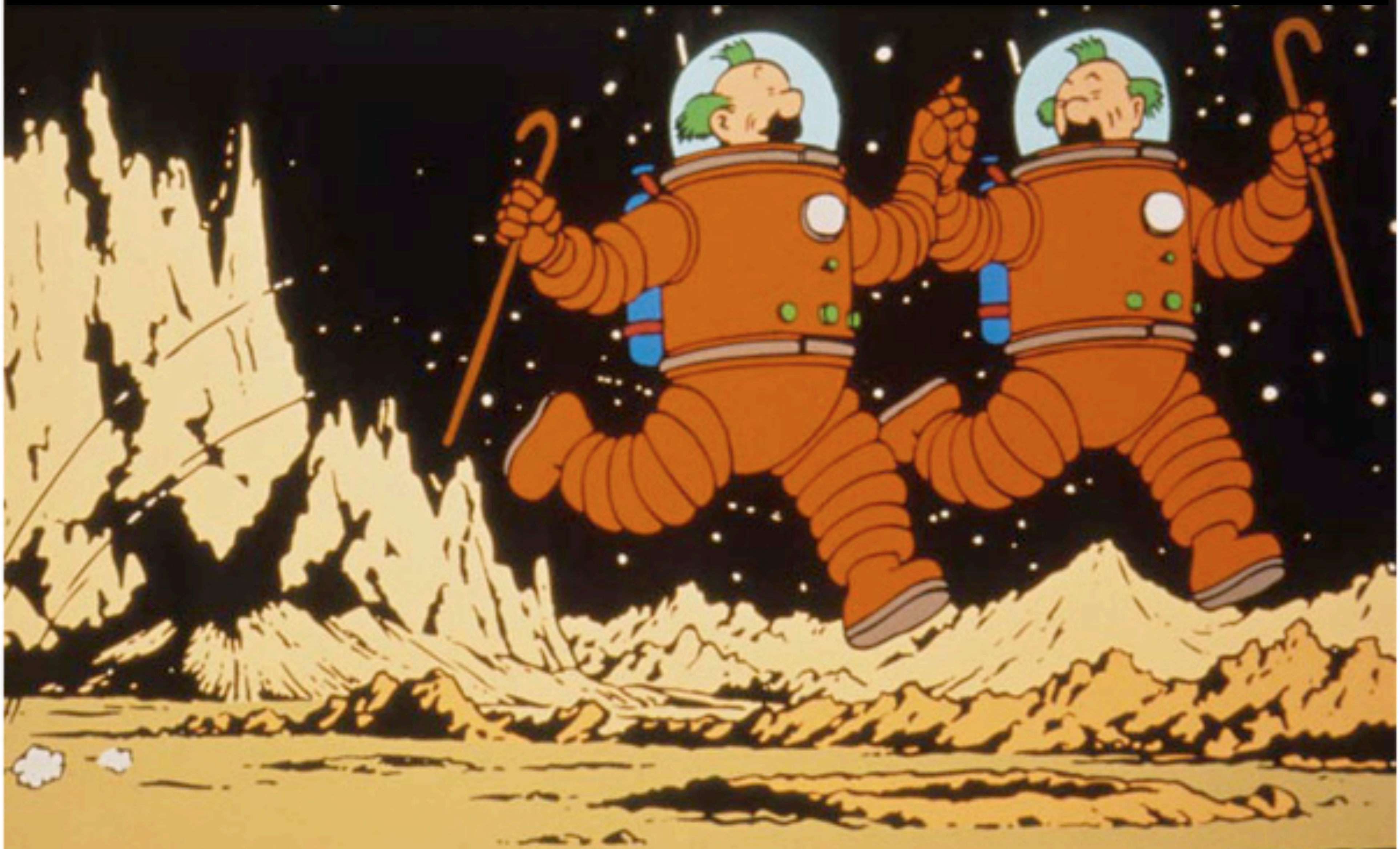
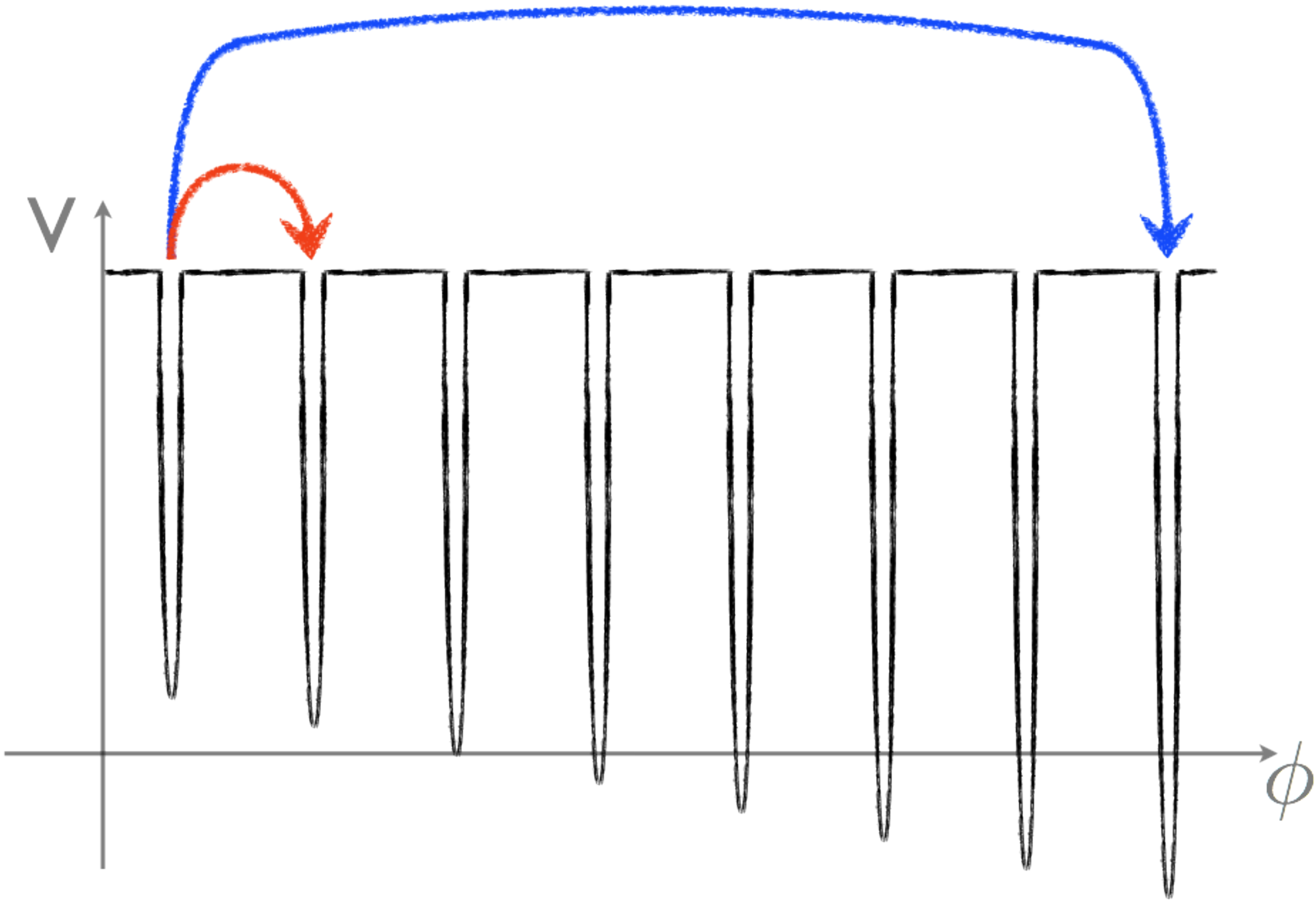
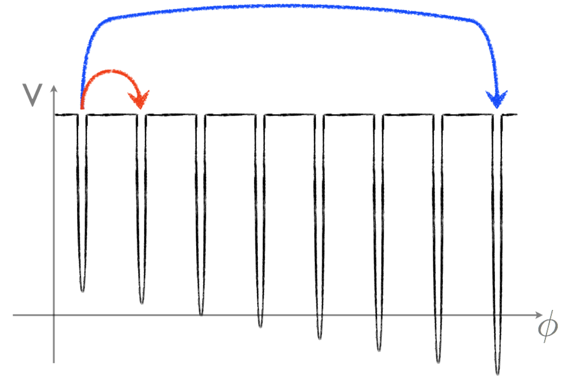
The Fastest Decay in the Landscape



Based on work with Adam Brown

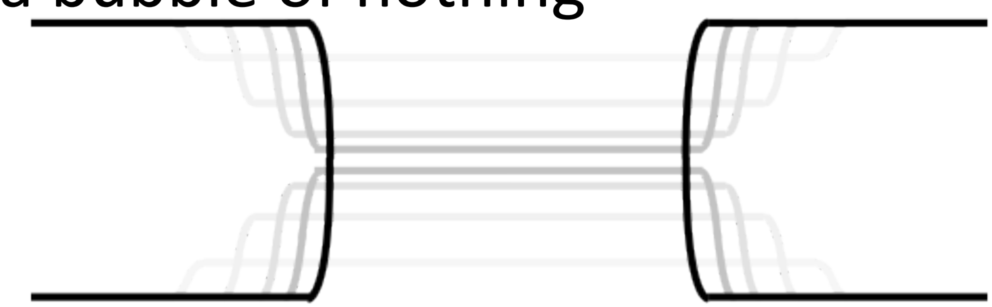

V
ϕ

1. This potential gives small steps



2. Flux compactifications with many fluxes give giant leaps
3. Monkey branes

4. Adding back-reaction
5. The giantest leap of all is a bubble of nothing



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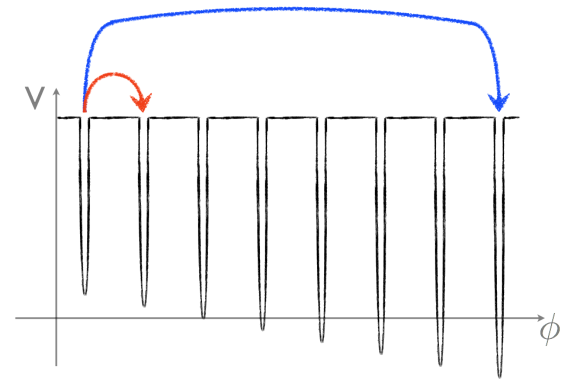

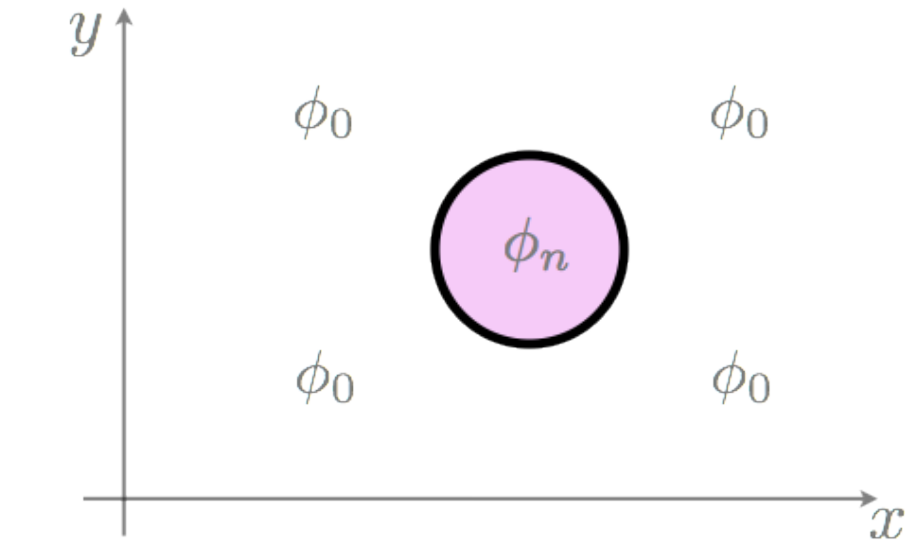

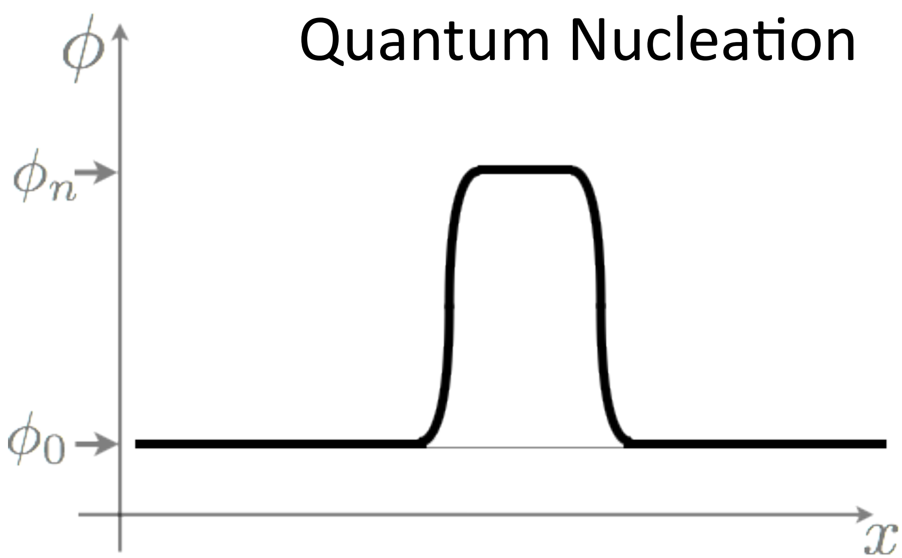

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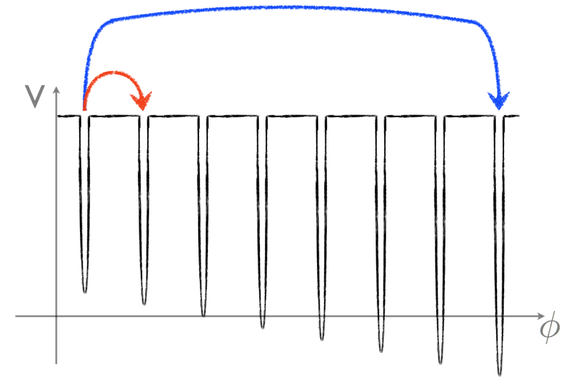
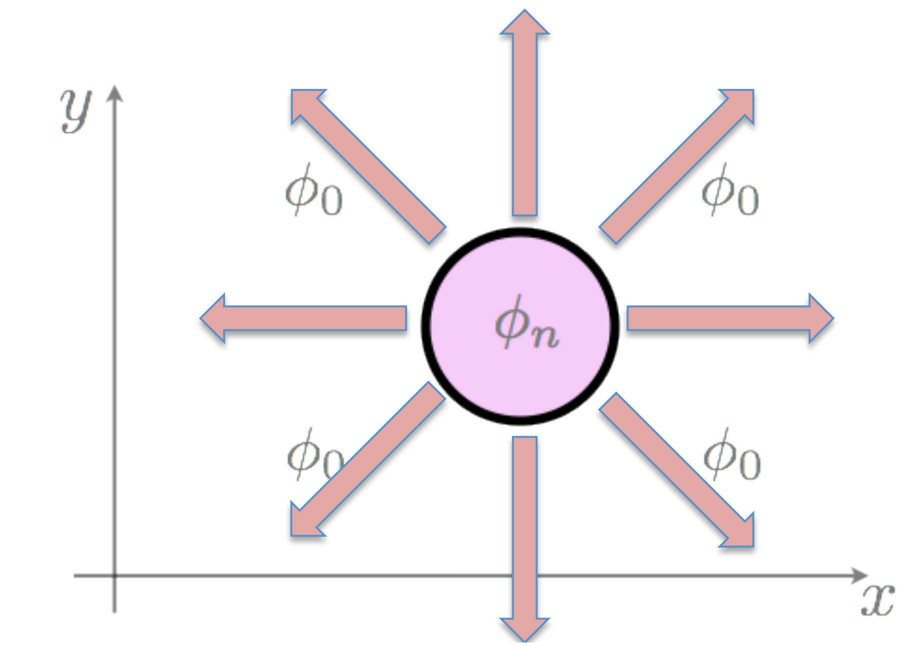
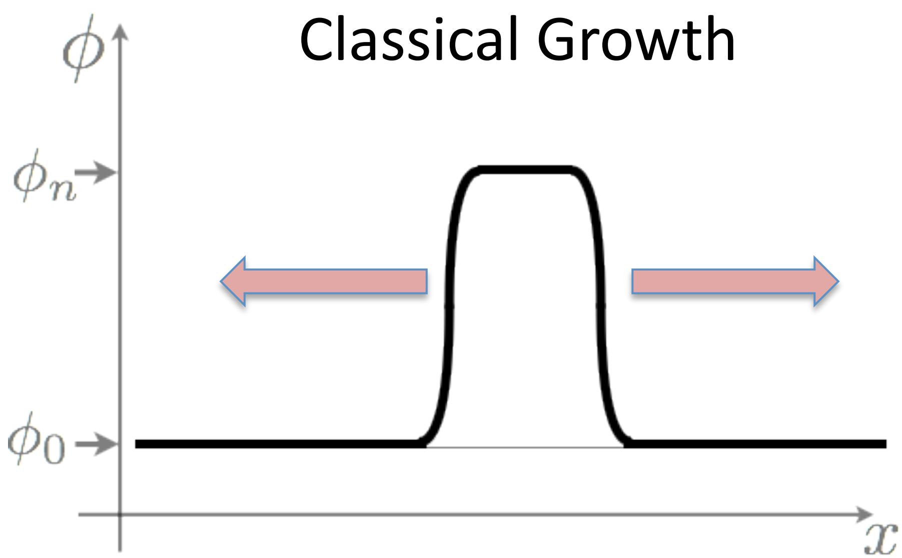




Classical Growth



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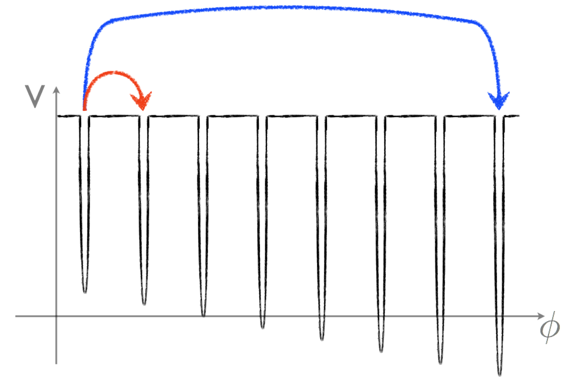
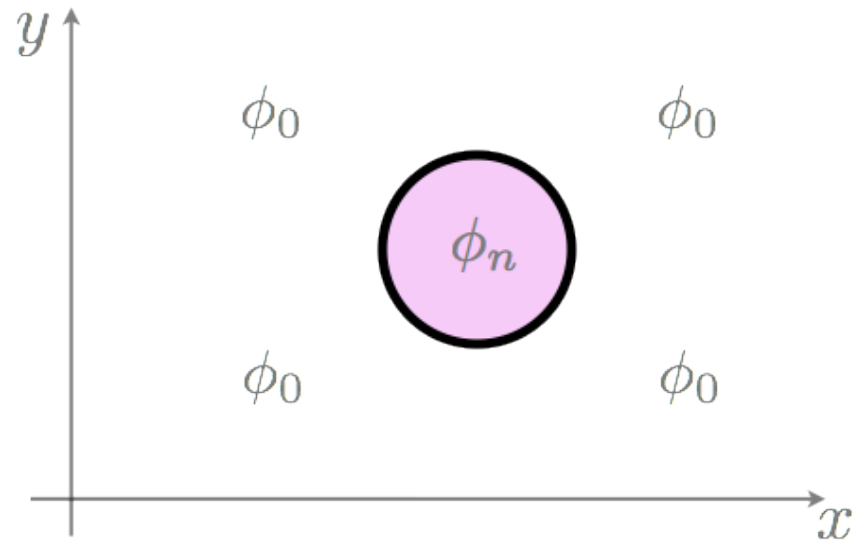
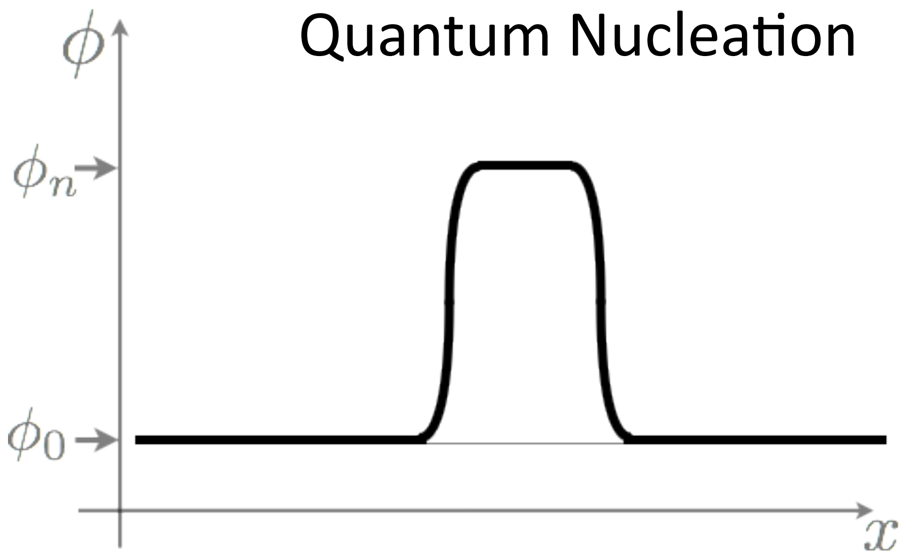




- thin wall
- flat spacetime

Quantum Nucleation



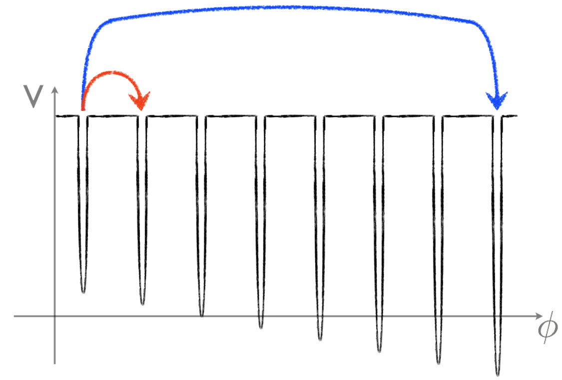
$$\Gamma_n \sim \exp[-\frac{\#}{\hbar}\frac{\sigma_n^4}{\epsilon_n^3}]$$

Coleman (1977)

$$\sigma_n \equiv \int_{\phi_0}^{\phi_n} d\phi \sqrt{2[V(\phi) - V(\phi_0)]}$$

$$\epsilon_n \equiv V(\phi_0) - V(\phi_n)$$

1. This potential gives small steps



$$\sigma_n = n\sigma_1$$

$$\epsilon_n = n\epsilon_1$$

$$\frac{\sigma_n^4}{\epsilon_n^3} = n\frac{\sigma_1^4}{\epsilon_1^3}$$

- thin wall
- flat spacetime

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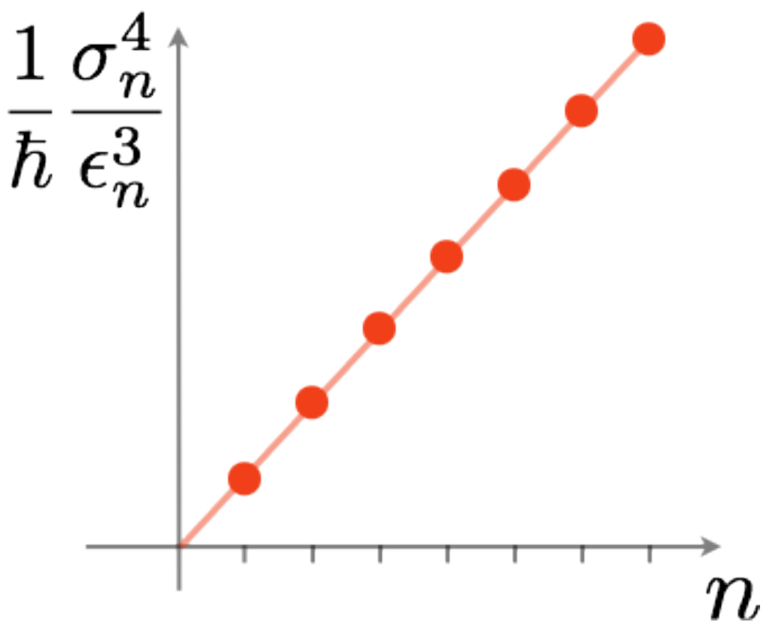

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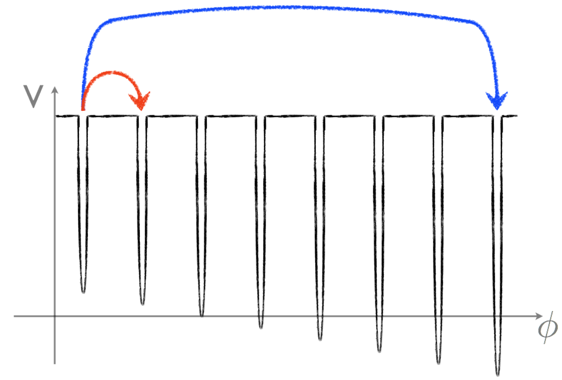

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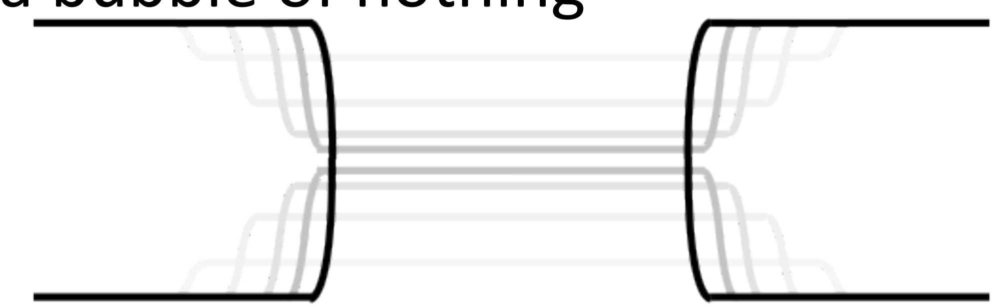


Flux Landscapes

There are many non-cosmological reasons to consider extra dimensions

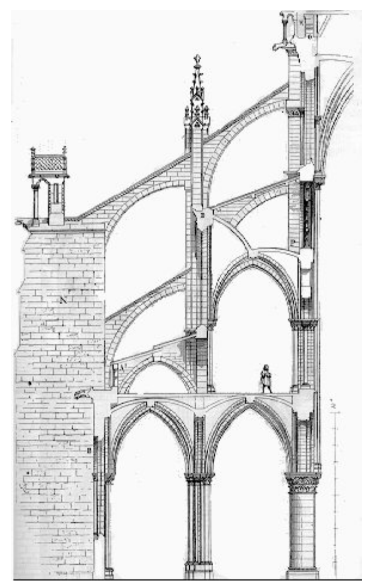
Extra dimensions and flux naturally give rise to a landscape of vacua

Flux shifts cosmological constant

$$\Lambda_{\text{eff}} = \Lambda_0 + \frac{1}{2}F^2$$

Flux stabilizes extra dimensions

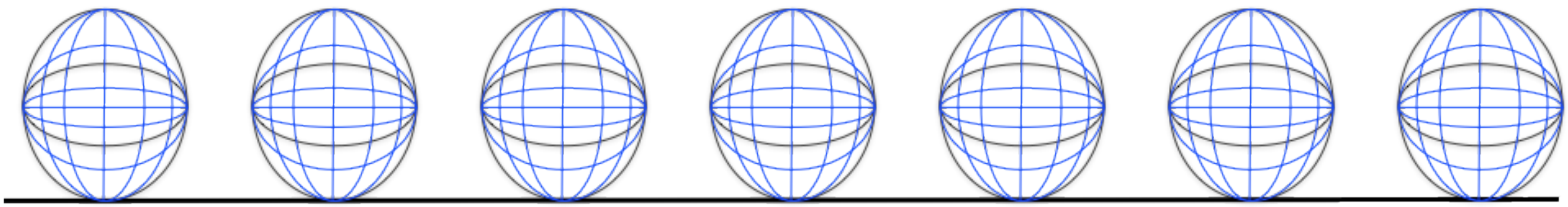
If you build a compactification, it will flux decay



What will our Universe decay to?
Where did it come from?

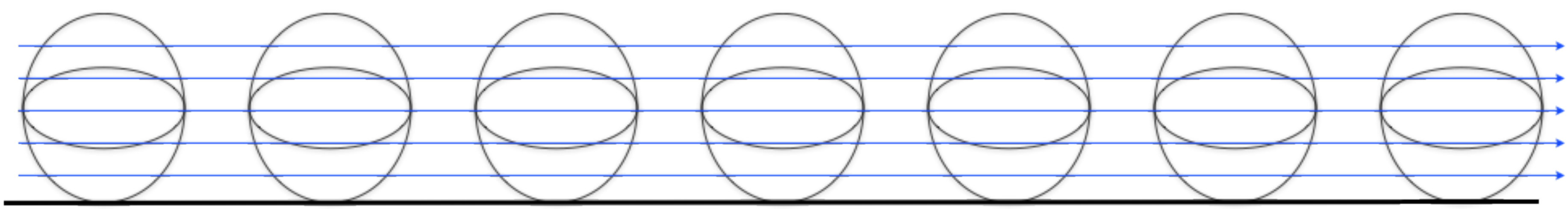
Consider flux tunneling in 1+1+2 dimensions

space time sphere



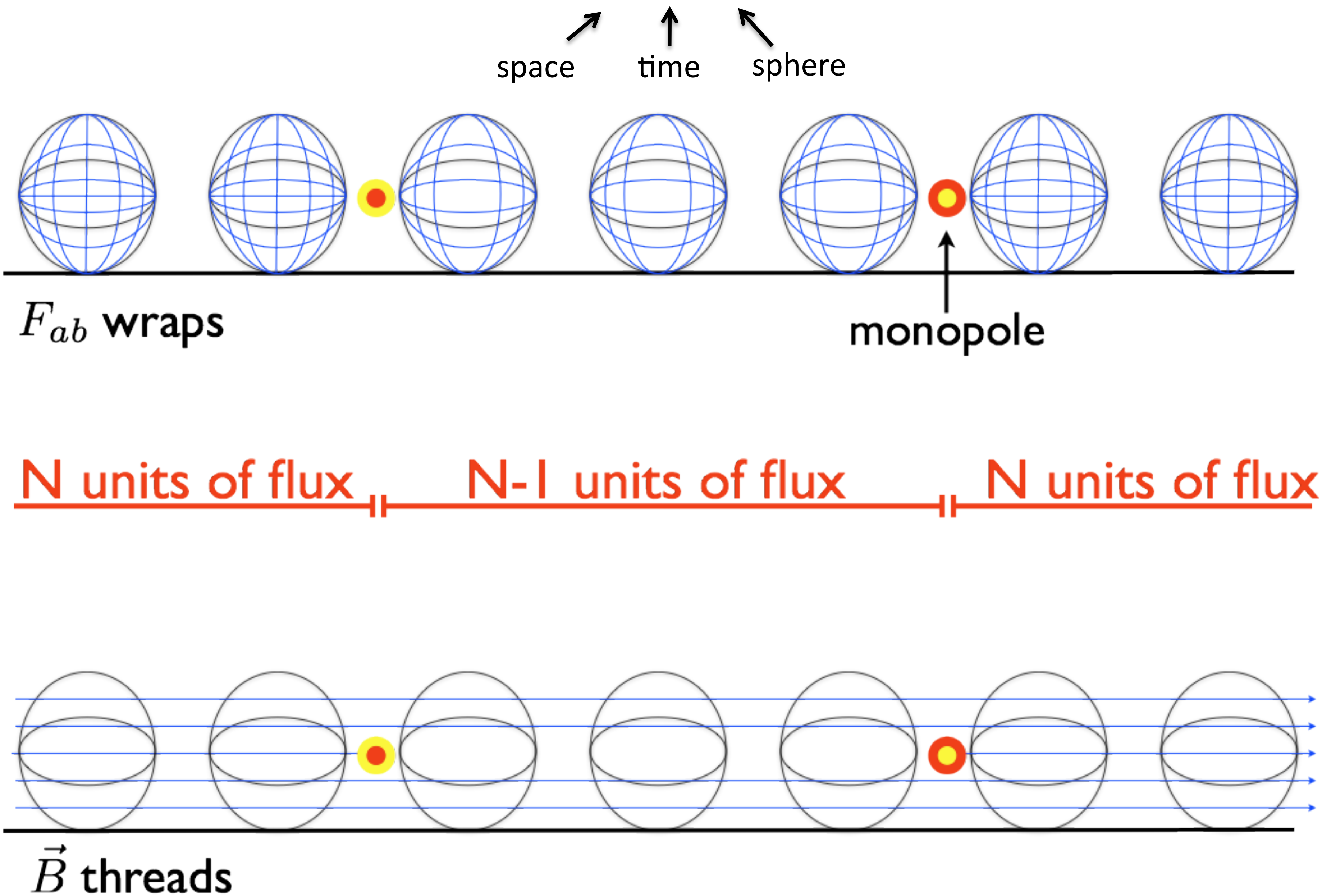
F_{ab} wraps

N units of flux N units of flux N units of flux



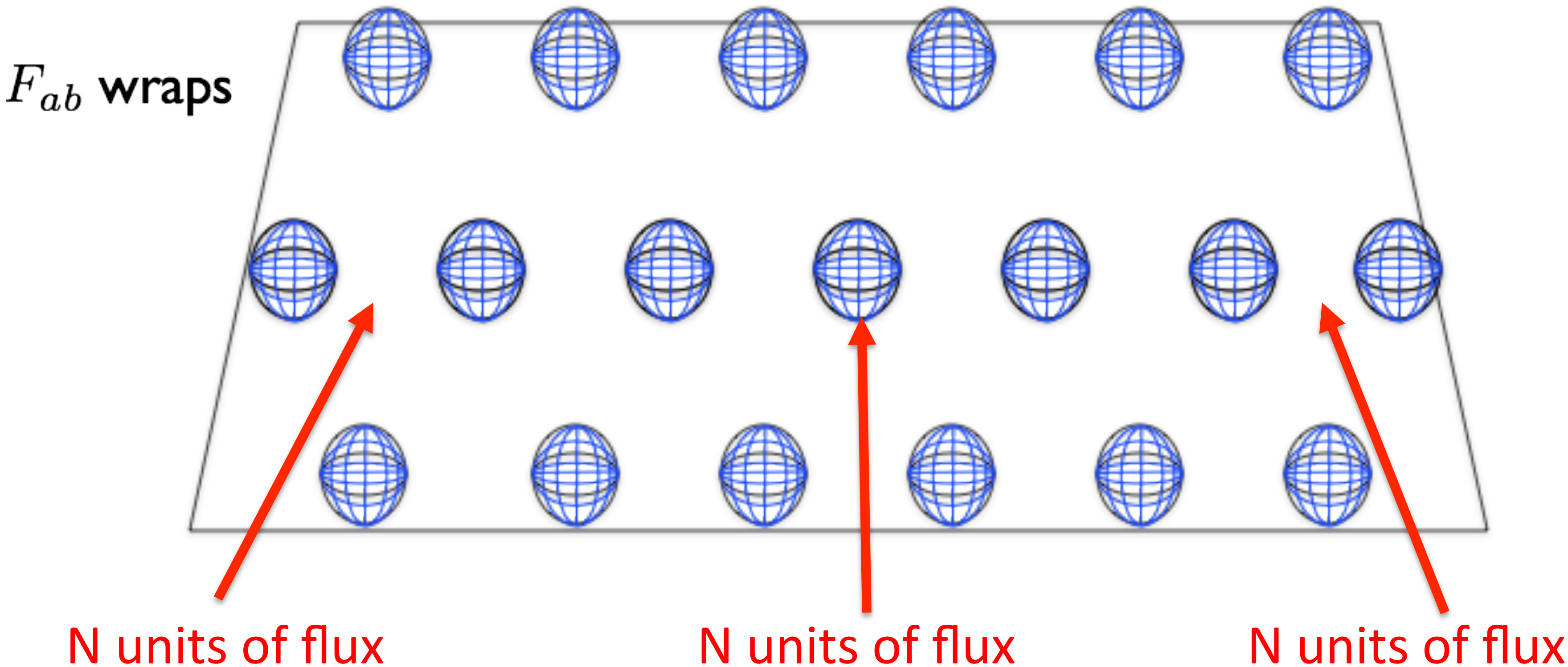
$\vec{B}$ threads

Consider flux tunneling in 1+1+2 dimensions



Consider flux tunneling in 3+1+2 dimensions

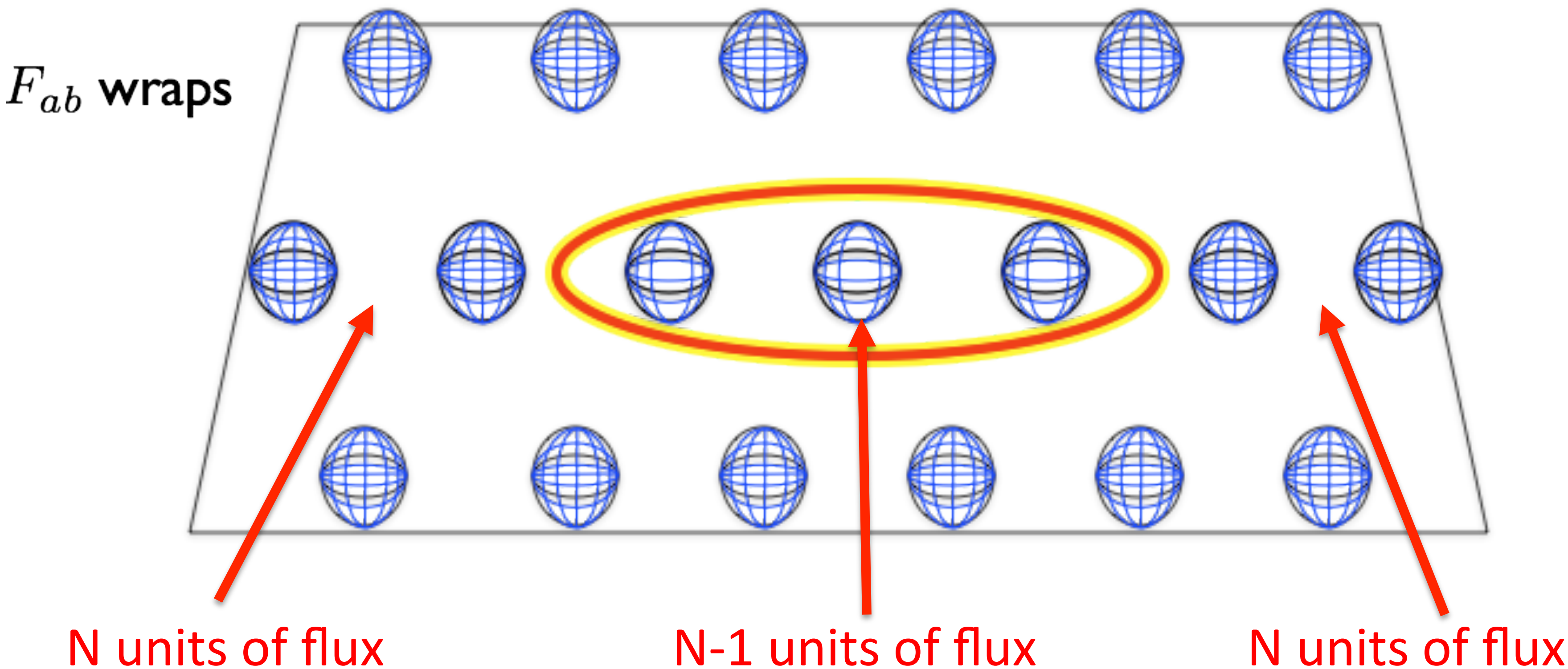
space time sphere



Consider flux tunneling in 3+1+2 dimensions

space time sphere

Nucleate an extremal black 2-branes



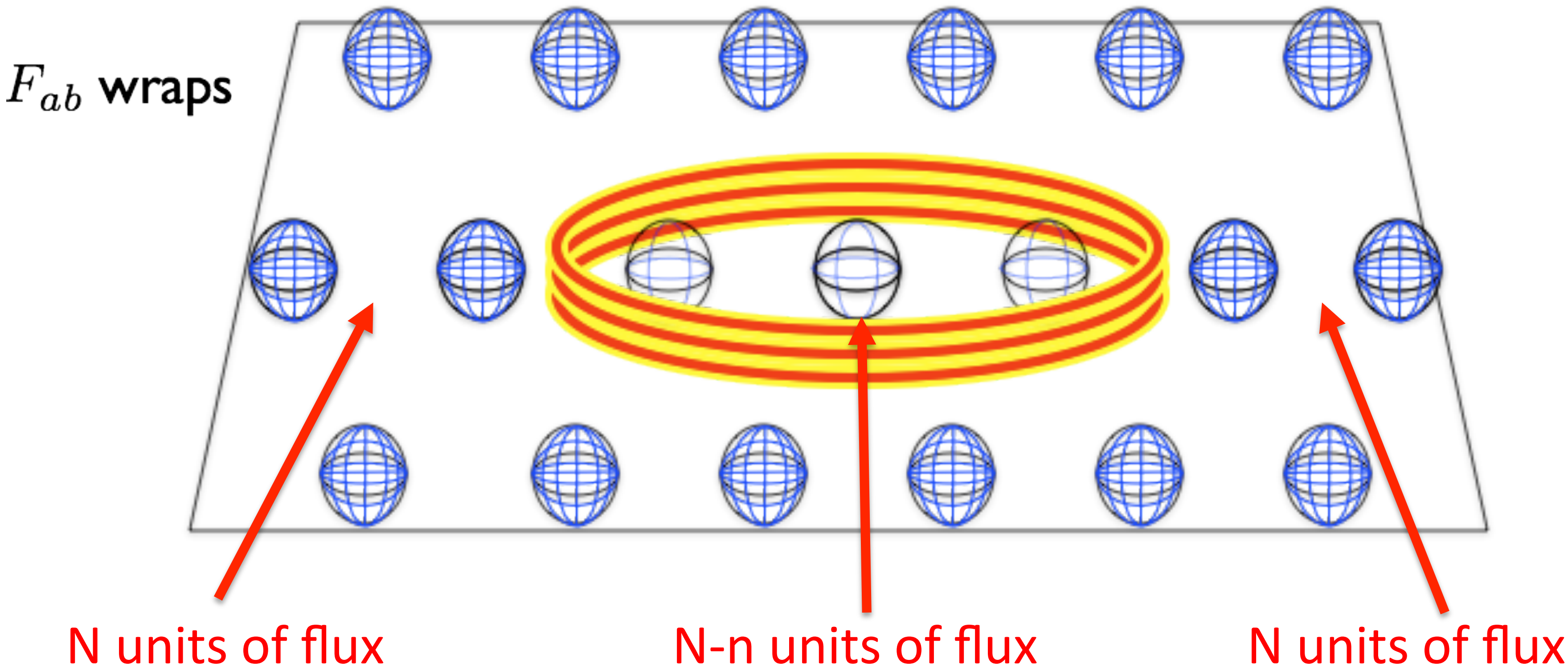
Blanco-Pillado, Schwartz-Perlov, Vilenkin (2009)

Consider flux tunneling in 3+1+2 dimensions

space time sphere

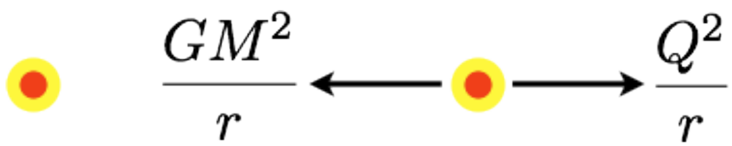
Giant Leaps?

Nucleate a stack of n 2-branes



What’s the tension of the brane?

as light as possible, given its charge



$$M = Q$$

What's the tension of the brane?

as light as possible, given its charge

$$\frac{GM^2}{r}$$

$$\frac{Q^2}{r}$$

$$\frac{GM^2}{r}$$

$$\frac{Q_1^2}{r} + \frac{Q_2^2}{r}$$

$$M = Q$$

$$M = \sqrt{Q_1^2 + Q_2^2}$$

What’s the tension of the brane?

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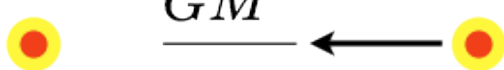
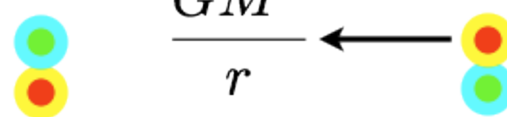


$$\frac{GM^2}{r} \longleftarrow \quad \longrightarrow \frac{Q^2}{r}$$



$$\frac{GM^2}{r} \longleftarrow \quad \longrightarrow \frac{Q_1^2}{r} + \frac{Q_2^2}{r}$$

$$M = Q$$

$$M = \sqrt{Q_1^2 + Q_2^2}$$

$$T \sim \left(\sum_{i=1}^{\mathfrak{N}} g_i^2 n_i^2 \right)^{1/2}$$

Large landscape: many different types of fluxes

$$F^2 = \sum_{i=1}^{\mathfrak{N}} g_i^2 N_i^2 \qquad\qquad T \sim \left(\sum_{i=1}^{\mathfrak{N}} g_i^2 n_i^2 \right)^{1/2}$$

Large landscape: many different types of fluxes

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Two decay directions:

MONOFLUX decay

MULTIFLUX decay

Large landscape: many different types of fluxes

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Two decay directions:

MONOFLUX decay

I. $T_n \sim n$

MULTIFLUX decay

I. $T_n \sim \sqrt{n}$

Large landscape: many different types of fluxes

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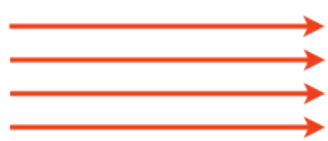
Two decay directions:

MONOFLUX decay

I. $T_n \sim n$

II. $\Delta(F^2) \sim (2N - n)n$



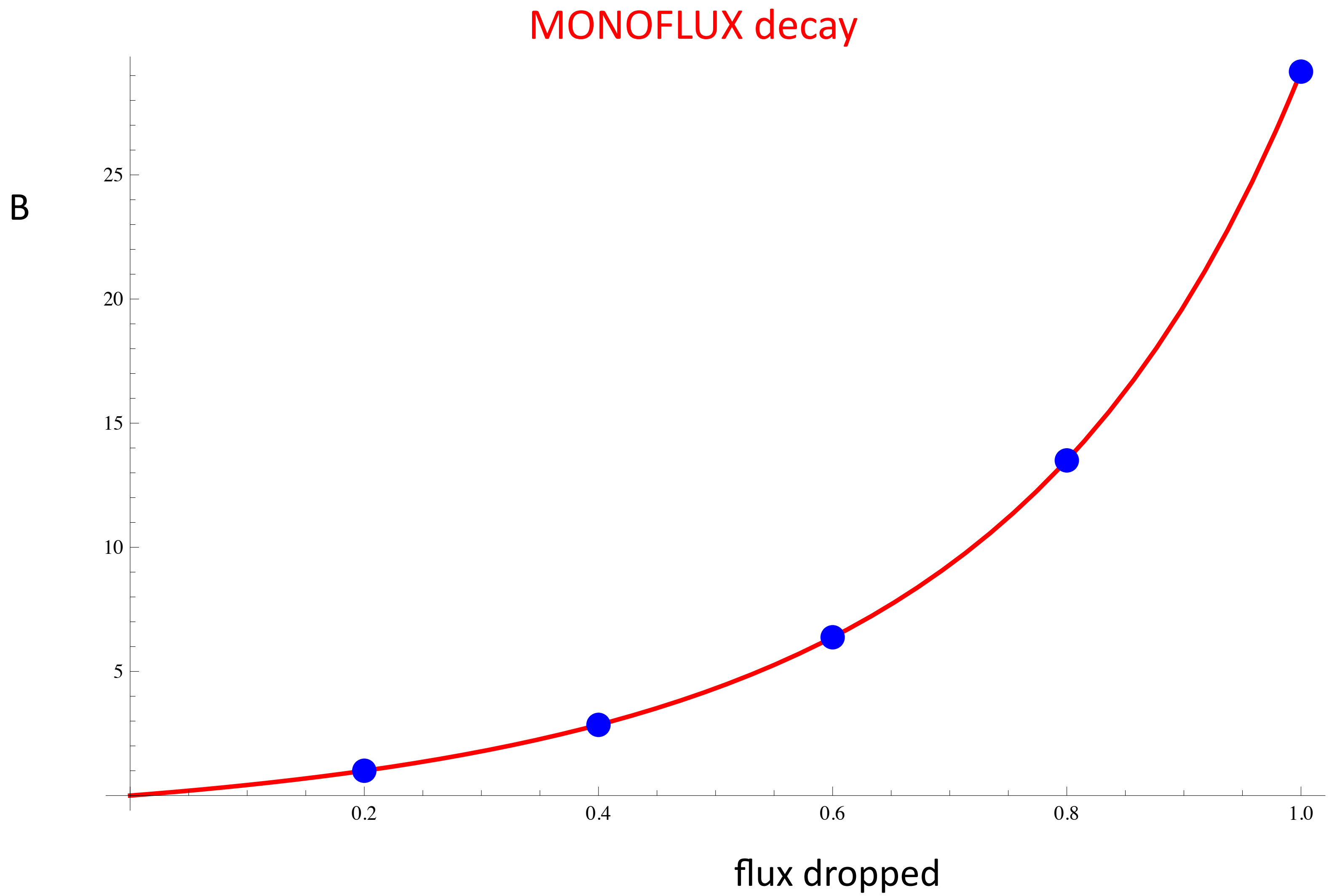
like flux lines repel

MULTIFLUX decay

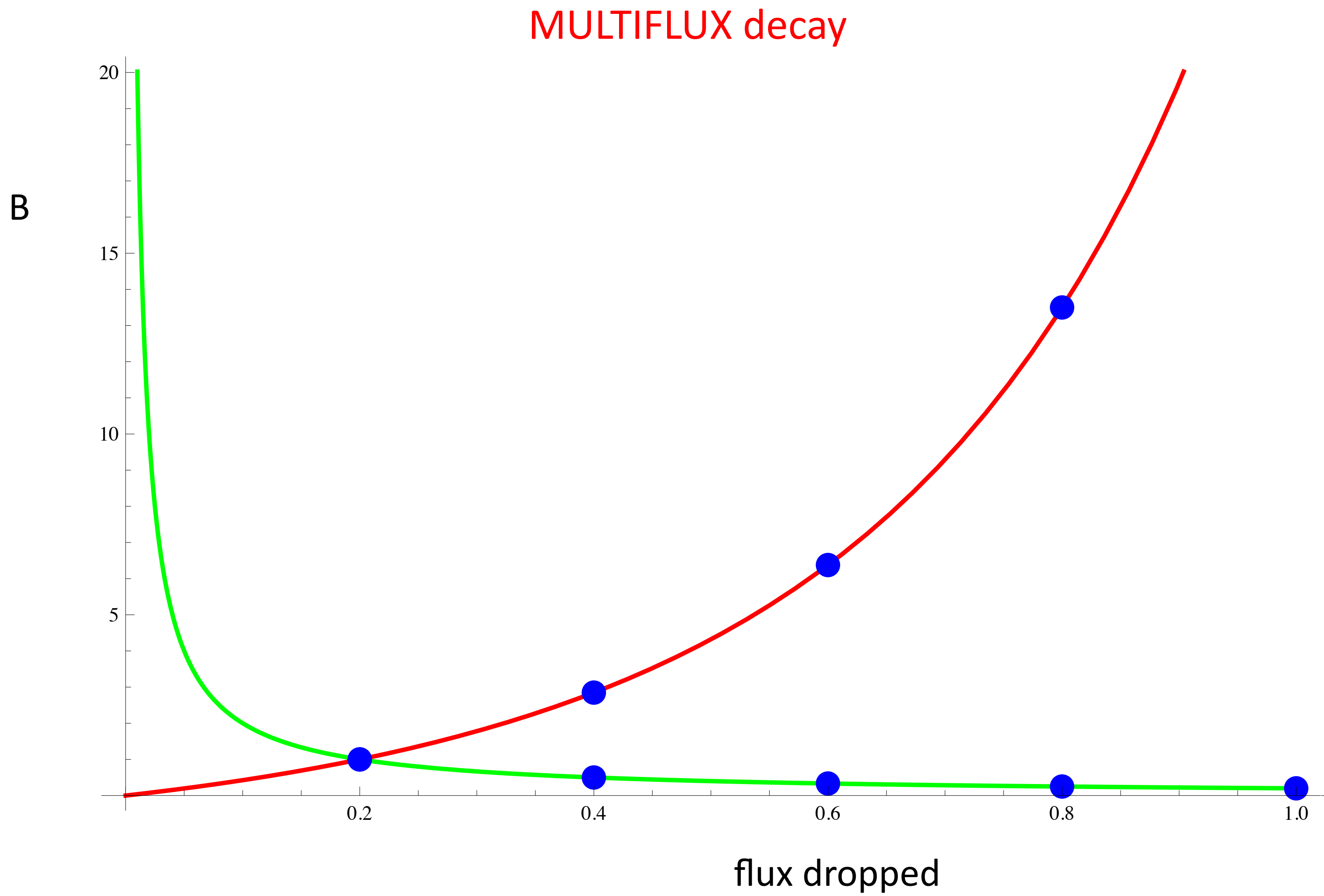
I. $T_n \sim \sqrt{n}$

II. $\Delta(F^2) \sim n$

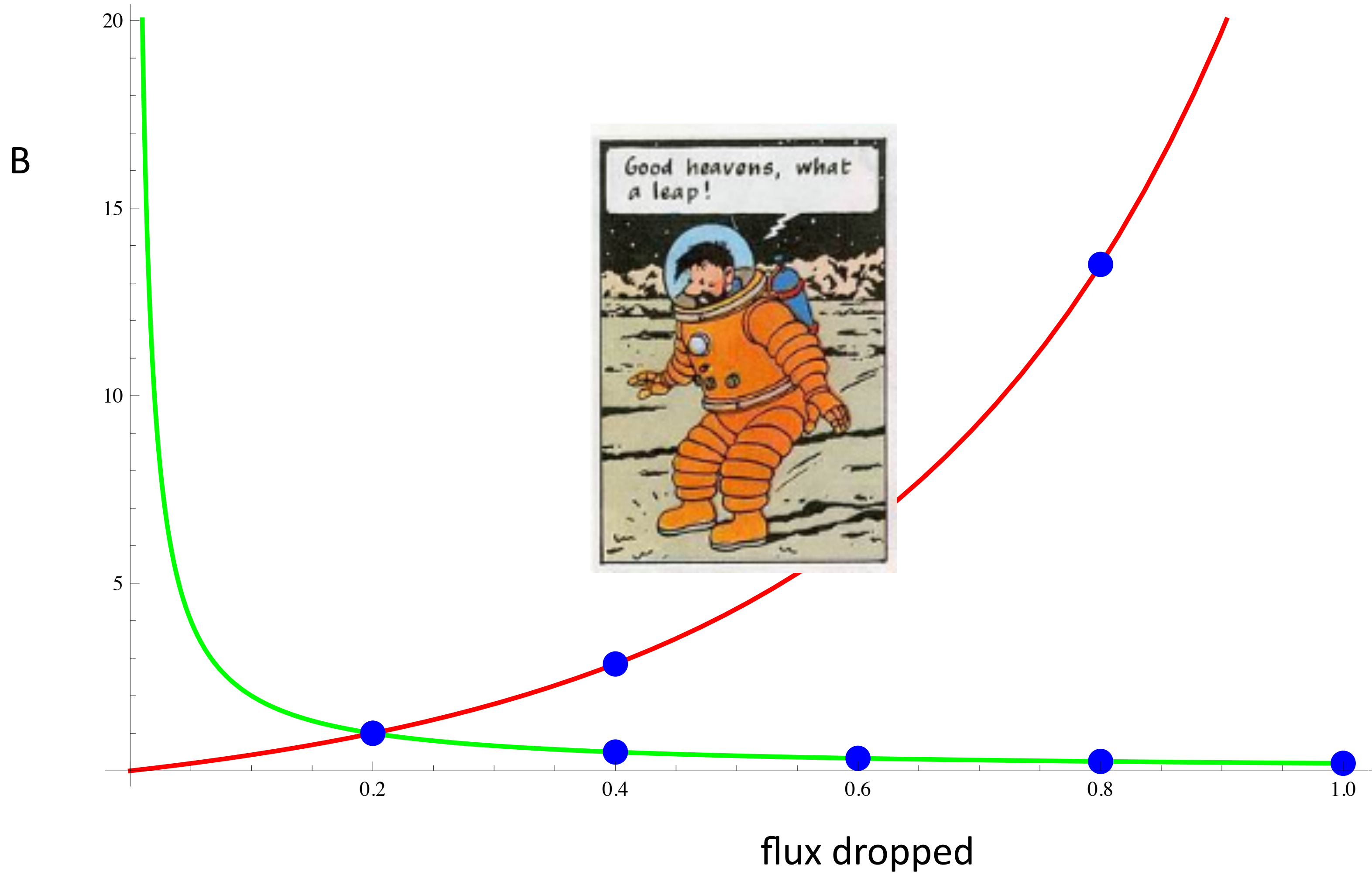
unlike flux lines don’t



MONOFLUX decay
B
25
20
15
10
5
0.2
0.4
0.6
0.8
1.0
flux dropped


MULTIFLUX decay
B
20
15
10
5
0.2
0.4
0.6
0.8
1.0
flux dropped

MULTIFLUX decay



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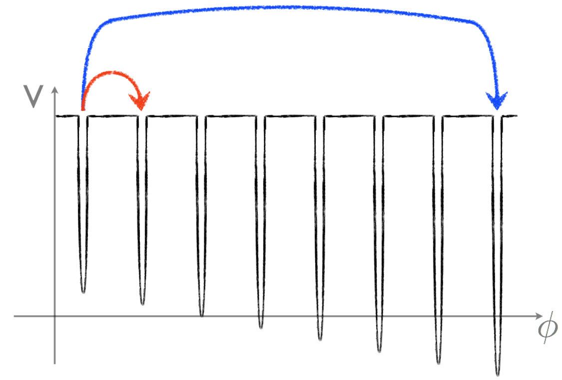

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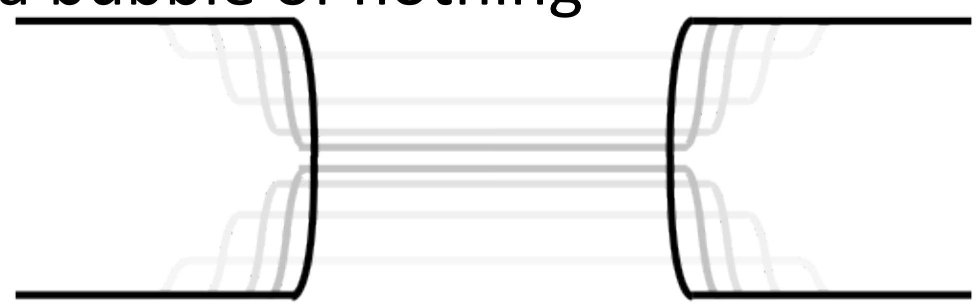


Lifting to Higher Dimensions

A single higher dimensional flux that wraps many distinct cycles in the internal manifold. $\Longrightarrow$ Many fluxes

Bousso-Polchinski model

To what extent does the story stay true?

(fix the radion)

$$F^2 = \sum_{i=1}^{\mathfrak{N}} g_i^2 N_i^2 \, ?$$

$$T \sim \left(\sum_{i=1}^{\mathfrak{N}} g_i^2 n_i^2 \right)^{1/2} ?$$

Lifting to Higher Dimensions

q-form $\mathbf{F}$

flat m-torus T^m

$$\mathbf{F} = \sum_{b=1}^{\mathfrak{N}} F_b \, dw_{i_1} \wedge \cdots \wedge dw_{i_q}$$

F must point ALL legs down the extra dimensions

	t	r	θ	ψ	w_1	$\ldots$	w_q	$\ldots$	w_m
$\mathbf{F}$					x	x	x		
$\star\mathbf{F}$	x	x	x	x				x	x

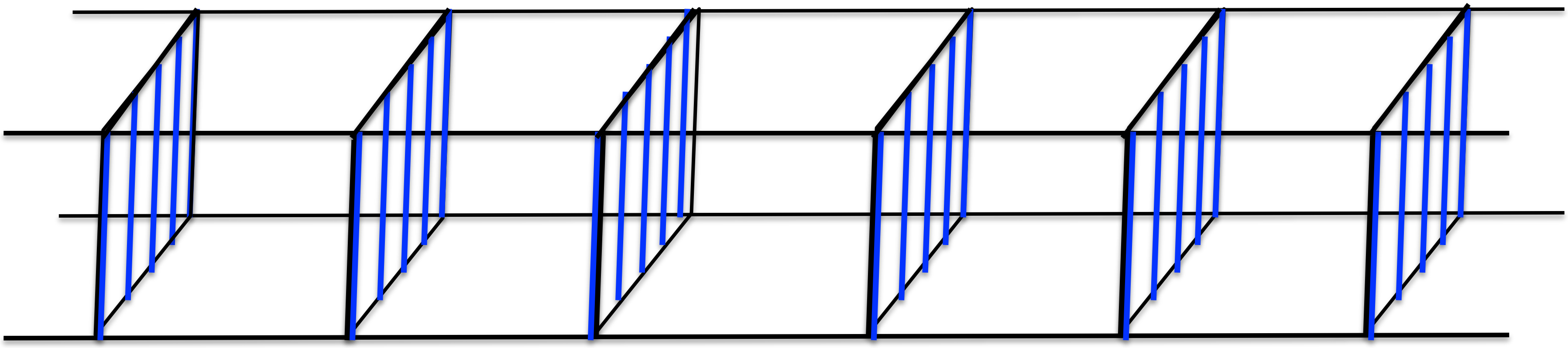
$$\mathfrak{N} = \binom{m}{q}$$

$$\frac{1}{2}\mathbf{F}^2 \to \sum_{b=1}^{\mathfrak{N}} F_b^2$$

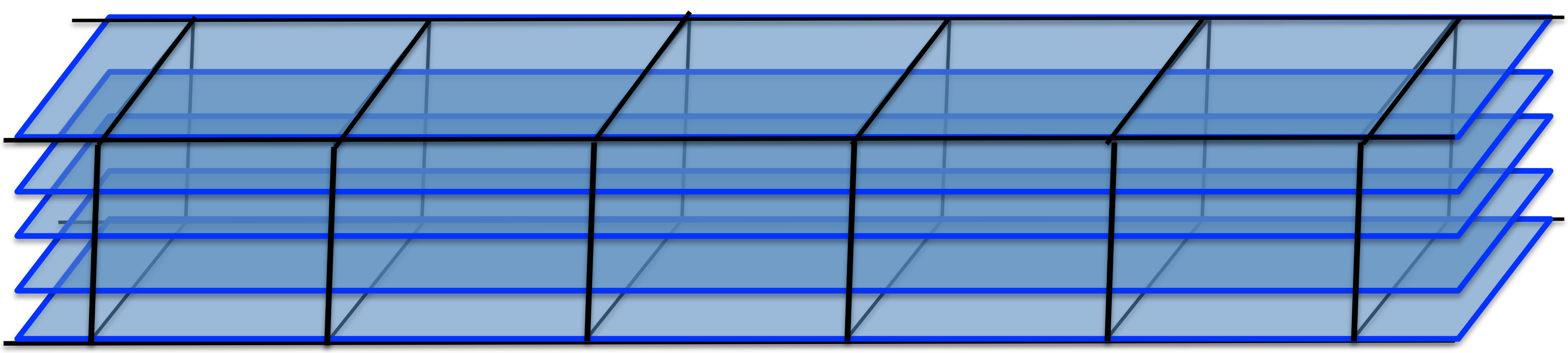
How to discharge?

Consider flux tunneling in 1+1+2 dimensions

space time sphere



N units of flux N units of flux N units of flux



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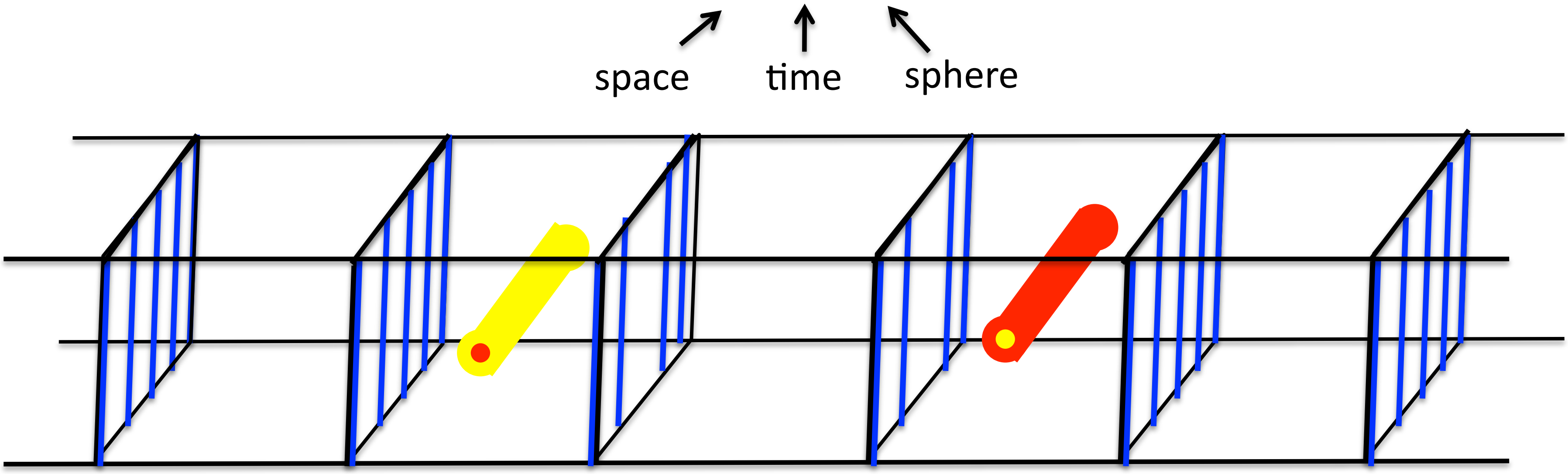

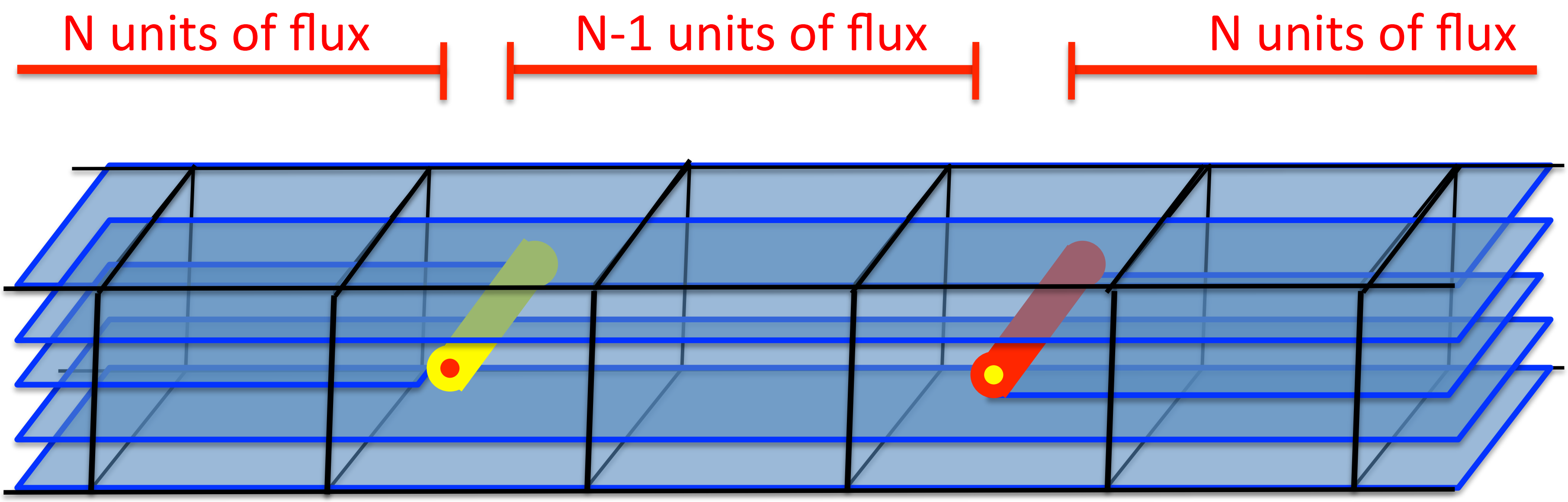

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	t	r	θ	ψ	w_1	$\ldots$	w_q	$\ldots$	w_m
$\mathbf{F}$					x	x	x		
$\star\mathbf{F}$	x	x	x	x				x	x
brane	x		x	x				x	x

Brane makes a bubble in the extended directions
wraps the dual cycle

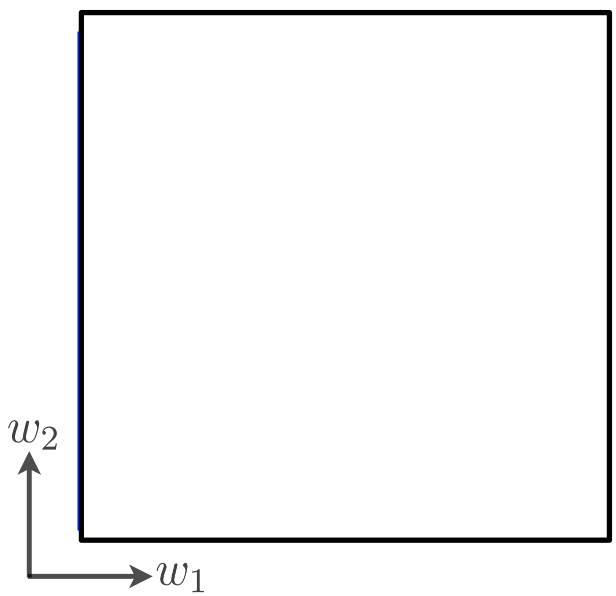
Let's see how this works in some specific cases

Lifting to Higher Dimensions

1-form $\mathbf{F}$

flat 2-torus T^2

$$\mathfrak{N} = \binom{2}{1} = 2$$



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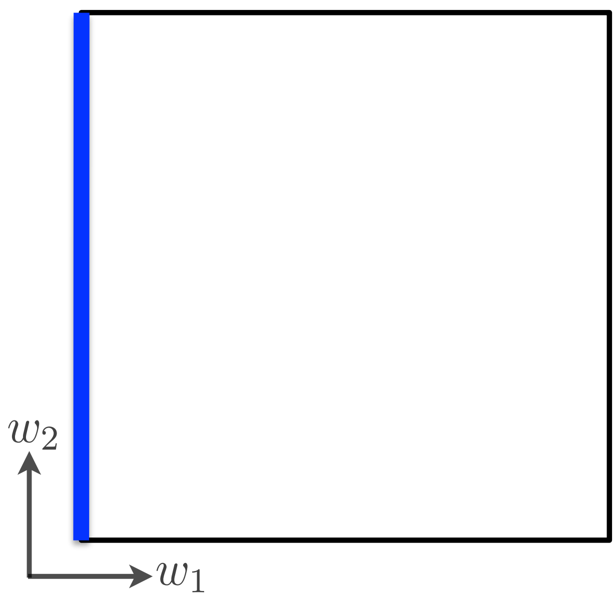

$$\Delta\mathbf{F} = dw_1$$

Lifting to Higher Dimensions

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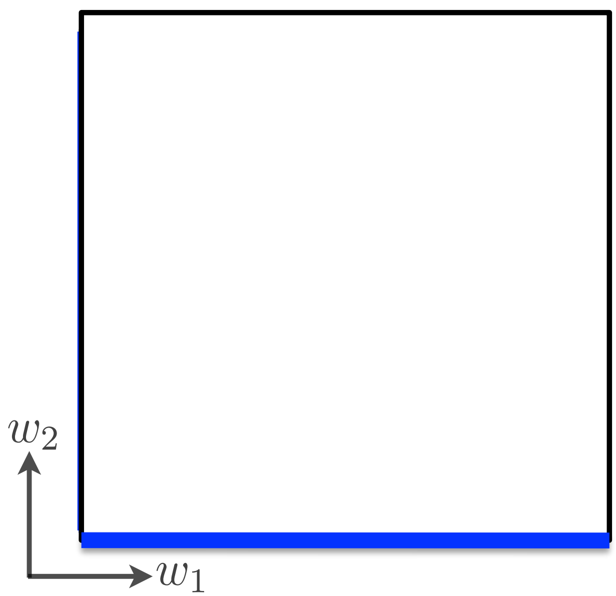
flat 2-torus T^2

$$\mathfrak{N} = \binom{2}{1} = 2$$



$$\Delta\mathbf{F} = dw_2$$

Lifting to Higher Dimensions

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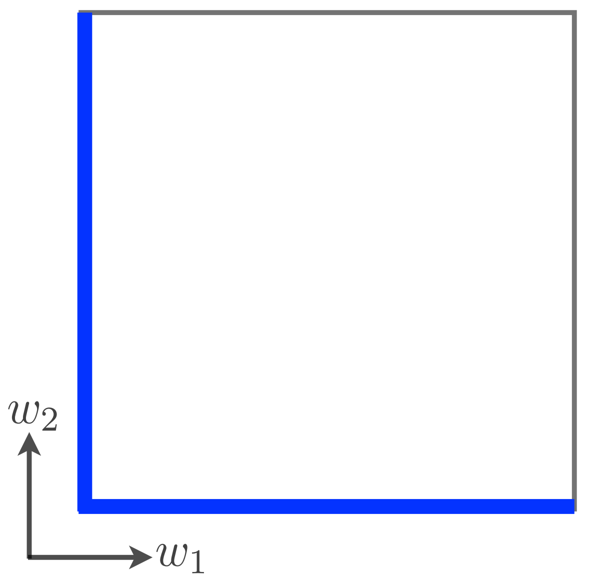
flat 2-torus T^2

$$\mathfrak{N} = \binom{2}{1} = 2$$



Drop one unit of both $T \sim n$?

Lifting to Higher Dimensions

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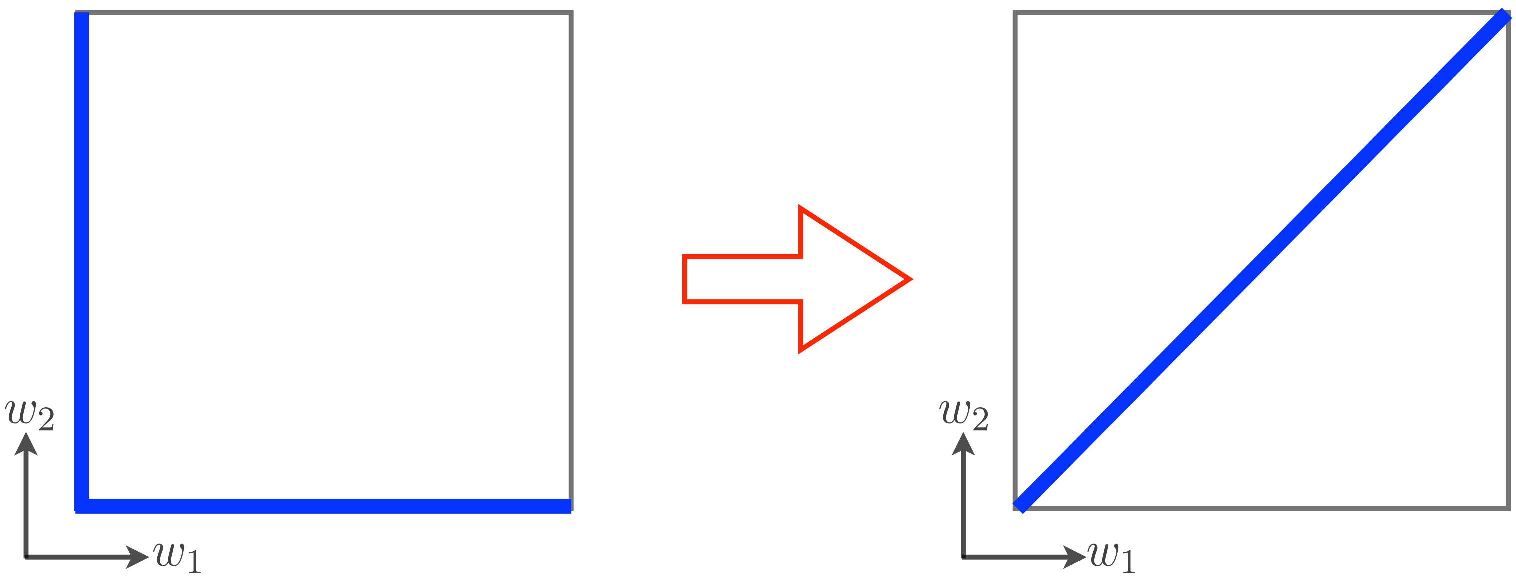
flat 2-torus T^2

$$\mathfrak{N} = \binom{2}{1} = 2$$



Drop one unit of both $\cancel{T \sim n}$? $T \sim \sqrt{n}$.

Lifting to Higher Dimensions

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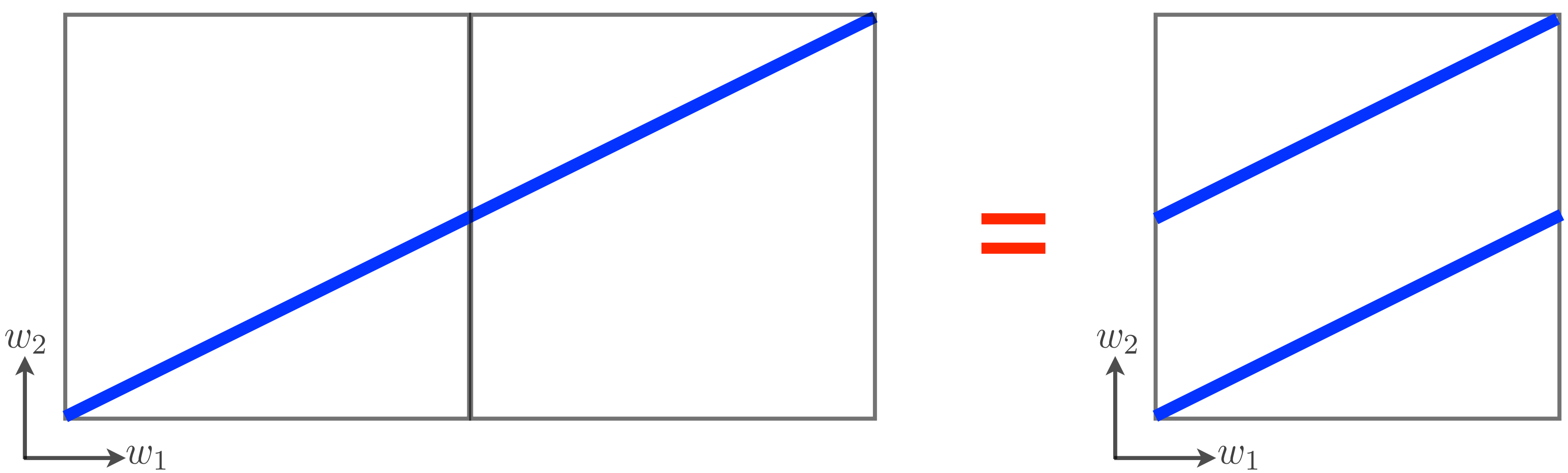
flat 2-torus T^2

$$\mathfrak{N} = \binom{2}{1} = 2$$



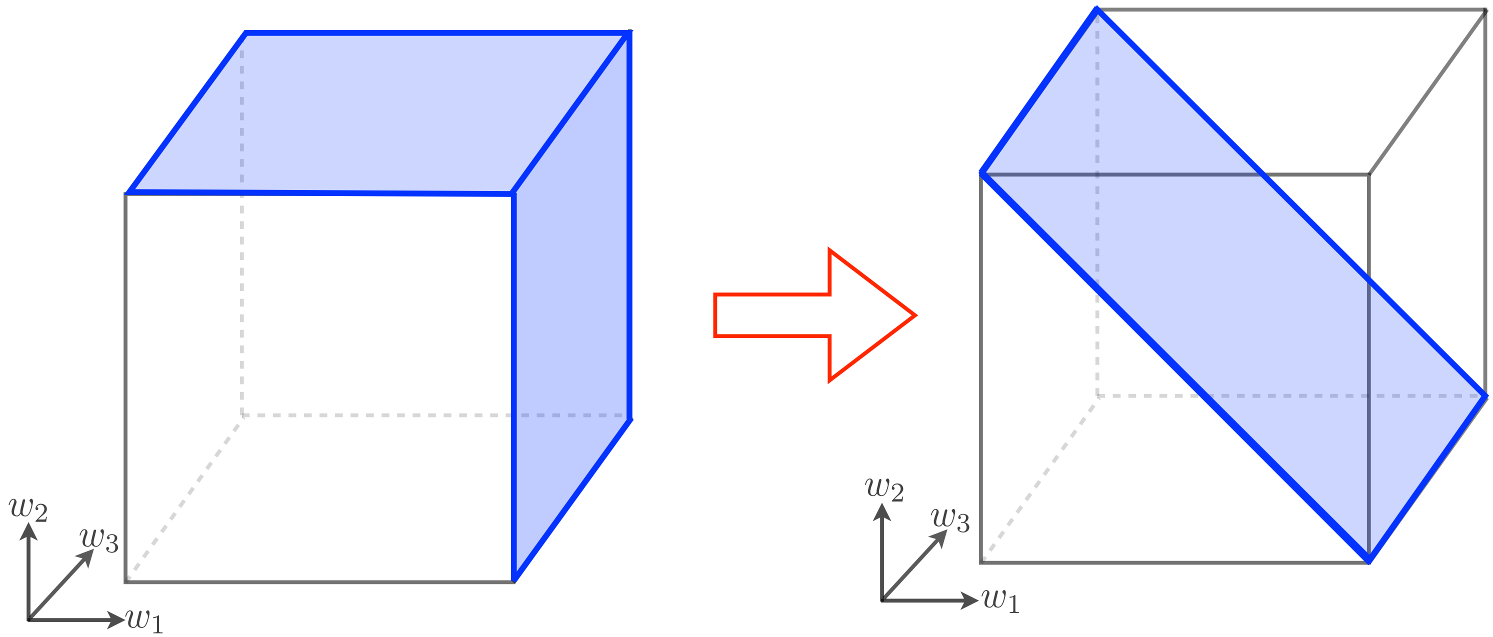
$$T \sim \left(\sum_{i=1}^{\mathfrak{N}} g_i^2 n_i^2 \right)^{1/2}$$ = Pythagoras' Theorem

Lifting to Higher Dimensions

1-form $\mathbf{F}$

flat 3-torus T^3

$$\mathfrak{N} = \binom{3}{1} = 3$$



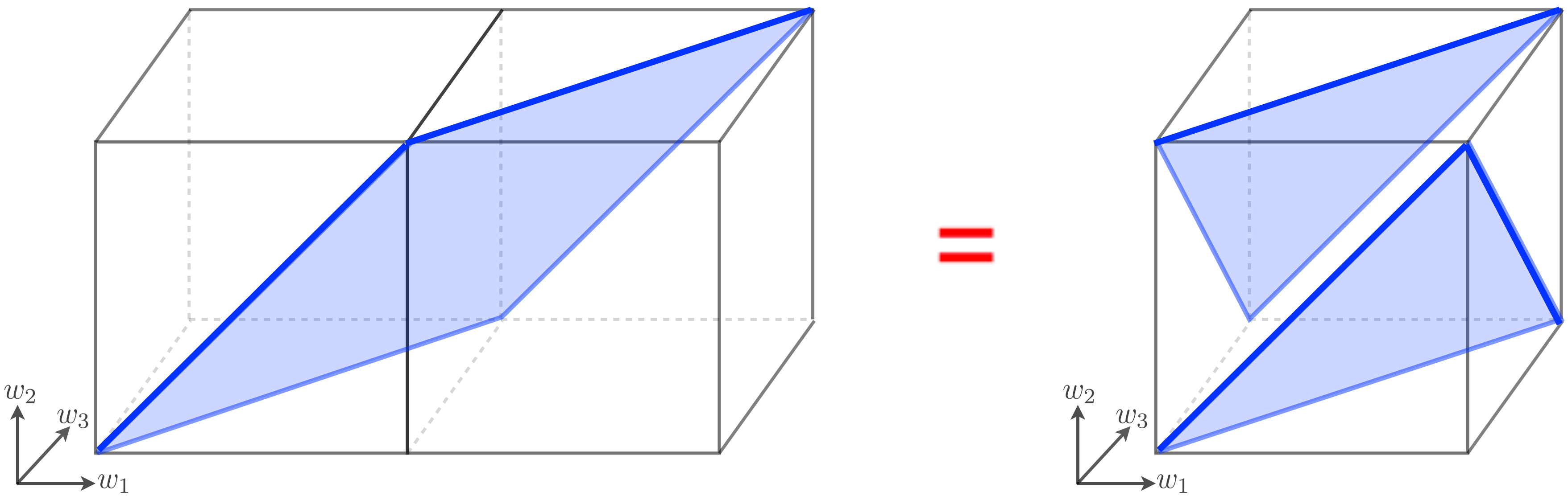
Still true

Lifting to Higher Dimensions

1-form $\mathbf{F}$

flat 3-torus T^3

$$\mathfrak{N} = \binom{3}{1} = 3$$



Still true

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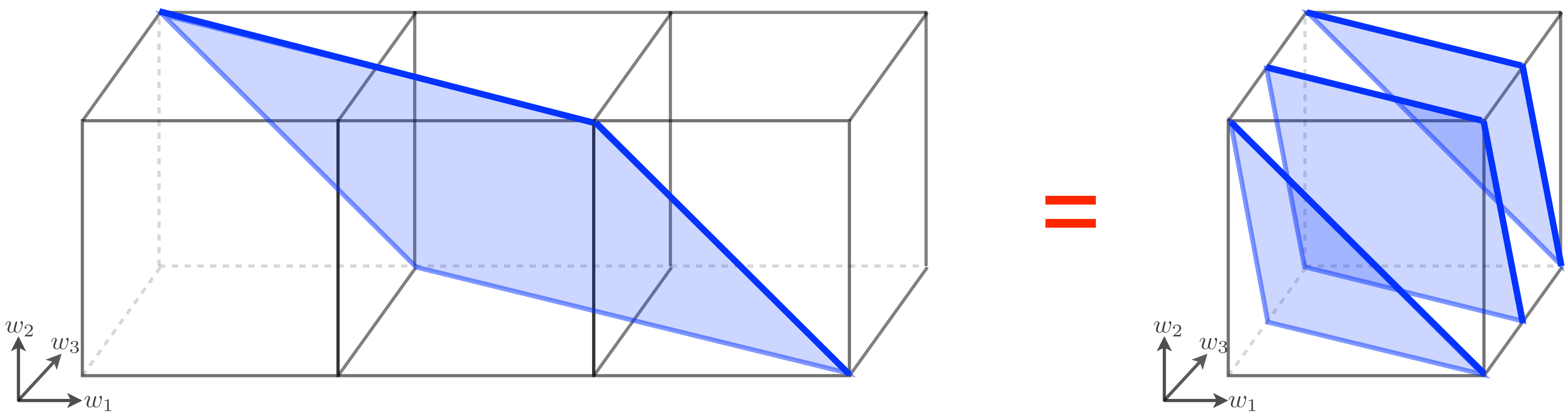
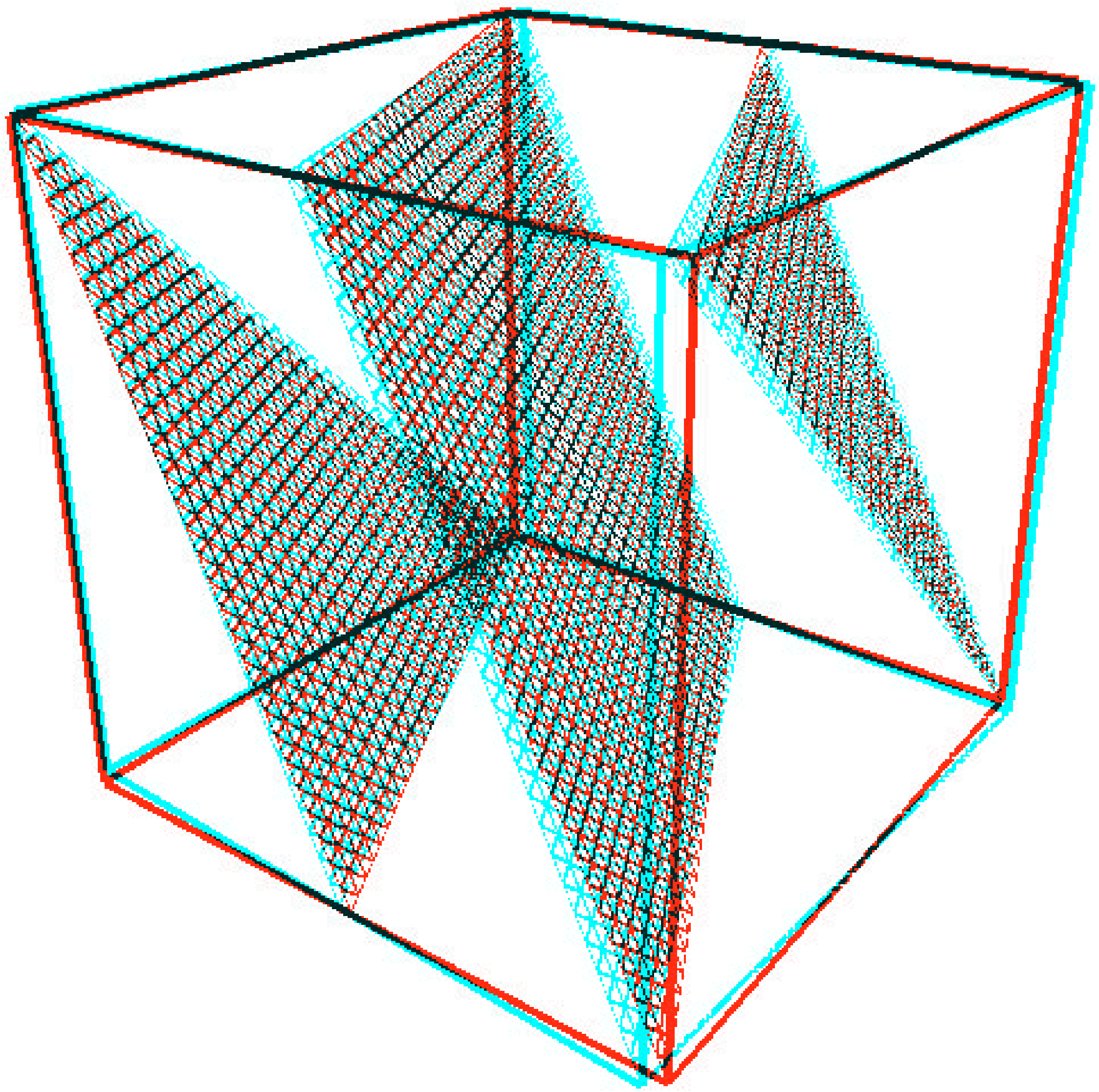


Still true



Lifting to Higher Dimensions

2-form $\mathbf{F}$

flat 4-torus T^3

$$\mathfrak{N} = \binom{4}{2} = 6$$

$$\Delta\mathbf{F} = dw_1 \wedge dw_2 + dw_3 \wedge dw_4$$

Lifting to Higher Dimensions

2-form $\mathbf{F}$

flat 4-torus T^3

$$\mathfrak{N} = \binom{4}{2} = 6$$

$$\Delta\mathbf{F} = dw_1 \wedge dw_2 + dw_3 \wedge dw_4$$

No longer true!

Requires 2 branes $\quad T \sim n$

Lifting to Higher Dimensions

The general case

$$\mathbf{dF} = \star\mathbf{j}$$

$$\Delta\mathbf{F} = \star g\mathbf{Y}_1 \wedge \cdots \wedge \mathbf{Y}_q$$

This tells us when a single, flat brane can be found.

DECOMPOSABILITY

When it can be, $T \sim \sqrt{n}$.

Otherwise worse

Lifting to Higher Dimensions

The general case

	w_1	w_2	w_3	w_4
1	x	x		
2	x		x	
3		x	x	
4			x	x
5		x		x
6	x			x

T is intermediate

$T \sim \sqrt{n}$ $\qquad$ $T \sim n$

Clustering

Ideal configuration is CURVED

Breaks rotation symmetry of landscape

$$\mathbf{\Delta F} = dw_1 \wedge dw_2 + dw_2 \wedge dw_3$$ ✓

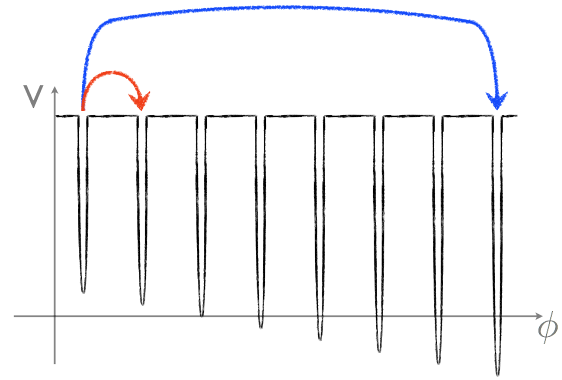
$$\mathbf{\Delta F} = dw_1 \wedge dw_2 + dw_3 \wedge dw_4$$ ✗

Breaks reflection symmetry of landscape

$$\mathbf{\Delta F} = dw_1 \wedge dw_3 + dw_1 \wedge dw_4 + dw_2 \wedge dw_3 + dw_2 \wedge dw_4$$ ✓

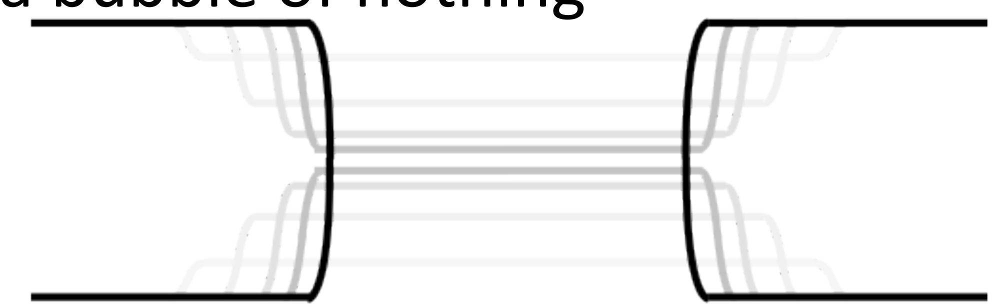
$$\mathbf{\Delta F} = dw_1 \wedge dw_3 + dw_1 \wedge dw_4 - dw_2 \wedge dw_3 + dw_2 \wedge dw_4$$ ✗

1. This potential gives small steps



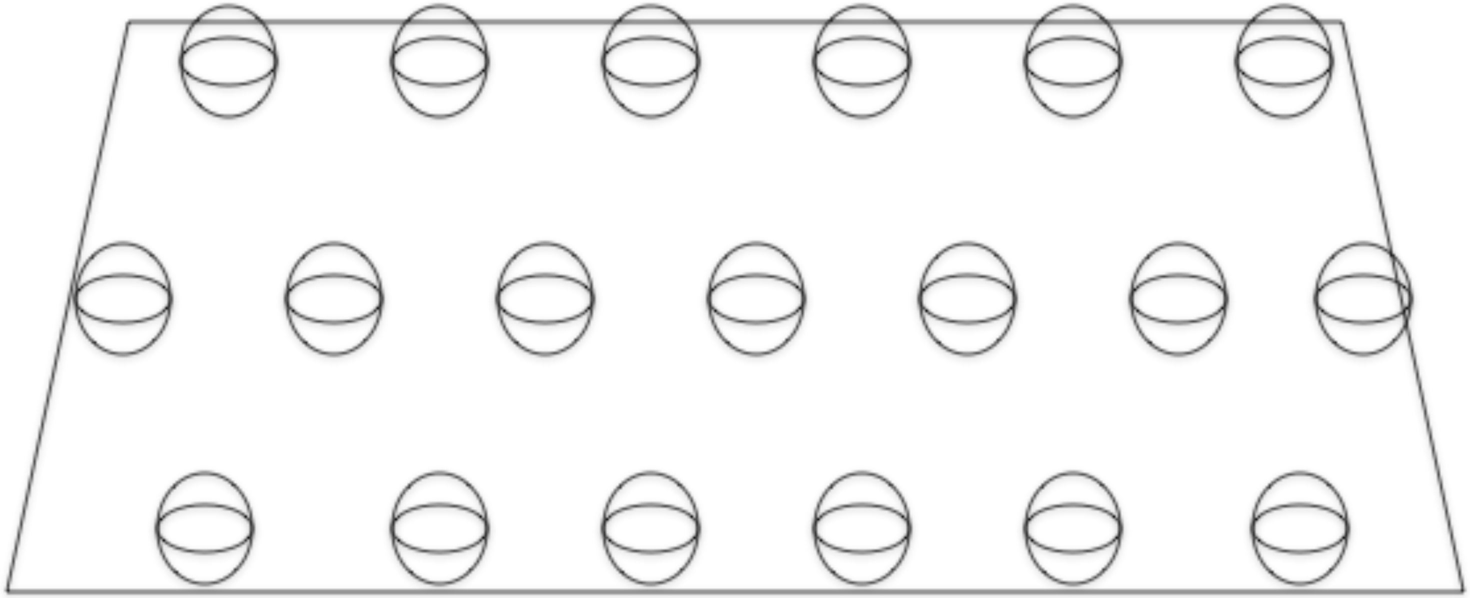
2. Flux compactifications with many fluxes give giant leaps
3. Monkey branes

4. Adding back-reaction
5. The giantest leap of all is a bubble of nothing



Simplest possible model with stabilized XDs that supports Minkowski and de Sitter 4D slices is 6D Einstein-Maxwell

$$ds^2 = \underbrace{g_{\mu\nu}}_{\text{4D dS, Min, or AdS}} dx^\mu dx^\nu + \underbrace{R^2 d\Omega_2^2}_{\text{2D sphere}}$$



three ingredients:

- spatial curvature of 2-spheres
- 2-form F_{ab} flux wrapping 2-spheres
- 6D cosmo-constant

i.e. Maxwell magnetic flux

$$S_{\rm EM} = \int d^6x \sqrt{-G}\left(\frac{1}{2}\mathcal{R}^{(6)} - \frac{1}{4}F_{AB}F^{AB} - \Lambda_6\right)$$

Freund Rubin (1980)

Effective 4D theory:

$$ds^2 = e^{-\psi(x)/M} g_{\mu\nu}dx^\mu dx^\nu + e^{\psi(x)/M} R^2 d\Omega_2^2$$

$\mathfrak{N}$ different two-form fluxes, each with field strength

$$\mathbf{F}_i = \frac{g_i N_i}{4\pi}\sin\theta\, d\theta \wedge d\phi, \qquad F^2 = \sum_{i=1}^{\mathfrak{N}} g_i^2 N_i^2$$

$$S = \int d^4x\sqrt{-g}\left(\frac{1}{2}M^2\mathcal{R}^{(4)} - \frac{1}{2}\partial_\mu\psi\partial^\mu\psi - V(\psi)\right)$$

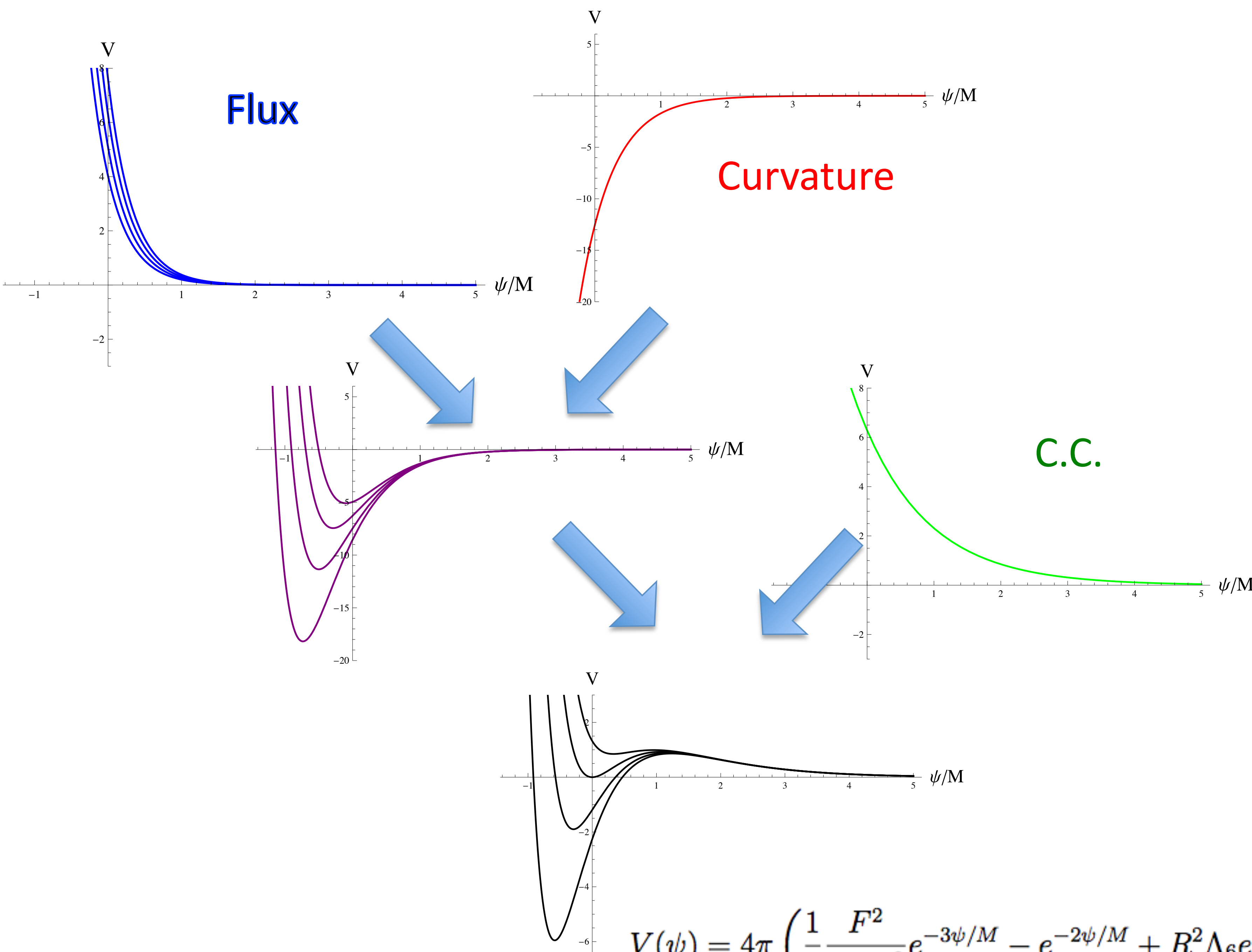
$$V(\psi) = 4\pi\left(\frac{1}{2}\frac{F^2}{4\pi M^2}e^{-3\psi/M} - e^{-2\psi/M} + R^2\Lambda_6 e^{-\psi/M}\right)$$

canonically
normalized
RADION

FLUX
'repulsive'
short-range

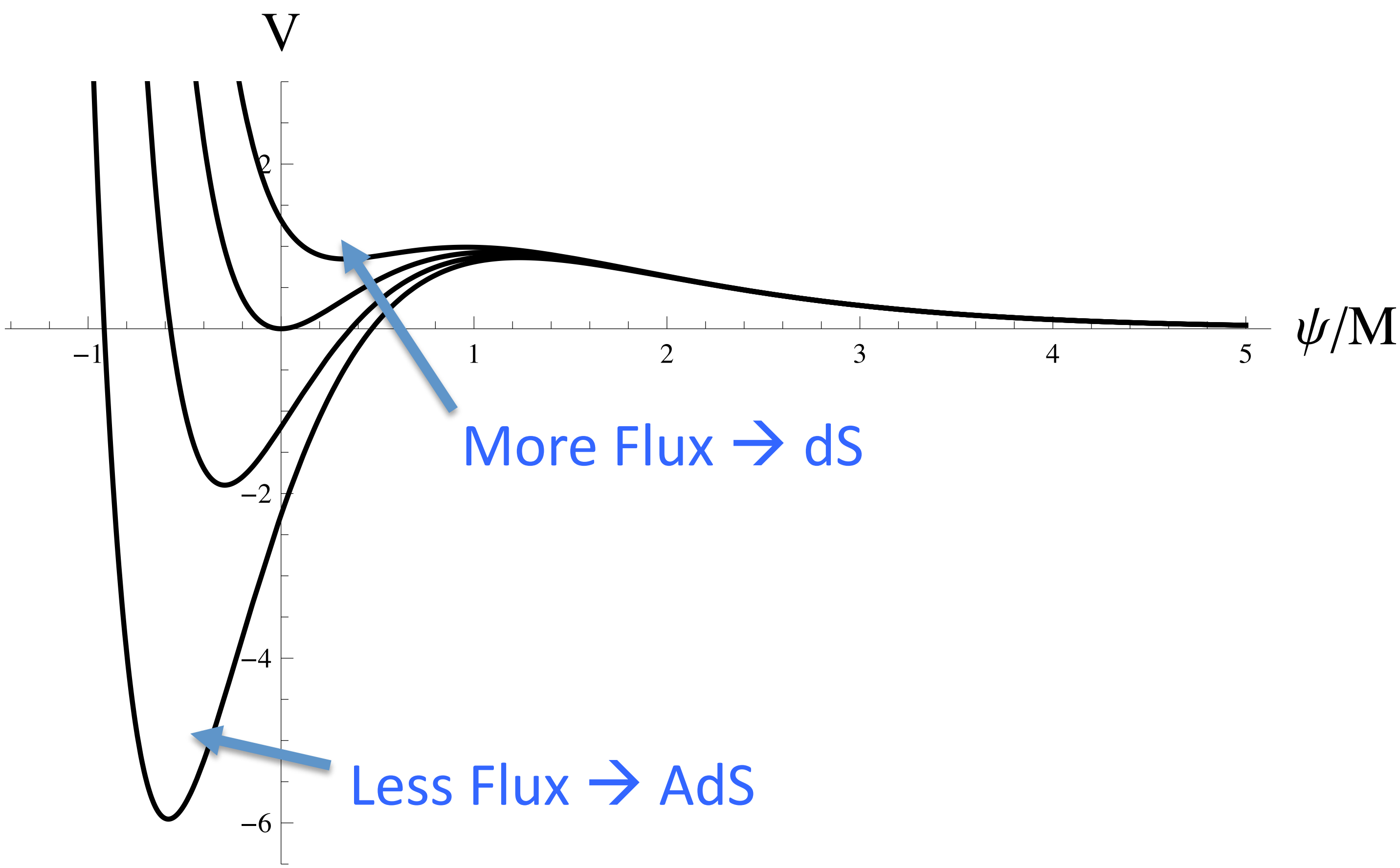
CURVATURE
'attractive'
medium-range

C.C.
'reulsive'
long-range

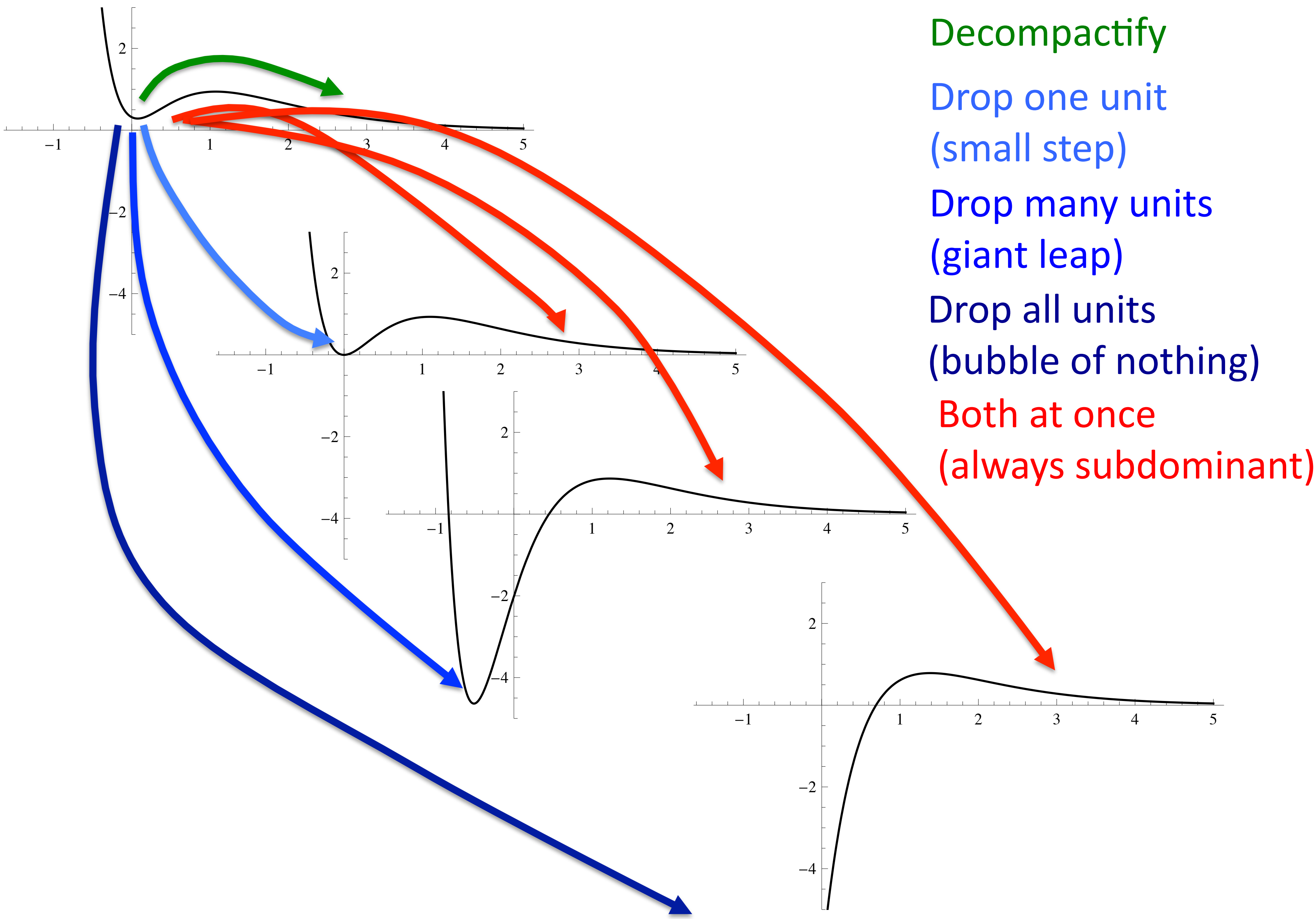


$$V(\psi) = 4\pi\left(\frac{1}{2}\frac{F^2}{4\pi M^2}e^{-3\psi/M} - e^{-2\psi/M} + R^2\Lambda_6 e^{-\psi/M}\right)$$

A landscape of (discrete) vacua



But how to transition?



Decompactify
Drop one unit
(small step)
Drop many units
(giant leap)
Drop all units
(bubble of nothing)
Both at once
(always subdominant)

2 reasons back-reaction helps giant leaps

Radion mediates attractive force

$$S_{\text{brane tension}} = -T \int_\Sigma \sqrt{-\gamma} d^3\xi \qquad ds^2 = e^{-\psi(x)/M_4} g_{\mu\nu} dx^\mu dx^\nu + e^{\psi(x)/M_4} R^2 \, d\Omega_2^2$$

$$S_{\text{brane tension}} = -T e^{-3\psi(\xi)/2M_4} \times (\text{surface area})$$

2 reasons back-reaction helps giant leaps

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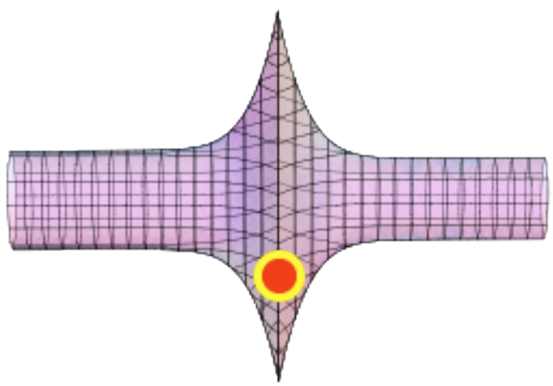

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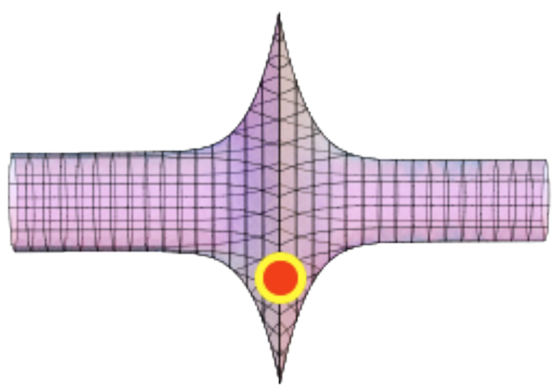
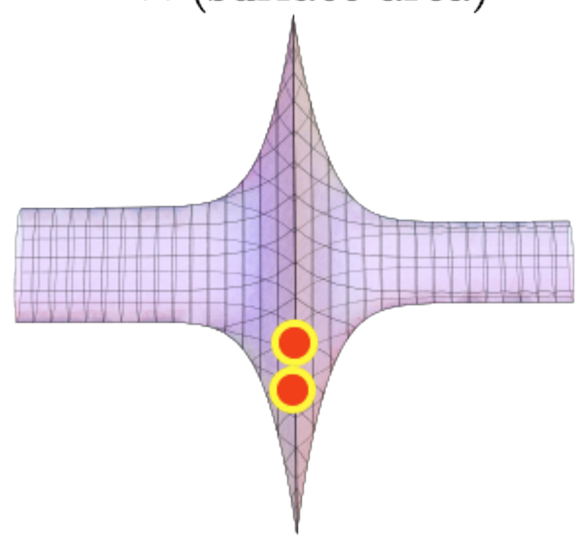
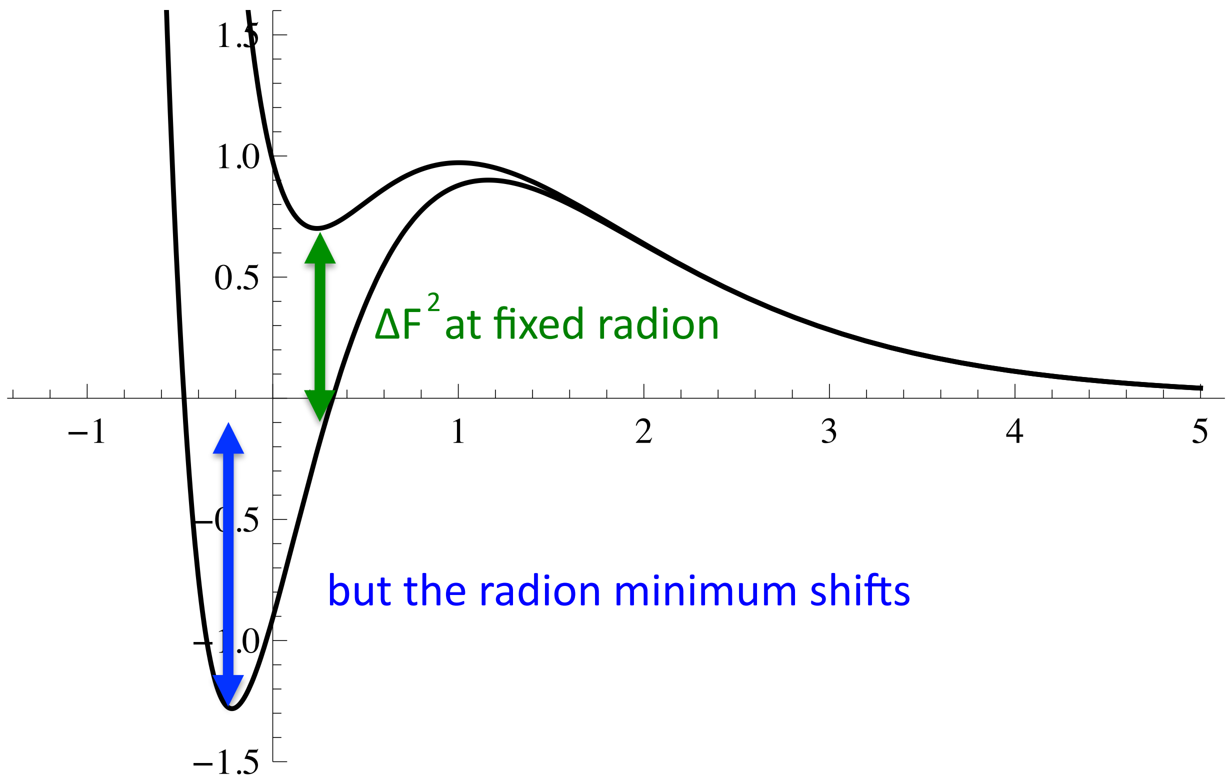




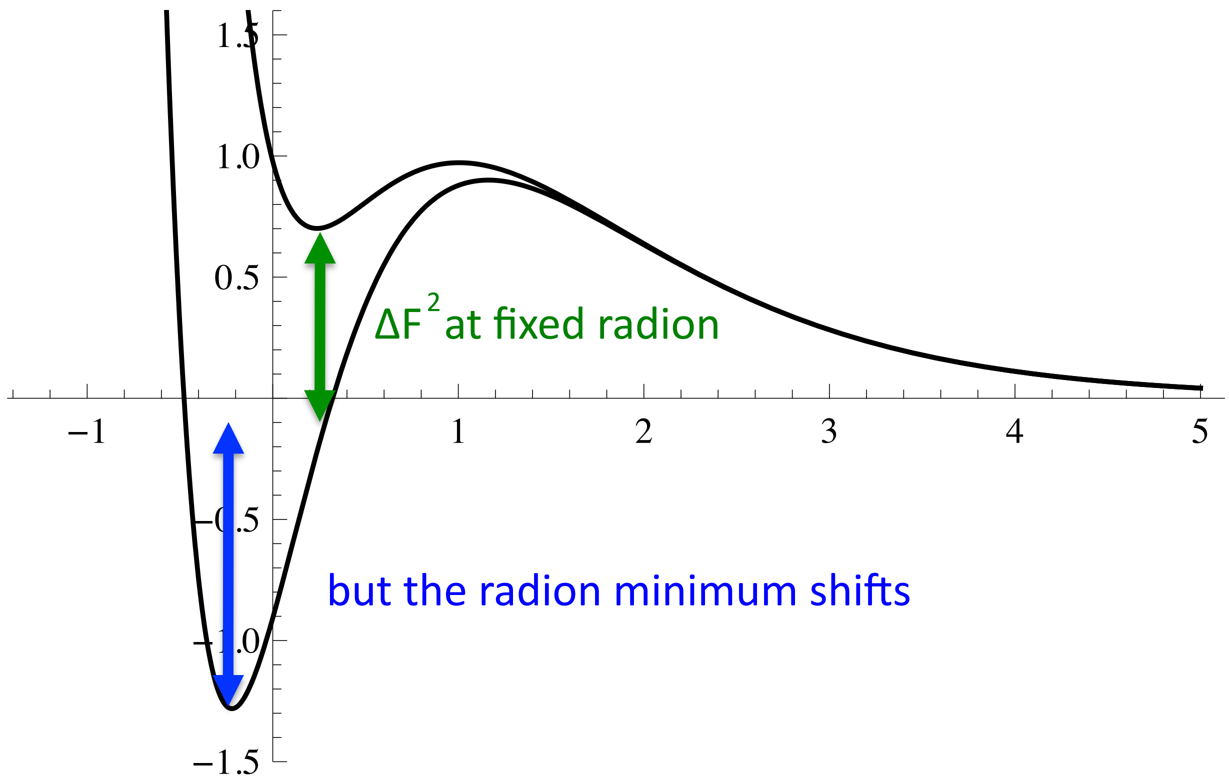
2 reasons back-reaction helps giant leaps

Radion can readjust for extra energy



2 reasons back-reaction helps giant leaps

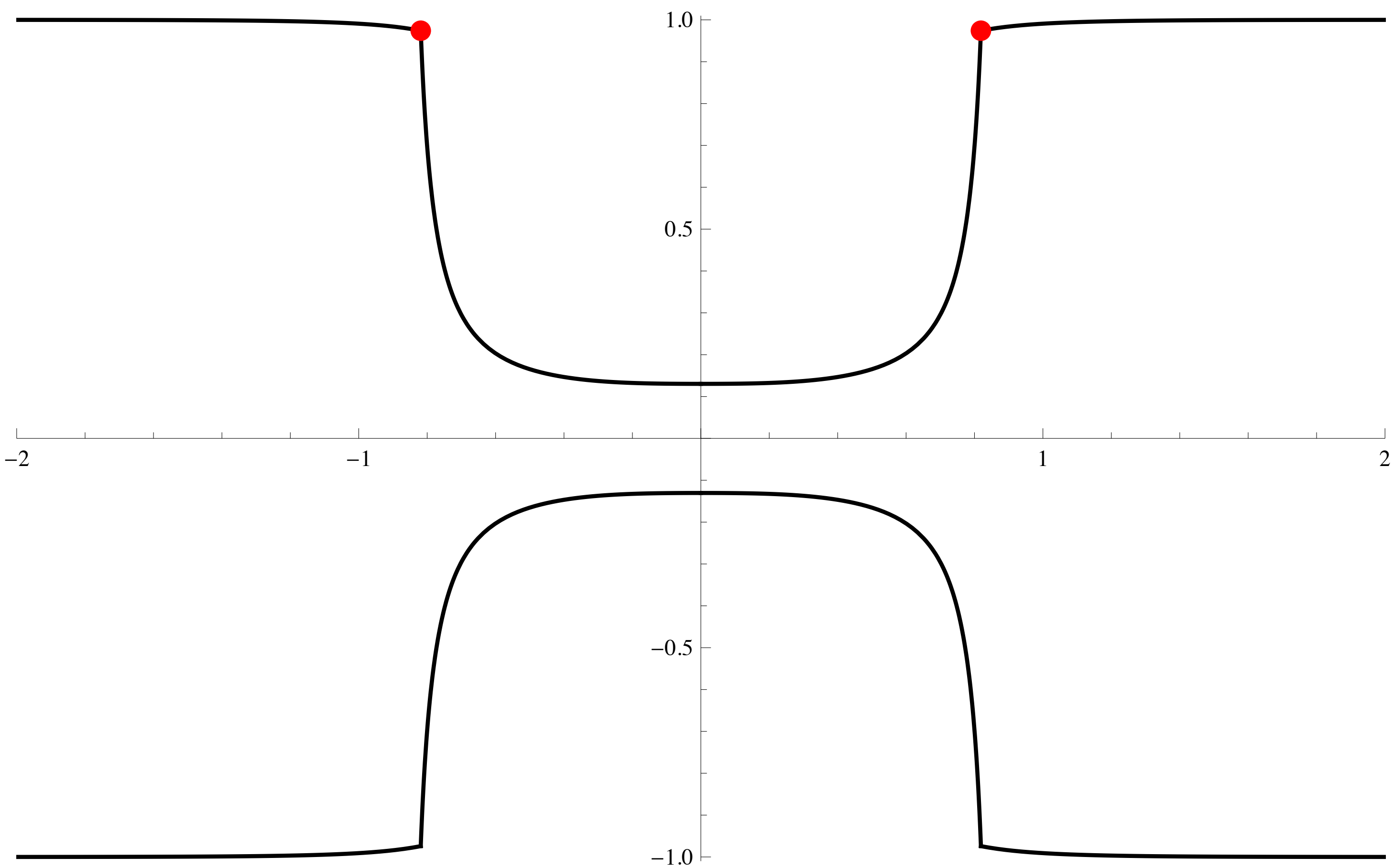
Radion can readjust for extra energy



1 reason it hurts giant leaps:

Thick wall means less region in the true vacuum

Sample instanton profile



Let's look at two extreme examples

$$F^2 = \sum_{i=1}^{\mathfrak{N}} g_i^2 N_i^2$$

$$T = \frac{2}{\sqrt{3}} \left(\sum_{i=1}^{\mathfrak{N}} g_i^2 n_i^2 \right)^{\frac{1}{2}}$$

MONOFLUX

A single type of flux and many units of it

$$\mathfrak{N} = 1 \quad N \gg 1 \quad F^2 = g^2 N^2$$

MULTIFLUX

Many different types of flux, each with a single unit

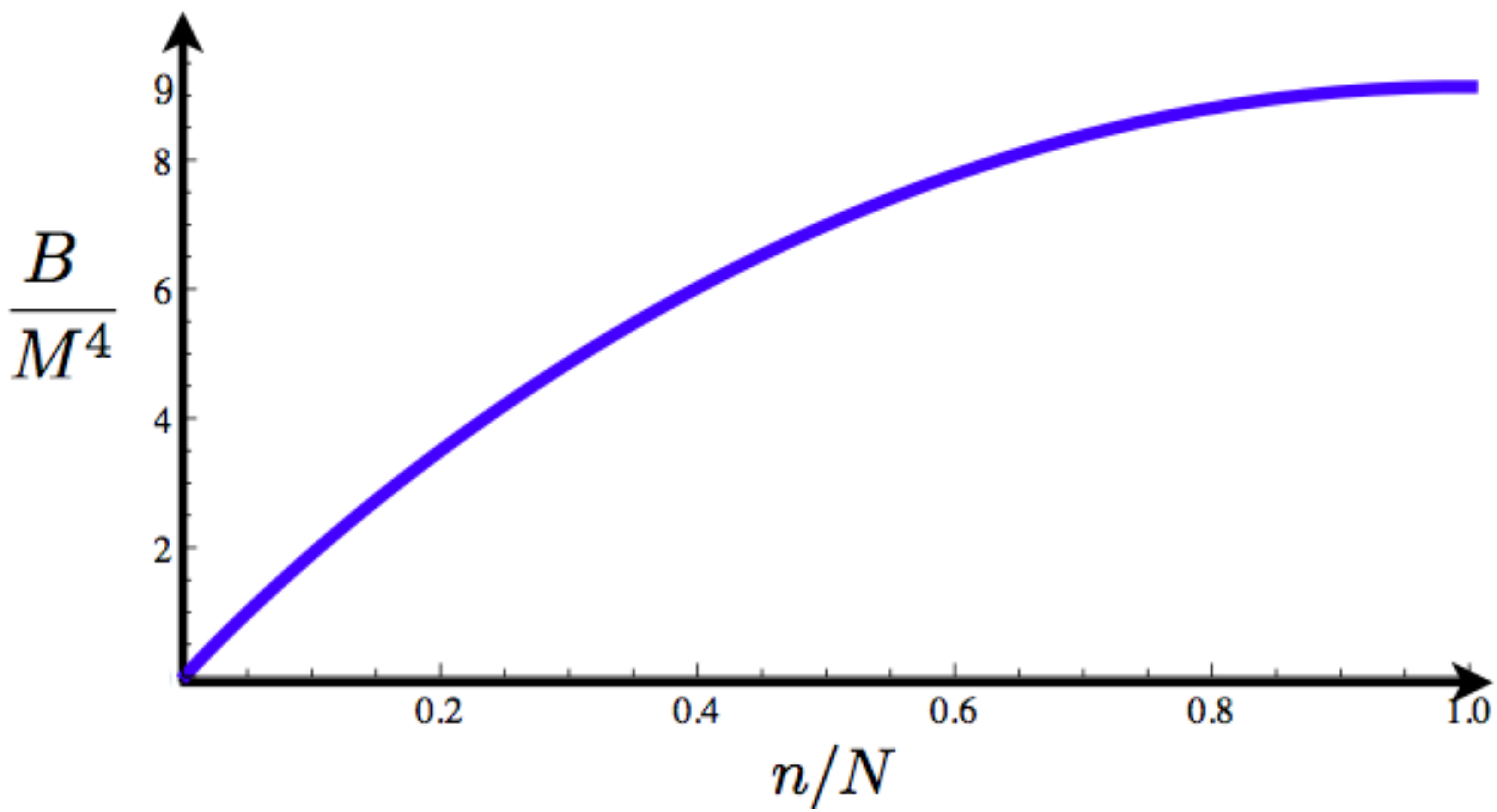
$$\mathfrak{N} \gg 1 \quad N_i = 1 \quad F^2 = g^2 \mathfrak{N}$$

Decay Rates

$$\Gamma \sim e^{-B/\hbar}, \qquad B = S_E(\text{instanton}) - S_E(\text{false vacuum})$$

MONOFLUX

From V=0

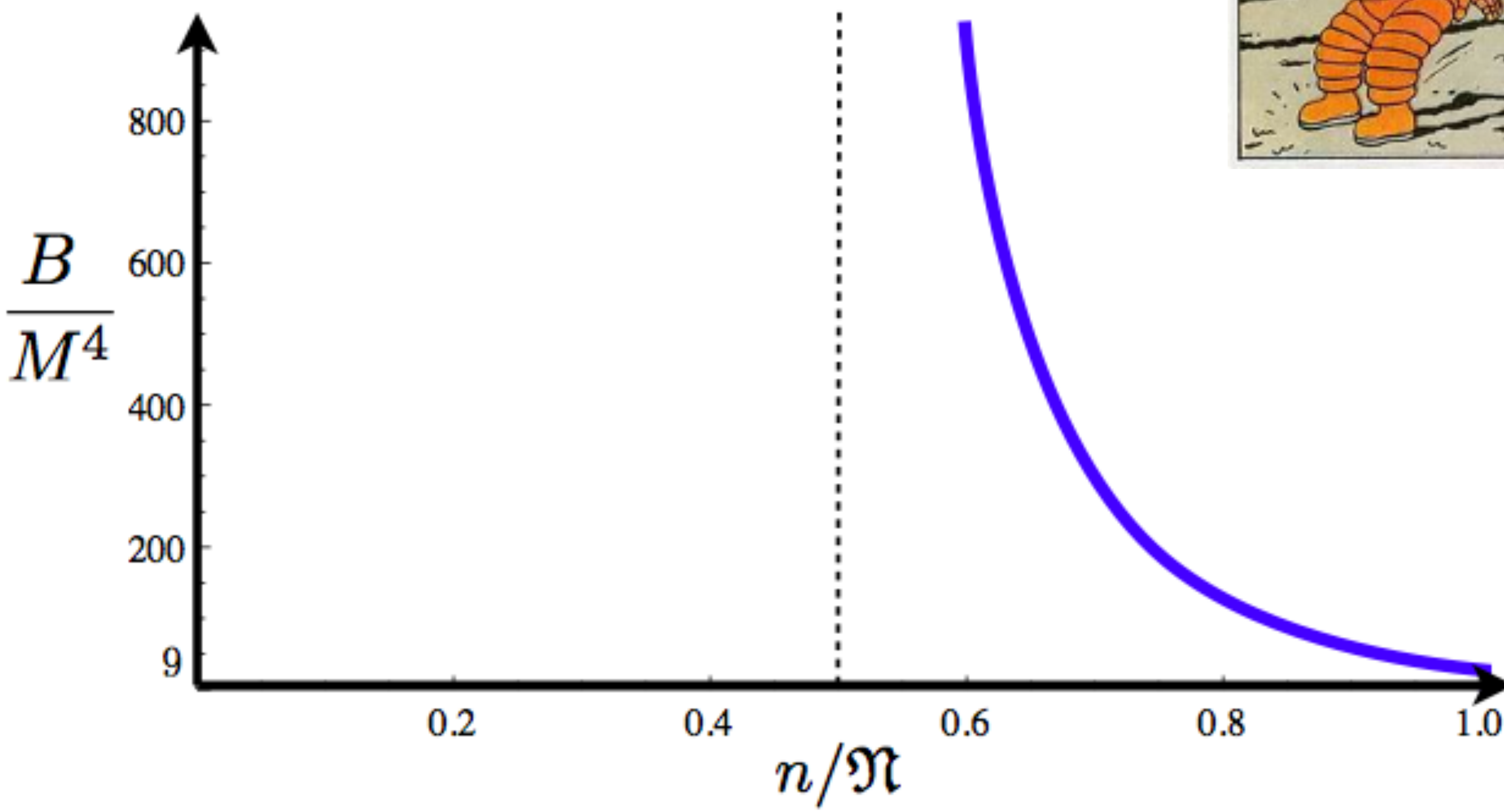


SMALL STEPS WIN

Decay Rates

MULTIFLUX

From V=0

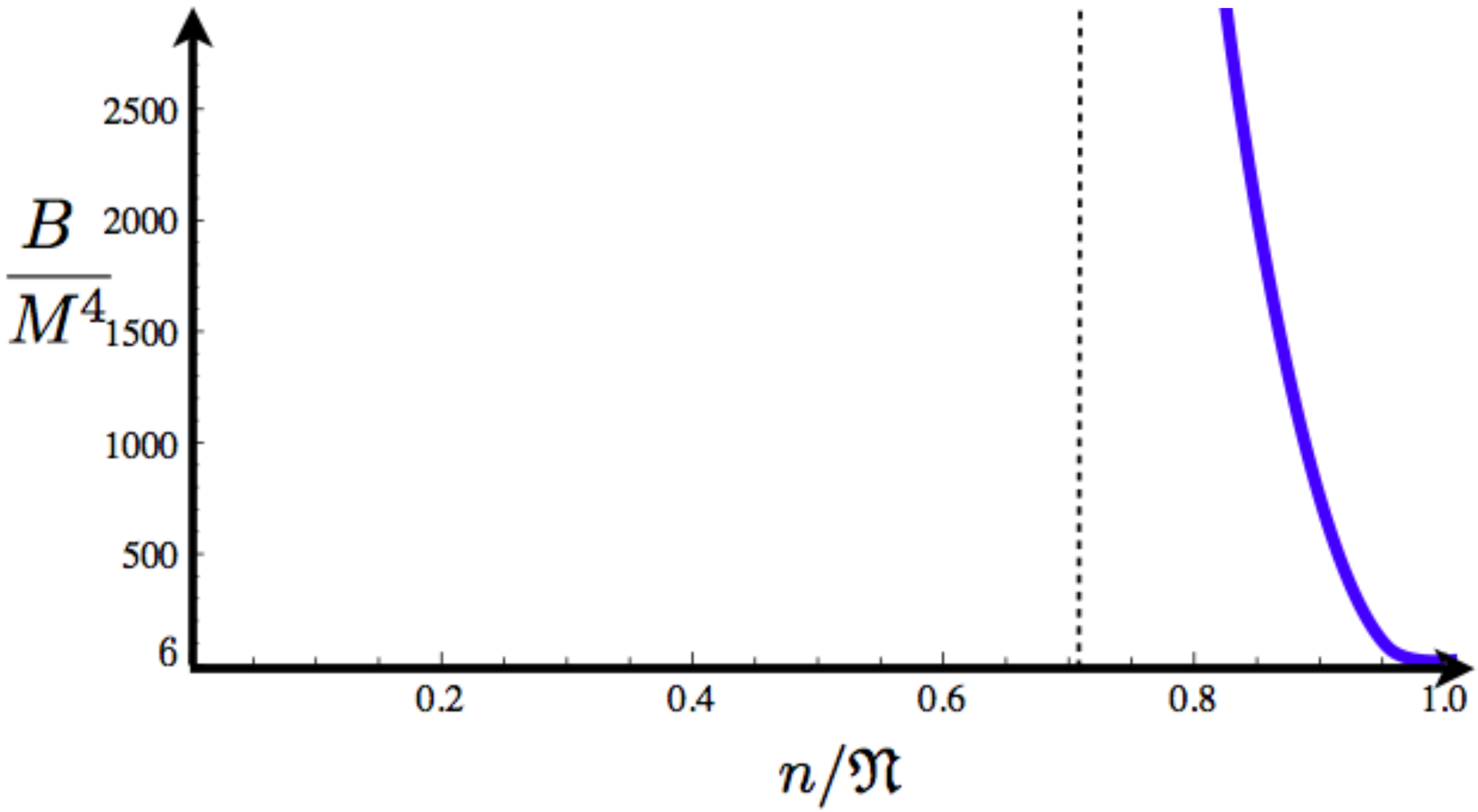


GIANT LEAPS WIN

Decay Rates

MULTIFLUX

From V<0

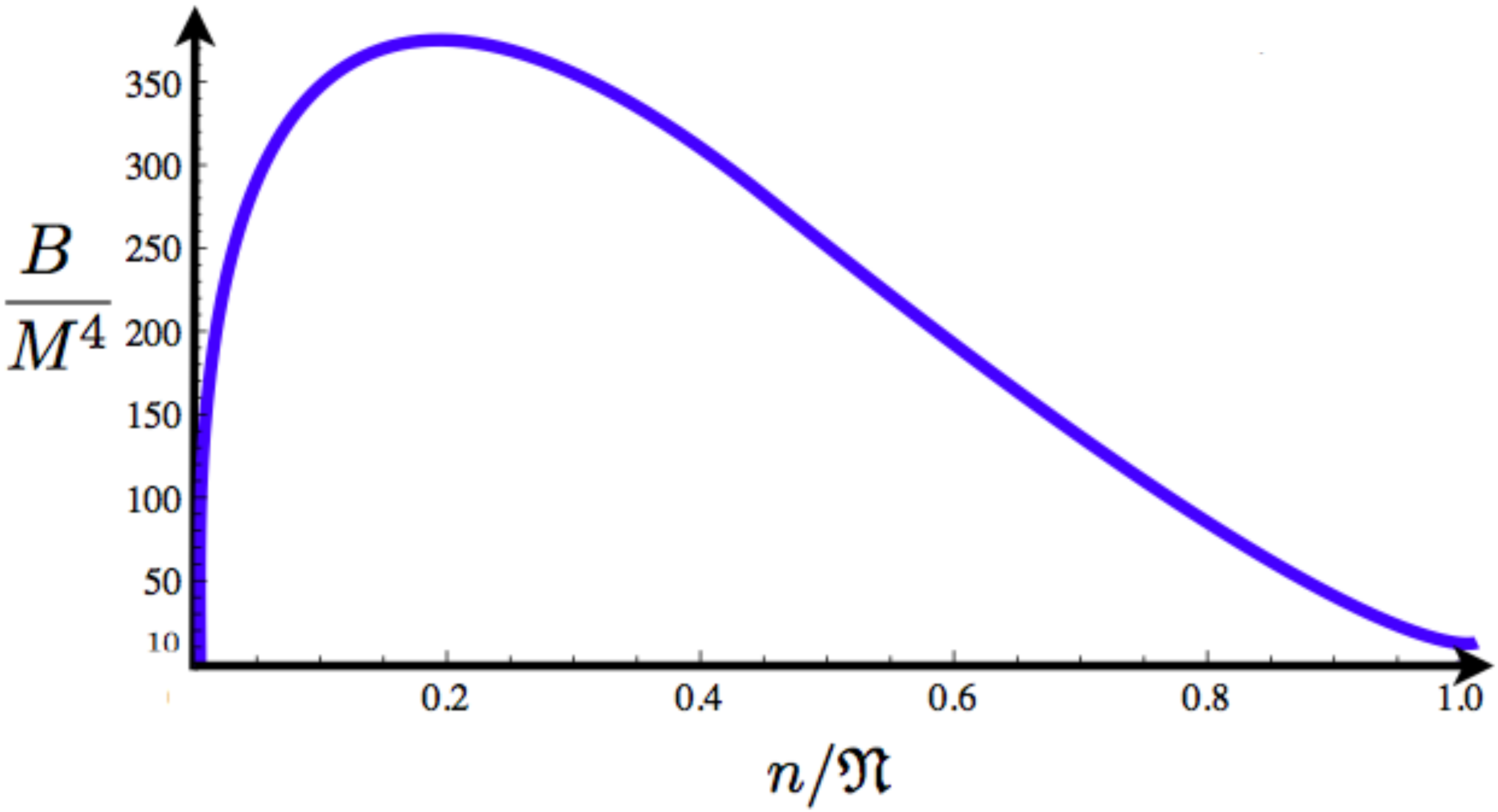


GIANT LEAPS WIN

Decay Rates

MULTIFLUX

From V>0

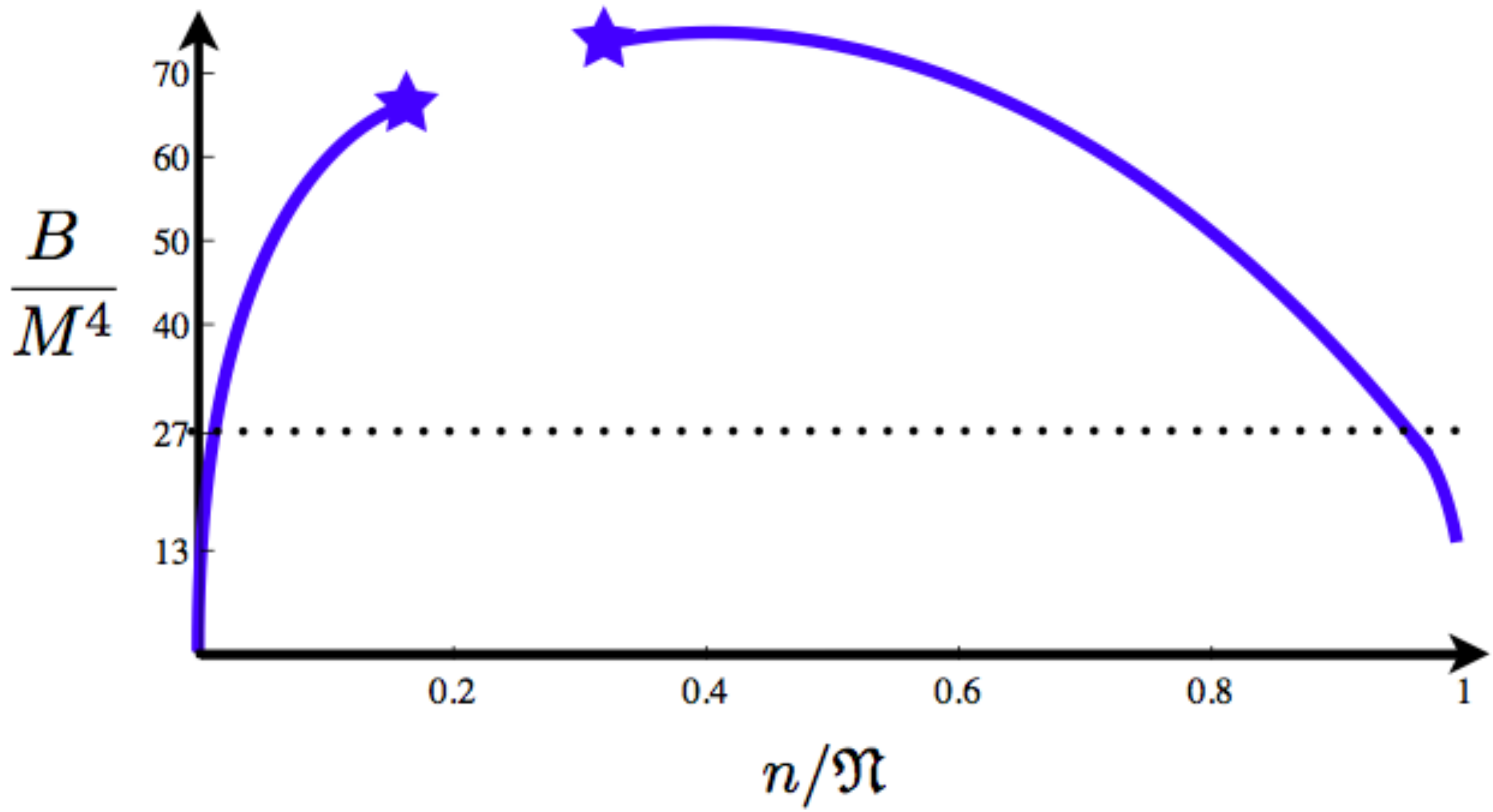


GIANT LEAPS MAY WIN

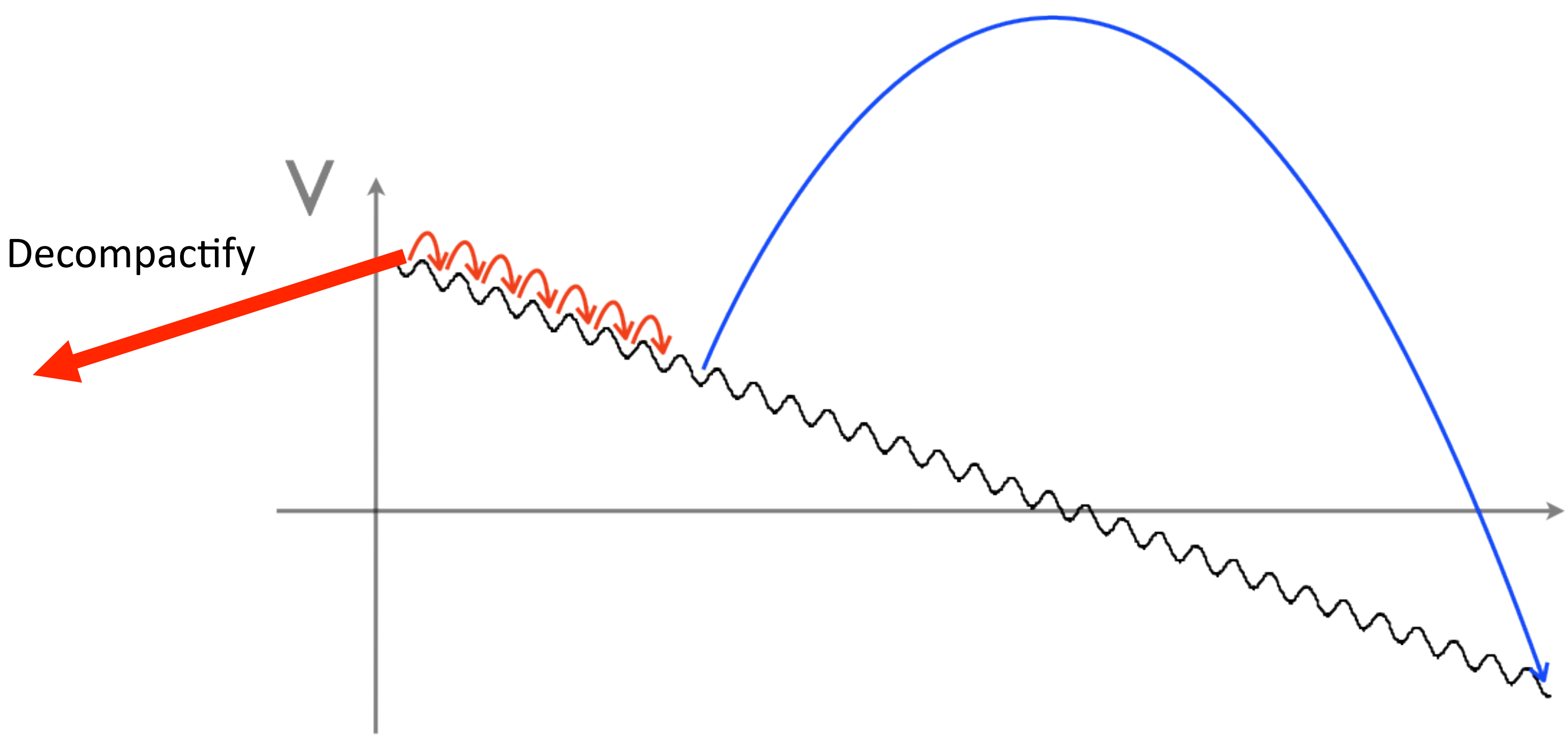
Decay Rates

MULTIFLUX

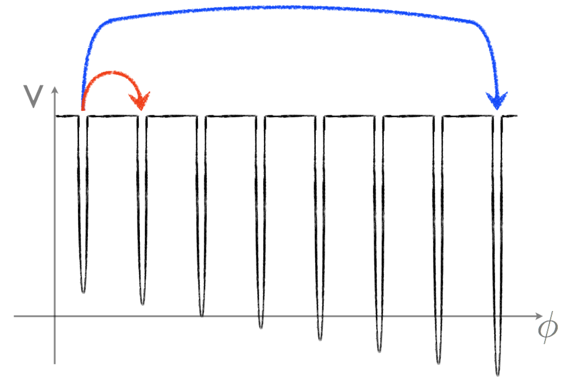
From V>>0



DECOMPACTIFICATION WINS


V
Decompactify

1. This potential gives small steps



2. Flux compactifications with many fluxes give giant leaps
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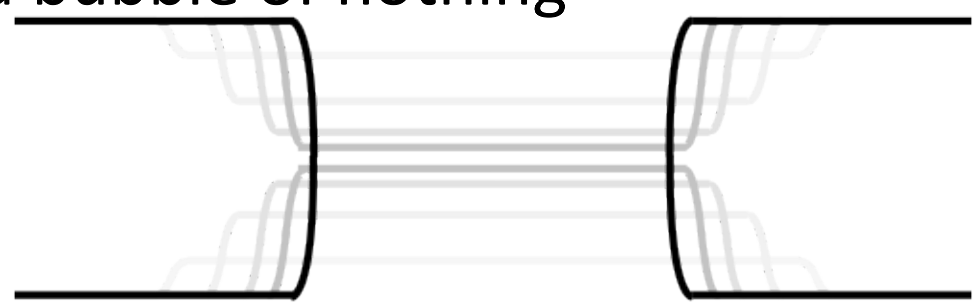
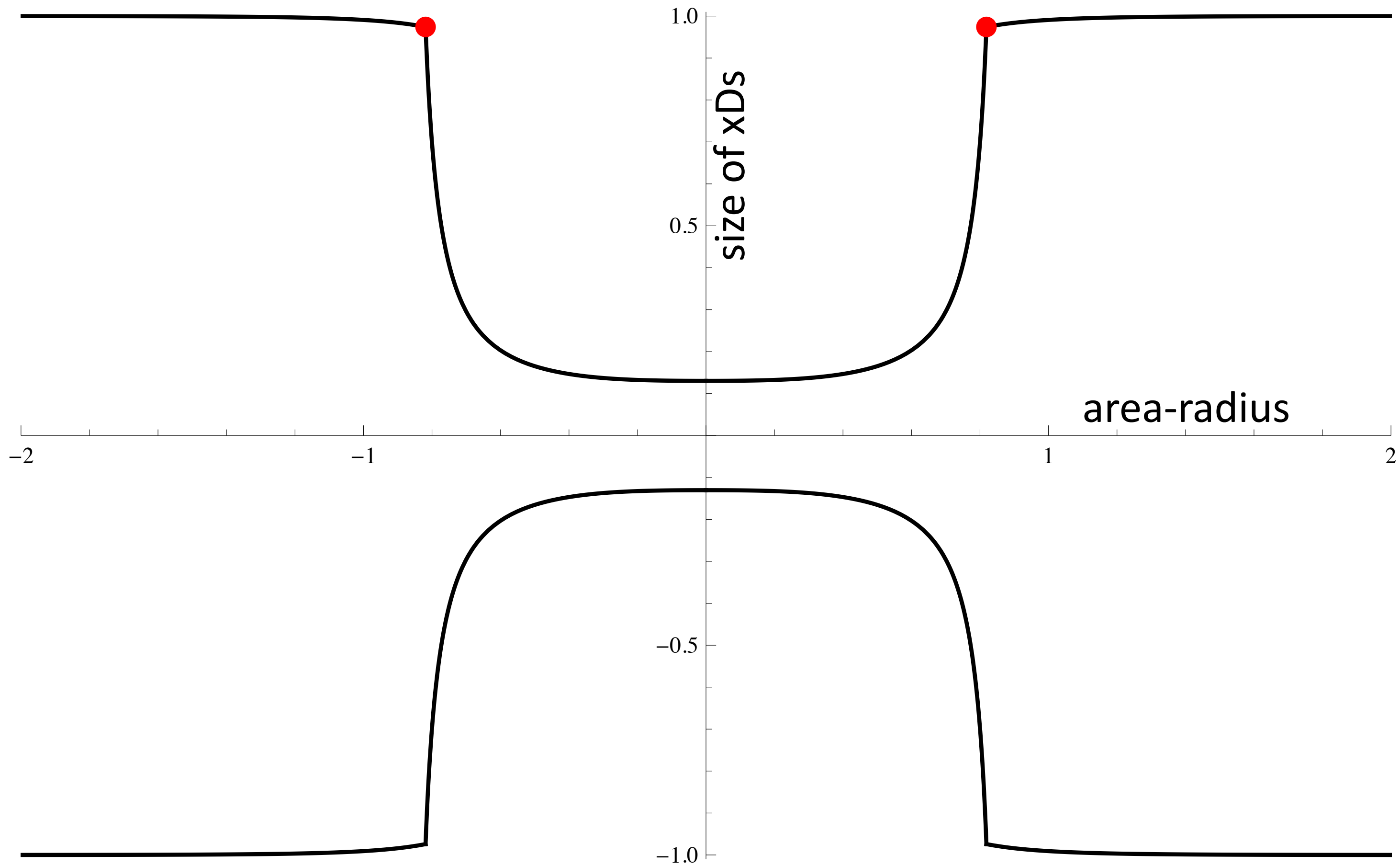
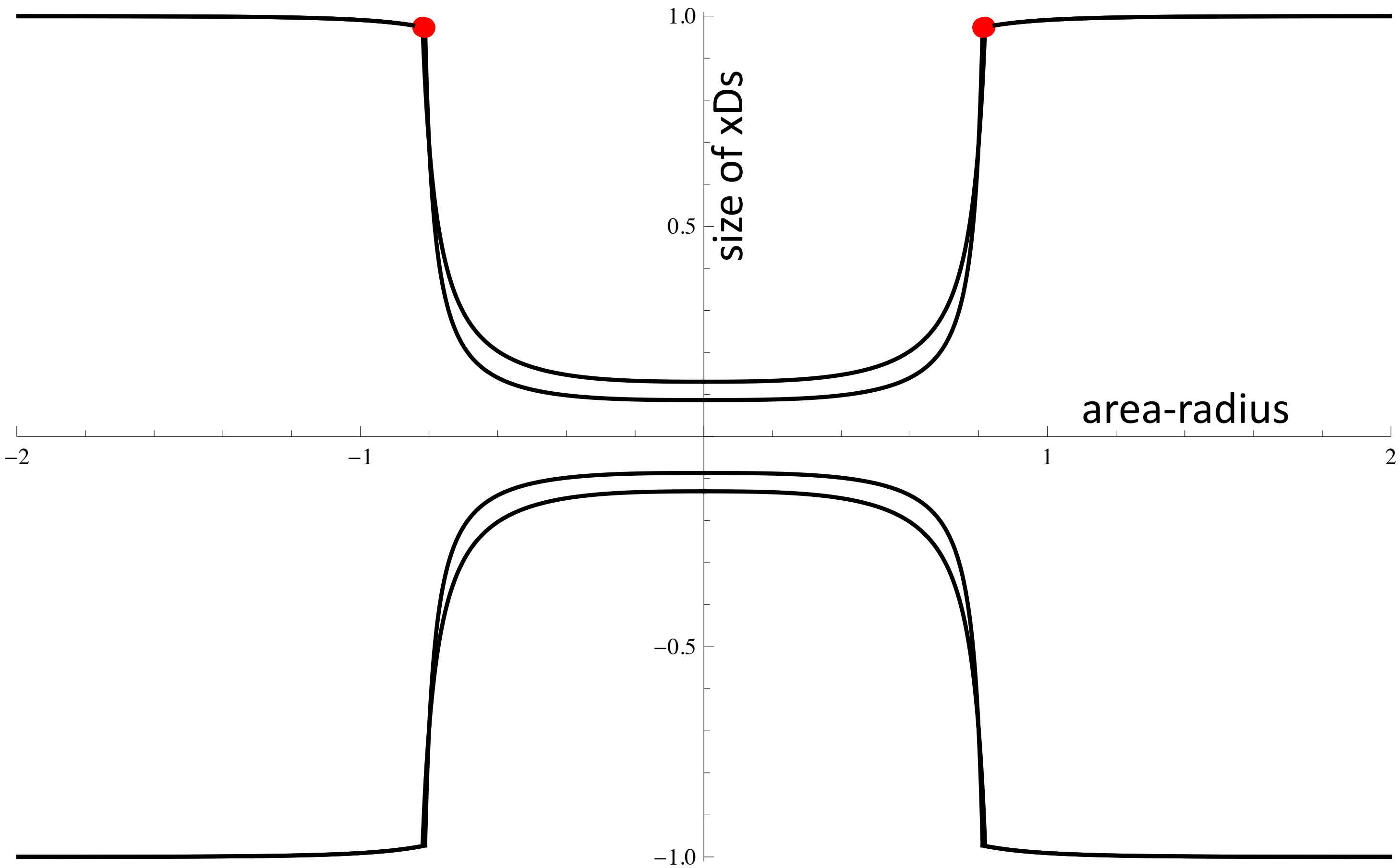



size of xDs
area-radius
1.0
0.5
−0.5
−1.0
−2
−1
1
2



size of xDs
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0.5
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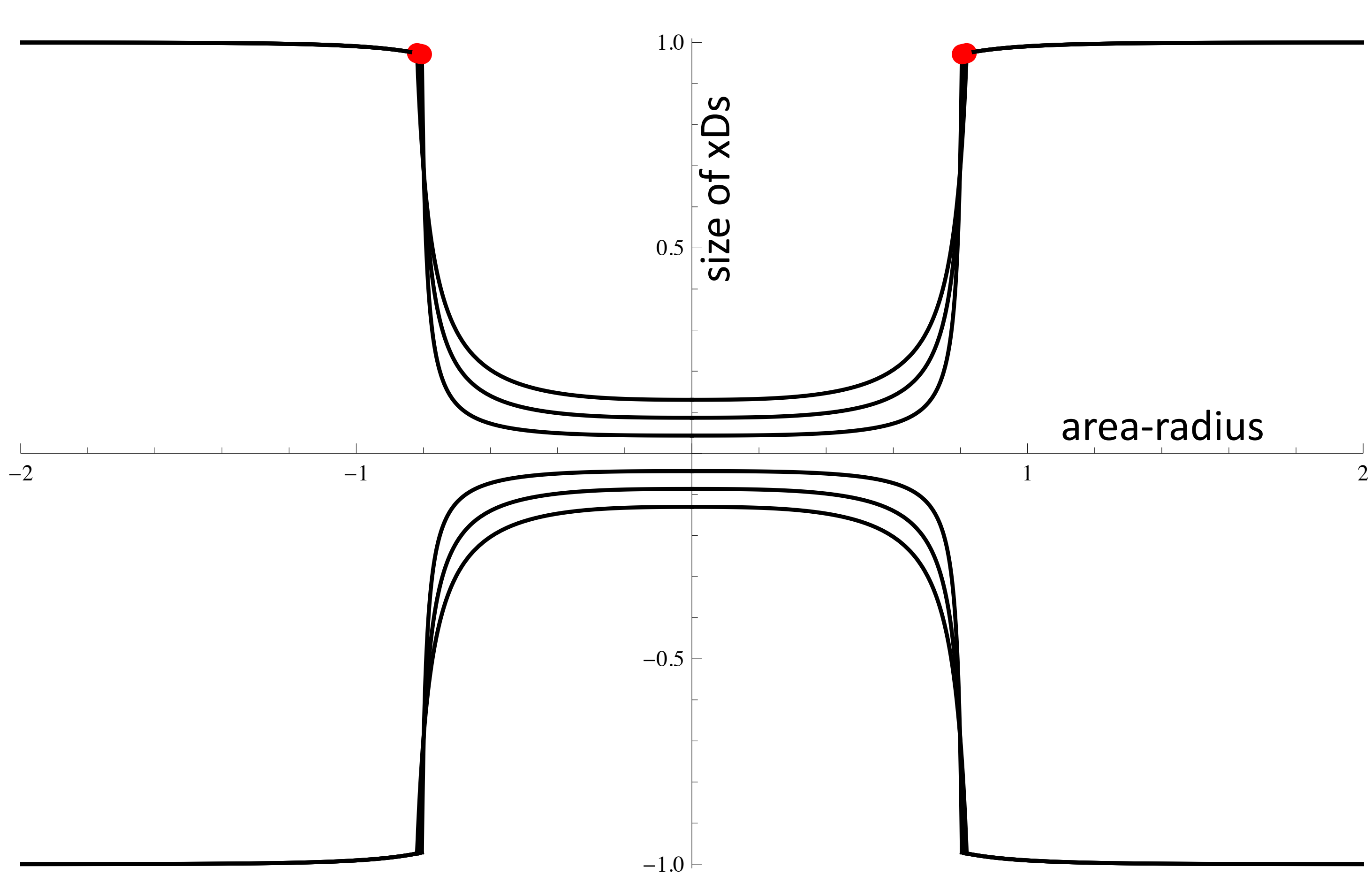
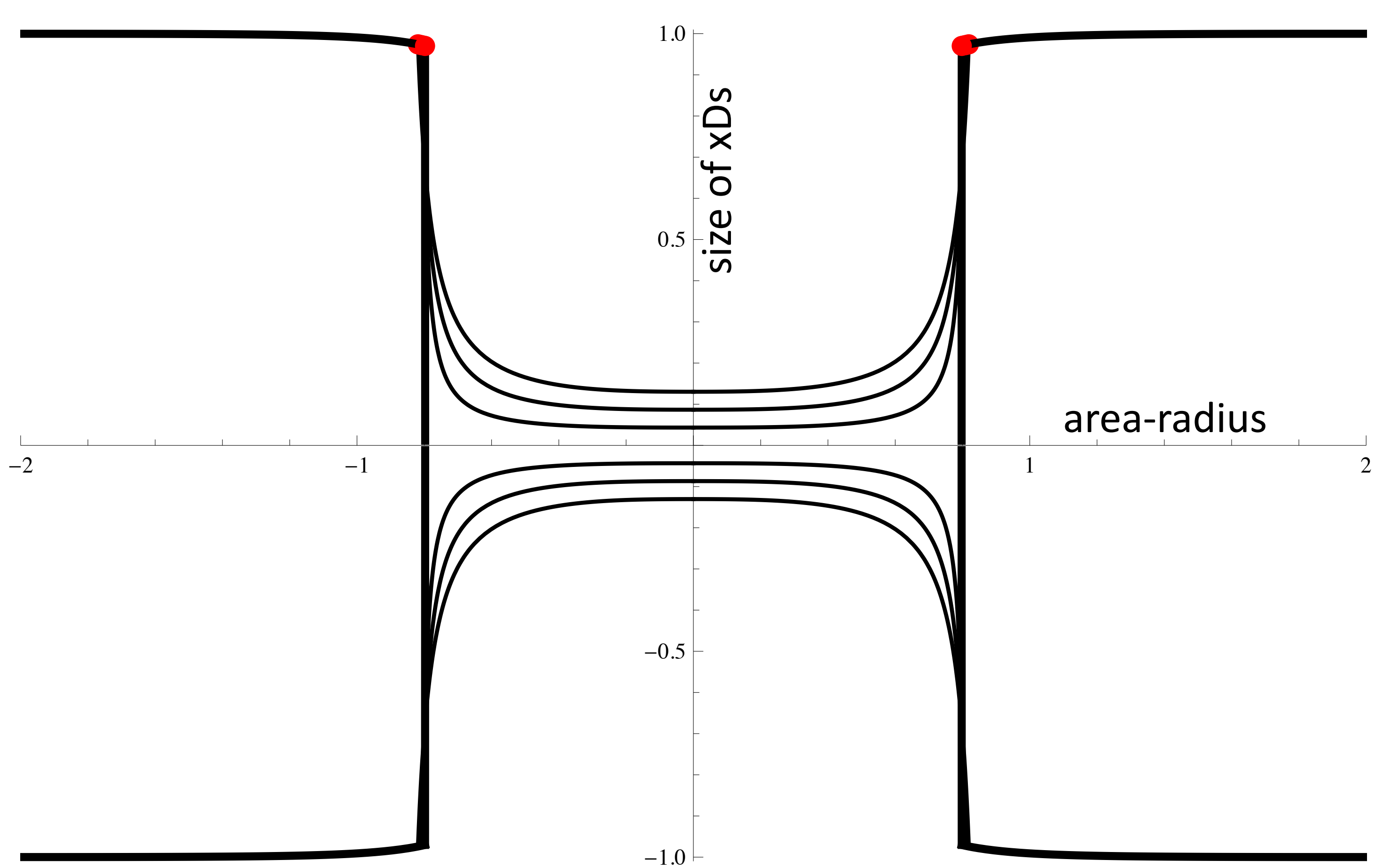

size of xDs
area-radius
1.0
0.5
−0.5
−1.0
−2
−1
1
2

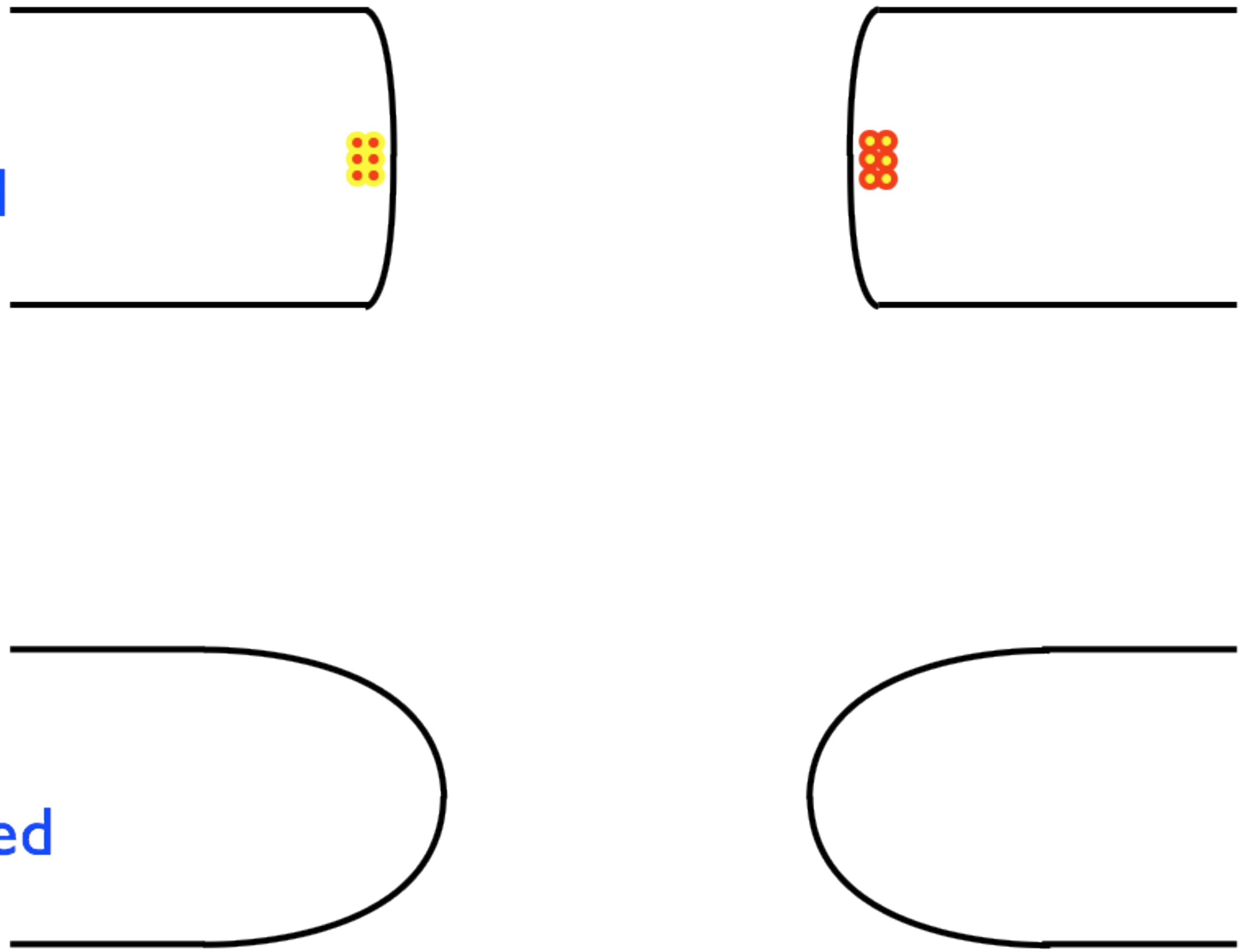


1.0
0.5
−0.5
−1.0
−2
−1
1
2
size of xDs
area-radius

Bubble of Nothing

6d
stabilized

5d
unstabilized



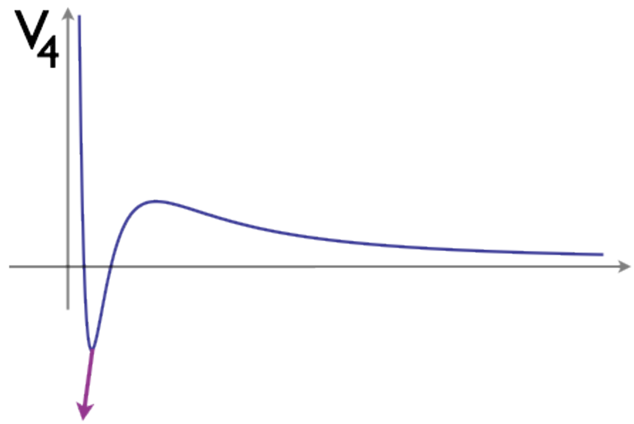
Witten, 1981

In the limit that ALL flux discharged:

I. Extra dimensions shrink to zero size

II. What about the 3-volume of a slice through the bubble?

like an infinitely thin pancake?



negative V

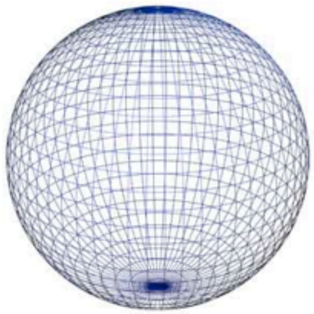
↓

negative curvature

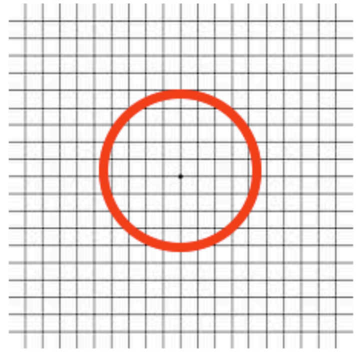
(AdS)

11. What about the 3-volume of a slice through the bubble?

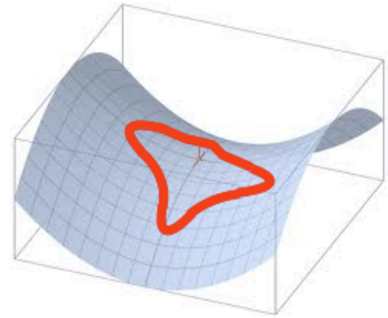
like an infinitely thin pancake?



$\text{Area} > \pi r^2$

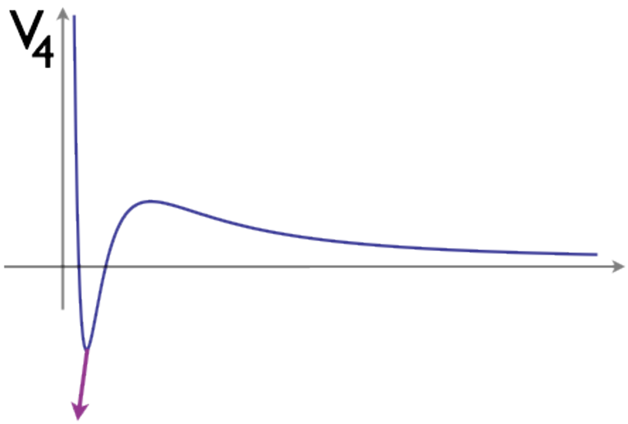


$\text{Area} = \pi r^2$



$\text{Area} < \pi r^2$

$\text{Area} \sim r\, l_{curv}$



negative V

↓

negative curvature

(AdS)

11. What about the 3-volume of a slice through the bubble?

like an infinitely thin pancake?

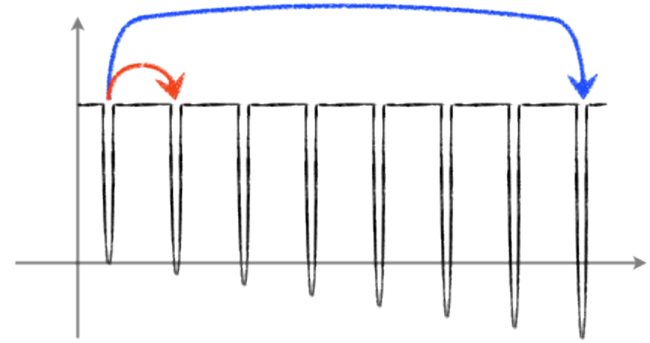
$$\text{Volume} \sim \text{Area} \times l_{curv}$$

$$l_{\text{curv}} \to 0$$

11. What about the 3-volume of a slice through the bubble?

like an infinitely thin pancake?

1. This potential gives small steps



2. Flux compactifications with many fluxes give giant leaps
3. Monkey branes

4. Back-reaction on the compactification

5. The giantest leap of all is a bubble of nothing

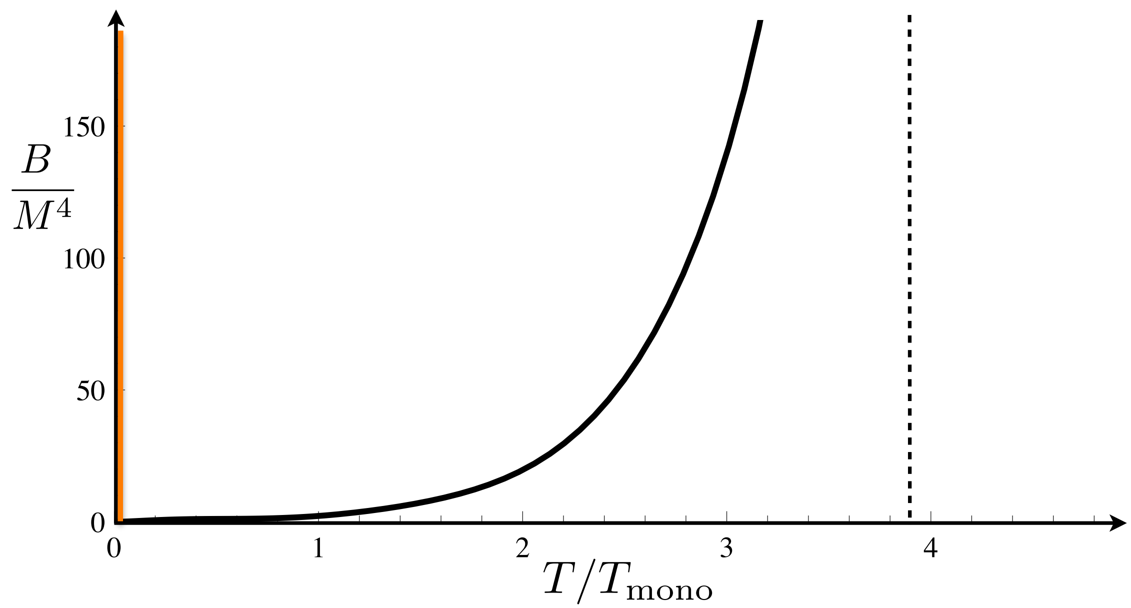
Summary

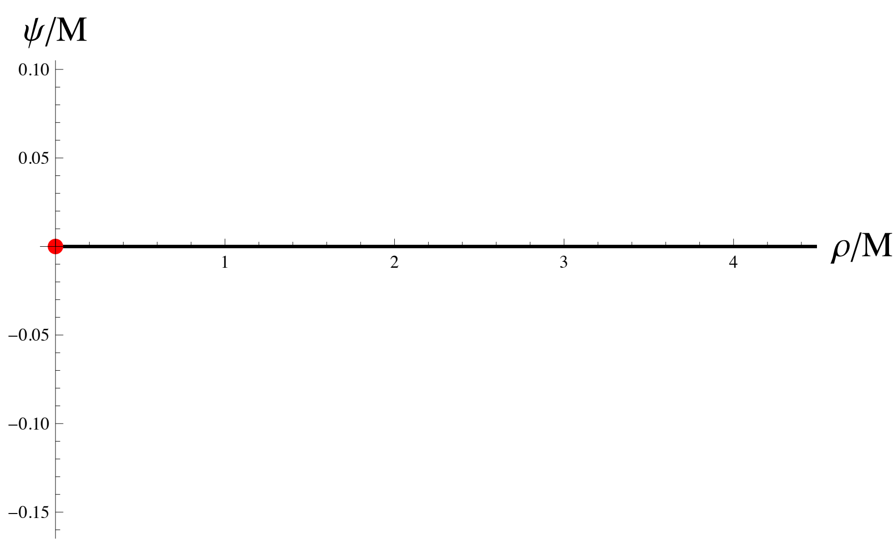
- Giant leaps beat small steps in landscapes
- The bubble of nothing can be the fastest decay
- It is realized smoothly as the limit of flux tunneling
- When the many fluxes come from higher dimensional model, still expect enhancement. Richer behavior.

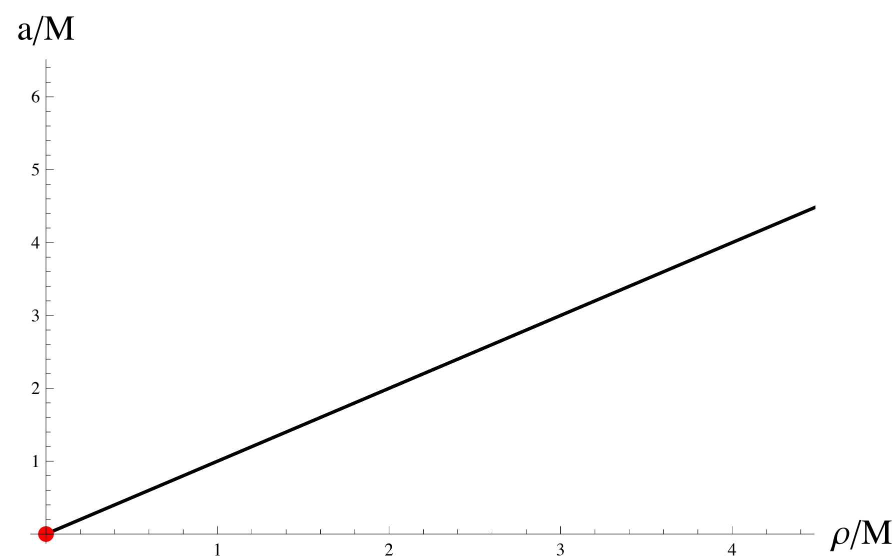
- If we live in a multiflux landscape, then we draw two conclusions. We got here by an exponentially subdominant decay, and we will leave here by a bubble of nothing.

the end

Case 1:
Decay from
Minkowski







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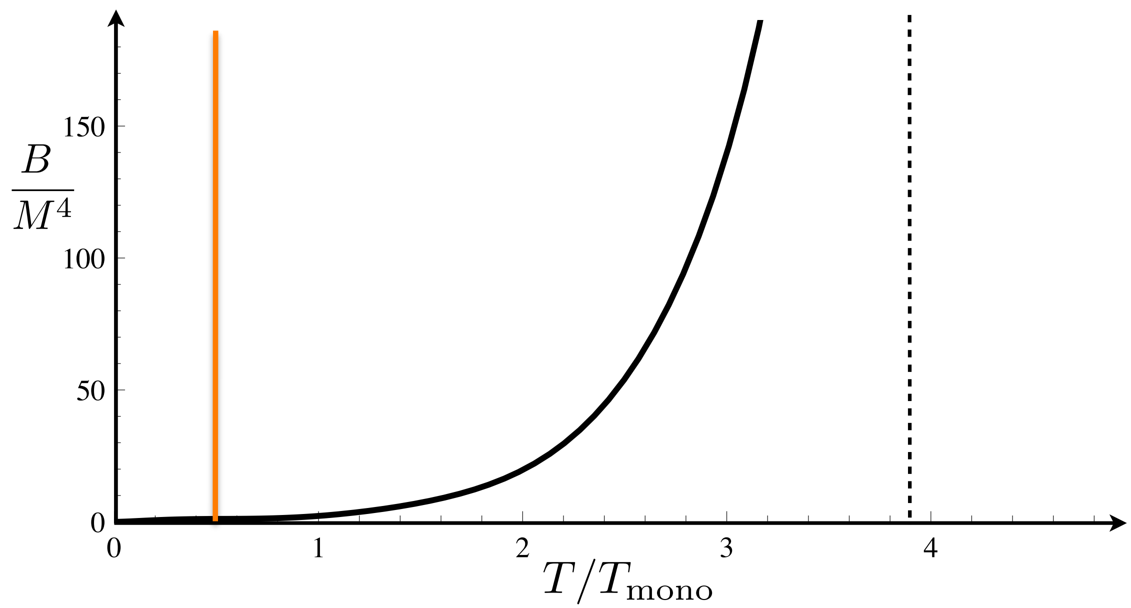
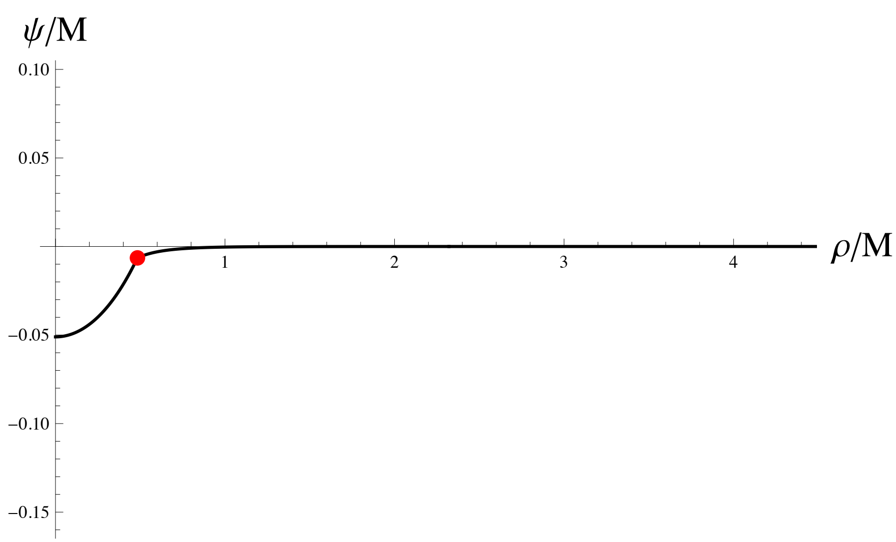
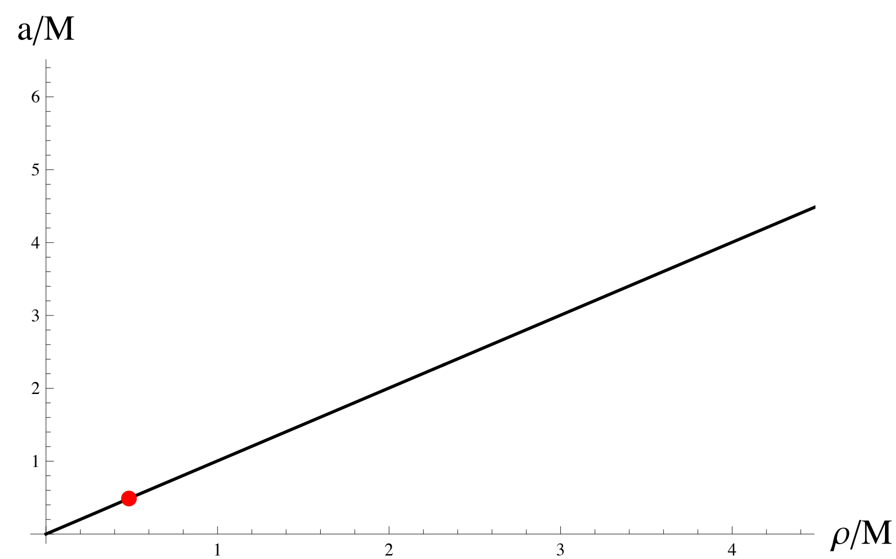
Decay from
Minkowski







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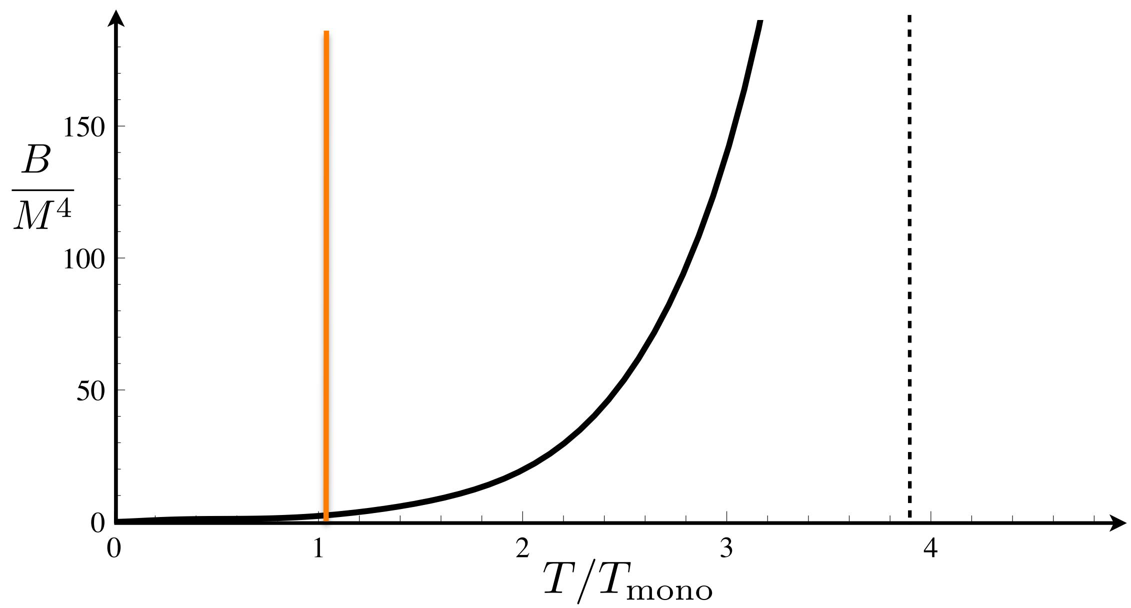

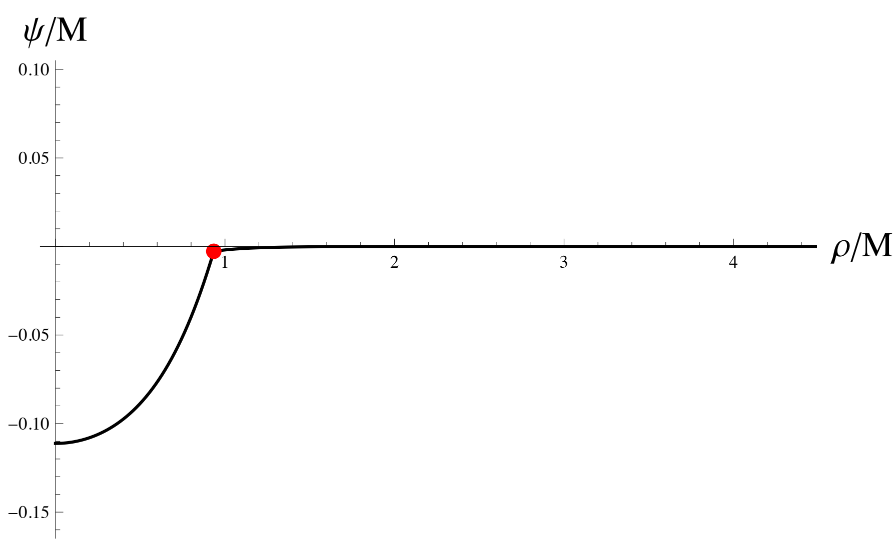

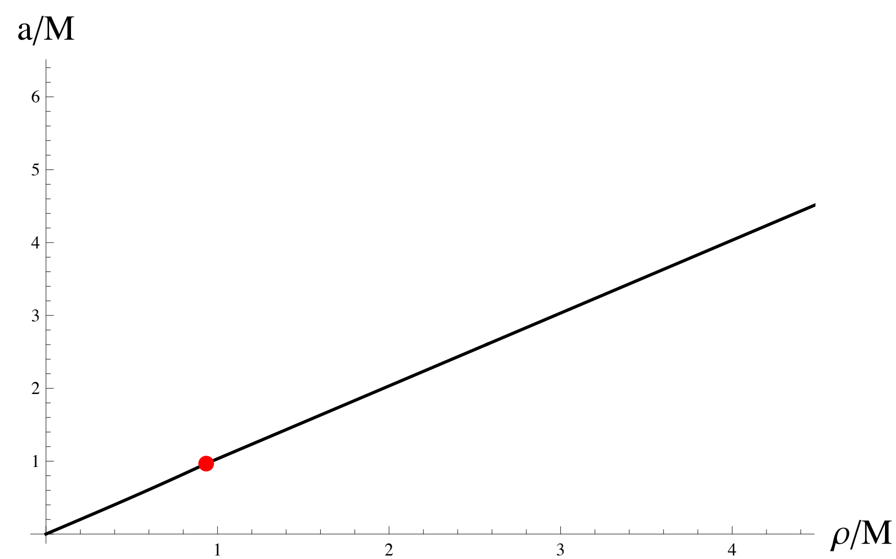

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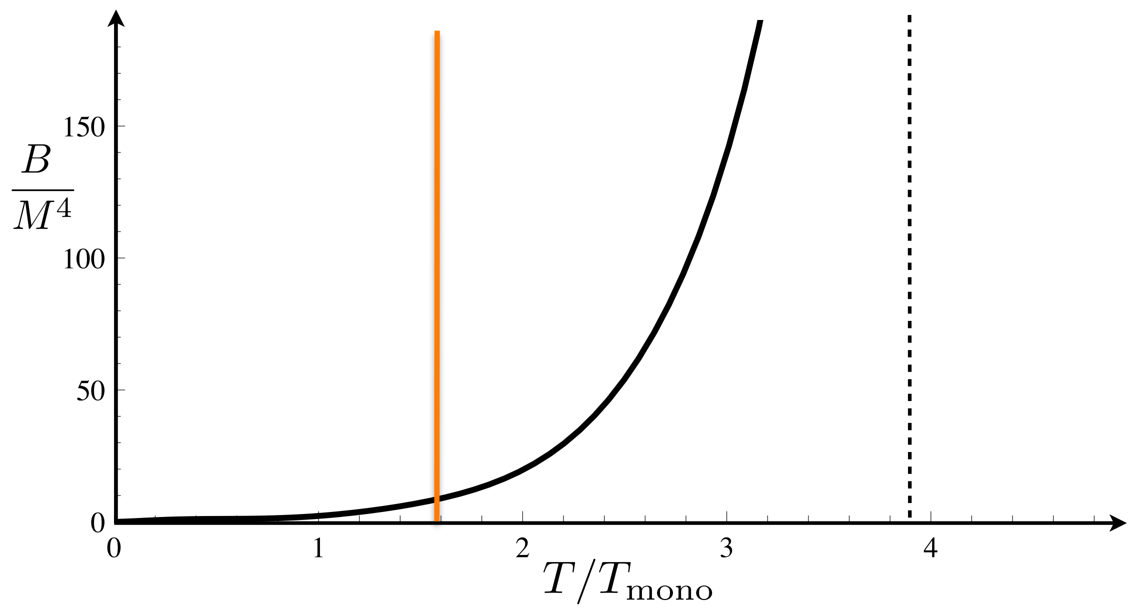
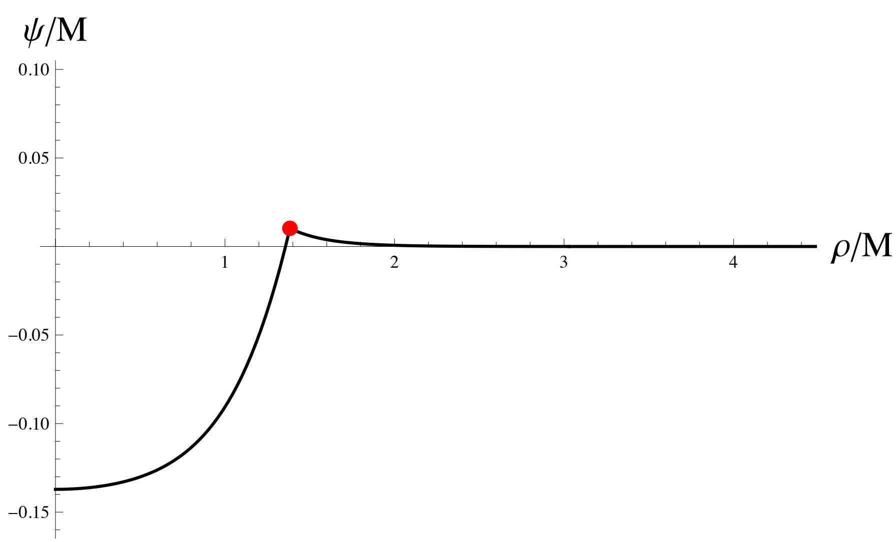
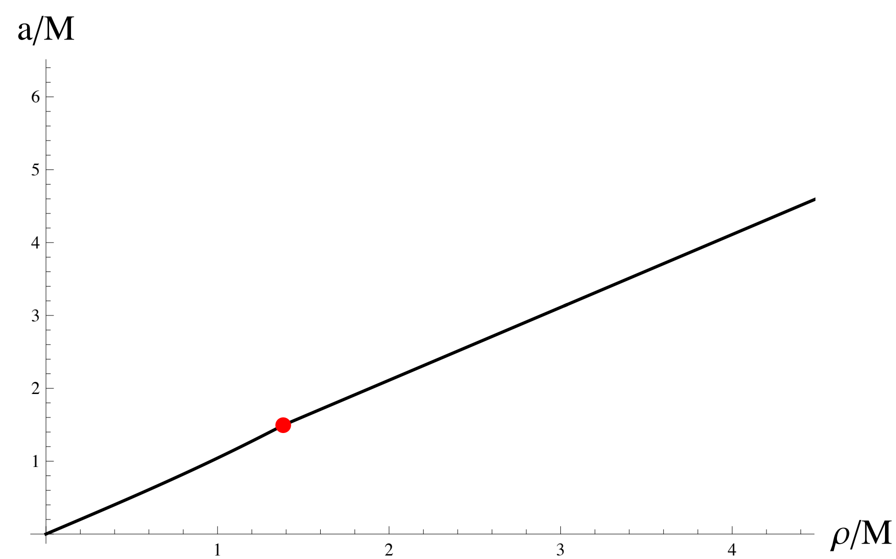
Decay from Minkowski







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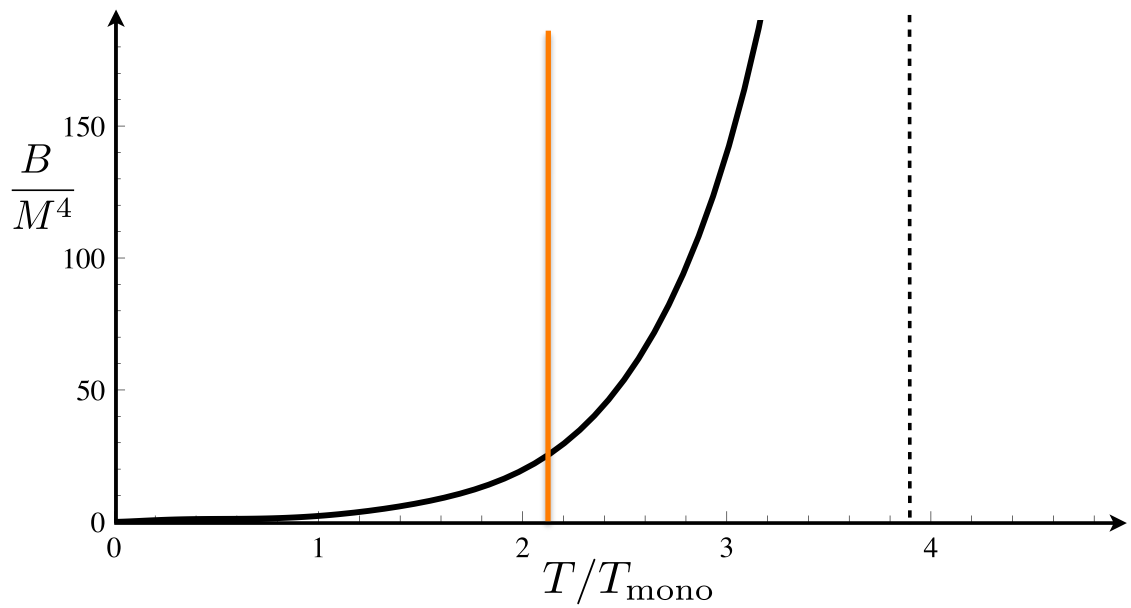
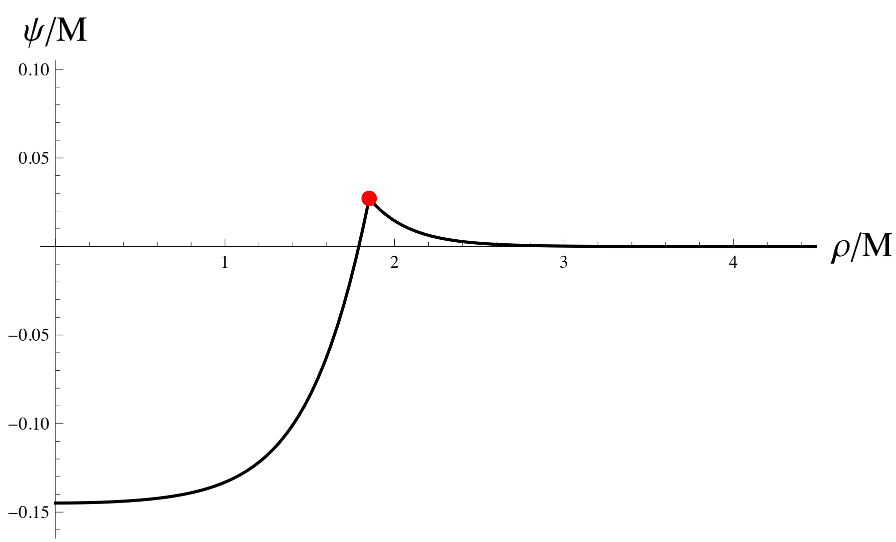
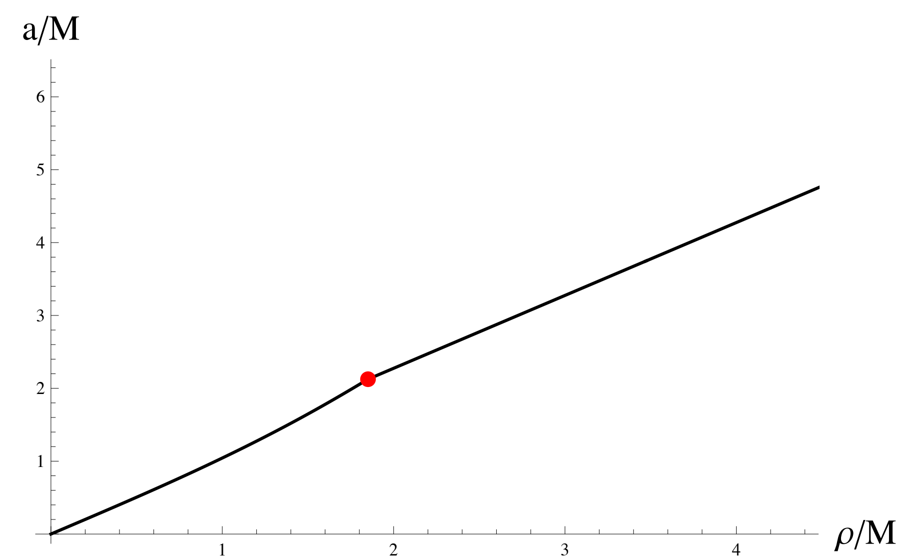
Decay from
Minkowski







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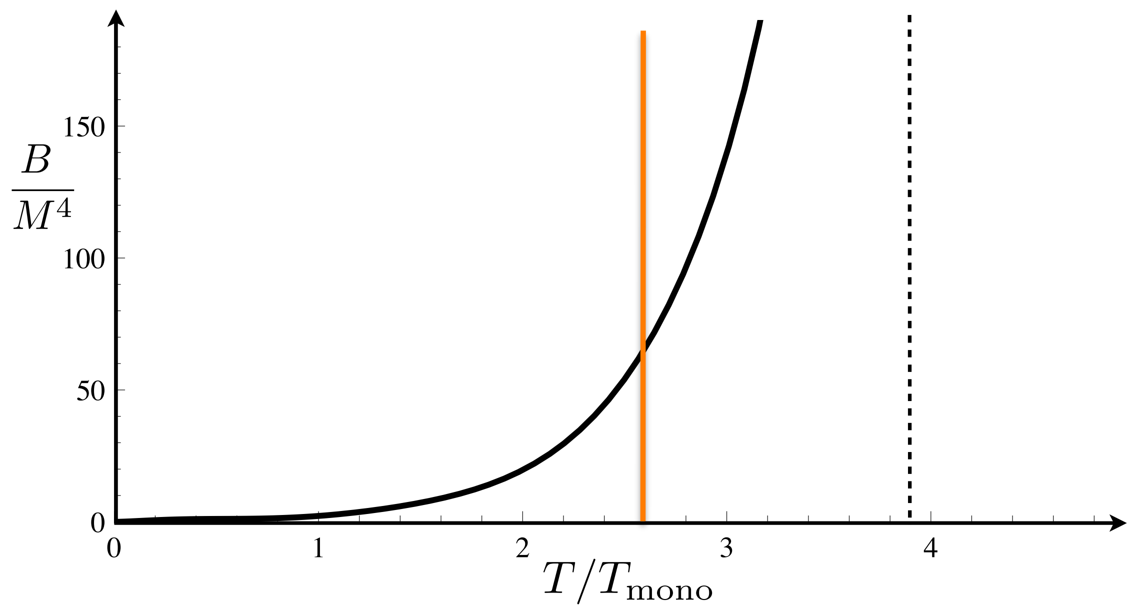
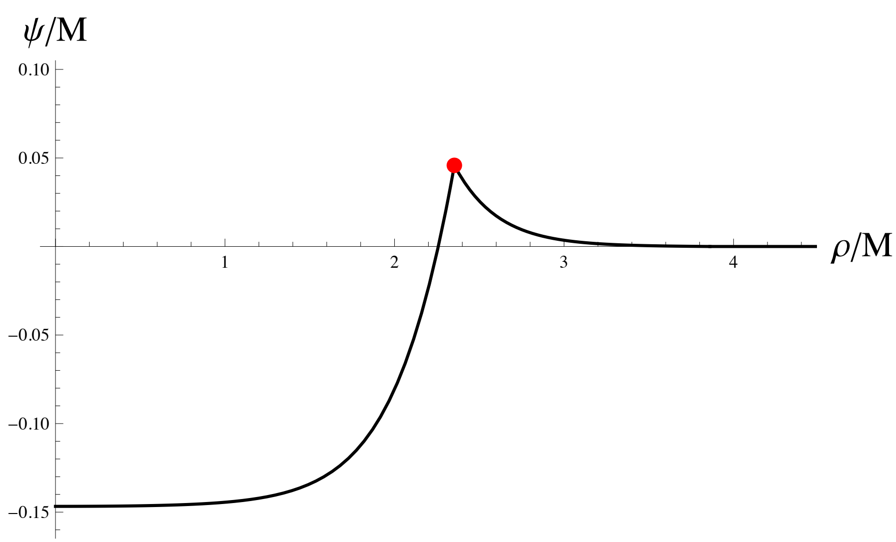
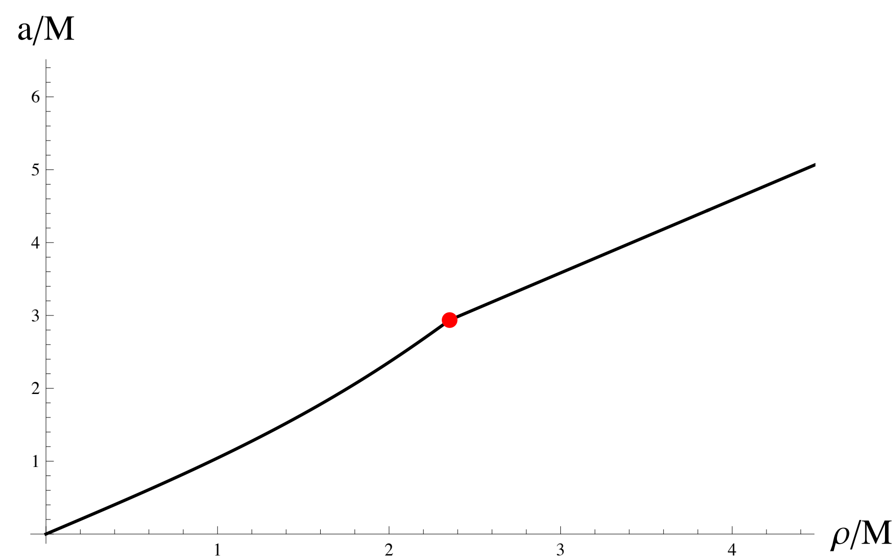
Decay from
Minkowski







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Decay from
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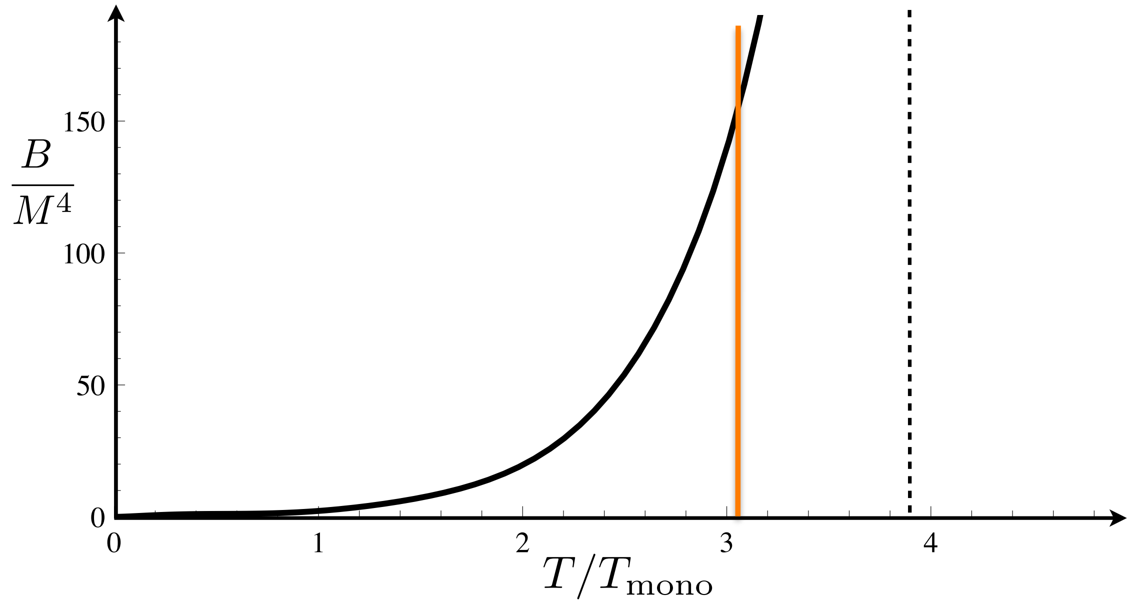

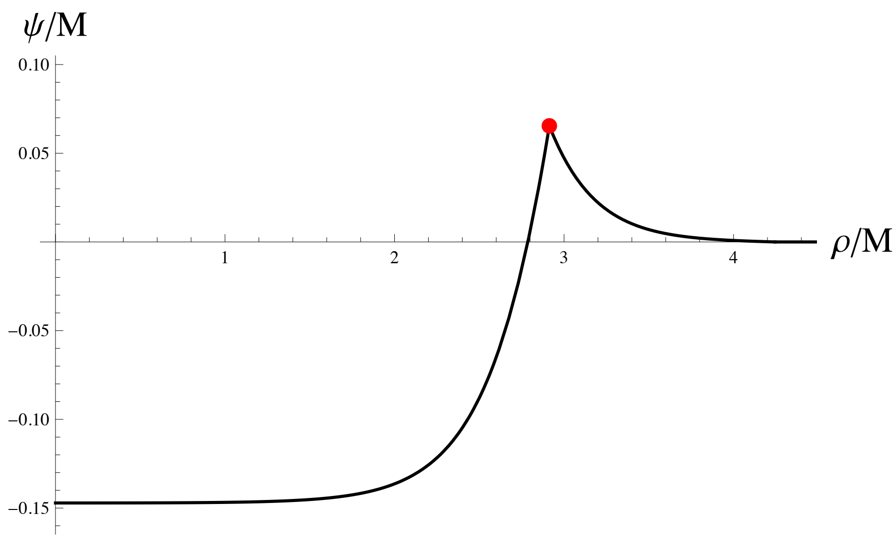

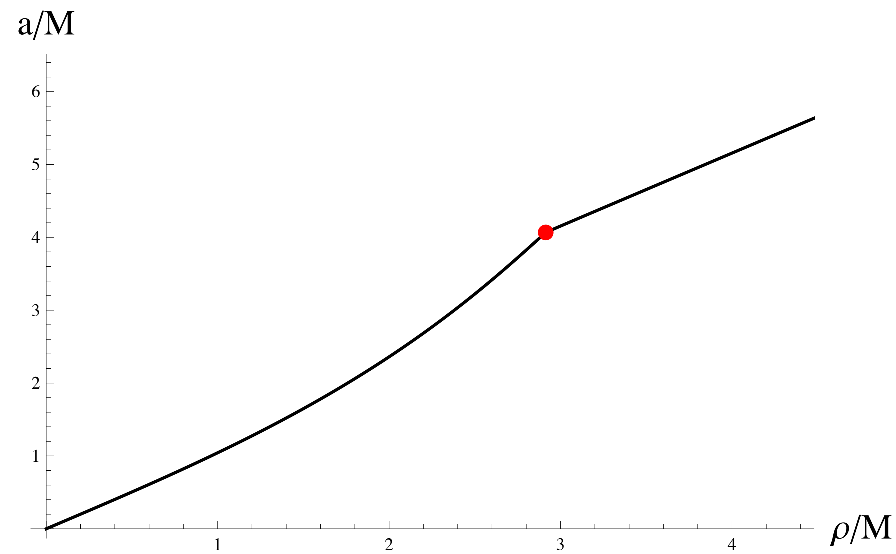

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Decay from
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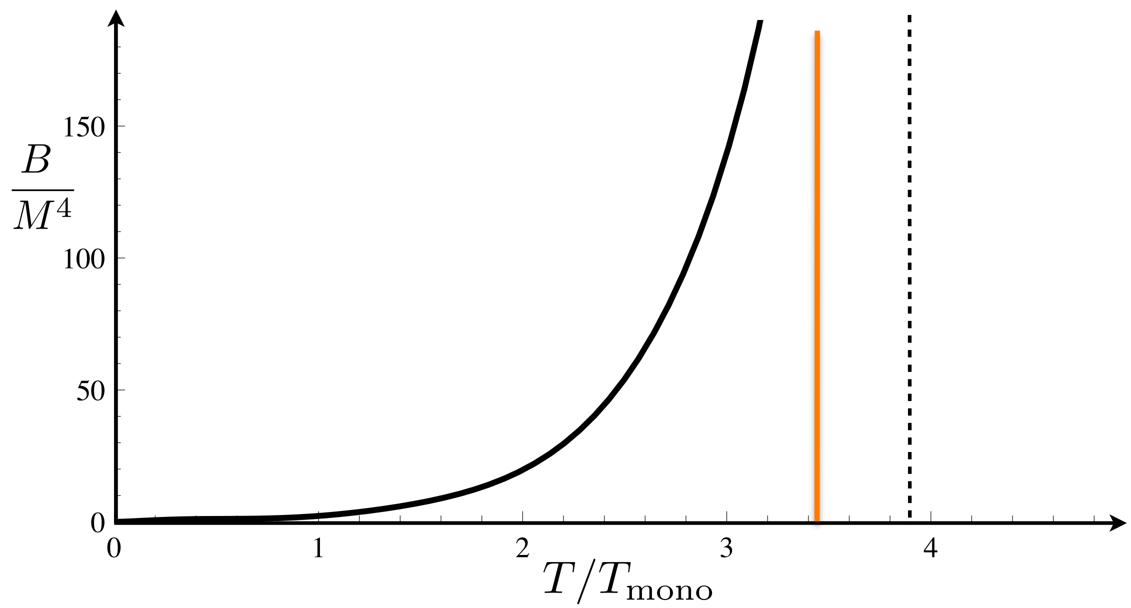
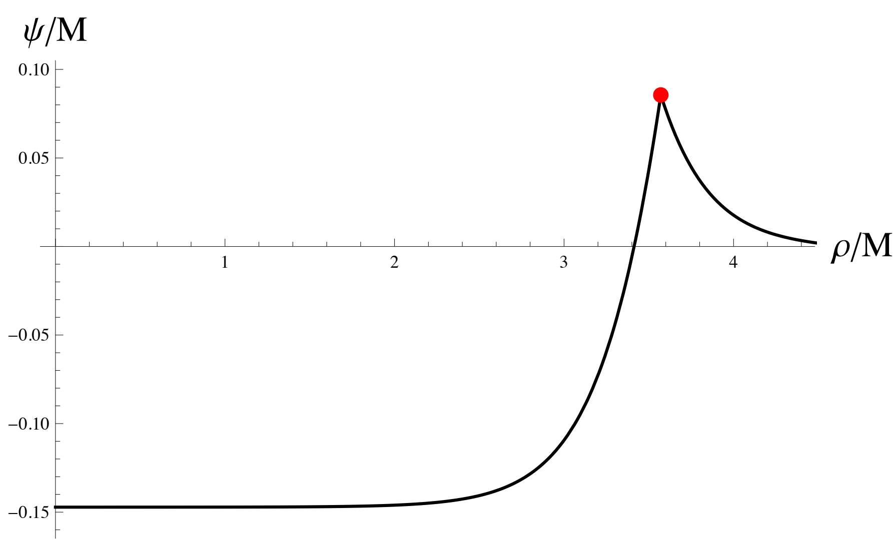
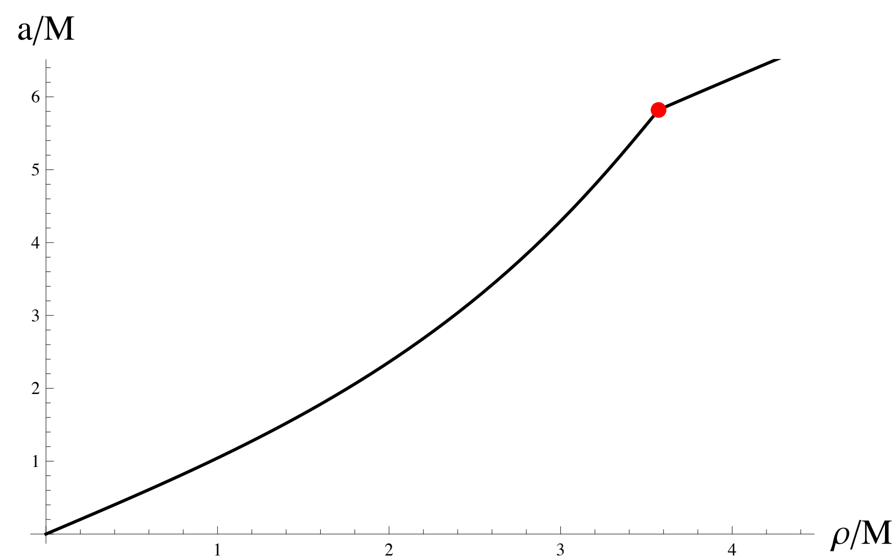
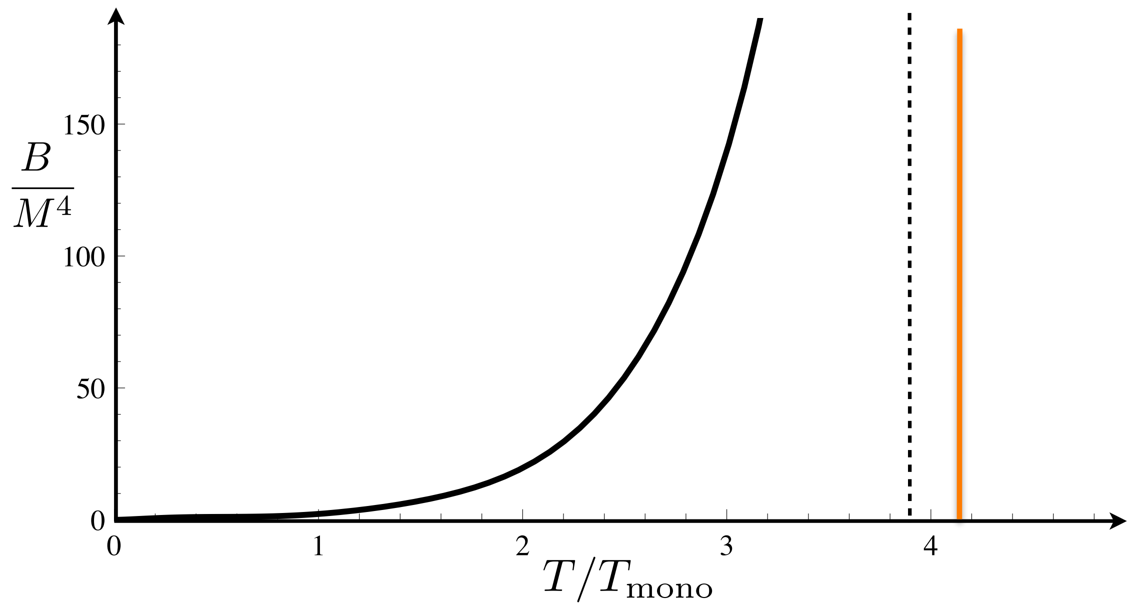


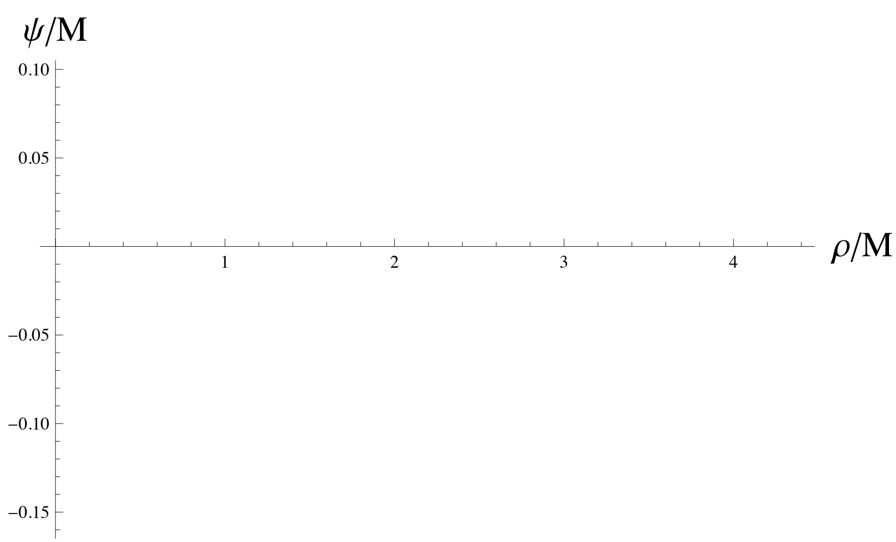


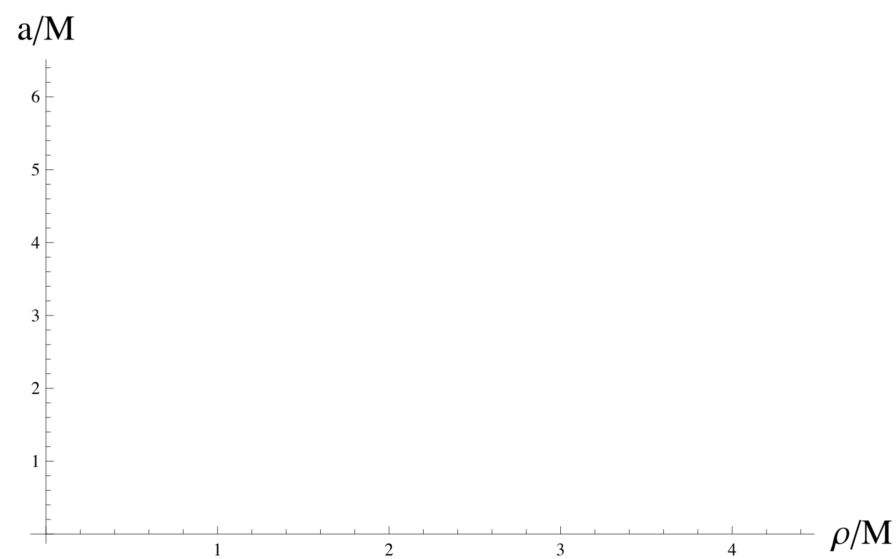


Case 1:
Decay from Minkowski

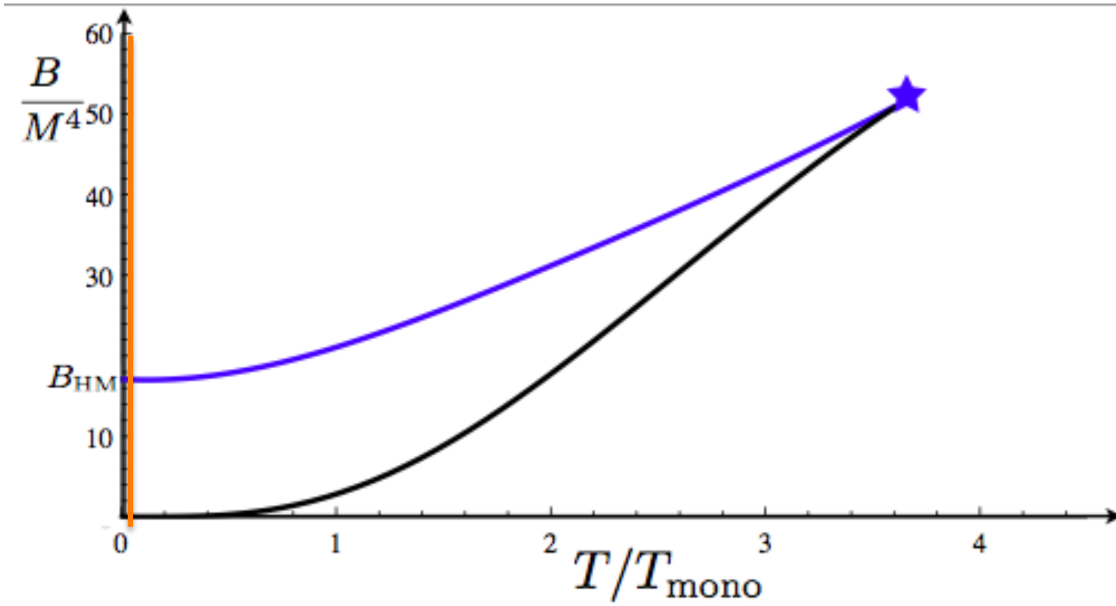
Gravitational Blocking

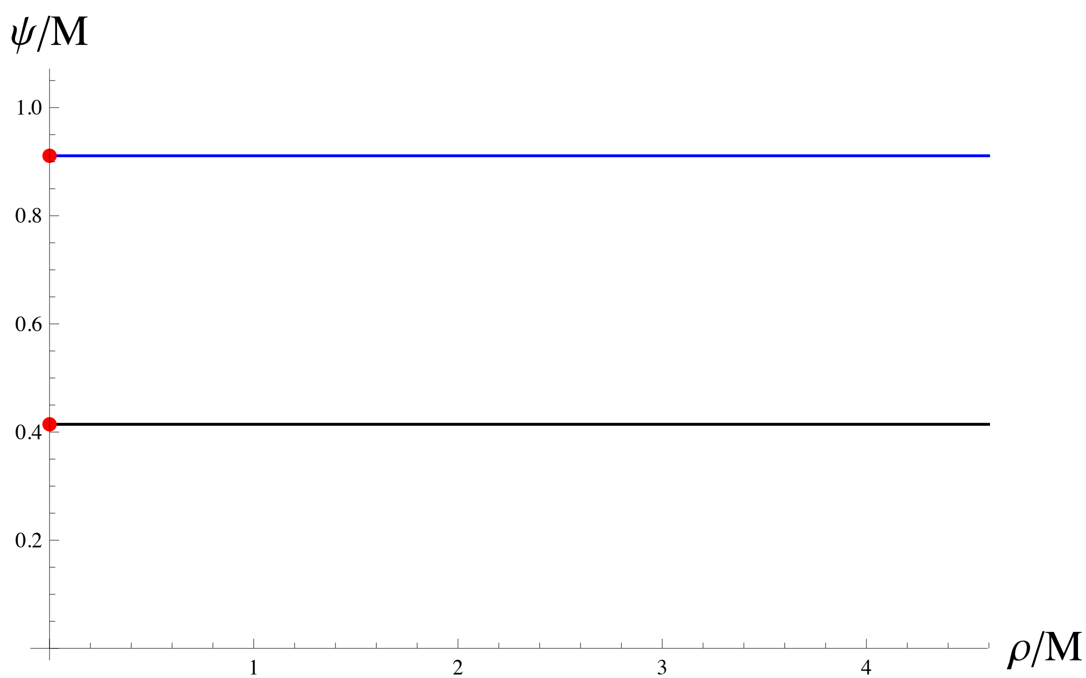




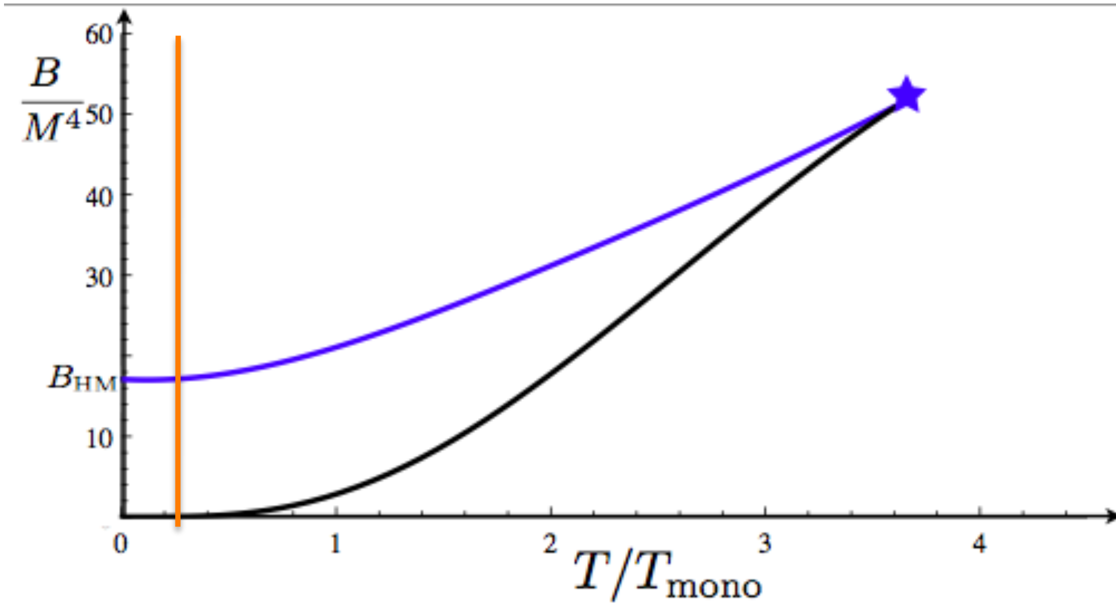


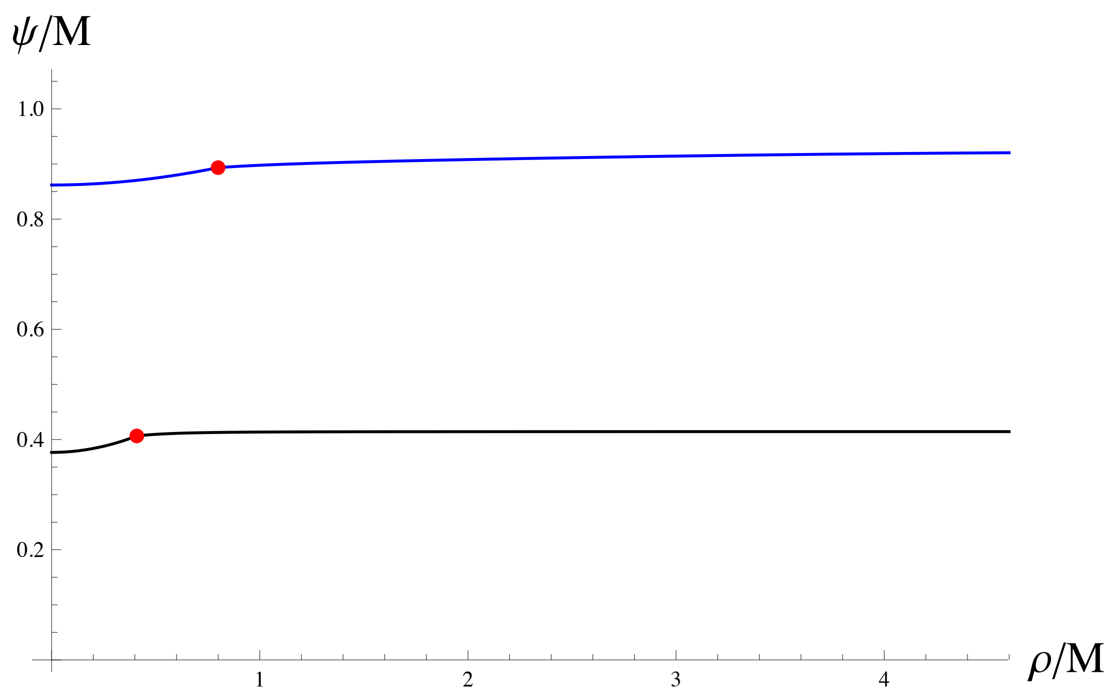
Case 2a:
Decay from
high dS



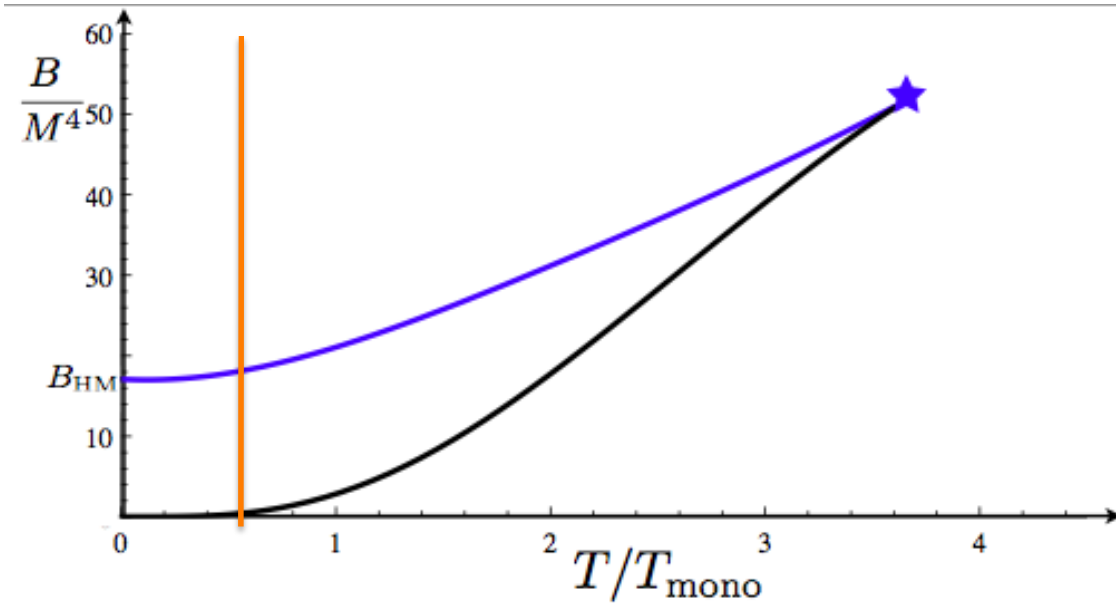


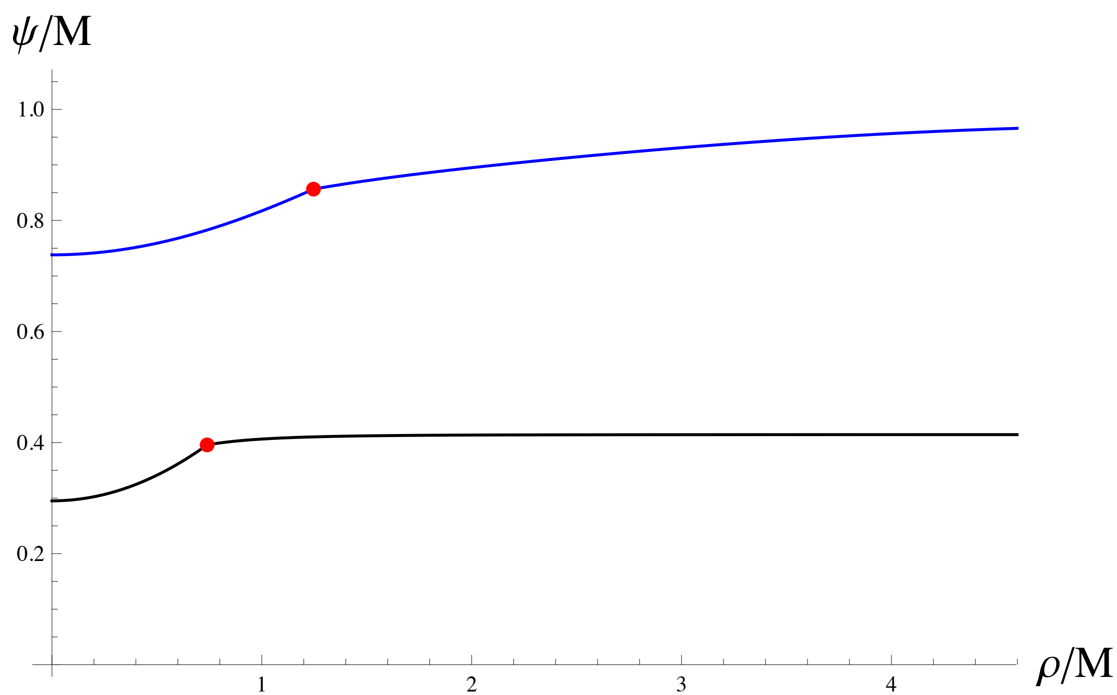
Case 2a:
Decay from
high dS



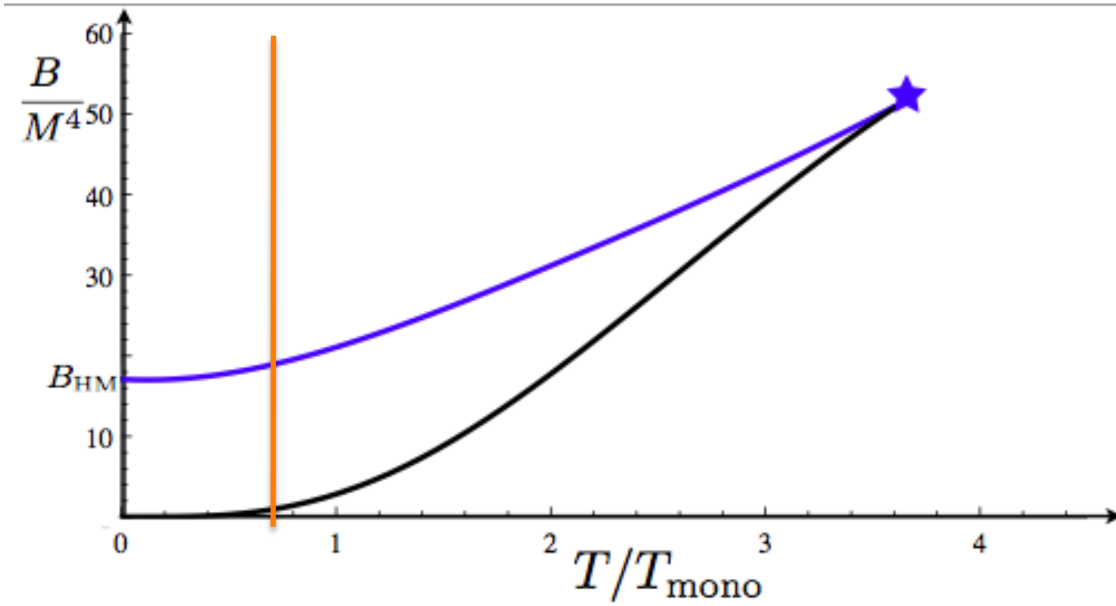


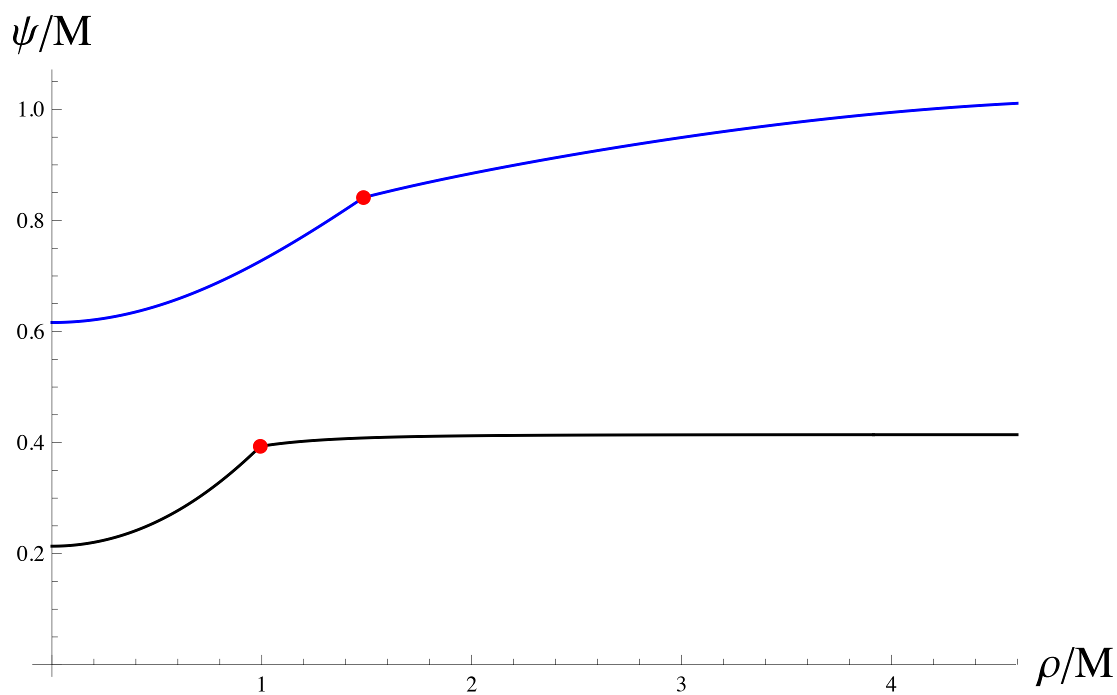
Case 2a:
Decay from
high dS



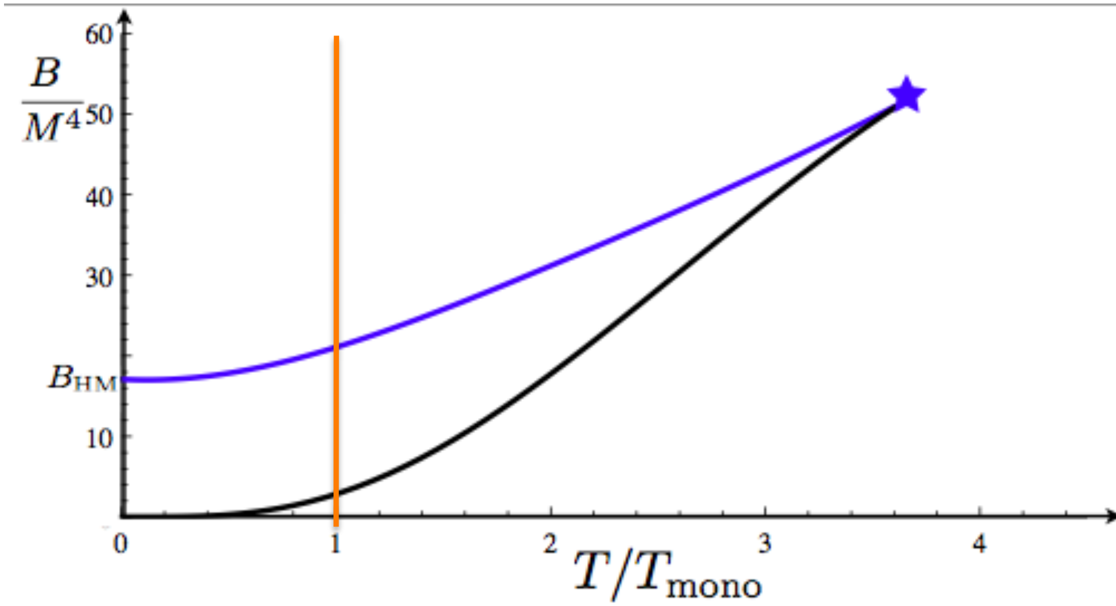


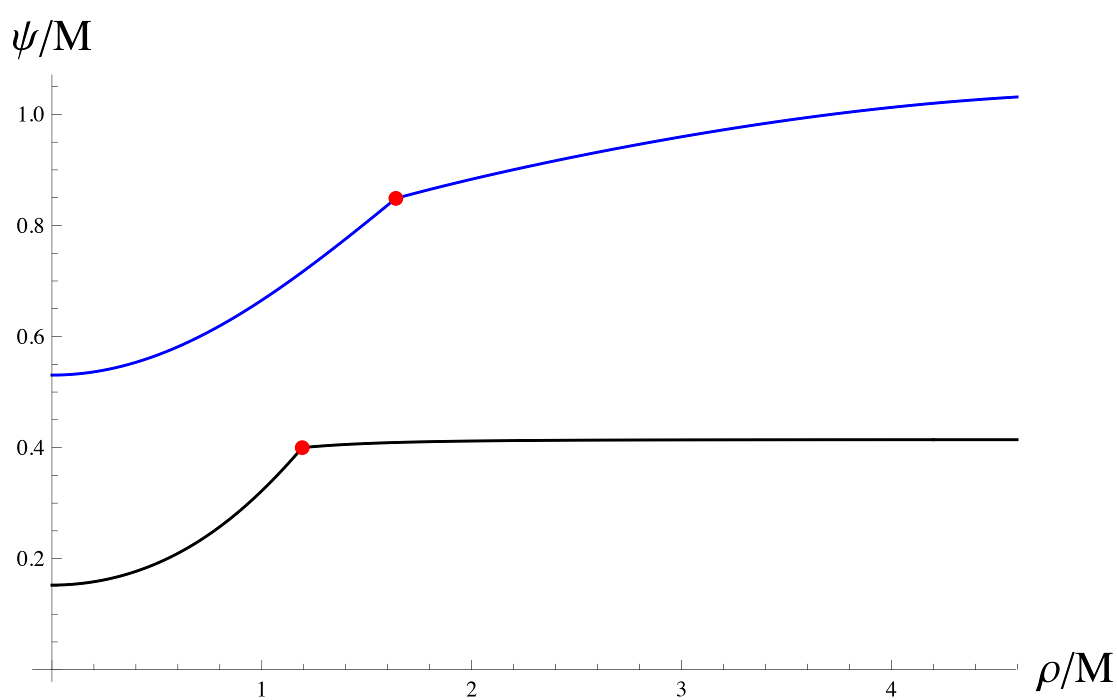
Case 2a:
Decay from
high dS



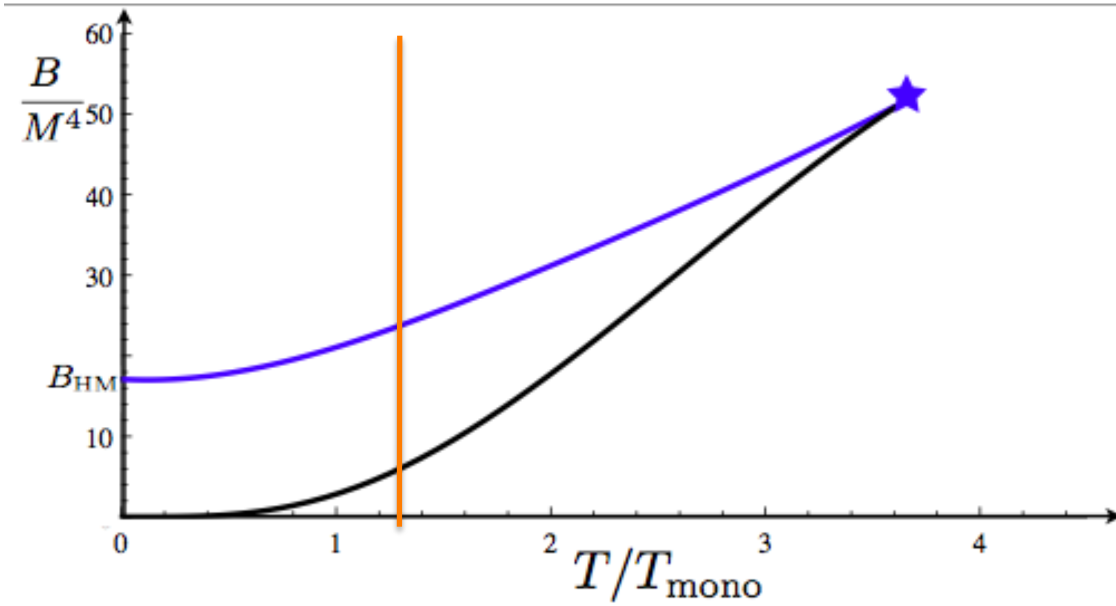


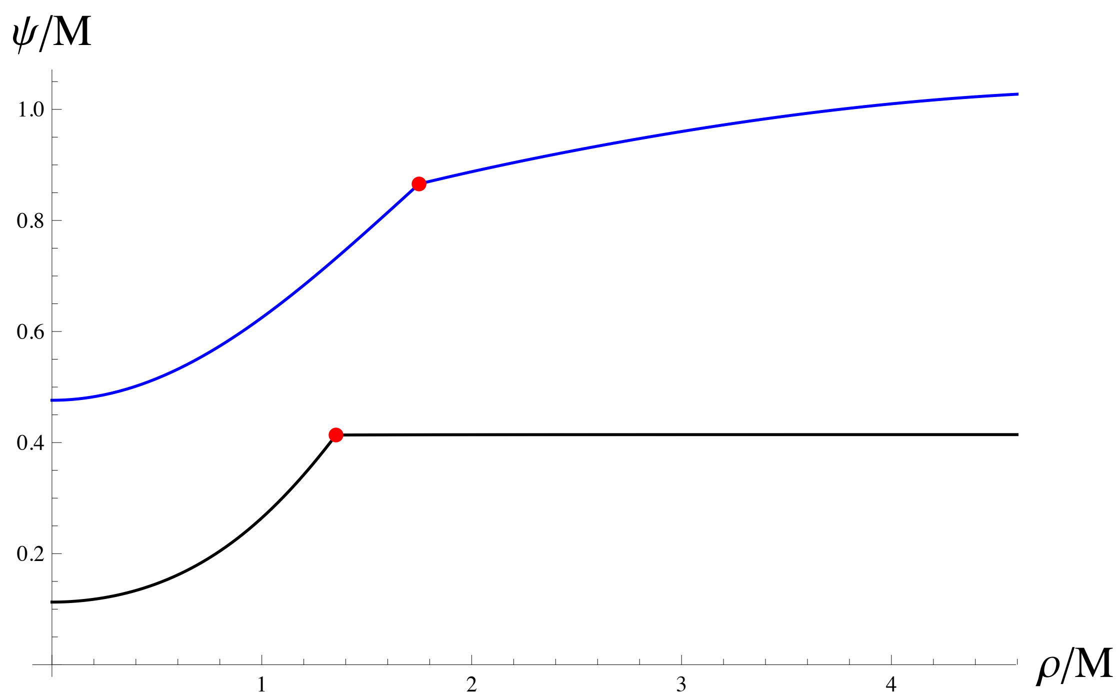
Case 2a:
Decay from
high dS



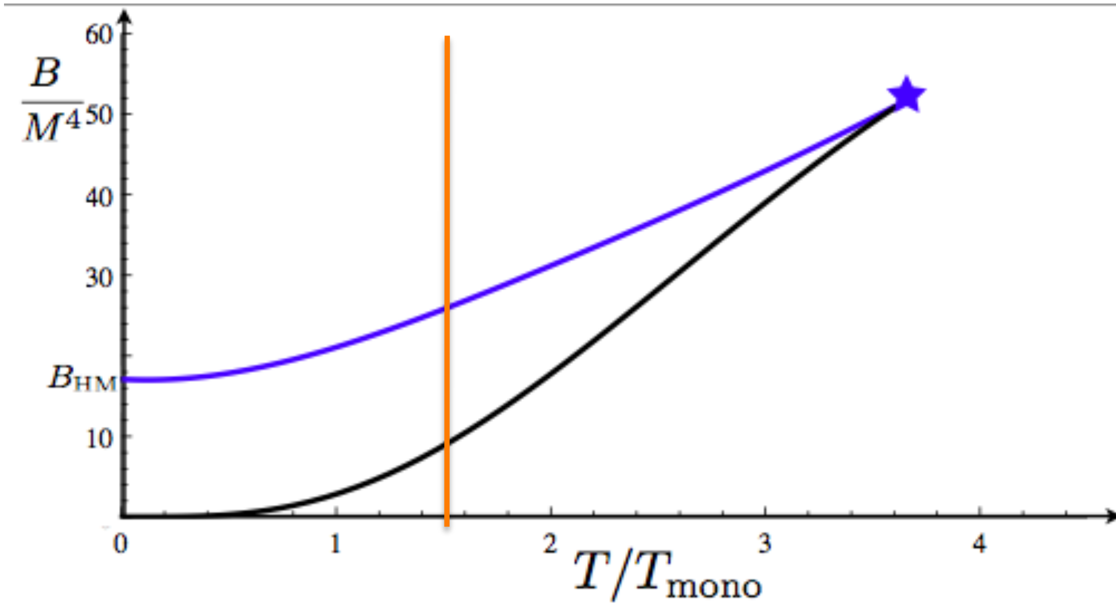


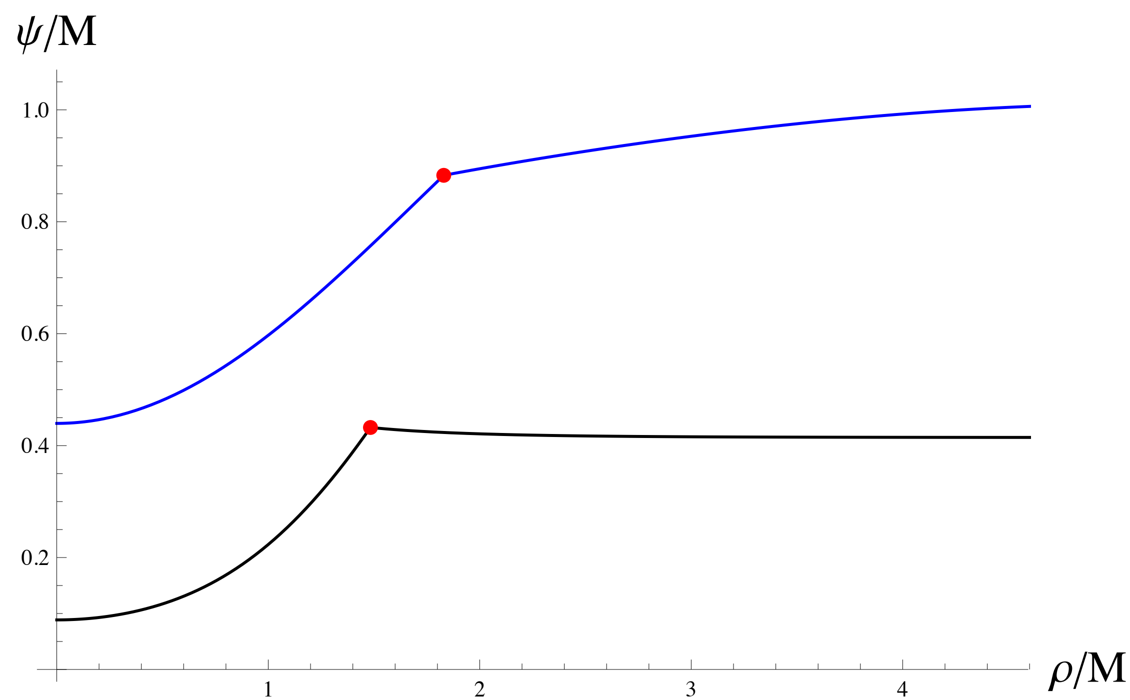
Case 2a: Decay from high dS



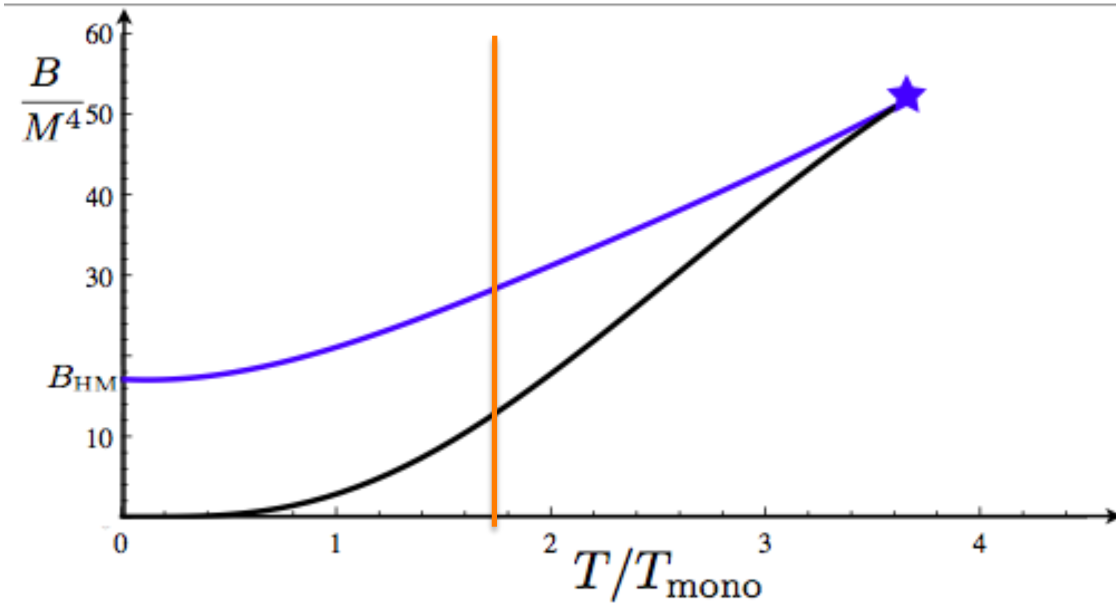


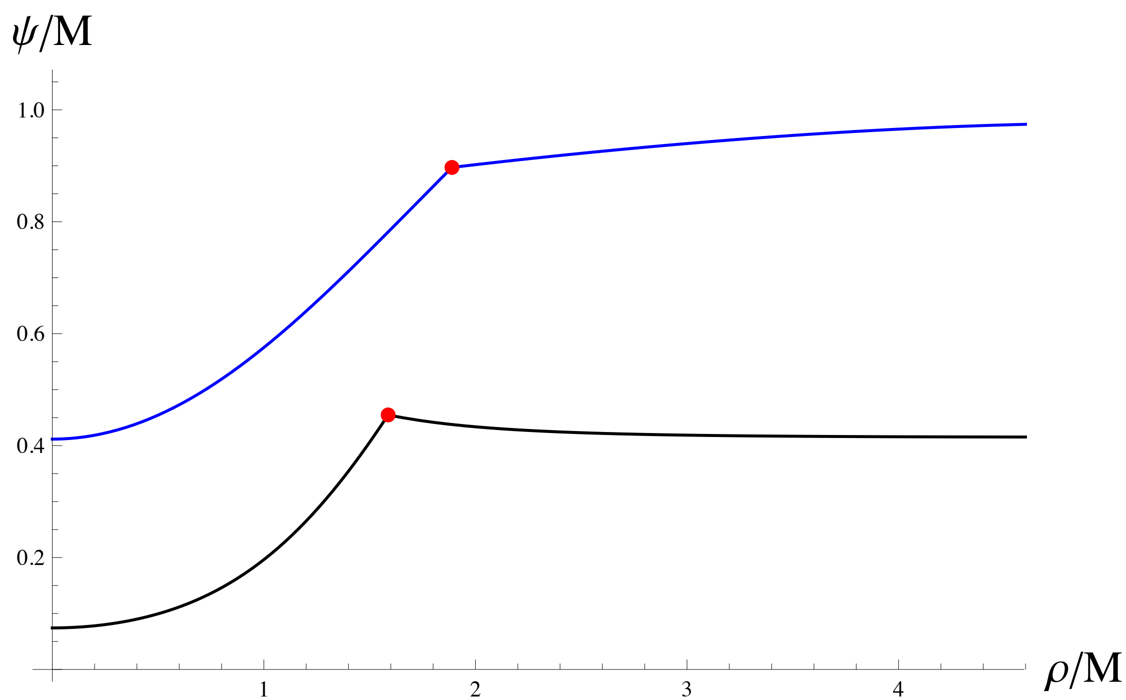
Case 2a: Decay from high dS



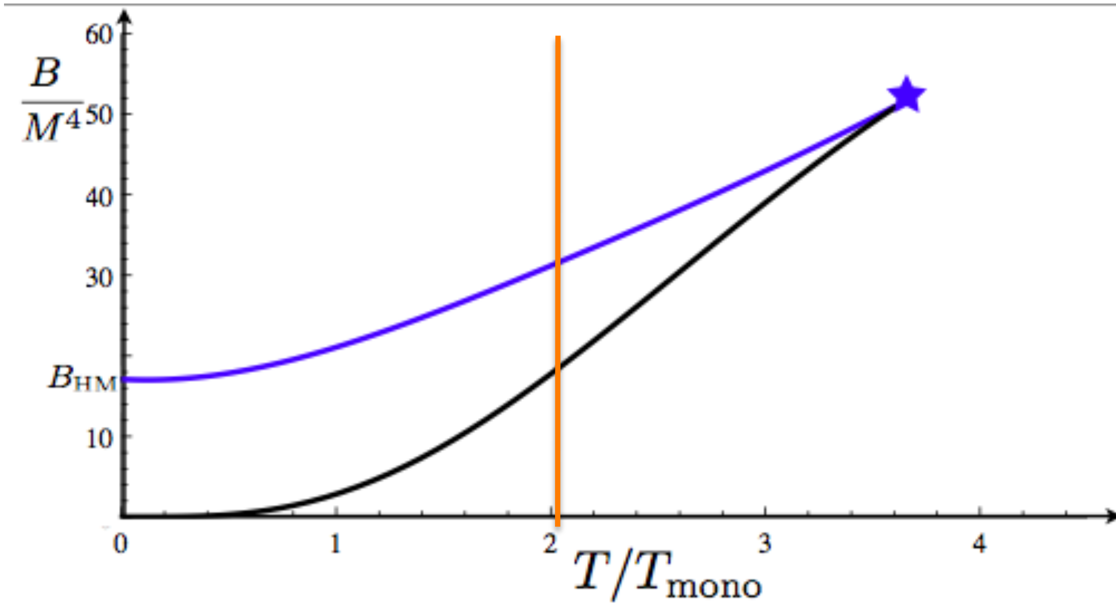


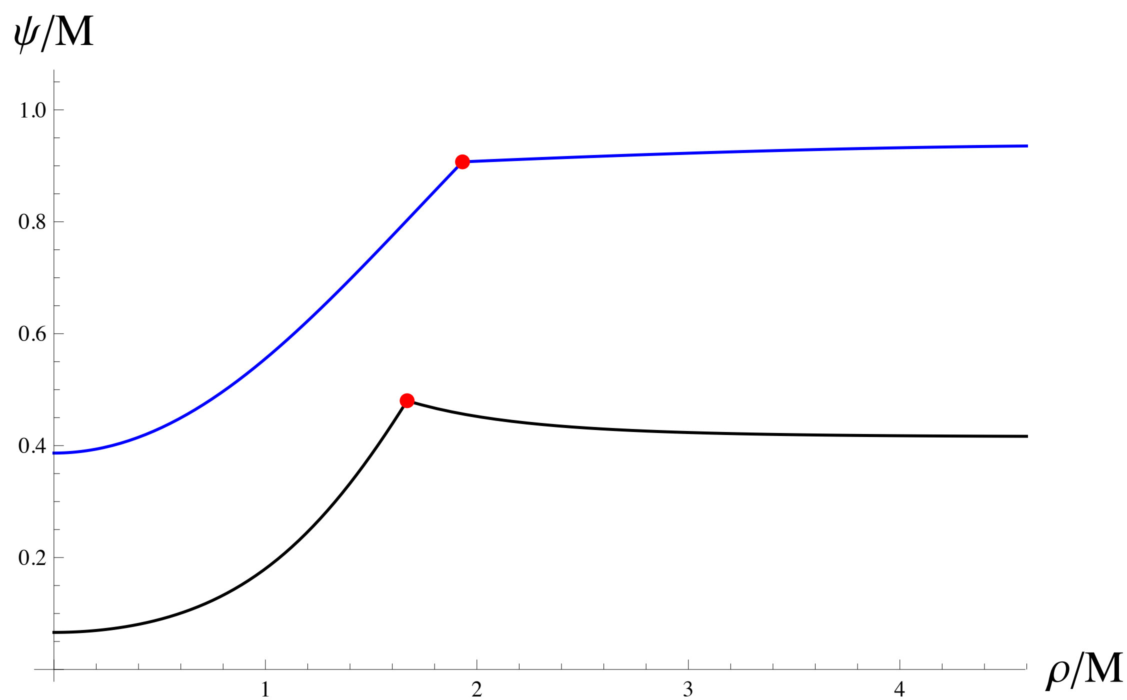
Case 2a:
Decay from
high dS



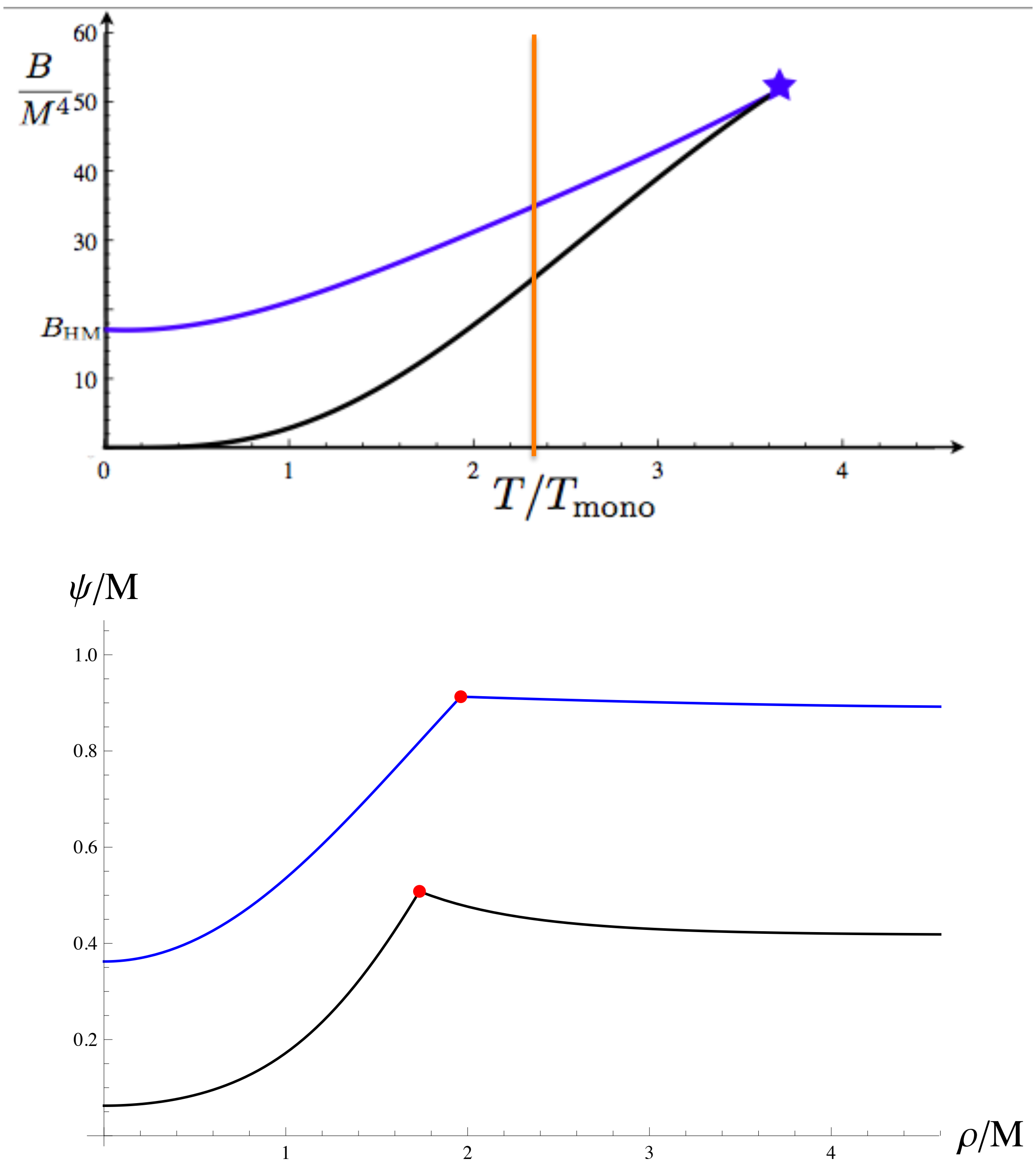


Case 2a:
Decay from
high dS

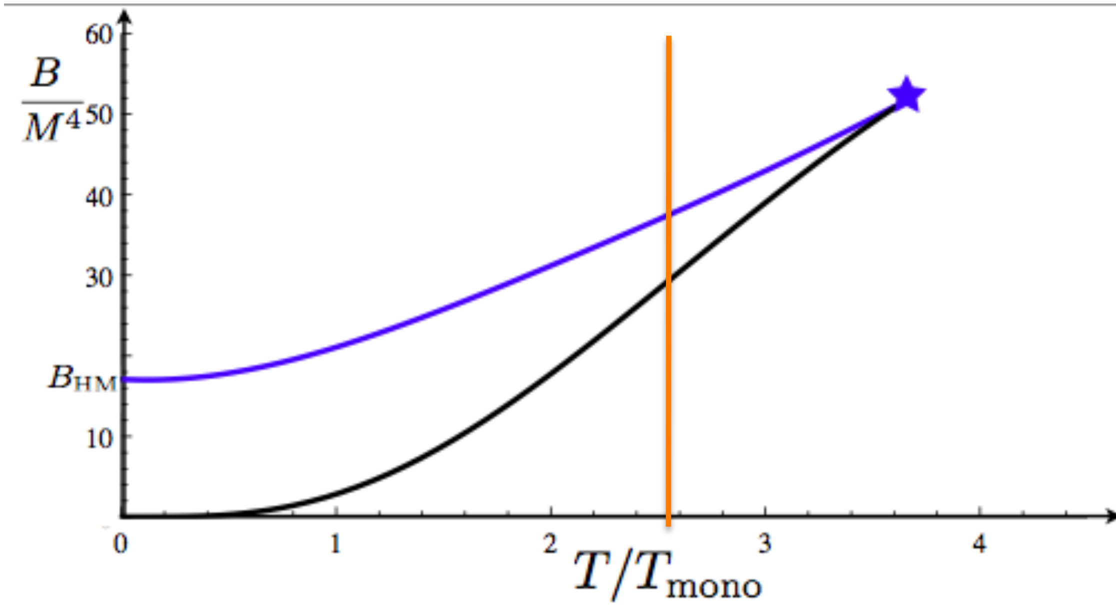


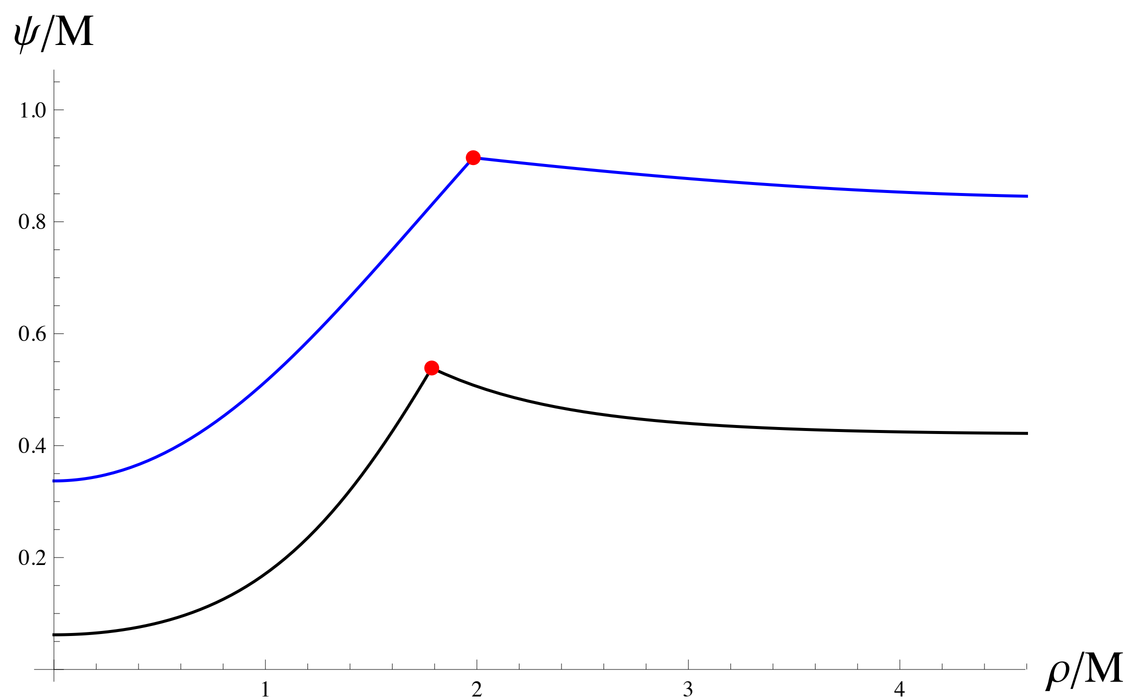


Case 2a: Decay from high dS

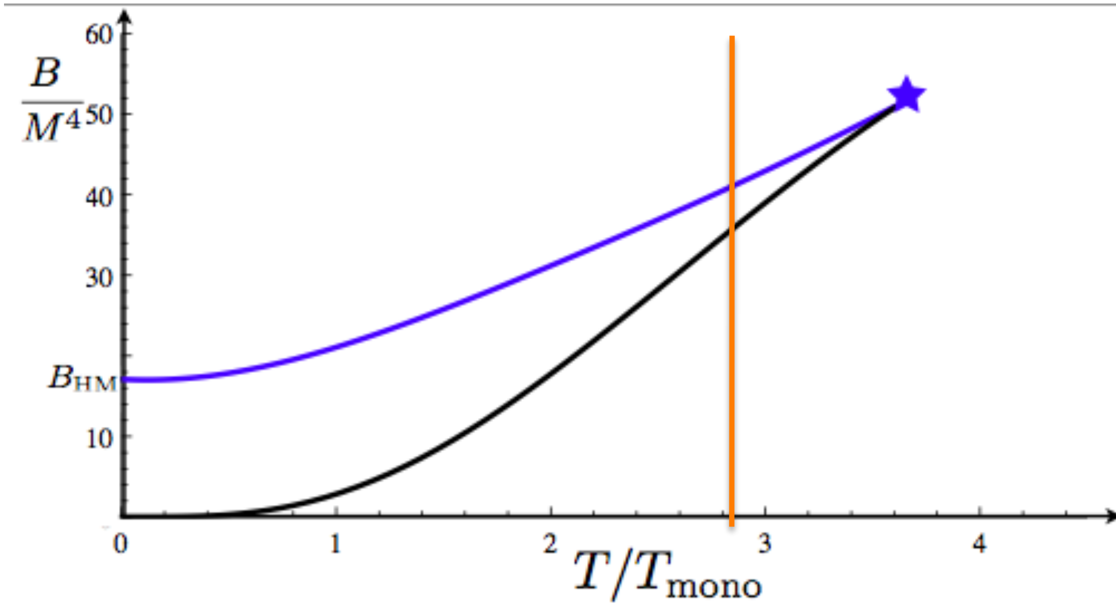


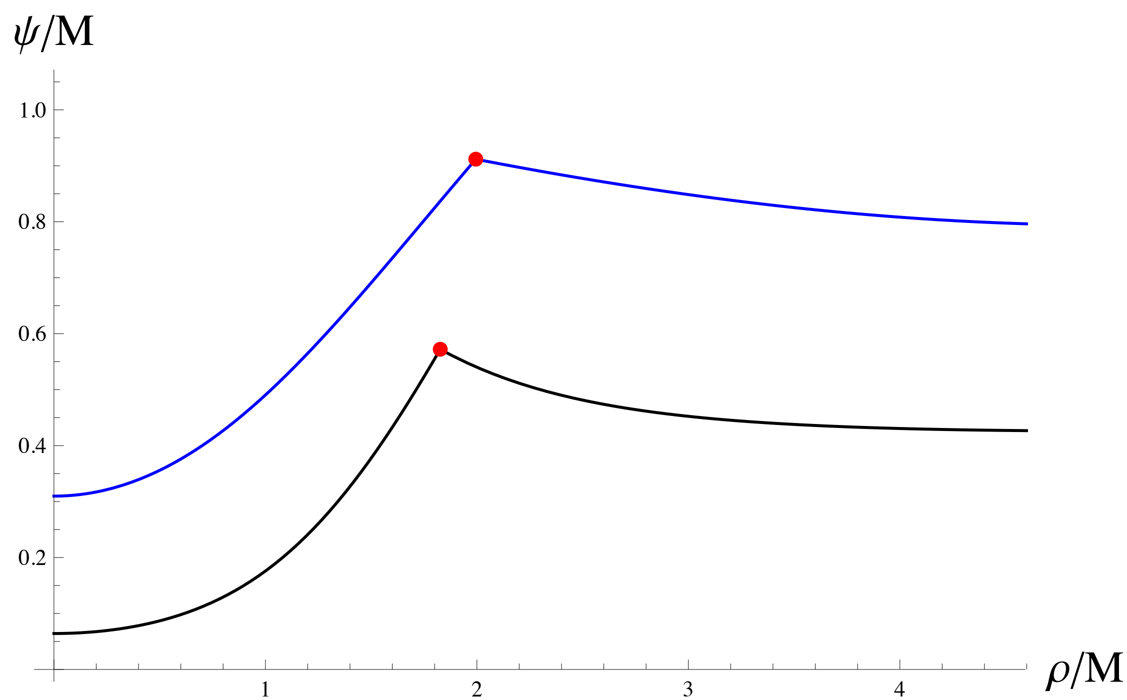
Case 2a:
Decay from
high dS



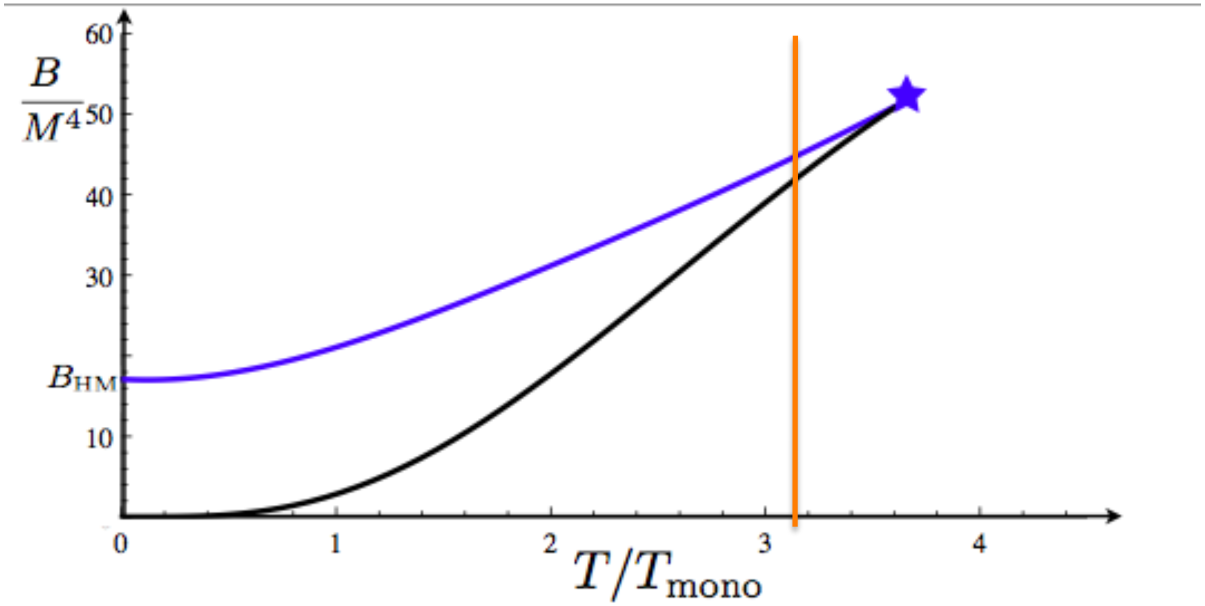


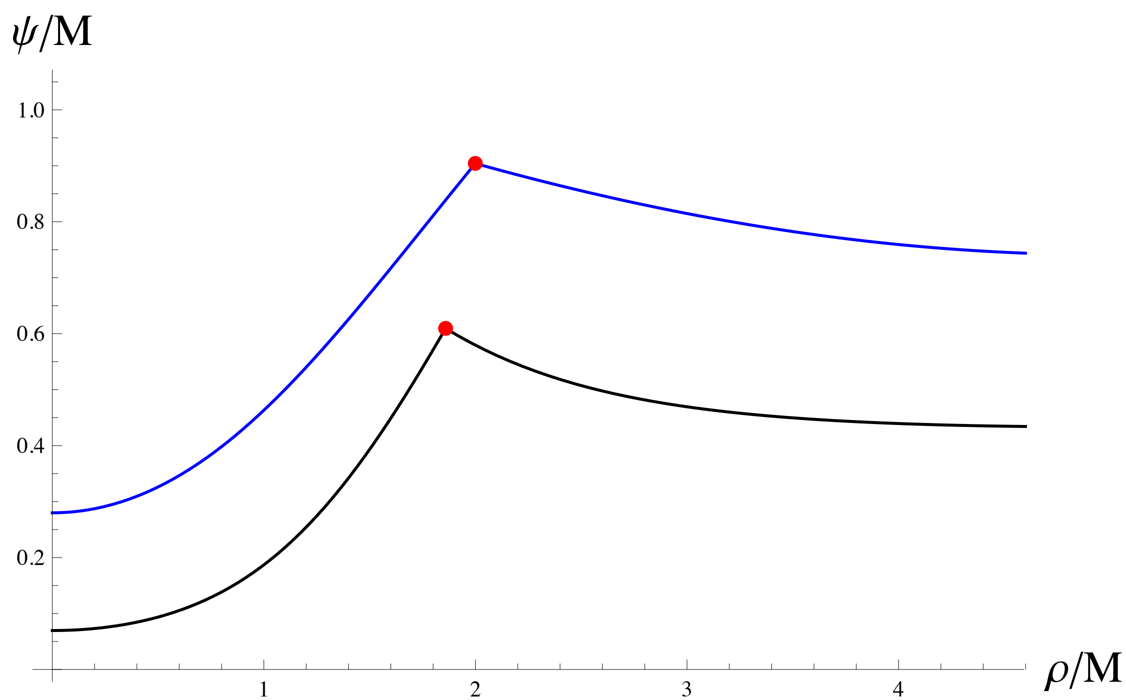
Case 2a:
Decay from
high dS



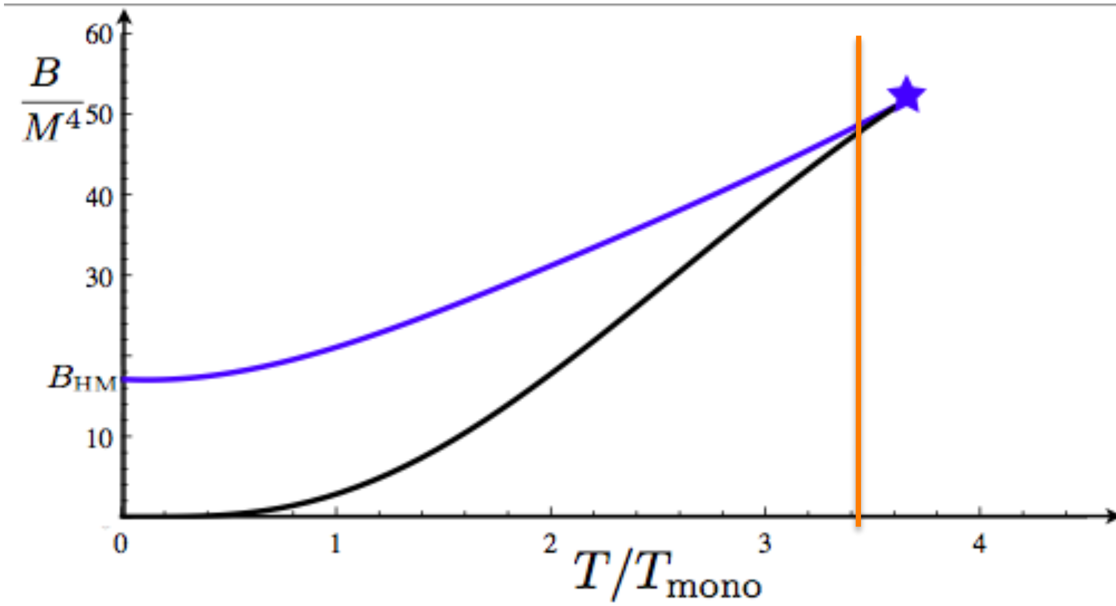


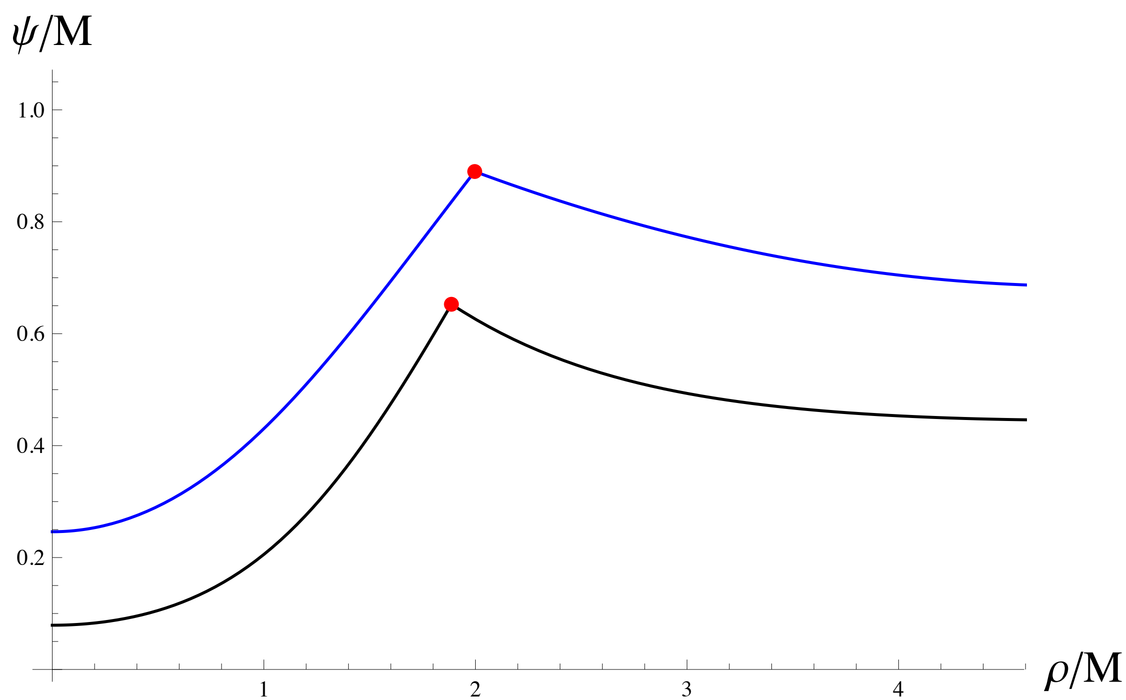
Case 2a:
Decay from
high dS



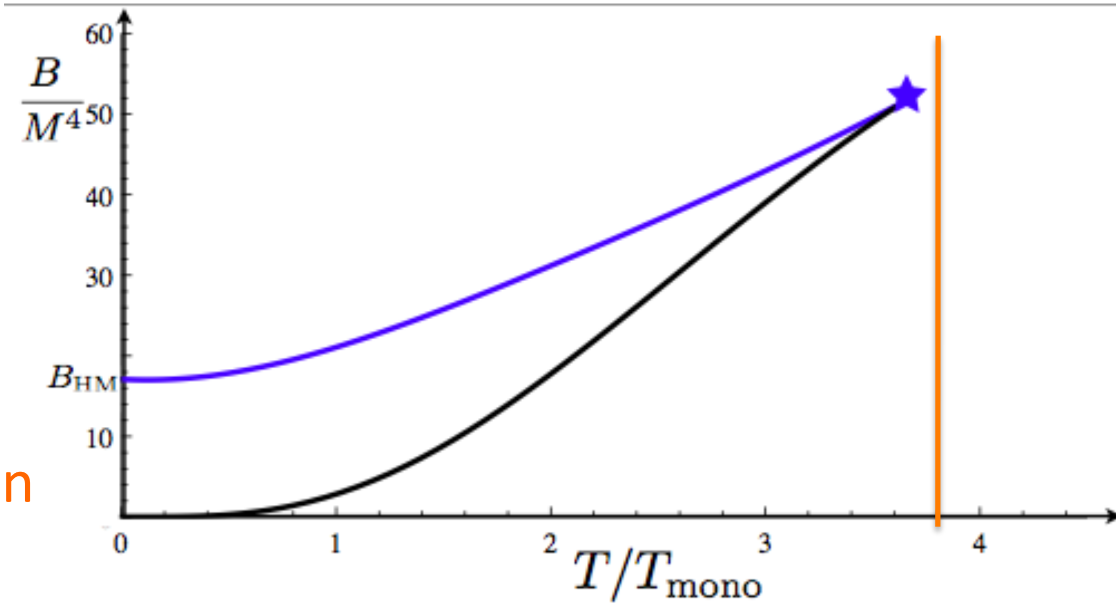


Case 2a:
Decay from
high dS

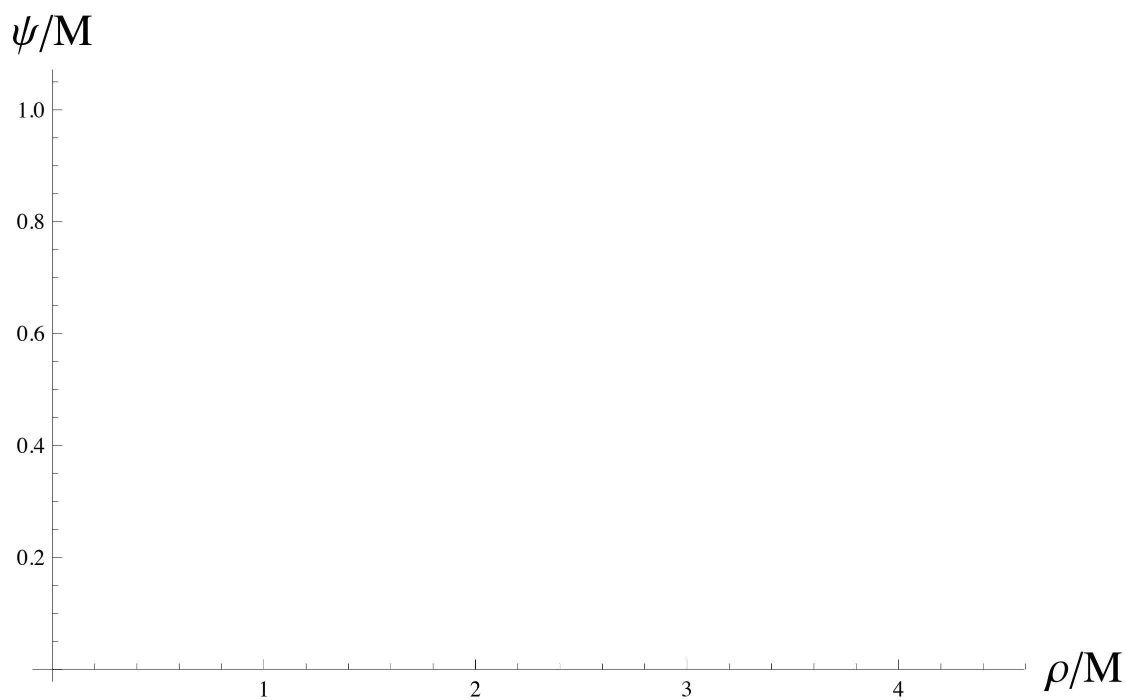




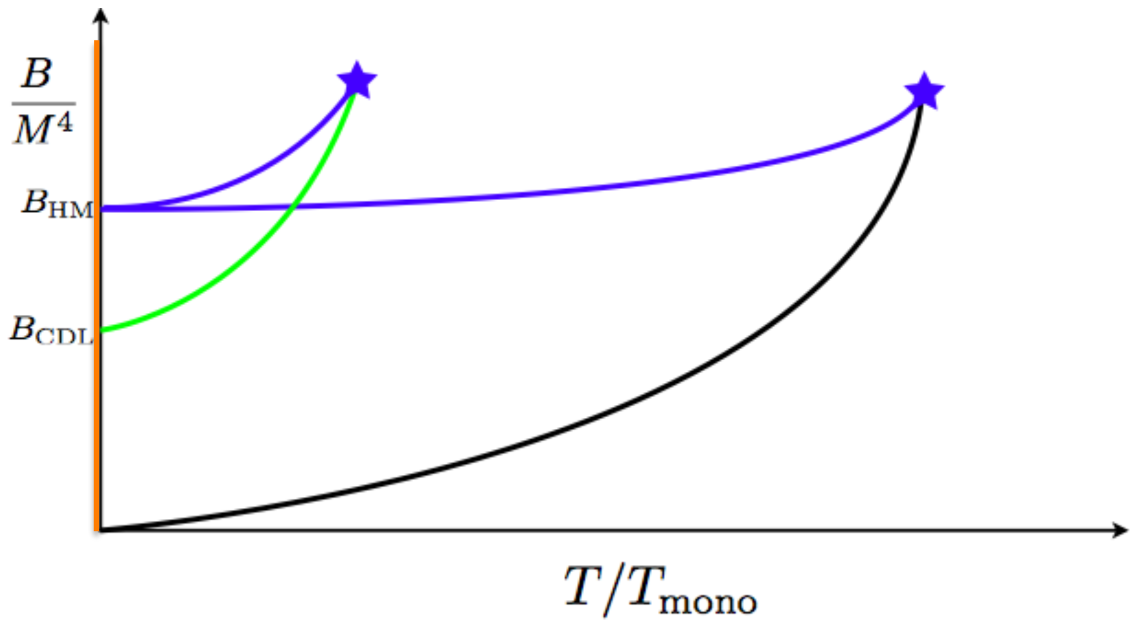
Case 2a:
Decay from
high dS

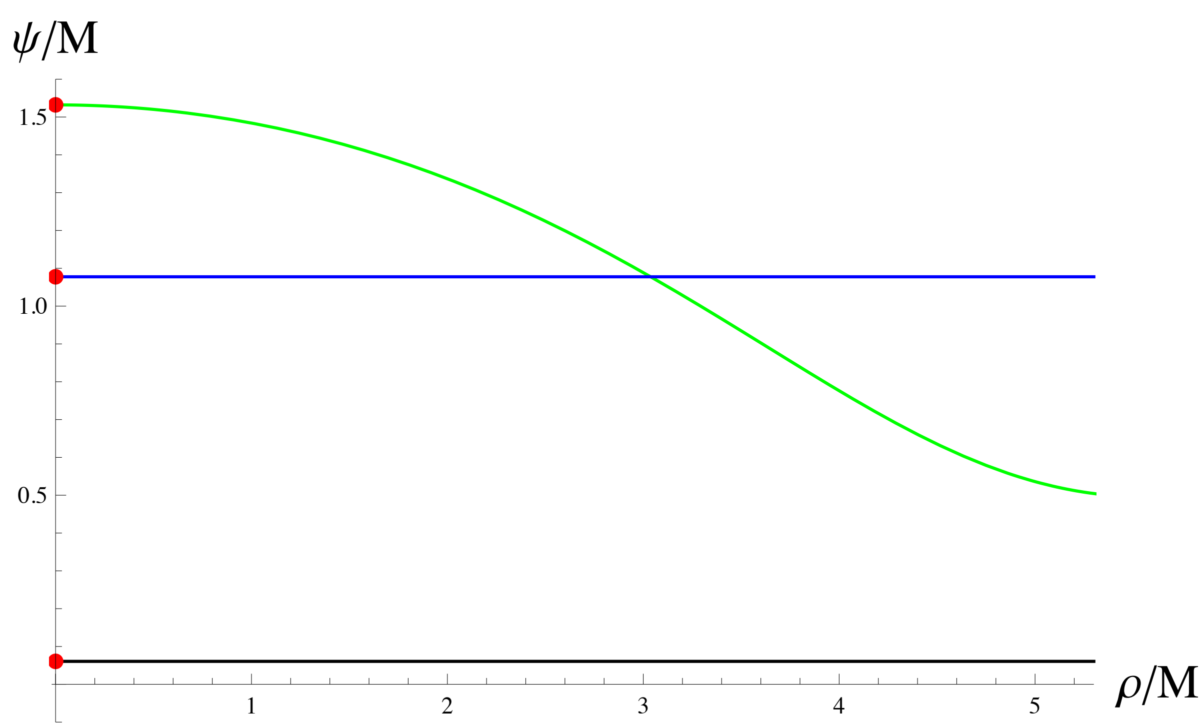


Instanton
Annihilation

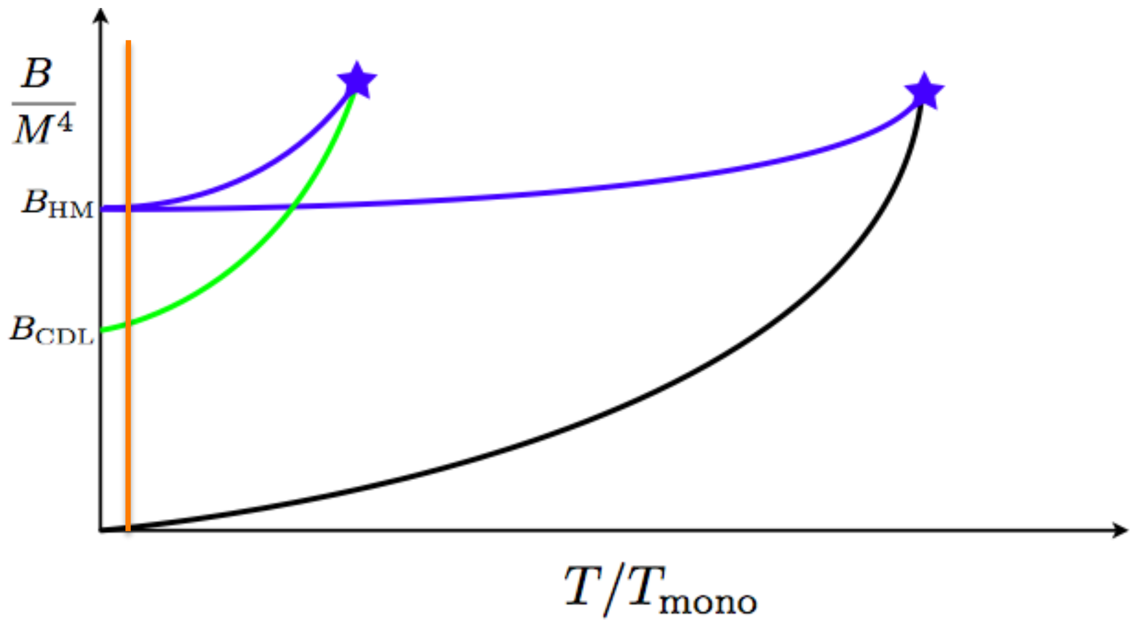


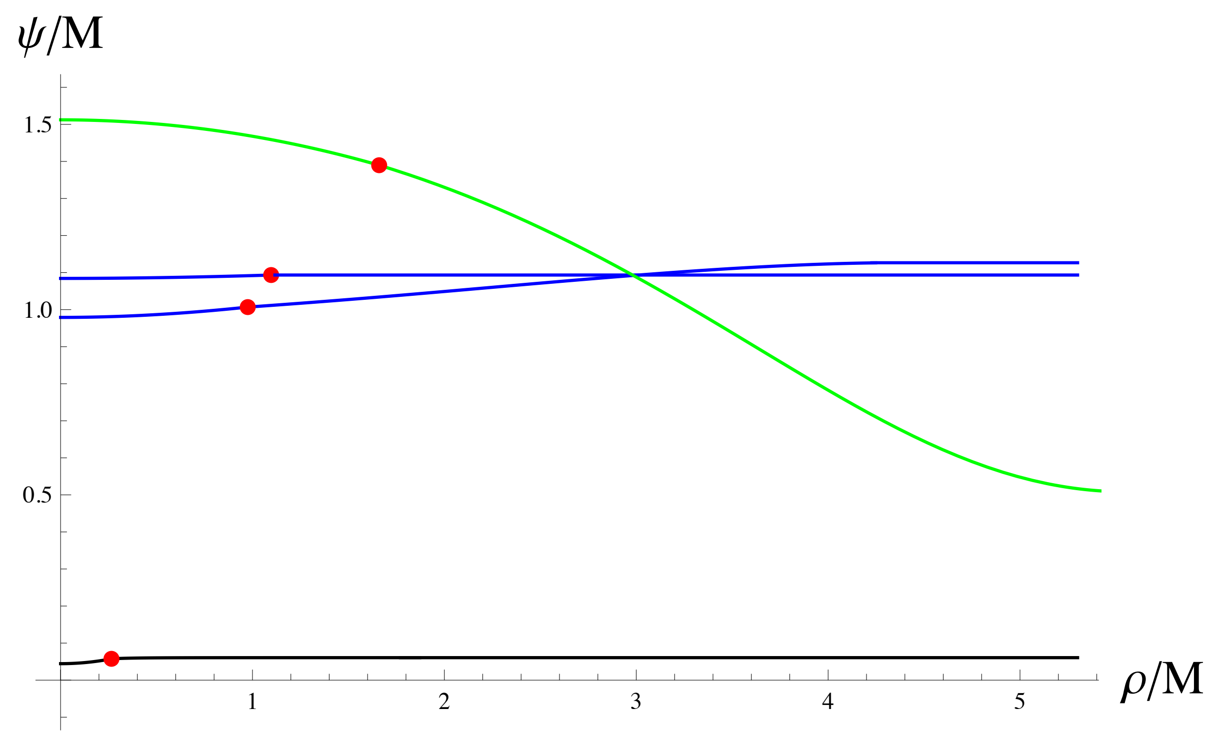
Case 2b:
Decay from
low dS



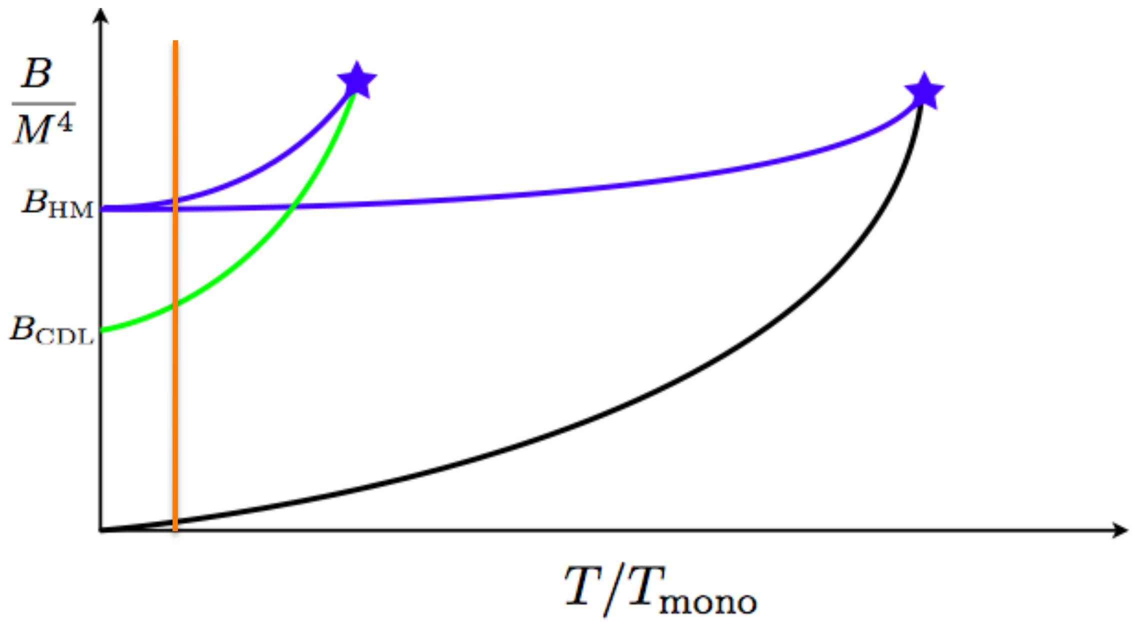


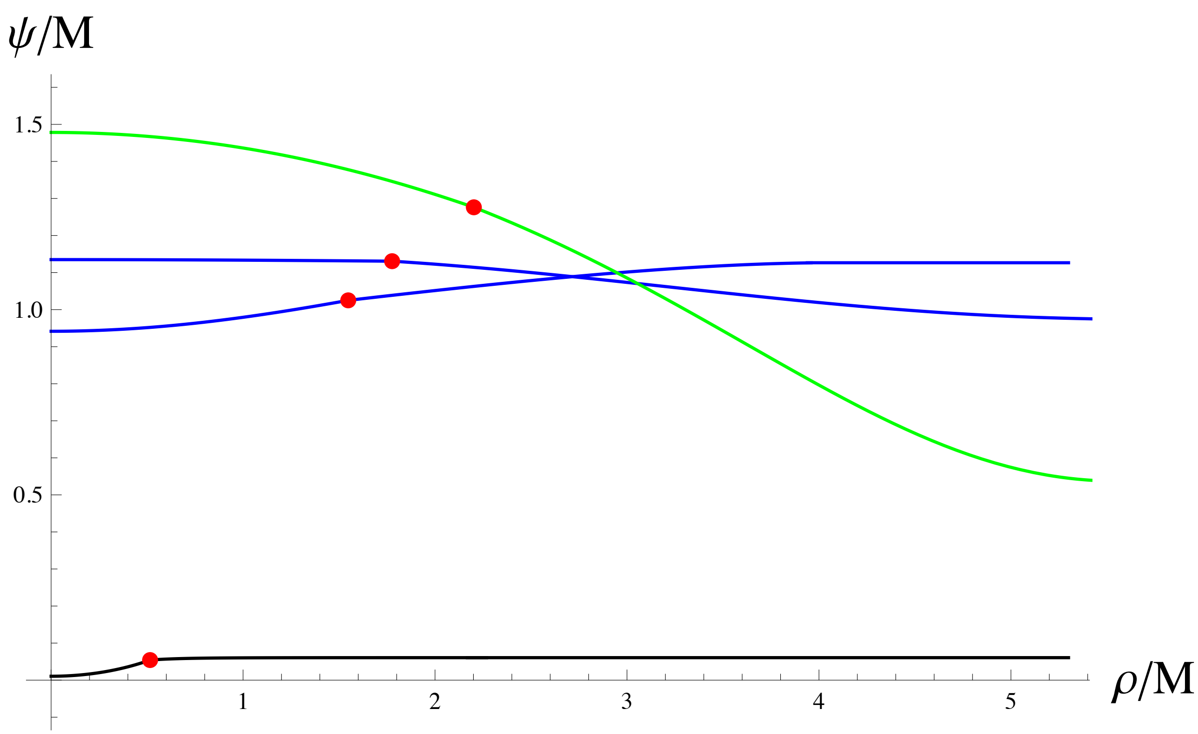
Case 2b:
Decay from
low dS



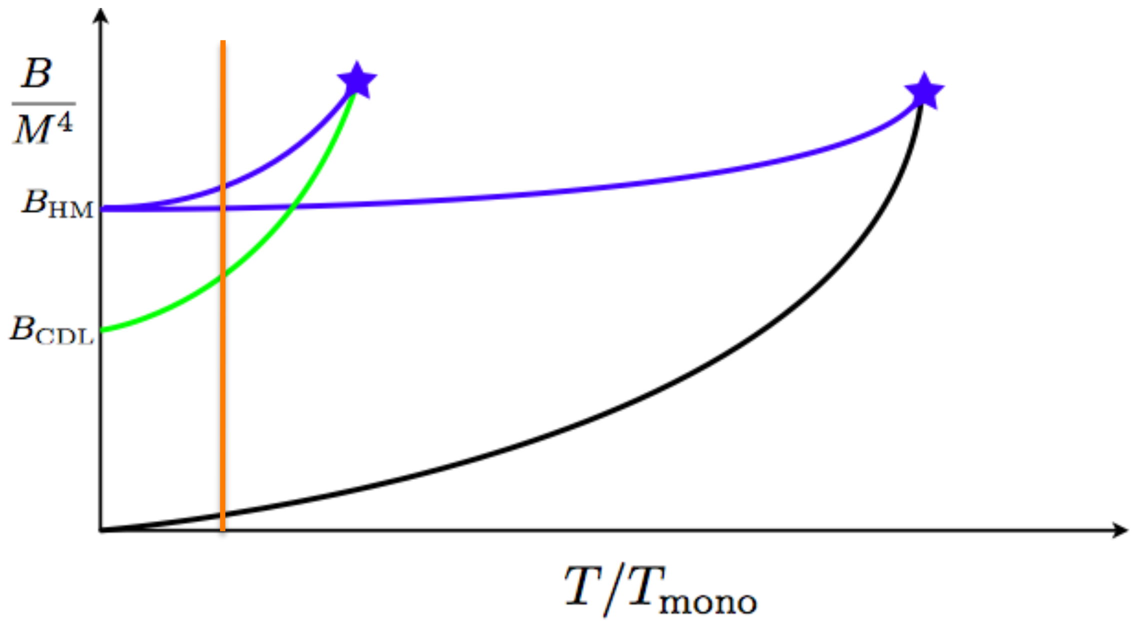


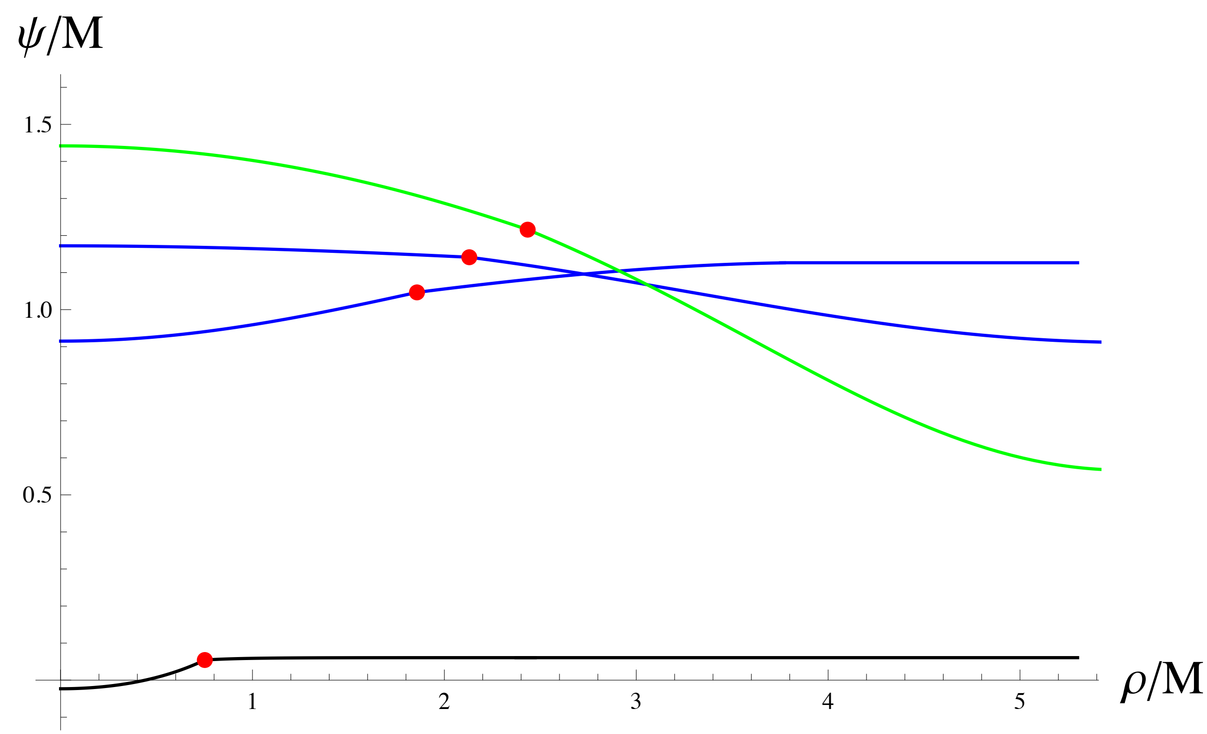
Case 2b:
Decay from
low dS



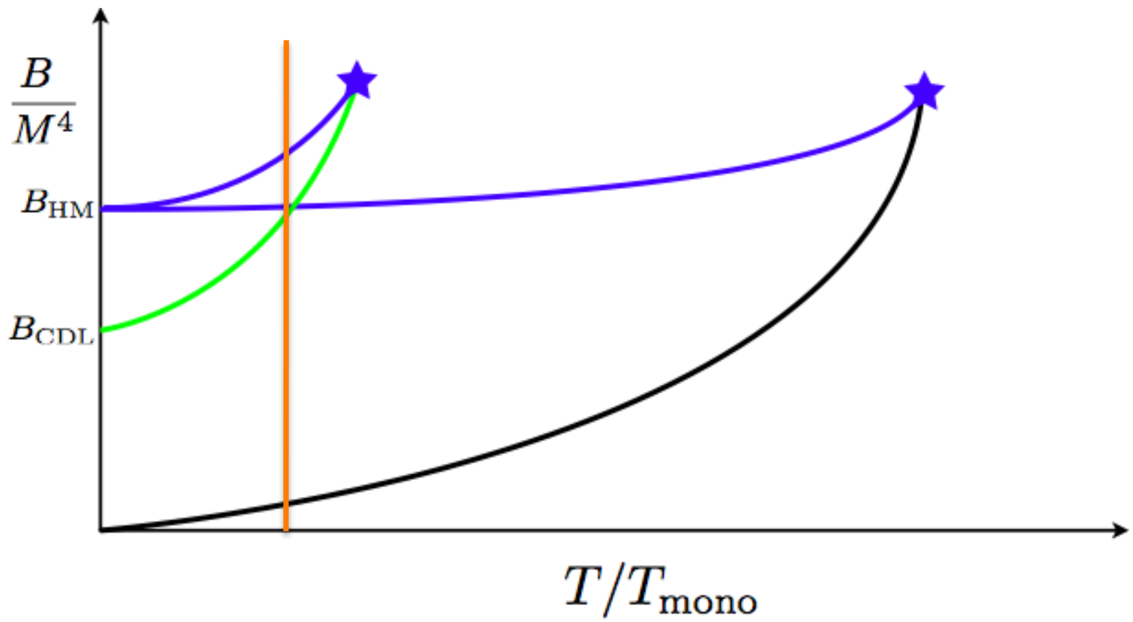


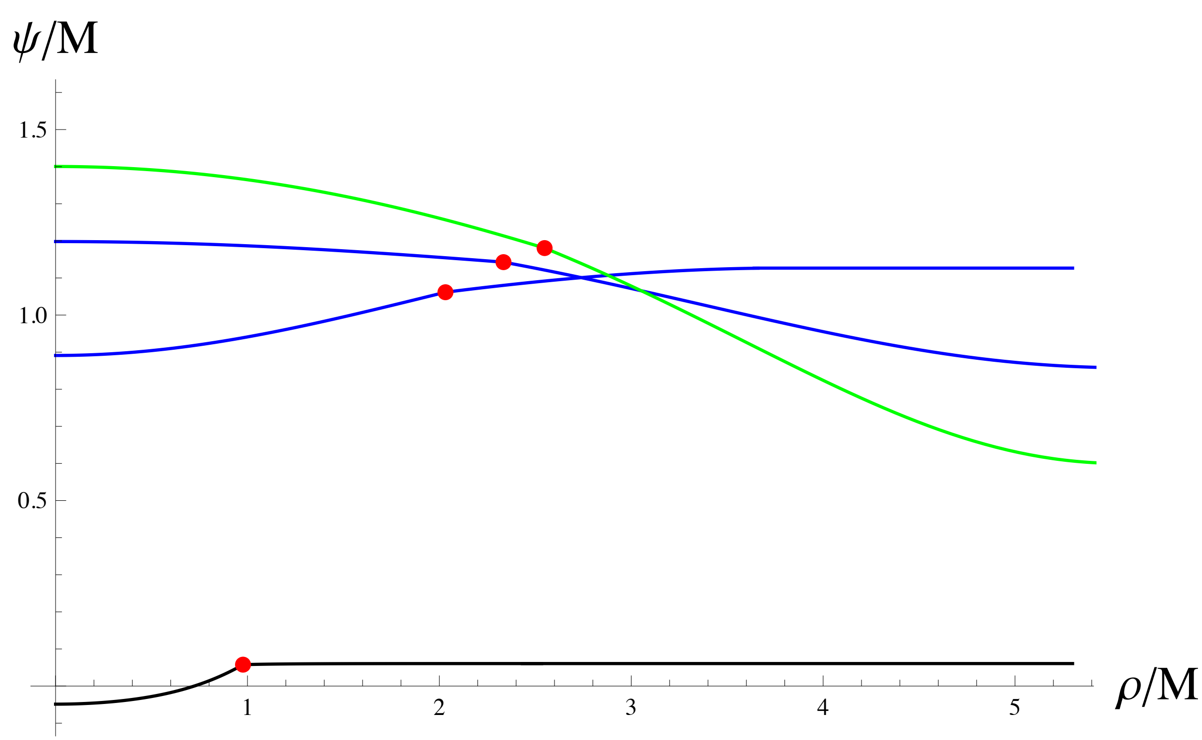
Case 2b: Decay from low dS



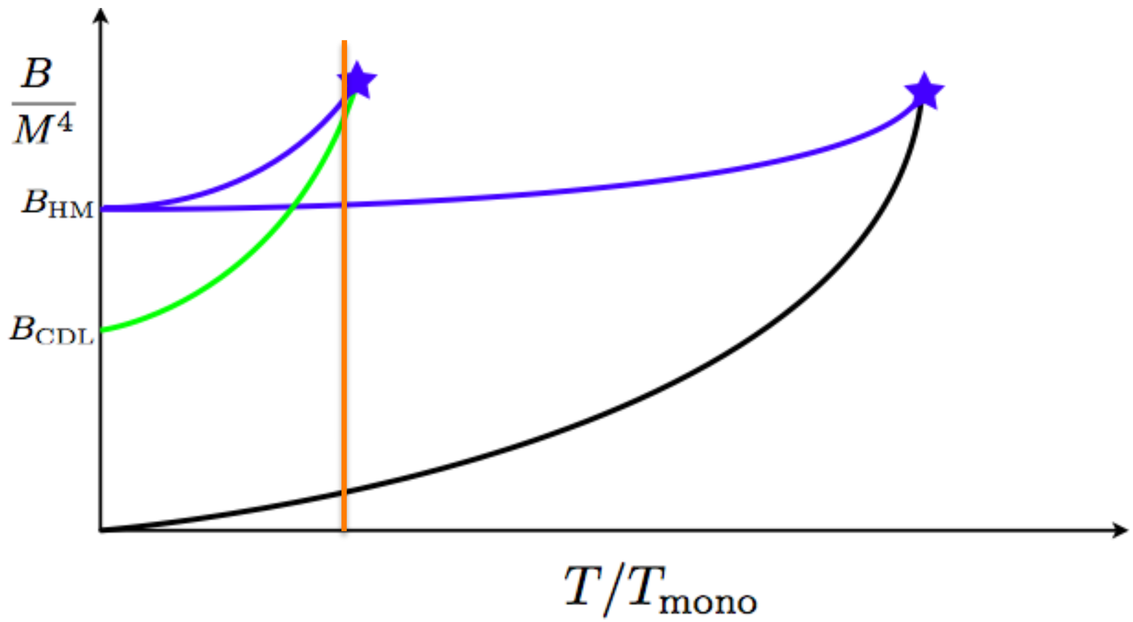


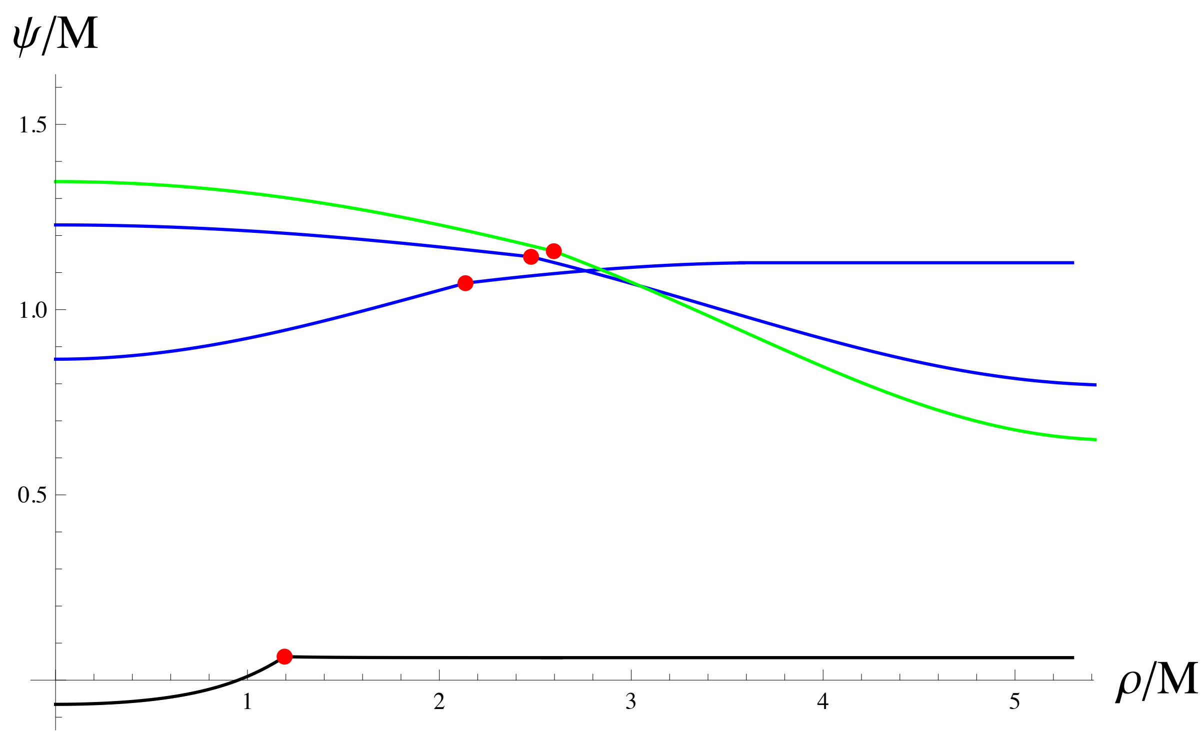
Case 2b:
Decay from
low dS



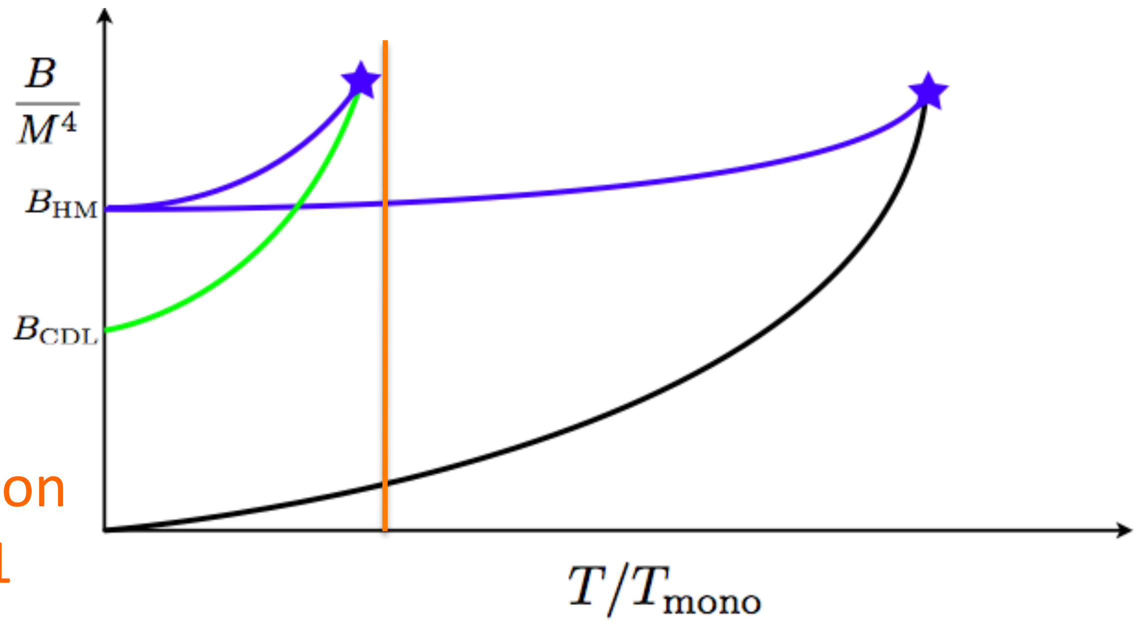


Case 2b:
Decay from
low dS

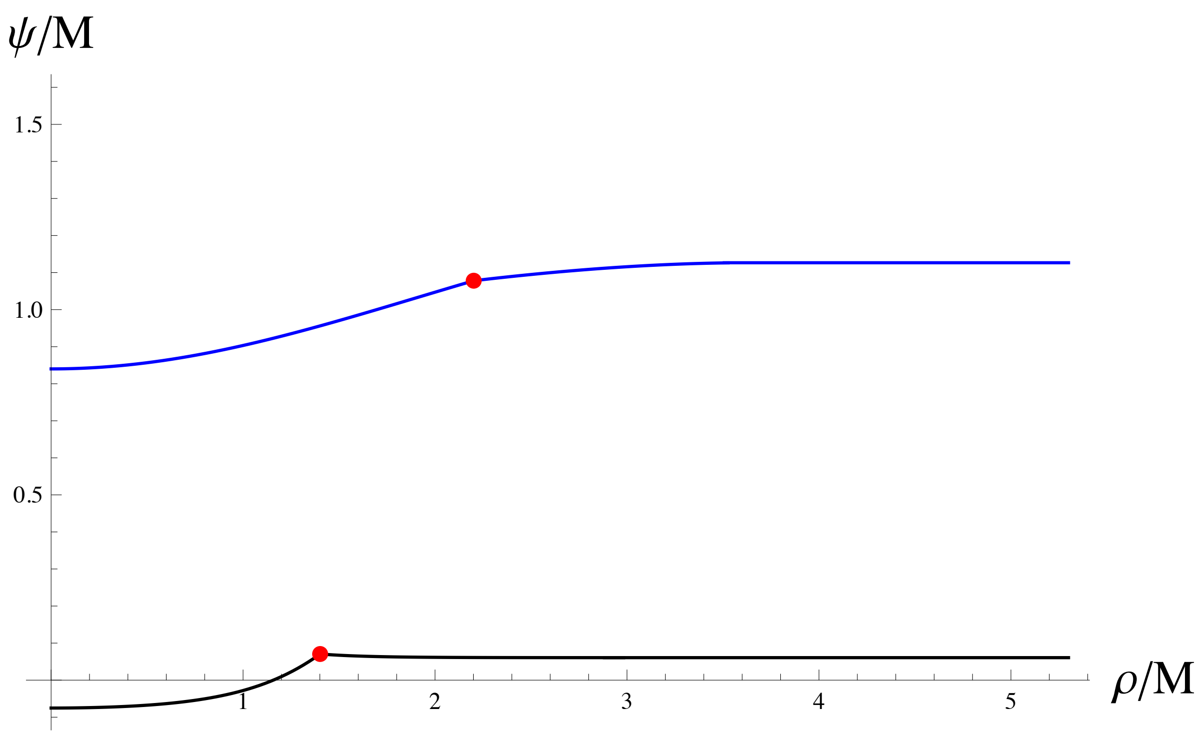




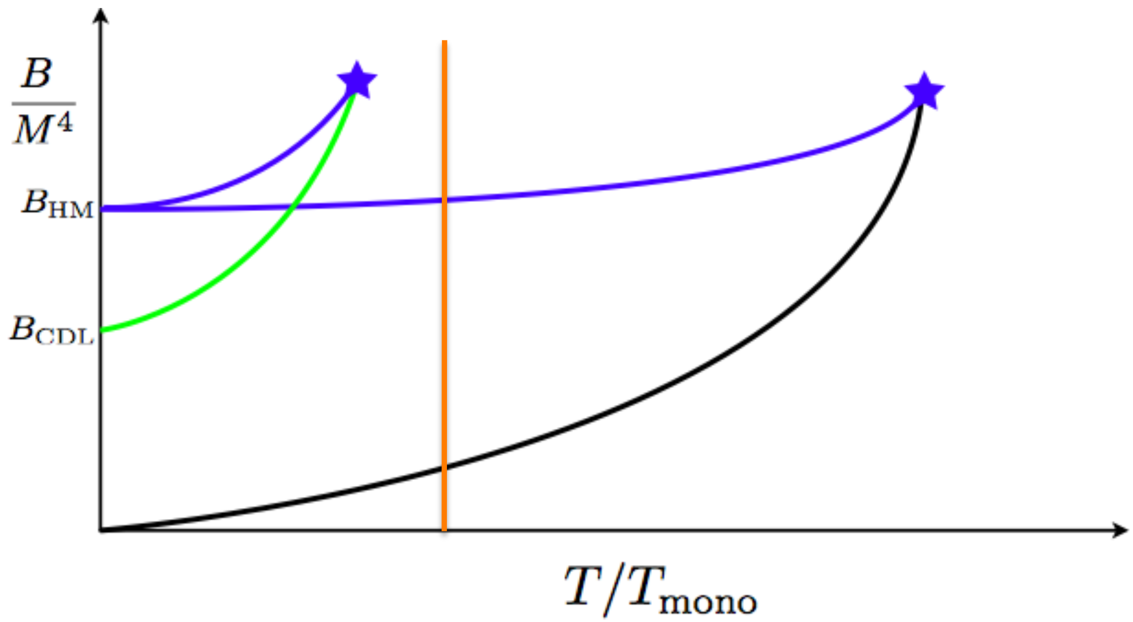
Case 2b:
Decay from
low dS

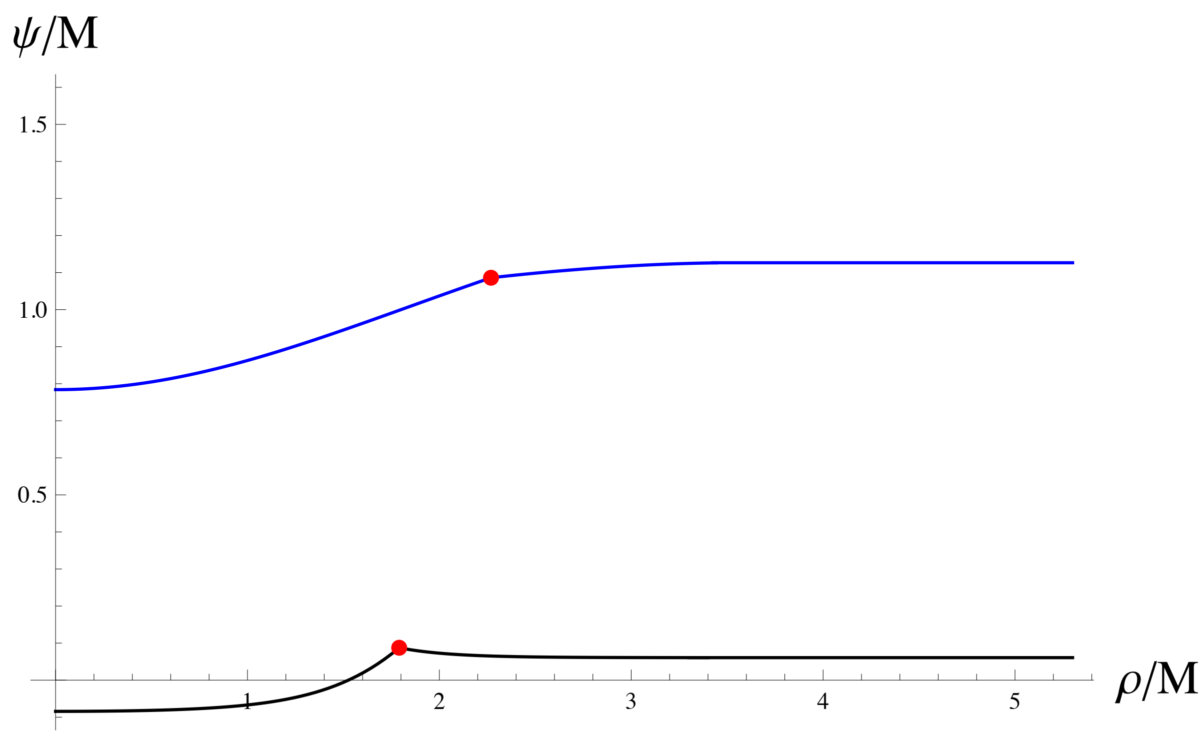


Instanton
Annihilation
Number 1

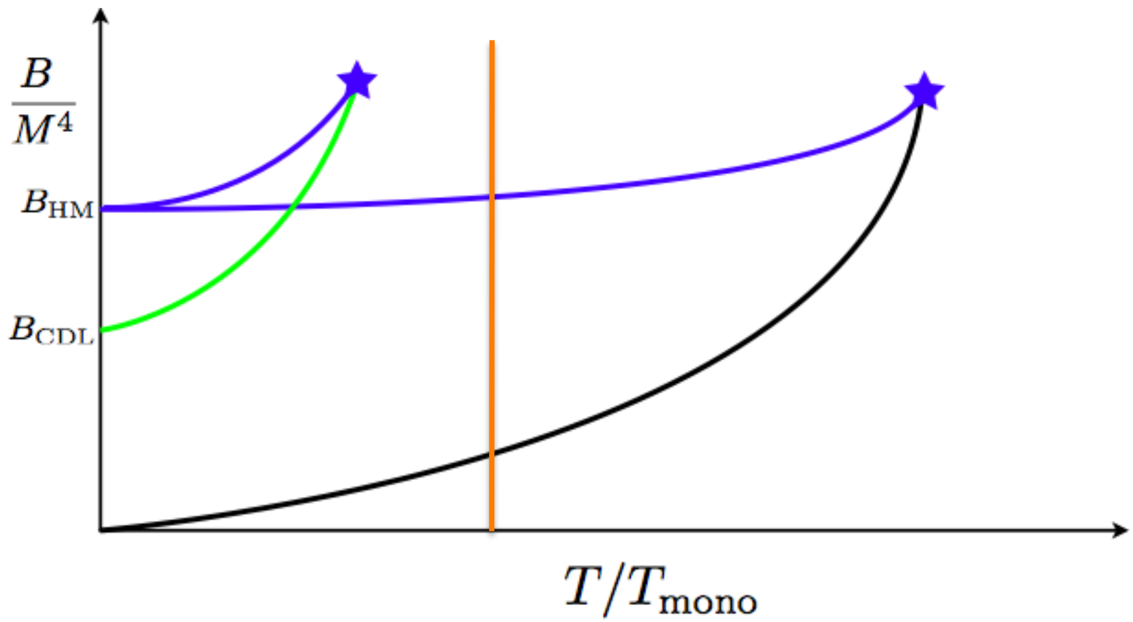


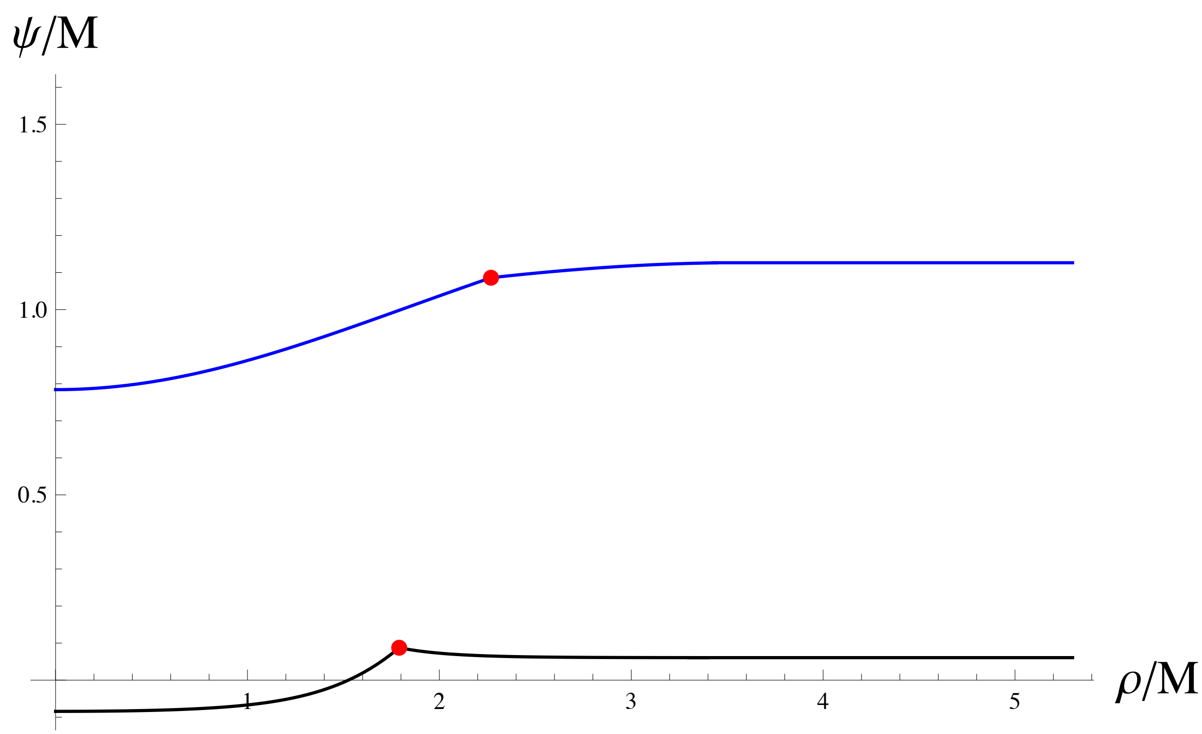
Case 2b:
Decay from
low dS



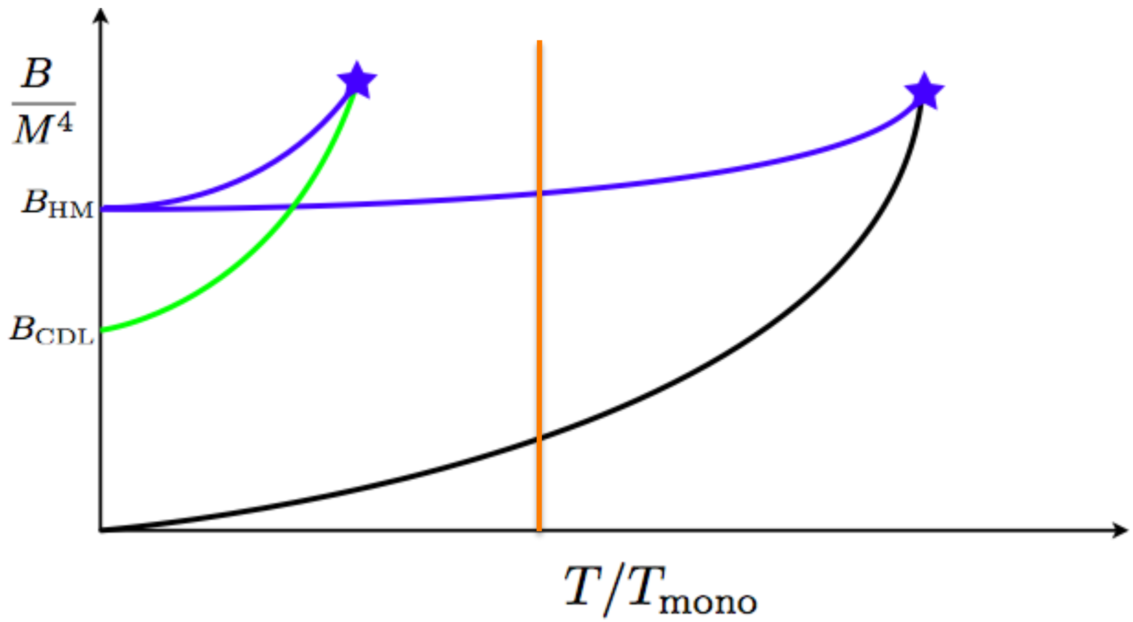


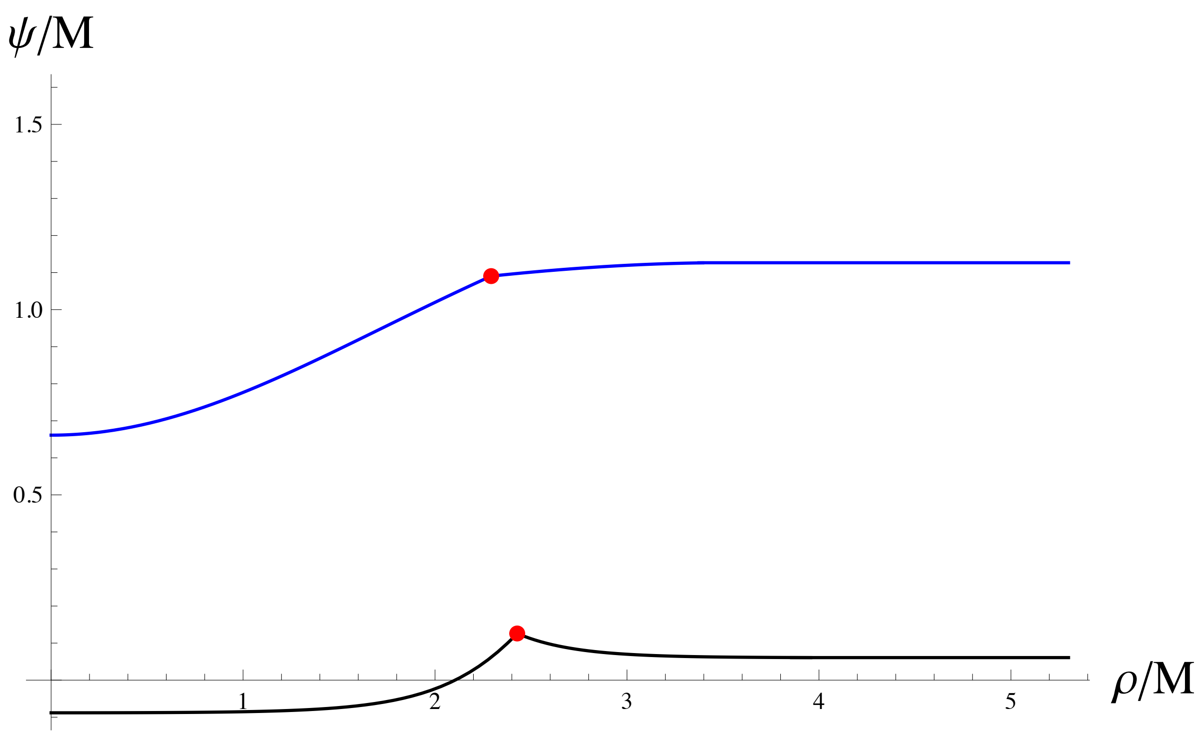
Case 2b:
Decay from
low dS



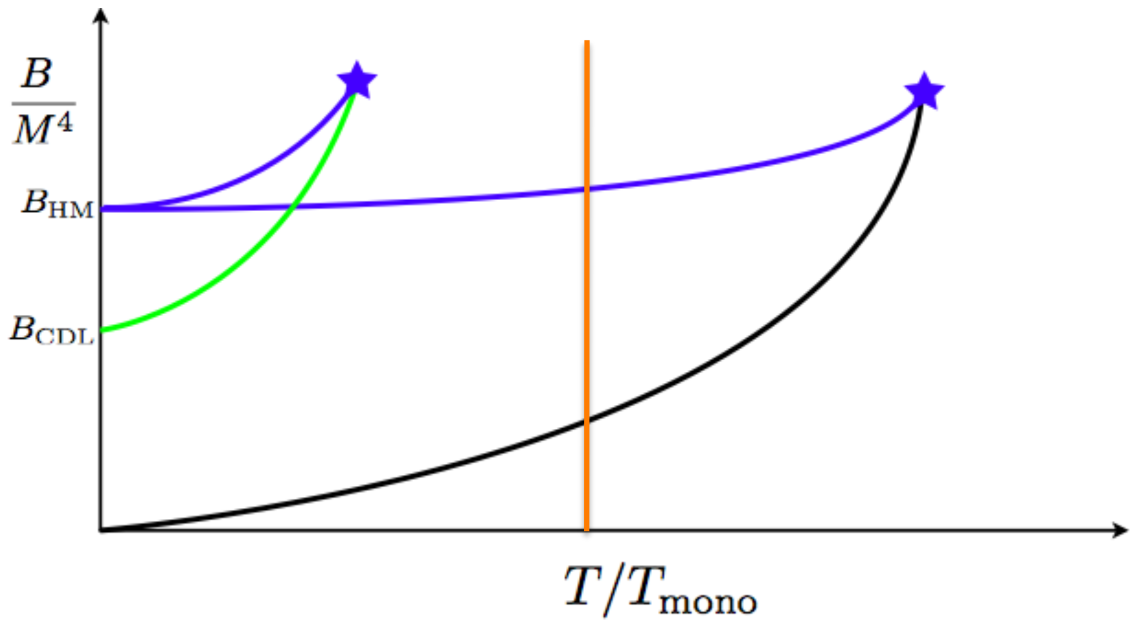


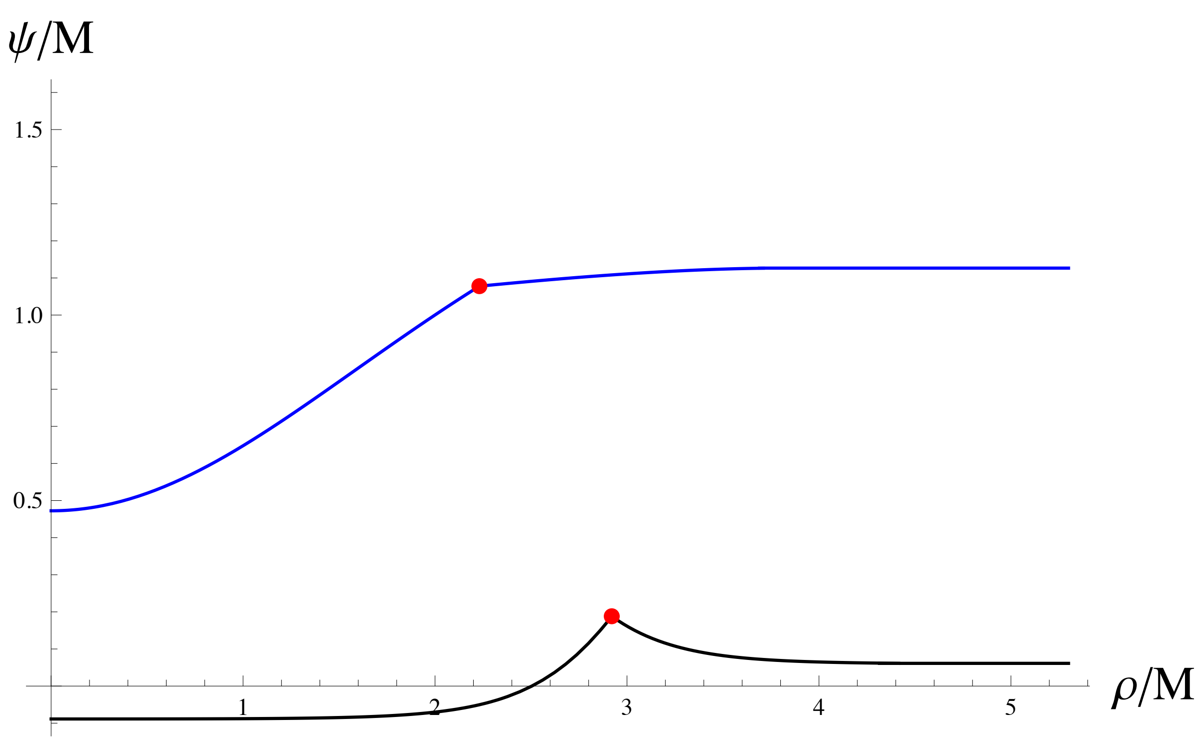
Case 2b:
Decay from
low dS



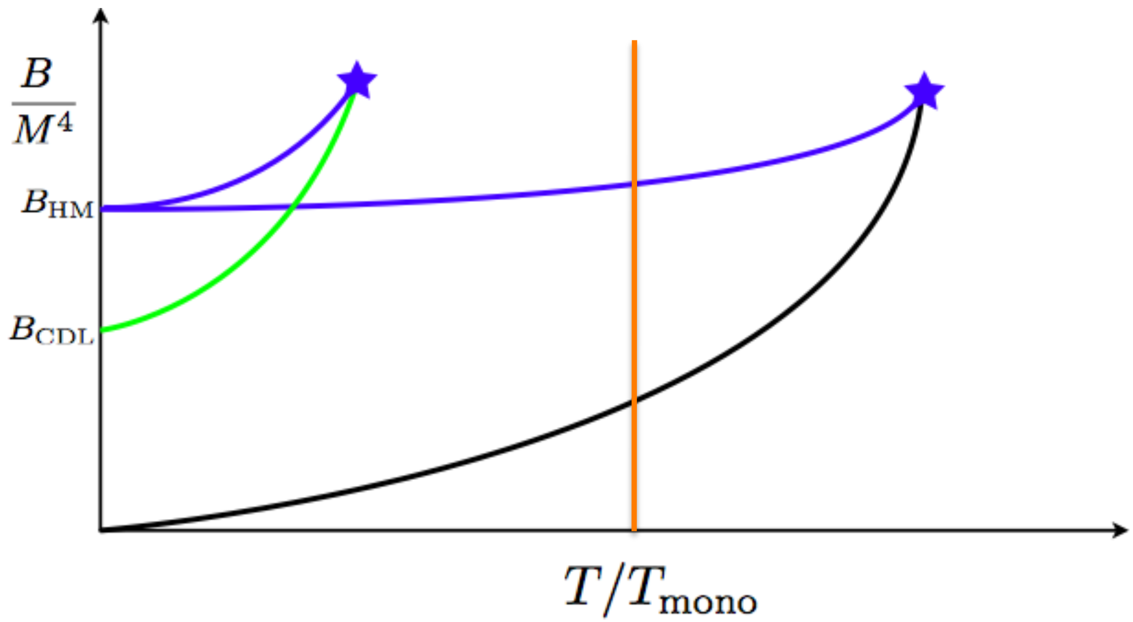


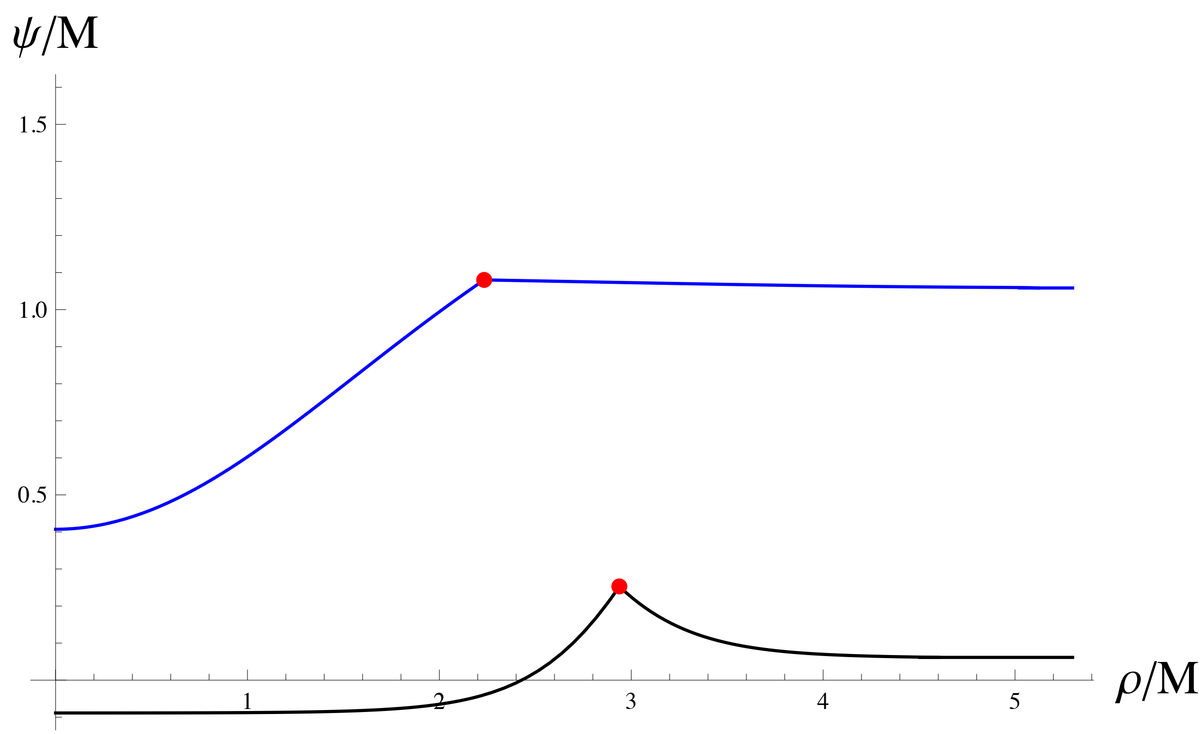
Case 2b:
Decay from
low dS



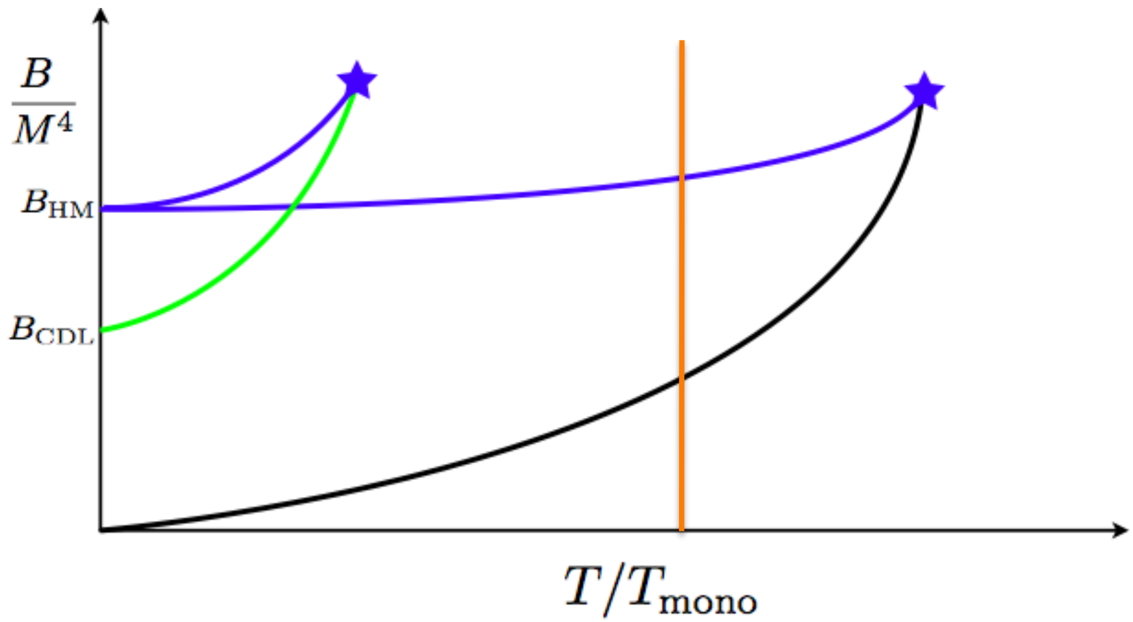


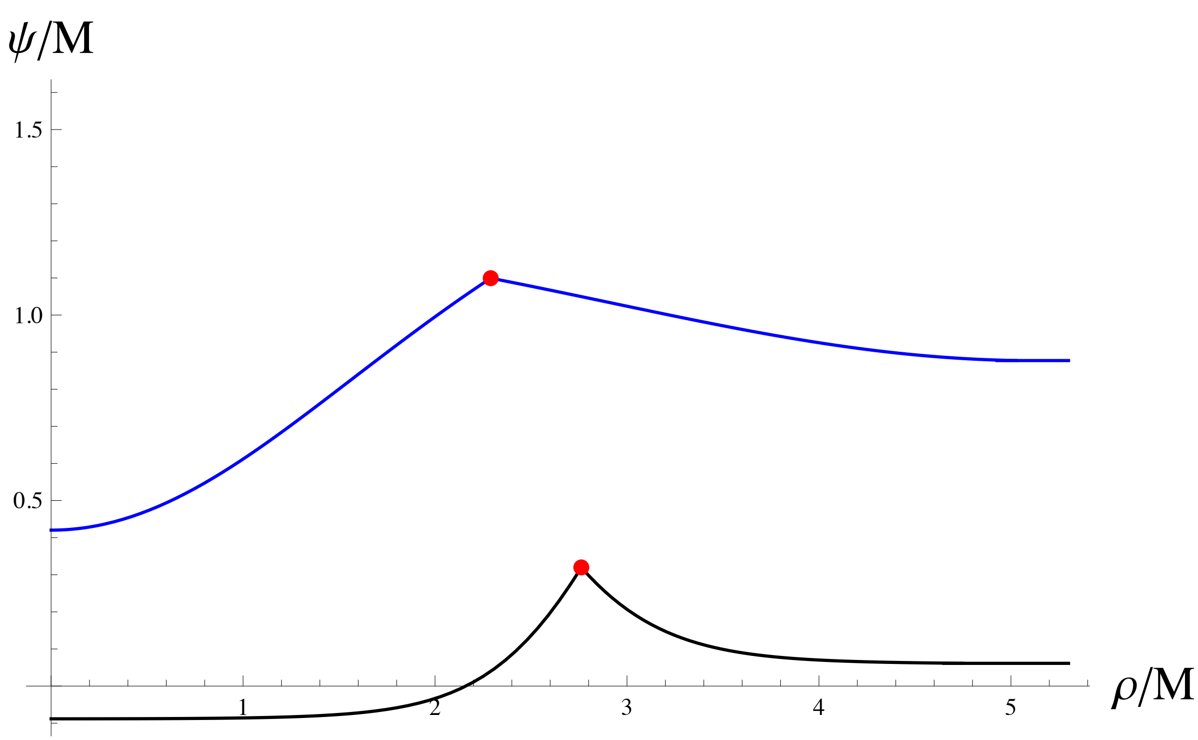
Case 2b:
Decay from
low dS



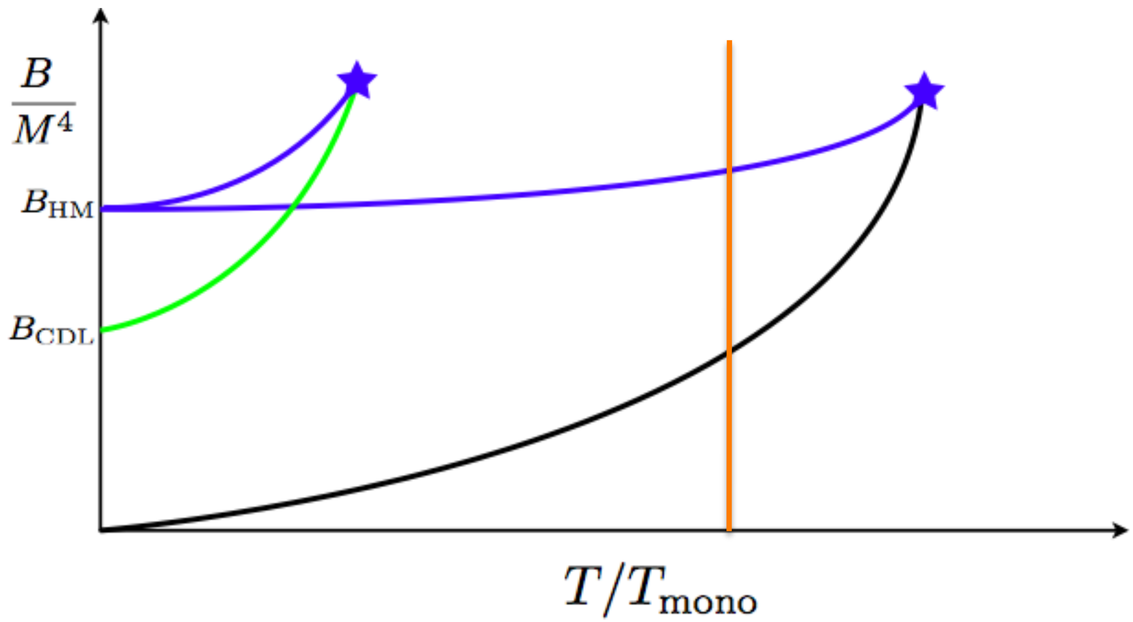


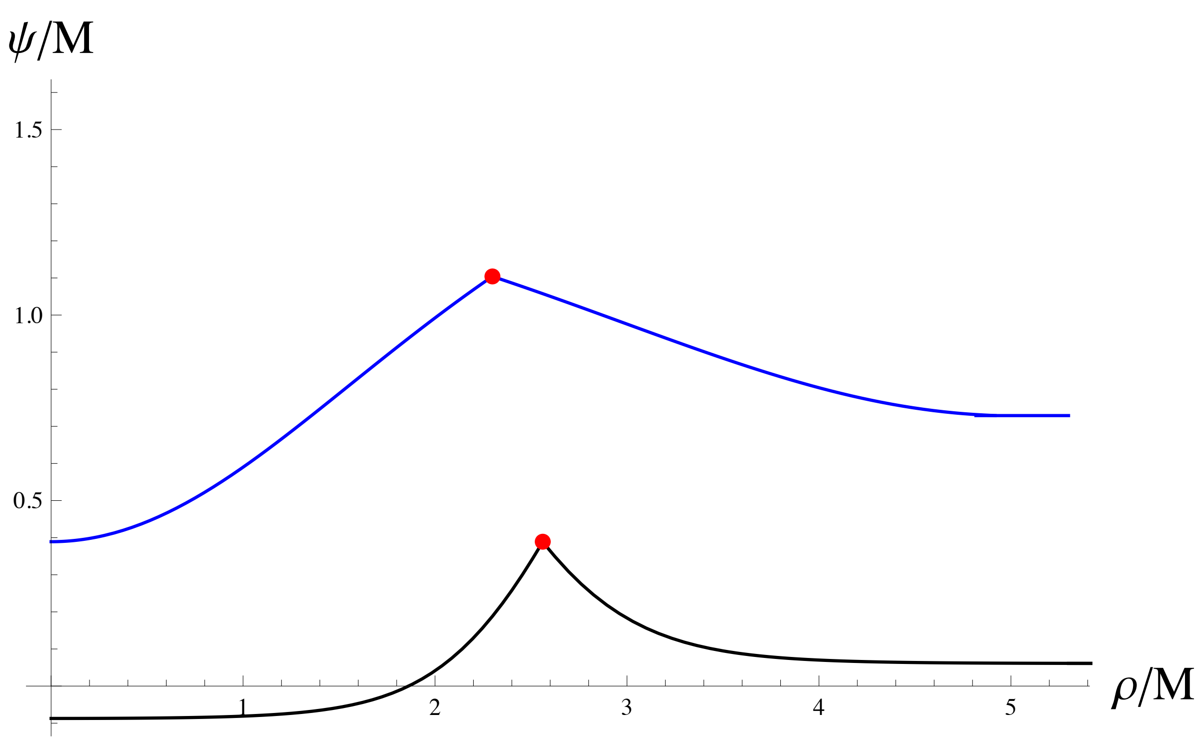
Case 2b:
Decay from
low dS



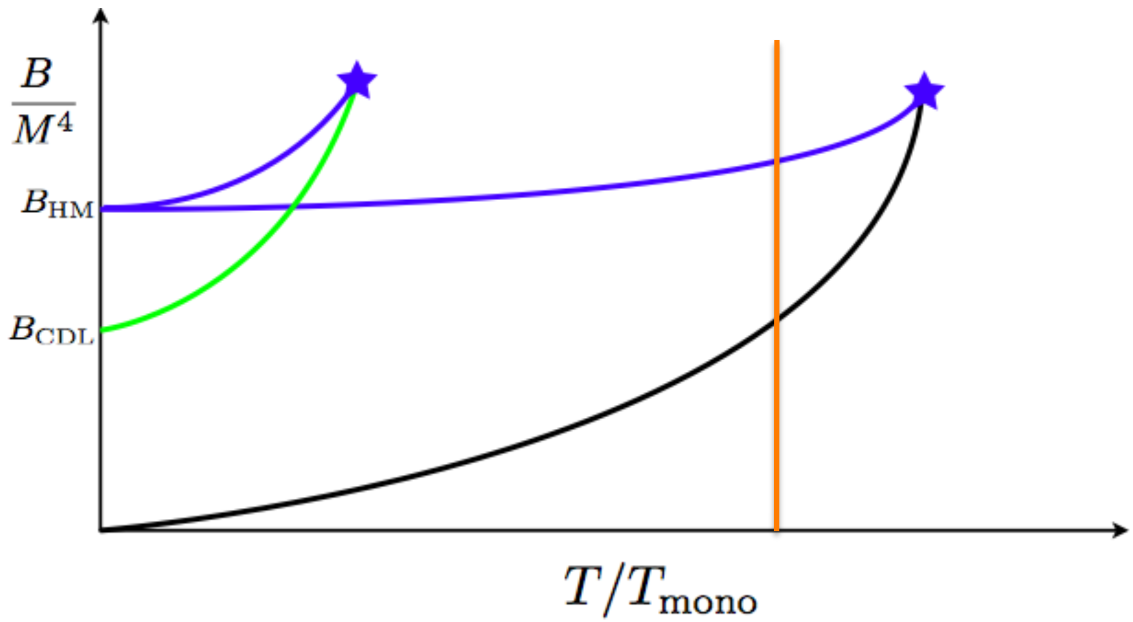


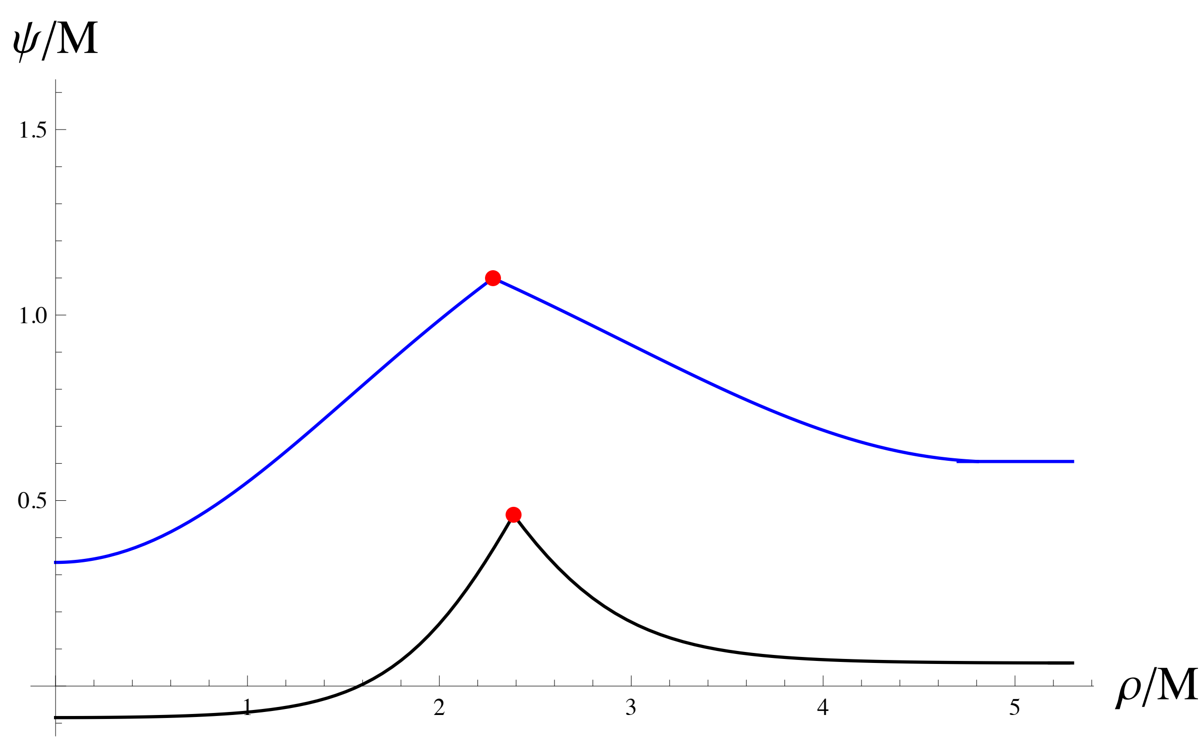
Case 2b:
Decay from
low dS



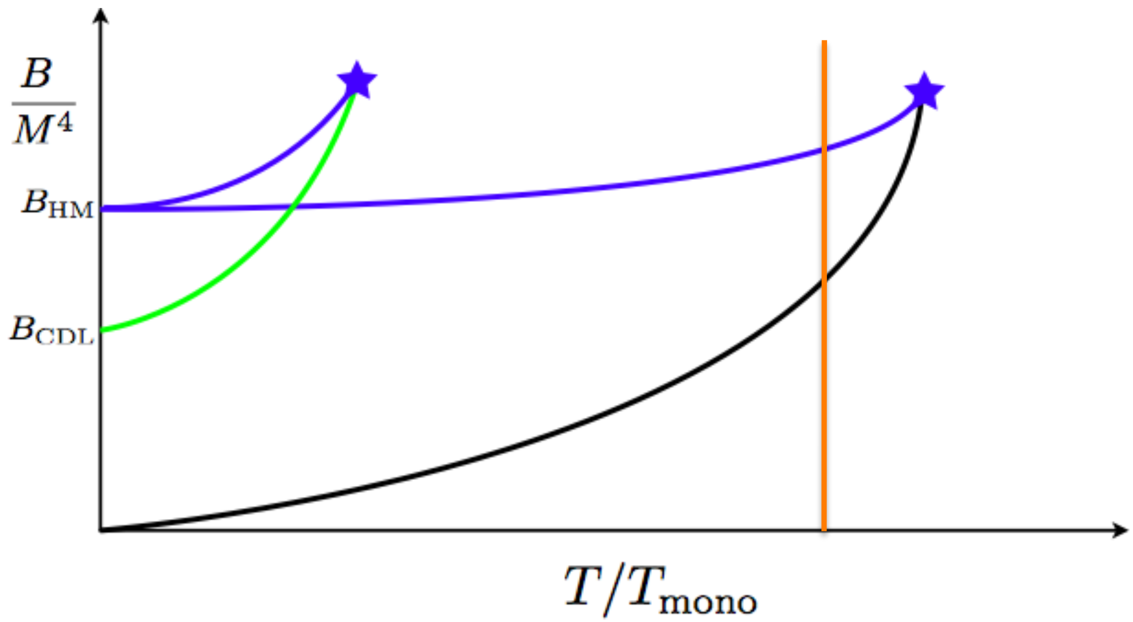


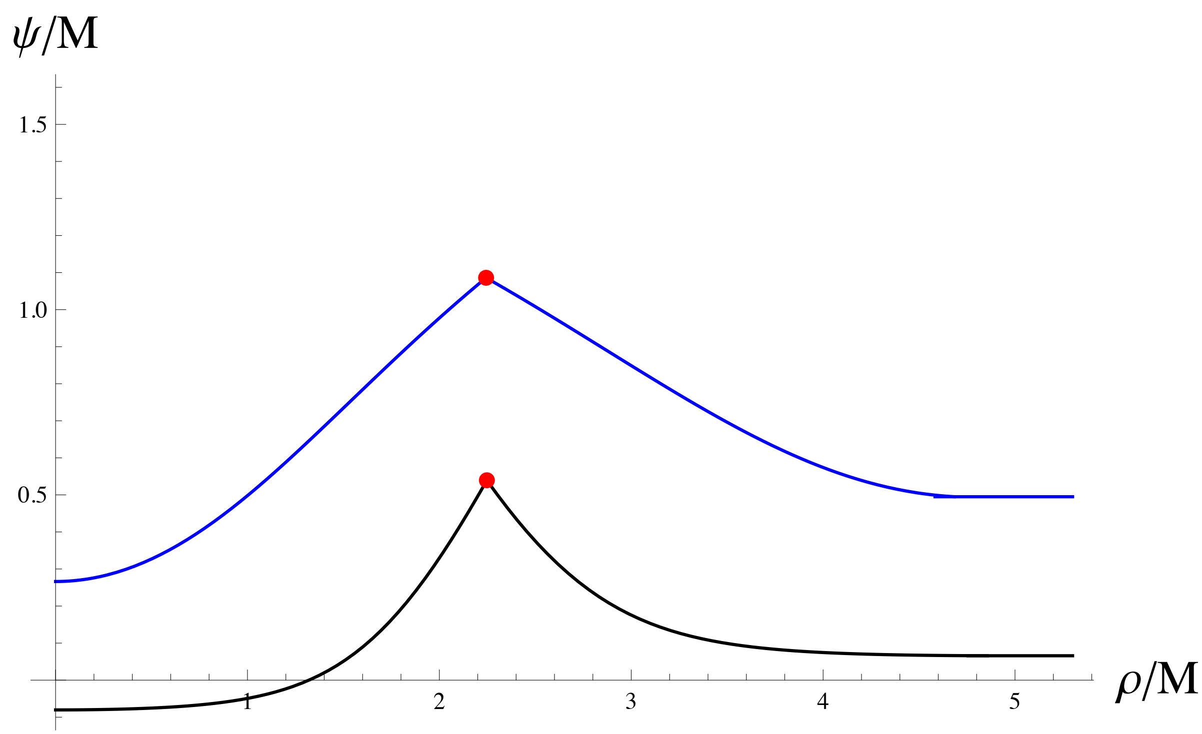
Case 2b: Decay from low dS



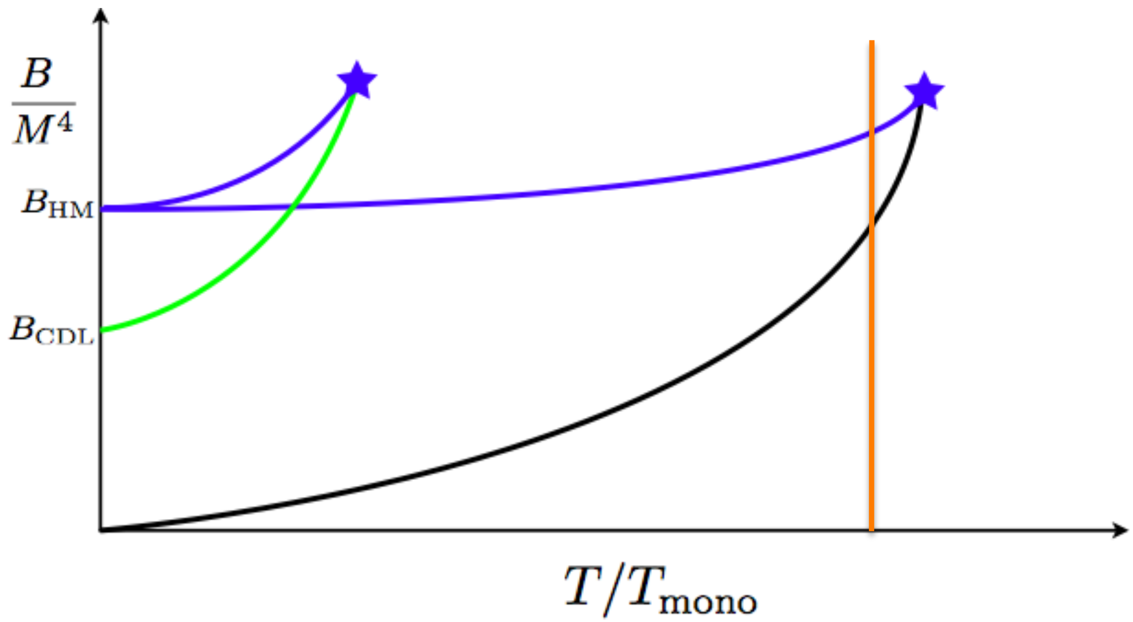


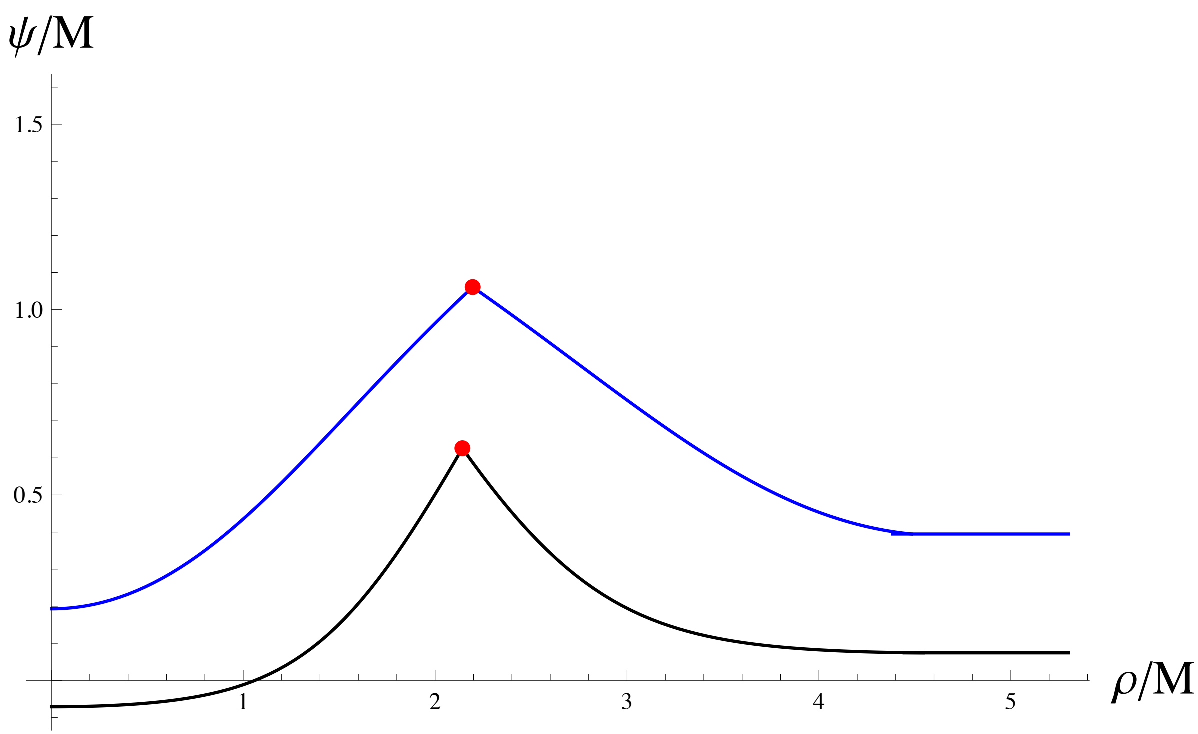
Case 2b:
Decay from
low dS



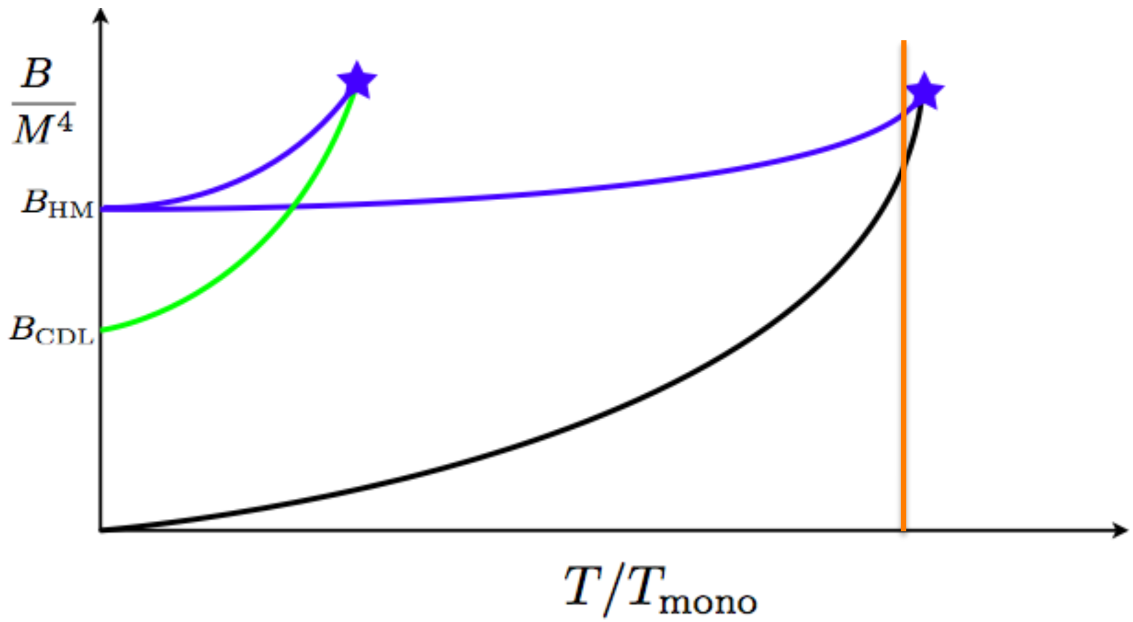


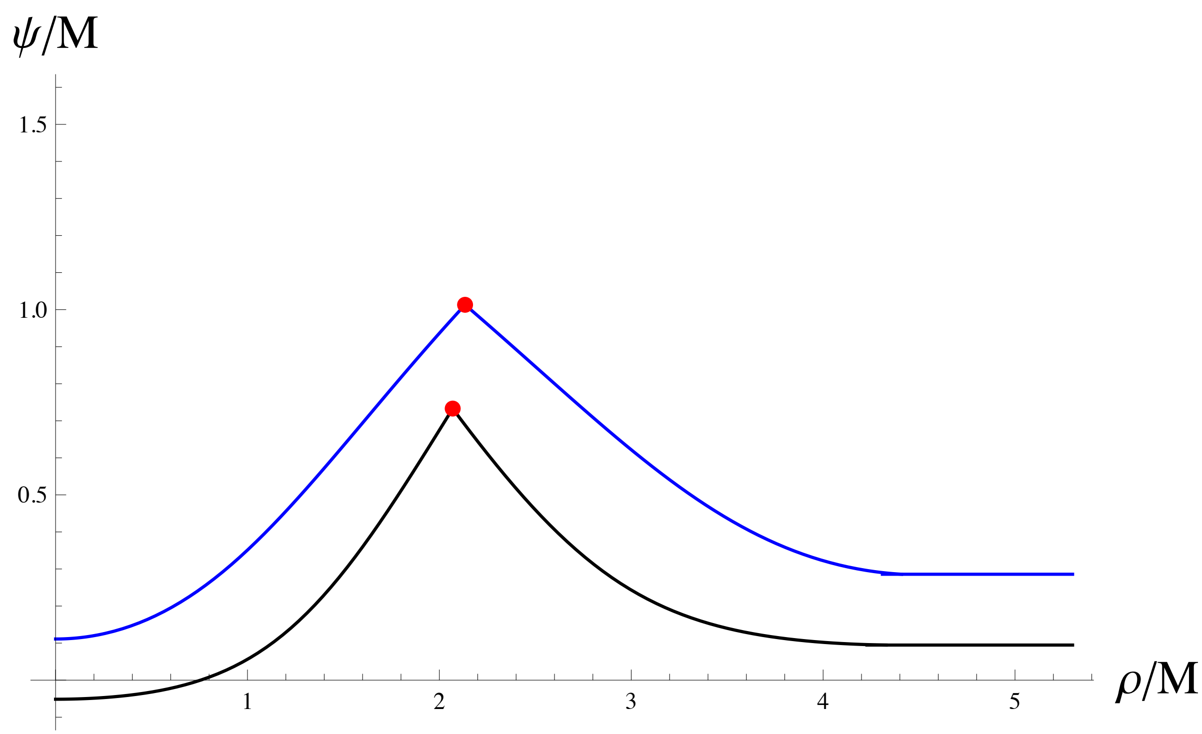
Case 2b:
Decay from
low dS



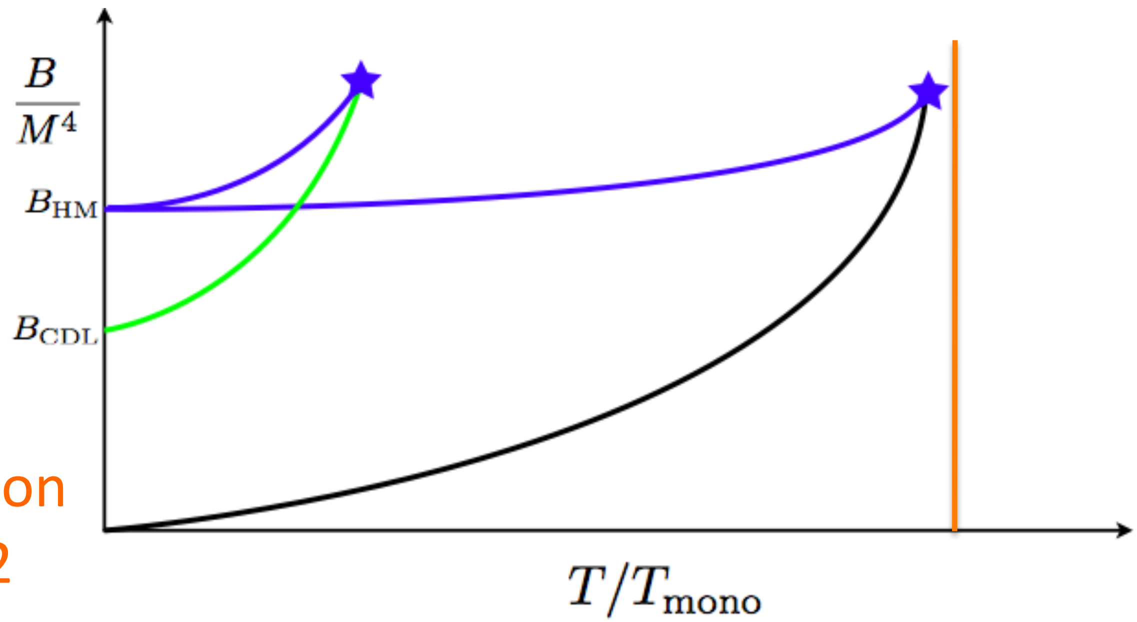


Case 2b: Decay from low dS





Case 2b:
Decay from
low dS



Instanton
Annihilation
Number 2