Cosmological and astrophysical signatures of Warm Dark Matter

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AMS 2014: Positrons > 30 GeV: DM decay?

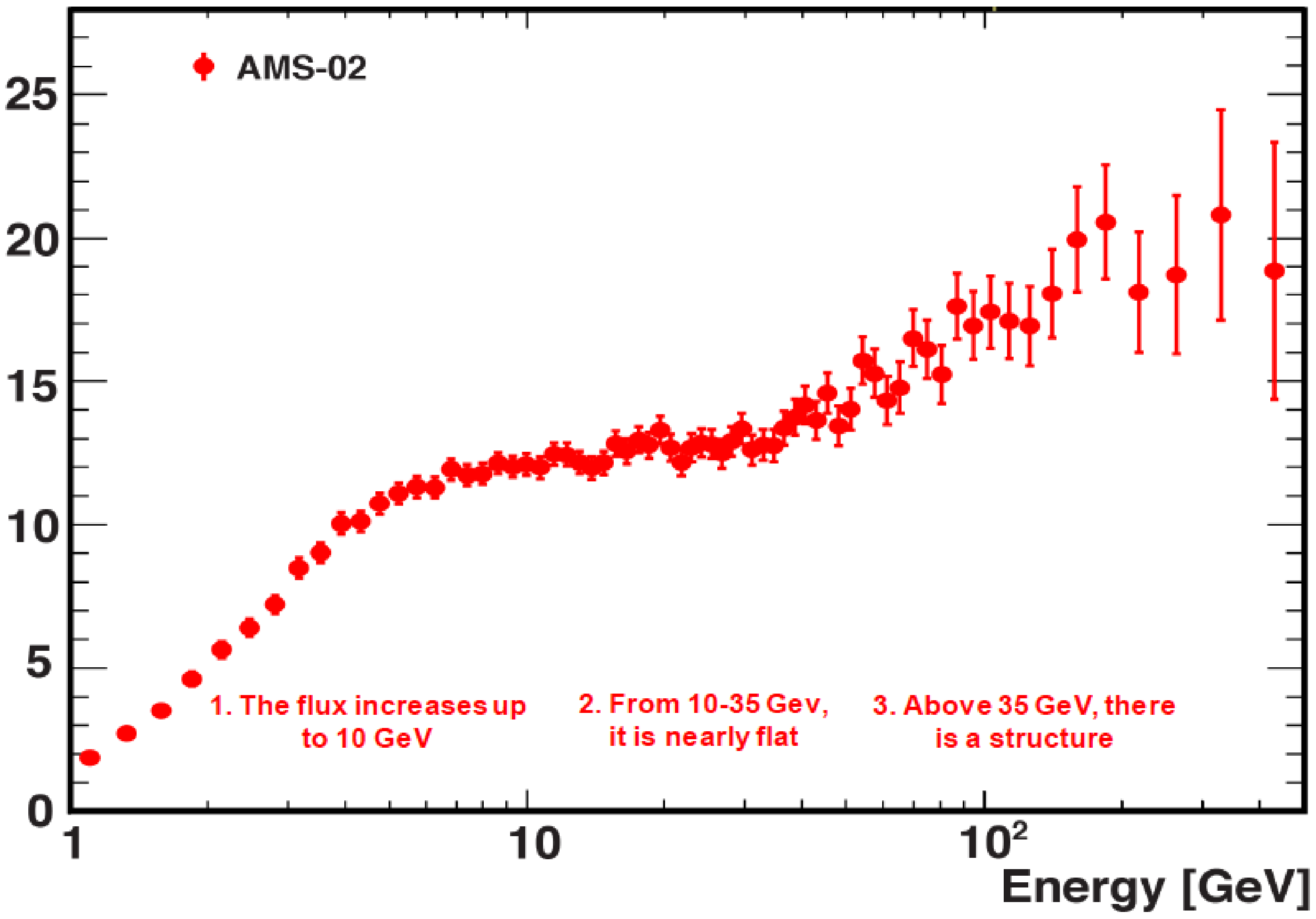


Figure 1 The cosmic ray positrons in AMS data. Source AMS-Coll. 2014

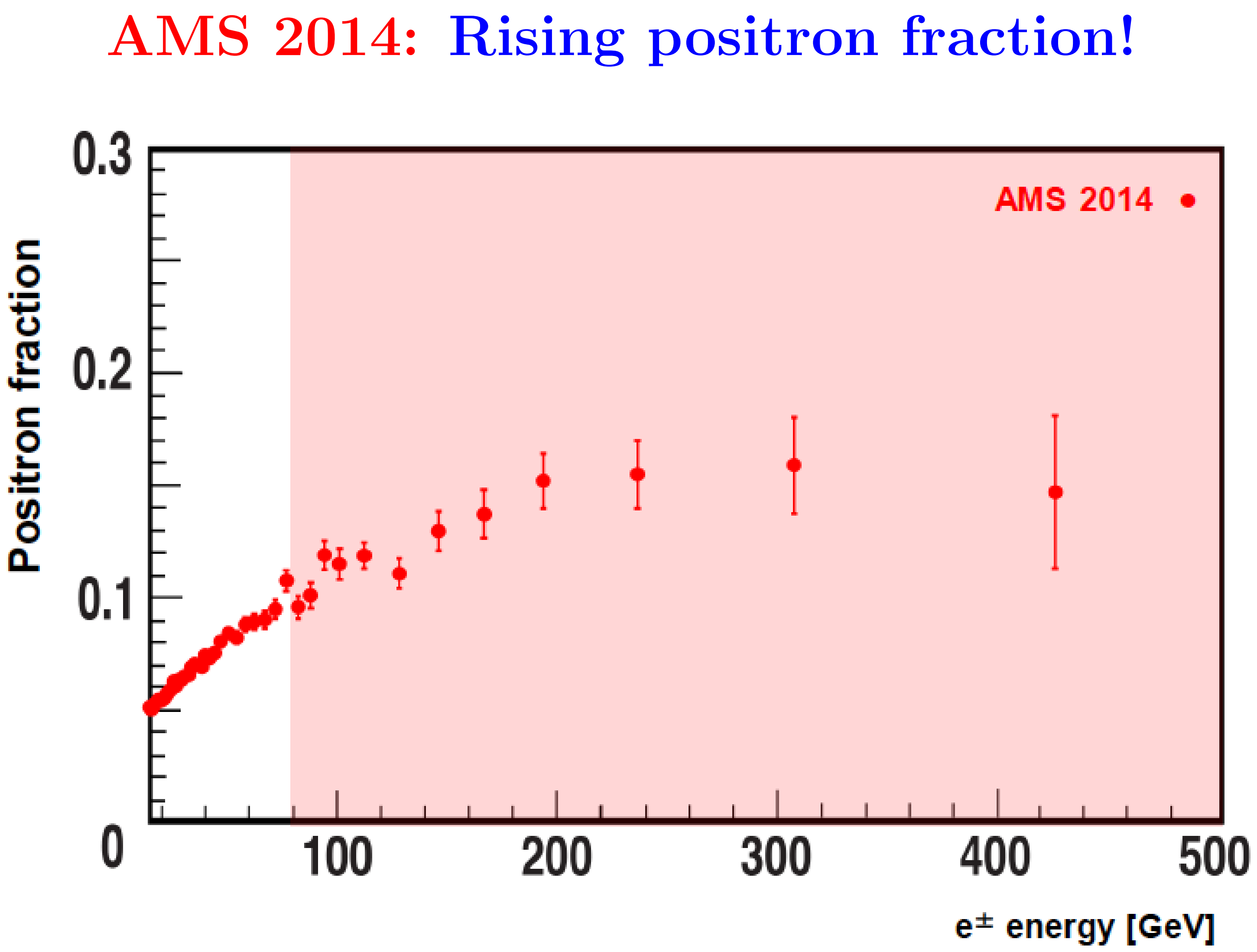
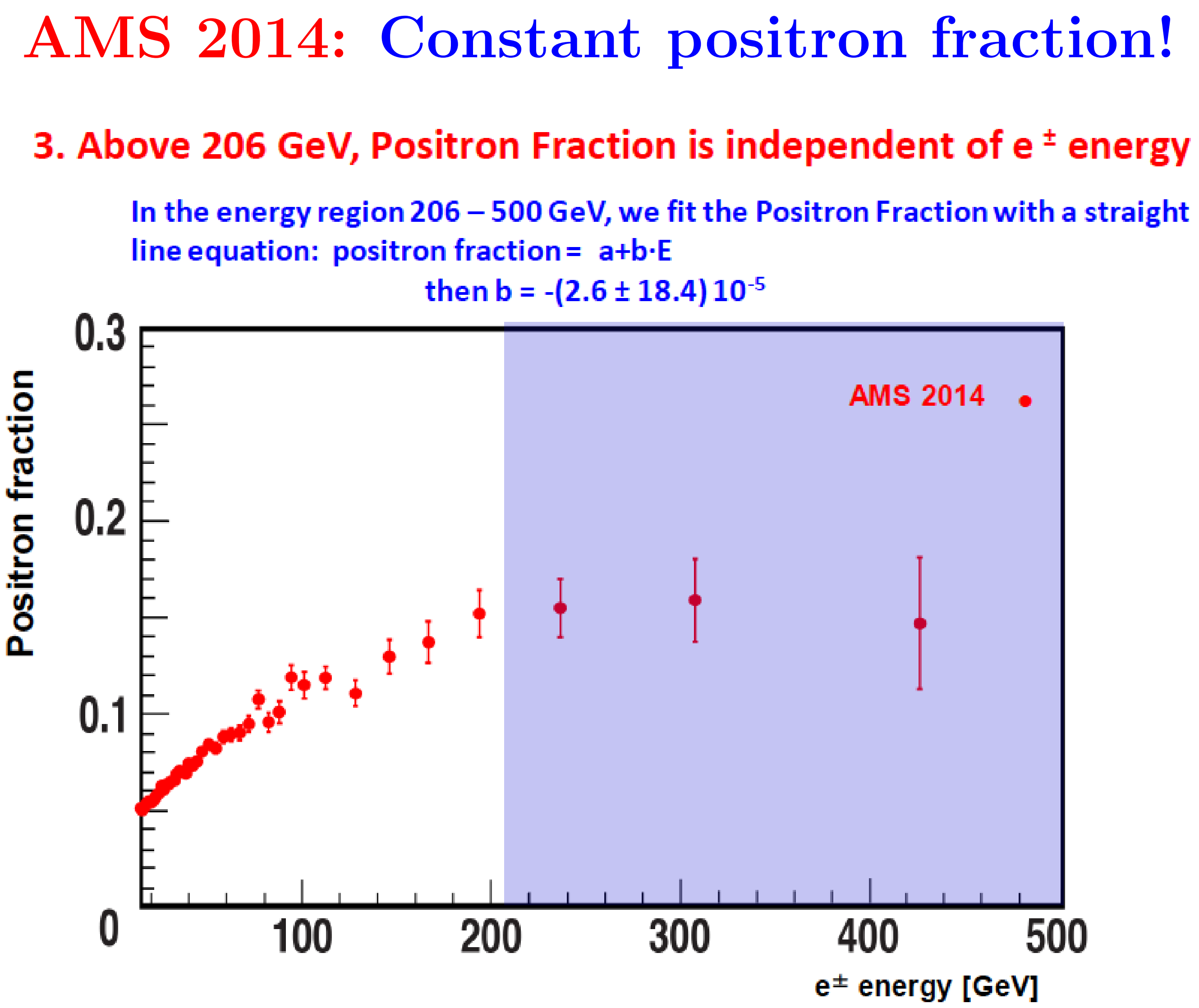


Figure 2 The cosmic ray positron fraction in AMS data. Source AMS-Coll. 2014



AMS 2014: Constant positron fraction!

3. Above 206 GeV, Positron Fraction is independent of e ± energy

In the energy region 206 – 500 GeV, we fit the Positron Fraction with a straight line equation: positron fraction = a+b·E

then b = -(2.6 ± 18.4) 10^{-5}

Figure 3 The cosmic ray positron fraction in AMS data. Source AMS-Coll. 2014

AMS 2014: e^- and e^+: $>$ 200 GeV plateau?

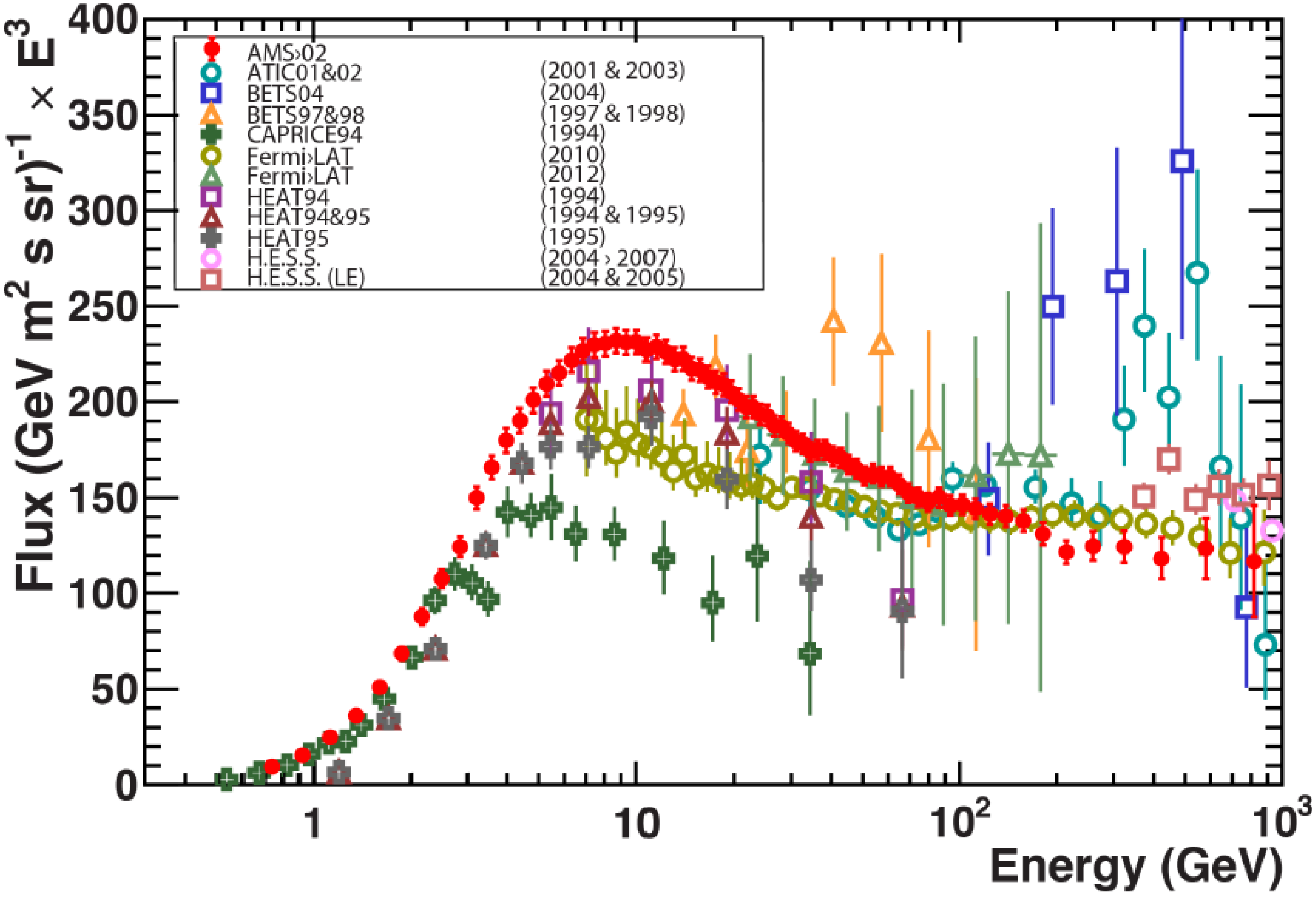


Figure 4 The cosmic ray electrons plus positrons in AMS data. Source AMS-Coll. 2014

AMS 2014: Interpretation attempts

- **Dark matter decay ?** Possible to fit all data? Gamma ray data with the same ansatz? Predictive power?
- **Pulsars ?** Can we fit the data? Predictive power?
- Many other possible and quite plausible sources:
- **Supernova remnants ?** with enhancement of magnetic fields: Weibel 1959, Bell & Lucek 2001
- **Active stars ?** GRBs, microquasars ?
- **OB super-bubbles ?** Binns et al. from 2005
- **Geminga ?** Yüksel et al. 2009
- **Explosions of stars into their winds ?** predictions 1993

A massive star and its magnetic field

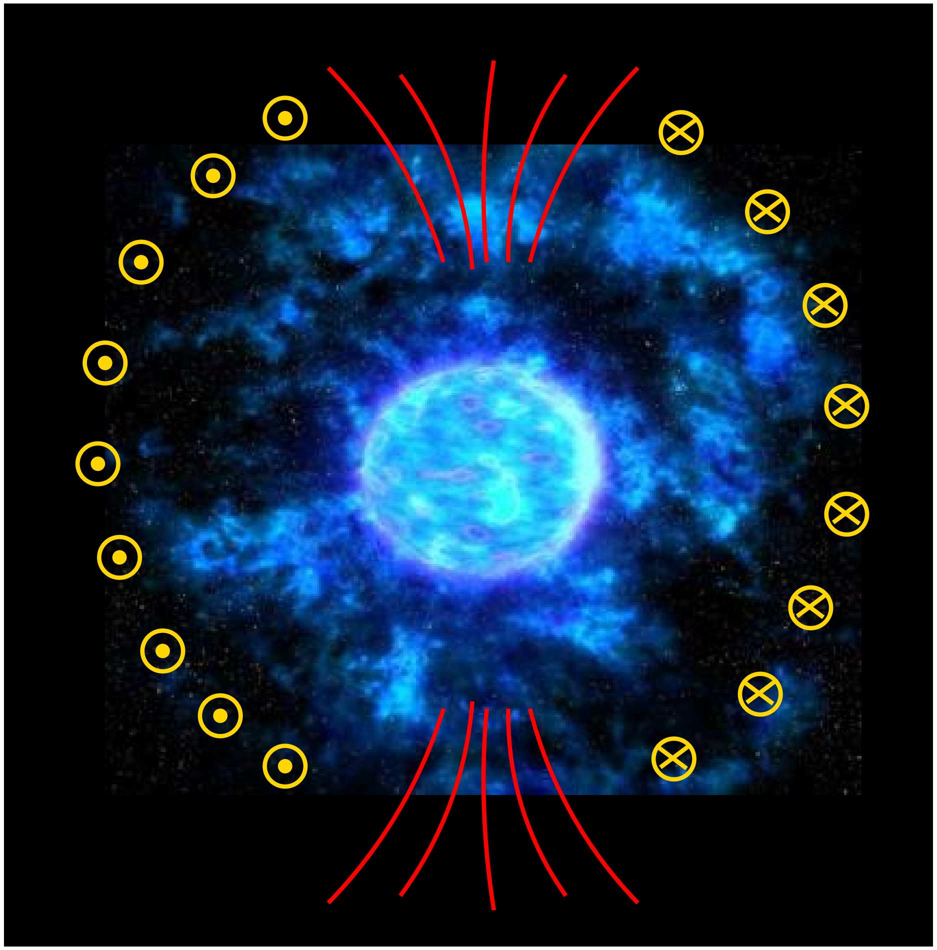


Figure 5 Magnetic field topology around a massive star in its wind: Graph following Parker 1958; central graph NASA, Wolf Rayet star WR124

Polar cap component E^{-2} in source: 1993

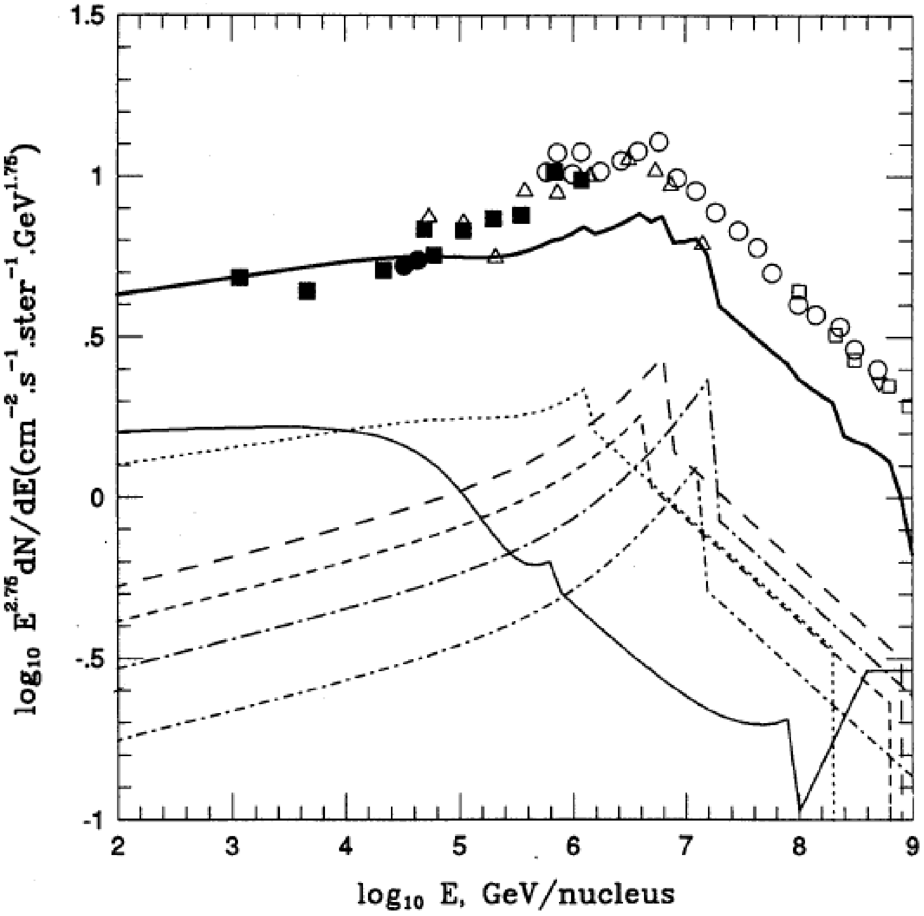


Figure 6 Spectral and chemical structure at the knee. Element groups are H, He, CNO, Ne-S, Cl-Mn, and Fe. Kink at $\sim 10\,Z$ TeV. Source: Stanev et al., paper CR-IV 1993

Explosion into winds? + 1993 + 2001 + 2009

- Massive stars explode into magnetic wind with a shell
- Winds have Archimedian spiral magnetic field
- Explosion leads to shock racing through wind and wind shell, **spectrum** $\boldsymbol{E^{-7/3}}$ at source, $\boldsymbol{4\pi}$-component
- **Polar cap** component, where magnetic field locally radial, either at pole or in some turbulent elements, **spectrum** $\boldsymbol{E^{-2}}$ at source
- Interaction has more time in **polar cap**, so secondary polar cap component shifted down in energy relative to $\boldsymbol{4\pi}$-component
- **2009** (PLB et al. PRL): positron fraction $\boldsymbol{E^{+1/3}}$; test with 511 keV data (PLB et al. 2010 ApJL); consistent with AMS 2014 to almost 200 GeV

New versus old physics ? AMS 2014

- **Positron flux**: up to 10 GeV threshold effect - Ray Protheroe 1982 ApJ; however, only 1 g/cm^2 for protons (Nath et al. 2012 MNLett), based on new data; about 10 g/cm^2 for nuclei, based on CR-isotopes, so **interaction in wind-shells** or OB-association bubble shell much better for lots of positrons

- 10 - 35 GeV: **polar cap component**

- Positron fraction $E^{+1/3}$ until CR-electrons also hit polar cap component, then flat

- $>$ 35 GeV: could this be **triple pair production** $->$ cutoff (work by **Eberhard Haug**, 1975 - 2014)?

Triple pair production $\frac{d\sigma}{d\epsilon_+}$: Eberhard Haug

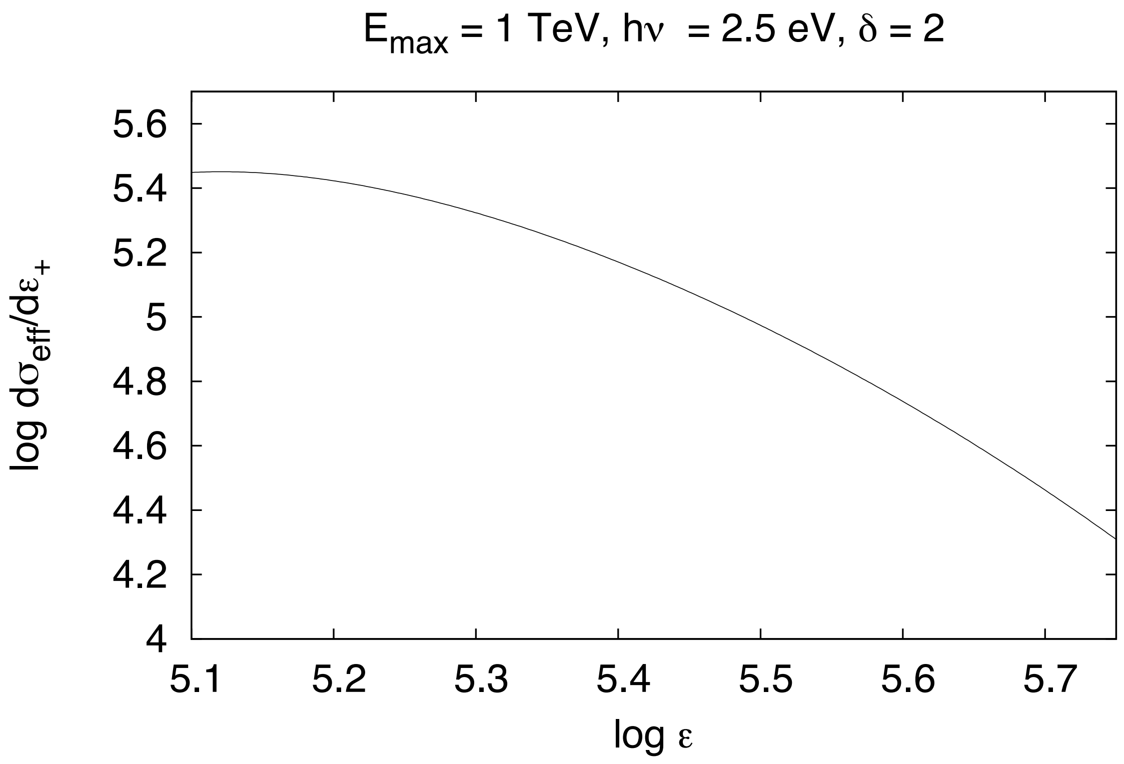


Figure 7 Triple pair production spectrum $\frac{d\sigma}{d\epsilon_+}$, with $E_{e^+} = \epsilon_+ \times m_e c^2$; this function has to be multiplied by ϵ_+^2 to make it comparable in shape to observed positron spectrum, which is in loss limit (Kardashev 1963), so steeper by 1 in slope; in terms of observed positron spectrum (multiplied by E^3, to compensate the losses) this example here (multiplied by E_e^2) reaches a maximum at an electron energy of 110 GeV (equivalent to $\epsilon_+ = 5.34$). This uses a δ-fct of photons, using a $E_{e^-}^{-2}$-spectrum in source: adding different photon spectra together a more general triple-pair production function can be constructed. Source: E. Haug 2014

Open question after AMS 2014?

- **Upturn for nuclei** near 10 Z TeV !
- **Upturn for electrons** in source near 200 GeV?
- Injection conditions different for parallel magnetic fields (**polar cap** component) and nearly perpendicular magnetic field (most of $\boldsymbol{4\pi}$)?
- Source of radiation field for triple pair production (Eberhard Haug)? predicts cutoff !
- Light from binary partner star? Basically all upper main sequence stars are in binary systems (e.g. Chini et al.). Combined light from **OB association**!
- **How to distinguish from other contributions?**

Check on positron origin
Massive star explosions into winds

- Work with Andreas Brunthaler, Athina Meli, Eun-Suk Seo, Todor Stanev, & Julia Becker Tjus

- Radio data now available for radio supernovae, one red supergiant star explosion, others WR star explosions
- Maximal containable energy $\sim (R\,B)$, possible for highly oblique shocks (Jokipii 1987),
- Energy gains in shocks depends on drifts, as moving through a magnetic field engenders an electric field, in which charged particles drift gaining energy (Jokipii 1987)

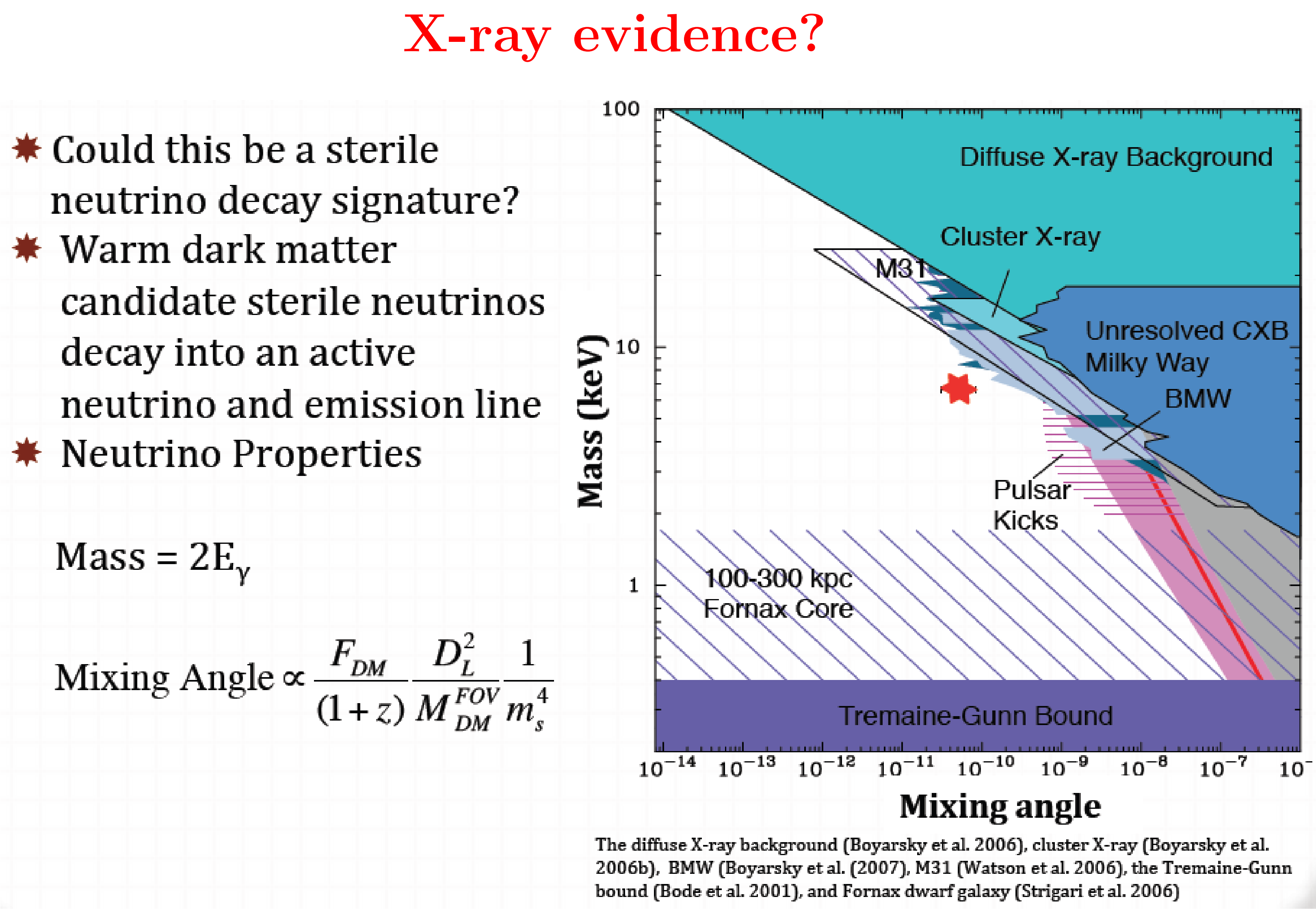
Knee and ankle energies

- Critical energy for drift energy gain $\sim R\,B\,(V_{sh}/c)^2$.
- Average of $\log\{R\,B\}$ is 15.9 ± 0.2;
- $->$ $\boldsymbol{E_{max} \;=\; Z\;\; 10^{17.3\pm0.2}}$ eV: **CR ankle**,
- Average of $\log\{R\,B\,(V_{sh}/c)^2\}$ is 14.3 ± 0.3;
- $->$ $\boldsymbol{E_{kink} \;=\; Z\;\; 10^{15.3\pm0.3}}$ eV: **CR knee** ; (See PLB 1994): fit data separately (e.g. PLB & de Souza 2012). But, this stems from **many SNe**
- **Explosions into stellar winds: ankle and knee**
- **Problem/prediction? all wind-SNe similar!**
- **ISM-SNe, pulsar winds, active stars match ?**
- **Consistency check on AMS positrons/electrons!**

DM particle decay: Early star formation

- Sterile neutrino decays, X-ray photon ionizes IGM
- Claim: line at 3.5 keV: 1402.2301 (Bulbul et al., ApJ in press) and 1402.4119: DM particle **mass at 7 keV**
- In PLB & Kusenko 2006 PRL used **4 keV** & **7 keV**
- **If** early density spike given by Zeldovich and an unusual phase space distribution, **then**:
- Higher ionization, more H_2, more **cooling** possible?
- $\boldsymbol{z < 100}$: $\boldsymbol{\tau_{cool} < \tau_{Compt} < \tau_{coll}}$; for **7 keV**.
- $->$ **Star formation may start from** $z < 100$
- Detectable via **HD$^+$ absorption lines**

Strong testable prediction by ΛWDM!



X-ray evidence?

- Could this be a sterile neutrino decay signature?
- Warm dark matter candidate sterile neutrinos decay into an active neutrino and emission line
- Neutrino Properties

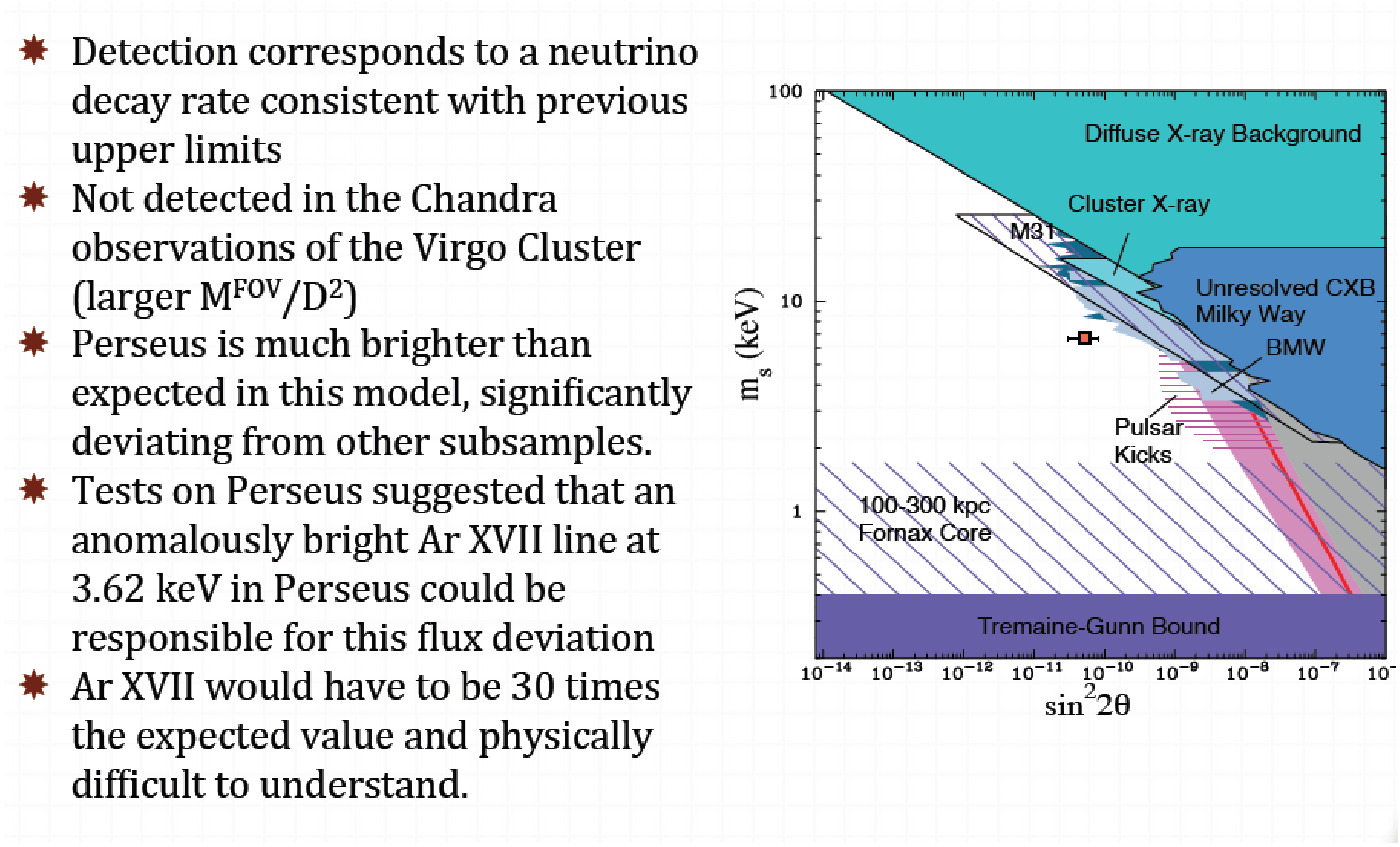
Mass = $2E_\gamma$

$$\text{Mixing Angle} \propto \frac{F_{DM}}{(1+z)} \frac{D_L^2}{M_{DM}^{FOV}} \frac{1}{m_s^4}$$

The diffuse X-ray background (Boyarsky et al. 2006), cluster X-ray (Boyarsky et al. 2006b), BMW (Boyarsky et al. (2007), M31 (Watson et al. 2006), the Tremaine-Gunn bound (Bode et al. 2001), and Fornax dwarf galaxy (Strigari et al. 2006)

Figure 8 The X-ray evidence. Source Esra Bulbul lecture Chalonge 2014 Meudon, p.49

Emission line? Excited by echo (W. Keel)?



- Detection corresponds to a neutrino decay rate consistent with previous upper limits
- Not detected in the Chandra observations of the Virgo Cluster (larger M^{FOV}/D^2)
- Perseus is much brighter than expected in this model, significantly deviating from other subsamples.
- Tests on Perseus suggested that an anomalously bright Ar XVII line at 3.62 keV in Perseus could be responsible for this flux deviation
- Ar XVII would have to be 30 times the expected value and physically difficult to understand.

Figure 9 The X-ray evidence. For echo effects see Keel et al.. Source Esra Bulbul lecture Chalonge 2014 Meudon, p.55

Observed echoes (W. Keel)!

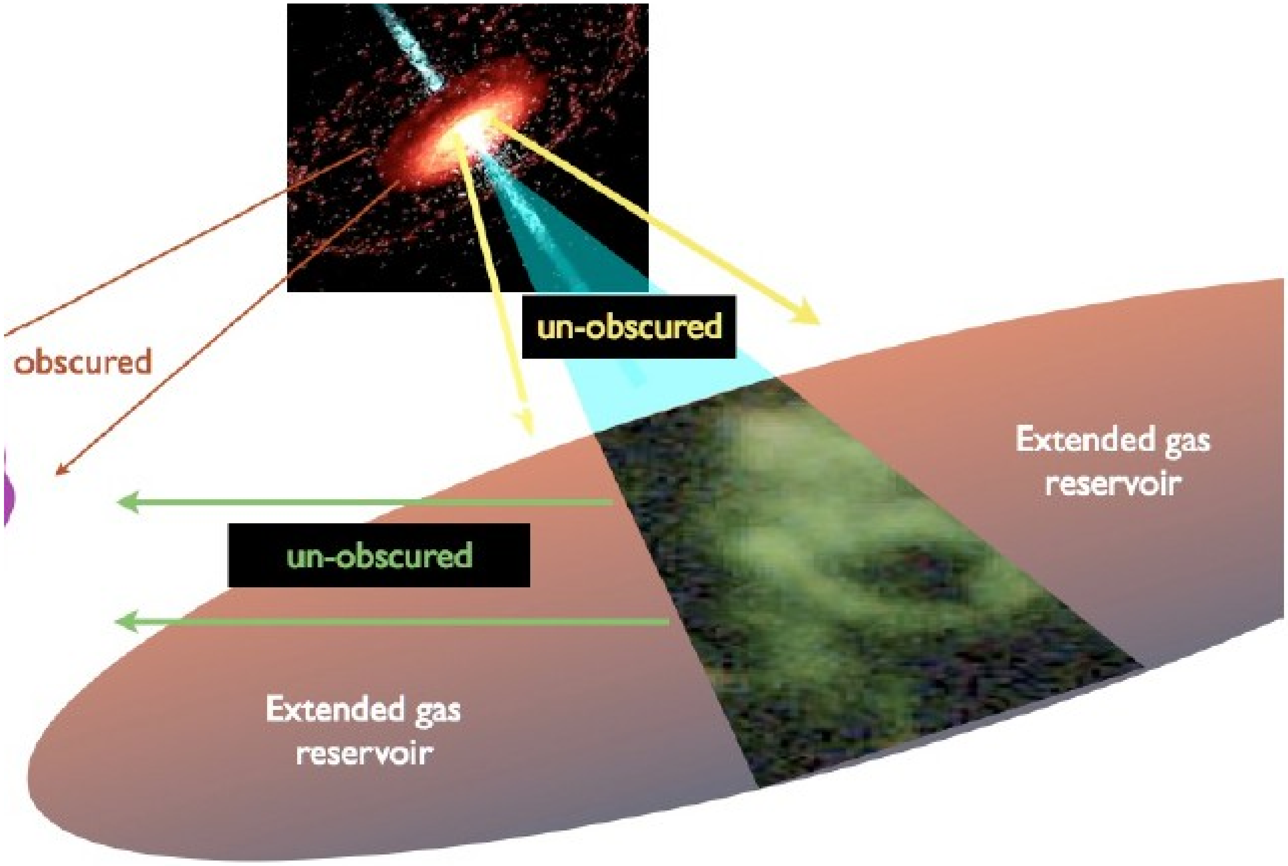
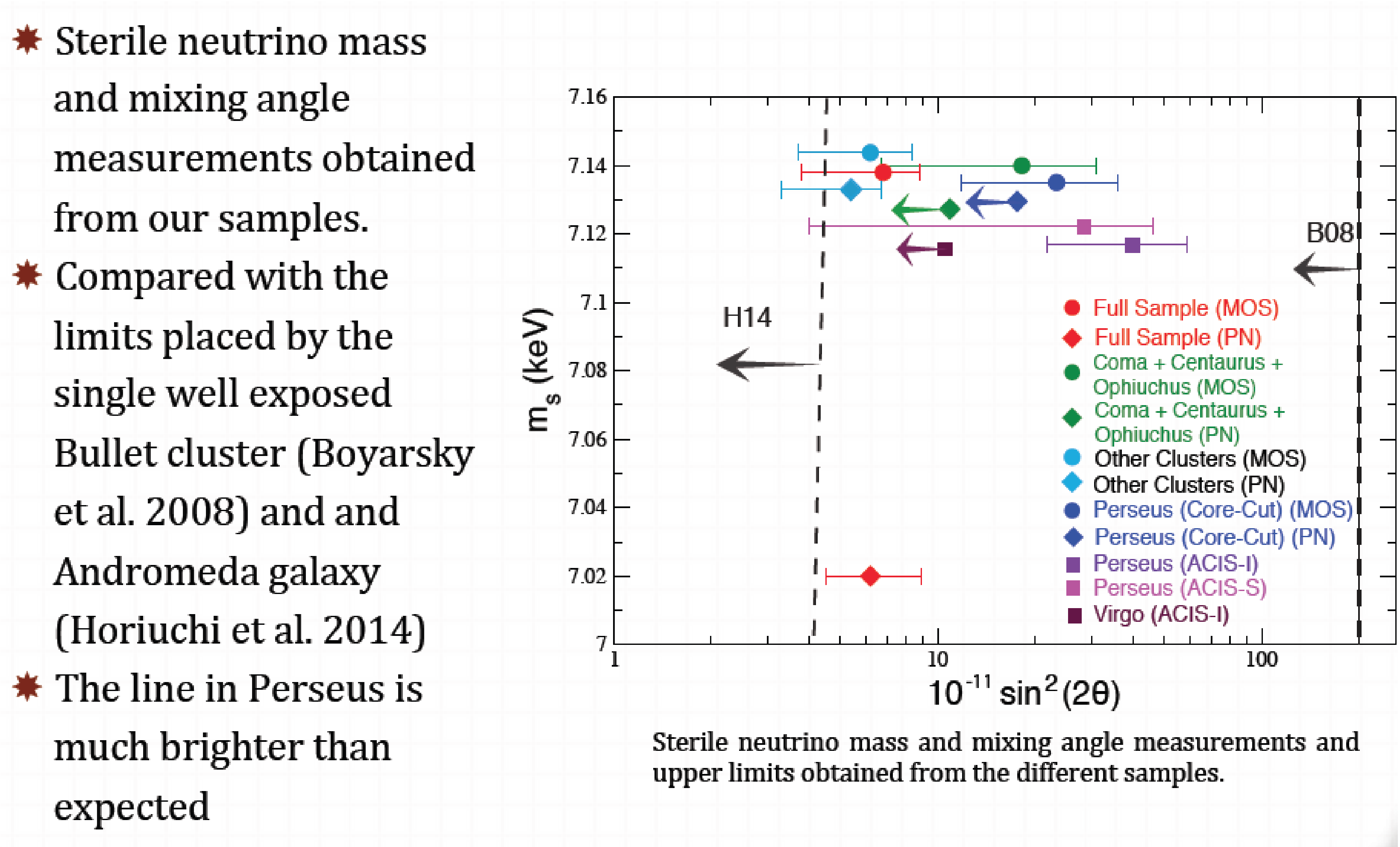


Figure 10 A real echo detected in optical. Source W. Keel et al. 2011.2784, Fig.2

Mixing angle $\sin^2\{2\theta\}$?



- Sterile neutrino mass and mixing angle measurements obtained from our samples.
- Compared with the limits placed by the single well exposed Bullet cluster (Boyarsky et al. 2008) and and Andromeda galaxy (Horiuchi et al. 2014)
- The line in Perseus is much brighter than expected

Sterile neutrino mass and mixing angle measurements and upper limits obtained from the different samples.

Figure 11 The X-ray evidence. Source Esra Bulbul lecture Chalonge 2014 Meudon, p.50

Phase space in dwarf galaxies

- Casey Watson's work (Millikin Univ., Illinois, USA) – see his lecture
- Consider a sequence of well-measured dwarf elliptical galaxies
- The highest phase space density Q must refer to the purest (oldest ?) system
- Do they all have same mass (Gilmore et al.: yes) ?
- Do all dwarf galaxies in thin disk distributions around our Galaxy or M31 (Ibata et al. 2013 Nature, Pawlowski et al. 2013 MNRAS) show a decreased Q ?
- Given mass, and first virialized clumps (can we start with Zeldovich?) we can obtain a redshift dependent phase space distribution

Molecular Hydrogen H_2 formation

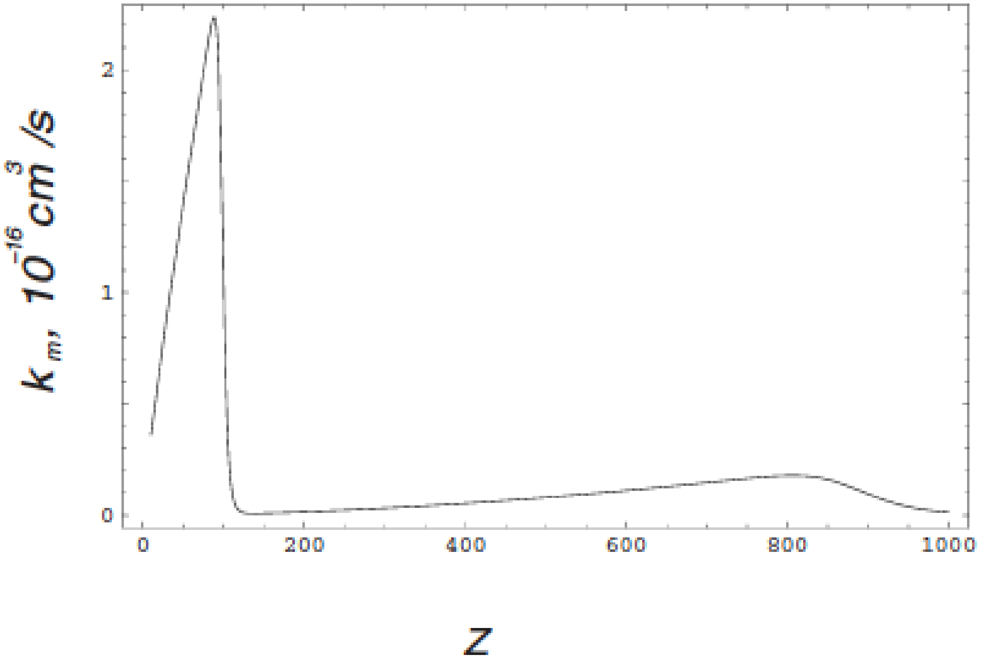


Figure 12 k_m given in the graph; the degree of ionization x_e depends on ionization agents, such a energetic photons from WDM decay. Source PLB & Kusenko 2006 PRL

$$\frac{d\,f_{H_2}}{d\,t} \simeq k_m(t)\,n_H(t)\,x_e(t)$$

Density of virialized clumps?

- Using **Press & Schechter (1974)** density of clumps
- Using **Zeldovich (1970)** density cusps on pancakes
- What effect of partially degenerate (Fermi-Dirac) phase space distribution?
- Are both approaches relevant on different scales?
- Can we obtain a serious instability from the very steep slope of the cluster cooling function?
- WDM decay –> ionization, –> H_2 molecules, –>
- Cooling –> contraction, –> higher DM density, –> more molecules and more cooling
- Can this lead to **run-away cooling and star formation**? what is the mass scale? redshift?

What are cosmic backgrounds?

After recombination and all its ripples:

- First stars (**earlier in ΛWDM**)
- First supernovae
- First super-massive stars, their hyper-novae, their super-massive black holes

all produce backgrounds in

- **Radio, far-infrared, X-rays, γ-rays**
- **Neutrinos**
- **Gravitational waves**
- As do **Galaxies and Active Galactic Nuclei** all along

Galaxies and Active Galactic Nuclei

- Galaxies and starburst galaxies show correlation between FIR emission, radio emission and X-ray emission
- **Thermal + non-thermal emissions related!**
- They probably show a similar **correlation with their neutrino emission.**
- Active Galactic Nuclei (AGN) show a dichotomy in these correlations, with the strongest variation due to radio emission: radio-loud and radio-weak
- AGN all seem to have a relativistic jet; if that jet is pointed at us, huge selection effects, and sometime flat spectra right from radio through the infrared (as for example compact flat spectrum r.s. S5 1803+78)

Radio background

- Three papers (Fixsen et al., Kogut et al., and Seiffert et al. 2011) claim the detection of an isotropic cosmic radio background, with a relatively flat spectrum.
- All known foregrounds have been subtracted (WMAP methods essentially). But see **new Planck results (May 2014 on arXiv)**.
- This background compares with the known radio backgrounds such, that there is **no known radio source population** that could explain it (Condon et al. 2012).
- This background is also so **smooth**, that it again defies all known radio sources (e.g. Holder 2014).

Neutrino background

- The high energy neutrino background has been **detected** (IceCube-Coll. 2013, 2014), also with a relatively flat spectrum, and no identified sources at the location of the published events.
- The spectrum (slightly steeper than $\sim \boldsymbol{E^{-2}}$) seems to cut off around several PeV. No evidence for cut-off if the spectrum is $\sim \boldsymbol{E^{-2.3}}$ or even steeper
- This neutrino background appears to be **isotropic**, but has a weak non-significant clustering near the Galactic Center, providing a clear limit to any anisotropy.

Black holes > $3 \cdot 10^7\, M_\odot$: colors are distance: Black, Blue, Green, Orange, Red

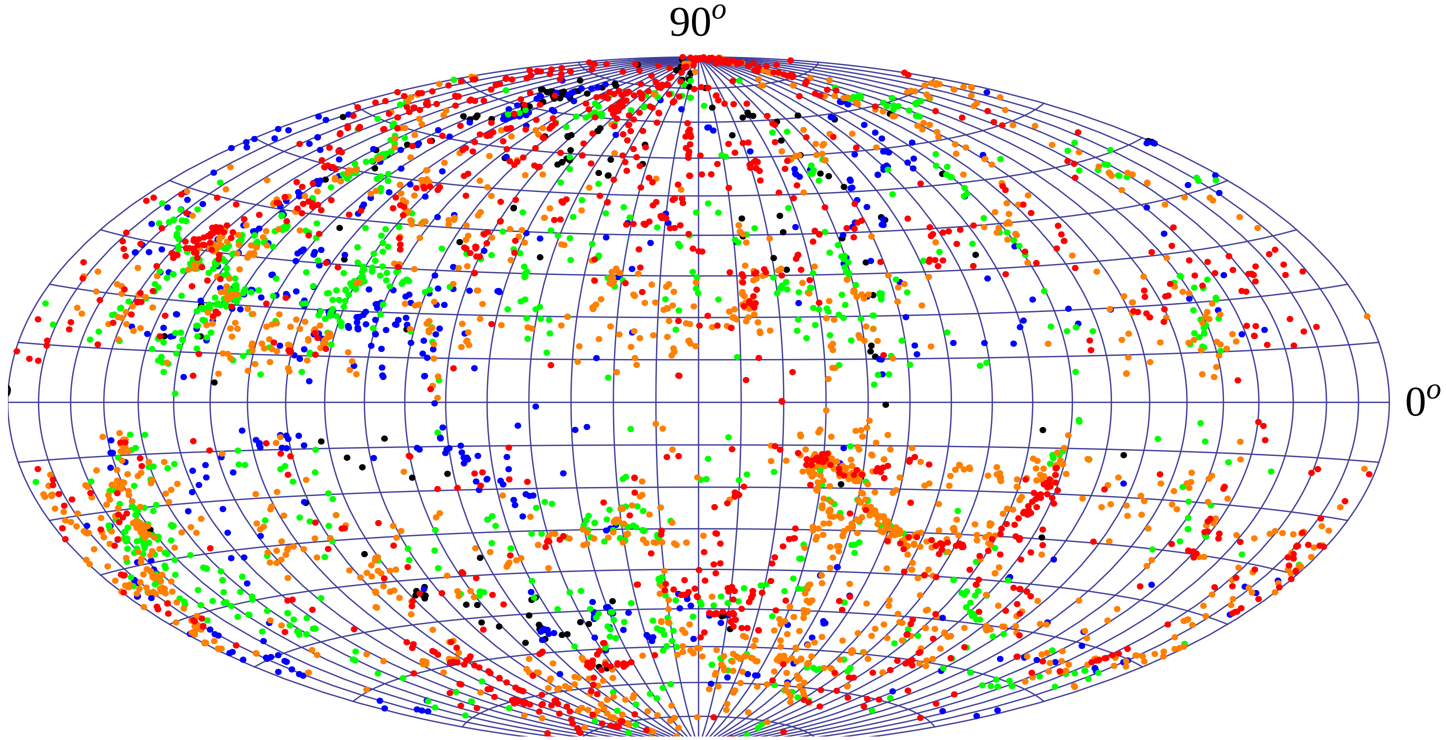


Figure 13 The sky in black holes, $\gtrsim 3 \cdot 10^7\ M_\odot$: The color code corresponds to distance: Black, Blue, Green, Orange, Red for the redshifts intervals 0, 0.005, 0.01, 0.015, 0.02, 0.025, corresponding to distance intervals of 0, 60, 120, 180, 240, and 300 million light-years: (−> Caramete & PLB 2011); coordinate system with Galactic plane across center, and Galactic center at the right edge

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

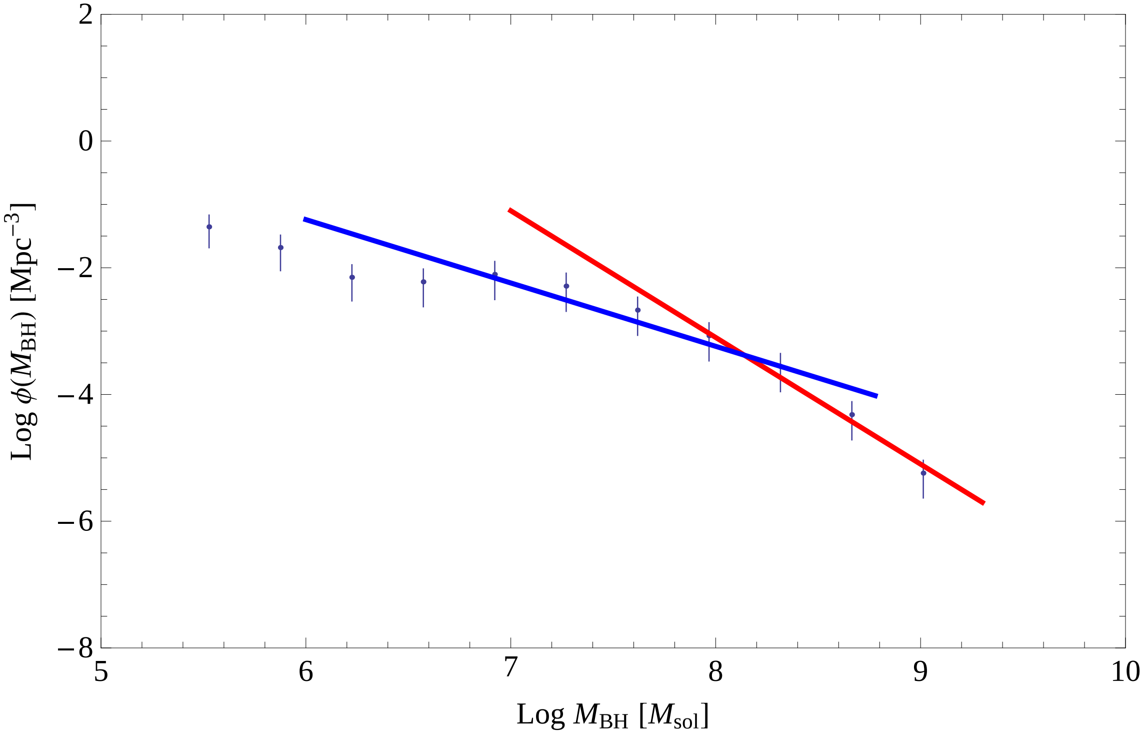


Figure 14 Integral mass function corrected for Hubble type sampling, 2928 objects, the slope of the lines is: red −2.0 fitting $> 10^8\, M_\odot$, and blue −1.0 fitting between $10^7\, M_\odot$ and $10^8\, M_\odot$. See Caramete & PLB, *Astron. & Astroph.* **521**, id.A55 (2010); arXiv:0908.2764. This mass function suggests that black holes start near $3 \cdot 10^6\, M_\odot$, possibly at redshift of order $\sim$ 30 to 80, and grow by merging (see PLB & Kusenko 2006, PRL)

What origin of BH mass distribution?

- Explained as multiple merging from initial narrow mass distribution of seed black holes (Silk & Takahashi 1979), peaking near $\mathbf{3 \cdot 10^6}\, M_\odot$
- **Coagulation equation (Smoluchowski 1916)**, approximate solution using Laplace transform techniques
- Power-law with an exponential cutoff

$$N(m,t) \;=\; C_1\, m^{-2} t^{-2} \exp\{-C_2\, m^{1/3}/t\}$$

- Coagulation in the "gravitational focussing limit", when gravitational forces dominate the cross section

Why this mass of around $3 \cdot 10^6\, M_\odot$?

- Massive stars form in dense groups, that agglomerate rapidly to form more massive star **in DM clump**
- Massive stars have winds, driven by radiation interaction with heavy elements (Lucy & Solomon 1970): maximum several hundred $M_\odot$ (Yungelson et al. 2008)
- At zero heavy element abundance massive stars can grow to much higher mass, close to $\sim 10^6\, M_\odot$
- Radiation pressure with GR gives instability (Appenzeller & Fricke 1972)
- Alternative degenerate DM star, mass depends on DM particle mass (Munyaneza & PLB 2005, 2006)

Black hole mass distribution gives dark matter particle mass estimate !

Original number density of black holes?

- If all growth by mergers, mass is conserved

$$\boldsymbol{N_{BH,0} \; = \; 10^{-1.1 \pm 0.40} \left(\frac{M_{BH,min}}{3 \cdot 10^6 \, M_{\odot}} \right)^{-1} \; Mpc^{-3} \; .}$$

- Allowing extra factor of 10 from **selection effects, statistics, incompleteness and sampling errors**

$$\boldsymbol{N_{BH,0} \; = \; 1.0 \, Mpc^{-3}}$$

allowed (comoving); at redshift somewhere between 20 and perhaps 100 (PLB & Kusenko 2006 PRL).

The explosion energy

- The observations show that the (perhaps initial) black holes have a mass between about $10^6\, M_\odot$ and $10^7\, M_\odot$
- Super-nova explosions leading to black holes give BH mass of about 5 - 10 $M_\odot$
- They produce anywhere between 10^{51} ergs and 10^{52} ergs in visible energy, depending on what type of SN is used (980425 was extreme)
- Assuming that the energy scales with BH mass we obtain an energy running from 10^{56} ergs to $10^{58.3}$ ergs
- As reference we use $10^{57}\, E_{57}$ ergs
- Relative to $M_{BH}\, c^2$ this corresponds to an efficiency of $\boldsymbol{10^{-3.8}\, E_{57}/M_{BH,6.5}}$ – **why so inefficient?**

The radio and neutrino background I

PLB, Nath, B.B., Caramete, L.I., Harms, B.C., Stanev, T., Tjus, J.B., *Month. Not. Roy. Astr. Soc.* **441**, 1147 - 1156 (2014); arXiv:1403.3804

Super-massive stars form and explode, making a **big black hole**, producing a radio remnant:

- Magnetic fields and cosmic rays:

$$B \approx 10^{-5.44}\,\eta_{B,-1}^{1/2}\,E_{57}^{1/5}\,z_{1.3}^{9/10}\,\{\Delta t\}_{15}^{-3/5}\,\text{Gauß}$$

$$C \approx 10^{-6.9}\,\eta_{CR,e,-1}\,E_{57}^{2/5}\,z_{1.3}^{9/5}\,\{\Delta t\}_{15}^{-6/5}\,,$$

- Luminosity at radio wave-lengths:

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

The radio and neutrino background II

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

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

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

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

The radio and neutrino background III

Predicted (2012) neutrino flux - observed (IceCube 2013).

$$\boldsymbol{F_{neutr} \; = \; 10^{-7.5} \, N_{BH,0,0} \, E_{57} \, \eta_{CR,p,-1} \, z_{1.3}^{0.8}}$$
$$\mathbf{GeV \, cm^{-2} \, s^{-1} \, sr^{-1}} \, ,$$

matches observation. With radio bg condition

$$E_{57}^{0.32} \frac{\eta_{B,-1} \, \eta_{CR,e,-1}}{\eta_{CR,p,-1}} \; \simeq \; 10^{1.3} \; >> \; 1 \quad \textbf{Problem}?$$

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

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

Can explain **the very many massive bulge-less disk galaxies** and their high redshift growth (Conselice et al.): **Most galaxies never merged!**

The radio and neutrino background IV

- Can we rule out galactic contribution to claimed background with certainty?
  Spectrum, polarization, and correlations ?
- However, several new papers consider the flux and spectrum and argue against this possibility
- Why so smooth? Many extended overlapping sources, the hyper-nova remnants
- Source counts? Poisson noise of many overlapping extended sources equivalent to very many point sources
- Spectrum: as expected for expansion into a non-magnetic plasma
- Trade-off: observations “give” $N_{BH}(1+z)^{0.8}$, so increasing redshift from 20 to, say 50, gives factor of 2

The polarization of the radio background

- Analogy with normal SNRs, with several patches, a patch may reach **$>$ 20 %** in polarization
- Each hyper-nova remnant (HNR) polarized
- Many of them overlapping, uncorrelated averaging
- With lower wave-number larger angle, larger number of HNRs, more uncorrelated averaging
- If magnetic fields **primordial, correlation possible** $->$ different slope of wave-number dependence
- Predicted polarization of radio bg fluctuations **strongly increasing function of wave-number**
- **One** contributor to polarization, one of many

The gamma and neutrino background

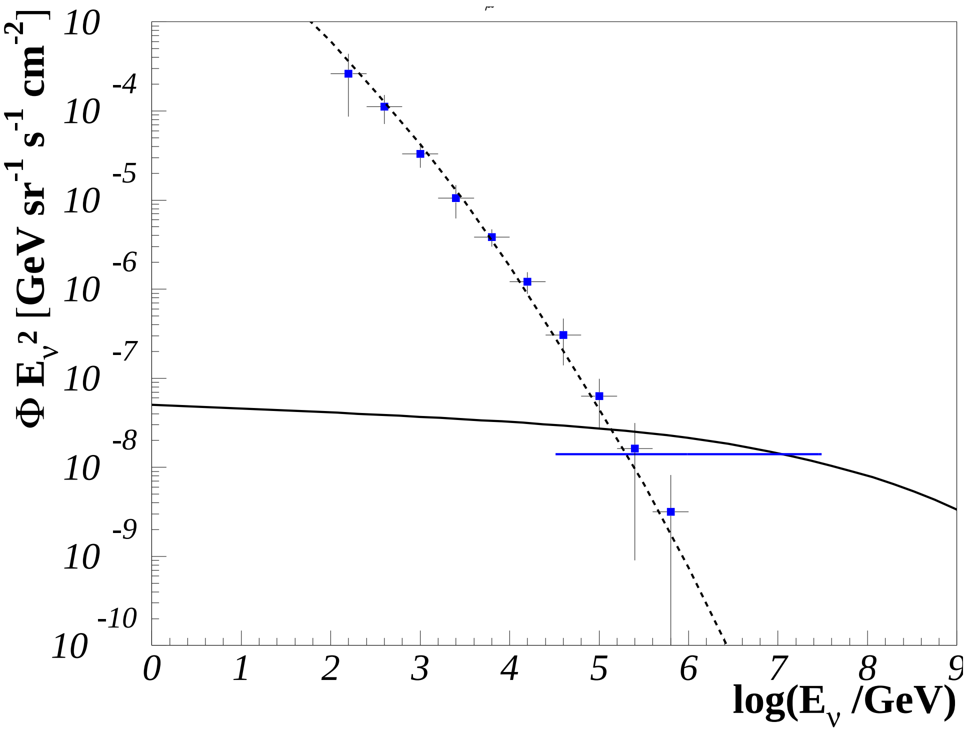


Figure 15 Predicted background neutrino flux and IceCube data: source Julia Becker Tjus 2013, included in paper PLB et al. 2014. The Limit is an integral for an assumed spectrum of $E-2$ without cutoff; here we have $E^{-2.2}$ and a cutoff, so it is consistent. There is a accompanying γ-ray background close to what is observed.

Radio source counts

- If we assume that radio background is cosmological and unresolved, then **no known population of radio sources** can explain the radio background (Condon et al. 2012)
- Also, no known radio source population can explain the smoothness of this radio background (Holder 2014)
- **Observed radio source counts** have been used!
- Under this assumption galaxies, starbursts and AGN all **fail**.
- If we just focus on neutrino background, then all these source classes **pass**!
- Key difference then **neutrino spectrum**!

Galaxies and starbursts

- Galaxies and starburst galaxies dominate FIR background (e.g. Dole & Lagache 2005)
- Galaxies and starburst with neutrino spectrum corresponding to observed spectrum of CR particles, with neutrino **turn-off near 100 TeV** due to “CR-knee”;
- Spectrum just below turn-off of about $\boldsymbol{E^{-2}}$ if most interaction very near sources, and $\boldsymbol{E^{-2.3}}$ if ISM.
- At lower energies $\boldsymbol{E^{-2.7}}$ if interaction in ISM.
- As starbursts evolve, ratio protons to C/O-nuclei extremely variable and so **neutrino/FIR ratio** from interaction correspondingly extreme range
- In AGN using starburst as seed for UHECR particles, same range

Radio galaxies, blazars and quasars

- The average radio galaxy has an implied CR spectrum of about $\boldsymbol{E^{-2.6}}$ (Gregorini et al. 1984) and so should show a corresponding neutrino spectrum again to very high energy.
- Since the strongest emission from the outer lobes, losses ought to be cosmic backgrounds, so relatively low, but strongly redshift-dependent.
- Seyfert galaxies and similar quasars have most interaction near the center of activity (e.g. Nellen et al. 1993), so maximal energy is limited by extreme losses, so $< \mathbf{PeV}$

Highest energies?

- AGN pointed at us may have a spectrum close to $\boldsymbol{E^{-2}}$, as observed in some radio hot spots, reach neutrino energies $>$ **EeV**.
- In relativistic radio jets maximal neutrino energy from trade-off between losses and magnetic field-power correlation (Lovelace 1976), maximum around **50 EeV**,
- with boosting possibly $\lesssim$ **10 ZeV**

Cosmologically local sources

- In the background integral (e.g. Olbers 1826) different distances D contribute equally
- As volume rises with D^3, and observed flux with D^{-2}
- Turnoff at fully cosmological distances, redshift of order unity and beyond
- Given a sufficiently large number of neutrino events, some should come from recognizably “small” distances
- So even a single certain identification of a HE neutrino source will help
- At some level our own galaxy ought to contribute
- If CR sources do most interaction, spectrum corresponding

Odd coincidence for SMBH model

- What energy budget when making a black hole? Limit is (1/2) $M_{BH}\, c^2$ for spin zero BH.
- Then energy density of order

$$\frac{1}{2}\, \boldsymbol{N_{BH,0}\, M_{BH}\, c^2 (1 + z_\star)^3}$$

- Gravitational waves?
- For $N_{BH,0} \simeq 1\, Mpc^{-3}$, $M_{BH} \simeq 10^7\, M_\odot$, and $z_\star \simeq 30$ the number is $\sim 10^{-8}\, erg/cc$, rather close to DE
- Large uncertainties in $N_{BH,0}$, M_{BH}, and also $z_\star$.
- Can energy supply from "outside" mimic an equation of state of $P = -\rho\, c^2$? Answer is yes (PLB & Harms).

Original explosion making first generation of SMBHs detectable?

- Their mass requires local potential well commensurate with free-streaming length of keV Fermion
- **Energies?** 10^5 times more energetic
- **Time scale?** at least 10^5 times slower
- **Luminosity?** days to weeks instead of seconds
- **Redshift?** **? $\sim$ 20 to about $\sim$ 70**
- **Spectrum** even more redshifted...
- **Largest unknown:** Mass overburden, highly relativistic?

How to confirm the dark matter particle?

(a) X-ray detection: —> **DM particle mass** $m_{DM,1}$
(b) Minimum galaxy —> **DM particle mass** $m_{DM,2}$
(c) Original density —> galaxy mass —> **consistent ?**
(d) z star formation: —> **DM particle mass** $m_{DM,3}$
(e) All Σ: —> **DM phase space distrib. & formation**

Confirmation:

(1) Identify the **oldest dwarf ellipticals**
(2) Detect the **explosions** giving SMBHs
(3) Detect massive shells around these explosions in **HD^+ absorption**

Thank you!

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