Search for Primordial Black Hole Evaporation with VERITAS

Simon Archambault, for the VERITAS Collaboration

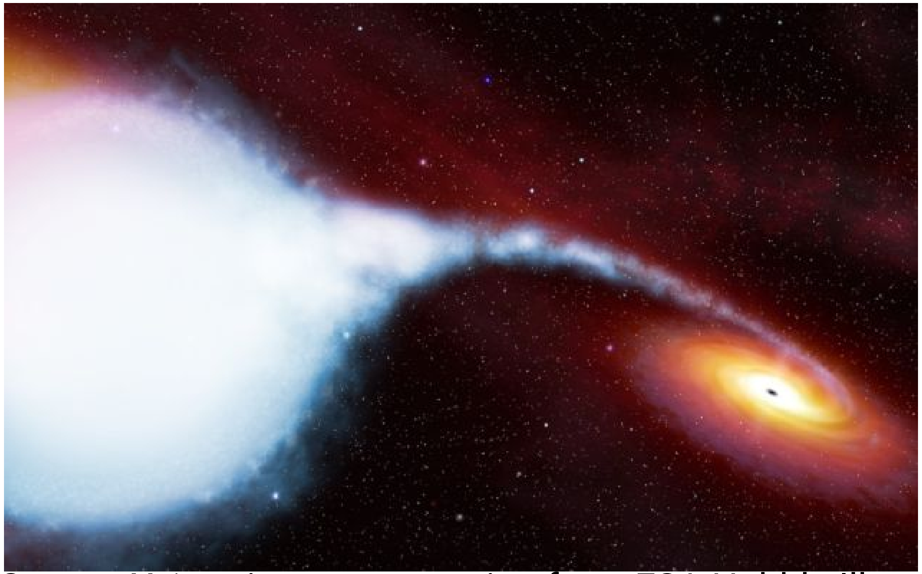
20/07/2017

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)



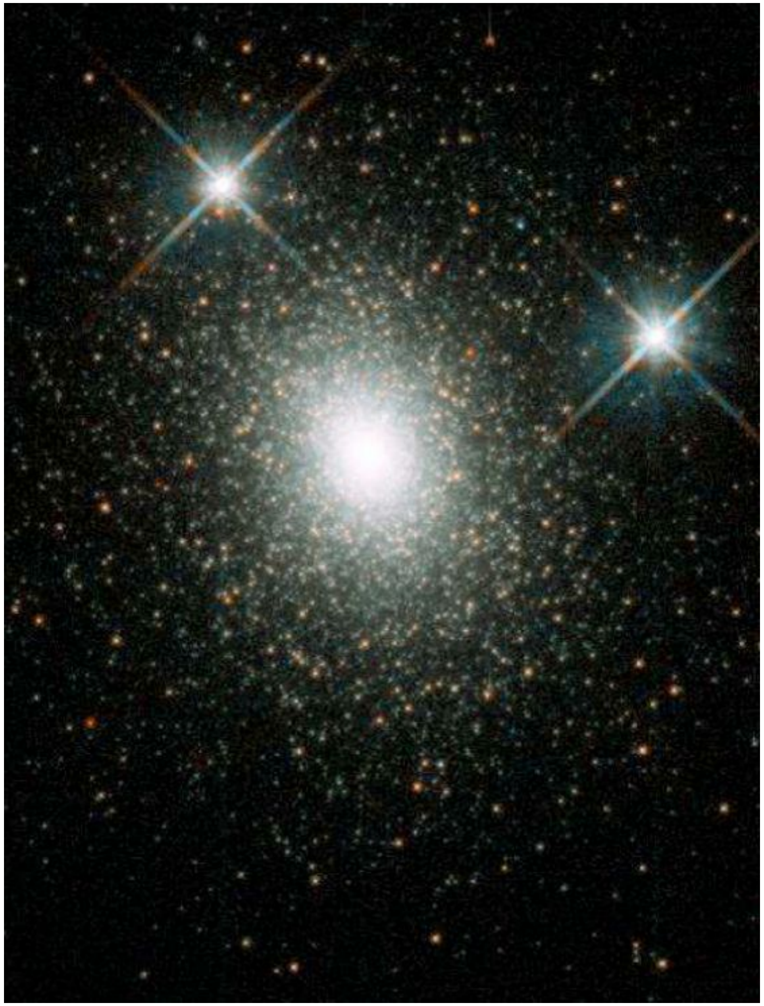
Cygnus X-1, artist representation from ESA Hubble Illustration

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



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

- 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

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 ~$5x10^{14}$g (10^{-18} 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

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

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

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

- 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

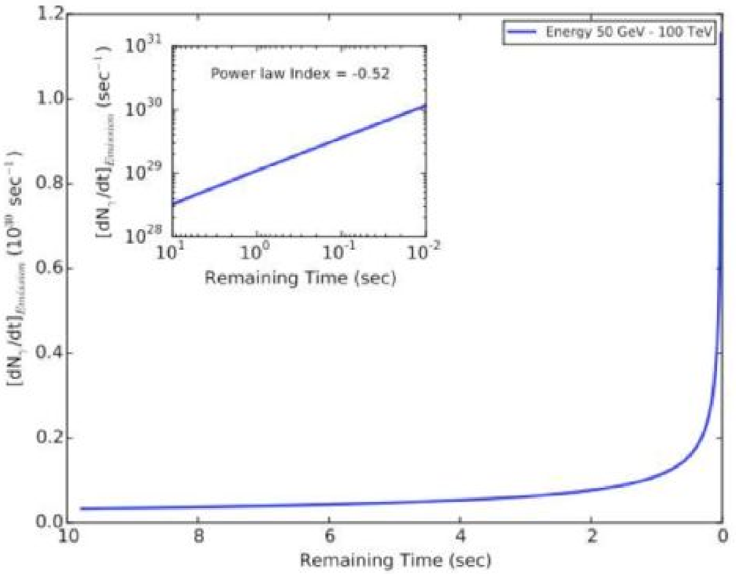
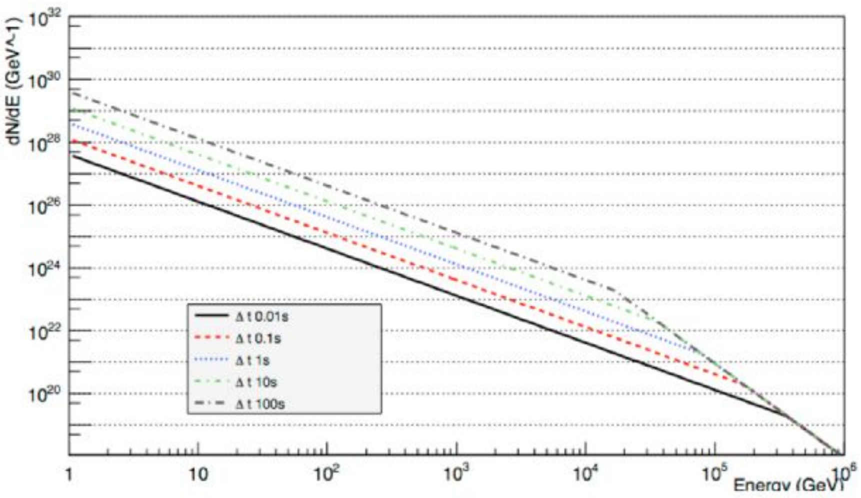


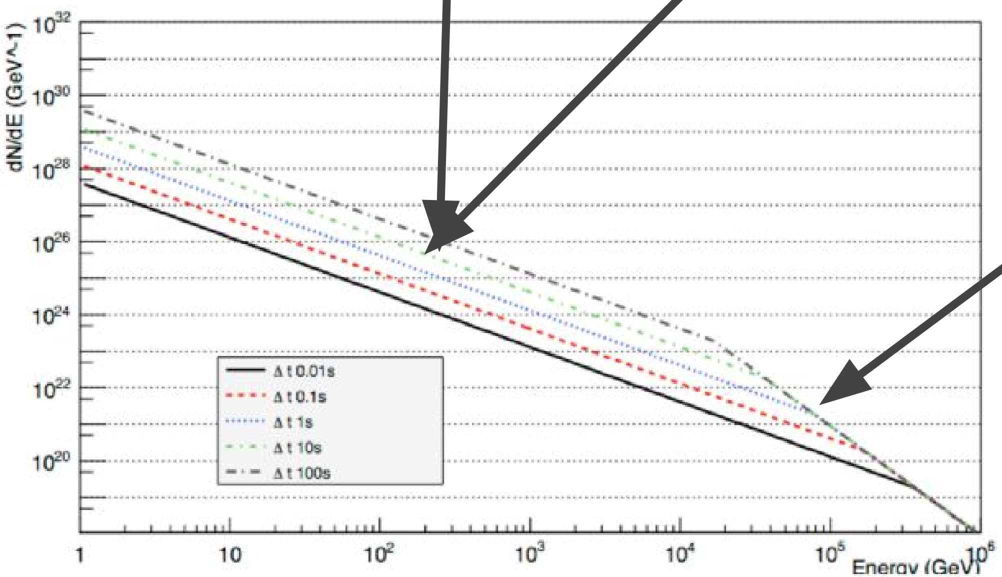
Figure from T.Ukwatta et al, Astrop. Phys **80**, 90, 2016

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



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

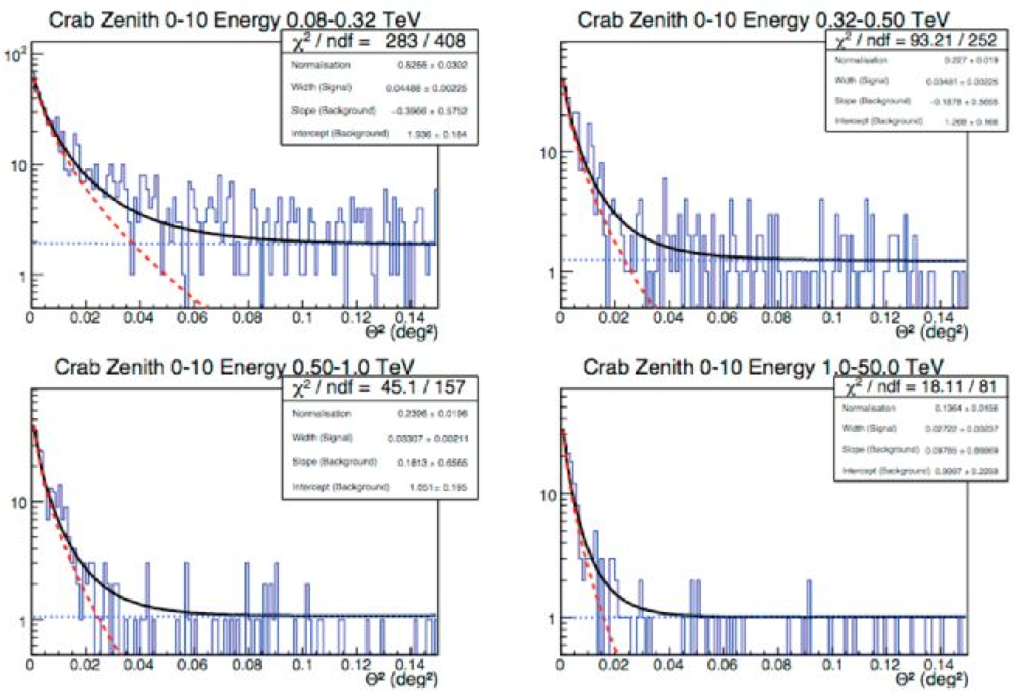
Search for PBHs with VERITAS

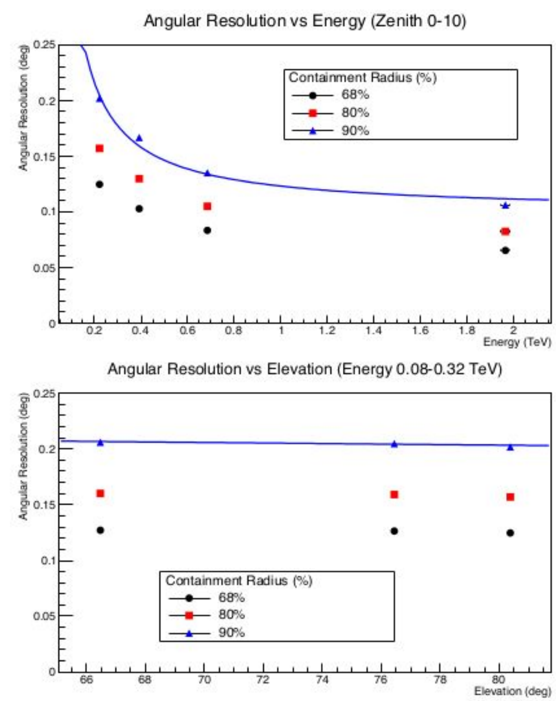
- Look for burst in archival data
  - For a given run, get a list of gamma-like events
    - Use of Boosted Decision Trees* (BDTs)
      - Reduce background and increase sensitivity
  - Look for events arriving within a certain time of each other (e.g. 1 second)
    - Explore different burst duration
      - 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

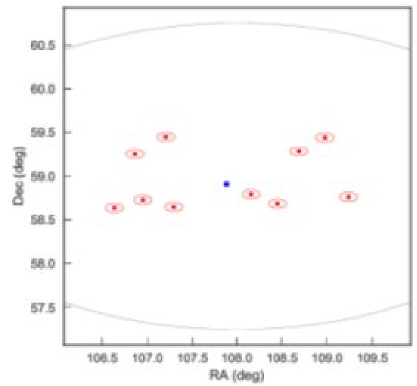
- Look for events with similar arrival direction, consistent with coming from same source
  - VERITAS angular resolution (at 68% C.L.) is <0.1° at 1 TeV
  - True, and this was used as the angular separation in previous searches for PBH evaporation
  - However, angular resolution depends on the energy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

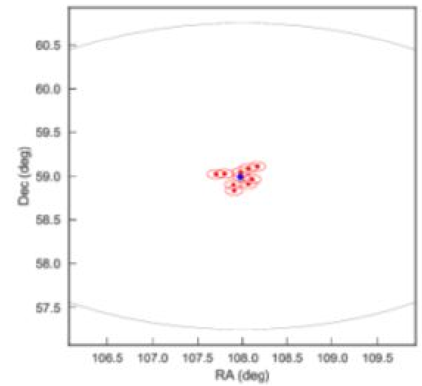


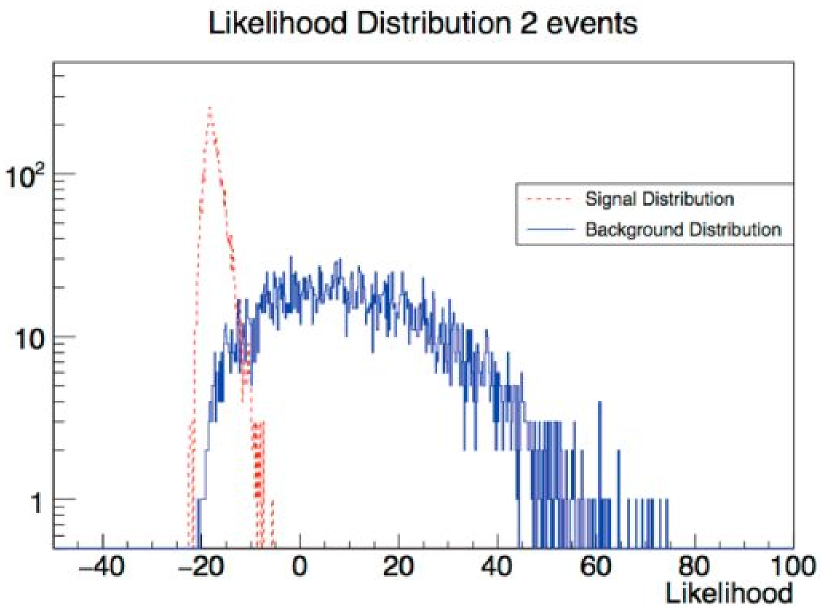


Search for PBHs with VERITAS

- 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



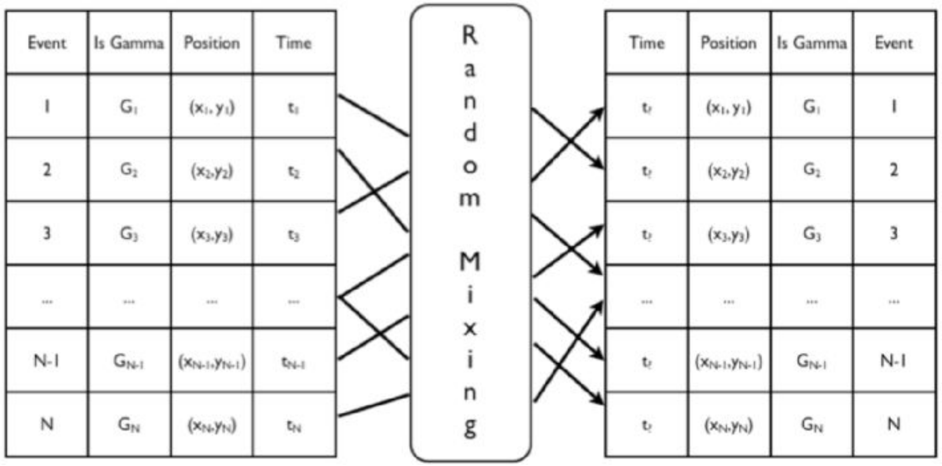




- Comparing likelihood between background and simulated signal gives a means to identify groups events coming from the same position

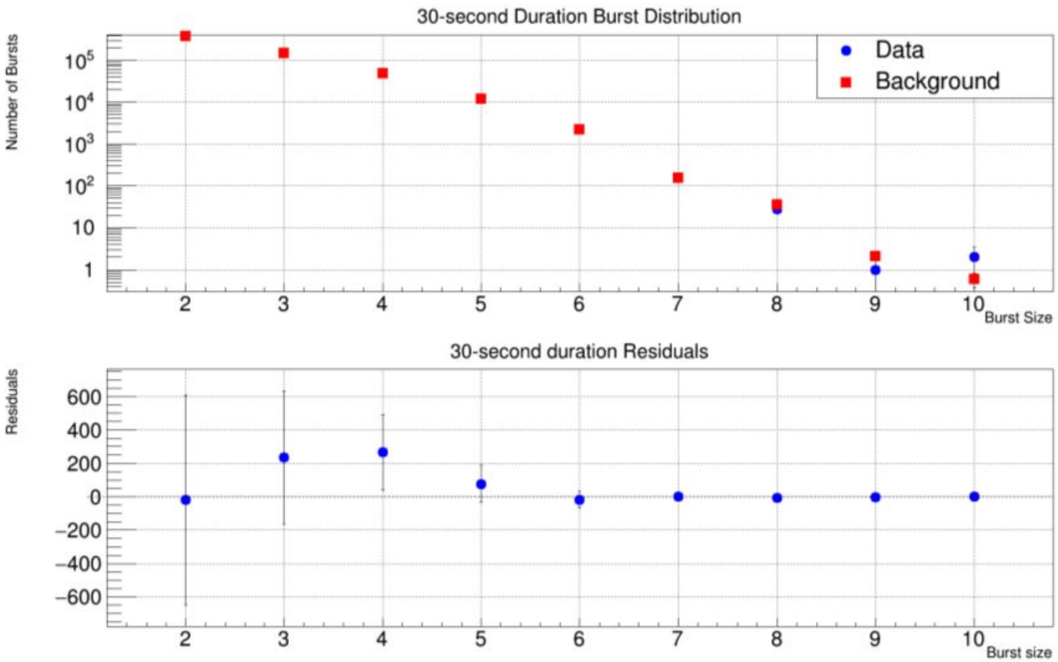
Search for PBHs with VERITAS

- For background estimation, scramble the arrival times of the events and repeat the analysis
  - Removes fake bursts and creates new ones
  - This can 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



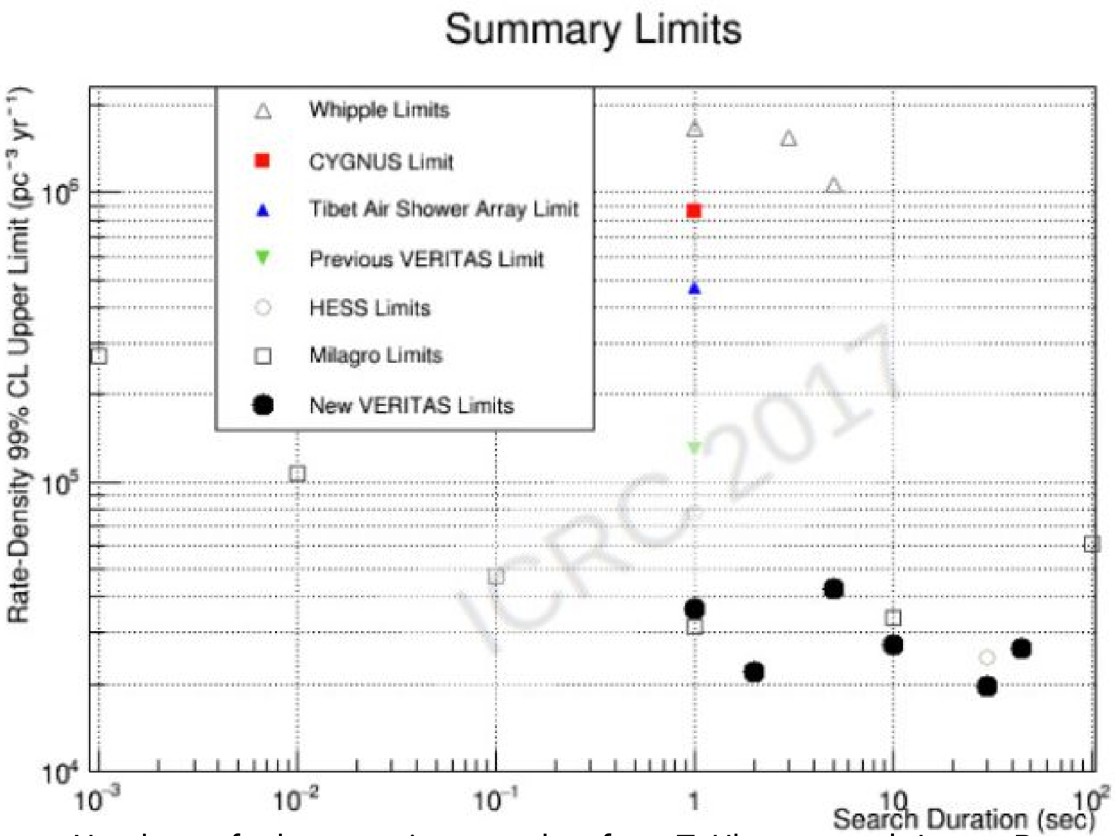
Results

- 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



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

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

Conclusion

- With 747 hours of data, VERITAS reaches its best limits of 2.22×10^4 pc^{-3} yr^{-1}, using a burst duration of 30 seconds.
- Previous VERITAS results got 1.29×10^5 pc^{-3} 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

K. Schwarzschild, Zeitschrift fur Mathematik und Physik **7**, 189, 1916

S. Hawking, MNRAS **152**, 75, 1971

S. Hawking, Nature **248**, 30, 1974

J. MacGibbon, Phys. Rev. D **44**, 376, 1991

H.Kim et al., Phys. Rev. D **59**, 063004, 1999

P. Nasel'skii, Soviet Astronomy Letters **4**, 387, 1978

Y. Zeldovich et al, JETP Letters **24**, 571, 1976

J. Barrow, Surveys in High Energy Physics **1**, 183, 1980

B. Vainver et al, Soviet Astronomy Letters **4**, 185, 1978

G. Tesic, Journal of Physics: Conference Series **375**, 2012

J. Glicenstein et al, Proc of the 33rd ICRC, 2013

A. Abdo et al, Astrop Phys **64**, 4, 2015

M. Krause et al, Astrop Phys **89**, 1, 2017

K. Meagher, Proc of the 34th ICRC, 2015

T. Ukwatta et al, Astrop Phys **80**, 90, 2016