Search for Primordial Black Hole Evaporation with VERITAS

Simon Archambault, for the VERITAS Collaboration
Black Holes

- 4 types of black holes
  - Stellar-mass black holes
  - Supermassive black holes
  - Intermediate-mass black holes
  - Primordial black holes
Black Holes

- 4 types of black holes
  - 1. Stellar-mass black holes
    - Formed at the end of the life of a massive star (>~25 solar mass)

Cygnus X-1, artist representation from ESA Hubble Illustration
Black Holes

- 4 types of black holes
  - 2. Supermassive black holes
    - Million to more than one billion solar masses
    - Unclear how they are formed
    - Present at the center of most galaxies, including those with an active nucleus (AGNs)

Optical image of M87, from the Hubble Space Telescope
Black Holes

- 4 types of black holes
  - 3. Intermediate-mass black holes
    - 100 to million solar masses
    - Unclear whether they exist, or how they would be formed

GI globular cluster, the object at its center is a candidate for an intermediate-mass black hole. Image from the Hubble Space Telescope
Primordial Black Holes

- Last type of black holes: Primordial black holes
- Formed during density fluctuations of the early universe
- PBHs could be the origin of supermassive or intermediate-mass black holes
- VERITAS (and other IACTs) are sensitive to PBHs of mass of $\sim 5 \times 10^{14} \text{g} \ (10^{-18} \text{ solar mass})$
- The search for PBHs can give information on:
  - Relic density of PBHs
  - Effects on nucleosynthesis, baryogenesis, etc.
  - Dark matter
Primordial Black Holes

- Stephen Hawking: black holes have entropy, hence a temperature
- The lower the mass of the black hole, the higher the temperature

\[ k_B T_{BH} = \frac{\hbar c^3}{8\pi GM} = 1.06 \left( \frac{M}{10^{13} \text{g}} \right)^{-1} \text{GeV} \]

- With this temperature, the black hole will emit as a black body, following the Hawking radiation spectrum

\[ \frac{d^2 N}{dE dt} = \frac{\Gamma_s(ME)}{2\pi \hbar} \left[ \exp\left( \frac{E - n\hbar\Omega - Q\Phi}{k_B T_{BH}} \right) - (-1)^s \right]^{-1} \]

- The PBH will emit particles (based on the available degrees of freedom at the given temperature) following that spectrum
- Increasing the temperature opens up more degrees of freedom, allowing PBHs to emit more particles and particle types
- Leads to PBH evaporation

\[ M(t) = (M_i^3 - 3\alpha t)^{1/3} \]
Primordial Black Holes

- As PBHs lose mass, the temperature increases, allowing to emit more particles, accelerating the mass loss, leading to a final burst of particles.

- Integrating over a PBH’s remaining lifetime, one can calculate a theoretical spectrum of gamma-ray emissions.

Figure from T. Ukwatta et al, Astrop. Phys 80, 90, 2016
Primordial Black Holes

- Power-law index of -1.5
- Come from PBHs emitting quarks according to Hawking radiation
  - Quarks hadronizing into neutral pions
    - Pions decaying into gamma rays
- PBHs also emit photons directly, following Hawking radiation

Power-law index of -3
Only contribution is direct photon emission from PBHs
VERITAS

- Four 12-m Imaging Atmospheric Cherenkov Telescopes
- Located at the Fred Lawrence Whipple Observatory (FLWO) in southern Arizona (31 40N, 110 57W, 1.3 km a.s.l.)
- Fully operational since 2007

- Energy range: 100 GeV to >30 TeV
- Field of view of 3.5°
- Point source sensitivity: 5σ detection at 1% Crab in <25 h
Search for PBHs with VERITAS

- We know the spectrum, we know the burst behavior, VERITAS can use this to look for PBHs’ signatures
- Look for burst in archival data
  - For a given run, get a list of gamma-like events
  - Look for events arriving within a certain time of each other (e.g. 1 second)
  - In that list, look for events with similar arrival direction, consistent with coming from the same source
  - For background estimation, scramble the arrival times of the events and repeat the analysis
Search for PBHs with VERITAS

- Look for burst in archival data
  - For a given run, get a list of gamma-like events
    - Use of Boosted Decision Trees* (BDTs)
      - Reduce background and increase sensitivity
  - Look for events arriving within a certain time of each other (e.g. 1 second)
    - Explore different burst duration
      - High times, background-dominated
      - Look for band of optimal sensitivity
      - Different durations allow to search for different remaining PBH evaporation times

* M. Krause et al, Astrop Phys 89, 1, 2017
Search for PBHs with VERITAS

- Look for events with similar arrival direction, consistent with coming from same source
  - VERITAS angular resolution (at 68% C.L.) is <0.1° at 1 TeV
  - True, and this was used as the angular separation in previous searches for PBH evaporation
  - However, angular resolution depends on the energy and arrival direction of the gamma ray
Search for PBHs with VERITAS

- The angular resolution dependence in energy and elevation is used to give an uncertainty to the reconstructed position of each event.
- This is used to calculate a centroid position based on a weighted mean of all the events.

- Comparing likelihood between background and simulated signal gives a means to identify groups events coming from the same position.
Search for PBHs with VERITAS

- For background estimation, scramble the arrival times of the events and repeat the analysis
  - Removes fake bursts and creates new ones
  - This can be done with Monte Carlo, however, using scrambled data will be more representative of the running conditions
  - This includes effects of:
    - Weather
    - Anisotropies in the cosmic-ray background
    - Stable sources in the field of view
  - Repeated 10 times to increase statistics and reduce errors
Results

- These tools are used to get distributions of bursts as a function of the number of events in a burst (burst size)
Results

- These distributions are used to compute limits using a maximum-likelihood technique

![Summary Limits](image)

- Minimum value of $2.22 \times 10^4$ pc$^{-3}$ yr$^{-1}$ at 99% C.L. with a burst duration of 30 seconds, using 747 hours of data

Numbers of other experiments taken from T. Ukwatta et al, Astrop Part 80, 90, 2016
Conclusion

- With 747 hours of data, VERITAS reaches its best limits of $2.22 \times 10^4 \text{ pc}^{-3} \text{ yr}^{-1}$, using a burst duration of 30 seconds.
- Previous VERITAS results got $1.29 \times 10^5 \text{ pc}^{-3} \text{ yr}^{-1}$ with 700 hours of data, for a burst duration of 1 second.
- Differences
  - Boosted Decision Trees
  - Expansion of the burst duration investigated
  - Accounting for the angular resolution’s dependence in energy and elevation
References

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