Dark Matter, Super-Massive Black Holes and Gravitational Waves

Peter L. Biermann[1,2,3,4]

July 21, 2016; lecture at Meudon/Nijmegen/Paris

[1] MPI for Radioastronomy, Bonn, Germany; [2] Dept. of Phys., Karlsruhe Inst. for Tech. K.I.T.; [3] Dept. of Ph. & A., Univ. of Alabama, Tuscaloosa, AL, USA; [4] Dept. of Phys. & Astron., Univ. Bonn; and W. de Boer (K.I.T.), L.I. Caramete (ISS Bucharest, MPIfR Bonn), I. Gebauer (K.I.T.), L.Á. Gergely (Univ. Szeged), B.C. Harms (UA Tuscaloosa), E. Haug (Univ. Tübingen), P.P. Kronberg (Univ. Toronto), E. Kun (Univ. Szeged), P.A. Mason (Univ. NM), A. Meli (Univ. Gent), I.F. Mirabel (Buenos Aires, Paris), B.B. Nath (RRI Bangalore), E.-S. Seo (Univ. Maryland), T. Stanev (Bartol, Delaware), J.B. Tjus (Univ. Bochum), & C.R. Watson (U. Millikin, IL.)

Challenging steps

- **1 Evidence for dark matter (DM)**
- **2 CR-e^{+}, CR-$\bar{p}$, Galactic Center GeV excess**
- **3 How do Super-Massive Black Holes (SMBHs) form and evolve?**
- **4 The great arc of SMBHs**
- **5 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
- Hot gas in Ell. gal. NGC5846 (PLB + 1983)
- Dwarf ell. gal. (Hogan & Dalcanton; Destri, Gilmore, Salucci, Sanchez, de Vega, ...)

Dark matter in small galaxies

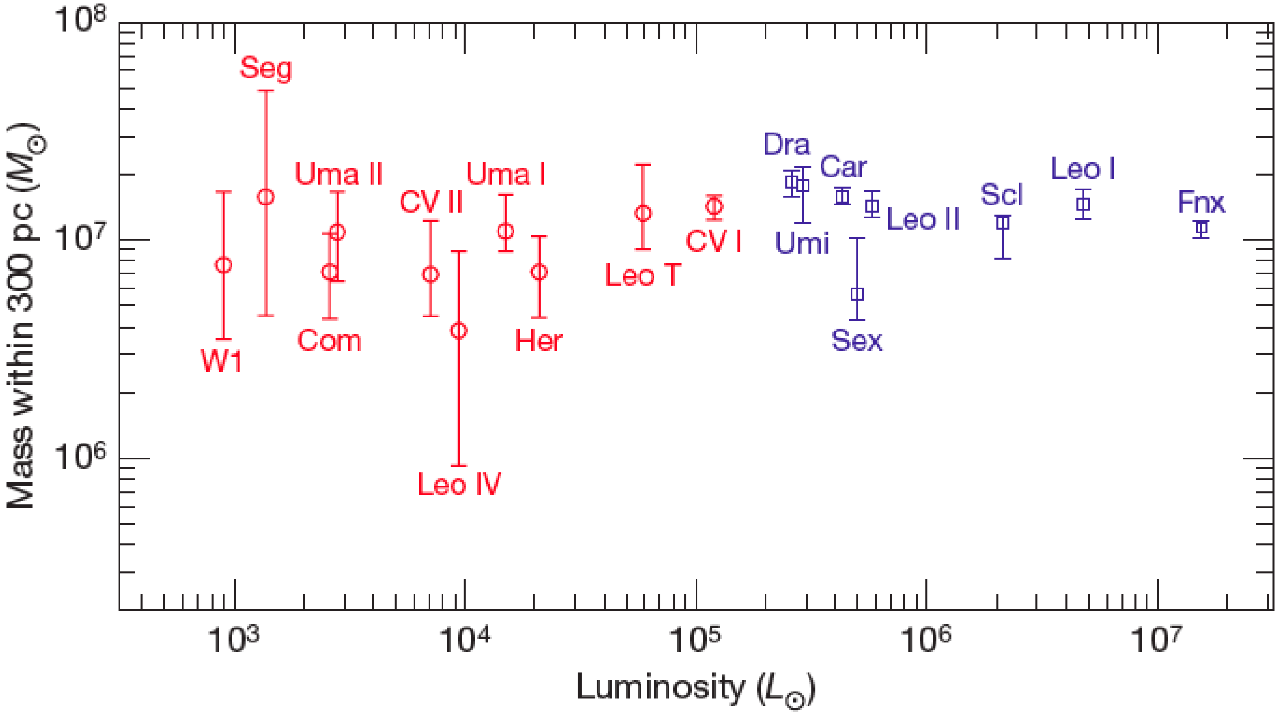


Figure 1 | The integrated mass of the Milky Way dwarf satellites, in units of solar masses, within their inner 0.3 kpc as a function of their total luminosity, in units of solar luminosities. The circle (red) points on the left

Figure 1 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)

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, C. Watson, + + +

Gives **keV mass** directly from data.

Antimatter Positrons

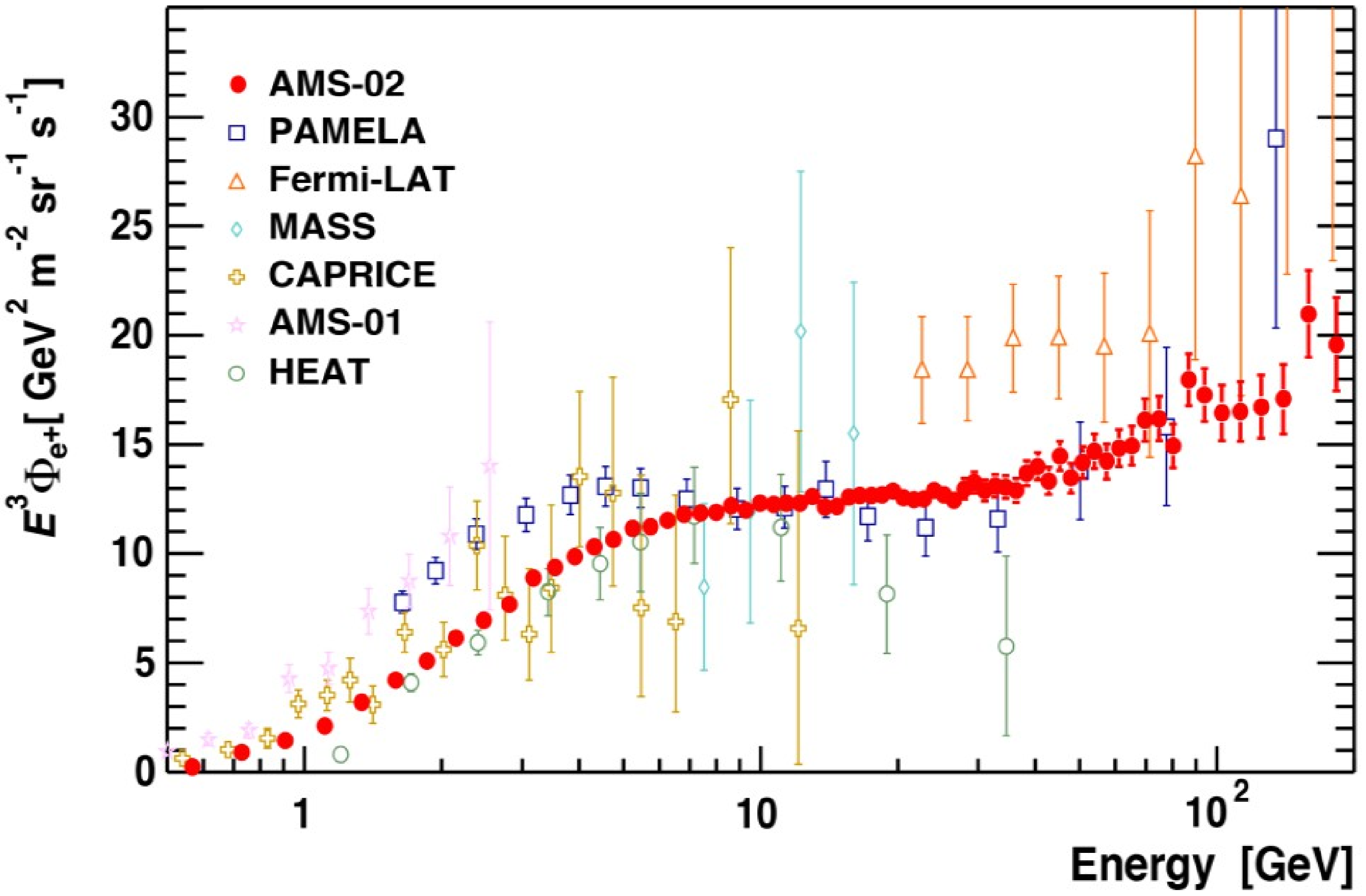


Figure 2 AMS positrons. Source: AMS-CERN Ting lecture Apr 2015

Triplet-pair production of positrons

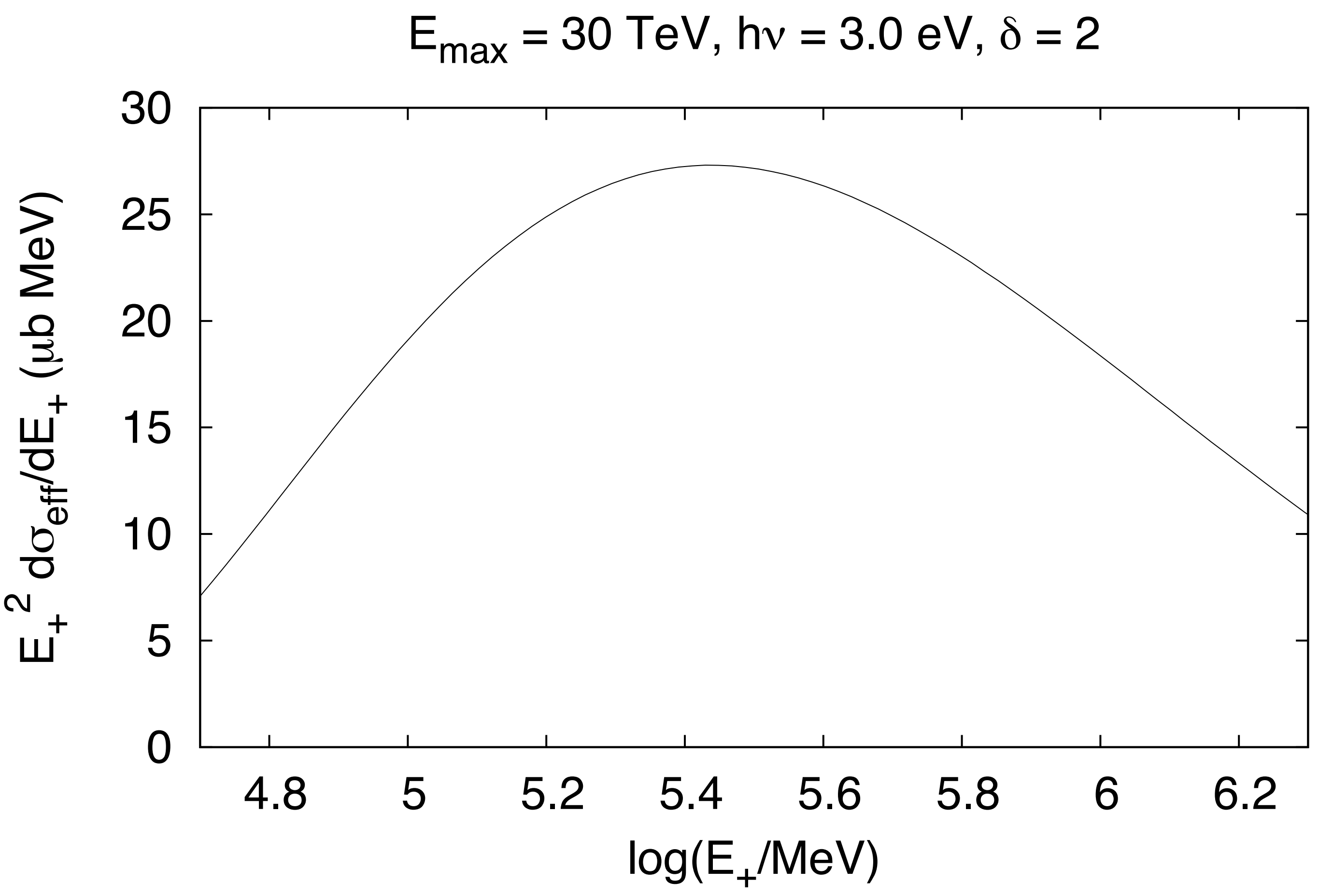


Figure 3 Positrons from the triplet-pair production using $(h\nu) = 3.0$ eV, $E_{e,max} = 30$ TeV, and electron-spectrum with slope $\delta = 2$. **Key prediction: fall off !** Source: **Eberhard Haug 2014+**

Antimatter Anti-protons

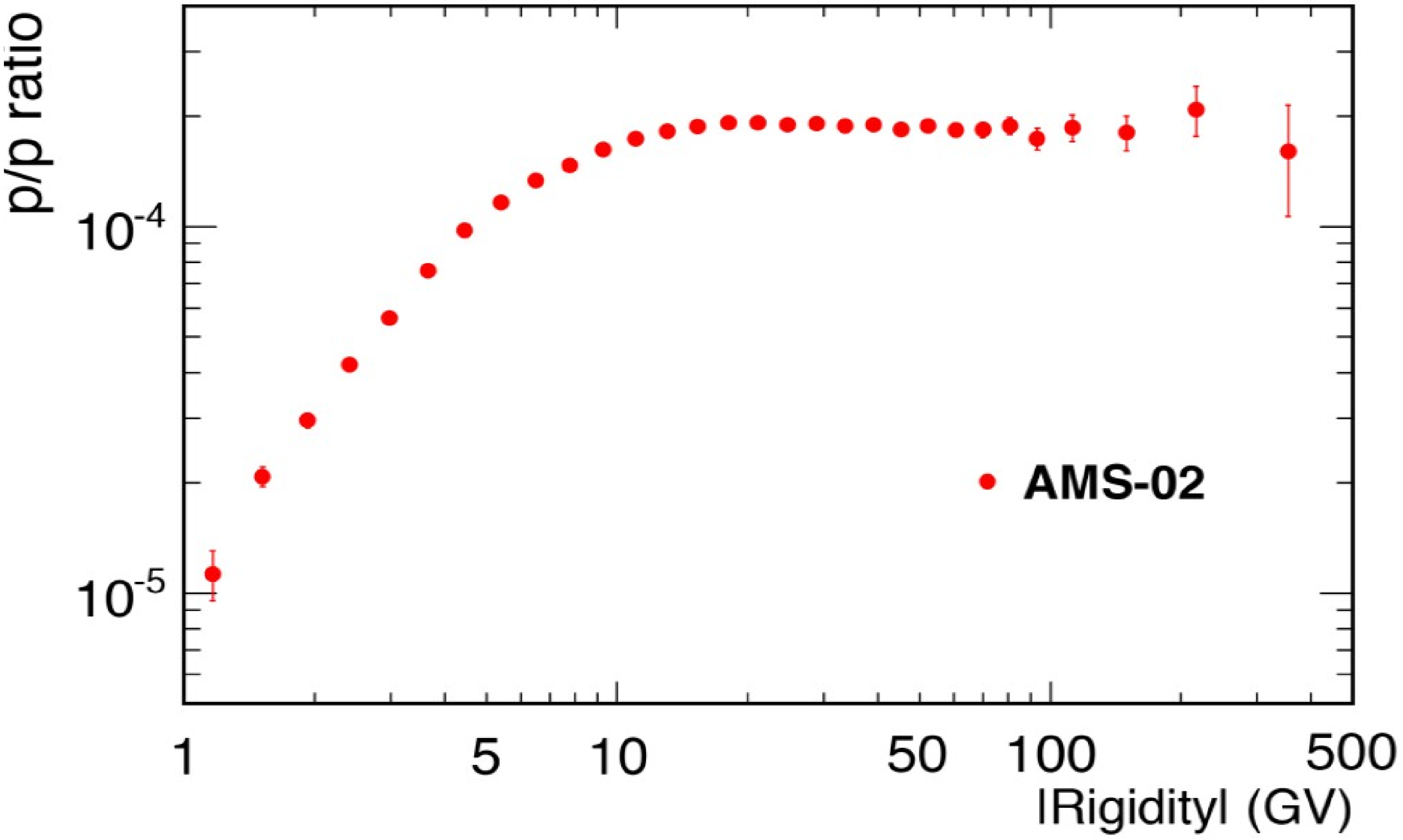


Figure 4 AMS antiproton fraction. Source: AMS-CERN Ting lecture Apr 2015. Can easily be fitted with proton interaction, **protons from massive star explosions**

Galactic Center GeV excess

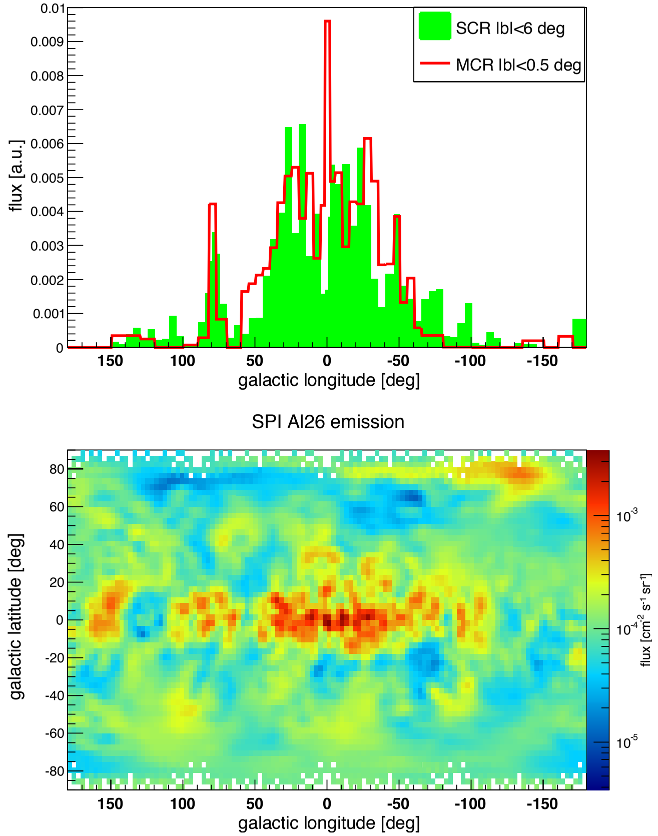


Figure 5 Galactic Center GeV excess fitted with model of CRs inside Molecular clouds (MCRs), source CRs (SCRs), and the corresponding Al^{26} emission, using templates. **Apparent spherical extent due to 3 kpc arm**. Key physics ingredient is magnetic shielding, effectively **proto-stars have already the same mass-to-magnetic-flux ratio as main sequence massive stars**. Source preprint **de Boer et al. 2016**

Σ : CR-e^+, CR-$\bar{p}$, Galactic Center GeV excess

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

No evidence for DM particle decay in these data !

- **All due to the physics of very massive stars,
from proto-stars to explosion !**

New work with **W. de Boer and I. Gebauer**

Star formation in the early Universe

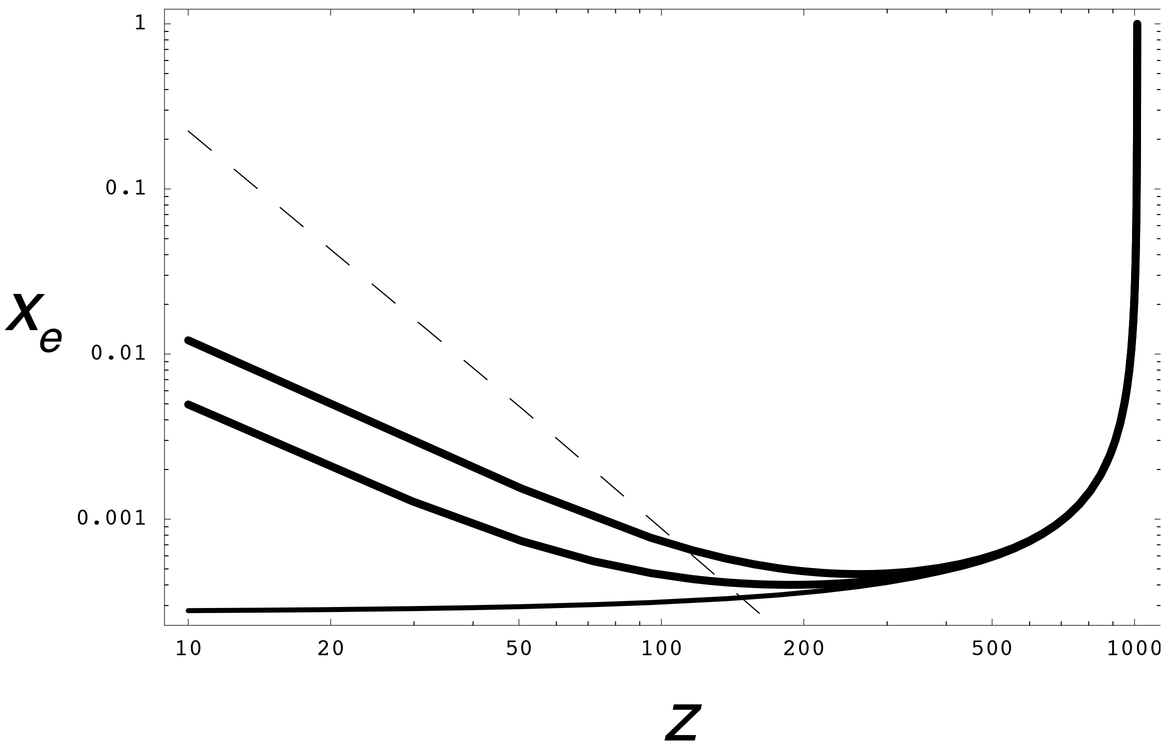


Figure 6 Degree of ionization in the early universe for different assumed masses of the **DM sterile neutrino, here 4 and 7 keV**; **extra ionization leads to stronger formation of molecular Hydrogen.. Molecular Hydrogen allows strong cooling, and this in turn allows early star formation**. Source PLB & Kusenko 2006 PRL.

Very early star formation: runaway

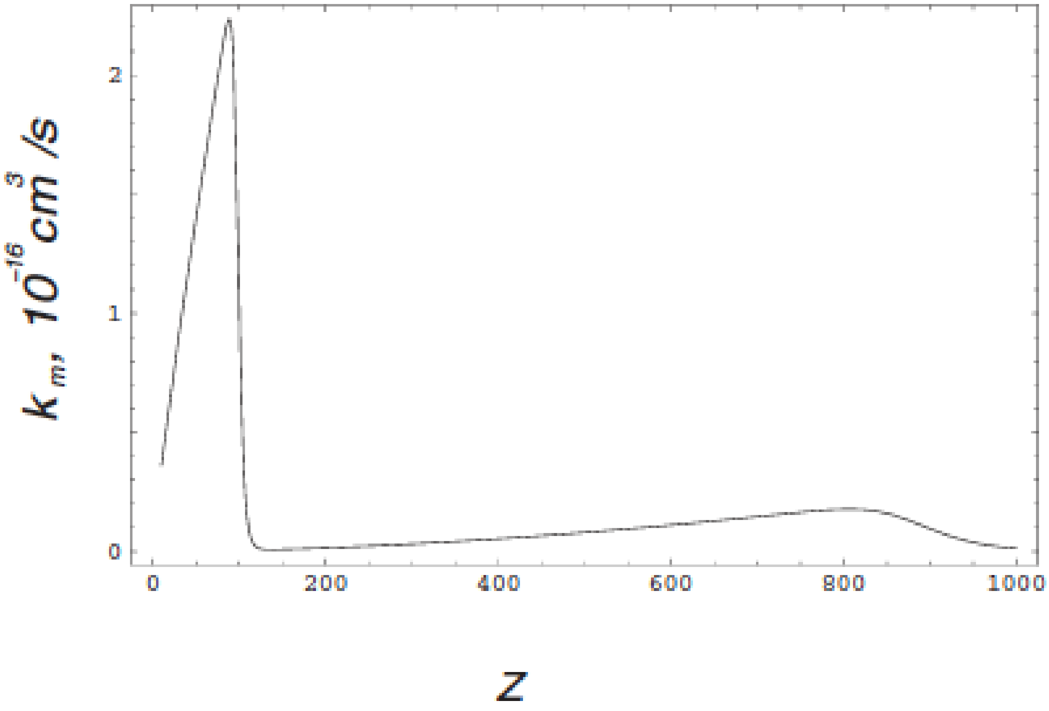


Figure 7 **Molecular Hydrogen creation rate** coefficient; this allows extreme cooling and **star formation**. **Maximum redshift allowed is 100**. Source PLB & Kusenko 2006 PRL.

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

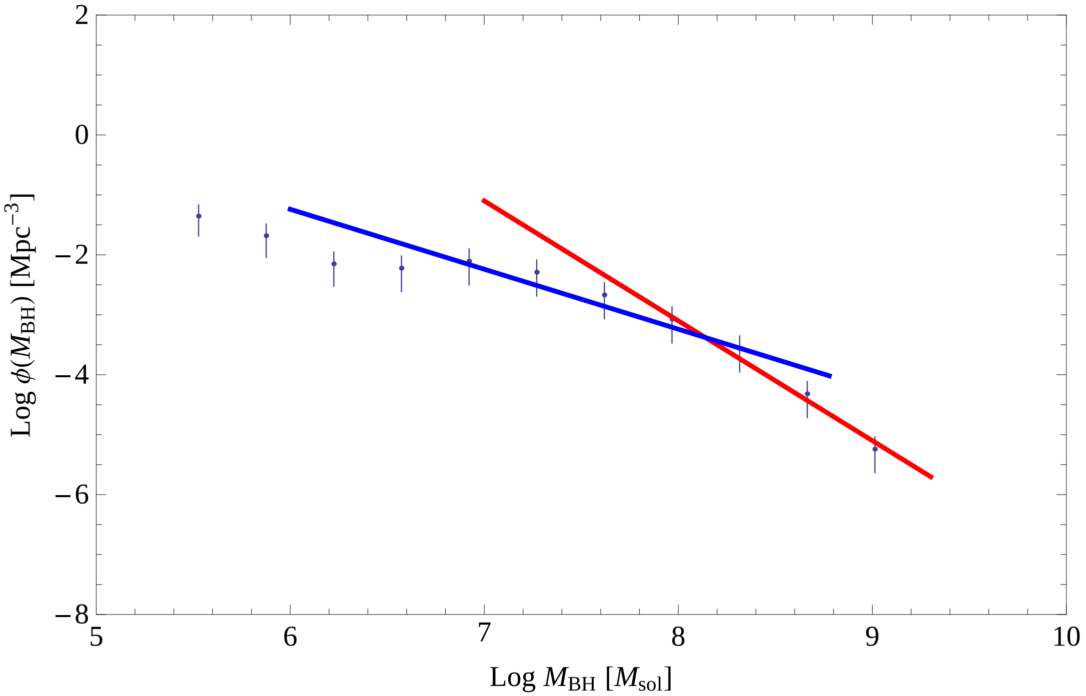


Figure 8 Integral mass function corrected for Hubble type sampling, 2928 objects, the slope of the lines is: red -2.0 fitting $> 10^8\, M_\odot$, and blue -1.0 fitting between $10^7\, M_\odot$ and $10^8\, M_\odot$. See Caramete & PLB, *Astron. & Astroph.* **521**, id.A55 (2010); arXiv:0908.2764. This 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; Gergely & PLB 2012): Note that redshift 100 corresponds to only 13 million years after Big Bang

The mass function of small galaxies at high z

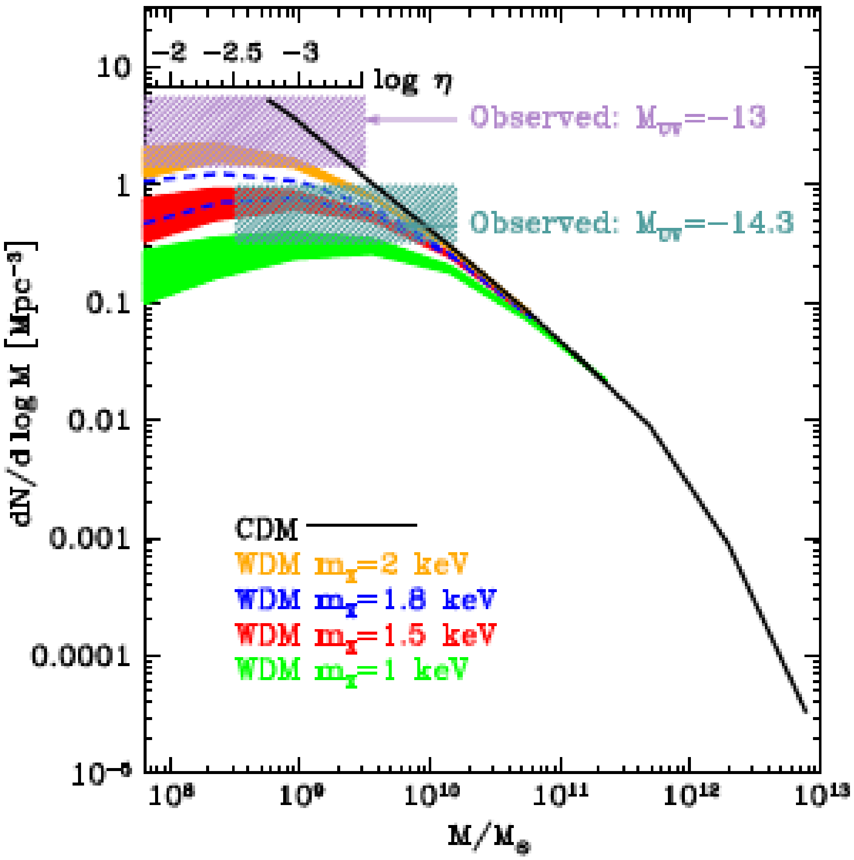


Figure 9 The The mass distribution of small galaxies at high redshift of small galaxies ($z \simeq 2$). This peaks at around 3 Mpc^{-3}; η is a star formation parameter used in Alavi et al. (2014) to interpret the data from lensing. Source: **N. Menci et al. 2016 ApJ.**

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

- Massive stars form in dense groups in gravitational potential of **DM of dwarf galaxy**: stars agglomerate
- Massive stars also have **winds**, driven by photons interacting with heavy elements (Lucy & Solomon 1970 +): Maximum mass $\sim$ **300** $M_\odot$ (Yungelson + 2008)
- At $Z_{ch} \simeq 0$ massive stars can grow to $10^6\ M_\odot$
- Massive stars hit **instability**, combining radiation pressure with General Relativity (Appenzeller & Fricke 1972+)
- So with infall the mass of about $3 \cdot 10^6\ M_\odot$ possible
- **Stellar BH forms at $Z_{ch} = 0$, eats degenerate DM $->$ SMBH** (Munyaneza & PLB 2005/2006)

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).

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

Shell (Kormendy + 2010, 2011; Conselice + 2011 +)

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

- Can explain **massive bulge-less disk galaxies**
- **Fermi-bubble blowout galaxies** also (+ Mirabel)

Where are the sources? IceCube 2015

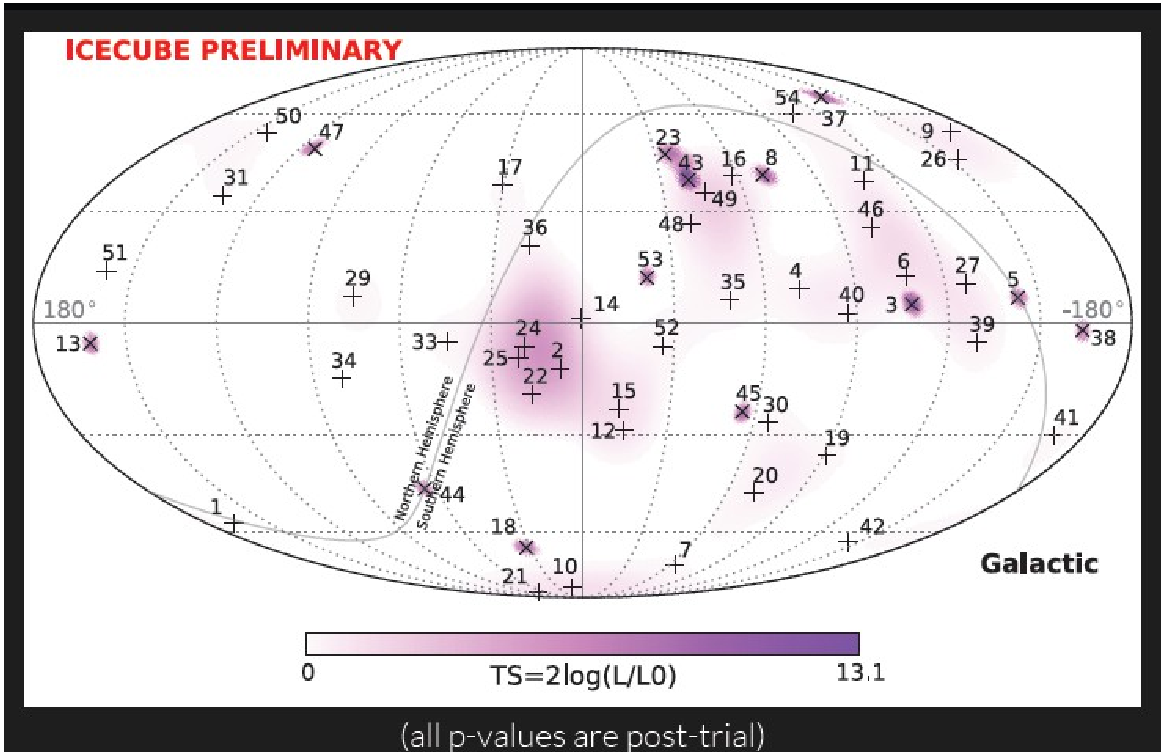


Figure 10 The HE neutrino events 2015; ”x”-symbols are better directions than crosses. GC at center. **Fresh SMBH mergers – the candidates – are flat spectrum radio sources at high redshift**, since merger rate steeply rising fct of redshift. Source ICRC 2015 talk.

Orbital angular momentum wins in a merger

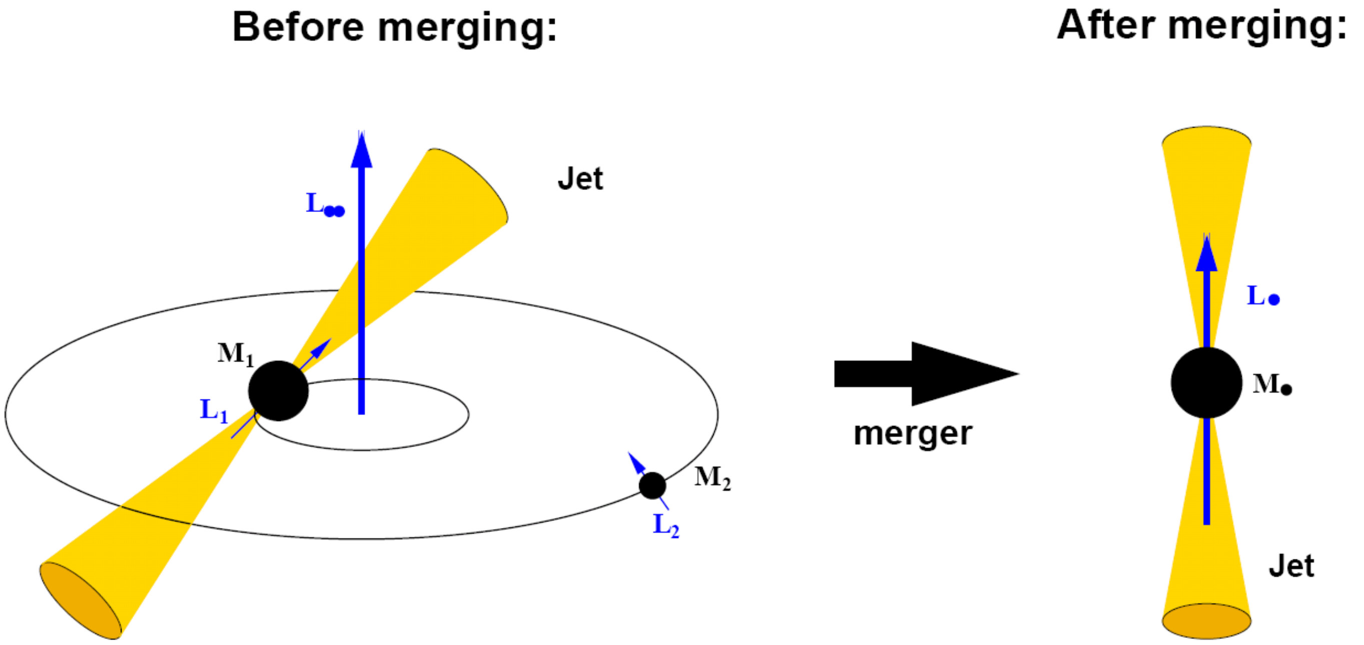


Figure 11 This figure illustrates the change of the direction of the spin of the BH, induced by the merger of 2 massive BHs, and consequently the change of the direction of the jet. Basically the orbital spin wins over the two intrinsic spins. The left panel shows the situation before the merger, when the jet is aligned with the individual spin of the primary black hole of the binary system (Zier & PLB 2001, 2002 AA).

The new spin of the merged Black Hole

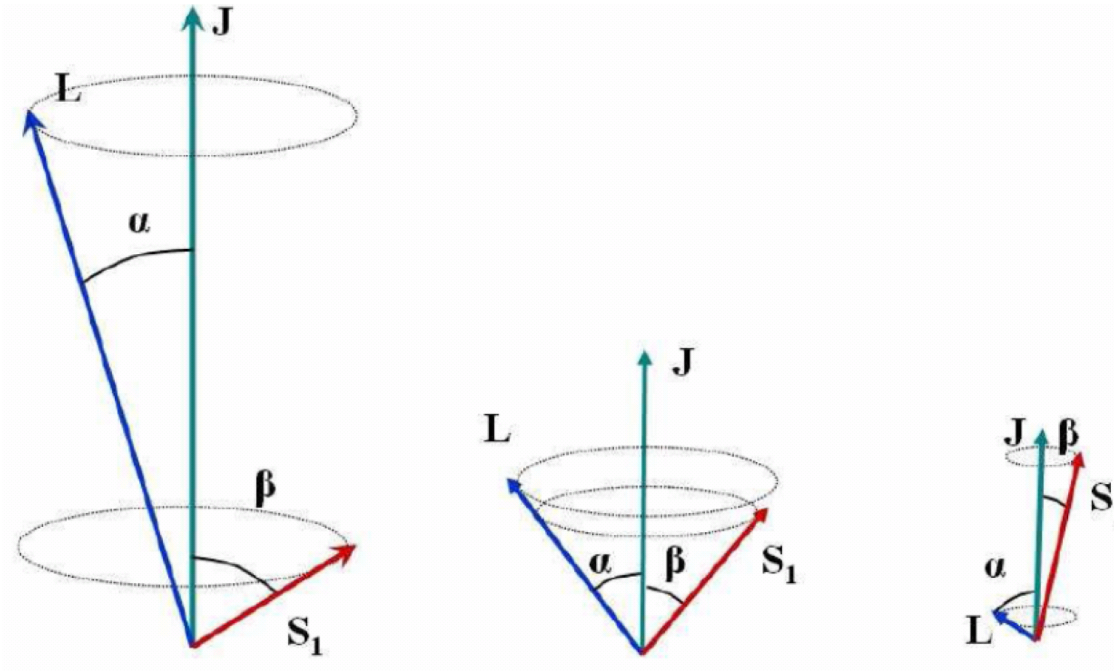


Figure 12 The spin-flip phenomenon in supermassive black hole binary mergers: Individual BH spin is $\boldsymbol{S}$, orbital angular momentum is $\boldsymbol{L}$, and total angular momentum is $\boldsymbol{J}$. These three steps show the envisaged **temporal evolution of the final stages of the merger**. L.A. Gergely & PLB: 2009 ApJ

M87: two axes: a recent merger

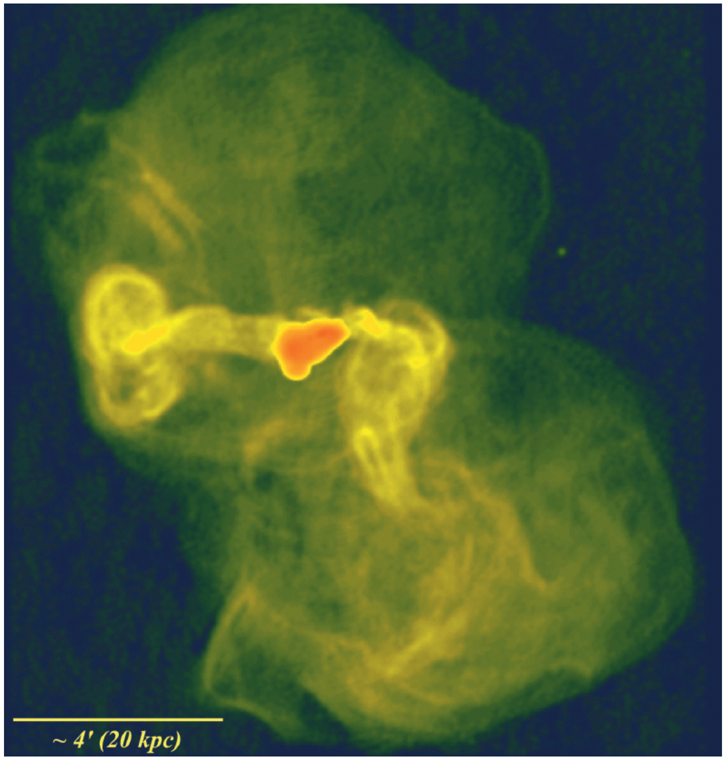


Figure 13 The M87 jet and counter-jet, clearly demonstrating a spin-flip. Source Owen et al. 2000 ApJ

Cen A: two axes: a recent merger

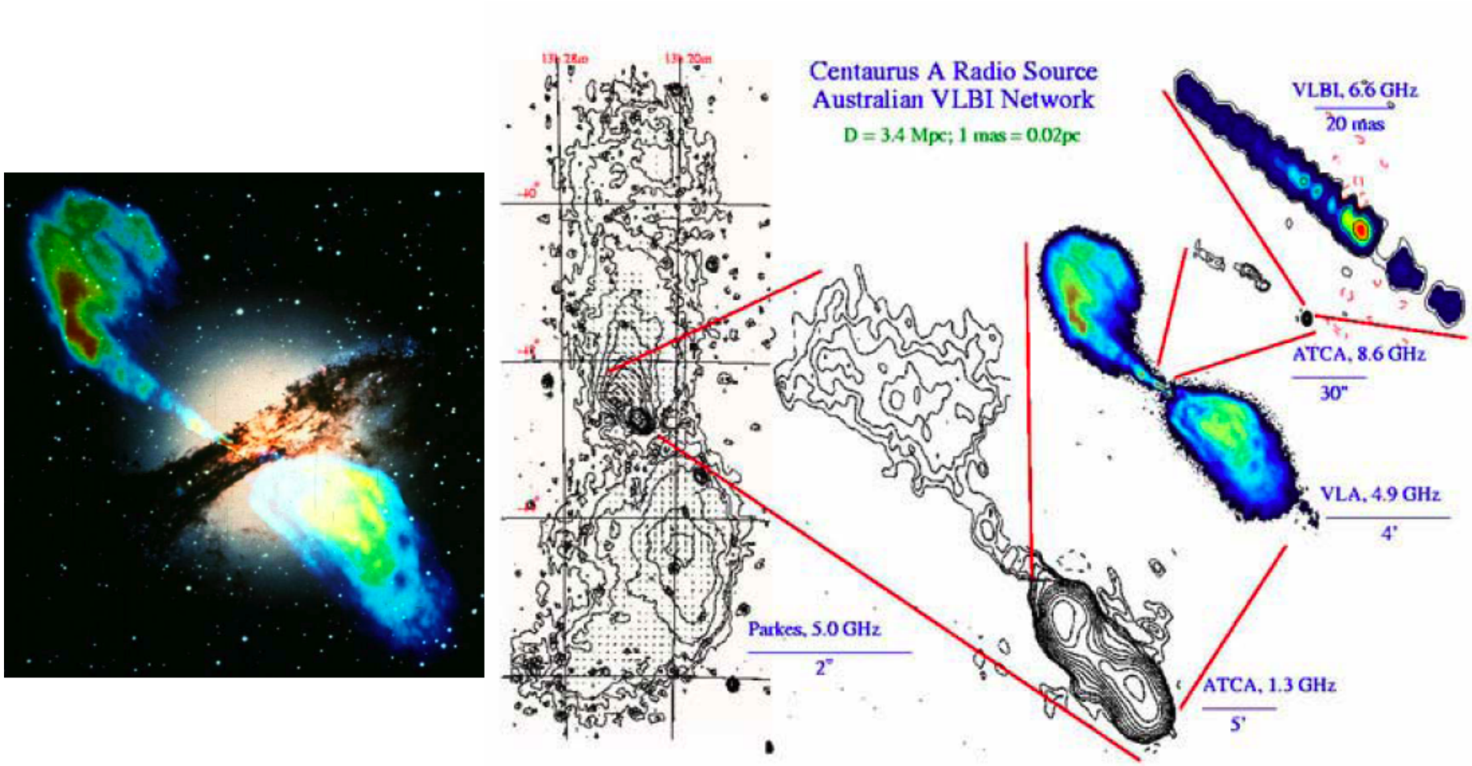


Figure 14 The radio galaxy Cen A with old and new structures, clearly demonstrating a spin-flip. **Spin near 1 to spin near 1? Do SMBH mergers always yield near spin 1?** Source S. Britzen lectures

Identifying the IceCube events I

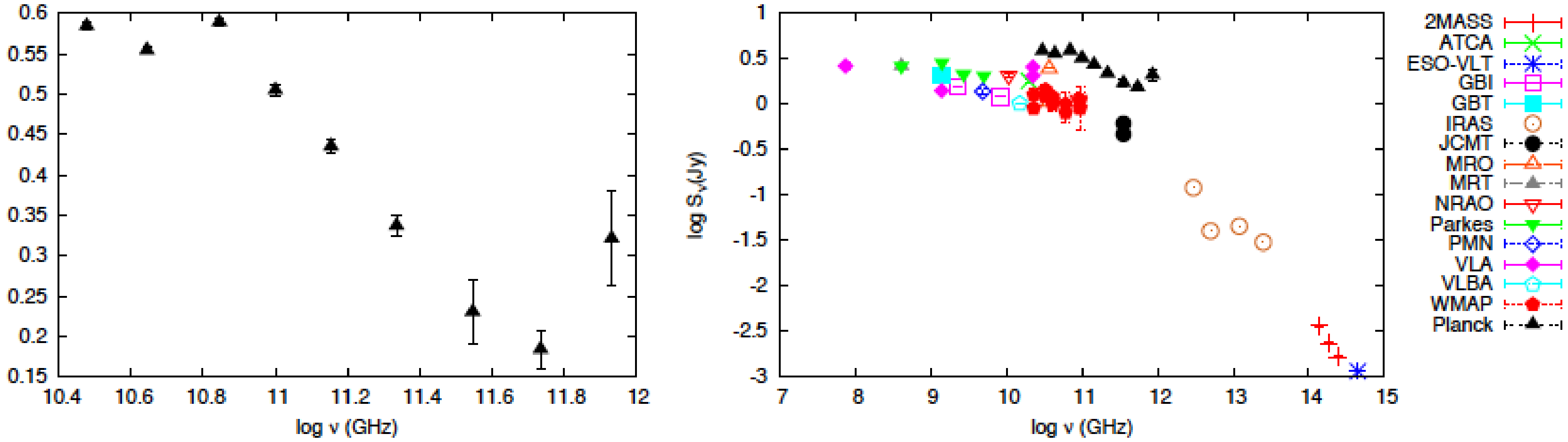


Figure 15 The spectrum of **PKS 0723-008**, identified with neutrino track event no. 5. Source **preprint E. Kun et al. 2016.**

Identifying the IceCube events II

- Pick **complete sample of flat spectrum radio sources**, NRAO-Bonn at 5 GHz, or Parkes at 2.7 GHz
- Then sub-select all the **flat spectrum radio sources**, Gregorini et al. (1984) spectrum between 2.7 GHz and 5 GHz flatter than -0.5: all **variable**.
- Then sub-select again those that **extend their emission to Planck, WMAP or IRAS** frequencies
- **This is an extremely small number.**
- And yet, **two IceCube track events** - pointing uncertainty little more than a degree - identify with this very rare sub-class
- **PKS 0723-008 with event No. 5, and 4C+00.81 with event No. 44**: **E. Kun et al. 2016.**

Σ : How do SMBHs form and evolve?

- **Super-massive BHs** start early, evolve by merging
- Each merger ejects **gravitational waves**
- Each merger **reorients dominant spin** (Gergely +)
- New jet has to **plow fresh channel** (Becker Tjus +)
- Maximizing injection, acceleration and **interaction**
- Ubiquitous energetic particles, **electrons, protons and nuclei** (**inj. gal. CRs**: Gopal-Krishna + 2010)
- Interaction: **−> TeV γ-rays and HE neutrinos**
- **Prediction 2009: Neutrino emitter is jet pointed at us, so relativistically boosted, but with all the hallmarks in radio emission of**

very recent merger

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

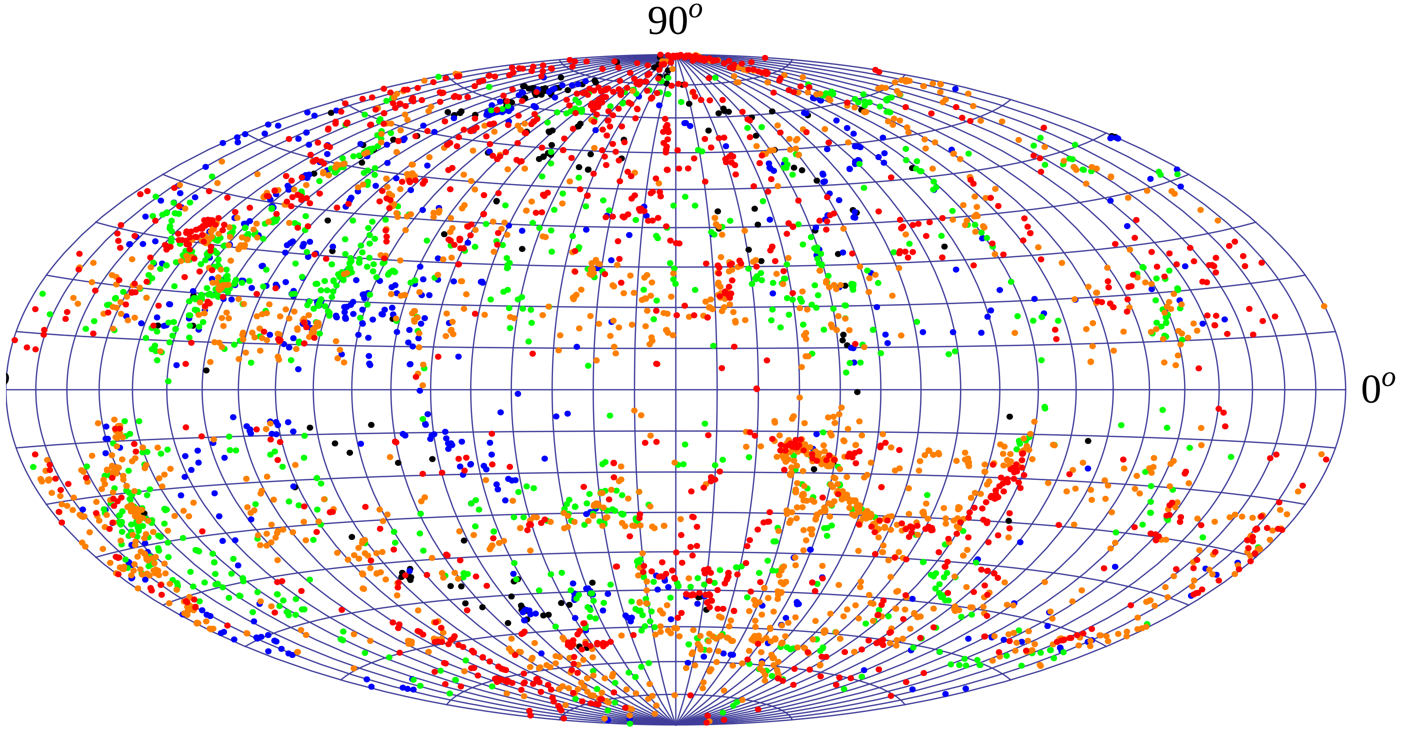


Figure 16 The sky in black holes, $\gtrsim 3 \cdot 10^7 \ M_\odot$, showing the giant arc, a coherent feature: The color code corresponds to distance: **Black**, Blue, Green, Orange, **Red** for the redshifts intervals 0, 0.005, 0.01, 0.015, 0.02, 0.025, corresponding to distance intervals of 0, 60, 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

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

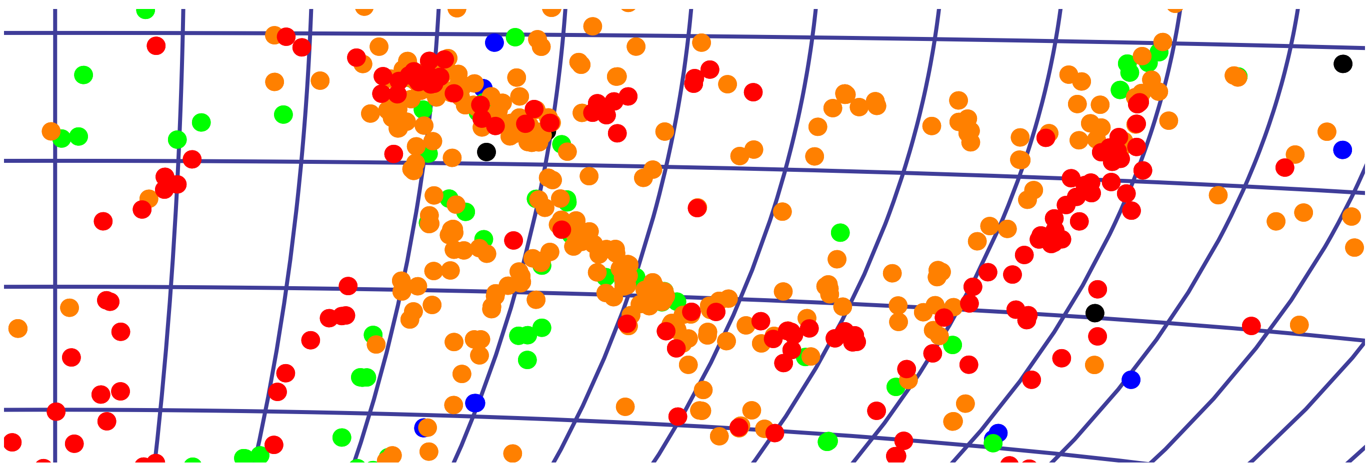


Figure 17 The sky in black holes, $\gtrsim 3 \cdot 10^7\ M_\odot$, showing the giant arc, a coherent feature: The color code corresponds to distance: **Black**, Blue, Green, Orange, Red for the redshifts intervals 0, 0.005, 0.01, 0.015, 0.02, 0.025, corresponding to distance intervals of 0, 60, 120, 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

The semi-circular giant arc in Super-Massive Black Holes (SMBHs) $> 1 \cdot 10^8 M_\odot$

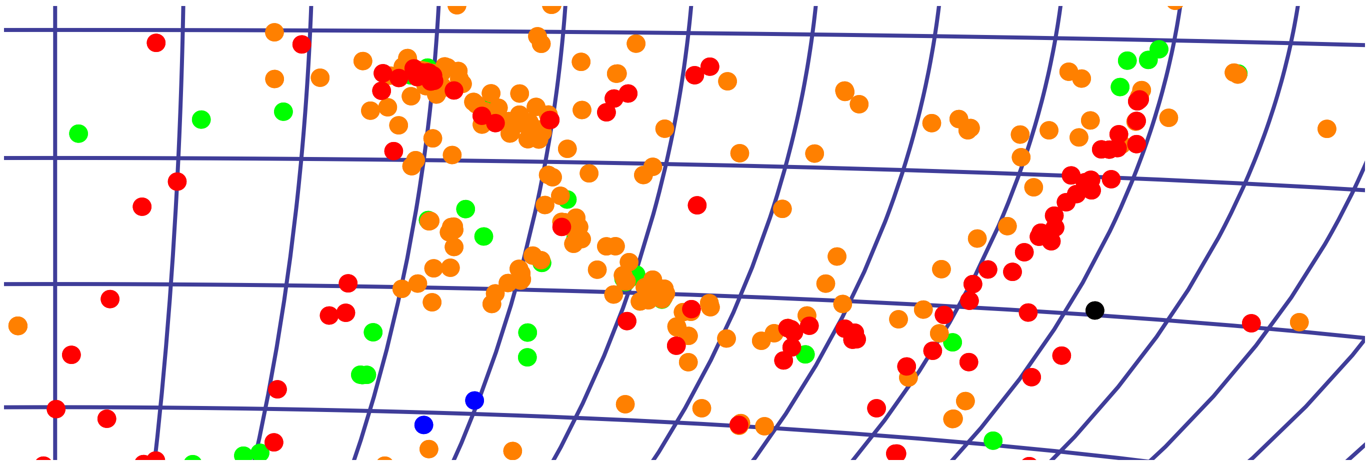


Figure 18 The sky in black holes, $\gtrsim 1 \cdot 10^8 M_\odot$, showing the giant arc, a coherent feature: The color code corresponds to distance: **Black**, **Blue**, **Green**, **Orange**, **Red** for the redshifts intervals 0, 0.005, 0.01, 0.015, 0.02, 0.025, corresponding to distance intervals 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

The semi-circular giant arc in Super-Massive Black Holes (SMBHs) > $3 \cdot 10^8\ M_\odot$

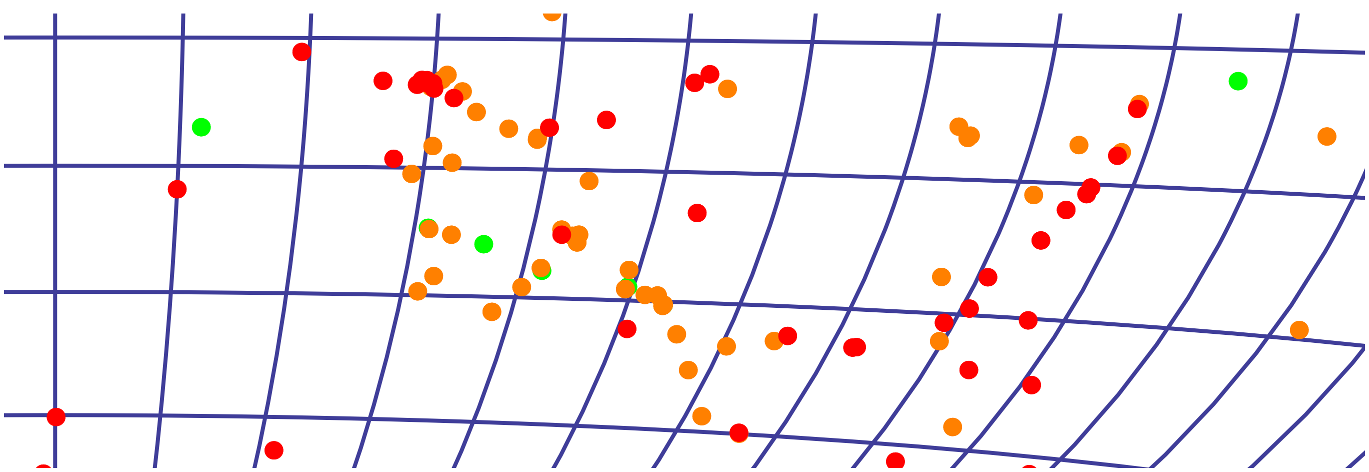


Figure 19 The sky in black holes, $\gtrsim 3 \cdot 10^8\ M_\odot$, showing the giant arc, a coherent feature: The color code corresponds to distance: **Black**, **Blue**, **Green**, **Orange**, **Red** for the redshifts intervals 0, 0.005, 0.01, 0.015, 0.02, 0.025, corresponding to distance intervals 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

The semi-circular giant arc in Super-Massive Black Holes (SMBHs) $> 1 \cdot 10^9 \, M_\odot$

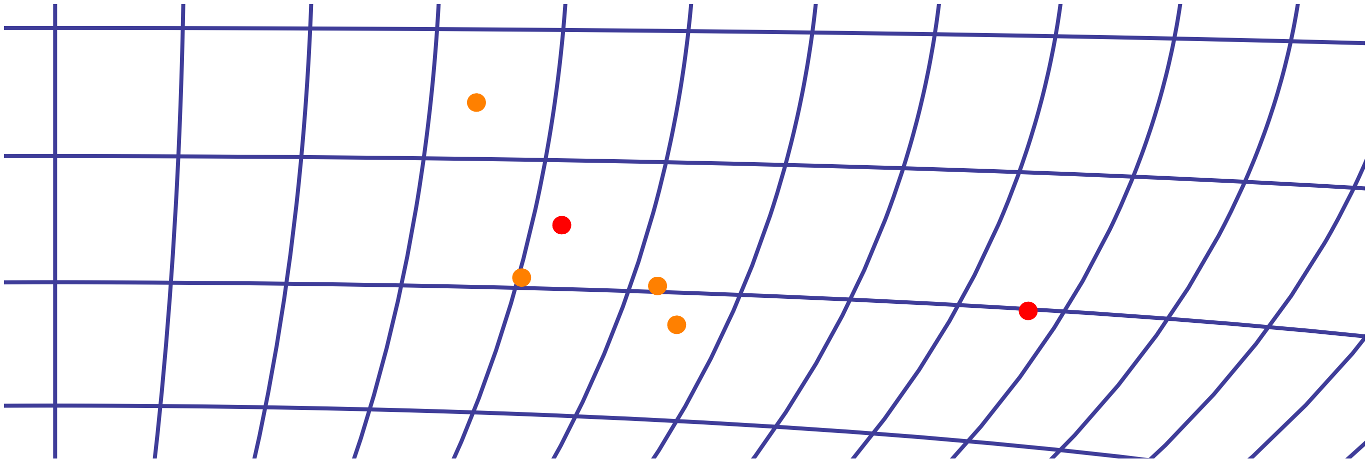


Figure 20 The sky in black holes, $\gtrsim 1 \cdot 10^9 \; M_\odot$, showing the **giant arc**, a coherent feature: The color code corresponds to distance: **Black**, **Blue**, **Green**, **Orange**, **Red** for the redshifts intervals 0, 0.005, 0.01, 0.015, 0.02, 0.025, corresponding to distance intervals 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

Lecture 2015 by G. Smoot, and following discussion

- **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 ?**
- **Cut by baryonic spherical shell through Zeldovich DM sheet ?**
- **From percent density contrast to SMBHs ?**

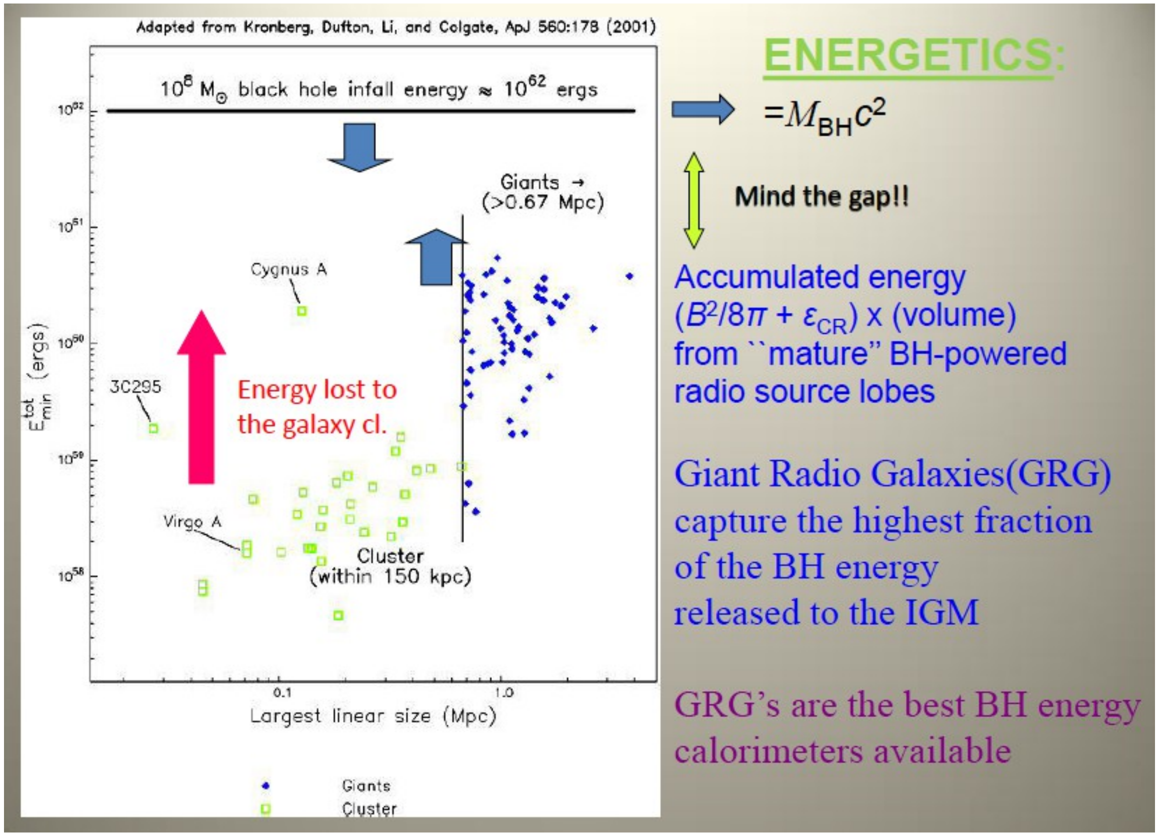
The cosmic amplifier

- 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**
- Baryonic spherical cut through **DM Zeldovich pancake gives an arc** - segment of a circle
- **If** dark matter is a sterile neutrino (PLB & Kusenko 2006), then 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 ?**
- Predicts **starting near redshift 100**

Σ : The great arc of SMBHs

- **Spherical baryonic disturbance** travels outwards
- **Slow-down –> reverse waves**
- Cuts through **Zeldovich DM pancake**
- **Super-sonic flow** between **DM** and baryons: **shocks**
- **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**
- **SMBH mergers may explain the HE νs** (**work with E. Kun and L. Gergely**)
- Original geometry frozen: –> **Great arc**

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



ENERGETICS:

$= M_{BH} c^2$

Mind the gap!!

Accumulated energy
($B^2/8\pi + \varepsilon_{CR}$) x (volume)
from ``mature" BH-powered
radio source lobes

Giant Radio Galaxies(GRG)
capture the highest fraction
of the BH energy
released to the IGM

GRG's are the best BH energy
calorimeters available

Figure 21 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

GW limits and detections at various redshifts

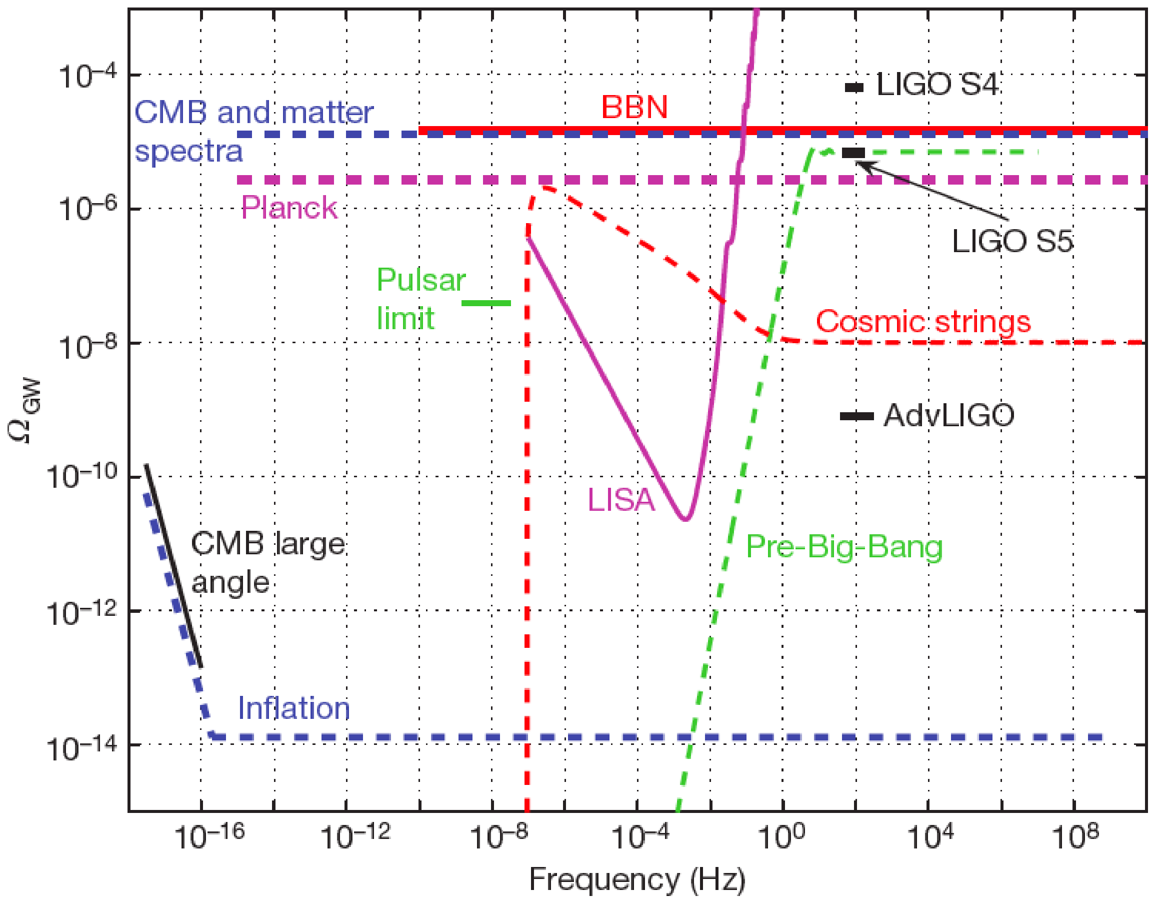


Figure 22 Limits on gravitational waves at various redshifts; now GWs detected. **Does Lisa-Path-Finder provide limits here?** Source: Virgo and Ligo Coll. Nature 2009, PRL 2016a, b

Σ : SMBHs and 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 !

Early universe visible !

- Only keV sterile neutrino DM allows very early star, SMBH and giant arc formation, starts at $z_\star \simeq 100$!
- Radio continuum and line background !
- HE ν activity and low frequency GW events due to fresh binary SMBH mergers !
- Test I: SZ signatures of great arcs !
- Test II: Get z from HD^+ absorption !
- Test III: Detect first SMBH activity !

Thank you!