Primordial Black Holes as Dark Matter

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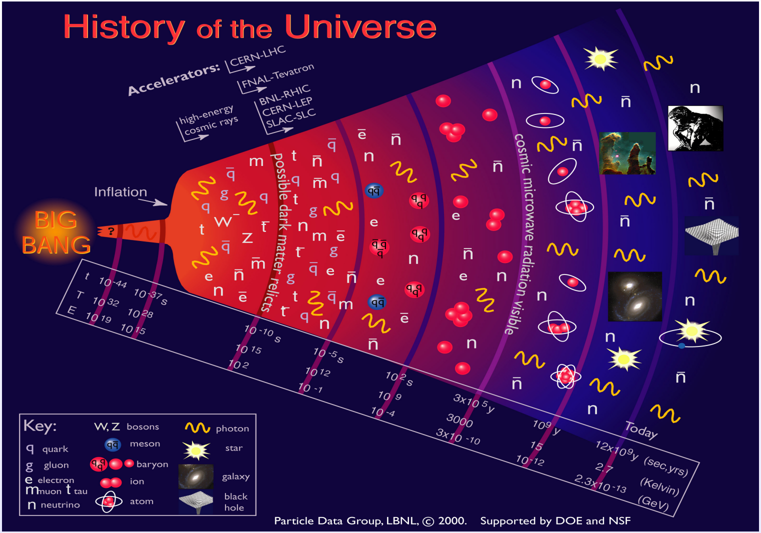
Introduction

History of the Universe



Recombination (and emission of cosmic microwave backgroud) constitutes a limit between the dark times and the observable Universe

What happened during the dark times before recombination?

T

- How to describe the beginning of the Universe ($\sim$ Planck energy)?
  Quantum gravity? Brane theories? Other gravitation theories?
- What did drive **inflation** in the early Universe? When did it end?
- Do/did **topological defects** (magnetic monopoles, domain walls, ...) exist?
- What did happen during **leptogenesis**?
- What did happen during **baryogenesis**?
- Where does the **particle-antiparticle asymmetry** come from?
- Did the **relic dark matter particle freeze-out** happen, how and when?
- Do we fully understand the properties of the **QCD-dominated plasma**?
- Do we fully understand **Big-Bang nucleosynthesis**?

What about (Primordial) Black Holes??

Primordial black holes

Black holes: metrics

In the following we place ourselves in the natural unit system with $c = \hbar = k_B$ $(= G) = 1$.

Schwarzschild metric for a static compact object of mass M

$$d\tau^2 = \left(1 - \frac{2GM}{r}\right) dt^2 - \frac{dr^2}{1 - \dfrac{2GM}{r}} - r^2(d\theta^2 + \sin^2\theta\, d\phi^2)$$

One defines the Schwarzschild radius: $R_s = 2GM$.
If the mass M is completely within $r < R_s$, the radius $r = R_s$ consistutes a horizon.

$\longrightarrow$ Black Hole!

Kerr metric for a static compact object of mass M and angular momentum J

$$\begin{aligned} d\tau^2 &= (dt - a\sin^2\theta d\phi)^2\frac{\Delta}{\Sigma} - \left(\frac{dr^2}{\Delta} + d\theta^2\right)\Sigma \\ &\quad - ((r^2 + a^2)d\phi - adt)^2\frac{\sin^2\theta}{\Sigma} \end{aligned}$$

$$a = J/M,\ \Sigma = r^2 + a^2\cos^2\theta,\ \Delta = r^2 - R_s r + a^2,\ R_s = 2GM$$

The horizon exists but is deformed and flattened$\longrightarrow$ Kerr (Rotating) Black Hole!

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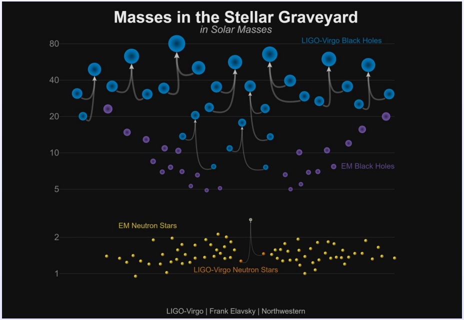
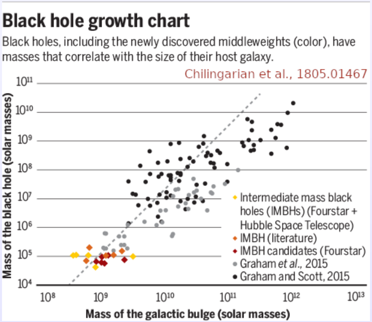
Observed black holes

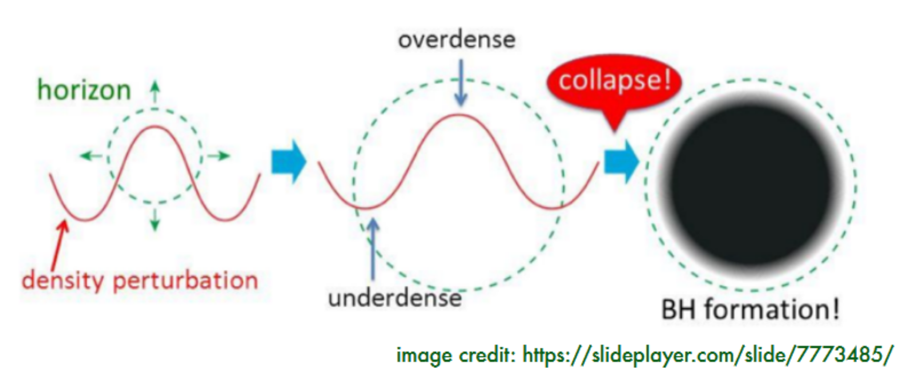
Three types of black holes have been discovered

- Stellar black holes
  BHs originated in the explosion of massive stars/supernovae, $\sim 3 - 100 M_\odot$
- Intermediate mass black holes (IMBH)
  New class of recently discovered BHs, $\sim 10^3 - 10^6 M_\odot$
- supermassive black holes (SMBH)
  BHs at the center of galaxies, $\sim 10^6 - 10^9 M_\odot$





Origin of primordial black holes



Origin of primordial black holes

Multiple inflationary origins

- collapse of large primordial overdensities
- phase transitions
- collapse of cosmic strings, domain walls

Mass predictions

Assuming that one PBH can be formed in a Hubble volume in the early Universe, one gets

$$M_{\rm PBH} \sim M_{\rm Planck} \times \frac{t_0}{t_{\rm Planck}} \sim 10^{38}\ {\rm g}\ \times t_0({\rm s})$$

where t_0 is the creation time.

We get:

- $M \sim 10^{-5}$ g for $t_0 \sim 10^{-43}$ s $\rightarrow$ Planck black holes
- $M \sim 10^{15}$ g for $t_0 \sim 10^{-23}$ s $\rightarrow$ lightest black holes still (possibly) existing
- $M \sim 10^{5}\ M_\odot$ for $t_0 \sim 1$ s $\rightarrow$ IMHB? seeds for SMBH?

Angular momentum of primordial Black Holes

Angular momentum given by dimensionless parameter $a^* \equiv J/M^2$

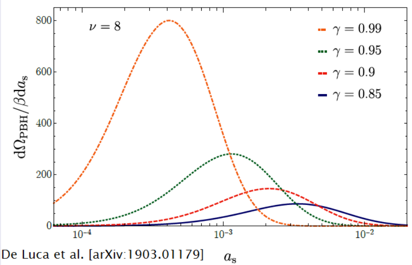
$a^* \in [0, 1]$

$a^* = 0$ for Schwarzschild BHs, $a^* = 1$ for extremal Kerr BHs

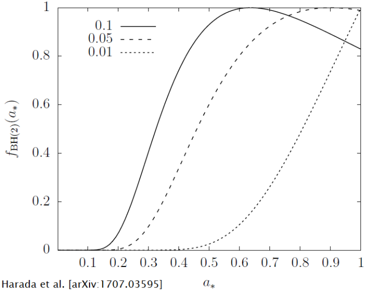
Spin predictions

Standard inflationary model
$\Longrightarrow$ low spin ($a^* \sim 0$)

Transient matter domination
$\Longrightarrow$ high spin



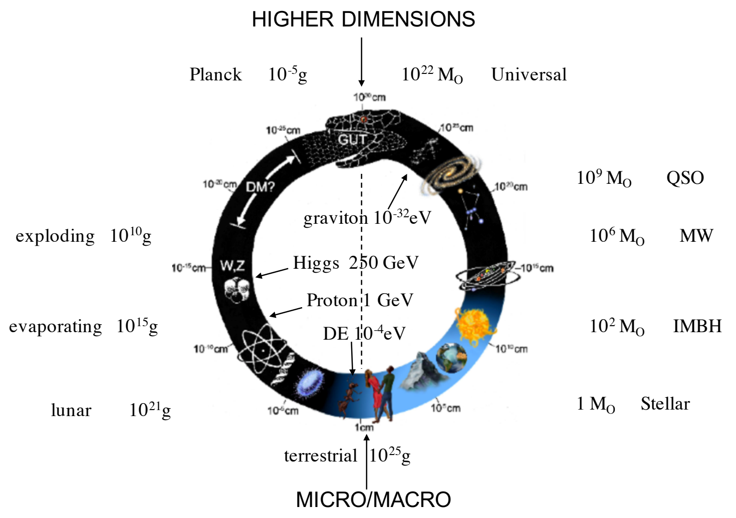
De Luca et al. [arXiv:1903.01179]



Harada et al. [arXiv:1707.03595]

The Cosmic Uroboros

A cosmic vision of PBHs by B. Carr (from arXiv:1703.08655)

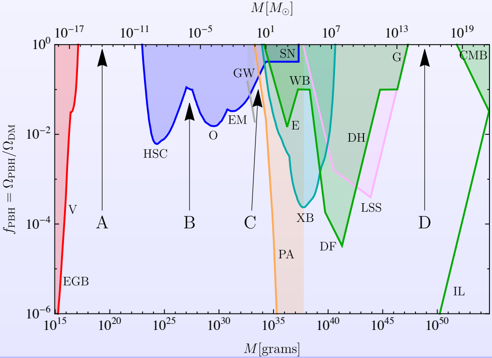


Constraints on Primordial Black Holes

Plausible dark matter candidates

- no need for Standard Model / General Relativity extension
- dynamically cold
- BH existence (somehow) proven
- mass ranges still available for BHs to represent all of dark matter

Constraints on PBHs – from Carr & Kuhnel, 2006.02838



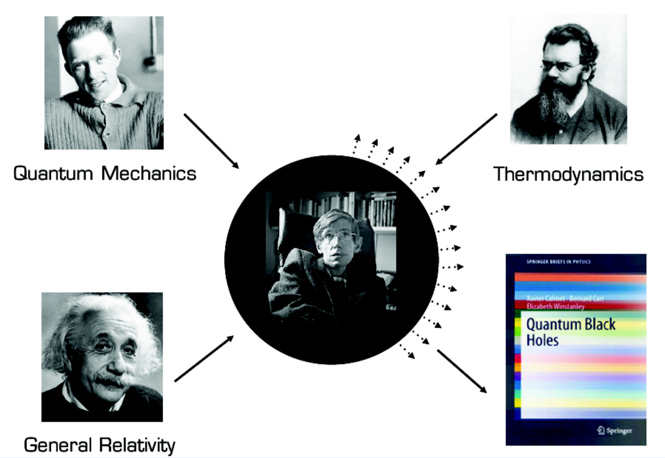
red: evaporation
blue: lensing
gray: gravitational waves
light blue: accretion
orange CMB distortions
green: dynamical effects
purple: large scale structure

A-D: possible open windows

Hawking radiation

Why are PBHs so special?

Light PBHs cannot be described only with General Relativity...



from B. Carr

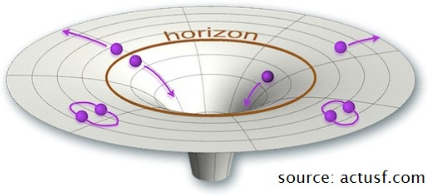
... because they emit Hawking radiation and evaporate!

Different scales, different times...

What Hawking radiation tells us...

- $M \sim 10^{-5}$ g $\rightarrow$ Planck mass BHs $\rightarrow$ probes of quantum gravity
- $M \sim 10^{15}$ g $\rightarrow$ PBHs emitting a lot of particles today $\rightarrow$ cosmic rays, gamma rays, ...
- $M \gg 10^{15}$ g $\rightarrow$ PBHs with low Hawking emission $\rightarrow$ BHs as dark matter
- $M \ll 10^{15}$ g $\rightarrow$ PBHs which evaporated (and disappeared?) long ago
  $\rightarrow$ generated by inhomogeneities, phase transitions, ...
  $\rightarrow$ imprints in the primordial gravitational wave background?

Black hole Hawking radiation



Fundamental equation for Kerr BHs

Rate of emission of Standard Model particles i at energy E by a BH of mass M and spin parameter a^*:

$$Q_i = \frac{\mathrm{d}^2 N_i}{\mathrm{d}t\mathrm{d}E} = \frac{1}{2\pi} \sum_{\mathrm{dof.}} \frac{\Gamma_i(M, E, a^*)}{e^{E'/T(M,a^*)} \pm 1}$$

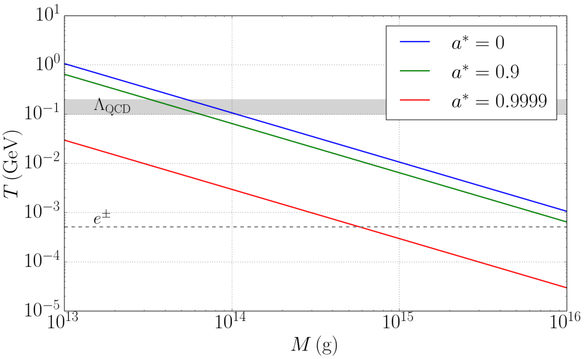
Γ_i is the greybody factor ($\sim$ absorption coefficient in Planck's black-body law)

Hawking temperature

Hawking temperature for Kerr BHs

$$T(M,a^*) = \frac{1}{4\pi M}\left(\frac{\sqrt{1-(a^*)^2}}{1+\sqrt{1-(a^*)^2}}\right) \xrightarrow[a^*=0]{\text{Schwarzschild}} \frac{1}{8\pi M}$$

Comparison with the $e^{\pm}$ rest mass and QCD scale $\Lambda_{\rm QCD}$



BHs get warmer when they lose energy via Hawking radiation.

Kerr Hawking radiation equations

Kerr metric

$$\mathrm{d}s^2 = \left(1 - \frac{2Mr}{\Sigma^2}\right)\mathrm{d}t^2 + \frac{4a^* M^2 r \sin^2\theta}{\Sigma^2}\mathrm{d}t\,\mathrm{d}\phi - \frac{\Sigma^2}{\Delta}\mathrm{d}r^2$$
$$- \Sigma^2 \mathrm{d}\theta^2 - \left(r^2 + (a^*)^2 M^2 + \frac{2(a^*)^2 M^3 r \sin^2\theta}{\Sigma^2}\right)\sin^2\theta \mathrm{d}\phi^2$$

$\Sigma \equiv r^2 + (a^*)^2 M^2 \cos^2\theta$ and $\Delta \equiv r^2 - 2Mr + (a^*)^2 M^2$

Equations of motion in free space

$$\mathrm{Dirac:}\ (i\not{\partial} - \mu)\psi = 0\ \mathrm{(fermions)}$$
$$\mathrm{Proca:}\ (\Box + \mu^2)\phi = 0\ \mathrm{(bosons)}$$

μ = rest mass

Kerr Hawking radiation equations

Teukolsky radial equation

$$\frac{1}{\Delta^s}\frac{\mathrm{d}}{\mathrm{d}r}\left(\Delta^{s+1}\frac{\mathrm{d}R}{\mathrm{d}r}\right)+\left(\frac{K^2+2i\,s(r-M)K}{\Delta}-4i\,sEr-\lambda_{slm}-\mu^2r^2\right)R=0$$

R radial component of ψ/ϕ

$K\equiv(r^2+a^2)E+a\,m$, $s=$ spin, $l=$ angular momentum and $m=$ projection

Transformation into a Schrödinger equation

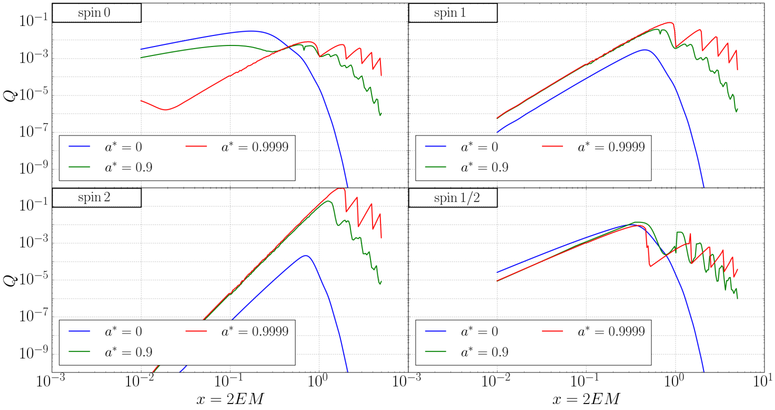
Change $\psi/\phi\longrightarrow Z$ and $r\longrightarrow r^*$ (generalized Eddington-Finkelstein coordinate system) (Chandrasekhar & Detweiler 1970s)

$$\frac{\mathrm{d}^2Z}{\mathrm{d}r^{*2}}+(E^2-V(r^*))Z=0$$

Solved with purely outgoing solution $Z\underset{r^*\to-\infty}{\longrightarrow}e^{-i\,Er^*}$

Transmission coefficient $\Gamma\equiv|Z_{\rm out}^{+\infty}/Z_{\rm out}^{\rm horizon}|^2$

Hawking radiation of particles



All particles can be emitted by a black hole!

Including gravitons / gravitational waves... and even new physics particles!

Hawking radiation is enhanced for particles of spin 1 or 2.

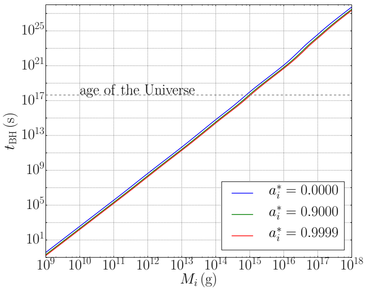
Black hole lifetime

Evolution equations

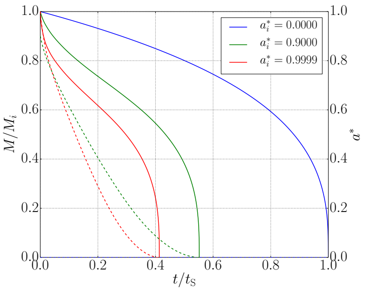
$$\frac{\mathrm{d}M}{\mathrm{d}t} = -\frac{f(M,a^*)}{M^2} \qquad f \sim \int_E ener. \times emiss.$$

$$\frac{\mathrm{d}a^*}{\mathrm{d}t} = \frac{a^*(2f(M,a^*) - g(M,a^*))}{M^3} \qquad g \sim \int_E ang.\ mom. \times emiss.$$

BH lifetime



BH mass (solid) and spin (dotted) evolution

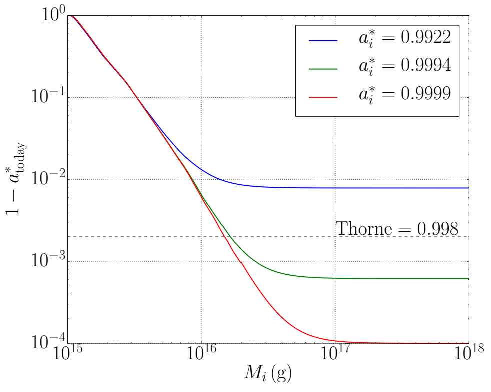


AA, J. Auffinger, J. Silk, MNRAS 494 (2020) 1257

Extremal spin today?

Could high spin BHs exist today? Can we get over Thorne's limit on the spin of rotating BHs from disk accretion?
$\rightarrow$ Yes, with sufficiently massive and extremal PBHs

PBH spin today as a function of its initial mass



AA, J. Auffinger, J. Silk, MNRAS 494 (2020) 1257

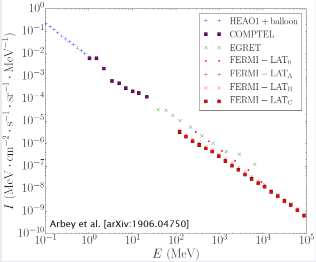
Light primordial black holes

Isotropic gamma ray background (IGRB) constraints

Origin

Diffuse background +

- Active galactic nuclei
- Gamma ray bursts
- DM annihilation/decay?
- Hawking radiation?



Flux estimation for BHs

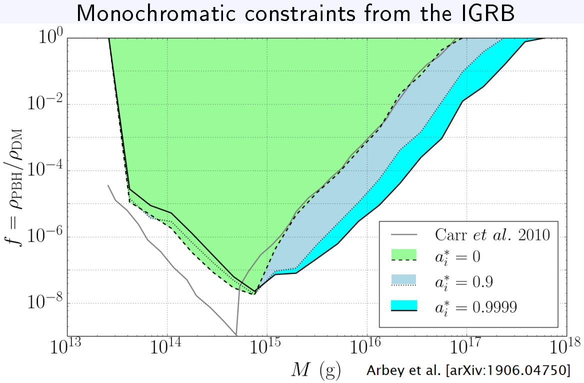
AA *et al.*, arXiv:1906.04750

$$I \approx \frac{1}{4\pi} E \int_{t_{\rm CMB}}^{t_{\rm today}} (1+z(t)) \times \int_M \left[\frac{{\rm d}n}{{\rm d}M} \frac{{\rm d}^2 N}{{\rm d}t{\rm d}E}(M,(1+z(t))E)\,{\rm d}M \right] {\rm d}t$$

IGRB and Kerr PBHs: monochromatic mass distributions

Main spin effects

- enhanced luminosity $\Rightarrow$ stronger constraints
- reduced temperature $\Rightarrow$ reduced emission energy $\Rightarrow$ weaker constraints



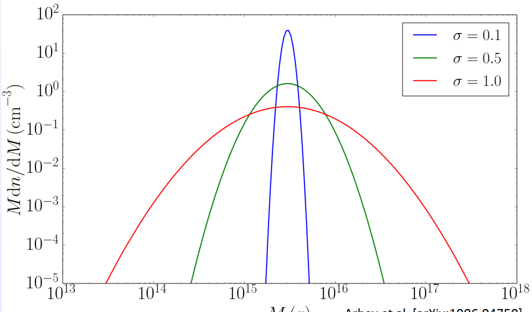
Log-normal distributions

Definition

$$\frac{\mathrm{d}n}{\mathrm{d}M} = \frac{A}{\sqrt{2\pi}\sigma M} \exp\left(-\frac{(\log(M/M_*))^2}{2\sigma^2}\right)$$

M^* = central mass, σ = width (dimensionless)

Log-normal distributions (normalized to unity, $M^* = 3 \times 10^{15}$ g)

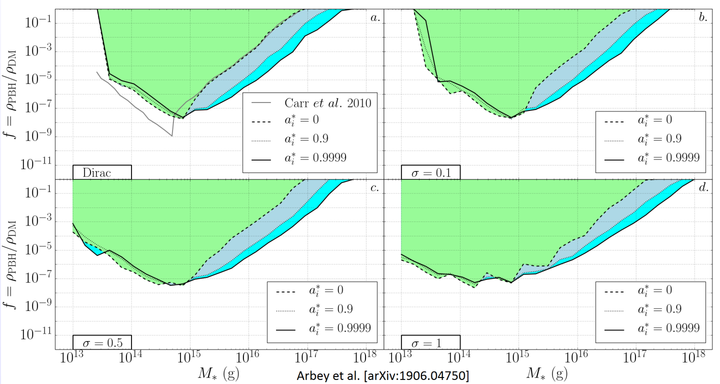


Arbey et al. [arXiv:1906.04750]

IGRB and Kerr PBHs: Extension to broad mass functions

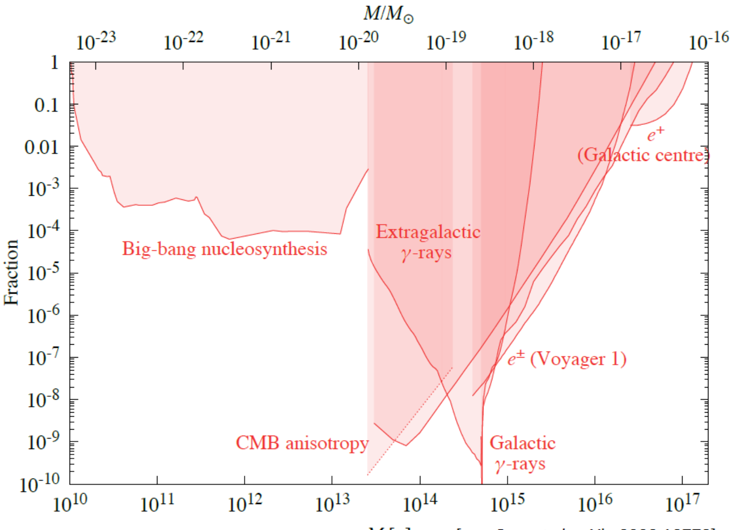
Main width effects

- broadening of the spectrum ⇒ stronger constraint
- broadening of the mass distribution ⇒ greater DM total density ⇒ weaker constraint



Arbey et al. [arXiv:1906.04750]

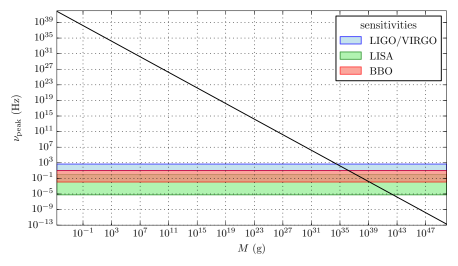
Complementary constraints



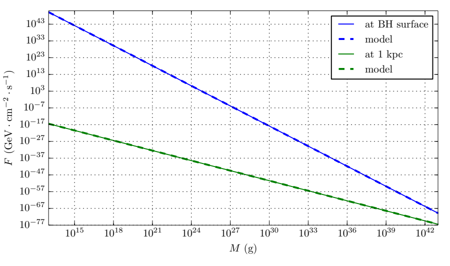
[see Carr *et al.* arXiv:2002.12778]

Hawking gravitational waves and detection

Emission of gravitational waves by BHs



Preliminary



Supermassive BHs emit at frequencies of LIGO-VIRGO/LISA/BBO

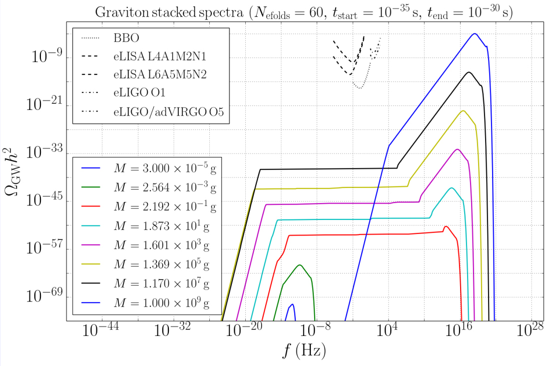
Unfortunately the fluxes of such heavy BHs are too small!

Gravitational waves from very primordial BHs

Gravitational waves emitted by very light PBH which vanished before or after inflation

$\rightarrow$ cosmological background of gravitational waves

Preliminary

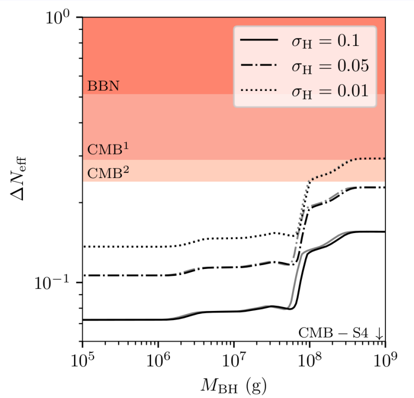


Discovering gravitational waves emitted via Hawking radiation would validate the existence of the graviton!

Light PBHs and new physics particles

Even if light PBHs have vanished in the very early Universe, they can have played a role in the particle history of the Universe

Example: emission of gravitons/dark radiation behaving as effective neutrino degrees of freedom during an early matter domination period

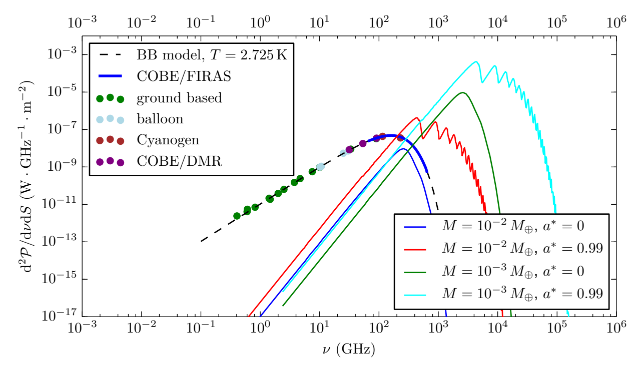


AA, J. Auffinger, P. Sandick, B. Shams Es Haghi, K. Sinha, arXiv:2104.04051

Heavy primordial black holes

Black holes in the Solar System?

Possibility to have planet-mass black holes in the Solar System



AA, J. Auffinger, 2006.02944

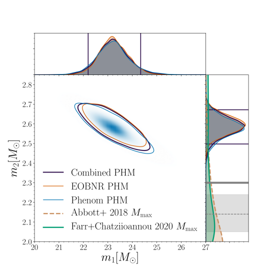
$\rightarrow$ Hawking radiation may be detected by an *in situ* satellite in orbit.

Primordial black holes in the LIGO/Virgo data?

It is extremely difficult to distinguish a BH of primordial origin from a BH of stellar origin, because they are identical (no-hair theorem)

However, BHs of stellar origins are expected to have masses above 3 solar masses

Event GW190814 — LIGO Scientific and Virgo Collaborations, arXiv:2006.12611

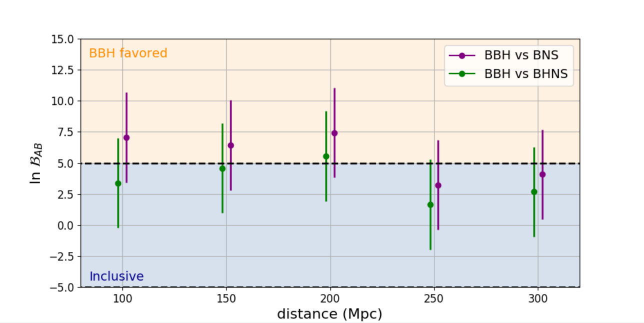


Merger of a 23 $M_\odot$ black hole with a 2.6 $M_\odot$ compact object (black hole or neutron star)

$\rightarrow$ Need for more detections to understand if a population of light BHs exists

Distinguishing PBHs from neutron stars

If a GW from the merger of two light PBHs (BBH) is detected, can we distinguish it from binary neutron star (BNS) mergers or black hole-neutron star (BHNS) mergers?



J.-F. Coupechoux, AA, R. Chierici, H. Hansen, J. Margueron, V. Sordini, arXiv:2106.05805

Very difficult with the current sensitivities, needs close-by mergers

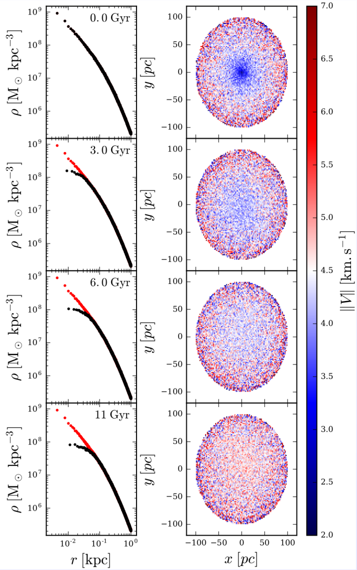
Solving the cusp-core problem with PBHs

In presence of heavy PBHs, possible transition from cusp to core

On the right: N-body simulation of dwarf galaxy with $10^7\ M_\odot$ halo made of 50% of dark matter in the form of 100 $M_\odot$ PBHs and 50% of 1 $M_\odot$ DM particles. From Boldrini et al. [1909.07395].

Gravitational heating by heavy PBHs:

- Dynamical friction of DM particles on PBHs
- Two body relaxation between PBHs



Non-standard black holes

The case of static spherically-symmetric metrics

AA, J. Auffinger, M. Geiller, E. Livine, F. Sartini, arXiv:2101.02951 + 2107.03293

$$\mathrm{d}s^2 = -G(r)\mathrm{d}t^2 + \frac{1}{F(r)}\mathrm{d}r^2 + H(r)\mathrm{d}\Omega^2$$

Equations of motion:

$$\partial^2_{r^*} Z + \Big(\omega^2 - V\big(r(r^*)\big)\Big) Z = 0$$

where $\mathrm{d}r^*/\mathrm{d}r \equiv 1/\sqrt{FG}$ and the spin-dependent potentials V are related to F, G, H.

Transmission coefficient: $\Gamma_i \equiv |Z_{\rm out}^{+\infty}/Z_{\rm out}^{\rm horizon}|^2$

Rate of emission of one degree of freedom i per unit time t and energy E:

$$\frac{\mathrm{d}^2 N_i}{\mathrm{d}t\,\mathrm{d}E} = \sum_{l,m} \frac{1}{2\pi} \frac{\Gamma_i(E, M, x_j)}{e^{E/T} - (-1)^{2s_i}} \,,$$

where s_i is the spin of the particle i and T is its Hawking temperature given by

$$T = \frac{1}{4\pi} \left.\frac{F^{1/2} G'}{G^{1/2}}\right|_{\rm hor}$$

where "hor" denotes the horizon $r = r_{\rm H}$.

Extra-dimensional PBHs

Metric:

$$F(r) = G(r) \equiv 1 - \left(\frac{r_\mathrm{H}}{r}\right)^{n+1}, \quad H(r) = r^2$$

where $n > 0$ is the number of extra dimensions.

Horizon radius is given by

$$r_\mathrm{H} = \frac{1}{\sqrt{\pi} M_*} \left(\frac{M}{M_*}\right)^{1/(n+1)} \left(\frac{8\Gamma\left((n+3)/2\right)}{n+2}\right)^{1/(n+1)}$$

where Γ is the Euler gamma function and the rescaled Planck mass is

$$M_\mathrm{Pl}^2 = M_*^{n+2} R^n$$

with R the radius of the extra-dimension(s).

Temperature:

$$T_n = \frac{\kappa_n}{2\pi} = \frac{n+1}{4\pi r_\mathrm{H}}$$

Remark: Schwarzschild metric retrieved for $n = 0$.

Extra-dimensional PBHs

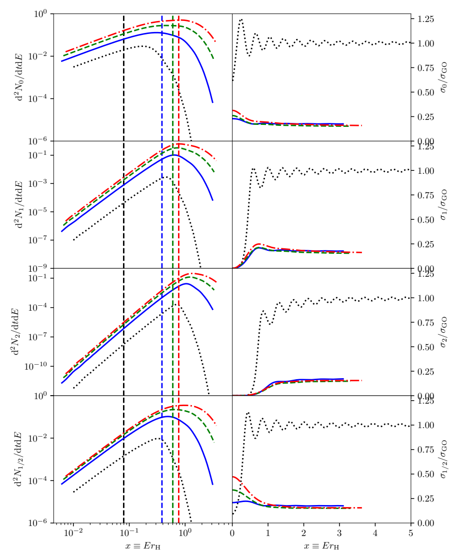
Hawking radiation spectra

dotted black: Schwarzschild

blue: $n = 2$

green: $n = 4$

red: $n = 6$



LQG-inspired PBHs

Schwarzschild BHs are singular at the center $\rightarrow$ non-physical $\rightarrow$ quantum gravity?

Loop Quantum gravity (LQG): structure of spacetime described by spin networks.

Metric inspired by LQG, regularising the naked singularity at the center of the Schwarzschild metric:

$$G = \frac{(r-r_+)(r-r_-)(r+\sqrt{r_+ r_-})^2}{r^4 + a_0^2}\,, \quad F = \frac{(r-r_+)(r-r_-)r^4}{(r+\sqrt{r_+ r_-})^2(r^4+a_0^2)}\,, \quad H = r^2 + \frac{a_0^2}{r^2}\,.$$

Two roots: $r_+ = \dfrac{2M}{(1+P)^2}$ and $r_- = \dfrac{2MP(\varepsilon)^2}{(1+P)^2}$

M: (ADM) mass

$P(\varepsilon) = \dfrac{\sqrt{1+\varepsilon^2}-1}{\sqrt{1+\varepsilon^2}+1}$: polymerization factor

a_0: minimal area in loop quantum gravity, typically of the Planck scale

$\varepsilon \geq 0$: typical scale of the geometry fluctuations (a priori independent parameter)

Temperature: $T_{\rm LQG} = \dfrac{r_+^2(r_+ - r_-)}{4\pi(r_+^4 + a_0^2)}$

LQG-inspired PBHs

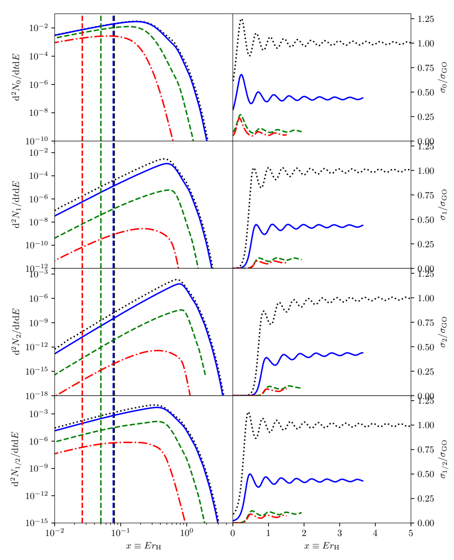
Hawking radiation spectra

dotted black: Schwarzschild

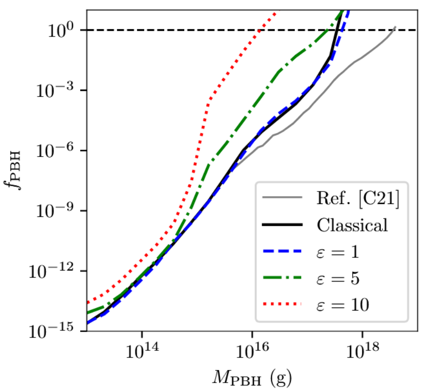
blue: $\epsilon = 1$

green: $\epsilon = 4$

red: $\epsilon = 10$



LQG-inspired PBHs



Predictions for the sensitivity of the AMEGO gamma-ray experiment to classical and polymerised LQG-inspired PBHs

ε: scale of deformation of spacetime due to polymerisation in Loop Quantum Gravity

AA, J. Auffinger, M. Geiller, E. Livine, F. Sartini, arXiv:2101.02951 + 2107.03293

→ Theories beyond General Relativity predict very different signals of Hawking radiation.

Open questions

Domains related to black holes

- Gravity
  - tests of general relativity
  - nature of singularities, horizons, ...
  - links with wormholes, white holes, extradimensions, ...
  - portal to new physics?
- Quantum physics
  - Hawking radiation
  - physics at Planck scale
  - links with quantum gravity
- Astrophysics
  - formation mechanisms
  - nature of black holes
  - distinction between neutrons stars and black holes
- Cosmology and astroparticles
  - candidate for dark matter
  - tests of mechanisms in the early Universe
  - links with particle and astroparticles physics
  - relation with inflation

Research axes

- Formal aspects
  - theories and models of black holes
  - information theory and thermodynamics
  - quantum gravity theories and consequences on black holes
  - string theory and consequences on black holes
- Models and simulations
  - structure formation and dynamics in presence of black holes
  - formation of black holes
  - mergers of black holes
- Cosmological and astrophysical searches
  - gravitational lensing
  - telescopes
- Multi-messenger searches
  - gravitational waves
    - from mergers (LIGO, Virgo, ...)
    - from formation mechanisms (eLISA, future experiments)
    - from Hawking radiation
  - astroparticles: electrons and positrons (e.g. Voyager-2, AMS-02, ...), antiprotons (AMS-02), photons (X-rays, gamma-rays, ...)
    - from Hawking radiation of PBHs
    - from accretion discs and asymmetric mergers

Selected questions

- Do Planck relics exist? In other words, do BHs evaporate down to *stable* objects?
- Can PBHs leave imprints in the CMB or in the stochastic GW background?
- Are mixed DM particle-PBH scenarios realistic?
- What are realistic distributions of PBHs?
- Are General Relativity BHs realistic?
- Which tools may be useful to study PBHs?
- How late can PBHs have been formed? And how heavy can they be?
- Were there PBH-domined phases in the early Universe?
- Can we distinguish BHs from other objects (i.e. boson stars)?
- Is Hawking radiation a realistic description of quantum effects around BHs?
- Can BHs solve the cusp-core problem?
- How could PBHs have affected cosmology?

Backup

Backup

Kerr Hawking radiation equations

Chandrasekhar potentials

$$V_0(r) = \frac{\Delta}{\rho^4}\left(\lambda_{0\,lm} + \frac{\Delta + 2r(r-M)}{\rho^2} - \frac{3r^2\Delta}{\rho^4}\right)$$

$$V_{1/2,\pm}(r) = (\lambda_{1/2\,lm}+1)\frac{\Delta}{\rho^4} \mp \frac{\sqrt{(\lambda_{1/2,l,m}+1)\Delta}}{\rho^4}\left((r-M) - \frac{2r\Delta}{\rho^2}\right)$$

$$V_{1,\pm}(r) = \frac{\Delta}{\rho^4}\left((\lambda_{1\,lm}+2) - \alpha^2\frac{\Delta}{\rho^4} \mp i\alpha\rho^2\frac{\mathrm{d}}{\mathrm{d}r}\left(\frac{\Delta}{\rho^4}\right)\right)$$

$$V_2(r) = \frac{\Delta}{\rho^8}\left(q - \frac{\rho^2}{(q-\beta\Delta)^2}\left((q-\beta\Delta)\left(\rho^2\Delta q'' - 2\rho^2 q - 2r(q'\Delta - q\Delta')\right)\right.\right.$$
$$\left.\left. + \rho^2(\kappa\rho^2 - q' + \beta\Delta')(q'\Delta - q\Delta')\right)\right)$$

$\rho^2 \equiv r^2 + \alpha^2$ and $\alpha^2 \equiv a^2 + am/E$

$$q(r) = \nu\rho^4 + 3\rho^2(r^2 - a^2) - 3r^2\Delta$$

$$q'(r) = r\left((4\nu+6)\rho^2 - 6(r^2 - 3Mr + 2a^2)\right)$$

$$\beta_\pm = \pm 3\alpha^2$$

$$\kappa_\pm = \pm\sqrt{36M^2 - 2\nu(\alpha^2(5\nu+6) - 12a^2) + 2\beta\nu(\nu+2)}$$

Evolution parameters

Page parameters (Page 1976)

$$f(M,a^*) \equiv -M^2\frac{\mathrm{d}M}{\mathrm{d}t} = M^2\int_0^{+\infty}\sum_{\mathrm{dof.}}\frac{E}{2\pi}\frac{\Gamma(E,M,a^*)}{e^{E'/T}\pm 1}\mathrm{d}E$$

$$g(M,a^*) \equiv -\frac{M}{a^*}\frac{\mathrm{d}J}{\mathrm{d}t} = \frac{M}{a^*}\int_0^{+\infty}\sum_{\mathrm{dof.}}\frac{m}{2\pi}\frac{\Gamma(E,M,a^*)}{e^{E'/T}\pm 1}\mathrm{d}E$$

Evolution equations (Page 1976)

$$\frac{\mathrm{d}M}{\mathrm{d}t} = -\frac{f(M,a^*)}{M^2}$$

$$\frac{\mathrm{d}a^*}{\mathrm{d}t} = \frac{a^*(2f(M,a^*) - g(M,a^*))}{M^3}$$

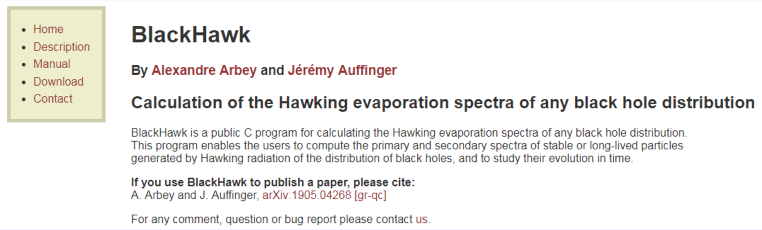
BlackHawk

Public C code computing Hawking radiation:

- Schwarzschild & Kerr PBHs + non-standard BHs
- primary spectra of all Standard Model fundamental particles
- secondary spectra of stable particles
- extended mass and spin functions
- time evolution of the PBHs

Download: `http://blackhawk.hepforge.org`

Manual: arXiv:1905.04268, Eur.Phys.J. C79, 693
+ arXiv:2108.02737, Eur.Phys.J. C81, 10



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BlackHawk

By Alexandre Arbey and Jérémy Auffinger

Calculation of the Hawking evaporation spectra of any black hole distribution

BlackHawk is a public C program for calculating the Hawking evaporation spectra of any black hole distribution. This program enables the users to compute the primary and secondary spectra of stable or long-lived particles generated by Hawking radiation of the distribution of black holes, and to study their evolution in time.

If you use BlackHawk to publish a paper, please cite:
A. Arbey and J. Auffinger, arXiv:1905.04268 [gr-qc]

For any comment, question or bug report please contact us.

BlackHawk

Secondary spectra

Particles produced via Hawking radiation are not all stable: hadronisation, decay, fragmentation...

Schematical description

Metric $\xrightarrow{\texttt{BlackHawk}}$ Primary spectra $\xrightarrow[\text{particle physics codes}]{\text{Interface with}}$ Secondary spectra

Interfaces

Low energies		Collider energies (LHC)		High energies
$E_{\rm cdm} \sim 1\,\mathrm{keV} - 5\,\mathrm{GeV}$	$<$	$E_{\rm cdm} \sim 5\,\mathrm{GeV} - 100\,\mathrm{TeV}$	$<$	$E_{\rm cdm} \sim 100\,\mathrm{TeV} - E_{\rm P}$
$\rightarrow$ **Hazma**		$\rightarrow$ **PYTHIA, HERWIG**		$\rightarrow$ HDMSpectra