Dicke's Superradiance - From millisecond fast radio bursts to multiyear maser bursts

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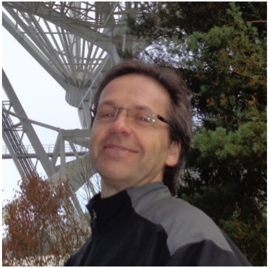
Sept 28, 2018



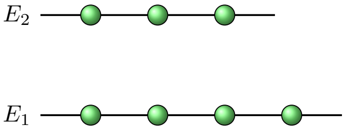
Prof. Martin Houde

Outline

Maser - Inverted Medium

- Maser stands for microwave **amplification by stimulated emission** of radiation.
- Amplification by stimulated emission can be achieved in an inverted medium.

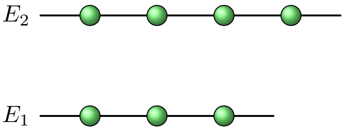
Normal medium



$$\frac{n_2}{n_1} = \frac{g_2}{g_1} \exp\left(-\frac{E_2 - E_1}{kT}\right)$$

Local Thermodynamic (LTE)

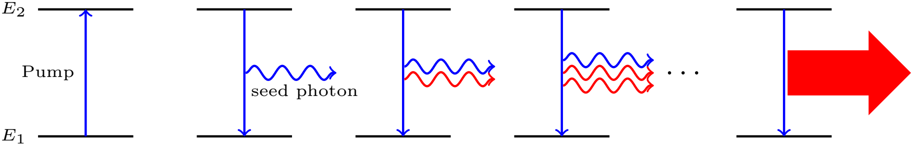
Inverted medium



$$\frac{n_2}{n_1} \neq \frac{g_2}{g_1} \exp\left(-\frac{E_2 - E_1}{kT}\right)$$

Non-LTE

Maser - Stimulated Emission Process



- **A series of successive stimulated events results in a maser.**
- **A maser can be described using distributed quantum systems.**

Dicke's Superradiance

PHYSICAL REVIEW VOLUME 93, NUMBER 1 JANUARY 1, 1954

Coherence in Spontaneous Radiation Processes

R. H. DICKE
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received August 25, 1953)

By considering a radiating gas as a single quantum-mechanical system, energy levels corresponding to certain correlations between individual molecules are described. Spontaneous emission of radiation in a transition between two such levels leads to the emission of coherent radiation. The discussion is limited first to a gas of dimension small compared with a wavelength. Spontaneous radiation rates and natural line breadths are calculated. For a gas of large extent the effect of photon recoil momentum on coherence is calculated. The effect of a radiation pulse in exciting "super-radiant" states is discussed. The angular correlation between successive photons spontaneously emitted by a gas initially in thermal equilibrium is calculated.

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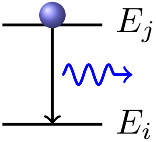
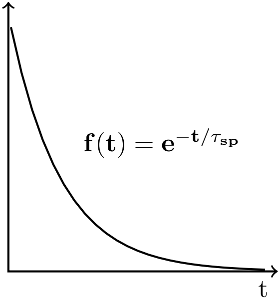
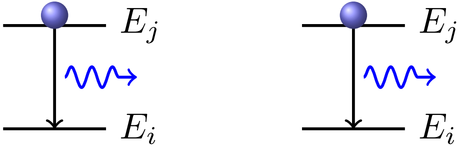
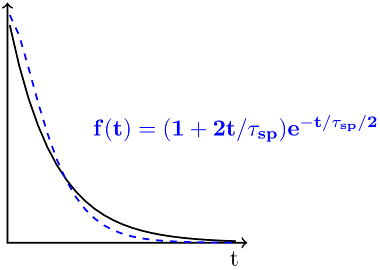
Dicke's Superradiance - Spontaneous Decay Time-scale

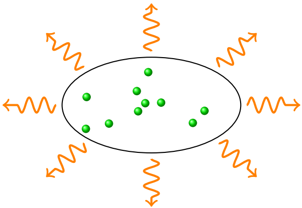






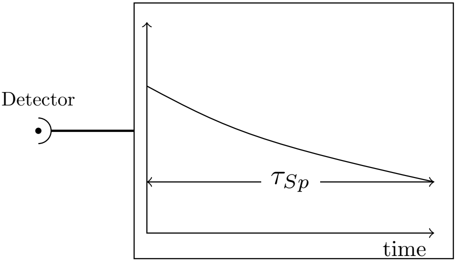


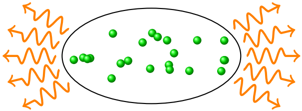
Dicke's Superradiance - Intensity



$\mathbf{I} \propto \mathbf{N}$

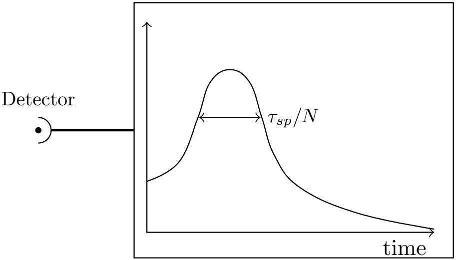
Non-coherent System





$\mathbf{I} \propto \mathbf{N^2}$

Coherent System
(Superradiance)



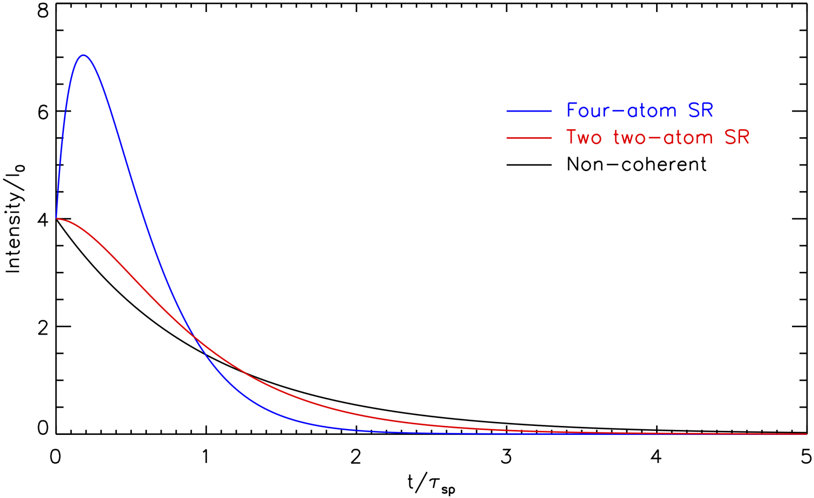
Dicke's Superradiance - Intensity

Dicke (symmetric) states	Intensity
$\|eeee\rangle$	
$\downarrow$	$4I_0$
$\frac{1}{2}\left[\|geee\rangle + \|egee\rangle + \|eege\rangle + \|eeeg\rangle\right]$	
$\downarrow$	$6I_0\left[= \frac{1}{2}N\left(N-1\right)\right]$
$\frac{1}{\sqrt{6}}\left[\|ggee\rangle + \|gege\rangle + \|geeg\rangle + \|egge\rangle + \|egeg\rangle + \|eegg\rangle\right]$	
$\downarrow$	$6I_0\left[= \frac{1}{2}N\left(N-1\right)\right]$
$\frac{1}{2}\left[\|eggg\rangle + \|gegg\rangle + \|ggeg\rangle + \|ggge\rangle\right]$	
$\downarrow$	$4I_0$
$\|gggg\rangle$	

Dicke's Superradiance - Intensity

Four independent atoms	Superradiance
$\|eeeg\rangle$	$\|3\rangle = \frac{1}{2}\left(\|eeeg\rangle + \|eege\rangle + \|egee\rangle + \|geee\rangle\right)$
$\|eegg\rangle$	$\|2\rangle = \frac{1}{\sqrt{6}}\left(\|ggee\rangle + \|gege\rangle + \|geeg\rangle + \|egge\rangle + \|egeg\rangle + \|eegg\rangle\right)$
$\langle eeeg\|\hat{d}\|eegg\rangle$	$\langle 2\|\hat{d}_1 + \hat{d}_2 + \hat{d}_3 + \hat{d}_4\|3\rangle = \frac{12}{2\sqrt{6}}\langle eeeg\|\hat{d}\|eegg\rangle$
$\downarrow$	$\downarrow$
$(N = 4\times) I_0$	$6I_0 = \frac{N}{2}\left(\frac{N}{2}+1\right) I_0$

Dicke's Superradiance - Intensity



Superradiance vs. Maser

Superradiance $\neq$ maser

- Cooperative (coherent) vs. collective phenomena
- Single vs. distributed quantum mechanical events
- Intensity of radiation (N-atoms) :

$$I_{\mathrm{SR}} \propto N^2 \text{ vs. } I_{\mathrm{maser}} \propto N$$

"Search for superradiance in masing regions"

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"Search for superradiance in masing regions"

Dicke's Superradiance - Requirements

Some requirements similar as for maser action:

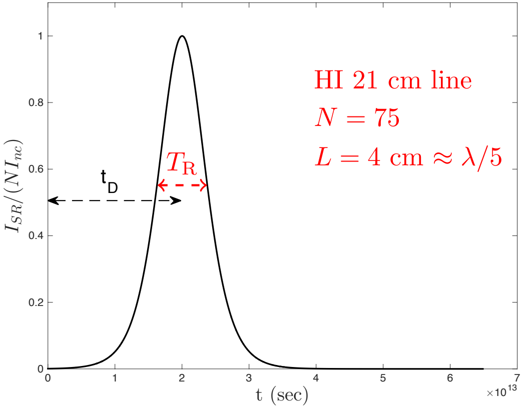
- **Population inversion**
- **High velocity coherence**

Further requirements:

- **Dephasing/relaxation timescales (e.g., collisions) longer than superradiance timescale (T_{R}, $\tau_{\mathrm{D}} < T'$)**

Superradiance - Small-sample

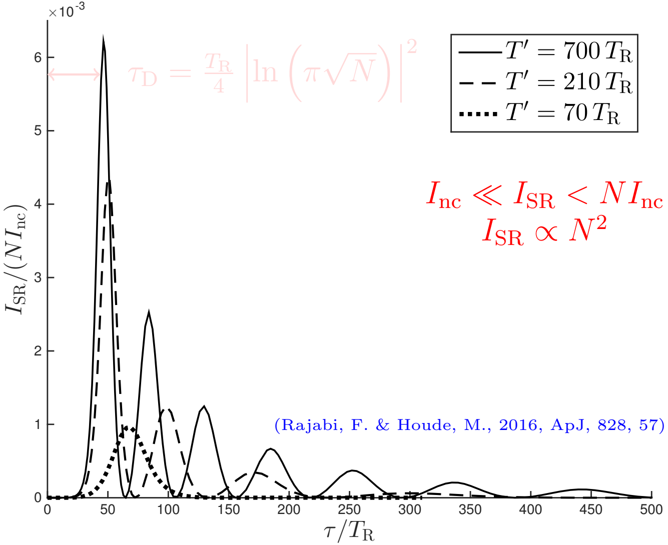
- Volume $\ll \lambda^3$
- Short decay timescales ($T_{\mathrm{R}} = \tau_{\mathrm{sp}}/N$, $t_{\mathrm{D}} = T_{\mathrm{R}} \ln(N)$)
- Very directional radiation beam
- Burst-like phenomenon ($I_{\mathrm{S}R} = N I_{\mathrm{nc}} \propto N^2$)



(Rajabi, F. & Houde, M., 2016, ApJ, 826, 216)

Superradiance - Large-sample

- Volume $\gg \lambda^3$
- Timescale $T_\mathrm{R} = \frac{8\pi\tau_{sp}}{3\lambda^2(nL)}$, (nL) column density



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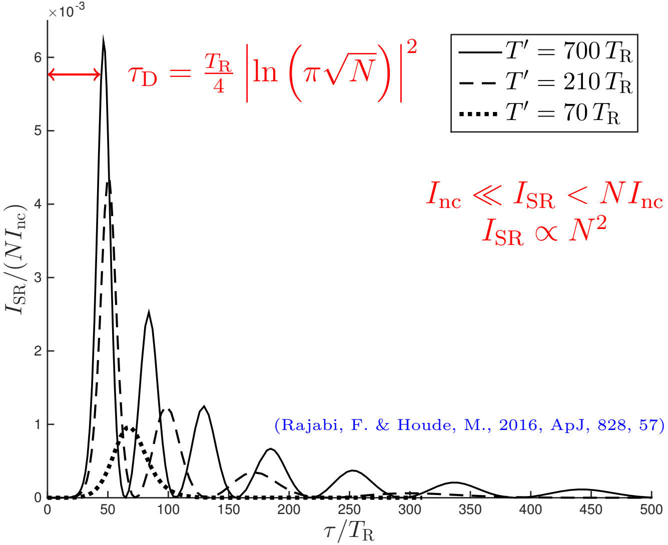
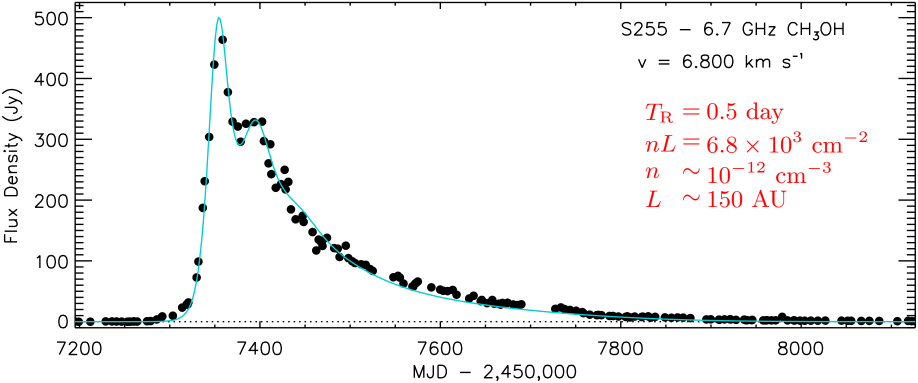


Dicke's Superradiance in Astrophysics

Superradiance - Methanol 6.7 GHz (preliminary results)

S255: massive star-forming region, 1.78 kpc away



(Rajabi, F., Houde M. et al. , in preparation)

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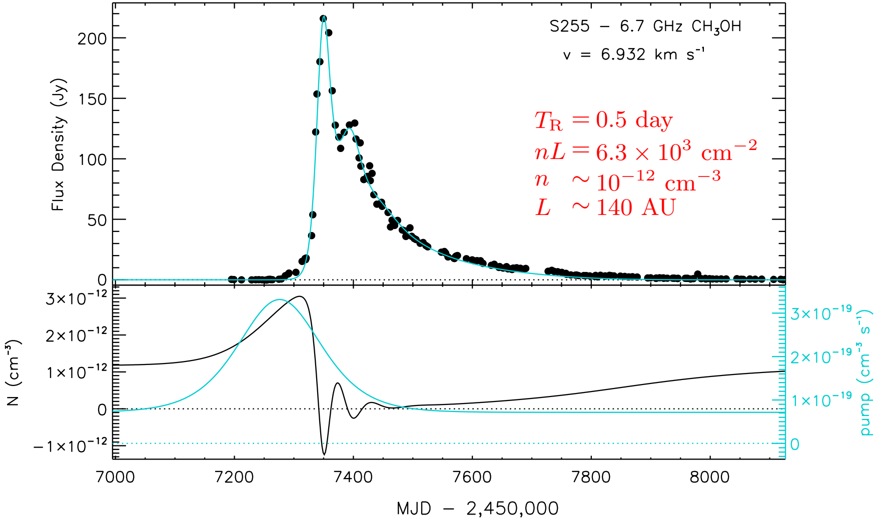
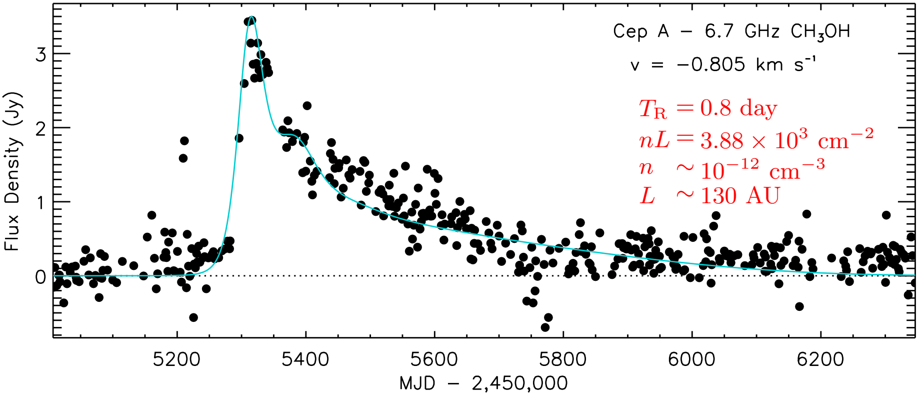


(Rajabi, F., Houde M. et al. , in preparation)

Superradiance - Methanol 6.7 GHz (preliminary results)

Cepheus A: massive star-forming region, 0.7 kpc away



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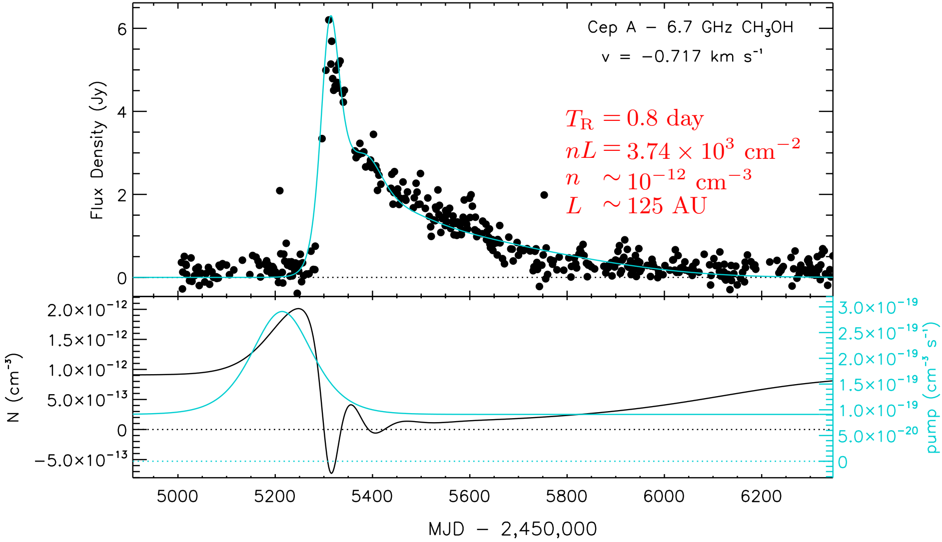


(Rajabi, F., Houde M. et al. , in preparation)

Maser vs. Superradiance

One of the requirements (dephasing):

$$T_{\mathrm{R}}, \tau_{\mathrm{D}} < T' \quad \text{where} \quad \begin{cases} T_{\mathrm{R}} = \frac{8\pi\tau_{\mathrm{sp}}}{3\lambda^2(nL)} \\ \tau_{\mathrm{D}} \simeq \frac{T_{\mathrm{R}}}{4}\left|\ln\left(\pi\sqrt{N}\right)\right|^2 \end{cases}$$

Implies the existence of a threshold

$$(nL)_{\mathrm{crit}} \simeq \frac{2\pi}{3\lambda^2}\frac{\tau_{\mathrm{sp}}}{T'}\left|\ln\left(\pi\sqrt{N}\right)\right|^2$$

$(nL) < (nL)_{\mathrm{crit}} \quad \rightarrow \quad$ Maser.

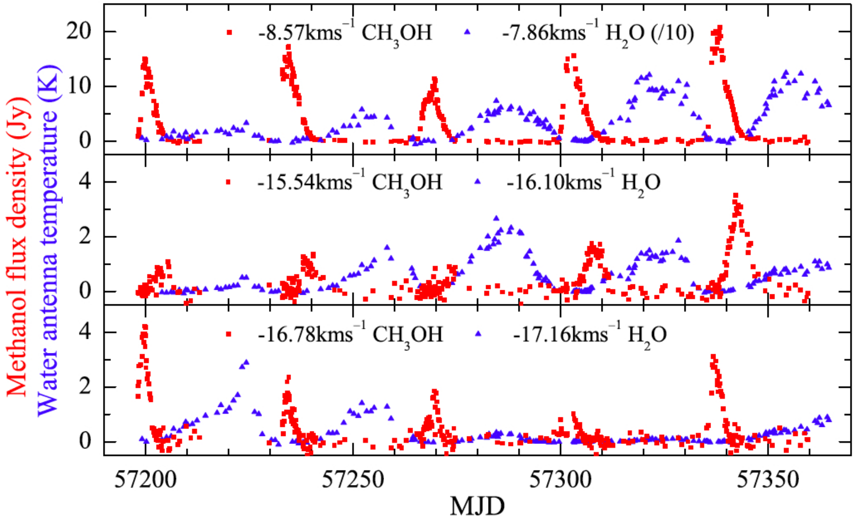
$(nL) > (nL)_{\mathrm{crit}} \quad \rightarrow \quad$ Maser breaks into a very large number of superradiant samples.

(Rajabi & Houde 2017, Science Advances, 3, e1601858)

Methanol 6.7 GHz + Water 22 GHz

HMYSO G107.298+5.639

Szymczak et al. (2016, MNRAS, 459, L56)



Methanol 6.7 GHz + Water 22 GHz

$$T_{\mathrm{R}} \propto \left[\frac{\tau_{\mathrm{sp}}}{\lambda^2} \cdot \frac{1}{(nL)}\right]$$

For simplicity, we assume $(nL)_{\mathrm{CH_3OH}} = (nL)_{\mathrm{H_2O}}$:

$$\frac{T_{\mathrm{R}}\,(\mathrm{H_2O})}{T_{\mathrm{R}}\,(\mathrm{CH_3OH})} = \frac{\tau_{\mathrm{sp}}\,(\mathrm{H_2O})}{\tau_{\mathrm{sp}}\,(\mathrm{CH_3OH})} \cdot \frac{\lambda^2\,(\mathrm{H_2O})}{\lambda^2\,(\mathrm{CH_3OH})} \simeq 8.7$$

$\downarrow$

Water burst is expected to have a longer duration and delay...

Simultaneously triggered superradiance pulses reproduce the observed duration and time-ordering of the methanol and water bursts?

Methanol 6.7 GHz + Water 22 GHz

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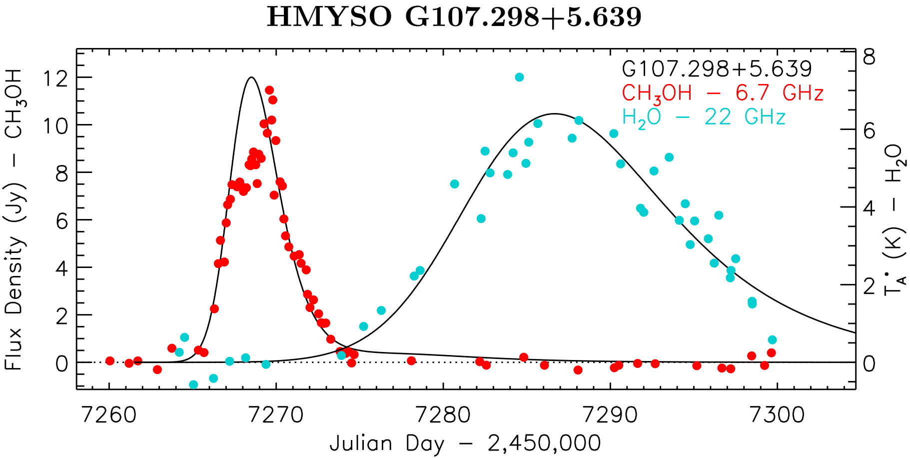


$$\langle T_R \rangle_{CH_3OH} = 2.1\text{hrs}, \quad T'_{CH_3OH} = 90\,\langle T_R \rangle_{CH_3OH}, \quad \langle nL \rangle_{CH_3OH} \approx 3.5 \times 10^4 \text{cm}^{-2}$$

$$\langle T_R \rangle_{H_2O} = 7.7\text{hrs}, \quad T'_{H_2O} = 70\,\langle T_R \rangle_{H_2O}, \quad \langle nL \rangle_{H_2O} \approx 8.4 \times 10^4 \text{cm}^{-2}$$

(Rajabi, F. & Houde, M., 2017, Science Advances, Vol. 3, no. 3, e1601858)

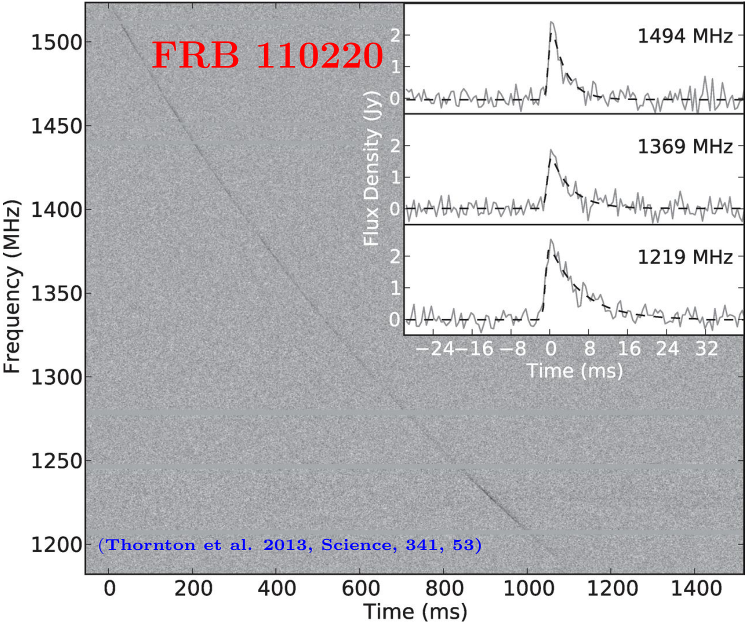
Superradiance and Fast Radio Bursts

Abhilash Mathews now a PhD student at MIT

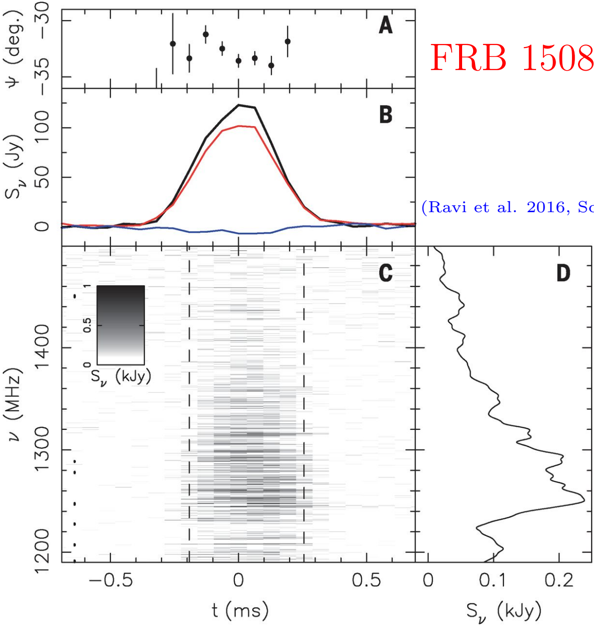
Superradiance - FRBs

- Very short duration (~ 1) millisec
- Extremely bright
- Large spectral bandwidth (~ 100 MHz at 1.4 GHz)
- Extragalactic sources, propagation through cold diffuse plasma:
  - Large dispersion measures (DM)
  - Propagation delay is a function of frequency $\delta t \propto DM \cdot \nu^{-2}$
  - Pulse temporal width $W \propto \nu^{-4}$
- About 30 FRBs so far detected
- Detection rate of 0.1 s^{-1} is estimated
- Nature and source(s) of FRBs are unknown

Superradiance - FRBs



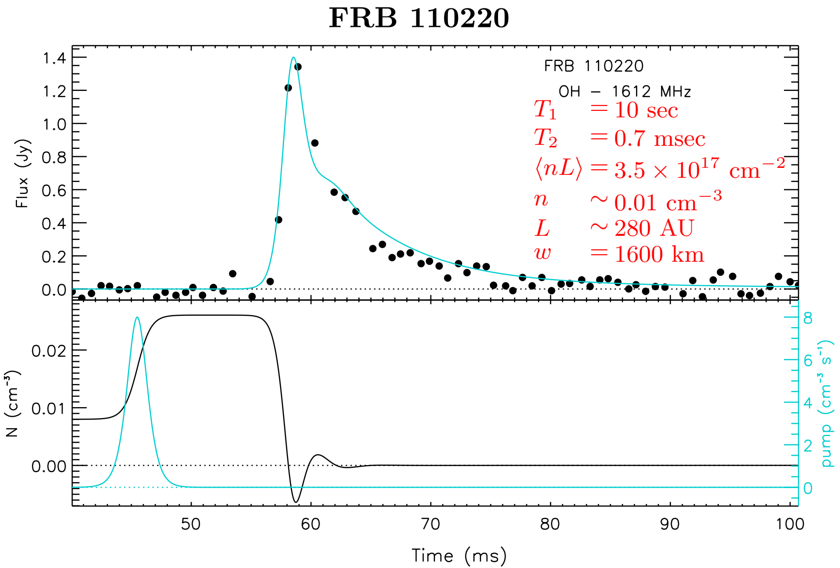
Superradiance - FRBs



FRB 150807

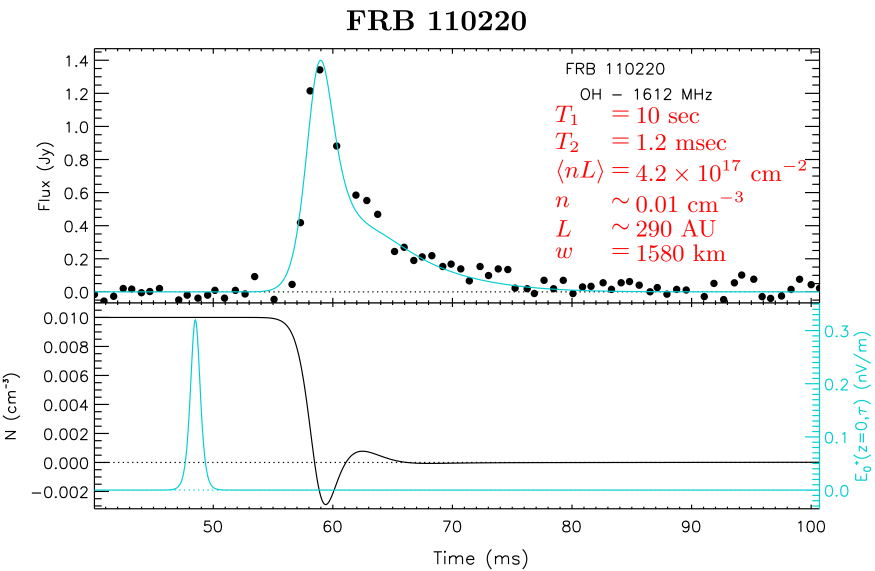
(Ravi et al. 2016, Science, 354, 1249)

Superradiance - FRBs



See Houde, M., Mathews. A, & Rajabi, F., 2017, MNRAS, 475, 514

Superradiance - FRBs



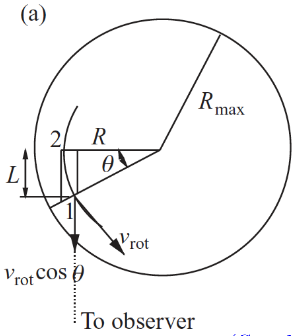
See Houde, M., Mathews. A, & Rajabi, F., 2017, MNRAS, 475, 514

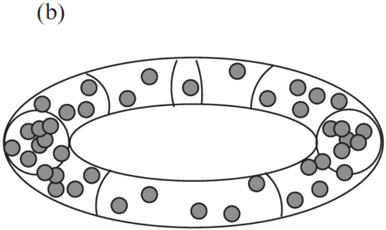
Dicke's Superradiance - Summary

- Superradiance is a coherent, burst-like phenomenon over a wide range of time-scales.
- Superradiance was only studied in laboratory context so far.
- Observational evidences in OH 1612 MHz, methanol 6.7 GHz and water 22 GHz.
- Superradiance can provide a simple explanation for FRB mystery.

Superradiance - FRBs

- Parameters obtained (L and nL) are close to those observed for "megamasers" in active galactic nuclei (AGN) and starburst galaxies
  - The observed redshifts explain the central emission frequency
  - Relativistic systematic velocities are needed to explain the spectral bandwidth of FRBs ($\sim$ 100 MHz at 1.4 GHz)



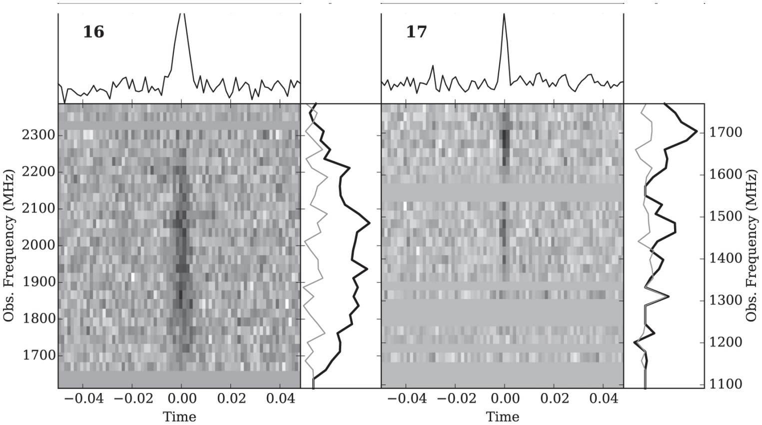


(Gray M., 2012, Maser Sources in Astrophysics. Vol. 50, Cambridge)

Superradiance - FRB 121102

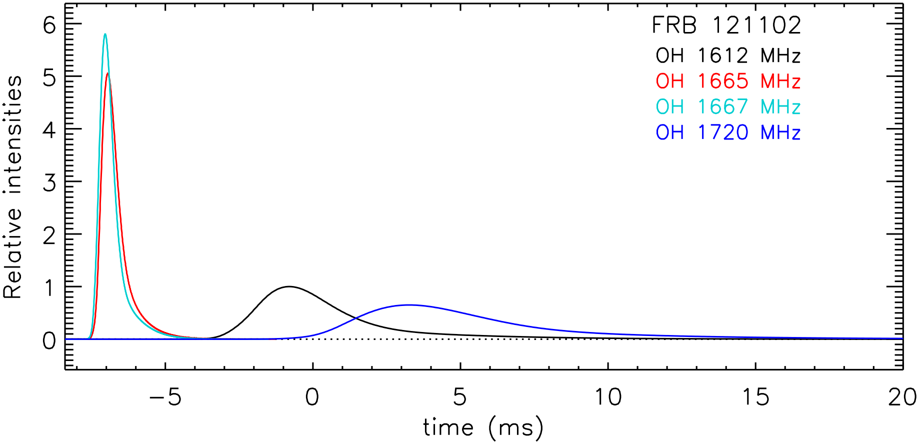
FRB 121102 is recurrent, detected in 3 spectral bands, and source galaxy at $z = 0.193$:

- 1.4 GHz $\rightarrow$ OH 1.6 - 1.7 GHz (4 lines)
- 2.5 GHz $\rightarrow$ CH 3.3 GHz (3 lines)
- 4-8 GHz $\rightarrow$ OH 4.7 GHz or H_2CO 4.8 GHz,...



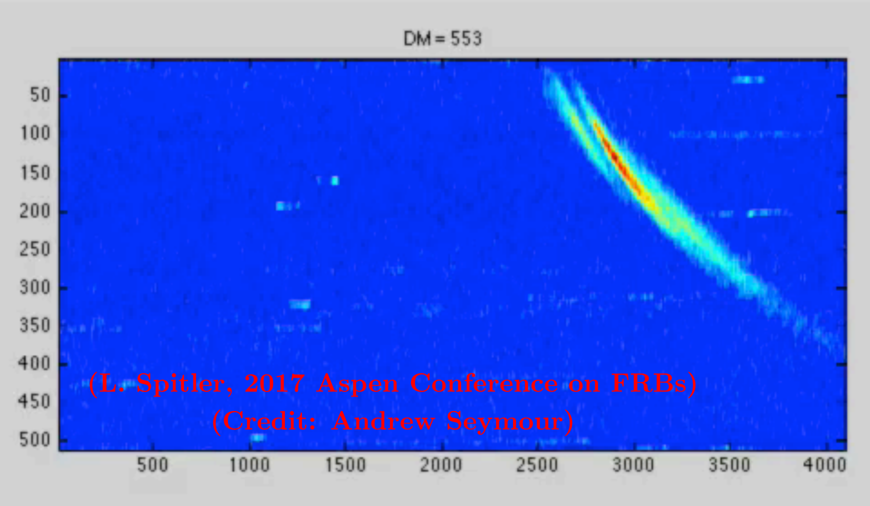
(Sholz et al. 2016, ApJ, 833, 177)

Superradiance - FRB 121102



- If different lines are active, signals of different durations with relative delays are expected...

Superradiance - FRB 121102



(L. Spitler, 2017 Aspen Conference on FRBs)
(Credit: Andrew Seymour)