The beginning of an inflationary universe out of a Kerr-AdS$_5$ black hole

Recent Progress of Quantum Cosmology
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Paper in preparation

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Our 4D Universe

Ooguri, Palti, Shiu and Vafa' 19
Martin and Brandenberger' 01
Bedroya, Brandenberge, Loverde and Vafa' 20

Our universe is expanding, and this expansion is accelerating

This acceleration is often explained by de Sitter (dS) spacetime that has a positive cosmological constant (CC)

In string theory, vacuum structure is complicated and still not understood well

It is difficult to construct dS spacetime in string theory

Recently, there are some conjectures about dS spacetime

dS conjecture

dS conjecture & TCC

Ooguri, Palti, Shiu and Vafa' 19
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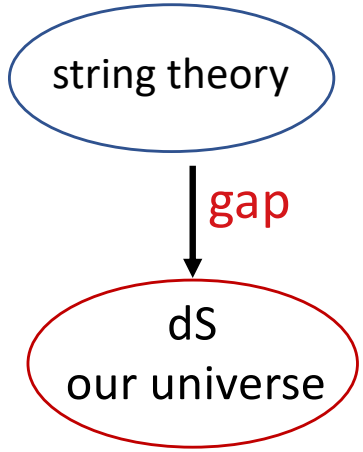
Bedroya, Brandenberge, Loverde and Vafa' 20

dS conjecture : string theory cannot construct dS

dS conjecture conflicts our universe

There is a gap between string theory and our universe



Bubble universe setup is one of the solutions of gap

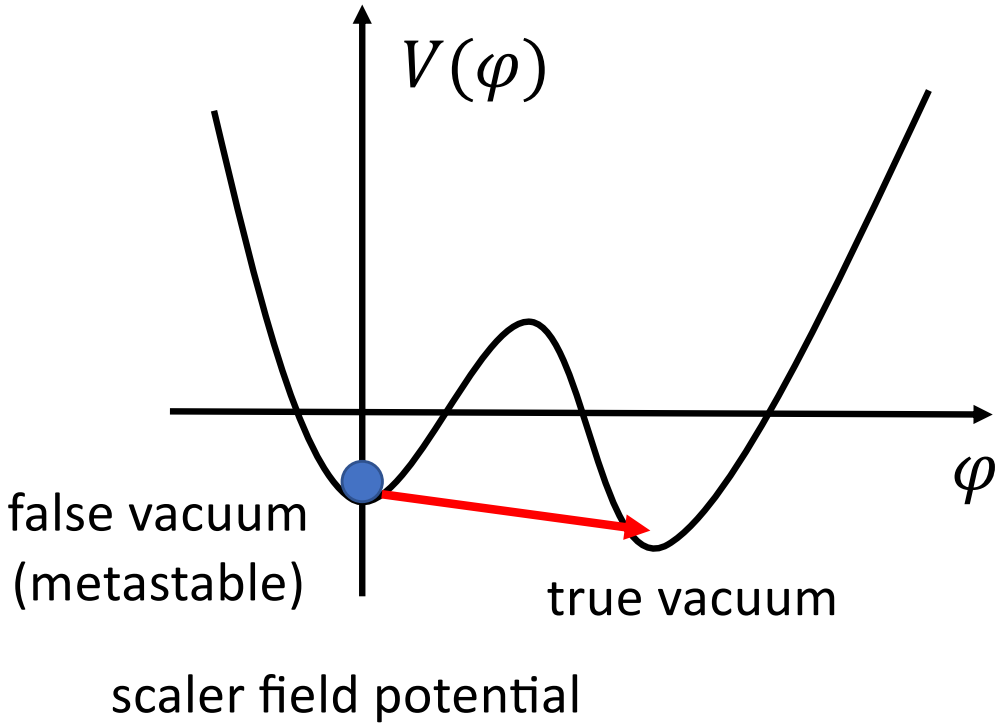
[Dnielsson et al.]

We use and studied this setup

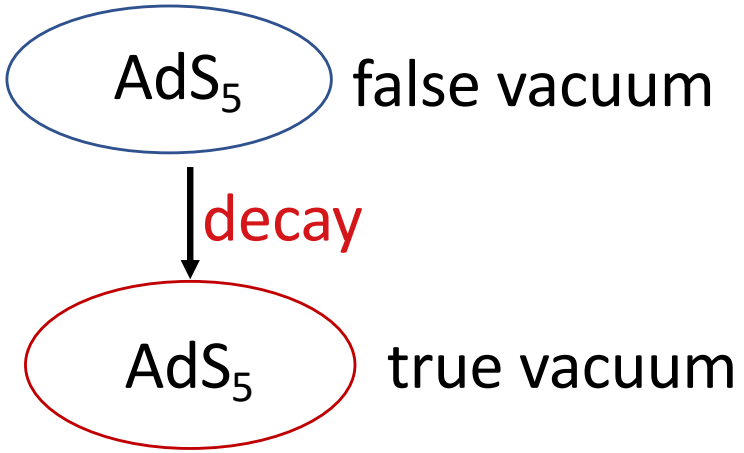
Vacuum decay & Bubble Universe

Coleman' 77

Consider metastable AdS_5 decay



scaler field potential



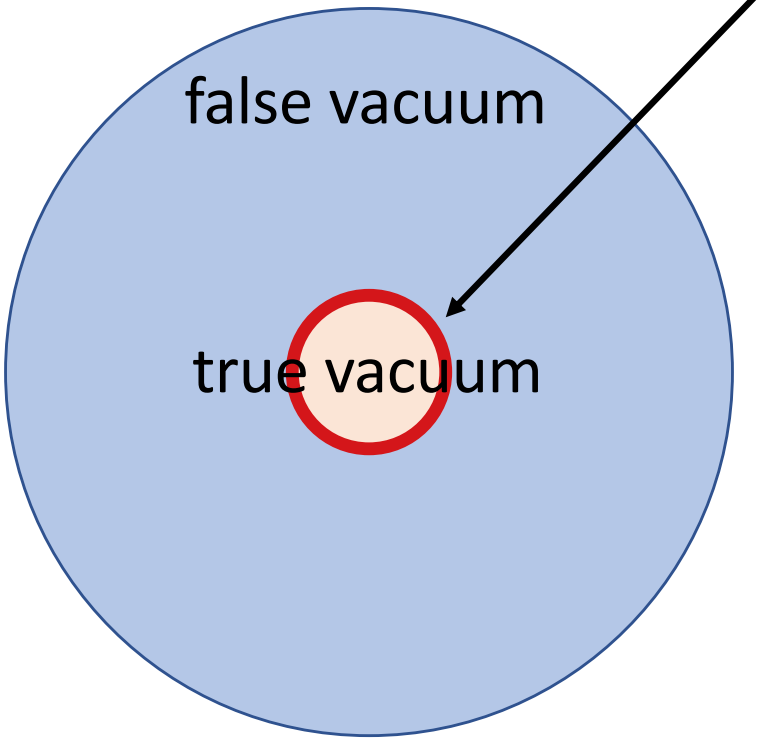
metastable false vacuum decay into true vacuum via tunneling process

Creation of Bubble Universe

Banerjee, Danielsson, Dibitetto, Giri and Schillo' 2019
Coleman and De Luccia' 1980

Decay process picture

Bubble is nucleated in false vacuum, its inside is true vacuum



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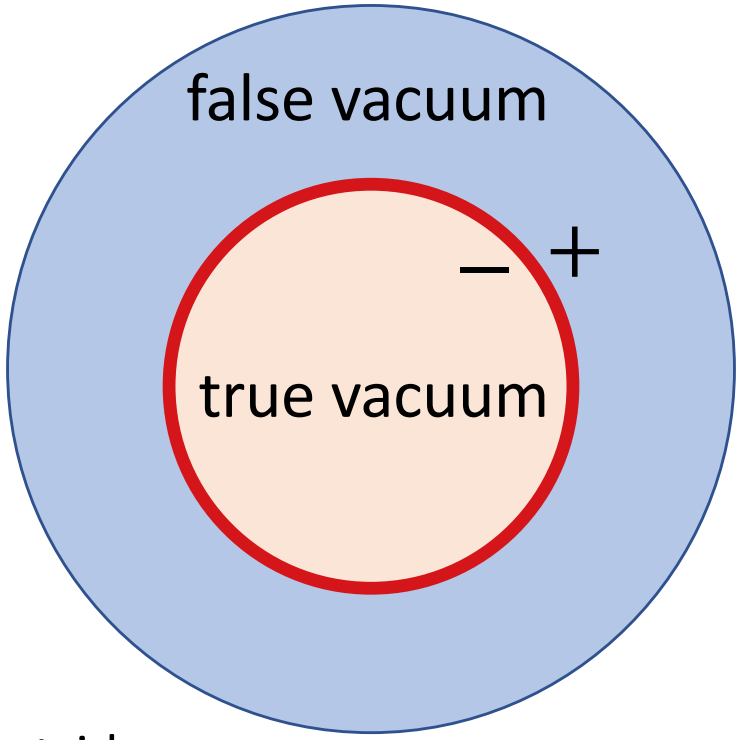


outside : +
inside : –

Bubble is nucleated in false vacuum
inside the bubble is true vacuum

Decay proceeds as bubble expands

In the decay of AdS_5, bubble surface is 4D

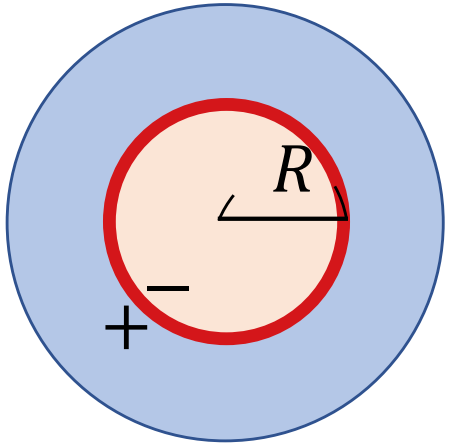
Our 4D universe is constructed on this bubble surface

⟶ Bubble Universe

Bubble Universe

Israel, 1966

We see the universe is realized by Friedman eq. level



5D metric $$ds^2 = -f_{\pm}(r)dt^2 + \frac{dr^2}{f_{\pm}(r)} + r^2 d\Omega_3^2$$

metric on bubble $$ds_b^2 = -d\lambda^2 + R^2(\lambda)d\Omega_3^2$$

Bubble is boundary of two spacetime

There is junction condition on bubble

$$\sqrt{\frac{f_+}{R^2} + \frac{\dot{R}^2}{R^2}} - \sqrt{\frac{f_-}{R^2} + \frac{\dot{R}^2}{R^2}} = -\frac{8\pi G_5 \sigma}{3}$$

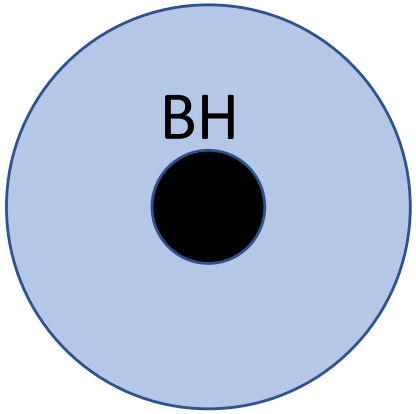
σ : tension of bubble

from these terms, we get Friedman eq. of bubble universe

A Black Hole acts as a “seed”

Dafermos and Holzegel’ 2006
Bizon and Rostworowski’ 2011
Gregory, Moss and Withers’ 2014

AdS_5
false vacuum



AdS seems to be nonlinearly unstable

⟶ Black hole formation

✓ Bubble nucleation with BH is a realistic situation

Static BH enhances the vacuum decay rate in 4D

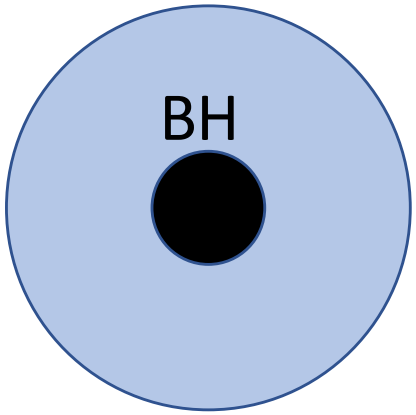
[Gregory et al. ‘2014]

BH act as a “seed” for a decay

A Black Hole acts as a "seed"

IK, Ookouchi' 2019
Gregory, Moss and Withers' 2014

false vacuum



Static BH in AdS_5 enhance the decay

[IK, Ookouchi' 2019]

✓ Rotating effect in 5D is not understood yet

⟶ Studied bubble potential and decay rate of vacuum decay nucleated by Kerr AdS_5

2 questions

Does spin enhance or suppress the decay?

Is expanding bubble realized for rotating BH?

Parameters

BH mass parameter $M_\pm$

AdS radius $-\frac{6}{\Lambda_\pm} = l_\pm^2$

BH spin parameter $a_\pm$

Bubble wall energy m_0
thin-wall approx.

l_- l_+ m_0 ⟵ fix by hand (potential shape)

M_+ a_+ ⟵ changed and studied effect (seed BH)

M_- a_- ⟵ determined by static bounce condition

Metric & Junction condition

Delsate, Rocha and Starelli' 2014

$$ds^2 = -f(r)^2 dt^2 + g(r)^2 dr^2 + r^2 \hat{g}_{ab} dx^a dy^b + h(r)^2 \left[d\psi + A_a dx^a - \Omega(r) dt \right]^2,$$

$$A = \frac{1}{2} \cos\theta d\phi \ , \ g(r)^2 = \left(1 + \frac{r^2}{l^2} - \frac{2M\Xi}{r^2} + \frac{2Ma^2}{r^4} \right)^{-1} \ , \ h(r)^2 = r^2 \left(1 + \frac{2Ma^2}{r^4} \right) ,$$

$$\Omega(r) = \frac{2Ma}{r^2 h(r)^2} \ , \ f(r) = \frac{r}{g(r)h(r)} \ , \ \Xi = 1 - \frac{a^2}{l^2} \ , \ \hat{g}_{ab} dx^a dx^b = \frac{1}{4}(d\theta^2 + \sin^2\theta d\phi^2),$$

$$M_+ a_+^2 = M_- a_-^2$$

$$\beta_+ - \beta_- = -\frac{m_0^{1+3w/2}}{R^{2(1+w)} h(R)^{w/2}}$$

junction condition

$$\beta_\pm = \sqrt{f_\pm(R) + f_\pm(R) g_\pm(R) \left(\frac{dR}{d\tau} \right)^2}$$

this term corresponds bubble dynamics

Expansion of bubble

We get the formula about bubble dynamics

$$\frac{\dot{\mathcal{R}}^2}{\mathcal{R}^2} = -\frac{1}{l_-^2} + \frac{1}{4}\left[\frac{1}{l_-^2} - \frac{1}{l_+^2} + \frac{1}{m_0}\right]^2 m_0 - \left(\frac{1}{\mathcal{R}}\right)^2 - \frac{\alpha}{\mathcal{R}^4} - \frac{2Ma^2}{\mathcal{R}^6} + o(\mathcal{R}^{-8}),$$

$$\alpha = 2\left(1 - \frac{a_+^2}{l_+^2}\right)M_+ - 2\left(1 - \frac{a_-^2}{l_-^2}\right)M_- - \frac{1}{2}\left(\frac{1}{l_-^2} - \frac{1}{l_+^2} + \frac{1}{m_0}\right)m_0\left[-2a^2\left(\frac{1}{l_-^2} - \frac{1}{l_+^2}\right)M + \frac{2Ma^2}{m_0} - 2\left(1 - \frac{a_-^2}{l_-^2}\right)M_-\right]$$

Bubble dynamics obey Friedman like eq.

⟶ Expanding bubble is realized for rotating BH case!

Decay rate estimation

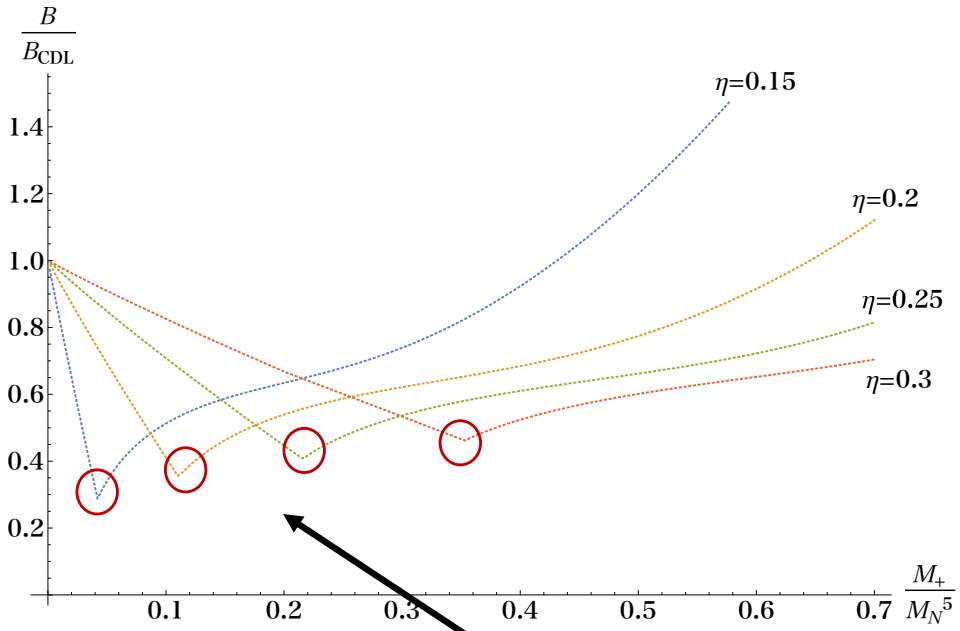
IK, Ookouchi' 2019

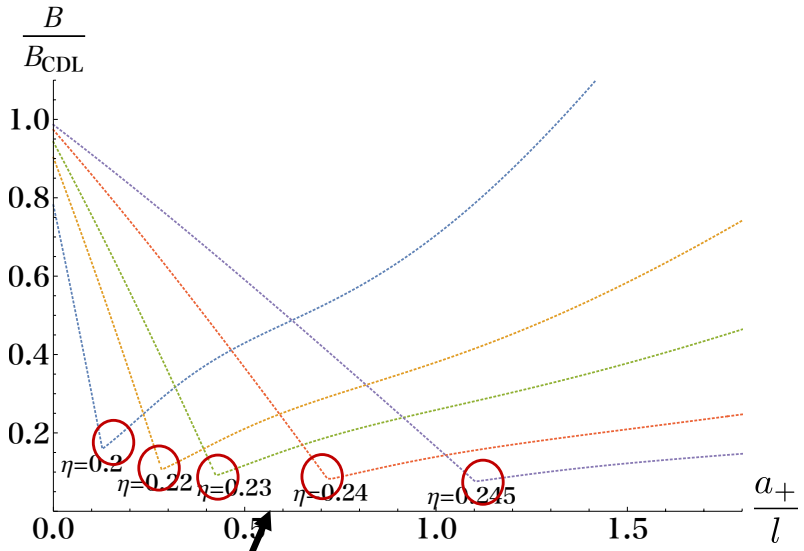
$$\Gamma \sim e^{-B}$$

decay rate

Euclidean action

Decay rate is estimated by Euclidean action





static Euclidean action

Decay rate estimation

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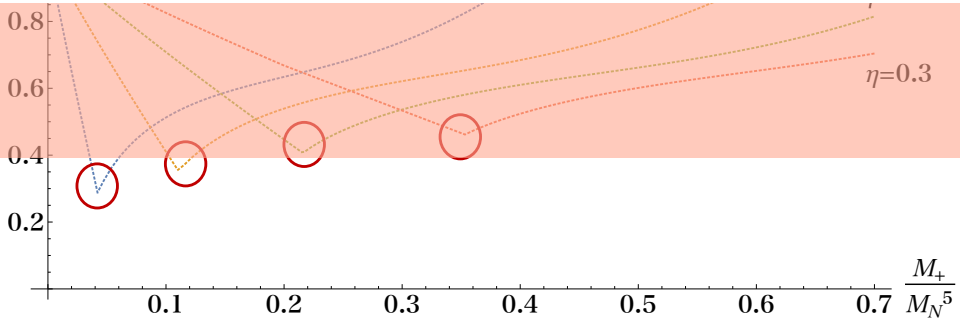
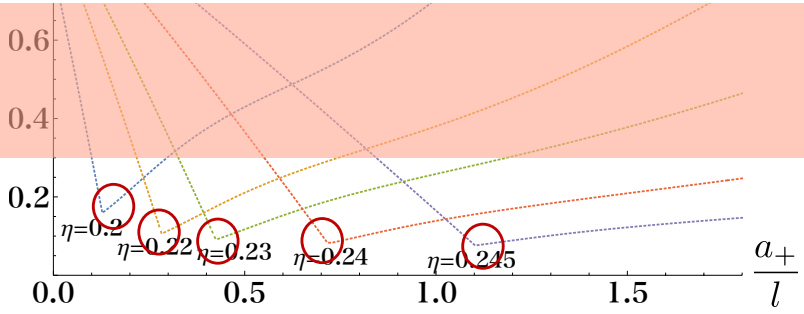
Decay rate is estimated by Euclidean action

From previous study, we assume static action dominate the decay

Focus on only the static action





Static Euclidean action

$$\Gamma \sim e^{-B}$$

decay rate

Euclidean action

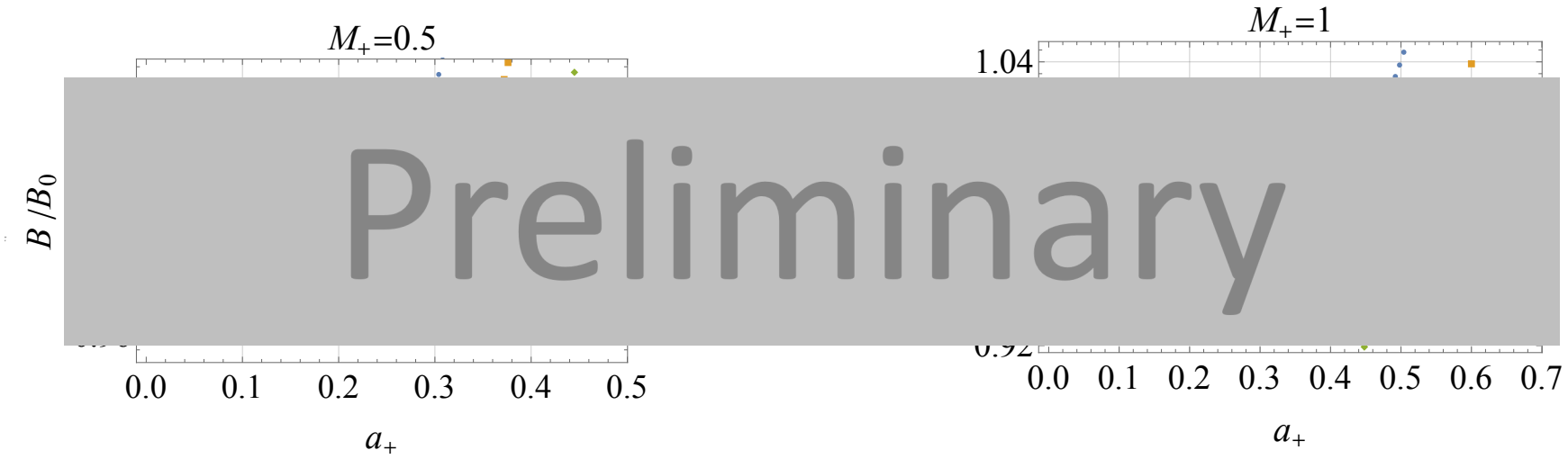
Bubble wall contribution is zero for static solution

✓Only horizon area contribute the action for static case

$$B = \frac{1}{4G_5}\left(\mathcal{A}_+ - \mathcal{A}_-\right)$$

Static Bounce Solution $l_+ = 7, l_- = 4$

Plot of bounce action ratio



B_0 is action of zero spin case

$B/B_0 < 1$ show that spin enhances the decay

$$\Gamma \sim e^{-B}$$

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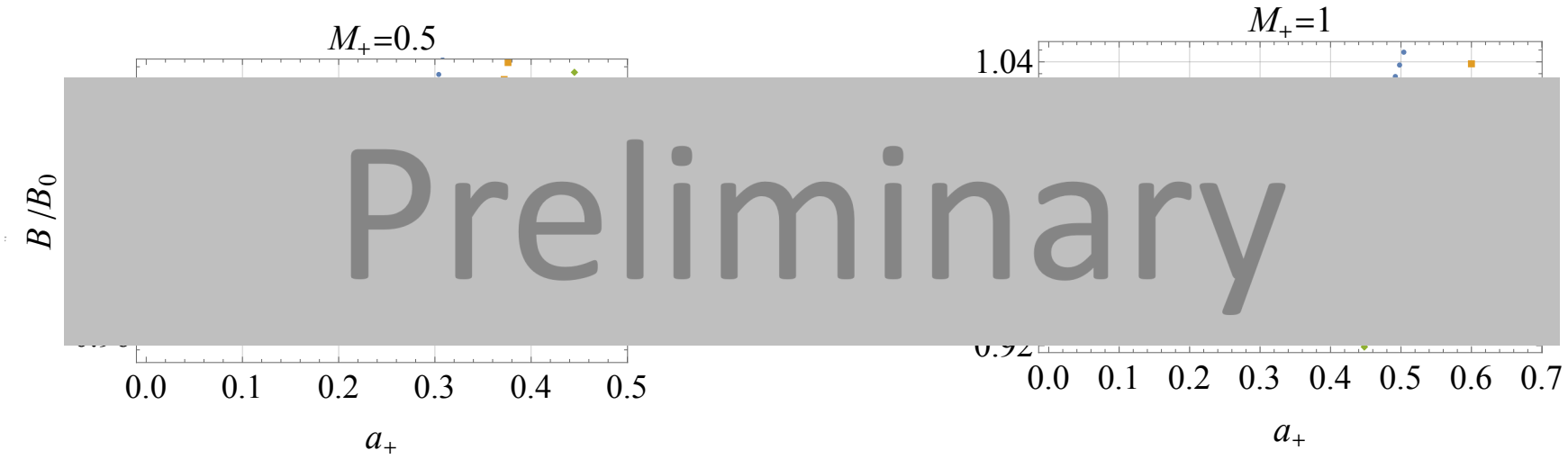

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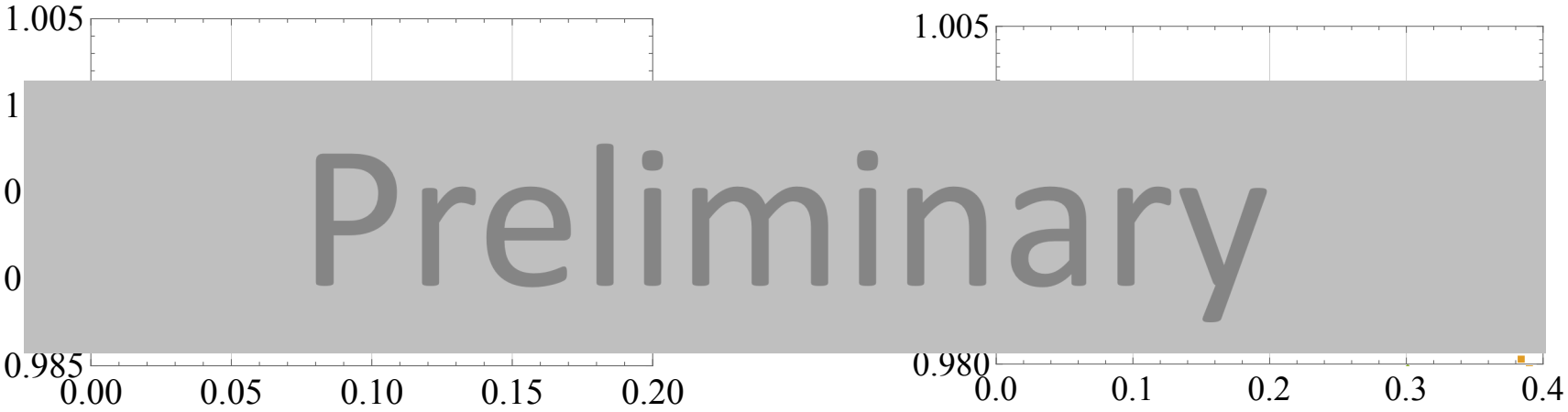

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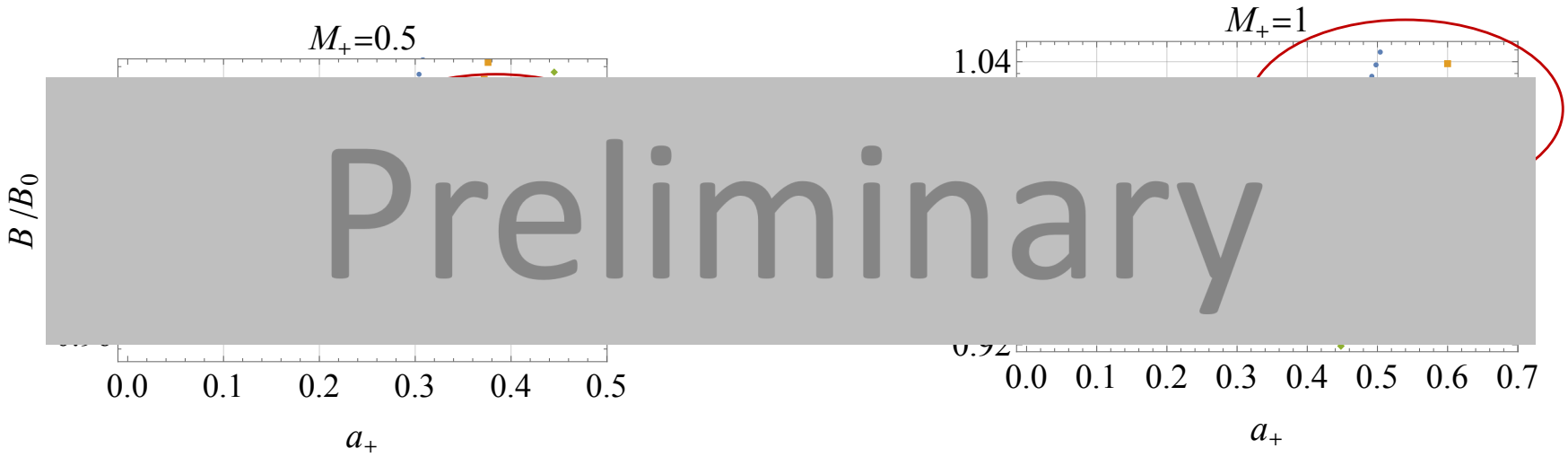

$B/B_0 > 1$ suppress the decay

- ✓ Small spin enhances the decay
- ✓ Large spin suppress the decay

Summary

We realized inflationary universe by the bubble universe set up

Studied vacuum decay induced by “rotating ” black hole

Expanding bubble is realized for rotating BH case

From static bounce action calculation, we showed
small spin enhances the decay
large spin suppress the decay

✓Study more about the geometry of bubble universe