ASTROPHYSICS OF WARM DARK MATTER

Peter L. Biermann[1,2,3,4,5] with help from
Laurenţiu I. Caramete[1,6], László Á. Gergely[7], Nayantara Gupta[8], Benjamin C. Harms[3], Gopal Krishna[9], Athina Meli[10], Biman B. Nath[8], Eun-Suk Seo[11], Vitor de Souza[12], Todor Stanev[13] & Julia Becker Tjus[14],

[1] MPI for Radioastronomy, Bonn, Germany; [2] Dept. of Phys., Karlsruher Institut für Technologie KIT, Germany, [3] Dept. of Phys. & Astr., Univ. of Alabama, Tuscaloosa, AL, USA; [4] Dept. of Phys., Univ. of Alabama at Huntsville, AL, USA; [5] Dept. of Phys. & Astron., Univ. of Bonn, Germany ;

[6] Institute for Space Sciences, Bucharest, Romania; [7] Department of Theoretical Physics, University of Szeged, Szeged, Hungary; [8] Raman Research Institute, Bangalore, India; [9] NCRA, Tata Institute, Pune, India; [10] University of Gent, Gent, Belgium; [11] Dept. of Physics, Univ. of Maryland, College Park, MD, USA; [12] Universidade de S$\tilde{a}$o Paulo, Instituto de Física de S$\tilde{a}$o Carlos, Brazil; [13] Bartol Research Inst., Univ. of Delaware, Newark, DE, USA[14] Dept. of Phys., Univ. Bochum, Bochum, Germany;

AMS positron fraction: data 2013

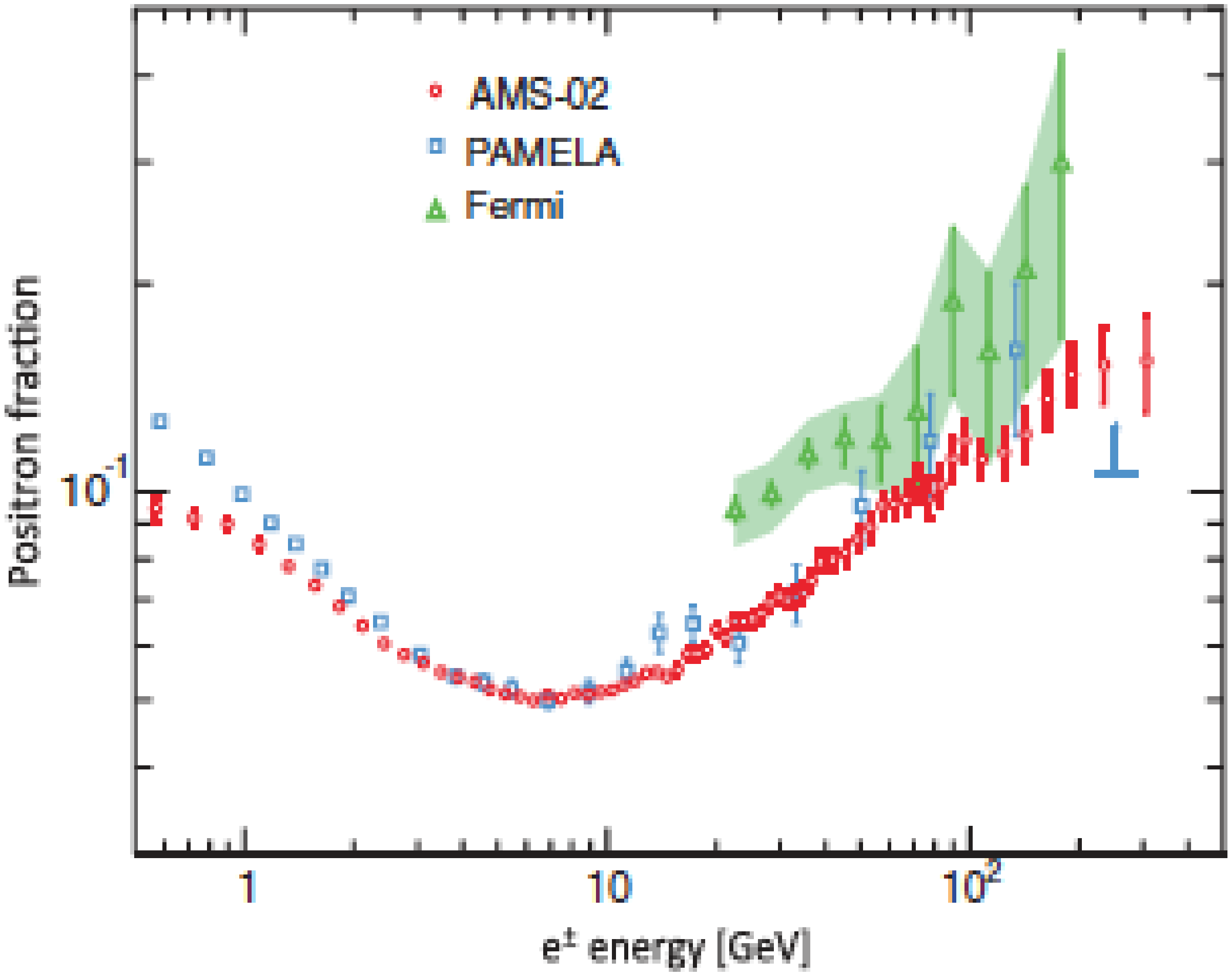

Figure 1 AMS energetic positron fraction; source AMS-Coll. (2013) PRL. To quote: ”These observations show the existence of new physical phenomena, whether from a particle physics or an astrophysical origin.“

AMS positron fraction 2013: explanation?

- Dark matter decay? Beautiful candidate!
- Nearby special source? Pulsars?
- Cosmic ray physics? CR-positron fraction should show a gradual decay (Protheroe 1982)
- Spallation along the way, so interaction and transport coupled? Spallation near source?
- Consider magnetic field structure in wind of very massive stars, Maxwell laws in magnetic stellar wind; Parker (1958): Polar cap component at source E^{-2}: upturn of all CR spectra (**1993**: 2009+); interaction stronger in polar cap region, so more secondaries, so in spectrum secondaries shifted to lower energy, giving a $E^{+1/3}$ prediction for positron fraction leveling off to a constant.

CR positron fraction: prediction 2009 - match

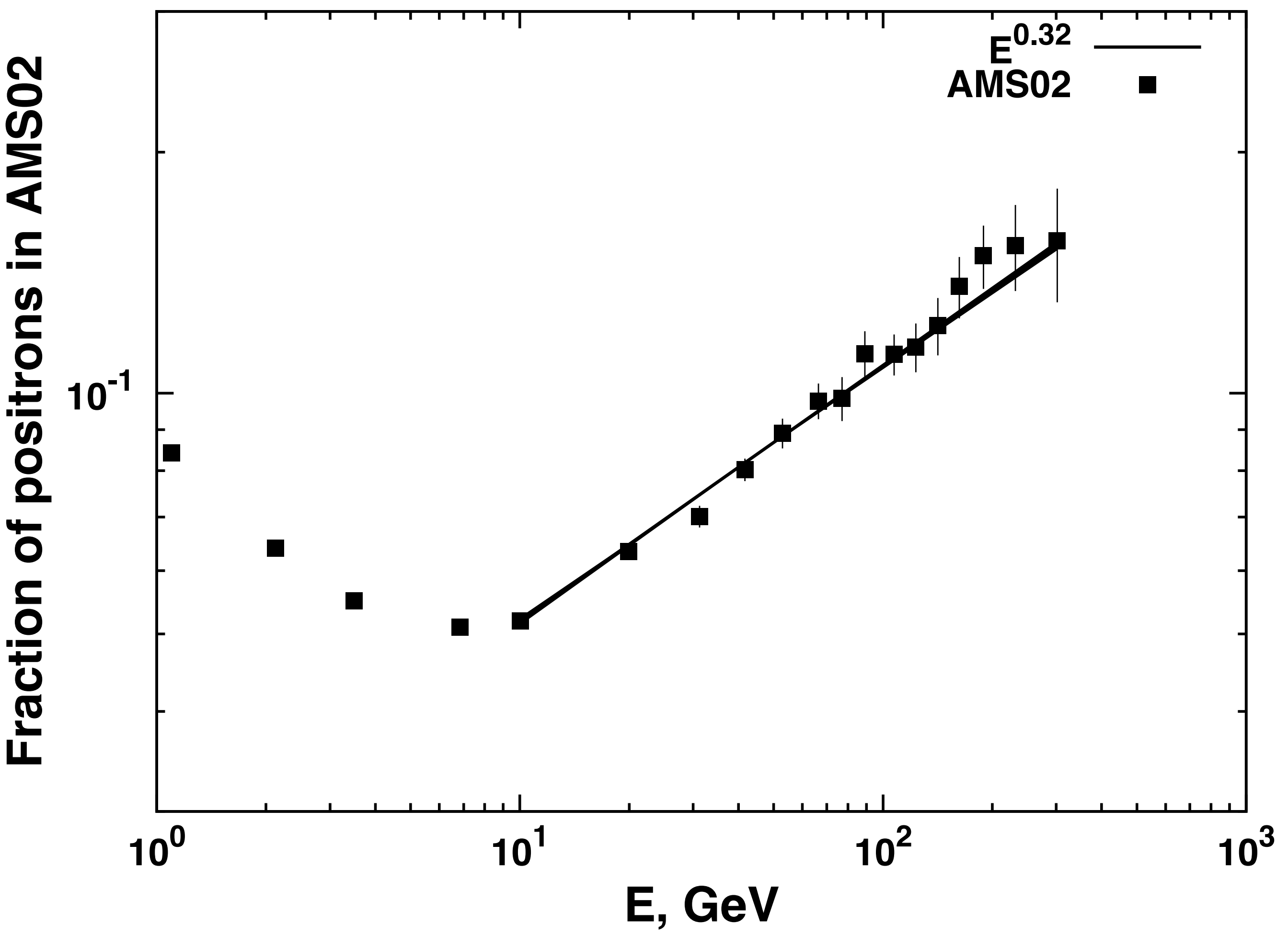

Figure 2 Fitting our 2009 prediction, with power law 0.014 ± 0.019 off the predicted slope of 1/3 without using any zero-point; original source Biermann et al. (2009) PRL. At low energy matches Protheroe prediction, at high energy there is an indication of the expected leveling off.

The universe: Planck 2013

Planck 2013 XVI (Table 2 ff):
Term “dark matter” due to **Oort (1933)**

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

$$\Omega_\Lambda \,=\, 0.692 \pm 0.010$$

$$\Omega_{dm} \,=\, 0.2582 \pm 0.0047$$

$$\Omega_b \,=\, 0.0482 \pm 0.00076$$

$$\Omega_k = 1 - \Omega_\Lambda - \Omega_{dm} - \Omega_b \,=\, -0.0005 \pm 0.0066$$

$$H_0 \,=\, 67.8 \pm 0.77\,\mathrm{km/s/Mpc}$$

Assuming gradual re-ionization

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

Thomson depth: $\tau_T \,=\, 0.092 \pm 0.013$

The age of the universe:

$$t_0 \,=\, (13.798 \pm 0.037) \cdot 10^9\,\mathrm{yr}$$

80 years: what is dark matter?

Supersymmetry! Evidence?

- **Supersymmetric massive particles decay** and might explain many observations
- Upturn in CR-e^+/CR-e^- ratio and CR-e^- in cosmic rays (Pamela, Fermi, ATIC, AMS)
- Fermi haze/bubble; 511 keV + 130 GeV line: Galactic Center region synchrotron and IC
- Cygnus cocoon spectrum
- WMAP + Planck haze spectra
- IceCube high energy neutrino background

A massive star and its magnetic field

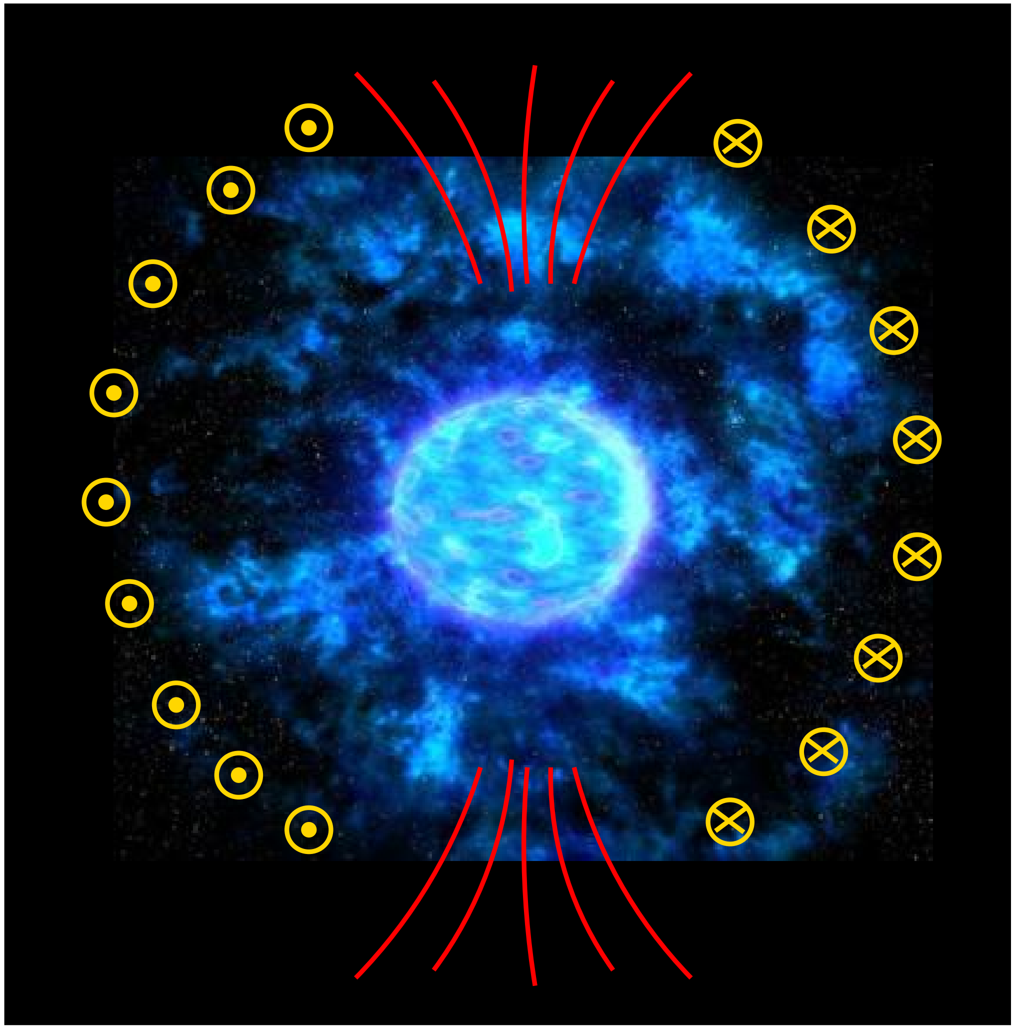

Figure 3 Magnetic field topology around a massive star in its wind: Graph following Parker 1958 ApJ; central graph NASA, Wolf Rayet star WR124: Remember Maxwell's laws! Magnetic field radial in polar cap, Archimedean tangential over the rest, most of 4π. Gives CR-spectra of E^{-2} in polar cap, and $E^{-7/3}$ for rest.

Cosmic ray knee: paper CR-IV, 1993

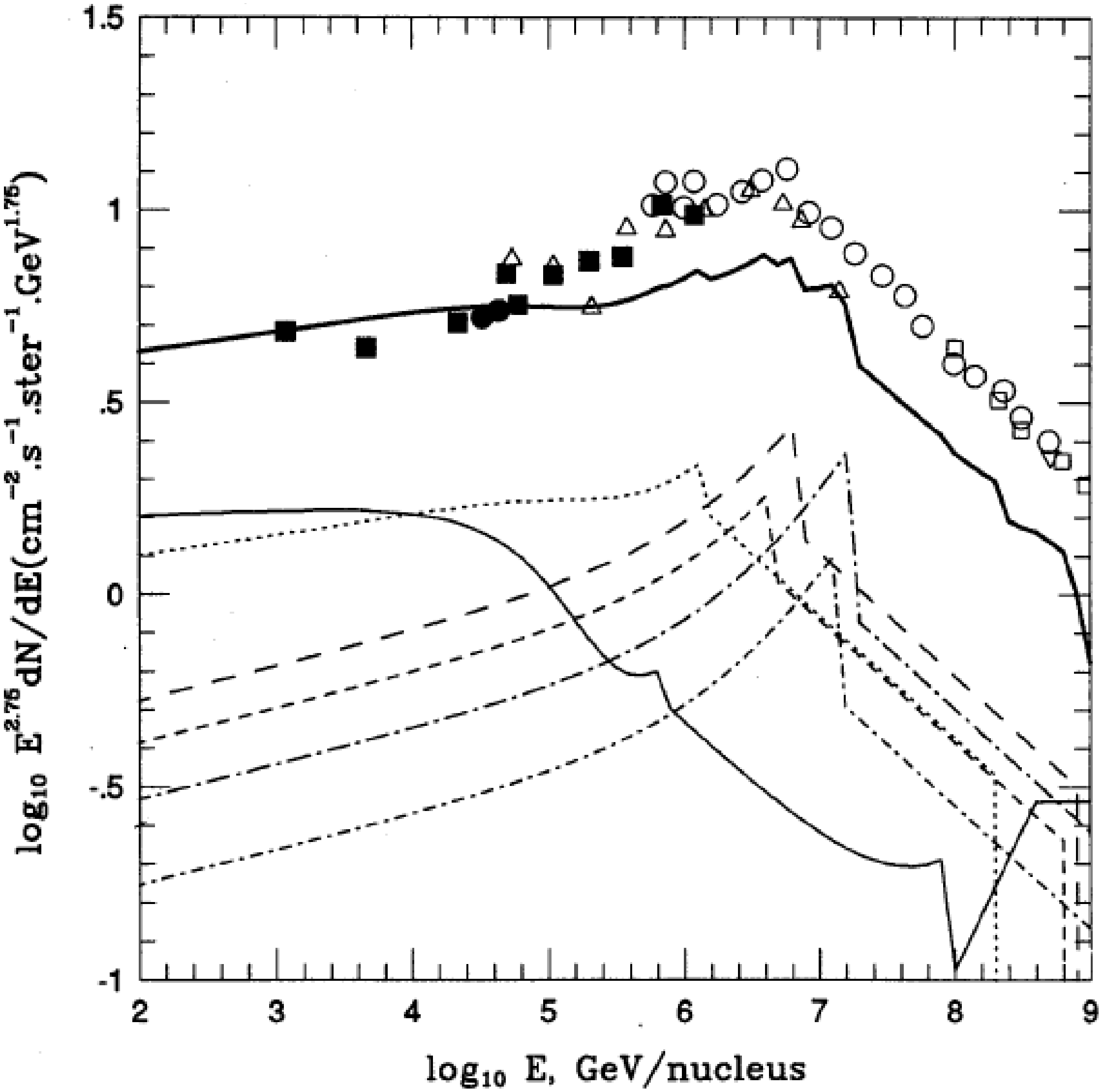

Figure 4 Spectral and chemical structure at the knee, *CR-e^- and CR-e^+ components*?, to be *shifted to high energy*? Element groups are H, He, CNO, Ne-S, Cl-Mn, and Fe. Source: Stanev et al., paper CR-IV 1993

Planck, WMAP, Fermi haze/bubble, 511 keV

- **Polar cap CR-electron** component: with diffusion $E^{-7/3}$, radio spectrum $\nu^{-2/3}$
- In GC region transition between diffusion dominance and loss dominance shifted to higher particle energy – smaller scale height: Reproduces flux, radial profile
- Spectrum predicted: $\nu^{-2/3}$, ν^{-1}, $\nu^{-3/2}$: confirmed by Fermi haze (2010), consistent with Planck haze (2012), the IC component: flat in $E_\gamma^2 \, F(E_\gamma)$
- Fermi bubble: unstable galactic magnetic wind driven by CRs from non-steady star-formation?
- Correct number of positrons for 511 keV emission: grammage for ISM-SN-CRs about 1 gm/cm^2, and for wind-SN-CRs about 10 gm/cm^2 (Nath et al. MN Lett 2012)
- PLB et al., ApJL **710**, L53 (2010): Planck haze data!

130 GeV line interpreted ?

- Recent claims that 130 GeV emission line in Galactic Center region, Su & Finkbeiner 1206.1616; Buckley & Hooper 1205.6811; Weniger 1204.2797; Bringmann et al. 1203.1312.
- Decay of dark matter particle?
- Work with N. Gupta & B. Nath (RRI, Bangalore)
- Consider secondary CR-lepton spectrum, flat in $E^3 J(E)$, sharp cutoff from CR-knee
- Consider radiation field, Moskalenko et al. 2006, peaks at 1 μ and at 100 μ
- Pair production at edge of distribution gives narrow feature: Inverse Compton by these CR-electrons/positrons fully explains the weak line in IC!
- Confirms that CR-electron spectra similar in GC region

KASCADE, KASCADE-Grande and Auger

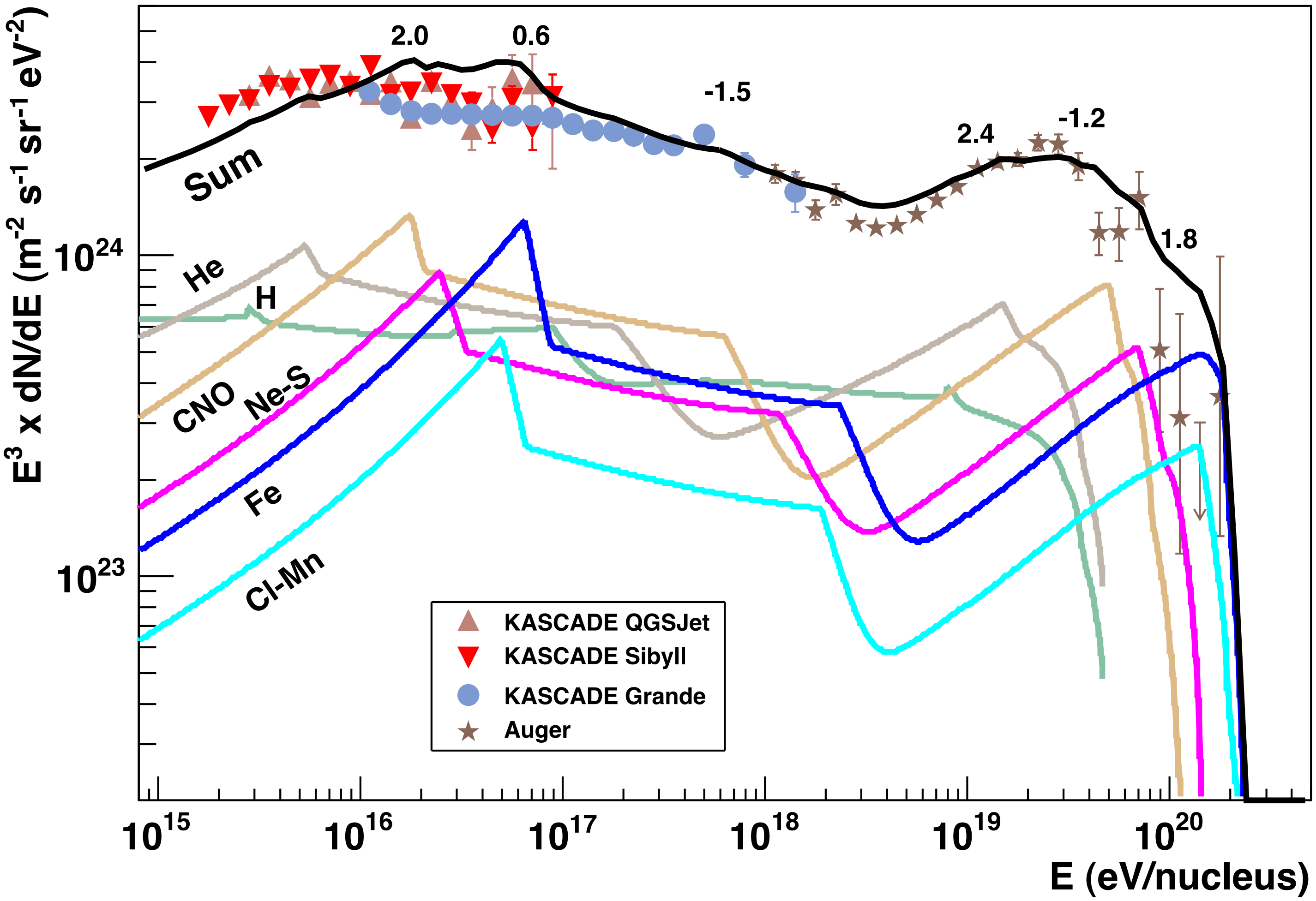

Figure 5 KASCADE, KASCADE-Grande, and Auger data interpreted as arising from a combination of Galactic CRs plus galactic CRs from another active galaxy, shifted up in a relativistic kick (Gopal-Krishna et al. 2010 ApJL; PLB & de Souza 2012 ApJ). The numbers give (model - data)/(experimental error): this 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

- Quantitative predictions from 1993: Tests since 2009
- Occam's razor simplicity: **CR-I to IV (1993) model suffices to explain the 2009 - 2013 data**
- **Polar cap CRs of exploding stars with magnetic winds** : CR positron fraction, Galactic haze, 511 keV line, γ-ray continuum and 130 GeV line
- CR spectrum possibly explained with our Galaxy and radio galaxy Cen A
- **Below GZK no other source population required by the data**: magnetic horizon (Ryu et al. 2008+)
- Can be falsified: very different abundances? magnetic wind of our Galaxy (Everett et al. 2008)? Neutrinos ?

Predictions for CR data

- Protons $E^{-2.78}$ and weaker component with $E^{-2.66}$, turn up to $E^{-2.33}$, sharp knee cutoff feature, and approximately $E^{-3.1}$ beyond
- From Helium all nuclei with $E^{-2.66}$, turn up to $E^{-2.33}$, sharp knee, and approximately $E^{-3.1}$ beyond
- Fe flatter due to substantial differential spallation
- B/C ratio $E^{-5/9}$ in relativistic regime, $->$ constant
- Positron fraction $E^{+1/3}$ in relativistic regime, approaching a constant, with a sharp cutoff at TeV
- Electron spectrum combination of primary spectrum as protons and nuclei combined, shifting to loss dominance, so $E^{-2.75}$ at first, then $E^{-3.33}$, and finally E^{-3}
- 1993 (ICRC summary) predictions had error bars

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 may not be in thermodynamic equilibrium, possibly sub-thermal
- From increased early ionization **star formation possible from about redshift 80** (PLB & Kusenko 2006; Stasielak et al. 2007; Loewenstein et al. 2009)
- Consistent with same phase space density ρ_{DM}/σ_{DM}^3 (e.g. Hogan & Dalcanton 2000; de Vega & Sanchez 2010 - 2013, Destri et al. 2012+, de Vega et al. 2012+)

The sky in black holes $\gtrsim 3 \cdot 10^7\ M_\odot$: colors are distance

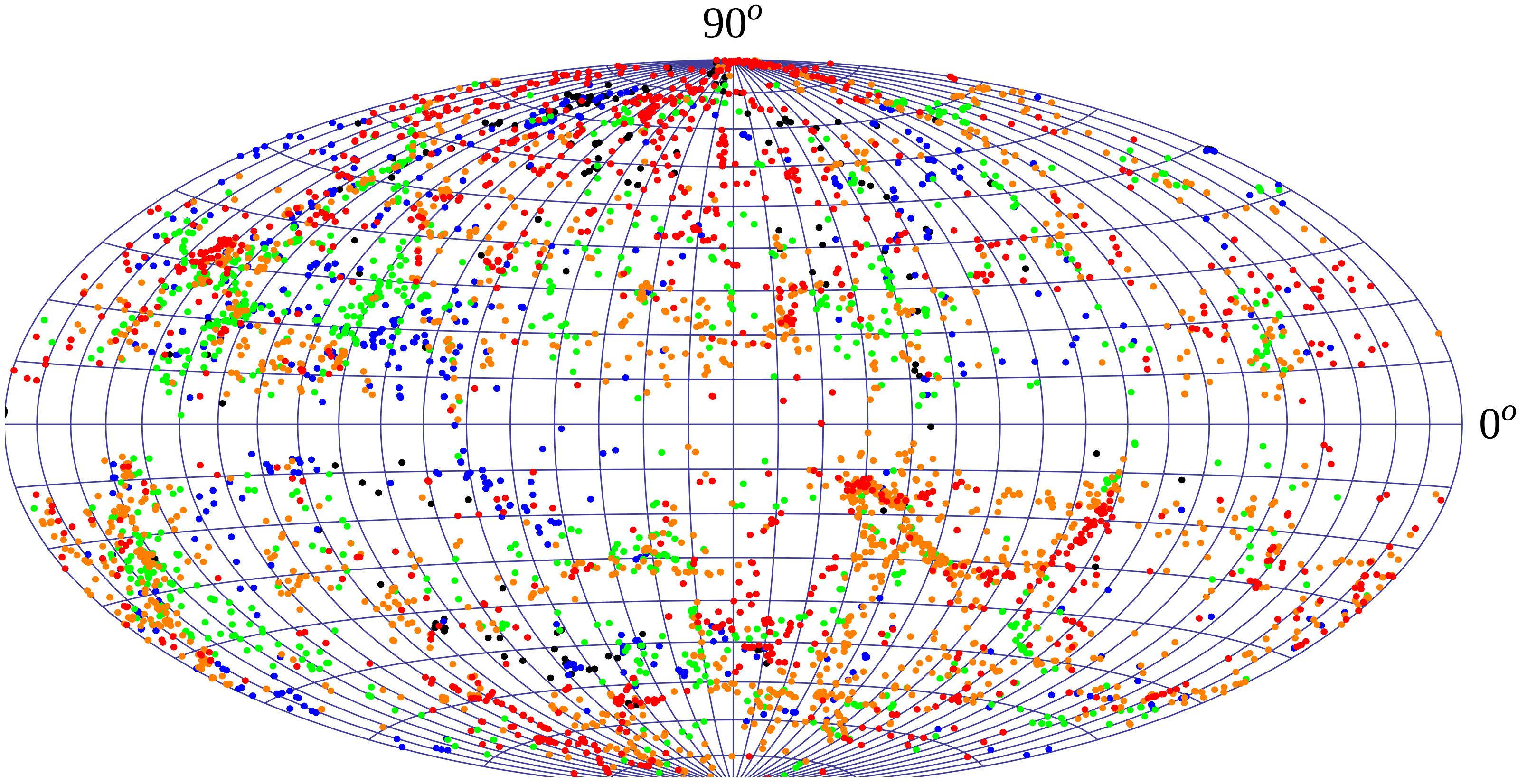

Figure 6 The sky in black holes, $\gtrsim 3 \cdot 10^7\ M_\odot$: The color code corresponds to distance: Black, Blue, Green, Orange, Red for the redshifts intervals 0, 0.005, 0.01, 0.015, 0.02, 0.025, corresponding to distance intervals of 0, 60, 120, 180, 240, and 300 million light-years: (–> Caramete & PLB 2011); coordinate system with Galactic plane across center, and Galactic center at the right edge

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

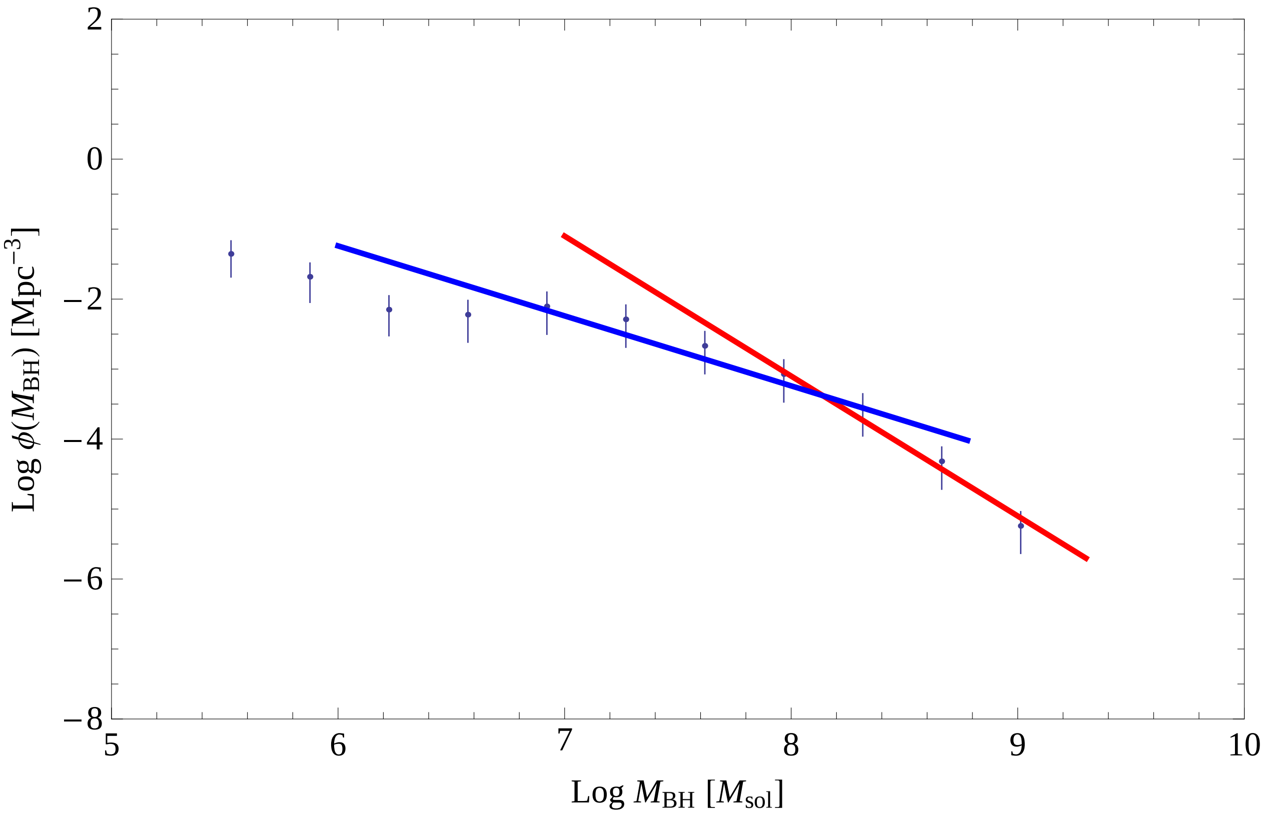

Figure 7 Integral mass function corrected for Hubble type sampling, 2928 objects, the slope of the lines is: red -2.0 fitting $> 10^{8}\,M_{\odot}$, and blue -1.0 fitting between $10^{7}\,M_{\odot}$ and $10^{8}\,M_{\odot}$. See Caramete & PLB, *Astron. & Astroph.* **521**, id.A55 (2010); arXiv:0908.2764. 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 PLB & Kusenko 2006, PRL)

Massive and supermassive stars at very low metal 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 soft X-rays
- Time scale of a few seconds shifted to minute
- Search strategy to detect extremely high-z GRBs?

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

- Stars form in a potential well defined by DM properties (Munyaneza & PLB 2005, 2006): **weakly degenerate supermassive Fermion galaxy cores**
- Massive stars form first, helped by the first molecular Hydrogen (PLB & Kusenko 2006): DM ν_s decay
- 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 + residual: 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 to form SMS

- 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
- Free-fall time in DM clump about $10^{7.1}$ yrs, so from redshift $\sim$ 100 matter can fall into these clumps
- Also, relaxation time scale must be about 3 crossing times or less, implying (Lightman & Shapiro 1978) about 300 or fewer stars
- Instability of SMS sets in at $5 \cdot 10^5\,M_\odot$, and infall will enhance the mass of the final black hole
- Therefore initial massive stars of order $\gtrsim 10^3\,M_\odot$

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_2^+, H_3^+
- 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: line equivalent width $->$ mass scale

A fully degenerate fraction of DM? I

- In any flat phase space distribution there is a minimum where $\Delta p \times \Delta x = \hbar/2$, with $(\Delta x)^{-3} = n$.
- How fast does such a particle change its momentum?
- Stars in the young system: can their mottled gravity cause rapid momentum change of DM particles?
- Slow growth of one fully degenerate core? Many such cores, that then agglomerate? Quantum cascade?
- In dwarf ellipticals central DM of about $10^5\,M_\odot$ possibly fully degenerate
- Prediction: BH will eat it (Munyaneza & PLB 2005, 2006), so no fully degenerate DM with BHs
- Prediction: BHs eating fully degenerate DM allows to obtain very big BHs without merger
- Open question then on statistics of BHs

A fully degenerate fraction of DM? II

$$M_{DM} \simeq \pi\, m_{Pl} \left(\frac{\sigma}{c}\right)^{3/2} \left(\frac{m_{Pl}}{m_{DM}}\right)^{2},$$

which translates to

$$M_{DM} \simeq 10^{6.1}\, M_{\odot} \left(\frac{\sigma}{30\,\mathrm{km/s}}\right)^{3/2} \left(\frac{2\,\mathrm{keV}}{m_{DM}}\right)^{2},$$

which for most observed BH masses is to the right of the observed BH-mass velocity dispersion relation of

$$M_{BH} \simeq 10^{5}\, M_{\odot} \left(\frac{\sigma}{30\,\mathrm{km/s}}\right)^{4},$$

consistent within the large observational errors in BH mass determinations. This hypothesis allows new estimate of dark matter particle mass.

The radio and neutrino background I

Super-massive stars form and explode, producing a radio remnant:

$$R \;\sim\; 10^{22.76}\,\mathrm{cm}\,E_{57}^{1/5}\,z_{1.3}^{-3/5}\,\{\Delta t\}_{15}{}^{2/5} \tag{1}$$

Magnetic fields and cosmic rays:

$$\begin{aligned} B &\approx 10^{-5.44}\,\eta_{B,-1}^{1/2}\,E_{57}^{1/5}\,z_{1.3}^{9/10}\,\{\Delta t\}_{15}^{-3/5}\,\mathrm{Gauß} \\ C &\approx 10^{-6.9}\,\eta_{CR,e,-1}\,E_{57}^{2/5}\,z_{1.3}^{9/5}\,\{\Delta t\}_{15}^{-6/5}\,, \end{aligned} \tag{2}$$

Luminosity at radio wave-lengths:

$$L_\nu \;=\; 10^{29.82}\,\eta_{B,-1}^{0.80}\,\eta_{CR,e,-1}^{+1}\,E_{57}^{1.32}\,z_{1.3}^{3.34}\,\nu_{9.0}^{-0.60}\,\mathrm{ergs}^{-1}\mathrm{Hz}^{-1}\,. \tag{3}$$

The radio and neutrino background II

Radio background (detected: Fixsen et al., Kogut et al., Seiffert et al. 2011):

$$F_\nu \approx 10^{-19.8} N_{BH,0,0}\, \eta_{B,-1}^{0.80}\, \eta_{CR,e,-1}^{+1}\, E_{57}^{1.32}\, z_{1.3}^{+0.84} \nu_{9.0}^{-0.60}\, \mathrm{ergs}^{-1}\mathrm{Hz}^{-1}\mathrm{cm}^{-2}\mathrm{sr}^{-1}\,. \tag{4}$$

Single sources (Condon et al. 2012: $S_\nu < 60$ nJy):

$$S_\nu \;=\; 10^{-31.2}\, \eta_{B,-1}^{0.80}\, \eta_{CR,e,-1}^{+1}\, E_{57}^{1.32}\, z_{1.3}^{+1.34} \nu_{9.0}^{-0.60}\, \mathrm{erg\,cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{Hz}^{-1} \tag{5}$$

Angular size of remnant (so about 12 arc-sec):

$$\theta \;=\; 10^{-4.2}\, E_{57}^{1/5}\, z_{1.3}^{-1/5}\, \mathrm{rad} \tag{6}$$

The radio and neutrino background III

Predicted (2012) neutrino flux - observed now (IceCube 2013, ICRC Rio de Janeiro: match!).

$$F_{neutr} \; = \; 10^{-10.2} \, N_{BH,0,0} \, E_{57} \, \eta_{CR,p,-1} \, f_{neutr,-1} \, z_{1.3}^{0.5} \; \mathrm{erg \, cm^{-2} \, s^{-1} \, sr^{-1}} \, , \tag{7}$$

Mass of shell in gas (Kormendy et al. 2010, 2011)

$$M_{shell} \; = \; 10^{10.4} \, \mathrm{M}_{\odot} \, E_{57}^{3/5} \, z_{1.3}^{-3/5} \tag{8}$$

Thomson depth through remnants (detected 0.09):

$$\tau_{Th,\Sigma} \; = \; 10^{-1.6} \, N_{BH,0,0} \, E_{57}^{3/5} \, z_{1.3}^{+9/10} \tag{9}$$

FIR back ground contribution (matches limit):

$$F_{IR} \; = \; 10^{-6.0} \, \mathrm{erg \, cm^{-2} \, s^{-1} \, sr^{-1}} \; N_{BH,0,0} \, M_{SMS,6.5} \, z_{1.3}^{-1}$$

The radio and neutrino background IV

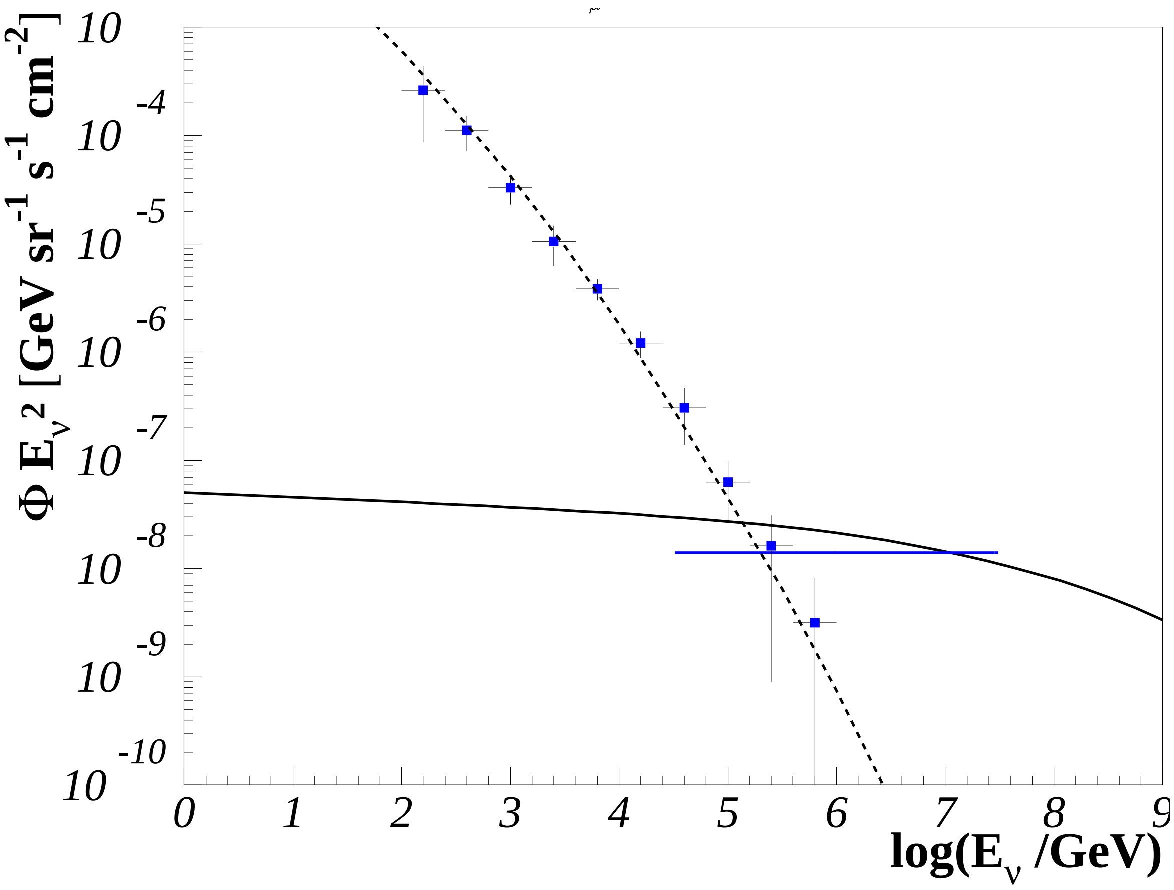

Figure 8 Predicted background neutrino flux and IceCube data: source Julia Becker Tjus 2013, to be included in forthcoming paper PLB et al. 2013. The Limit is an integral for an assumed spectrum of $E{-}2$ without cutoff; here we have $E^{-2.2}$ and a cutoff, so it is consistent.

The radio and neutrino background V: tests

- Radio background – detected, match
- Neutrino background – detected, match
- Gamma background – limits obeyed
- Source counts – limits obeyed
- Reionization – Thomson depth detected, matched: Spatial structure of ionization column – prediction
- Residual Thomson depth without structure gives from minimum ionization in DM keV model (PLB & Kusenko 2006) the DM particle mass
- Bulge-less disk galaxies – detected, large population (Spitzer survey): very large galaxies without merger
- FIR background – limits matched
- Molecular Hydrogen lines in absorption – prediction

DE from $\sim 3\,10^6\,M_\odot$ BH formation ?

FRW (Lemaitre 1927, 1931), energy conservation:

$$\left(\frac{\dot{a}}{a}\right)^2 \;=\; H^2(z) \;=\; \frac{8\pi G_N}{3}\rho$$

$$\dot{\rho} \;=\; -3H(z)\left(\rho + \frac{P}{c^2}\right) + S_{inj} + 4H(z)\rho_{DE}$$

$$\frac{\ddot{a}}{a} \;=\; -\frac{4\pi G_N}{3}\left(\rho + 3\frac{P}{c^2}\right) + \frac{4\pi G_N}{3}\left(4\rho_{DE}\right) + \frac{4\pi G_N}{3H(z)}\left(S_{inj}\right)$$

$$S_{inj}\,c^2 \;\simeq\; \frac{1}{2}\,\dot{N}_{BH,0}\,M_{BH}\,c^2\,(1{+}z_\star)^3\,;\;\; \rho_{DE} = \int S_{inj}dt$$

DE gravitational waves, source strong gravity brane, transferring energy by stimulated emission. Reproduces results seen by PLANCK. No DE in this model at recombination: consistent with the PLANCK data.

? ? Weakly Interacting Neutrino = WIN ? ?

- **Prediction: ISM-SNe, wind-SNe and Cen A account for cosmic rays** (quantitative model from 1993 +, applied 2009 - 2013)
- **Prediction: At redshift of order $\lesssim$ 80 first** massive star formation, energetic CR particles, GRBs and first BHs, supermassive BHs (starting near $3\,10^6\,M_{\odot}$), high luminosity GWs
- **Prediction**: radio background, neutrino background, BH formation explosion remnant Thomson depth, bulge less disk galaxies - all detected, match
- **Prediction**: Radio background structure with residual Thomson depth; reionization by SMS and explosion remnant; same structure in γ-ray, X-ray and FIR bg
- **Prediction: At redshift of order $\lesssim$ 80** H_3^+, H_2^+, and H_2 forest of absorption lines

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2 Abstract

Dark matter has been first detected 1933 (Zwicky) and basically behaves like a non-EM-interacting gravitational gas of particles. Particle physics suggests with an elegant argument that there could 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 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.a) the 511 keV annihilation line also near the Galactic Center, via.b) a tentative

detection of a 130 GeV emission line, 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, eliminating any argument from supersymmetry. These explanations build 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 Tremaine & Gunn (1979), 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, with high probability constrained to within 2 - 4 keV Fermion, without using any specific model. 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 (weakly degenerate Fermion galaxy cores). The supermassive star gives rise to a large HII region, possibly dominating the Thomson depth observed by WMAP. 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.

References

[1] Zwicky, F., Helvetica Physica Acta, Vol. 6, p. 110-127 (1933)

[2] Greisen, K., *Phys. Rev. Letters* **16**, 748 (1966)

[3] Zatsepin, G. T., Kuz'min, V. A., ZhETF Pis'ma Redaktsiiu **4**, p.114 (1966); transl. Journal of Exper-

imental and Theoretical Physics Letters **4**, 78 (1966)

[4] Ryu, D., Kang, H., Cho, J., Das, S.,*Science***320**, 909 (2008)

[5] Das, S., Kang, H., Ryu, D., Cho, J., *Astrophys. J.* **682**, 29 (2008)

[6] Boyanovsky, D., de Vega, H. J., Sanchez, N. G., *Phys. Rev.* **D 77**, id. 043518 (2008)

[7] Kusenko, A., Segre, G., *Phys. Lett.* **B 396**, 197 (1997)

[8] Fuller, G. M., Kusenko, A., Mocioiu, I., Pascoli, S., *Phys. Rev.* **D 68**, id. 103002 (2003)

[9] Kusenko, A., *Int. J. of Mod. Phys.* **D 13**, 2065 (2004)

[10] Kusenko, A., Takahashi, F., Yanagida, T. T., *Phys. Lett.* **B 693**, 144 (2010)

[11] Adulpravitchai, A., Gu, P.-H., Lindner, M., *Phys. Rev.* **D 82**, id. 073013 (2010)

[12] Kusenko, A., *Phys. Rep.* **481**, 1 (2009)

[13] Cosmic Ray Electrons and Positrons from Supernova Explosions of Massive Stars, Biermann, P. L., Becker, J. K., Meli, A., Rhode, W., Seo, E.- S., Stanev, T., *Phys. Rev. Letters* **103**, 061101 (2009); arXiv:0903.4048

[14] The WMAP haze from the Galactic Center region due to massive star explosions and a reduced cosmic ray scale height, Peter L. Biermann, Julia K. Becker, Gabriel Caceres, Athina Meli, Eun-Suk Seo, & Todor Stanev, *Astrophys. J. Letters* **710**, L53 - L57 (2010); arXiv:0910.1197

[15] The origin of cosmic rays: Explosions of massive stars with magnetic winds and their supernova mech-

anism, Peter L. Biermann, Julia Becker, Jens Dreyer, Athina Meli, Eun-Suk Seo, and Todor Stanev, *Astrophys. J.* **725** 184 - 187 (2010); arXiv: 1009.5592

[16] Ultra high energy cosmic rays from Centaurus A: jet interaction with gaseous shells, Gopal-Krishna, Peter L. Biermann, Vitor de Souza, Paul J. Wiita, *Astrophys. J. Letters* **720**, L155 - L158 (2010); arXiv:1006.5022

[17] Centaurus A: the one extragalactic source of cosmic rays with energies above the knee, Peter L. Biermann & Vitor de Souza, *Astrophys. J.* (in press) (2012); arXiv: 1106.0625

[18] Spectrum and ionization rate of low energy Galactic cosmic rays, Nath, B. B., Gupta, N., Biermann, P. L., *Month. Not. Roy. Astr. Soc.* Lett. (in press) (2012); eprint arXiv:1204.4239

[19] Bringmann, T., et al., eprint 1203.1312 (2012)
Title: Fermi LAT Search for Internal Bremsstrahlung Signatures from Dark Matter Annihilation
Authors: Torsten Bringmanna Xiaoyuan Huangb Alejandro Ibarrac Stefan Voglc Christoph Wenigerd

[20] Weniger, Ch., eprint 1204.2797 (2012)
Title: A Tentative Gamma-Ray Line from Dark Matter Annihilation at the Fermi Large Area Telescope

[21] Buckley, M.R., & Hooper, D., eprint 1205.6811 (2012)
Title: Implications of a 130 GeV Gamma-Ray Line for Dark Matter

[22] Su, M., & Finkbeiner, D.P., eprint 1206.1616 (2012)
Title: STRONG EVIDENCE FOR GAMMA-RAY

[23] Predicted power in ultra high energy cosmic rays from active galaxies, Laurentiu I. Caramete, Oana Tascau, Peter L. Biermann and Todor Stanev, submitted *Astron. & Astroph.* (2011); arXiv:1106.5109

[24] Cosmic rays I. The cosmic ray spectrum between 10^4 GeV and $3\,10^9$ GeV, Peter L. Biermann, *Astron. & Astroph.* **271**, 649 (1993), astro-ph/9301008

[25] Cosmic rays II. Evidence for a magnetic rotator Wolf-Rayet star origin, Peter L. Biermann, & Joseph P. Cassinelli, *Astron. & Astroph.* **277**, 691 (1993); astro-ph/9305003

[26] Cosmic Rays III. The cosmic ray spectrum between 1 GeV and 10^4 GeV and the radio emission from supernova remnants, Peter L. Biermann, & Richard G.

Strom, *Astron. & Astroph.* **275**, 659 (1993), astro-ph/9303013

[27] Cosmic rays IV. The spectrum and chemical composition above 10^4 GeV, Todor Stanev, Peter L. Biermann, & Thomas K. Gaisser; *Astron. & Astroph.* **274**, 902 (1993), astro-ph/9303006

[28] Cosmic rays: origin and acceleration - what can we learn from radio astronomy, Peter L. Biermann; invited plenary lecture at 23rd International Conference on Cosmic Rays, in Proc. "Invited, Rapporteur and Highlight papers"; Eds. D. A. Leahy et al., World Scientific, Singapore, 1994, p. 45

[29] Dalcanton, J. J., Hogan, C. J., *Astrophys. J.* **561**, 35 - 45 (2001); arXiv:astro-ph/0004381

[30] "The observed properties of dark matter on small scales", Gilmore et al. (2007); astro-ph/0703308

[31] Relic keV sterile neutrinos and reionization, Biermann, Peter L., Kusenko, Alexander, *Phys. Rev. Letters* **96**, 091301 (2006); astro-ph/0601004

[32] Thermal evolution of the primordial clouds in warm dark matter models with keV sterile neutrinos, Jaroslaw Stasielak, Peter L. Biermann, & Alexander Kusenko, *Astrophys. J.* **654**, 290-303 (2007); astro-ph/0606435

[33] Active Galactic Nuclei: Sources for ultra high energy cosmic rays?, Biermann, P. L., Becker, J. K., Caramete, A. Curutiu, L., Engel, R., Falcke, H., Gergely, L. A., Isar, P. G., Maris, I. C., Meli, A., Kampert, K. -H., Stanev, T., Tascau, O., Zier, C., invited review for the conference CRIS2008, Malfa, Salina Island, Italy, Ed. A. Insolia,*Nucl. Phys. B, Proc. Suppl.* **190**, 61 - 78 (2009); arXiv: 0811.1848v3

[34] Universality of galactic surface densities within one dark halo scale-length, Gentile, G., Famaey, B., Zhao, H., Salucci, P., *Nature* **461**, 627 - 628 (2009)

[35] “A Large Dark Matter Core in the Fornax Dwarf Spheroidal Galaxy?”, Strigari, L. E. *et al.*., (2006); astro-ph/0603775

[36] de Vega, H. J.; Sanchez, N. G., *Month. Not. Roy. Astr. Soc.* **404**, 885 - 894 (2010); arXiv:0901.0922 (2009)

[37] de Vega, H. J.; Sanchez, N. G., eprint arXiv:0907.0006 (2009)

[38] Pulsar kicks from neutrino oscillations, A. Kusenko, Int. J. Mod. Phys. D **13**, 2065 (2004); astro-ph/0409521

[39] New limits on Sterile Neutrinos from Suzaku Observations of the Ursa Minor Dwarf Spheroidal galaxy,

M. Loewenstein, A. Kusenko, P.L. Biermann, *Astrophys. J.* **700**, 426 - 435 (2009); arXiv:0812.2710

[40] The mass function of nearby black hole candidates, Laurentiu I. Caramete, Peter L. Biermann, *Astron. & Astroph.* **521**, id.A55 (2010); arXiv:0908.2764

[41] The catalog of nearby black hole candidates, Laurentiu I. Caramete, Peter L. Biermann, submitted (2011); arXiv:1107.2244

[42] "Observed properties of dark matter on small spatial scales", Wyse, & Gilmore (2007); arXiv/0708.1492