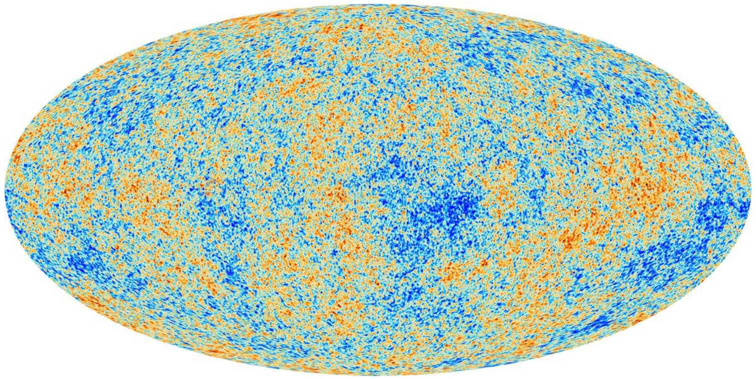
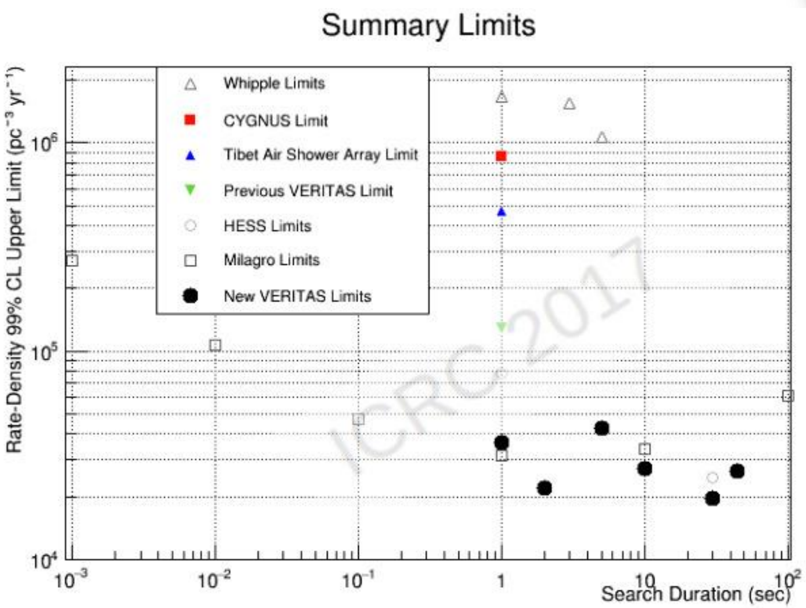
Search for primordial black hole evaporations in VERITAS data





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on behalf of the VERITAS Collaboration
McGill University/Columbia University

Primordial black holes (PBHs) could form from overdense regions in the early universe

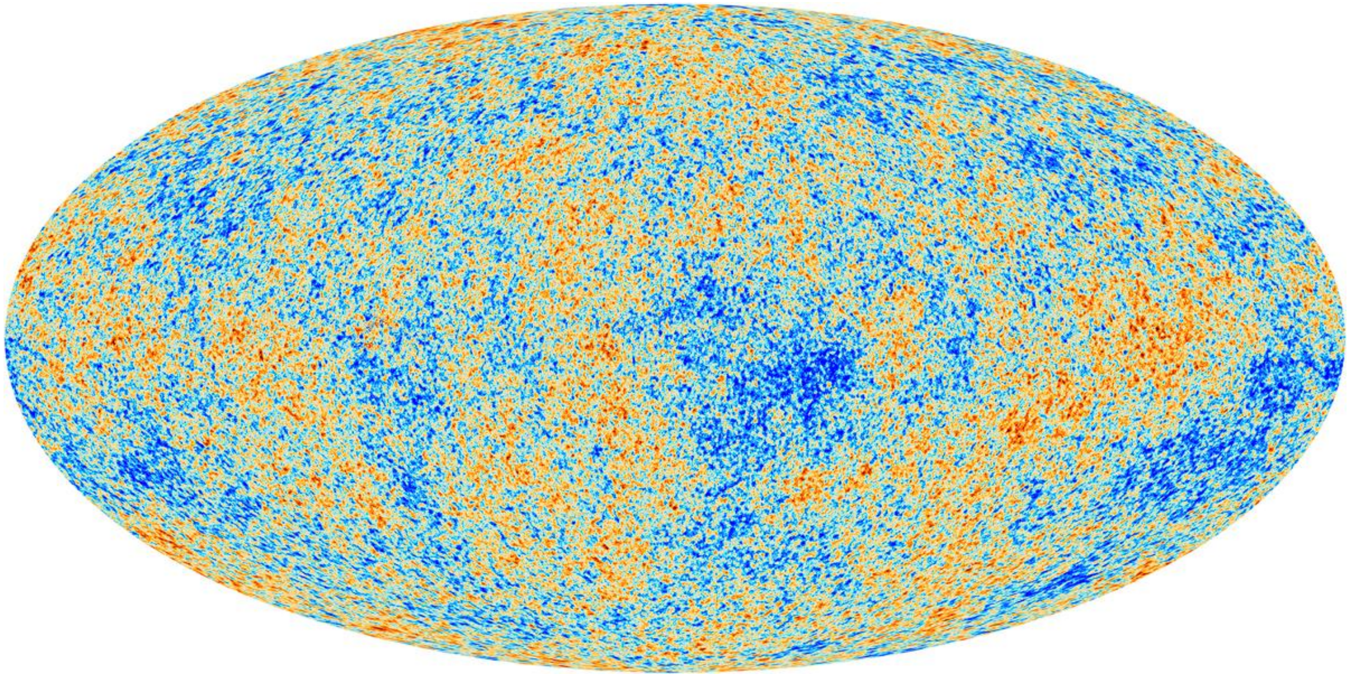


Image: Planck ESA

PBHs could have been formed:

- At very early universe (exact time uncertain)
- With a wide range of masses

$$M \sim \frac{c^3 t}{G} \sim 10^{15}\left(\frac{t}{10^{-23}\ \mathrm{s}}\right)\ \mathrm{g}$$

M: Initial mass of a PBH;
t: time after the Big Bang when a PBH is formed (particle horizon time)

Why search for PBHs?

Discovery of PBHs would:

- Confirm Hawking radiation
- Probe particle physics processes at the highest energy scale (through Hawking radiation)
- Provide insights into cosmological models of phase transitions
- Quantify mass of primordial seeds and probe structure formation

Hawking Radiation would lead to BH evaporation

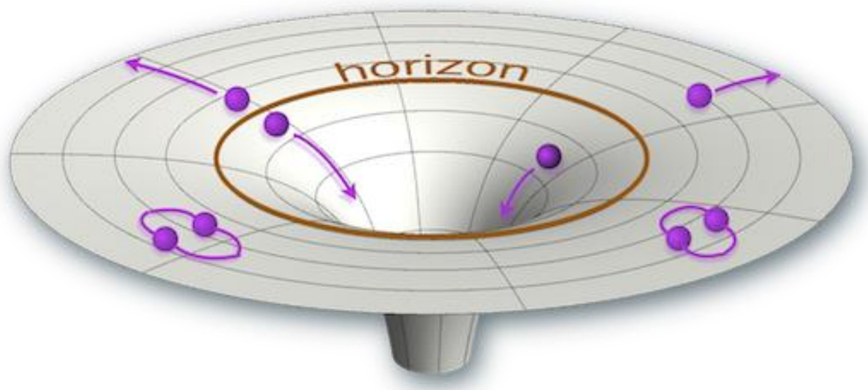


Image: [MuonRay: March 2014]

$$T_{\rm BH} = \frac{\hbar c^3}{8\pi G M k_{\rm B}} \sim 10^{-7}\left(\frac{M}{M_\odot}\right)^{-1}\ {\rm K} \qquad\qquad \tau \sim 400(M_{BH}/10^{10}{\rm g})^3{\rm s}$$

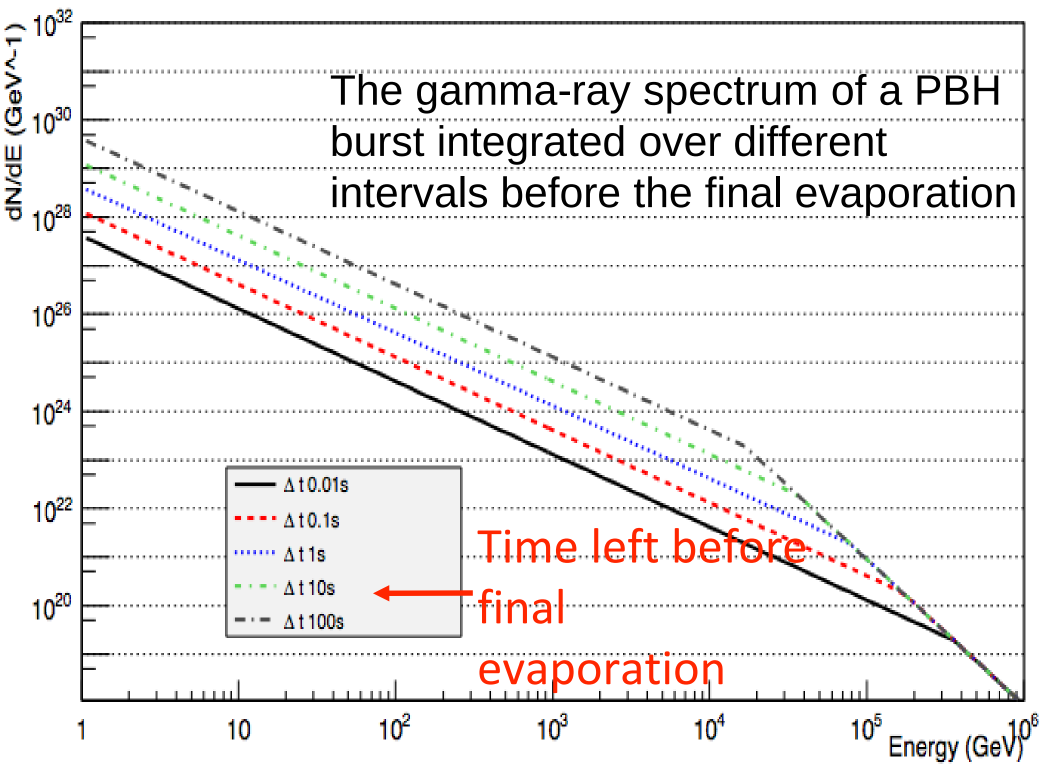
- A BH could radiate elementary particles with a black body spectrum due to quantum effects - Hawking radiation.
- Gamma rays can be produced by low-mass BHs, the spectrum can be calculated from standard model, which predicts a gamma-ray bursts of duration of the order of seconds.
- A PBH of mass 10^{15} g (born at $\sim 10^{-23}$s) would evaporate at current epoch.

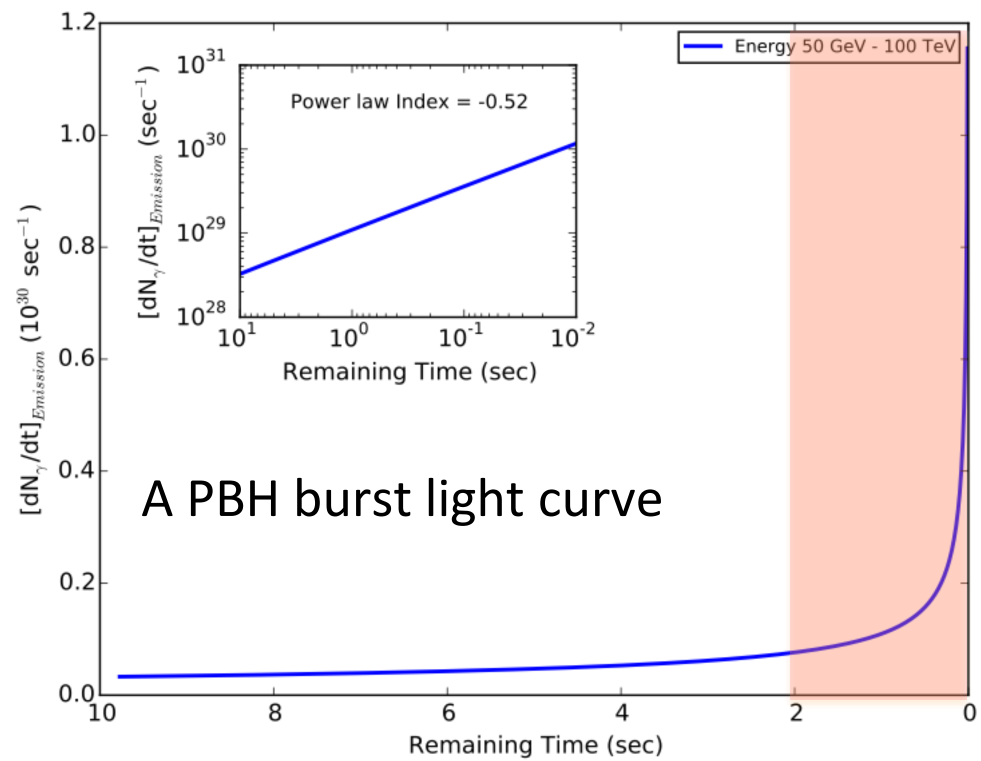
Gamma rays from PBH evaporation (standard model)

$$T_{\mathrm{BH}} = \frac{\hbar c^3}{8\pi G M k_{\mathrm{B}}} \sim 10^{-7}\left(\frac{M}{M_\odot}\right)^{-1}\ \mathrm{K}$$

Gamma rays are produced either directly (black-body from the BH itself) or from decays of particles radiated by the BH.
As the PBH temperature increases, heavier particles are produced.

The evaporation rate depends on temperature $T_{BH} \propto M^{-1}$;
as M drops, radiation rises, leading to a thermal run-away —> a burst of gamma rays!



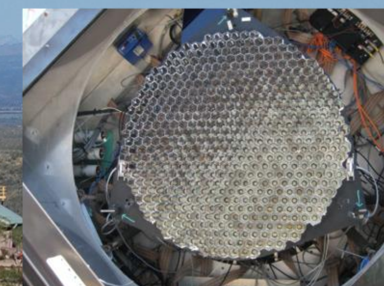


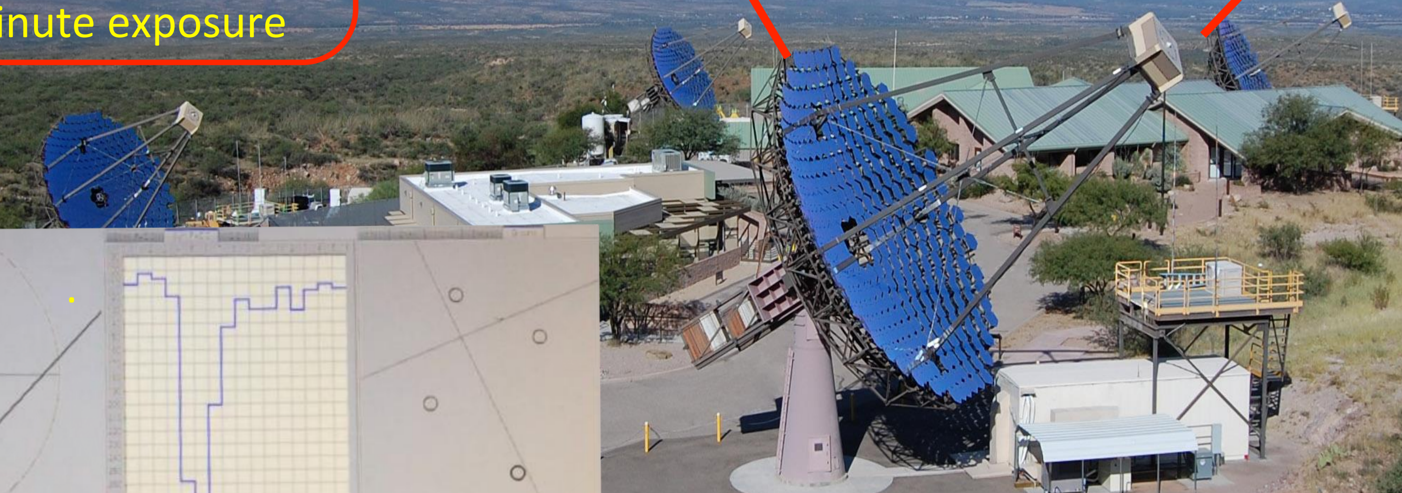
VERITAS OVERVIEW

Very Energetic Radiation Imaging Telescope Array System (VERITAS)
in southern Arizona, USA

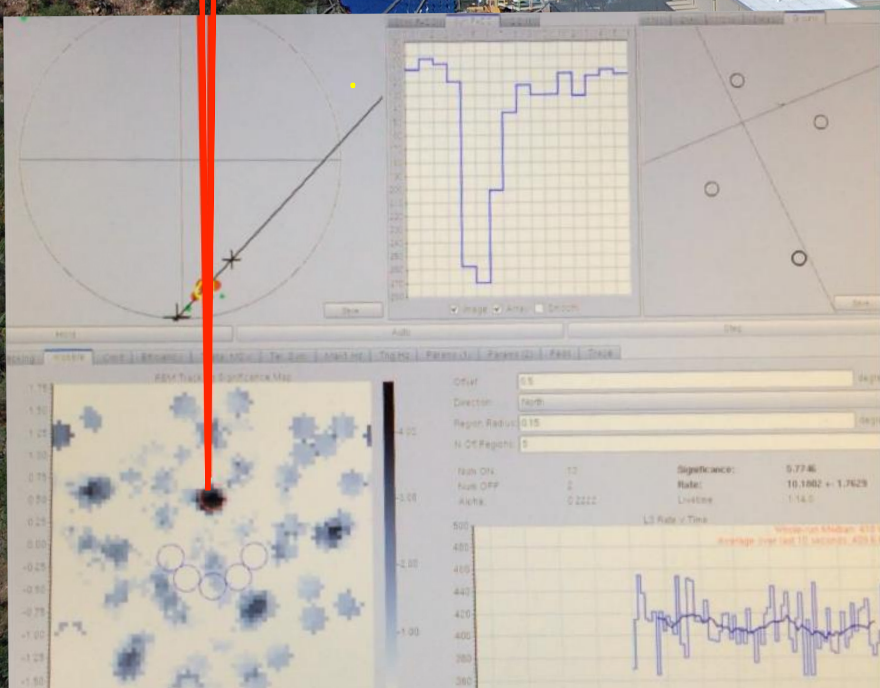
12-m mirrors,

cameras:
499 photomultiplier tubes (PMT),
~3.5 deg field of view,
~0.08 deg angular resolution @1TeV.





real-time analysis:
5-sigma detection on Crab
with 1-minute exposure



15-20% energy resolution;
~85GeV-30TeV energy range;
1% Crab detection in ~25 hr;
10% Crab detection in ~25 min;
~20% systematic uncertainty on flux;
~0.1 sys. unc. on spectral index.
~10^5 m^2 effective area

arXiv: 1510.01269

Atmospheric Cherenkov Technique

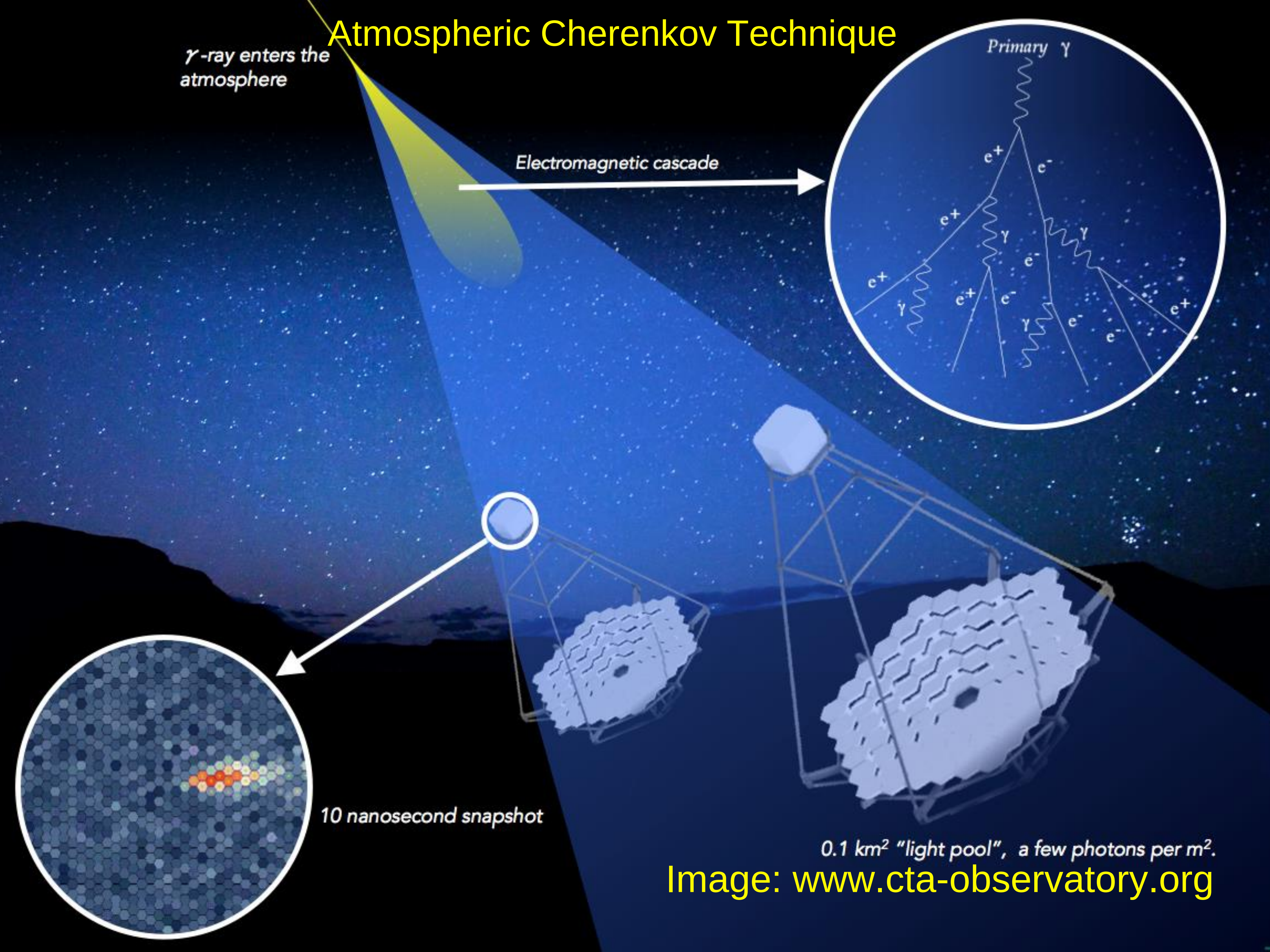


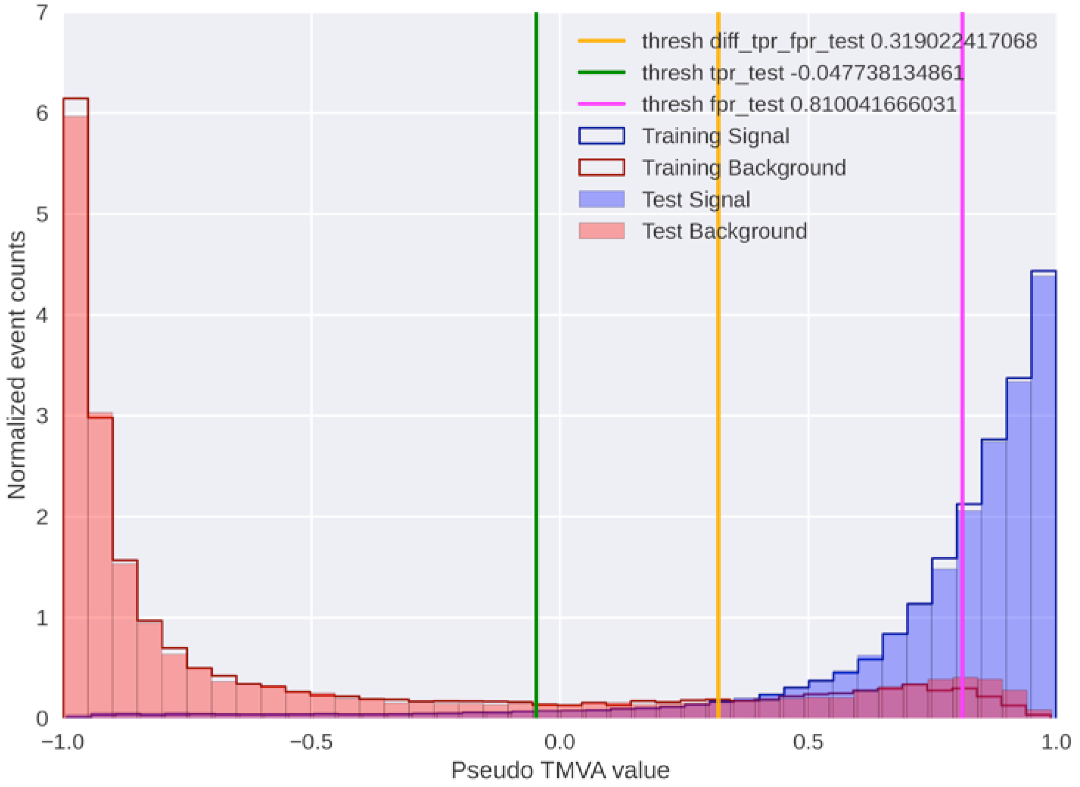
Image: www.cta-observatory.org

The search for PBH evaporation with VERITAS

- PBHs should be roughly locally homogenous and isotropic, and their evaporation happens randomly in time.
- No new or special observations required, can be searched for in archival data
- PBH searches => searching for point-like gamma-ray transients in the entire field-of-view in all data:
  1. Get all gamma-like events (based on gamma-ray analysis using a machine-learning algorithm, boosted decision tree) in a sliding time window;
  2. Determine if a subset of these events are consistent with a point source (whose probability distribution should follow the gamma-ray point spread function), if so, keep the group of events as a PBH burst candidate (**"burst search"**);
  3. Randomize the arrival time of all gamma-like events and perform "burst search" to estimate the rate of random bursts not from PBHs to determine a background estimate;
  4. Constrain the rate density of PBH evaporation from the number bursts found in data and background (using standard model and VERITAS instrument response function).

1. Boosted decision tree analysis

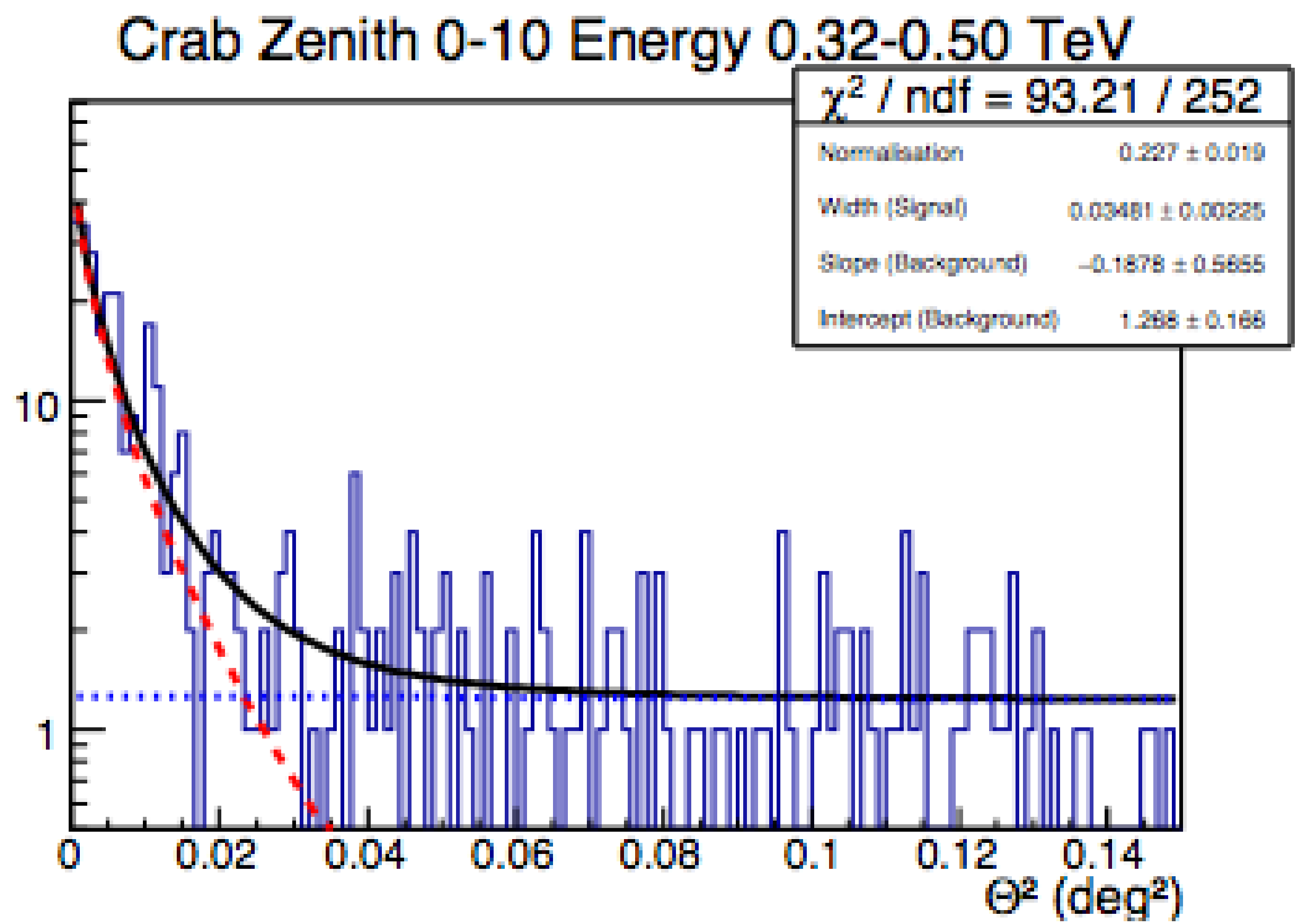
- Majority of IACT backgrounds are showers initiated by cosmic rays (e.g. protons, helium, electrons)
- Improved sensitivity using BDT compared to box cuts, requiring 10-25% less time to detect a weak source.
- Provided capability to measured diffuse emission (e.g. cosmic electrons arXiv:1508.06597)



2. PSF function

- Hyperbolic secant function used to empirically determine PSF as a function of elevation and energy
- use to weight events in clustering analysis

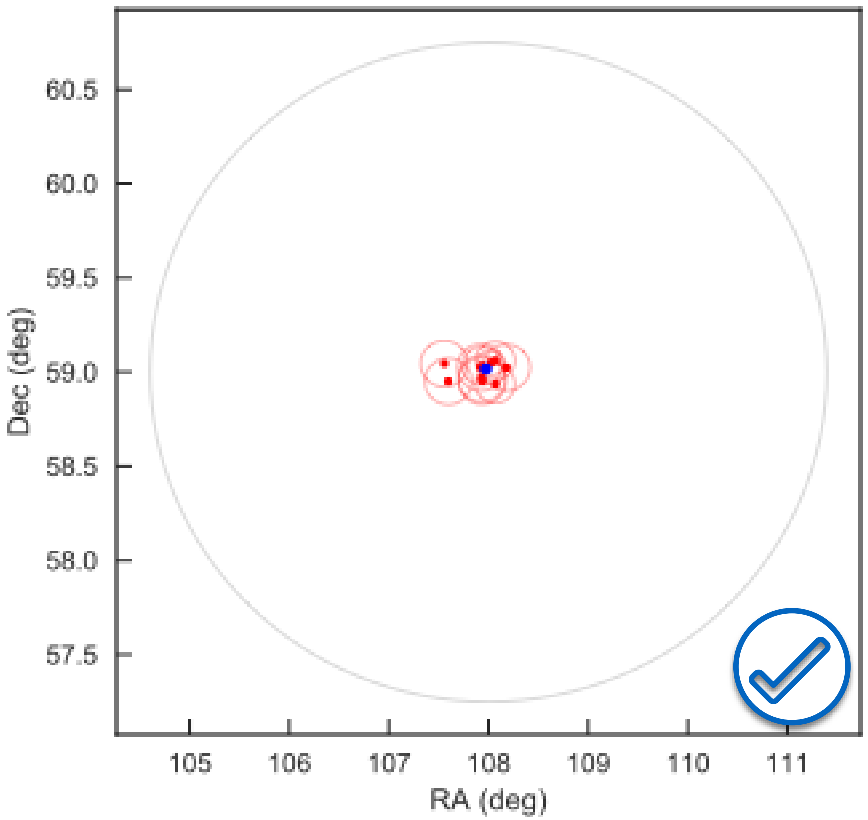
$$S(\theta^2, w) = \frac{1.71N}{2\pi w^2}\mathrm{sech}(\sqrt{\theta^2}/w)$$

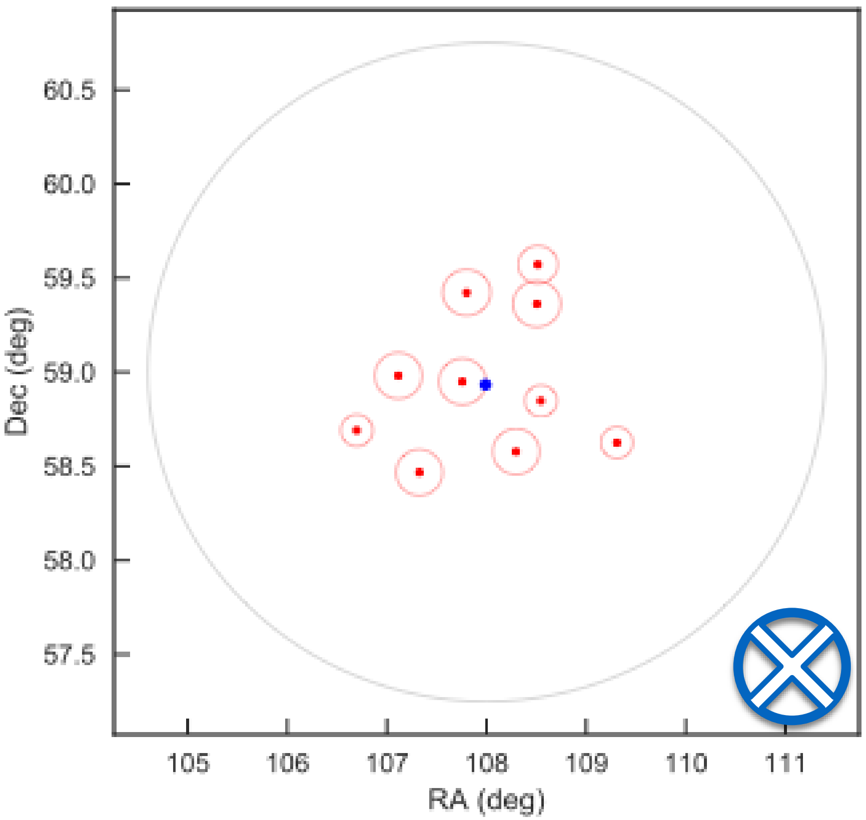


3. simulated sky maps of PBH burst and random events

$$L = \prod_i \frac{1.71}{\pi w_i^2} \mathrm{sech}(\sqrt{(\theta_i - \mu)^2}/w_i)$$

Likelihood equation to help determine whether a group of events is consistent with a point source.

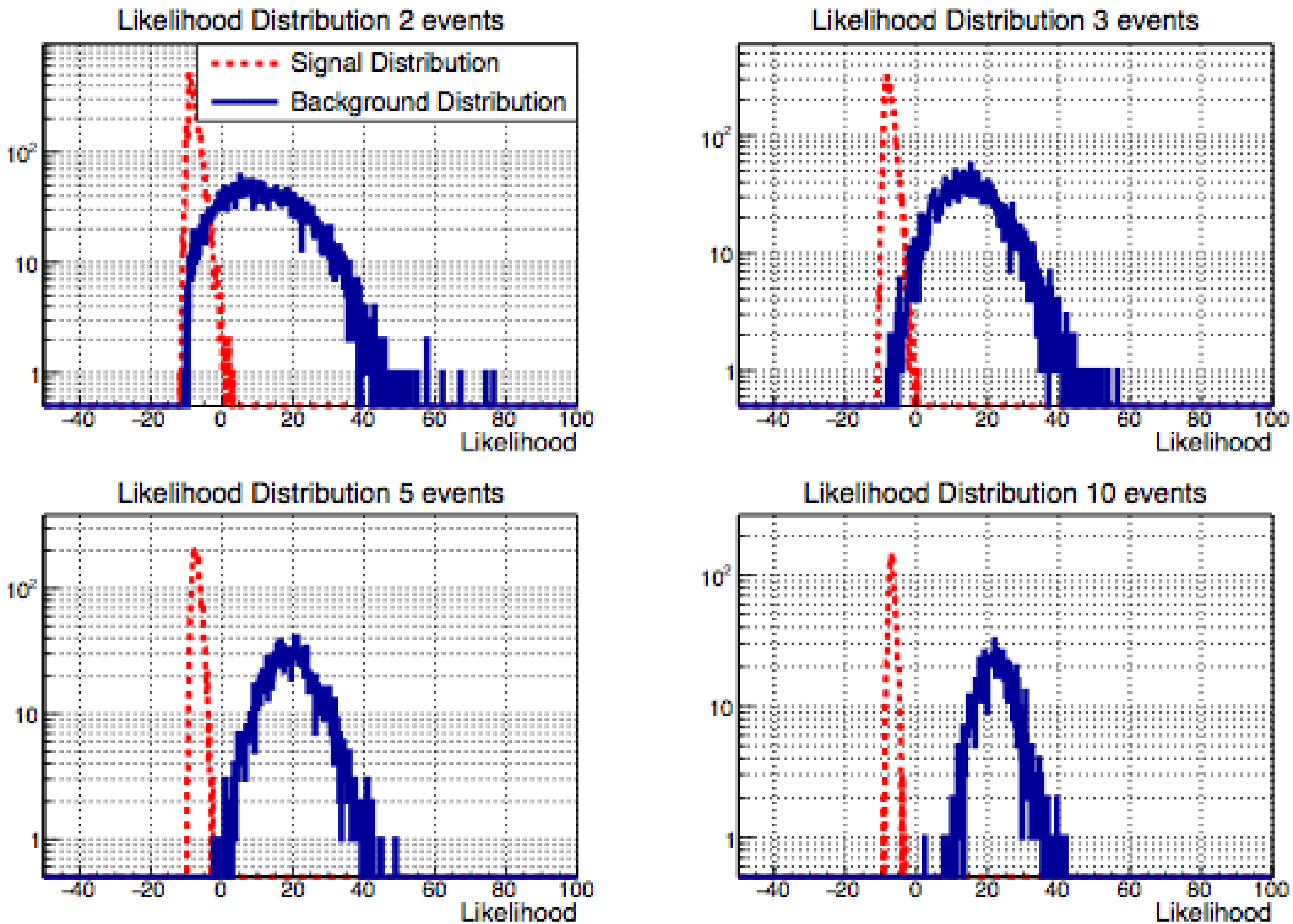




4. likelihood distributions of simulated PBH bursts and background

$$L = \prod_i \frac{1.71}{\pi w_i^2} \mathrm{sech}(\sqrt{(\theta_i - \mu)^2}/w_i)$$

A 90% efficiency cut is applied for background rejection.

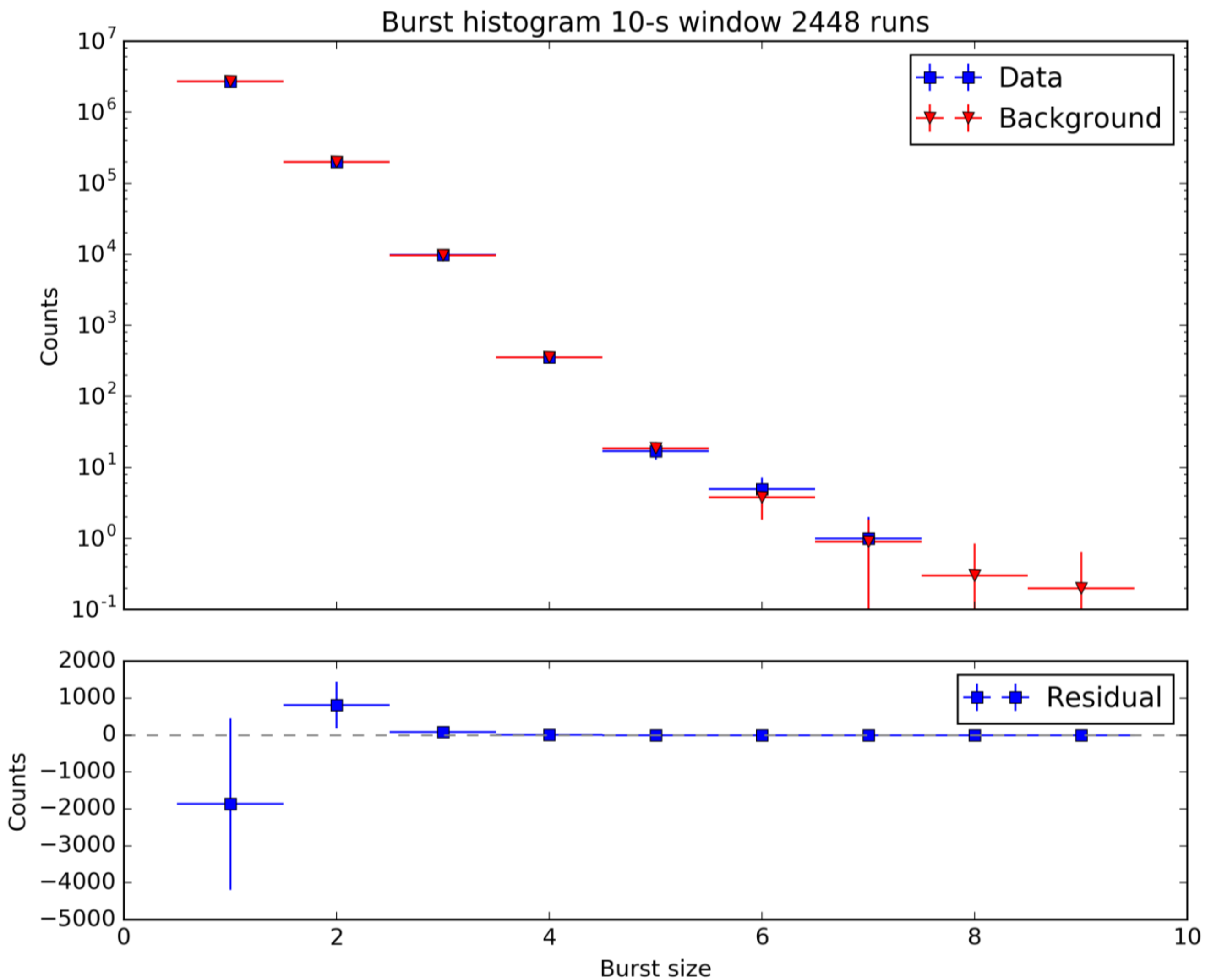


5. Burst histograms

- Burst searches on scrambled data as background estimation.
- Any signal from PBH would be eliminated when events are shuffled in time.
- Eliminates systematics due to deadtime, etc.

n_{on} n_{off}

Scramble the arrival time of the events to generate off data



6. Effective volume

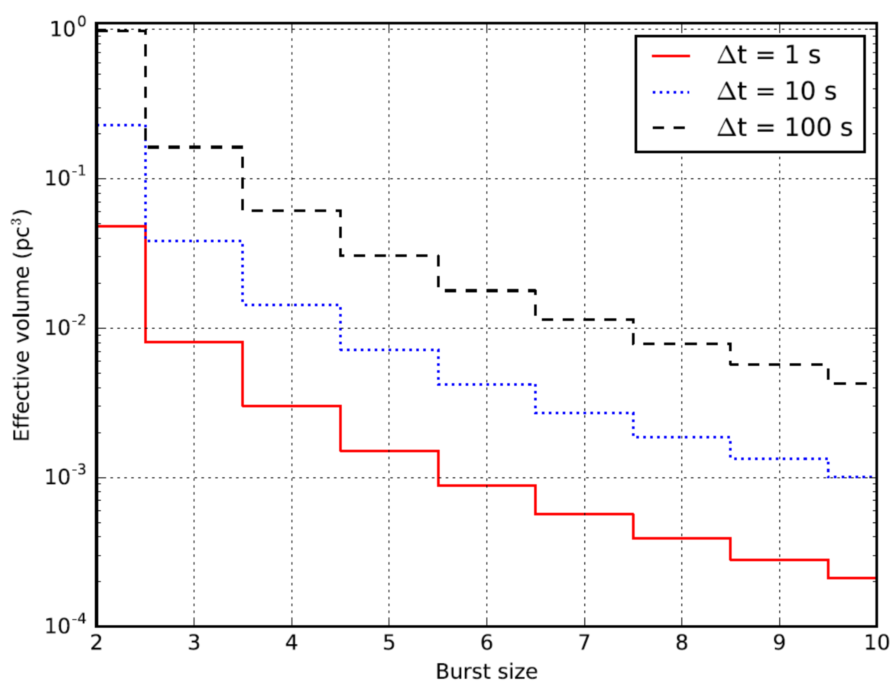
Our goal is to constrain the PBH evaporation rate density: $n_{exp}(b, \Delta t) = \dot{\rho}_{PBH} \times T_{obs} \times V_{eff}(b, \Delta t)$

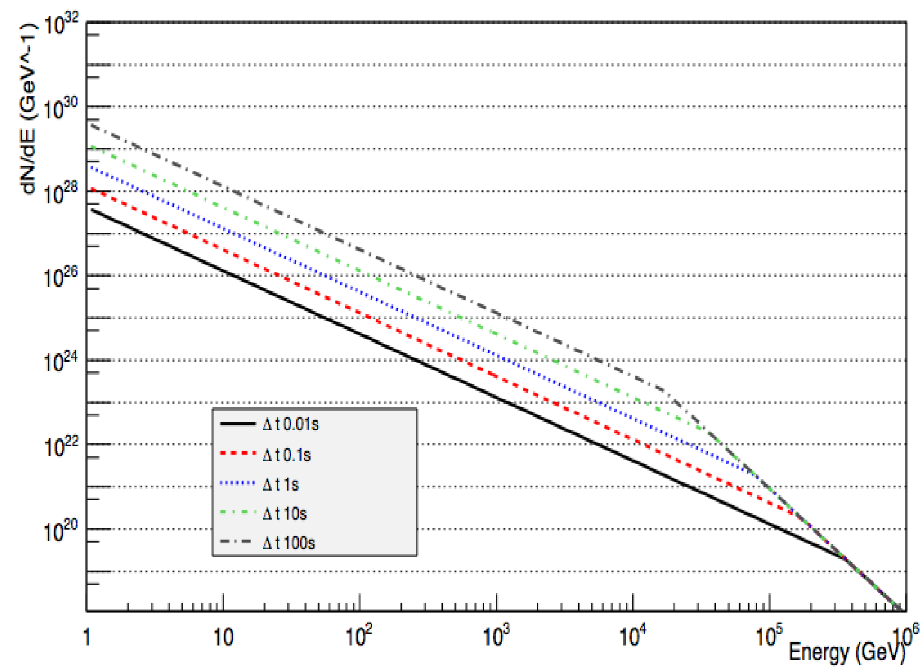
VERITAS instrument response function is characterized into the effective volume:

$$V_{eff}(b, \Delta t) = \int_{\Delta\Omega} d\Omega \int_0^\infty dr r^2 P(b, N_\gamma(r, \alpha, \delta, \Delta t)) \qquad \text{where:} \quad P(b, N_\gamma(r, \alpha, \delta, \Delta t)) = \exp(-N_\gamma)\frac{N_\gamma^b}{b!}$$

N_γ is the number of expected gamma rays:

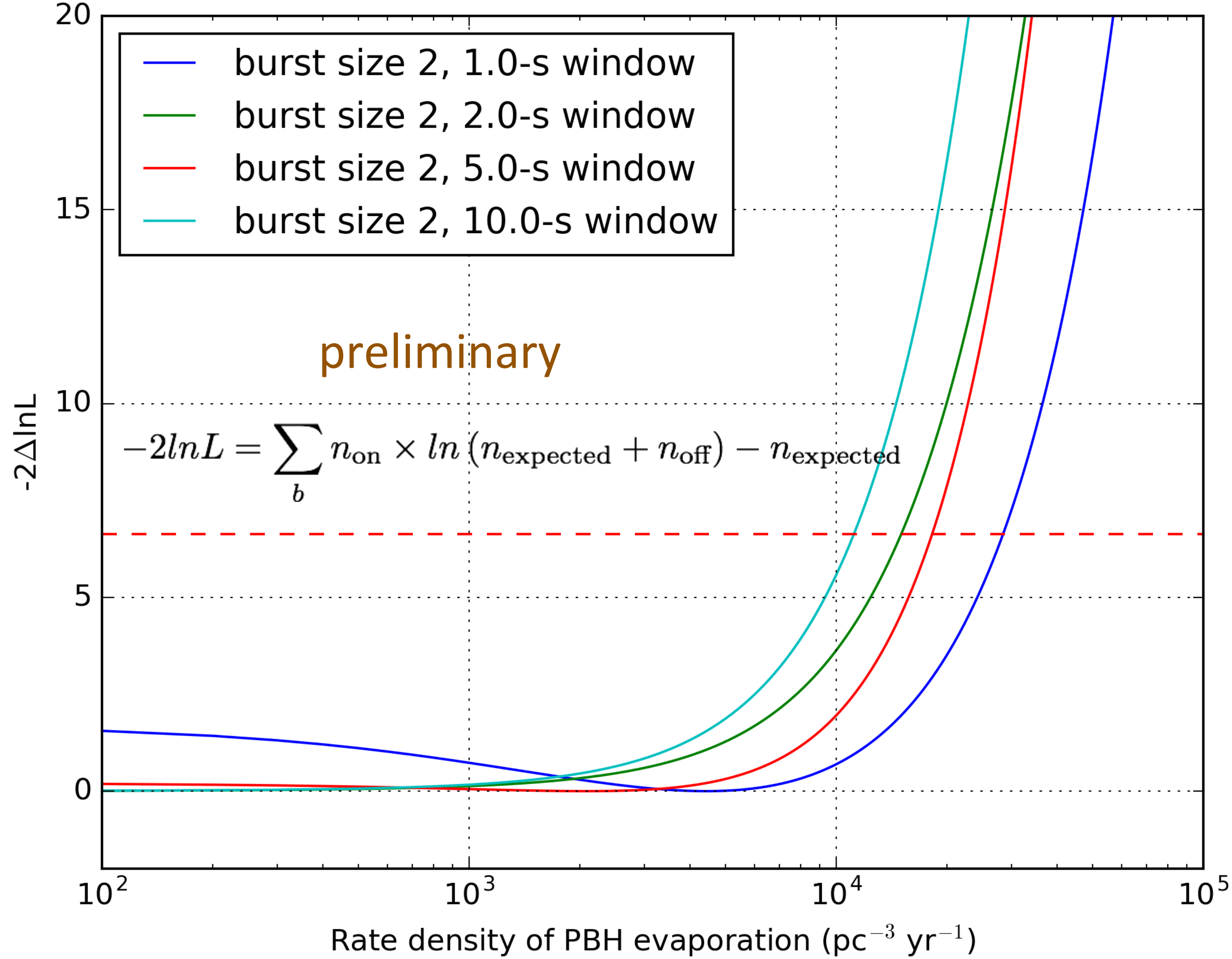
$$N_\gamma(r, \alpha, \delta, \Delta t) = \frac{1}{4\pi r^2}\int_0^\infty \frac{dN}{dE}(E_\gamma, \Delta t) A(E_\gamma, \theta_z, \theta_w, \mu, \alpha, \delta) dE_\gamma$$





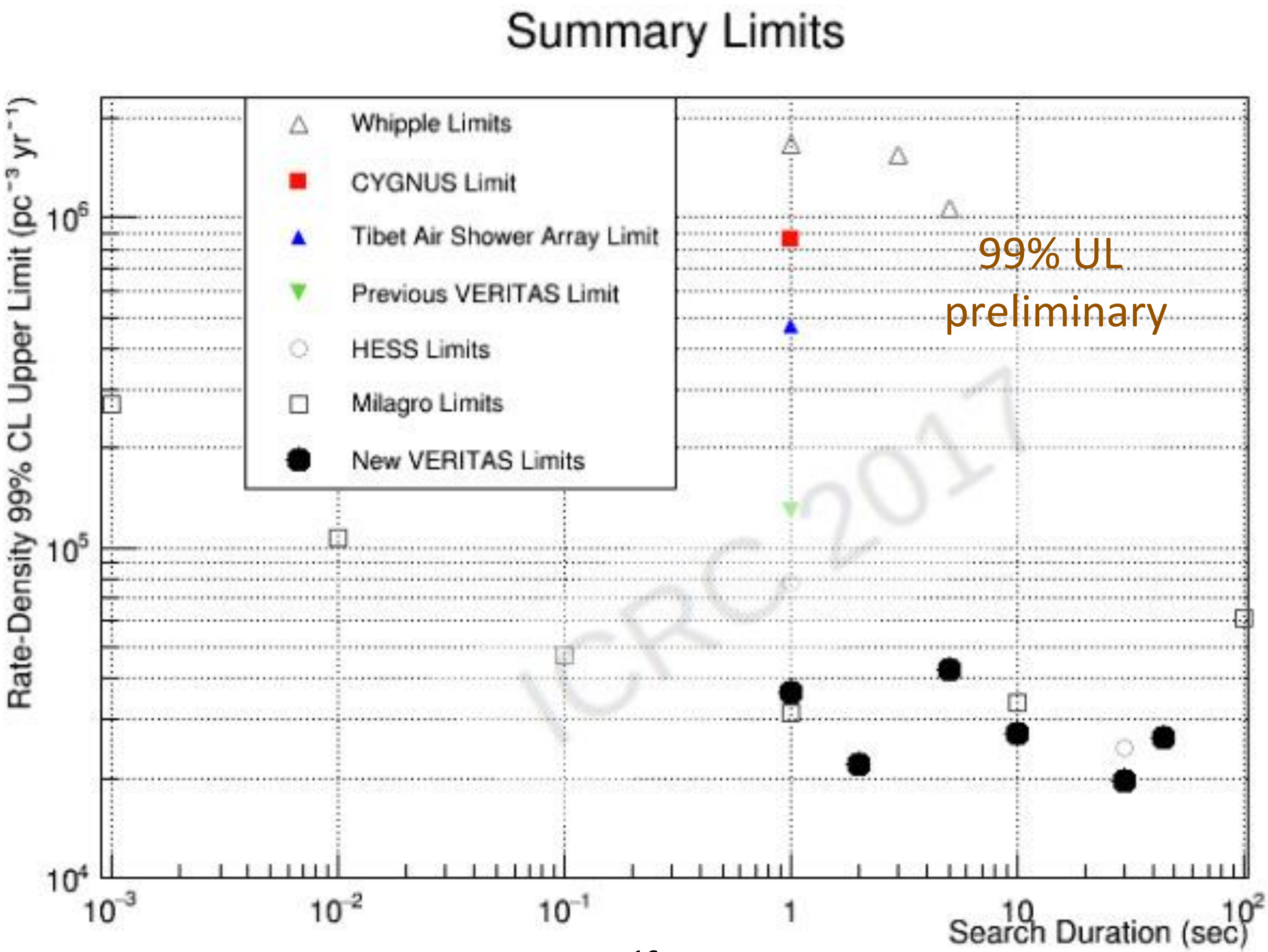
6. Log likelihood vs rate density

~760-hr VERITAS V5 data; window size 1, 2, 5, and 10 s.



7. The final limit on the PBH rate density

~760-hr VERITAS V5 data; window size 1, 2, 5, 10, 30, and 45 s.



Summary

- 760-hr VERITAS gives a competitive upper limit on the PBH evaporation rate density when compared to previous limits.
- Search in archival data – no special observing requirements
- Energy dependent point spread function and boosted decision tree analysis improved the sensitivity in the PBH search compared to previous VERITAS search.
- More window sizes were analyzed compared to previous work.