
STAY IN LANE
FUTURE
PAST

Top Ten Physics World Breakthroughs of the Year for 2018

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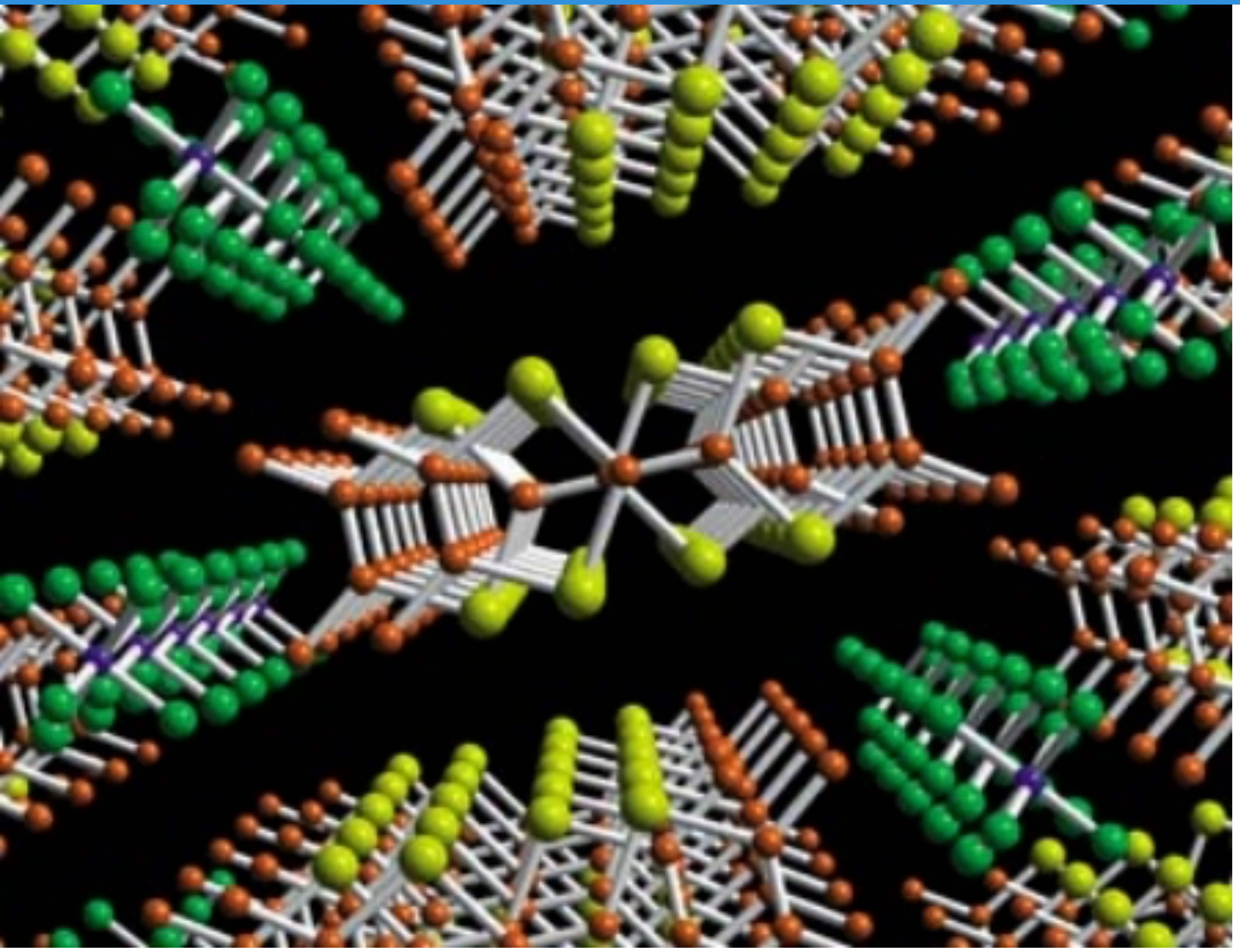
EQUS
Engineered Quantum Systems
Australian Research Council
Centre of Excellence

Physics World is the membership magazine of the *Institute of Physics*

Physics World ***Breakthrough of the Year*** awarded annually since 2009

1



Superconductivity is a phenomenon of exactly zero electrical resistance

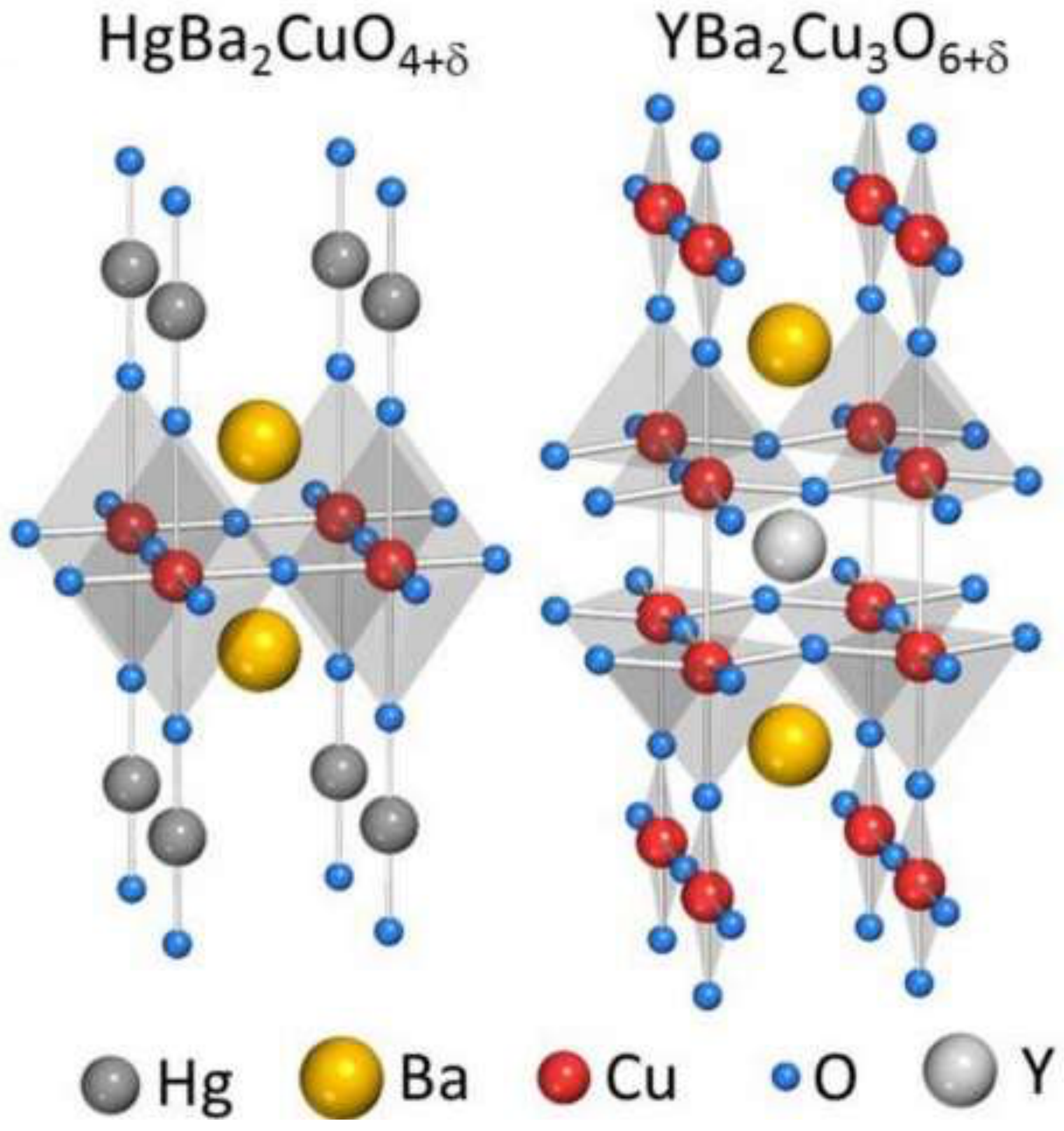
Unconventional superconductors are a class of strongly-correlated materials

heavy-fermion & organic superc
relatively low T_C, ~few to ~few 10s

iron pnictides and cuprates
can have T_C> 100 K

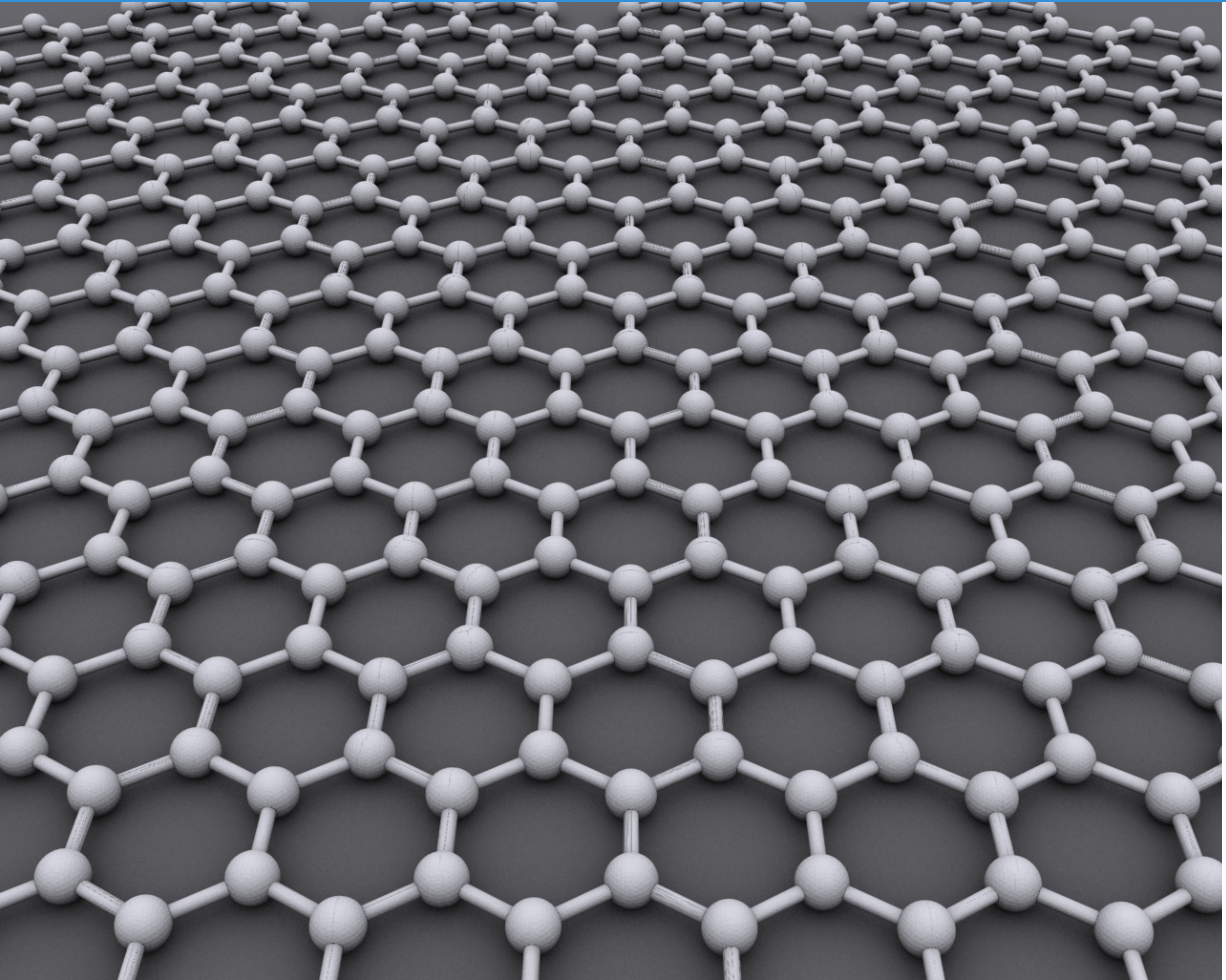
Possible high TC superconductivity in the Ba-La-Cu-O system
Bednorz & Mueller, *Zeitschrift für Physik B* **64**, 189–193 (1986)

1987



Extensive experiments, but unconventional superconductors are challenging to study theoretically because models *too complicated* to solve exactly

Graphene

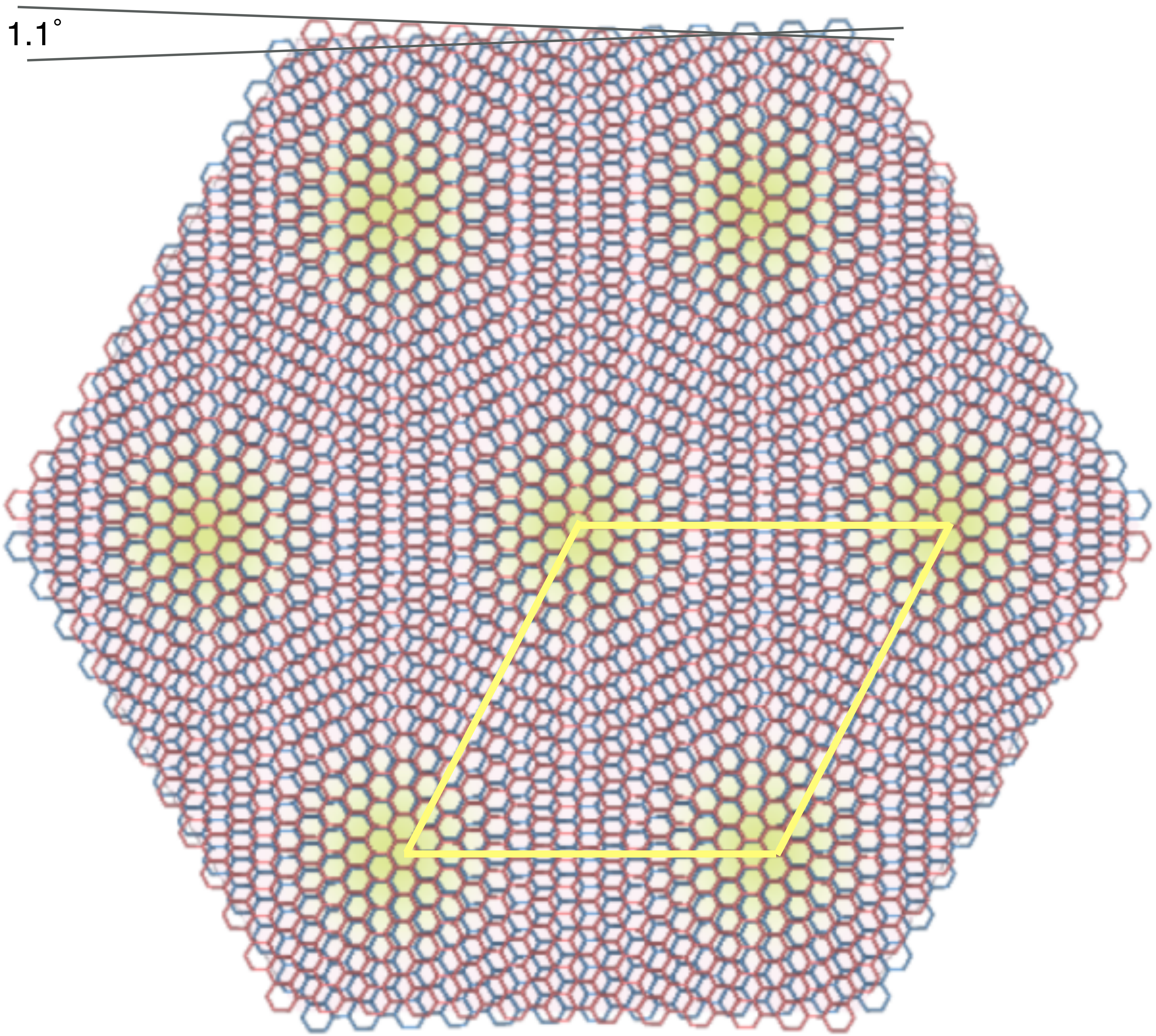


an intact sheet of carbon atoms — graphene — could be lifted off a block of graphite with a piece of Scotch tape

2010

Electric Field Effect in Atomically Thin Carbon Films
Novoselov et al., *Science* **306**, 666-669 (2004)

#1 Magic-angle graphene



It's exceptionally difficult to twist two sheets of graphene exactly 1.1 degrees out of alignment.

"Magic angle" leads to extraordinary effects. "I couldn't believe it," said one scientist. "I mean I actually found it beyond belief."

Magic-angle graphene behaves like a high-temperature superconductor

Among superconductors with strongest pairing strength between electrons … but simple!

Twistronics

Correlated insulator behaviour at half-filling in magic-angle graphene superlattice
Cao, et al., *Nature* **556**, 80–84 (2018)

Unconventional superconductivity in magic-angle graphene superlattices
Cao, et al., *Nature* **556**, 43–50 (2018)

2

Carbon fibres

Carbon fibres—aka graphite fibres—are about 5–10 micrometres in diameter

Several advantages including: high stiffness, high tensile strength, low weight, high chemical resistance, high temperature tolerance and low thermal expansion

Very popular in aerospace, civil engineering, military, and competition sports … but relatively expensive compared to glass or plastic fibres

Batteries

Batteries still make up a significant part of the weight for devices such as laptops and even cars


for carbon fibre composite vehicles, e.g. cars or aircraft, where
the energy storing capability is introduced inside the material.

#2 Multifunctional carbon fibres enable "massless" energy storage

Exploiting the electrochemical properties of carbon fibres used for structural support could drop device masses by as much as 50%.

Graphitic microstructure and performance of carbon fibre Li-ion structural battery electrodes
Fredi et al., *Multifunctional Materials* **1**, 015003 (2018)

3

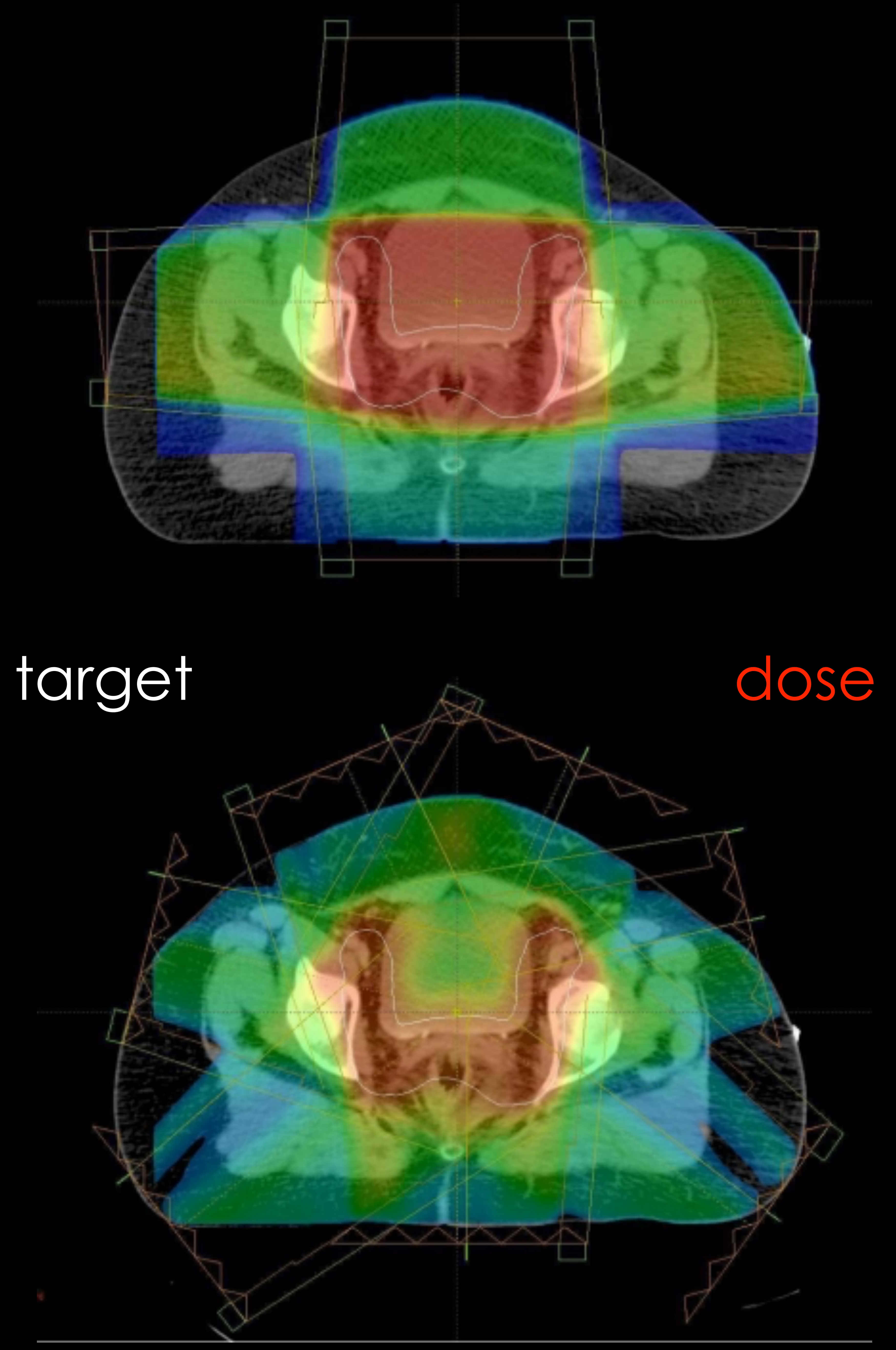
Intensity-Modulated Radiation Therapy

Radiation therapy damages the DNA and stops cancer cells from dividing and growing, thus slowing or stopping tumor growth

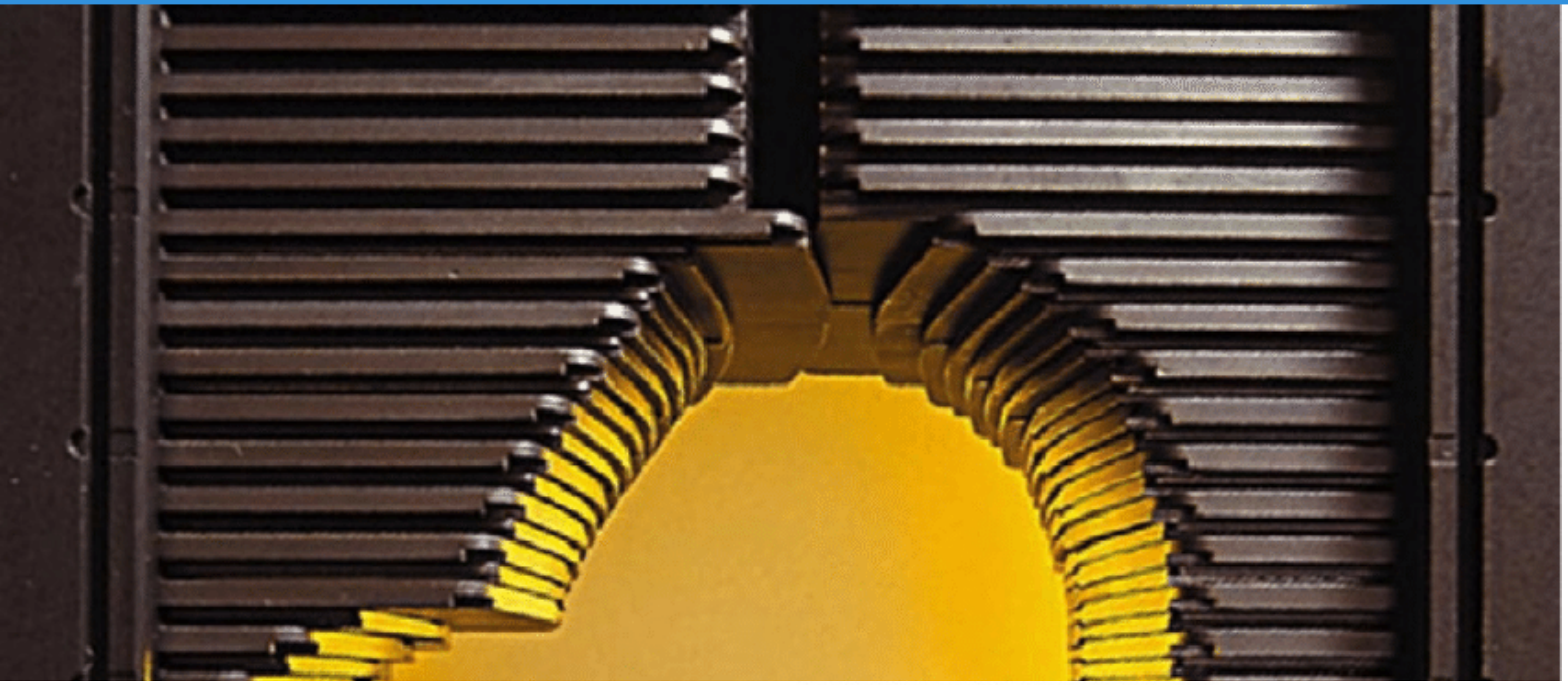
Intensity-modulated radiation therapy (IMRT) is an advanced mode of high-precision radiotherapy that uses computer-controlled linear accelerators

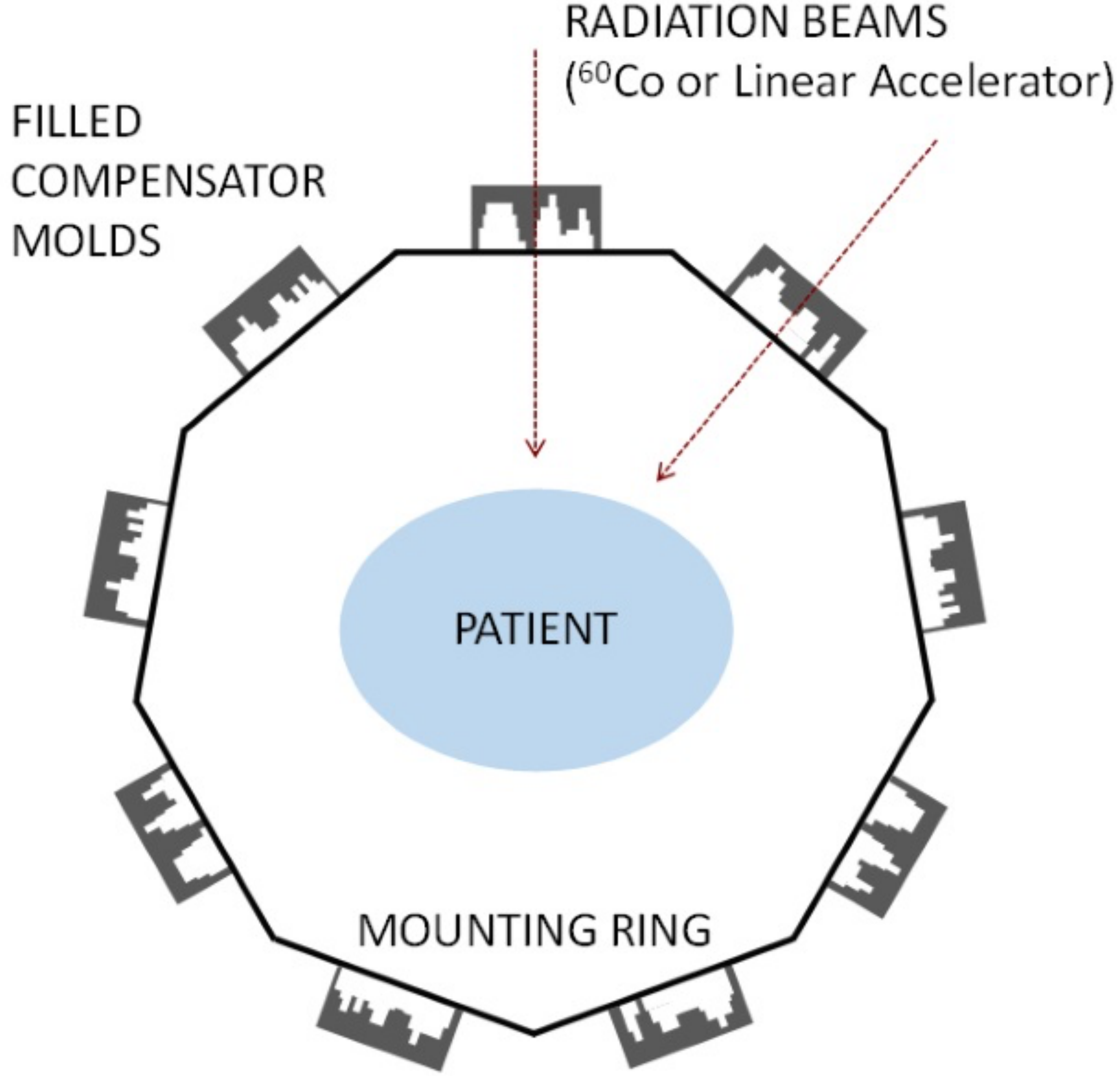
It delivers precise radiation doses to a more precisely defined area, allowing higher radiation doses while minimizing the dose to surrounding normal critical structures

Available in essentially all radiotherapy clinics in high-income countries, it is largely absent in vast regions of low- and middle-income countries.



Intensity-Modulated Radiation Therapy





IMRT uses *multi-leaf collimator*: plates of high atomic-numbered material—usually tungsten—which move independently in and out of the path of a particle beam in order to block it

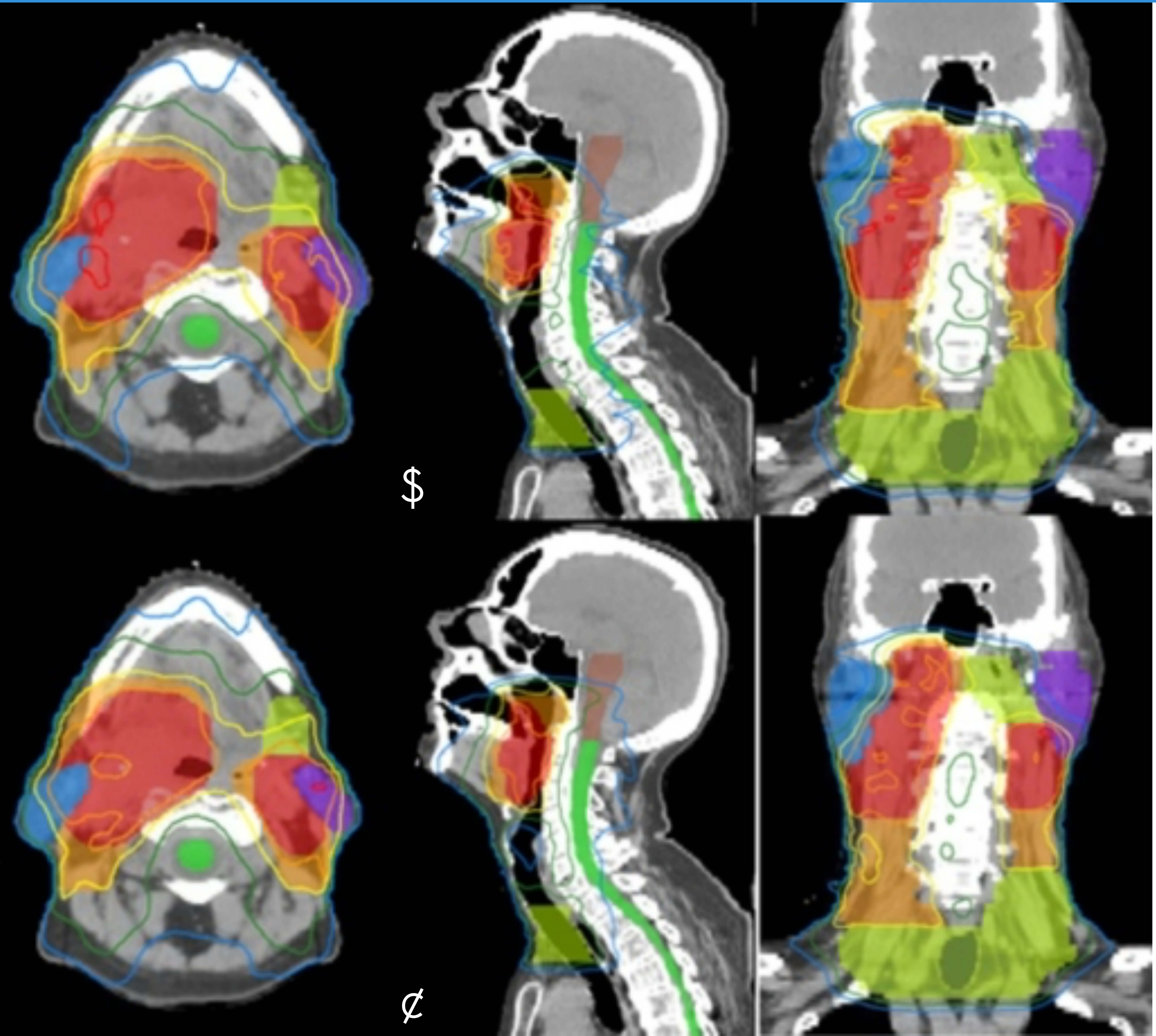
expensive

Instead use *compensators*: plastic moulds—lightweight & easy to manufacture—filled with attenuating material such as tungsten beads

After each treatment attenuator can be emptied from the moulds and re-used for another patient, minimizing the required amount of expensive attenuating material.

cheap and effective

#3 Compensator expands global access to advanced radiotherapy

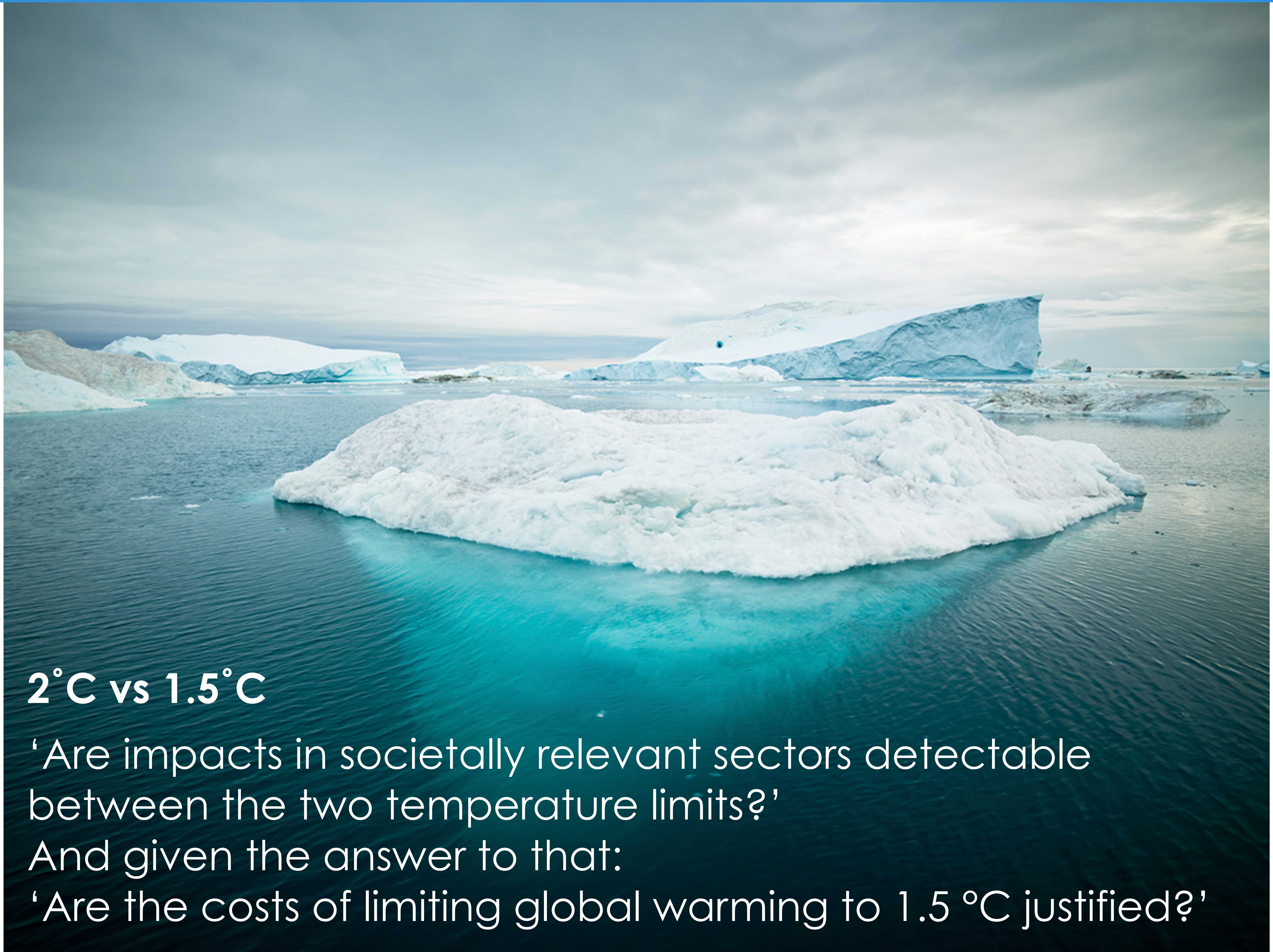


Device can be retrofitted to existing linac and cobalt teletherapy units – allowing clinics to add IMRT without having to purchase a new treatment system

A ring-based compensator IMRT system optimized for low- and middle-income countries: Design and treatment planning study
Van Schelt, et al., *Medical Physics* **556**, 80–84 (2018)

4

Climate change



2˚C vs 1.5˚C

‘Are impacts in societally relevant sectors detectable between the two temperature limits?’
And given the answer to that:
‘Are the costs of limiting global warming to 1.5 °C justified?’

#4 IPCC Special Report on 1.5 °C climate change

91 authors and review editors from 40 countries

Report resulted from Paris climate talks in 2015

Q1. Is 1.5 °C possible? ✔

Q2. are impacts in societally-relevant sectors detectable between the two temperature limits? ✔

Q3. Are the costs of limiting global warming to 1.5 °C justified?" ✔

Meeting the 1.5 °C target by the end of this century—instead of the more common 2 °C goal—will save the world $20 trillion

Large potential reduction in economic damages under UN mitigation targets
Burke, Davis & Diffenbaugh, *Nature* **557**, 549–553 (2018)

https://www.ipcc.ch/sr15/

A UQ Physics Connection

https://skepticalscience.com

Stage 1: Deny the Problem Exists

Stage 2: Deny We're the Cause

Stage 3: Deny It's a Problem

Stage 4: Deny We can Solve It

Stage 5: It's too Late

Stage 2b: Consensus Denial

97 percent consensus on this question in the peer-reviewed scientific literature.

Quantifying the consensus on anthropogenic global warming in the scientific literature
Cook et al, *Environmental Research Letters* **8** 024024 (2013)

5

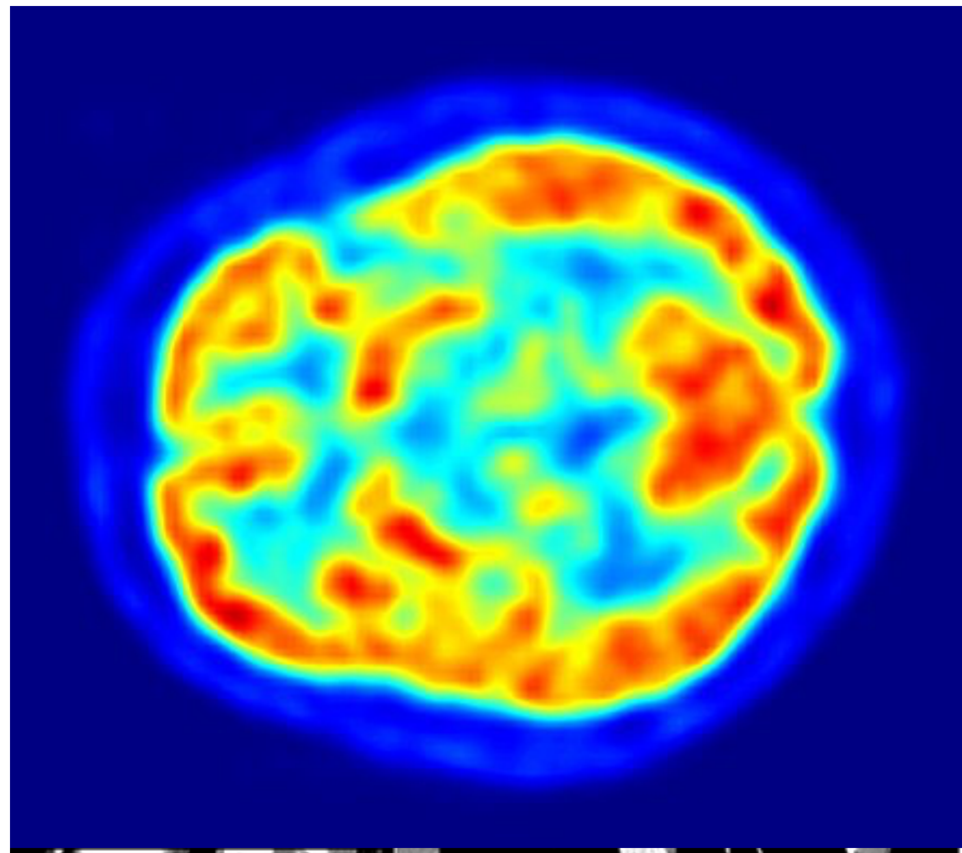
PET/CT

Combines in a a single gantry:

Positron Emission Tomography (PET) scanner

uses anti-matter

detects pair of γ-rays emitted by a positron-emitting tracer, commonly fluorine-18



Computed tomography (CT) scanner

formerly computerized axial tomography scan, CAT scan

can use X-rays, positrons, single-photons

#5 EXPLORER PET/CT produces first total-body scans

UC Davis envisioned creating a full-body scanner in 2005

2011 $1.5M from National Cancer Institute to establish a consortium of researchers

2015 $15.5M from National Institute of Health to team up with commercial partner

2018 First human images presented by Dr. Eric Berg in Sydney at the IEEE MIC 2018 Total-Body PET workshop, 17 Nov

40 times faster

https://explorer.ucdavis.edu

6

aviation remains a noisy and heavily polluting business

increasing concerns over the carbon footprint

Drones are going to become common: traffic & air pollution monitoring, delivery…

Both use same propeller thrust, both prone to the same noise…

Is there another way?

#6 Combustion-free, propeller-free plane takes flight

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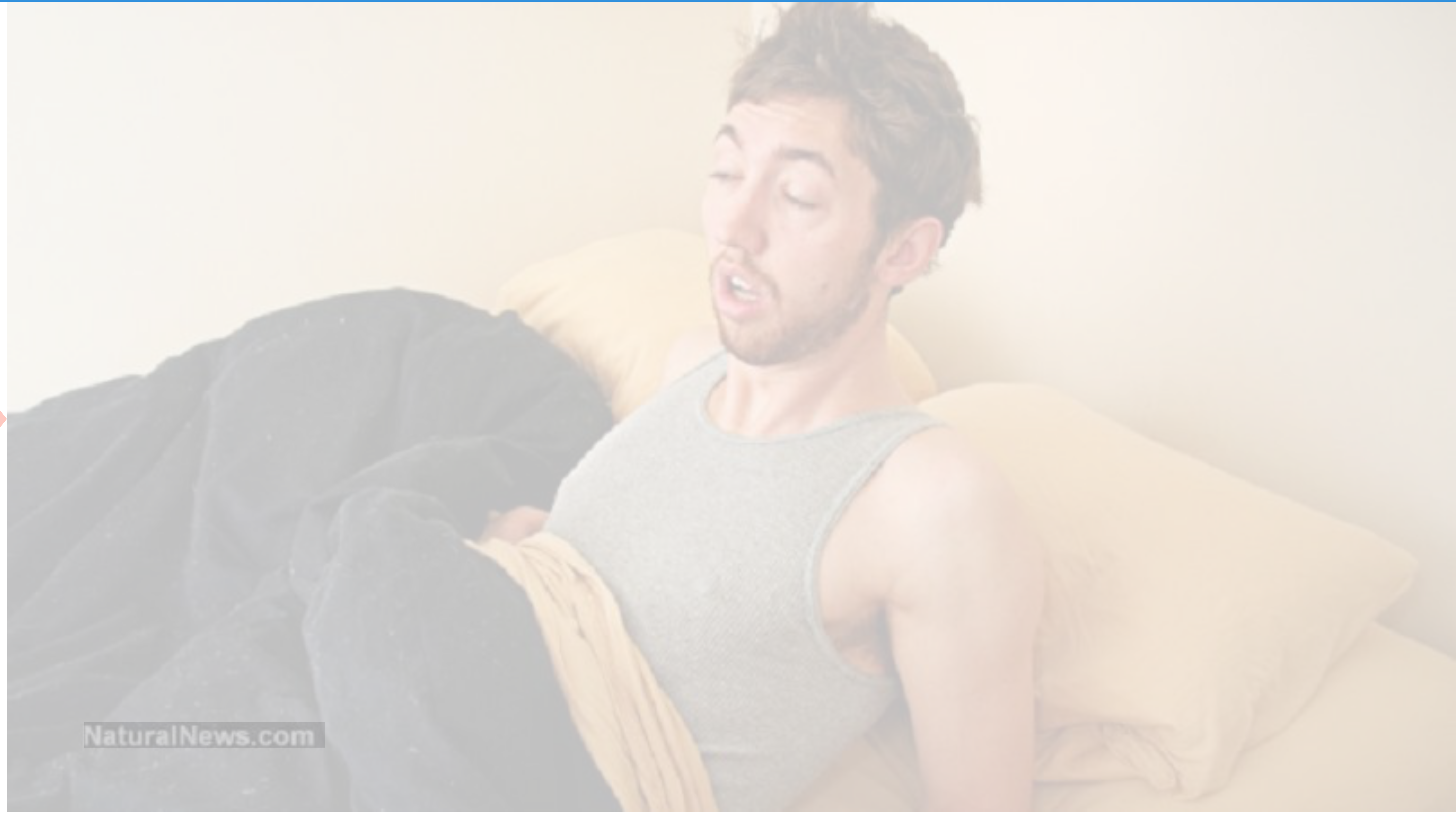
"…trying to get permission from the aviation authorities to fly an untested plane design powered by a 40,000 V electric field outdoors was unlikely to meet with success."

Flight of an aeroplane with solid-state propulsion
Xu, et al., *Nature* **563**, 532–535 (2018)

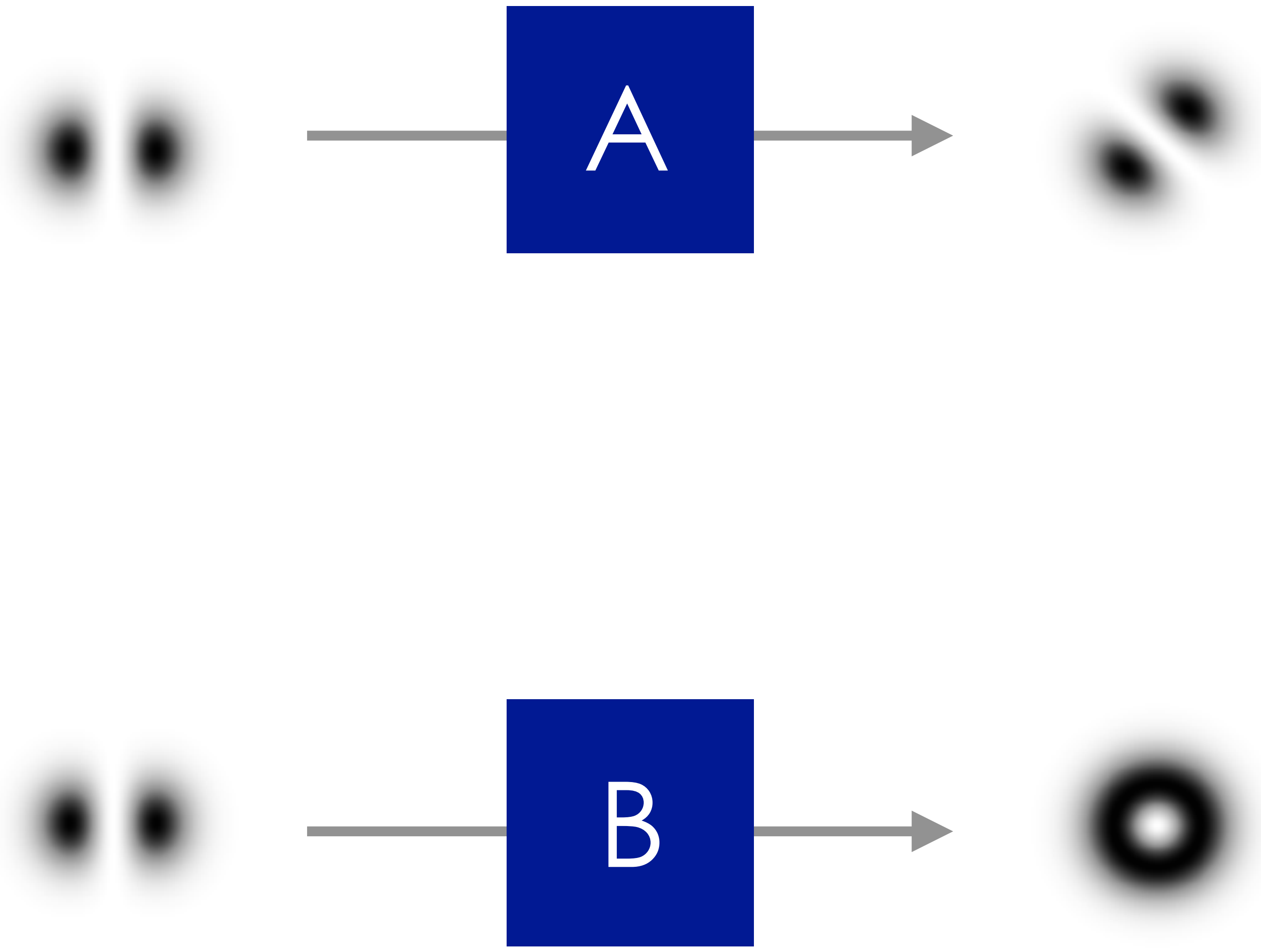
7

Causal order

Causal order



#7 Quantum mechanics defies causal order, experiment confirms



Goswami et al, *Physical Review Letters* **121**, 090503 (2018)

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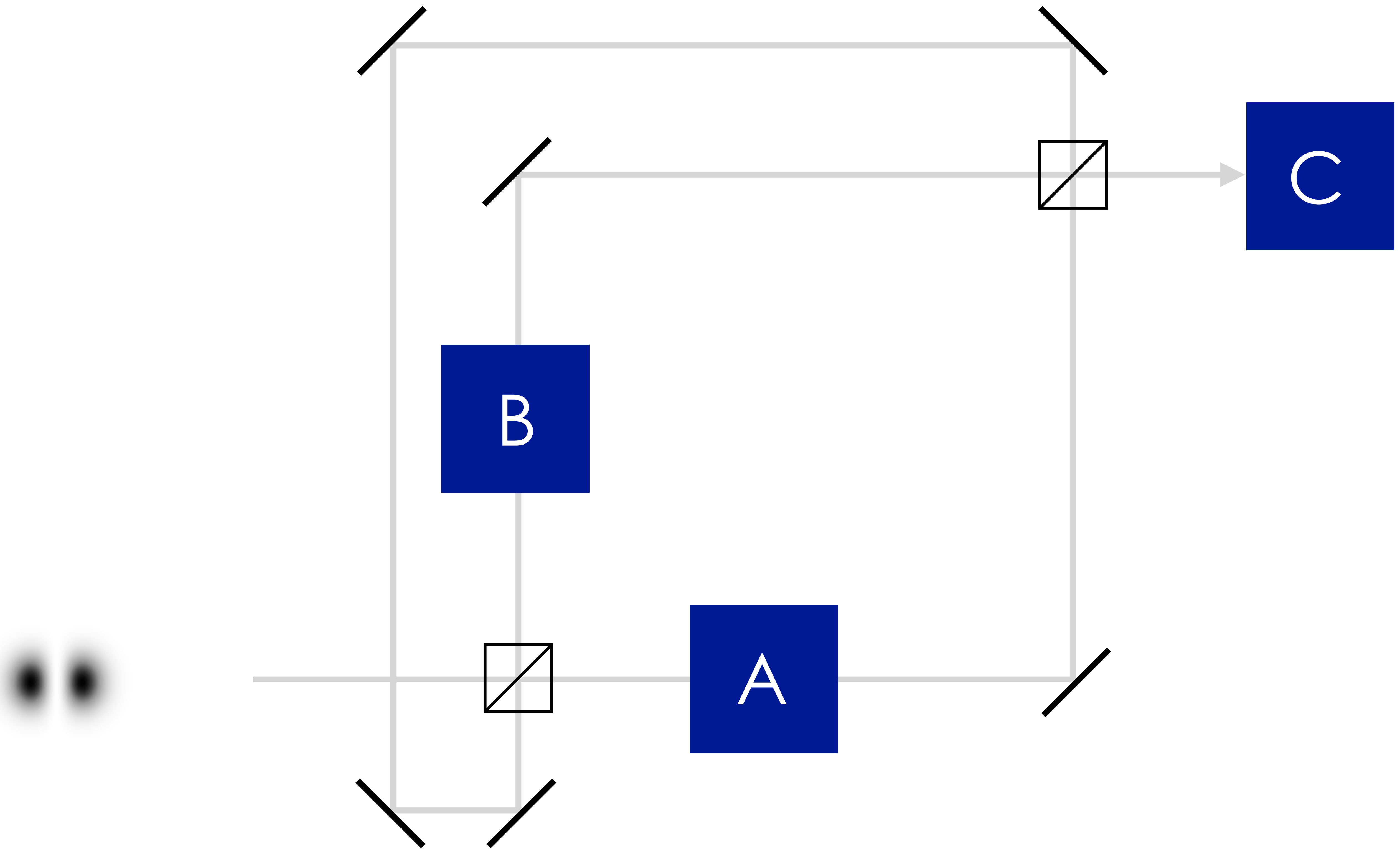

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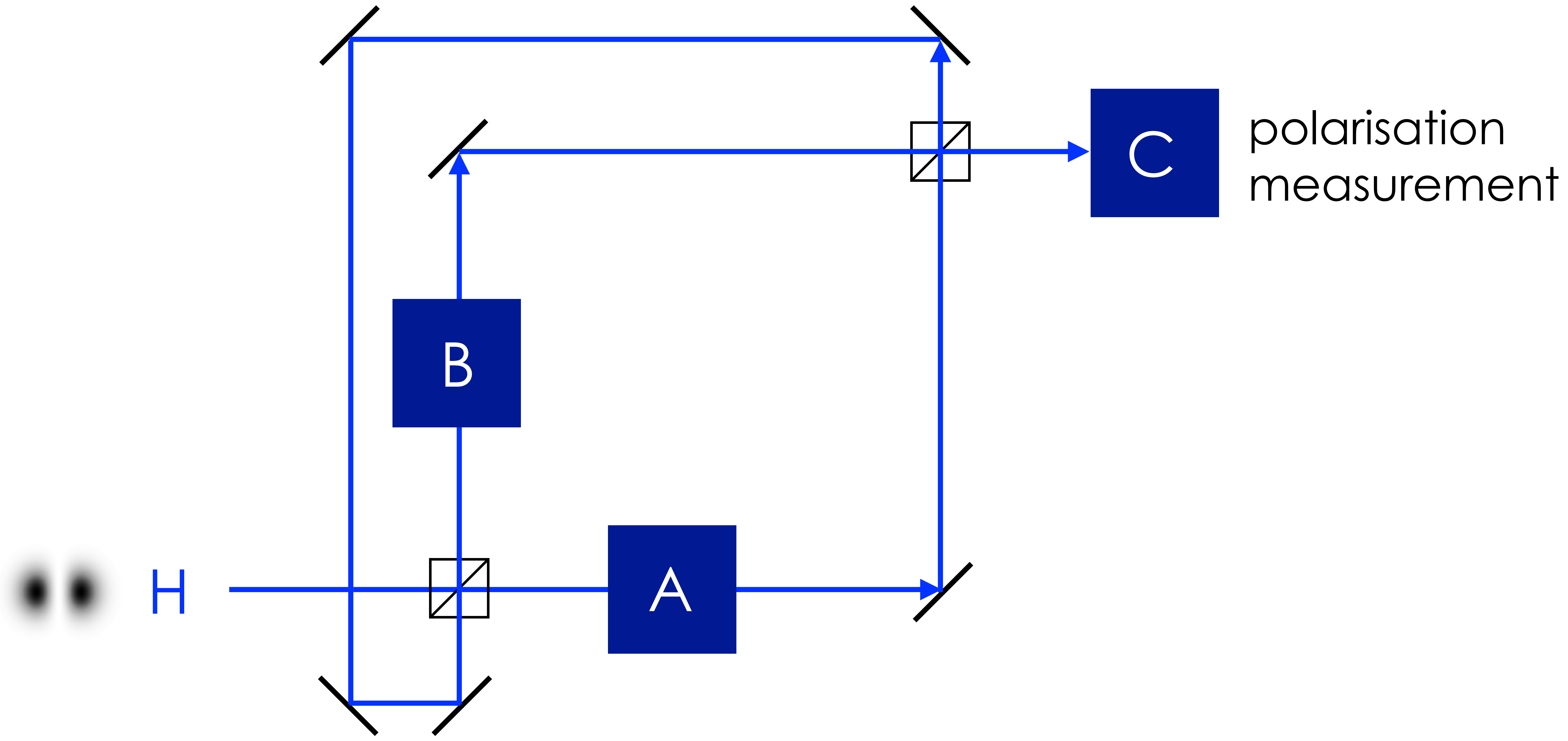

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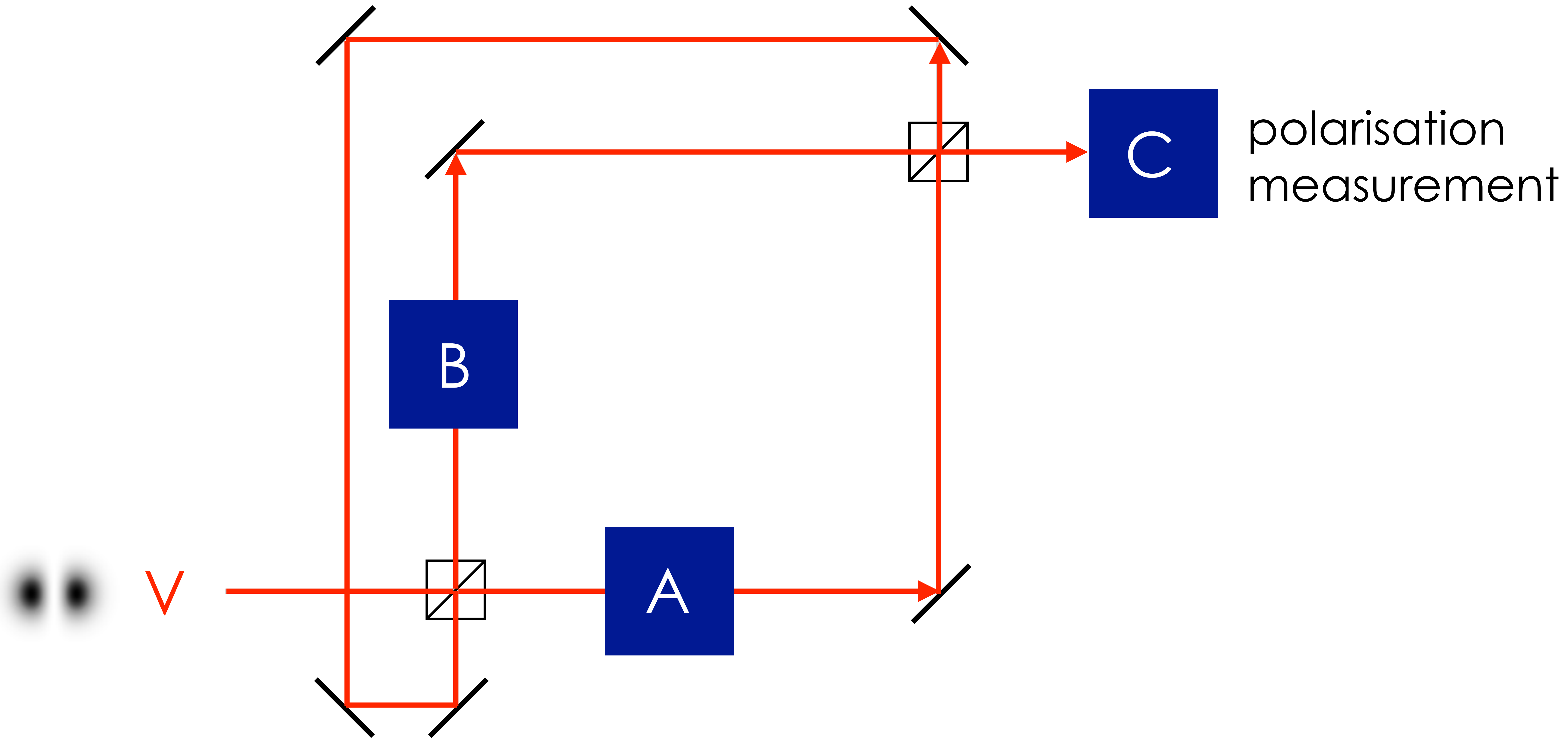

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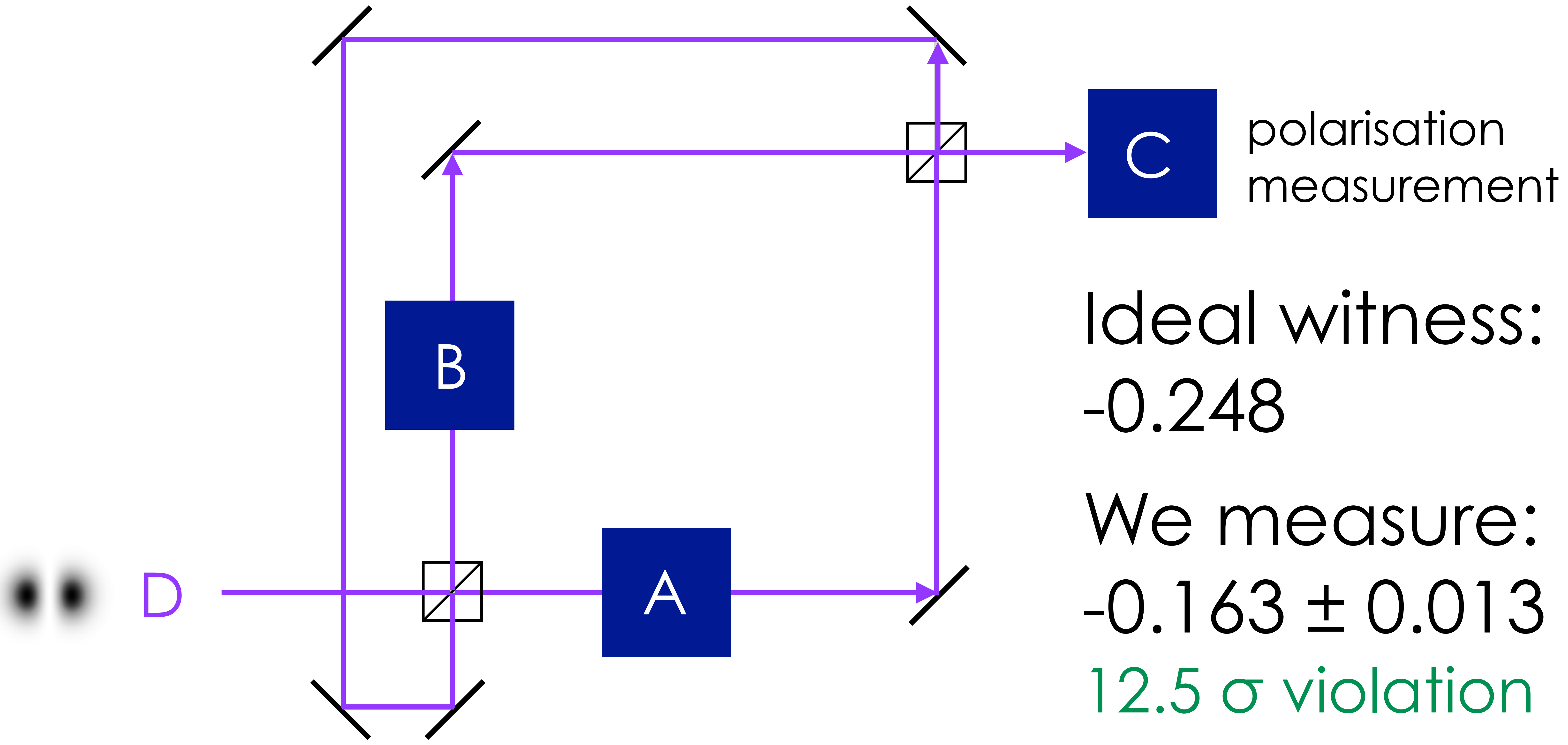


Ideal witness:
-0.248

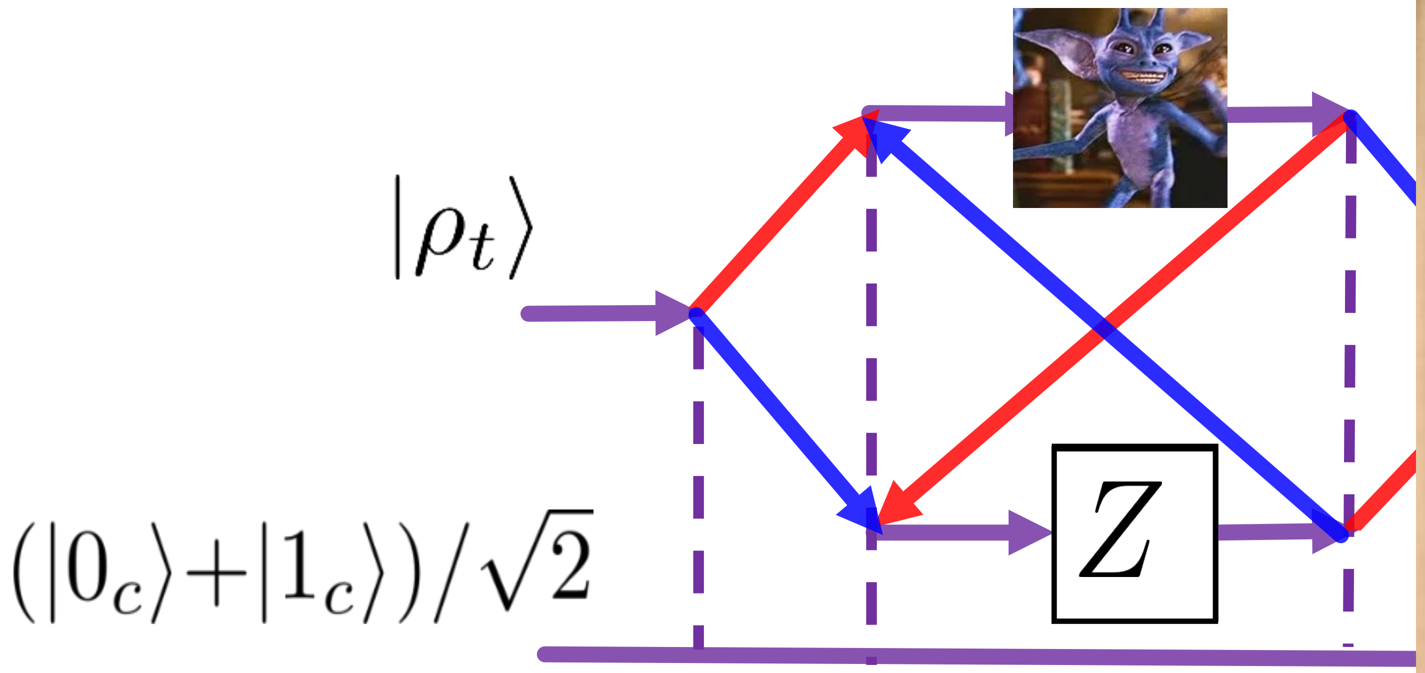
We measure:
-0.163 ± 0.013
12.5 σ violation

The quantum switch has
indefinite causal order

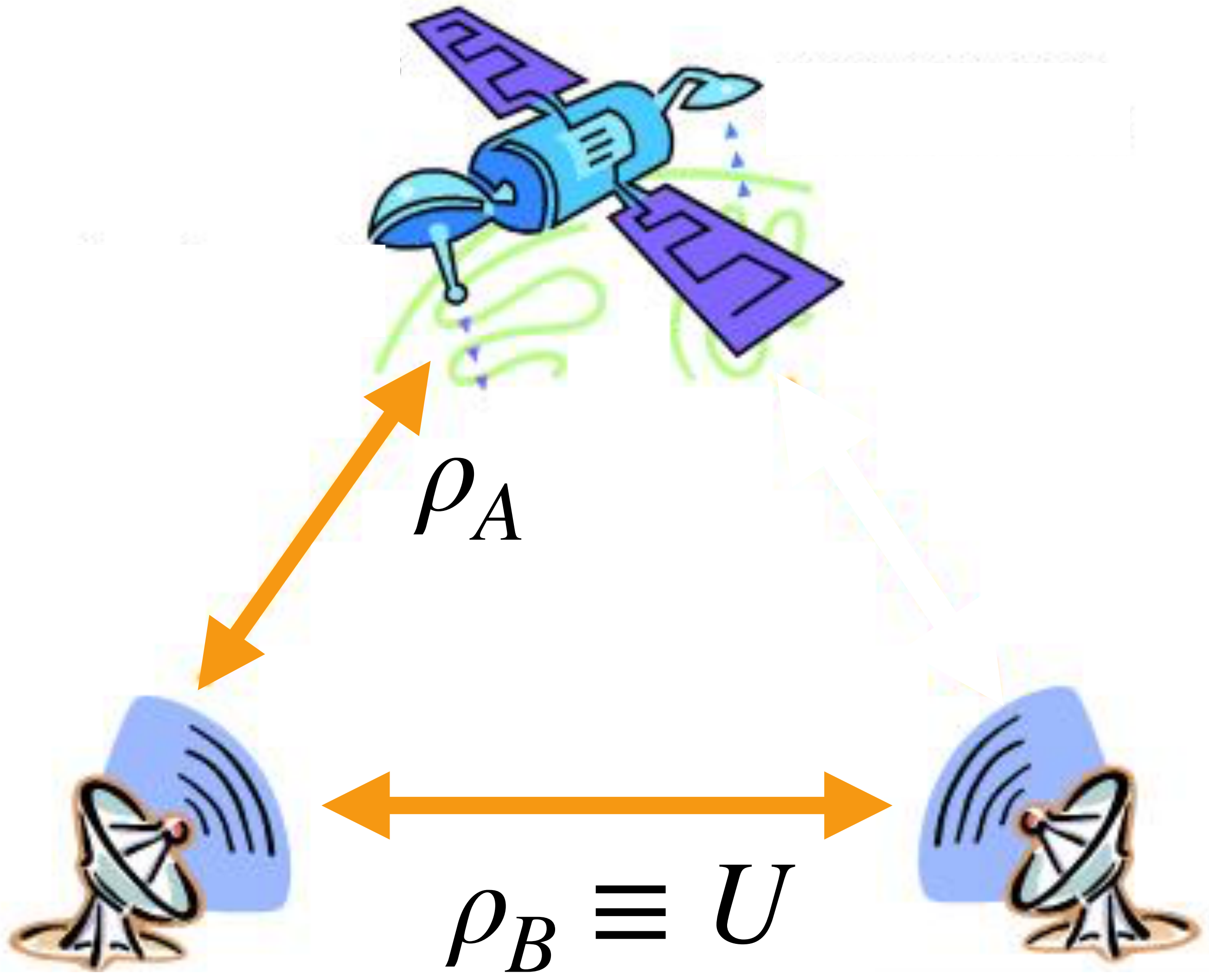
Goswami et al, *Physical Review Letters* **121**, 090503 (2018)

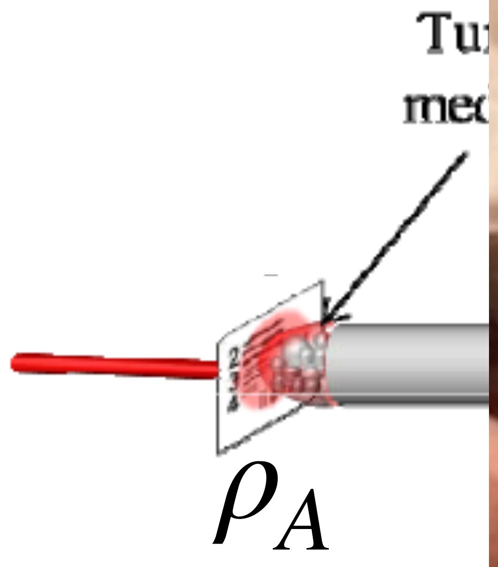
#7 Quantum mechanics defies causal order, experiment confirms

sending encrypted information



sending through turbulent media





Goswami et al, *Physical Review Letters* **121**, 090503 (2018)

8

Retinal stem cells

Müller glia—aka Müller cells—retinal cell found in vertebrate retina, serve as support cells for the neurons

Most common type of glial cell found in the retina & span across the entire retina

In cold-blooded vertebrates MG cells act as retinal stem cells that replenish damaged retinal neurons and restore vision

Doesn't work for mammals…

#8 Activating retinal stem cells restores vision in mice

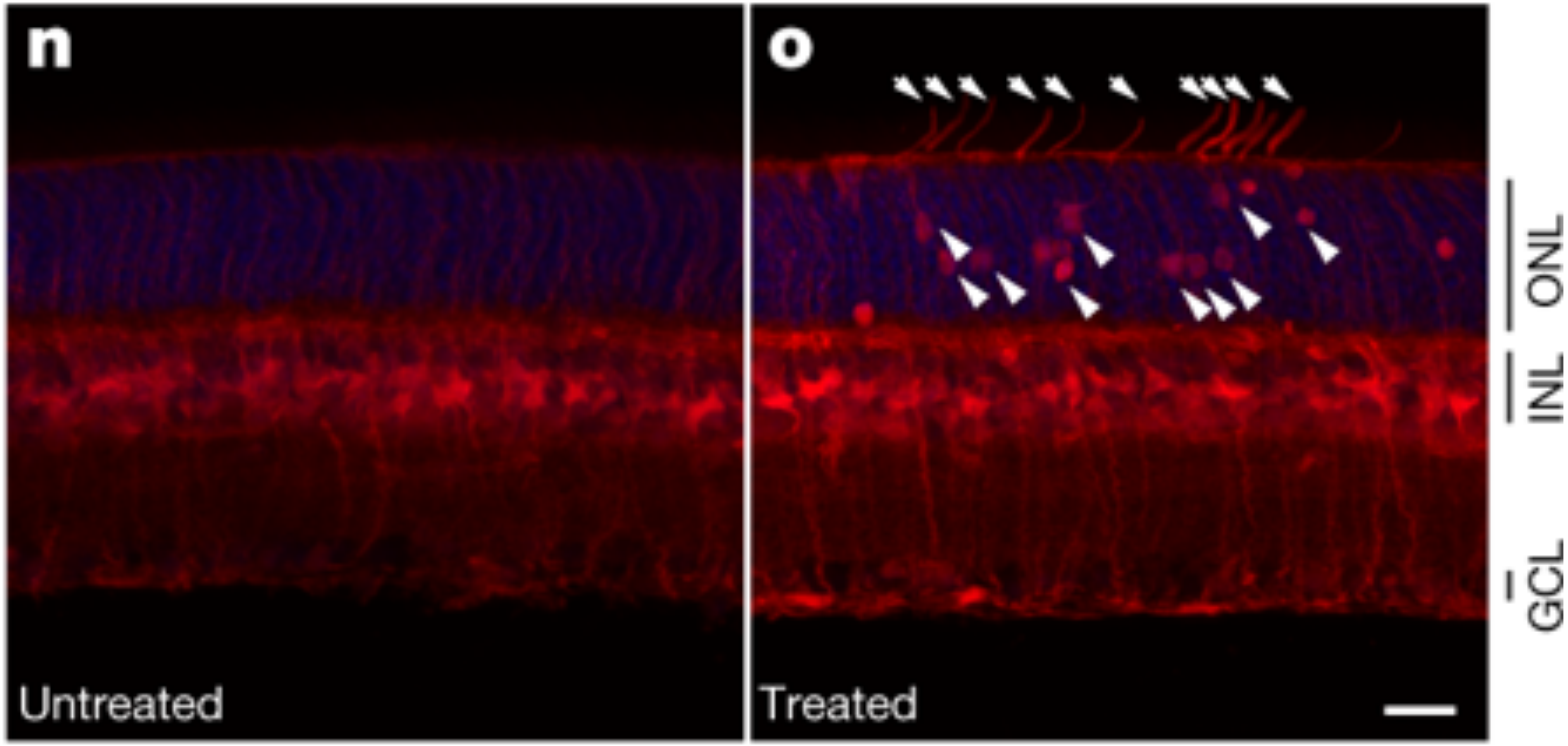
First step
Use gene transfer process to activate dormant stem cells—turns them into active stem cells

Second step
Use another gene transfer to tell stem cells to develop into rod photoreceptor cells, the most abundant cell type in the retina

Did it work?

Restoration of vision after de novo genesis of rod photoreceptors in mammalian retinas
Yao et al., *Nature* **560**, 484–488 (2018)

cActivating retinal stem cells restores vision in mice

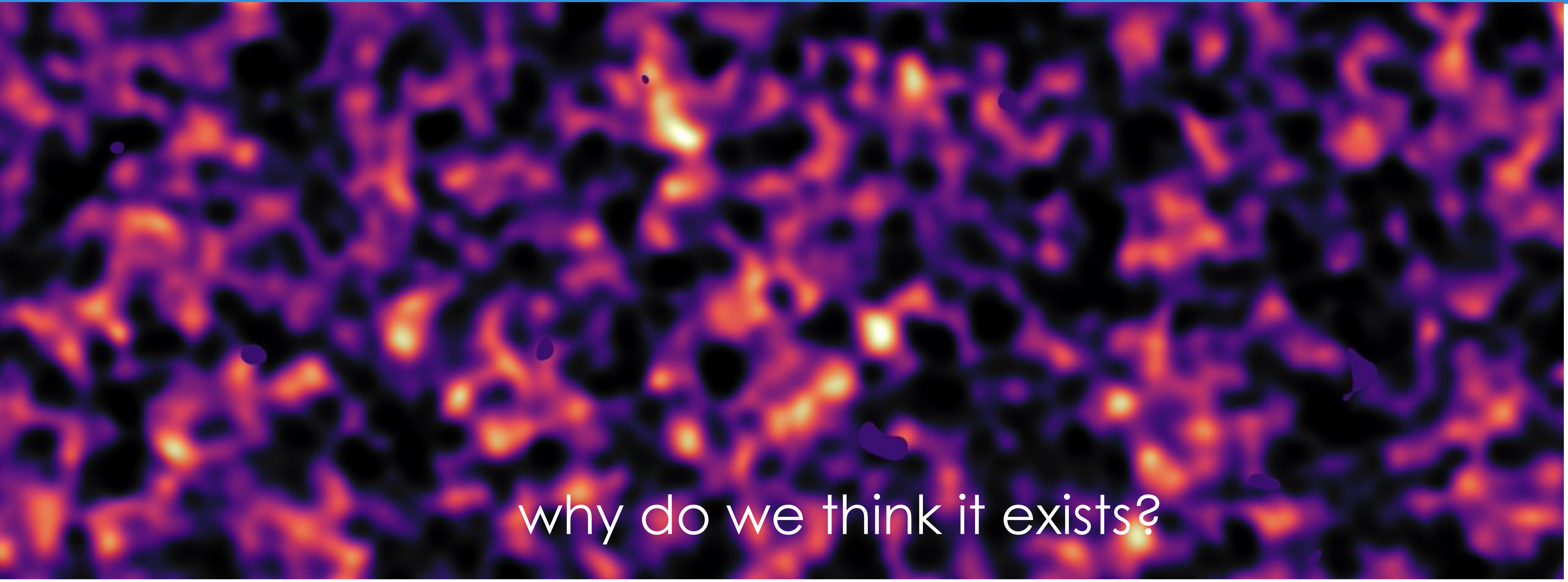


No difference between these new cells and real rod photoreceptor cells

Between four and six weeks after the reprogramming, the blind mice were able to sense light and regained their vision—never been achieved before

Restoration of vision after de novo genesis of rod photoreceptors in mammalian retinas
Yao et al., *Nature* **560**, 484–488 (2018)

9



We know what makes up 15% of matter in universe

We don't know what the other 85% is…

…does not interact with electromagnetic fields—light—so it's called dark

Observational evidence

- Galaxy rotation curves
- Velocity dispersions
- Galaxy clusters
- Gravitational lensing
- Structure formation
- Bullet Cluster
- Type Ia supernova distance measurements
- Sky surveys and baryon acoustic oscillations
- Redshift-space distortions
- Lyman-alpha forest

What is it?

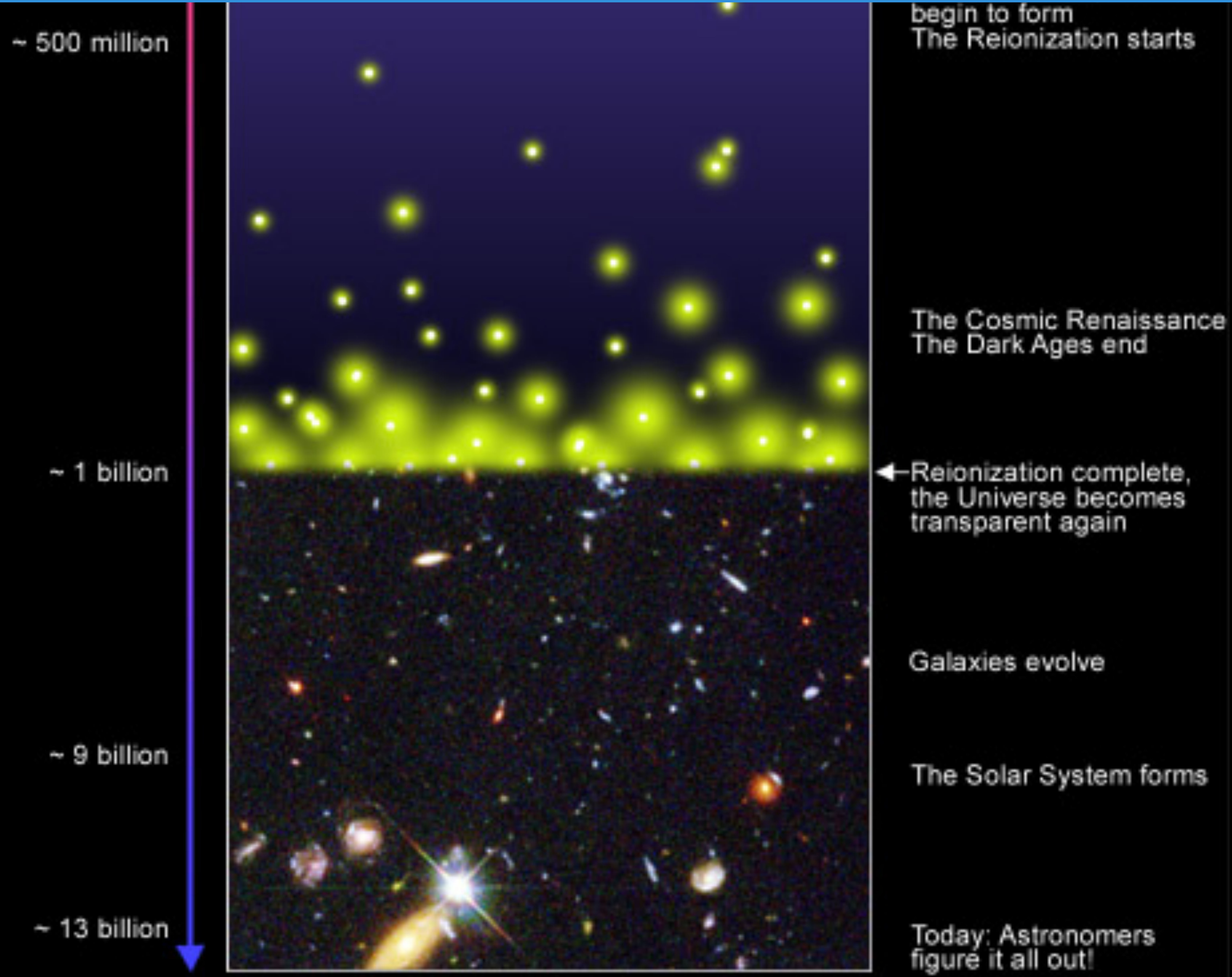
Looking at ancient hydrogen

located at the Murchison Radio-astronomy Observatory (MRO) in Western Australia

EOR is “Epoch of Reionisation”

Looking at ancient hydrogen

Looking at ancient hydrogen



#9 Ancient hydrogen reveals clues to dark matter’s identity

When the first stars lit up, their ultraviolet radiation was absorbed by hydrogen atoms, causing the single electrons in hydrogen atoms to undergo a small jump, releasing 21 cm (1420 MHz) radio emission

Sees signal from 180 million years after Big Bang…

Amplitude of the signal is twice as large as predicted, why?

Consistent with gas being colder than expected, 3K instead of 6K, how?

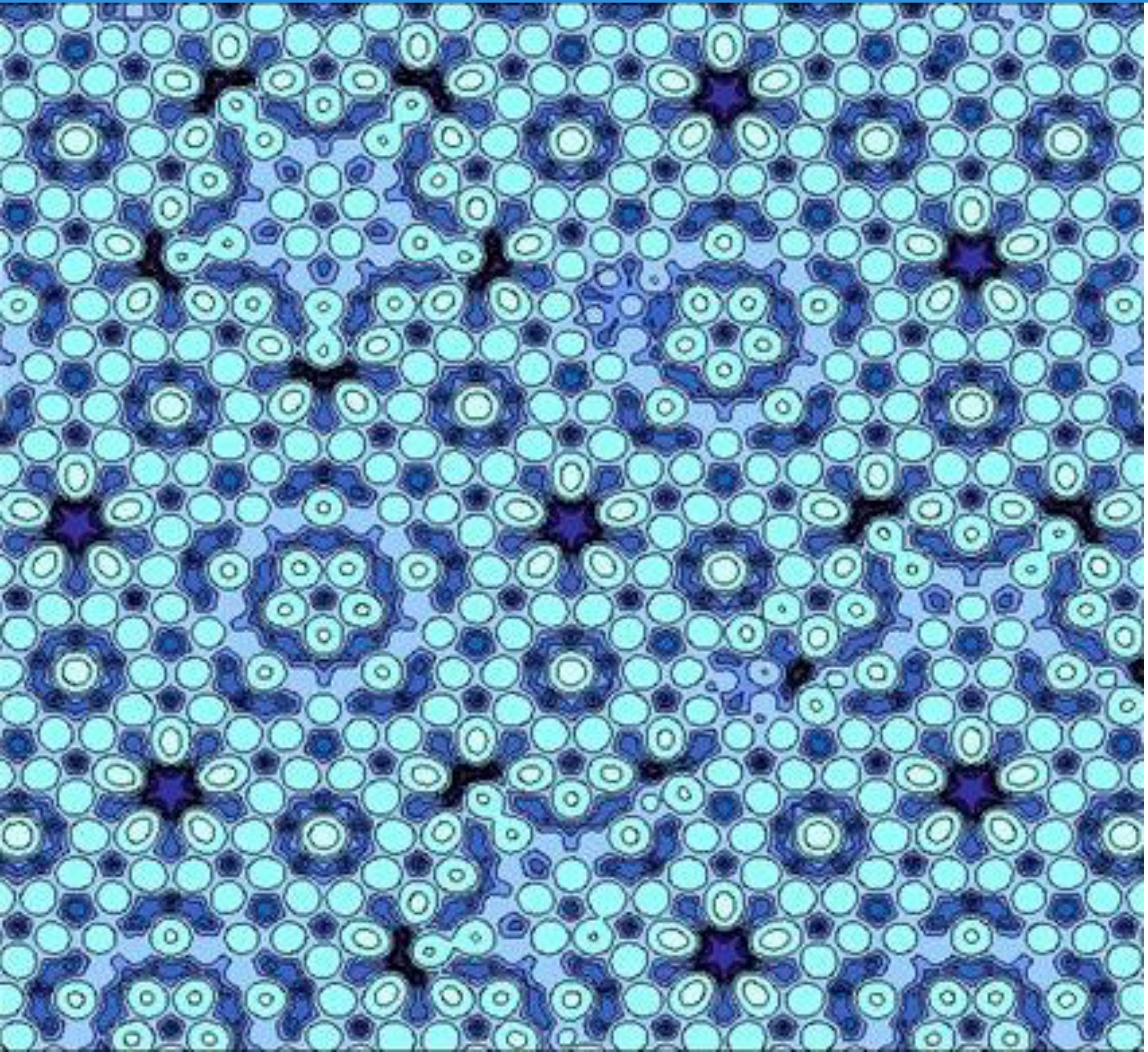
Back then, only matter colder than hydrogen was dark matter…

…if dark matter particles and hydrogen atoms scattered off one another, removes heat from the hydrogen atoms.

If confirmed, first direct observational indication of a non-gravitational interaction

10

Quasicrystals



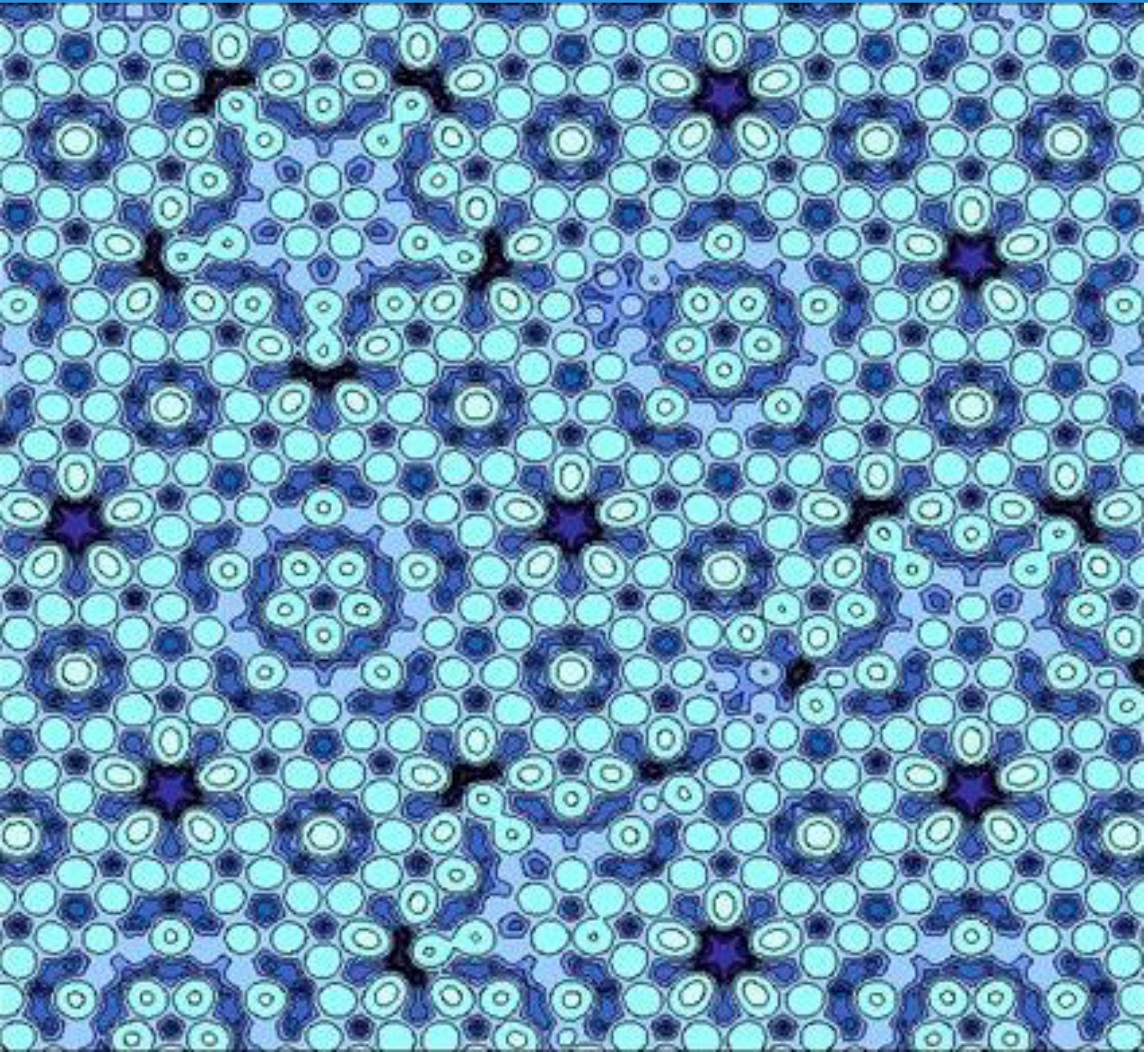
A structure that is ordered but not periodic

"all hell broke loose"

Linus Pauling—two-time Nobel laureate, for Chemistry and Peace—at a science conference in front of an audience of hundreds claimed, "Danny Shechtman is talking nonsense, there are no quasi-crystals, just quasi-scientists."

Metallic Phase with Long-Range Orientational Order and No Translational Symmetry
Shechtman et al., *Physical Review Letters* **53** 1951 (1984)

Quasicrystals



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2011

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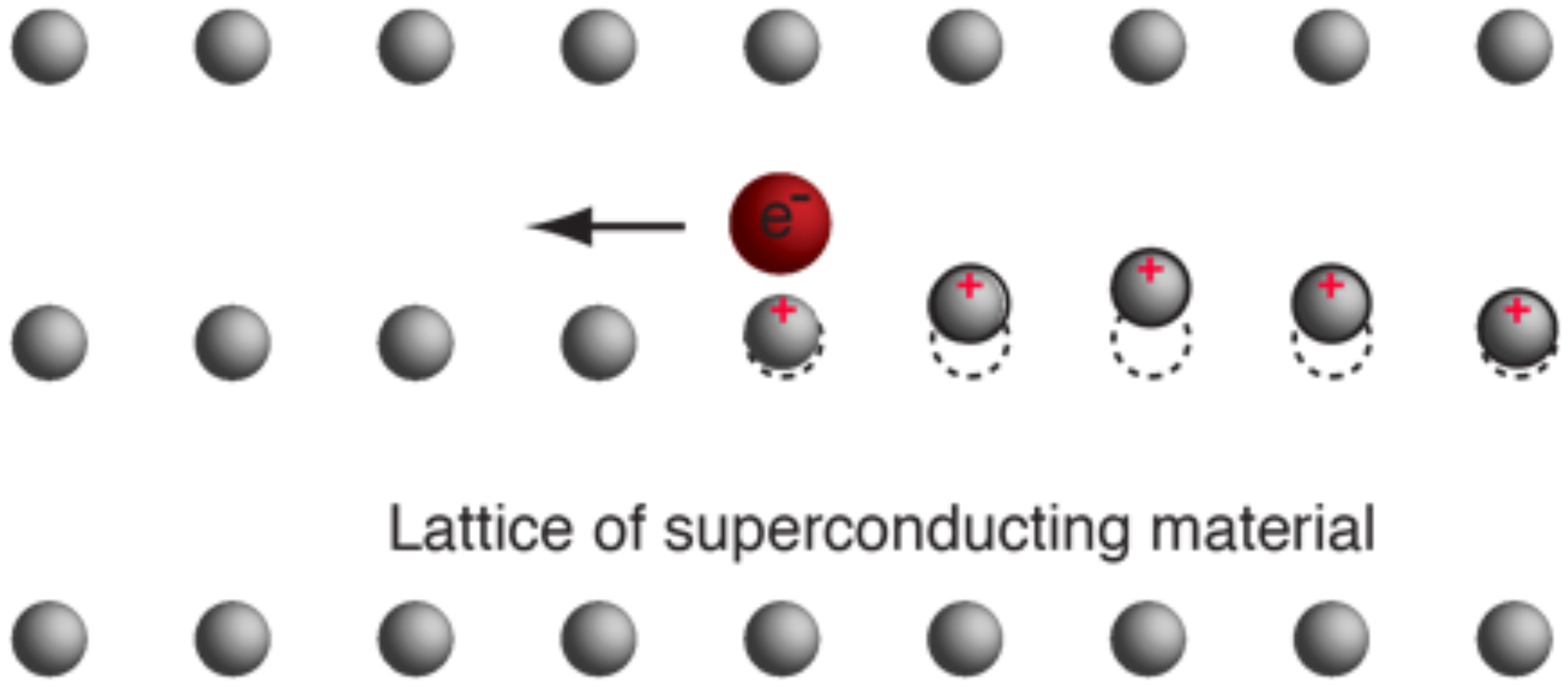
Superconductors

Superconductivity is a phenomenon of exactly zero electrical resistance



A passing electron attracts the lattice, causing a slight ripple toward its path

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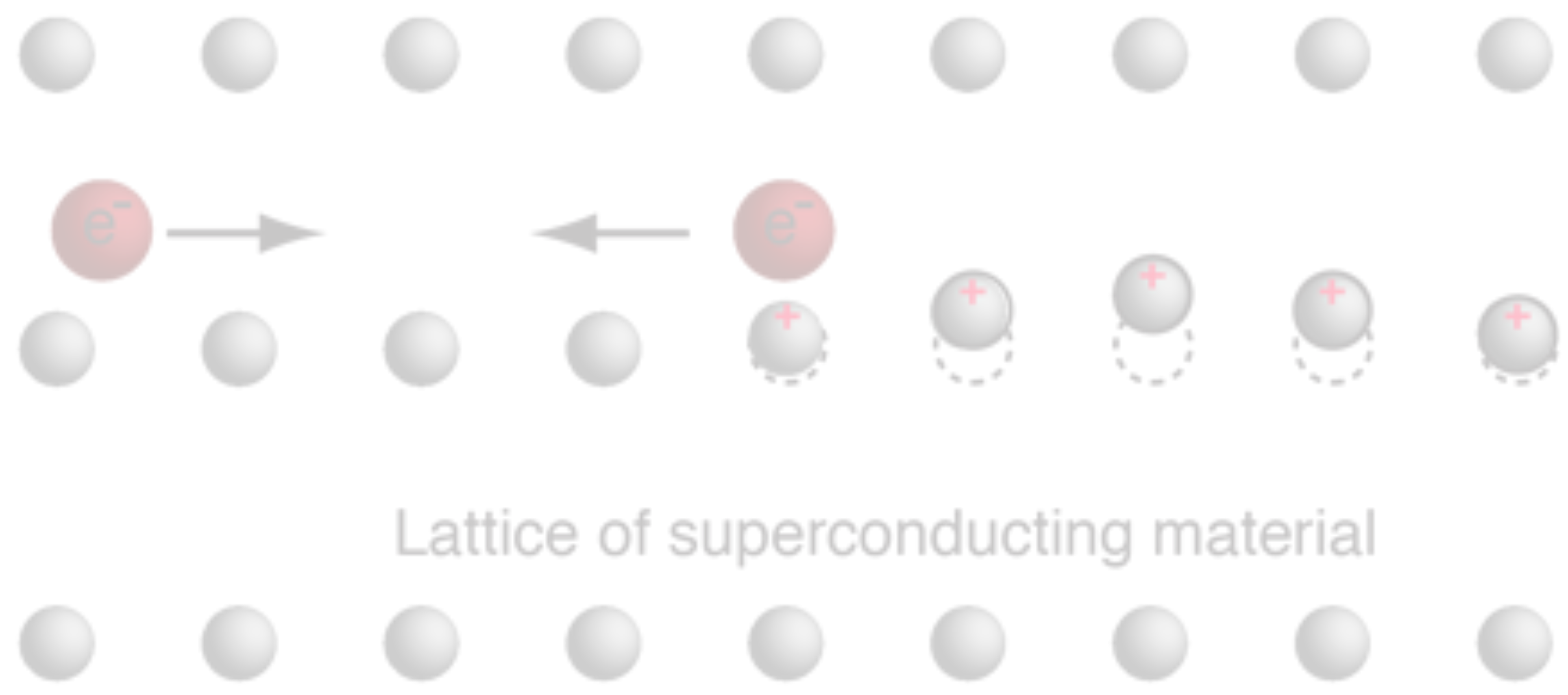

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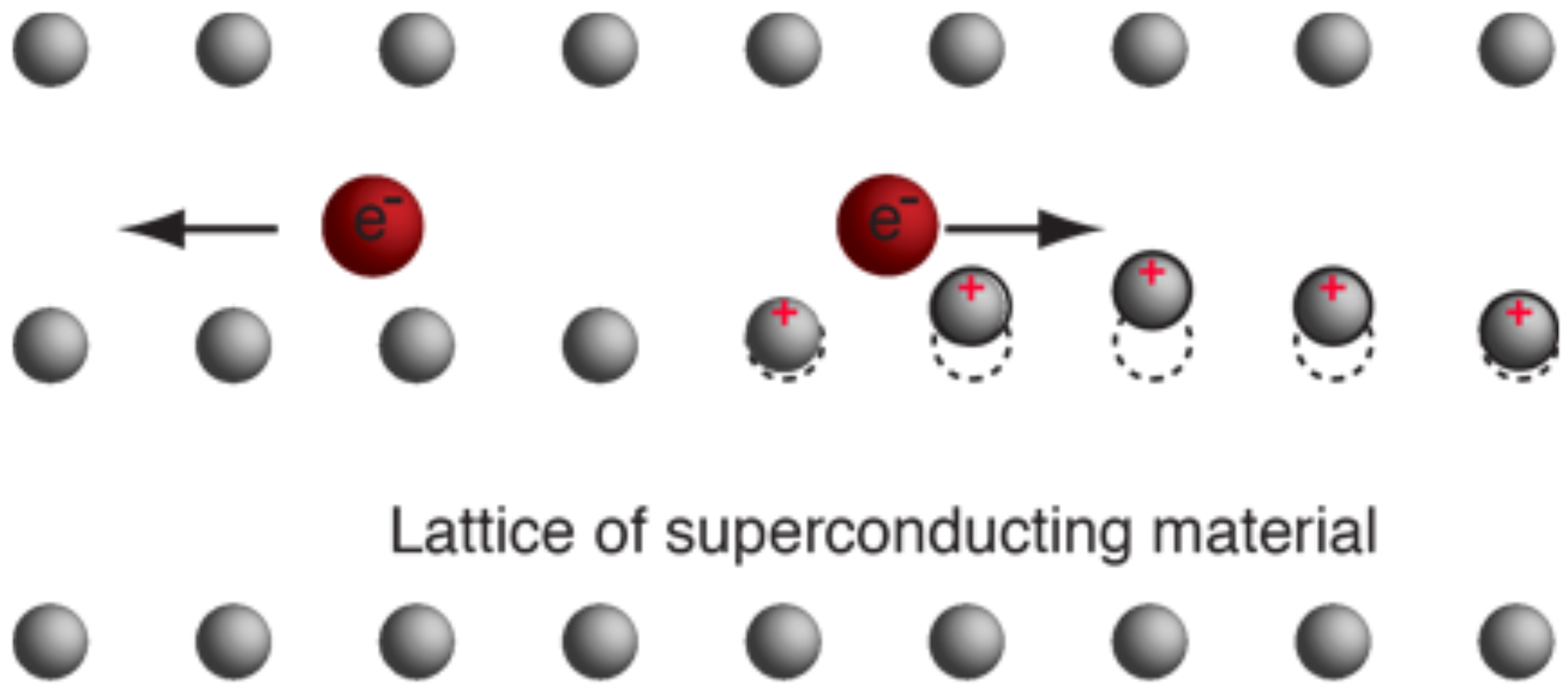

Another electron passing in the opposite direction is attracted to that displacement

Superconductors

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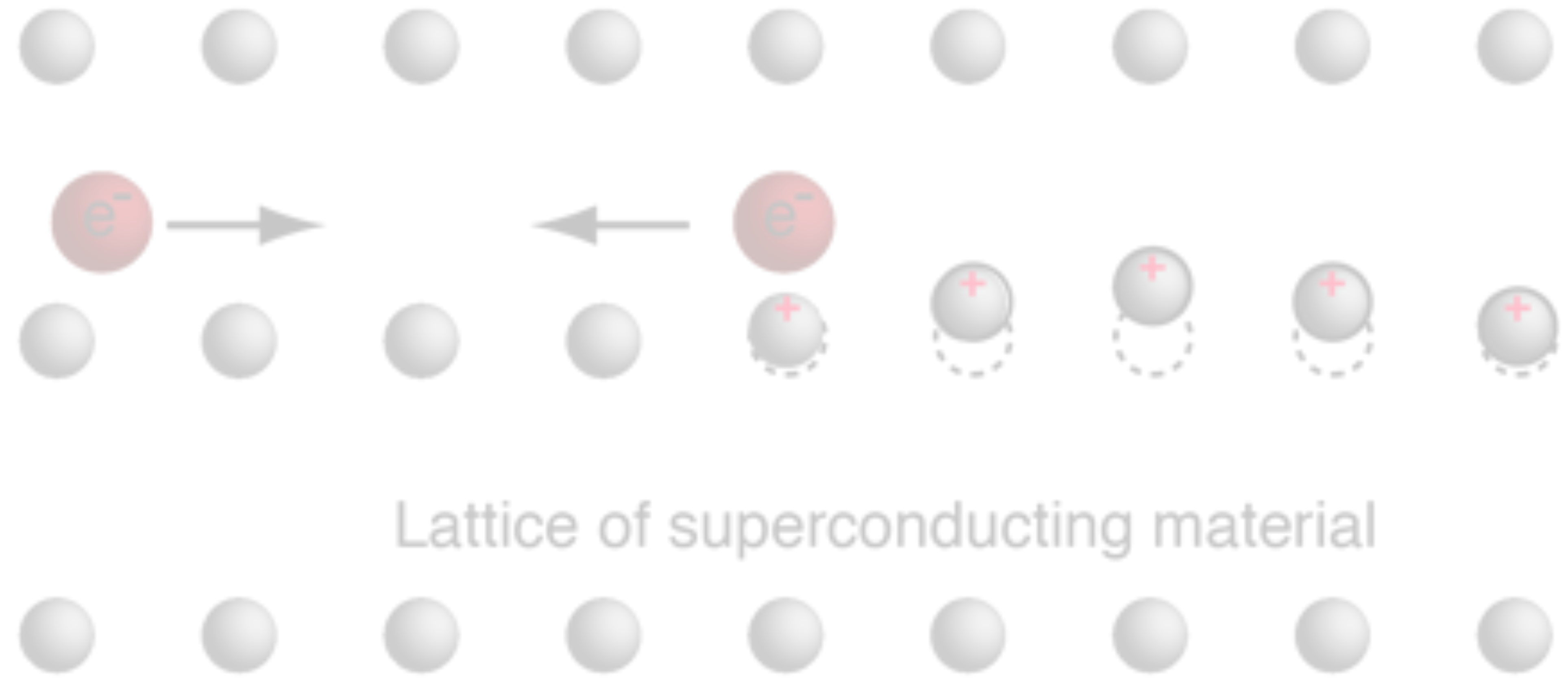

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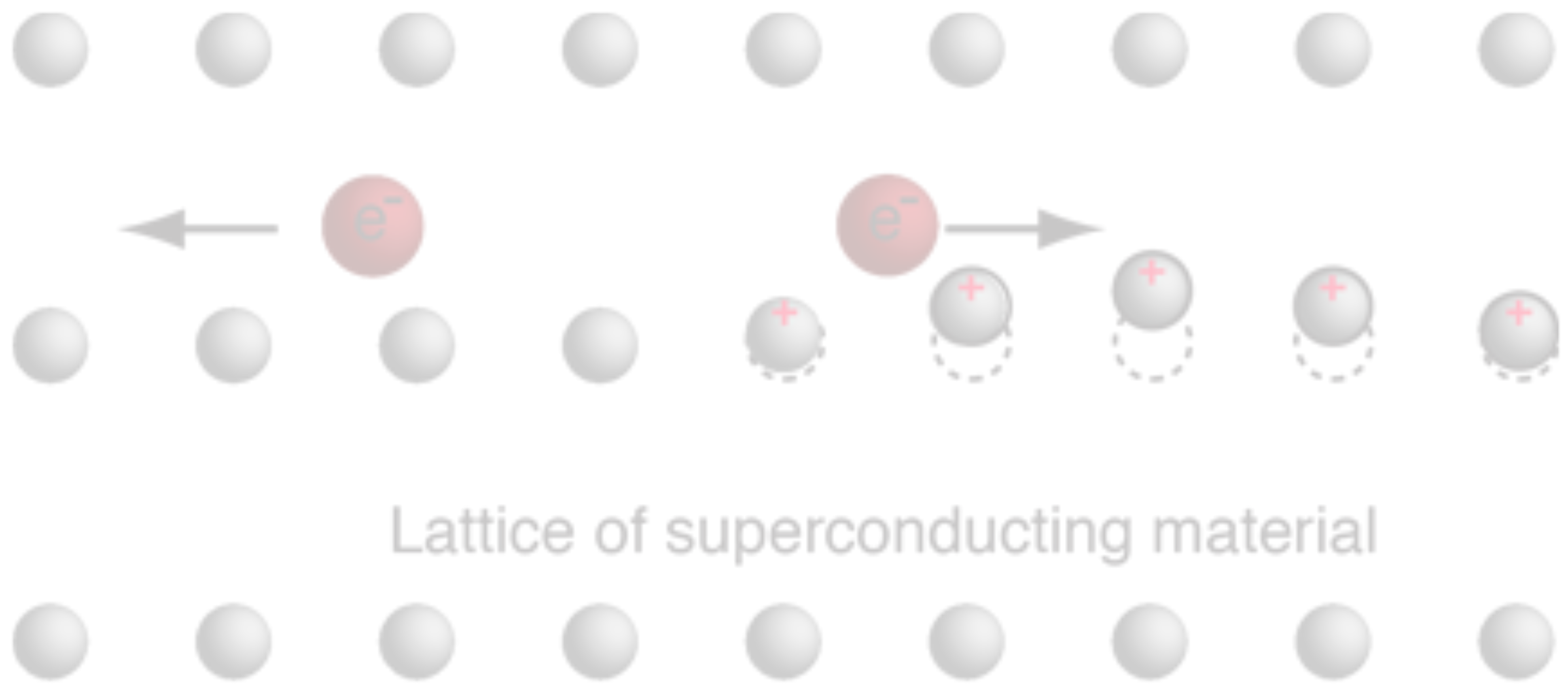
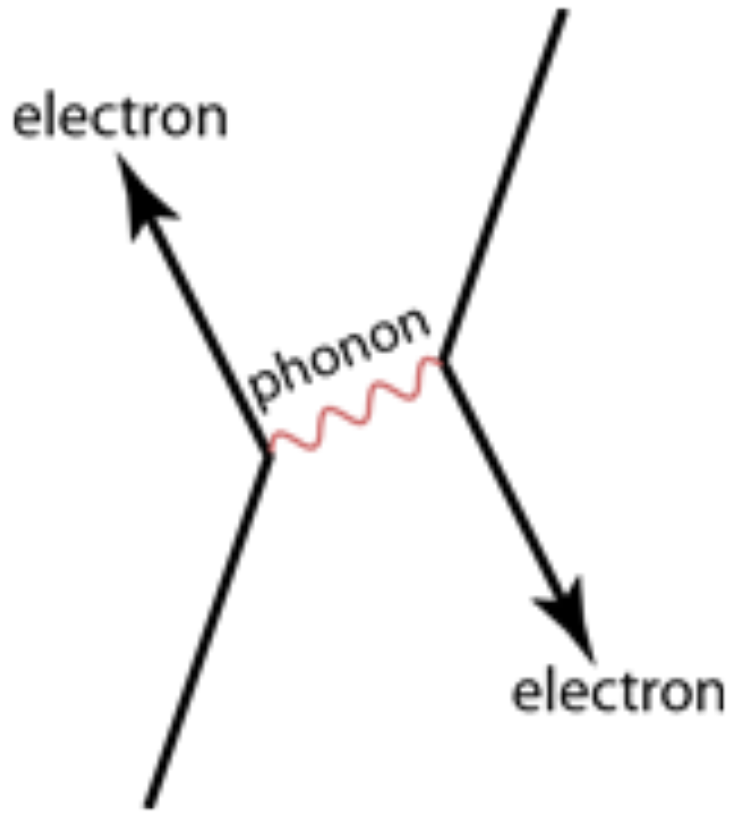


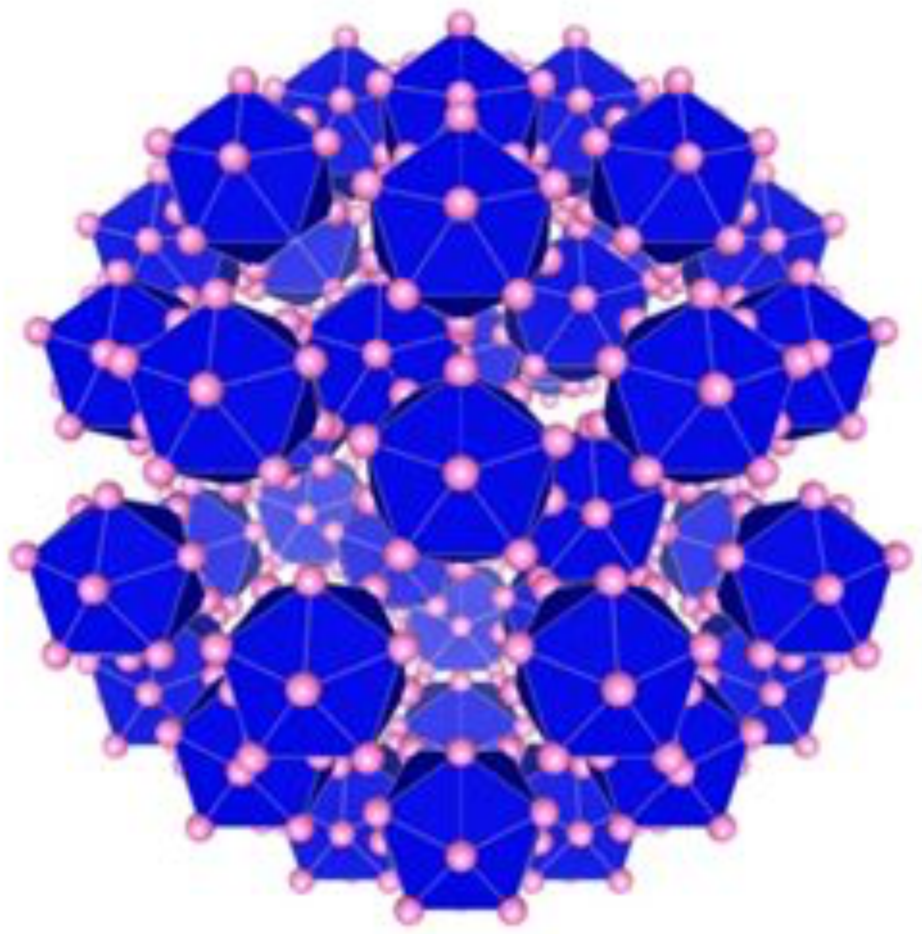
Another electron passing in the opposite direction is attracted to that displacement

constitutes a coupling between electrons



Unlike single electrons, which are fermions, Cooper pairs are bosons and so condense at low temperatures to form a superconductor

#10 Superconductivity spotted in a quasicrystal

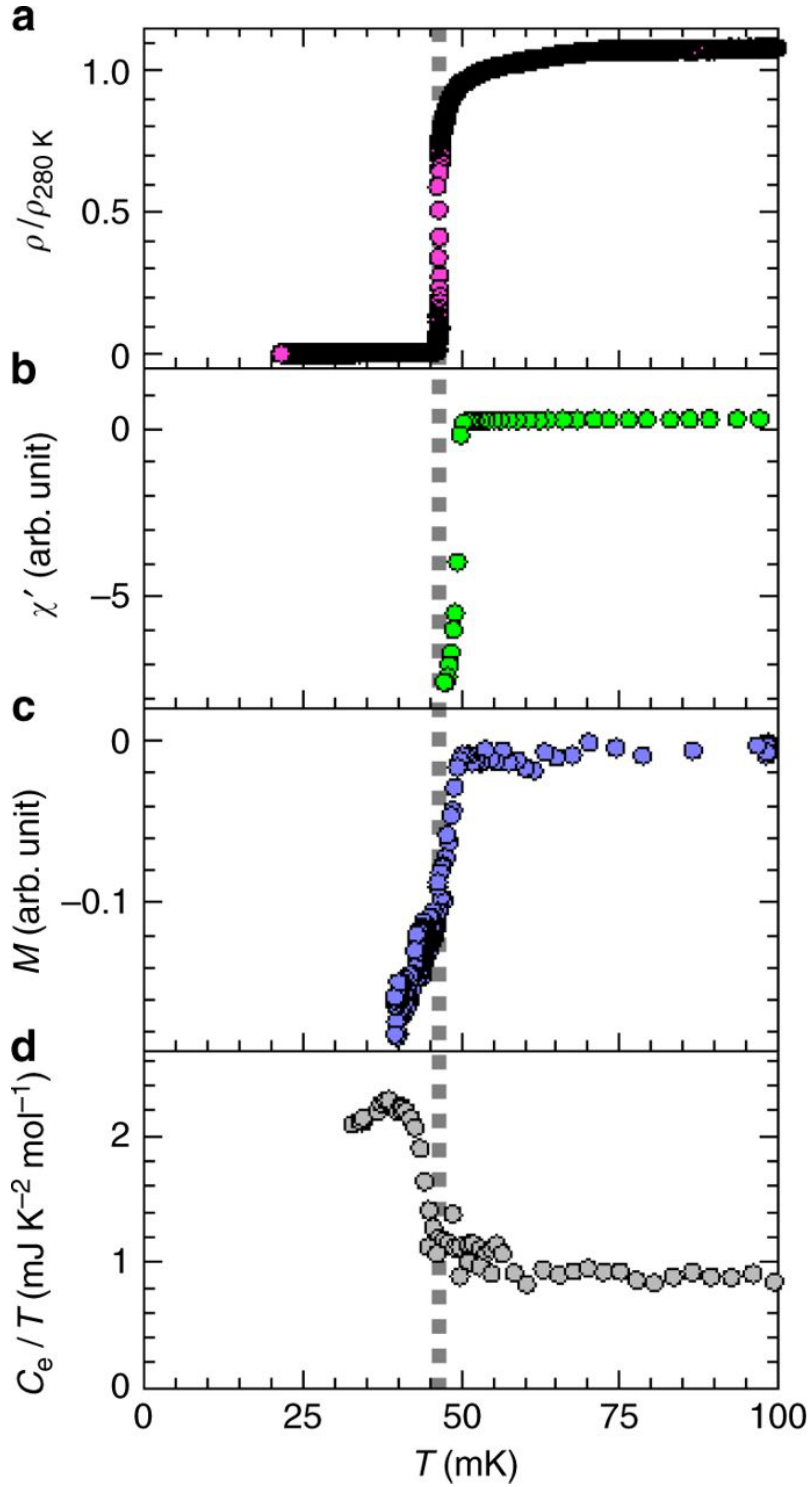


normalized electrical resistivity

real part of the ac magnetic susceptibility

dc magnetization at external magnetic field of approximately 4 mOe

the electronic part of the specific heat divided by temperature



Discovery of superconductivity in quasicrystal
Kamiya, et al., *Nature Communications* **9**, 154 (2018)

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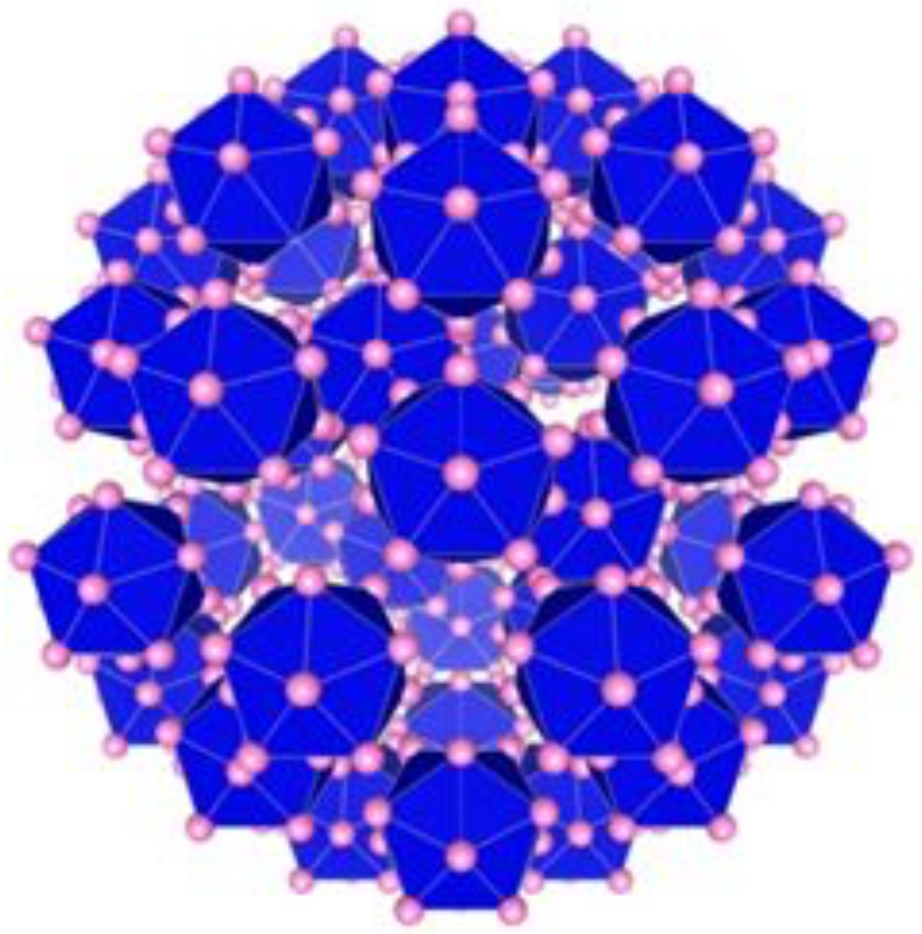


formation of Cooper pairs arises from *weak*-coupling of electrons

might be "dirty superconductivity" that occurs in imperfect crystals

might be "fractal superconductivity" predicted for quasicrystals

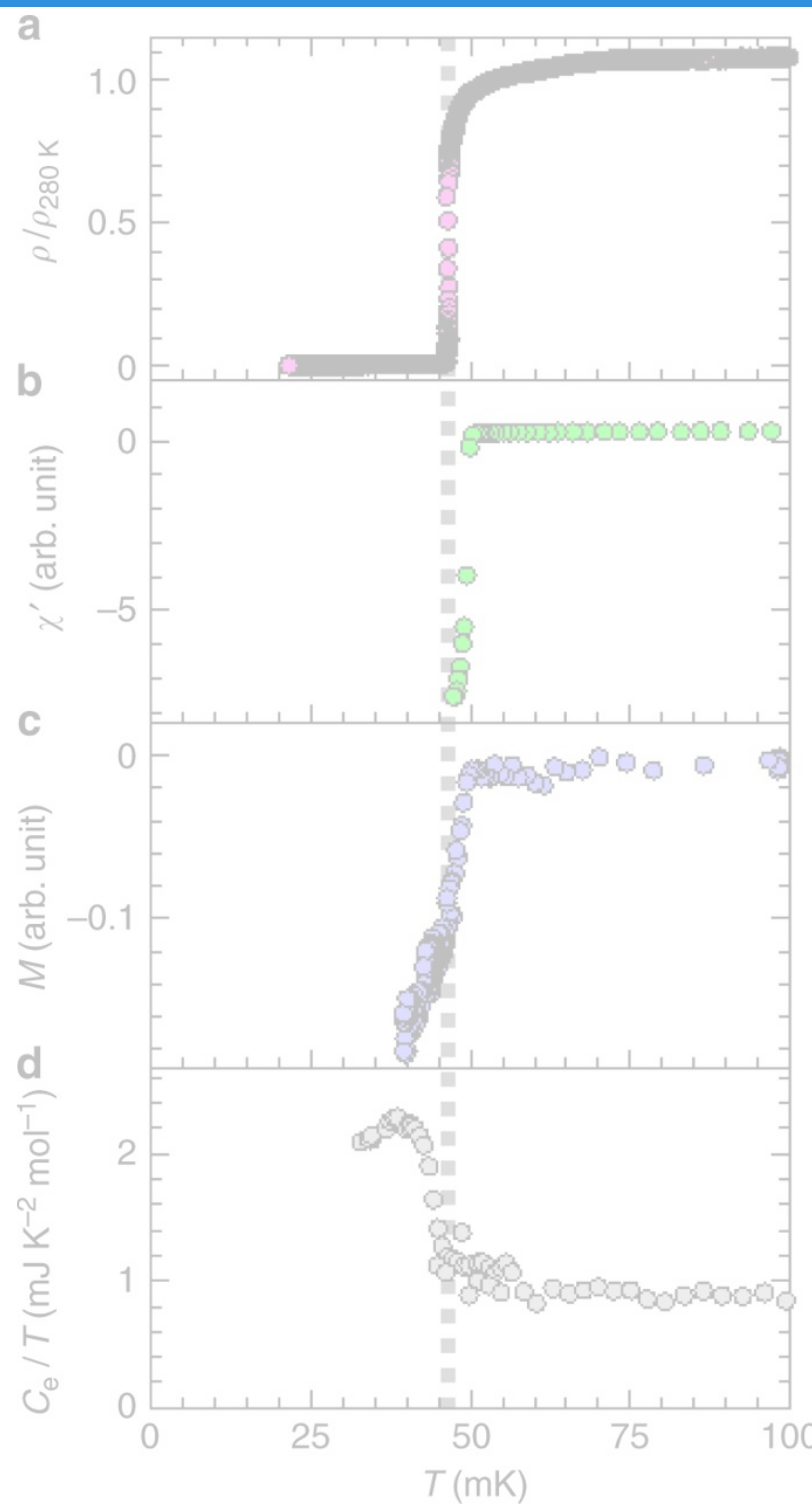
new area of superconductivity: interplay fractal geometry and weak coupling of electron pairs

normalized electrical resistivity

real part of the ac magnetic susceptibility

dc magnetization at external magnetic field of approximately 4 mOe

the electronic part of the specific heat divided by temperature



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Thank you!