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: We have discovered i) an upturn in the CR-positron fraction, ii) an upturn in the CR-electron spectrum, iii) a flat radio emission component near the Galactic Center (WMAP haze), iv) a corresponding IC component in gamma rays (Fermi haze and Fermi bubble), v) the 511 keV annihilation line also near the Galactic Center, and most recently, vi) an upturn in the CR-spectra of all elements from Helium, with a hint of an upturn for Hydrogen, vii) A flat γ-spectrum

at the Galactic Center (Fermi), and viii) have the complete cosmic ray spectrum available through 10^{15} to 10^{18} eV (KASCADE-Grande). All these features can be quantitatively explained with the action of cosmic rays accelerated in the magnetic winds of very massive stars, when they explode (Biermann et al. 2009 - 2011): 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, and also simpler than using the decay of a postulated particle. 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 2011). 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). 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) 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. 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. This readily explains the supermassive black hole mass function (Caramete & Biermann 2010). The formation of the first super-massive stars might be detectable among the point-source contributions to the fluctuations of the MWBG at very high wave-number (Atacama); their contribution is independent of redshift. The corresponding gravitational waves are not constrained by any existing limit, and could have given a substantial energy contribution at high redshift.

Our conclusion is that a right-handed neutrino of a mass of a few keV is the most interesting candidate to constitute dark matter.

Dark matter is required to explain

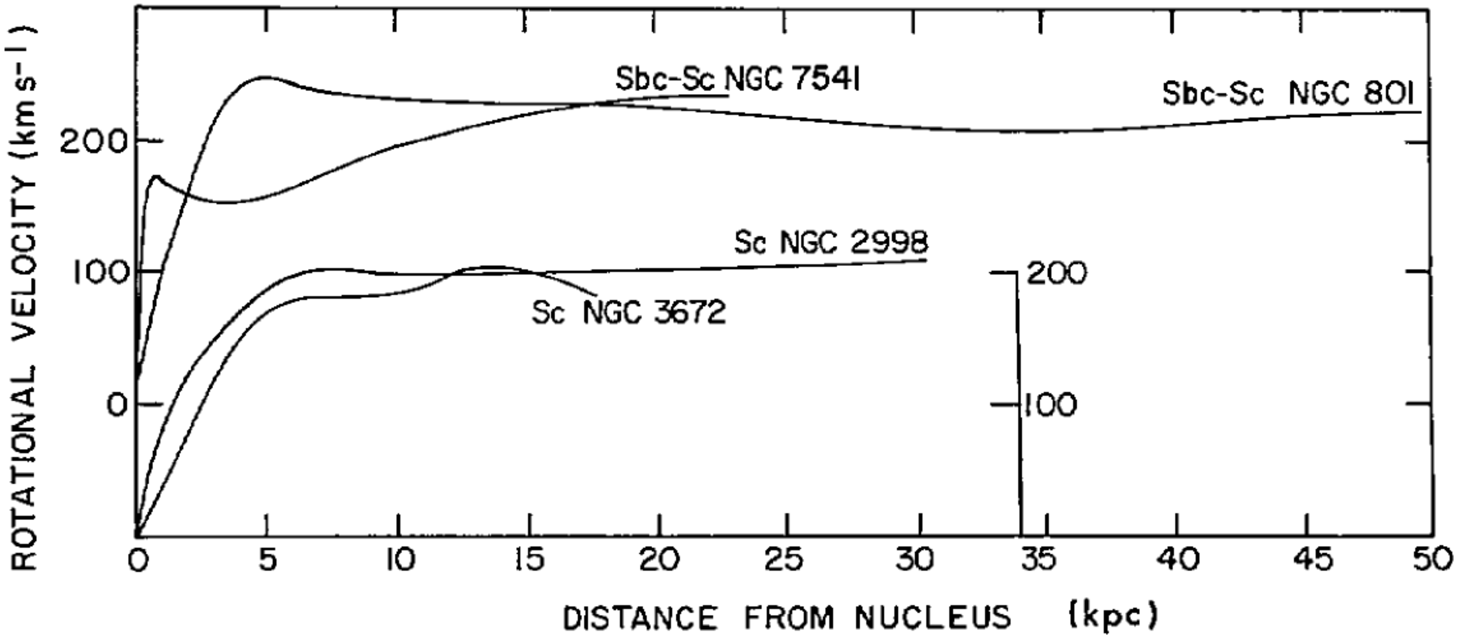


Figure 1 Rotation curves (–> Rubin et al. 1978)

- stability of thin disk galaxies (e.g. Ostriker & Peebles 1973)
- rotation curves (e.g. Rubin 1978)
- motions of galaxies in groups and clusters (Zwicky 1933)
- containing the hot gas in groups and clusters

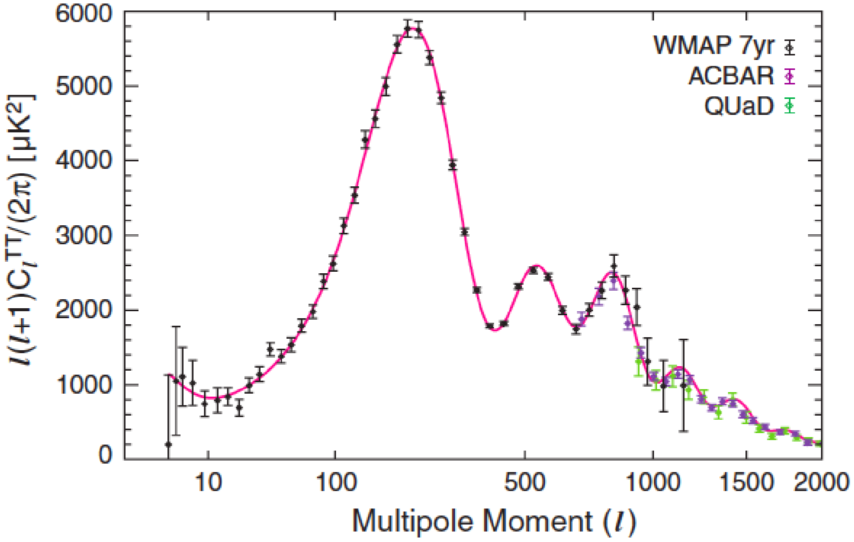


Figure 7. ***WMAP*** seven-year temperature power spectrum (Larson et al. 2011), along with the temperature power spectra from the ACBAR (Reichardt et al. 2009) and QUaD (Brown et al. 2009) experiments. We show the ACBAR and QUaD data only at $l \geqslant 690$, where the errors in the *WMAP* power spectrum are dominated by noise. We do not use the power spectrum at $l > 2000$ because of a potential contribution from the SZ effect and point sources. The solid line shows the best-fitting six-parameter flat ΛCDM model to the ***WMAP*** data alone (see

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

- to explain the large scale structure formation in the universe
- to explain the mathematically flat geometry of the universe (Spergel et al. 2003, 2007; Larson et al. 2011)

The universe: WMAP7

Komatsu et al. 2011

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

$$\Omega_\Lambda \;=\; 0.725 \pm 0.016$$

$$\Omega_{dm} \;=\; 0.229 \pm 0.015$$

$$\Omega_b \;=\; 0.0458 \pm 0.0016$$

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

$$H_0 \;=\; 70.2 \pm 1.4\,\mathrm{km/s/Mpc}$$

Assuming instantaneous re-ionization (corresponds to about $3. \cdot 10^8$ yr)

$$z_{re-ion} \;=\; 10.6 \pm 1.2$$

The age of the universe:

$$t_0 \;=\; (13.76 \pm 0.11) \cdot 10^9\,\mathrm{yr}$$

78 years: what is dark matter?

Leading proposal: Heavy particles

- **Supersymmetric massive particles decay** and might explain many observations

- Upturn in positron fraction in cosmic rays (Pamela)
- Upturn in CR-e^- spectrum (Fermi, ATIC)
- WMAP haze: Galactic Center region
- Fermi haze and bubble: Galactic Center region
- 511 keV emission line: Galactic Center region
- General upturn in all nuclei from Helium (CREAM)
- Fermi flat spectrum near Galactic Center
- KASCADE-Grande data for 10^{15} eV through 10^{18} eV

Pamela, ATIC, H.E.S.S., Fermi,...

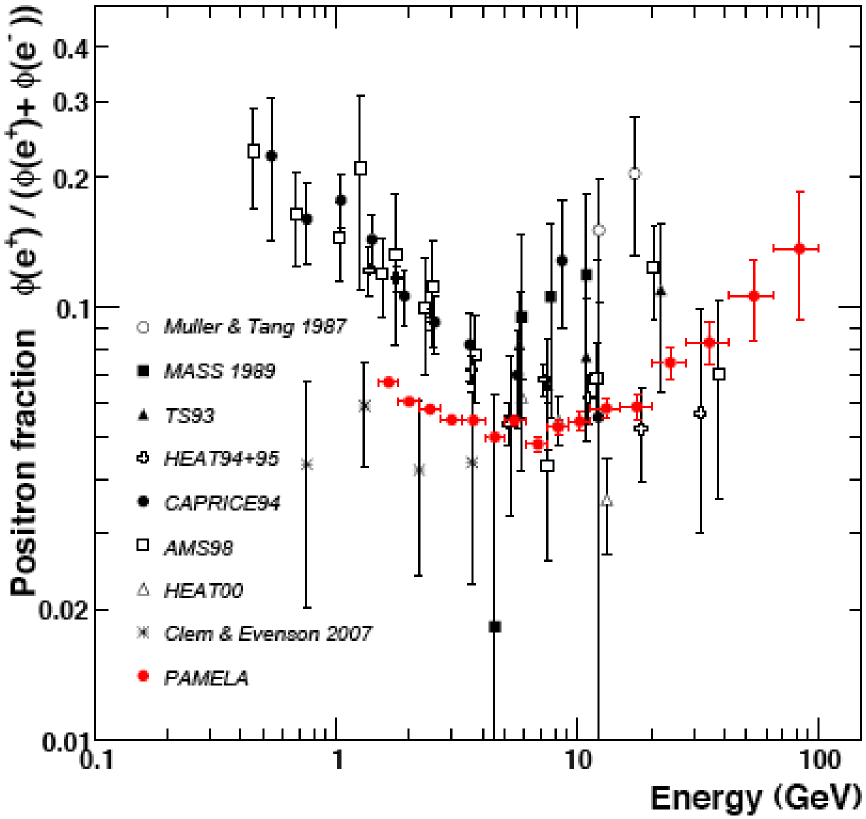


FIG. 3: **PAMELA positron fraction with other experimental data.** The positron fraction measured by the PAMELA experiment compared with other recent experimental data[24, 29, 30, 31, 32, 33, 34, 35]. One standard deviation error bars are shown. If not visible, they lie inside the data points.

Figure 3 Pamela data on positron fraction, 2008: Dark matter/SUSY ???

A massive star and its magnetic field

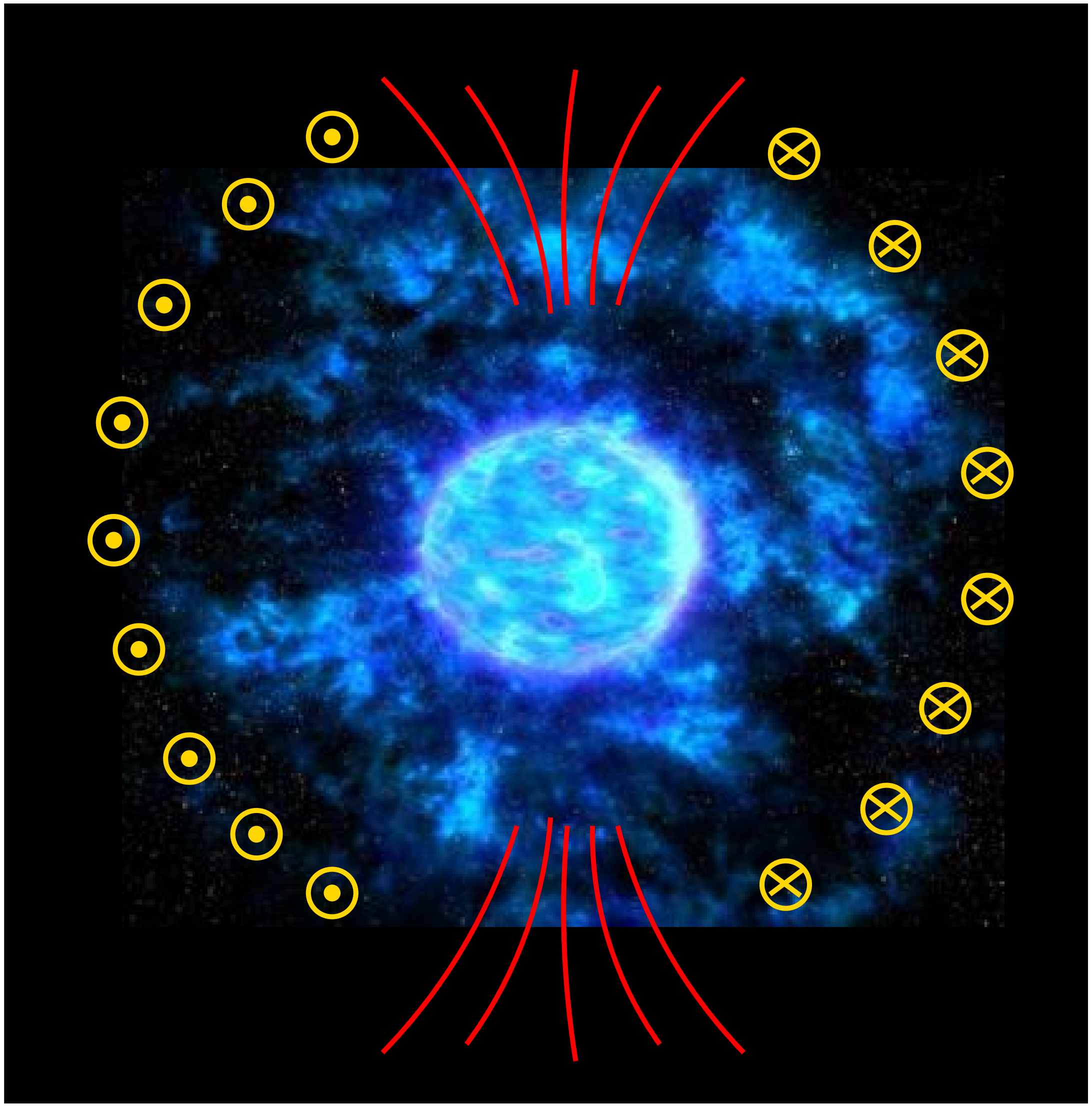


Figure 4 Magnetic field topology around a massive star in its wind: Graph following Parker 1958; central graph NASA, Wolf Rayet star WR124: Remember Maxwell's laws!

Cosmic ray knee: paper CR-IV, 1993

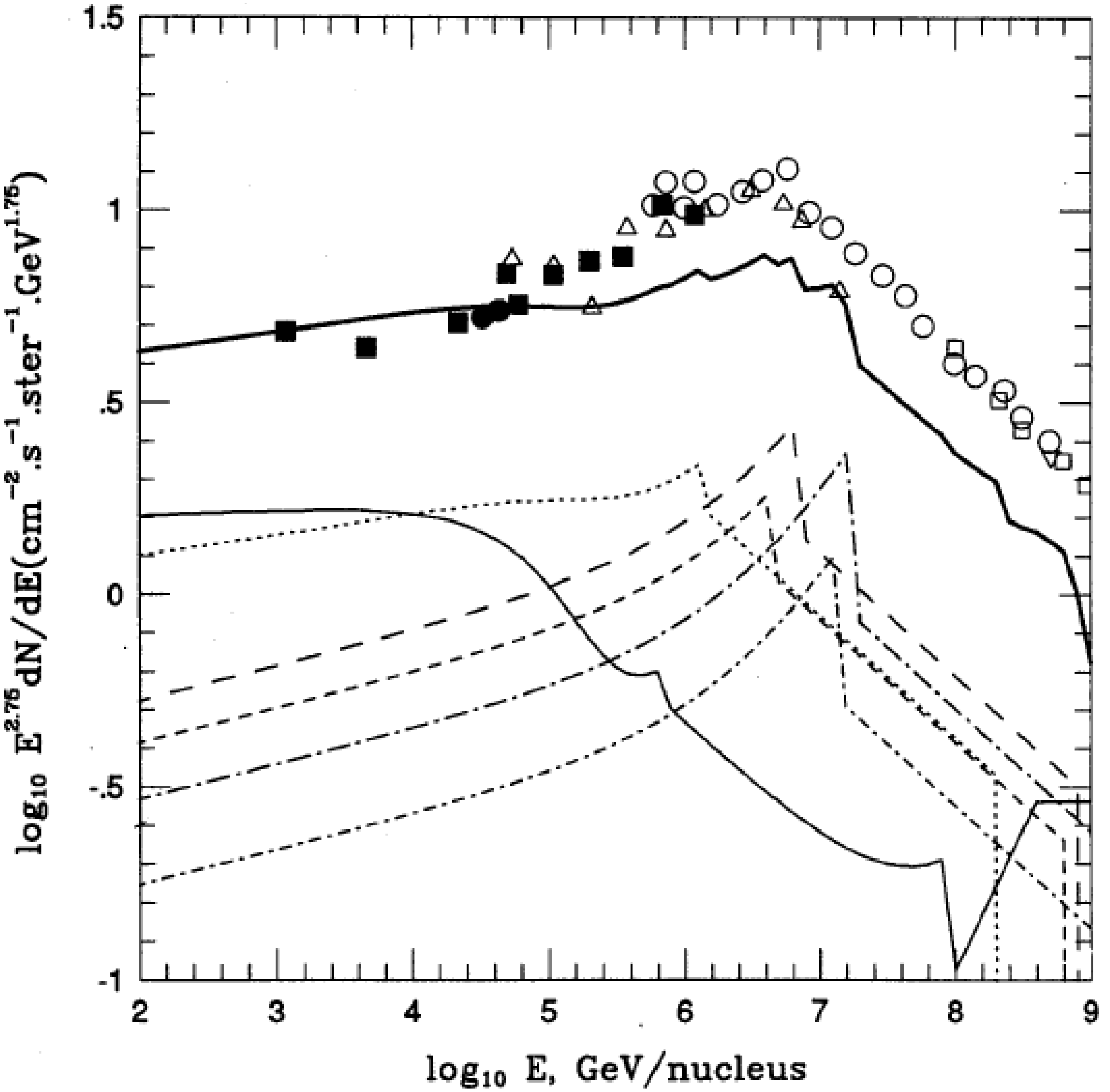


Figure 5 Spectral and chemical structure at the knee, *CR-e^- and CR-e^+ components?*, to be *shifted to high energy?* Element groups are H, He, CNO, Ne-S, Cl-Mn, and Fe. Source: Stanev et al., paper CR-IV 1993

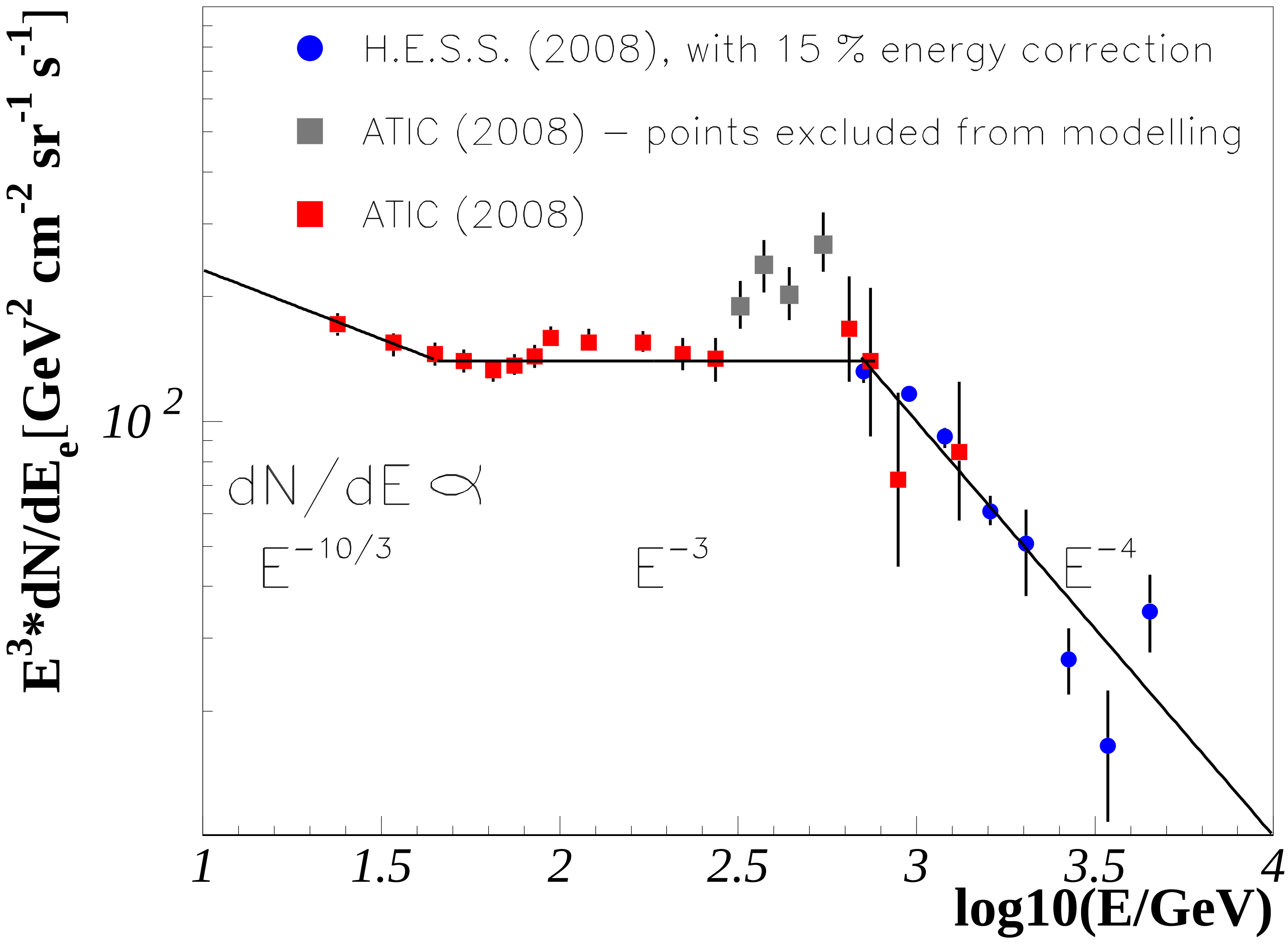


Figure 6 Model prediction with ATIC and H.E.S.S data for cosmic ray electrons: $E^{-10/3}$, E^{-3}, and E^{-4}. Source Biermann et al. 2009 *Phys. Rev. Letters* **103**, 061101 (2009)

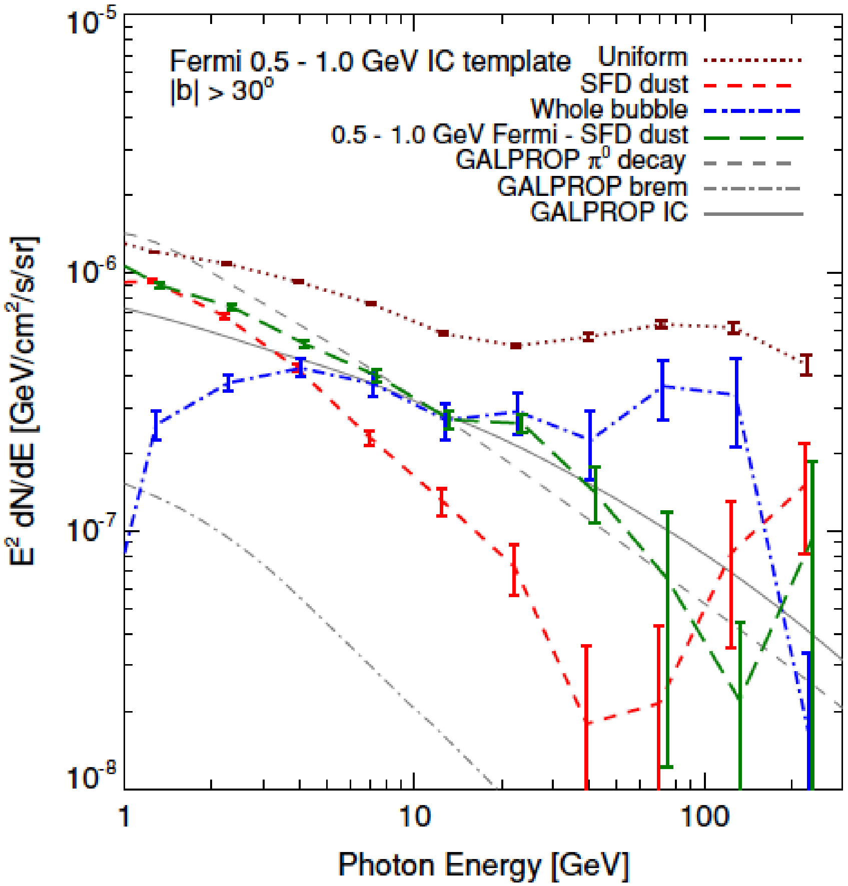


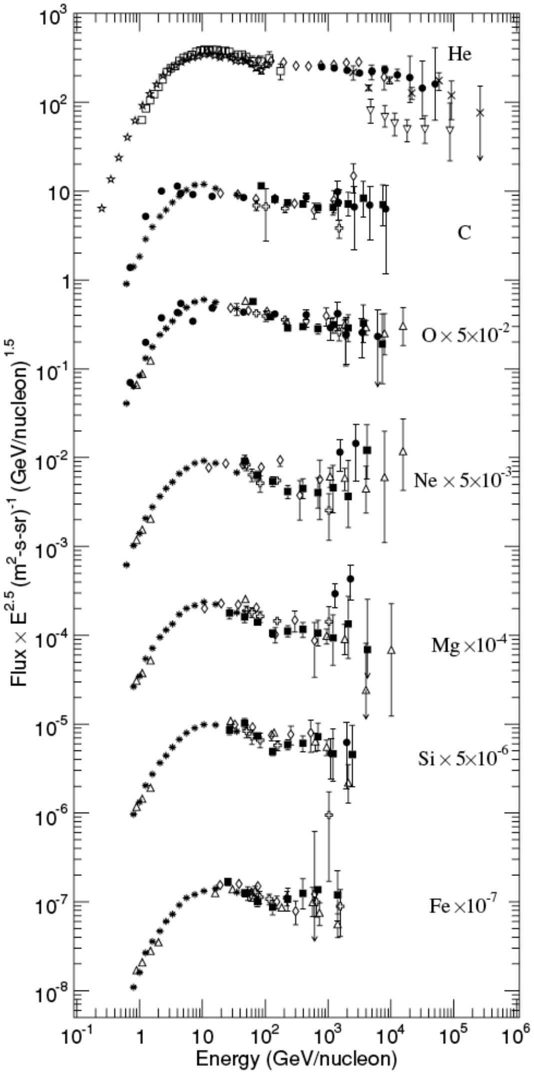
Figure 14. Same as Figure 12, but correlation spectra for the 4-template fit employing the *Fermi* 0.5–1 GeV residual map (after subtracting the SFD dust) as a template for the starlight IC. The line style is the same as Figure 12. Again, we find that the spectrum correlated with the *Fermi* bubble template (blue dot-dashed line) is harder (consistent with flat in $E^2 dN/dE$) 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 7 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 - L57 (2010); arXiv:0910.1197

CREAM: CR spectral upturn



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

Figure 8 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 - 187 (2010); arXiv: 1009.5592

Galactic Center in radio and γ-emission

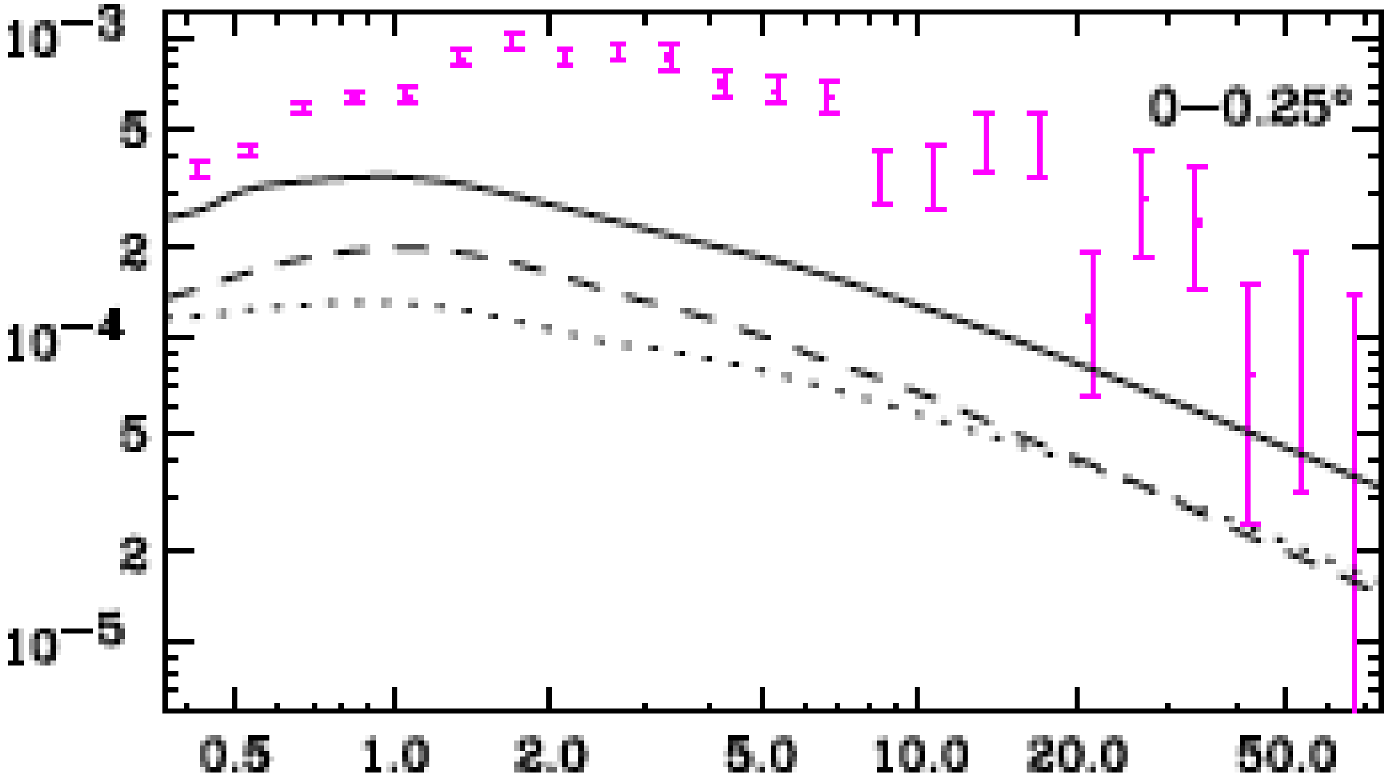


Figure 9 Fermi data: GC central region, excess: source Hooper & Goodenough 2011 *Phys. Lett.* **B**

- Many radio filaments exist in the GC region, often with inverted or very flat radio spectrum (Yusef-Zadeh)
- Modelling the Fermi-γ emission as a fct of disk, spheri-

cal component and plausible emission processes suggests extra emission component, with also an inverted spectrum

- Both consistent with the decay of a heavy particle producing secondary leptons (Hooper & Goodenough 2011, Linden, Hooper, & Yusef-Zadeh 2011): the injection is at high energy, and so below that energy emission spectra inverted
- Other interpretations also possible: predicted ${E_\gamma}^{+1/3}$, ${E_\gamma}^{0}$, and ${E_\gamma}^{-1/2}$ in $E_\gamma^2\ F(E_\gamma)$, so inverted at lower energies, as observed.
- Magnetic filaments can squeeze a particle population undergoing repeated reflection, and so produce flat spectra in energy, or inverted spectra in radio emission.
- Conclusion: evidence for lepton spectra given by particle decay not cogent: Astrophysics sufficient

KASCADE, KASCADE-Grande and Auger

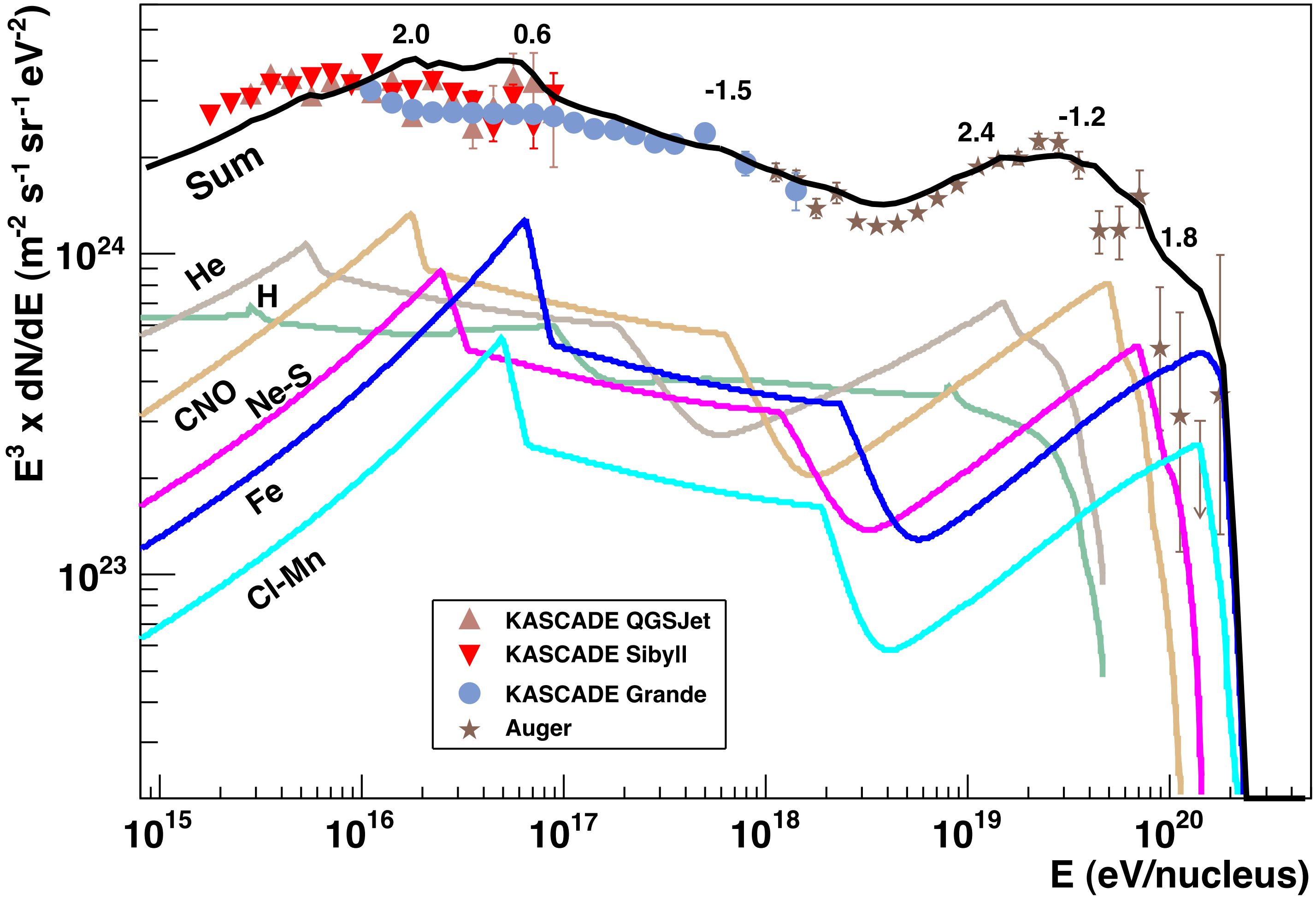


Figure 10 KASCADE, KASCADE-Grande, and Auger data interpreted as arising from a combination of Galactic CRs plus galactic CRs from another active galaxy, shifted up in a relativistic kick (Gopal-Krishna et al. 2010; Biermann & de Souza 2011). The numbers give (model - data)/(experimental error): this 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 source population at all necessary at particle energies below the GZK turn-off.

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?
- Predicts CR spectra of chemical elements from 10^9 to 10^{21} eV

DM proposal: 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 (see Hogan & Dalcanton 2000; Dalcanton & Hogan 2001, Boyanovsky et al. 2008, de Vega & Sanchez 2010)

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

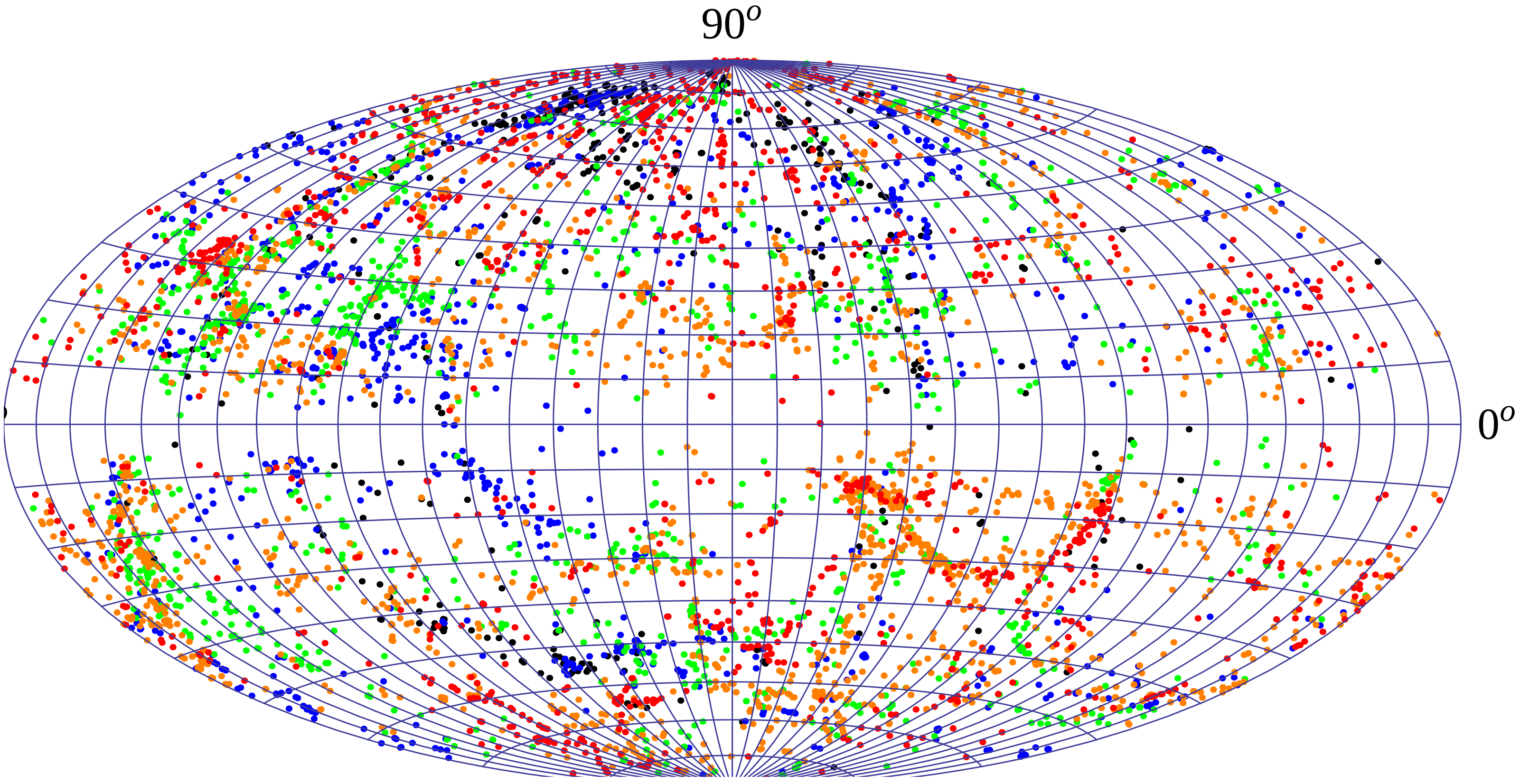


Figure 11 The sky in black holes, $\gtrsim 10^7\ M_\odot$: The color code corresponds to distance: Black, Blue, Green, Orange, Red for the redshifts intervals 0, 0.005, 0.01, 0.015, 0.02, 0.025, corresponding to distance intervals of 0, 60, 120, 180, 240, and 300 million light-years: (–> Caramete & Biermann 2011); coordinate system with Galactic plane across center, and Galactic center at the right edge

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

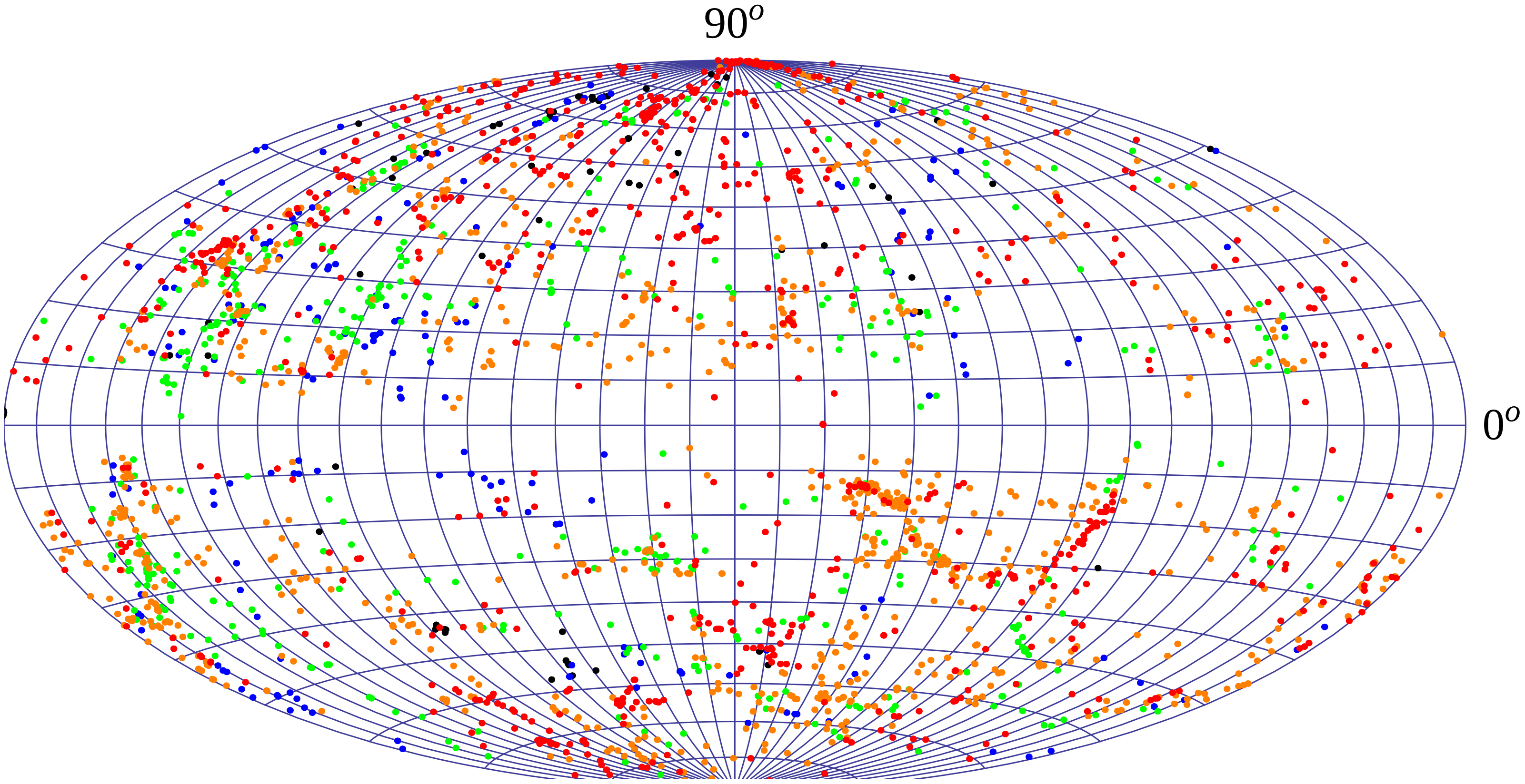


Figure 12 The sky in black holes, $\gtrsim 10^8\ M_\odot$: The color code corresponds to distance: Black, Blue, Green, Orange, Red for the redshifts intervals 0, 0.005, 0.01, 0.015, 0.02, 0.025, corresponding to distance intervals of 0, 60, 120, 180, 240, and 300 million light-years: (–> Caramete & Biermann 2011); coordinate system with Galactic plane across center, and Galactic center at the right edge

Integral black hole mass function

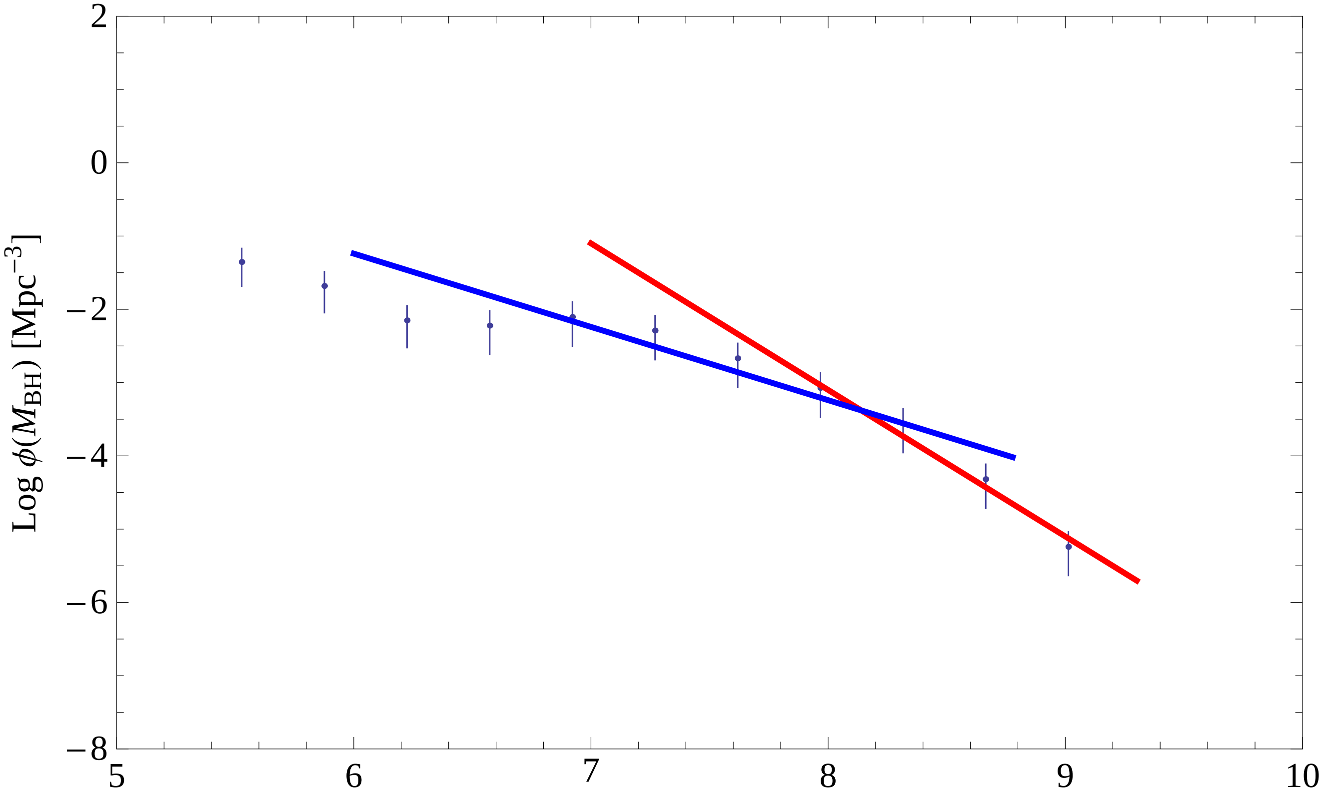
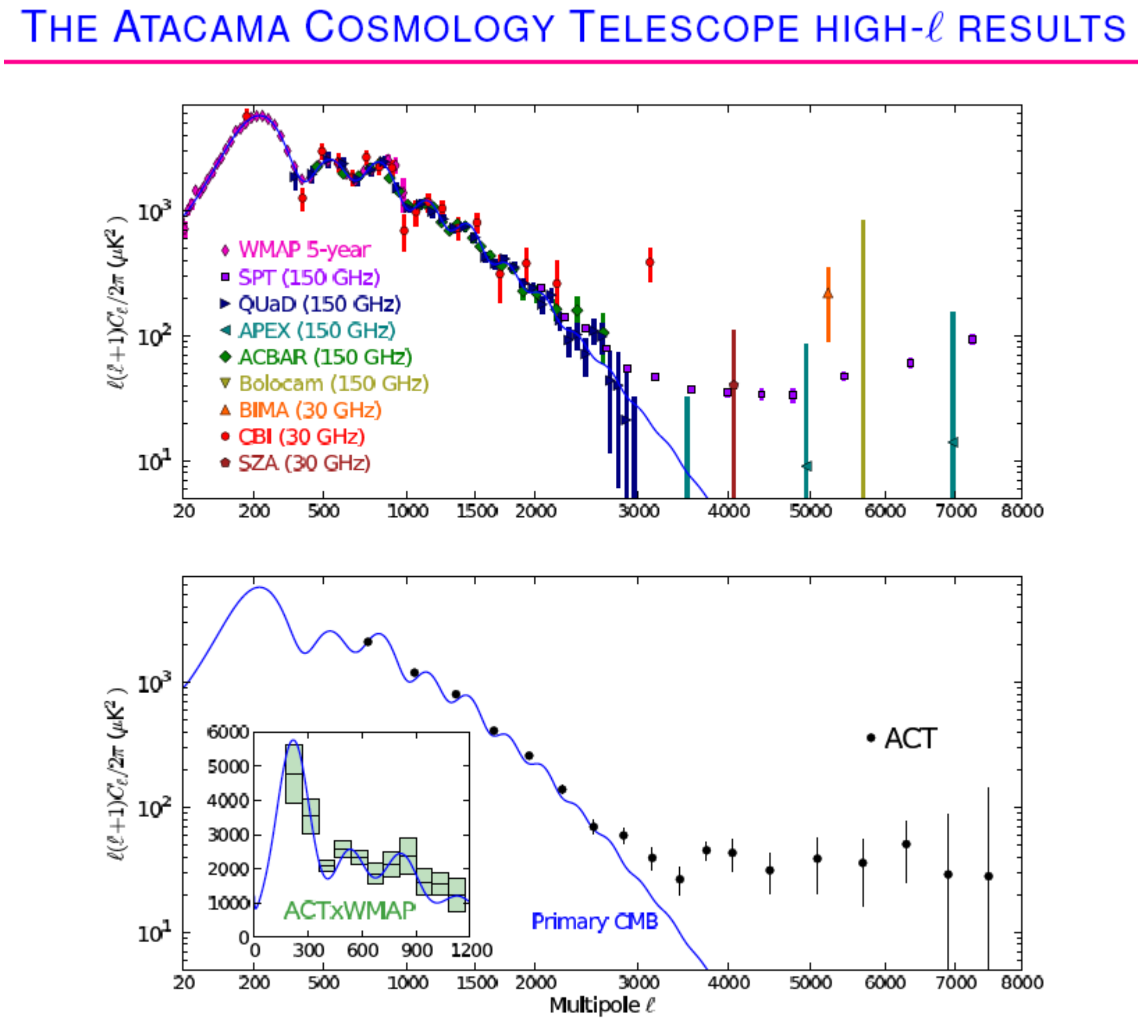


Figure 13 Integral mass function corrected for Hubble type sampling, 2928 objects, the slope of the lines is: red −2.0 fitting $>\ 10^8\,M_\odot$, and blue −1.0 fitting between $10^7\,M_\odot$ and $10^8\,M_\odot$. See Caramete & Biermann, *Astron. & Astroph.* **521**, id.A55 (2010); arXiv:0908.2764. 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)

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)
- Supermassive stars turn unstable near $\sim 10^6\,M_\odot$ (Appenzeller & Fricke 1972)
- Supermassive stars close to Eddington limit, radiate
- Supermassive stars live briefly, lifetime independent of mass
- Surrounded by molecular Hydrogen, excited easily by energetic particles: Absorption line forest?

The point sources at high l in the MWBG



THE ATACAMA COSMOLOGY TELESCOPE HIGH-ℓ RESULTS

Figure 14 Cosmic mwbg high-l measurements: Fowler et al. 2010, here quoted from Lasenby lecture (Paris): point sources in huge numbers are seen, implying angular scale $\lesssim 1$ arcmin: Could this imply many starburst galaxies at moderate redshift, weak AGN, or the birth of super-massive stars and BHs? Location Atacama desert in Chile! We will argue for galaxies and supermassive stars.

The visibility of the super-massive stars in MWBG fluctuations I

Assume redshift 50 (drops out at the end):

$$M_{DM,unit} \simeq 5\,10^7\,M_\odot; \quad M_b \simeq 10^7\,M_\odot \tag{1}$$

$$M_{SMS} = 3\,10^6\,M_{6.5}\,M_\odot; \quad L = 10^{44.6}\,M_{6.5}\,\mathrm{erg/s} \tag{2}$$

$$T_b = \frac{c^2 S_\nu}{2\nu^2 k_B} = 10^{-8.52}\,f_{red}\,M_{6.5}\,\mu K \tag{3}$$

$$r(z) = \int_0^z \frac{c dz'}{H(z')} \tag{4}$$

$$H(z) = H_0 \left(\Omega_M (1+z)^3 + \Omega_{DE}\right)^{1/2} \tag{5}$$

The visibility of the super-massive stars in MWBG fluctuations II

Source counts run as (Frieman et al., 2008, eq 14)

$$F_N \;=\; \frac{c\, r^2(z)}{H(z)}\, \Delta z\, \Delta\Omega \tag{6}$$

Density of BHs is $5.73\, 10^{-3} \;=\; 10^{-2.24}\, Mpc^{-3}$ today (Caramete & Biermann 2010).

$$\Delta z \;=\; \tau_{stars}\, (1+z) H(z) \tag{7}$$

$\tau_{stars} \gtrsim$ 2.5 million years (Heger et al. 2005). Therefore at $l = 3000$ (Holder 2002), now independent of z

$$C_l l(l+1)/(2\pi) = 10^{+3.015}\, f_{red}^2\, M_{6.5}^2\, (\mu K)^2 \tag{8}$$

Observed $11 \pm 3.3\, (1\sigma)\, (\mu K)^2$ (Fowler et al. 2010).

The visibility of the super-massive stars in MWBG fluctuations III

- Independent of exact redshift, except through assumption, that observed peak of emission is $\gtrsim 10^{11.2}$ Hz, and we allow for that and unknown opacity with factor $f_{red}\, M_{6.5}$.

- Flux and spectrum in Atacama data consistent with galaxy predictions (Dole et al., 2004, 2006, 2010; and Lagache et al., 2003, 2005): weaker sources in Spitzer FIR counts galaxies with redshift near $\lesssim 0.9$.

- Contributions to point source population, SMS: Molecular lines in absorption at very high z, and independence on cutoff flux density in sampling: Molecular Hydrogen (H_3^+ and/or H_2^+) forest: in observer frame sub-mm wavelength or shorter (see Becker et al. 2011)

First gravitational wave signals?

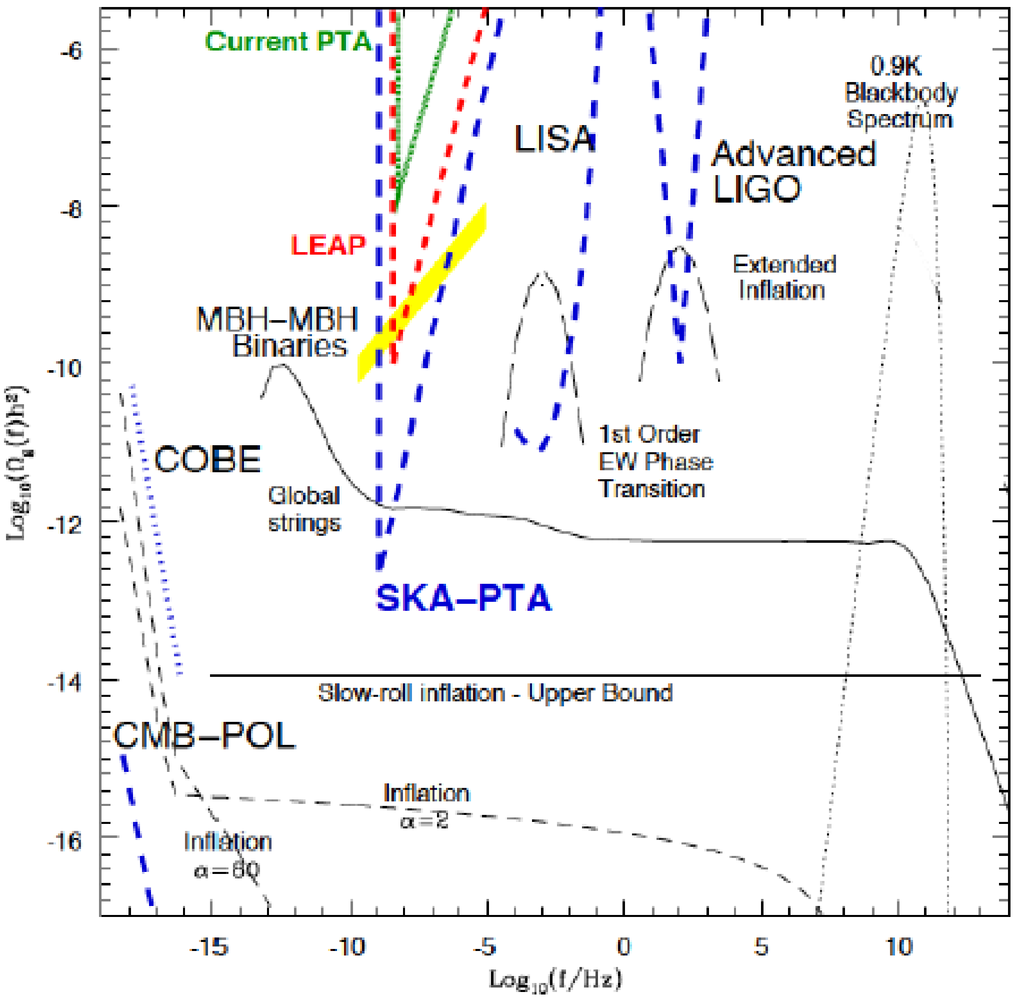


Figure 15 Upper limits to GW signals (M. Kramer 2011). The first mergers could start near $10^{-3.2}$ Hz, and the first stellar black holes near $10^{+3.3}$ Hz, but their amplitude is uncertain. Any signal would be a superposition. A signal from redshift $\lesssim 80$ would be invisible until PTA gets 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 - 2011)
- **Prediction**: Future particle physics lab Cen A
- Much depends on property of DM particle:
- Massive star formation in DM clump naturally leads to supermassive stars by agglomeration
- **Prediction: At redshift of order $\lesssim$ 80 first** star formation, reionization, magnetic fields, energetic cosmic ray particles, black holes (BH), supermassive BHs, supermassive BH mergers, energetic GWs)
- **Prediction: At redshift of order $\lesssim$ 80** H_3^+ and/or H_2^+ forest of absorption lines

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