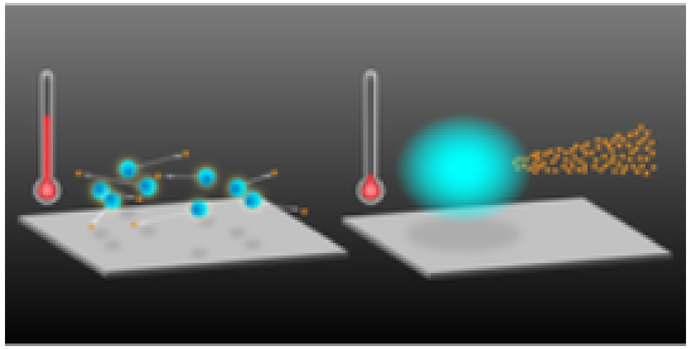
Can Bose-Einstein condensates modify radioactive decay of atoms

Wolfgang Ketterle
Massachusetts Institute of Technology
MIT-Harvard Center for Ultracold Atoms

January 14, 2026

Workshop on the intersections of Quantum Information Science and Nuclear Physics
UMass, Boston

FEATURED IN PHYSICS | EDITORS' SUGGESTION



Superradiant Neutrino Lasers from Radioactive Condensates

B. J. P. Jones and J. A. Formaggio

Phys. Rev. Lett. **135**, 111801 (2025) - Published 8 September, 2025

A Bose-Einstein condensate of radioactive atoms could turn into a source of intense, coherent, and directional neutrino beams, according to a theoretical proposal.

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VIEWPOINT

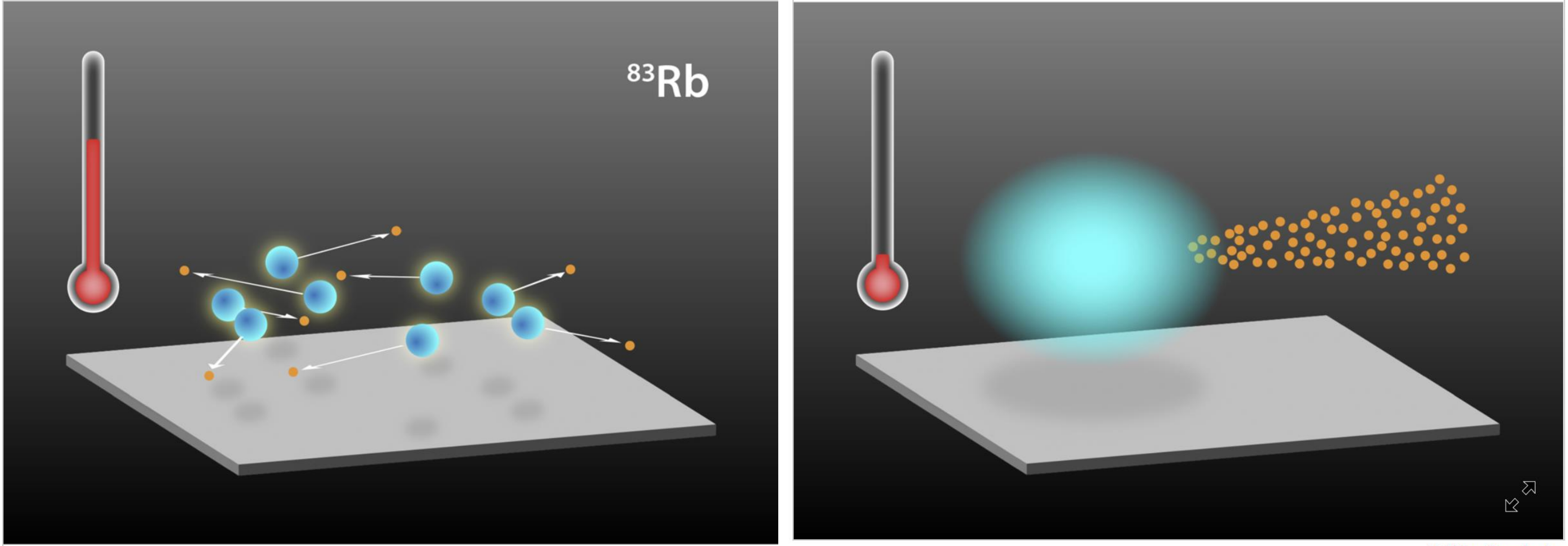
Envisioning a Neutrino Laser

Kyle G. Leach

Department of Physics, Colorado School of Mines, Golden, CO, US

September 8, 2025 • *Physics* 18, 157

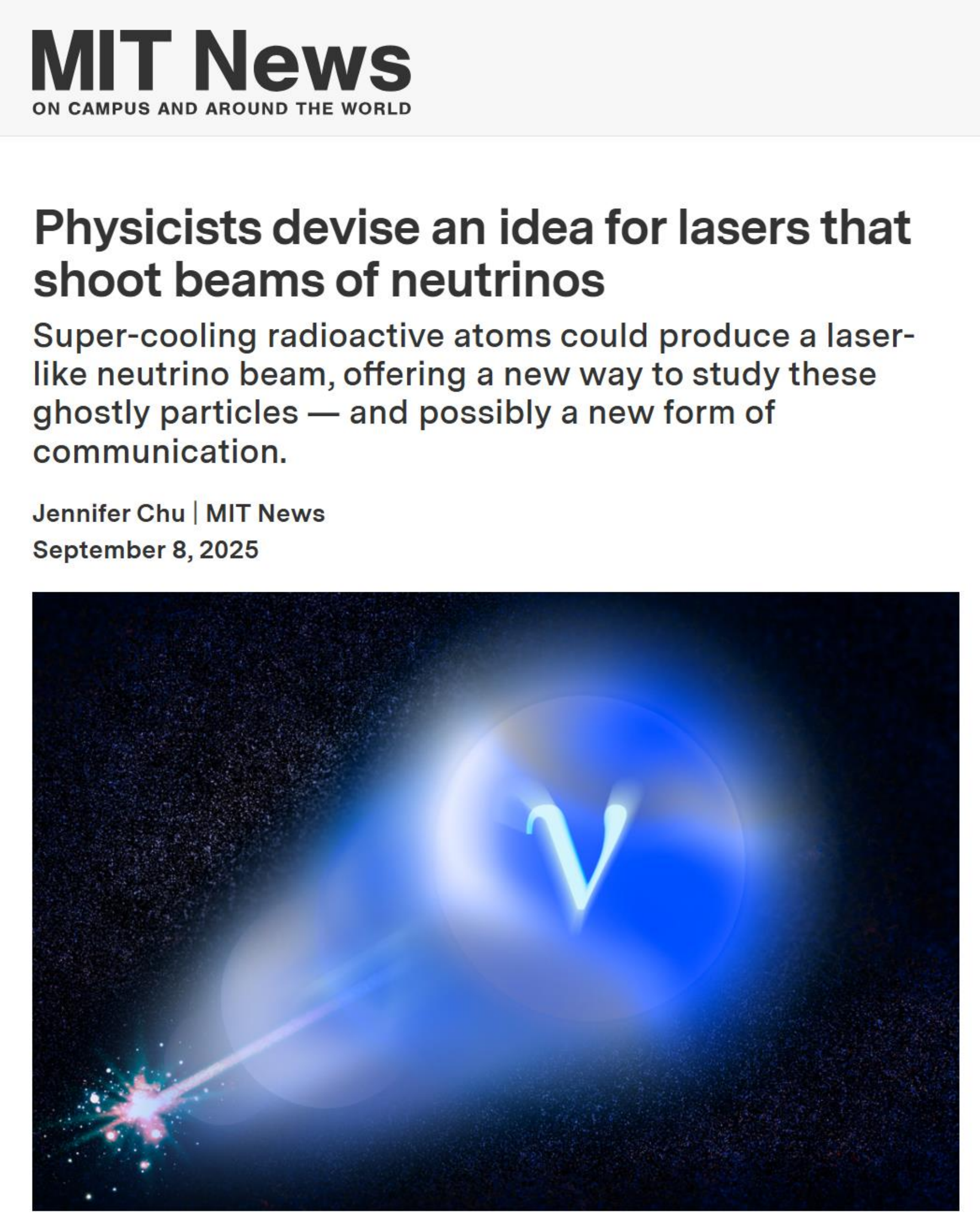
A Bose-Einstein condensate of radioactive atoms could turn into a source of intense, coherent, and directional neutrino beams, according to a theoretical proposal.



APS/Alan Stonebraker

Figure 1: Top: At high temperature, rubidium atoms decay radioactively through electron capture, releasing neutrinos incoherently. Bottom: At sufficiently low temperatures, the atoms form a Bose-Einstein condensate that could act as a “neutrino laser,” emitting a bright, coherent, directional beam of neutrinos.

The “half-life would be shortened by nearly a factor of 50,000: from 86.2 days to about 2.5 minutes”.

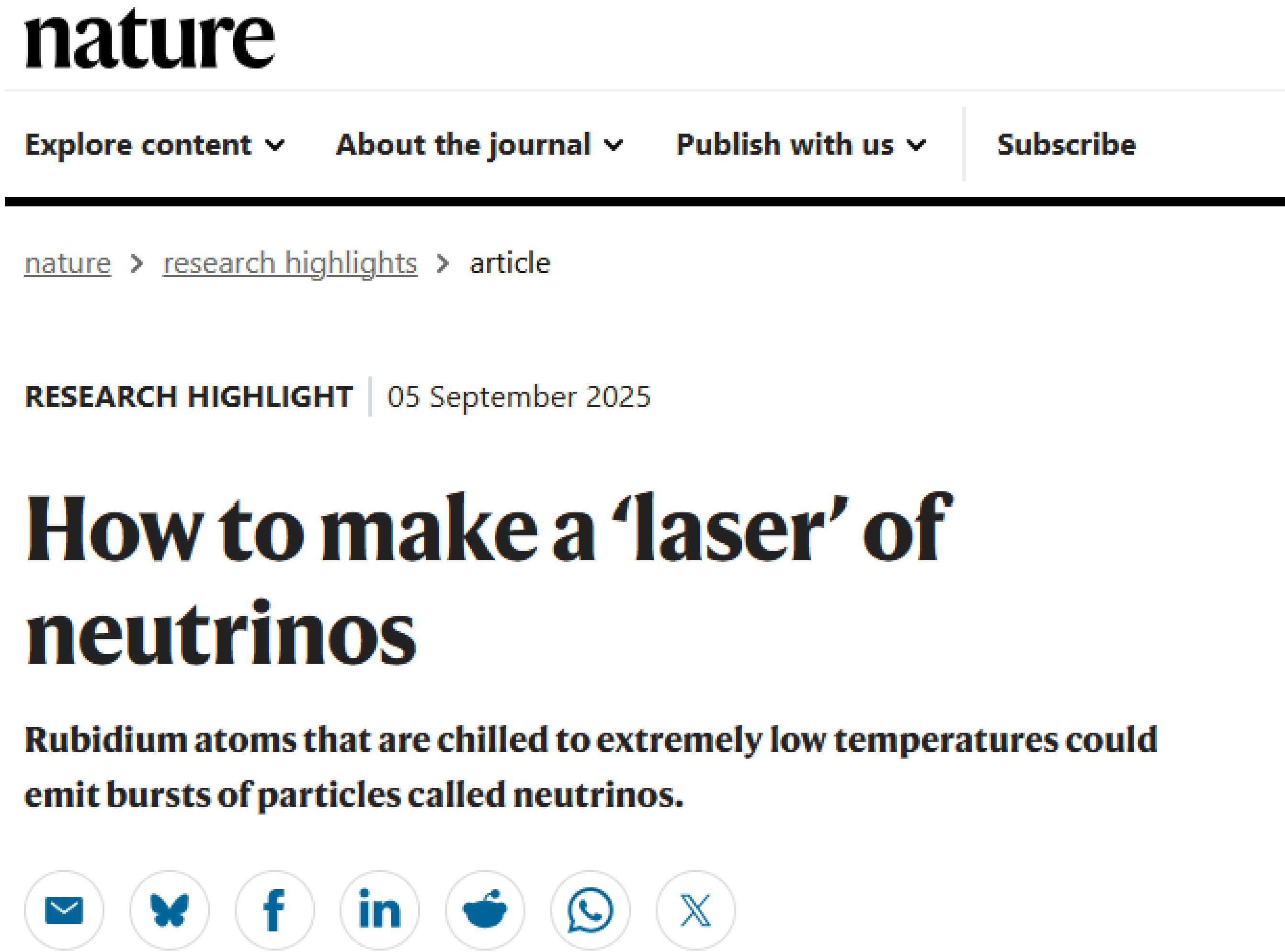


MIT News
ON CAMPUS AND AROUND THE WORLD

Physicists devise an idea for lasers that shoot beams of neutrinos

Super-cooling radioactive atoms could produce a laser-like neutrino beam, offering a new way to study these ghostly particles — and possibly a new form of communication.

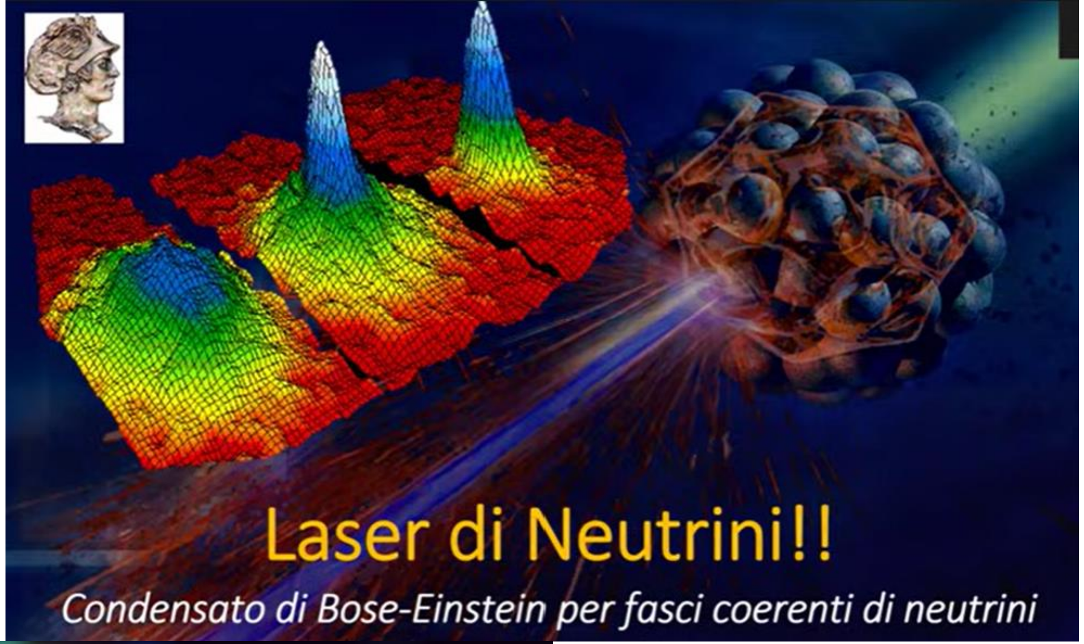
Jennifer Chu | MIT News
September 8, 2025



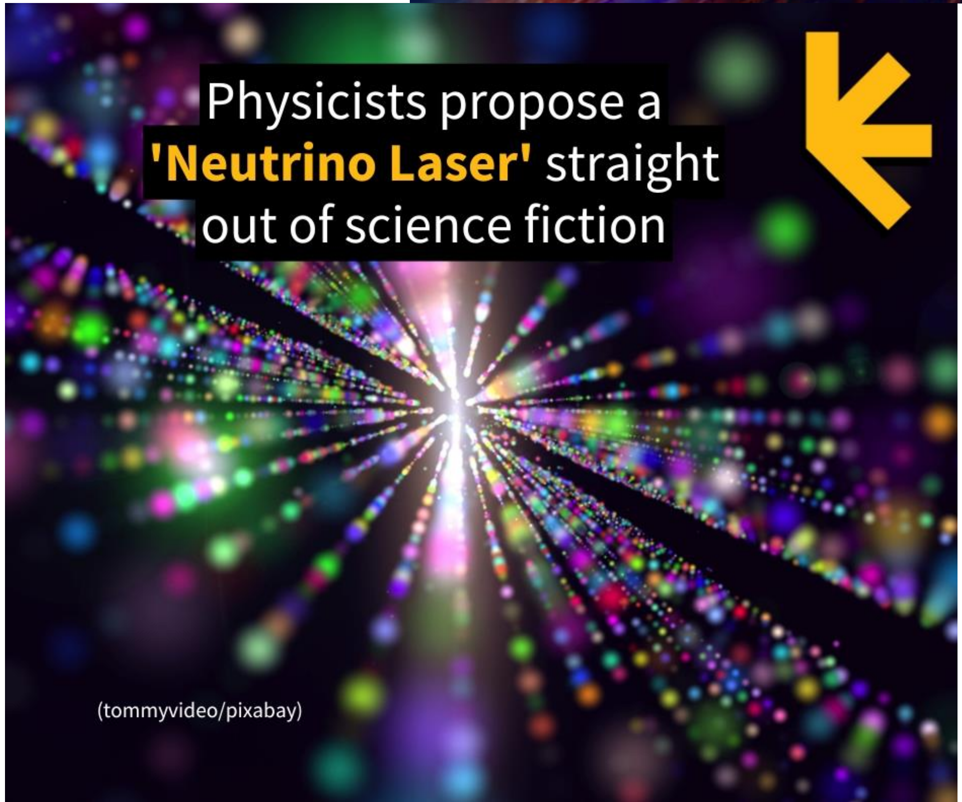
RESEARCH HIGHLIGHT | 05 September 2025

How to make a ‘laser’ of neutrinos

Rubidium atoms that are chilled to extremely low temperatures could emit bursts of particles called neutrinos.


Laser di Neutrini!!
Condensato di Bose-Einstein per fasci coerenti di neutrini


MIT scientists just found a way to build the **world's first neutrino laser**


Physicists propose a **'Neutrino Laser'** straight out of science fiction
(tommyvideo/pixabay)

SPECIAL FEATURE

Highlights of the Year

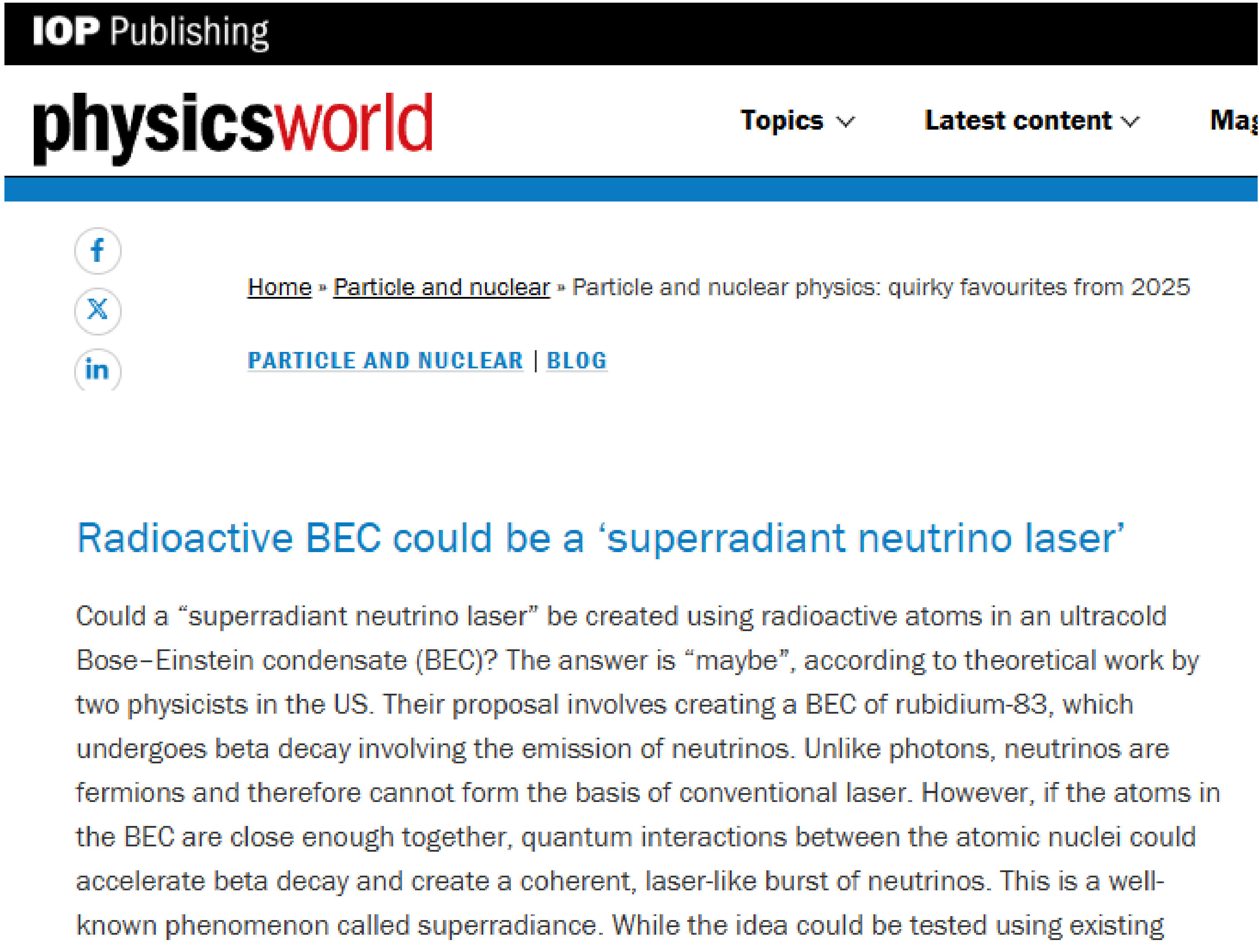
December 15, 2025 • *Physics* 18, 191

Physics Magazine Editors pick their favorite stories from 2025.

Imagining a Neutrino Laser

Neutrinos barely interact with anything, so a collective laser-like
science fiction. But researchers believe that this so-called super
quantum condensate of radioactive atoms (see **Viewpoint: Envi**
proposed scheme, ultracold rubidium-83 atoms—which emit a
placed in the same quantum state. One atom's decay triggers ot

Particle and nuclear physics: quirky favourites from 2025



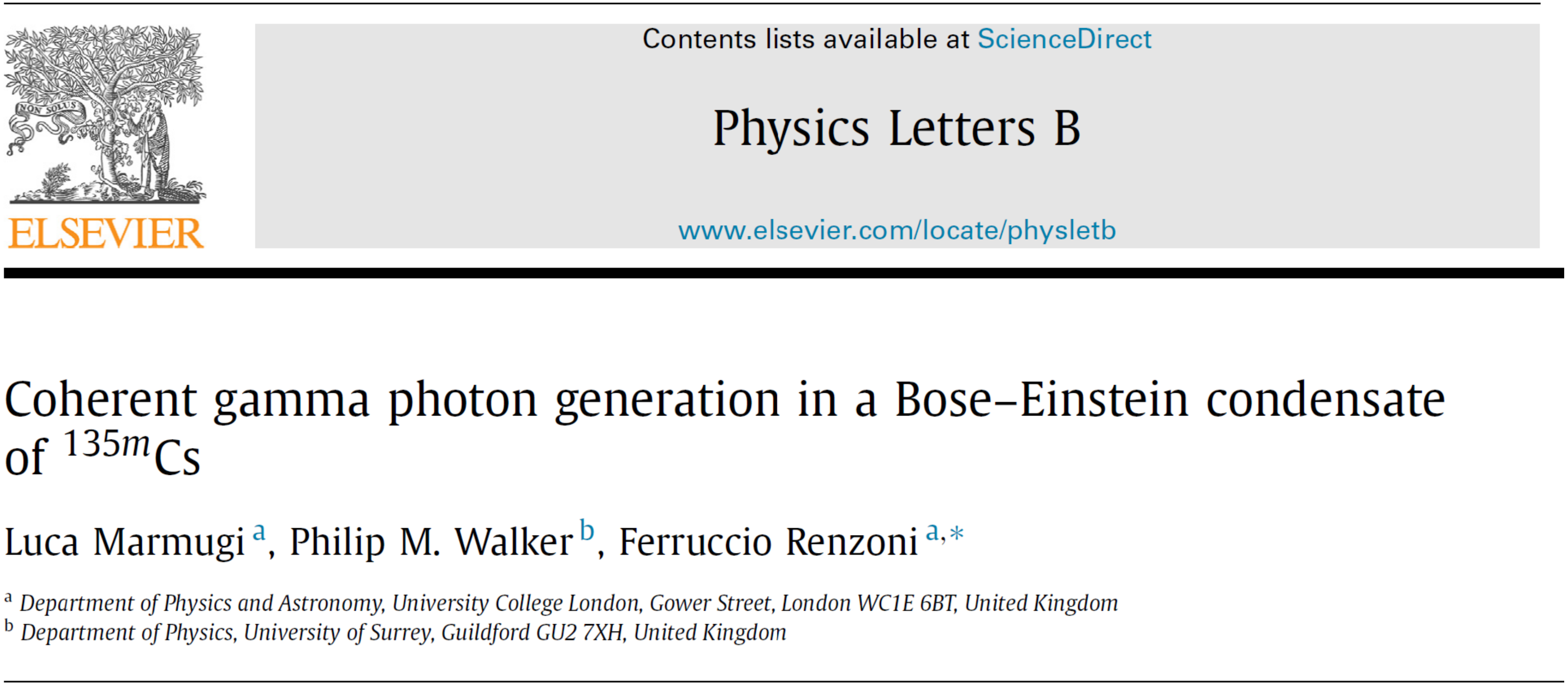
Home » Particle and nuclear » Particle and nuclear physics: quirky favourites from 2025

PARTICLE AND NUCLEAR | BLOG

Radioactive BEC could be a 'superradiant neutrino laser'

Could a "superradiant neutrino laser" be created using radioactive atoms in an ultracold Bose–Einstein condensate (BEC)? The answer is "maybe", according to theoretical work by two physicists in the US. Their proposal involves creating a BEC of rubidium-83, which undergoes beta decay involving the emission of neutrinos. Unlike photons, neutrinos are fermions and therefore cannot form the basis of conventional laser. However, if the atoms in the BEC are close enough together, quantum interactions between the atomic nuclei could accelerate beta decay and create a coherent, laser-like burst of neutrinos. This is a well-known phenomenon called superradiance. While the idea could be tested using existing

Another fantastic use for Bose-Einstein condensates?



Contents lists available at ScienceDirect

Physics Letters B

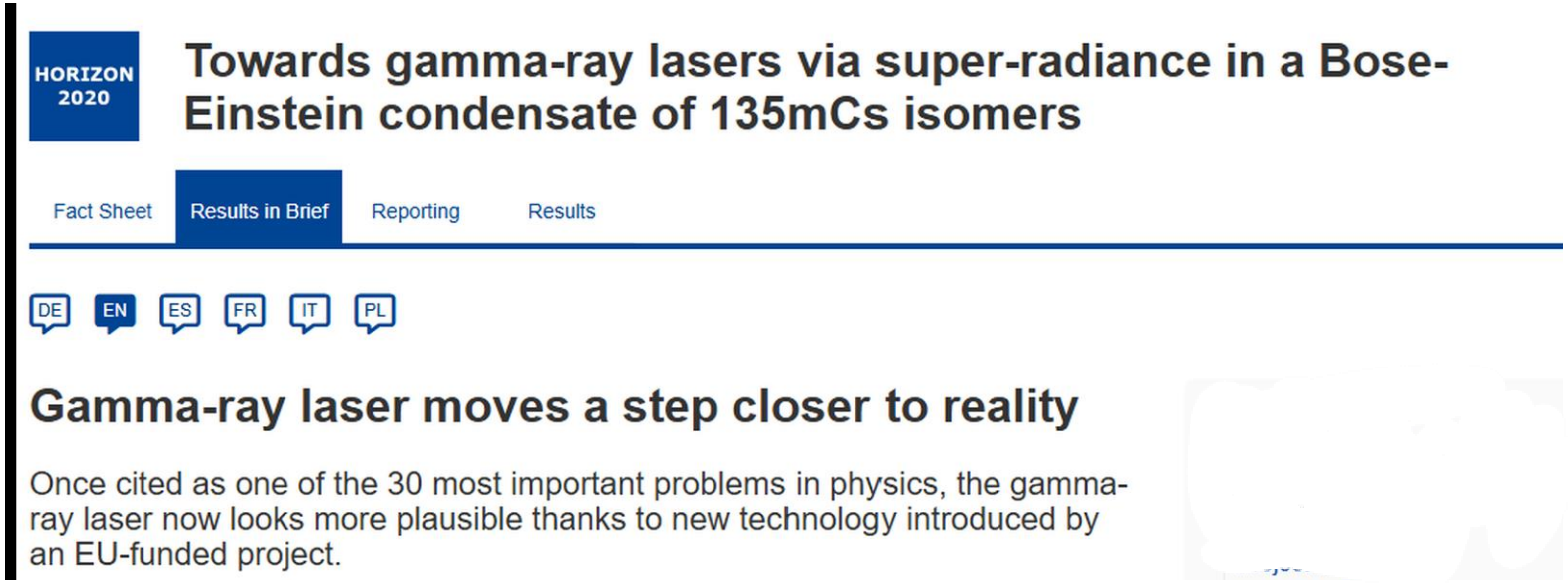
www.elsevier.com/locate/physletb

Coherent gamma photon generation in a Bose–Einstein condensate of ^{135m}Cs

Luca Marmugi [a], Philip M. Walker [b], Ferruccio Renzoni [a,*]

[a] *Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, United Kingdom*
[b] *Department of Physics, University of Surrey, Guildford GU2 7XH, United Kingdom*

Prediction: A condensate of 10^6 atoms can stimulate emission of gamma by 3 – 4 orders of magnitude


HORIZON 2020

Towards gamma-ray lasers via super-radiance in a Bose-Einstein condensate of 135mCs isomers

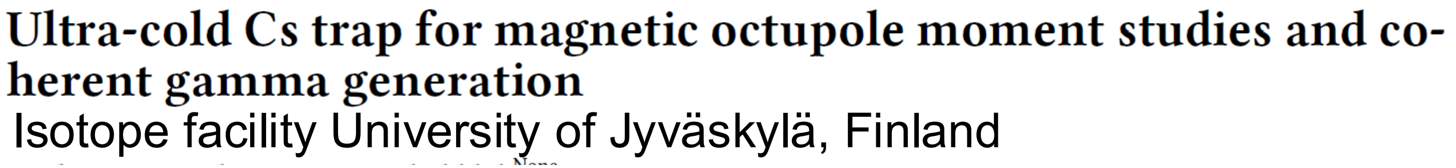
Fact Sheet | Results in Brief | Reporting | Results

DE EN ES FR IT PL

Gamma-ray laser moves a step closer to reality

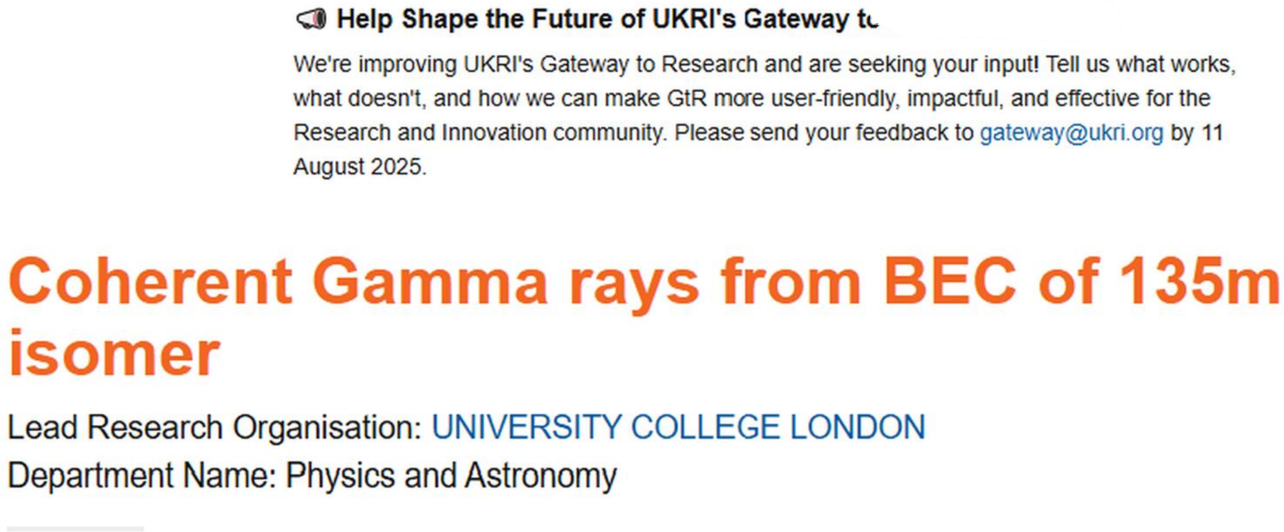
Once cited as one of the 30 most important problems in physics, the gamma-ray laser now looks more plausible thanks to new technology introduced by an EU-funded project.

Plenary / 81


Ultra-cold Cs trap for magnetic octupole moment studies and coherent gamma generation

Isotope facility University of Jyväskylä, Finland

UK Research and Innovation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Coherent Gamma rays from BEC of 135mCs isomer

Lead Research Organisation: UNIVERSITY COLLEGE LONDON

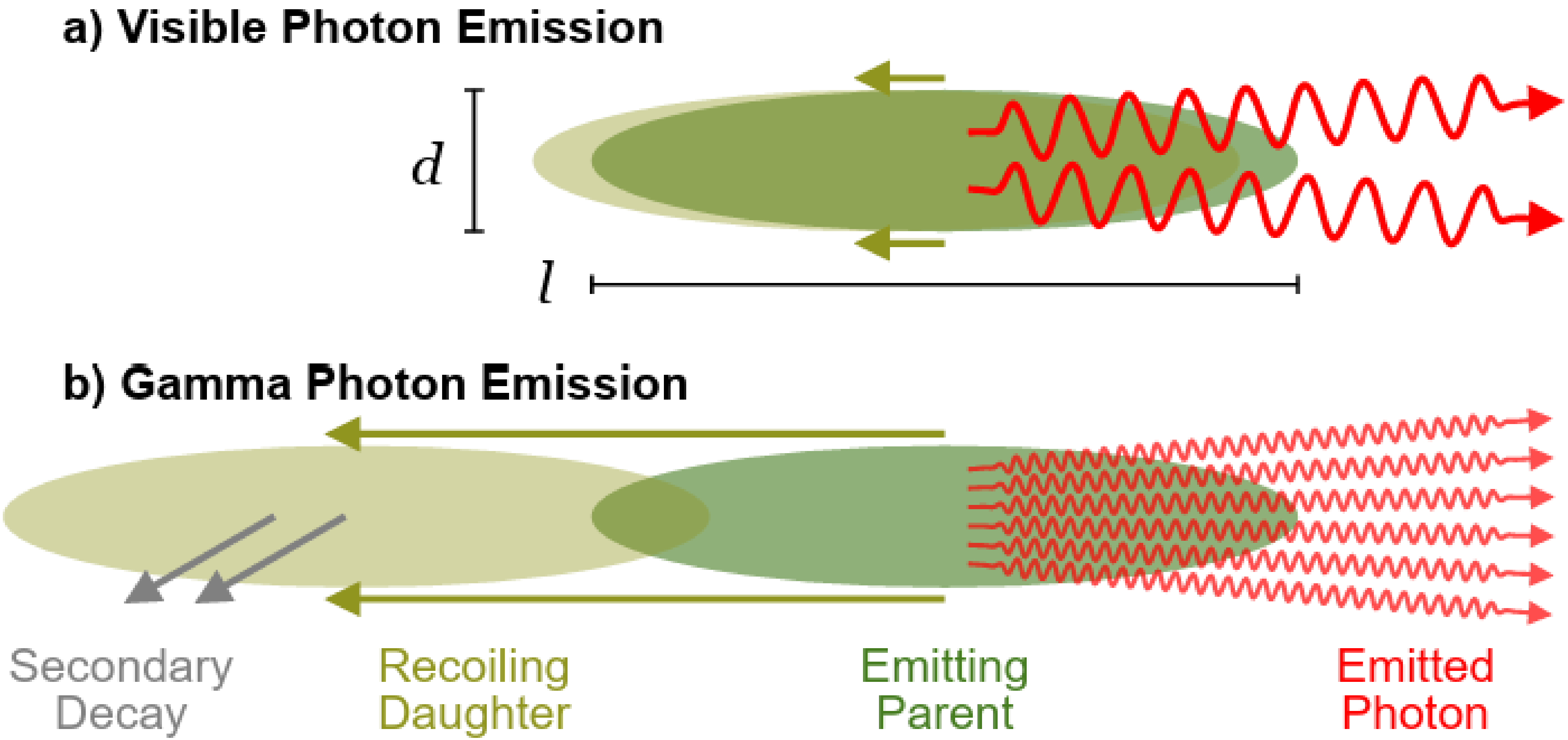
Department Name: Physics and Astronomy

- Y.-K. Lu, H. Lin and W. Ketterle

Fundamental impossibility of a superradiant neutrino laser.
Preprint, https://arxiv.org/abs/2510.21705

- H. Lin, Y.-K. Lu and W. Ketterle

Can Bose-Einstein condensates enhance radioactive decay?
Preprint, https://arxiv.org/abs/2510.21692


a) Visible Photon Emission
d
l
b) Gamma Photon Emission
Secondary Decay
Recoiling Daughter
Emitting Parent
Emitted Photon

Fundamental principles

1. Singe-body decay is immutable, i.e. it cannot be modified by many-body physics (correlations, BEC, Luttinger liquid).

Lindblad master equation for the density matrix ρ:

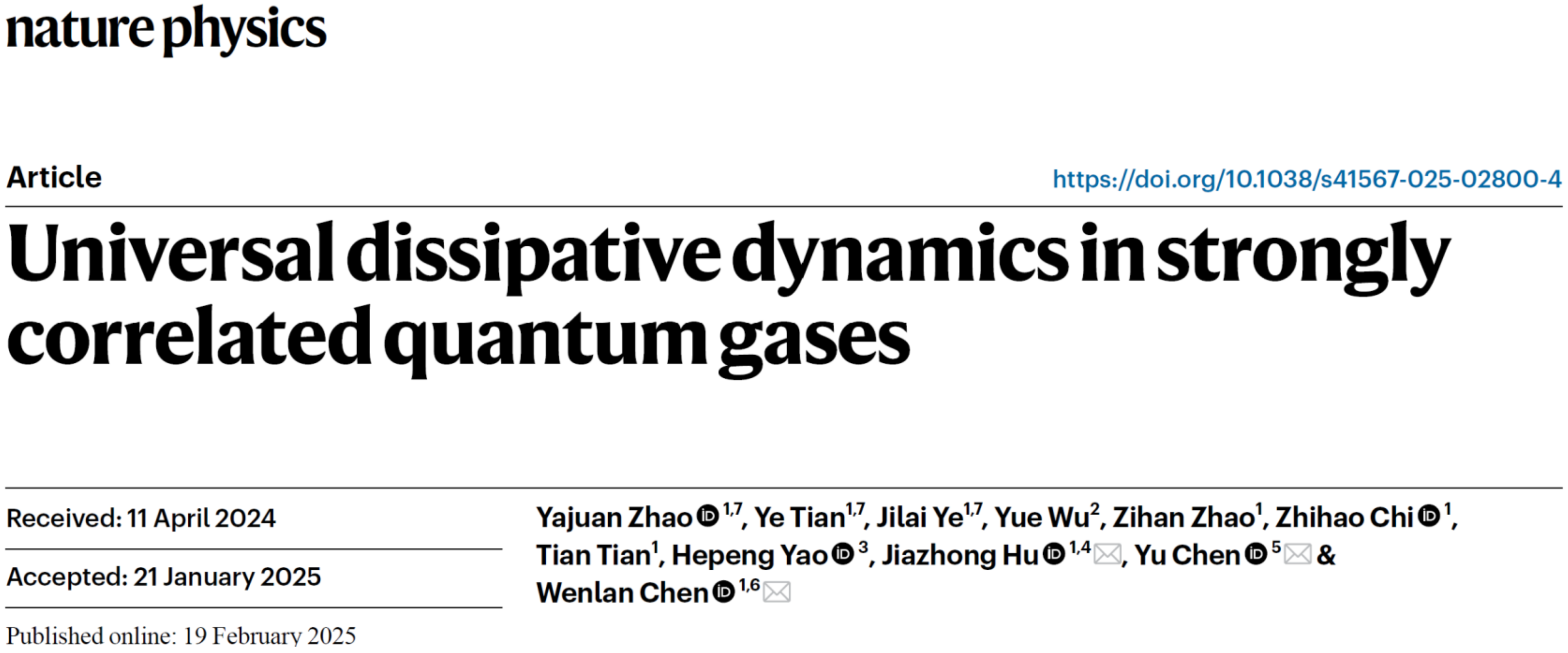
$$\frac{d\rho}{dt} = -i[H,\rho] + \sum_i \left(L_i \rho L_i^\dagger - \frac{1}{2}\{L_i^\dagger L_i, \rho\} \right)$$

$L_i = \sqrt{\gamma} a_i$ are the quantum jump operators for single-particle loss.

For an arbitrary N-body density matrix ρ:

$$\langle \hat{N}(t) \rangle = \langle \hat{N}(0) \rangle e^{-\gamma t}.$$

⇒ single-particle decay cannot be modified by many-body physics



nature physics

Article
https://doi.org/10.1038/s41567-025-02800-4

Universal dissipative dynamics in strongly correlated quantum gases

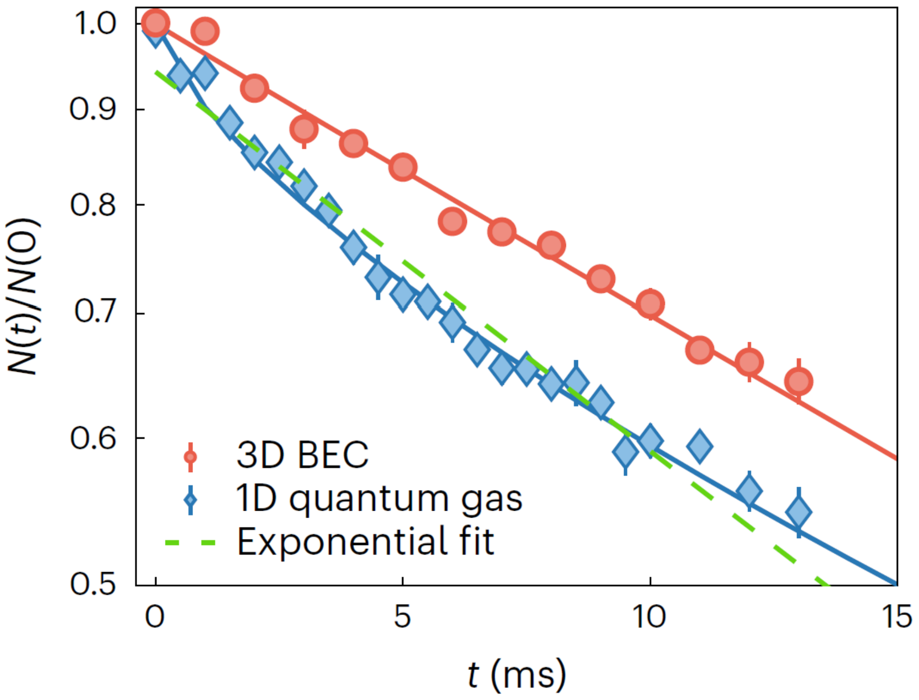
Received: 11 April 2024

Accepted: 21 January 2025

Yajuan Zhao[1,7], Ye Tian[1,7], Jilai Ye[1,7], Yue Wu[2], Zihan Zhao[1], Zhihao Chi[1], Tian Tian[1], Hepeng Yao[3], Jiazhong Hu[1,4] ✉, Yu Chen[5] ✉ & Wenlan Chen[1,6] ✉

Claim: single-particle decay in a Luttinger liquid is non-exponential and has a stretched-exponential form

$$N(t) = N(0)\,\exp\left[-\left(\frac{t}{\tau_0}\right)^{\alpha}\right]$$



(2) Particle decay can only be enhanced by the presence of the decay products.

- Photon: optical amplification, laser
- Particle in final state (ground state, daughter atoms): Dicke superradiance

Superradiant gain G

$$G = N\Gamma$$

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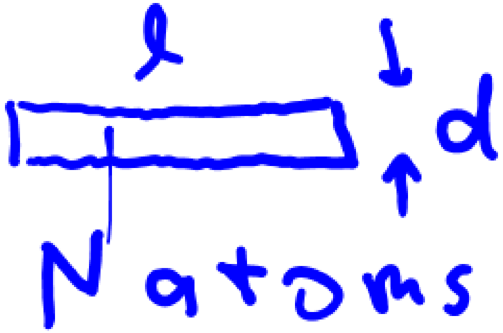
Superradiant gain G

$$G = N \Gamma \frac{\lambda^2}{d^2}$$



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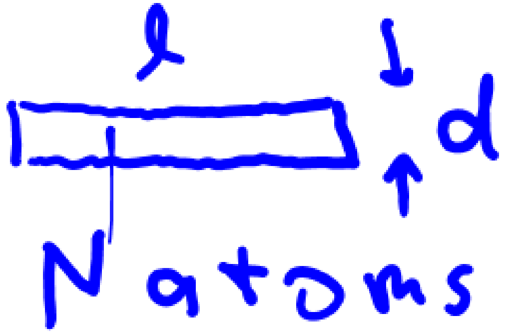

$\frac{d^2}{\lambda^2}$ # of modes $\approx 10^{12}$ for $\lambda = 1 pm$

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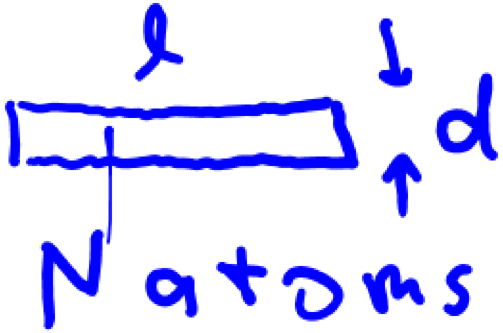

$\frac{d^2}{\lambda^2}$ # of modes $\approx 10^{12}$ for $\lambda = 1$ pm

Necessary criterion for superradiance $N \frac{\lambda^2}{d^2} > 1$

(3) Superradiance is only possible if the condition $N(\lambda/d)^2 > 1$ is fulfilled. Otherwise, the number of modes exceeds the number of atoms.

Gain > Loss

Dicke (1964) “The memory of the previously emitted electromagnetic field is burned into the radiating system” so that “the probability of radiating a photon in a particular direction is given by the normal incoherent intensity multiplied by the total number of photons previously radiated in that direction plus 1.”

Requirement: system has to emit the second photon, before the memory of the first photon emission is lost

$$G = N\Gamma \frac{\lambda^2}{d^2} > L = \begin{cases} \Gamma \\ \frac{1}{t_{coh}} \end{cases}$$

Loss rate L $$L = \frac{1}{\tau_{coh}} = \frac{v_{recoil}}{\ell} \quad \left(= \Delta\omega_{Doppler} \right)$$

Onset for superradiance: $G > L$

Figure of merit: g= G/L

g > 1 Superradiance

g < 1: Single-pass gain 1 + g

$$g = N \Gamma \frac{\lambda^2}{d^2} \frac{\ell}{v_{recoil}}$$

(4) Superradiant enhancement of radioactive decay has to occur faster than the coherence time set by Doppler broadening or further decay. The transit time of the recoiling atom is an upper bound for the coherence time.

$$g \simeq N \Gamma \frac{\lambda^2}{d^2} \frac{l}{v_{recoil}}$$

Condensate: 10^6 atoms, l=1 mm, d=3 μm, density 10^{14} cm^{-3}

1 MeV gamma rays or neutrinos: v_{recoil}= 3500 m/s
λ = 1 pm, Γ is 1/86 days = 1/(5 10^6 sec) (Rb-83), 1/53 min = 1/ 3000 sec (Cs-135)

$$g \simeq 10^6 \frac{1}{3000s} 10^{-13} \, 0.3\mu s = 10^{-17} \ (Cs\text{-}135)$$

$$< 10^{-20} \ (Rb\text{-}83)$$

$$g = N\,\Gamma\,\frac{\lambda^{2}}{d^{2}}\,\cancel{\frac{\ell}{v_{recoil}}}\qquad \frac{1}{\tau_{Decay}}$$

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$$g = 10^{6}\,\frac{1}{3000\,s}\,10^{-13}\,\overset{50\,ps}{\cancel{0.3\,\mu s}} = 10^{-\overset{20}{\cancel{17}}}\ (Cs\text{-}135)$$

$$< 10^{-\overset{24}{\cancel{20}}}\ (Rb\text{-}83)$$

$\tau_{Kr} \approx 1\,fs$

$\tau_{\nu} \approx 3\,ps$

$$g = N \Gamma \frac{\lambda^2}{d^2} \frac{\cancel{l}}{v_{recoil}} \qquad \frac{1}{\tau_{Decay}}$$

Condensate: 10^6 atoms, l=1 mm, d=3 μm, density 10^{14} cm^{-3}

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$$< 10^{-\overset{24}{\cancel{20}}} \quad (Rb\text{-}83)$$

$\tau_{Kr} \approx 1\,fs$

$\tau_{\nu} \approx 3\,ps$

Photons→gamma rays: $\lambda \approx 1\,\mu m \rightarrow 1\,pm, \quad g \longrightarrow g \cdot 10^{-18}$

Dicke memory has to be local.

(5) Stimulation of decay requires local overlap between the emitting atoms and the decay products

Neutrino laser proposal:

even after the daughter atoms have undergone further decay, escaped and have hit a detector, they are still entangled with the remaining condensate atoms in a symmetric Dicke state and therefore superradiant decay will occur.

“.... the correlations among trapped parent atoms within the decaying condensate are sufficient to preserve SR enhancement”

Incorrect

Superradiance is driven by coherences BETWEEN initial and final states, and NOT by correlations WITHIN the parent atoms.

The gamma ray laser proposal:

“The process … is different from conventional single-pass amplification and super-radiance, takes advantage of the ultra-low temperature and the coherence of the BEC.”

“In this sense, the key enabling factor is the coherence of the emitting medium: indistinguishable nuclei in the BEC imprint the coherence of the boson field in the photon field. In fact, this process could not happen in mere cold atomic samples.”

“ the fact that all the excited quantum oscillators are already comprised of a single wavefunction automatically establishes stable phase-coupling among all the emitters …”

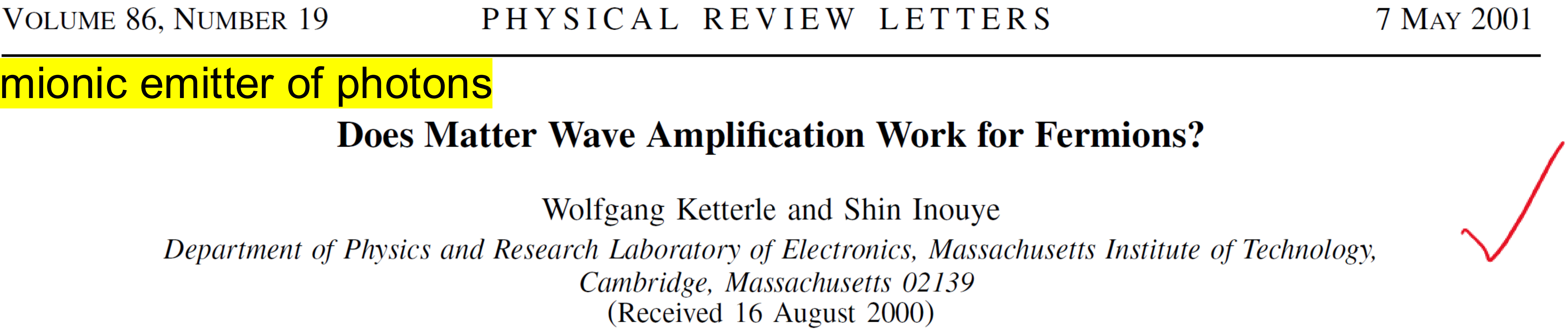
(6) The properties of a Bose-Einstein condensate are not relevant for emission of light or scattering of light. There is no condensate “magic”.

optical properties of a BEC are identical to a non-condensate medium with the same density and Doppler width
BEC helps to reduce the Doppler width!

Fundamental principles

1. Singe-body decay is immutable, i.e. it cannot be modified by many-body physics (correlations, BEC, Luttinger liquid).
2. Particle decay can only be enhanced by the presence of the decay products.
3. Superradiance is only possible if the condition $N(\lambda/d)^2 > 1$ is fulfilled. Otherwise, the number of modes exceeds the number of atoms.
4. Superradiant enhancement of radioactive decay has to occur faster than the coherence time set by Doppler broadening or further decay. The transit time of the recoiling atom is an upper bound for the coherence time.
5. Stimulation of decay requires local overlap between the emitting atoms and the decay products
6. The properties of a Bose-Einstein condensate are not relevant for emission of light or scattering of light. There is no condensate “magic”.
7. Dicke superradiance works in principle for fermionic emitters, but not for fermionic radiation.

Fermionic emitter of photons



VOLUME 86, NUMBER 19 PHYSICAL REVIEW LETTERS 7 MAY 2001

Does Matter Wave Amplification Work for Fermions?

Wolfgang Ketterle and Shin Inouye
Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology,
Cambridge, Massachusetts 02139

(Received 16 August 2000)

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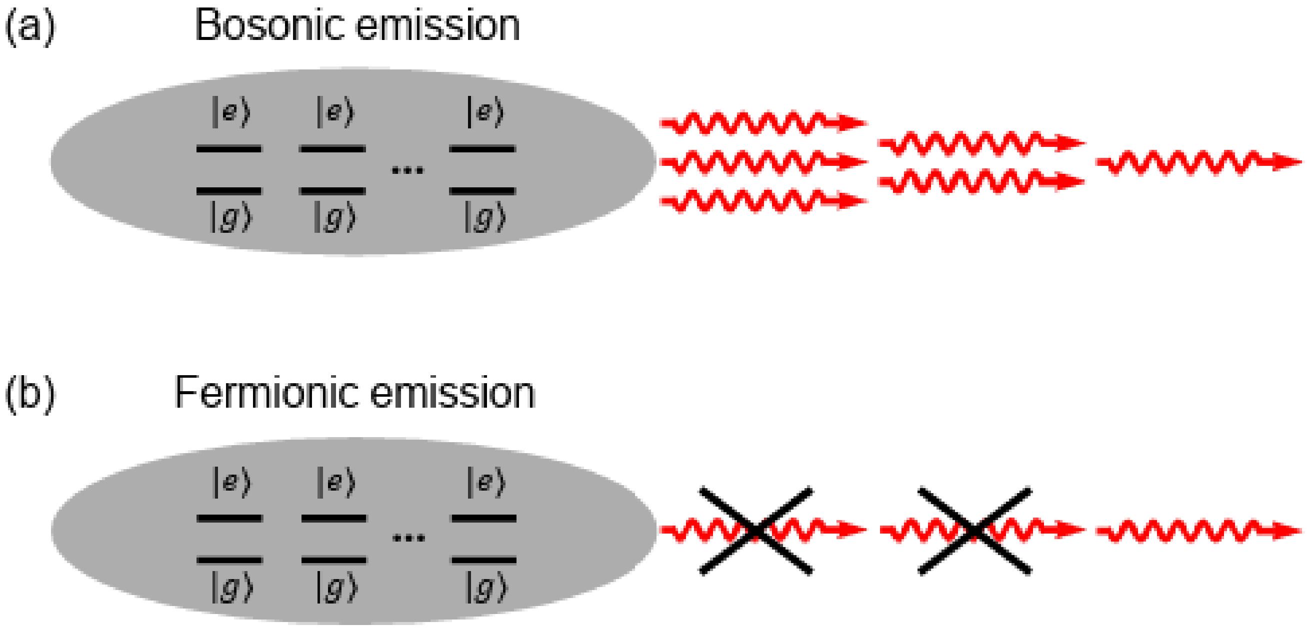

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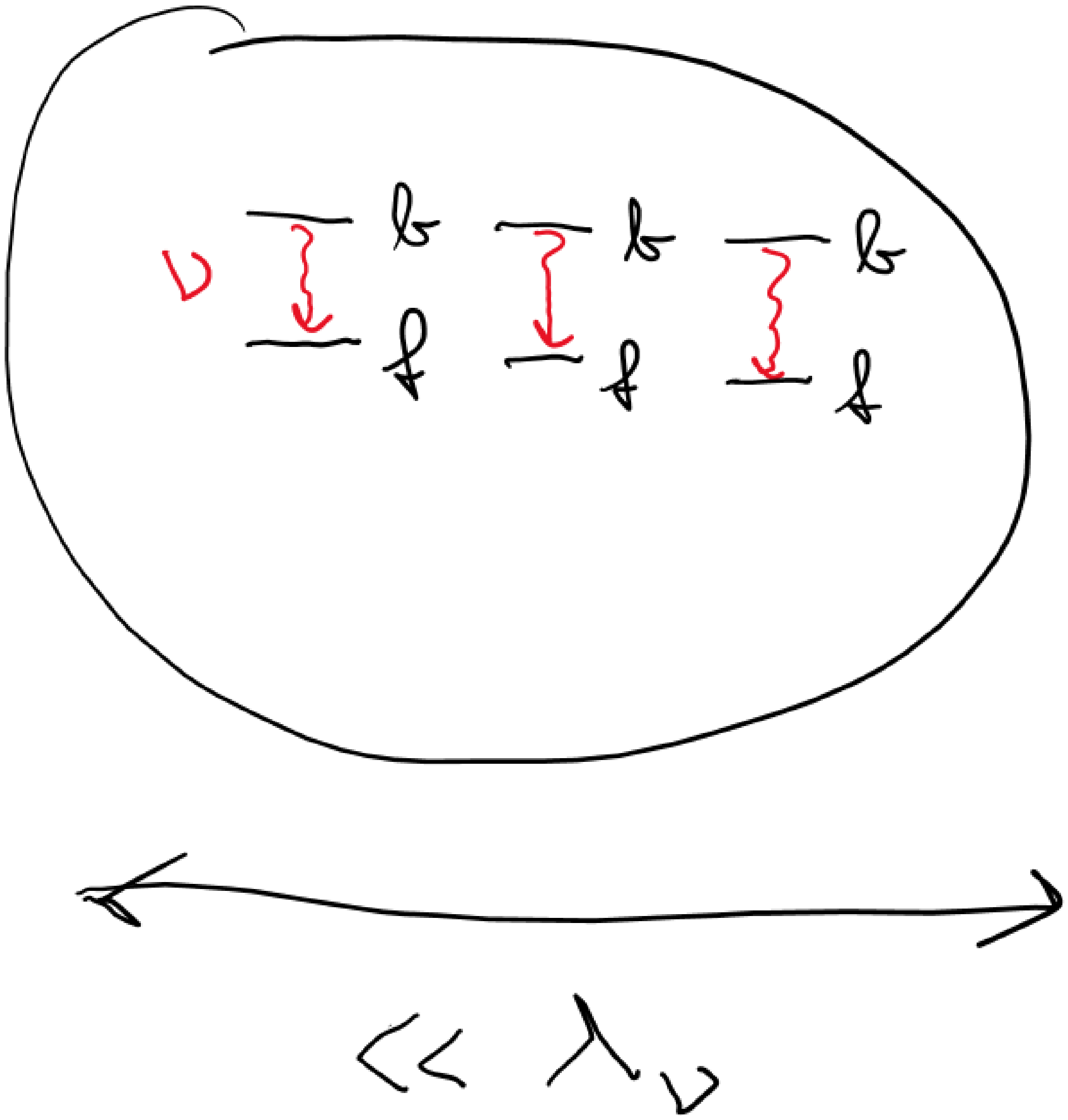
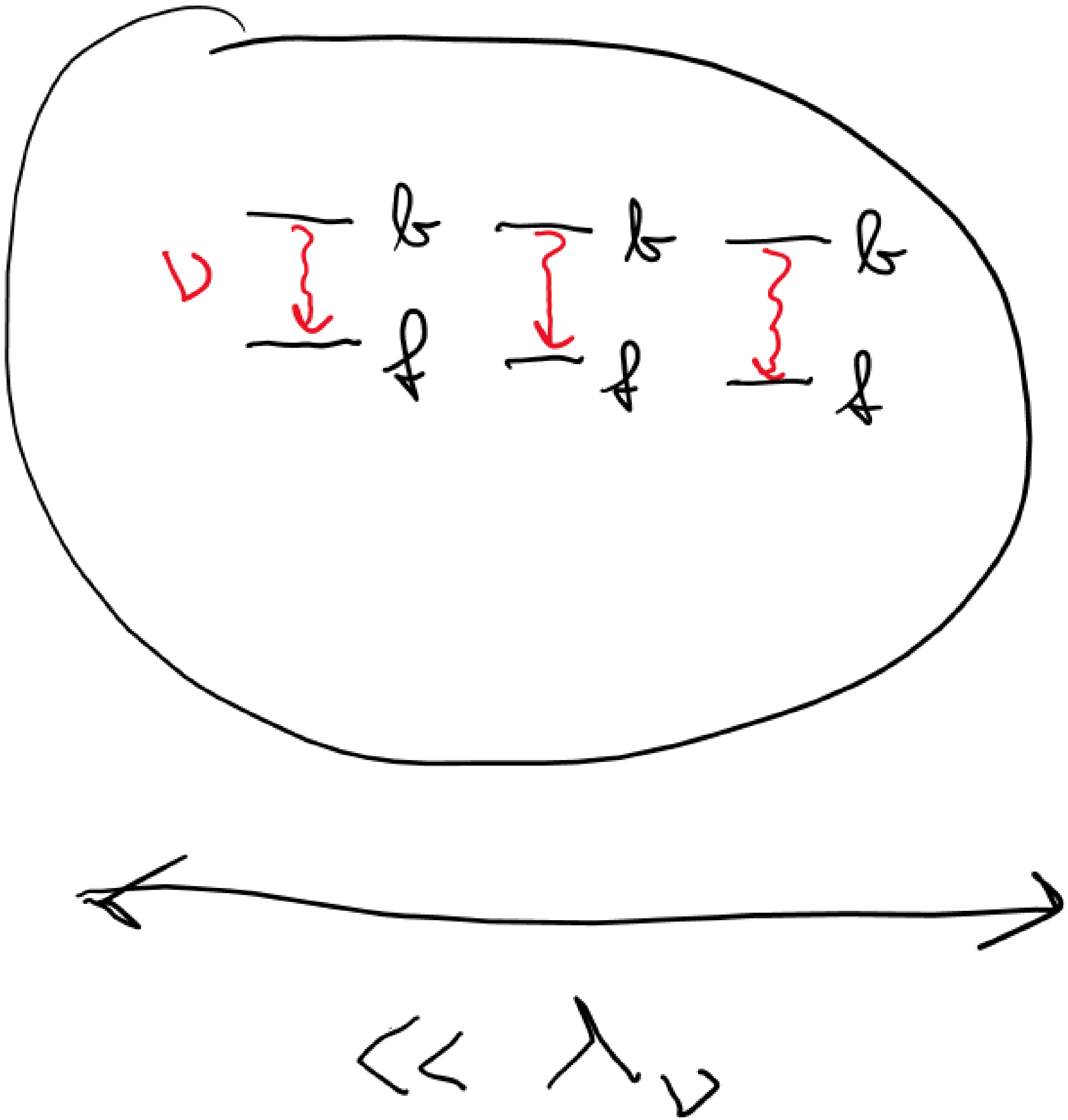
Bosonic emitter of neutrinos

Idealized fermionic Dicke system



Idealized fermionic Dicke system



Collective Decay operator

$$L = \sqrt{\Gamma_0} \sum_i f_i^\dagger b_i$$

Fermionic!

For photon emission:

$$L = \sqrt{\Gamma_0}\, S^-$$

Bosonic!

Immediate consequences:

No coherent addition of fermionic amplitudes

Prepare all emitters in a superspostion state: $\left(|g\rangle + e^{i\alpha_i}|e\rangle\right)/\sqrt{2}$

Bosons: $R_{max} = \Gamma_0 N(N+1)/4$ for $\alpha_i = \alpha$

Fermions: $R_{max} = \Gamma_0 \left(N - \frac{1}{2}\right)$ for $\alpha_{i+1} = \alpha_i + \pi$

Immediate consequences:

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Bosons: $R_{max} = \Gamma_0 N(N+1)/4$ for $\alpha_i = \alpha$

Fermions: $R_{max} = \Gamma_0 (N - \frac{1}{2})$ for $\alpha_{i+1} = \alpha_i + \pi$

No emission cascade for fermionic radiation

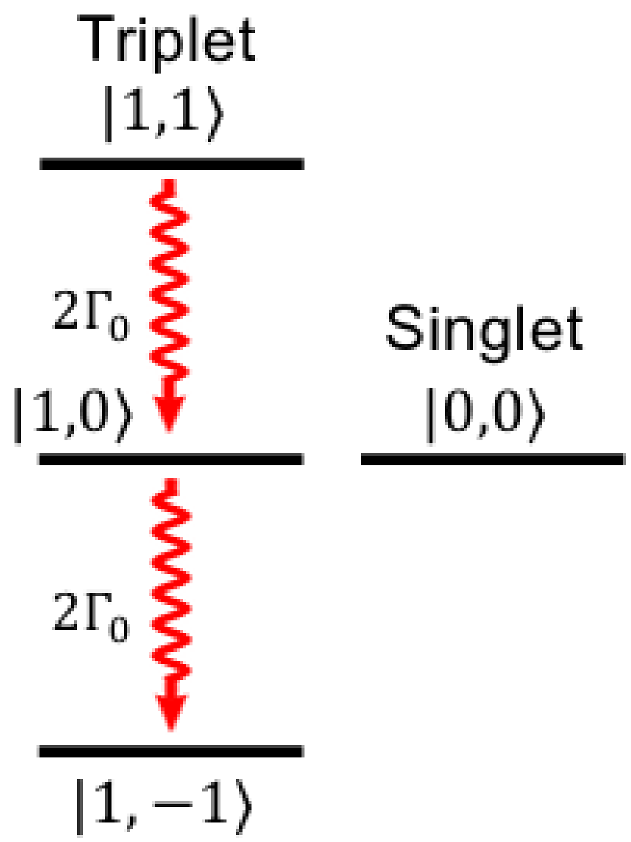
Collective emission operator L: $L^2 = 0$

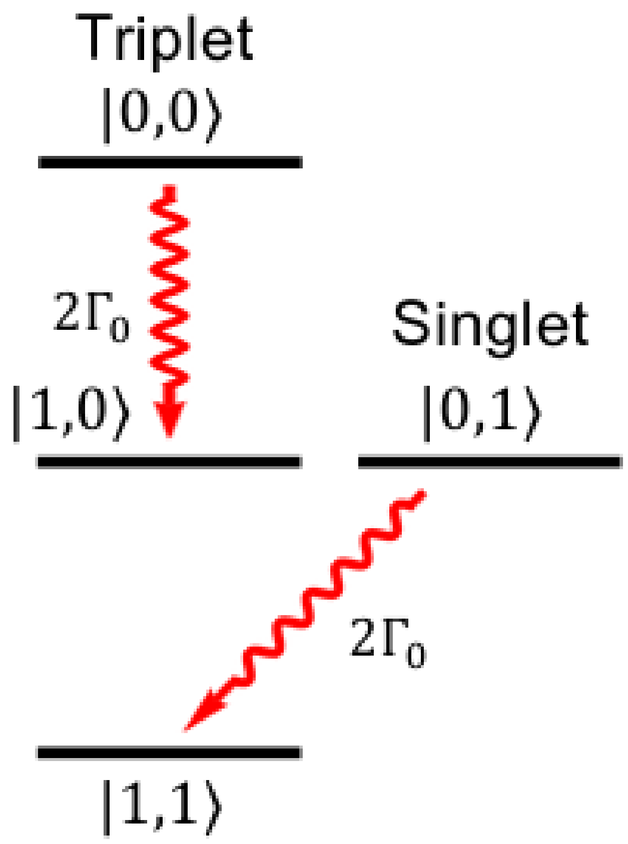
Only one neutrino emitted. NOT Pauli blocking of neutrinos (which escape), NOT Pauli blocking by fermionic daughter atoms (localized), but Pauli blocking by a fermionic collective excitation of the whole system

2 atoms

Bosonic emission
States labeled by $|S, M\rangle$

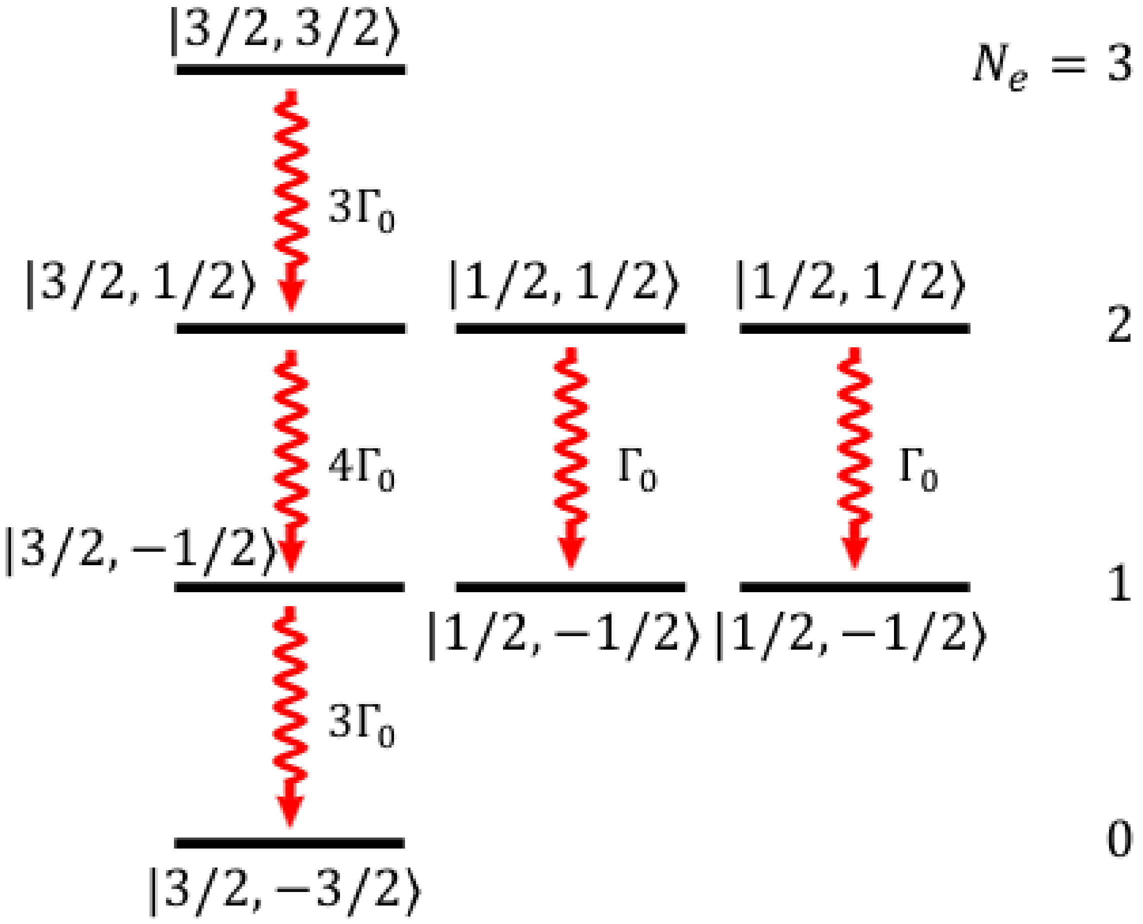
Fermionic emission
States labeled by $|n_0, n_1, \ldots\rangle$



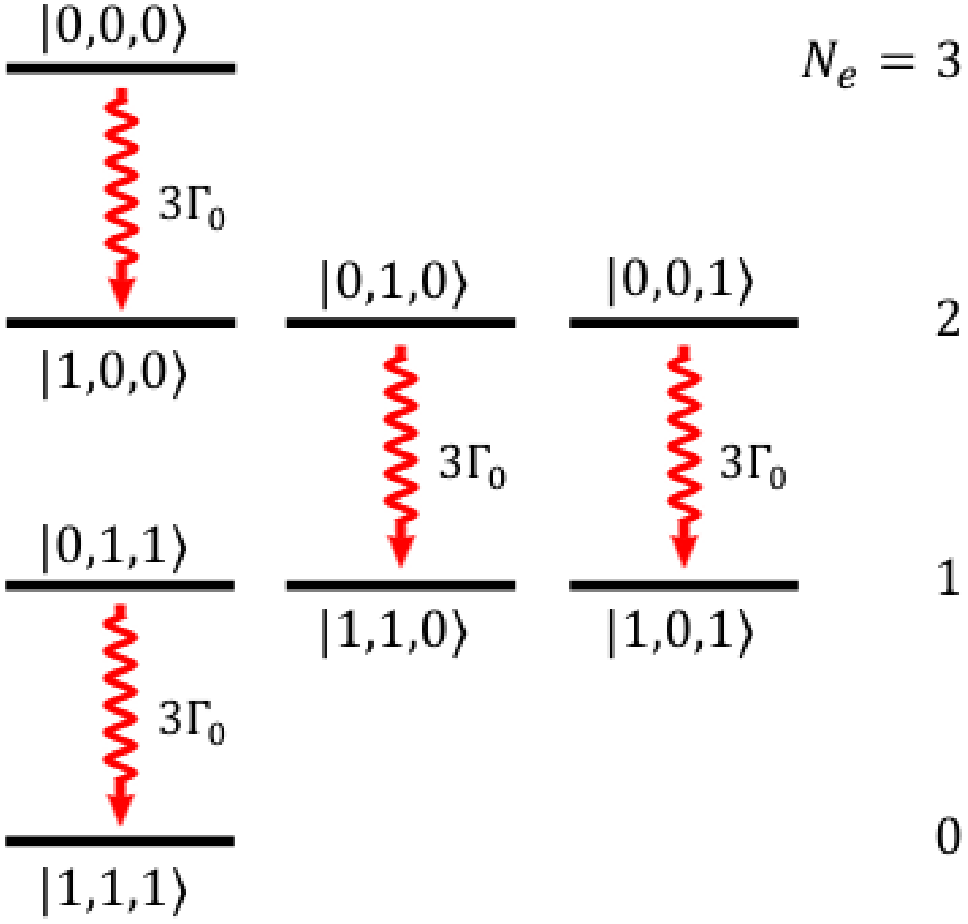


3 atoms

Bosonic emission



Fermionic emission



Extension to m modes: System can now emit m neutrinos at a maximum rate of $m\Gamma_0$

m>N: no dependence on statistics

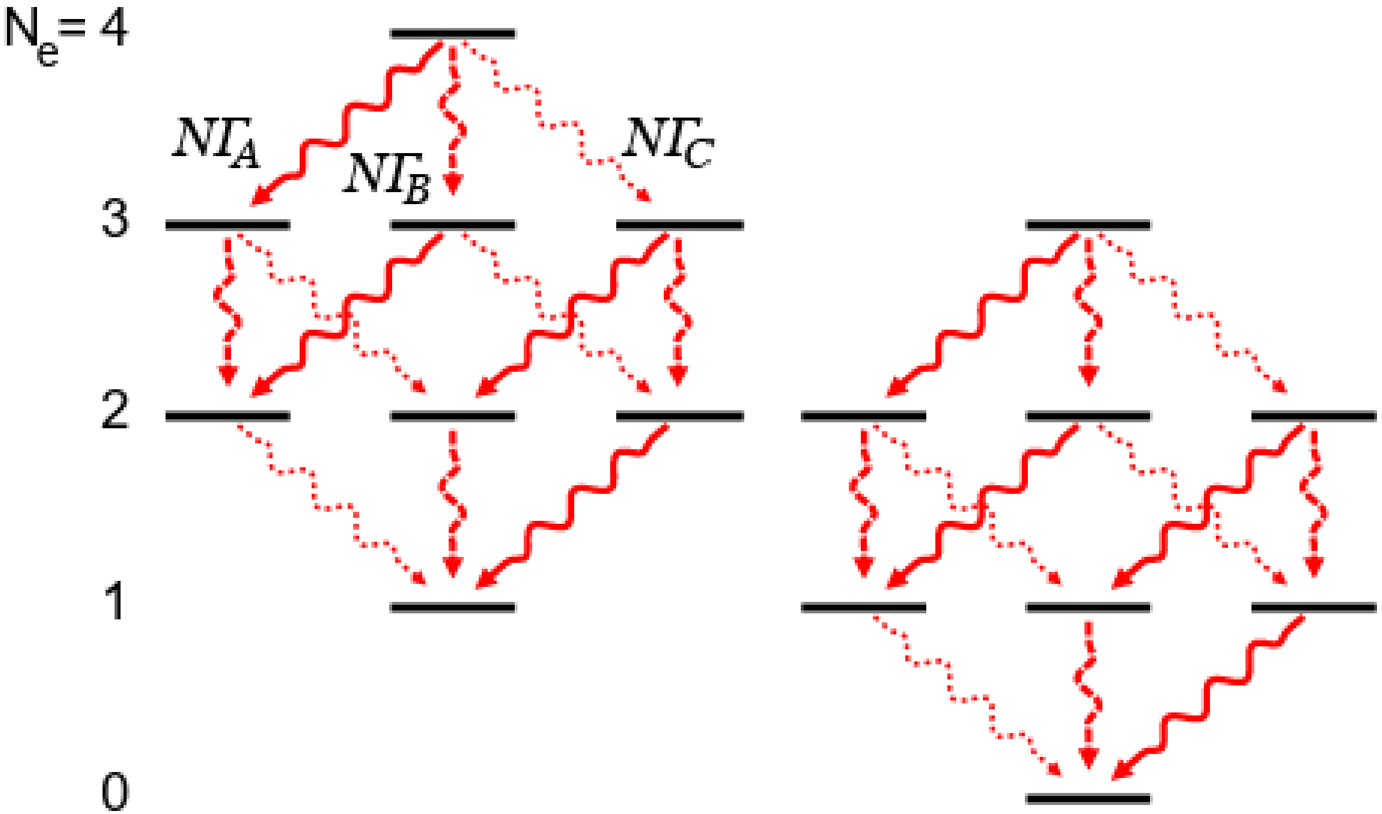


FIG. 3. Fermion emission structure for 4 atoms and 3 modes.

Dicke memory

We have shown the dramatic difference between fermionic and bosonic emission. In the bosonic case, the first emitted photon leaves behind a bosonic excitation (collective spin, phonon, magnon etc.) — this is, in the words of Dicke, the memory of the emitted photon, which enhances further excitation in the same mode (via bosonic stimulation).

Fermionic emission is also imprinted into the memory of the emitting system, but via a collective fermionic excitation that blocks any further emission into the same mode.

Neutrino laser proposal is impossible for 4 reasons:

- number of modes >> number of atoms
- short coherence time due to recoil
- even shorter coherence time (1 fs) due to K shell decay
- fundamental impossibility of fermionic superradiance

Gain g is not 10^{-24}, but ZERO

- Y.-K. Lu, H. Lin and W. Ketterle:
Fundamental impossibility of a superradiant neutrino laser.
Preprint, https://arxiv.org/abs/2510.21705
- H. Lin, Y.-K. Lu and W. Ketterle
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