ASTROPHYSICS OF WARM DARK MATTER

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1 Abstract

Dark matter has been first detected 1933 (Zwicky) and basically behaves like a non-EM-interacting gravitational gas of particles. From particle physics Supersymmetry suggests with an elegant argument that there should be a lightest supersymmetric particle, which is a dark matter candidate, possibly visible via decay in odd properties of energetic particles and photons: Such discoveries were made: i) an upturn in the CR-positron fraction, ii) an upturn in the CR-electron spectrum, iii) a cosmic ray anisotropy in data from Tibet, SuperK, Milagro, and now at two energies, in arriving cosmic rays at 20 TeV and 400 TeV with IceCube, iv) a flat radio emission component near the Galactic Center (WMAP haze), v) a corresponding IC component in gamma rays (Fermi haze and Fermi bubble), and a flat γ-spectrum at the Galactic Center

(Fermi), vi) the 511 keV annihilation line also near the Galactic Center, vii) an upturn in the CR-spectra of all elements from Helium, with a hint of an upturn for Hydrogen, viii) a derivation of the interaction grammages separately for CR-protons and CR-heavy nuclei, and ix) the complete cosmic ray spectrum with a steep powerlaw leading to a dip near $3\,10^{18}$ eV in terms of $E^3\,(dN/dE)$, then a broad bump near $5\,10^{19}$ eV, turning down towards 10^{21} eV (KASCADE, IceTop, KASCADE-Grande, Auger). All these features can be quantitatively explained building on the action of cosmic rays accelerated in the magnetic winds of very massive stars, when they explode (Biermann et al. 2009 - 2012): this work is based on predictions from 1993 (Biermann 1993, Biermann & Cassinelli 1993, Biermann & Strom 1993, Stanev et al 1993; review at ICRC Calgary 1993); this approach is older and simpler than adding WR-star supernova CR-contributions with pulsar wind nebula CR-contributions, is also simpler than using magnetic field enhancement in ISM-shocks, and also simpler than using the decay of a postulated particle; this approach also gave quantitative predictions from 1993 which can now be tested. This concept gives an explanation for the cosmic ray spectrum as Galactic plus one extragalactic source, Cen A (Gopal-Krishna et al. 2010, Biermann & de Souza 2012). The data do not require any extra source population below the MWBG induced turnoff - commonly referred to as the GZK-limit: Greisen (1966), Zatsepin & Kuzmin (1966); in fact the cut-off observed in the spectrum may well derive from an energy limit in the source due to spatial limits. All this is possible, since the magnetic horizon appears to be quite small (consistent with the cosmological MHD simulations of Ryu et al. 2008). It also entails that Cen A is our highest energy physics laboratory accessible to direct observations of charged particles. All this allows to go back to galaxy data to derive the key properties of the dark matter particle: Work by Hogan & Dalcanton (2000), Gilmore et al. (from 2006, 2009), Strigari et al. (2008), Boyanovsky et al. (2008), Gentile et al. (2009) and de Vega & Sanchez (2010 - 2012), de Vega et al. (2012), Destri et al. (2012) clearly points to a keV particle. A right-handed neutrino is a Fermion candidate to be this particle (e.g. Kusenko & Segre 1997; Fuller et al. 2003; Kusenko 2004; also see Kusenko et al. 2010, and Lindner et al. 2010; for a review see Kusenko 2009; Biermann & Kusenko 2006; Stasielak et al. 2007; Loewenstein et al. 2009): This particle has the advantage to allow star formation very early, near redshift 80, and so also allows the formation of supermassive black holes: they possibly formed out of agglomerating massive stars, in the gravitational potential well of the first DM clumps, whose mass in turn is determined by the properties of the DM particle. The supermassive star gives rise to a large HII region, possibly dominating the Thomson depth observed. This black hole formation can be thought of as leading to a highly energetic supernova remnant, a Hyper Nova Remnant (HNR). Black holes in turn also merge, but in this manner start their mergers at masses of a few million solar masses, about ten percent of the baryonic mass inside the initial dark matter clumps, and at a fraction of $10^{-4.5}$ of the baryonic mass in their sphere of influence to the next such black hole. This readily explains the supermassive black hole mass function (Caramete & Biermann 2010). The action of the formation of the first super-massive black holes allows a possible path to determine the dark matter particle mass, under the proviso that it is a right-handed neutrino, as advocated by some (e.g., Kusenko 2009): a) Determine the Galactic radio background spectrum, and check for residual all-sky emission; b) Determine the extragalactic radio background spectrum, if possible (Kogut et al. 2011); c) Match it with various models, such a the Hyper Nova Remnants radio emission, d) Such a match implies angular fine structure of this emission on the sky, which may be detectable; e) Determine the Thomson depth through to recombination, match it with the HII regions, HNRs, the action by X-rays from the early stellar black holes, or any other model, and determine, if possible its angular structure on the sky - each have their specific signature in size and Thomson depth; f) If there is a residual Thomson depth which is not structured, then all the normal mechanisms fail due to their spatial distribution, including the HII regions and HNRs, and only a very distributed source of ionization could explain it; g) The strength of the residual Thomson depth directly scales with the action of the decay of a dark matter particle such as a right-handed neutrino: This gives the mass of the particle, given sufficient accuracy. Our conclusion is that a right-handed neutrino of a mass of a few keV is the most interesting candidate to constitute dark matter. Its mass determination seems feasible.

Dark matter is required to explain

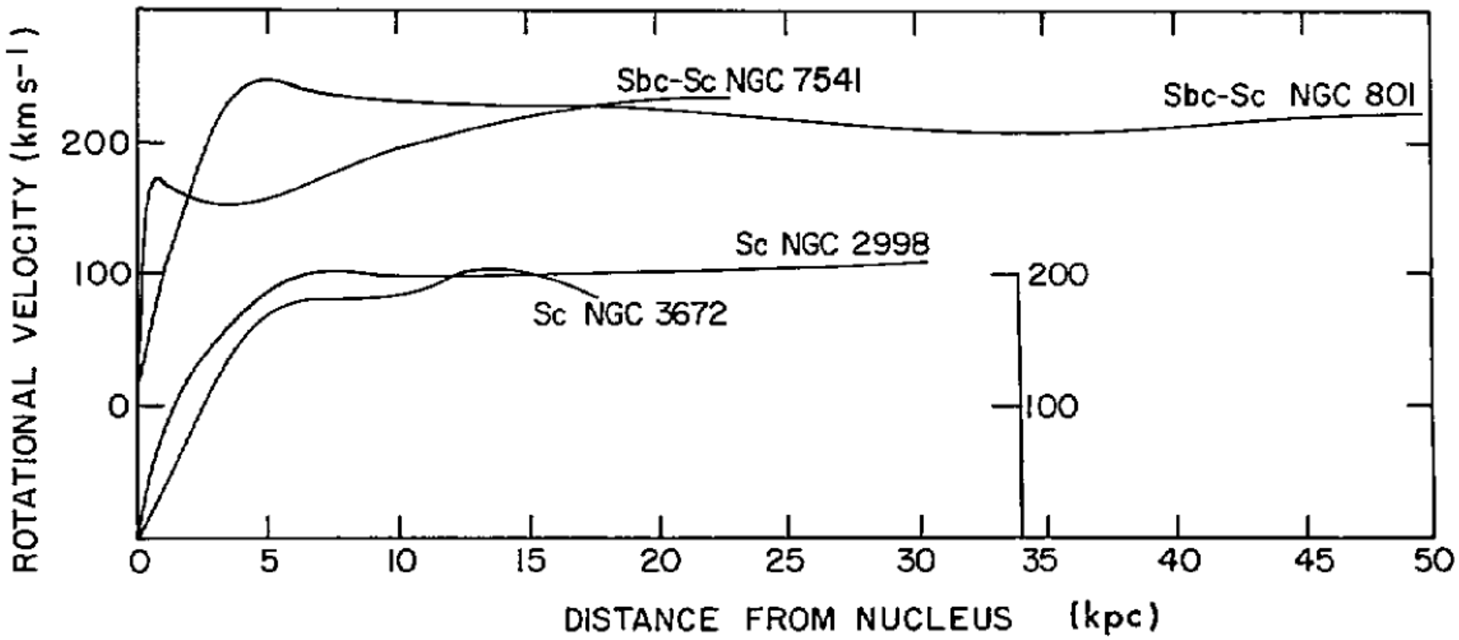


Figure 1 Rotation curves (–> Rubin et al. 1978)

- motions of galaxies in groups and clusters (Zwicky 1933)
- motion of Andromeda towards us (Kahn & Woltjer 1959)
- stability of thin disk galaxies (e.g. Ostriker & Peebles 1973)

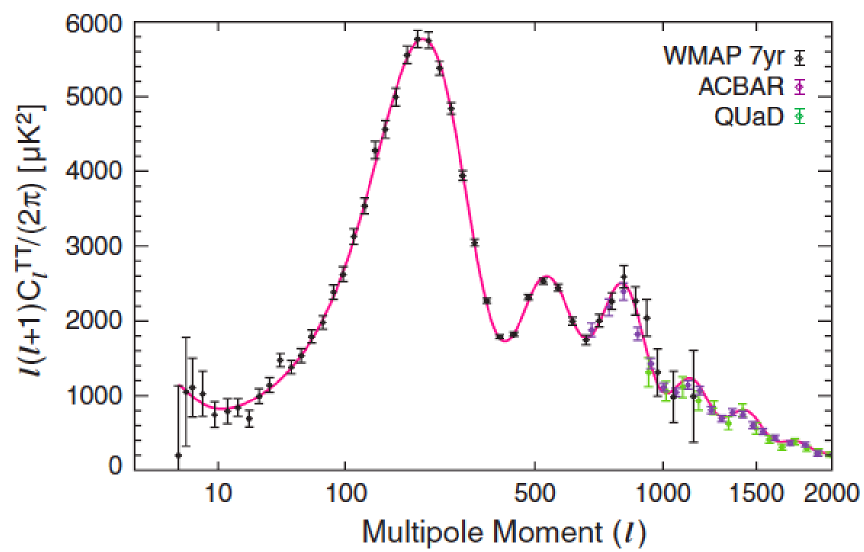


Figure 2 The WMAP 7 year fluctuations in the microwave background from the big bang (–> Larson et al. 2011)

- rotation curves (e.g. Rubin 1978)
- containing the hot gas in groups and clusters
- large scale structure formation in the universe
- mathematically flat geometry of the universe (Spergel et al. 2003, 2007; Larson et al. 2011)

The universe: WMAP7

Jarosik et al. 2011

The sum of all contributions is very close to unity, critical density: “flat” geometry, like a perfect tabletop:

$$\Omega_\Lambda = 0.728 \pm 0.016$$

$$\Omega_{dm} = 0.227 \pm 0.014$$

$$\Omega_b = 0.0456 \pm 0.0016$$

$$\Omega_k = 1 - \Omega_\Lambda - \Omega_{dm} - \Omega_b = -0.0125^{+0.0064}_{-0.0067}$$

$$H_0 = 70.4 \pm 1.4\,\mathrm{km/s/Mpc}$$

Assuming gradual re-ionization

$$z_{re-ion,init} \gtrsim 20$$

Thomson depth: $\tau_T = 0.087 \pm 0.014$

The age of the universe:

$$t_0 = (13.75 \pm 0.11) \cdot 10^9\,\mathrm{yr}$$

79 years: what is dark matter?

Proposal: Supersymmetry! Evidence?

- Upturn in CR-e^+/CR-e^- ratio and CR-e^- in cosmic rays (Pamela, Fermi, ATIC)
- Anisotropy in CR arrival directions at 20 and 400 TeV (EAS-TOP, SuperK, Milagro, SuperK, Tibet, IceCube)
- WMAP haze; Fermi haze and bubble; 511 keV emission line: Galactic Center region synchrotron and IC
- Grammages for interaction for CR-p and CR-C, O, Fe
- General upturn in all nuclei from Helium (CREAM, Tracer, Pamela, IceTop)
- Lacking association of HE neutrinos with GRBs (IceCube)
- KASCADE-Grande and IceTop data for 10^{15} eV through 10^{18} eV
- Auger spectrum

A massive star and its magnetic field

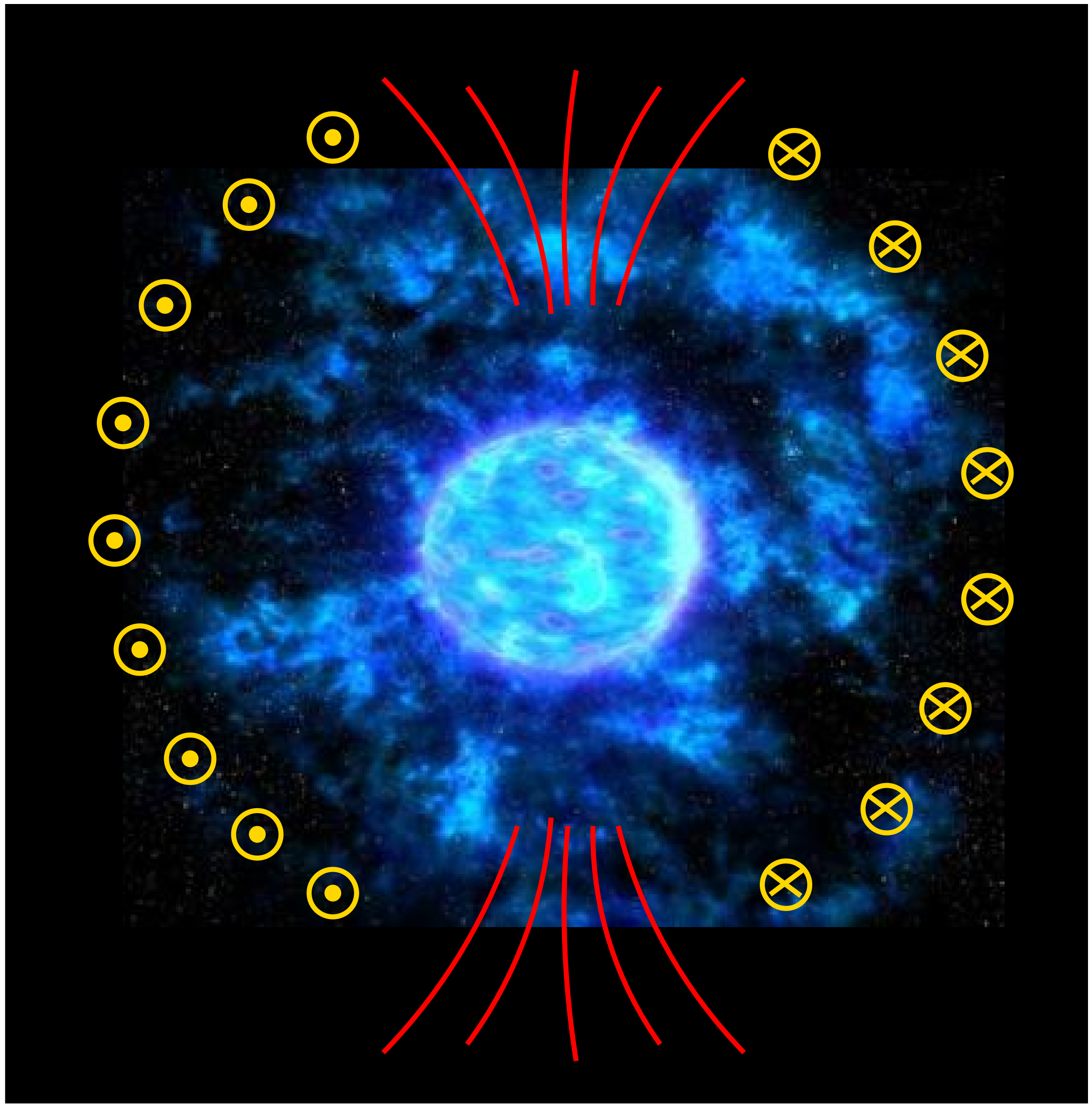


Figure 3 Magnetic field topology around a massive star in its wind: Graph following Parker 1958; central graph NASA, Wolf Rayet star WR124: Remember Maxwell's laws!

Cosmic ray knee: paper CR-IV, 1993

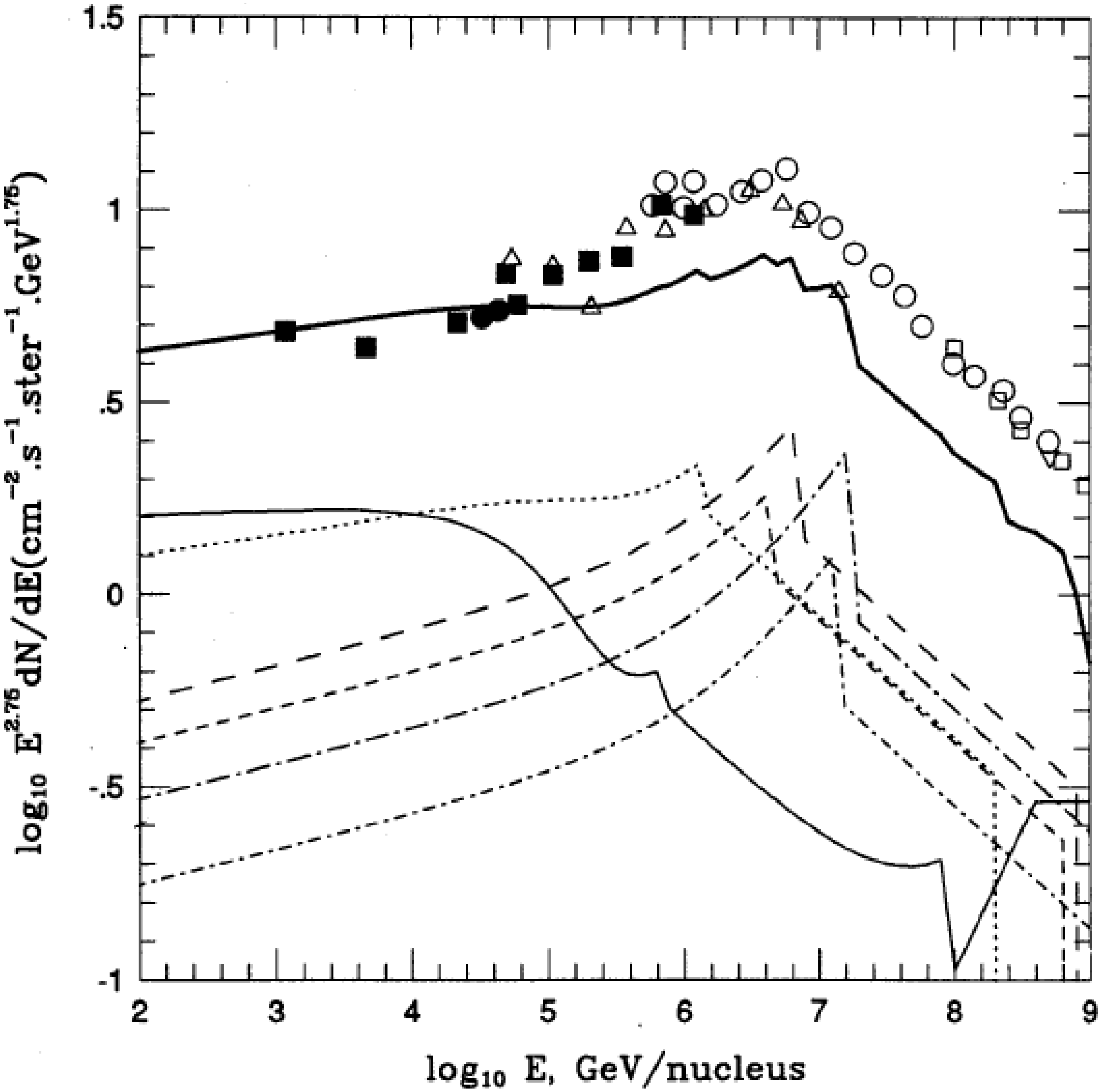


Figure 4 Spectral and chemical structure at the knee, *CR-e^- and CR-e^+ components*?, to be *shifted to high energy*? Element groups are H, He, CNO, Ne-S, Cl-Mn, and Fe. Source: Stanev et al., paper CR-IV 1993

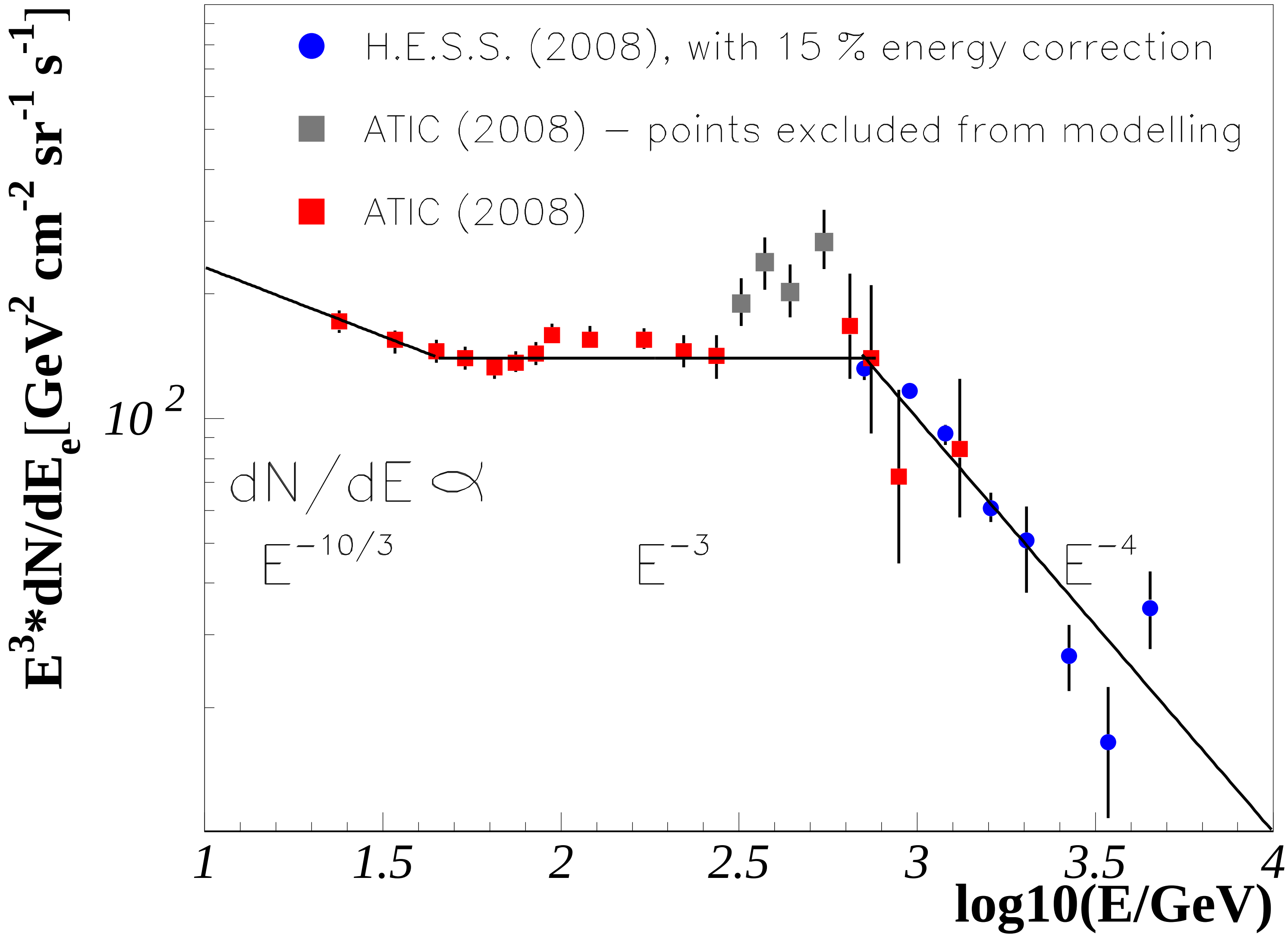


Figure 5 Model prediction with ATIC and H.E.S.S data for cosmic ray electrons: $E^{-10/3}$, E^{-3}, and E^{-4}. Note typo in ordinate, should be m^{-2}, not cm^{-2}. Source Biermann et al. 2009 *Phys. Rev. Letters* **103**, 061101 (2009)

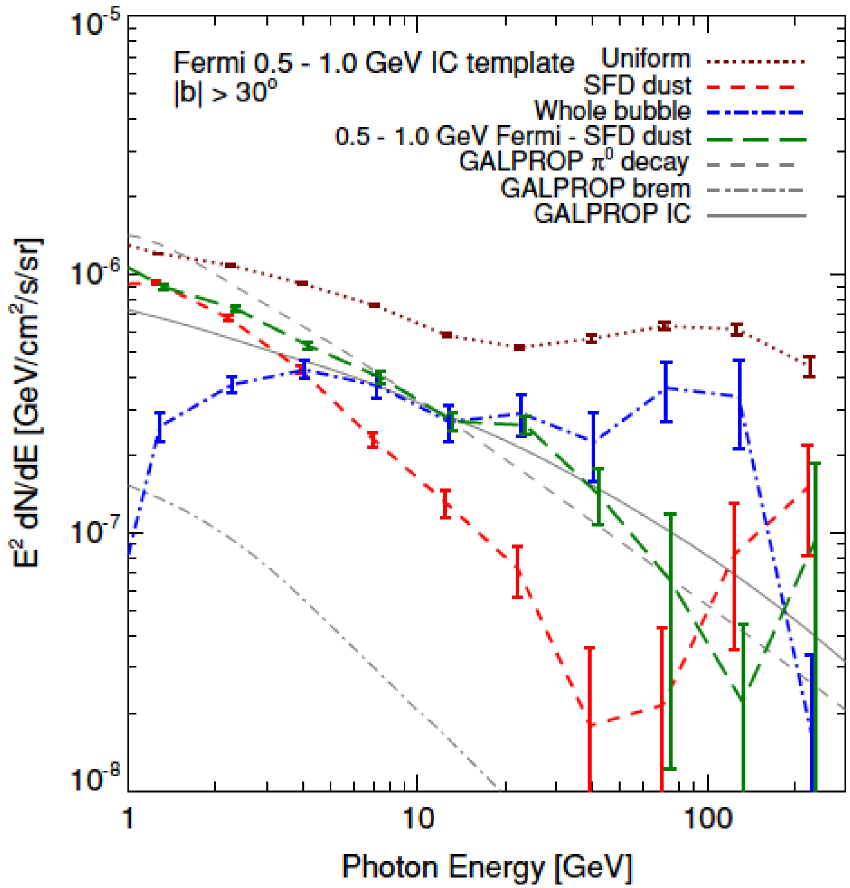


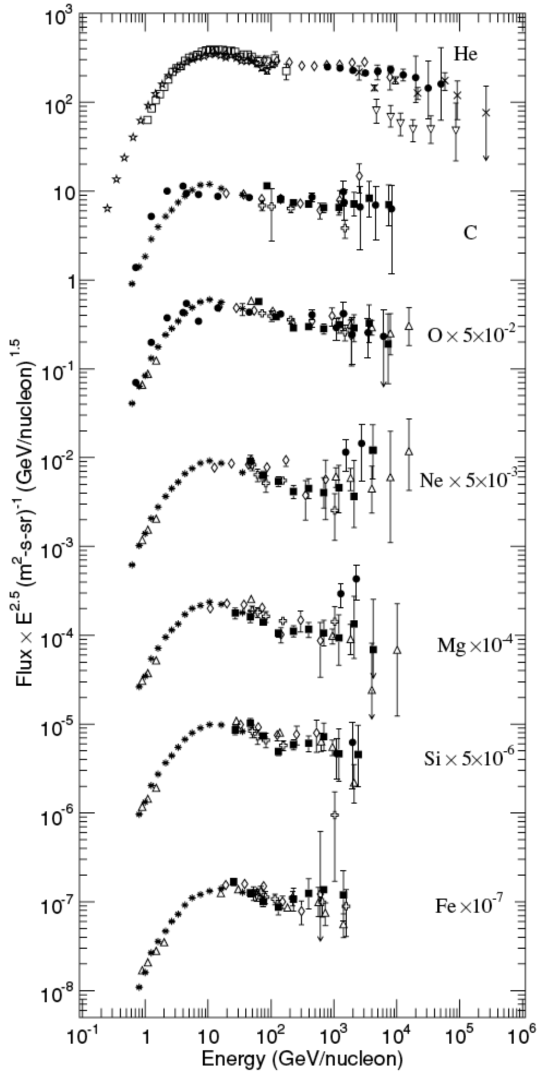
Figure 14. Same as Figure 12, but correlation spectra for the 4-template fit employing the *Fermi* 0.5–1 GeV residual map (after subtracting the SFD dust) as a template for the starlight IC. The line style is the same as Figure 12. Again, we find that the spectrum correlated with the *Fermi* bubble template (blue dot-dashed line) is harder (consistent with flat in E^2dN/dE) than the spectra correlated with the other templates, and the models for the various emission mechanisms generated from GALPROP, indicating that the *Fermi* bubbles constitute a distinct gamma-ray component with a hard spectrum. The

Figure 6 The hard Fermi bubble spectrum: flat (Su et al., 2010). A spectrum here with $E_\gamma^2 F(E_\gamma) \sim const$ interpreted as IC emission is equivalent to Synchrotron emission in flux density running as $S_\nu \sim \nu^{-1}$.

WMAP, Fermi haze and bubble, 511 keV line

- Polar cap CR-electron component: with diffusion $E^{-7/3}$, radio spectrum $\nu^{-2/3}$
- Transition between diffusion dominance and loss dominance shifted to much higher particle energy – smaller scale height: Reproduces flux, and radial profile
- Spectrum predicted in order of increasing frequency: $\nu^{-2/3}$, ν^{-1}, $\nu^{-3/2}$: confirmed by Fermi haze (2010), the IC component: equivalent to ν^{-1} flat in $E_\gamma^2 \, F(E_\gamma)$
- Fermi bubble: instability in galactic magnetic wind driven by CRs?
- Allows the correct number of positrons to explain the 511 keV emission
- Biermann et al., *Astrophys. J. Letters* **710**, L53 (2010)

CREAM: CR spectral upturn



'igure 4. Compilation of helium and heavier nuclei data. The CREA

Figure 7 CREAM data: straight spectrum with $E^{-2.67}$ not compatible with data, requires upturn (Ahn et al. 2010 *Astrophys. J. Letters*): Biermann et al., ApJ **725**, 184 (2010)

KASCADE, KASCADE-Grande and Auger

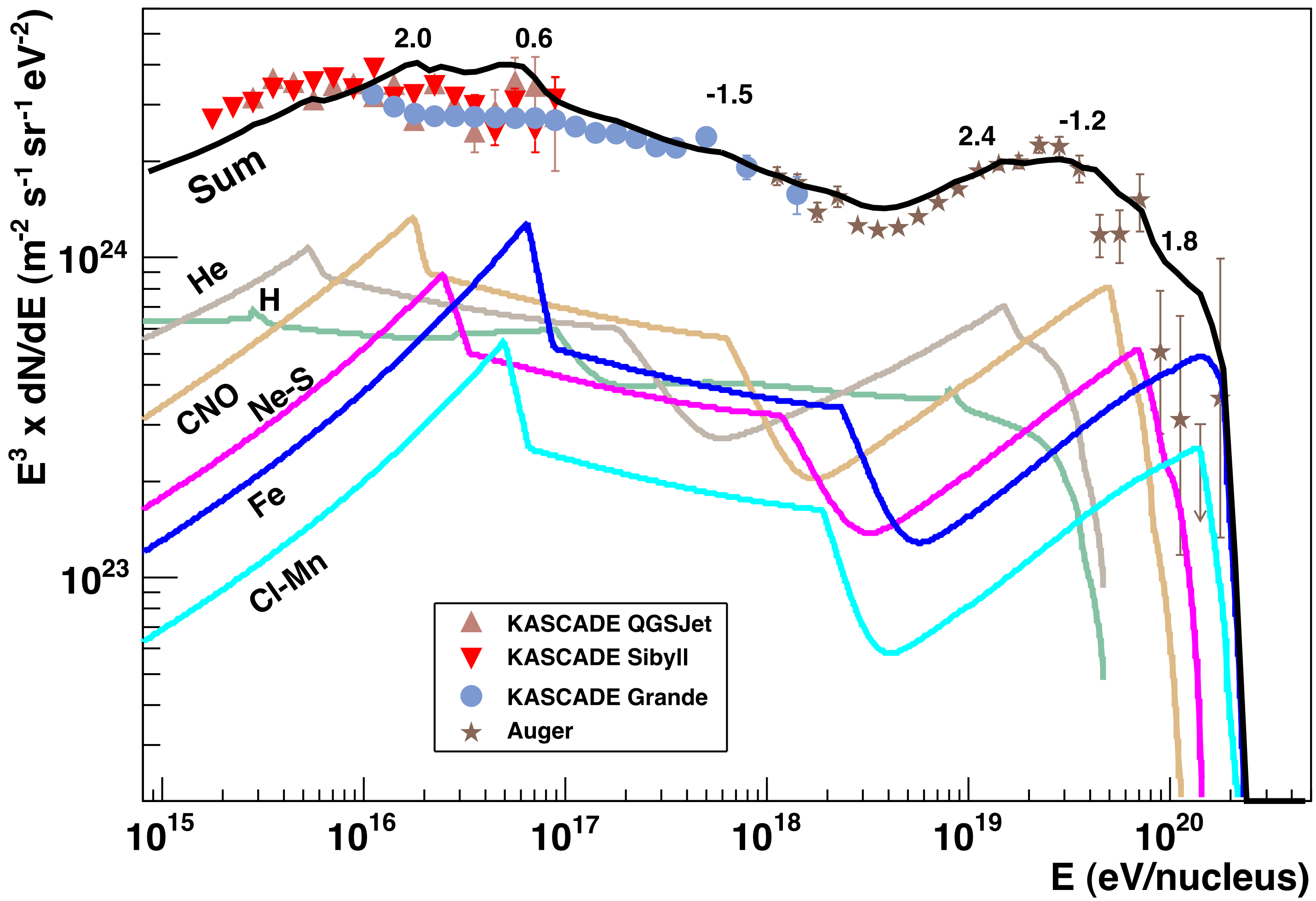


Figure 8 KASCADE, KASCADE-Grande, and Auger data interpreted as arising from a combination of Galactic CRs plus galactic CRs from another active galaxy, shifted up in a relativistic kick (Gopal-Krishna et al. 2010 ApJL; Biermann & de Souza 2012 ApJ). The numbers give (model - data)/(experimental error): this suggests a good fit beyond the knee, and a single extragalactic source, only Cen A: contrary to the expectation since 1966 (Greisen, Zatsepin, Kuzmin) there is no other extragalactic source population necessary.

Summary cosmic ray particles

- Occam's razor simplicity: **CR-IV (1993) model suffices to explain the 2011 data**
- Polar cap CRs of exploding stars with magnetic winds
- Kick from relativistic shock shifts entire spectrum (Achterberg et al. 2001)
- CR spectrum possibly explained with our Galaxy and radio galaxy Cen A
- **Below GZK no other source population required by the data**: consistent with cosmological magnetic field simulations (Ryu et al. 2008+)
- Can be falsified: very different abundances? magnetic wind of our Galaxy (Everett et al. 2008)? Neutrinos? GRBs (IceCube limits)?

DM proposal: Heavy or light particles?

- One alternative: **right-handed neutrinos**, interact only weakly with normal left-handed neutrinos in low mass range, of order a few keV (review Kusenko 2009)
- 2010 supporting particle physics arguments using the see-saw mechanism (Kusenko et al., Lindner et al.)
- Most important decay channel: active, normal, left-handed neutrino and a photon; the photon has half the energy, and so can ionize matter. They are never in thermodynamic equilibrium, probably far sub-thermal
- From increased early ionization **star formation possible from about redshift 80** (Biermann & Kusenko 2006; Stasielak et al. 2007; Loewenstein et al. 2009)
- All consistent with same phase space density ρ_{DM}/σ_{DM}^3 (e.g. Hogan & Dalcanton 2000; de Vega & Sanchez 2010 - 2012, Destri et al. 2012, de Vega et al. 2012)

The sky in black holes $\gtrsim 10^8\ M_\odot$: colors are distance

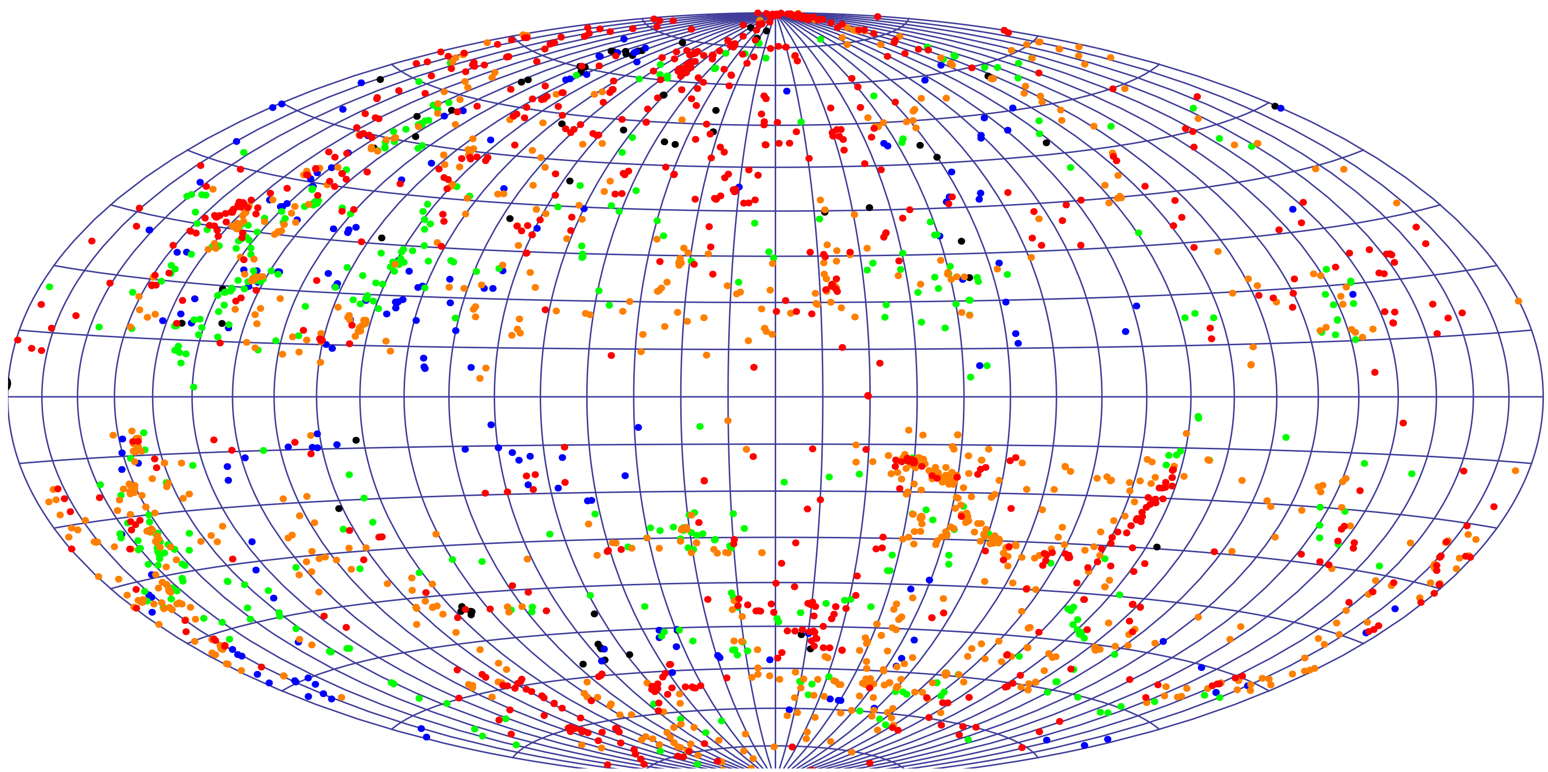


Figure 9 The sky in black holes, $\gtrsim 10^8\ M_\odot$: The color code corresponds to distance: Black, Blue, Green, Orange, Red for the redshifts intervals 0, 0.005, 0.01, 0.015, 0.02, 0.025, corresponding to distance intervals of 0, 60, 120, 180, 240, and 300 million light-years: (–> Caramete & Biermann 2011); coordinate system with Galactic plane across center, and Galactic center at the right edge

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

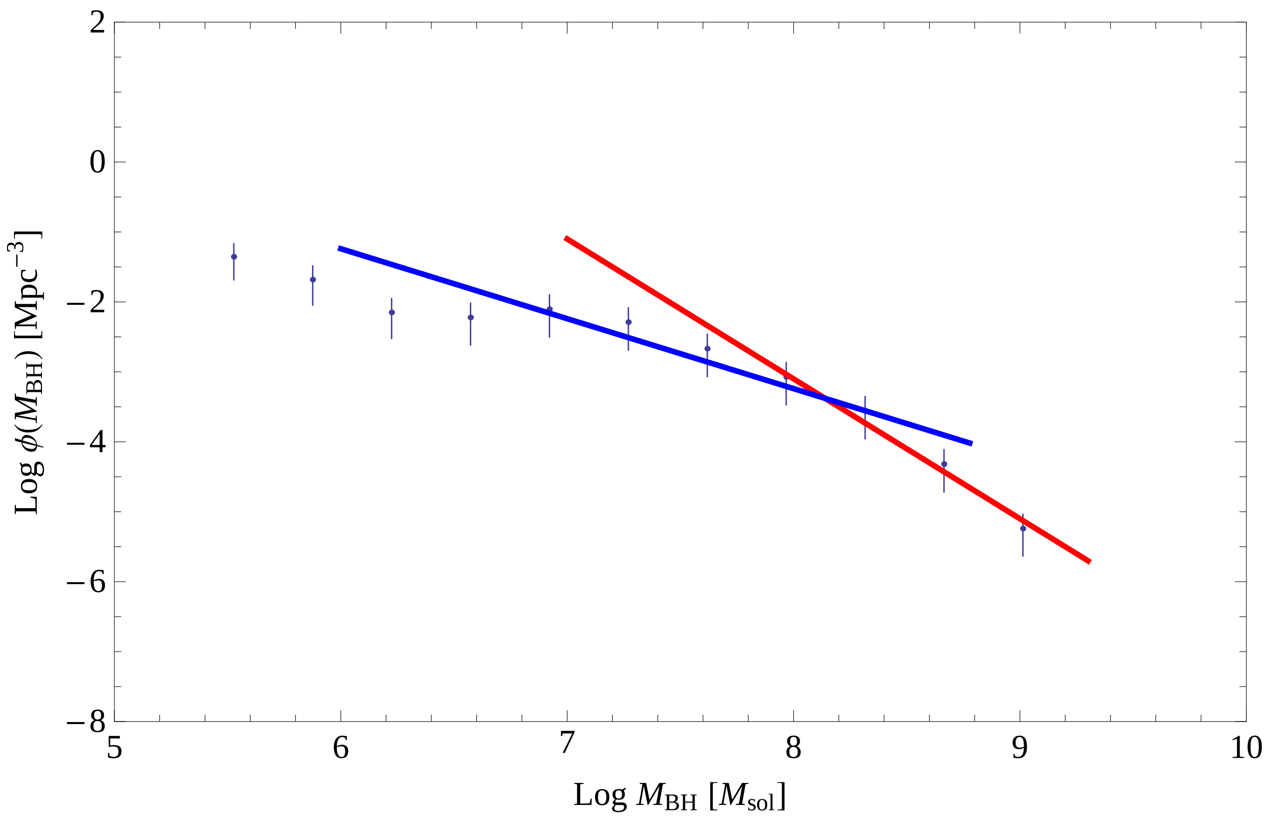


Figure 10 Integral mass function corrected for Hubble type sampling, 2928 objects, the slope of the lines is: red −2.0 fitting $> 10^8\,M_\odot$, and blue −1.0 fitting between $10^7\,M_\odot$ and $10^8\,M_\odot$. See Caramete & Biermann, *Astron. & Astroph.* **521**, id.A55 (2010); arXiv:0908.2764. This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

Massive and supermassive stars at very low abundances

- Massive star formation from redshift 80?
- Massive star HII region
- Massive star explosions?
- Hyper Nova Remnant (HNR)
- Stellar mass black holes?
- Gamma Ray Bursts?
- Gamma emission redshifted to X-rays
- Time scale of a few seconds shifted to minute
- Search strategy to detect high-z GRBs? sliding window of 1 minute?

How did these $\sim 3\,10^6\,M_\odot$ black holes start?

- Stars form in a potential well defined by DM properties
- Massive stars form first, helped by the first molecular Hydrogen (Biermann & Kusenko 2006)
- Supermassive stars form by agglomeration of massive stars (Sanders 1970, Portegies Zwart et al. 2004), only with zero heavy elements (Yungelson et al. 2008)
- Supermassive stars + HII regions: Thomson depth
- Supermassive stars turn unstable near $\sim 10^6\,M_\odot$ (Appenzeller & Fricke 1972): Hypernova remnant (HNR)
- These HNRs both emit non-thermal radio emission, but also provide additional Thomson absorption depth

Stellar agglomeration conditions

- Massive stars form in groups
- Mass available at most about $10^7\,M_\odot$ from baryonic mass fraction, using total mass of $5 \cdot 10^7\,M_\odot$ in primordial galaxy (Gilmore et al. 2007)
- Life time of massive stars about $2 \cdot 10^6$ years, independent of mass
- Relaxation time must be this time or less
- Also, relaxation time scale must be about 3 crossing times or less, implying (Lightman & Shapiro 1978) about 300 or fewer stars
- Instability sets in at $5 \cdot 10^5\,M_\odot$, and infall will enhance the mass of the final black hole
- Therefore initial massive stars about $10^3\,M_\odot$ or more

Absorption line forest, excited by cosmic rays

- These stars make magnetic fields, explode, and then make cosmic rays:
- These cosmic rays excite characteristic transitions in massive gaseous shells of molecular surrounding the HNR
- Absorption line forest: H_2^+, H_3^+
- We need to identify groups of lines, originating from specific HNRs, and in the beam-adding need to be able to identify each HNR separately
- In any beam of a telescope many such lines, so very high signal to noise required
- If such lines confirmed, key signature for a) cosmic rays, and by inference b) magnetic fields - and all at a known redshift

The Radio background and Thomson depth

The path:

- Observe Galactic radio background, taking into account CR-e and radio polarization data
- Observe extragalactic radio background (detected ? Su et al. 2008, Everett et al. 2010, Kogut et al. 2011+)
- Angular structure of the extragalactic background, including polarization
- Test models like: i) early stellar BHs (Mirabel et al. 2011), ii) early galaxies and AGN, or iii) SMS HII region free-free absorption and HNR radio emission
- Observe Thomson absorption depth to recombination
- Observe its angular structure, if possible
- Residual constant component

Spatial structure of the Thomson depth I

- Problem 1: The expected spatial structure far too small to be detectable with Planck individually: expect about a few arc-sec to a few arc-minutes
- Problem 2: There are numerous sources, with arbitrary small scale, especially flat spectrum radio sources
- Problem 3: There are numerous clusters of galaxies, giving a Sunyaev-Zeldovich effect, so also a Thomson scattering effect; low redshift
- Radio interferometer angular scale, but sensitivity? May take very long observation with radio-interferometer, capable of arc-min observations at high radio frequency, best two frequencies including polarization, with extremely high signal-to-noise ratio.

Spatial structure of the Thomson depth II.a

- Super-massive stars at stability limit ionize Hydrogen: HII region

$$\frac{4\pi}{3} n_0 (1+z)^3 \alpha_2(T) R^3 \;=\; \epsilon L_{edd,\odot} \frac{M_{SMS}}{M_\odot} (h\nu_{ion})^{-1} \tag{1}$$

- Radius of HII region about 30 kpc (at redshift 50)

$$R_{kpc} \;=\; 10^{1.5} \left(\frac{51}{1+z}\right) \left(\frac{M_{SMS}}{10^{6.5} M_\odot}\right)^{1/3} \epsilon_{-0.5}^{1/3} \tag{2}$$

- Individual optical depth about $10^{-3.1}$

$$\tau_{Th,one} \;=\; 10^{-3.1} \left(\frac{1+z}{51}\right)^2 \left(\frac{M_{SMS}}{10^{6.5} M_\odot}\right)^{1/3} \epsilon_{-0.5}^{1/3} \tag{3}$$

Spatial structure of the Thomson depth II.b

- Cumulative optical depth about $10^{-1.7}$, not far from what is observed

$$\tau_{Th,sum} = 10^{-1.7}\left(\frac{1+z}{51}\right)^4 \left(\frac{M_{SMS}}{10^{6.5} M_\odot}\right)\epsilon_{-0.5} \quad (4)$$

most of the probable errors increasing the value, by up to more than an order of magnitude.

- Angular scale about 25 arc-sec, very sensitive observations might detect the structure implied in polarization

$$\theta_{HII,one} = 10^{-3.9}\left(\frac{M_{SMS}}{10^{6.5} M_\odot}\right)^{1/3} \epsilon_{-0.5}^{1/3} \quad (5)$$

which is independent of redshift assumed: H_2^+, H_3^+ as well in absorption

Spatial structure of the Thomson depth III.a

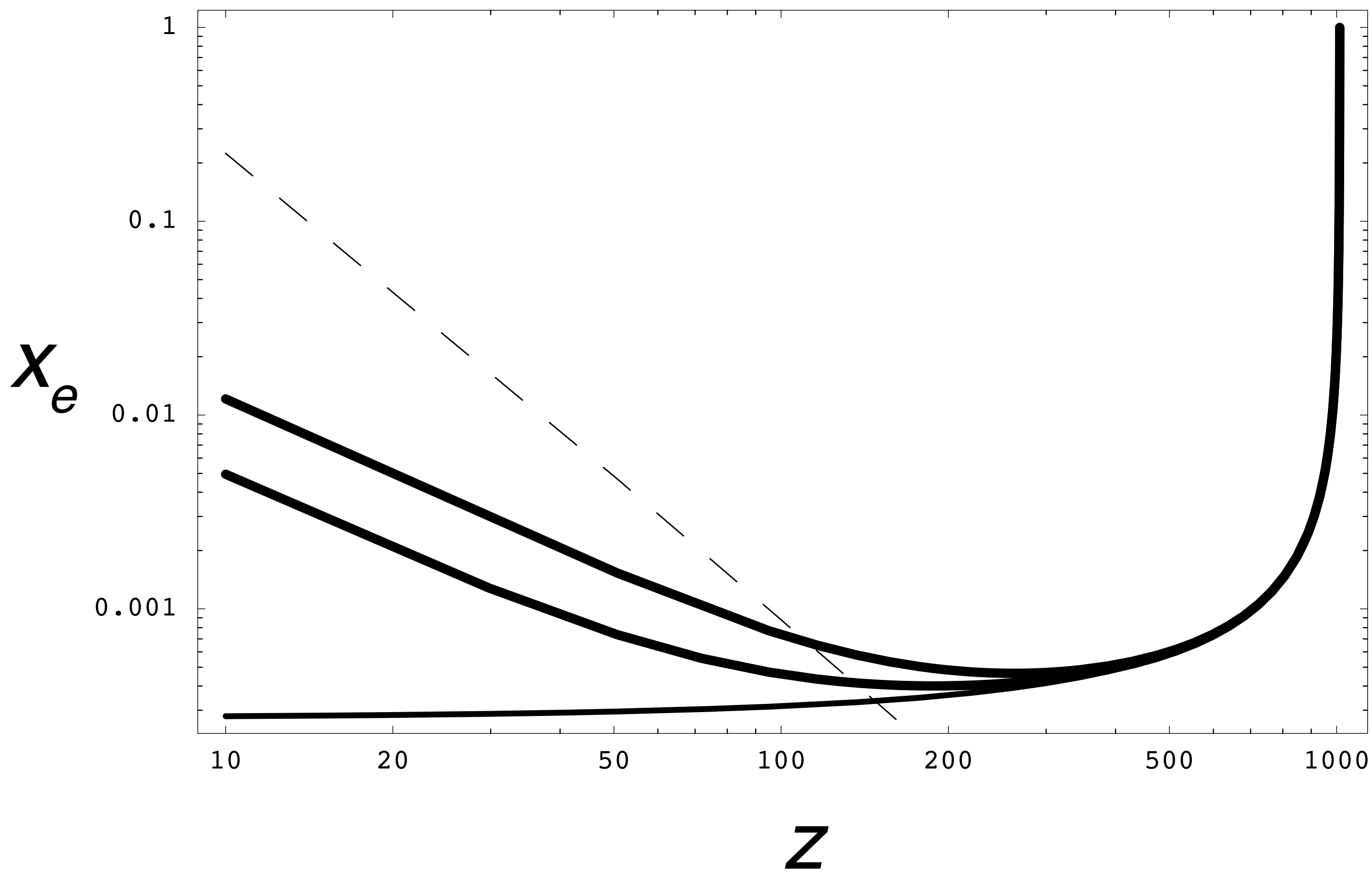


Figure 11 The run of ionization with redshift for various DM particle mass; upper curve 7 keV, lower curve 4 keV, lowest curve zero mass; dashed line lower limit for Compton cooling relevance. The contribution at redshift near 100 can give a significant distributed site of optical depth (Biermann & Kusenko 2006, PRL)

Spatial structure of the Thomson depth III.b

- A constant residual component with no spatial structure?
- Galaxy and AGN models give spatial structure (Bouwens et al. 2010, Labbé et al. 2010)
- Early stellar Black Holes give spatial structure (Mirabel et al. 2011)
- Early massive star formation gives spatial structure (Biermann & Kusenko 2006): HII regions may explain large fraction of observed Thomson depth
- The action of the decay of a right handed neutrino as a dark matter particle does not give spatial structure
- Its effect runs linear with mass, and depending on accuracy, we can determine the mass

First GWs from $\sim 3\,10^6\,M_\odot$ BH mergers ?

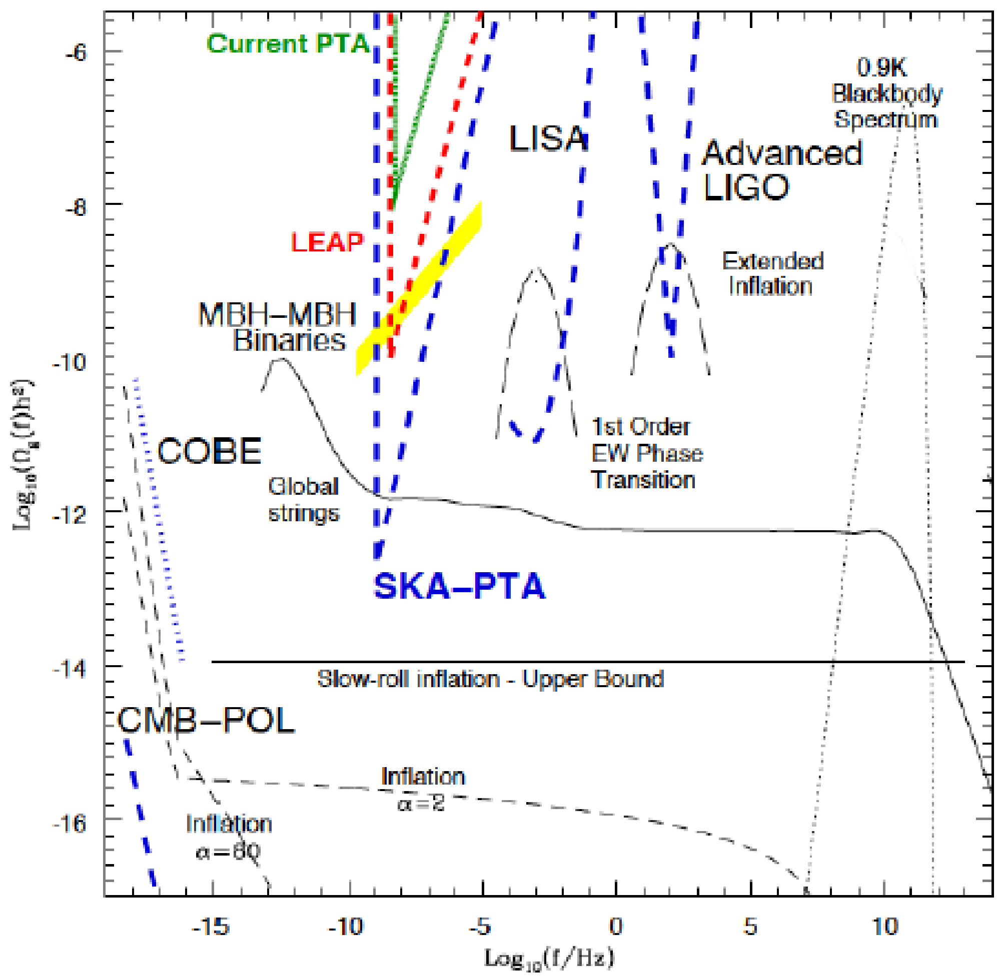


Figure 12 Upper limits to GW signals (M. Kramer 2011). The first mergers of super-massive black holes could start near $10^{-3.5}$ Hz, and the first stellar black holes near $10^{+2.5}$ Hz at high redshift, and their lower frequency side spectrum would be a steep power-law, but their amplitude is uncertain. Any signal would be a superposition. A signal from redshift $\lesssim 80$ would be invisible until PTA gets much more sensitive, or LISA comes.

? ? Weakly Interacting Neutrino = WIN ? ?

- **Prediction: ISM-SNe, wind-SNe and Cen A account for cosmic rays** (quantitative model from 1993 +, applied 2009 - 2012)
- **Prediction: At redshift of order $\lesssim$ 80 first** massive star formation, first very large HII regions, energetic CR particles, GRBs and first BHs, supermassive BHs (starting near $3\,10^6\,M_{\odot}$), high luminosity GWs (observable by PTA ?)
- **Prediction**: SMS-HII Thomson depth, HNR radio background
- **Prediction: At redshift of order $\lesssim$ 80** H_3^+ and/or H_2^+ forest of absorption lines
- **Prediction**: Residual distributed Thomson depth contribution to recombination directly scales with DM particle mass

2 Acknowledgements

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