Warm Dark Matter and its astrophysical signatures

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Hector de Vega - in memoriam

Challenges

- 1 **Evidence for dark matter**
- 2 **Energetic positrons**
- 3 **Anti-protons**
- 4 **X-ray data**
- 5 **Early star and Black Hole formation**
- 6 **The neutrino horizon**

Evidence for dark matter

- Clusters of galaxies (Zwicky 1933)
- Galaxy rotation curves (Rubin)
- Stability of galactic disks (Ostriker, Peebles)
- Matching MWBG fluctuations (Planck 2013):

  $\Omega_\Lambda = 0.692 \pm 0.010$

  $\Omega_{dm} = 0.2582 \pm 0.0047$ DARK MATTER

  $\Omega_b = 0.0482 \pm 0.00076$

  $\Omega_k = 1 - \Omega_\Lambda - \Omega_{dm} - \Omega_b = -0.0005 \pm 0.0066$
  −> "flat" geometry, like a perfect tabletop
- Ell. gal., e.g. NGC5846 (PLB et al. 1983)
- Dwarf elliptical galaxies (Hogan & Dalcanton and very many later papers)

Evidence for dark matter in galaxies

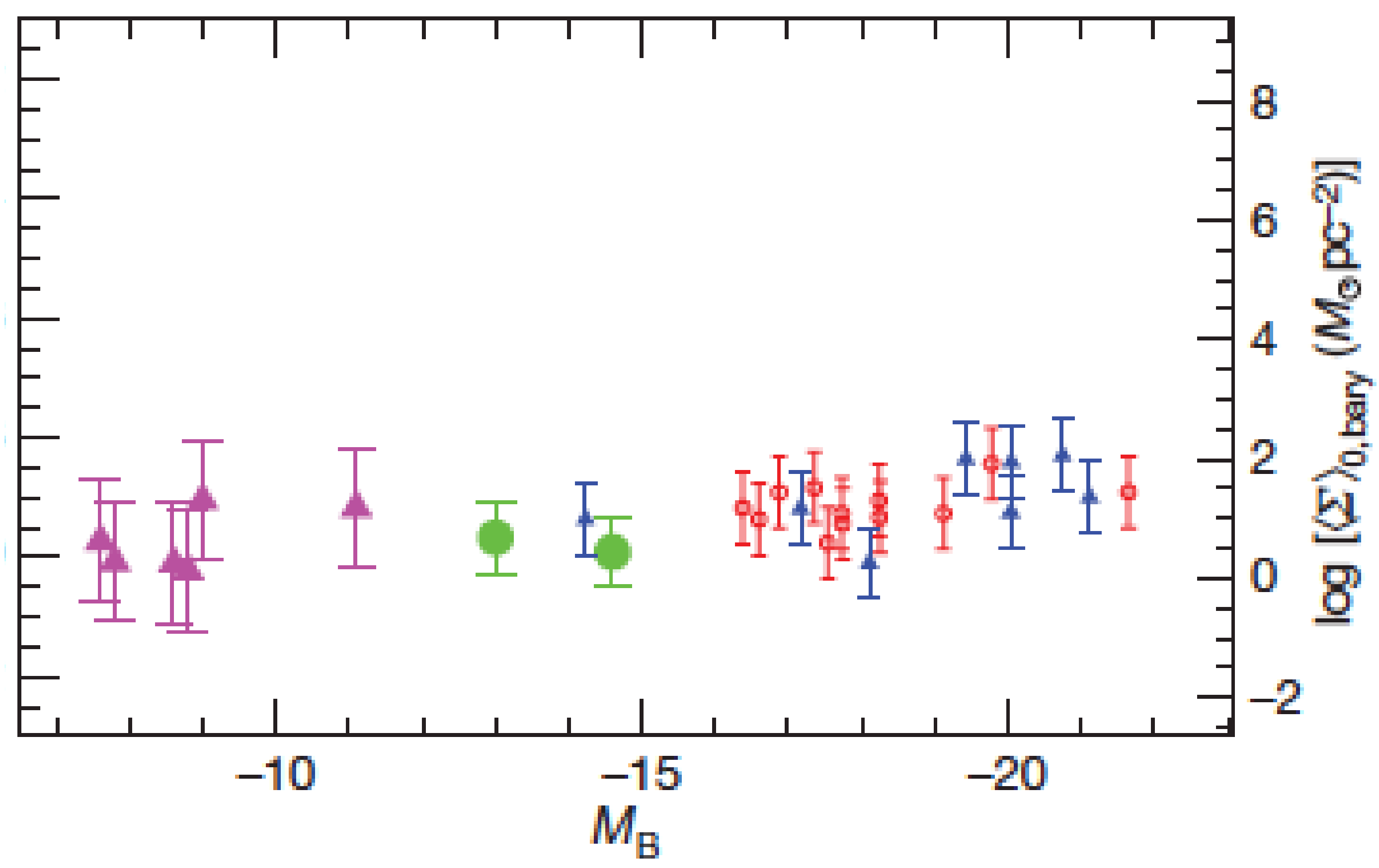


Figure 1 The central surface density in galaxies. Source: Gentile et al. 2009 Nature

Latest AMS results

- **Protons**
- **Electrons**
- **Positrons: secondary**
- **Anti-protons: secondary**
- **Helium**
- **Carbon**
- **B/C ratio: B secondary**
- **Lithium: mostly secondary**

Evidence for DM particle decay in these data?

AMS Positrons

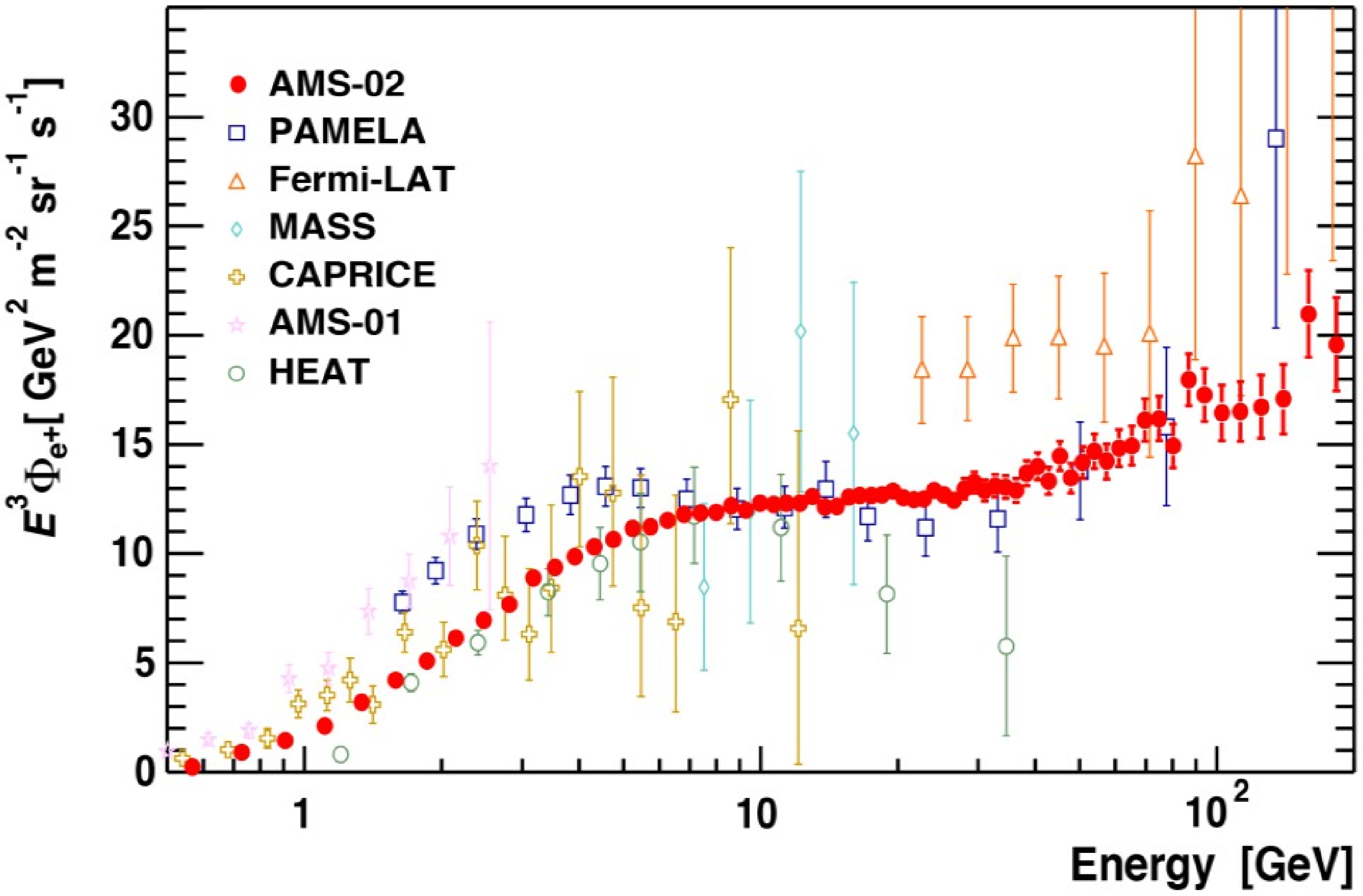


Figure 2 AMS positrons. Source: AMS-CERN Ting lecture Apr 2015

Positrons: triplet pair production I

- Total **cross-section for triplet pair production**

  $$\boldsymbol{\sigma_{3,tot} = \alpha r_0^2 \left(\frac{28}{9} \ln\{2k\} - \frac{218}{27} + \frac{1}{k}\mathrm{terms}\right)}$$

  with $\alpha r_0^2 = 10^{-27.3}\,\mathrm{cm}^2$

  $\boldsymbol{k = (h\nu \cdot E_e)/(m_e c^2)^2}$, with $\boldsymbol{k = 2}$ threshold.

- Using 3.0 eV and 30 TeV gives then as total cross-section (using just the first term) $\boldsymbol{10^{-26.05}\,\mathrm{cm}^2}$

- **Distort CR-e spectrum** $\boldsymbol{\sigma_{3,tot}\tau_{CR} c n_{ph} = 1/3.}$

- In OB-superbubble photon density condition

$$\boldsymbol{\frac{\tau_{CR}}{10^6\,\mathrm{yrs}} \; \frac{n_{ph}}{10^{1.7}\,\mathrm{cm}^{-3}} > 1}$$

just **somewhat higher than in the GC region.**

Positrons: triplet pair production II

- The Red Super-Giant (RSG) stars have a slow wind, with instabilities leading to shock-waves giving $\boldsymbol{k^{-2}}$ turbulent wave-field spectrum, so already at low energy **secondary spectrum unchanged** from primary spectrum (PLB et al. 2009).
- **Secondary CR-e^+ from p-p collisions original spectrum**, so same as primaries. Most interaction in polar cap (PLB et al. 2009). Triplet pair production additional.
- Graph: Positrons from the triplet-pair production using $\boldsymbol{(h\nu) = 3.0}$ **eV**, $\boldsymbol{E_{e,max} = 30}$ **TeV, and electron-spectrum with slope** $\boldsymbol{\delta = 2}$. Work with **Eberhard Haug 2014** (priv.comm.)

Interstellar radiation field

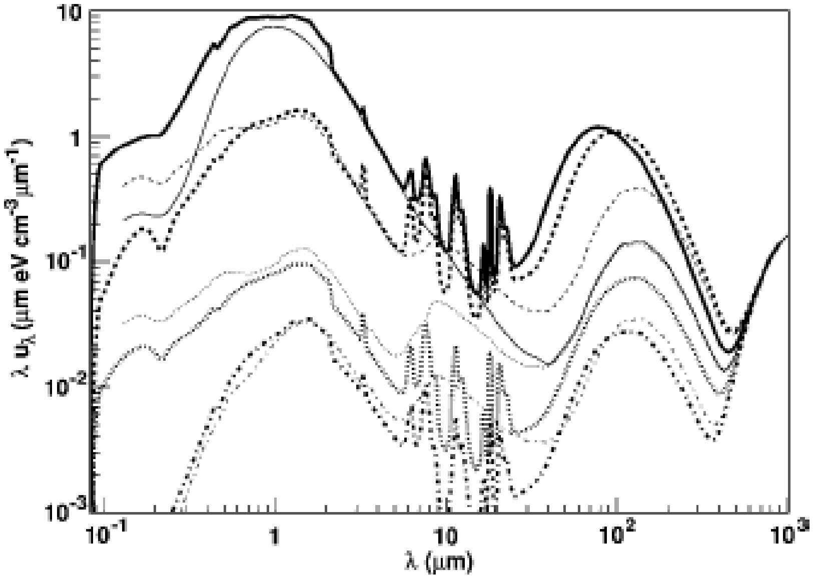


Fig. 1.—Interstellar radiation field energy density. *Top*: Local interstellar radiation field. *Thick solid line*, total radiation field including CMB; *thick dashed line*, contribution by stars; *thick dotted line*, scattered light; *thick dot-dashed line*, infrared; *thin solid line*, local ISRF from Strong et al. (2000). Data: *Squares*, *Apollo* (Henry et al. 1980); *triangles*, DIRBE (Arendt et al. 1998); *circles*, FIRAS (Finkbeiner et al. 1999). *Bottom*: Interstellar total radiation field radial variation. *Solid lines*, $(R, z) = (0$ kpc, 0 kpc); *dashed lines*, $(R, z) = (4$ kpc, 0 kpc); *dotted lines*, $(R, z) = (12$ kpc, 0 kpc); *dash-dotted lines*, $(R, z) = (16$ kpc, 0 kpc). Thick lines are for our ISRF; thin lines are for the ISRF of Strong et al. (2000).

Figure 3 Interstellar radiation field in Galactic Center region; we assume here that in a OB-superbubble the radiation is similar, but yet more intense, and perhaps slightly bluer. Source: Moskalenko & Strong 2006 ApJL 640, L155, 2006

Triplet-pair production of positrons

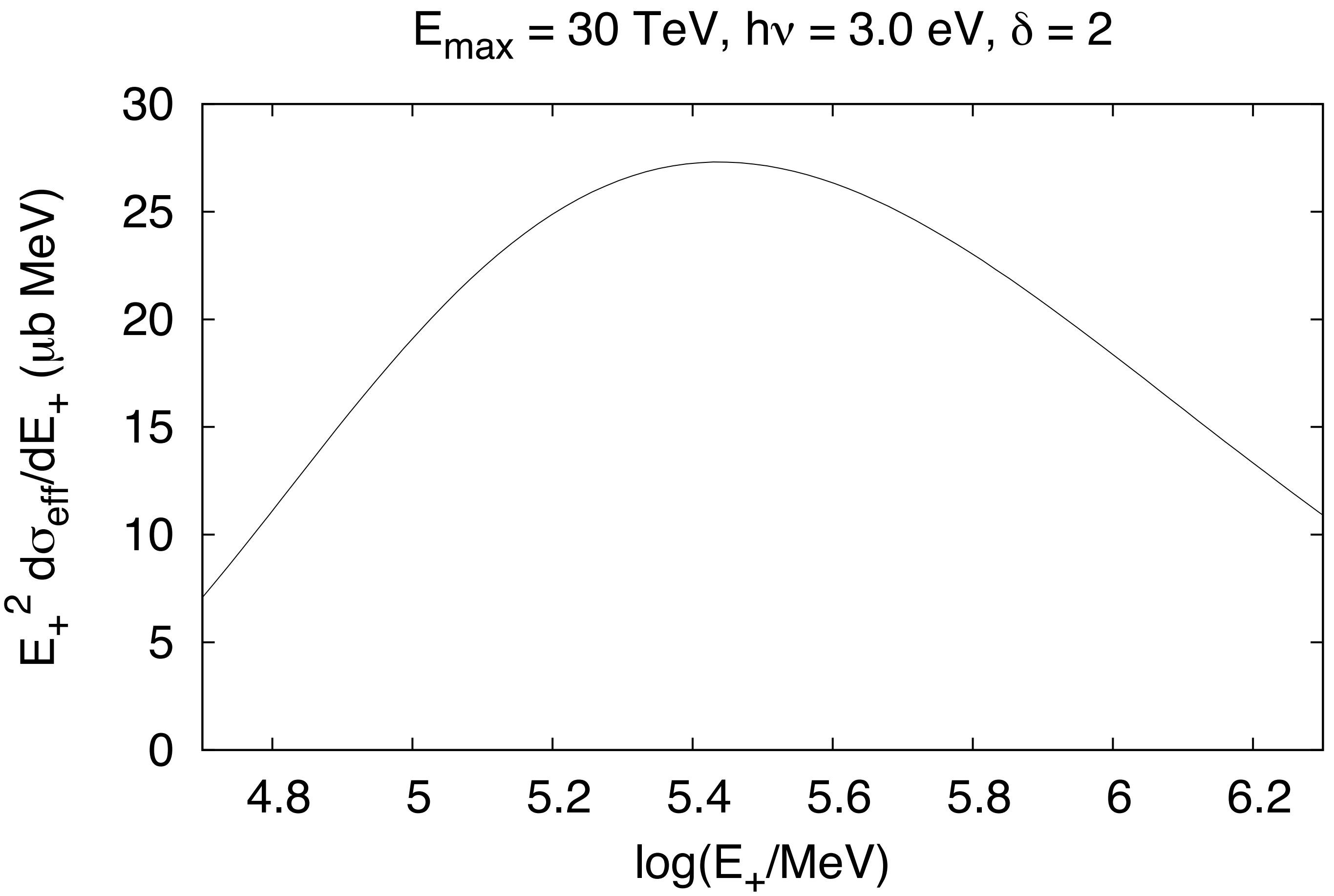


Figure 4 Positrons from the triplet-pair production using $(h\nu) = 3.0$ eV, $E_{e,max} = 30$ TeV, and electron-spectrum with slope $\delta = 2$. Source: Eberhard Haug 2014

AMS Anti-proton fraction

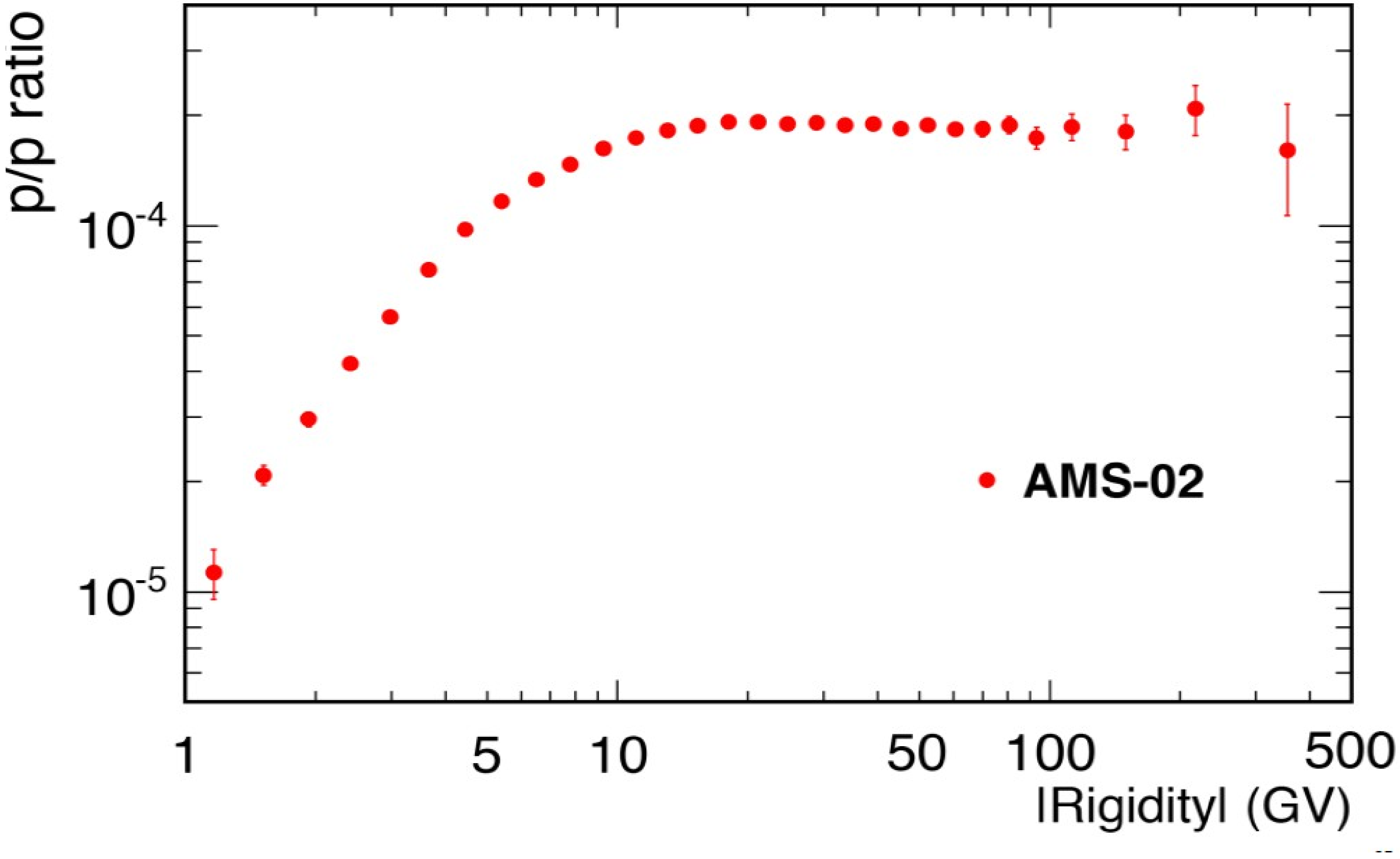


Figure 5 AMS antiproton fraction. Source: AMS-CERN Ting lecture Apr 2015

AMS Anti-proton fraction - numbers I

- Anti-protons: **First match ISM-CR-protons and RSG-wind-CR-protons, cross-over around TeV**
- Predicts for Red Super-Giant (RSG) stars already at low energy secondaries same spectrum as primaries (PLB et al. 2009).
- This implies that anti-proton to proton ratio runs as

$$\frac{F_{\bar{p}}(E)}{F_p(E)} = \frac{a_{ISM,sec}\, E^{-3.11} + a_{RSG,sec}\, E^{-2.67}}{a_{ISM,prim}\, E^{-2.78} + a_{RSG,prim}\, E^{-2.67}}$$

AMS Anti-proton fraction - numbers II

- Just crudely fitting first the proton data and then the anti-proton data allows for the three parameters:
- $\boldsymbol{a_{ISM,sec}/a_{RSG,prim} \ = \ 5.28 \cdot 10^{-5}}$**,**
- $\boldsymbol{a_{ISM,sec}/a_{RSG,prim} \ = \ 4.05 \cdot 10^{-4}}$**, and**
- $\boldsymbol{a_{ISM,prim}/a_{RSG,prim} \ = \ 1.29}$
- using as reference energy 100 GeV. With these specific parameter examples the anti-proton fraction varies a few percent from 10 GeV to 300 GeV. **Upper limit for** $\boldsymbol{a_{ISM,sec}/a_{RSG,prim}}$ **- small**.

AMS Anti-proton fraction - prediction

- **Maxwell's laws** require that over some small fraction over a spherically symmetric surface in a wind the magnetic field is radial. Polar cap in real space or in phase space: $\boldsymbol{E^{-2}}$ **at source**
- Transition energy $\boldsymbol{E_{trans}}$ for WR stars observed at a few TeV; if same for RSG stars $\boldsymbol{E_{trans}} = \mathbf{5}$ TeV
- The **interactions in polar cap have more time by** $\boldsymbol{A}$, and so **transition of secondaries** of polar cap component is shifted down by $\boldsymbol{A^{-3}}$.
- Anti-proton to proton ratio changes to $\boldsymbol{E^{+1/3}}$ **behavior from about** $\mathbf{165}\,\boldsymbol{(A/3)^{-3}\,(E_{trans}/\{5\mathrm{TeV}\})}$ **GeV to** $\boldsymbol{E_{trans}}$**, and then approaches a constant again**.

Latest AMS results: Evidence for DM decay ?

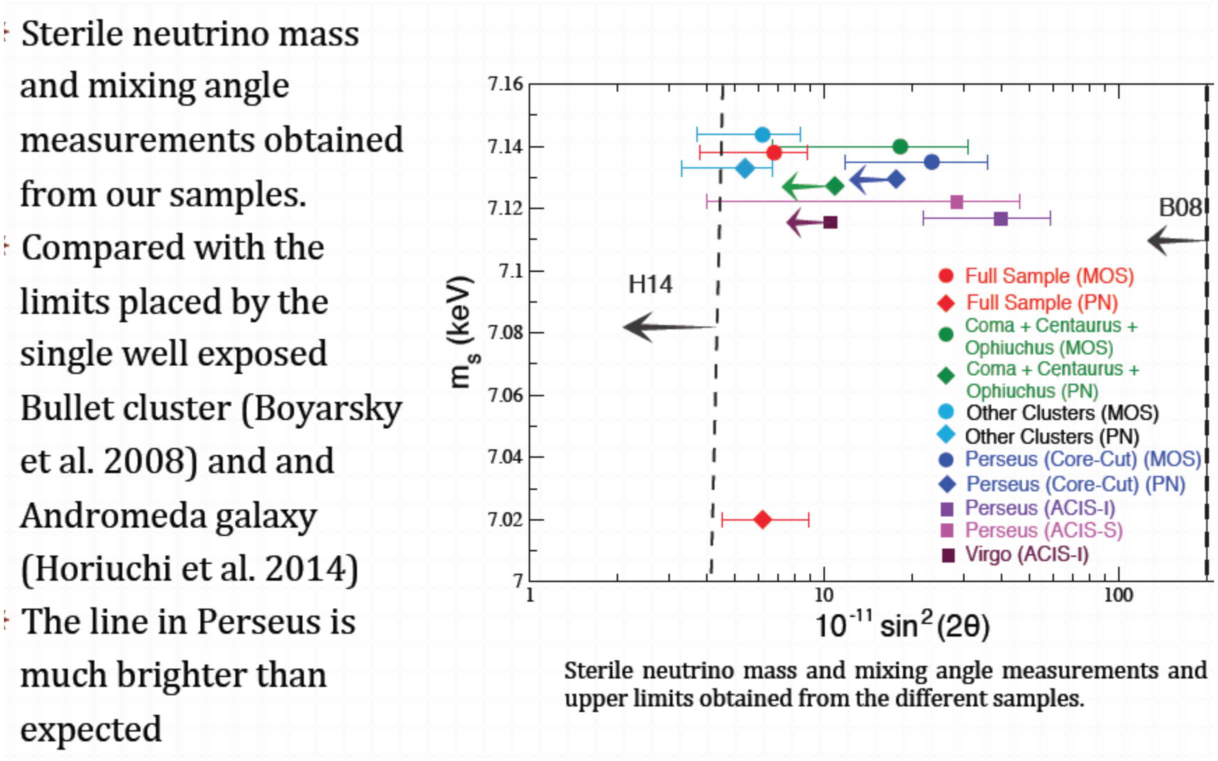
- **Positrons: secondary**
- **Anti-protons: secondary**

<u>No evidence</u> for DM particle decay in these data !

X-ray evidence ? 2×3.55 keV seen

- Assume **sterile neutrino** of a few keV, based on dwarf elliptical galaxies and cores of larger galaxies:
- **Decay** into left-handed neutrino and **X-ray photon**
- **Phase-space distribution**: Fermi-Dirac with tail
- **Integrate** for density law, and gravitational field
- **Predict** radial run of X-ray emissivity
- **Iterate** to obtain match to observational data: detection or limit
- **Problem:** Phase-space distribution may **not** be **isotropic**
- **Problem:** **Outer regions of clusters** of galaxies **not** in **hydrostatic equilibrium**

X-ray evidence ? Why Perseus strongest ?



- 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 6 Limits on X-ray detection. **Perseus is strongest, WHY ? Perhaps, because the cluster is merging and has three central galaxies with a SMBH, NGC1270 and NGC1277, apart from the dominant galaxy NGC1275** (Bosch et al., Fabian et al.). Source Esra Bulbul lecture 2014.

Star formation in the early Universe

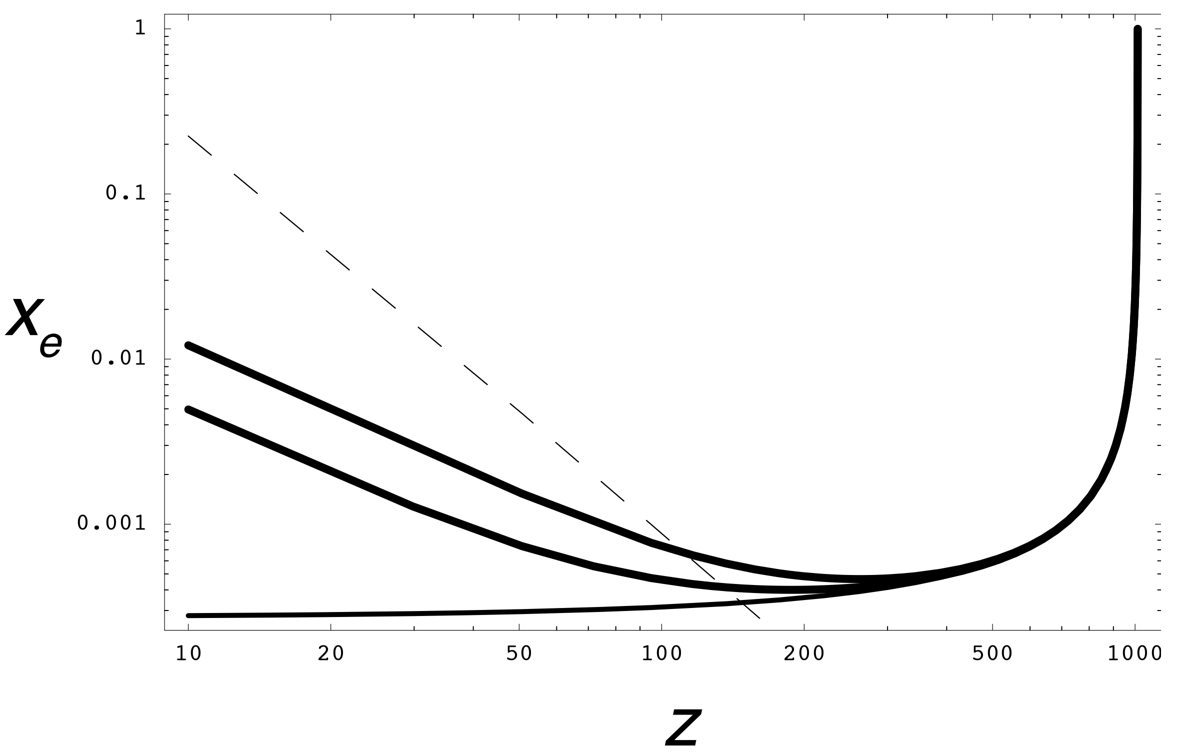


Figure 7 Degree of ionization in the early universe for different assumed masses of the **DM sterile neutrino, here 4 and 7 keV**; **extra ionization leads to stronger formation of molecular Hydrogen.. Molecular Hydrogen allows strong cooling, and this in turn allows early star formation**. Source PLB & Kusenko 2006 PRL.

Star formation near redshift 100

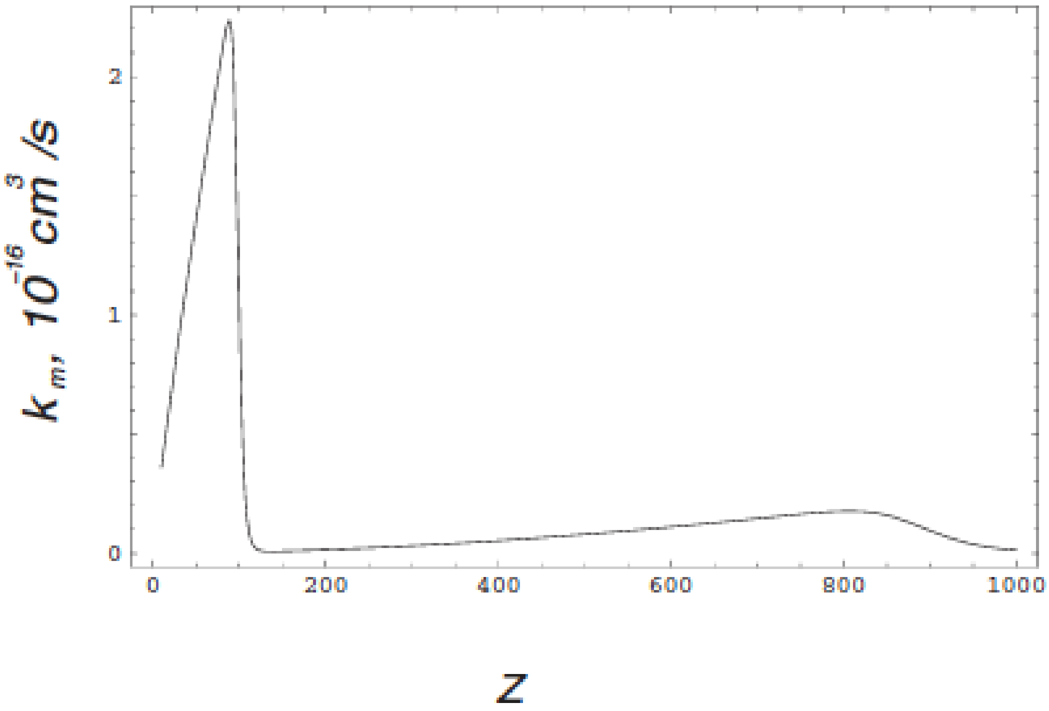


Figure 8 **Molecular Hydrogen cooling function** coefficient for different assumed masses of the DM sterile neutrino; this allows extreme cooling and **star formation**. Source PLB & Kusenko 2006 PRL.

Where are the sources? IceCube 2014

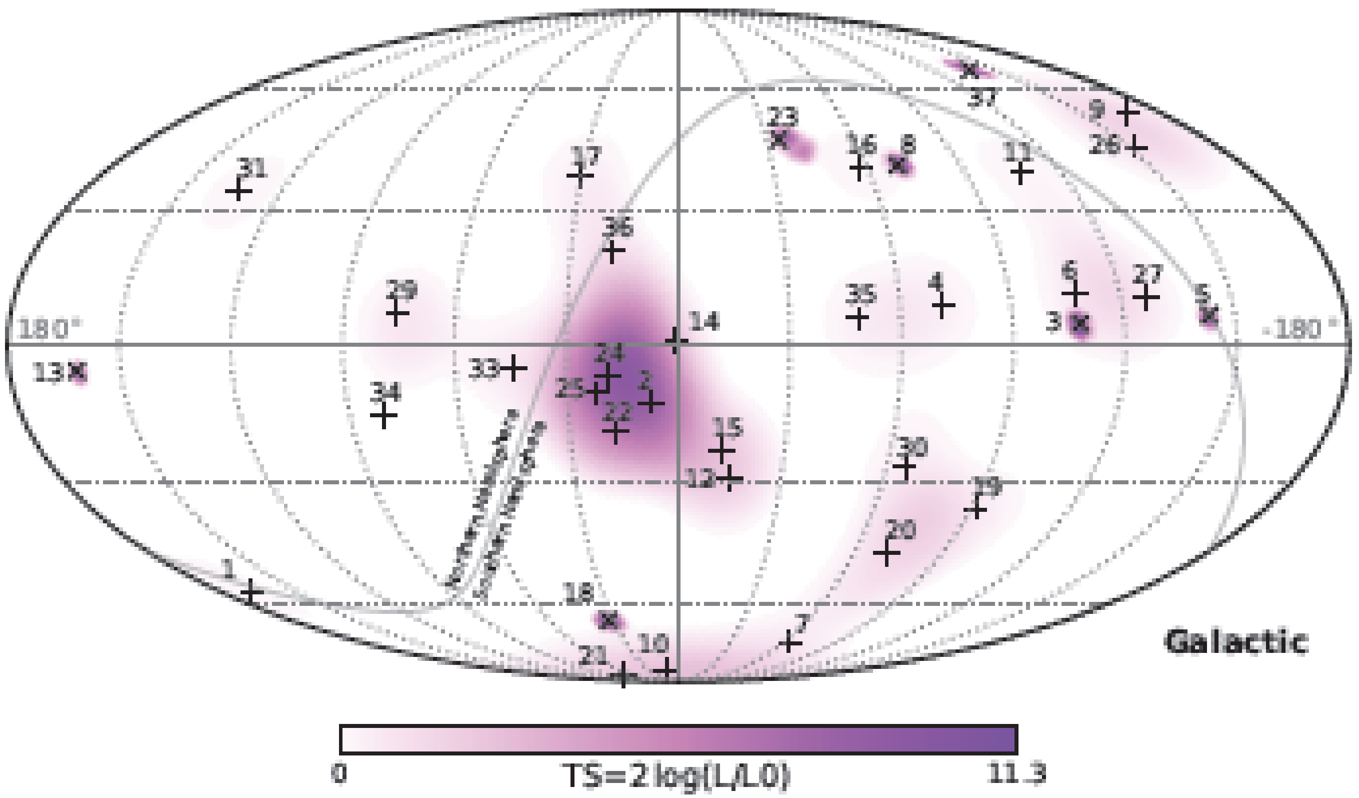


Figure 9 Neutrino events on the sky 2014. GC at center. Source IceCube 1405.5303.

Neutrino $z_{sources} \sim 2$, or $>> 2$

$\lesssim$ **50 Mpc**: Some ? Or low redshift, max $\sim$ **2** :

$$F_\nu \sim \int N_z \, z^2 \, \frac{L}{z^2} \, dz \sim \Delta z,$$

Normal sources $N_z \sim (1+z)^3$, $z_{sources} \sim 2$
Some classes N_z inversely with heavy elements Z:

$$F_\nu \sim \int N_z \frac{L}{(1+z)^{7/2}} \, dz \sim \int \frac{N_z \, L \, dt}{(1+z)},$$

For Δt fixed lifetime $\Delta z \sim (1+z)^{5/2} \Delta t$ stronger contribution at very high redshift, for $N_z \sim (1+z)^{1+\epsilon}$ for $\epsilon > 0$; $\int L \, dt$ fixed, $->$ $z_{sources} >> 2$:

Are neutrino sources visible at $z < 100$?

- $\boldsymbol{z}$ **up to 100** possible for first star formation (PLB & Kusenko 2006 PRL), **key enhanced $\mathbf{H_2}$ cooling**
- **High energy neutrinos interact !**
- $\boldsymbol{\Omega_b = 0.0482 \pm 0.00076}$ (Planck 2013 XVI)
- Baryonic mass density $\boldsymbol{\rho_{bar} \sim (1+z)^3}$
- Radiation energy density $\boldsymbol{\rho_{rad} \sim (1+z)^4}$
- Work with **Todor Stanev 2015** (priv.comm.)
- For PeV neutrinos: **Maximum redshift about 18**
- So, if observed spectrum cuts off at PeV, then sources probably **at higher redshift**; if observed spectrum continues, redshift **below this limit !**

Odd coincidence

- What energy ejected **forming black hole**? Limit (1/2) rest mass energy for spin zero BH. Budget $\frac{1}{2} N_{BH,0}\, M_{BH}\, c^2 (1+z_\star)^3 \sim 10^{-8}\, \mathrm{erg/cc}$
- as **DE**, for $N_{BH,0} = 1\, Mpc^{-3}$, $M_{BH} = 3 \cdot 10^6\, M_\odot$, $z_\star = 50$: **Gravitational waves?**
- Large **uncertainties** in 1/2, $N_{BH,0}$, M_{BH}, and $z_\star$.
- **Einstein and conserv. eqs. in 5D, solution**. Work with **Ben Harms 2015** (priv.comm.).
- Energy transfer from **strong brane** (Planck density) to **weak brane** (us) mimics e.o.s. $P = -\rho\, c^2$!

IF so, prediction: detectable GW bg !

QUESTIONS: Early universe visible ?

- **keV sterile neutrinos allow very early star and BH formation, from $z \lesssim 100$**
- **Neutrinos ? $z \simeq 2$ or $z >> 2$, and $z < 18$**
  - **Radio background ?**
- **Low frequency GW background from BHs ?**
- **Massive shells $->$ Massive disk galaxies ?**
  - **Test I: Identify the HE ν-sources !**
  - **Test II: Get z from HD^+ absorption !**
  - **Test III: Detect first SMBH activity !**

Thank you!