

# Gamma-ray absorption and pair echos at very high-redshifts: probing radiation and magnetic fields in the cosmic reionization era

Susumu Inoue<sup>\*</sup>, Ruben Salvaterra<sup>†</sup>, Tirth Roy Choudhury<sup>‡</sup>, Andrea Ferrara<sup>§</sup>, Raffaella Schneider<sup>¶</sup>,  
Benedetta Ciardi<sup>||</sup>, Keitaro Takahashi<sup>\*\*</sup> and Kiyotomo Ichiki<sup>\*\*</sup>

<sup>\*</sup>Department of Physics, Kyoto University, Kyoto 606-8502, Japan

<sup>†</sup>INAF, Osservatorio Astronomico di Brera, 23807 Merate, Italy

<sup>‡</sup>Centre for Theoretical Studies, Indian Institute of Technology, Kharagpur 721302, India

<sup>§</sup>Scuola Normale Superiore, 56126 Pisa, Italy

<sup>¶</sup>Osservatorio Astrofisico di Arcetri, 50125 Firenze, Italy

<sup>||</sup>Max-Planck-Institut für Astrophysik, 85748 Garching, Germany

<sup>\*\*</sup>Department of Physics and Astrophysics, Nagoya University, Nagoya 464-8602, Japan

**Abstract.** We discuss expectations for the absorption of high-energy gamma-rays by pair production with intergalactic radiation fields (IRF) at very high redshifts ( $z \sim 5 - 20$ ). For the evolving IRF, a semi-analytic model including Population III stars is employed which is consistent with a wide variety of existing high- $z$  observations. We find that the UV IRF below the Lyman edge energy can cause appreciable attenuation above several GeV at  $z \gtrsim 5$  with notable differences up to  $z \sim 8$ , which may be observable in the spectra of high- $z$  GeV sources such as blazars or gamma-ray bursts by *Fermi* and/or the proposed 5@5 facility, providing invaluable information on cosmic reionization and early star formation. We also briefly address the possibility of probing early cosmic magnetic fields through pair echos, i.e. inverse Compton gamma-rays from the secondary pairs.

**Keywords:** gamma-rays, diffuse radiation, magnetic fields, early universe, gamma-ray bursts, blazars

## I. INTRODUCTION

Some time after the epoch of cosmic recombination at  $z \sim 1100$ , the bulk of the intergalactic gas in the universe must have been somehow reionized by  $z \sim 6$ , as indicated observationally from the spectra of high- $z$  quasars and the polarization of the cosmic microwave background (CMB). However, the sources, history and nature of this cosmic reionization process are still largely unknown, as most of this redshift range has yet to be explored through direct observations. Because the first stars and galaxies in the universe must have formed during this period, the primary suspect is photoionization by UV radiation from such objects, potentially involving metal-free, Population (Pop) III stars. Cosmic reionization also profoundly affects the ensuing formation of stars and galaxies, so elucidating this era is one of the most pressing issues in cosmology today [1], [2].

In the majority of scenarios for reionization of hydrogen (H) in the intergalactic medium (IGM), the main protagonists are UV photons with energies above the

Lyman edge ( $\epsilon \geq \epsilon_{\text{LE}} = 13.6$  eV). Although those with lower energies do not contribute to photoionization, they are also crucial since i) they give indications as to the strength and nature of the ionizing radiation, ii) those in the Lyman-Werner band ( $\epsilon = 11.2 - 13.6$  eV) can photodissociate  $\text{H}_2$  molecules and suppress early star formation, and iii)  $\text{Ly}\alpha$  photons ( $\epsilon = \epsilon_\alpha = 10.2$  eV) can strongly affect the HI spin temperature and the associated cosmological 21 cm signatures. Thus, observational methods to probe the evolution of UV radiation fields in the cosmic reionization era are of paramount importance. However, direct detection of this diffuse emission from high- $z$  is extremely difficult if not impossible.

An indirect but powerful means of probing diffuse radiation fields is through photon-photon ( $\gamma\gamma$ ) absorption of high-energy gamma-rays [3]. Gamma-rays with energy  $E$  emitted from extragalactic sources will be absorbed during intergalactic propagation by interacting with photons of the diffuse radiation field with energy  $\epsilon$  to produce electron-positron pairs ( $\gamma + \gamma \rightarrow e^+ + e^-$ ), as long as there is sufficient opacity for energies satisfying the threshold condition  $E\epsilon(1 - \cos\theta) \geq 2m_e^2c^4$ , where  $\theta$  is the incidence angle of the two photons. The observed spectra of the gamma-ray sources should then exhibit corresponding attenuation features, from which one can effectively infer or limit the properties of the diffuse radiation. This method has been utilized in recent TeV observations of blazars by ground-based Cherenkov telescopes to set important constraints on the extragalactic background light in the near infrared to optical bands at relatively low redshifts [4], [5].

As first discussed by [6], [7], UV intergalactic radiation fields (IRFs) with sufficient intensities to cause IGM reionization are also likely to induce significant  $\gamma\gamma$  absorption in gamma-ray sources at  $z \gtrsim 6$  at observed energies in the range of a few to tens of GeV. However, these estimates i) were made before *WMAP* observations indicating an early start of reionization and were limited to  $z \leq 10$ , and ii) did not include the

possibility of metal-free Pop III stars, which may have been active during the first epochs of star formation and are more prodigious UV emitters compared to normal stars. The recent launch of the *Fermi* satellite operating in the 0.1-100 GeV range motivates us to reevaluate the  $\gamma\gamma$  absorption opacity at very high- $z$ , incorporating more recent observational and theoretical developments concerning the cosmic reionization era.

For this purpose, we employ the semi-analytic models of [8], [9] that self-consistently describe inhomogeneous reionization of the IGM, accounting for both Pop II and Pop III stars and their radiative and chemical feedback effects. With only a few free parameters, they are able to fit a wide variety of high- $z$  observations. Using the evolving IRF as predicted by this model, the  $\gamma\gamma$  opacity is evaluated for the redshift range  $z = 5 - 20$ . We also assess the detectability of the resultant absorption features in high- $z$  objects such as blazars or gamma-ray bursts (GRBs) with current and future gamma-ray facilities.

## II. GAMMA-RAY ABSORPTION BY UV INTERGALACTIC RADIATION FIELDS

### A. Intergalactic Radiation Field Model

The salient features of the semi-analytic models of [8], [9] are as follows. 1) Adopting a lognormal distribution of IGM inhomogeneities, the ionization and thermal histories of the neutral, HII and HeII phases of the IGM are tracked simultaneously and self-consistently. 2) The formation and evolution of dark matter halos are described by a Press-Schechter-based approach. 3) Three types of radiation sources are considered: a) metal-free Pop III stars with a Salpeter initial mass function (IMF) in the mass range 1-100  $M_{\odot}$ , with spectra according to [10] and including nebular and Ly $\alpha$  emission lines; b) low-metallicity (0.02 solar abundance) Pop II stars with spectra according to [11], otherwise being the same as Pop III; and c) QSOs with power-law spectra and luminosities depending on a certain power of the host halo masses. 4) Pop III and Pop II stars each form from gas in virialized halos with efficiencies  $\varepsilon_{*,\text{III}}$  and  $\varepsilon_{*,\text{II}}$ , respectively. Included self-consistently are the consequent effects of radiative feedback that suppresses star formation in sufficiently small halos, as well as chemical feedback that induces the transition from Pop III to Pop II star formation.

The adopted cosmological parameters are  $h = 0.73$ ,  $\Omega_m = 0.24$ ,  $\Omega_{\Lambda} = 0.76$ ,  $\Omega_b h^2 = 0.022$ ,  $\sigma_8 = 0.74$ ,  $n_s = 0.95$  and  $dn_s/d\ln k = 0$  [12]. The free parameters of the model are  $\varepsilon_{*,\text{III}}$ ,  $\varepsilon_{*,\text{II}}$ ,  $\eta_{\text{esc}}$  that fixes the escape fraction of ionizing photons from host halos, and  $\lambda_0$  related to the mean free path of ionizing photons in high-density regions. These are ascertained so as to simultaneously reproduce a large set of high- $z$  observational data: i)  $z$ -evolution of Lyman-limit absorption systems; ii) IGM effective optical depths for Ly $\alpha$  and Ly $\beta$  from quasar spectra; iii) electron scattering optical depth from *WMAP* 3rd year results [12] (also consistent with 5th

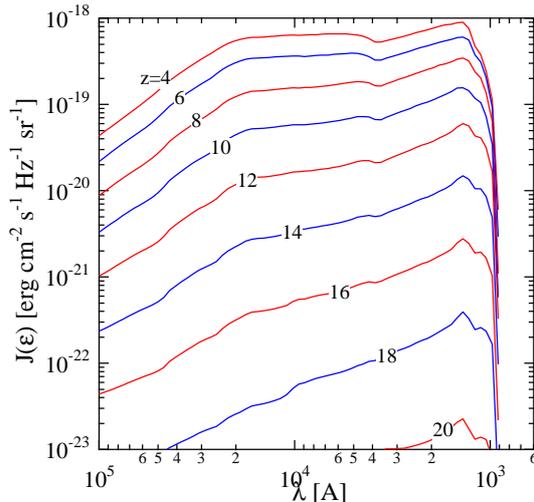


Fig. 1: Volume-averaged intensity of the intergalactic radiation field vs. wavelength at different  $z$  as labelled for the fiducial model of [9].

year results [13]); iv) temperature of the mean IGM; v) cosmic star formation history; and vi) limits on J-band source counts from NICMOS HUDF. The fiducial, best-fit model of [9] implies that H reionization begins rapidly at  $z \sim 15$ , initially driven by Pop III stars, and is 90 % complete by  $z \sim 10$ . Thereafter it is slowed down by feedback effects and taken over by Pop II stars and QSOs at  $z \gtrsim 7$ , finally reaching completion by  $z \sim 6$ .

Shown in Fig.1 is the volume-averaged intensity of the IRF as calculated from this model, which declines monotonically with  $z$  following the evolution of the star formation rate. We caution that at  $z \gtrsim 6$  before intergalactic HII regions have completely overlapped, the IRF is expected to be inhomogeneous and fluctuating along different lines of sight, particularly strongly for  $\epsilon \geq \epsilon_{\text{LE}}$  ( $\lambda \leq 912\text{\AA}$ ). However, it is also evident that ionizing photons are strongly absorbed by the neutral IGM and the mean IRF spectrum cuts off very sharply above  $\epsilon_{\text{LE}}$ , so that this portion has negligible effects on the  $\gamma\gamma$  opacity [6], [7]. On the other hand, UV radiation with  $\epsilon < \epsilon_{\text{LE}}$  have much longer mean free paths in the IGM, and the concept of a nearly uniform background may still be appropriate for this regime, which is also the most relevant for  $\gamma\gamma$  absorption. Note in particular the band  $\epsilon = 10.2 - 13.6$  eV ( $\lambda = 912 - 1216\text{\AA}$ ) where the spectrum dips somewhat due to blanketing by the Lyman series lines, but which nevertheless should be important for the  $\gamma\gamma$  opacity.

Being optimized for cosmic reionization, the main shortcoming of the present model is that it does not account for Pop I stars or dust that become important at low  $z$ . Predictions are available only down to  $z = 4$  and are less reliable for the lower  $z$  range.

### B. $\gamma\gamma$ absorption opacity

We first estimate the “local  $\gamma\gamma$  optical depth” at each  $z$  by the optical depth across a Hubble radius  $l_H(z) =$

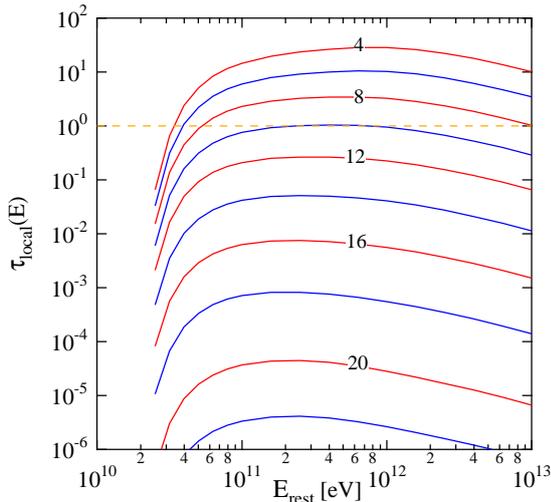


Fig. 2: Local  $\gamma\gamma$  optical depth vs. rest-frame gamma-ray energy at different  $z$  as labelled for the fiducial model.

$$c/H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda},$$

$$\tau_{\text{local}}(z, E) = l_H(z) \int_{\epsilon_{th}}^{\infty} d\epsilon n(\epsilon, z) \times \frac{1}{2} \int_{-1}^1 d\mu (1 - \mu) \sigma_{\gamma\gamma}(E, \epsilon, \mu), \quad (1)$$

where  $n(\epsilon, z)$  is the IRF photon number density,  $\mu = \cos\theta$ ,  $\epsilon_{th} = 2m_e^2c^4/E(1-\mu)$  is the threshold energy, and  $\sigma_{\gamma\gamma}(E, \epsilon, \mu)$  is the energy- and angle-dependent pair production cross section. Displayed in Fig.2 as a function of the rest-frame gamma-ray energy  $E_{\text{rest}}$ , we see that opacity may be significant out to  $z \sim 10$  for  $E_{\text{rest}} \sim 0.1 - 1$  TeV. Note the steep drop in  $\tau_{\text{local}}$  at  $E_{\text{rest}} < E_{\text{LE}} \sim (m_e c^2)^2/\epsilon_{\text{LE}} \simeq 18$  GeV, corresponding to the sharp cutoff in the IRF spectrum above the Lyman edge. As pointed out by [6], [7], this is crucial in that it allows appreciable contributions to the total  $\gamma\gamma$  opacity from higher  $z$  even when the IRF intensity is relatively weaker, and which should be uncontaminated from absorption at lower  $z$ . However, we also see that due to the declining UV intensity together with the reduced path length, the opacity from  $z \gtrsim 10$  is likely to be quite small.

This can be seen more explicitly in Fig.3 where we show the integrated  $\gamma\gamma$  optical depths for different source redshifts  $z$ ,

$$\tau(z, E) = \int_0^z dz' \frac{dl}{dz'} \int_{\epsilon_{th}}^{\infty} d\epsilon n(\epsilon, z') \times \frac{1}{2} \int_{-1}^1 d\mu (1 - \mu) \sigma(E(1+z'), \epsilon, \mu), \quad (2)$$

where  $dl/dz' = l_H(z')/(1+z')$  and  $E$  is the observed gamma-ray energy at  $z = 0$ . As mentioned above, the lower limit of  $z$ -integration than can be taken in the model is actually  $z = 4$ ; for additional absorption from  $z = 0 - 4$ , we can only consult other available

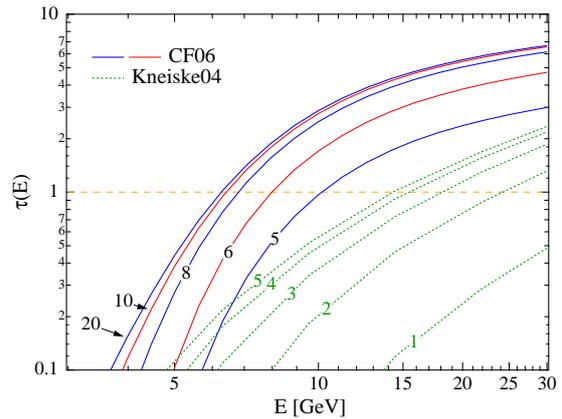


Fig. 3: Integrated  $\gamma\gamma$  optical depth vs. observed gamma-ray energy for different source  $z$  as labelled. Solid: fiducial model of [9]; dotted: low- $z$  model of [14].

models at the moment such as [14], also shown here for comparison.

As we inferred from Fig.2, the model predicts appreciable opacity below 10 GeV for sources at  $z \gtrsim 5$ , with notable differences out to  $z \sim 8$ . However, the effects of further absorption from  $z \gtrsim 8$  may be practically indiscernible. Nevertheless, the spectral attenuation feature itself should be observable in high- $z$  gamma-ray sources by current or future gamma-ray facilities, and possibly distinguishable in the range  $z \sim 5 - 8$  for sufficiently bright objects. Owing to the drop in  $\gamma\gamma$  opacity at  $E_{\text{rest}} < 18$  GeV (Fig.2), the differences in absorption in this redshift range are caused in-situ by the evolution of UV IRFs just below the Lyman edge energy, including the crucial Ly $\alpha$  and Lyman-Werner bands. We also recall that in the fiducial model, Pop III stars continued to be significant contributors to the UV IRF down to  $z \gtrsim 7$  (where they are comparable with Pop II stars and QSOs for ionizing photons). Measurements of these effects would thus provide an important test of current models of cosmic reionization in its latter stages, as well as a unique and invaluable probe of evolving UV IRFs in the era of early star formation.

In Fig.4, we plot the spectral attenuation factor  $\exp(-\tau(E))$ . Here we also compare the fiducial results with those of a variant model where the radiative feedback effects are calculated with the more realistic, filtering mass prescription of [15], and which give nearly equally good fits to the existing high- $z$  observations. The resulting differences in  $\gamma\gamma$  absorption are not very conspicuous, and distinguishing them in real data may be quite challenging. Conversely, the fiducial model prediction may be considered reasonably robust, at least for the relative  $\gamma\gamma$  opacity at  $z \gtrsim 5$ .

### C. Detectability

Are the effects discussed above observable in real sources with current or future gamma-ray instruments? For blazars, the most prominent and numerous extragalactic sources of GeV gamma-rays, the highest redshift

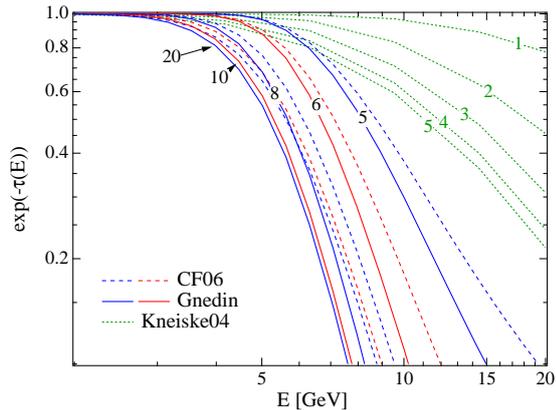


Fig. 4: Spectral attenuation factor vs. observed gamma-ray energy for different source  $z$  as labelled. Solid: fiducial model of [9]; dashed: model with filtering mass prescription for feedback; dotted: low- $z$  model of [14].

confirmed so far is  $z \sim 3$  [16]. However, objects similar to the most powerful known blazars such as 3C279 with apparent GeV luminosities  $L \sim 10^{48} \text{erg s}^{-1}$  should be firmly detectable by *Fermi* out to  $z \sim 8 - 10$  if they exist [17]. Utilizing the blazar evolution model of [18] which is consistent with the observed statistics of the blazar population and takes into account aspects such as the blazar spectral sequence and luminosity-dependent evolution (i.e. “cosmic downsizing”), a new study by [19] finds that *Fermi* may detect a few to several blazars above  $z \sim 6$  during its survey period. Deep, pointed followup observations of such sources may indeed reveal the IRF absorption features described above.

GRBs are also promising as they are expected to arise out to the very first epochs of star formation in the universe [20]. Although the spectral properties of GRBs in the GeV domain are still rather uncertain and currently being explored by *Fermi*, the recent detection of GRB 080916C at  $z \sim 4.3$  [21] demonstrates that at least some GRBs have luminous emission extending above 10 GeV. A similar burst should still be detectable by *Fermi* at  $z \sim 10$ , and even out to higher  $z$  if the spectrum was somewhat harder. Even better would be the proposed 5@5 array with a nominal 5 GeV energy threshold and much larger effective area [22], which should be powerful for studying the spectra of very high- $z$  GRBs.

Even if IRF-induced spectral features can be measured, a generic problem for  $\gamma\gamma$  absorption studies is distinguishing them from spectral cutoffs intrinsic to the source. In this regard, spectral variability should provide an important handle. Both GRBs and blazars are highly variable gamma-ray emitters, and generally speaking, changes in physical conditions of the source that lead to variations in flux should also be accompanied by variations of the intrinsic cutoff energy. In contrast, cutoffs of IRF origin should be stable in time and independent of the variability state of each individual object.

Acquisition of time-resolved spectra for each source should allow the deconvolution of intrinsic and IRF cutoff effects. Another clue may come from statistical studies of a sufficiently large sample of measurements. IRF-related cutoffs should occur at similar energies for sources at similar  $z$ , and also exhibit a systematic evolution toward lower energies for higher  $z$ , whereas there is no strong reason to expect this for intrinsic cutoffs. Both strategies motivate the construction of a future, high-sensitivity GeV facility such as 5@5, which may effectively probe UV IRFs in the cosmic reionization era through  $\gamma\gamma$  absorption in very high- $z$  sources.

### III. PAIR ECHOS AND MAGNETIC FIELDS AT HIGH REDSHIFT

Finally, we very briefly touch upon the prospects for probing cosmic magnetic fields at very high  $z$ . As discussed above,  $\gamma\gamma$  interactions of high-energy gamma-rays with the IRF produce high-energy pairs, which can subsequently upscatter ambient CMB photons to generate secondary gamma-rays (pair echos). Since the charged pairs can be deflected by weak magnetic fields in their production region before emitting the echo, there is an associated time delay that depends quite sensitively on the field strength. Measurements of the echo emission can then be utilized to probe the magnetic fields [23], [24]. At sufficiently high  $z$ , this phenomena becomes interesting since the only relevant target photons for  $\gamma\gamma$  interactions is the CMB with much shorter mean free paths, and consequently much stronger magnetic fields on parsec scales can be probed. The resulting pair echos may constitute an ideal probe of magnetic fields in Pop III star forming regions. More details will be presented in an upcoming paper.

### REFERENCES

- [1] B. Ciardi and A. Ferrara, *Sp. Sci. Rev.* 116, 625 (2005).
- [2] T. R. Choudhury, [arXiv:0904.4596].
- [3] J. R. Primack, J. S. Bullock, R. S. Somerville, [arXiv:astro-ph/0502177].
- [4] F. A. Aharonian et al., *Nature* 440, 1018 (2006).
- [5] J. Albert et al., *Science* 320, 1752 (2008).
- [6] S. P. Oh, *Astrophys. J.* 553, 25 (2001).
- [7] J. Rhoads, [arXiv:astro-ph/0111030].
- [8] T. R. Choudhury and A. Ferrara, *Mon. Not. R. Astron. Soc.* 361, 577 (2005).
- [9] T. R. Choudhury and A. Ferrara, *Mon. Not. R. Astron. Soc.* 371, L55 (2006).
- [10] D. Schaerer, *Astron. Astrophys.* 382, 28 (2002).
- [11] G. Bruzual and S. Charlot, *Mon. Not. R. Astron. Soc.* 344, 1000 (2003).
- [12] D. N. Spergel et al., *Astrophys. J. Supp.* 170, 377 (2007).
- [13] J. Dunkley et al., *Astrophys. J. Supp.* 180, 306 (2009).
- [14] T. M. Kneiske et al., *Astron. Astrophys.* 413, 807 (2004).
- [15] N. Y. Gnedin, *Astrophys. J.* 542, 535 (2000).
- [16] A. A. Abdo et al., *Astrophys. J.*, submitted [arXiv:0902.1559].
- [17] R. W. Romani et al., *Astrophys. J.* 610, L9 (2004).
- [18] Y. Inoue and T. Totani, [arXiv:0810.3580].
- [19] Y. Inoue et al., in preparation.
- [20] V. Bromm & A. Loeb, *Astrophys. J.* 642, 382 (2006).
- [21] A. A. Abdo et al., *Science* 323, 1688.
- [22] F. A. Aharonian et al., *Astropart. Phys.* 15, 335 (2001).
- [23] R. Plaga, *Nature* 374, 430 (1995).
- [24] K. Ichiki, S. Inoue and K. Takahashi, *Astrophys. J.* 682, 127 (2008).