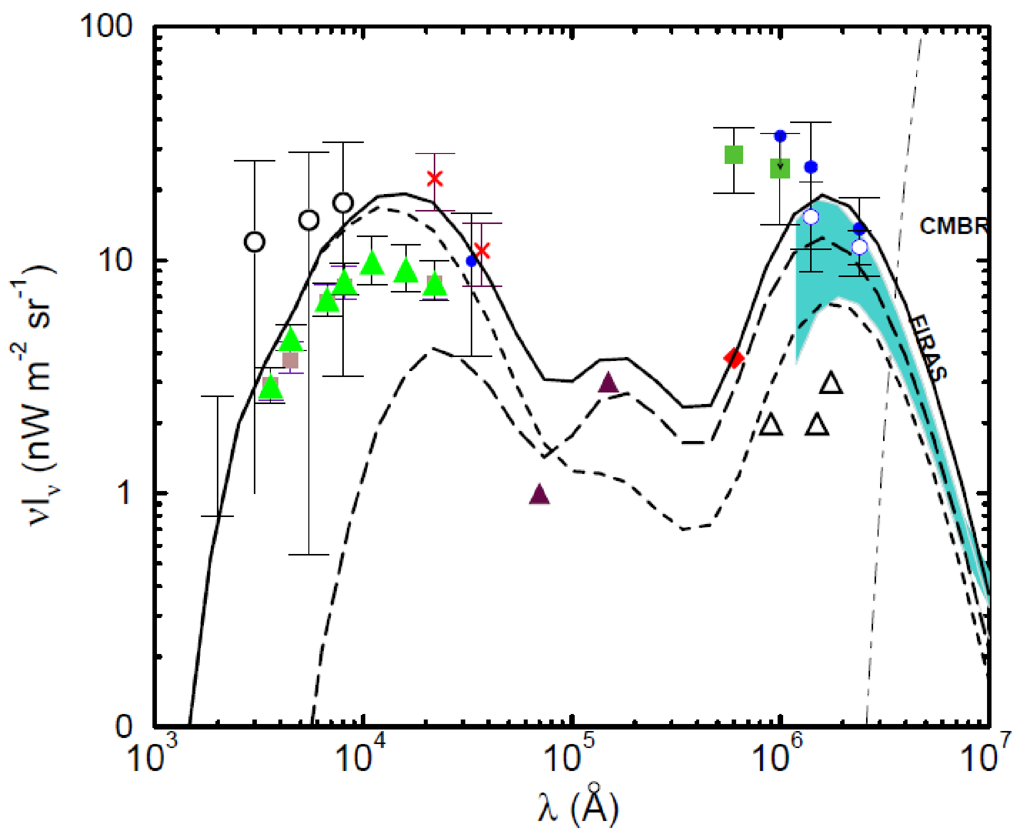
$$dN_\gamma/dE_\gamma \propto E_\gamma^{-2.2}, \text{ for } 0.1 \text{ TeV} < E_\gamma < E_{\rm cut} = 10 \text{ TeV}$$
$$E^{\rm iso}_{\gamma,[0.1,10]} = 3 \times 10^{53} \text{ erg}$$

CIB model

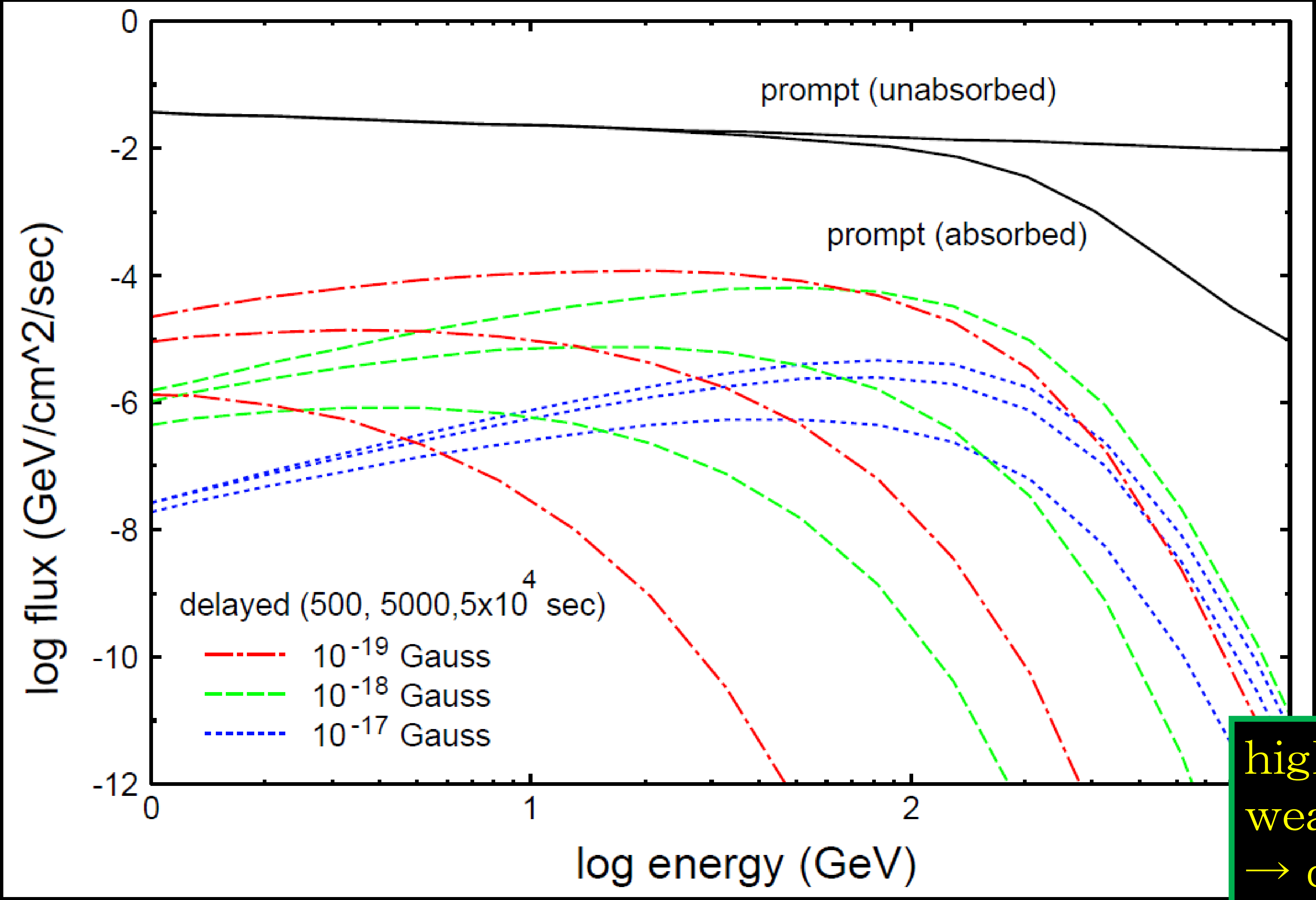
“best fit” model

(“low SFR” model)

of Kneiske et al. 02, 04

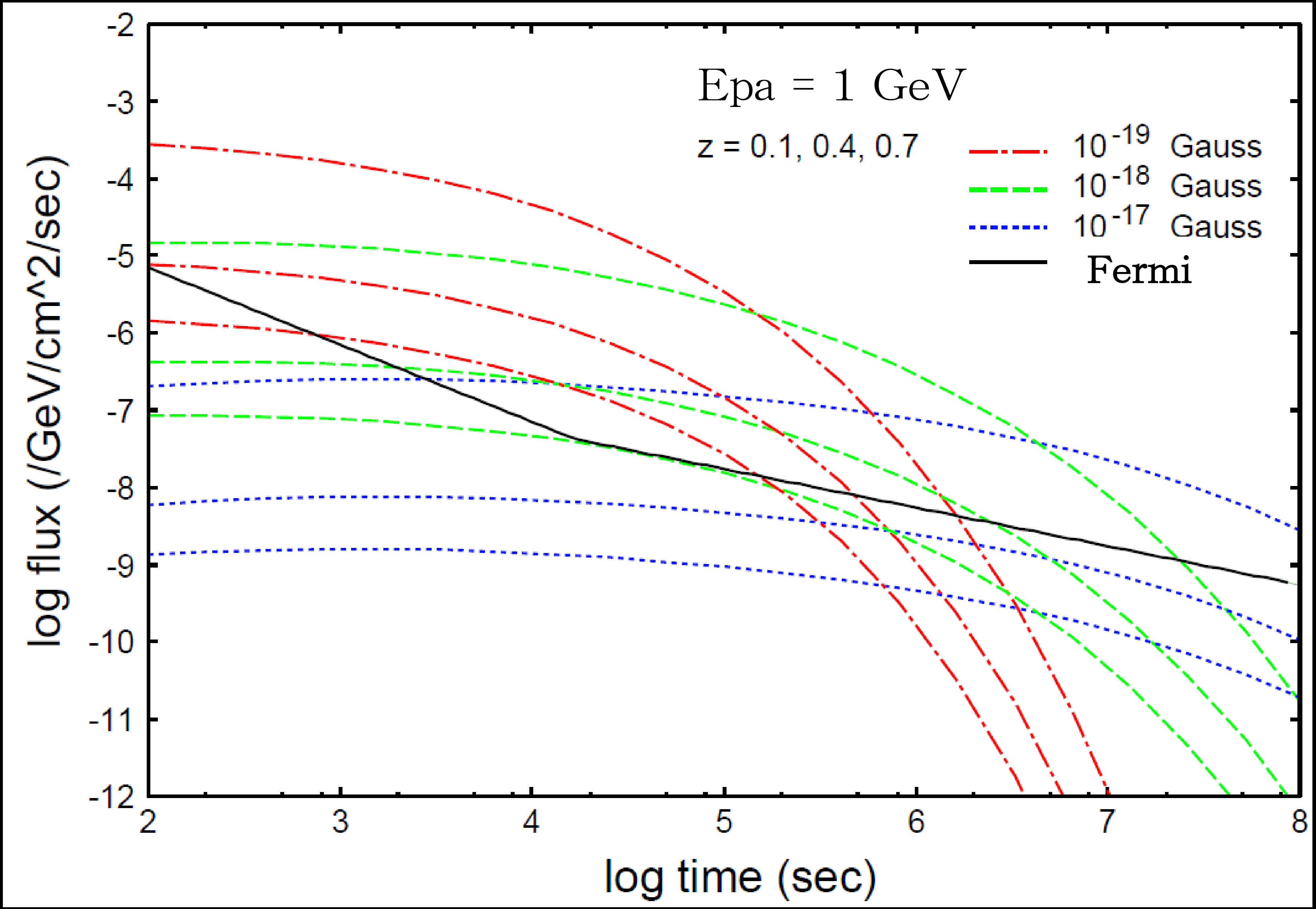


pair echo spectrum

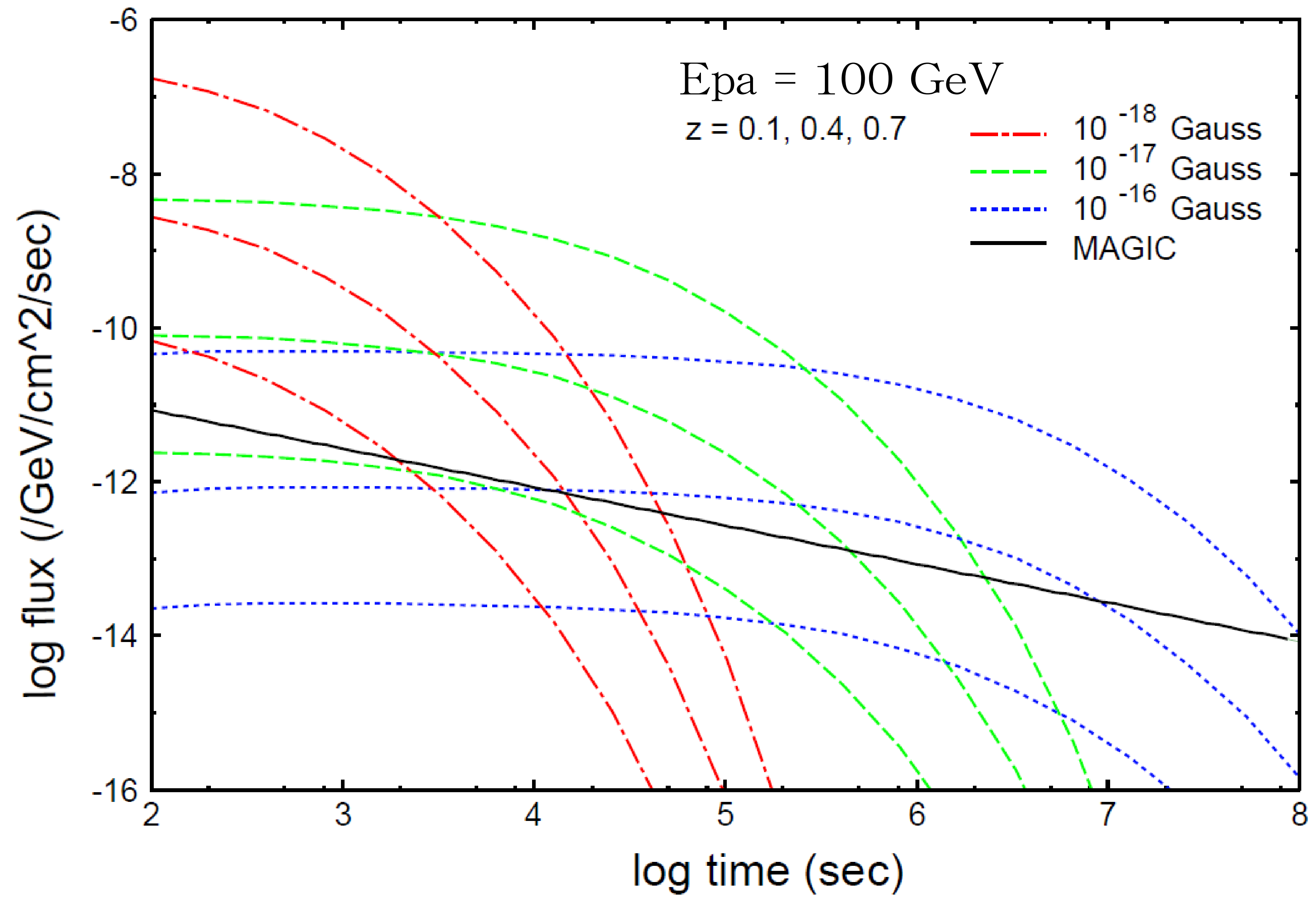


high energy
weak B
→ decay faster

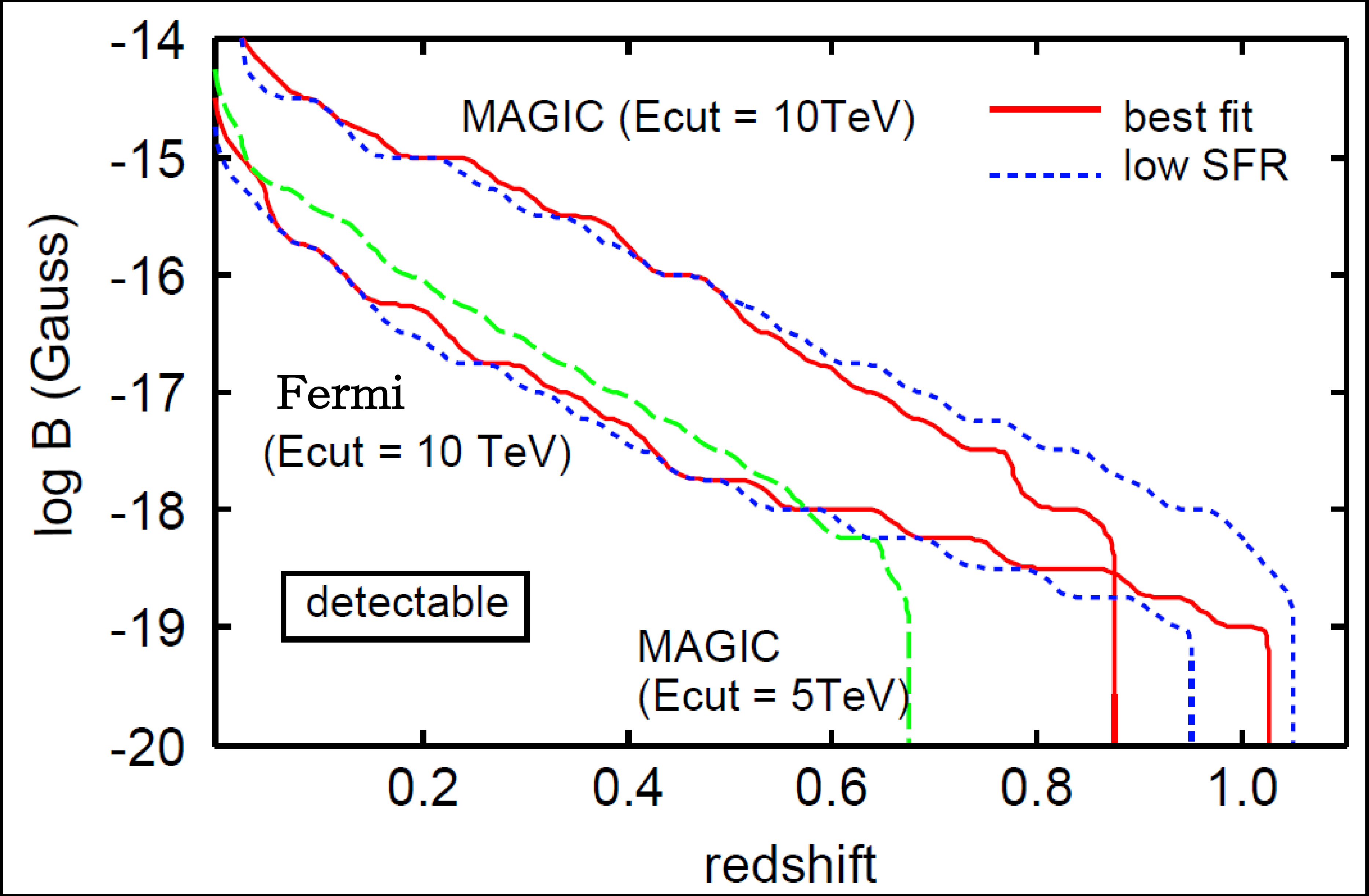
light curve at 1 GeV & Fermi



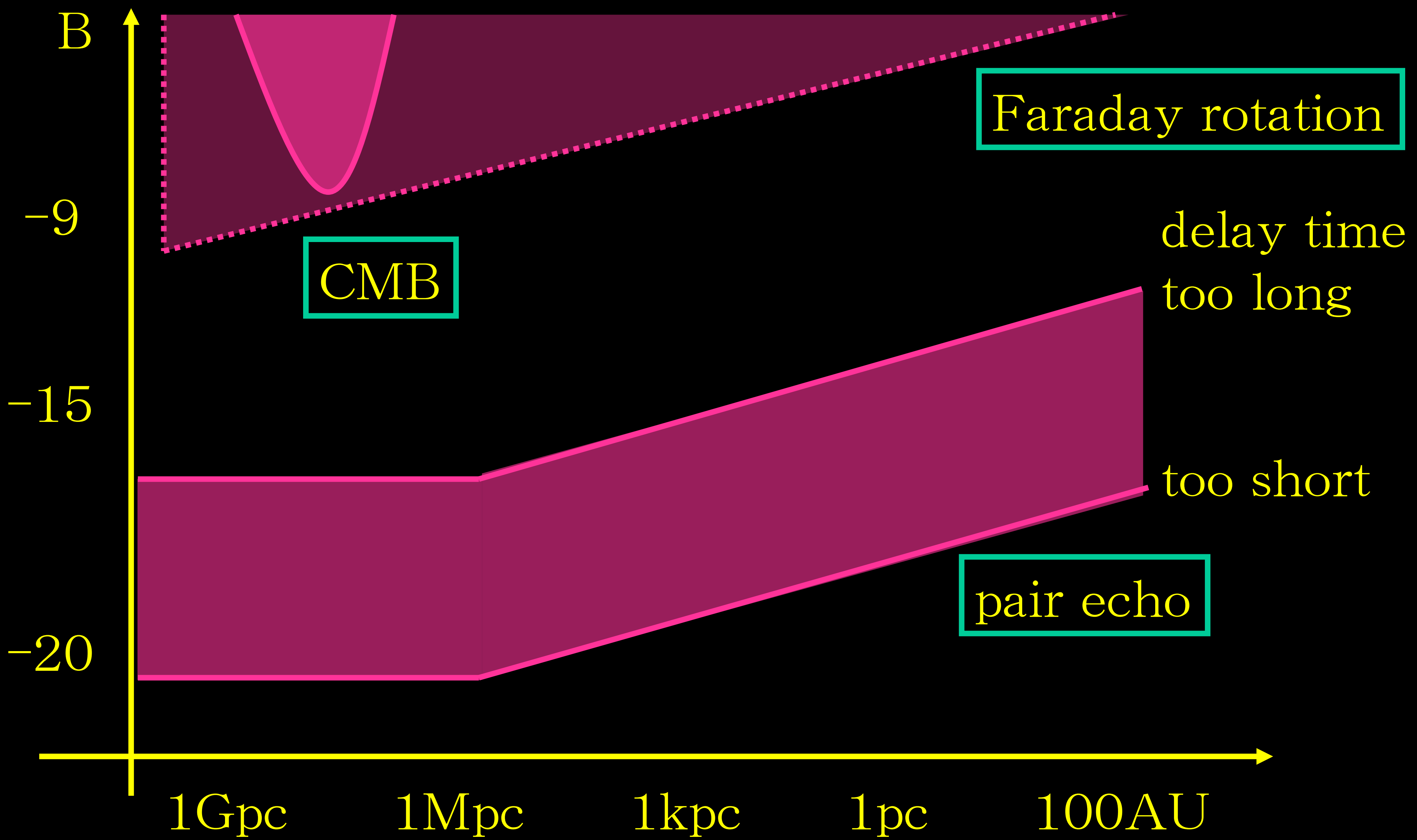
light curve at 100 GeV & MAGIC



observability of pair echo



expected constraints on B



summary of pair echo

- probe tiny B fields with pair echo from distant high-energy sources
- TeV γ-ray
  - + CIB → TeV e pair
  - + CMB → GeV γ-rays
- path is deflected by pair creation, IC, B fields → induce time delay
- sensitive to $10^{-15} \sim 10^{-20}$ G
- GRB with $z < 1$
- high-z GRB?

summary of this talk

generation and observation of cosmic magnetic field

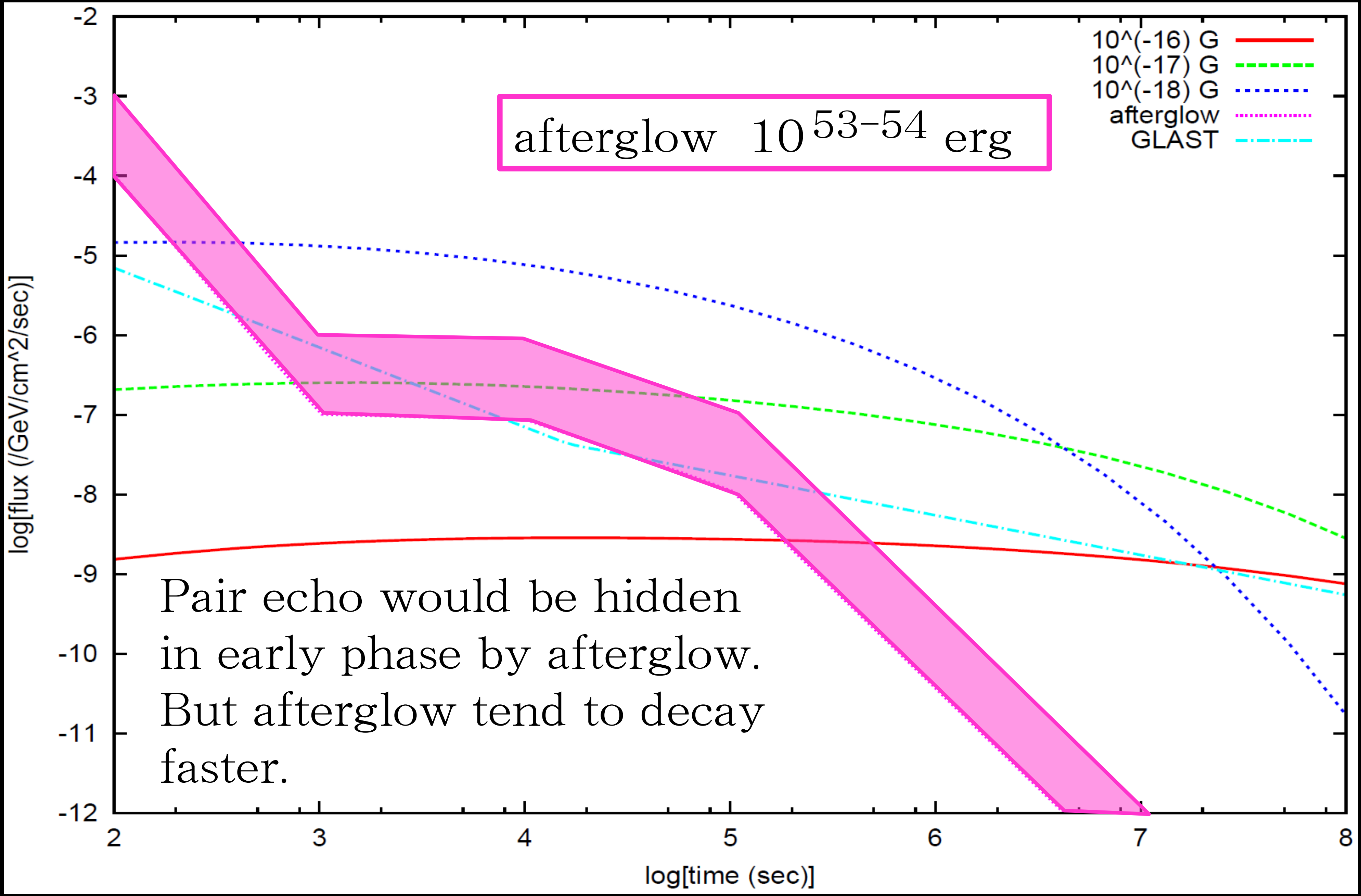
generation

- cosmological perturbation before recombination
- photons, protons, electrons, EM fields
- 2nd order perturbation
- robust prediction

observation

- pair echo from GRBs and blazars
- time delay due to B field
- observe tiny B fields in void region
- sensitive to $10^{-17} \sim 10^{-20}$ Gauss
- probe early universe, reionization

comparison with afterglow



afterglow 10^{53-54} erg

Pair echo would be hidden in early phase by afterglow. But afterglow tend to decay faster.