Black hole gas in the early universe

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  - ADD
  - Randall-Sundrum
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  A black hole in an expanding Universe
- The scenario
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Motivations

✳ The fundamental scale of gravity

$$M_{Pl} = G_N^{-1/2} \sim 10^{19}\mathrm{GeV}$$

☆ Extra dimensions ⟹ fundamental scale of gravity: $M_D \rightarrow M_D \ll M_{Pl}$

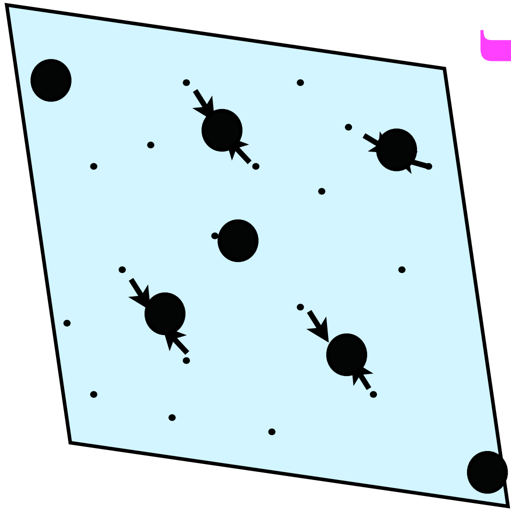
In particular $M_D \sim \mathrm{TeV}$ interesting since solves hierarchy problem.
Various escenarios: ADD gravity, Randall-Sundrum...

NEW PHYSICS !

The Transplanckian regime (collisions at center of mass energies > M_D) dominated by gravity → 2 particles of $s > M_D^2$ form a mini Black Hole!

➥ LCH, early universe T~ M_D

3+n Universe
after inflation
inflaton reheats
the Universe



γ's gas $T \leq M_D$

↓

BH's gas

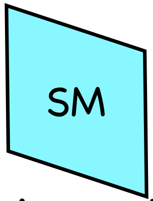
TeV gravity models

ADD gravity

(Arkani-Hamed, Dimopooulos, Dvali, 1998)

Higher dimensional spacetime which is a product of a 4-dim spacetime with a n-dim compact space .

gravitons



$$\boxed{{M_{Pl}}^2 \sim {M_D}^{2+n} L^n}$$

$M_D \sim m_{EW} \sim TeV$ hierarchy problem solved!

SM in the brane
(4+n)-d graviton in the bulk

in 4d
SM + graviton and its KK excitations, 1/L for each extra dim.

KK tower

$$m_n = \frac{n}{L}$$

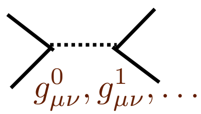
$g^0_{\mu\nu}, g^1_{\mu\nu}, g^2_{\mu\nu} \cdots$ couple $\dfrac{\sqrt{s}}{M_{Pl}}$

n=1, L $\sim 10^{13}$cm, $m_c = 1/L \sim 10^{-29}$GeV
n=2, L $\sim 10^{-4}$m, $m_c \sim 10^{-13}$ GeV
n=3, L $\sim 10^{-9}$m, $m_c \sim 10^{-7}$ GeV

- At the energy scale $\sqrt{s}$ 4d gravity :

$$\rightarrow \left(\frac{\sqrt{s}}{M_{Pl}}\right)^2 \times 1 \sim 1 \text{ @ } \sqrt{s} = M_{Pl}$$

- In (4+n)-d:



$$\rightarrow \left(\frac{\sqrt{s}}{M_{Pl}}\right)^2 \times \left(\frac{\sqrt{s}}{m_c}\right)^n \sim 1 \text{ @ } \sqrt{s} = M_D$$

$$\rightarrow M_D^{2+n} = M_{Pl}^2 / L^n$$

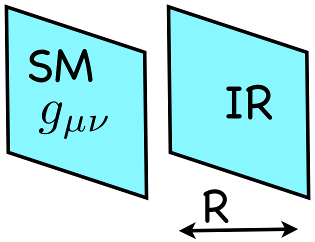
Randall Sundrum

(Randall, Sundrum, 1999)

Higher dimensional spacetime with a warped extra dimension.

$$ds^2 = e^{2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2\,, \quad 0 \le |y| \le \pi R$$

$$M_{Pl}{}^2 = \frac{M_D{}^3}{k}(e^{2kR\pi} - 1)$$



KK tower

$$J_o\left(\frac{m_n}{k}e^{kR\pi}\right) = 0 \rightarrow m_n \sim (n\pi - 0.7)ke^{-kR\pi}$$

massless graviton couples $\frac{\sqrt{s}}{M_{Pl}}$

massive gravitons couple $\mathcal{O}\left(\frac{\sqrt{s}}{M_D}\right)$

$m_c \sim \mathcal{O}(M_D)$

When is gravity of order 1?

ADD

$$10^{31} \; (n=1)$$

$$m_c = 10^{-28} GeV$$

$$\left(\frac{\sqrt{s}}{M_{Pl}}\right)^2 \times \left(\frac{\sqrt{s}}{m_c}\right) = 1 \ @ \ \sqrt{s} = M_D$$

RS

$$4$$

$$m_c = 500 GeV$$

$$\left(\frac{0.5\sqrt{s}}{M_D}\right)^2 \times \left(\frac{\sqrt{s}}{m_c}\right) = 1 \ @ \ \sqrt{s} = M_D$$

! cosmological & astrophysical problems

In general safe if $m_c \geq 1 GeV$

More General-hybrid model with a light warp factor

$$\left(\frac{\sqrt{s}}{M_{Pl}}\right)^2 \rightarrow \left(\frac{\sqrt{s}}{M_D}\right)^2 \left(\frac{m_c}{M_D}\right)^n$$

$m_c \sim M_D (M_D/M_{Pl})^{2/n}$

$$\left(\frac{\sqrt{s}}{M_{Pl}}\right)^2$$

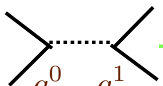
ADD

$m_c \sim M_D$

$$\left(\frac{0.5\sqrt{s}}{M_D}\right)^2$$

RS

$m_c \sim 1 GeV$



$g^0_{\mu\nu}, g^1_{\mu\nu}, \ldots$

$$\left(\frac{\sqrt{s}}{M_D}\right)^2 \left(\frac{m_c}{M_D}\right)^n \times \left(\frac{\sqrt{s}}{m_c}\right)^n = 1 \ @ \ \sqrt{s} = M_D$$

Hybrid model

(Giudice, Plehn, Strumia, 2004)

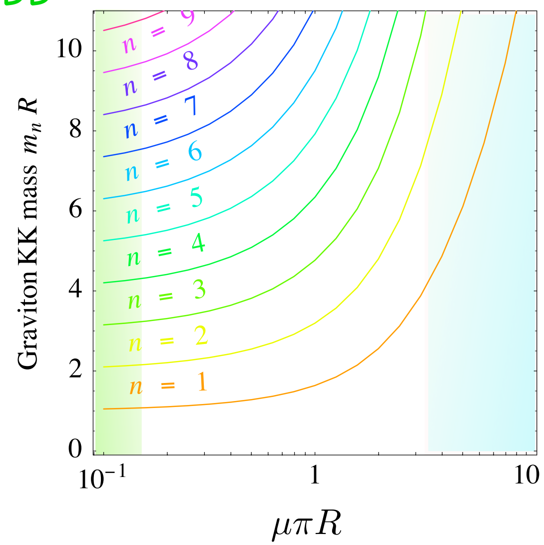
Higher dimensional spacetime with a **slightly** warped extra dimension by introducing a small warp factor.

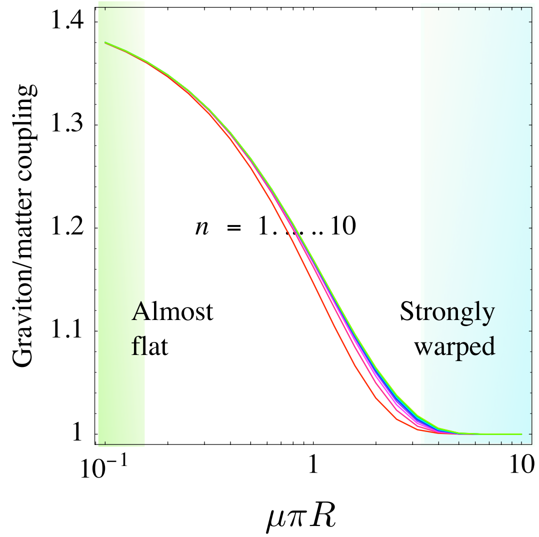
$$ds^2 = e^{2\mu|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2\,, \quad 0 \le |y| \le \pi R$$

$$\boxed{{M_{Pl}}^2 = \frac{{M_D}^3}{\mu}(e^{2\mu R\pi} - 1)}$$

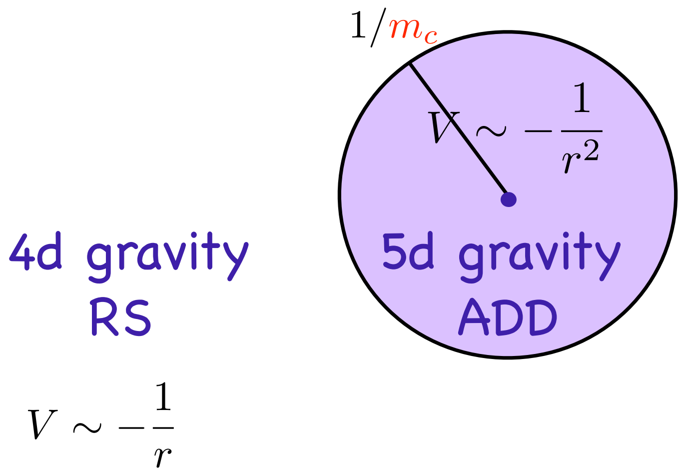
☞ $\mu \ll R^{-1}$ → ADD

☞ $\mu \sim k$ → Randall Sundrum





There is a family of models by changing (μ, R).



$1/m_c$
$V \sim -\frac{1}{r^2}$
5d gravity
ADD
4d gravity
RS
$V \sim -\frac{1}{r}$

Crucial differences

(4+n)-d Universe | **Black Holes** | 4-d Universe

Black holes are colder and live longer in (4+n)-d than in 4-d

$$M_{BH} = 10^{25}\mathrm{GeV}$$

(4+n)-d Universe	4-d Universe
$r_H \sim 10^4 GeV^{-1}$	$r_H \sim 10^{-13} GeV^{-1}$
$T_{BH} \sim 10^{-5} GeV$	$T_{BH} \sim 10^{12} GeV$

(4+n)-d Universe | **Expanding Universe** | 4-d Universe

The Hubble time H^{-1} sets the time scale for the expansion, roughly the scale factor doubles in a Hubble time.

$$H^{-1} \sim \frac{1}{\sqrt{G_N \rho}}$$

For $T \sim M_D$

$$H^{-1} \sim \frac{M_{Pl}}{M_D} \left(\frac{m_c}{M_D} \right)^{n/2} \frac{1}{M_D}$$

For $T \sim M_{Pl}$

$$H^{-1} \sim \frac{M_{Pl}}{M_{Pl}} \frac{1}{M_{Pl}} \sim \frac{1}{M_{Pl}}$$

One black hole

* A black hole in a plasma at temperature T.

Consider n extra dimensions, M_D and $m_c \geq 1$ GeV.

The evolution of the BH basically follows 3 phases:

1. $r_H < 1/m_c$ BH is (4+n)-dimensional :

- $r_H = \frac{a_n}{M_D}\left(\frac{M}{M_D}\right)^{1/(n+1)}$,
- $T_{BH} = \frac{n+1}{4\pi r_H}$

- $$\frac{dM}{dt} \sim \sigma_4 A_4 (T^4 - T_{BH}^4) + \sigma_{4+n} A_{4+n} (T^{4+n} - T_{BH}^{4+n})$$
$$\sim \frac{\pi}{480}\left(\frac{n+1}{T_{BH}}\right)^2 \left(g_\star (T^4 - T_{BH}^4) + g_b c_n \left(\frac{T^n}{T_{BH}^n} T^4 - T_{BH}^4\right)\right)$$

- $\frac{dM}{dt} < \frac{4\pi^3 t^2}{30} T^4 \left(g_\star + g_b c_n \frac{T^n}{m_c^n}\right)$ causal contact

2 $r_H = 1/m_c$ & $M_1 \sim M_D(M_D/(a_n m_c))^{n+1}$

The BH size doesn't grow,

$r_H \sim \mathrm{const}, T_{BH} \sim \mathrm{const}$.

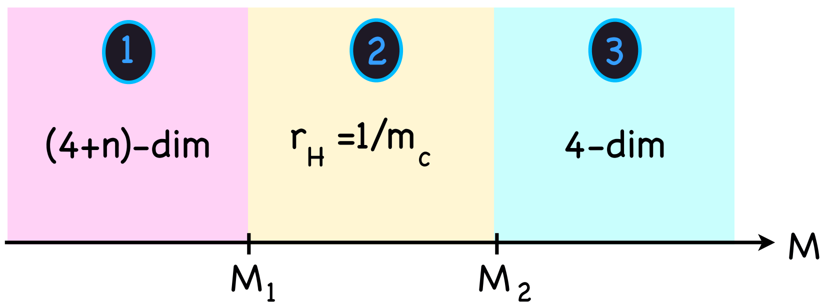
It keeps gaining mass if $T > T_{BH} \sim m_c$.

3 BH is 4 dimensional.

The BH mass reaches a value $M_2 \sim M_P^2/m_c$ corresponding to $r_{H\,(4d)} = 1/m_c$.

Its radius grows larger than $1/r_c$.

- $T > m_c \rightarrow \dfrac{dM}{dt} \sim \dfrac{\pi}{480}\left(g_\star + g_b c_n \dfrac{T^n}{m_c^n}\right)\dfrac{T^4}{T_{BH}^2}$
- $T < m_c \rightarrow \dfrac{dM}{dt} \sim \dfrac{\pi}{480}\left(\dfrac{T^4}{T_{BH}^2} - T_{BH}^2\right)$



A light BH, hotter than the plasma will evaporate.

A heavy BH, colder than the plasma will gain mass,
heat will flow from the hot plasma to the cold BH,
it will make it more massive and colder.

The expansion of the universe

We assume the extra dimensions are frozen. The large values of m_c → large enough couplings with brane photons → the KK modes of mass larger than T negligible.

$$T > m_c \quad \begin{cases} \rho_{rad} \sim \dfrac{\pi^2}{30} T^4 \left(g_\star + g_b c_n \dfrac{T^n}{m_c^n} \right) \\ \dfrac{\dot{R}^2}{R^2} = \dfrac{8\pi G_N}{3} \rho_{rad} \end{cases}$$

Brane energy dominates → $T \sim t^{1/2}$

Bulk energy dominates → $T \sim t^{2/(4+n)}$

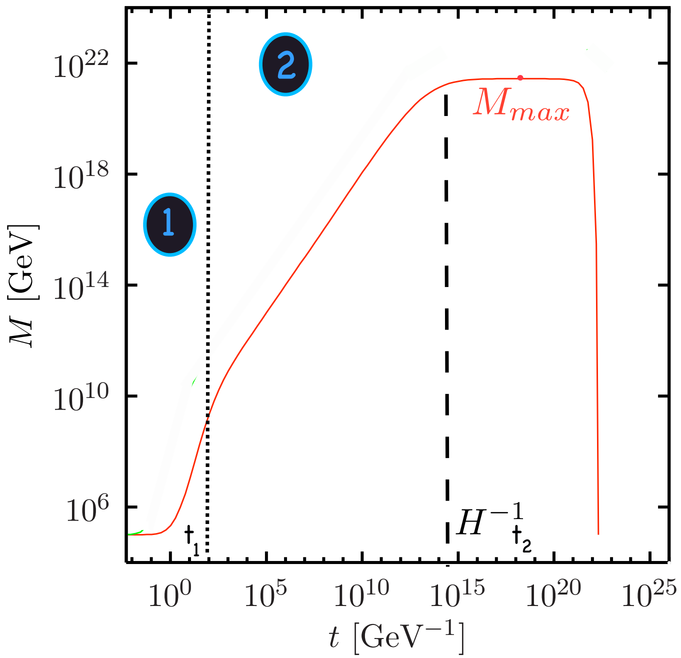
Toy model $M_D = 1\mathrm{TeV}$, $n = 1$,and just photons, $g_\star = 2$, and gravitons, $g_b = 5$, at $T_0 = 100\mathrm{GeV}$

$$H^{-1} = 9.2 \times 10^{-9} s.$$

- $M_0 < M_{\mathrm{crit}} \to \tau \sim 6.5 \times 10^{-28} s.$
- $M_0 = 100\mathrm{TeV} \to T = 8.7\mathrm{GeV}$

  $t_1 \sim 17\mathrm{GeV}^{-1} \to M \sim 10^7\mathrm{GeV} \to r_H \sim 0.1\mathrm{GeV}^{-1}$

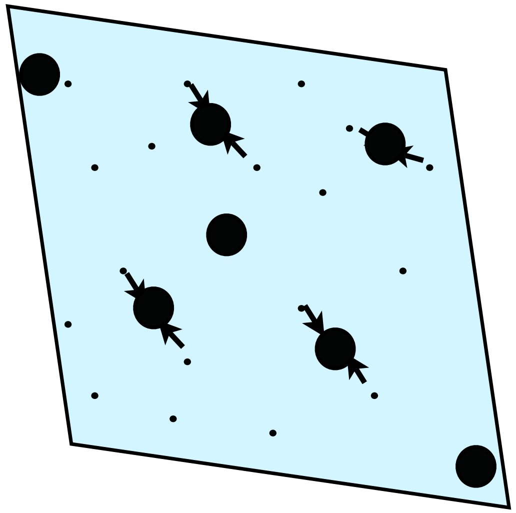
  $T = T_{BH} \to M_{max} \sim 10^{21}\mathrm{GeV}$, $t_2 \sim 10^{18}\mathrm{GeV}^{-1}$



Phase 3 would be reached for $M > 10^{37}\mathrm{GeV}$, and could be obtained either increasing n and/or the ratio M_D/m_c .

The Scenario

5d hybrid model, the Universe at $T \leq M_D$, with 4d photons from reheating after a period of inflation and gravitons in the bulk.



$f(M,t)$

number of BH's of mass M at time t in the Universe per unit mass and unit volume.

- Do BH's dominate the energy density of the Universe?
- How big they grow?
- Do they evaporate? When?
- How high can the initial T_{Univ} be?

☞ BH's are non-relativistic matter $M_{BH} \gg M_D \gg T_{rad}$

$$E_{BH} \sim M_{BH}\,, \quad v_{BH} = \sqrt{2T_{rad}/M_{BH}}$$

2-component thermodynamic system
BLACK HOLE GAS

- radiation at $T(t)$
- BH's with a distribution of masses $f(M,t)$;

$$T_{BH} \sim M_D \left(\frac{M_D}{M_{BH}}\right)^{1/2}$$

$$\rho(t) = \rho_{rad}(t) + \rho_{BH}(t) \sim \frac{\pi^2}{30} T^4 \left(g_\star + g_b c_n \frac{T^n}{m_c^n}\right) + \int dM\, M f(M,t)$$

Dynamics of a black hole gas

1. BH's formation from a thermal distribution of photons at T_{rad}: photons will collide with a cross section $\sigma(M) \sim \pi r^2$ to form a BH of mass $M \sim \sqrt{s}$

$$\frac{df(M,t)}{dt} \sim \int \frac{d^3k_1}{(2\pi)^3}\frac{d^3k_2}{(2\pi)^3} f(\vec{k}_1) f(\vec{k}_2)\sigma(M)|\vec{v}_1 - \vec{v}_2|\delta(\sqrt{(k_1^\mu + k_2^\mu)^2} - M)$$

$$\sim \frac{g_\star^2 a_n^2}{16\pi^3} T M^2 \left(\frac{M}{M_D}\right)^{\frac{4+2n}{1+n}} K_1(M/T)$$

We neglect the BH production in collisions of bulk particles (although KK modes dominate the energy density, their cross section is smaller → order one contribution)

2. BH's of mass M_1 & M_2 collide to form one of $M = M_1 + M_2$:

$$\frac{df(M,t)}{dt} \sim \int dM_1 dM_2 f(M_1) f(M_2) \sigma(M_1, M_2)\langle v(M_1,M_2)\rangle \delta(M_1 + M_2 - M)$$

$$\sigma(M_1, M_2) \sim \pi(r_1 + r_2)^2$$

where the BH velocity is $v_i = \sqrt{2T/M_i}$ and $v_{12} = \langle|\vec{v_1} - \vec{v_2}|\rangle$.

3. A BH of mass M may collide with one of M_1 reducing the BH's of mass M:

$$\frac{df(M,t)}{dt} \sim -\int_{M_D}^{\infty} dM_1 f(M_1) f(M) \sigma(M_1, M)\langle v(M_1, M)\rangle$$

4. The change on the # of BH of mass M due to evaporation/absorption of T_{rad} :

$$\frac{dM}{dt} \sim \frac{\pi}{480}\left(\frac{n+1}{T_{BH}}\right)^2 \left(g_\star(T^4 - T_{BH}^4) + g_b c_n \left(\frac{T^n}{T_{BH}^n} T^4 - T_{BH}^4\right)\right)$$

A BH of mass M will have a mass M+dM at time t+dt:

$$f(M,t) = f(M+dM, t+dt) \quad \Longrightarrow \quad \frac{df(M,t)}{dt} = -\frac{df}{dM}\frac{dM}{dt}$$

5. The effect of expansion:

$$\frac{\dot{R}^2}{R^2} = \frac{8\pi G_N}{3}(\rho_{rad} + \rho_{BH})$$

this dilutes the number of BHs at a rate: $\left.\frac{\partial f(M,t)}{\partial t}\right|_{exp} = -3f(M,t)\frac{\dot{R}}{R}$

1+2+3+4+5

+ energy conservation

$$\dot{\rho}_{BH} = \int dM\, M\, \frac{\partial f(M,t)}{\partial t}$$

$$d(\rho_{rad}R^3) + d(\rho_{BH}R^3) = -\frac{1}{3}\rho_{rad}dR^3$$

$$R^3(1+\alpha)d\rho_{rad} = -\frac{4}{3}\rho_{rad}dR^3 \qquad \alpha = \left(\frac{\partial\rho_{BH}}{\partial\rho_{rad}}\right)_{R=cons}$$

for a small interval where $\alpha = const$:

$$\rho_{rad} \sim \rho_{rad0}\left(\frac{R_0}{R}\right)^{\frac{4}{1+\alpha}}$$

The Scenario

Consider an initial configuration with only radiation, no BH's at a given temperature $T(0) = T_0$, then there are two generic scenarios depending on T_0 :

* Black hole dominated plasma for high T_0 :
  a large number of BHs is produced that grow and absorb all the radiation before a Hubble time.

* Radiation dominated plasma for low T_0 :
  a small number of BHs is produced that grow at basically constant temperature up to a Hubble time.

Black hole dominated plasma

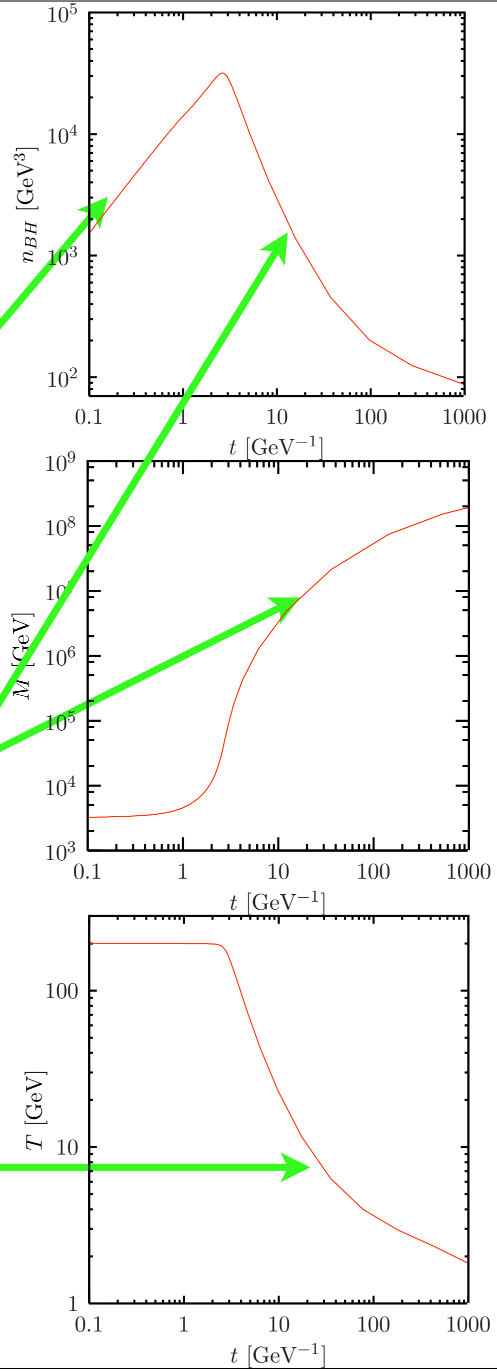
Toy model with $n=1$, $g_*=2$, $g_b=5$, $m_c=10\,\mathrm{GeV}$, $M_D=1\,\mathrm{TeV}$ and $T_0=200\,\mathrm{GeV}$ $M_c=3\,\mathrm{TeV}$.

Distinguished by 4 phases:

I BHs of $M>M_{crit}$ are produced at constant rate and absorb radiation.

As the number of BHs grows the collisions between 2 BHs become important, increasing their average mass, but reducing the number of BHs.

At times close to 2 GeV^{-1} BHs start dominating the energy density and the temperature of radiation drops. They are 5 dim (phase 1).



II The drop in the temperature stops the production of BHs in $\gamma + \gamma$.
Lighter BHs become hotter than plasma, evaporate and feed T_{rad}.
The evaporation reduces the number of BHs while its average mass keeps growing (energy transfer from light to massive BHs).
When the BHs reaches a mass around 10^7GeV their radius stops growing (they enter into phase 2).

III At times close to 10^4GeV^{-1} the temperature of the radiation equals the one of the BHs close to 1 GeV.
The slow growth of the heavier BHs compensates the decay of the lighter $\rightarrow$ T_{rad} is basically constant.
The energy density is BH (matter) dominated.

IV At a Hubble time, 10^{13}GeV^{-1}, the expansion cools the radiation.
The BHs decay fast and the universe becomes radiation dominated.
The lightest KK modes also decay fast and only 4 dim photons survive below temperatures of 1 GeV.

Remarks

- ☞ In models with lower values of m_c/M_D two types of matter, baryons and BHs could coexist.
  So, in a more complete set up one should include baryons at temperatures below 0.1 GeV.

- ☞ This generic case, with M_D >5 TeV avoiding bounds from colliders and including all standard model species, could define a realistic set up since the predictions for primordial nucleosynthesis would be consistent with observations.

Radiation dominated plasma

Toy model with $n=1$, $g_*=2$, $g_b=5$, $m_c=10GeV$, $M_D=1TeV$ and $T_0=100GeV$. $M_c=12TeV$.

Distinguished by 3 phases:

I At times less than a Hubble time, BHs are produced in $\gamma+\gamma$.
The number of BHs is so small that collisions are neglected.
All the BHs grow like in the case of a single BH.

II When the expansion drops the temperature, the BH production drops exponentially and the BH growth slow down.
The Universe is always radiation dominated.
At times of $10^{18}GeV^{-1}$ the photon gas becomes colder than the BHs.

III All BHs evaporate at times of $10^{22}GeV^{-1}$.

Remarks

- ☞ This generic scenario is in principle consistent with primordial nucleosynthesis, since the small fraction of BHs doesn't alter the expansion rate.

- ☞ In this case the BHs decay at temperatures of 0.01 GeV, but by increasing M_D/m_c one can obtain BHs that become 4d with longer lifetimes. Their late decay could introduce distortions in the diffuse gamma ray background.

- ☞ A more complete set up including baryons and structure formation they might work as seeds for primordial BHs and/or dark matter.

Conclusions

- The presence of extra dimensions opens up the possibility for $M_D \sim \mathrm{TeV}$ or below the Planck scale.

NEW PHYSICS

In particular if the maximum temperature of the Universe after reheating is $\sim M_D$, the formation of a **gas of Black Holes** in the Early Universe is an important effect which can totally change the Standard Cosmology.

Contrary to elementary particles, the heavier the BHs the longer their life-time are.

Observational constraints can limit the maximum temperature after reheating in these models.

This work is a first step in the search for observable effects from these BHs.

We are working in a realistic model by

- better modeling of the growth of the BH radius in phase 2
- including of all the SM species

which predictions for primordial nucleosynthesis will be consistent with observations.

The end