Emergent phenomena in quantum (matter-light) systems

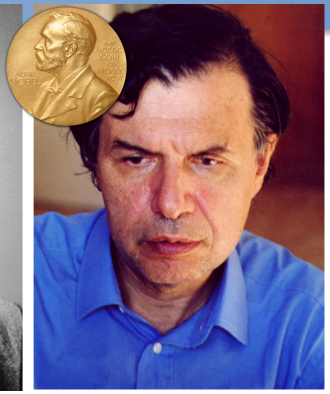
Francesca Maria Marchetti

UAM Universidad Autónoma de Madrid

IFiMaC

Trajectory



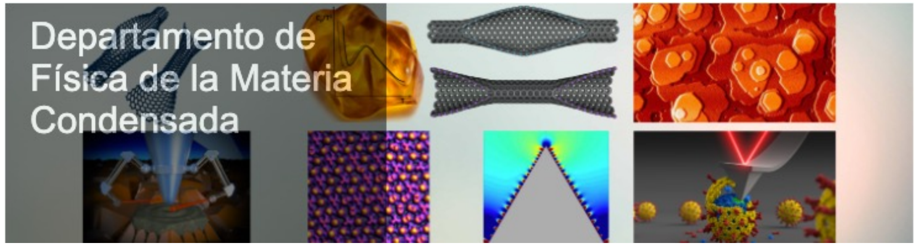
- 1998 Degree in Theoretical Physics
  University of Rome “La Sapienza”

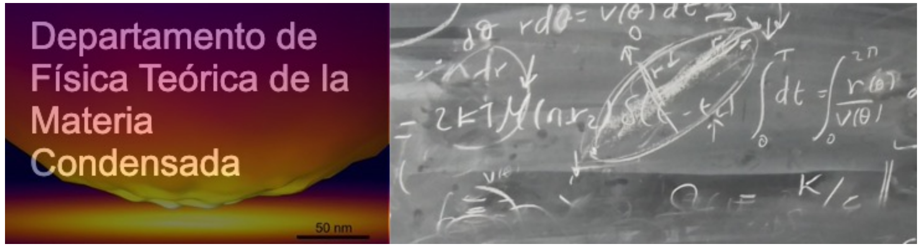
- 2002 PhD in Physics
  Scuola Normale Superiore, Pisa
- 2002-2006 Post-doc & EPSRC Fellow
  University of Cambridge
- 2006-2008 Post-doc & EPSRC Advanced Fellow
  University of Oxford
- 2008-... Ramón y Cajal Fellow & A/Prof. UAM / IFiMaC

theory of
condensed matter

Physics @IFiMaC – Condensed Matter Physics Center

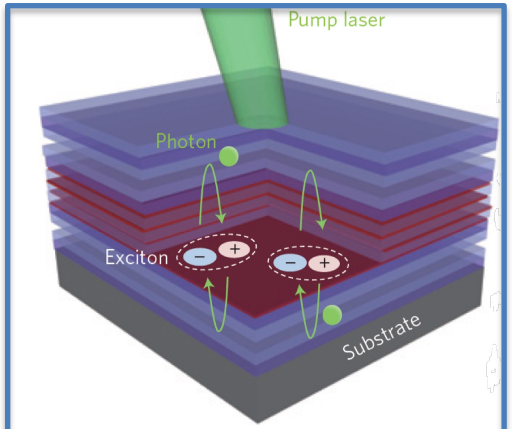
EXCELENCIA MARÍA DE MAEZTU



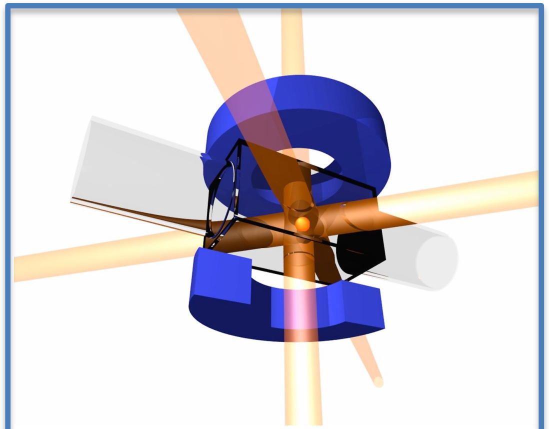


- ▷ Quantum Optics
- ▷ Advanced materials
- ▷ First principles simulations and modelling
- ▷ Nanophysics
- ▷ Soft condensed matter & biophysics

- I am a theorist, and my research focuses on



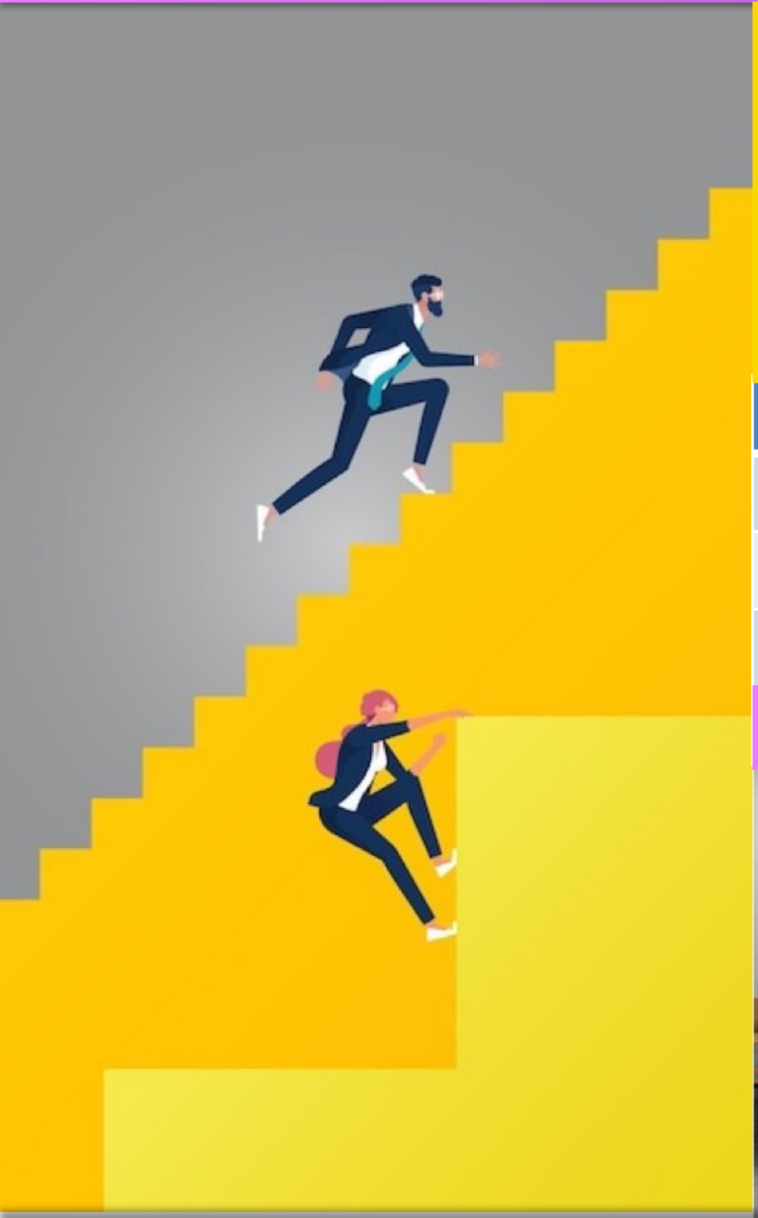
solid state systems



ultracold atoms

Collective phenomena in strongly correlated systems, macroscopic phase coherence, superfluidity in and out of equilibrium, ...

Programa de Mentoría @IFIMAC para estudiantes de física @UAM

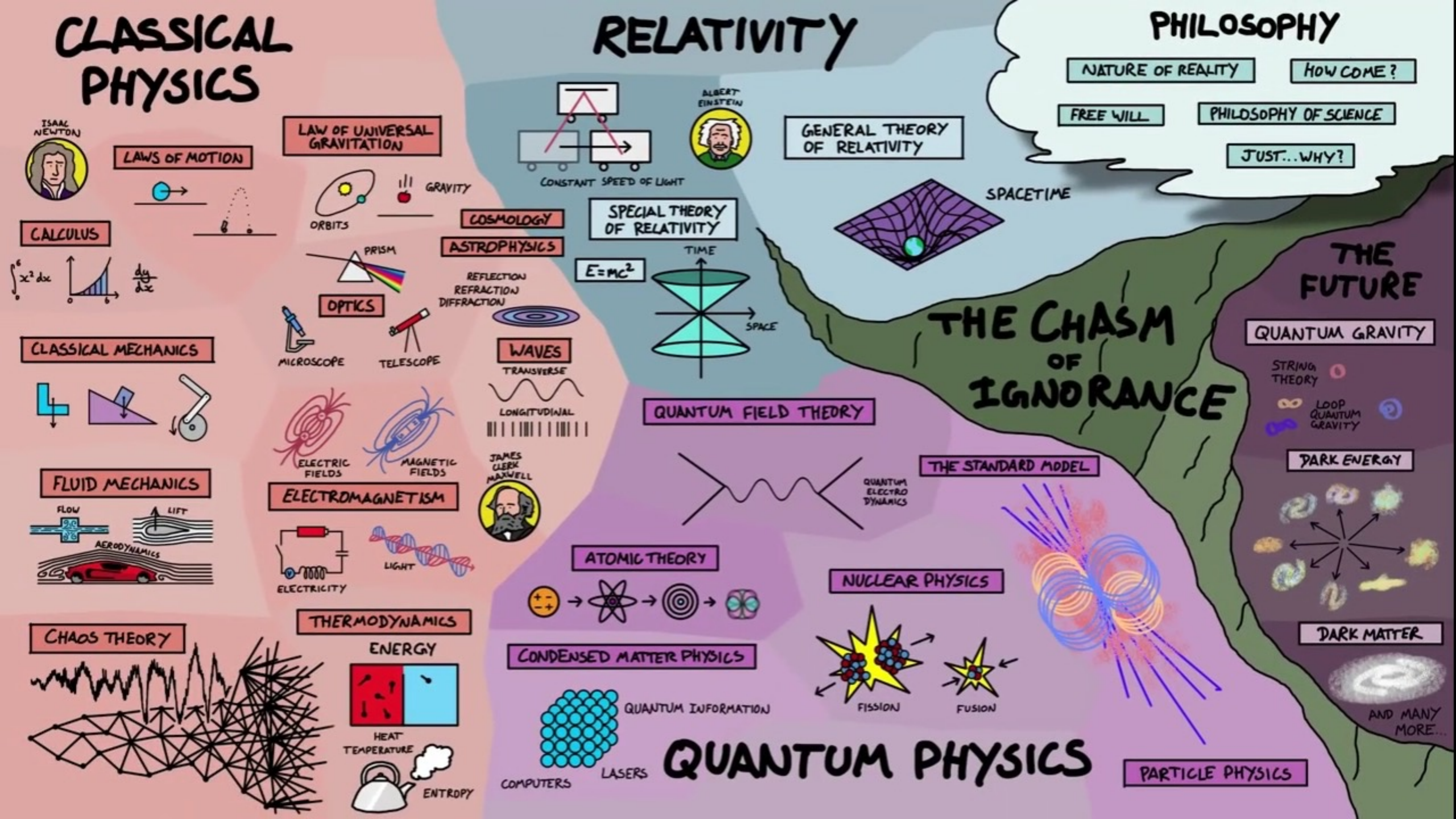


- it provides female role models
- it raises awareness & empowers mentors
- it establishes a network for women in academia.

	Mentors ⚦	mentees
2022-2023	34 (30% ♀)	34
2023-2024	38 (40% ♀)	38
2024-2025	41 (39% ♀)	41

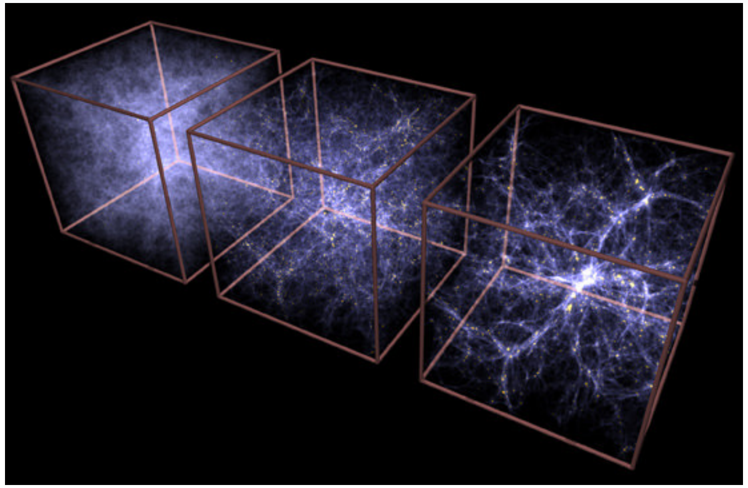
https://www.ifimac.uam.es/mentoring-24-25/

What is condensed matter physics?

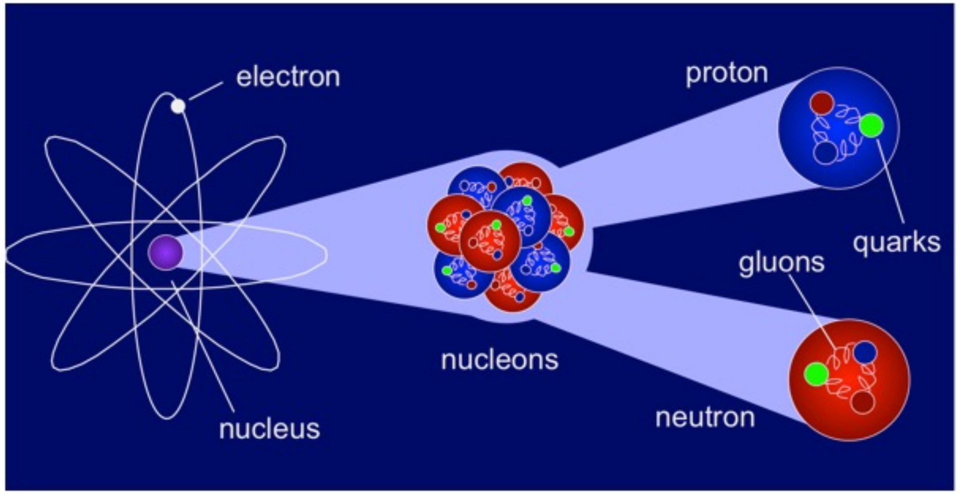

CLASSICAL PHYSICS
ISAAC NEWTON
LAWS OF MOTION
LAW OF UNIVERSAL GRAVITATION
CALCULUS
ORBITS
GRAVITY
COSMOLOGY
ASTROPHYSICS
PRISM
OPTICS
REFLECTION
REFRACTION
DIFFRACTION
MICROSCOPE
TELESCOPE
CLASSICAL MECHANICS
WAVES
TRANSVERSE
LONGITUDINAL
ELECTRIC FIELDS
MAGNETIC FIELDS
JAMES CLERK MAXWELL
FLUID MECHANICS
FLOW
LIFT
AERODYNAMICS
ELECTROMAGNETISM
ELECTRICITY
LIGHT
CHAOS THEORY
THERMODYNAMICS
ENERGY
HEAT
TEMPERATURE
ENTROPY
RELATIVITY
CONSTANT SPEED OF LIGHT
ALBERT EINSTEIN
GENERAL THEORY OF RELATIVITY
SPECIAL THEORY OF RELATIVITY
E=mc²
TIME
SPACE
SPACETIME
PHILOSOPHY
NATURE OF REALITY
HOW COME?
FREE WILL
PHILOSOPHY OF SCIENCE
JUST...WHY?
THE CHASM OF IGNORANCE
THE FUTURE
QUANTUM GRAVITY
STRING THEORY
LOOP QUANTUM GRAVITY
DARK ENERGY
DARK MATTER
AND MANY MORE...
QUANTUM FIELD THEORY
QUANTUM ELECTRO DYNAMICS
THE STANDARD MODEL
ATOMIC THEORY
NUCLEAR PHYSICS
CONDENSED MATTER PHYSICS
FISSION
FUSION
QUANTUM INFORMATION
COMPUTERS
LASERS
QUANTUM PHYSICS
PARTICLE PHYSICS

Three infinities in physics *[J. Dalibard]*

- Infinitely big (structure of the Universe)

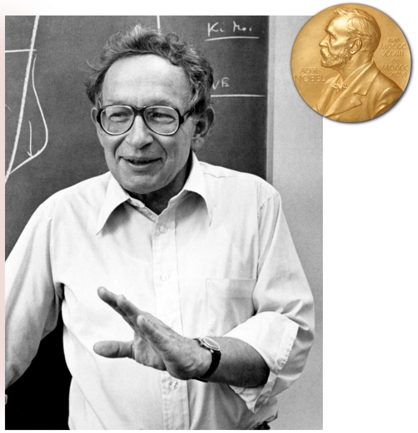


- Infinitely small (elementary particles)



- Infinitely complex
  - ⇒ condensed matter physics, a way to enter this realm!
  - ⇒ **cut a complex material apart to its smallest constituents not always the best strategy!**

- Quantum & classical many-body systems



"More is different" [P.W. Anderson]

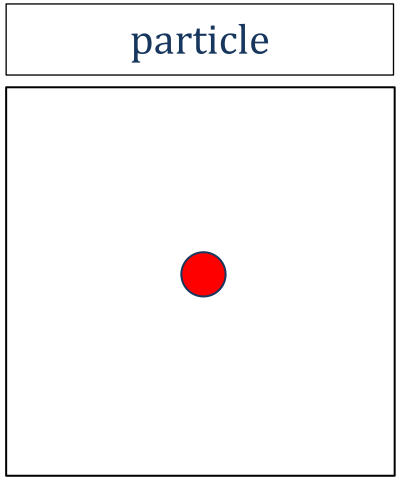
Emergence

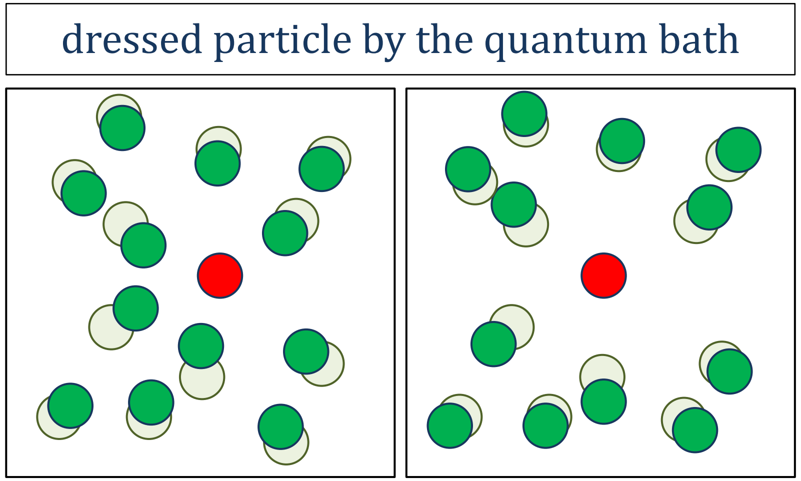
Emergence

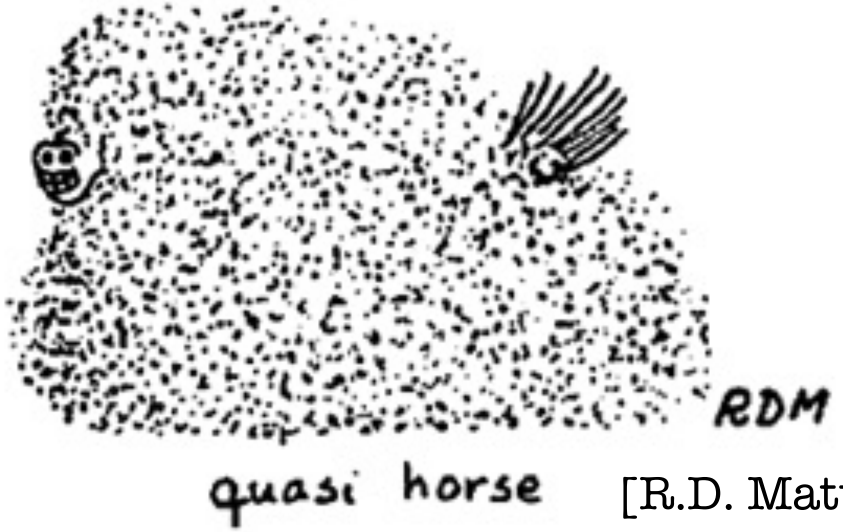
Emergent behaviour in quantum systems

Quasiparticles

- Excitation of a multi-particle system with particle dispersion: dressed particle

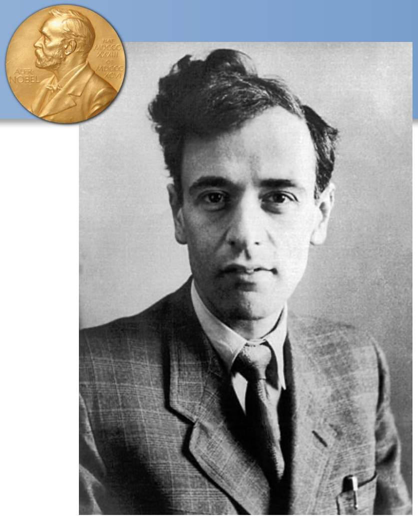






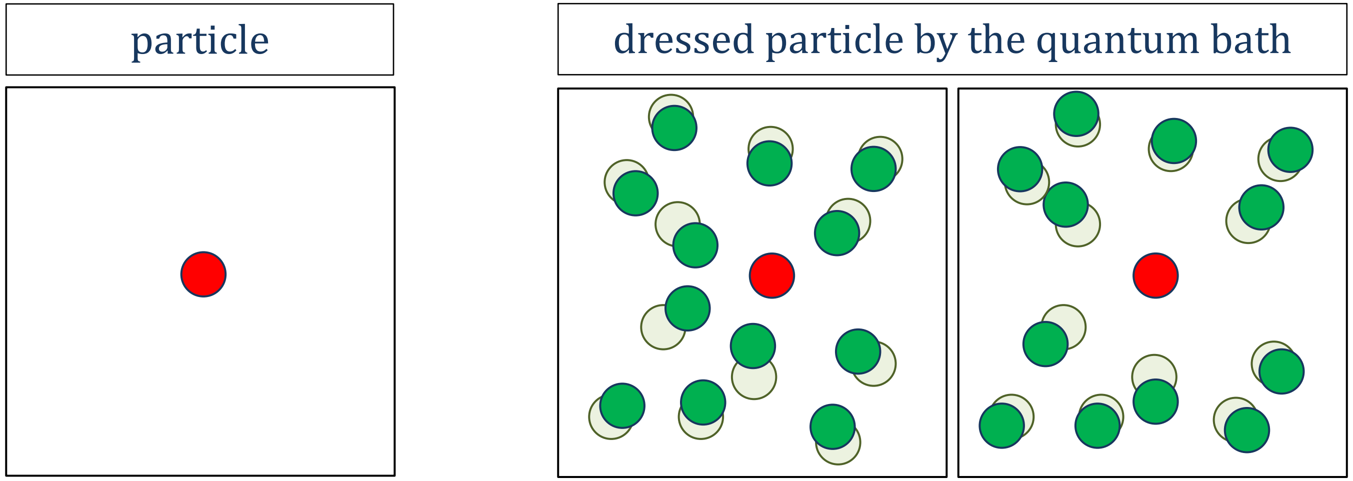
[R.D. Mattuck]

Quasiparticles and the impurity problem (polaron)



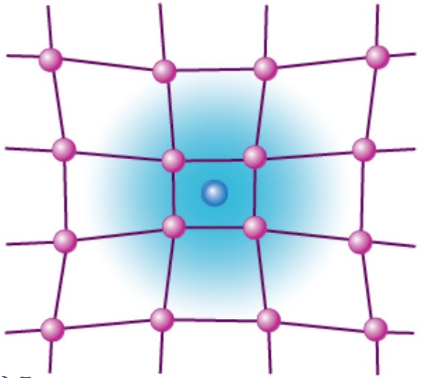
[L. Landau]

- Excitation of a multi-particle system with particle dispersion: dressed particle



Landau (1933) & Pekar (1946)

Fröhlich (1950)

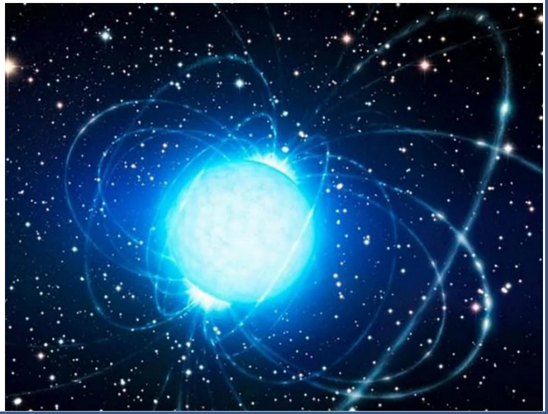


[Chevy Physics (2016)]

~90 years of polaron history!

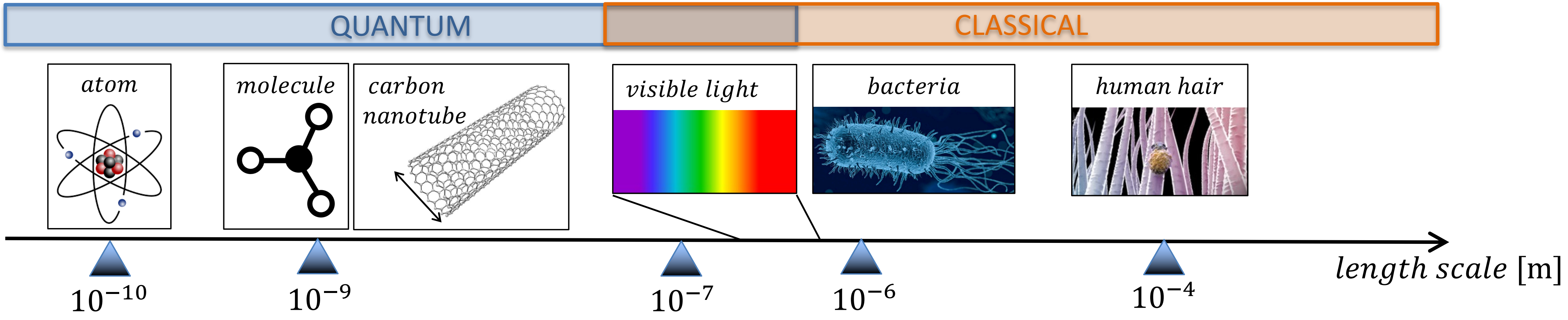
Multiple realisations

▷ ... proton impurity in a neutron star!



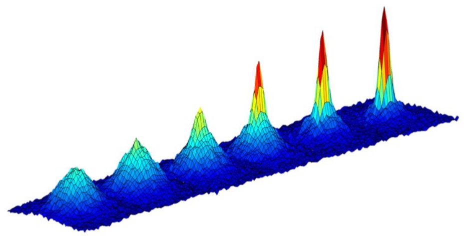
Other examples of emergent behaviour in quantum matter

- Quantum collective behaviour at "macro" scales?

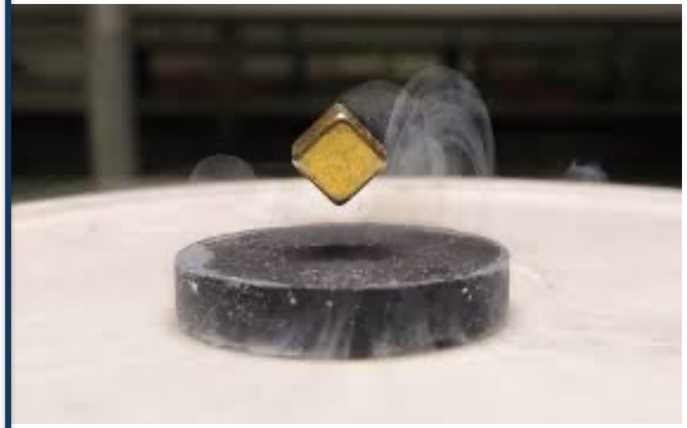


- Collective macroscopic quantum phase coherence

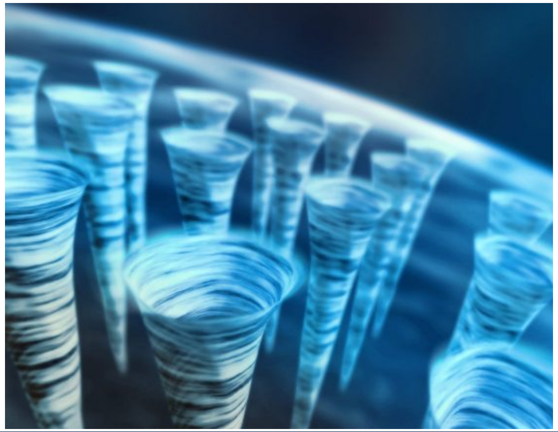
Condensados atómicos de Bose-Einstein



Superconductores



Superfluidos



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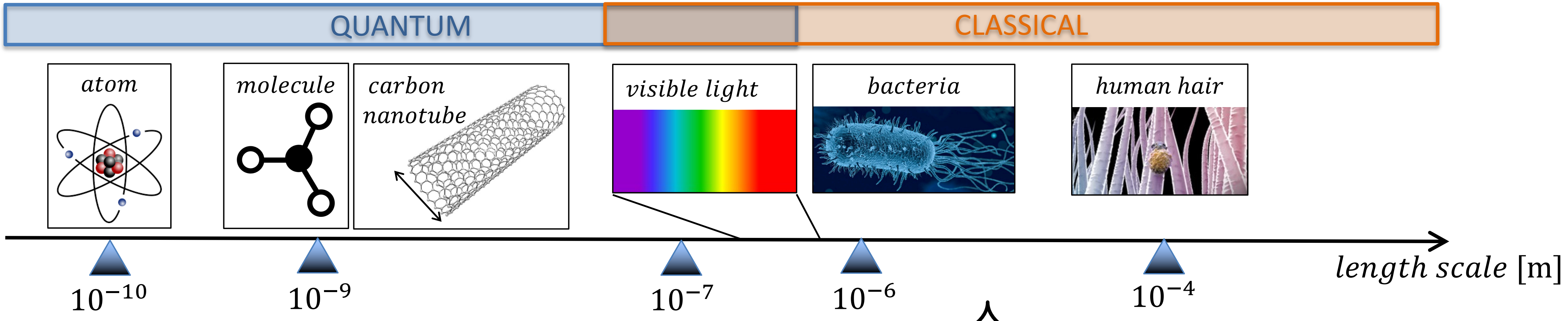
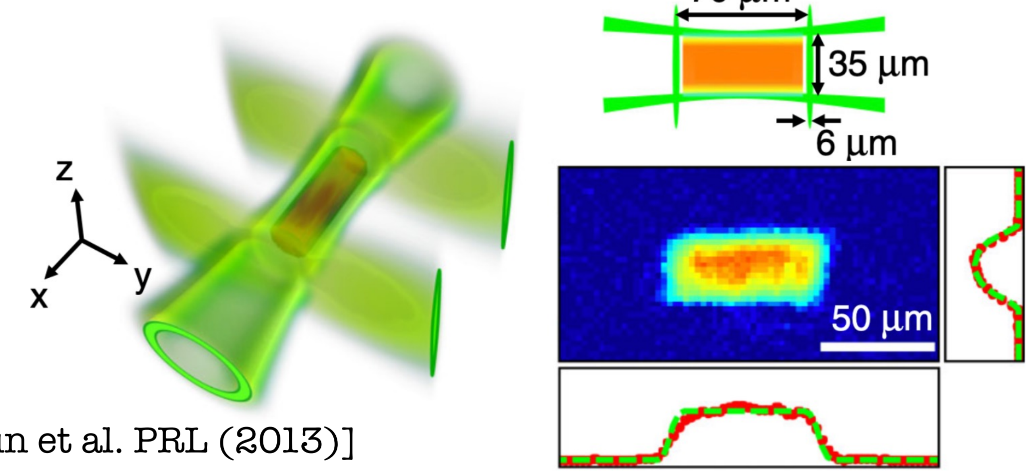


- Collective macroscopic quantum phase coherence

Bose-Einstein condensation



[Gaun et al. PRL (2013)]

$N \sim 10^6$ *atoms*

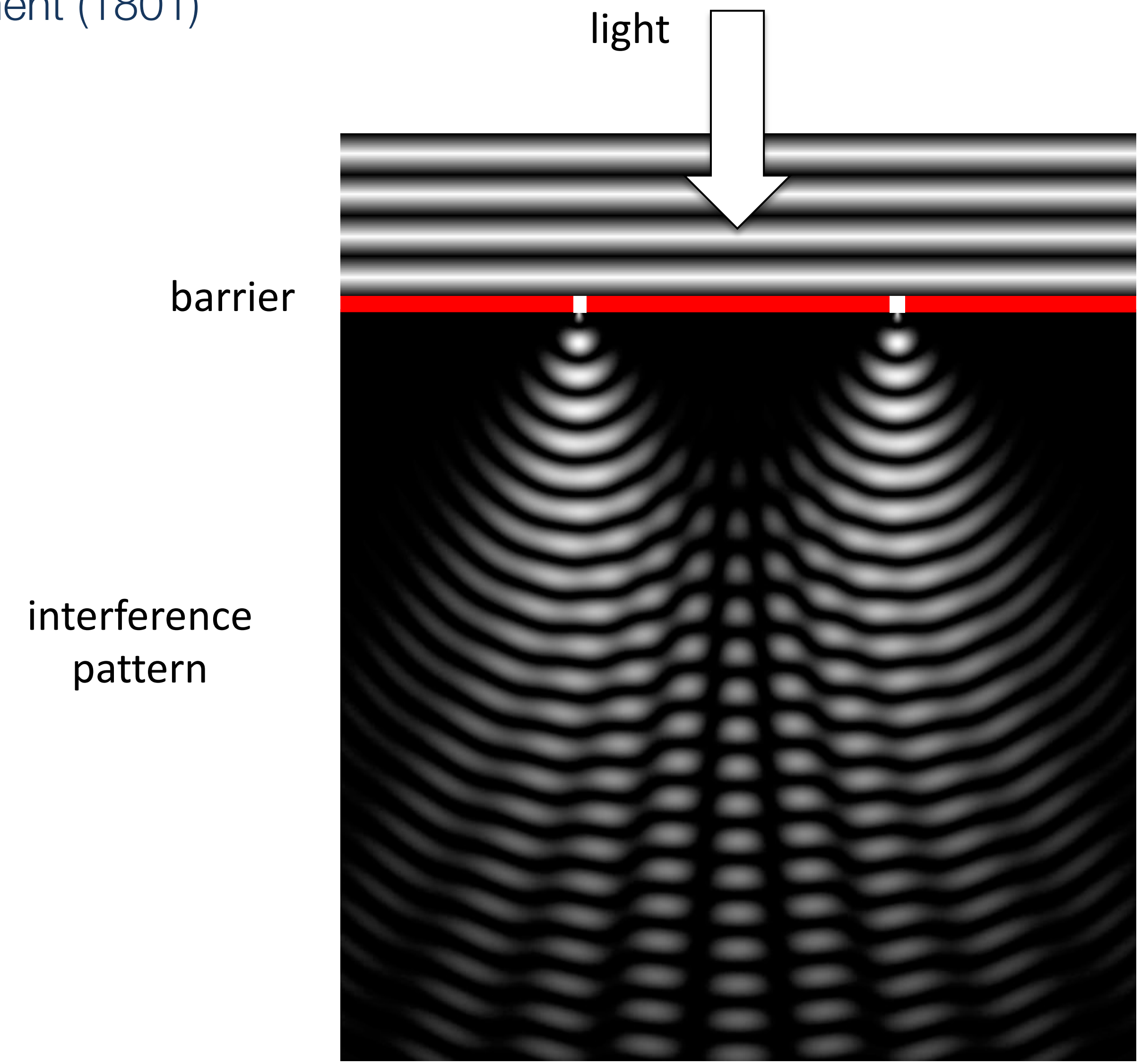
$n \sim 10^{12}$ cm^{-3}

$T \sim 100$ nK

coolest systems in the universe

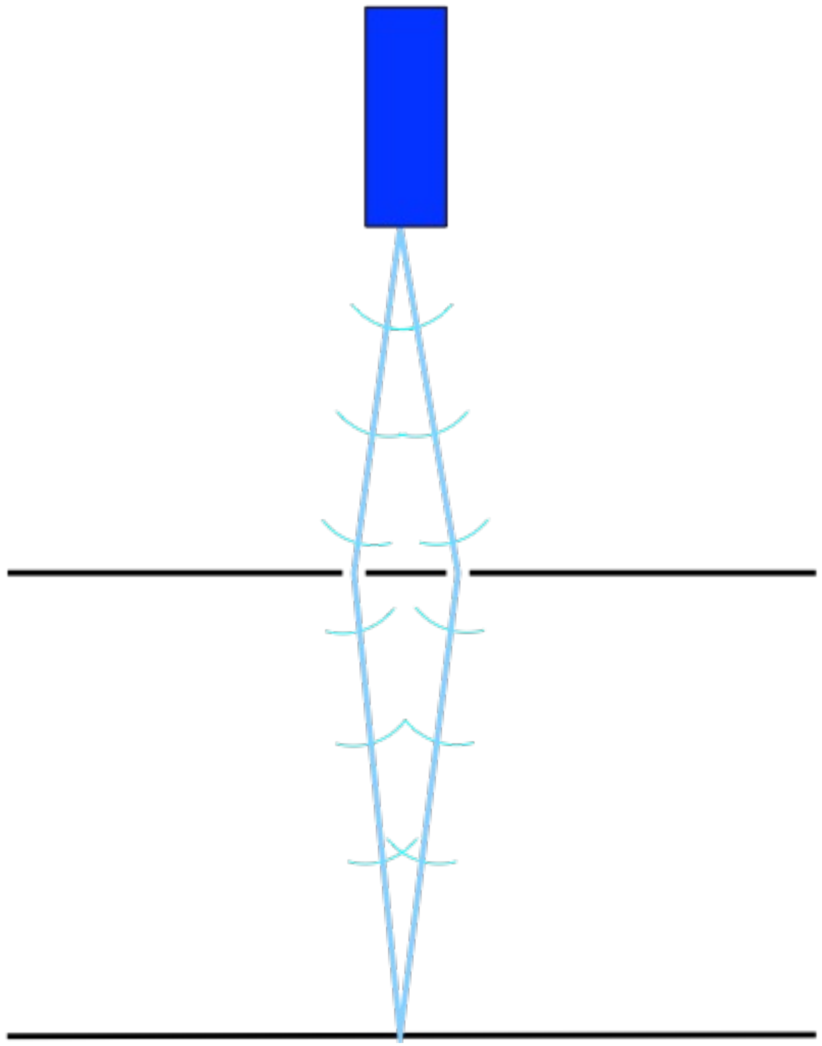
Light interference

✧ Double-slit experiment (1801)



Particles as waves

- Double-slit experiment (1801)
- With particles (e.g., electrons) (1961)



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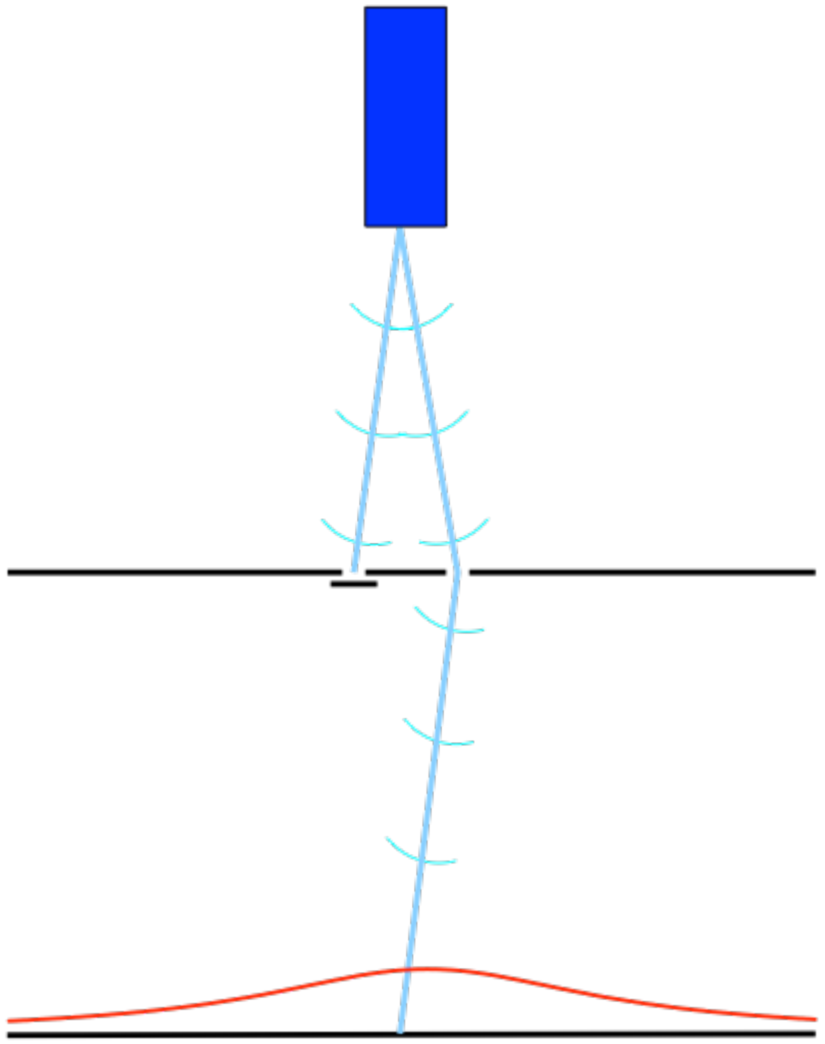

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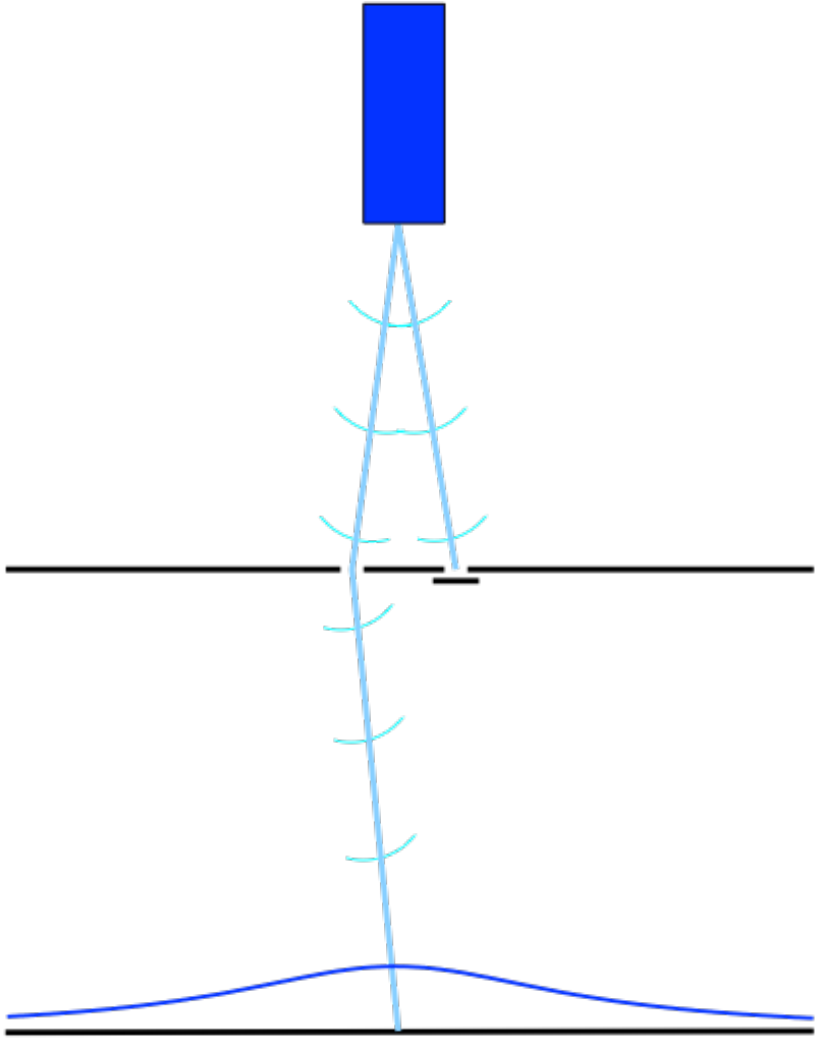

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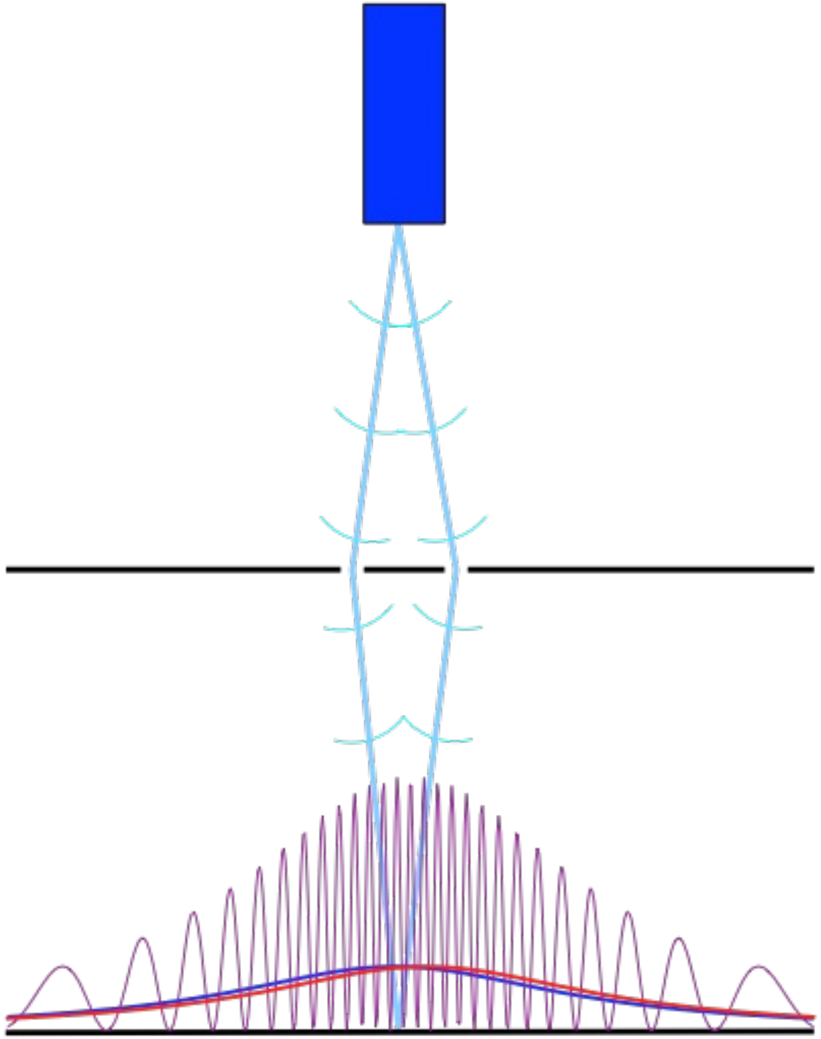

the electron is interfering with itself

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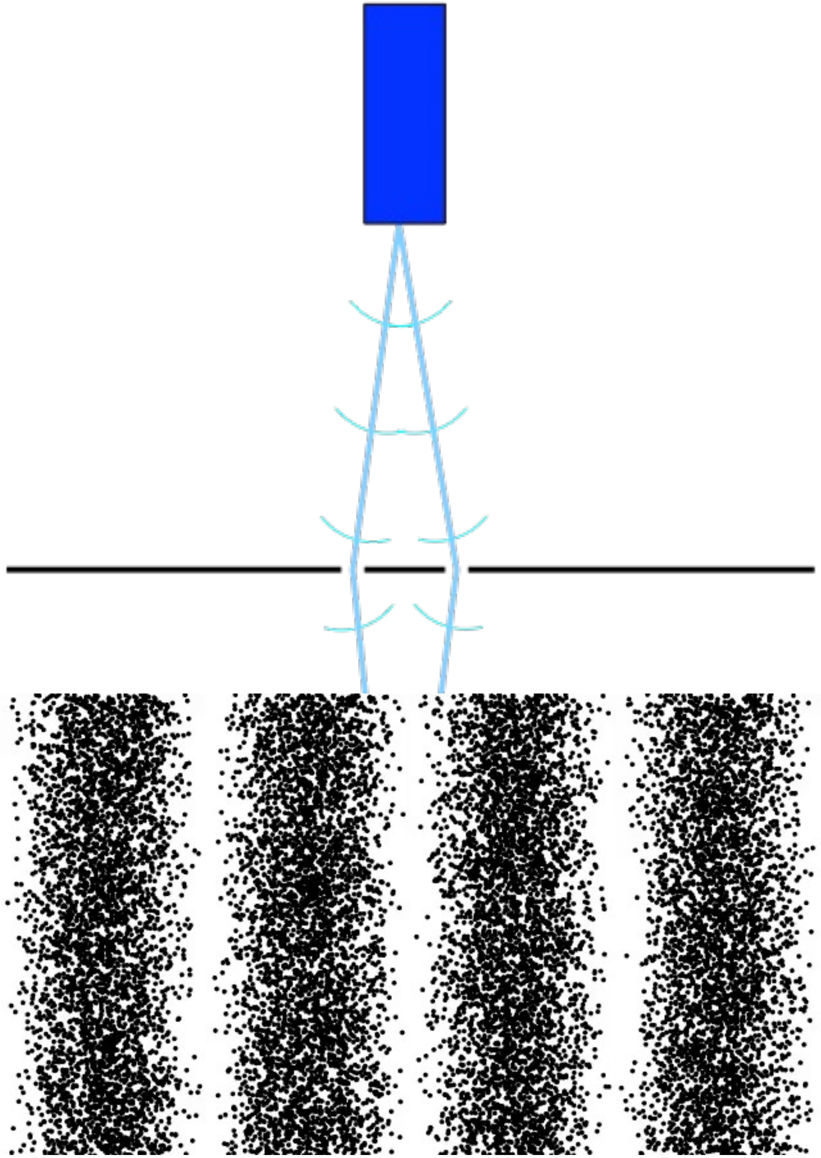
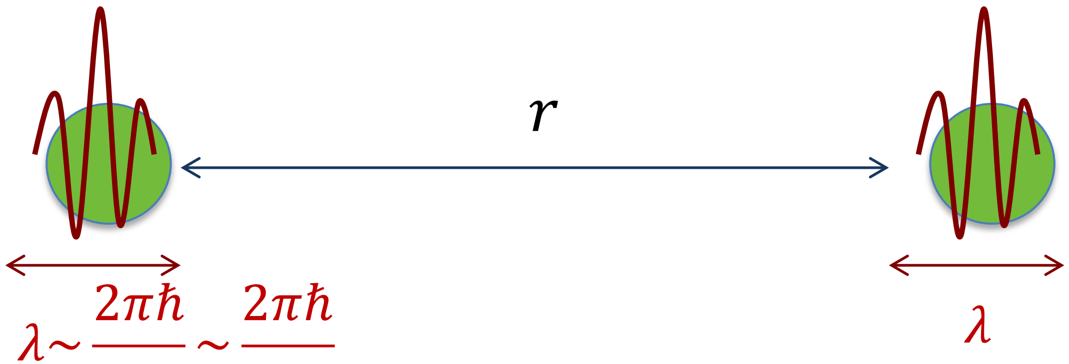


the electron is interfering with itself

Dualidad onda-partícula

- ¿A qué escala de longitud se manifiestan las propiedades ondulatorias (cuánticas) de las partículas?



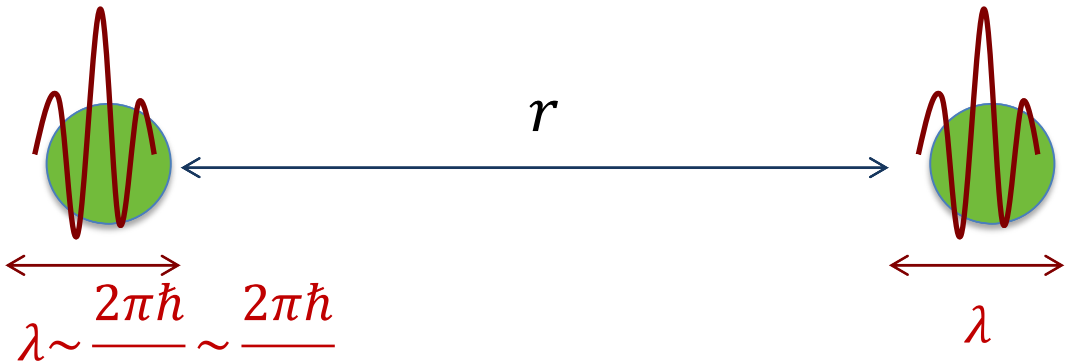
$$\lambda \sim \frac{2\pi\hbar}{p} \sim \frac{2\pi\hbar}{mv}$$

Dualidad onda-partícula

- ¿A qué escala de longitud se manifiestan las propiedades ondulatorias (cuánticas) de las partículas?

> ▷ pelota de tenis $m = 60\ \mathrm{g}$
> $v = 10\ \mathrm{ms}^{-1}$
> $\lambda \sim 10^{-33}\ \mathrm{m}$

> ▷ electrón en un metal $\lambda \sim 10^{-8}\ \mathrm{m} = 10\ \mathrm{nm}$



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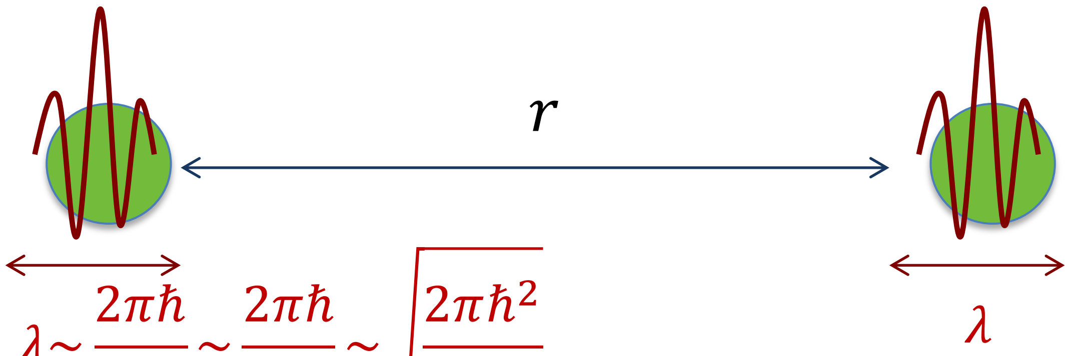
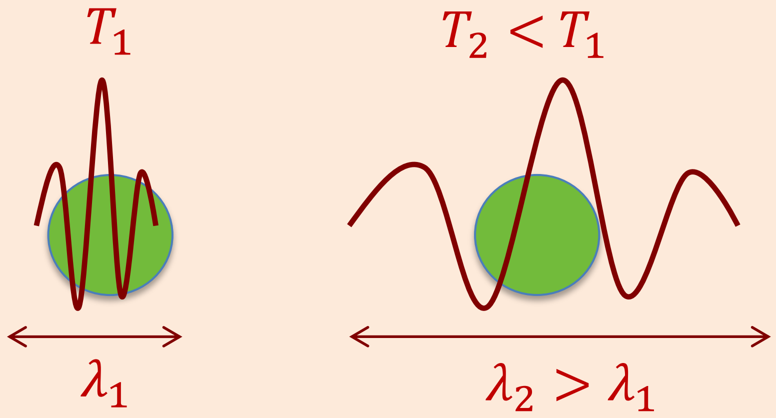


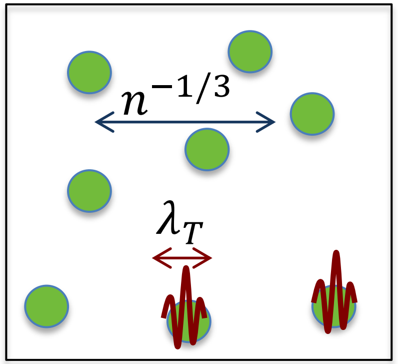
$$\lambda \sim \frac{2\pi\hbar}{p} \sim \frac{2\pi\hbar}{mv} \sim \sqrt{\frac{2\pi\hbar^2}{mT}}$$

- ¿A qué temperaturas?



Quantum at macro scales?

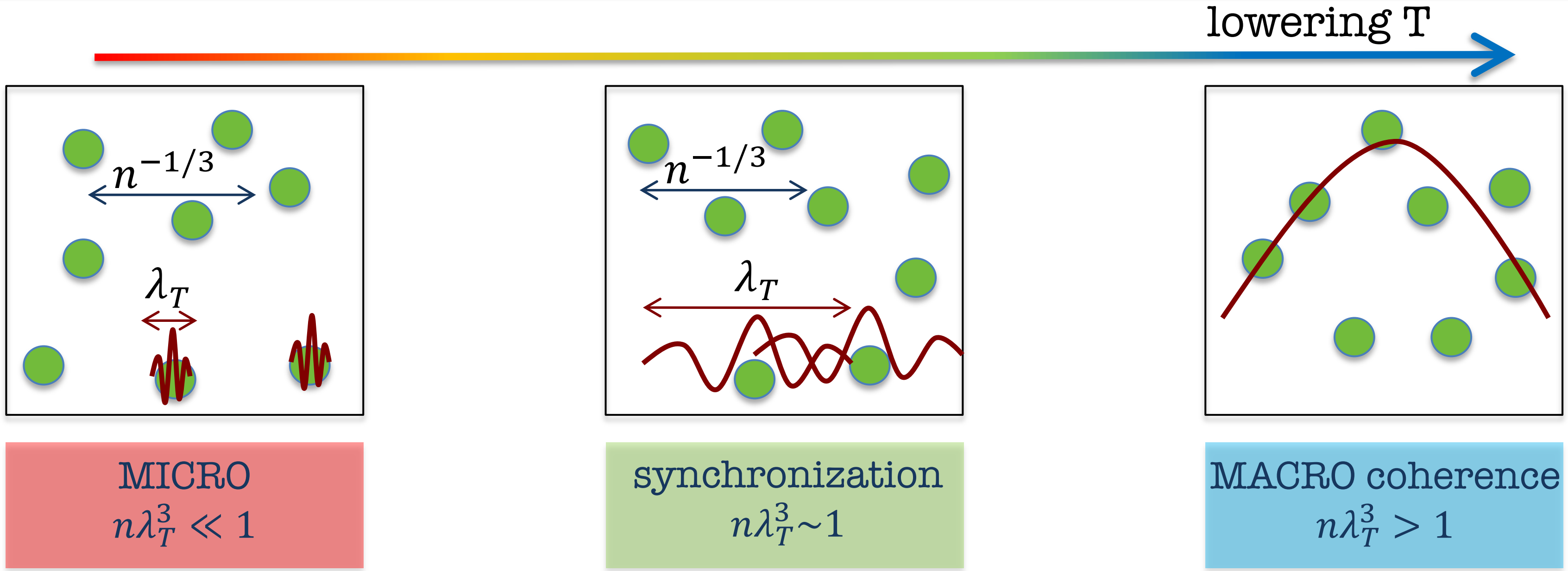
$$\lambda_T = \frac{2\pi\hbar}{p}$$



MICRO
$n\lambda_T^3 \ll 1$

Quantum at macro scales? Quantum condensates

$$\lambda_T = \frac{2\pi\hbar}{p}$$



Quantum at macro scales? Quantum condensates

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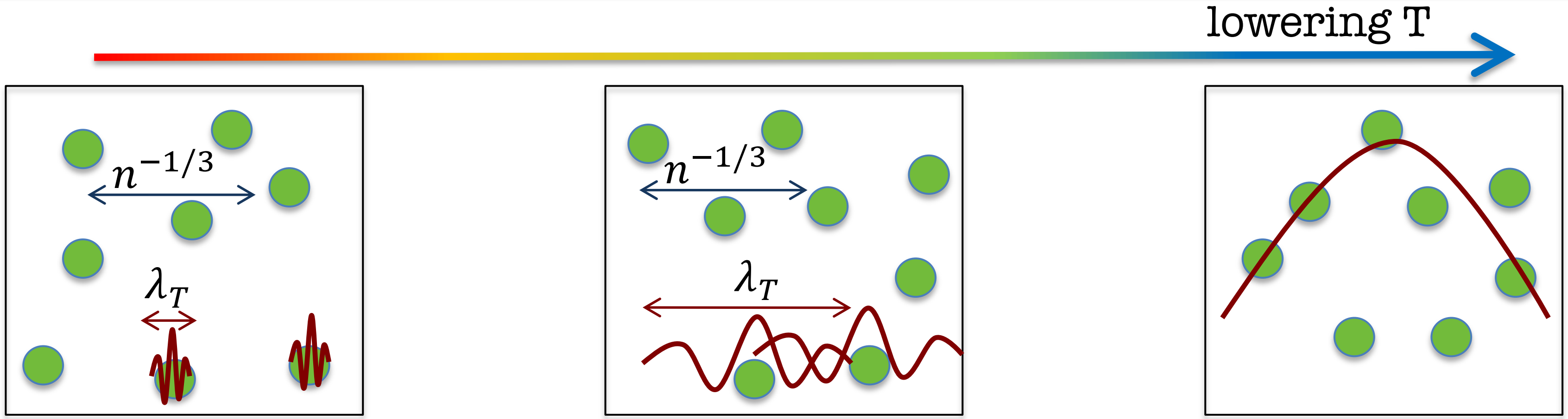
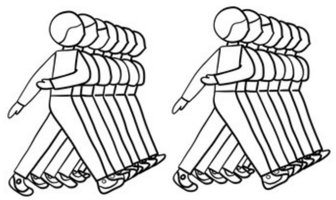
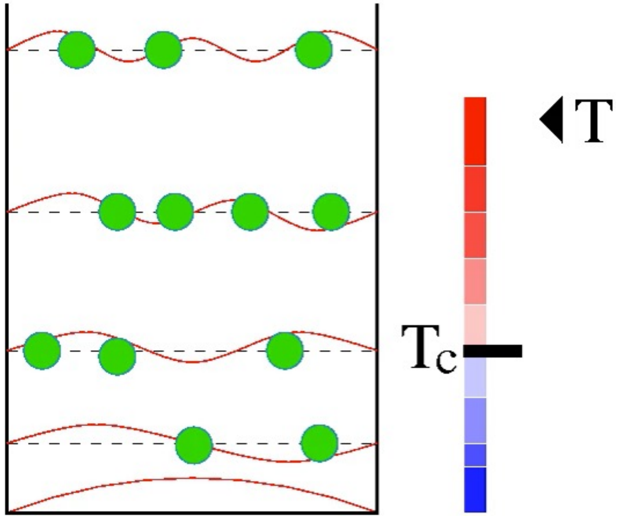




MICRO	synchronization	MACRO coherence
$n\lambda_T^3 \ll 1$	$n\lambda_T^3 \sim 1$	$n\lambda_T^3 > 1$

Bose-Einstein condensation

Quantum-statistical phase transition
(it occurs even in absence of interactions)

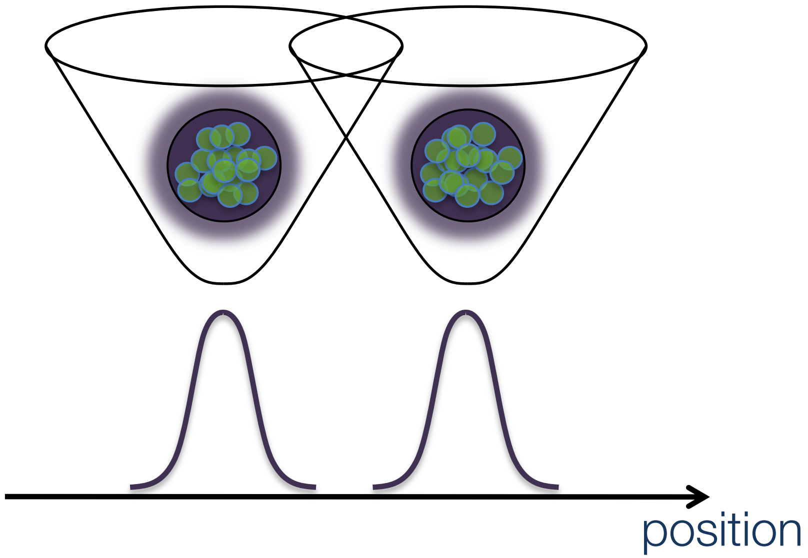


Quantum statistical syncronisation

Macroscopic quantum phase coherence

✧ The double-slit experiment with two condensates

⇒ all atoms in a single quantum state --- GIANT MATTER WAVE



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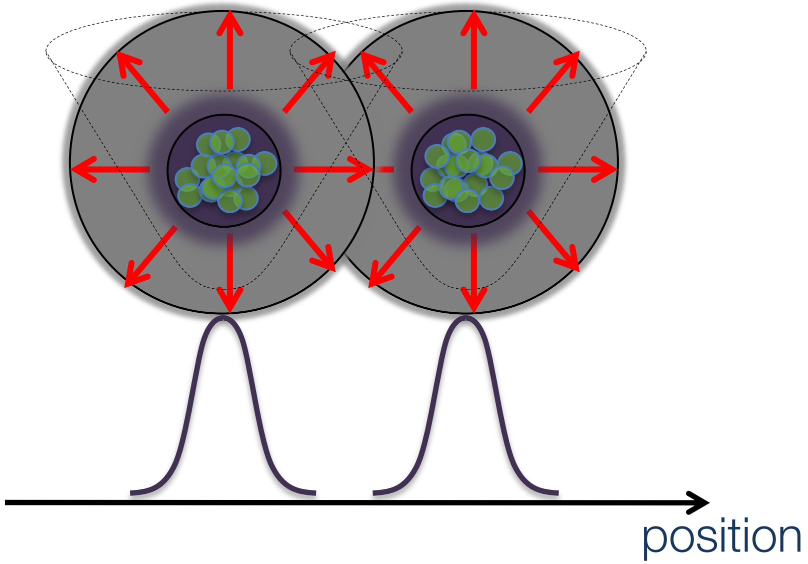

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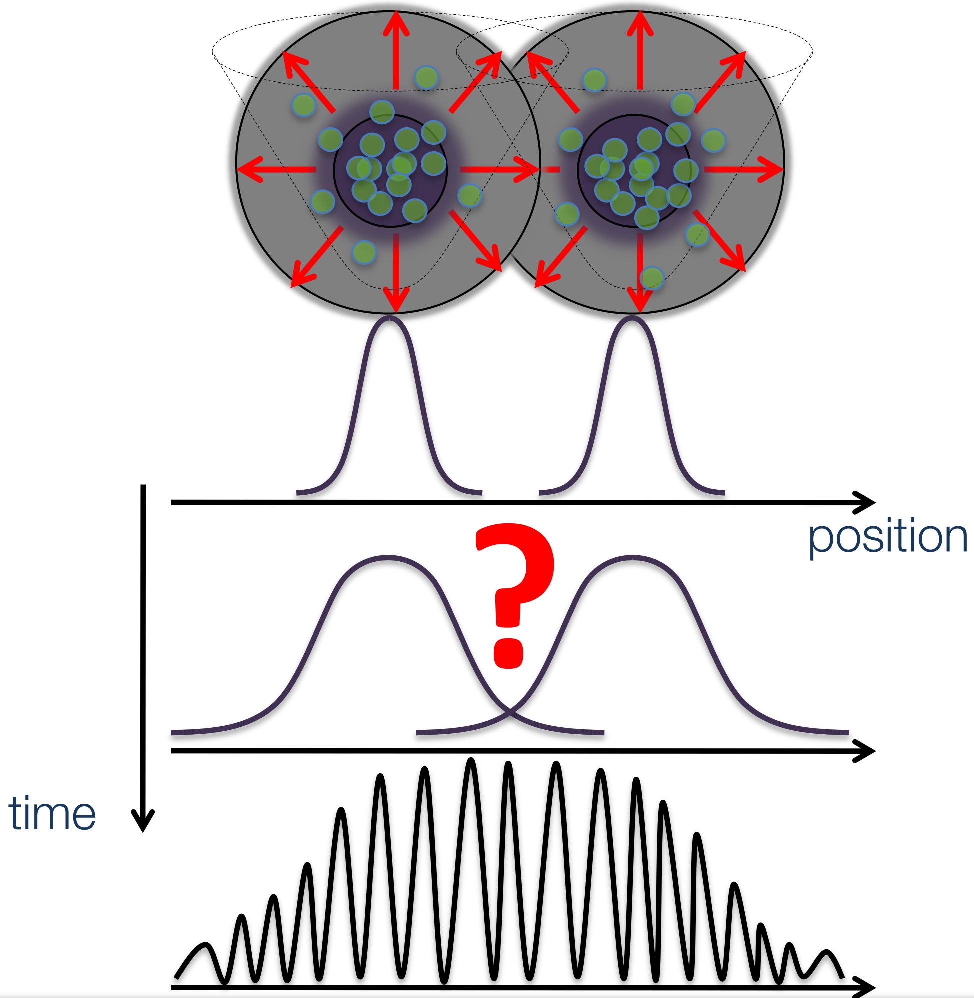

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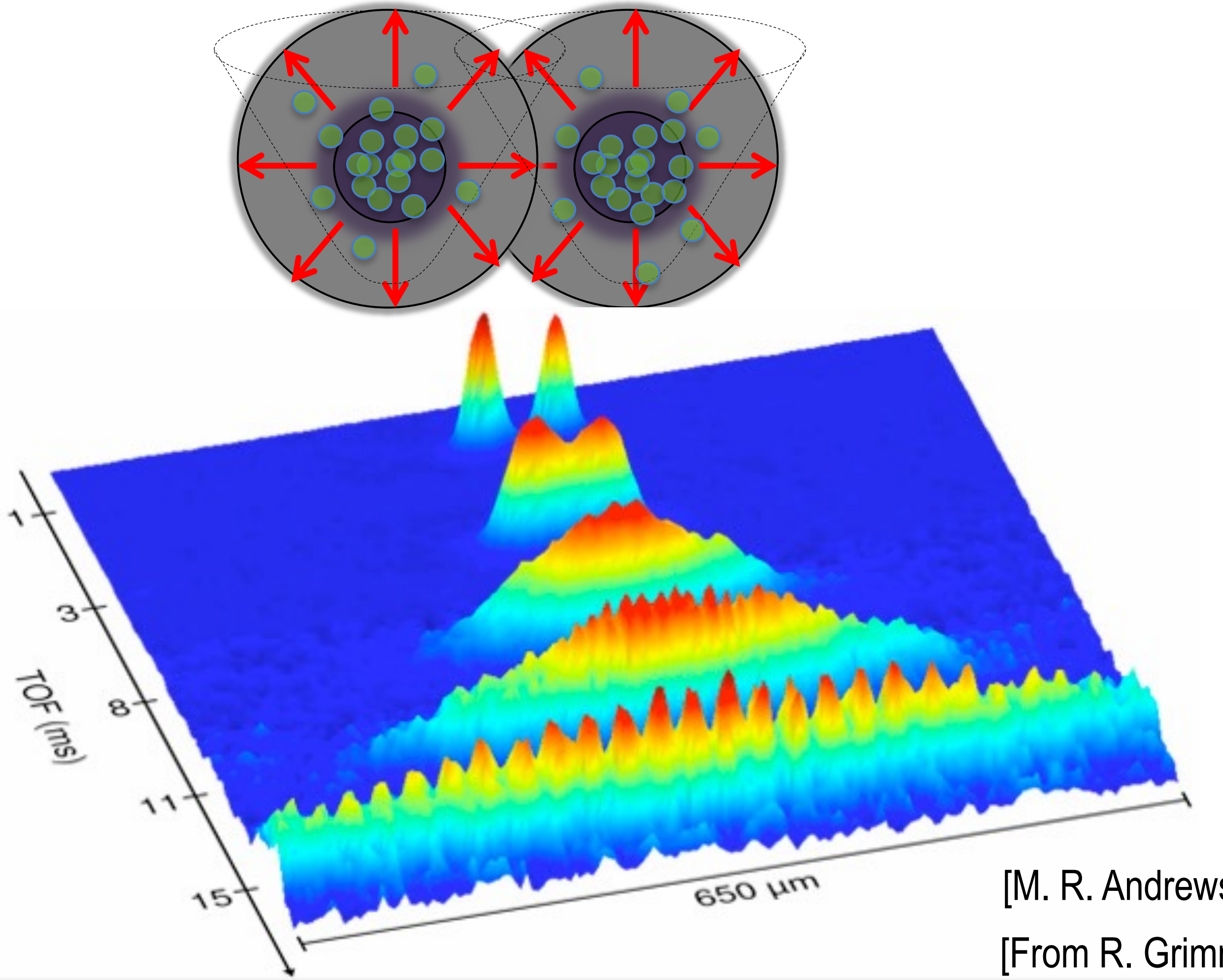


[M. R. Andrews *et al*. Science **275**, 637 (1997)]

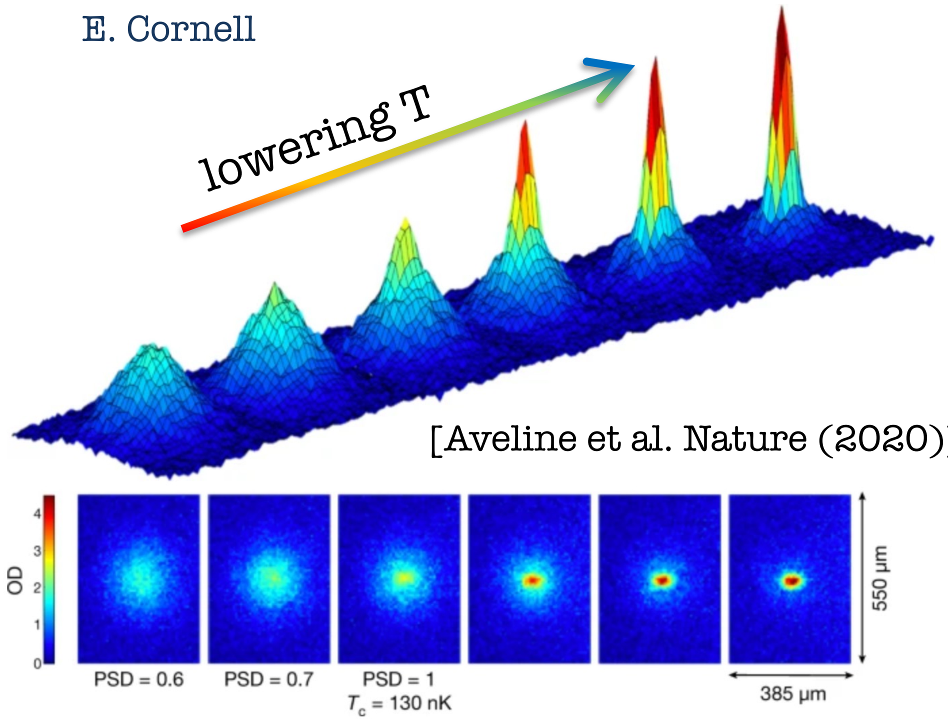
[From R. Grimm's group (recent)]

A revolutionary (& long) history of Bose-Einstein condensates

- 1924: A. Einstein
- 1995: first BEC in alkali atoms (^{87}Rb, ^{23}Na, ^{7}Li, …)
- Today
  - ▷ tuning the interactions
  - ▷ reduced dimensions
  - ▷ optical lattices
  - ▷ …→ ultracold atoms for quantum simulations
- Now on board of the ISS!!!

A. Einstein - C. Wieman & E. Cornell W. Ketterle

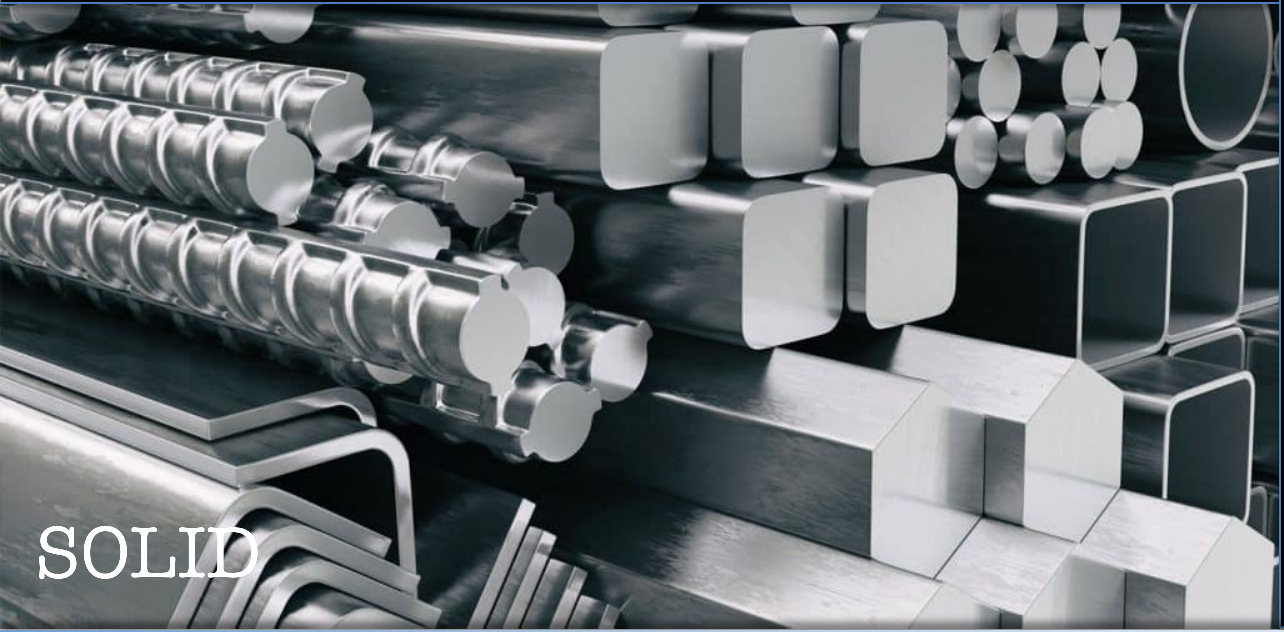
cold atom lab

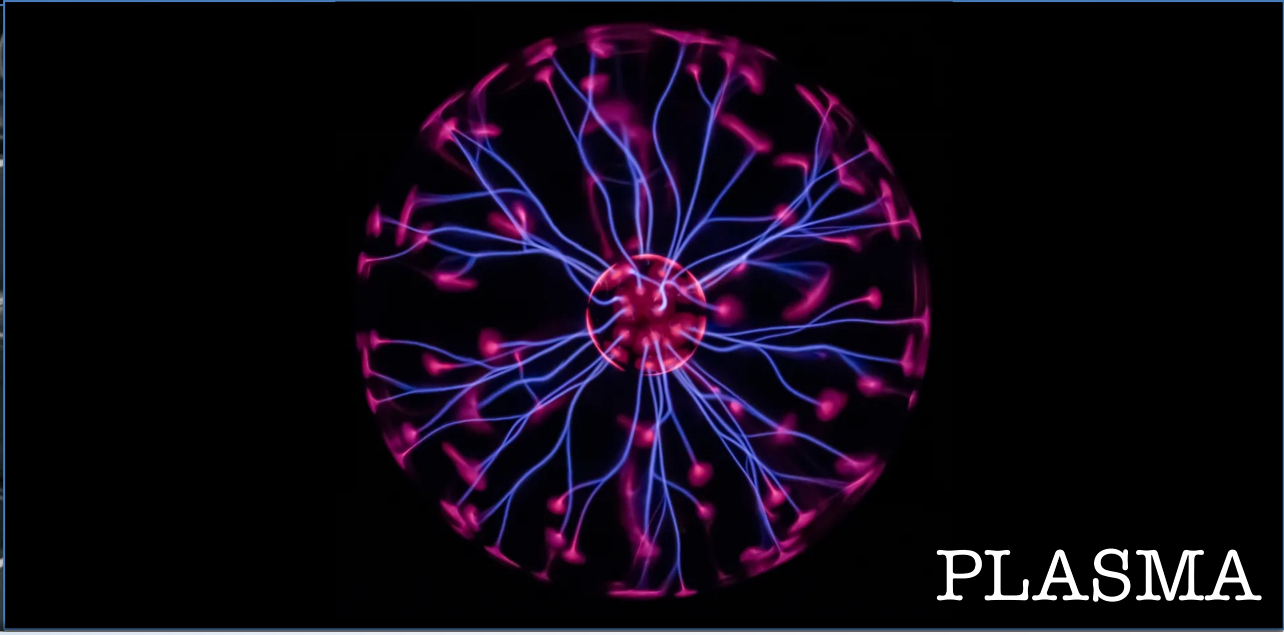


[Aveline et al. Nature (2020)]

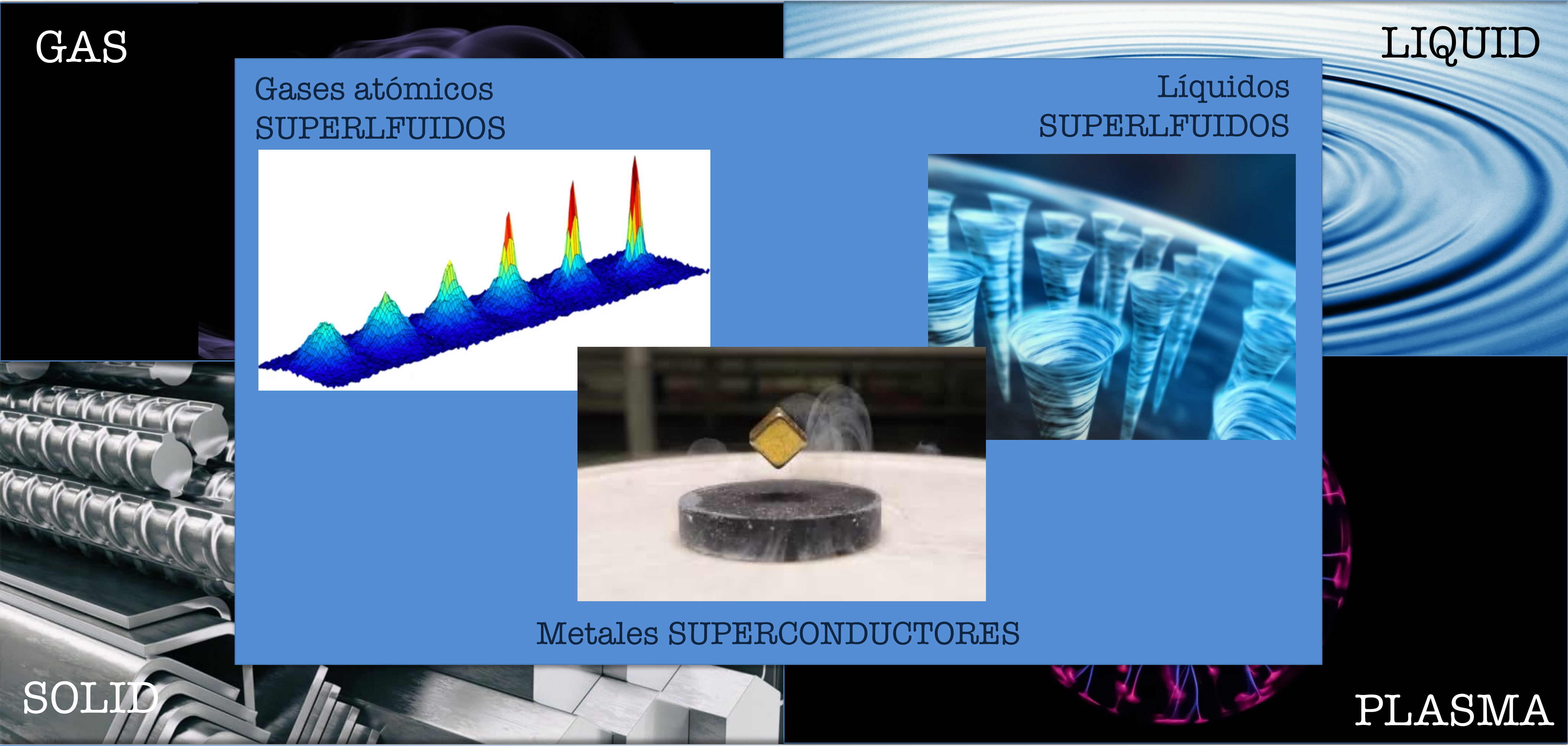
¿Qué hace tan únicos a los condensados cuánticos?

4 estados de la materia

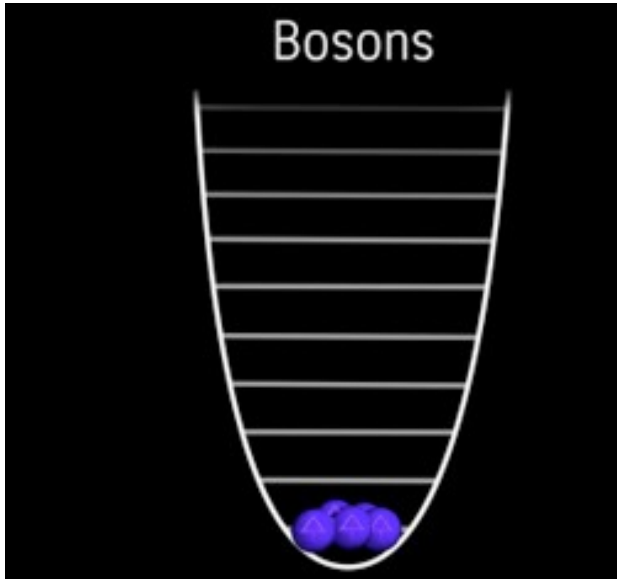




El 5º estado de la materia: ¡¡los SUPERS!!



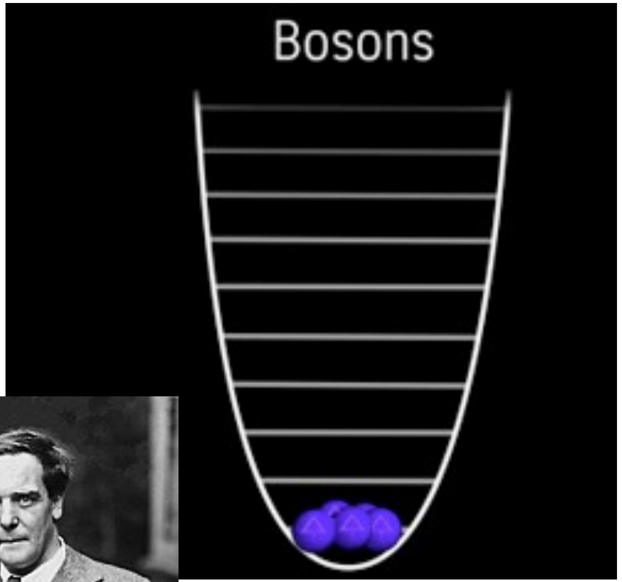
Bosons

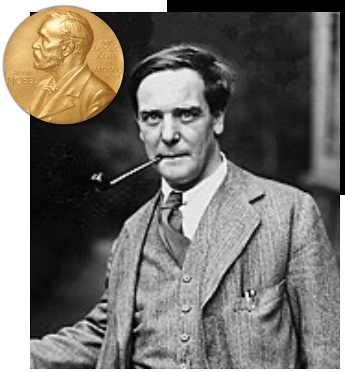


gregarious

condensación

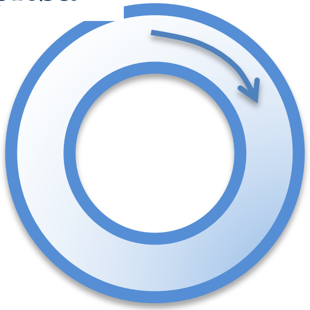
Bosons





P. Kapitsa

gregarious

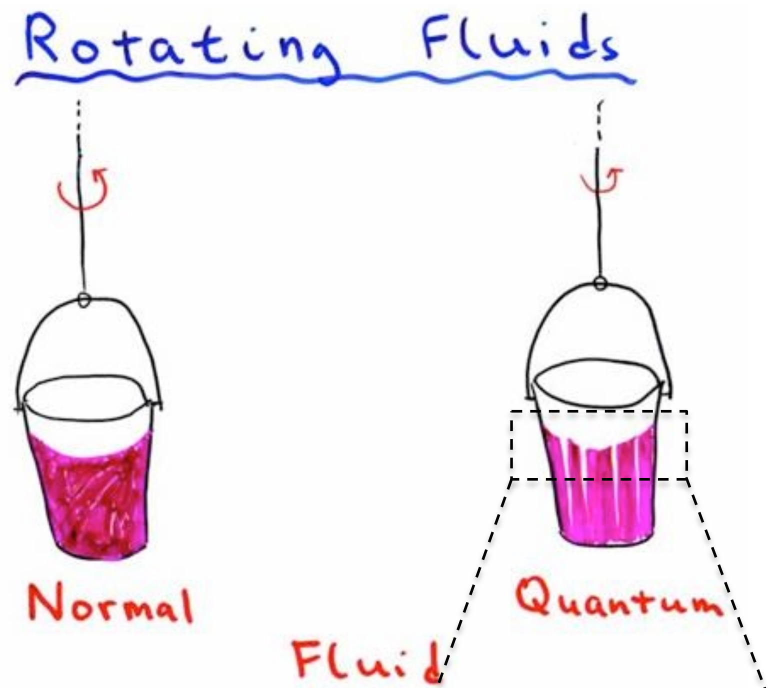


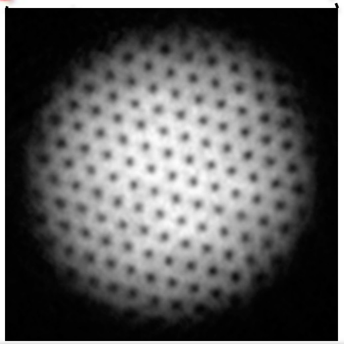
flujo sin fricción

superfluidez

condensación

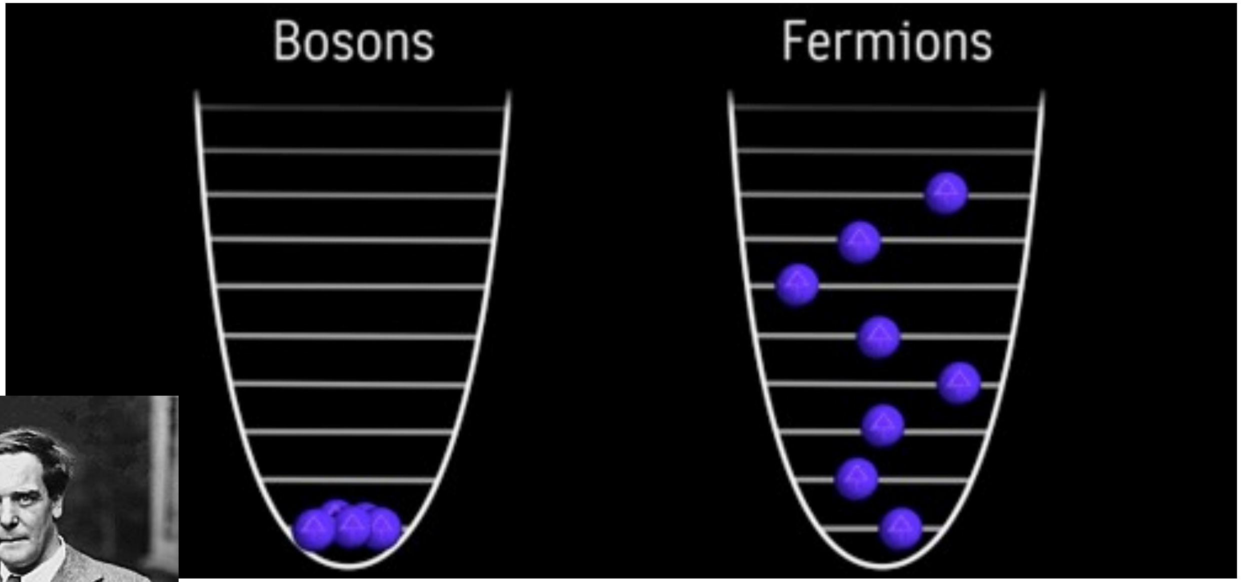
A superfluid cannot not rotate as an ordinary fluid (rigid body)





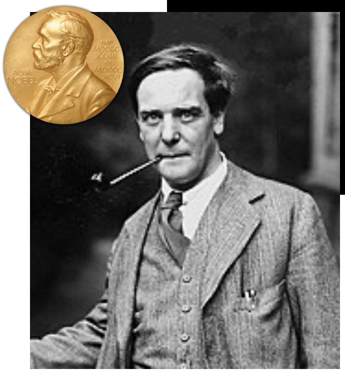
[from W. Ketterle's web page]

Bosons vs Fermions

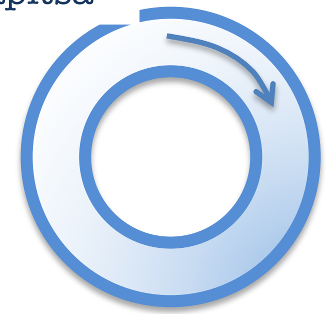


gregarious

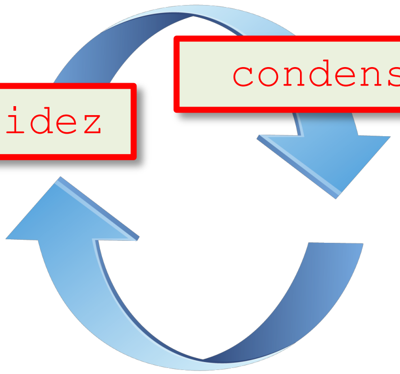
quantum individualists



P. Kapitsa



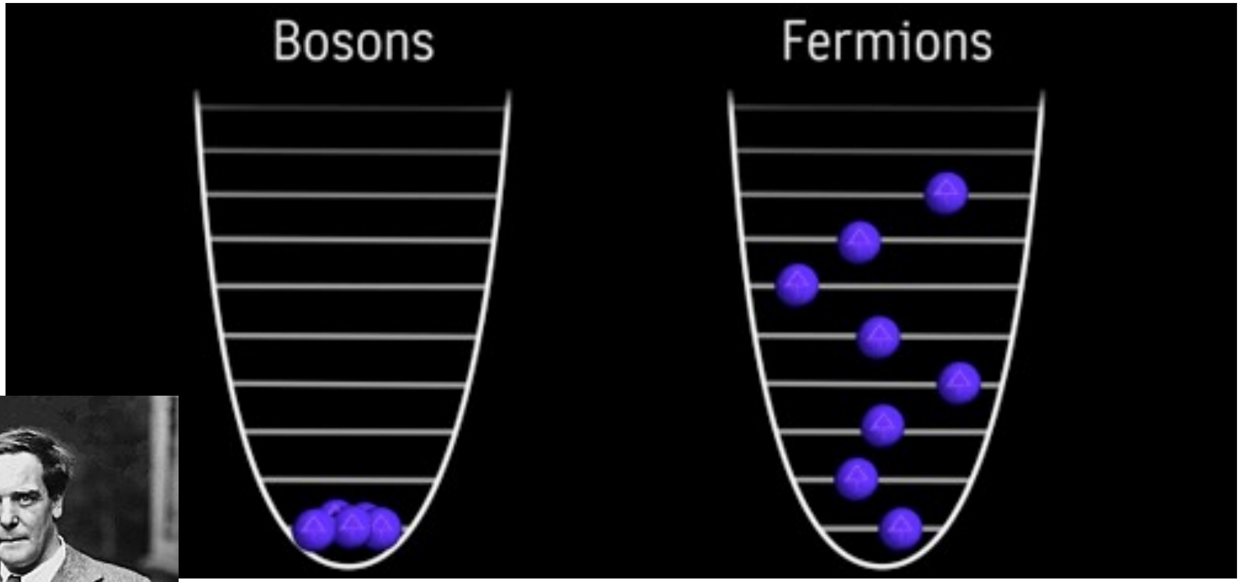
flujo sin fricción

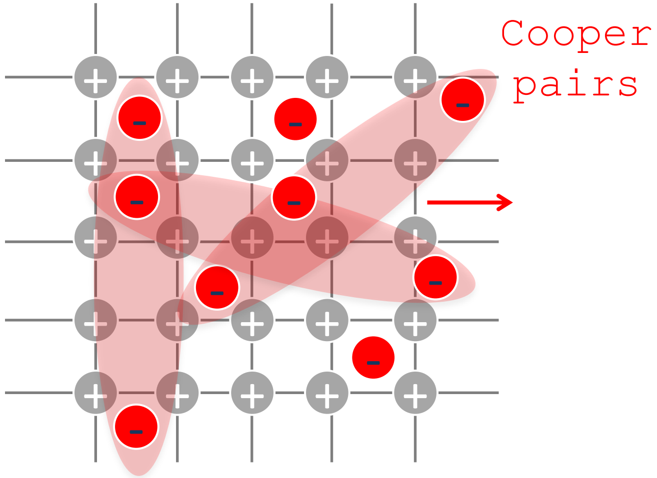


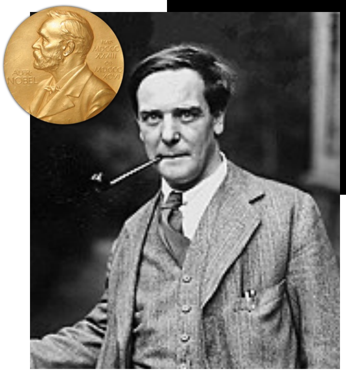
superfluidez

condensación

Bosons vs Fermions



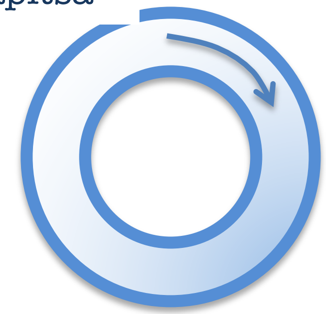


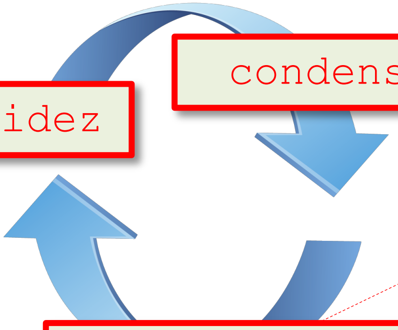

P. Kapitsa

gregarious

quantum individualists

can condense
in pairs!

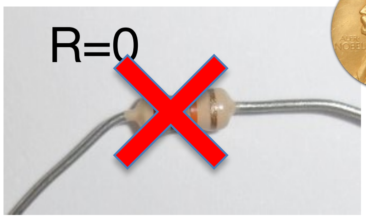

flujo sin fricción



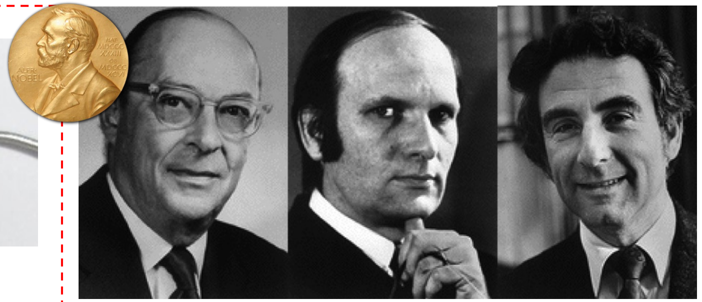
superfluidez

condensación

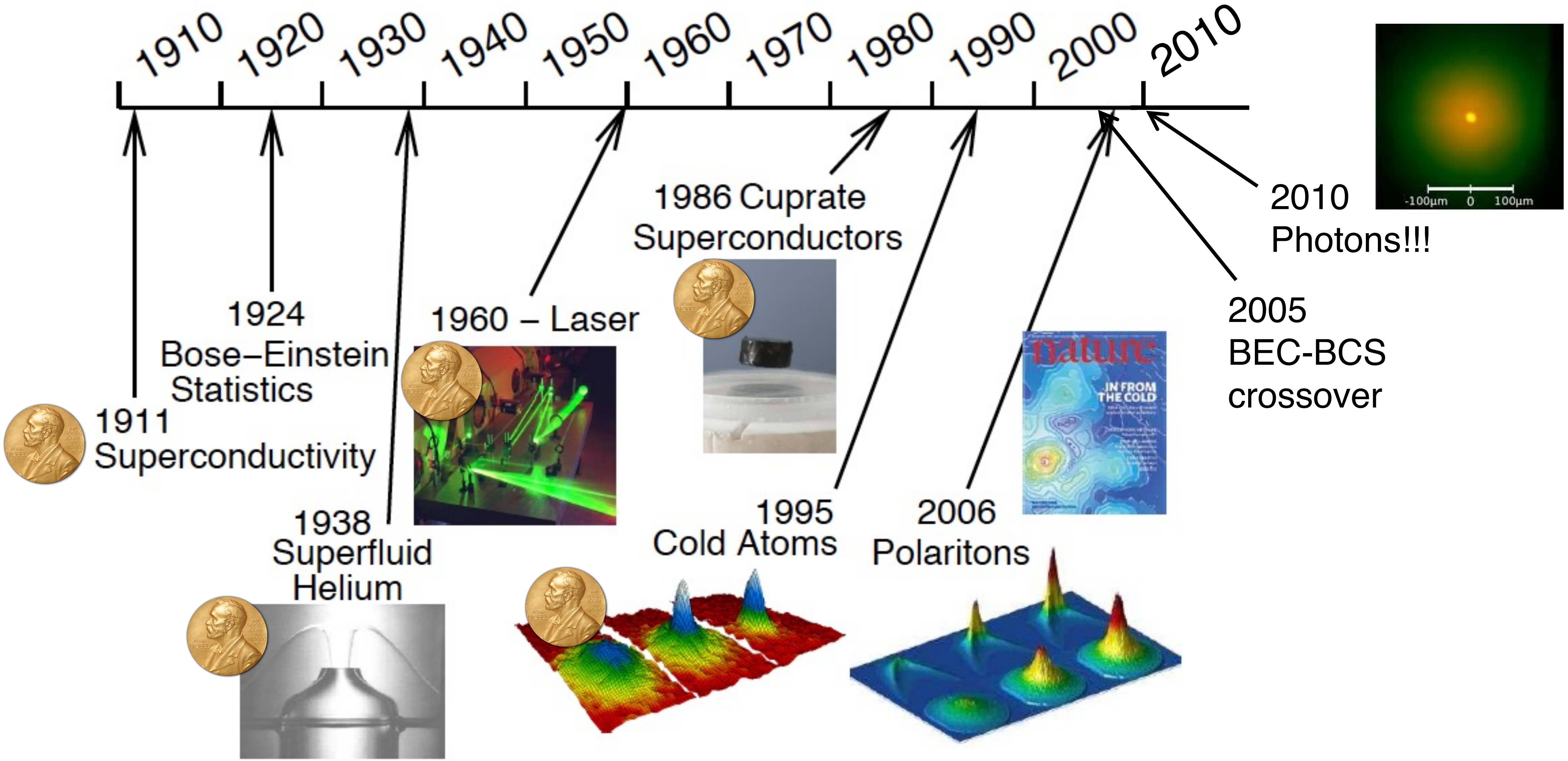
superconductividad



zero electrical
resistance


J. Bardeen J. Schrieffer L. Cooper

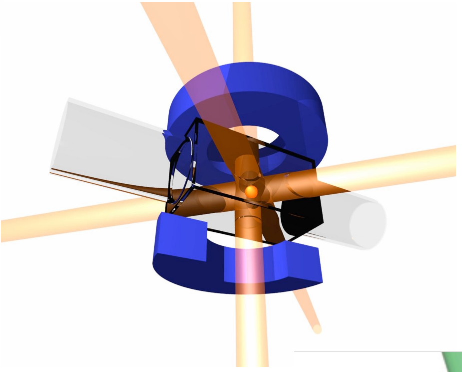
History of quantum condensates

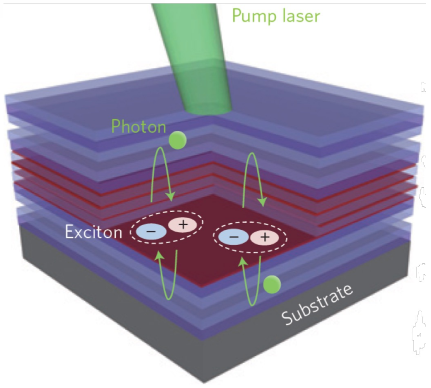


Some of these themes are thought in the 4th year FMC course

Condensation of bosons, fermion pairs, and polaron physics can occur in the same system:

1. ultracold atoms
2. excitons & polaritons in semiconductor heterostructures

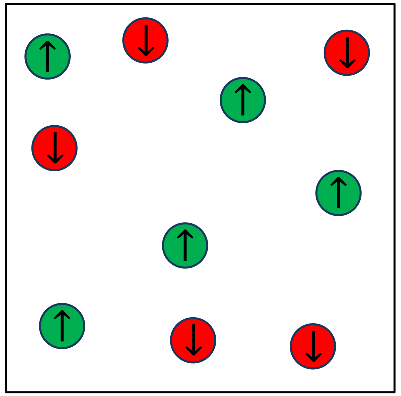




BEC-BCS crossover in ultracold atoms

- Balanced Fermi mixtures

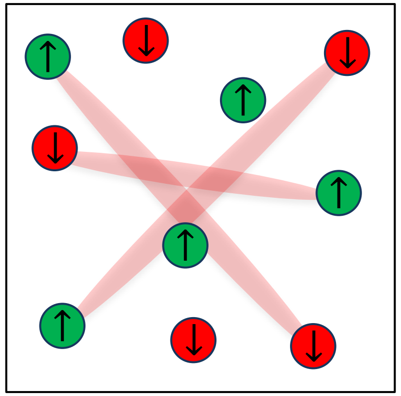
$$0 \qquad \longrightarrow \qquad \frac{1}{k_F a}\ (interaction)$$



BEC-BCS crossover & polaron physics in ultracold atoms

- Balanced Fermi mixtures

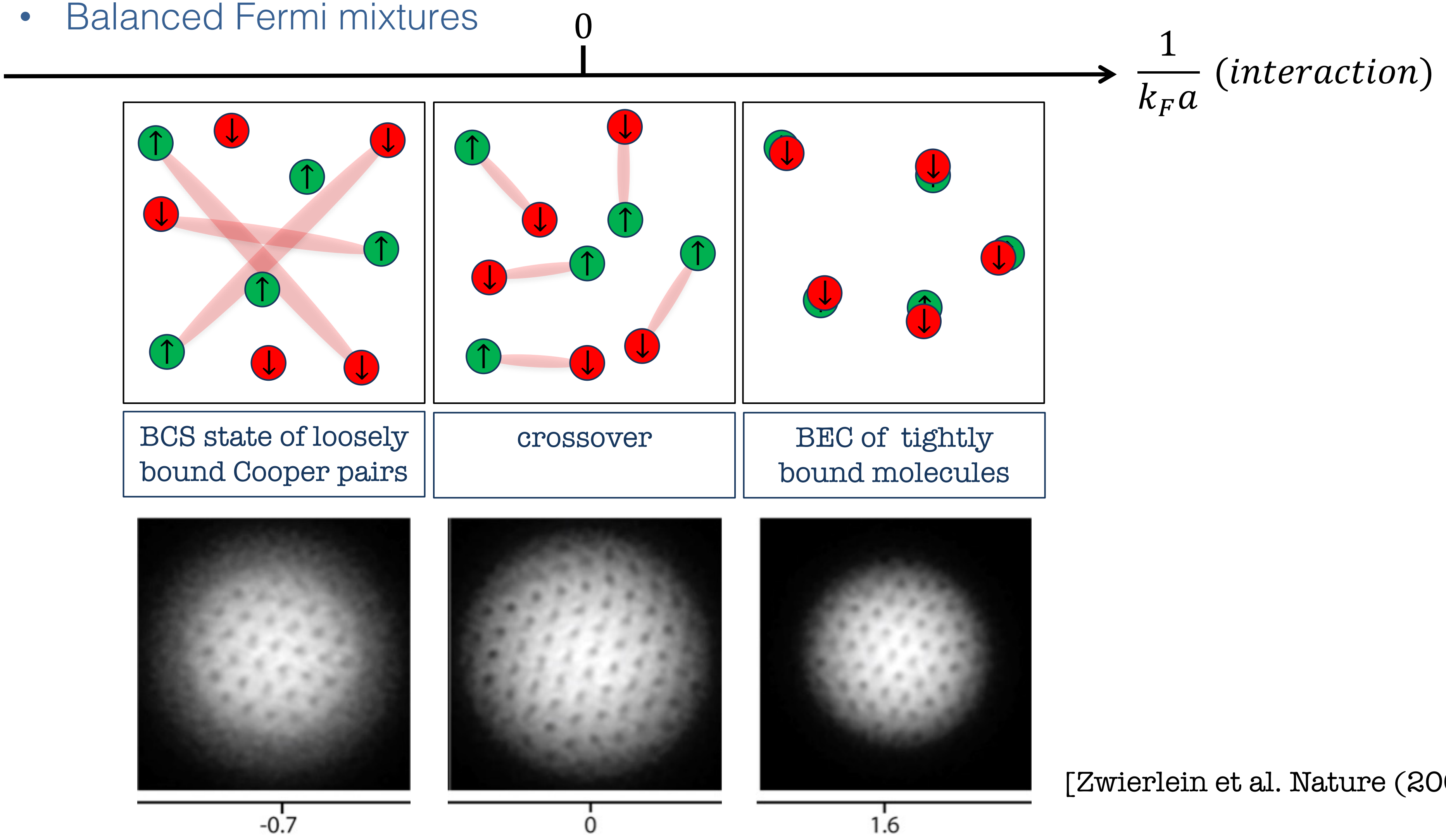
$$\xrightarrow{\quad 0 \quad} \quad \frac{1}{k_F a}\ (interaction)$$



BCS state of loosely bound Cooper pairs

BEC-BCS crossover in ultracold atoms

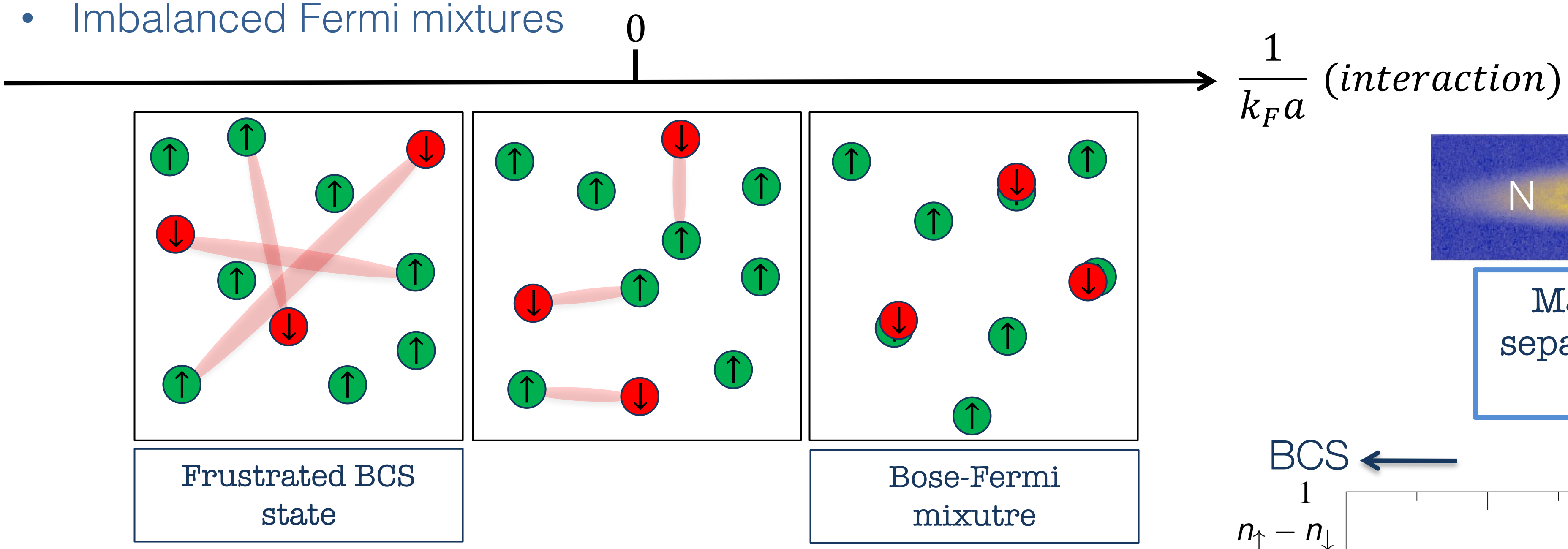
- Balanced Fermi mixtures



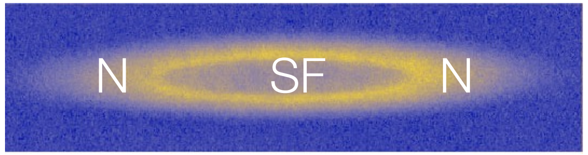
[Zwierlein et al. Nature (2005)]

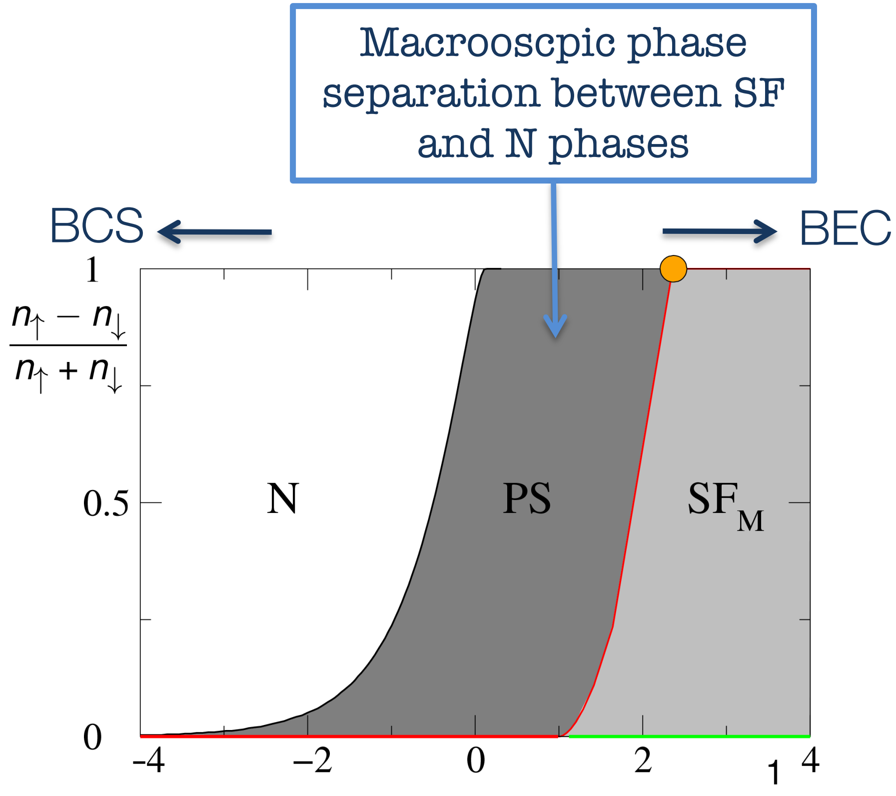
BEC-BCS crossover in ultracold atoms

- Imbalanced Fermi mixtures



[Shin *et al.* PRL (2006)]

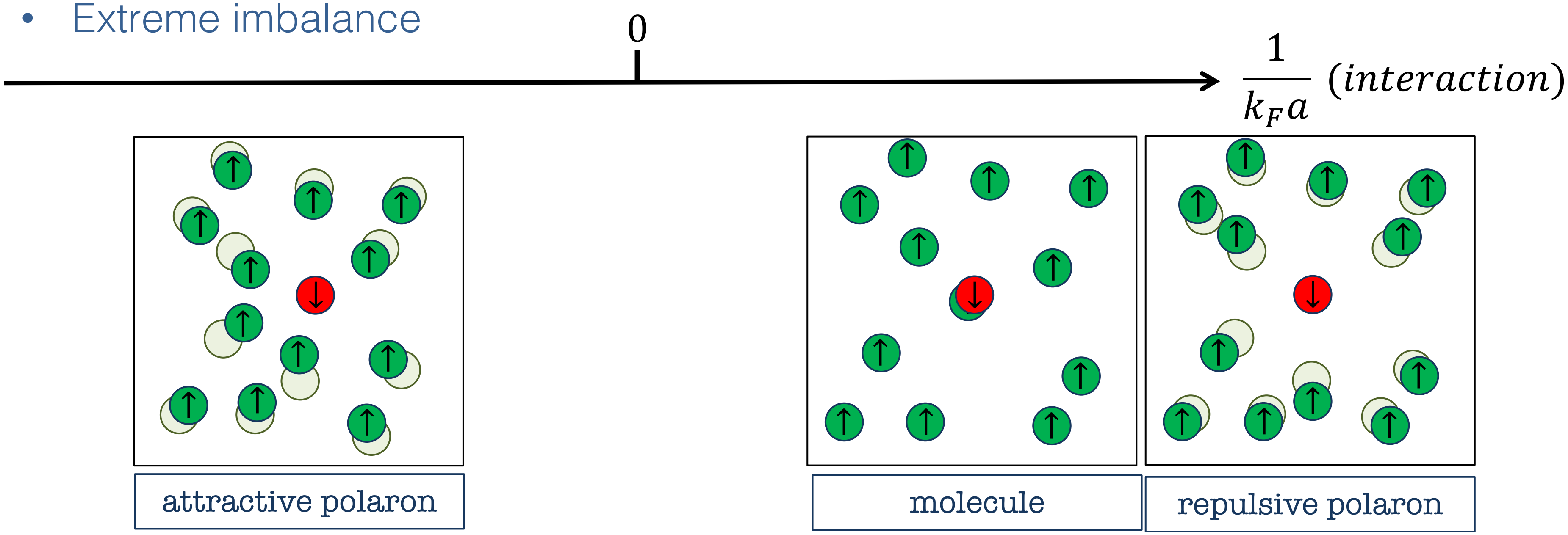




[Parish, Marchetti et al. Nature Physics (2007)]

Polaron physics in ultracold atoms

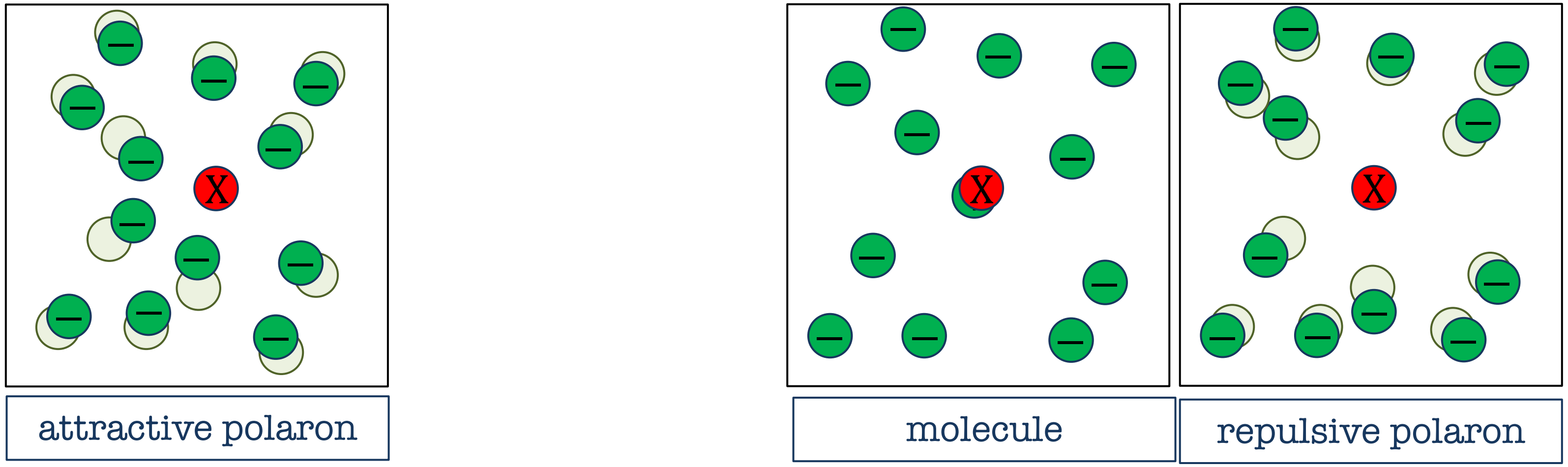
- Extreme imbalance



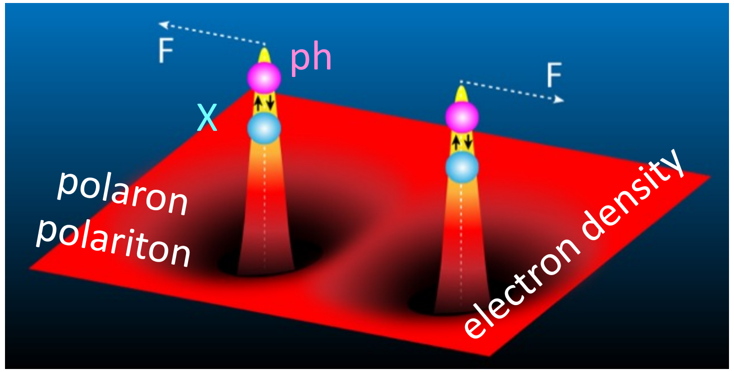
Polaron physics in semiconductor heterostructures

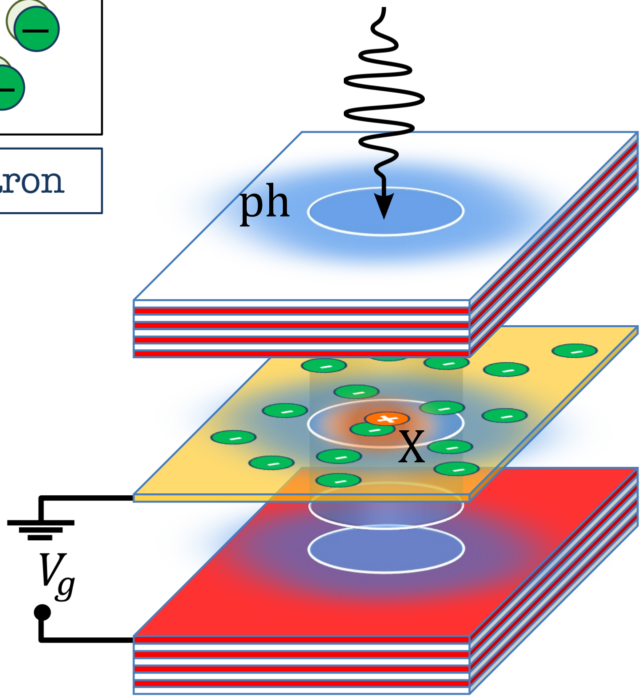
- Extreme imbalance

entangled superposition $|matter\rangle + |light\rangle + |charge\rangle$



[Tan et al PRX (2020)]
[Carusotto Physics (2020)]

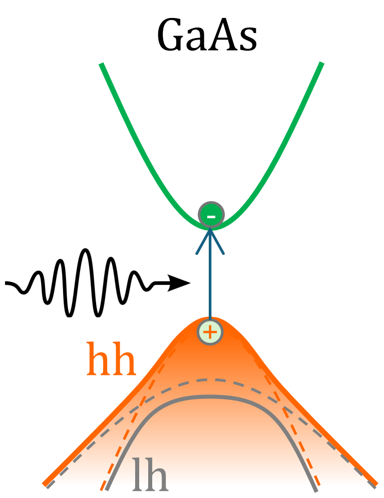


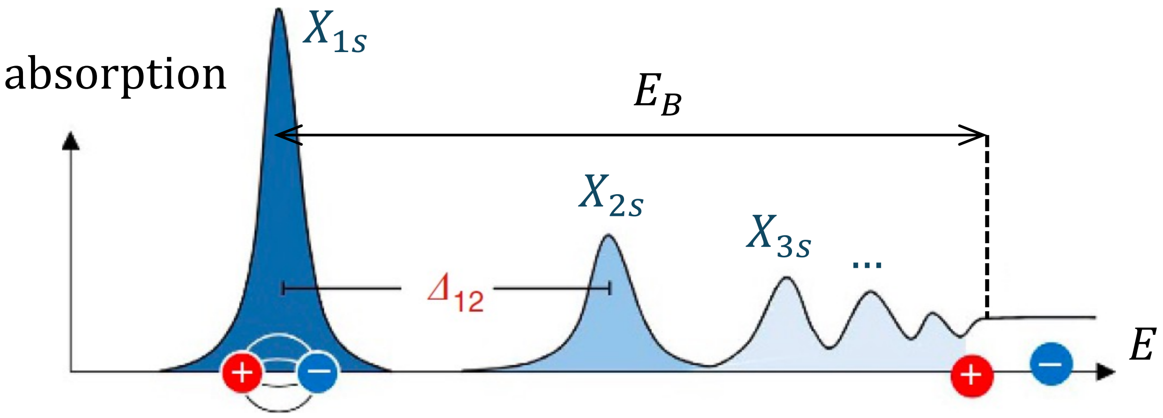


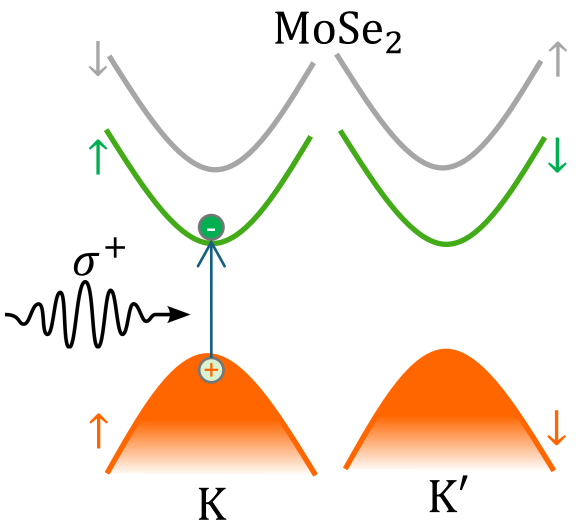
Semiconductor structures with strong matter-light interactions: polaritons

excitons in QWs

excitons in TMD monolayers

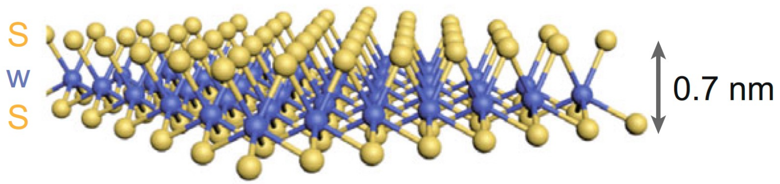






$E_B = 7 - 15$ meV

$E_B = 200 - 500$ meV $\gg k_B T_{\mathrm{room}}$

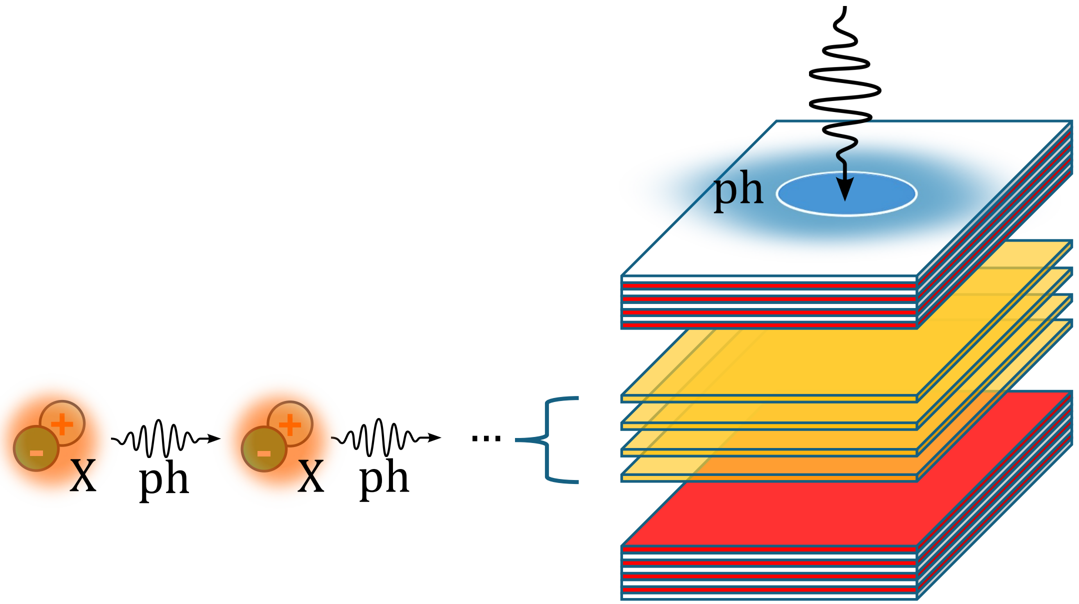


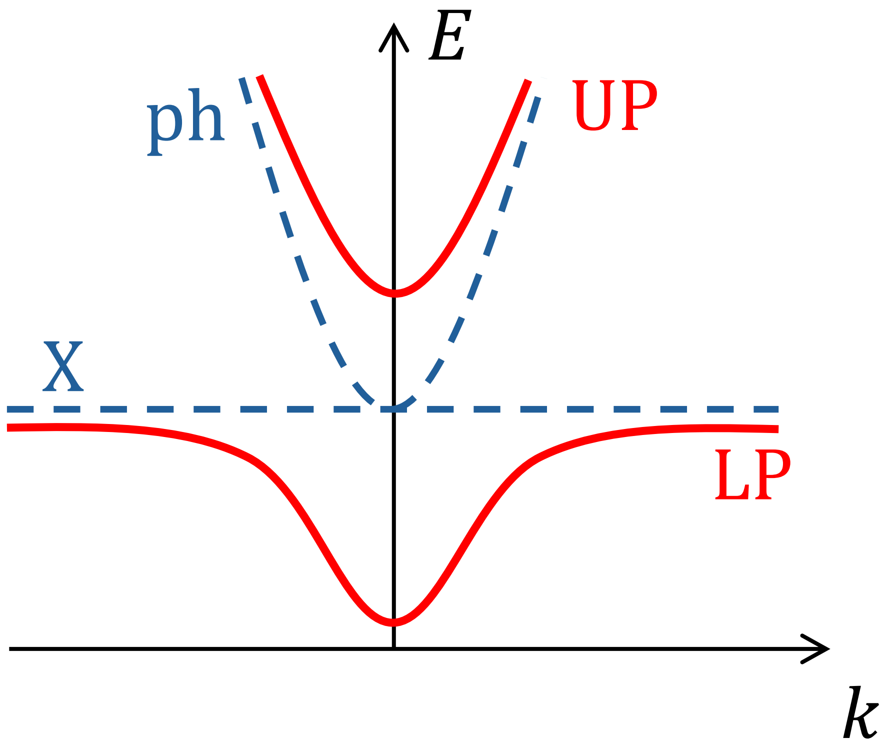
Strong light-matter coupling: polaritons

▷ Light-matter coupling $g \propto \frac{\Omega}{2}$

$g > \gamma$	strong	energy transfer between excitons and photons
$g \sim E_B$	very strong	hybridization of different excitonic levels

$|polaritons\rangle = |matter\rangle + |light\rangle$

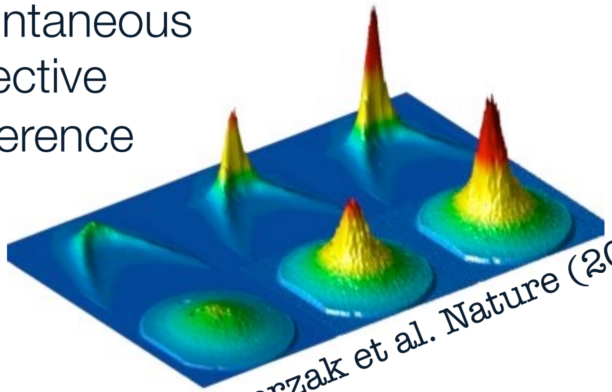




Polariton condensation and beyond

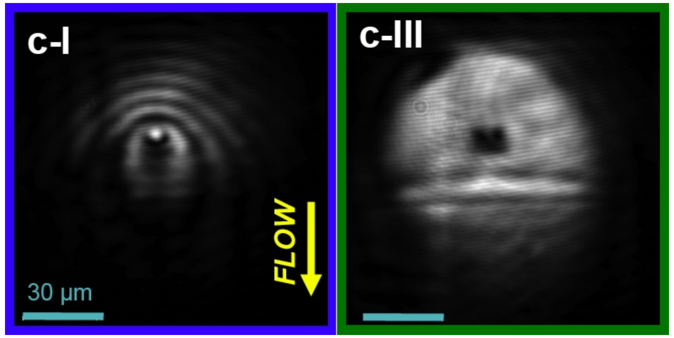
PHENOMENOLOGY OF NON-LINEAR CLASSICAL WAVES

▷ Spontaneous collective coherence



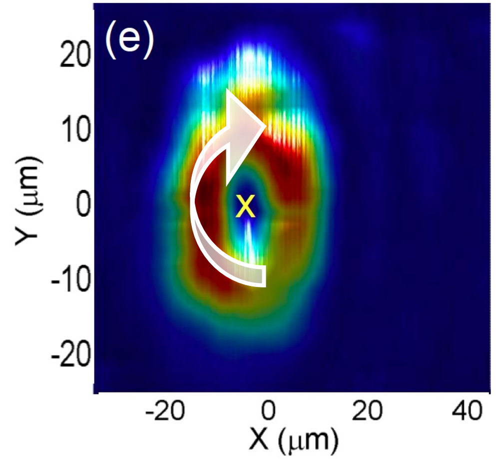
[Kasprzak et al. Nature (2006)]

▷ Suppression of scattering



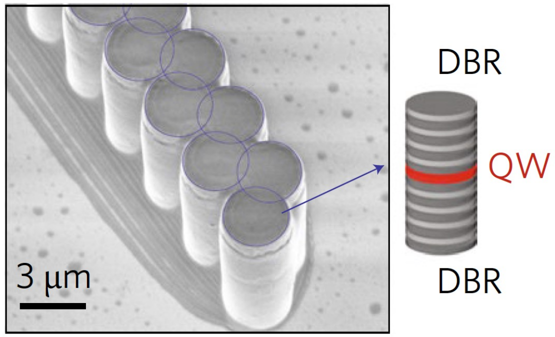
[Amo et al. Nat Phot (2009)]
[Lerario et al. Nat Phys (2017)]

▷ Persistency of currents



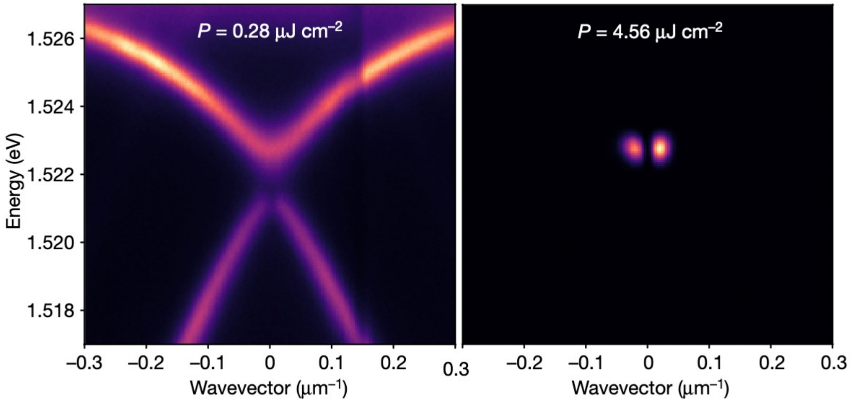
[Sanvitto, FMM et al. Nat Phys (2010)]

▷ Lattice structures



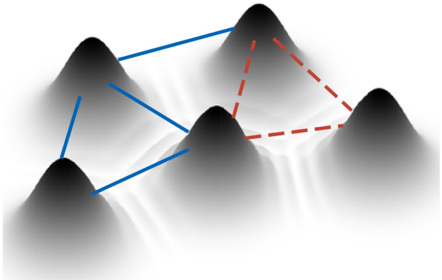
[St-Jean et al. Nat Phot (2017)]

▷ Condensation in topological BIC



[Ardizzone et al. Nature (2022)]

▷ Polariton simulators

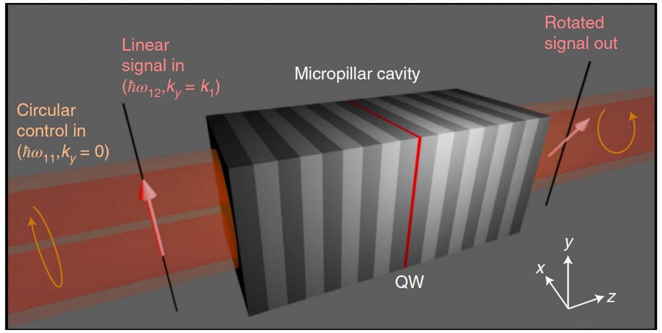


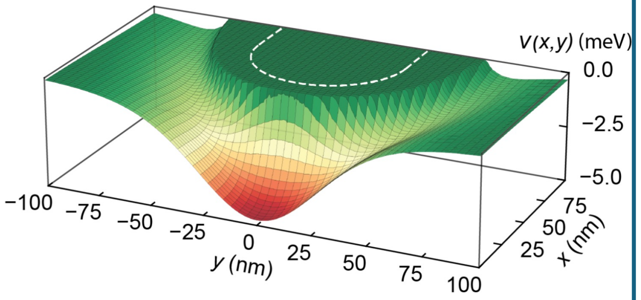
[Berloff et al. Nat Mat (2017)]

Towards strongly interacting polaritons

▷ Enhancing non-linearities by full confinement

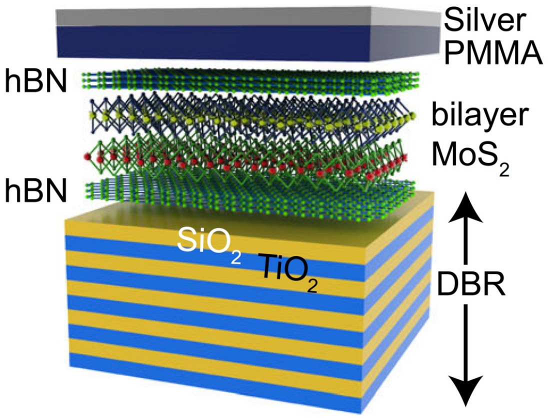
[Kuriakose et al. Nat Phys (2022)]

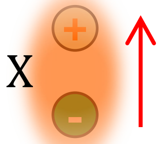




[Thureja et al. ArXiv (2024)]

▷ Dipolar polaritons



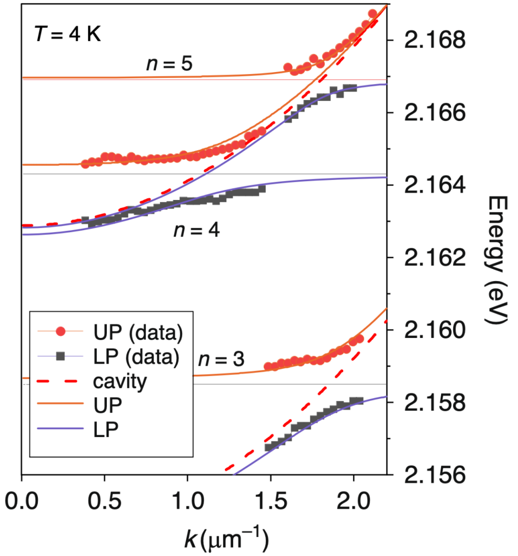


[Datta et al. Nature Comm (2022)]
[Louca et al. Nature Comm (2023)]

▷ Rydberg polaritons

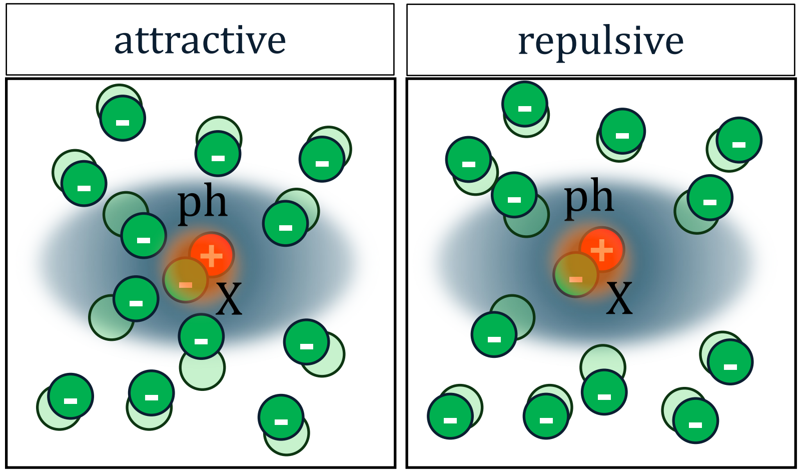
[Makhonin et al. *Light: Sci&App* (2024)]

[Orfanakis et al. Nat Mat (2022)]

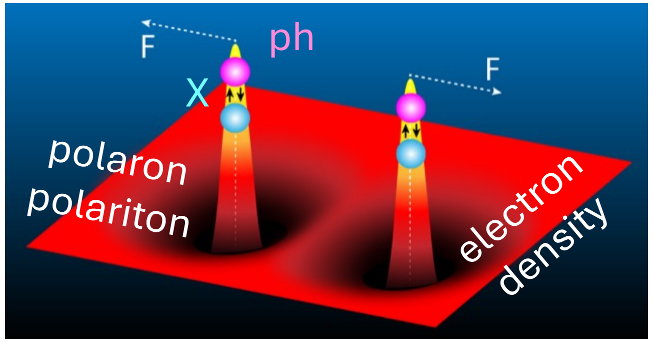


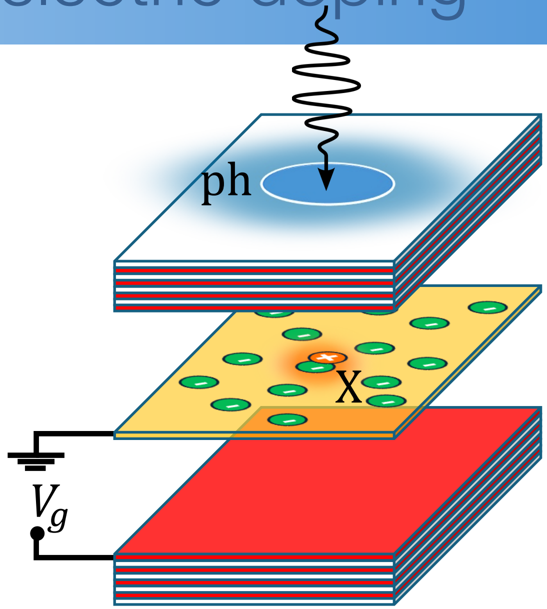
Interplay between strong light-matter coupling and electric doping

▷ Fermi polaron

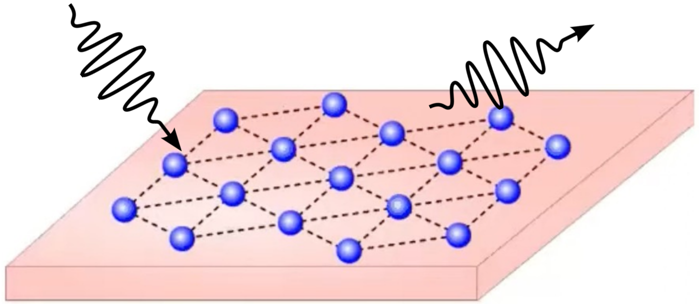


[Tan et al PRX (2020)]
[Carusotto Physics (2020)]



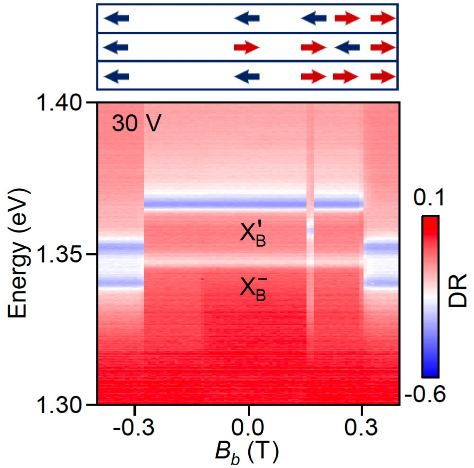


▷ Optical sensors of strongly correlated electronic phases



[Smolenski et al Nature (2021)]
[Shimazaki et al PRX (2021)]

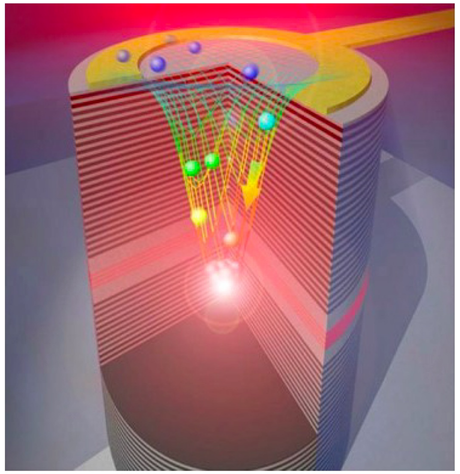
▷ + magnetism (CrSBr)



[Tabataba et al Nat Comm (2024)]

▷ Electrically driven condensation

[Schneider et al, Nature (2013)]
[Bhattacharya et al, PRL (2013)]



Thanks