Dark Matter, Super-Massive Black Holes and Gravitational Waves

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Challenging questions

- 1 Evidence for dark matter (DM)
- 2 CR-e^+, CR-$\bar{p}$, Galactic Center GeV excess
- 3 Dwarf ellipticals: DM keV mass
- 4 The great semi-circular arc of SMBHs
- 5 Early star formation
- 6 The cosmic amplifier
- 7 Early Super-Massive Black Holes (SMBHs)
- 8 SMBHs and Gravitational Waves

Evidence for dark matter

- Clusters of galaxies (Zwicky 1933)
- Galaxy rotation curves (Rubin)
- Stability of galactic disks (Ostriker, Peebles)
- Matching MWBG fluctuations (Planck 2015):

  $\Omega_\Lambda = 0.6911 \pm 0.0062$ DARK ENERGY

  $\Omega_{dm} = 0.2603 \pm 0.0062$ DARK MATTER

  $\Omega_b = 0.04860 \pm 0.00031$ WHERE ?

  $\Omega_k = 1 - \Omega_\Lambda - \Omega_{dm} - \Omega_b = +0.0008 \pm 0.0040$

  −> "flat" geometry, like a perfect tabletop
- Ell. gal., e.g. NGC5846 (PLB et al. 1983)
- Dwarf ell. gal. (Hogan & Dalcanton; Destri, Gilmore, Salucci, Sanchez, de Vega, ...)

DM limits: IceCube 2015

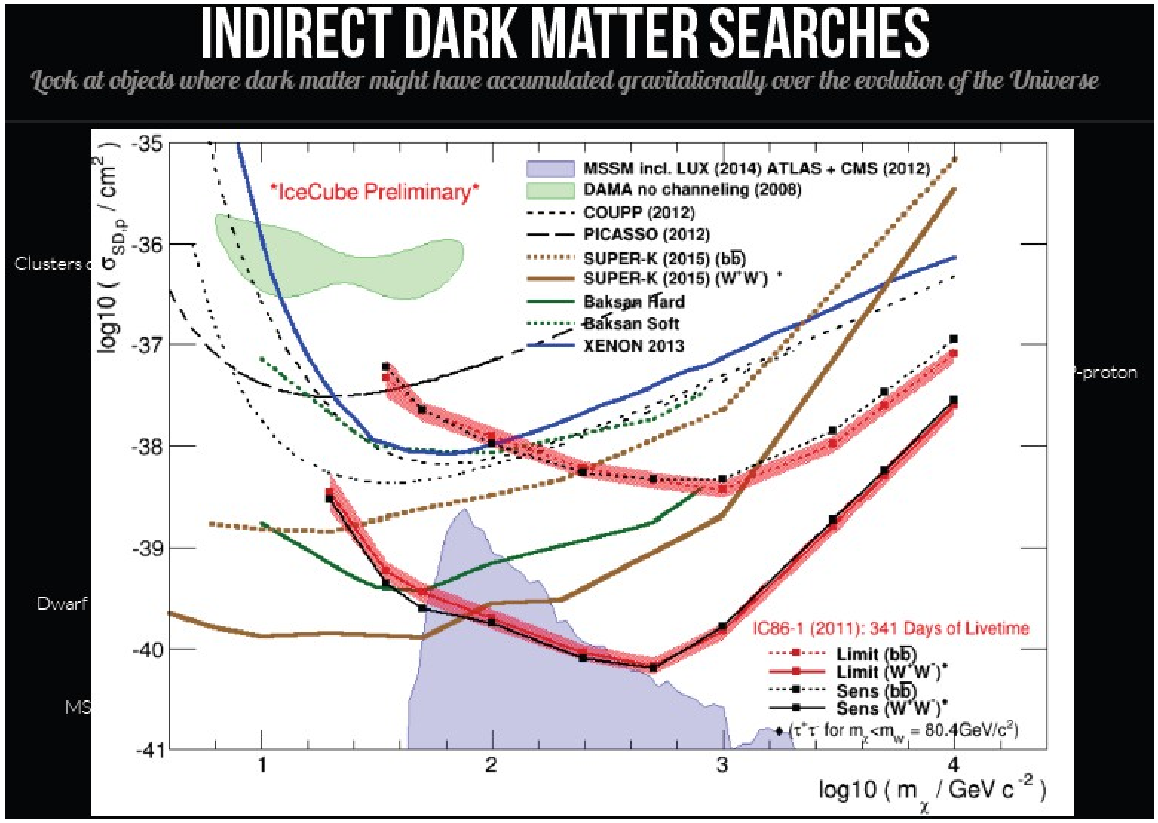

Figure 1 DM annihilation limits from IceCube. Source ICRC 2015 IceCube talk.

Dark matter in galaxies

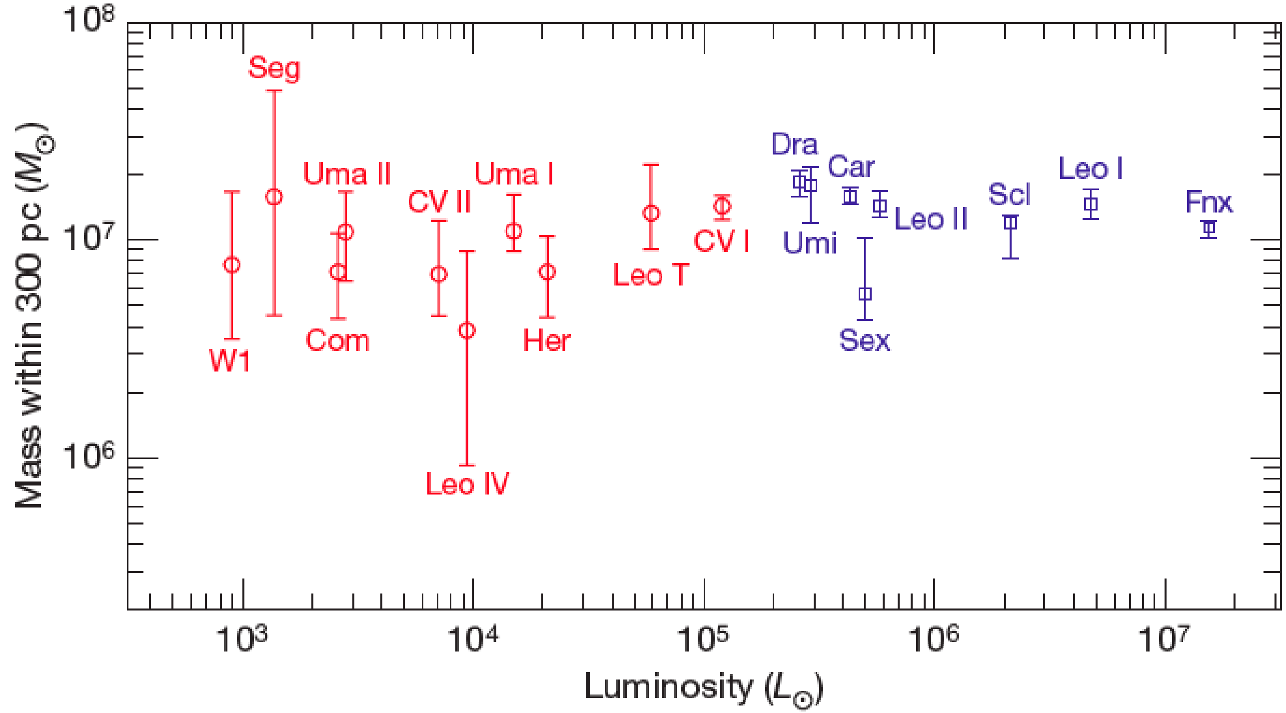

Figure 1 | The integrated mass of the Milky Way dwarf satellites, in units of solar masses, within their inner 0.3 kpc as a function of their total luminosity, in units of solar luminosities. The circle (red) points on the left

Figure 2 The dark matter mass of small galaxies. Source: Strigari et al. 2008 Nature. Using these numbers and a simple phase-space distribution gives the mass of the particle, **about keV** (Hogan & Dalcanton 2000)

Antimatter Positrons

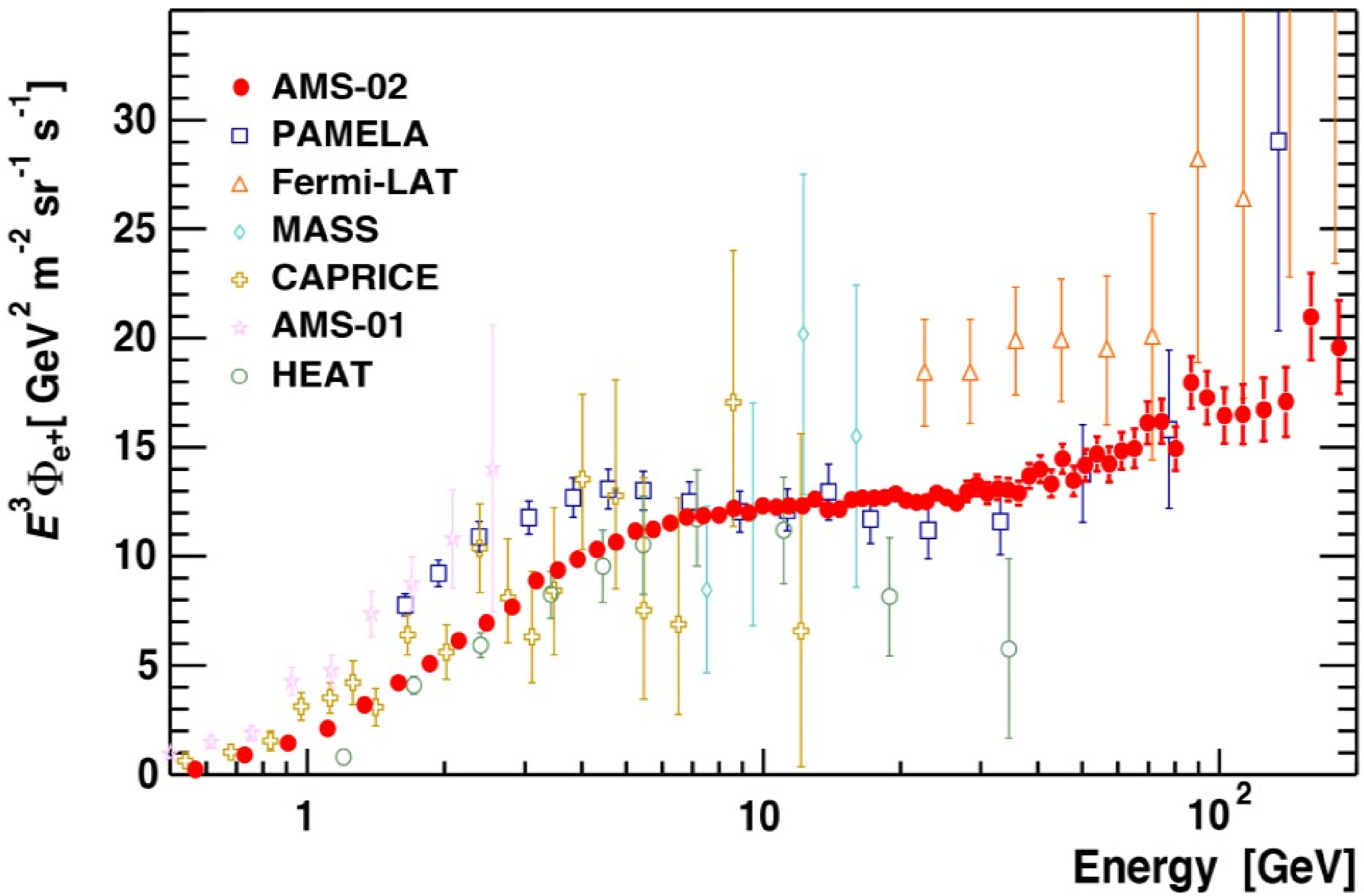

Figure 3 AMS positrons. Source: AMS-CERN Ting lecture Apr 2015

Triplet-pair production of positrons

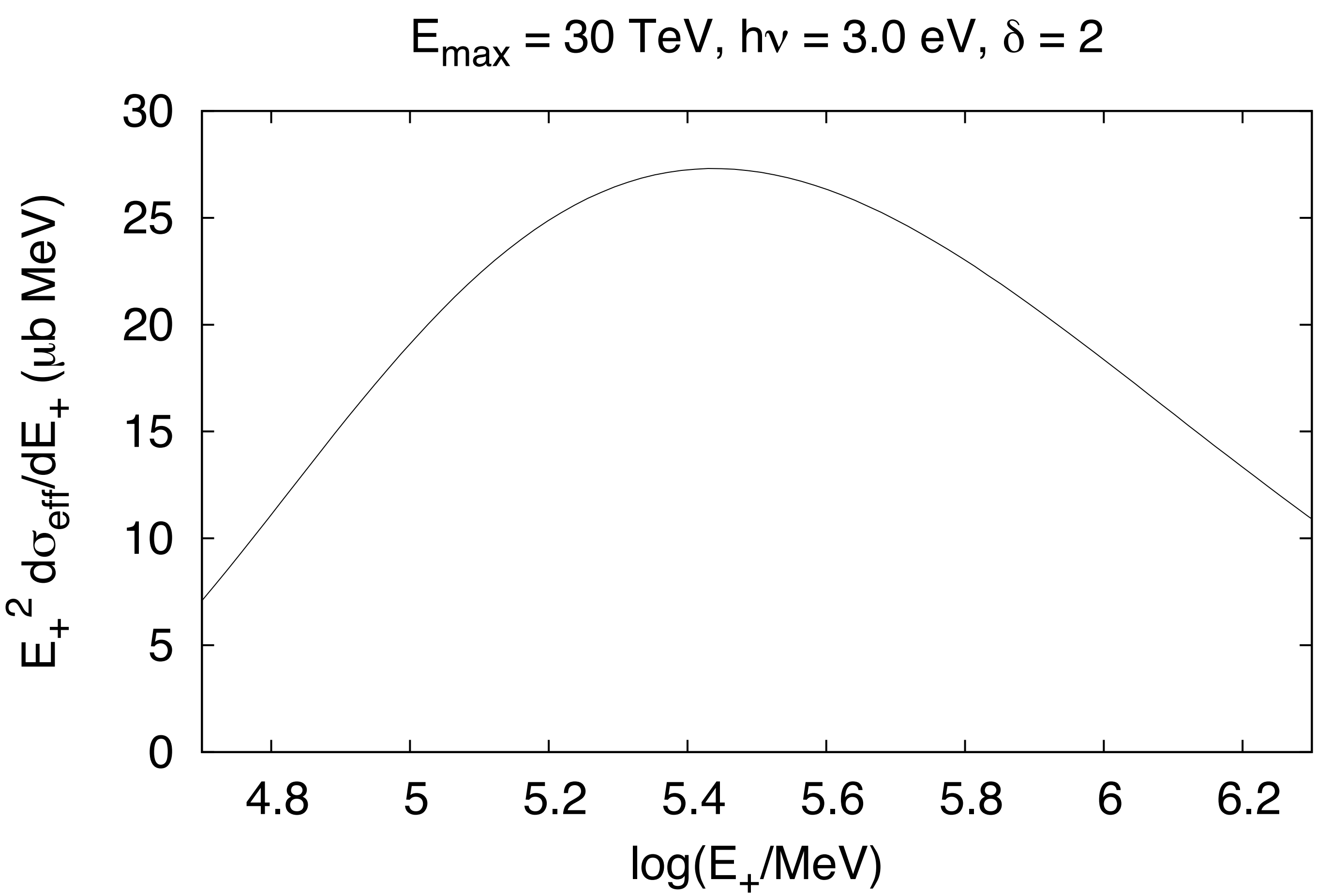

Figure 4 Positrons from the triplet-pair production using $(h\nu) = 3.0$ eV, $E_{e,max} = 30$ TeV, and electron-spectrum with slope $\delta = 2$. **Key prediction: fall off !** Source: Eberhard Haug 2014

Antimatter Anti-protons

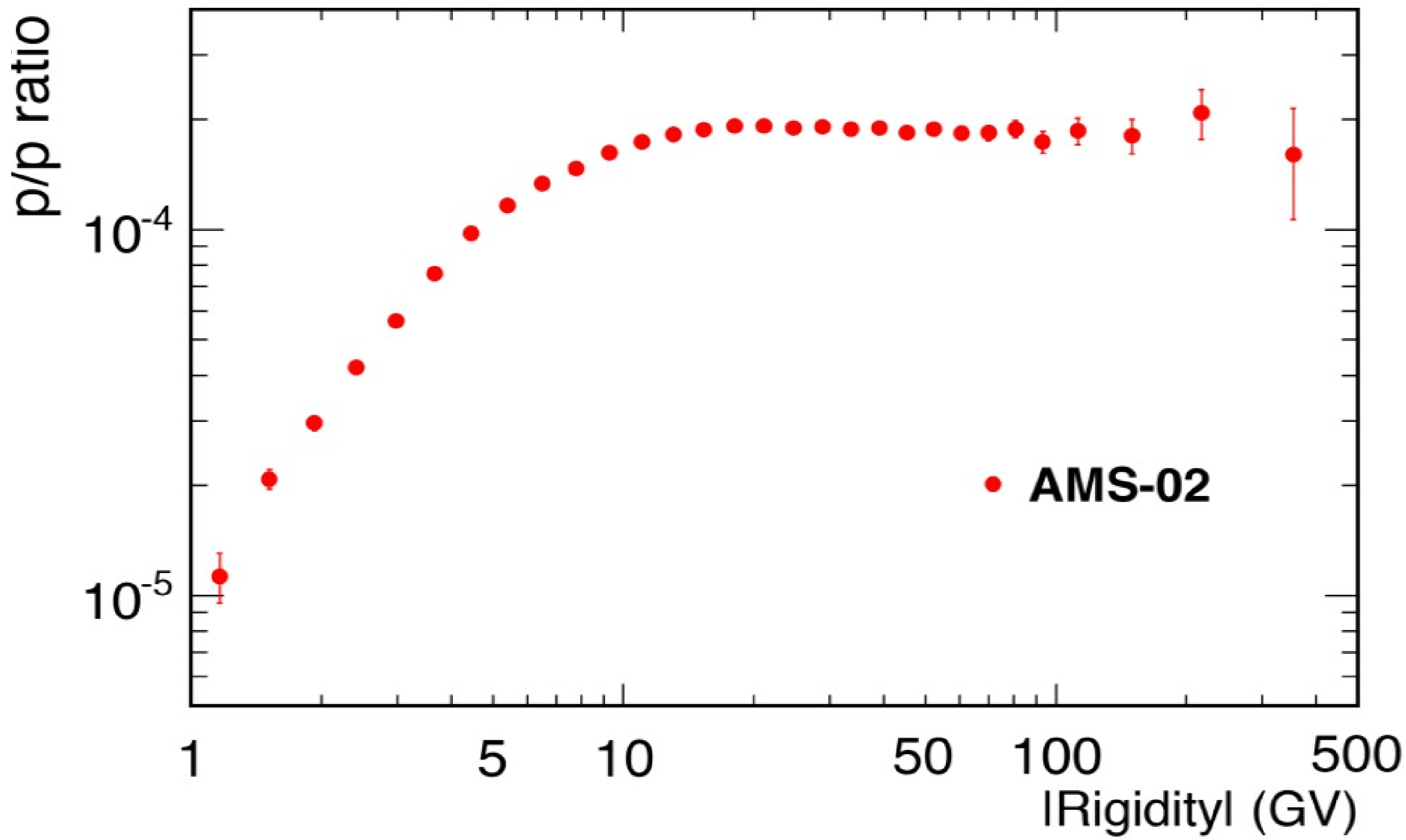

Figure 5 AMS antiproton fraction. Source: AMS-CERN Ting lecture Apr 2015. Can easily be fitted with proton interaction, **protons from massive star explosions**

Latest AMS results: Evidence for DM decay ?

- **Positrons: secondary**
- **Anti-protons: secondary**
- **Spectra can be fitted quantitatively**

All due to the physics of very massive stars !

No evidence for DM particle decay in these data !

New work with W. de Boer and I. Gebauer

Galactic Center GeV excess

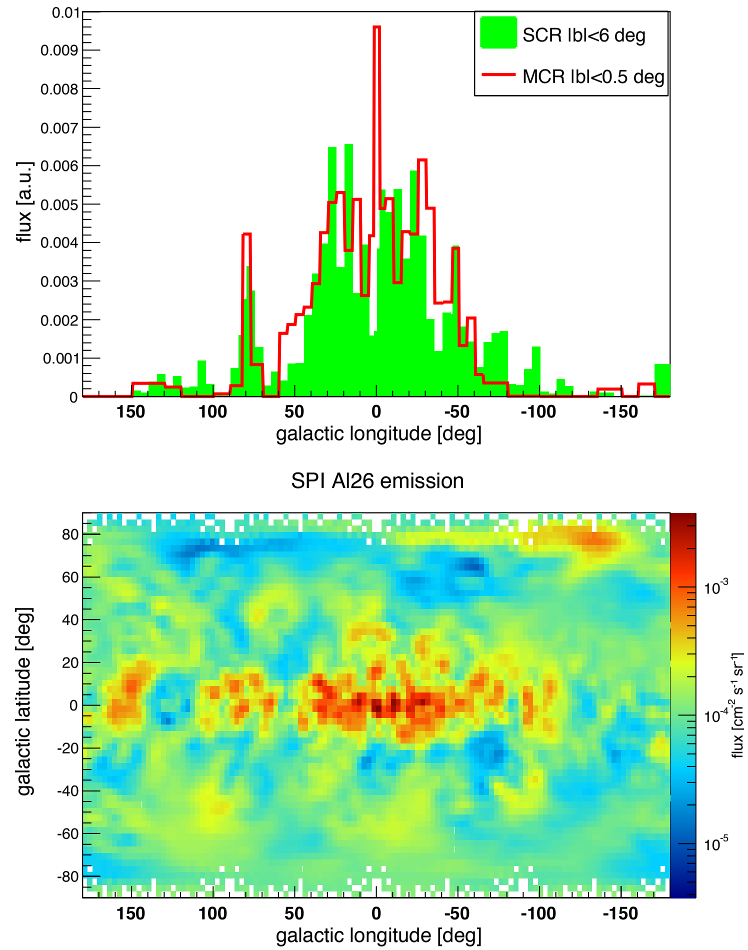

Figure 6 Galactic Center GeV excess fitted with model of CRs inside Molecular clouds (MCRs), source CRs (SCRs), and the corresponding Al^{26} emission, using templates. Source preprint **de Boer et al. 2016**

Dwarf ellipticals: WDM of keV

- (Hogan & Dalcanton 2000 PRD): g spin degrees of freedom, n density, P pressure, f distribution fct

$$n \sim \frac{g}{(2\,\pi)^3} \int f\, d^3p \text{ and } P \sim \frac{g}{(2\,\pi)^3} \int \frac{p^2}{3E}\, f\, d^3p$$

- $< v^2 > = \frac{3\,P}{n\,m}$, phase density $\boldsymbol{Q} = \frac{\boldsymbol{\rho}}{\boldsymbol{<v^2>^{3/2}}}$, non-relativistic case: Obtain $\boldsymbol{Q = q\,g\,m^4}$ with q numerical coefficient depending on nature of particle, degeneracy, etc. **Can we fit it ?**
- **Questions**: DM particles vs. stars? Isotropy ?
- Many papers by C. Destri, G. Gilmore, P. Salucci, N. Sanchez, H. de Vega, et multae aliae, multi alii

Gives **keV mass** directly from data.

Super-Massive Black Hole in a Group

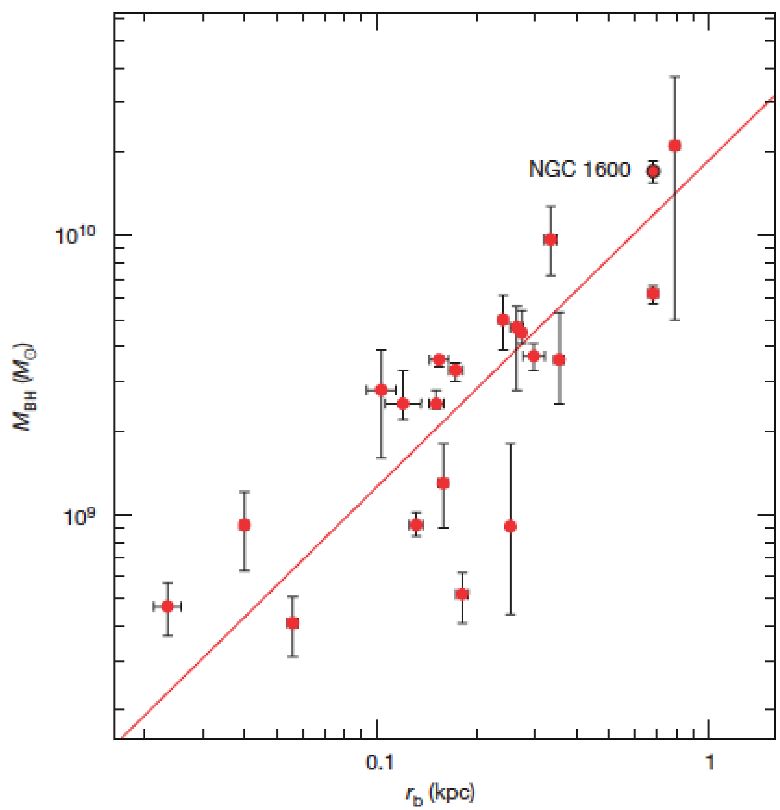

Figure 7 A SMBH in a group: Black hole mass and galaxy core radius: **How did it grow ?**. Source Thomas et al., Nature 532, 340, 2016.

The semi-circular giant arc in Super-Massive Black Holes (SMBHs) $> 3 \cdot 10^7 M_\odot$

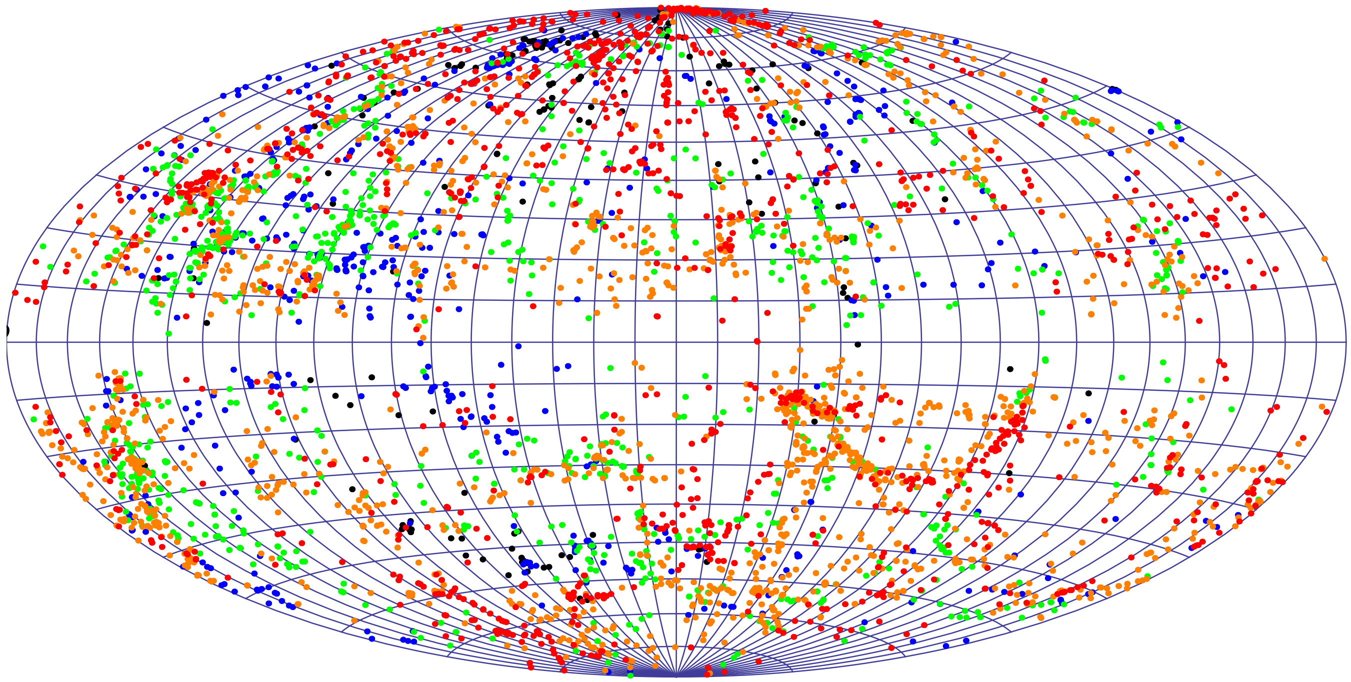

Figure 8 The sky in black holes, $\gtrsim 3 \cdot 10^7 \ M_\odot$, showing the giant arc, a coherent feature: The color code corresponds to distance: **Black**, **Blue**, **Green**, **Orange**, **Red** for the redshifts intervals 0, 0.005, 0.01, 0.015, 0.02, 0.025, corresponding to distance intervals of 0, 60, 120, 180, 240, and 300 million light-years: (−> Caramete & PLB 2011); coordinate system with Galactic plane across center, and Galactic Center (GC) at the right edge

Giant arc in SMBHs: radius about 44 Mpc

- **Giant spherical shells** of radius about 160 Mpc radius (Bashinsky & Bertschinger 2001, 2002, Percival et al. 2007): **outwards travelling disturbances**
- Slow-down initiates reverse waves
- **Baryonic acoustic oscillations** at wave-number l of about 220, 520 and 800
- Latter correspond to a shell radius of about 44 Mpc: **Could this be what we see in projection ?**
- May require **cut by spherical shell through a Zeldovich sheet**
- **Why such an enormous enhancement in density contrast ?**

Star formation in the early Universe

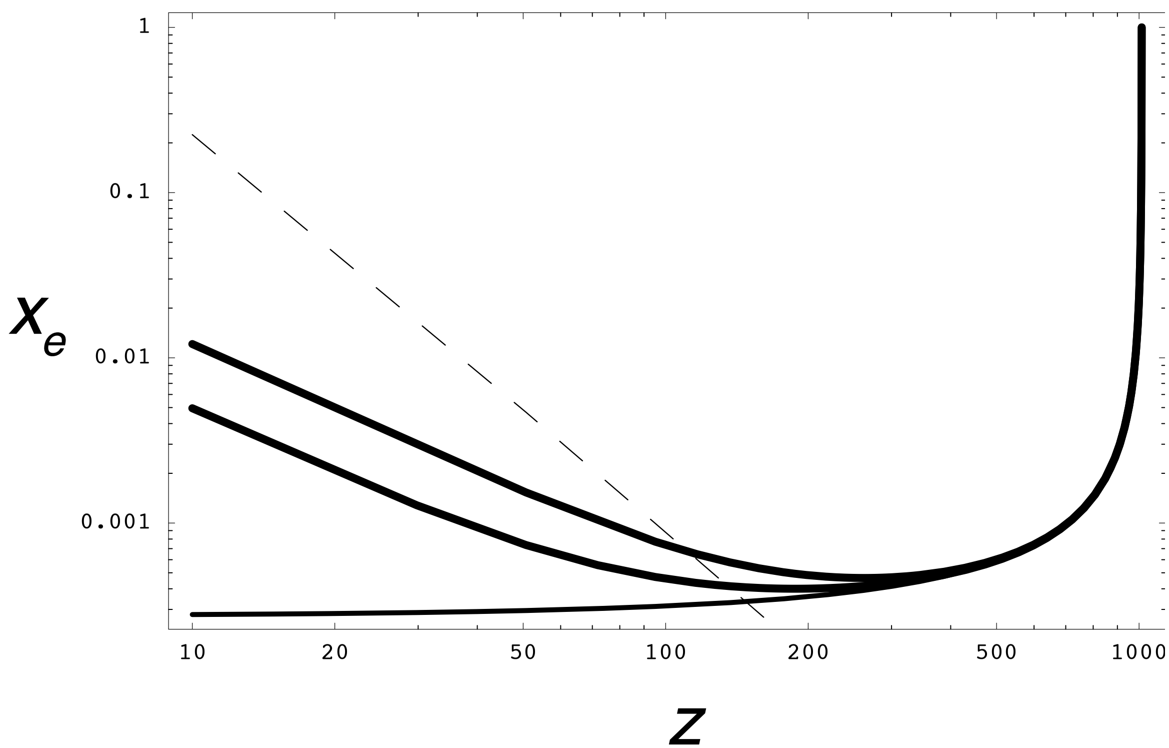

Figure 9 Degree of ionization in the early universe for different assumed masses of the **DM sterile neutrino, here 4 and 7 keV**; **extra ionization leads to stronger formation of molecular Hydrogen.. Molecular Hydrogen allows strong cooling, and this in turn allows early star formation**. Source PLB & Kusenko 2006 PRL.

Very early star formation: HD absorption test

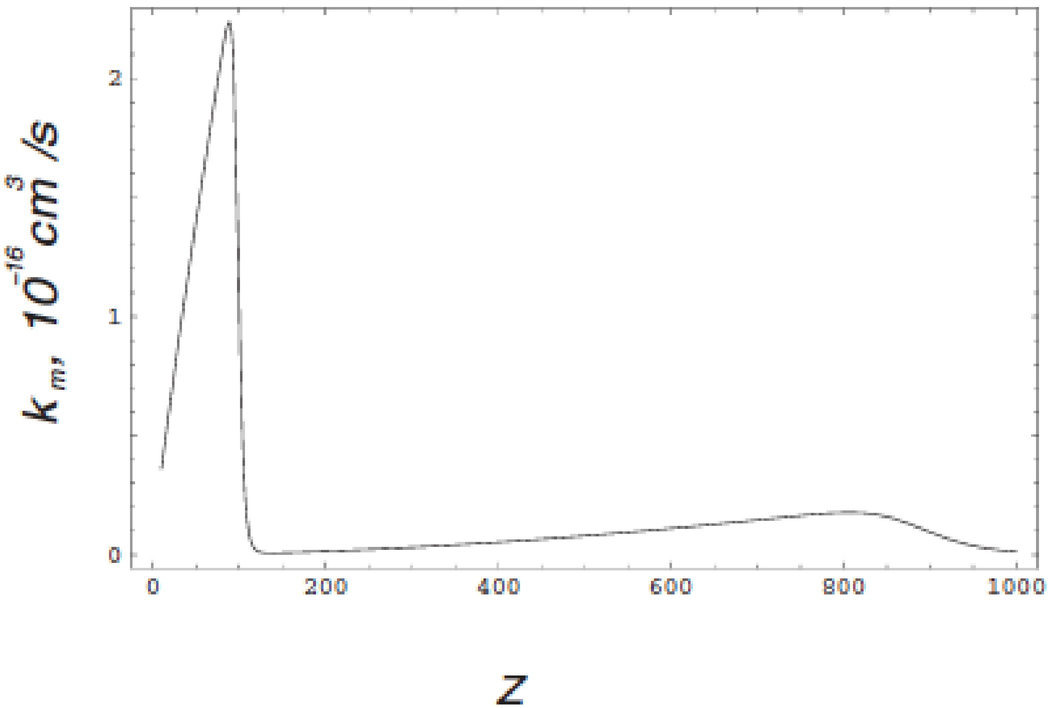

Figure 10 **Molecular Hydrogen creation rate** coefficient; this allows extreme cooling and **star formation**. **Maximum redshift allowed is 100**. Source PLB & Kusenko 2006 PRL.

The cosmic amplifier

- Flow between baryonic matter and dark matter **supersonic since recombination** (review Fialkov 2014)
- **Mach-number about 5 −> shock-waves**
- In these shock-waves **enhanced cooling by H_2**
- Cut through DM **Zeldovich pancake gives an arc**
- **If** dark matter is a sterile neutrino (PLB & Kusenko 2006), then an order of magnitude **more H_2** possible
- Could we have **isothermal shocks ?** Jeans-mass ?
- **Start of baryonic non-linear structure ? Very early SMBHs ? Giant arc of SMBH ?**
- Does this help with structure formation of a **partially degenerate fluid** ?

Again phase density $Q = \frac{\rho}{<v^2>^{3/2}}$

- Blumenthal et al. 1986 ApJ 301, 27: dissipative infall
- **"... baryons sink dissipatively by $\sim$ 10 in radius during galaxy formation"** - to disk
- This corresponds to an **increase of the velocity, decreasing Q by a factor Z**
- Sanchez & de Vega 2010 MN 404, 885: They estimate **Z to be in the range between 1 and 10^4**
- The Blumenthal et al argument corresponds to a **decrease of Q by a factor Z of about 30**
- The proposal here is that this is **key process allowing galaxy and SMBH formation to be early**

Dwarf spheroidals: Casey Watson :

- Compression of baryons by factor $\sim$ 10, as Blumenthal et al.; leads to more concentrated Burkert DM halo; parameters governed by **half-light radius r_{hf} correlations** inferred from observations (Watson +):
- $\rho(0) = (1.13 \pm 0.15)\, M_{\odot} pc^{-3}\, r_{hf}^{-1.63 \pm 0.2}$
- **Baryonic compression appears to fundamental, underlying mechanism** that leads to observed correlations between **r_{hf} and DM spherical (Burkert) halo parameters !**
- Remarkable relationships between final and initial mass distributions of both baryons and DM exhibit (apparent) **scale invariance** - for r_{hf} ranging between 25 pc and 1000 pc - AND consistent with observations

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

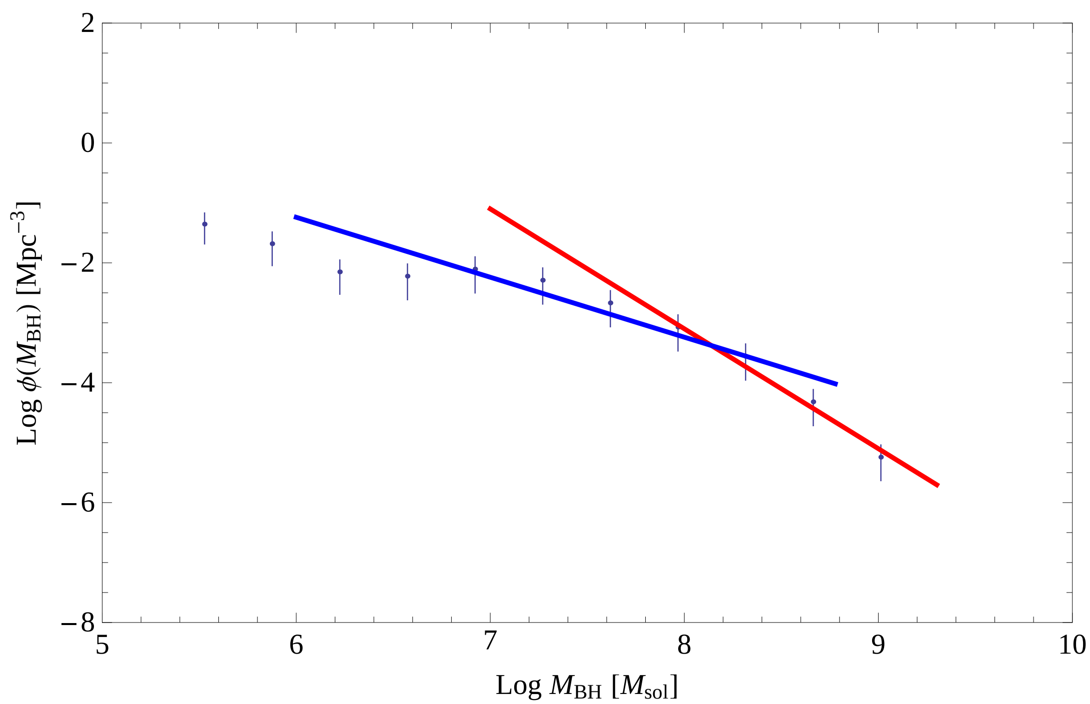

Figure 11 Integral mass function corrected for Hubble type sampling, 2928 objects, the slope of the lines is: red -2.0 fitting $> 10^8 \, M_\odot$, and blue -1.0 fitting between $10^7 \, M_\odot$ and $10^8 \, M_\odot$. See Caramete & PLB, *Astron. & Astroph.* **521**, id.A55 (2010); arXiv:0908.2764. This mass function suggests that black holes start near $3 \cdot 10^6 \, M_\odot$, possibly at redshift of order ~ 30 to 100, and grow by merging (see PLB & Kusenko 2006, PRL): Note that redshift 100 corresponds to only 13 million years after Big Bang

Why Black Holes of around $3 \cdot 10^6\ M_\odot$?

- First massive stars form in dense groups in gravitational potential of **DM of dwarf galaxy**: stars agglomerate rapidly to form 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 $\sim$ **300** $M_\odot$ 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

Early super-massive black holes

Super-massive stars form and explode, making first **Super-Massive Black Holes (SMBHs)**, back-grounds (PLB et al. 2014 MNRAS):

$$F_{rad} = 10^{-19.8} N_{BH,0,0} \eta_{B,-1}^{0.8} \eta_{CR,e,-1}^{+1} E_{57}^{1.3} z_{1.3}^{+0.8} \nu_{9.0}^{-0.60} \, \mathrm{ergs}^{-1} \mathrm{Hz}^{-1} \mathrm{cm}^{-2} \mathrm{sr}^{-1} \, .$$

- Predicted (2012) neutrinos - observed (IceCube 2013).

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

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. 2011 +)

Great arc physics?

- **Spherical baryonic disturbance** travels outwards
- **Slow-down –> reverse waves**
- Cuts through **Zeldovich DM pancake**
- After recombination **super-sonic flow** between DM and baryons: **shocks**
- **Stronger cooling from sterile neutrino decay**
- **Only with sterile neutrino decay** early: $z \lesssim 100$
- Greatly enhanced post-shock density: **rapid collapse**
- Forms first DM clumps, stars, star agglomeration, **SMBHs**
- Galaxies with SMBHs merge **–> bigger SMBHs**
- Original geometry frozen: **Great arc**

Black Hole energetics $\lesssim (1/2)\,\Delta\, M_{BH}\, c^2$

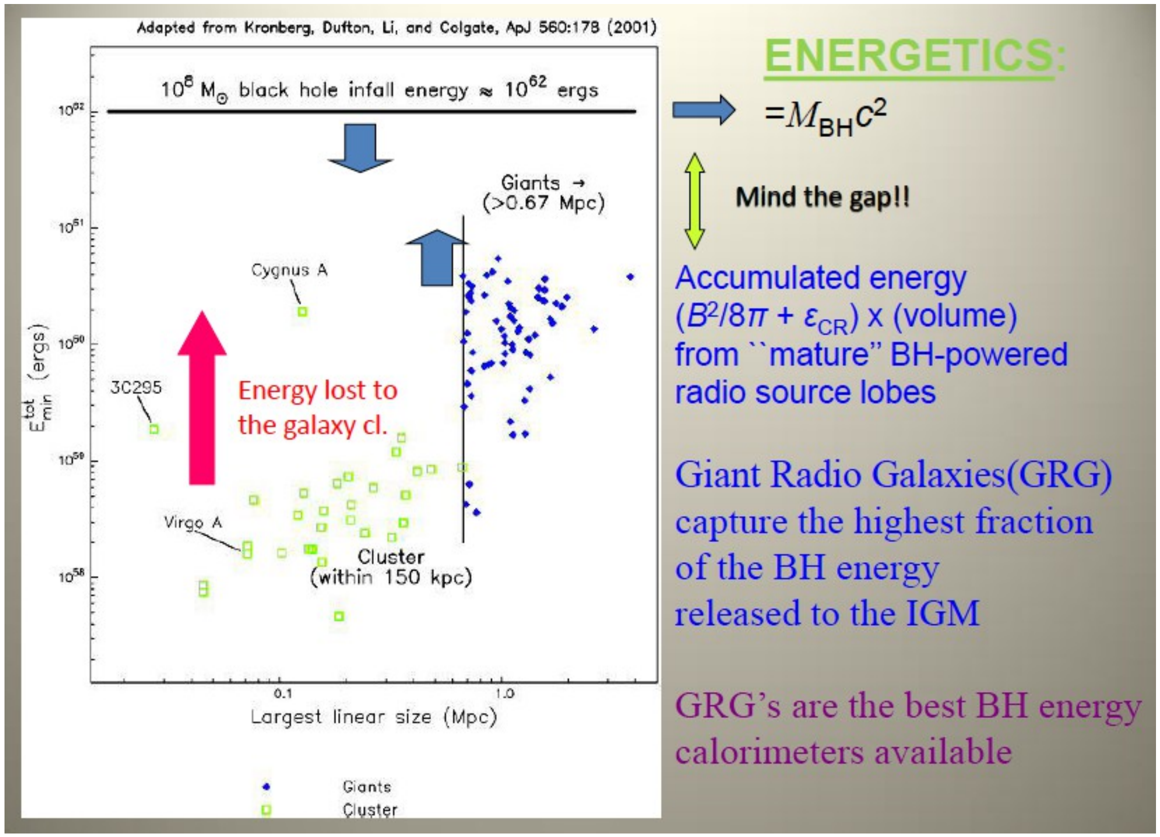

Figure 12 Radio galaxies and their visible energetics, outside clusters and inside. These authors used $10^8\, M_\odot$, but in a typical merger very much less energy might be available, so the efficiency required is quite high: source lecture **P.P. Kronberg** at DRAO Nov 2015

Black Holes & Gravitational Waves

- **Form/Merge SMBH**? Limit $\sim$ $(1/2)\, M_{BH}\, c^2$

  $$\frac{1}{2} N_{BH,0}\, M_{BH}\, c^2 (1 + z_\star)^3 \sim 10^{-8}\, \mathrm{erg/cc}$$

- 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 $z_\star$.
- **Ben Harms: Einstein and conserv. eqs. in 5D, seek solution**. **5th dimension $\sim$ 300 Planck lengths: strong brane and weak brane.**
- Energy transfer from **strong brane** (Planck density) to **weak brane** (us) **can mimic** E.O.S. $P = -\rho\, c^2$!

  Prediction: detectable GW bg !

Limits on GWs obtained at various redshifts

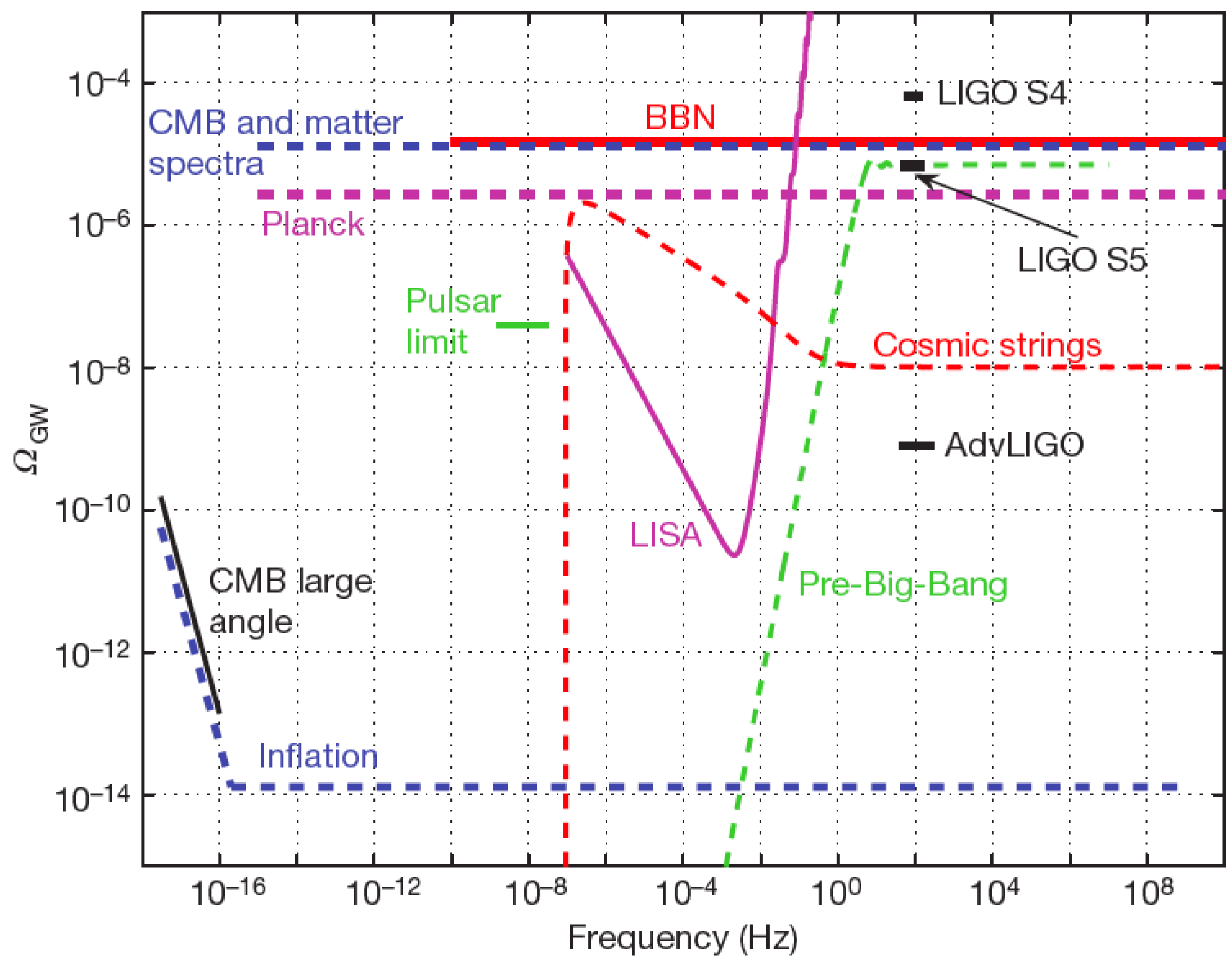

Figure 13 Limits on gravitational waves. Source: Virgo and Ligo Coll. Nature 2009

Early universe visible !

- **Only keV sterile neutrino DM allows very early star, SMBH and giant arc formation, $z \lesssim 100$!**
- **Radio continuum and line background !**
- **HE activity and low frequency GWs due to fresh binary SMBH mergers!**
- **Test I: Identify the HE and GW-sources !**
- **Test II: Get z from HD^+ absorption !**
- **Test III: Detect first SMBH activity !**

Thank you!

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Abstract:

Dark matter was discovered 1933 by F.Zwicky in clusters of galaxies; the term is due to J.Oort 1932. Today we know that dark matter is most of matter in the universe, but we do not know what it is. Particle Physics suggests that it could be a heavy particle, and it could be produced in the right quantity. Astronomy suggests

that it is a light particle, from simple phase space arguments of old compact galaxies. If the first approach is correct, then the particle ought to be visible in some strange interaction, producing odd positrons, neutrinos, etc. Many unexpected photons, positrons, anti-protons and other particles have been detected, but none of them securely point to anything unusual. All can be quantitatively explained with normal star explosions. If the second approach is correct, then of course things are even more difficult: One particle physics candidate for the second approach is a sterile neutrino of about 2 - 8 keV mass. We may have a chance to detect it via a decay yielding an X-ray photons: such X-ray photons greatly enhance the formation of molecular Hydrogen in the early universe. The relative motion between baryonic matter and dark matter is super-sonic right from recombination; shocks ensue. With a sterile neutrino these shocks have a much larger cooling efficiency due to much larger fraction of molecular Hydrogen; this process is a great amplifier, since the density jump of baryonic matter may reach order 10, while the density disturbance of dark matter is still $<< 1$. In the post-shock region this allows the formation of clumps, and they also allow strong star formation in the early universe. In the combination they may support the formation of the first super-massive black holes. Since disturbances give rise to an expanding spherical shell, we might expect gigantic arcs of super-massive black holes in projection - we do observe this at the 44 Mpc scale. We speculate on the role of these first super-massive black holes: could they be connected to dark energy? What are the critical tests of all such ideas about dark matter?