Primordial Black Holes

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General Relativity black holes

(Natural unit system with $c = \hbar = 1$.)

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

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

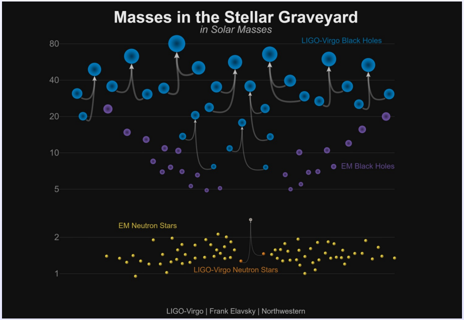
$$a = J/M,\ \Sigma = r^2 + a^2\cos^2\theta,\ \Delta = r^2 - R_s r + a^2,\ R_s = 2GM$$

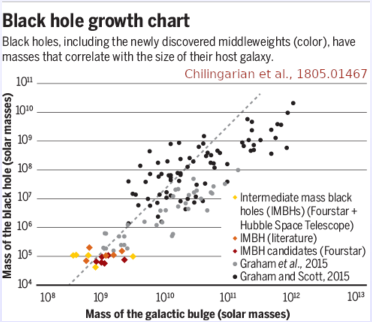
The horizon exists but is deformed and flattened $\longrightarrow$ Kerr (Rotating) Black Hole!

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

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

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

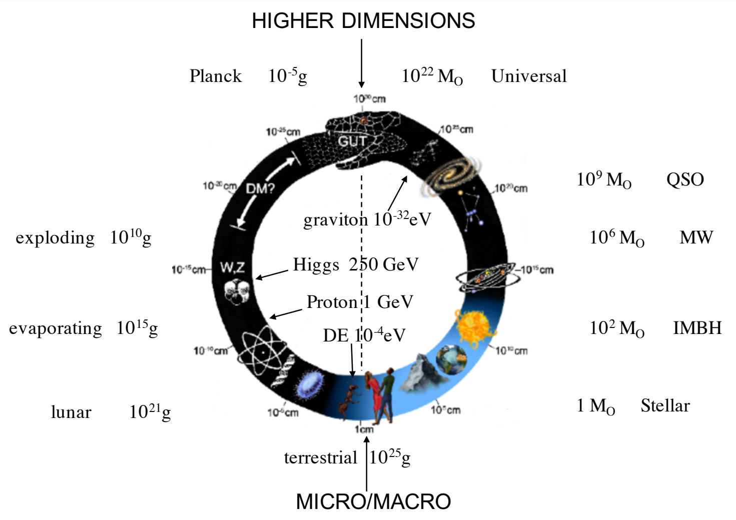
where t_0 is the creation time.

We get:

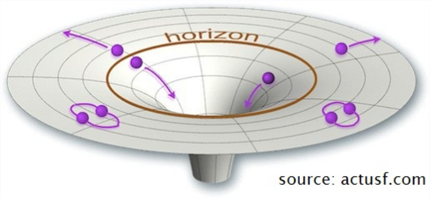
- $M \sim 10^{-5}$ g for $t_0 \sim 10^{-43}$ s $\rightarrow$ Planck black holes
- $M \sim 10^{15}$ g for $t_0 \sim 10^{-23}$ s $\rightarrow$ lightest black holes still (possibly) existing
- $M \sim 10^{5}\ M_\odot$ for $t_0 \sim 1$ s $\rightarrow$ IMBH? seeds for SMBH?

The Cosmic Uroboros

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



Black hole Hawking radiation



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 $\rightarrow$ probes of inhomogeneities, phase transitions, ...

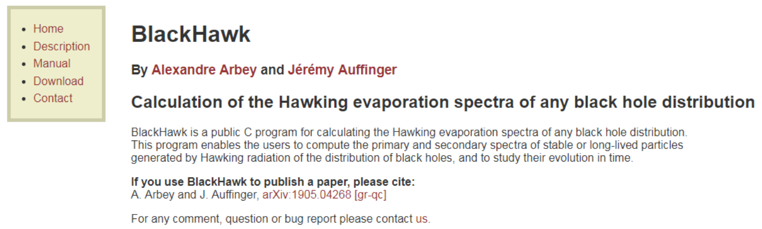
Advertisement: BlackHawk

First public C code computing Hawking radiation:

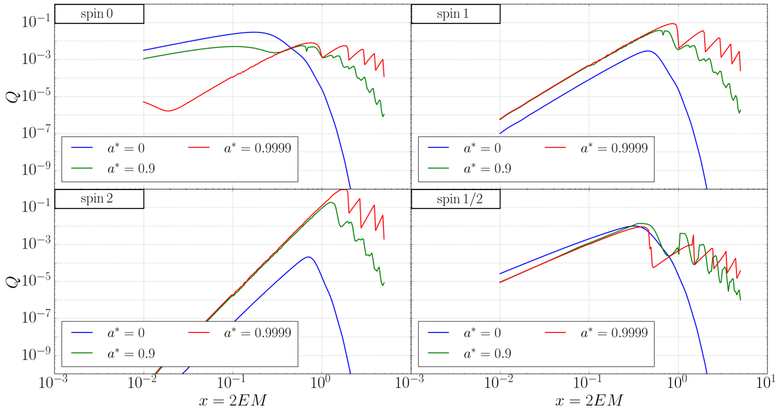
- Schwarzschild & Kerr PBHs
- primary spectra of all Standard Model fundamental particles
- secondary spectra of stable particles (hadronization with PYTHIA or HERWIG)
- extended mass functions
- time evolution of the PBHs

Download: http://blackhawk.hepforge.org

Manual: arXiv:1905.04268, Eur.Phys.J. C79 (2019) 693



Hawking radiation of particles



All particles can be emitted by a black hole!

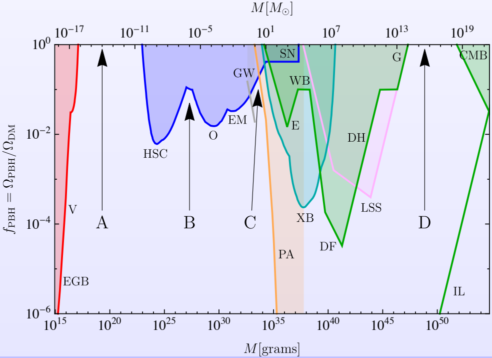
Including gravitons / gravitational waves...

Constraints

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

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
  - 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

Summary

- Primordial black holes are under scrutiny
- They originate from primordial cosmology
- They are linked to different domains of fundamental physics
- Gravitational wave observations have opened a new way to probe black holes
- Primordial black holes are also connected to astroparticle physics

Primordial black holes are prototypical examples of the physics of the two infinities!

THANK YOU FOR YOUR ATTENTION!