Setting Upper Limits on the Local Burst Rate Density of Primordial Black Holes Using HAWC

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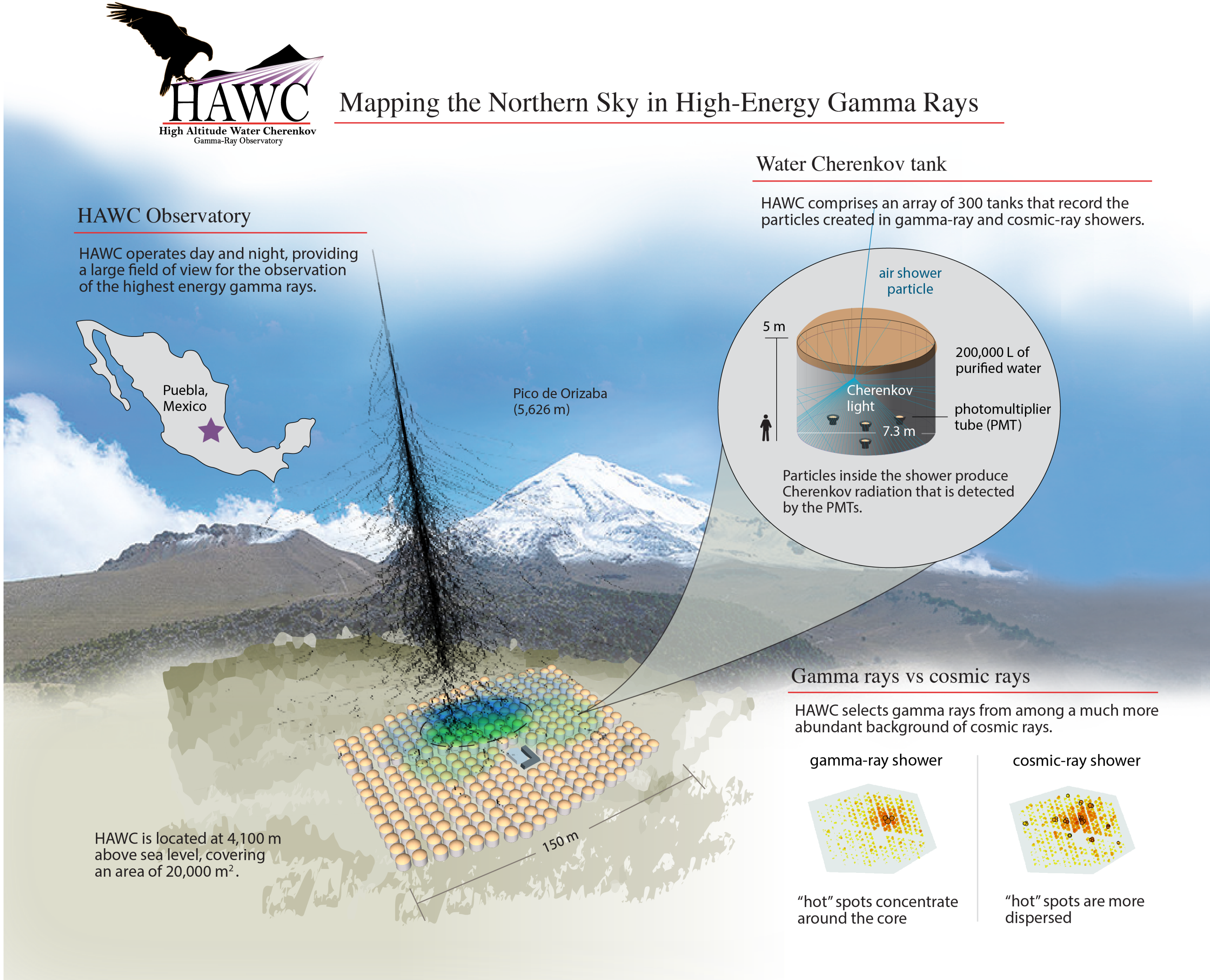
What is a PBH?

- Primordial Black Holes (PBHs) are believed to have been created by density fluctuations in the early Universe
  - PBHs in certain mass ranges proposed as dark matter candidates
- Like all black holes, PBHs undergo Hawking Radiation
- PBHs could be as large as supermassive black holes or as small as the Planck scale
  - PBHs with an initial mass of $\sim 5 \times 10^{14}$ g are expected to be expiring today, emitting a burst of gamma rays in HAWC's energy range (GeV—TeV) during the final seconds of their lives

The HAWC Observatory

- HAWC's wide field-of-view, day & night, eliminates the statistical restrictions other detectors may experience

- Previous approaches using Milagro (and early HAWC) data were not optimized for PBHs



HAWC Blind Transient Search

All-sky transient search

- 2.1° x 2.1° bins in right ascension and declination
- Sliding time windows of length 0.2, 1, and 10 seconds
- Stores the probability value (p-value) for all events that pass a reporting threshold

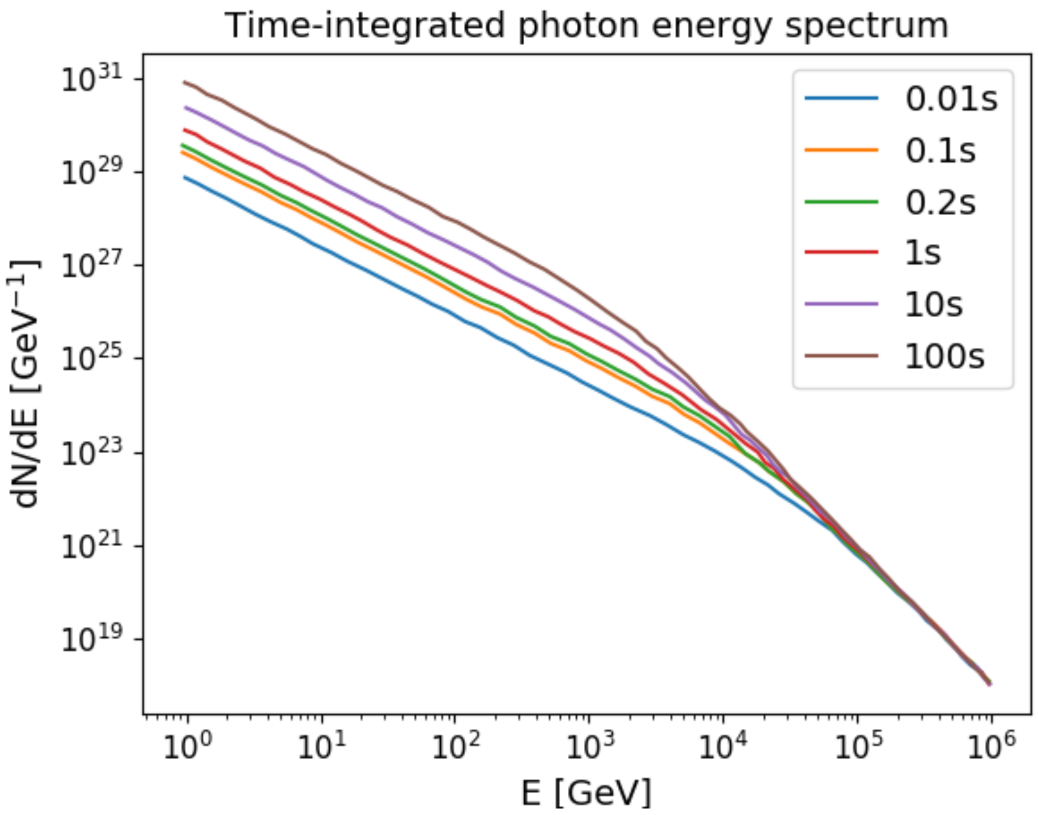
This PBH Analysis

- Designed based on the format of the transient search data
- Uses 3 years of HAWC data
- No significant detection → places an upper limit

PBH Energy Spectrum

$$\frac{dN_\gamma}{dE_\gamma} \approx 9 \times 10^{35} \begin{cases} \left(\frac{1GeV}{T}\right)^{3/2}\left(\frac{1GeV}{E_\gamma}\right)^{3/2} & GeV^{-1} for E_\gamma < T \\ \left(\frac{1GeV}{E_\gamma}\right)^{3} & GeV^{-1} for E_\gamma \geq T \end{cases}$$

$$T \simeq \left[4.8 \times 10^{11}\left(\frac{1sec}{\tau}\right)\right]^{1/3} GeV$$



Adapted from arXiv:1510.04372

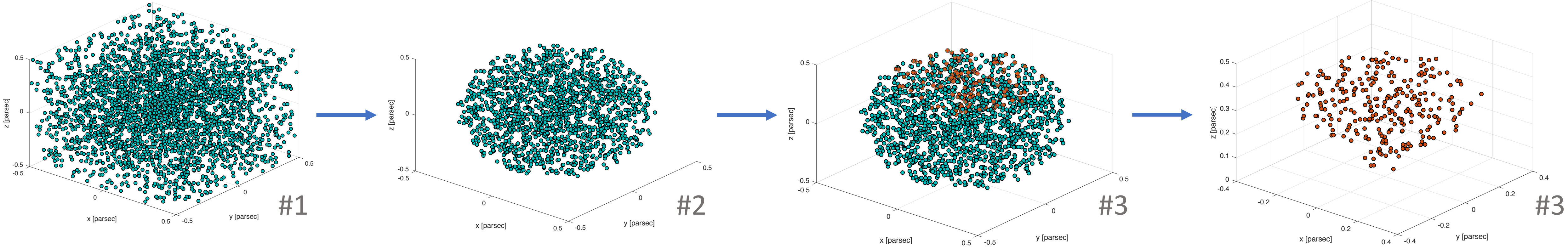
Our Analysis

1. Simulate PBH burst source points in HAWC's FoV
2. Use software to determine expected signal at HAWC from each of these points
3. Combine with "burst" data and background from blind transient search to form a model and calculate log likelihoods
4. Calculate a test statistic and iterate analysis over the burst rate to determine the 99% CL upper limit

PBH Source Point Monte Carlo

1. Generate points uniformly in x, y, and z
2. Throw out points with $r = \sqrt{x^2 + y^2 + z^2} > 0.5$ pc
   - Creates uniform sphere
3. Throw out points with zenith angle $\theta > 50°$

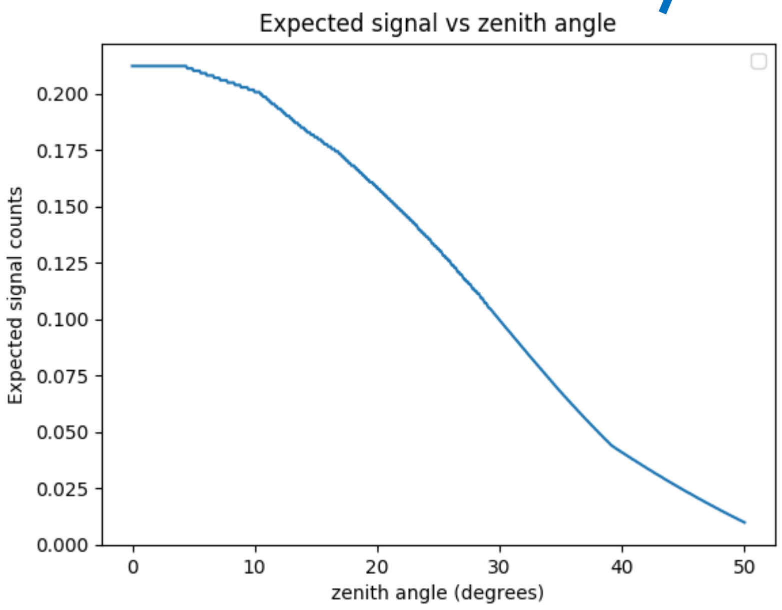
➡ **Results in 18% of events in HAWC's FoV**

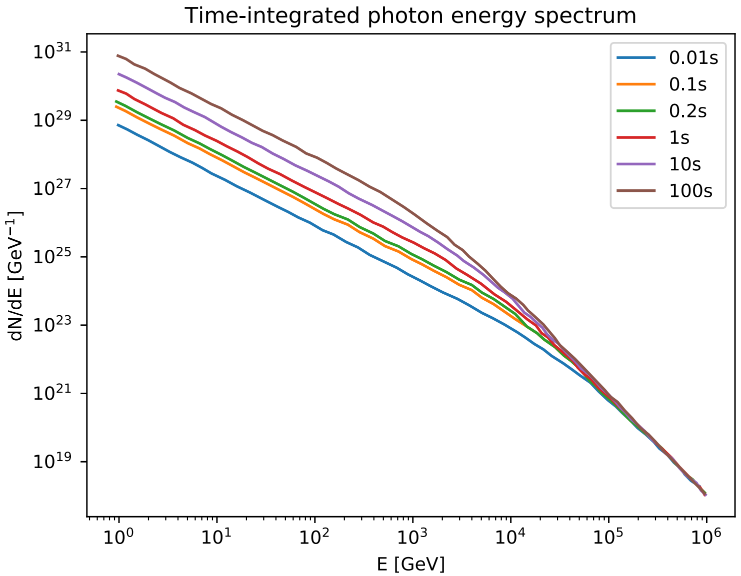


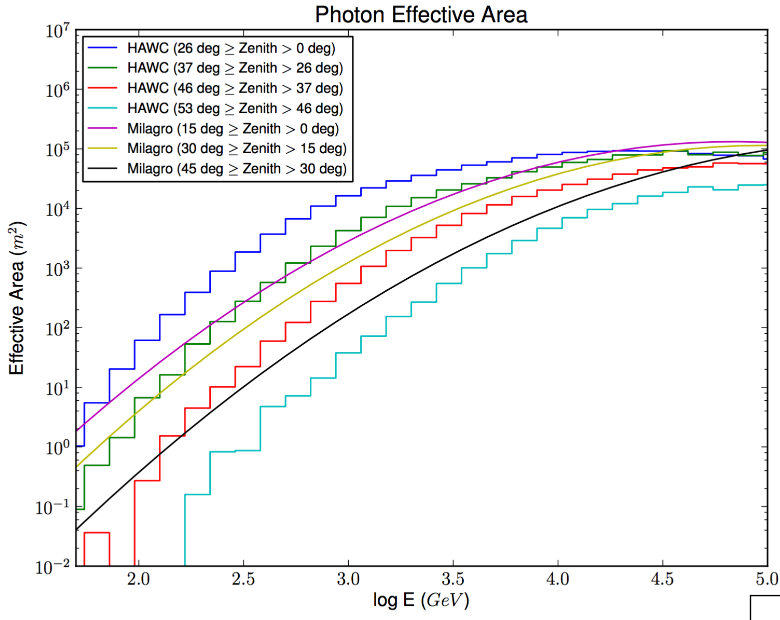
Estimating Photons from a PBH in HAWC

- The number of expected photons from a PBH can be expressed in terms of the PBH spectrum and the effective area of the detector (convolved using internal HAWC software)

$$\mu(r,\theta,\tau) = \frac{1}{4\pi r^2}\int_{E_1}^{E_2} \frac{dN(\tau)}{dE} A(E,\theta)\, dE$$







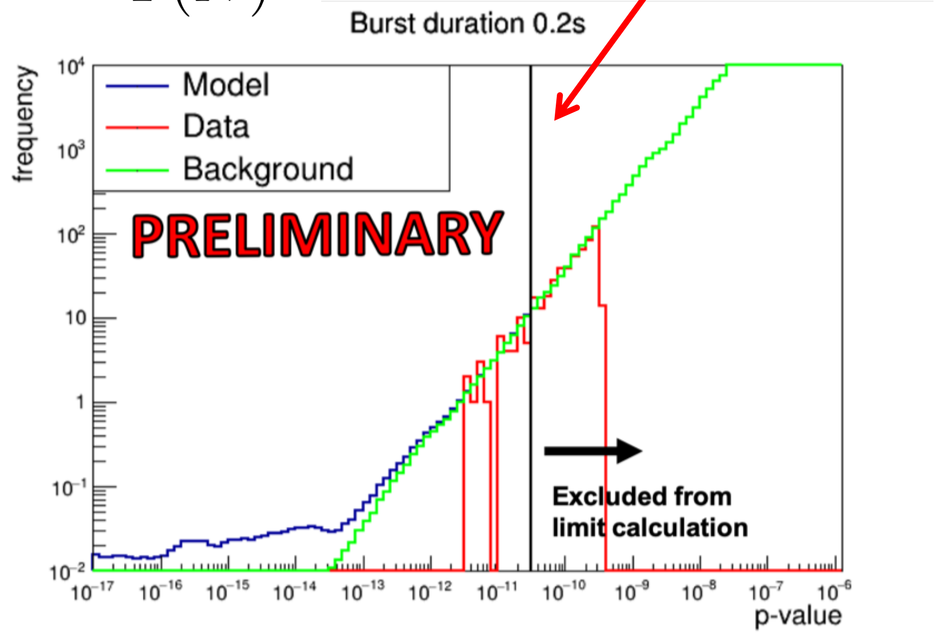
arXiv:1407.1686

Building a Model

- Using the expected signal, $\mu(r,\theta,\tau)$, we can calculate the probability of obtaining N counts given the background, B, for each event (the "p-value")

$$prob(\geq N) = \sum_{i=N}^{\infty} \frac{B^i \exp(-B)}{i!} = 1 - \frac{\Gamma(N,B)}{\Gamma(N)}$$

p_{thresh} cutoff



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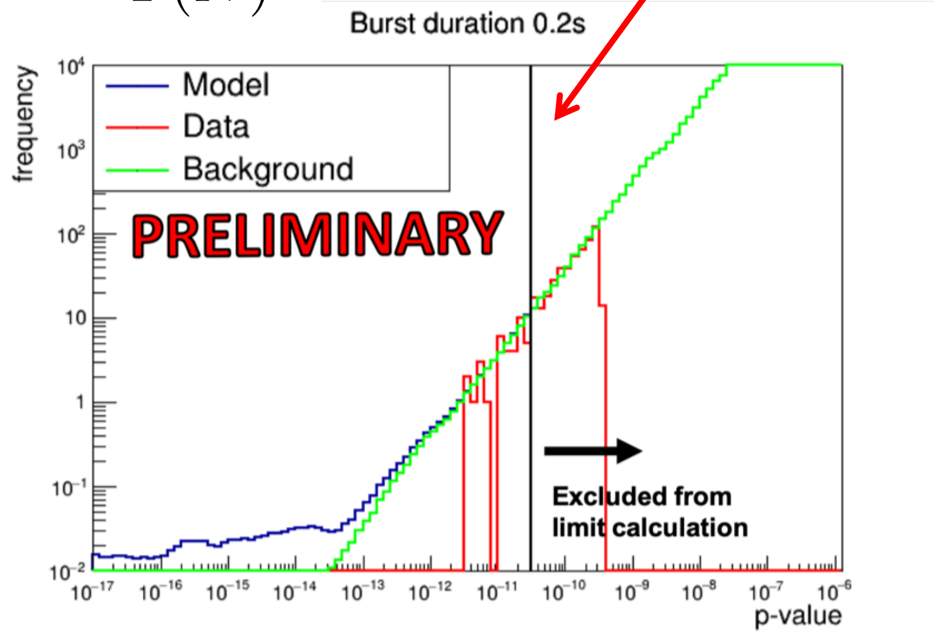
$H_{pbh}(p)$

p_{thresh} cutoff



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$H_{pbh}(p)$

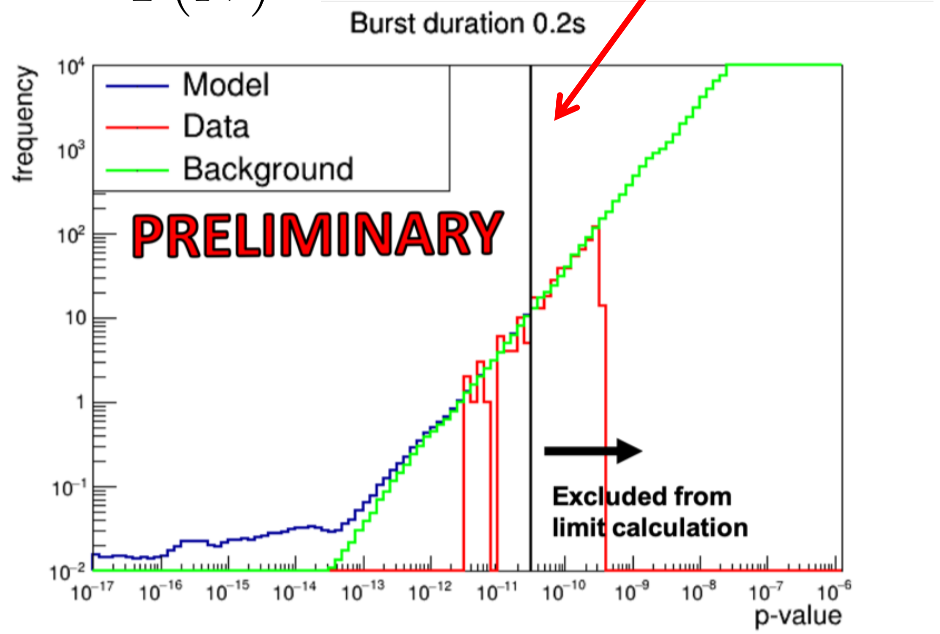
- Calculate H_{model}, defined as:

$$H_{model}(p) = H'_{bkg}(p) + H'_{pbh}(p)$$

PBH distribution scaled to search time and burst rate

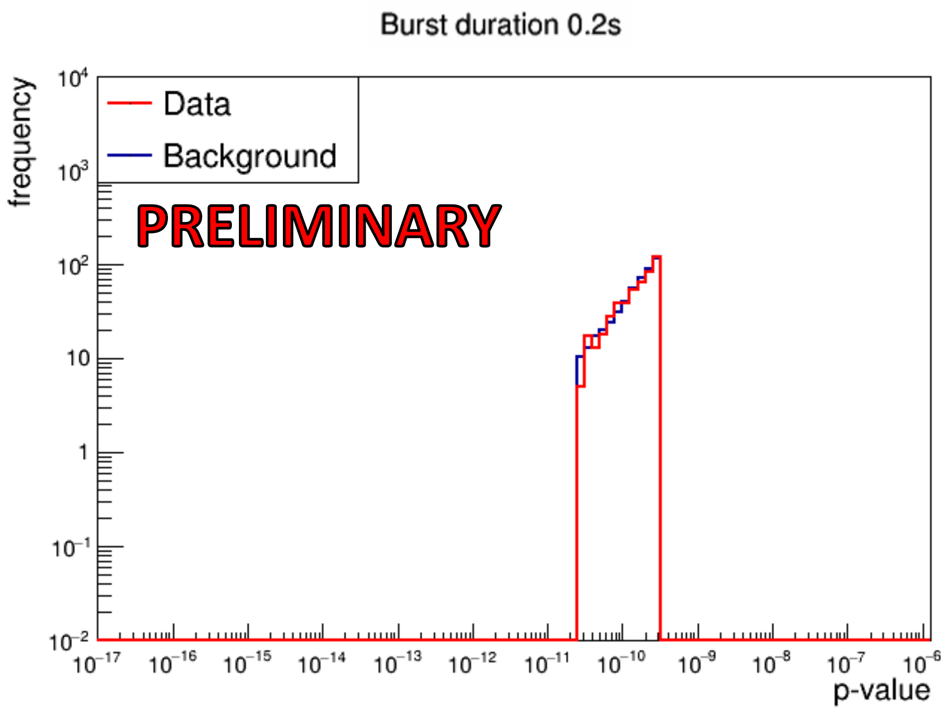
Background distribution scaled to the time of the searched data

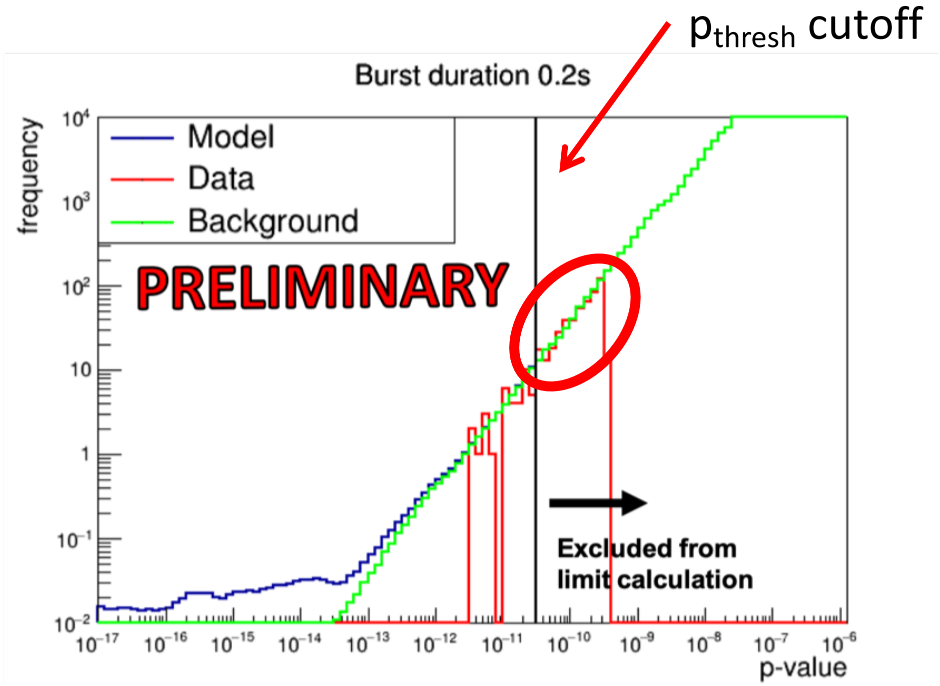
p_{thresh} cutoff



Fiducial Region

- Above our passing threshold (p_{thresh} cutoff), we have a fiducial region in which we can verify independently of the analysis that our background and data are statistically equivalent





Calculating Upper Limits

For each value of D (the PBH burst duration):

1. Calculate the background Poisson log-likelihood

$$\ln \mathcal{L}_0 = \sum_p [H_{data}(p) \ln\left(H'_{bkg}(p)\right) - H'_{bkg}(p)]$$

Observed "bursts" from GRB transient search

Background distribution scaled to the time of the searched data

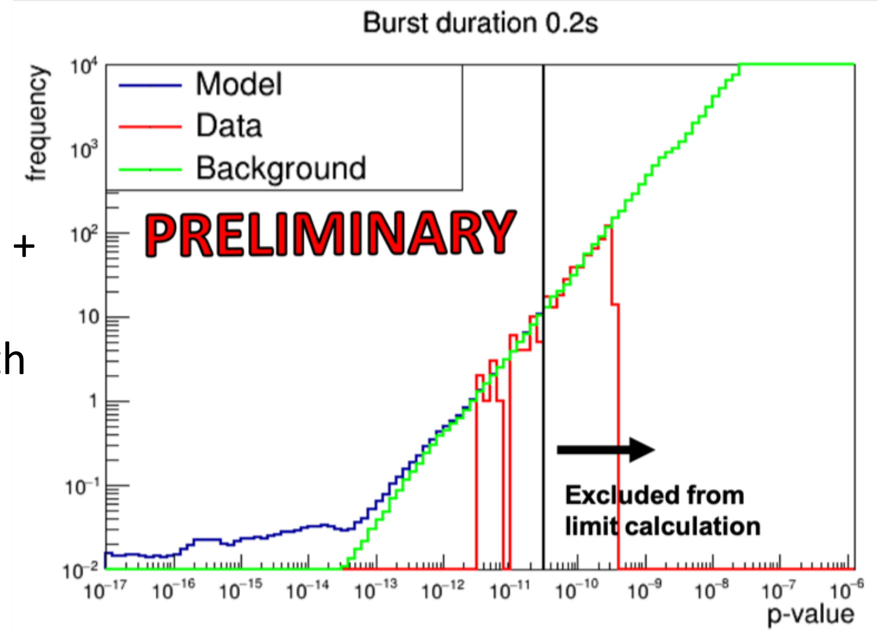
2. Calculate the model Poisson log-likelihood

$$\ln \mathcal{L}_1 = \sum_p [H_{data}(p) \ln(H_{model}(p)) - H_{model}(p)]$$

Observed "bursts" from GRB transient search

PBH distribution + background distribution (both scaled)

*factorial term neglected as it will cancel out later



Calculating Upper Limits

For each value of D (the PBH burst duration):

3. Define a test statistic (from Wilks' Theorem), and calculate for the rate of PBH bursts, R, being evaluated

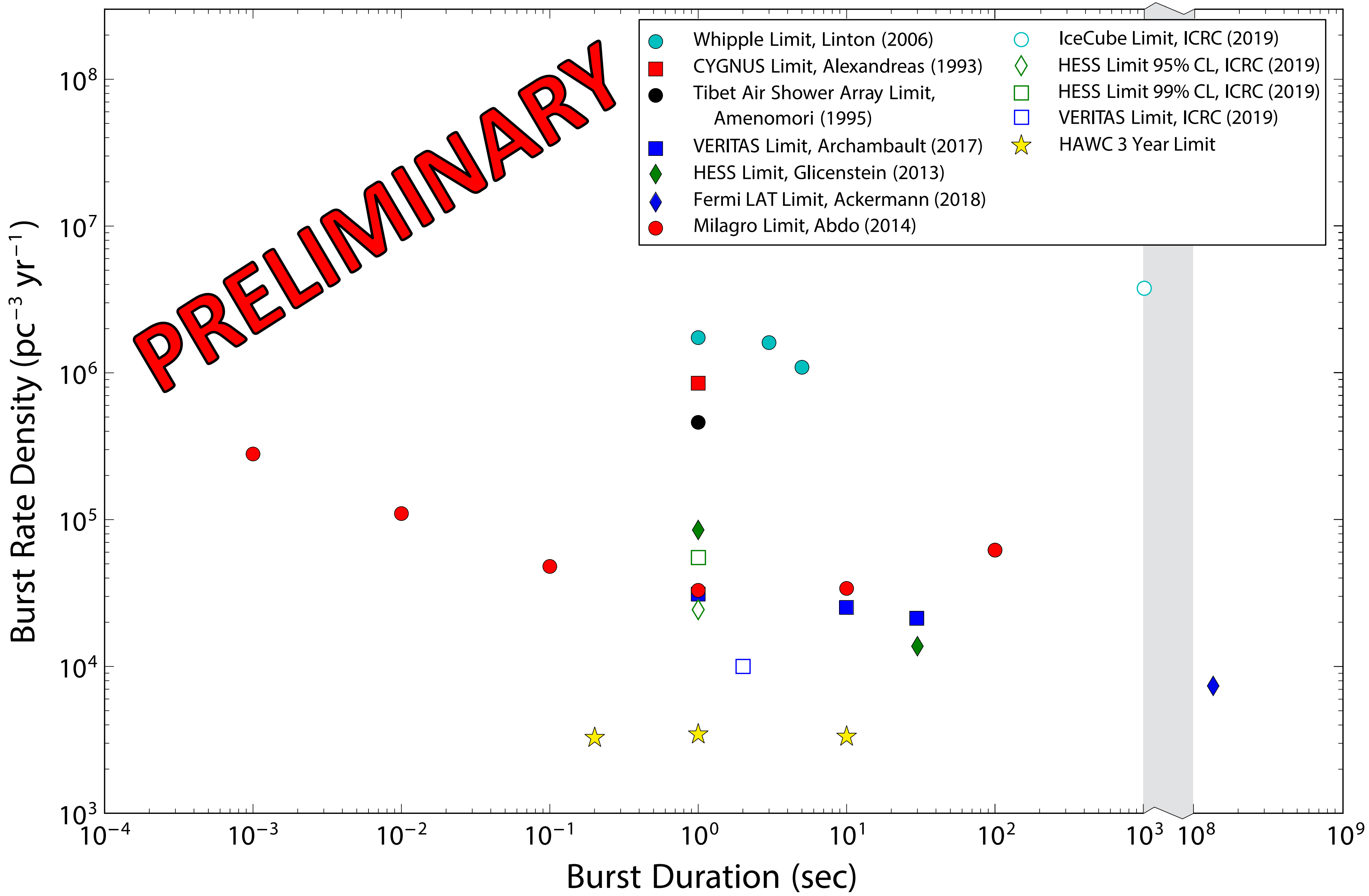
$$TS = 2\left[\ln \mathcal{L}_1 - \ln \mathcal{L}_0\right]$$

Find the largest possible value of TS: TS_{max}

4. Iterating over R, the burst rate that satisfies the TS value corresponding to a 99% confidence level is the upper limit

$$TS_{99} = TS_{max} - 5.41$$

PBH Burst Rate Density Upper Limits



Results

Experiment	Burst Rate Upper Limit	Optimal Search Duration	Reference
Milagro	36000 $pc^{-3}\ yr^{-1}$	1s	Abdo et al., 2014
VERITAS	22200 $pc^{-3}\ yr^{-1}$	30s	Archambault et al., 2017
H.E.S.S.	14000 $pc^{-3}\ yr^{-1}$	30s	Glicenstein et al., 2013
Fermi-LAT	7200 $pc^{-3}\ yr^{-1}$	1.26×10^8 s	Ackermann et al., 2018
HAWC 3 yr.	3300 $pc^{-3}\ yr^{-1}$	0.2s	This Work

Summary

- Using 3 years of HAWC data, we have placed an upper limit on the local burst rate density of PBHs as $\dot{\rho} > 3300\ pc^{-3} yr^{-1}$
  - This is the most constraining limit to date

Future Work

- Immediate Future:
  - Statistical uncertainties
  - Systematics
- Extended Outlook:
  - Independent PBH study

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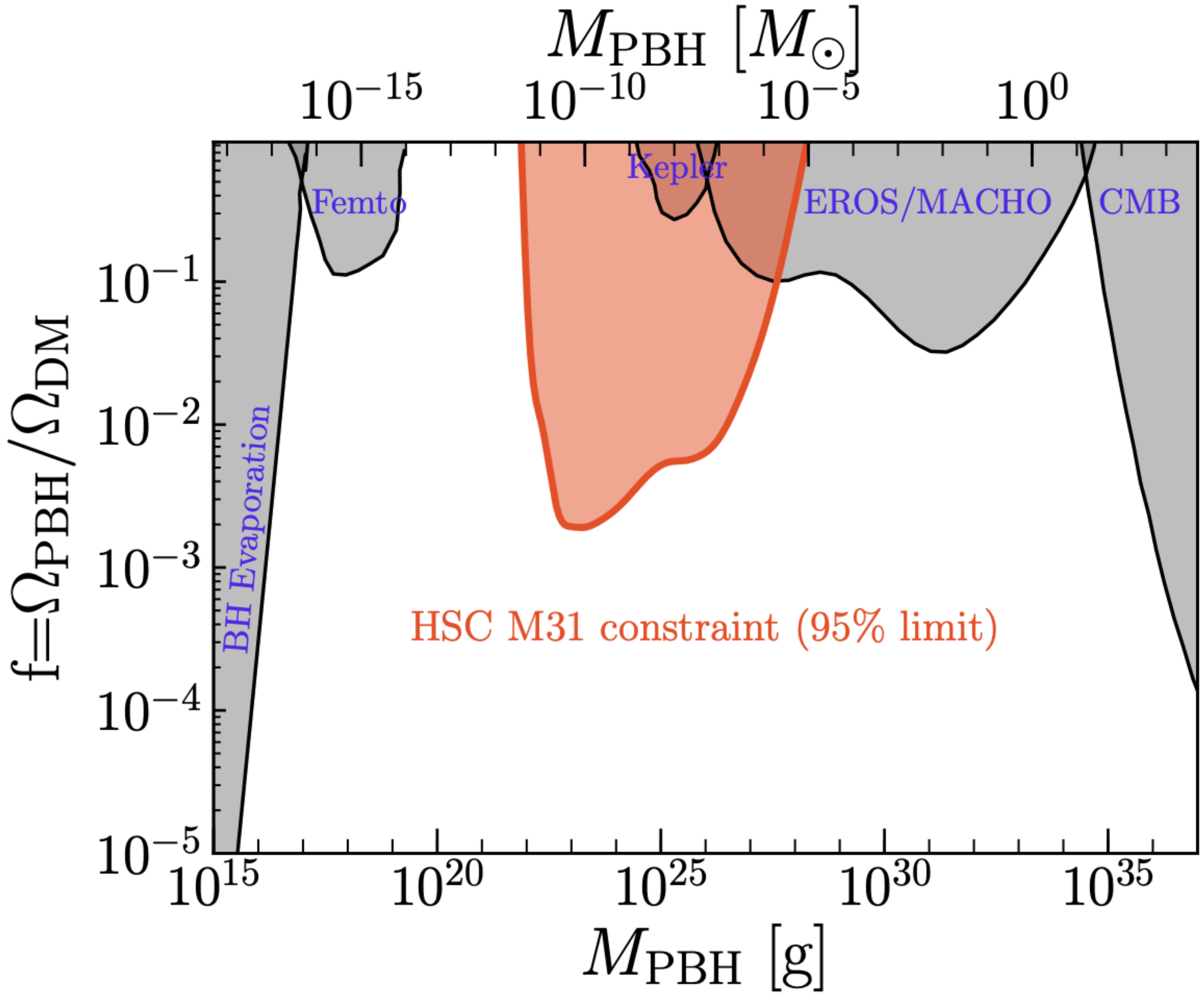
BACKUP

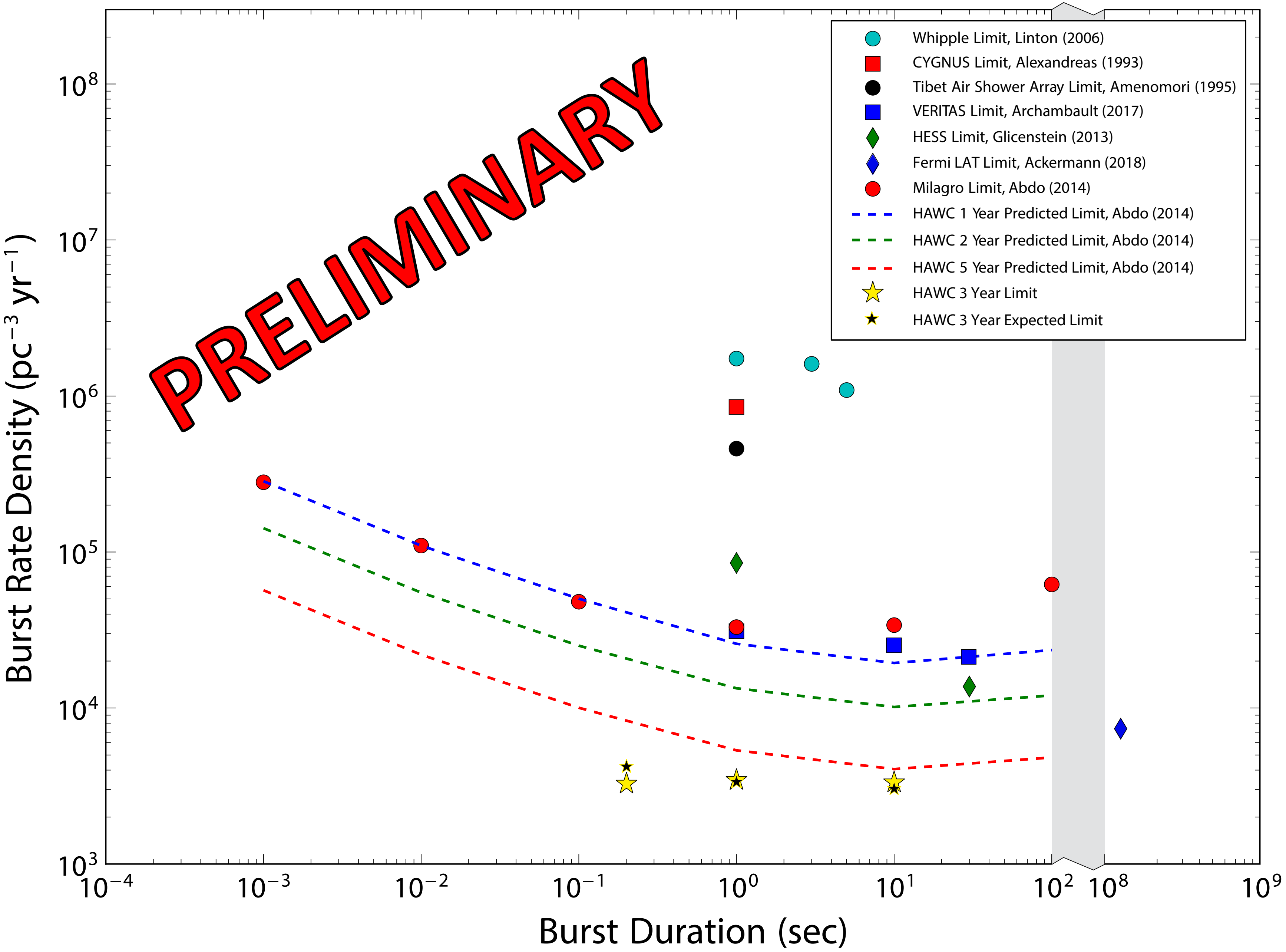
Dark Matter Fraction w.r.t. PBHs



arXiv:1701.02151

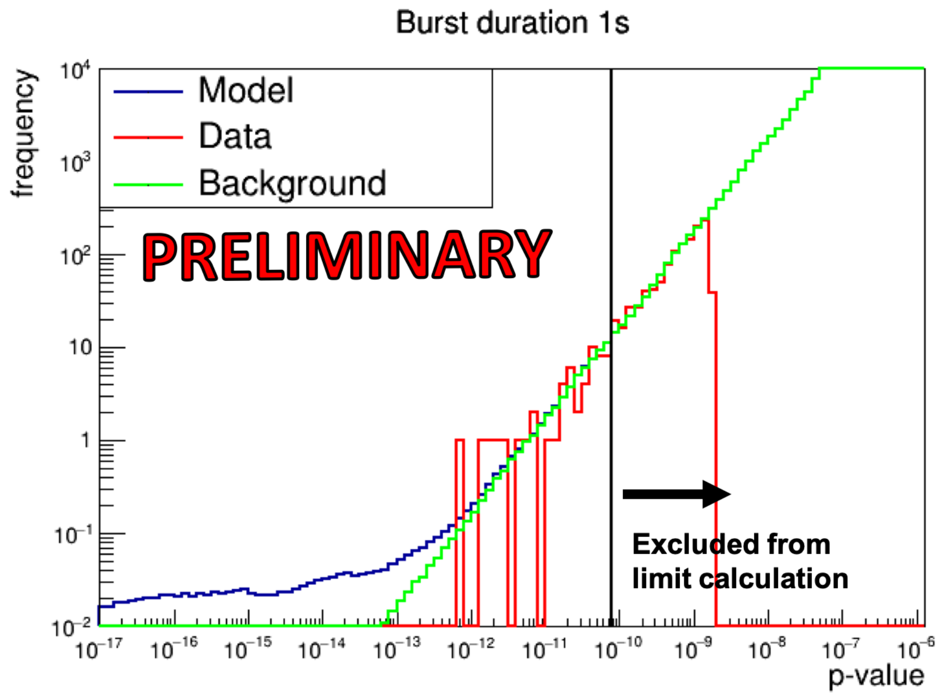
B1

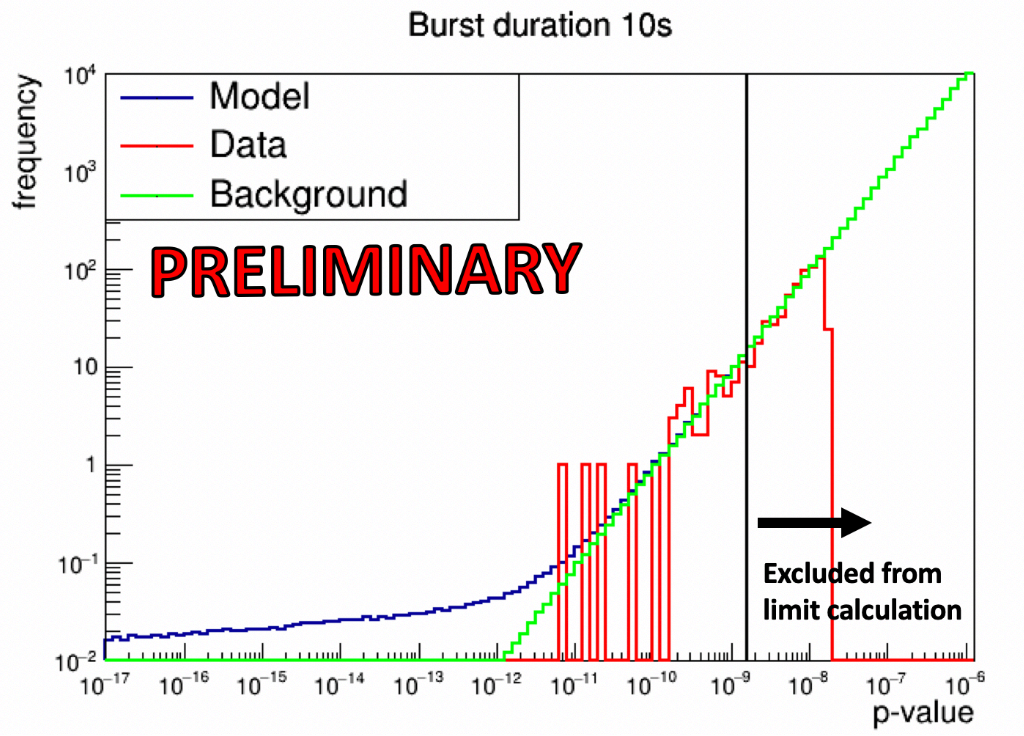
PBH Burst Rate Density Upper Limits



B2

Building a Model –
Other Durations to Search

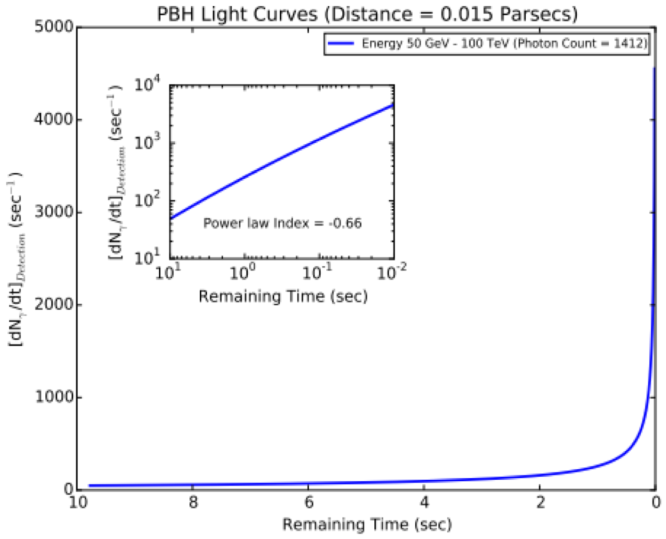




Data exclusion region based on where our data and Monte Carlo background were in agreement; chosen to be BG = 10 counts for all three durations for consistency.

PBHs vs. GRBs

- Optimize data from a previous HAWC Gamma-Ray Burst (GRB) analysis
- PBHs we're looking for are more analogous to short GRBs
- PBHs have a harder spectral index than GRBs
  - This means it is more plausible that HAWC would see a PBH burst than a GRB



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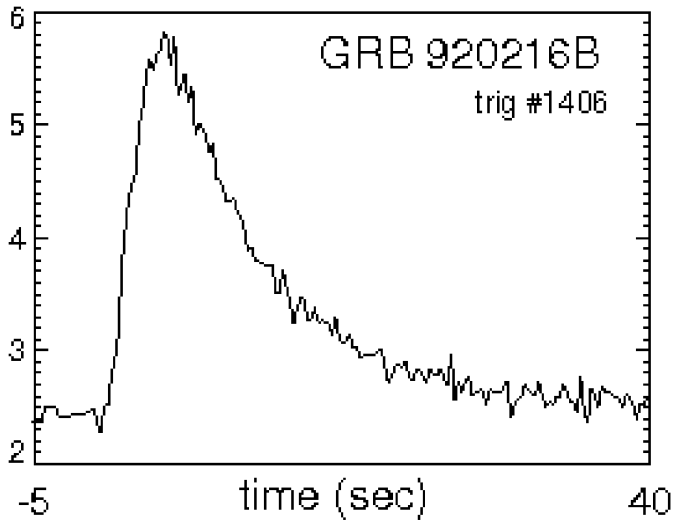

arXiv:astro-ph/9903205

Radial Distance and Significance

- Confirmed that past 0.5 pc, even if located at HAWC's zenith, the signal from a potential PBH was not significant enough to contribute to this limit