THE FIRST COSMIC RAYS

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Integral BH mass fct starts at $\sim 3\,10^6\,M_\odot$

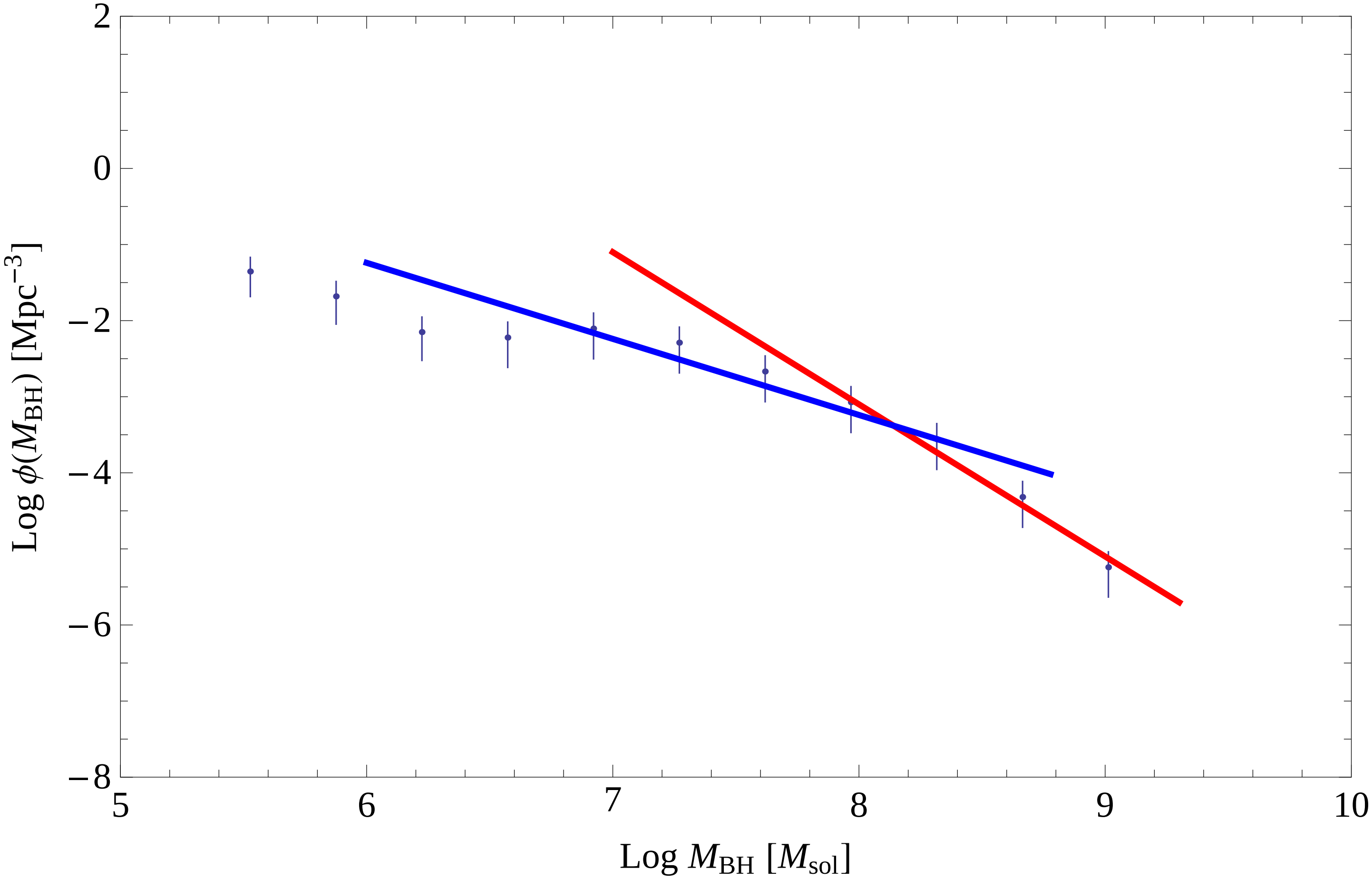

Figure 1 Integral mass function corrected for Hubble type sampling, 2928 objects, the slope of the lines is: red -2.0 fitting $> 10^8\,M_\odot$, and blue -1.0 fitting between $10^7\,M_\odot$ and $10^8\,M_\odot$. See Caramete & PLB, *Astron. & Astroph.* **521**, id.A55 (2010); arXiv:0908.2764 (also see Greene et al. since 2006). This mass function suggests that black holes start near $3\,10^6\,M_\odot$, possibly at redshift of order $\lesssim 50$, and grow by merging (PLB & Kusenko 2006, PRL)

Massive stars agglomerate

- Massive stars can form first, at very high redshift, due to formation of molecular hydrogen
- Maximal redshift 80 (PLB & Kusenko 2006)
- Massive stars agglomerate (Spitzer 1969; Sanders 1970; Portegies Zwart et al. 2004 and later) and can form a super-massive star
- Stellar winds depend on heavy element abundance, and so do not cause mass-loss at zero heavy elements (Yungelson et al. 2008): Only possible then
- Super-massive stars close to instability due to dominance of radiation pressure (Chandrasekhar 1939)
- General Relativity pushes them over the cliff of instability at about $10^6\,M_\odot$ (Appenzeller & Fricke 1972a,b)
- They explode and form a super-massive black hole

Radio remnant

- Explosion self-similar (Sedov 1954; Cox 1972; Voit 1996), steady excitation of waves in plasma
- Magnetic fields

$$B = 10^{-4.8}\,\eta_{B,-1}^{1/2}\,E_{56}^{1/5}\,z_{1.7}^{+9/10}\,t_{14}^{-3/5}\,\text{Gauß} \tag{1}$$

- Cosmic ray electrons

$$C = 10^{-6.7}\,\eta_{CR,e,-2}\,E_{56}^{2/5}\,z_{1.7}^{33/10}\,t_{14}^{-6/5}\,, \tag{2}$$

- Spectral radio luminosity on average

$$L_\nu = 10^{26.8}\,\eta_{B,-1}^{0.80}\,\eta_{CR,e,-2}^{+1}\,E_{56}^{1.32}\,z_{1.7}^{+4.44}\,f_t^{-1}\,\nu_{9.0}^{-0.60}\,\text{ergs}^{-1}\text{Hz}^{-1}\,. \tag{3}$$

Background radio emission

- Other options? Yes, could be local (Sun et al. 2010; Everett et al. 2010), most detailed modeling of new data (Fixsen et al., Kogut et al., Seiffert et al. 2011) suggests not local
- Background (Frieman et al. 2008)

$$F_\nu = N_{BH}(z) \frac{c\,r(z)^2}{H(z)} \frac{L_\nu}{4\pi d_L^2} \Delta z \tag{4}$$

- Radio background

$$F_\nu = 10^{-20.7} N_{BH,0,-2.2}\, \eta_{B,-1}^{0.80}\, \eta_{CR,e,-2}^{+1}\, E_{56}^{1.32}\, z_{1.7}^{+4.94}\, \nu_{9.0}^{-0.60}\, \mathrm{ergs}^{-1}\mathrm{Hz}^{-1}\mathrm{cm}^{-2}\mathrm{sr}^{-1}\,. \tag{5}$$

- Observations (Fixsen et al., Kogut et al., Seiffert et al. 2011; Condon et al. 2012) scaled to 1 GHz

$$F_\nu = 10^{-18.5}\, \mathrm{ergs}^{-1}\mathrm{Hz}^{-1}\mathrm{cm}^{-2}\mathrm{sr}^{-1} \tag{6}$$

Number of contributing sources

- Number counts of known sources (Condon et al., 2012), modeling them and extrapolating in flux density and numbers
- Flux density on average ($< 10\,\mathrm{nJy}$)

$$S_{\nu} = 10^{-35.4}\, \eta_{B,-1}^{0.80}\, \eta_{CR,e,-2}^{+1}\, E_{56}^{1.32}\, z_{1.7}^{+2.44}\, f_t^{-1}\, \nu_{9.0}^{-0.60}\, \mathrm{erg cm^{-2} s^{-1} sr^{-1} Hz^{-1}} \quad (7)$$

- Number of sources from redshift interval (Frieman et al. 2008)

$$N_{obs} = N_{BH}(z)\, \frac{c\, r(z)^2}{H(z)}\, \Delta z \quad (8)$$

- Number of sources from redshift interval here ($> 10^{12}\mathrm{sr}^{-1}$)

$$N_{obs} = 10^{14.3}\, N_{BH,0,-2.2}\, f_t\, z_{1.7}^{2.5} \quad (9)$$

so here $N_{BH,0,-2.2}\, f_t\, z_{1.7}^{2.5} > 10^{-2.3}$

Background γ-ray and hard X-ray emission

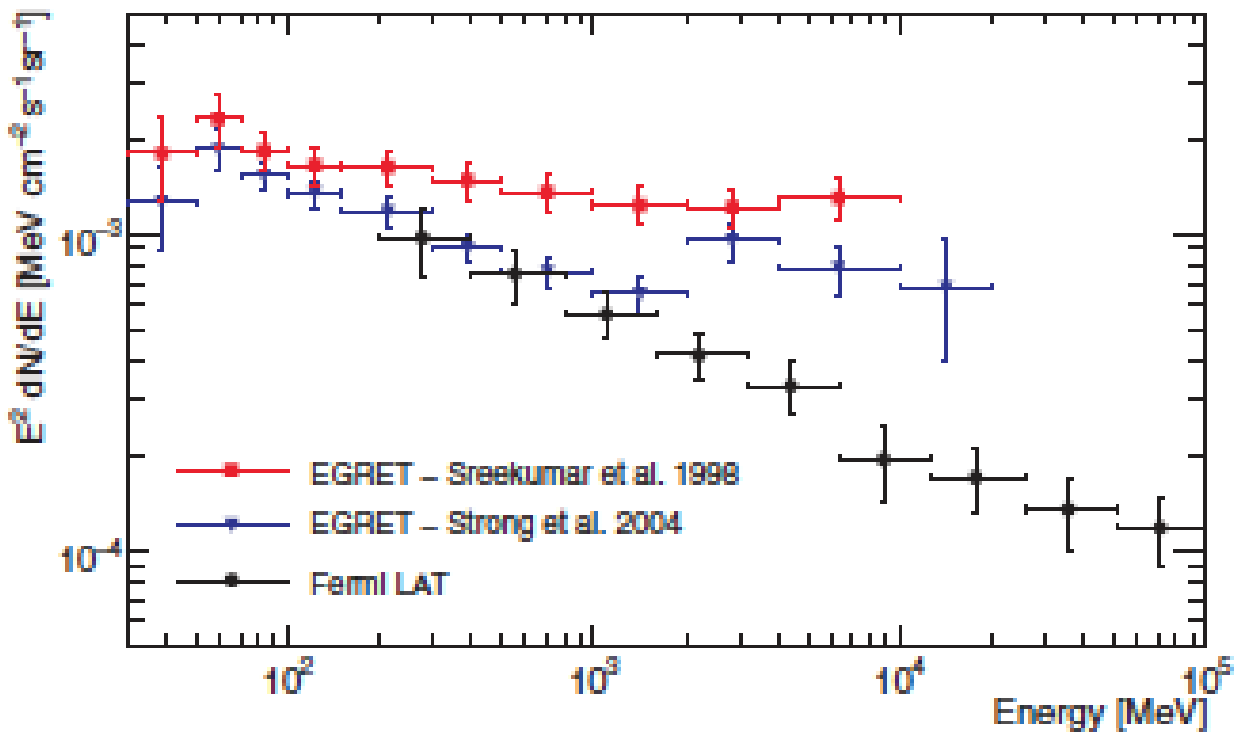

FIG. 4 (color). EGB intensity derived in this work compared with EGRET-derived intensities taken from Rable 1 in [2] and Table 3 in [24]. Our derived spectrum is compatible with a simple power law with index $\gamma = 2.41 \pm 0.05$ and intensity $I(>100\ \mathrm{MeV}) = (1.03 \pm 0.17) \times 10^{-5}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$ where the uncertainties are systematics dominated.

Figure 2 The Fermi-LAT γ-ray background (Abdo et al. 2010)

- Flux > 100 MeV

$$10^{-4.8}\, N_{BH,0,-2.2}\, E_{56}\, f_t\, \eta_{CR,p,-1}\, z_{1.7}^{3.3}\; \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,, \quad (10)$$

remarkably close to the observed flux of (Abdo et al. 2010),

$$(1.03 \pm 0.17)\, 10^{-5}\, \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1} \quad (11)$$

- Hard X-rays, only residual flux (Moretti et al. 2003)

$$10^{-8.1}\, \mathrm{erg}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1} \quad (12)$$

here all IC emission: This is the most important energy sink, which limits the active life-time.

Background neutrino emission

- Matching both radio and gamma ray emission suggests N_{BH} higher and f_t smaller - higher original BH density and shorter active time
- Model prediction

$$F_{neutr} = 10^{-11.1} N_{BH,0,-2.2} E_{56} z_{1.7}^{3.3} f_t \eta_{CR,p,-1} f_{neutr,-1} \,\mathrm{erg\,cm^{-2}\,s^{-1}\,sr^{-1}}, \quad (13)$$

at 100 TeV observed neutrino energy, or in terms of GeV $10^{2.8}$ more, so at nominal parameter values

- just below the current upper limit of ν_μ-flux of

$$8.9\,10^{-9}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}} \quad (14)$$

energy range between 35 TeV and 7 PeV (Abbasi et al. 2011).

Summary

- Radio emission and spectrum: match
- Most detailed modeling of new and complete data suggests observed emission not local
- Number of individual sources: match
- Flux of individual sources: match
- No associated FIR emission: match
- γ-rays $>$ 100 MeV: match
- Hard X-rays: match
- Re-ionization, galaxy formation, black hole history,...
- **Neutrino background: prediction**

1 Abstract

The statistics of black holes and their masses strongly suggests that their mass distribution has a cutoff towards lower masses near $3\,10^6\ M_\odot$. This suggests a classical formation mechanism from the agglomeration of the first massive stars in the universe, forming a super-massive star which then explodes, turning some its mass into a black hole. At extremely low metal content stellar winds could not prevent this growth, so the mechanism requires near-zero heavy elements. However, when the masses of the stars approach $10^6\,M_\odot$ the stars become unstable and collapse; with some fall-back they could thus form the first generation of cosmological black holes. Such a scenario, which has a long history in the literature, would readily explain the formation and early growth of super-massive black holes. Coupled with further growth from

either merging or accretion, this scenario would explain the observations of high black hole masses in the early universe. Direct observational confirmation of these formation events of the first million solar mass black holes would greatly strengthen such a picture. Here we speculate that the claimed detection of an isotropic radio background by Kogut et al. (2011), Fixsen et al. (2011), and Seiffert et al. (2011) may constitute such evidence, since their data are compatible in spectrum and intensity with synchrotron emission from the remnants of the explosions forming the first super-massive black holes. The model proposed fulfills all conditions for the background deduced by Condon et al. (2012), in terms of single source strength, number of sources, and negligible far-infrared emission. We then work out the corresponding gamma-ray background, which is consistent with the Fermi result in both flux and spectrum, as is the hard X-ray residual background spectrum. Furthermore the corresponding neutrino background is only half an order of magnitude below current upper limits. Confirmation by spectroscopic data, e.g., in the form of an absorption line forest in H_2^+ or H_3^+, would confirm the redshift. As a corollary it would show the formation of the first super-massive black holes, with consequences for galaxy evolution. Most importantly it would also constitute observational evidence for the first cosmic rays ever in the universe, and could be refuted or confirmed by the detection of a neutrino background with the flux and spectrum derived from the radio and γ-ray data.

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