Generating Large-scale Magnetic Fields from Cosmological Density Fluctuations

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Contents

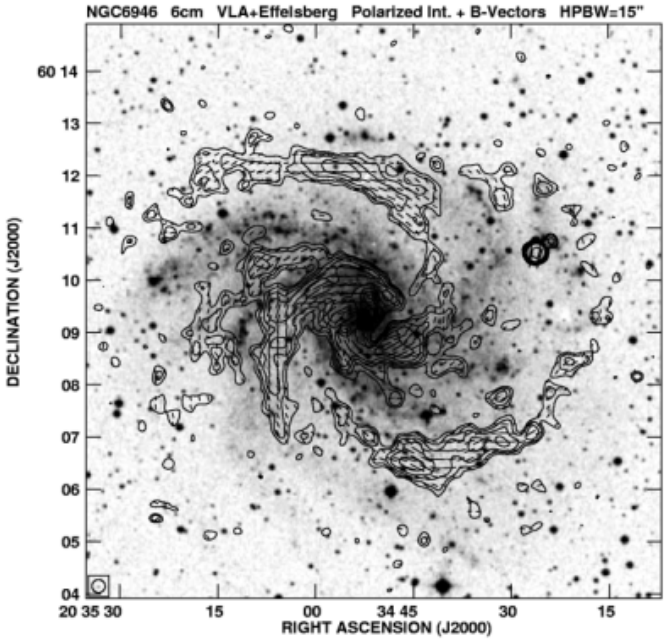
- Introduction
  - existence of large scale magnetic fields
  - magnetic field generation from cosmological fluctuations

    (K.I, Takahashi, Ohno, Hanayama, Sugiyama, science, (2006))
- Toward a detection of weakest cosmological magnetic fields
  - using time-delays of emissions from γ-ray burster

    (K.I, Inoue, Takahashi, (to be submitted))
- summary

Cosmic Magnetic Fields (what is the origin?)

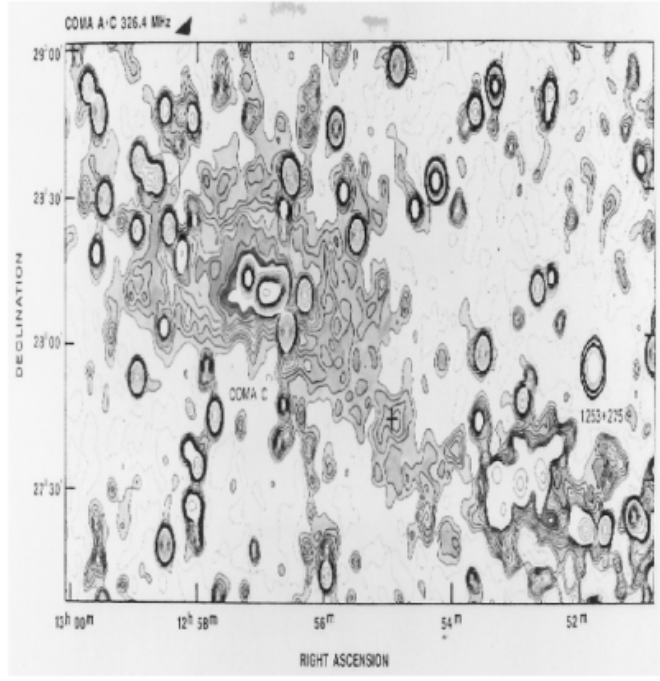
coherent magnetic fields at large scales



Beck and Hoernes, Nature, (1996)

NGC 6946

B $\sim \mu$G may be associated with density spiral structure.



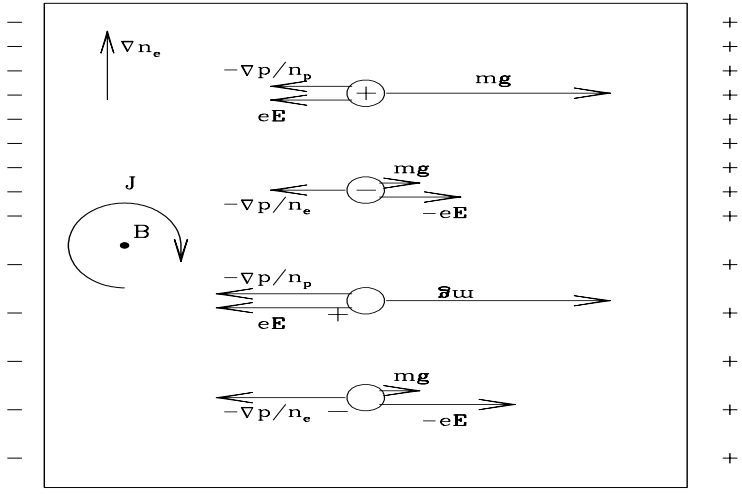
Kim et al., Nature, (1989)

1.5Mpc “bridge” between clusters from Coma to Abell 1367

$0.2 \sim 0.6 \mu$G (derived by minimum energy)

What is the Origin(s)? – astrophysics

- Astrophysical activities during structure formation until today
  - Biermann Battery (Biermann 1950) + dynamo amplification
    - primordial SNs: $B \sim 10^{-16}$G(Hanayama et al, 2005)
    - protogalaxy formation: $B \sim 10^{-21}$G (Kulsrud et al., 1997)
    - Reionization: $B \sim 10^{-18}$G(Gnedin et al, 2000)
  - Weibel instability in structure formation shocks: $B \sim 10^{-8}$G (Fujita et al., 2005)



- Well known physics
- strong enough
- can not predict their spectrum
  - coherence length?
- many uncertainties about predictions

What is the Origin(s)? – Cosmological

- magnetic field generation during inflation
  - need to break conformal invariance of EM fields
    - $\left(\frac{\partial^2}{\partial\eta^2} - \nabla^2\right)(a^2\vec{B}) = 0 \rightarrow \vec{B} \propto a^{-2}$
    - couplings to gravity: $R_{\mu\nu}A^\mu A^\nu$, $RF^{\mu\nu}F_{\mu\nu}$
      $B \sim 10^{-9}$G (Turner, 1988)
    - coupling to inflaton: $e^\phi F^{\mu\nu}F_{\mu\nu}$
      $10^{-65} \lesssim B \lesssim 10^{-10}$G (Ratra, 1992)

- strength and spectrum of mag. fields are predictable
- results are strongly model dependent
  (which is correct?)

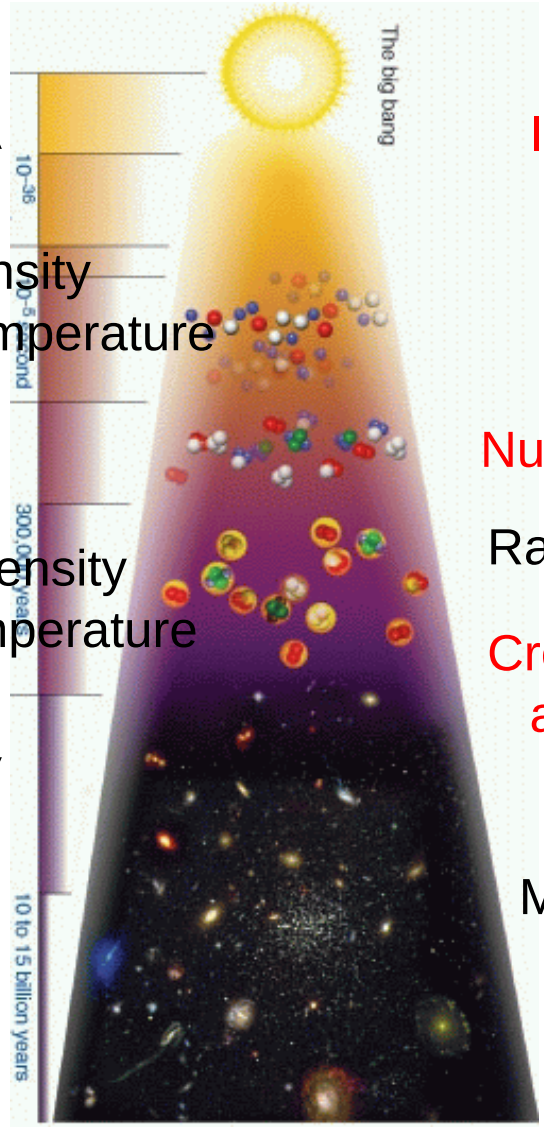
Our proposal – Cosmo-Physical approach

- magnetic field generation *befor recombination*.
  - photons push electrons preferentially to protons by Compton scattering ($m_e \ll m_p$)
    - difference in fluid velocity between photons and baryons ($v_\gamma - v_b$) induces that between protons and electrons.(Harrison (1970), Gopal&Sethi(2004))
    - anisotropic stress of photons (Π_γ) pushes electrons in a different way from protons (new!!)
      $\rightarrow$electric current$\rightarrow$magnetic fields
- ($v_\gamma - v_b$), and Π_γ originate from density fluctuations.

  $\longrightarrow$ no assumption needed for existence.

- Besed on well-established cosmological perturbation theory (and observations)
- large coherence length
- field strength is small (10^{-30}G $\sim 10^{-20}$G)

History of the universe



rger density
gher temperature

maller density
wer temperature

time

Inflation

Big-Bang Nucleosynthesis

Radiation Dominated

Creation of CMB anisotropies

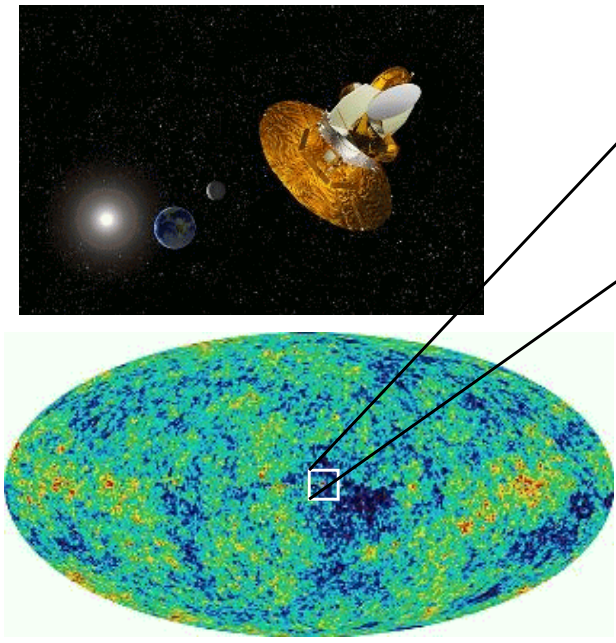
Matter Dominated

Present Universe

- In the primordial plasma, all materials exist as
  - protons
  - electrons
  - photons
- these are essential materials for generating magnetic fields

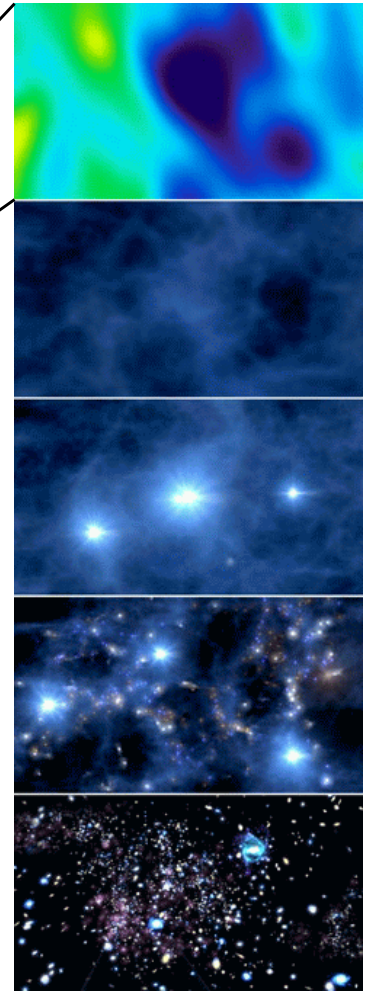
Density Fluctuation: 'Seed' for every structures

Alghough the universe is almost isotropic and homogeneous, we have small inhomogeneities as perturbations on it.



temperature anisotropy: temperature inhomogeneity at 380,000 yr after the big-bang

赤：higher temp (higher density)
青：lower temp (lower density)



３８万年
recombination
(neutralization)

higher density regions
→ stronger gravity
→ collect matters
→ higher density
→ form objects

first object
２億年

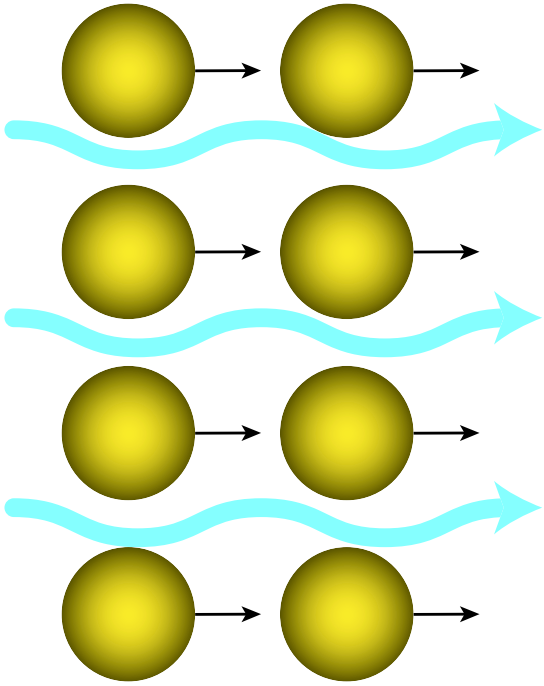
stars → galaxy
galaxies → cluster

present universe
１３７億年

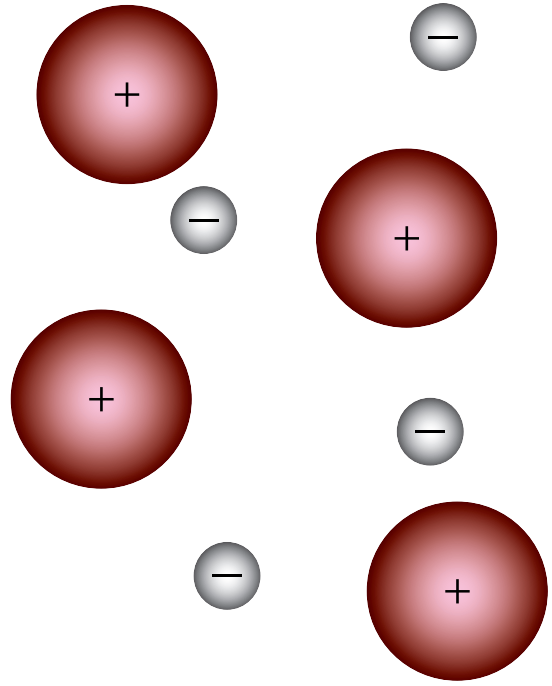
magnetic fields generation from density fluctuations

Density fluctuation of photons

–> ’photon wind’ blows from high density regions



photon 「wind」



primordial plasma

magnetic fields generation from density fluctuations

Density fluctuation of photons

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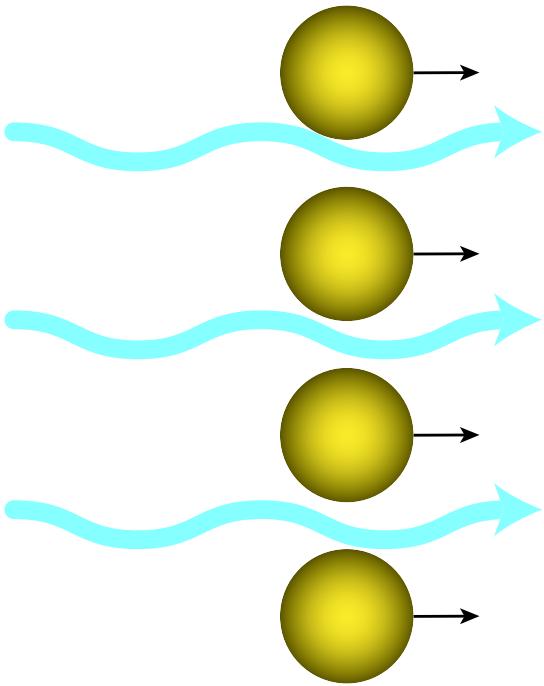

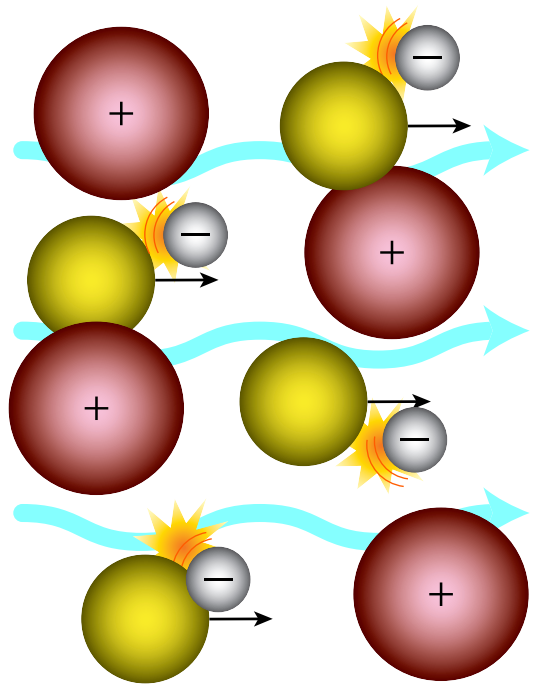

photons push only electrons

magnetic fields generation from density fluctuations

Density fluctuation of photons

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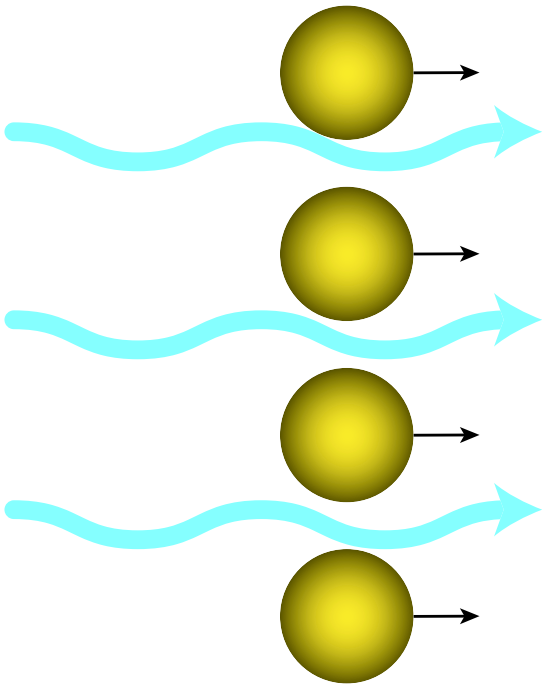
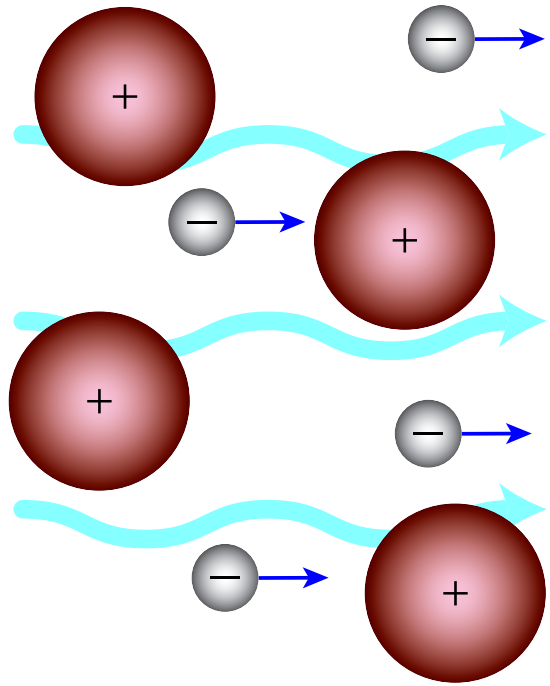


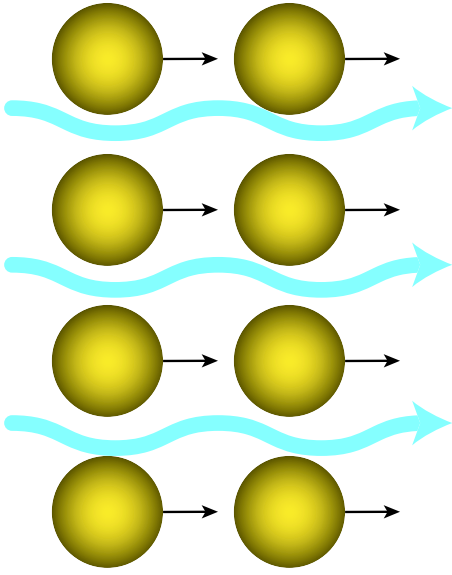
photon 「wind」



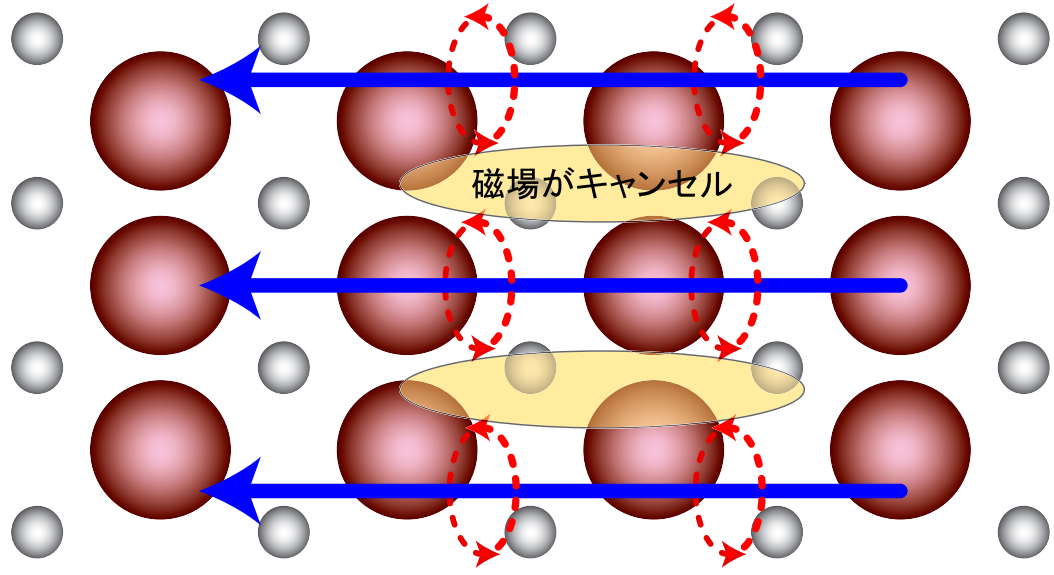
electric current –> mag fields

An Essence to Generate Mag Fields

If you work in the standard 'linear' perturbation theory•••



photon 「wind」

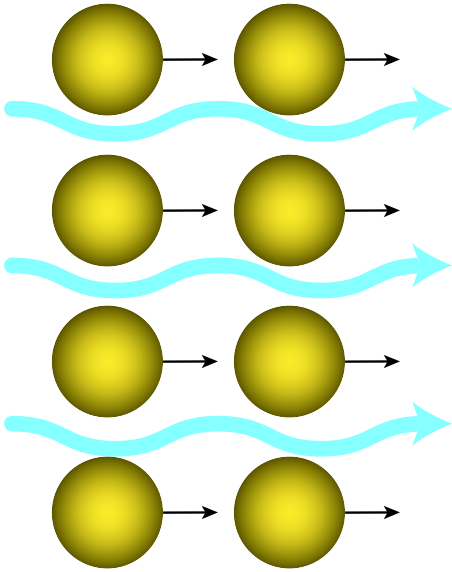


homogenious matter distribution

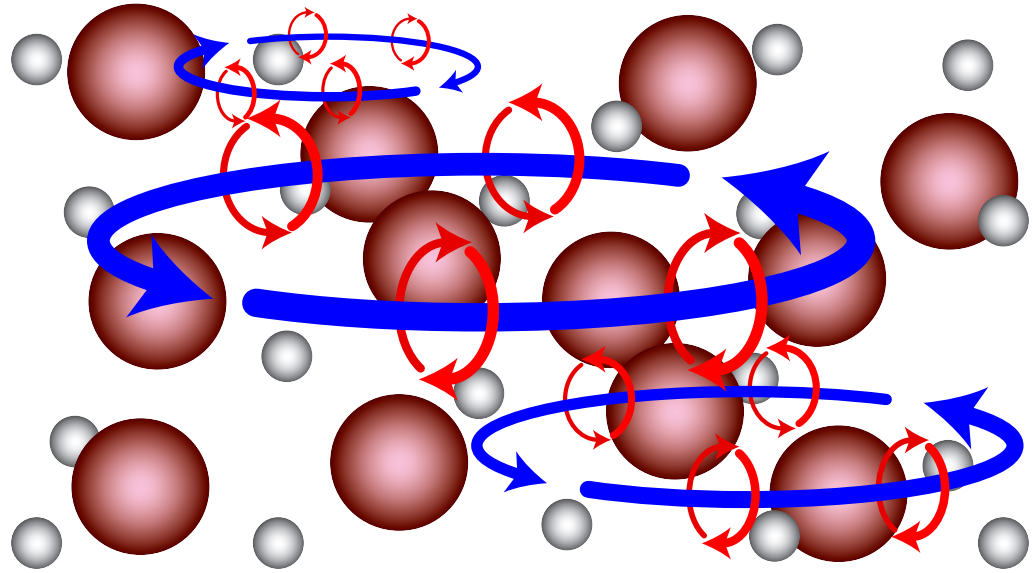
- No magnetic fields can be generated

An Essence to Generate Mag Fields

If you consider second order couplings into account•••



photon 「wind」



inhomogeneous matter distribution

- magnetic field should be generated
  - in particular, aniostropic distribution of photons is important
- coupling between photon wind and inhomogeneous matter distribution (second order effect)

Evolution equation for Magnetic Fields

Vorticity difference: intrinsically second order

$$\dot{B}^i = -\epsilon^{ijk} C_{j,k}$$

$$= \frac{4\sigma_T \overset{(0)}{\rho}_\gamma}{3e} \epsilon^{ijk} \left[\boxed{\overset{(1)}{\delta}_{\gamma\,,k} \left(\overset{(1)}{u}_{ej} - \overset{(1)}{u}_{\gamma j} \right)} + \left(\overset{(2)}{u}_{ej,k} - \overset{(2)}{u}_{\gamma j,k} \right) \right.$$

$$\left. + \boxed{\frac{1}{8} \left(\overset{(1)}{u}_{el,k} \overset{(1)}{\Pi}{}^l_{\gamma j} + \overset{(1)}{u}_{el} \overset{(1)}{\Pi}{}^l_{\gamma j,k} \right)} \right],$$

$\square$: photon push

$\square$: anisotropic pressure of photons

We can evaluate (1st order) $\times$ (1st order) terms by non-linear convolution of perturbation spectra.

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ALL TERMS are at SECOND ORDER!!

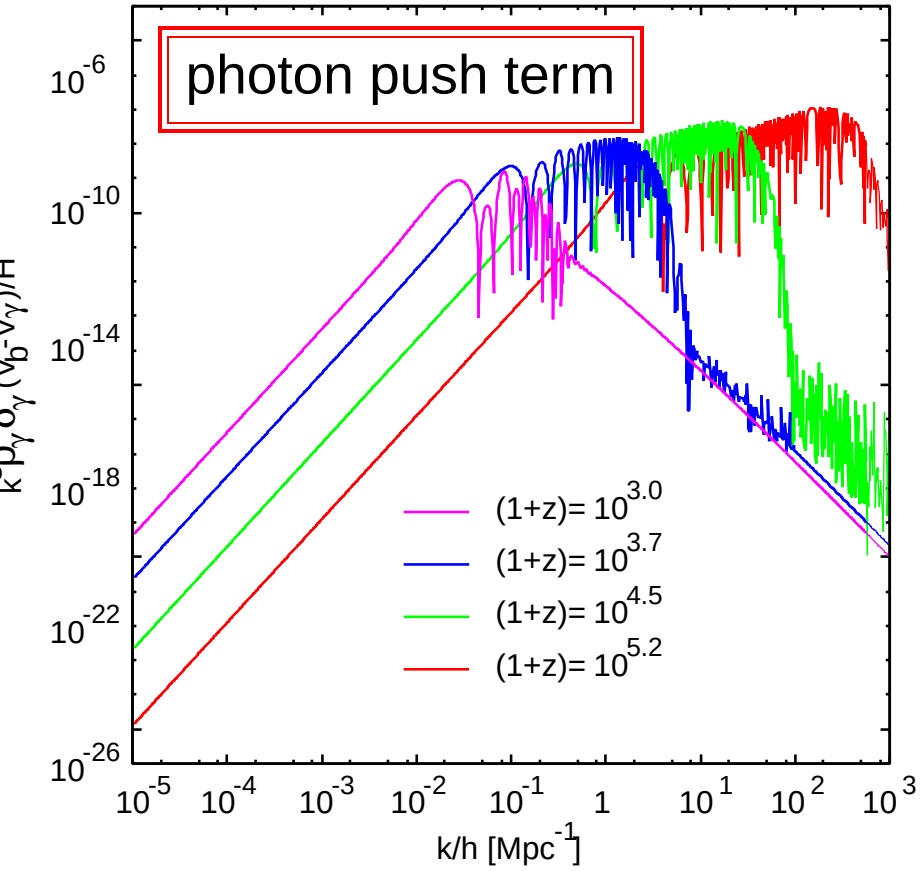
: photon push

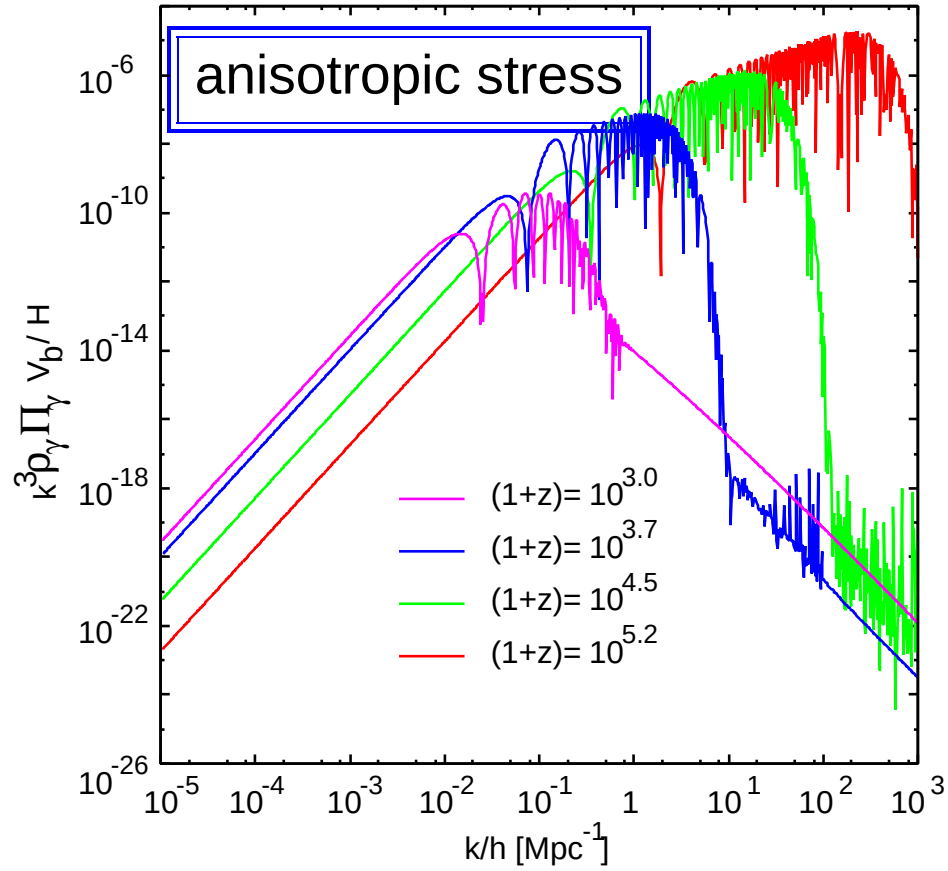
: anisotropic pressure of photons

We can evaluate (1st order) $\times$ (1st order) terms by non-linear convolution of perturbation spectra.

source terms at various redshifts

magnitudes of source terms per $\log z$. Magnetic fi elds can be obtained by time integration and non-linear convolution of these spectra.





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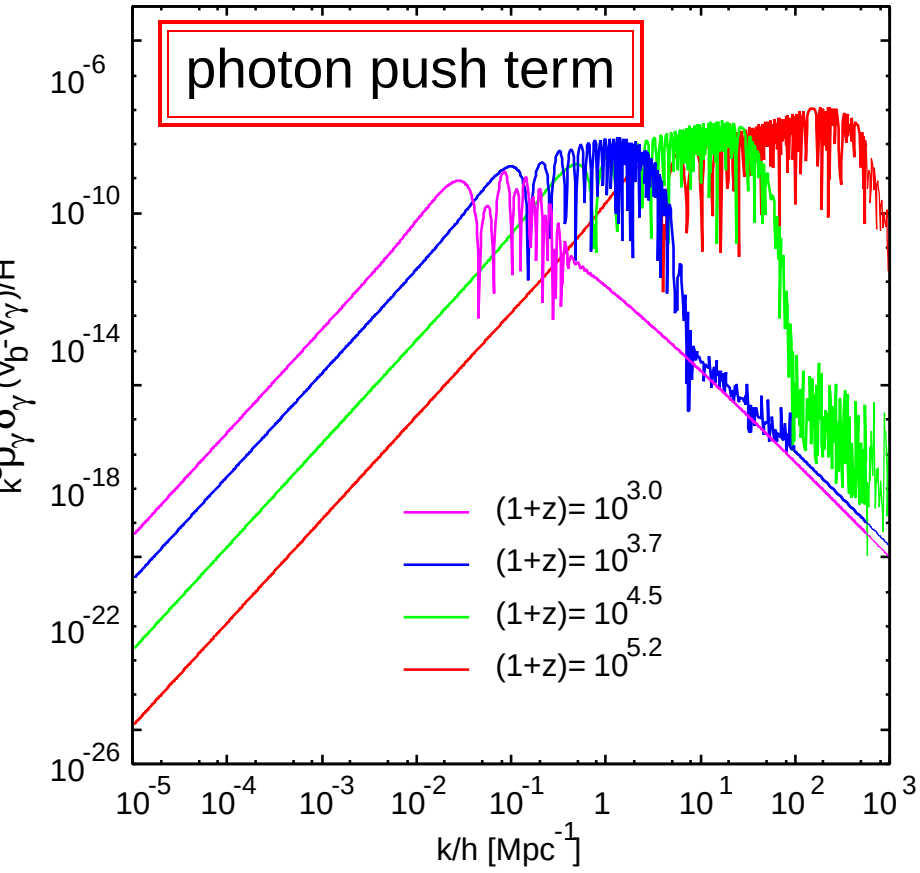
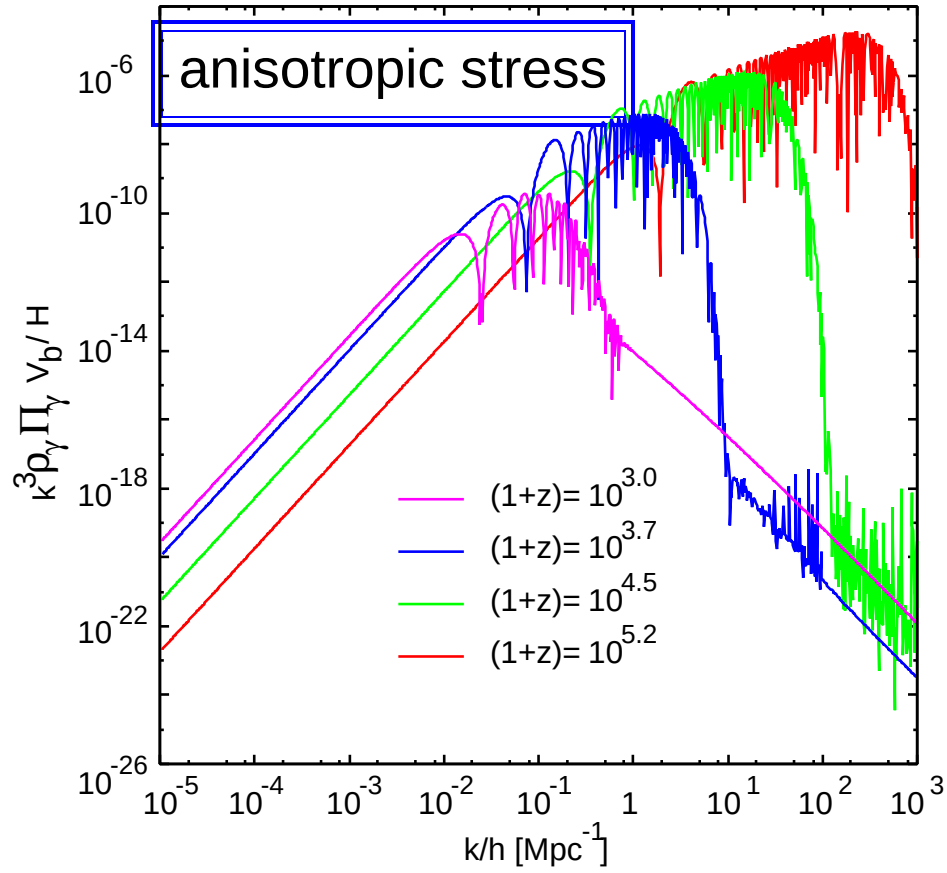
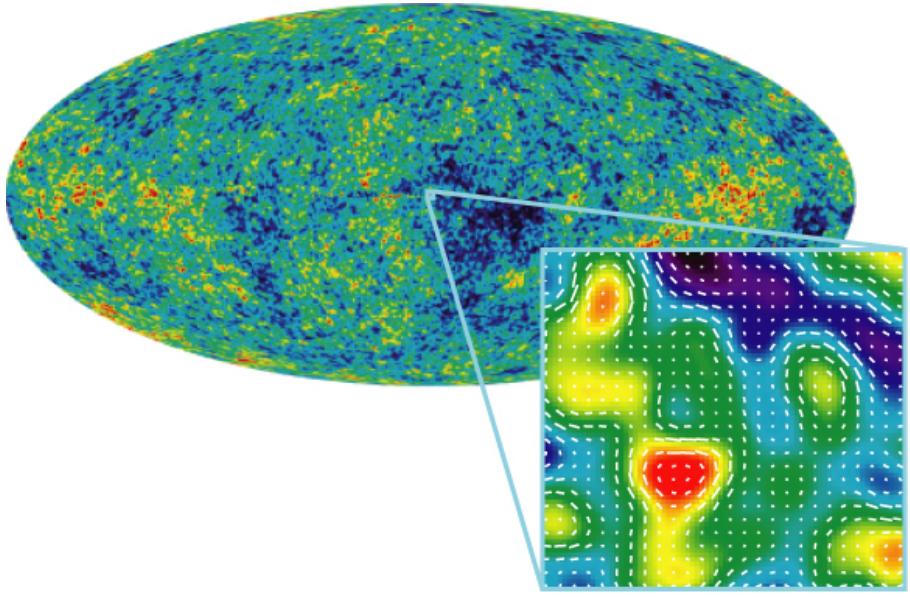
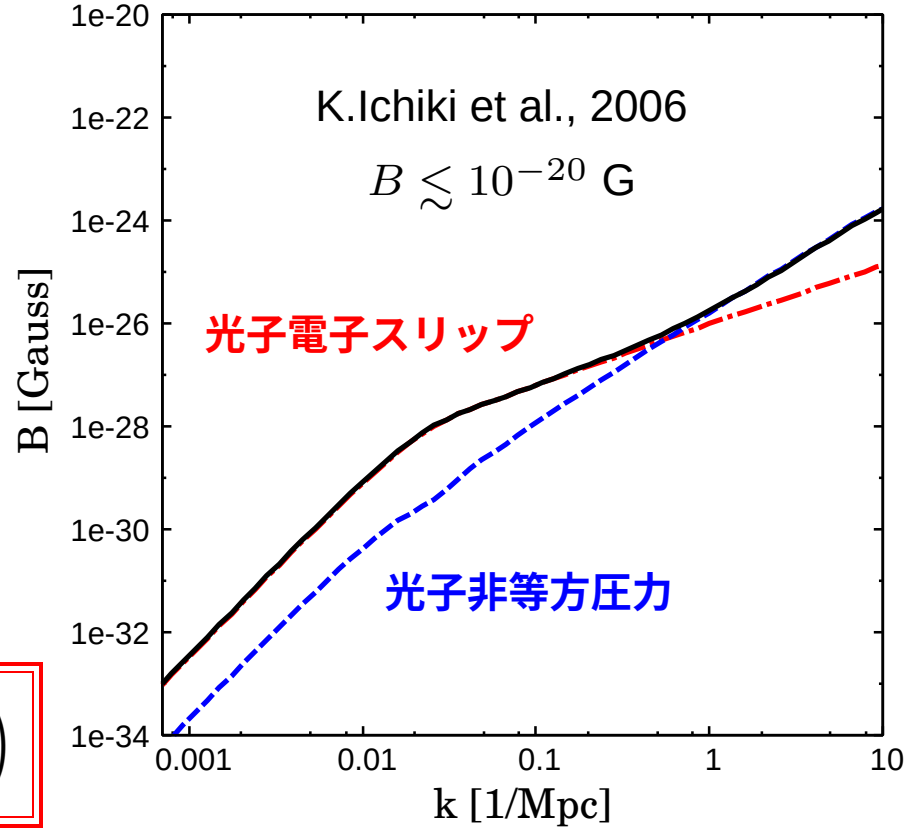




B fields at the smaller scales are generated at the earlier epochs

Cosmological Magnetic Fields from Density Perturbations





$$\dot{B}^i = \frac{4\sigma_T \overset{(0)}{\rho}_\gamma}{3e}\epsilon^{ijk}\left[\overset{(1)}{\delta}_{\gamma\,,k}\left(\overset{(1)}{u}_{ej} - \overset{(1)}{u}_{\gamma j}\right)\right.$$

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K. Takahashi et al., (2005)

Brief Summary

magnetic field generation from cosmological perturbations

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magnetic field generation from cosmological perturbations

- density fluctuation $\rightarrow$ photon wind $\rightarrow \vec{j} \rightarrow \vec{B}$
- generated from second order effect, no assumptions (unavoidable generation)
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Brief Summary

magnetic field generation from cosmological perturbations

- density fluctuation $\rightarrow$ photon wind $\rightarrow \vec{j} \rightarrow \vec{B}$
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- fields are correlated with CMB and Large scale structure
- characteristic values
  - 10^{-20} G @ 10 kpc
    $\rightarrow$ sufficient for galactic dynamo
  - 10^{-24} G @ 1 Mpc
    $\rightarrow$ strict lower bound at intergalactic fields

An Interesting Speculation

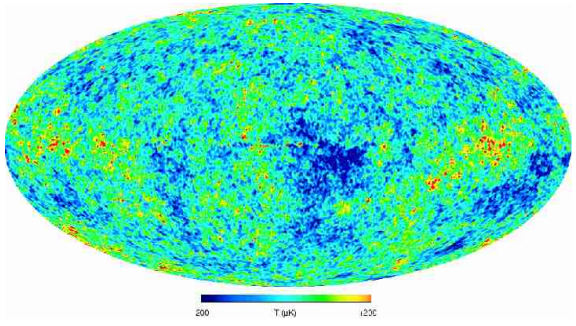
Inflation
generation of density perturbations

$$ds^2 = (g_{\mu\nu} + h_{\mu\nu})dx^\mu dx^\nu$$

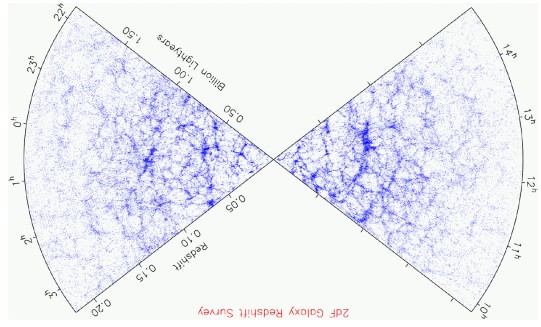
$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

cosmological density perturbation theory

CMB anisotropies



Large Scale Structure



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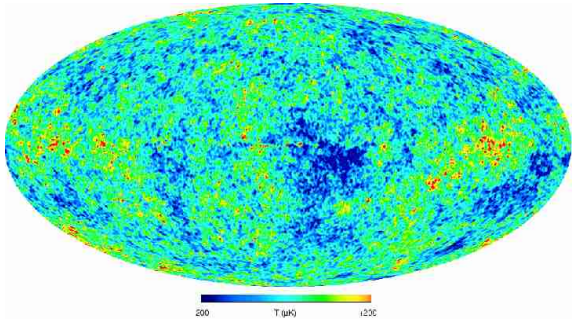
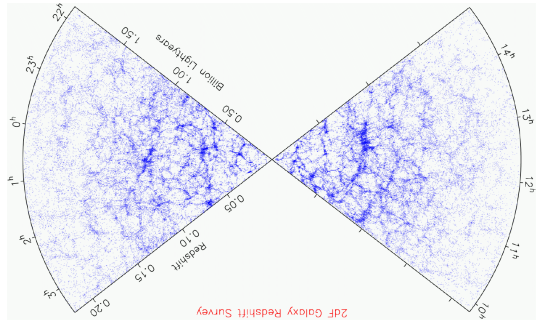
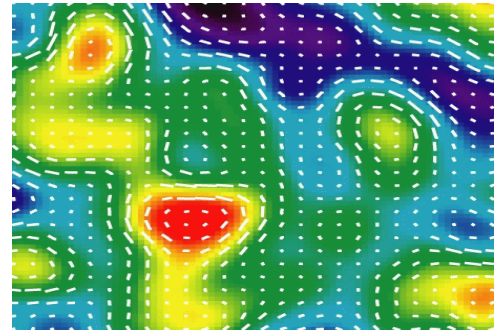
cosmological density perturbation theory

K. Ichiki et al., *Science*, (2006)

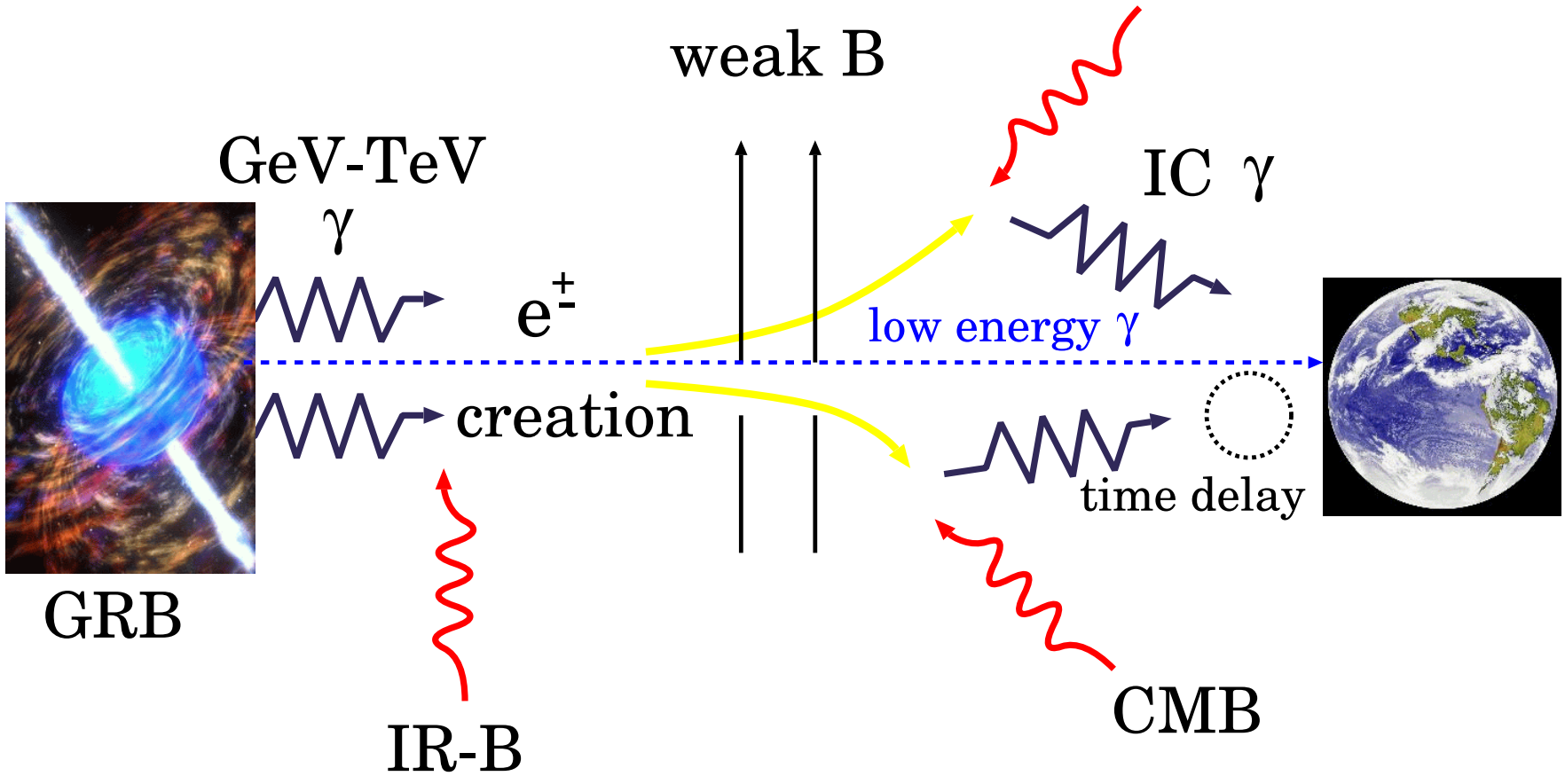
CMB anisotropies | Large Scale Structure | Cosmic B fields







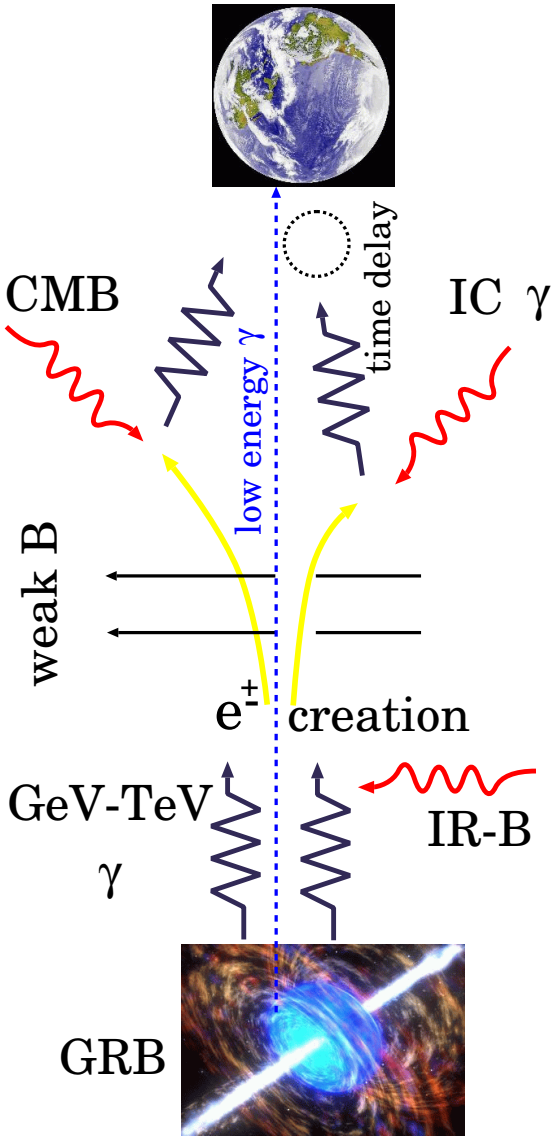
Detectability (R. Plaga, *Nature* 1995)



- arrival time should be delayed in the presence of intergalactic magnetic fields.

Our model to predict delayed emission

improved version of Razzaque et al., ApJ (2004)



$$\frac{d^2 N^{\rm IC}_{\rm delay}}{dt dE_\gamma} = \int d\gamma_e \frac{dN_e}{d\gamma_e dt} t_{\rm GRB} \frac{d^2 N^{\rm IC}_\gamma}{dt dE_\gamma} \left(\frac{t_{\rm IC}}{\Delta t}\right) e^{-\tau_{\gamma\gamma}(E_\gamma)}$$

↑

delayed Δt + re-emitting γ-rays by IC

↑

$\epsilon_\gamma \rightarrow 2m_e\gamma_e$ ($e^\pm$ **生成**), $\tau_{\gamma\gamma}$: optical depth of IRB

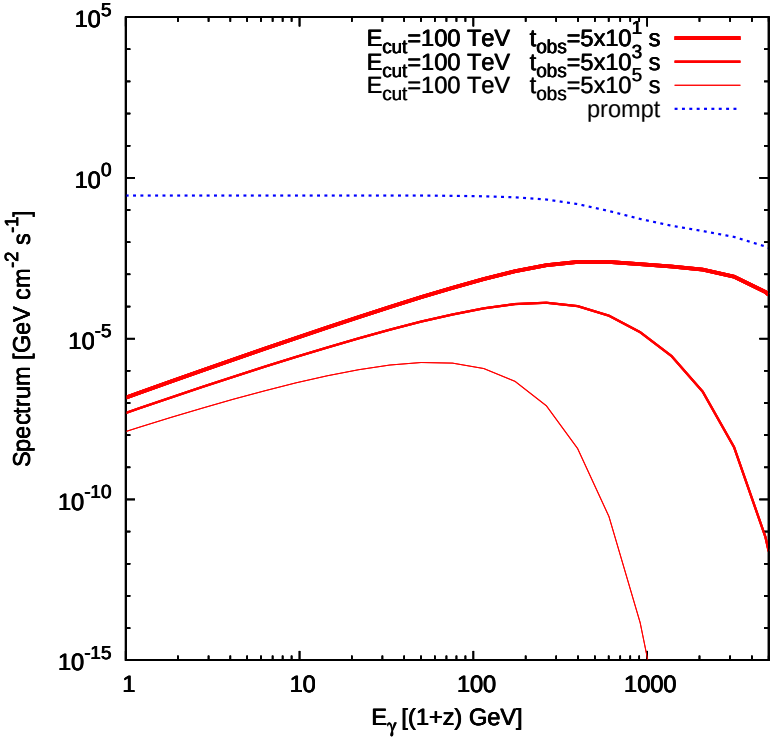
$$\frac{d^2 N_e}{2m_e d\gamma_e dt} = \frac{L_{\gamma,\rm iso}}{4\pi D_{\rm L}^2} \frac{\alpha-1}{\epsilon^2_{\gamma,\rm pk}} \left(\frac{2m_e\gamma_e}{\epsilon_{\gamma,\rm pk}}\right)^{-\alpha} \left(1 - e^{-\tau_{\gamma\gamma}(2m_e\gamma_e)}\right)$$

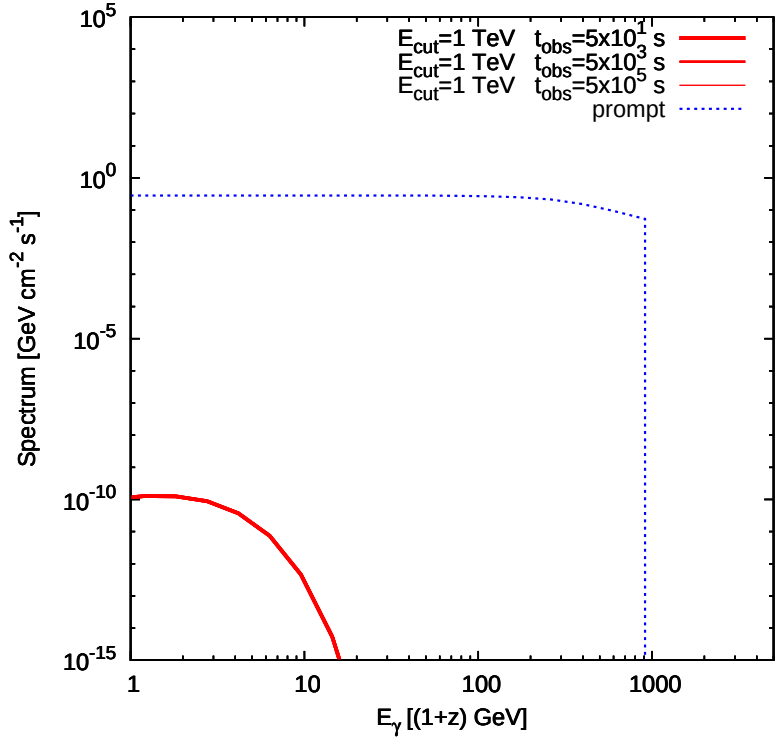
↑

simplest power law (synchrotron) spectrum

$$\frac{d^2 N_\gamma}{d\epsilon_\gamma dt} = \frac{L_{\gamma,\rm iso}}{4\pi D_{\rm L}^2} \frac{\alpha-1}{\epsilon^2_{\gamma,\rm pk}} \left(\frac{\epsilon_\gamma}{\epsilon_{\gamma,\rm pk}}\right)^{-\alpha} (\epsilon_\gamma > \epsilon_{\gamma,\rm pk})$$

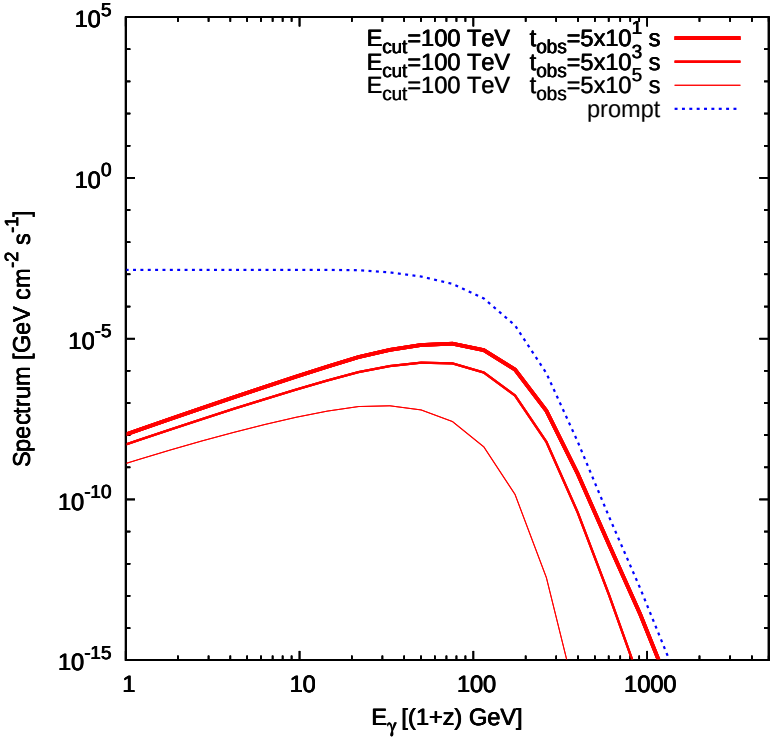
Delayed spectrum (B=10^{-18}G; z=0.1)

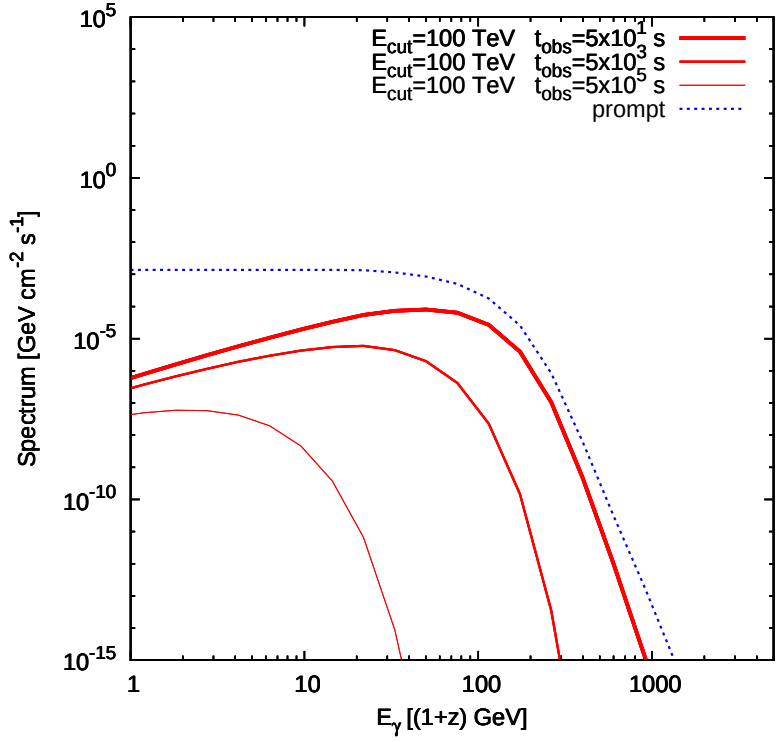




- IRB absorption will be important $E_\gamma > 100$GeV, but not significant for γ-ray bust at $z = 0.1$.

Delayed spectrum (B=10^{-18}G; z=1.0)

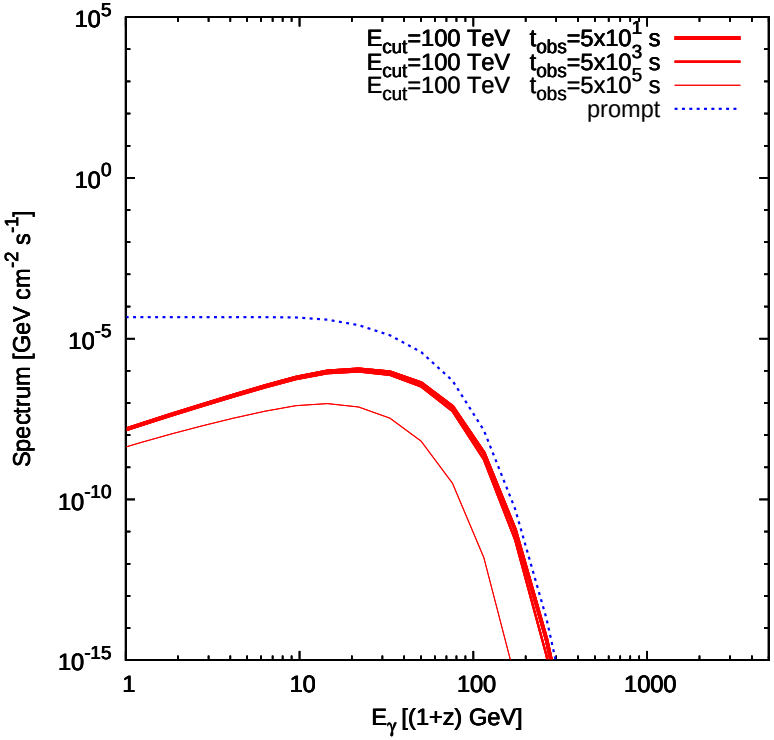


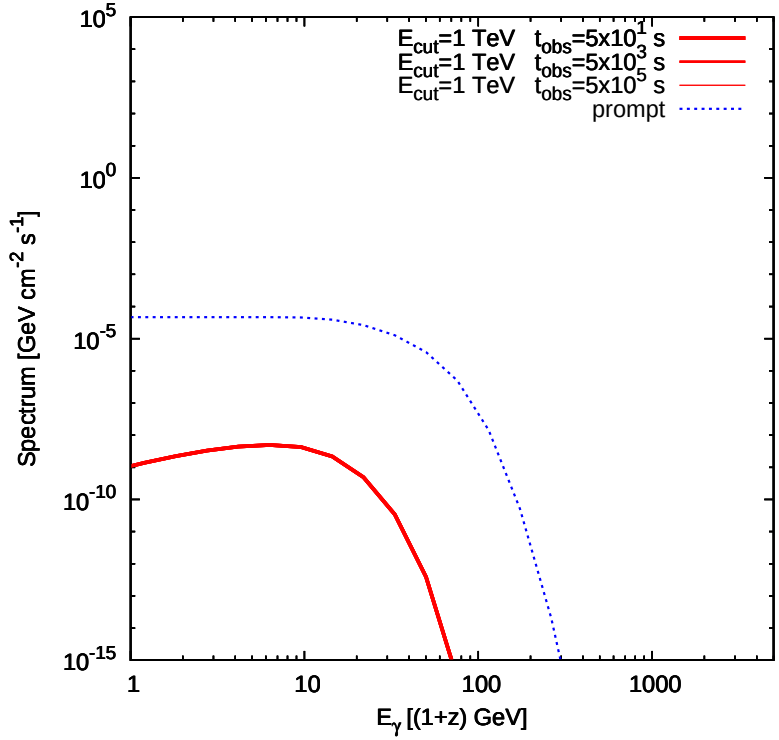


- Time dependence of the delayed spectra depends on the magnetic field configuration.

  $\rightarrow$information on magnetic field spectrum

Delayed spectrum (B=10^{-18}G; z=4.0)



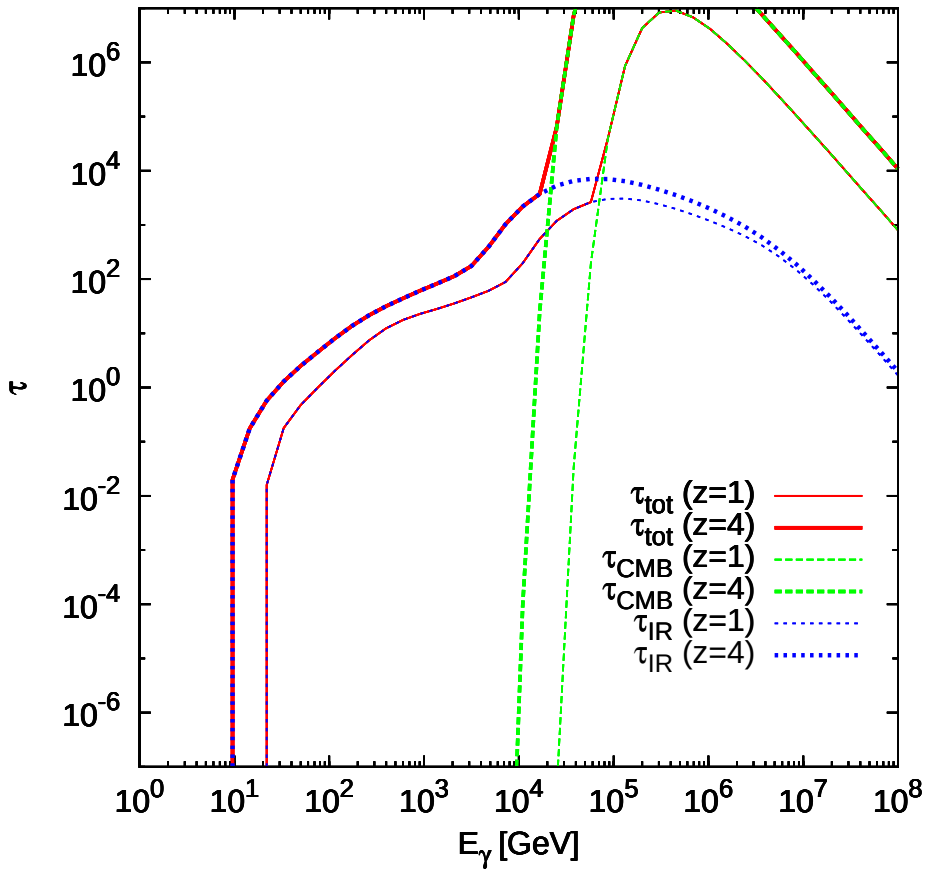


- Delayed IC-photons are absorbed once again for γ-ray bursts at $z = 4$.

Summary

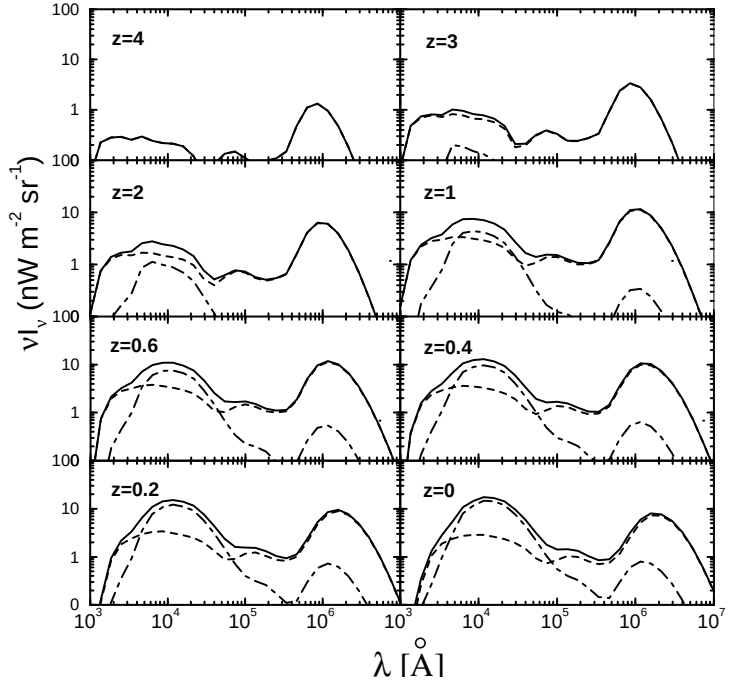
- The origin of large scale magnetic fields is still unknown
  - Cosmological ? (predictable (but model dependent))
  - Astrophysical ? (well known physics, but highly uncertain)
  - We showed that cosmological density fluctuations naturally generate magnetic fields (alghough very weak).
  - characteristic values
    - 10^{-20} G @ 10 kpc
      $\rightarrow$ sufficient for galactic dynamo
    - 10^{-24} G @ 1 Mpc
      $\rightarrow$ strict lower bound at intergalactic fields
- Magnetic fields in void regions can be probed by GeV-TeV delayed photons from γ-ray bursters
  - Fields as weak as $B \sim 10^{-18}$G may be detectable.
  - Amplification mechanisms are needed for cosmologically generated magnetic fields to be detectable and/or dynamically important.

optical depth for $\gamma + \gamma \rightarrow e^{\pm}$



- Model employed for IRB

  Kneiske et al., A&A, 386, 1, (2002)



important scales involved

Can we probe magnetic fields in void regions?

- energy of electrons produced by γ-rays with $E_\gamma = 20\mathrm{TeV}$:
  - $E_e = 10.0\mathrm{TeV}\left(\frac{E_\gamma}{20\mathrm{TeV}}\right),\ \gamma_e = 2\times 10^7\left(\frac{E_\gamma}{20\mathrm{TeV}}\right)$
  - $\lambda_{\gamma\gamma} \sim \frac{1}{\sigma_T n_{IR}} = 6\mathrm{Mpc}\left(\frac{n_{IR}}{1\mathrm{cm}^{-3}}\right)$ ($\leftarrow$ creation time)
  - $e^\pm$ creation in void

- How long distance can this $e^\pm$ propagate?
  - $\lambda_{IC} = \frac{3m_e}{4\gamma_e\sigma_T u_{\mathrm{cmb}}}$
    $= 100\mathrm{kpc}\left(\frac{E_\gamma}{20\mathrm{TeV}}\right)^{-1}$
  - cool down in void