Nonideal complex Plasmas in the Universe and in the lab

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4th Summer Institute „Complex Plasmas“, Seton Hall University, August 2014

Chair Statistical Physics - Research Directions

Strongly correlated Coulomb systems

Classical Coulomb systems

Dusty plasmas
Coulomb liquids
Coulomb crystals
Anomalous transport
Plasma-surface interaction

Quantum Coulomb systems

Warm Dense matter
Astrophysical plasmas
Correlated bosons, excitons
Atoms, dense matter interacting with lasers and x-rays
Quark-gluon plasma

First principle simulations
Statistical Physics, Quantum Kinetic Theory
Nonequilibrium Green Functions

Acknowledgements

C | A | U

Bundesministerium
für Bildung
und Forschung

DAAD

DFG

TR 24
complex plasmas

HLRN

Torben: first-principle MD simulations
Patrick: multiscale/dynamical screening dynamics
Hanno, Ingmarl: kinetic and fluid theory
Hauke: laser heating, phase transitions
Jan Willem, „Erwin“, Kenji: plasma-solid surface interaction

Plasma

= System of many charged particles,
dominated by Coulomb interaction

Wikipedia: „*More than 99 % of the visible matter in our universe is in the Plasma state*“

I. Langmuir/L. Tonks (1929): ionized gas - „plasma“

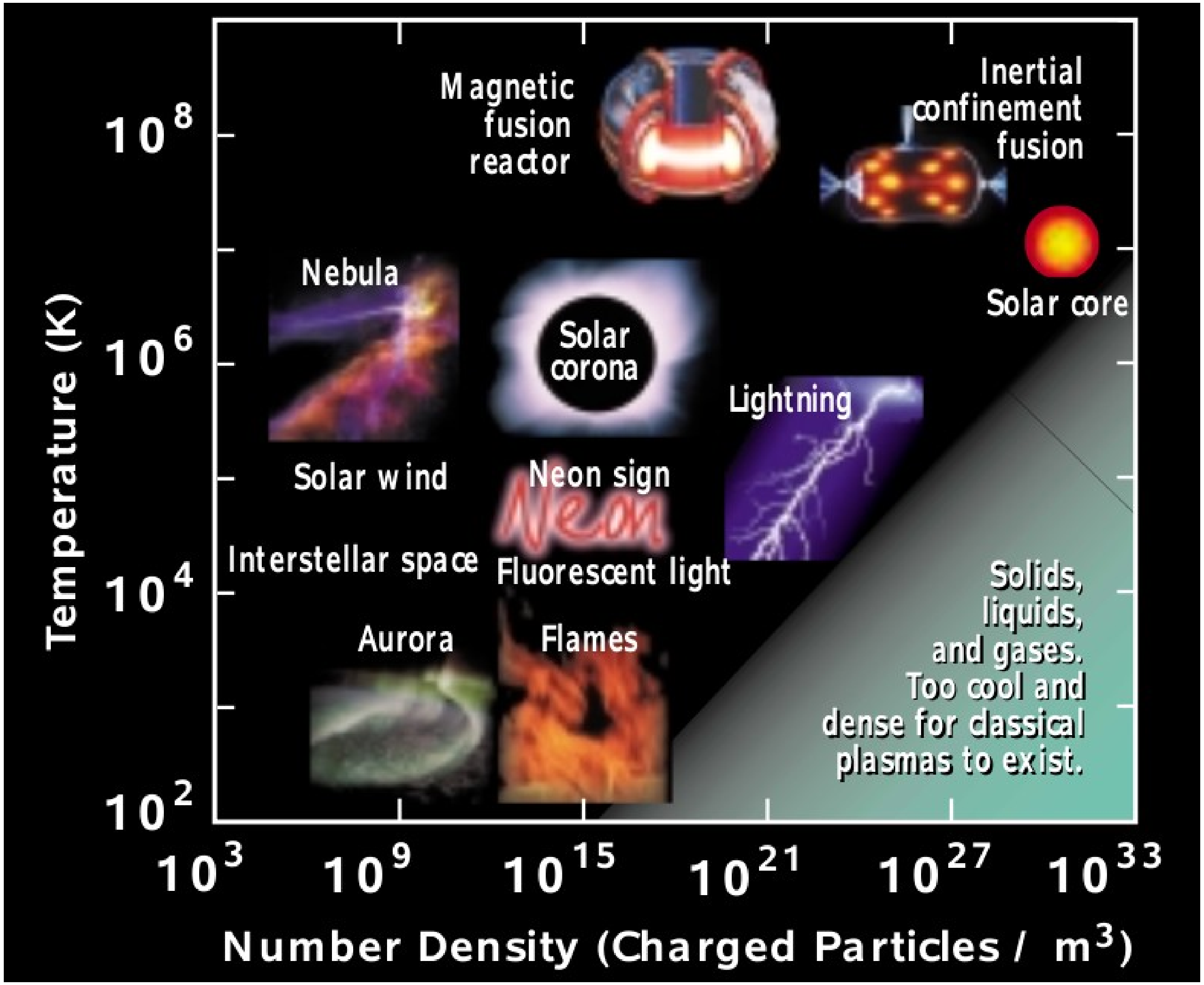
„4th state of matter“: solid → fluid → gas → plasma

ideal hot classical gas

made of electrons and ions

Occurences of Plasma

Contemporary Physics Education Project (CPEP)http://www.cpepweb.org/



Nonideal Laboratory & astrophysical plasmas

Plasma

= System of many charged particles,
dominated by Coulomb interaction

I. Langmuir/L. Tonks (1929): ionized gas - „plasma“
„4th state of matter“: solid → fluid → gas → plasma
ideal hot classical gas
made of electrons and ions

BUT: there exist unusual („complex“) plasmas which
- are „non-ideal“,
- often contain non-classical electrons,

[- may contain other particles, chemically reactive]

Contents

High pressure laboratory plasmas

Atmospheric pressure plasmas

- cold and dense
- microplasmas

- 760 Torr or 100 kPa
- electron density: 10^15...10^18 per cc

→ very unusual plasma properties

More examples of dense plasmas

1. **Plasma in the center of giant planets (Jupiter, Saturn):**
- mostly hydrogen, helium
- T ~ 10,000K … 1 million K
- density of 10^20...10^24 particles per cc.

2. Electron „plasma“ in metals („electron gas“)
- quantum electrons in the periodic crystal potential of ions
- T ~ 300K
- density of 10^21...10^23 particles per cc.

3. „Electron-hole plasma“ in semiconductors
- T ~ 300K
- density of 10^16...10^20 particles per cc.

These plasmas are all very different from an ideal gas

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2. Matter at extreme density
   - White dwarf and neutron stars
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3. From atoms to quarks and the Big Bang

4. Plasma compression in the laboratory
   - Inertial confinement fusion

5. Theory of nonideal plasmas

Occurences of Plasma

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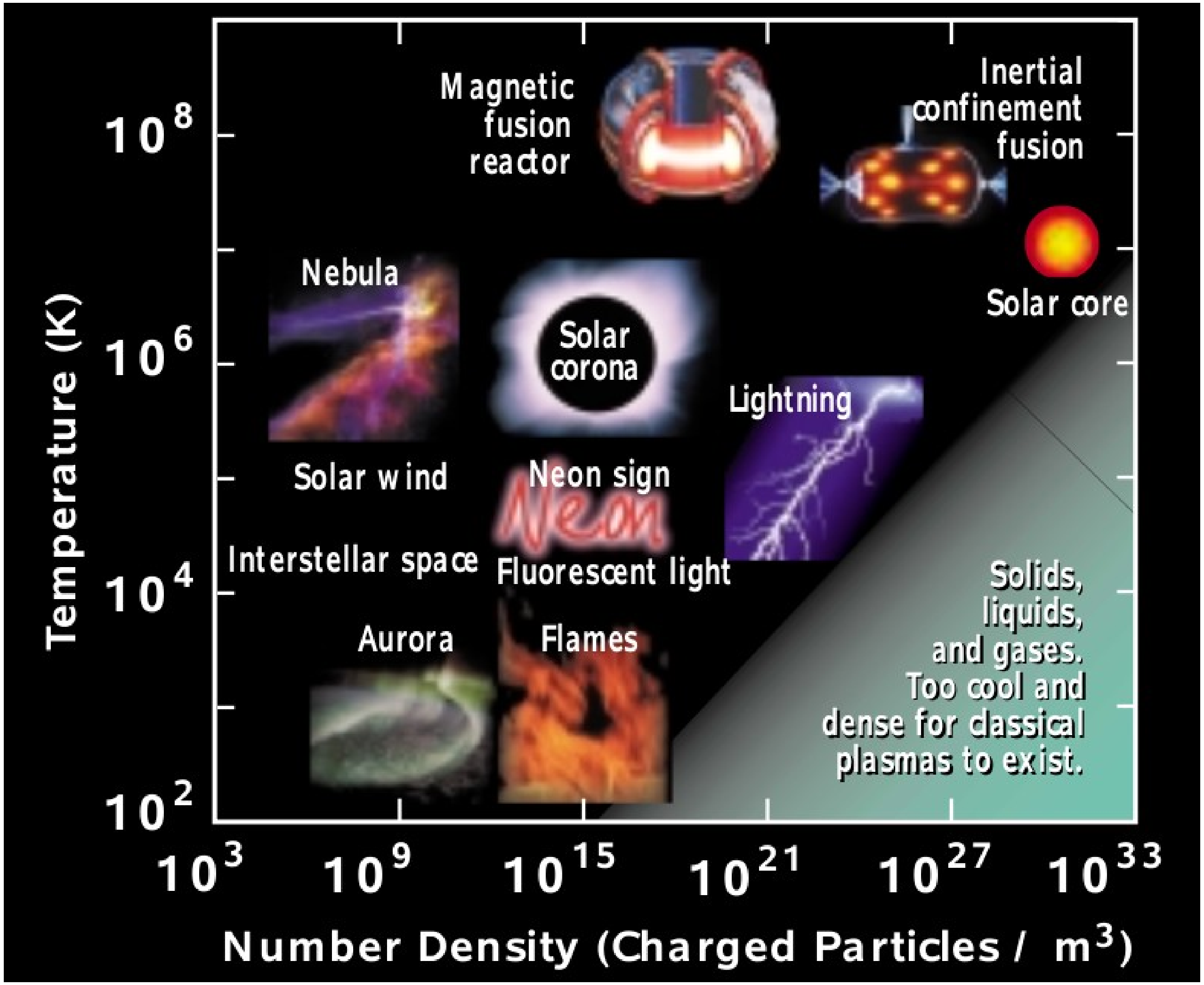


White dwarfs

Plasma theory of white dwarfs

- Starting in the 1960s: Van Horn, DeWitt, Ichimaru, Chabrier…

- At extreme densities matter is expected to be fully ionized… (?)

- Energy of electron-ion plasma (neutral) in thermodynamic equilibrium:

K – kinetic energy, G – gravitation, U – Coulomb interaction

$$H = K_i + K_e + G_{e+i} + U_{ee} + U_{ii} + U_{ei}$$

Plasma theory of white dwarfs

K – kinetic energy, G – gravitation, U – Coulomb interaction

$$H = K_i + \underbrace{K_e + G_{e+i}}_{H_0[n(M)] \approx const} + \underbrace{U_{ee} + U_{ii} + U_{ei}}_{\text{U (small)}}$$

- Electrons exptected to be spatially homogeneous, quantum degenerate, weakly interacting

- **One-component plasma model (OCP, jellium)**, TD equilibrium:

$$\langle H \rangle(T,n) - H_0 - U_{e,back} = \langle K_i \rangle + \langle U_i \rangle = \langle K_i \rangle [1 + \Gamma_i(T,n)]$$

→ Plasma state defined by single „coupling“ parameter

Thermodynamics of OCP

Classical „one-component plasma“ (OCP)

$$\Gamma = \frac{|\langle U \rangle|}{\langle E_{KIN} \rangle} = \frac{e^2}{k_B T \, \bar{r}}$$

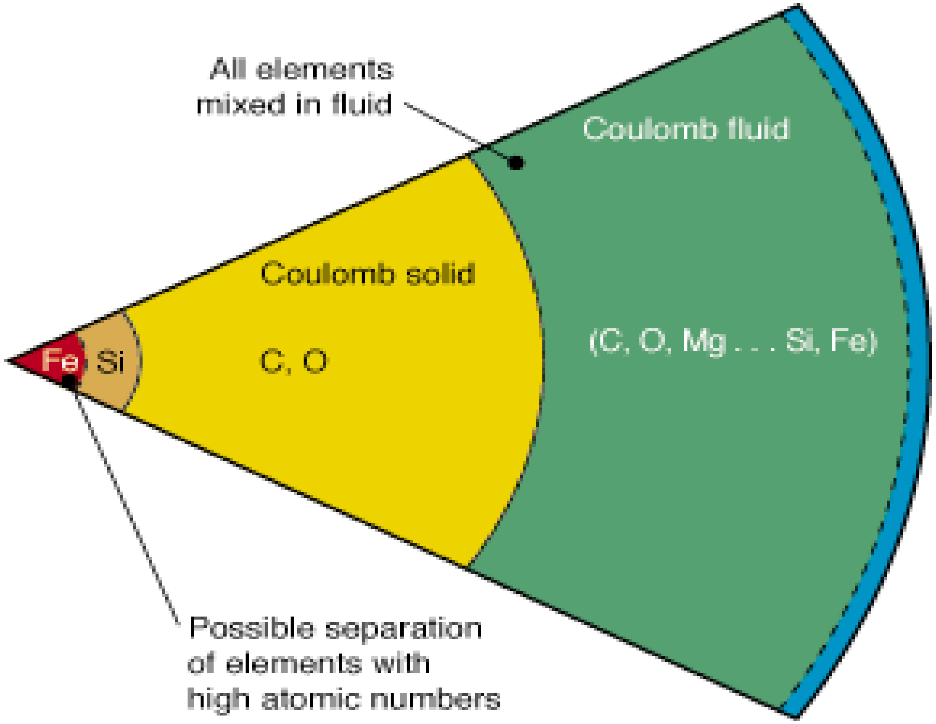
Liquid-solid transition below critical temperature (above critical coupling strength).

$$\Gamma_{cr} \approx 175 \, (2D : 137)$$

2D MD simulation of OCP cooling/heating, Periodic b.c., Torben Ott

Predicted by **Wigner** 1934 for the electron gas in metals.

White dwarf star



Structure of the interior of a white dwarf star, showing how the elements are distributed. EBIT–RETRAP recreates the thermodynamic conditions shown in the yellow section, where the ion plasmas crystallize.

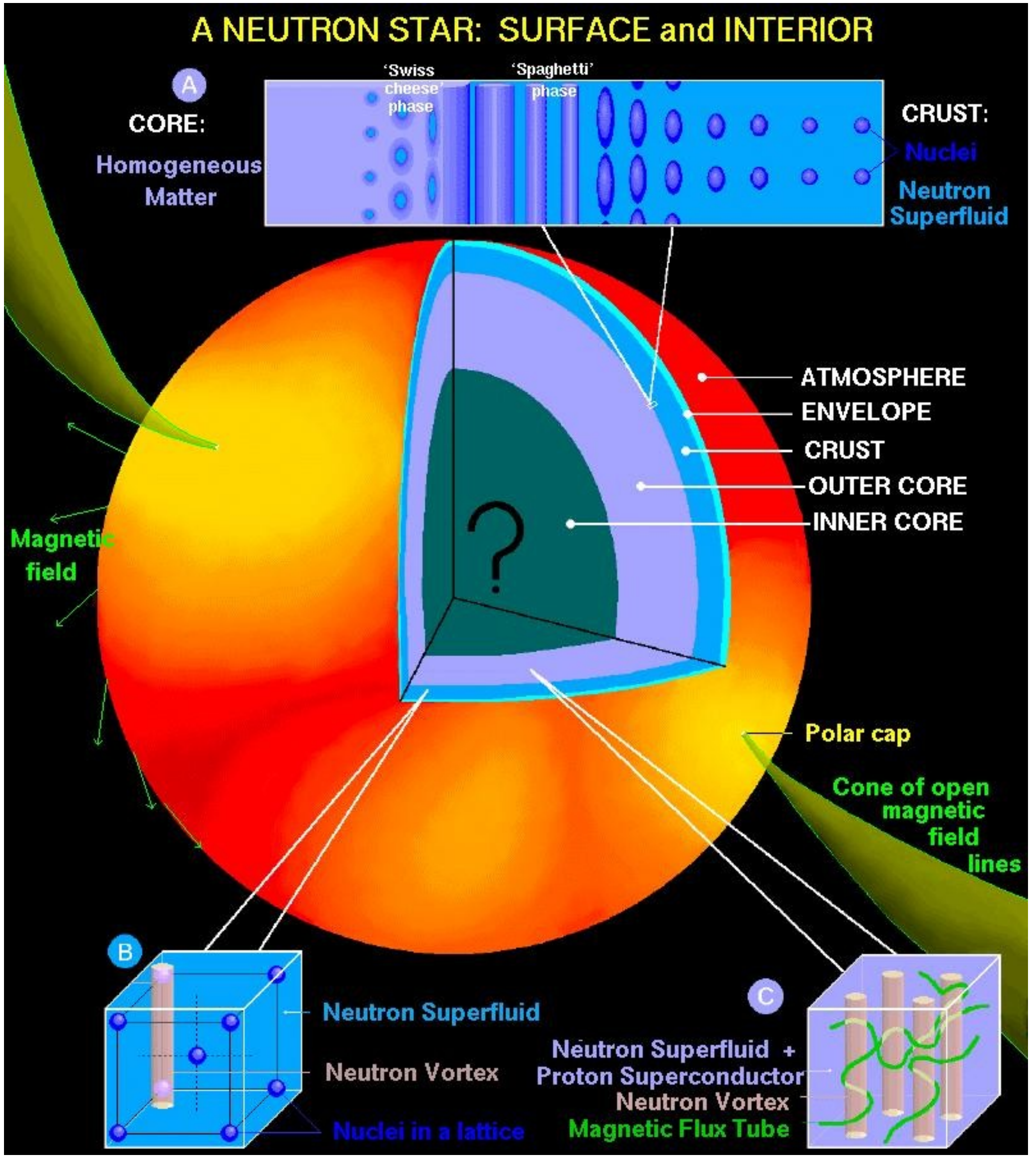
D. Schneider, LLNL

classical
fluid and crystal
in „quantum sea“
of electrons

Size ~ our Earth
Mass ~ our Sun
→density:

$$\rho \cong 10^6 \ \rho_{ERDE}$$

Neutron star



Envelope:
crystal and
quantum fluid
of Fe-nuclei
(Why?)
in „quantum sea“
of electrons

Radius ~ 10km
Mass ~ our Sun

$$\rho \cong 10^{15}\, g\, cm^{-3}$$

Source: Coleman, UMD

Universality of one-component plasmas

OCP with same coupling parameter(s)
show same behavior

M. Bonitz, Physik Journal 7/8 (2002)

Can we realize the same coupling as in stars
in the lab? Can we realize Coulomb crystals?

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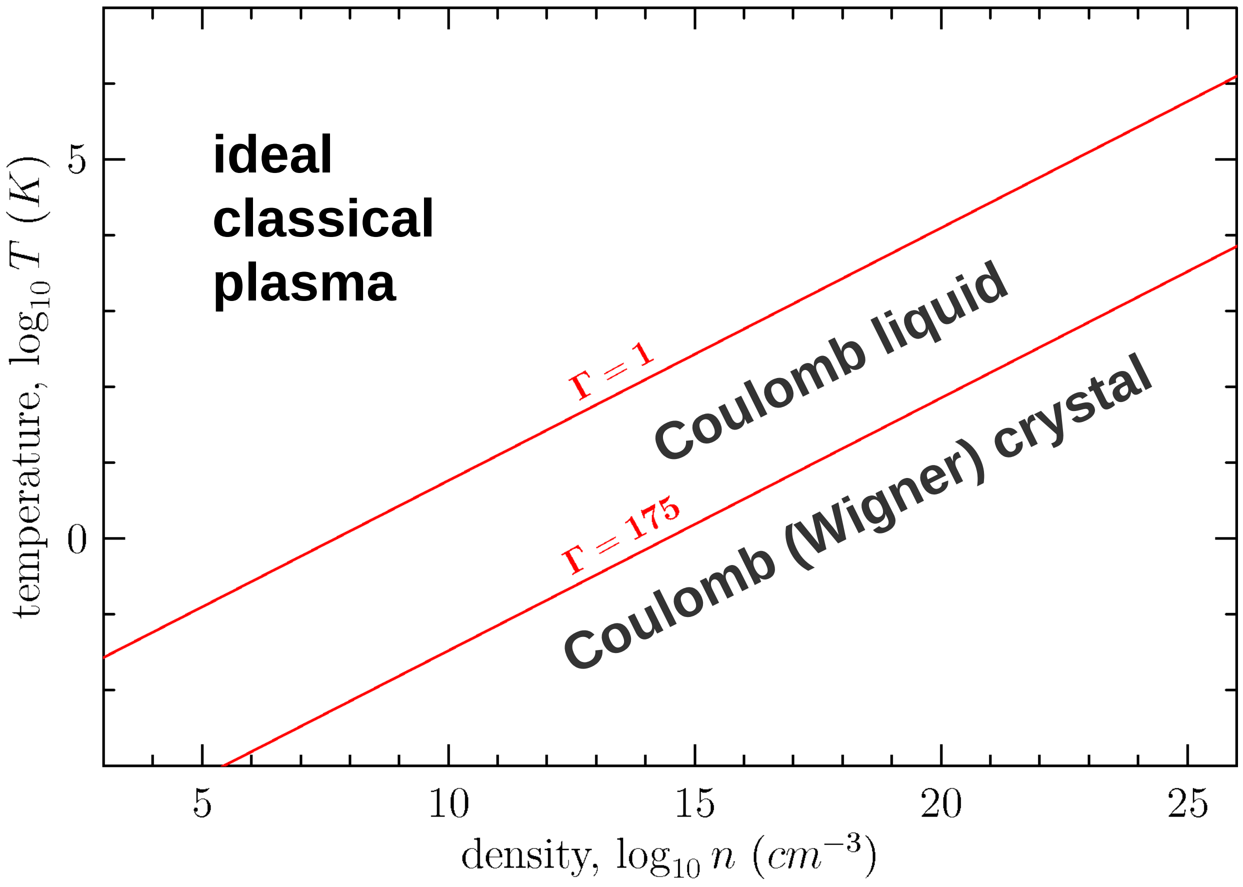
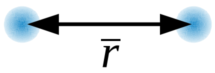
Strongly coupled Coulomb systems

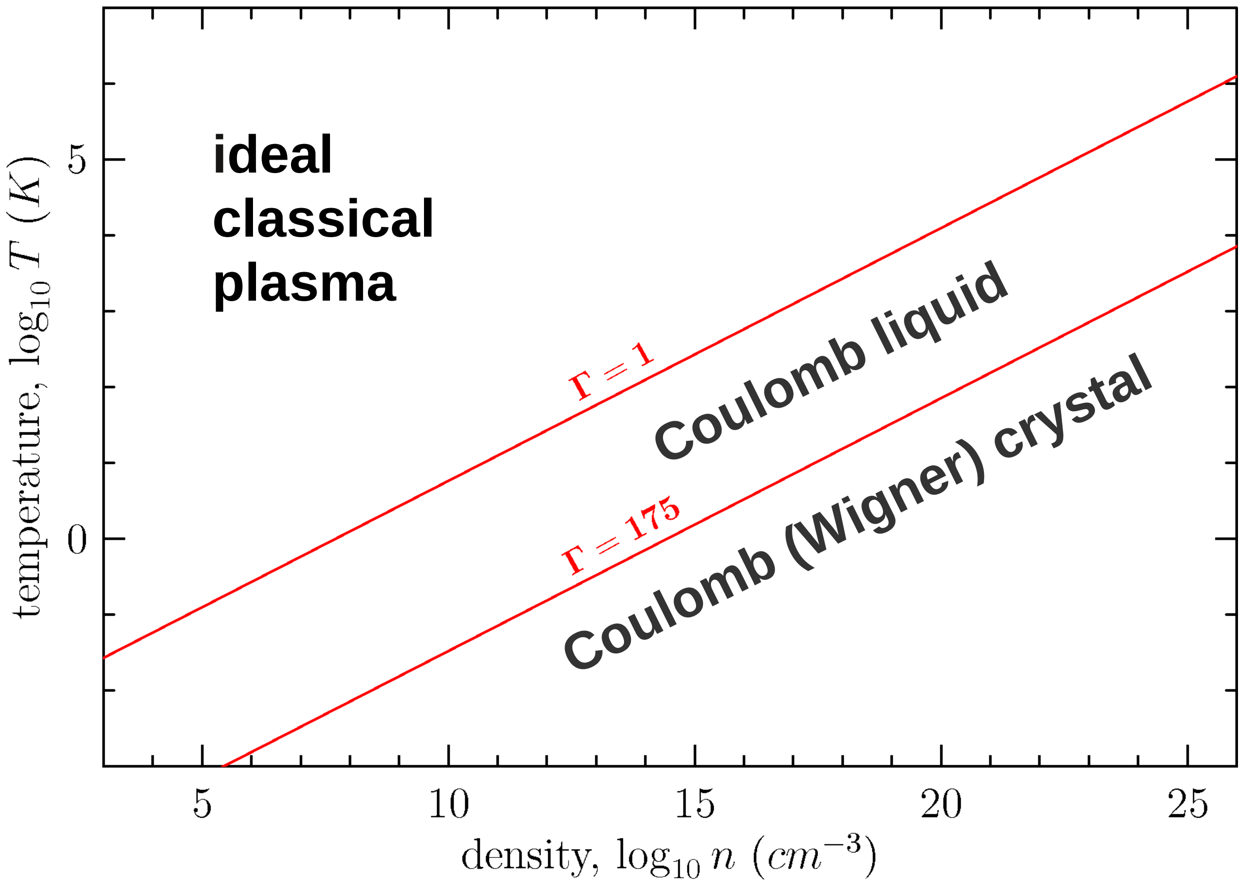


Coulomb interaction



$$\Gamma \equiv \frac{Q^2}{\bar{r}\, k_B T}$$

How to achieve Coulomb crystallization (1)



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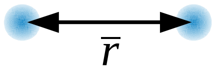


$$\Gamma \equiv \frac{Q^2}{\bar{r}\, k_B T}$$

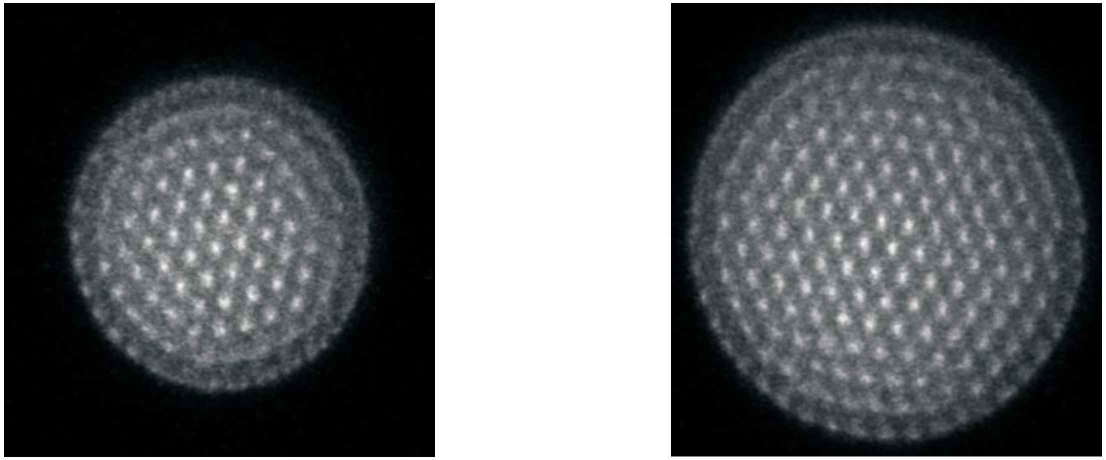
→ **cooling**

Ions in traps, mk temperature

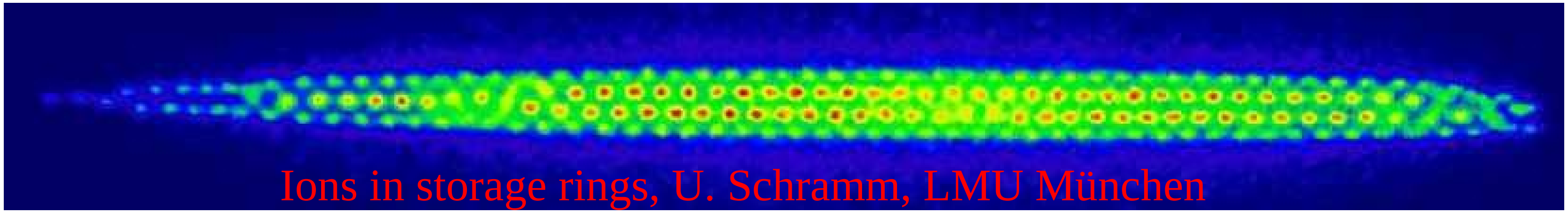
Ion crystals in traps

1987 first realization in Paul trap via laser cooling (Ca, Mg,…)
Bollinger et al. (NIST), Walther et al. (true 1-component plasma)

Today many active groups in Innsbruck (Blatt), Aarhus (Drewsen)…



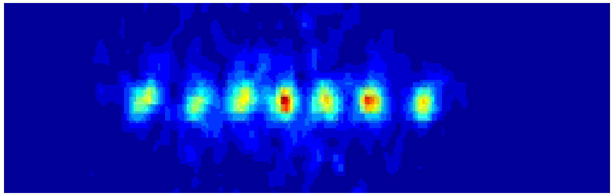
Drewsen



Ions in storage rings, U. Schramm, LMU München

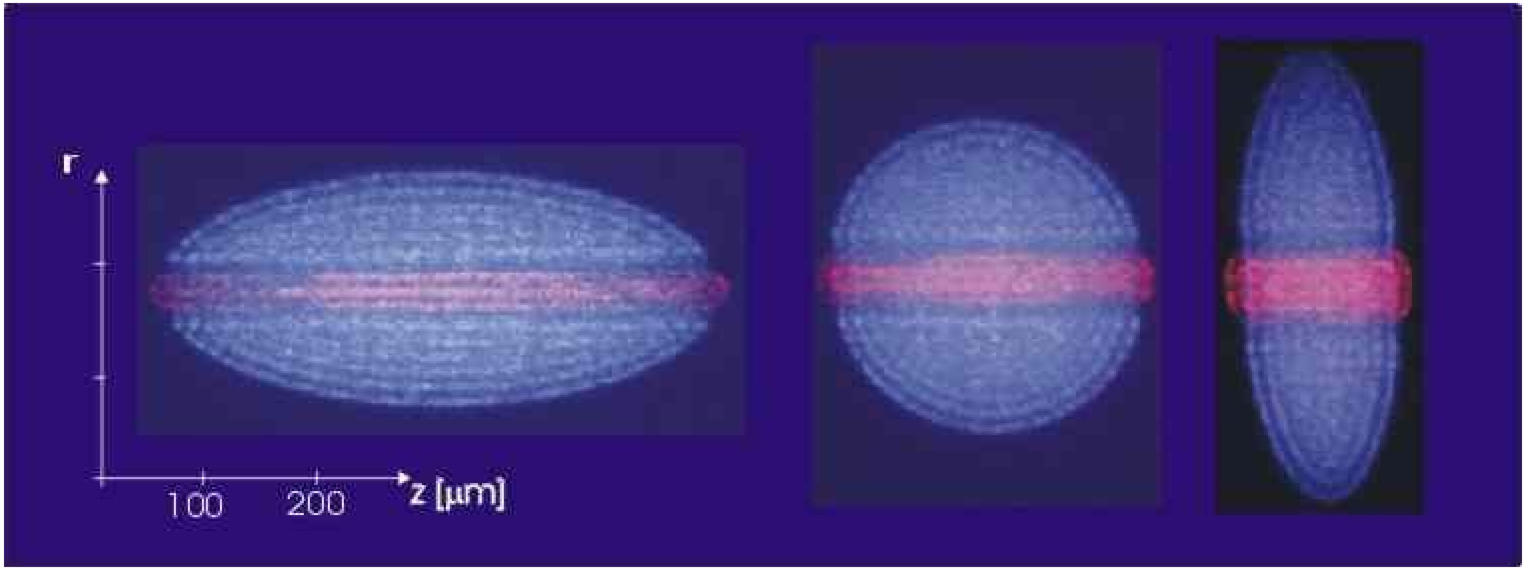
Ion crystals in traps (2)

Applications: atomic physics, quantum optics,
collective excitations, quantum computing…

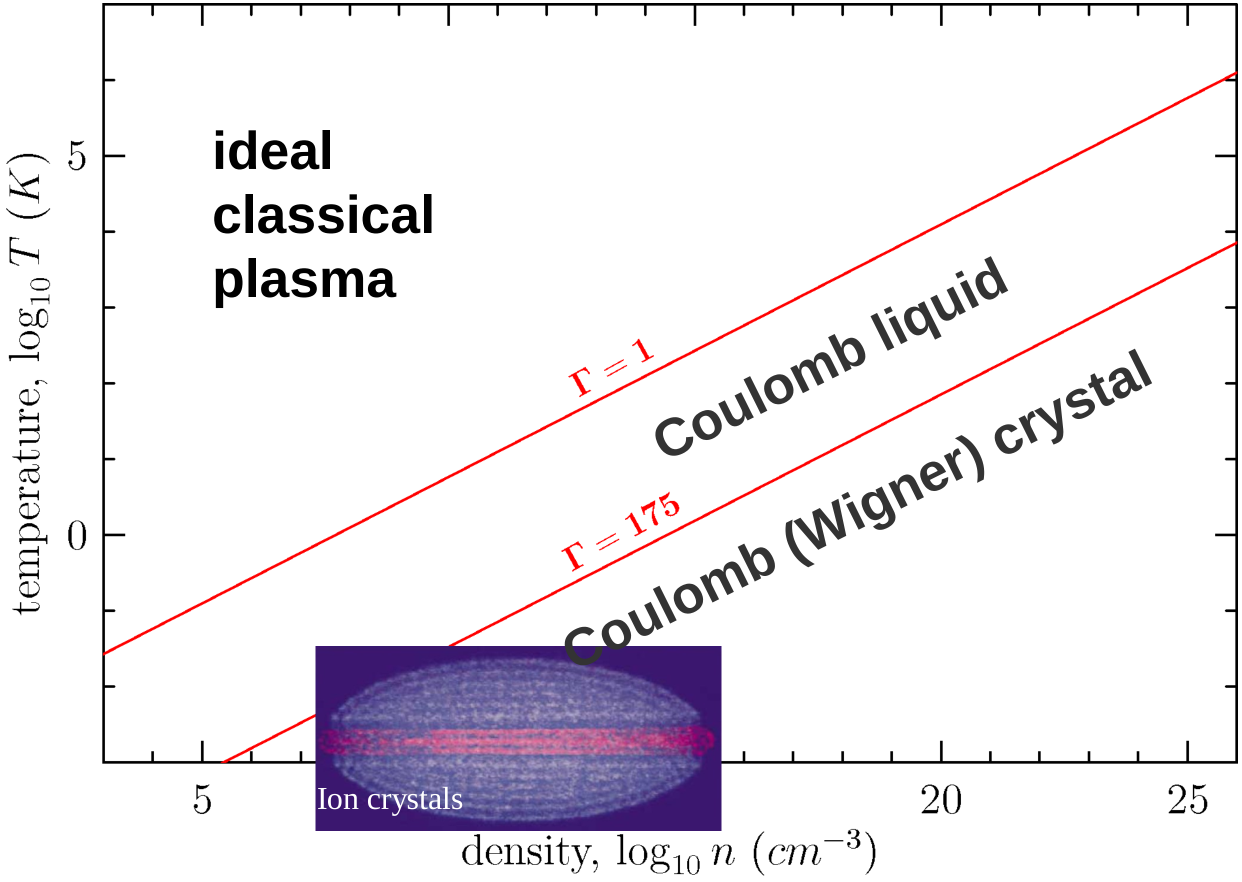


R. Blatt, Uni Innsbruck

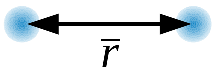
Measured oscillation of bi-crystal, Drewsen, Aarhus



How to achieve Coulomb crystallization (2)



Coulomb interaction



$$\Gamma \equiv \frac{Q^2}{\bar{r}\, k_B T}$$

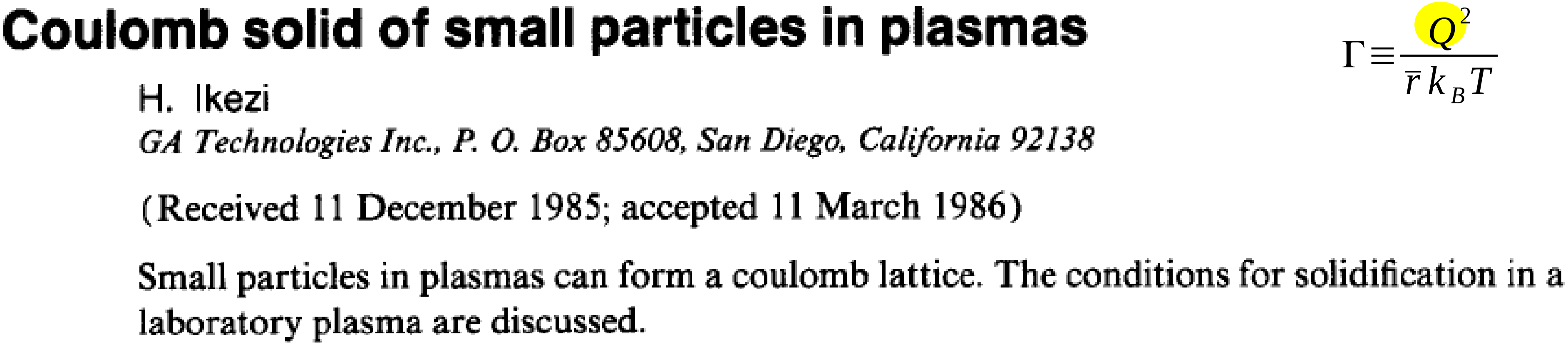
→ **charging**

?

Ions in traps, mk temperature

Coulomb crystal in complex plasma

1986: Theoretical prediction Phys. Fluids **29**, 1764 (1986)



Coulomb solid of small particles in plasmas

H. Ikezi
GA Technologies Inc., P. O. Box 85608, San Diego, California 92138

(Received 11 December 1985; accepted 11 March 1986)

Small particles in plasmas can form a coulomb lattice. The conditions for solidification in a laboratory plasma are discussed.

$$\Gamma \equiv \frac{Q^2}{\bar{r}\, k_B T}$$

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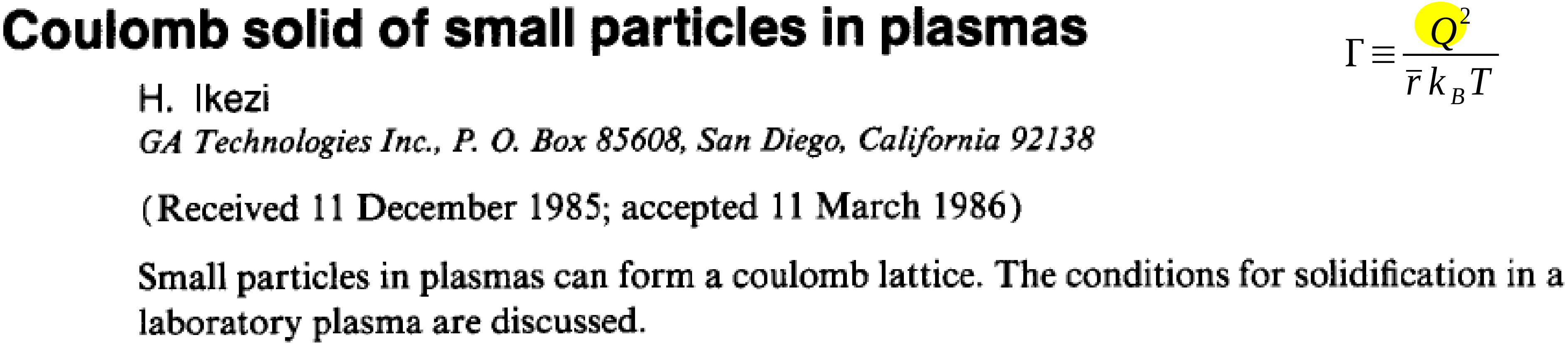

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1994: Experimental observation

Y. Hayashi et al., Jap J. Appl. Phys. **33**, L 804 (1994)

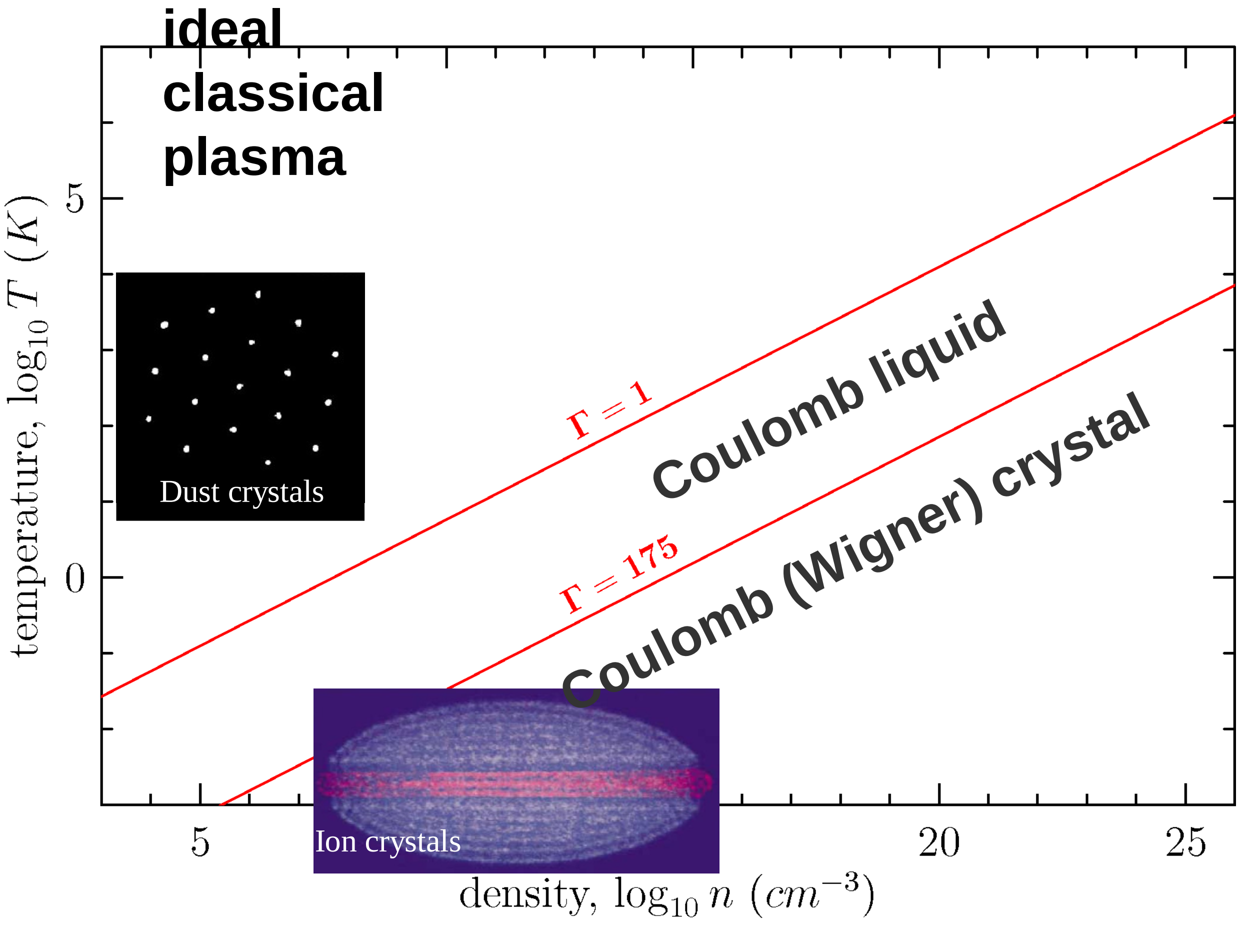
H. Thomas et al., Phys. Rev. Lett. **73,** 652 (1994)

A. Melzer et al., Phys. Lett. A **191**, 301 (1994)

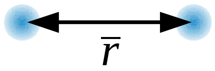
Tremendous activity by many groups...

→ talks by E. Thomas and J. Goree

Coulomb crystal in complex plasma



Coulomb interaction



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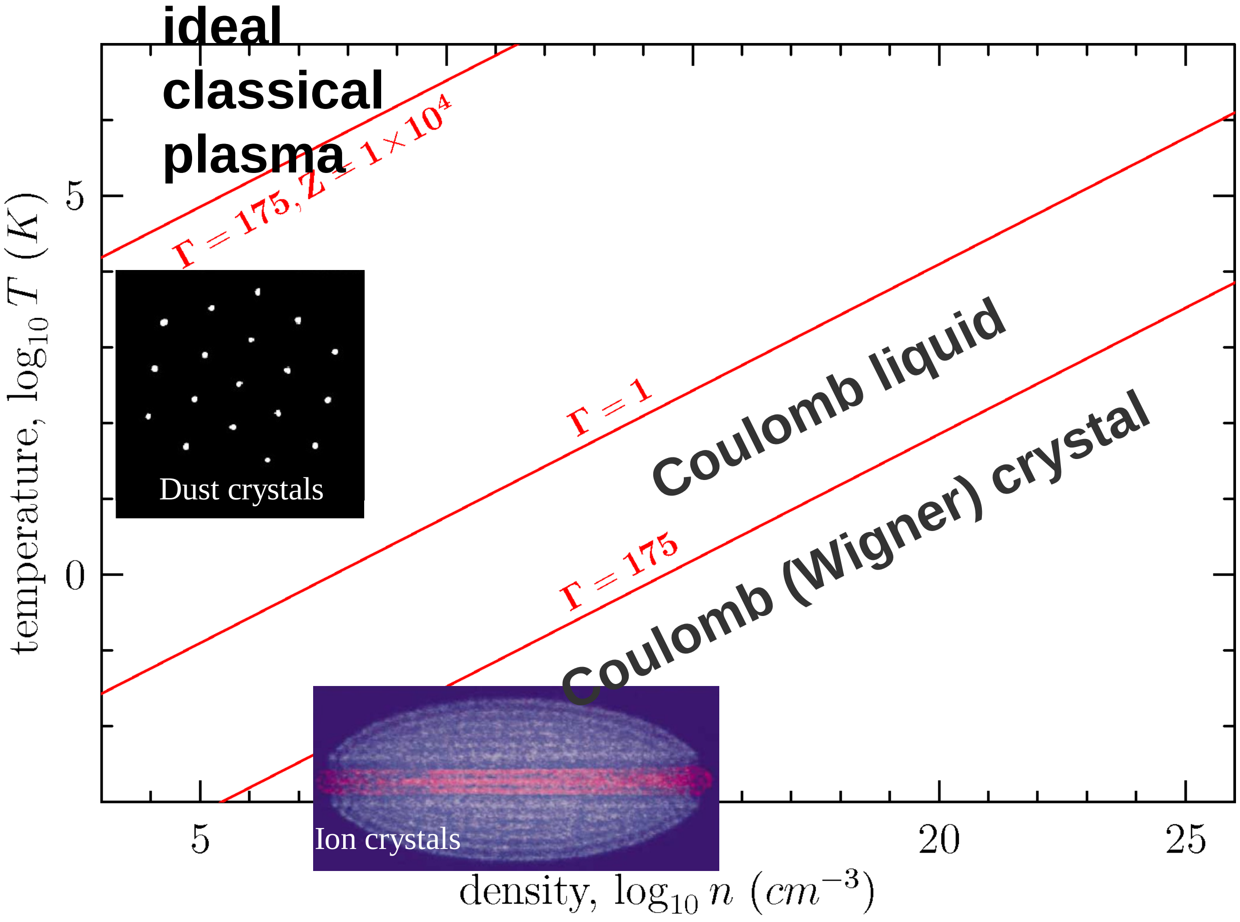
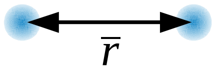
→ **charging**

Coulomb crystal in complex plasma



Coulomb interaction



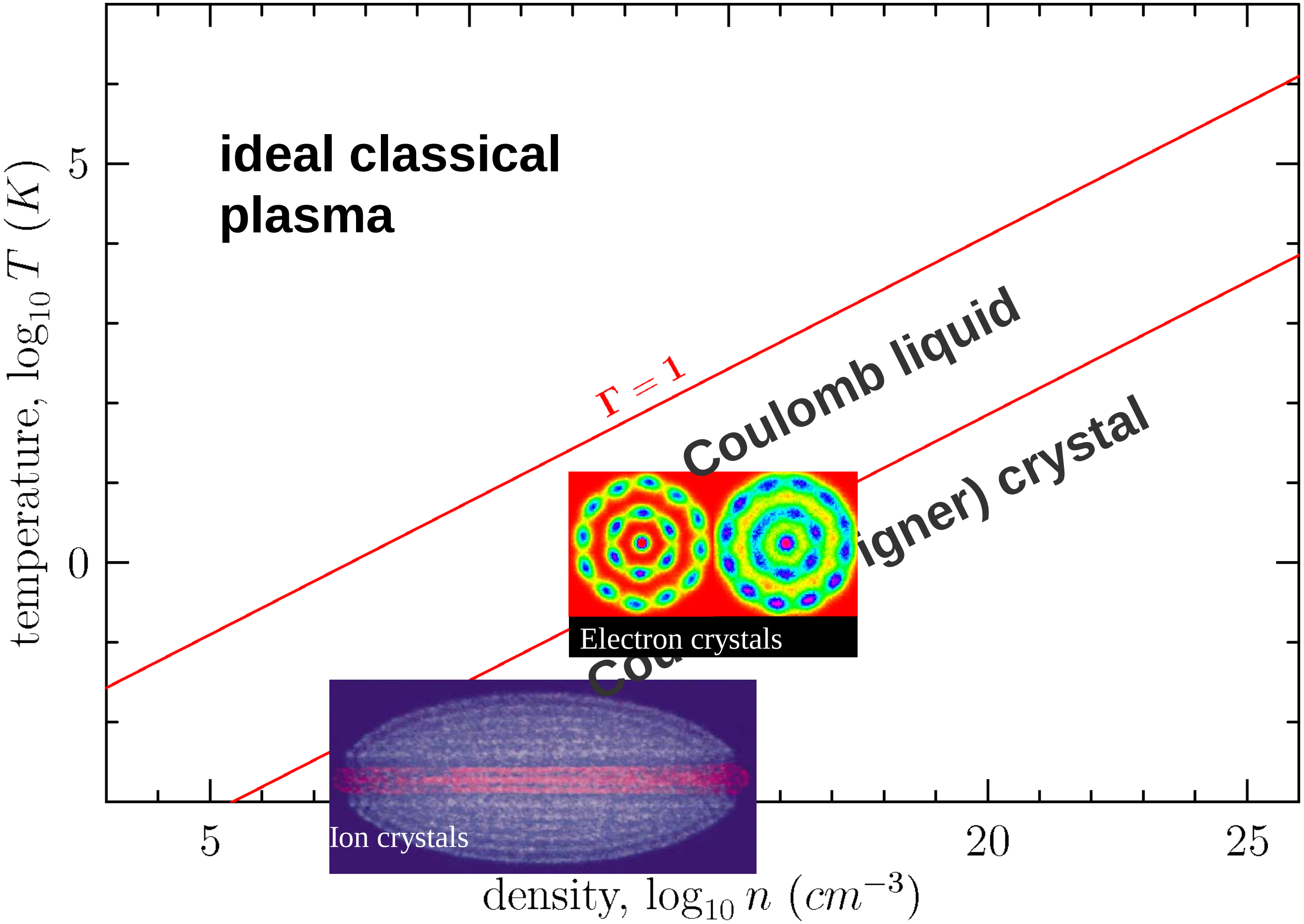
$$\Gamma \equiv \frac{Q^2}{\bar r\, k_B T}$$

→ **charging**

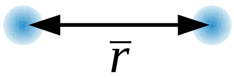
Q=10,000 …
100,000

Ions in traps, mk temperature

How to achieve Coulomb crystallization (3)



Coulomb interaction



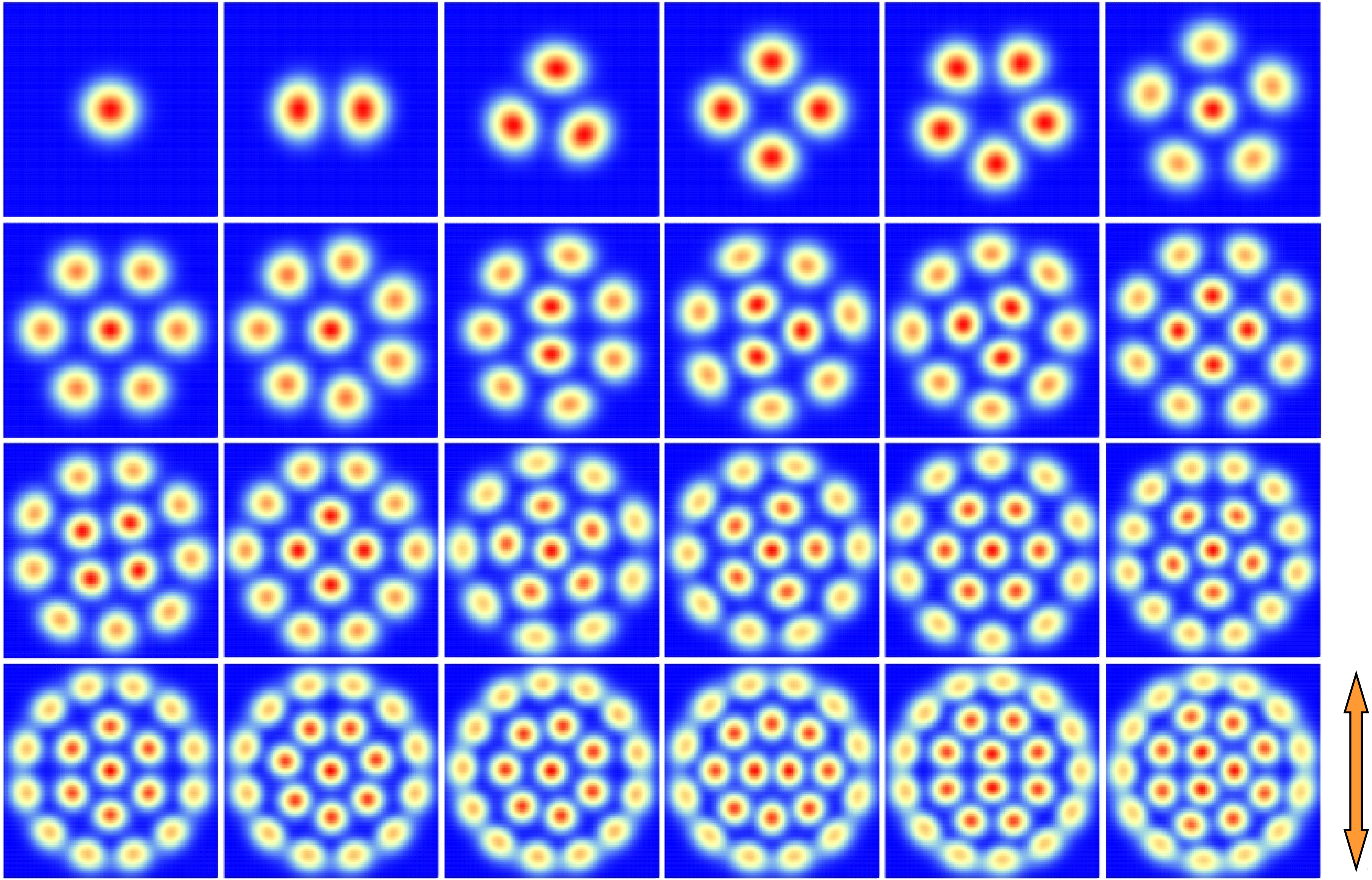
$$\Gamma \equiv \frac{Q^2}{\bar{r} k_B T}$$

→ **compression**

Ions in traps, mk temperature

electrons in quantum dots (predicted)

„Artificial atoms“ (electrons in quantum dots)



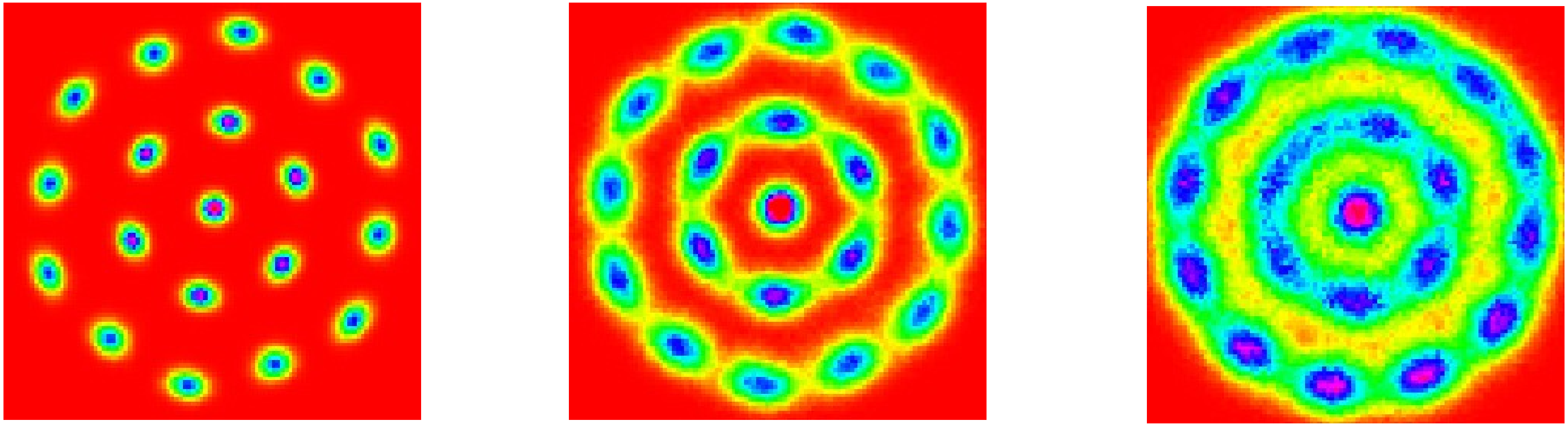
Noneq.-Green functions-Simulation: Lasse Rosenthal (length 0.001mm, T=1K)

Mesoscopic quantum Coulomb clusters in quantum dots

Prediction of electron crystallization: A.Filinov, MB, Yu. Lozovik, PRL **86**, 3851 (2001)

quasi-2-dimensional system, First-principle path integral Monte Carlo results

compression →



Density increase → quantum („cold“) melting of „crystal“ !

Phys. Rev. Focus (April 2001), Sciences et Avenir, Scientific American, FAZ 1.8. 2001…

Quantum coupling parameter

Need: $\Gamma^Q = r_s \propto \dfrac{\bar{r}}{a_B} \ge r_s^{cr}$

$$\Gamma^Q = \frac{|\langle U \rangle|}{\langle E_{KIN} \rangle} \sim \frac{e^2}{E_F\,\bar{r}} \propto \frac{e^2 n^{1/3}}{n^{2/3}} \propto n^{-1/3}$$

Quantum degeneracy

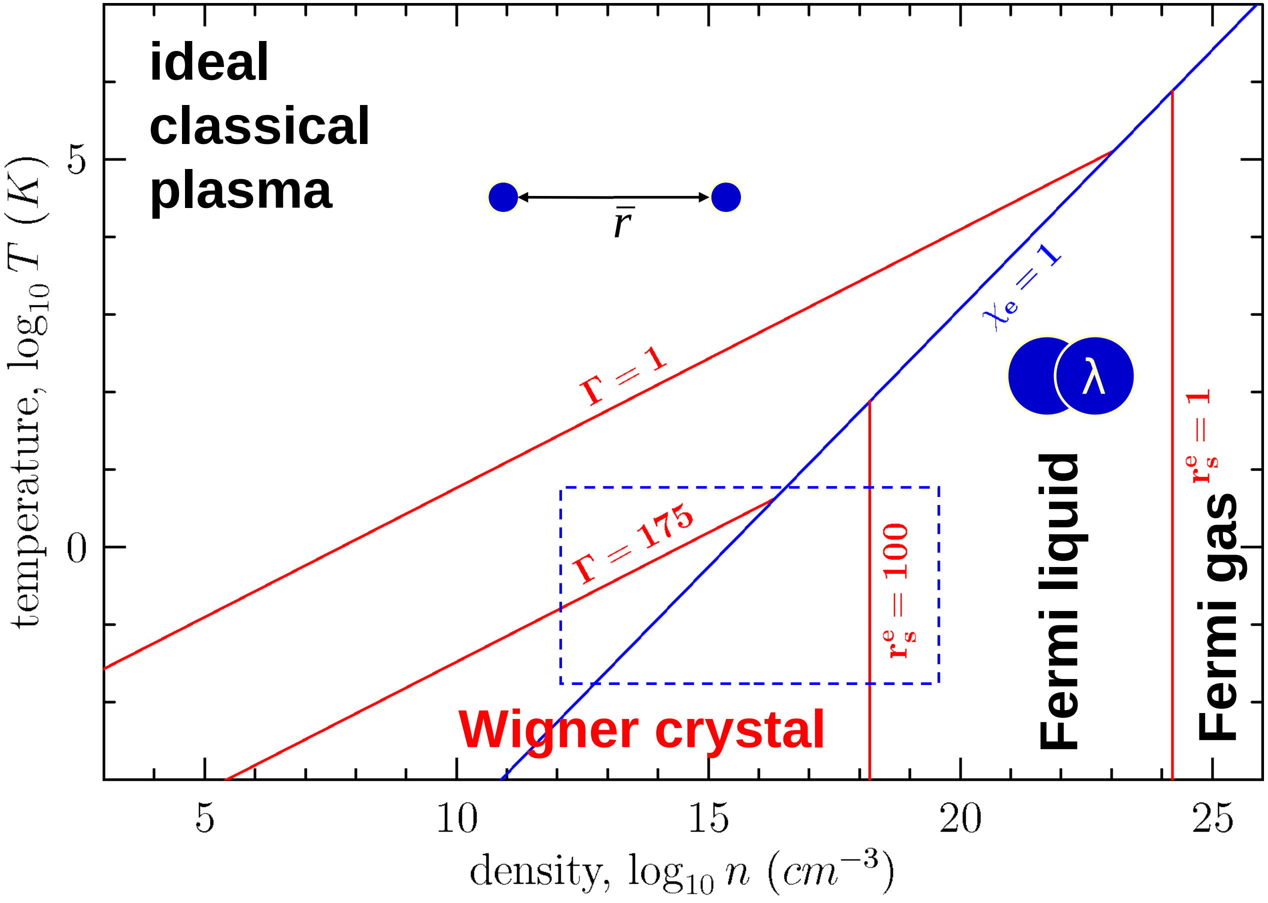
$$\chi = n\lambda^3$$

DeBroglie
wave length

$$\lambda = h / \sqrt{2\pi m k_B T}$$

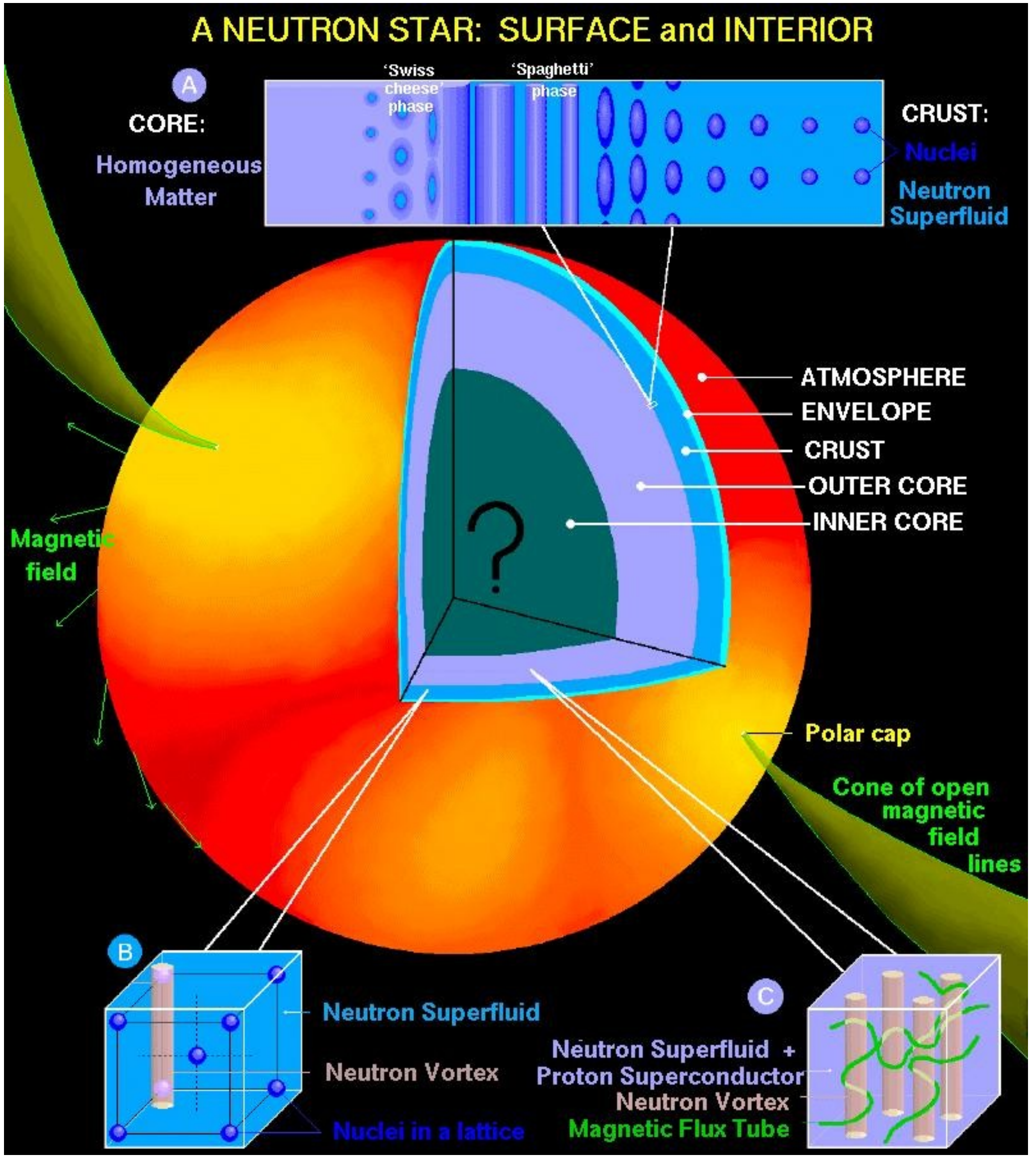
$r_s^{cr} \approx 34 \ldots 37\ (2D)$

Ceperley et al.,
A. Filinov, MB



plasmas with same Gamma no longer equivalent!

Neutron star



- Envelope: crystal and
- towards center: quantum fluid of Fe-nuclei

in „quantum sea“ of electrons

Radius ~ 10km
Mass ~ our Sun

$$\rho \cong 10^{15}\, g\, cm^{-3}$$

Source: Coleman, UMD

Summary: Universal behavior of OCP

- classical plasma described by single parameter Γ
- quantum OCP described by two parameters (n, T)

Application:

Mapping of white dwarf and neutron star properties on entirely different laboratory plasmas

But: can we really assume that the light component(s)
is just a rigid background?
Are the electrons only static spectators?

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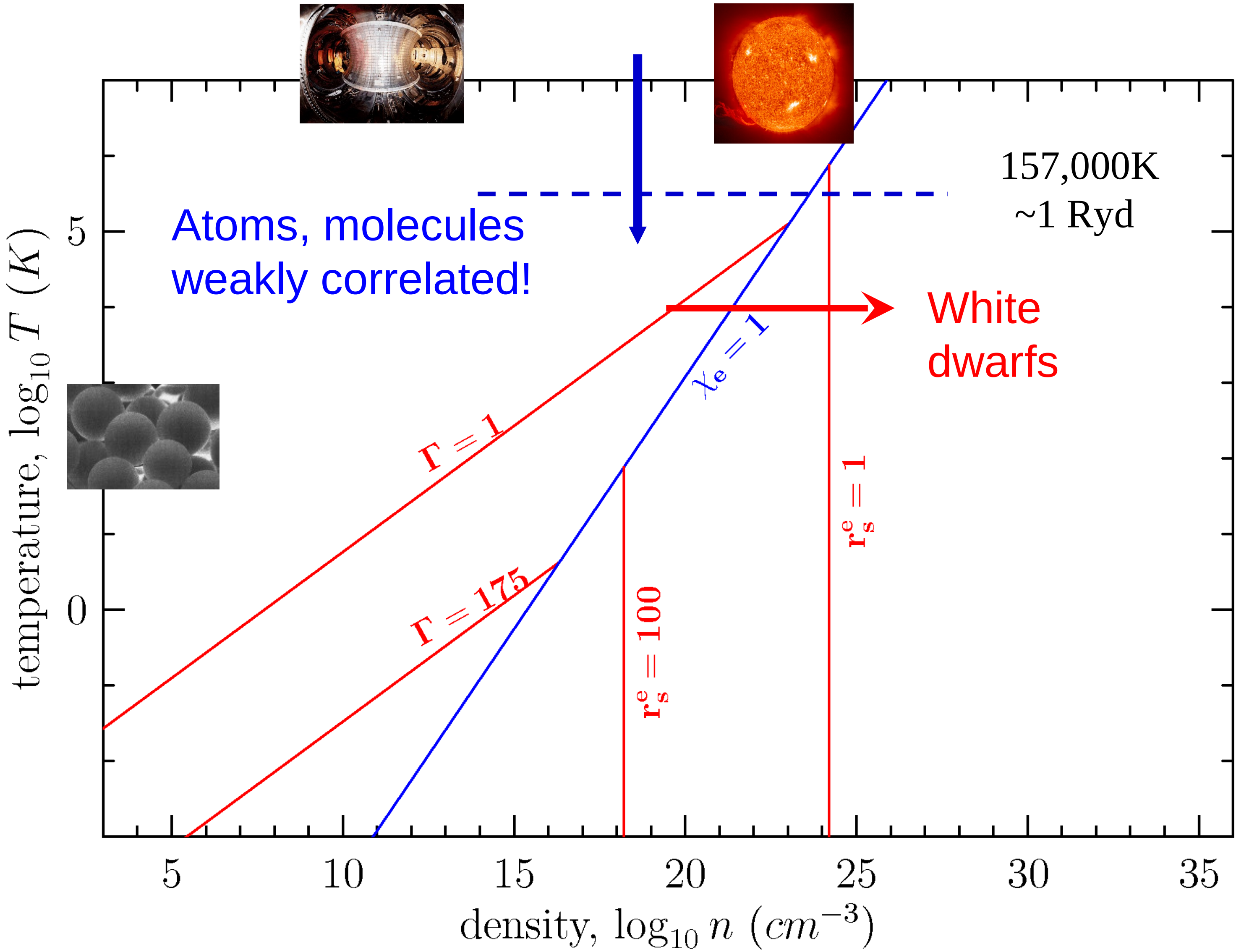
Phase diagram of 2-comp. plasmas

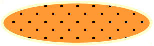


157,000K
~1 Ryd

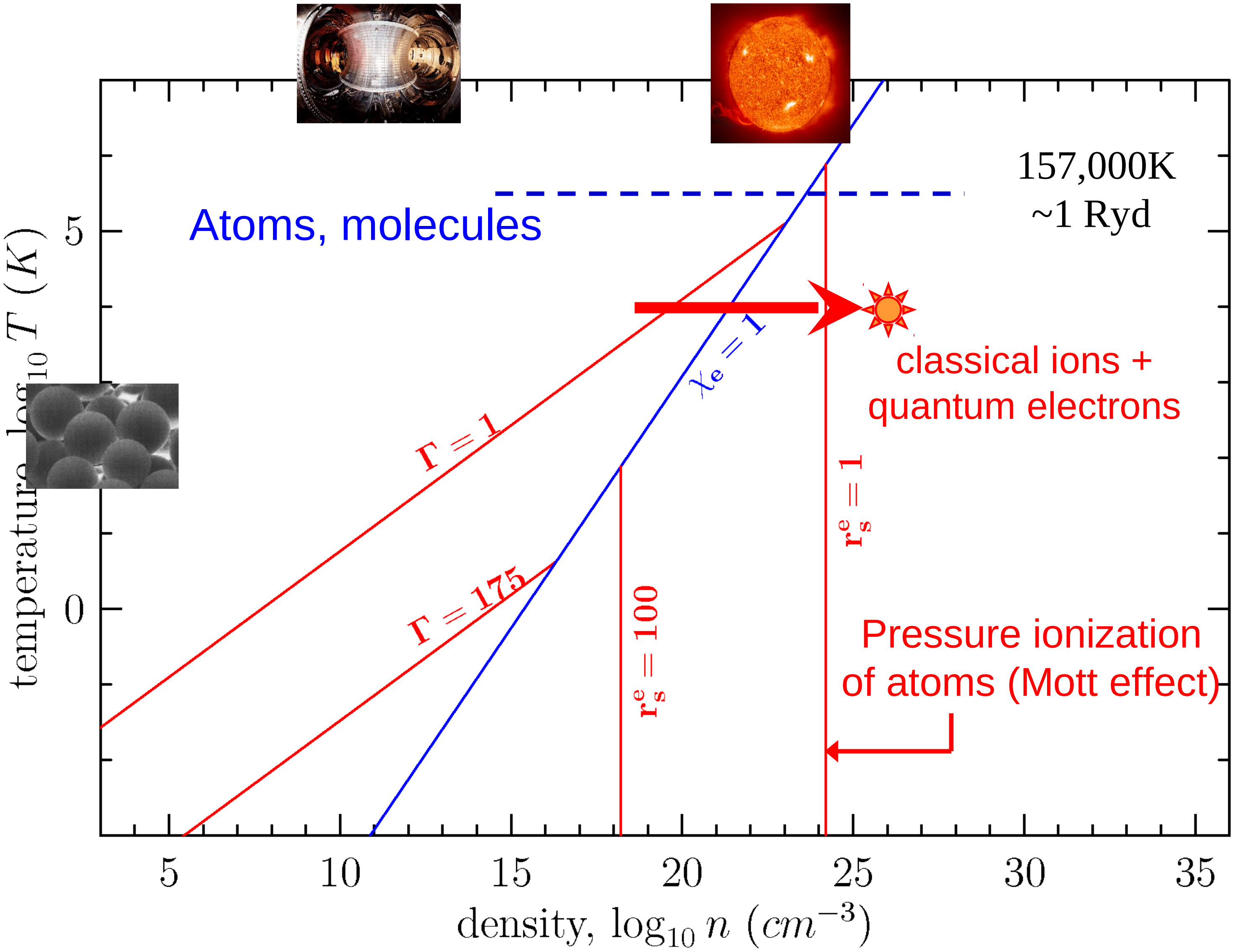
Atoms, molecules
weakly correlated!

White
dwarfs

Neutron
stars



Ultradense neutral plasmas



157,000K
~1 Ryd

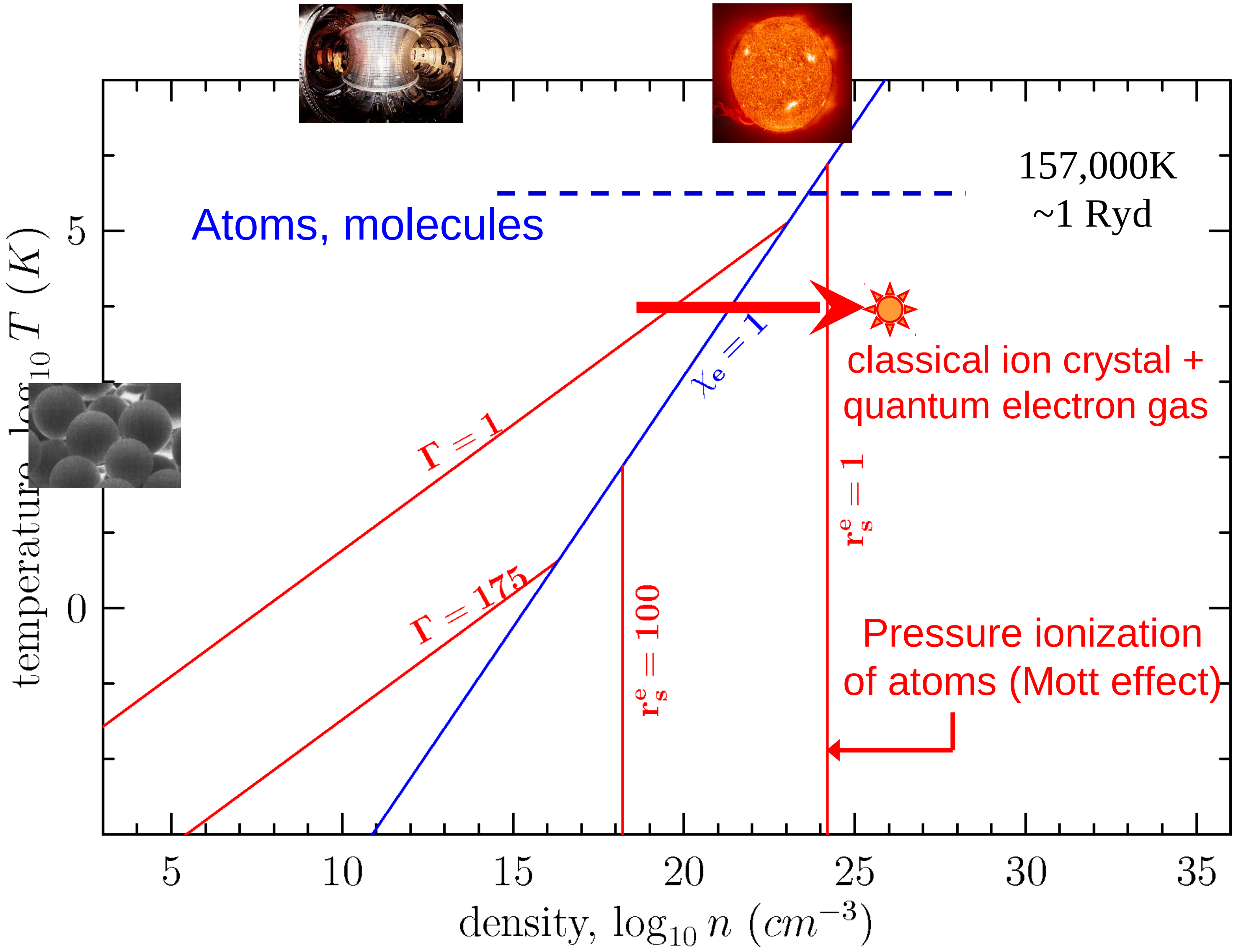
Atoms, molecules

classical ions + quantum electrons

Pressure ionization of atoms (Mott effect)

● Successfully achieved with strong lasers

Ultradense neutral plasmas



Atoms, molecules

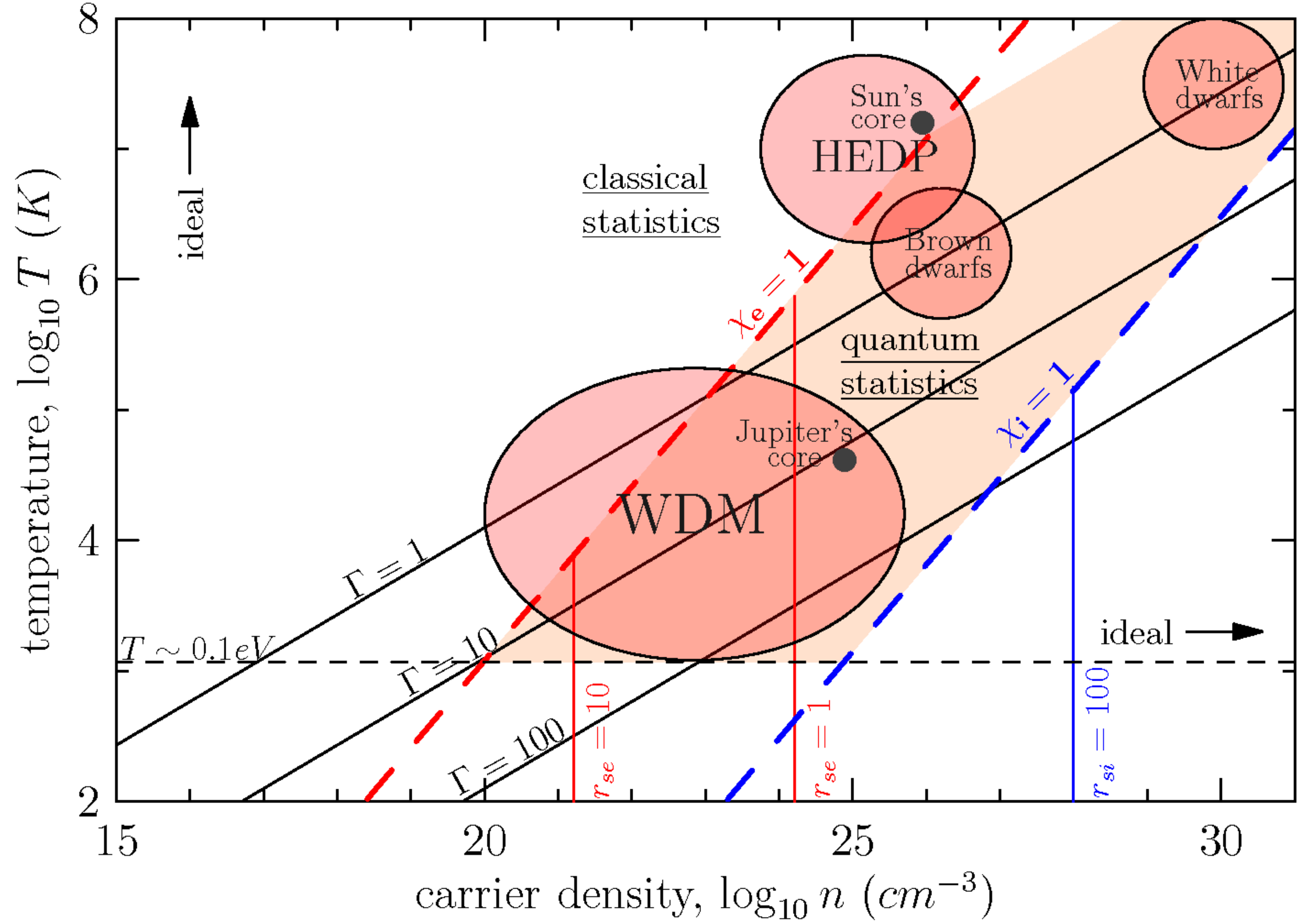
classical ion crystal +
quantum electron gas

Pressure ionization
of atoms (Mott effect)

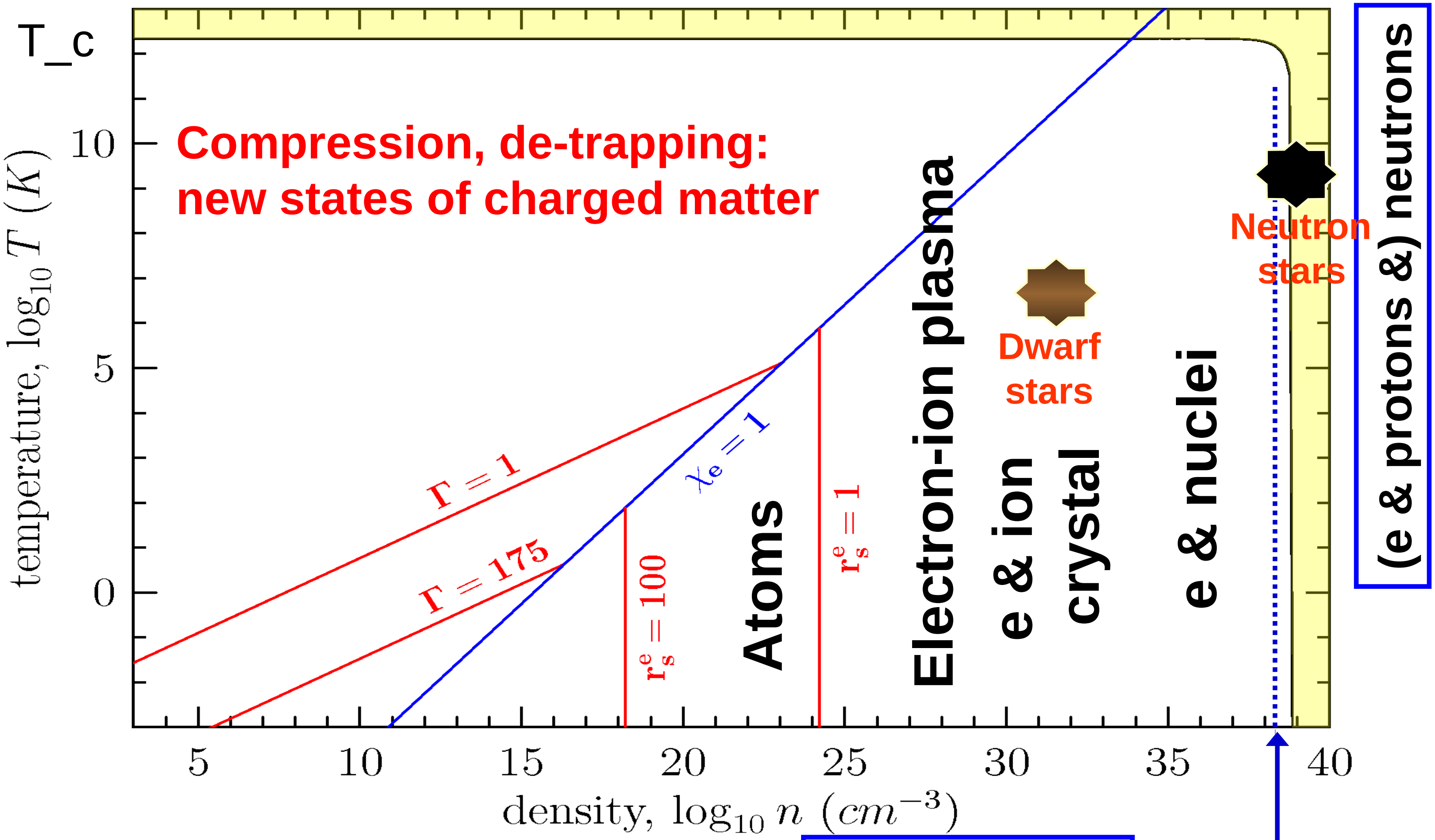
Filinov, Bonitz, Fortov, JETP Letters **72**, 245 (2000)

What happens to the plasma upon further compression?

From white dwarfs to neutron stars



From nuclei to nuclear matter



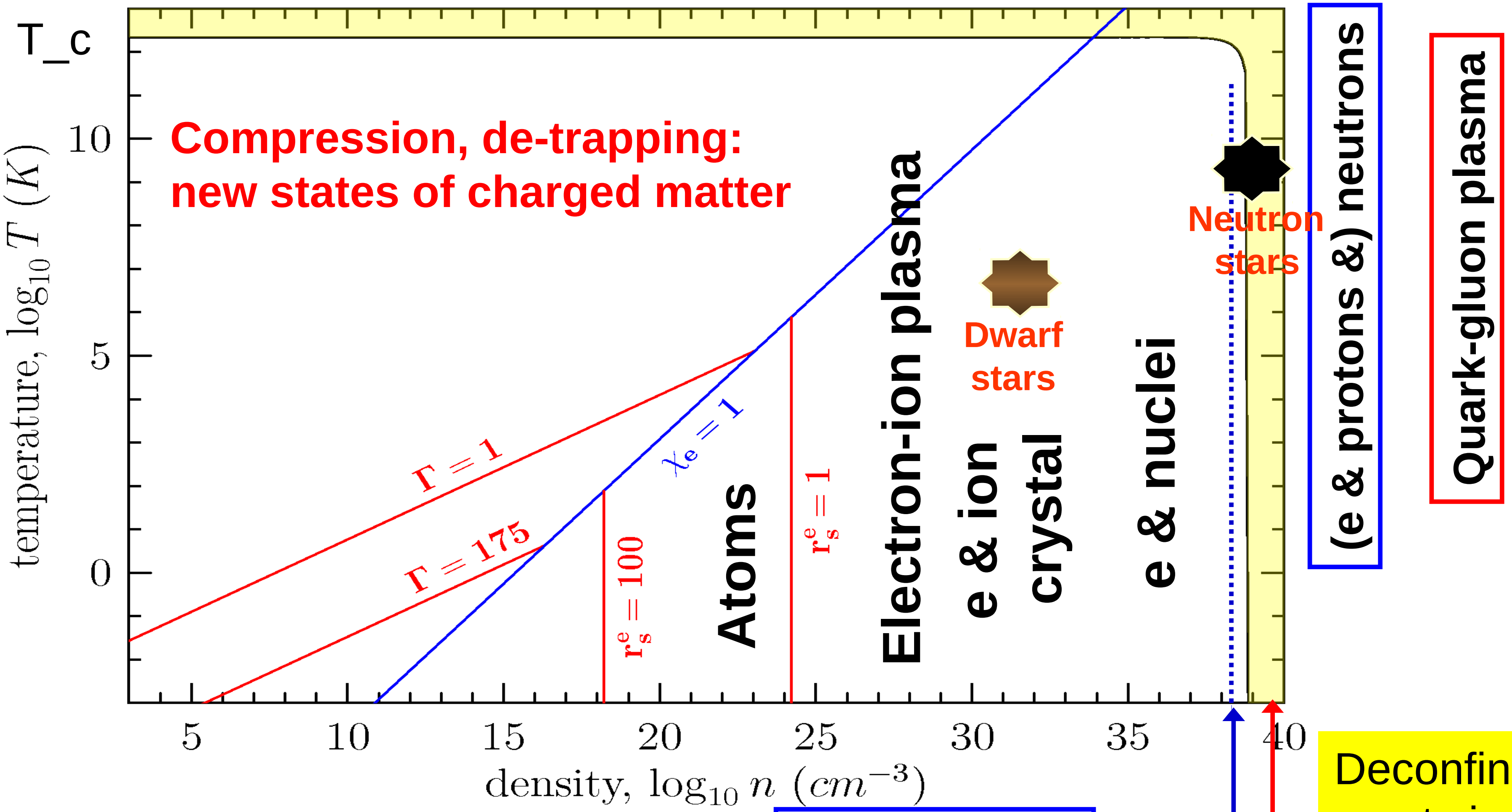
Compression, de-trapping: new states of charged matter

$$\rho_N = \frac{0.17\ baryons}{fm^3}$$

$$1\,fm = 10^{-13}\,cm$$

$$T_C = 175\,MeV$$

From nuclear matter to quarks



$$1\,fm = 10^{-13}\,cm$$

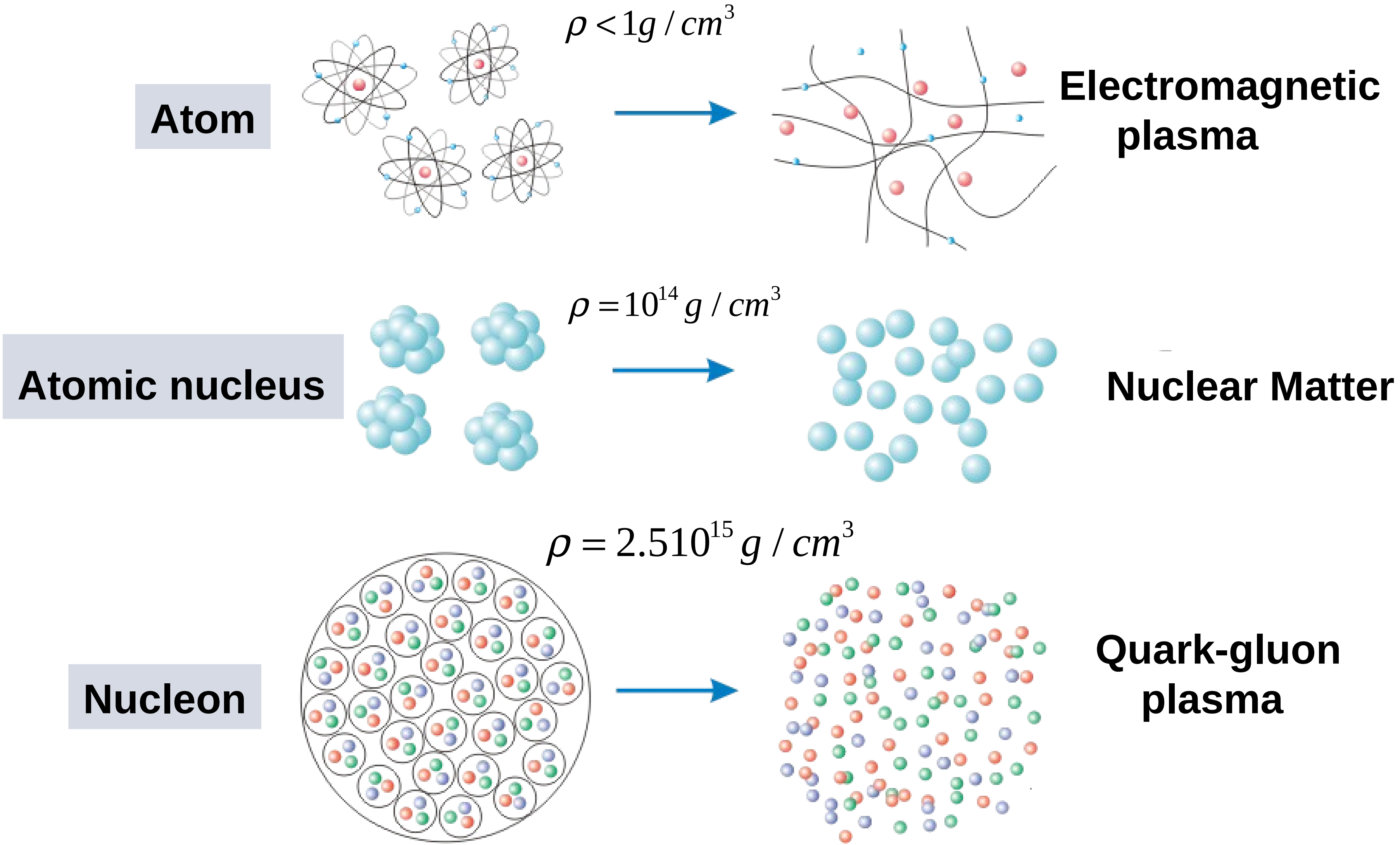
$$T_C = 175\,MeV$$

$$\rho_N = \frac{0.17\ baryons}{fm^3}$$

deconfinement $(5 \ldots 10)\rho_N$

Deconfinement via compression or heating

Matter transformation at high energy density



Atom

$\rho < 1 g / cm^3$

Electromagnetic plasma

Atomic nucleus

$\rho = 10^{14} g / cm^3$

Nuclear Matter

Nucleon

$\rho = 2.510^{15} g / cm^3$

Quark-gluon plasma

When the plasma is becoming too dense...

The fate of compact stars:

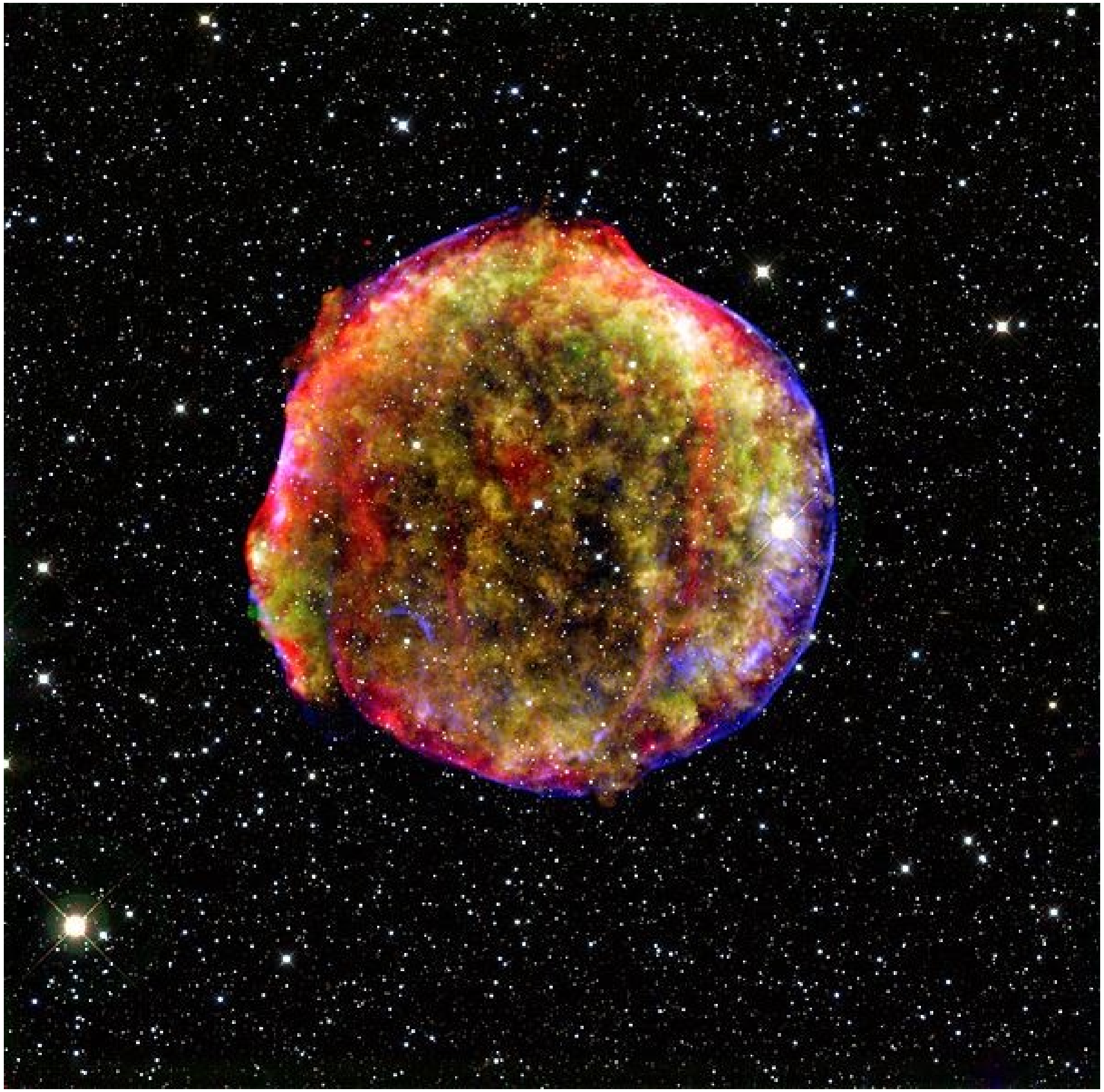
depending on their mass, different fusion reactions may be possible that generate heat (pressure)

Consequence:

- further collaps: black hole or

- explosion

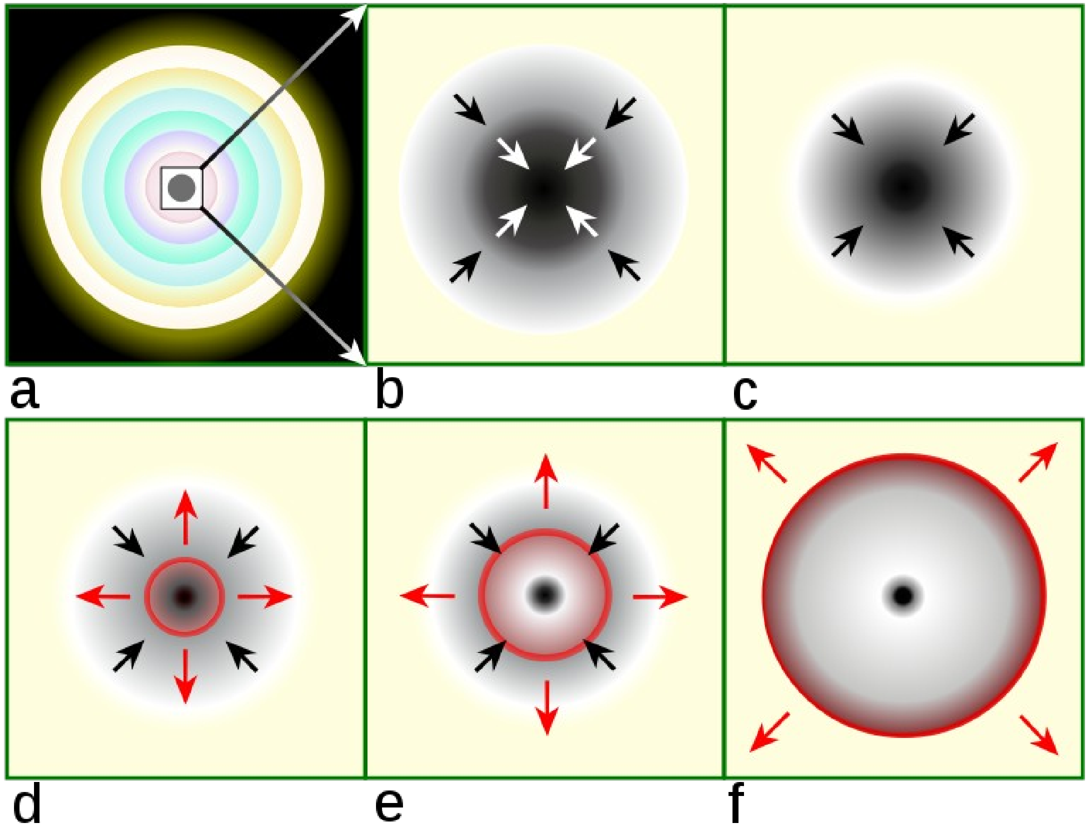
Supernova explosion



The remnant of "Tycho's Supernova", a huge ball of expanding plasma. The outer shell shown in blue is X-ray emission by high-speed electrons.

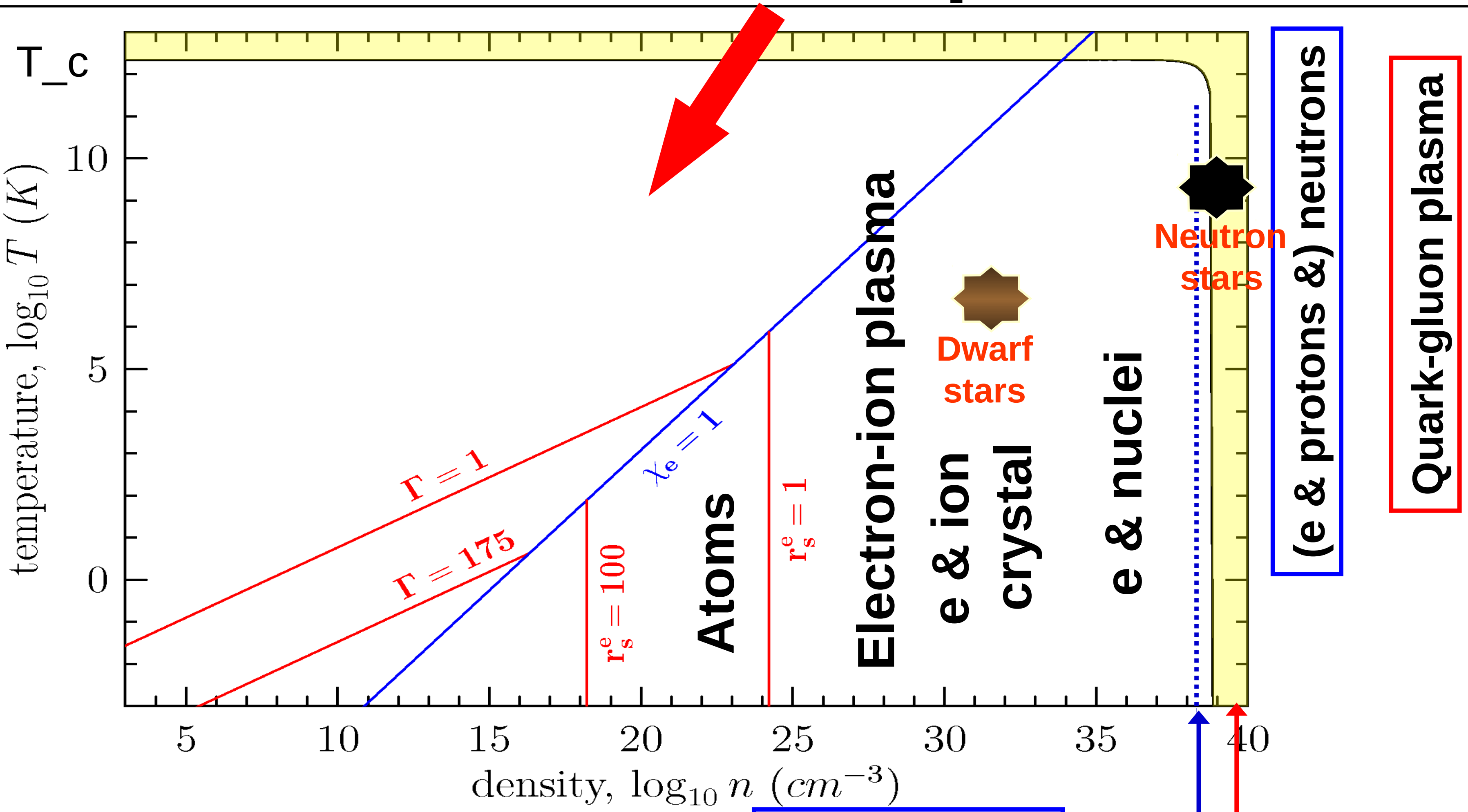
Source: Wikipedia

Supernova explosion



(a) A massive, evolved star has onion-layered shells of elements undergoing fusion. An inert iron core is formed from the fusion of Silicon in the inner-most shell. (b) This iron core reaches Chandrasekhar-mass and starts to collapse, with the outer core (black arrows) moving at supersonic velocity (shocked) while the denser inner core (white arrows) travel sub-sonically; (c) The inner core compresses into neutrons and the gravitational energy is converted into neutrinos. (d) The infalling material bounces off the nucleus and forms an outward-propagating shock wave (red). (e) The shock begins to stall as nuclear processes drain energy away, but it is re-invigorated by interaction with neutrinos. (f) The material outside the inner core is ejected, leaving behind only a degenerate remnant.

The ultimate explosion



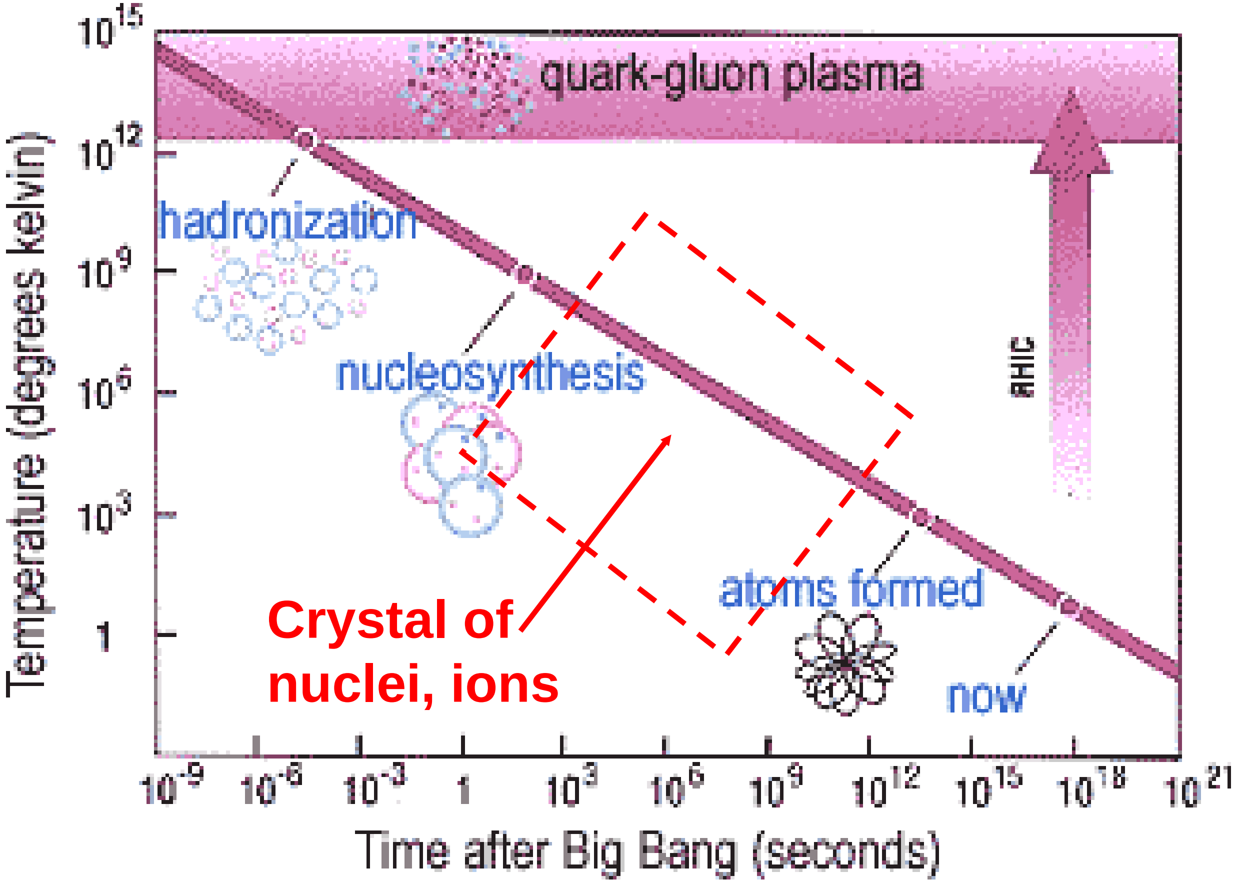
$$1\, fm = 10^{-13}\, cm$$

$$T_C = 175 MeV$$

$$\rho_N = \frac{0.17\ baryons}{fm^3}$$

deconfinement $(5 \ldots 10)\rho_N$

Big bang: trapping of charged matter



Crystal of nuclei, ions

Quark-gluon plasma realized at:
Relativistic Heavy ion collider, Brookhaven
Large Hadron collider, CERN

Source: RHIC web site

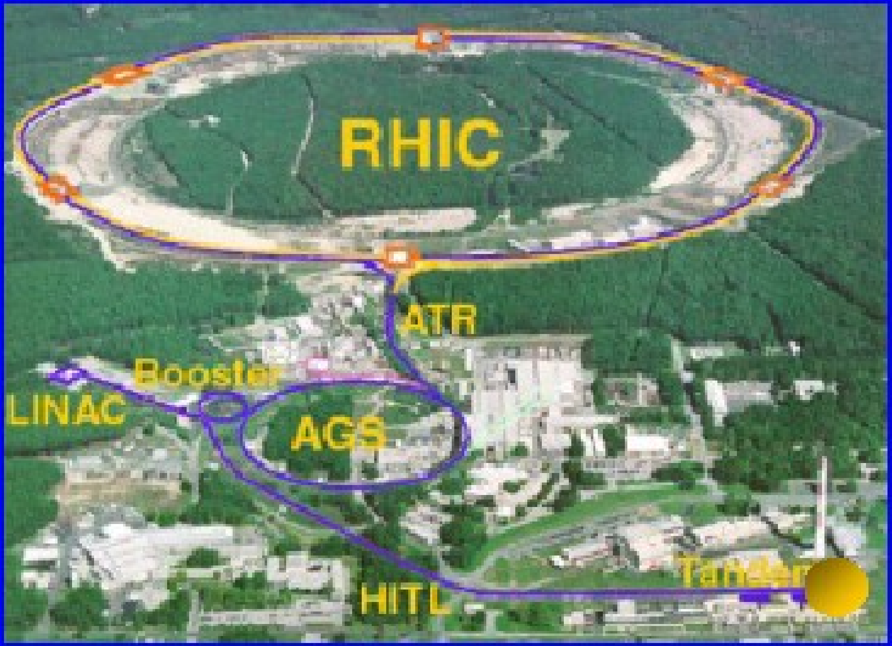
Can one verify this experimentally ?

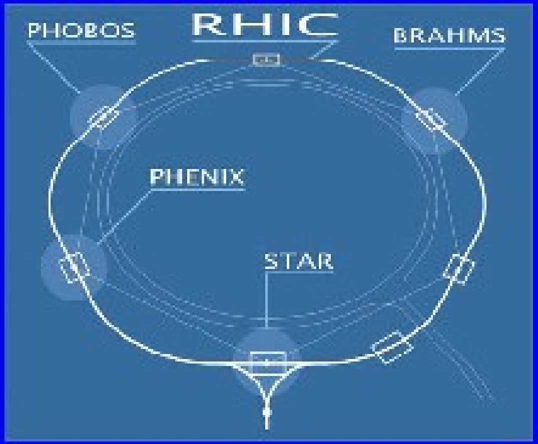
To **produce a quark-gluon plasma**
huge densities and
particle energies are needed

big particle colliders in the U.S. and Europe
produce and study the properties
of the quark-gluon plasma

Creating high energy density matter in the lab

Relativistic Heavy Ion Collider (Brookhaven) since 2000. Colliding beams 100 GeV/A
Large Hadron Collider (CERN) in 2008-9. 2700 GeV/A

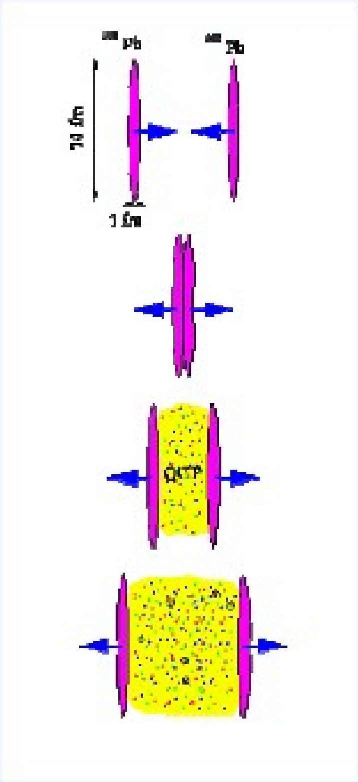


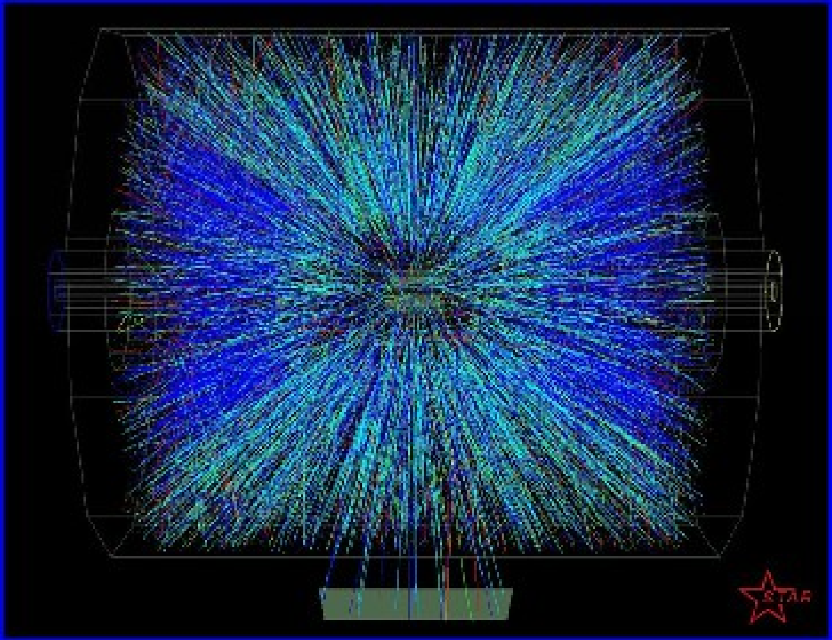


100 GeV per nucleon

Au(197 × 100)+Au(197 × 100)

G. Baym





What collisions actually look like in the lab. STAR detector

Schematic collision:
Two Lorentz contracted nuclei collide, pass through each other, leaving highly excited state of vacuum in between.

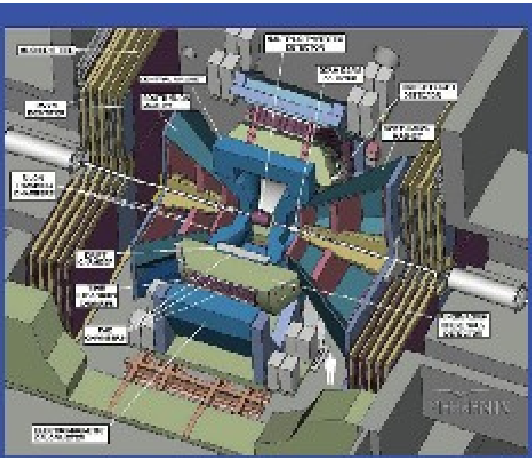
G. Baym

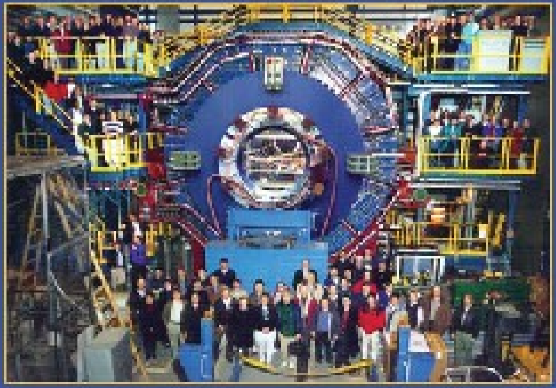
Two major detectors at RHIC

- PHENIX
- STAR

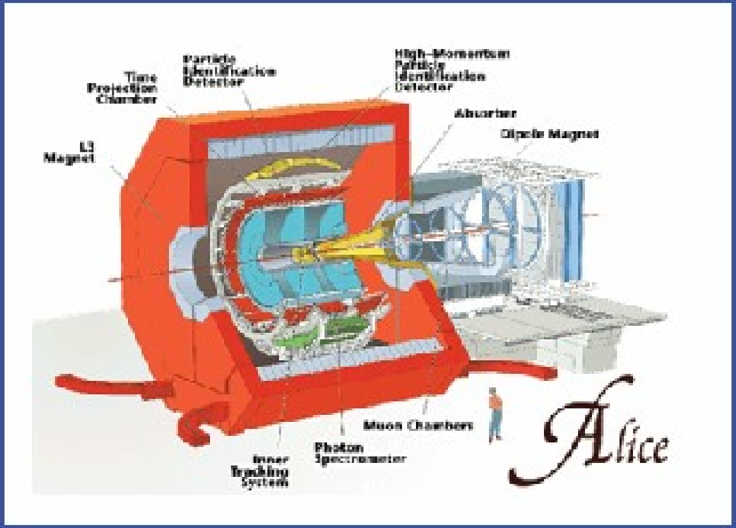
Two smaller detectors

- BRAHMS
- PHOBOS





ALICE detector at LHC



G. Baym

Quark-gluon plasma

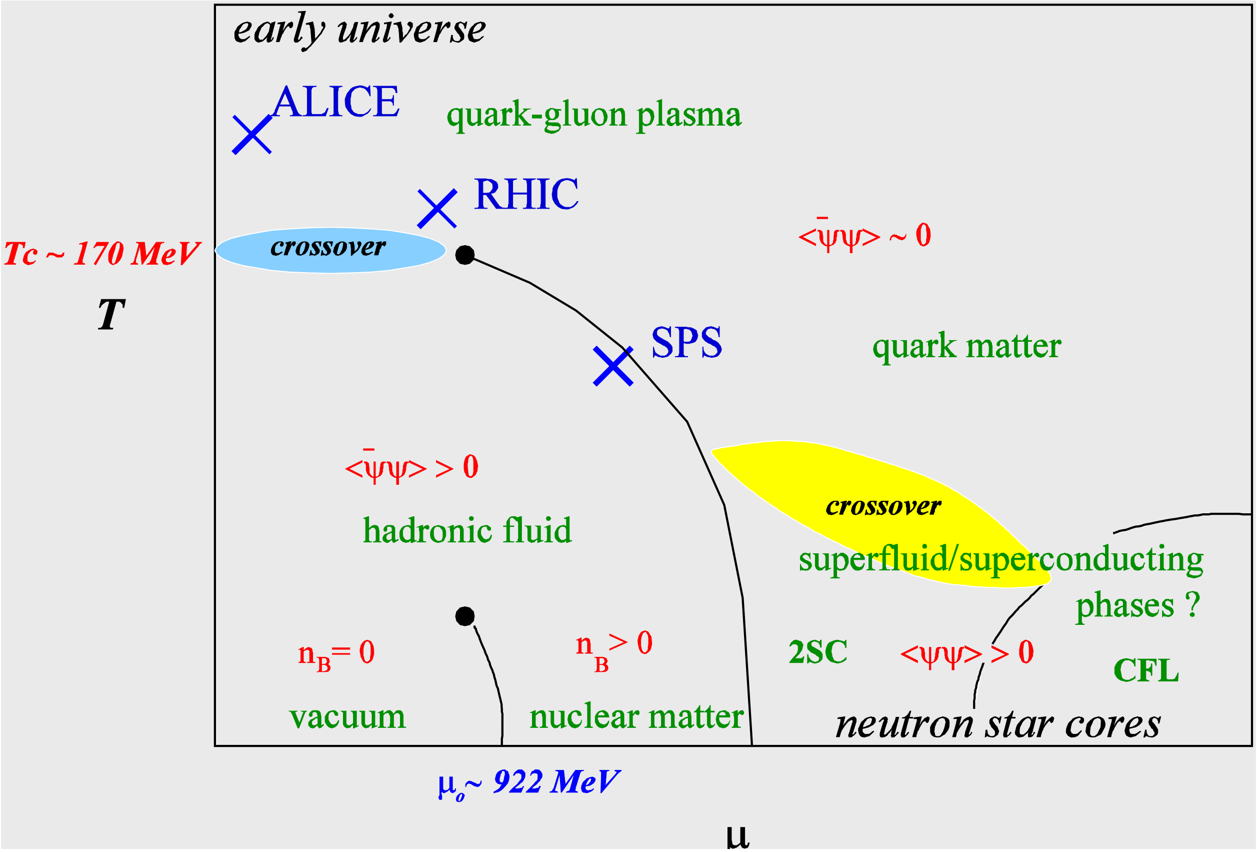
→The quark-gluon plasma
has been first observed at RHIC
it is now routinely
produced at the LHC at CERN

→The particles in the QGP plasma interact
via the (color) Coulomb potential

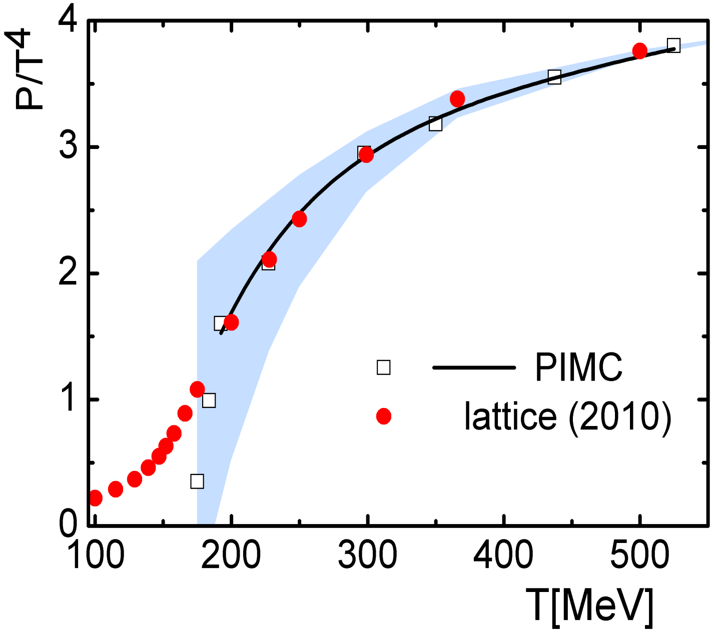
→First results were surprising:
the QGP is a non-ideal plasma, liquid-like

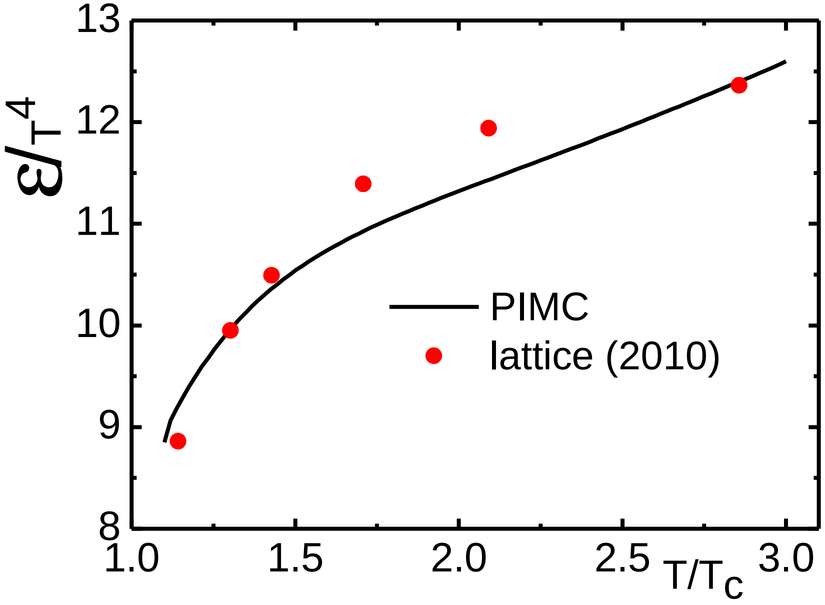
New applications of non-ideal plasma physics!

Phase diagram of quark matter



Quantum MC simulations of quark-gluon plasma





Quantum plasma of quarks (fermions), gluons (bosons) and anti-particles
Color Coulomb interaction, SU(3) group

V. Filinov et al., Contrib. Plasma Phys. **49**, 536 (2009);
Physics of Atomic Nuclei, **74,** 1364 (2011),
Phys. Rev. C **87**, 035207 (2013)

Contents

1. Introduction: Examples of dense nonideal plasmas

2. Matter at extreme density

   - White dwarf and neutron stars
   - Coulomb liquids and crystals in the lab

3. From atoms to quarks and the Big Bang

4. Plasma compression in the laboratory
   - Inertial confinement fusion

Plasma compression in the lab (without accelerators)

- Diamond anvil cells
- explosive cells (Russia)
- shock wave compression, multiple shocks
- Z pinches
- ion beams
- x-rays (Free electron lasers)
- high-power laser beams

Experimentalists now routinely achieve plasma pressure $p \sim 1$ Mbar = 100 GPa: Hydrogen ionized (Mott effect)

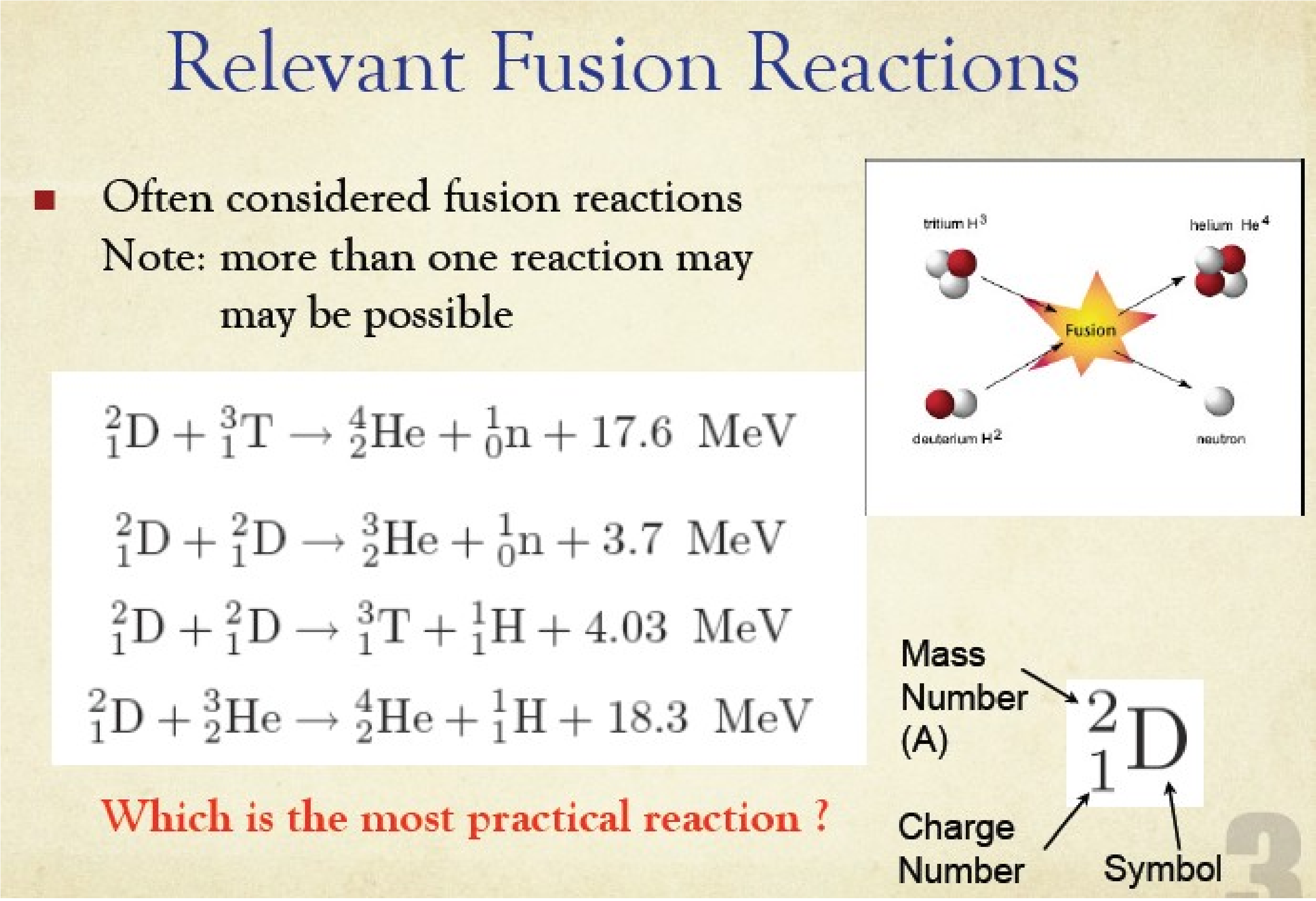
Plasma compression with lasers

Use radiation pressure: p=I/c
→ heating, compression or acceleration

Sun: I ~ 1370 W/m^2=0.137W/cm^2 → p ~ 4.6 μPa

Laser with I = 10^12 W/cm^2 → p ~ 10 MPa
I = 10^17 W/cm^2 → p ~ 100 GPa
Field ionization of hydrogen
I = 10^21 W/cm^2 → relativistic electrons
Electron-positron pairs
I = 10^23 W/cm^2 planned (ELI)

Can we reach Nuclear Fusion?



Relevant Fusion Reactions

- Often considered fusion reactions
  Note: more than one reaction may
  may be possible

$${}^2_1\mathrm{D} + {}^3_1\mathrm{T} \rightarrow {}^4_2\mathrm{He} + {}^1_0\mathrm{n} + 17.6\ \mathrm{MeV}$$

$${}^2_1\mathrm{D} + {}^2_1\mathrm{D} \rightarrow {}^3_2\mathrm{He} + {}^1_0\mathrm{n} + 3.7\ \mathrm{MeV}$$

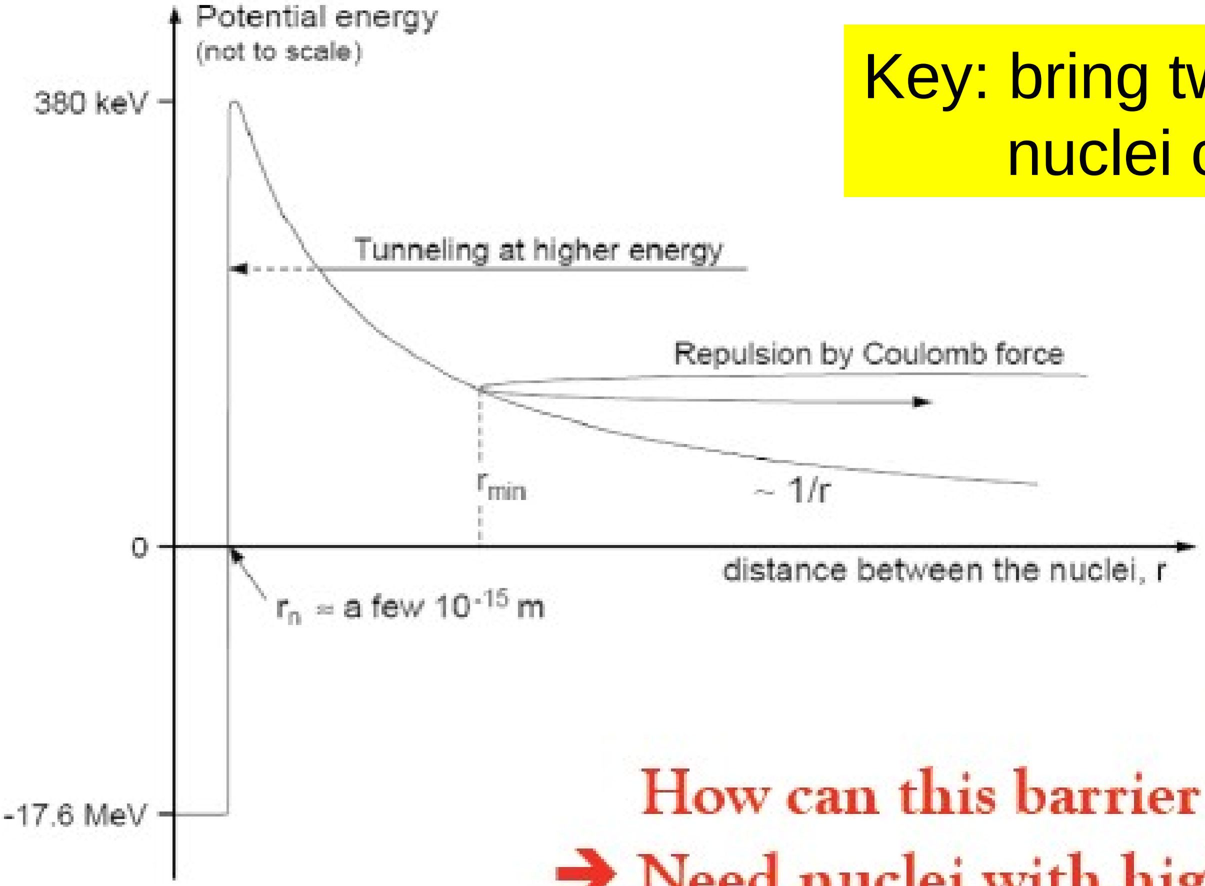
$${}^2_1\mathrm{D} + {}^2_1\mathrm{D} \rightarrow {}^3_1\mathrm{T} + {}^1_1\mathrm{H} + 4.03\ \mathrm{MeV}$$

$${}^2_1\mathrm{D} + {}^3_2\mathrm{He} \rightarrow {}^4_2\mathrm{He} + {}^1_1\mathrm{H} + 18.3\ \mathrm{MeV}$$

Which is the most practical reaction ?

Can we reach Nuclear Fusion?

Key: bring two hydrogen nuclei close together

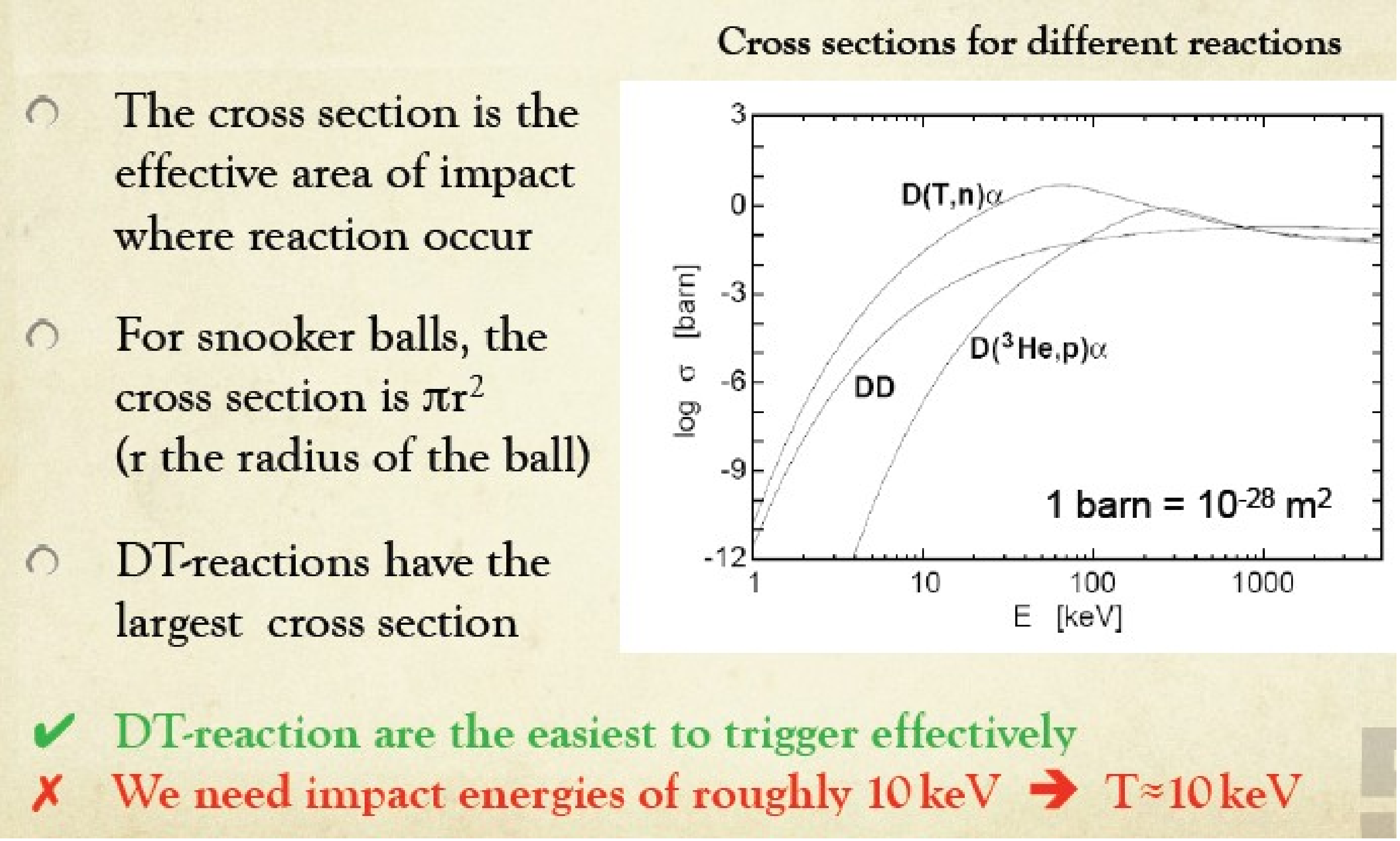


How can this barrier overcome?

➔ Need nuclei with high energies!

D. Gericke

Fusion cross sections



Cross sections for different reactions

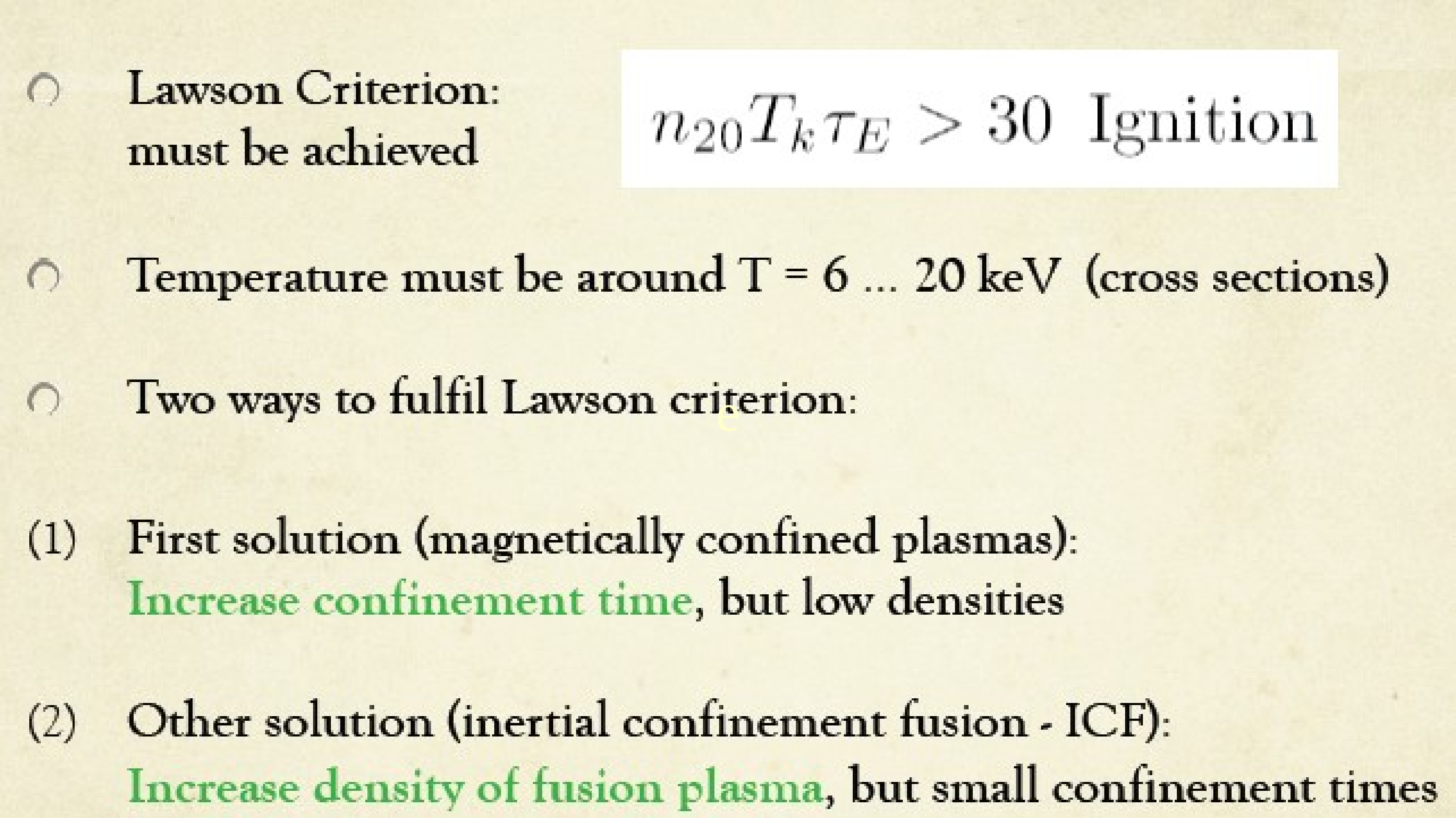
- The cross section is the effective area of impact where reaction occur
- For snooker balls, the cross section is πr^2 (r the radius of the ball)
- DT-reactions have the largest cross section

✔ DT-reaction are the easiest to trigger effectively

✗ We need impact energies of roughly 10 keV ➔ T≈10 keV

D. Gericke

Lawson criterion



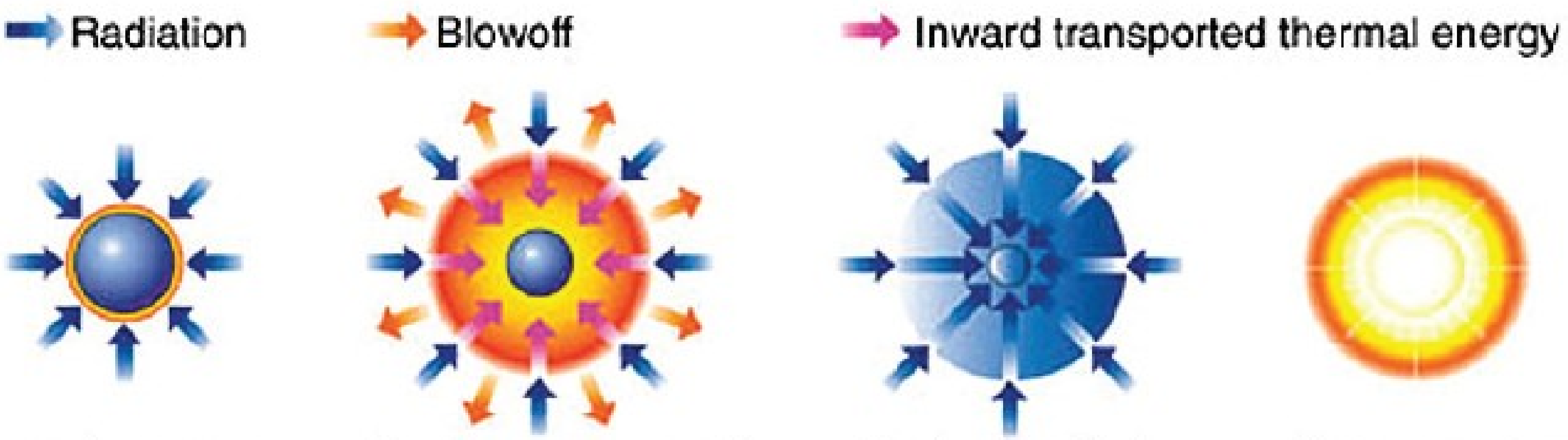
- Lawson Criterion: must be achieved $n_{20}T_k\tau_E > 30$ Ignition
- Temperature must be around T = 6 … 20 keV (cross sections)
- Two ways to fulfil Lawson criterion:

(1) First solution (magnetically confined plasmas):
Increase confinement time, but low densities

(2) Other solution (inertial confinement fusion - ICF):
Increase density of fusion plasma, but small confinement times

(3) Magnetized linear ion fusion (Z-pinch, Sandia)

Idea of laser fusion (ICF)



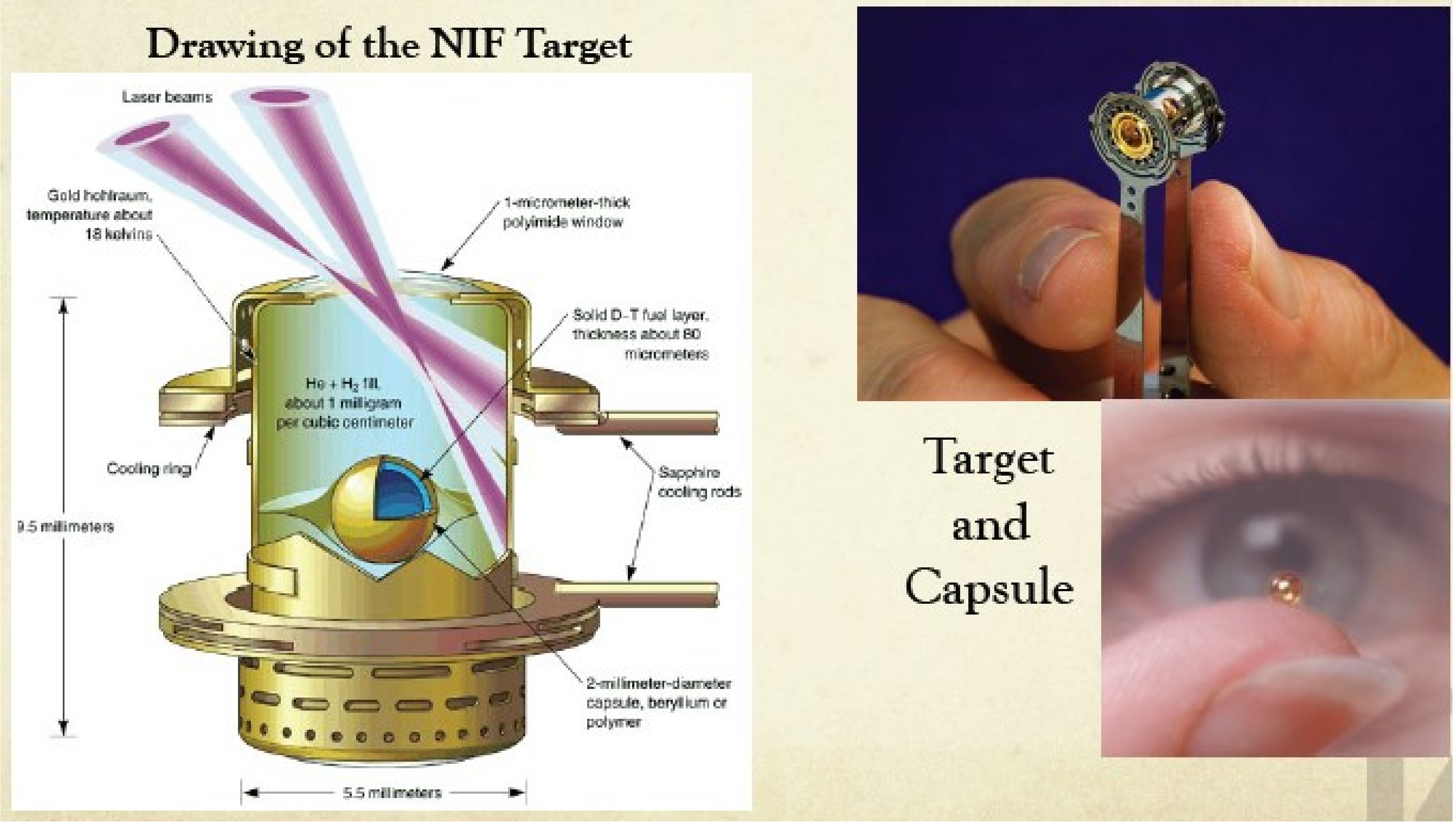
Laser beams or laser-produced x rays rapidly heat the surface of the fusion target, forming a surrounding plasma envelope.

Fuel is compressed by the rocketlike blowoff of the hot surface material.

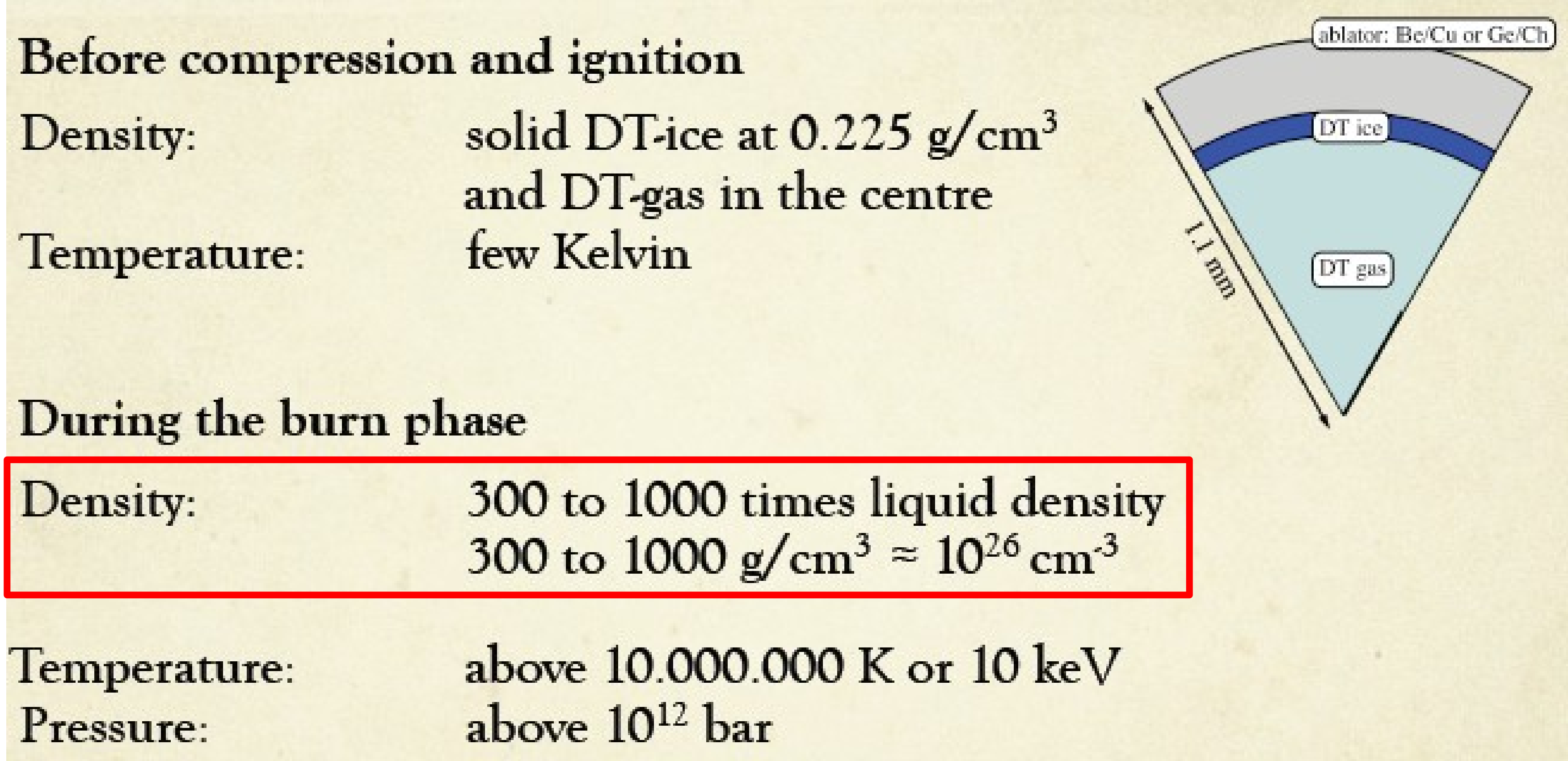
During the final part of the capsule implosion, the fuel core reaches 20 times the density of lead and ignites at 100,000,000°C.

Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy.

Laser fusion targets



Necessary parameters



Before compression and ignition

Density: solid DT-ice at 0.225 g/cm^3 and DT-gas in the centre

Temperature: few Kelvin

During the burn phase

Density: 300 to 1000 times liquid density
300 to 1000 g/cm^3 $\approx 10^{26}$ cm^{-3}

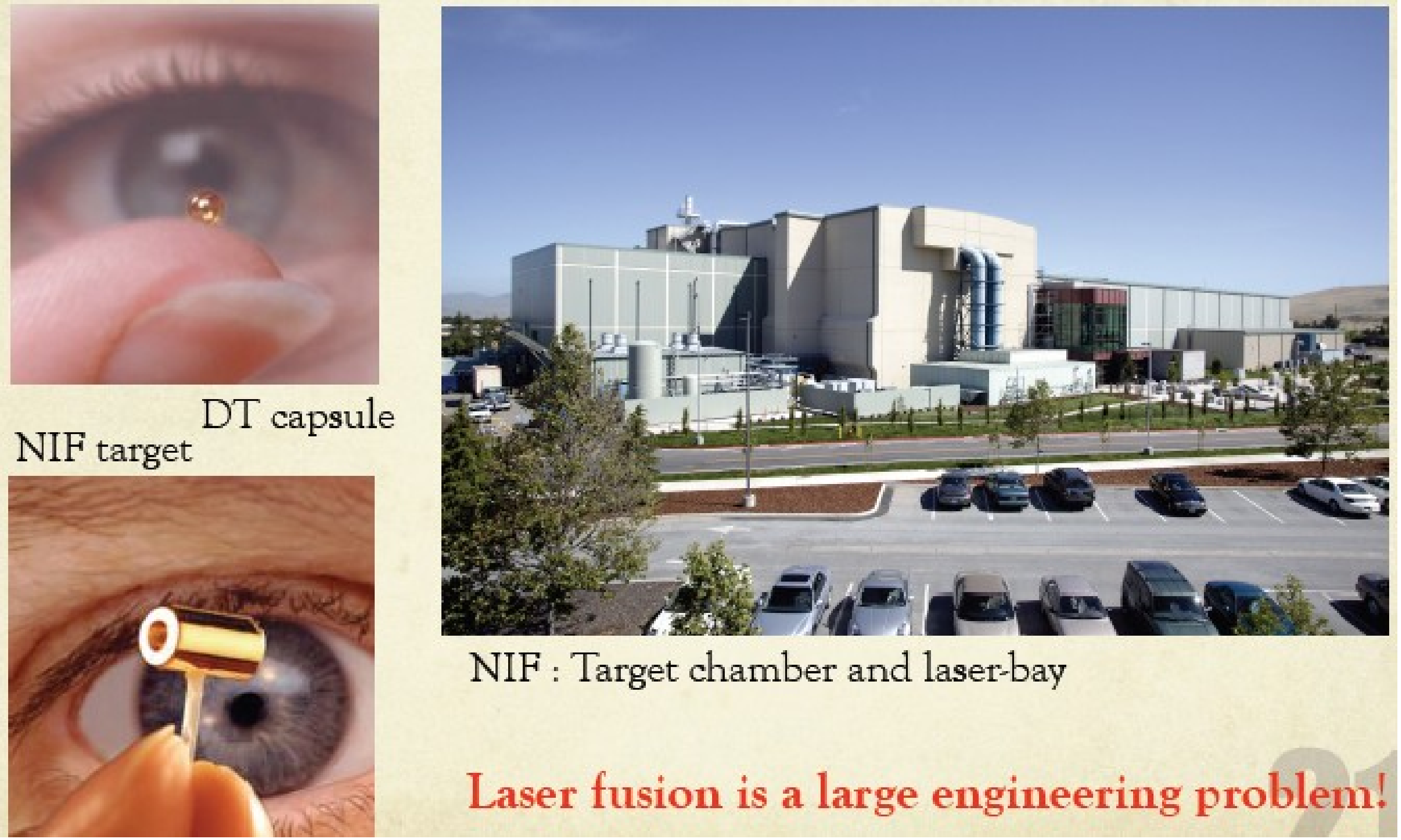
Temperature: above 10.000.000 K or 10 keV

Pressure: above 10^{12} bar

Confinement time: 200 ps
Energy to compress a few mg of DT: 1...2MJ

Same energy as in a hamburger...

National Ignition Facility (NIF)



DT capsule

NIF target

NIF : Target chamber and laser-bay

Laser fusion is a large engineering problem!

National Ignition Facility (NIF)

Laser bay 2
2007...2014

Source: Wikipedia

National Ignition campgain, LLNL

National Ignition facility (NIF) at Livermore NL (CA)

192 high power laser beams focused on fusion target

- Completion 2009
- March 15 2012: Record shot with 2MJ laser energy
- July 5 2012: short pulse, dt~3ns with energy 1.85MJ
  → record laser power: P=500TW
- Sept 30 2012 end of NIC, critical review of project
- 2014: improved pulse shaping, capsule design etc.
  --> fusion and alpha heating observed
- need a factor 2...4 more efficiency for selfsustained fusion
- alternative: magnetized linear ion fusion

National Ignition campgain, LLNL

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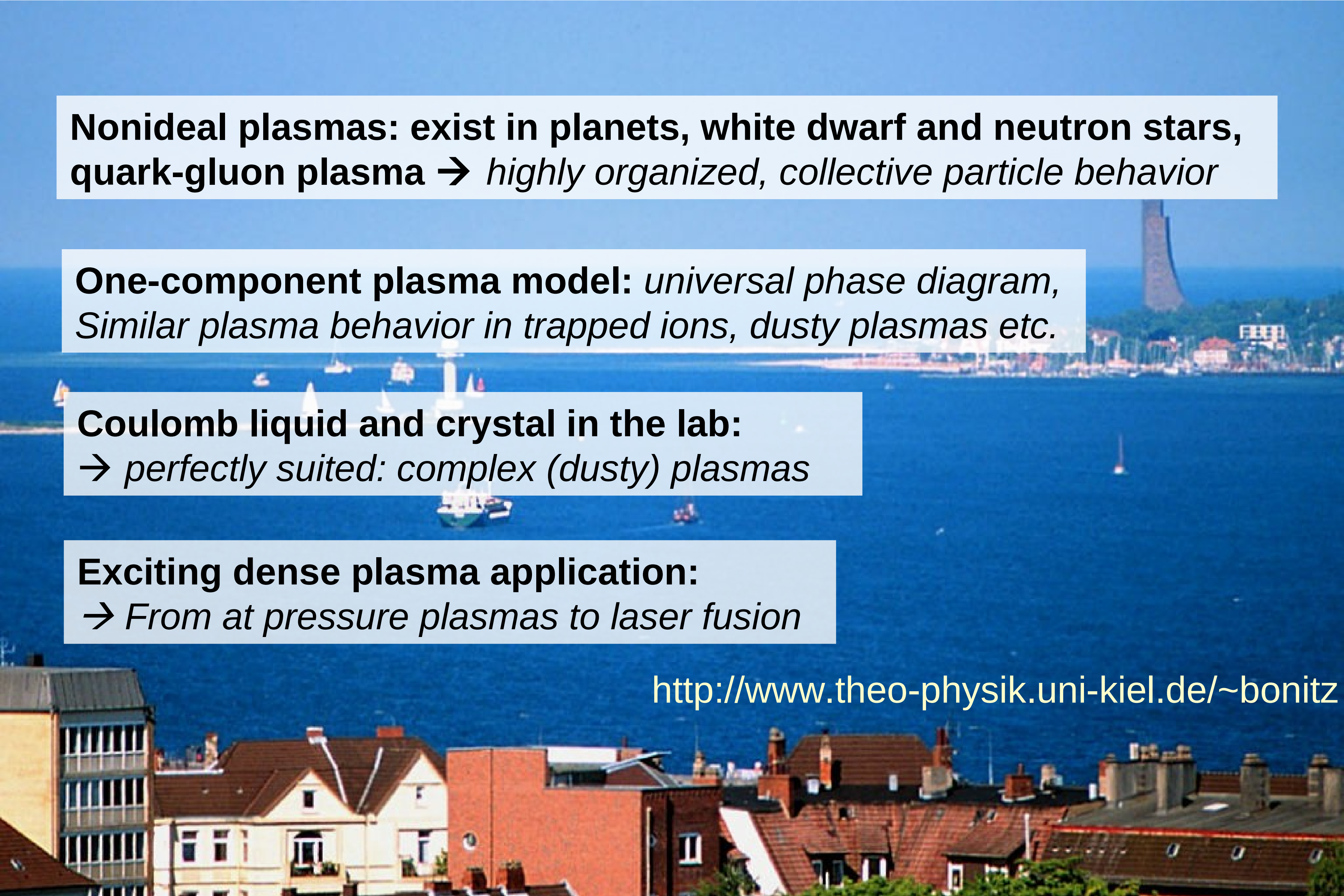
→ Exciting field for (nonideal/complex) plasma research
On the border between plasma, solid state and atomic physics

Summary



Nonideal plasmas: exist in planets, white dwarf and neutron stars, quark-gluon plasma → *highly organized, collective particle behavior*

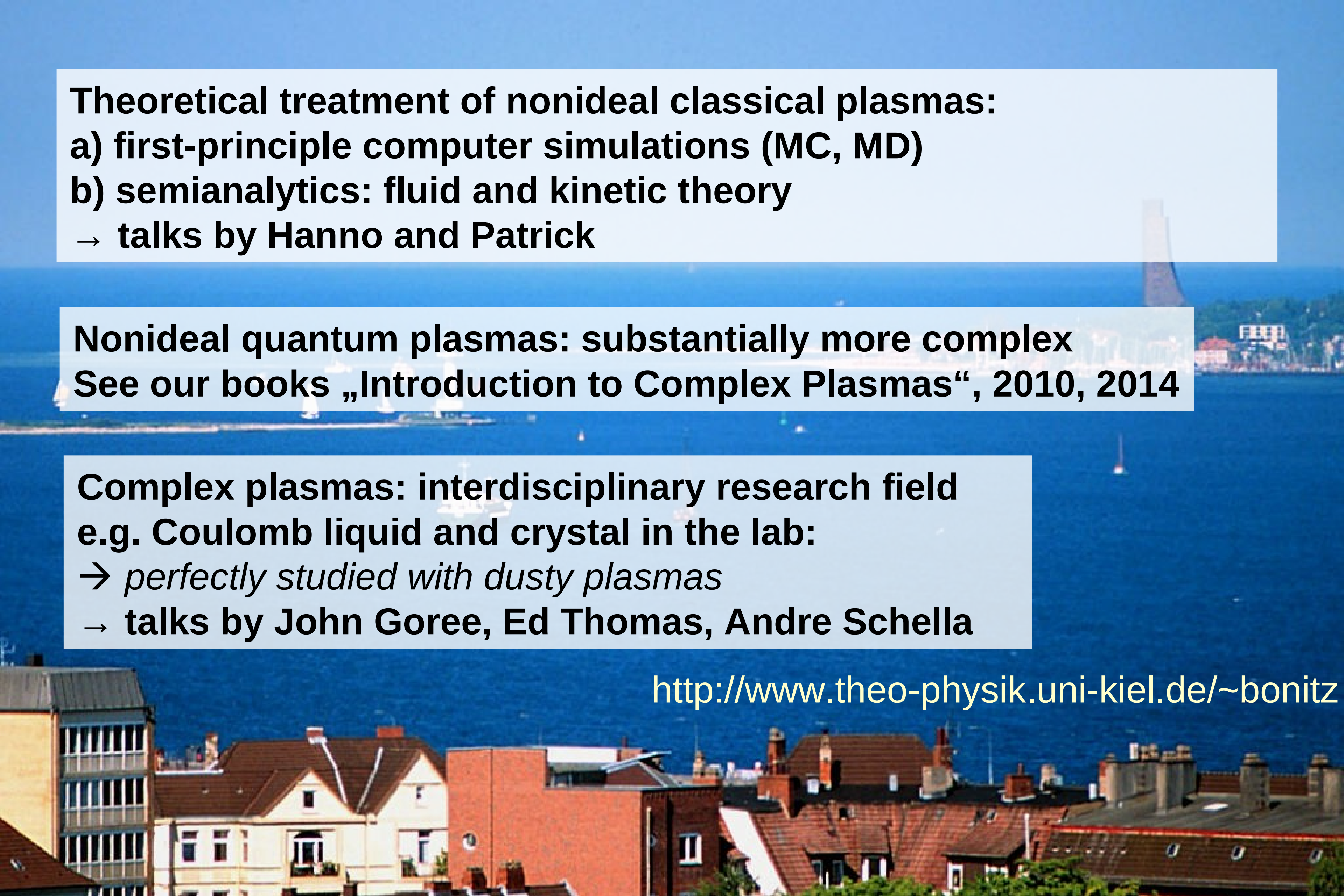
One-component plasma model: *universal phase diagram, Similar plasma behavior in trapped ions, dusty plasmas etc.*

Coulomb liquid and crystal in the lab:
→ *perfectly suited: complex (dusty) plasmas*

Exciting dense plasma application:
→ *From at pressure plasmas to laser fusion*

http://www.theo-physik.uni-kiel.de/~bonitz

Summary



Theoretical treatment of nonideal classical plasmas:
a) first-principle computer simulations (MC, MD)
b) semianalytics: fluid and kinetic theory
→ talks by Hanno and Patrick

Nonideal quantum plasmas: substantially more complex
See our books „Introduction to Complex Plasmas“, 2010, 2014

Complex plasmas: interdisciplinary research field
e.g. Coulomb liquid and crystal in the lab:
→ *perfectly studied with dusty plasmas*
→ talks by John Goree, Ed Thomas, Andre Schella

http://www.theo-physik.uni-kiel.de/~bonitz