Physics in the XXIst century

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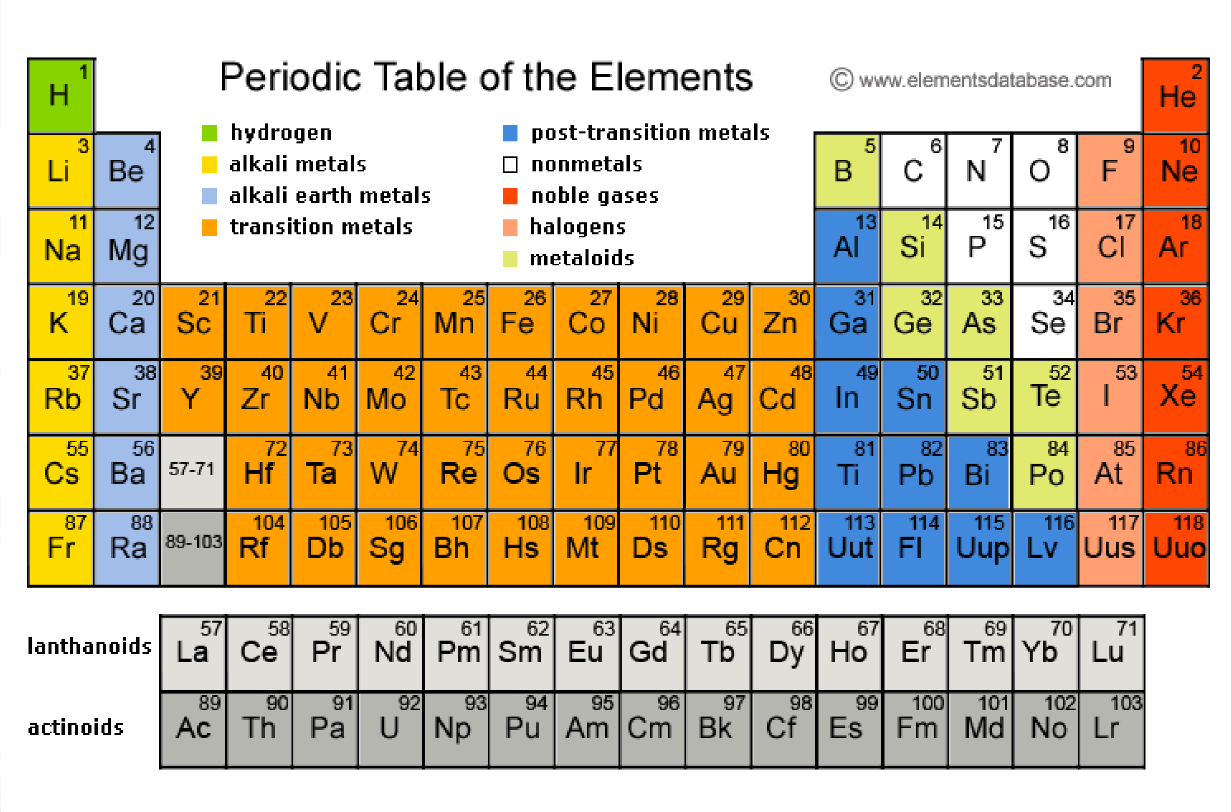
Matter

By far the most active field of physics with interfaces & applications to many domains : mathematics, chemistry, biology, geology, medicine, engineering, industry, every day life....

Quantum matter is a pleonasm, since matter, its structure and many of its properties are implicitly quantum manifestations/processes

Quantum mechanics, atomic and nuclear physics explained the periodic table



Periodic Table of the Elements

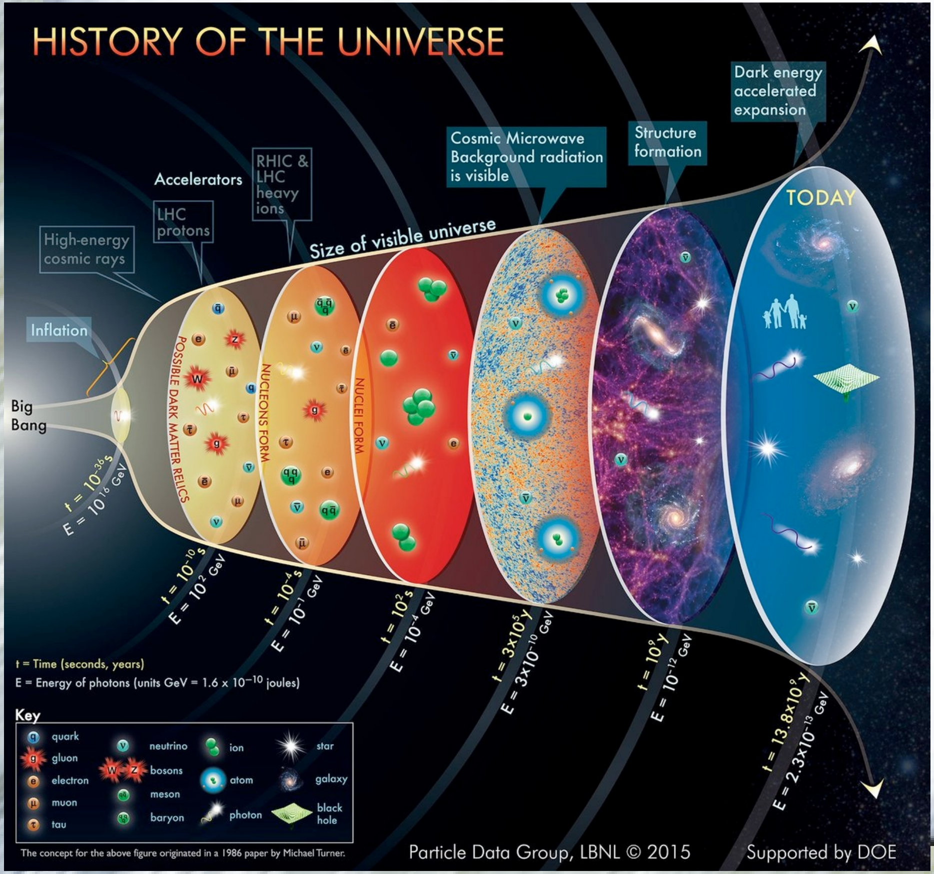
© www.elementsdatabase.com

- 🟩 hydrogen
- 🟨 alkali metals
- 🟦 alkali earth metals
- 🟧 transition metals
- 🟦 post-transition metals
- ☐ nonmetals
- 🟥 noble gases
- 🟧 halogens
- 🟨 metaloids

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57-71	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Ti	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89-103	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo

lanthanoids	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
actinoids	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

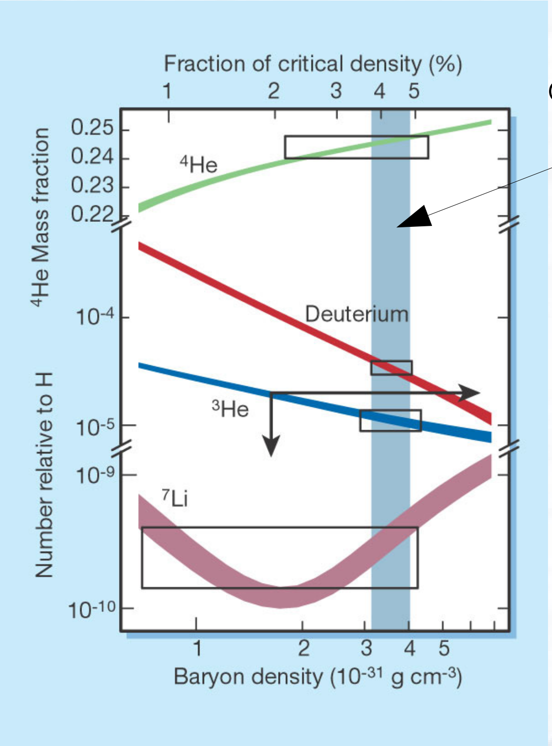
Big Bang Nucleosynthesis (BBN) of light elements



The concept for the above figure originated in a 1986 paper by Michael Turner.

Particle Data Group, LBNL © 2015

Supported by DOE



as observed today

Primordial nuclei :

H : ~ 75 %

^{4}He : ~ 25 %

Took place when

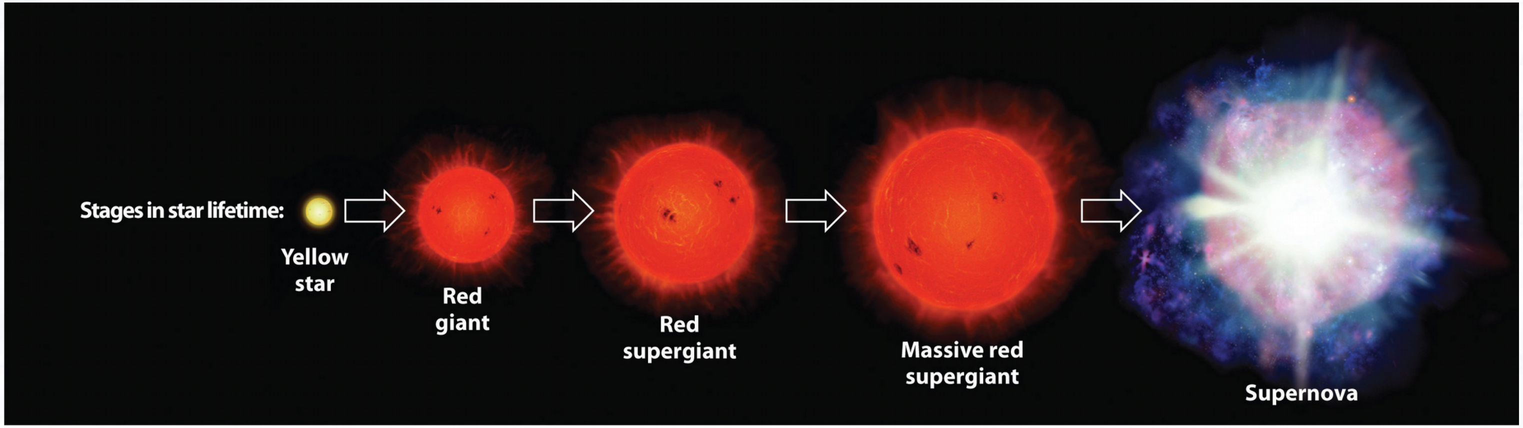
T ~ 11 GK

in between

1 - 3 minutes

after t_0

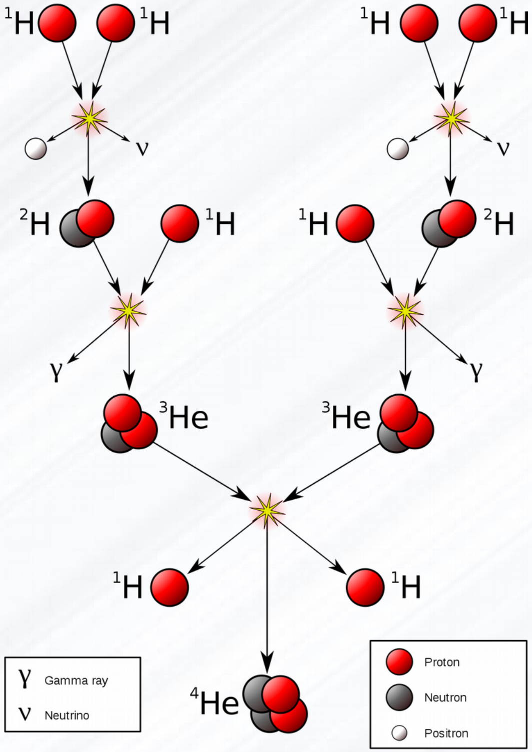
Heavier elements



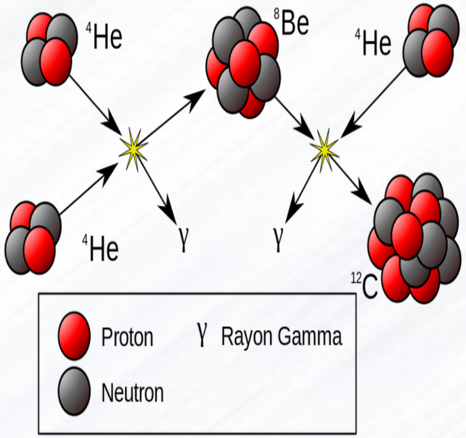
Core Temperature:	1.5×10^7 K	2×10^8 K	7×10^8 K	3×10^9 K	1×10^{11} K
Primary Nuclear Reaction:	^{1}H fusion	^{4}He fusion	$^4He + ^{12}C$ $^{12}C + ^{12}C$ $^{12}C + ^{16}O$	Proton–neutron exchange reactions	Multiple neutron captures
Elements Formed:	He	C, O, Ne, Mg	Na, Si, S, Ar, Ca	Fe, Ni	Elements with $Z > 28$

~ 99,9 % of matter in universe is made of hot plasma

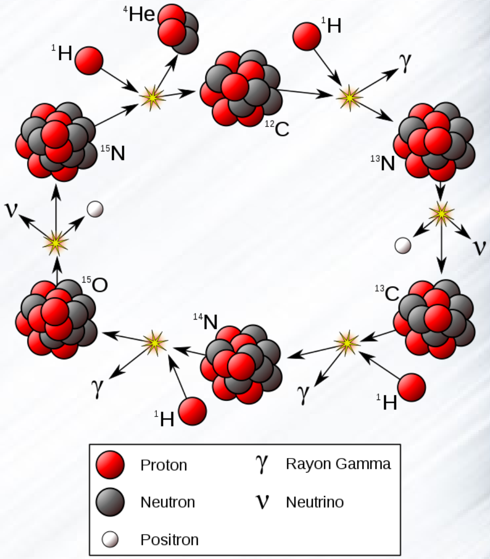
Heavier elements



Proton-proton chain

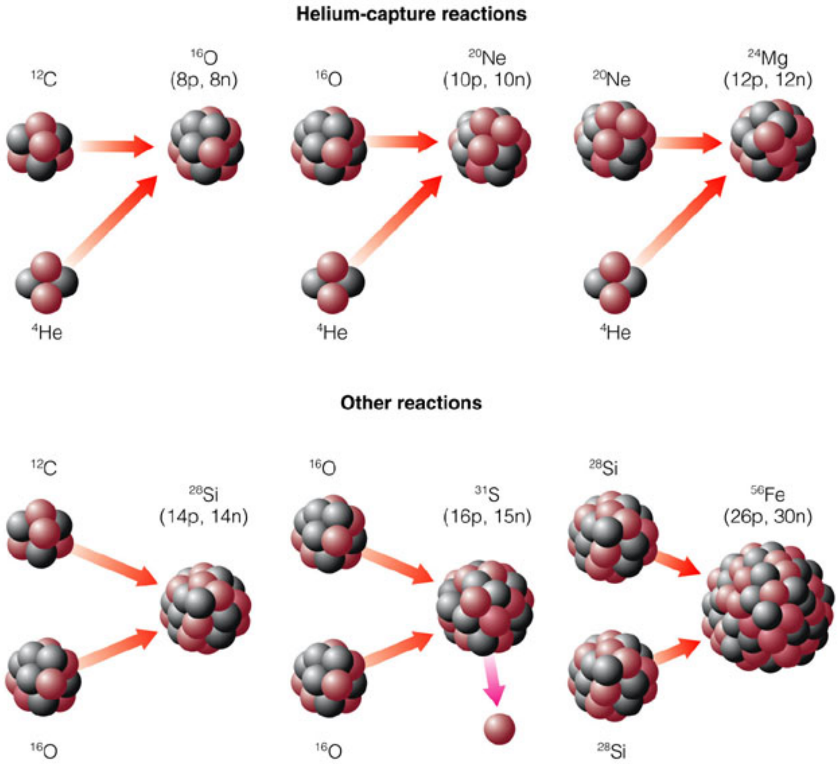


Triple alpha chain

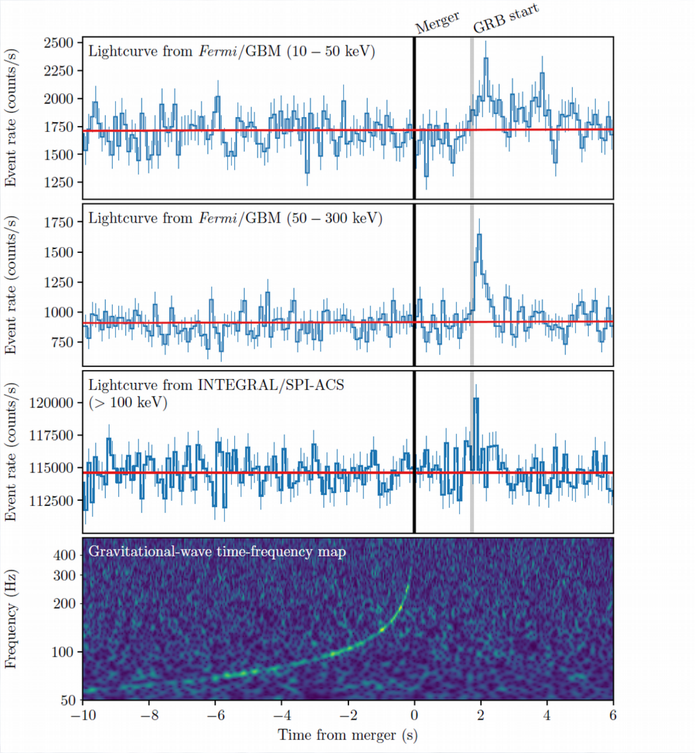


CNO cycle (for hotter and more massive stars)

Heavier elements



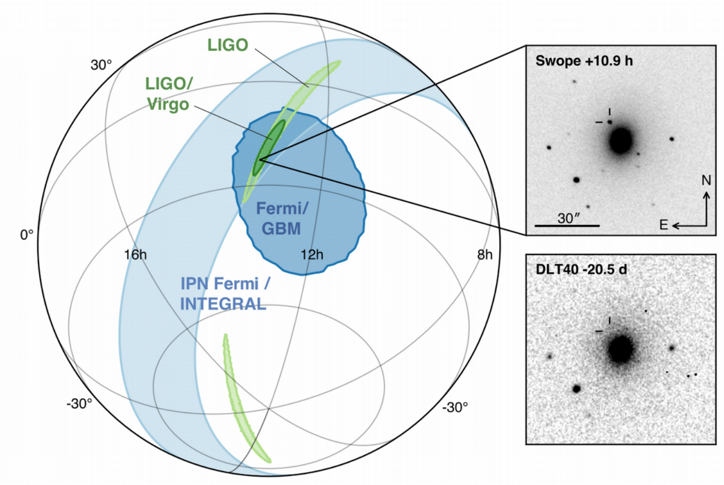
Kilonova

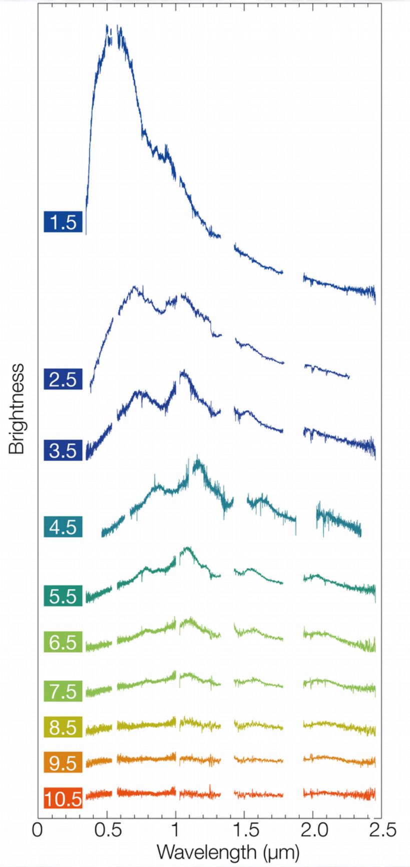


Fusion of two neutron stars producing a supernova with r-process

Discovered in 2017 : GW170817 by gravitational wave astronomy.

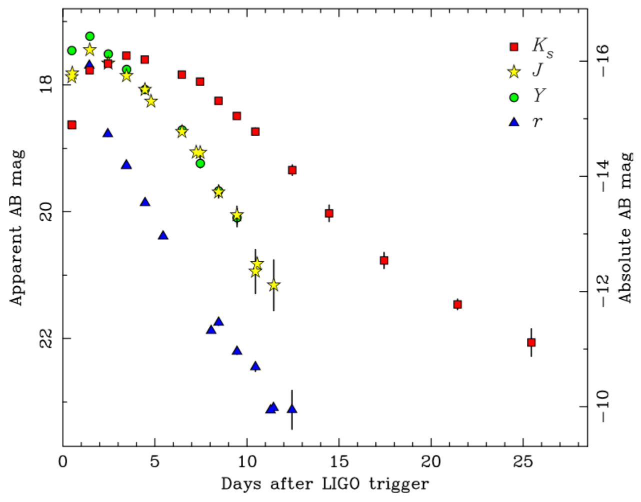
Birth of multi-messenger astronomy !





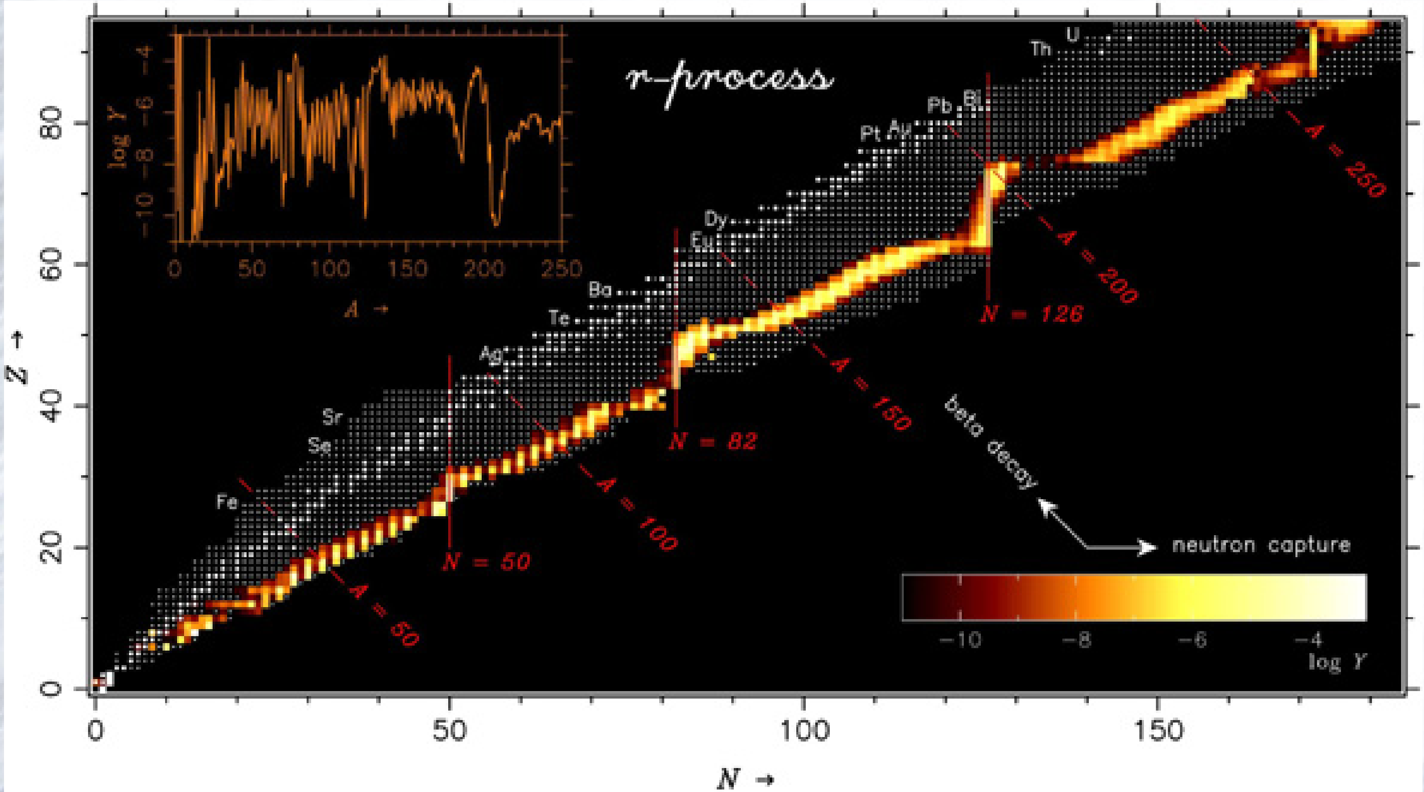
Kilonova AT 2017gfo in NGC 4993

Optical spectra measured over 12 days after GW170817 measured at VLT



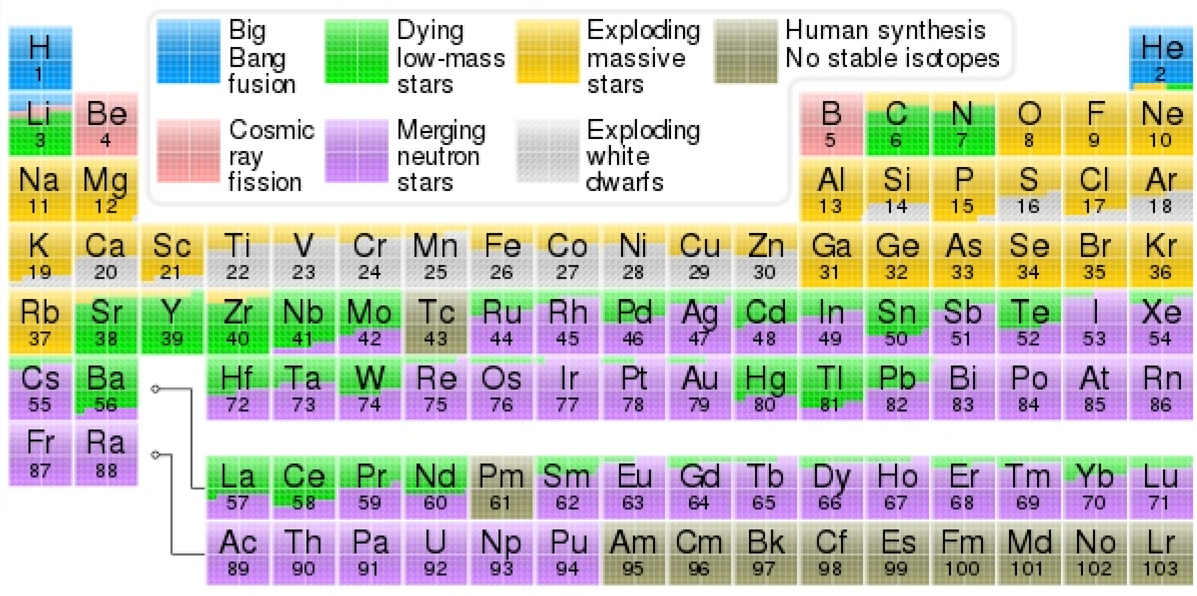
ESO

Heavy elements - R-Process



Neutron density :
10^{24} neutrons cm^{-3}

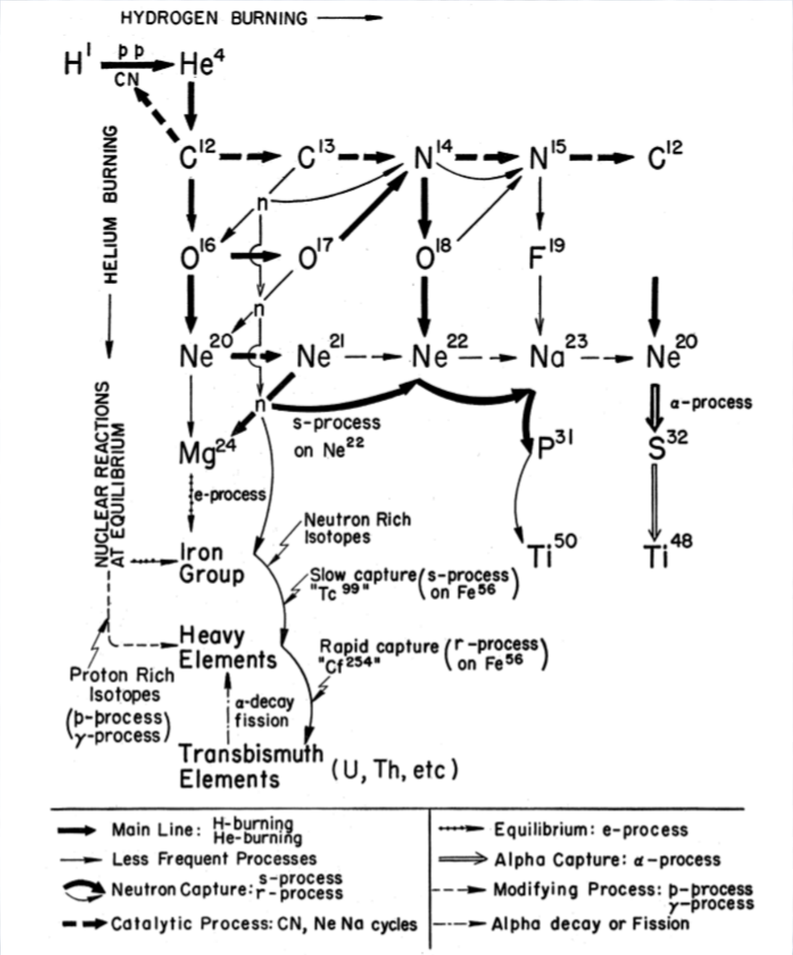
Matter elements are mainly big bang relic and star dust



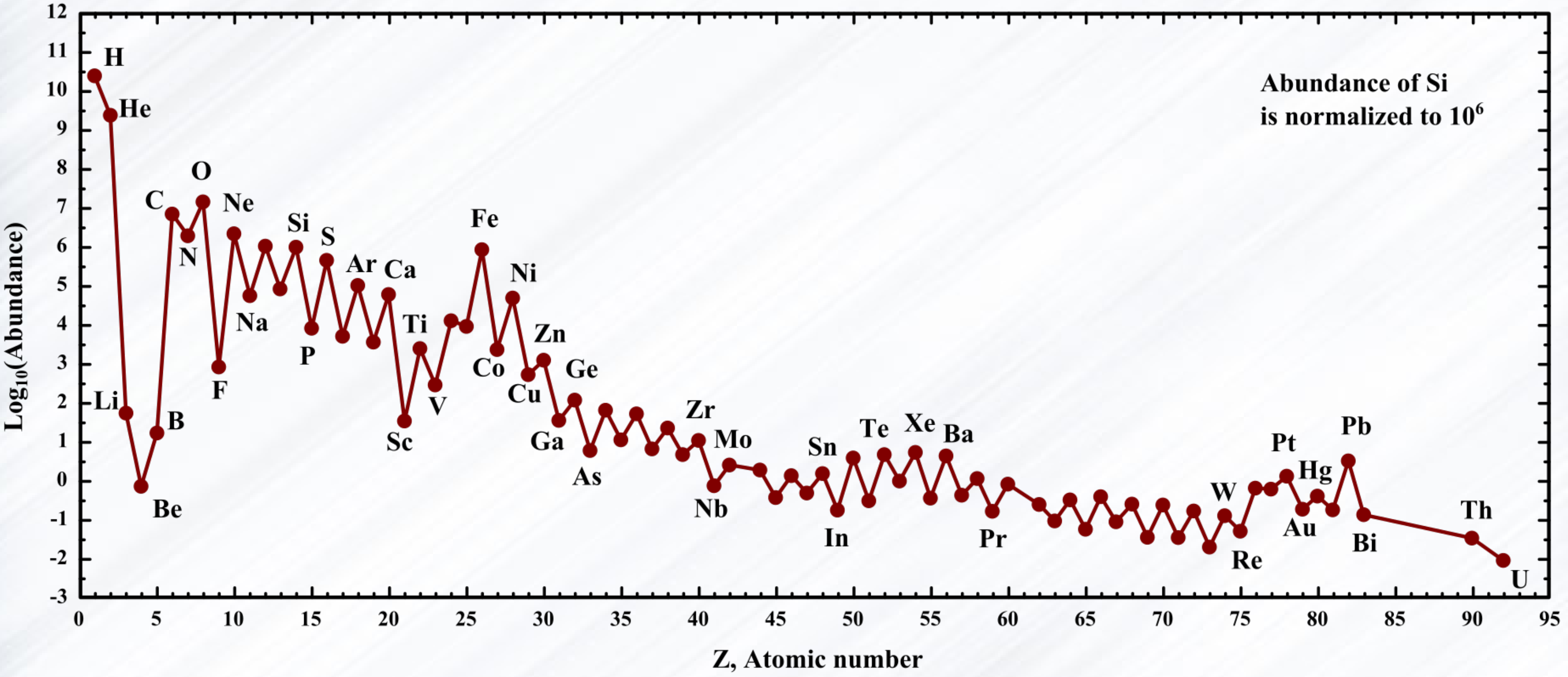
B^2FH paper : Review of Modern Physics 1957 , M. Burbridge, G. Burbridge, W. Fowler, F. Hoyle

1983 Nobel Prize : W. Fowler

B^{2}FH paper :
schematic diagram of
nuclear processes



Element abundances in solar system



data from : http://iopscience.iop.org/article/10.1086/375492/pdf

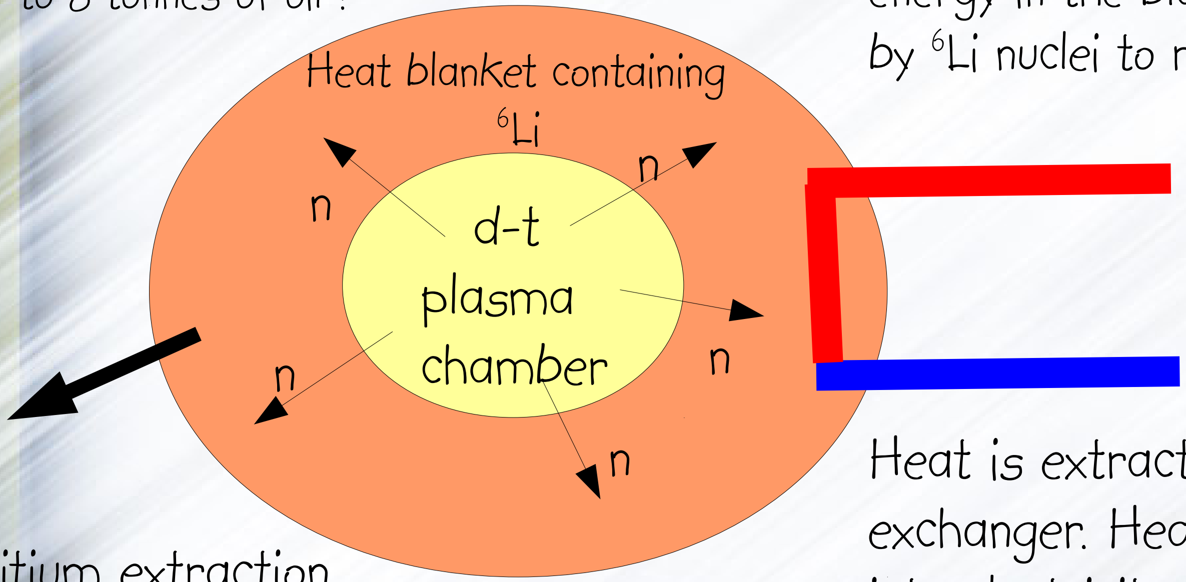
Mimicking the energy production in stars ?

The fusion reaction considered in the controlled production of thermonuclear energy is the following : $d + t \rightarrow \alpha\,(3{,}5\ \mathrm{MeV}) + n\,(14\ \mathrm{MeV})$

1 g of d+t fuel produces the energy equivalent to 8 tonnes of oil !

Charged alpha particles stop in the plasma and keep it hot. The neutrons come out of the plasma, deposit their energy in the blanket they heat. They are then captured by ^{6}Li nuclei to regenerate tritium.

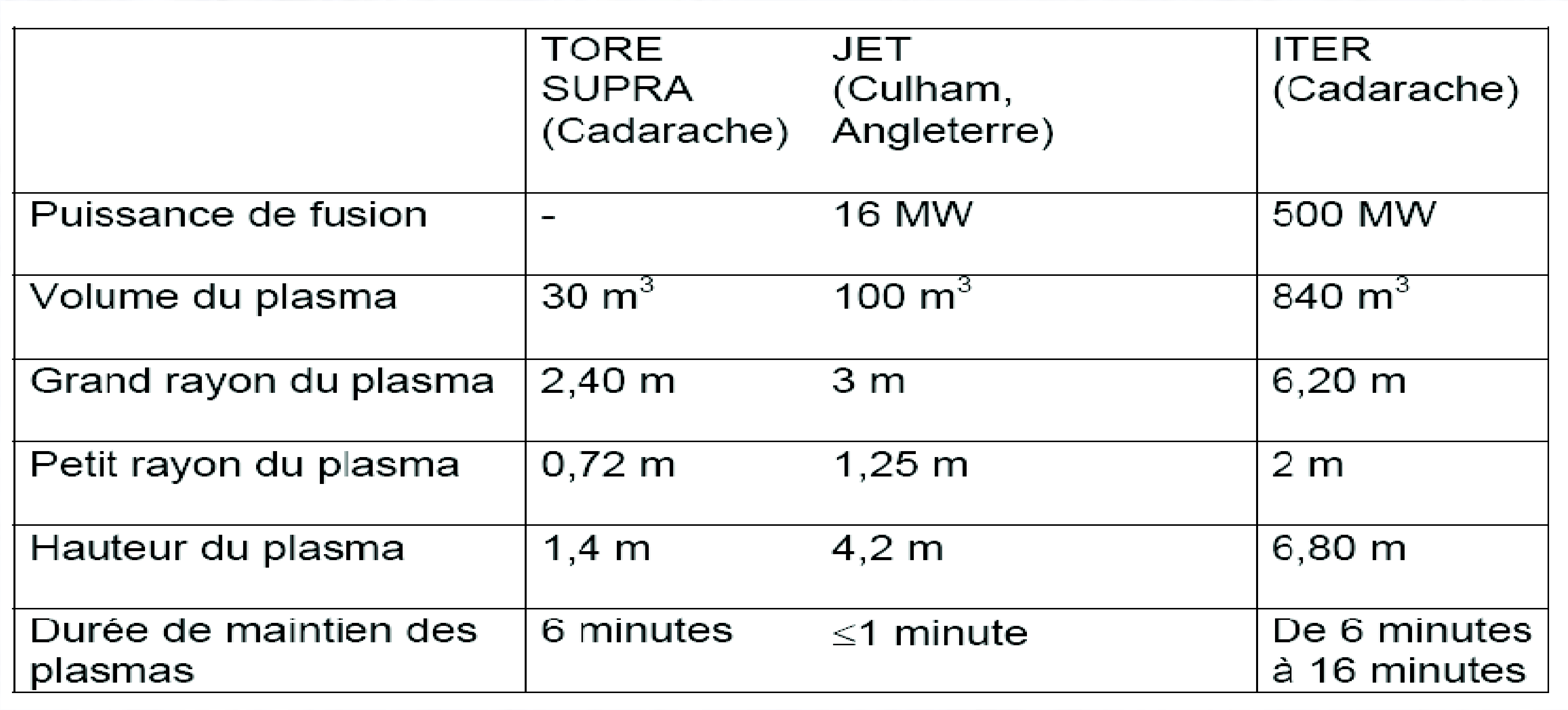
$$n + {}^6Li \rightarrow \alpha + t$$



Tritium extraction

Heat is extracted from the blanket by the exchanger. Heat can then be converted into electricity in a turbine.

D-T TOKAMAK fusion reactor protoypes

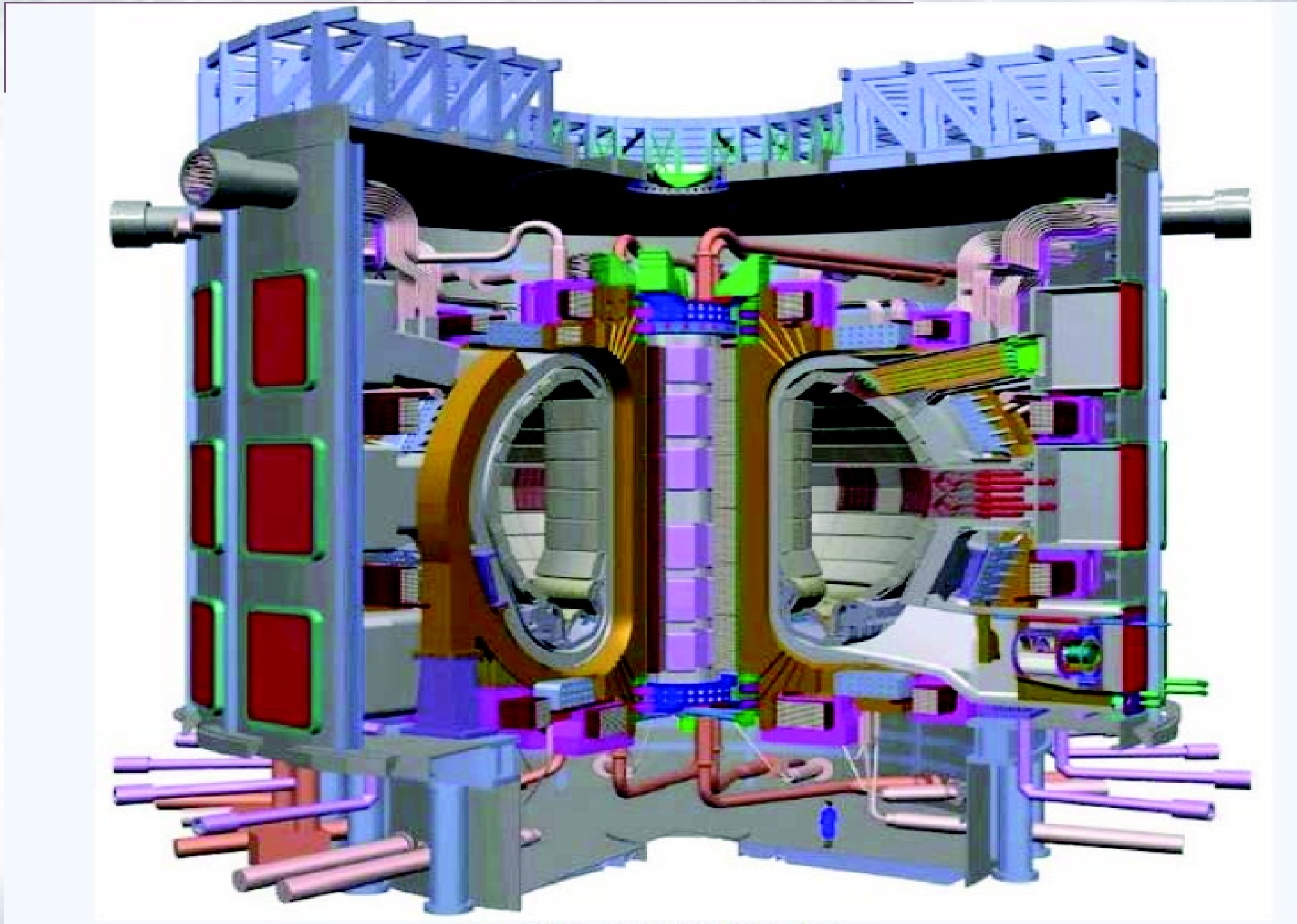


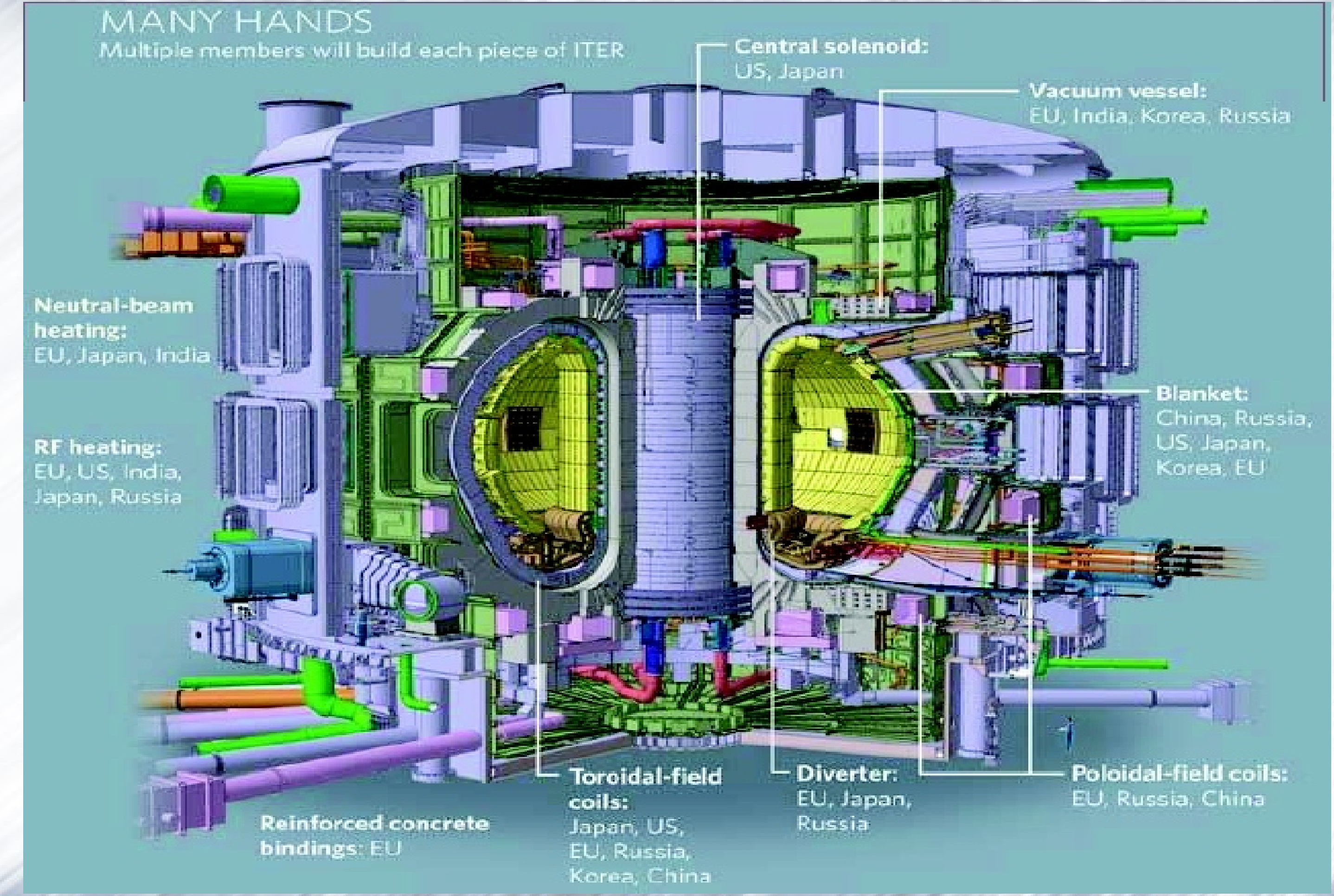
	TORE SUPRA (Cadarache)	JET (Culham, Angleterre)	ITER (Cadarache)
Puissance de fusion	-	16 MW	500 MW
Volume du plasma	30 m^3	100 m^3	840 m^3
Grand rayon du plasma	2,40 m	3 m	6,20 m
Petit rayon du plasma	0,72 m	1,25 m	2 m
Hauteur du plasma	1,4 m	4,2 m	6,80 m
Durée de maintien des plasmas	6 minutes	$\leq$1 minute	De 6 minutes à 16 minutes

ITER

Tokamak , toroïdal chamber with magnetic coils

Invented by :
Igor Tamm
Andreï Sakharov
Oleg Lavrentiev
in the 50's



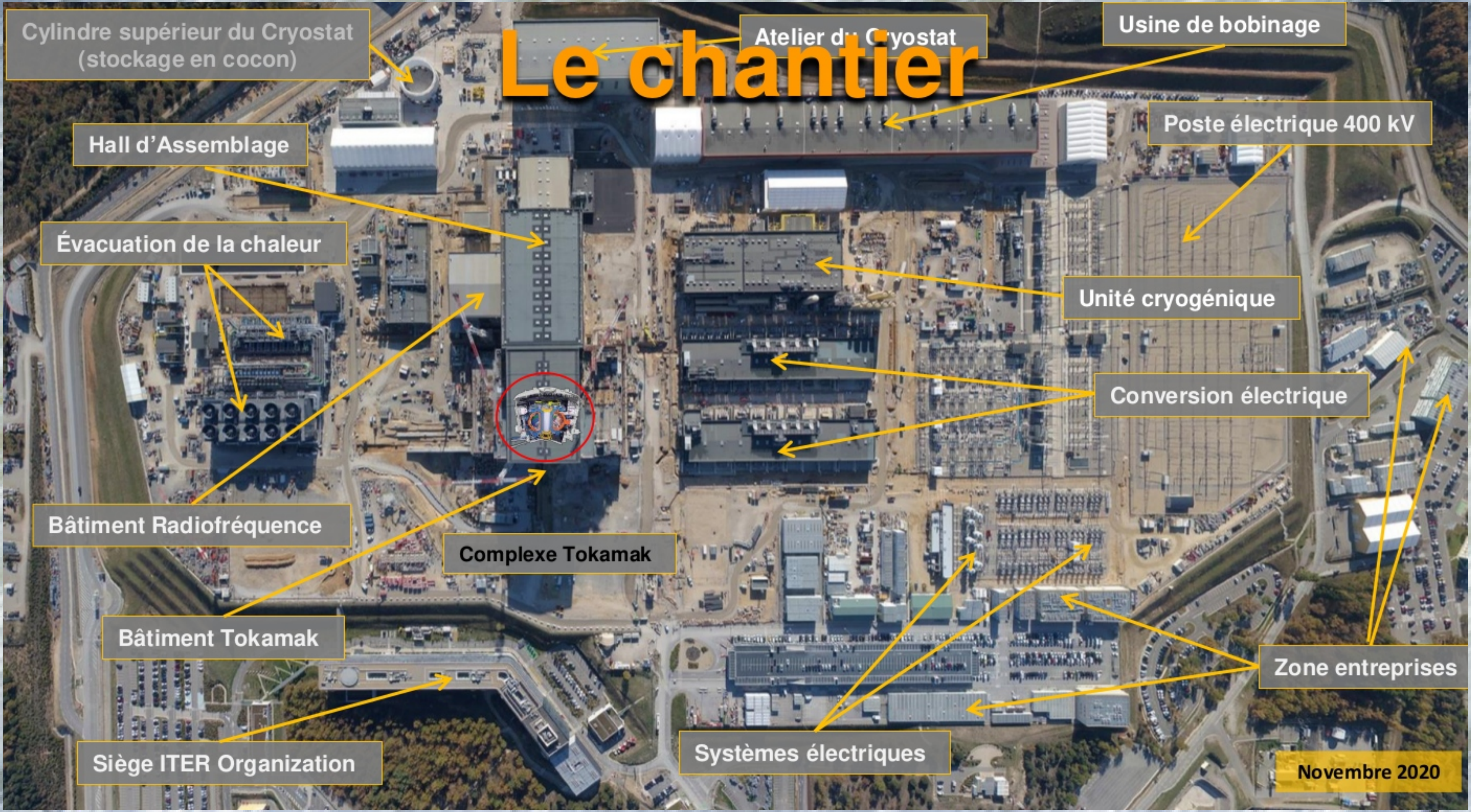

MANY HANDS

Multiple members will build each piece of ITER

ITER : construction in progress in 2019 in Cadarache

In 2020

Le chantier



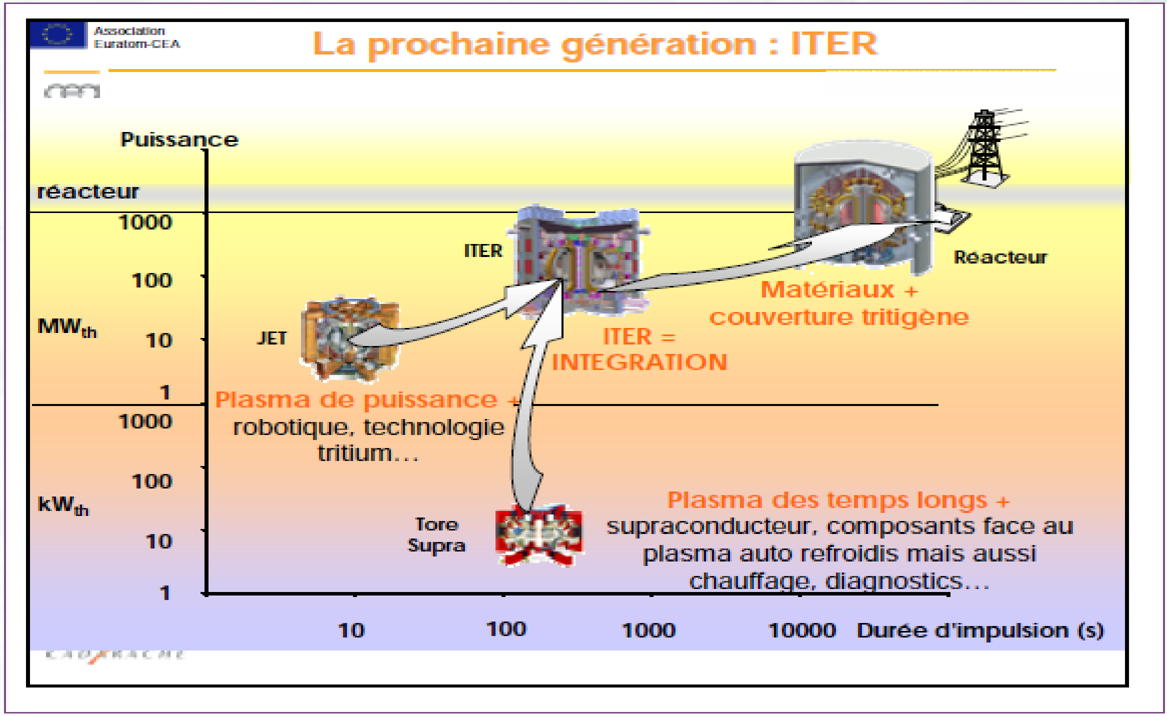
Novembre 2020

First ITER plasma in 2025

Nominal power in 2035.

Next step : industrial prototype

DEMO , 1200 MW$_{th}$, 500 MW$_{e}$



Association Euratom-CEA

La prochaine génération : ITER

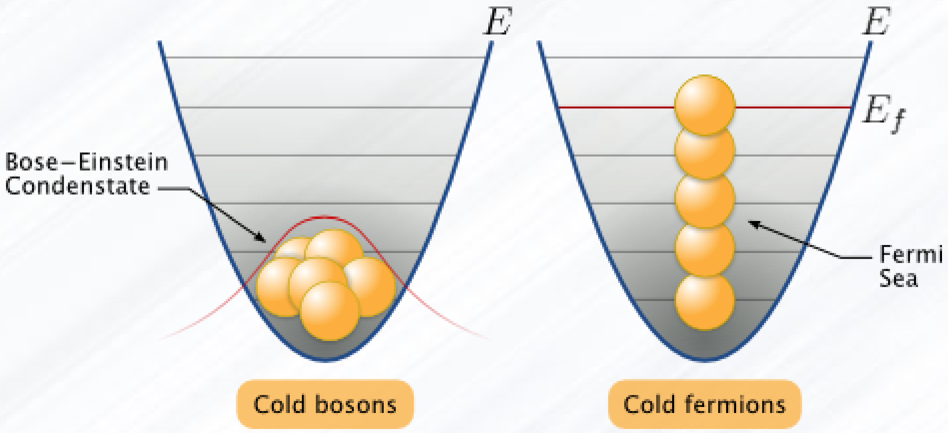
Plasma de puissance + robotique, technologie tritium…

ITER = INTEGRATION

Matériaux + couverture tritigène

Plasma des temps longs + supraconducteur, composants face au plasma auto refroidis mais aussi chauffage, diagnostics…

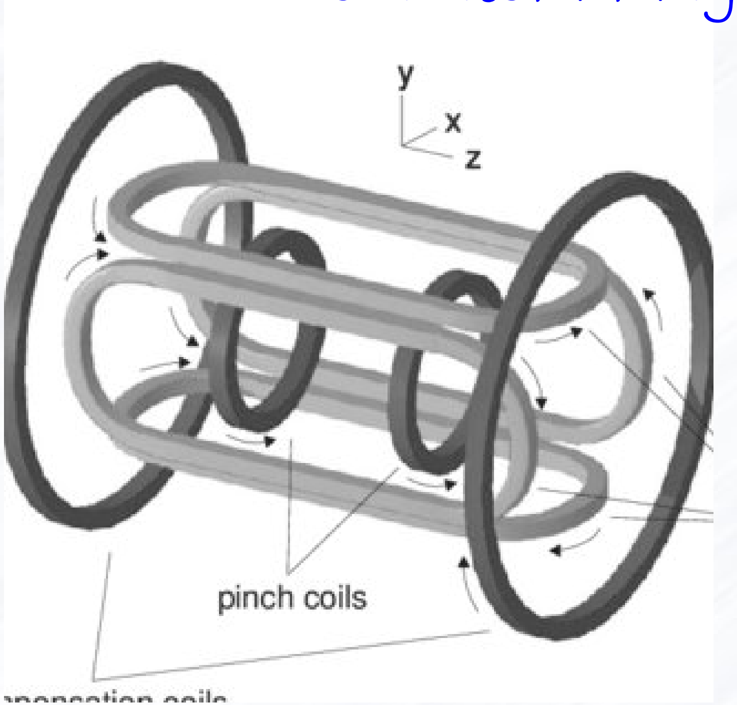
Bosons and fermions



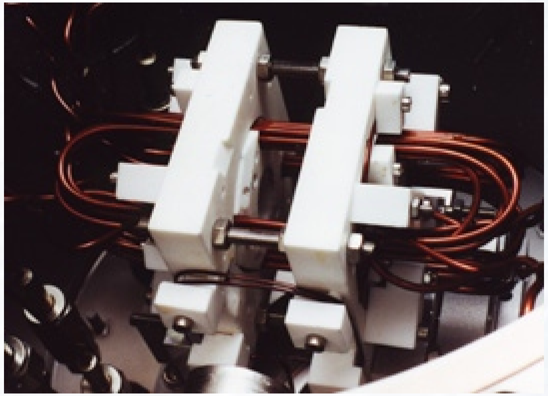
Bosons : spin is integer multiple of ħ (Bose-Einstein condensation, superconductivity, superfluidity, laser, interaction messengers)

Fermions : spin is half-integer multiple of ħ (atomic shells , atomic forces, conductivity ....)

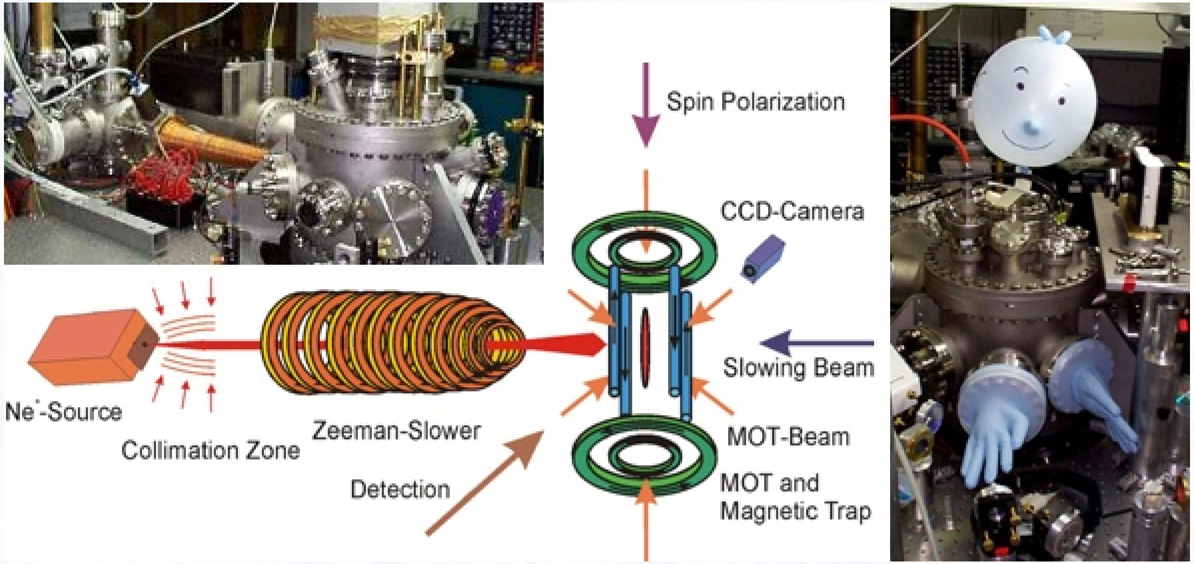
Cold atom magnetic trap



Ioffe-Pritchard magnetic trap

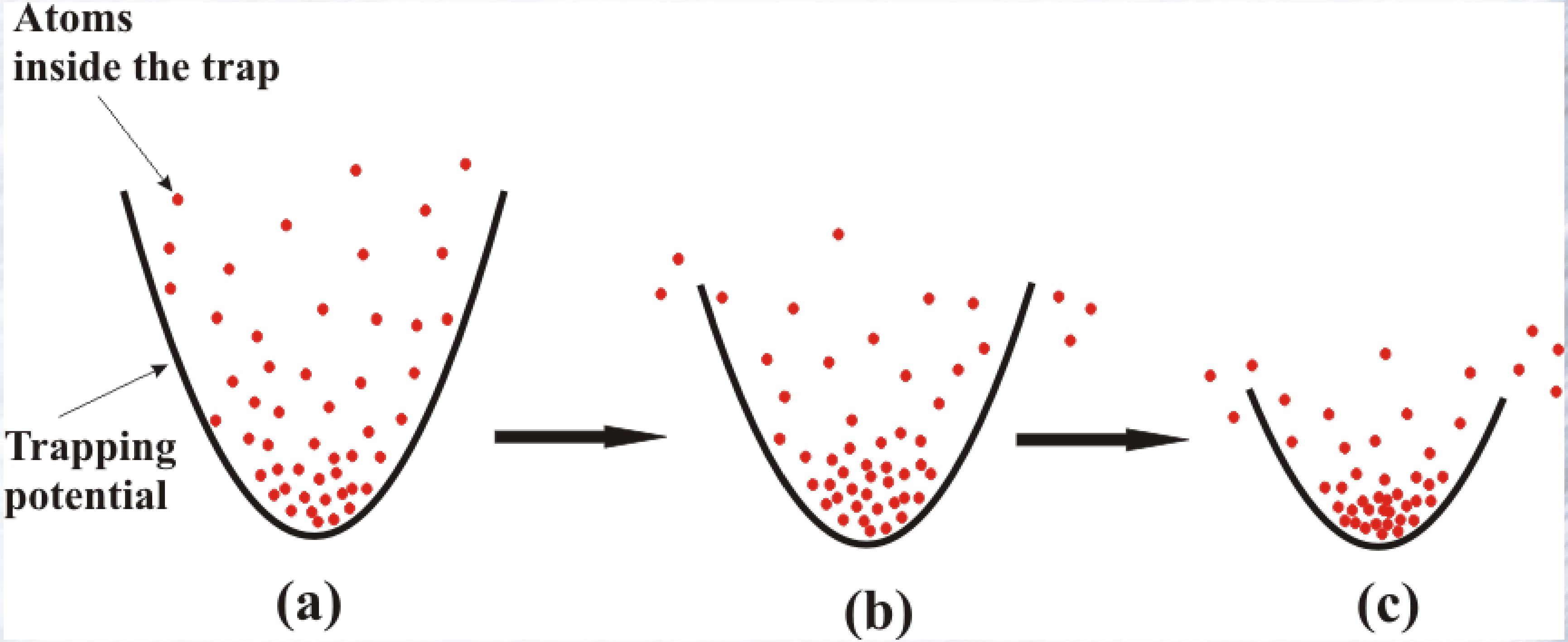


Setup to prepare ultracold Ne* atoms : Magneto-Optical Trap

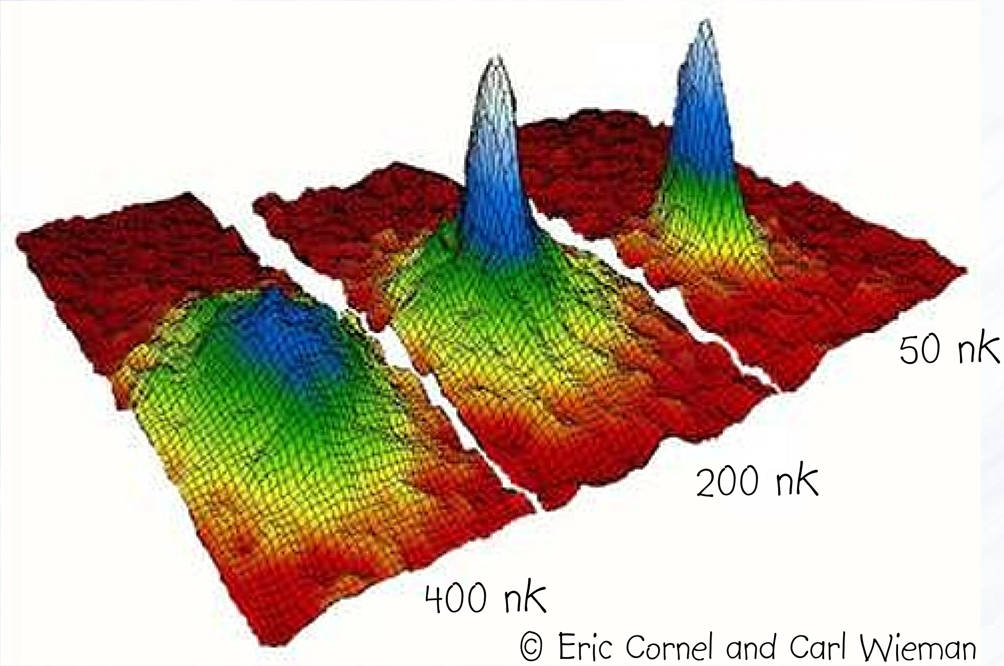


W. van Drunen, N. Herschach, G. Birkl, W. Ertmer : TU Darmstadt

Evaporative cooling



Bose-Einstein condensation (BEC)



© Eric Cornel and Carl Wieman

low density gas of
Rubidium atoms (bosons)
at very cold T

At 200 nK Rb atoms start condensing into BEC

At 50 nK, BEC is almost pure

Intially observed with 2000 remaining atoms, but more recent experiments achieve more than a million atoms

2001 Nobel Prize :
E. Cornel
C. Wieman
W. Ketterle

Exercise

- Show that the average de Broglie wavelength of atoms, is given by :

$$ƛ = \frac{\hbar c}{\sqrt{3 m c^2 k T}}$$

  where k is Boltzmann's constant.
  Hint : At thermal equilibrium, the average kinetic energy of atoms is
  E = 3/2 k T

- Knowing that $\hbar c$ = 197 MeV fm and $mc^2 \approx A \times 931$ MeV , compute the de Broglie wavelength of 200 nK and 50 nK ^{87}Rb atoms.

- Conclude

Solution of exercise

$$p = m\,v = \frac{\hbar}{\lambdabar}$$

$$E = \frac{1}{2} m\,v^2 = \frac{3}{2} k\,T$$

$$\lambdabar = \frac{\hbar}{m\,v} = \frac{\hbar\,c}{\sqrt{3\,m\,c^2\,k\,T}}$$

$$\hbar\,c = 197 \quad \text{MeV fm}$$

$$k = 0.86\,10^{-10}\,\text{MeV K}^{-1}$$

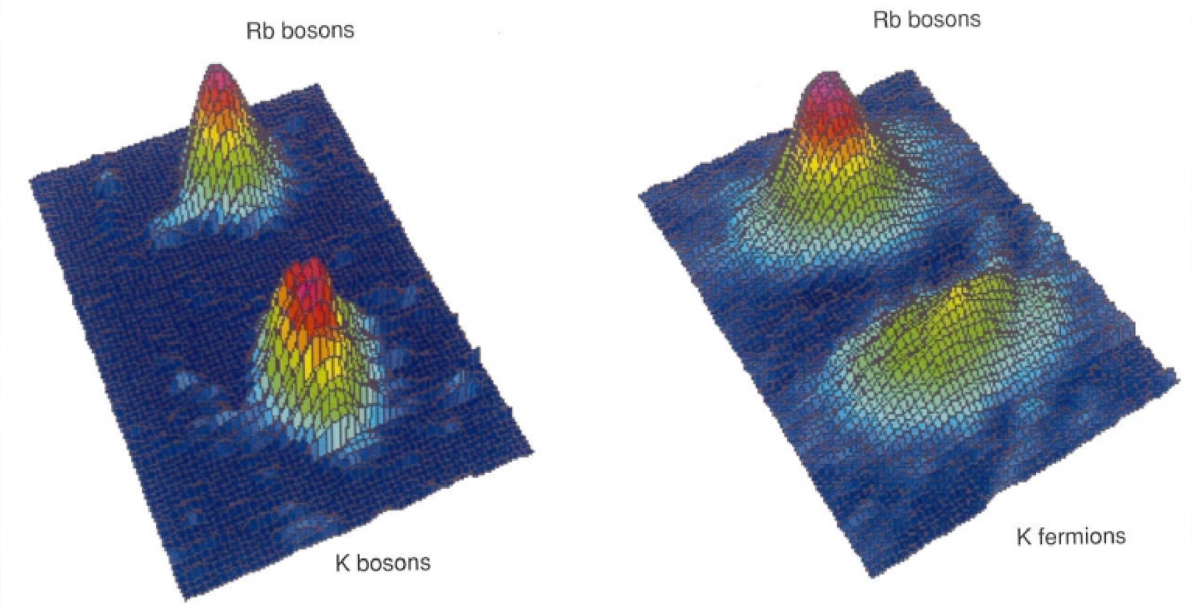
200 nK and 50 nK ^{87}Rb atoms

$$\lambdabar(200\,\text{nK}) = 96\,\text{nm}$$

$$\lambdabar(50\,\text{nK}) = 192\,\text{nm}$$

De Broglie wavelength much bigger than atom size

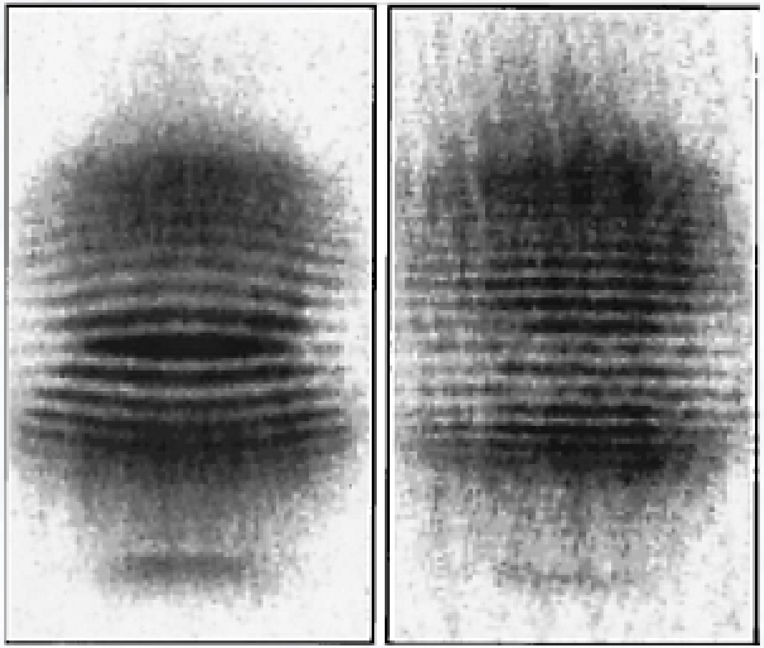
Bose-Einstein condensation



BEC observed
for bosons only

© Massimo Inguscio, University of Florence

Interference of two BEC

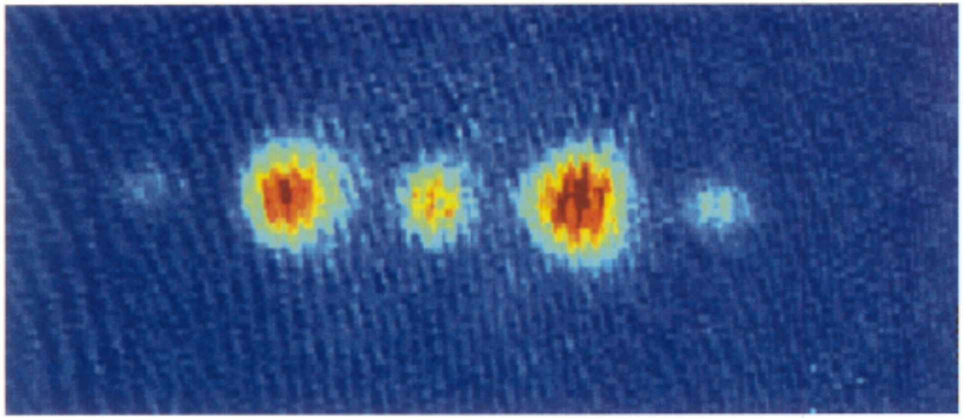


M.R. Andrews et al., Science 275, 637-641 (1997)

Interference pattern of two sodium BEC when made to overlap.

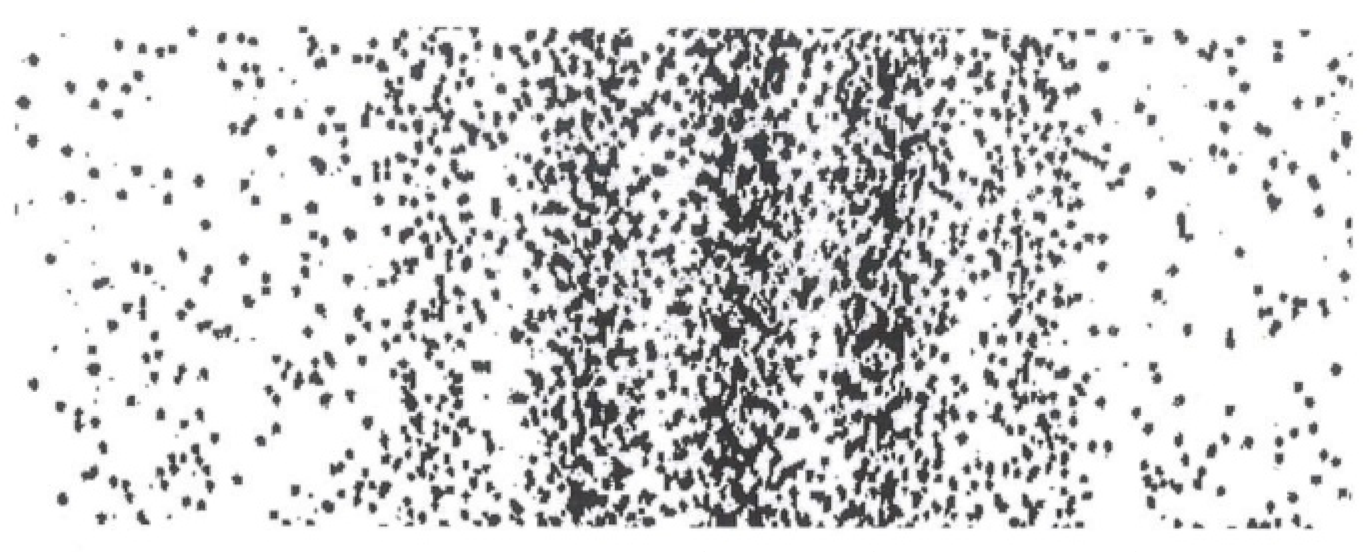
Bragg diffraction of cold atoms.

Cold atoms localized in an optical lattice and set free.
Atom waves from regular lattice form a Bragg diffraction pattern.



© R. Godum, V. Boyer, D. Cassettari, G. Smirne, Oxford

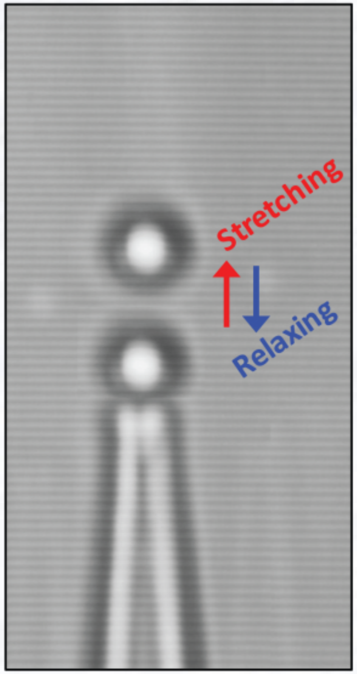
Young fringes of de Broglie atom waves



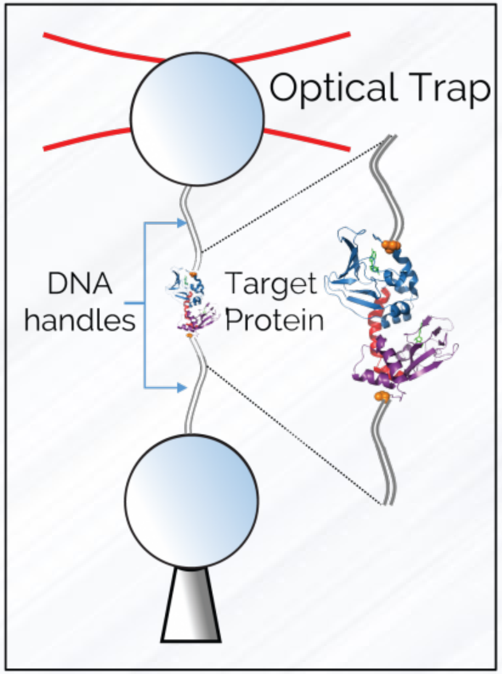
© F. Shimizu, University of ToKyo

Cold atom cloud above a plate pierced with two slits. After behing released, fringes are observed on detection plane localized on the other side of plate.

Optical tweezers



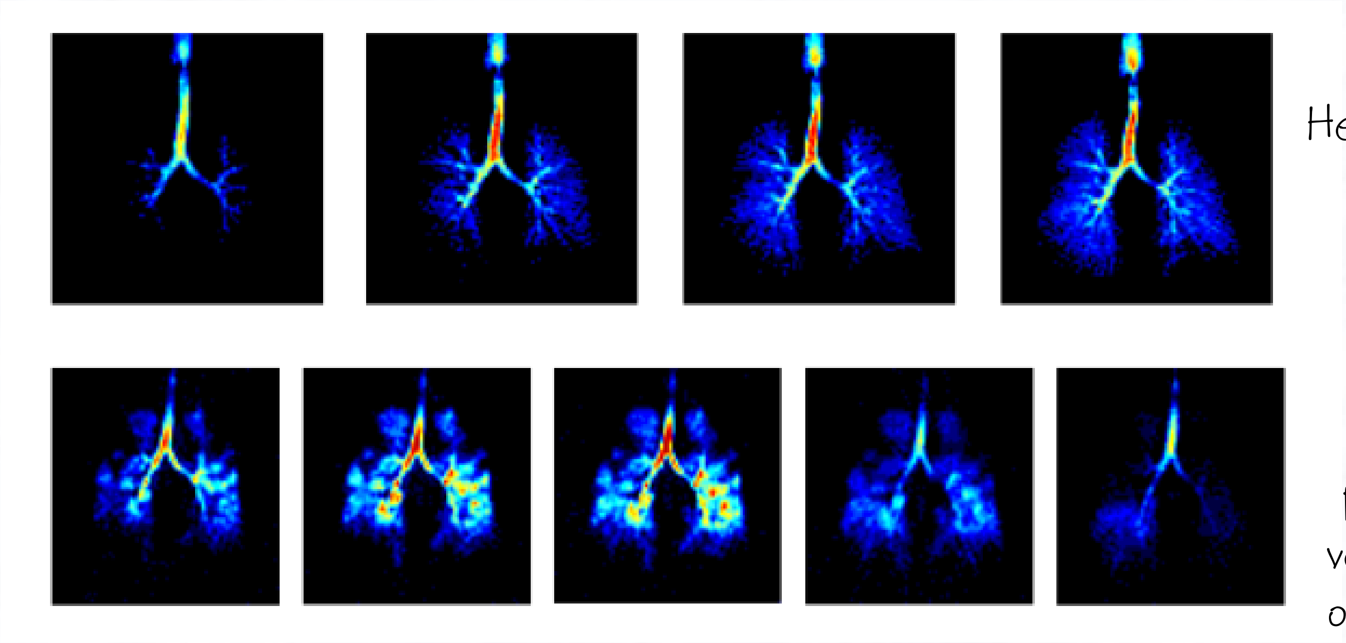
Real Experiment



Schematic Representation

2018 Physics Nobel Prize : A. Ashkin

Polarized-He3 MRI lung imaging



Healthy patient

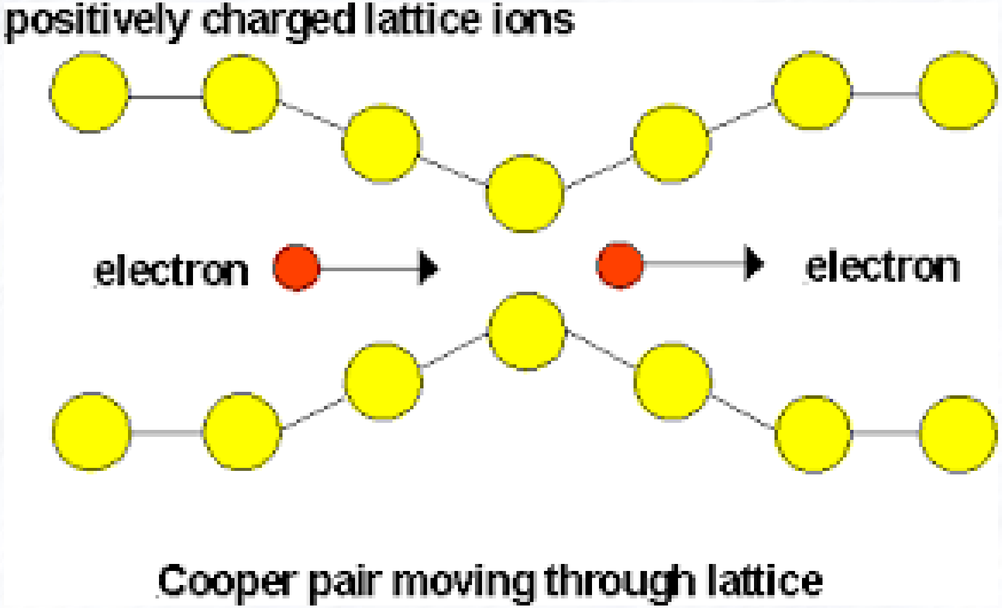
patient showing ventilation obstructions

Polarized-He3 obtained by optical pumping

M. Leduc and P. Jean Nacher

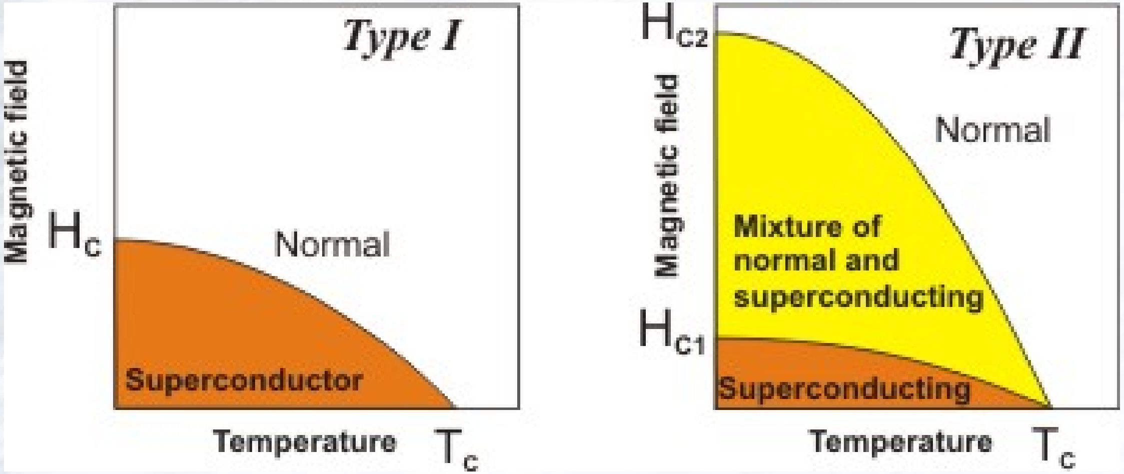
Superconductivity

J. Bardeen
L. Cooper
J.R. Schrieffer
1972 Physics
Nobel Prize

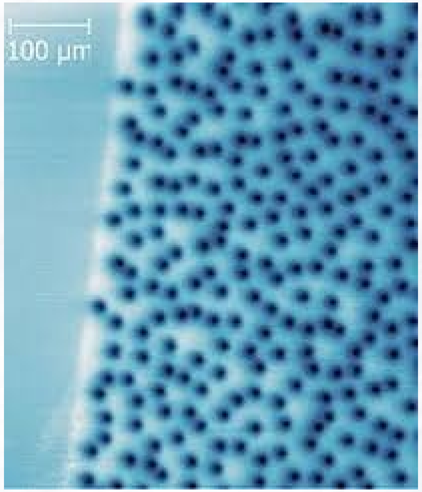


Electron Cooper pairs form bosons and may then condensate in one coherent macroscopic state.

Type I and II superconductors

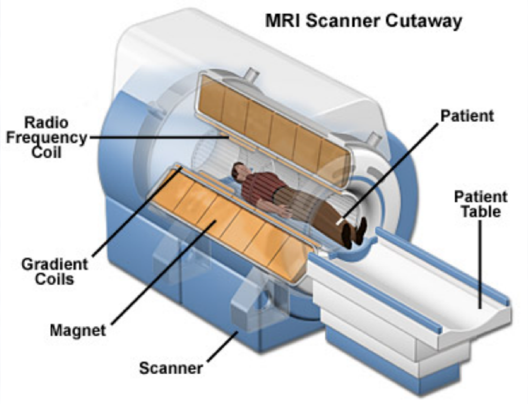


Type II may be used in technological applications

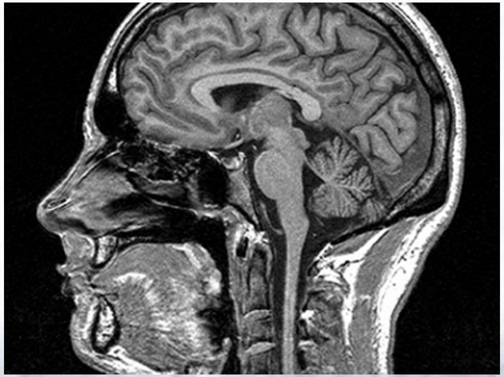


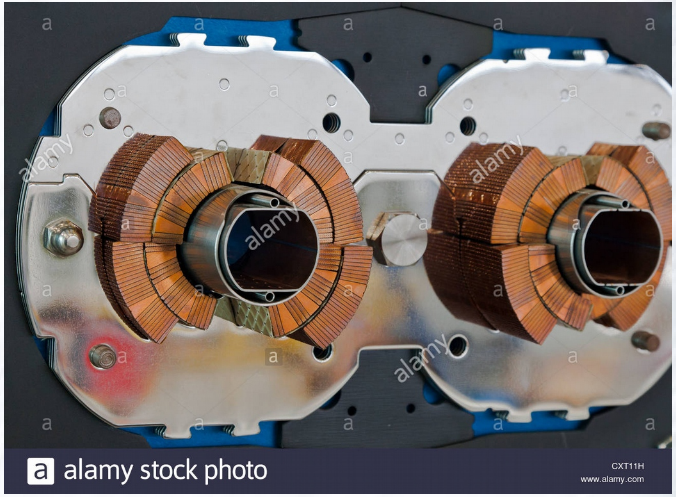
Vortices in Type-II superconductors

Superconductivity applications



MRI magnets
up to 11 T



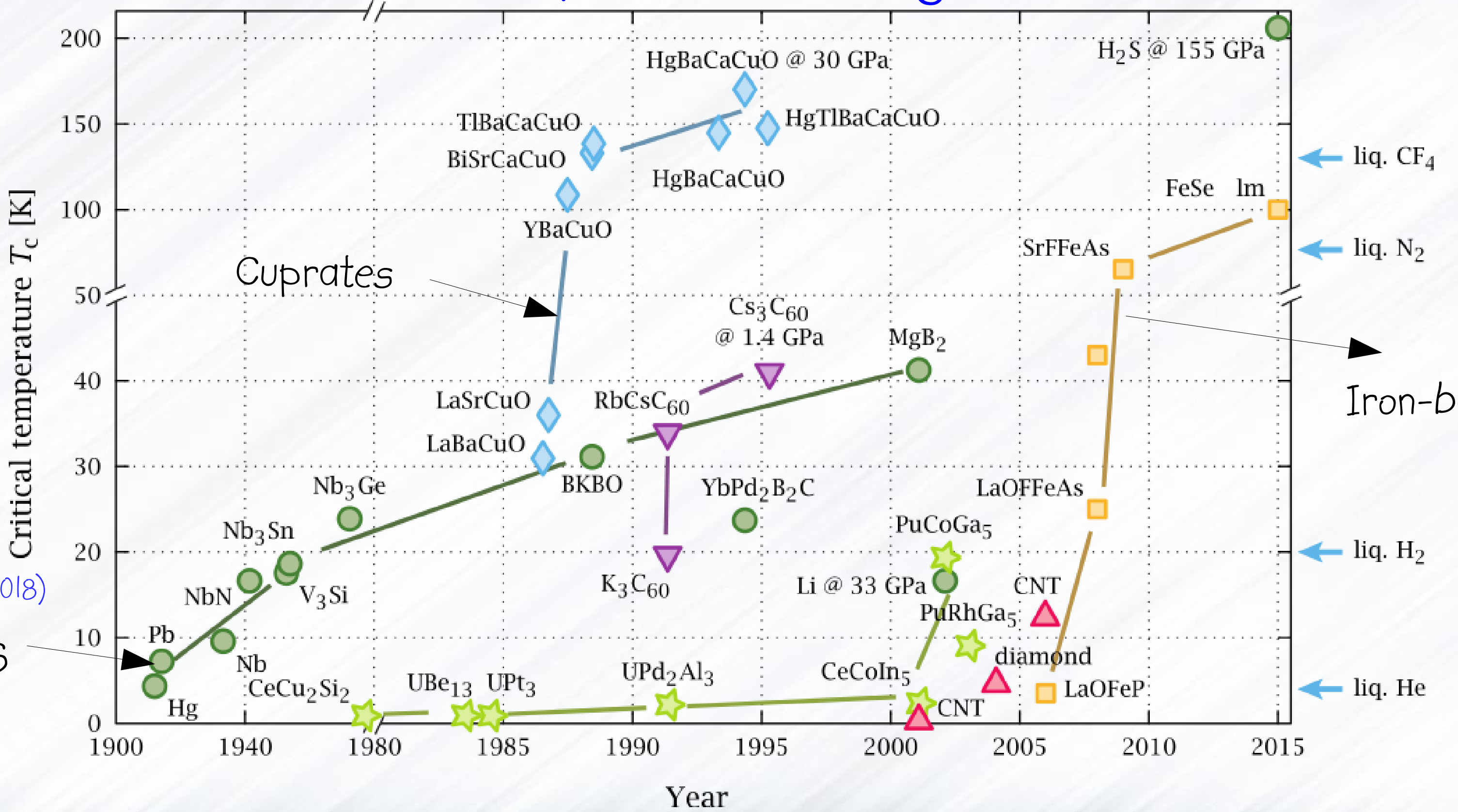


LHC dipole magnets - 8.3 T

Research on superconducting materials

J.G. Bednorz
K.A. Müller
1987 Physics
Nobel Prize

Graphene was also found to be superconducting in 2018 at 1.7 K
Nature 556,43-50 (2018)



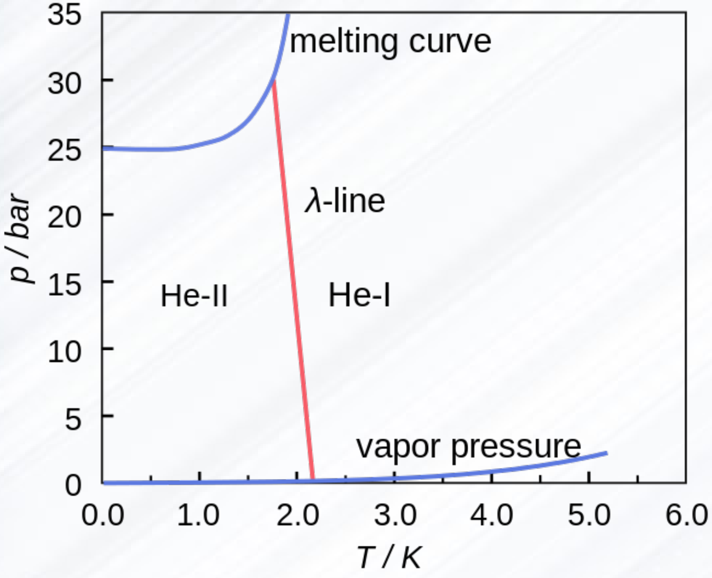
Cuprates

Iron-based

BCS

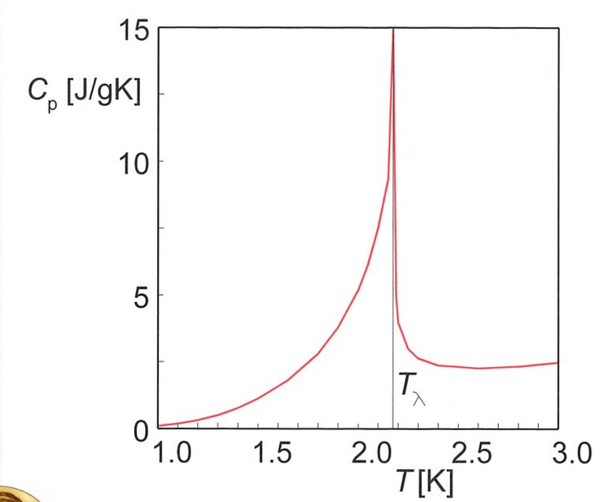
The theory of high-temperature superconductors is still an outstanding challenge !

Superfluidity of ^{4}He



Phase diagram of liquid ^{4}He

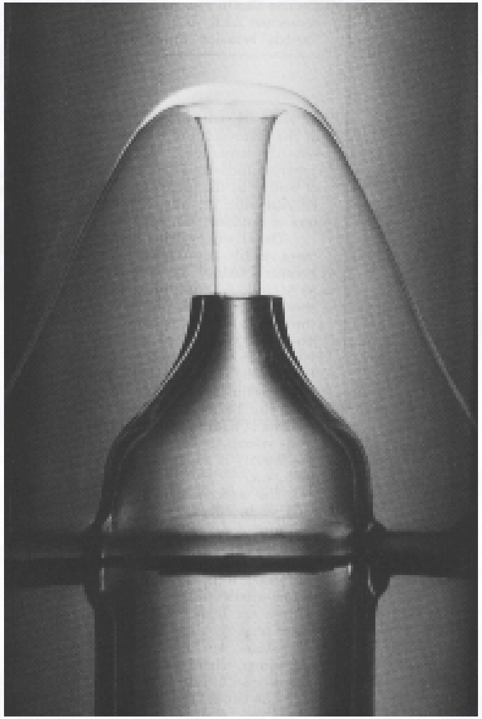
Viscosity drops to zero and heat capacity raises.



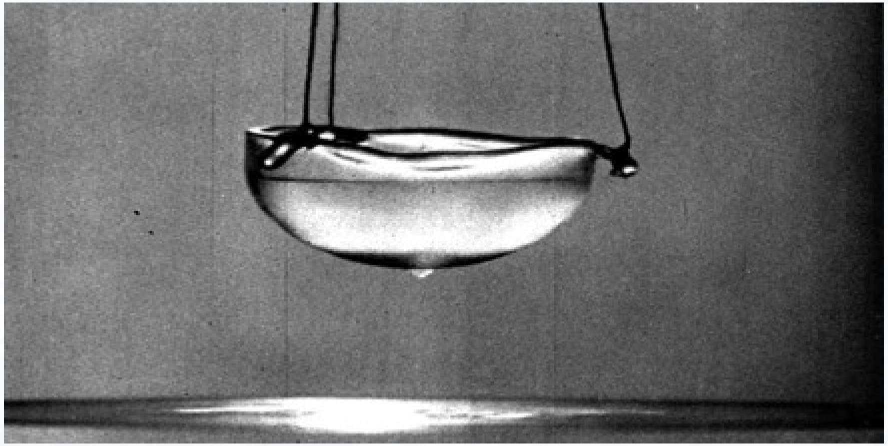
Lev Landau , 1962 Physics Nobel prize

A. Leggett, V. Ginzburg, A. Abrikossov
2003 Physics Nobel prize

Superfluidity of ^{4}He

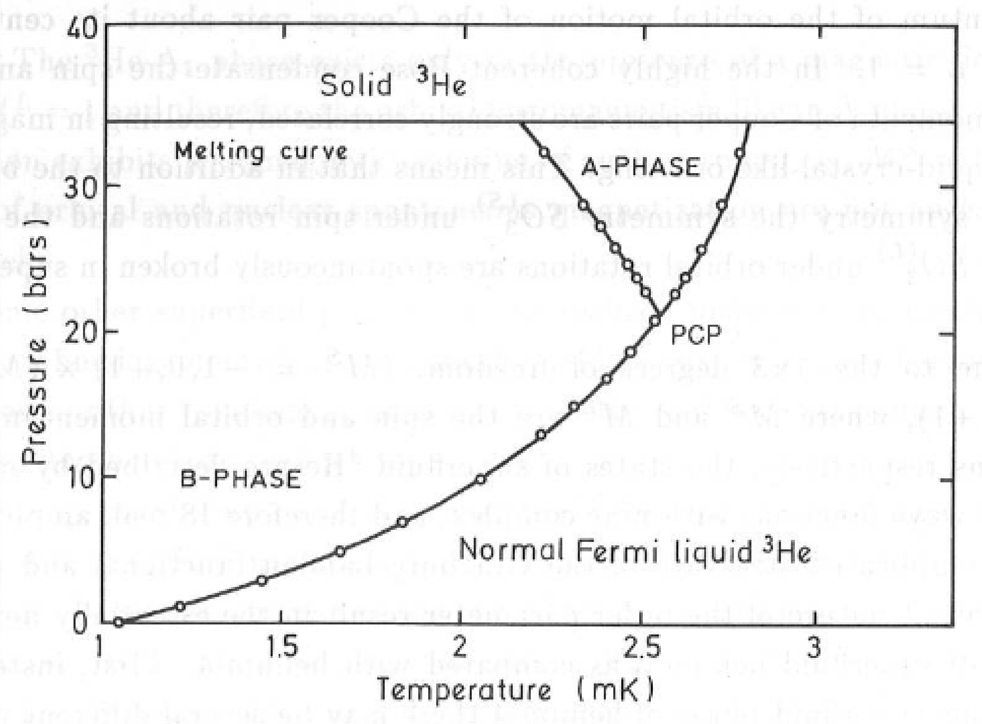


Fountain effect produced by heating. LHe flows through fine powder at the bottom.



Dripping off a cup after being lifted above the container surface level - Superfluid He flows through adsorbed surface film.

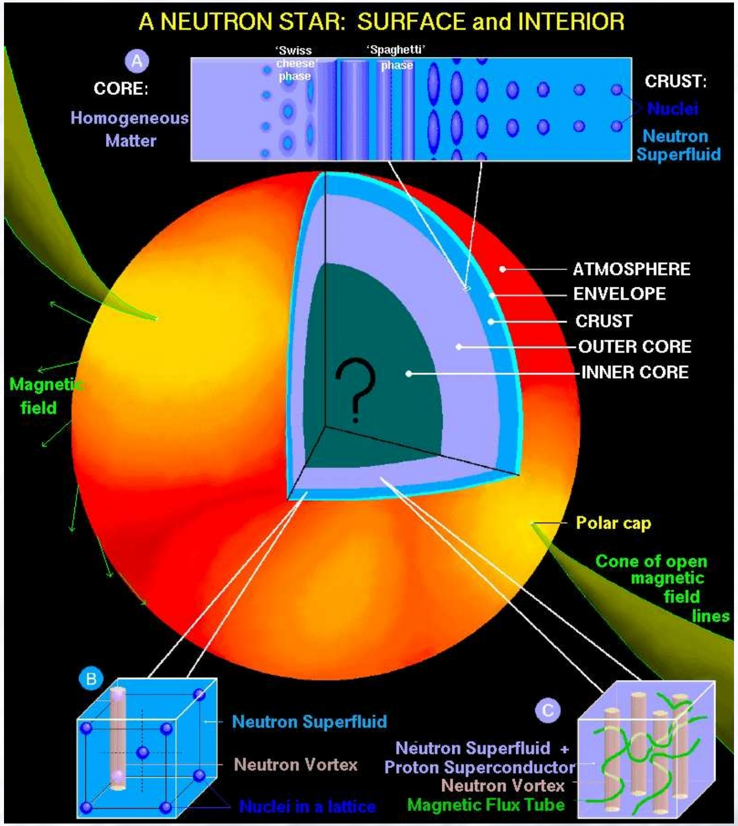
Superfluidity of ^{3}He



D. Lee
R. Richardson
D. Osheroff
1996 Physics
Nobel Prize

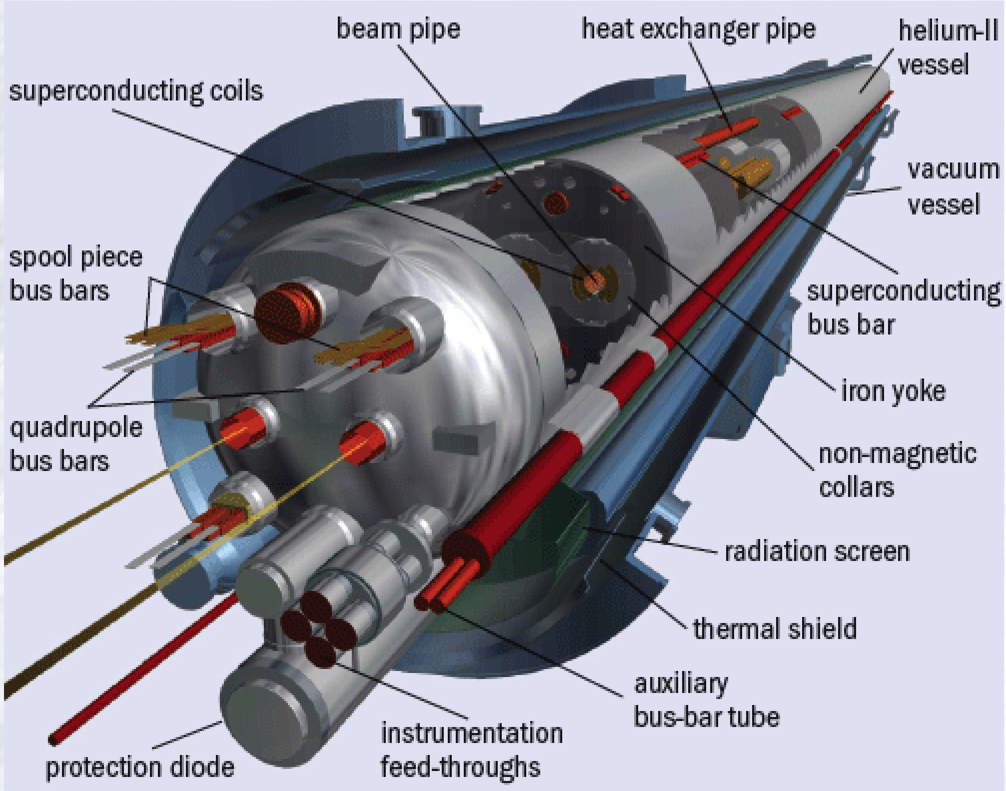
^{3}He is a fermion but at low enough T, ^{3}He atoms pair (like Cooper pairs) but in $S=1$ pairs. As a consequence three phases (A, A_1, B) are observed with different physical properties.

Superconductivity and superfluidity in neutron stars



Superfluids and superconductors
are also foreseen in astrophysical objects
under extreme conditions !

Application of superfluidity

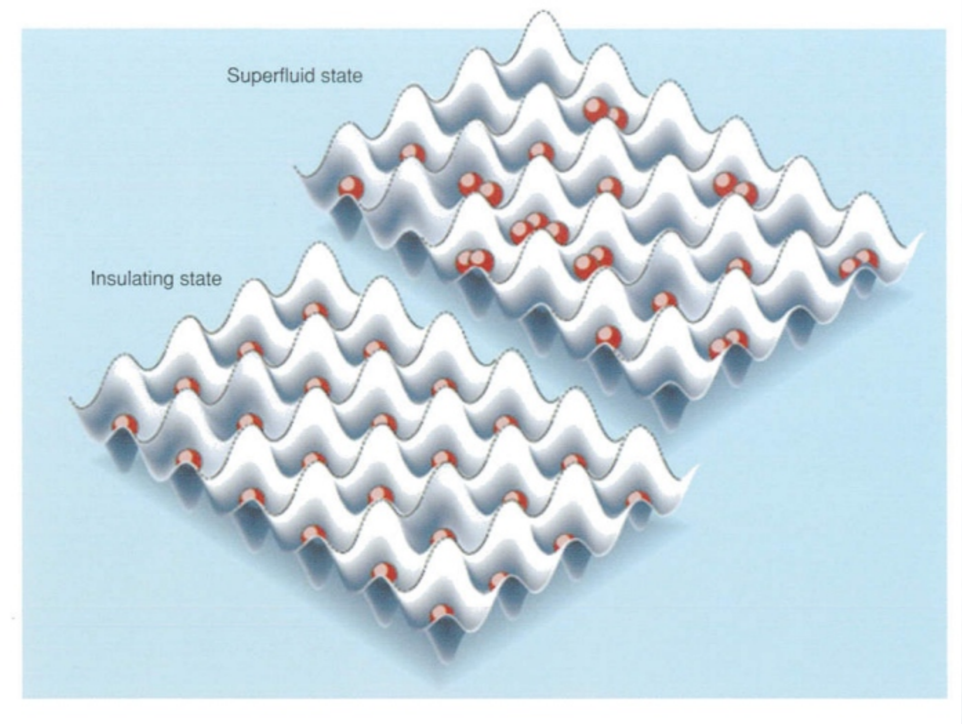


Cooling of LHC superconducting magnets

120 tonnes of superfluid ^{4}He at 1.9 K to cool LHC superconducting magnets.

Quantum phase transitions in BEC

Atoms from a BEC in magneto optical trap are transferred to an optical lattice created by standing waves of laser light.



Weak potential strength

High potential strength

Quantum phase transitions in BEC

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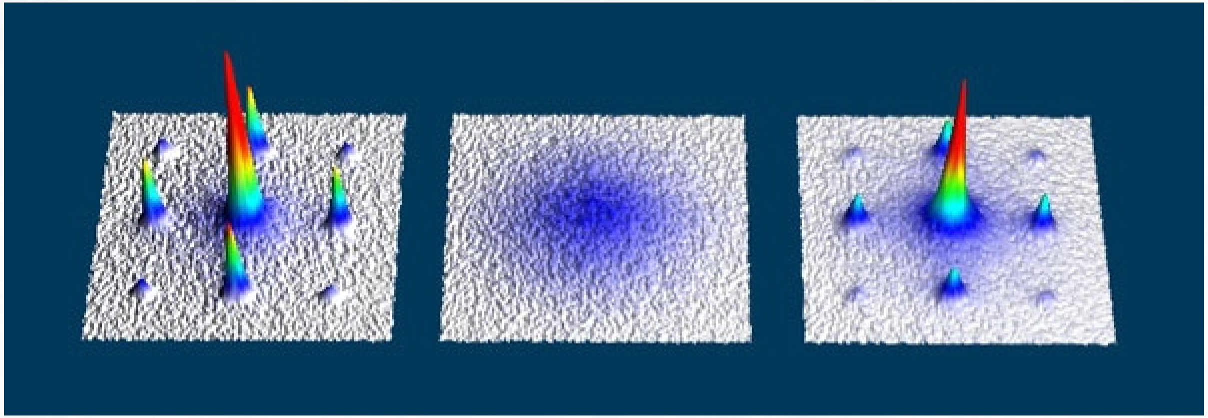
atoms undergo repulsive interaction

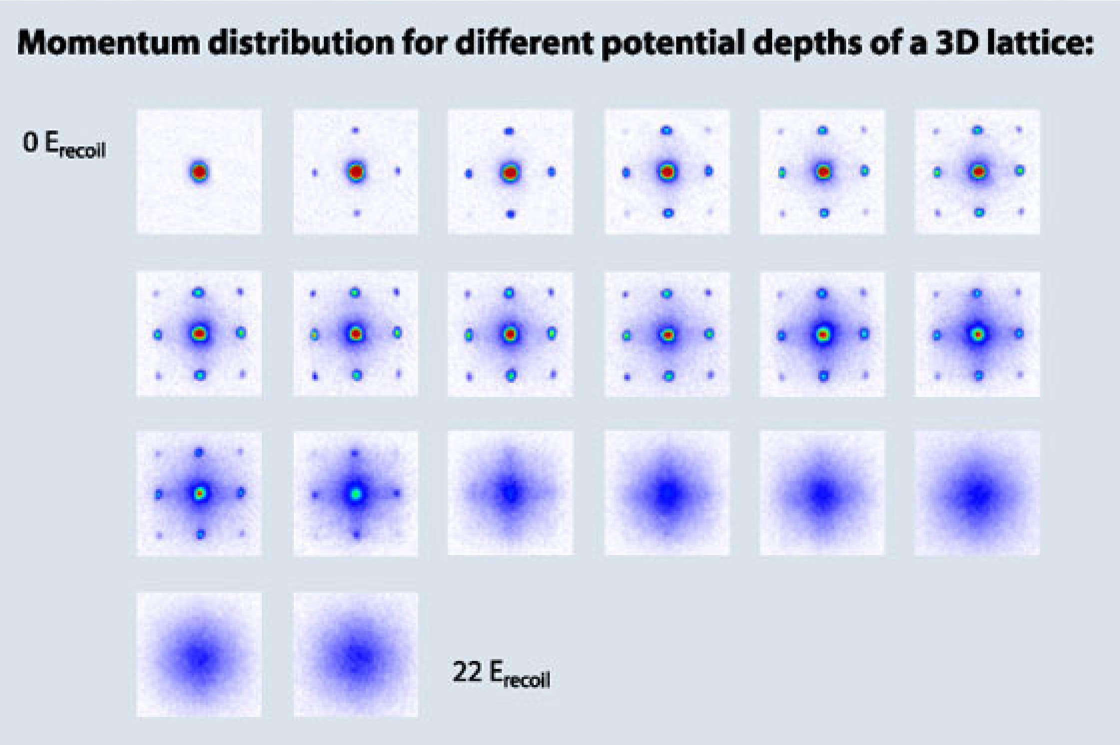


Superfluid
coherent state
at low potential
strength

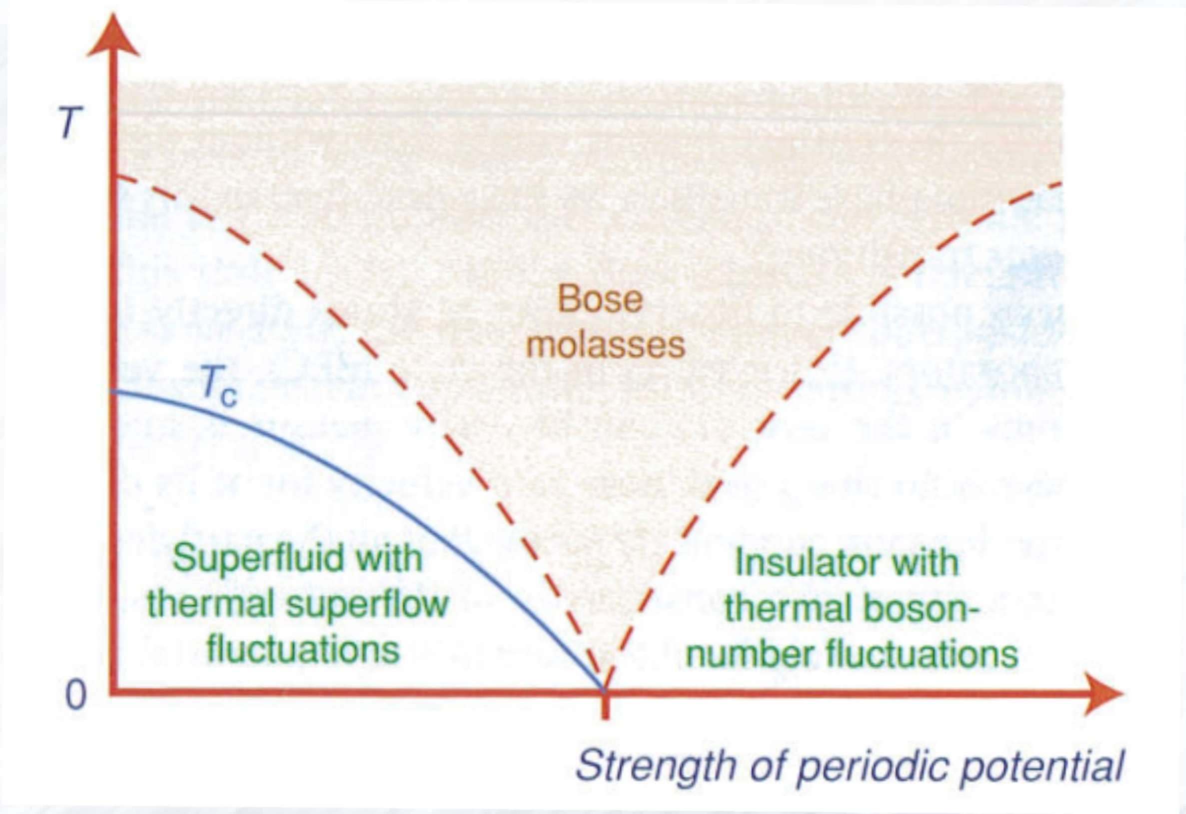
Insulator
at high potential
strength

Superfluid
coherent state
restored

Quantum phase transitions in BEC


Momentum distribution for different potential depths of a 3D lattice:

Quantum phase transitions in BEC



For further reading :

- The new physics for the twenty-first century : edited by Gordon Fraser, Cambridge University Press