BLACK HOLES FROM COSMIC INFLATION

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Black hole puzzles

1. Supermassive black holes

$M \sim 10^6 - 10^{10} M_\odot$, already present at *z* ~ 7.

How were they formed?

2. LIGO observations

Gravitational waves from in-spiraling and colliding black holes.

More massive than expected: $M \sim 30 M_\odot$

⇨ *Primordial black holes formed in the early universe?*

Most scenarios predict unacceptably large spectral distortions of the CMB (for $M > 10^4 M_\odot$).

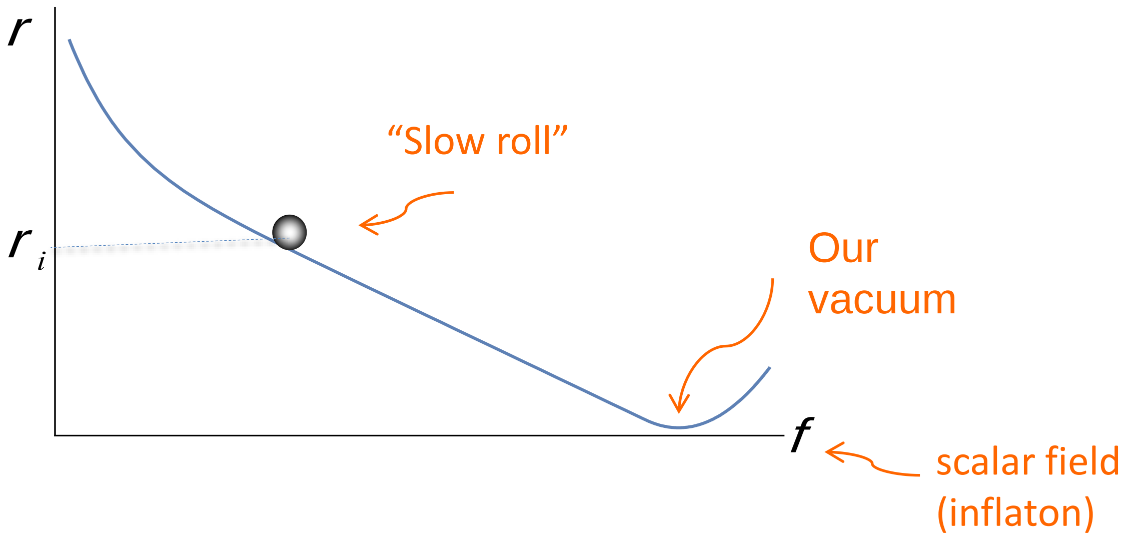
This talk: a new mechanism of black hole formation.

- Vacuum bubbles spontaneously nucleate during inflation.
- They expand to very large sizes and collapse to black holes after inflation ends.

⇨ BH distribution with a very wide spectrum of masses.

Work with Jaume Garriga, Jun Zhang, Heling Deng and Masaki Yamada

Inflation – a period of accelerated expansion driven by the potential energy of a scalar field.

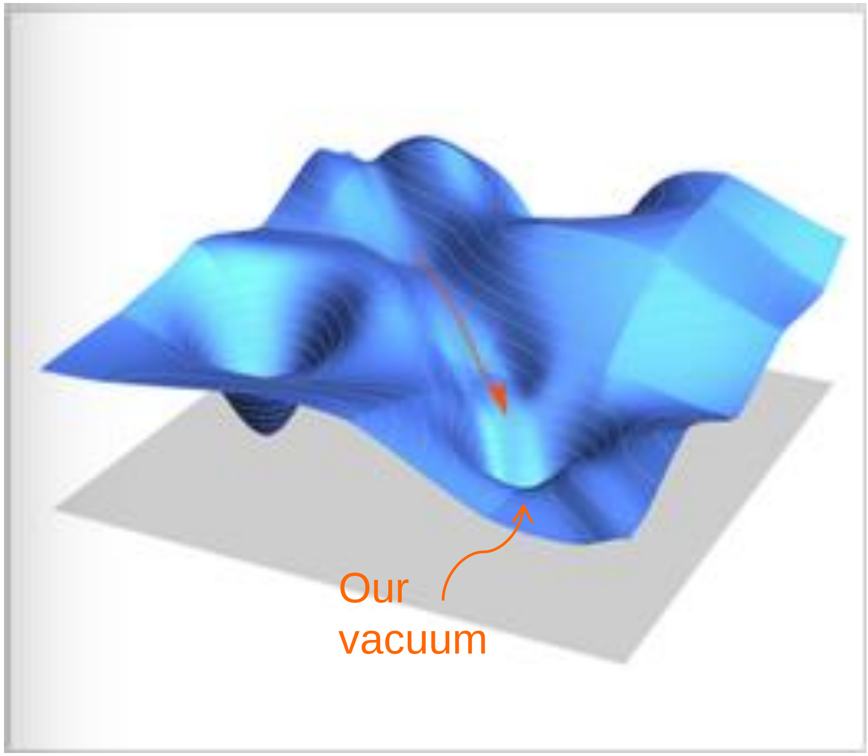


$$a(t) \text{ » } \exp(H_i t)$$

$$H_i = \left(8pGr_i / 3\right)^{1/2}$$

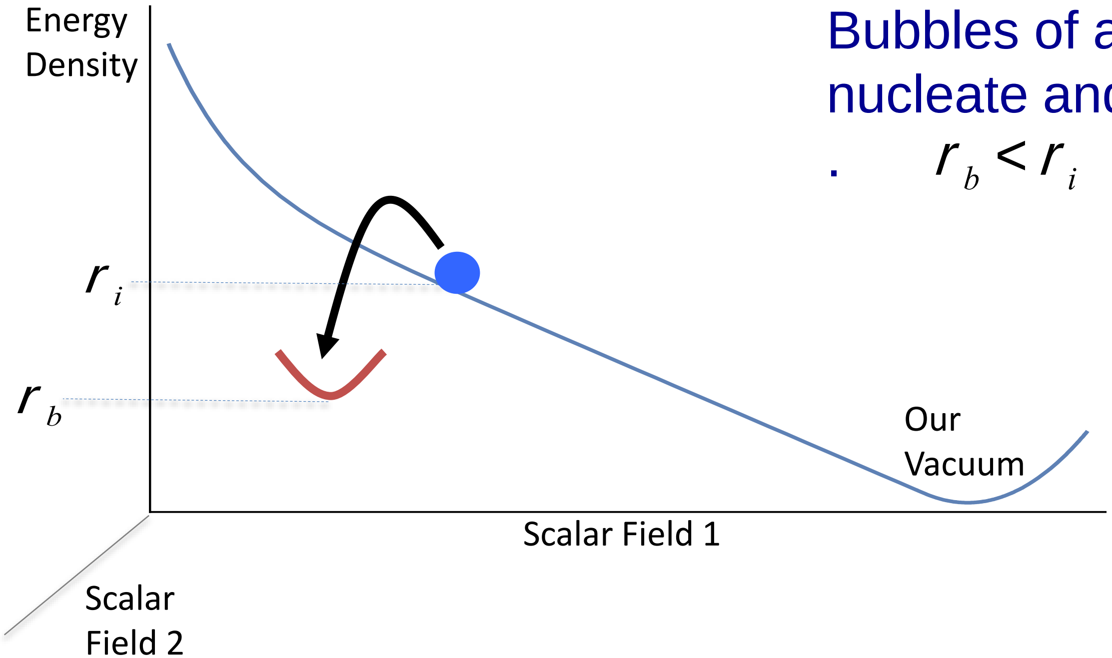
Bubble nucleation

- Particle physics models generally include a number of scalar fields. Then the "ball" rolls in a multi-dimensional landscape.
- Each local minimum represents a vacuum state.
- As the field rolls towards our vacuum, it can tunnel to another vacuum.



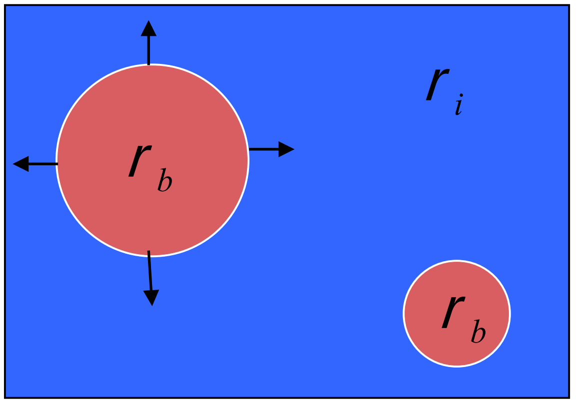
Bubble nucleation

Coleman & De Luccia (1980)



Bubbles of a lower-energy vacuum nucleate and expand during the slow roll:

. $r_b < r_i$



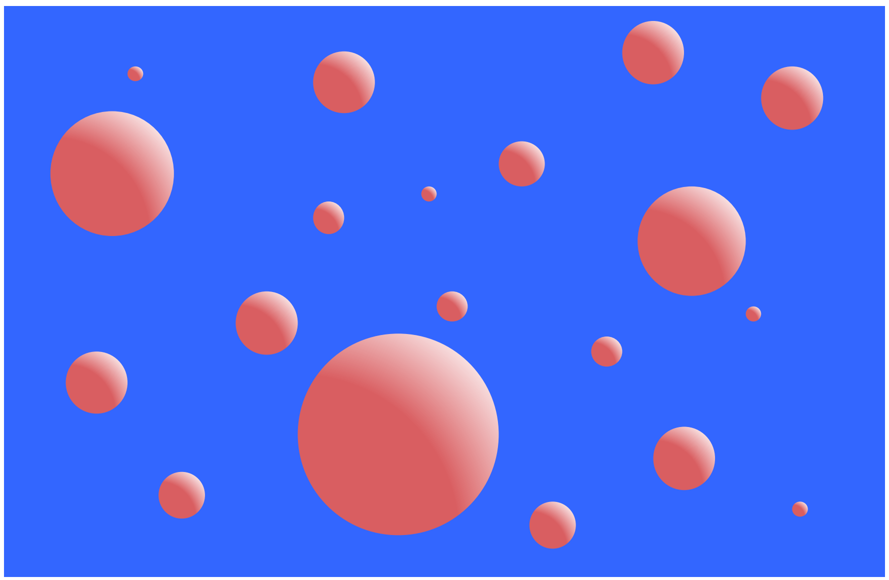
Bubble nucleation

Coleman & De Luccia (1980)

Bubble radius:

$$R \,\mu\, e^{H_i t}$$

$$H_i = \left(8pGr_i / 3\right)^{1/2}$$

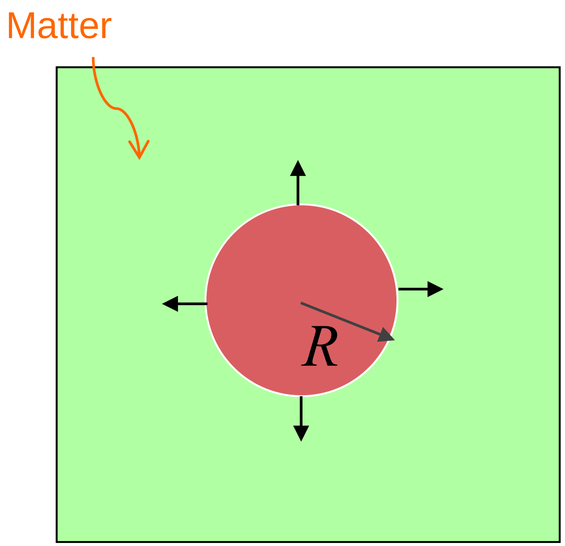


Bubble size distribution:

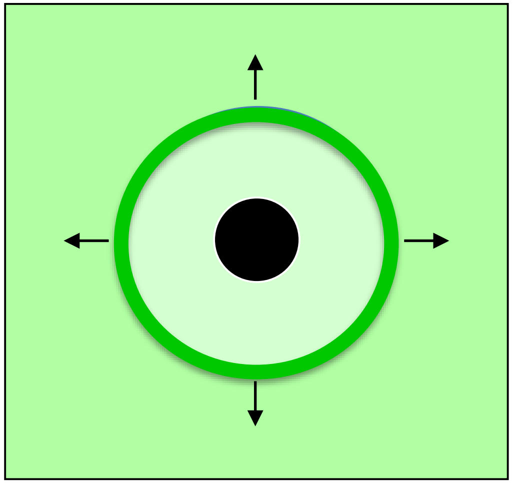
$$dn \sim l \;\frac{dR}{R^4}$$

Nucleation rate

What happens to the bubbles when inflation ends?



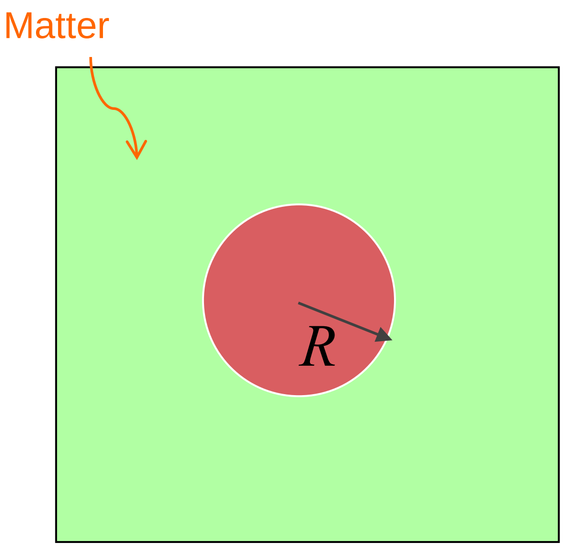
- The bubble wall initially expands relativistically relative to matter.
- It is quickly slowed down by particle scattering.
- An expanding relativistic shell of matter is formed (a shock wave).



- The bubble eventually collapses to a black hole.

But there is more to the story…

What happens inside the bubble?



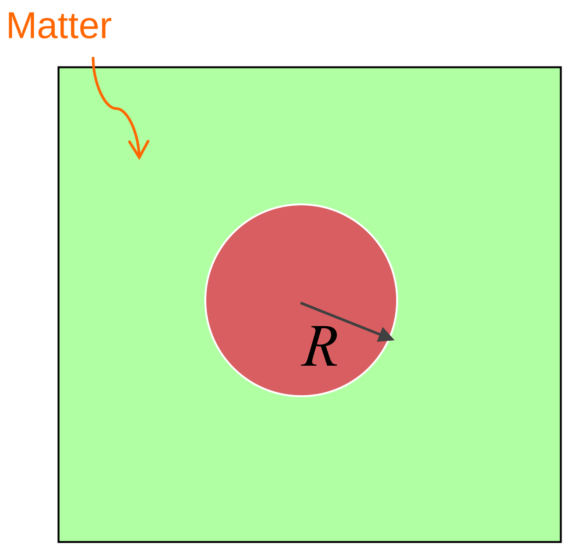
- Bubbles of radius

  $$R < H_b^{-1}$$

  collapse to a singularity.

$$H_b^{-1} = (8\pi G\rho_b/3)^{-1/2}$$

What happens inside the bubble?



- Bubbles of radius

$$R < H_b^{-1}$$

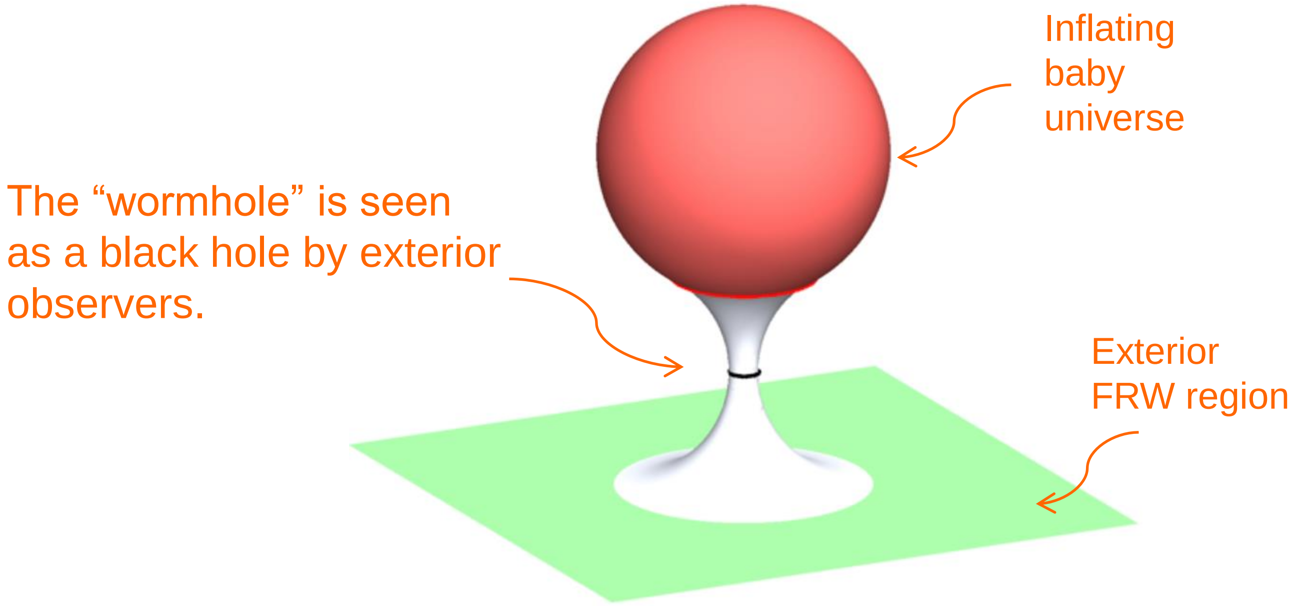
collapse to a singularity.

$$H_b^{-1} = (8\pi G \rho_b / 3)^{-1/2}$$

- If the bubble expands to a radius $R > H_b^{-1}$,

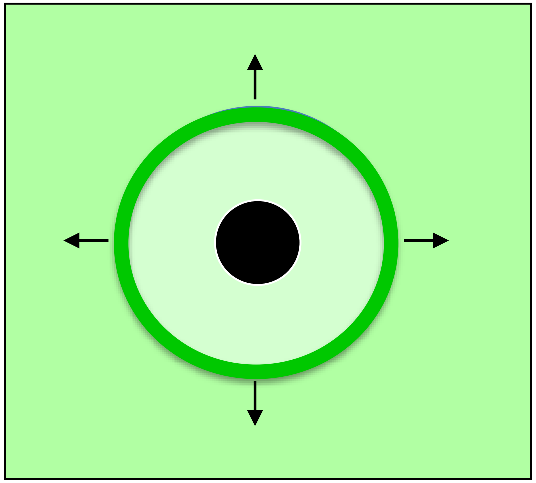
  its interior begins to inflate: $a(t) \propto \exp(H_b t)$

But the universe outside the bubble is expanding much slower.



Black holes bigger than a certain critical size have inflating baby universes inside.

Upper bound on BH mass



- The shocked region expands as $R = R_i \left(t / t_i \right)^{1/2}$.

  The universe outside of it is unperturbed.

- The size of this region when it comes within the horizon $(R_H \sim t)$ is $R \sim R_i^2 / t_i$.

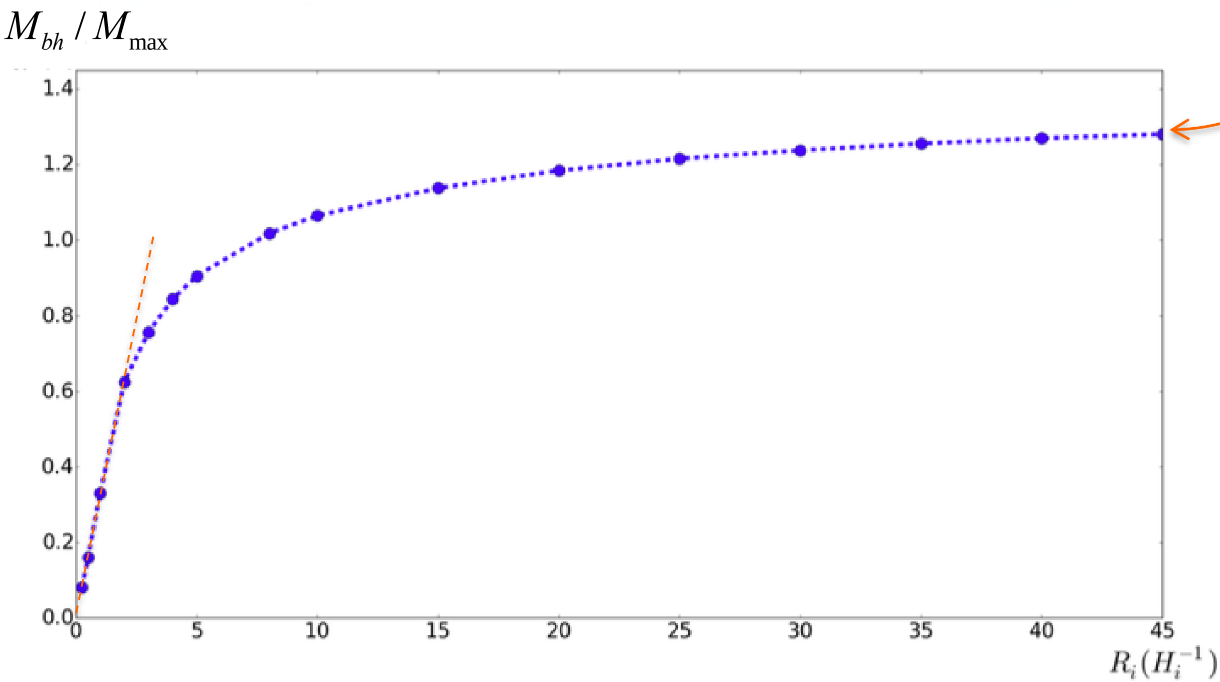
- The largest BH that can fit into this region has mass

$$M_{\max} \sim \frac{R_i^2}{G t_i}$$

Need numerical simulations to determine M_{bh}.

Numerical simulations

Heling Deng & A.V. (2017)



$M \sim M_{max}$

$$M_{\max} \sim \frac{R_i^2}{G t_i}$$

$$M \sim \begin{cases} \dfrac{4\pi}{3} \rho_b R_i^3 & (M < M_*) \\ H_i R_i^2 / G & (M > M_*) \end{cases}$$

$$M_* \sim \frac{M_{Pl}^3 \rho_i^{3/2}}{\rho_b^2}$$

Depending on microphysics, M_* may take a wide range of values.

Mass distribution of black holes

Fraction of dark matter density
in black holes of mass ~ M :

$$f(M) = \frac{M^2}{r_{DM}} \frac{dn}{dM}$$

Use $dn = / \dfrac{dR_i}{R_i^4}$ and $M(R_i)$.

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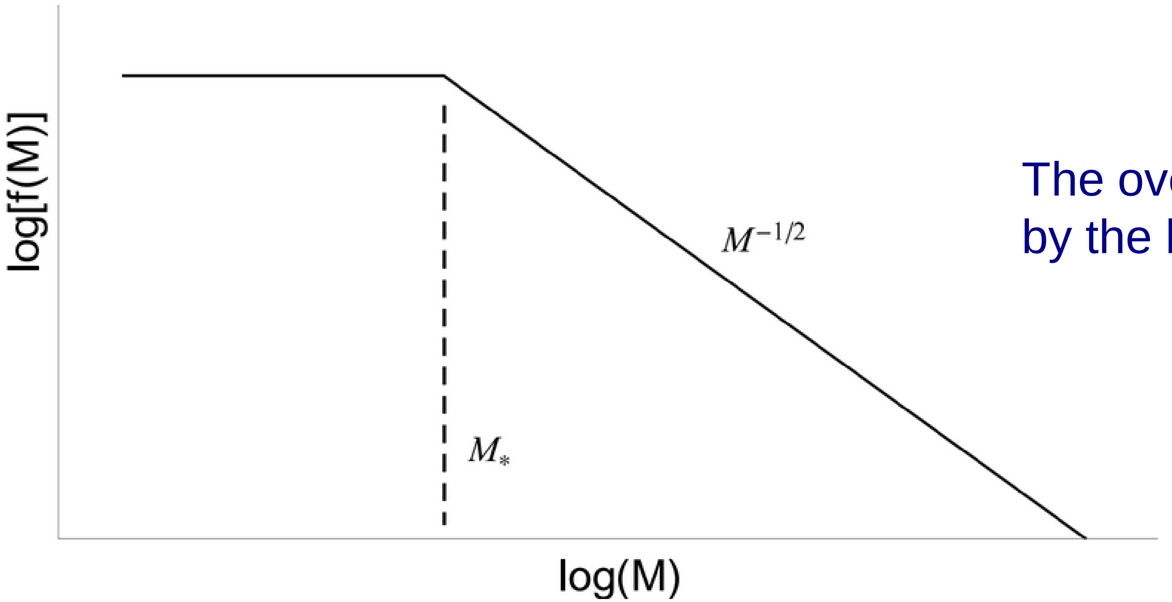
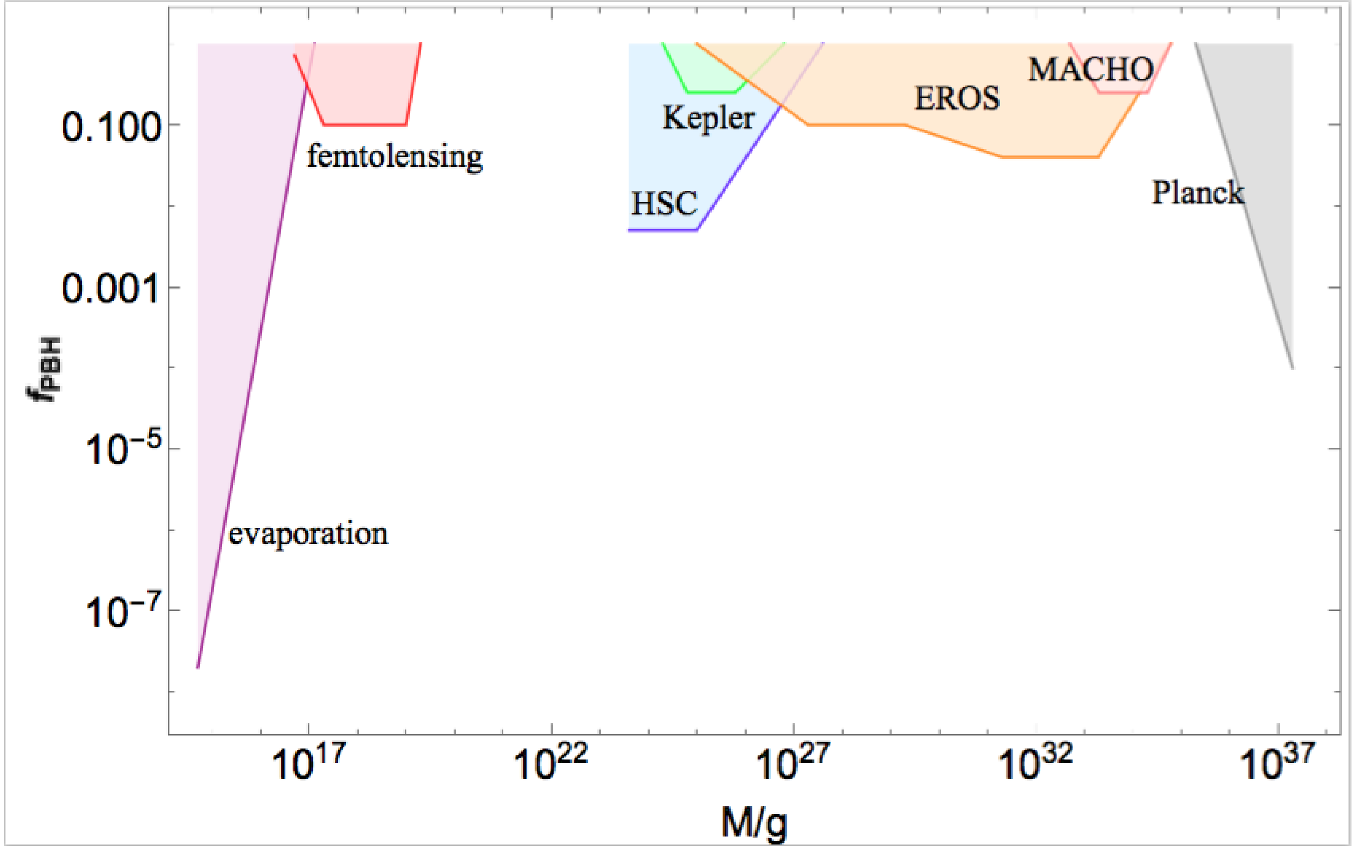


The overall magnitude is determined by the bubble nucleation rate $/$.

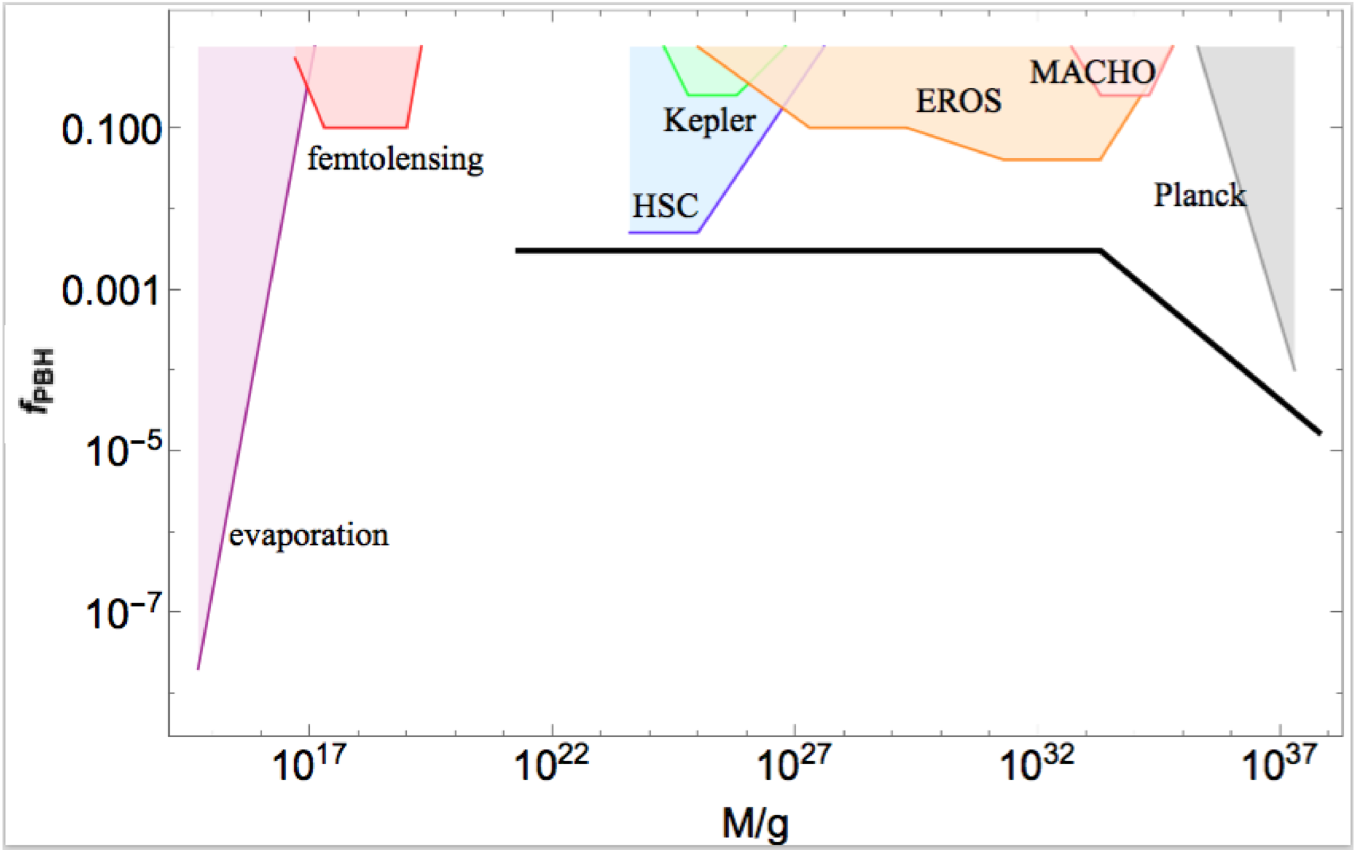
The mass distribution depends on 2 parameters: $/ ,\ M_*$

It generally has upper and lower cutoffs.

Observational bounds



Accounting for LIGO observations



$$f \sim 10^{-12}$$

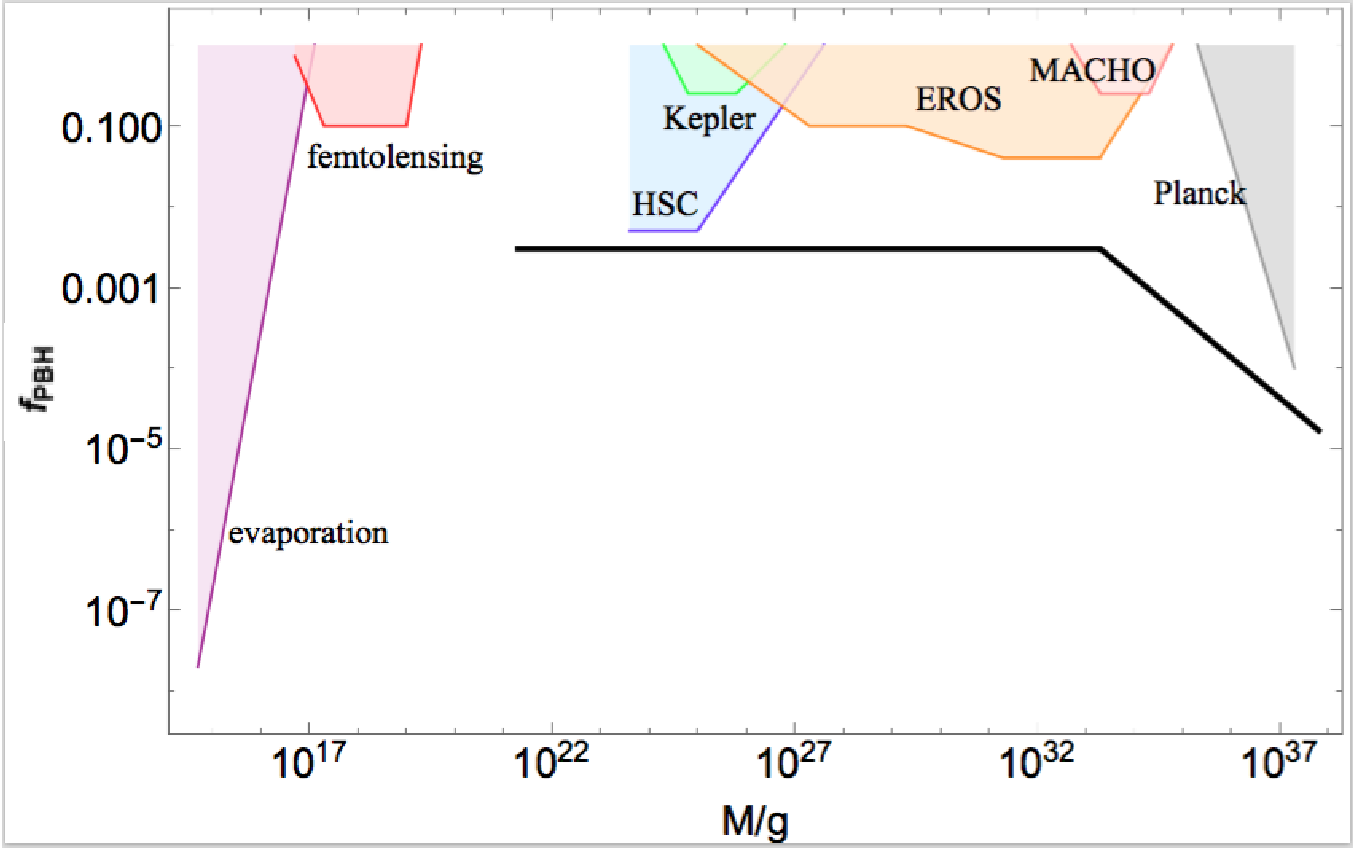
$$M_* \sim 100 M_\odot$$

BH merger rate observed by LIGO requires $f \sim 10^{-3}$ for $M_{bh} \sim 30 M_\odot$.

Sasaki et al (2016)

Note: BH produced by bubbles are *non-rotating*.

Supermassive black holes



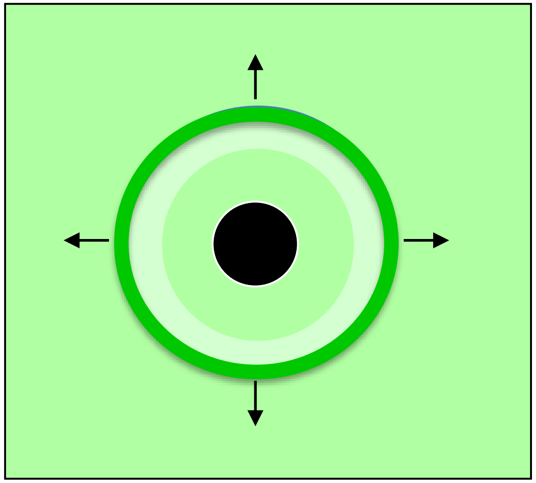
$/ \sim 10^{-12}$

$M_* \sim 100 M_\odot$

- The largest BH we can expect to find in a galaxy has mass $M \sim 10^6 M_\odot$.

CMB spectral distortion

Deng, A.V. & Yamada (2018)

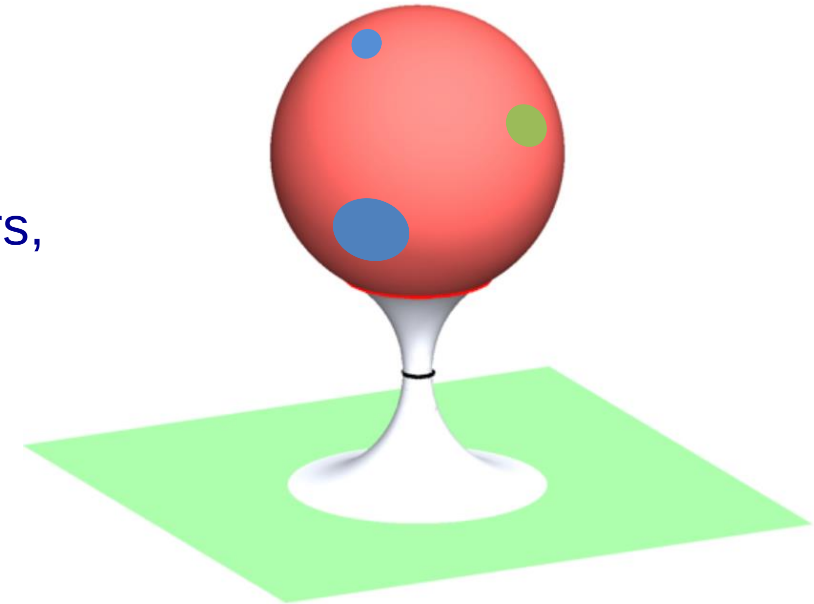


- Photon diffusion from the shock distorts the Planck spectrum.
- Photons develop a chemical potential (μ- distortion).
- $\langle \mu / T \rangle < 10^{-10}$ – unobservably small.
- But potentially detectable spectral distortion on angular scale ~ 10’ around the most massive BHs.

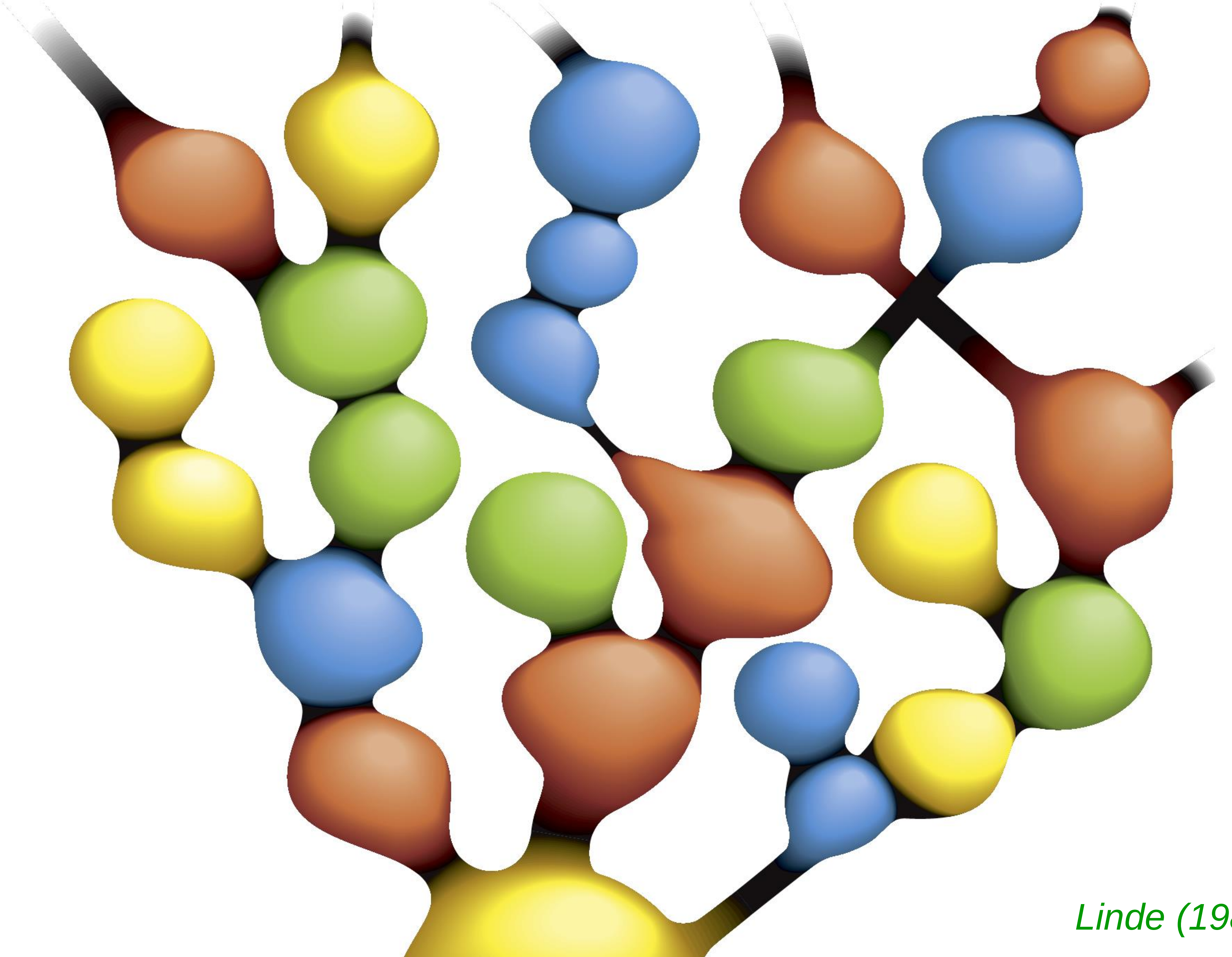
Global structure of spacetime

- The baby universes will inflate eternally.

- Bubbles of all possible vacua, including ours, will be formed.



The big picture



Linde (1988)

Conclusions

- Vacuum bubbles may nucleate during inflation, leading to the formation of black holes with a wide spectrum of masses.
- These black holes have inflating universes inside.
- A discovery of black holes with the predicted distribution of masses would provide evidence for inflation – and for nontrivial spacetime structure of the universe.
- These BH might act as seeds for supermassive BH and might have formed the binaries observed by LIGO.
- Early formation of quasars; spiky spectral distortion.

Early formation of galaxies and quasars

Deng, A.V. & Yamada (2018)

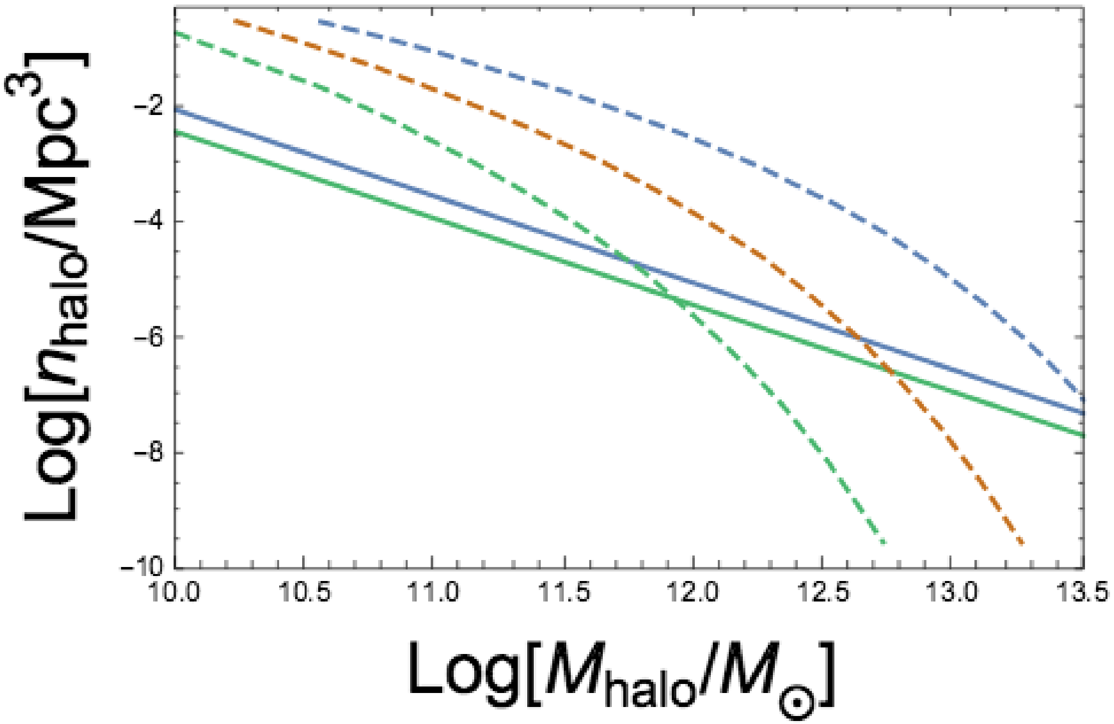
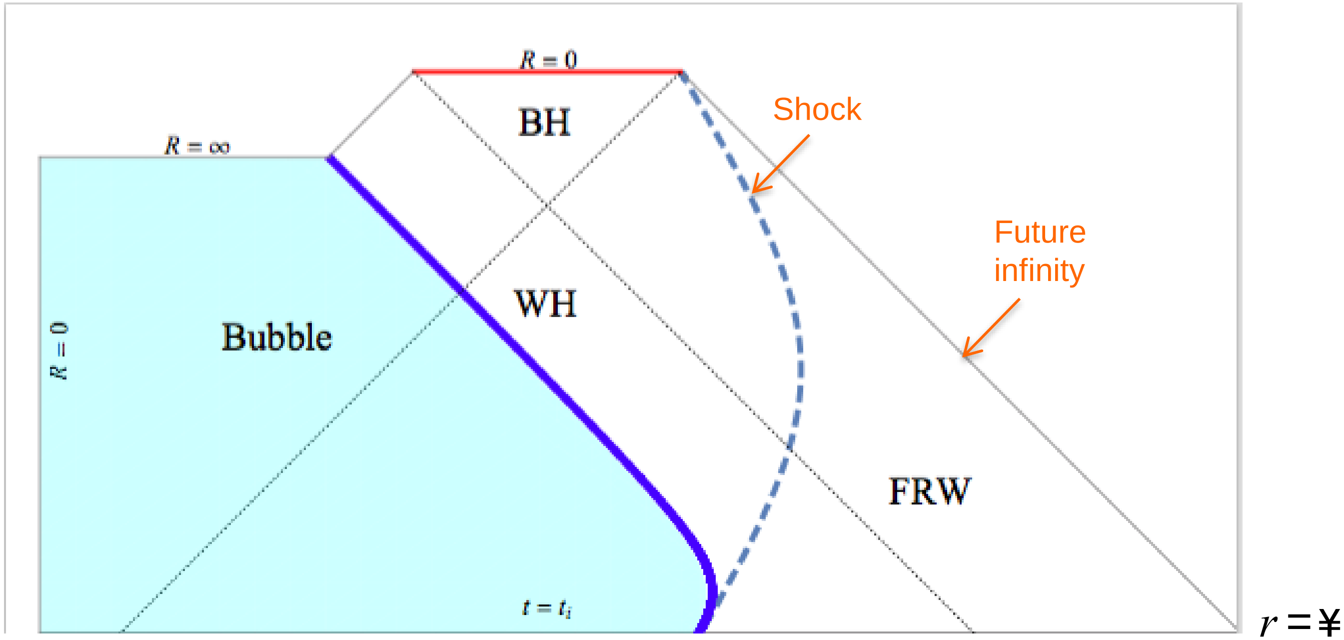
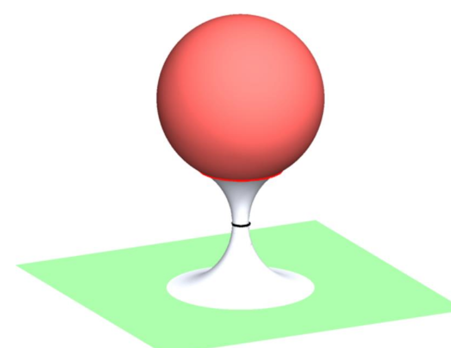


Figure 2. Halo number densities (3.6) with $\Gamma = 10^{-12}$ at $z = 4, 8$ (solid lines). The Sheth-Tormen halo distributions for $z = 4, 6, 8$ are shown by dashed lines. In both cases the redshift increases from top to bottom.

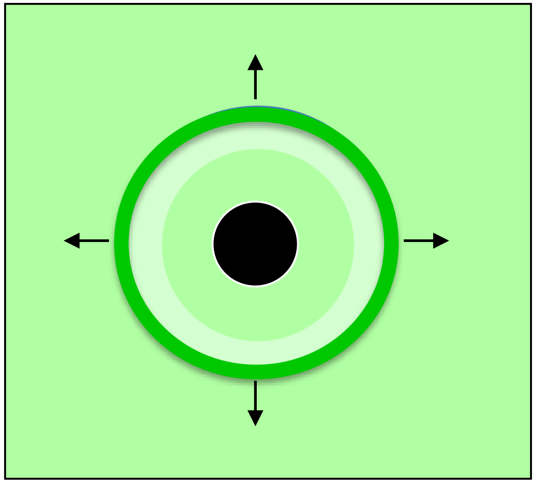
Penrose diagram



Light propagates at 45^o.



Shock propagation



- At later times the BH is surrounded by a thin overdense shell, followed by a thicker underdense shell, propagating in a nearly uniform radiation.

- The overall mass deficit in the shells is . $\Delta M = - M_{bh}$