Sensitivity of HAWC to Primordial Black Hole Bursts

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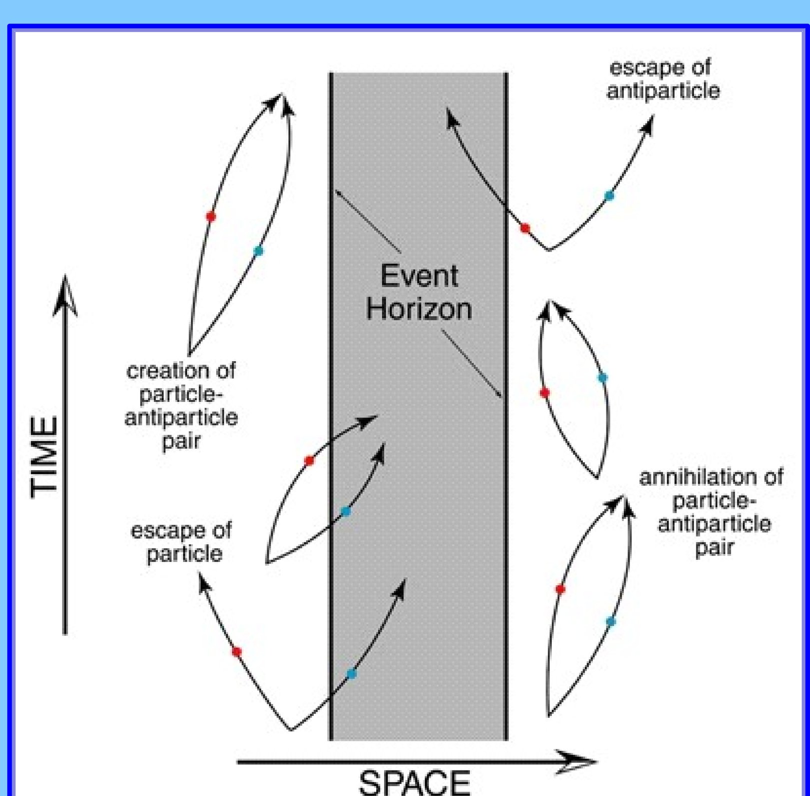
Introduction

Primordial Black Holes (PBHs) are black holes that may have been created in the early Universe and could be as large as supermassive black holes or as small as the Planck scale. It is believed that a black hole has a temperature inversely proportional to its mass and will thermally emit all species of fundamental particles. PBHs with initial masses of 5.0 x 10^{14} g should be expiring today with bursts of high-energy gamma radiation in the GeV/TeV energy range. The High Altitude Water Cherenkov (HAWC) observatory is sensitive to the high end of the PBH gamma-ray burst spectrum. Due to its large field of view, duty cycle above 95% and sensitivity up to 100 TeV, the HAWC observatory is well suited to perform a search for PBH bursts. We report that if the PBH explodes within 0.25 light years from Earth and within 26 degrees of zenith, HAWC will have a 95% probability of detecting the PBH burst at the 5 sigma level. Conversely, a null detection from a 2 year or longer HAWC search will set PBH upper limits which are significantly better than the upper limits set by any previous PBH search.

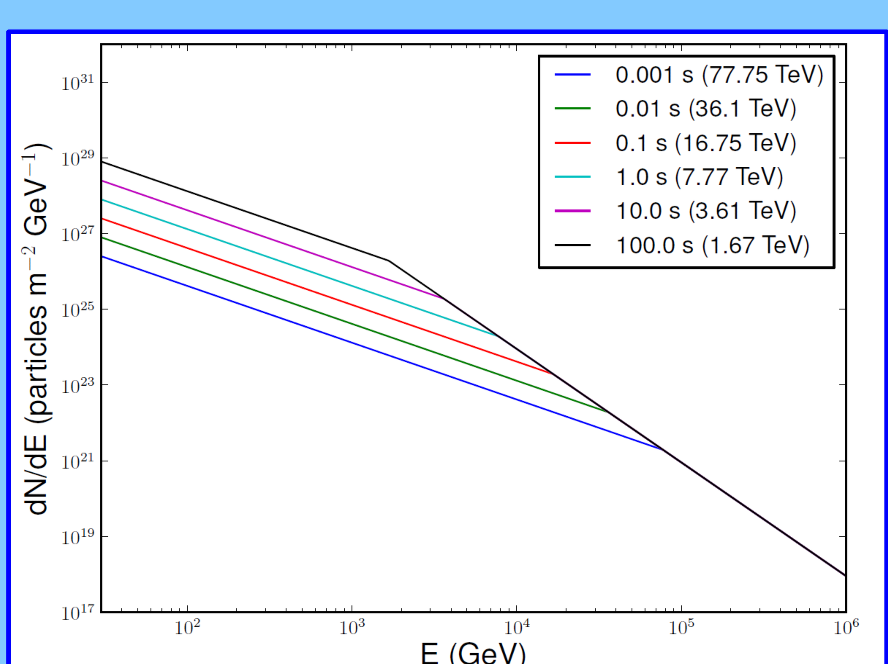
Primordial Black Holes (PBHs)

Primordial black holes (PBHs) are hypothetical black holes that may have been formed from extreme density fluctuations of matter present during the early Universe. It is believed that a black hole possesses a temperature inversely proportional to its mass and emits with a thermal spectrum all species of fundamental particles. PBHs with initial masses of ~ 5.0 x 10^{14} g should be expiring now with bursts of high-energy particles, including gamma rays in the MeV – TeV energy range, making them candidates for gamma-ray burst (GRB) progenitors.



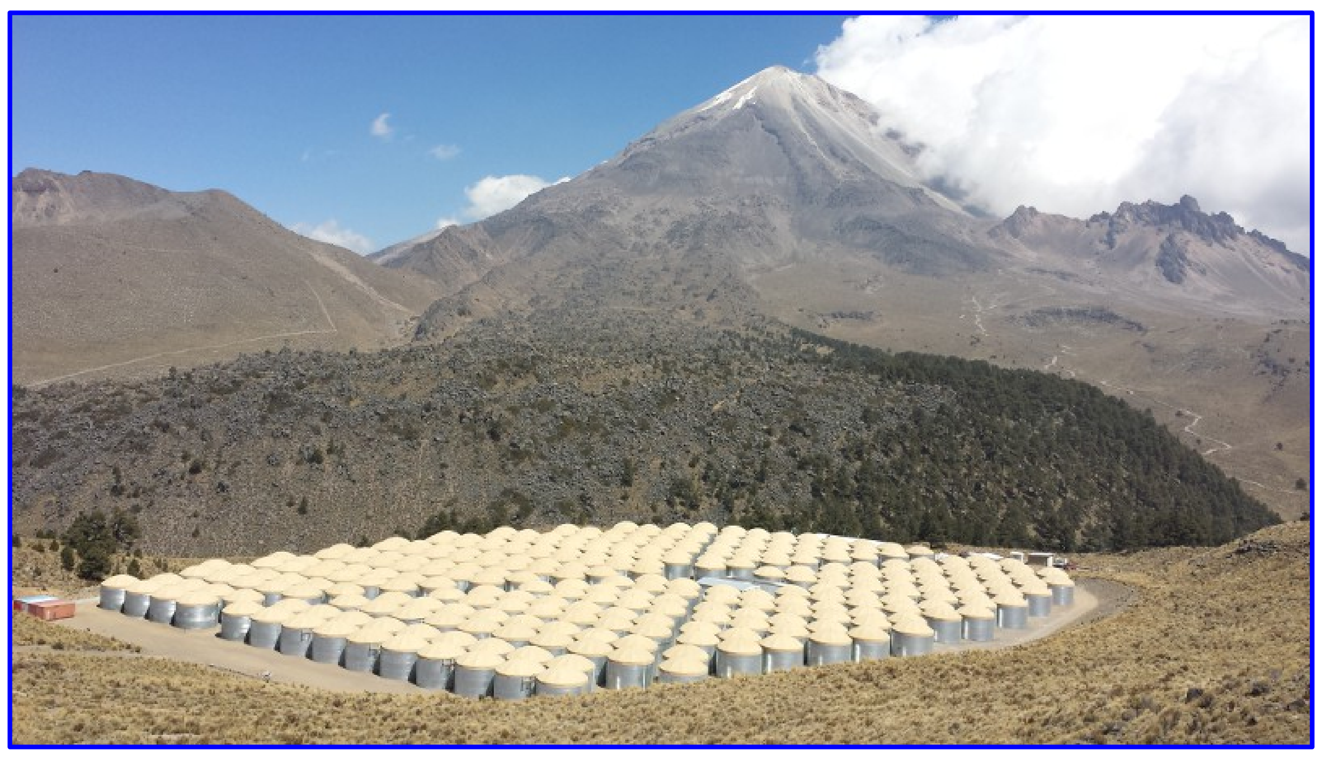
Time Integrated PBH Burst Gamma-ray Spectrum

The time integrated PBH burst spectra of several PBH remaining lifetimes is shown below. These spectra are based on the Standard Evaporation Model (SEM) which utilizes the Standard Model of particle physics. At each remaining lifetimes, the corresponding starting temperture is also shown.

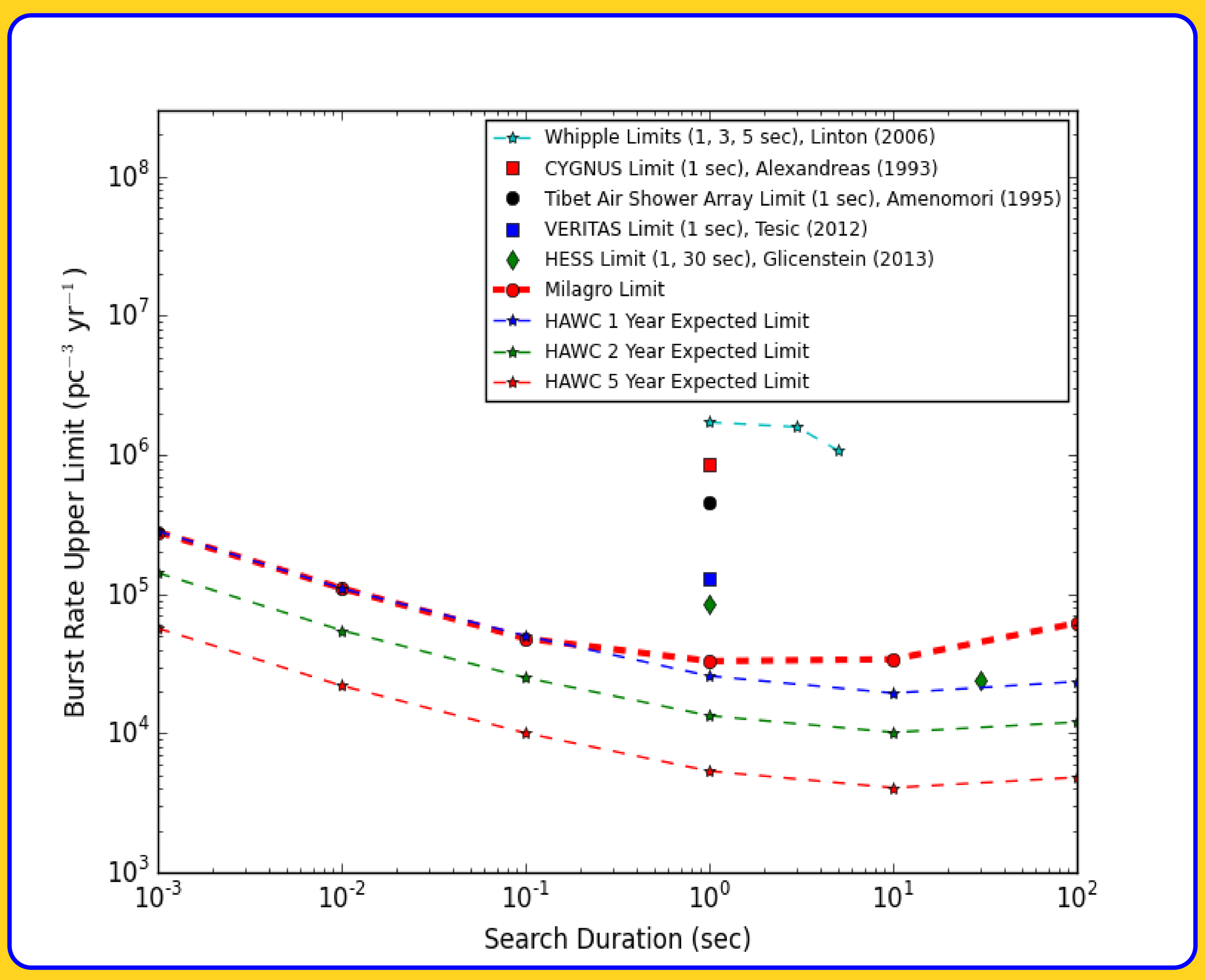


HAWC Observatory

HAWC is a very-high-energy observatory that recently finished construction in Mexico at an altitude of 4,100 m. It consists of 300 water tanks with 4 photomultiplier tubes (PMT) each and detects Cherenkov light from secondary particles created in extensive air showers induced by very-high-energy gamma rays in the energy range from ~50 GeV to 100 TeV. The direction of the original primary particle may be resolved with an error between 0.1 and 2.0 degrees depending on its energy and location in the sky. HAWC has a large field-of-view (FOV ~ 2 sr) and will have a high duty cycle of >95%.



Monte Carlo simulation is used to model the interaction of photons and cosmic rays with the atmosphere and the response of HAWC to the extensive air showers they generate. The effective area is equated to the ratio of the number of events that satisfies a given set of cuts to the total number of events multiplied by the total throw area of the Monte Carlo simulation. The cuts are comprised of a trigger cut, an angle cut and a gamma-hadron separation cut. For the trigger cut, HAWC accepts events with the number of PMTs hit by the air shower, nHit, greater than a certain value. The angle cut is used to specify the direction of the photons and is a measure of HAWC's angular resolution.



Methodology

In order to calculate the PBH rate-density upper limits, it is essential to calculate the PBH detectable volume (V) for a given detector. Since PBH bursts are not bright enough to be detectable beyond our Galaxy, we can ignore TeV photon absorption due to the extra-galactic backgound light. From the luminosity of the burst we can calculate the photon flux at the detector for a given distance.

Using Monte Carlo simulations, it is possible to calculate the minimum number of photons needed to have a 5-sigma detection at the HAWC detector for various search durations. By equating photon flux at the detector to the photon flux needed for a 5-sigma detection, we can calculate the maximum detectable distance (r) of a PBH burst with a given mass,

$$V \approx \frac{4\pi}{3} \sum r^3 \times \frac{\mathrm{FOV}}{4\pi}.$$

If the PBHs are uniformly distributed in the solar neighborhood and P is the total observation period, the 99% confidence level upper limit to the rate-density of PBH bursts will be

$$UL_{99} = \frac{4.6}{V \times P}.$$

Because we seek the sensitivity in the case where there is no prior knowledge of the burst location, we need to take into account the number of trials performed for the search. The optimum spatial bin-size depends on the search duration, the trigger criteria, and the value of the gamma-hadron separation parameter. The number of time bins is estimated by dividing the total search period (estimated as 5 years for HAWC) by the search duration. Thus, the total number of trials depends on the search duration, the optimal spatial bin-size, the trigger criterion and the value of the gamma-hadron separation cut. In order to find the optimum set of cuts, we performed a simple parameter search and identified the set of values which give the strongest PBH burst rate upper limit.

Results and Discussion

Above figure displays the PBH Burst Rate Density Upper Limits projected for HAWC, compared with limits from previous direct search experiments. The HAWC projected PBH rate density limit is strictest around 10 seconds. The general features of the figure, which shows limits as a function of search duration, can be understood as follows.

Better sensitivity corresponds to smaller number of signal photons required for detection of a signal, and a stricter PBH limit. For a source at a given distance (that is, at the outer edge of the volume considered), photons from the PBH burst captured decreases when the search interval is smaller, and produces a weaker PBH limit. Shorter intervals incur less background events but fewer source photons. In this case, the number of signal photons required is dominated by statistical fluctuations, in particular those associated with the detector background rate, while number of captured PBH photons is dominated by the PBH emission time profile, slightly modified by the energy-dependent effective area of the detector. These dependencies are both power laws, and despite their very different physical origins, nearly cancel. Secondary effects such as the larger number of trials incurred for shorter intervals, and the ability to optimize background rates for larger search durations for which the detection efficiency is higher, give the residual search duration dependence seen in our Figure.

The HAWC estimated sensitivity presented above was based on choosing a single set of selection criteria for each search window duration. However, current HAWC analyses employ multi-bin selection cuts. We evaluated HAWC's PBH sensitivity using several cuts tuned for these other HAWC analyses and see a factor of 1.3 improvement in the expected PBH burst-rate-density limit for 1 and 10 s search durations.

Conclusions

- The HAWC observatory has the ability to directly detect very high energy gamma-ray emission from nearby PBH bursts.
- A confirmed direct detection of an evaporating PBH would provide unparalleled insight into high energy particle physics and general relativity
- In the case of a null detection, the HAWC observatory will be able to set upper limits which are significantly better than upper limits set by any previous burst search.

References: Hawking (1974); Page (1976); MacGibbon & Webber (1990); MacGibbon & Carr (1991); MacGibbon (1991); Abdo et. al., Astroparticle Physics 64, 4-12 (2015); Ukwatta et. al., in preparation (2015)