Super-radiance during reheating

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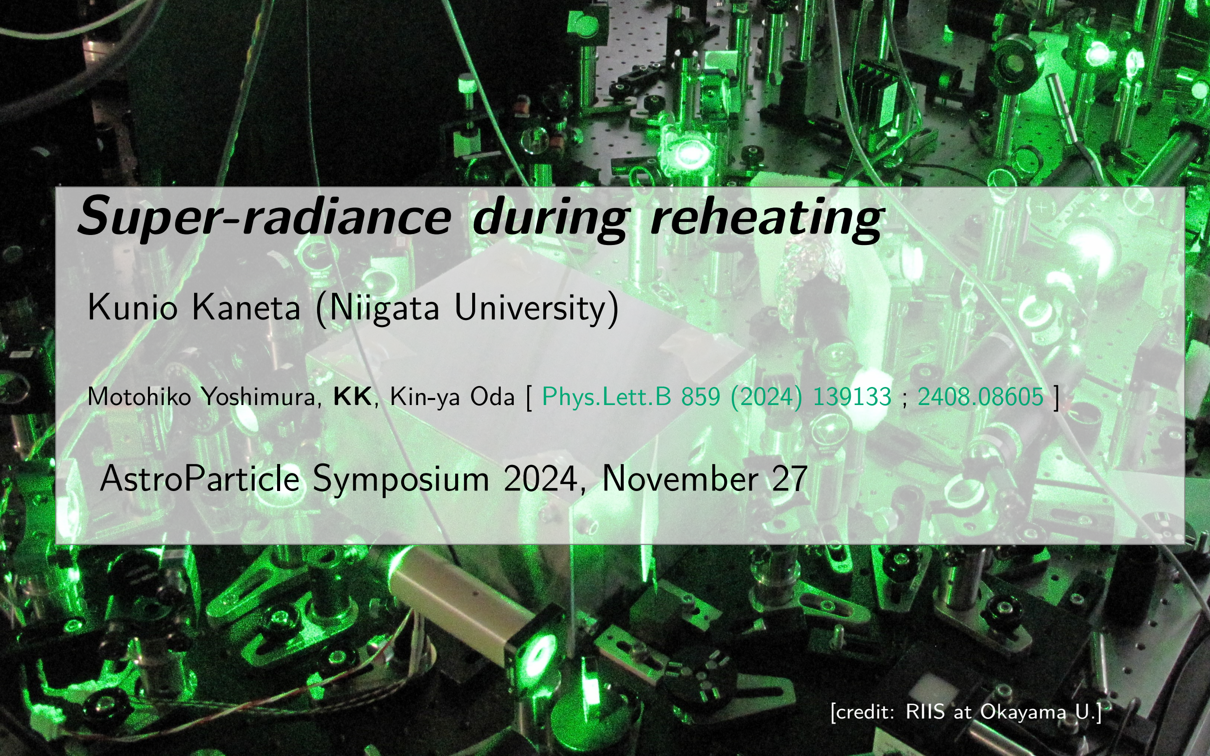
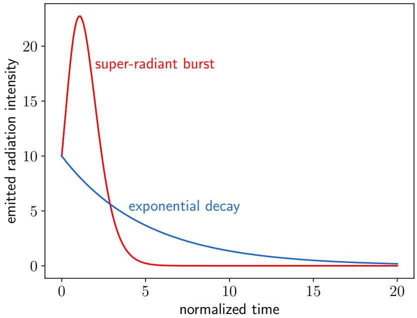


[credit: RIIS at Okayama U.]

Outline



- Introduction
  - Dicke super-radiance
  - Beyond Dicke
- Macro-coherence during reheating
  - Preheating in Schrödinger picture
  - Parametrically amplified macro-coherence
- Abrupt end of reheating
  - Dicke model during reheating
  - Super-radiant burst

- Introduction

Dicke's work on super-radiance

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Coherence in Spontaneous Radiation Processes

R. H. Dicke
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

(Received August 25, 1953)

[Princeton U.]

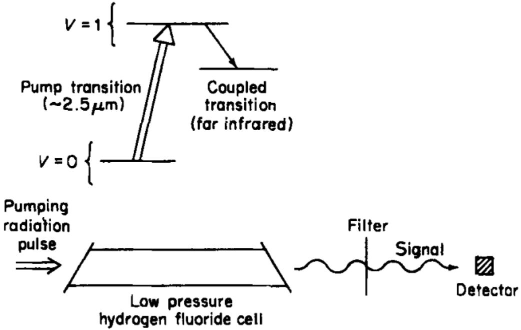
Consider a totally excited two-level atomic system:

- Spontaneous emission happens when
  - atoms are well-separated and random
  - separation between atoms $\gg$ photon wave length
  - $\Rightarrow$ exponential decay
- Super-radiant emission happens when
  - atoms are close and phase-aligned
  - separation between atoms $\ll$ photon wave length
  - $\Rightarrow$ pulse-like burst

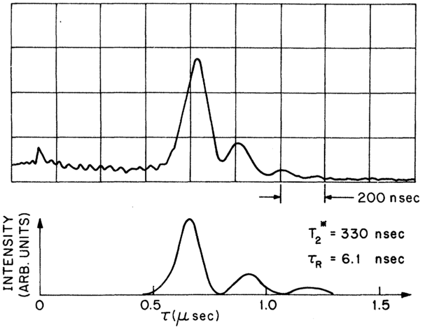
Coherence of radiated photon is a key for super-radiance

Super-radiance in laboratories

MIT group observed super-radiance for the first time [Skribanowitz et al, '73]



[Macgillivray et al, 81]



[Skribanowitz et al, '73]

- Irradiated atoms by laser emit puls-like radiation
- Radiated light is highly directional (phase-aligned)

Beyond Dicke super-radiance

- Super-radiant region for single photon emission is limited to the laser direction
  - dipole transition:

$$|\psi\rangle = c_e|e\rangle + c_g|g\rangle, \qquad H = \begin{pmatrix} \hbar\omega_0/2 & d_{eg} \\ d_{ge} & -\hbar\omega_0/2 \end{pmatrix}$$

  - single photon emission (wavelength $\lambda \sim 1/k$):

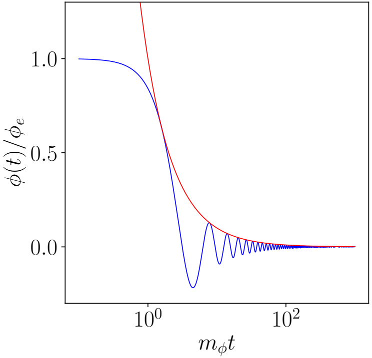
$$d_{ge} \quad \text{from} \quad \langle g|H_{\rm NR}|e\rangle \sim \sum_{a=1}^{N} \vec{d}\cdot\vec{A}(\vec{r}_a) \sim \sum_{a=1}^{N} \vec{d}\cdot\vec{\epsilon}_\lambda e^{i\vec{k}\cdot\vec{r}_a}$$

$$N \gg 1 \quad \Rightarrow \quad \text{(transition amp.)} \propto \int d^3r e^{i\vec{k}\cdot\vec{r}} \sim \begin{cases} \text{vol.} \times (kR)^{-2} & (R \gg 1/k) \\ \text{vol.} & (R \ll 1/k) \end{cases}$$

  - super-radiant emission only when (target length) $\ll$ (photon wavelength)
- Macro-coherence to extend the super-radiant region [Yoshimura et al, '08]
  - photon pair emission: $|e\rangle \to |g\rangle + \gamma(k_1) + \gamma(k_2)$
  - kinematically $\vec{k} = \vec{k}_1 + \vec{k}_2 \quad \Rightarrow \quad$ easily $k \to 0$ for the collimated photons
  - macroscopic coherence (phase alignment) may be realized

- Macro-coherence during reheating

Preheating after the end of inflation



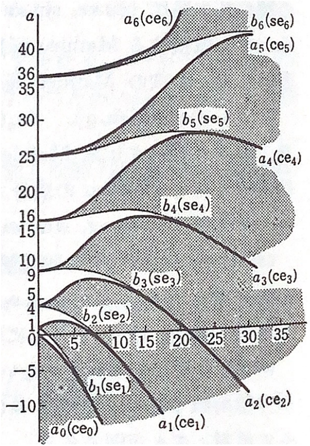
- Focus on the reheating stage
  - Harmonic oscillator approximation:

$$V(\phi) \simeq \frac{1}{2} m_\phi^2 \phi^2$$

- Particle creation
  - Suppose ϕ decays into a pair of photons
  - $\phi(\vec{k}=0) \to \gamma(\vec{k}_1)\gamma(\vec{k}_2)$, then $\vec{k}_2 = -\vec{k}_1$
  - Phase of the decay products is aligned
- **Macro-coherence may naturally be realized during preheating**

Parametric resonance during preheating

- Consider the $\{\phi, \gamma\}$-system, and neglect expansion of the Universe (for simplicity)
- E.g. ϕ-γ-γ coupling: $\mathcal{L}_{\rm int} = -\frac{1}{4}K\phi(F_{\mu\nu})^2 \quad (K \sim b\alpha/4M_P$ for conformal anomaly$)$



- EoM: $\ddot{\vec{A}}_k + k^2\vec{A}_k + \frac{K\dot{\phi}}{1+K\phi}\dot{\vec{A}}_k = 0$
- After field redefinition and some approximation, each polarization satisfies

$$A_k'' + (a - 2q\cos 2\tau)A_k = 0$$
$$(\tau = m_\phi(t+\pi)/2, a = (2k/m_\phi)^2, q = K\phi_e)$$

- $q \ll 1$ (narrow resonance)
  - perturbative production around $a = n^2$ $(n = 1, 2, 3, \cdots)$
  - corresponds to $n \times \phi \to \gamma\gamma$
- $q \gg 1$ (broad resonance)
  - non-perturbative production for $a \leq 2q$
  - occupation number grows exponentially

Parametrically amplified macro-coherent state

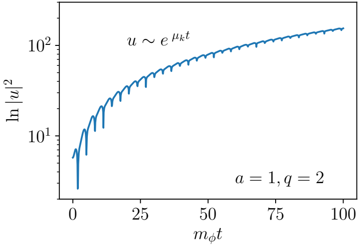
- Consider parametric resonance in Schrödinger picture [Yoshimura '95]
- Hamiltonian of a bosonic field b may be given by

$$H = \int d^3x \frac{1}{2}\left[\pi_b^2 + (\vec{\nabla} b)^2 + m_b^2(t) b^2\right], \qquad m_b^2(t) \sim m_0^2 + f(\phi(t))$$

  - For each Fourier mode b_k, the wave functional ψ satisfies the Schrödinger eq.:

$$i\frac{\partial \psi}{\partial t} = -\frac{1}{2}\frac{\partial^2 \psi}{\partial b_k^2} + \frac{1}{2}\omega_k^2(t) b_k^2 \psi \quad \Rightarrow \quad \psi(b_k, t) = \left(\frac{\mathrm{Re}D}{\pi}\right)^{1/4} e^{-(D/2)b_k^2}$$

  - $D = \pi/|u|^2 - (i/2)\frac{d}{dt}\ln|u|^2$ with $\ddot{u} + \omega_k^2(t) u = 0 \quad \Leftrightarrow \quad$ Mathieu equation

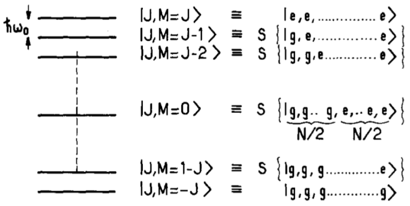


- $\mathrm{Im}D \sim \frac{d}{dt}\ln|u|^2 \sim$ const. (related to the Floquet exponent)
  - Phase in ψ aligns after a number of oscillations
  - Macro-coherent state is achieved, leading to super-radiant decay of inflaton

- Abrupt end of reheating

Dicke model during reheating

- Super-radiance becomes possible when $\mathrm{Im}D \to$ const. (phase aligned)
  - Analogy: atoms $\leftrightarrow$ harmonic oscillators of inflaton
  - Number of oscillator per Hubble volume: $\mathcal{N}_\phi \sim n_\phi / H^3 \sim \rho_\phi / m_\phi H^3 \sim 10^{12}$
- Excitation and de-excitation of the oscillators may be described by the algebra of the total angular momentum [Dicke '53]
  - For the ath oscillator, $[R_i^{(a)}, R_j^{(a)}] = i\epsilon_{ijk} R_k^{(a)}$
  - Raising/lowering ops. $R_\pm^{(a)} = R_1^{(a)} \pm i R_2^{(a)}$ to describe excitation and de-excitation
  - For the entire system, $R_i = \sum_{a=1}^{\mathcal{N}_\phi} R_i^{(a)}$, satisfying $[R_i, R_j] = i\epsilon_{ijk} R_k$



[Gross,Haroche '82]

- System expressed as the eigenstate of R^2 and R_3:

$$R^2|J,M\rangle = J(J+1)|J,M\rangle,$$
$$R_3|J,M\rangle = M|J,M\rangle$$

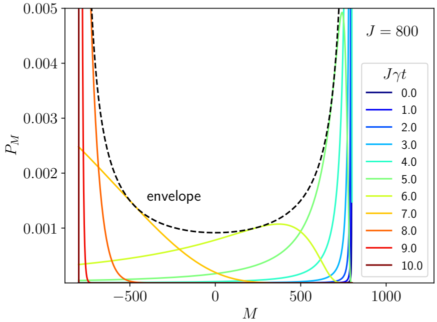
- $J \sim \mathcal{N}$ (number of excited states):

$$\mathcal{N} \sim \underbrace{\mathcal{N}_\phi}_{\text{number of oscillators}} \times \underbrace{M_P/m_\phi}_{\text{number of levels}} \sim 10^{15}$$

Evolution of population probability

- The probability $P_M(t)$ of finding the system at $|J, M\rangle$:

$$\frac{dP_M}{dt} = \gamma \left(\underbrace{|\langle J, M+1|R^+|J, M\rangle|^2 P_{M+1}}_{\text{populate } M \text{ state by annihilating } M+1 \text{ state}} - \underbrace{|\langle J, M-1|R^-|J, M\rangle|^2 P_M}_{\text{annihilate } M \text{ state}} \right)$$



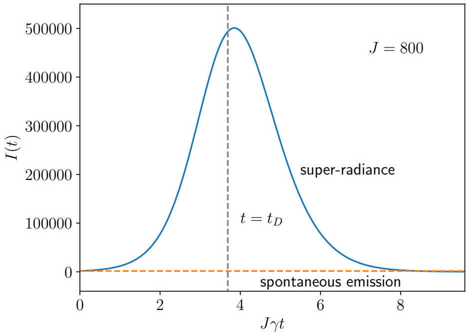
- γ: the decay rate of a single inflaton oscillator
- $R^{\pm} \equiv R_1 \pm iR_2$: excitation and de-excitation operators
- $|\langle J, M \pm 1|R^{\pm}|J, M\rangle|^2 = (J \mp M)(J \pm M + 1)$
- Initial condition: $P_M(t=0) = \delta_{J,M}$

- Stays $M \sim J$ until $J\gamma t \sim 6$, then quickly decays to reach the grand state

Delay time and the end of reheating

- Duration to deplete all excited states (delay time t_D)
  - $2n = J - M$ photons are emitted
  - Decay rate of $M \to M-1$: $\Gamma_{M\to M-1} = \gamma(J+M)(J-M+1) \sim \gamma J n \sim \gamma \mathcal{N} n$
  - $t_1 = (\gamma\mathcal{N})^{-1}$, $t_2 = (2\gamma\mathcal{N})^{-1}$, $t_3 = (3\gamma\mathcal{N})^{-1}$,...

$$t_D \sim t_1 + t_2 + t_3 + \cdots + t_{\mathcal{N}} \sim \frac{\ln\mathcal{N}}{\mathcal{N}} \times \frac{1}{\gamma} \ll \frac{1}{\gamma}$$

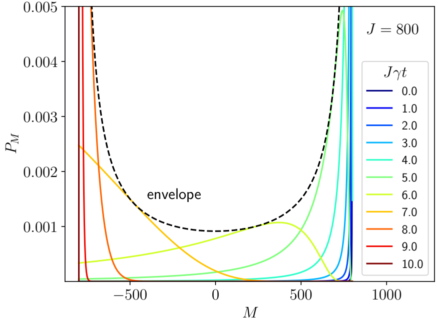


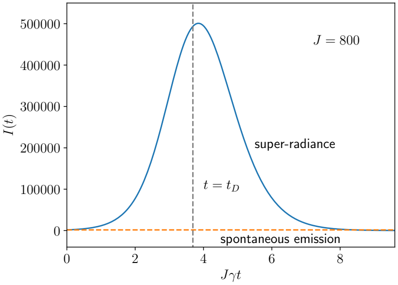
- Intensity (number of photons emitted per unit time)

$$I(t) = -\frac{d}{dt}\langle M\rangle = -\frac{d}{dt}\sum_{M=-J}^{J} M P_M(t)$$

  - Peak at $t \sim t_D$
  - $\gamma_{\rm eff} \sim \gamma \times \mathcal{N}/\ln\mathcal{N}$
  - Crudely, $T_{\rm RH} \sim \sqrt{\gamma M_P} \times (\mathcal{N}/\ln\mathcal{N})^{1/2}$

Summary





- Summary
  - **Reheating by super-radiance is proposed**
  - The phase of decay products is aligned during preheating, leading to the super-radiance
  - Super-radiant decay of inflaton is faster by a factor of $\ln \mathcal{N}/\mathcal{N}$ than the spontaneous decay
- Outlook
  - More precise study is needed (e.g. expansion rate, backreaction, etc)
  - De-phasing effects should be incorporated (e.g. interactions among decay products)
  - Implications (e.g. DM, BAU, etc)