ACORDO DE COOPERAÇÃO INTERNACIONAL

UFSCar
Nº 08 / 2020
Proc. 23112.109953/2019-99

Acordo de cooperação acadêmica, científica e técnica entre a Universidade Federal de São Carlos (Brasil) e o Centro Nacional de Pesquisa Científica (França)

A Universidade Federal de São Carlos, com sede no *campus* São Carlos, na Rodovia Washington Luís, km 235, em São Carlos (SP), Brasil, representada neste ato por sua reitora, Prof.ª Dr.ª Wanda Aparecida Machado Hoffmann; e o Centro Nacional de Pesquisa Científica, estabelecimento científico e tecnológico público com sede em *rue* Michel-Ange, n.º 3 –75794 Paris *Cedex* 16, França, Número no Sistema de Identificação do Diretório de Empresas (SIREN) 180089013, Atividade Principal da Empresa/Nomenclatura da Atividade Francesa (APE/NAF) 7219Z, representado por seu presidente, sr. Antoine Petit, delegando poderes de assinatura deste acordo à sr.ª Aurélie Philippe, delegada regional da Delegação *Côte d'Azur*;

CONSIDERANDO o amplo interesse comum das instituições em atividades de pesquisa, especialmente na área e/ou acerca de temas relativos a espalhamento de luz por átomos frios, doravante denominados "Área de Pesquisa/Temas", e, em razão disso, o interesse de ambas no desenvolvimento conjunto de atividades de pesquisa em tal campo do conhecimento e/ou sobre tais tópicos;

CONSIDERANDO a ciência da Universidade Federal de São Carlos e do Centro Nacional de Pesquisa Científica a respeito de que a referida colaboração pode resultar em seu fortalecimento e avanço contínuos;

CELEBRAM ESTE ACORDO, que se rege pelos termos e condições a seguir:

CLÁUSULA PRIMEIRA – PROPÓSITO

A Universidade Federal de São Carlos e o Centro Nacional de Pesquisa Científica concordam em promover cooperação acadêmica, científica e técnica entre elas, especialmente com base em sua *expertise* na Área de Pesquisa/Temas, a qual se consubstancia no projeto de pesquisa descrito nos Anexos A e B ao presente instrumento.

Tal colaboração pode incluir as seguintes atividades:

a) Mobilidade de professores e pesquisadores.
b) Desenvolvimento conjunto de projetos de pesquisa, nomeadamente o projeto "Átomos frios, fótons, e correlações quânticas" (Anexos A e B).
c) Coorganização de eventos acadêmicos, científicos e culturais, tais como: congressos, simpósios, seminários e colóquios.
d) Cessão e troca de informações e publicações científicas e técnicas.
e) Mobilidade de estudantes.
f) Mobilidade de funcionários técnicos e administrativos.
g) Outras atividades acadêmicas, científicas e técnicas do interesse de ambas as Partes e que correspondam aos objetivos institucionais de cada uma delas.

CLÁUSULA SEGUNDA – IMPLEMENTAÇÃO

A realização de qualquer das atividades previstas na cláusula anterior, a ser implementada no âmbito deste Acordo, deve observar as normas das duas Partes, está sujeita a programas ou projetos formais que tenham sido aprovados previamente pelas autoridades ou órgãos competentes das instituições, deve apresentar-se no formato disponível no Anexo A, e depende da disponibilidade dos recursos financeiros necessários.

CLÁUSULA TERCEIRA – FINANCIAMENTO

As Partes envidarão esforços para obter fundos oriundos de fontes internas e/ou externas de fomento, a fim de tornar possível a realização de atividades acadêmicas, científicas e técnicas no âmbito deste Acordo. As Partes não estão obrigadas a fornecer garantia de disponibilidade de fundos.

CLÁUSULA QUARTA – EXIGÊNCIAS

Professores, pesquisadores, estudantes e funcionários técnicos e administrativos que participarem de atividades no âmbito deste Acordo deverão cumprir os requisitos de imigração do país da instituição anfitriã e contratar seguro internacional de cobertura médico-hospitalar, contra acidentes pessoais, de responsabilidade civil e de repatriação sanitária e funerária para toda a sua respectiva estadia no exterior.

As Partes também devem observar e sustentar as políticas de seguros necessárias a reparar perdas e danos a bens e pessoas os quais possam ser causados em conexão com a execução deste Acordo. No âmbito desta Cláusula, entende-se que a regra conforme a qual "O Estado é sua própria seguradora" aplica-se tanto à Universidade Federal de São Carlos como ao Centro Nacional de Pesquisa Científica. Desse modo, cada Parte assegura a reparação, pelo respectivo orçamento, de quaisquer perdas e danos pelos quais seja declarada legalmente responsável.

CLÁUSULA QUINTA – TAXAS ACADÊMICAS

Os estudantes participantes de mobilidades no âmbito deste Acordo devem recolher as taxas acadêmicas, quando exigíveis, à sua respectiva instituição de origem, não lhes sendo cobradas taxas equivalentes pela instituição anfitriã em hipótese alguma.

CLÁUSULA SEXTA – DIREITOS DE PROPRIEDADE INTELECTUAL

Cada Parte possuirá a propriedade intelectual (PI) que for gerada por seus respectivos professores, pesquisadores, alunos e funcionários no desenvolvimento de projetos e atividades no âmbito deste Acordo. Considerando que o presente instrumento é relevante para o avanço da ciência e para a produção de conhecimento e tecnologia, as Partes concordam em fornecer uma à outra licenças mútuas não exclusivas e não onerosas para a utilização da PI para fins não comerciais em atividades acadêmicas de cada uma delas.

Na hipótese de ambas as Partes serem responsáveis pela geração conjunta de PI, a propriedade dessa PI será compartilhada em conformidade com a contribuição de cada uma delas na invenção, observadas as respectivas legislações nacionais aplicáveis, as convenções internacionais em vigor sobre a matéria e, quando for o caso, também a política para PI da(s) instituição(ões) responsável(is) pelo financiamento das equipes de pesquisa.

Toda geração conjunta de PI está sujeita a um acordo de copropriedade e exploração a ser celebrado entre as Partes coproprietárias antes de qualquer utilização industrial e/ou comercial direta ou indireta, principalmente com as finalidades de: disciplinar a gestão da copropriedade; quando for o caso, estipular as condições de manutenção, extensão e defesa dos resultados protegidos por títulos de propriedade industrial; e estabelecer as condições jurídicas e financeiras para a exploração industrial e/ou a utilização comercial direta e indireta dos resultados correspondentes.

CLÁUSULA SÉTIMA – PUBLICAÇÃO DE RESULTADOS

As Partes deverão publicar em conjunto os resultados decorrentes da cooperação objeto deste Acordo, respeitadas a prática acadêmica usual e suas respectivas políticas. No caso de publicação a ser feita por uma das Partes, esta solicitará o consentimento por escrito da outra Parte com antecedência mínima de 30 (trinta) dias. Caso tal consentimento não seja dado dentro desse prazo, considerar-se-á autorizada a publicação.

As Partes terão a liberdade de utilizar quaisquer informações científicas e técnicas criadas ou transferidas no decorrer do desenvolvimento das atividades previstas na Cláusula Primeira, para os objetivos de seus projetos de pesquisa e desenvolvimento. Não obstante, a utilização, por qualquer das Partes, com objetivo de pesquisa e desenvolvimento, de informações resultantes das atividades e experiências da outra Parte estará sujeita a um acordo específico separado.

CLÁUSULA OITAVA – CONFIDENCIALIDADE DE INFORMAÇÕES

Este Acordo e todos os documentos e informações disponibilizados por uma Parte à outra, no âmbito de ou em conexão com o presente instrumento ou qualquer compromisso contratual subsequente, serão tratados com confidencialidade ("Informação Confidencial"), nos termos das políticas de cada Parte e das respectivas legislações nacionais. A Informação Confidencial não poderá ser utilizada a não ser para os objetivos aos quais ela foi disponibilizada e não poderá ser revelada, por qualquer das Partes, para nenhuma outra parte sem o consentimento prévio, por escrito, da outra Parte.

Não obstante, nenhuma das Partes descumprirá a obrigação de manter a confidencialidade da Informação Confidencial ou de não a divulgá-la a terceiros caso:

i. a Informação Confidencial seja conhecida, antes de seu recebimento, pela Parte que a divulgar e caso não esteja sujeita a nenhuma obrigação de confidencialidade pela outra Parte; ou
ii. a Informação Confidencial seja ou torne-se conhecida publicamente sem a violação deste Acordo ou de qualquer outro compromisso de confidencialidade; ou
iii. a Informação Confidencial tenha sido obtida de terceiros pela Parte que a divulgar sob circunstâncias em que esta não possuía motivos para crer que tivesse havido violação de dever de confidencialidade; ou
iv. a Informação Confidencial tenha sido desenvolvida de modo independente pela Parte que a divulgar; ou
v. a Informação Confidencial seja divulgada em conformidade com lei, regulamento ou ordem de qualquer órgão judicial de jurisdição competente, e se a Parte que houver sido obrigada a fazer a divulgação tenha informado a Parte à qual pertencia a informação, dentro de prazo razoável após o recebimento da ordem de divulgação, de que fora obrigada a fazer a divulgação e de qual informação tivera de divulgar; ou
vi. a Informação Confidencial seja aprovada para divulgação por escrito por um representante autorizado da Parte à qual ela pertença.

CLÁUSULA NONA – VIGÊNCIA

Este Acordo entra em vigor na data da última assinatura pelas Partes e permanecerá vigente pelo prazo de 5 (cinco) anos.

CLÁUSULA DEZ – TERMOS ADITIVOS

Qualquer alteração nas disposições deste Acordo, incluindo a prorrogação de seu prazo de vigência, fixado na cláusula anterior, deve ser efetuada mediante termo aditivo devidamente firmado pelas Partes.

CLÁUSULA ONZE – COORDENAÇÃO

Como coordenadores deste Acordo, são designadas as seguintes pessoas: pela Universidade Federal de São Carlos, Prof. Dr. Romain Pierre Marcel Bachelard, do Departamento de Física; e pelo Centro Nacional de Pesquisa Científica, Dr.ª Mathilde Fouché, pesquisadora na área de Átomos Frios.

CLÁUSULA DOZE – RESCISÃO

Este Acordo pode ser rescindido a qualquer momento por qualquer das Partes, por meio de notificação fundamentada por escrito à outra Parte, apresentada com antecedência mínima de 3 (três) meses e aviso de recebimento. As atividades eventualmente em curso na ocasião da rescisão serão concluídas adequadamente.

CLÁUSULA TREZE – RESOLUÇÃO DE CONTROVÉRSIAS

Em caso de qualquer controvérsia que possa surgir entre as Partes referente à interpretação e/ou execução deste Acordo, elas deverão procurar chegar a uma solução amigável para tal controvérsia.

Todas as controvérsias entre as Partes referentes à validade, vigência, interpretação, execução e extinção deste Acordo ou de qualquer uma de suas Cláusulas, as quais as Partes não consigam resolver amigavelmente dentro do prazo de 6 (seis) meses, serão levadas perante a jurisdição competente.

As Partes firmam o presente instrumento em quatro vias idênticas, sendo duas em português e duas em inglês. Cada uma dessas vias é igualmente válida, mas em caso de controvérsia, inconsistências e/ou diferenças em sua interpretação, prevalecerá a versão na língua inglesa.

São Carlos, São Paulo (Brasil), 23/01/2020 Paris (França), February 6th, 2020

Wanda Hoff

Prof.ª Dr.ª Wanda Aparecida Machado Hoffmann
Reitora
Universidade Federal de São Carlos

UNIVERSIDADE FEDERAL DE SÃO CARLOS ufscar

Sr.ª Aurélie Philippe

Delegada regional da Delegação *Côte d'Azur*
Centro Nacional de Pesquisa Científica

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE
DÉLÉGATION DE LA CÔTE D'AZUR
250, Rue Albert Einstein
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ANEXO A – Formato de apresentação da atividade acadêmica, científica e/ou técnica específica a ser implementada

Natureza/Título da atividade	Projeto de pesquisa conjunto "Átomos frios, fótons, e correlações quânticas", selecionado pela Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) em setembro de 2019 no âmbito da Chamada de Propostas FAPESP – ANR (Agência Nacional de Pesquisa) para o Programa "*Generic Call for Proposals* 2020", nos termos do acordo de cooperação entre FAPESP e ANR celebrado em 22 de dezembro de 2011, para receber financiamento de ambas as agências de fomento
Fontes de Financiamento	Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) e ANR (Agência Nacional de Pesquisa), relativamente ao Programa "*Generic Call for Proposals* 2020", resultante do acordo de cooperação entre FAPESP e ANR celebrado em 22 de dezembro de 2011
Responsável direto – Universidade Federal de São Carlos	Prof. Dr. Romain Pierre Marcel Bachelard
Responsável direto – Centro Nacional de Pesquisa Científica	Dr.ª Mathilde Fouché
Assinatura – representante da Universidade Federal de São Carlos	Nome: Prof.ª Dr.ª Wanda Aparecida Machado Hoffmann Cargo: reitora Wanda Profa. Dra. Wanda A. Machado Hoffmann REITORA UNIVERSIDADE FEDERAL DE SÃO CARLOS Data: 23/01/2020
Assinatura – representante do Centro Nacional de Pesquisa Científica	Nome: Aurélie Philippe Cargo: delegada regional da Delegação *Côte d'Azur* Data: February 6th 2020

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE
C.N.R.S.

ANEXO B – Projeto de pesquisa a ser desenvolvido em conjunto

Ver projeto anexo.

QuaCor
Cold atoms, photons, and quantum correlations

Proposal summary

Devices for quantum information computation and communication require the combined use of different quantum systems: photons can transmit informations over large distances, cold trapped atoms can be manipulated to enable quantum information processing, and atomic ensemble are suited for long-lived quantum memories, as well as non-linear generation of non-classical correlations. Cold atoms are a promising platform to manipulate light, and in this project we will focus on two specific quantum information tools: sources of correlated photons and memories, exploiting collective, multimode quantum states of atomic ensembles. We will address cooperative scattering in large atomic clouds to enhance these properties, i.e., we aim at showing how dipole-dipole interactions make it possible to tune both the lifetime and the optical coherences of the emitted light.

We will take advantage of the correlations between photons emitted in the spectrum of saturated atoms to show how multi-atom clouds can be a controllable source of correlated photons. Detecting correlations in a large quantum system can be a challenge, and the French and Brazilian teams will adopt different experimental setups to tackle this goal. The French team will also address the issue of memory in large dilute cloud, that manifests under the form of subradiant modes. The objective is to harness more efficiently the potential of these long-lived states, both in terms of coupling and of extraction of information. The Brazilian team will investigate experimentally the opposite regime of dense clouds, where mean-field optics breaks down due to the rise of correlations between the atomic dipoles. Finally, a theoretical objective is to determine how to achieve and detect quantum correlations between the atoms of large dilute clouds, through collective Rabi oscillations or synchronization.

Summary table: persons involved in the project

Country	University /Institution	Last Name	First Name	Position	p. m.	Role in the project
France	CNRS	FOUCHE	Mathilde	CR CNRS	20	Consortium coordinator Principal investigator INPHYNI Scientific coordinator of Rb1 experiment
France	CNRS	GUERIN	William	CR CNRS	10	Scientific coordinator of Rb2 experiment
France	CNRS	KAISER	Robin	DR CNRS	10	Rb1 and Rb2 experiments
France	FAPESP	De NEGREIROS MOREIRA	Raoni Savio	Post-doc	8	Rb1 experiment
France	CNRS	---	---	Post-doc	24	Rb1 and/or Rb2 experiments
Brazil	UFSCAR	BACHELARD	Romain	Assistant Prof	18	Principal investigator UFSCAR Scientific coordinator for theory
Brazil	UFSCAR	CELISTRINO TEIXEIRA	Raul	Assistant Prof	18	Scientific coordinator of Sr experiment
Brazil	IFSC-USP	COURTEILLE	Philippe	Associate Prof	8	Sr experiment
Brazil	IFSC-USP	DIAS	Pablo	PhD student (+sandwich)	48	Sr experiment (Brazil) and Rb1 experiment (France)
Brazil	IFSC-USP	MAGNANI	Pedro	PhD student	48	Sr experiment
Brazil	UFSCAR	SANTOS	Andre	Post-doc	18	Theory
Brazil	UFSCAR	DARSHESHDAR	Elnaz	Post-doc	18	Theory

I. Proposal's context, positioning and objective(s)

Remarks on the references:

Bold: *References for which one or more of the authors are involved in the project*
Red: References published in the framework of the French-Brazilian collaboration

a. Objectives and research hypothesis

Cold atoms coupled to photons are a promising platform for quantum information, computation and communication: atoms are adequate systems to store and/or correlate photons, while the photons themselves can be efficient carriers of information over great distances. In this project, we will focus on two specific tools: sources of correlated photons and memories, exploiting collective, multimode quantum states of atomic ensembles. The main scientific objectives of this project, detailed in Sections I.b. and I.c., are:

Objective 1: Explore a new kind of correlated photon source based on a multi-atom ensemble.

Correlated photon source or heralded photon source, in which one photon indicates the presence of exactly one other photon, is a prerequisite for many different kinds of quantum optical applications: from quantum processing to quantum communication. The key parameters are a controlled and deterministic generation, and a high brightness. A large variety of these sources already exists, based on electromagnetically induced transparency, parametric down-conversion or four-wave mixing. Quite recently, another kind of process has been used based on the Mollow triplet: the fluorescence spectrum of a quantum emitter, resonantly excited and above saturation, consists of three different components between which strong correlations exist. This topic recently showed a strong resurgence of interest especially in the field of quantum dot emitters[1,2,3].

Our goal is to explore a new kind of source of photons, based on the correlations inside the **Mollow triplet**, and using a **many-atom system** such as a cold atomic cloud. Taking advantage of the large number of emitters (10^8 to 10^9 atoms), this could pave the way to the generation of **intense beams of correlated photons**. Such quantum correlations are usually observed on single emitters (atom, ion, quantum dot, etc) and are hidden when the number of emitters is increased. The main barrier to be lifted will be to find an experimental configuration which will enable detecting **quantum correlations** between the photons scattered by a **multi-atom source.**

Objective 2: Long-lived quantum memories with atomic ensembles.

Quantum memory is an essential building block for any kind of quantum information systems. Among the different key parameters, one can cite storage efficiency, fidelity, bandwidth, directivity and storage lifetime. Different kind of protocols exists, based on quantum dot, single ion, NV center or atomic ensemble. The last example appears as a nice candidate for novel long-lived quantum memories[4] as it can store excitations over hundreds of atomic lifetime thanks to the subradiance effect[5,6].

Our goal is to exploit **collective subradiant states of atomic ensembles** as novel memories. Optimization of the storage of classical and quantum information[7] will be investigated. Readout by applying a control field will be tested with a special focus on collection efficiency of the output field. Thus, our goal is here to show that subradiance in atomic clouds can be a **harvestable** resource, and that it may be used to store **quantum correlations**.

b. Position of the project as it relates to the state of the art

The existence of correlations in the photon radiation of an atom has been known for many years, with the anti-bunching effect[8] which brings the important notion of single-photon source. Equally important is the notion of correlations between the photons emitted in different spectral components of the atom[9,10,11], as the emission of a photon can be "heralded" by another correlated one. While at first studied in the context of atoms, in the last decade the promising platform of quantum dots already took over, demonstrating that heralded photons can be achieved in these controllable systems[1,2].

A challenge that remains very largely open is using many-emitter systems to produce such sources, with the obvious objective of obtaining an intense source as compared to the ones based on single emitters. The coupling of the emitters is then necessary to prevent for the emission of many particles to incoherently add up. Yet, even the theoretical treatment of the correlated emission of few bodies is a challenge, be it for atoms[12] or quantum dots[13]. This is naturally due to the fast-growing dimension of the Hilbert space of a many-body problem, for which analytical or "exact" numerical methods quickly reach the limit of a few scatterers[14].

In this project, we tackle this many-body problem from the opposite side. Having in mind the atomic clouds of 10^6-10^{10} particles routinely produced in cold atom laboratories, we aim at demonstrating that photon correlations can be achieved in these systems. Beyond a pure phase-matching condition[15], we also intend to address quantum correlations between the atoms, and show how these show up in a large disordered system. This represents both an experimental and a theoretical challenge, which is the reason why most many-body effects have been addressed in small systems, usually in 1D[16] and 2D[17] for atoms, whereas fibers and metamaterials are naturally 1D and 2D systems. The field of Rydberg atoms also brought important challenges and techniques in terms of many-body dynamics in 2D[18]

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[17] S. S. Kondov *et al.*, Phys. Rev. Lett. **114**, 083002 (2015).
[18] H. Labuhn et al., Nature 534, 667 (2016).

and 3D[19], in particular to describe superatoms and their interactions. Important efforts are also devoted to atoms coupled through dipole-dipole interactions, yet in the subwavelength regimes where near-field terms bring important corrections to the energy levels in atomic clocks[20,21], for example. Yet the case of large dilute systems coupled through the dipole-dipole interaction is essentially unexplored.

Regarding the memory effect that can be achieved using subradiance, the first experimental observation for dilute clouds has been achieved in the INPHYNI group in 2016[6], in the linear optics regime. Only classical correlations are expected between the atoms in this regime, where only the single-excitation subspace is explored[22]. And despite the existence of superradiance is known to imply that of a wealth of subradiant modes[23], theoretical and experimental studies have focused on the former rather than the latter. A notable recent development, though, is the theoretical investigation of "extraordinary subradiance"[24,25], where the long lifetimes of subwavelength periodic systems are shown to scale very favourably with the particle number.

Once more, our approach is that of large disordered systems, with the aim of identifying how strongly driven atomic samples can preserve memory of the imprinted excitation, but also questioning the presence (and preservation) of quantum correlations. The Nice group has a strong experience in the study of coherent effects in large disordered systems[26], and the São Carlos group is joining them in this effort. While their previous studies addressed mostly classical effects, this project will cast both groups fully in the quantum realm. Their work over the past couple of years already took that path, with the first observation of single-atom Mollow triplet with cold atoms[27] and the study of intensity correlations in cold atoms and stars[28]. The true challenge is now to tackle many-body physics in these large disordered systems, and this is precisely the goal of this project.

c. Methodology and risk management

- ***Methodology***

The methodology is clearly exploratory but largely based on already **mastered experimental techniques** as well as **well-tested theoretical tools** which limits the risk of failure. We will use the experimental platforms that already exist in Nice, and the development of the experiment in Brazil to reach the dense regime (for which the atomic density ρ is such that $\rho>1/\lambda^3$, with λ the probe wavelength), and rely on the collaborative efforts to implement in Brazil the different diagnostic tools already tested in Nice (to measure intensity correlations or superradiance for example). We will finally continue the collaborative work between experiments and theory, theorists guiding the choice for the experimental parameters or configurations and experimentalists suggesting new experimental possibilities or constraints.

The experimental part of this project is based on three different experiments (**Rb1, Rb2, Sr** in the following), with their own specificities, while theory support will accompany each when relevant, in addition to dedicated theoretical objectives.

– **Rb1 experiment** (France): This experiment consists in a cold atomic cloud of ^{85}Rb produced by a magneto-optical trap (MOT) that can contain up to a few 10^9 atoms with an optical thickness b_0 of more than 100. This experiment has already been running for several years, and will thus only requires minor upgrades to perform the different tasks. This experiment will focus on the **Mollow triplet and photon correlations**. The main diagnostic tools needed is an intensity correlation setup, which has been already developed in our group and successfully tested on this experiment. It allowed in particular observing the effect of multiple scattering on the fluorescence spectrum[29] (a technique known as diffusing-wave spectroscopy) and recently to measure the spectrum when the atoms are excited above saturation (the Mollow triplet)[27].

The setup is described in details in Ref. [27]. The scattered spectrum is extracted through the measurement in

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[29] **A. Eloy *et al.***, Phys. Rev. A 97, 013810 (2018).

the photon counting regime of the electric (scattered) field correlation $g^{(1)}(t)$ using a beatnote technique with a local oscillator. The combination of both techniques (single-photon counting and heterodyne technique) allows us to measure the spectrum with a good signal-to-noise ratio even with a weak signal. The experimental setup is shown in Fig. 1, as well as a typical Mollow triplet obtained in our experiment. This will be the starting point of WP1.

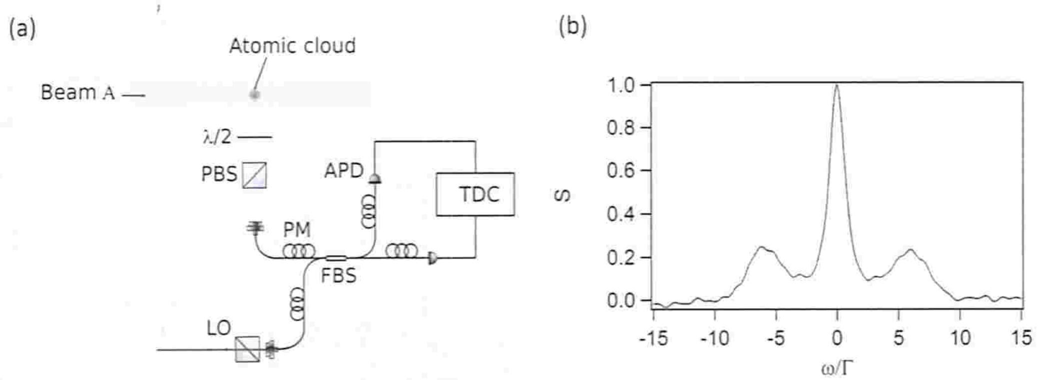


Fig. 1: (a): Experimental setup to measure the spectrum of the light scattered by the cold atomic cloud and driven by laser beam A. (b): Typical spectrum measured on our experiment with $\Omega_0 \approx 6\Gamma$ and $b_0 \approx 1$. For more details, see Ref. [27].

– <u>Rb2 experiment</u> (France): This experiment is based on a ^{87}Rb cold atomic cloud, provided by a MOT. The total number of atoms is typically a few 10^9, with a maximum optical thickness of more than 200. This experiment will focus on **super and subradiance effects**, a subject already investigated in Nice over the past few years[6,30,31]. The experimental technique relies on a setup allowing weak signal measurements, with a high dynamic range as well as a good temporal resolution.

The setup is described in Ref. [31] and sketched in Fig. 2. The cloud is excited with a probe beam. After a fast switch-off the scattered light is collected with a hybrid photomultiplier (HPM) and the signal is recorded with a multichannel scaler (MCS). A typical signal of super and subradiance is also shown in Fig. 2. This setup will be the starting point of WP2.

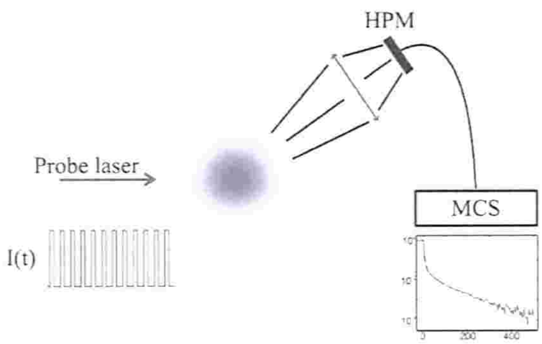


Fig. 2: Experimental setup and typical signal of super and subradiance. See Ref. [31] for more details.

– <u>Sr experiment</u> (Brazil): This experiment is currently operating in the dilute regime ($\rho << 1/\lambda^3$) with Sr atoms, loading from a blue and red MOT. It currently produces ultracold clouds of 5.10^6 atoms at 1.5 µK, with variable geometry due to the flexibility of configurations of the narrow-line MOT. Transferring this cloud to a confining optical dipole trap (ODT) will allow us to reach the **spatially dense regime** for light scattering, which is the second task of WP3. Nevertheless, it already provided some scientific results, especially on the mirror-assisted backscattering effect in the linear optics regime[32]. The experimental setup is shown in Fig. 3 with a typical signal recorded on a CCD camera, showing some fringes from which one can extract the fringe spacing and the contrast. This setup will be used to study the effect of saturation in the first task of WP3.

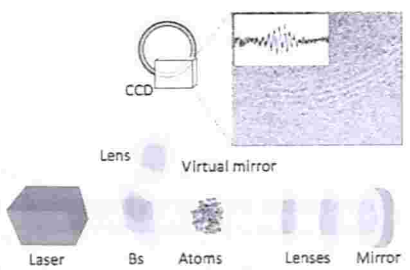


Fig. 3: Experimental setup to observe the m-CBS effect. See Ref. [32] for more details.

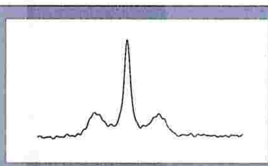
– <u>Theory</u> (Brazil): The theory group in Brazil has a strong expertise in light-atom interactions and their

[30] M. O. Araujo *et al.*, Phys.Rev.Lett. 117, 073002 (2016).
[31] P. Weiss *et al.*, New J. Phys. 20, 063024 (2018).
[32] P.H. Moriya *et al.*, Phys. Rev. A 94, 053806 (2016).

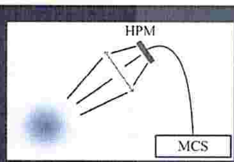
collective effects. Focusing on 1D (optical cavities), 2D and 3D (free space) scattering, the group has focused on long-range effects that rise from the dipole-dipole coupling. Recently, tools to study the light scattering by a many-body cloud, addressing quantum correlations, have been developed[33,34], which will be particularly useful for this project. An active collaboration has been maintained with the experimental groups in Nice and São Carlos for several years.

The project is divided in 4 scientific workpackages:

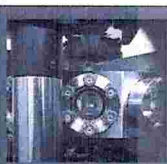
WP1 – Correlated photon source – Mollow triplet (Rb1)
Task 1.1: Quantum cooperative effect – Baby Mollow
Task 1.2: Correlations inside the Mollow triplet in multi-atom ensemble
Task 1.3: Correlations between the main and Mollow baby sidebands



WP2 – Quantum memory – Super and subradiance (Rb2)
Task 2.1: Subradiance enhancement
Task 2.2: Quantum subradiance
Task 2.3: Recovering excitations from the subradiant dynamics



WP3 – Correlations in the dense regime (Sr)
Task 3.1: Mirror-assisted coherent backscattering with the Mollow triplet
Task 3.2: Beyond mean-field optics: the dense regime
Task 3.3: Superradiance in the dense regime



WP4 – Theory – Quest for collective quantum effects
Task 3.1: Collective Rabi oscillations in dilute atomic clouds
Task 3.2: Classical and quantum synchronization of atomic dipoles in 3D

The first workpackages (WP1, WP2 and WP3) are distributed over the 3 different experiments: two experiments in Nice (Rb1 and Rb2) and one experiment in Brazil (Sr). Rb1 will focus on correlations inside the Mollow triplet (WP1), Rb2 will be involved in the super and subradiance effects (WP2), and finally the experiment in Brazil will investigate the dense regime (WP3), complementary to the dilute regime in Nice. Theory support needed for these experiments are also part of these workpackages and are spread over the different tasks. A fourth workpackage (WP4) is specifically dedicated to theory, to prospect for other quantum effects in cold atomic gases. Finally, a last workpackage (WP5) focuses on management and knowledge dissemination.

- ***Risk management***

In this project, high ambitions goals are balanced by the high success probability of the first steps of the project. The first task of each "experimental" workpackage (Tasks 1.1, 2.2 and 3.1) are based on theoretical predictions, some of those already published. The experimental techniques have been already well tested on the existing setups. The last tasks of each scientific workpackages are clearly more risky, and the experimental ones will be strongly accompanied by theory efforts in this case. Nevertheless, the balance between the different phenomena and levels of risk involved makes that most objectives are likely to be completed.

The last workpackage (WP5) focuses on management: regular meetings, especially between the experimentalist partners and the theoretical partner, will enable, if necessary, to readapt the project goals at each step, depending on the results obtained in the simulations or on the experimental constraints. It is important to note that this collaboration has already been working successfully over the past years, and showed its capacity to publish jointly high-quality results (as shown by the red references).

The tasks and risks associated to each workpackage are detailed in the next section.

[33] **L. Pucci *et al.***, Phys. Rev. A 95, 053625 (2017).
[34] **E. Suarez *et al.***, New J. of Phys. (2019).

- ***Description of the tasks***

WP 1: Correlated photon source – Mollow triplet (Rb1)

Scientific coordinator : Mathilde Fouché (INPHYNI, France)

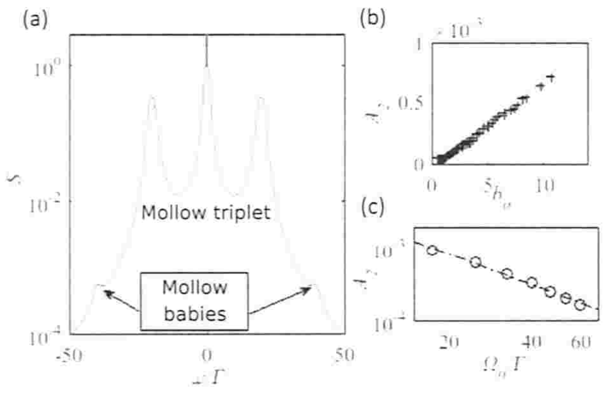
The first workpackage will be specifically addressed by one of the two Rb experiments in Nice (Rb1, with ^{85}Rb). The general goal is to study the possibility to detect **quantum correlations** between the photons scattered by a **multi-atom source**, correlations which are usually observed on single emitters and become hard to detect when the number of emitters is increased. The Mollow triplet is a well-known effect for which strong correlations exist between the two sidebands and the carrier[11]. In this workpackage, we want to demonstrate that quantum correlations, both between atoms and between photons, can also be detected in a multi-atom source.

Task 1.1: Quantum cooperative effect – Mollow baby

The first quantum effect that we want to address is a **genuine signature of quantum correlations between atoms**, at this time theoretically studied in the framework of our collaboration in 2017[33]. An even more challenging goal, explained in details in the last task of this workpackage, is to see if such quantum collective behaviour also leaves signatures in the different frequencies of the Mollow spectrum.

The Mollow triplet corresponds to the three peaks observed in the spectrum of the light scattered by a saturated 2-level system, and it was observed for the first time with a cold atomic cloud in 2018 on our experiment[27]. However, in a multi-emitter ensemble, if one increases the resonant optical thickness b_0, some additional sidebands appear at frequencies $\pm 2\Omega_0$ from the central component, with Ω_0 the Rabi frequency. It has been shown in Ref. [33] that this effect is identified as proper quantum effects that cannot occur in the absence of genuine quantum correlations between the atoms. More specifically, they are generated by two-time two-atom quantum correlations $\langle \hat{\sigma}_j(t)\, \hat{\sigma}_m(t+\tau)\rangle$ (that cannot be factorized as $\langle \hat{\sigma}_j(t)\rangle\langle \hat{\sigma}_m(t+\tau)\rangle$), and witness the correlations between the fluctuations of the different atomic dipoles. A typical spectrum is plotted in Fig. 4. One clearly sees the three peaks of the Mollow triplet, but also two small additional sidebands, that we label "**Mollow babies**".

Fig. 4: (a) Theoretical fluorescence spectrum for a cloud driven at resonance, with Ω_0=20Γ and b_0=5. We see the appearance of additional sidebands, that are a signature of atom-atom correlations: the Mollow babies. (b) Amplitude of the Mollow babies as a function of b_0 (Ω_0=20Γ). (c) Amplitude of the Mollow babies as a function of Ω_0 (b_0 =10). See Ref. [33] for more details.



The goal of this task is to observe experimentally these new sidebands. To this end, we will use the same setup that we have already implemented to observe the Mollow triplet with our cold atomic cloud, detailed in section "Methodology – Rb1 experiment" and shown in Fig. 1. The key experimental ingredients are:

– *Well-resolved Mollow sidebands:* This implies a compromise between high Rabi frequency and thus high laser intensity (focused laser) and a homogeneous Rabi frequency for all atoms (plane-wave). This has already been achieved on our experiment (see Fig. 1(b)).

– *A Rabi frequency of 10Γ or more:* The maximum current value on our experiment is 8Γ, but divided into two beams switched on alternatively. Applying all the power in one beam will give 16Γ which should be enough according to the predictions (see Fig. 4(c)).

– *A large optical thickness, much larger than unity:* As shown on Fig. 4(b), the amplitude of the Mollow babies scales linearly with the optical thickness (see Fig. 4(b)). The maximum available optical thickness is of the order of 100 on our experiment.

– *A signal-to-noise ratio larger than unity:* The spectra are normalized to one (amplitude of the carrier). With b_0 = 100 and Ω_0 = 16Γ, we expect an amplitude of the order of 10^{-2} for the Mollow babies. The noise measured in Fig.

1(b) is typically a few 10^{-3} for a typical integration time of a few hours (with $b_0\approx1$). The improvement on the experiment can be done mostly on the time integration, but also by improving the duty cycle and the number of collected photons (a factor of 2 or more is expected). Thus, the Mollow babies could be observed within **a few hours to a few days of integration**.

Deliverable: Scientific results (report and/or publication)

Risk: **Low**. The predictions are already done and published, for on and off resonance excitation. For the experimental part, we have already demonstrated our capacity to measure the Mollow triplet with well-resolved sidebands. A good signal-to-noise ratio is needed to observe the Mollow babies but this appears feasible with the current setup.

Task 1.2: Correlations inside the Mollow triplet in multi-atom ensemble

The next step is to observe a signature of correlations in the Mollow triplet. This effect has been studied in the 80s with, for example, the results of Ref. [11]. It remained the state of the art until the re-emergence of this effect in quantum dots[1,2,3]. This kind of correlations is a typical single-emitter effect, that is usually smeared out when the number of emitters is increased: the rate of true coincidences (two photons emitted by the same emitter) scales with the number of emitters N, while the accidental coincidences scales as N^2.

We typically have 10^8-10^9 atoms in our cold atomic cloud, so an arbitrary configuration to observe correlations is clearly not applicable. Well-chosen configurations need to be implemented, such as the phase-matching one that allowed to observe photon antibunching (also a single-emitter effect) in a many-atom source[15]. One theoretical objective will be to determine whether this setup or a variant is viable.

Another strategy is to measure the correlations in the forward direction. This kind of configuration is studied in Ref. [35], where the correlations within one sideband or between the sidebands of the Mollow triplet were calculated. It has been shown that for some specific experimental parameters, in particular for a given angle of detection compared to the incident driving laser, the various combinations of photon correlations exhibit bunching with **super-Poissonian** or **sub-Poissonian statistics**. In addition, it was shown that the **Cauchy-Schwarz inequality is violated**: $\chi<1$, with a Cauchy-Schwarz parameter defined as:

$$\chi = \frac{g^{(2)}_{\mathrm{LL}}(0)g^{(2)}_{\mathrm{RR}}(0)}{\left[g^{(2)}_{\mathrm{LR}}(0)\right]^2} = \frac{g^{(2)}_{\mathrm{LL}}(0)g^{(2)}_{\mathrm{RR}}(0)}{\left[g^{(2)}_{\mathrm{RL}}(0)\right]^2}$$

where L and R stand for the photons scattered in the left and right sidebands, and $g^{(2)}(0)$ corresponds to the photons (cross-)correlation at time t=0. According to these calculations, for a detection angle of $0.01\pi\approx1°$ in the forward direction (see Fig. 5), one expects $\chi\approx0.3$. Since the quantity $g^{(2)}_{RL}(0)$ is close to 2 , this corresponds to:

$$\sqrt{g^{(2)}_{\mathrm{LL}}(0)g^{(2)}_{\mathrm{RR}}(0)} \approx 1.1$$

thus far from a pure photon bunching of 2.

The experimental setup that we will implement is shown in Fig. 5. Two Fabry-Perot (FP) cavities (requested in this proposal) with a typical linewidth of 2Γ, used as optical filters to select the photons coming from the blue- or red-detuned sidebands, are placed symmetrically around the incident laser direction. Each FP resonant frequency will be adjusted on the frequency of one of the sidebands thanks to a PZT placed on one of the cavity mirror. The resonant frequency will be stable enough (typically a few 100 kHz per day according to the company Stable Laser System) to measure the correlations over a few hours.

The technique used to measure the correlations between the photons collected in each direction is then the same as the one already developed on our experiment[29,31]. Since the setup is already single-mode fibered, from the collection of the scattered photons to the APDs, the mode-matching should be almost perfect and the transmission through the Fabry-Perot cavities will be close to the specifications. Finally, given the signal to noise ratio already measured on our experiment, we expect to be able to measure a Cauchy-Schwarz parameter of the order of 0.3, which is actually quite a large violation from photon bunching, within a **few hours of integration time**.

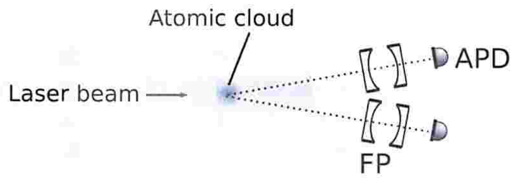


Fig. 5: Principle of the detection of correlations in the forward direction between sidebands of the Mollow triplet.

[35] L. Jin *et al.*, Phys. Rev. A 84, 043814 (2011).

Deliverable: Setup to filter the sidebands of the Mollow triplet, code to address correlations, scientific results (report and/or publication)

***Risk:* Moderate.** This work is based on calculations published in Ref. [35], which show a clear signature of non-classical effects in the forward direction. It is still important to adapt these predictions to our experimental parameters. For the experimental part, the detection is clearly feasible, even if challenging: we need to implement the Fabry-Perot cavities to filter the sidebands of the Mollow triplet and optimize the experiment to get a good signal-to-noise ratio within a reasonable integration time (from a few hours to a few days). The rest of the setup is the same as the current one and thus already validated.

Task 1.3 Correlations between the main and Mollow baby sidebands

The last task will be dedicated to the study of correlations between the sidebands, including the Mollow babies. As said before, it is well-known that correlations exist between the sidebands of the single-atom Mollow triplet. Our goal is to identify correlations between photons that result from the dipole-dipole interaction, i.e., signatures of the correlations between the fluctuations of different atomic dipoles. The challenges in this multi-atom quantum system are here both theoretical and experimental.

Theoretically: As a natural first step, we intend to study the N=2 case, as it represents a relatively tractable case to understand the nature of the correlations between the different Mollow sidebands. These correlations can be expected both between baby sidebands, or between a baby sideband and a main sideband, or even between the two main sidebands. Indeed, in our theoretical work[33], an asymmetry between the main Mollow sidebands, that resulted from the atom-atom quantum correlations, was observed. This suggests that even the correlations between the main Mollow sidebands may be altered. This situation is very interesting as it represents a much higher number of photons in the experiment, as compared to those involving the baby sidebands. It may also be particularly interesting to engineer higher-order photon correlations such as $g^{(3)}(t)$[3,36,37].

This case study will guide our investigation for larger systems, as we will then determine how these correlations transpose to the many-atom case. As mentioned earlier, signatures of quantumness such as photon antibunching are then notoriously more difficult to observe. We will take advantage of the phase-matching configuration[15] discussed in task 1.2, or of the four-wave mixing design, to identify correlations robust to the cloud disorder. To tackle with this problem analytically, the results of the simpler N=2 case can be used to study the many-atom case by assuming that only correlations involving at most two atoms are present. Numerically, the transition to larger number of atoms can be studied using "exact" solutions for up to a ten of atoms, for example, with toolboxes such as Qutip[38]. To understand how the correlations scale in the large size limit, truncated schemes based on a hierarchy of correlations, with which the São Carlos node has experience, can be used to simulate hundreds of atoms.

Experimentally: Based on the predictions from the theoretical work, the Rb1 setup will address the challenging task of detecting correlations between sidebands in the multi-atom case. The most critical part will be the number of collected photons when the quantum-pair-generated sidebands are probed. We should be able to observe the photon correlations between the sidebands of the Mollow triplet within a few hours of integration quite easily (task 1.2). But for the Mollow babies, the number of collected photons will be much lower, by a factor of 100 or 1000 (see Fig. 4). We will need to optimize carefully the experiment and in particular find the best configuration in terms of detuning, optical density and detection angle, to maximize the emission in these sidebands. The challenge is that such correlation measurement is largely compensated by the wealth of correlations that can be probed from it, from cross-sideband correlations to higher-order photon correlations.

Deliverable: Code to address the correlations, scientific results (report and/or publication)

***Risk:* High.** This task is strongly linked to the two first tasks 1.1 and 1.2, and thus will strongly depend on what has been previously observed, in particular in terms of signal-to-noise ratio. However, there is almost no doubt that correlations exist between the Mollow babies, and so that we will be able to theoretically investigate them.

[36] A. Dot *et al.*, Phys. Rev. A **85**, 02389 (2012).
[37] E.A. Rojas Gonzalez *et al.*, Phys. Rev. Lett. **120**, 043601 (2018).
[38] J. R. Johansson *et al.*, Comput. Phys. Commun. **183**, 1760 (2012).

WP 2: Quantum memory – Super and sub-radiance (Rb2)

Scientific coordinator : William Guerin (INPHYNI, France)

This workpackage will be carried out by the second Rb experiment in Nice (Rb2, with ^{87}Rb), with the general goal of demonstrating the **potential of subradiance for use as a memory.** More specifically, we intend to improve its lifetime and the access to its stored excitation at late times, but also to understand how, in the strong-driving regime, it can be used to hold quantum correlations.

Task 2.1 Subradiance enhancement

The practical use of subradiance for quantum protocols critically depends upon the robustness of this effect and its measurability. Regarding its robustness, preliminary works have shown that it is robust against multiple scattering[39] and thermal motion [article in preparation]. However, subradiance experiments are still very delicate and demanding because of the very low relative population of subradiant states, typically of the order of 10^{-3}.

In this task we want to address this issue. The goal is to find a **protocol to enhance the subradiant state population**. Following the suggestion of Ref.[[40]], a first idea that we will implement is to drive the atomic sample by a probe beam with a phase profile such that half of the beam has a π phase shift compared to the other half. Preliminary simulations[41] have shown an increase of a factor 6-8 of the subradiant population compared to driving the system with a plane wave.

Beyond this first step we will look for optimized intensity and/or phase profile of the driving beam to maximize the coupling to subradiant states. Indeed, superradiant modes are associated to rather uniform phase profiles whereas subradiant ones correspond to strongly modulated ones[42]. The efficiency of speckle fields in populating subradiant modes will first be investigated numerically, before the optimal pump profile is tested in the experiment.

Deliverable: Scientific results (report and/or publication)

Risk: **Moderate**. It is likely that the populations of subradiant modes can be increased by shaping the pump profile. It is however difficult to predict if the enhancement will be strong enough to make subradiance a harvestable resource.

Task 2.2 Quantum subradiance

Over the last years, super and subradiance have been largely investigated in the "single-photon" limit. In that case the atomic ensemble behaves essentially like a collection of coupled antennas driven by a classical field.

In this task we aim at studying subradiance in the quantum regime, when quantum correlations between the atoms rise. Experimentally this regime is explored by increasing the power of the driving field such as to get a saturation parameter above unity. In this configuration, many spurious effects have to be carefully calibrated and accounted for in the analysis, for instance the radiation pressure force on the atoms and optical pumping effects.

We will characterize subradiance in the **strong driving regime** by monitoring both the subradiant-state population and the subradiant decay rate, as a function of the saturation parameter. Preliminary simulations show that there is only a minor decrease of the subradiance lifetime, down to a constant non-trivial value, a prediction that a mean-field approach fails to reproduce (see Fig. 6). Subradiance in this regime may thus be related to the presence of quantum correlations in the system, an analysis that we intend to carry thoroughly, both experimentally and theoretically.

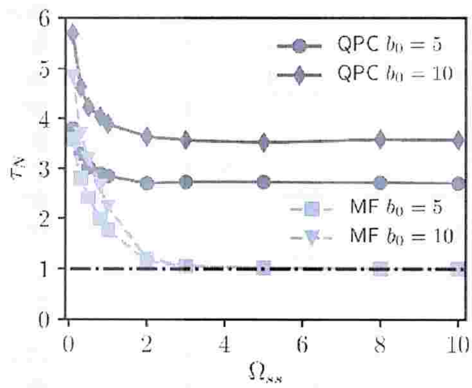


Fig. 6: Subradiant lifetime (in unit of inverse atomic linewidth) as a function of the Rabi frequency of the probe beam, as predicted by the quantum-pair correlation (QPC) and mean-field (MF) model.

Deliverable: Scientific results (report and/or publication)

[39] **P. Weiss *et al.*, New J. Phys. 20, 063024 (2018).**
[40] M. O. Scully, Phys. Rev. Lett. 115, 243602 (2015).
[41] **M. O. Araújo, W. Guerin, R. Kaiser, J. Mod. Opt. 65, 1345 (2018).**
[42] **F. Cottier et al., Phys. Rev A 98, 013622 (2018).**

Risk: **Low**. This task relies on theoretical predictions which are already well advanced. Experimentally, there is no major technical obstacle to the increase of the probe beam power.

Task 2.3 Recovering excitations from the subradiant dynamics

Subradiance appears as a promising candidate for memories, as it can hold excitations over hundreds of atomic lifetimes. Yet it is necessary to design a scheme to **recover efficiently this excitation**, i.e., to "read" it using an extra pulse. A beam with a low Rabi frequency cannot address the subradiant state since, in the linear optics regime, it will only add population to the previously existing one. Nevertheless, an intense beam can in principle allow to address it, as one enters the regime of nonlinear optics.

We here propose to modify the Hamiltonian at a chosen time during the decay dynamics, so the long-lived subradiant population now turns into a fast-decaying one. This could be achieved using a strong speckle field that imprints a random energy shift to the two-level atoms, turning their light-mediated interaction ineffective. The Stark shift thus allows to introduce diagonal disorder in addition to the off-diagonal disorder associated to the random distance between the atoms. In absence of dipole-dipole coupling, the excited population is then expected to be emitted at the single-atom rate, so the stored information could be recovered on a time scale of the atom lifetime.

The shift of the level energy needs to be realized using a different transition, so the radiated light can be isolated from that of the speckle field. One can for example use the 776 nm transition, from $5P_{3/2}$ to $5D_{3/2}$, to only shift the excited state.

Let us mention that the control of diagonal disorder opens interesting perspectives in terms of localization and synchronization: while diagonal disorder in this system was proposed as a possible way to achieve Anderson localization of light in cold atoms[43], it also introduces a decoupling between the atoms that requires collective modes to synchronize the dipoles. The theoretical study of this problem is the topic of Task 4.2.

Deliverable: Scientific results (report and/or publication)

Risk: **Moderate**. The implementation of the speckle does not present any major obstacle *a priori*. Whether the emission of the recovered excitation could be made directional, in order to make its detection easier, is more uncertain.

WP 3: Correlations in the dense regime (Sr)

Scientific coordinator : Raul C. Teixeira (UFSCAR, Brazil)

The São Carlos strontium experiment aims at investigating the **dense regime**, when very strong correlations develop between the scatterers due to near-field terms. The first task addresses the dilute regime, in which the experiment is currently operating, and consists in observing interference patterns from large clouds of strongly driven atoms[44], which configures a signature of correlations between photons of the Mollow sidebands. Such patterns originate in the correlations between photons of the Mollow sidebands in a setup called mirror-assisted coherent backscattering[32] (m-CBS), and can be used to discriminate spatially different spectral components. The next objective is to probe deviations from mean-field optics in the dense regime, in which recent experimental and theoretical reports are conflicting[45]. Strontium presents the crucial advantage of behaving like a true two-level system, so it appears as an ideal candidate to measure, for example, beyond-mean-field transmissions. Finally, we will investigate the single-photon superradiance in the dense regime, looking for signatures of correlations that may alter the emission rate, such as Van der Waals dephasing[23]. Considering that superradiance could be used to "write" information in an efficient way, identifying its efficiency and limitations in denser systems is an important task.

Task 3.1: Mirror-assisted coherent back scattering with the Mollow triplet

This task addresses the observation of interference patterns in a large cloud based on the Mollow triplet. Large atomic clouds in front of a mirror are known to present a series of interference fringes due to the reciprocity between the scattering paths through atoms and their mirror images, and despite the disordered nature of the cloud[46,47]. Interestingly, it was shown theoretically in 2016[44] that the **photon correlations from the different**

[43] **L. Celardo *et al.*, https://arxiv.org/abs/1702.04506**
[44] **N. Piovella *et al.*, Phys. Rev. A 96, 053852 (2017).**
[45] S. Jennewein *et al.*, Phys. Rev. A **97**, 053816 (2018).
[46] J.-J. Greffet, Waves Random Media **1**, S65 (1991).
[47] **G. Labeyrie *et al.*, J. Opt.** B 2, 672 (2000).

sidebands can actually enhance the fringes, as a suitable distance between the atoms and the mirror allows each spectral component to gain the appropriate optical path. The experimental observation of the predicted revivals of the fringes for increasing Rabi frequencies (see Fig. 7) will be a demonstration of correlations between the Mollow sidebands in a large atomic cloud. The experimental setup is based on the one already developed for the m-CBS (see Fig. 3).

Deliverable: Scientific results (report and/or publication)

Risk: **Low**. The effect has been characterized theoretically in details, as the result of a previous collaboration between partners of the project, and the São Carlos experimental group has already achieved a m-CBS experiment in the saturated optics regime[32].

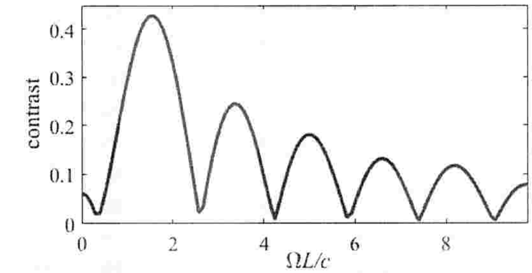


Fig. 7: m-CBS experiment: revival of the fringes contrast as a function of the Rabi frequency and of the optical path from the atoms to the mirror. See Ref. [44].

Task 3.2: Beyond mean-field optics: transmission in the dense regime

Dense clouds of cold atoms are prone to strong correlations due to near-field terms in the dipole-dipole coupling, which in turn challenge the validity of mean-field optics[45,48]. For example, it is responsible for important divergences between the predicted and reported frequency shifts at high densities[49,50,51]. Experimental reports[45] on scattering from a dense rubidium cloud, which multilevel structure was brought down to a two-level one in Ref. [45] using a strong magnetic field, were in disagreement with ab-initio calculations based on the coupled dipole model. For rubidium, however, the resulting excited level is a combination of different orbital sublevels, which differs from the 461nm J(=L)=0 $\rightarrow$ J(=L)=1 electronic transition present in bosonic strontium in absence of magnetic field. Considering the fundamental question of our representation of samples of two-level systems, especially in the high-density regime, which is for example used in atomic clocks or for photonic quantum memories, it is urgent to address the validity of the used model.

We here aim at tackling the dense regime using the J(=L)=0 $\rightarrow$ J(=L)=1 level structure of strontium. The objective is to find agreement between experiment and theory for the coherent transmission of the atomic cloud at high densities, probing modifications of the mean-field Beer law and collective Lamb frequency shift. Determining precisely frequency shifts is of importance to evaluate the scattering mean free path of the medium, and most of its transport properties; but it also has important consequences for atomic clocks[52], for example. This study of the **steady-state coherent transmission in the dense regime** will open up the path to the more general study of the transport properties of the cloud, and in particular of the long-standing question of the 3D Anderson localization of light[53,54], for which the scattering properties and the role of near-field terms were shown to be critical[55,56]. The dense regime in the São Carlos experiment will be achieved by transferring our cold atomic cloud to an ODT. A supplementary cooling stage of our strontium MOT allows us to achieve a cloud of T=1.5 µK and $N\approx 5\times10^6$, that we will further transfer to a crossed ODT of wavelength 1064 nm, 2.4 W power in each arm and trapping frequencies of $2\pi\times$(234, 235, 803)Hz. We aim at achieving a 50% transfer efficiency in the number of atoms, keeping the cloud temperature of T=1.5 µK, following recent developments[57] for a scheme for narrow-line cooling of atoms which is insensitive to the light shifts induced by the dipole trap light. The densities to be achieved, of about 10^{15} cm^{-3}= $80\lambda^{-3}$, with λ=461 nm the wavelength of the broad strontium atomic transition, sets our cloud deep into the dense regime.

Deliverable: A dense Sr cloud, with 2.5×10^6 atoms and a density of 10^{15} cm^{-3}, for further studies on the dense regime; a theoretical model for the dense regime, validated by the experiment with isotropic cold atoms; scientific results (report and/or publication)

48 J. Javanainen *et al.*, Phys. Rev. Lett. **112**, 113603 (2014).
49 J. Pellegrino *et al.*, Phys. Rev. Lett. **113**, 133602 (2014).
50 S. Jennewein *et al.*, Phys. Rev. Lett. **116**, 233601 (2016).
51 L. Corman *et al.*, Phys. Rev. A **96**, 053629 (2017).
52 M. D. Swallows et al., Science **331**, 1043 (2011).
53 D. S. Wiersma *et al.*, Nature **390**, 671 (1997).
54 T. Sperling *et al.*, Nature Photonics **7**, 48 (2012).
55 S. E. Skipetrov and I. M. Sokolov, Phys. Rev. Lett. **112**, 023905 (2014).
56 S. E. Skipetrov and J. H. Page, New J. Phys. **18**, 021001 (2016).
57 M. A Norcia *et al.*, New J. Phys. **20**, 023021 (2018).

Risk: **Moderate.** The transfer to the ODT has already been achieved before in similar experiments with similar densities, and the continuous cooling of the atomic species has been verified for similar other situations, as reported in [48], and theoretically at hand. The agreement between theory and experiment for the coherent transmission can be precluded by density effects created by the radiation pressure of the scattered photons and s-wave scattering effects.

Task 3.3: Superradiance in the dense regime

Cold atom clouds possess both short (superradiant) and long (subradiant) time scales (see an example in Fig. 8), and the control of these is particularly important in the context of memories: superradiant states allows one to couple a write/read fields efficiently, subradiant states to store them[5]. In the dilute and weak driving regime, both phenomena have been extensively studied experimentally and theoretically[6,30,58]. The dense regime yields promises of even more extreme lifetimes as the cooperation between the atoms could become even stronger, especially in the subwavelength regime where it could couple to a unique light mode. Yet, detrimental effects such as Van der Waals dephasing due to near-field fields may actually break the cooperation, as is known from the superradiant cascade for a fully inverted system[23]. This task addresses the theoretical and experimental characterization of **superradiance from dense clouds with a weak probe**, focusing on the role of polarization and near-field effects. Differently from the full superradiant cascade[59], the weak driving regime addresses only its last step, once the laser has imprinted a given phase profile with a single excitation. Our aim is to understand the limitations that near-field terms may impose to the full cooperation reached in optical cavities, where it scales directly with the particle number.

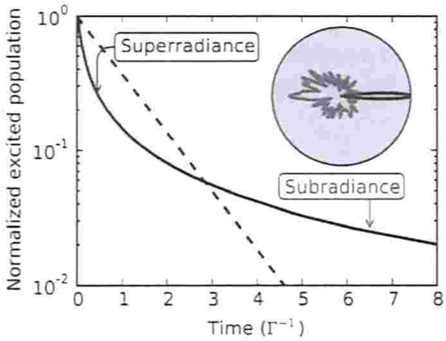


Fig. 8: Decay of the excited population in an optically dense cloud (plain) as compared to the single atom decay (dashed). The upper right diagram depicts the cloud emission pattern, with coherent (blue) and incoherent (red) scattering.

The theoretical work will first focus on the transition from the dilute regime, where collective lifetimes are determined by the number of particles per optical mode (that is, the cloud resonant optical thickness), to the dense case, where near-field terms are known to break this picture. In a second step, the São Carlos setup will be adapted to detect the fast response (ns) of the strontium cloud in a switch-off configuration. The measurement of the superradiant behavior of the fluorescence decay of our cloud will need a clean and fast switch off of the excitation light, in a timescale of, or better than, 1ns for the strontium transition of λ=461 nm. For that, an EOM and a photomultiplier with very low after-ringing will be needed. The expertise of the group at Nice in measuring the superradiant decay of their rubidium clouds will greatly help the São Carlos group.

Deliverable: Scientific results (report and/or publication)

Risk: **High.** The characterization of the superradiant emission requires both a fast detection and a fast switch-off of the driving field. Moreover, the small deviations need to be probed in a weak signal given after switch off of the probe light by a cloud of about 10^6 atoms in the weak excitation regime, with a solid angle of at most 5% of the total 4π sr, limited by the optical access of our experiment.

WP 4: Theory – Quest for collective quantum effects

Scientific coordinator : Romain Bachelard (UFSCAR, Brazil)

This workpackage is dedicated to prospective investigations of **quantum collective behaviours** (between the atoms), and their **potential experimental observation** (when photons are detected). The first objective is to determine a regime where a blockade effect can be achieved, which represents a strongly entangled state for the atoms, and leaves a visible signature in the radiated field, i.e., collective Rabi oscillations. The second objective is to study the synchronization of the atomic dipoles in presence of a dephasing mechanism (here originating in the diagonal disorder generated by the external speckle field discussed in task 2.3). This workpackage is complementary to the

[58] S.J. Roof *et al.*, Phys. Rev. Lett. **117**, 073003 (2016).
[59] N. Skribanowitz *et al.*, Phys. Rev. Lett. **30**, 309 (1973).

theory support that will be brought to the other workpackages (WP 1-3), which are largely driven by the experiments and their constraints. Yet it focuses on more fundamental aspects, and the possibility of observing the associated phenomena in the experiments involved in the project is less certain.

Task 4.1 – Collective Rabi oscillations in dilute atomic clouds

The Mollow babies are a signature of quantum pair correlations between the atoms, yet in general it is very challenging to detect entanglement from a large set of particles. The objective is here to show how collective Rabi oscillations [60], a **hallmark of entanglement between atoms**, could be achieved in dilute clouds. These oscillations are possible thanks to the energy splitting of the different modes due to interactions. Considering the simple case of a pair of two-level atoms[61] (with states |g> and |e>), Rydberg systems present a shift in energy in the |ee> state, which, if large enough, can prevent a double excitation (blockade effect). For the dipole-dipole interaction, there is rather a symmetric shift in the superradiant and subradiant states ((|ge>±|eg>)/√2, up to phase terms), as compared to the single atom case; thus, if the detuning to the atomic transition is properly chosen and the shift large enough, it is in principle possible to address only the superradiant state, and recover a blockade effect. This requires two very close atoms, for the energy gap to be of several transition linewidths at least.

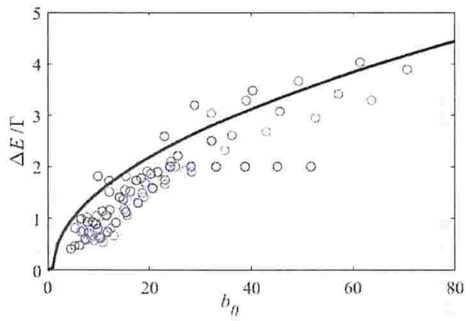


Fig. 9: Energy shift of the superradiant mode in the Rb2 experiment, as a function of the resonant optical thickness (different colors correspond to different detuning values). The continuous line corresponds to a linear-dispersion calculation.

In dilute clouds, the large distance between atoms and the consequent weak coupling between them are compensated by the sum over many of them. As a result, recent measurements of the shift in energy of the superradiant state in the Rb2 experiment has shown shifts of several transition linewidths (see Fig. 9), thus opening the exciting possibility to investigate blockade effects in such systems. This task is dedicated to evaluating through analytical and numerical methods how this blockade effect can be achieved. Linear-dispersion theory can, for example, be used to evaluate the shift in energy of the superradiant state, in the fashion of Ref. [[62]]. The modelling and simulations of a large system is much more challenging, as for Rydberg atoms[63], and truncated methods will be used to that end. Interestingly, realizing the blockade effect in dilute clouds of two-level atoms does not involve highly-excited levels (which are very sensitive to external parasite fields, for example), so that such a setup would have many advantages over a Rydberg atoms one[64].

Deliverable: Scientific results (report and/or publication)

***Risk:* High.** The presence of collective modes has been identified at this point, yet the possibility to address only a specific one is not clear, due to the huge number of modes present (they have been well characterized only in the linear-optics regime). All in all, the potential of this task is high, but may be directly observable on the Rb2 experiment if theory predicts a clear effect.

Task 4.2 – Classical and quantum synchronization of atomic dipoles in 3D

As mentioned in task 2.3, diagonal disorder introduces a random shift in the frequency of the oscillating dipoles. This naturally brings us to the paradigmatic Kuramoto model, in which a spread in the oscillators frequencies competes with a global coupling between them. The oscillators phases are given by the following dynamical equations:

$$\frac{d\,\theta_j}{dt} = \omega_j + \frac{K}{N}\sum_j \sin(\theta_j - \theta_m),$$

where θ_j corresponds to the dipole amplitude, ω_j to the shift in energy of the associated atom, and K to the coupling constant (provided by the dipole-dipole coupling in our case). In our 3D problem, the cooperation between

[60] Y. O. Dudin, L. Li, F. Bariani, and A. Kuzmich, Nature Physics 8, 790 (2012).
[61] A. Gaëtan *et al.*, Nature Physics **5**, 115 (2009).
[62] Y. Zhu *et al.*, Phys. Rev. Lett. **64**, 2499 (1990).
[63] J. T. Young *et al.*, Phys. Rev. A **97**, 023424 (2018).
[64] E.A. Goldschmidt *et al.*, Phys. Rev. Lett. **116**, 113001 (2016).

the atoms is typically given by the resonant optical thickness, that describes the number of atoms per optical mode to which the system can couple. The question we want to address is thus whether **cooperativity between the atoms** is able to **synchronize the dipoles in presence of a dephasing mechanism** (the diagonal disorder in the present case).

At first, we intend to address this problem from a classical point of view, that is, when the atomic dipoles behave like point-like antennas. This draws a direct analogy with the Kuramoto synchronization problem, yet in a 3D context where many modes may compete and where dissipation (from spontaneous emission) needs to be compensated by a permanent pumping. If our theoretical work is successful in demonstrating a synchronization mechanism, we will try to identify a signature of the dynamical transition on the radiated light, in order to provide observables for an experiment. In general, one expects the cloud to switch from an emission dominated by diffusive processes to coherent ones throughout the synchronization transition.

A challenging second step is to move to a strong driving of the atoms, where they start behaving as quantum emitters rather than classical antennas. One then enters the realms of quantum synchronization of atomic ensembles[65], a process that is intimately linked to the existence of sub- and superradiant modes[66]. Previous works addressed mainly 1D configurations (optical cavities), or ordered systems[67]. We here aim at showing that collective modes, whose strength scales with the resonant optical thickness in a 3D disordered system, can allow for quantum synchronization. The competition here takes place between diagonal disorder, collective open channels (from collectively-emitted photons) and Hamiltonian coupling terms (from virtual photons). Finally, note that quantum synchronization is particularly interesting in a gain configuration, where superradiant lasing can then be achieved[68]. Predictions on quantum synchronization would thus open promising perspectives for the lasing setup operated in the French group[69].

Deliverable: Scientific results (report and/or publication)

***Risk:* Moderate.** Demonstrating classical synchronization appears very likely, considering the ingredients present in the system, and since the radiation depends on the synchronization of the atomic dipoles, the synchronization transition is very likely to leave a detectable signature in the cloud emission. The quantum synchronization is more challenging, and the strong dissipative component of the system may prevent a full synchronization.

WP 5: Management and dissemination

The management includes **administrative and scientific implementation** of the project as well as a good communication between the different partners. For the French part on one side, and the Brazilian part on the other side, the persons already work in strong collaboration with day-to-day discussions. Concerning the coordination between the French and Brazilian teams, a special attention will be paid to implement **regular scientific discussions** via videoconference, at least once every 2 months between the experimental partners and once a month between the experimental and theoretical partners. Several **travels** are also planned, essential to ensure a successful collaboration, either to exchange some know-how on the experiments or to discuss more deeply the theoretical and experimental progress. A minimum of 2 travels per year from both sides are planned, with a duration of stay from a few days to a few weeks for researchers, as it has already been done over the recent years. For students, longer stays will be organized, for example, for the Brazilian PhD student Pablo Dias who will realize a one-year stay in Nice.

Dissemination will be done mainly through two channels: **international conferences** and **publications**. Beyond this, we will also organize at least **two international workshops** related to the topics developed in this proposal and two **international schools**. More informations are given at this end of this proposal (section III).

[65] M. Xu *et al.*, Phys. Rev. Lett. 113, 154101 (2014).
[66] B. Bellomo *et al.*, Phys. Rev. A 95, 043807 (2017).
[67] B Zhu *et al.*, New J. of Phys. 17, 083063 (2015).
[68] J. G. Bohnet *et al.*, Nature **484**, 78 (2012).
[69] **Q. Baudouin *et al.*,** Nature Physics 9, 357 (2013).

- ***Gantt chart (48 months)***

	Year 1	Year 2	Year 3	Year 4
WP 1: Correlated photon source – Mollow triplet				
Task 1.1: Quantum cooperative effect – Mollow baby				
Task 1.2: Correlations inside the Mollow triplet				
Task 1.3: Correlations between the Mollow sidebands				
WP 2: Quantum memory – Super and sub-radiance				
Task 2.1: Subradiance enhancement				
Task 2.2: Quantum subradiance				
Task 2.3: Recovering excitations from the subradiant dynamics				
WP 3: Correlations in the dense regime				
Task 3.1: m-CBS with the Mollow triplet				
Task 3.2: Beyond mean-field optics: the dense regime				
Task 3.3: Superradiance in the dense regime				
WP 4: Theory – Quest for collective quantum effects				
Task 4.1: Collective Rabi oscillations in atomic clouds				
Task 4.2: Synchronization of atomic dipoles in 3D				
WP 4: Management and dissemination				

II. Organisation and implementation of the project

a. Scientific coordinator and its consortium / its team

- ***Scientific coordinators***

<u>Coordinator of the project – French part:</u> Mathilde Fouché, Institut de Physique de Nice (INPHYNI), CR CNRS

The coordinator of the project for the French part is Mathilde Fouché, a CNRS researcher since September 2006. She obtained her PhD in 2005 at the Institut d'Optique, supervised by Alain Aspect on elongated Bose-Einstein condensates. She then did a post-doc at Observatoire de Paris on an optical clock supervised by Pierre Lemonde. She first started her permanent researcher carrier in Toulouse (LCAR and LNCMI) working on propagation of light in a magnetic field and more precisely on a "light shining through the wall" experiment looking for hypothetical particles called axions. She then turned to the so-called BMV (Vacuum Magnetic Birefringence) experiment with Carlo Rizzo and was in charge of the whole optical setup. She was co-awarded (with Rémy Battesti and Philippe Nussbaumer) in 2011 by OSEO prize for innovation technology.

She finally came back to the cold atoms field in 2015, working in the group of Robin Kaiser. She is now in charge of one of the cold-atom experiments and mainly focuses on classical or quantum correlations of light scattered by a cold atomic cloud. She is also involved in the so-called HBT project whose goal is to re-implement intensity correlations (or intensity interferometry) for stellar physics measurements with modern technologies. She wrote 44 papers (h=18, citations=1615). She will dedicate 40 % of her time to the present project.

<u>Coordinator of the project – Brazilian part:</u> Romain Bachelard, Departamento de Fisica, Universidade Federal de São Carlos

Romain Bachelard is an assistant professor working on light-matter interactions since his PhD, awarded in 2008 at the Aix-Marseille University. He initially investigated free electron lasers and dynamical aspects of long-range interactions, before moving to light scattered by cold atoms in 2011, when he settled in São Carlos. Since then, he has worked on self-organized processes in optical cavities (1D) and light scattering in free space (3D). He is a theorist, with regular collaborations with experimental cold atom groups (in São Carlos and Tübingen, Germany, in addition to the INPHYNI group).

He has been awarded a FAPESP Young Researcher grant (2014-2018), a Royal Society Advanced Fellowship (2019-2020) and several other grants from Brazilian agencies (FAPESP Outgoing Research Scholarship (2018-2019), to realize a sabbatical at the INPHYNI), Universal Call from CNPq (2014-2017 and 2018-2020), Grants for Event Organization from FAPESP and Brazilian CAPES), and is involved in several international collaborations (with the

INPHYNI group, but also with Germany, EU, South Africa, UK). He supervised 1 post-doc and 3 PhD students, wrote 45 papers (h=14, citations=541) and will dedicate 37% of this time to the project.

Name of the researcher	Person. month	Call, funding agency, grant allocated	Project's title	Name of the scientific coordinator	Start - End
M. Fouché	x	Région PACA	Intérférométrie d'Intensité à Calern	R. Kaiser	2019-2021
M. Fouché R. Bachelard	x	COFECUB	Classical and quantum correlations in cold atomic cloud	P. Courteille and R. Kaiser	2017-2020
R. Bachelard	x	CAPES-DAAD PROBRAL	Boundary-conditions-driven dynamics and radiation of cold atoms	P. Courteille and A. Pelster	2018-2021
R. Bachelard	x	Royal Society	Dynamics of matter waves undergoing Bloch oscillations in a ring cavity	R. Bachelard and G. Robb	2019-2020
R. Bachelard	x	ColOpt/ITN	Collective Effects and Optomechanics in Ultra-cold Matter	T. Ackemann	2018-2020
R. Bachelard	x	FAPESP Thematic	Development of Quantum Sensors based on Ultracold Atoms	P. Courteille	2014-2019

Table 1: Implication of the scientific coordinators in on-going projects

- ***Consortium***

The consortium brings together 2 internationally recognized partners with their own expertise: one experimental team in France and one experimental and theory team in Brazil. Due to the close connection between the theoretical and experimental goals in this project, the partners will work in close collaboration. They will also share at least one sandwich PHD student between the two experiments in France and Brazil. The two teams are already strongly collaborating, as illustrated by the 6 joint publications emphasized in red in the text, thanks to several mobility projects between the two groups: COFECUB-CAPES(2017-2020), CNRS-FAPESP (2016-2018), CNPq Special Visiting Professor for Robin Kaiser (2014-2017), COFECUB-USP (2011-2014) and FP7-People-IRSES Coscali (2011-2015). The present **joint research grant** aims at strengthening even further the collaboration.

French partner: Institut de Physique de Nice (INPHYNI), Université Côte d'Azur (UCA), CNRS

The INPHYNI partner involves several academic staff forming part of the "cold atoms" team of INPHYNI: **Mathilde Fouché**, coordinator; **William Guerin**, CNRS research fellow; **Robin Kaiser**, CNRS senior research fellow (head of the team). This group runs two experiments on Rb laser-cooled atoms and several projects using room-temperature or hot atomic vapors. It gained an international recognition in the physics of light interaction and propagation in atomic ensembles, and technical expertise in light detection such as intensity correlations. The research of the team is mainly devoted to collective effects in the interaction of light with atoms and light propagation in disordered media.

Brazilian partner: Departamento de Fisica, Universidade Federal de São Carlos (UFSCAR), and Instituto de Fisica de São Carlos, Universidade de São Paulo (IFSC-USP)

The Brazilian partners are located in two laboratories in São Carlos: the main effort will be lead by the UFSCar members **Romain Bachelard** and **Raul C. Teixeira**, Assistant Professors, who started a "cold atom" group a few years ago (with three other professors). A cold strontium experiment (Sr used in this project) has been built at the IFSC-USP over the past years, under the supervision of **Philippe W. Courteille**, and will be transferred to UFSCAR. The IFSC-USP is running another strontium experiment, with an optical cavity.

The **collaborative aspect** of this project is essential in several ways:

– Experiments (France and Brazil) and theory (Brazil): The complementarity between theory and experimental goals is very strong, with several experiments relying heavily on prior theoretical predictions. Indeed, some predictions are already well established but some others are clearly still missing to drive the experiments, such as predictions on photon correlations in the Mollow sidebands, or the role of correlations in the dense regime. The collaboration between the theory node and the experimental ones has been working successfully for many years, with numerous publications resulting from it.

– Exchange of know-how: The two experiments in France and the one in Brazil are not at the same stage of development. While the two in France are fully operational and already gave results related to this proposal, the one in Brazil is still partially under development. It has already produced results in the dilute regime[51,70,71], and now requires

[70] **P.H. Moriya *et al.*, J. Phys. Comm. 2, 125008 (2018).**
[71] **C.J.H. Pagett *et al.*, Rev. Sci. Instr. 87, 053105 (2016).**

the implementation of the dipole trap needed to reach the dense regime. The exchange of know-how will be thus mainly from France to Brazil, and will in particular concern the implementation of the setup to measure the superradiance effect. Such techniques have been developed over the last years and are now well mastered in the French team, it will thus help the Brazilian team to save a precious time. Furthermore, it is planned to send some Brazilian students for extended stays (6-12 months, at the PhD or post-doc level) to the French group, for example with Brazilian "outgoing scholarships": these students will benefit from the strong expertise from the French group and bring this know-how back to their group, but they will also represent a valuable manpower for the French group.

– Complementarity: Finally, the scientific objectives in this collaboration have very complementary aspects that could not be fully addressed by a single experiment, such as the dilute and dense regimes, the narrow (Sr) and broad (Rb) transitions, or the effect of light polarization. Yet the techniques do address them present a strong overlap. The different complementary aspects, without being exhaustive, are summarized in Table 2.

	Rb1 (France)	Rb2 (France)	Sr (Brazil)	Theory (Brazil)
Correlated photon source	✓		✓	✓
Memory		✓	✓	✓
Quantum collective effect	✓	✓	✓	✓
Dilute regime	✓	✓		✓
Dense regime			✓	✓
Insensitive to polarization			✓	
Dynamical behavior		✓	✓	✓
Intensity correlations	✓			✓

Table 2: Complementarity between the different partners

b. Implemented and requested resources to reach the objectives

- ***Requested mean to achieve the objectives***

The total cost is 376 k€, with the following repartition between the partners:

		Partner *INPHYNI (France)*	Partner *UFSCAR (Brazil)*
Staff expenses		147 k€	
Instruments and material costs		99 k€	52 k€
Outsourcing / subcontracting		5 k€	5 k€
General and administrative costs & other operating expenses	**Travel costs**	10 k€	8 k€
	Administrative management & structure costs (8%)	20.9 k€	6.5 k€
Sub-total		**282 k€**	**94 k€**
Requested		**282 k€**	**94 k€**

Note that the Brazilian call does not cover scholarships. These are rather obtained through dedicated individual proposals, facilitated by the fact that the main project requires them. Finally, as presented in the table of people involved in the project, the Brazilian group already has several PhD students and post-docs at the moment.

- ***Detailed requested means***

Partner 1: *INPHYNI (France)*

The core of the two experiments at INPHYNI already exists. The requested funding will be used to hire a postdoctoral researcher and to upgrade the two setups to achieve the objectives of this project.

Staff expenses: Manpower is critical to daily run cold atom experiments. One Brazilian PhD student (Pablo DIAS) will spend a year at INPHYNI, in the framework of a sandwich PhD. The team will also consist in two PhD students (funding not requested here), one in each French experiment, and a post-doctoral fellow. We request the funding for **a two-**

year postdoctoral researcher. A special attention will be paid to first work on the less risky tasks. He/She will work either on correlations inside the Mollow triplet (WP1, Tasks 1.2 and 1.3) or on quantum subradiance and intensity correlations (WP2, Tasks 2.2).

Instruments and material: The two Rb experiments in Nice are built and are currently running. We request **8 k€** per year for **consumables** to update the experiments on the different tasks (optical and optomechanical components, acousto-optics, fibers, electronics,...)

An intensity correlation setup is already used on one of the Rb experiment but not specifically dedicated to it since it also used for the experiment done in collaboration with the astrophysicists to revive intensity interferometry in astrophysics. Rb1 will need this setup (WP1, tasks 1.2 and 1.3) and sharing the same device is hardly feasible regarding the long integration time needed to perform the different experiments. We thus request the funding of a new complete device: **a time to digital convertor** (**40 k€**, from the Swabian Instruments company, TDC already tested in our group and particularly adapted to avoid spurious correlations), and **two single-photon detectors** (**12 k€** in total).

Finally, funding is requested for **two Fabry-Perot cavities** (**15 k€** in total), necessary to filter the different components of the Mollow triplet (WP1, tasks 1.2 and 1.3).

Publications: This includes **5 k€** for publication charge in open-access journals

Travel costs: This project is a collaboration between teams in different countries. Travel is thus essential for a fruitful collaboration, either to make a strong connection between the theoretical results and the experimental feasibility, or to exchange know-how. We presently benefit from a COFECUB-CAPES project, which funds 2 travels per side and per year until the end of 2020. More bilateral mobilities will be requested. The travel costs requested for this project, which include participation to conferences, sum up to **8 k€**.

Partner 1: ***UFSCAR (Brazil)***

To simplify the analysis between the two partners, all expenses for the Brazilian partners are presented in euros. Importantly, the Brazilian call covers only material (equipment, consumables, travel costs), the scholarships being obtained through other channels (including FAPESP scholarships).

Instruments and material: We request the funding dedicated to reach the dense regime (WP3, Task 3.2) with improved stability on number of atoms, and the superradiance measurement (WP3, Task 3.3).

For the stability on the number of atoms, we need to stabilize the frequency of our 497 nm repumper. We need for that a **fibered EOM (4 k€)** and a **PID control (4.5 k€)** as well as a **quadrant photodetector (1k€)** for monitoring the alignment of our optical dipole trap.

For scanning the 461 nm excitation laser over a long range (hundreds of MHz), we need to make a small portion of light pass through a **fibered EOM (4 k€)** before the stabilization scheme. **Power supplies (2x1.5 k€)** are needed to guarantee the power to generators and amplifiers.

Finally, for the superradiance measurement, we need a **multichannel scaler (13 k€)** to record the histogram of arrival times of the photons with 400 ps typical temporal resolution and a **control electronic board (2.5 k€)** with input and output channels with better temporal resolution.

We request **5 k€ of consumables per year** of project.

Publications: This includes **5 k€** for publication charge in open-access journals

Travel costs: As already explained in the travel costs of the French partner, we request **8 k€** for mobility for our collaboration and participation in conferences.

III. Impact and benefits of the project

• ***Expected impact and relation to the ANR call***

Our project belongs to the "Quantum Technologies" pillar of "plan d'Action 2019". We more specifically address the topic **"fundamental research and development of new concepts to implement quantum technologies"** (see fifth sector in "Appel à projets générique 2019") and the key words related to our project are "quantum optics, quantum source, memory, quantum systems: atoms".

This project belongs to fundamental research with the test of new possibilities for quantum memories and correlated photon sources based on multi-atom cold ensembles. In the long term, if successful, our results can stimulate new devices based on cold atoms, or similar quantum emitters. The goal is actually to give some new insights on quantum collective effects and their possible applications in quantum technologies. It is clear that 4 years are too short to implement, for example, a new kind of functional memory, but our objective is rather to **pave the way to new conceptual building blocks** for quantum communication or quantum calculations.

Finally, even if this project fully addresses the objectives of the "quantum technologies" pillar, the results can have an impact on a different communities, such as mesoscopic physics.

- ***Dissemination***

Dissemination to the scientific community will be first done through the two standards channels: **international conferences** and **publications**. The results obtained in this project can undoubtedly address the **leading peer-reviewed international journals**. Whenever possible, publications will be also deposited on the arXiv and HAL servers. We will finally pay attention to give the opportunity to the PhD students and postdoctoral researchers to present their work in international conferences.

Our collaboration is already involved in the organization of different **international events**, such as CoScaLi (Workshop on Collective Scattering of Light) organized in 2016 and 2018 by Romain Bachelard and Robin Kaiser in Brazil. We are already planning the next session in 2020 (co-organizers: R. Bachelard, R. Kaiser and M. Fouché) in France and the goal is to keep this event every 2 years. In parallel, we will also participate to the PhD student training through **international summer schools**. We will mainly focus on a school organized every two years at the ICTP-SAIFR in São Paulo (see editions of 2017 and 2019). The school in 2021 will be organized by Romain Bachelard, Raul Teixeira and Mathilde Fouché and some specific lectures will be dedicated to the different topics developed in this proposal.

Finally, communication to a more general audience will be addressed, making the results of this project accessible to a broad audience. The **websites** of the French and Brazilian teams will be either created or updated to include this project and its goals, the results and a list of the publications. We will also participate to different **outreach actions** such as "La fête de la science" in France or the "Semana de Optica" in São Carlos, but also continue some specific actions such as the development of **small transportable outreach experiments** on the topics of "light scattering". This last point has been already started, in collaboration with some undergrad' students of Université Côte d'Azur. For example, a small breadboard is now ready to explain and illustrate the coherent backscattering effect to a large audience.

- ***Balance between the scientific contributions and added value for France and Brazil***

This proposal relies on a strong collaboration between the two groups, and its main collaborative aspects have already been detailed in section II a. To summarize, the most important aspects are:

– Theoretical predictions (Brazil) to guide the experiments (France and Brazil): The guidance of theory is essential to complete the entire experimental project, in particular for the French part for which the researchers are mainly experimentalists. This collaboration has already published different results related to this proposal, with either purely theoretical predictions or both experimental and theoretical results.

– Complementarity: This collaboration will allow addressing complementary issues that could not be fully addressed by only one experiment (see Table 2 for a summary of the scientific complementarity). In particular, the Brazilian part will have access to the dense regime, not accessible for the moment on the French experiments, as well as narrow transition with an atom close to a pure two-level system.

– Exchange of know-how: As said before, the different experiments are not at the same stage of development, so the exchange of know-how will be mainly from France to Brazil. However, almost unilateral exchange of know-how does not mean no fallout for the French part. Several trips are scheduled from Brazil to French, and receiving experienced researchers for a few weeks is a strong benefit for any of the groups. For example, the observation of the Mollow triplet in July 2018 was triggered by the visit of Raul C. Teixeira from São Carlos.