BLACK HOLES FROM THE MULTIVERSE

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A new mechanism of black hole formation during inflation

- Spherical domain walls or vacuum bubbles spontaneously nucleate during inflation.
- They are stretched to very large sizes and collapse to black holes after inflation ends.

A new mechanism of black hole formation during inflation

- Spherical domain walls or vacuum bubbles spontaneously nucleate during inflation.
- They are stretched to very large sizes and collapse to black holes after inflation ends.

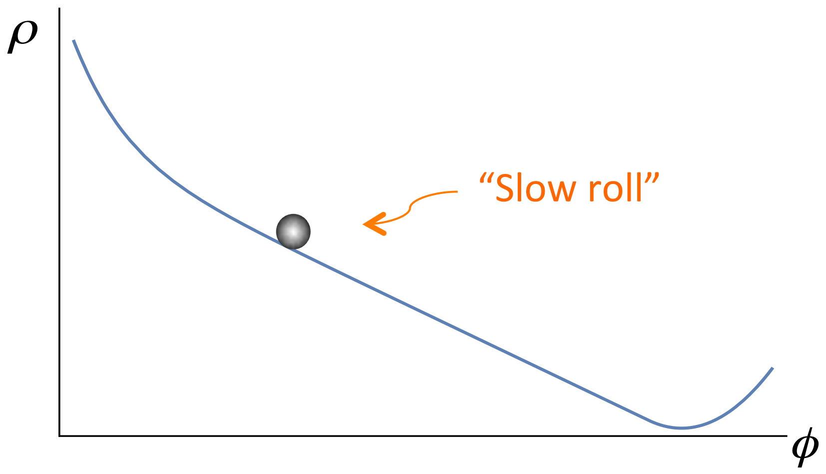
Special features:

- A scaling distribution of PBH with a very wide spectrum of masses.
- BH larger than certain critical mass have inflating universes inside.
- For some parameter values, these BH can have significant observational effects.

First review some relevant features of inflation.

INFLATION

Guth (1981); Linde (1982)



- *During inflation:*

$$\rho \approx const$$

$$E = \rho V$$

- *Negative pressure (tension):*

$$P = -\frac{\partial E}{\partial V} = -\rho$$

- *Repulsive gravity:*

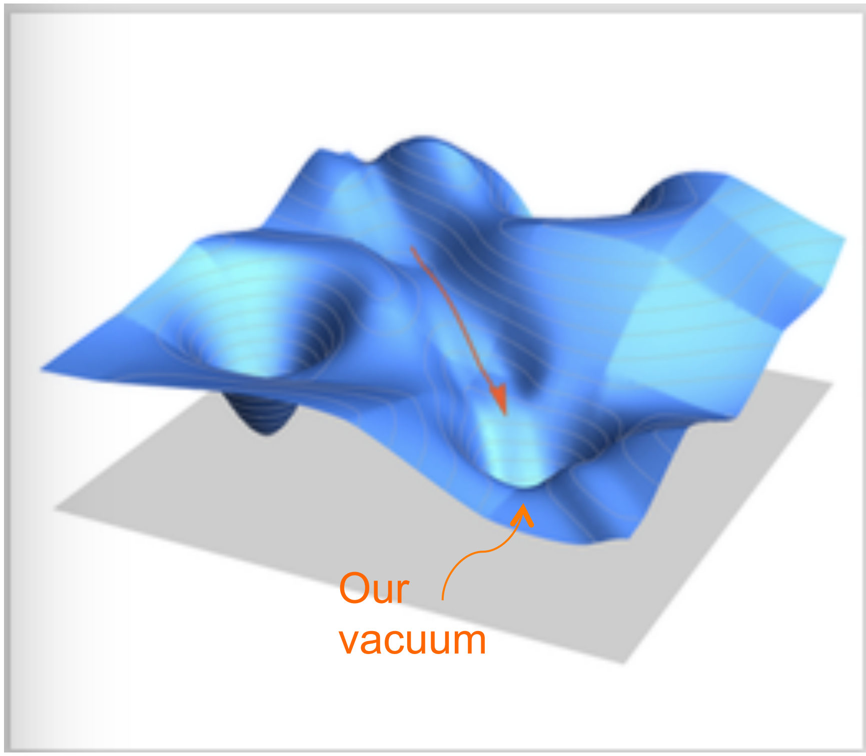
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) > 0$$

$$a(t) \propto \exp(Ht)$$

$$H = (8\pi G\rho / 3)^{1/2}$$

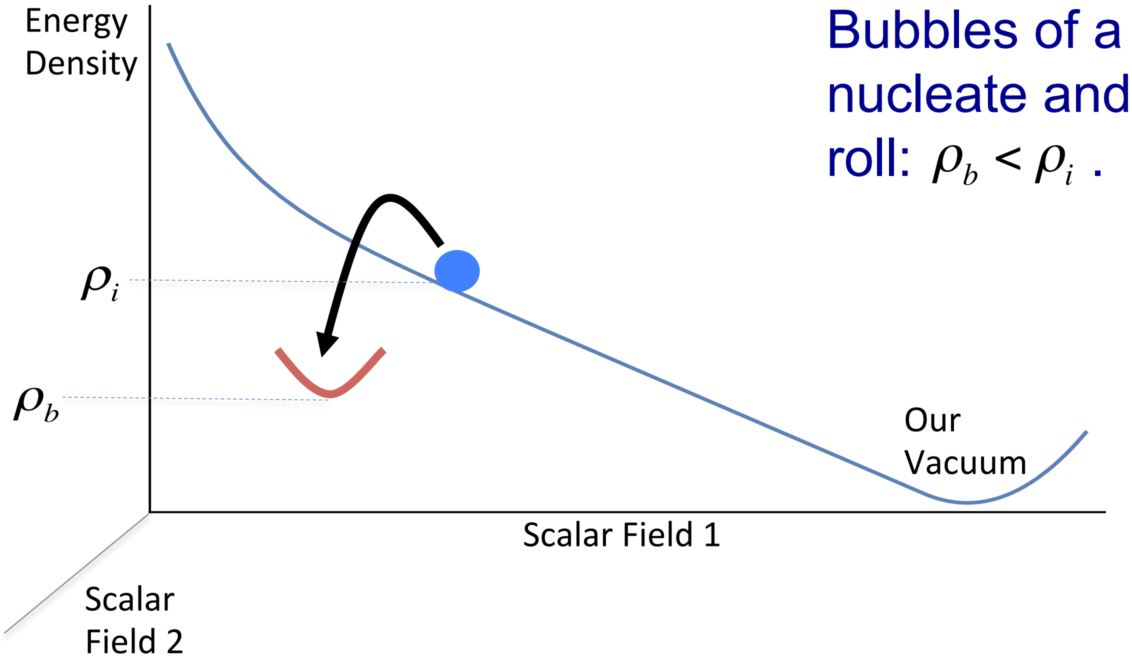
Bubble nucleation

- Particle physics models generally include a number of scalar fields. Then the inflaton field rolls in a multifield energy landscape.
- As it rolls towards our vacuum, it can tunnel to another vacuum state.

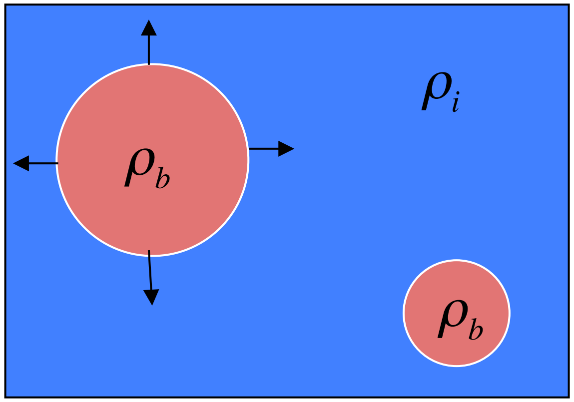


Bubble nucleation

Coleman & De Luccia (1980)



Bubbles of a lower-energy vacuum nucleate and expand during the slow roll: $\rho_b < \rho_i$.



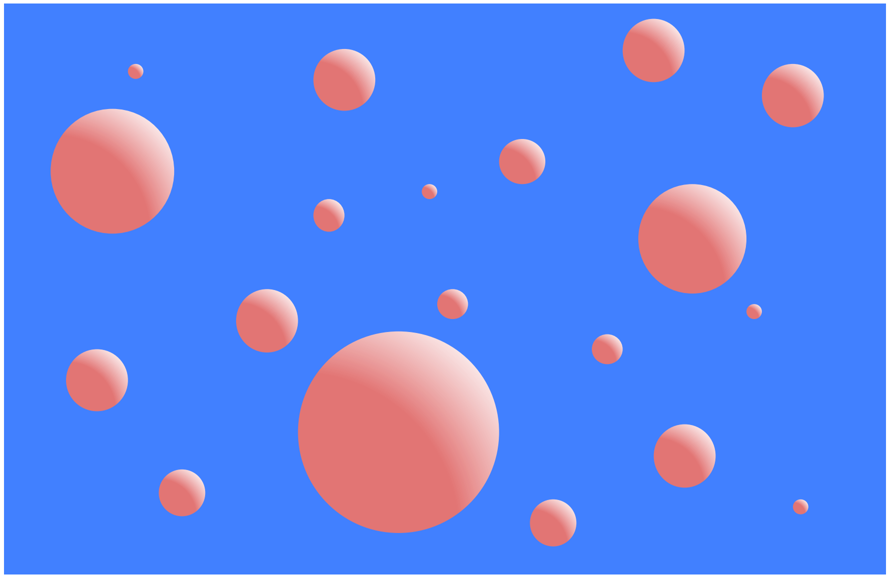
Bubble nucleation

Coleman & De Luccia (1980)

Time of nucleation $t = t_n$:

At $t > t_n$: $R \approx H_i^{-1} e^{H_i (t - t_n)}$

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



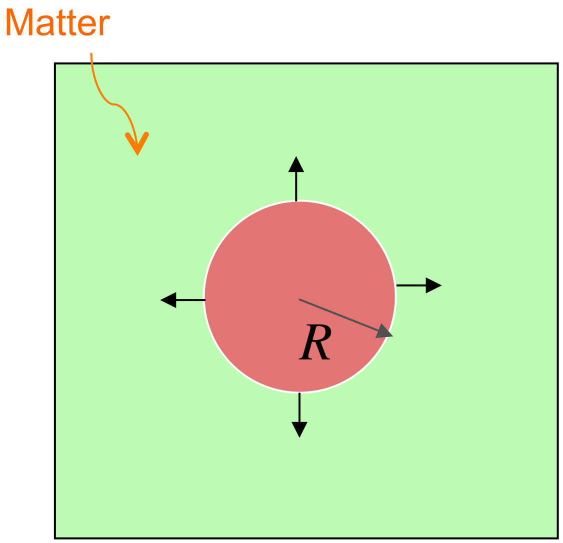
Scale-invariant size distribution:

$$dN \sim \underset{\uparrow}{\lambda}\, \frac{dR}{R^4}\, dV$$

Nucleation rate

What happens to the bubbles when inflation ends?

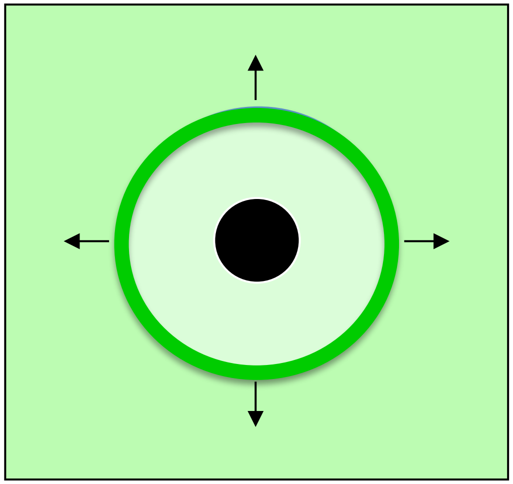
1. Exterior view



Assume that matter particles
are reflected from the bubble wall.

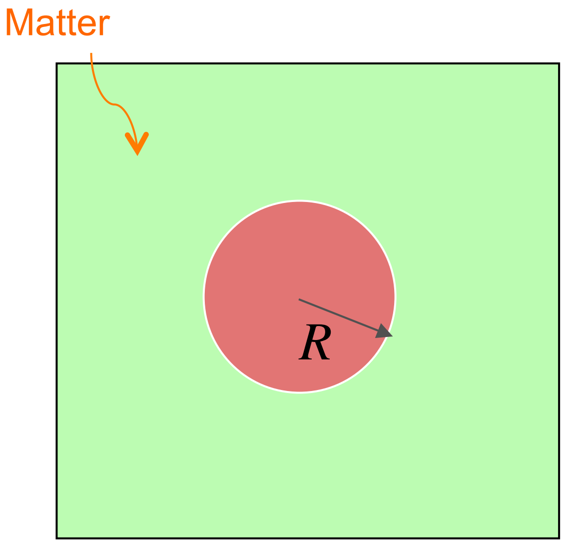
- The bubble wall initially expands relativistically relative to matter.
- It is quickly slowed down by particle scattering.
- An expanding relativistic shell of matter is formed.

Similar to shocks in supernova explosions.



- The bubble collapses to a black hole.

2. Interior evolution of the bubble depends on its size.



For *subcritical bubbles*, with

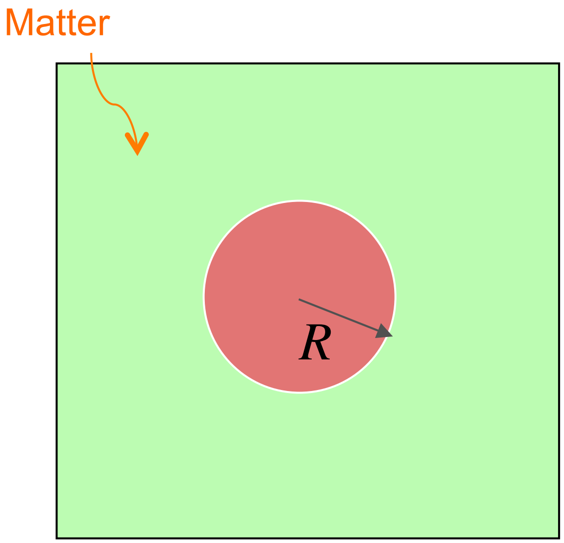
$$R < H_b^{-1}$$

an “ordinary” black hole forms.

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

$$M_{bh} \approx \frac{4\pi}{3}\rho_b R^3$$

2. Interior evolution of the bubble depends on its size.



For *supercritical bubbles*, with

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

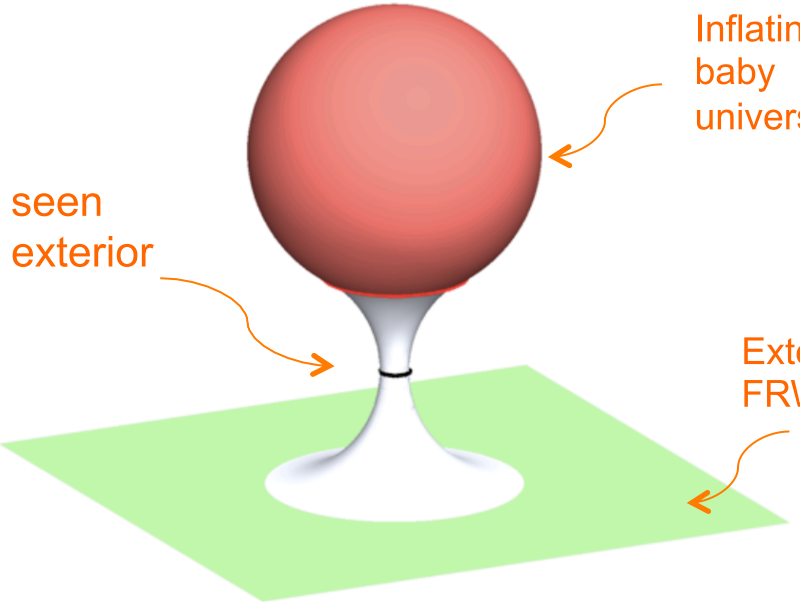
the interior begins to inflate:

$$a(t) \propto \exp(H_b t)$$

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

But the universe outside the bubble is expanding much slower.

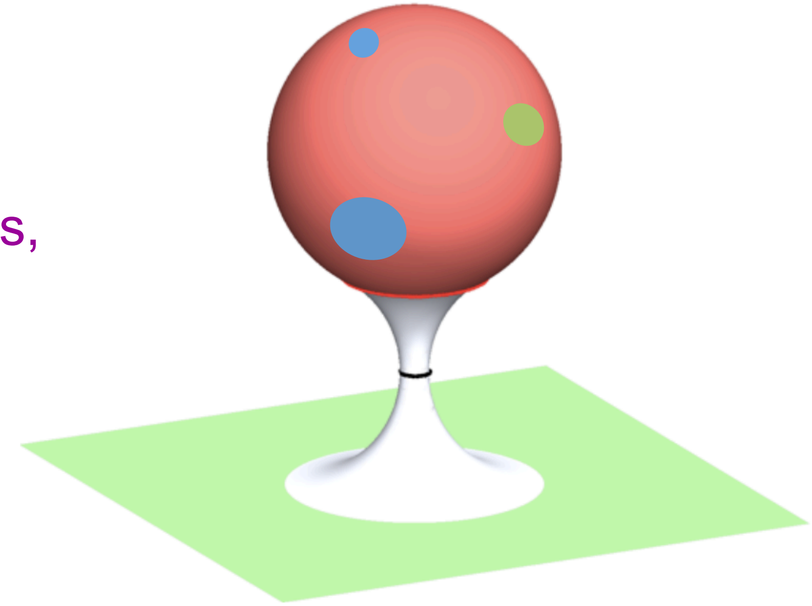
How is this possible?

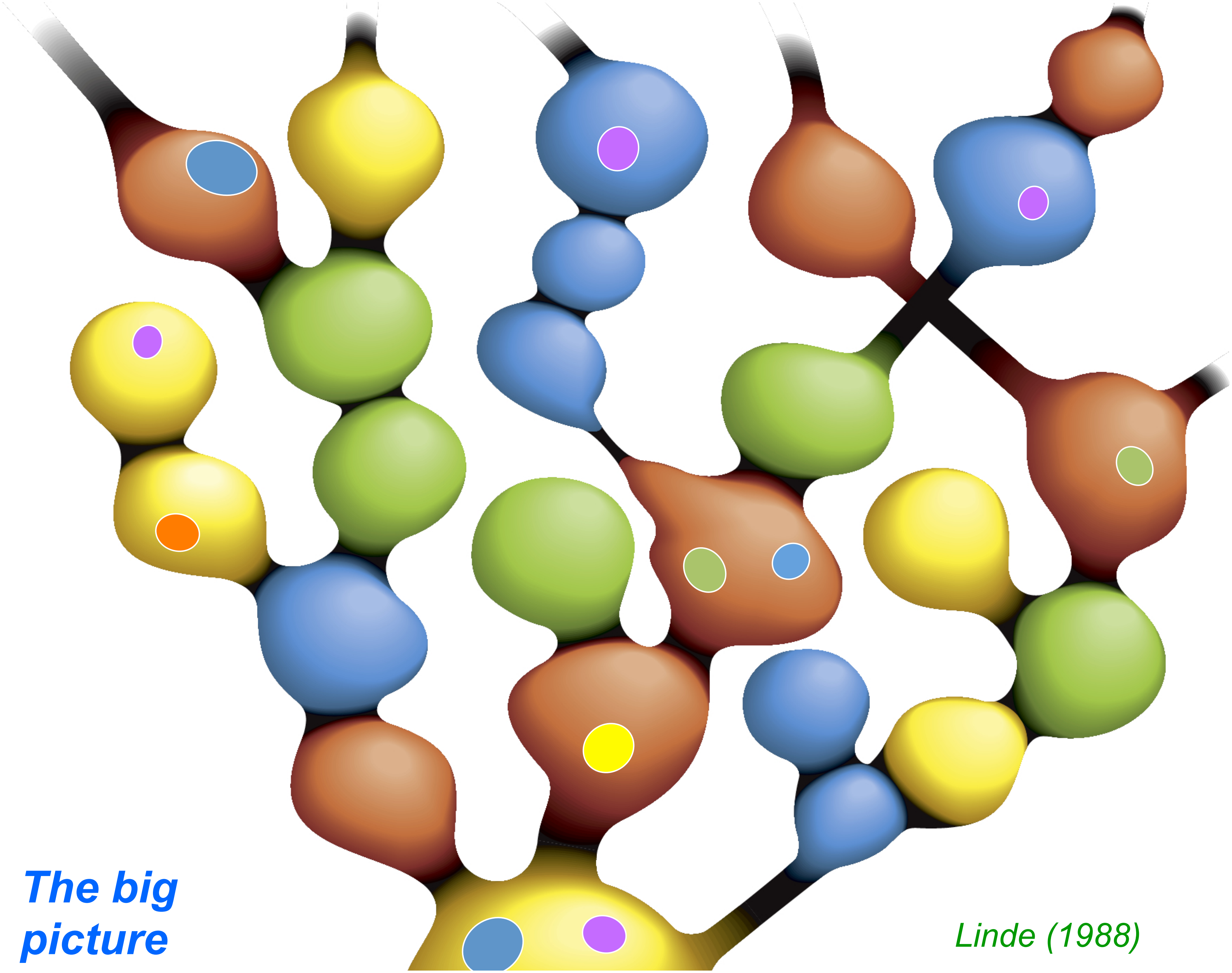


Black holes of mass $M > M_{cr} \sim \rho_b H_b^{-3}$ have inflating baby universes inside.

Global structure of spacetime

- The baby universes will inflate eternally.
- Bubbles of all possible vacua, including ours, will be formed.
- A multitude of inflating regions connected by wormholes.

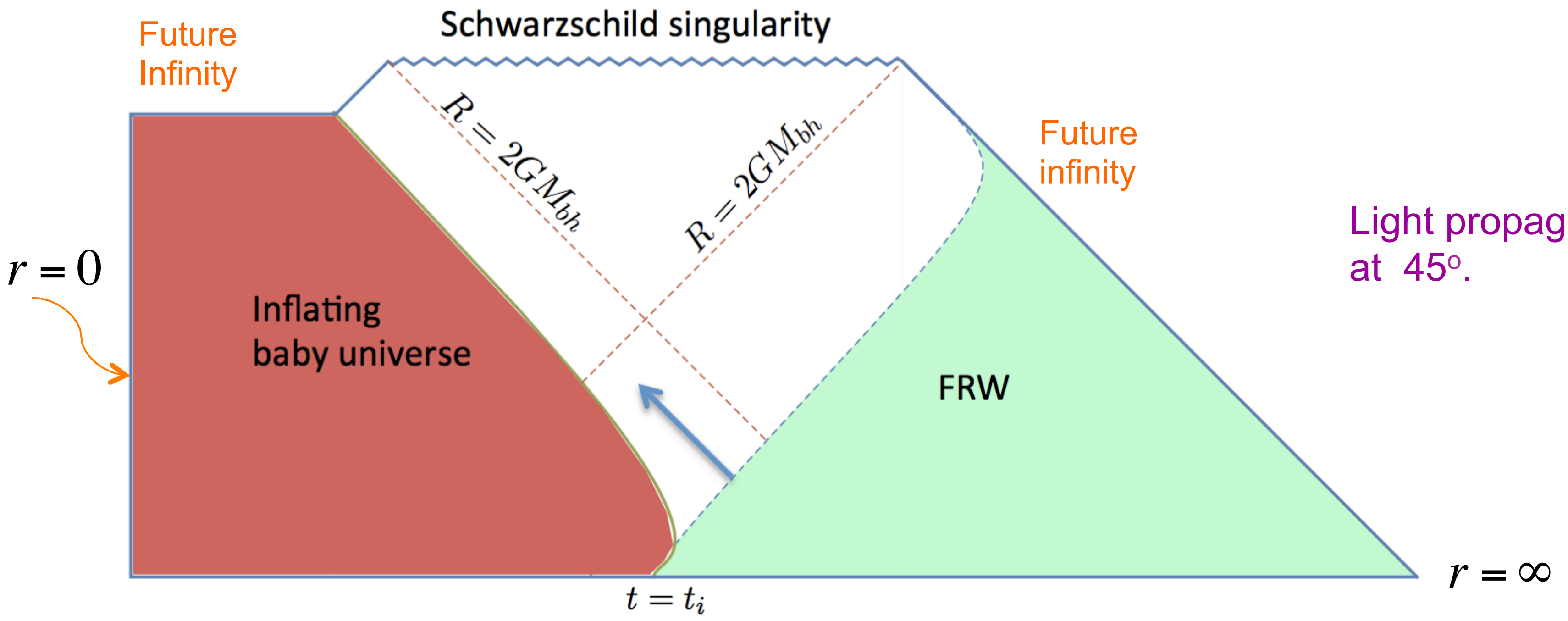




The big picture

Linde (1988)

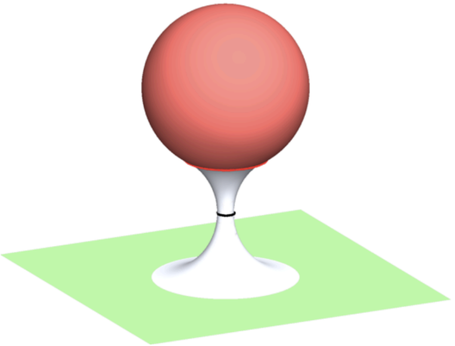
Penrose diagram



Light propagates at 45°.

- The wormhole closes in about a light crossing time.
- Some matter follows the bubble into the wormhole. .
  Need numerical simulation to determine M_{bh}.

  (work in progress)

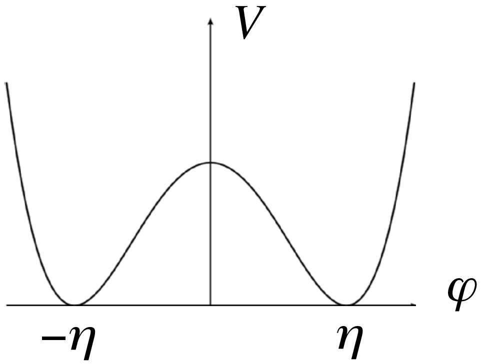


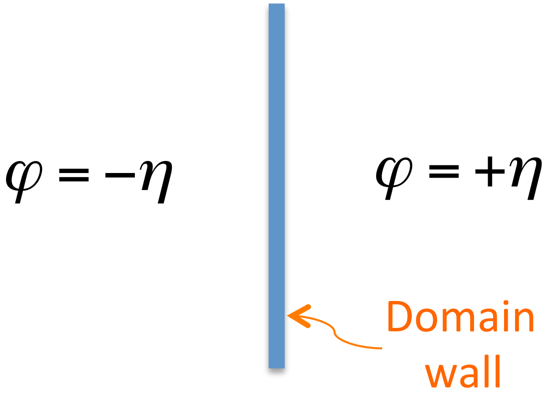
BLACK HOLES FROM DOMAIN WALLS

Domain walls

Form when a discrete symmetry is broken.

Two degenerate vacua: $\varphi = \pm\eta$





$\varphi = -\eta$

$\varphi = +\eta$

Domain wall

Mass per unit area: $\sigma \sim \eta^3.$

Tension $= \sigma$

Domain walls

Form when a discrete symmetry is broken.

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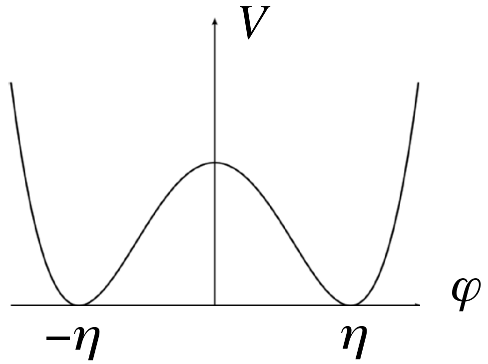
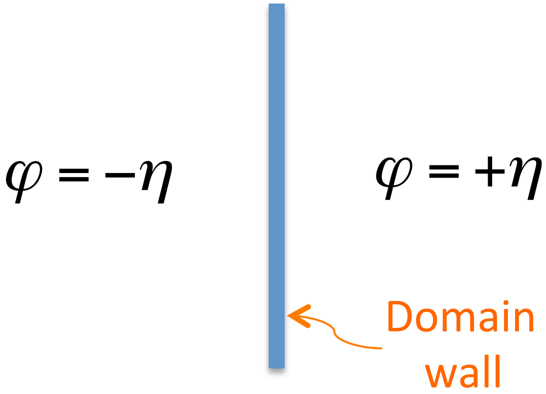




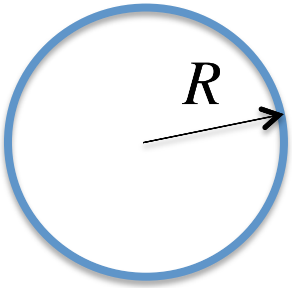
Mass per unit area: $\sigma \sim \eta^3$.

Tension = σ

Wall gravity is repulsive

$$\boxed{R_\sigma = (2\pi G\sigma)^{-1}}$$

A.V. (1983)
Ipser & Sikivie (1984)



Spherical walls of radius $R > R_\sigma$ inflate:

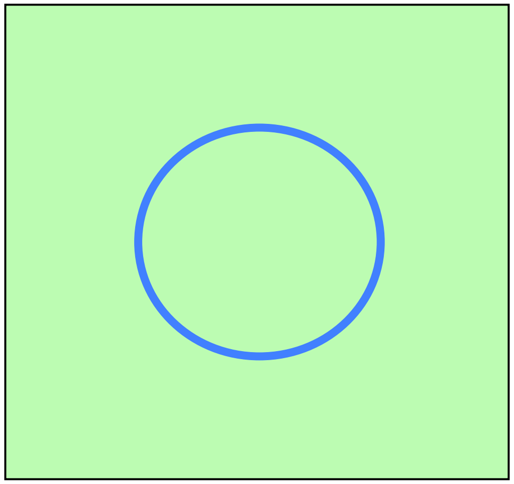
$$R(\tau) \propto \exp(\tau / R_\sigma)$$

Spherical domain walls of initial radius $R(t_n) = H_i^{-1}$ *spontaneously nucleate during inflation.*

$$R \approx H_i^{-1} e^{H_i(t-t_n)}$$

Basu, Guth & A.V. (1991)

Nucleation rate: $\lambda \sim \exp\left(-\frac{2\pi^2\sigma}{H_i^3}\right)$



Scale-invariant size distribution: $dN \sim \lambda \frac{dR}{R^4} dV$

After inflation

Subcritical walls come within the horizon having radius $R_H < R_\sigma$.

They collapse to BH of mass $M_{bh} \sim 4\pi R_H^2 \sigma$.

After inflation

Subcritical walls come within the horizon having radius $R_H < R_\sigma$.

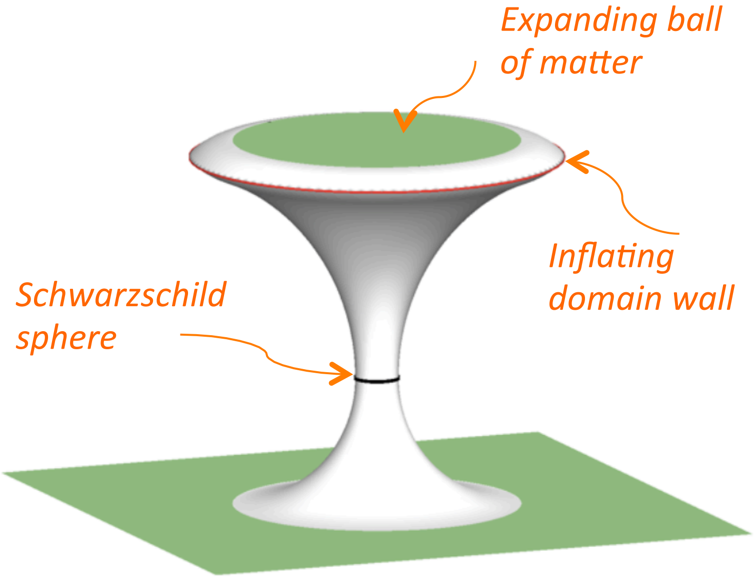
They collapse to BH of mass $M_{bh} \sim 4\pi R_H^2 \sigma$.

A *supercritical wall* reaches radius $R > R_\sigma$ before horizon crossing.

It inflates in a baby universe. .

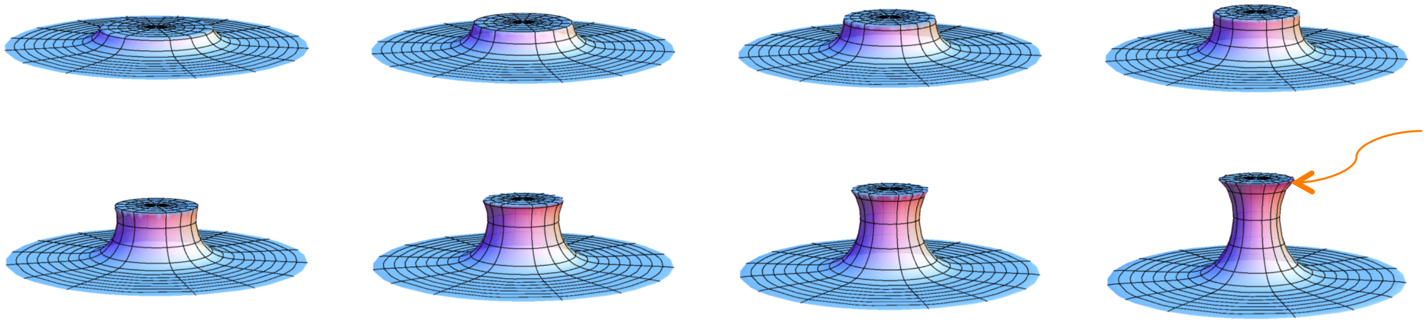
Transition between the two regimes is at

$$M_{bh} = M_{cr} \sim 1/G^2\sigma$$



Numerical simulation of supercritical collapse

Deng, Garriga & A.V. (2016)

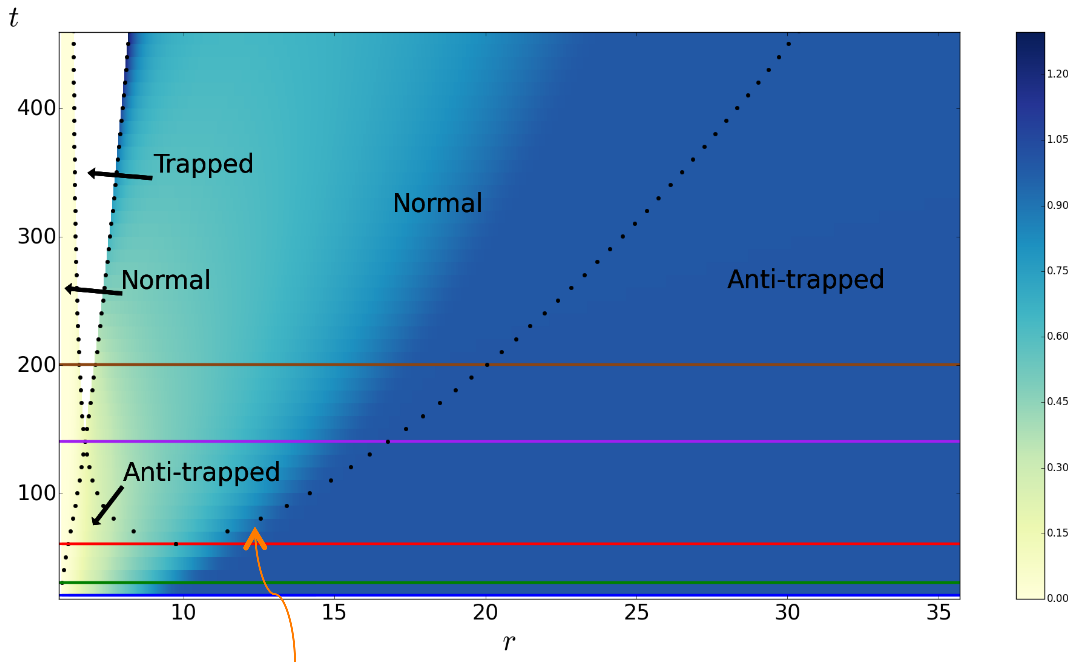


Domain wall

$$2GM_{bh} \approx R_H / 2$$

Radius of the affected region at horizon crossing

BH mass grows by a factor ~ 2 due to accretion.

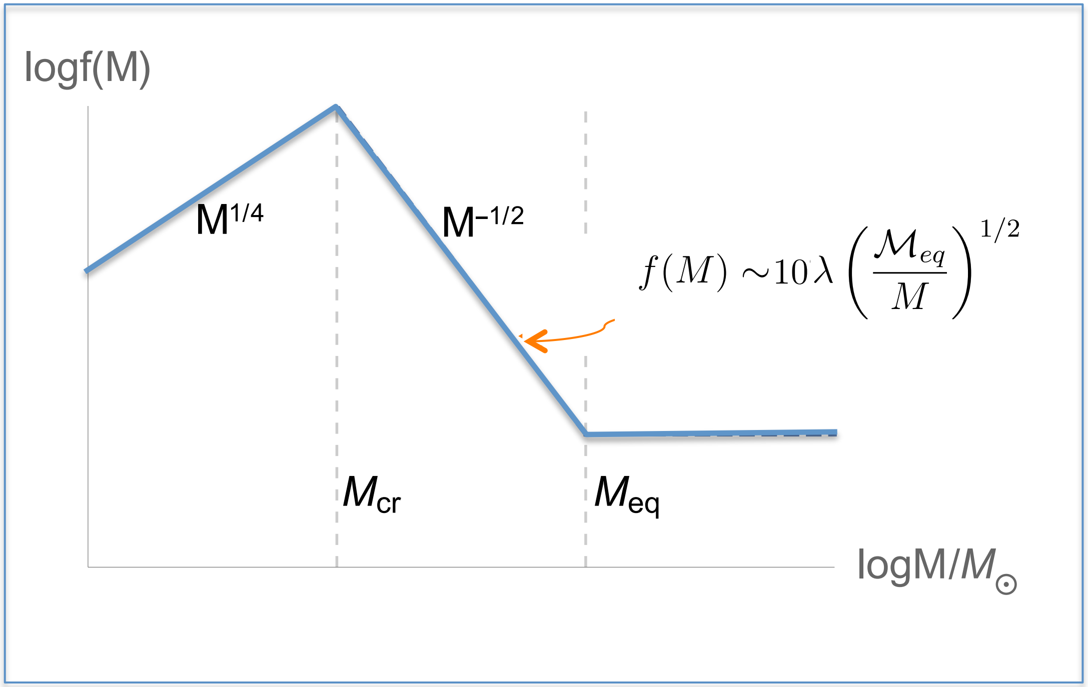


Horizon crossing

Mass distribution of black holes

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

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

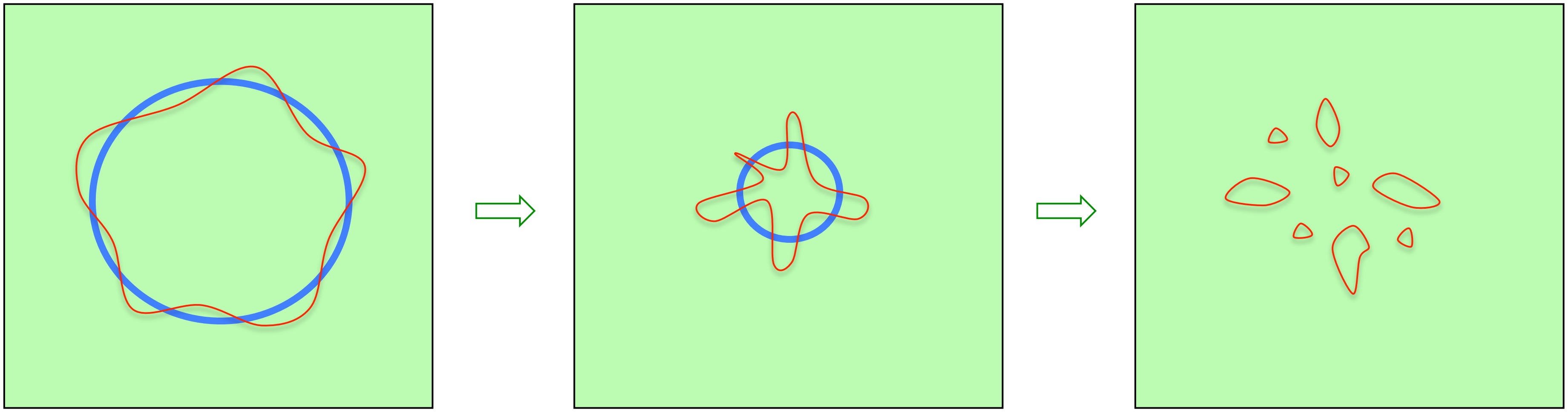


$$M_{cr} \sim 1/G^2\sigma$$

$$M_{eq} \sim 10^{17} M_\odot$$ – mass within the horizon at t_{eq}.

Effect of quantum fluctuations on subcritical walls

Garriga & A.V. (1992)



$$\frac{\delta R}{R} \sim B^{-1/2}$$

$B \lesssim 100$ – tunneling action

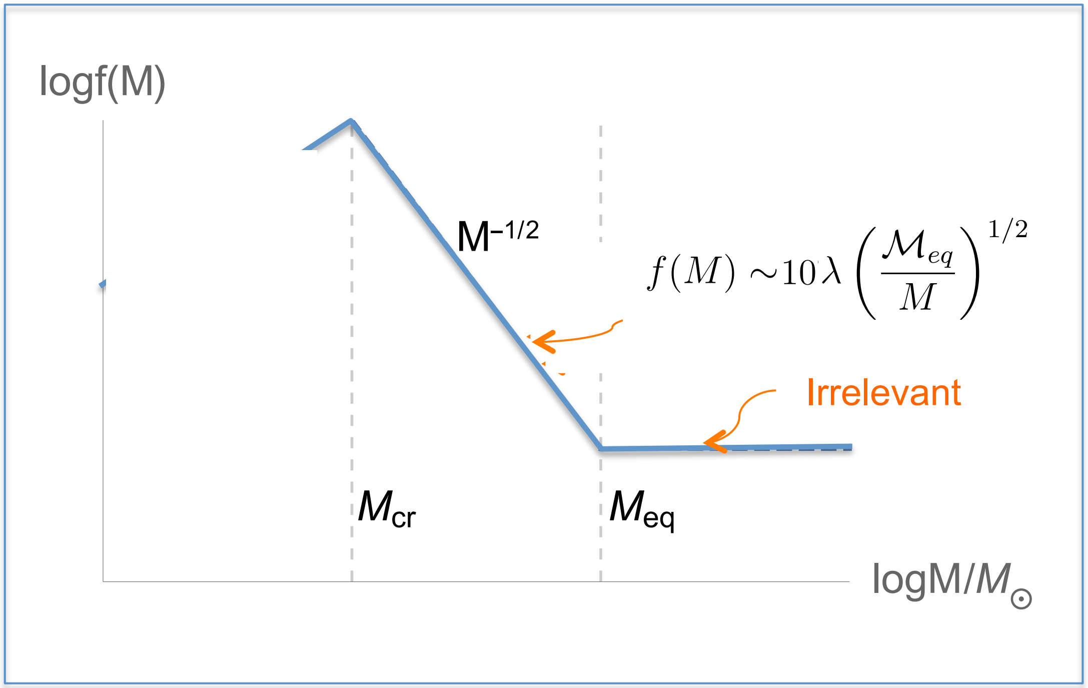
$$B = \frac{2\pi^2\sigma}{H_i^3}$$

$\delta R \approx const$ during the wall collapse. *Widrow (1989)*

BH forms only if $\delta R \lesssim 2GM \Longrightarrow M \gtrsim \frac{M_{cr}}{B}$

Quantum fluctuations have little effect on supercritical walls.

Mass distribution of black holes



- The spectrum has a universal shape with a cutoff at ~ M_{cr} .
- Normalization depends only on the wall nucleation rate.

- *The critical mass:*

  For $100\ GeV < \eta < 10^{16}\, GeV$

  we have $10\ kg < M_{cr} < 10^{15}\, M_{\odot}$

- The BH are (almost) non-rotating at formation.

- A similar picture for nucleating bubbles.

A discovery of black holes with the predicted mass distribution would provide evidence for inflation – and for baby universes.

Observational bounds

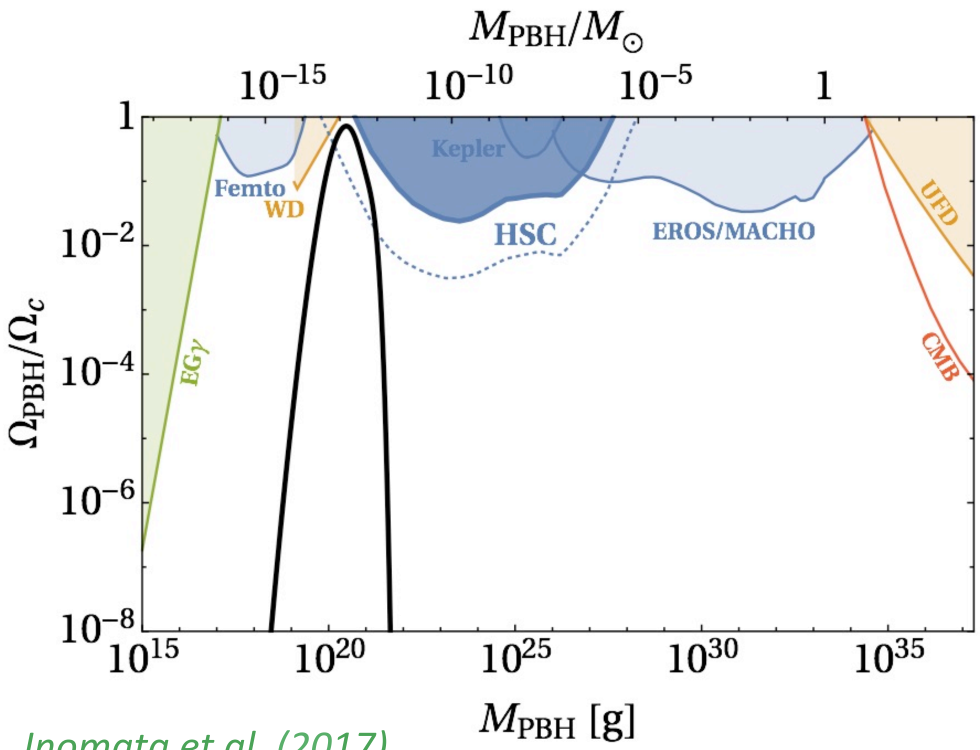
Garriga & Zhang (2017)

1-Gamma-ray background from BH evaporation with $M_{bh} \sim 10^{15} g$

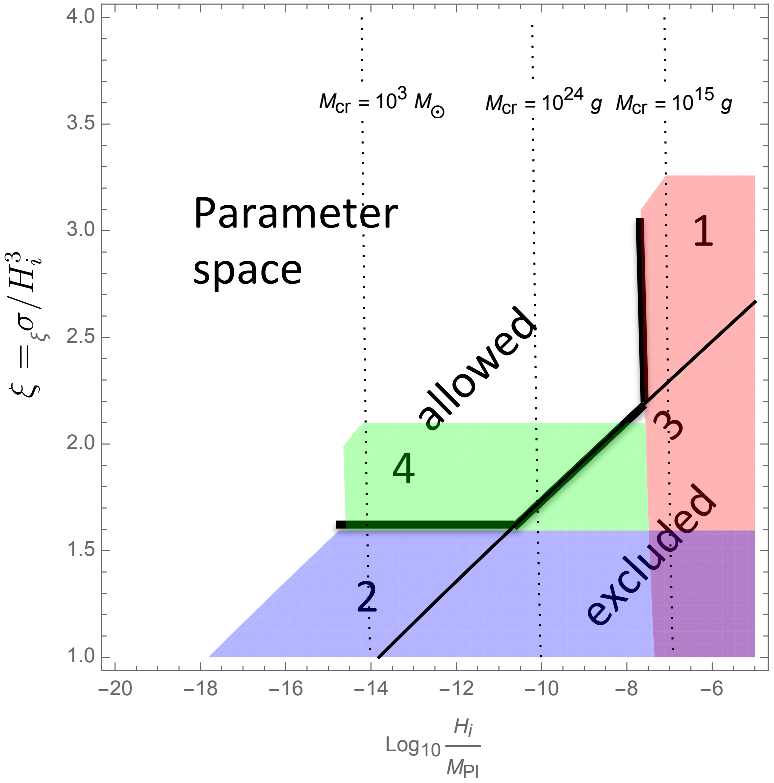
2-CMB spectral distortions by radiation emitted by gas accretion onto BH with $M_{bh} \gtrsim 10^{3} M_{\odot}$:

3-Overdensity bound : $f(M) < 1$

Nucleation rate: $\lambda \sim \xi^2 e^{-2\pi^2 \xi}$



Inomata et al. (2017)



Supermassive black hole seeds: $M_{bh} > 10^{3} M_{\odot}$

4 - At least one seed per galaxy.

Observational bounds

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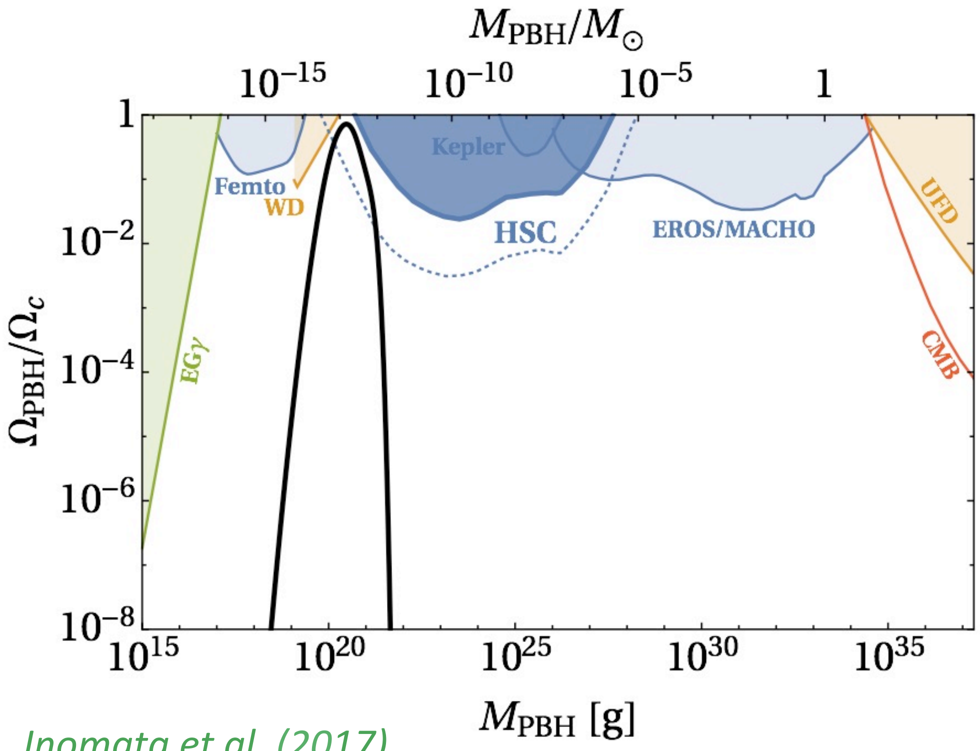

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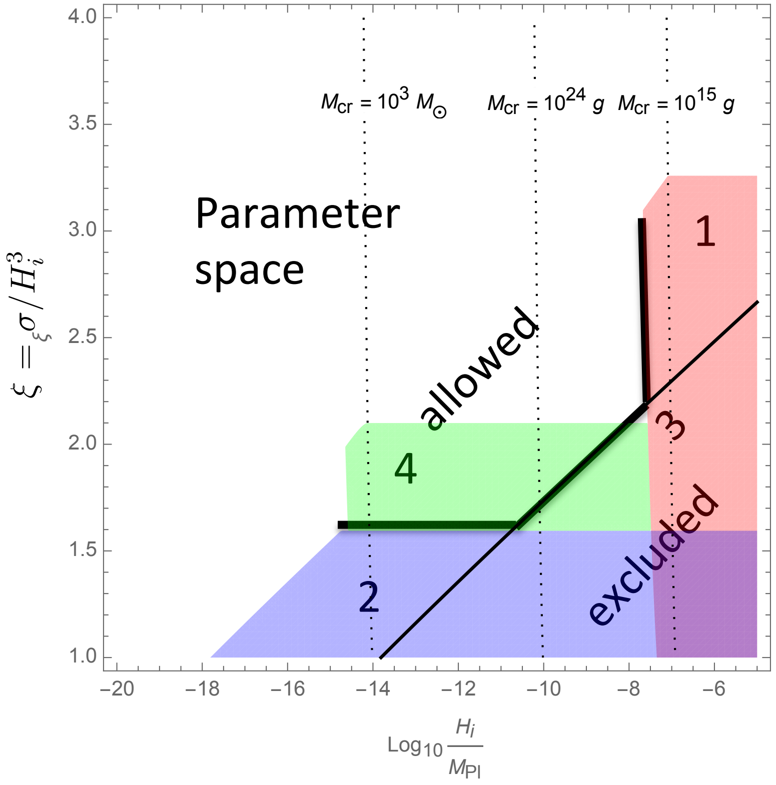

Consider some interesting parameter choices.

Observational bounds

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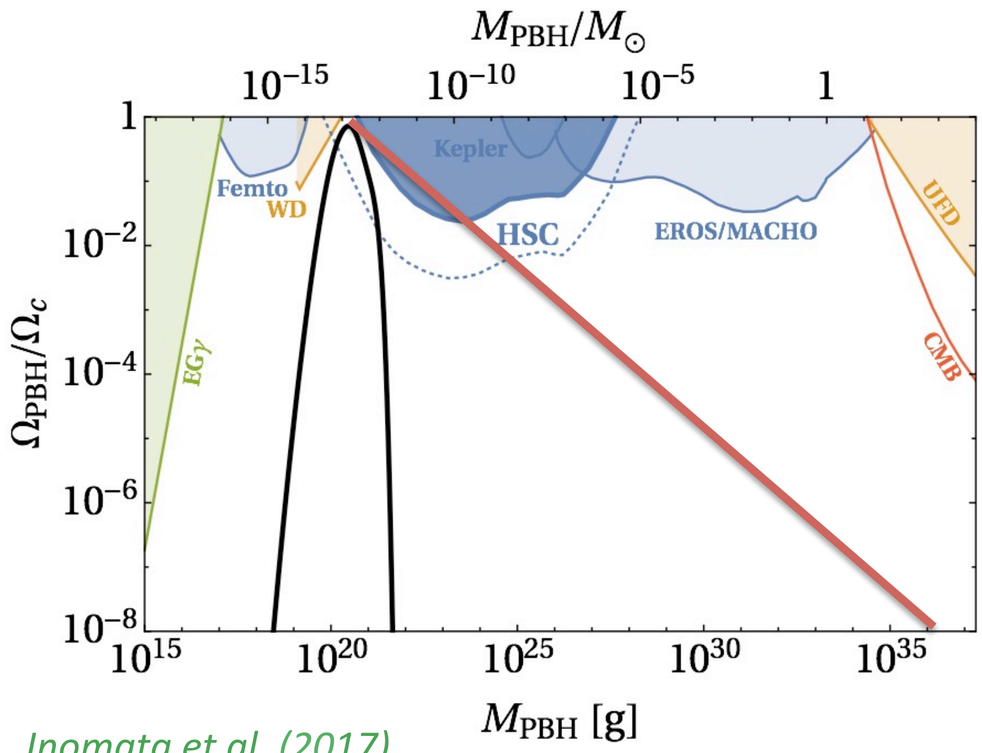

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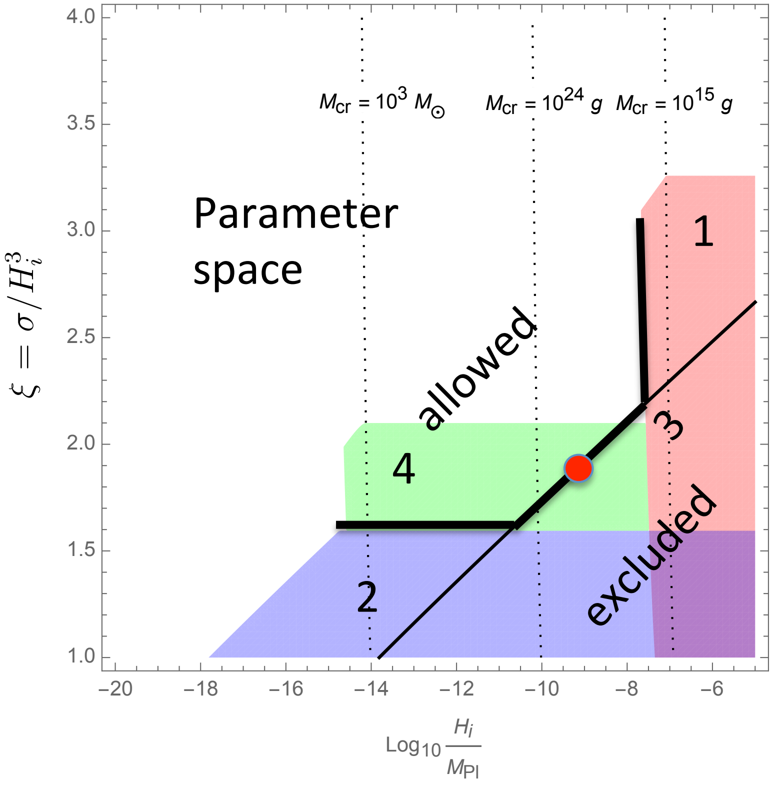

$M_{cr} \sim 10^{20}\ g$

Accounts for DM and SMBH with seeds of $\sim 10^3\ M_{solar}$.

Observational bounds

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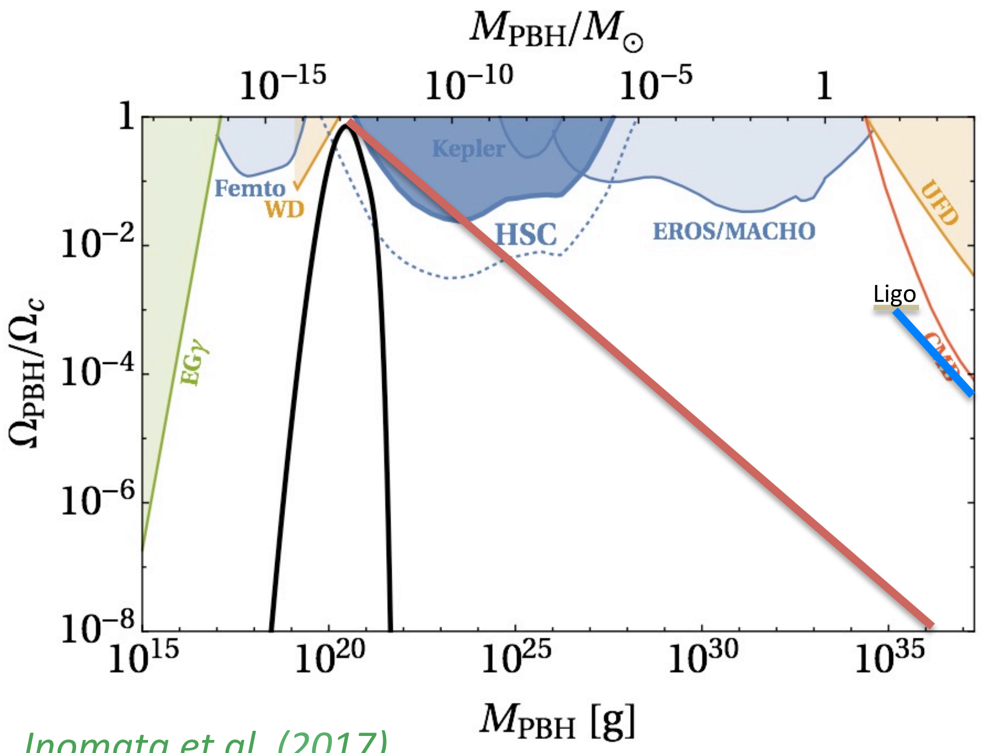

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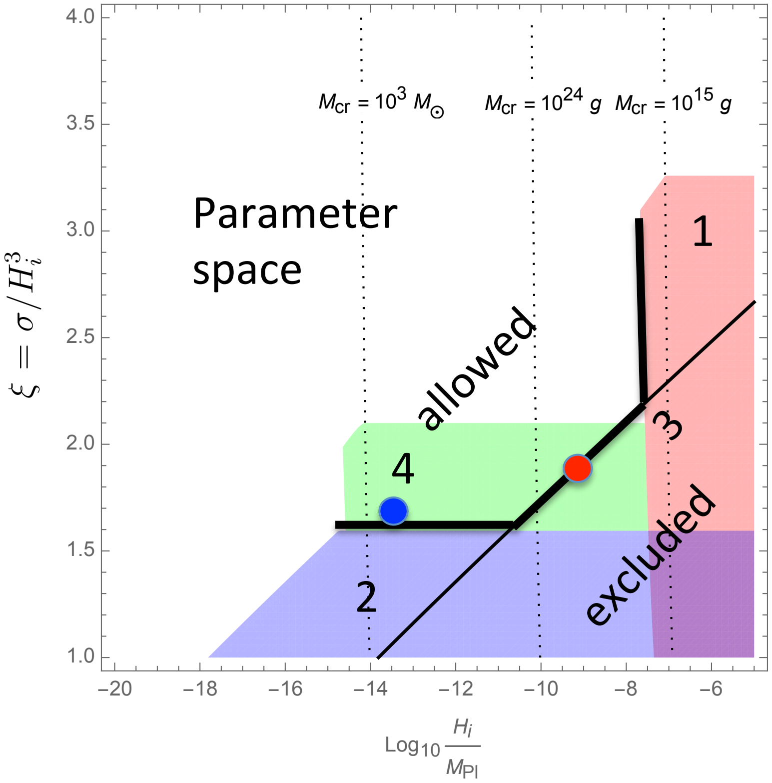


Merger rate observed by LIGO requires

$f \sim 10^{-3}$ for $M_{bh} \sim 30 M_\odot$

Sasaki et al (2016)

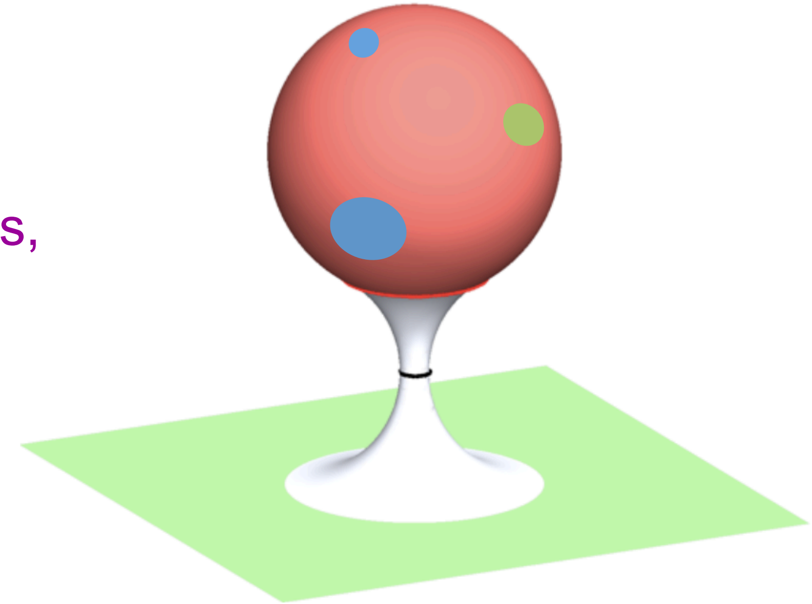
$$\boxed{M_{cr} \sim 30 M_\odot}$$

Accounts for LIGO and SMBH with seeds of $10^6\ M_{solar}$.

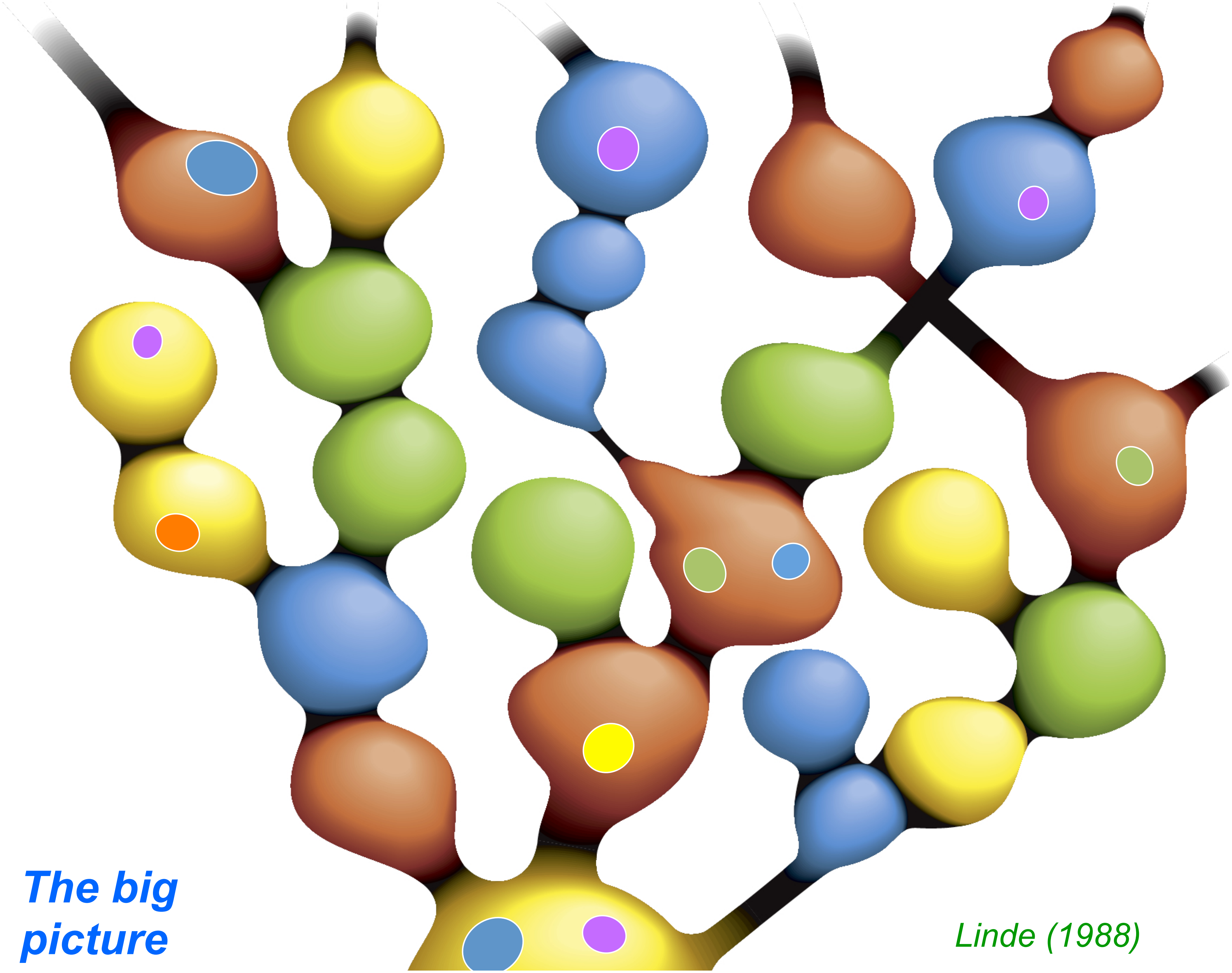
Summary

- Spherical domain walls and vacuum bubbles may nucleate during inflation, leading to the formation of primordial black holes with a universal power-law spectrum of masses.
- These black holes have inflating baby universes inside
- A discovery of black holes with the predicted distribution of masses would provide evidence for inflation – and for the existence of baby universes.
- They might act dark matter and as seeds for supermassive BH.
- They may have formed the binaries LIGO is currently observing. If so, they may also cause marginally detectable spectral distortions in the CMB, and seed SMBH.

Global structure of spacetime



- The baby universes will inflate eternally.
- Bubbles of all possible vacua, including ours, will be formed.
- A multitude of inflating regions connected by wormholes.



The big picture

Linde (1988)