Micro black hole back-to-back decay signature searches

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TeV scale Black Holes

- In 4D the scale of gravity is approximately 10^{16} TeV.
- TeV range micro Black Holes appear in brane world models.
  - Standard Model fields live on our “brane” while gravity propagates in the large extra-dimensional volume and so the Planck scale can be anywhere between a few TeV and 10^{16} TeV.
  - Black holes can have any mass above M_{PL}:
    - $M_{PL} < M < 5\ M_{PL}$: quantum black holes;
    - $M > 5\ M_{PL}$: semi-classical black holes.
  - *Hoop conjecture*: “a black hole forms whenever the impact parameter *b* of two colliding objects (of negligible spatial extension) is shorter than the radius of the would-be-horizon (roughly, the Schwarzschild radius, if angular momentum can be neglected) corresponding to the total energy M of the system.”

$$b \lesssim \frac{2\, l_{Pl}\, M}{M_{Pl}}$$

Non-thermal Black Holes @ the LHC

No non-thermal Black holes @ the LHC!
...so far! (upgrades in progress!)

- At cosmic ray observatories:
  - Ground based;
  - Space based.
- Neutrino telescopes.

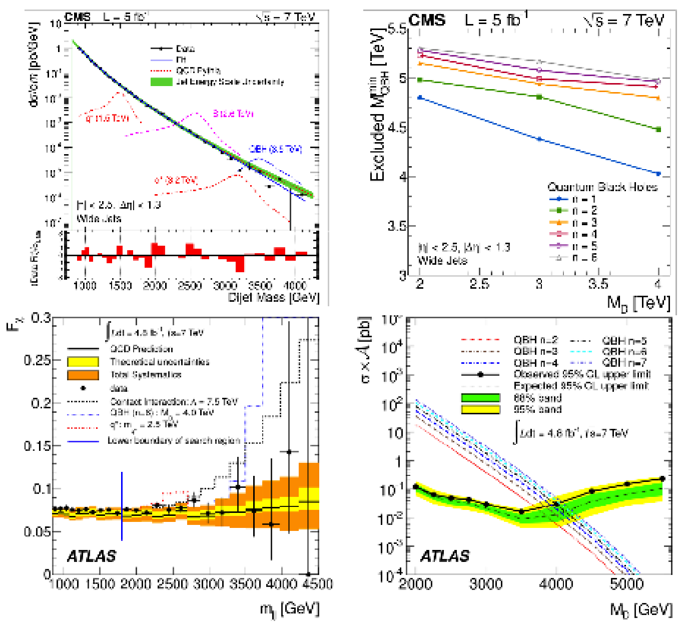
Non-thermal Black Holes (QBH)

- LHC parton energy needs to be high relative to M_D for black hole to Hawking evaporate thermally.
- Black holes with threshold mass M_{th} near M_D probably do not decay thermally.
- Dijet decays assumed so far.
- QBH appears as bump in dijet mass spectrum.
- Increased discrimination power by using angles.
  - Define central region $\chi = \exp(|y_1 - y_2|) < 30.0$.

$$F_\chi(m_{jj}) \equiv \frac{dN_{central}/dm_{jj}}{dN_{total}/dm_{jj}}$$

18 March 2013 Doug Gingrich (COST Workshop)

Non-thermal Black Holes Results



JHEP 01 (2013) 013

$M_{th} > 4$-5.3 TeV
($n = 1$-6, $M_{th} > M_D$, $M_D = 2, 3, 4, 5$ TeV)

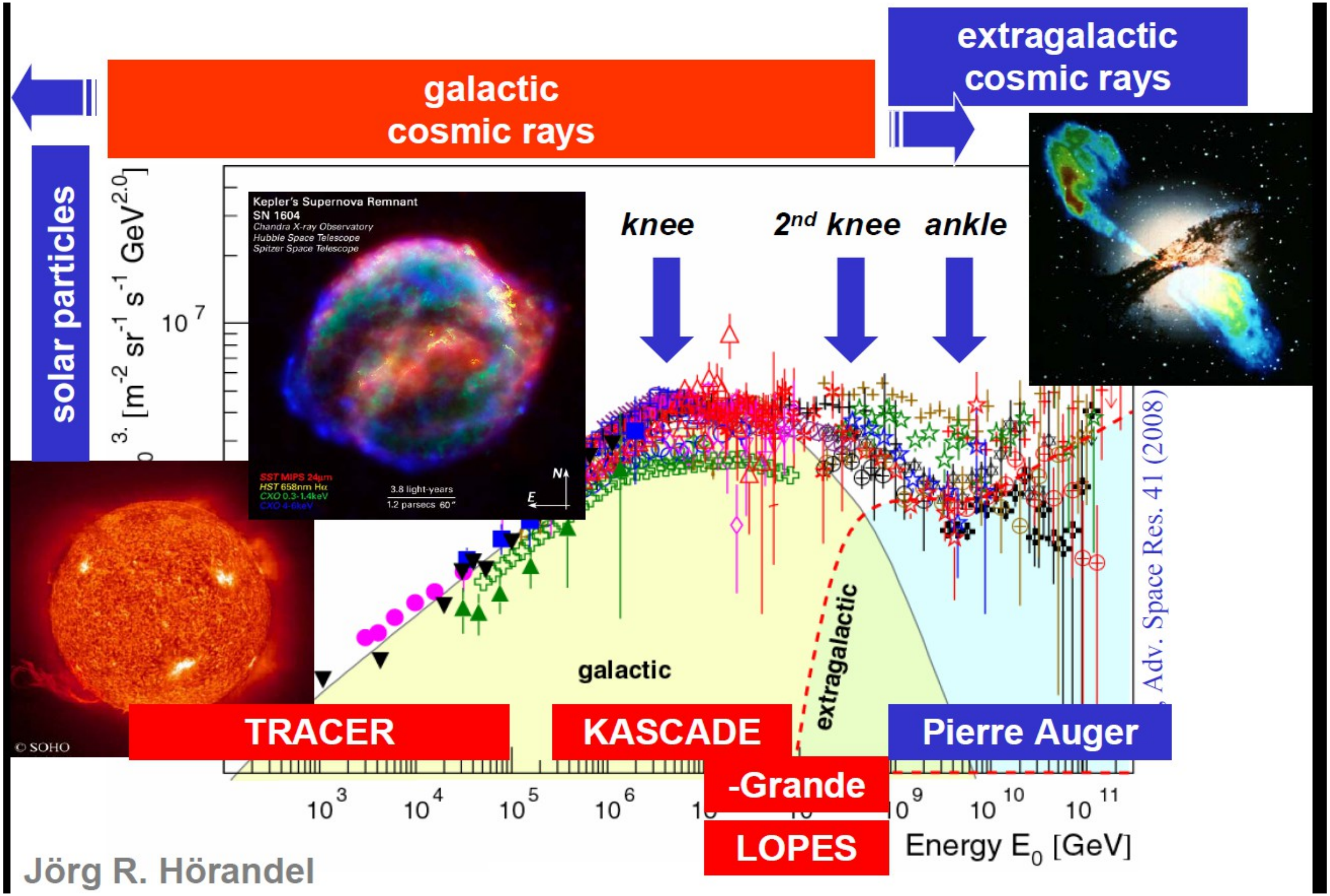
JHEP 01 (2013) 029

$M_{th} > 3.71$-4.07 TeV
($n = 2$-7, $M_{th} = M_D$)

18 March 2013 Doug Gingrich (COST Workshop) 18/21

Micro black holes in cosmic rays data

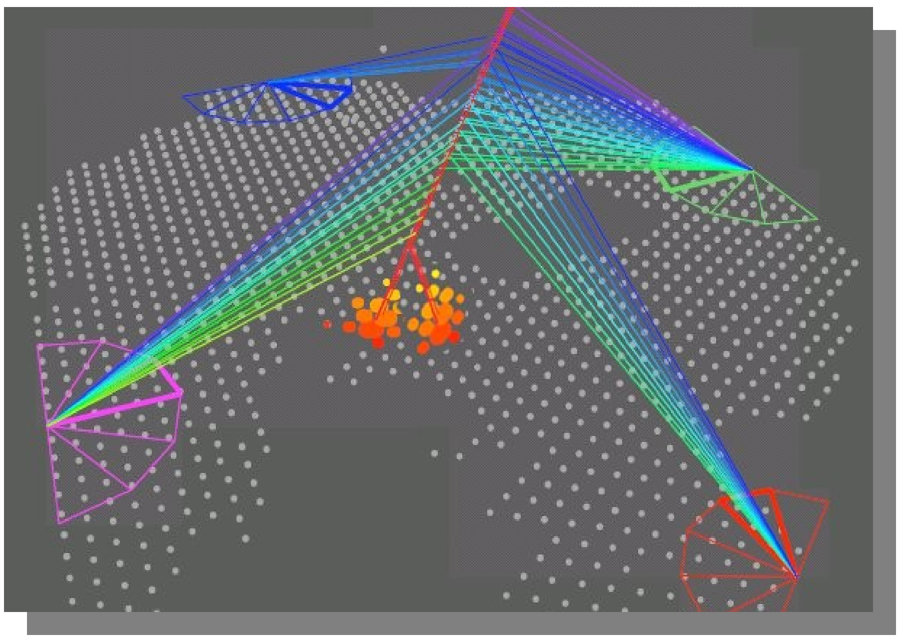
- What other ultra-high energy data do we have available?



Micro black holes in cosmic rays & neutrino data

"A long time ago in a galaxy far, far away..."

...about a year ago at a “Black Holes in a Violent Universe” COST meeting (European Cooperation in Science and Technology), the idea of a unique micro black hole signature which could be discovered in the cosmic ray data came up.



- If micro black holes with the masses close to the Planck mass, which are non-thermal, are formed in high energy collisions, the main decay channel for these objects is a „back-to-back“ decay into two particles!

- If black holes form as a result of the impact between UHECRs or neutrinos with particles in the upper atmosphere, it is possible for simultaneous double shower events to be observed!

Micro black holes in cosmic rays & neutrino data

X. Calmet, L.I. Caramete and O. Micu. JHEP **1211**, 104 (2012); arXiv:1204.2520 [hep-ph].

- The number of events expected to seen by a cosmic rays experiment:

$$N = \int dE N_A \frac{d\Phi}{dE} \sigma(E) A(E) T$$

- Assuming the collision between a particle $(\gamma_1 m_1 c, \gamma_1 m_1 \vec{v})$ with a particle $(m_2 c, 0)$ at rest, the resulting black holes...
  - Have a mass of:

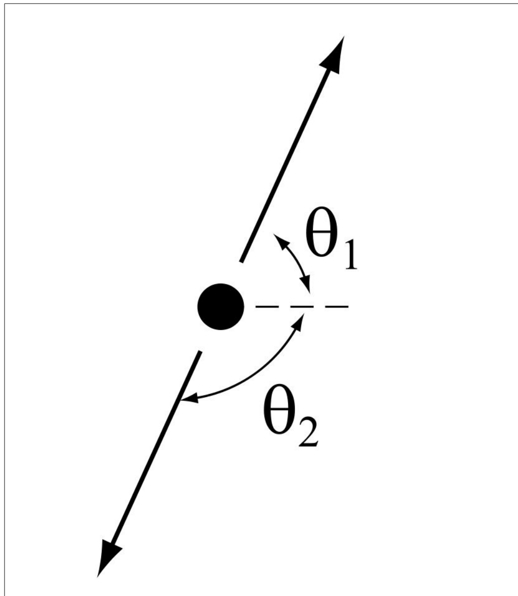
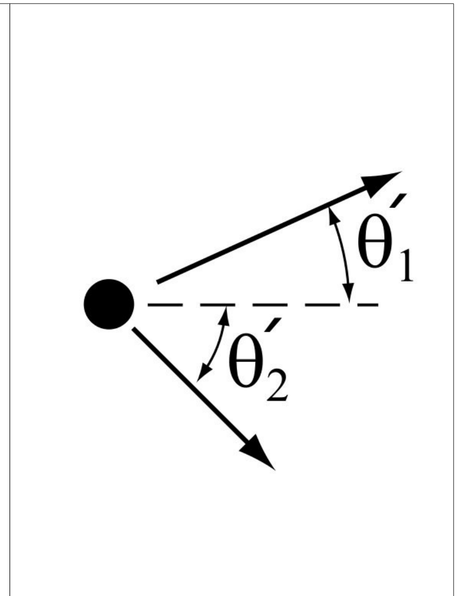
$$M_{BH} = \sqrt{m_1^2 + m_2^2 + 2\gamma_1 m_1 m_2}$$

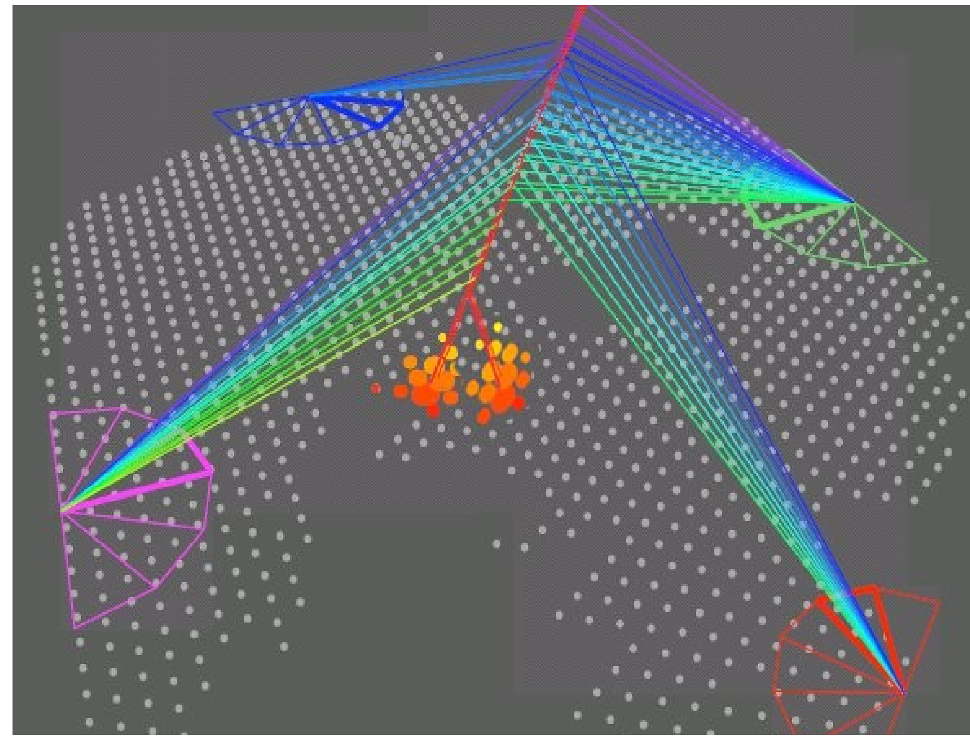
  - And move relativistically with a Lorentz factor of:

$$\gamma_{BH} = \frac{\gamma_1 m_1 + m_2}{M_{BH}}$$

UHECR Energy (TeV)	Black hole mass (TeV)
10^5	7
10^6	25
10^7	79
10^8	250

Micro black holes in cosmic rays & neutrino data

	
Center of Momentum Frame	Laboratory/Earth Frame

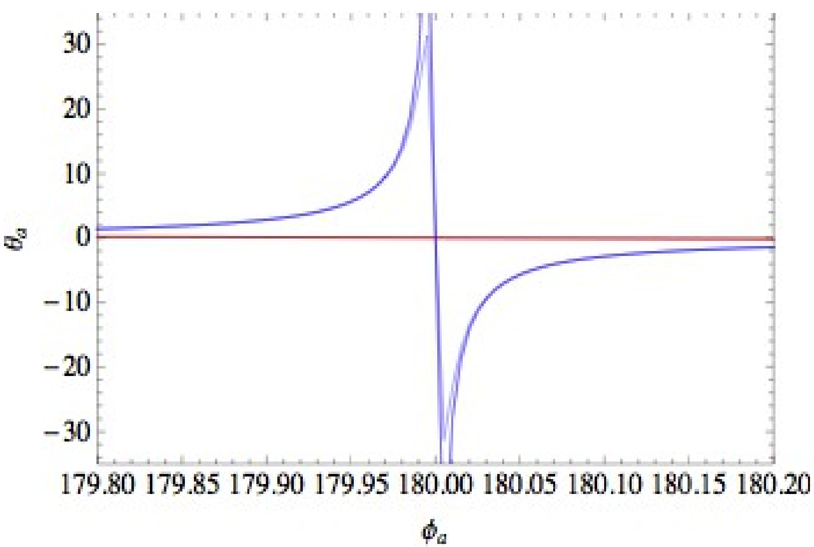


- Lorentz transformed angles

$$\tan\theta_i' = \frac{\sin\theta_i}{\gamma_{BH}\beta_{BH}\frac{E_i}{p_i} + \gamma_{BH}\cos\theta_i}$$

Micro black holes in cosmic rays & neutrino data

- Case study: Pierre Auger Observatory
  - For the Planck mass in the 10 TeV range,
  - UHECR or neutrino energies larger than 10^6 TeV
  - Back-to-back decay into two standard model particles



Angle $'_1$ as function of the mass m_1 for m_d = 4.8 MeV, m_{muon} = 105.7 MeV, m_{tau} =1.777 GeV (all in blue) and m_{top} = 171 GeV (in red).

→ Two showers can be observed for about 0.11% of the total number of back-to-back decays!

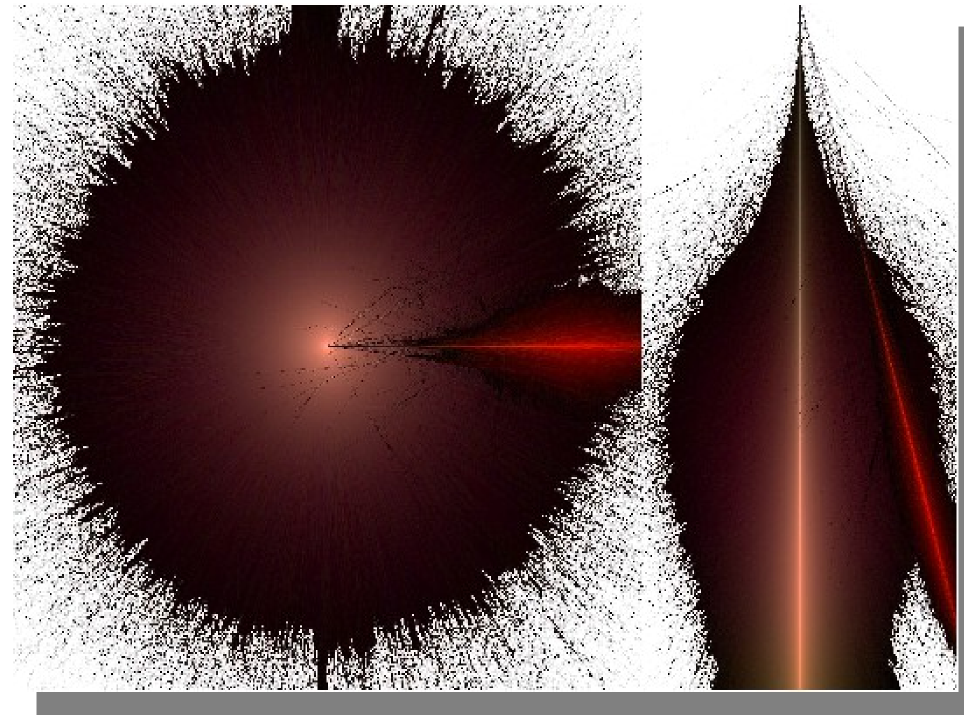
→ These events are rare but one might still hope to observe them.

No. of extra dimensions	No. of events/year
1	81
4	460
5	609
6	765
7	925

Back-to-back decay signature @ UHECR observatories

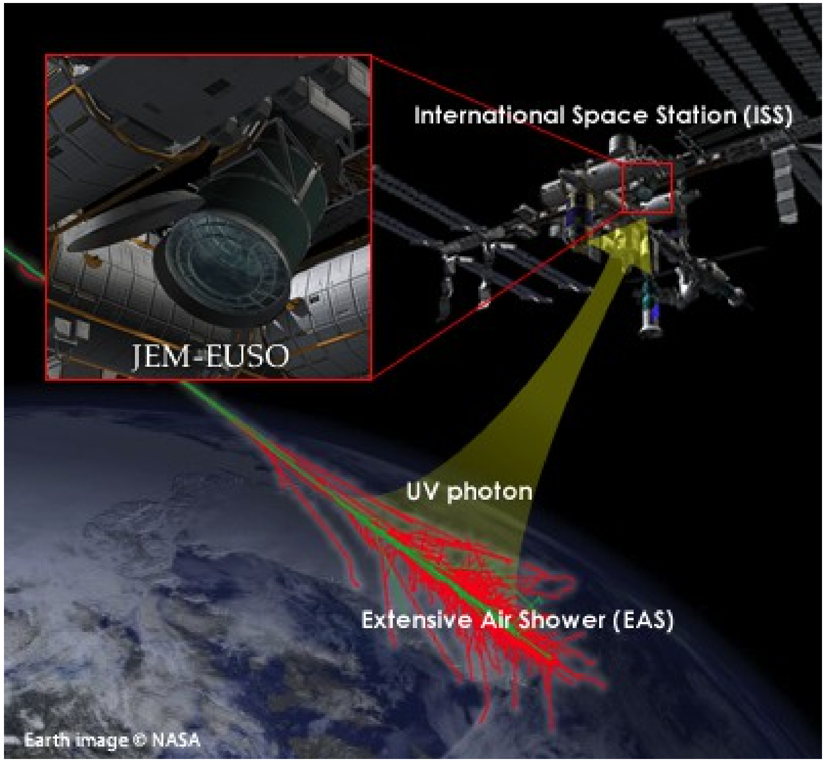
Back-to-back decay simulations CORSIKA
COsmic Ray SImulations for Kascade
(20º separation between the showers)

- Showers overlap for large parts of their development!
- For smaller angles they overlap even more!
- The identification of the two separate showers by the ground detectors depends on the altitude at which they are produced!
- One will have to also tell apart oval shaped imprints due to two showers from single showers oriented at an angle wrt. the Earth.



CORSIKA simulations of two showers (10^{13} eV & 9×10^{16} eV) developing from a height of 30 Km. The angle between the showers in the Earth frame is 20º.

Back-to-back decay signature @ space observatories

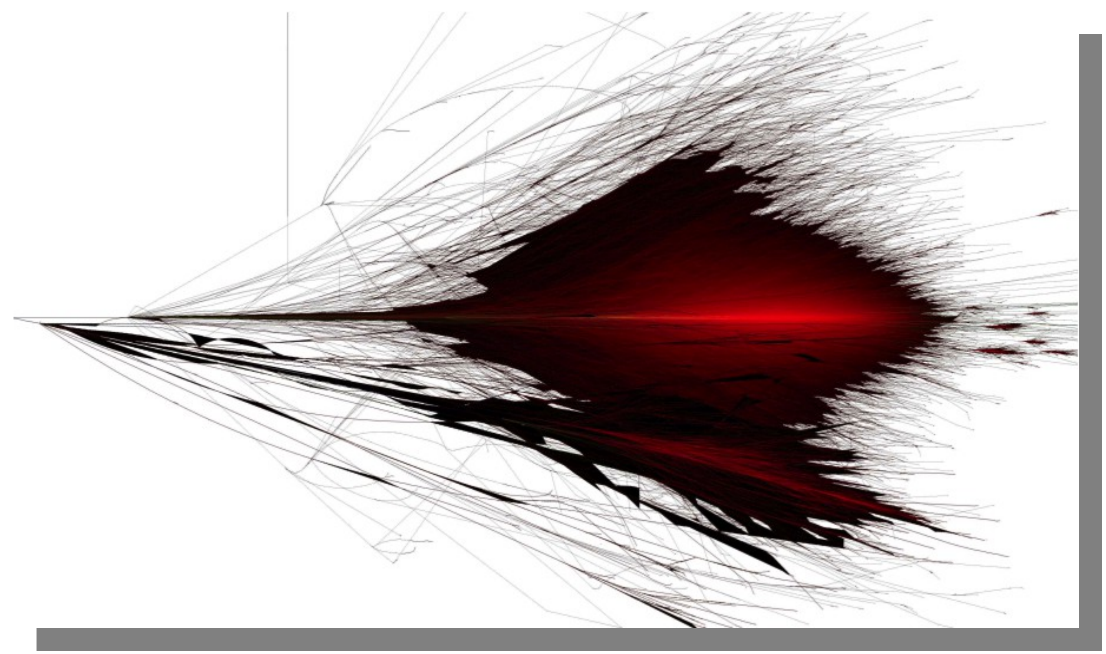


Advantages:

- A more than 20 times larger acceptance!
- The entire fluorescence showers would be visible which would make the features of a two-shower event to be distinguishable!

JEM-EUSO
Extreme Universe Space Observatory
http://jemeuso.riken.jp/en/

Will observe a volume 50 – 250 times larger than the Pierre Auger Observatory.



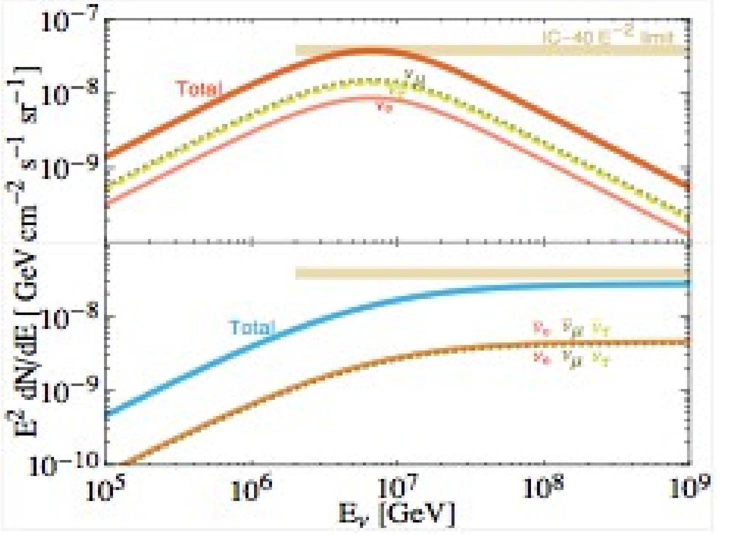
Back-to-back decay signature @ neutrino observatories

N. Arsene, X. Calmet, L.I. Caramete and O. Micu. arXiv:1303.4603 [hep-ph].

- QBHs produced by highly energetic neutrinos:

$$\nu + N \rightarrow BH$$

- Neutrino observatories (telescopes)
  - ✓ Detect the muons induced by high energy neutrinos (Cherenkov light).
  - ✓ The direction of propagation is derived with high accuracy!
  - ✗ There are many models which lead to very different values for the flux at high energies!!!

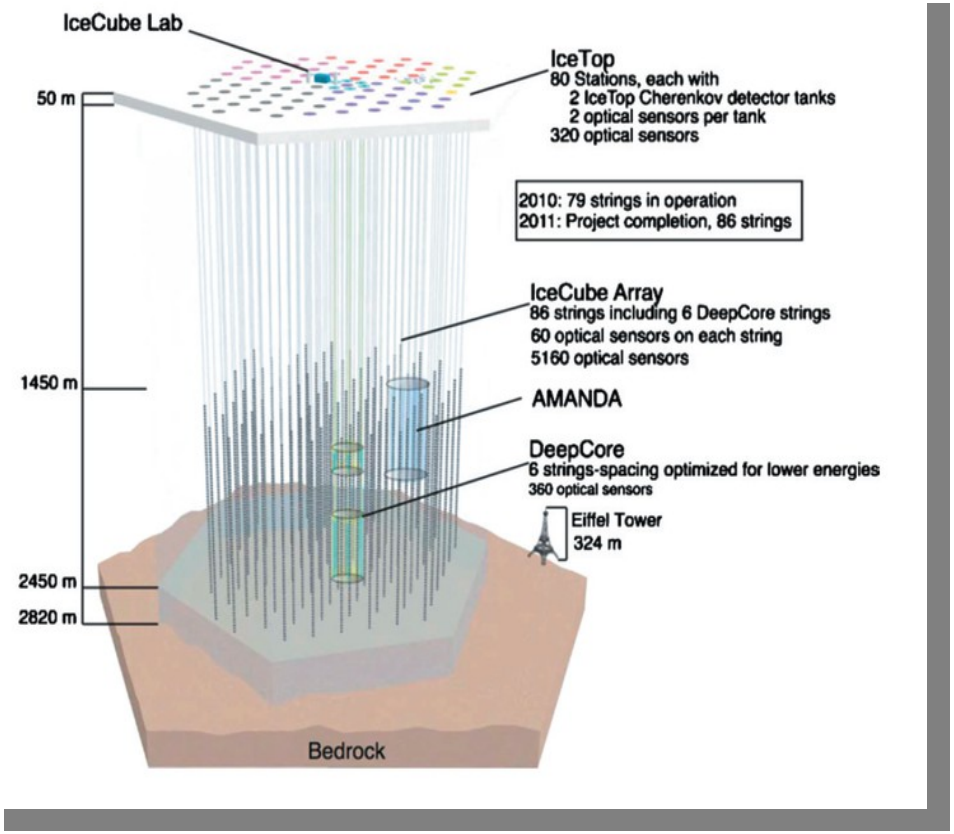


Neutrino flux at high energies:

M. Kistler, T. Stanev, H. Yüksel. arXiv:1301.1703 [astro-ph]

- The range of interaction lengths for neutrino energies between 10^{16} - 10^{18} eV is between 6.6×10^3km and 9.4×10^2 km water equivalent in rock!!!
  - ➔ The Earth is opaque for neutrinos with these energies and experiments can see neutrinos coming from above or the ones skimming the Earth!

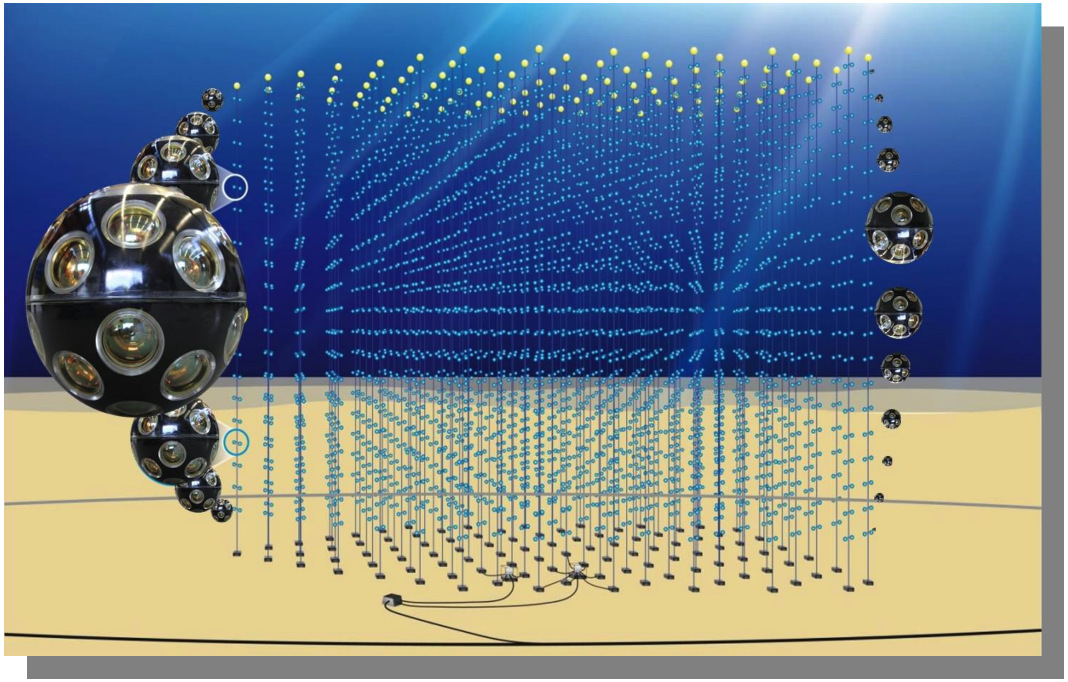
Back-to-back decay signature @ neutrino observatories



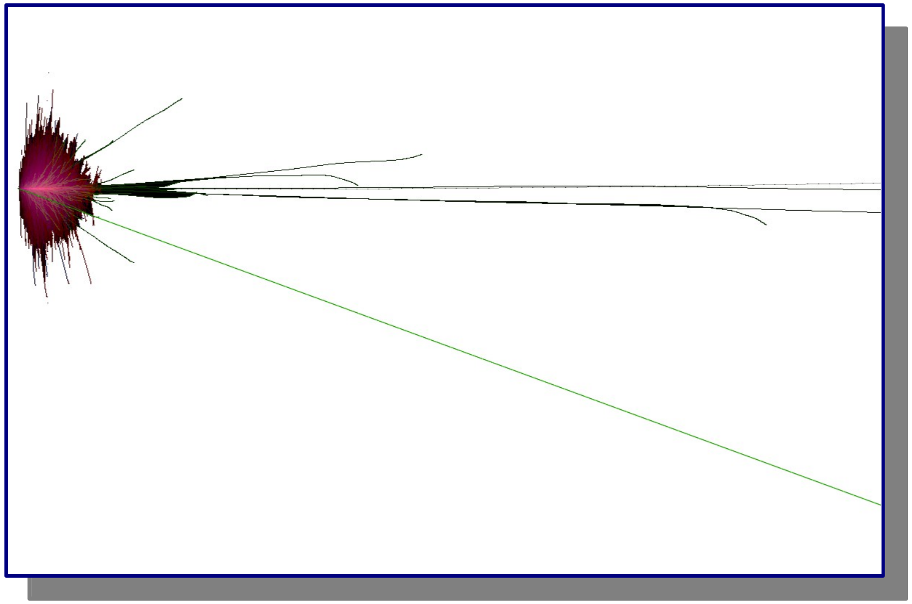
IceCube
South Pole Neutrino Observatory.
http://icecube.wisc.edu/

KM3NeT
http://www.km3net.org

...future multi km^3 sized neutrino telescope to be built on the bottom of the Mediteranean Sea.



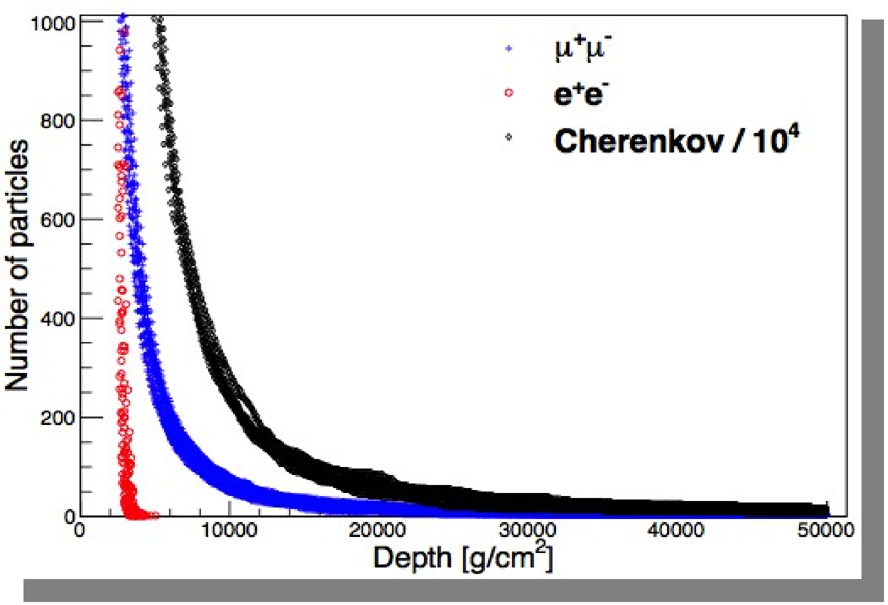
Back-to-back decay signature @ neutrino observatories

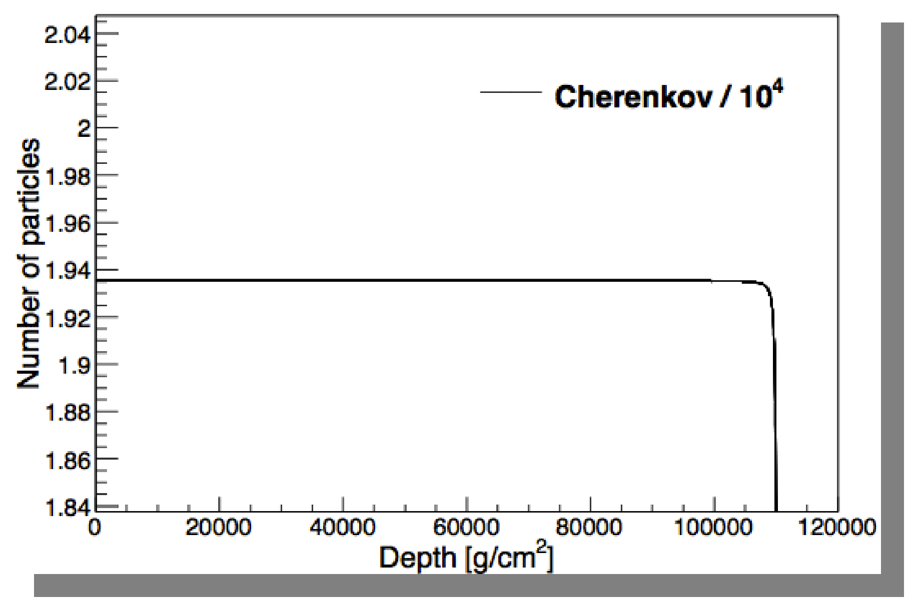


- $QBH \rightarrow \mu^- + p^+$ in water.

  10^{17} eV proton + 3 x 10^{11}eV muon

  - Angle in the Earth Frame: 5º.
  - The EM component of the p^+ shower dies out in about 50 meters!
  - Muons propagate for distances of 1- 2 km emitting Cherenkov light!

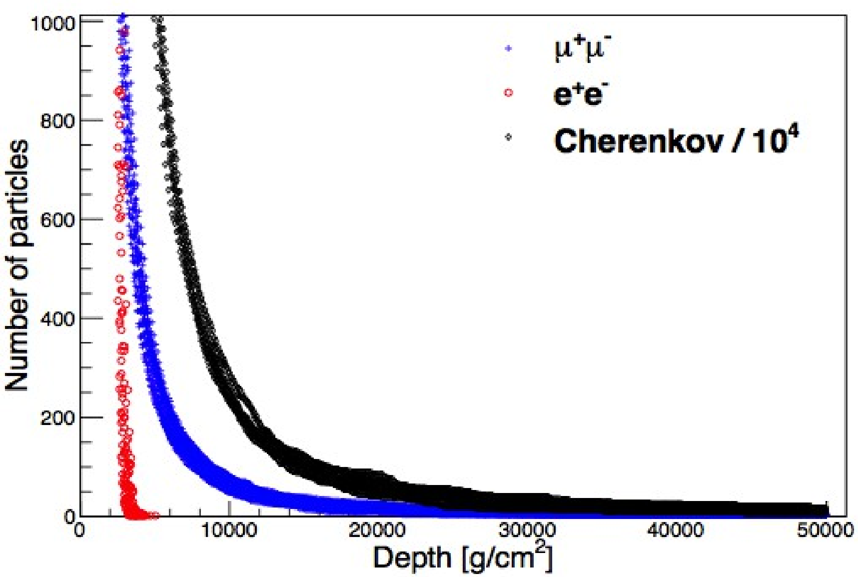


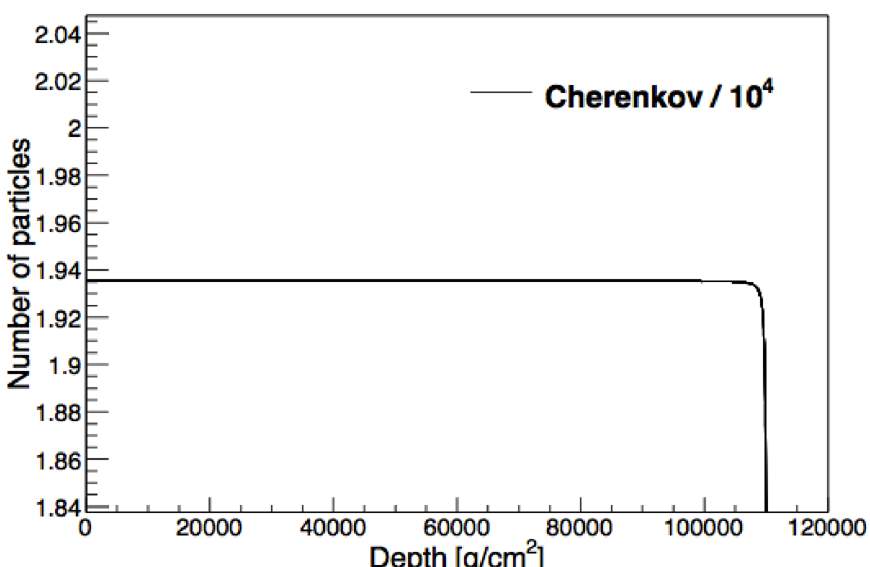


Back-to-back decay signature @ neutrino observatories

No. Extra-dimensions	Expected events @ IceCube
1	21
2	81
3	179
4	311
5	440
6	623

- $QBH \rightarrow \mu^{-} + p^{+}$ in ICE.
  - Angle in the Earth Frame: 5º.
  - The EM component of the p^{+} shower dies out in about 50 meters!
  - Muons propagate for distances of 1- 2 km emitting Cherenkov light!
- The picture looks identical in Ice!





Conclusions

- The back-to-back decay signature of Quantum Black Holes has some unique features:
  - ✓ Two simultaneous particle showers oriented at an angle and pointing to a common origin;
  - ✓ The reconstructed energies for the showers have specific values!
- With this there are two more kinds of experiments which can look for TeV scale black holes and in turn for the Planck scale:
  - @ cosmic rays experiments can look for higher mass values
    - Earth based experiments (Pierre Auger Observatory)
    - Future Space observatories (JEM-EUSO will have an acceptance 30 times larger than the Pierre Auger Observatory)
  - @ neutrino observatories
    - IceCube experiment (running)
    - KM3NeT future neutrino telescope (when running will have a volume several times higher than IceCube).