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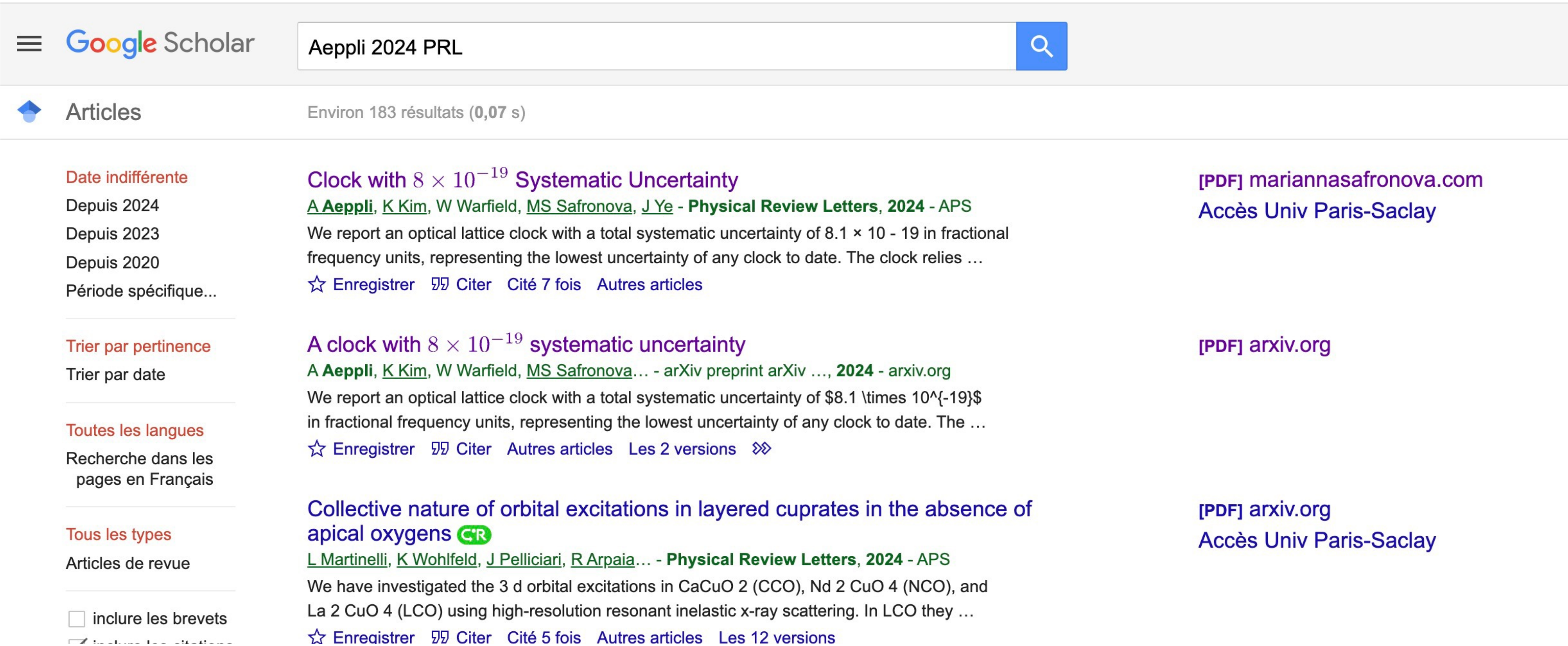

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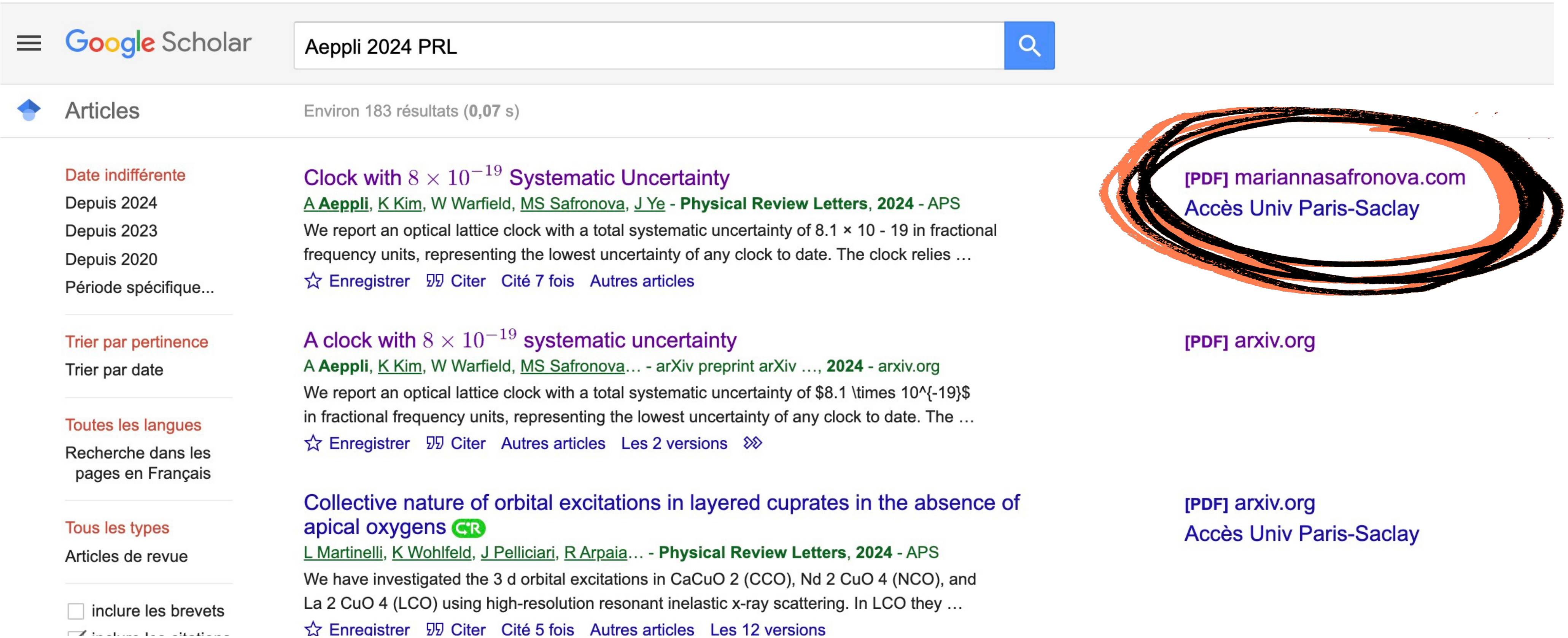

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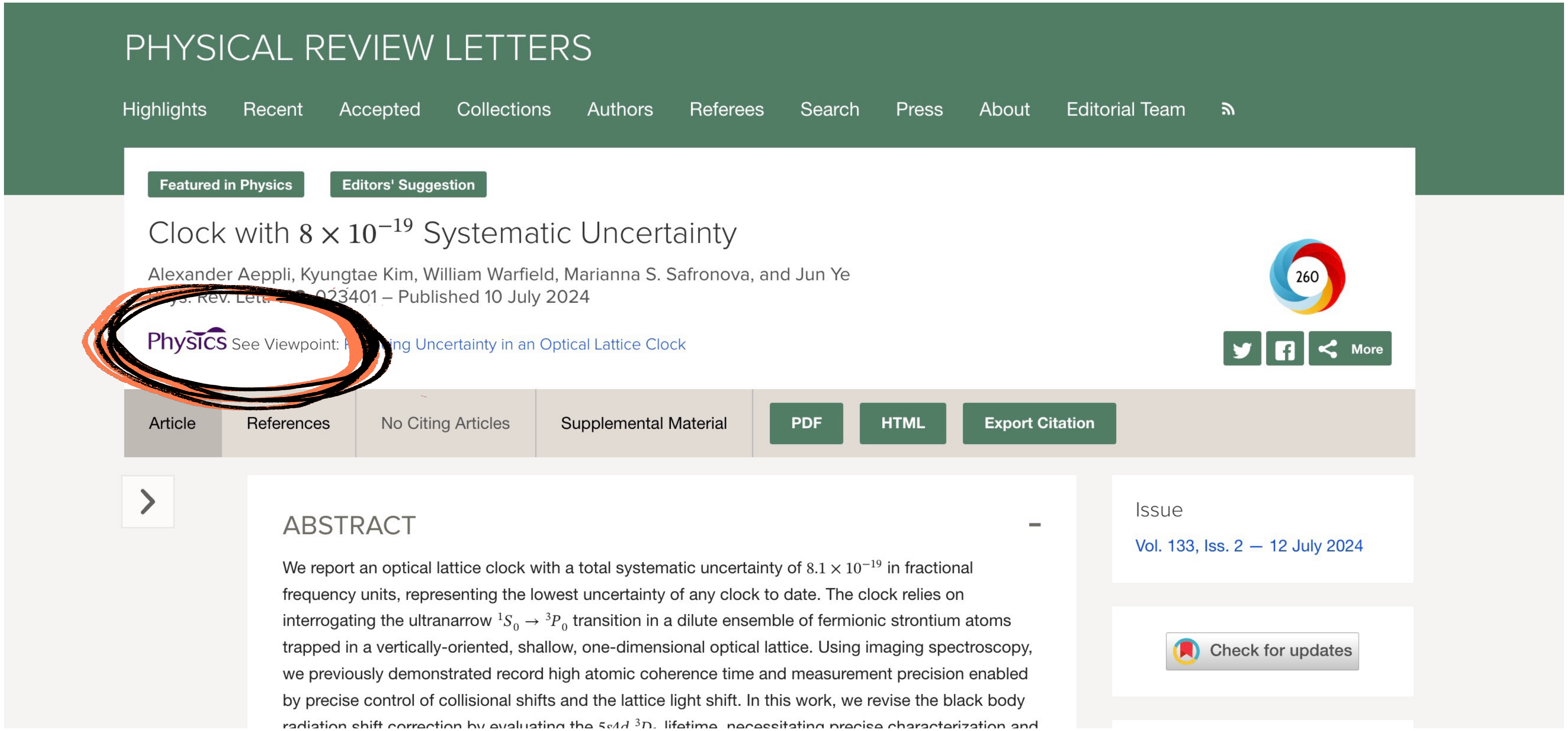

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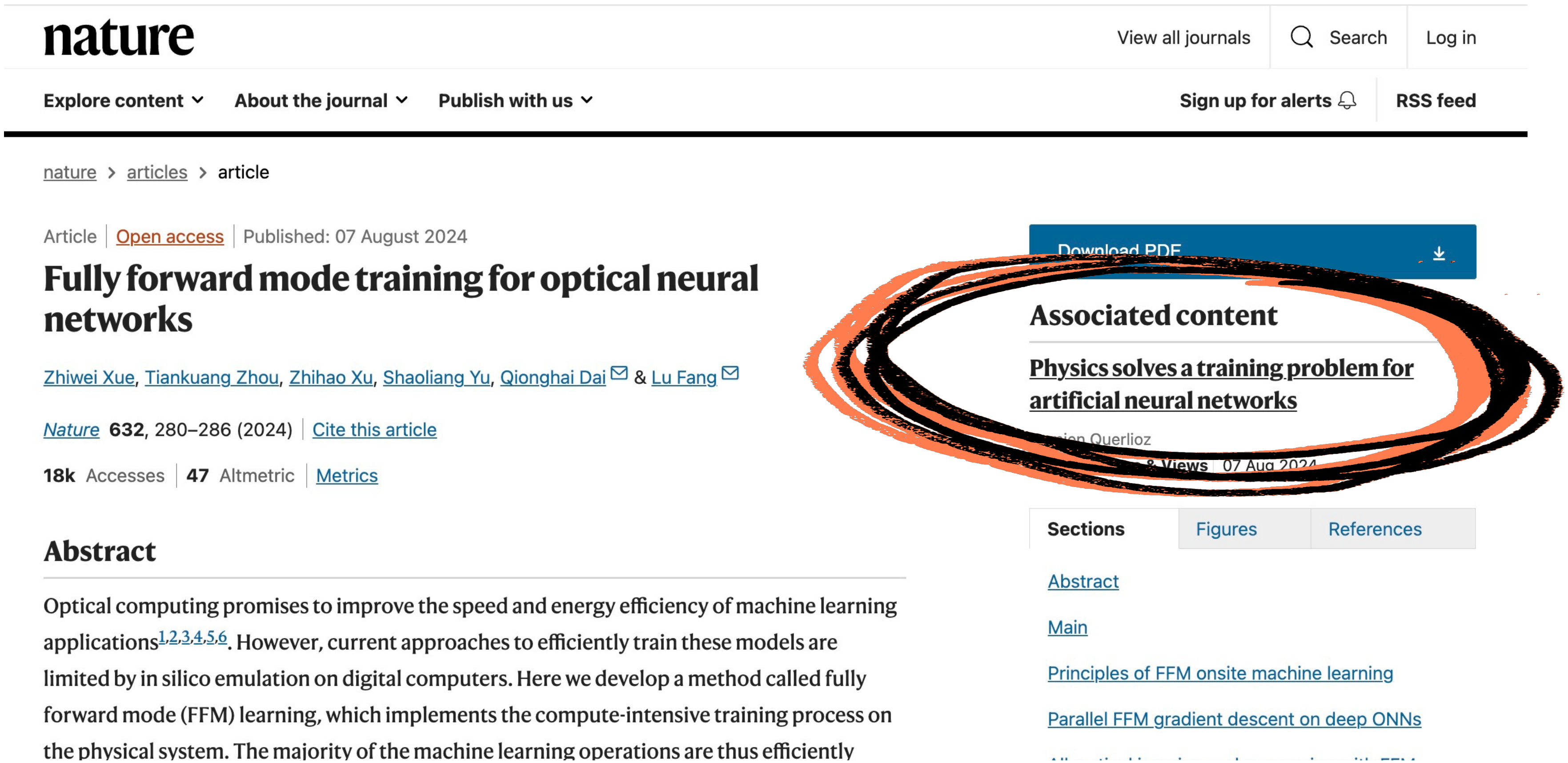

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Fully forward mode training for optical neural networks

Zhiwei Xue, Tiankuang Zhou, Zhihao Xu, Shaoliang Yu, Qionghai Dai & Lu Fang

Nature **632**, 280–286 (2024) | Cite this article

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Abstract

Optical computing promises to improve the speed and energy efficiency of machine learning applications[1,2,3,4,5,6]. However, current approaches to efficiently train these models are limited by in silico emulation on digital computers. Here we develop a method called fully forward mode (FFM) learning, which implements the compute-intensive training process on the physical system. The majority of the machine learning operations are thus efficiently

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Physics solves a training problem for artificial neural networks

Systems that emulate biological neural networks offer an efficient way of running AI algorithms, but they can't be trained using the conventional approach. The symmetry of these 'physical' networks provides a neat solution.

By Damien Querlioz

Huge changes are already under way in health care, industry and education as a result of advances in artificial intelligence (AI), but the costs could outweigh the benefits if AI's enormous energy consumption is not reined in. The problem is that AI relies heavily on deep neural networks, which are layered algorithms that involve millions or even billions of computations, requiring massive, energy-hungry access to the memories in conventional computers. One possible solution is to replace the computers with systems that more closely reflect the physical structure of biological neural networks, but such systems are typically incapable of performing one of the main steps in training the network. In a paper in *Nature*, Xue *et al.*[1] report an ingenious workaround that uses physics to overcome the problem.

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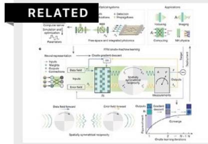

Read the paper: Fully forward mode training for optical neural networks

'Physical' neural networks can be designed using several platforms involving, for example, optics[2], nanoelectronics[3,4] or mechanics[5]. These systems naturally implement the unidirectional data flow of neural networks, and their physical parameters (which could be, for example, the refractive index of an optical filter, the electrical resistance of a component, or the stiffness of a spring) represent the parameters that encode the nodes and connections of the neural network[6]. However, training these networks efficiently remains a major hurdle.

The backbone of most software for training neural networks is a method called gradient descent, which involves calculating the error associated with a neural network's output, and

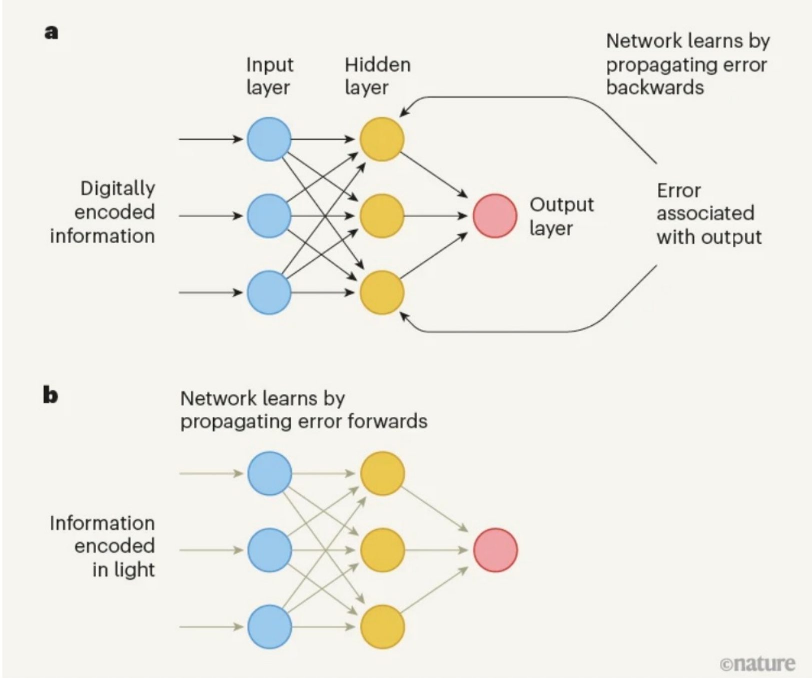

Figure 1 | Training a neural network. a, Most protocols for training artificial neural networks involve calculating the error associated with the network's output, and then minimizing error by updating its 'hidden' layers through a process called backpropagation. **b**, Optical networks (for example, those using laser light moving through optical fibre) could implement machine-learning algorithms more efficiently than can conventional computers, but they have clear inputs and outputs, so backpropagation is not possible. Xue *et al.*[1] developed an alternative approach called fully forward-mode learning, based on the physical principle that light can travel in one direction through an optical system just as easily as it can in the opposite direction. This means that backpropagation can be simulated without information needing to be propagated backwards.

A leading solution to this challenge involves using a mathematical model, and not the physical system itself, to perform the calculation[7]. Others rely on emerging learning schemes that avoid backpropagation altogether[8]. However, none of these solutions can match the accuracy of neural networks implemented in conventional computers when applied to complex tasks.

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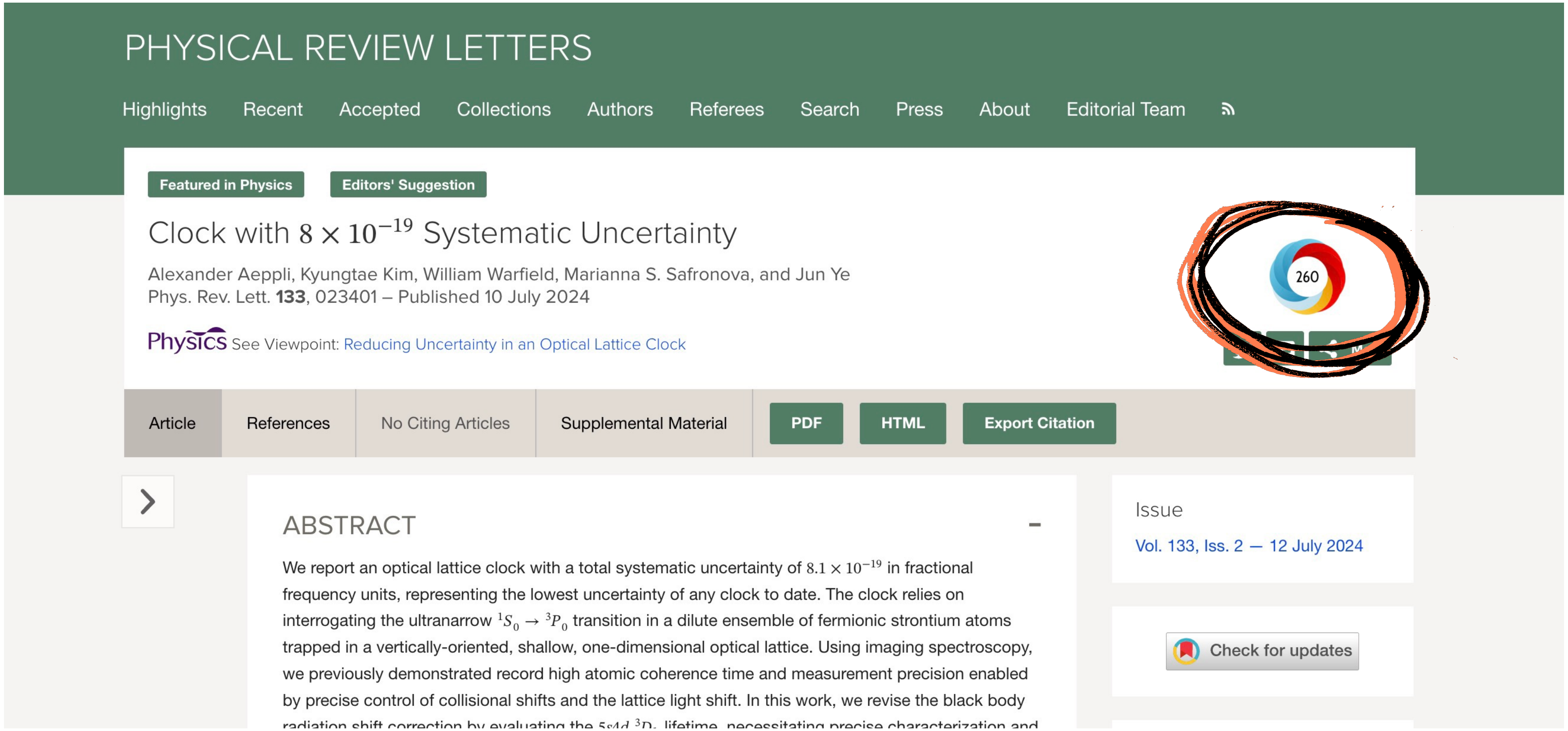

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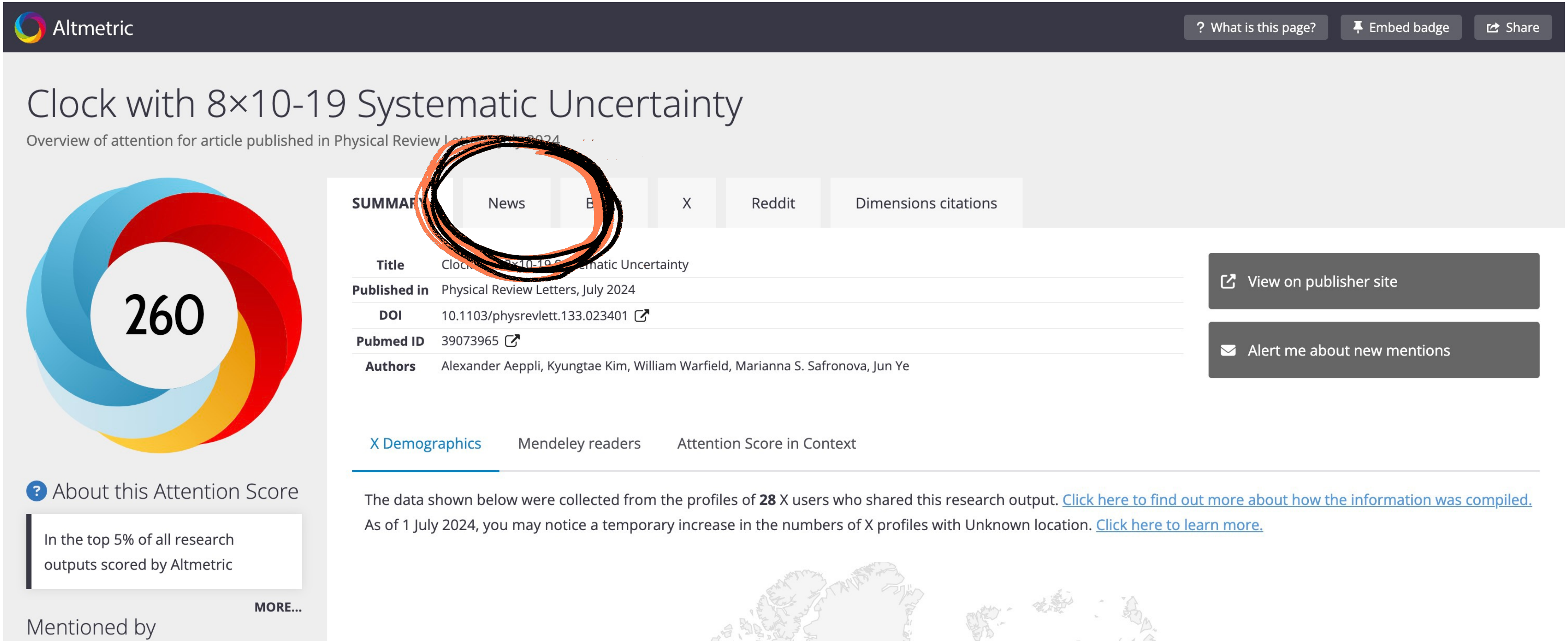

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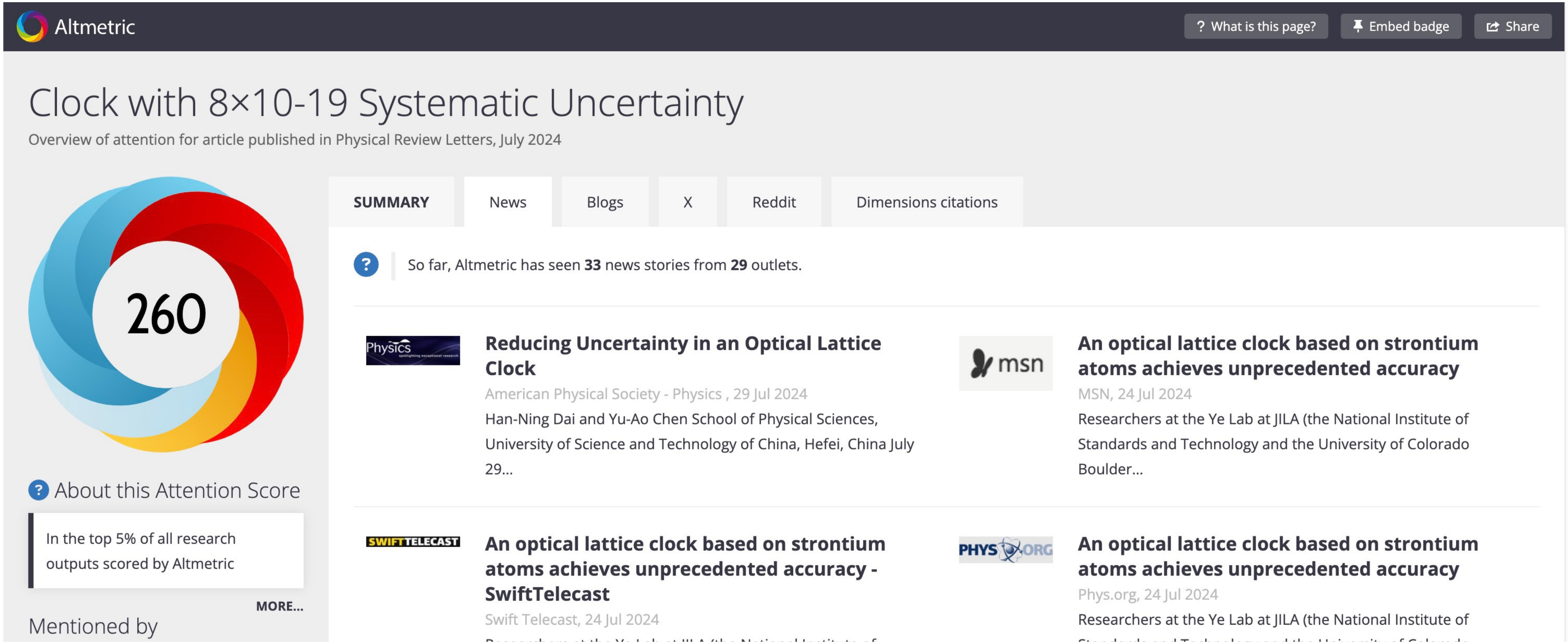

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For a clock updated by radio signals, see Radio clock. For the clock as a measure for risk of catastrophic destruction, see Doomsday Clock. For other topics, see Atomic Clock (disambiguation).

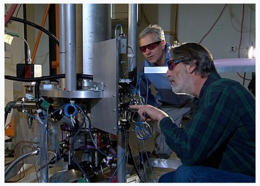
An **atomic clock** is a clock that measures time by monitoring the resonant frequency of atoms. It is based on atoms having different energy levels. Electron states in an atom are associated with different energy levels, and in transitions between such states they interact with a very specific frequency of electromagnetic radiation. This phenomenon serves as the basis for the International System of Units' (SI) definition of a second:

> The second, symbol s, is the SI unit of time. It is defined by taking the fixed numerical value of the caesium frequency, $\Delta\nu_{Cs}$, the unperturbed ground-state hyperfine transition frequency of the caesium-133 atom, to be 9 192 631 770 when expressed in the unit Hz, which is equal to s^{-1}.

This definition is the basis for the system of International Atomic Time (TAI), which is maintained by an ensemble of atomic clocks around the world. The system of Coordinated Universal Time (UTC) that is the basis of civil time implements leap seconds to allow clock time to track changes in Earth's rotation to within one second while being based on clocks that are based on the definition of the second, though leap seconds will be phased out in 2035.[2]

The accurate timekeeping capabilities of atomic clocks are also used for navigation by satellite networks such as the European Union's Galileo Programme and the United States' GPS.

Atomic clock



NIST physicists Steve Jefferts (foreground) and Tom Heavner with the NIST-F2 caesium fountain atomic clock, a civilian time standard for the United States

Classification	Clock
Industry	Telecommunications, science
Application	TAI, satellite navigation
Fuel source	Electricity
Powered	Yes

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- "There are no quantum jumps, nor are there particles!" by H. D. Zeh, *Physics Letters* **A172**, 189 (1993).
- Ball, Philip (June 5, 2019). "Quantum Leaps, Long Assumed to Be Instantaneous, Take Time". *Quanta Magazine*. Retrieved June 6, 2019.
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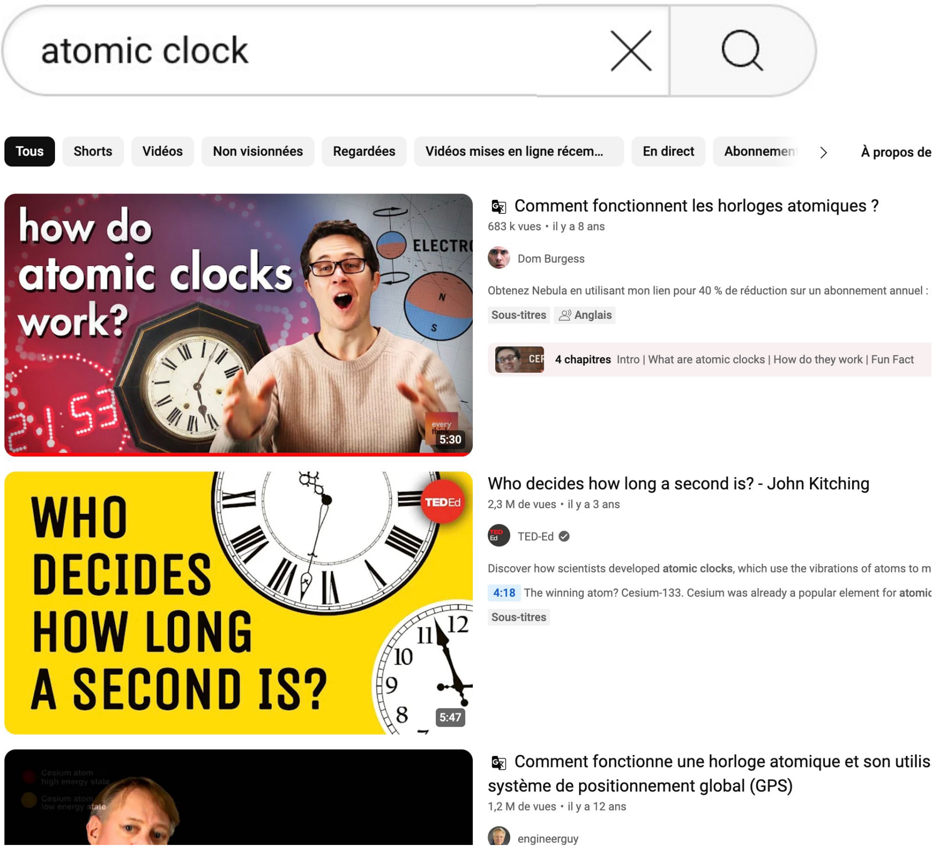

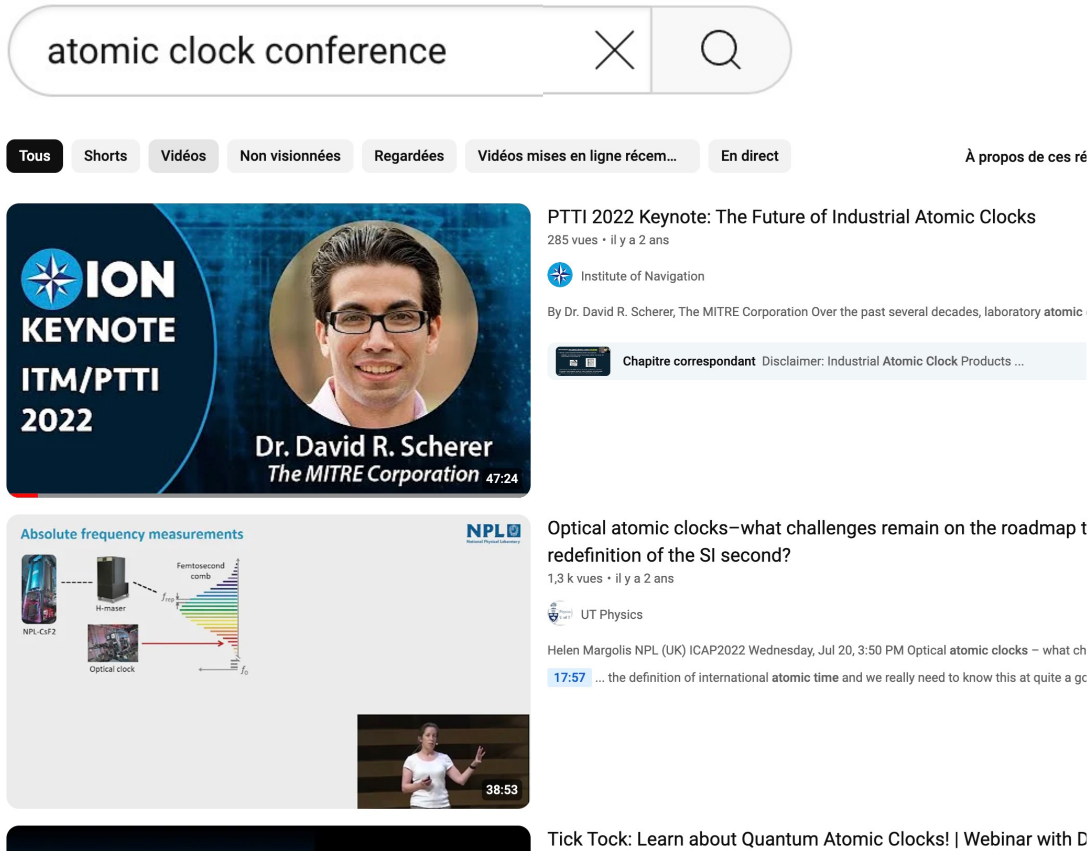

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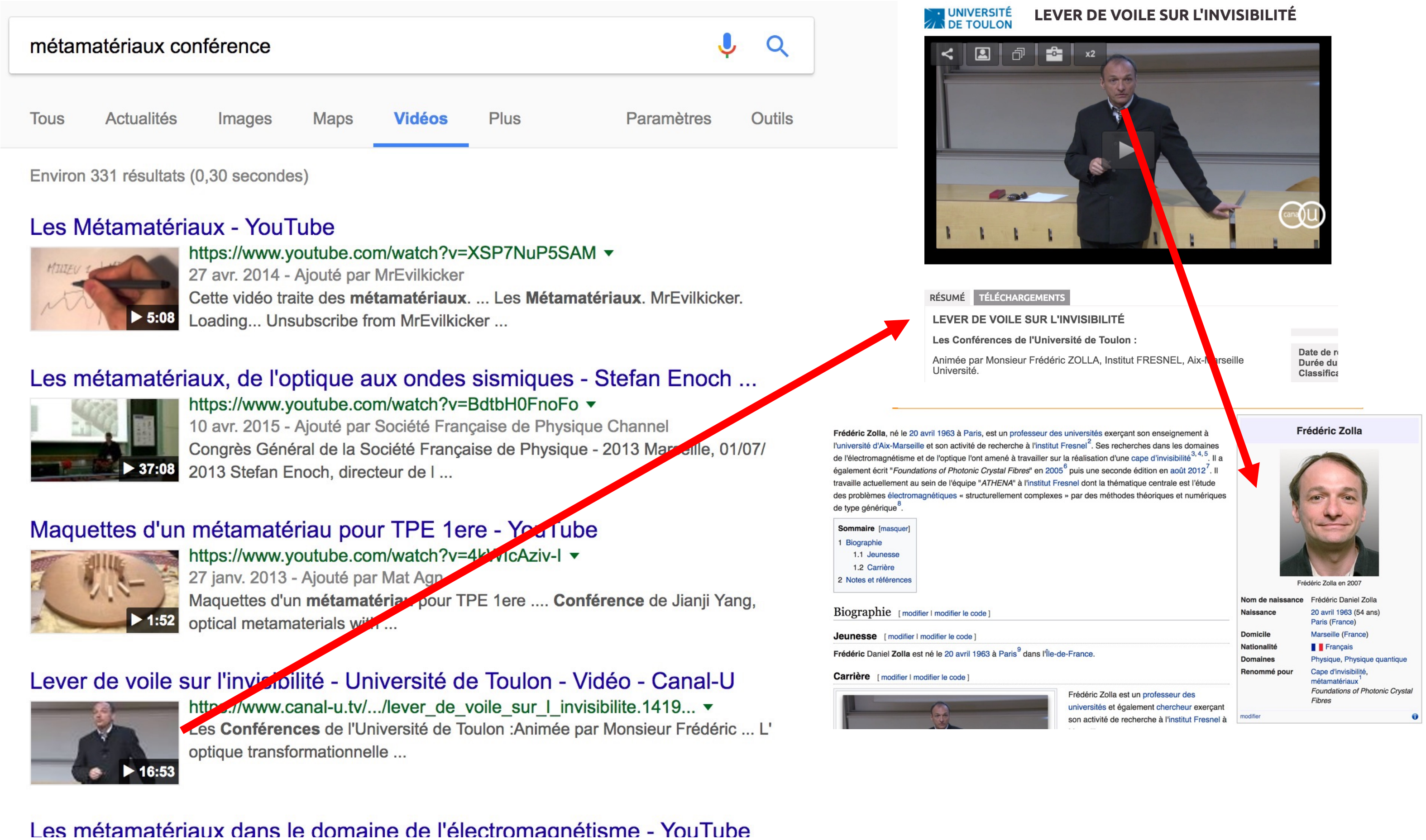

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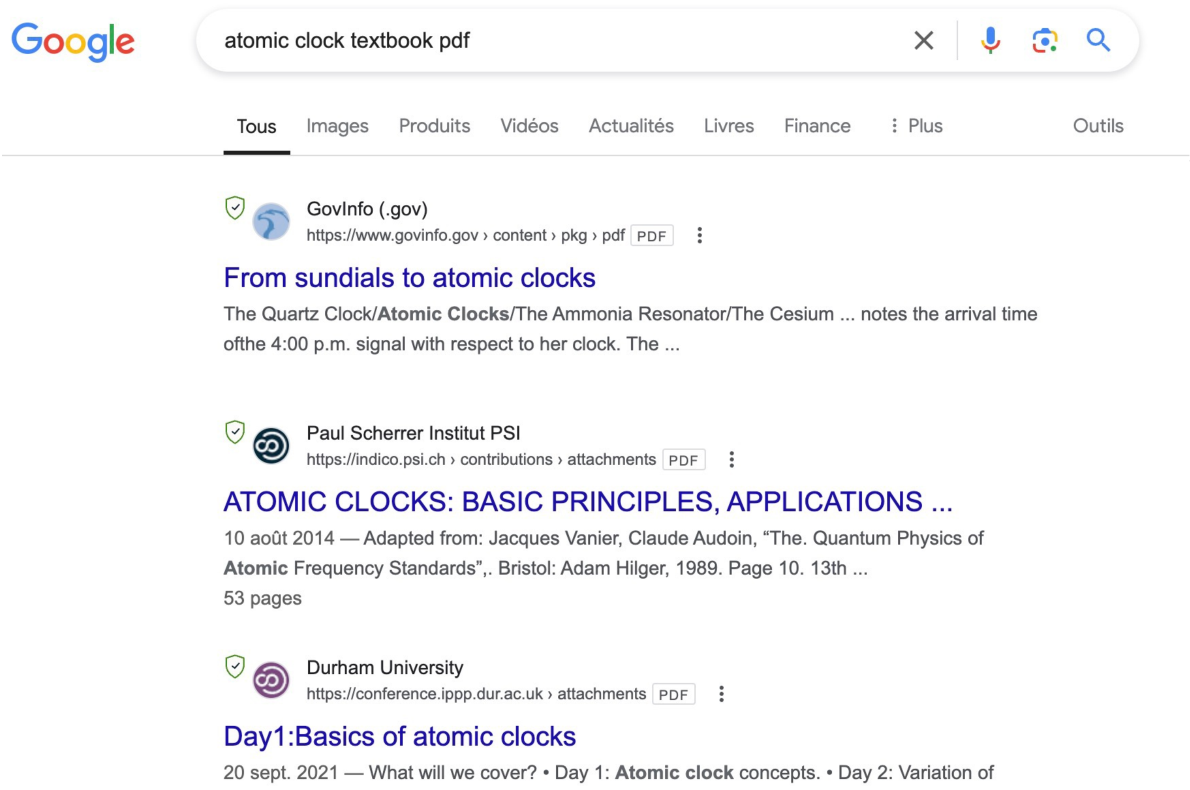

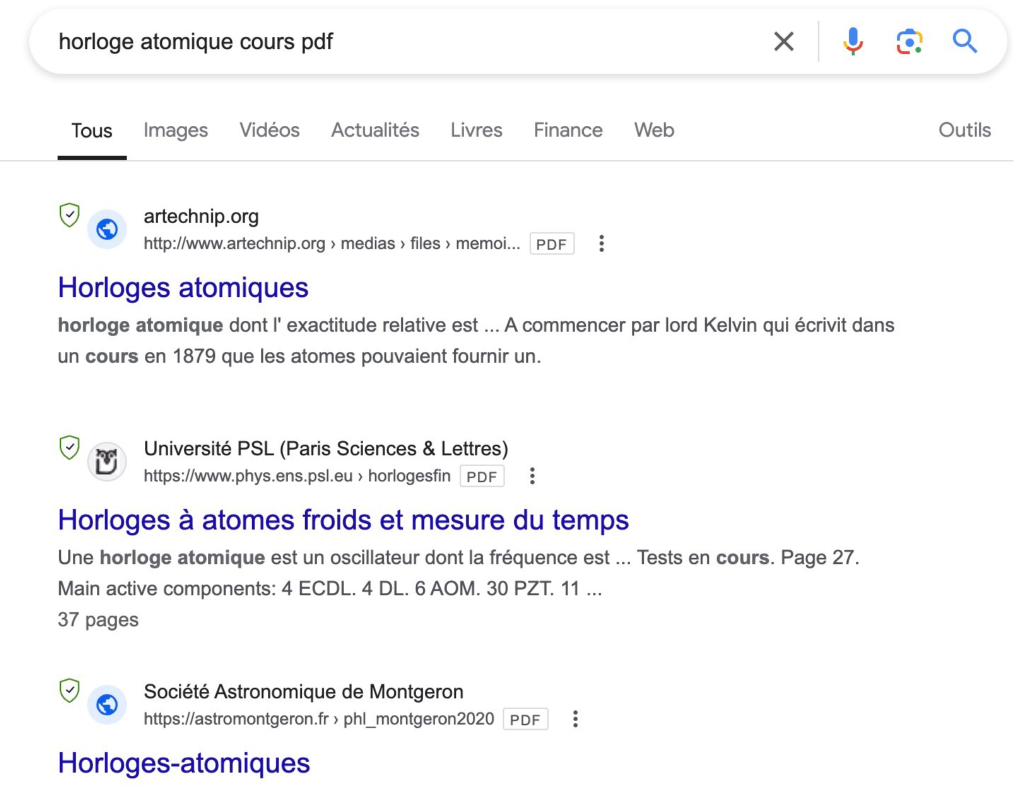

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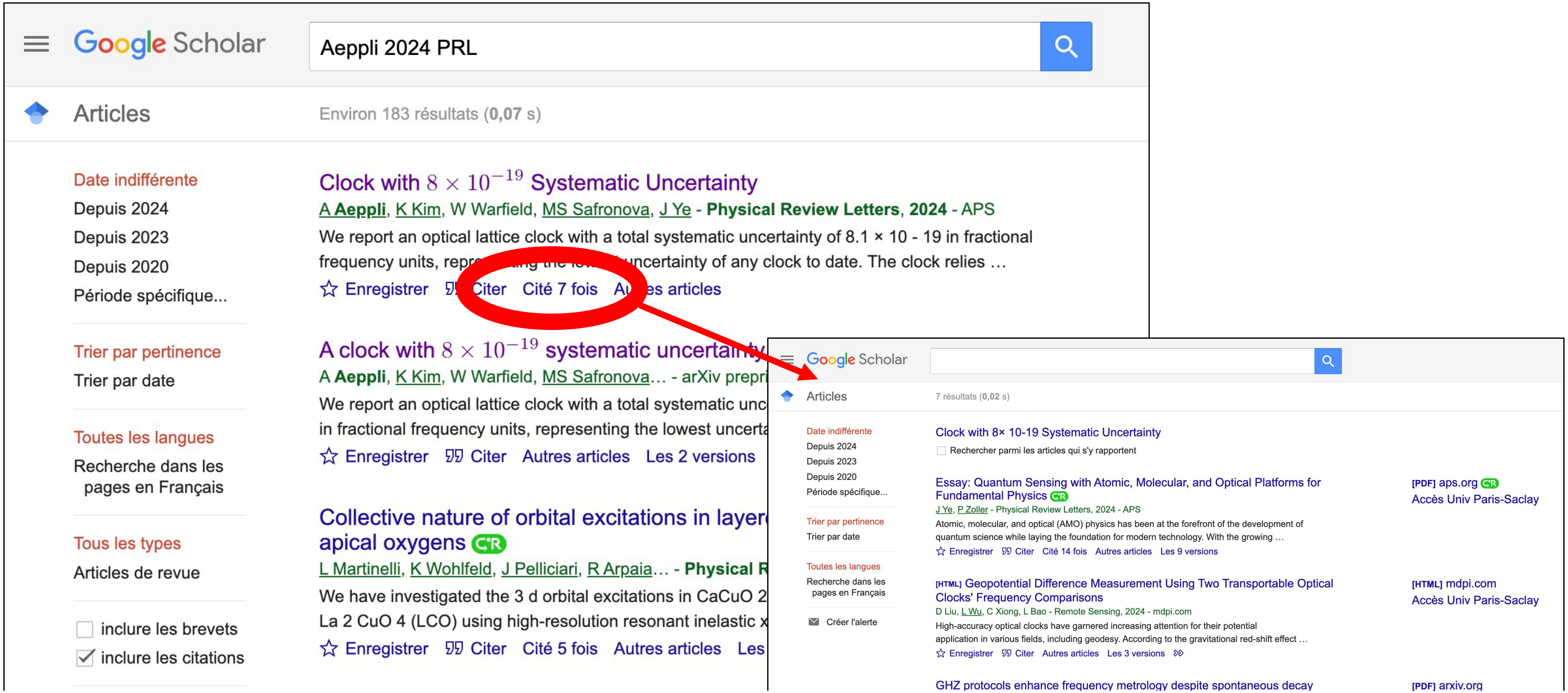

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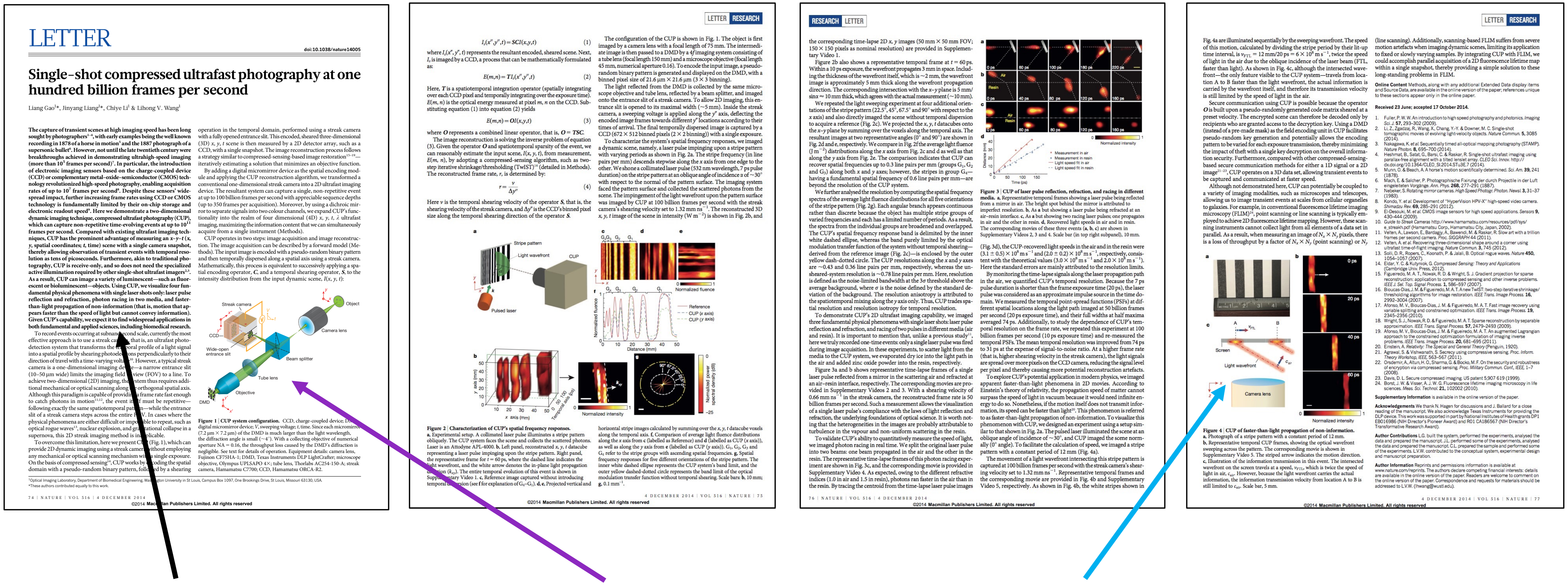

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