

8.962 Lectures 18 & 19
April 18 & 20, 2018

KRUSKAL SPACETIME

Kruskal Coordinates

The diagram shows a coordinate system with a vertical axis labeled T and a horizontal axis labeled R . The vertical axis ranges from -2 to 2, and the horizontal axis ranges from -3 to 3. Dashed lines represent lines of constant r and constant t . The regions are labeled with Roman numerals: I (top-right), II (top-center), III (top-left), and IV (bottom-center). The $r=0$ line is shown as a curve that is vertical in the center and curves outwards as it moves away from the center. The $t=0$ line is a horizontal line at $T=0$.

Figure 1: The Kruskal coordinate system and its relation to Schwarzschild coordinates t and r , in units of GM . (The quadrant numbering is different from Carroll.)

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Embedding Diagrams

The top part of the diagram shows a coordinate system with a vertical axis labeled r and a horizontal axis labeled t . The vertical axis ranges from 0 to 5, and the horizontal axis ranges from -2 to 2. Dashed lines represent lines of constant r and constant t . The regions are labeled with Roman numerals: I (top-right), II (top-center), III (top-left), and IV (bottom-center). The $r=0$ line is shown as a curve that is vertical in the center and curves outwards as it moves away from the center. The $t=0$ line is a horizontal line at $r=0$.

The bottom part of the diagram shows five diagrams labeled A, B, C, D, and E, illustrating the evolution of a false vacuum bubble. Diagram A shows a flat surface. Diagram B shows a small bubble forming. Diagram C shows a larger bubble with a label $r = 2GM$. Diagram D shows a bubble that has expanded and is now pinching off. Diagram E shows the bubble fully detached and floating away.

(From Sean Carroll, *Spacetime and Geometry*, Figs. 5.14 & 5.15.)

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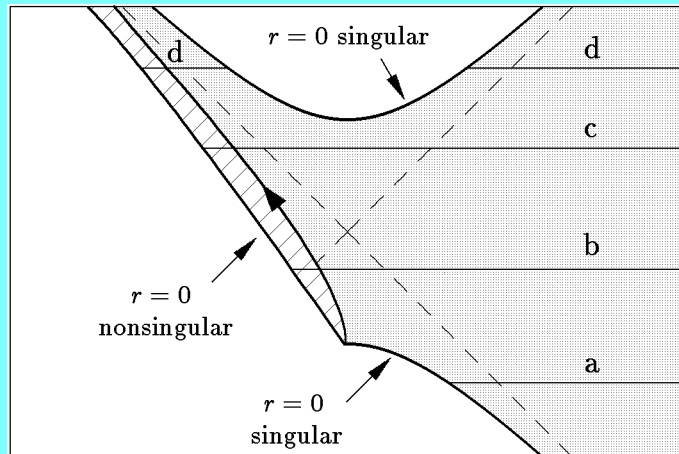
Evolution of False Vacuum Bubble

The diagram shows a coordinate system with a vertical axis labeled r and a horizontal axis labeled t . The vertical axis ranges from 0 to 5, and the horizontal axis ranges from -2 to 2. Dashed lines represent lines of constant r and constant t . The regions are labeled with Roman numerals: I (top-right), II (top-center), III (top-left), and IV (bottom-center). The $r=0$ line is shown as a curve that is vertical in the center and curves outwards as it moves away from the center. The $t=0$ line is a horizontal line at $r=0$.

The diagram shows the evolution of a false vacuum bubble. The bubble is shown as a shaded region that expands and eventually pinches off. The $r=0$ line is shown as a curve that is vertical in the center and curves outwards as it moves away from the center. The $t=0$ line is a horizontal line at $r=0$. The region between the $r=0$ line and the $t=0$ line is labeled "False Vacuum". The region to the right of the $r=0$ line is labeled "True Vacuum". The $r=0$ line is labeled "nonsingular" in the region where it is vertical and "singular" in the region where it curves outwards.

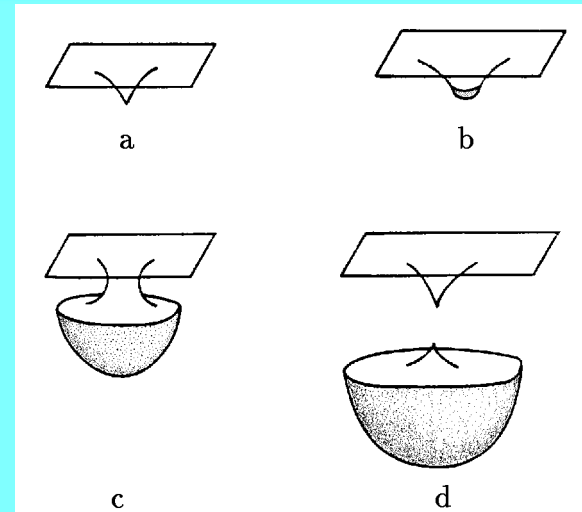
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Evolution of False Vacuum Bubble



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Evolution of False Vacuum Bubble



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References

- ★ S. K. Blau, E. I. Guendelman, & A. H. Guth, *The dynamics of false vacuum bubbles*, Phys. Rev. D **35**, 1747 (1987).
- ★ E. Farhi and A. H. Guth, *An obstacle to creating a universe in the laboratory*, Phys. Lett. B **183**, 149 (1987). This paper shows, using classical equations and the null energy condition, that the false vacuum bubbles that grow without bound must trace back to an initial singularity.
- ★ E. Farhi, A. H. Guth and J. Guven, *Is it possible to create a universe in the laboratory by quantum tunneling?*, Nucl. Phys. B **339**, 417 (1990). In this paper we explored the possibility of avoiding an initial singularity by first producing a false vacuum bubble that is too small to classically grow without bound, but then to have it tunnel to a larger bubble (of the same mass) which would then grow without bound. Is it possible? Maybe. This is still unresolved.

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