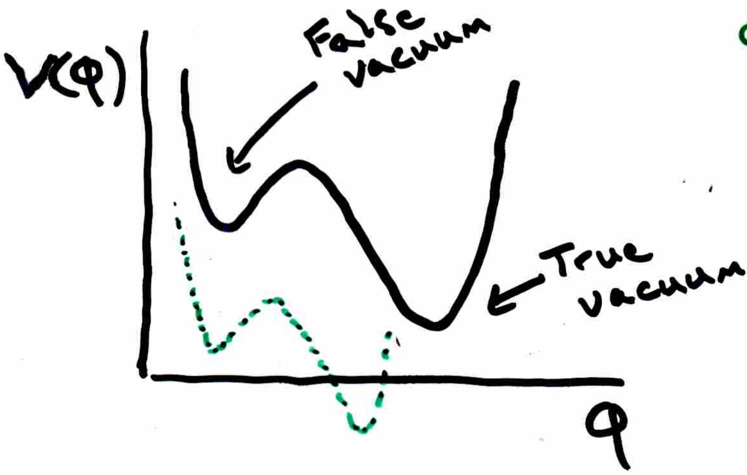
Quantum Transitions Between Vacua

Motivation: String Landscape
how are states populated?
(which are populated
w/ what probability TBD...)

Testing ground for semi-classical
+ quantum gravity.

Basic Model:



Coleman + company
- FV is generally metastable.
- Tunneling corresponds to bubble nucleation.

Lee + Weinberg
- If $V(\varphi_T) > 0$, then you can tunnel up as well.

No Gravity (Coleman, Callan + Coleman)

In WKB : $\dfrac{\Gamma}{V} = A\, e^{-S_E}$

O(4)-invariant instanton has lowest action:

$\varphi = \varphi(\rho)$; $\rho \equiv \vec{x}^2 + t^2$

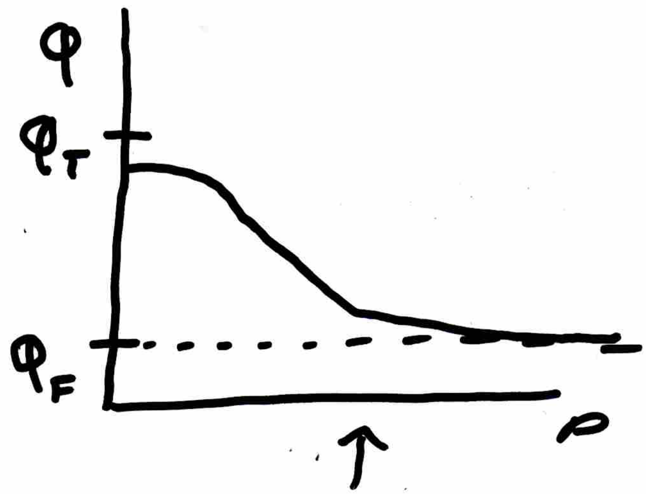
EOM: $\dfrac{\partial^2\varphi}{\partial\rho^2} + \dfrac{3}{\rho}\dfrac{\partial\varphi}{\partial\rho} = \dfrac{\partial V}{\partial\varphi}$

BC: $\varphi(\rho\to\infty) = \varphi_F$ (Far away, field is in FV)

$\varphi(\rho=0) \simeq \varphi_T$ (near origin, field approaches the TV)

$\left.\dfrac{\partial\varphi}{\partial\rho}\right|_{\rho=0} = 0$ (EOM non-singular)

Solution:



$t \to it$: This is profile at nucleation.

$$\boxed{\text{This has a clear interpretation as a localized event}}$$

With Gravity: Coleman + de Luccia

In WKB $\quad \Gamma = A e^{-S_E} \qquad S_E = S_I - S_{BG}$

$$S_I = -\int d^4x_E \sqrt{g}\; V(\varphi(x))$$

$$S_{BG} = -\int d^4x_E \sqrt{g}\; V(\varphi_{tp}) \simeq -\frac{3}{8\,V_{T,F}}$$

Assume $O(4)$-invariant:

$$ds^2 = dz^2 + \rho^2(z)\, d\Omega_3^2$$

EOM: $$\frac{d^2\varphi}{dz^2} + \frac{3}{\rho}\frac{d\varphi}{dz}\frac{d\rho}{dz} = \frac{\partial V}{\partial\varphi}$$

$$\left(\frac{d\rho}{dz}\right)^2 = 1 + \frac{8\pi}{3}\rho^2\left(\frac{1}{2}\left(\frac{d\varphi}{dz}\right)^2 - V(\varphi)\right)$$

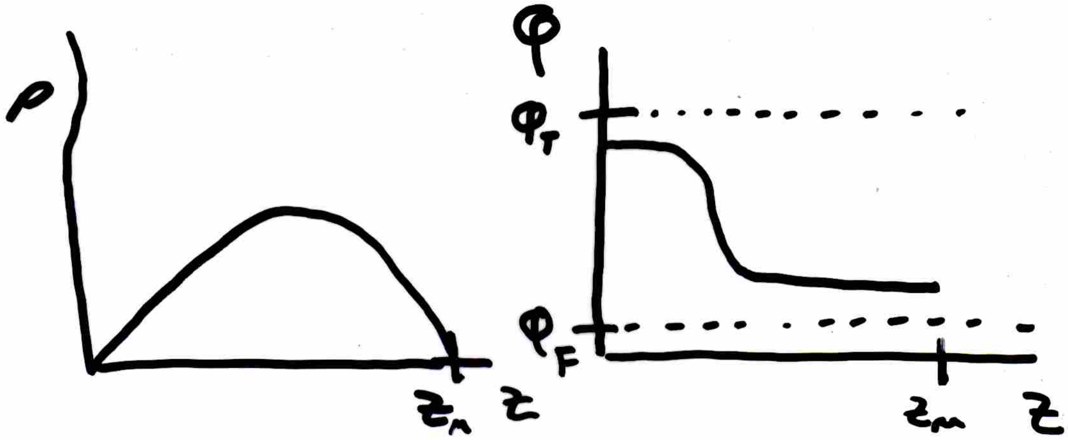
BC: IF $V_F > 0$, instanton is compact (ρ has 2 zeros)

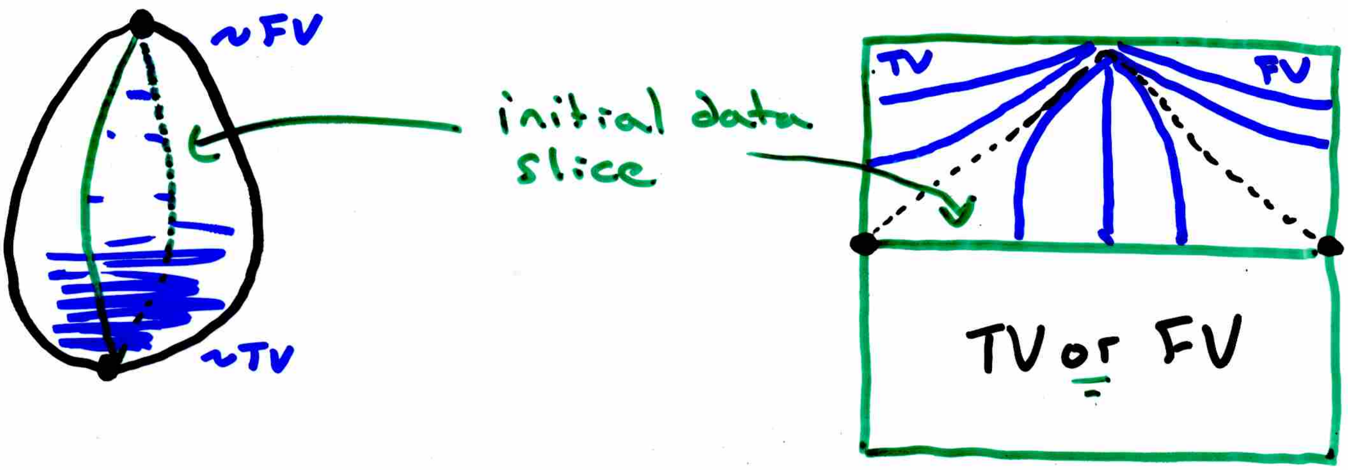
$$\rho(z=0) = 0 \quad ; \quad \rho(z_m) = 0$$

$$\left.\frac{d\varphi}{dz}\right|_{z=0} = 0 \quad ; \quad \left.\frac{d\varphi}{dz}\right|_{z=z_m} = 0$$

$$\varphi(z=0) \simeq \varphi_T \quad ; \quad \varphi(z_m) \simeq \varphi_F$$

Solution:





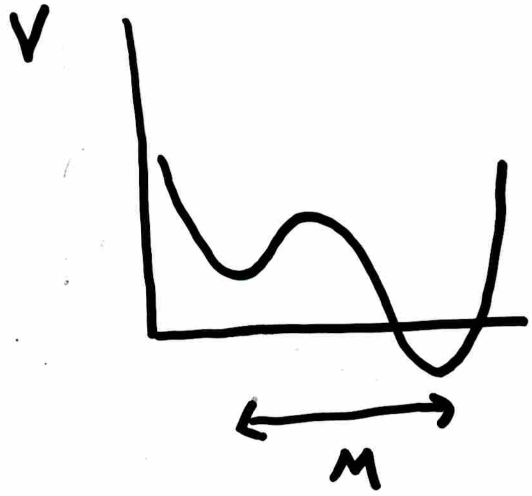
! Very Different w/ Gravity!

1) No part of instanton contains φ_T or φ_F.

2) No nice interpretation as a localized fluctuation.

3) Solutions can have diverse properties:
   - $V_F = 0$ vacua can be stabalized.
   - Multiple-pass instantons.
   - Hawking-Moss instanton.

The Great Divide (Aguirre, Banks, + Johnson)



As $V_T \to 0$, $S_{BL} \to \infty$

Does S_I cancel this?

For $M < M_c$: Yes

For $M > M_c$: NO

Above the divide: $\Gamma \sim e^{-\frac{8}{3V_T}}$

Downward transitions entropically suppressed

This, together w/ detailed balance

for $V_{T,F} > 0$, suggests interpretation

of TV as finite quantum system w/

transitions as rare fluctuations.

Below the divide: Unclear interpretation.

Decays can be very fast:

$$S_E = \frac{8\pi^2}{M_{3/2}^2} \frac{(c-1)^4}{c^2(2c-1)^2} \qquad c = \frac{|V_F^{susy}|}{|V_T^{susy}|}$$

(Ceresole et al.)

Euclidean action of this trajectory:

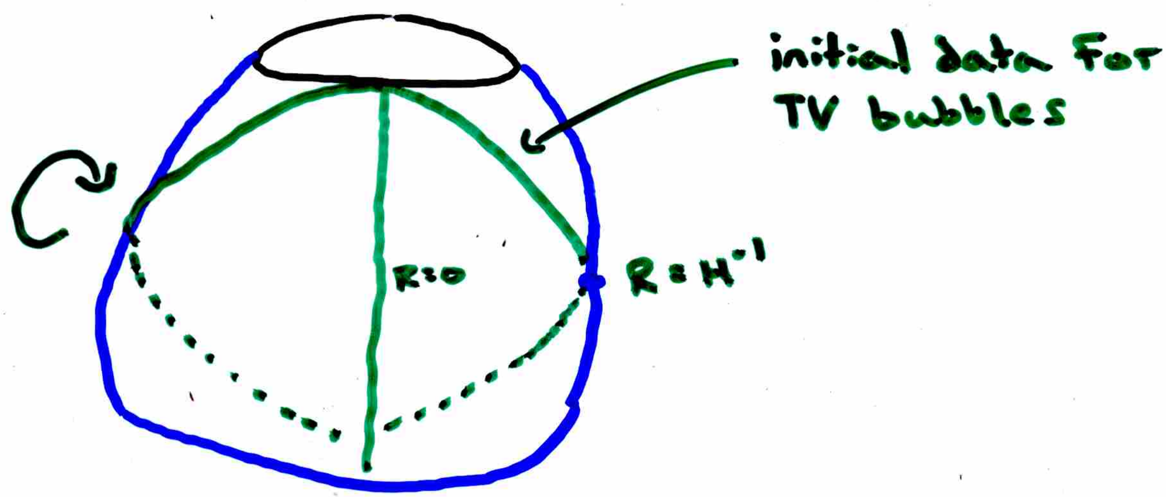
$$S_E = \frac{27\pi^2 \sigma^4}{2(V_F - V_T)^3} F(\sigma, V_F, V_T)$$

$\uparrow$ Flat space result

$\uparrow$ gravitational "correction"

More on the interpretation:

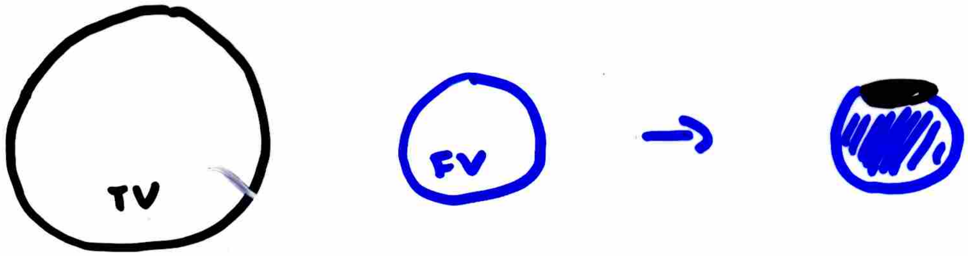
$$ds^2_{T,F} = (1 - H^2_{T,F} R^2)\, dt^2 + (1 - H^2_{T,F} R^2)^{-1} dR^2 + R^2 d\Omega^2$$

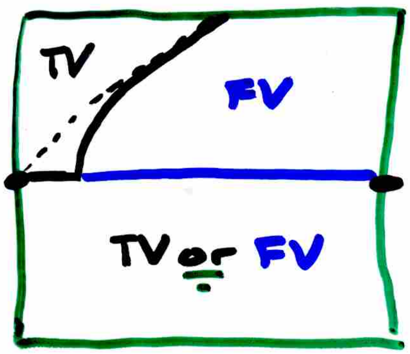


Note: no initial data surface for FV bubbles (or on the real instanton ...)

Thin-wall Approximation

Match 2 dS spheres:



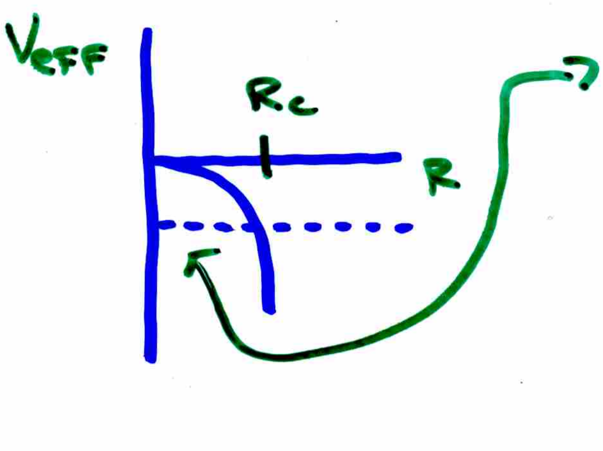


1) TV bubbles, when small, look similar to the flat-space case.

2) FV bubbles involve very large fluctuations.

3) The radius of the wall becomes a collective coordinate to describe tunneling:

Dynamics determined by: σ, V_T, V_F



Tunneling from $R=0$ to R_c found from Euclidean EOM:

$$\left(\frac{dR}{dz}\right)^2 + \left(\frac{R}{R_c}\right)^2 = 1$$

Lorentzian thin-wall CDL - Matching 2 dS

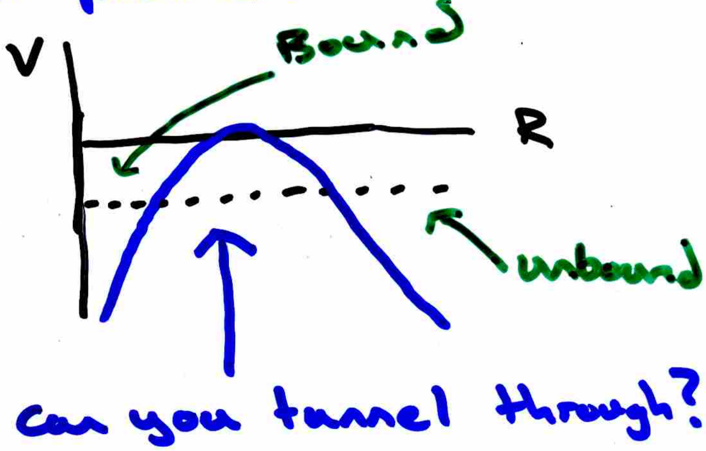
=> Wall + volume energies cancel

What if they don't?

=> Exterior is now SdS
new parameter M

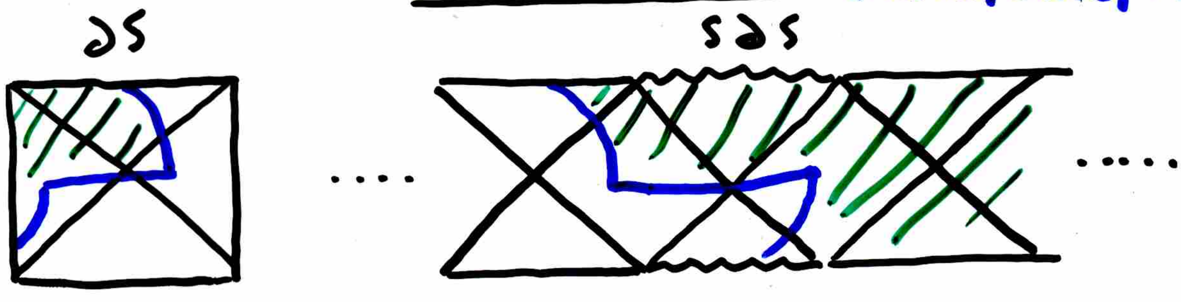
Still have 1-D potential problem:

$$\left(\frac{dR}{d\tau}\right)^2 - V(R,M) = -1$$

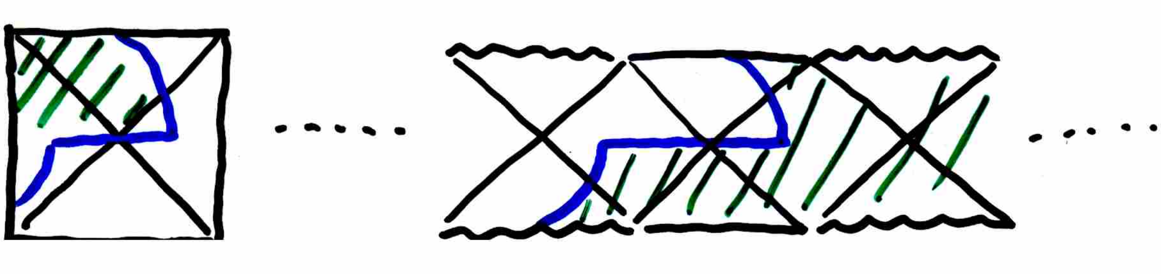


Semi-classically, seems like Yes!

L Geometry (Farhi, Guth, + Guven)

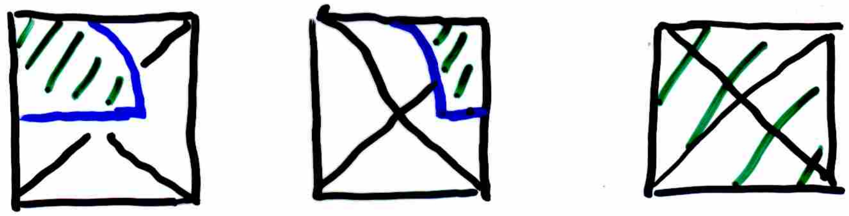


R Geometry



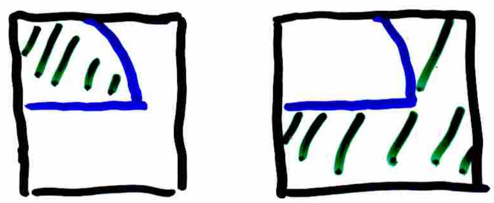
Zero-Mass limit:

L geometry:



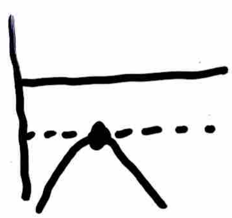
FV bubble universe created from nothing!

R geometry:



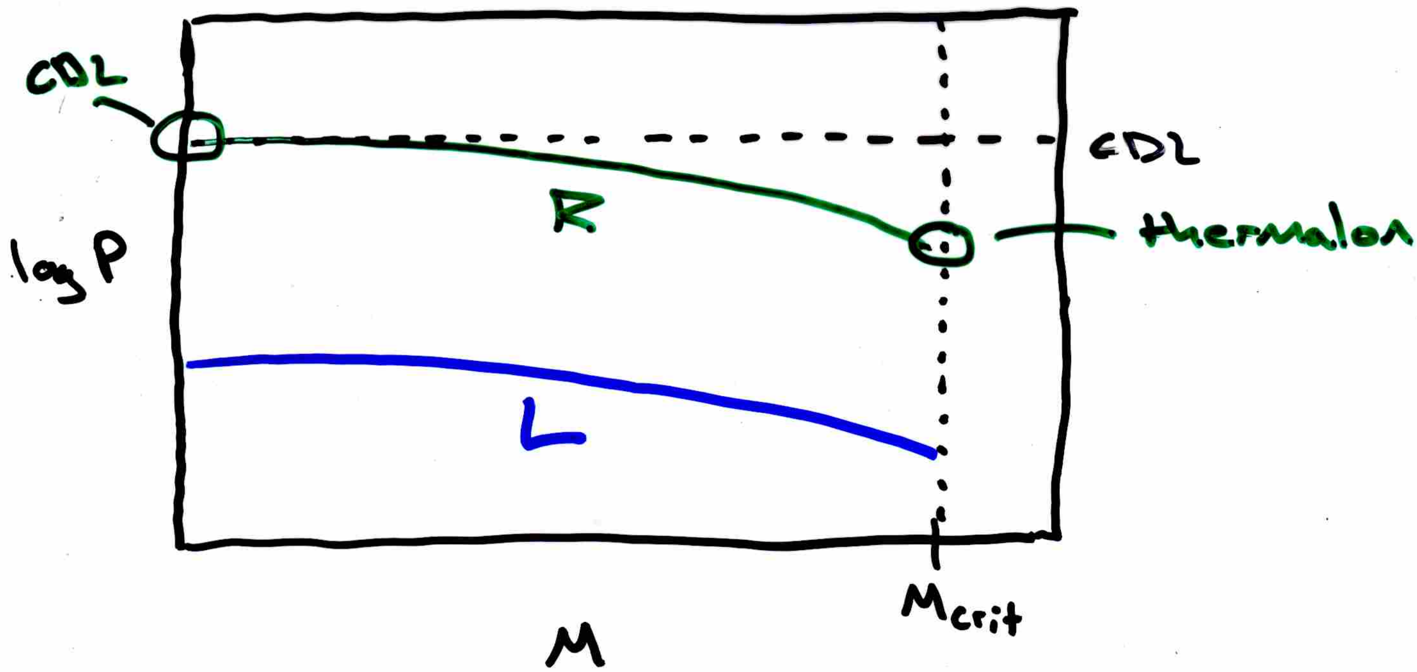
Standard LW FV bubble

There is also an O(3) invariant instanton:

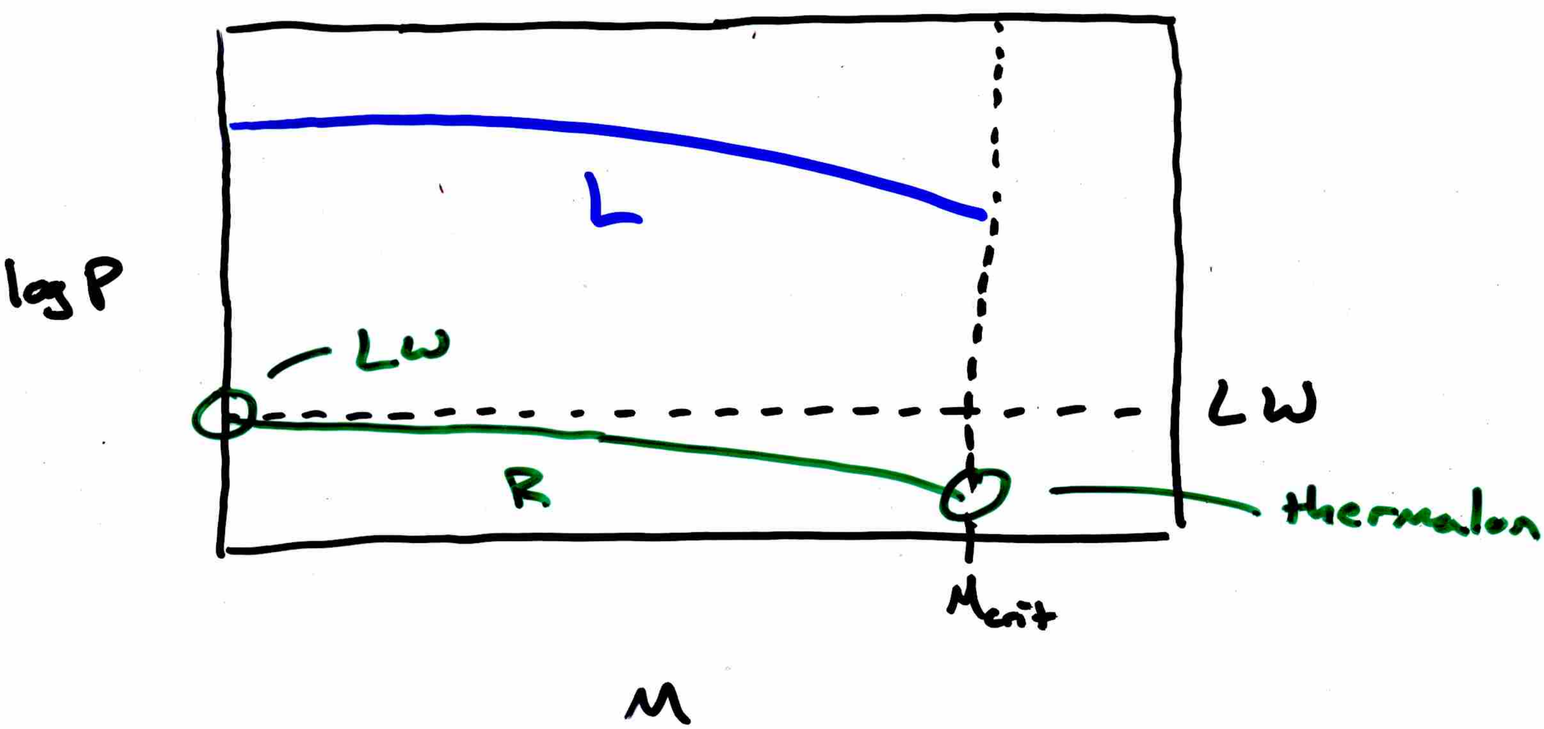


Thermal activation of dS (Garriga + Megevand)

Relative Rates : TV



Relative Rates: FV



Puzzles : What is allowed?

Not surprisingly, puzzles arise when gravity is important : FV bubbles

1) Interpolating geometry - when turning points are separated by a horizon, not a manifold.....
   problem w/ FV bubbles and L geometry TV bubbles

2) AdS/CFT (Freivogel et al) - L geometry is not a unitary transition.
   Perhaps not surprising :

region behind the wormhole was not there before the tunnel...

3) Bound solutions are violently unstable :

can we assume spherical symmetry?

Effects on pre-factor ?