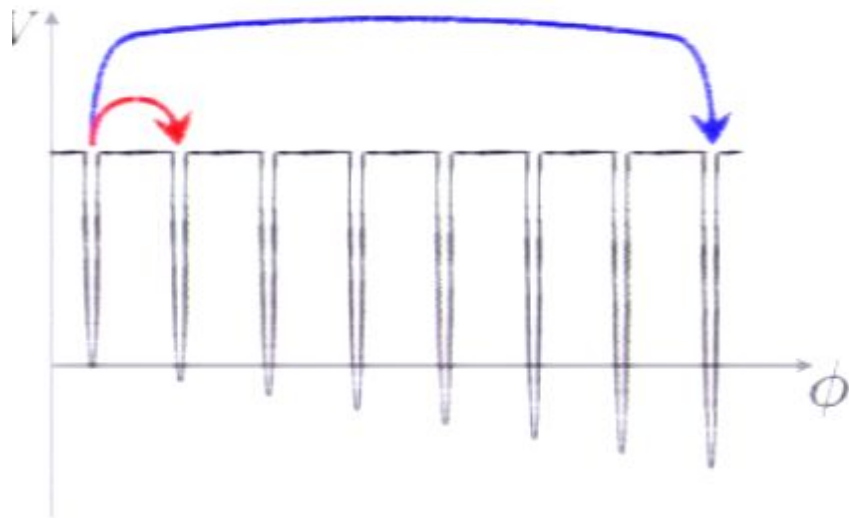


Title: Bubbles of nothing and the big bang

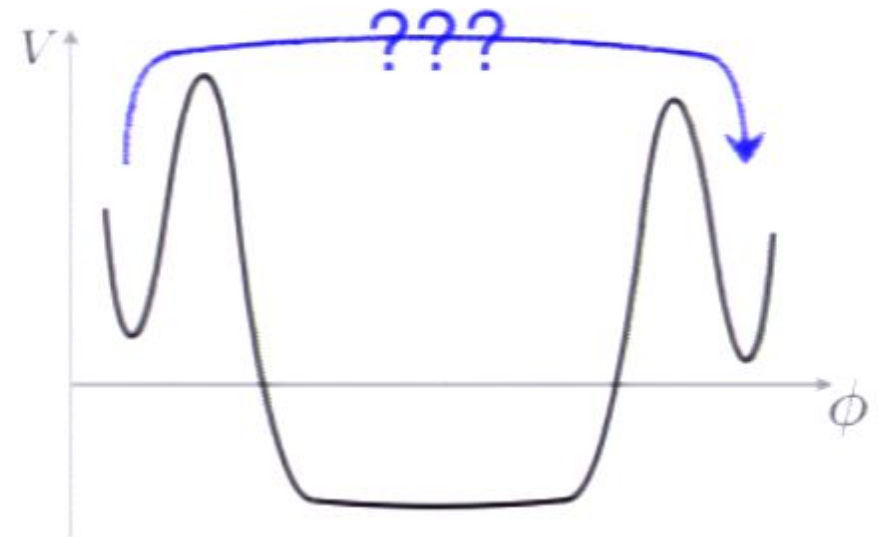
Date: Jun 21, 2011 11:50 AM

URL: <http://pirsa.org/11060047>

Abstract: TBA



what's the fastest decay?

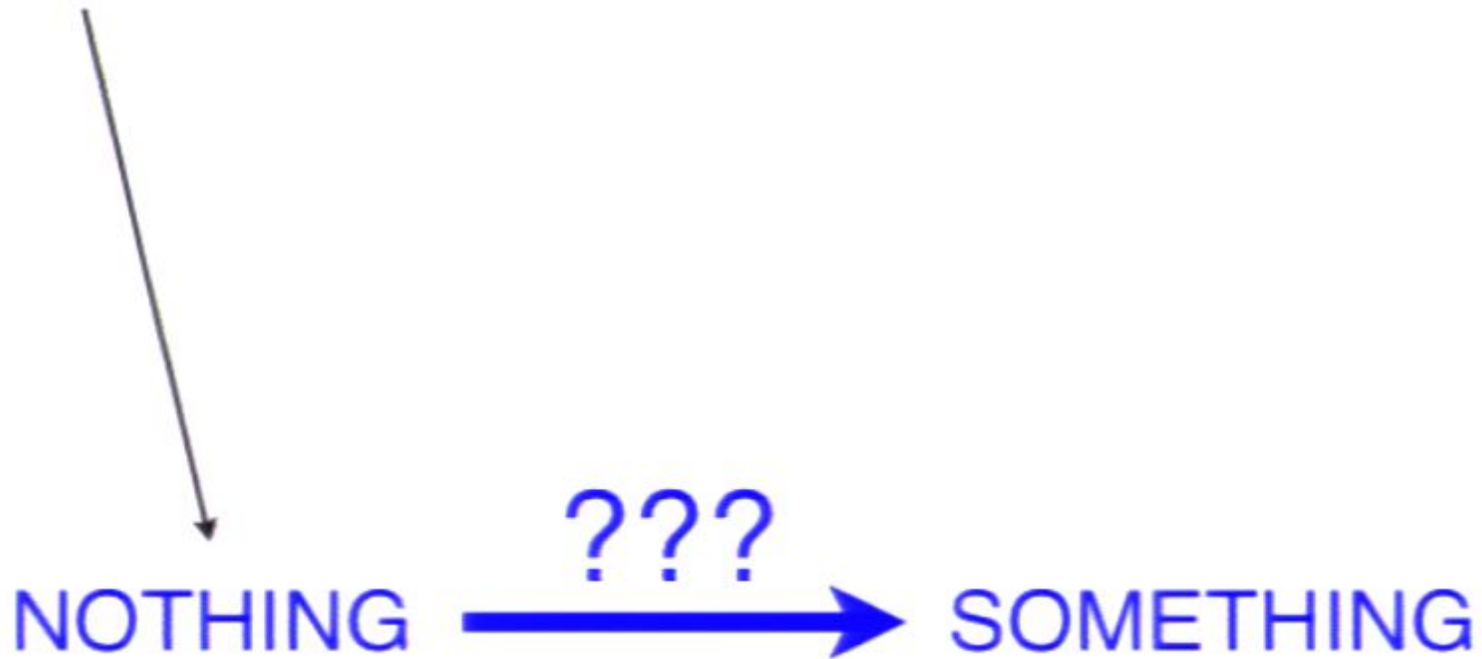


can you get everywhere?

NOTHING  $\xrightarrow{???}$  SOMETHING

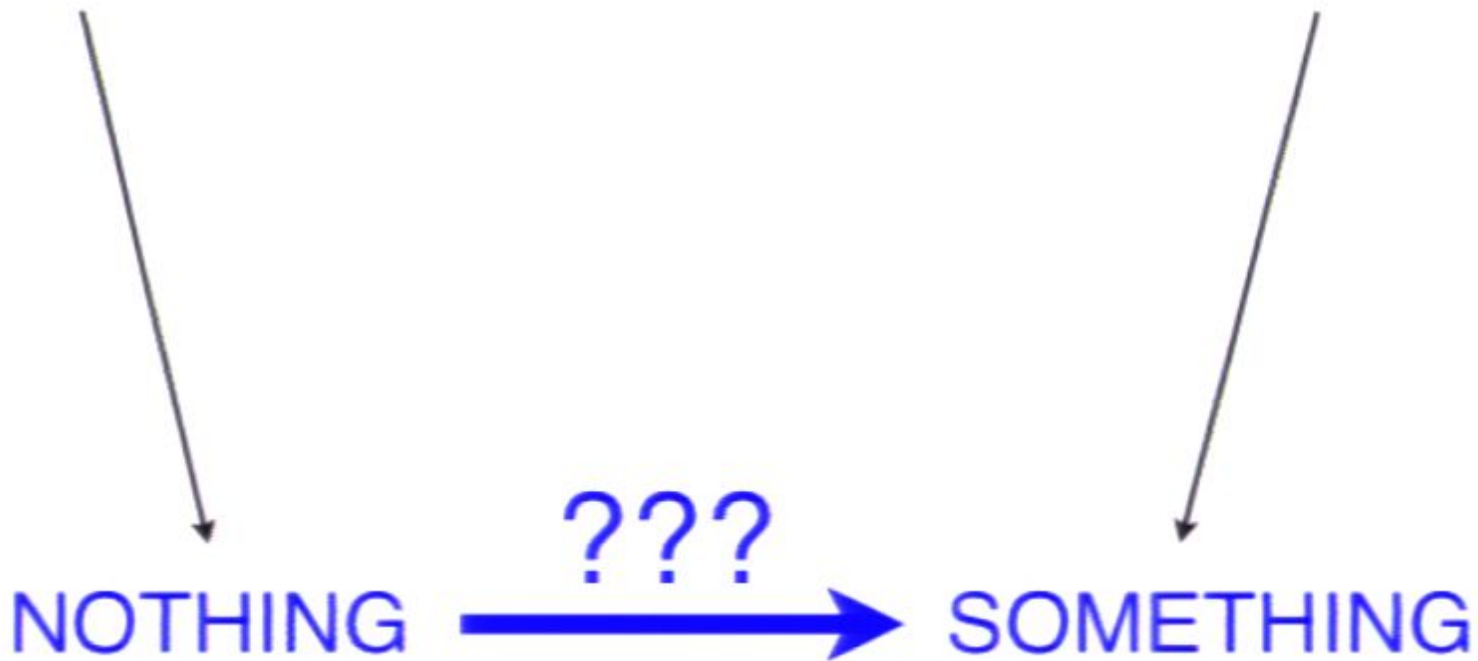
can you make a Universe from nothing?

NOT empty spacetime  
literally nothing  
no space  
no time



NOT empty spacetime  
literally nothing  
no space  
no time

an open Universe  
a la Hawking-Turok



can you make a Universe from nothing?

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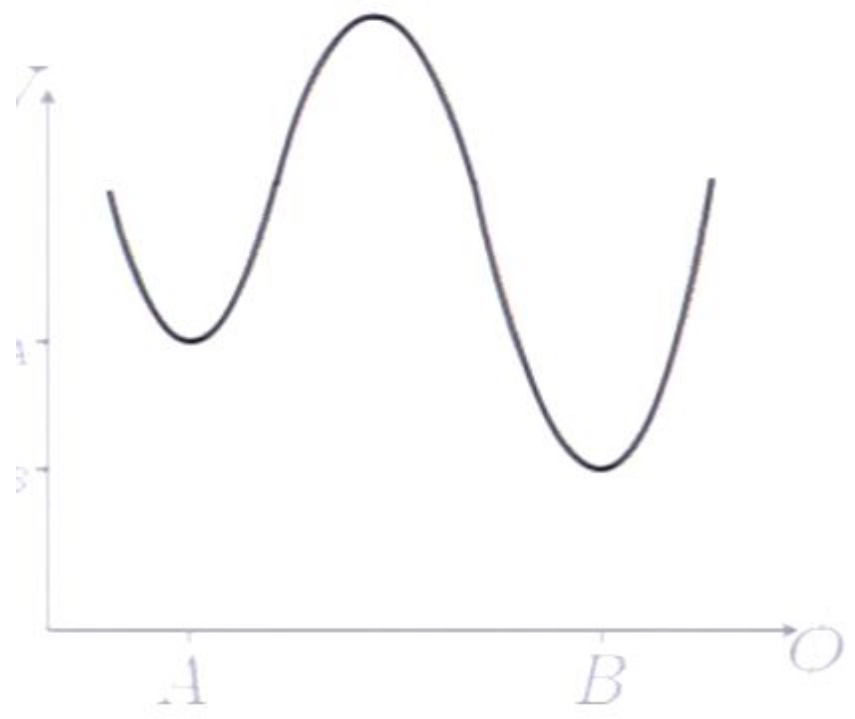
an open Universe  
a la Hawking-Turok

NOTHING  SOMETHING

can you make a Universe from nothing?

**no**

# Tunneling in flat spacetime



NOT empty spacetime  
literally nothing  
no space  
no time

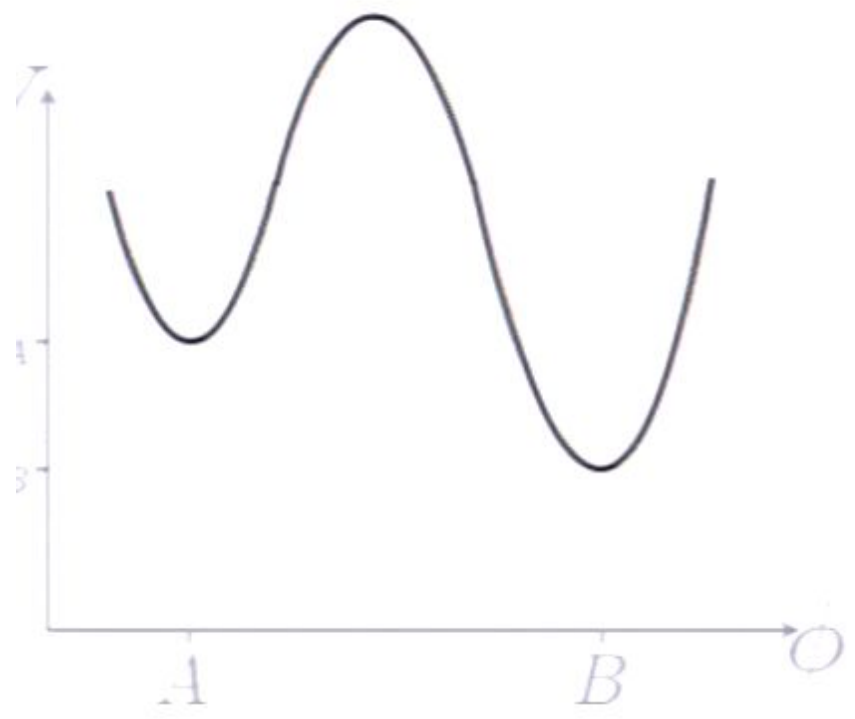
an open Universe  
a la Hawking-Turok

NOTHING  SOMETHING

can you make a Universe from nothing?

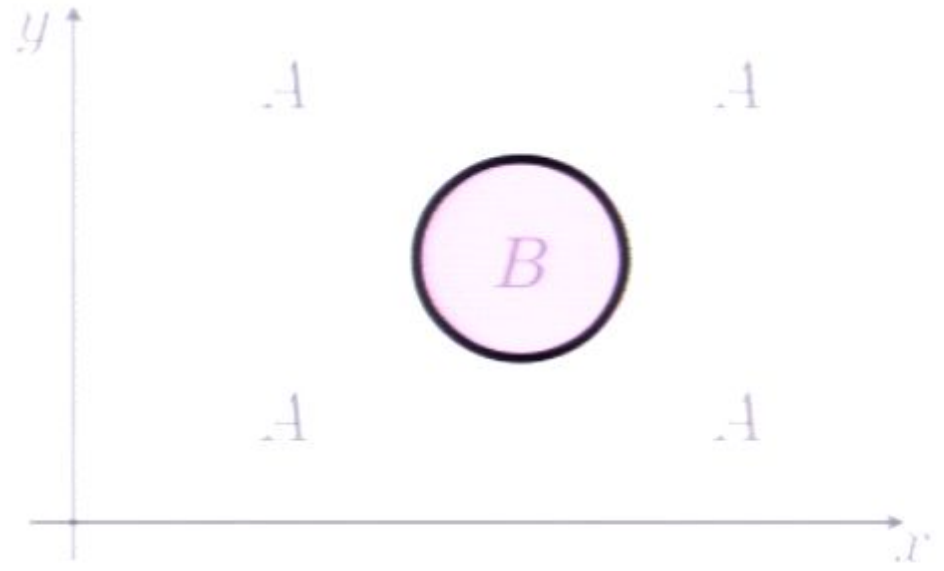
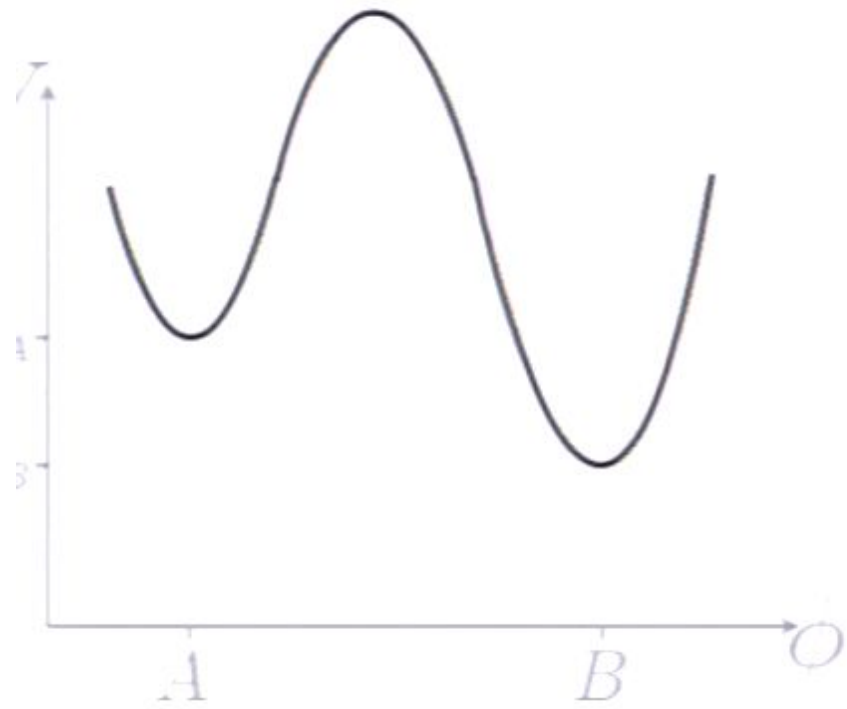
**no**

# Tunneling in flat spacetime





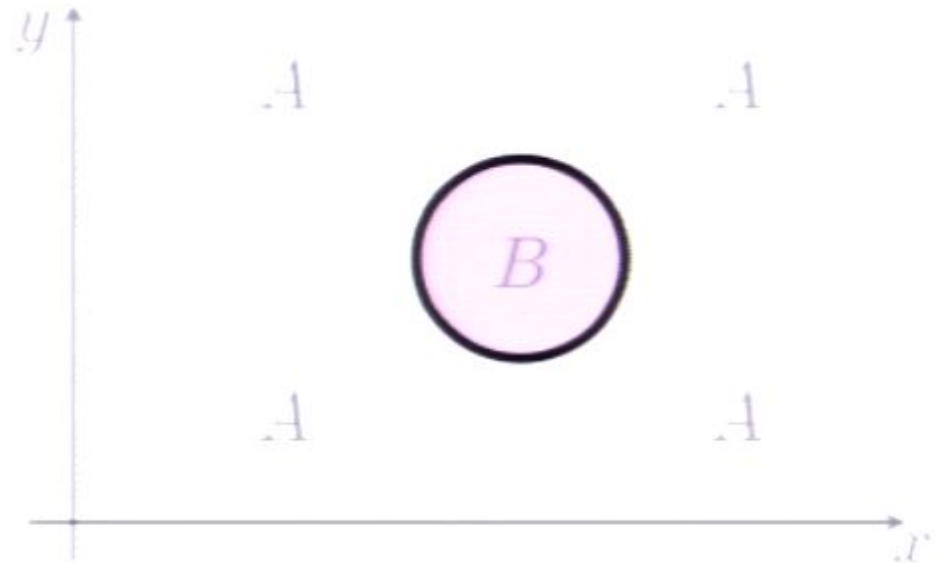
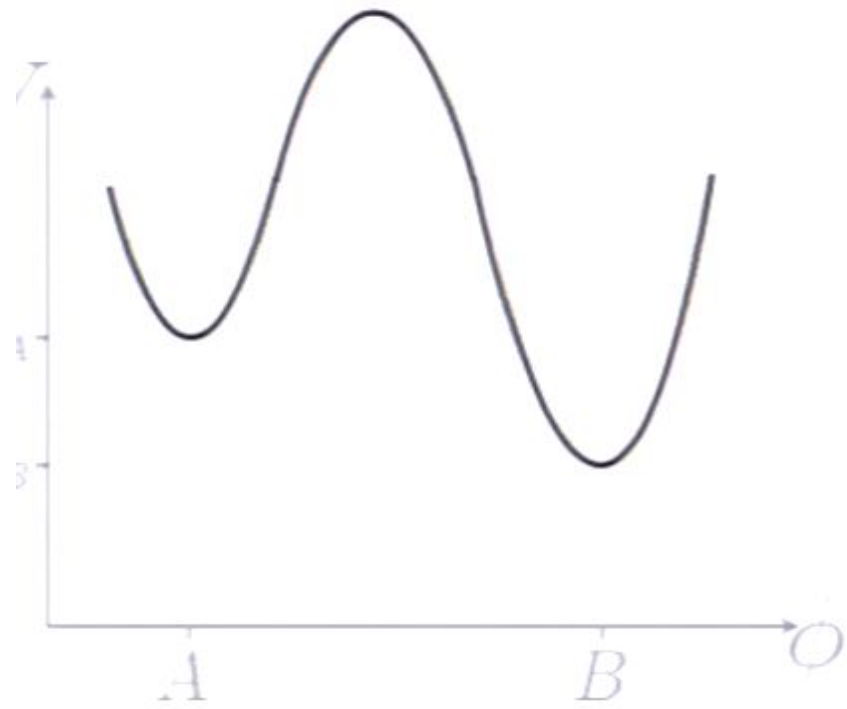
# Tunneling in flat spacetime



QUANTUM



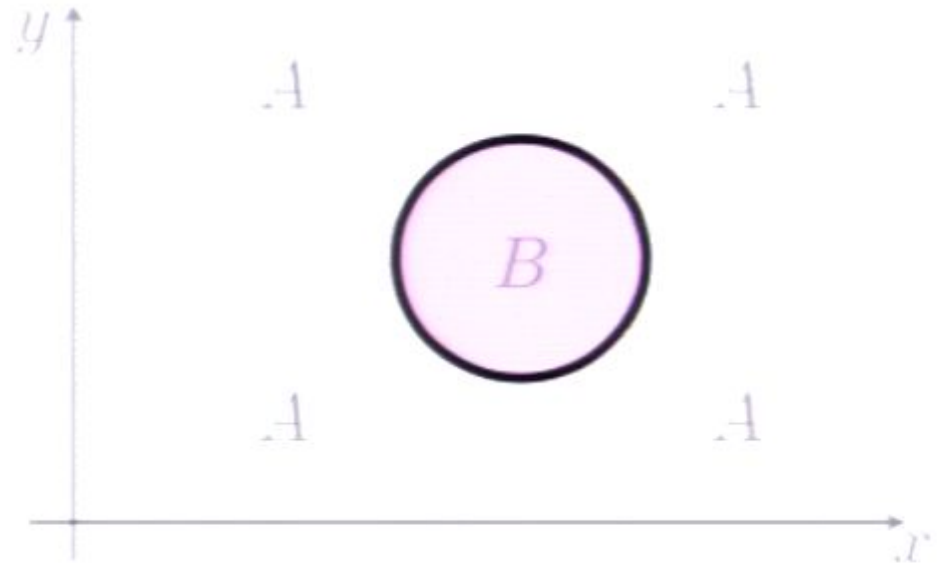
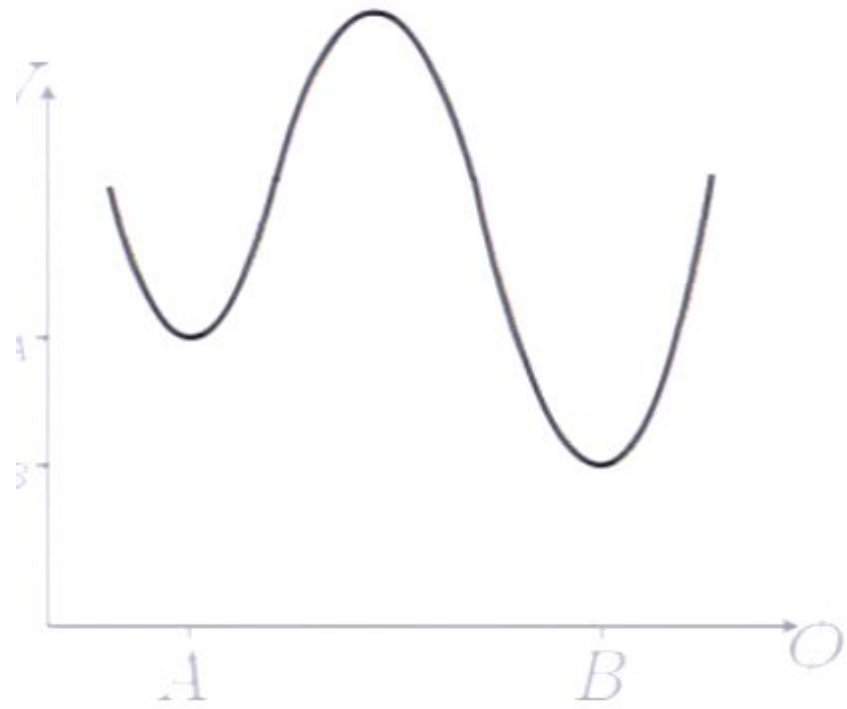
# Tunneling in flat spacetime



CLASSICAL



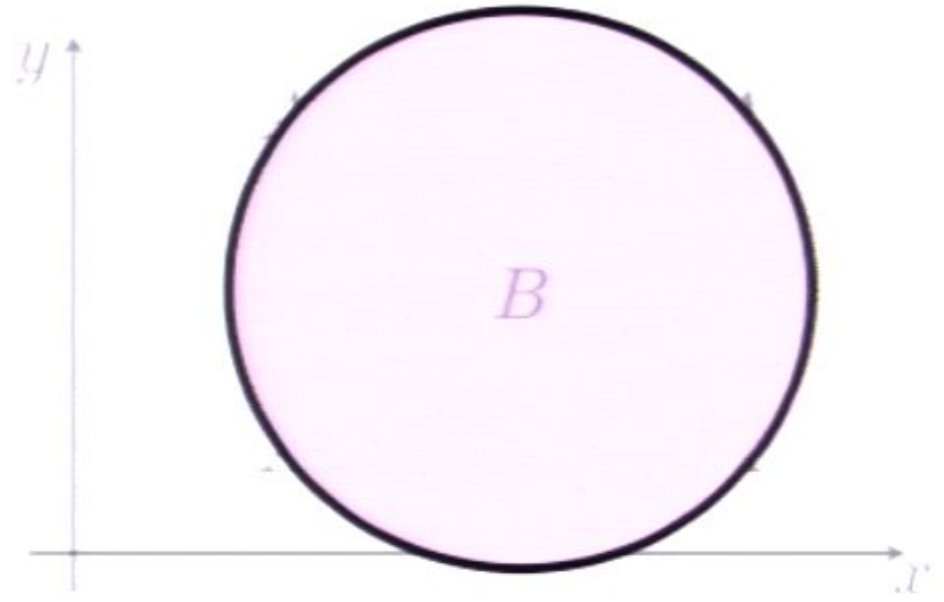
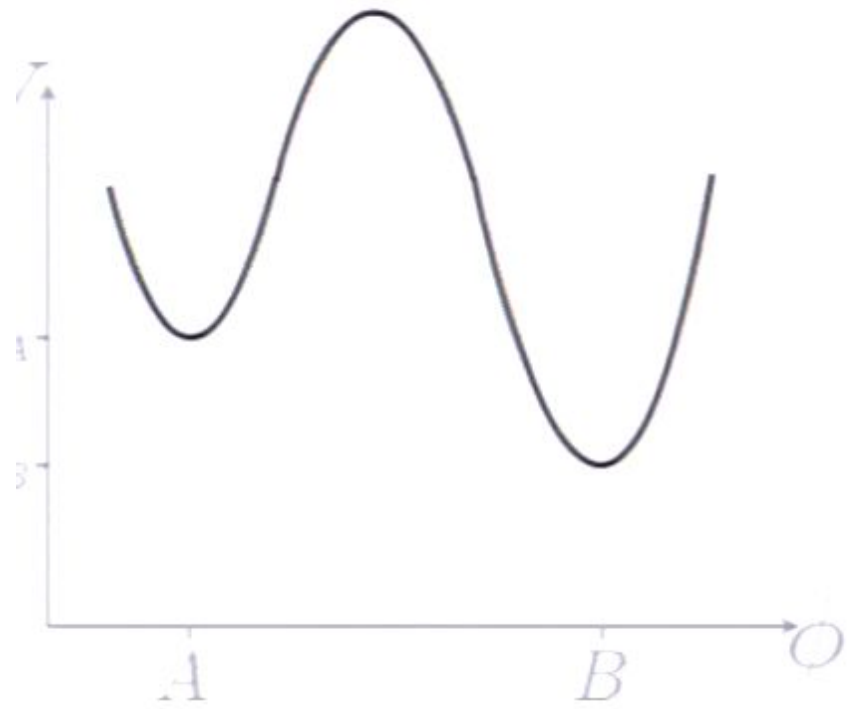
# Tunneling in flat spacetime



CLASSICAL



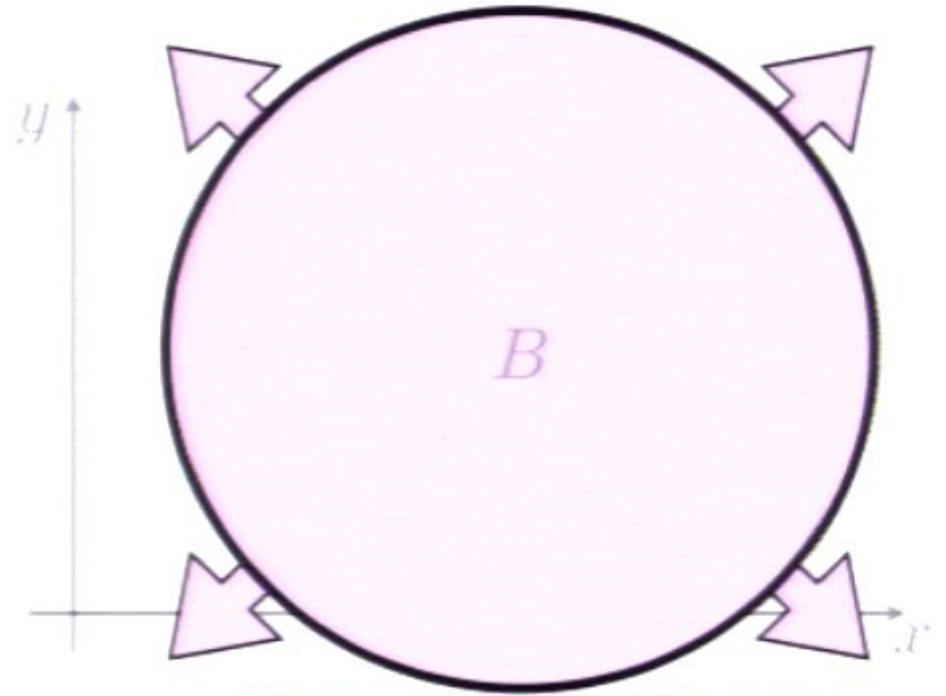
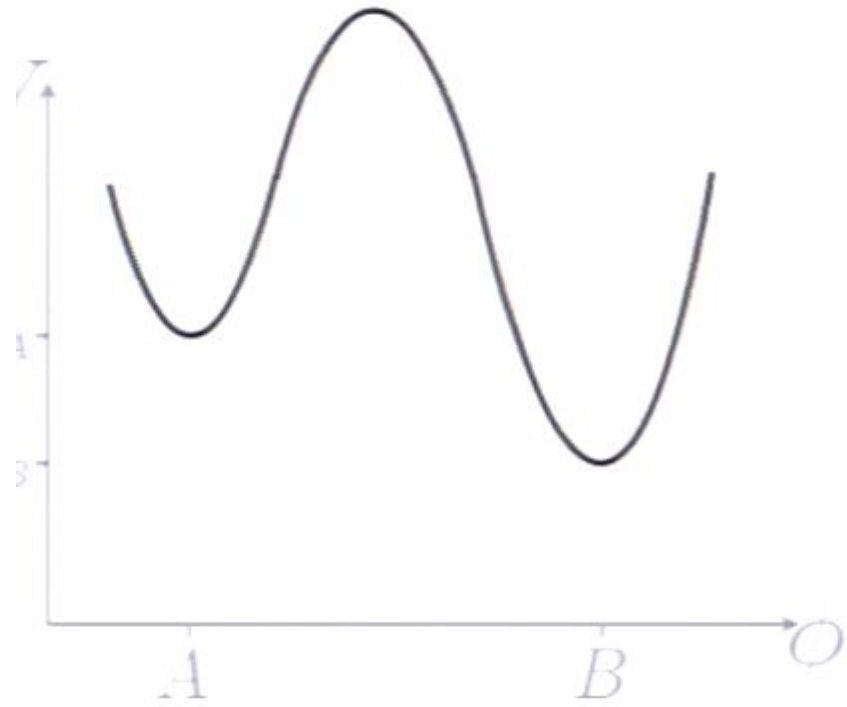
# Tunneling in flat spacetime



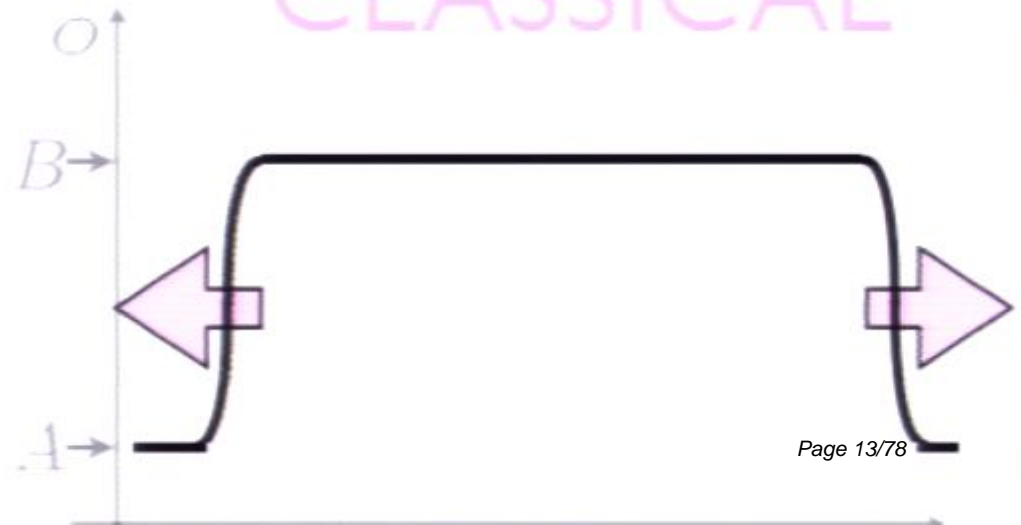
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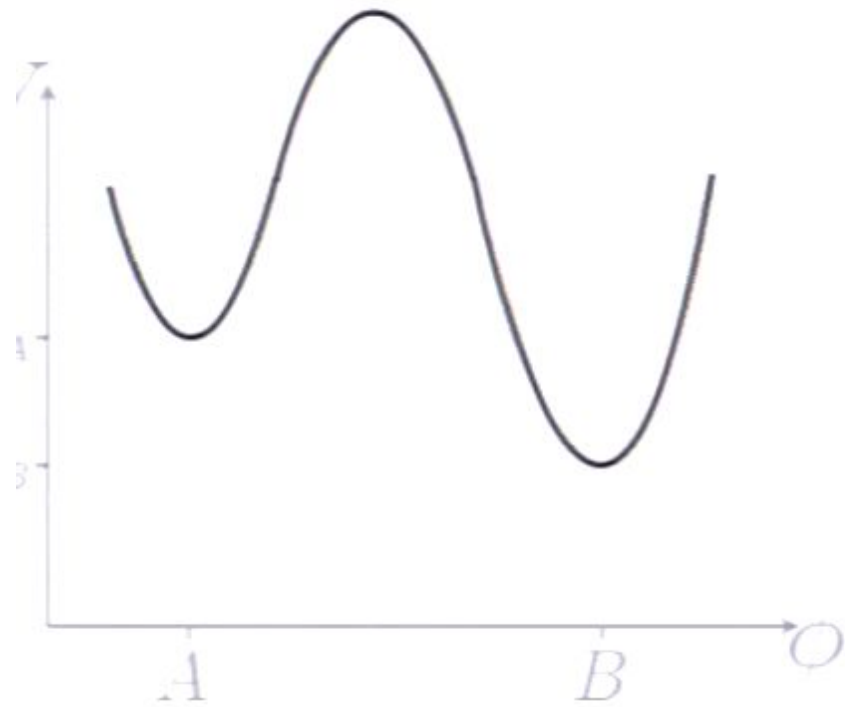
# Tunneling in flat spacetime



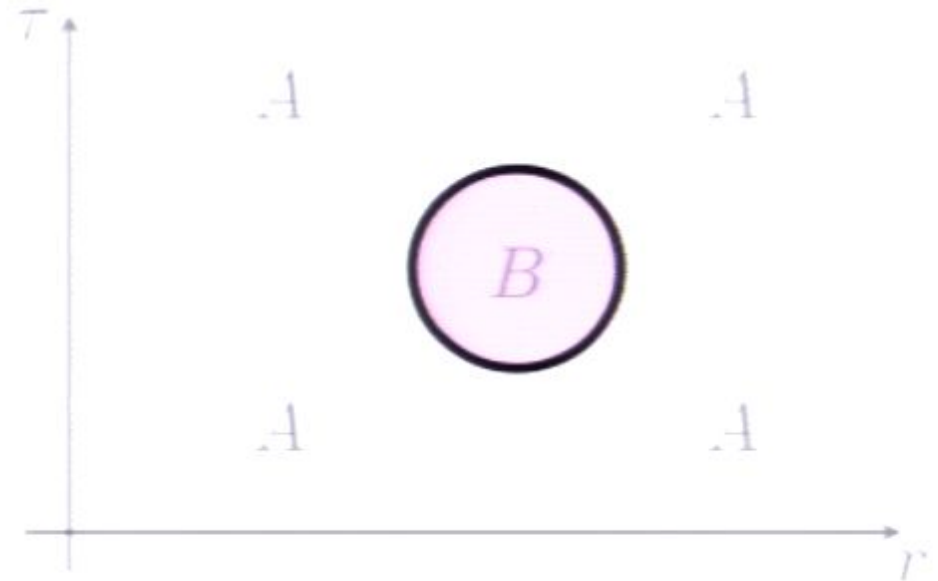
CLASSICAL



## Tunneling in flat spacetime



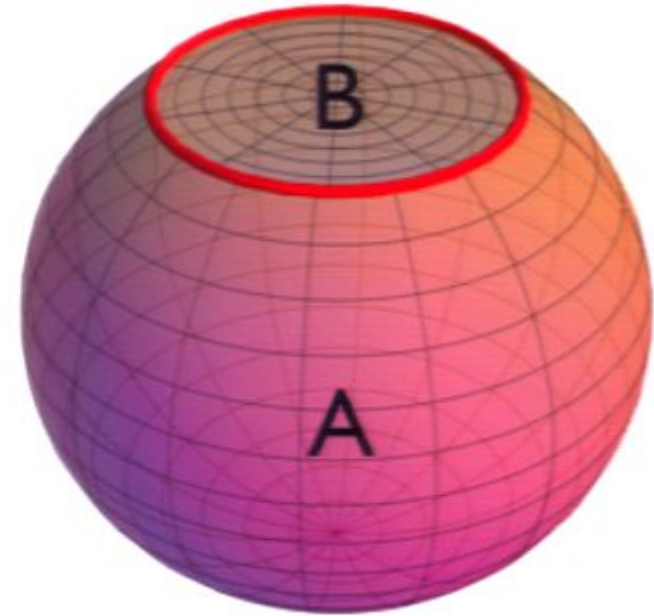
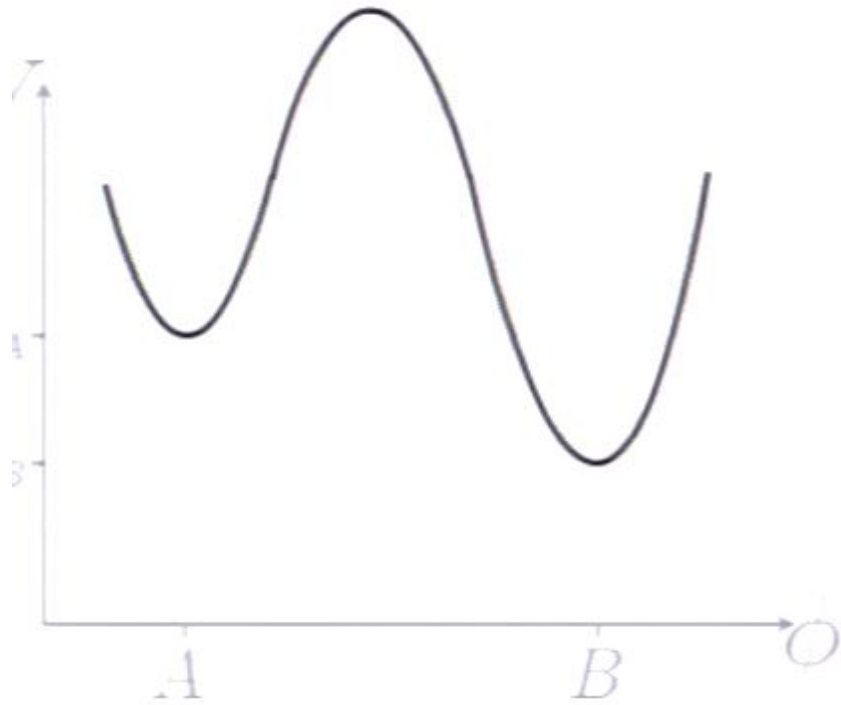
instanton lives on  $\mathcal{R}^4$



$$\Gamma_{A \rightarrow B} = \exp[-S_E(\text{instanton}) + S_E(A)]$$

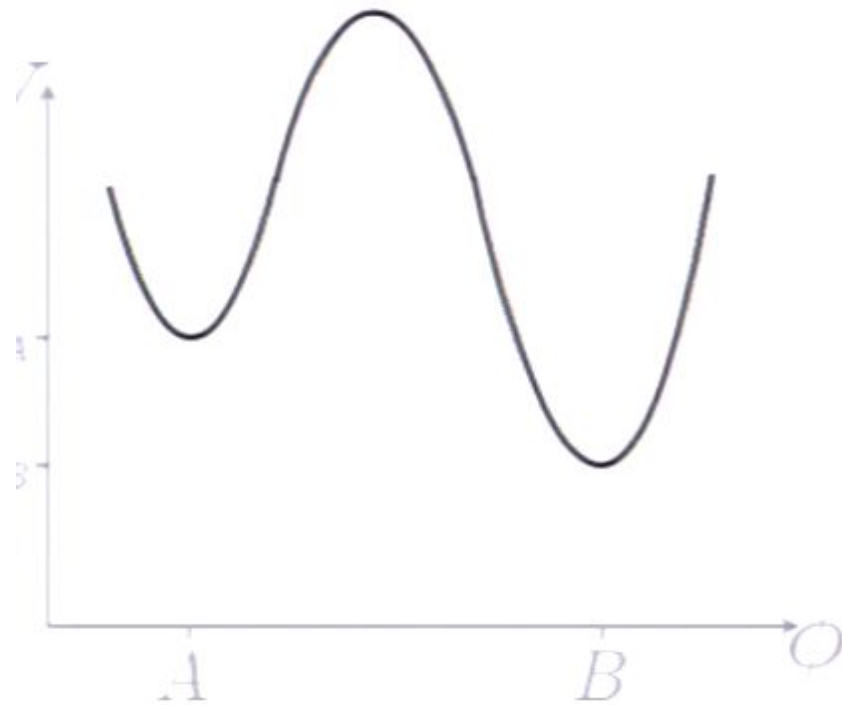
# Tunneling in dynamical spacetime

instanton lives on  $S^4$

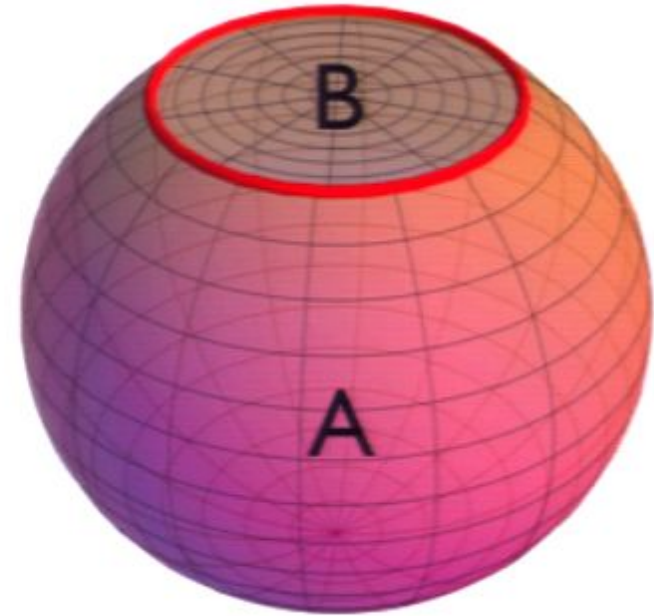


$$\Gamma_{A \rightarrow B} = \exp[-S_E(\text{instanton}) + S_E(A)]$$

## Tunneling in dynamical spacetime



instanton lives on  $S^4$

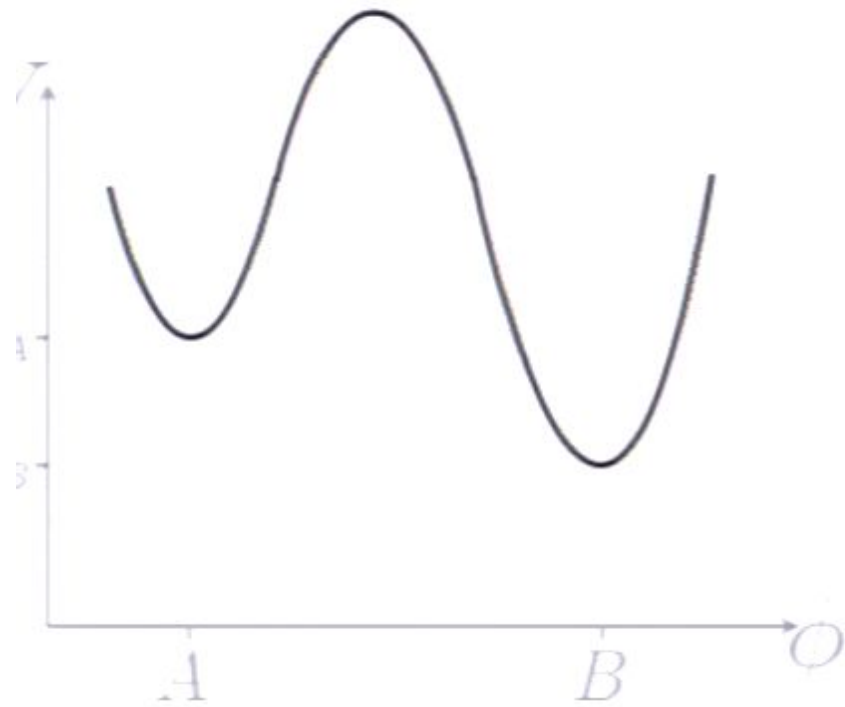


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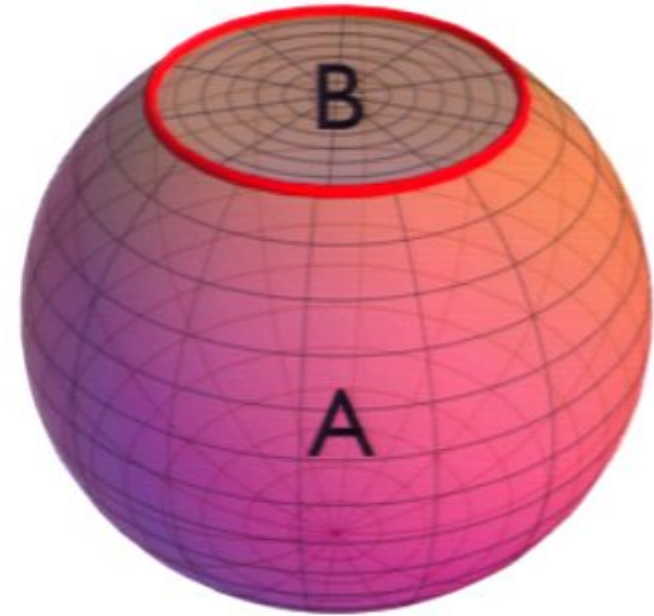
The SAME instanton governs tunneling in both directions



## Tunneling in dynamical spacetime



instanton lives on  $S^4$

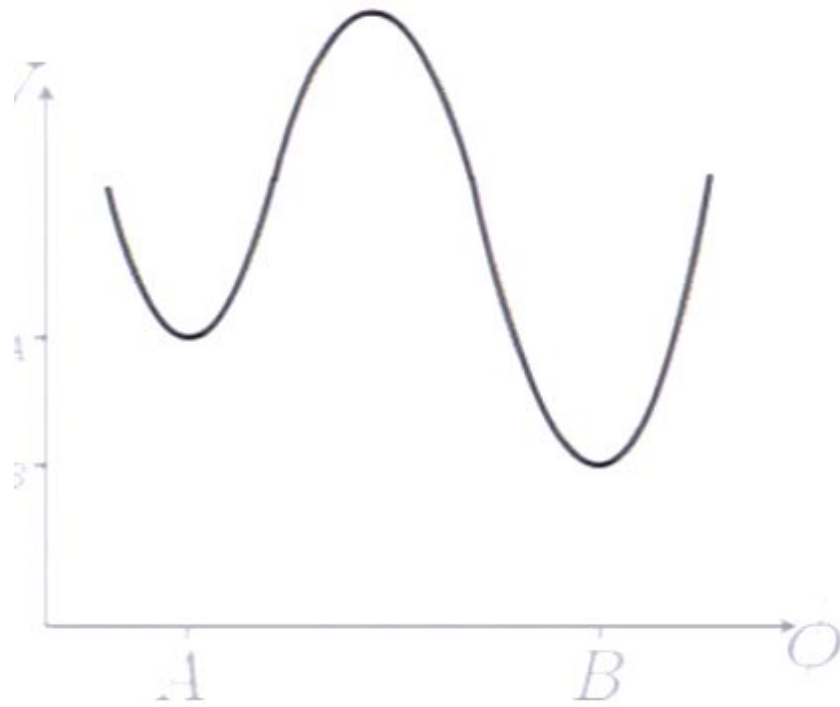


$$\Gamma_{A \rightarrow B} = \exp[-S_E(\text{instanton}) + S_E(A)]$$

The SAME instanton governs tunneling in both directions

$$\Gamma_{B \rightarrow A} = \exp[-S_E(\text{instanton}) + S_E(B)]$$

## Tunneling in dynamical spacetime



$$S_E(\text{instanton}) = \text{finite}$$

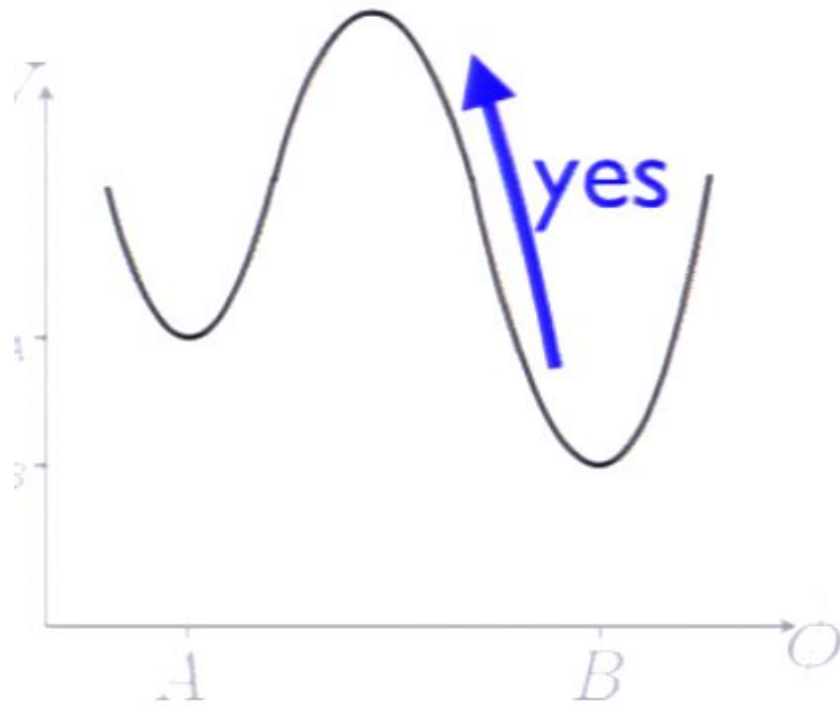
$$S_E(\text{de Sitter}) = -\frac{24\pi^2 M_{\text{Pl}}^4}{V}$$

$$\Gamma_{A \rightarrow B} = \exp[-S_E(\text{instanton}) + S_E(A)]$$

The SAME instanton governs tunneling in both directions

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## Tunneling in dynamical spacetime



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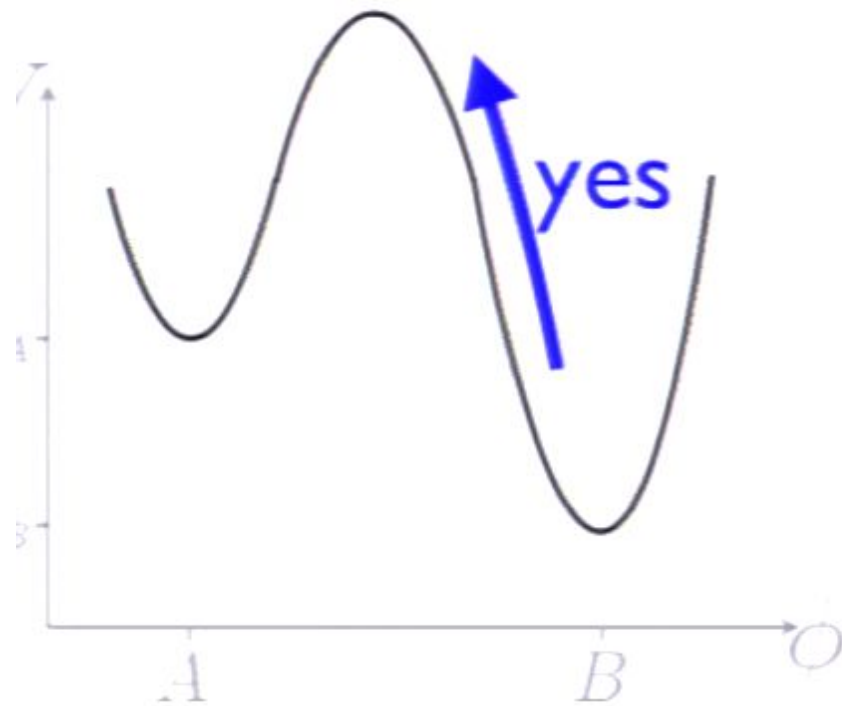
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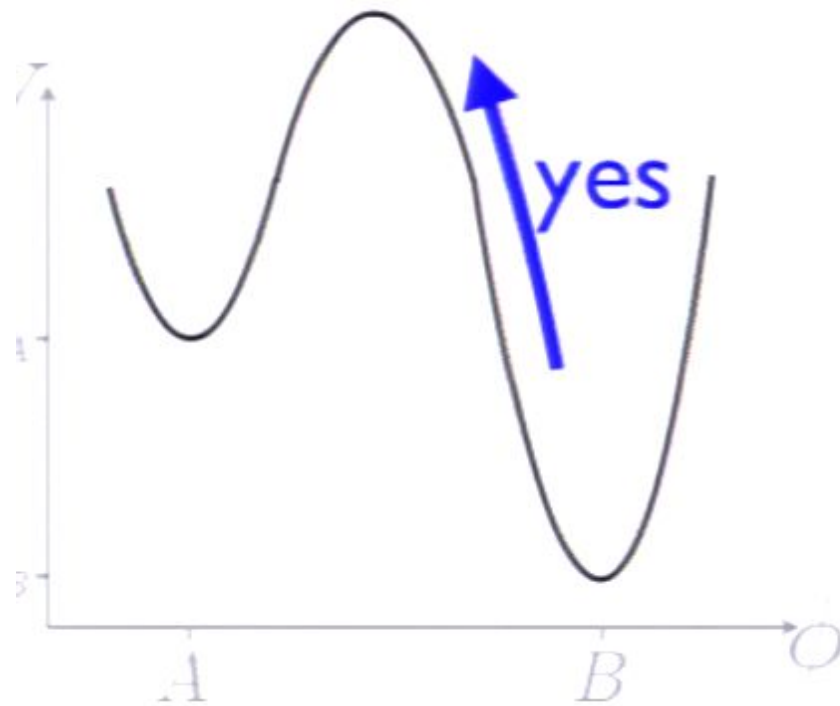
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## Tunneling in dynamical spacetime



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## Tunneling in dynamical spacetime



$$S_E(\text{instanton}) = \text{finite}$$

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$$S_E(\text{Minkowski}) = -\infty$$

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The SAME instanton governs tunneling in both directions

Uptunneling is possible from de Sitter

Uptunneling is impossible from Minkowski or AdS

## p-tunneling from Minkowski?

homogenously?

no (infinite volume)

inhomogenously?

no (null-energy condition)

(infalling 'normal' surface becomes 'anti-trapped')

Penrose  
Guth & Farhi

The SAME instanton governs tunneling in both directions

Uptunneling is possible from de Sitter

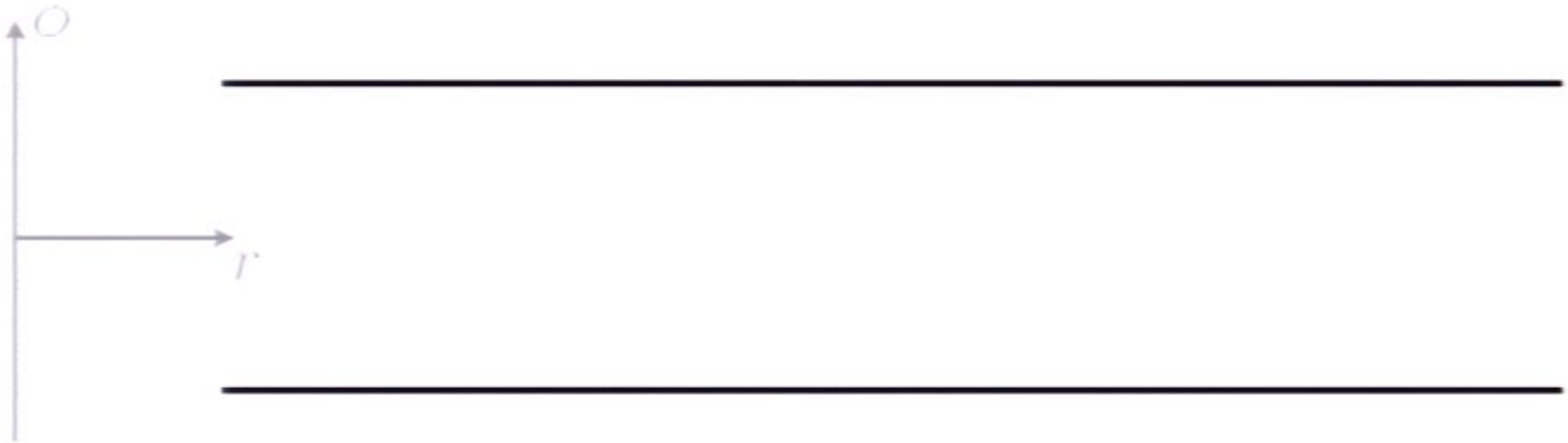
Uptunneling is impossible from Minkowski or AdS

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The SAME instanton governs tunneling in both directions

bubble of nothing

3+1+1 dim  
unstabilized  
Minkowski

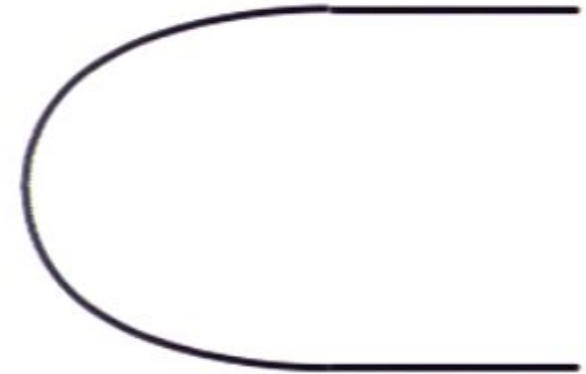
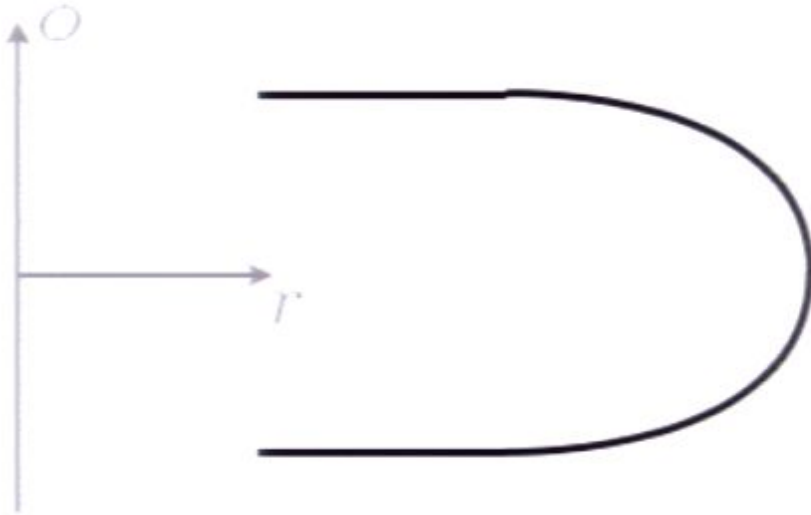


$$ds^2 = dr^2 + r^2 d\Omega_2^2 + d\phi^2$$

The SAME instanton governs tunneling in both directions

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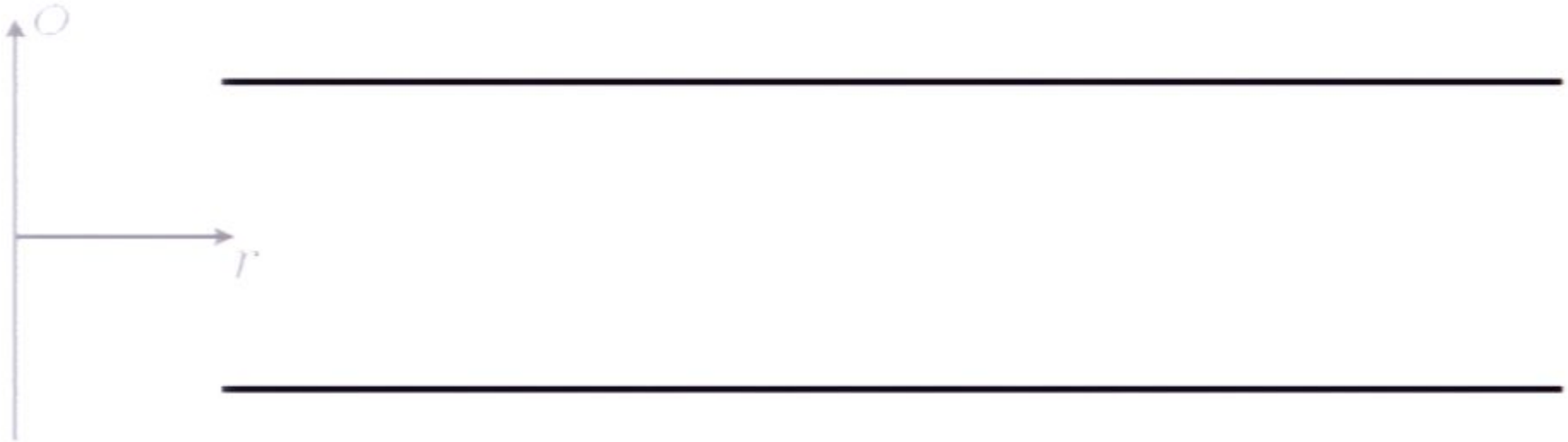


$$ds^2 = \frac{dr^2}{1 - 1/r^2} + r^2 d\Omega_2^2 + \left(1 - \frac{1}{r^2}\right) d\phi^2$$

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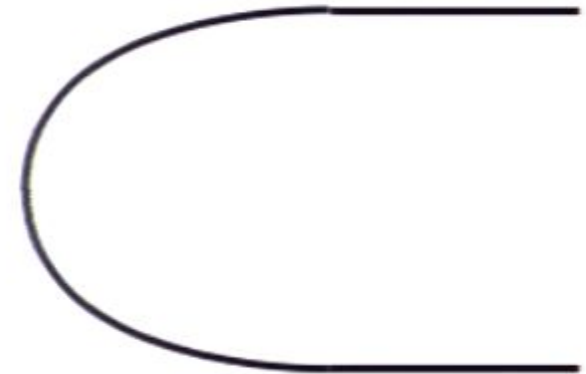
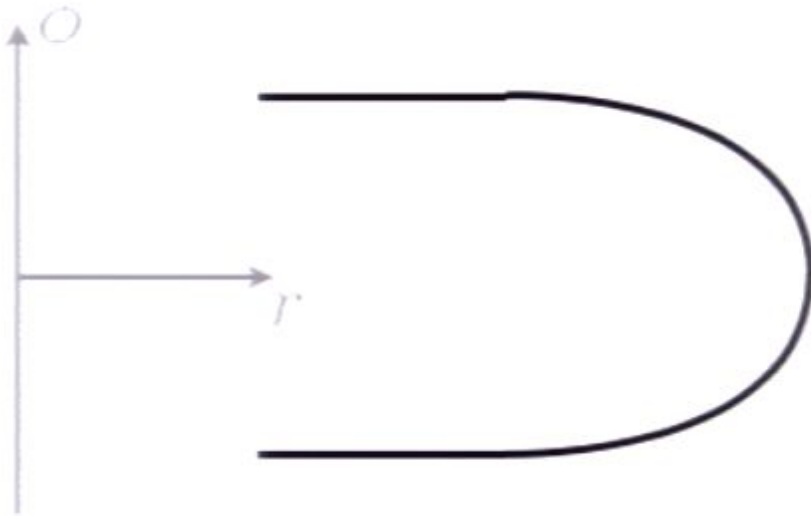


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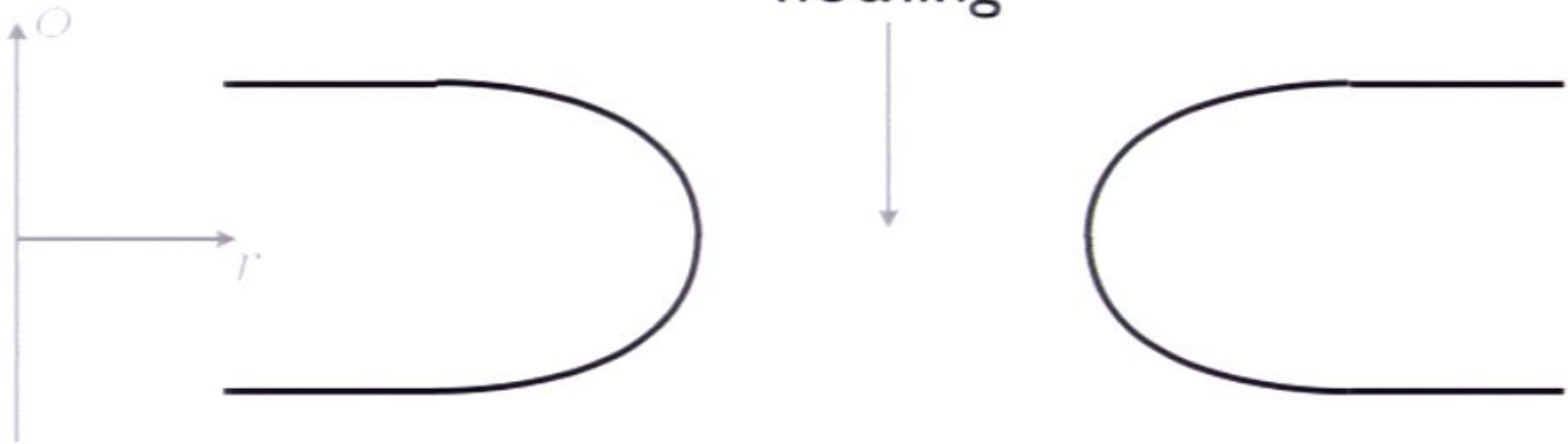


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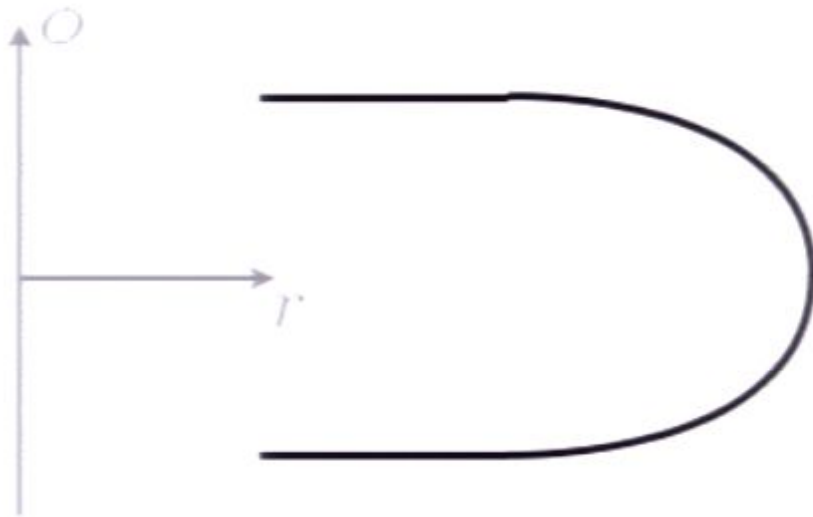
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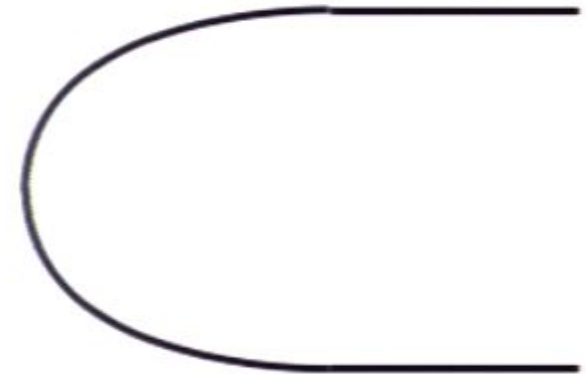


bubble of nothing

3+1+1 dim  
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nothing



$$ds^2 = \frac{dr^2}{1 - 1/r^2} + r^2 d\Omega_2^2 + \left(1 - \frac{1}{r^2}\right) d\phi^2$$

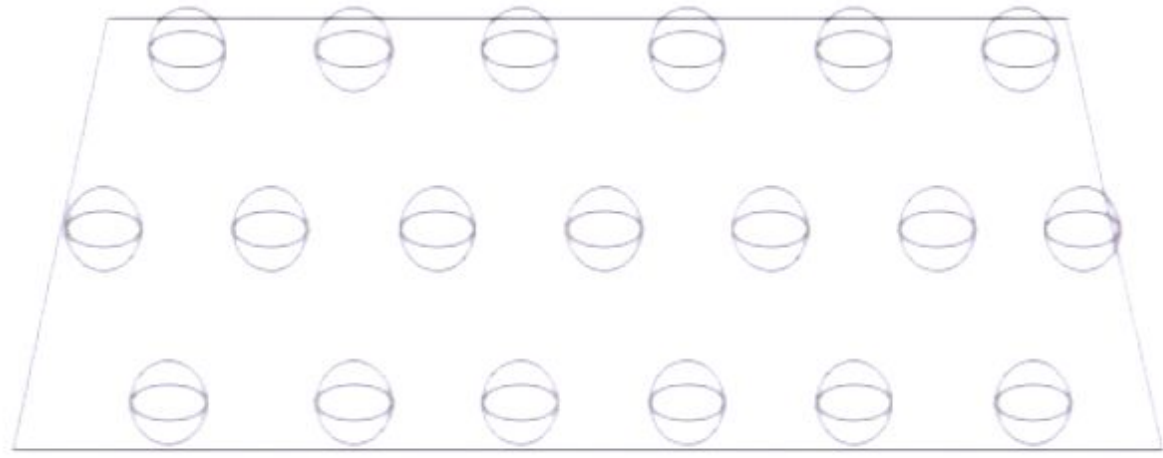
The SAME instanton governs tunneling in both directions

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

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu + R^2 d\Omega_2^2$$

4D dS, Min, or AdS

2D sphere

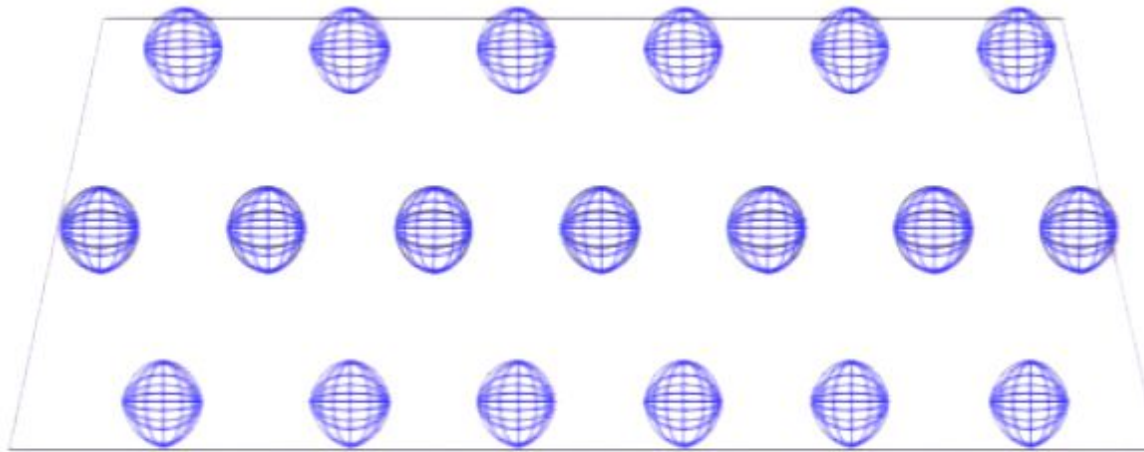


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4D dS, Min, or AdS

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

$$S = \int d^6x \sqrt{-\tilde{g}} \left( \frac{1}{2} \tilde{R}^{(6)} - \frac{1}{4} F_{MN} F^{MN} - \Lambda_6 \right)$$

Freund, Rubin (1980)

**Einstein**
**Maxwell**
**C.C.**

effective 4D theory:

$$ds^2 = e^{-\psi(x)/M_4} g_{\mu\nu} dx^\mu dx^\nu + e^{\psi(x)/M_4} R^2 d\Omega_2^2$$



$$S = \int d^4x \sqrt{-g} \left( \frac{1}{2} M_4^2 R^{(4)} - \frac{1}{2} \partial_\mu \psi \partial^\mu \psi - V_4(\psi) \right)$$

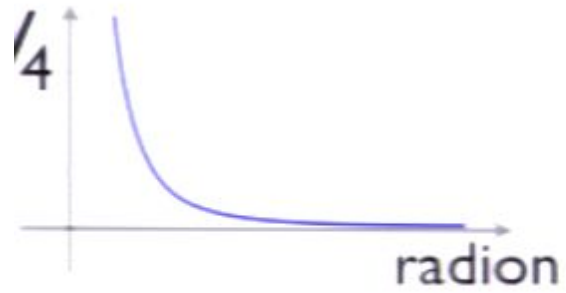
$$V_4(\psi) = 4\pi \left( \frac{\frac{1}{2} F^2}{16\pi^2 M_4^2} e^{-3\psi/M_4} - e^{-2\psi/M_4} + R^2 \Lambda_6 e^{-\psi/M_4} \right)$$

**canonically normalized RADION**
**FLUX**
**CURVATURE**
**C.C.**

‘repulsive’ short range
‘attractive’ medium range
‘repulsive’ long range

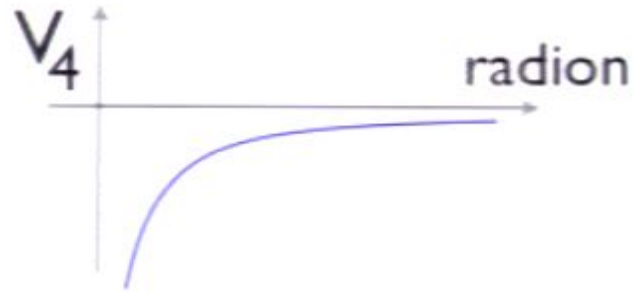
## flux

short-range, repulsive



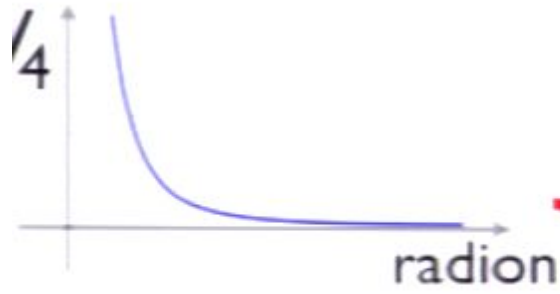
## curvature

medium-range, attractive



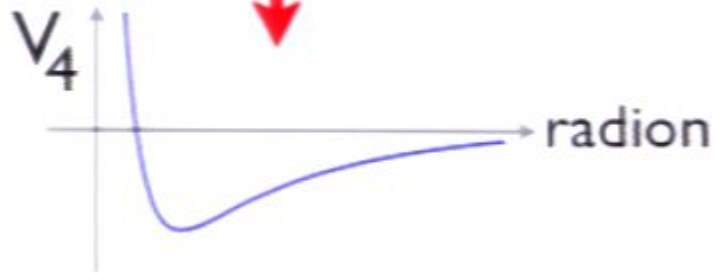
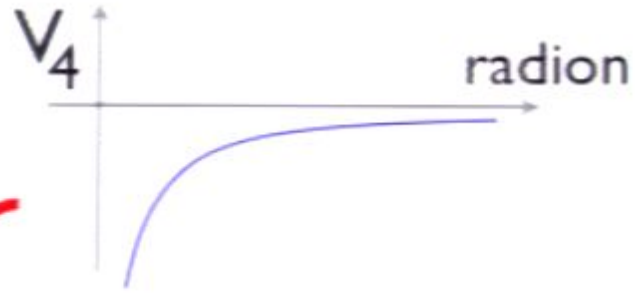
# flux

short-range, repulsive



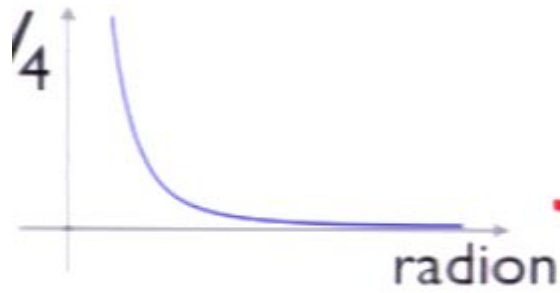
# curvature

medium-range, attractive



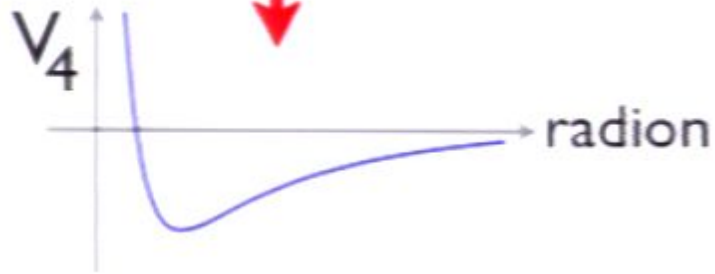
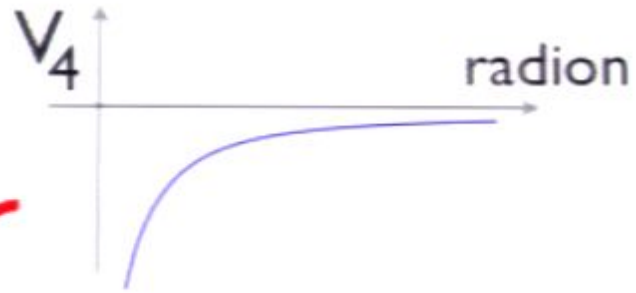
## flux

short-range, repulsive

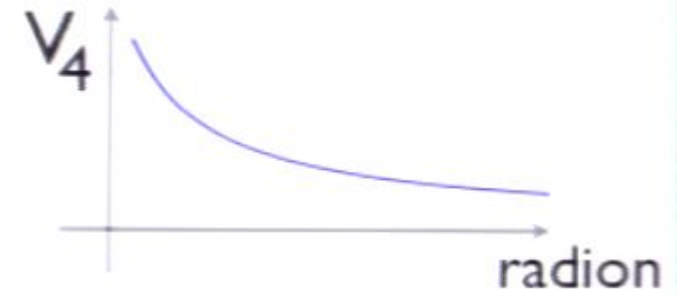


## curvature

medium-range, attractive

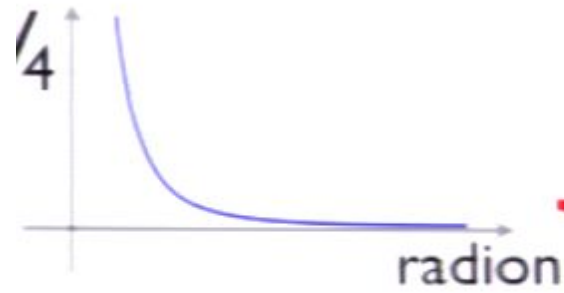


**6D +ve c.c.**  
long-range, repulsive



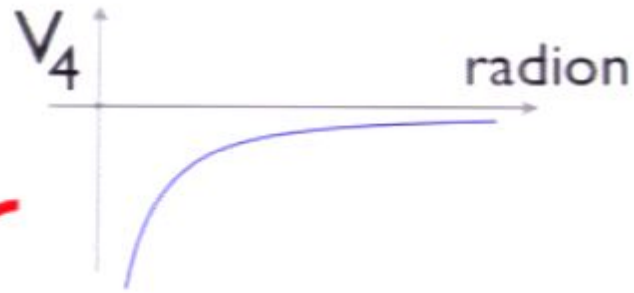
# flux

short-range, repulsive

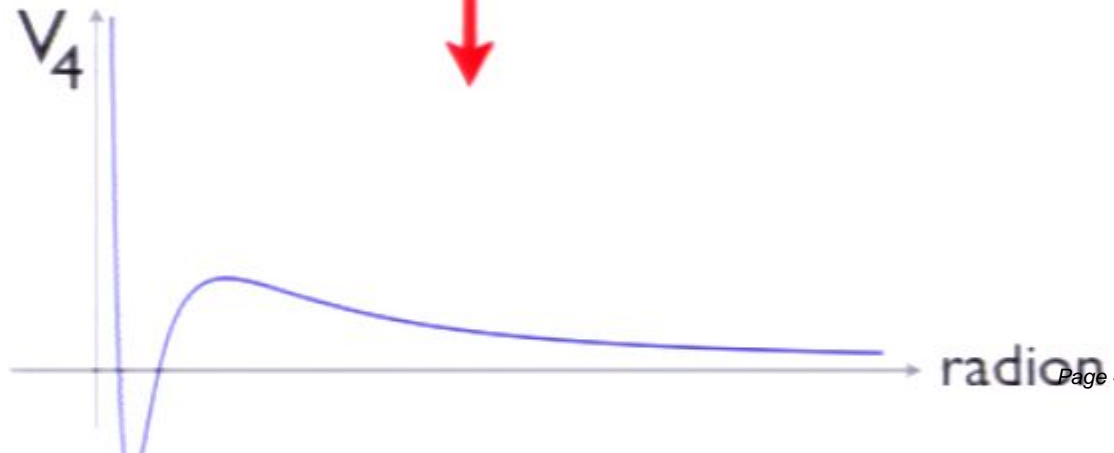
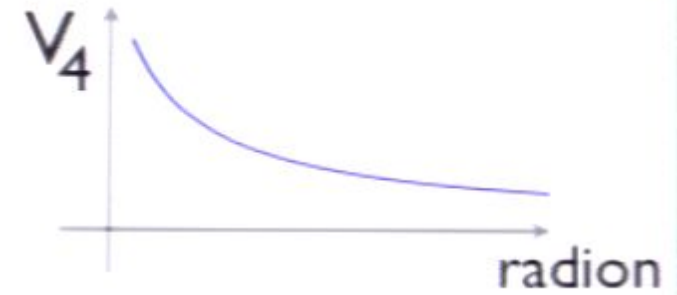
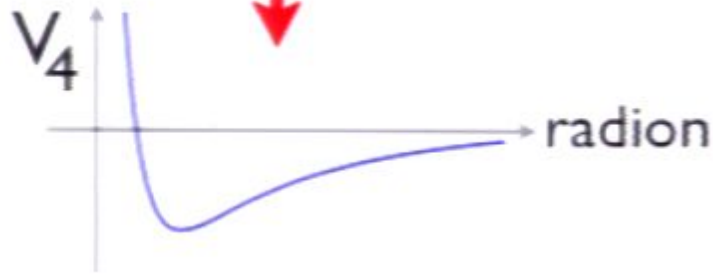


# curvature

medium-range, attractive



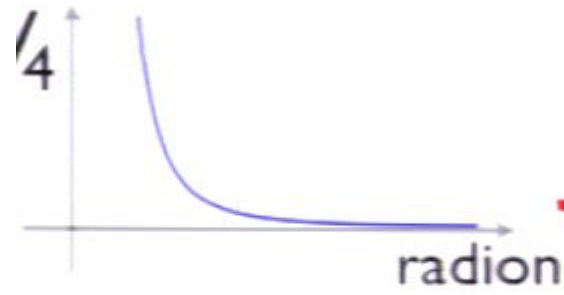
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long-range, repulsive





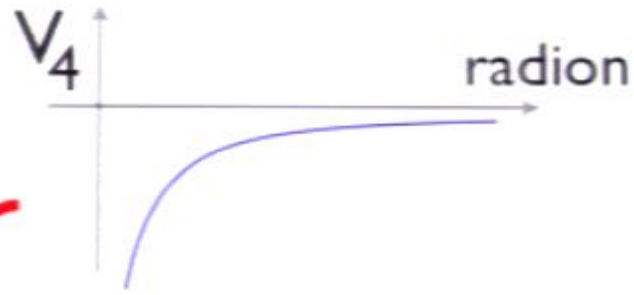
# flux

short-range, repulsive

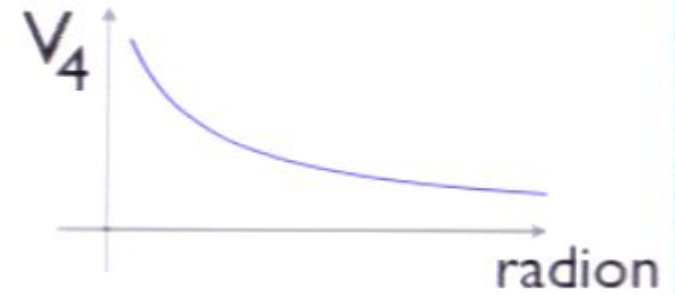
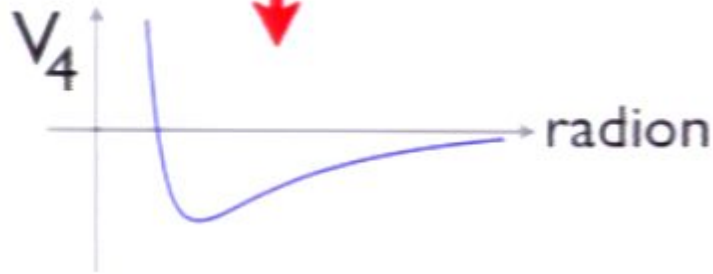


# curvature

medium-range, attractive

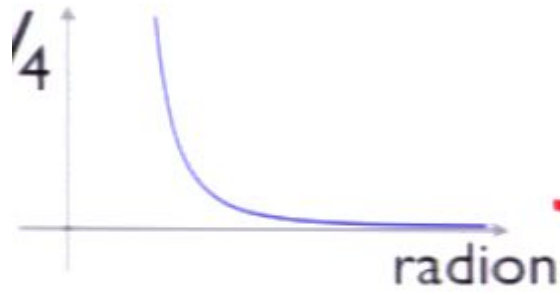


**6D +ve c.c.**  
long-range, repulsive



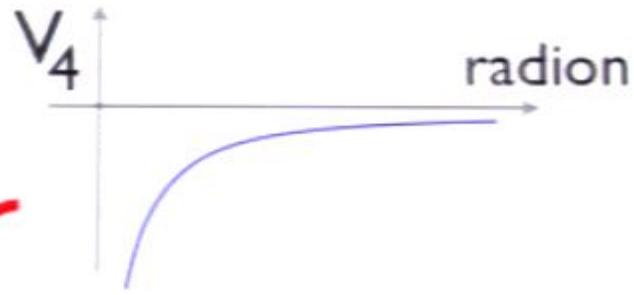
# flux

short-range, repulsive

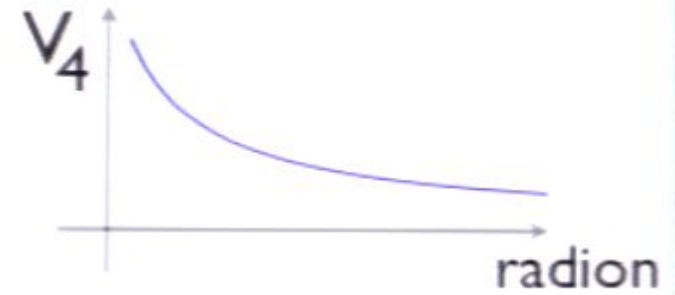
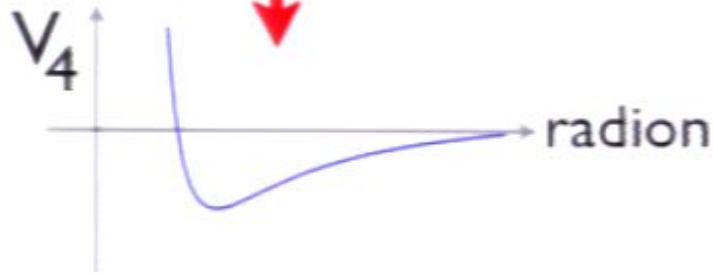


# curvature

medium-range, attractive

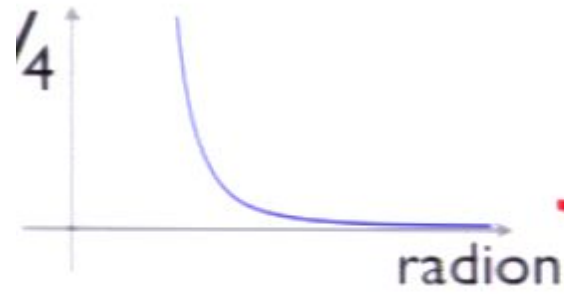


**6D +ve c.c.**  
long-range, repulsive



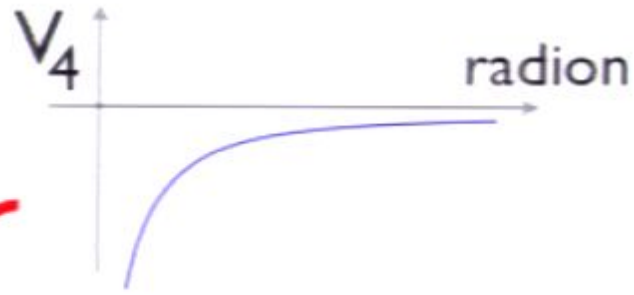
# flux

short-range, repulsive

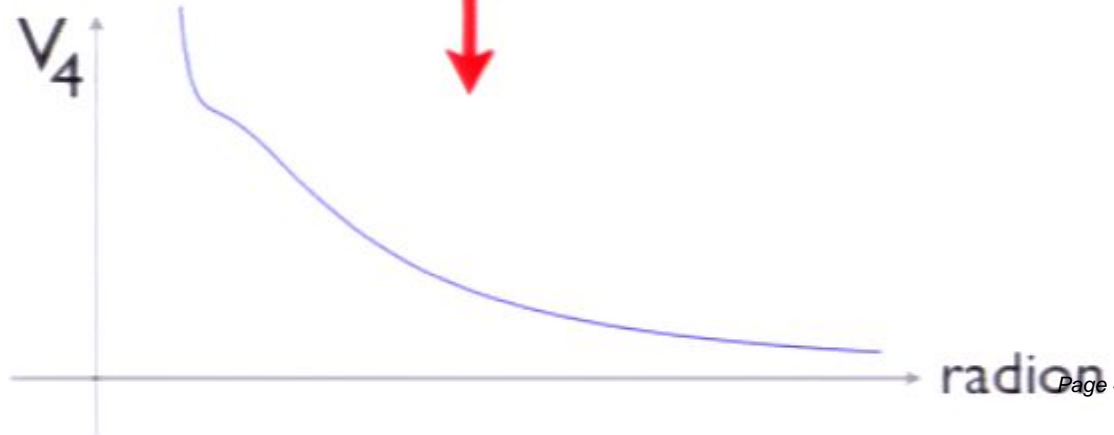
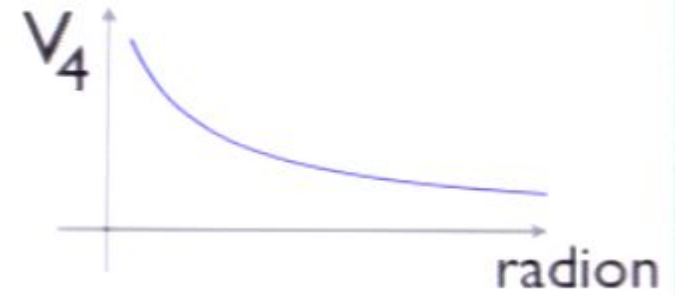
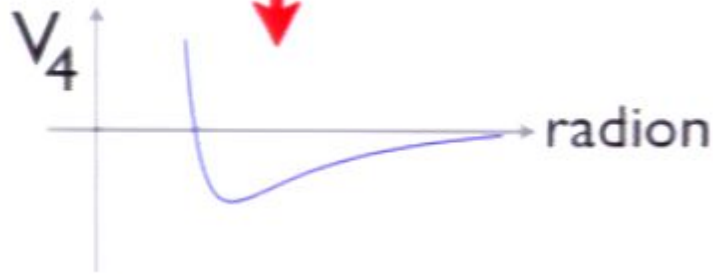


# curvature

medium-range, attractive

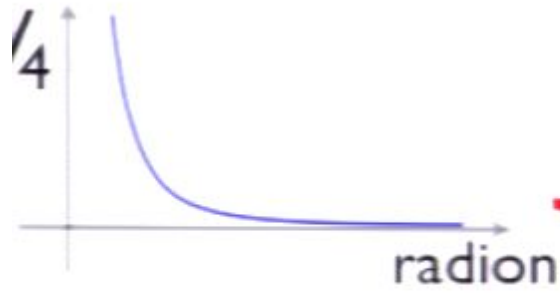


**6D +ve c.c.**  
long-range, repulsive



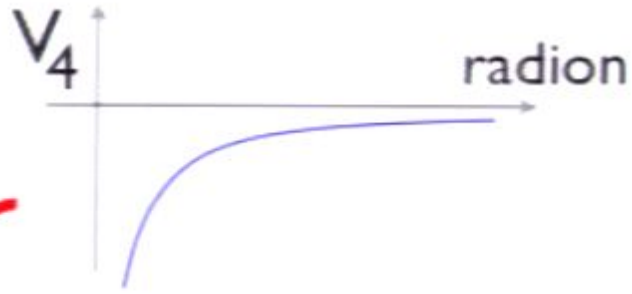
# flux

short-range, repulsive

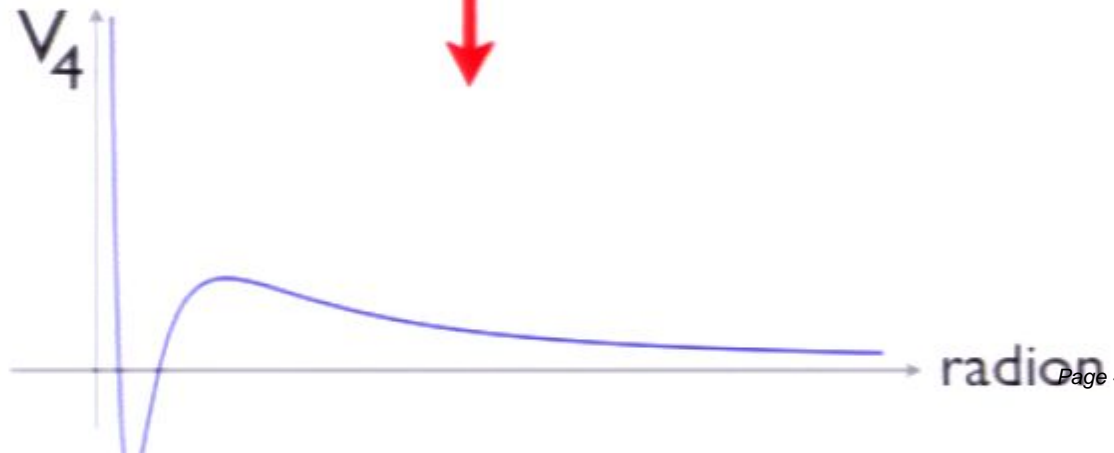
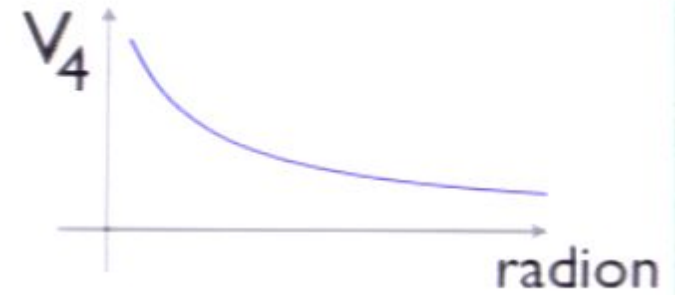
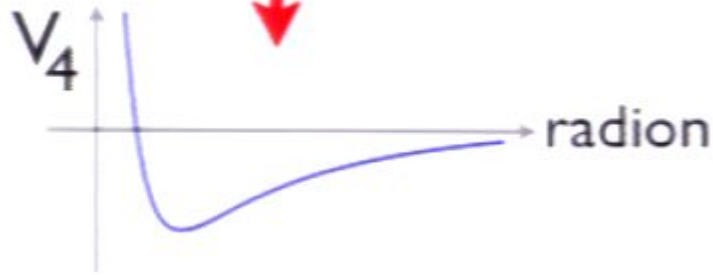


# curvature

medium-range, attractive

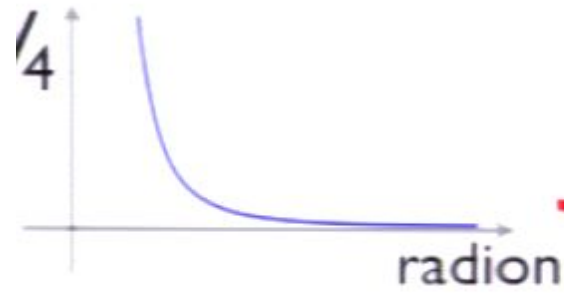


**6D +ve c.c.**  
long-range, repulsive



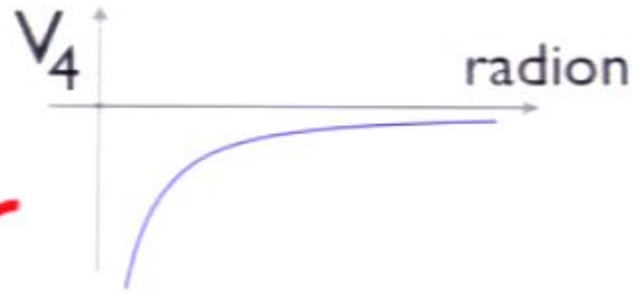
# flux

short-range, repulsive

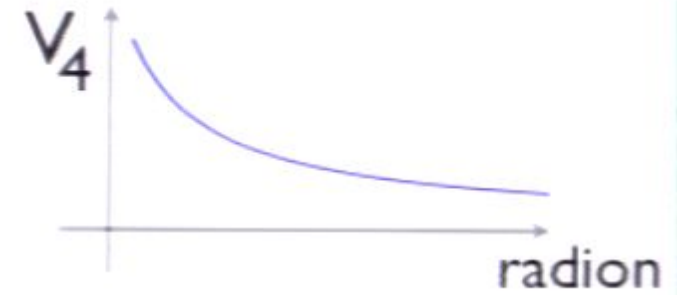
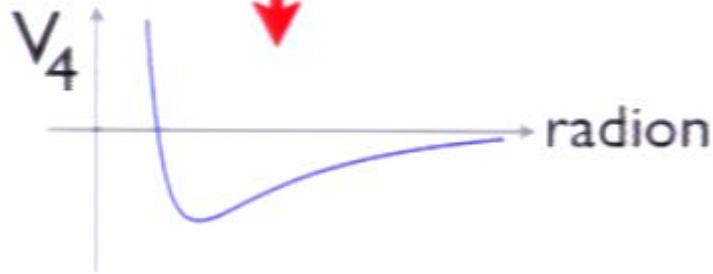


# curvature

medium-range, attractive

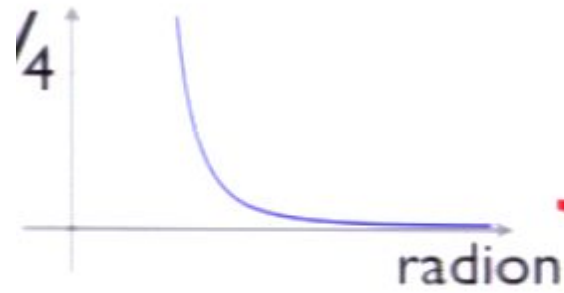


**6D +ve c.c.**  
long-range, repulsive



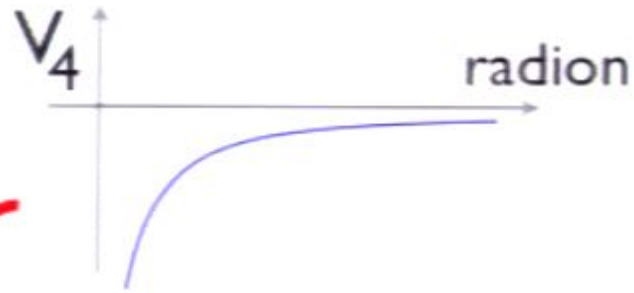
# flux

short-range, repulsive



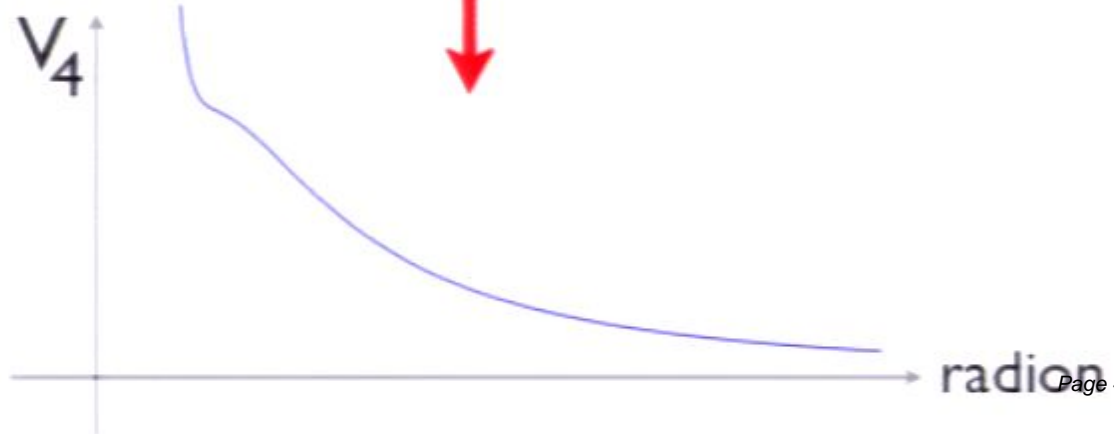
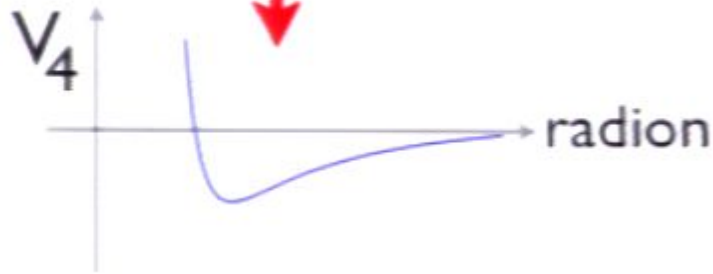
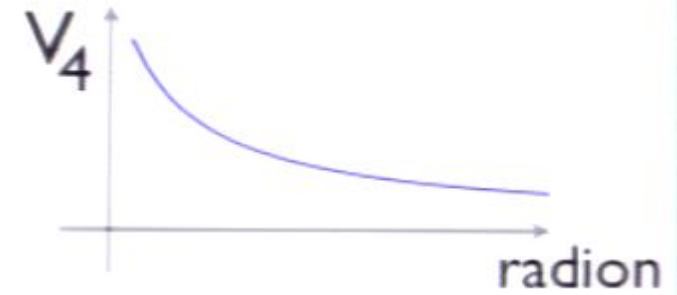
# curvature

medium-range, attractive

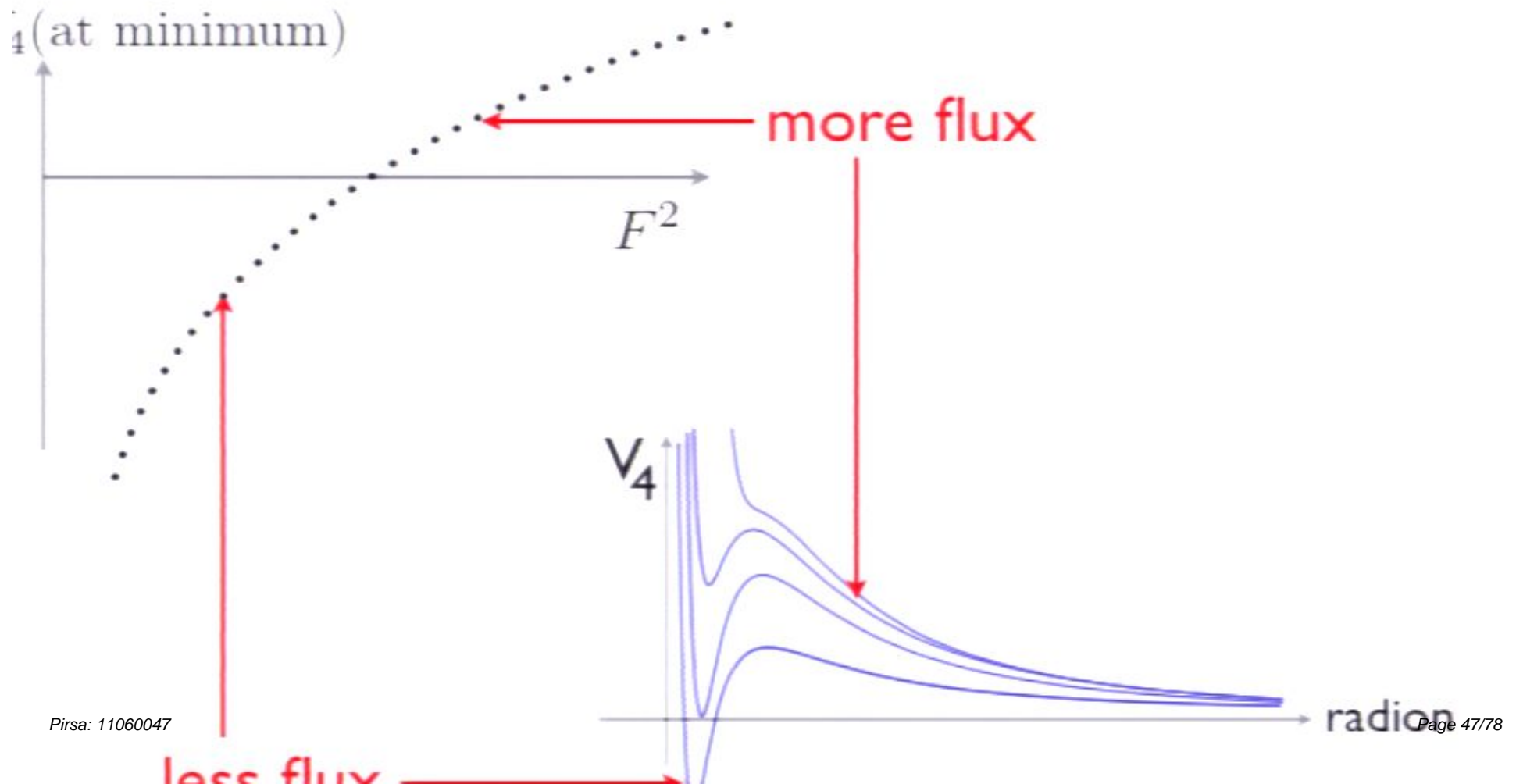


# 6D +ve c.c.

long-range, repulsive

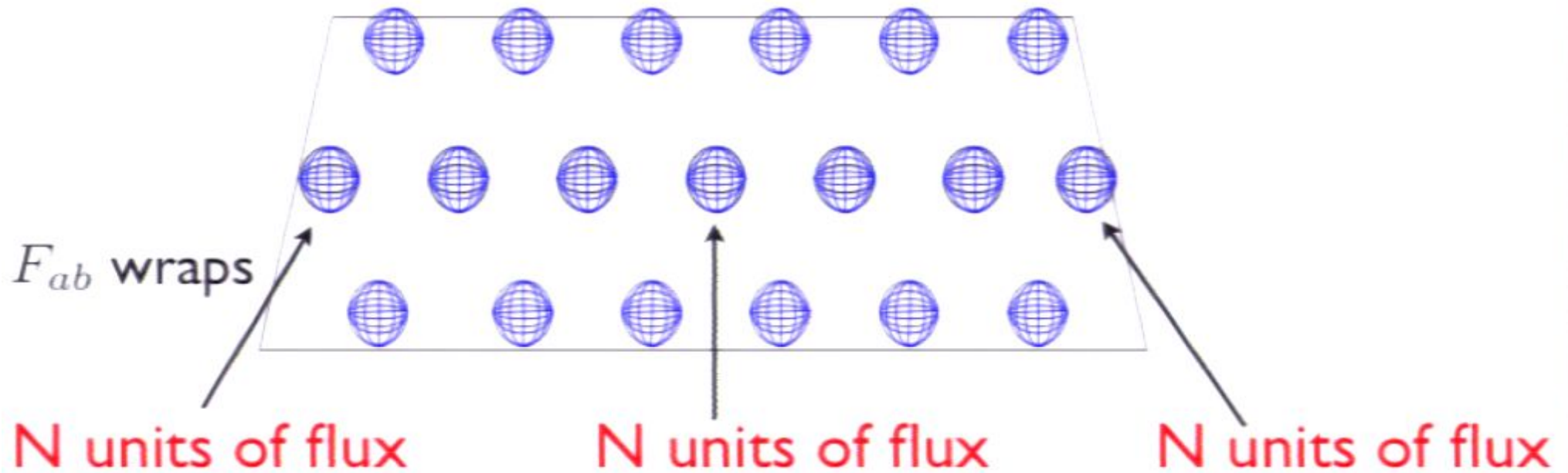


# a landscape of (discrete) flux vacua



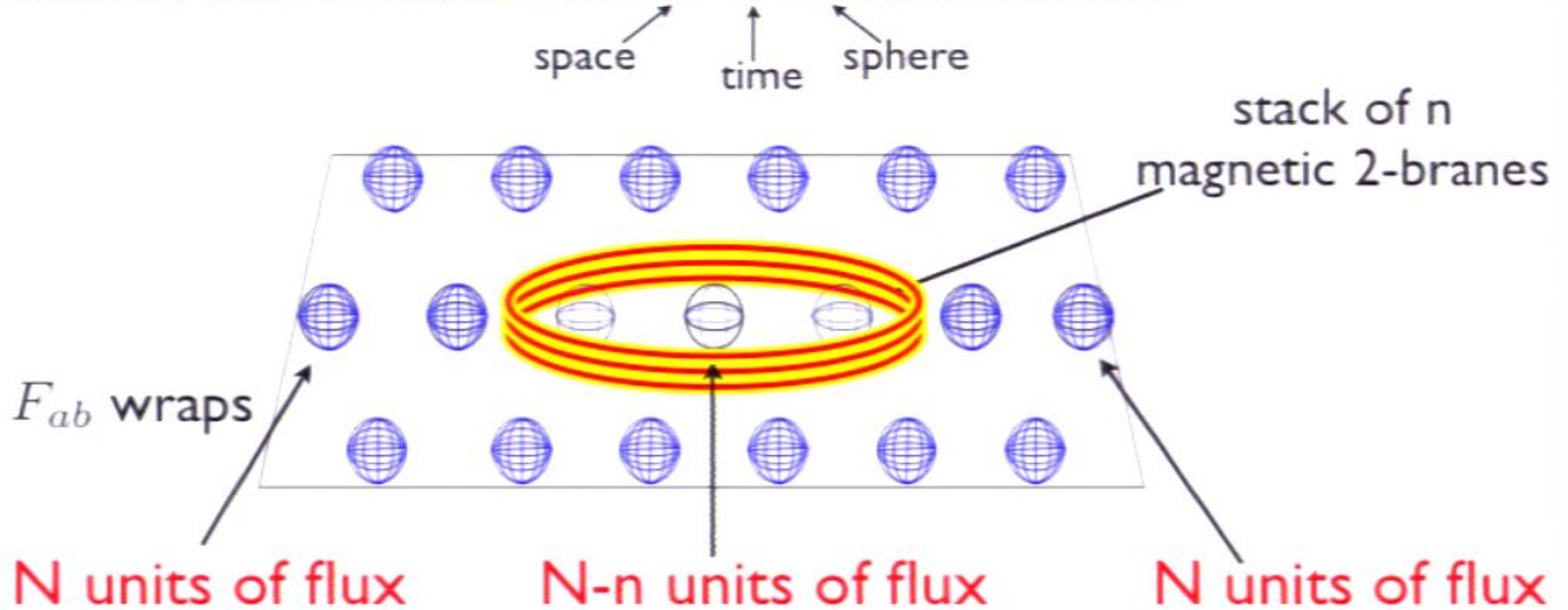
Consider the transition in  $3+1+2$  dimensions

space      time      sphere





Consider the transition in  $3+1+2$  dimensions



Consider the transition in  $3+1+2$  dimensions

space      time      sphere

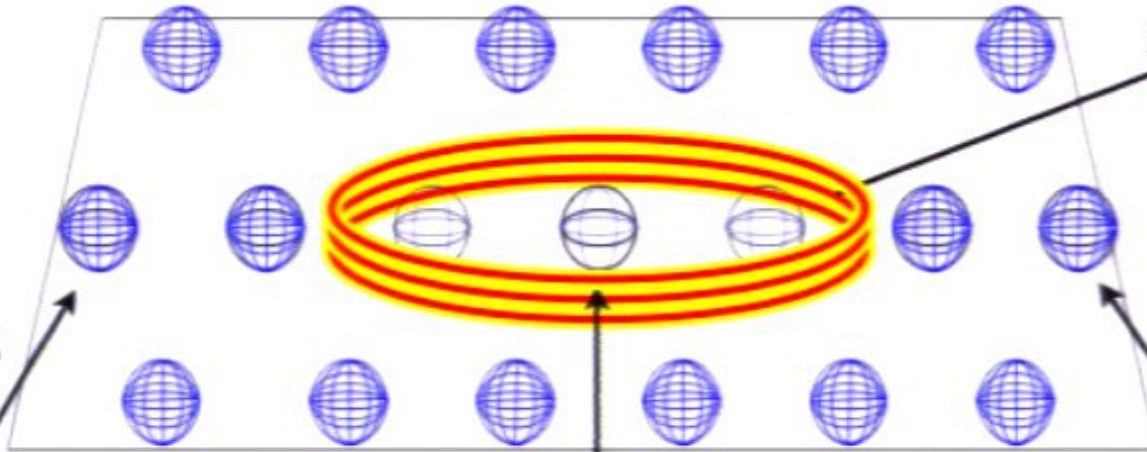
stack of  $n$   
magnetic 2-branes

$F_{ab}$  wraps

$N$  units of flux

$N-n$  units of flux

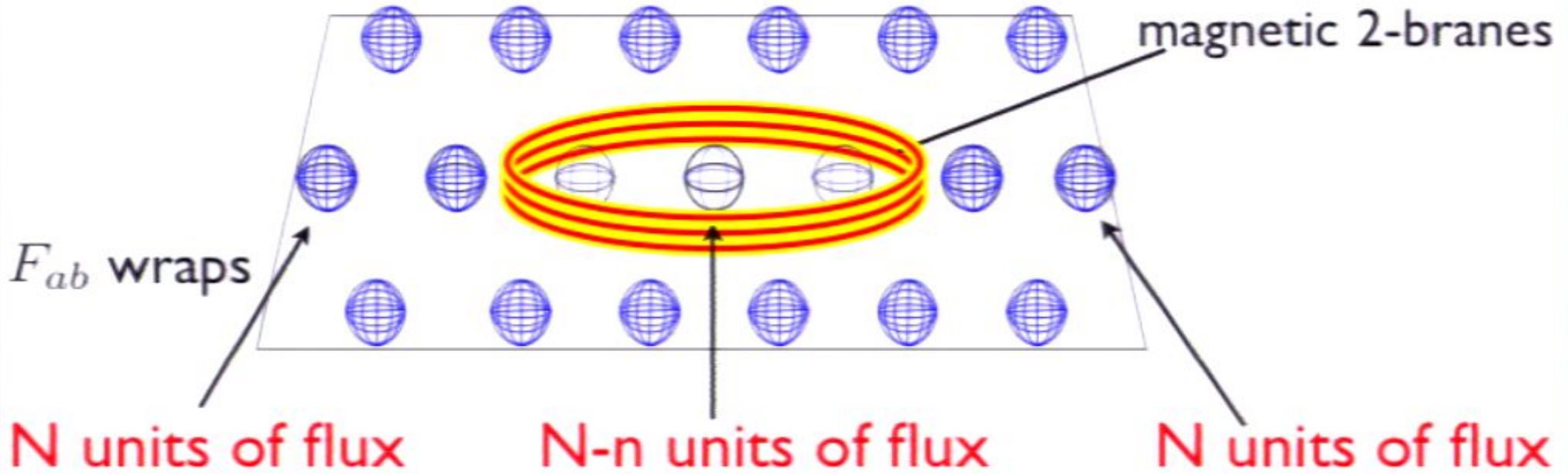
$N$  units of flux



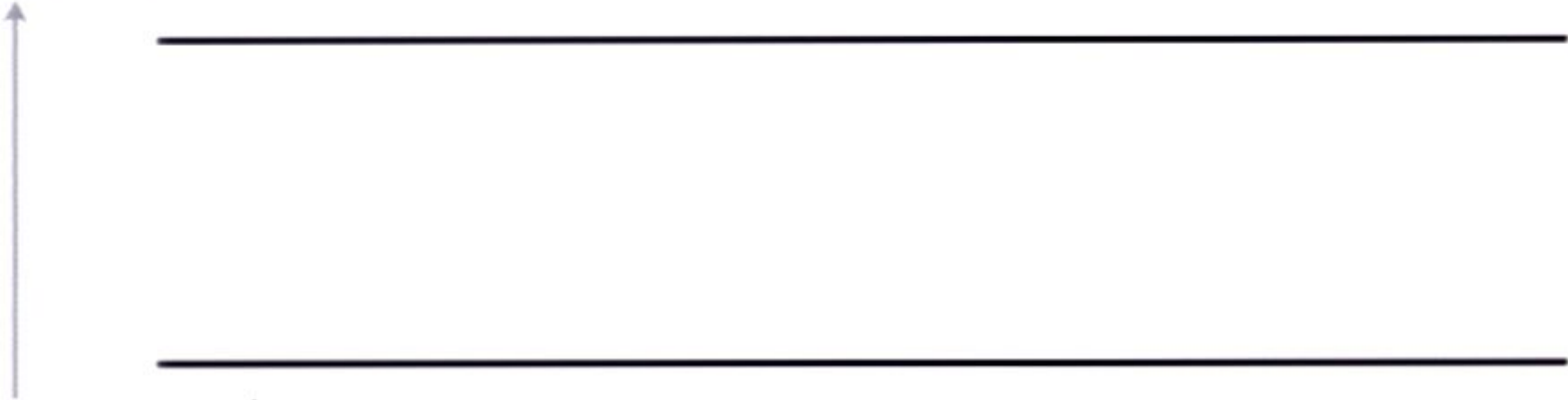
Consider the transition in  $3+1+2$  dimensions

space      time      sphere

stack of  $n$   
magnetic 2-branes



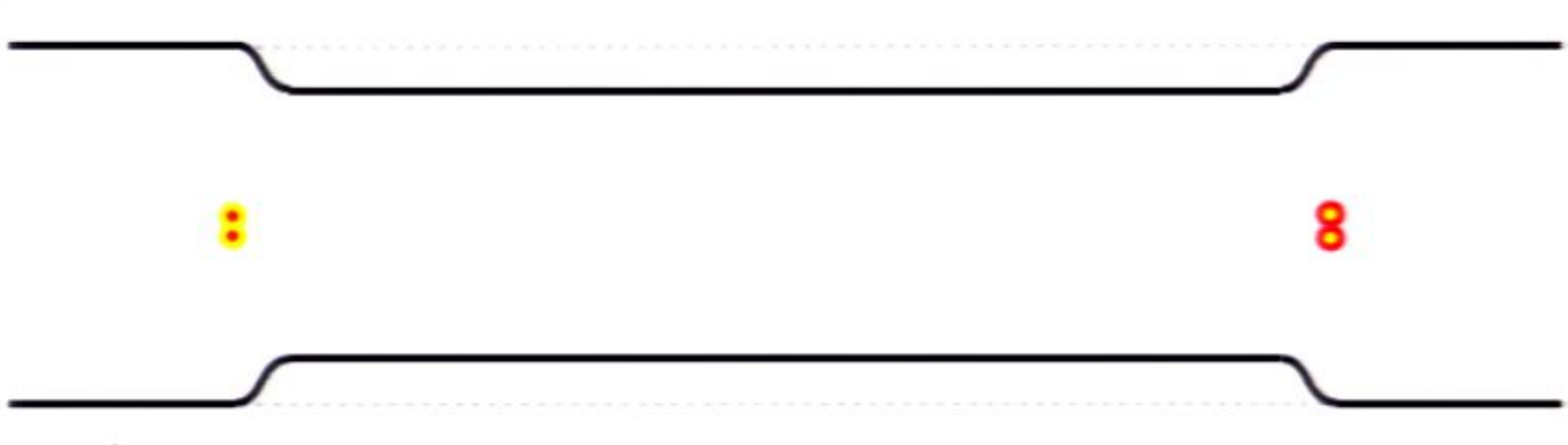
extra  
dimensions



**N units of flux**

**N units of flux**

extra  
dimensions



8

8

N units of flux

N-20 units of flux

N units of flux

extra  
dimensions

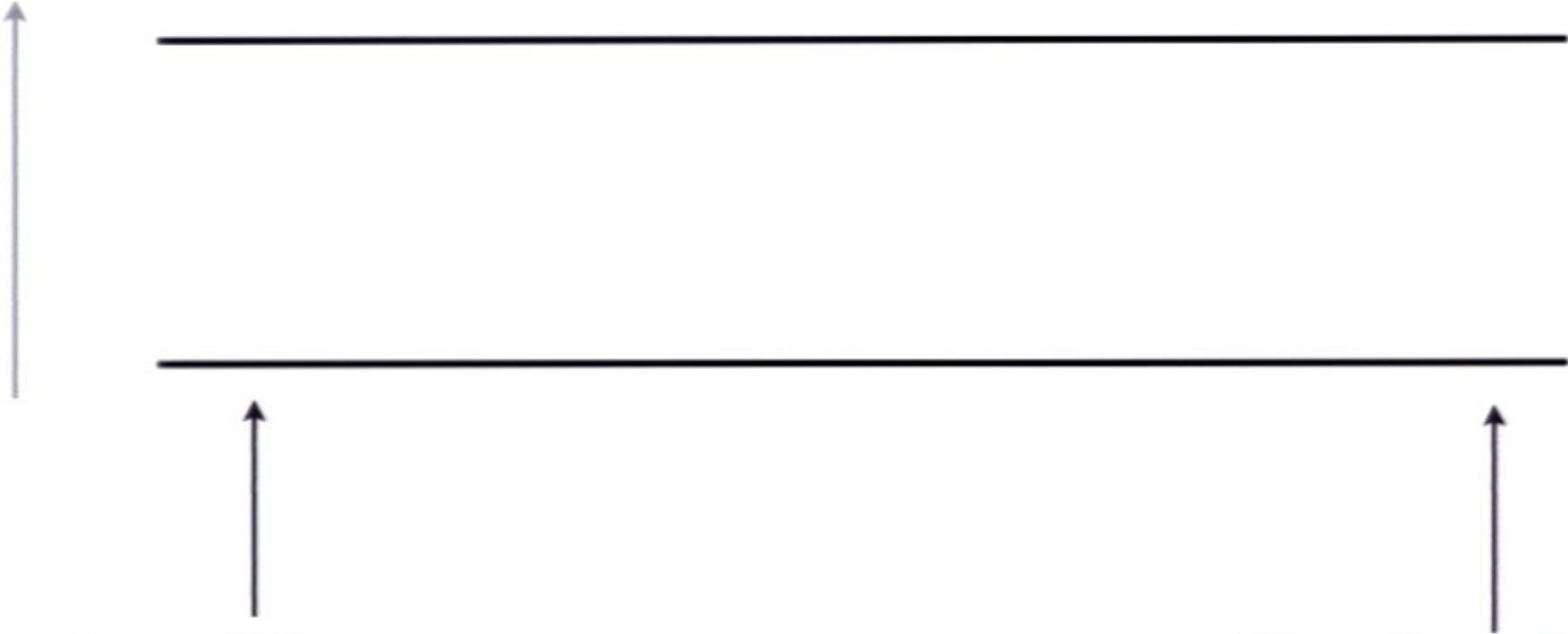


N units of flux

N-20 units of flux

N units of flux

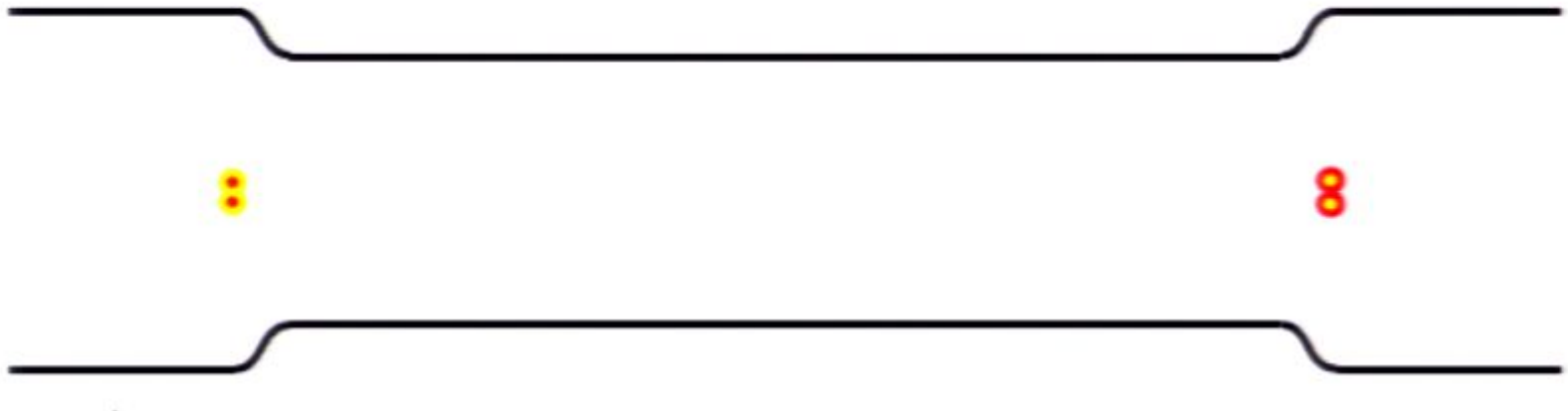
extra  
dimensions



N units of flux

N units of flux

extra  
dimensions



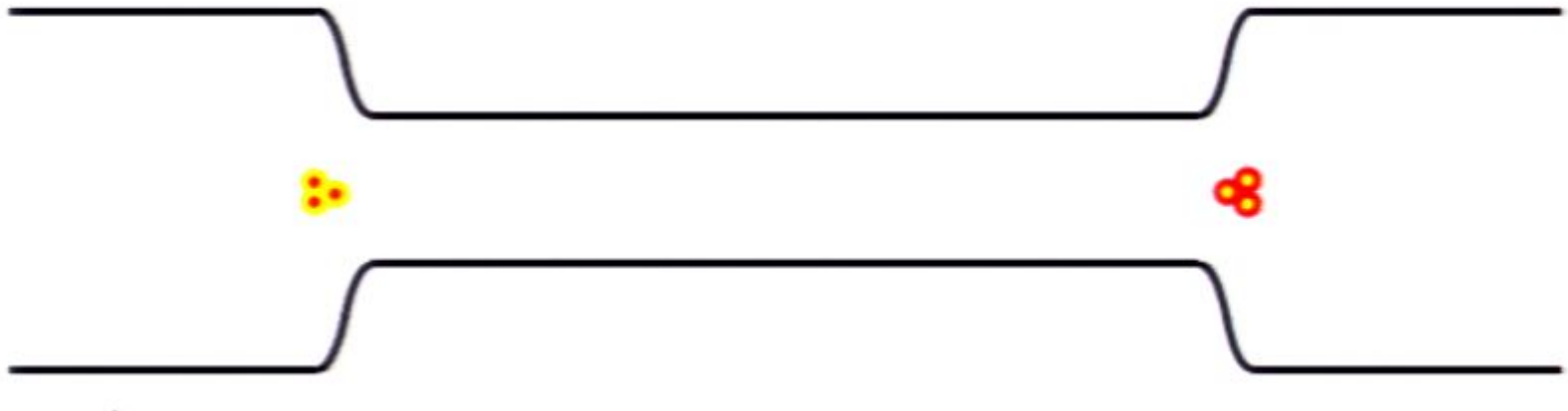
N units of flux

N-20 units of flux

N units of flux



extra  
dimensions

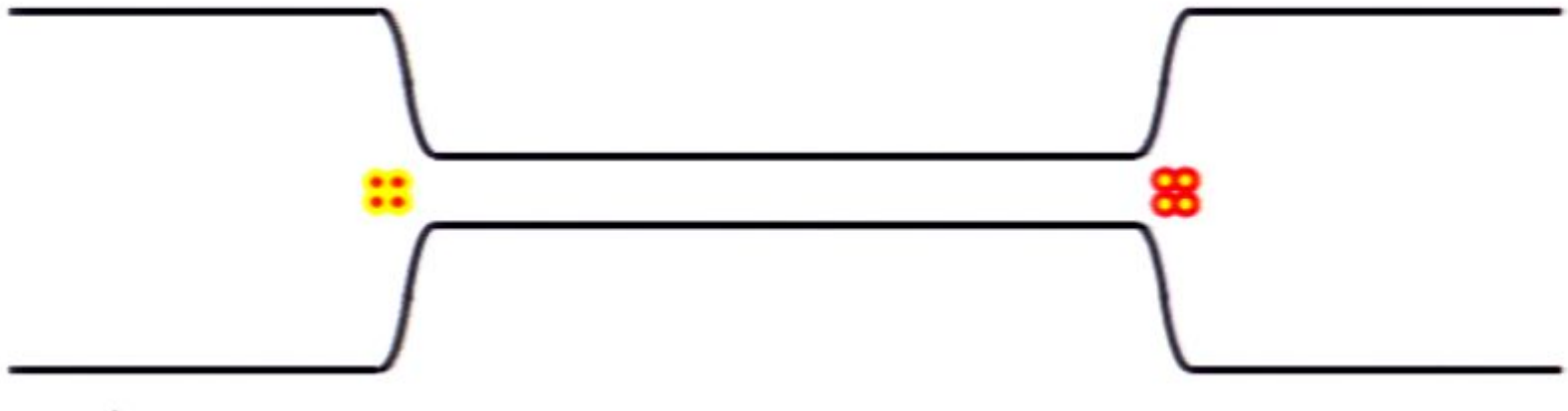


**N units of flux**

**N-30 units of flux**

**N units of flux**

extra  
dimensions

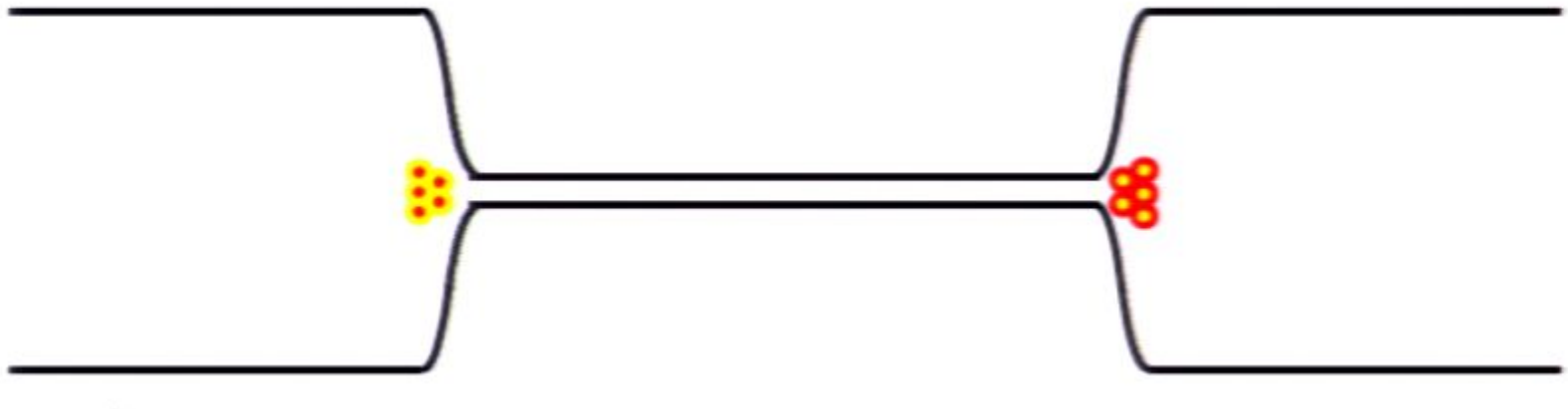


$N$  units of flux

$N-40$  units of flux

$N$  units of flux

extra  
dimensions



**N units of flux**

**N-50 units of flux**

**N units of flux**

extra  
dimensions



N units of flux

N-N units of flux

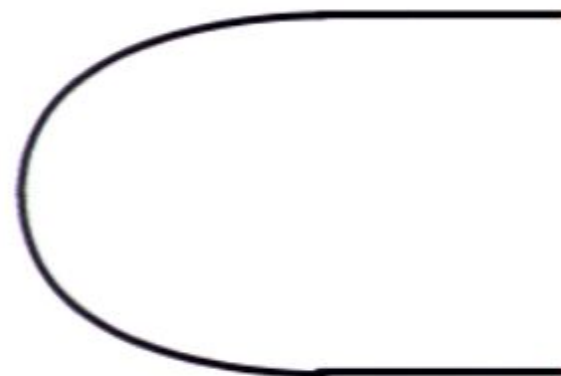
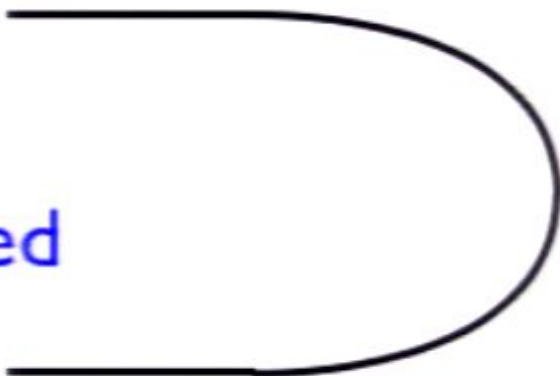
N units of flux

“bubble of nothing”

6d  
stabilized



5d  
unstabilized

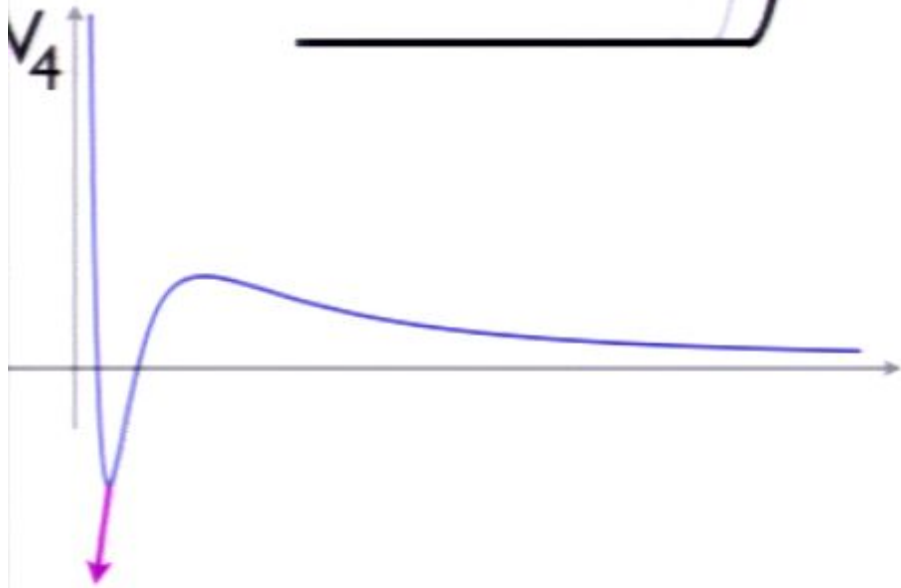
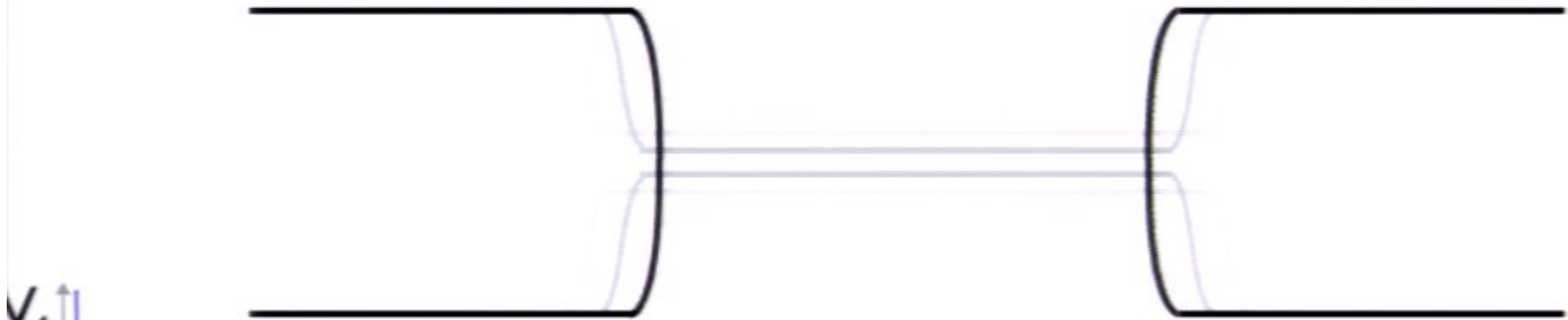




in the limit that **ALL** flux discharged:

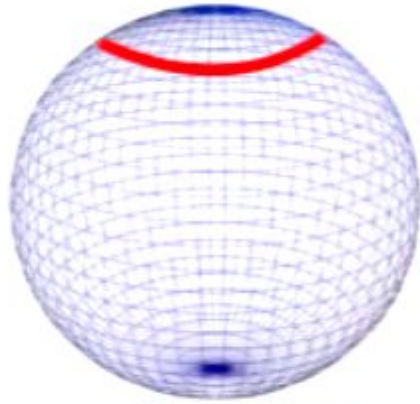
1. Extra dimensions shrink to zero size

1. What about the **3-volume** of a slice through the bubble?  
like an infinitely thin pancake?

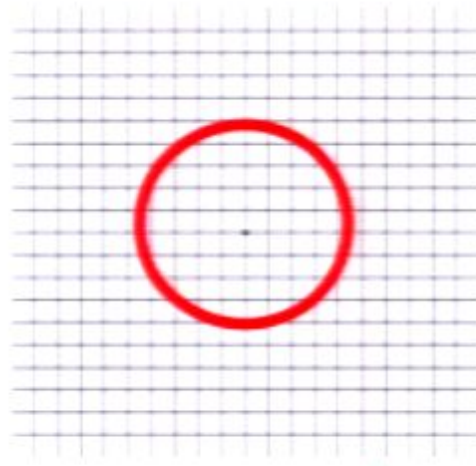


negative  $V$   
↓  
negative curvature  
(AdS)

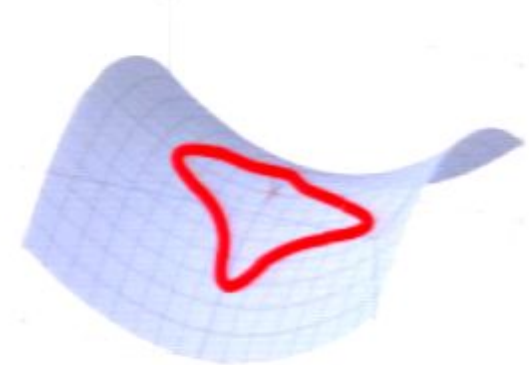
1. What about the **3-volume** of a slice through the bubble?  
like an infinitely thin pancake?



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

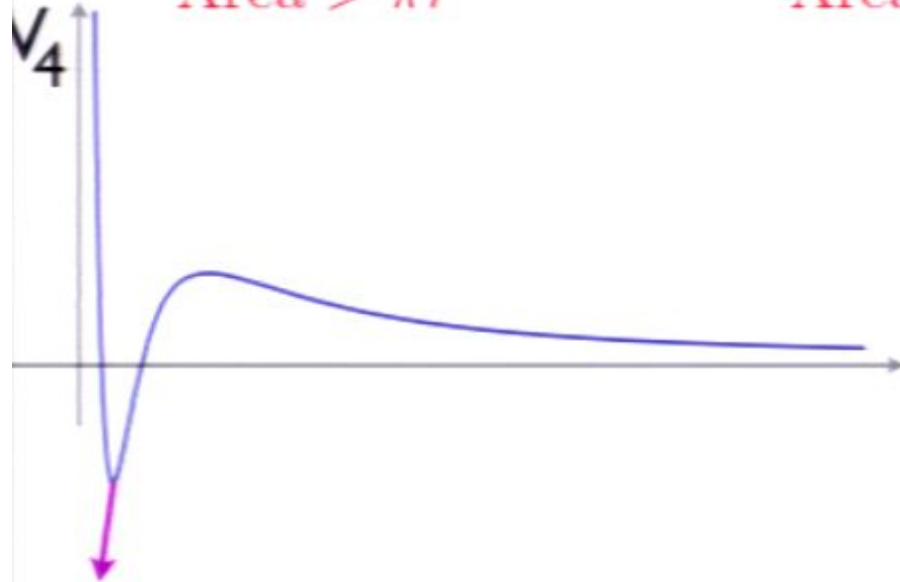


$$\text{Area} = \pi r^2$$



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

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



negative V



negative curvature  
(AdS)

1. What about the **3-volume** of a slice through the bubble?  
like an infinitely thin pancake?



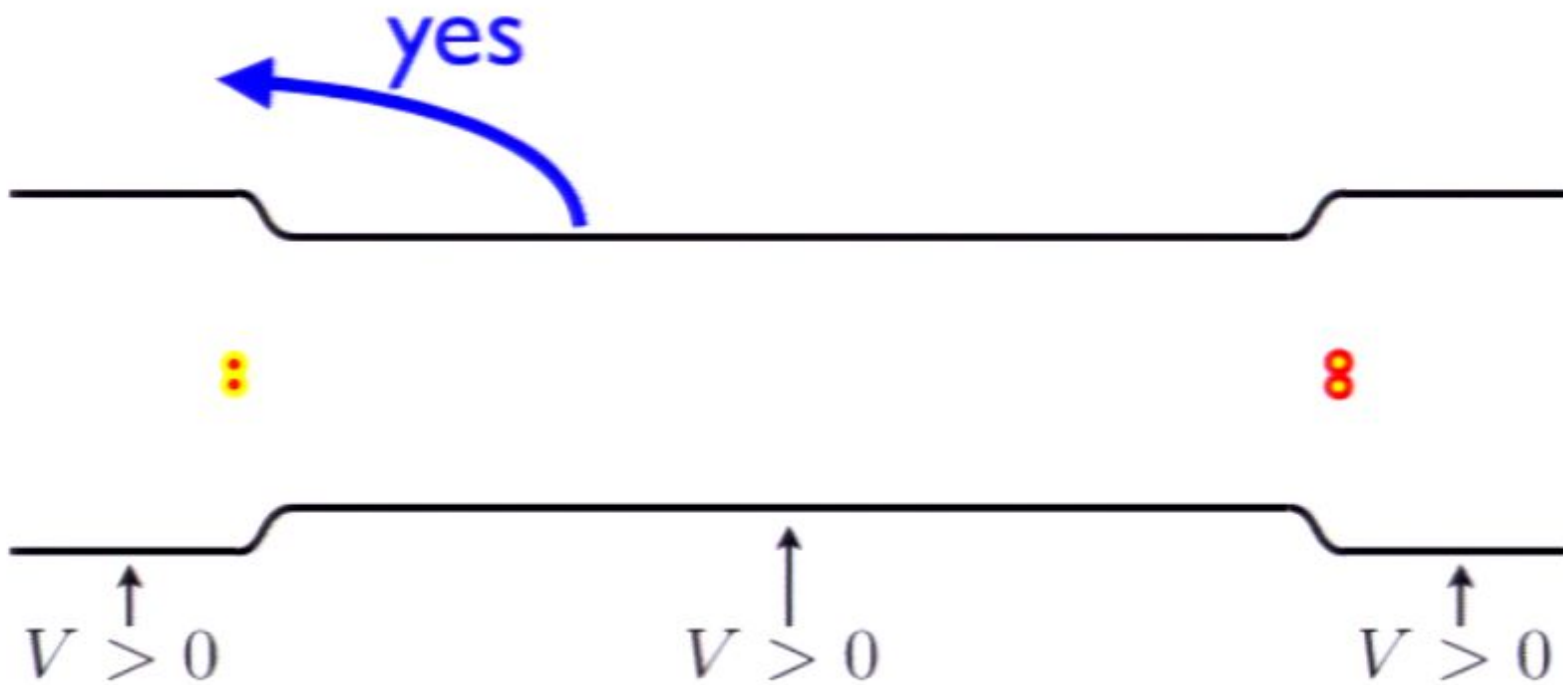
'Nothing' is AdS space (in the limit as  $l_{\text{AdS}} \rightarrow 0$ )

The SAME instanton governs tunneling in both directions

Uptunneling is possible from de Sitter

Uptunneling is **impossible** from Minkowski or AdS

'Nothing' is AdS space (in the limit as  $l_{\text{Planck}} \rightarrow 0$ )

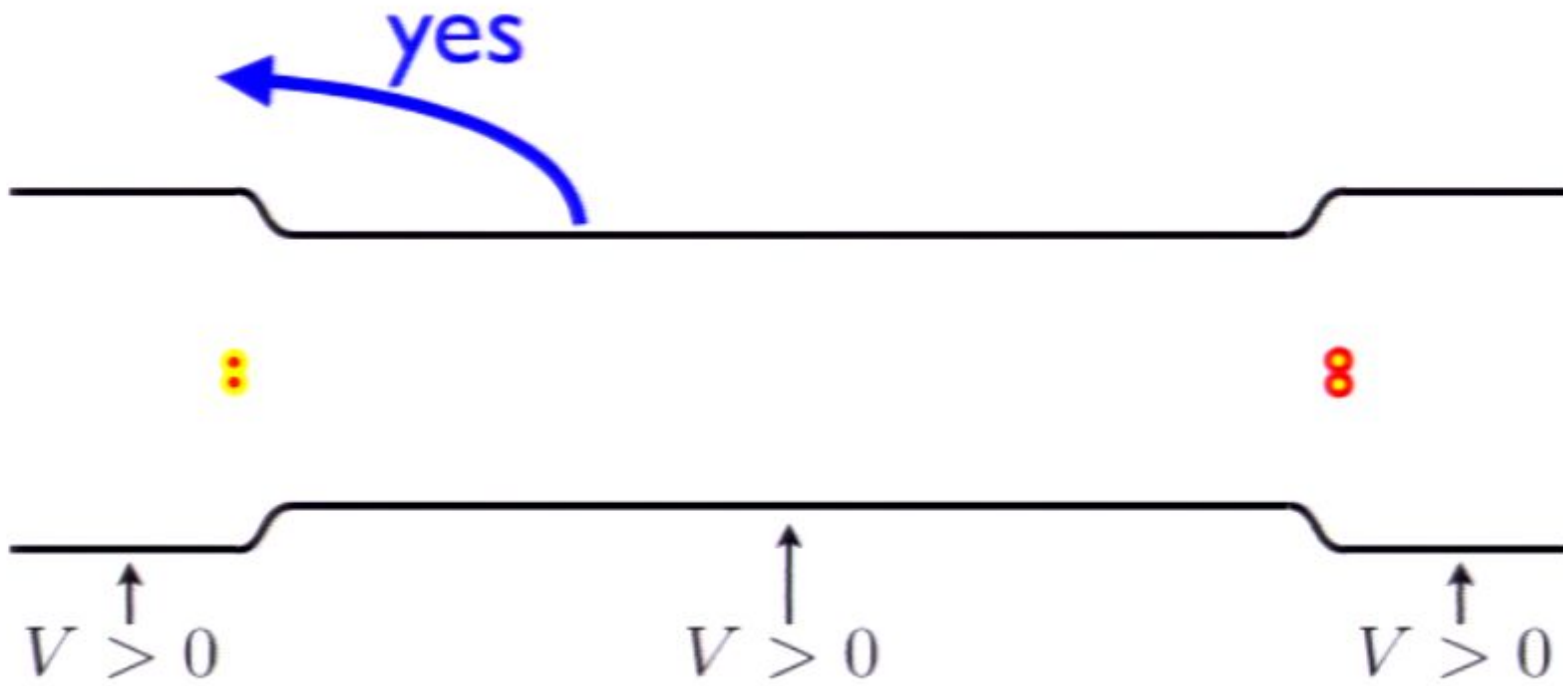


The SAME instanton governs tunneling in both directions

Uptunneling is possible from de Sitter

Uptunneling is impossible from Minkowski or AdS

'Nothing' is AdS space (in the limit as  $l_{\text{AdS}} \rightarrow 0$ )

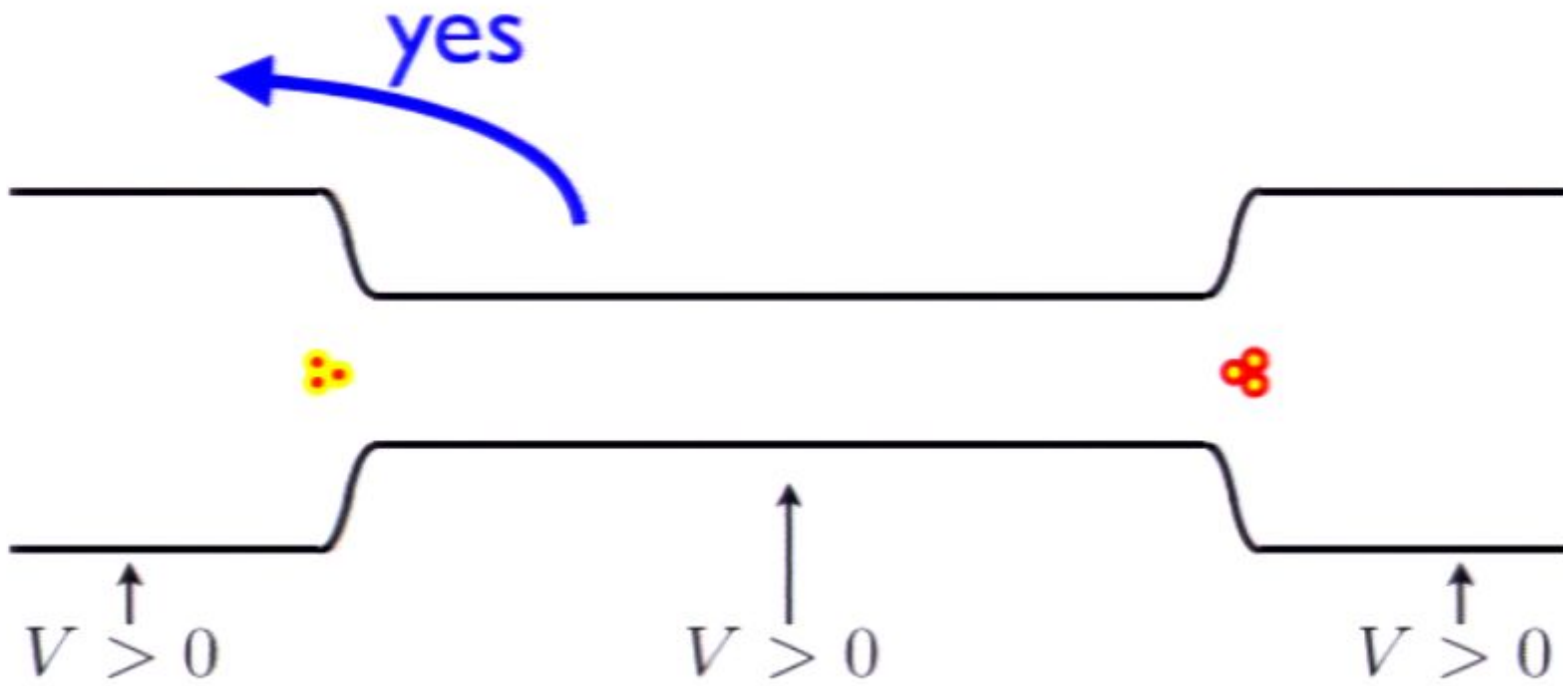


The SAME instanton governs tunneling in both directions

Uptunneling is possible from de Sitter

Uptunneling is impossible from Minkowski or AdS

'Nothing' is AdS space (in the limit as  $l_{\text{max}} \rightarrow 0$ )

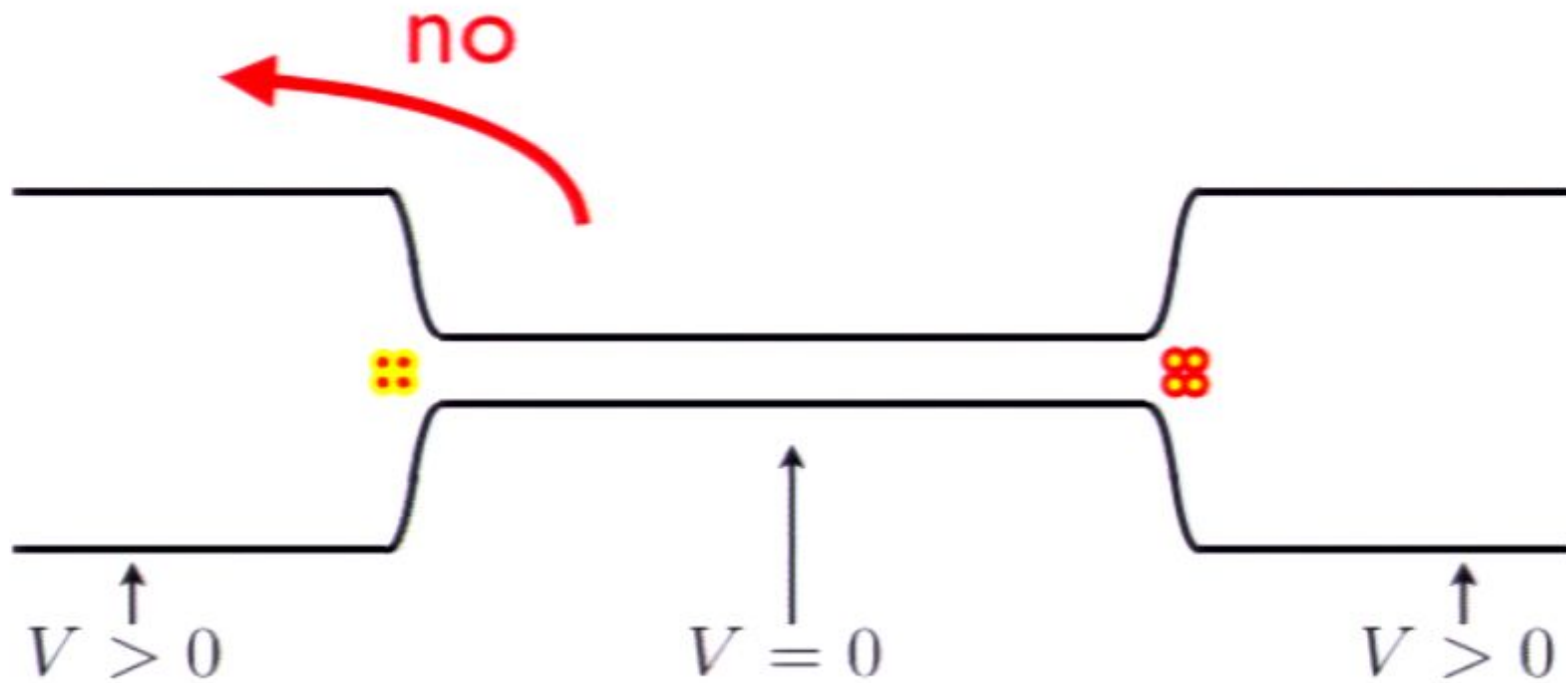


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Uptunneling is impossible from Minkowski or AdS

'Nothing' is AdS space (in the limit as  $l_{\text{AdS}} \rightarrow 0$ )

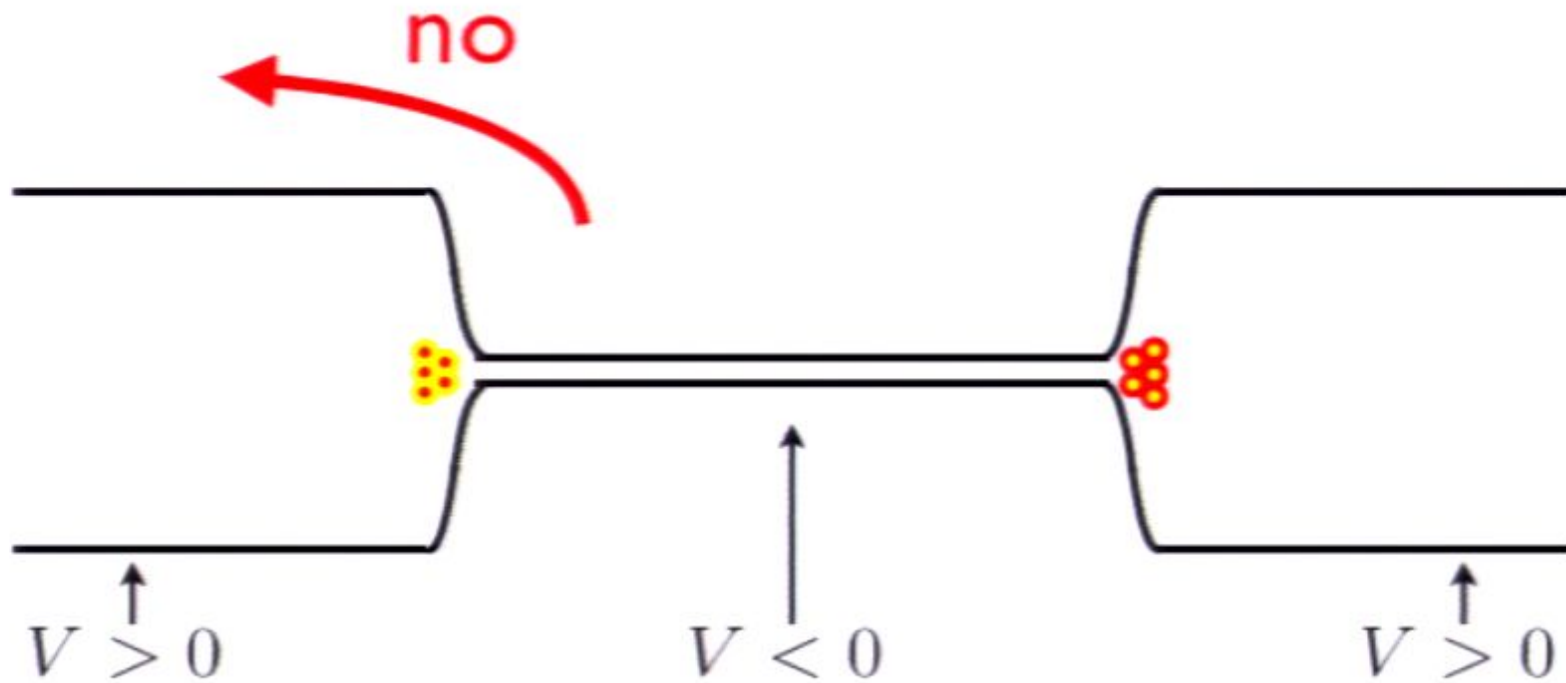


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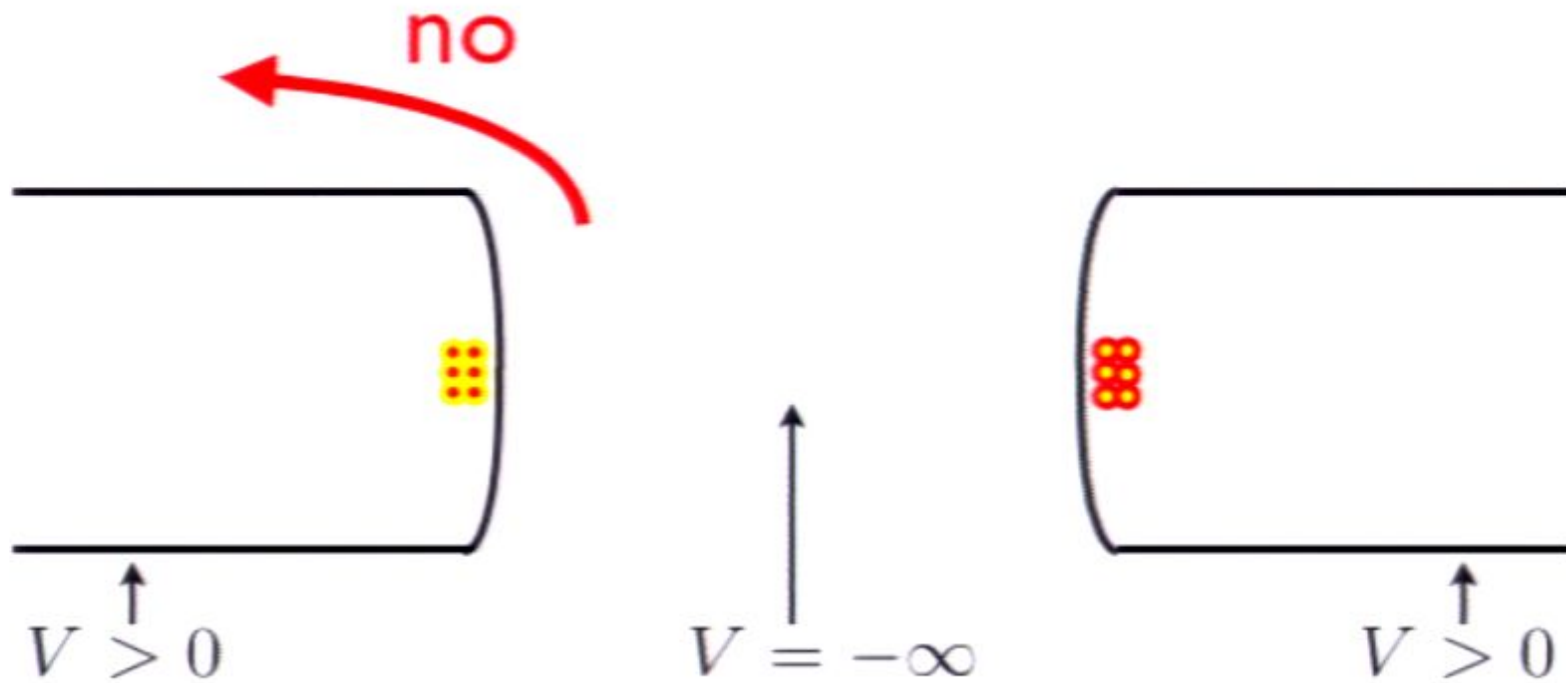


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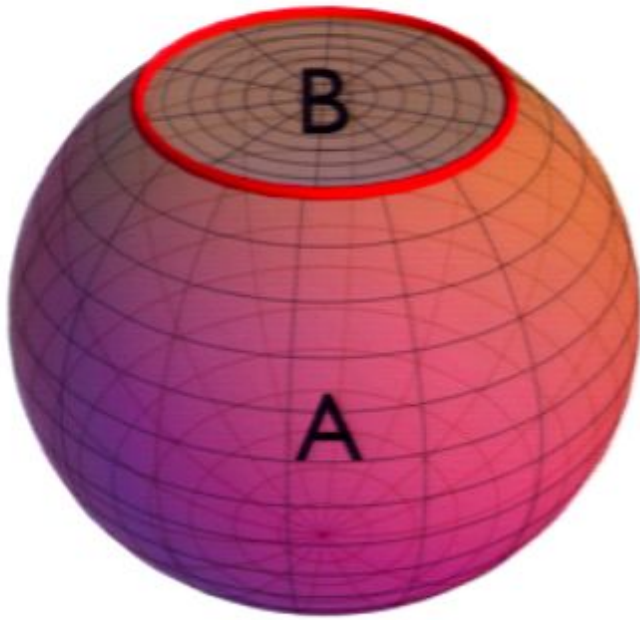
The SAME instanton governs tunneling in both directions

Uptunneling is possible from de Sitter

Uptunneling is impossible from Minkowski or AdS

'Nothing' is AdS space (in the limit as  $l_{\text{AdS}} \rightarrow 0$ )





$$S_E(\text{instanton}) = \text{finite}$$

$$S_E(\text{de Sitter}) = -\frac{24\pi^2 M_{\text{Pl}}^4}{V}$$

$$S_E(\text{Minkowski}) = -\infty$$

$$S_E(\text{AdS}) = -\infty$$

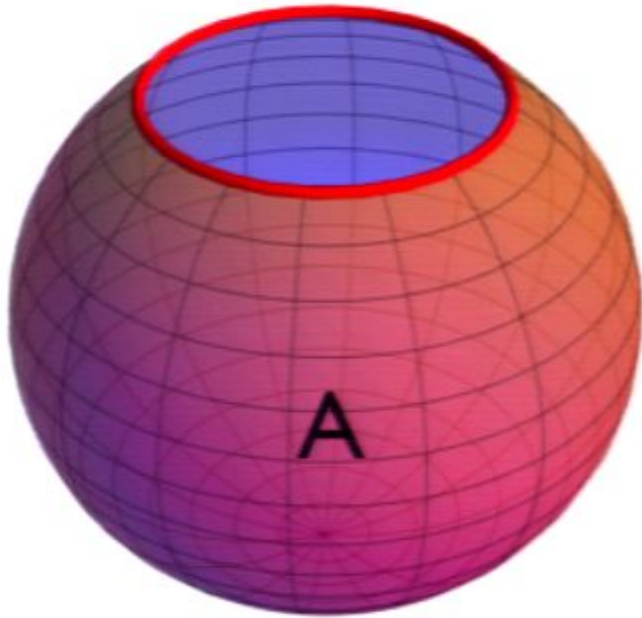
$$\Gamma_{B \rightarrow A} = \exp[-S_E(\text{instanton}) + S_E(B)]$$

The SAME instanton governs tunneling in both directions

Uptunneling is possible from de Sitter

Uptunneling is **impossible** from Minkowski or AdS

'Nothing' is AdS space (in the limit as  $\ell_{\text{AdS}} \rightarrow 0$ )



$$S_E(\text{instanton}) = \text{finite}$$

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$$S_E(\text{AdS}) = -\infty$$

$$S_E(\text{nothing}) = -\infty$$

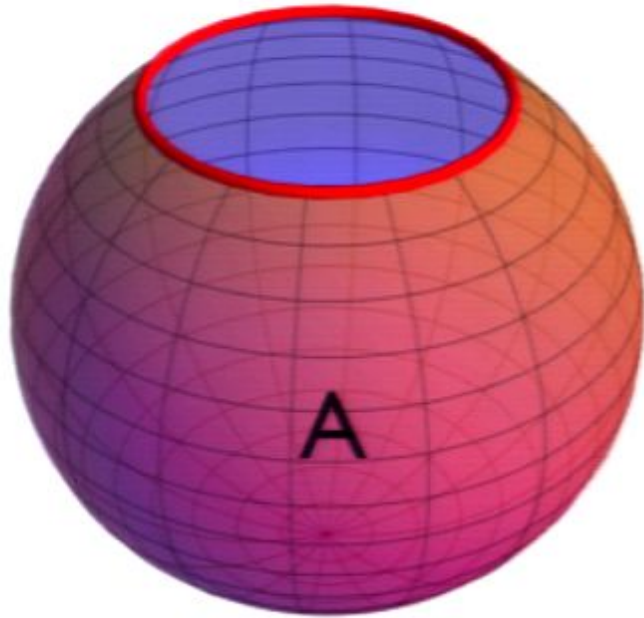
$$\Gamma_{\text{nothing} \rightarrow A} = \exp[-S_E(\text{instanton}) + S_E(\text{nothing})] = 0$$

The SAME instanton governs tunneling in both directions

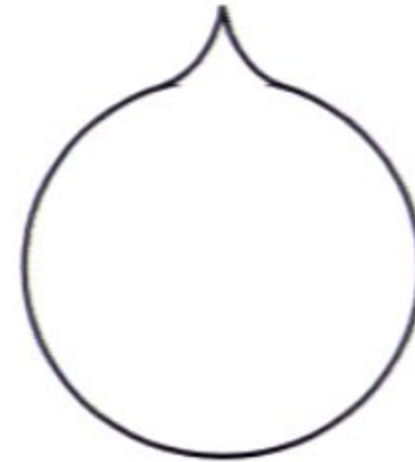
Uptunneling is possible from de Sitter

Uptunneling is **impossible** from Minkowski or AdS

'Nothing' is AdS space (in the limit as  $\ell_{\text{AdS}} \rightarrow 0$ )



4D  
Einstein  
Frame



Smooth 6D metric

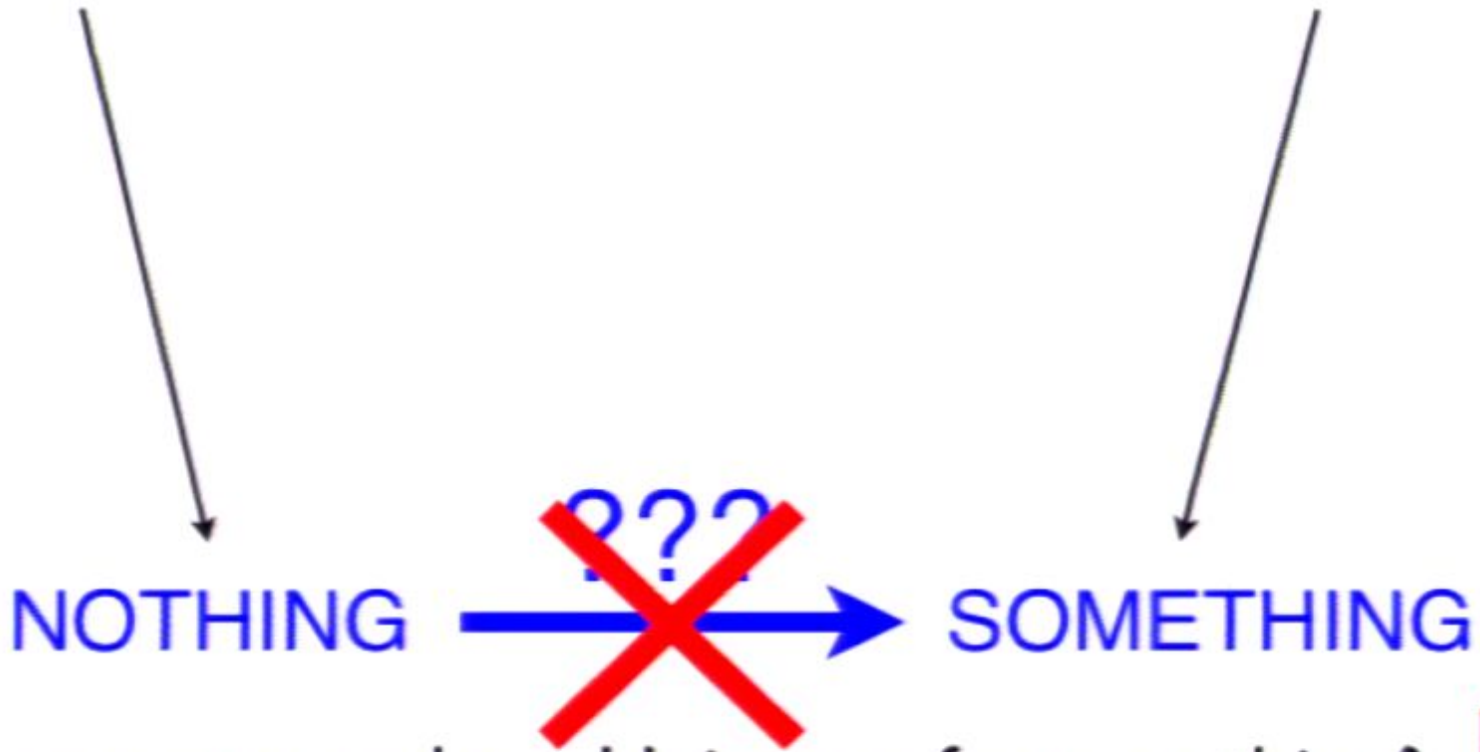
Singular 4D metric



Bubble of nothing instanton = Hawking-Turok instanton

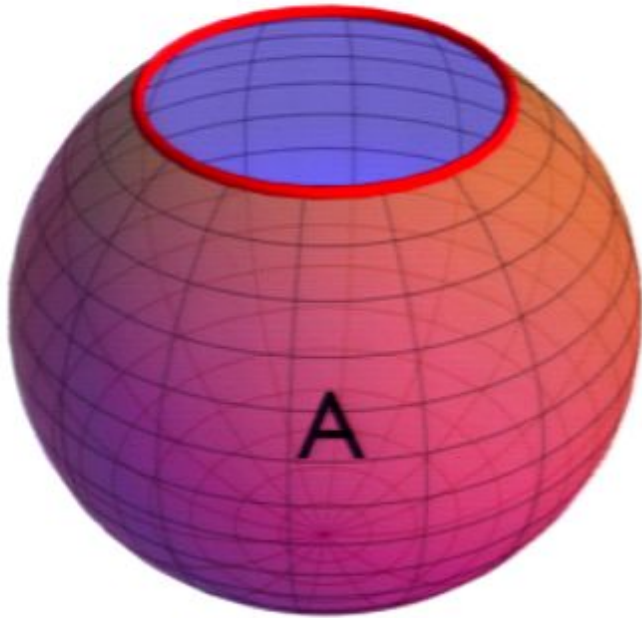
NOT empty spacetime  
literally nothing  
no space  
no time

an open Universe  
a la Hawking-Turok



can you make a Universe from nothing?

**no**



$$S_E(\text{instanton}) = \text{finite}$$

$$S_E(\text{de Sitter}) = -\frac{24\pi^2 M_{\text{Pl}}^4}{V}$$

$$S_E(\text{Minkowski}) = -\infty$$

$$S_E(\text{AdS}) = -\infty$$

$$S_E(\text{nothing}) = -\infty$$

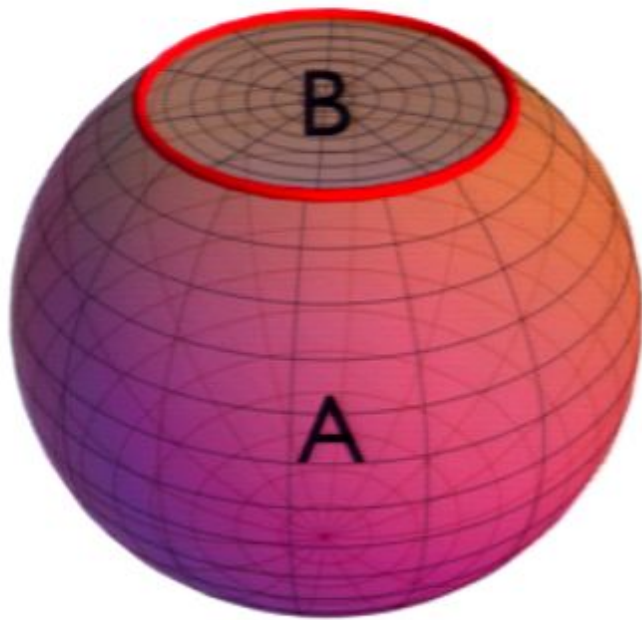
$$\Gamma_{\text{nothing} \rightarrow A} = \exp[-S_E(\text{instanton}) + S_E(\text{nothing})] = 0$$

The SAME instanton governs tunneling in both directions

Uptunneling is possible from de Sitter

Uptunneling is **impossible** from Minkowski or AdS

'Nothing' is AdS space (in the limit as  $\ell_{\text{AdS}} \rightarrow 0$ )



$$S_E(\text{instanton}) = \text{finite}$$

$$S_E(\text{de Sitter}) = -\frac{24\pi^2 M_{\text{Pl}}^4}{V}$$

$$S_E(\text{Minkowski}) = -\infty$$

$$S_E(\text{AdS}) = -\infty$$

$$\Gamma_{B \rightarrow A} = \exp[-S_E(\text{instanton}) + S_E(B)]$$

The SAME instanton governs tunneling in both directions

Uptunneling is possible from de Sitter

Uptunneling is **impossible** from Minkowski or AdS

'Nothing' is AdS space (in the limit as  $\ell_{\text{cosm}} \rightarrow 0$ )