Warm dark matter and its astrophysical signatures

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DM particle decay? Rising positron fraction!

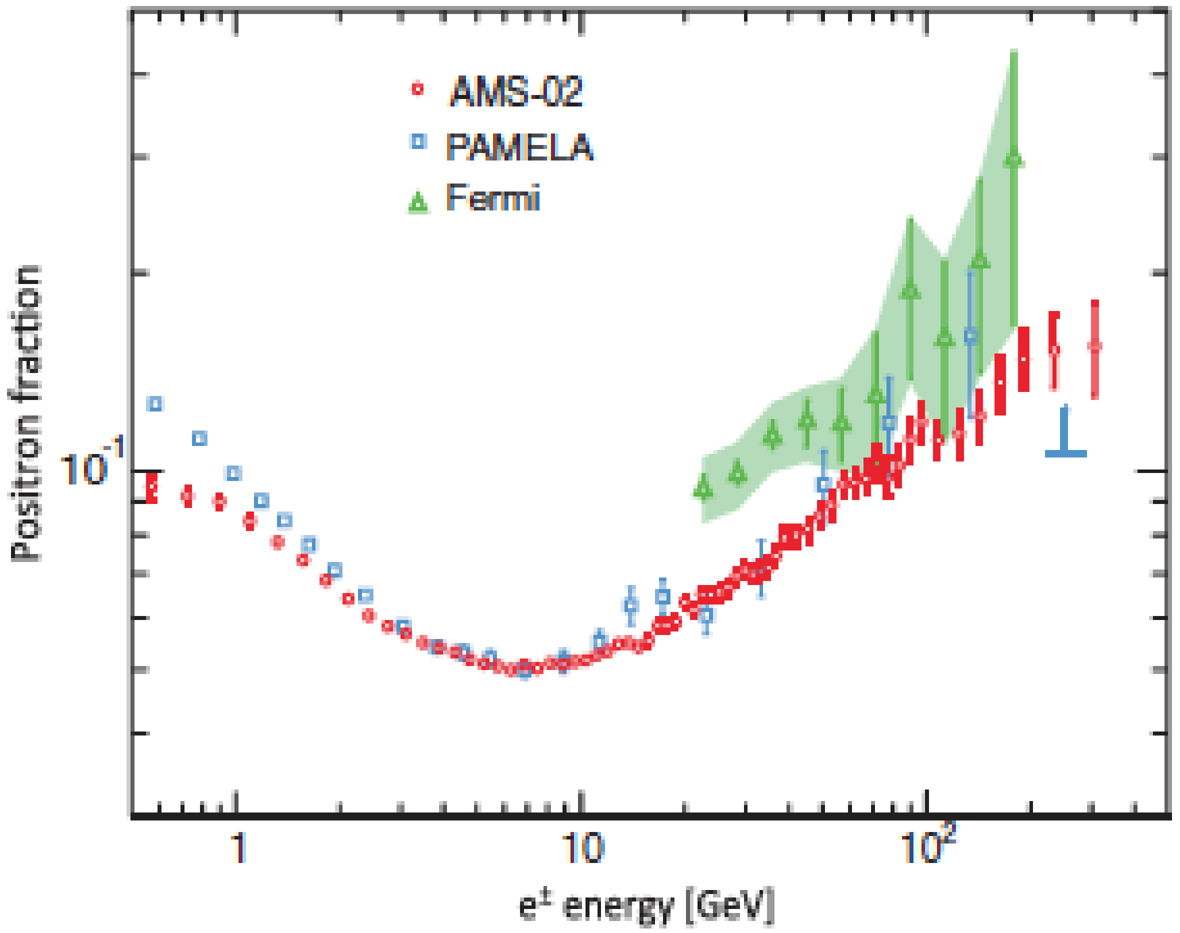

Figure 1 The cosmic ray positron fraction in AMS data. Source AMS-Coll. 2013 PRL

New versus old physics? I

- Cosmic rays have decreasing spectrum, about $E^{-2.7}$
- They traverse the ISM, with an escape time running as $E^{-1/3}$ (some believe even steeper)
- So the secondary fraction should also run as $E^{-1/3}$, so down
- So rising fraction must be **New Physics !**
- **Dark matter decay?**
- What properties are necessary?
- **Heavy dark matter particle?**

New versus old physics? II

- However, massive stars explode into their wind, a wind with a shell
- Winds have Archemedian spiral magnetic field
- Explosion leads to shock racing through wind and wind shell, predicted spectrum $E^{-7/3}$ at source
- Polar cap (in real space, or in momentum space) component for part of wind where magnetic field locally radial, there E^{-2} spectrum at source
- Interaction has more time in polar cap, so secondary polar cap component shifted down in energy relative to 4π-component
- **Prediction 2009** (PLB et al. PRL): positron fraction $E^{+1/3}$

Prediction 2009/data 2013! Star physics!

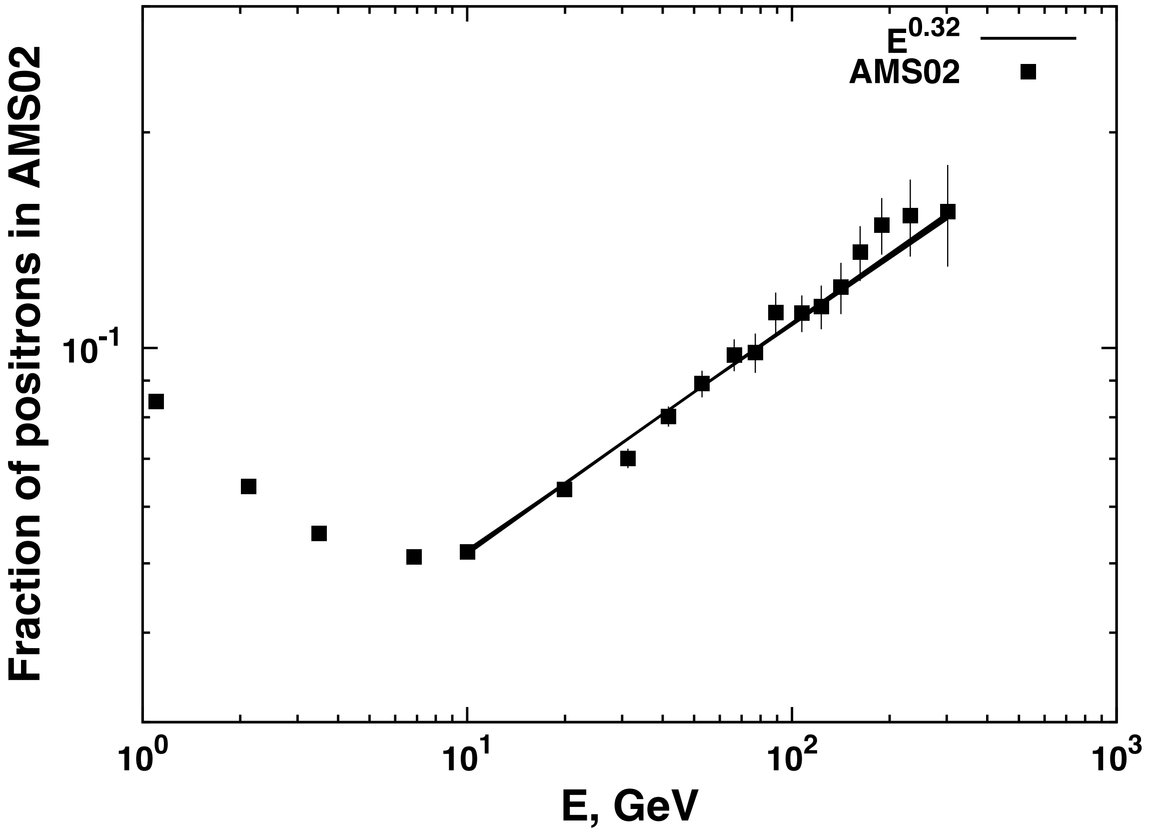

Figure 2 Cosmic ray positron fraction predicted 2009 fitted (Stanev) to AMS data 2013. Source AMS-Coll. 2013 PRL

New challenge?

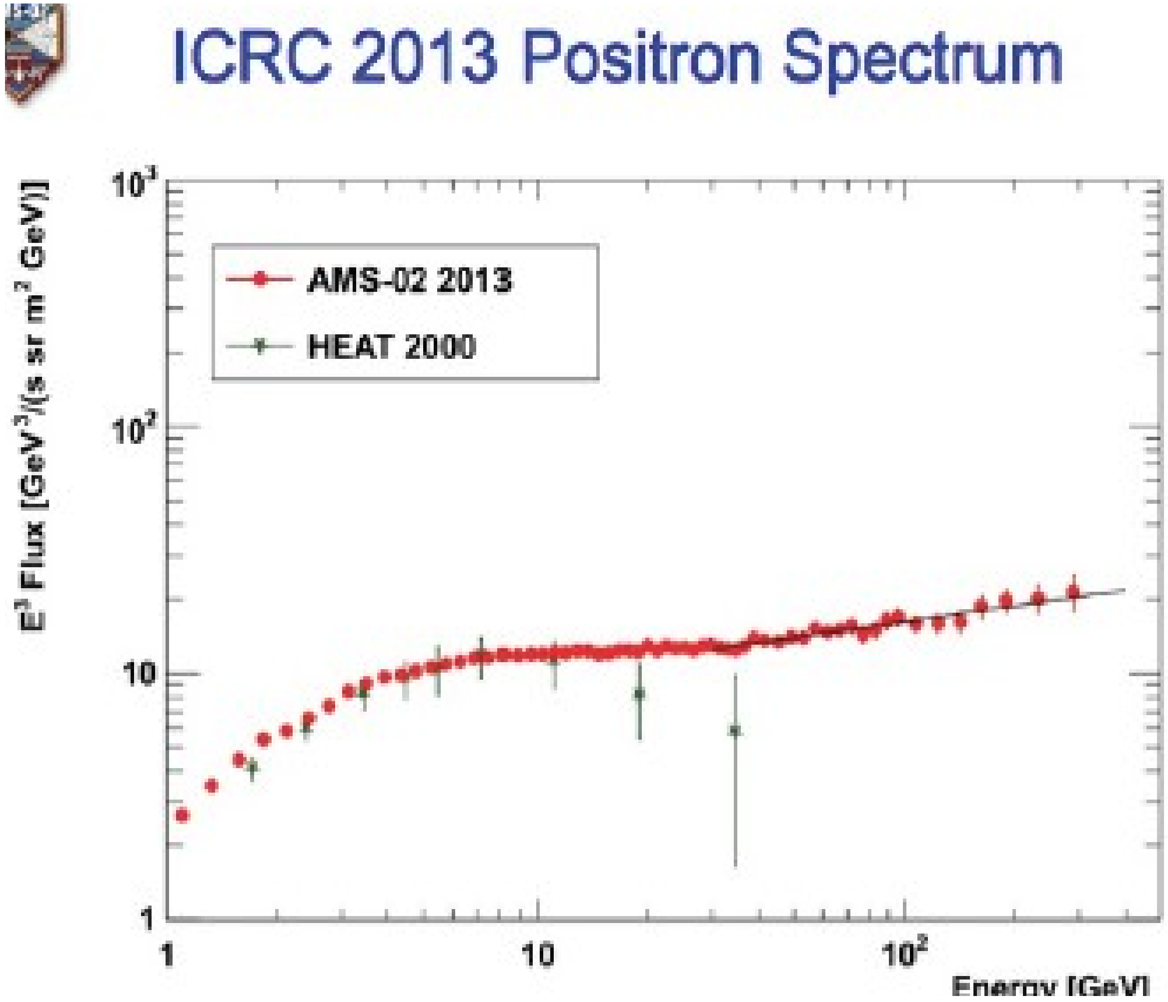

Figure 3 Cosmic ray positrons from latest AMS data. Source AMS-Coll. website

New versus old physics? III

- First new challenge from rise in positrons:
- Binary star physics required, as shown in work by E. Haug (2014)
- Second new challenge from radio spectra of these radio-supernova-remnants
- Most are steep, suggesting a particle spectrum a tad steeper than E^{-3},
- one is "normal", with a particle spectrum a tad steeper than E^{-2}
- Remember Kardashev (1962) ...

Massive star explosions into winds I

- If massive star winds are important for the positrons, we need to check whether they can explain the energetics of cosmic rays
- Radio data now available for radio supernovae, mostly WR star explosions
- Maximal containable energy $\sim (RB)$, possible for highly oblique shocks,
- 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)

Massive star explosions into winds II

- Work with Andreas Brunthaler (MPIfR Bonn, Germany), Athina Meli (Univ. Gent, Belgium), Eun-Suk Seo (Univ. Maryland, USA), Todor Stanev (Bartol, Univ. Delaware, USA), & Julia Becker Tjus (Univ. Bochum, Germany)
- Critical energy for drift energy gain is $\sim RB(V_{sh}/c)^2$.
- Beyond this energy drift energy gain strongly reduced
- Average of $\log\{RB\}$ is 15.9 ± 0.2;
- $-> E_{max} \;=\; Z\;\; 10^{17.3 \pm 0.2}$ eV: **CR ankle**,
- Average of $\log\{RB(V_{sh}/c)^2\}$ is 14.3 ± 0.3;
- $-> E_{kink} \;=\; Z\;\; 10^{15.3 \pm 0.3}$ eV: **CR knee**

Massive star explosions into winds III

- Immediate observational check (PLB & de Souza 2012): $E_{knee}/E_{ankle} \simeq (V_{sh}/c)^2$: data give $10^{-1.4}$,
- So inferred shock velocity of order $10^{-0.7}\,c$, observed in fact an average of $10^{-0.85\pm0.1}\,c$
- In sample of observations there is one red supergiant star, all others Wolf Rayet star winds (same in these two energies)
- This is to within the uncertainties what had been predicted (Biermann 1994): E_{knee} and E_{ankle} fit the data also separately (e.g. PLB & de Souza 2012).
- **So explosions into stellar winds can provide the two key energies, ankle and knee**
- **Consistency check on the positron arguments!**

Early star formation

- Right handed neutrino decays, X-ray photon half mass, ionizes IGM
- Claim: line at 3.5 keV: 1402.2301 and 1402.4119
- Implies DM particle **mass at 7 keV**
- In PLB & Kusenko 2006 PRL used **4 keV** & **7 keV**
- Higher ionization, more H_2, more **cooling** possible
- For $z < 100$: $\tau_{cool} < \tau_{Compt} < \tau_{coll}$; with **7 keV** .
- $->$ **Star formation may start from** $z < 100$
- Detectable via **HD$^+$ absorption lines**

Strong prediction by ΛWDM!

Phase space in dwarf galaxies I

- Casey Watson's work (Millikin Univ., Illinois, USA)
- 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 (e.g. Tegmark et al. 1997 ApJ) we can obtain a redshift dependent phase space distribution

Phase space in dwarf galaxies II

- From PLB & Kusenko 2006 PRL higher redshift –> higher **DM particle mass**
- To identify a virtualized clump with an elliptical dwarf galaxy we must have star formation, very low Z, and gas ejection (decrease in Q ?)
- We must also assume that the observed stars allow us to estimate properly the unseen dark matter

$$Q_{vir} \sim (1+z)^{3/2}$$

- Condition $Q_{vir} \geq Q_{obs}$: –> z limit
- z limit –> **DM particle mass limit**

Density of virialized clumps?

- Using Press & Schechter (1974) on can work out the density of clumps
- This leads to very small masses at redshift 100
- Can we obtain a serious instability from the very steep slope of the cooling function?
- WDM decay −> ionization, −> H_2 molecules, −>
- Cooling −> contraction, −> higher DM density, −> more molecules and more cooling
- Can this lead to a run-away cooling and star formation on large mass scales like massive stars and dwarf elliptical galaxy masses?
- What density of such clumps is possible?

What are cosmic backgrounds?

After recombination and all its ripples:

- First stars (**much 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**

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), also with a relatively flat spectrum, and no identified sources at the location of the published events.
- The spectrum seems to cut off around several PeV. This cut-off could be apparent if the spectrum is slightly steeper than E^{-2}
- This neutrino background appears to be isotropic, but has a weak non-significant clustering around 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

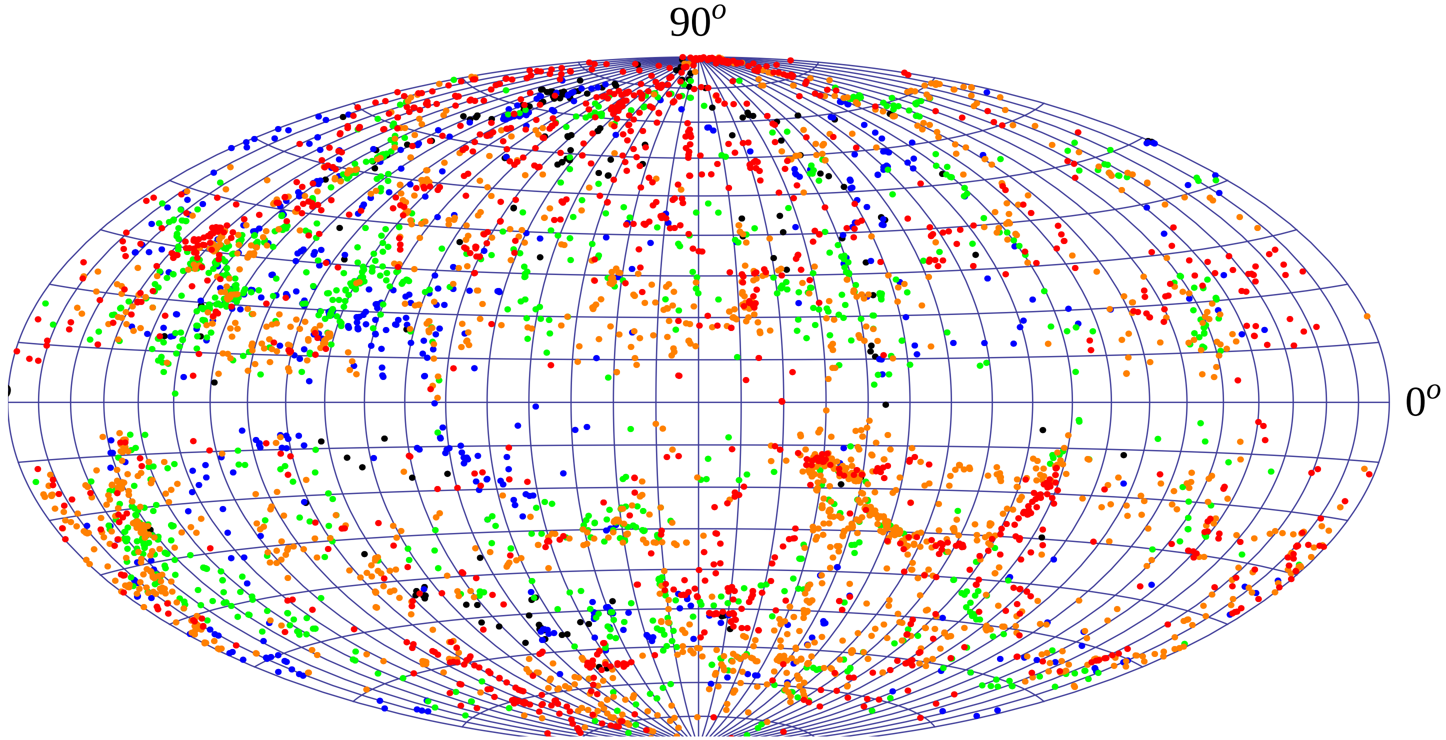

Figure 4 The sky in black holes, $\gtrsim 3 \cdot 10^7\, M_\odot$: The color code corresponds to distance: Black, Blue, Green, Orange, Red for the redshifts intervals 0, 0.005, 0.01, 0.015, 0.02, 0.025, corresponding to distance intervals of 0, 60, 120, 180, 240, and 300 million light-years: (−> Caramete & PLB 2011); coordinate system with Galactic plane across center, and Galactic center at the right edge

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

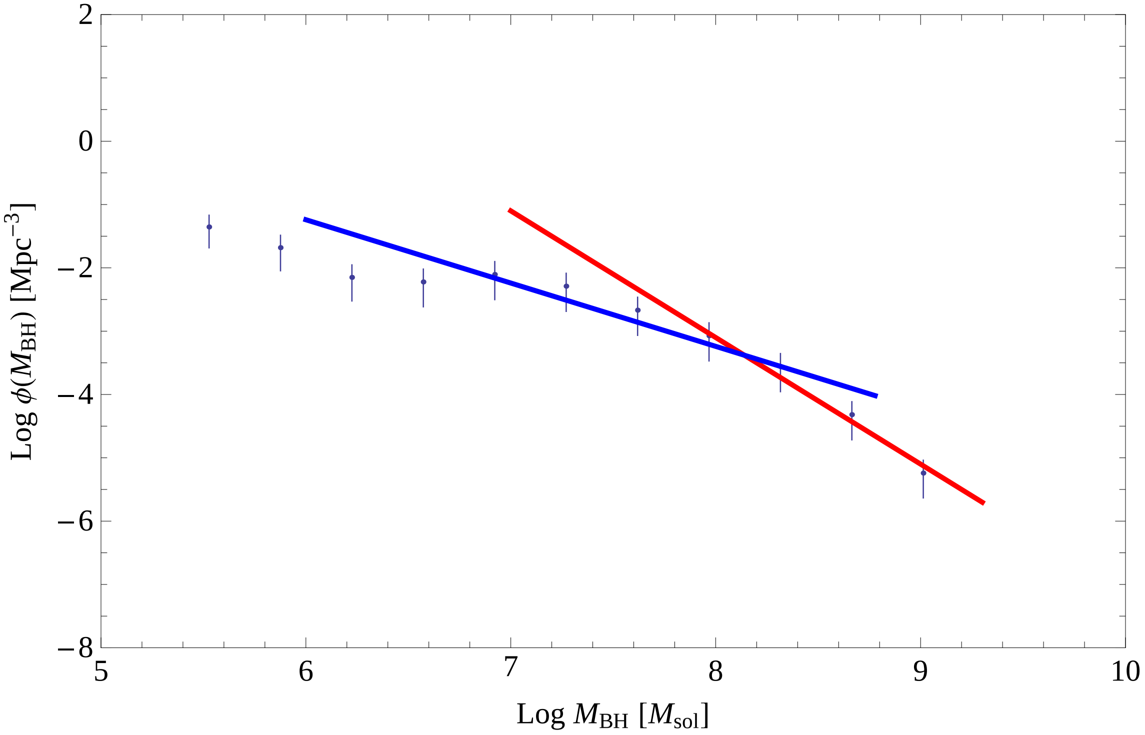

Figure 5 Integral mass function corrected for Hubble type sampling, 2928 objects, the slope of the lines is: red -2.0 fitting $> 10^8\, M_\odot$, and blue -1.0 fitting between $10^7\, M_\odot$ and $10^8\, M_\odot$. See Caramete & PLB, *Astron. & Astroph.* **521**, id.A55 (2010); arXiv:0908.2764. This mass function suggests that black holes start near $3 \cdot 10^6\, M_\odot$, possibly at redshift of order ~ 30 to 80, and grow by merging (see PLB & Kusenko 2006, PRL)

What origin of BH mass distribution?

- Most readily explained as multiple merging from an initial narrow mass distribution of seed black holes (Silk & Takahashi 1979), peaking near $3 \cdot 10^6 \, M_{\odot}$
- This BH mass distribution evolves through the process of coagulation (= merging):
  Coagulation equation (Smoluchowski 1916), approximate solution using Laplace transform techniques
- The entire distribution can be described using a power-law with an exponential cutoff

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

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

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

Alternatives:

- The degenerate DM star has a mass given by the **DM particle mass**, and the surrounding potential –>

$$m_{DM} \;=\; 7\,\mathrm{kev}\left(\frac{\sigma}{76\,\mathrm{km/s}}\right)^{3/4}\left(\frac{3\cdot 10^6\,M_\odot}{M_{deg}}\right)^{1/2} \qquad (2)$$

- Degenerate configurations accrete catastrophically onto a stellar black hole (Munyaneza & Biermann 2005, 2006) giving a SMBH
- Or just **star formation** and accretion in gravitational potential of DM of dwarf galaxy, determined by **DM particle mass**

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

- Massive stars form in dense groups, that agglomerate rapidly to form a more massive star
- Massive stars also have winds, driven by radiation interaction with heavy elements (Lucy & Solomon 1970 and many later papers): So maximum mass several hundred $M_\odot$ at most (Yungelson et al. 2008)
- At zero heavy element abundance massive stars can grow to much higher mass, close to $10^6\, M_\odot$
- Massive stars hit an instability, combining radiation pressure with subtle effects of General Relativity (Appenzeller & Fricke 1972a, b) just below this mass
- So with infall the mass of about $3 \cdot 10^6\, M_\odot$ possible

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

- Take this mass of $3 \cdot 10^6\ M_\odot$, multiply with the dark matter/baryonic matter ratio, we obtain $1.2 \cdot 10^7\ M_\odot$
- Assume an inefficiency for star formation of 20 percent, and so obtain a whole system mass (dark matter included) of about $6 \cdot 10^7\ M_\odot$
- Very close to the lower mass limit obtained by Gilmore et al. of $5 \cdot 10^7\ M_\odot$, DM mass within radius defined by stars
- −> Free streaming length −> **DM particle mass**

Black hole mass distribution gives dark matter particle mass estimate !

Original number density of black holes? I

- If all growth by mergers, mass is conserved

$$N_{BH,0} \;=\; 10^{-1.1\pm0.40}\,\left(\frac{M_{BH,min}}{3\cdot10^{6}\,M_{\odot}}\right)^{-1}\;Mpc^{-3}\;.$$

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

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

may be the reality. This is an allowed (comoving) number for the early density of super-massive black holes, at the time of formation, at redshift somewhere between 20 and perhaps 100 (PLB & Kusenko 2006 PRL).

Original number density of black holes? II

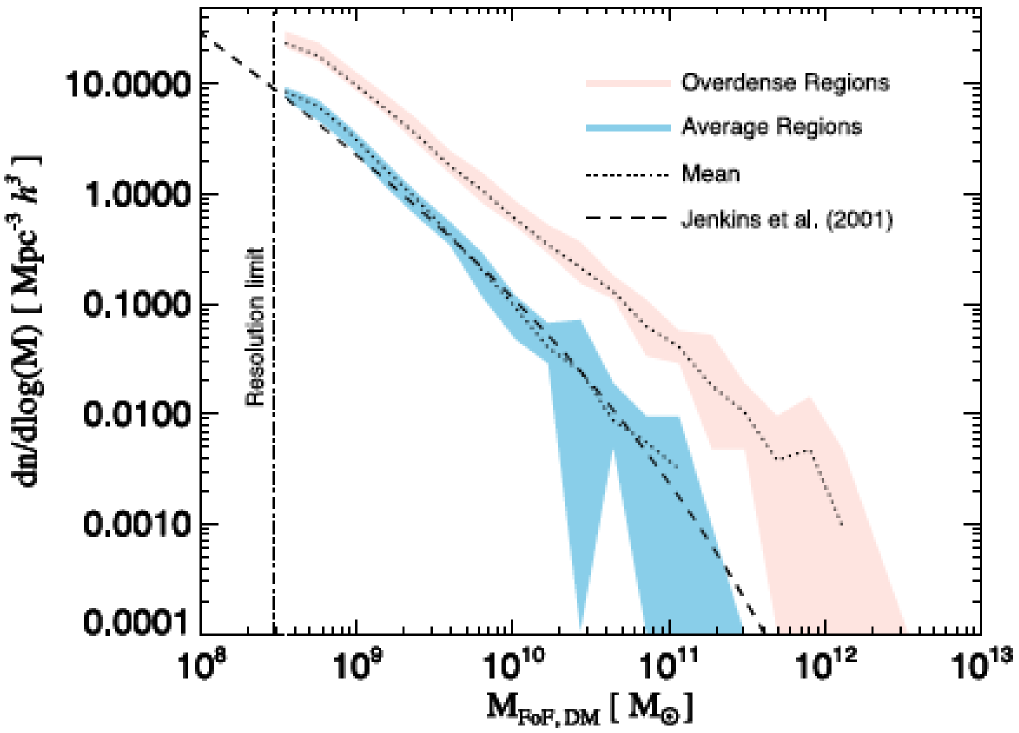

Figure 2. Dark matter mass functions of the FoF groups for all overdense

Figure 6 Clump distributions in standard cosmology simulations at redshift 6.2; FoF means “friends of friends”.
Source Costa et al. *Month. Not. Roy. Astr. Soc.* 2014

Original number density of black holes? III

- Clump size per super-massive black hole: $M \simeq 10^{9.8}\, M_\odot$
- Wolf et al. (2010 MN) find, that "all of the Milky Way dwarf spheroidal galaxies (MW dSphs) are consistent with having formed within a halo of a mass of approximately $3 \cdot 10^9\, M_\odot$ in standard cold dark matter cosmology."
- Difference to Gilmore et al. due to DM within radius of stars, or integrated out
- We assume here that the first super-massive black holes formed in such an environment
- Consistent with Costa et al. (2014) MN: From density to mass: Turning this around gives again a **DM particle mass**

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 (080425 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 $10^{-3.8}\,E_{57}/M_{BH,6.5}$ – **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:

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

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

- Luminosity at radio wave-lengths:

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

The radio and neutrino background II

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

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

Observations then show the condition

$$10^{1.3} \approx N_{BH,0,0}\, \eta_{B,-1}^{0.80}\, \eta_{CR,e,-1}^{+1}\, E_{57}^{1.32}\, z_{1.3}^{+0.84}\, \nu_{9.0}^{-0.60}\,.$$

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

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

The radio and neutrino background III

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

$$\begin{aligned} F_{neutr} \ &= \ 10^{-7.5}\, N_{BH,0,0}\, E_{57}\, \eta_{CR,p,-1}\, z_{1.3}^{0.8} \\ &\quad \mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}\,, \end{aligned}$$

matches observation. With radio bg condition

$$E_{57}^{0.32} \frac{\eta_{B,-1}\,\eta_{CR,e,-1}}{\eta_{CR,p,-1}} \ \simeq \ 10^{1.3} \tag{3}$$

For equality very weak radio background!

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

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

Can explain **massive bulge-less disk galaxies** and their high redshift growth (Conselice et al.)

The radio and neutrino background IV

- Can we rule out galactic contribution to the claimed background? Not yet for radio emission: **Spectrum, polarization, and correlations ?**
- 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 gamma and neutrino background

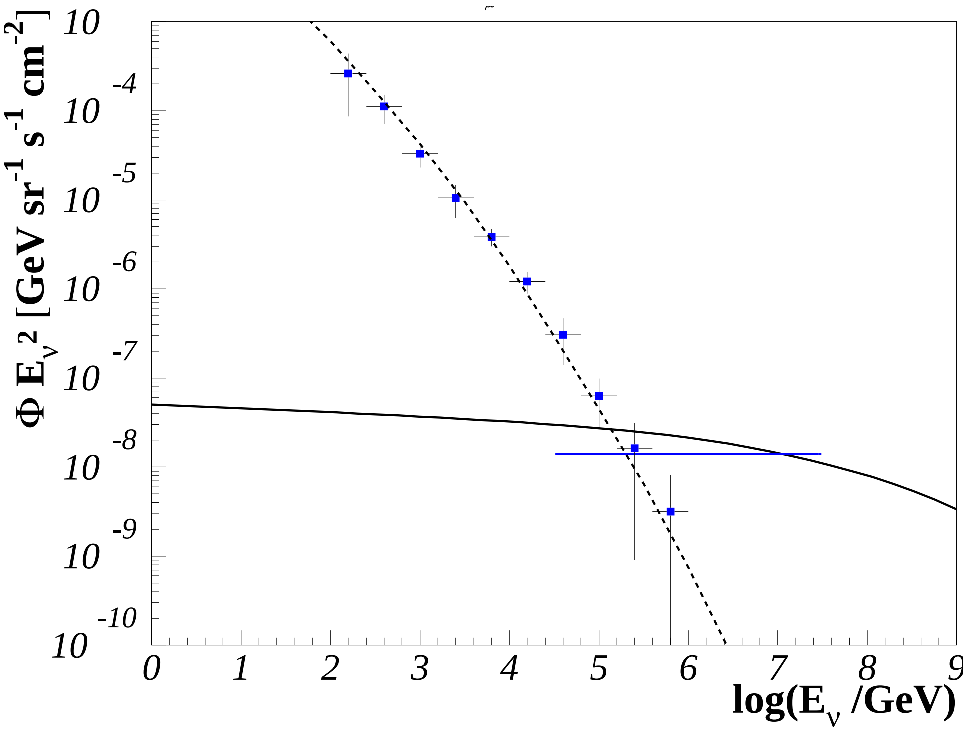

Figure 7 Predicted background neutrino flux and IceCube data: source Julia Becker Tjus 2013, included in paper PLB et al. 2014. The Limit is an integral for an assumed spectrum of $E-2$ without cutoff; here we have $E^{-2.2}$ and a cutoff, so it is consistent. There is a accompanying γ-ray background close to what is observed.

Odd coincidence

- What energy ejected when making a black hole? Limit is (1/2) for spin zero BH.
- Then energy budget of order

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

- Gravitational waves?
- For $N_{BH,0} = 1\, Mpc^{-3}$, $M_{BH} = 3 \cdot 10^6\, M_\odot$, and $z_\star = 50$ the number is $\sim 10^{-8}\, erg/cc$, same as 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 (arXiv:1305.0498).

Original explosion detectable?

- Energies? Compared to gamma ray bursts or supernovae, 10^5 times more energetic
- Largest unknown: Mass overburden, so is the explosion highly relativistic?
- Time scale? Compared to gamma ray bursts, at least 10^5 times slower
- Luminosity? Compared to gamma ray bursts, the same but days to weeks instead of seconds
- Redshift? Anything possible from about 20 to 70
- Spectrum even more redshifted...

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!

Cosmic backgrounds due to the formation of the first super-massive black holes

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We observe i) a high energy neutrino background, and there are repeated claims of a radio background, ii) a large number of super-massive black holes, with a low mass cut-off in their distribution around $3 \cdot 10^6\ M_\odot$, and iii) a large number of massive disk galaxies that never merged. We propose that a first generation of super-massive black holes forms by the agglomeration of massive stars; the en-

suing super-massive star blows up around $10^6\ M_\odot$ due to an instability, and forms a black hole. The explosion then produces a hyper-nova remnant, which gives rise to a background in radio emission, gamma emission, neutrino emission, matching the observations. This explosion distributes fairly strong magnetic fields. The explosion also produces a massive gaseous shell, allowing the formation of massive disk galaxies that never need to merge to grow. There has to be an ensuing background in polarized radio emission, as well as gravitational waves. This simple concept pulls together a large body of observational evidence, and allows predictions for future observational tests to be made. The paper is in *Month. Not. Roy. Astr. Soc.* **441**, 1147 - 1156 (2014); arXiv:1403.3804; coauthors are Biman B. Nath[5], Laurenţiu I. Caramete[1,6], Ben

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