Title: Quantum and Thermal decay in de Sitter space

Date: Dec 16, 2008 01:00 PM

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Abstract: What does vacuum decay look like in an inflating, de Sitter, spacetime? Is it predominantly a quantum process of tunneling through the barrier, or a thermal process of tunneling over the barrier?

Quantum and thermal vacuum decay in de Sitter

me

Adam Brown & Erick Weinberg

Phys. Rev. D 76, 064003 (2007)

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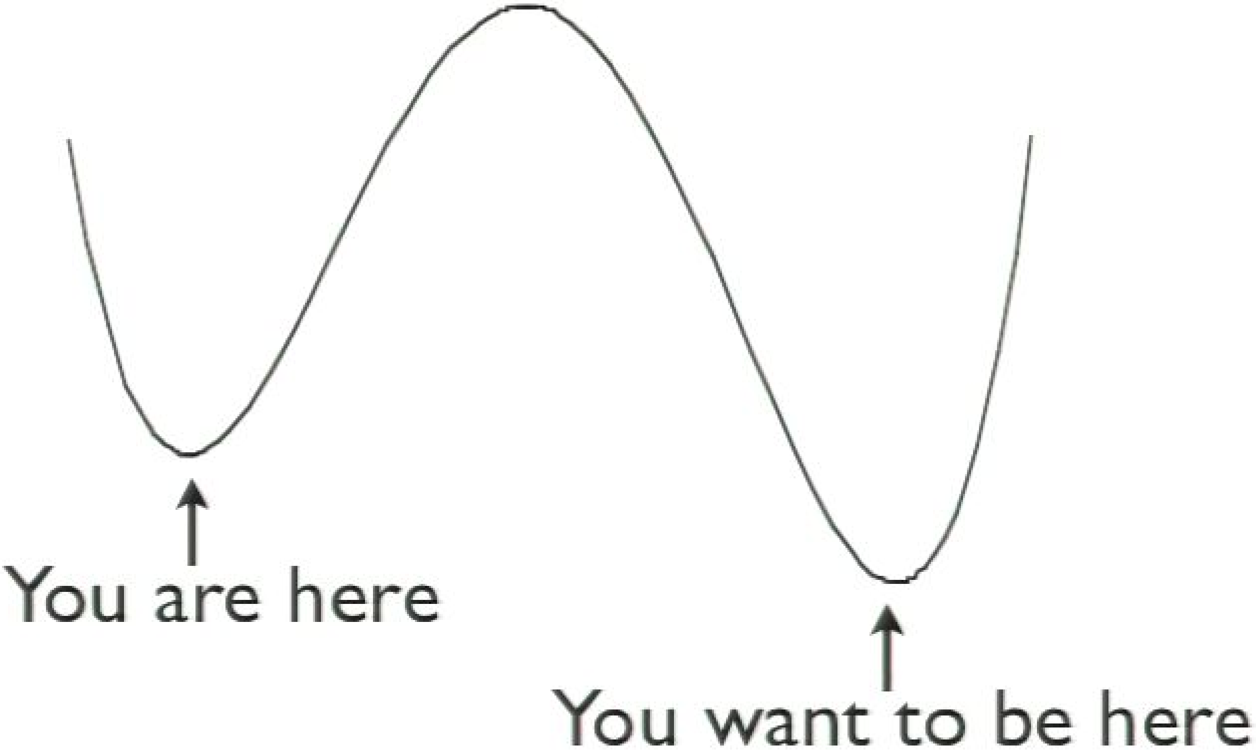

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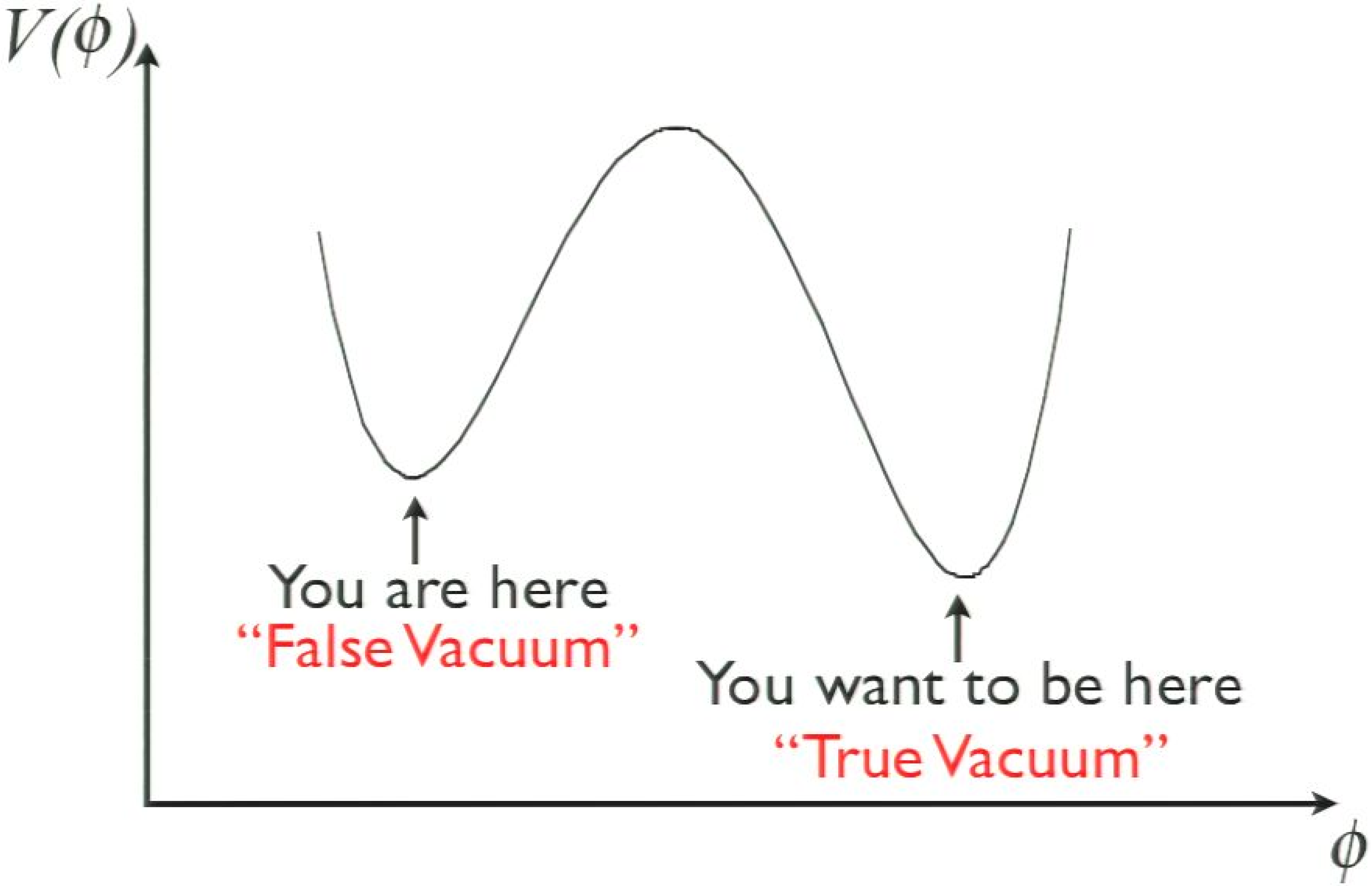
You want to be here

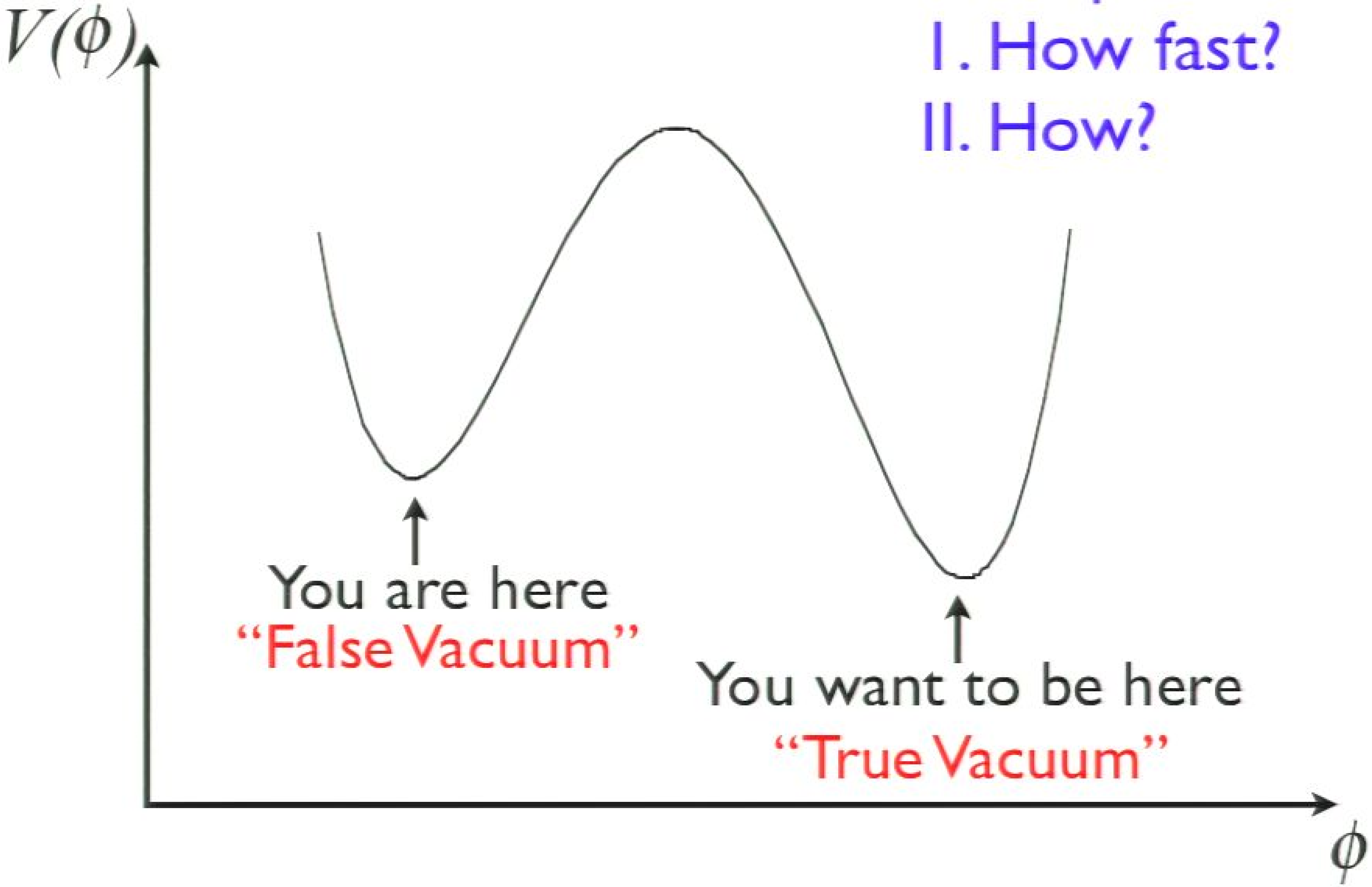


Scalar Field ϕ(x) in de Sitter space

Two questions:

I. How fast?

II. How?



You are here

"False Vacuum"

You want to be here

"True Vacuum"

Scalar Field ϕ(x) in de Sitter space

Tunneling in Minkowski space (no gravity) at T = 0

☑ Rate
☑ Initial conditions after tunneling

Tunneling in Minkowski space (no gravity) at T ≠ 0

☑ Rate
☑ Initial conditions after tunneling

Tunneling in de Sitter space (à la Coleman De Luccia)

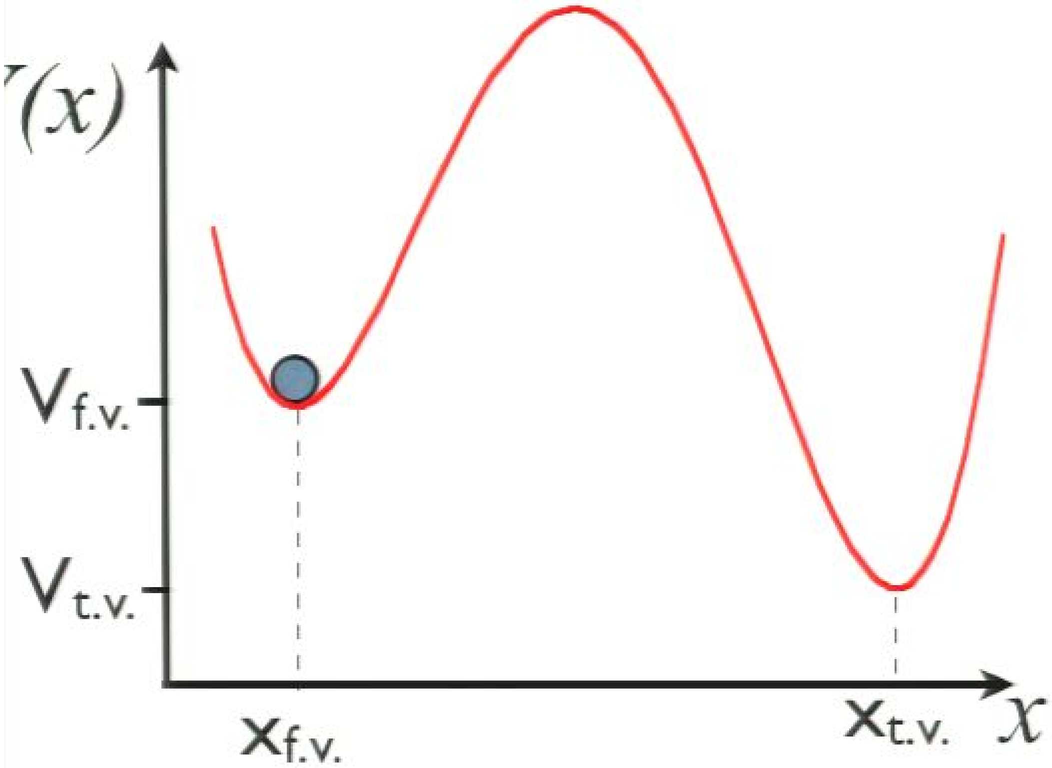
☑ Rate
??? Initial conditions after tunneling ???

Tunneling in de Sitter space (thermal approach)

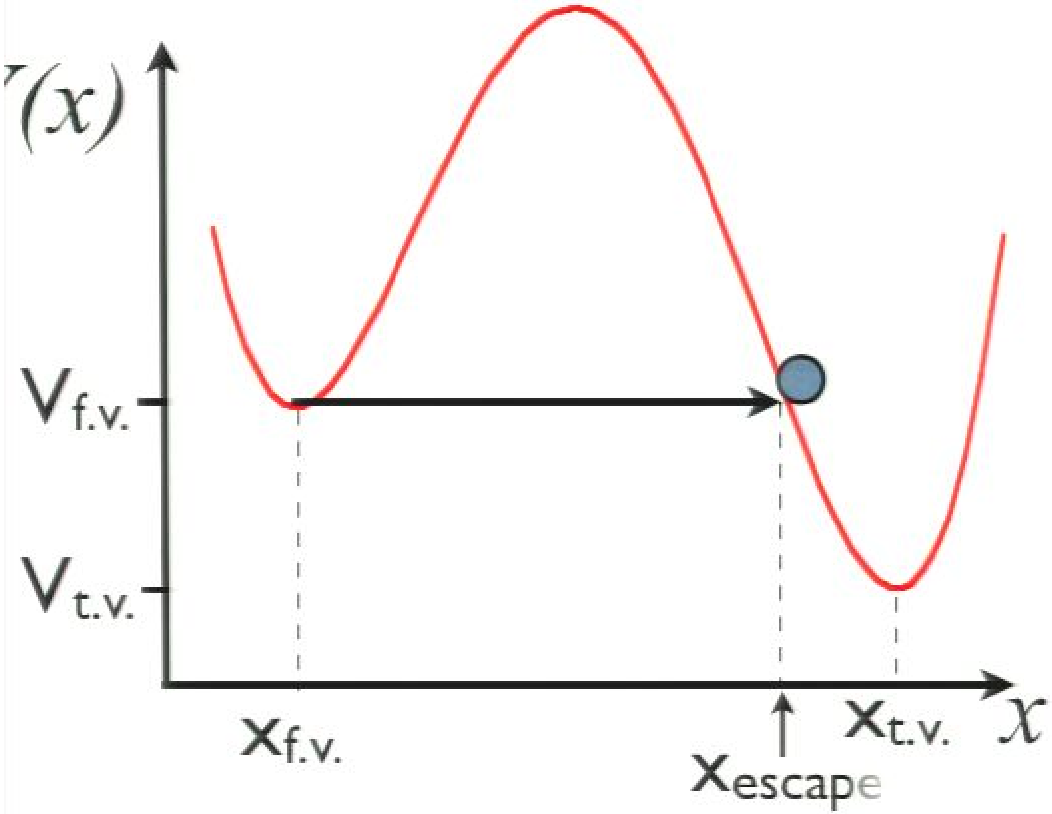
Is de Sitter decay predominantly quantum?
or predominantly thermal?

Concluding remarks

Particle tunneling at T = 0



Particle tunneling at T = 0



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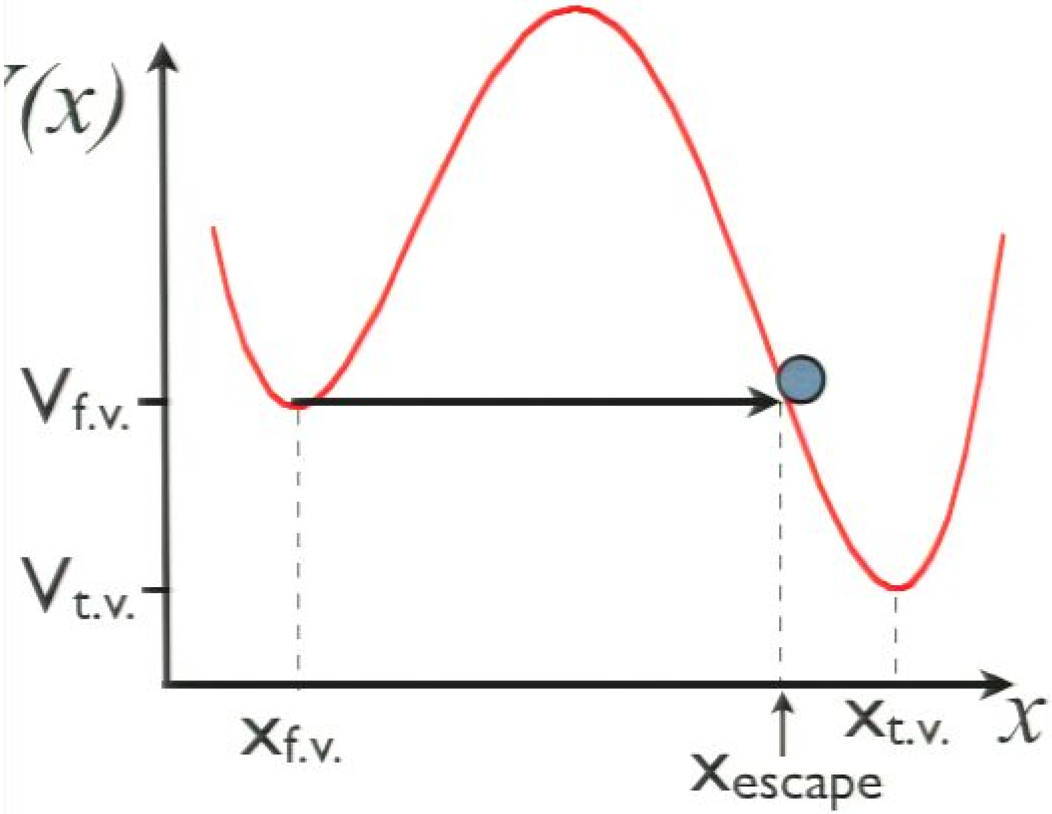
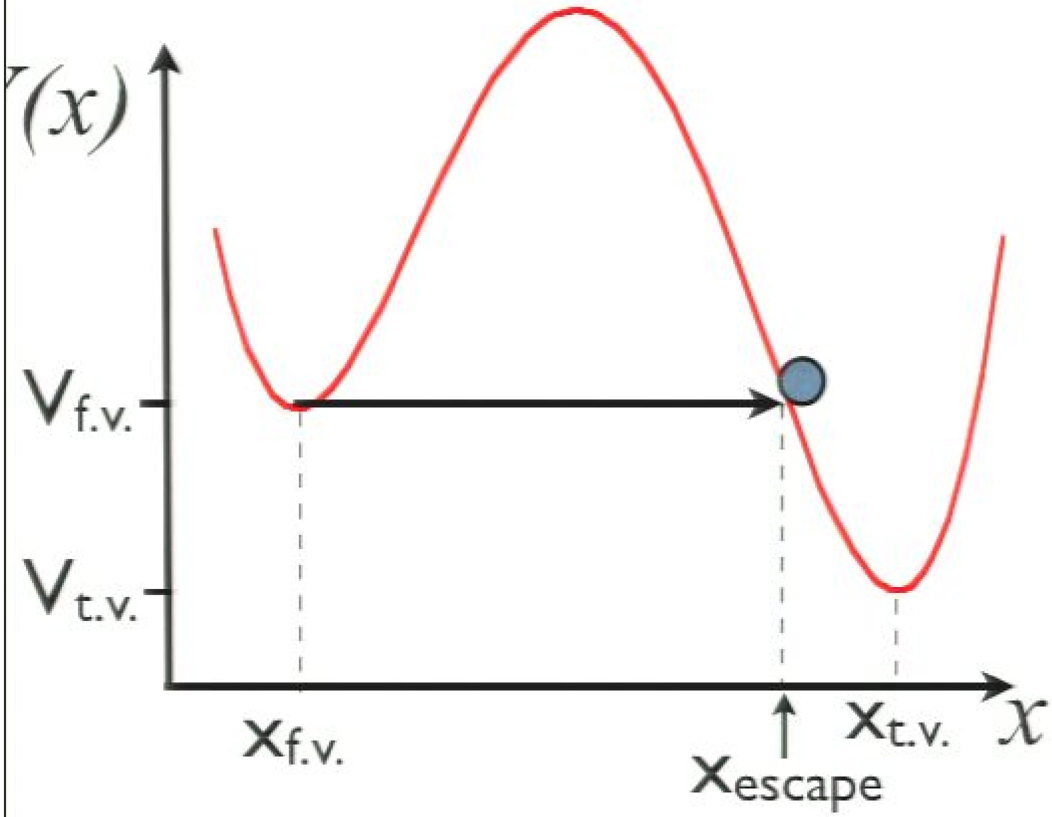


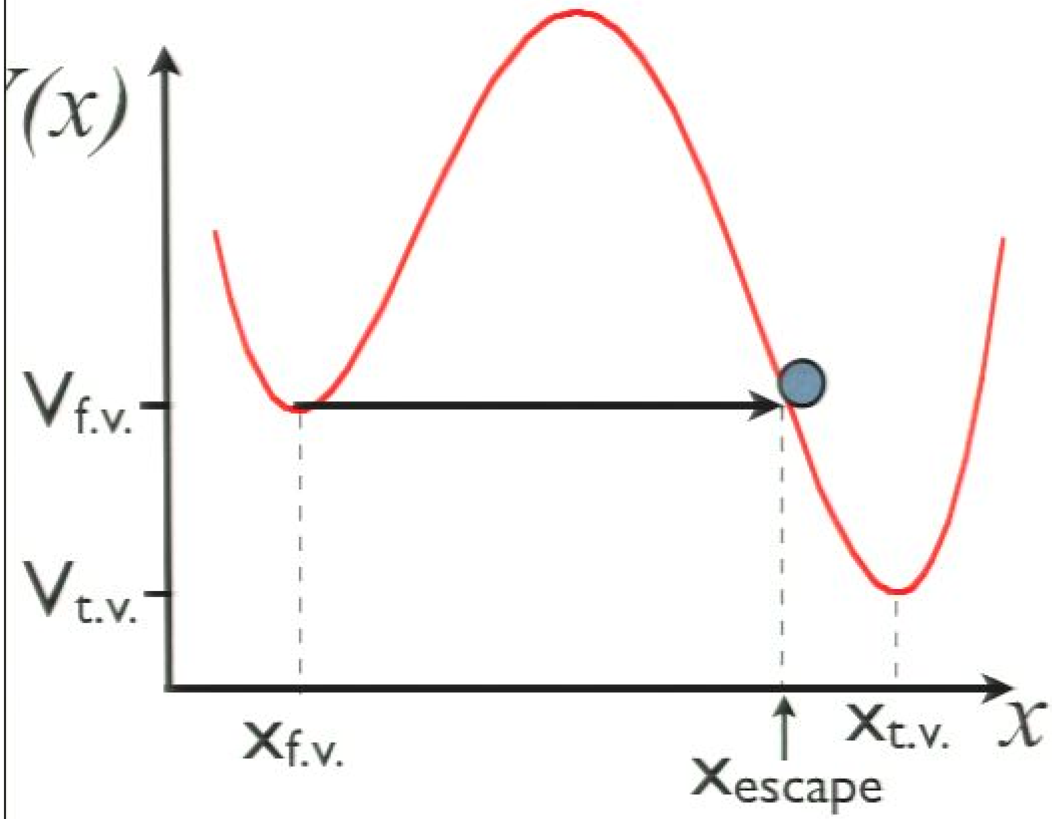
Particle tunneling at T = 0



$$\text{Rate} \quad \sim \quad e^{-B}$$

$$B = \frac{2}{\hbar}\int^{x_e} dx\sqrt{2(V(x) - V(f.v))}$$

Particle tunneling at T = 0



$$\text{Rate} \quad \sim \quad e^{-B}$$

$$B = \frac{2}{\hbar}\Big[S_E(\text{instanton}) - S_E(\text{f.v.})\Big]$$

$${}_E = \int d\tau \Big[\frac{1}{2}\dot{x}^2 + V(x)\Big]$$

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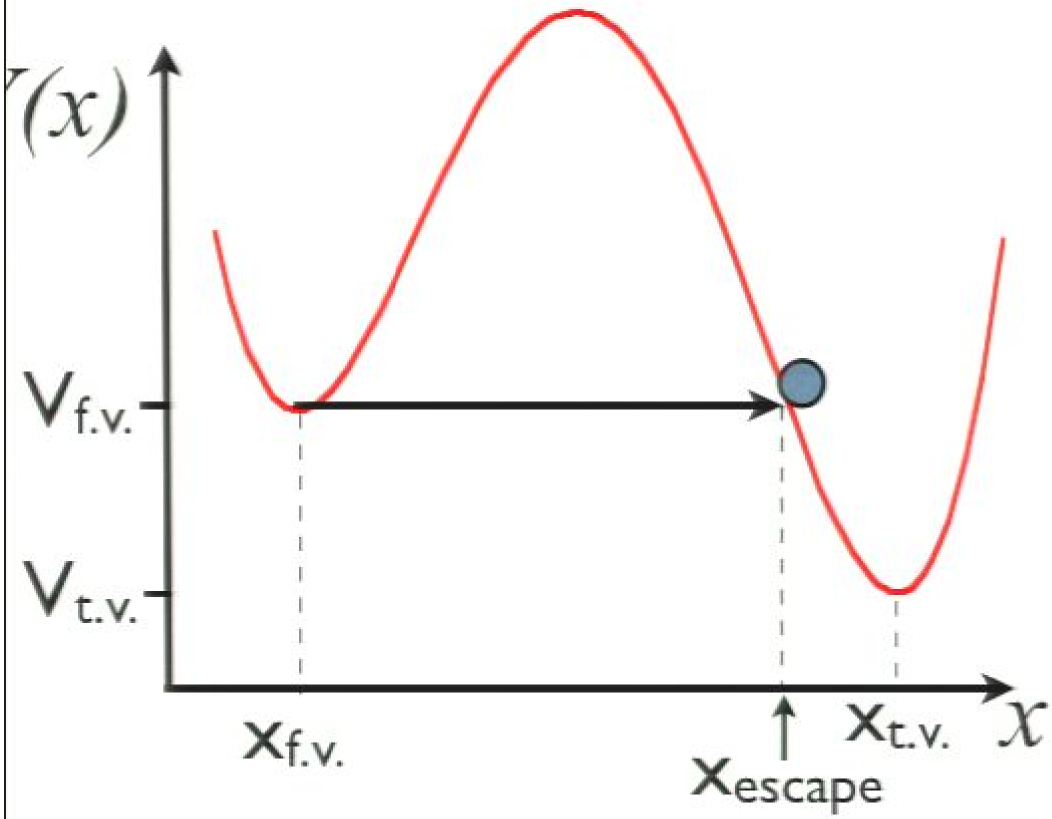

$$\text{Rate} \quad \sim \quad e^{-B}$$

$$B = \frac{2}{\hbar}\Big[S_E(\text{instanton}) - S_E(\text{f.v.})\Big] \qquad \Rightarrow \qquad \frac{1}{2}\dot{x}^2 = V(x) - V(f.v.)$$

$${}_E = \int d\tau \Big[\frac{1}{2}\dot{x}^2 + V(x)\Big] \qquad B = \frac{2}{\hbar}\int^{x_e} dx\sqrt{2(V(x) - V(f.v))}$$

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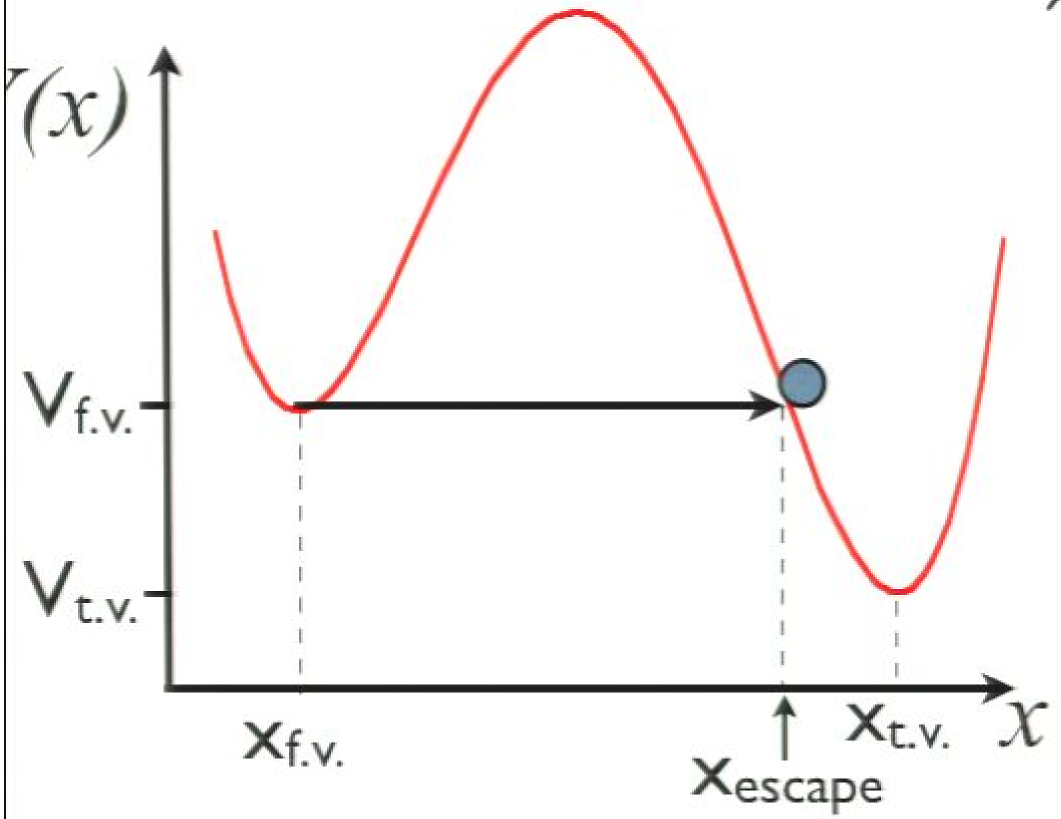

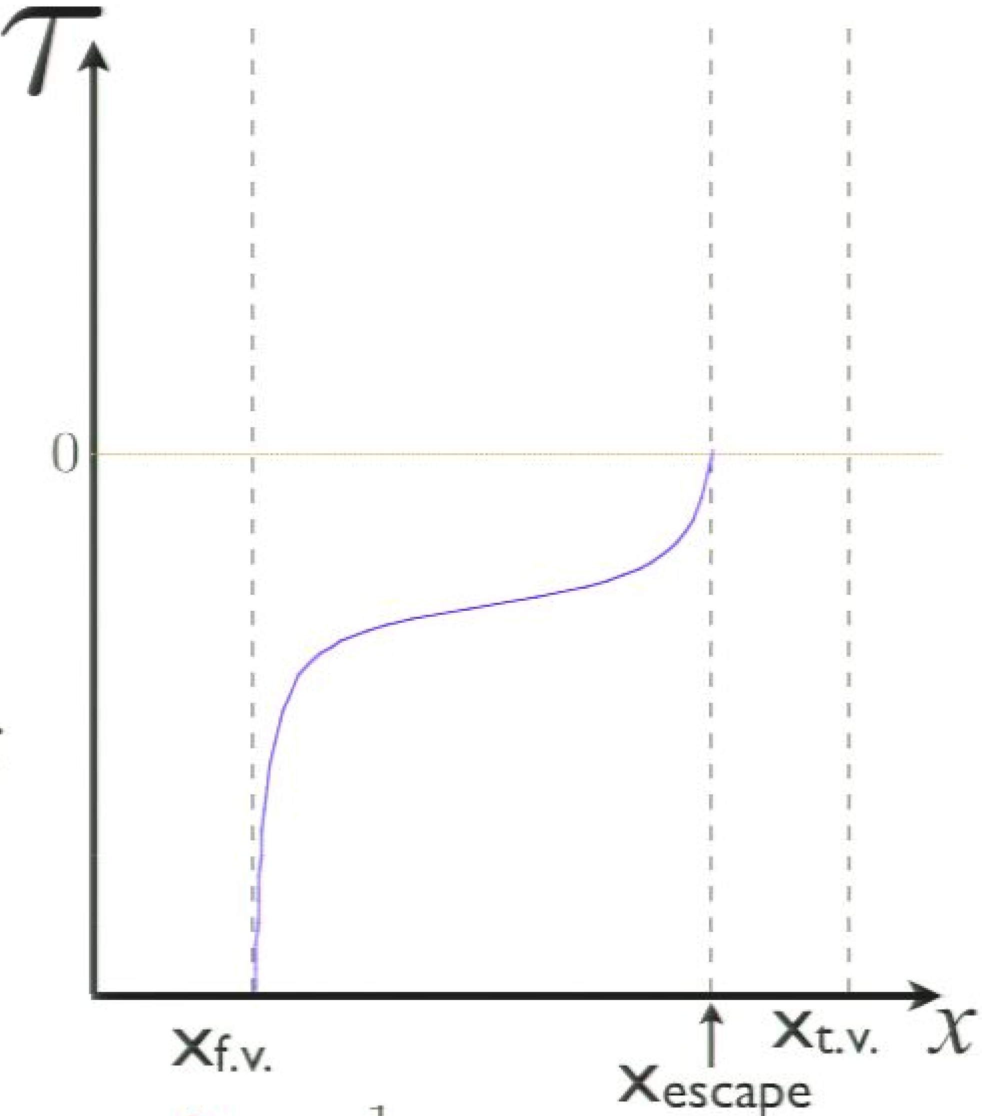

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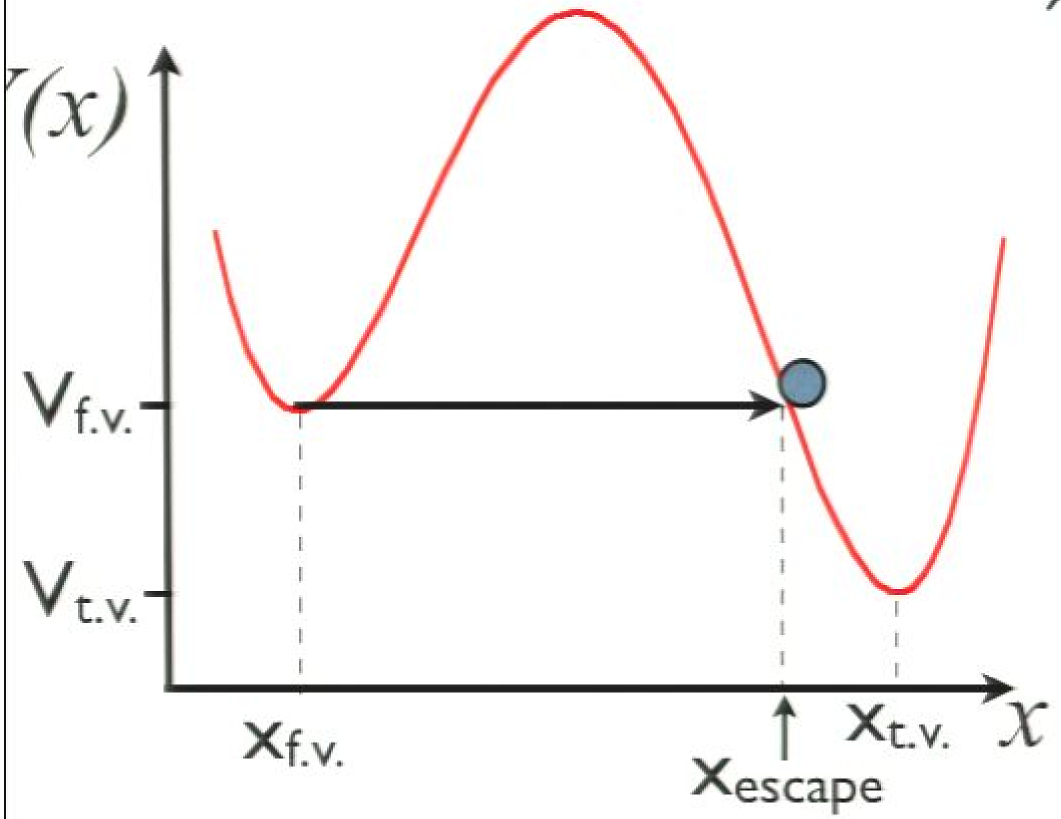
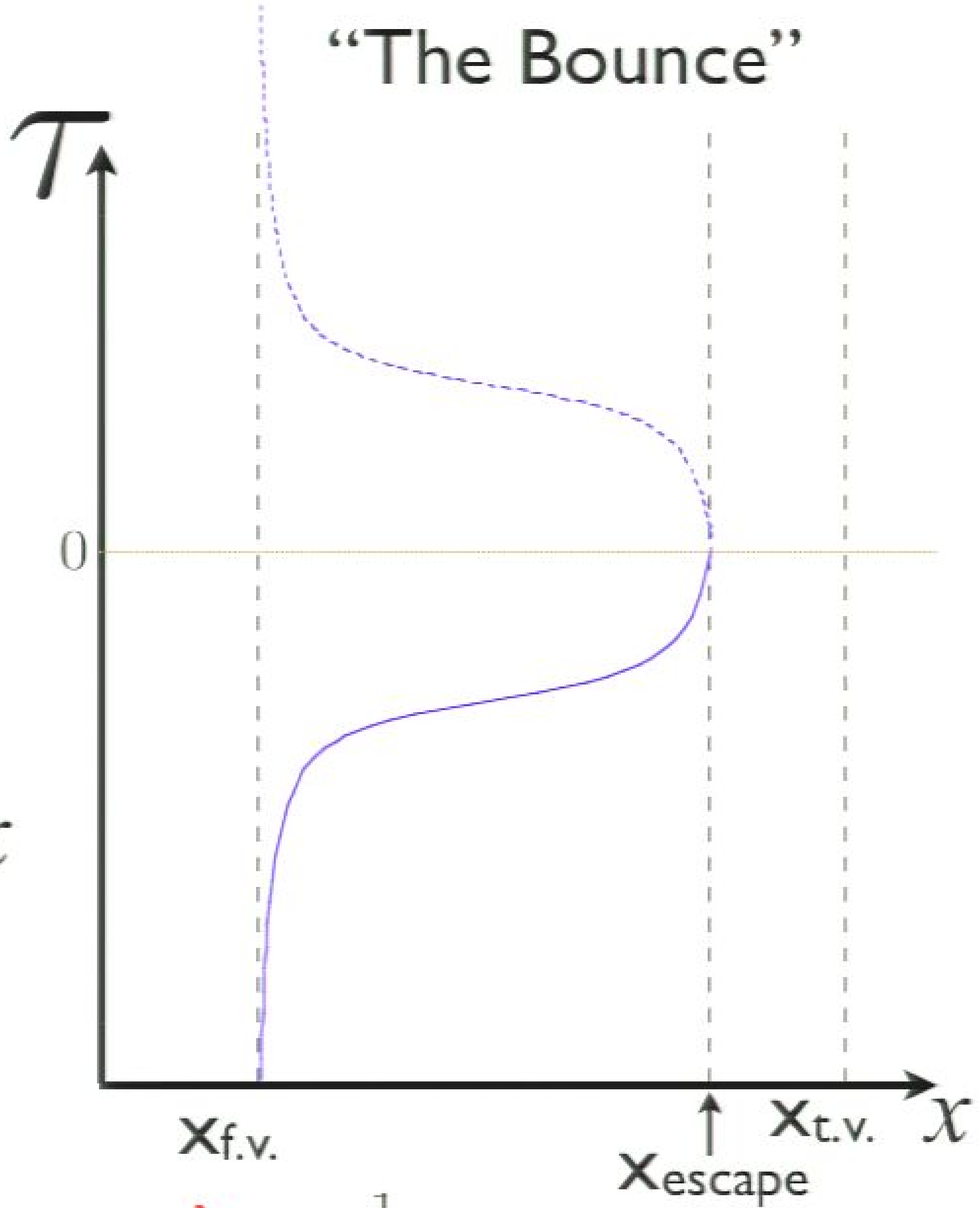


“The Bounce”



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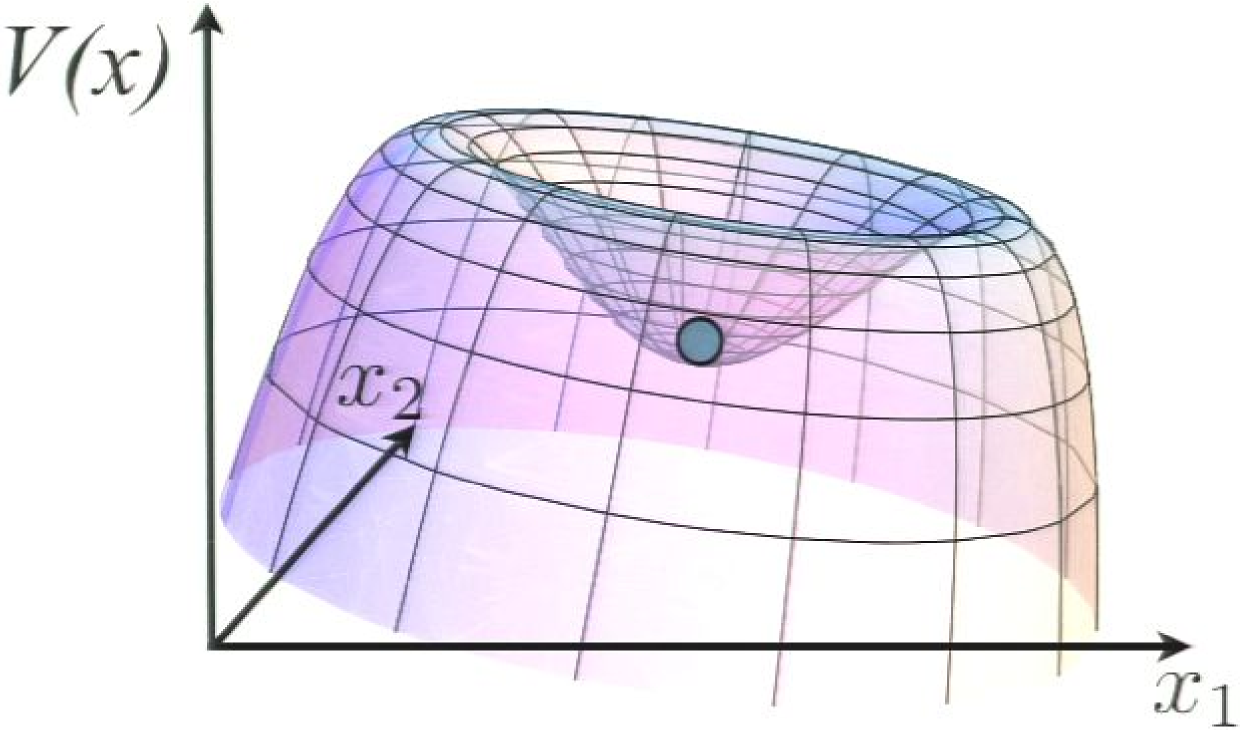
Many degrees of freedom tunneling at T = 0



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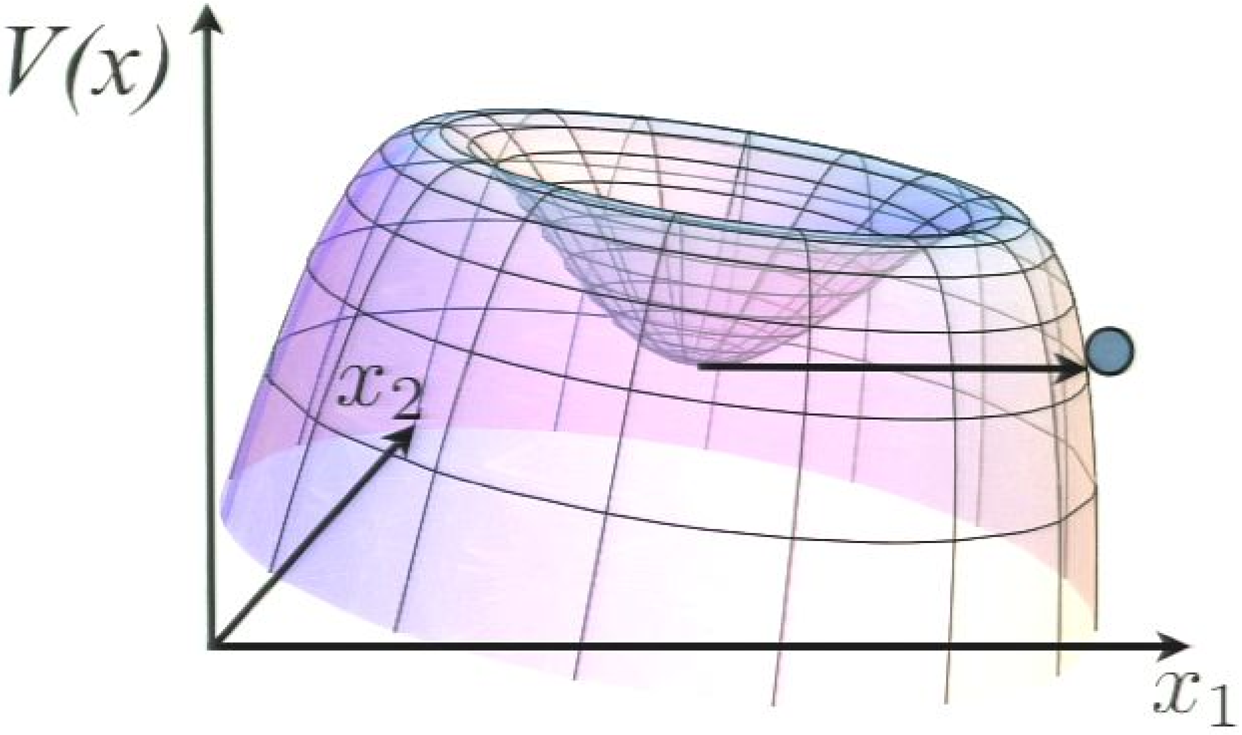

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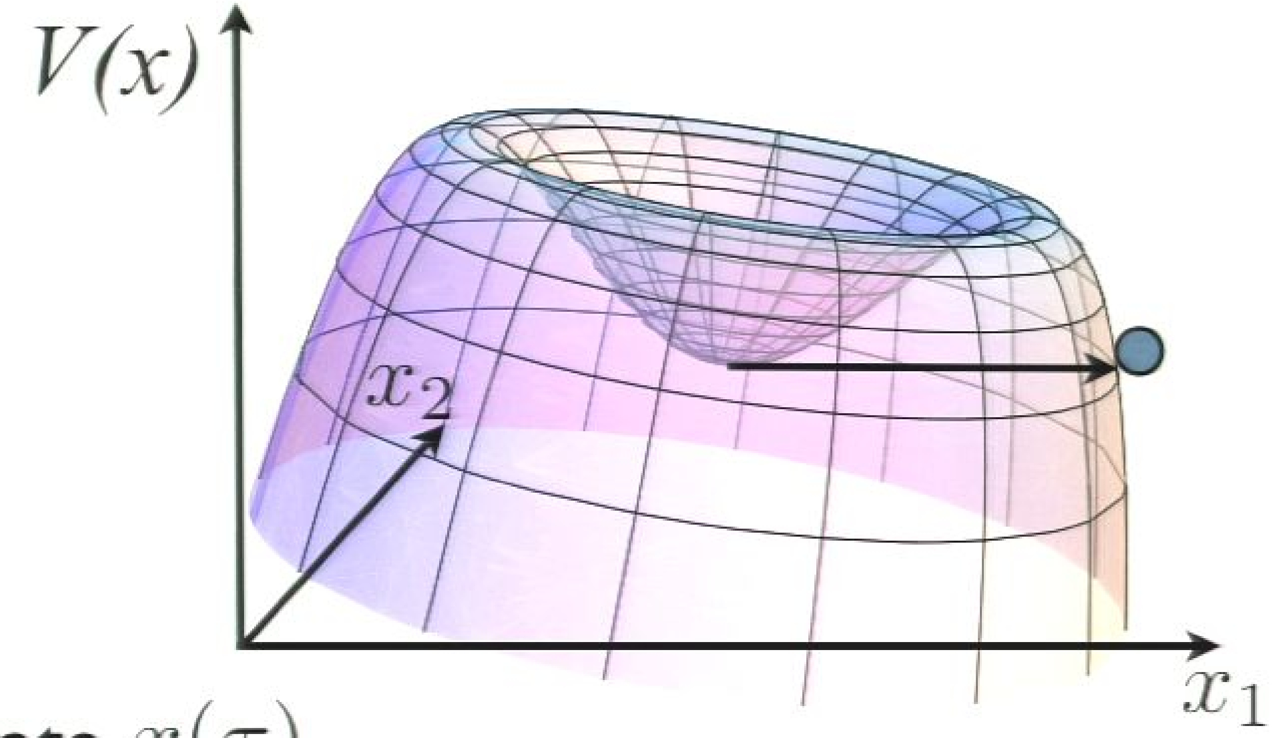

NE dimension

- choose optimal rate $x(\tau)$

ANY dimension

- choose optimal escape point
- choose optimal path
- choose optimal rate $x(\tau)$

Many degrees of freedom tunneling at T = 0

$$\text{Rate} \quad \sim \quad e^{-B}$$

$$B = \frac{2}{\hbar}\int_{x_i(f.v.)}^{x_i(e)} dx_i \sqrt{2(V(x_i) - V(f.v.))}$$

optimal path

Many degrees of freedom tunneling at T = 0

$$\text{Rate} \quad \sim \quad e^{-B}$$

$$B = \frac{1}{\hbar}\Big[S_E(\text{bounce}) - S_E(\text{f.v.})\Big]$$

$$S_E = \int d\tau \left(\sum_i \frac{1}{2} \dot{x}_i^2 + V(x_i) \right)$$

$$\Rightarrow \qquad B = \frac{2}{\hbar} \underset{\text{optimal path}}{\int_{x_i(f.v.)}^{x_i(e)}} dx_i \sqrt{2(V(x_i) - V(f.v.))}$$

Many degrees of freedom tunneling at T = 0

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QFT = many degree of freedom QM

= degree of freedom at every point

Many degrees of freedom tunneling at T = 0

$$S_E = \int d\tau \sum_x \left(\frac{1}{2}\dot{\phi}_x^2 + \underbrace{\frac{1}{2}\left(\frac{\phi_{x+\Delta} - \phi_x}{\Delta}\right)^2 + V(\phi_x)}_{U[\phi_x]} \right)$$

$$S_E = \int d\tau \int d\vec{x} \left(\frac{1}{2}\dot{\phi}(\vec{x})^2 + \frac{1}{2}(\nabla\phi(\vec{x}))^2 + V(\phi(\vec{x})) \right)$$

$$U[\phi(\vec{x})] = \int d\vec{x} \left(\frac{1}{2}(\nabla\phi(\vec{x}))^2 + V(\phi(\vec{x})) \right)$$

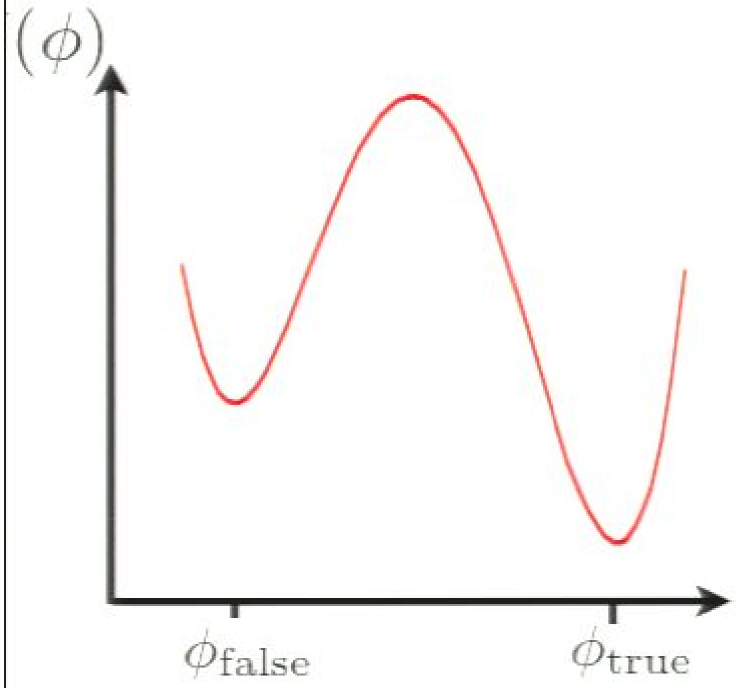
$$B = \frac{2}{\hbar}\int_{f.v.}^{\phi(\text{escape})} d\phi_x \sqrt{2(U[\phi_x] - U[f.v.]}$$

optimal path

QFT = many degree of freedom QM

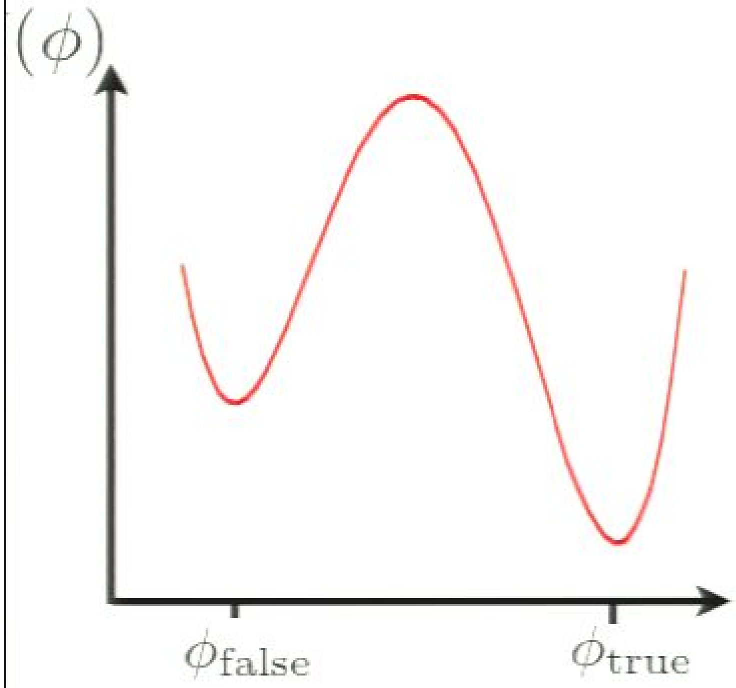
= degree of freedom at every point

Tunneling in Minkowski space (no gravity) at T = 0



$$S_E = \int d^4x \left[\frac{1}{2} (\partial_\mu \phi(x))^2 + V(\phi) \right]$$

Tunneling in Minkowski space (no gravity) at T = 0

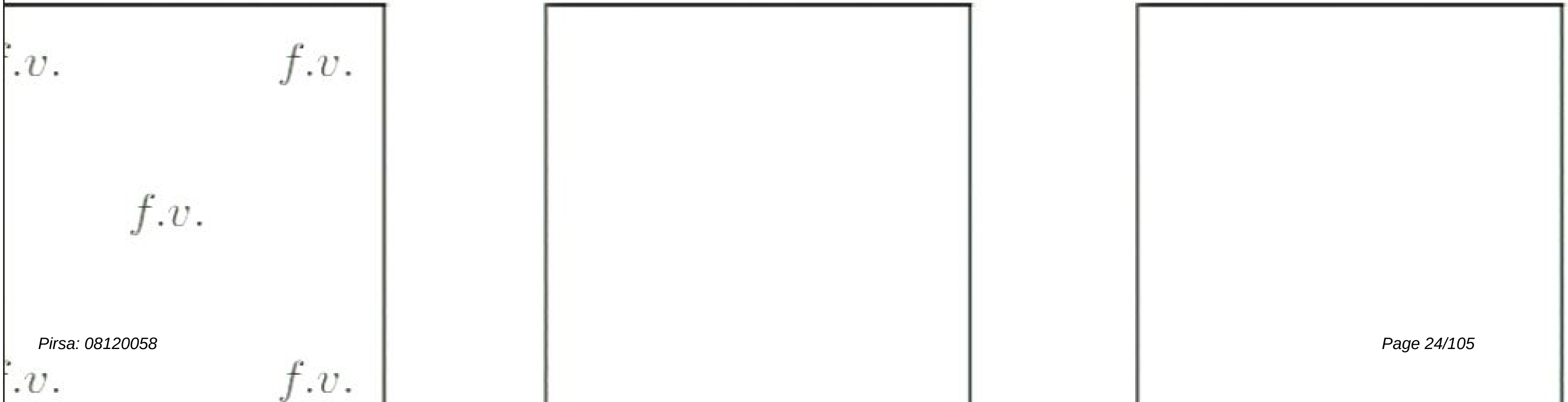


$$S_E = \int d^4x \left[\frac{1}{2} (\partial_\mu \phi(x))^2 + V(\phi) \right]$$

Subtlety:

No homogenous tunneling

Instead bubble nucleation



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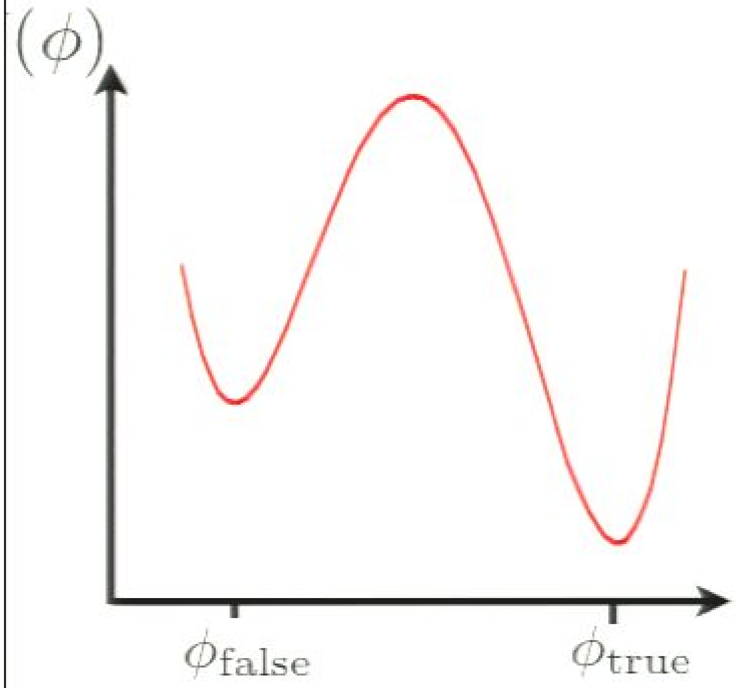

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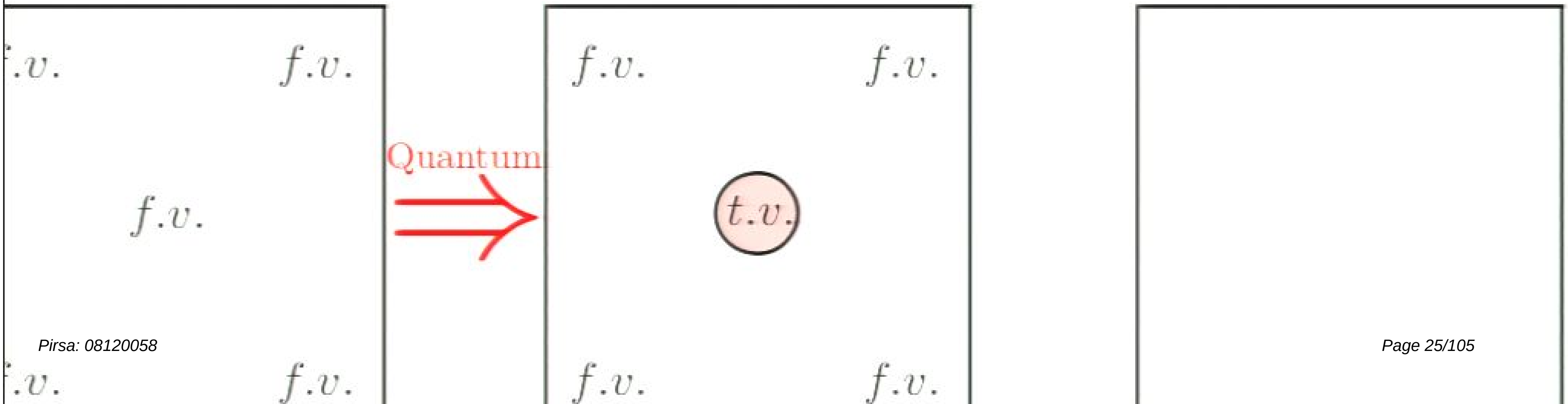

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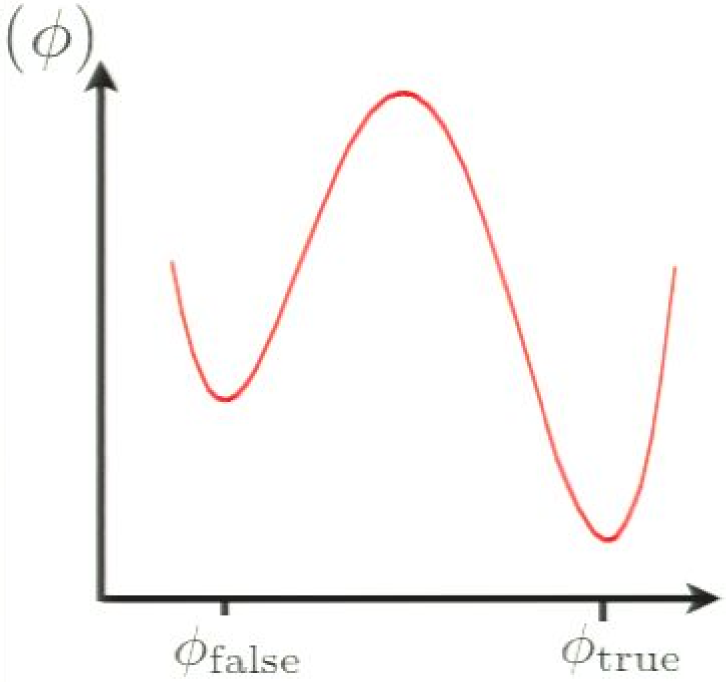

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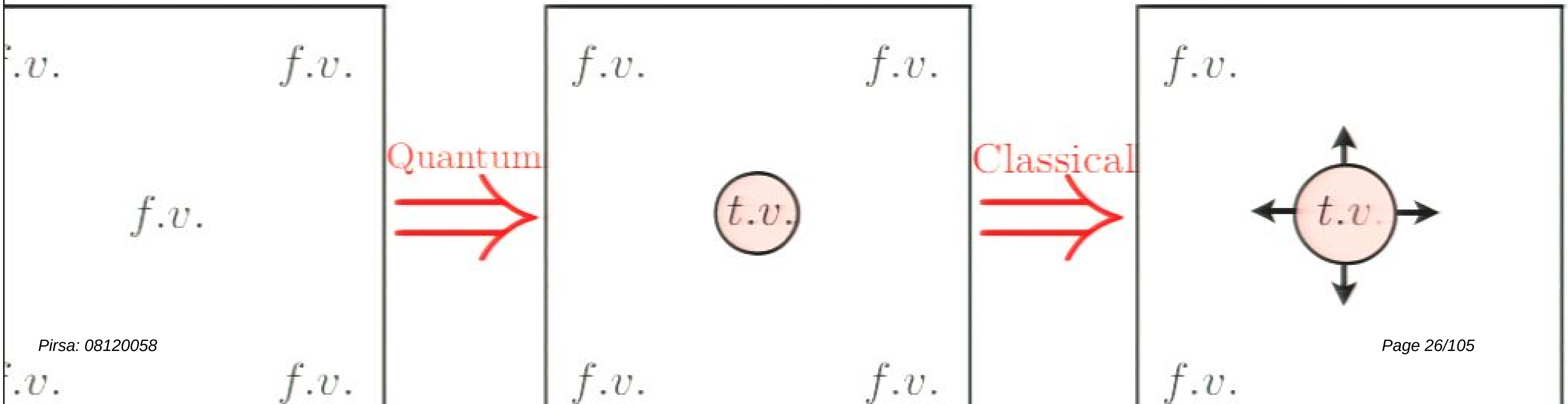

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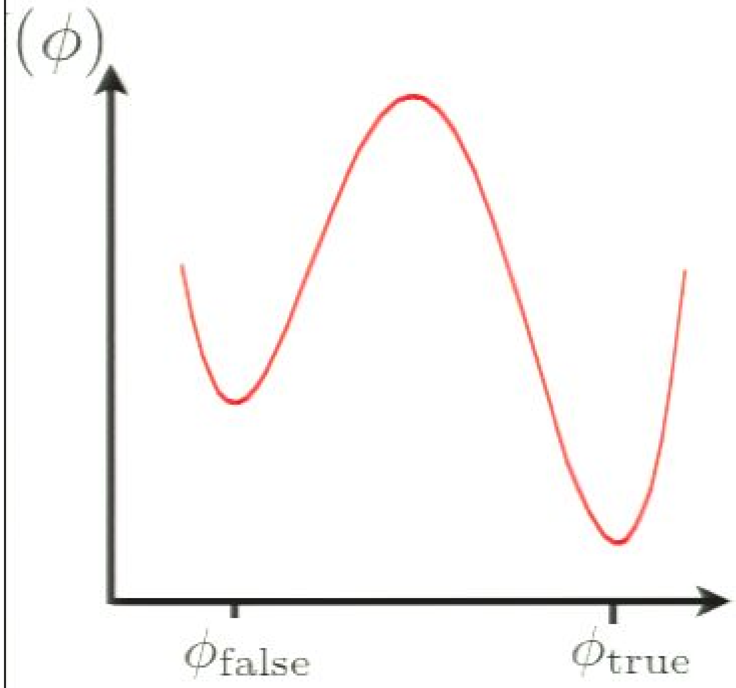

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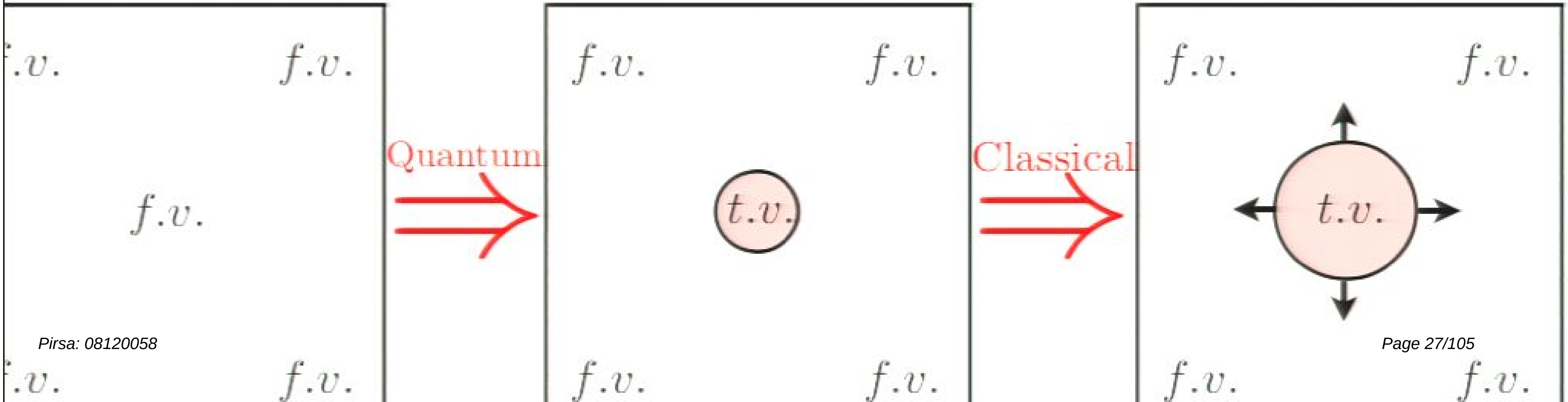

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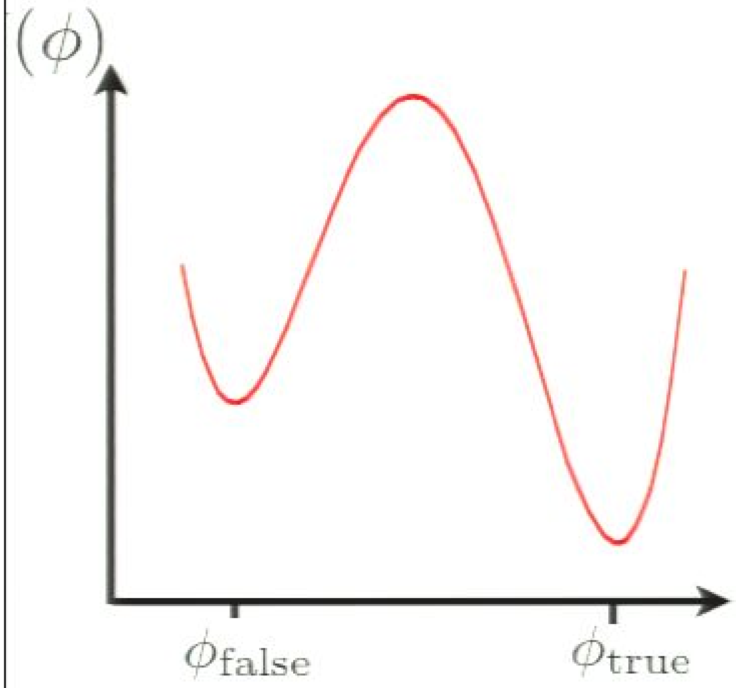

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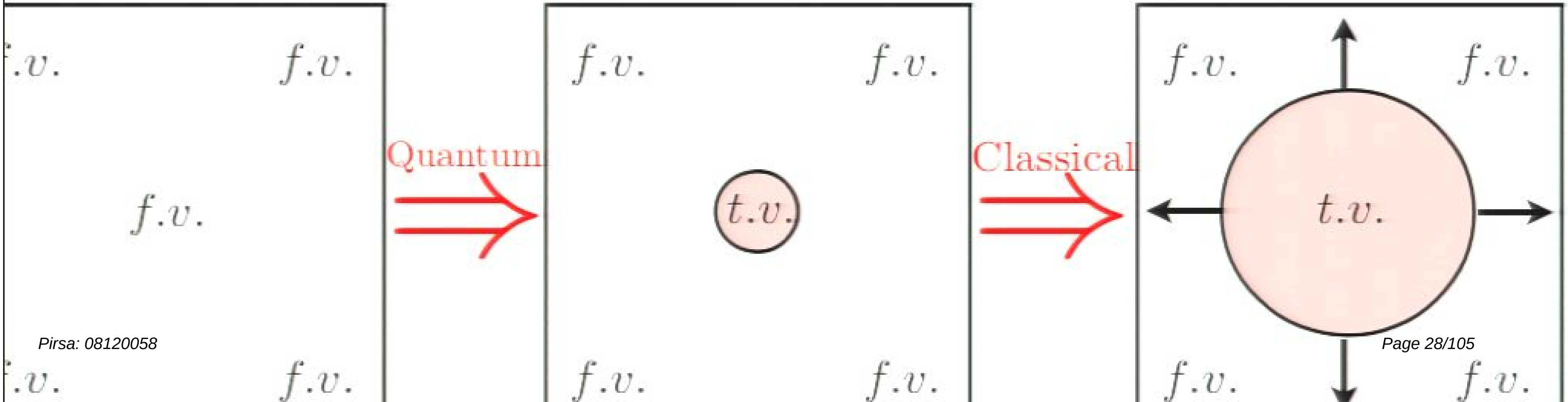

$$V(x) \xrightarrow{\times} V(\phi)$$

$$\xrightarrow{\checkmark} U[\phi(x)]$$

$$U[\phi(x)] = \int d^3x \left[\frac{1}{2} (\vec{\nabla}\phi)^2 + V(\phi) \right]$$

$$V(x) \not\longrightarrow V(\phi)$$

$$\xrightarrow{\checkmark} U[\phi(x)]$$

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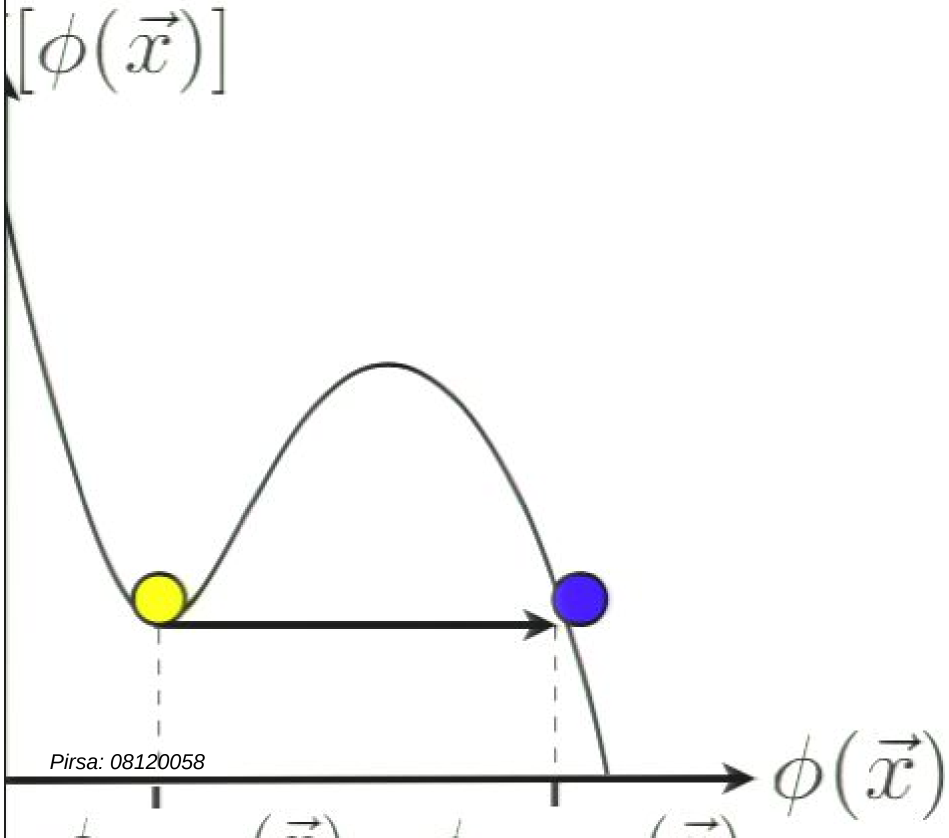

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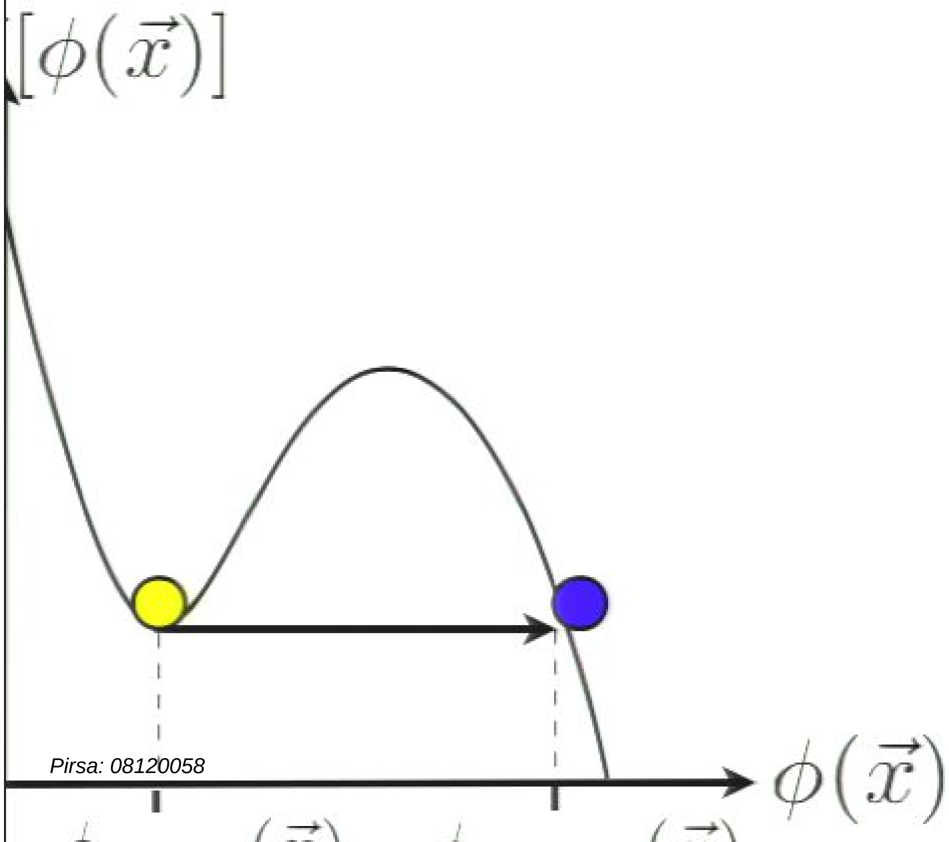

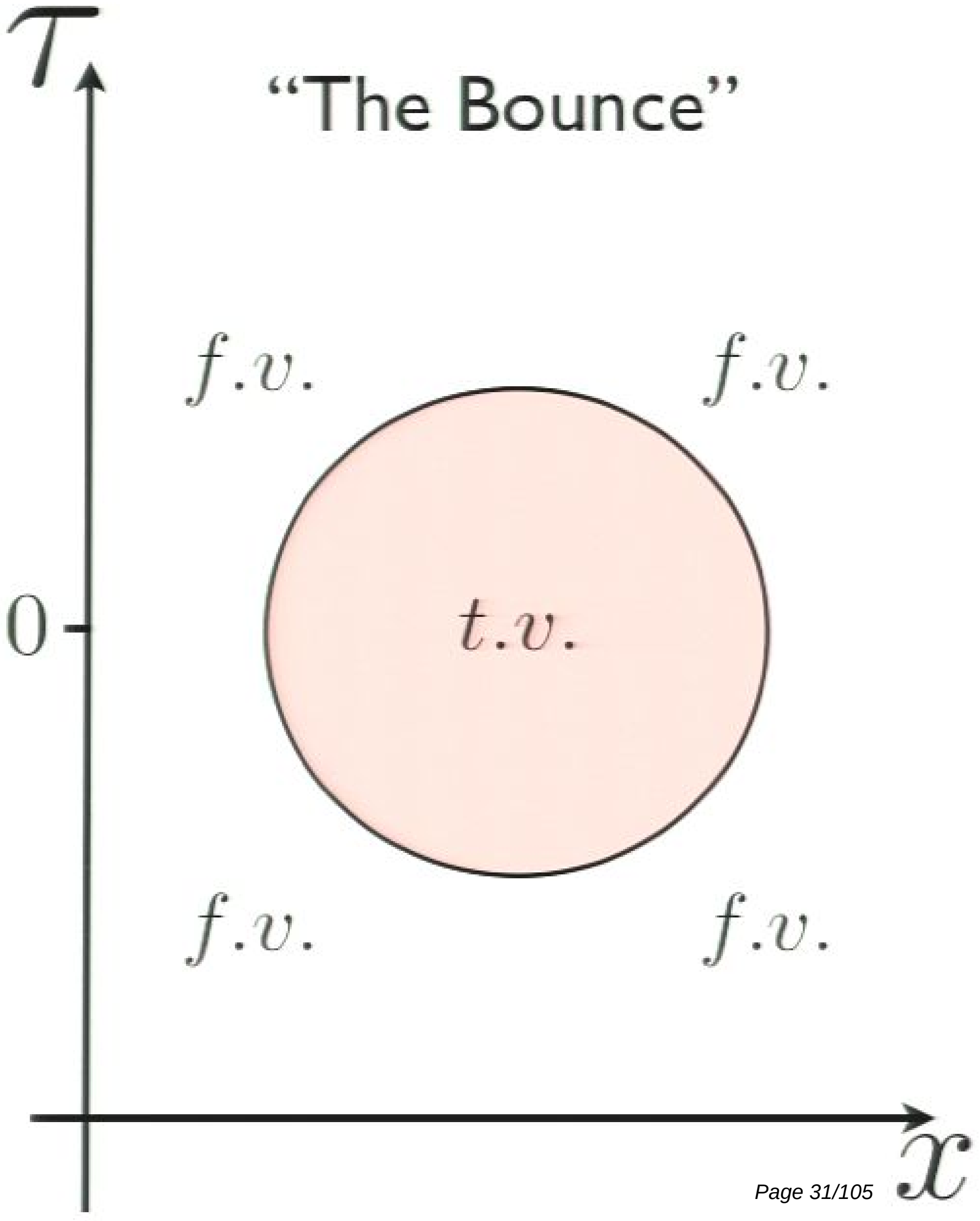

$$V(x) \xrightarrow{\times} V(\phi)$$

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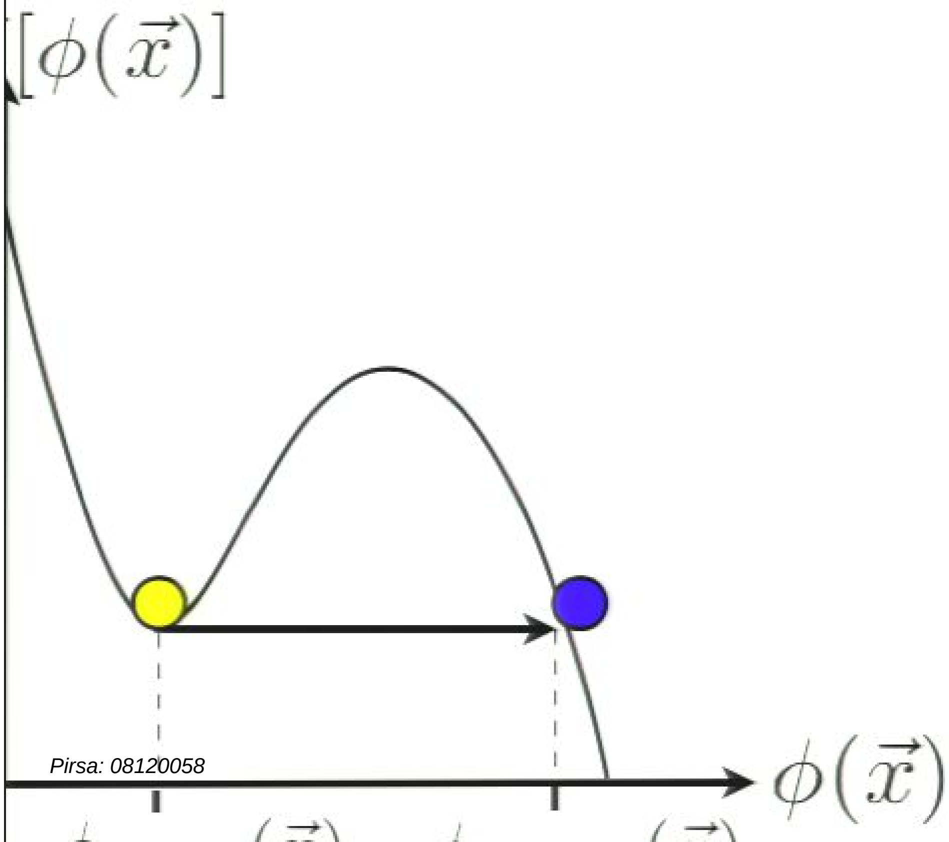

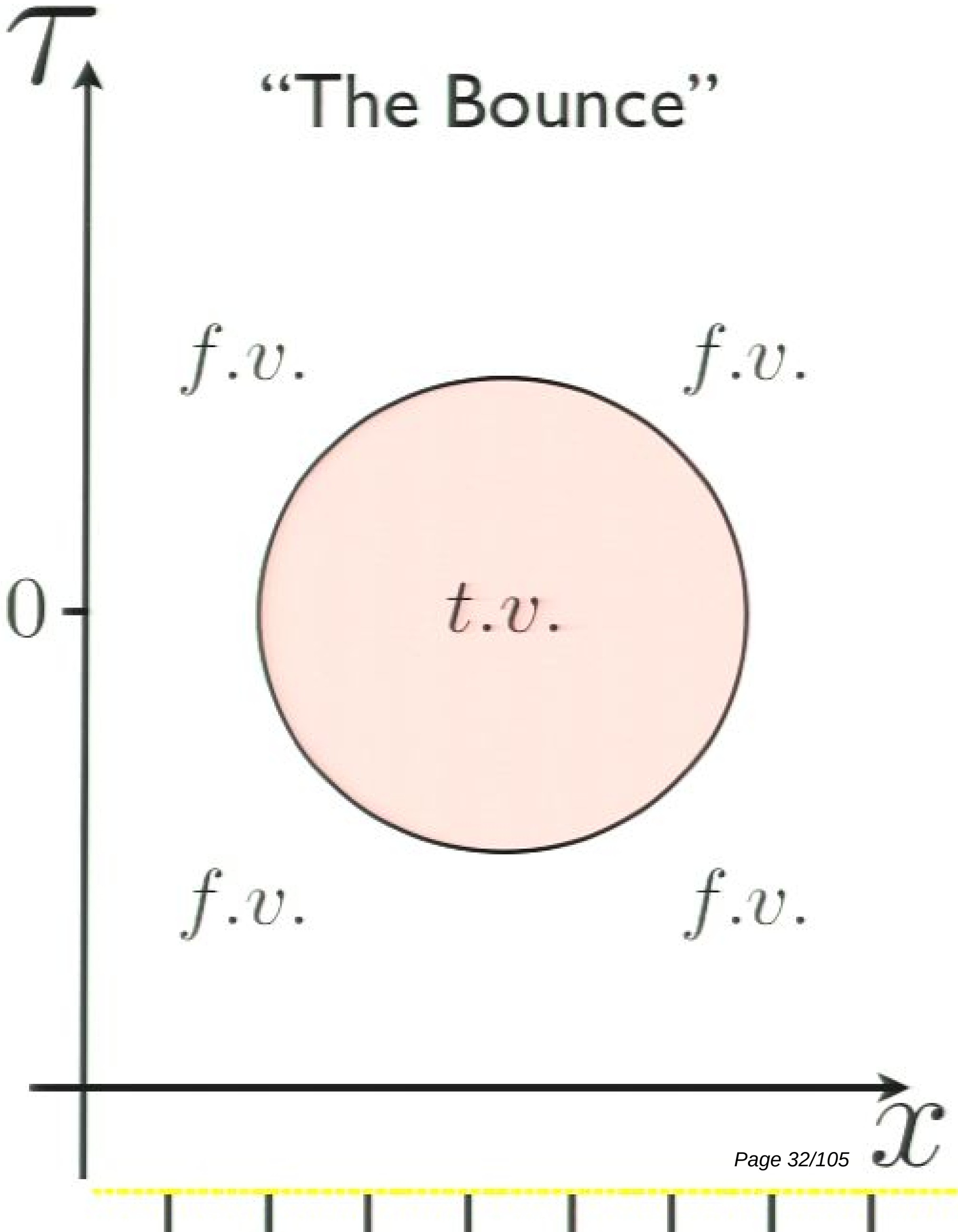
“The Bounce”

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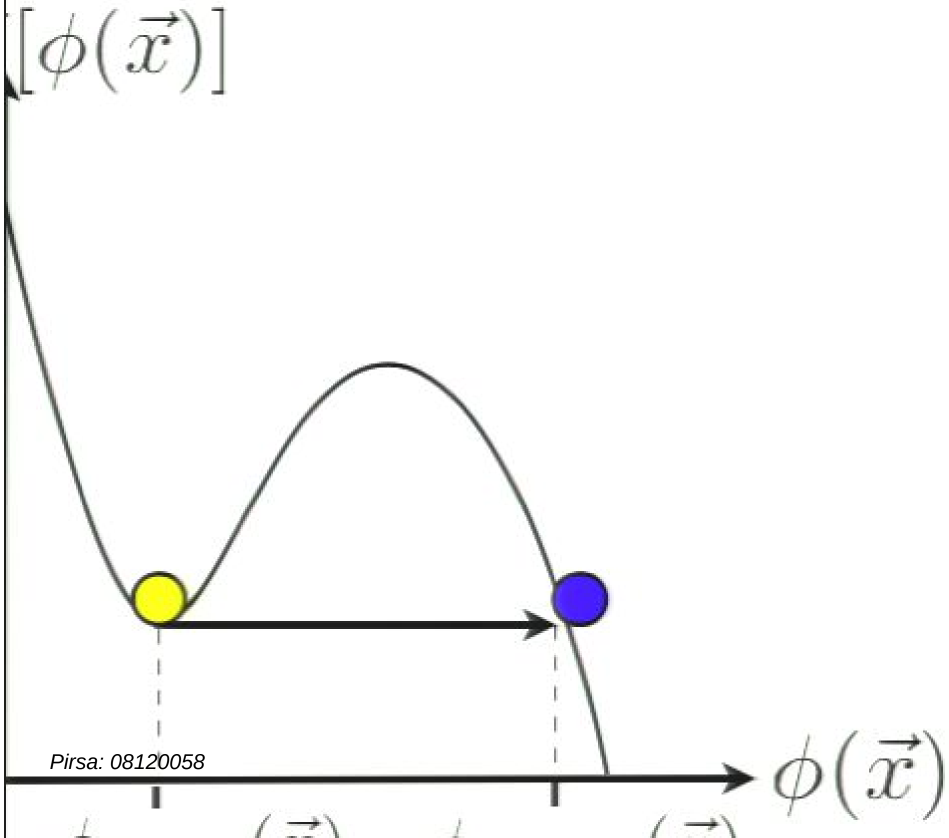
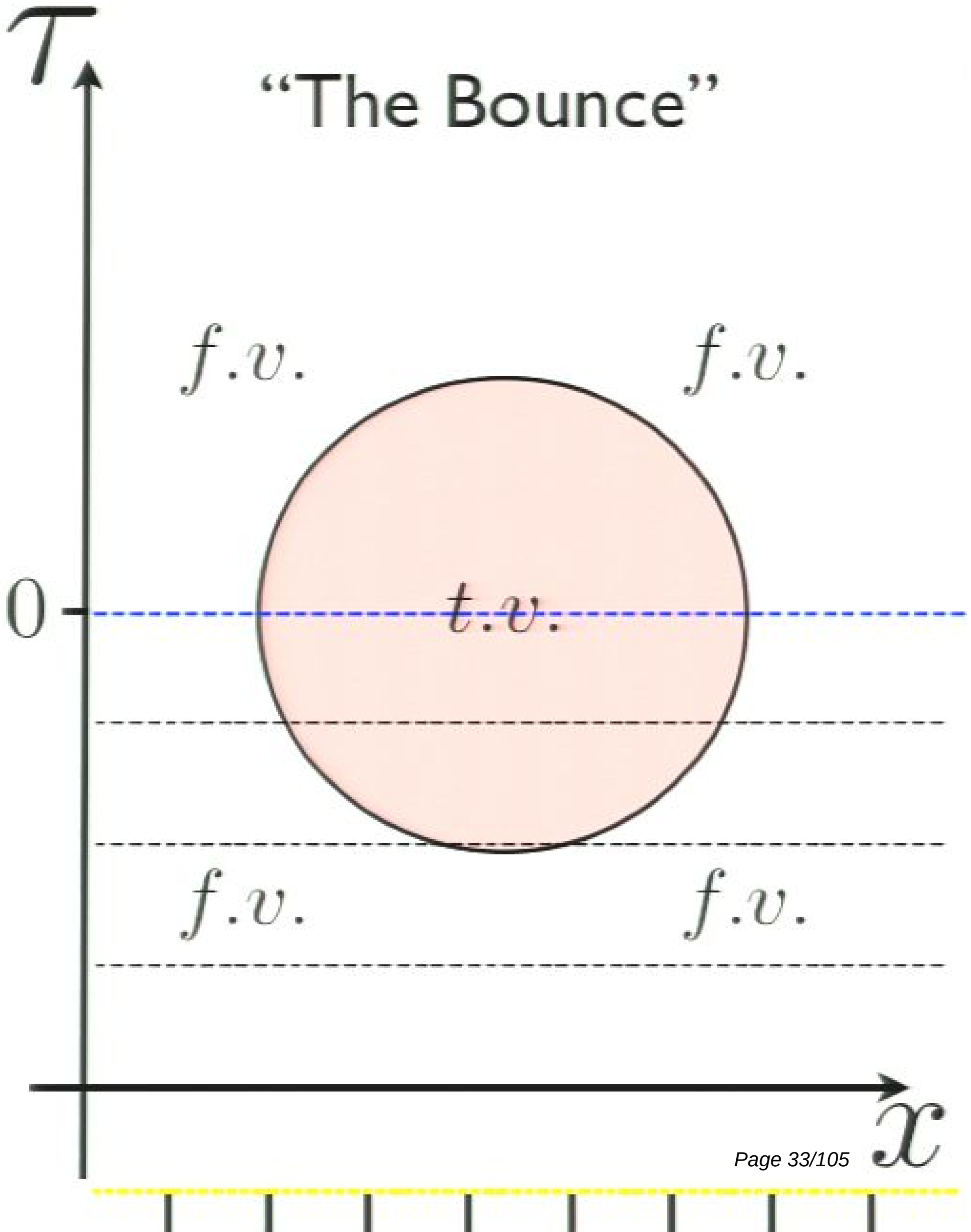



“The Bounce”

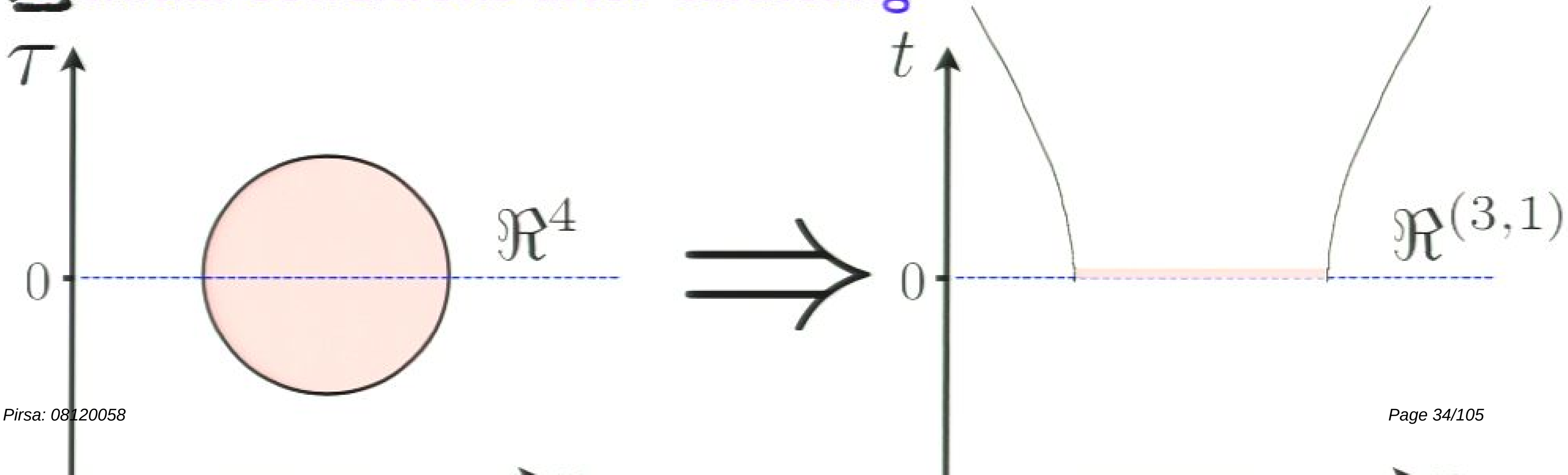
Tunneling in Minkowski space (no gravity) at T = 0

☑ **Rate**

$$\text{Rate} \sim e^{-B}$$

$$\begin{aligned} B &= \frac{1}{\hbar}\Big[S_E(\text{bounce}) - S_E(\text{f.v.})\Big] \\ &= \frac{1}{\hbar}\int_{-\infty}^{\infty} d\tau \Big(E[\phi_{\text{bounce}}] - E[\phi_{\text{f.v.}}]\Big) \end{aligned}$$

☑ **Initial conditions after tunneling**



Tunneling in Minkowski space (no gravity) at T = 0

☑ Rate
☑ Initial conditions after tunneling

Tunneling in Minkowski space (no gravity) at T ≠ 0

☑ Rate
☑ Initial conditions after tunneling

Tunneling in de Sitter space (à la Coleman De Luccia)

☑ Rate
??? Initial conditions after tunneling ???

Tunneling in de Sitter space (thermal approach)

Is de Sitter decay predominantly quantum?
or predominantly thermal?

Concluding remarks

✓ Tunneling i[illegible]inkowski space (no gravity) at $T = 0$

☑ Rate
☑ Initial conditions after tunneling

Tunneling in Minkowski space (no gravity) at $T \neq 0$

☑ Rate
☑ Initial conditions after tunneling

Tunneling in de Sitter space (à la Coleman De Luccia)

☑ Rate
??? Initial conditions after tunneling ???

Tunneling in de Sitter space (thermal approach)

Is de Sitter decay predominantly quantum?
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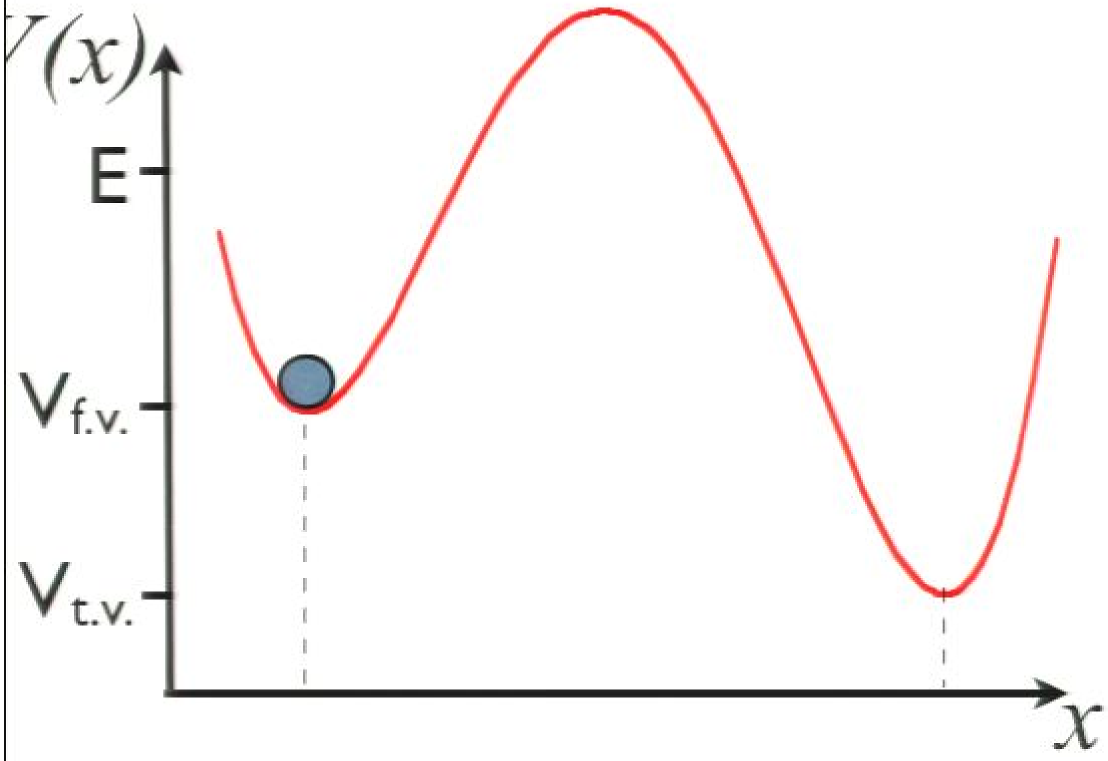
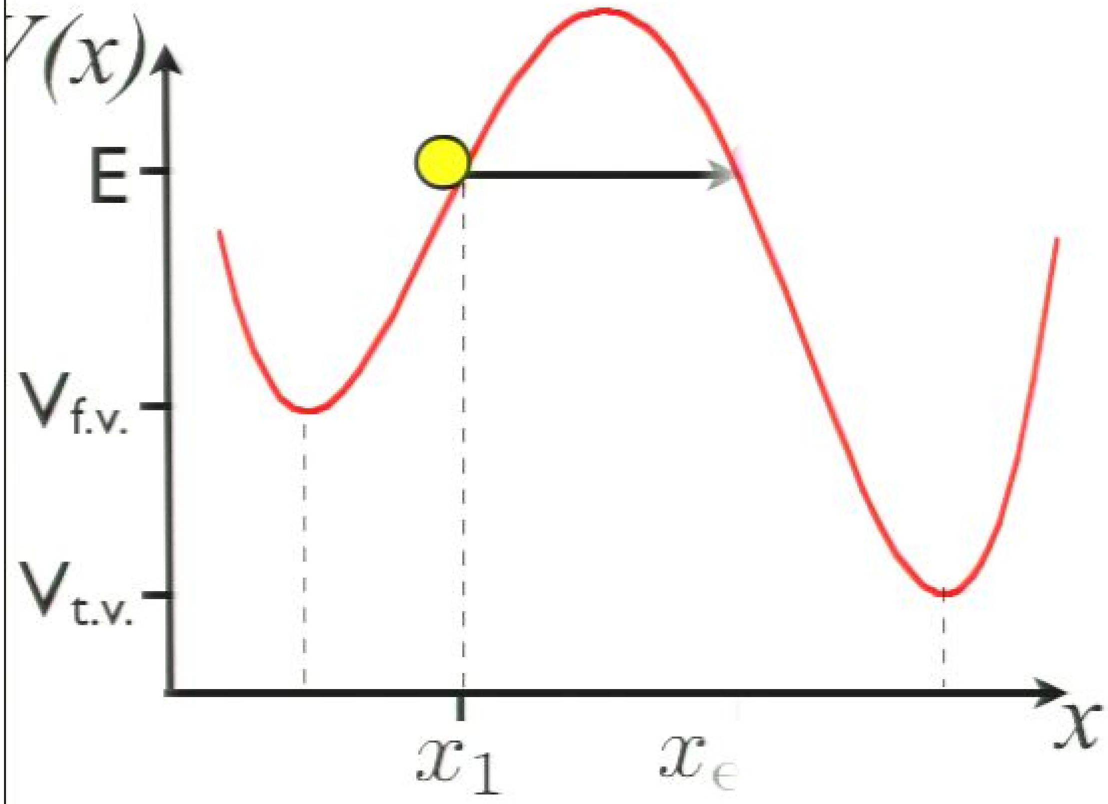
Concluding remarks

Particle tunneling at $T \neq 0$



. Particle tunneling at T ≠ 0



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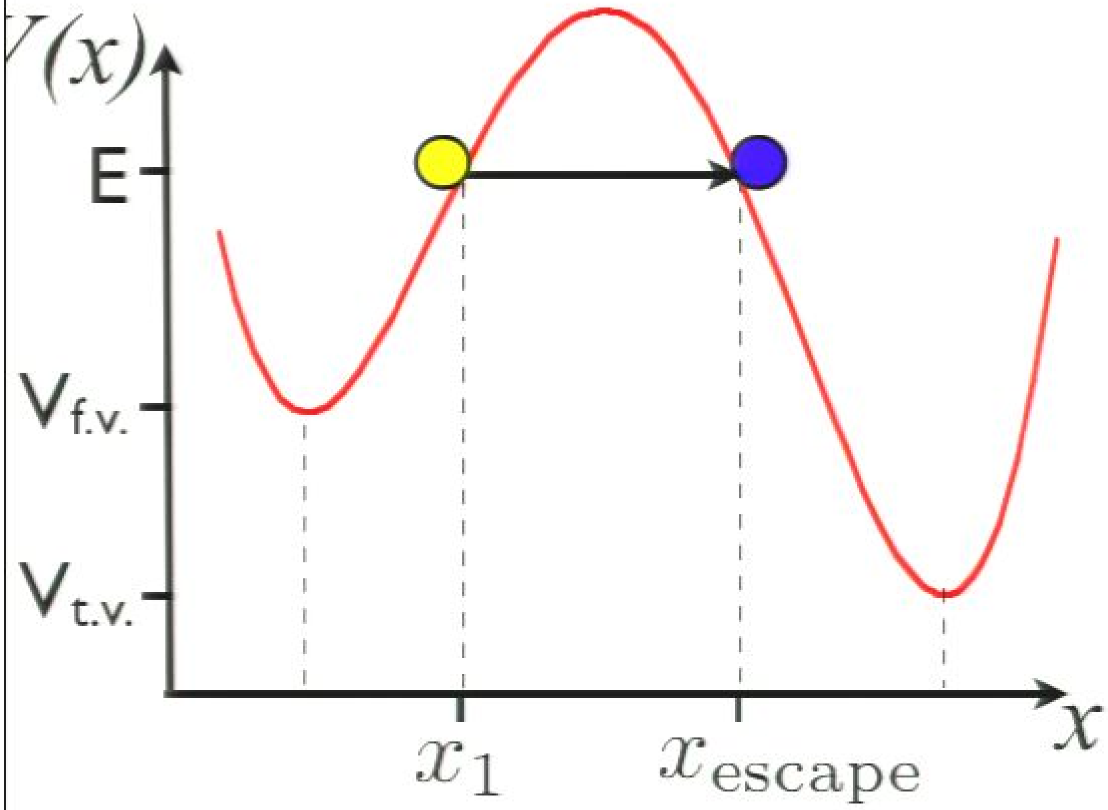
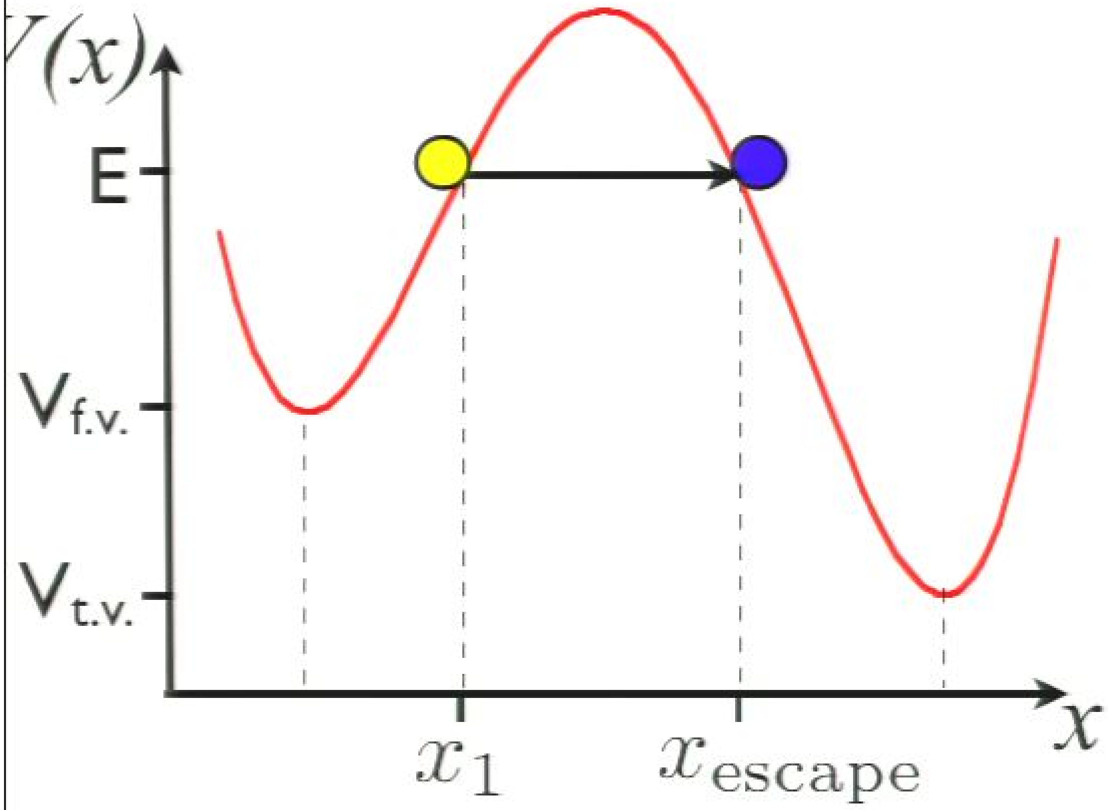


. Particle tunneling at T ≠ 0

$$\text{Rate} \sim e^{-\beta(E-V_{f.v.})}\, e^{-\frac{2}{\hbar}\int_{x_1}^{x_{esc.}} dx\sqrt{2(V(x)-E)}}$$



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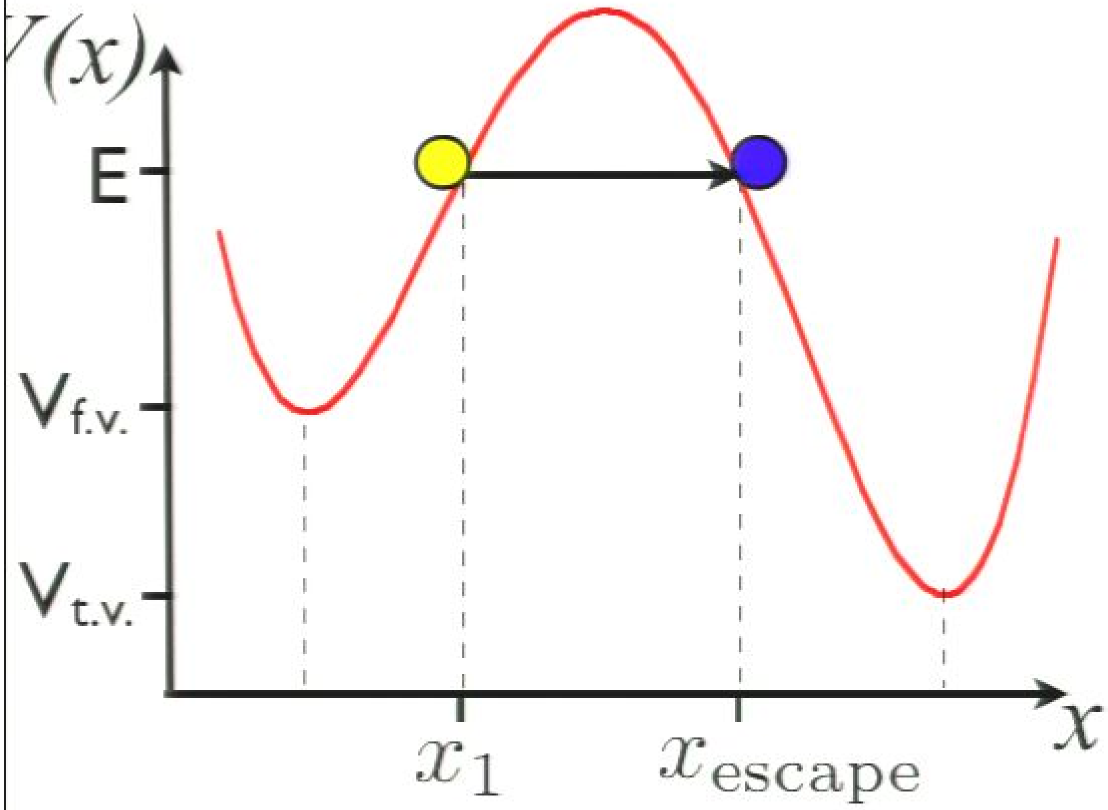

Optimal E?

$$\beta = \frac{2}{\hbar}\int_{x_1}^{x_{esc.}} \frac{dx}{\sqrt{2(V(x)-E)}}$$

$$\beta = \frac{2}{\hbar}\int_{x_1}^{x_{esc.}} \frac{dx}{\sqrt{\dot{x}^2}}$$

$$\beta = \frac{2}{\hbar}\left(\tau_{\text{escape}} - \tau_1\right)$$

Particle tunneling at T ≠ 0

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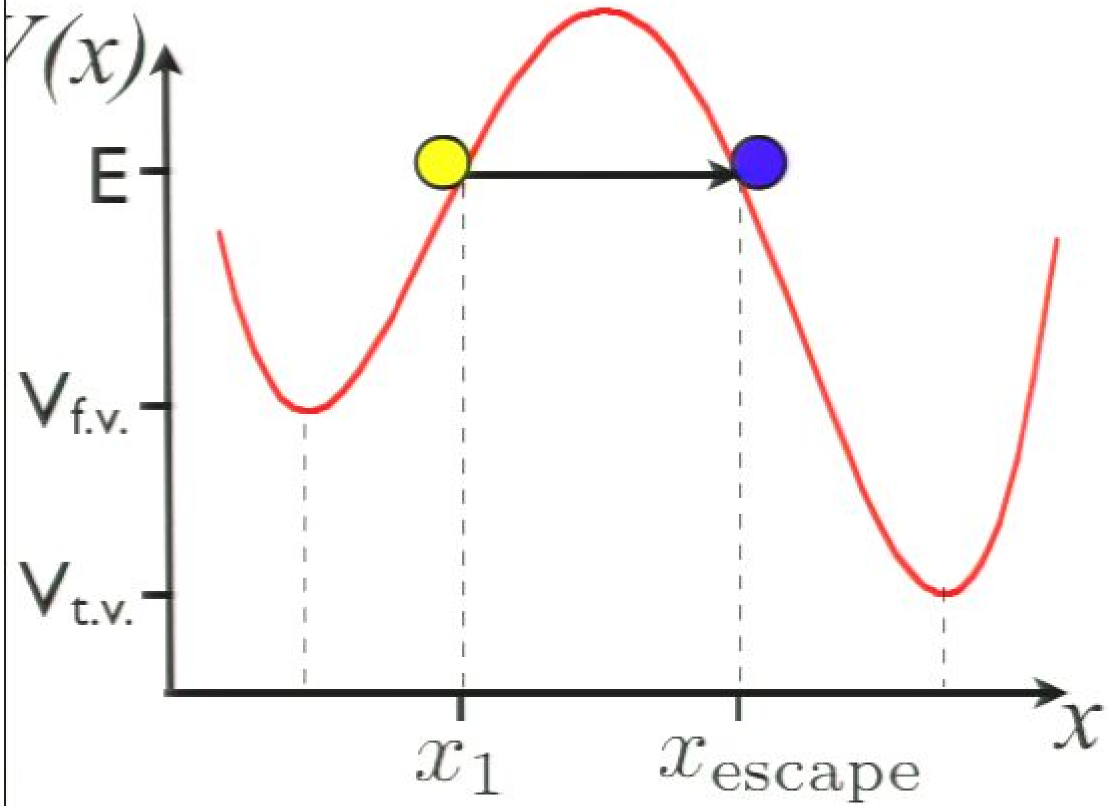

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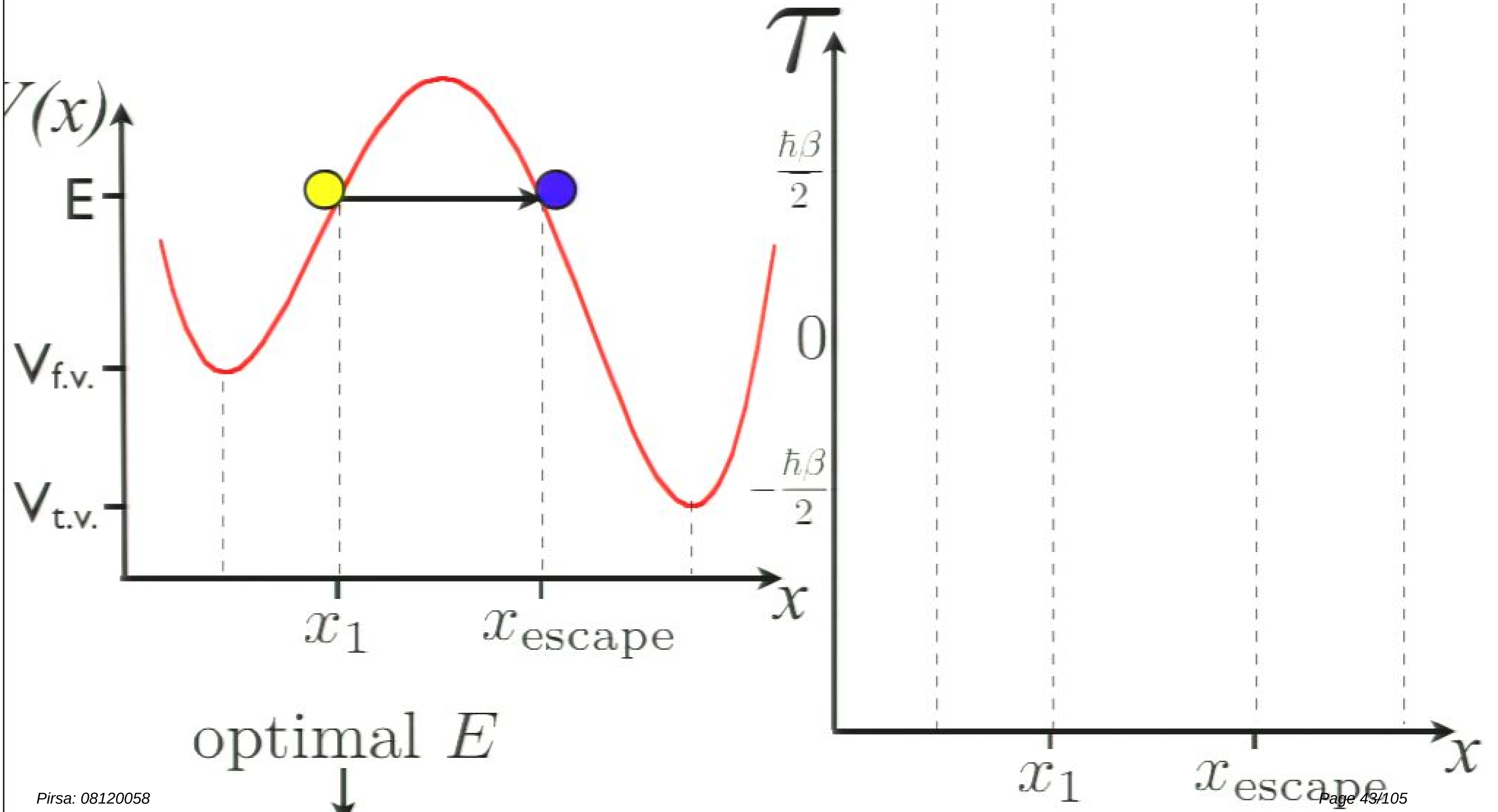
optimal E

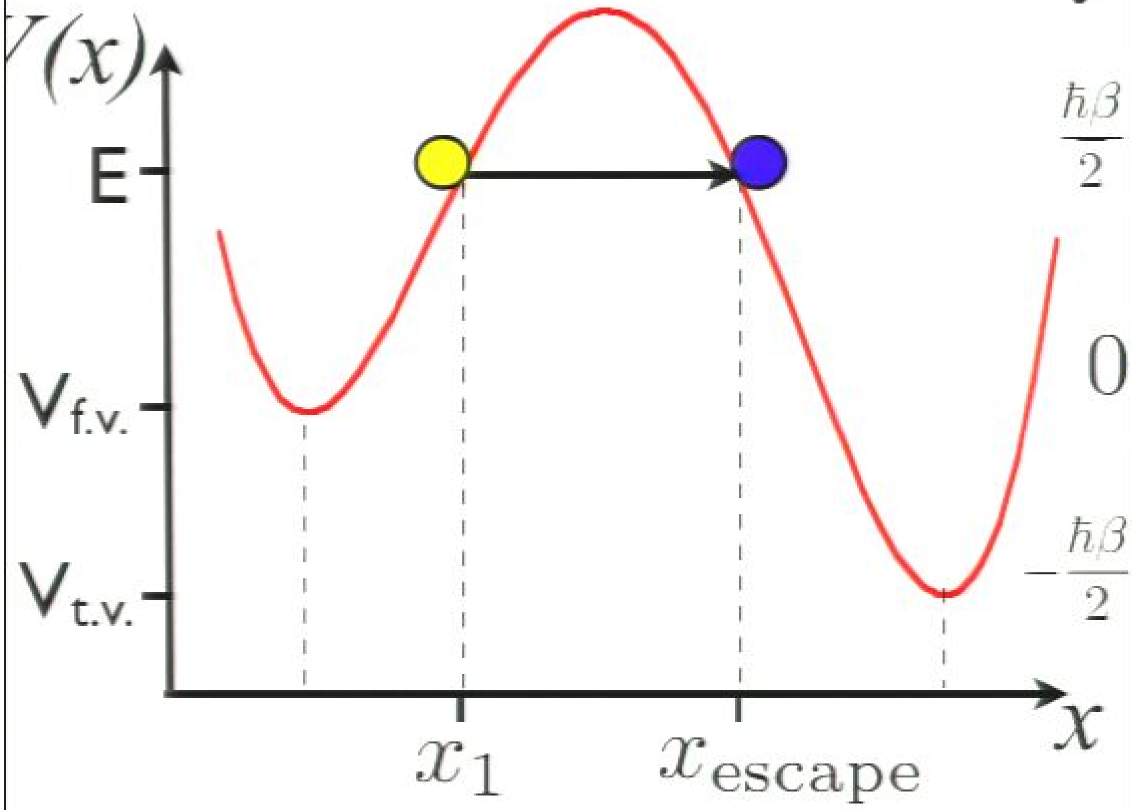
Particle tunneling at T ≠ 0

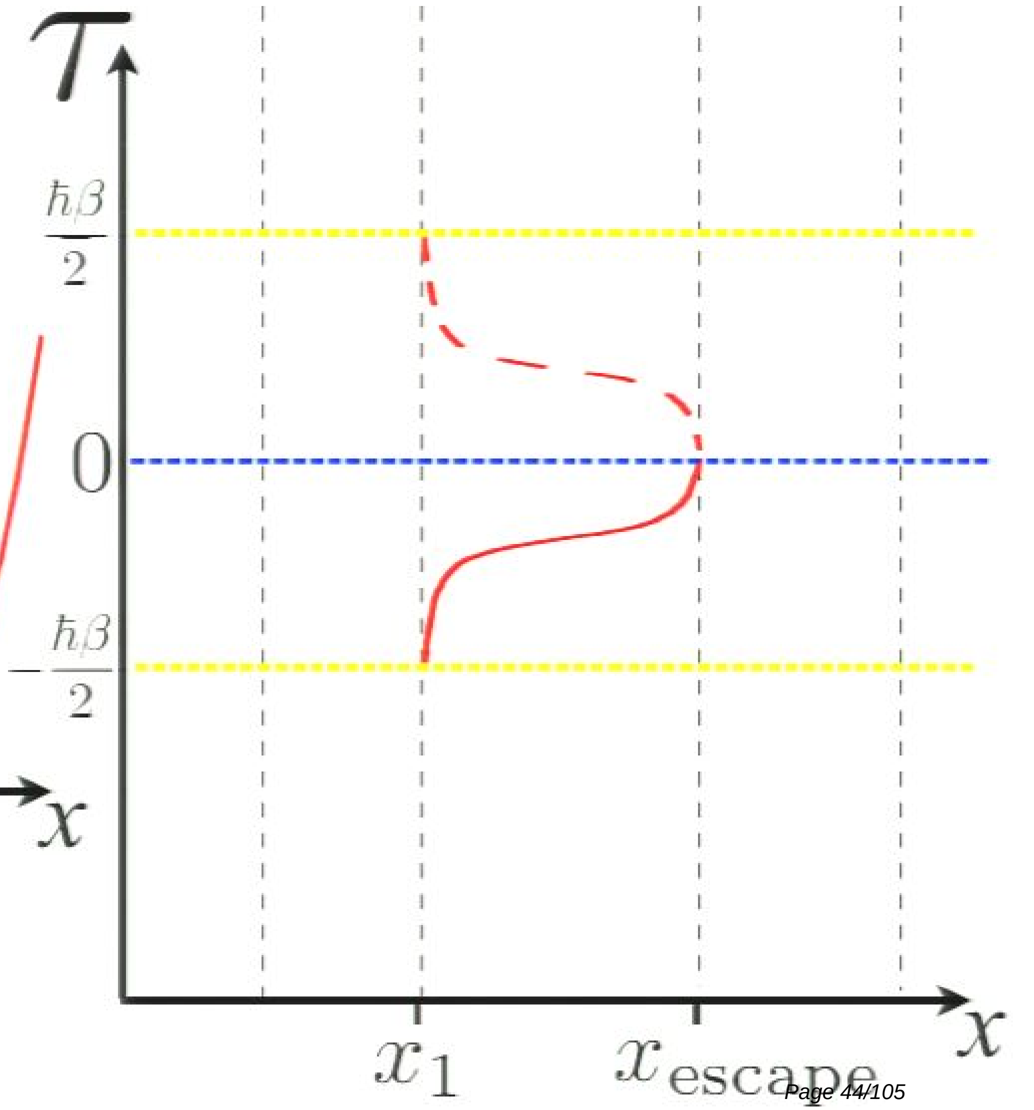


optimal E

↓

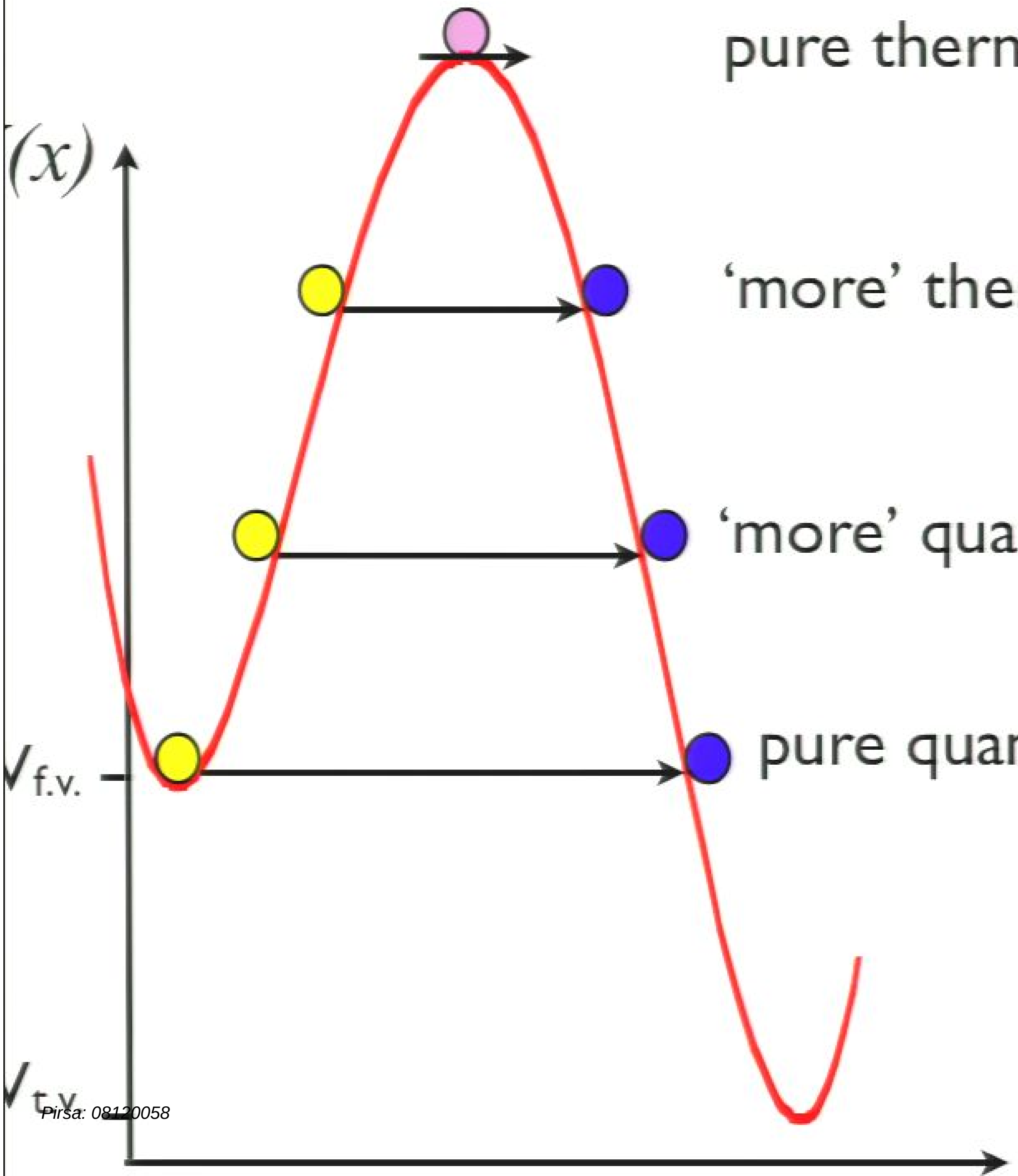
Particle tunneling at $T \neq 0$





optimal E

↓



pure thermal

‘more’ thermal

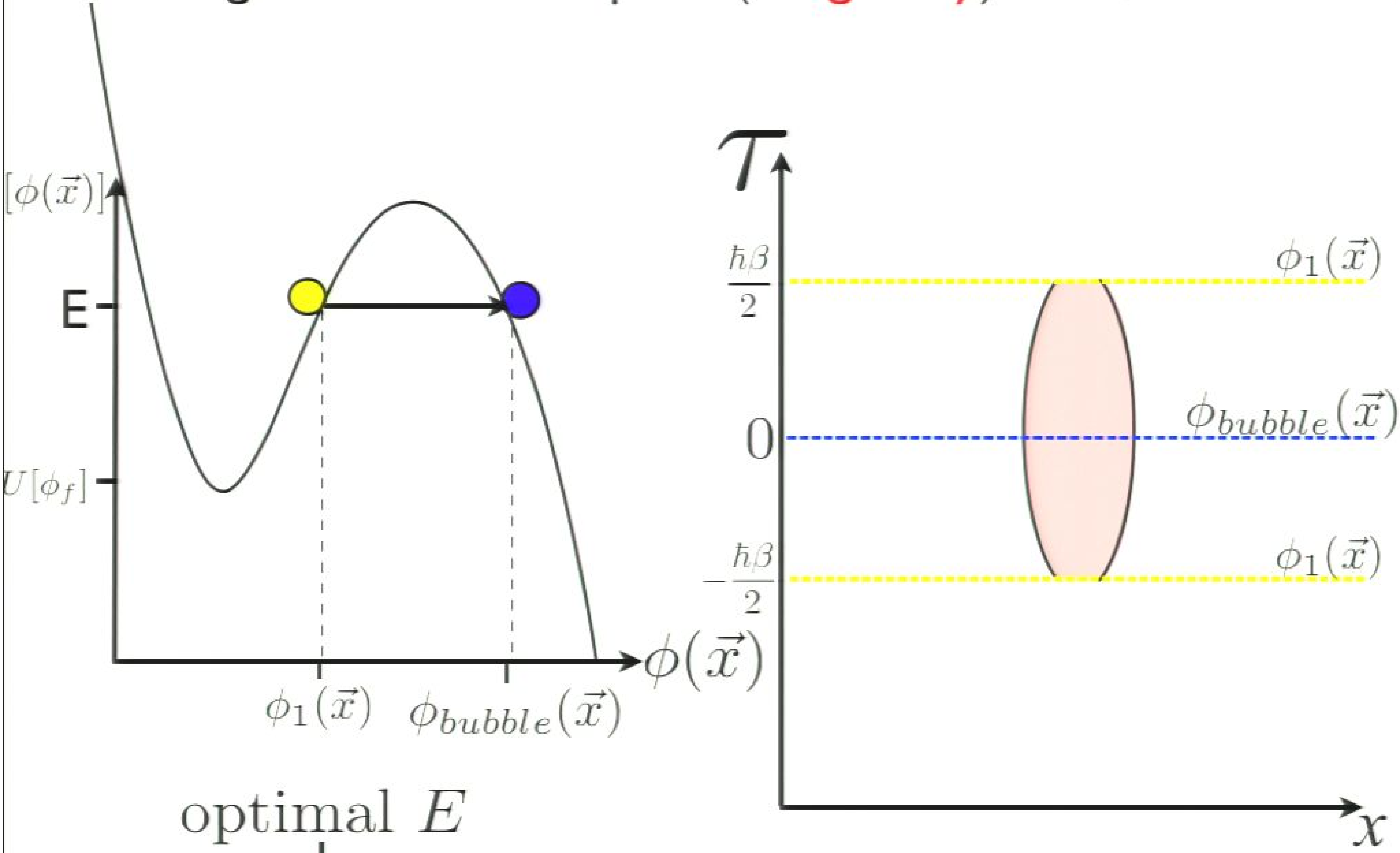
‘more’ quantum

pure quantum

Higher T
Flatter Barriers

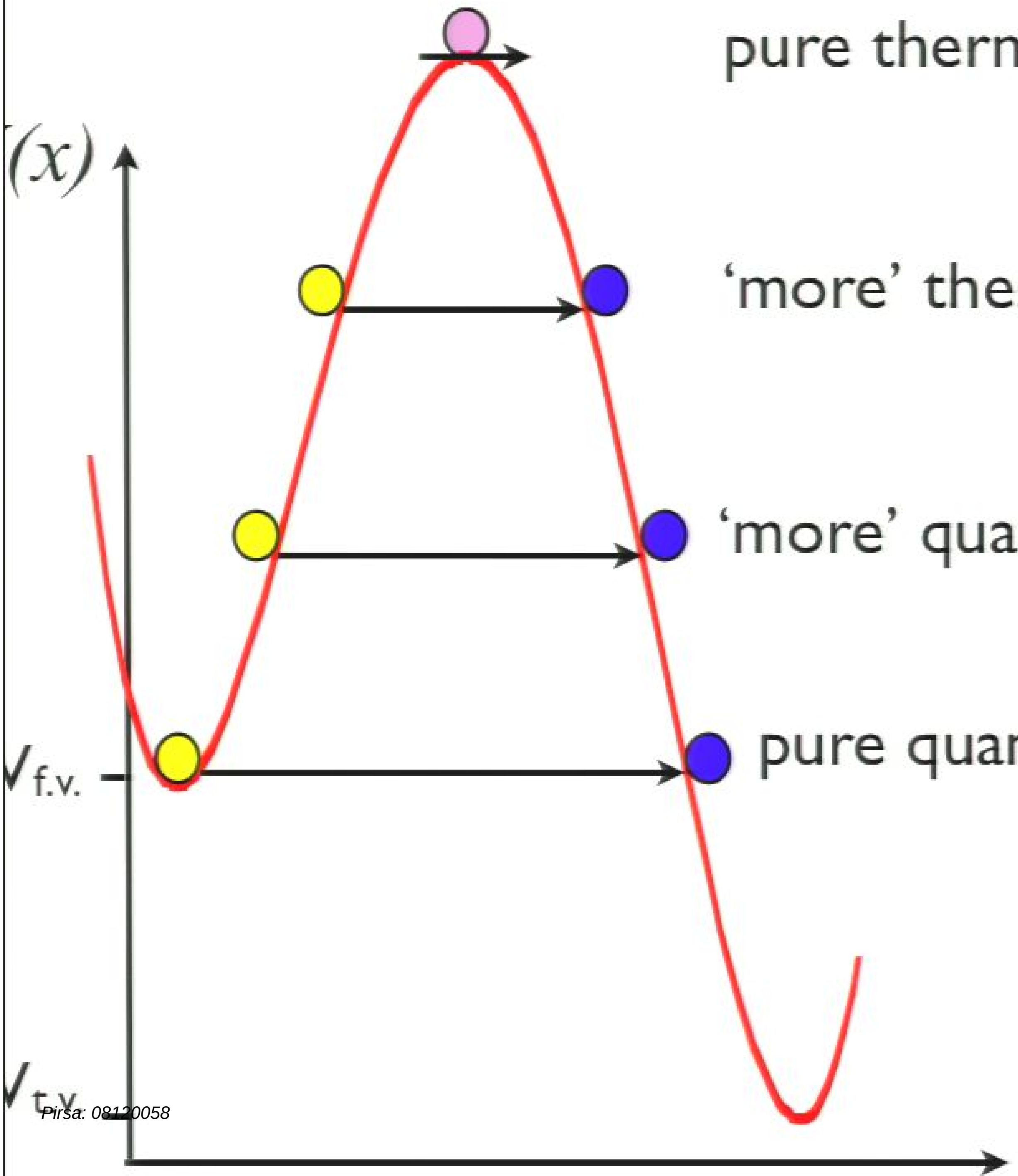
Lower T
Thinner Barriers

. Tunneling in Minkowski space (no gravity) at T ≠ 0



optimal E

↓



pure thermal

'more' thermal

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Higher T

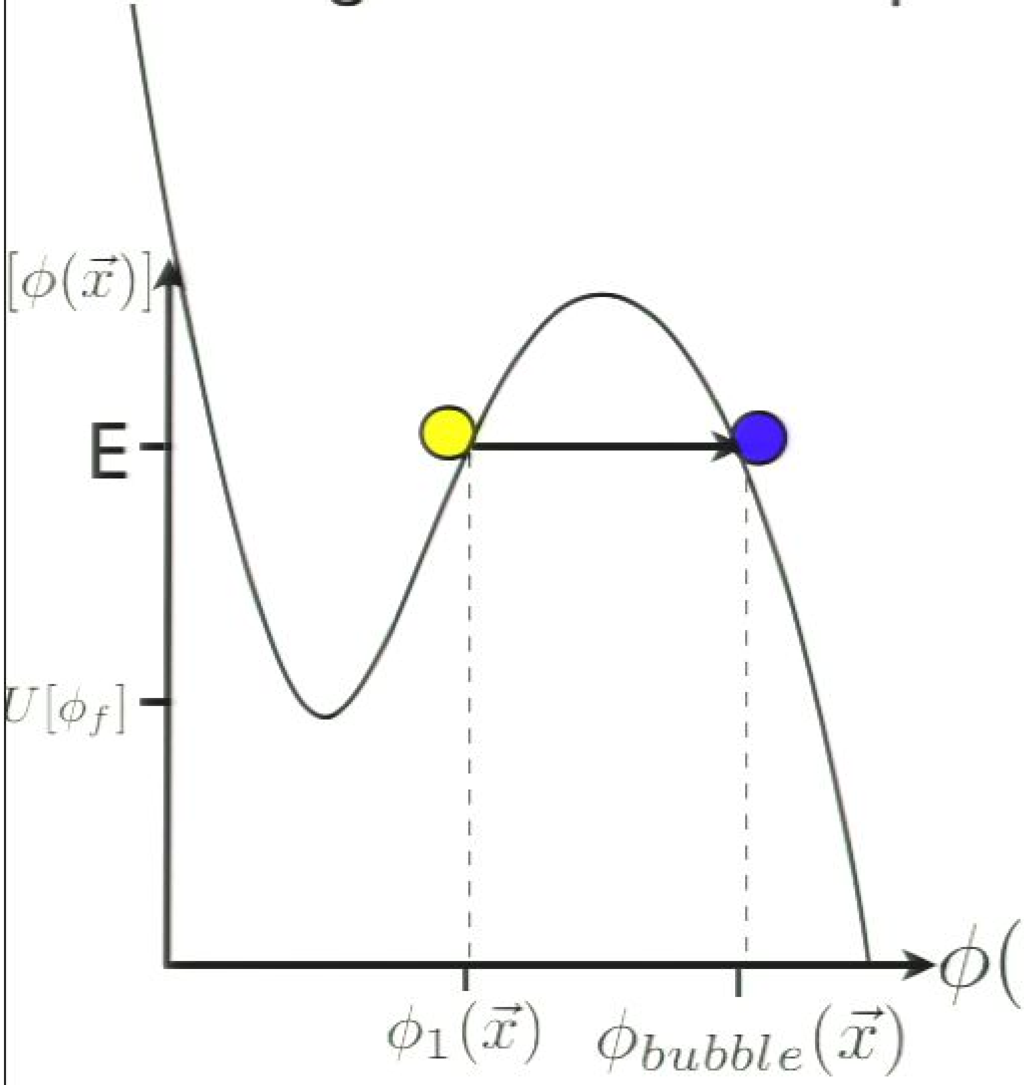
Flatter Barriers

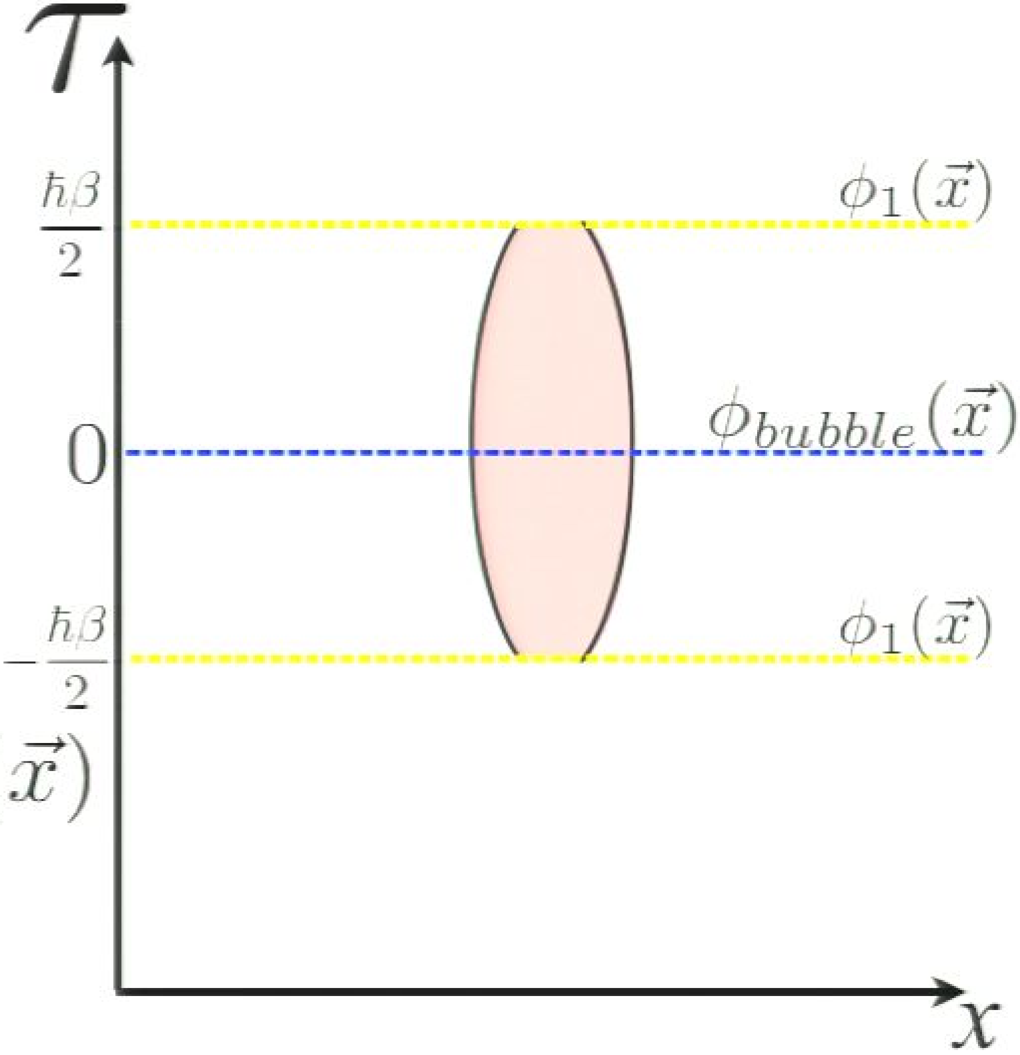
↕

Lower T

Thinner Barriers

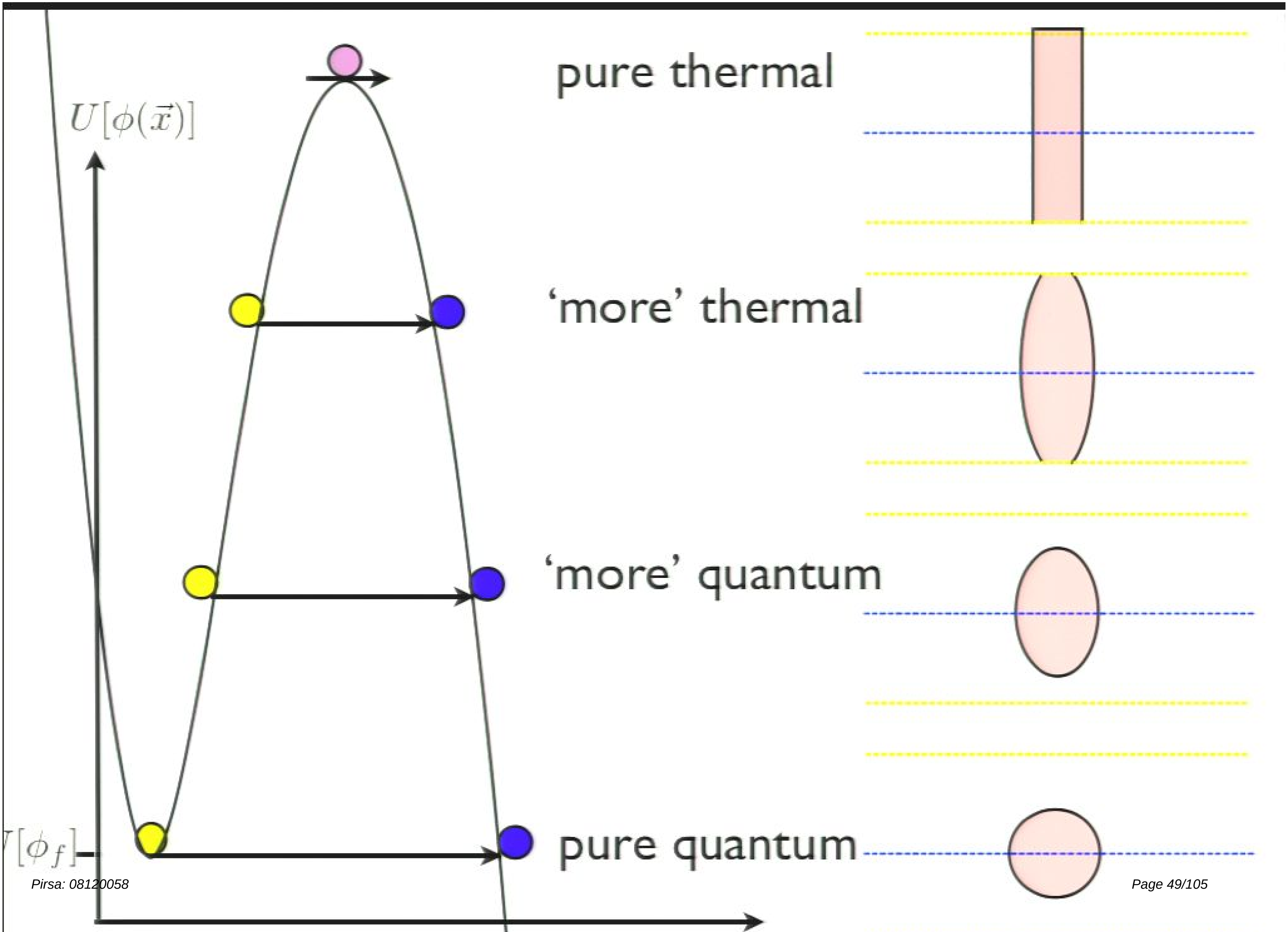
. Tunneling in Minkowski space (no gravity) at T ≠ 0





optimal E

↓



pure thermal

‘more’ thermal

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pure quantum

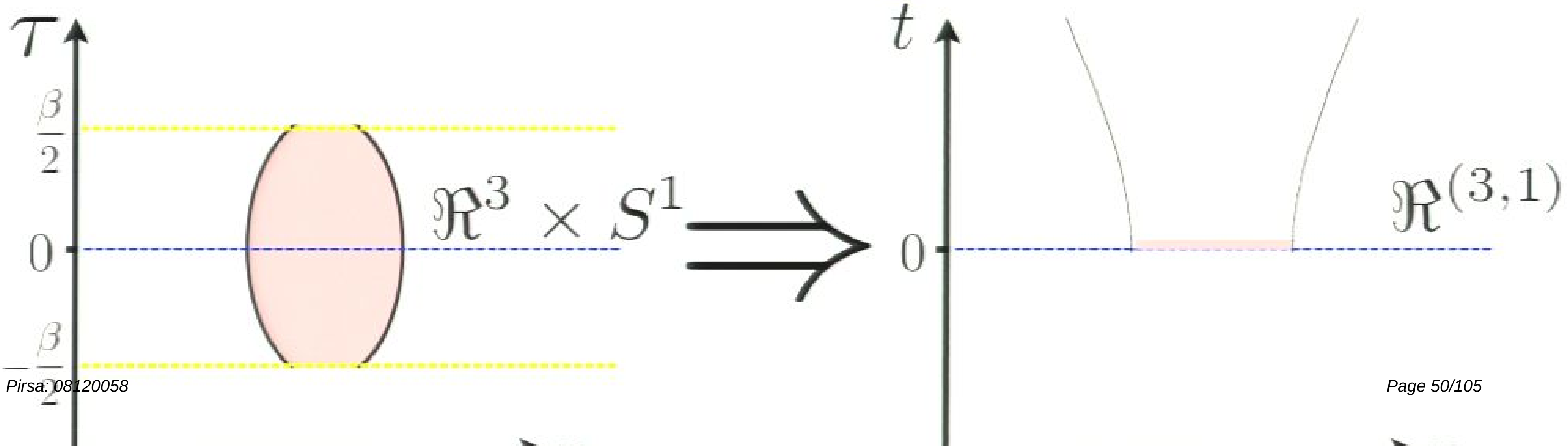
. Tunneling in Minkowski space (no gravity) at T ≠ 0

☑ Rate

$$\mathrm{Rate} \quad \sim \quad e^{-B}$$

$$B = \frac{1}{\hbar}\int_{-\frac{\hbar\beta}{2}}^{\frac{\hbar\beta}{2}} d\tau \Big(E[\phi_{\mathrm{bounce}}] - E[\phi_{\mathrm{f.v.}}] \Big)$$

☑ Initial conditions after tunneling



✓ Tunneling in Minkowski space (no gravity) at $T = 0$

- ☑ Rate
- ☑ Initial conditions after tunneling

Tunneling in Minkowski space (no gravity) at $T \neq 0$

- ☑ Rate
- ☑ Initial conditions after tunneling

Tunneling in de Sitter space (à la Coleman De Luccia)

- ☑ Rate
- ??? Initial conditions after tunneling ???

Tunneling in de Sitter space (thermal approach)

Is de Sitter decay predominantly quantum?
or predominantly thermal?

Concluding remarks

Tunneling in Minkowski space (no gravity) at $T = 0$

☑ Rate
☑ Initial conditions after tunneling

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☑ Rate
☑ Initial conditions after tunneling

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??? Initial conditions after tunneling ???

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Concluding remarks

Tunneling in de Sitter space

Including gravity:

→ $\phi[x]$ calculated on curved spacetime, possible with horizons

→ Spacetime is dynamical

Tunneling in de Sitter space

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→ ~~Spacetime is dynamical~~

FIXED BACKGROUND (de Sitter space)

Tunneling in de Sitter space

Including gravity:

→ $\phi[x]$ calculated on curved spacetime, possible with horizons

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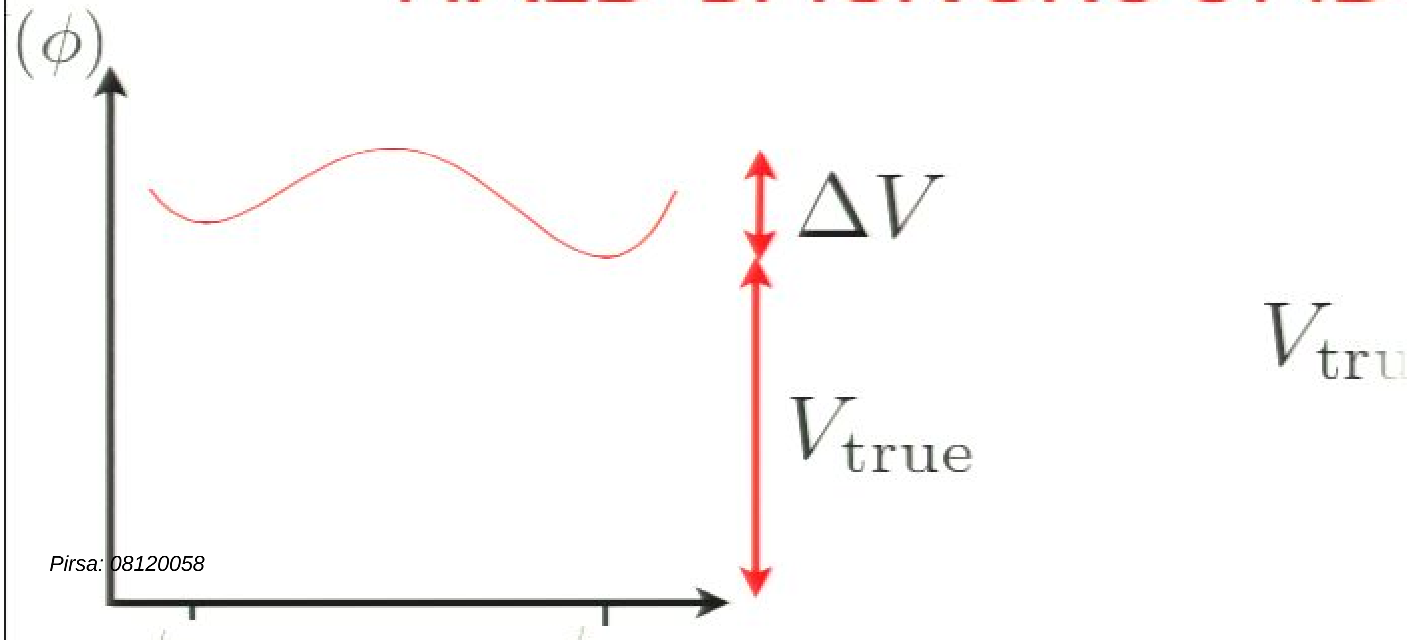
FIXED BACKGROUND (de Sitter space)



FIXED BACKGROUND (de Sitter space)

Vacuum energy density ↔ cosmological constant $H^2 = \frac{8\pi}{3} G \rho_{\text{vac}}$

$\rho_{\text{vac}} > 0$ $\Rightarrow$ de Sitter spacetime $\Rightarrow$ our past (inflation)
our future

FIXED BACKGROUND (de Sitter space)

Vacuum energy density ↔ cosmological constant $$H^2 = \frac{8\pi}{3} G \, \rho_{\rm vac}$$

$\rho_{\rm vac} > 0 \quad \Rightarrow$ de Sitter spacetime $\Rightarrow$ our past (inflation)
our future

$$ds^2 = -dt^2 + e^{2Ht} \times \Re^3$$

FIXED BACKGROUND (de Sitter space)

Vacuum energy density ↔ cosmological constant $$H^2 = \frac{8\pi}{3} G \, \rho_{\rm vac}$$

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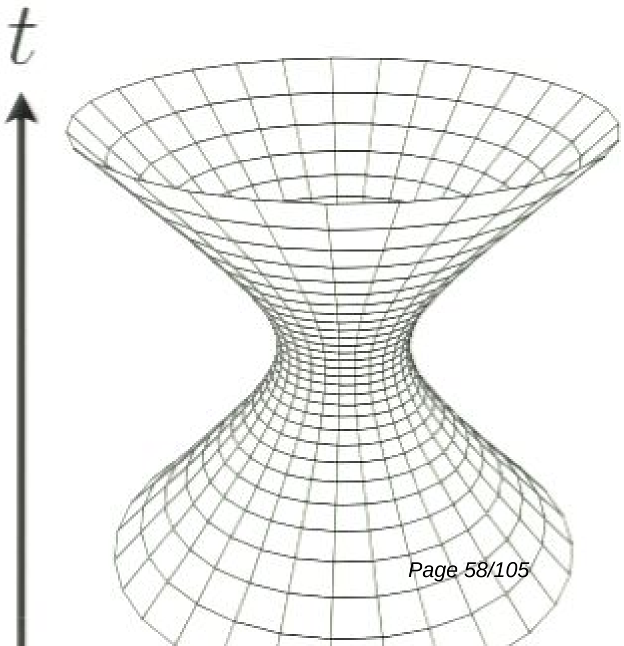
our future

$$ds^2 = -dt^2 + e^{2Ht} \times \Re^3$$

$$ds^2 = -dt^2 + \frac{\cosh^2 Ht}{H^2} \times S^3$$

"Global" de Sitter



FIXED BACKGROUND (de Sitter space)

exponential expansion

FIXED BACKGROUND (de Sitter space)

exponential expansion

↓

expansion can outrun speed of light

FIXED BACKGROUND (de Sitter space)

exponential expansion

↓

expansion can outrun speed of light

↓

$\Delta x > 2H^{-1} \rightarrow \text{non overlapping future light cones}$

"horizon"

FIXED BACKGROUND (de Sitter space)

exponential expansion

↓

expansion can outrun speed of light

↓

$\Delta x > 2H^{-1} \rightarrow$ non overlapping future light cones

"horizon"

↓

$\Delta E \Delta t \geq \frac{\hbar}{2} \quad \rightarrow$ Gibbons-Hawking temperature

$$T_{dS} = \frac{\hbar}{2\pi} H$$

Tunneling in de Sitter space

First studied by Coleman & De Luccia (=CDL)

Tunneling in de Sitter space

First studied by Coleman & De Luccia (=CDL)

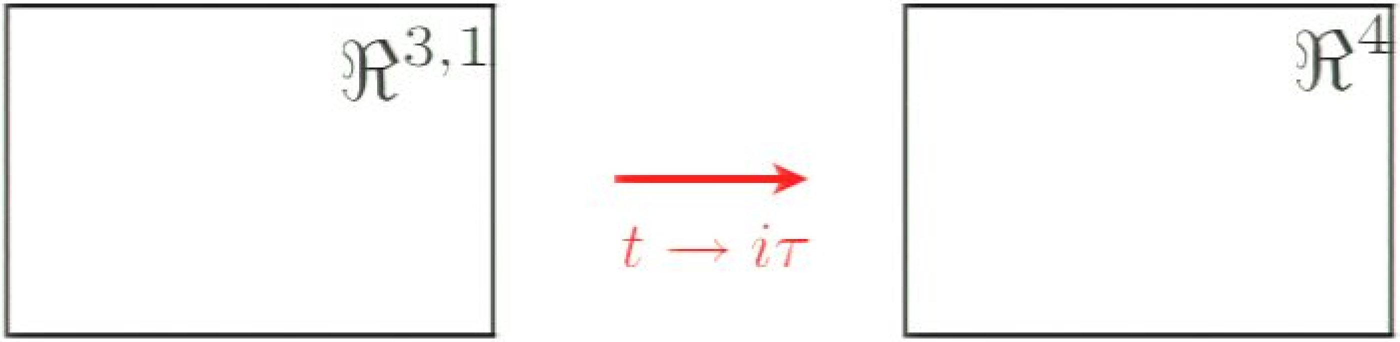
Flat
Spacetime

d

Tunneling in de Sitter space

First studied by Coleman & De Luccia (=CDL)

Flat Spacetime



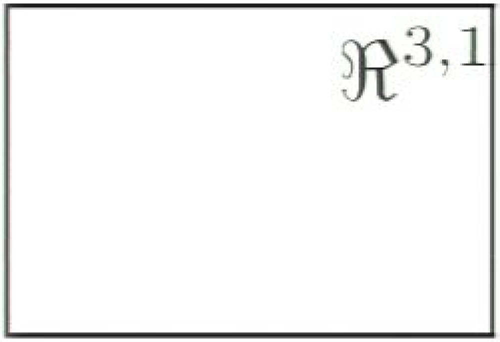
$\Re^{3,1}$ $\xrightarrow[t \to i\tau]{}$ $\Re^{4}$

$$ds^2 = -dt^2 + d\vec{x}^2 \qquad ds^2 = +d\tau^2 + d\vec{x}^2$$

Tunneling in de Sitter space

First studied by Coleman & De Luccia (=CDL)

Flat Spacetime

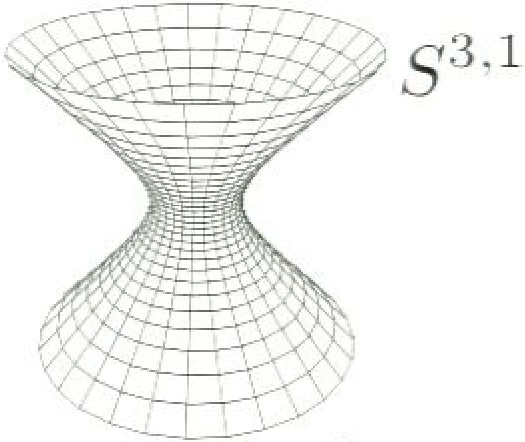


$t \rightarrow i\tau$

$$ds^2 = -dt^2 + d\vec{x}^2$$

$$ds^2 = +d\tau^2 + d\vec{x}^2$$

Curved Spacetime



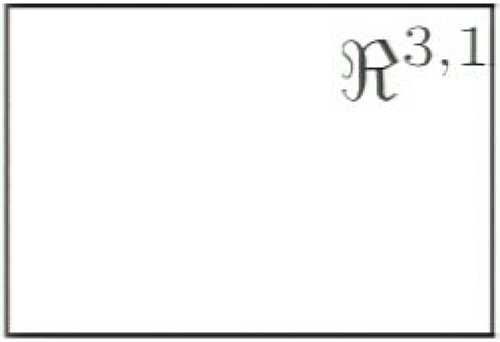
$t \rightarrow i\tau$

$$ds^2 = -dt^2 + \frac{\cosh^2 Ht}{H^2} \times S^3$$

Tunneling in de Sitter space

First studied by Coleman & De Luccia (=CDL)

Flat Spacetime



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$$ds^2 = -dt^2 + d\vec{x}^2$$

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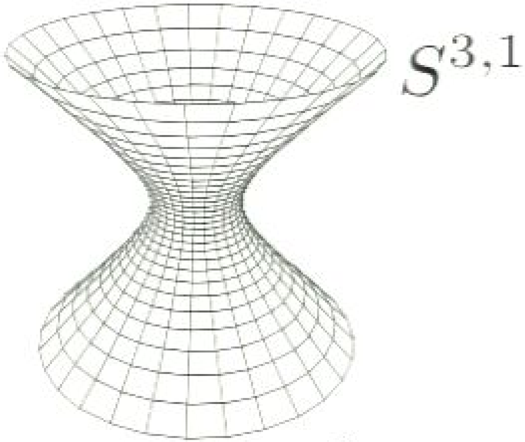
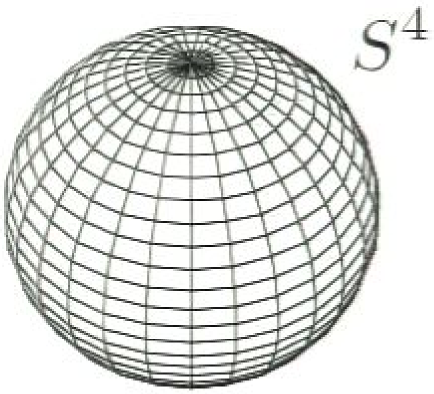
Curved Spacetime



$t \rightarrow i\tau$



$$ds^2 = -dt^2 + \frac{\cosh^2 Ht}{H^2} \times S^3$$

$$ds^2 = +d\tau^2 + \frac{\cos^2 Ht}{H^2} \times S^3$$

Tunneling in de Sitter space

☑ Rate $$\text{Rate} \quad \sim \quad e^{-B}$$

$$B = \frac{1}{\hbar}\Big[S_E(\text{bounce}) - S_E(\text{f.v.})\Big]$$

Tunneling in de Sitter space

☑ Rate

$$\text{Rate} \quad \sim \quad e^{-B}$$

$$B = \frac{1}{\hbar}\Big[S_E(\text{bounce}) - S_E(\text{f.v.})\Big]$$

$$S_E = \int d^4x \Big[\frac{1}{2}(\partial_\mu \phi(x))^2 + V(\phi)\Big]$$

Tunneling in de Sitter space

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$$\Big\downarrow \quad \Big\downarrow \quad \Big\downarrow \quad \Big\downarrow \quad \Big\downarrow \quad \Big\downarrow \quad \Big\downarrow \quad \Big\downarrow \quad \Big\downarrow \quad \Big\downarrow$$

$$S_E = \int d^4x \underset{\uparrow}{\sqrt{g}} \Big[\frac{1}{2}(\partial_\mu \phi(x))^2 + V(\phi) + \underset{\uparrow}{R}\Big]$$

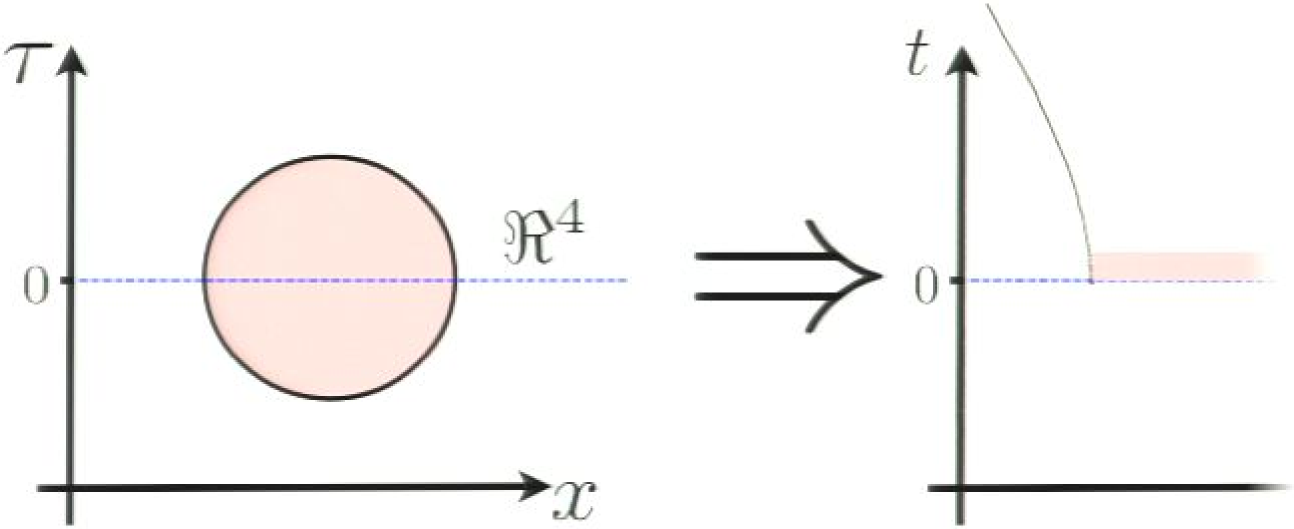
Tunneling in de Sitter space

??? Initial conditions after tunneling ???

Tunneling in de Sitter space

??? Initial conditions after tunneling ???

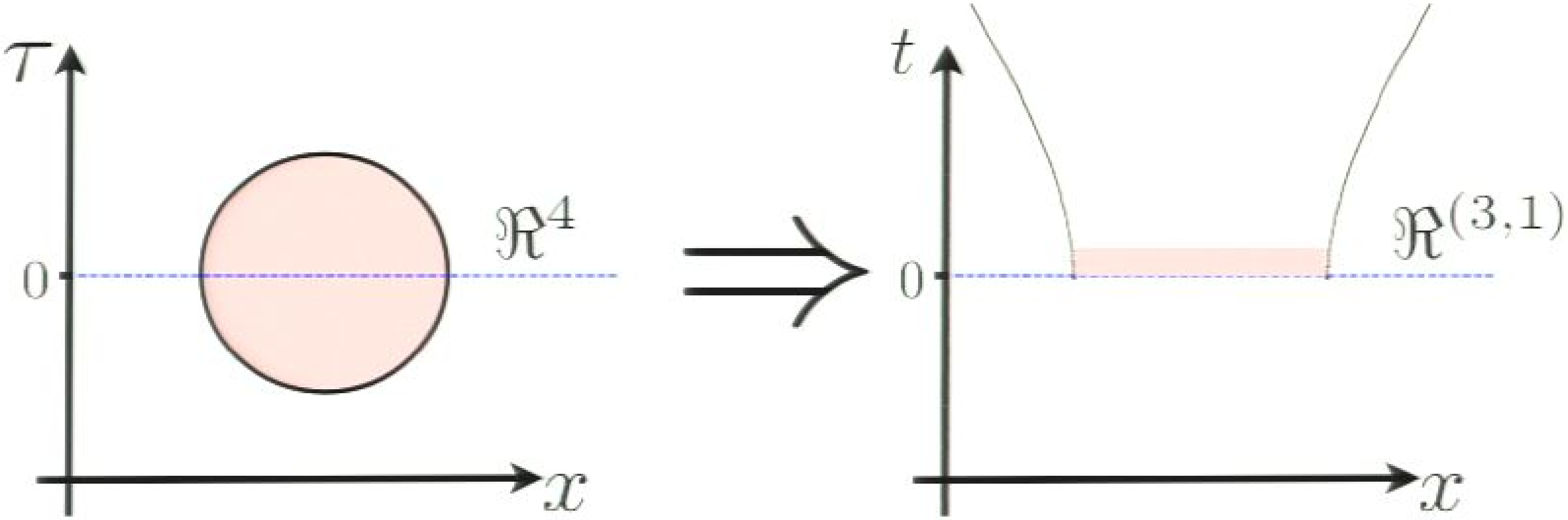
Flat Spacetime



Tunneling in de Sitter space

??? Initial conditions after tunneling ???

Flat Spacetime

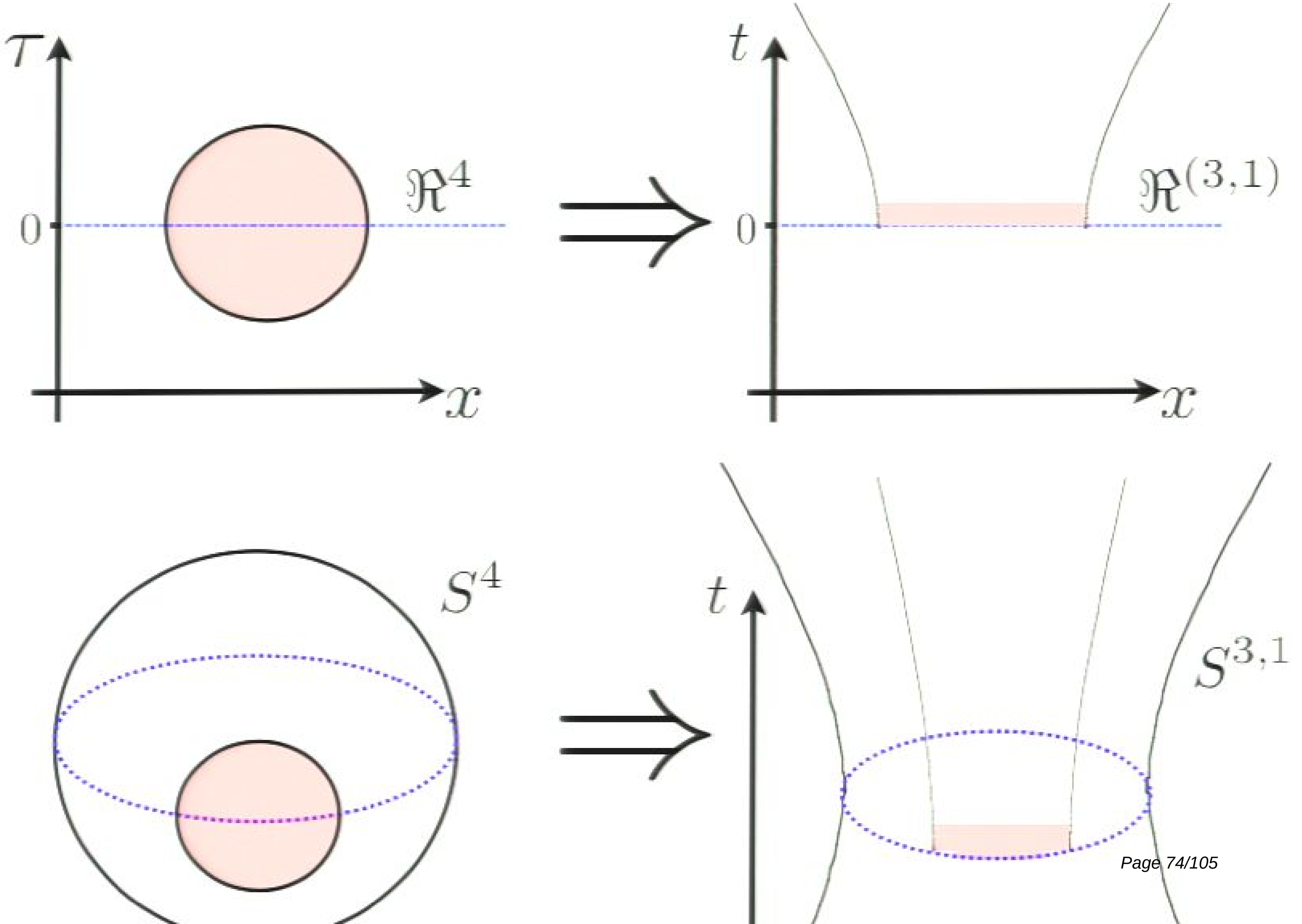


Tunneling in de Sitter space

??? Initial conditions after tunneling ???

Flat Spacetime

Curved Spacetime



Tunneling in de Sitter space

☑ Rate

&

??? Initial conditions after tunneling ???

reduce correctly to Minkowski result as $G \longrightarrow 0$

but no derivation ...

✓ Tunneling in Minkowski space (no gravity) at T = 0

- ☑ Rate
- ☑ Initial conditions after tunneling

✓ Tunneling in Minkowski space (no gravity) at $T \neq 0$

- ☑ Rate
- ☑ Initial conditions after tunneling

Tunneling in de Sitter space (à la Coleman De Luccia)

- ☑ Rate
- ??? Initial conditions after tunneling ???

Tunneling in de Sitter space (thermal approach)

Is de Sitter decay predominantly quantum?
or predominantly thermal?

Concluding remarks

✓ Tunneling in Minkowski space (no gravity) at $T = 0$

- ☑ Rate
- ☑ Initial conditions after tunneling

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- ☑ Rate
- ??? Initial conditions after tunneling ???

Tunneling in de Sitter space (thermal approach)

Is de Sitter decay predominantly quantum?
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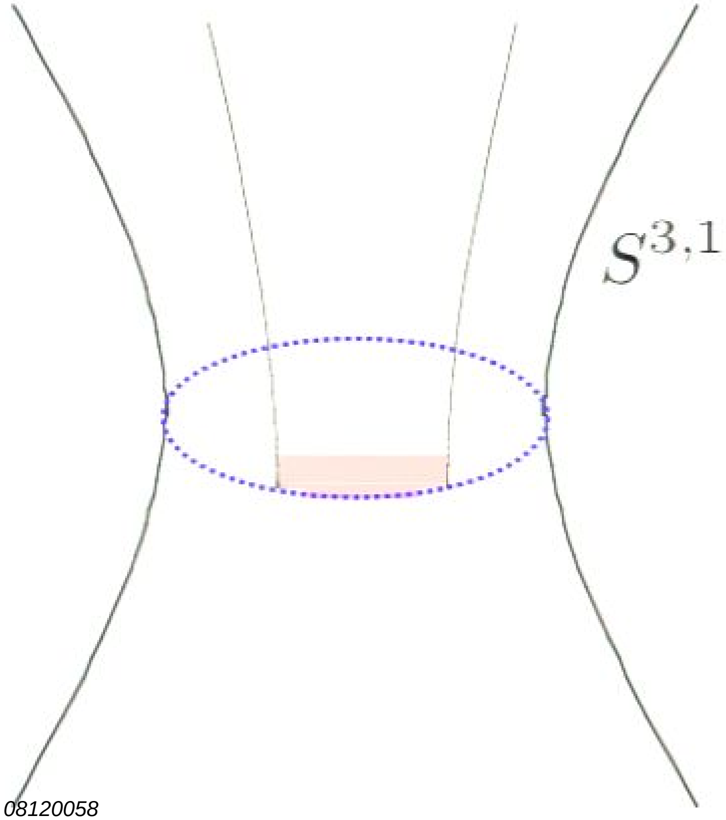
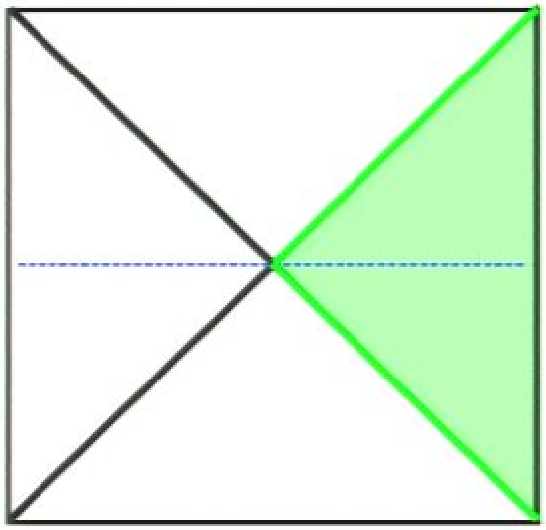
Concluding remarks

Why the question marks about initial conditions???

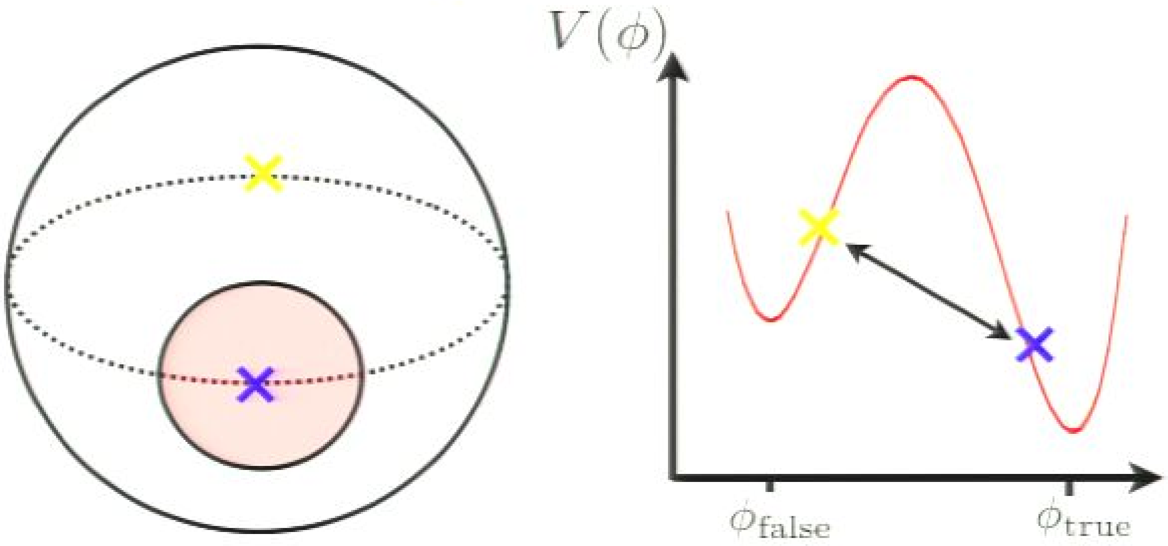
Global structure (universe is not de Sitter!)

Horizon complementarity

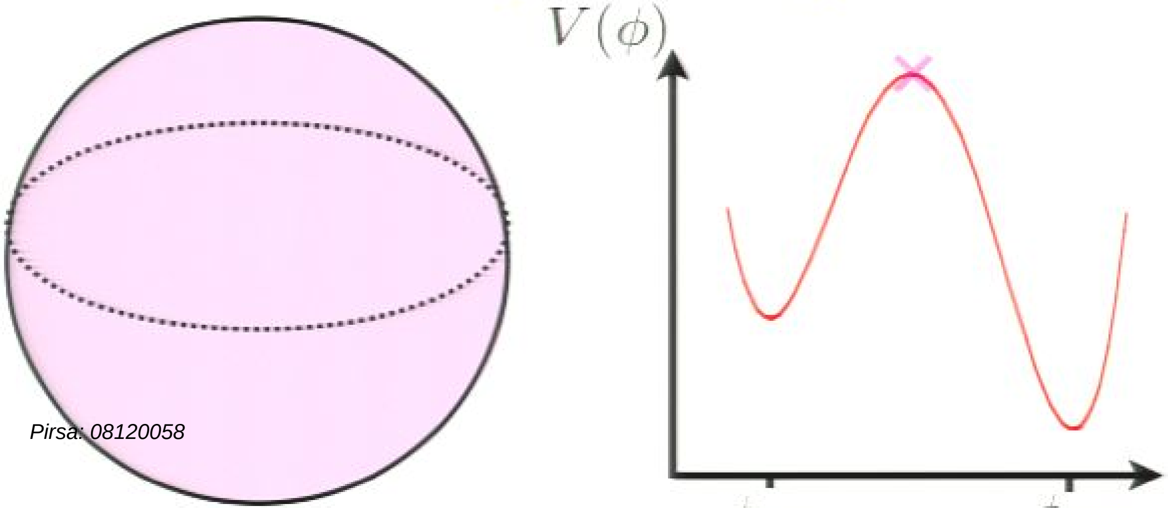




$\phi(x) \neq \phi_{false}$



Sometimes only Hawking Moss.



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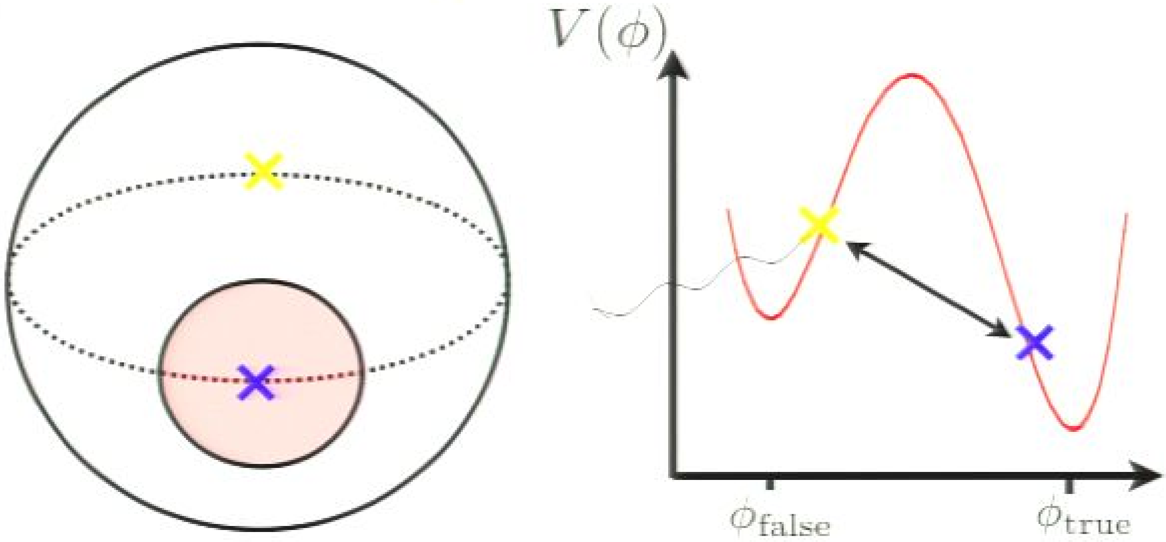

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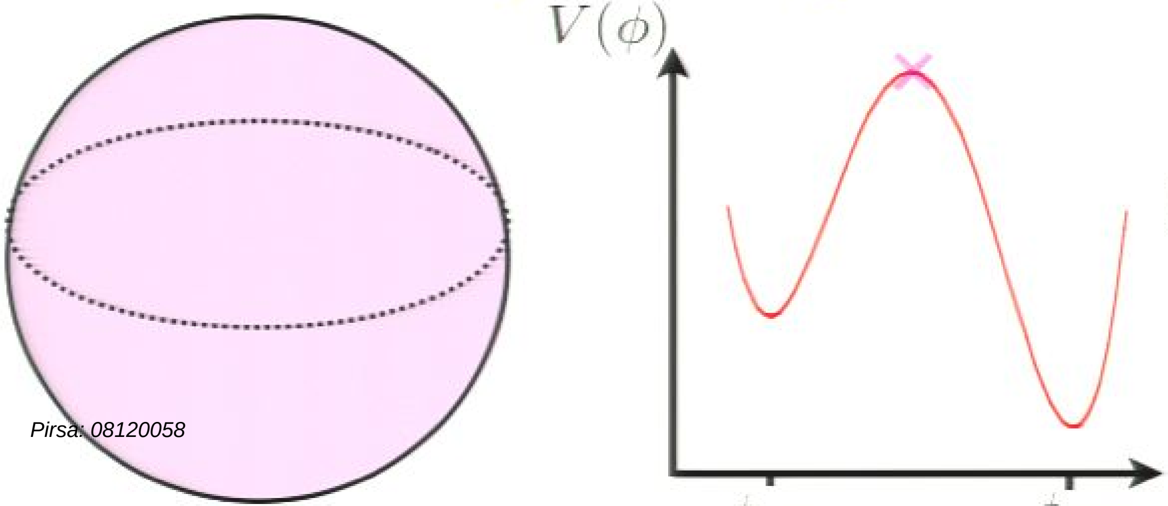
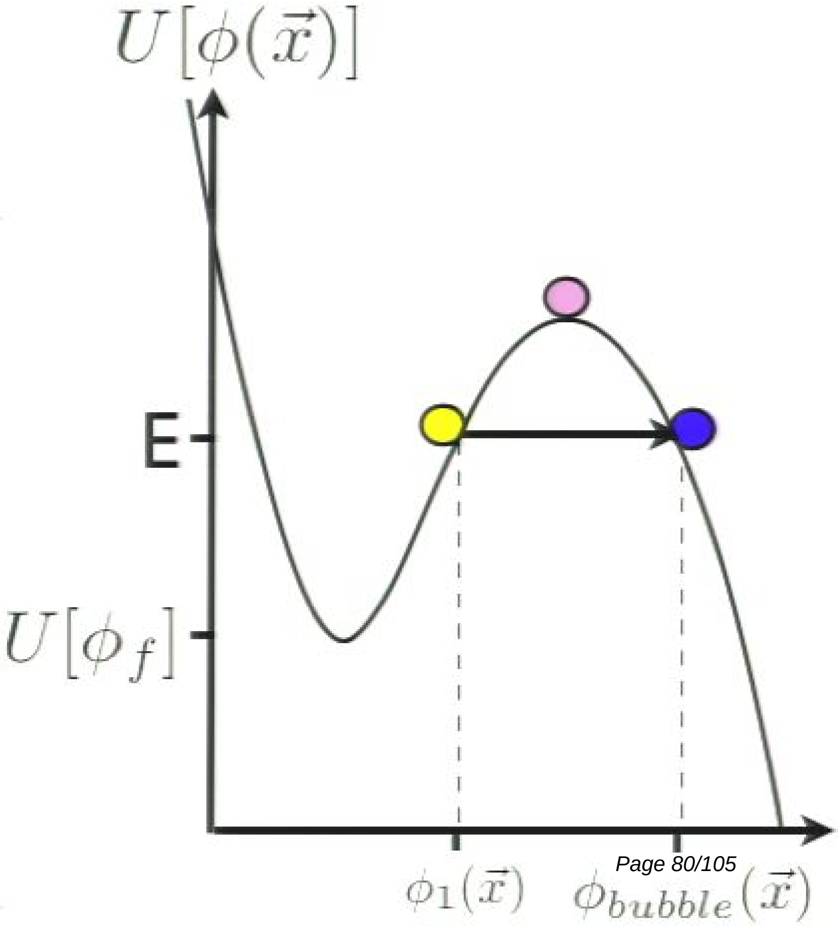


Thermal Interpretation



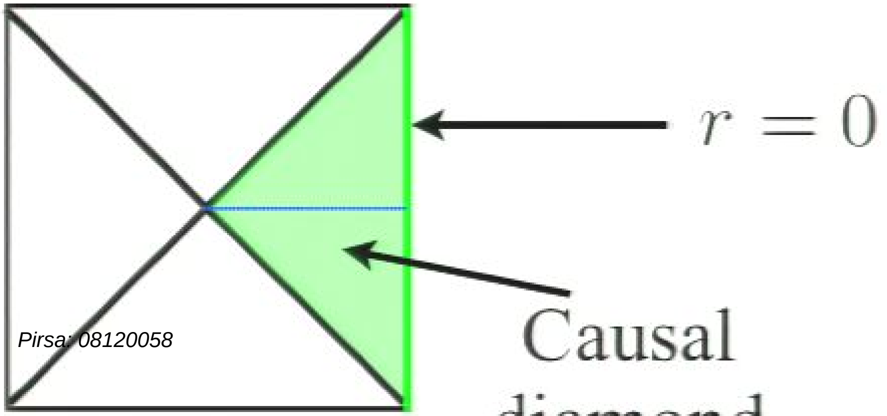
. Tunneling in de Sitter space (thermal approach)

Treat a single horizon volume as a thermal system
at the de Sitter temperature

tatic de Sitter coordinates $\Lambda \equiv H^{-1}$

$$ds^2 = -\underbrace{\left(1 - \frac{r^2}{\Lambda^2}\right)}_{A(r)} dt^2 + \underbrace{\left(1 - \frac{r^2}{\Lambda^2}\right)^{-1} dr^2 + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)}_{h_{ij}}$$

constant t slices are $\frac{1}{2}S^3$



horizon of
$r = 0$
is
$r = \Lambda$
(an S^2)

Treat a single horizon volume as a thermal system at the de Sitter temperature ← $\frac{\hbar}{2\pi\Lambda}$

$$ds^2 = -\underbrace{\left(1 - \frac{r^2}{\Lambda^2}\right)}_{A(r)} dt^2 + \underbrace{\left(1 - \frac{r^2}{\Lambda^2}\right)^{-1} dr^2 + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)}_{h_{ij}}$$

Treat a single horizon volume as a thermal system at the de Sitter temperature

$$\frac{\hbar}{2\pi\Lambda}$$

$$ds^2 = -\underbrace{\left(1-\frac{r^2}{\Lambda^2}\right)}_{A(r)} dt^2 + \underbrace{\left(1-\frac{r^2}{\Lambda^2}\right)^{-1} dr^2 + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)}_{h_{ij}}$$

$$\begin{aligned} S &= \int dt \int_{r\,\leq\,\Lambda} d^3x \sqrt{A}\sqrt{\det h}\left[\frac{1}{2}\frac{1}{A(r)}\left(\frac{d\phi}{dt}\right)^2 - \frac{1}{2}h^{ij}\partial_i\phi\partial_j\phi - V(\phi)\right] \\ &= \int dt\, L \end{aligned}$$

Treat a single horizon volume as a thermal system at the de Sitter temperature

$$\frac{\hbar}{2\pi\Lambda}$$

$$ds^2 = -\underbrace{\left(1-\frac{r^2}{\Lambda^2}\right)}_{A(r)} dt^2 + \underbrace{\left(1-\frac{r^2}{\Lambda^2}\right)^{-1} dr^2 + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)}_{h_{ij}}$$

$$S = \int dt \int_{r\,\leq\,\Lambda} d^3x \sqrt{A}\sqrt{\det h}\left[\frac{1}{2}\frac{1}{A(r)}\left(\frac{d\phi}{dt}\right)^2 - \frac{1}{2}h^{ij}\partial_i\phi\partial_j\phi - V(\phi)\right]$$

$$= \int dt\, L$$

$$E[\phi] = \int_{r\leq\Lambda} d^3x\sqrt{\det h}\left[\frac{1}{2\sqrt{A(r)}}\left(\frac{d\phi}{dt}\right)^2 + \frac{1}{2}\sqrt{A(r)}h^{ij}\partial_i\phi\partial_j\phi + \underset{\uparrow}{\sqrt{A(r)}}V(\phi)\right]$$

'redshift' factor

Treat a single horizon volume as a thermal system at the de Sitter temperature $\longleftarrow \frac{\hbar}{2\pi\Lambda}$

$$ds^2 = -\underbrace{\left(1-\frac{r^2}{\Lambda^2}\right)}_{A(r)} dt^2 + \underbrace{\left(1-\frac{r^2}{\Lambda^2}\right)^{-1} dr^2 + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)}_{h_{ij}}$$

$$E[\phi] = \int_{r\leq\Lambda} d^3x\sqrt{\det h}\left[\frac{1}{2\sqrt{A(r)}}\left(\frac{d\phi}{dt}\right)^2 + \frac{1}{2}\sqrt{A(r)}h^{ij}\partial_i\phi\partial_j\phi + \underset{\uparrow}{\sqrt{A(r)}}V(\phi)\right]$$

'redshift' factor

Treat a single horizon volume as a thermal system at the de Sitter temperature

$$\frac{\hbar}{2\pi\Lambda}$$

$$ds^2 = -\underbrace{\left(1-\frac{r^2}{\Lambda^2}\right)}_{A(r)} dt^2 + \underbrace{\left(1-\frac{r^2}{\Lambda^2}\right)^{-1} dr^2 + r^2\left(d\theta^2+\sin^2\theta\, d\phi^2\right)}_{h_{ij}}$$

$$E[\phi] = \int_{r\leq\Lambda} d^3x\sqrt{\det h}\left[\frac{1}{2\sqrt{A(r)}}\left(\frac{d\phi}{dt}\right)^2 + \frac{1}{2}\sqrt{A(r)}h^{ij}\partial_i\phi\partial_j\phi + \underset{\uparrow}{\sqrt{A(r)}}V(\phi)\right]$$

‘redshift’ factor

$$\text{rate} \sim e^{-B}$$

$$B_{\text{classical thermal}} = \beta\Big(E(\phi_{\text{top}}) - E(\phi_{\text{f.v.}})\Big)$$

Treat a single horizon volume as a thermal system at the de Sitter temperature ← $\frac{\hbar}{2\pi\Lambda}$

$$ds^2 = -\underbrace{\left(1-\frac{r^2}{\Lambda^2}\right)}_{A(r)} dt^2 + \underbrace{\left(1-\frac{r^2}{\Lambda^2}\right)^{-1} dr^2 + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)}_{h_{ij}}$$

$$E[\phi] = \int_{r\leq\Lambda} d^3x\sqrt{\det h}\left[\frac{1}{2\sqrt{A(r)}}\left(\frac{d\phi}{dt}\right)^2 + \frac{1}{2}\sqrt{A(r)}h^{ij}\partial_i\phi\partial_j\phi + \underset{\uparrow}{\sqrt{A(r)}}V(\phi)\right]$$

'redshift' factor

$$\text{rate} \sim e^{-B}$$

$$B_{\text{classical thermal}} = \beta\Big(E(\phi_{\text{top}}) - E(\phi_{\text{f.v.}})\Big)$$

$$B_{\text{quantum thermal}} = \frac{1}{\hbar}\int_{\hbar\beta}^{\frac{\hbar\beta}{2}} d\tau\Big(E(\phi_{\text{bounce}}) - E(\phi_{\text{f.v.}})\Big)$$

$$B = \frac{1}{\hbar}\int_{-\pi\Lambda}^{\pi\Lambda}\int_{r\leq\Lambda} d\tau d^3x\sqrt{\det h}\Bigg[\frac{1}{2\sqrt{A(r)}}\left(\frac{d\phi}{d\tau}\right)^2 + \\ +\frac{1}{2}\sqrt{A(r)}h^{ij}\partial_i\phi\partial_j\phi + \sqrt{A(r)}\Big(V(\phi) - V(\phi_{\mathrm{f.v.}})\Big)\Bigg]$$

$$B = \frac{1}{\hbar}\int_{-\pi\Lambda}^{\pi\Lambda}\int_{r\leq\Lambda} d\tau d^3x\sqrt{\det h}\Big[\frac{1}{2\sqrt{A(r)}}\Big(\frac{d\phi}{d\tau}\Big)^2 + \\ +\frac{1}{2}\sqrt{A(r)}h^{ij}\partial_i\phi\partial_j\phi + \sqrt{A(r)}\Big(V(\phi) - V(\phi_{\mathrm{f.v.}})\Big)\Big]$$

→ Compare to CDL prescription

$$\begin{aligned} y^1 &= \tilde{r}\sin\theta\cos\phi \\ y^2 &= \tilde{r}\sin\theta\sin\phi \\ y^3 &= \tilde{r}\cos\theta \\ y^4 &= \sqrt{\Lambda^2 - \tilde{r}^2}\cos(\tilde{\tau}/\Lambda \\ y^5 &= \sqrt{\Lambda^2 - \tilde{r}^2}\sin(\tilde{\tau}/\Lambda) \end{aligned}$$

$$ds^2 = (1 - \frac{\tilde{r}^2}{\Lambda^2})d\tilde{\tau}^2 + \frac{d\tilde{r}^2}{1 - \frac{\tilde{r}^2}{\Lambda^2}} + \tilde{r}^2 d\theta^2 + \tilde{r}^2\sin^2\theta d\phi^2$$

$$B = \frac{1}{\hbar}\int_{-\pi\Lambda}^{\pi\Lambda}\int_{r\leq\Lambda} d\tau d^3x\sqrt{\det h}\Big[\frac{1}{2\sqrt{A(r)}}\Big(\frac{d\phi}{d\tau}\Big)^2 + \\ +\frac{1}{2}\sqrt{A(r)}h^{ij}\partial_i\phi\partial_j\phi + \sqrt{A(r)}\Big(V(\phi) - V(\phi_{\text{f.v.}})\Big)\Big]$$

$\longrightarrow$ Compare to CDL prescription

$$\begin{aligned} y^1 &= \tilde r \sin\theta\cos\phi \\ y^2 &= \tilde r\sin\theta\sin\phi \\ y^3 &= \tilde r\cos\theta \\ y^4 &= \sqrt{\Lambda^2 - \tilde r^2}\cos(\tilde\tau/\Lambda \\ y^5 &= \sqrt{\Lambda^2-\tilde r^2}\sin(\tilde\tau/\Lambda) \end{aligned}$$

$$ds^2 = (1 - \frac{\tilde r^2}{\Lambda^2})d\tilde\tau^2 + \frac{d\tilde r^2}{1-\frac{\tilde r^2}{\Lambda^2}} + \tilde r^2 d\theta^2 + \tilde r^2\sin^2\theta d\phi^2$$

$$\downarrow$$

$$CDL = \int^{\pi\Lambda}\int d\tilde\tau d^3\tilde x\sqrt{A(\tilde r)\det h}\Big[\frac{1}{2A(\tilde r)}\Big(\frac{d\phi}{d\tilde\tau}\Big)^2 + \frac{1}{2}h^{ij}\partial_i\phi\partial_j\phi + \Big(V(\phi) - V(\phi_{\text{f.v.}})\Big)\Big]$$

$$B = \frac{1}{\hbar}\int_{-\pi\Lambda}^{\pi\Lambda}\int_{r\leq\Lambda} d\tau d^3x\sqrt{\det h}\Big[\frac{1}{2\sqrt{A(r)}}\Big(\frac{d\phi}{d\tau}\Big)^2 +$$
$$+\frac{1}{2}\sqrt{A(r)}h^{ij}\partial_i\phi\partial_j\phi + \sqrt{A(r)}\Big(V(\phi) - V(\phi_{\text{f.v.}})\Big)\Big]$$

→ Compare to CDL prescription

$$\begin{aligned} y^1 &= \tilde{r}\sin\theta\cos\phi \\ y^2 &= \tilde{r}\sin\theta\sin\phi \\ y^3 &= \tilde{r}\cos\theta \\ y^4 &= \sqrt{\Lambda^2 - \tilde{r}^2}\cos(\tilde{\tau}/\Lambda \\ y^5 &= \sqrt{\Lambda^2 - \tilde{r}^2}\sin(\tilde{\tau}/\Lambda) \end{aligned}$$

Rate same as CDL

$$ds^2 = (1 - \frac{\tilde{r}^2}{\Lambda^2})d\tilde{\tau}^2 + \frac{d\tilde{r}^2}{1 - \frac{\tilde{r}^2}{\Lambda^2}} + \tilde{r}^2 d\theta^2 + \tilde{r}^2\sin^2\theta d\phi^2$$

↓

$${}_{CDL} = \int^{\pi\Lambda}\int d\tilde{\tau}d^3\tilde{x}\sqrt{A(\tilde{r})\det h}\Big[\frac{1}{2A(\tilde{r})}\Big(\frac{d\phi}{d\tilde{\tau}}\Big)^2 + \frac{1}{2}h^{ij}\partial_i\phi\partial_j\phi + \Big(V(\phi) - V(\phi_{\text{f.v.}})\Big)\Big]$$

By treating the degrees of freedom in a

single horizon volume

as a

thermal system

at the

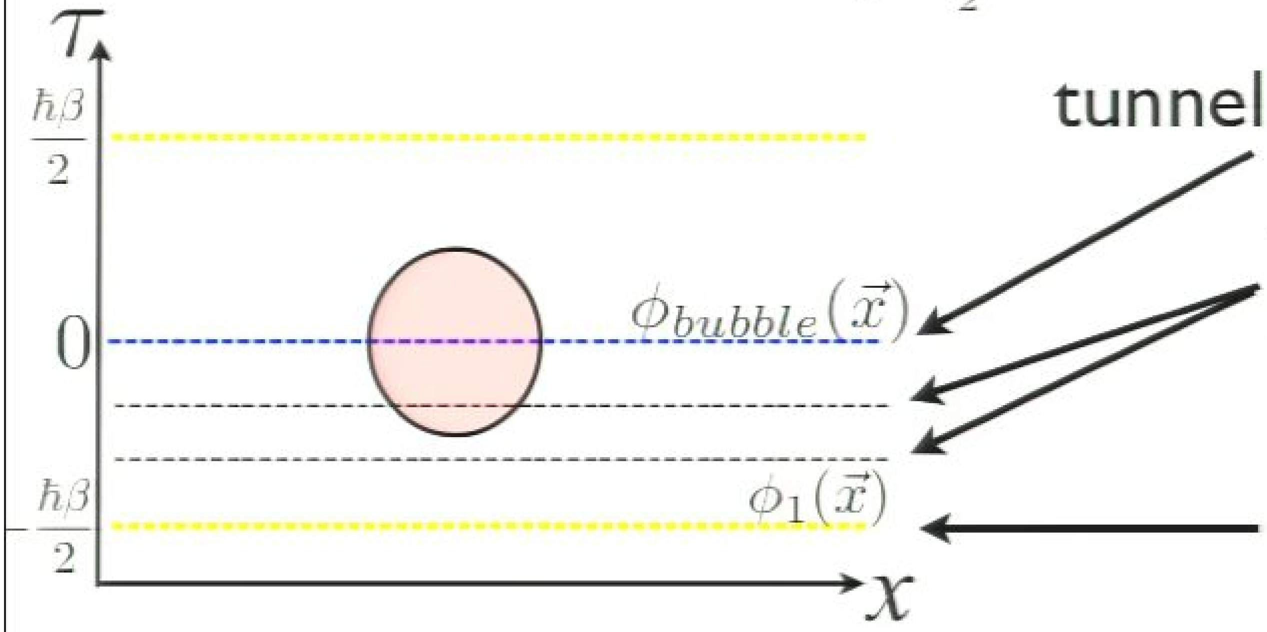
de Sitter temperature

can recover

CDL rate

☑ Rate

$$B_{\text{quantum thermal}} = \frac{1}{\hbar}\int_{-\frac{\hbar\beta}{2}}^{\frac{\hbar\beta}{2}} d\tau\Big(E(\phi_{\text{bounce}}) - E(\phi_{\text{f.v.}})\Big)$$

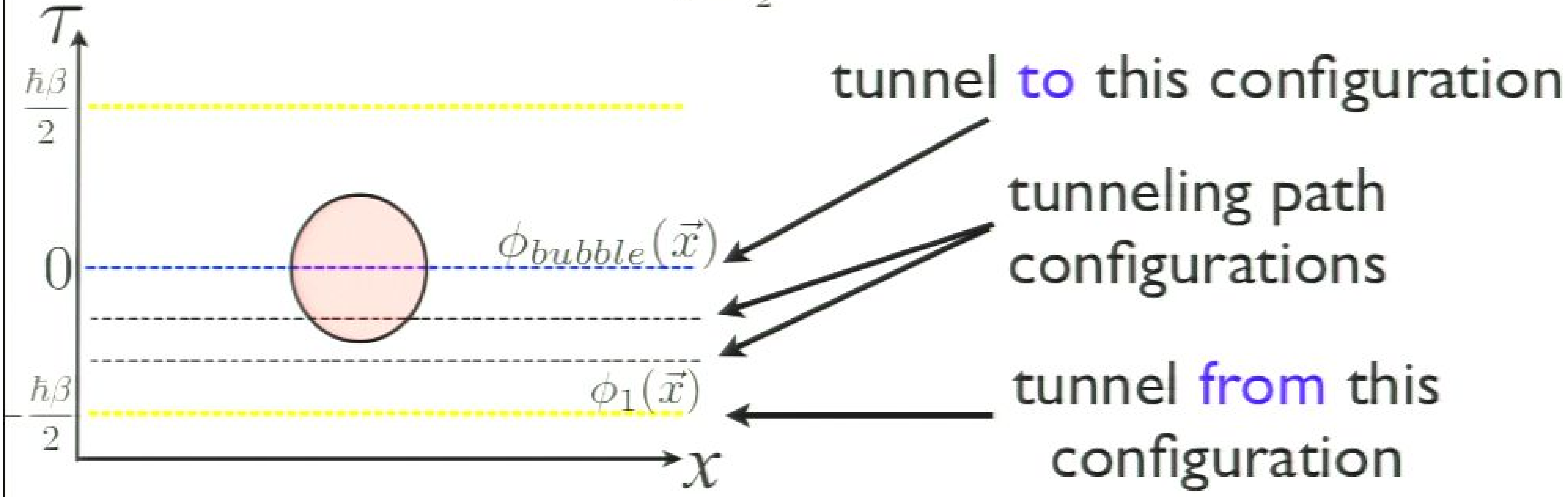


tunnel to this configuration

tunneling path configurations

tunnel from this configuration

$$B_{\text{quantum thermal}} = \frac{1}{\hbar}\int_{-\frac{\hbar\beta}{2}}^{\frac{\hbar\beta}{2}} d\tau \Big(E(\phi_{\text{bounce}}) - E(\phi_{\text{f.v.}}) \Big)$$



tunnel to this configuration

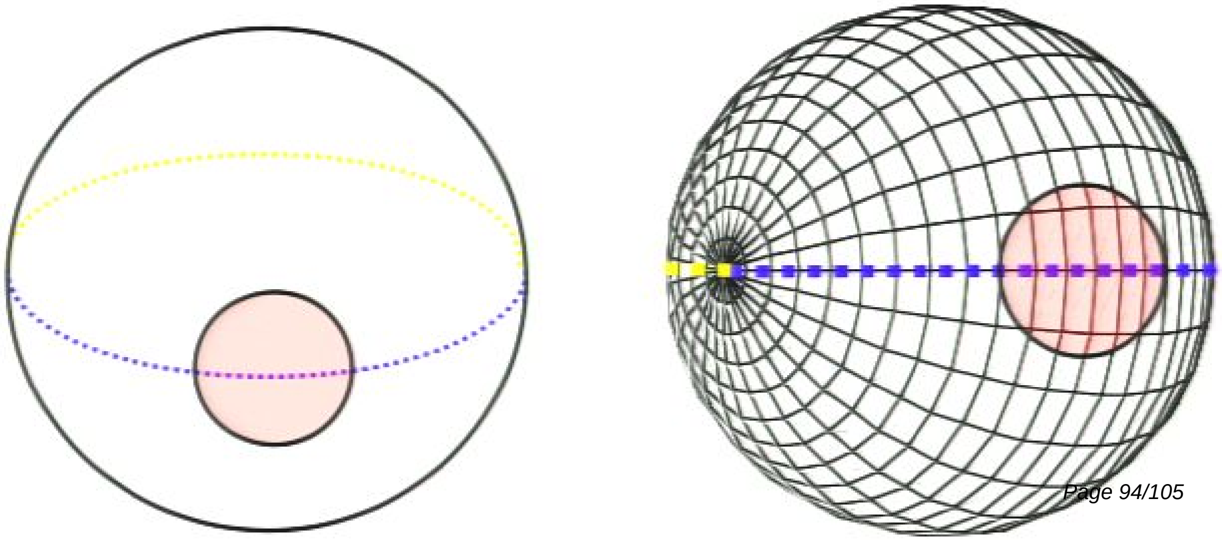
tunneling path configurations

tunnel from this configuration

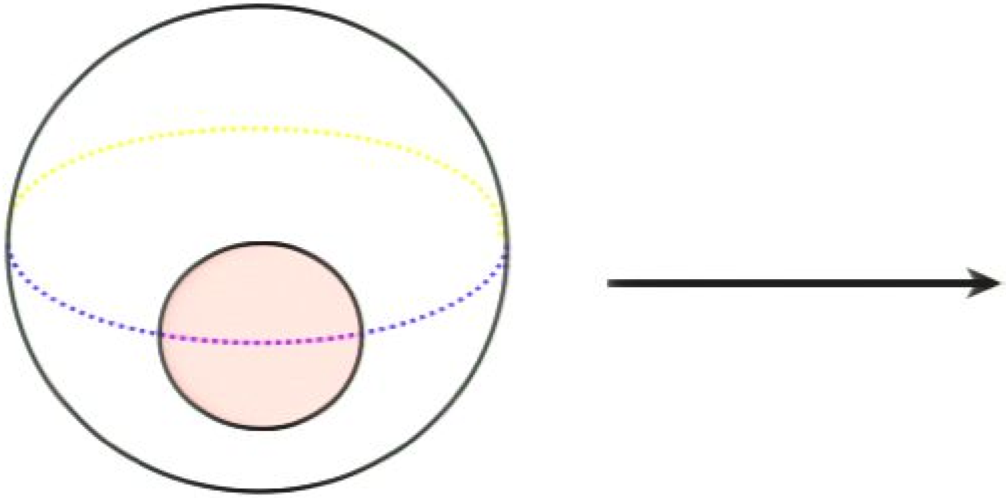
onstant τ surfaces become meridians

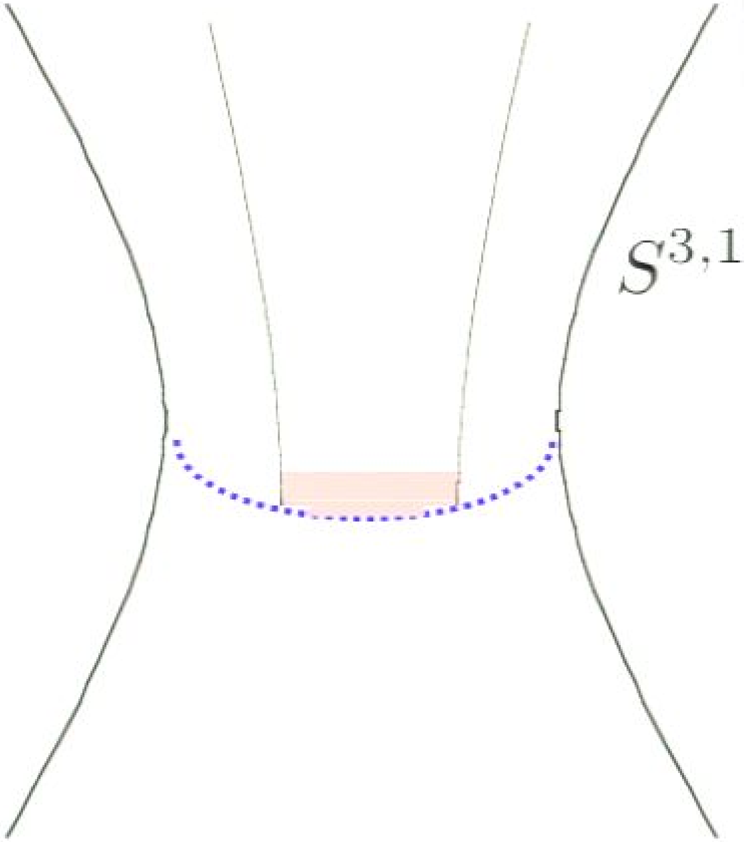
↓

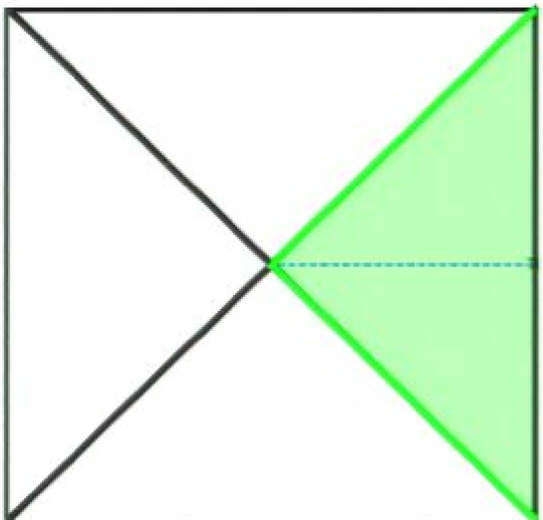
$\frac{1}{2}S^3$



Initial conditions after tunneling







Agree with CDL inside horizon

No information required or provided about outside horizon

✓ Tunneling in Minkowski space (no gravity) at T = 0

☑ Rate
☑ Initial conditions after tunneling

✓ Tunneling in Minkowski space (no gravity) at T ≠ 0

☑ Rate
☑ Initial conditions after tunneling

✓ Tunneling in de Sitter space (à la Coleman De Luccia)

☑ Rate
??? Initial conditions after tunneling ???

Tunneling in de Sitter space (thermal approach)

Is de Sitter decay predominantly quantum?
or predominantly thermal?

Concluding remarks

✓ Tunneling in Minkowski space (no gravity) at $T = 0$

- ☑ Rate
- ☑ Initial conditions after tunneling

✓ Tunneling in Minkowski space (no gravity) at $T \neq 0$

- ☑ Rate
- ☑ Initial conditions after tunneling

✓ Tunneling in de Sitter space (à la Coleman De Luccia)

- ☑ Rate
- ??? Initial conditions after tunneling ???

✓ Tunneling in de Sitter space (thermal approach)

Is de Sitter decay predominantly quantum?
or predominantly thermal?

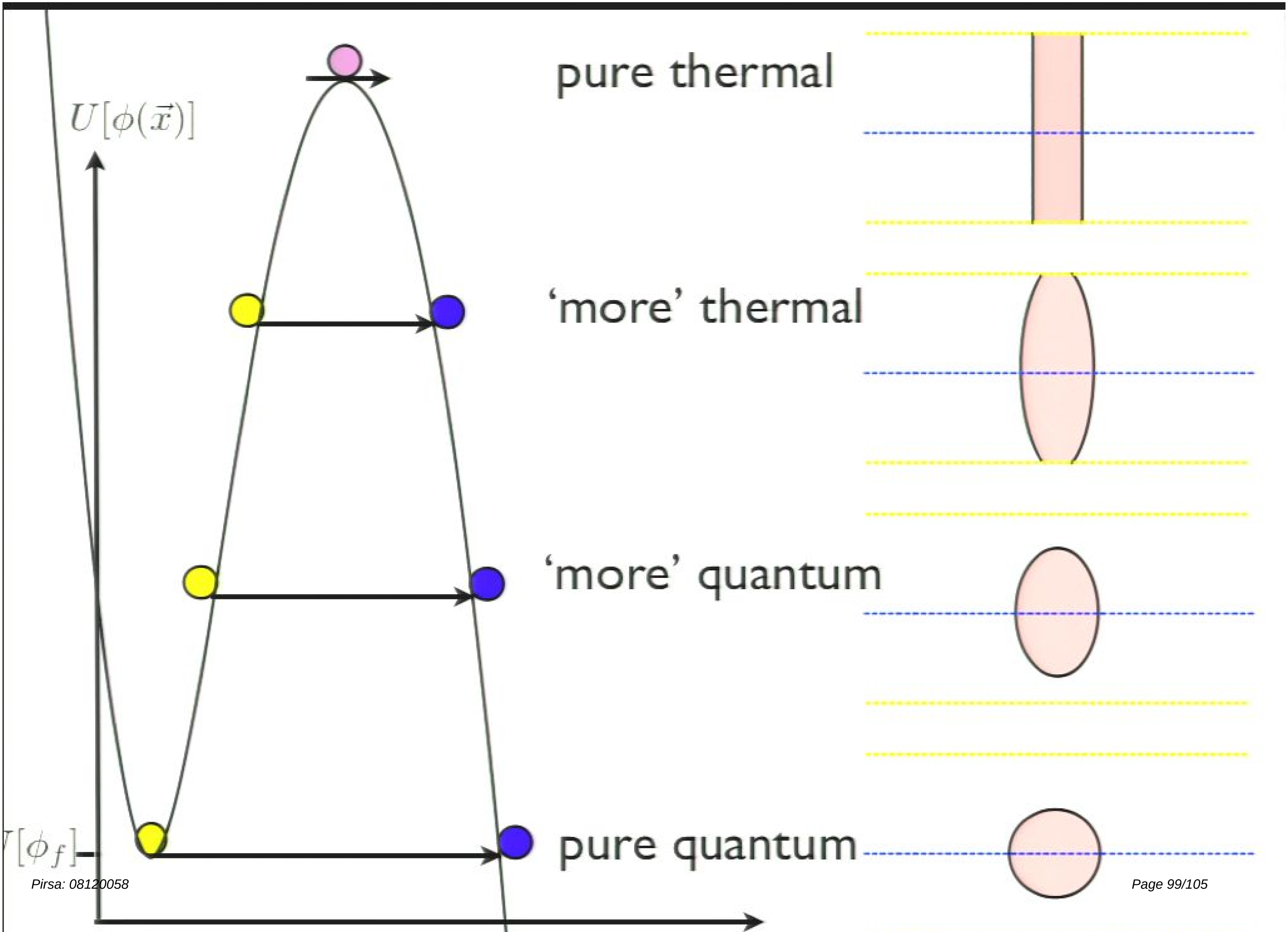
Concluding remarks

Thermal or Quantum?

Gibbons-Hawking temperature

$$T_{dS} = \frac{\hbar}{2\pi} H$$

Thermal IS Quantum



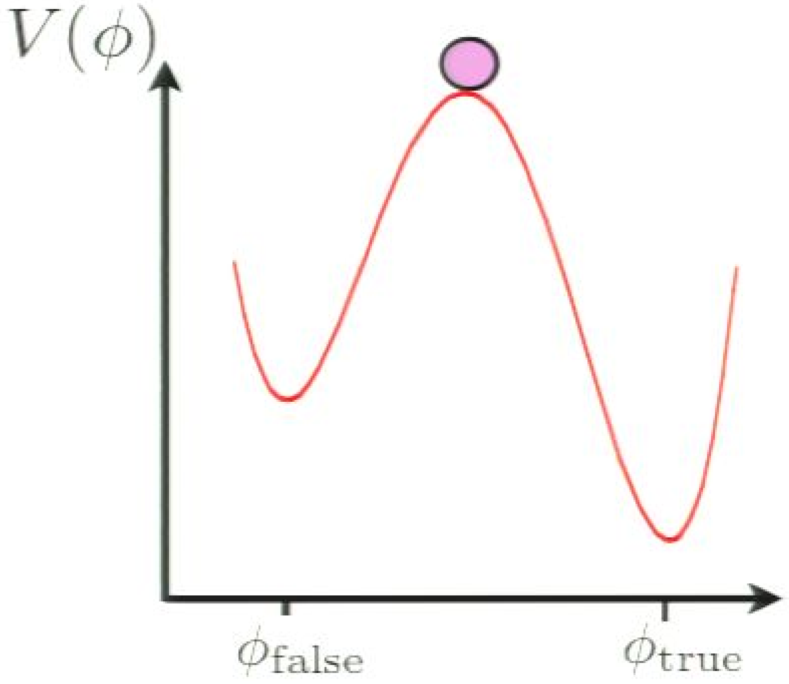
pure thermal

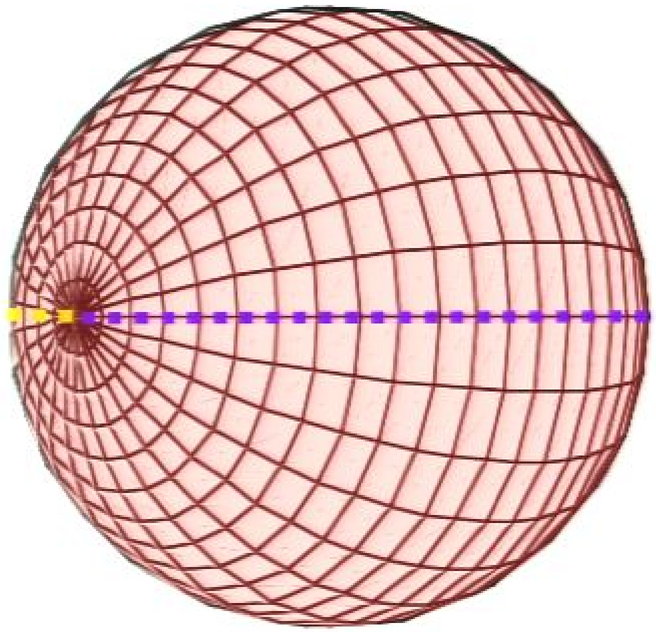
'more' thermal

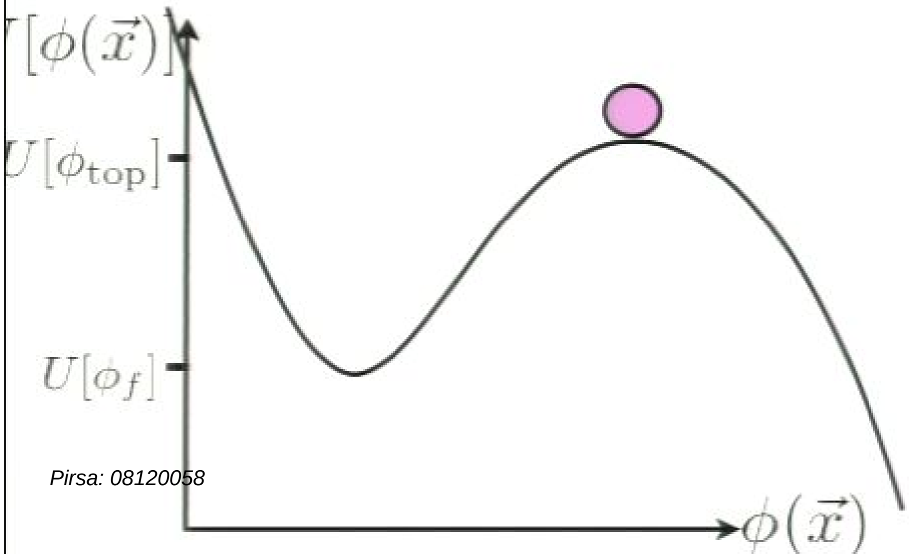
'more' quantum

pure quantum

Hawking-Moss is extreme THICK wall

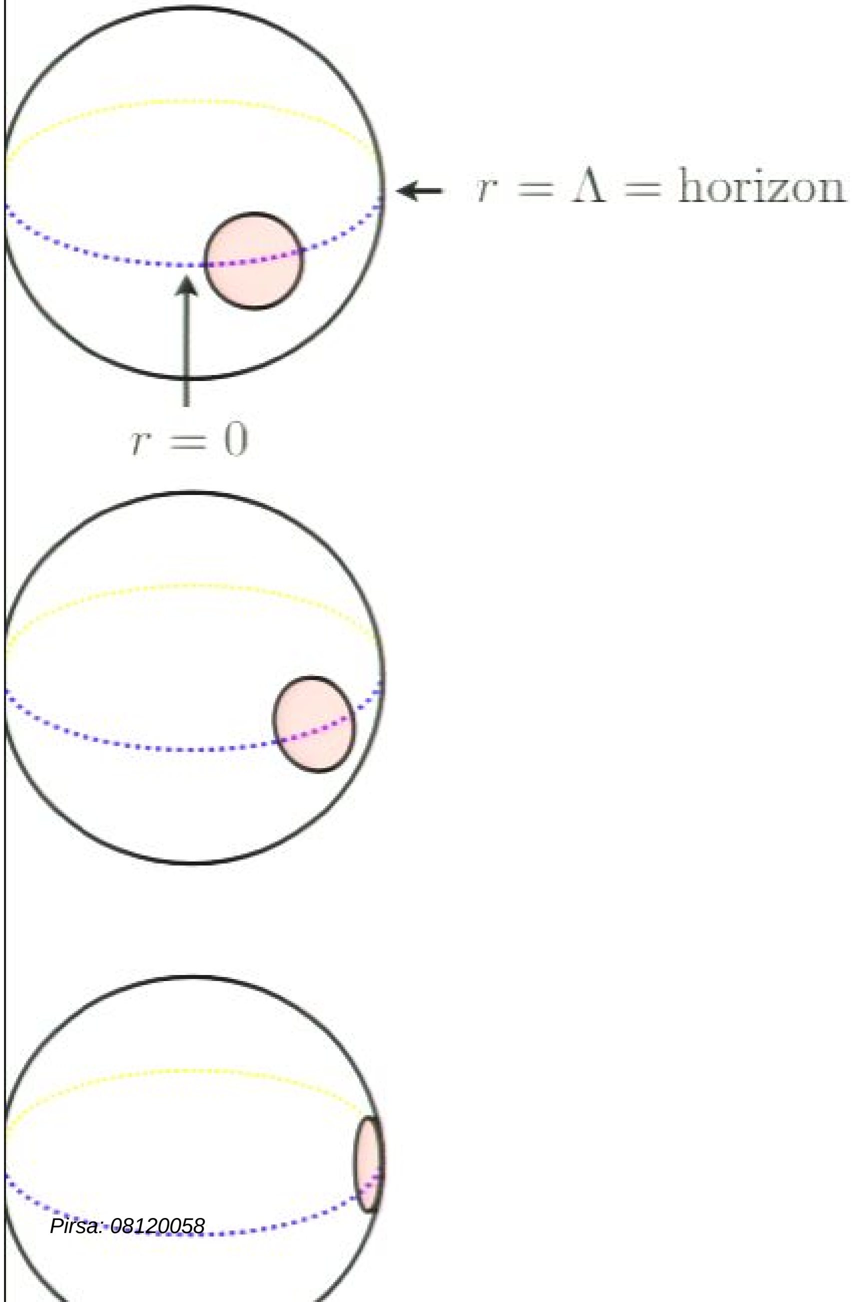




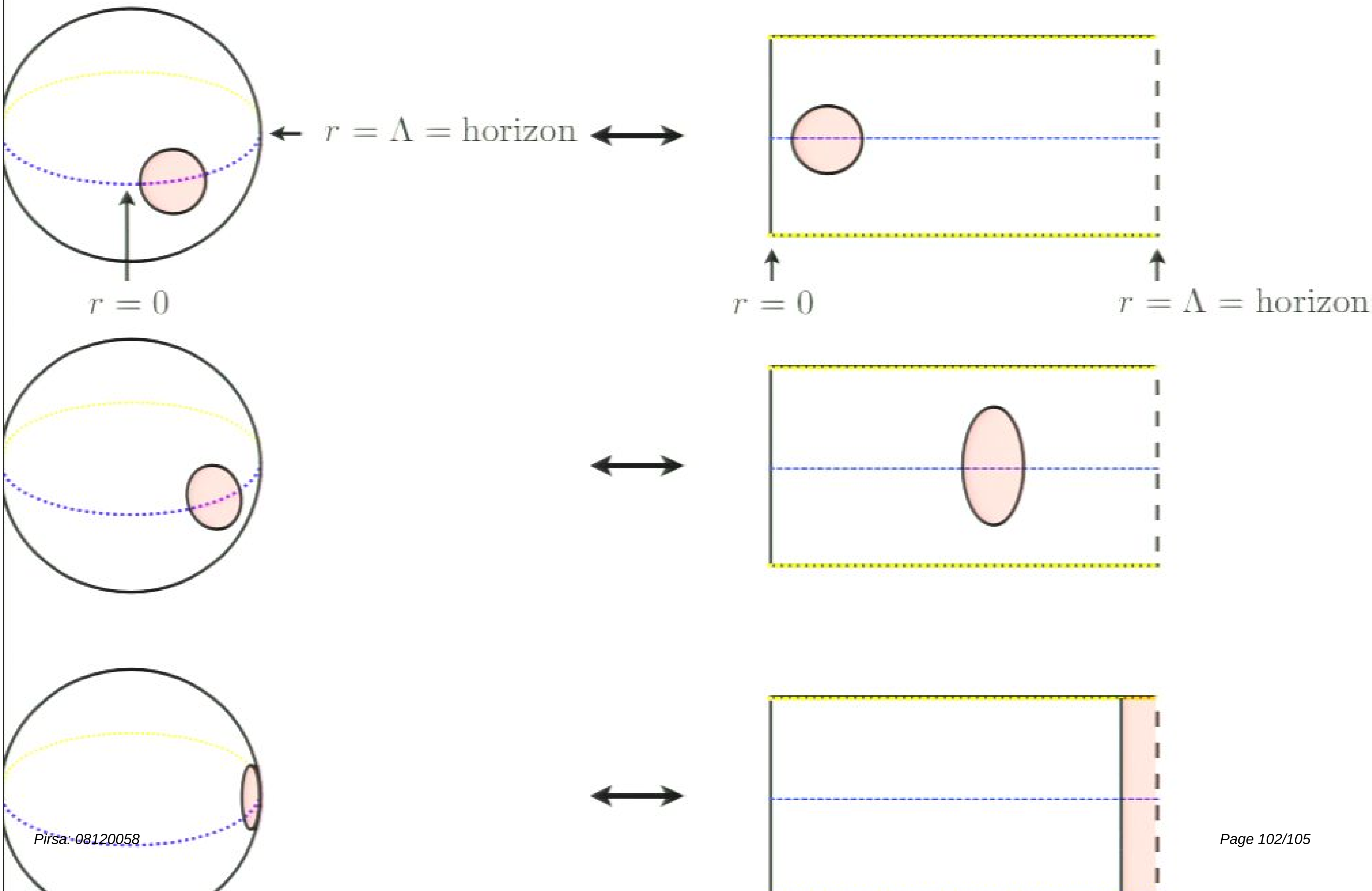


Hawking-Moss is pure thermal

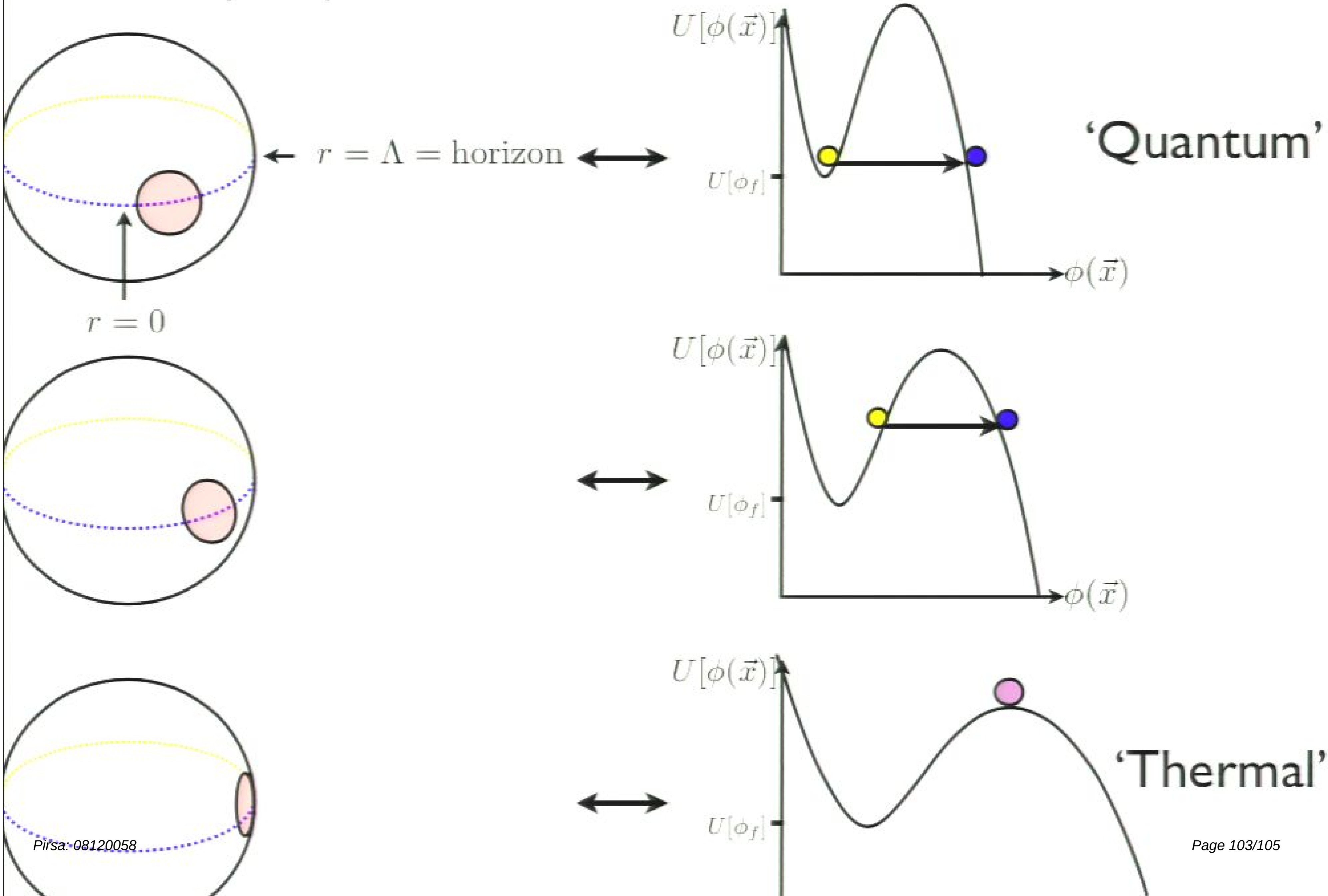
Different perspectives on the same bubble



Different perspectives on the same bubble



Different perspectives on the same bubble



- Tunneling in Minkowski space (no gravity) at T = 0

  ☑ Rate
  ☑ Initial conditions after tunneling

- Tunneling in Minkowski space (no gravity) at T ≠ 0

  ☑ Rate
  ☑ Initial conditions after tunneling

- Tunneling in de Sitter space (à la Coleman De Luccia)

  ☑ Rate
  ??? Initial conditions after tunneling ???

- Tunneling in de Sitter space (thermal approach)

- Is de Sitter decay predominantly quantum?
  or predominantly thermal?

Concluding remarks

Tunneling in Minkowski space (no gravity) at T = 0

☑ Rate
☑ Initial conditions after tunneling

Tunneling in Minkowski space (no grav[illegible] 0

☑ Rat[illegible]
☑ [illegible]ditions after tunneling

Tunneling in [illegible] space (à [illegible]an De Luccia)

[illegible]ions [illegible]

Tunneling in [illegible]ermal approach)

Is de Sitter dec[illegible]ominantly quantum?
or predominantly thermal?

Concluding remarks