Contribution Prospectives IN2P3 2020 - GT-04
γ-ray cosmology

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The list of co-authors features prominent members of the community interested in and contributing to this branch of γ-ray astronomy, from both the IN2P3 and INSU institutes of CNRS. Numerous colleagues from CEA, unable to sign these contributions, are also leading researchers in this field. With this document, we affirm the strong support of the French community to the development of γ-ray cosmology, and to the fostering of links across the different relevant communities. The principal author acknowledges self-plagiarism, in particular from the chapter "Gamma-ray cosmology" (Pueschel & Biteau, in prep.).

Glossary

- CIB: Cosmic Infrared Background
- CMB: Cosmic Microwave Background
- COB: Cosmic Optical Background
- CRPropa: Cosmic-Ray Propagation code
- CSFH: Cosmic Star Formation History
- CTA: Cherenkov Telescope Array
- DUNE: Deep Underground Neutrino Experiment
- EBL: Extragalactic Background Light
- ELMAG: ELectro-MAGnetic cascade code
- *Fermi*-LAT: *Fermi* Large Area Telescope
- GALEX: Galaxy Evolution Explorer
- GRB: Gamma-Ray Burst
- H.E.S.S.: High Energy Stereoscopic System
- IACT: Imaging Atmospheric Cherenkov Telescope
- IGMF: InterGalactic Magnetic Field
- JUNO: Jiangmen Underground Neutrino Observatory
- JWST: James Webb Space Telescope
- ΛCDM: Lambda - Cold Dark Matter
- MAGIC: Major Atmospheric Gamma-ray Imaging Cherenkov
- SKA: Square Kilometer Array
- SuperK-Gd: Super-Kamiokande Gadolinium
- UHECR: Ultra-High-Energy Cosmic Ray
- VERITAS: Very Energetic Radiation Imaging Telescope Array System

1 Extragalactic γ-ray sources as beacons for cosmology

The modern vision of the universe has emerged over the past 50 years from constraints on Big Bang nucleosynthesis, the cosmic distance ladder, the spectrum and anisotropies of the cosmic microwave background (CMB), and large-scale structures. Observations converge on the current ΛCDM model, largely dominated by dark matter and dark energy.

γ-ray astronomy, through observations discussed in the contribution "Extragalactic gamma-ray astrophysics", has further unveiled the electromagnetic content and skeleton of the universe. Full-sky observations by *Fermi*-LAT have uncovered $\sim$1,600 sources beyond 10 GeV, 80 % of them being associated to an extragalactic counterpart at other wavelengths [1]. These non-thermal sources emit over the whole electromagnetic spectrum and show tremendous bolometric luminosities, enabled by the relativistic motion of the radiative region along jets. With jets closely aligned with the line of sight, blazars [2] harbouring a super-massive black hole ($10^{6-10}\,M_\odot$) and γ-ray bursts (GRBs, [3]) associated to the death of massive stars or binary mergers can persistently or transiently outshine the billions of stars in the host galaxy. They provide us with copious amounts of γ-rays from the edge of the universe.

Hundreds of blazars have been detected at GeV and TeV energies by *Fermi*-LAT and imaging atmospheric Cherenkov telescopes (IACTs, led by H.E.S.S., MAGIC and VERITAS) out to redshifts $z \sim 2.5$ [1] and $z \sim 1$ [4, 5, 6], respectively. Three GRBs have also been detected with *Fermi*-LAT above 50 GeV (GRB 130427A at $z = 0.34$, GRB 140928A at an unknown redshift and GRB 160509A at $z = 1.17$ [7]) and higher-energy emission was recently discovered with IACTs from three others (GRB 180720B at $z = 0.65$, GRB 190829A at $z = 0.08$ and GRB 190114C at $z = 0.42$, see TeVCat [8]). These extragalactic γ-ray beacons probe the brightest diffuse photon field in the universe emerging from the emission of galaxies: the extragalactic background light (EBL), only surpassed at lower energies by the CMB. The EBL, which traces the cumulative cosmic star formation history (CSFH, [9]) since the beginning of reionization, acts as a target photon field for γ-rays above ~ 100 GeV, through electron-positron pair production [10, 11, 12]. The ensuing γ-ray absorption provides not only means to probe the EBL [13, 14, 15, 16, 17] and CSFH [18] but also acts as a distance ruler, providing a new probe for the parameters of the ΛCDM model [15, 19, 20]. The fate of the electron-positron pairs is governed either by cooling through plasma instabilities [21, 22, 23], providing a possible mechanism for heating the intergalactic medium that would suppress the formation of dwarf satellite galaxies ("missing satellite problem") and enable the formation of voids [24], or through inverse-Compton on the CMB, resulting in secondary γ-ray emission sensitive through its temporal, spectral and morphological properties to deflections of their parent electrons in the intergalactic magnetic field (IGMF, see [25, 26, 27, 28] and contribution "Cosmic magnetic fields").

This contribution is focused on the potential of γ-ray astronomy to constrain these two aspects, the fate of the primary and secondary γ-rays, as well as on the expected capabilities of upcoming instruments, led by the Cherenkov Telescope Array (**CTA**, [29]), to which a significant fraction of us are active contributors (dedicated CTA Consortium publication in preparation). It should be noted that exotic physics beyond the Standard Model [30], not treated here, can tremendously benefit from γ-ray cosmology, in particular through studies of deviation from classical absorption induced by Lorentz invariance violation beyond the Planck scale [15, 31, 32, 33]. Lorentz invariance can also be tested with energy-dependent time lags in the lightcurves of pulsars, blazars and GRBs [34], as pushed forward by the French community [35, 36]. Mixing with axion-like particles, which are weakly-interacting-slim-particle candidates for dark matter [37, 38, 39, 40, 41, 42], and the search for weakly interacting massive particles between few tens of GeV and a few TeV, in the Galactic halo or in satellite galaxies, also hold a fantastic potential for discovery with CTA [43]. As of today, γ-ray observations only scratch the surface of cosmology. The 2020-2030 decade will see the full emergence of this field, in close connection with major multi-messenger and multi-wavelength observatories under upgrade or construction (highlighted in boldface in this contribution).

2 Extragalactic background light in the local Universe

The history of star formation, embedded in the Hubble flow, dictates the evolution and spectrum of the EBL. Most of the emission from stars lies within $0.1 - 1000\,\mu$m: limited at its lower and higher ends by the Lyman limit and the CMB, respectively. Nearly half of the UV to near-infrared starlight escapes from galaxies and builds up the cosmic optical background (COB). The other half is absorbed by dust grains and reprocessed in the cosmic infrared background (CIB). Accretion onto super-massive black holes provides an additional source of UV and optical photons, half of which being absorbed and re-radiated at mid-infrared wavelengths. Measurements of galaxy counts in deep-field UV-infrared observations (*e.g.* GALEX, *Hubble*, *Spitzer*, *Herschel*) have enabled the reconstruction of cumulative galactic emission down to a point where the integral emission converges, resulting in a remaining uncertainty at the level of ~ 20% at most wavelengths [44, 45, 46]. Direct observations attempt to subtract off from the observed intensity of dark patches the foreground contamination from non-EBL light (zodiacal or Galactic light [47]), resulting nowadays in discrepancies with galaxy counts up to a factor of a few in intensity. Such discrepancies, an order of magnitude larger a decade ago, are often suggested by direct observers to arise from non-resolved contributions from reionization sources, intra-halo light, or any-truly diffuse component of exotic origin [48, 49], if not resulting from unaccounted foreground contamination. Three state-of-the-art EBL models [50, 51, 52] are compared in Fig. 1 to direct measurements and galaxy counts. Such models are used by γ-ray astronomers to quantify spectral attenuation beyond 100 GeV, thus providing an indirect measurements of the EBL.

The γ-ray optical depth, $\tau(E, z_0)$, increases with γ-ray energy in the observer's frame, E, and redshift of the source, z_0. Being the product of the pair-production cross section, $\sigma_{\gamma\gamma}$ (units of m^2), and of the EBL photon density, $\partial n/\partial\epsilon$ (units of m^{-3} eV^{-1}), integrated over cosmic ages, a measurement of the optical depth gives access to contributions to the EBL both from resolved and unresolved sources, as well as to parameters of the distance element, $\partial L/\partial z = c/H_0 \times \partial t/\partial z$ (units of m). The first γ-ray constraints simply assumed a scaling of the EBL photon density through a normalization factor relative to models. In this way, *Fermi*-LAT and H.E.S.S. (led by French researchers for the latter) discovered the attenuation signals at the 6 and 9σ significance level seven years ago [13, 14], yielding a close agreement with galaxy counts, and a $20-30\%$ accuracy measurement. Since then, we have developed model-independent approaches [15, 17], expanding the EBL density into a sum of independent components at fixed wavelengths and estimating their contribution to the optical depth:

$$\tau(E, z_0) = \int_0^{z_0} \mathrm{d}z \frac{\partial L(z)}{\partial z} \int_{-1}^{1} \mathrm{d}\cos\theta' \frac{1-\cos\theta'}{2} \int_0^{\infty} \mathrm{d}\epsilon' \sigma_{\gamma\gamma}(E', \epsilon', \cos\theta') \frac{\partial n(\epsilon', z)}{\partial \epsilon'}. \quad (1)$$

These γ-ray measurements led by French researchers are shown in Fig. 1. γ-ray astronomy probes EBL wavelengths up 100 μm, which starts to be relevant for photodisintegration losses of ultra-high-energy nuclei (UHECRs), to be observed with the upgraded **Pierre Auger Observatory** (see [53] and contribution "Towards uncovering the origin of UHECRs at the Pierre Auger Observatory"). The γ-ray measurements are currently limited by three aspects: i) the expansion into independent EBL-wavelength contributions is only valid when exploiting sources up to redshifts $z_0 \sim 0.6 - 0.7$ [15]; ii) the treatment of the parametrization of the intrinsic spectrum, $\theta_{\rm int}$, affects the statistical uncertainty on the EBL parameters, $\pi_{\rm EBL}$ [54], as the observed spectrum is a function of both the intrinsic emission and the cosmological absorption on the EBL: $\phi(E, z_0) = \phi_{\rm int}(E; \theta_{\rm int}(\pi_{\rm EBL})) \times \exp\left(-\tau(E, z_0; \pi_{\rm EBL})\right)$; iii) systematic uncertainties, induced *e.g.* by constraints on the energy scale of γ-ray observatories, limit the measurements as illustrated by the blue dashed lines in Fig. 1. An accurate treatment of the EBL evolution necessitates a closer look at constraints on the CSFH, together with the galaxy-count community, which is particularly strong in France [55, 56, 57, 58]. Systematic uncertainties are currently treated using bracketing estimates of the instrument response functions, not accounting for the decreasing quality of the fit with increasing deviation from the nominal

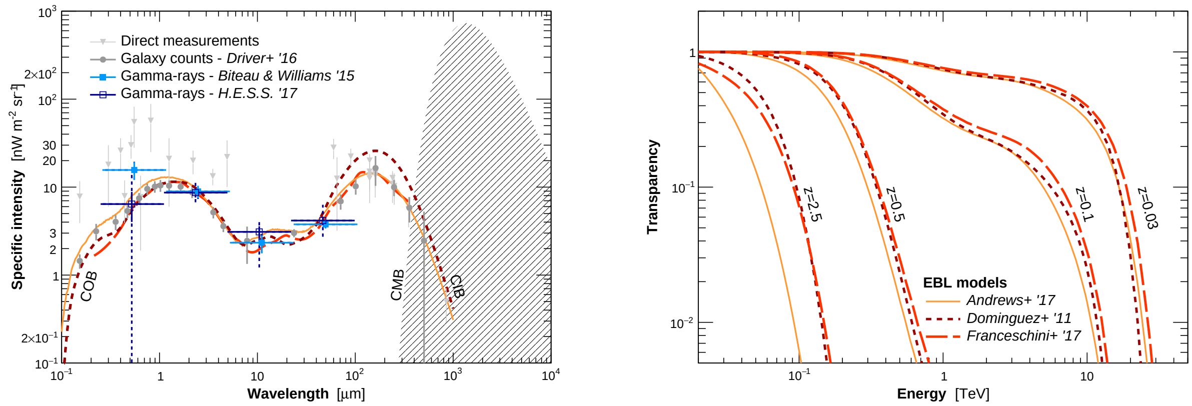

Figure 1: *Left:* Constraints on the specific intensity of the EBL at $z = 0$. *Right:* γ-ray transparency as a function of energy and redshift for three state-of-the-art EBL models. *Credits: Biteau.*

instrument response. Such performance and analysis aspects should be overcome in the upcoming decade with the arrival of high-accuracy data from **CTA** and the development of more advanced analysis approaches by the GeV-TeV communities. The focus on precision calibration of CTA will allow the energy- and flux-scale errors to be reduced. The increase in both quality and quantity of the spectra from blazars and GRBs will enable EBL measurements up to at least $z \sim 2.5$ (CTA Consortium, in prep.). The inauguration of CTA will mark the advent of the era of precision γ-ray cosmology, putting this new domain on par with the precise measurements of the cosmos obtained at other wavelengths.

3 Cosmic star-formation history and cosmological parameters

The specific intensity of the EBL, νI_ν (units of eV s^{-1} m^{-2} sr^{-1}) shown at $z = 0$ in Fig. 1, is probed by γ-ray astronomy as a target photon density, $\partial n/\partial\epsilon = 4\pi/c \times \nu I_\nu(\epsilon, z)/\epsilon^2$. The EBL density results from the accumulated luminosity density, j (units of m^{-3} s^{-1}), of each redshift layer since the ignition of the first stars: $\partial n/\partial\epsilon = (1+z)^3 \int_z^\infty \mathrm{d}z'\, \partial t/\partial z' \times j(\epsilon', z')/\epsilon'$, where $\epsilon' = (1+z')\epsilon$. For a given luminosity density, the mean dust extinction, A_ϵ, and the amount of light emitted per star-formation-rate unit, K_ϵ (units of $M_\odot$), determine the CSFH as: $\rho(z) = K_\epsilon \times 10^{0.4 A_\epsilon} \times j(\epsilon, z)$.

Applying the independent-wavelength expansion of [15] to the luminosity density instead of the EBL density, the *Fermi*-LAT Collaboration recently performed the first γ-ray measurement of the CSFH shown in Fig. 2 [18]. γ-ray results below the peak of the CSFH are a bit higher than but in good agreement with galaxy surveys. The UV luminosity density above $z = 4$, in line with the lowest values from Lyman-break galaxy surveys, is inferred from the integral nature of γ-ray measurements: high-redshift sensitivity is available to us despite the relative proximity of the γ-ray sources. Some room is left at $z \sim 6$ for an abundant UV field to drive reionization, yet γ-ray upper limits start to constrain the faint end of the luminosity function of reionizing sources. The deepest observations from *Hubble* have not enabled a conclusive view on the faintest early galaxies [59, 60, 61, 62]. Constraints on these faint objects are expected up to $z \sim 8$ from **JWST** [63]. A complete picture remains to be established in the decade to come, likely from the combination of near-infrared and γ-ray observations. Improved constraints on the CSFH are also crucial to estimate the diffuse MeV neutrino background from core-collapse supernovae, to be probed by **SuperK-Gd**, **JUNO** and **DUNE** (*e.g.* [64]).

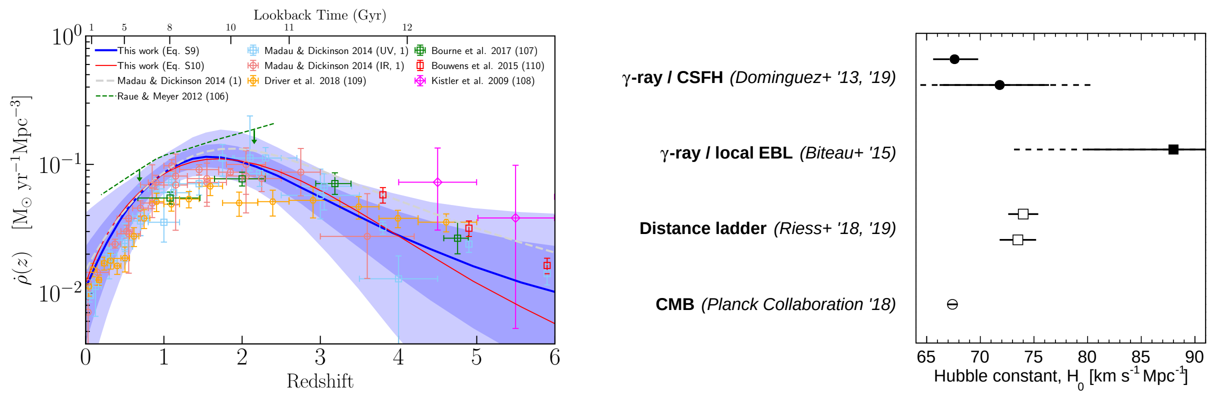

Figure 2: *Left:* Constraints on the CSFH, including 1 and 2σ shaded bands from γ-ray observations. *Credits: [18]*. *Right:* Constraints on the Hubble constant. *Credits: Biteau.*

An appealing application of optical-depth measurements, proposed from the early days of γ-ray astronomy [65, 66, 67], consists in inverting Eq. 1 to measure the Hubble constant, H_0. With the distance element scaling as H_0^{-1} and luminosity density as H_0^3, the EBL level inferred from γ-ray measurements scaled to the local EBL goes as H_0^{-1}, while γ-ray constraints normalized to luminosity functions inferred from galaxy counts go as H_0^2. The two approaches have been employed by different groups to constrain parameters of the ΛCDM cosmology [15, 19]. Results on the Hubble constant obtained for a flat ΛCDM model and a fixed value of $\Omega_{\rm M}$ are compared in Fig. 2 to measurements based on CMB data [68] and the distance ladder [69, 70] that show a $3.5-4.4\sigma$ tension.

The first γ-ray measurements exploiting the local ($\propto H_0^{-1}$, [15]) and evolutionary techniques ($\propto H_0^2$, [19]) are dominated by the systematic uncertainties discussed in Sec. 2 (dashed lines in Fig. 2), on the order of $10-15$ km s^{-1} Mpc^{-1}. Recently, [20] claimed a measurement with an accuracy of 2 km s^{-1} Mpc^{-1}, which taken at face value would be competitive with constraints from the distance ladder. Independent analyses are crucially needed to assess and compare the potential of such γ-ray constraints. If confirmed, current and future γ-ray observations could prove essential to test the current cosmological paradigm. The depth of the population of extragalactic γ-ray sources detectable by **CTA** and the ability to measure their redshift, particularly spectroscopically as actively undertaken by the French community [71], will be key in the development of γ-ray cosmology.

4 Cosmic magnetism

The strong magnetic fields in galaxies and galaxy clusters ($\sim \mu$G) require an initial "seed" to be amplified up to the observed value, *e.g.* through the Biermann battery [28, 72]. Two possibilities have been proposed: i) a primordial weak magnetic field is generated in the early universe, ii) magnetic fields are generated in astrophysical structures during their formation and evolution and ejected away into the intergalactic medium. The difference of generation time, shortly after the Big Bang or after the onset of galaxy formation, propagates to differences in the magnetic-field strength, correlation length, and in the evolution of the magnetic energy density with redshift. Zeeman splitting of the 21 cm hydrogen line in quasar spectra [73], Faraday rotation [74] and anisotropies in the CMB [75, 76] constrain the remnant of the "seed" magnetic field in voids, *i.e.* the IGMF, to lie below 10^{-9} G.

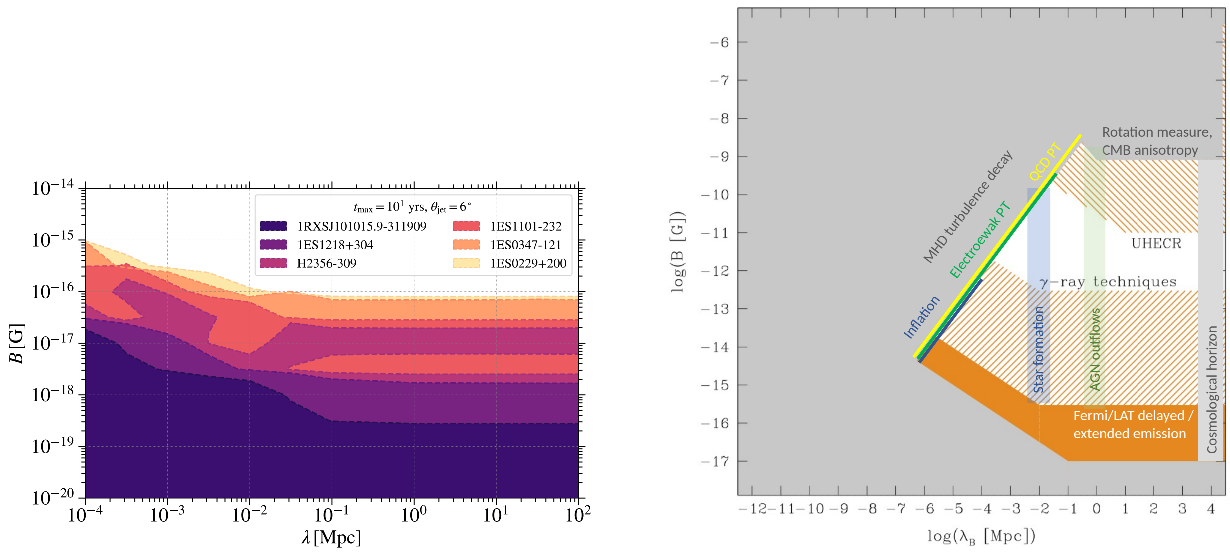

Figure 3: *Left:* Constraints on the IGMF strength, B, and coherence length, λ, from single-source observations by *Fermi*-LAT and IACTs. *Credits: [77]. Right:* Expected potential of future γ-ray and UHECR observations (orange) and already excluded zones (gray). *Credits: Neronov, see [28]*.

Provided inverse-Compton scattering dominates the cooling of the EBL-induced pair beam, γ-ray observations set a lower bound on the IGMF, as early noted and undertaken by the French community [73, 78]. As CMB photons are upscattered by electrons and positrons to the γ-ray range, an electromagnetic cascade develops with a temporal and spatial extent affected by the IGMF. The cascade can be numerically simulated with varying levels of detail in state-of-the-art codes (*e.g.* ELMAG [79], CRPropa [80] also used for UHECRs), including French developments [81], and then compared to GeV-TeV observations.

State-of-the-art γ-ray constraints are currently obtained from the joint spectral and morphology fitting of extreme blazars observed at GeV and TeV energies. As shown in Fig. 3, IGMF strengths smaller than 10^{-16} G for a 1 Mpc correlation length are disfavored from single-source observations, the combination of which improves the constraints by nearly an order of magnitude [77]. The search for an extended signal induced by larger IGMF strengths enabled H.E.S.S. and VERITAS to disfavor the 10^{-15-14} G range [82, 83]. Observational searches with IACTs have already shown the possibility to probe an uncharted territory in the parameter space of the IGMF. With a low energy threshold of a few tens of GeV and an angular resolution of a few arcminutes, **CTA** will doubtless improve our understanding of the origin of cosmic magnetism. The potential of future γ-ray spectro-morphological constraints is illustrated as a hashed region in Fig. 3.

In addition to its interest as a cosmological observable, the IGMF strength and structure is relevant for a number of measurements. UHECRs observed by the **Pierre Auger Observatory** are bent by the IGMF, although the effect is subdominant compared to deflections by the Galactic magnetic field for sources within a few tens of Mpc. Together with Faraday tomography, *e.g* observing fast radio bursts with **SKA** [84, 85], astroparticle physics promises to constrain the configuration of IGMF in voids today and to inform us on so-far elusive generation scenarios of cosmic magnetism.

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