Primordial Black Hole Bursts

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An update on PBH phenomenology *and* using it to improve sensitivity of searches

Collaborators:

MSU HAWC group + theorists

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(phenomenology work)

And

The HAWC Collaboration

(latest sensitivity estimates)

What are Primordial Black Holes (PBHs)?

Primordial = **created in early universe** when horizon ≤ BH size

PBH with initial mass ~ 5 x10^{11} kg are evaporating in the present epoch
created ~ 10^{-23} s after big bang (other masses not evaporating now)
BHs from SNe too long-lived to evaporate now

Hawking: a Black Hole has Temperature ~ 1/Mass

Remaining Lifetime

$$M(\tau) = 1.36\ 10^{6}\ \text{kg}\ (\tau/1\text{s})^{1/3}$$

Black Hole Temperature

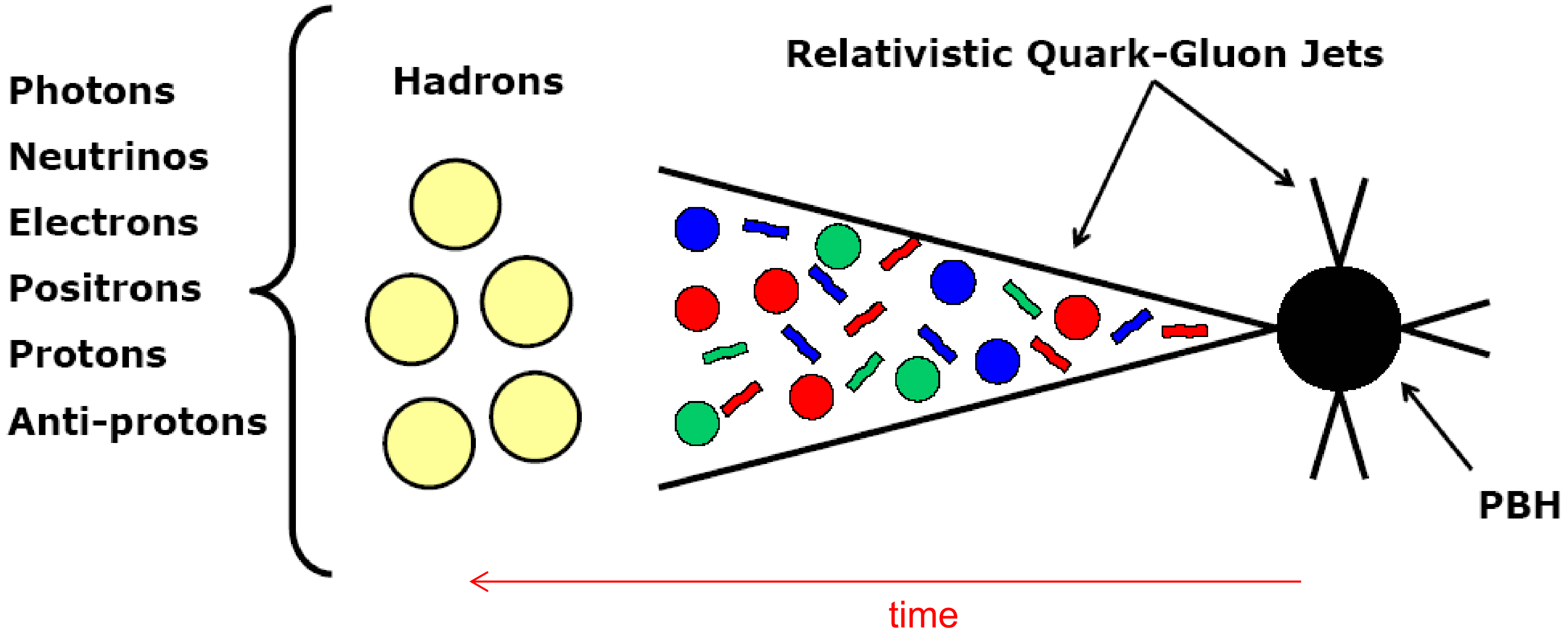
$$kT_{BH} = 7.8\ \text{TeV}\ (1\text{s}/\tau)^{1/3}$$

Black holes thermally emit any fundamental particles whose rest mass is comparable to the black holes' temperature, or smaller.

This emission means that BH's have a finite lifetime.

Final seconds of a black hole is a burst of high energy particles.

Primordial Black Hole Evaporation



When the temperature of the PBH goes above the Quantum Chromodynamics (QCD) confinement scale (250-300 MeV) the PBH starts to emit quarks and gluons. Each produces a jet of light particles very similar to jets produced in particle accelerators.

PBH in Various High-Energy Models

PBH evaporation rate is proportional to the number of available particle degrees of freedom (e.g. spin, charge, color)

Details of the final emission depends on the high energy model

kT (in TeV) vs. remaining time:

	600 s	100 s	30 s	10 s	1 sec	30ms	10ms
Standard Model	.91	1.7	2.5	3.6	7.8	25	35
500 GeV SUSY	.87	1.4	2.1	2.9	6.2	20	29

Another often-cited model is the Hagedorn Model which prescribes an exponentially increasing number of hadronic resonances.

Does not describe hadron spectrum at hadron colliders, nor in heavy ion collisions. **Thus use Standard Model emission here.**

Direct Search Strategy

HAWC, IACTs, Fermi: look for TeV/GeV γ rays

multiple photons clustered in space and time (at PBH position)

γ threshold ~TeV and thus kT ~ TeV

This sets τ ~ seconds to minutes

Choose search window $\Delta t \sim \tau$: final seconds of burst

most direct form of BH burst search (PBH or newer BH)

Limits *local* density of PBH bursts/year

only nearby PBH bright enough to emit multiple TeV photons

scale of a few parsecs

sensitive to *local* clumping

not the average galactic (dark matter-like) profile

(this has tighter limits from MeV γ, and antiprotons: most DM isn't PBH)

Photon Emission(E, t)

$\frac{d^2N}{dEdt}$ = function(x), $x = E/kT$ (here $E = E_{quark}$)

kT(τ) defines entire time dependence

E_{quark} peaks at 4.5 kT

$q \rightarrow \pi^o$ fragmentation (take $g \rightarrow \pi^o$ to be the same)

$D(z) = z^{-3/2}(1-z)^2$ $z = E_\pi / E_{quark}$

$\pi^o \rightarrow \gamma\gamma$ decay changes spectra only slightly

photon emission is then a function of

$$\xi_\gamma = E_\gamma / kT$$

below kT, dominated by $E_\gamma^{-3/2}$ (from D(z))

at higher $E\gamma$, see direct photon emission $E\gamma$ peaks at 6 kT

integrating over $E\gamma$

$$\boxed{dN/dt = A\,\tau^{-1/2} \quad (\gamma \text{ chirp})}$$

Parameterization of γ Emission

From quarks near peak

$$\left(\frac{d^2N_\gamma}{dE_\gamma dt}\right)_{\text{frag.}} = 6.339\times 10^{23}\,(\xi_\gamma)^{-3/2}[1-\Theta_S(\xi_\gamma-0.3)]$$

$$+\,1.1367\times 10^{24}\,\exp(-\xi_\gamma)[\xi_\gamma(\xi_\gamma+1)]^{-1}\,\Theta_S(\xi_\gamma-0.3)\ \text{GeV}^{-1}\ \text{s}^{-1}$$

Thermal tail of quarks above peak

$$\Theta_S(\lambda) = 0.5[1+\tanh(10\,\lambda)]$$

Soft step function

Thermal γ's about their peak

$$\left(\frac{d^2N_\gamma}{dE_\gamma dt}\right)_{\text{direct}} = 1.13\times 10^{19}(\xi_\gamma)^6(\exp(\xi_\gamma)-1)^{-1}\times F(\xi_\gamma)\ \text{GeV}^{-1}\ \text{s}^{-1}$$

$$F(\xi_\gamma) = 1.0\ \text{ for } \xi_\gamma \le 2$$

$$F(\xi_\gamma) = \exp([-0.0962-1.982(\ln\xi_\gamma-1.908)][1+\tanh[20(\ln\xi_\gamma-1.908)]])\ \text{ for } \xi_\gamma > 2$$

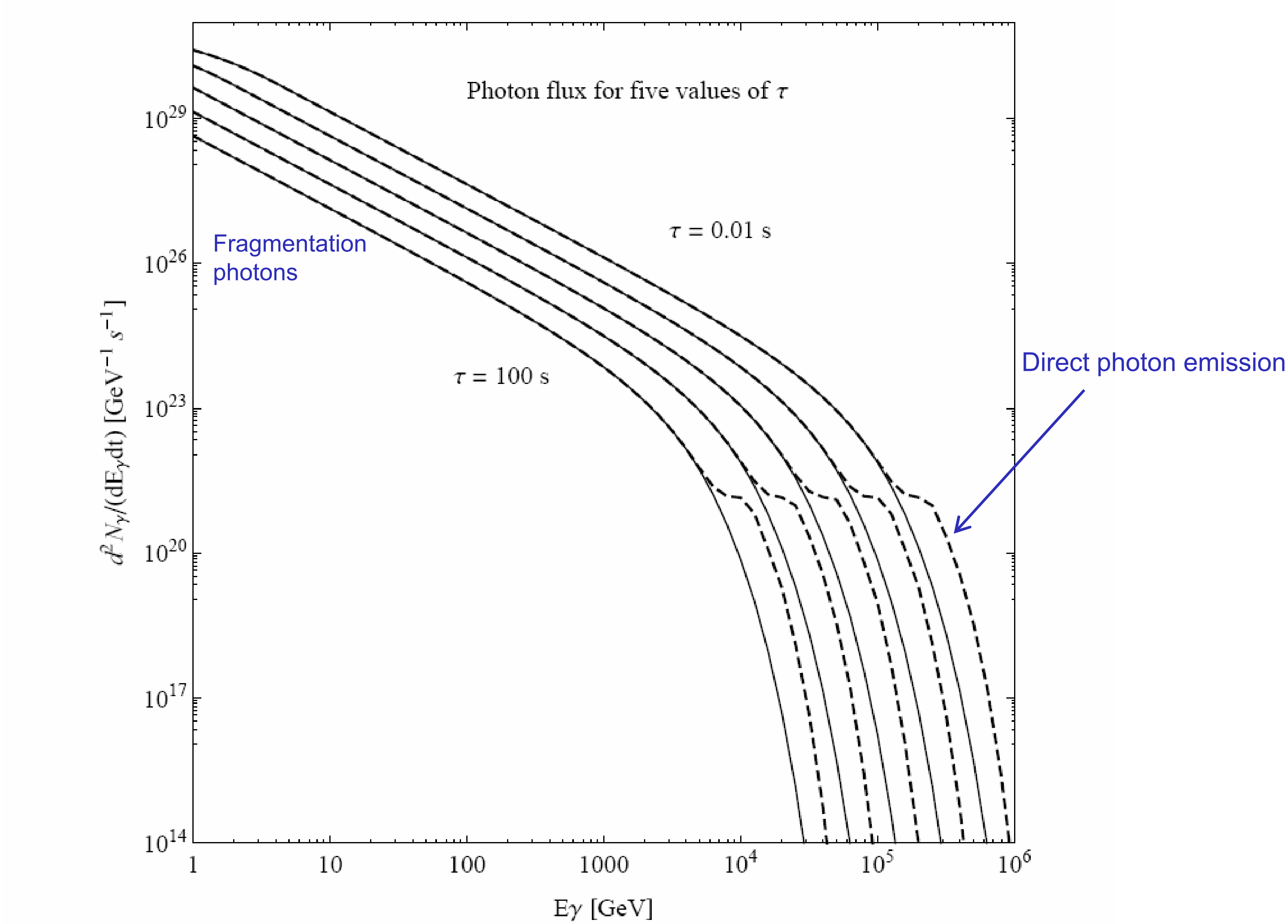
Soft step function

Parameterization is continuous

<5% error away from kT; < 30% nearer kT (oscillations)

Systematics could be up to 50%: D(z,Q), heavy quarks

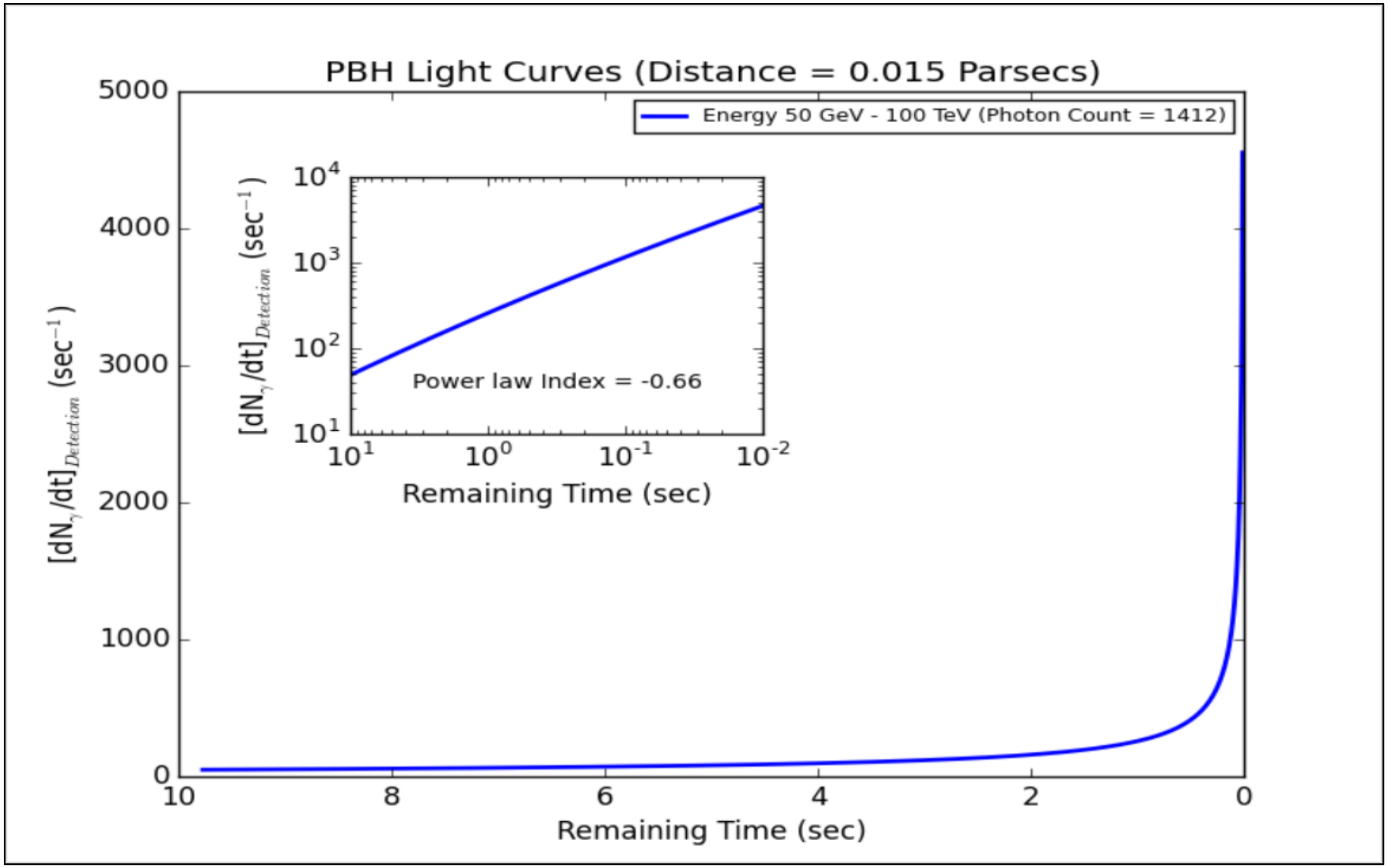
Energy Spectra (Emitted)



(HAWC Detected) Time Structure

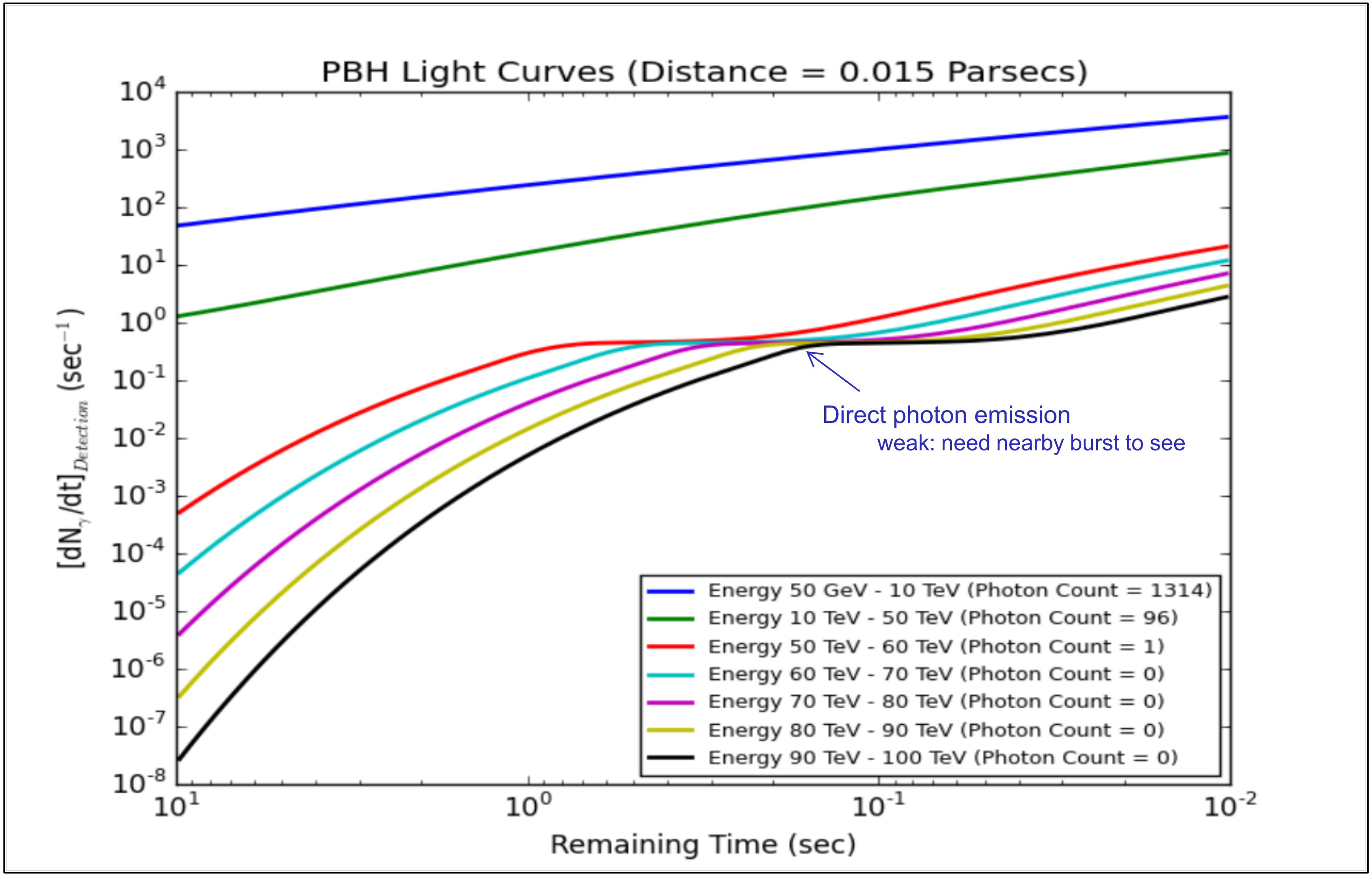
approximate power law;

effective area steepens power law from -1/2 to – 2/3

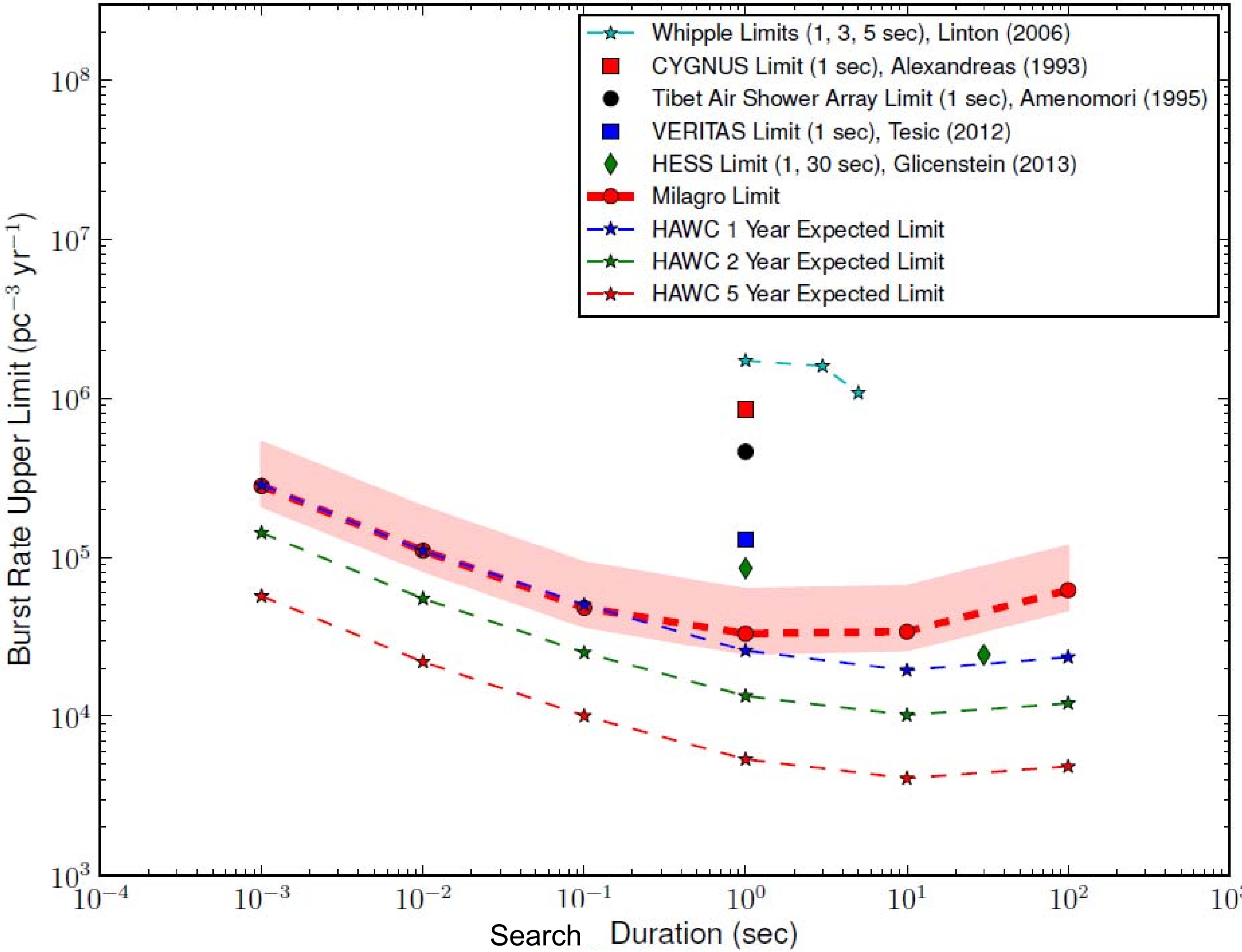


At high energies, time structure changes

start seeing direct emission



PBH Burst Rate Density Upper Limits from Milagro and projected for HAWC



Optimum HAWC search longer than Milagro's

Abdo et al, Astroparticle Physics 64 (2015) 4-12 (Milagro limit, HAWC sensitivity)

Time-Binned Likelihood Search

- We can attempt to utilize the expected time distribution of the signal photons to improve the search sensitivity.
- Construct log likelihood ratio to use as test statistic (fitting for signal amplitude):

$$\ln \lambda = \sum_{i=1}^{k} c_i \ln \left(1 + \frac{f_i S}{b} \right) - S. \tag{5}$$

- Preliminary analysis indicates a factor of 1.5 improvement in the burst-rate-density upper limit using this technique.

Improvements in Progress

compared to HAWC sensitivity paper

HAWC **hadron rejection** cuts:

optimize for event size (fraction of tubes hit)

lower background improves sensitivity

estimated improvement x 1.3 in limit

may make optimum search window longer?

ML fit using PBH time (and possibly energy) shape

x 1.5 in limit, possibly more

Tuning of statistical exclusion methods?

Combined, x2 or more improvement for HAWC limits is plausible

Analysis of early HAWC data is under way.

Likely HAWC PBH Search Strategy

Expect an “offline” search

Starting points:

- Low-E GRBs (SWIFT, Fermi, …)
  - look for cluster nearby in time
- HAWC untriggered GRB search candidates
  - search for clustering on various time scales
    - use a loose GRB selection
    - then apply PBH criteria

Differences between GRBs and PBH bursts

Gamma-ray Bursts (GRB)	PBH Bursts (PBHB)
Detected at cosmological distances	Unlikely to be detected outside our Galaxy
Softer spectrum; possible EBL cutoff	Harder spectrum
Most GRBs show hard-to-soft evolution	Soft-to-hard evolution is expected from PBHB
Hadrons are not expected from GRBs	Hadronic bursts may reach earth
Gravitational Wave signal is expected	No gravitational wave signal is expected
Time duration can range from fraction of second to few hours	Time duration of the burst more like seconds than hours
Fast Rise Exponential Decay (FRED) light curve	Exponential Rise Fast Fall (ERFF) light curve
X-ray, optical, radio afterglows are expected	No TeV or multi-wavelength afterglow is expected
Multi-peak time profile	Single-peak time profile

Summary and Conclusions

HAWC has the ability to directly detect emission from nearby PBH bursts in the TeV

With a null detection in 5 years, HAWC will be able to set upper limits which are significantly better than any previous direct search limits

HAWC will pass the current HESS limit in one year

Published expected limits are conservative
we might be able to do much better

Phenomenology paper in progress
short version at arXiv:1507.01648 (ICRC '15)

Backup

What are Primordial Black Holes (PBHs)?

Time since the Big Bang

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

Mass of the Black Hole

• They can have masses ranging from Planck mass (10^{-5} g) corresponding to Plank time (10^-43 sec) to ~10^5 M_{sun} corresponding to 1 sec after the big bang.

• In contrast, black holes forming at the present time cannot have masses less than M_{sun} except maybe at CERN. But direct burst searches also set limits on any light BH's bursting at present.

Page Function

$$\frac{d^2N}{dEdt} = \frac{\Gamma/2\pi\hbar}{e^x - (-1)^{2s}}\, n_{\mathrm{dof}}$$

$$x \equiv \frac{8\pi GME}{\hbar c^3} = \frac{E}{kT_{BH}}$$

$$\Gamma(M, E, s) = 27\left(\frac{x}{8\pi}\right)^2 \gamma_s(x)$$

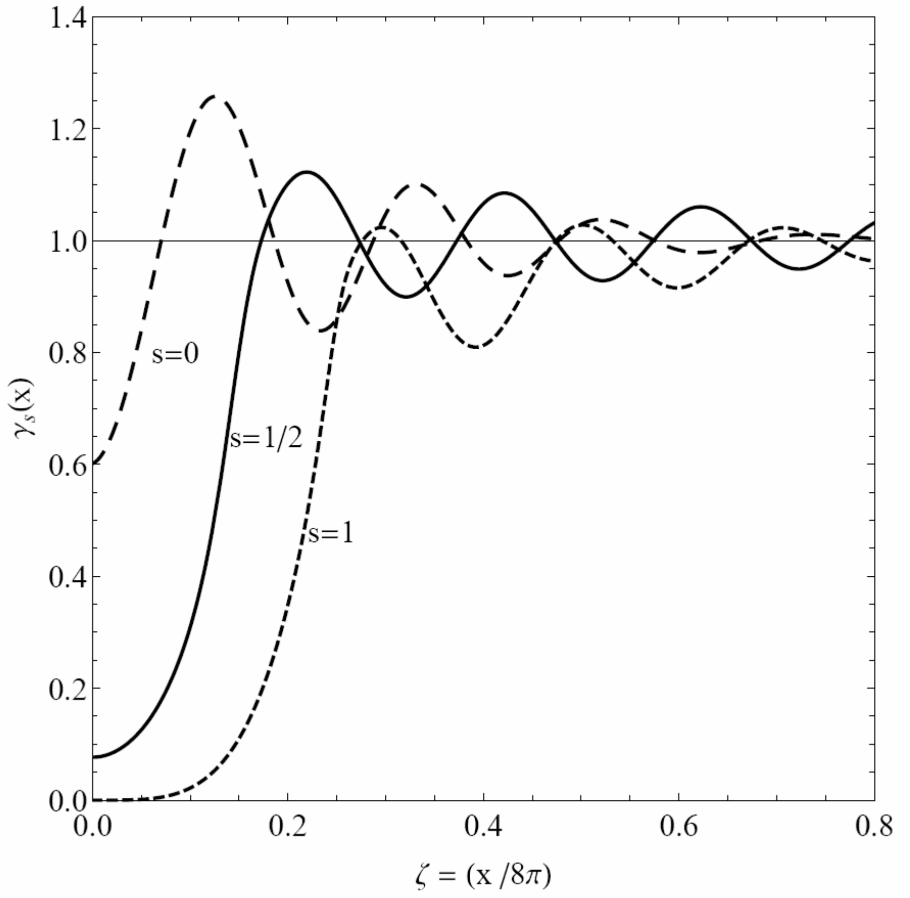
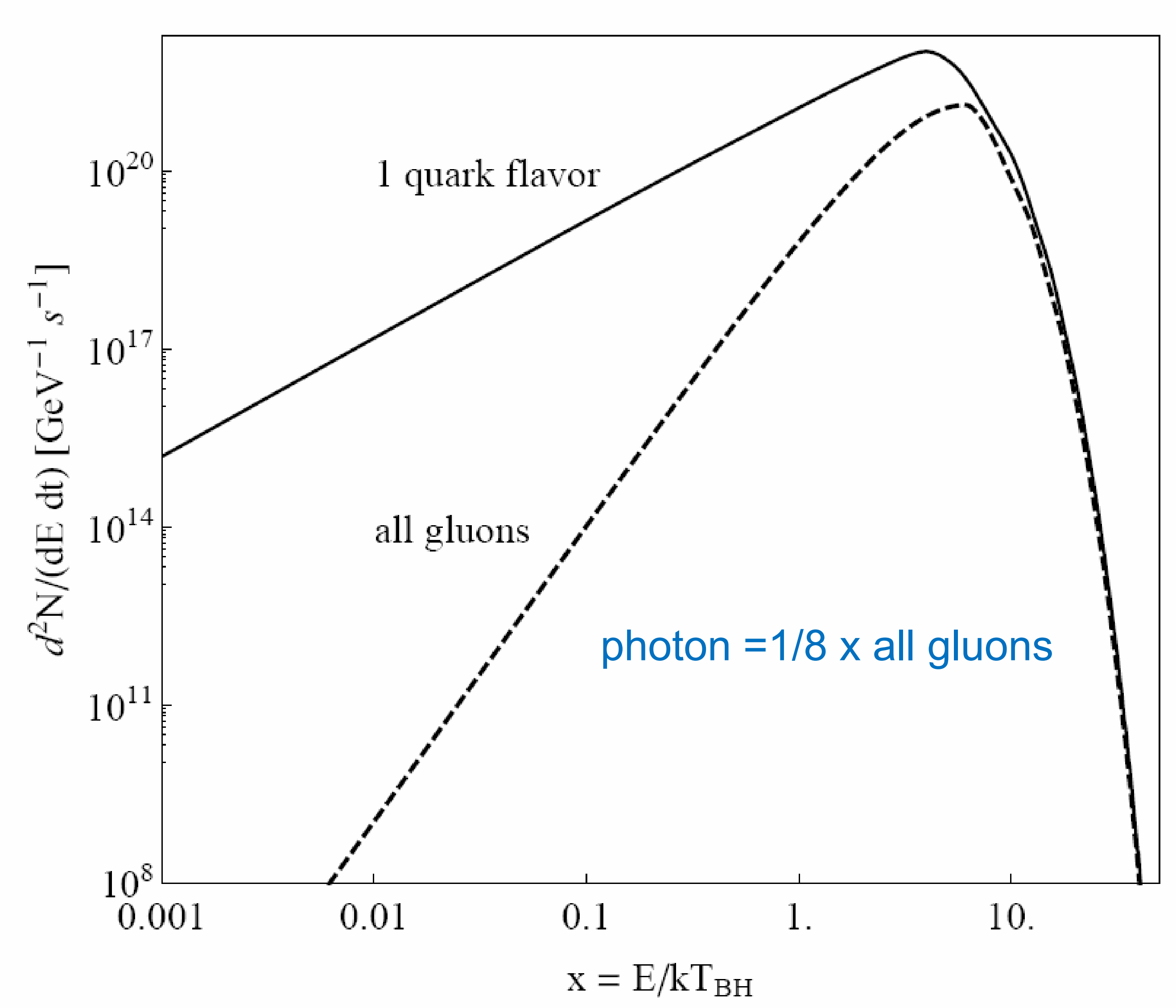


Figure 1: The functions $\gamma_s(x)$ for massless spin-0, spin-1/2 and spin-1 particles.

Direct Radiation



Background Rate Calculation

ATIC Flux

$$\frac{dN_p}{dE} = 7900 \times E^{-2.65} \quad \text{particles m}^{-2}\text{s}^{-1}\text{Sr}^{-1}\text{GeV}^{-1}$$

Effective Area for Protons

$$\mu_p(\theta) = \int_{E_1}^{E_2} \frac{dN_p}{dE} A_p(E, \theta)\, dE$$

Zenith Angle

$$R_b(\theta, \xi) = \mu_p(\theta) \times 2\pi(1.0 - \cos(\xi)) \times 1.2$$

Background Rate

DelAngle

Correction for other particle species

Upper Limit of Rate Density of PBH Burst

If PBH are uniformly distributed in the solar neighborhood, the X% confidence level upper limit to the rate density of PBH bursts is

Mean number of PBH bursts expected given zero bursts are observed at X% CL

$$UL_X = \frac{m}{V \times P}$$

Detectable Volume

Search Duration (5 years)

For X = 99%,

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

GRBs vs. PBH

Energy spectra of a GRB and PBH burst in HAWC