A New Mechanism of Cosmological Bubble Nucleation

aka How to Run Through Walls

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arXiv : 0907:3234
w/ J.T. Giblin, L. Hui, I-S. Yang
arXiv:0910:xxxx

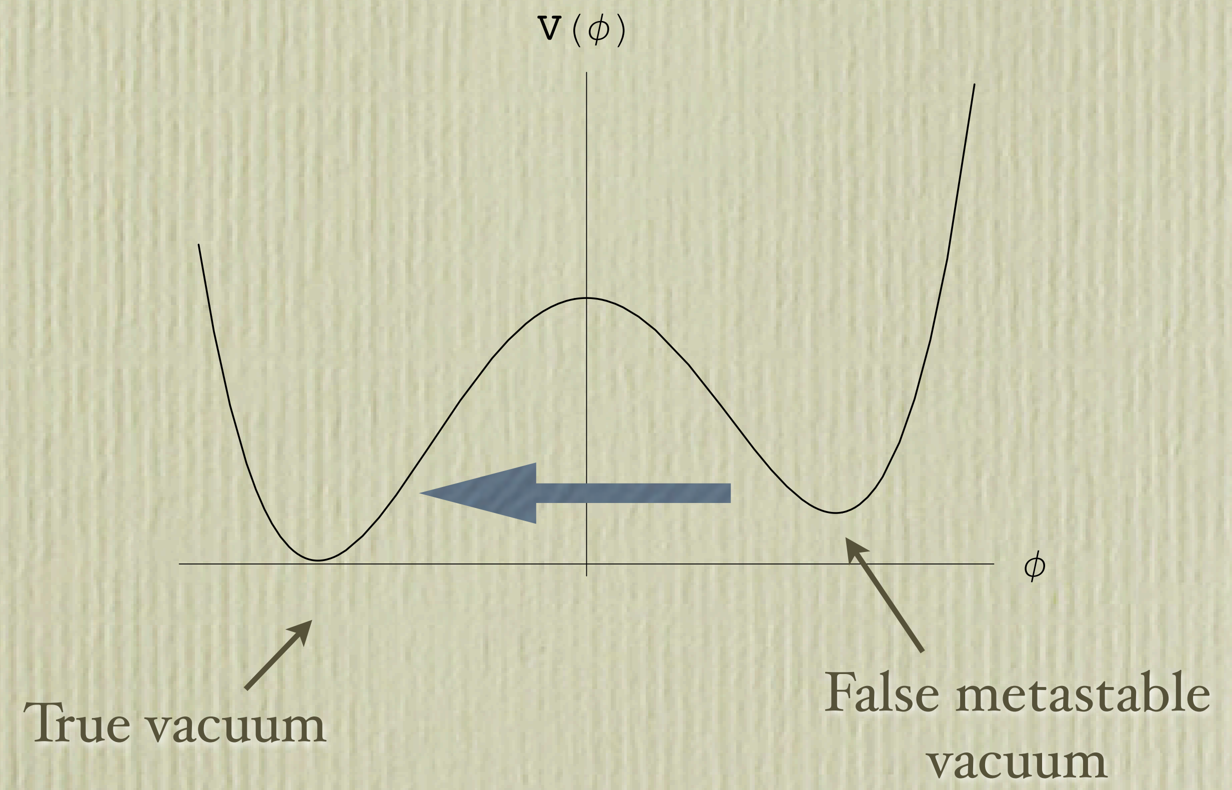
HEP Seminar (Nov 20 2009)
Cornell University

Outline

- The physics of Quantum Bubble Nucleation
- 3+1D Numerical Simulation of Cosmological Bubble Collisions : Nucleation
- Analytic description of bubble wall transition in 1+1D : *Free Passage Approximation*
- Open questions and summary

Quantum Nucleation of Bub

CDL tells us that the
probability
rate per 4-Volume

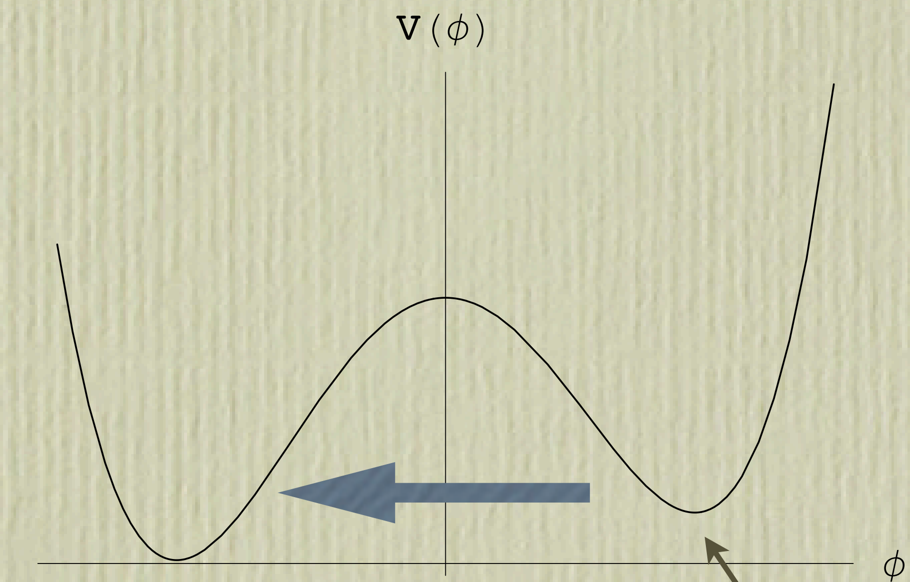


Coleman-De Luccia Tunneling :

$$\text{Rate } \frac{\Gamma}{V} = \text{constant} \times \exp(-S_0)$$

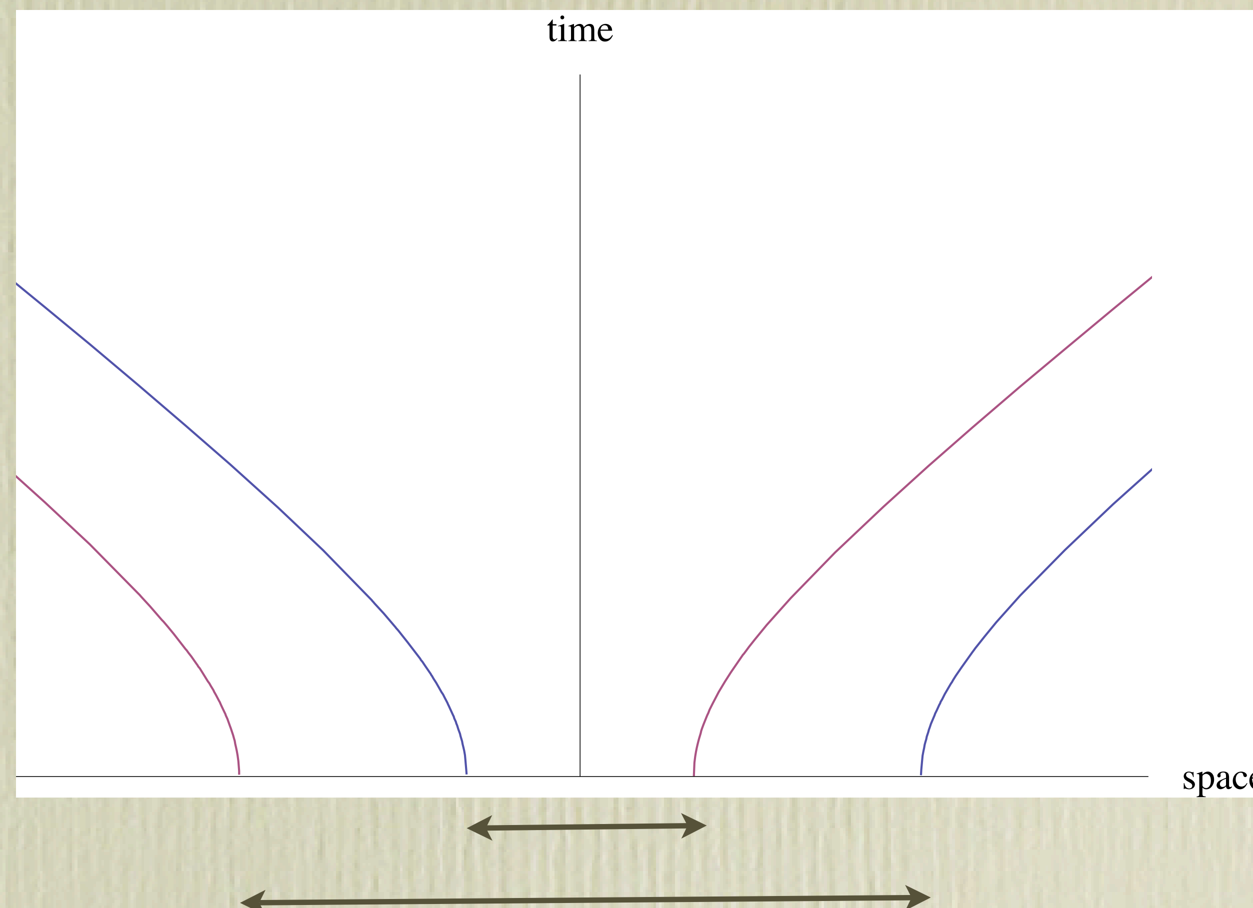
Instanton action
(depends on potential
barrier)

Quantum Nucleation of Bubbles



True vacuum

False metastable vacuum



Initial Bubble Size

$$\text{Radius} \propto \frac{\text{wall tension}}{\text{vac. energy difference)}}$$

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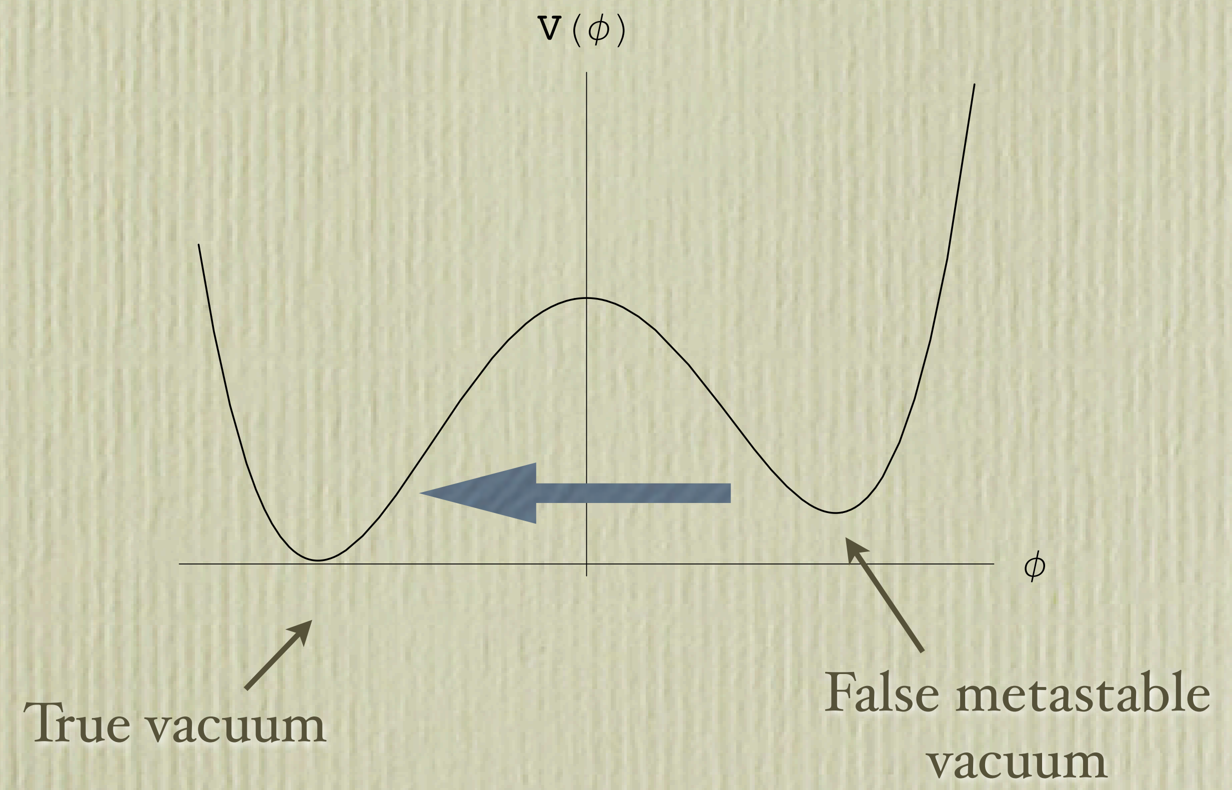

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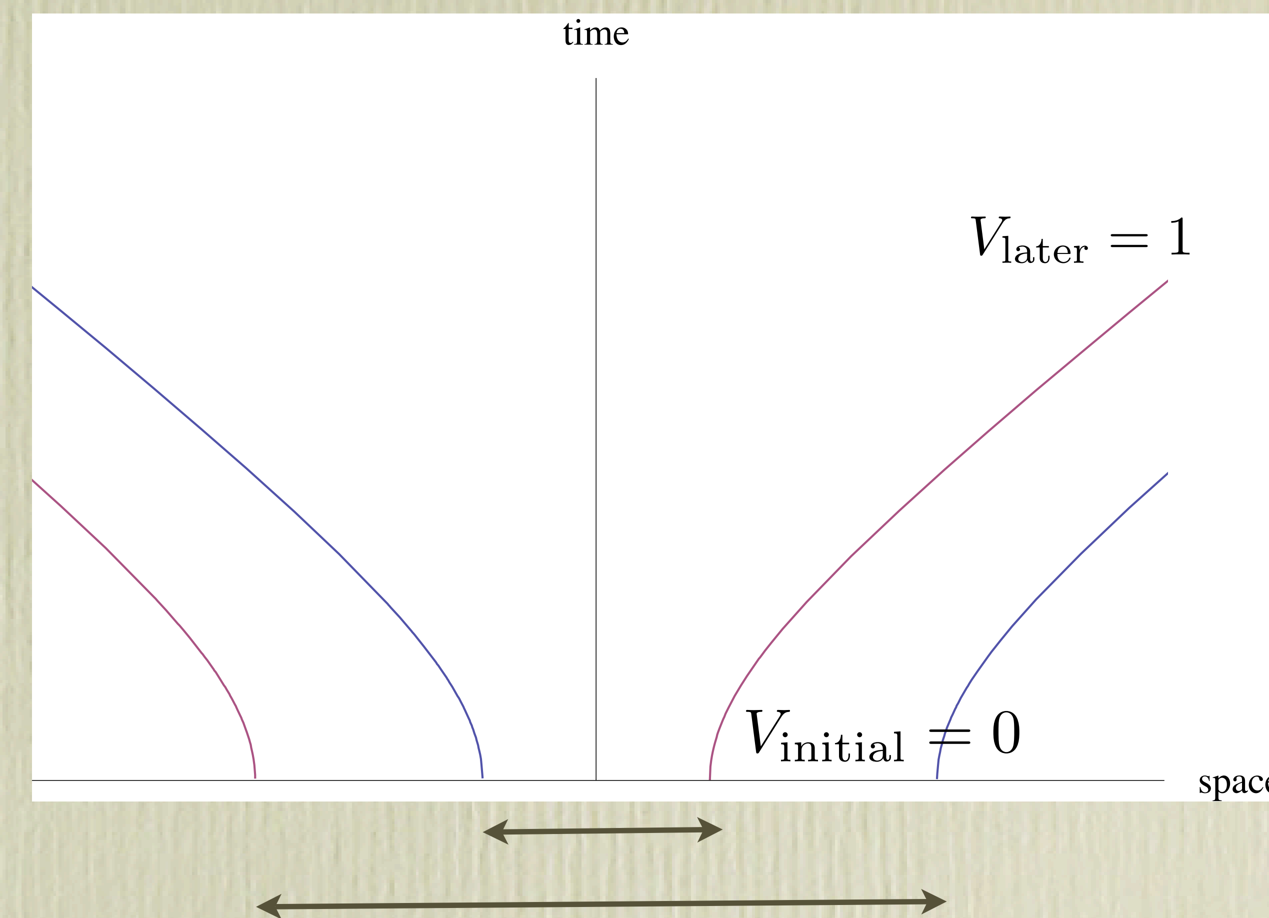


Initial Bubble Size

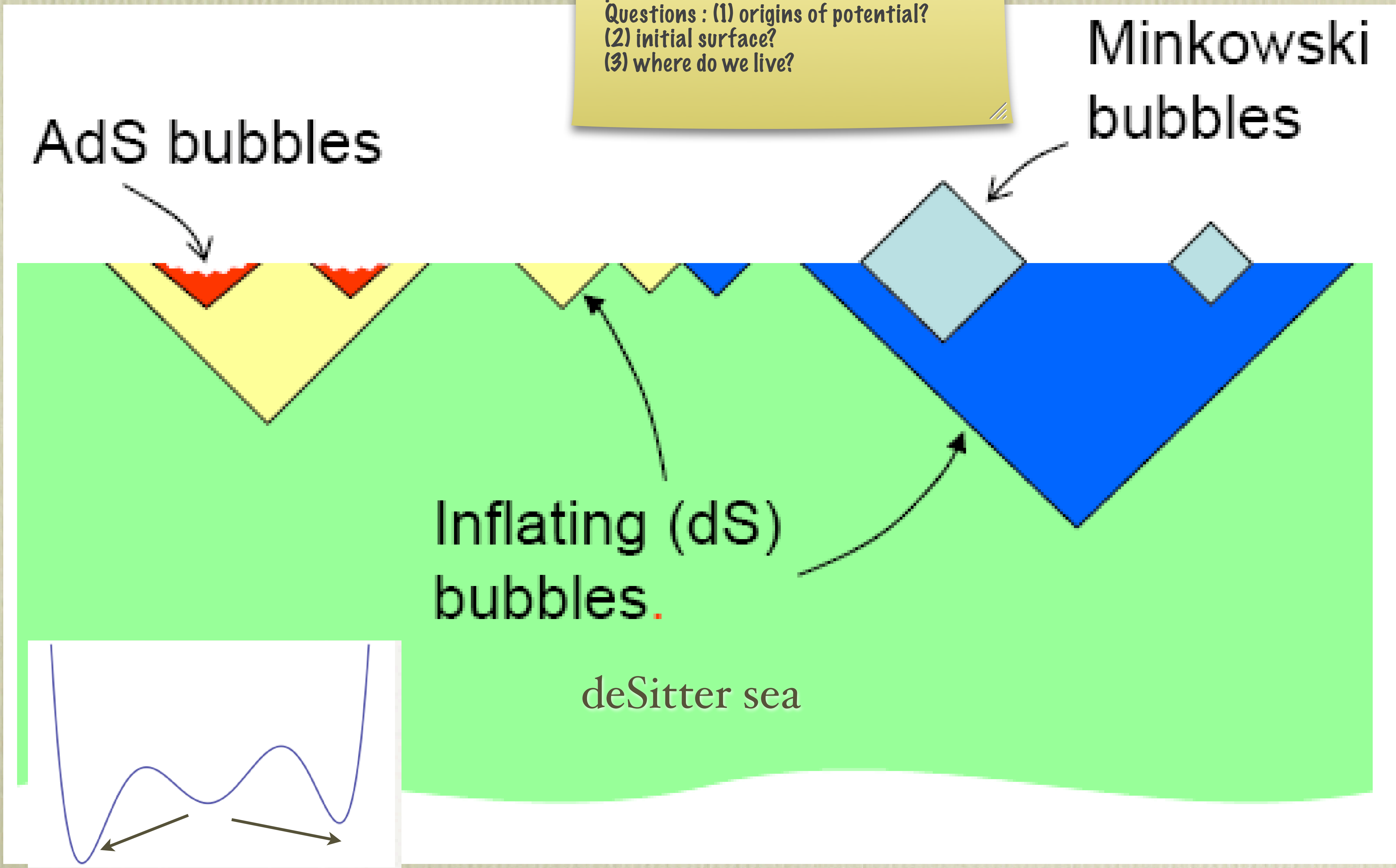
$$\text{Radius} \propto \frac{\text{wall tension}}{\text{vac. energy difference)}}$$

Pressure difference accelerates the bubble wall velocity

Inside a bubble is an open universe (which may be inflating at first)

An Omniscien … Multiverse

use colors
dS sea - Green
notice the simplification of a single point nucleation
Questions : (1) origins of potential?
(2) initial surface?
(3) where do we live?



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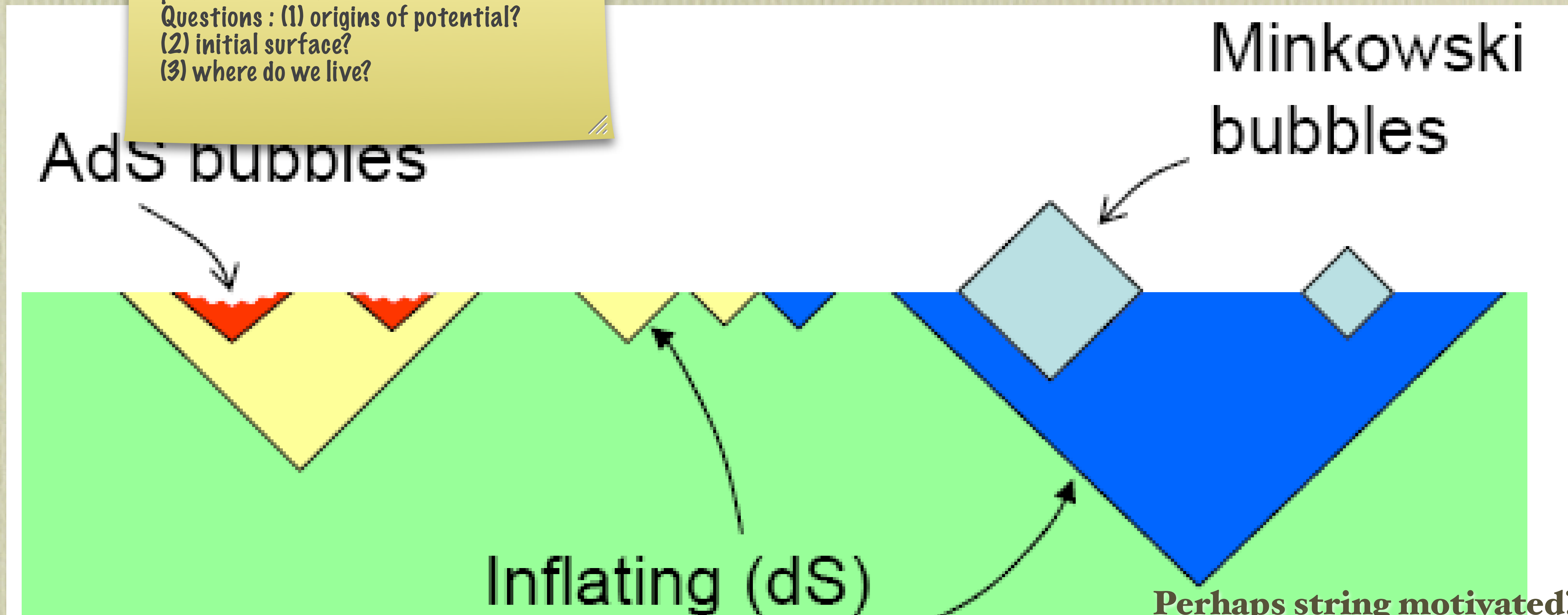
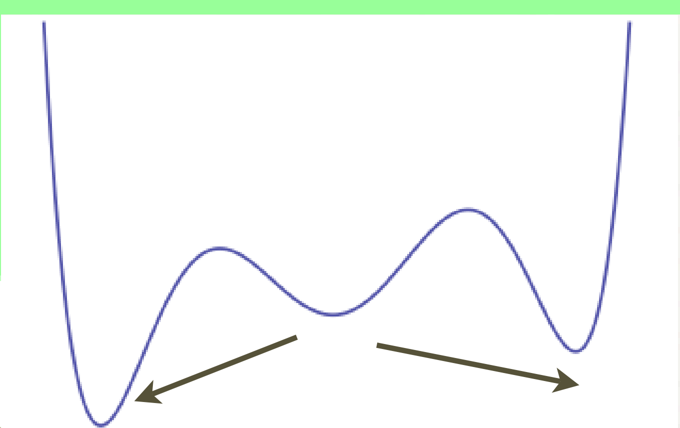
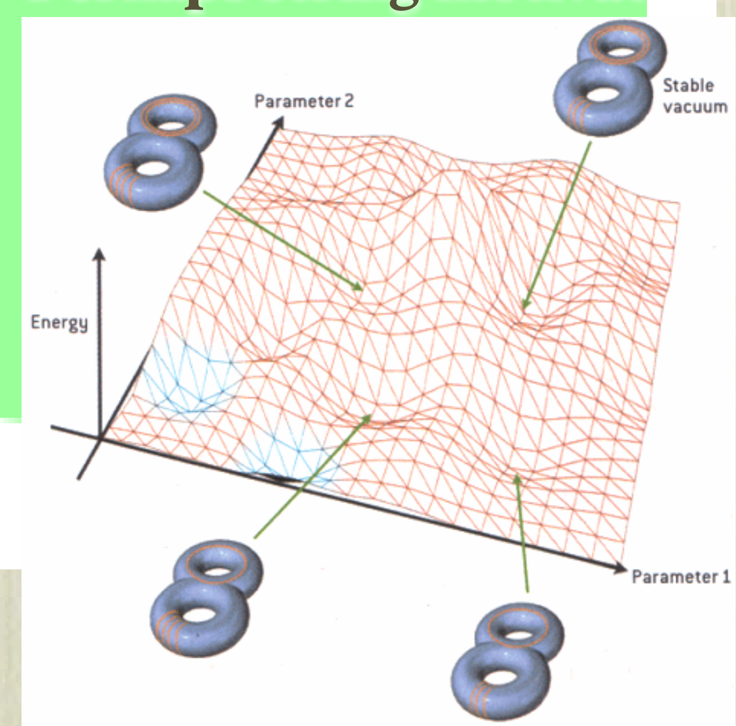




Perhaps string motivated?



"The Landscape" (Picture from *Scientific American*)

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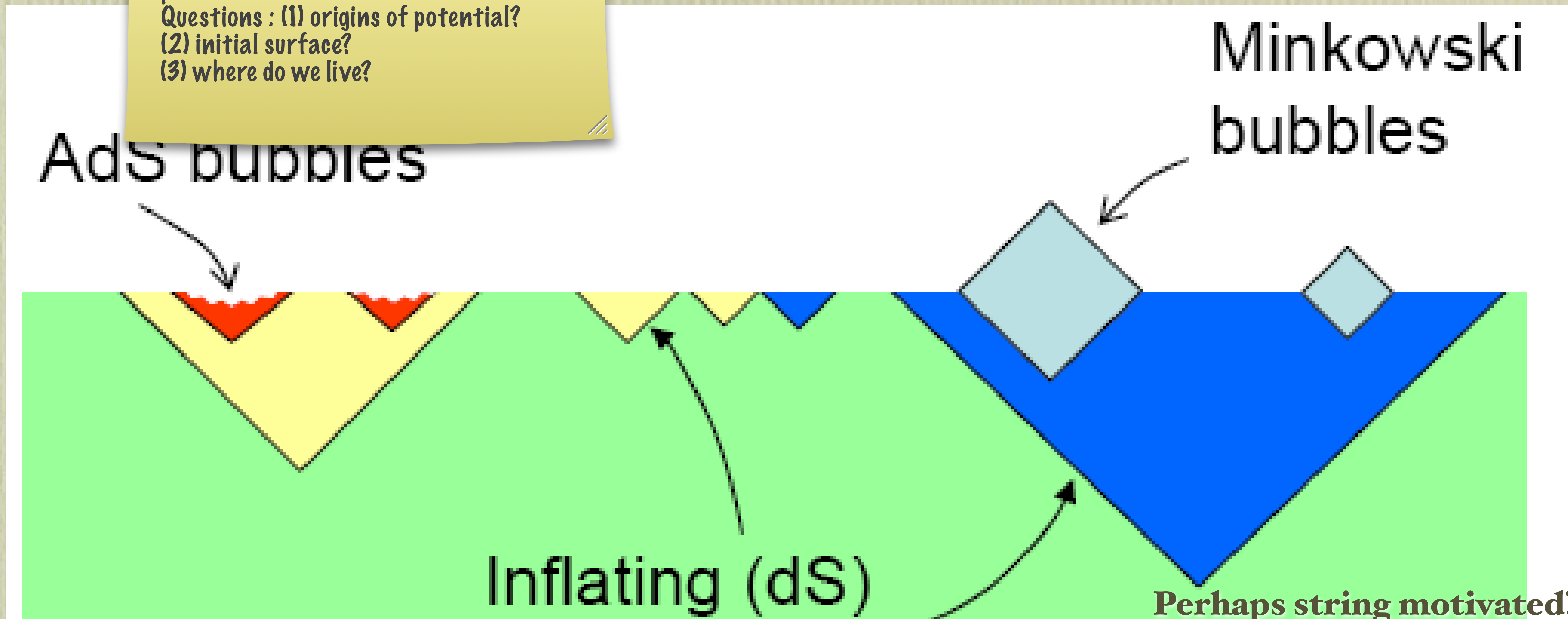

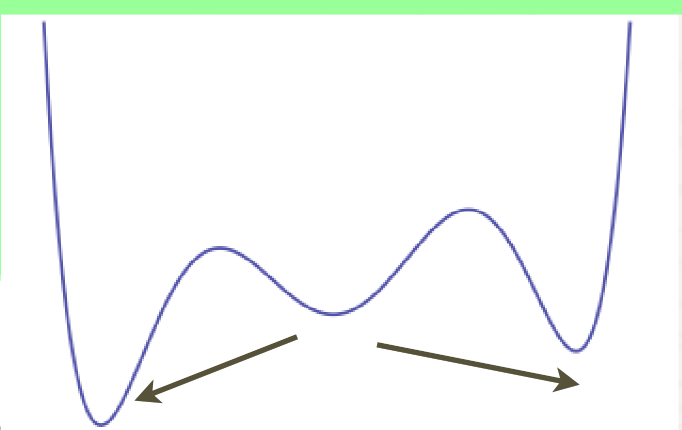

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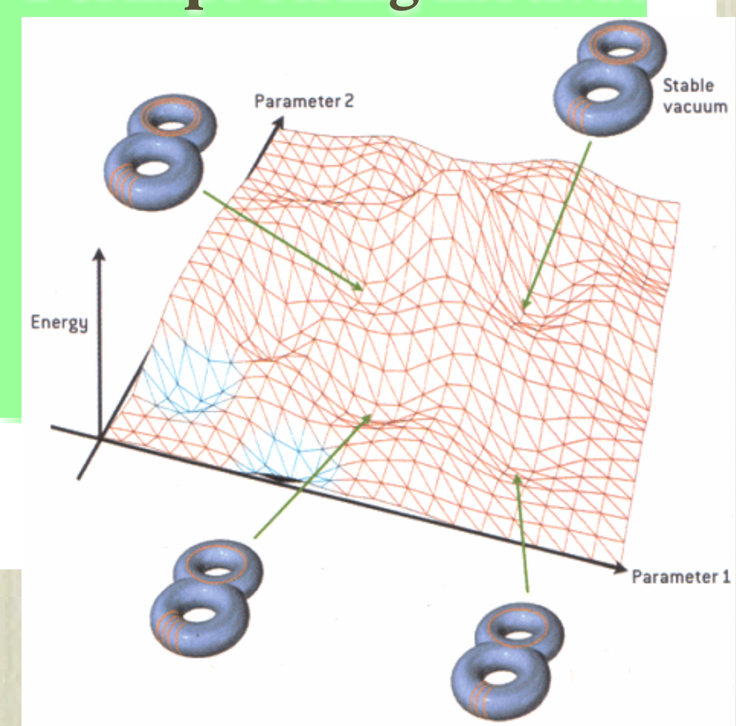

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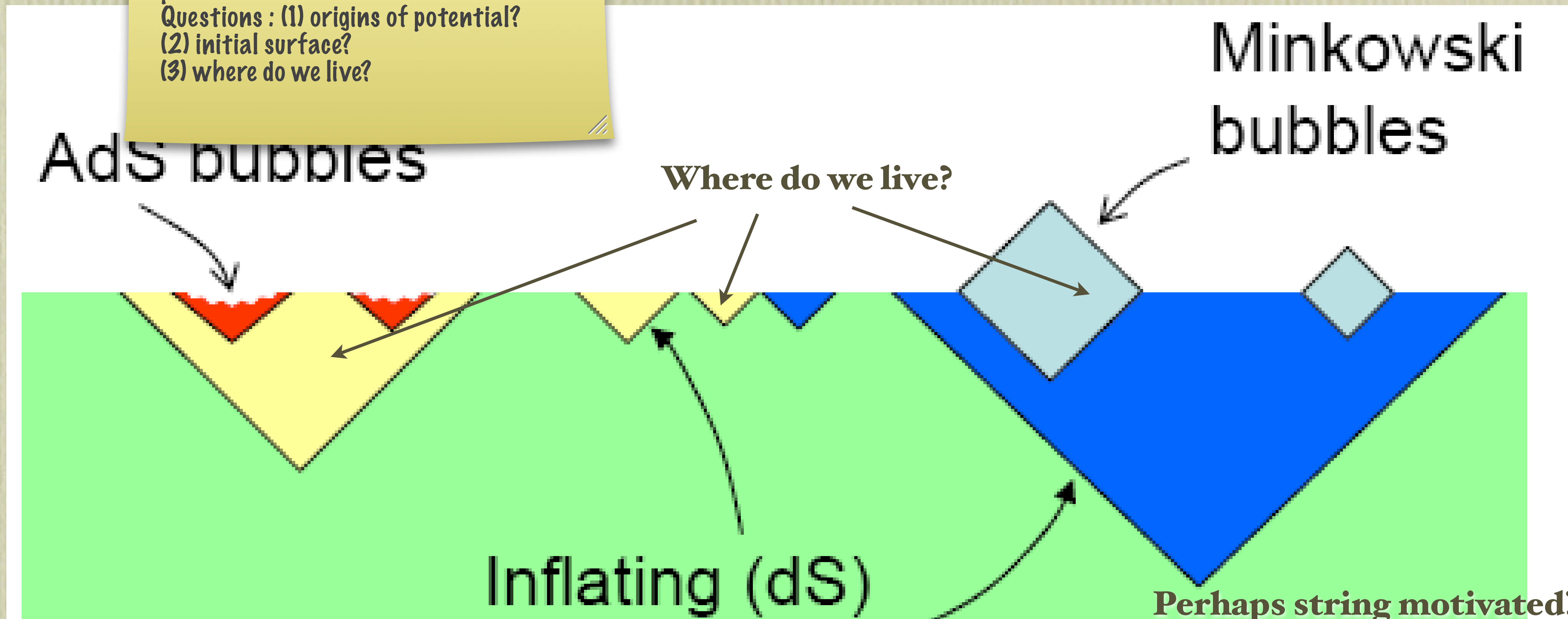

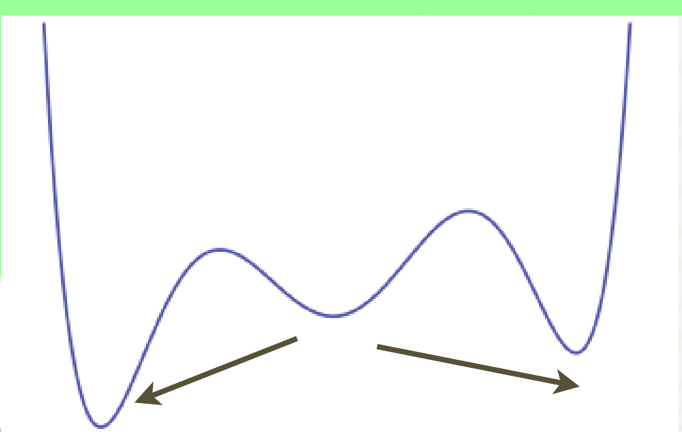

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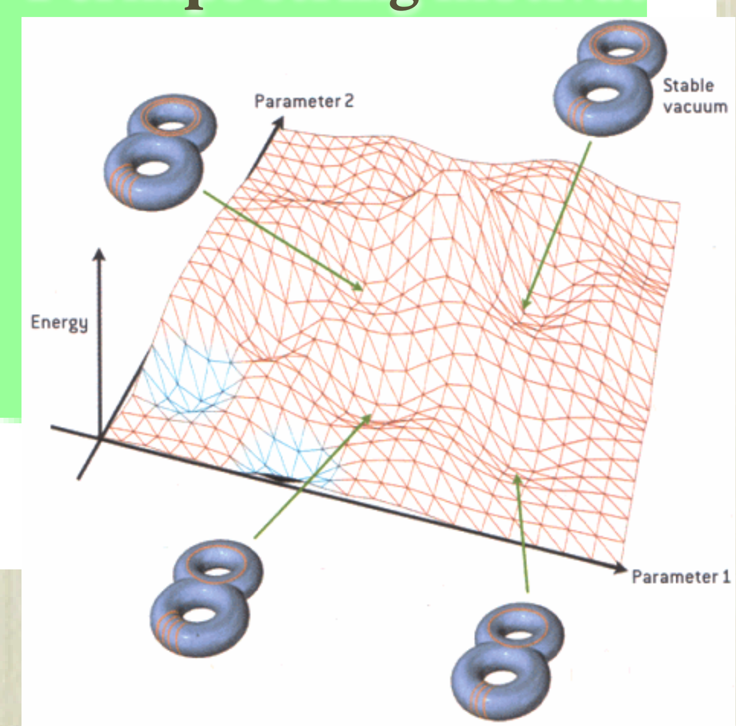

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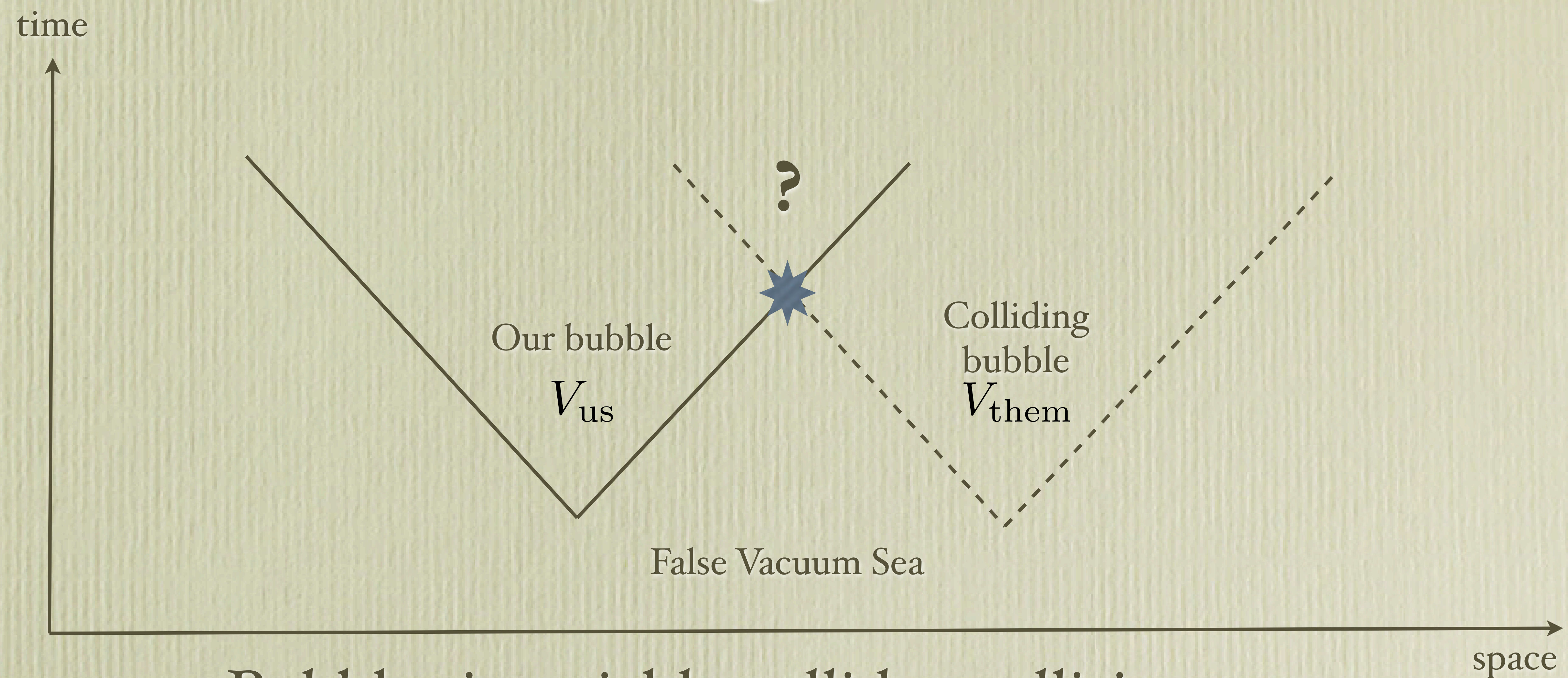
Bubbliology

Studying bubbles can teach us interesting things

- The distribution of bubbles *scans* the Landscape potential. Can we count them?
- What is the internal structure of these bubbles? What is a typical observer inside?
- More broadly : placeholders for non-perturbative objects (domain walls, solitons, D-branes etc.)
- What happens when they *collide*?

I didn't tell you that bubbles can collide

Colliding Bubbles

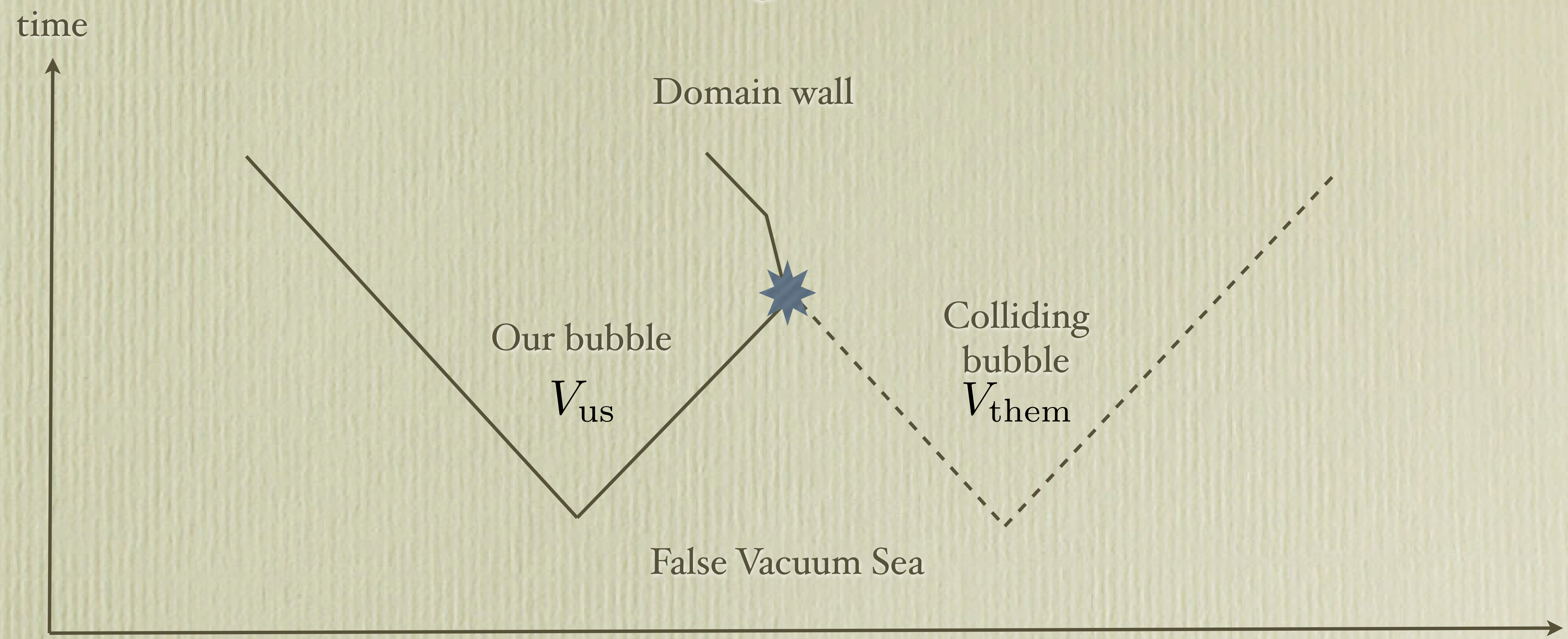


Bubbles invariably collide : collision rate depends on nucleation rate

"What happens then?"

Sidney Coleman, PRD D51, 2929 (1976)

Colliding Bubbles



They could merge smoothly, possibly forming a domain wall if $V_{\rm us} \neq V_{\rm them}$

Chang, Kleban, Levi (2007)
Aguirre, Johnson, Tysanner (2007)

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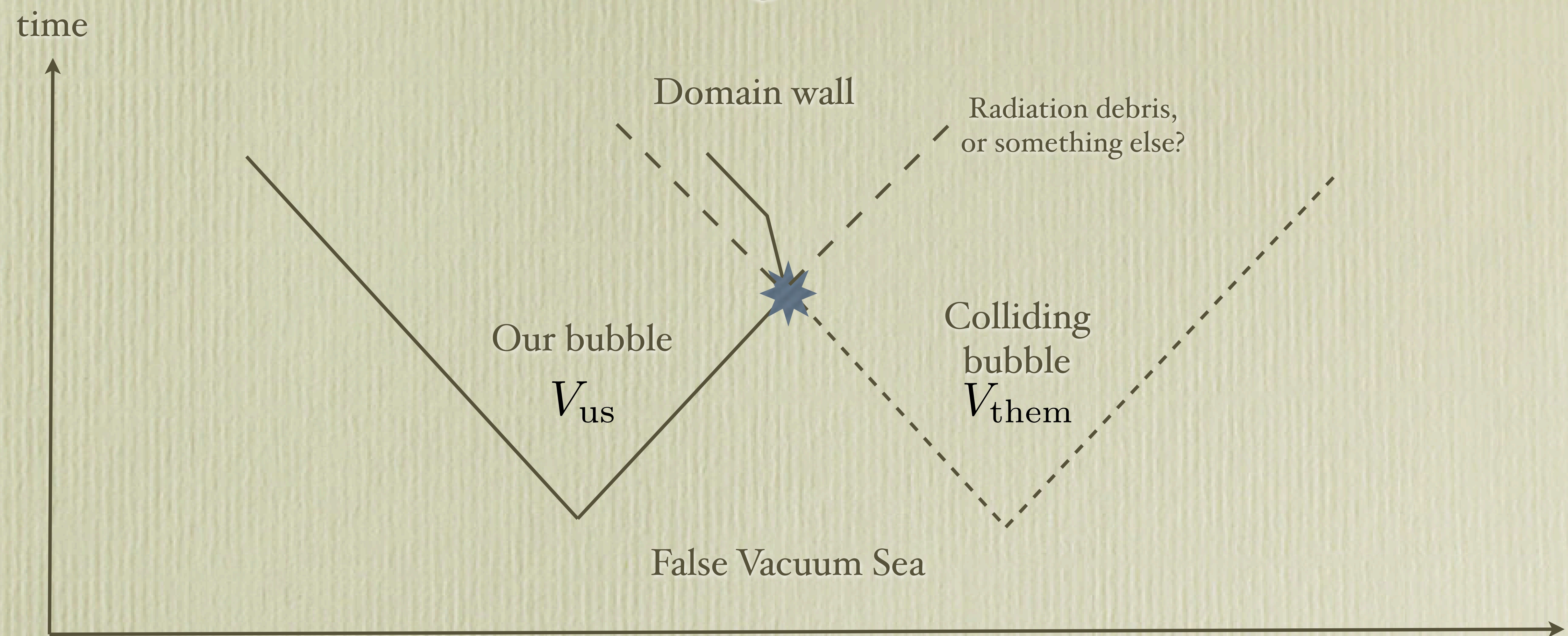

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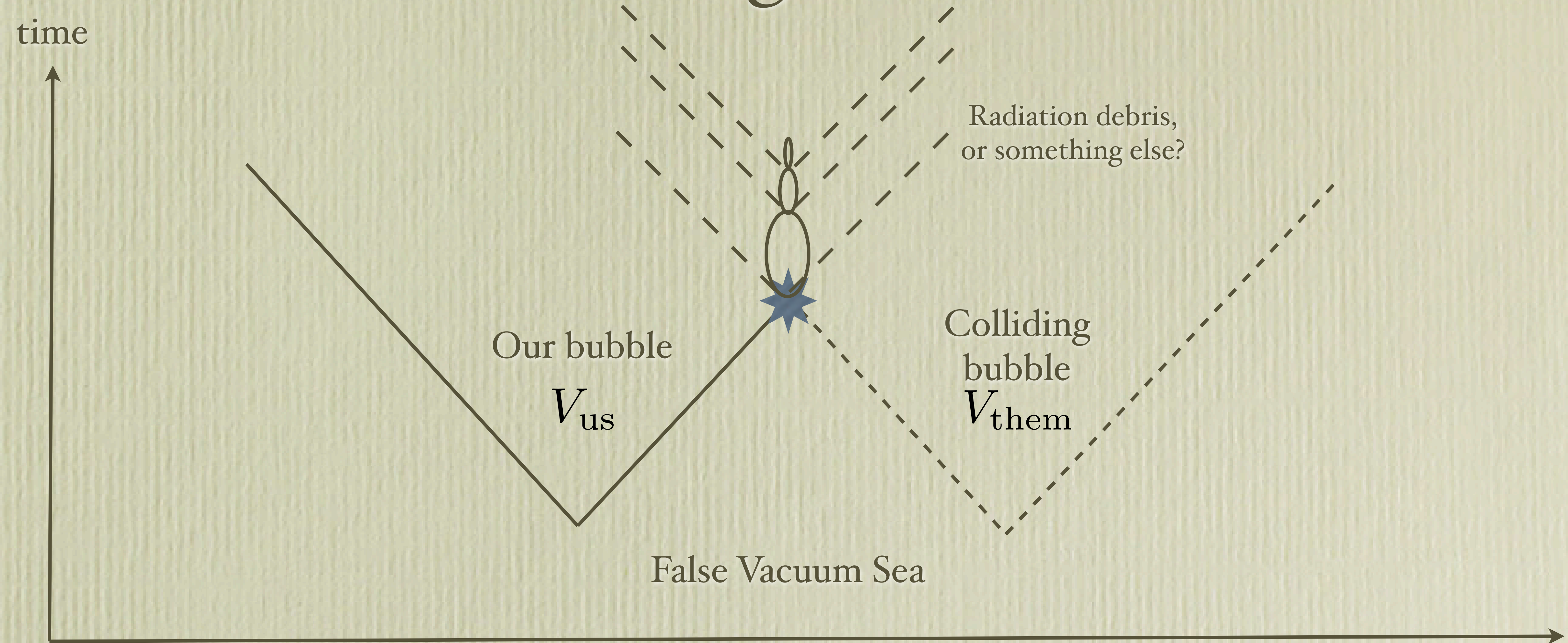
Energy conservation : debris might spew out if collision is *in-elastic.*

Colliding Bubbles



They could form oscillating pockets of the false vacuum. Hawking, Moss, Stewart (1982)

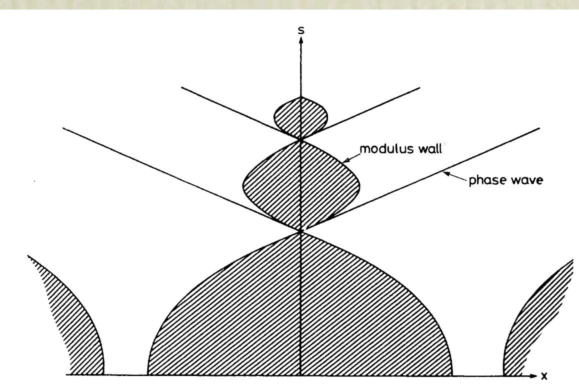


FIG. 2. The collision of two bubbles when $0<\alpha<1$. The kinetic energy of the walls is shared in each collision between a new pair of walls and a phase wave which travels outwards at the speed of light.

who would have thought Hawking is also one of the earliest pioneer of numerical cosmology!

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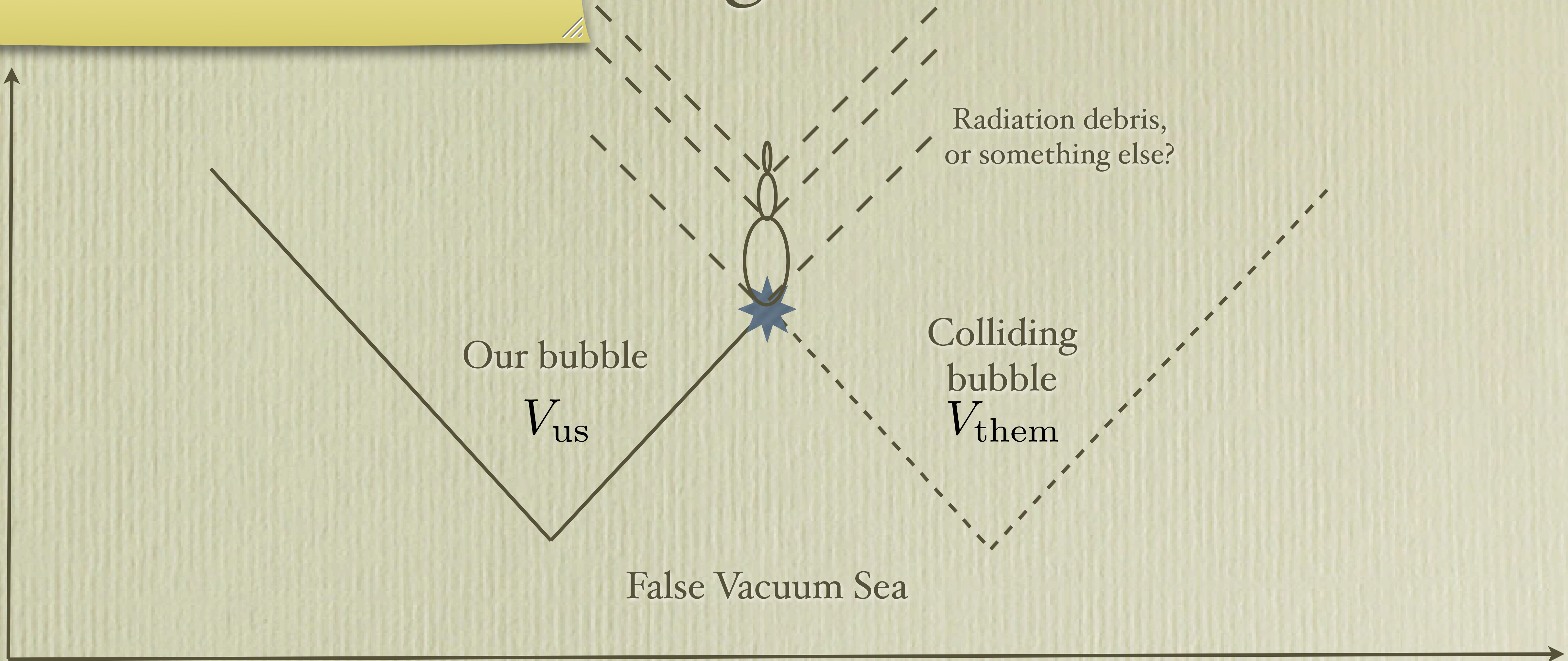

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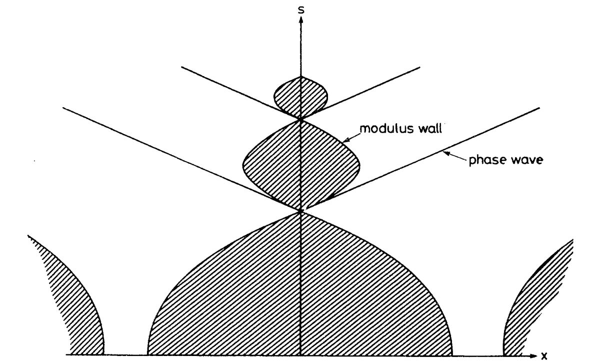
Lattice simulation c. 1982 :
1+1D, ~50 lattice points
IBM 370



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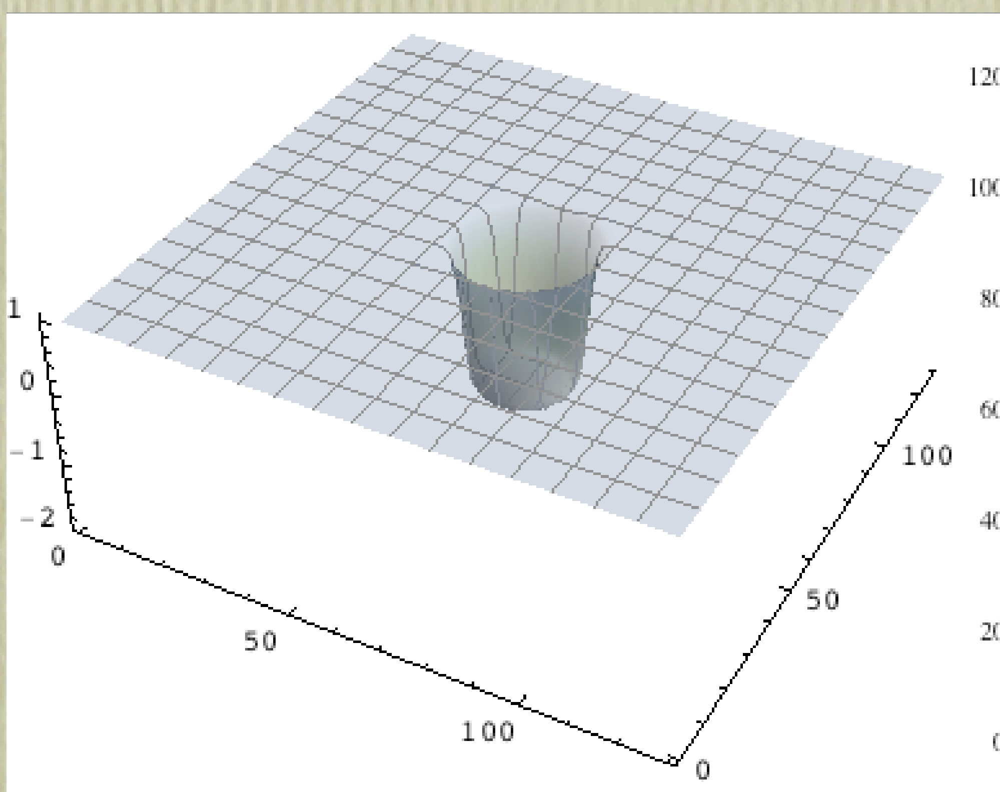
Numerical Bubbles

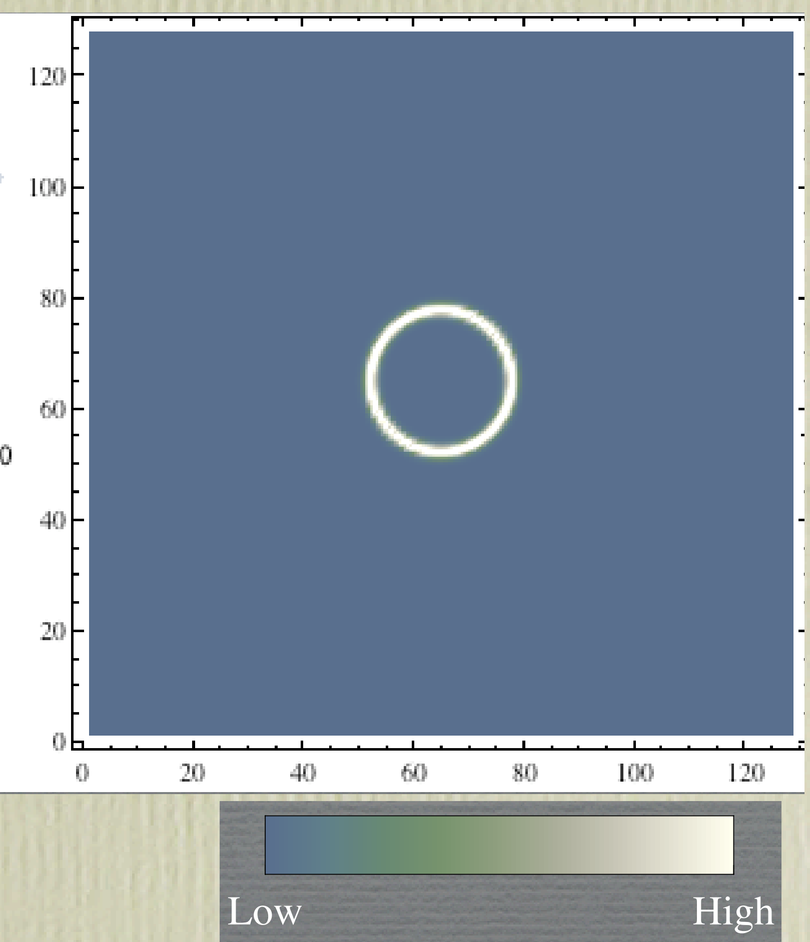
Biggest issue : numerical noise from high resolution
Sampling 1 per 8
explain the diagram (axis, energy density, slice)

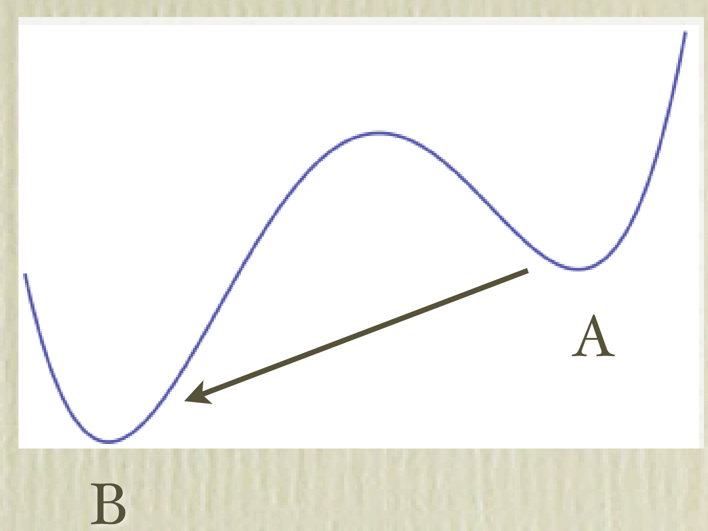
Lattice simulation circa. 2009 :
Full 3+1D, 1024^3 = 1073,741,824 lattice points

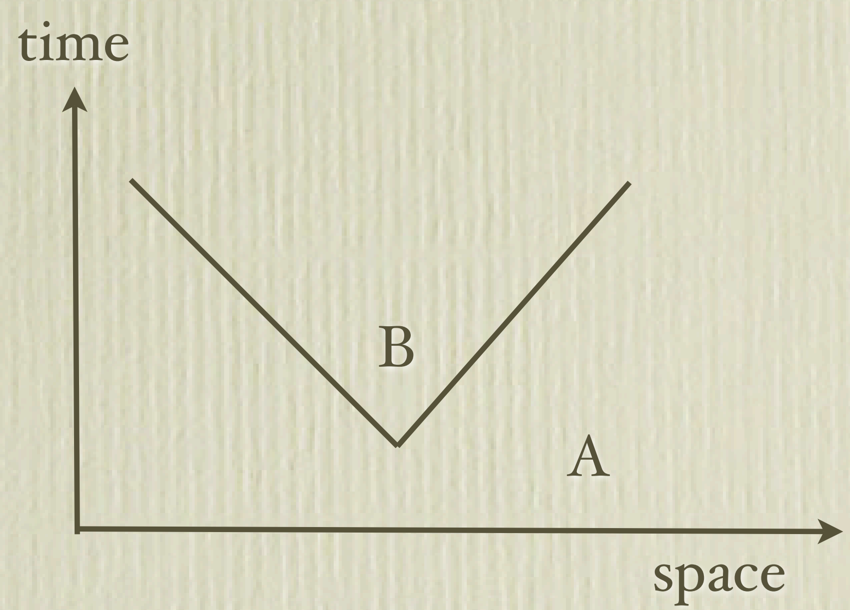
Slice of Field Values



Top down Energy density







Wall thickness Lorentz contract as it collects more energy

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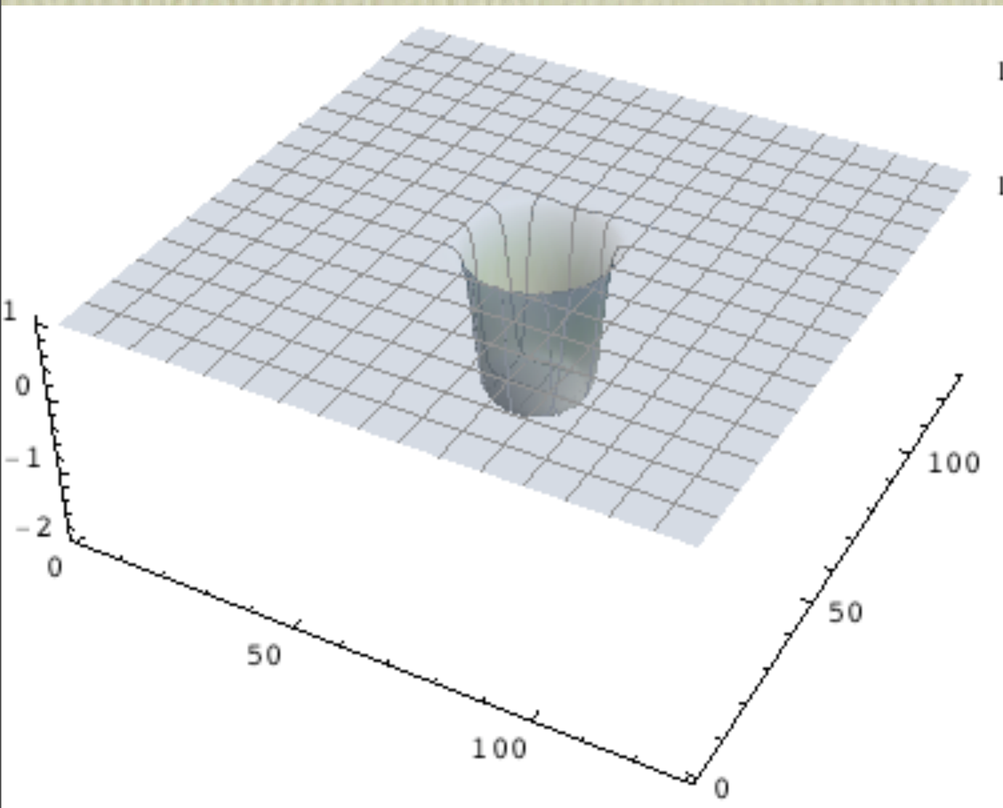

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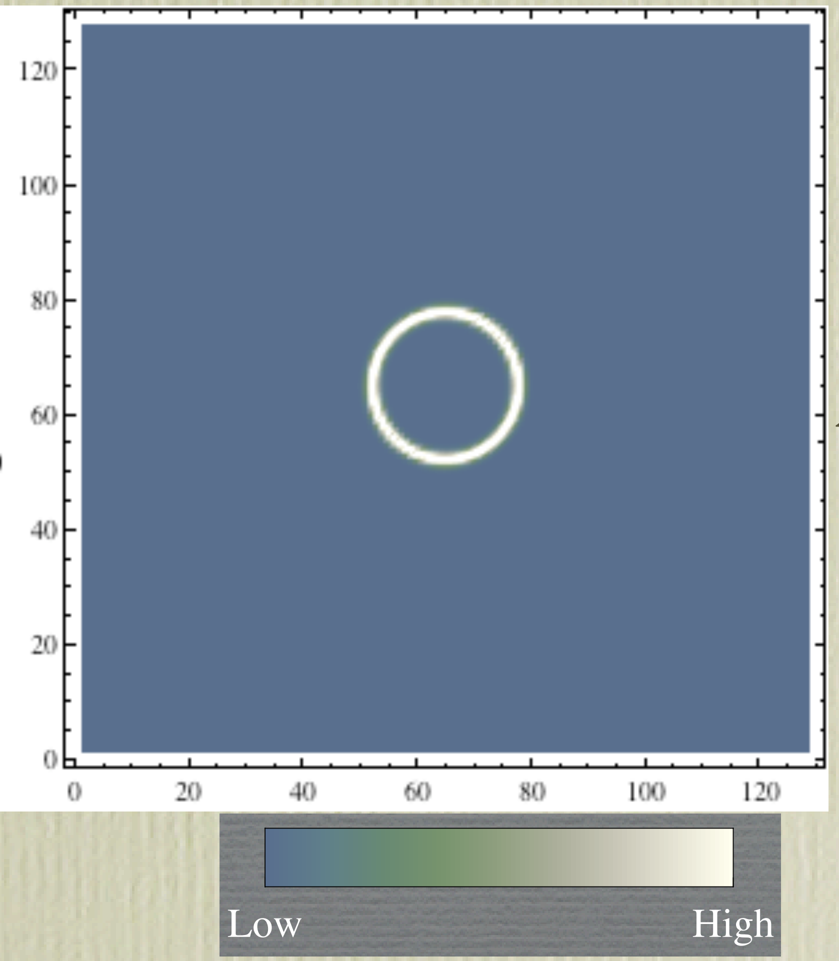
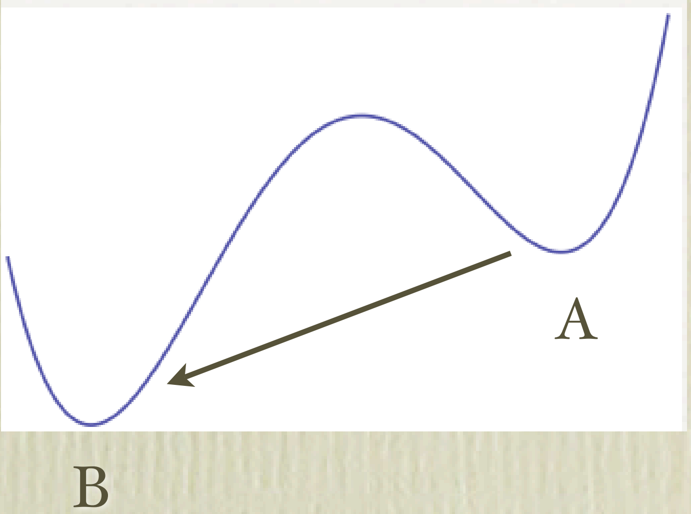
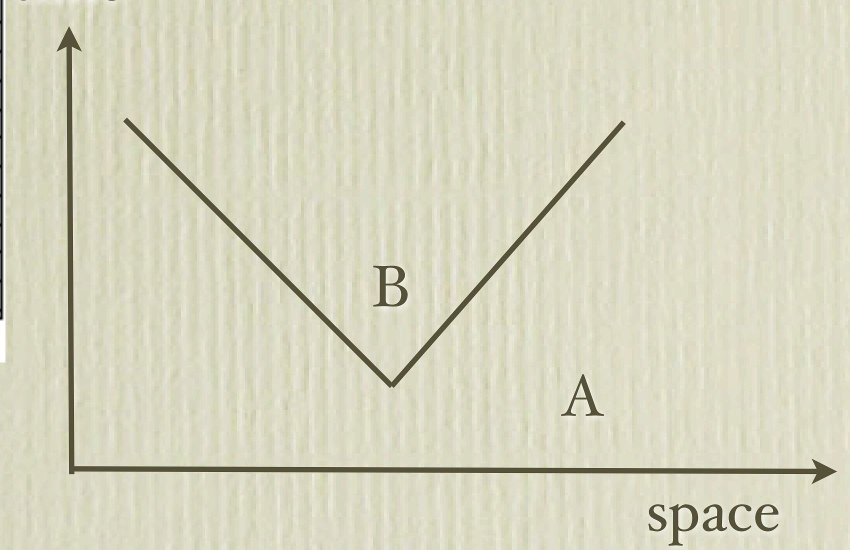


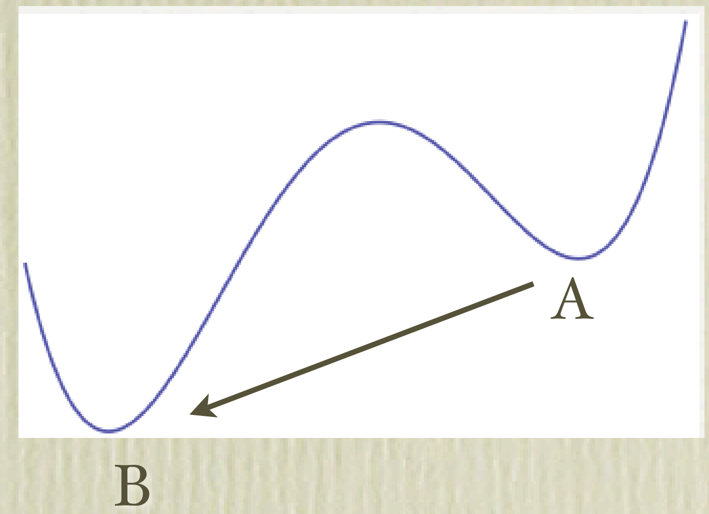


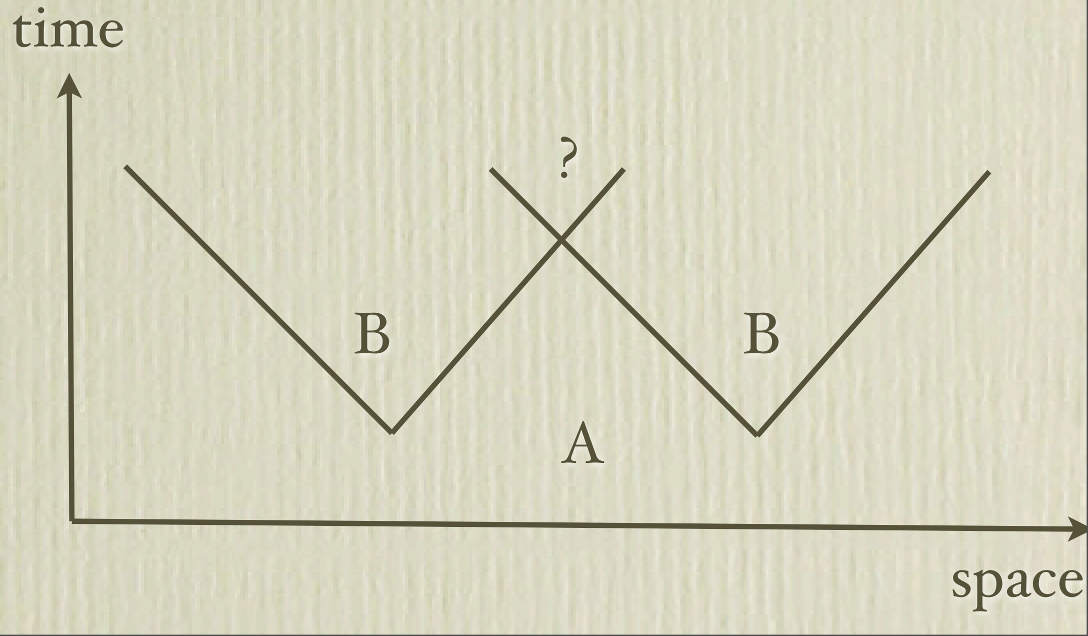


Wall thickness Lorentz contract as it collects more energy

Smashing Bubbles

- Colliding identical bubbles with 2 minima





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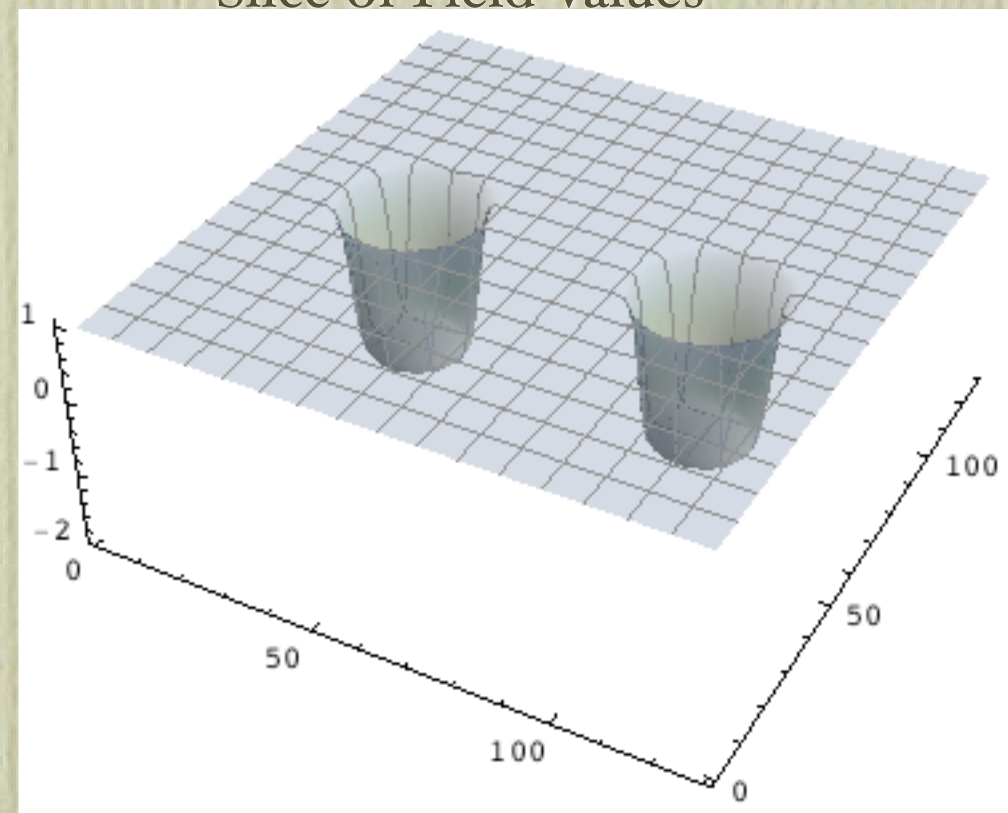

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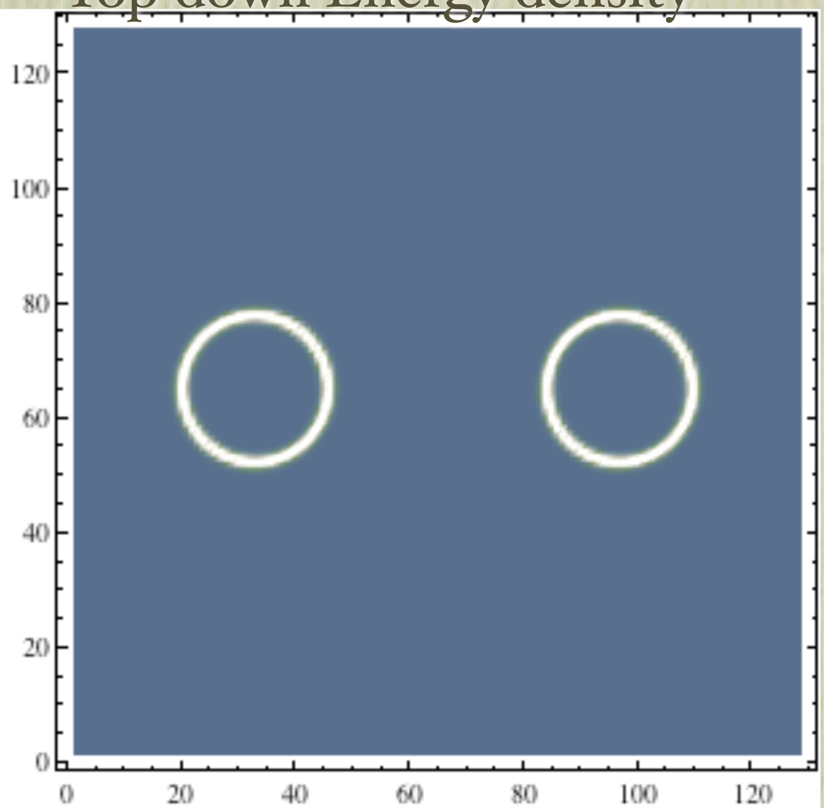
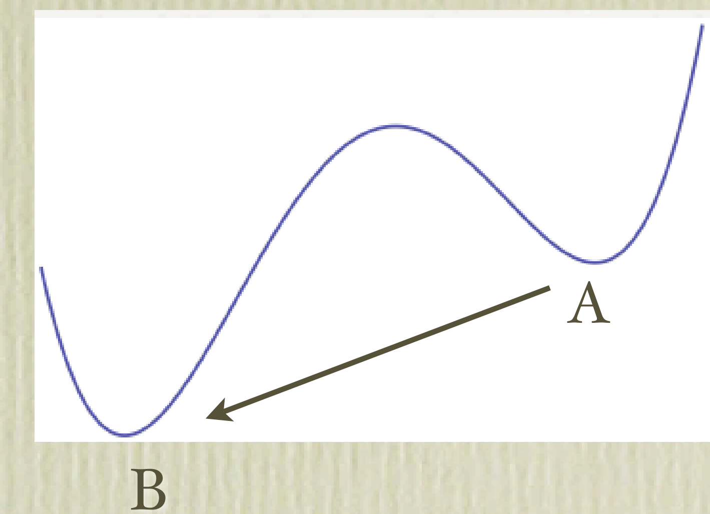
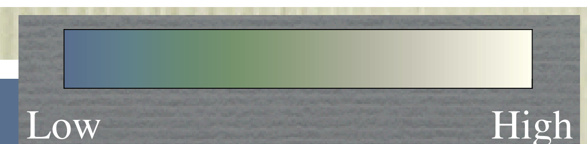
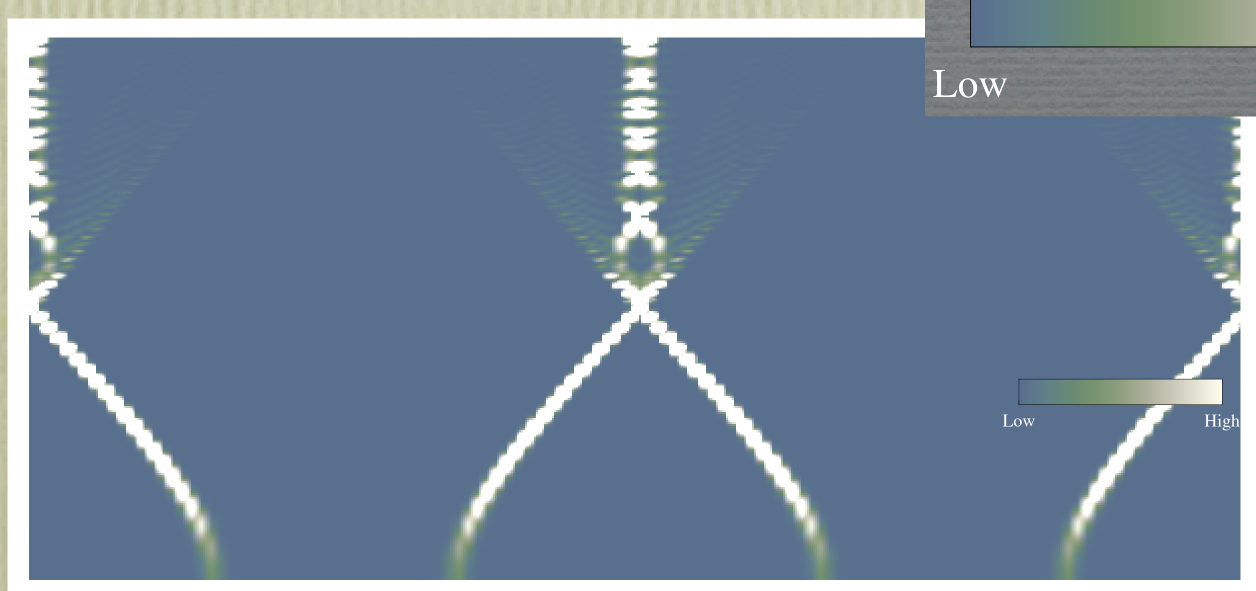
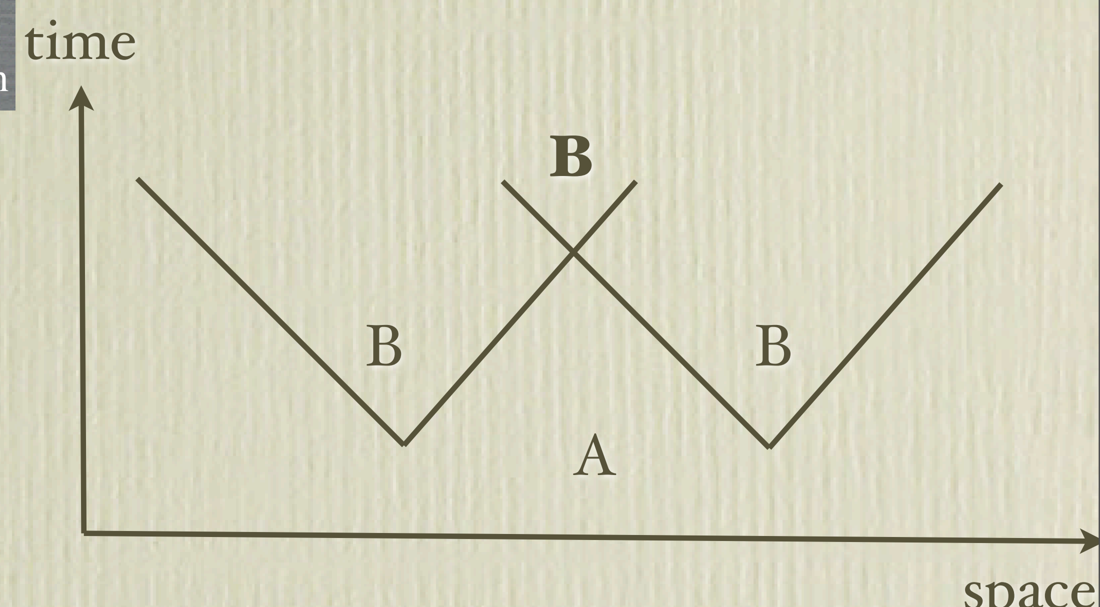




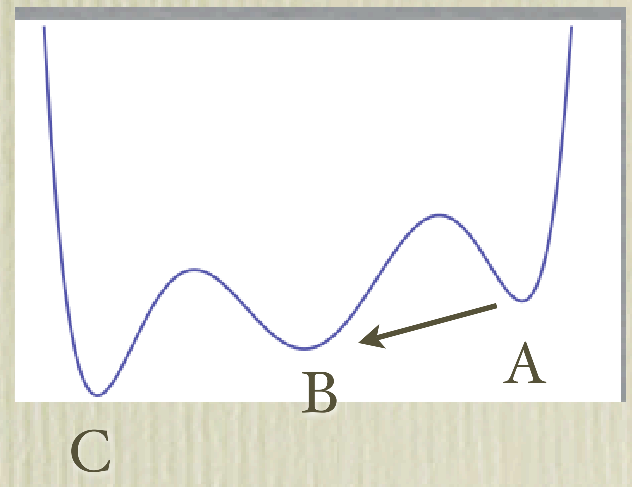


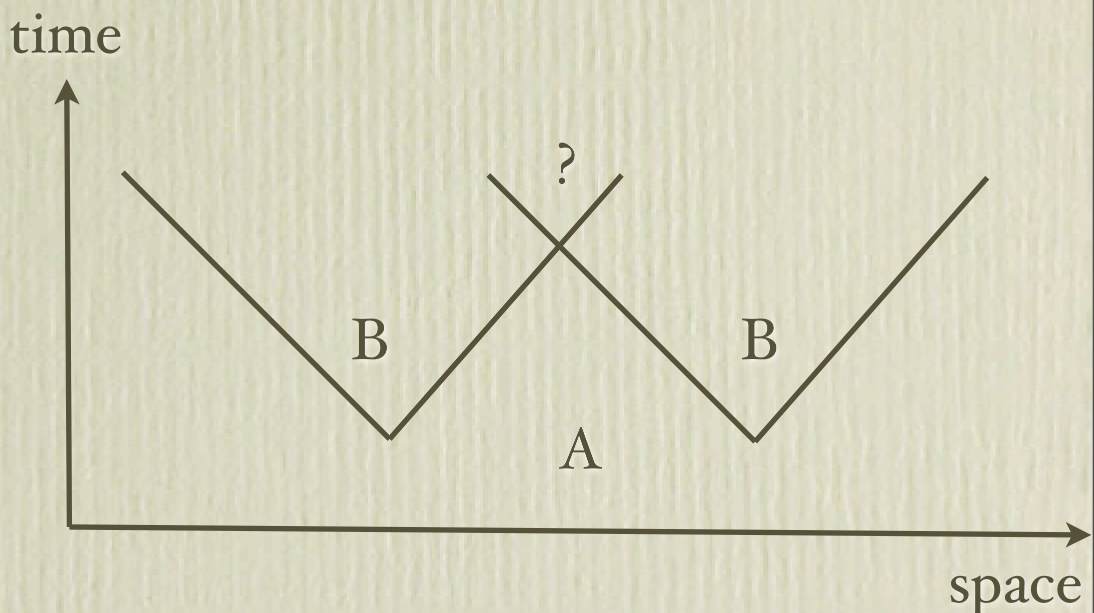




Classical Nucleation

- Colliding identical bubbles with 3 minima





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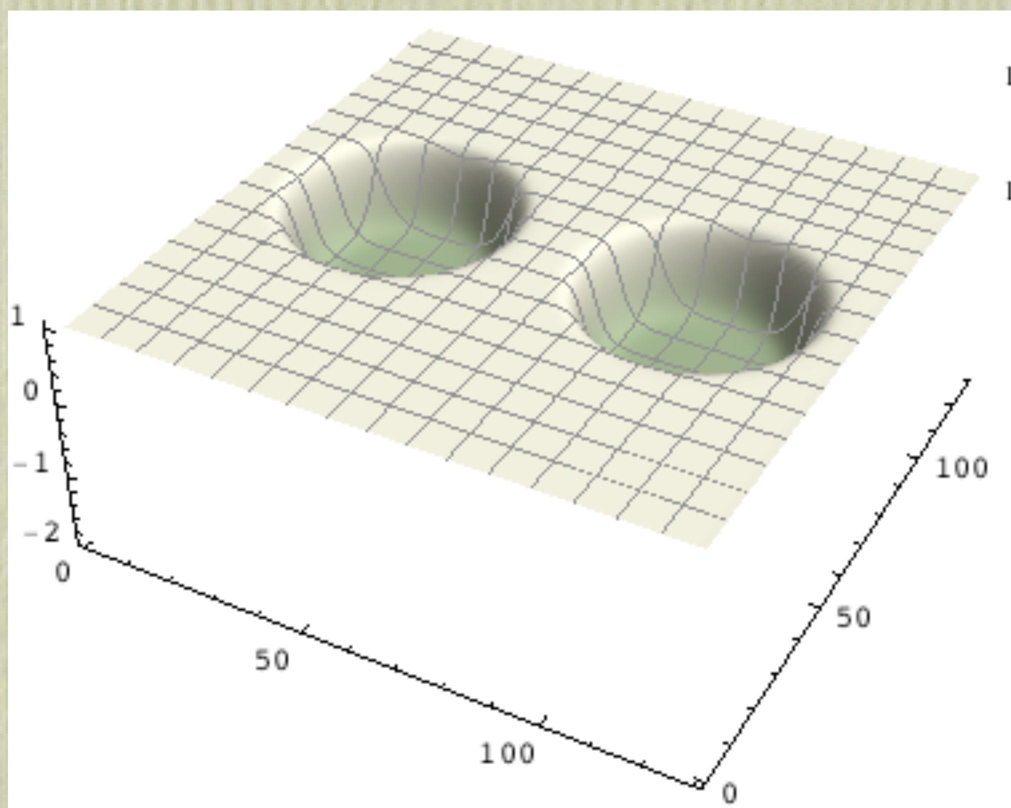

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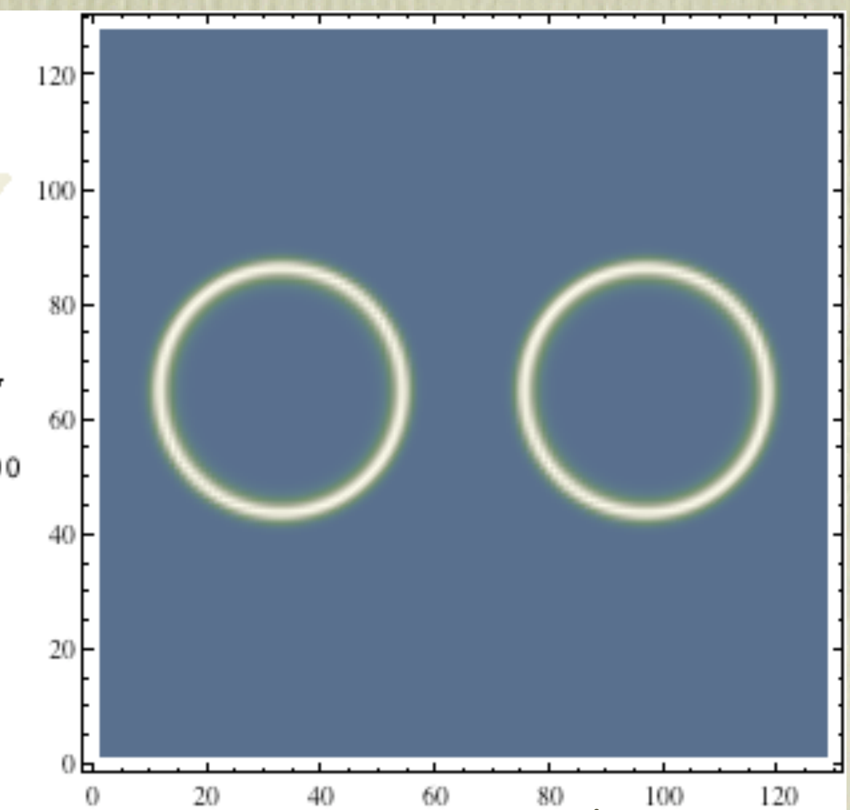
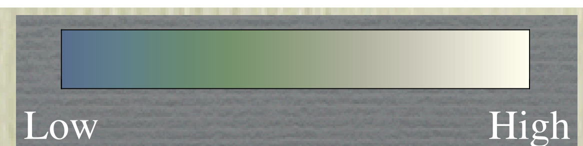
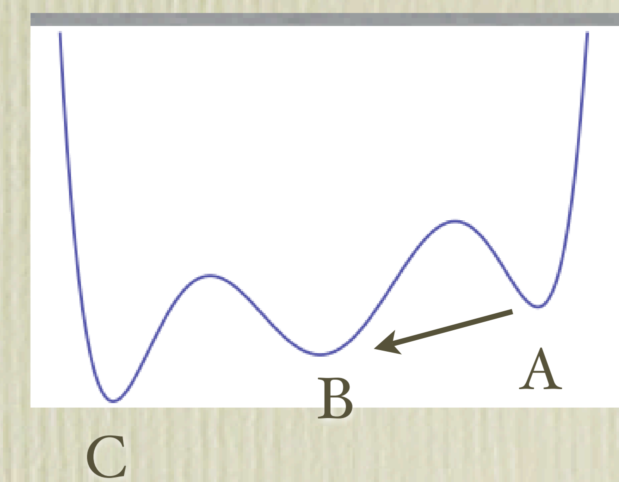
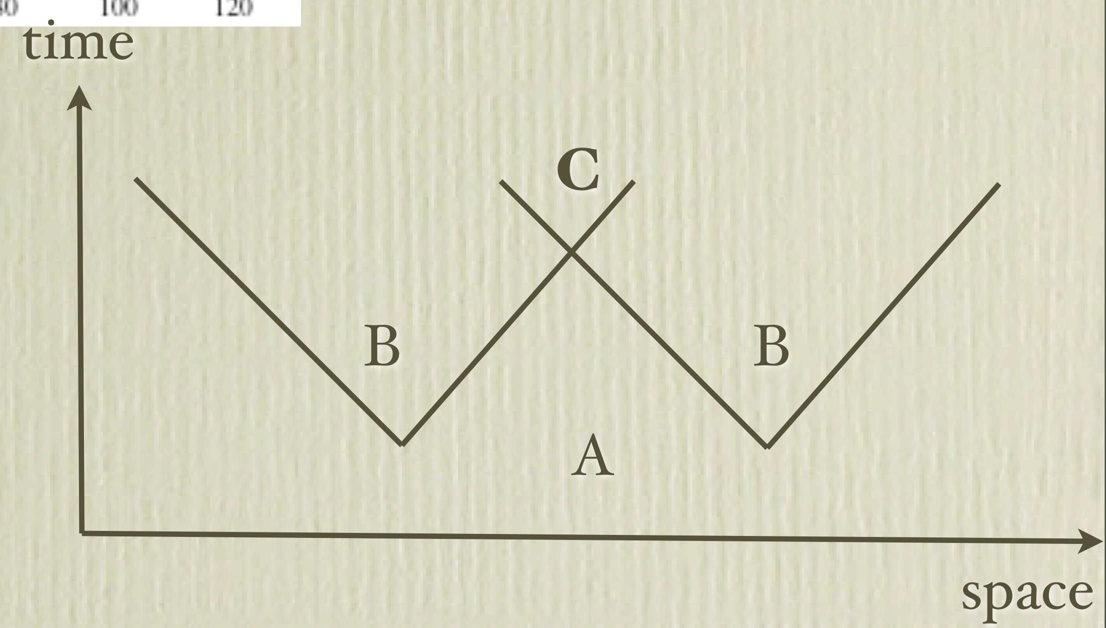




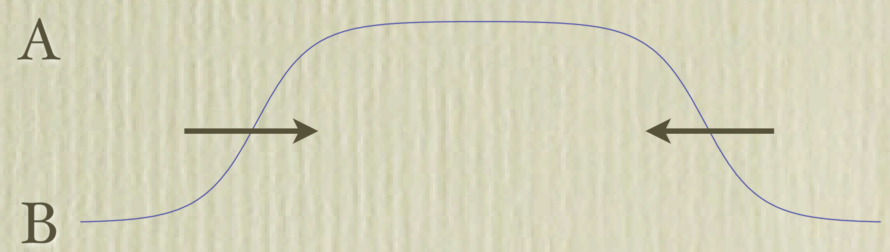


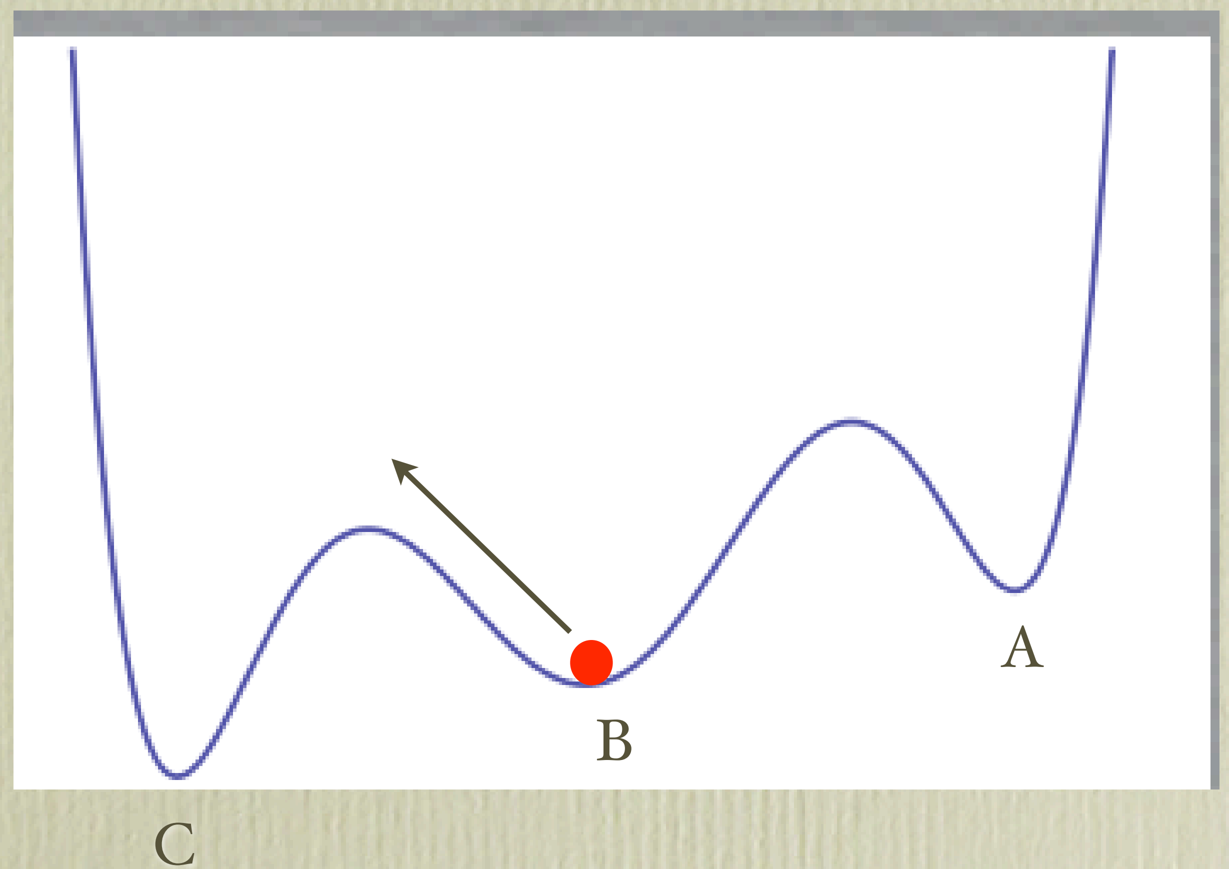


New *relativistic* walls *coherently* form!

Energetics?

Gradient Energy of walls ⟶ Field Kinetic Energy





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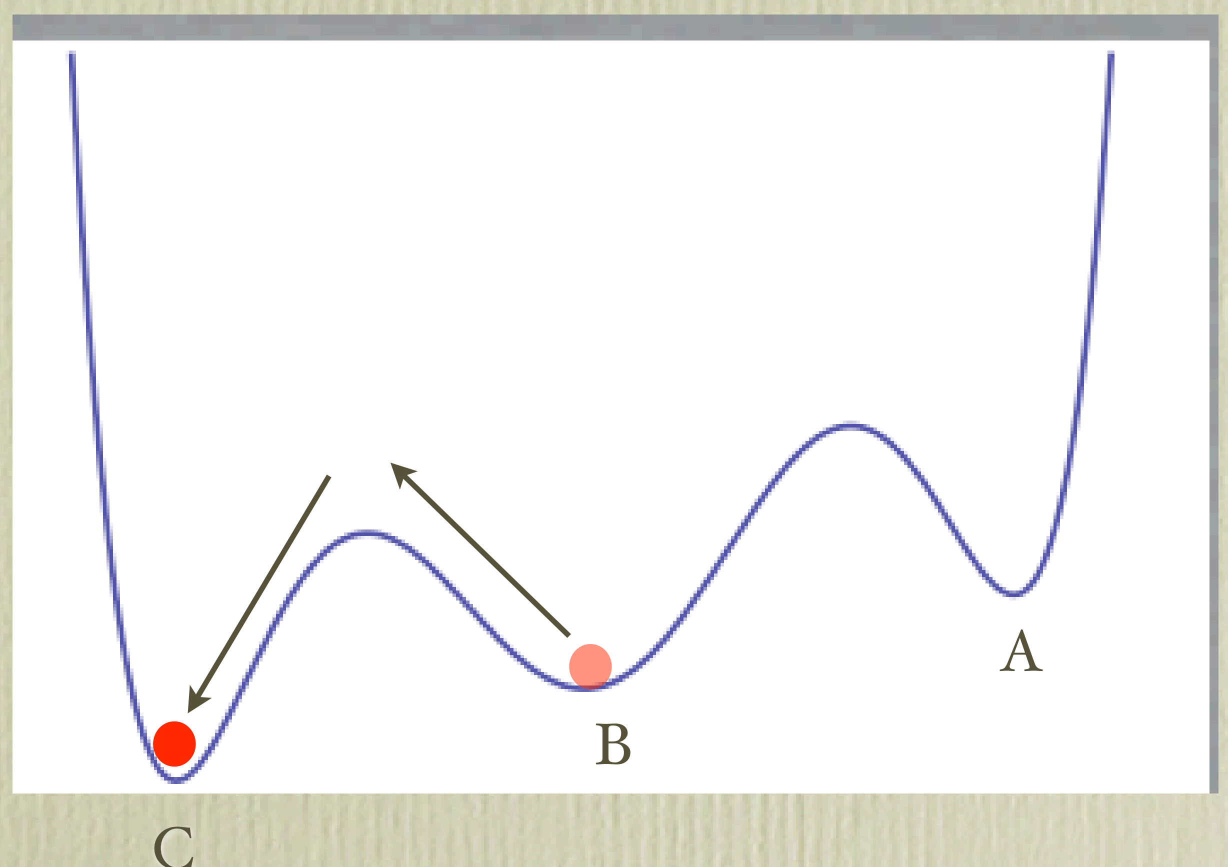
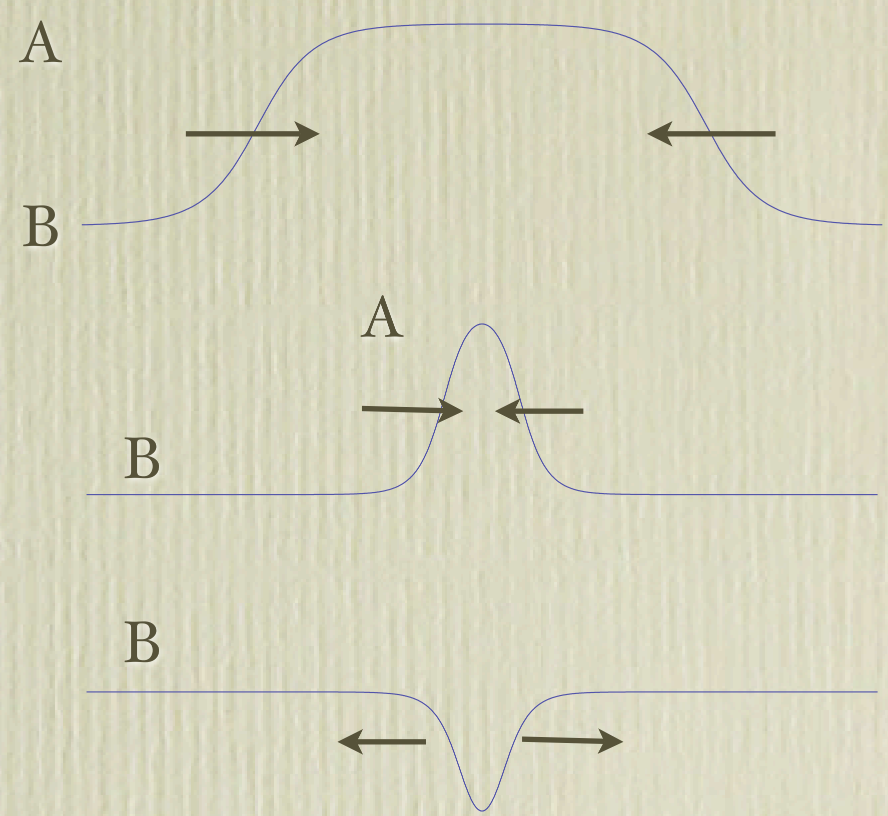
Sufficient Gradient Energy will push
the field over the 2nd barrier

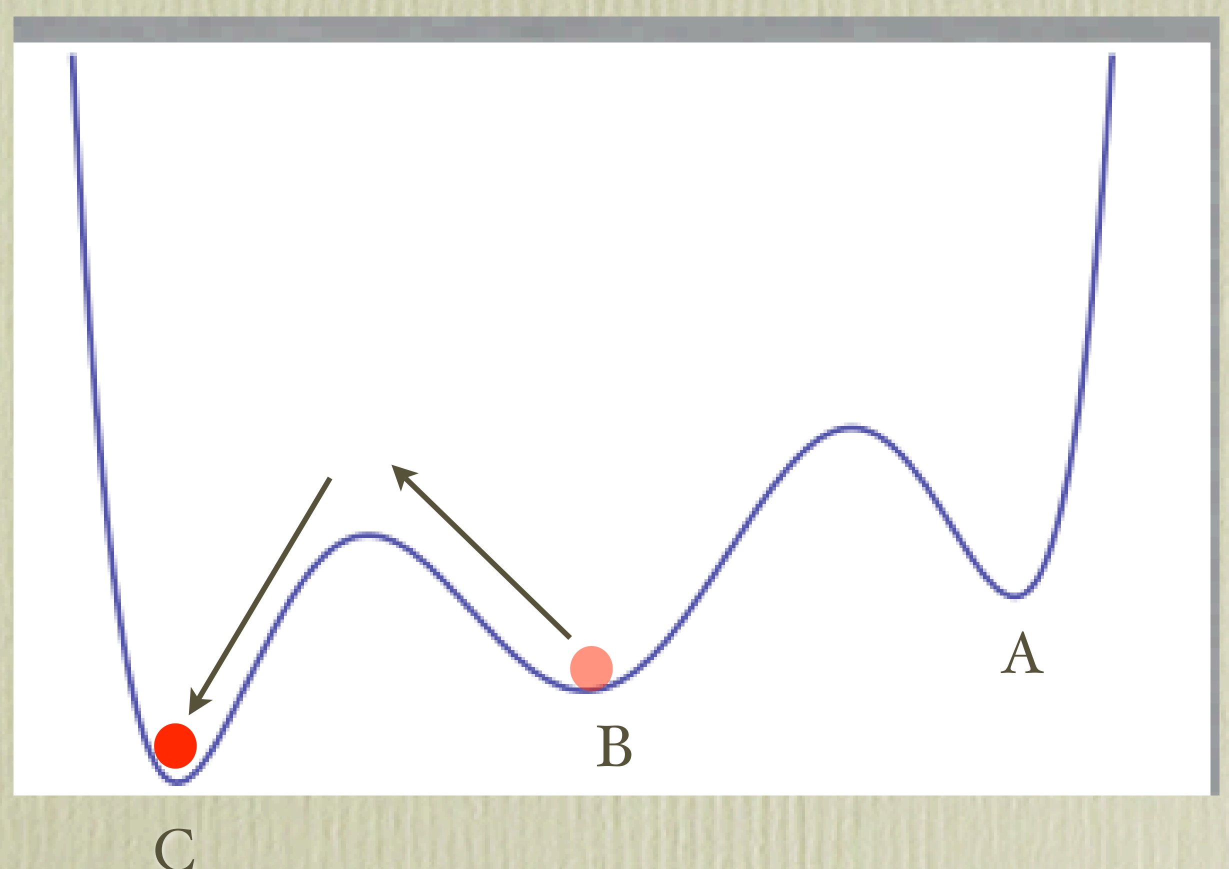


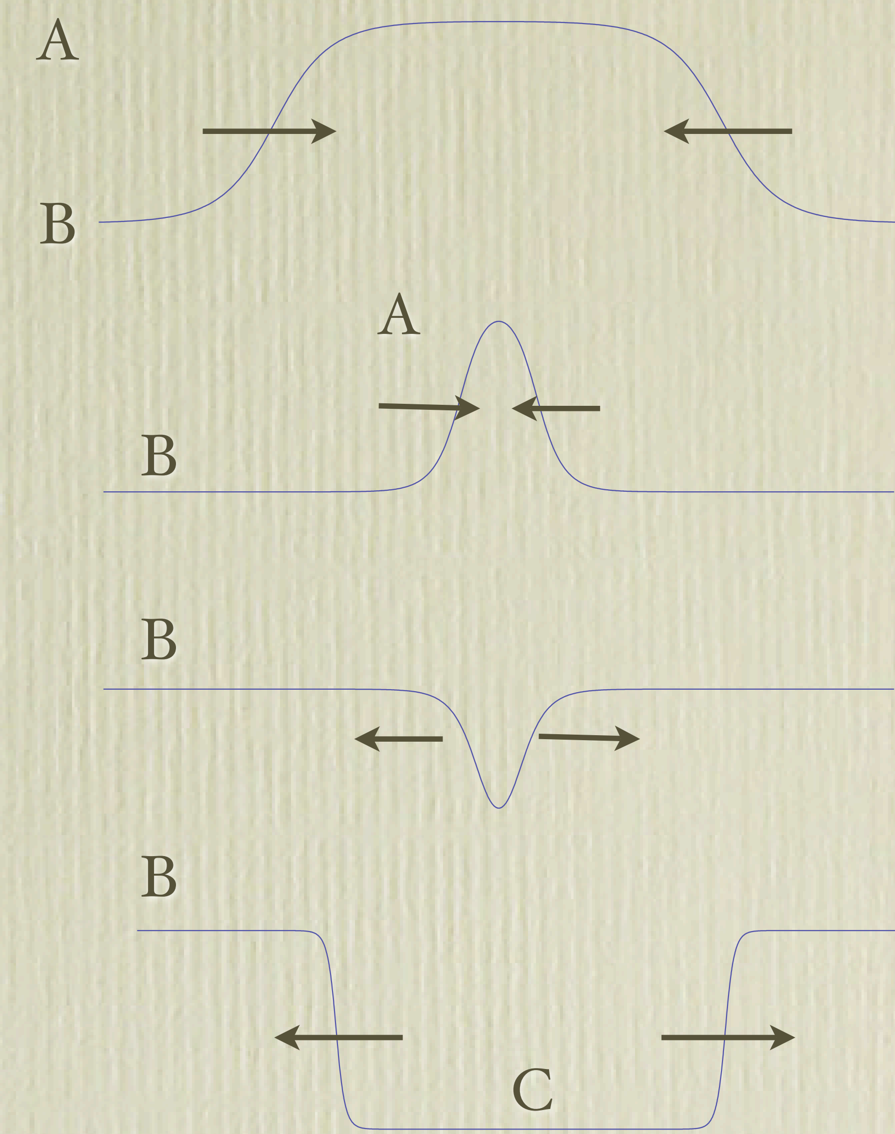


Energetics?

Gradient Energy of walls $\longrightarrow$ Field Kinetic Energy

Sufficient Gradient Energy will push the field over the 2nd barrier





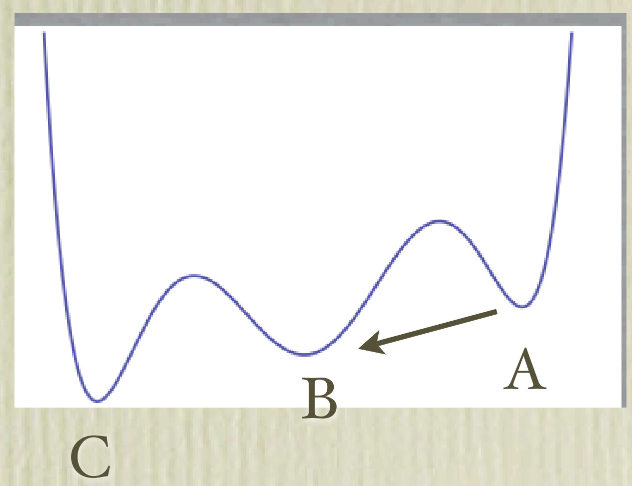
$$\text{Grad. Energy} \propto \gamma^2 > \frac{\Delta V_{BC}}{\Delta V_{AB}} \times \text{elastic coefficient}$$

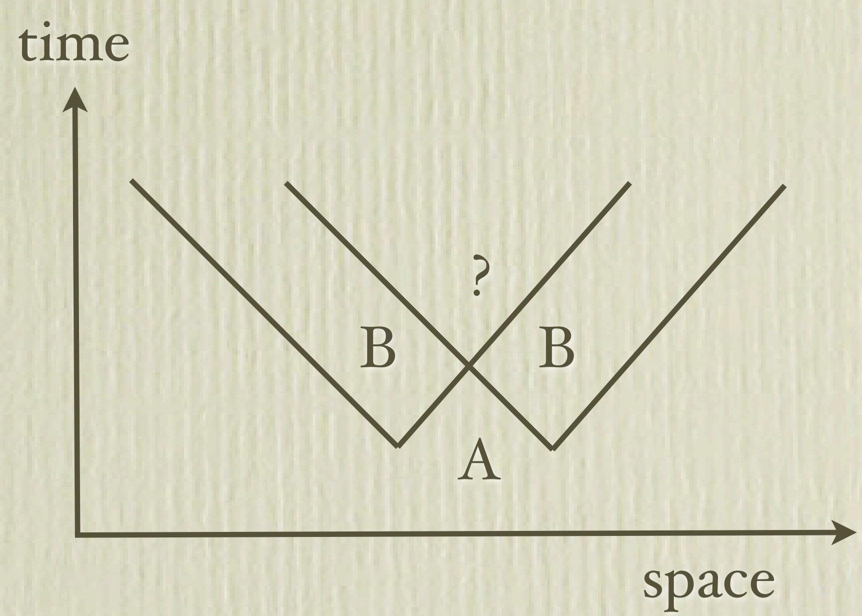
Lorentz Factor

No Transition Collision

Nucleate bubbles close together so Lorentz factor is small at collision

$$\gamma^2 < \frac{\Delta V_{BC}}{\Delta V_{AB}}$$





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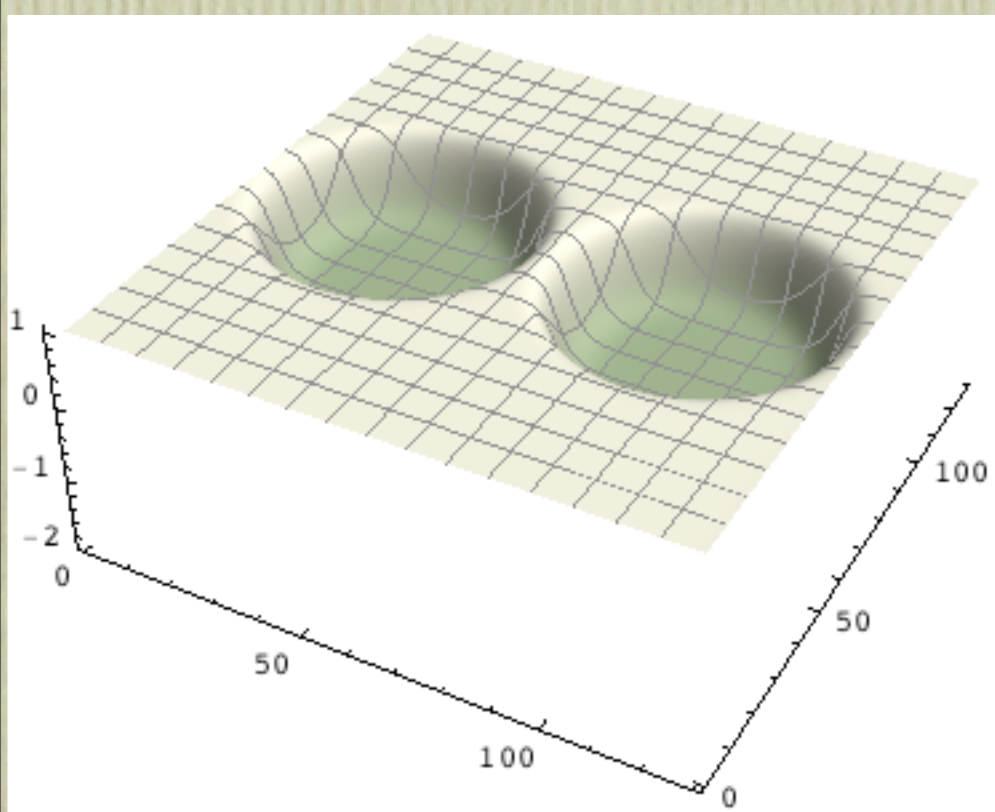
Slice of Field Values



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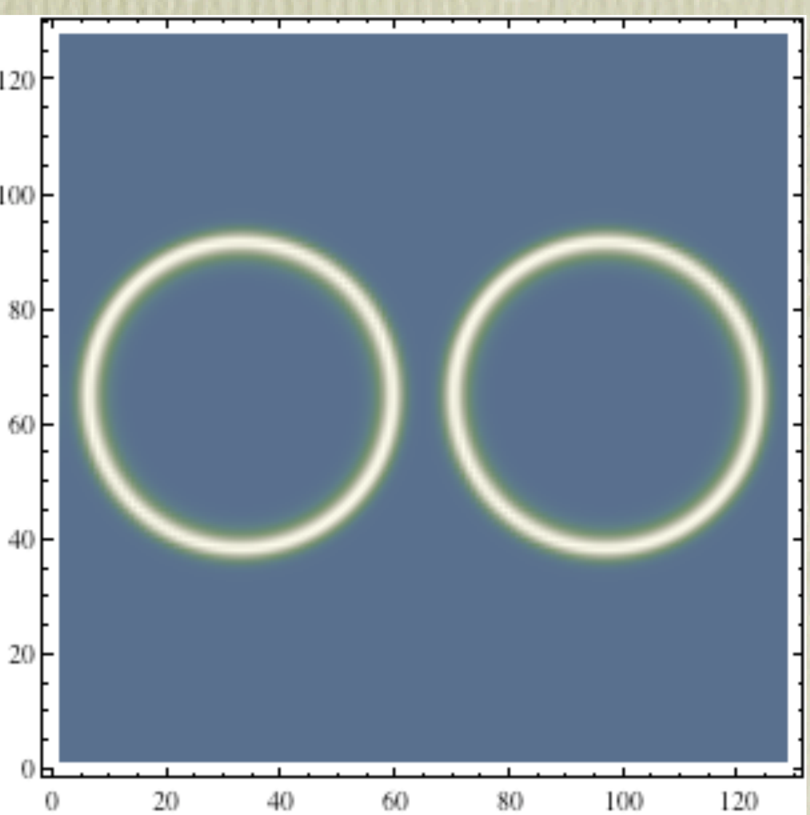
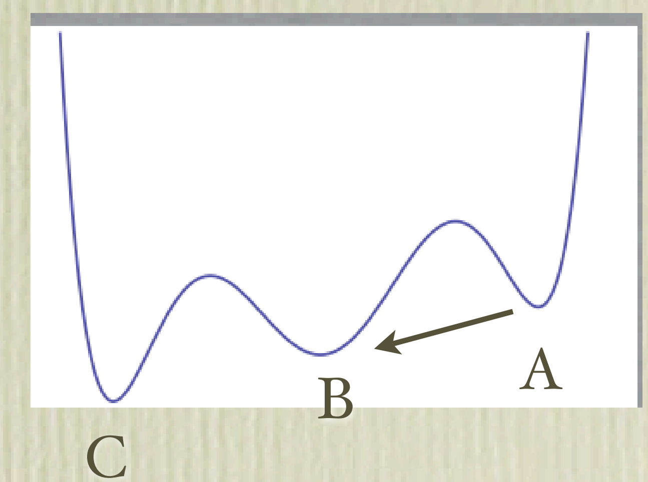
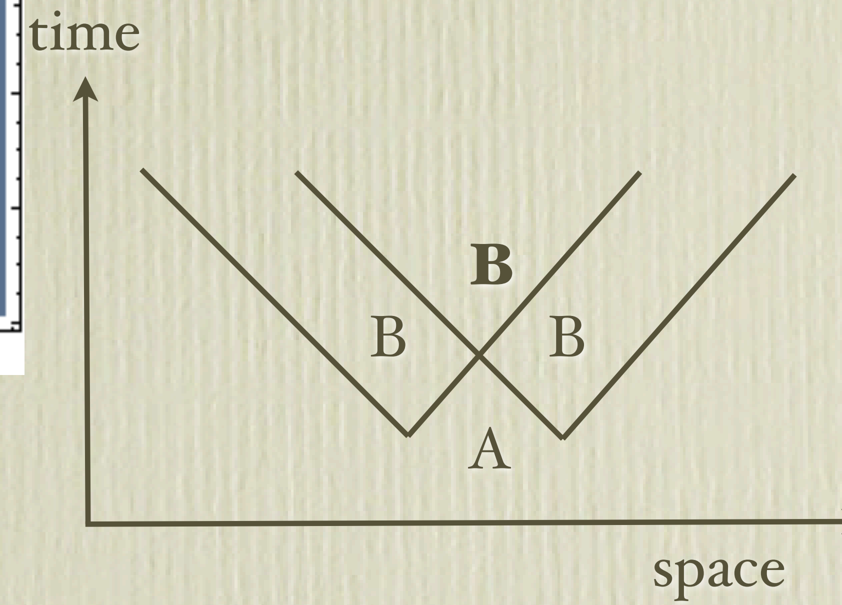


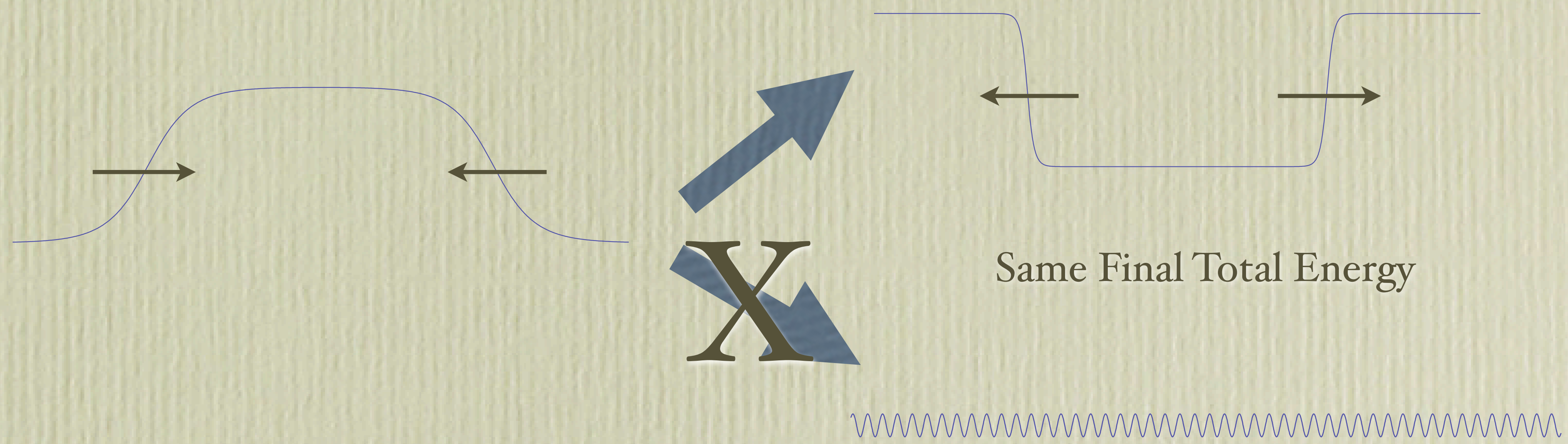




Wall energy is released as debris into the merged bubble.

A plethora of Questions

- New *coherent* walls between new barriers!



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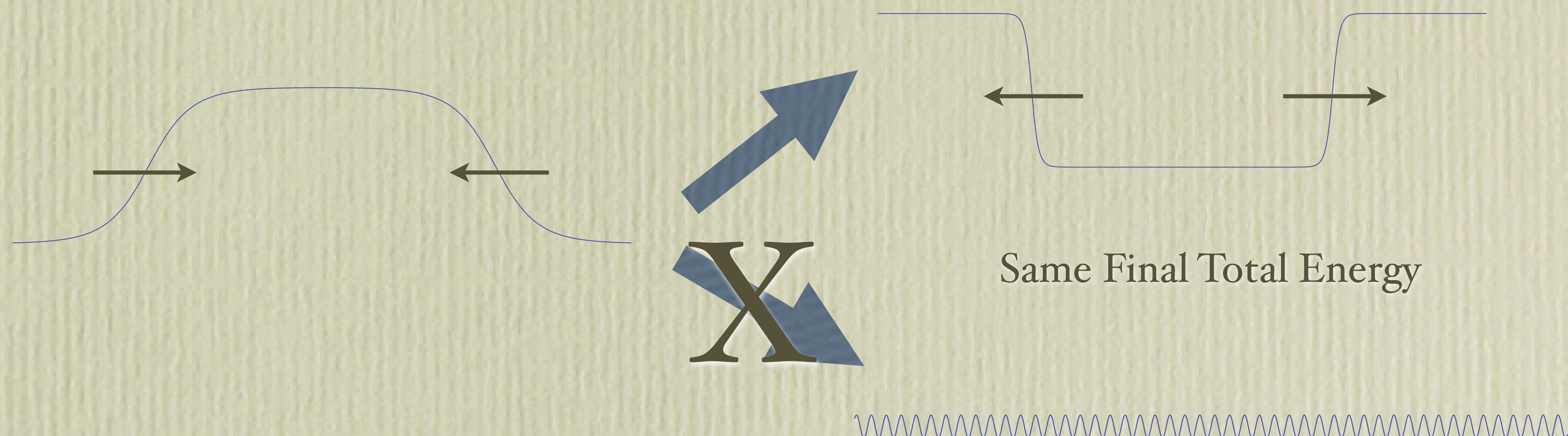
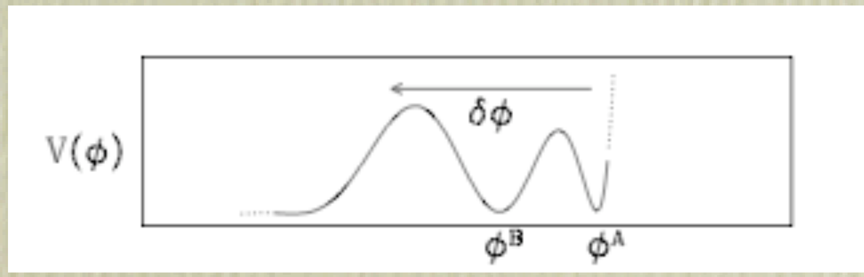


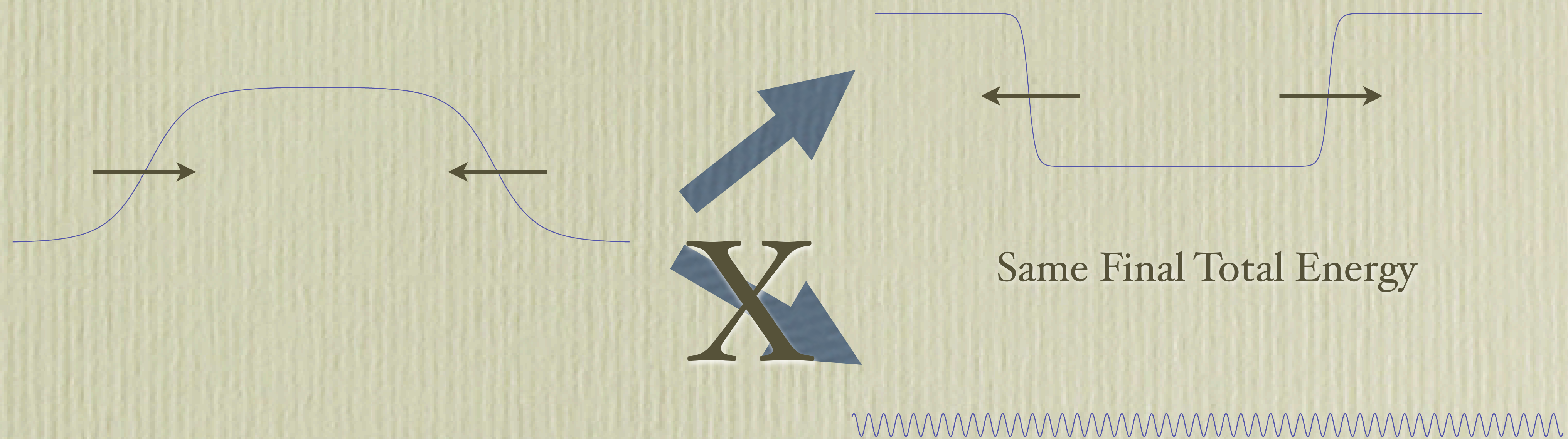
- How far can the field go in field space?
  Excursion Range/“Throw”



Large Collision Energy = Large Excursion ?

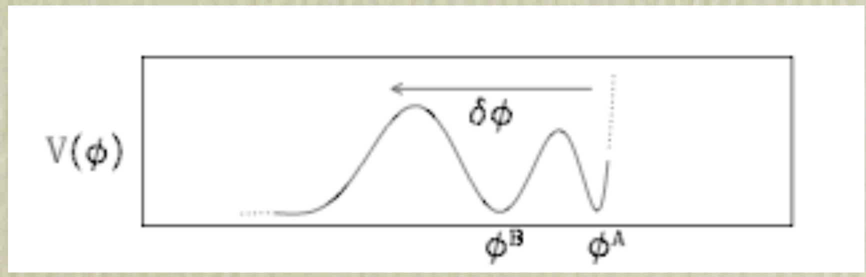
A plethora of Questions

- New *coherent* walls between new barriers!



Same Final Total Energy

- How far can the field go in field space? Excursion Range/“Throw”

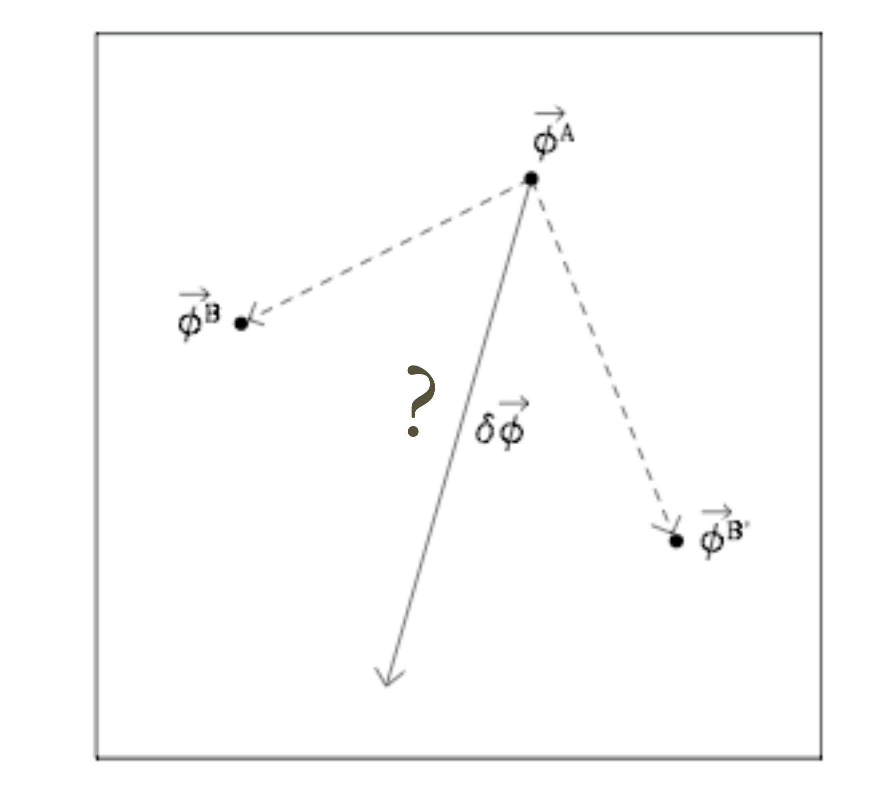


Large Collision Energy = Large Excursion ?

NO!

A plethora of Questions

- Where would the field go - Multifield model? “Kick”



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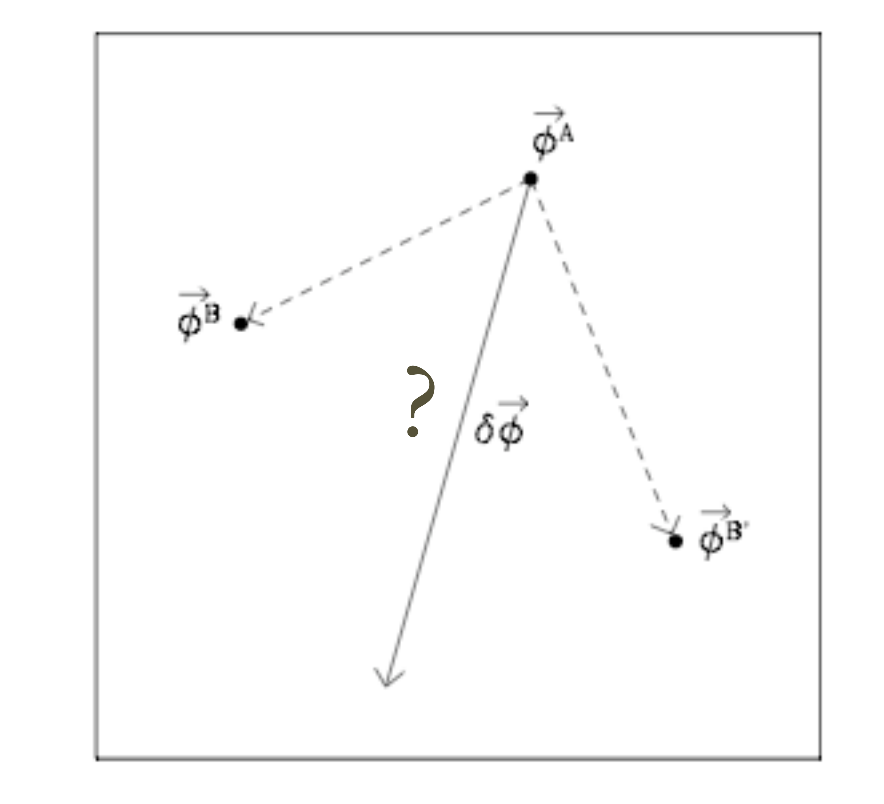
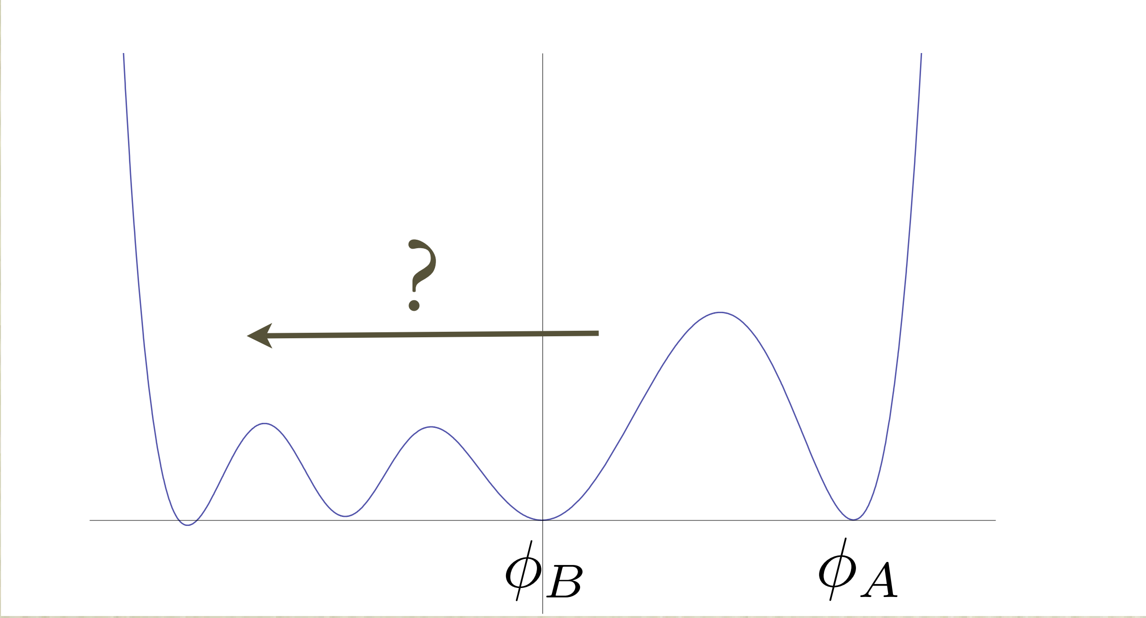


- Can it go over multiple barriers? Split Condition.



Some simplifications

- Our problem $\nabla^2\phi(x,t) = \frac{-dV}{d\phi}$
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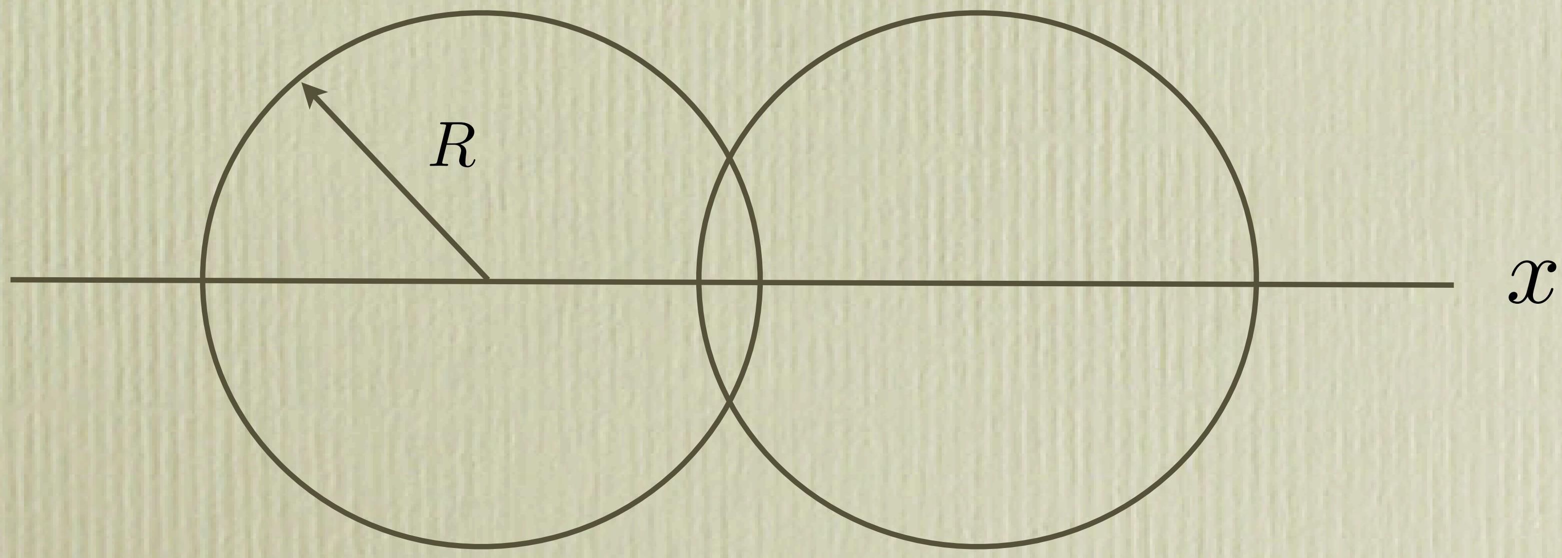
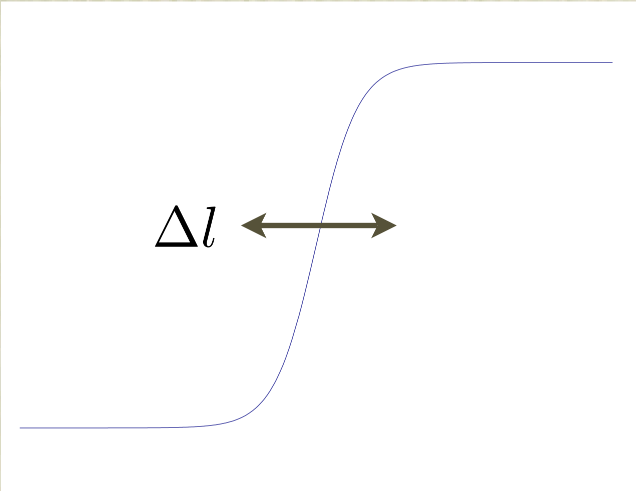
  Reduction to 1+1D solitons

$$\frac{\partial^2\phi}{\partial t^2} - \frac{\partial^2\phi}{\partial x^2} - \frac{\partial^2\phi}{\partial y^2} - \frac{\partial^2\phi}{\partial z^2} = -\frac{dV}{d\phi}$$





$$\frac{\Delta l}{R} \ll 1 \qquad \frac{\partial^2\phi}{\partial t^2} - \frac{\partial^2\phi}{\partial x^2} = -\frac{dV}{d\phi}$$

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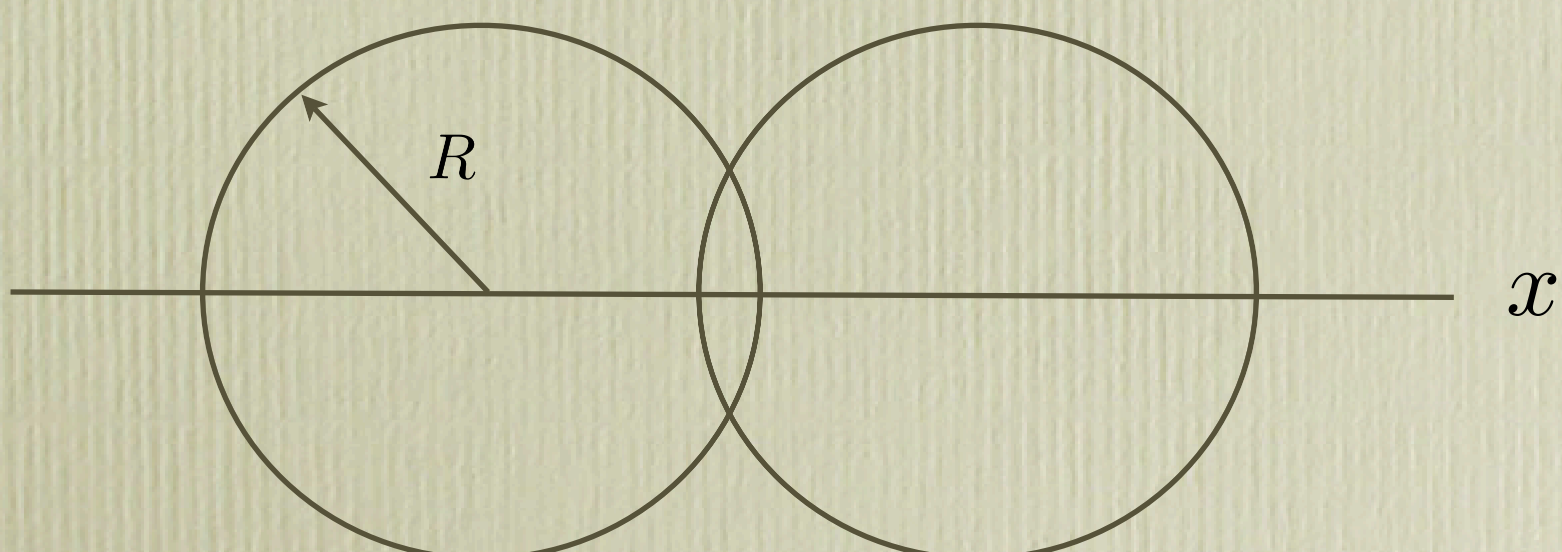

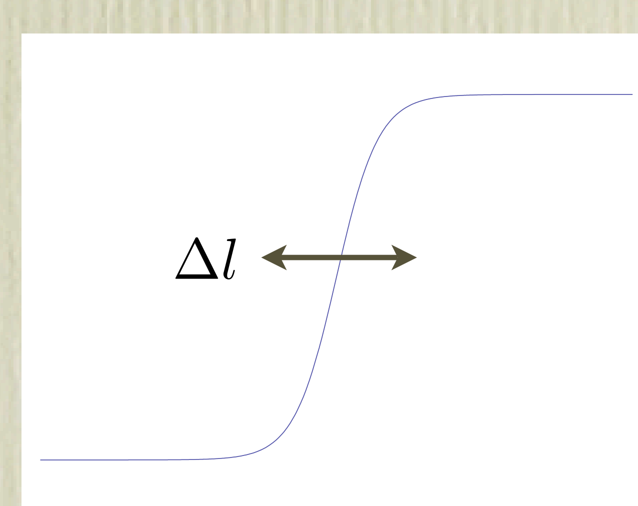

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1+1D Solitons

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- Solitons : stable field configuration which "locally" minimizes the total energy

$$\frac{\partial^2 \phi}{\partial t^2} - \frac{\partial^2 \phi}{\partial x^2} = -\frac{dV}{d\phi}$$ Invariant under Lorentz Trans. $$\phi\left(\frac{\pm(x-ut)}{\sqrt{1-u^2}}\right)$$

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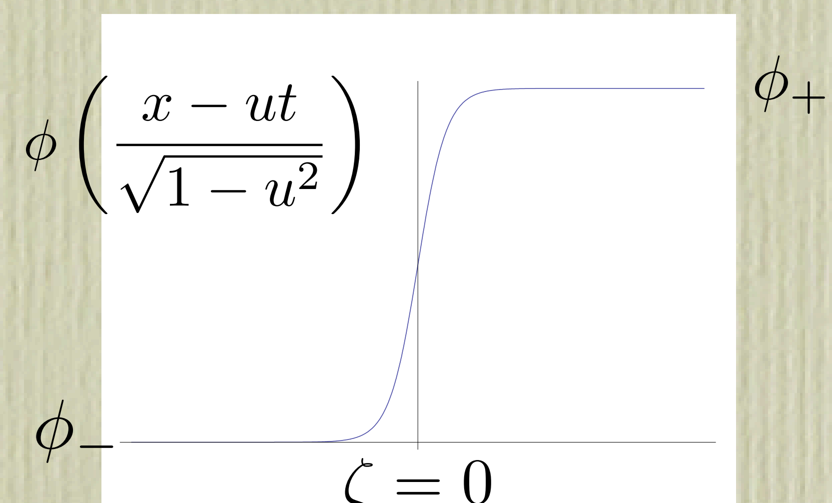
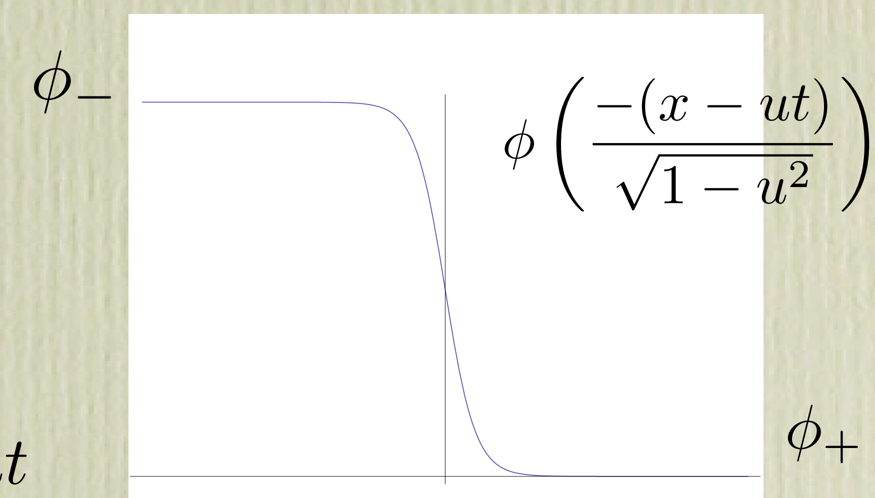


$\zeta = x - ut$



Soliton

Anti-Soliton

Bubble Wall collisions approximated by Soliton-(anti)soliton interactions

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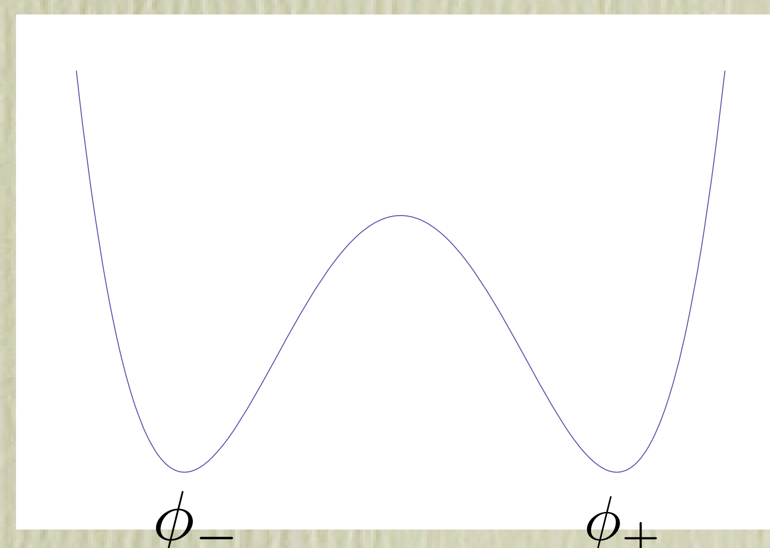
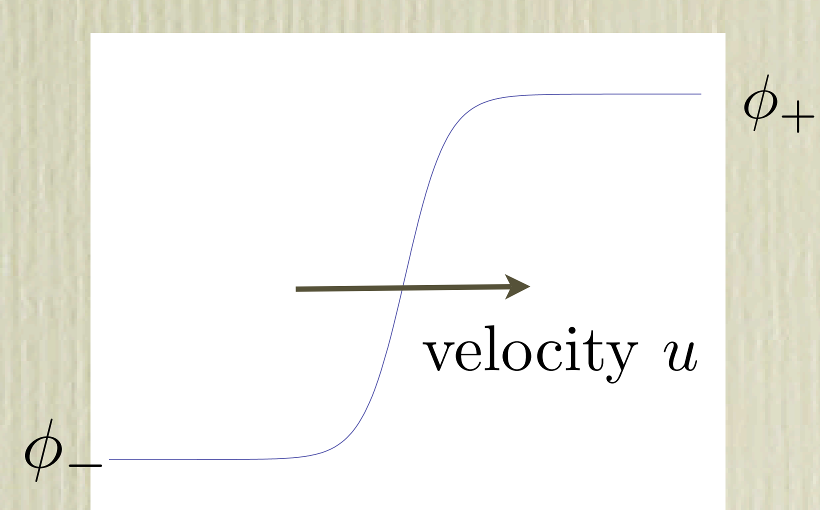
ϕ^4 Solitons

$$V(\phi) = (\phi - \phi_+)^2(\phi + \phi_-)^2$$





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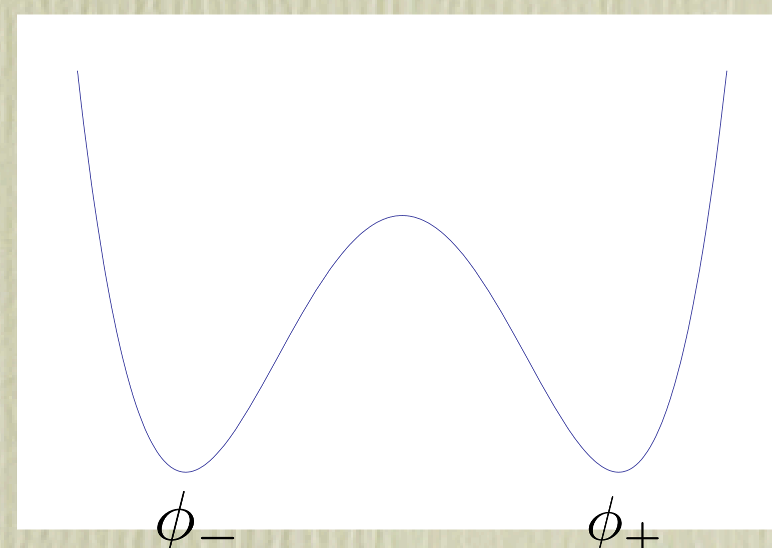
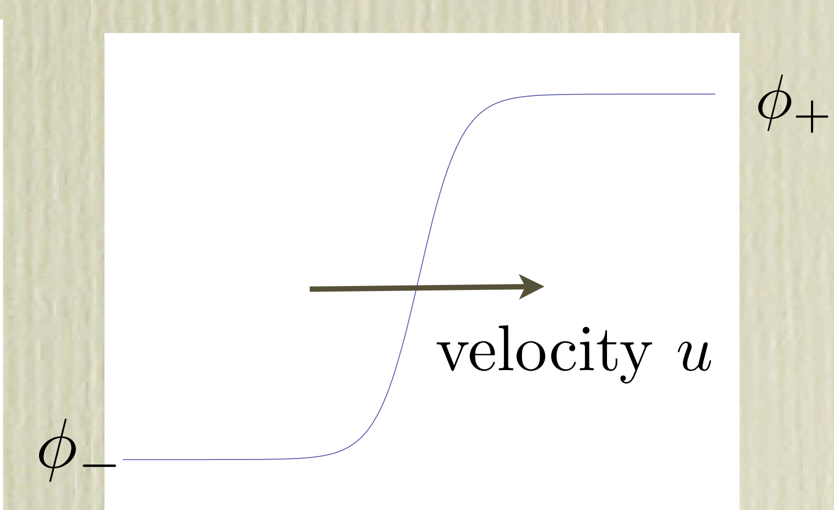
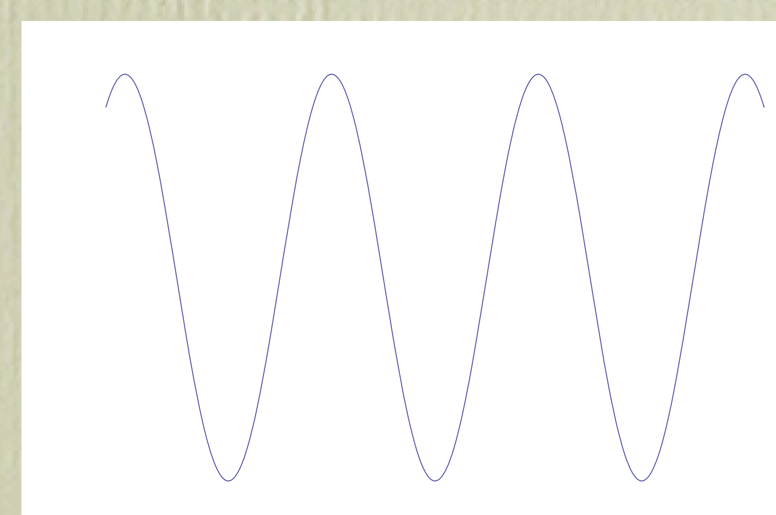
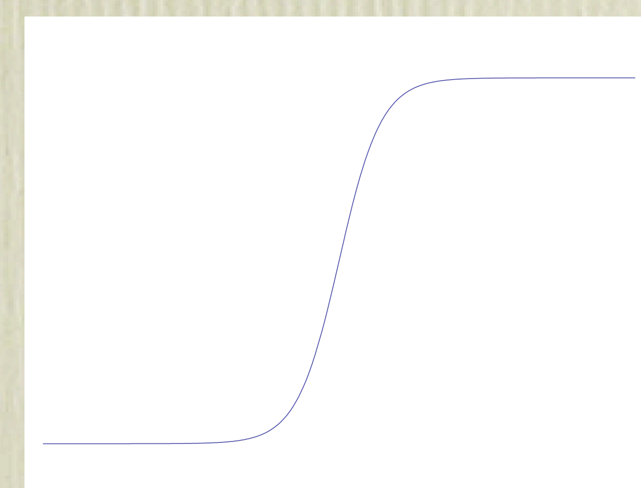




sine-Gordon Solitons

$$V(\phi) = 1 - \cos(\phi)$$

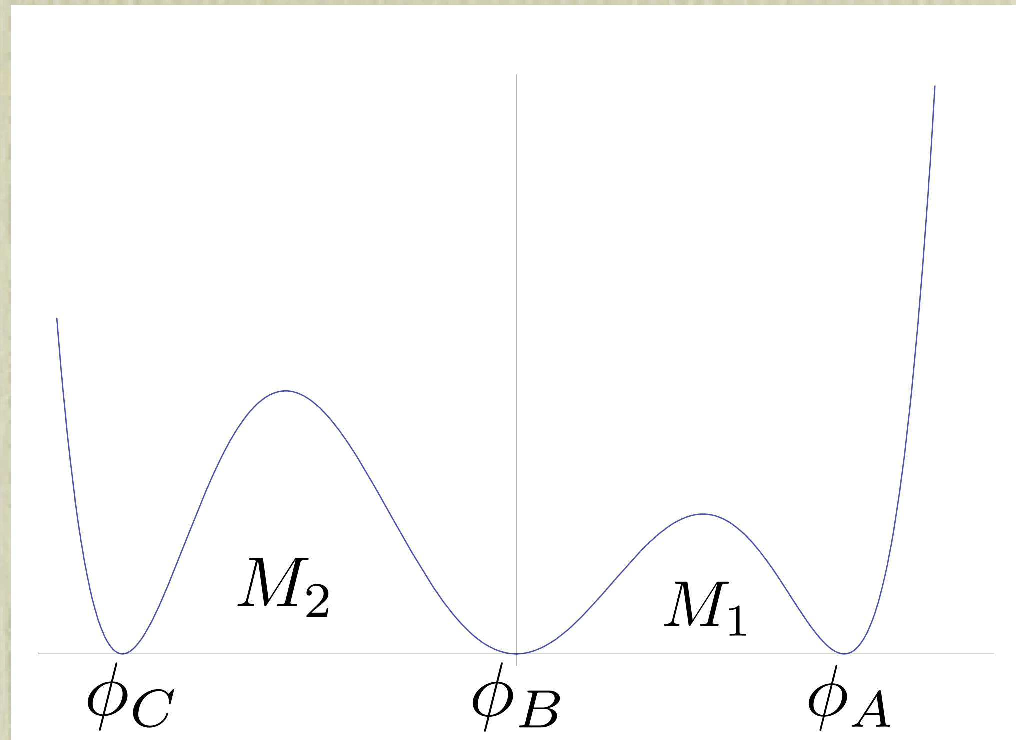




1+1D Solitons

- Rest Mass/Tension

$$M_1 = \int_{\phi_B}^{\phi_A} \sqrt{2V(\phi)}$$



- Exact Soliton Solutions

ϕ^4 : only single soliton solution exist

sine-Gordon : arbitrary N solitons/antisolitons solutions exist

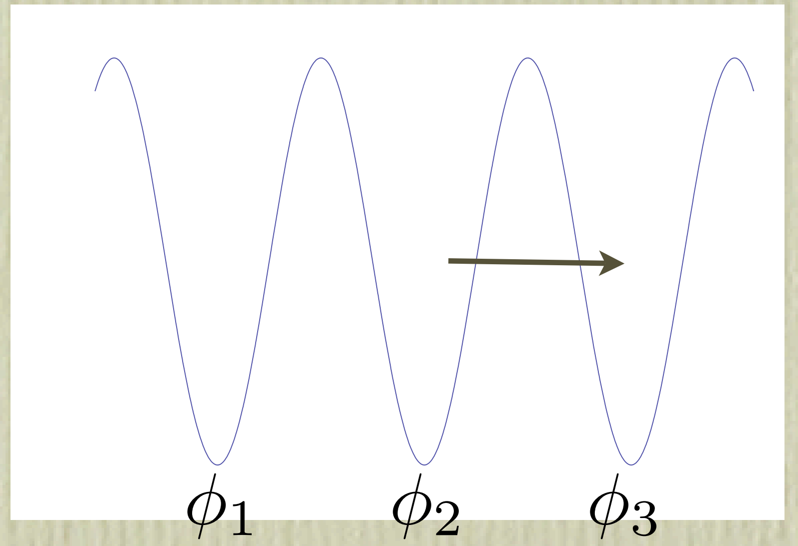
Clues from sine-Gordon

- Exact anti-soliton interaction solution

$$\phi(x,t) = 4\tan^{-1}\left[\frac{\sinh(\gamma u t)}{u\cosh(\gamma x)}\right]$$

Perring + Skyrme (1961)

Numerical -- Malaysia!!



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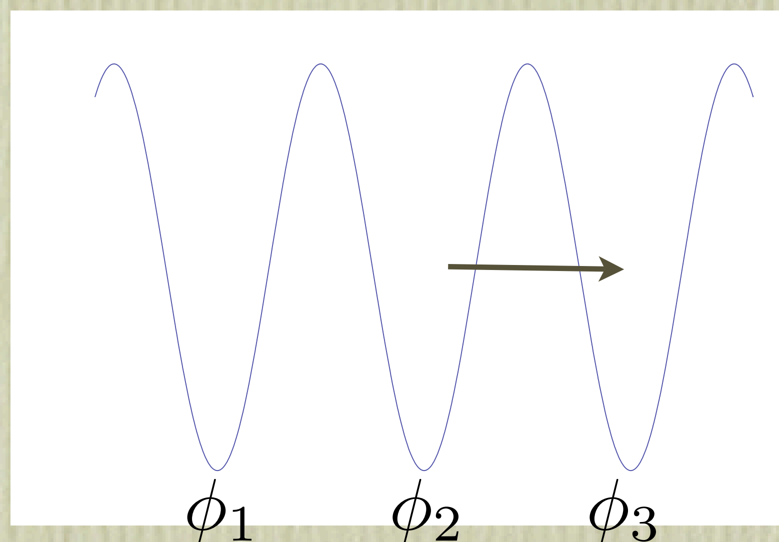

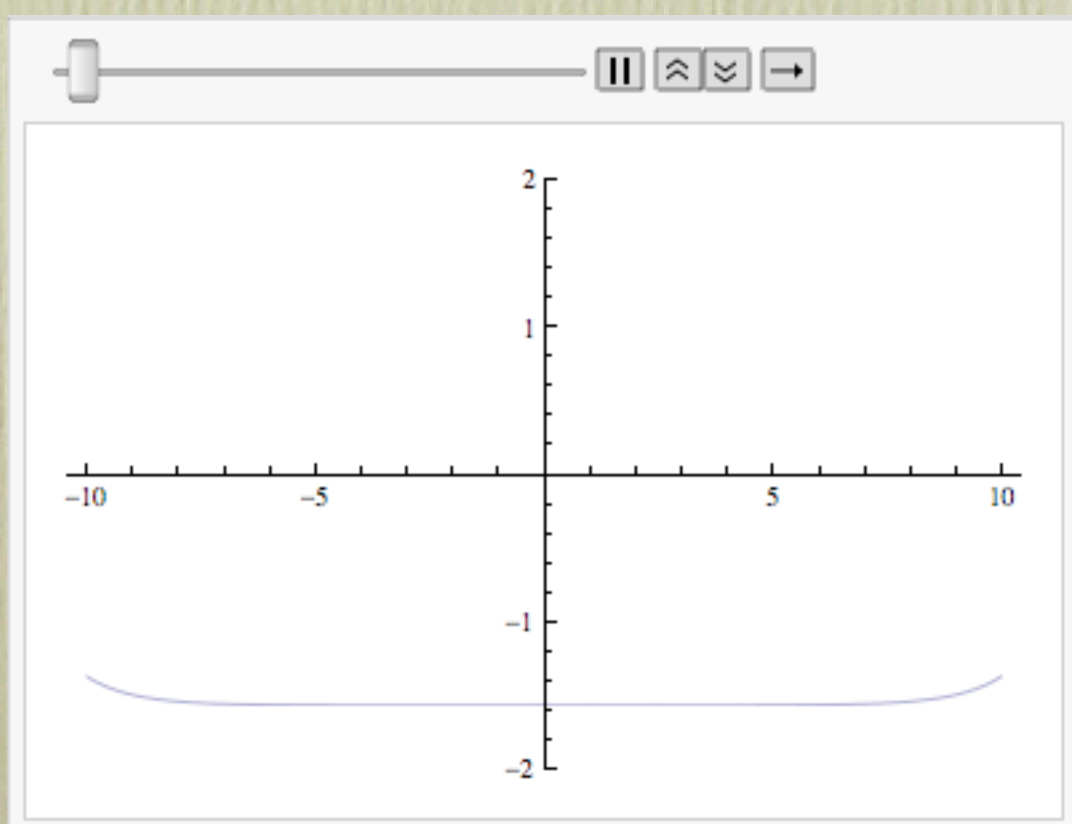

ϕ_3

ϕ_2

ϕ_1

Clues from sine-Gordon

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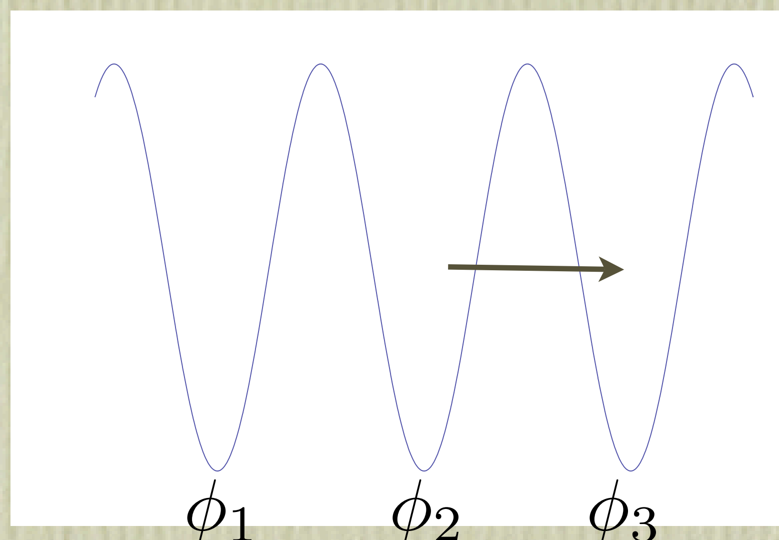
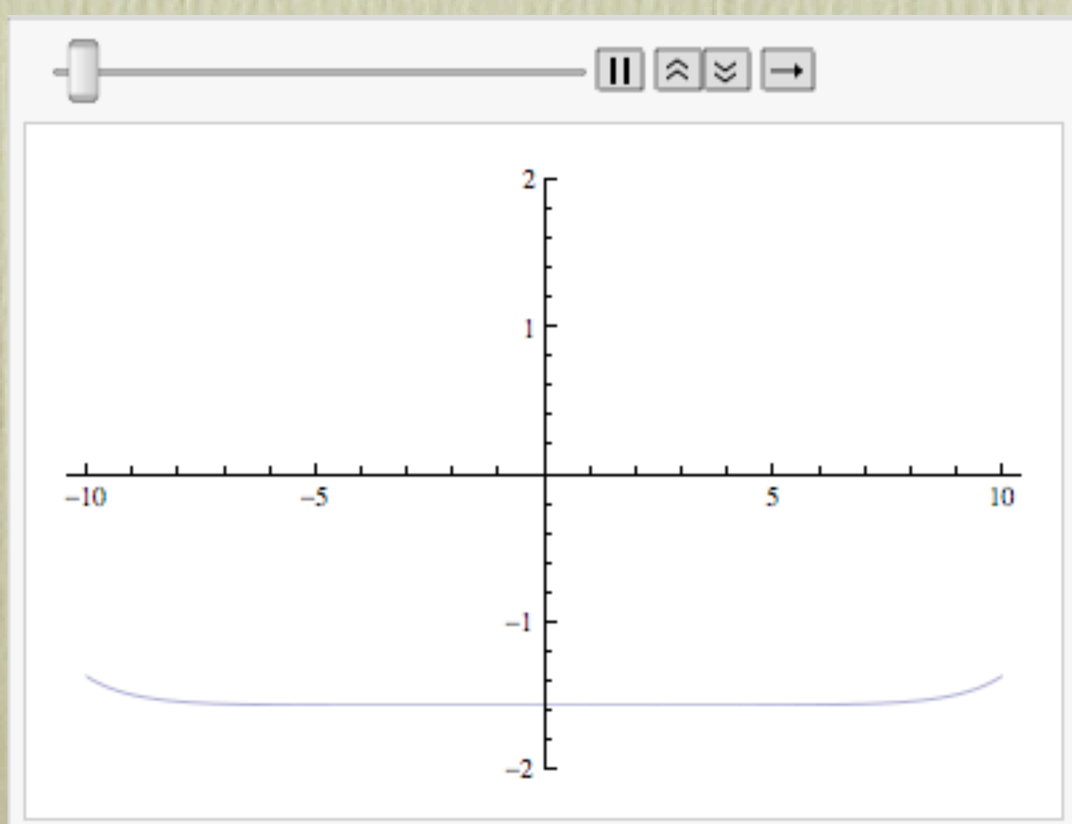


Completely Elastic -- no radiation losses

Only *single* barrier transition regardless of collision velocity



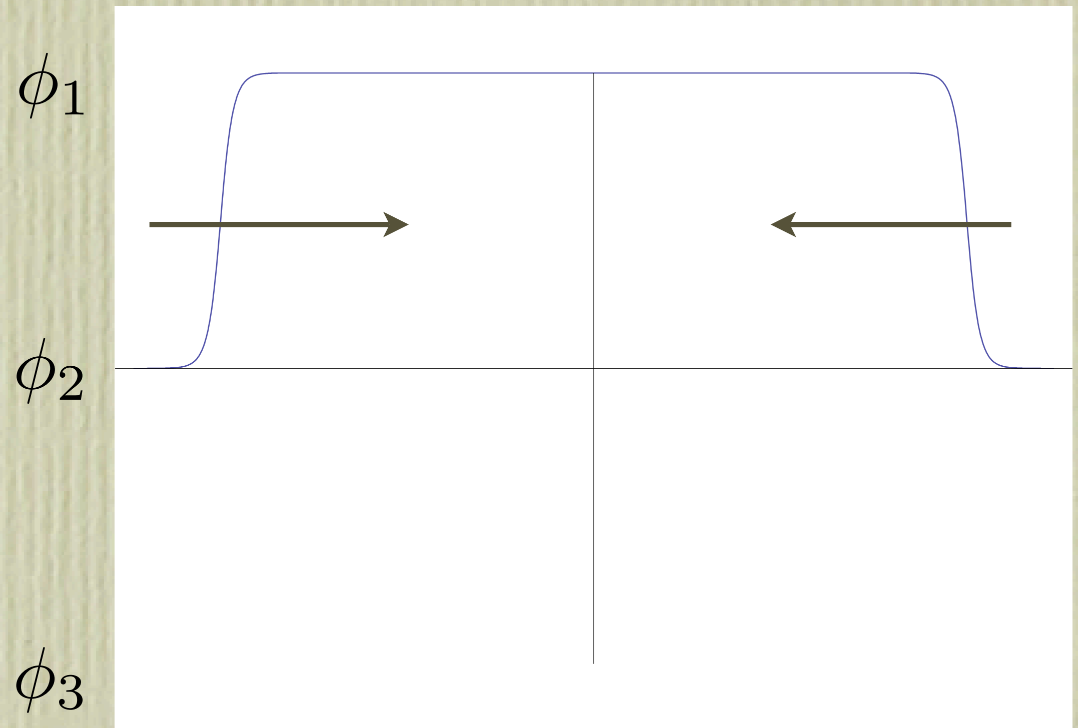
Transition regardless of velocity

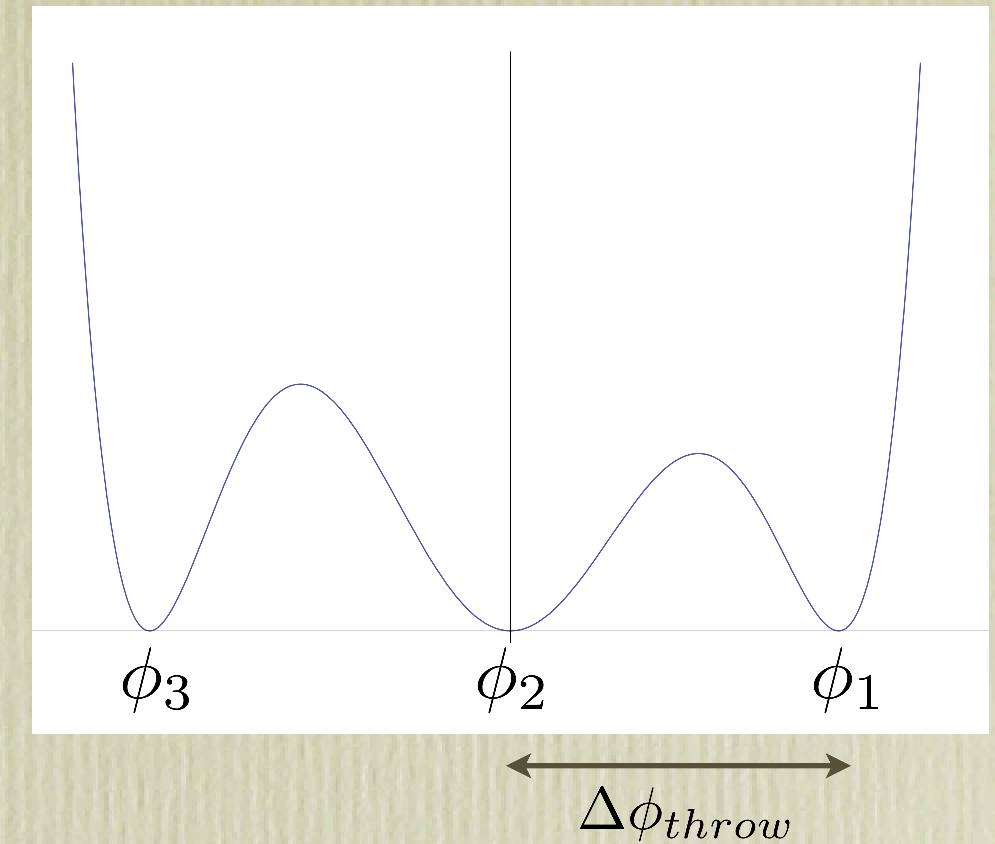
ϕ_3

ϕ_2

ϕ_1

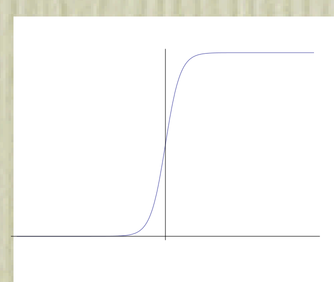
General Soliton Interaction

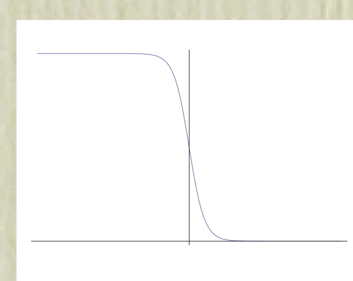




$$\phi(x, t \to -\infty) = \phi_0\left(\frac{x - ut}{\sqrt{1-u^2}}\right) + \phi_0\left(\frac{-(x+ut)}{\sqrt{1-u^2}}\right) - \Delta\phi_{throw}$$

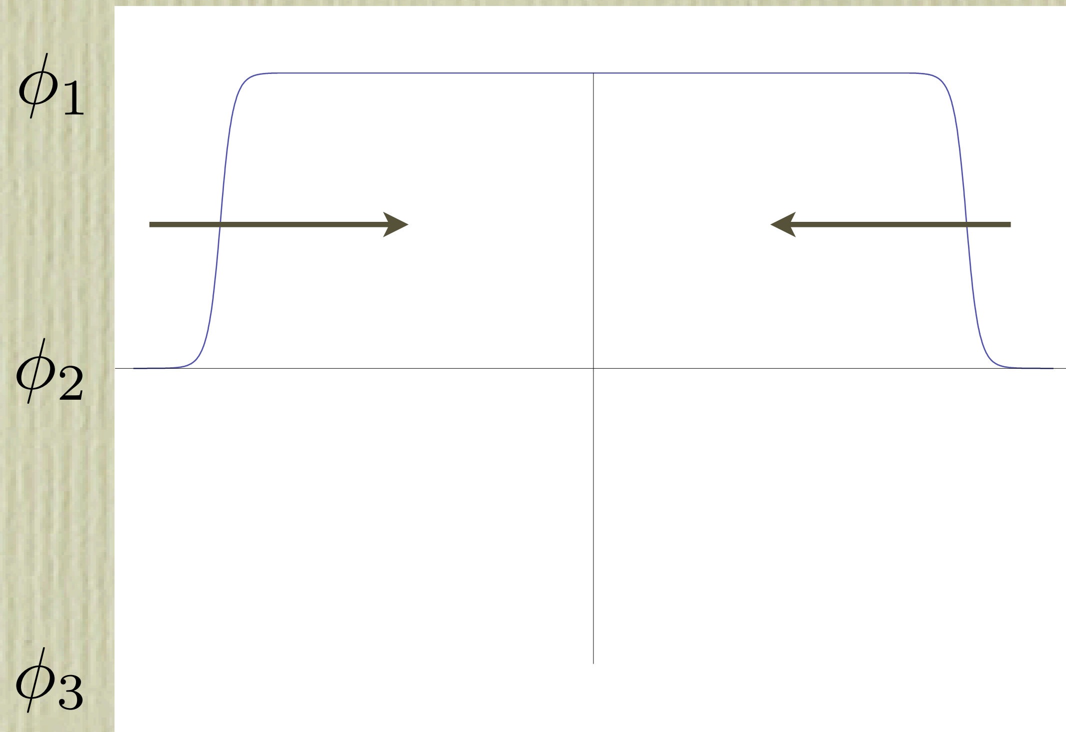
Collision at $t = 0$

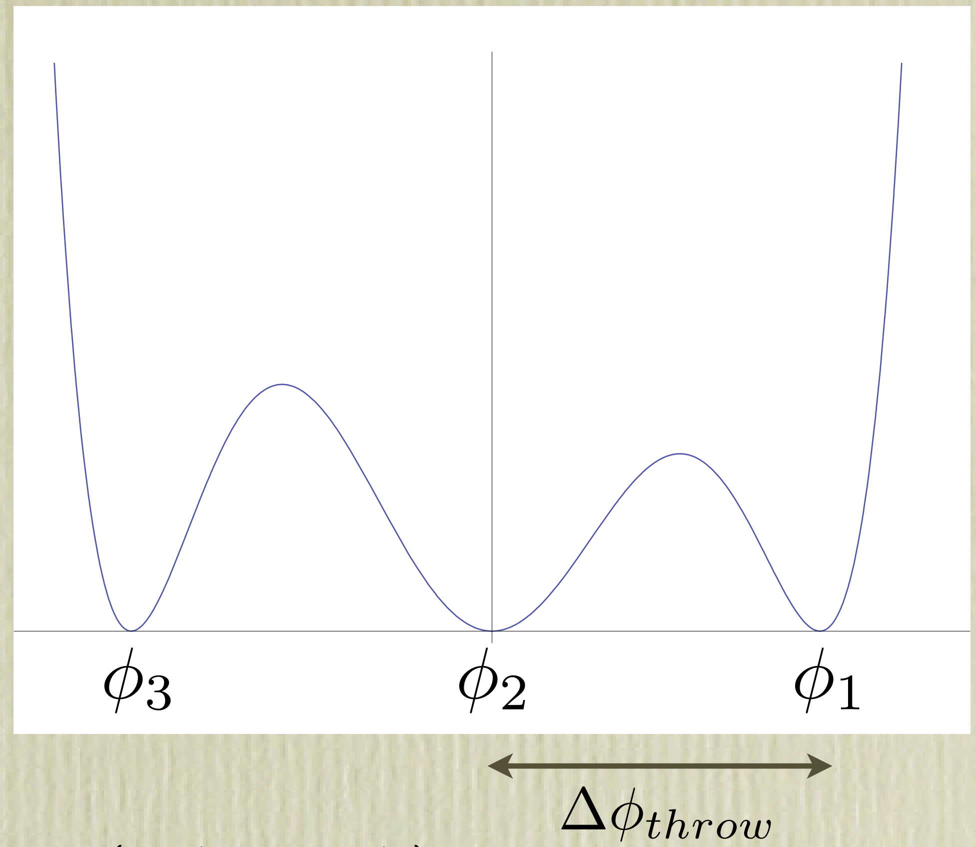




This equation breaks down as they approach and interact via the potential

General Soliton Interaction





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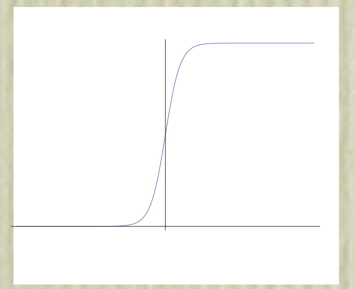

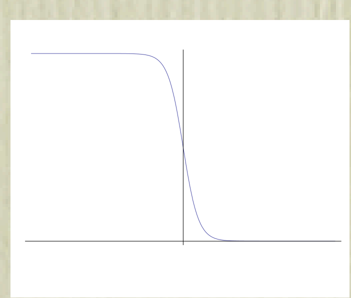

This equation breaks down as they approach and interact via the potential

Key observation : *But it is approximately good even during interaction* "Free Passage"

General Soliton Interaction: *Free Passage* Approximation

$$\frac{\partial^2 \phi_0}{\partial t^2} - \frac{\partial^2 \phi_0}{\partial x^2} = -\frac{dV}{d\phi}(\phi_0) \qquad \text{solution :} \qquad \phi_0\left(\frac{\pm(x-ut)}{\sqrt{1-u^2}}\right)$$

If velocity *u* is relativistic, $u \to 1$ hence $\frac{\partial^2 \phi_0}{\partial t^2} - \frac{\partial^2 \phi_0}{\partial x^2} \sim 0$

or $\text{Amplitude}\left(\frac{\partial^2 \phi_0}{\partial x^2}\right) \gg \text{Amplitude}\left(\frac{dV}{d\phi}\right)$

Solitons do not "feel" the potential initially during interaction!

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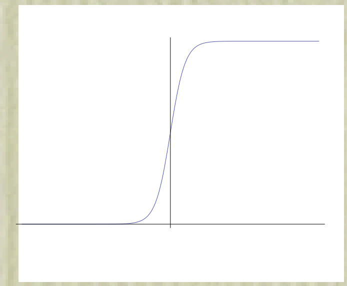
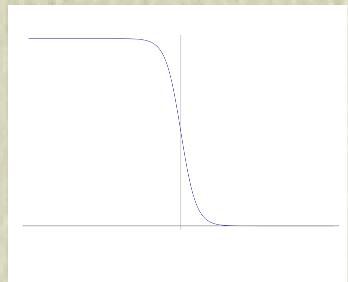
Time when approximation breaks down

$t_* > t$





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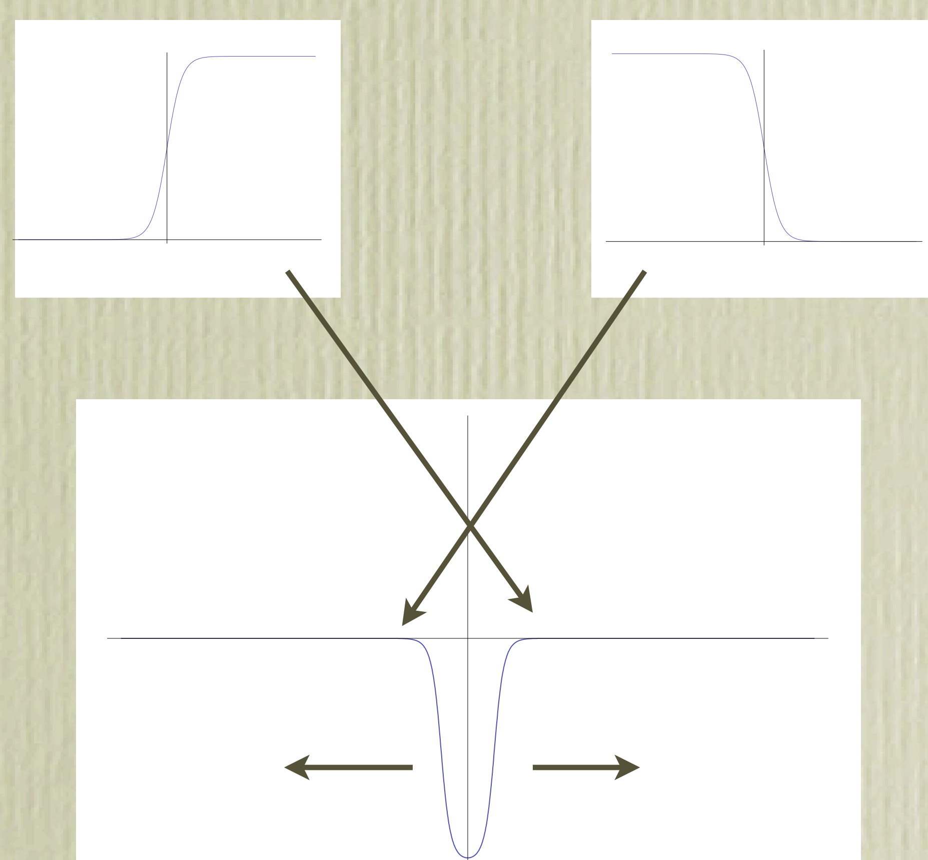

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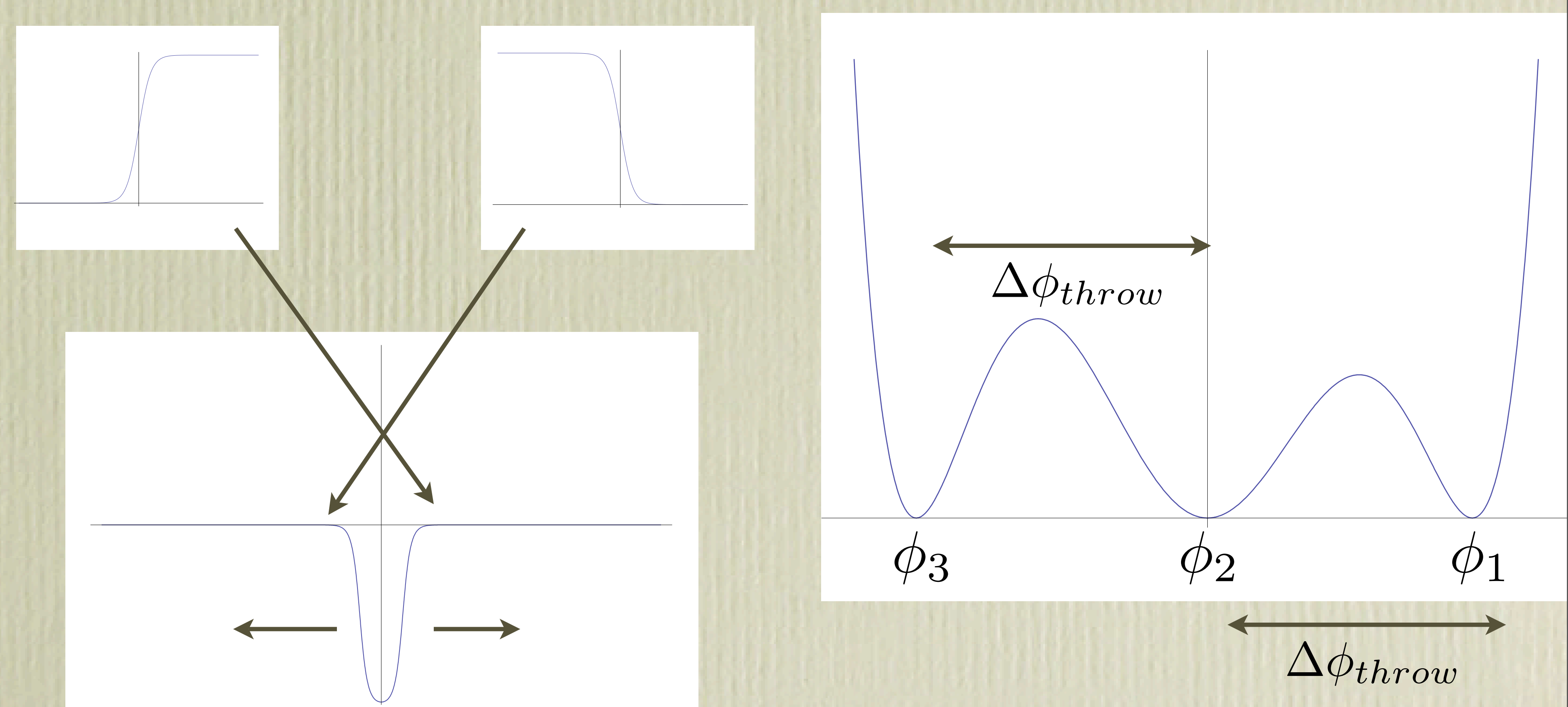

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Free Passage breaks down :

$$\text{Amplitude}\left(\frac{\partial^2 \phi_0}{\partial x^2}\right) \approx \text{Amplitude}\left(\frac{dV}{d\phi}\right)$$

$$\frac{1}{1-u^2}\frac{dV}{d\phi}(\phi_0(t_*)) \approx \frac{dV}{d\phi}(2\phi_0(t_*) - \Delta\phi_{throw})$$

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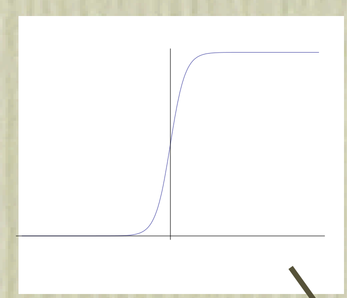
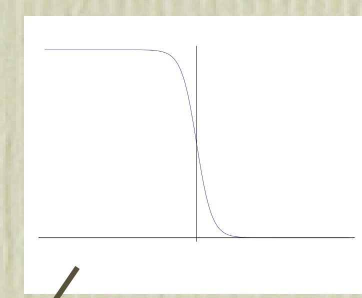
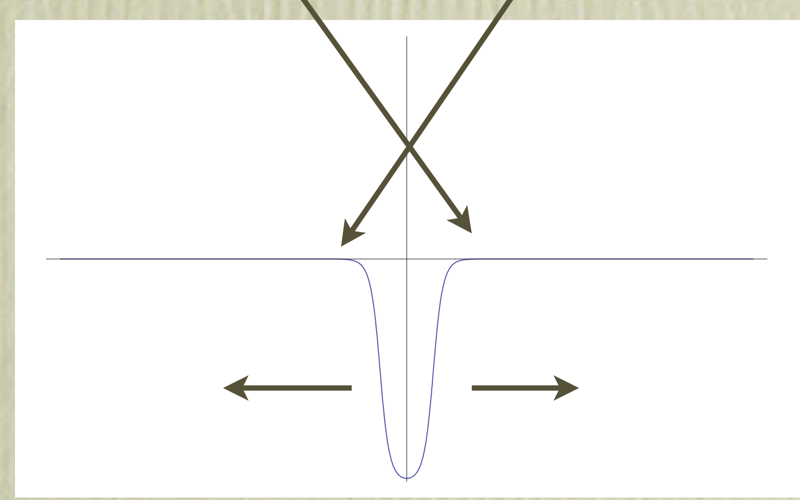
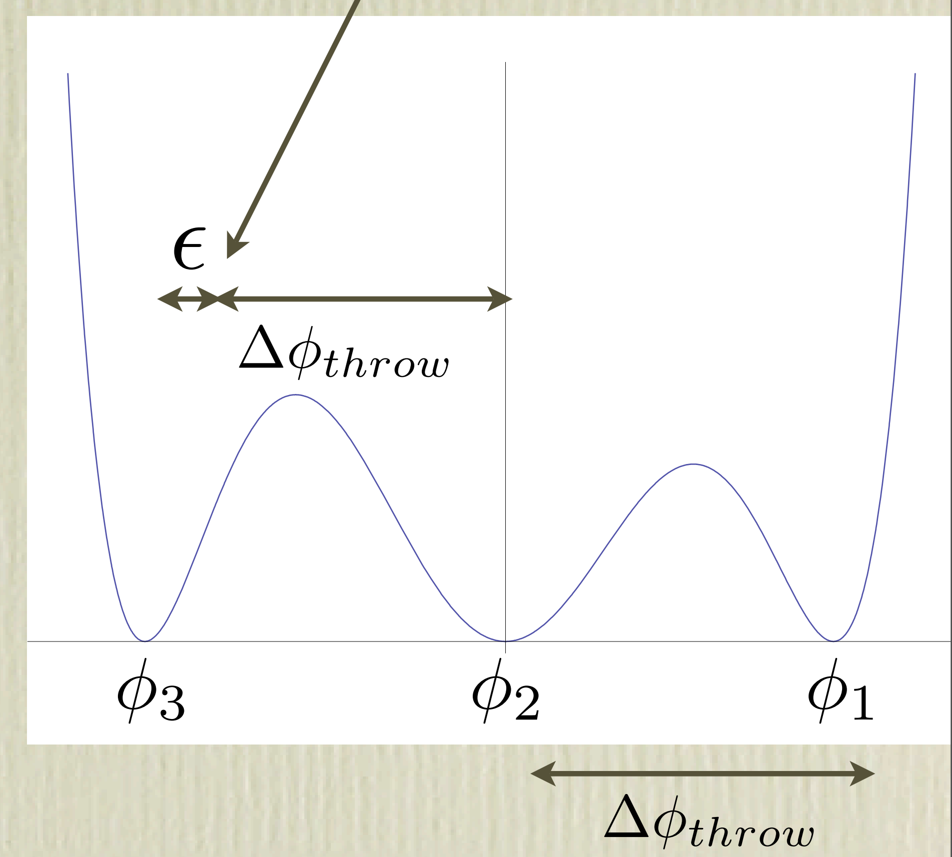
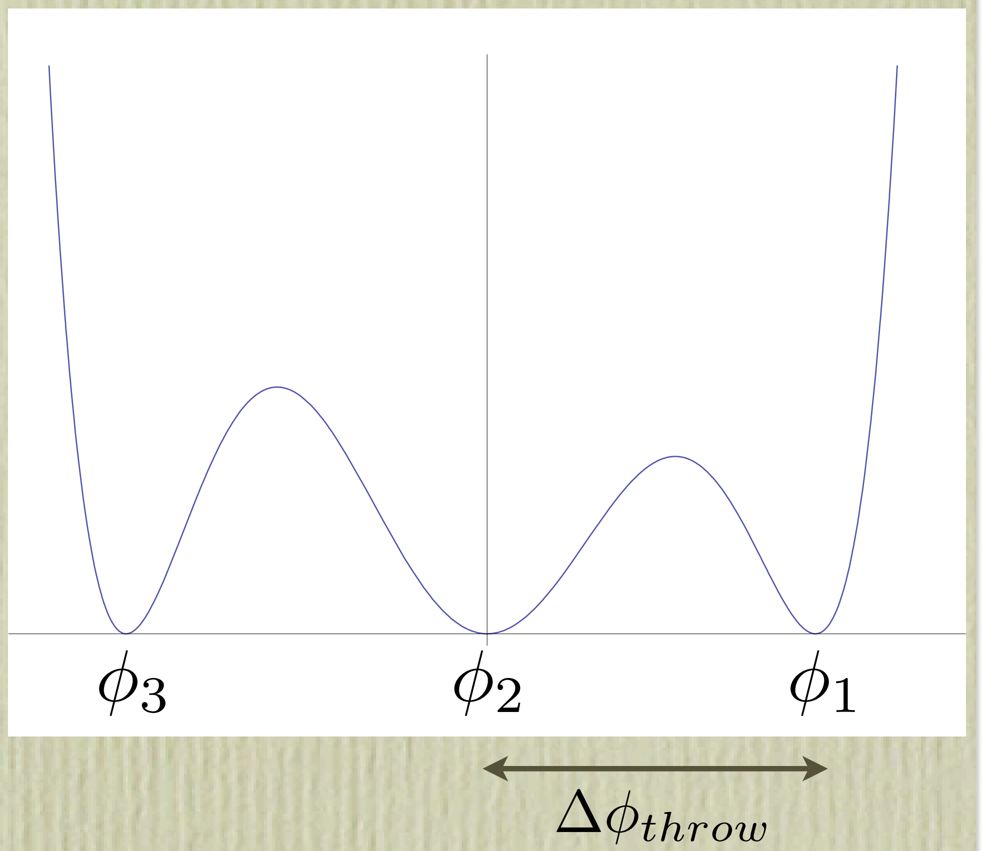


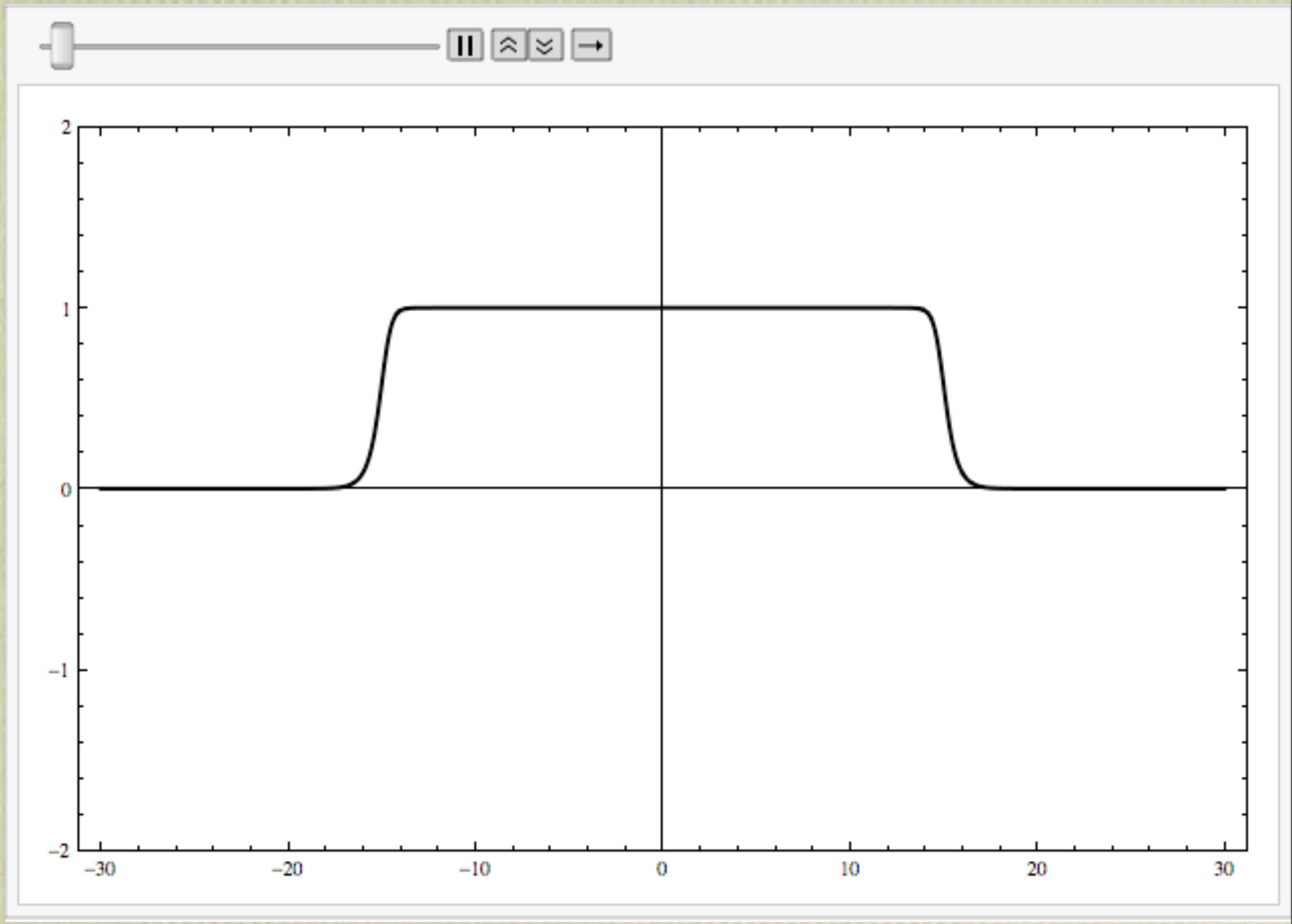






Free Passage in Action!



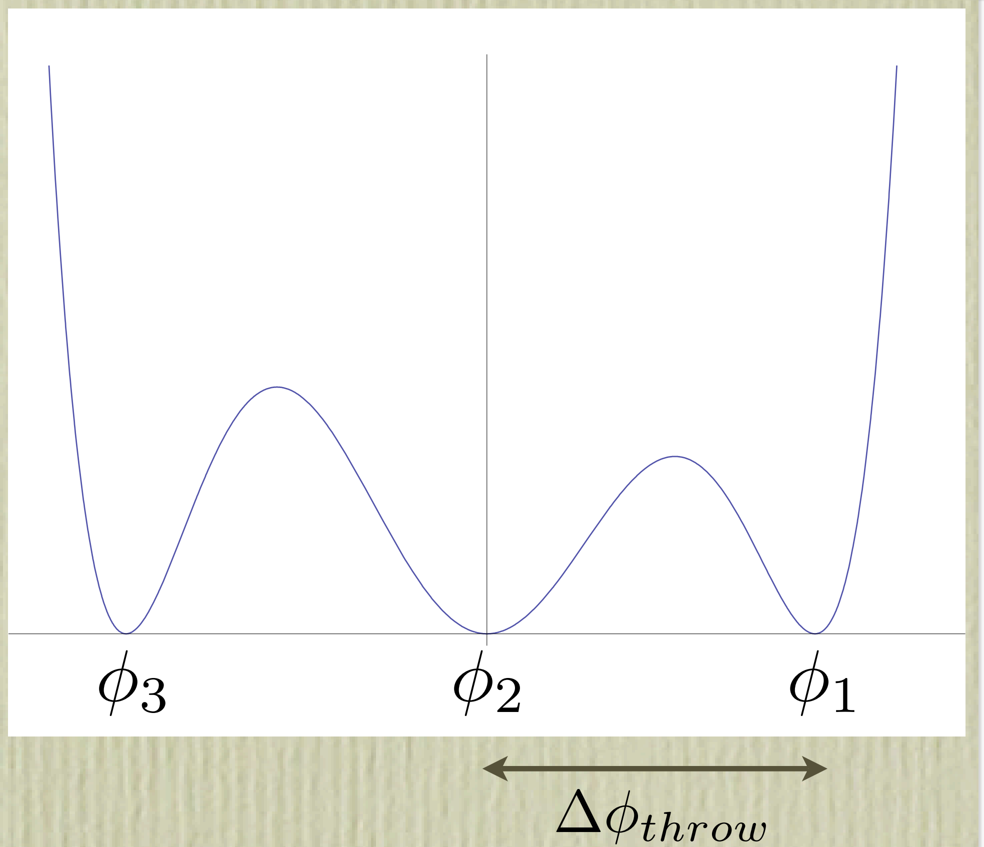


$$\gamma = \frac{1}{\sqrt{1-u^2}} = 3$$

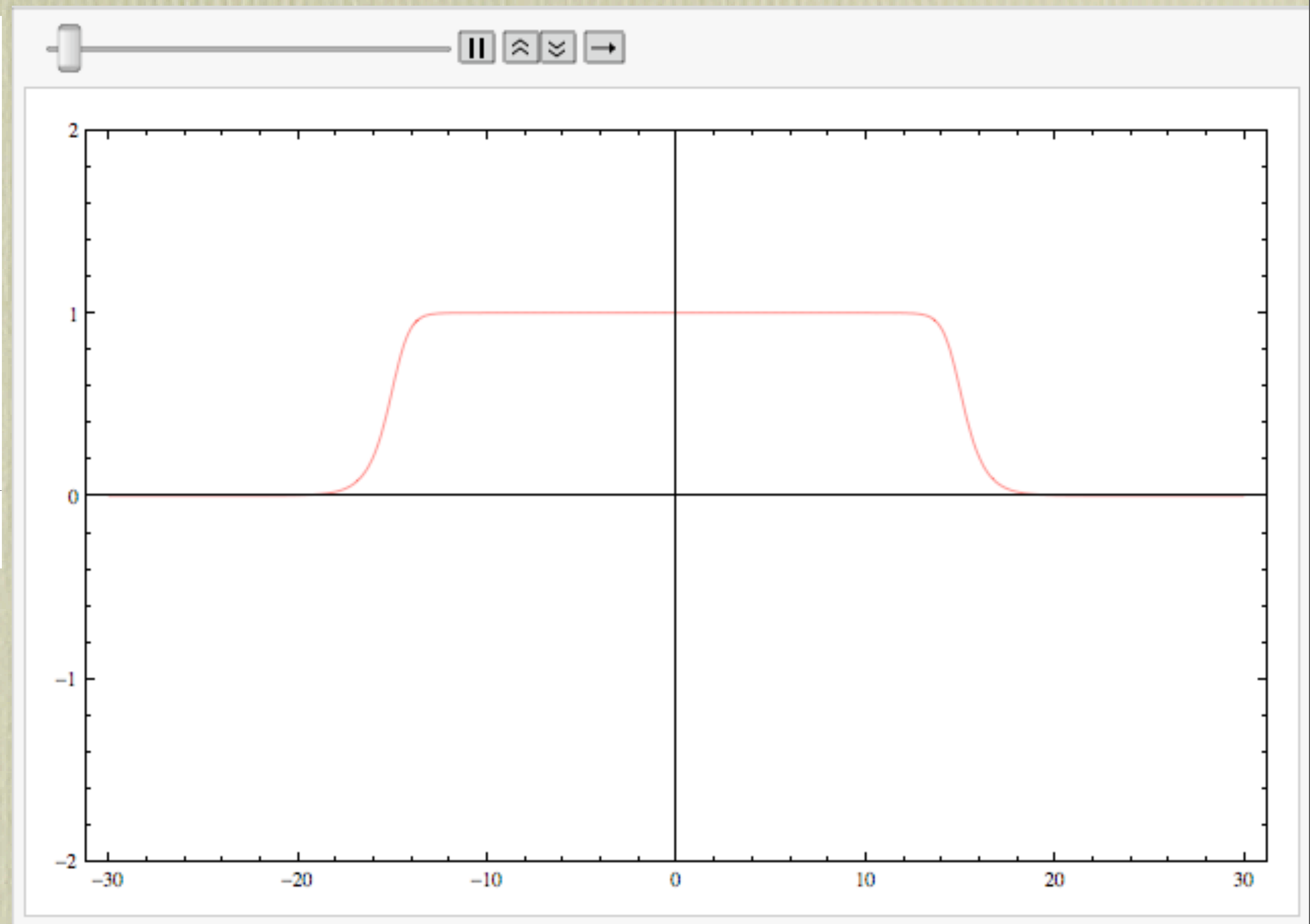
Red Line : Numerical
Black Line : Free Passage

1+1D soliton-antisoliton Collision with **transition**

Free Passage in Action!



$$\gamma = \frac{1}{\sqrt{1-u^2}} = 1.67$$



1+1D soliton-antisoliton Collision with **no transition**

Predictions of Free Passage

- Coherent walls generically form in high speed collisions

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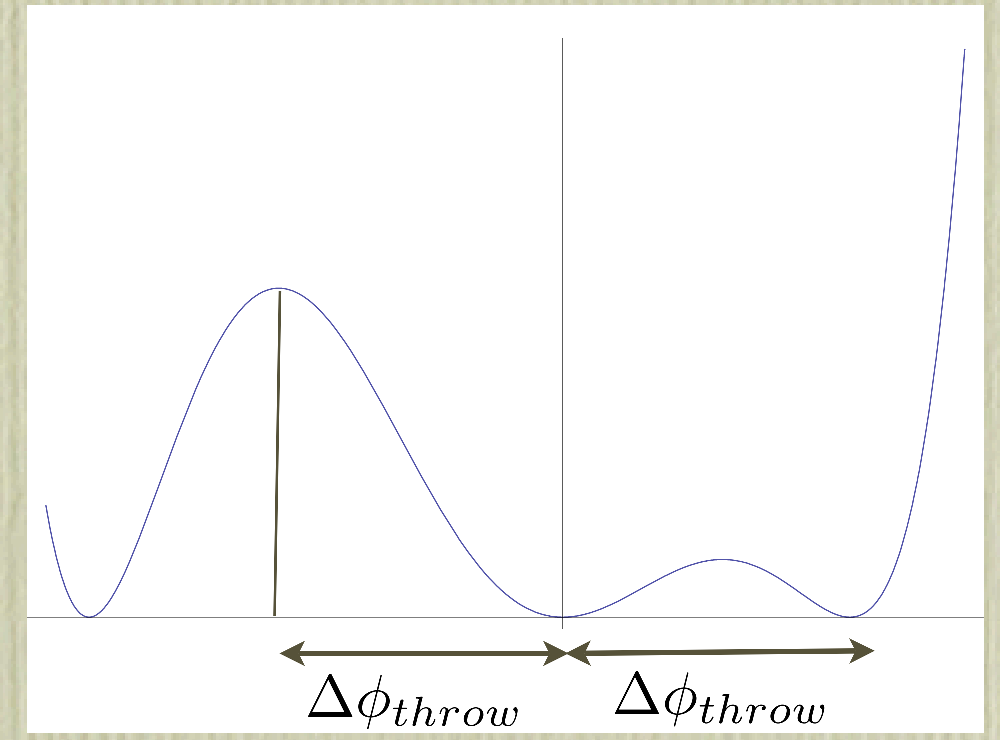
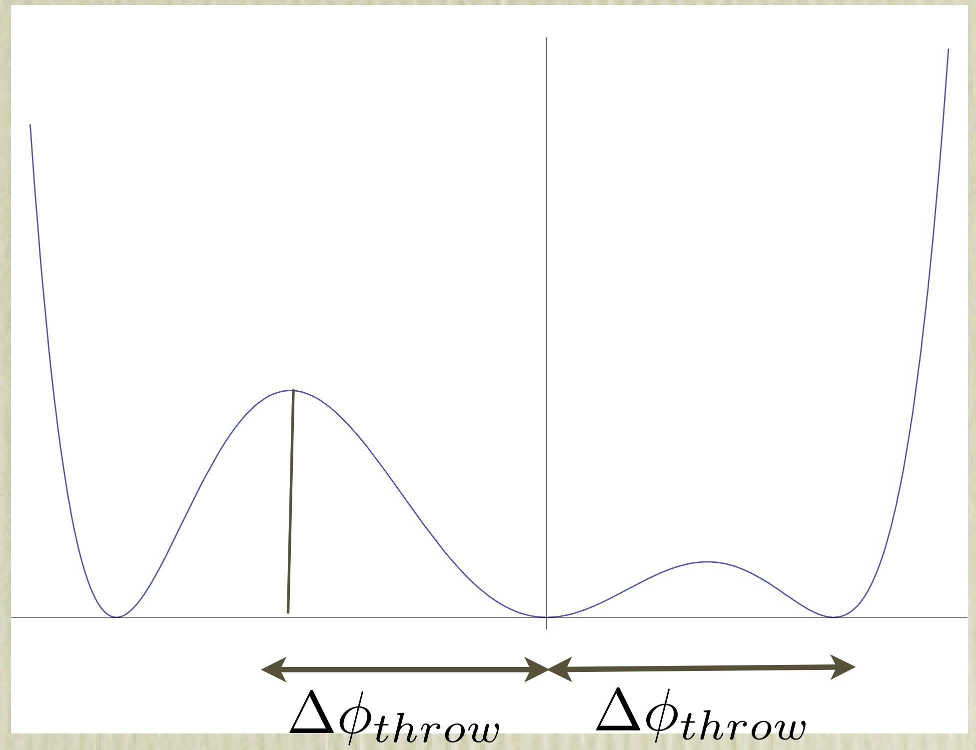
    - *Maximal* Excursion





$$\frac{\partial^2\phi(t_*)}{\partial t^2} = +\frac{\partial^2\phi(t_*)}{\partial x^2} - \frac{dV}{d\phi}(\phi(t_*)) > 0$$

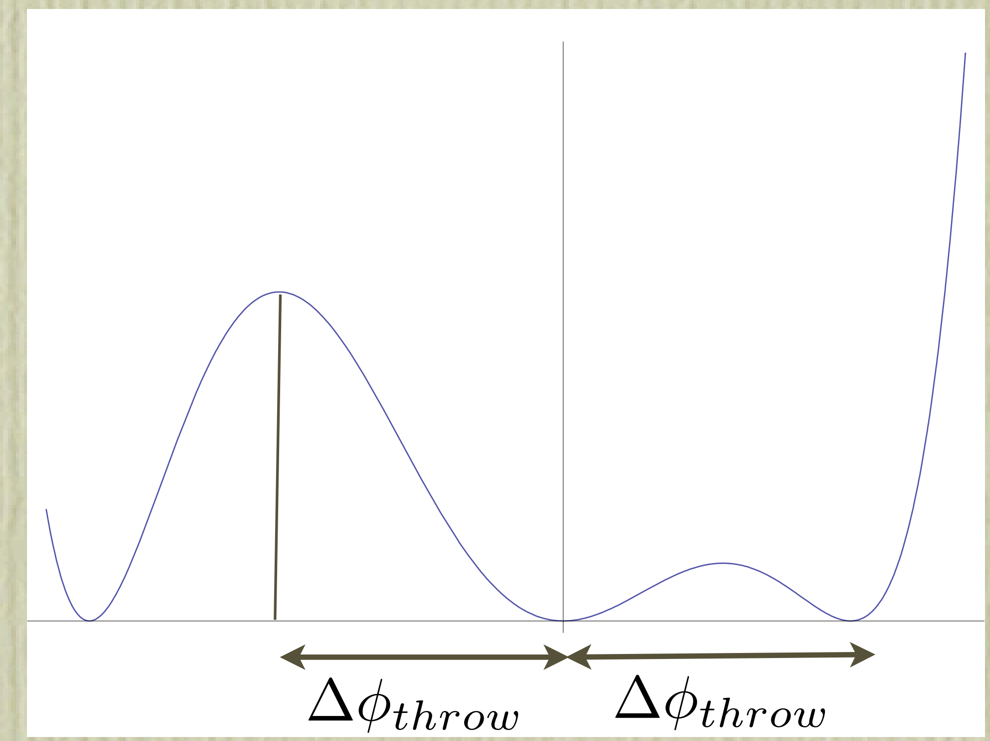
No Transition Possible : regardless of collision velocity!

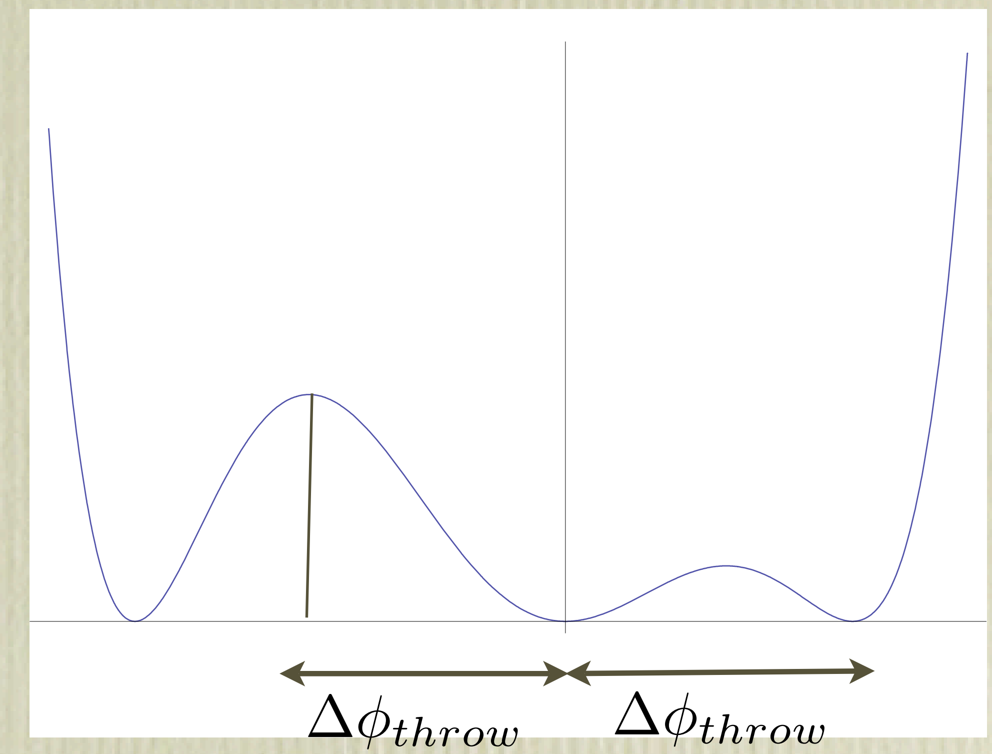
$$\frac{\partial^2\phi(t_*)}{\partial t^2} = +\frac{\partial^2\phi(t_*)}{\partial x^2} - \frac{dV}{d\phi}(\phi(t_*)) < 0 \text{ if } \gamma \gg 1$$

Transition Possible depending on collision velocity

Predictions of Free Passage

- Coherent walls generically form in high speed collisions
    - *Maximal* Excursion





$$\frac{\partial^2\phi(t_*)}{\partial t^2} = +\frac{\partial^2\phi(t_*)}{\partial x^2} - \frac{dV}{d\phi}(\phi(t_*)) > 0$$

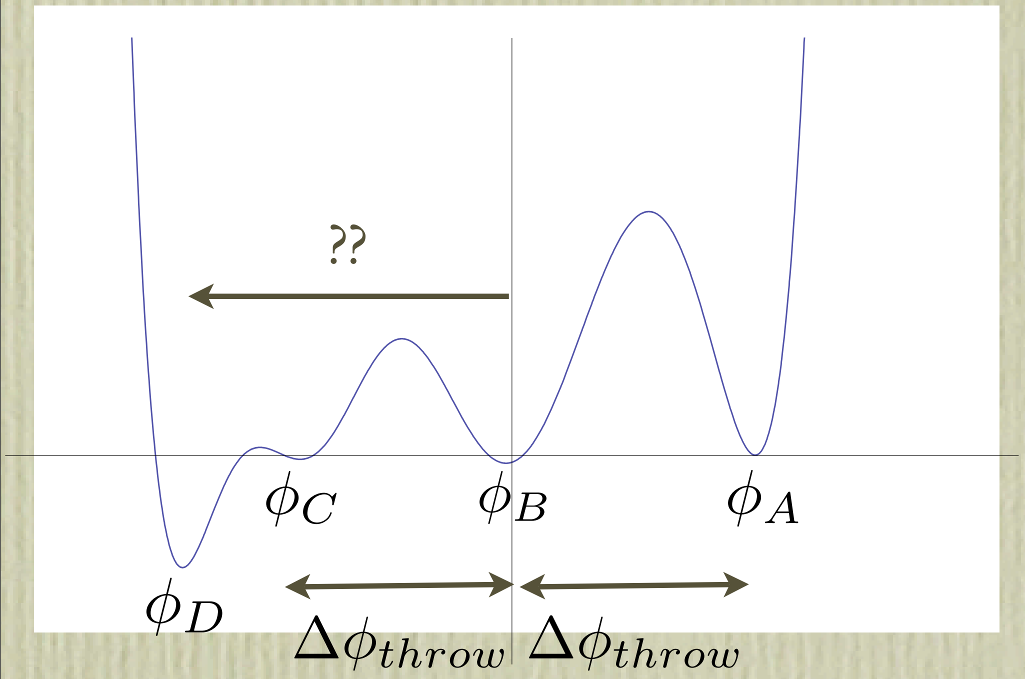
No Transition Possible : regardless of collision velocity!

$$\frac{\partial^2\phi(t_*)}{\partial t^2} = +\frac{\partial^2\phi(t_*)}{\partial x^2} - \frac{dV}{d\phi}(\phi(t_*)) < 0 \text{ if } \gamma \gg 1$$

Transition Possible depending on collision velocity

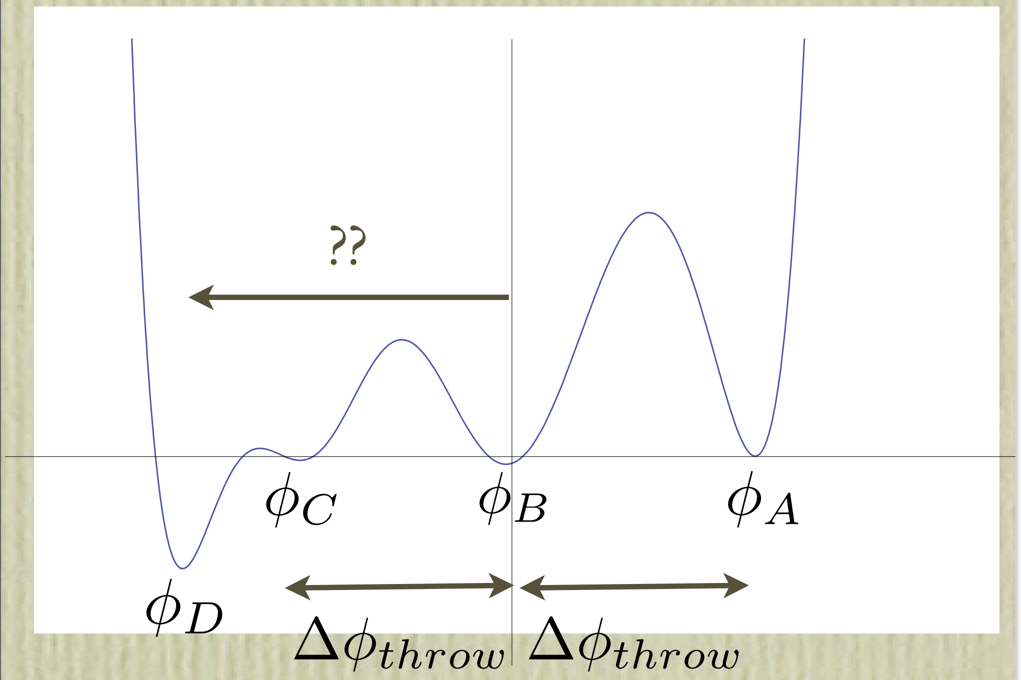
- "Kick" direction is the *vector sum* of field barrier differences.

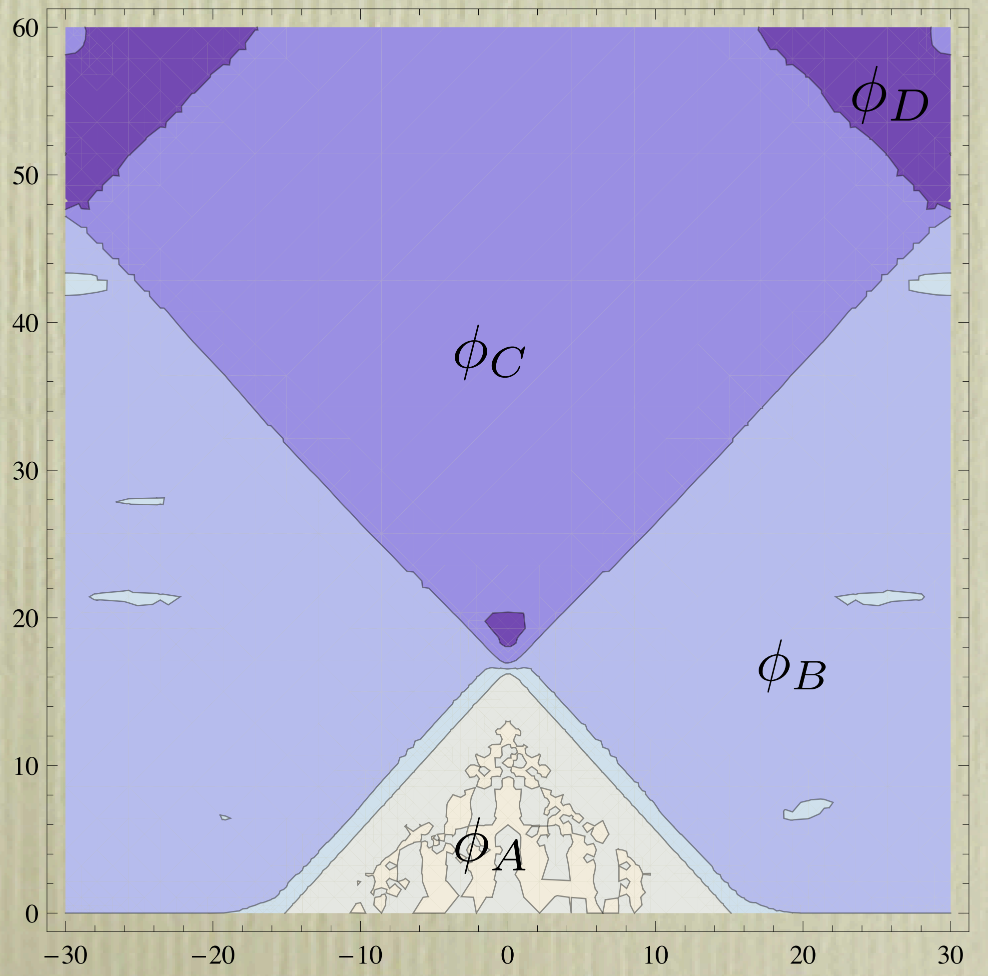
Free Passage in Action #2

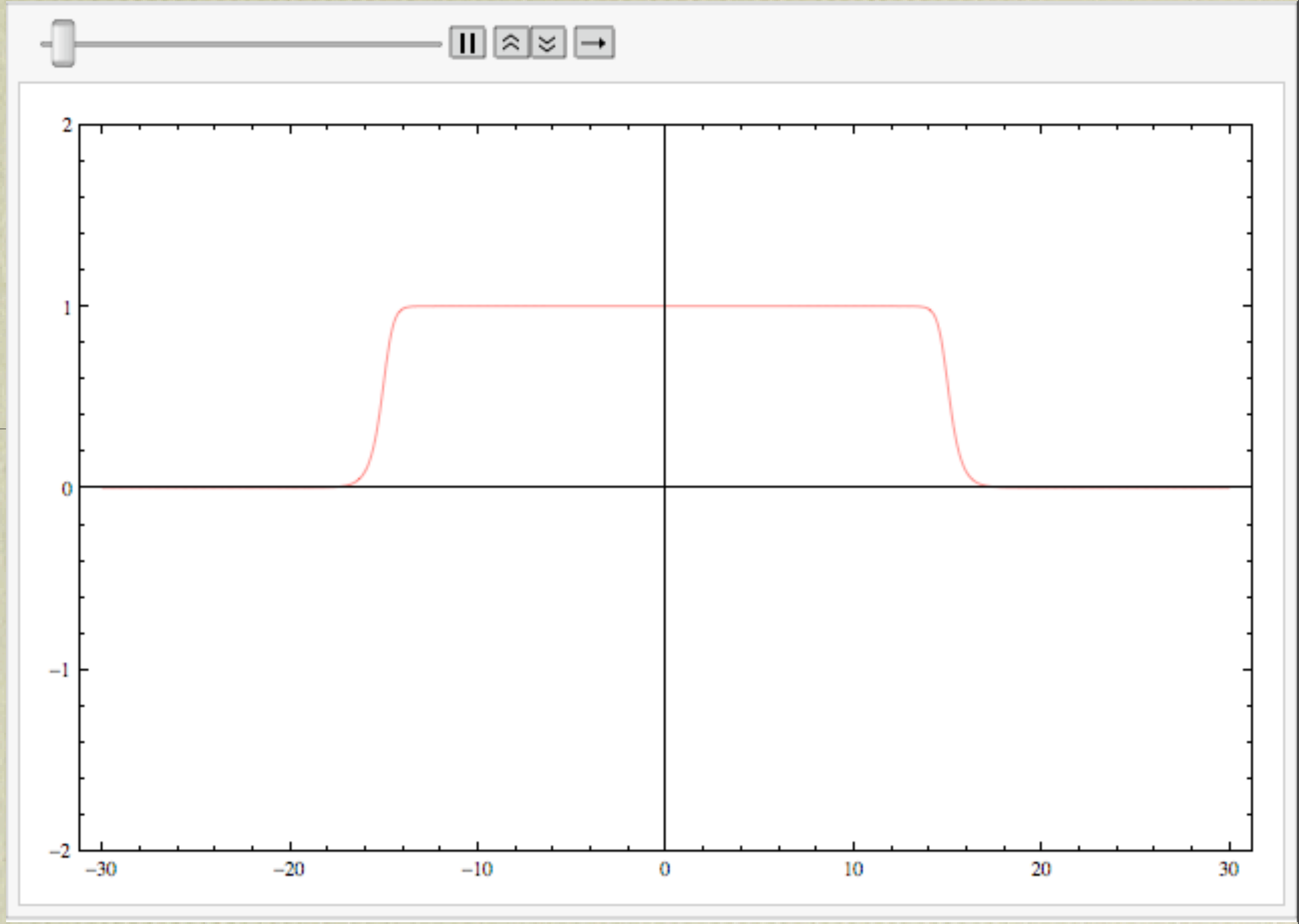


$\gamma = 3$

Free Passage in Action #2



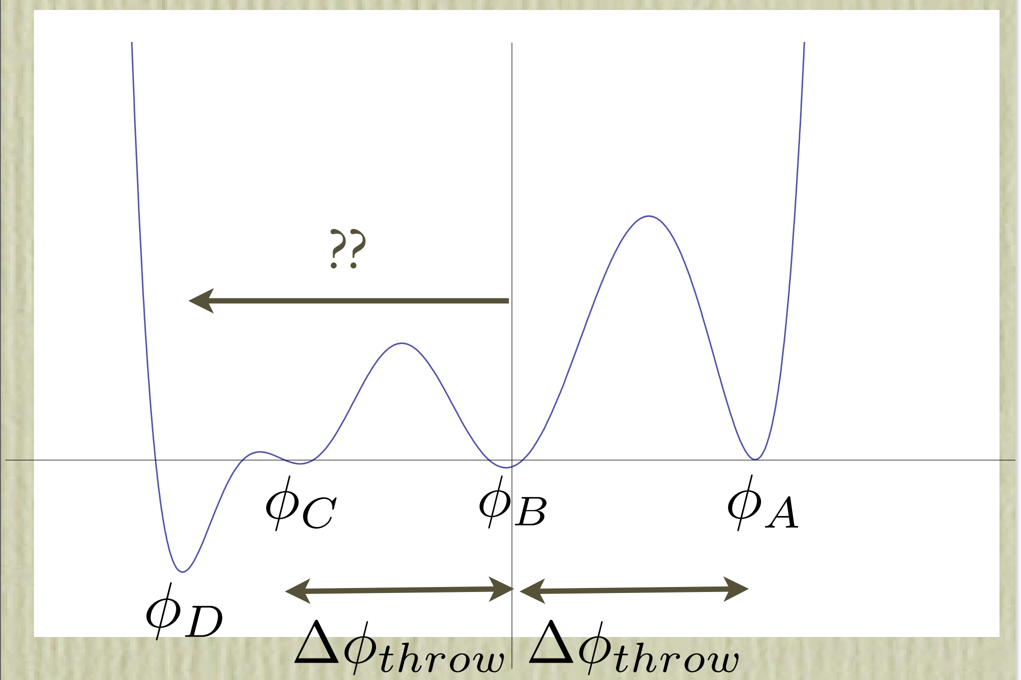


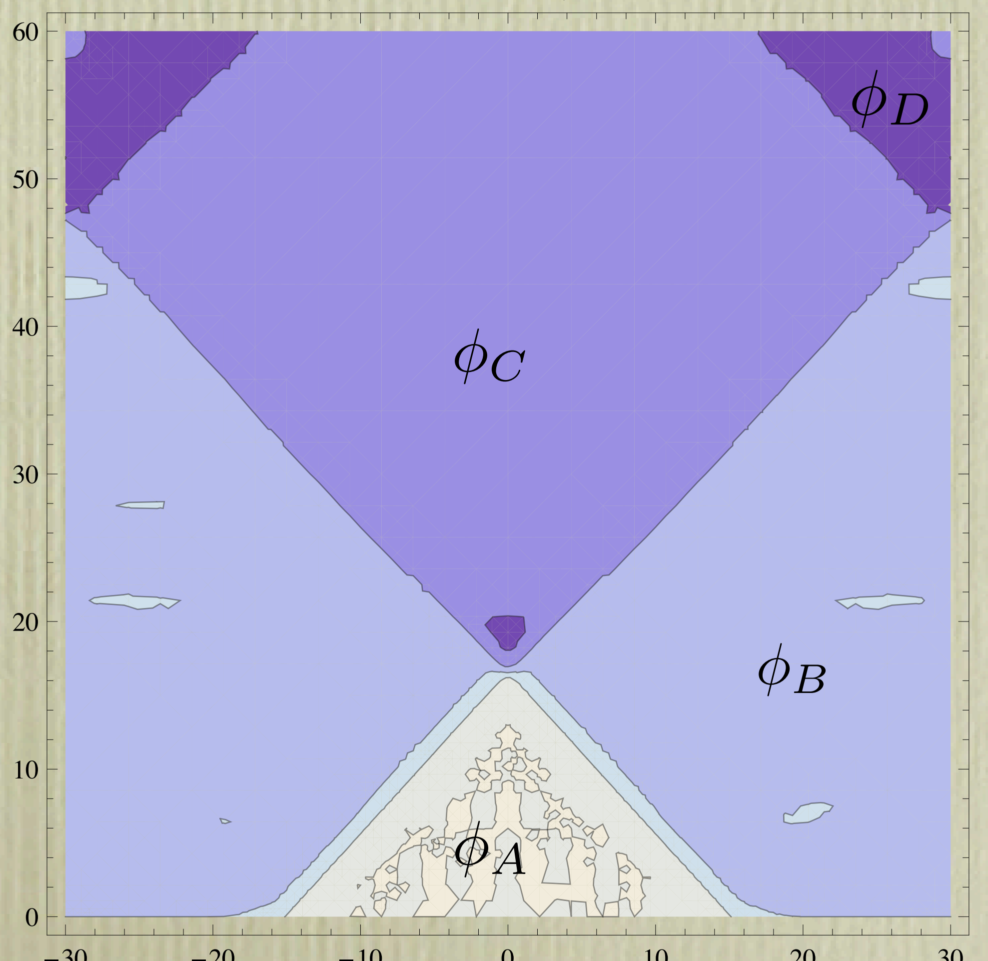


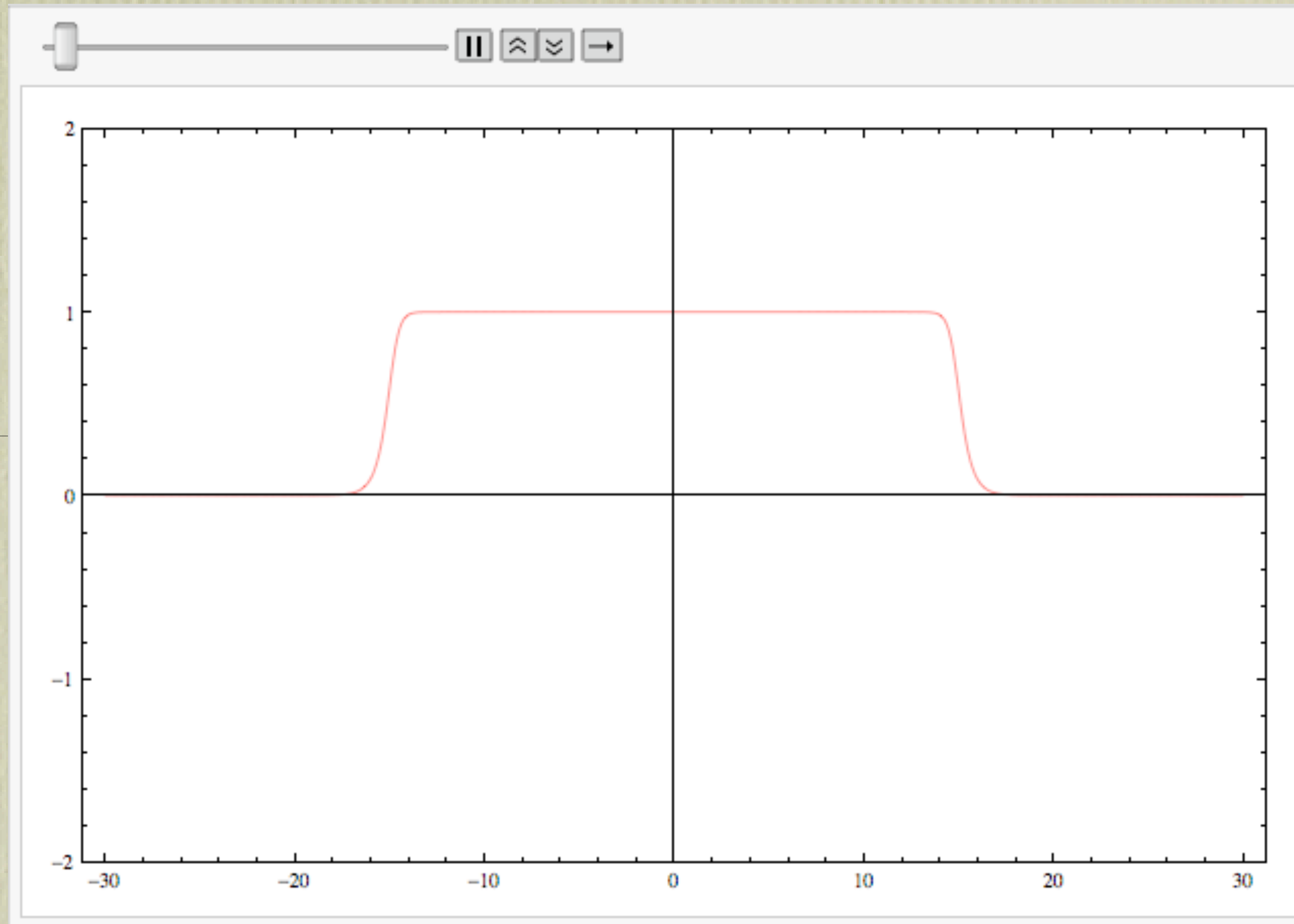
$\gamma = 3$

Maximal Excursion regardless of velocity!

Free Passage in Action #2







$\gamma = 3$

Maximal Excursion regardless of velocity!

"This is amazing!" L. Hui

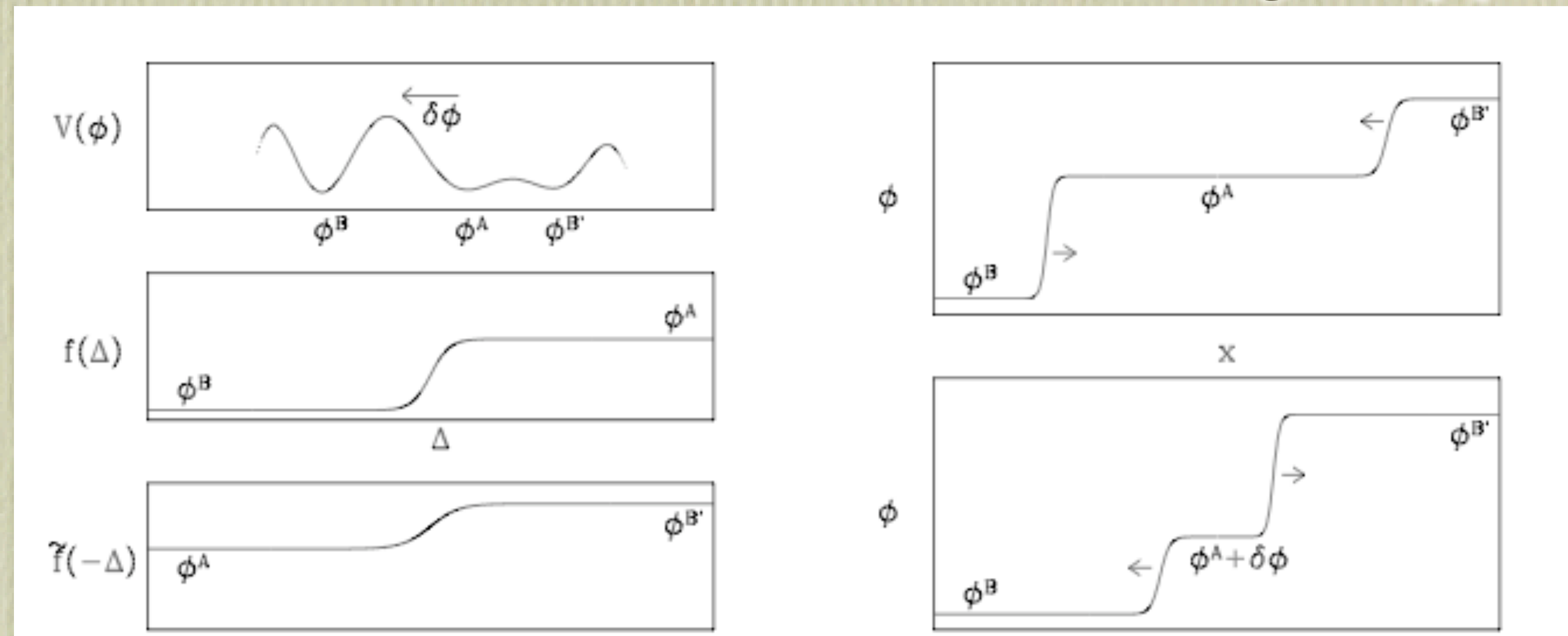
"I don't believe it!" T. Giblin

"This is crazy!" A. Nicolis

*"****!"* E. Lim

Kick Direction

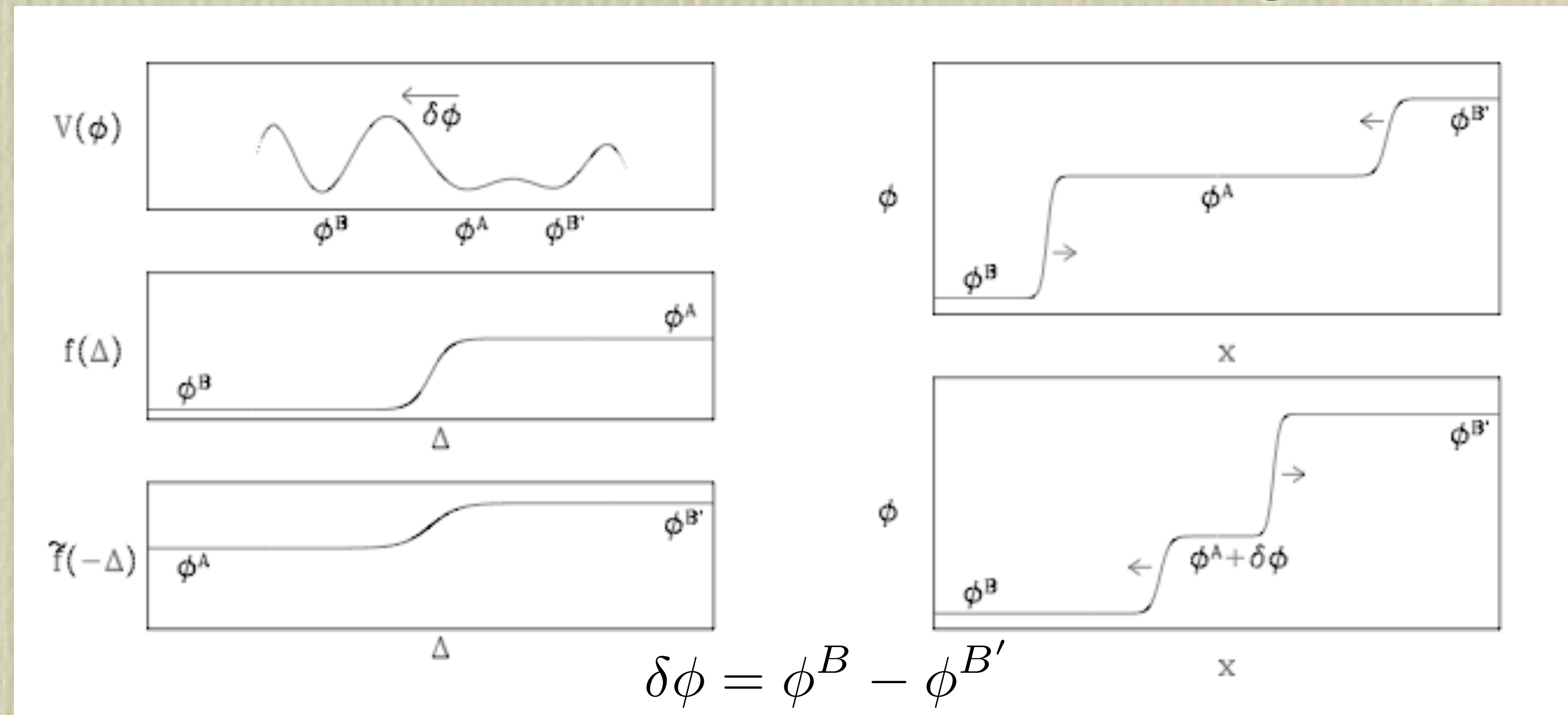
Soliton-soliton collision in the Free Passage Approximation



$$\delta\phi = \phi^B - \phi^{B'}$$

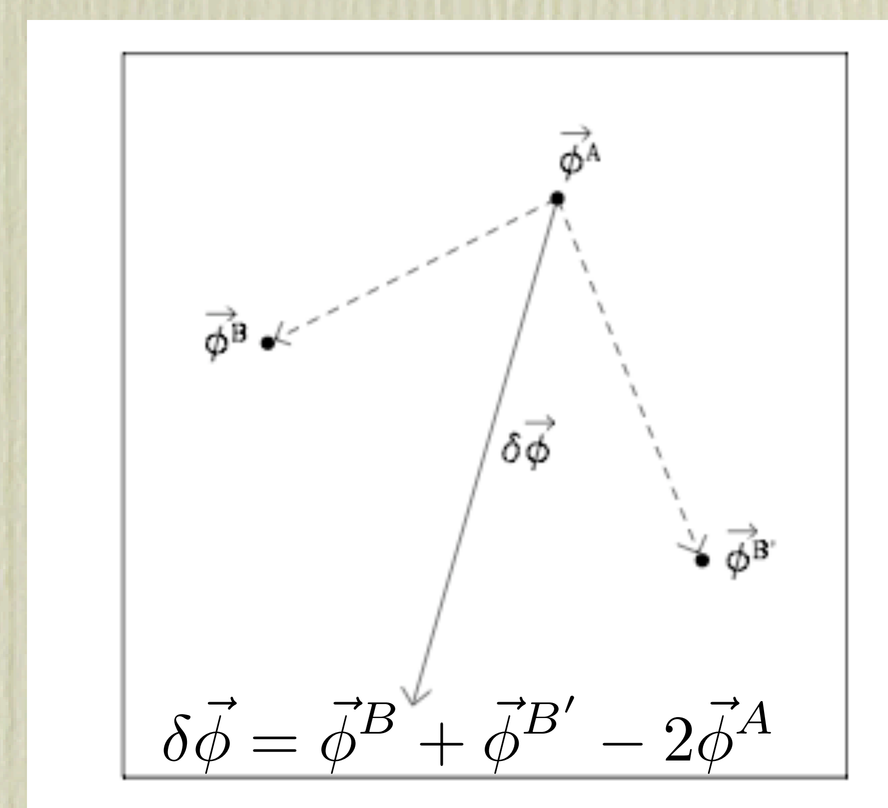
Kick Direction

Soliton-soliton collision in the Free Passage Approximation

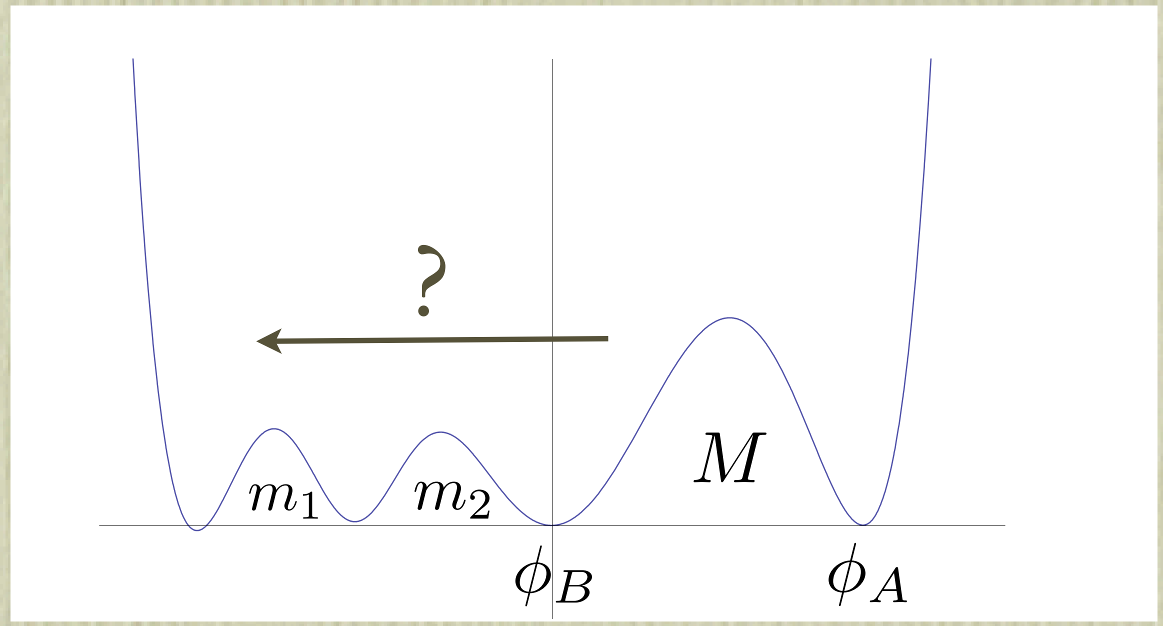


Generalization to Multifield potentials

New way of scanning the potential!



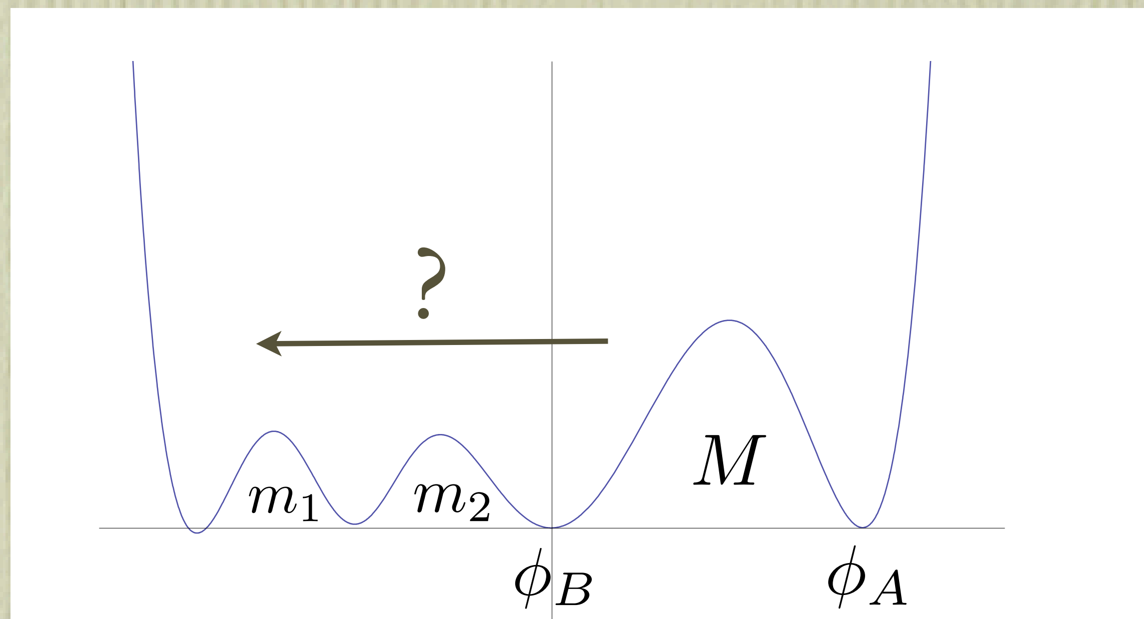
Multi-barrier Transitions



$$M = \int_{\phi_B}^{\phi_A} \sqrt{2V(\phi)}$$

Free Passage : $\Delta\phi_{throw}$ > both maxima

Multi-barrier Transitions



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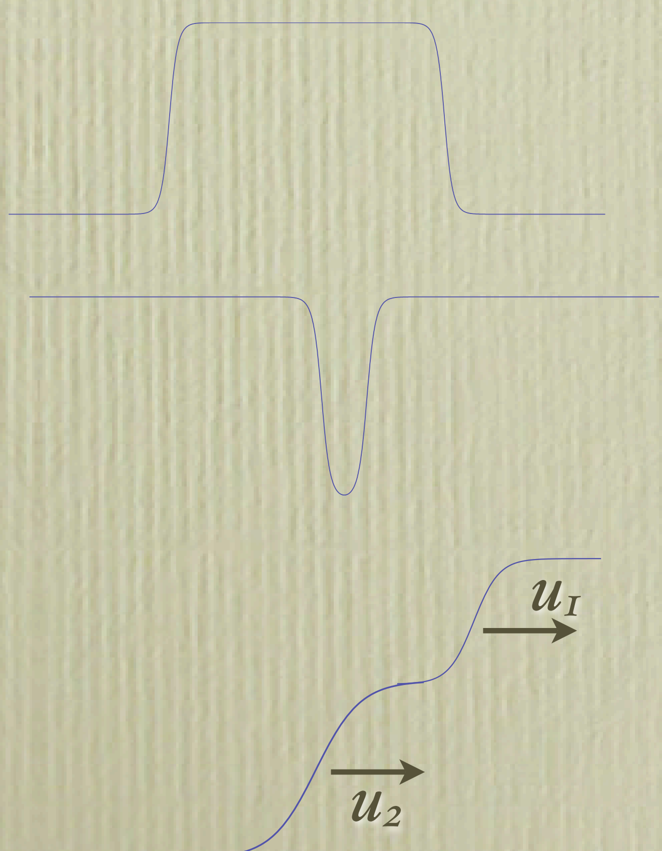
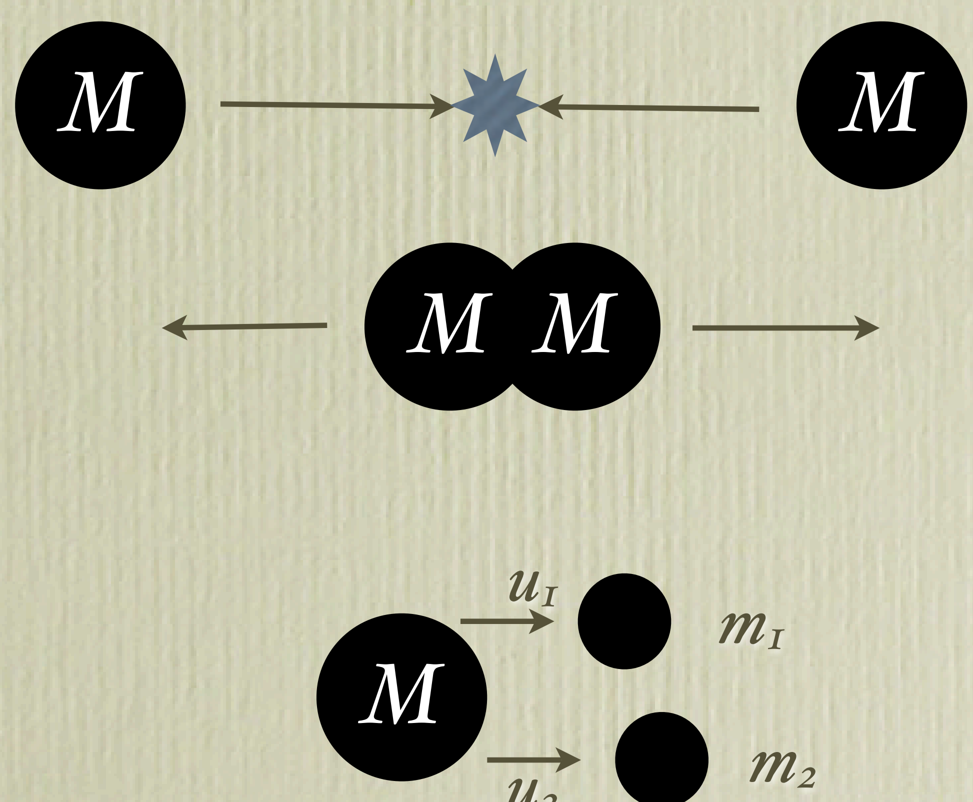
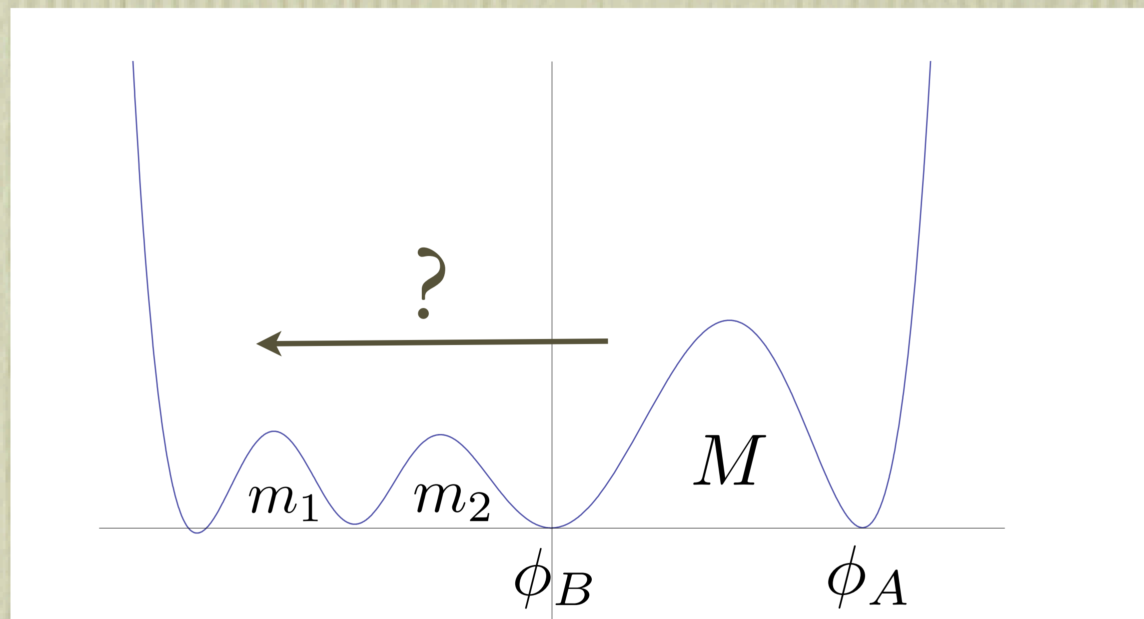




Multi-barrier Transitions



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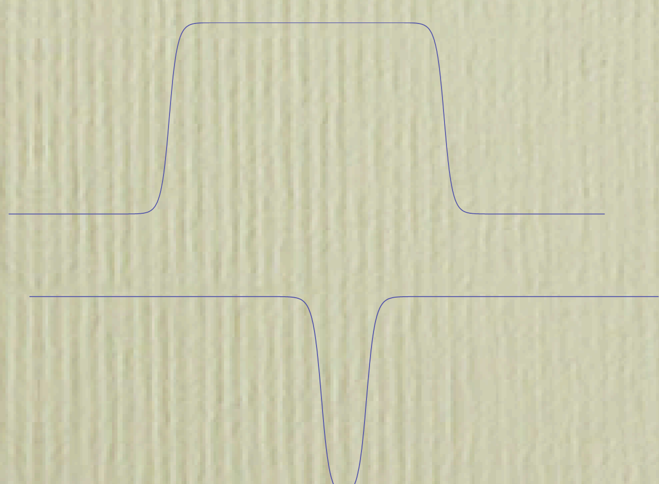
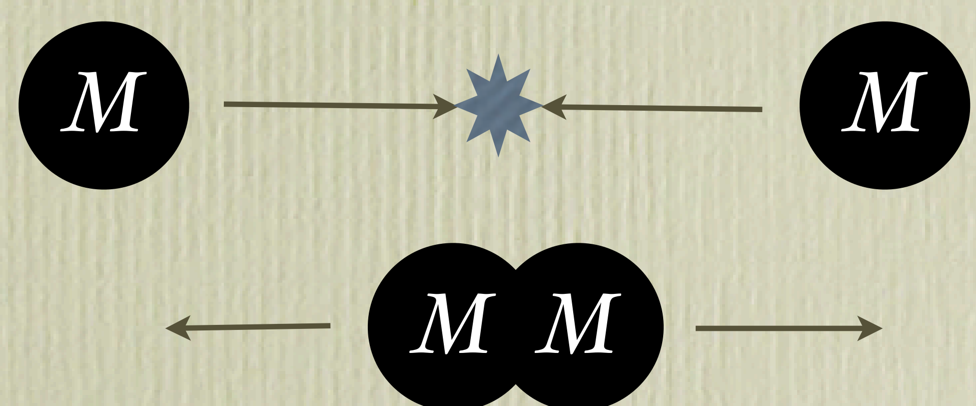
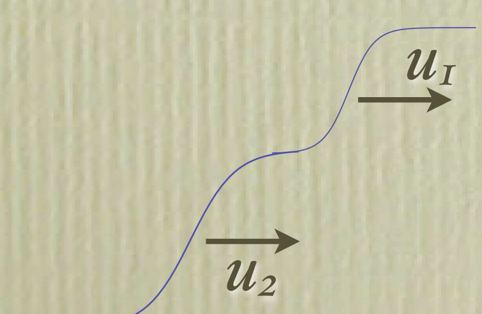
Kinetic Problem!

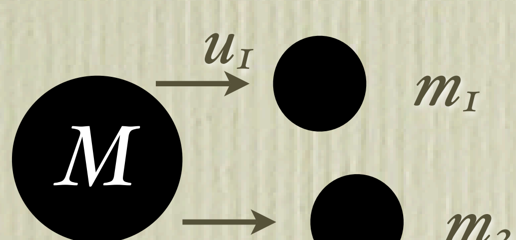




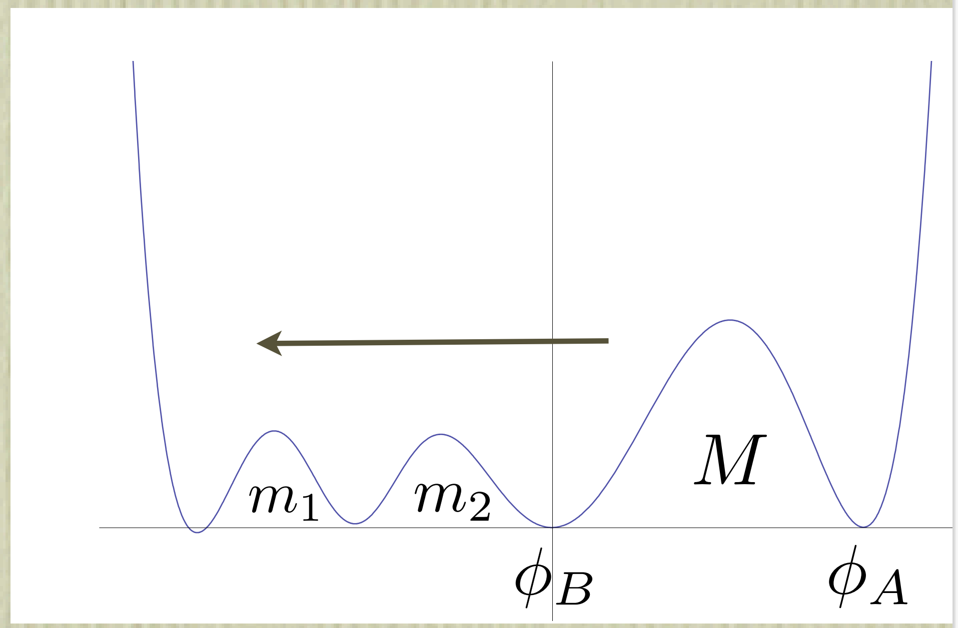
Multi-barrier transition
if $u_2 > 0$

Unknown :
more than 2 barriers

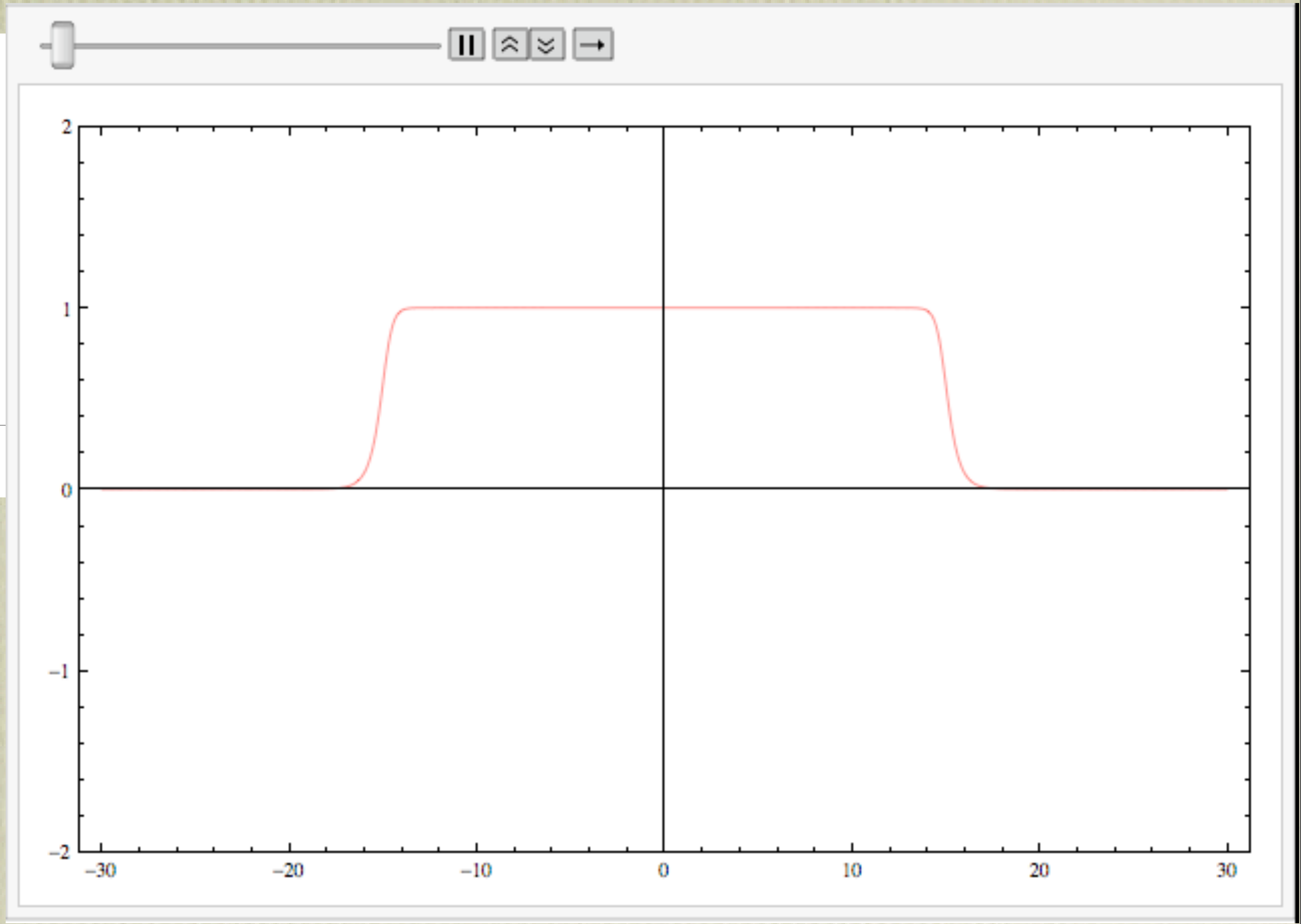




Multi-barrier Transitions

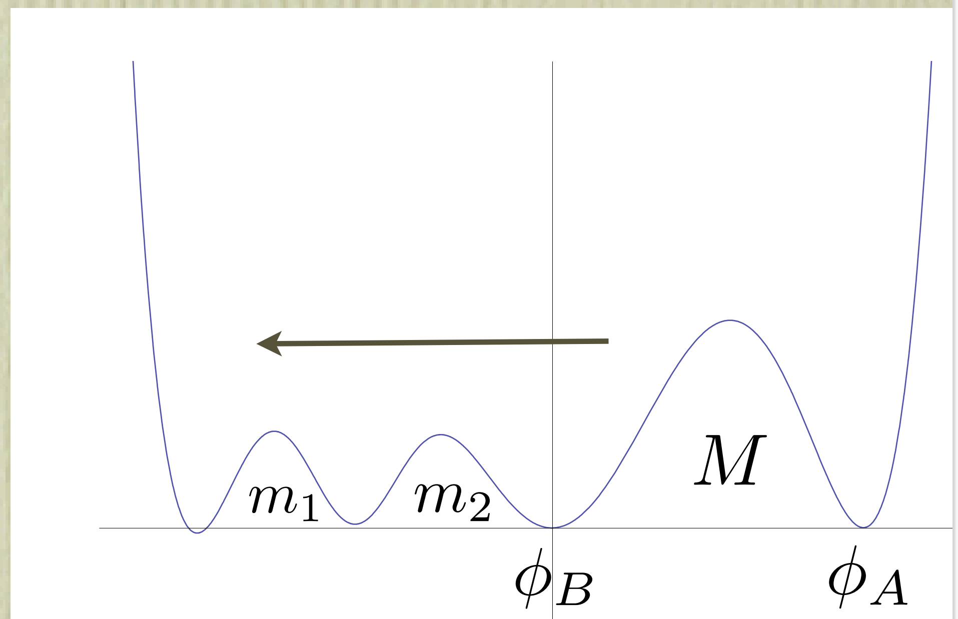


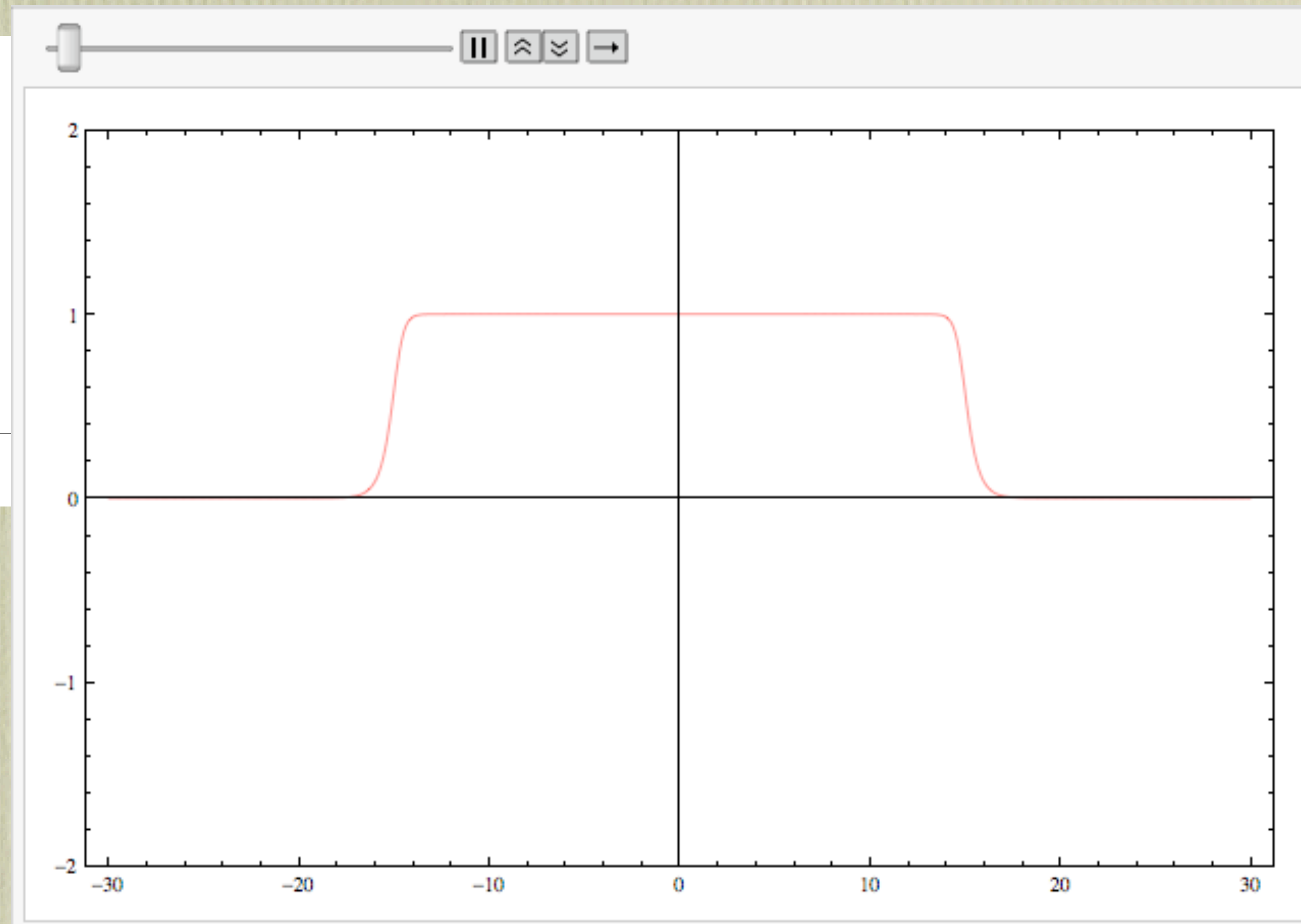
$$\gamma = 2.5$$
$$u_2 \sim 0.2 > 0$$



1+1D soliton-antisoliton with multi-barrier transition

Multi-barrier Transitions





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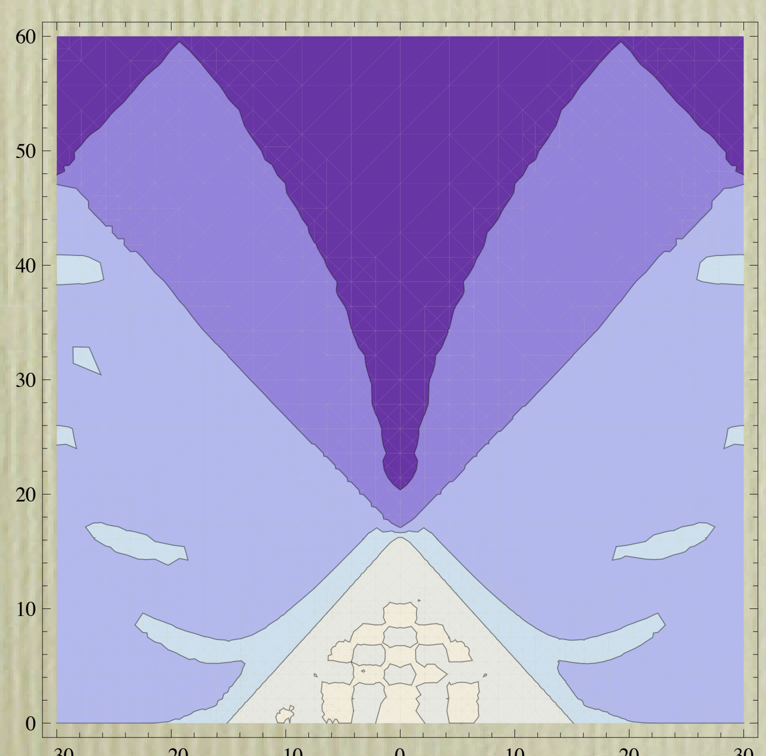
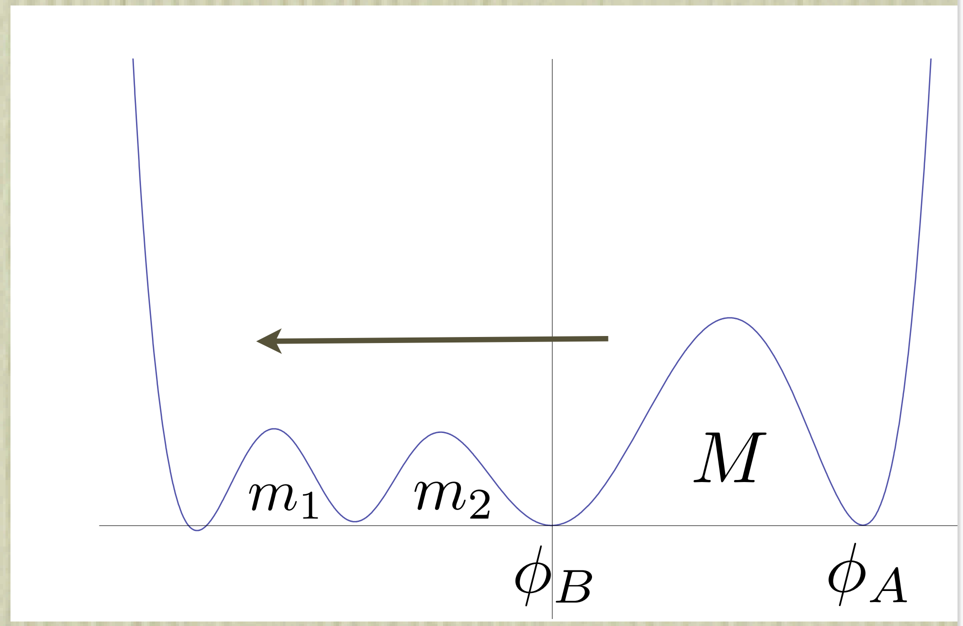
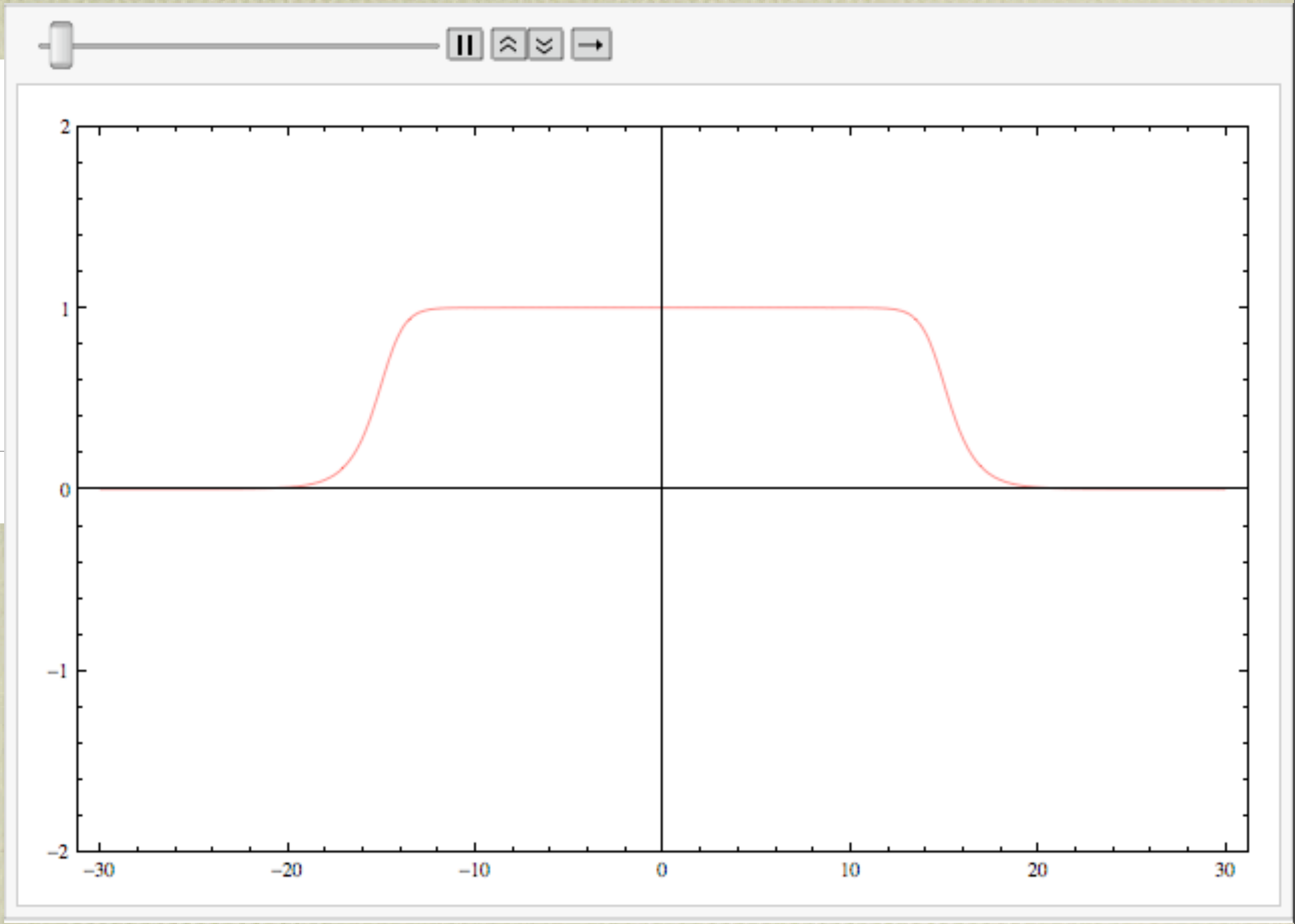


1+1D soliton-antisoliton with multi-barrier transition

Multi-barrier Transitions



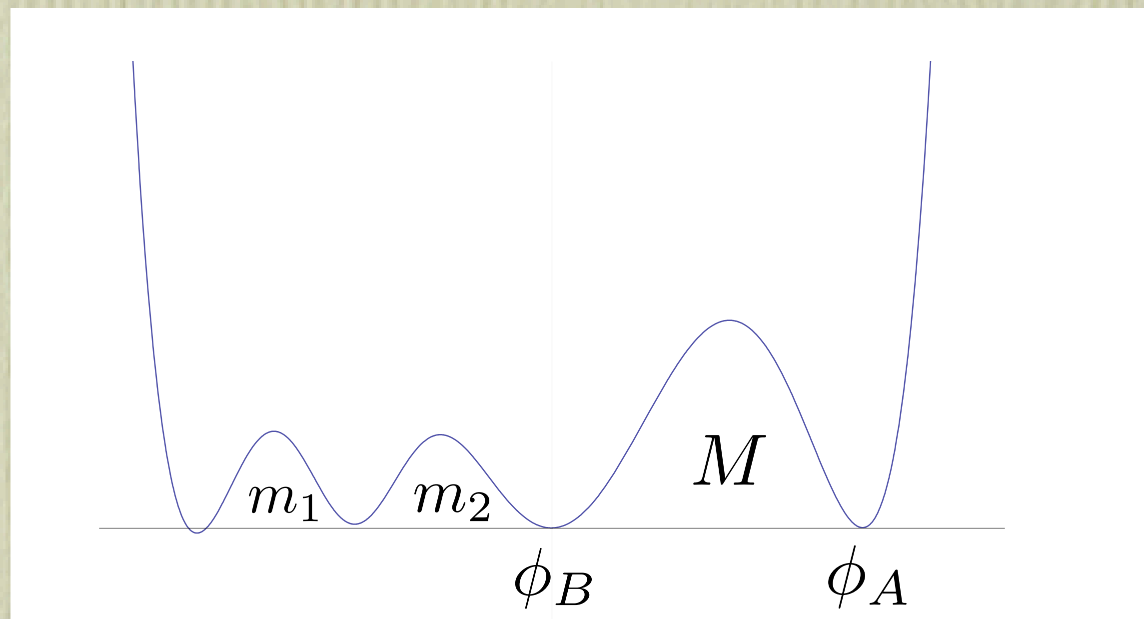


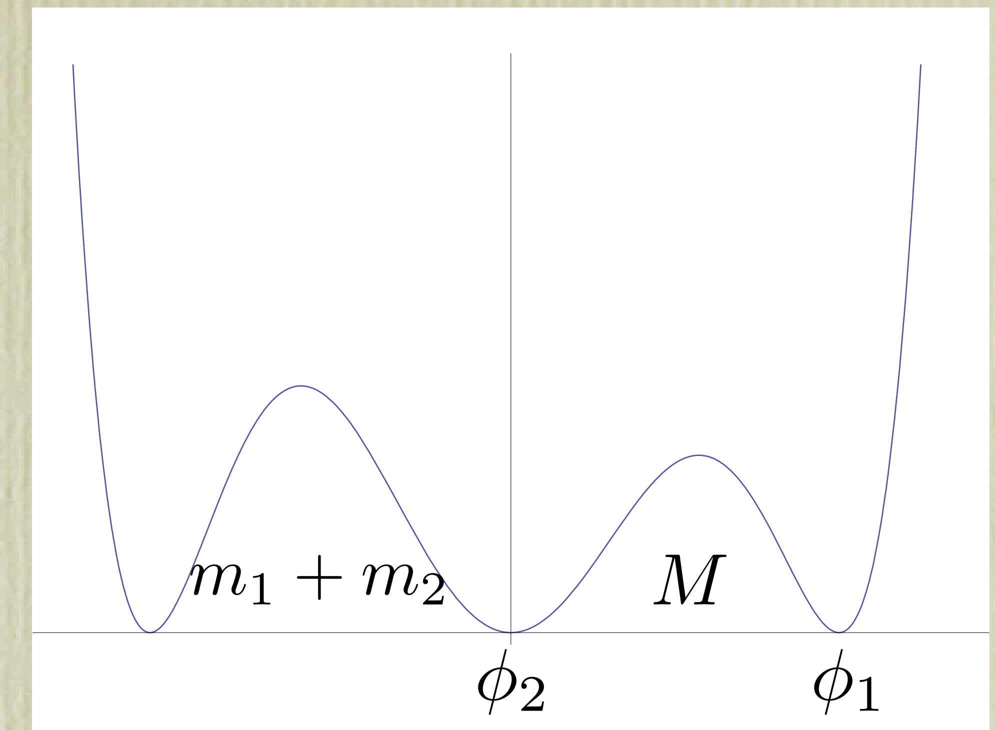
$$\gamma = 1.25$$

$$u_2 \sim -0.65 < 0$$

1+1D soliton-antisoliton with single barrier transition

Yet another crazy fact





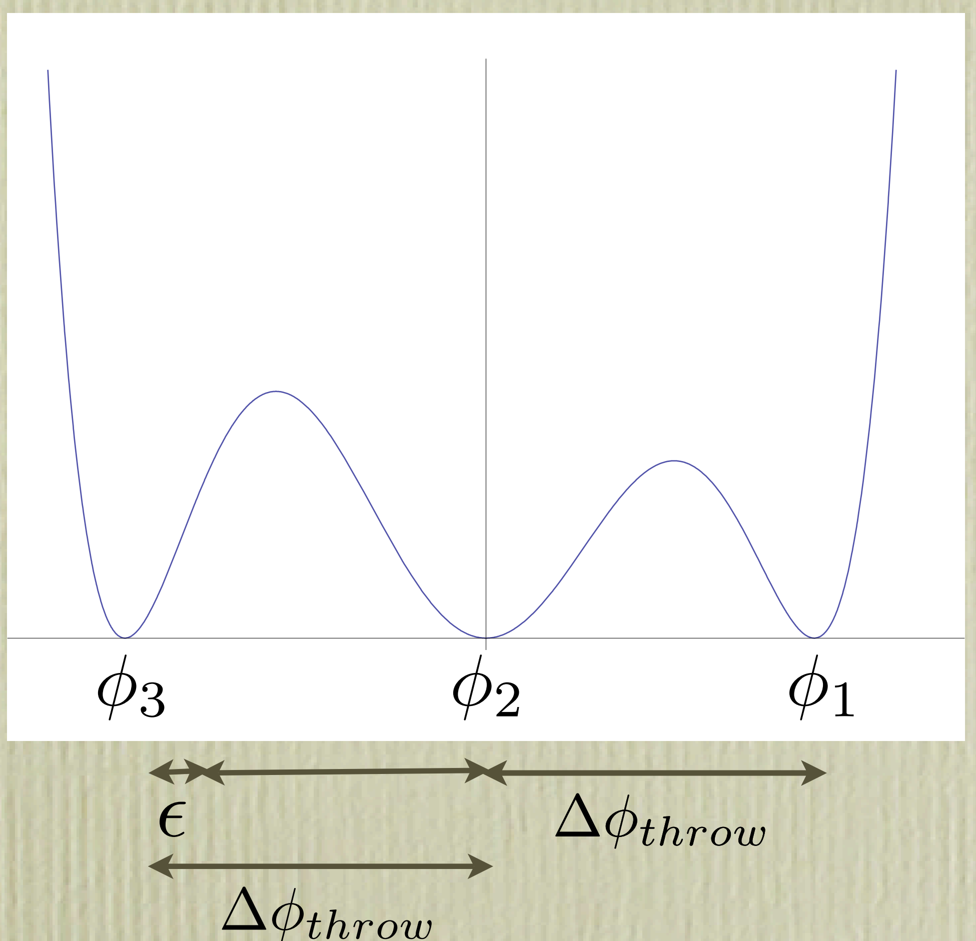
$$\gamma_{double} \geq \gamma_{transition}$$

Rest Frame of Resultant soliton

u_1 can be > u so can carry more energy away

Improved Transition Velocity Estimate

- "Old" condition $\quad \text{Grad. Energy} \propto \gamma^2 > \frac{\Delta V_{BC}}{\Delta V_{AB}} \times \text{elastic coefficient}$
- Using Free Passage :



$$E_{in}(t \to -\infty) = \frac{2}{\sqrt{1-u^2}} \int_{\phi_2}^{\phi_1} d\phi \sqrt{2V(\phi)}$$

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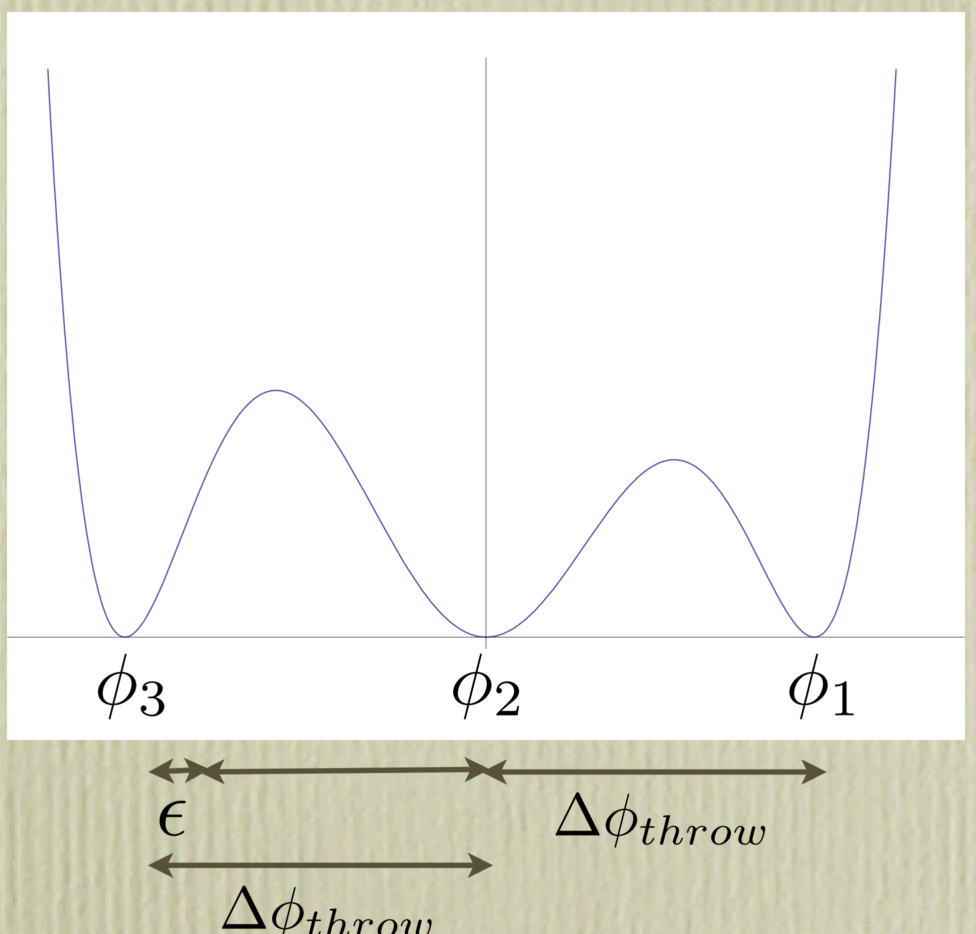

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$$E_{out}(t \to t_*) = \frac{1+u^2}{\sqrt{1-u^2}} \int_{\phi_2+\epsilon}^{\phi_1} d\phi \sqrt{2V(\phi)}$$

$$+\sqrt{1-u^2} \int_{\phi_2+\epsilon}^{\phi_1} d\phi \; V(\phi - \phi_1 + \phi_2) \sqrt{\frac{2}{V(\phi)}}$$

Transition when $E_{in} \geq E_{out}$

Improved Transition Velocity Estimate

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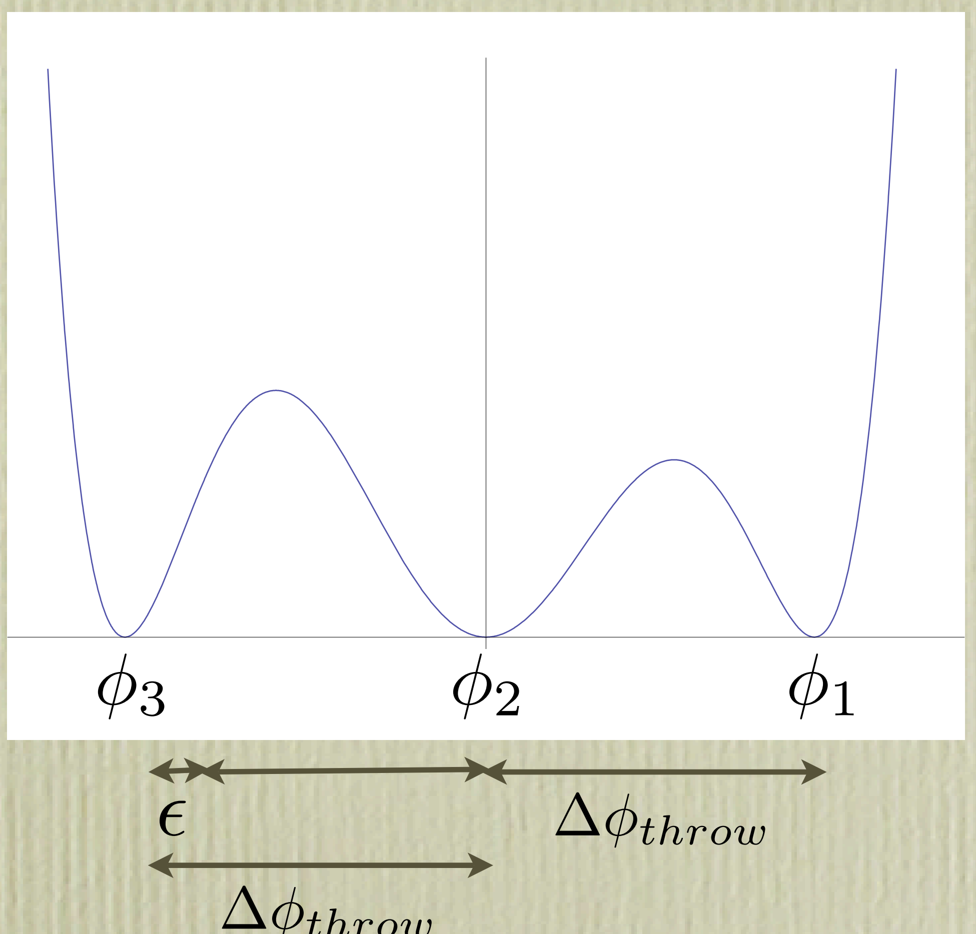

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Transition when $E_{in} \geq E_{out}$

Plug in sine-Gordon $V(\phi) = 1 - \cos\phi$ → $E_{in} = E_{out}$

Works very well numerically -- but we think we can do better.

Stuff in Progress

- What is the internal structure of the new bubbles? Can we live in one them?

Stuff in Progress

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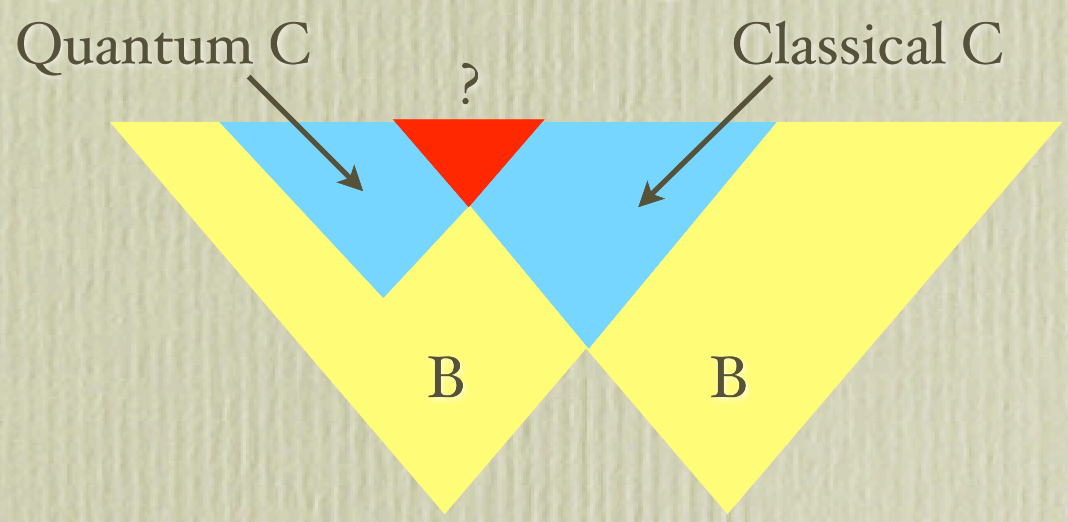
- Do they behave like quantum ones?



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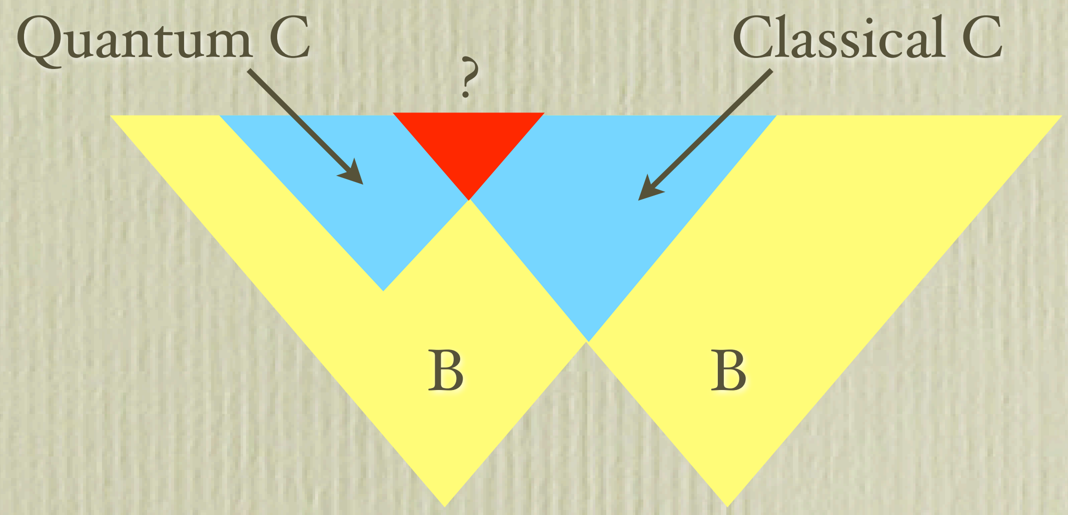

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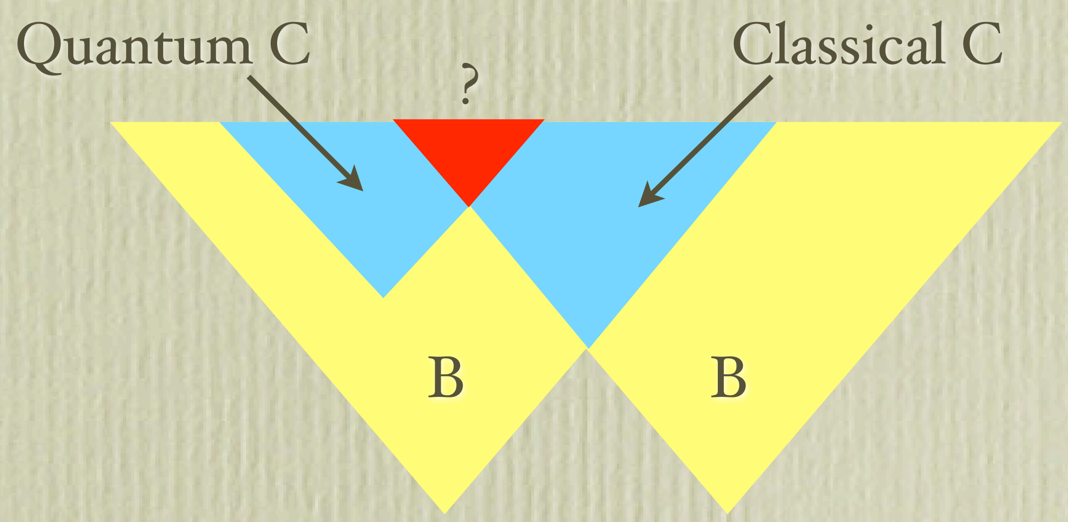

- Do we live in a Quantum or Classical (or a mix) of bubbles? Probability? Can we tell via observations?
- Perturbations? (3+1D numerical simulations will be highly useful)

More stuff in Progress

- Coupled multifields : extra decay channels?

  Easther, Greene, Johnson, Lim

- Decompactification via collisions?

- Applications to non-Cosmological bubbles? Brane-interactions? Condensed matter systems? etc.

Summary

- New *classical* mechanism of nucleating bubbles.
- Bubble wall collisions can *scan* the landscape -- perhaps to places hard to quantum tunnel to.
- *Free Passage* is key to understanding collision results : coherent walls, maximal excursion, multi-barrier transition, Kick direction

Take home message

Bubble collisions results depend on the *global shape of the landscape potential*.

A new way to probe the String theory landscape?