Primordial Black Holes with H.E.S.S. and beyond

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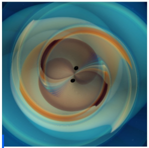
Tribute to Berrie Giebels

Outline

Figure – M.Pallavicini (president) and Berrie (vice president) renew the European Gravitational Observatory consortium (10/2020)



© N. Fischer, H. Pfeiffer, A. Buonanno (Max Planck Institute for Gravitational Physics), Simulating eXtreme Spacetimes (SXS) Collaboration

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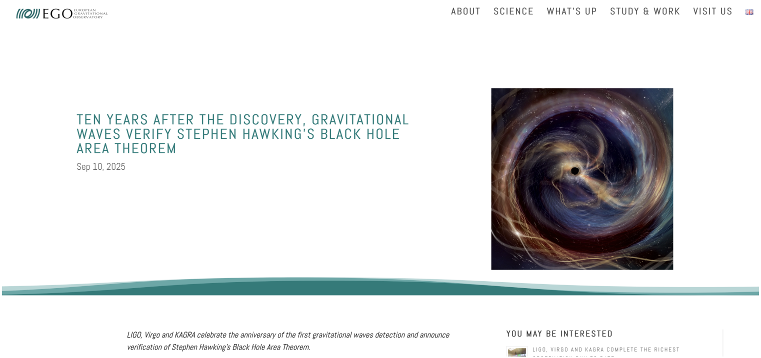
New populations of black holes revealed by gravitational waves

September 02, 2020 | UNIVERSE

The gravitational wave[1] detectors LIGO and Virgo have just chalked up their biggest catch yet, a black hole 142 times the mass of the Sun, resulting from the merger of two black holes of 85 and 65 solar masses. The remnant black hole is the most massive ever observed with gravitational waves, and it could give us some clues about the formation of the supermassive black holes that sit at the centres of some galaxies. The mass of one of the merging black holes, 85 solar masses, provides information that could improve our understanding of the final stages in the evolution of massive stars. The discovery, to which several CNRS teams contributed as part of the Virgo collaboration, is published on 2 September 2020 in the journals *Physical Review Letters* and *Astrophysical Journal Letters*.

PBH candidate



Discoveries by LIGO-VIRGO-KAGRA

- PBH candidates
- First evidences for BH entropy (area law)

- Primordial Black Holes (PBH) could be created by several mechanisms in the early universe.
- These mechanisms include
  - Collapse of overdense regions due to density fluctuations
  - Pressure reduction during cosmic phase transitions (relevant to MACHOs)
- Masses from 10^{-5}g to several tens of $M_{\odot}$.

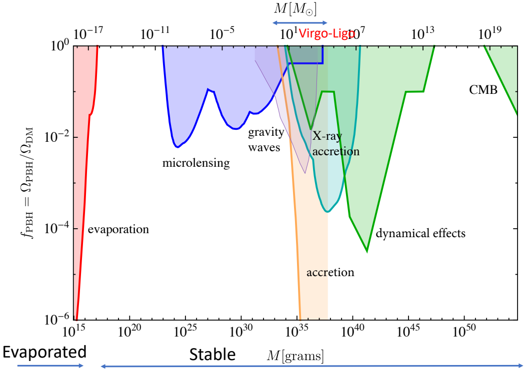


Figure – Current limits on PBH abundance (from B.Carr , F.Kuhnel (2025))

This talk focuses on

- "evaporated" part of PBH mass spectrum
- high energy gamma-ray instruments

Evaporation caused by Hawking temperature of PBH :

$$T_{\mathrm{BH}} = \frac{M_p^2}{8\pi M_{\mathrm{BH}}}$$

(M_p : Planck mass).

- when $M_{\mathrm{BH}} \downarrow$, $T_{\mathrm{BH}} \uparrow$, entropy $S(M_{\mathrm{BH}}) = 4\pi G M_{\mathrm{BH}}^2 \downarrow$
- the evolution is uncertain when $M_{\mathrm{BH}} \sim M_p$.
- "Standard model"
  - evaporation is assumed to end at M_p.
  - based on F.Halzen, E.Zas, J-H McGibbon & T.Weekes, Nature (1991)
  - particles emitted from standard model of particle physics

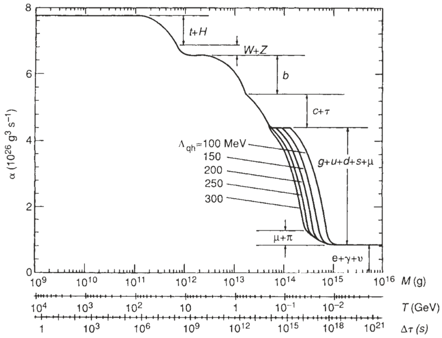


Figure – Evolution of α with time. From F.Halzen, E.Zas, J-H McGibbon & T.Weekes, Nature (1991)

– Evolution of M_{BH} with time

$$\frac{dM_{BH}}{dt} = -\frac{\alpha(M_{BH})}{M_{BH}^2}$$

– Black holes with $M_{BH} < 5\ 10^{14}\mathrm{g}$ have already evaporated.
– $M_{BH} \sim 10^9\mathrm{g} \rightarrow$ evaporation time $t_{ev} \simeq 1 - 10\mathrm{s}$
– $M_{BH} \leq 10^9\mathrm{g} \rightarrow$ temperatures $T_{BH} \geq$ a few TeV.
– PBH explosions can be observed directly (Cherenkov instruments and Fermi-LAT) or through the extragalactic photon background (Fermi-LAT).

Energy spectrum

Integrated spectrum (photons/m^2) emitted during the time Δt before total evaporation of the PBH and observed by a detector distant of r_0

- Several calculations available : Halzen et al (1991), et al 2008, Ukwatta et al 2016 (HAWC), public BlackHawk (Auffinger & Arbey 2019)
- General agreement within a factor 2
- Time dependent cut-off energy

$$Q = 40\text{TeV}(1\text{s}/\Delta\text{t})^{1/3}$$

- Low energy $(E < Q)$: integral slope -1/2

$$N(> E) = 0.18 \left(\frac{0.1\text{pc}}{r_0}\right)^2 (\frac{GeV}{Q})^2 (\frac{Q}{E})^{1/2}$$

- High energy $(E \geq Q,)$ integral slope -2

$$N(> E) = 0.22 \left(\frac{0.1\text{pc}}{r_0}\right)^2 (\frac{GeV}{E})^2 (1/42 + 1/150)$$

- typical PBH distance for detection : $r_0 = 0.1\text{pc} \rightarrow$ (very) local

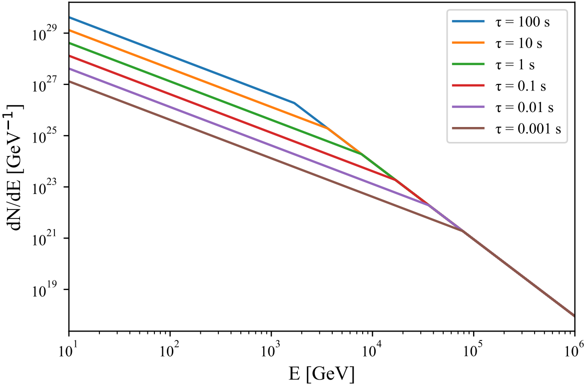
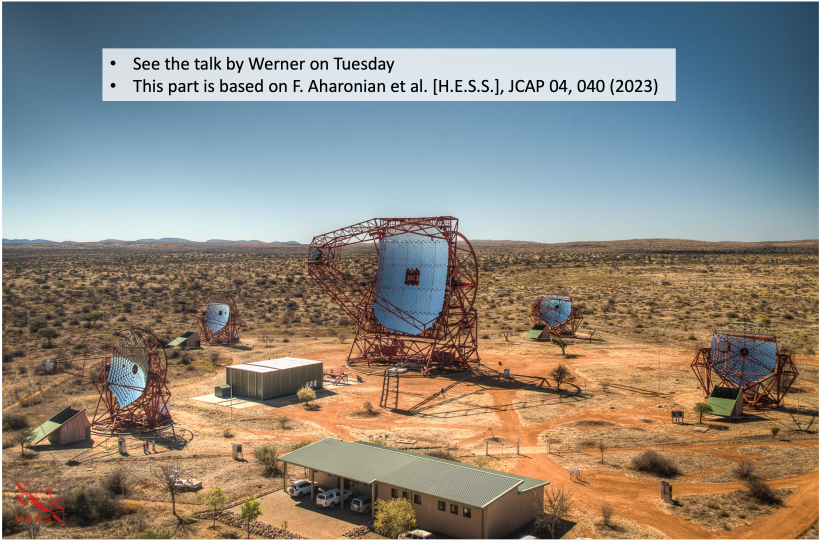


Figure – Time integrated PBH spectra. From C.Yan, J-D.Pan, X.Zhang, JCAP (2025)

- See the talk by Werner on Tuesday
- This part is based on F. Aharonian et al. [H.E.S.S.], JCAP 04, 040 (2023)



Dataset

- H.E.S.S. observations with four 12 m telescopes between January 2004 and January 2013.
- Some regions of the sky (Crab, LMC, SMC, SN 1006) excluded.
- Runs of poor quality (bad weather or technical problems) excluded.
- Photon/hadron separation and photon kinematics with the ImPACT program.
- Cross-checked with another calibration/reconstruction chain (ParisAnalysis)
- Use only runs available in both chains.
- Final dataset : 11494 28-minutes runs (4924 hours).

Effective volume

- Signature for PBH evaporation : few seconds photon burst.
- Average number of photons detected by H.E.S.S.

$$N_\gamma(r,\alpha,\delta,\Delta t) = \frac{1}{4\pi r^2}\int_0^{\Delta t} dt \int_0^{\infty} dE_\gamma \frac{d^2N}{dE_\gamma dt}(E_\gamma, t) A(E_\gamma,\alpha,\delta),$$

- Number of expected photon bursts of size b from all local PBH

$$n^i(b,\Delta t,\dot\rho_{\rm PBH}) = \dot\rho_{\rm PBH} V^i_{\rm eff}(b,\Delta t)$$

where :

- $\dot\rho_{\rm PBH}$ local PBH explosion rate
- Effective space-time volume of PBH detection per run i (runtime T$_i$)

$$V^i_{\rm eff}(b,\Delta t) = T_i\Omega_{\rm i}\frac{(r_0\sqrt{N_0})^3}{2}\frac{\Gamma(b-3/2)}{\Gamma(b+1)}$$

(N_0 : expected number of photons from a PBH at r_0)

- Universal burst size distribution

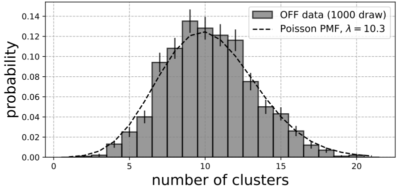
Analysis strategy

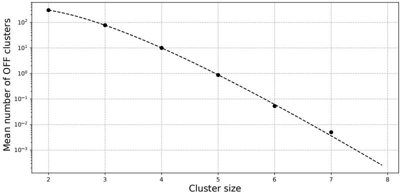
For search durations $\Delta t = 10, 30, 60, 120$ s :

- Find and count photon clusters in H.E.S.S. data using OPTICS based algorithm.
- Have a reliable estimation of the false positive background .
- Compare the background subtracted burst distribution to the expectation from PBH evaporations.
- Use a likelihood-based method to derive 99% CL UL limits.

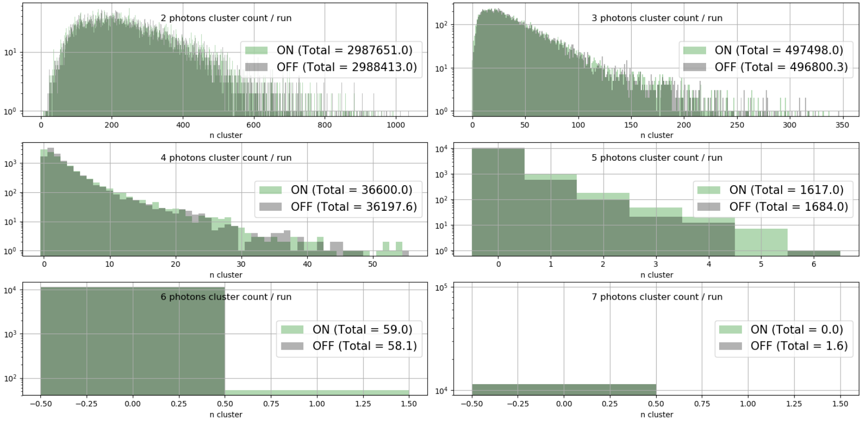
Background estimation

- Statistical background estimated for each run by scrambling the time of arrival of photons.
- $\sim$ 200 MC realisations for each run (hereafter OFF data).
- Probability distribution of the number of clusters of size b in a run well described by Poisson law.
- Number of clusters obtained by extrapolation for large cluster size.



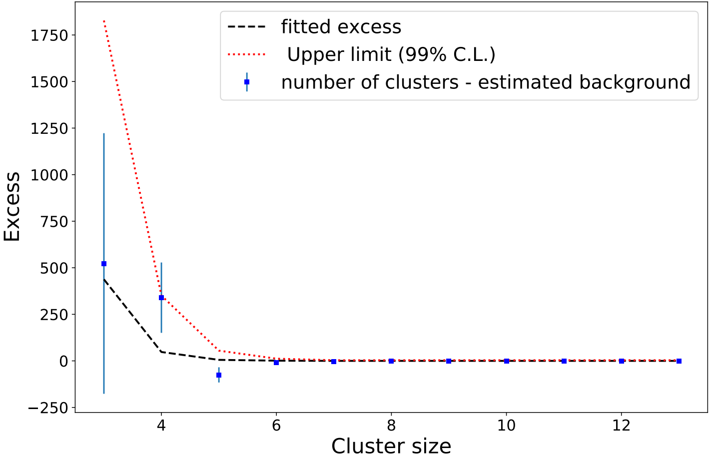


ON-OFF comparison ($\Delta t = 60\mathrm{s}$)

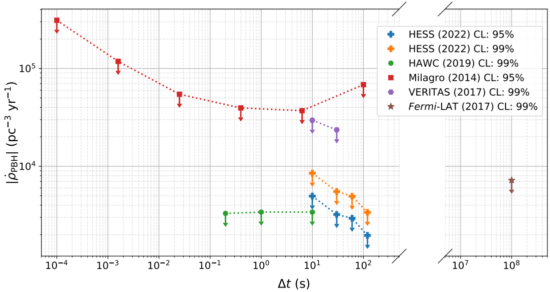


No significant excess.

ON-OFF comparison ($\Delta t = 60\mathrm{s}$)



Rate limits



– Best limit $\dot{\rho}_{\rm PBH} < 2000 \rm pc^{-3} yr^{-1}$ (95% C.L.) for $\Delta t = 120 \rm s$

LHASSO-WCDA results

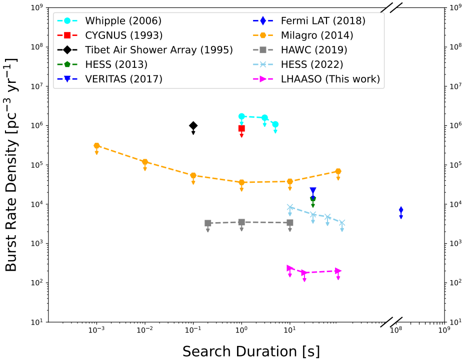


Figure – From Z.Cao et al. (LHAASO collaboration, Phys. Rev Letters (2025)

- Best limit $\dot{\rho}_{\rm PBH} < 181 {\rm pc}^{-3}{\rm yr}^{-1}$ (99% C.L.) for $\Delta t = 20{\rm s}$
- Detects GRB 221009A !

CTAO prospects

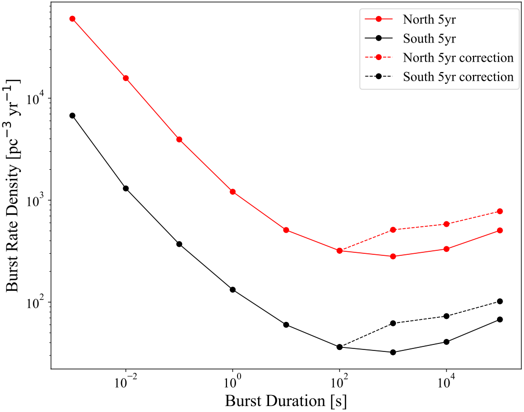


Figure – CTAO prospective limits on "local" PBH. From C.Yan, J-D.Pan, X.Zhang, JCAP (2025)

Could reach $\dot{\rho}_{\rm PBH} < 50 {\rm pc}^{-3}{\rm yr}^{-1}$ (99% C.L.) with CTAO South

SWGO prospects

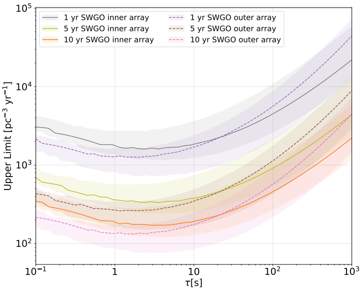


Figure – SWGO prospective limits on "local" PBH. From R. López-Coto, M. Doro, A. de Angelis, M. Mariotti, J. P. Harding JCAP (2021)

Could reach $\dot{\rho}_{\rm PBH} < 200 {\rm pc}^{-3}{\rm yr}^{-1}$ in $\sim$ 10 years

"Memory burden"

- Several alternative scenarios for evaporation exist.
- "Standard model" neglects backreaction of evaporation on the PBH due to information loss.
- Backreaction could stall PBH evaporation (G. Dvali et al, Phys. Rev. D (2020)).
- Model : when $M_{BH} < qM_{in}$,

$$\frac{dM_{BH}}{dt} = -\frac{\alpha(M_{BH})}{S(M_{BH})^k M_{BH}^2}$$

($q \simeq 1/2$, $k = 0, 1, 2, \ldots$ arbitrary parameters).

- PBHs with $M_{BH} < 5\ 10^{14}\mathrm{g}$ become stable on cosmological time-scale.
- However, they still radiate HE γ at a smaller rate $\rightarrow$ constraints from galactic/extragalactic background

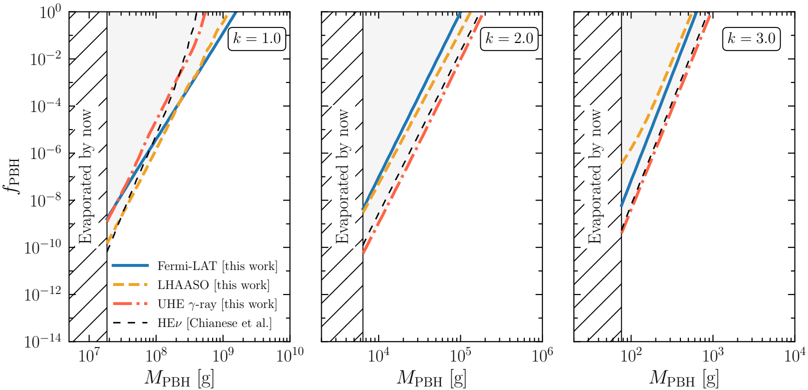


Figure – Limits on PBH abundance with memory burden. From M.Chianese, Phys. Rev. D (2025)

Assumes $q = 1/2$

Outlook

- Assuming the standard model of PBH evaporation, present (LHASSO) limit on PBH density is $\dot{\rho}_{\rm PBH} < 200 {\rm pc}^{-3} {\rm yr}^{-}1$ (99% C.L) an order of magnitude less than H.E.S.S 2023 result.
- CTAO south or SWGO could improve the limit by a factor of a few in ~ 5 years, assuming no background events (GRBs ?).
- Alternatives to the evaporation model might totally supress PBH explosions, leaving evaporation fingerprints only in photon background.