THE NATURE OF DARK MATTER

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1 Abstract

Dark matter has been detected since 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), 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. All these features can be quantitatively ex-

plained with the action of cosmic rays accelerated in the magnetic winds of very massive stars, when they explode (Biermann et al. 2009, 2010), based on predictions from 1993 (Biermann 1993, Biermann & Cassinelli 1993, Biermann & Strom 1993, Stanev et al 1993); this approach is simpler than adding WR-star supernova CR-contributions with pulsar wind nebula CR-contributions. 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; 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, possibly formed out of agglomerating massive stars. Black holes in turn also merge, but in this manner start their mergers at masses of a few million solar masses. This readily explains the supermassive black hole mass function (Caramete & Biermann 2010). 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: the proof

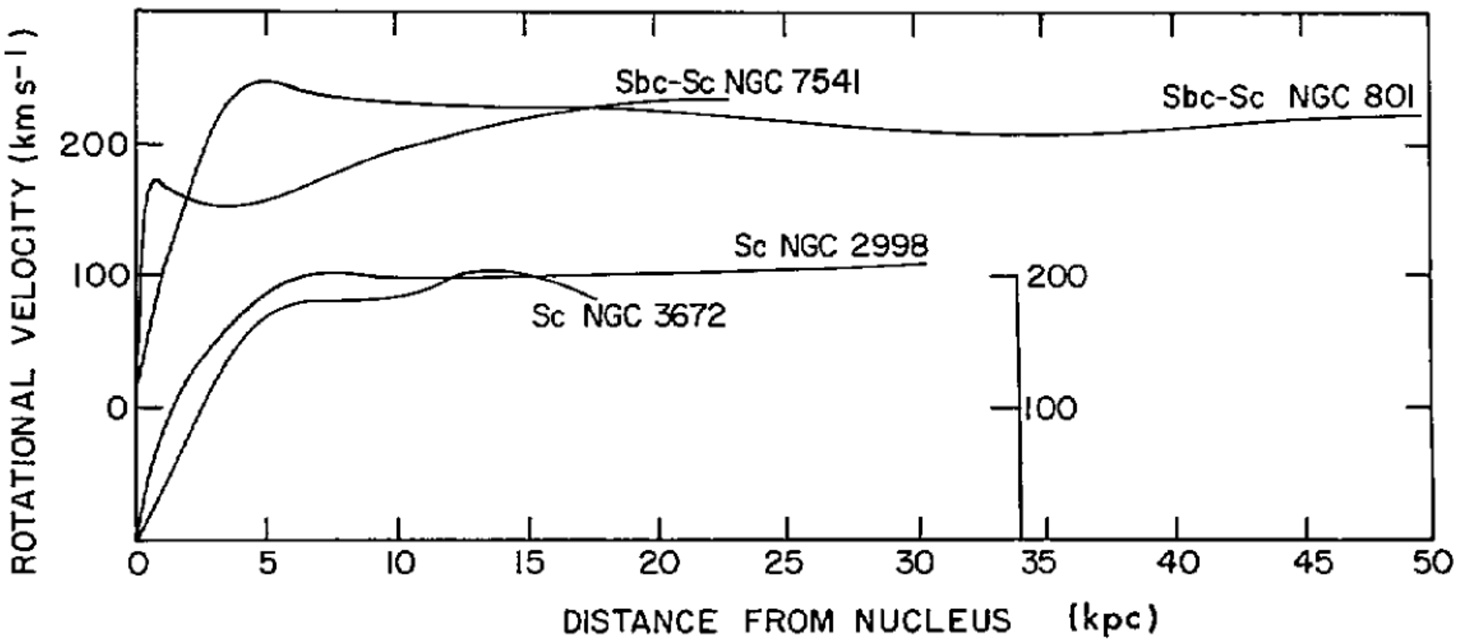


Figure 1 Rotation curves (–> Rubin et al. 1978)

- Dark matter is required:
- for the stability of thin disk galaxies (e.g. Ostriker)
- for the rotation curves (e.g. Rubin)

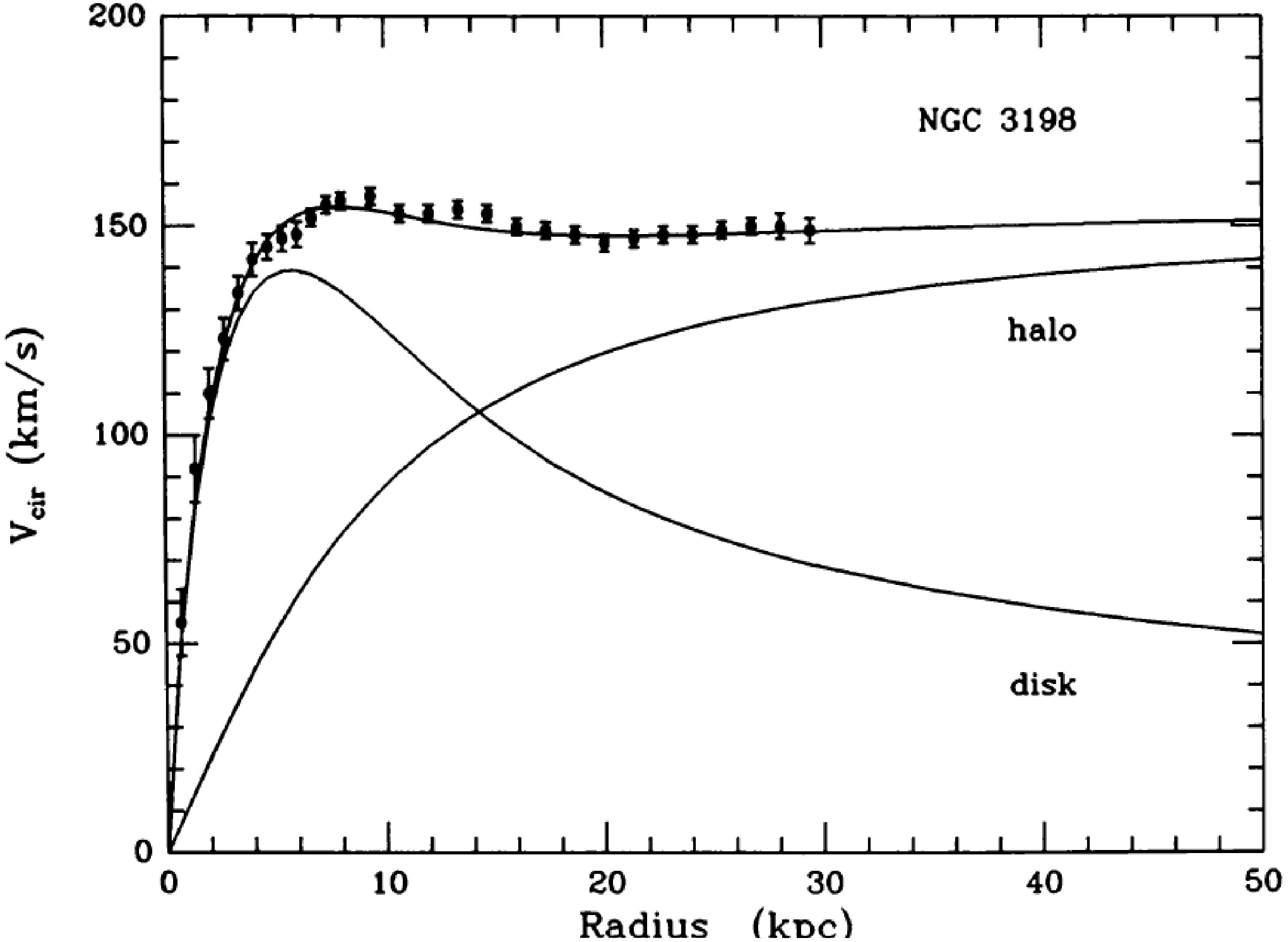


Figure 2 Rotation curves and interpretation (–> Sancisi 1987)

- Stars give a different picture

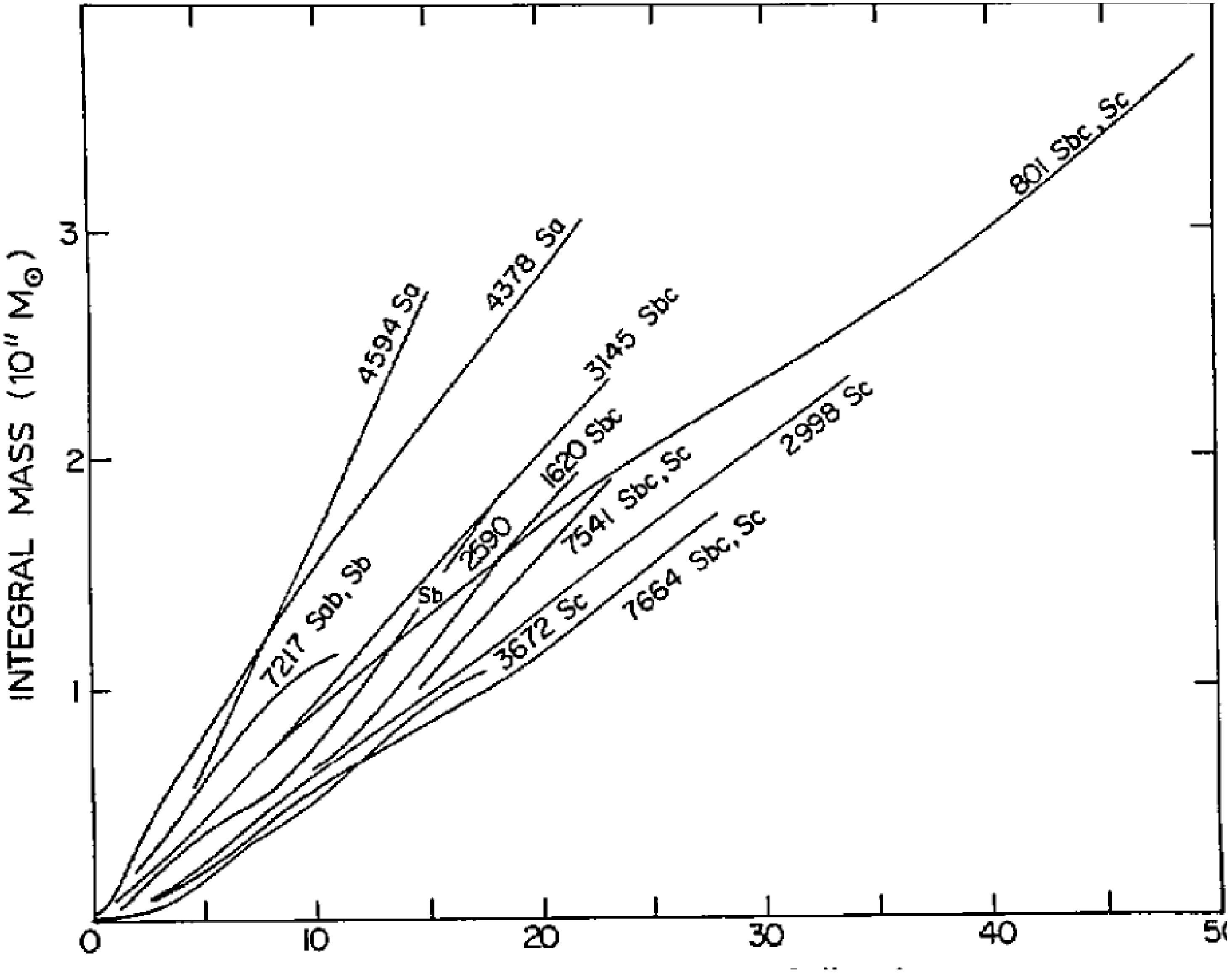
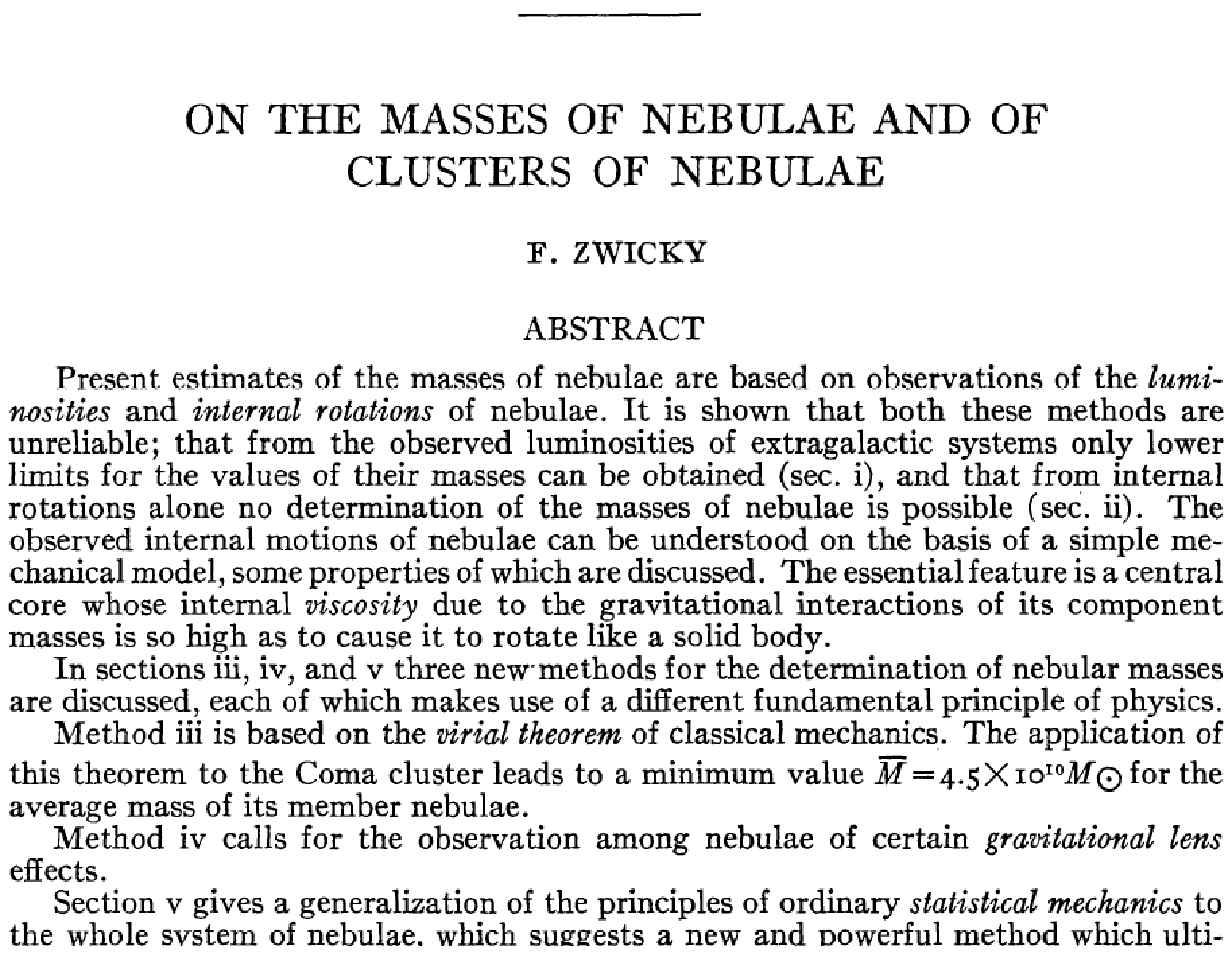


Figure 3 Mass distribution (–> Rubin et al. 1978)

- Mass distribution with no detectable outer boundary



ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

ABSTRACT

Present estimates of the masses of nebulae are based on observations of the *luminosities* and *internal rotations* of nebulae. It is shown that both these methods are unreliable; that from the observed luminosities of extragalactic systems only lower limits for the values of their masses can be obtained (sec. i), and that from internal rotations alone no determination of the masses of nebulae is possible (sec. ii). The observed internal motions of nebulae can be understood on the basis of a simple mechanical model, some properties of which are discussed. The essential feature is a central core whose internal *viscosity* due to the gravitational interactions of its component masses is so high as to cause it to rotate like a solid body.

In sections iii, iv, and v three new methods for the determination of nebular masses are discussed, each of which makes use of a different fundamental principle of physics.

Method iii is based on the *virial theorem* of classical mechanics. The application of this theorem to the Coma cluster leads to a minimum value $\overline{M} = 4.5 \times 10^{10} M_{\odot}$ for the average mass of its member nebulae.

Method iv calls for the observation among nebulae of certain *gravitational lens* effects.

Section v gives a generalization of the principles of ordinary *statistical mechanics* to the whole system of nebulae, which suggests a new and powerful method which ulti-

Figure 4 The Zwicky paper, in English (–> Zwicky 1933 German(Swiss Phys. J.)/1937 English)

- to explain the motions of galaxies in groups and clusters (e.g. Zwicky)

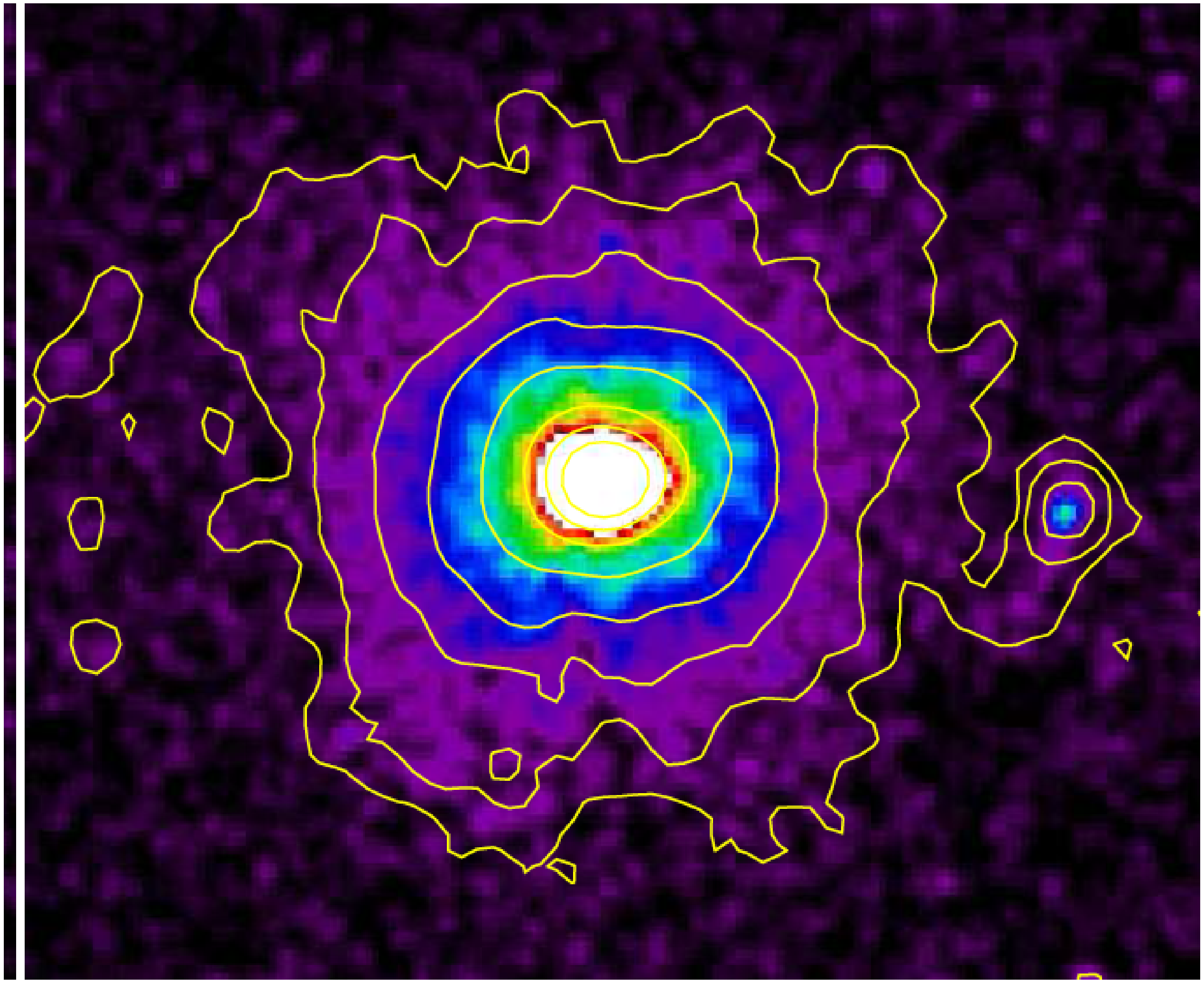


Figure 5 The X-ray emission from the hot gas in a cluster of galaxies (–> Zhang et al. 2006)

- to explain the radial distribution of hot gas in groups and clusters (e.g. Ensslin et al.)

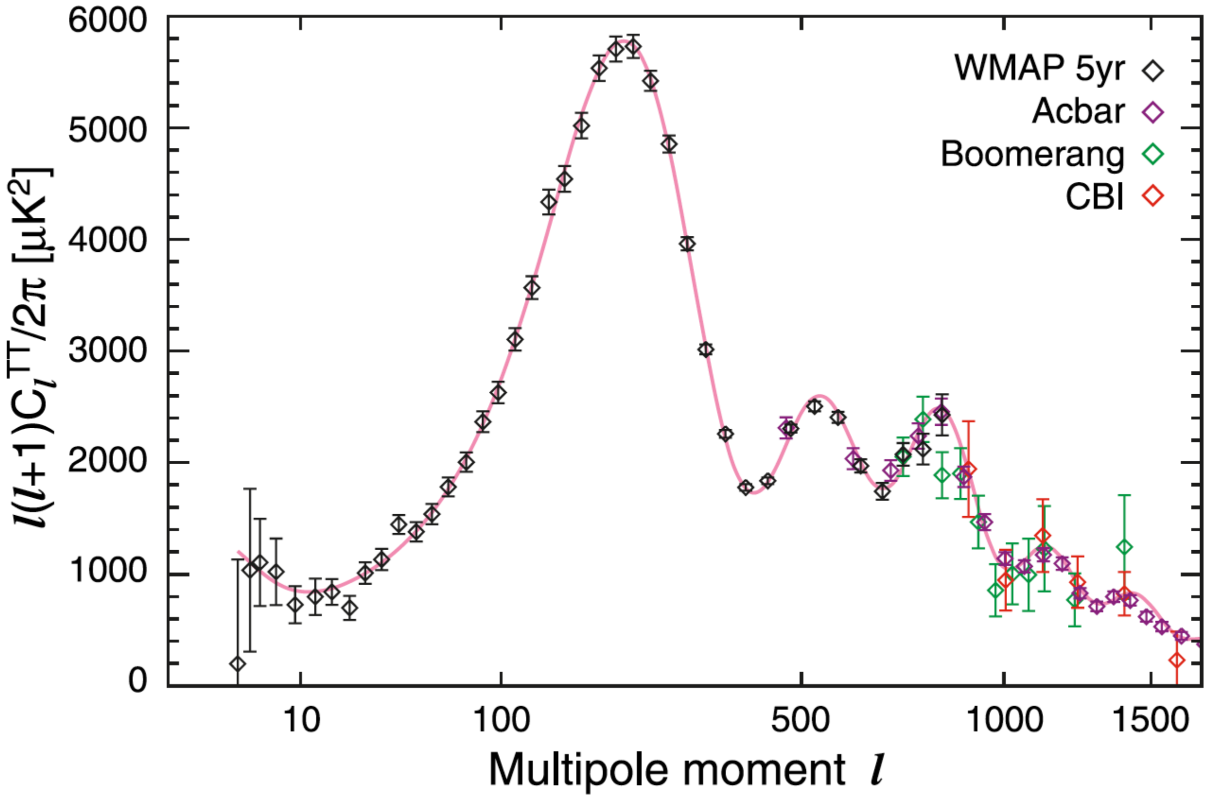
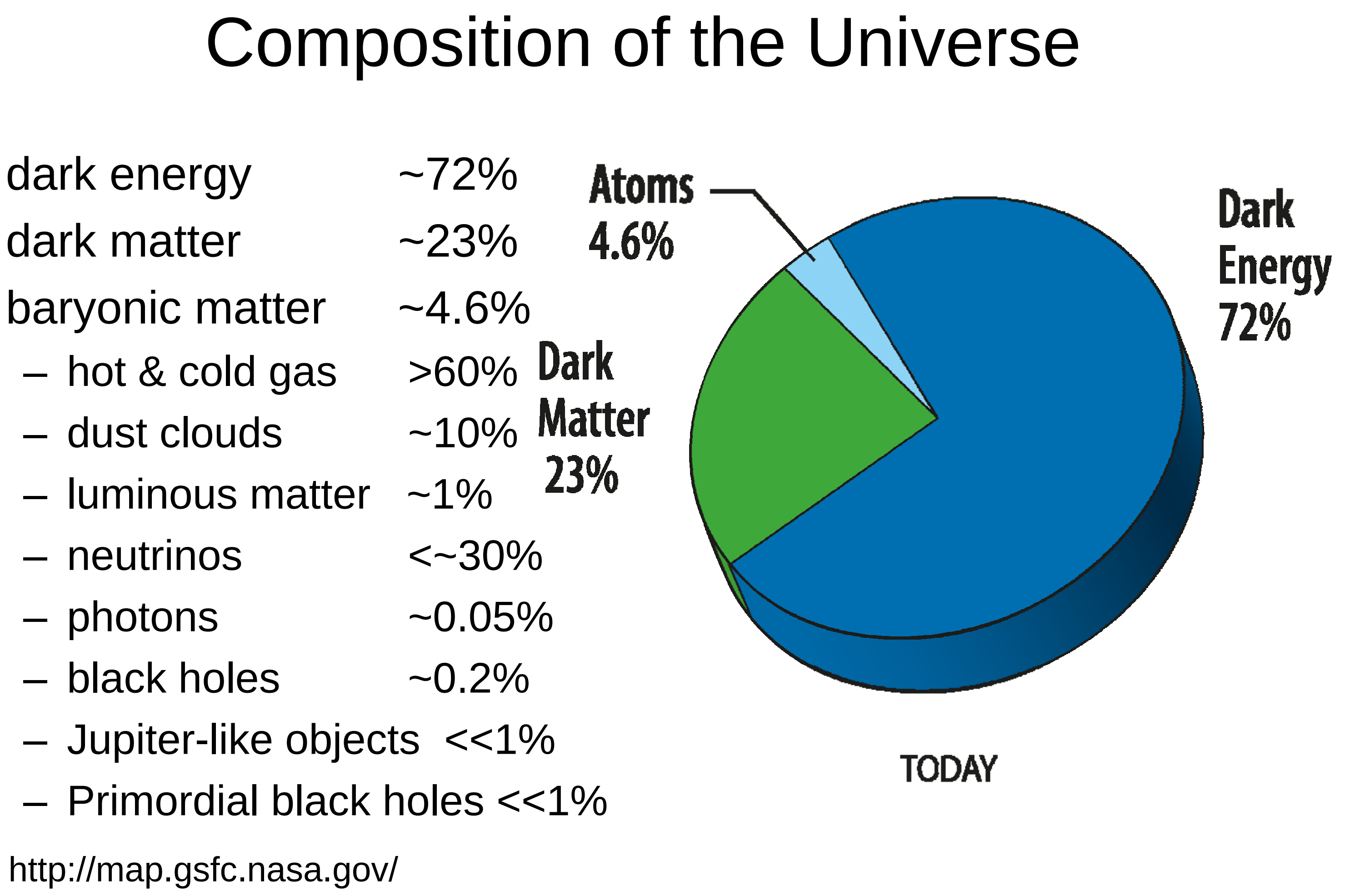


Figure 6 The WMAP 5 year fluctuations in the microwave background from the big bang (–> Nolta et al. 2008)

- to explain the large scale structure formation in the universe
- to explain the mathematically flat geometry of the universe (Spergel et al. 2003, 2007; Nolta et al. 2008)



Composition of the Universe

dark energy	~72%
dark matter	~23%
baryonic matter	~4.6%
– hot & cold gas	>60%
– dust clouds	~10%
– luminous matter	~1%
– neutrinos	<~30%
– photons	~0.05%
– black holes	~0.2%
– Jupiter-like objects	<<1%
– Primordial black holes	<<1%

http://map.gsfc.nasa.gov/

Figure 7 The WMAP 5 year mass and energy accounting (–> Komatsu et al. 2008)

The universe: WMAP5 and WMAP7

Komatsu et al. 2008 + Jarosik et al. 2010

The sum of all contributions is very close to unity, critical density; this implies that the universe has a "flat" geometry, like a perfect tabletop:

$$
\begin{aligned}
\Omega_\Lambda &= 0.728 \pm 0.016 \\
\Omega_{dm} &= 0.227 \pm 0.014 \\
\Omega_b &= 0.0456 \pm 0.0016 \\
-0.0054 < \Omega_k &= 1 - \Omega_\Lambda - \Omega_{dm} - \Omega_b < +0.0056 \\
H_0 &= 70.4^{+1.3}_{-1.4}\,\mathrm{km/s/Mpc}
\end{aligned}
$$

Assuming instantaneous re-ionization (corresponds to about $3.4 \cdot 10^8$ yr)

$$z_{re-ion} = 10.4 \pm 1.2$$

The age of the universe:

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

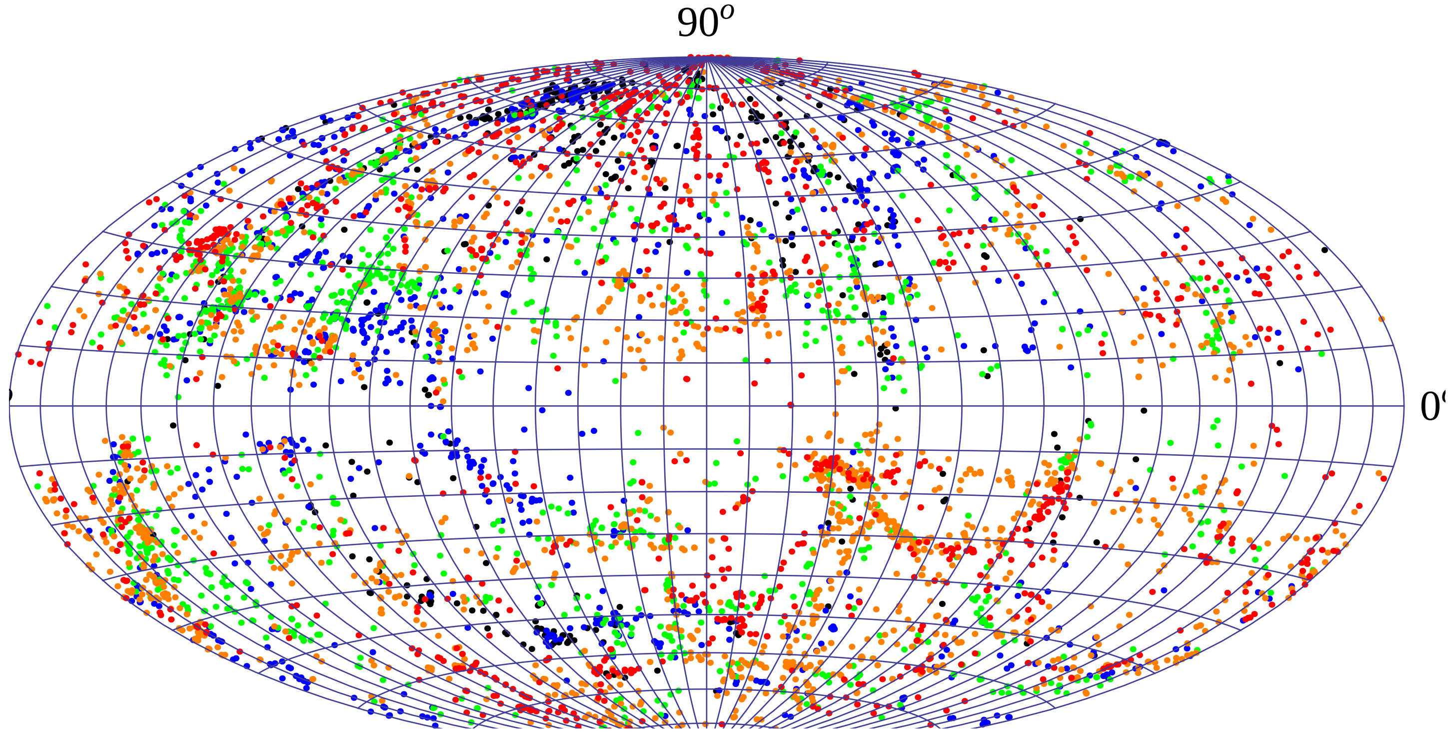


Figure 8 The sky in black holes, $\gtrsim 10^7\ M_\odot$: The color code corresponds to distance: Black, Blue, Green, Orange, Red for the redshifts intervals 0, 0.005, 0.01, 0.015, 0.02, 0.025, corresponding to distance intervals of 0, 60, 120, 180, 240, and 300 million light-years: (–> Caramete & Biermann 2010); coordinate system with Galactic plane across center, and Galactic center at the right edge

- The sky in black holes

70 years: what is dark matter?

Proposal: Heavy particles

- Leading theory:
  massive particles from supersymmetry

- Upturn in positron fraction in cosmic rays (Pamela)
- Upturn in electron spectrum in cosmic rays (Fermi, ATIC)
- WMAP haze: Galactic Center region
- Fermi haze: Galactic Center region
- 511 keV emission line: Galactic Center region
- General upturn in all nuclei from Helium (CREAM)

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

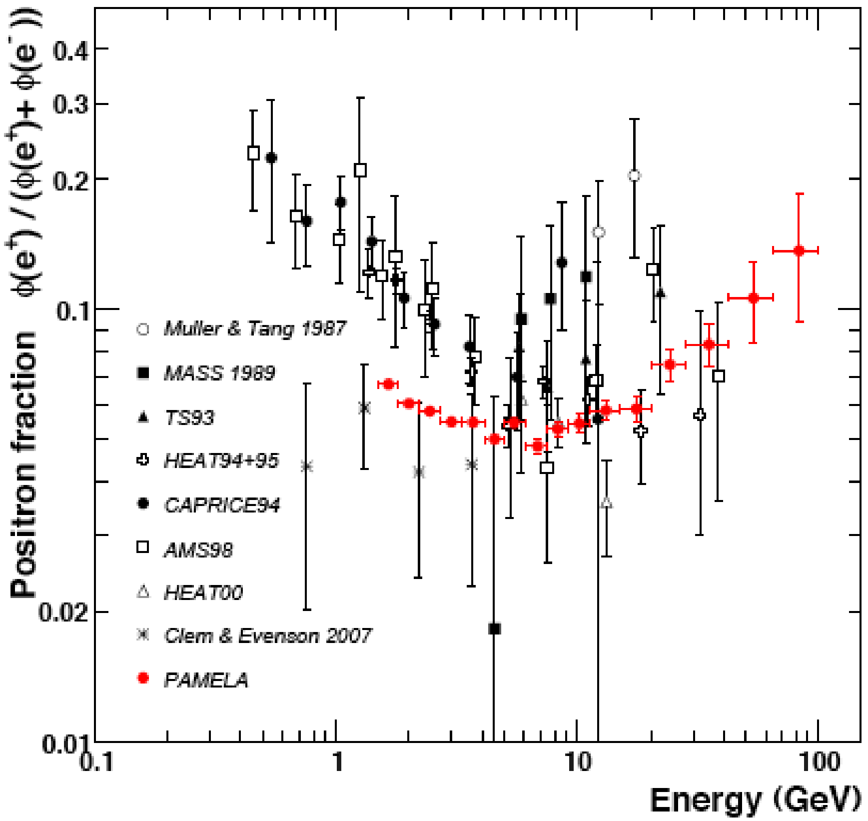


FIG. 3: **PAMELA positron fraction with other experimental data.** The positron fraction measured by the PAMELA experiment compared with other recent experimental data[24, 29, 30, 31, 32, 33, 34, 35]. One standard deviation error bars are shown. If not visible, they lie inside the data points.

Figure 9 Pamela data on positron fraction, 2008: Dark matter/SUSY ???

A massive star and its magnetic field

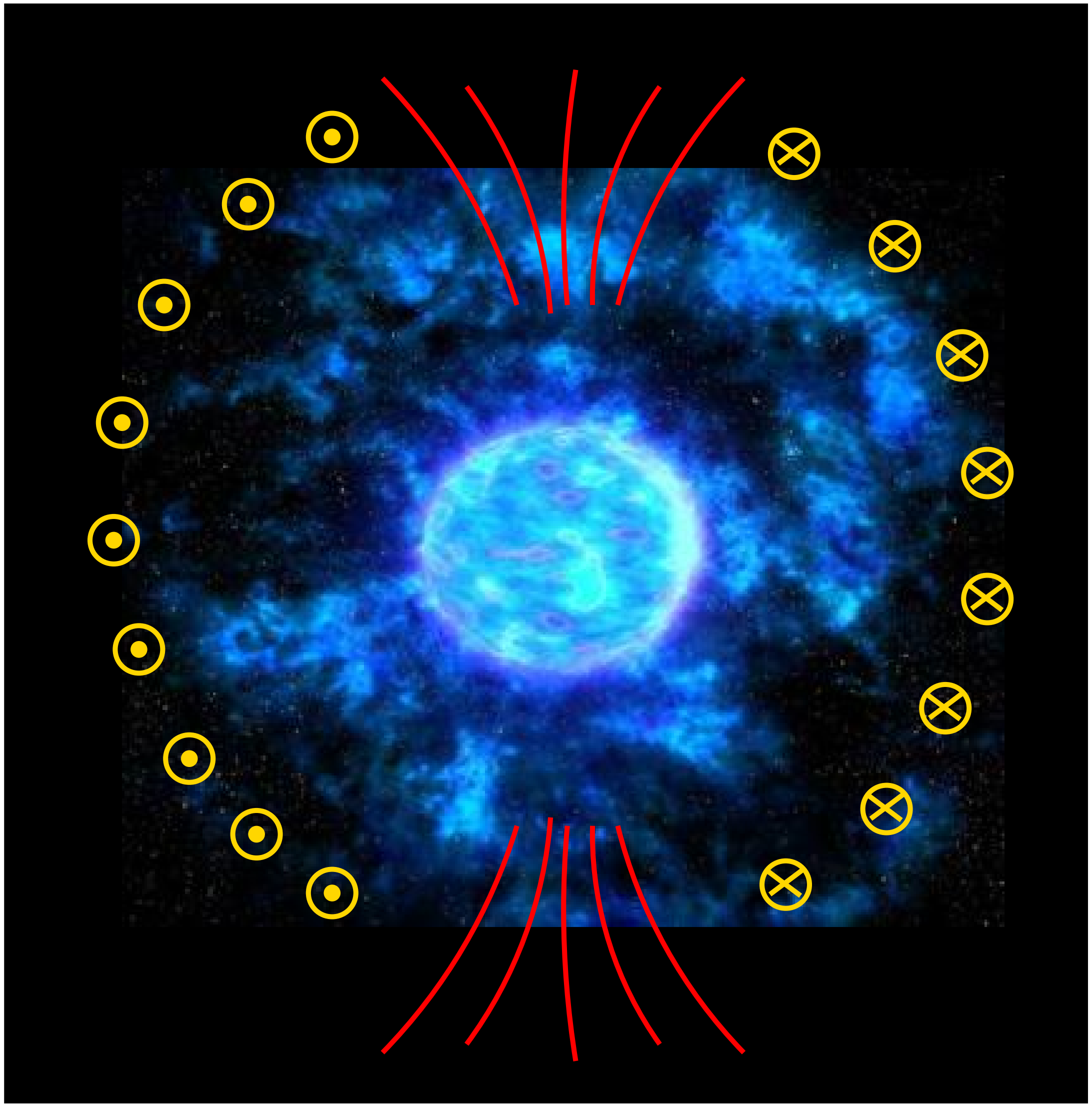


Figure 10 Magnetic field topology around a massive star in its wind: Graph following Parker 1958; central graph NASA, Wolf Rayet star WR124: Remember Maxwell's laws!

Cosmic ray knee: paper CR-IV, 1993

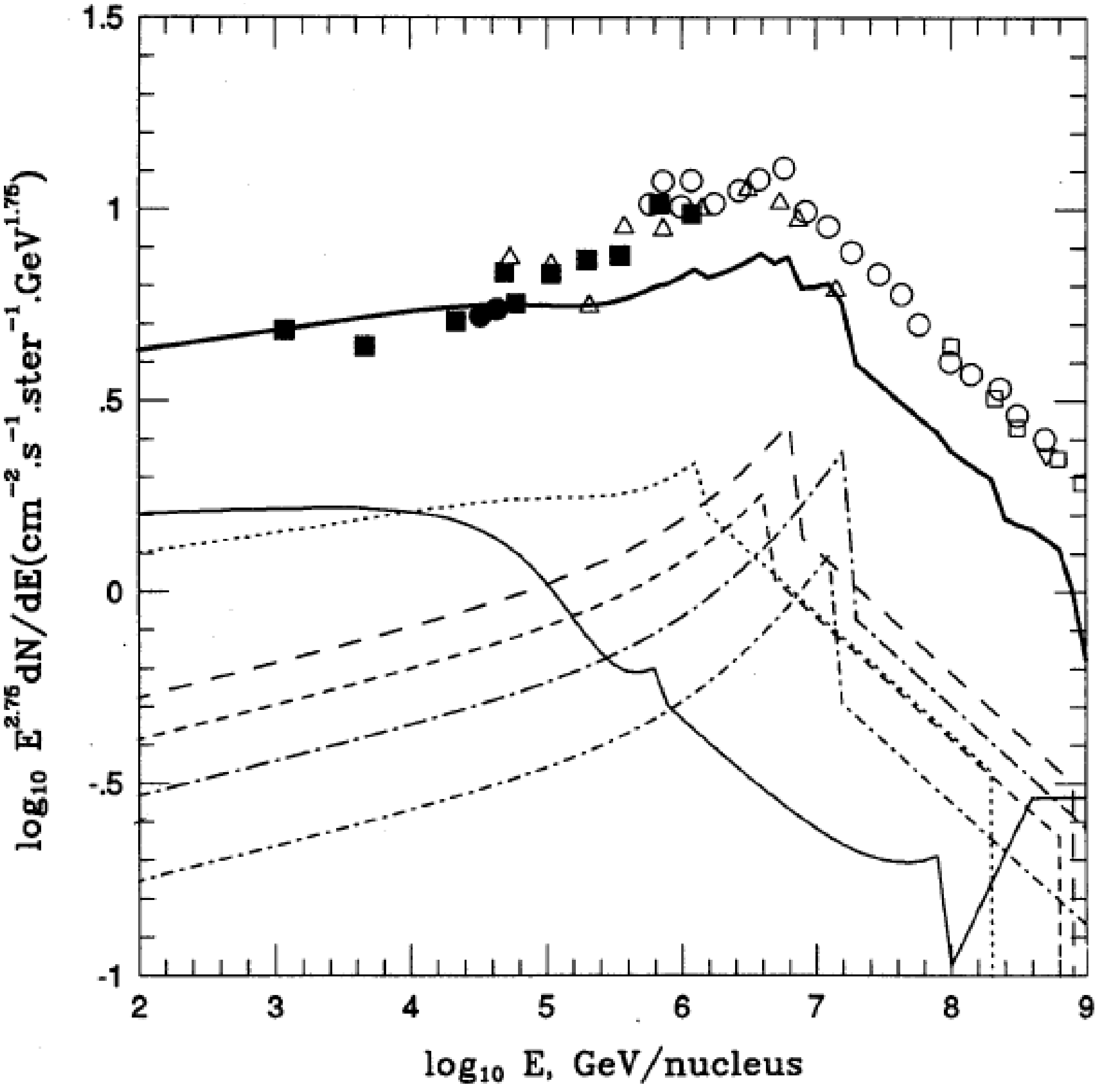


Figure 11 Spectral and chemical structure at the knee, *CR-e$^-$ and CR-e$^+$ components*?, to be *shifted to high energy*? Element groups are H, He, CNO, Ne-S, Cl-Mn, and Fe. Source: Stanev et al., paper CR-IV 1993

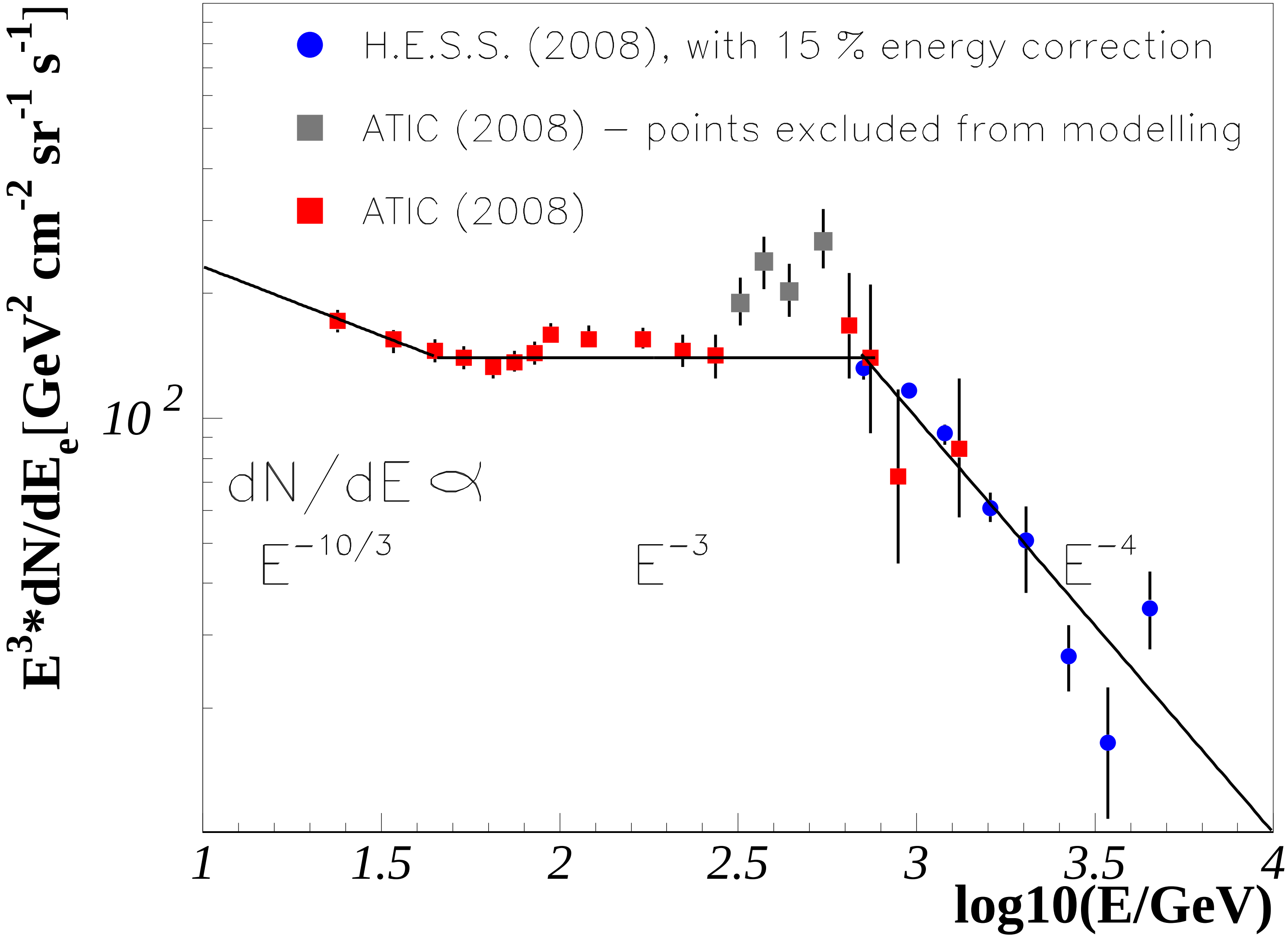


Figure 12 Model prediction with ATIC and H.E.S.S data for cosmic ray electrons: $E^{-10/3}$, E^{-3}, and E^{-4}. Source Biermann et al. 2009

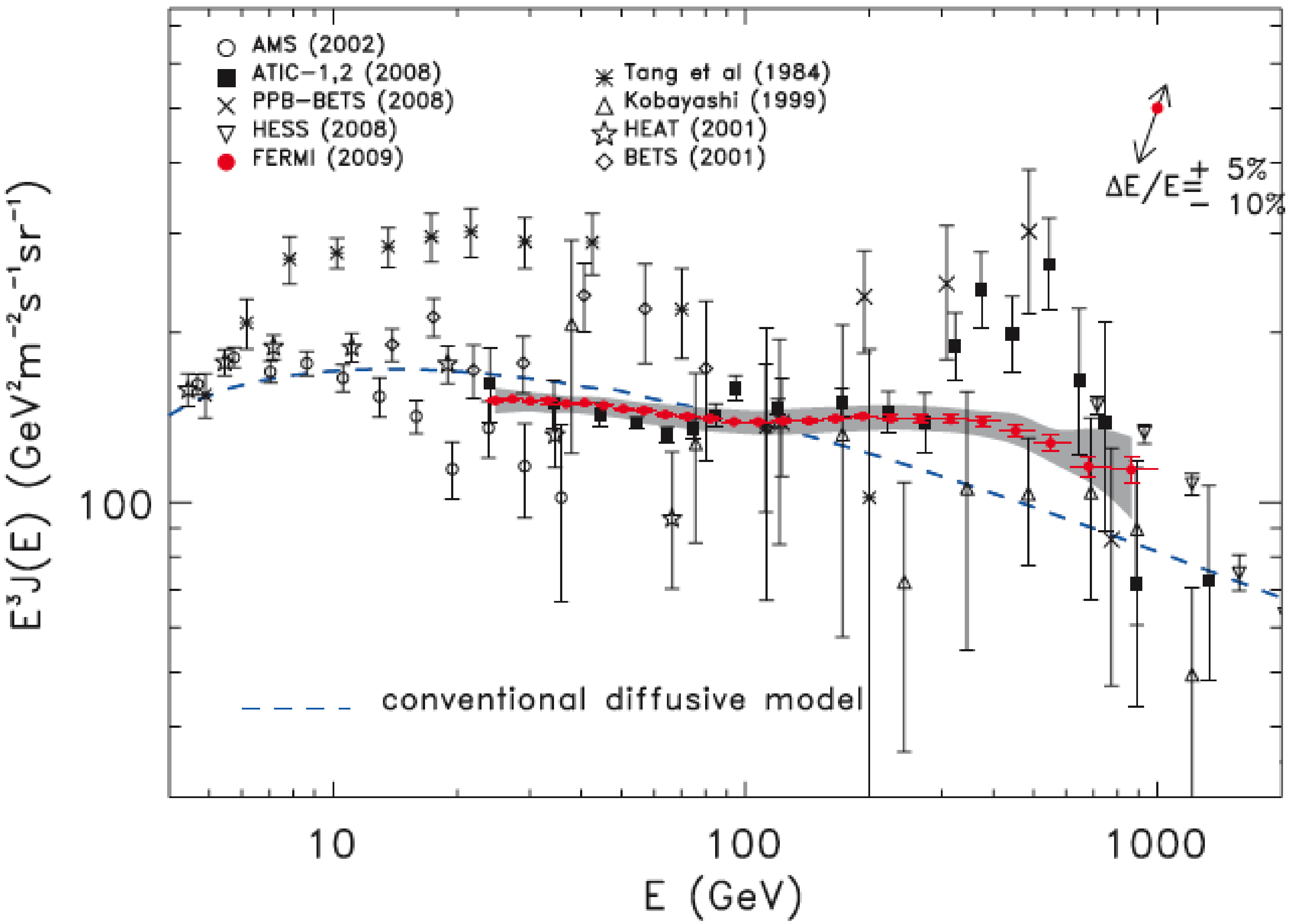


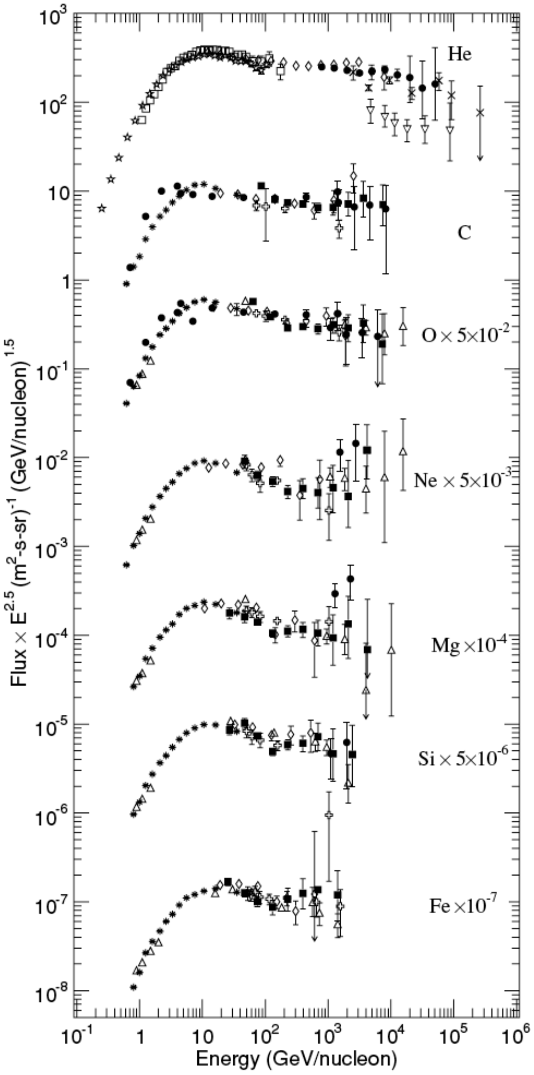
FIG. 3 (color). The Fermi LAT CR electron spectrum (red

Figure 13 Latest Fermi data confirming the spectrum proposed (April 30, 2009).

WMAP and Fermi haze

- Now further consequences: WMAP haze, flat spectrum high frequency component around Galactic Center
- 2010 in *Astrophys. J. Letters* **710**, L53 - L57 (2010)
- 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
- gives the correct number of positrons to explain the 511 keV emission

CREAM: CR spectral upturn



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

Figure 14 CREAM data showing upturn (Ahn et al. 2010 *Astrophys. J. Letters*)

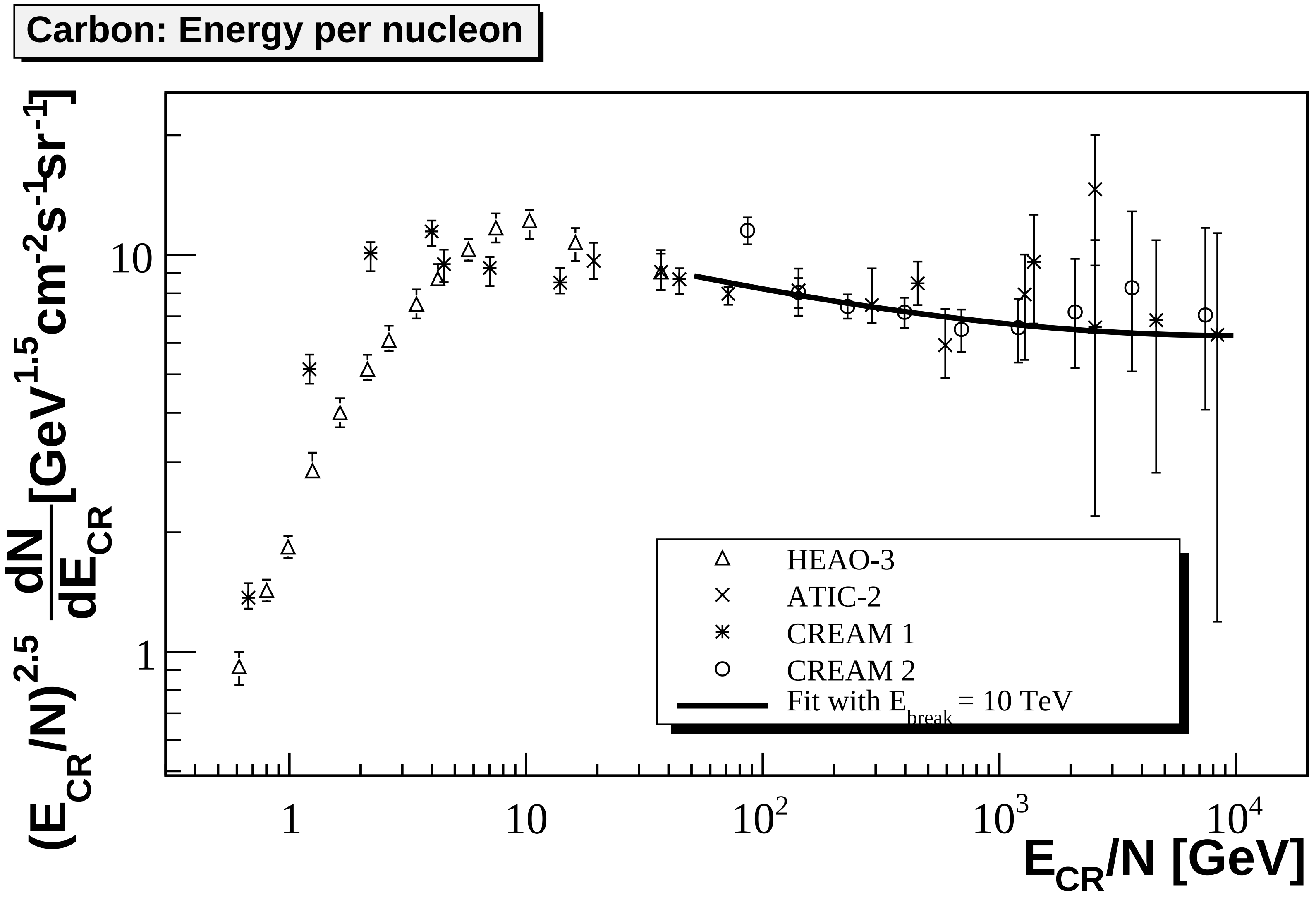


Figure 15 Fit to CR-Carbon data with spectral shape given 1993: Biermann et al. 2010

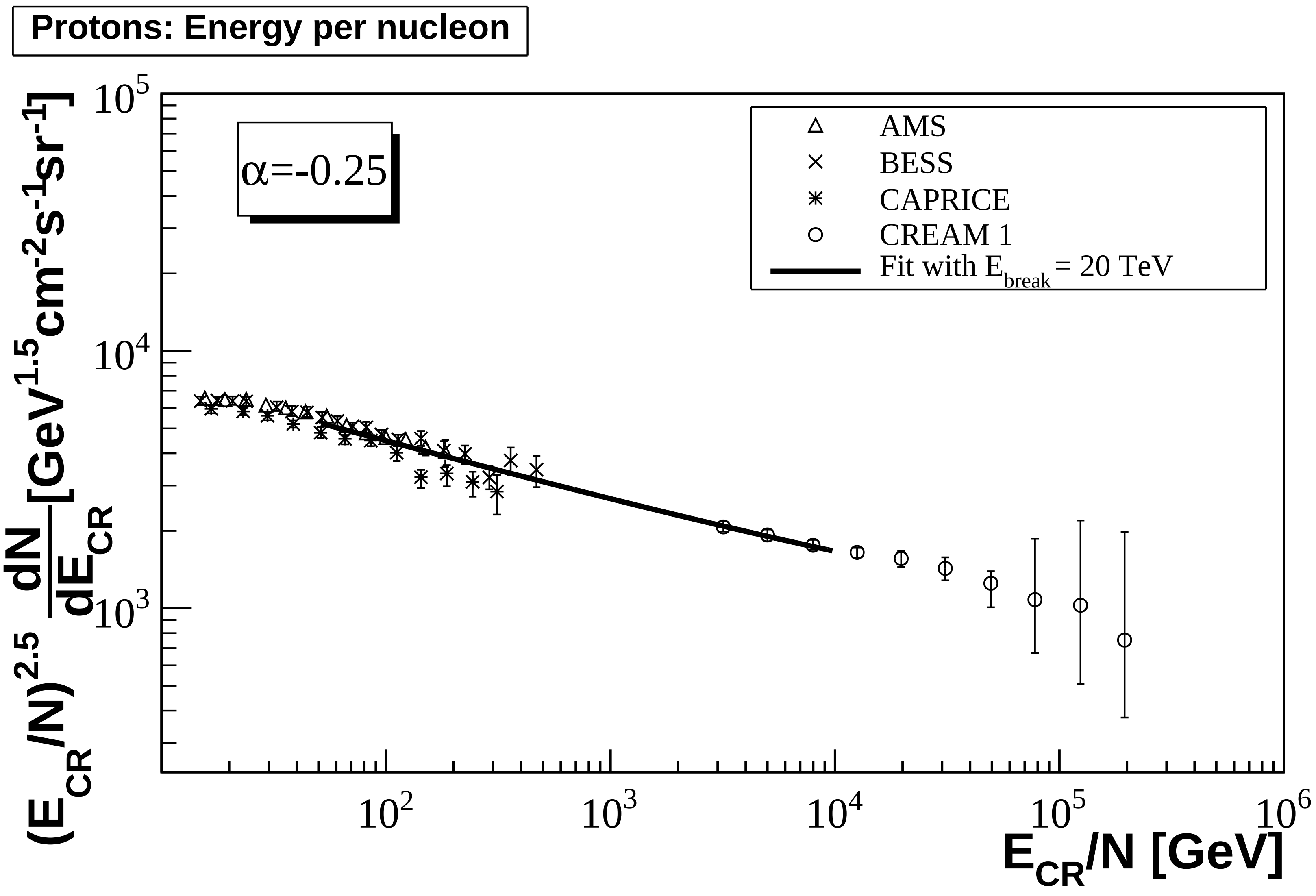


Figure 16 Fit to CR proton data with spectral shape given 1993: Biermann et al. 2010

Auger: UHECRs from polar cap CR-component

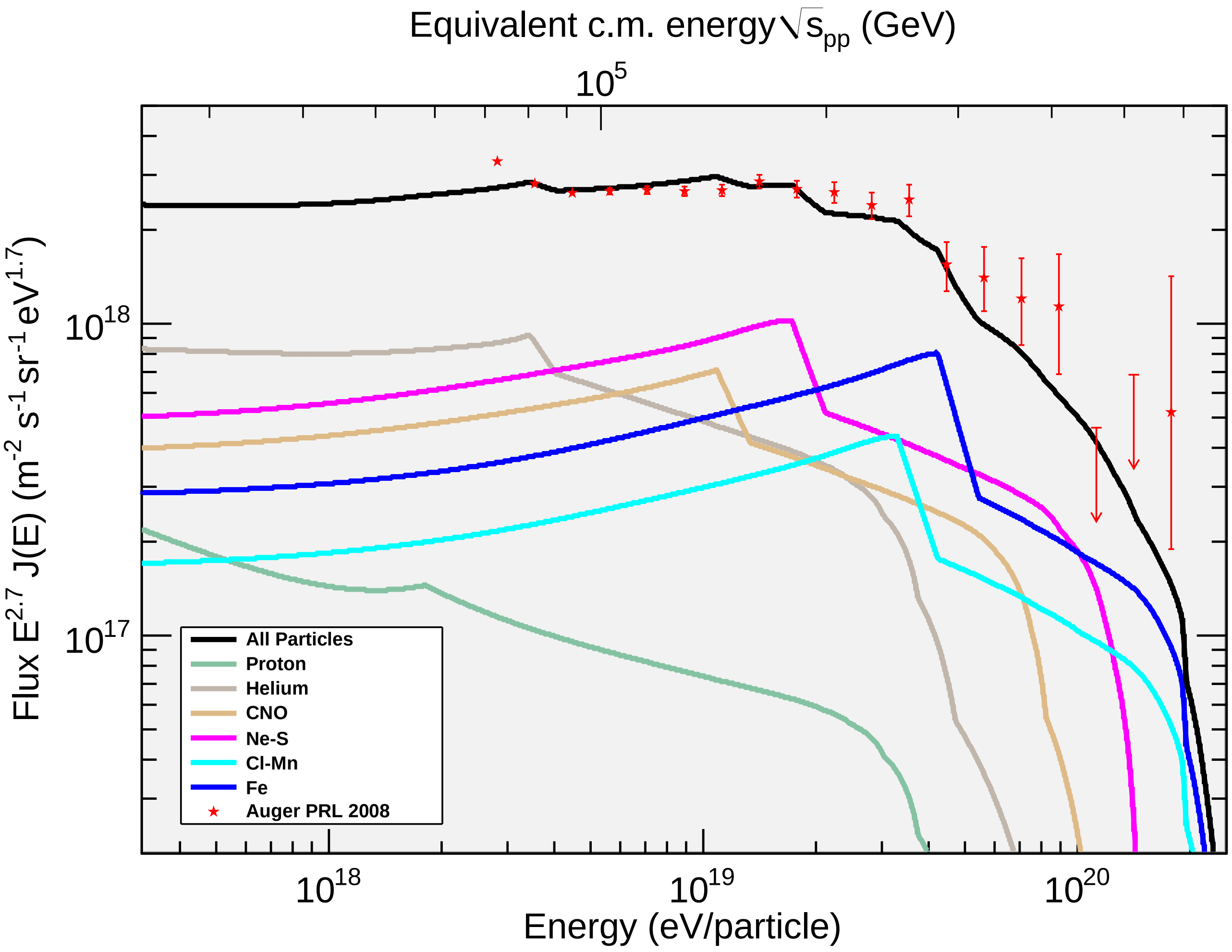


Figure 17 Auger data interpreted as arising from WR-polar cap boosted (Gopal-Krishna et al. 2010 *Astrophys. J. Letters*)

Astrophysical alternative: pulsar wind nebula

- CR-Leptons vs CR-hadrons? Very different contributions!
- Pulsar wind nebula driven by spin-down power, sufficient by orders of magnitude to supply energy to CR-leptons
- Would simplify the solution of the injection problem (energetic electrons do not “see” a shock readily)
- Could supply both the CR-positron as well as the CR-electron excess
- However, would fail as an explanation for the CREAM-upturn
- WR-CR-contributions both natural consequence of Maxwell’s laws (Parker 1958): Apply Occam’s razor $->$ all WR contributions

Massive stars and their explosions

- **Polar cap proposal (1993) now confirmed (2009): hard spectrum component E^{-2} at injection**:
- Upturn after transport from $E^{-8/3}$ towards $E^{-7/3}$ now seen in CREAM data (Ahn et al., 2009, 2010)
- CR-H: cf. PLB; & Strom; & Cassinelli; Stanev et al., all 1993: ISM $E^{-2.75}$ and wind $E^{-8/3}$
- Observed CR-e$^-$ $E^{-10/3}$, then E^{-3}, E^{-4}
- Fraction CR-e$^+$ low energy $E^{-5/9}$, then $E^{+1/3}$
- GC haze spectrum predicted in order to frequency range: $\nu^{-2/3}$, ν^{-1}, $\nu^{-3/2}$: confirmed by Fermi haze (2010), and positron production confirmed by the 511 keV line
- Application to UHECRs: all from Cen A? (Gopal-Krishna et al. 2010): direct fit to Auger data

Proposal: Light particles

- Since much evidence for the decay of a heavy particle is now gone, look elsewhere (review Kusenko 2009)
- One alternative: **right-handed neutrinos**, interact only weakly with normal left-handed neutrinos in low mass range $2\,\text{keV} \lesssim m_{DM}\,c^2 \lesssim 20\,\text{keV}.$
- Lifetime order of $\tau = 2 \cdot 10^8 \times$ age of the universe.
- These particles decay very slowly, 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

Biermann & Kusenko 2006 PRL

- ! Transition from active left-handed neutrino to right-handed neutrino eliminates scattering in supernova $- >$ SN-explosion with a kick!
- Pulsar velocities up to 1000 km/s – Guitar nebula – (Kusenko 2004; review Kusenko 2009) Mass range: 2 to 20 keV
- ! Early growth of black holes from dark matter (Munyaneza & Biermann 2005)
  Mass range: 12 - 450 keV: ! Fermion
- Aspen September 2005: overlapping range - Eureka!
- From increased early ionization star formation possible from about redshift 80, (Biermann & Kusenko 2006; Stasielak et al. 2007; Loewenstein et al. 2009) – this refuted the biggest counter-argument against light dark matter (Yoshida *et al.* 2003)

Pulsar kicks

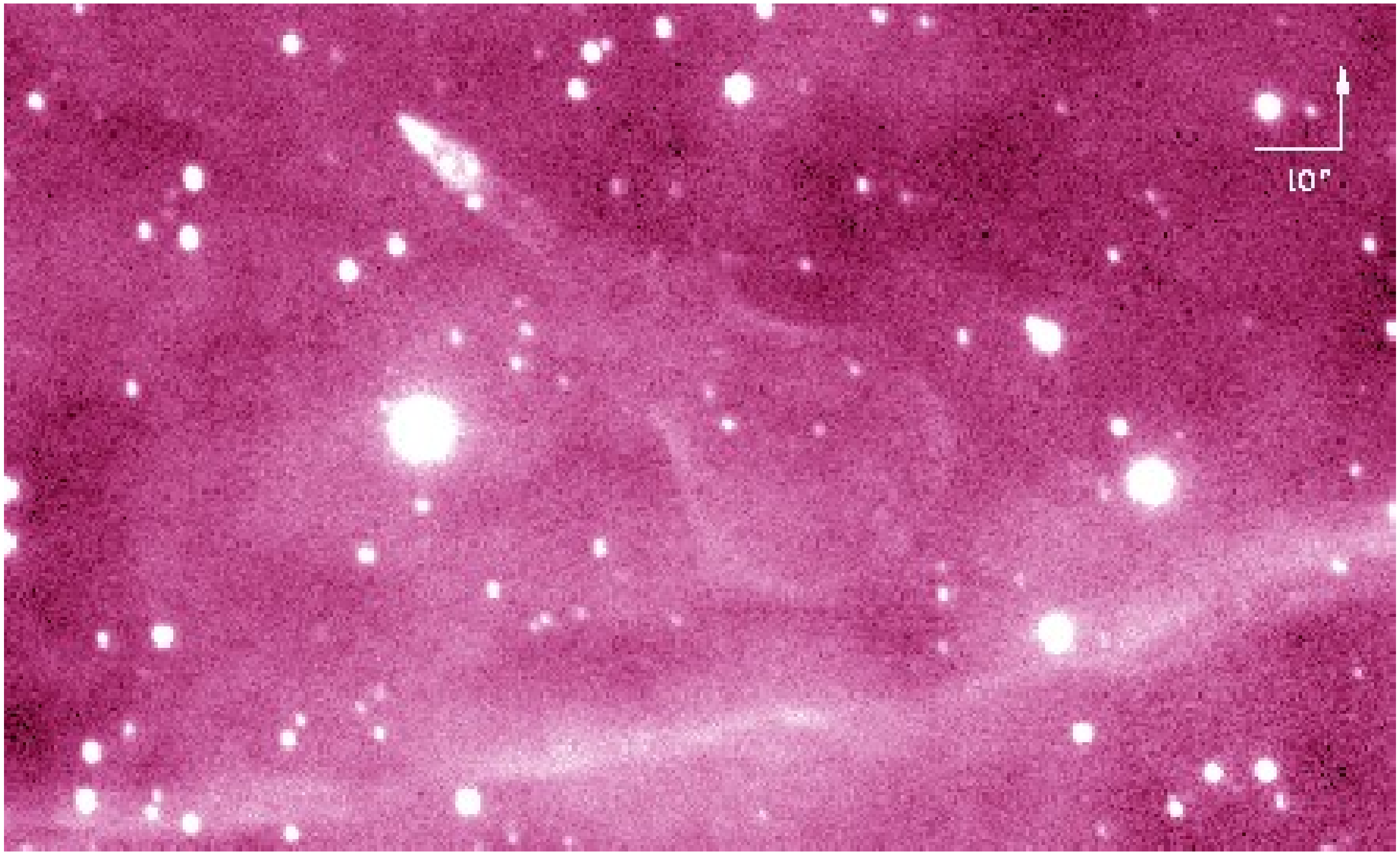


Figure 18 The fast moving pulsar in the guitar nebula (–> HST)

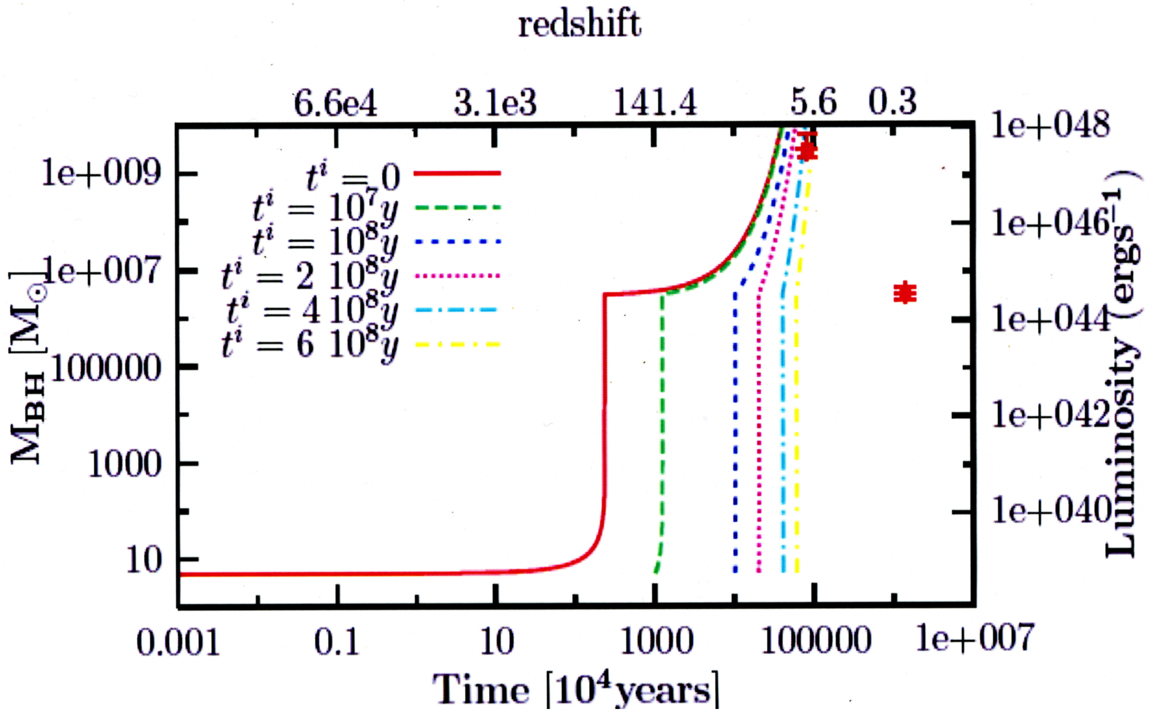


Figure 19 (–> Munyaneza & Biermann, 2006)

- Proposal: Massive black holes first feed on dark matter, up to about our black hole; then feeding on normal matter, the second stage slowed down by radiation back reaction ("Eddington-limit"); variant: assisted agglomeration (all stars explode above about $10^6\, M_\odot$)

Galaxies with black holes

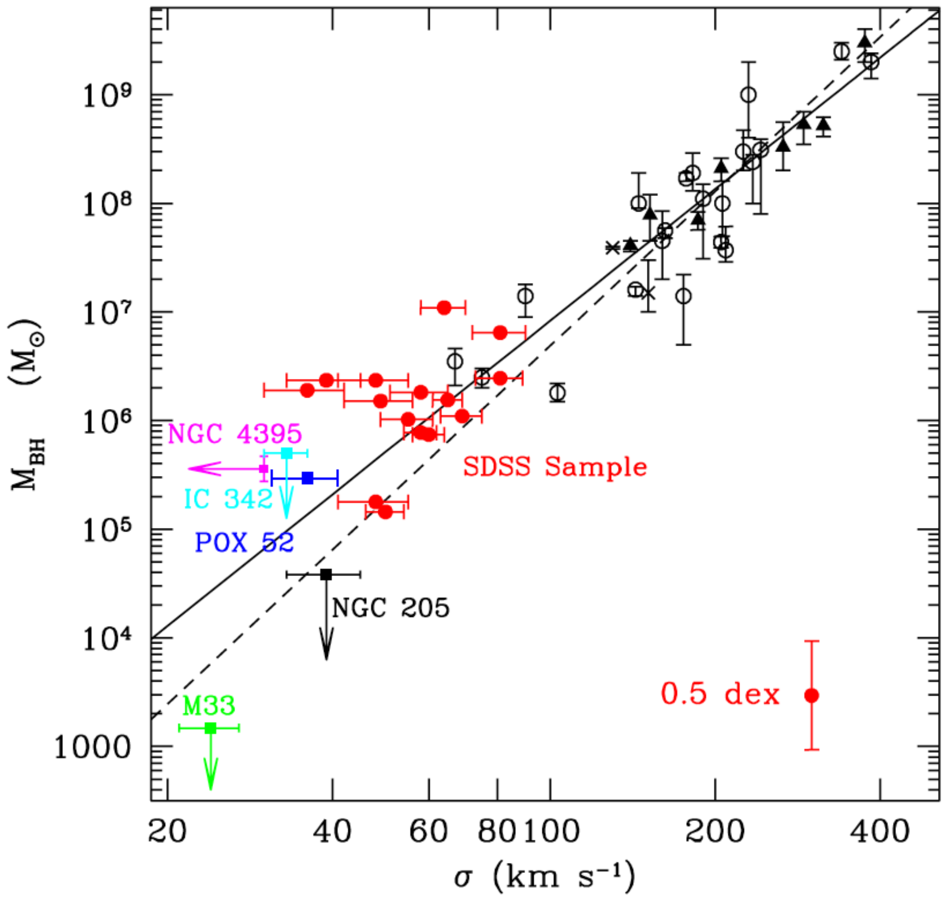


Figure 20 The black holes of “low” mass (–> Greene et al. 2006)

Between 10 and about $10^6\,M_\odot$ there are very few black holes. Alternative to direct dark matter force-feeding: assisted agglomeration of massive stars and explosion

Dwarf Galaxies: without black holes

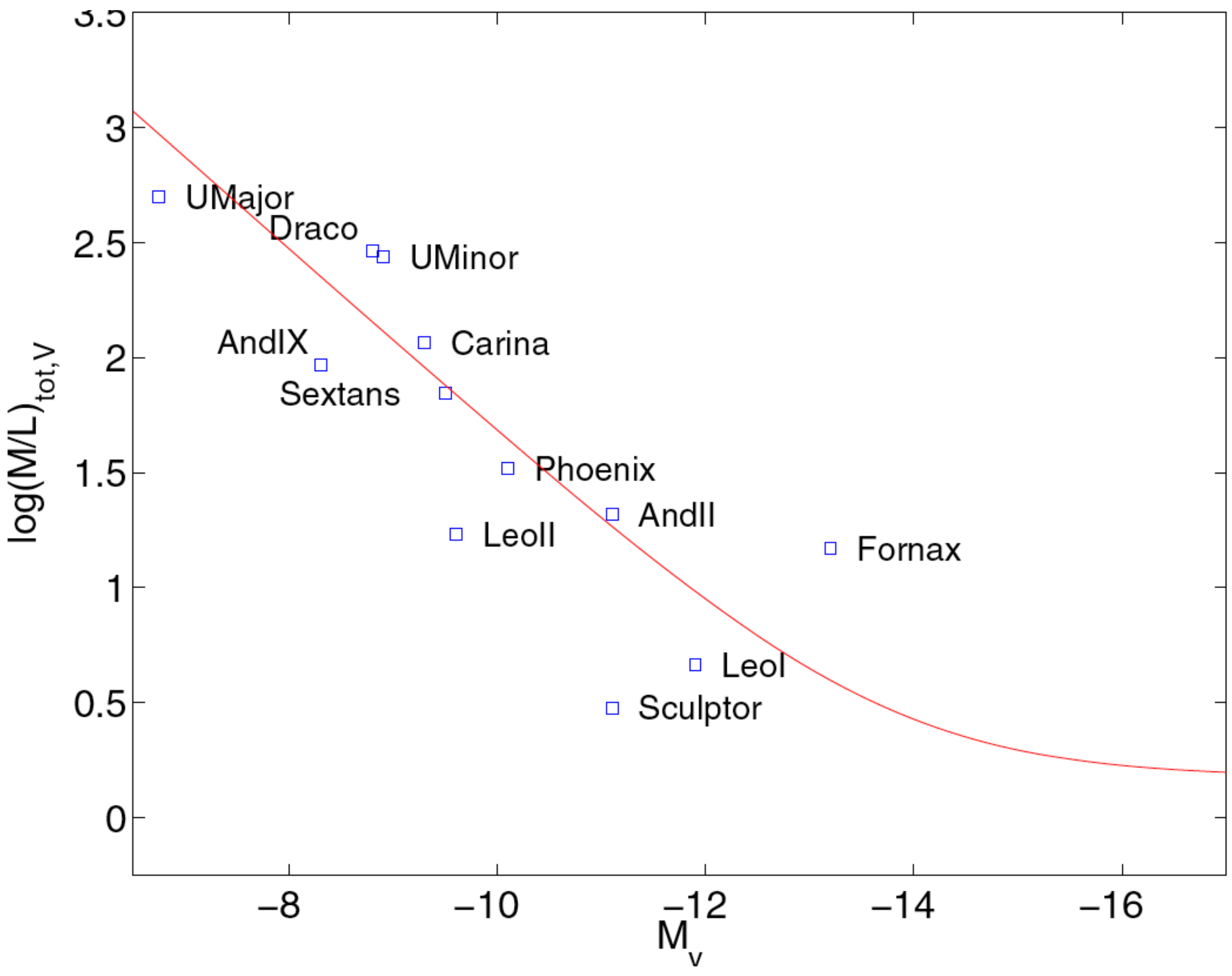


Figure 21 The masses of dwarf elliptical galaxies (–> Gilmore et al. 2007)

- All consistent with same low total dark matter mass in these dwarf elliptical galaxies of $5 \cdot 10^7\ M_\odot$

Dwarf galaxies: central density in DM

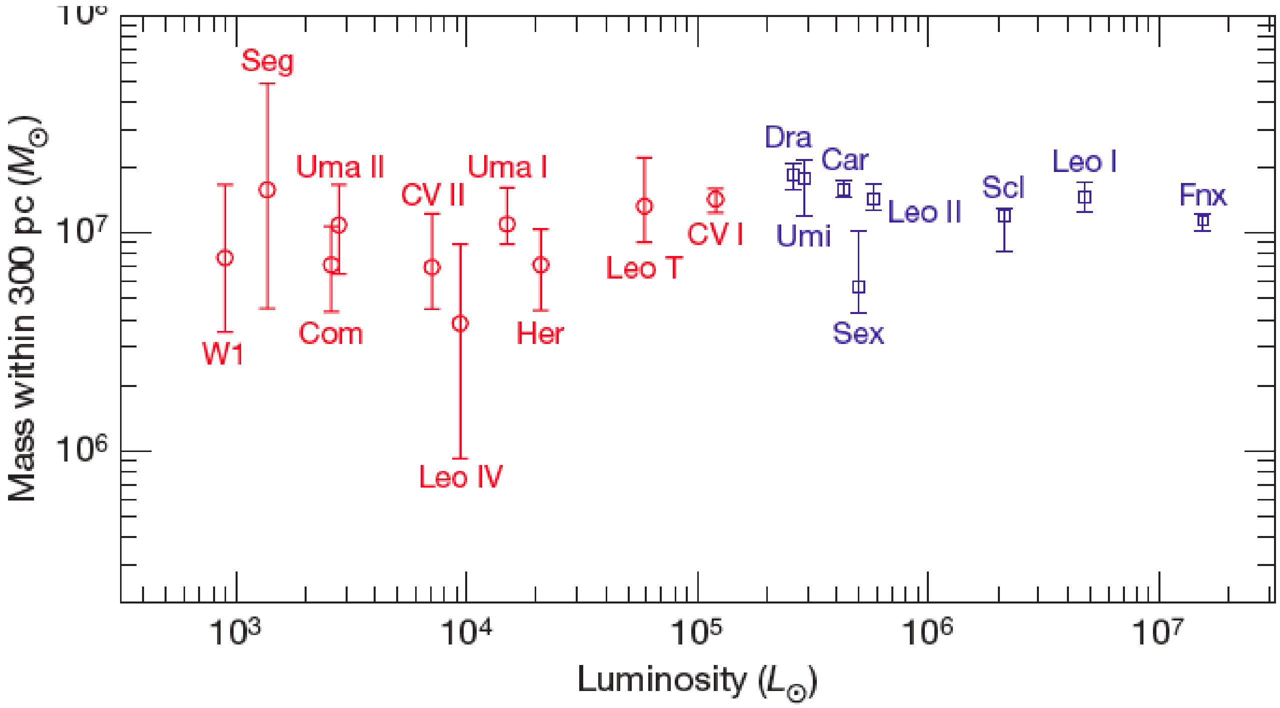


Figure 1 | The integrated mass of the Milky Way dwarf satellites, in units of solar masses, within their inner 0.3 kpc as a function of their total luminosity, in units of solar luminosities. The circle (red) points on the left

Figure 22 The central densities of dwarf elliptical galaxies (–> Strigari et al. Nature 2008); similar results Gentile et al. Nature 2009

- All consistent with same phase space density ρ_{DM}/σ^3_{DM} (see Hogan & Dalcanton 2000; Dalcanton & Hogan 2001, Boyanovsky et al. 2008, de Vega & Sanchez 2010)

Galaxies and dwarf Galaxies: scales

- Free streaming length kpc scale (Gilmore et al. 2006 - 2009)
- Same central density of central dark matter (Strigari et al. 2008, Gentile et al. 2009)
- i) Virial theorem, ii) phase space density conservation, iii) same central density, three parameters, three unknowns, three relationships: gives free streaming length, and mass, so momentum of DM particle at decoupling (using Hogan & Dalcanton 2000; Dalcanton & Hogan 2001)
- Result (Boyanovsky et al. 2008; de Vega & Sanchez 2009a, b, 2010): **dark matter particle keV scale**

First star formation

- Star formation of massive stars
- First magnetic fields
- Reionization of the neutral universe
- Supernovae and Gamma Ray Bursts
- Chemical enhancement, first dust
- Stellar black holes
- Supermassive black holes
- Cosmic ray particles of high energy
- High energy photons and neutrinos
- Mergers of supermassive black holes
- Black hole mass function
- First gravitational waves: energy input

Integral black hole mass function

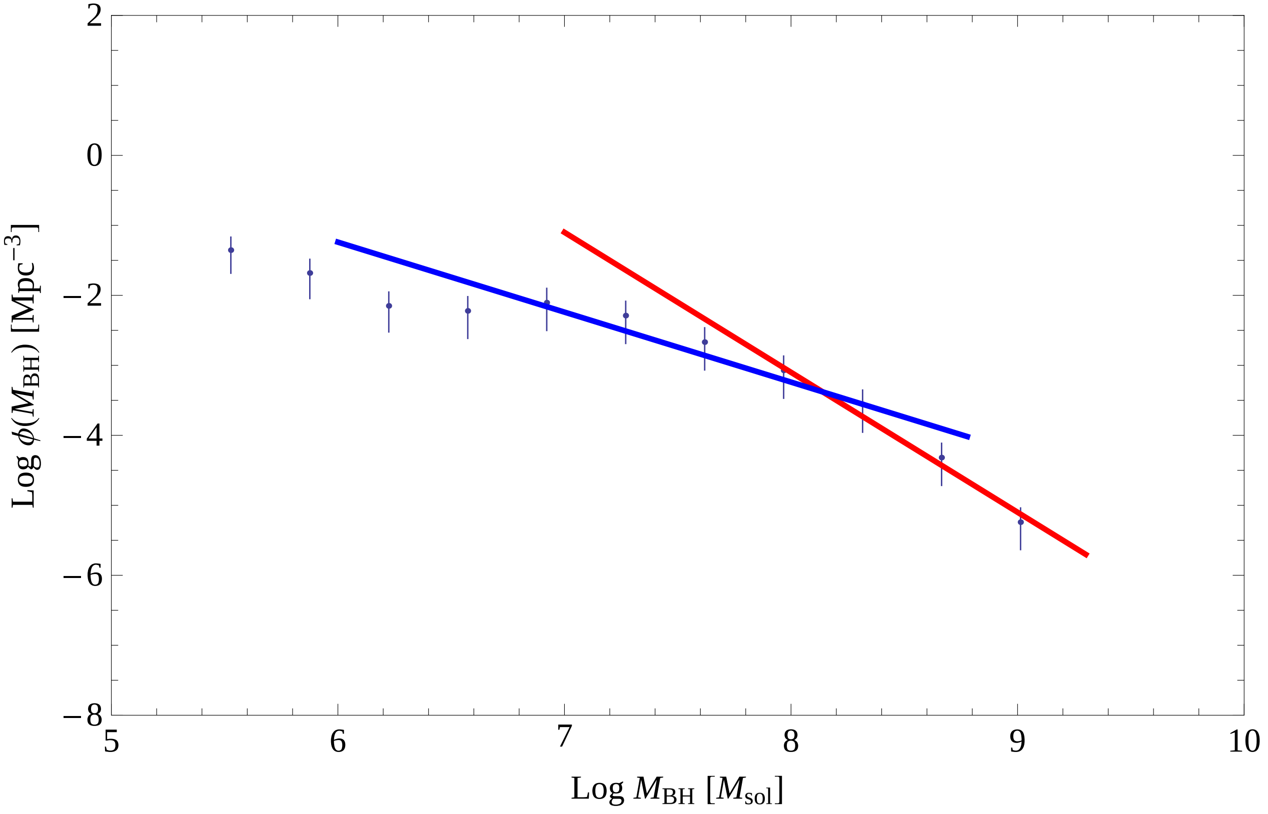


Figure 23 Integral mass function corrected for Hubble type sampling, 2928 objects, the slope of the lines is: red -2.0 fitting $> 10^8\,M_\odot$, and blue -1.0 fitting between $10^7\,M_\odot$ and $10^8\,M_\odot$. Integrates black hole entropy independent of details; source Caramete & Biermann 2010. This mass function suggests that black holes start near 3 $10^6\ M_\odot$ at very high redshift, of order 50, and grow by merging (see Biermann & Kusenko 2006)

First gravitational wave signals?

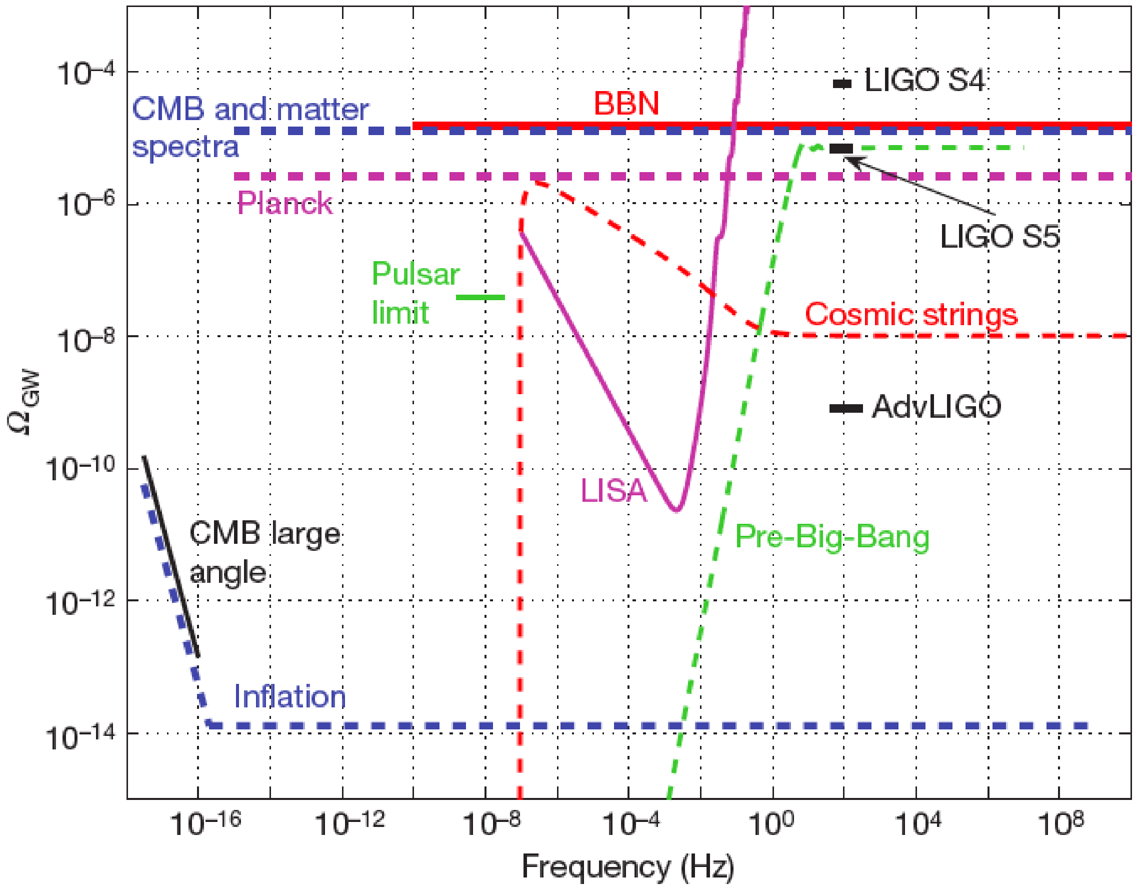


Figure 2 | Comparison of different SGWB measurements and models. The 95% upper limit presented here, $\Omega_0 < 6.9 \times 10^{-6}$ (LIGO S5), applies in the frequency band 41.5–169.25 Hz, and is compared to the previous LIGO S4 result[22] and to the projected Advanced LIGO sensitivity[25]. Note that the

Figure 24 Upper limits to GW signals (LIGO Nature 2009). The first mergers could start near 10^{-5} Hz

Summary: WIN ?

- Lightest super-symmetric particle?
- Lots of evidence from energetic particle spectra and photon spectra traceable to massive star explosions (quantitative model from 1993, confirmed 2009 & 2010)
- Dwarf galaxy scales / velocity dispersion: $->$ keV particle
- Right handed neutrinos? Sub-thermal?
- **Prediction: At redshift of order 80** star formation, reionization, magnetic fields, energetic cosmic ray particles, black holes (BH), supermassive BHs, supermassive BH mergers, energetic GWs)

$$\sim 2\ \mathrm{keV} \lesssim m_s\, c^2 \lesssim\ \sim 4\ \mathrm{keV}$$

Weakly Interacting right-handed Neutrinos

2 Acknowledgements

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References

[1] "The Field of Streams: Sagittarius and Its Siblings", Belokurov, V. *et al.*, *Astrophys. J. Letters* **642**, L137 - L140 (2006); astro-ph/0605025

[2] "The detection of hot intergalactic gas in the NGC 3607 group of galaxies with the Einstein satellite", Biermann, P., Kronberg, P. P.; Madore, B. F., *Astrophys. J. Letters* **256**, p. L37-L40 (1982)

[3] "Detection of 10^{10} $M_\odot$ of hot gas in the normal elliptical galaxy NGC 5846 with the Einstein satellite", Biermann, P., Kronberg, P. P., *Astrophys. J. Letters* **268**, p. L69-L73 (1983)

[4] "Relic keV sterile neutrinos and reionization", P.L. Biermann & A. Kusenko, 2006, *Phys. Rev. Letters* **96**, 091301 (2006); astro-ph/0601004

[5] "Ultra high energy cosmic rays from sequestered X bursts [rapid communication]", P.L. Biermann & P. Frampton 2006, *Physics Letters B*, **634**, p. 125-129 (2006); astro-h/0512188

[6] 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

[7] The mass function of nearby black hole candidates, Laurentiu I. Caramete, Peter L. Biermann, in press *Astron. & Astroph.* (2009); arXiv:0908.2764

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

[9] "Cosmic-ray protons and magnetic fields in clusters of galaxies and their cosmological consequences", Torsten A. Enßlin, Peter L. Biermann, Philipp P. Kronberg, and Xiang P. Wu, *Astrophys. J.* **477**, 560 (1997); astro-ph/9609190

[10] “The Origin of the Bifurcation in the Sagittarius Stream”, Fellhauer, M., *et al.*, (2006); astro-ph/0605026

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

[12] Supermassive black hole spin-flip during the inspiral, Gergely, László Á., Biermann, Peter L., Caramete, Laurentiu I., *Classical and Quantum Gravity* in press (2010); arXiv:1005.2287

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

[14] Ultra high energy cosmic rays from Centaurus A: jet interaction with gaseous shells, Gopal-Krishna, Peter

L. Biermann, Vitor de Souza, Paul J. Wiita, in press *Astrophys. J. Letters* (2010); arXiv:1006.5022

[15] "The smallest AGN host galaxies", Greene, J.E., Barth, A.J., Ho, L.C., *New Astron. Rev.* **50**, 739 - 742 (2006); astro-ph/0511810

[16] Hogan, C. J., Dalcanton, J. J., *Phys. Rev.* **D 62**, id.063511 (2000); arXiv:astro-ph/0002330

[17] Jarosik, N. et al. , Seven-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Sky Maps, Systematic Errors, and Basic Results, (2010) eprint arXiv:1001.4744

[18] "Five-year WMAP observations: Cosmological interpretation", Komatsu, E. et al., submitted *Astrophys. J. Suppl.* (2008); arXiv:0803.0547

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

[20] "Fast Growth of supermassive black holes in Galaxies", F. Munyaneza & P.L. Biermann, *Astron. & Astroph.* **436**, 805 - 815 (2005); astro-ph/0403511

[21] "The force exerted by the stellar system perpendicular to the galactic plane and some related problems", Oort, J.H., *Bull. Astron. Inst. Netherl.* , **VI**, 249 (1932)

[22] "First-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Determination of Cosmological Parameters", Spergel, D.N., *et al.*, *Astrophys. J. Suppl.* **148**, 175 (2003); astro-ph/0302209

[23] "Wilkinson Microwave Anisotropy Probe (WMAP) Three Year Results: Implications for Cosmology",

Spergel, D.N., *et al.*, *Astrophys. J. Suppl.* **170**, 377 - 408 (2007); astro-ph/0603449

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

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

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

[27] "Signatures for a Cosmic Flux of Magnetic Monopoles", Stuart D. Wick, Thomas W. Kephart, Thomas J. Weiler, Peter L. Biermann, Astro. Part. Phys. **18**, 663 - 687 (2003), astro-ph/0001233

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

[29] Zwicky, F. *Helv. Phys. Acta* **6**, 110 (1933)

[30] "On the masses of nebulae and of clusters of nebulae", Zwicky, F., *Astrophys. J.* **86**, 217 (1937)