Cosmology without scalars: Inflation, reheating & baryogenesis in a **superfluorescent** Universe

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HIDDeN & ASYMMETRY Webinar
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References

- Alicki, Barenboim & AJ, "Quantum thermodynamics of de Sitter space", *PRD* (in press) [arXiv:2307.04800 [gr-qc]]

- "The irreversible relaxation of inflation", arXiv:2307.04803 [gr-qc]

- "Baryogenesis: A thermodynamic approach", in preparation

Gravity & thermo.

- work by Zel'dovich, Bekenstein & Hawking in 1970s leads to **black-hole thermodynamics**

- ⇒ solutions to Einstein's classical field eqs. have thermal properties (unlike, e.g., Maxwell eqs.)

- **Entropy counting** points to an underlying quantum theory of gravity

- see, e.g., ***It from Qubit***: *Simons Collaboration on Quantum Fields, Gravity & Information*

Expanding Universe

- Schrödinger found that accelerated expansion leads to "alarming phenomena" of **particle production/annihilation**, due to mixing of positive & negative frequencies

  Schrödinger, *Physica* **6**, 899 (1939)

- **de Sitter (dS) space** associated with temperature $T_{\mathrm{dS}} = h/2\pi$, for Hubble parameter h

  Gibbons & Hawking, *PRD* **15**, 2738 (1977)

- dS thermodynamics remains poorly understood and contentious

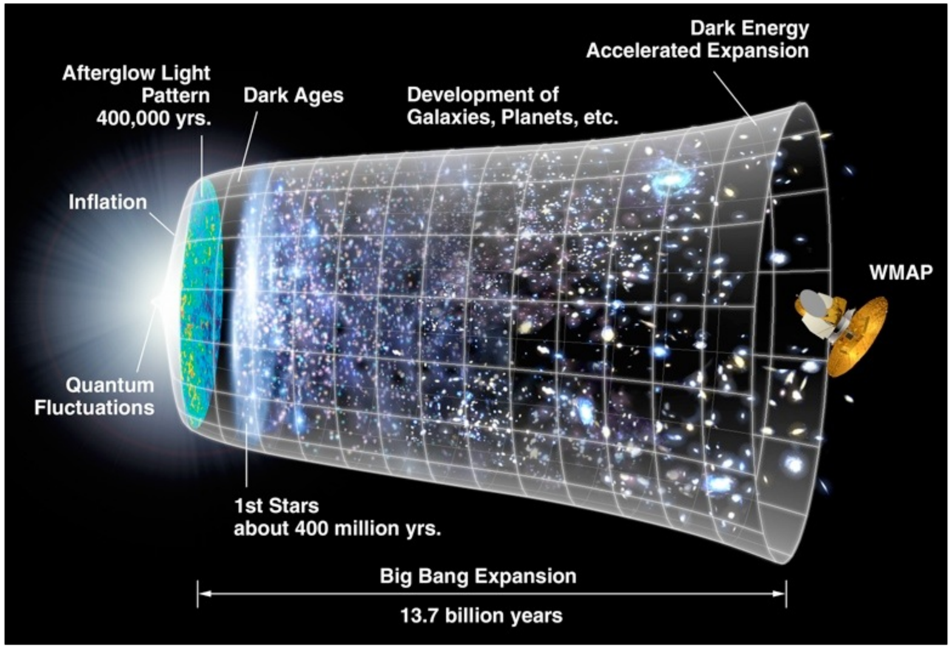
  see, e.g., Chandrasekaran, Longo, Penington & Witten, *JHEP* **2302**, 082 (2023); Susskind, arXiv:2304.00589; de Alwis, arXiv:2304.07885

- Our goal here is to describe expansion as **irreversible process**

Modern cosmology

- In 1981, Guth proposed short-lived dS phase of very early Universe
- This **inflation** solves horizon, flatness & monopole problems in standard Big-Bang cosmology
- Can account for primordial perturbations that seed structure formation
- "paradigm in search of a model"

— Kolb & Turner, *The Early Universe* (CRC, 2018 [1990])



Source: WMAP scientific group (NASA)

Open problems

A. account for very special (i.e., low-entropy) **initial state**

B. explain why **inflation ended** abruptly, after ≳ 60 e-folds

C. explain how energy that drove inflation was converted into thermal radiation ("**reheating**"), generating observed entropy

D. explain why **accelerated expansion** re-started recently, at far slower rate of exponential growth

- Here, we'll apply analytical techniques of **quantum thermodynamics** to the early Universe
- significant consequences for B, C, and possibly A
- Currently working on D (not covered in this talk)

Fun with scalars

Source: Angelo Caravano, Facebook group: *Grand Unified Physics Memes*, 23 April 2020

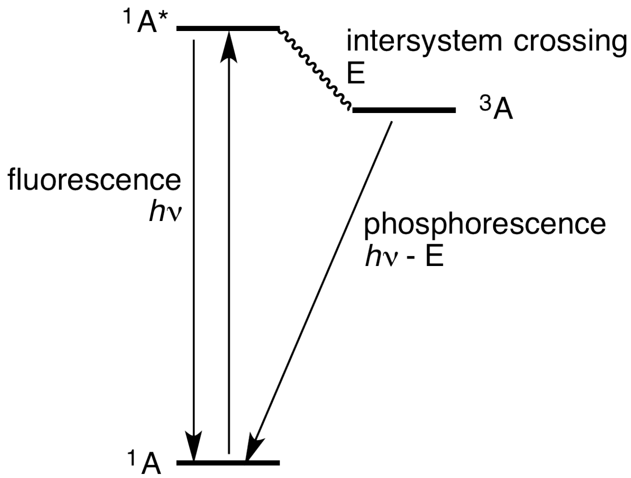
Stimulated emission

The stimulated radiation
of cosmic media affords
a fascinating occupation
for proletarians and lords

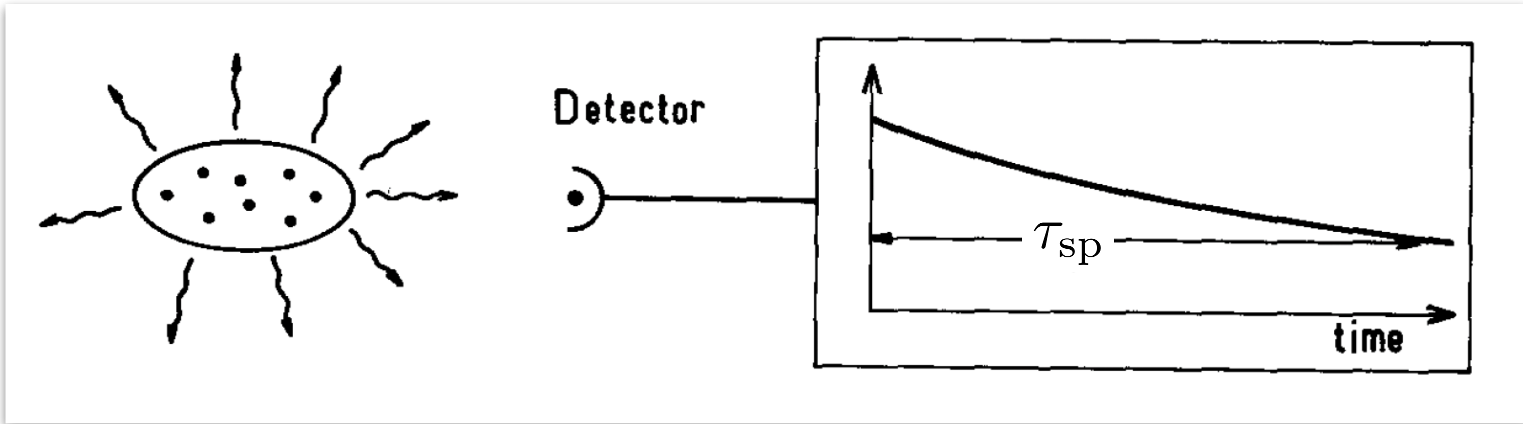
— A. M. Polyakov
(after Nabokov)

Fluorescence

Jablonski diagram:



Source: Wikipedia

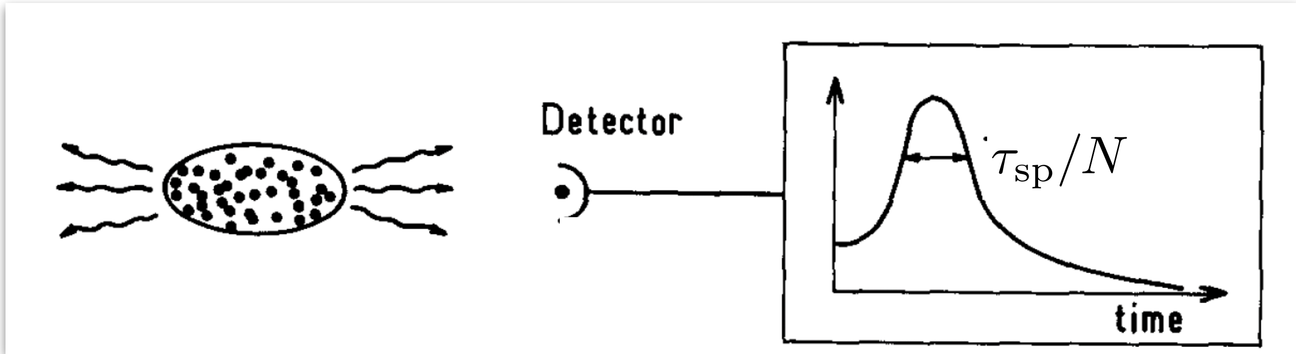


Source: Gross & Haroche, *Phys. Rep.* **93**, 301 (1982)

Superfluorescence I

- Large ensemble of *N* symmetric two-level "atoms", with splitting ω_A
- no interaction with each other, but **collectively coupled to E&M field** at zero temp.
- Initially excited, relax to ground state by emitting **narrow pulse** of coherent radiation

Dicke, *Phys. Rev.* **93**, 99 (1954)



Source: Gross & Haroche

- (independent of **maser/laser** invention at around same time)
- Dicke called this "super-radiant"

Superfluorescence II

- Assume product structure for initial density matrix (Boltzmann's *Stossahlansatz*). MME preserves this structure:

$$\hat{\rho}_N(t) = \hat{\rho}(t) \otimes \hat{\rho}(t) \otimes \cdots \otimes \hat{\rho}(t) \;\text{ for }\; \hat{\rho}(t) = \begin{pmatrix} p(t) & z(t) \\ z^*(t) & 1 - p(t) \end{pmatrix}$$

- $p(t)$ is fraction of atoms in excited state; $z(t)$ is "**quantum coherence**"
- consistency conditions: $0 \le p(t) \le 1$ and $|z(t)|^2 \le p(t)[1 - p(t)]$
- Macroscopic dynamics of system governed by **nonlinear** eqs. of motion:

$$\dot{p} = -\gamma_N |z|^2 \;,$$

$$\dot{z} = -i\omega_A z + \gamma_N \left(p - \frac{1}{2}\right) z \;,$$

- where $\gamma_N = N\gamma_e$ is **decay rate** given by the single-atom spontaneous emission rate γ_e

Kinetic equation

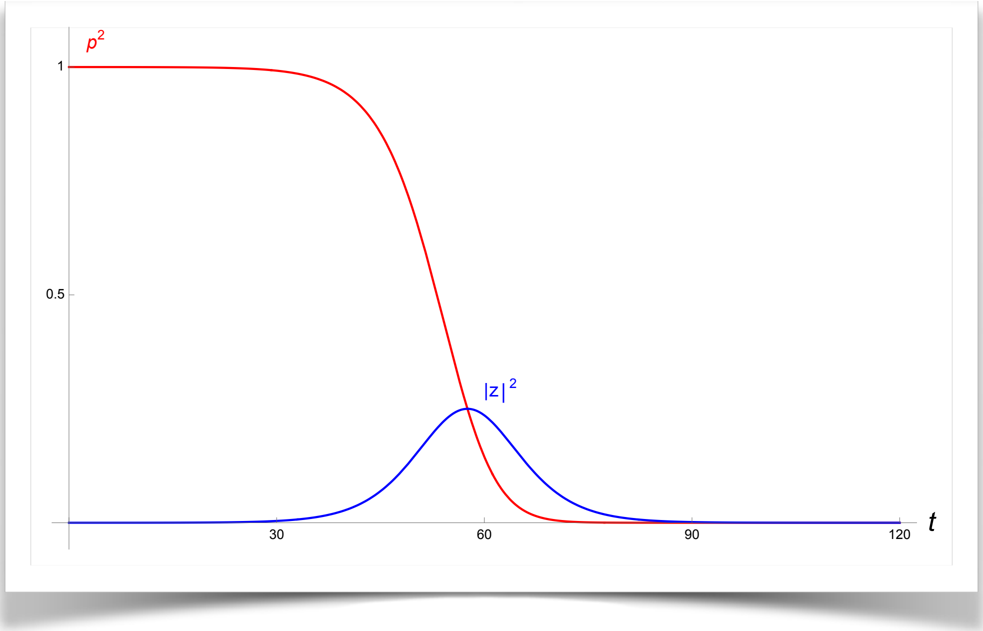
- Although superfluorescence is **irreversible** (due to tracing over subspace of E&M field) single-atom ρ stays pure: $\mathrm{Tr}\,\rho^2(t) = 1$

- thus, $|z(t)|^2 = p(t) - p^2(t)$

- *p* obeys **kinetic eq.**

$$\dot{p} = -\gamma_N p(1-p)\,,$$

with unstable fixed point at $p = 1$ and stable fixed point at $p = 0$



$p(0) = 1 - 10^{-5}$, $\gamma_N = 0.2$

Purity-preserving

- Similar level of description to **Boltzmann eq.** for gas, but with **macroscopic coherence** (quantum) effects: $z(t)$
- Superfluorescence is irreversible ($\Delta S > 0$)
- However, for large N we obtained **non-linear** but purity preserving evolution eqs. for the single-atom state ρ
- $\Rightarrow$ entropy must scale more slowly that $O\left(N^1\right)$
- Might be analogous to **holography** in quantum gravity

FLRW

- **Homogenous, isotropic & Euclidean universe** may be described by Friedmann-Lemaître-Robertson-Walker (FLRW) metric:

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

- $(t, \mathbf{x}) = (t, x, y, z)$ are space-time coordinates in "**cosmic rest frame**"
- Scale factor: $a(t) > 0$
- Hubble parameter: $h(t) \equiv \dot{a}(t)/a(t)$
- de Sitter (dS) solution corresponds to $h =$ const.

Friedmann equations

- Einstein's field eqs. for GR become:

1st Friedmann eq.: $h^2 = \dfrac{8\pi\rho}{3}$;

2nd Friedmann eq.: $\dot{h} = -\dfrac{3}{2}h^2 - 4\pi p$,

Cosmic fluid with energy density ρ

and pressure p

- Natural units: $c = \hbar = k_B = G = M_{\rm Pl}^{-2} = 1$

Cosmic fluid

- co-variant energy "conservation": $\dot{\rho} = -3h(\rho + p)$
- **Eq. of state**: $w \equiv p/\rho$

(a) **radiation** (ultra-relativistic) has $w = 1/3$; $\rho \propto a^{-4}$; $a \sim t^{1/2}$

(b) **matter** (non-relativistic) has $w = 0$; $\rho \propto a^{-3}$; $a \sim t^{2/3}$

(c) **dark energy** (or "**cosmological constant**") has $w = -1 \;\Rightarrow\; \rho =$ const.; $a \sim e^{ht}$ (dS space)

Local physics in expanding space

- If **local system** in static space described by $\hat{H}$, then embedded in expanding space it may be described by

$$\hat{H}_D(t) = \hat{H} + h(t)\hat{D},$$

where $\hat{D}$ is dilation op.

- For wavefuntion $\psi(\mathbf{x})$, acts as $\left[e^{-i\lambda\hat{D}}\psi\right](\mathbf{x}) = e^{-\frac{3}{2}\lambda}\psi\left(e^{-\lambda}\mathbf{x}\right)$
- Therefore $\hat{D} = \dfrac{1}{2}\left(\hat{\mathbf{x}}\cdot\hat{\mathbf{p}} + \hat{\mathbf{p}}\cdot\hat{\mathbf{x}}\right)$, which is a squeezing op.
- Note that dilation term breaks CPT, even for $h = \mathrm{const}$.

Two-body system

- For classical 2-body system

$$H(\mathbf{x}, \mathbf{p}; t) = \frac{\mathbf{p}_A^2}{2m_A} + \frac{\mathbf{p}_B^2}{2m_B} + U(\mathbf{x}_A - \mathbf{x}_B) + h(t)\left(\mathbf{x}_A \cdot \mathbf{p}_A + \mathbf{x}_B \cdot \mathbf{p}_B\right)$$

- eqs. of motion can be expressed in terms of center-of-mass $\mathbf{X} = M^{-1}(m_A \mathbf{x}_A + m_B \mathbf{x}_B)$ for $M = m_A + m_B$, and relative position $\mathbf{x} = \mathbf{x}_A - \mathbf{x}_B$:

$$\ddot{\mathbf{X}} = \left[h^2(t) + \dot{h}(t)\right] \mathbf{X},$$

$$\ddot{\mathbf{x}} = -\frac{1}{\mu} \frac{\partial}{\partial \mathbf{x}} U(\mathbf{x}) + \left[h^2(t) + \dot{h}(t)\right] \mathbf{x}, \quad \text{for} \quad \mu = \frac{m_A m_B}{m_A + m_B}$$

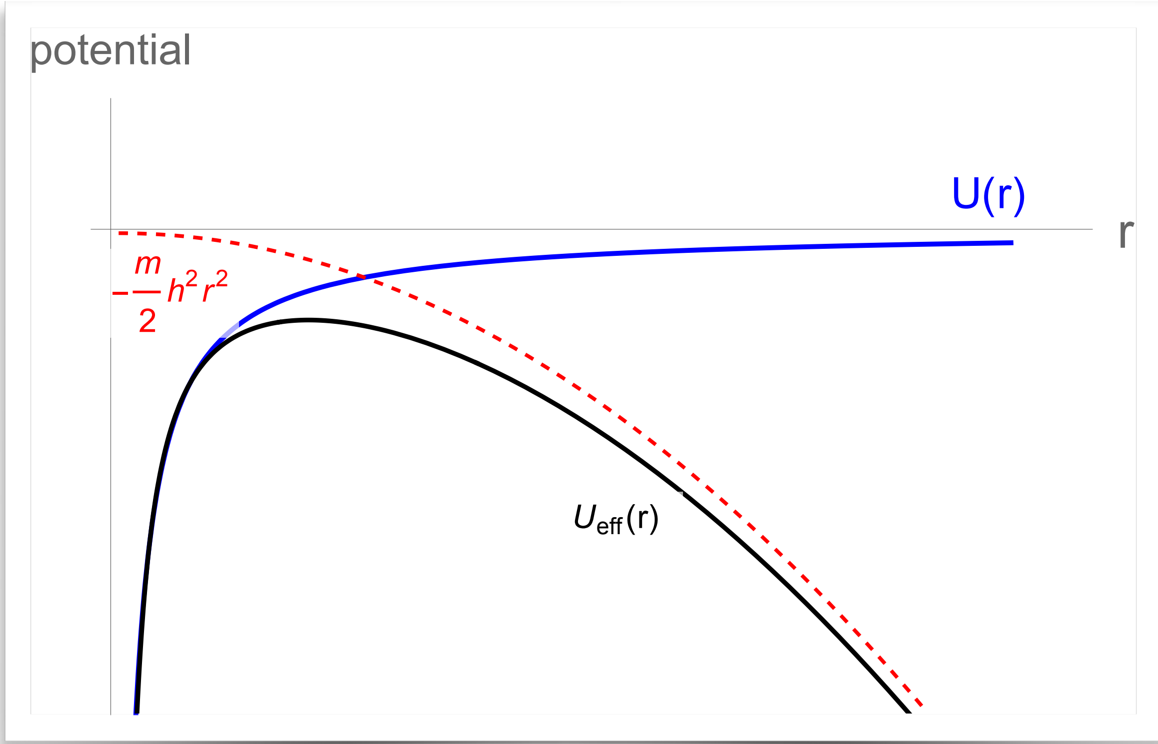
- "**All or nothing**": strongly bound states evolve with <u>bounded</u> $|\mathbf{x}|$, with only slight disturbance

see Price & Romano, *Am. J. Phys.* **80**, 376 (2012);
Faraoni & Jacques, *PRD* **76**, 063510 (2007)

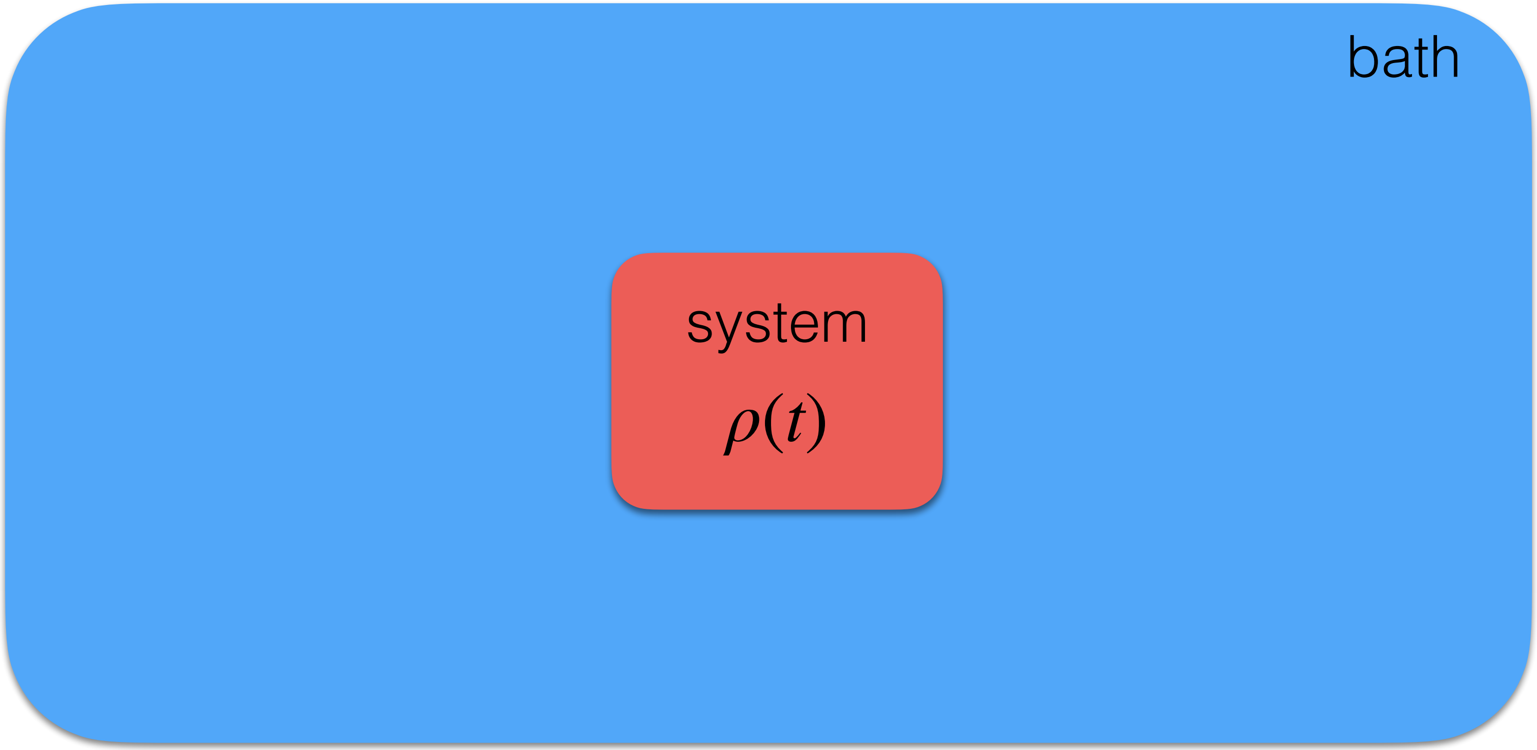
IR instability

- In **quantum** mechanics, expansion turns bound states into **resonances**
- Decay by tunneling through barrier
- This points to an **infrarred (IR) instability** of dS space

cf. Myrhvold ('83); Ford ('85); Mottola ('85); Antoniadis, Iliopoulous & Tomaras ('85); Tsamis & Woodard ('96, '98); Polyakov ('08, '12); Dvali & Gomez ('14); Akhmedov, Moschella & Popov ('19)



Open systems I



Reduced dynamics:

$$\rho(t) = \mathrm{Tr}_{\mathrm{bath}} \left\{ U_{\mathrm{full}}(t) \left[\rho(0) \otimes \sigma_{\mathrm{bath}} \right] U_{\mathrm{full}}^{\dagger}(t) \right\}$$

Open systems II

- For weak coupling, correlations in bath decay fast enough to allow Markovian (i.e., history-independent) approximation:

$$\dot{\rho} = -\frac{i}{\hbar}\left[H_S, \rho\right] + \mathscr{L}\rho$$

- Often called “Lindblad eq.” or “GKLS eq.”

Gorini, Kossakowski & Sudarshan, *J. Math. Phys*. **17**, 821 (1976);
Lindblad, *Commun. Math. Phys*. **48**,119 (1976)

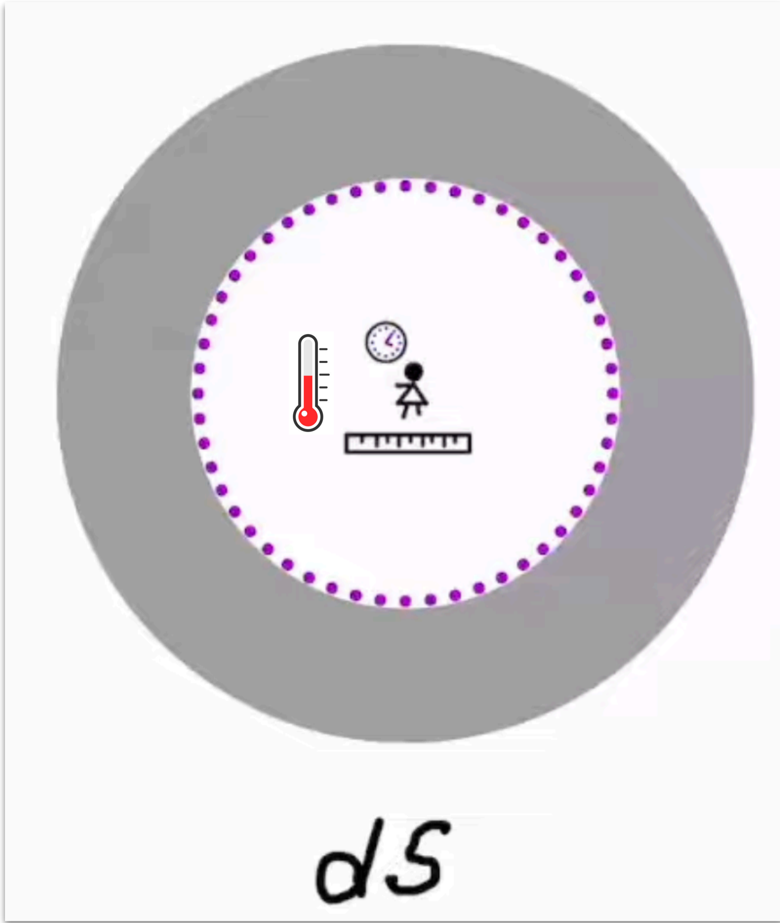
- We’ll say “**Markovian Master Equation**” (**MME**)
- Provides analytical foundation for **quantum thermodynamics**
- see, e.g., Alicki & Lendi, *Quantum Dynamical Semigroups & Applications*, Lect. Notes Phys. **717**, 1 (2007)

Local physics in dS

- What does observer in dS obverse with **local measurement devices**?

  cf. Chandrasekaran, Longo, Penington & Witten, *JHEP* **2302**, 082 (2023); Susskind, arXiv:2304.00589

- Here we'll be concerned with <u>local thermal probe</u> (**thermometer**):
  - **Open system**, weakly coupled to quantum fields in dS
  - We'll use analytical machinery of **quantum thermo.**, based on **MME**



<u>Source</u>: Susskind, "Observers and Observations in de Sitter Space", IAS HET seminar, 23 Aug. 2023, https://youtu.be/vRwamoJKcac

Markovian dynamics

- Let **system** be harmonic oscillator, $\hat{H} = \omega \hat{b}^\dagger \hat{b}$, with $\left[\hat{b}, \hat{b}^\dagger\right] = 1$, where ω is the **renormalized** frequency
- weakly coupled to regularized quantum field $\hat{H}_{\text{int}} = \lambda \left(\hat{b} + \hat{b}^\dagger\right) \otimes \hat{\phi}_\Lambda(0)$, where $\hat{\phi}_\Lambda(0) = \int \frac{d^3k}{\sqrt{2\omega(\mathbf{k})}} e^{-\omega(\mathbf{k})/\Lambda} \left[\hat{a}(\mathbf{k}) + \hat{a}^\dagger(\mathbf{k})\right]$
- **MME** of the form:

$$\frac{d}{dt}\hat{\rho}(t) = -i\left[\hat{H}, \hat{\rho}(t)\right] + \frac{1}{2}\left(\gamma_\downarrow\left(\left[\hat{b}, \hat{\rho}(t)\hat{b}^\dagger\right] + \left[\hat{b}\hat{\rho}(t), \hat{b}^\dagger\right]\right) + \gamma_\uparrow\left(\left[\hat{b}^\dagger, \hat{\rho}(t)\hat{b}\right] + \left[\hat{b}^\dagger\hat{\rho}(t), \hat{b}\right]\right)\right)$$

- with damping $\gamma_\downarrow = \lambda^2 \tilde{G}(\omega)$, and pumping $\gamma_\uparrow = \lambda^2 \tilde{G}(-\omega)$ rates,
- in terms of ***spectral density*** $\tilde{G}(\omega)$, given by Fourier transform of ***bath correlation function*** $G(t)$

Time evolution

- For single **massless scalar boson**, $\hat{H}_D(t) = \hat{H} + h(t)\hat{D}$, with $\hat{H} = |\mathbf{k}|$ and $\hat{D} = i\left(\mathbf{k}\frac{\partial}{\partial \mathbf{k}} + i\frac{3}{2}\right)$
- $\left[\hat{D}, \hat{H}\right] = i\hat{H}$ and Baker-Hausdorff lemma $\Rightarrow e^{-i\alpha\hat{D}}\hat{H}e^{i\alpha\hat{D}} = e^{\alpha}\hat{H}$
- Time-evolution operator $\hat{U}(t)$ **factorizes** nicely:

$$\hat{U}(t) = \mathbf{T}\,\exp\left[-i\int_0^t ds\,\left(\hat{H} + h(s)\hat{D}\right)\right] = \underbrace{e^{-i\nu(t)\hat{D}}}_{\text{dilation}} \cdot \underbrace{e^{-i\tau(t)\hat{H}}}_{\text{propagation}}$$

- Compute

$$\hat{U}'(t) = -\,i\nu'(t)\hat{D}\hat{U}(t) + e^{-i\nu(t)\hat{D}}\left(-i\tau'(t)\hat{H}\right)e^{-i\tau(t)\hat{H}} = -\,i\left[\nu'(t)\hat{D} + \tau'(t)e^{-i\nu(t)\hat{D}}\hat{H}e^{i\nu(t)\hat{D}}\right]\hat{U}(t)$$

$\Rightarrow$ solves Schrödinger eq. $\hat{U}'(t) = -\,i\hat{H}_D(t)\,\hat{U}(t)$, for $\hat{U}(0) = 1$, as long as

$$\nu(t) = \int_0^t ds\,h(s) \quad \text{and} \quad \tau(t) = \int_0^t ds\,e^{-\nu(s)}$$

- For $h =$ const. $\Rightarrow$ $\nu(t) = ht$ and $\tau(t) = \dfrac{1 - e^{-ht}}{h}$
- "**Freezing in**" of super-horizon modes can be understood in these terms

Bath correlation function

$$G_\Lambda^{dS}(t) = \langle \Omega | e^{i\hat{H}_{\mathrm{dS}}t} \hat{\phi}_\Lambda(0) e^{-i\hat{H}_{\mathrm{dS}}t} \hat{\phi}_\Lambda(0) | \Omega \rangle \; ,$$

where $\hat{H}_{\mathrm{dS}}$ is second quantization of single-boson $\hat{H}_D$

- Thus, $G_\Lambda^{dS}(t) = \langle g_\Lambda | \hat{U}(t) | g_\Lambda \rangle$, where $\hat{U}(t)$ is time-evolution op. obtained previously and

$$\langle \mathbf{k} | g_\Lambda \rangle = \frac{e^{-|\mathbf{k}|/\Lambda}}{\sqrt{2|\mathbf{k}|}}$$

for **massless field** (i.e., $\omega(\mathbf{k}) = |\mathbf{k}|$)

- For $h = \mathrm{const}.$ we find: $G_\Lambda^{dS}(t) = \dfrac{\pi}{2} \left(\dfrac{h\Lambda}{h \cosh \frac{ht}{2} + i\Lambda \sinh \frac{ht}{2}} \right)^2$

Spectral density

- This gives

$$\tilde{G}^{dS}_{\Lambda}(\omega) = 2\pi^2\Lambda^2 \frac{\omega}{h^2+\Lambda^2} \operatorname{csch}\left(\frac{\pi\omega}{h}\right) \exp\left[\frac{2\omega}{h} \arcsin\left(\frac{\Lambda}{\sqrt{h^2+\Lambda^2}}\right)\right]$$

- Note that $\tilde{G}^{dS}_{\Lambda}(\omega) > 0$, as per Bochner's theorem
- Has **KMS property** $e^{-\beta\omega} = \dfrac{\tilde{G}^{\mathrm{dS}}_{\Lambda}(-\omega)}{\tilde{G}^{\mathrm{dS}}_{\Lambda}(\omega)}$, with $\beta = \dfrac{4}{h} \arcsin\left(\dfrac{\Lambda}{\sqrt{\Lambda^2+h^2}}\right)$
- $\Lambda \to \infty$ gives temperature $T_{\mathrm{dS}} = \dfrac{1}{\beta} = \dfrac{h}{2\pi}$
- Spectral density is *exactly* **black body**:

$$\tilde{G}^{dS}(\omega) \equiv \lim_{\Lambda\to\infty} \tilde{G}^{dS}_{\Lambda}(\omega) = 2\pi^2\omega \operatorname{csch}\left(\frac{\omega}{2T_{\mathrm{dS}}}\right) e^{\omega/2T_{\mathrm{dS}}} = \frac{(2\pi)^2\omega}{1-e^{-\omega/T_{\mathrm{dS}}}}$$

Temperature

- Same T_{dS} found by Gibbons & Hawking

- They took it to be equivalent for any observer on time-like geodesic, due to $SO(3,1)$ isometry of dS

- Our result applies only to "**cosmic rest frame**"; other observers won't see bath in equilibrium

- Boosts spoil **KMS condition** $e^{-\beta\omega} = \tilde{G}(-\omega)/\tilde{G}(\omega)$, due to Doppler shifts $\omega \to \omega' = \omega - \mathbf{V} \cdot \mathbf{k}$

  Sewell, *J. Phys. A.: Math. Theor.* **41**, 382003 (2008)

- It's known that finite entropy breaks classical dS isometries

  Goheer, Kleban & Susskind, *JHEP* **0307**, 056 (2003)

Stefan-Boltzmann

- Energy density of dS bath obeys Stefan-Boltzmann law

$$\rho_{\rm dS} = \frac{g_f \pi^2}{30} T_{\rm dS}^4$$

- g_f is effective number of polarizations (fermion counts as $7/8$)

- In terms of Hubble parameter,

$$\rho_{\rm dS} = \sigma h^4, \text{ for } \sigma = \frac{g_f}{480\pi^2}$$

- In Standard Model (SM), $\sigma \simeq 0.1$

Cosmological contribution

- Total energy density:

$$\rho = \rho_{\rm dS} + \rho_r = \sigma h^4 + \rho_r$$

- Total pressure:

$$p = p_{\rm dS} + p_r = -\sigma h^4 + w_r \rho_r$$

- Using **1st Friedmann eq.**:

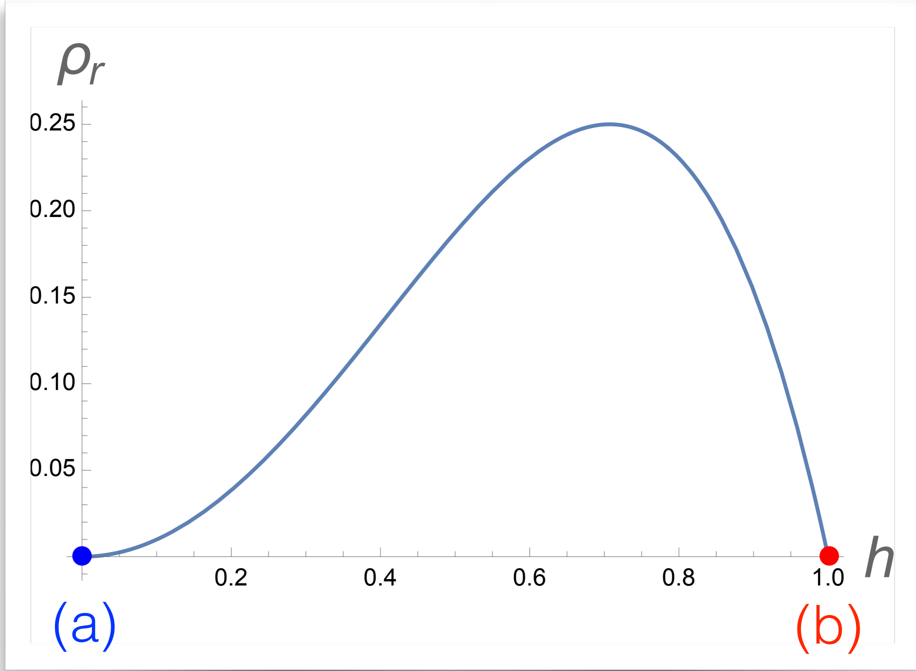
$$\rho_r = \frac{3}{8\pi} h^2 - \sigma h^4$$

- Two solutions with $\rho_r = 0$:

(a) $h = 0$ (Minkowski vacuum)

(b) $h = h_{\rm BD} \equiv \sqrt{\frac{3}{8\pi\sigma}} = 6\sqrt{\frac{5\pi}{g_f}}$,

(Bunch-Davies vacuum)



Horizontal scale in units of $h_{\rm BD}$; vertical scale in units of $\sigma h_{\rm BD}^4$

Note that $h > h_{\rm BD}$ is **forbidden** by $\rho_r \geq 0$

Analogy

- **2nd Friedman eq.** becomes:

$$\dot{h} = -\frac{3}{2}(1 + w_r)\left(\frac{h}{h_{\rm BD}}\right)^2 (h_{\rm BD}^2 - h^2)$$

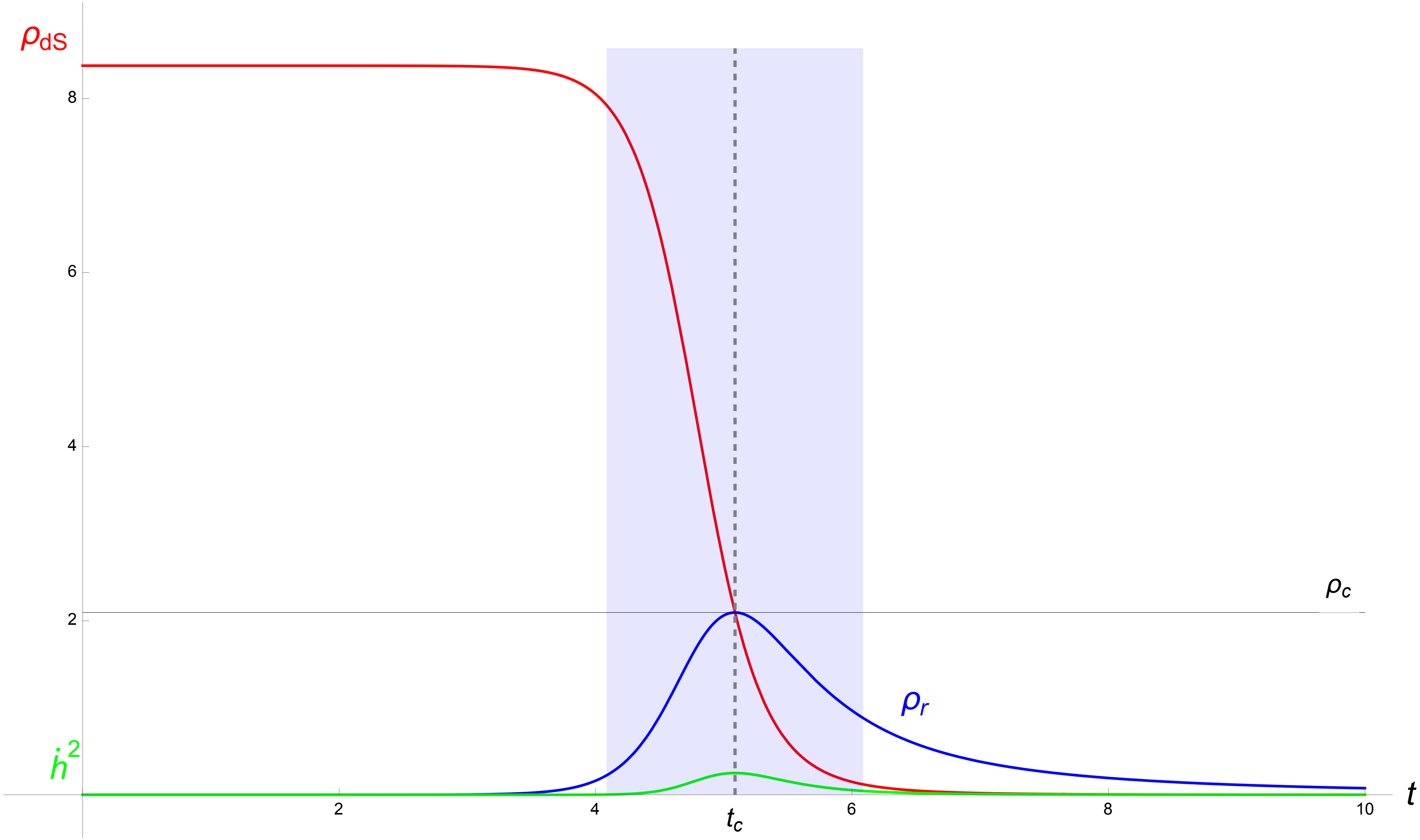
- Compare to **superfluorescent** kinetic eq., $\dot{p} = -\gamma_N p(1-p)$

- Stable fixed point at $h = 0$ (Minkowski), unstable fixed point at $h = h_{\rm BD}$ (Bunch-Davies)

- **Irreversible** relaxation $h \to 0$ solves "**large cosmological constant**" problem

- $|z(t)|^2 = p(t) - p^2(t)$ (**coherence**) analogous to $\rho_r = \frac{3}{8\pi}h^2 - \sigma h^4$ (**regular particle content**)

Irreversible relaxation



$$w_r = 1/3,\ h(0) = h_{BD} \cdot \left(1 - 10^{-9}\right)$$

Initial condition I

- We write $h(t) = 1 - \epsilon(t)$, so that our cosmological evolution eq. becomes
$$\dot{\epsilon} = \frac{3}{2}(1 + w_r)\left[(1-\epsilon)^2 - (1-\epsilon)^4\right] = 3(1+w_r)\epsilon + O\left(\epsilon^2\right)$$
- Inflation ends when $\epsilon(t) \ll 1$ no longer holds
- To get $\gtrsim 60$ e-folds of inflation we need $\epsilon(0) \ll e^{-180(1+w_r)}$
- For $w_r = 1/3$ this becomes $\epsilon(0) \ll e^{-240} \simeq 10^{-104}$
- Might seem absurdly fine-tuned, but analogy to **superfluorescence** suggests nicer interpretation

Initial condition II

- Suppose $\epsilon = 1 - h \geq 0$ is mean value of the ***square*** of collective observable:

$$\epsilon = \langle \hat{e}_N^2 \rangle, \text{ for } \hat{e}_N = \frac{1}{N} \sum_{j=1}^{N} \hat{\xi}_j$$

- If the N-"atom" state is approximately a product or coherent state

$$\epsilon(0) \simeq \frac{1}{N^2} \sum_{j,k=1}^{N} \langle \xi_j \xi_k \rangle = \frac{1}{N^2} \sum_{j=1}^{N} \langle \xi_j^2 \rangle = O\left(N^{-1}\right),$$

assuming $\langle \xi_k \rangle = 0$ and $\langle \xi_k^2 \rangle = O(1)$

- Getting enough e-folds now implies $N \gtrsim 10^{104}$

- Consistent with current estimates of total entropy or "**number of bits**" for Universe

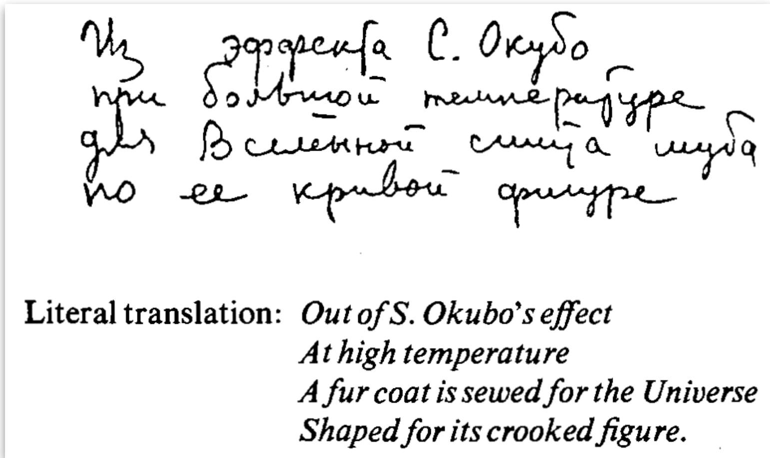
Egan & Lineweaver, *ApJ* **710**, 1815 (2010)

Sakharov conditions

- Relativistic QFT implies existence of **anti-matter** and requires microscopic *CPT* invariance

- Visible Universe contains no anti-matter, baryon-to-photon ratio $\eta = n_B/n_\gamma \simeq 10^{-9}$ far too large to be statistical fluctuation

- Problem usually framed in terms of Sakharov conditions:
    1. Violation of baryon *B* or lepton number *L*
    2. Violation of *C* and *CP* symmetries
    3. Thermodynamic non-equilibrium



Source: Sakharov, *Sov. Phys. Usp.* **34**, 392 (1991); reprinting of *JETP Lett.* **5**, 24 (1967)

Baryogenesis

- *B* and *L* expected to be violated a high energies
- **not conserved by gravity**; e.g., black hole only knows about mass, angular momentum & charge ("no hair")
- Weak force breaks *C* completely, but *CP* only very weakly
- 50+ years of theoretical work on **electroweak** baryogenesis / leptogenesis
- Models typically require **new scalar particles** at high energies
- None yet detected

Spontaneous baryogenesis

- "…all but one are just variations on the theme of out-of-equilibrium decay" — Kolb & Turner, sec. 6.9

- Cohen & Kaplan *PLB* **199**, 251 (1987):

  $\langle\dot{\phi}\rangle \neq 0$ spontaneously breaks *CPT*, allowing baryogenesis without *CP* violation & with *B*-violating interactions in equilibrium

- effective **chemical potential** $\mu \propto \langle\dot{\phi}\rangle$, leading to $e^{\beta\mu} = n_B/\bar{n}_B$ in early Universe

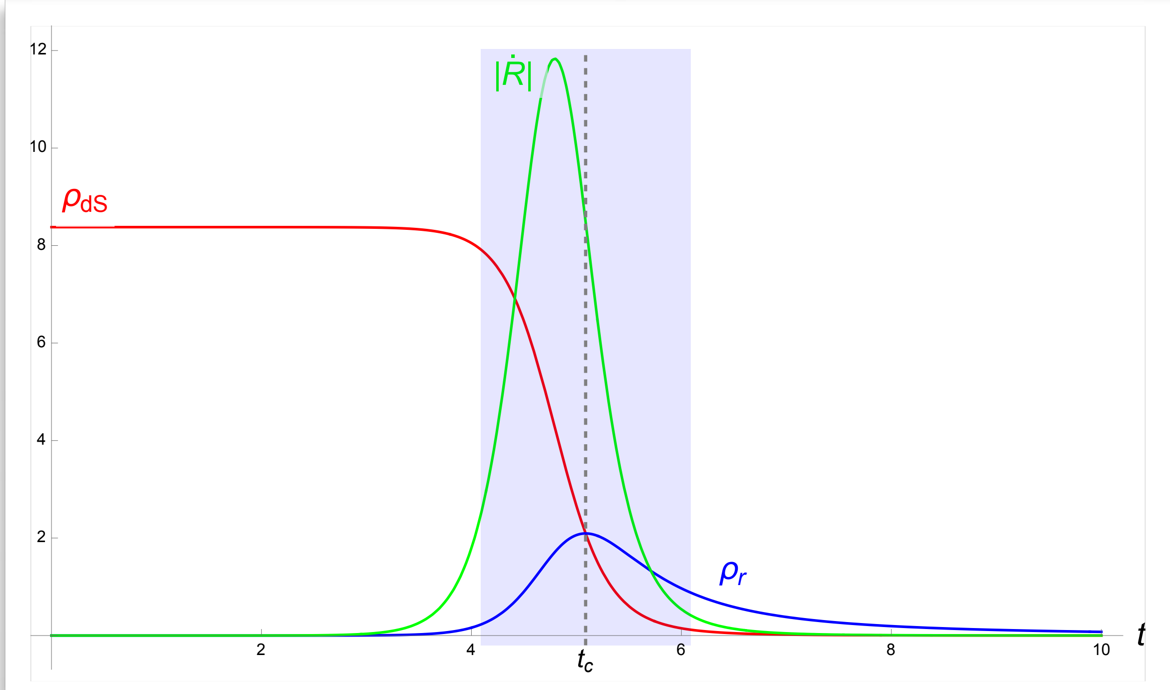
- later $\mu \to 0$, but by then $B - \bar{B}$ is **frozen out**

- **Gravitational baryogenesis**: use gravitational *B* violation & take $\mu \propto \dot{R}$

  Davoudiasl, Kitano, Kribs, Murayama & Steinhart, *PRL* **93**, 201301 (2004)

Gravitational baryogenesis

- In our case, no macroscopic *CPT* invariance due to thermodynamic **irreversibility** (no *detailed balance*)
- Significant matter-antimatter asymmetry during particle production at around $t_{\rm eq}$
- Only time when ordinary particles were in equilibrium with $T_{\rm dS} = h/2\pi$
- Only unknown parameter is proportionality in $\mu \propto \dot{R}$



$$S_{\rm int} = \frac{\hbar}{c}\left(\frac{\hbar}{M_* c^2}\right)^2 \int d^4x \sqrt{|g|}\left(\partial_\mu R\right) j_B^\mu$$

Summary

- We want to understand Universe's expansion as explicitly **irreversible process**

- We've applied analytical methods of **quantum thermodynamics**

- Obtained Gibbons-Hawking $T_{\mathrm{dS}} = h/2\pi$, but only in **cosmic rest frame**

- Extending **Stefan-Boltzmann law** to non-constant h adiabatically, and including contribution of physical bath in Friedmann eqs.

- $\Rightarrow$ inflation without inflaton + **graceful exit**

Outlook

- classical isometries of dS space are **anomalous**
- Agrees with arguments about **IR-instability of dS** by Polyakov, Dvali & Gomez, and many others
- Analogy to **superfluorescence** may point to underlying quantum theory ("*it from qubit*")
- Provides natural implementation of **gravitational baryogenesis**
- May simplify our picture of early Universe's dynamics