Evaporation of the de Sitter horizon

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arXiv:1703.06898 (....)
arXiv:1610.06637 (JCAP)
arXiv:1609.01738 (JCAP)

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Outline

de Sitter space (FLRW)

- Einstein's equation

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \underbrace{M_{\mathrm{pl}}^{-2} T_{\mu\nu}}_{=0}$$

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$$ds^2 = -dt^2 + a(t)^2 d\mathbf{x}^2$$

(Not the form used by de Sitter originally)

- The de Sitter solution:

$$H = \dot{a}(t)/a(t) = \sqrt{\Lambda/3} \quad \Leftrightarrow \quad \dot{H} = 0 \quad \Leftrightarrow \quad a(t) = e^{Ht}$$

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- Early and late Universe evolution $\approx$ dS

Stability

- Stability in a quantized theory has been studied by many:

Stable

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- ...

Not stable

- Mottola (85) & (86)
- Tsamis & Woodard, many papers, e.g. (93)
- Abramo, Brandenberger & Mukhanov (97)
- Goheer, Kleban & Sussking (03)
- Polyakov (07)
- Anderson & Mottola (14)
- Dvali, Gomez & Zell (17)
- and many more, see TM (16a,b) & (17)

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An instability could be important for inflation, the cosmological constant problem and the fate of the Universe !

Friedmann equations

- A system with vacuum energy and matter:

$$\rho_\Lambda \quad \text{and} \quad \rho_m$$

- Homogeneous and isotropic spacetime

$$\begin{cases} 3H^2 M_{\rm pl}^2 & = \rho_m + \rho_\Lambda \\ -(3H^2 + 2\dot{H}) M_{\rm pl}^2 & = p_m + p_\Lambda \end{cases}$$

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particles:
$\rho_m + p_m > 0$
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A Simple instability argument

- Consider a conformal field, e.g. a photon

trace vanishes: $T_\mu{}^\mu = 0 \quad \Leftrightarrow \quad p_m = \frac{1}{3}\rho_m$

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(Naive) conclusion:

$\rho_m \neq 0 \quad \Leftrightarrow \quad \dot{H} \neq 0$

(see Clifton & Barrow (17))

Open quantum systems and decoherence

Schrödinger's Cat

image: http://braungardt.trialectics.com/sciences/physics/quantum-mechanics/schrodingers-cat/

$$|\text{cat}\rangle = \frac{1}{\sqrt{2}}|\text{alive}\rangle + \frac{1}{\sqrt{2}}|\text{dead}\rangle$$

Coarse Graining & Decoherence

- Observable system, $\mathcal{S}$; hidden environment, $\mathcal{E}$

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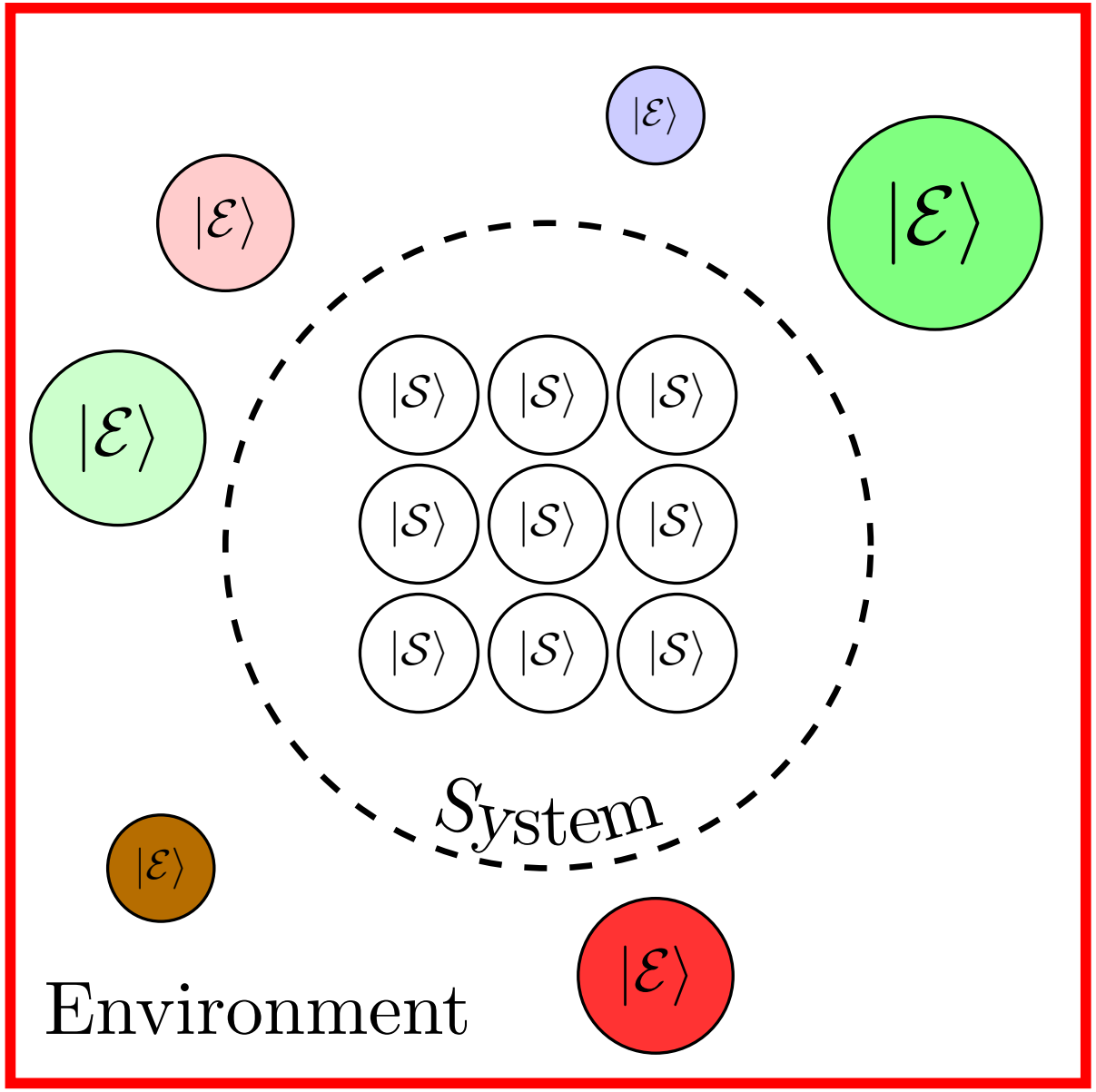
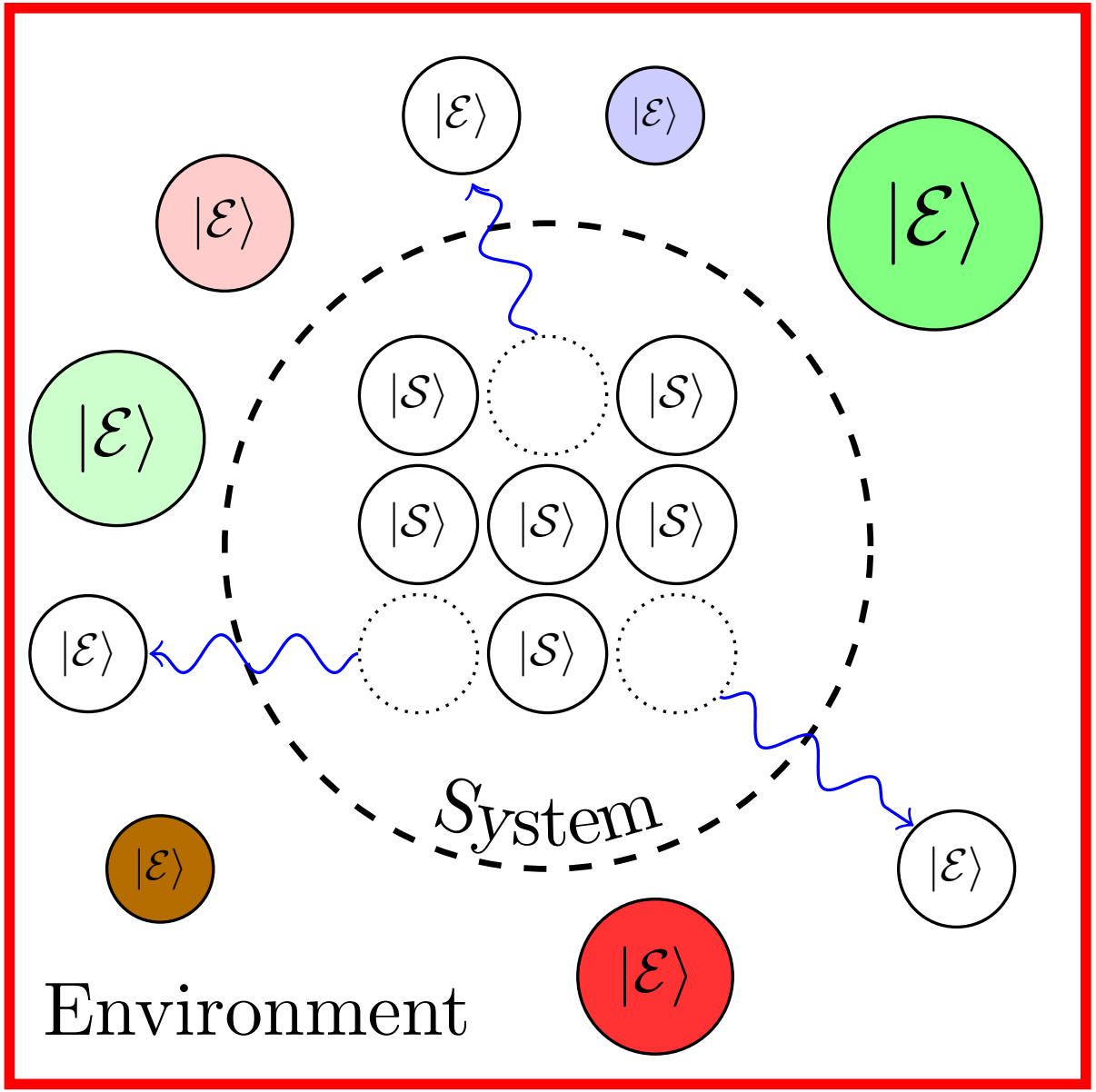
Coarse graining breaks symmetries!

Initially the System and the Environment are separable

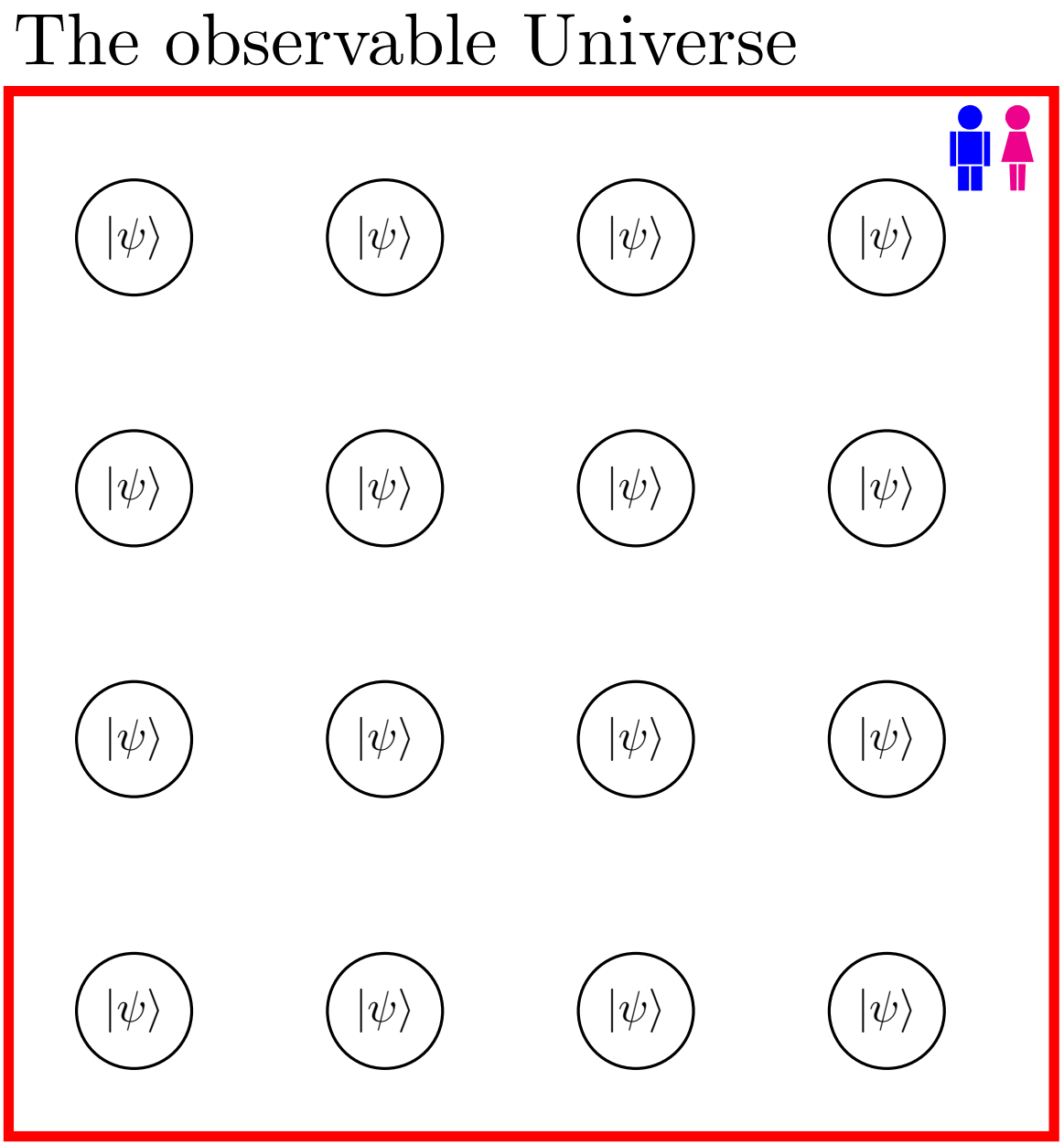


Interactions lead to entanglement

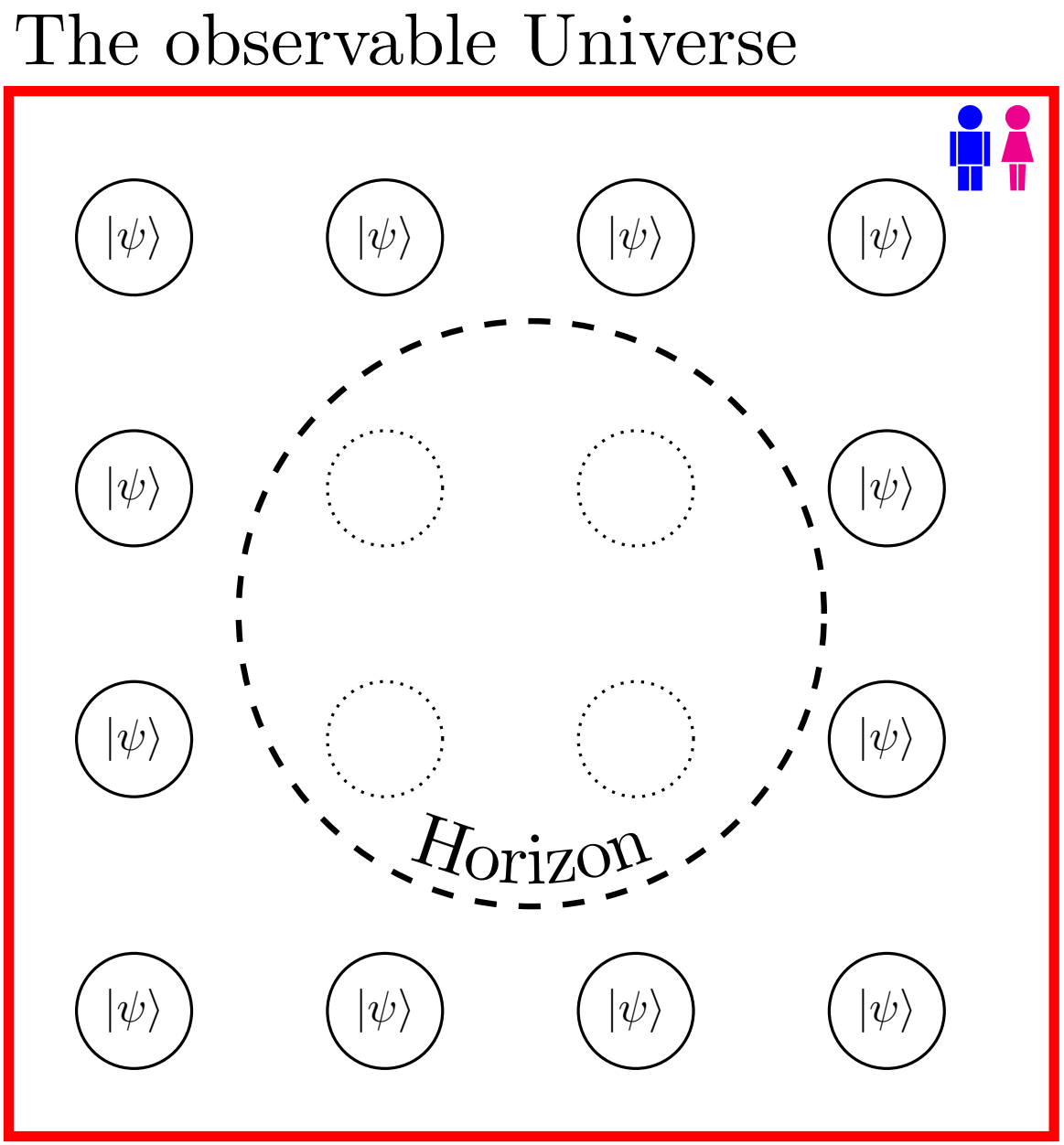


Loss of information from a Horizon

Black Hole I: Initially, complete information



Black Hole II: Loss of information from the BH horizon



Spacetimes with horizons

- Black hole evaporation; Hawking (75), the Unruh effect; Unruh (76) and thermality of de Sitter; Gibbons & Hawking (77)

- A horizon divides the initial state into $\mathcal{S}$ and $\mathcal{E}$
  - Crucial for the information paradox, Hawking (76)

pure state $\Rightarrow$ thermal state

(For a local observer)

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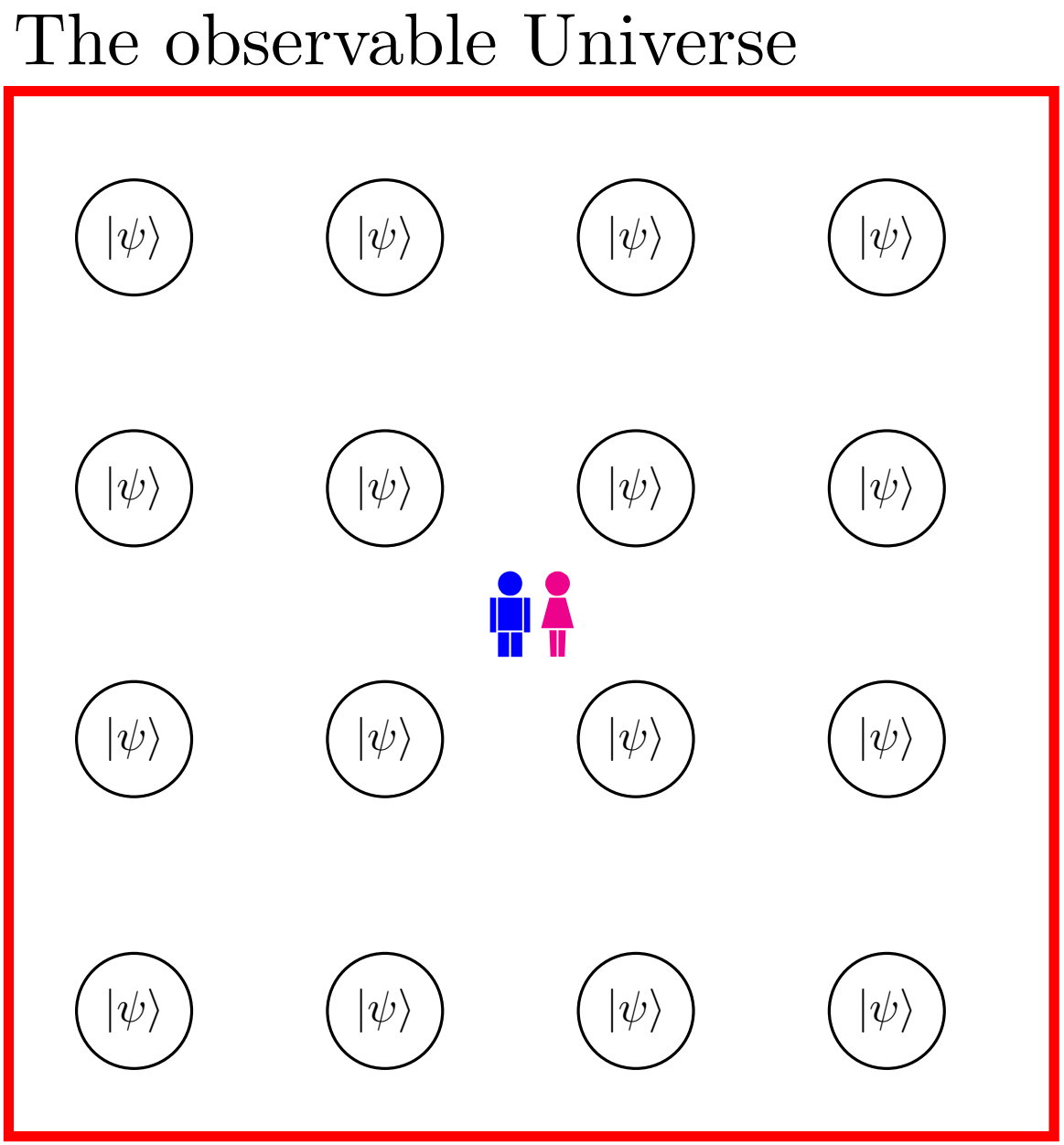
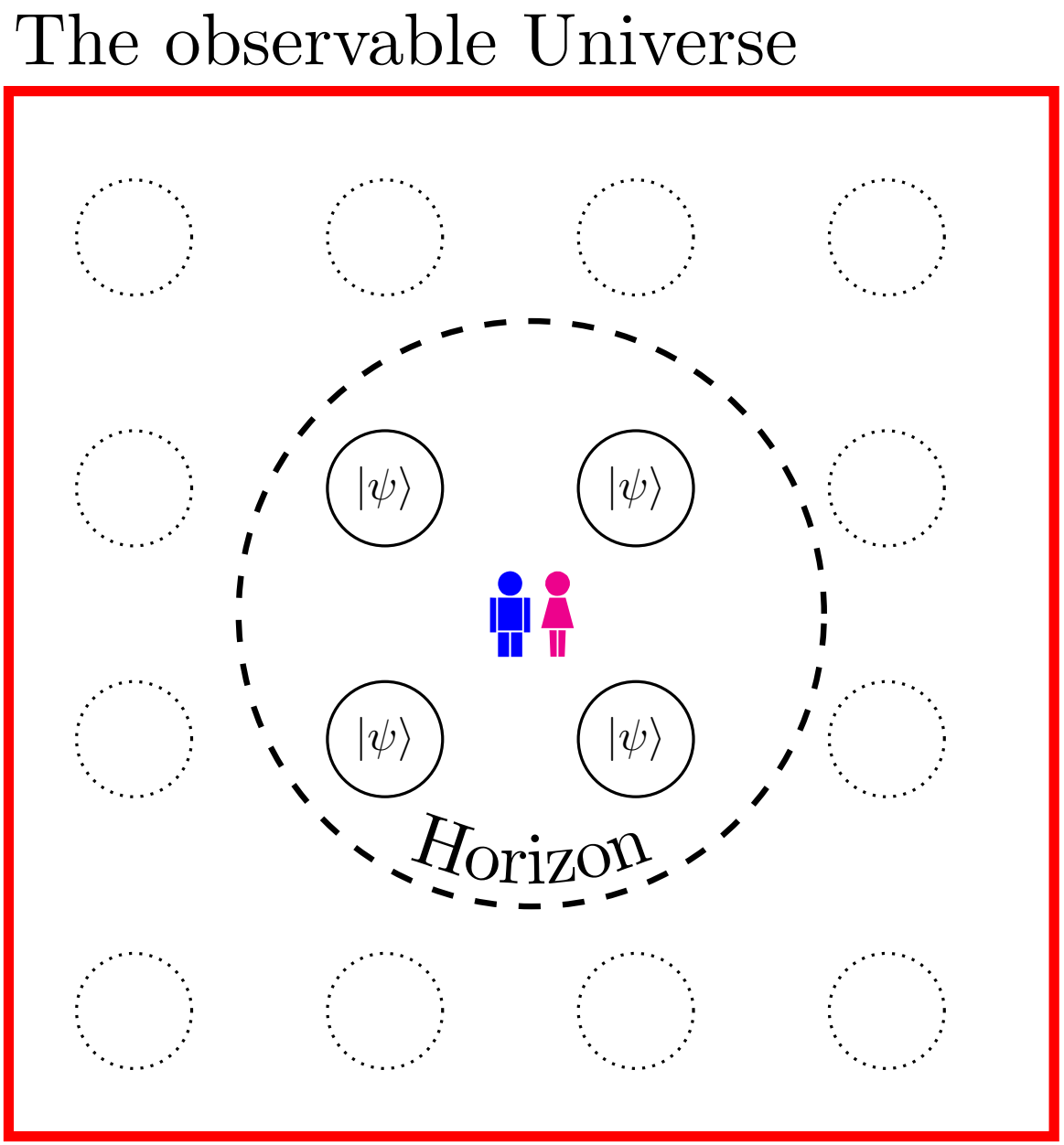
Here a completely different focus than in a calculation of primordial perturbations!

dSI: Initially, complete information



dSII: Information loss from the cosmological Horizon



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- For simplicity use a conformal non-interacting scalar field

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  (3) Calculate the energy-momentum tensor

$$\langle \hat{T}_{\mu\nu}\rangle \equiv \mathrm{Tr}\left\{\hat{T}_{\mu\nu}\hat{\rho}\right\} \quad \neq \quad \langle 0^{\mathrm{BD}}|\hat{T}_{\mu\nu}|0^{\mathrm{BD}}\rangle$$

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- Can be done in 4-dimensions unlike for a BH
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The energy-momentum (far from the horizon)

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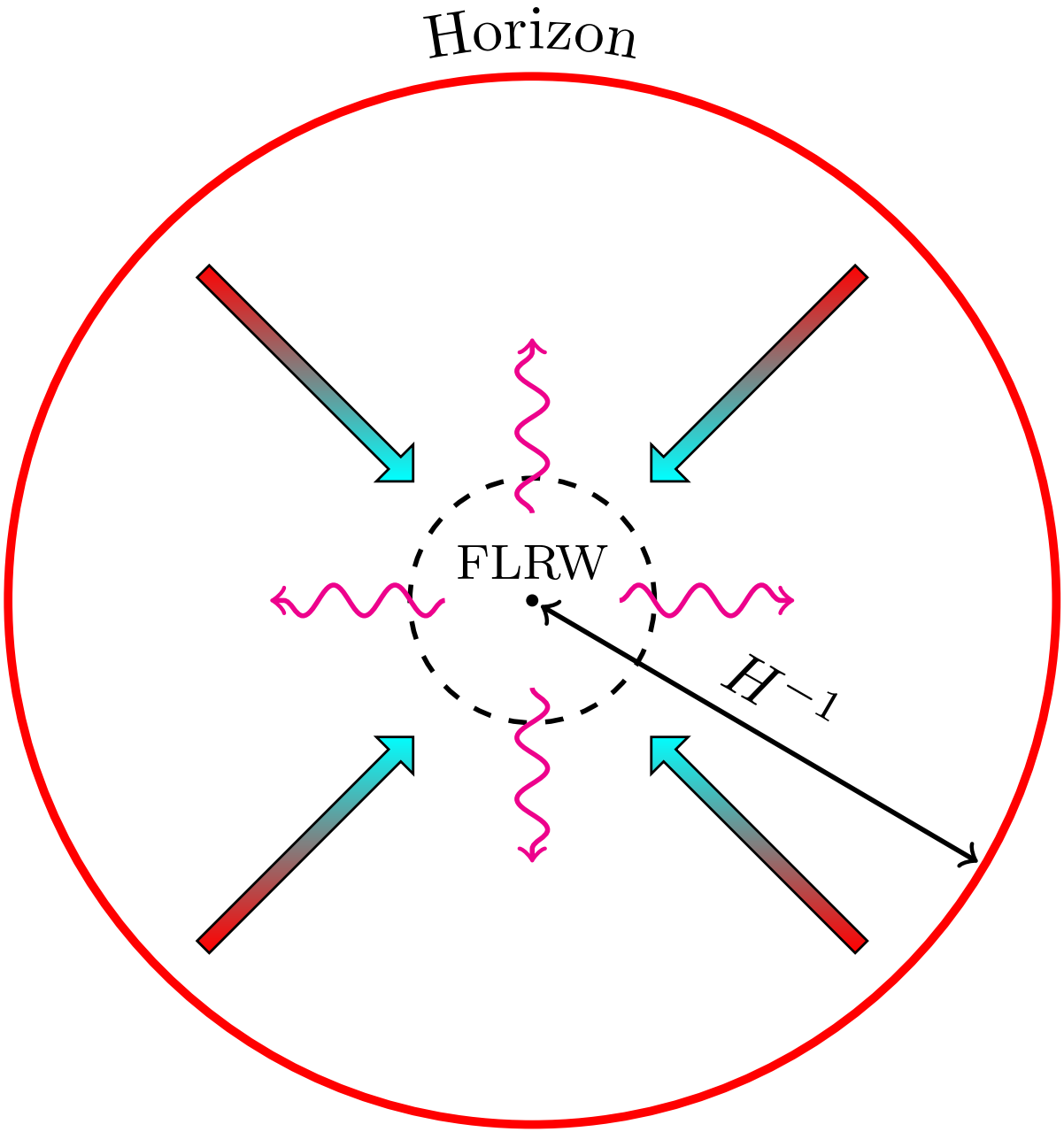
$$f_{m,i} \equiv \langle \hat{T}_{0i} \rangle / a = H x^i a \left(\rho_m + p_m\right) \qquad \text{(flux)}$$



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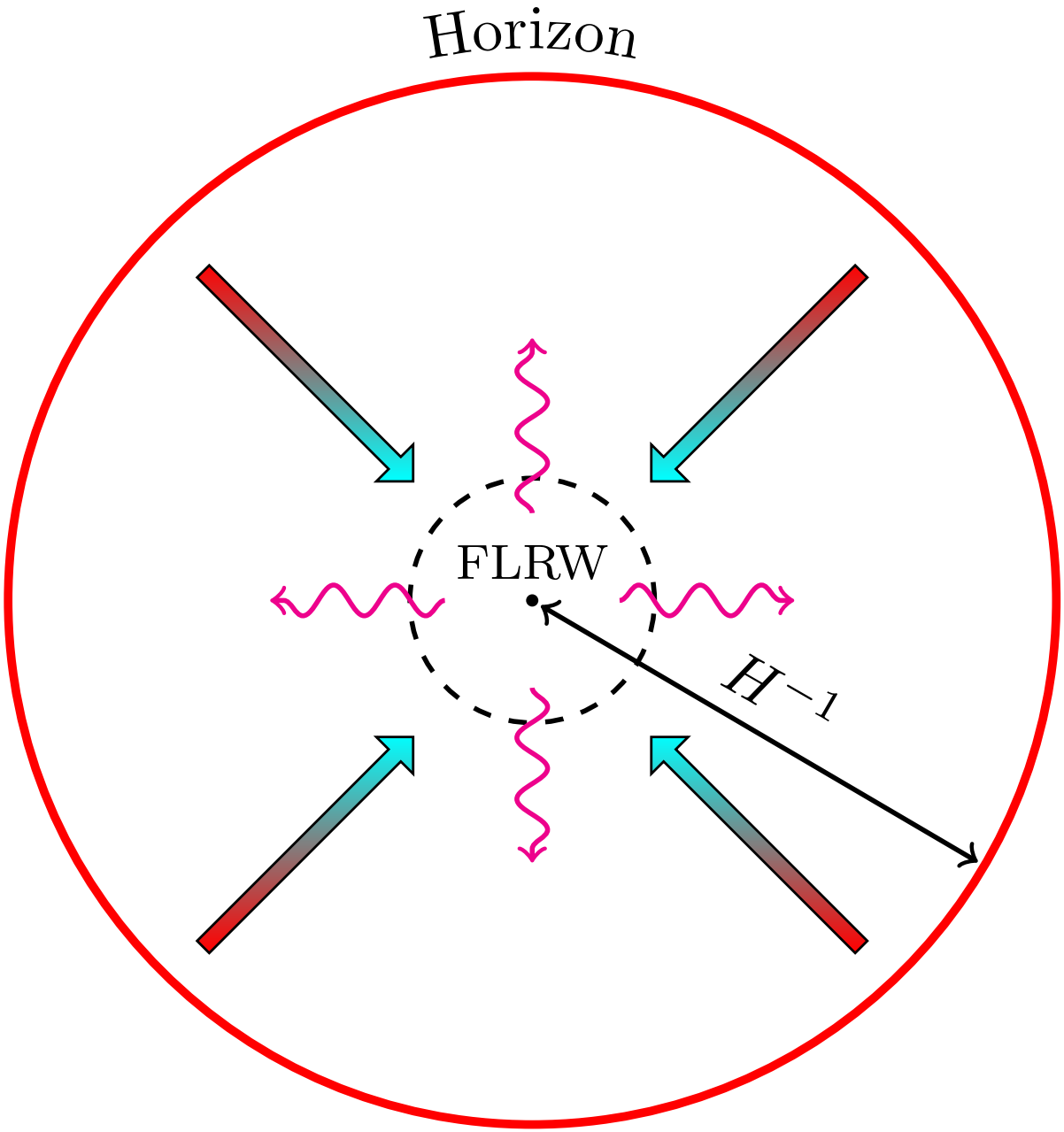

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Horizon sources continuous particle creation !

Backreaction

Backreaction and coarse graining

Which object to use as $\langle \hat{T}_{\mu\nu} \rangle$ in the (semi-clas.) Friedmann,

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Solving the system self-consistently, assumptions:

- Homogenuity and isotropy (FLRW)
- Backreaction is weak $\Rightarrow$ use the dS results for $\langle \hat{T}_{\mu\nu} \rangle$
- Thermal ρ_m and p_m with $T_H = H/(2\pi)$

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The evaporating horizon

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$$\Rightarrow \quad \frac{H}{H_0} = \left(\frac{H_0^3 t}{240\pi^2 M_{\rm pl}^2} + 1\right)^{-1/3}; \quad H(0) \equiv H_0$$

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- De Sitter destabilized after

$$t \sim \frac{M_{\rm pl}^2}{H_0^3} \qquad \text{(see, Dvali, Gomez \& Zell (17))}$$

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The first law of thermodynamics in de Sitter

$$dU = TdS - PdV$$

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- Classically $\rho_\Lambda = \Lambda M_{\rm pl}^2$, how can a parameter change?!
- Quantization $\Rightarrow$ $\rho_\Lambda = \Lambda M_{\rm pl}^2 +$ zero-point energies

$$\int \frac{d^{n-1}\mathbf{k}}{(2\pi)^{n-1}} \frac{\sqrt{\mathbf{k}^2+m^2}}{2} + \int \frac{d^{n-1}\mathbf{k}}{(2\pi)^{n-1}} \frac{\mathbf{k}^2}{2(n-1)\sqrt{\mathbf{k}^2+m^2}} = 0$$

$\Rightarrow$ Particle creation $\Leftrightarrow$ negative vacuum energy ('holes')

- Precisely as for a black hole (Hawking (75))

The first law of thermodynamics in de Sitter

$$dU = TdS - PdV \qquad \Leftrightarrow \qquad 2\dot{H}M_{\rm pl}^2 = \frac{\dot{\rho}_\Lambda}{3H} \qquad \text{for},$$

$$dU = -d\left(\rho_\Lambda \frac{4\pi}{3H^3}\right), \quad TdS = \frac{H}{8\pi G} d\left(\frac{4\pi}{H^2}\right), \quad PdV = -p_\Lambda d\left(\frac{4\pi}{3H^3}\right)$$

- First principle result and thermodynamic derivation agree!

Conclusions

Summary

De Sitter evaporation

- Trace over the hidden states leads to a thermal state
  - $\Rightarrow$ Unstable under backreaction in FLRW
- ρ_Λ decays
- After a time $\sim M_{\rm pl}^2/H^3$ the system is no longer de Sitter
- A complete thermodynamic interpretation

Thank You!

De Sitter evaporation

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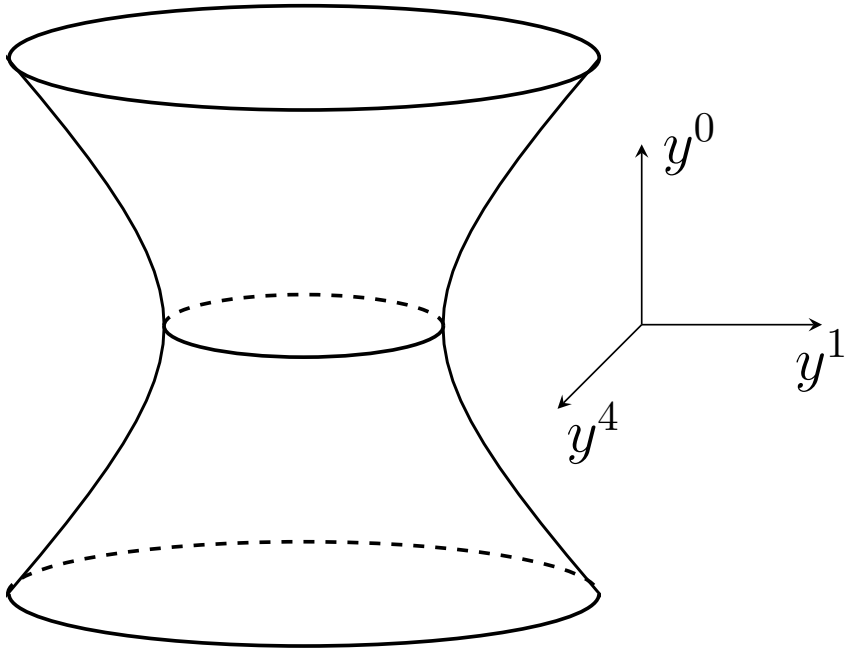
- A complete thermodynamic interpretation

de Sitter space

- The complete de Sitter spacetime is a hyperboloid



$$ds^2 = -(dy^0)^2 + (dy^1)^2 + (dy^2)^2 + (dy^3)^2 + (dy^4)^2$$
$$H^{-2} = -(y^0)^2 + (y^1)^2 + (y^2)^2 + (y^3)^2 + (y^4)^2$$

De Sitter in expanding FLRW coordinates (2-dim.)

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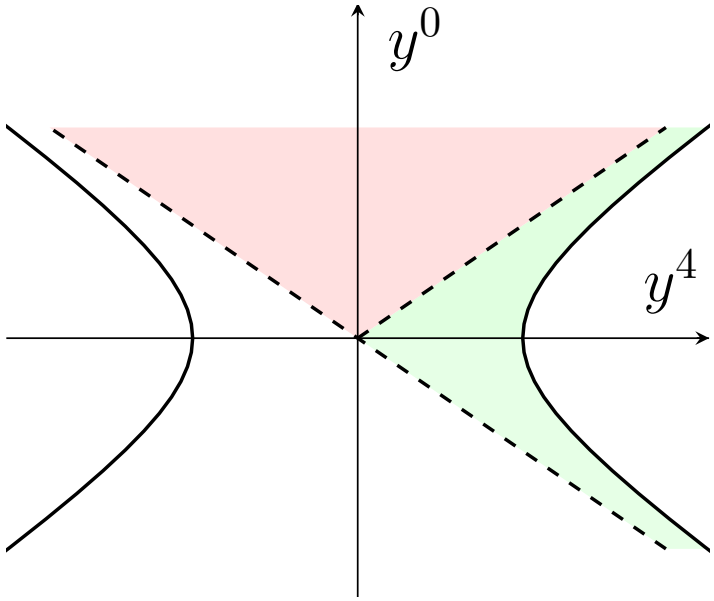
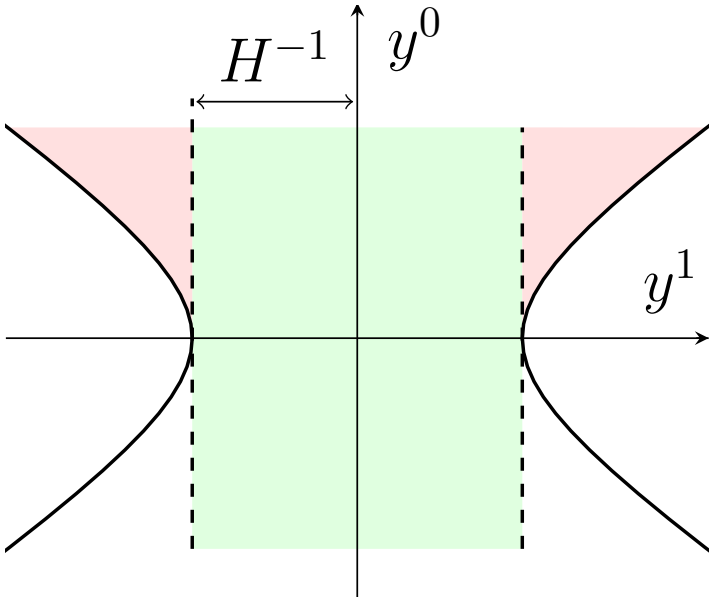
- FLRW coordinates cover only half of the manifold





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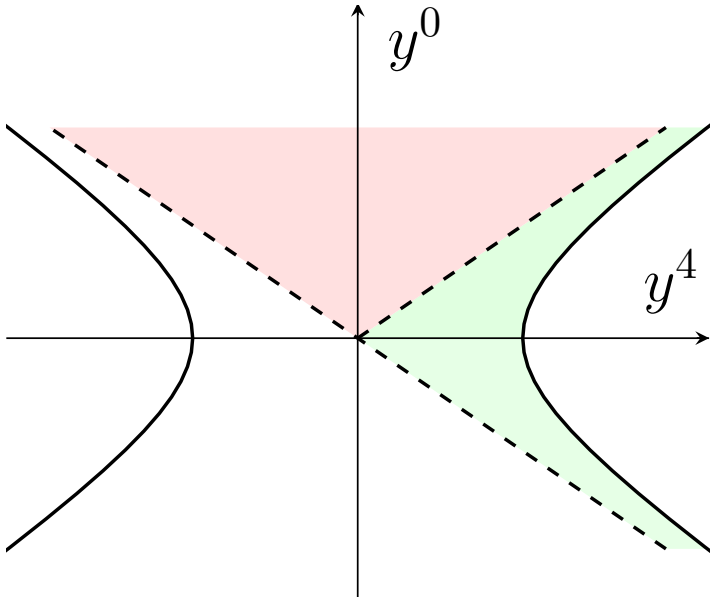
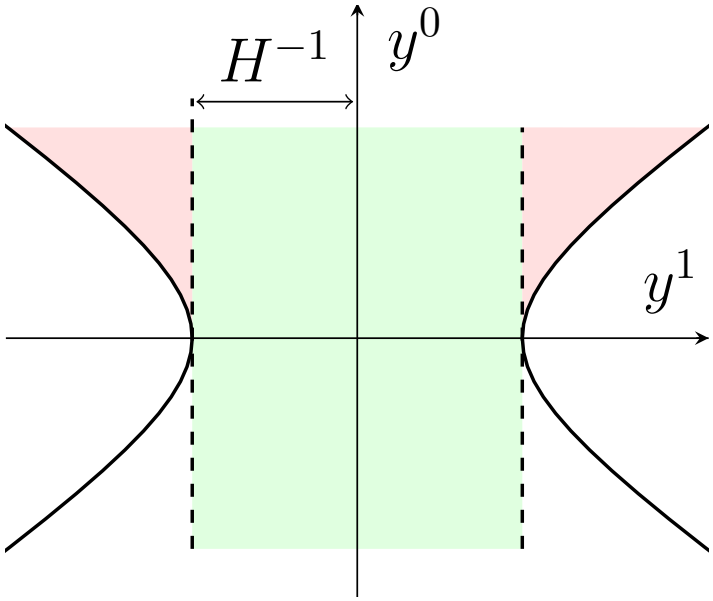
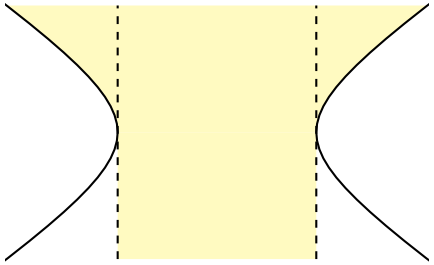




- Only part of the FLRW patch (green) is observable

Coordinates in dS



FLRW

$$\begin{cases} y^0 &= H^{-1}\sinh(Ht) + (H/2)|\mathbf{x}|^2 e^{Ht} \\ y^i &= e^{Ht}x^i \\ y^4 &= H^{-1}\cosh(Ht) - (H/2)|\mathbf{x}|^2 e^{Ht} \end{cases}$$

FLRW : $\quad ds^2 = -dt^2 + e^{2Ht}d\mathbf{x}^2$

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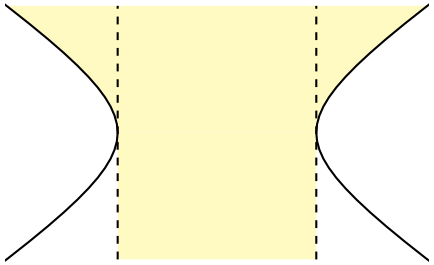

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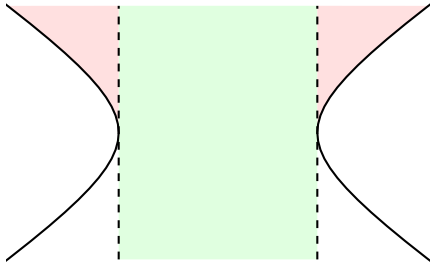

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$$\begin{cases} y^0 &= (H^{-2} - r^2)^{1/2}\sinh(Ht) \\ y^i &= x^i \\ y^4 &= (H^{-2} - r^2)^{1/2}\cosh(Ht) \end{cases}$$

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IN/OUT : $ds^2 = -\left[1-(Hr)^2\right]dt^2 + \left[1-(Hr)^2\right]^{-1}dr^2 + r^2\left(d\theta^2 + \sin^2\theta d\varphi^2\right)$

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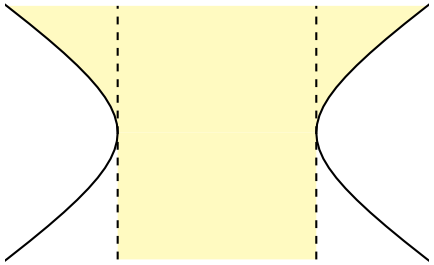

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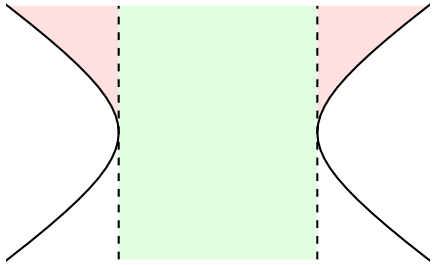

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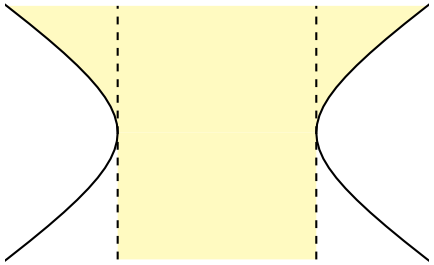
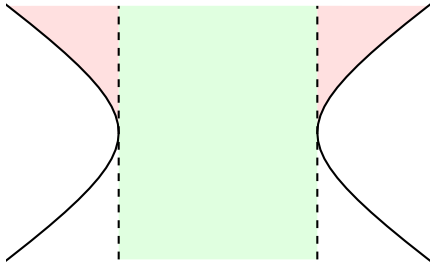
Coordinates in dS



FLRW

$$\hat{\phi} = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} \int_0^{\infty} dk \left[\psi_{\ell mk} \hat{a}_{\ell mk} + \mathrm{H.C} \right]$$

$$\psi_{\ell mk} = \sqrt{k/\pi} j_\ell(kr) Y_\ell^m e^{-ik\eta}/a \quad \Leftrightarrow \quad |0^{\mathrm{BD}}\rangle$$



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