Title: Asymmetric Hawking Radiation : Baryogenesis from Hawking Radiation

Date: Jul 29, 2014 01:00 PM

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Abstract: We show that in the presence of a chemical potential, black hole evaporation generates baryon number. If the inflaton or Ricci scalar is derivatively coupled to the B-L current, the expansion of the universe acts as a chemical potential and splits the energy levels of particles and their anti-particles. The asymmetric Hawking radiation of primordial black holes can thus be used to generate a B-L asymmetry. If dark matter is produced by the same mechanism, the coincidence between the mass density of visible and dark matter can be naturally explained.


Asymmetric Hawking Radiation
Baryogenesis from Hawking Radiation
Anson Hook
IAS
1404.0113: AH

Motivation

- We observe a universe that is full of matter but not anti-matter
- Our universe has a net baryon number
- Why do we have to explain this number?
  - Arbitrary initial condition
  - Inflation inflates away any original asymmetry

Popular Mechanisms of Baryogenesis

- Electroweak baryogenesis
  - Use a bubble from a strong first order phase transition to generate a net B+L
- Freeze out and decay
  - Standard GUT way of doing baryogenesis

Popular Mechanisms of Baryogenesis

- Dirac leptogenesis
  - Don't generate a net B but separate it into two separate sectors (right handed neutrinos, dark matter, …)
- Affleck-Dine baryogenesis
  - Use a coherent scalar field excitations
- Spontaneous Baryogenesis
- …

New Physics?

- We know of a force which breaks baryon number
- Gravity!
  - No hair theorem says that black holes do not carry charges other than Q and spin (>4 dimensions can find solutions with scalar hair)
  - Create a black hole out of neutrinos and it forgets that it had any charge and evaporates thermally (symmetrically)
  - Every known example of quantum gravity has no global symmetries

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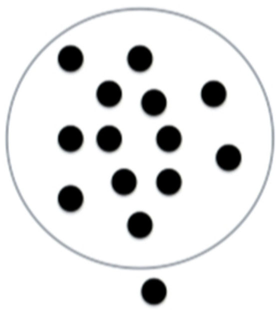
Gravity and Global Symmetries

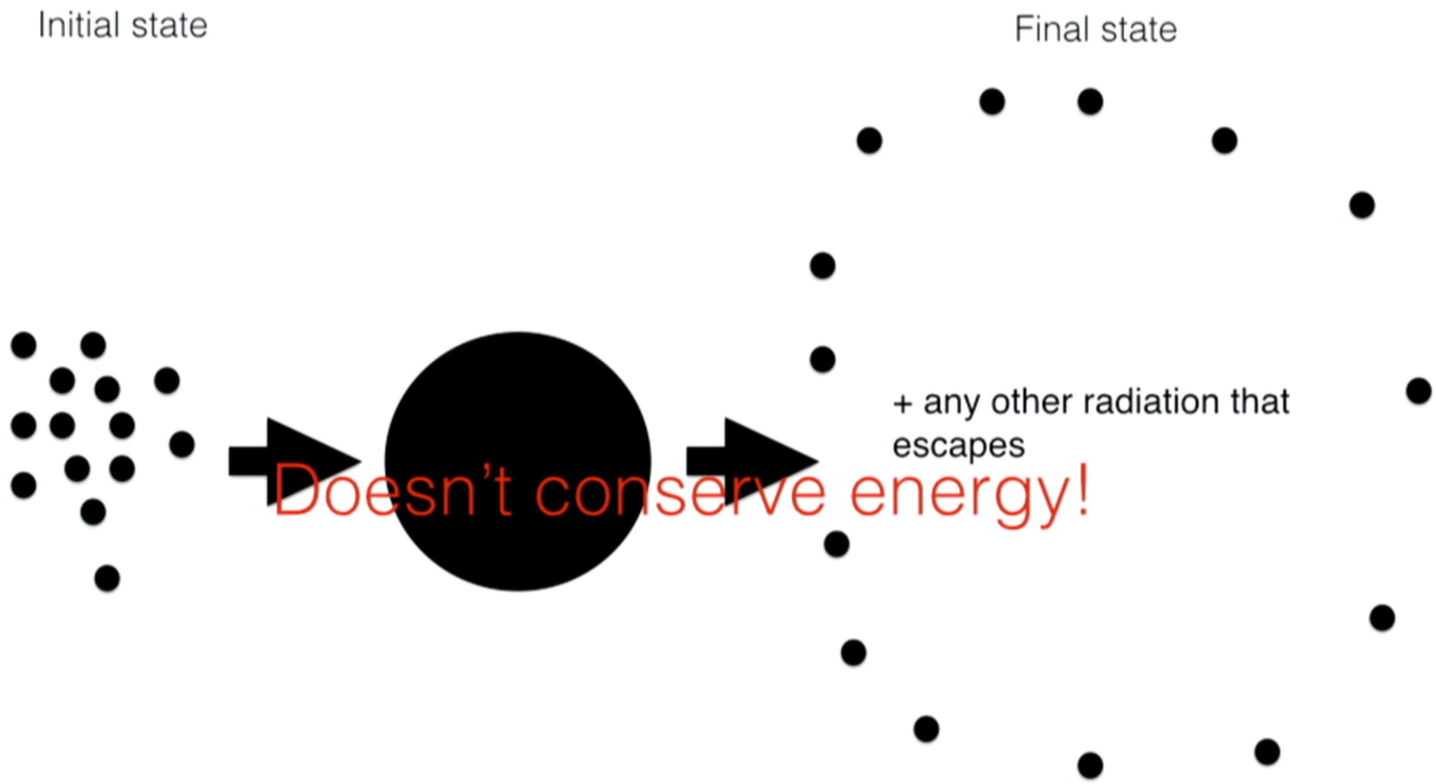


Assume black holes conserve B-L and derive a contradiction

Create a black hole out of neutrinos at rest

To make dynamical say almost a black hole with a single neutrino about to fall in and make a black hole

Gravity and Global Symmetries



Gravity + us = baryogenesis

- Any one of us could implement baryogenesis if a black hole is present
- Throw anti-baryons into a black hole
  - B-L number destroyed by black hole
- A baryogenesis mechanism present in the SM!
- Of course we don't exist in the early universe so we need black holes to generate B-L rather than destroy it

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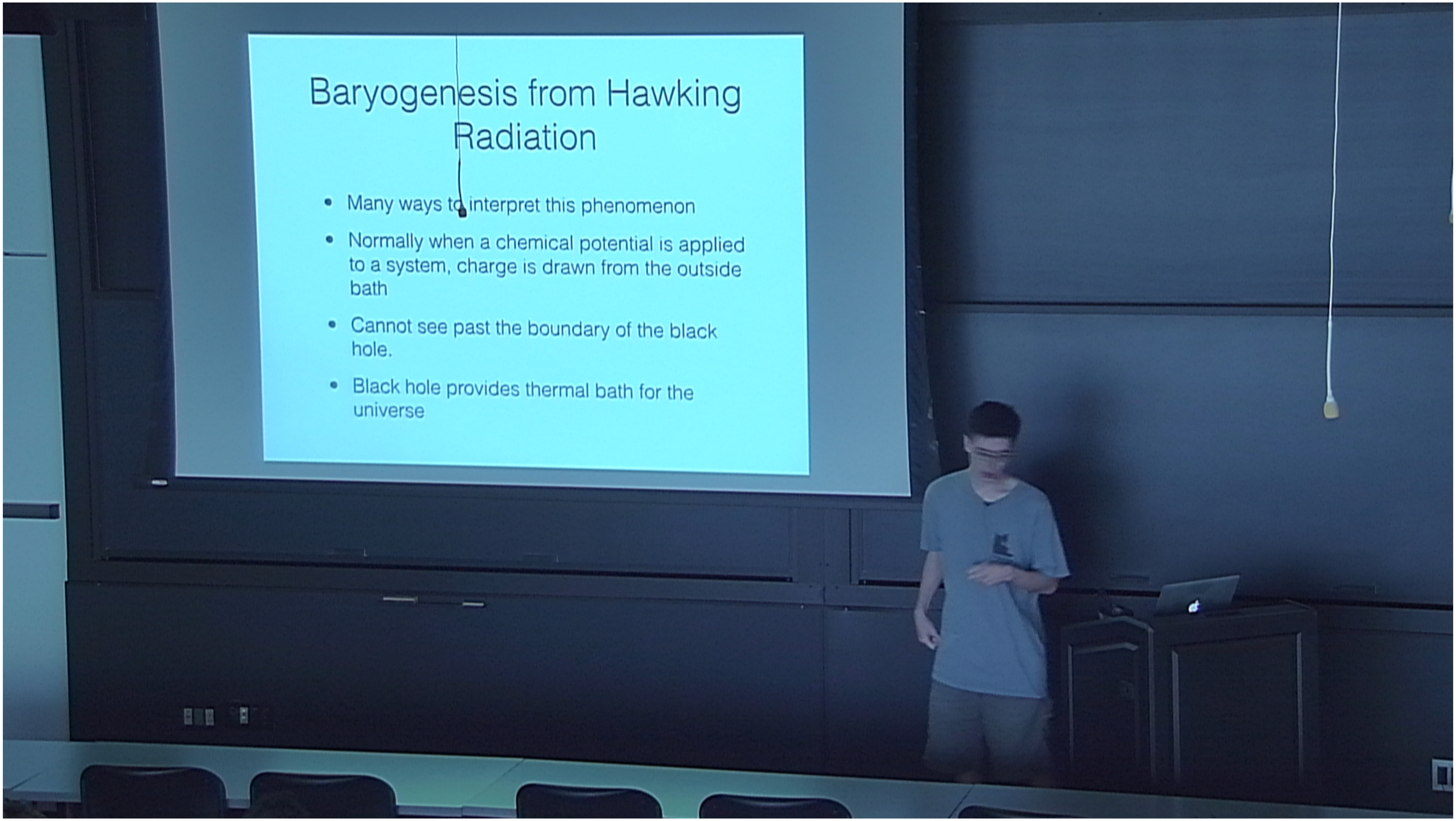
Toy example

- Analogy with right handed neutrinos
  - Black holes can decay to smaller black holes via emission of neutrinos or anti-neutrinos
  - These decays happen equally with a rate that turns out to be thermal with a Hawking temperature
- How does a Black hole decay in the presence of a chemical potential?
- Thermal systems carry a charge when there is a chemical potential!
  - The thermal nature destroyed charge before and now it generates charge!


Baryogenesis from Hawking Radiation
Many ways to interpret this phenomenon
Normally when a chemical potential is applied to a system, charge is drawn from the outside bath
Cannot see past the boundary of the black hole.
Black hole provides thermal bath for the universe

SM + Gravity/Inflation

- Gravity describes the universe very accurately
- Standard Model should be augmented by an inflaton describing inflation and dynamical gravity
- As effective field theorists, we write down all Planck suppressed operators consistent with symmetries

SM + Gravity/Inflation

- To get a flat potential, the inflaton typically has a shift symmetry
  - Potential should depend on derivatives of inflaton
- Leading operator coupling the inflaton to the SM is

$$\mathcal{L} \supset \int dx^4 \sqrt{-g}\,\frac{\partial_\mu \phi}{M_\star}\,J^\mu_{B-L}$$

SM + Gravity/Inflation

- When coupling to gravity, one of the leading Planck suppressed operators is

Davoudiasl, Kitano, Kribs, Murayama, Steinhardt : hep-ph/0403019

$$\mathcal{L} \supset \int dx^4 \sqrt{-g}\lambda \frac{\partial_\mu \mathcal{R}}{M_p^2} J^\mu_{B-L}$$

- The expansion of the universe results in a chemical potential!

$$\mu_i = \lambda q_i \frac{\dot{\mathcal{R}}}{M_p^2} = -9\lambda q_i (1+w)(1-3w)\frac{H^3}{M_p^2}$$

Hawking Radiation

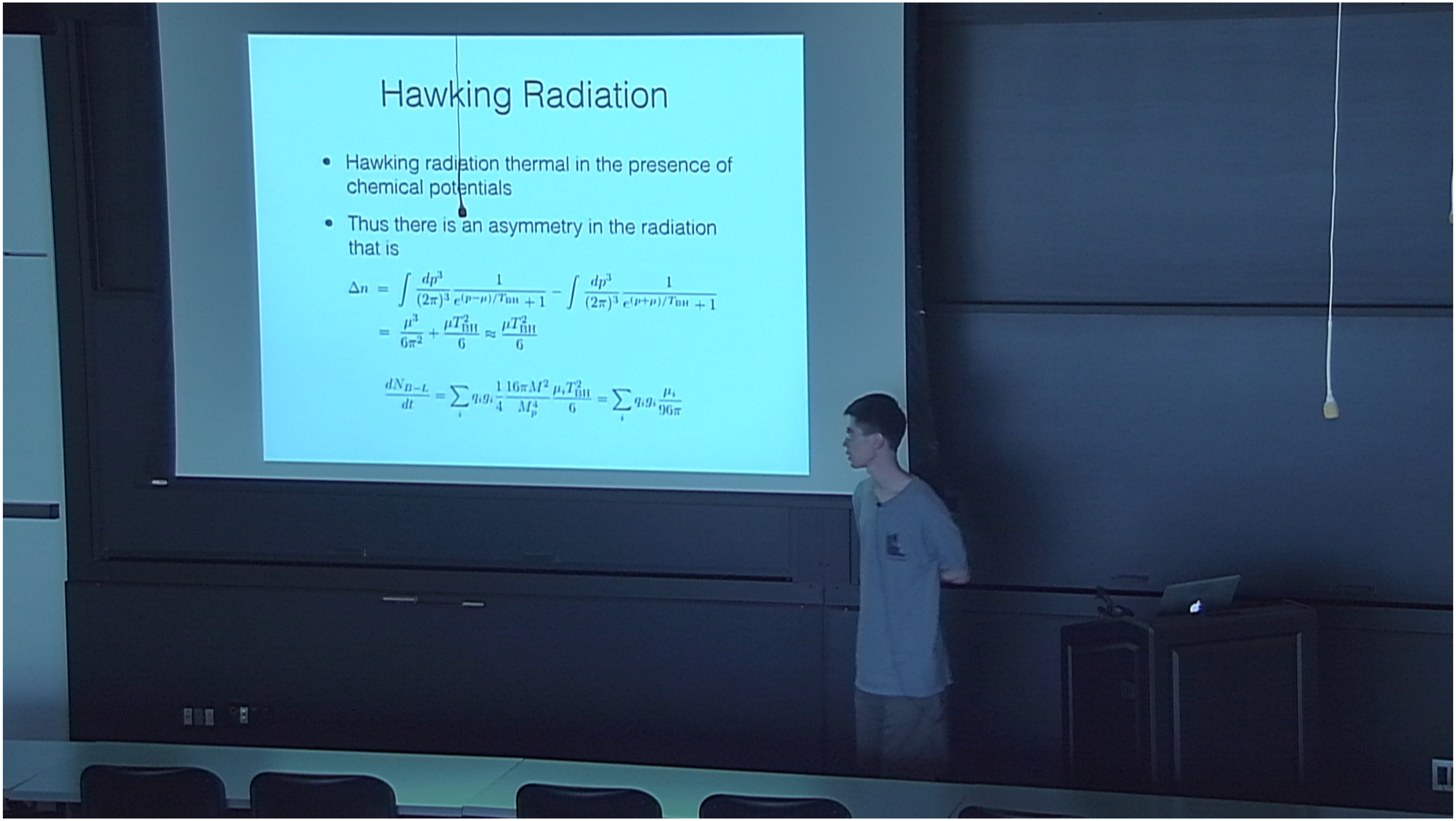
- Black holes have a temperature
- Easiest derivation
  - Analytically continue the space time to Euclidean space
  - Require that there are no deficit angles
  - Time is forced to be periodic with the Hawking temperature!
- No reference made to matter content or chemical potentials
  - Correct temperature regardless of matter content and chemical potentials

Hawking Radiation

- Hawking radiation thermal in the presence of chemical potentials
- Thus there is an asymmetry in the radiation that is

$$\Delta n = \int \frac{dp^3}{(2\pi)^3} \frac{1}{e^{(p-\mu)/T_{\rm BH}} + 1} - \int \frac{dp^3}{(2\pi)^3} \frac{1}{e^{(p+\mu)/T_{\rm BH}} + 1}$$
$$= \frac{\mu^3}{6\pi^2} + \frac{\mu T_{\rm BH}^2}{6} \approx \frac{\mu T_{\rm BH}^2}{6}$$

$$\frac{dN_{B-L}}{dt} = \sum_i q_i g_i \frac{1}{4} \frac{16\pi M^2}{M_p^4} \frac{\mu_i T_{\rm BH}^2}{6} = \sum_i q_i g_i \frac{\mu_i}{96\pi}$$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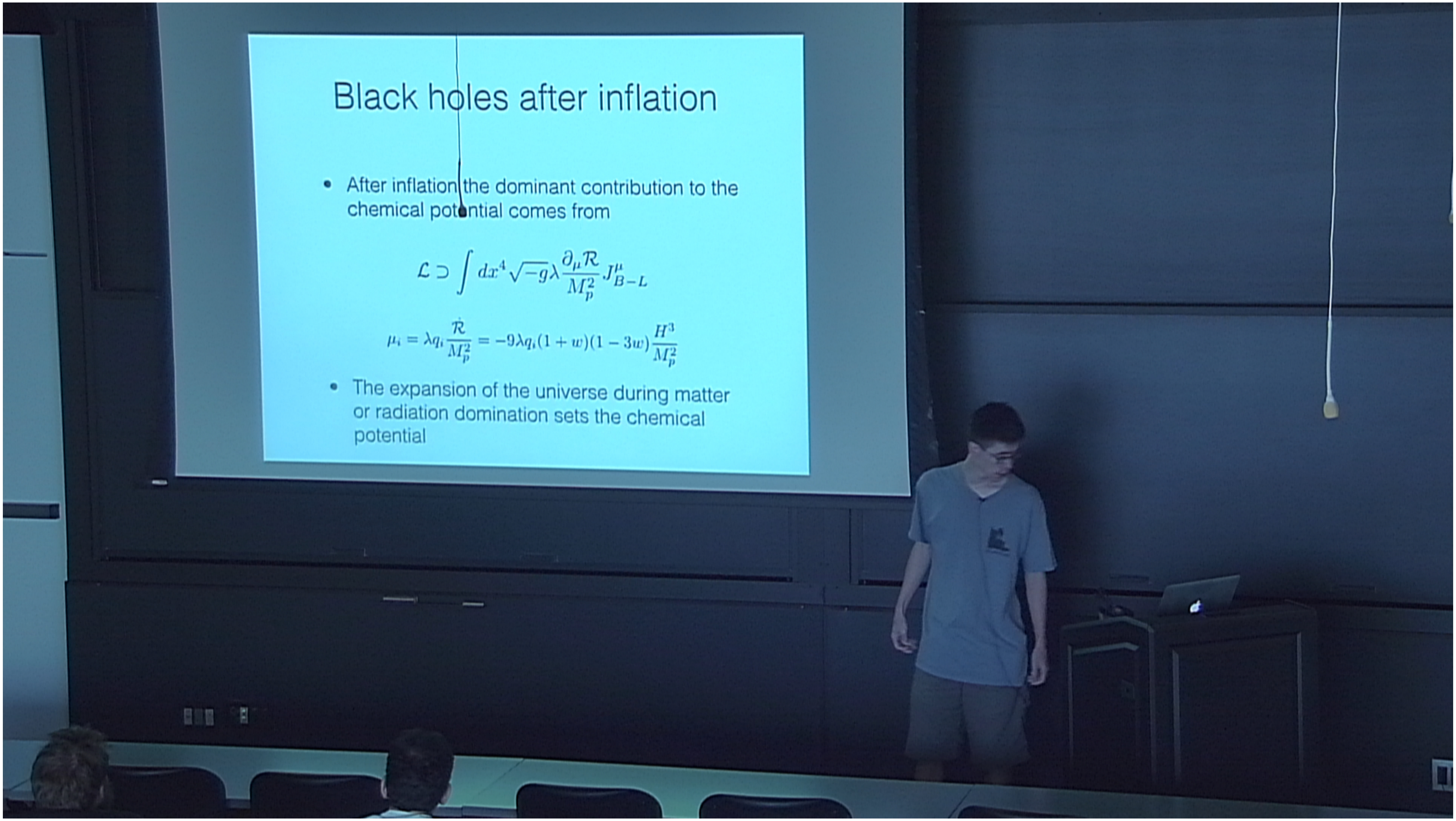
Source of black holes

- We will be agnostic about the source of black holes
- After inflation : many standard stories
  - Hybrid inflation : Large density perturbations result in black holes
  - Smaller density perturbations can result in gravitational collapse
- During inflation : much more difficult
  - Production from brane collisions
  - Inflaton decays into black holes in warm inflation type models
  - Only needs to be produced in the last e-foldings of inflation


Black holes after inflation
After inflation the dominant contribution to the chemical potential comes from
$\mathcal{L} \supset \int dx^4 \sqrt{-g} \lambda \frac{\partial_\mu \mathcal{R}}{M_p^2} J^\mu_{B-L}$
$\mu_i = \lambda q_i \frac{\dot{\mathcal{R}}}{M_p^2} = -9\lambda q_i (1+w)(1-3w) \frac{H^3}{M_p^2}$
The expansion of the universe during matter or radiation domination sets the chemical potential

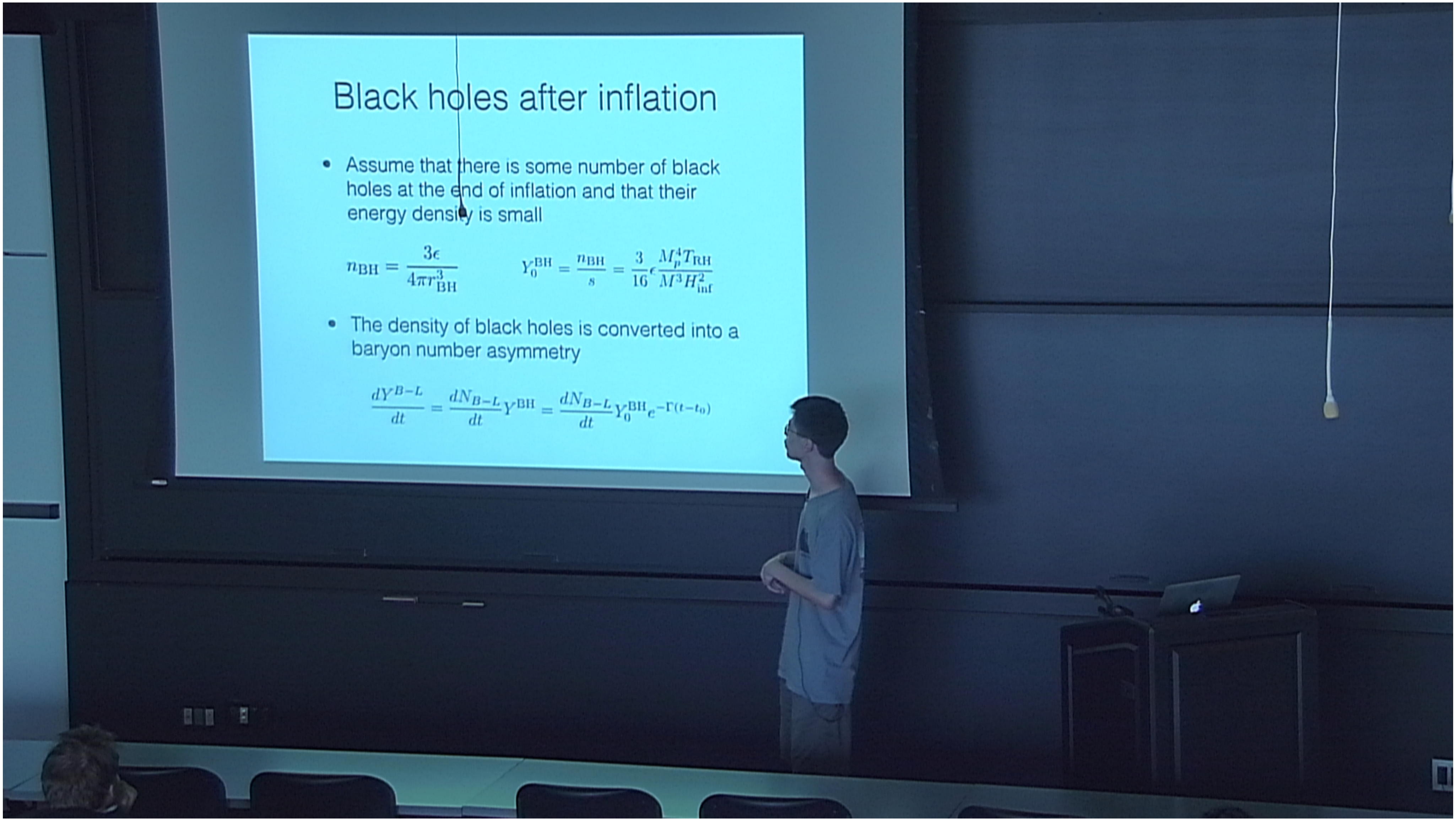
Black holes after inflation

- At leading order, during radiation domination the chemical potential vanishes
- At the loop level, the running of the gauge coupling constant gives the result

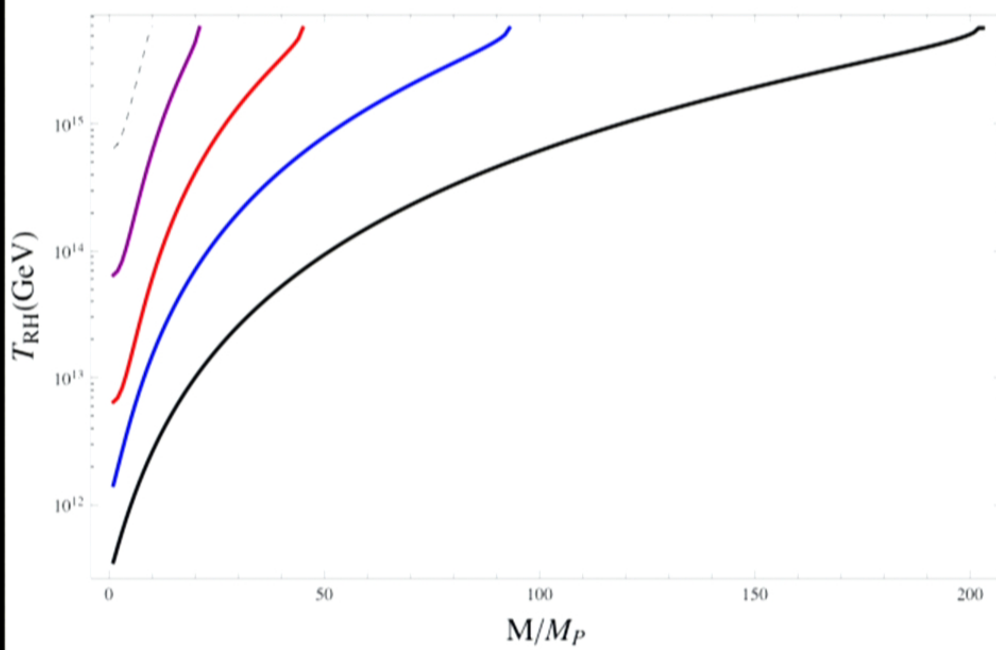
$$1 - 3w = \frac{5}{6\pi^2} \frac{g^4}{(4\pi)^2} \frac{(N_c + \frac{5}{4}N_f)(\frac{11}{3}N_c - \frac{2}{3}N_f)}{2 + \frac{7}{2}(N_c N_f/(N_c^2 - 1))}$$

- Part per thousand for the SM, but can be much larger if the matter content is non-minimal

Kajantie, Laine, Rummukainen, Schroder : hep-ph/0211321


Black holes after inflation
Assume that there is some number of black holes at the end of inflation and that their energy density is small
$n_{\rm BH} = \frac{3\epsilon}{4\pi r_{\rm BH}^3}$
$Y_0^{\rm BH} = \frac{n_{\rm BH}}{s} = \frac{3}{16}\epsilon\frac{M_p^4 T_{\rm RH}}{M^3 H_{\rm inf}^2}$
The density of black holes is converted into a baryon number asymmetry
$\frac{dY^{B-L}}{dt} = \frac{dN_{B-L}}{dt}Y^{\rm BH} = \frac{dN_{B-L}}{dt}Y_0^{\rm BH}e^{-\Gamma(t-t_0)}$

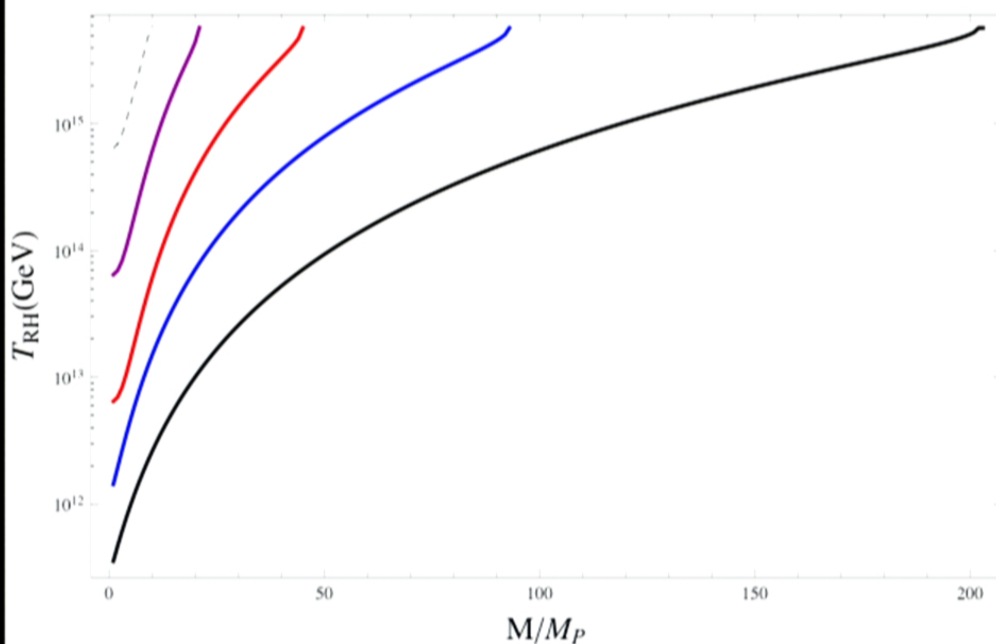
Black holes after inflation



Numerical solution for contours of the correct abundance as a function of mass of the black hole and reheat temperature

Black, Blue, Red, Purple, Dashed Black lines correspond to $\lambda\epsilon$ = 100, 10, 1, 0.1, 0.01

Black holes after inflation



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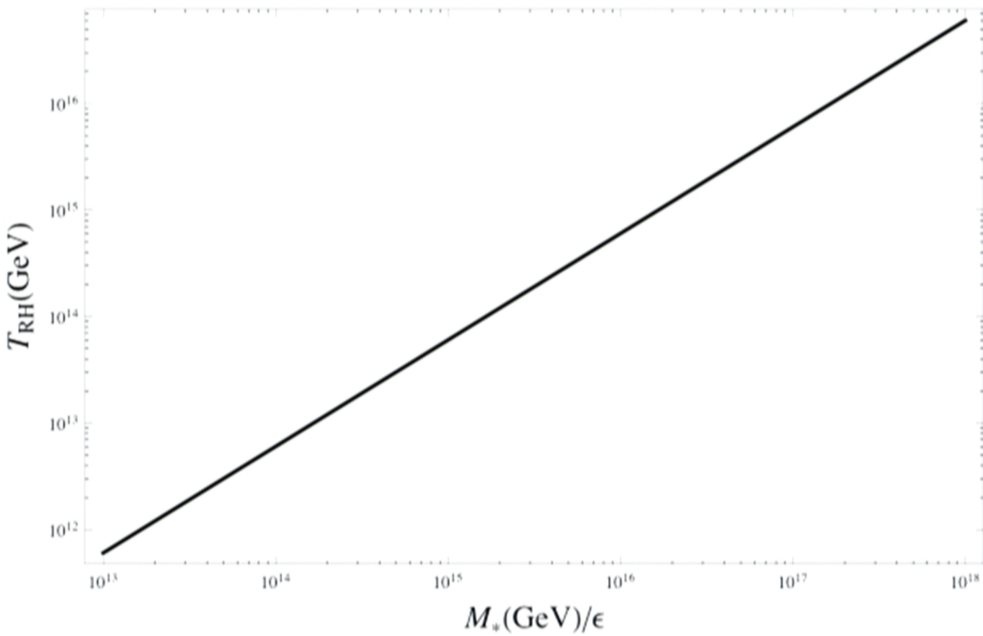

No large numbers are needed

If inflaton couples to the SM through GUT scale suppressed operators, there is already plenty of parameter space available

Black holes during inflation

- We are implicitly assuming that the black holes are significantly smaller than the Hubble radius
- We understand black holes that are in equilibrium
  - We are considering black holes in the first 1/H seconds of their life, they need to equilibrated by then
- Large black holes also behave strangely
  - Depending on initial conditions, can actually anti-evaporate!

Bousso, Hawking : gr-qc/9606052

Conclusion + Future directions

- The leading order terms connecting the SM to gravity or the inflaton act as chemical potentials due to expansion of the universe
- Baryogenesis can be obtained by utilizing the fact that black holes break global symmetries to extract B-L asymmetry from black holes
- Provides an alternative to electroweak baryogenesis in the context of the SM + gravity

Conclusion + Future directions

- Other terms can act as a chemical potential. Maybe alleviates the problem of large couplings?
- Understanding chemical potential at horizon
- Observational consequences?
  - Hubble much smaller today so difficult