Physics of dense plasmas – correlations, magnetic fields and quantum effects

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Helmholtz-Institut Jena, 22. Mai 2013

C A U
Christian-Albrechts-Universität zu Kiel

TR 24
complex plasmas

Collaborations, Support

A. Piel, D. Block, F. Faupel (Kiel),

A. Melzer, H. Fehske (Greifswald), T. Ott, H. Löwen (Düsseldorf)

Yu. Lozovik, V. Filinov, V. Fortov (Moscow), S. Smolyansky (Saratov),

J.W. Dufty (Florida), H. Kählert, G. Kalman (Boston),

P. Hartmann, Z. Donko (Budapest),

K. Balzer, M. Drescher (Hamburg), T. Brabec (Ottawa)

DFG

DAAD

Bundesministerium
für Bildung
und Forschung

U.S. DEPARTMENT OF ENERGY

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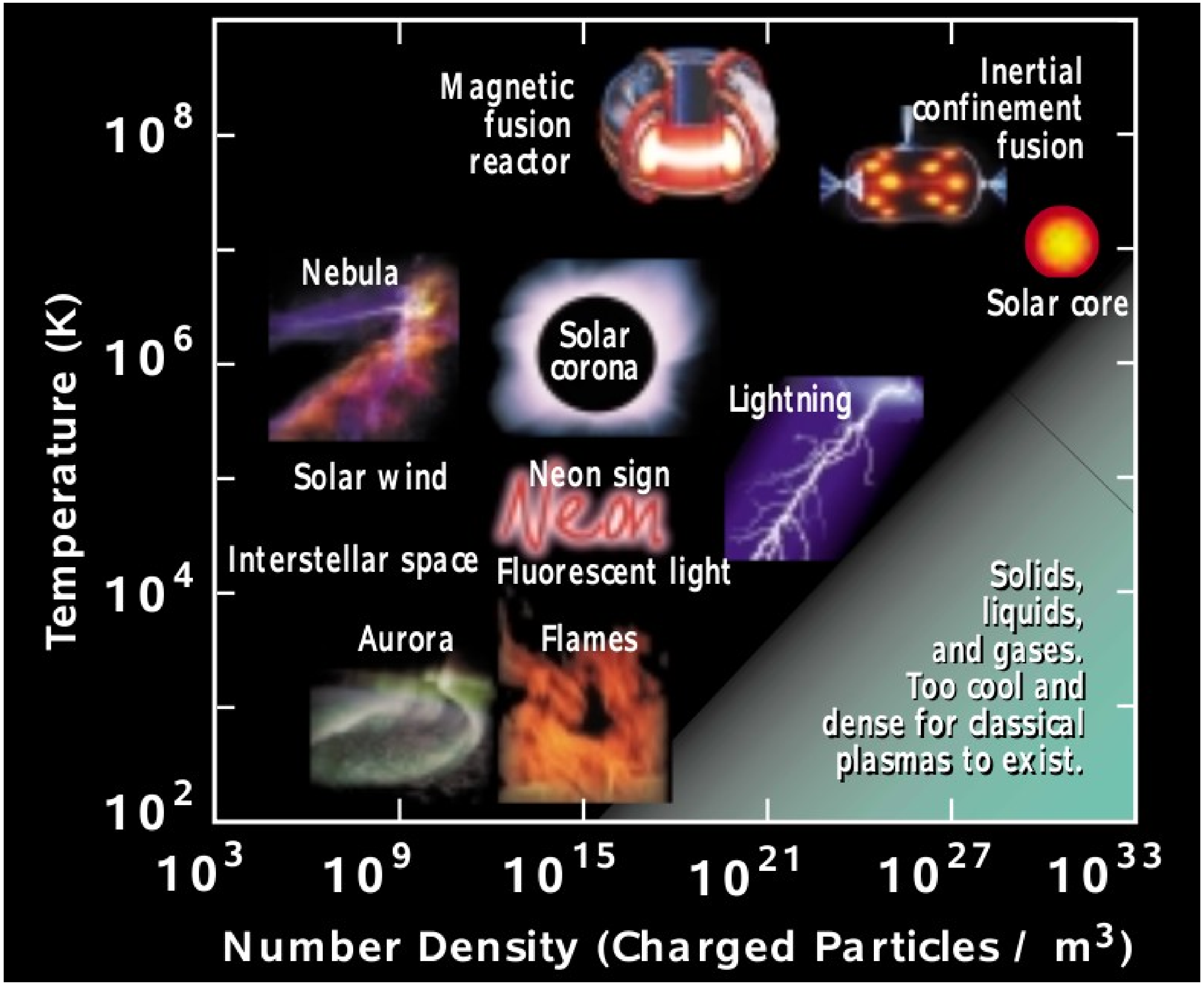
complex plasmas

National Science Foundation
WHERE DISCOVERIES BEGIN

Plasmas in the Universe and in the Lab



Plasma: hot gas of
charged particles

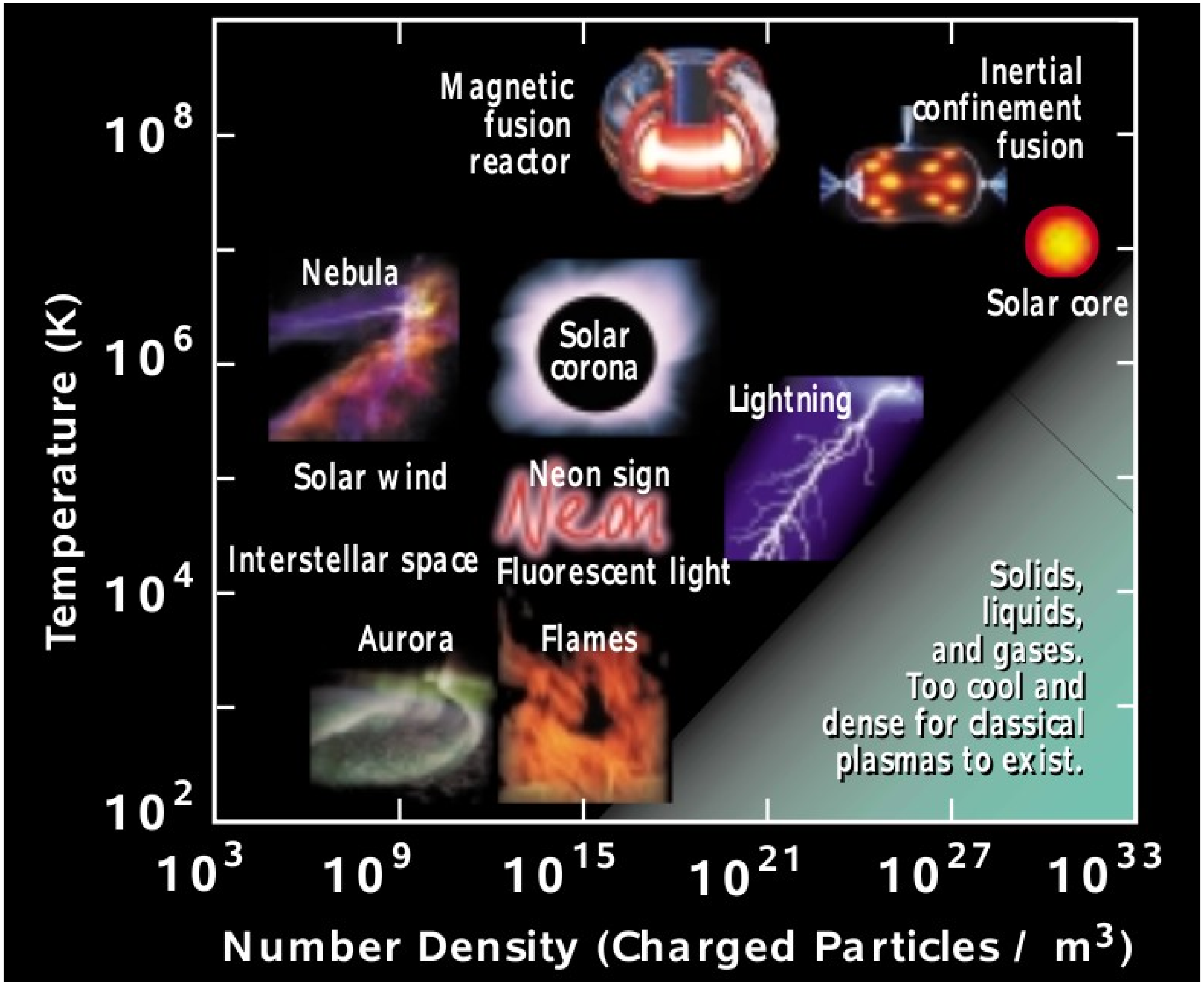
Ideal gas
Simple physics

?

From Contemporary physics education project 2010 (NSF, DOE sponsored)

http://www.cpepphysics.org/fusion.html

Plasmas in the Universe and in the Lab



Lots of exciting plasmas missing!

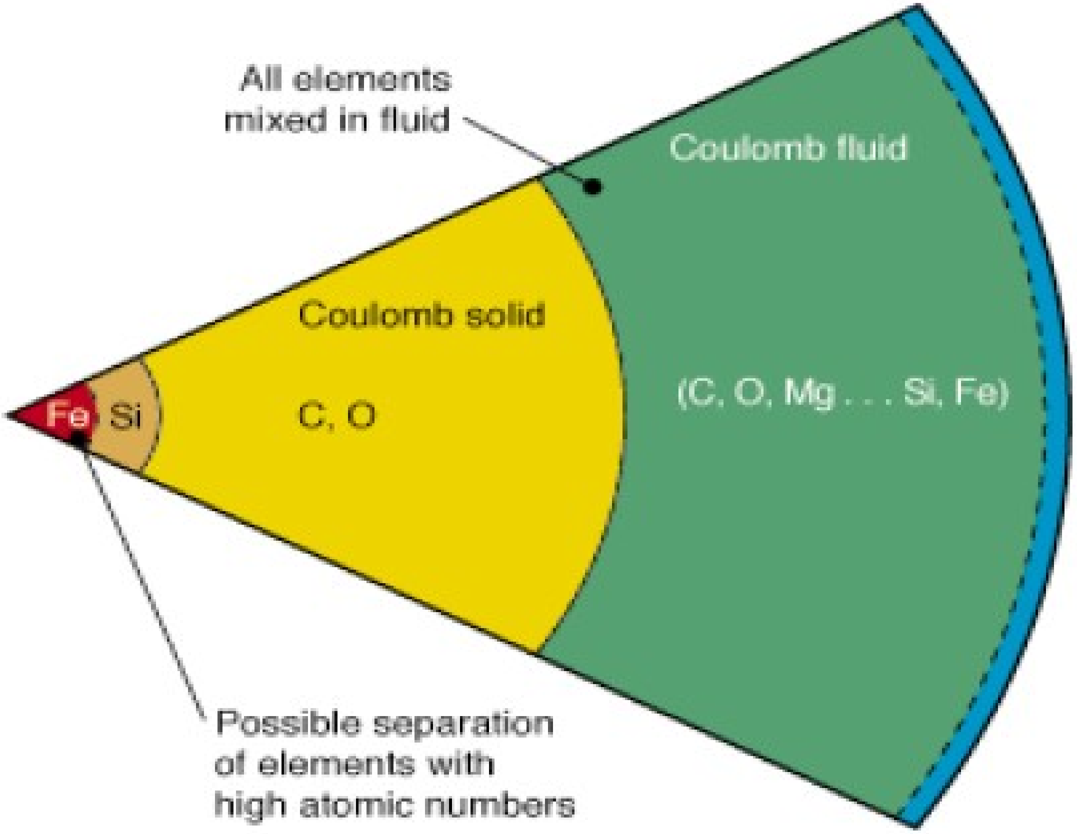
Dense space plasmas:

- Cores of giant planets
- dwarf stars
- neutron stars

From Contemporary physics education project 2010 (NSF, DOE sponsored)

http://www.cpepphysics.org/fusion.html

Dense plasma in 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

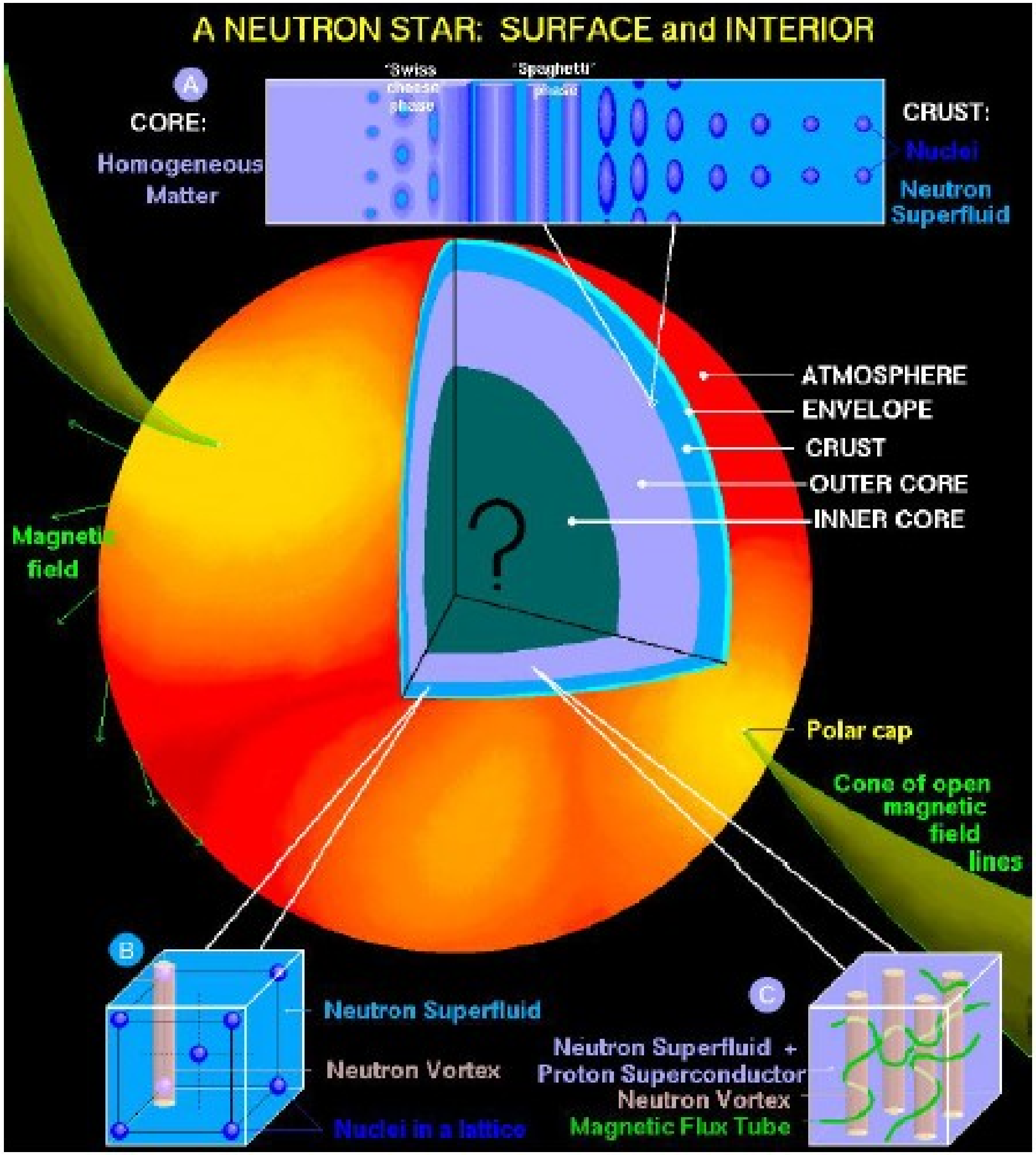
classical
fluid and crystal
in „quantum sea“
of electrons

Size ~ our Earth
Mass ~ our Sun
→density:

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

$$B = 10^3 \ldots . 10^7 T$$

Dense plasma in Neutron stars



crystal and
quantum fluid
of Fe-nuclei

in „quantum sea“
of electrons

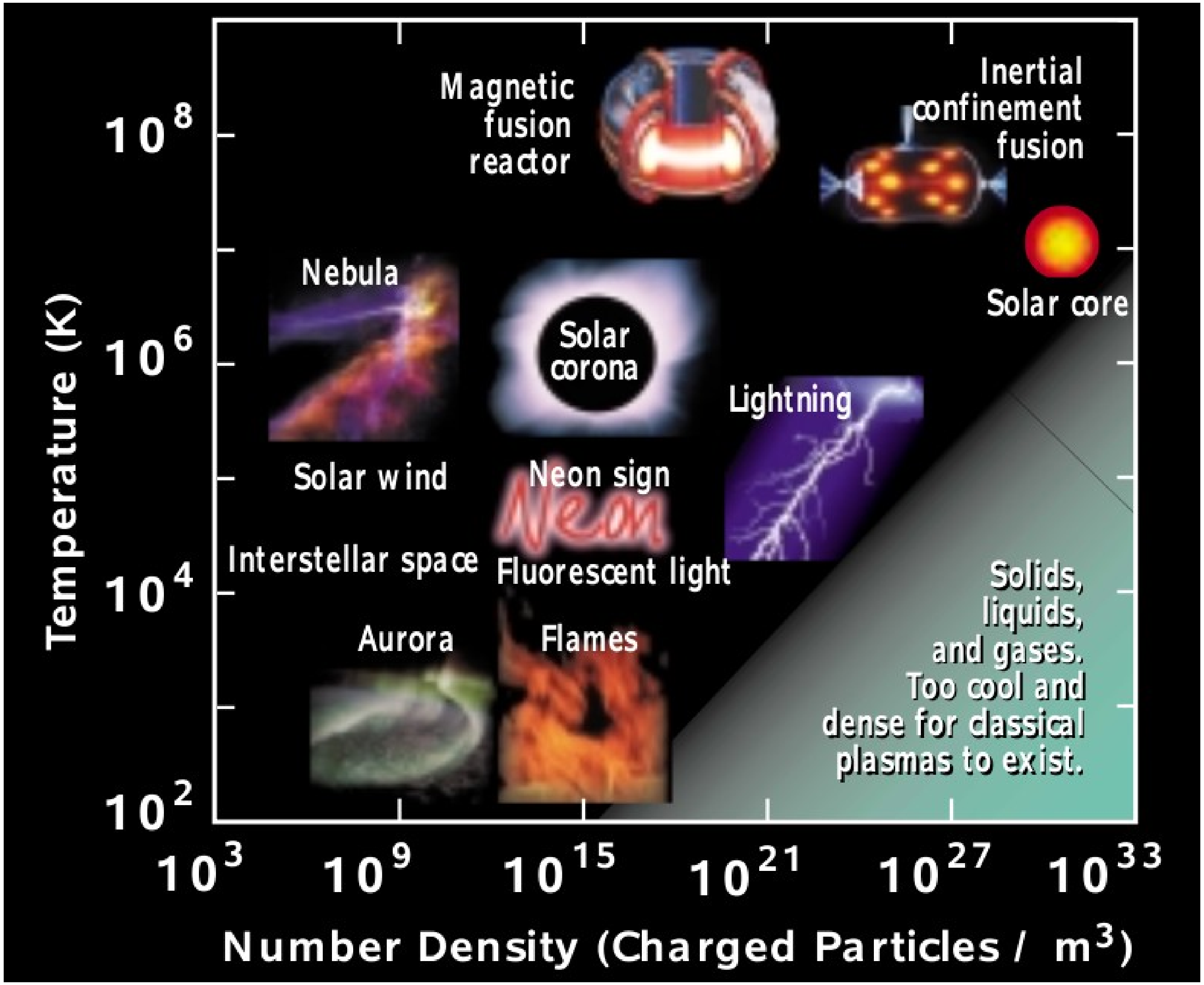
Radius ~ 10km
Mass ~ our Sun

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

$$B = 10^{6} \ldots . 10^{11}\, T$$

Source: Coleman, UMD

Plasmas in the Universe and in the Lab



Lots of exciting plasmas missing!

Dense space plasmas:

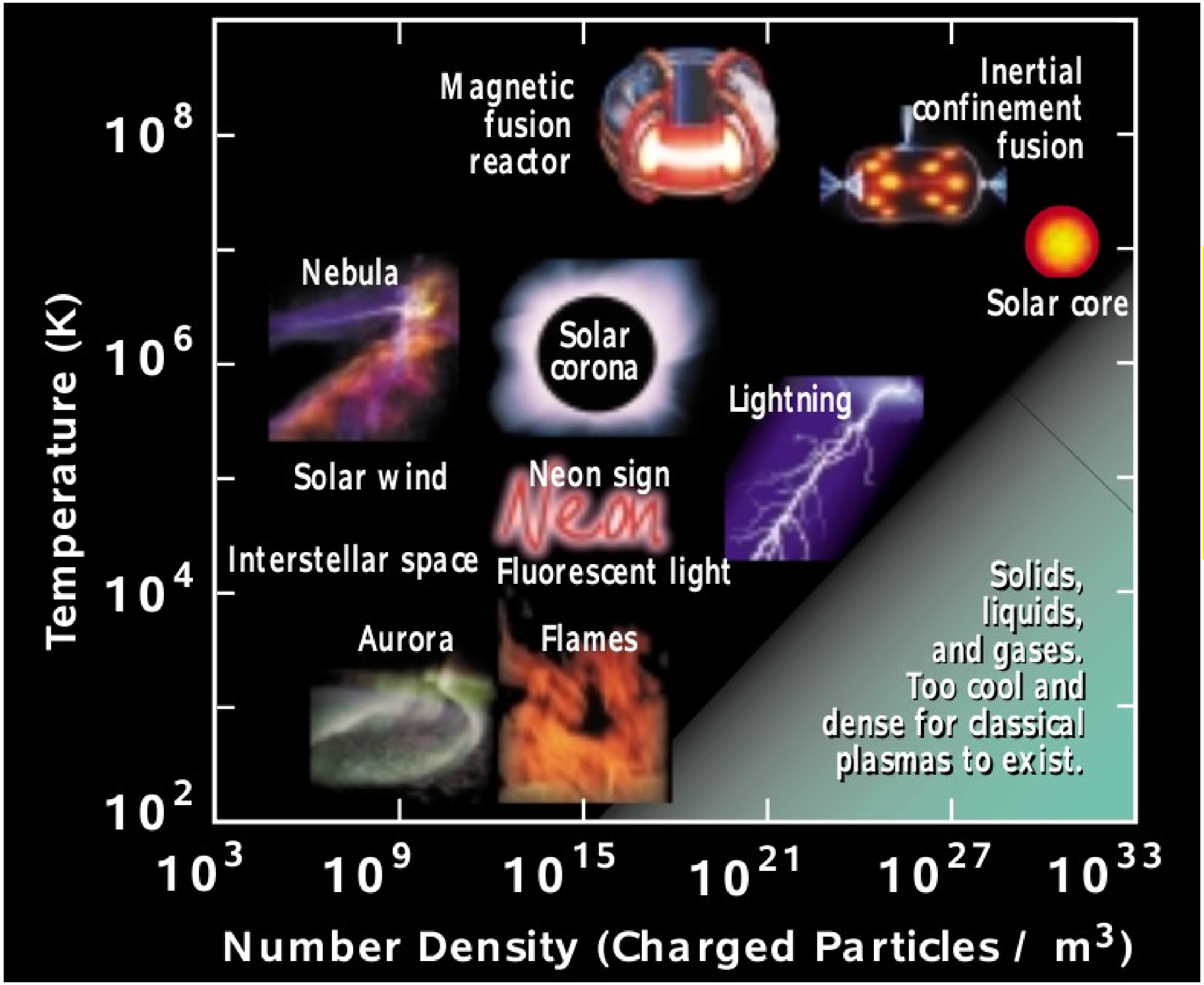
- Cores of giant planets
- dwarf stars
- neutron stars

Dense laboratory plasmas:
- laser plasmas
- ion beam produced plasmas
- ICF

From Contemporary physics education project 2010 (NSF, DOE sponsored)

http://www.cpepphysics.org/fusion.html

Plasmas in the Universe and in the Lab



Lots of exciting plasmas missing!

Strong correlations
Cooperative behavior

Coulomb liquid and crystal states

- mass asymmetry
- quantum effects
- nonequilibrium
- magnetic fields

→ **Theory challenging!**

From Contemporary physics education project 2010 (NSF, DOE sponsored)

http://www.cpepphysics.org/fusion.html

Outline

1. **Correlation effects in plasmas: liquids and crystals**
    - dusty plasmas: the perfect test system

2. **Attraction of identical particles**
    - from balls to strings

3. **Dense plasmas in a strong magnetic field**
    - diffusion, normal modes
    - „Magnetizing“ a complex plasma without a magnet

4. **Dense two-component quantum plasmas**
    - status of the theory
    - towards multi-scale simulations

5. **Conclusions and outlook**

Selforganization in charged particle systems

Prediction of spontaneous spatial ordering (crystallization)

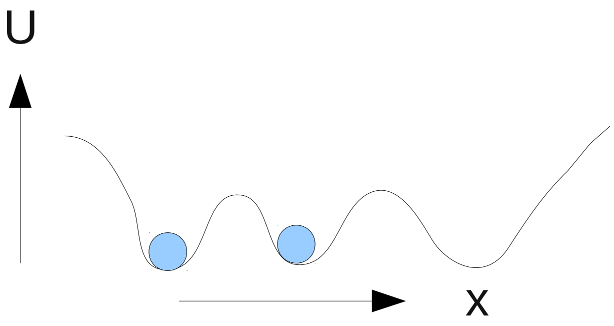
E. Wigner, Physical Review ***46,*** *1002 (1934):*

computed exchange and correlation energy of the electron gas in metals

„If the electrons had no kinetic energy, they would settle in configurations which correspond to the absolute minima of the potential energy. These are close-packed lattice configurations, with energies very near to that of the body-centered lattice....“

But: no electron crystal in metals observed yet

Ongoing search with other types of charged particles



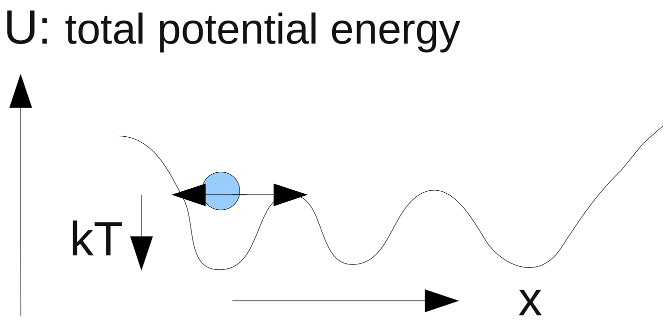
Coulomb crystallization upon cooling

Gradual crystallization upon cooling

Particles settle in potential minima when kinetic energy below threshold

MD simulation (Torben Ott): steady cooling

video →

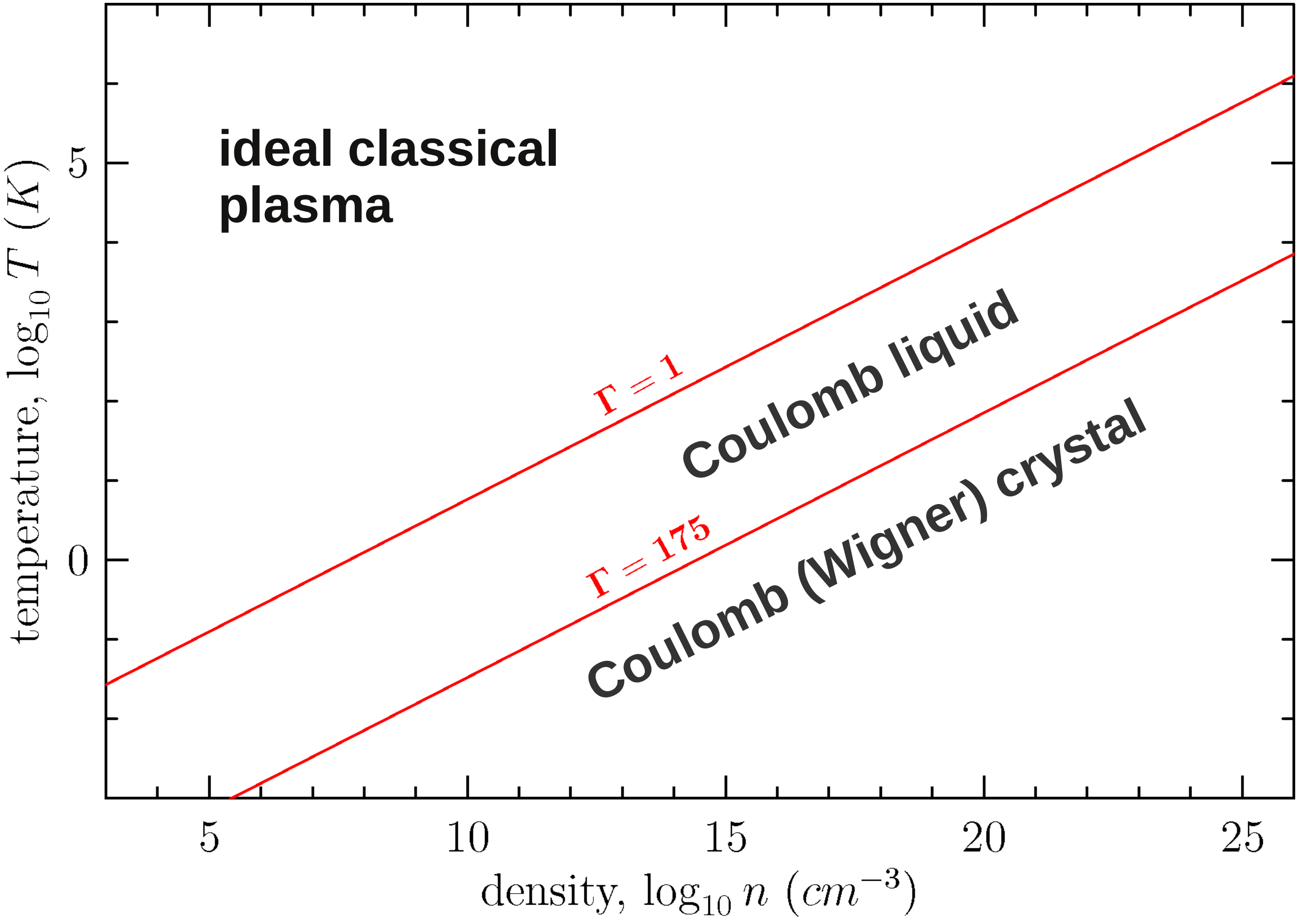


Coulomb coupling parameter

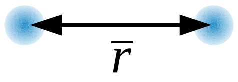
$$\Gamma \equiv \frac{Q^2}{\bar{r}\, k_B T}$$

Freezing for Gamma > 175

Strongly coupled Coulomb systems

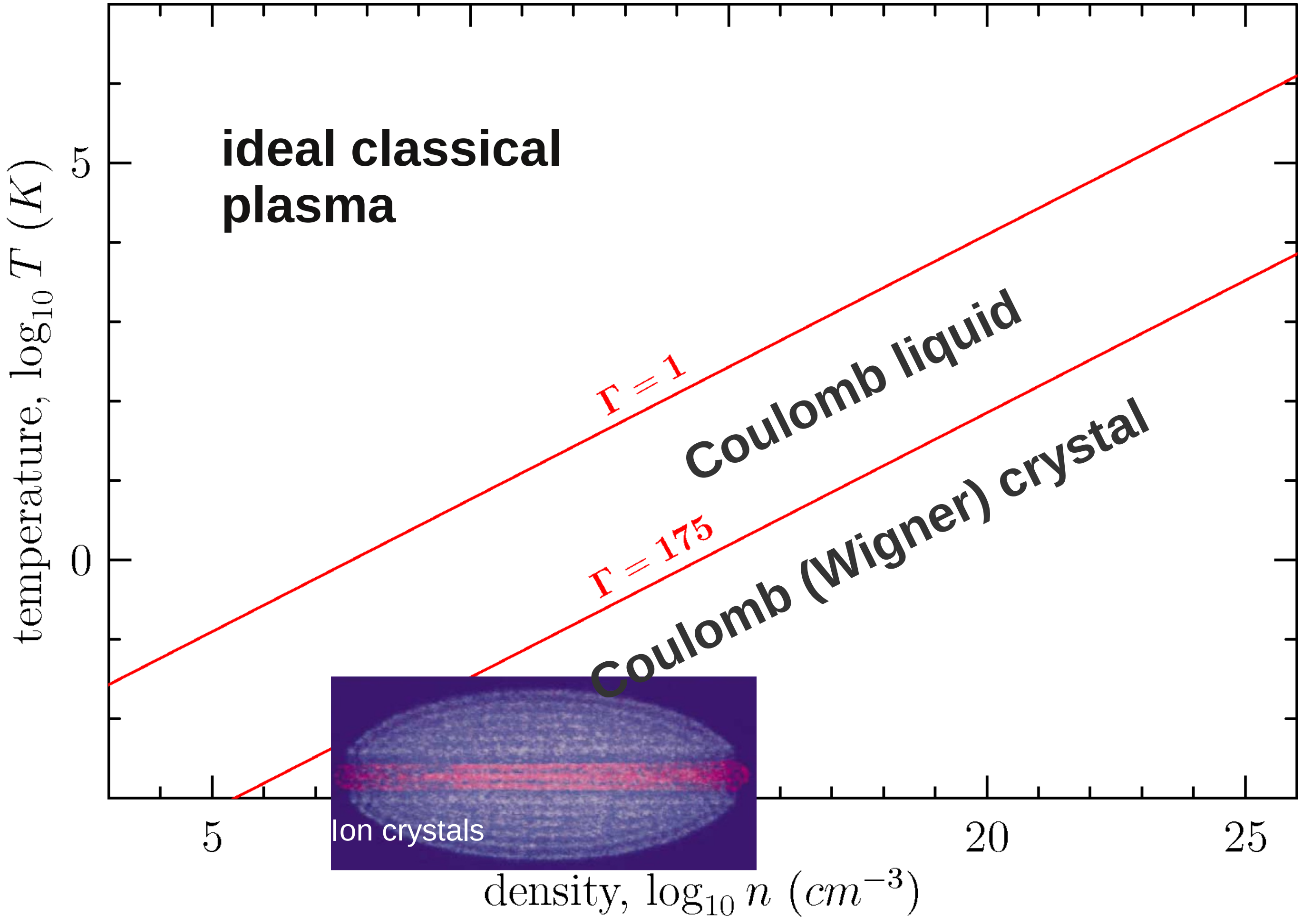


Coulomb interaction



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

How to achieve Coulomb crystallization (1)



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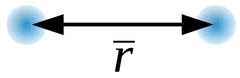
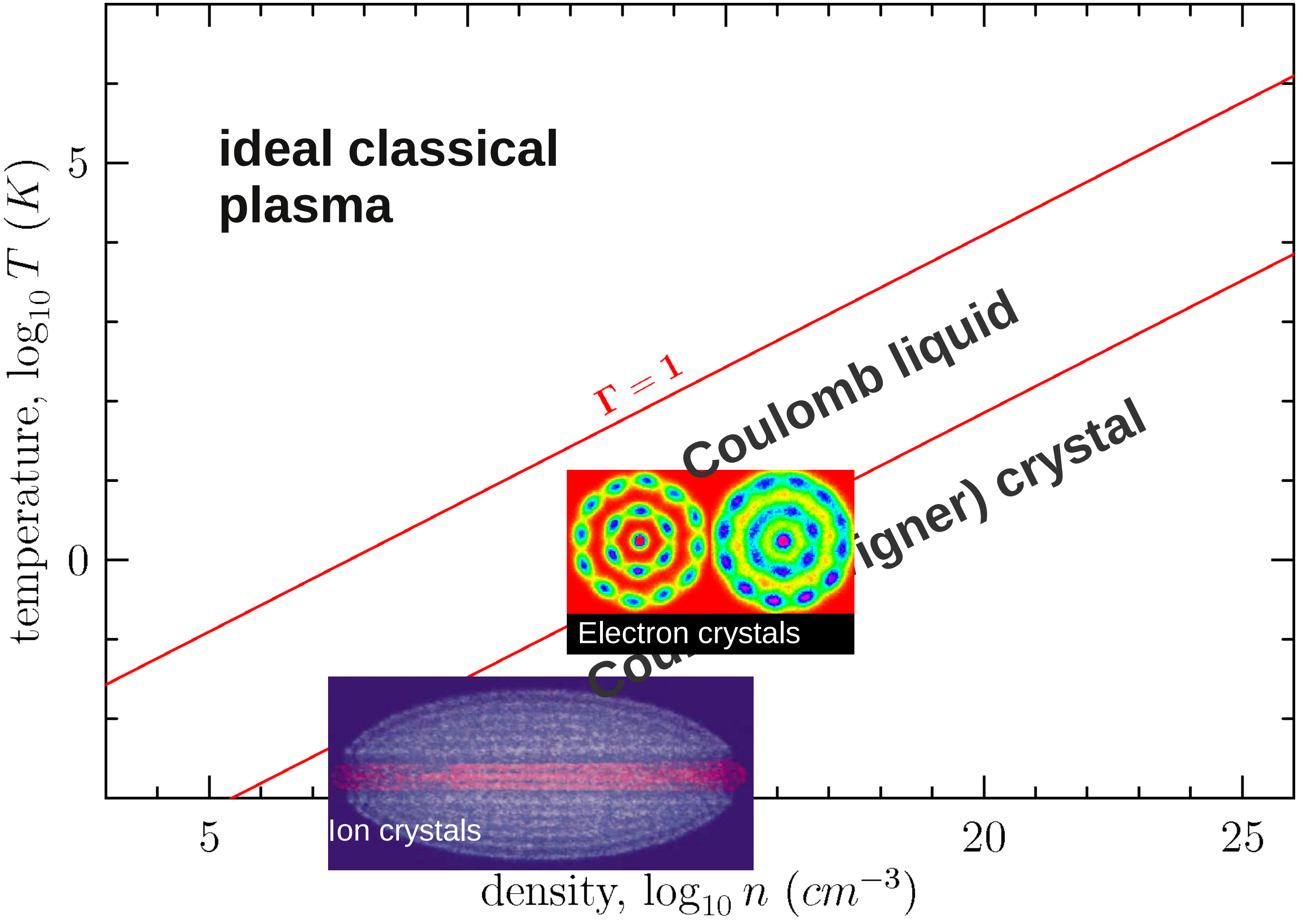


$$\Gamma \equiv \frac{Q^2}{\overline{r}\, k_B T}$$

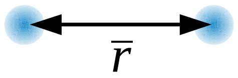
→ **cooling**

Ions in traps, mk temperature

How to achieve Coulomb crystallization (2)



Coulomb interaction



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

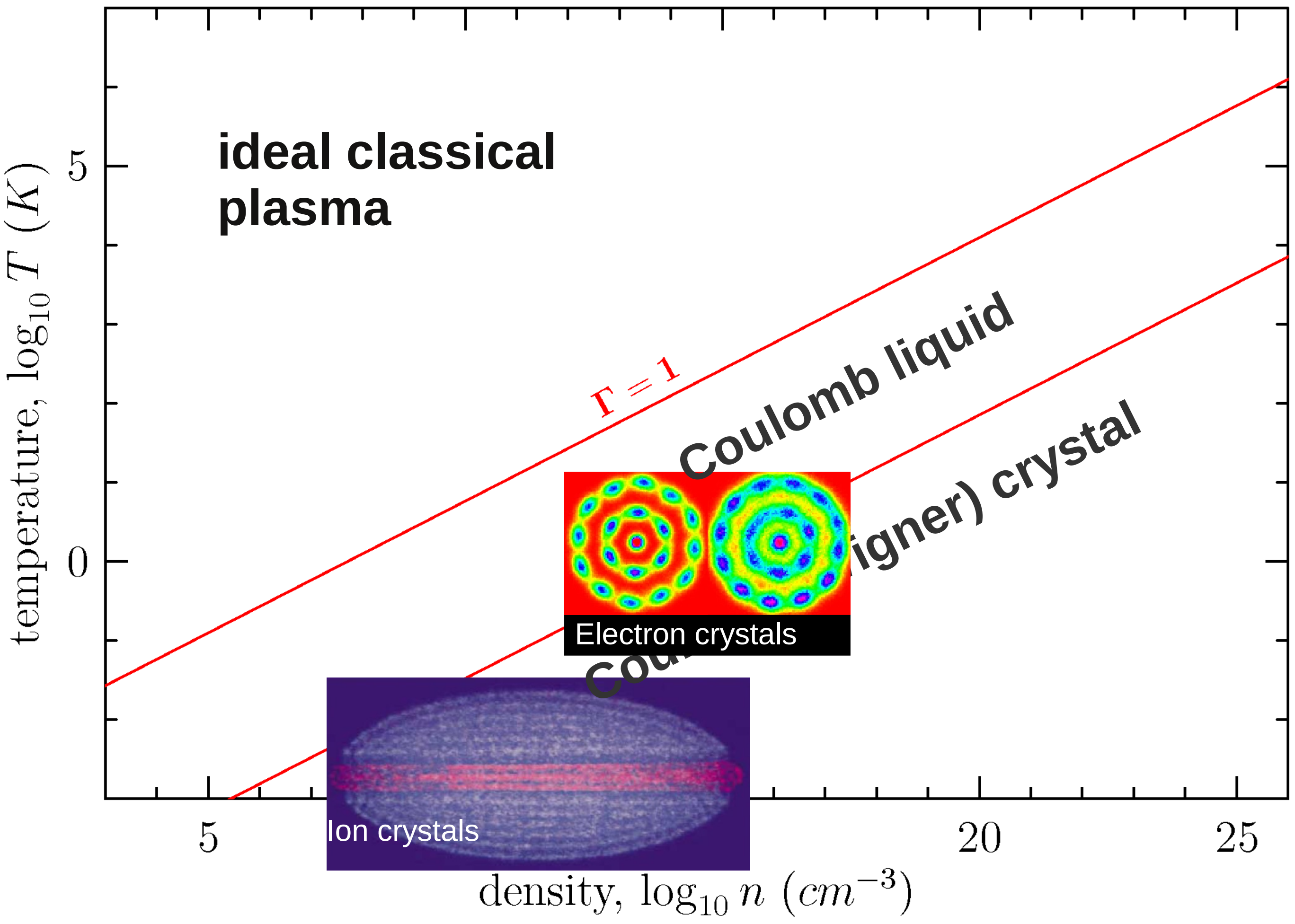
→ **compression**

Ions in traps, mk temperature

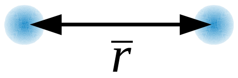
electrons in quantum dots (predicted)

Filinov, Bonitz, Lozovik, PRL 2001

How to achieve Coulomb crystallization (3)



Coulomb interaction



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

→ **charging**

?

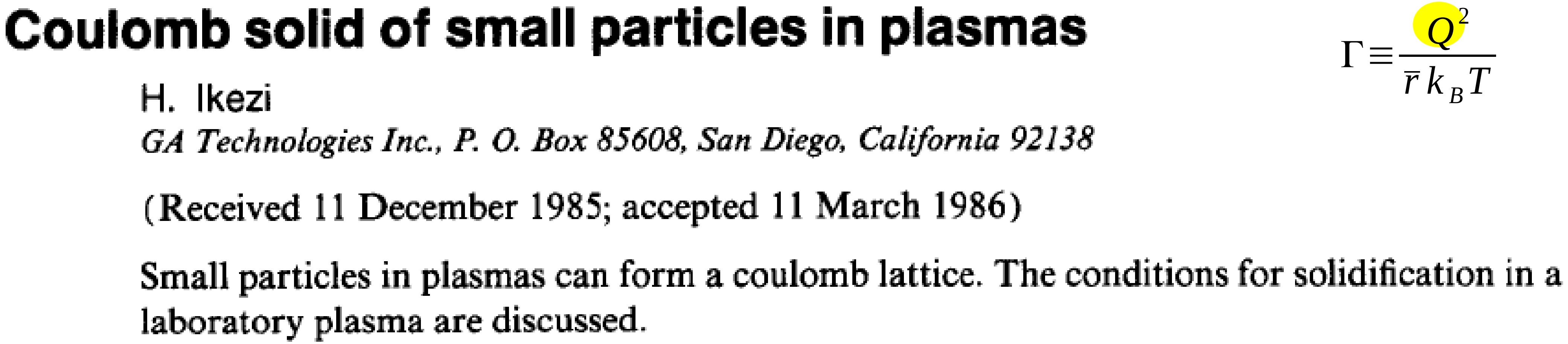
Ions in traps, mk temperature

electrons in quantum dots (predicted)

Filinov, Bonitz, Lozovik, PRL 2001

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.

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

Coulomb crystal in complex plasma

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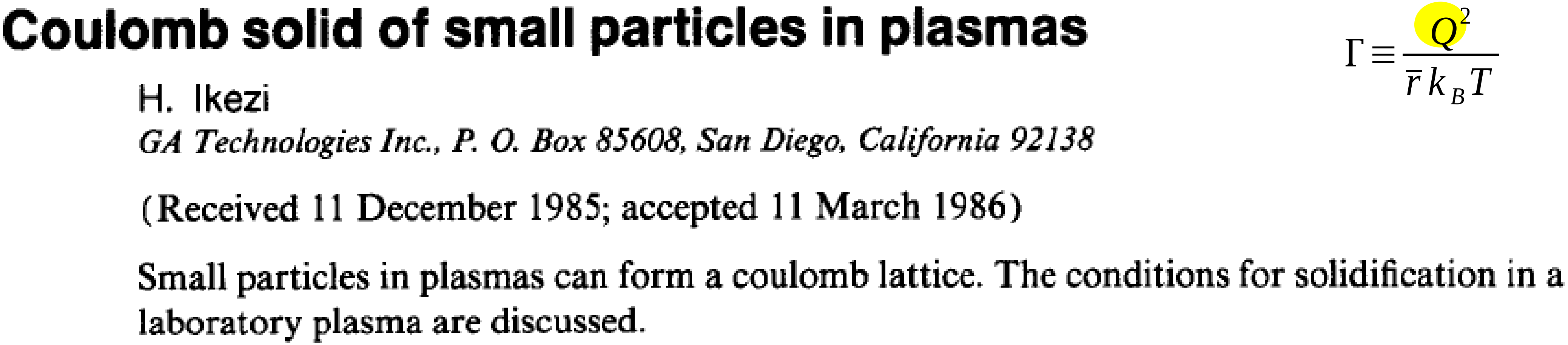

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1994: Experimental observation

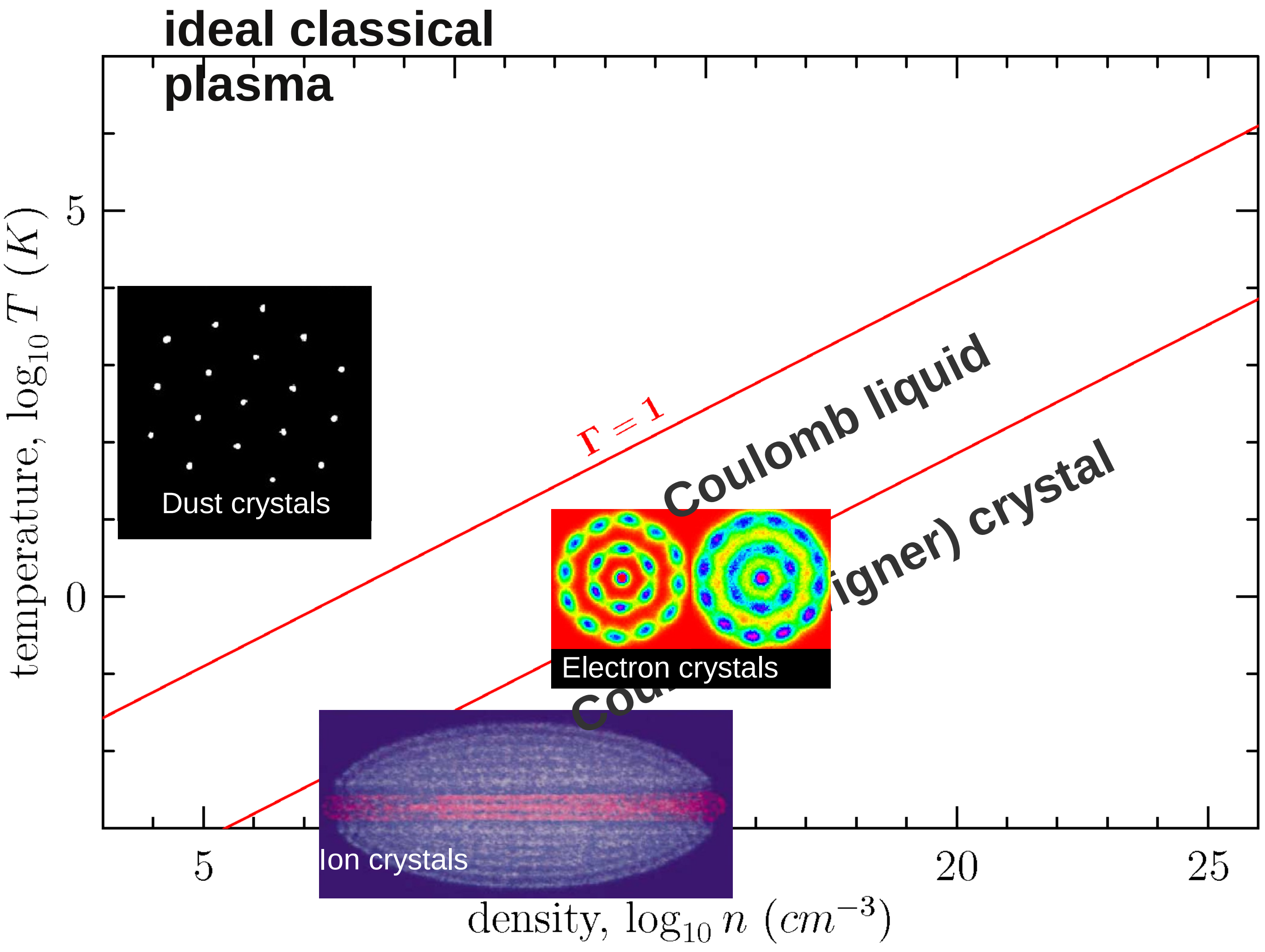
Y. Hayashi et al., Jap J. Appl. Phys. **33**, L 804 (1994)

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

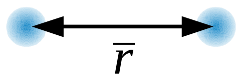
A. Melzer et al., Phys. Lett. A **191**, 301 (1994)

Tremendous activity
By many groups...

Coulomb crystal in complex plasma



Coulomb interaction



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

→ **charging**

Ions in traps, mk temperature

electrons in quantum dots (predicted)

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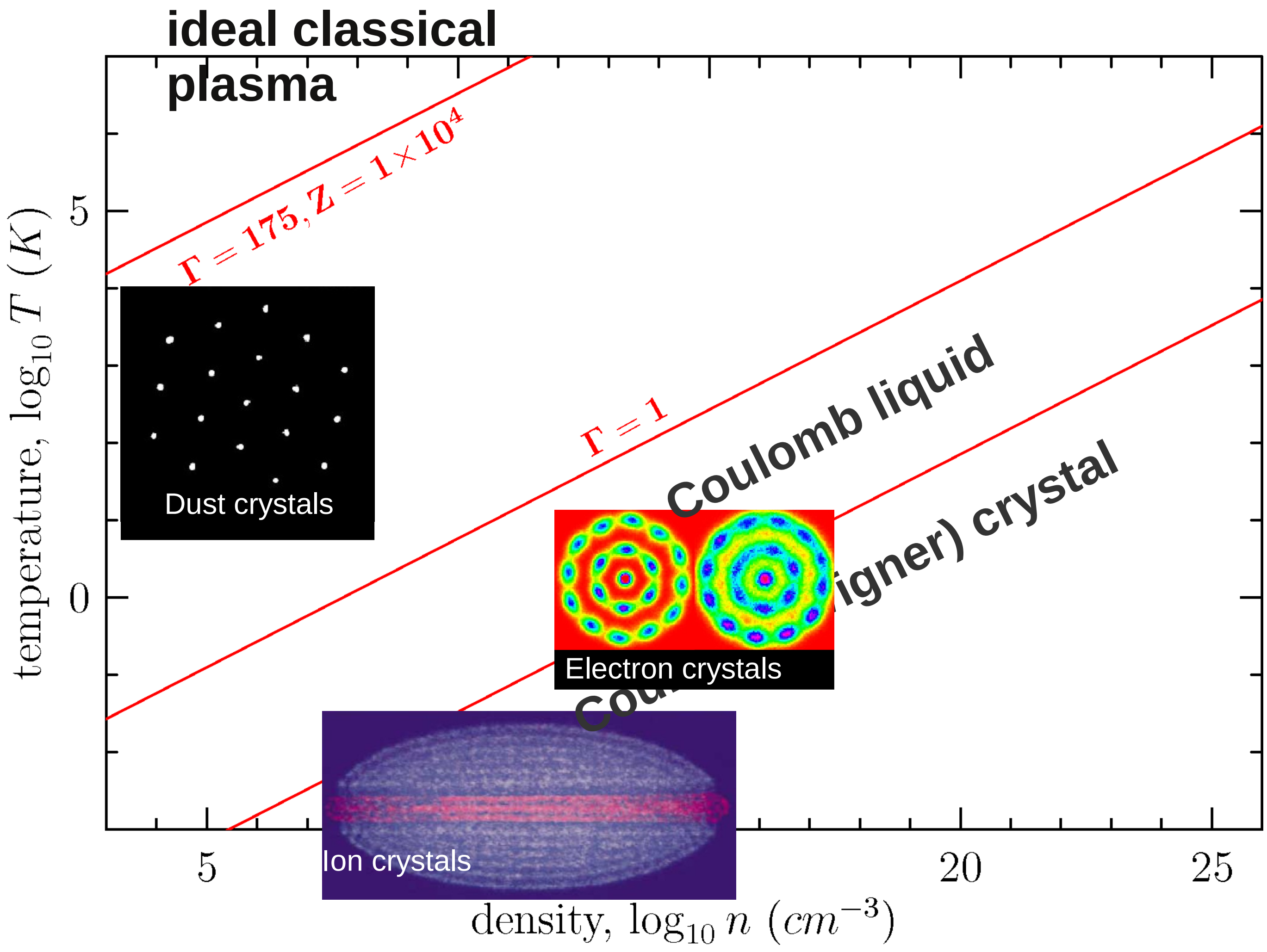
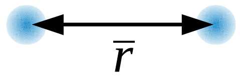


Coulomb interaction



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

→ **charging**

Q=10,000 …
100,000

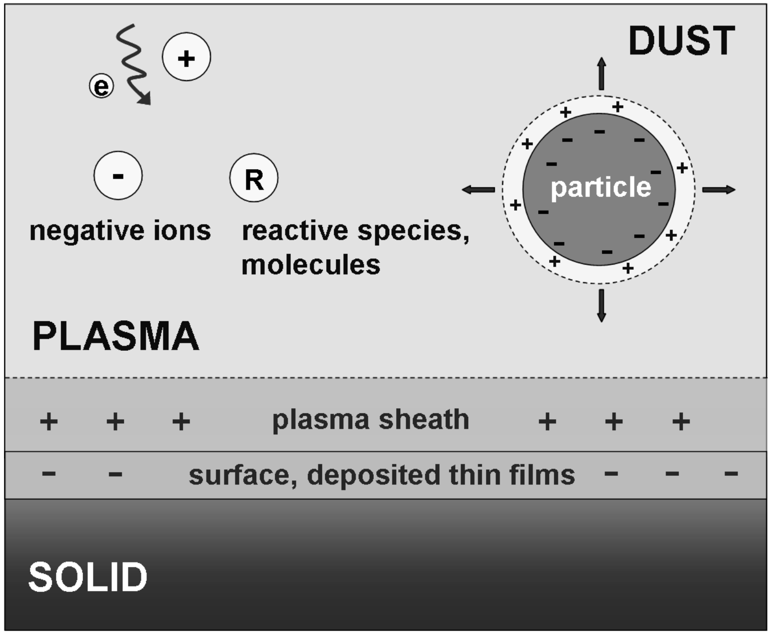
Ideal test system
for Coulomb correlations

Ions in traps, mk temperature

electrons in quantum dots
(predicted)

Filinov, Bonitz, Lozovik, PRL 2001

Complex Plasmas



Transregional Research Center
„Fundamentals of Complex Plasmas“

Speaker: J. Meichsner

- Kiel University
- Greifswald University
- INP Greifswald

DFG

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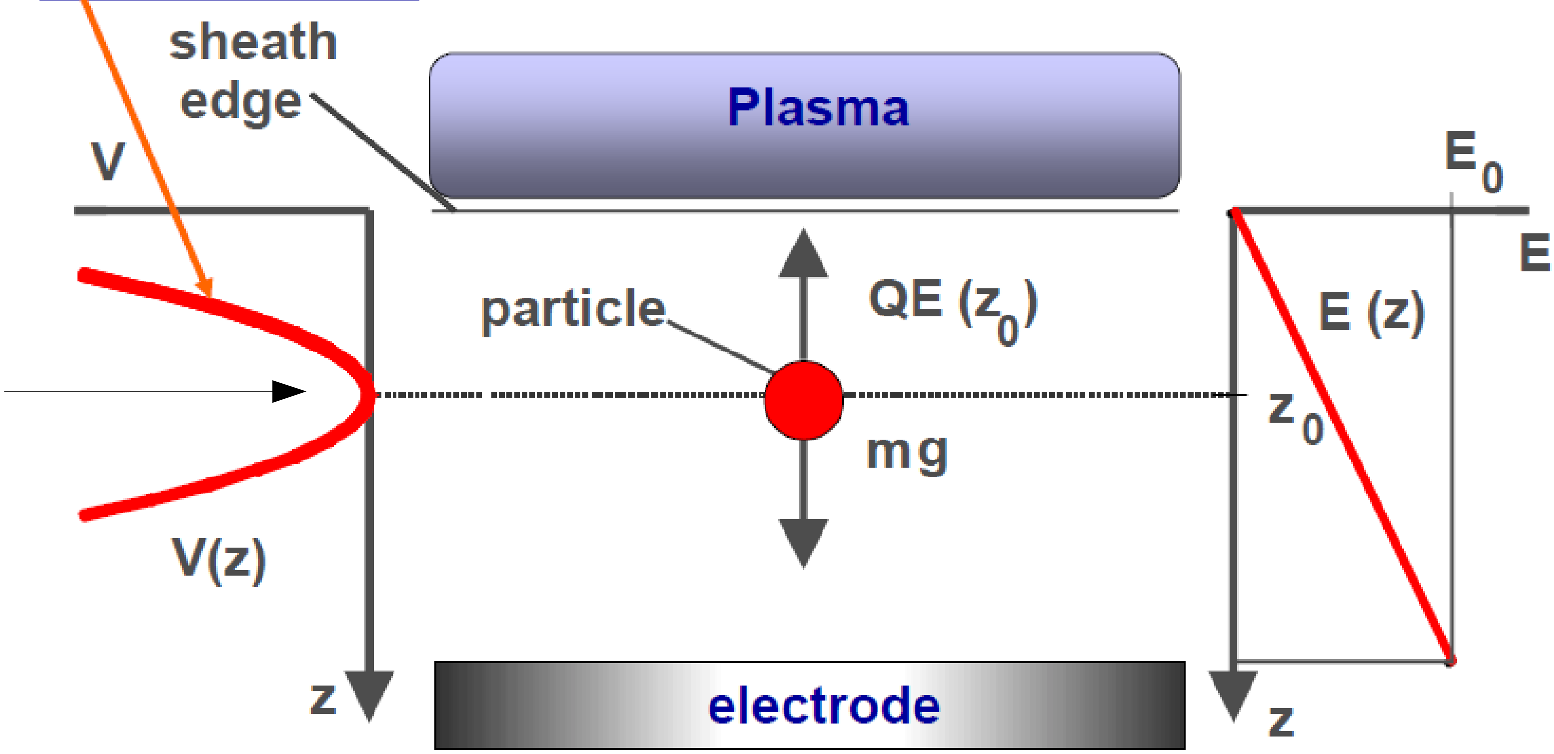
complex plasmas

Challenging large parameter space and the diversity of physical conditions

Plasma size:	From large and stable plasmas to *micro and nano plasmas*
Plasma pressure:	From low pressure to *atmospheric and higher pressure*
Plasma chemistry:	From rather **simple rare-gas plasmas** to more complex and *reactive molecular plasmas* (e.g., oxygen, hydrocarbons, fluorocarbons) and their interaction with condensed matter
Time scales:	From electron and ion dynamics to *chemical reactions* and ***Collective behaviour* of massive dust particles**

Trapping of Complex (Dusty) Plasma layer

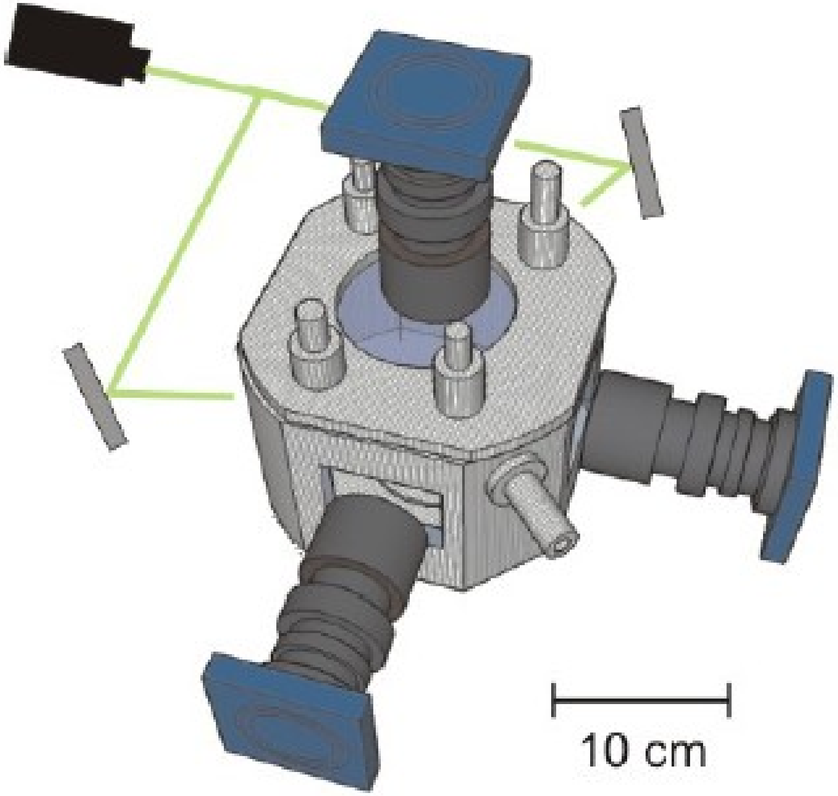
$$\omega_0^2 = \frac{Q_0 E'}{m}$$

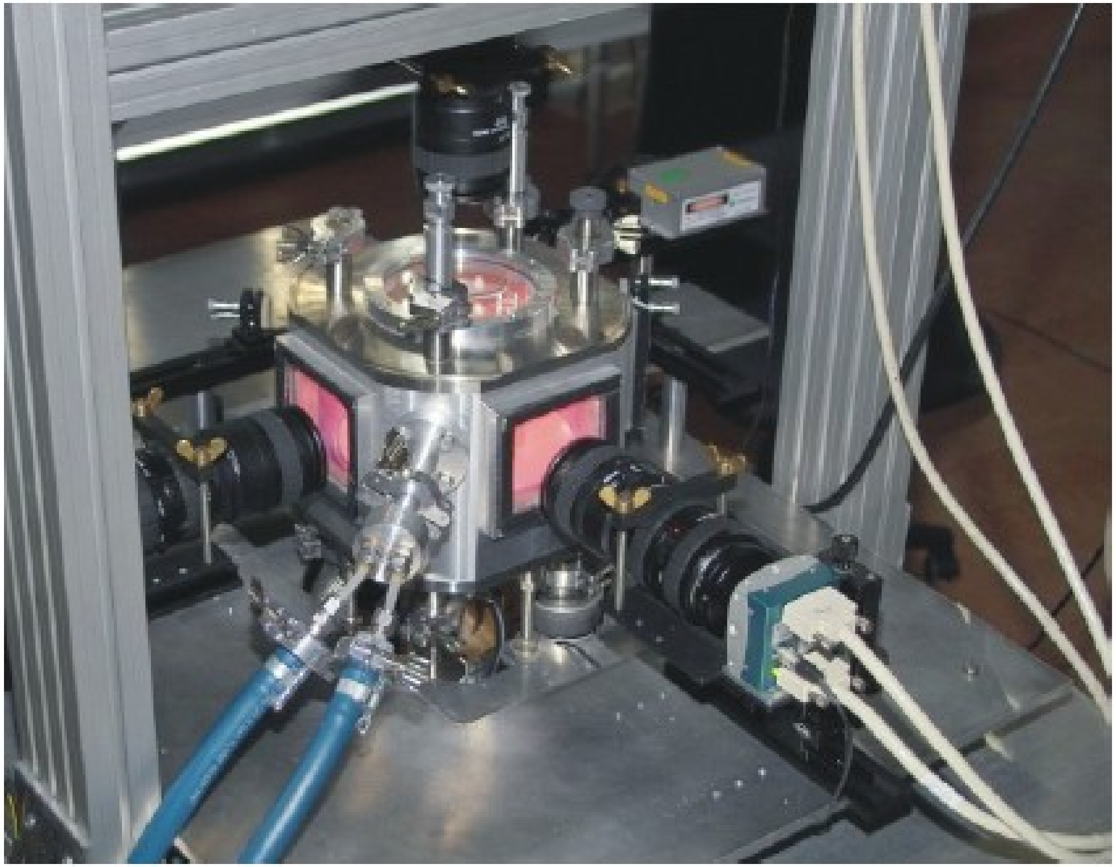


Slight curvature of electrode provides lateral confinement

Picture: A. Melzer

Stereoscopic imaging: 3 video cameras





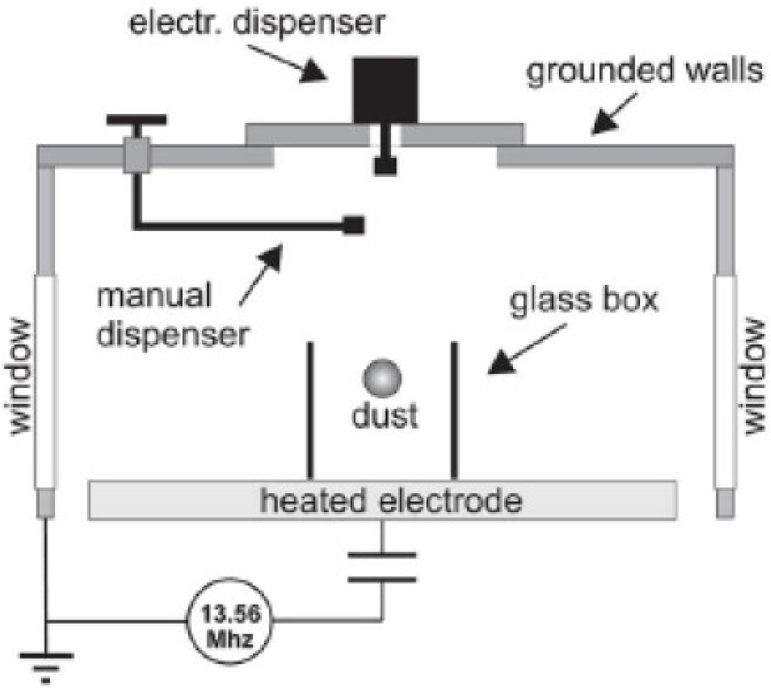
Plasma optically transparent
Slow time scales, room temperature
→ single-particle resolution!
Unique diagnostics of correlation effects!

AG Melzer, EMAU Greifswald

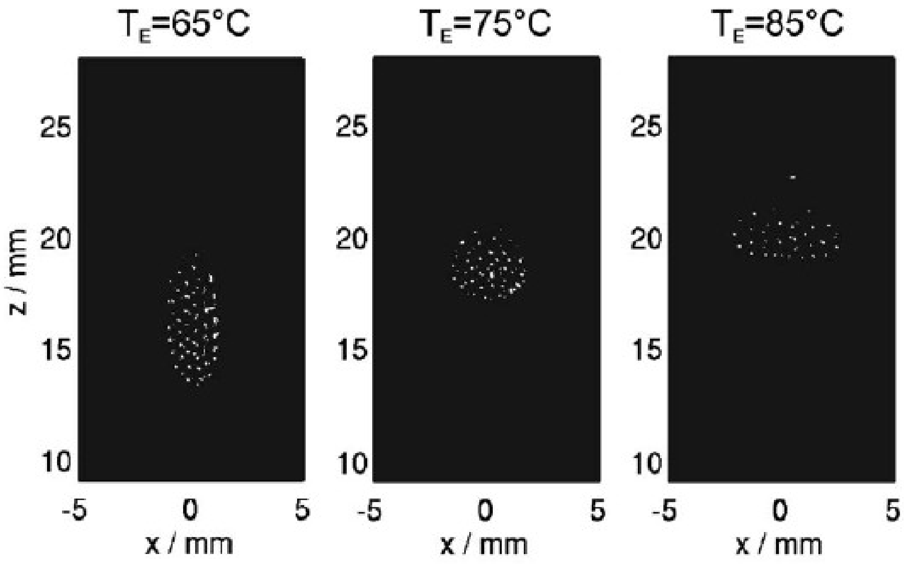
M. Bonitz, Ch. Henning, and D. Block, Rep. Progr. Phys. **73**, 066501 (2010)

3D dust crystals without void

RF discharge, Argon



3D Coulomb balls



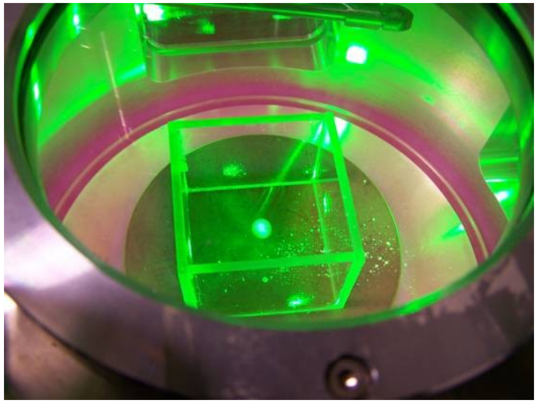
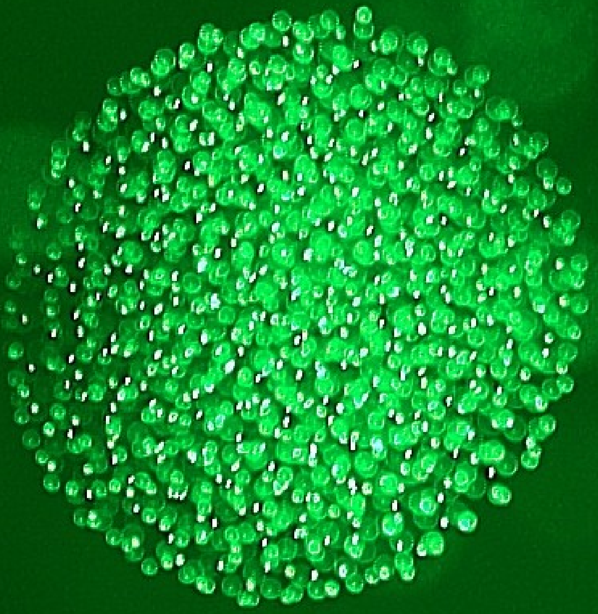


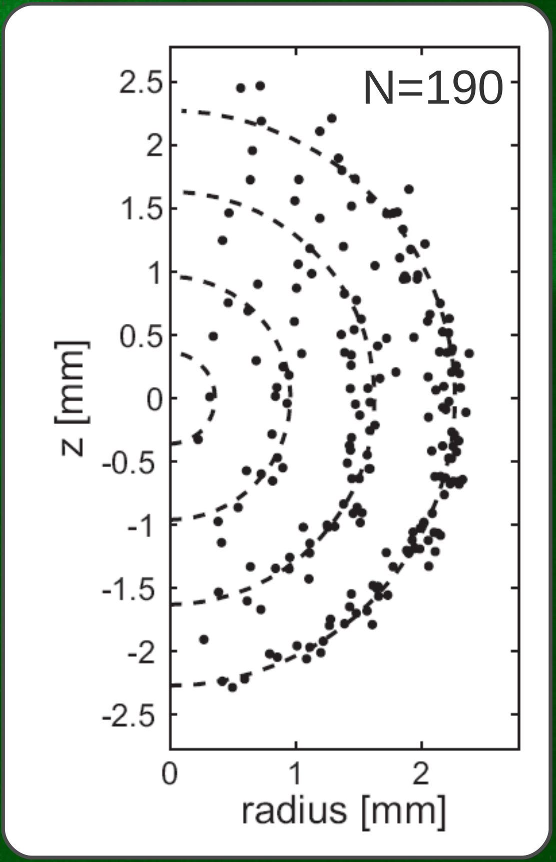
Foto: S. Käding, U Greifswald

- gravity compensated by thermophoretic force and electric fields
- glass box prevents formation of void region inside the dust cloud
- confinement (almost) isotropic
- dust in plasma bulk (slowly streaming ions)

O. Arp et al., Phys. Plasmas **12**, 122102 (2005)

3D Spherical Dust Crystals





- Particles arranged on concentric spherical shells
- Optically transparent crystal

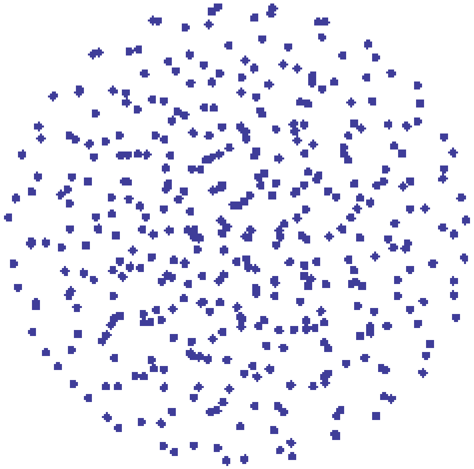
Accurate diagnostics:
- Video stereoscopy or
- Digital holography

Arp, Block, Piel & Melzer, Phys. Rev. Lett. **93**, 165004 (2004)

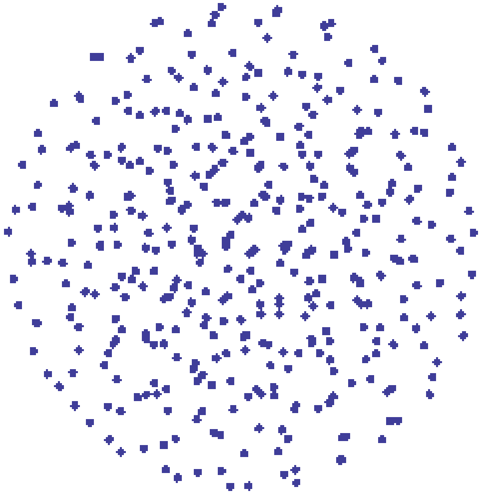
shell structure theoretically explained by Yukawa potential:
Bonitz et al. Phys. Rev. Lett. **96**, 075001 (2006)

Collective excitations: Multipole oscillations

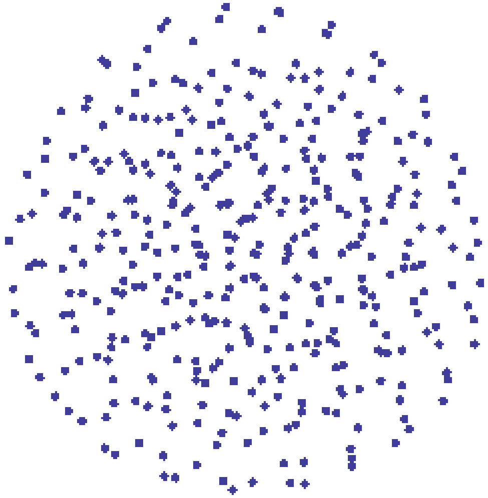
monopole



quadrupole



octupole

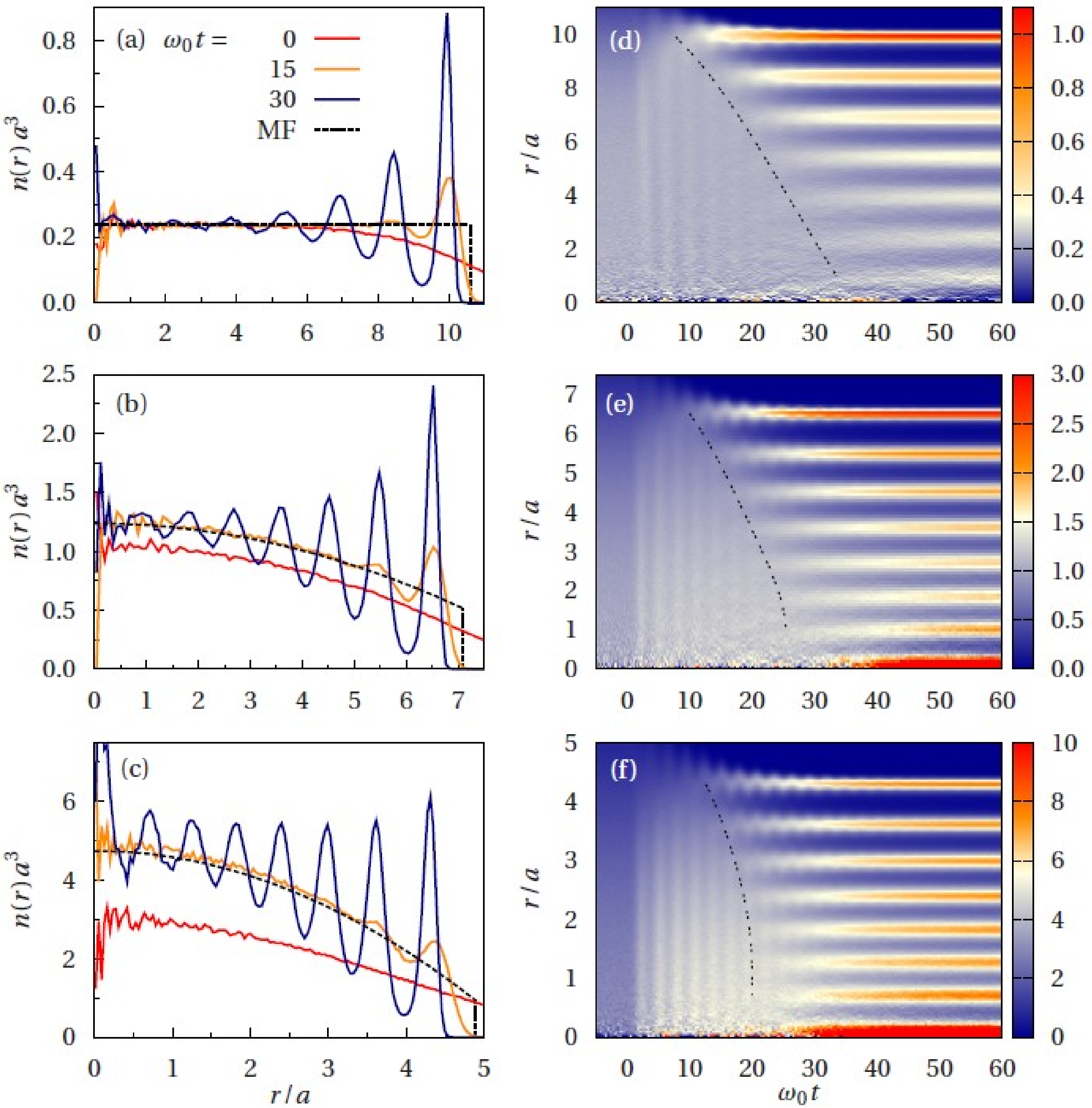


Cold fluid theoy for Yukawa systems

Sensitive diagnostics. Direct comparison with simulations and experiment
Current work: inclusion of correlations [Kählert, Bonitz, Kalman 2013]

Kählert, MB, Phys. Rev. E **82**, 036407 (2010)
Kählert, MB, Phys. Rev. E **83**, 056401 (2011)

Crystallization (Shell Formation) Dynamics



Rapid cooling of weakly coupled initial state

screening

H. Kählert and M. Bonitz, PRL **104**, 015001 (2010)

Outline

1. **Correlation effects in plasmas: liquids and crystals**
    - dusty plasmas: the perfect test system

2. **Attraction of identical particles**
    - from balls to strings

3. **Dense plasmas in a strong magnetic field**
    - diffusion, normal modes
    - „Magnetizing“ a complex plasma without a magnet

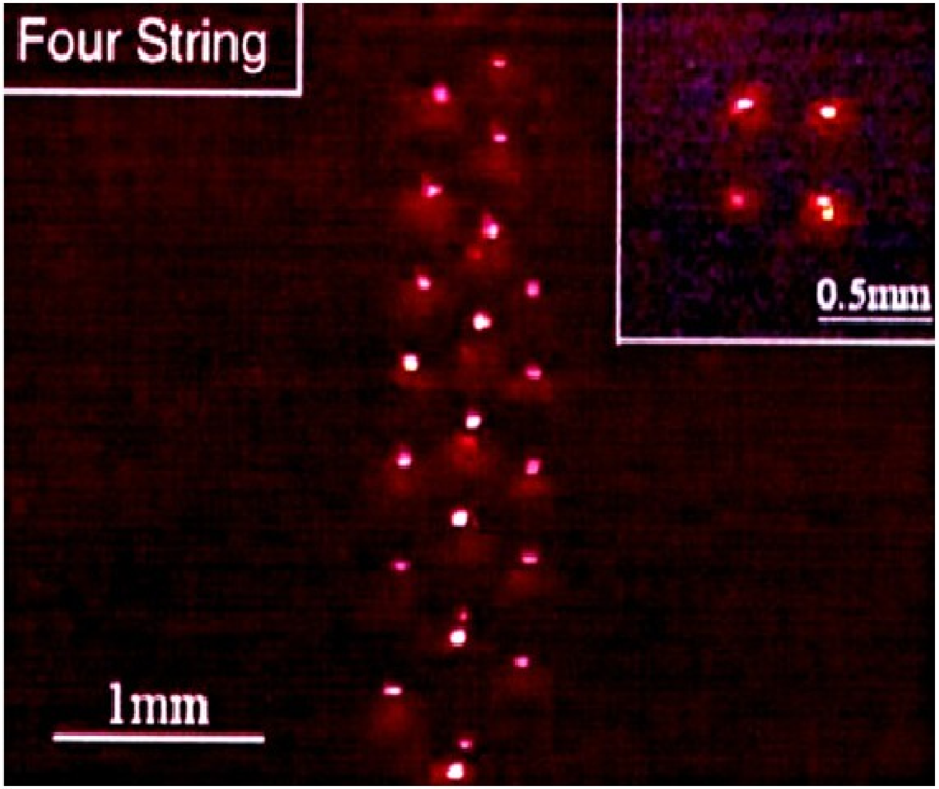
4. **Dense two-component quantum plasmas**
    - status of the theory
    - towards multi-scale simulations

5. **Conclusions and outlook**

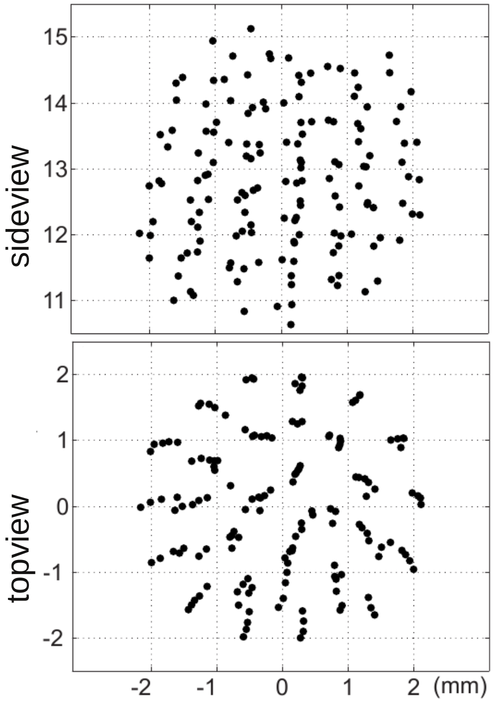
Close to electrode: dust-dust attraction

String Formation in Vertically Elongated 3D Confined Dusty Plasmas

→ **VIDEO**



N. Sato et al. (2001)

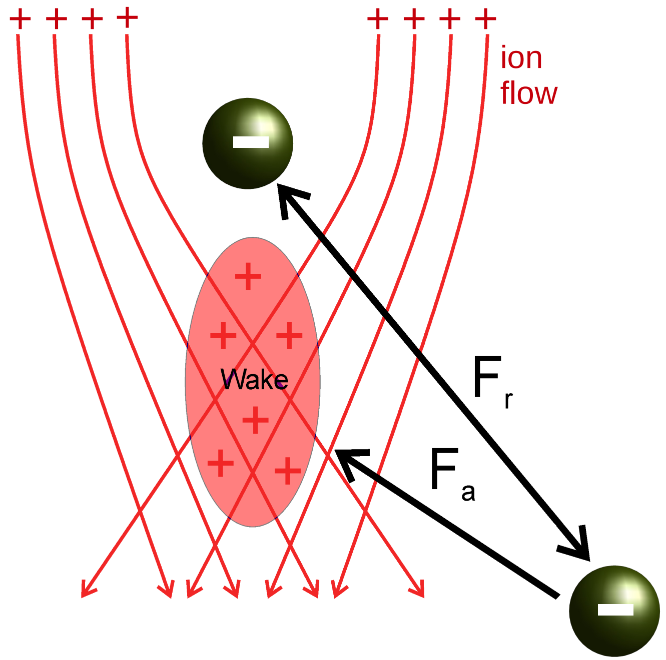


M. Kroll, J. Schablinski, D. Block, and A. Piel, Phys. Plas. **17**, 013702 (2010)

⇨ Vertical alignment not explainable with repulsive Yukawa potential!
Effective particle-particle attraction

Origin of attractive force

1997 Schweigert, Melzer, Piel...

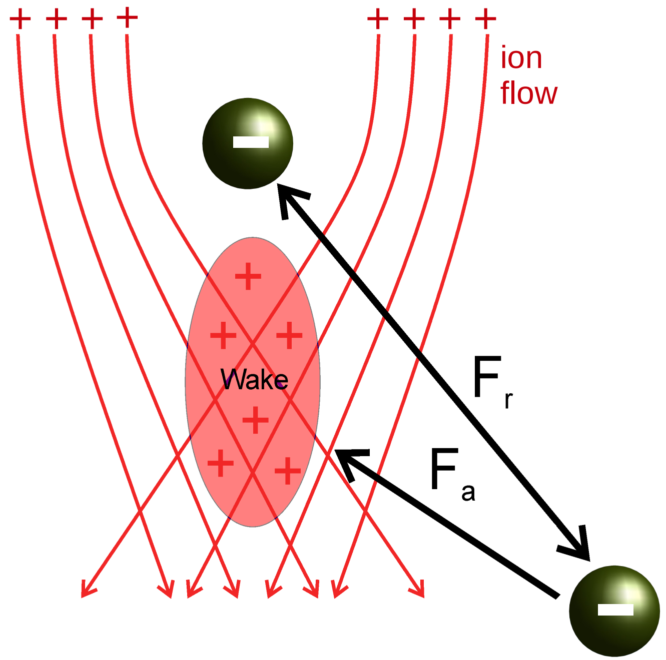


wake-field behind charged grain
→ non-reciprocal grain interaction
→ vertical grain alignment

Fig: J. Carstensen

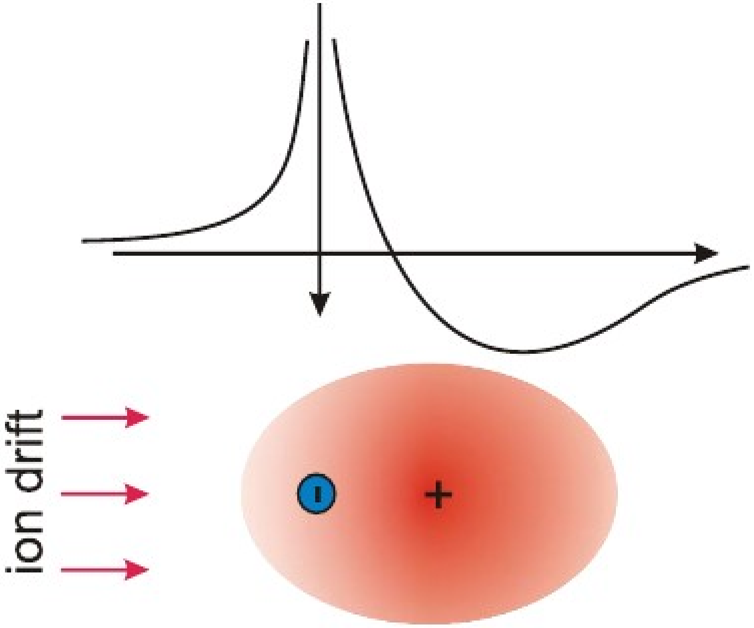
Origin of attractive force

1997 Schweigert, Melzer, Piel...



wake-field behind charged grain
→ non-reciprocal grain interaction
→ vertical grain alignment

Effective potential of single particle

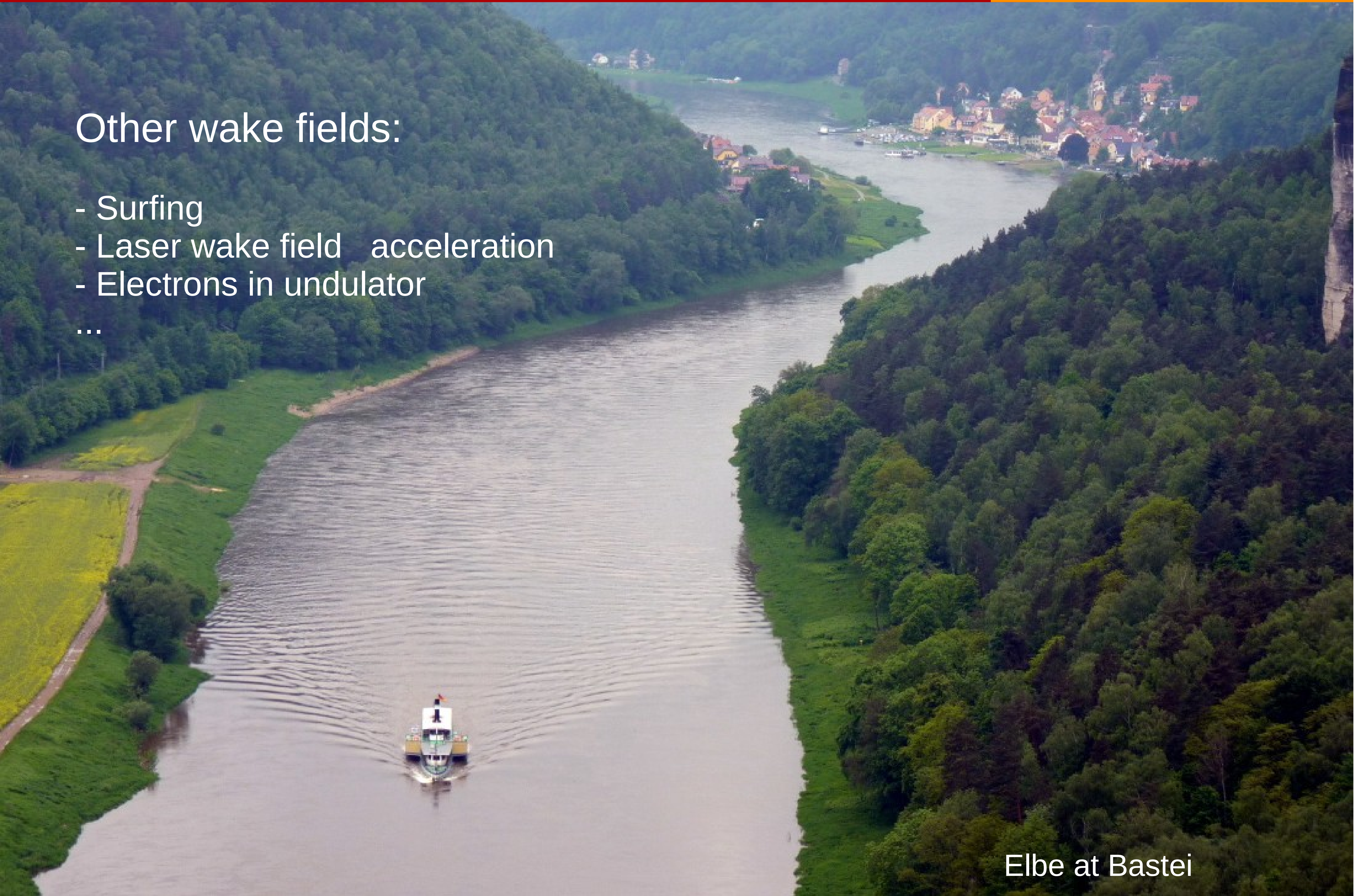


Confirmed by simulations (PIC):
Hutchinson, Schneider, Miloch...

But: can treat only 1...3 particles

Fig: J. Carstensen

Fig.: Ivlev et al, PRL **100**, 095003 (2008)



Other wake fields:

- Surfing
- Laser wake field acceleration
- Electrons in undulator

...

Elbe at Bastei

Linear response: dynamically screened potential

$$\Phi_i(\mathbf{r},t) = \int \frac{d^3k}{2\pi^2} \boxed{\frac{q}{k^2}} \frac{e^{i\mathbf{k}\cdot(\mathbf{r}-\mathbf{v}_i t)}}{\epsilon^{\mathrm{l}}(\mathbf{k},\mathbf{k}\cdot\mathbf{v}_i)}$$

Dust grains are „dressed“,
mediated by dielectric function

Fourier transform of bare Coulomb potential

Linear response: dynamically screened potential

$$\Phi_i(\mathbf{r},t) = \int \frac{d^3k}{2\pi^2}\,\frac{q}{k^2}\,\frac{e^{i\mathbf{k}\cdot(\mathbf{r}-\mathbf{v}_i t)}}{\epsilon^{\mathrm{l}}(\mathbf{k},\mathbf{k}\cdot\mathbf{v}_i)}$$

Dust grains are „dressed“, mediated by dielectric function

Dielectric function for a (shifted) Maxwellian plasma with BGK-type collisions included

$$\epsilon^{l}(\mathbf{k},\underset{\mathbf{k}\cdot\mathbf{v}_i}{\omega}) = 1 + \frac{1}{k^2\lambda_{De}^2} + \frac{1}{k^2\lambda_{Di}^2}\left[\frac{1+\zeta_i Z(\zeta_i)}{1+\frac{i\nu_{in}}{\sqrt{2}kv_{T_i}}Z(\zeta_i)}\right]$$

electrons: statical screening ($u_e \ll V_{Te}$)
ions: dynamical screening ($T_i < T_e$)
(collisionless)

$$\lambda_{D\alpha}^2 = \frac{v_{T\alpha}^2}{\omega_p^2} = \frac{\varepsilon_0 k_{\mathrm{B}} T_\alpha}{n_\alpha q_\alpha^2}$$

bar Coulomb potential

static screening → Yukawa potential

dynamical screening → wake effects

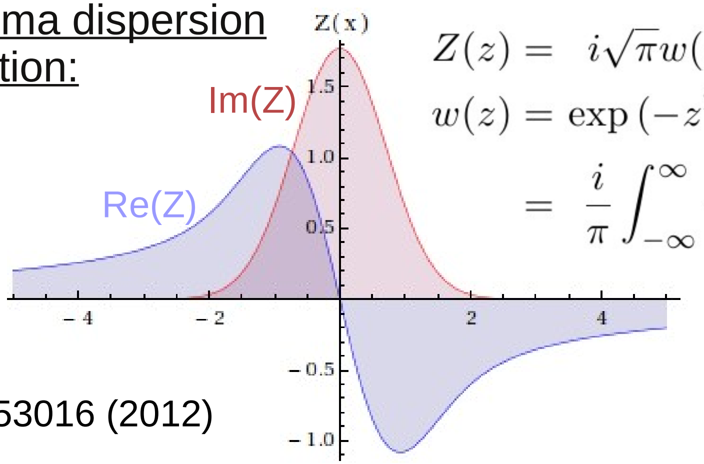
Ion-neutral scattering → collisional damping

$$\zeta_i = \frac{\mathbf{k}(\mathbf{v}_d - \mathbf{u}_i) + i\nu_{in}}{\sqrt{2}kv_{T_i}}$$

ion neutral collison frequency

thermal velocity $v_{T_\alpha} = \sqrt{\frac{k_B T_\alpha}{m_\alpha}}$

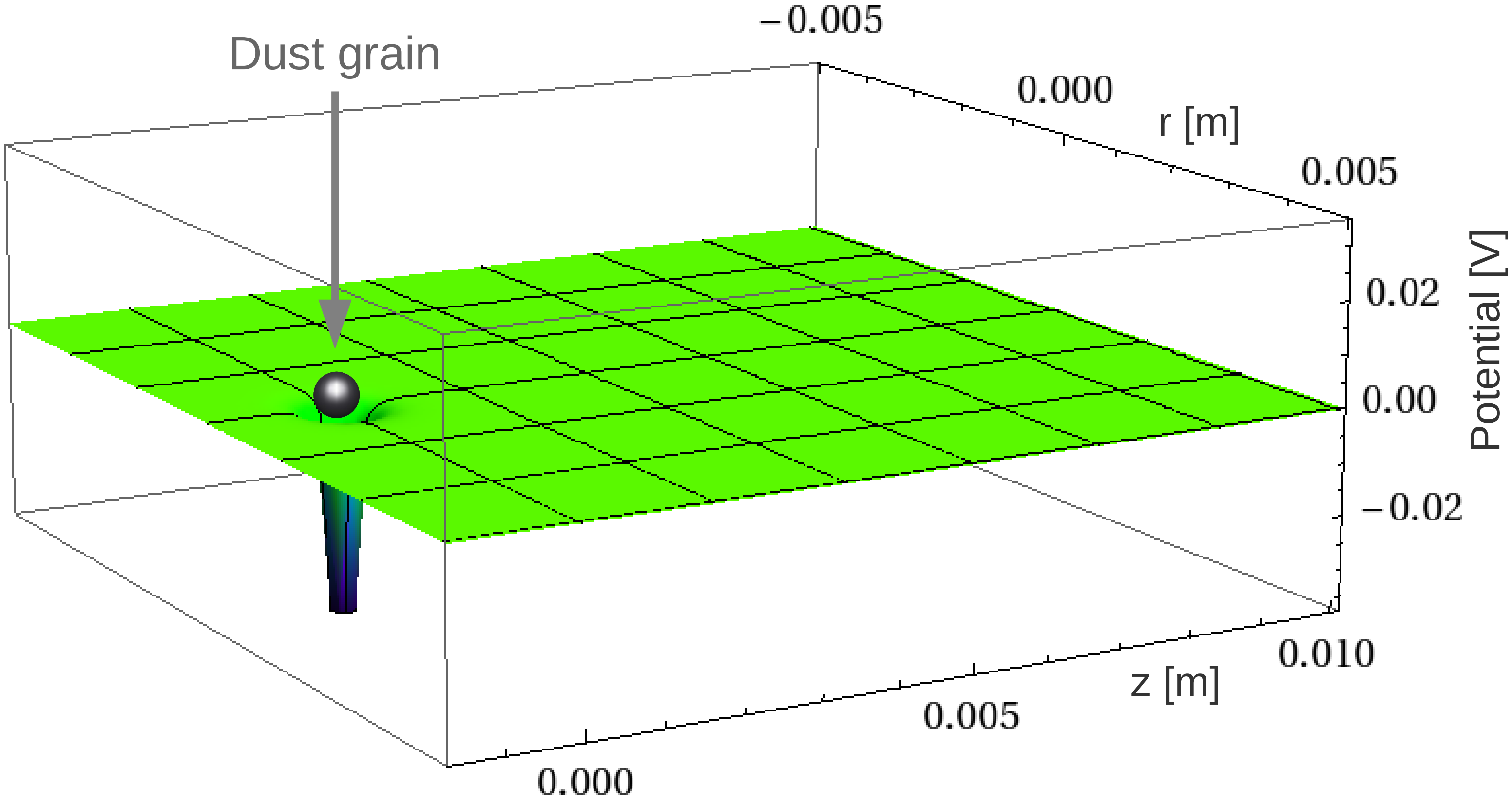
Plasma dispersion function:



$$Z(z) = i\sqrt{\pi}w(z)$$
$$w(z) = \exp(-z^2)\mathrm{Erfc}(-iz) = \frac{i}{\pi}\int_{-\infty}^{\infty}\frac{exp(-t^2)}{z-t}dt$$

M. Lampe, G. Joyce, et al., Phys. Plasmas **7**, 3851 (2000)
P. Ludwig, W. Miloch, H. Kählert, and M. Bonitz, New J. Phys. **14**, 053016 (2012)

No ion flow: Yukawa Potential



Statically screened Coulomb (Yukawa) potential

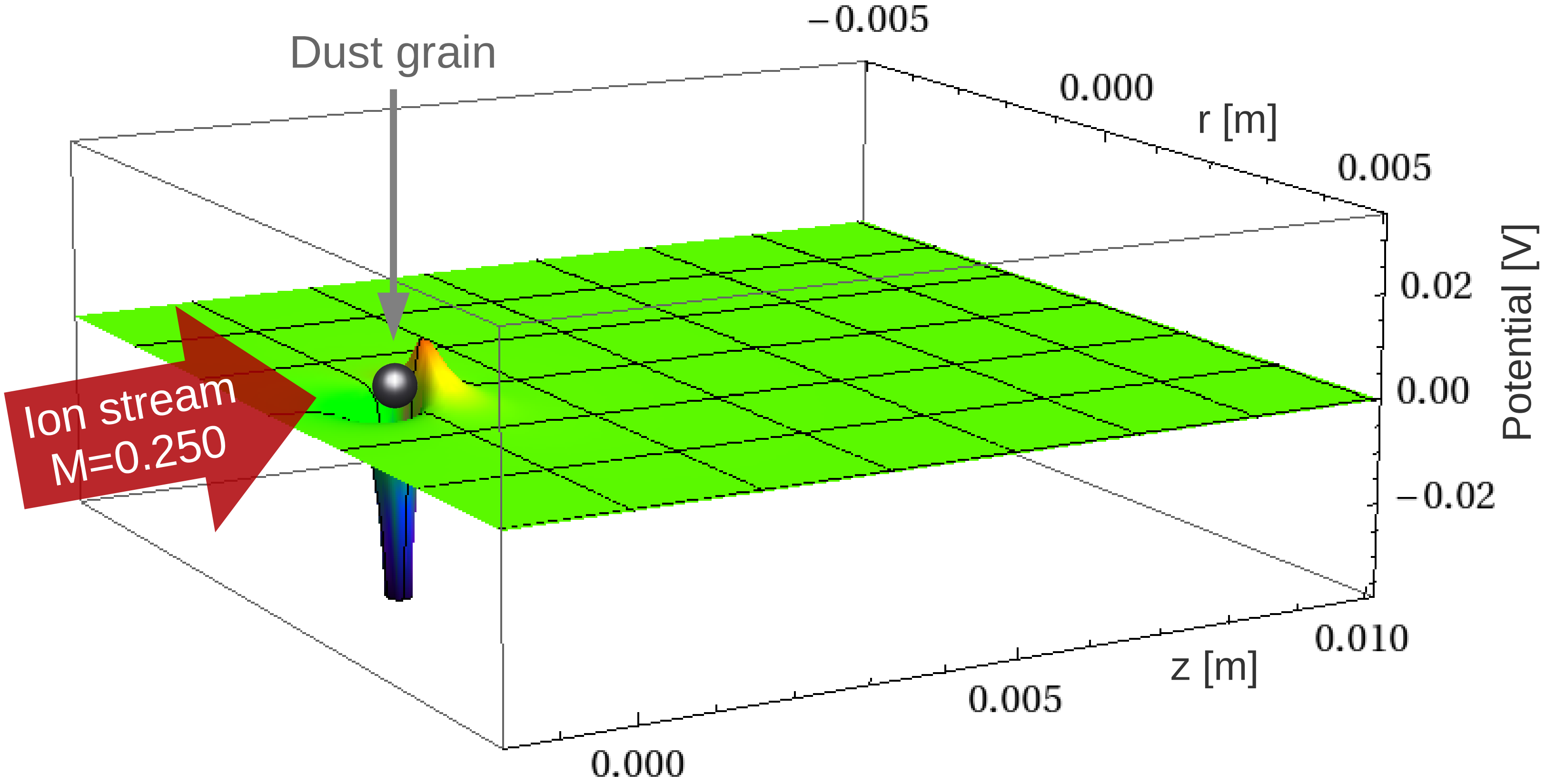
$$\frac{(Ze)^2 e^{-\kappa\cdot|r_i-r_j|}}{|r_i-r_j|}$$

$$\kappa=\frac{1}{\lambda_D}$$

$$\lambda_D^2=\sum_a \frac{k_B T_a}{e^2 n_a}$$

Plasma parameters (Argon): $n=2\times10^8\,\mathrm{cm}^{-3}$, $T_e=2.585\,\mathrm{eV}$ (30 000K), $T_e/T_i=30$, $\upsilon_{in}=0.1\omega_{pi}$, $\lambda_{De}=0.845\,\mathrm{mm}$

Potential for Streaming Ions: M=0.250



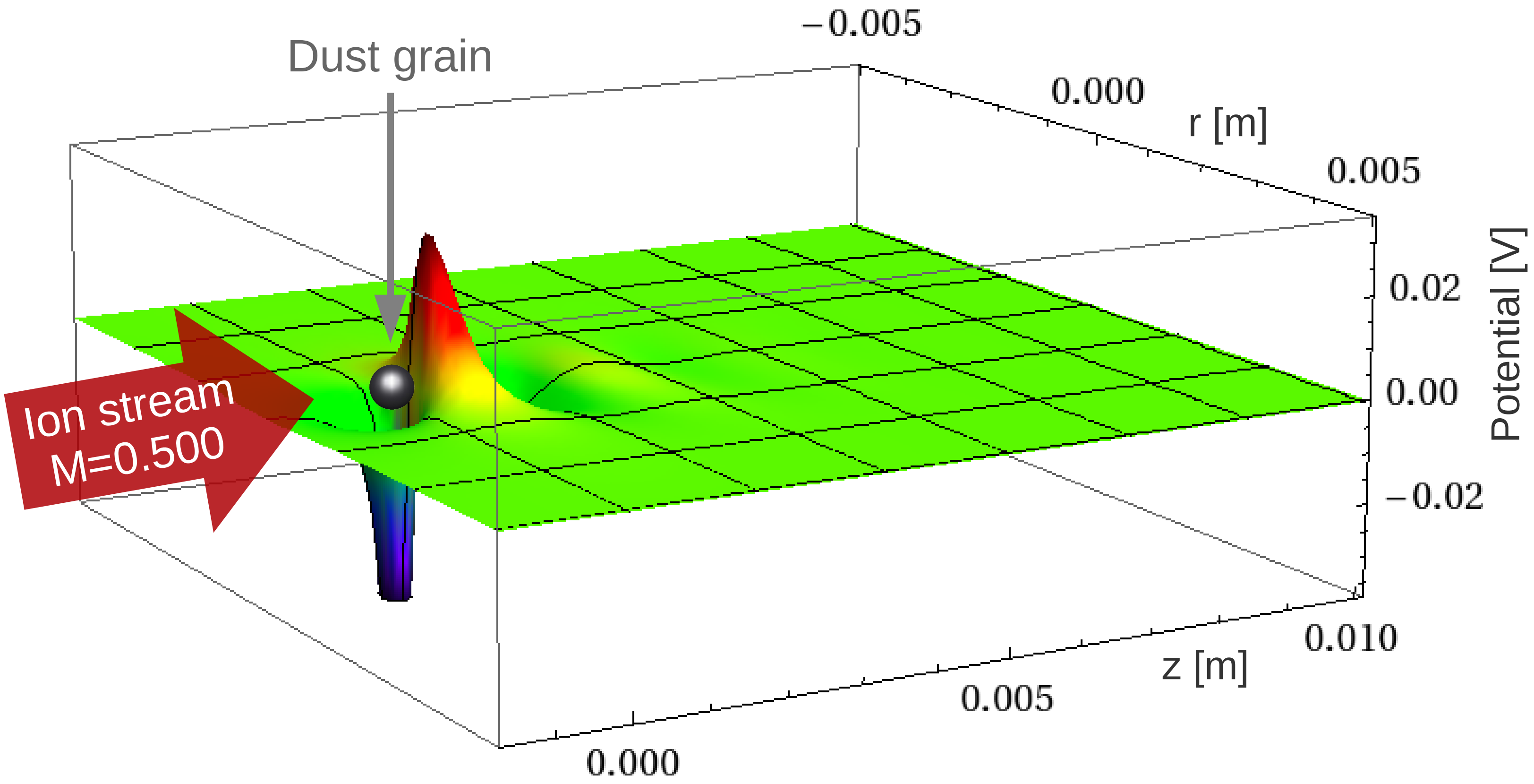
Dynamically screened Coulomb potential: 'wake' potential
(first peak height: 10.9mV @ z=0.29mm)

Mach number $M \equiv \frac{u_i}{c_s}$, Bohm speed $c_s \equiv \sqrt{\frac{k_\mathrm{B} T_e}{m_i}}$

P.Ludwig, W.J. Miloch,
H. Kählert, M. Bonitz,
New J. Phys. **14**,
053016 (2012)

Plasma parameters (Argon): $n=2\mathrm{x}10^8\mathrm{cm}^{-3}$, T_e=2.585eV (30 000K), T_e/T_i=30, $\upsilon_{in}=0.1\omega_{pi}$, λ_{De}=0.845mm

Potential for Streaming Ions: M=0.500



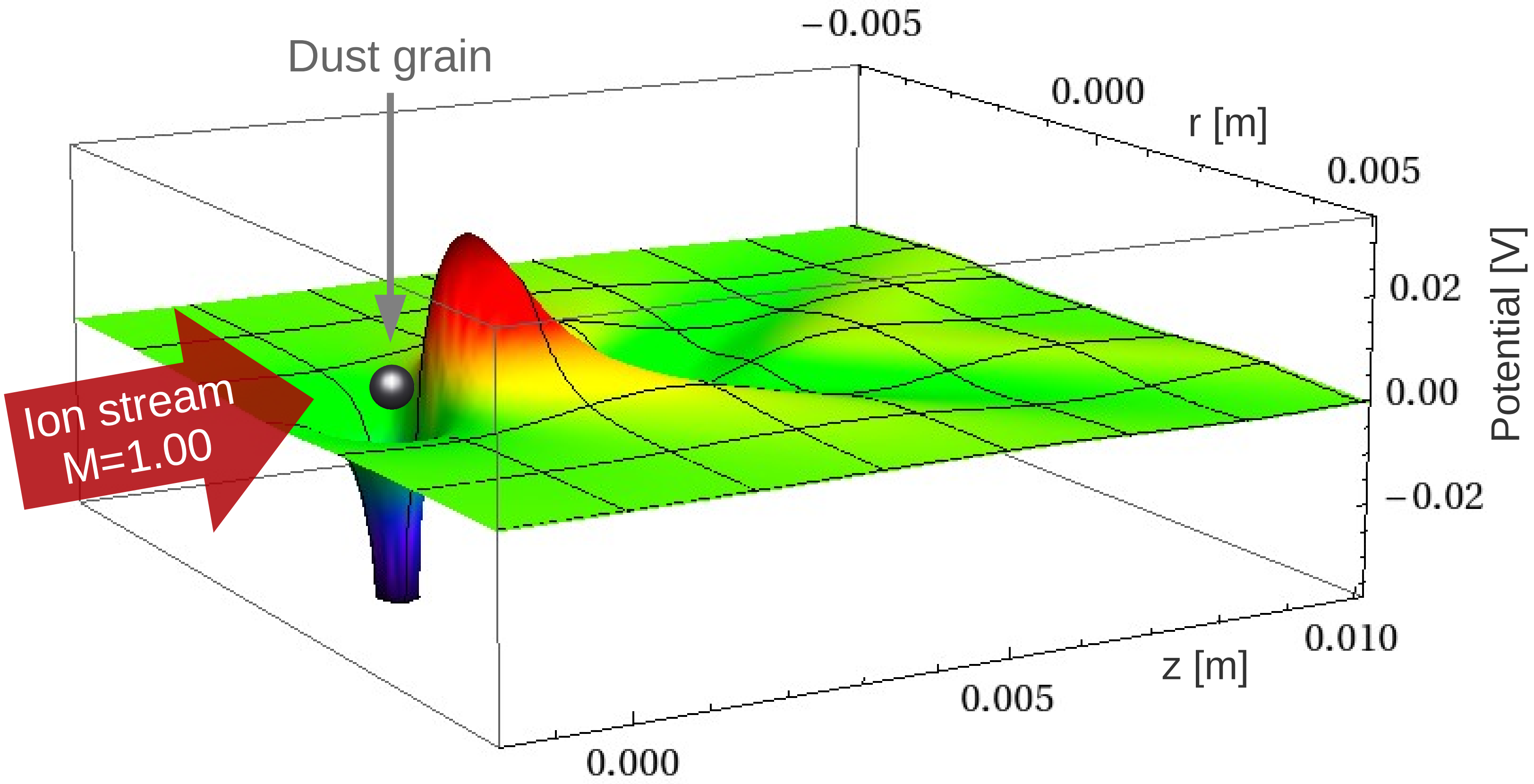
Dynamically screened Coulomb potential: 'wake' potential
(first peak height: 31.2mV @ z=0.46mm)

Mach number $M \equiv \frac{u_i}{c_s}$, Bohm speed $c_s \equiv \sqrt{\frac{k_B T_e}{m_i}}$

P.Ludwig, W.J. Miloch,
H. Kählert, M. Bonitz,
New J. Phys. **14**,
053016 (2012)

Plasma parameters (Argon): $n=2\text{x}10^{8}\text{cm}^{-3}$, $T_e=2.585\text{eV}$ (30 000K), $T_e/T_i=30$, $\upsilon_{in}=0.1\omega_{pi}$, $\lambda_{De}=0.845\text{mm}$

Potential for Streaming Ions: M=1.00



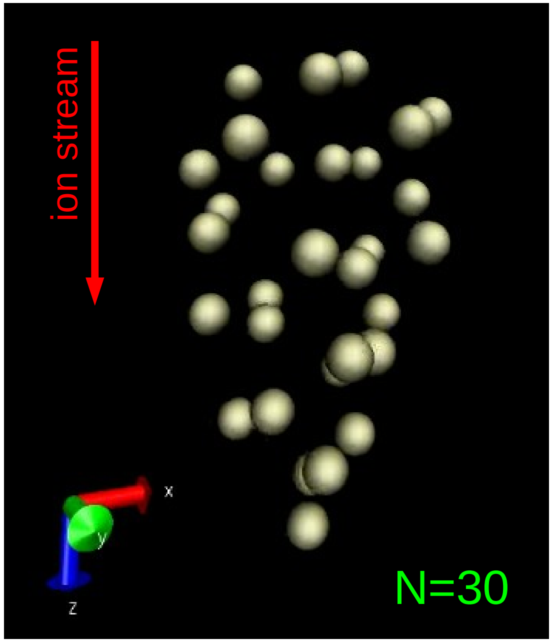
Dynamically screened Coulomb potential: 'wake' potential
(first peak height: 29.9mV @ z=0.97mm)

Mach number $M \equiv \frac{u_i}{c_s}$, Bohm speed $c_s \equiv \sqrt{\frac{k_B T_e}{m_i}}$

P.Ludwig, W.J. Miloch, H. Kählert, M. Bonitz, New J. Phys. **14**, 053016 (2012)

Plasma parameters (Argon): $n=2\times10^8\,\mathrm{cm}^{-3}$, $T_e=2.585\,\mathrm{eV}$ (30 000K), $T_e/T_i=30$, $\upsilon_{in}=0.1\omega_{pi}$, $\lambda_{De}=0.845\,\mathrm{mm}$

N-particle simulations using effective potential



Mixed structure of Yukawa ball and Strings

Langevin dynamics scheme:

$$m_d \ddot{\mathbf{r}}_k = -\nabla V_k^{\text{eff}}(\mathbf{r},t) - \omega_0^2 m_d \mathbf{r}_k - \nu_{dn} m_d \dot{\mathbf{r}}_k + \mathbf{f}_k(t)$$

$$V_k^{\text{eff}}(\mathbf{r},t) = \sum_{l \neq k}^{N_d} q_d \Phi_l(\mathbf{r},t)$$

friction coefficient, Gaussian random force, and plasma temperature are related by the fluctuation-dissipation theorem

$$\langle \mathbf{f}_i^\alpha(t) \mathbf{f}_j^\beta(t') \rangle = 2 m \nu_{dn} k_B T \delta_{ij} \delta_{\alpha\beta} \delta(t-t'), \;\; \alpha, \beta \in \{x, y, z\}$$

Accurate nonequilibrium multi-sclae simulation

VIDEO

Benchmark against full nonlinear PIC simulations
Ludwig et al., New J. Phys. **14**, 053016 (2012)

Pioneered by G. Joyce, M. Lampe,
See also: Murillo, Jenko et al.

Outline

1. **Correlation effects in plasmas: liquids and crystals**
    - dusty plasmas: the perfect test system

2. **Attraction of identical particles**
    - from balls to strings

3. **Dense plasmas in a strong magnetic field**
    - diffusion, normal modes
    - „Magnetizing“ a complex plasma without a magnet

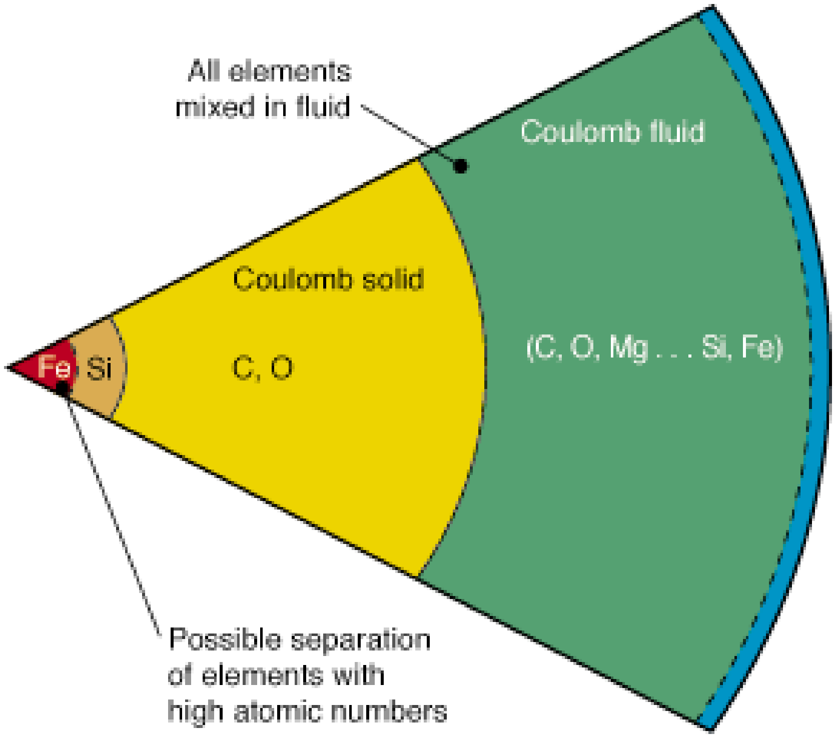
4. **Dense two-component quantum plasmas**
    - status of the theory
    - towards multi-scale simulations

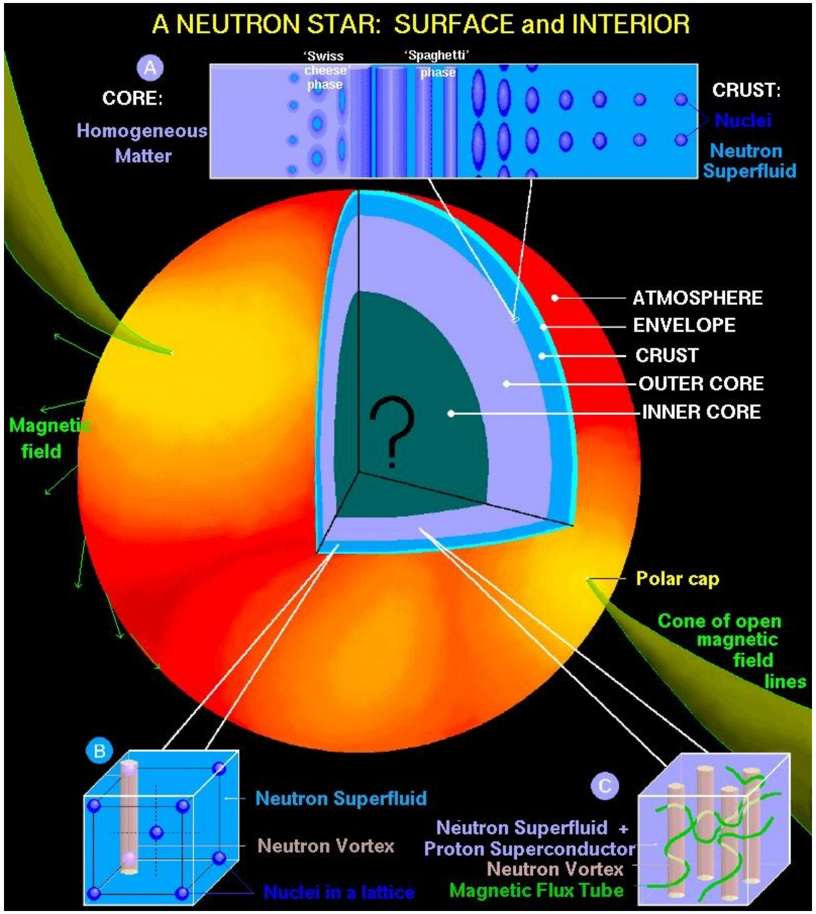
5. **Conclusions and outlook**

Strongly correlated plasmas in strong B-field

$B=10^{3}....10^{7}T$

$B=10^{6}....10^{11}T$





? Effect of magnetic field on plasma
? when is a field strong/relevant

Figures: D. Schneider, LLNL, Coleman , UMD

Transport of <u>ideal</u> plasma in a magnetic field

B-field: Larmor precession of charged particles
→ **reduced mobility across field**

Known behavior of diffusion coefficient:

$D_\perp(B) \sim 1/B^2$, weak field

$\sim 1/B$, strong field (Bohm diffusion)

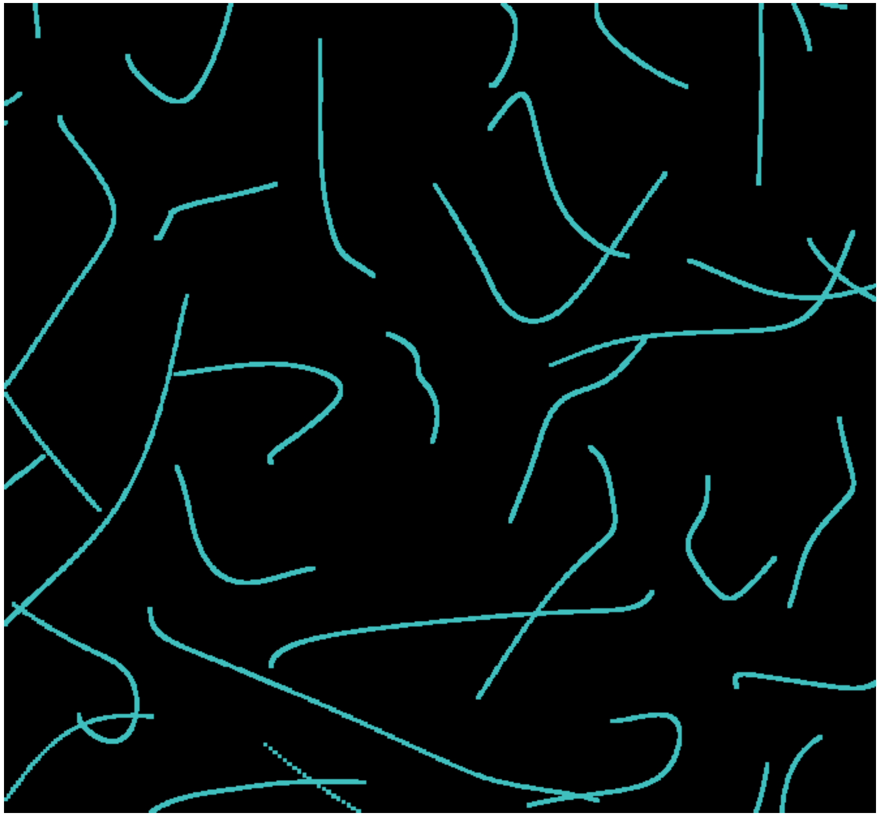
$D_\parallel(B) \sim \text{const}$

Behavior at strong coupling?

T. Ott and M. Bonitz, Phys. Rev. Lett. **107,** 135003 (2011)

Trajectories in a correlated plasma (B=0)

Moderate coupling, Γ=2



Coupling parameter $\Gamma = Q^2 / (4 \pi \epsilon_0 a k_B T)$

Thermal velocity, plasma frequency, mean distance: v_T, ω_0, a

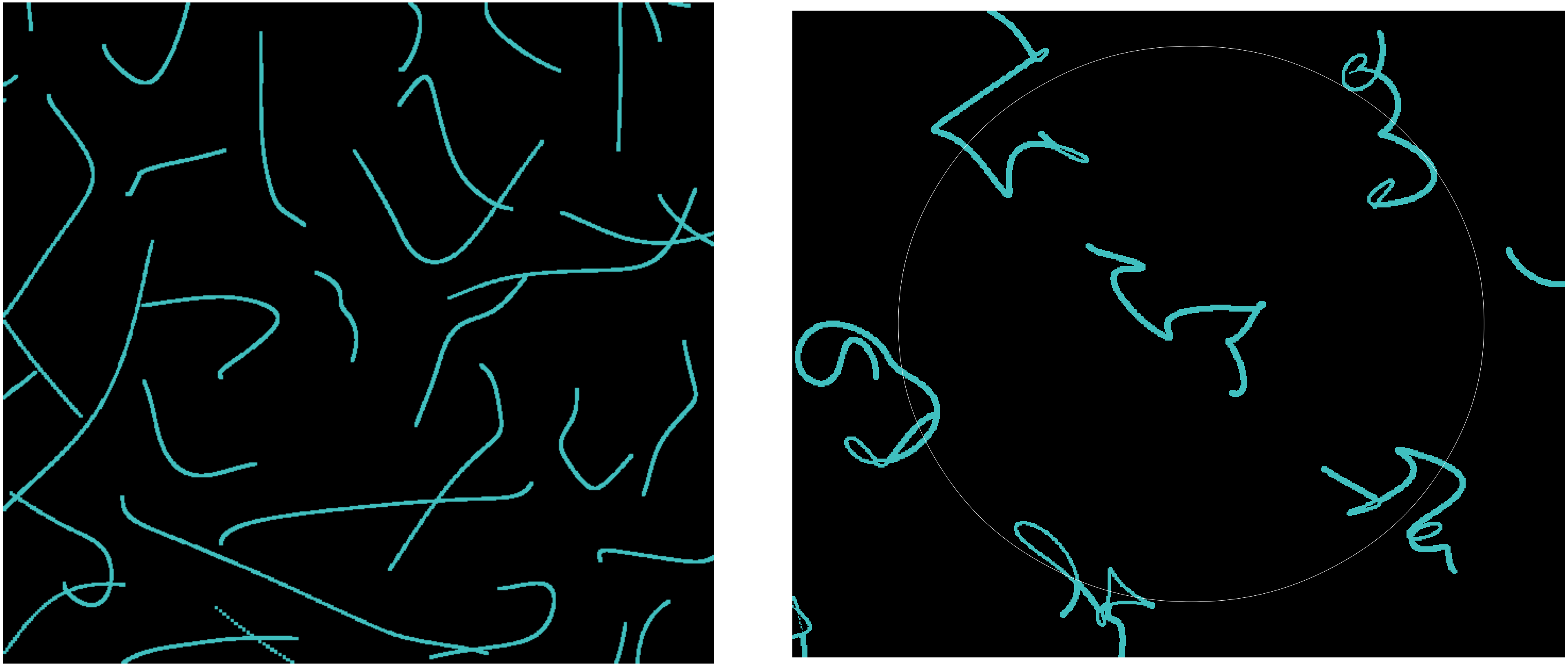
---

2D one-component plasma during 5 plasma periods, MD simulation by T. Ott

Trajectories in a correlated plasma (B=0)

Moderate coupling, Γ=2

Strong coupling, Γ=100

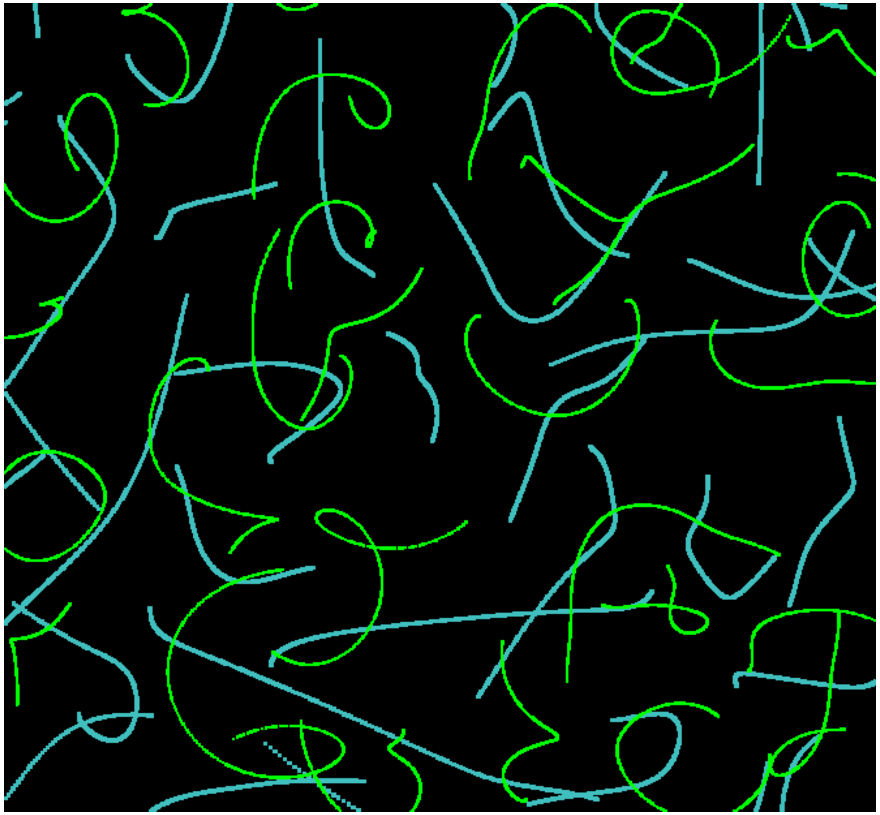


Coupling parameter $\Gamma = Q^2 / (4\pi\epsilon_0 a k_B T)$

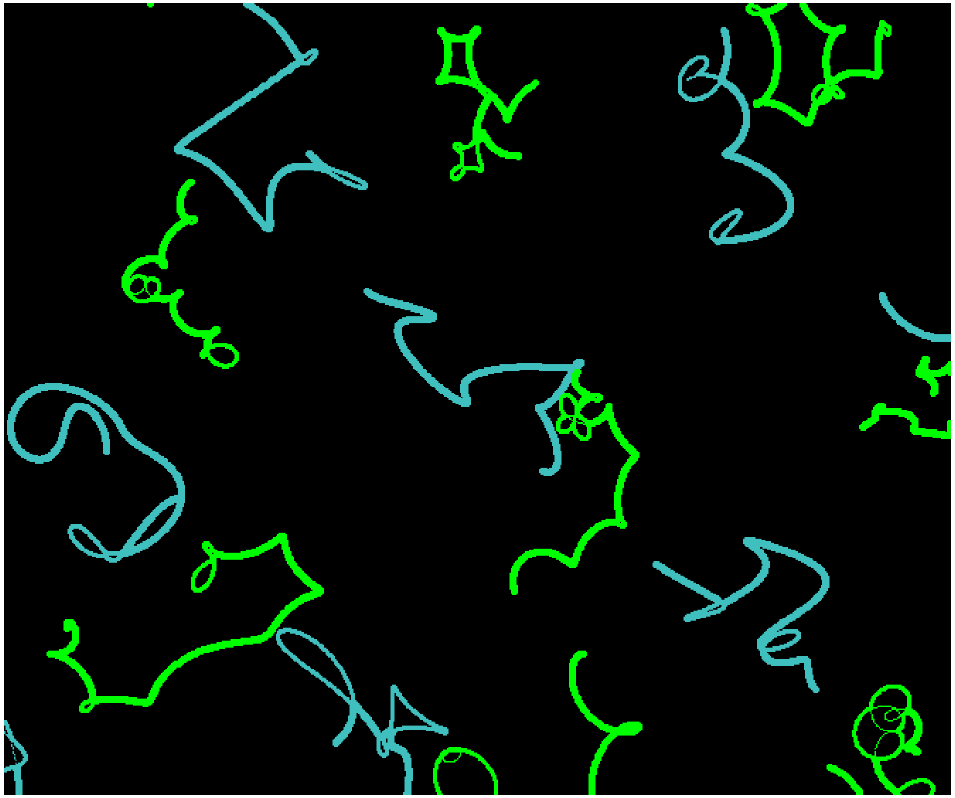
2D one-component plasma during 5 (50) plasma periods, MD simulation by T. Ott

Moderate magnetic field

Moderate coupling, Γ=2



Strong coupling, Γ=100



Cyclotron frequency: $\omega_c = QB/mc$

Larmor radius: $r_L = v_T/\omega_c$

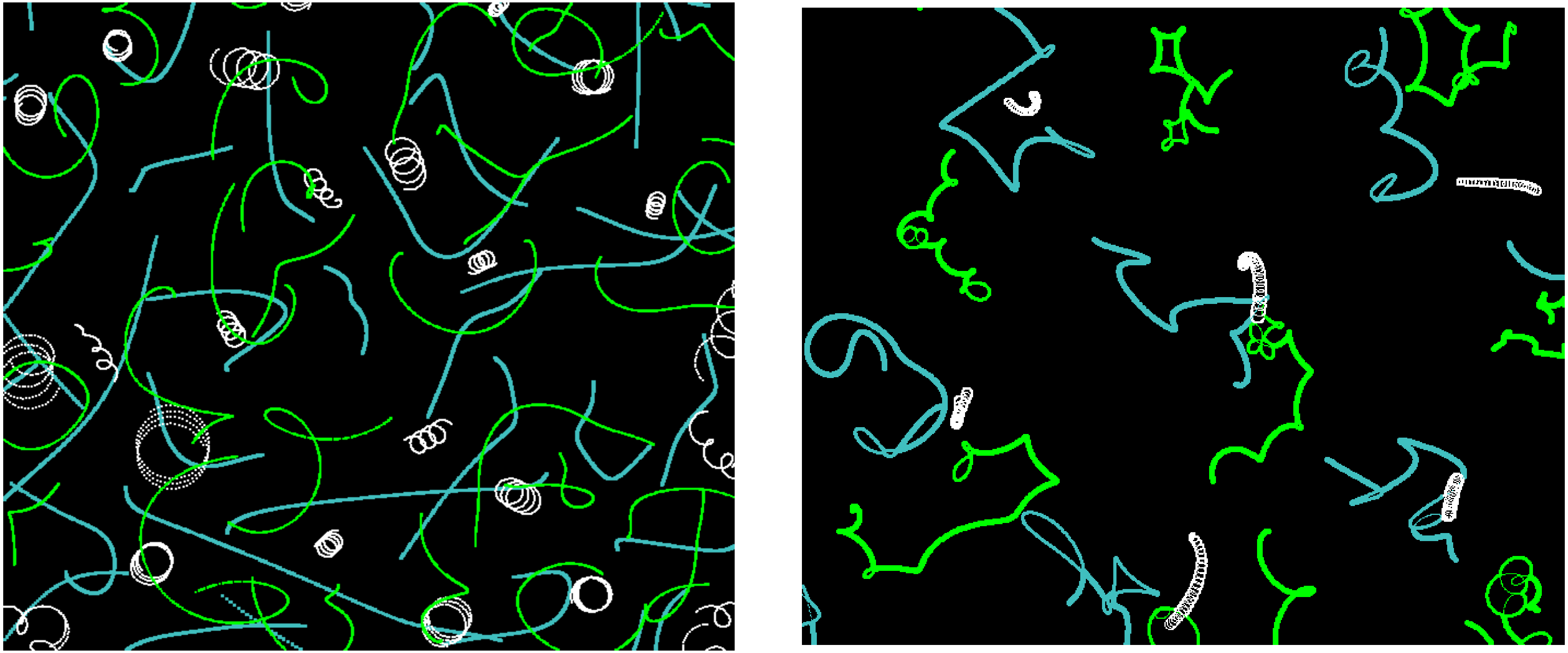
β=0.0
β=1.0

$$\beta = \omega_c/\omega_0$$

$$\delta = r_L/a \propto 1/\Gamma^{0.5}$$

2D one-component plasma during 5 (50) plasma periods, MD simulation by T. Ott

Strong magnetic field



Moderate coupling, Γ=2

Strong coupling, Γ=100

Cyclotron frequency: $\omega_c = QB/mc$

Larmor radius: $r_L = v_T/\omega_c$

β=0.0
β=1.0
β=4.0

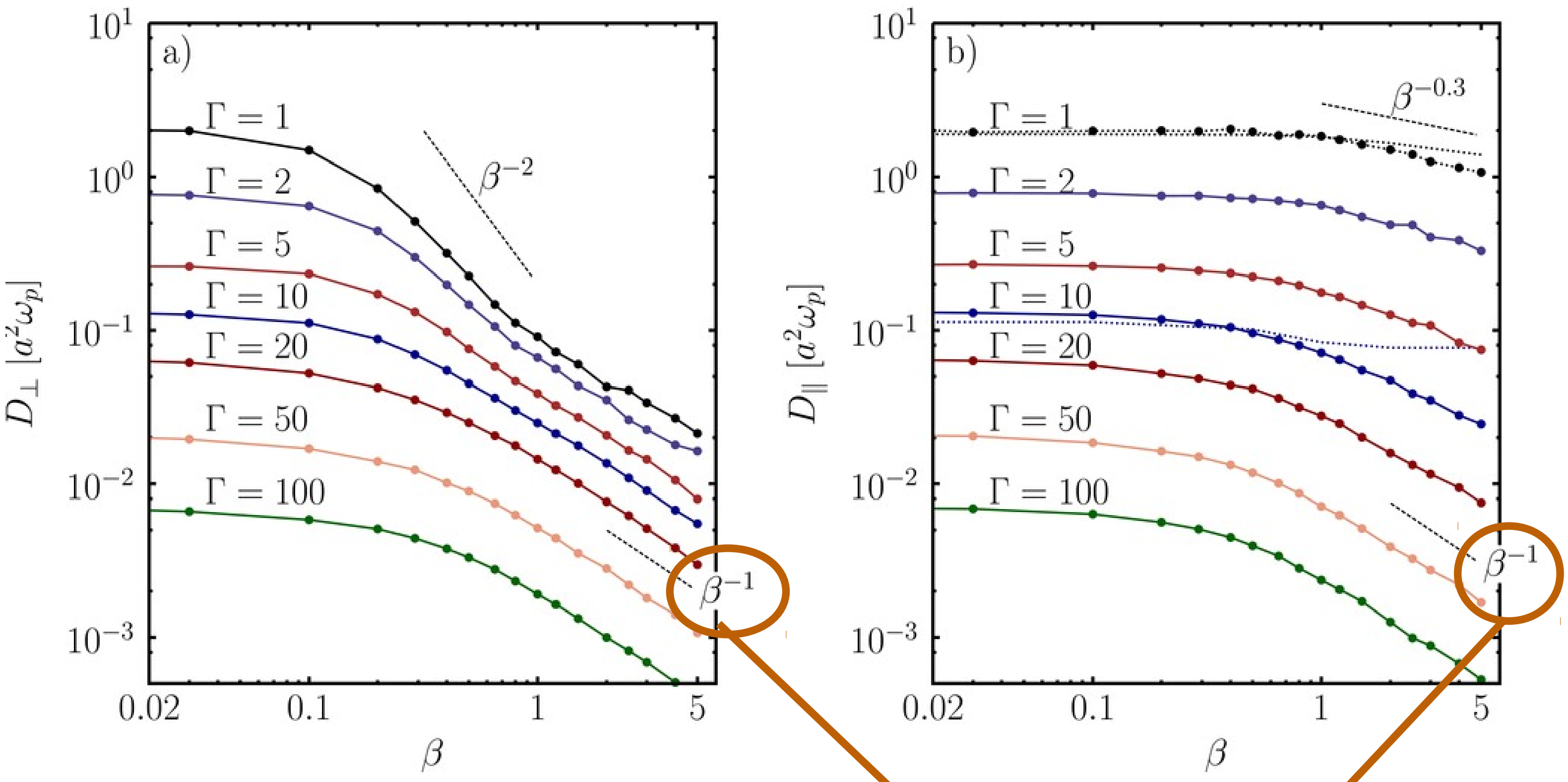
$$\beta = \omega_c / \omega_0$$

$$\delta = r_L / a \propto 1/\Gamma^{0.5}$$

2D one-component plasma during 5 (50) plasma periods, MD simulation by T. Ott

Diffusion in a magnetized 3D complex plasma

First-principle MD simulations: T. Ott and M. Bonitz, Phys. Rev. Lett. **107,** 135003 (2011)
(One-component plasma model)



Large B: Cohen, Suttorp (1984): for any coupling saturation of $D_{||}$ (not confirmed)

Simulation result: large coupling: Bohm diffusion
small coupling: slower algebraic decay

Magnetic field effects in correlated plasmas

Superposition of Coulomb correlations and B-field leads to new effects:

→ radically altered transport properties (diffusion, heat conduction, viscosity etc.)

→ strongly modified collective excitation spectrum,
- Shear modes (Kalman, Golden)

- „correlation-dressed“ Bernstein modes:
  2D: M. Bonitz, Z. Donkó, T. Ott, H. Kählert, P. Hartmann, PRL **105**, 055002 (2010)

  3D: T. Ott, H. Kählert, A. Reynolds, M. Bonitz, PRL **108**, 255002 (2012)

- inhibition of crystallization: T. Ott, H. Löwen, and M. Bonitz, PRL (2013)

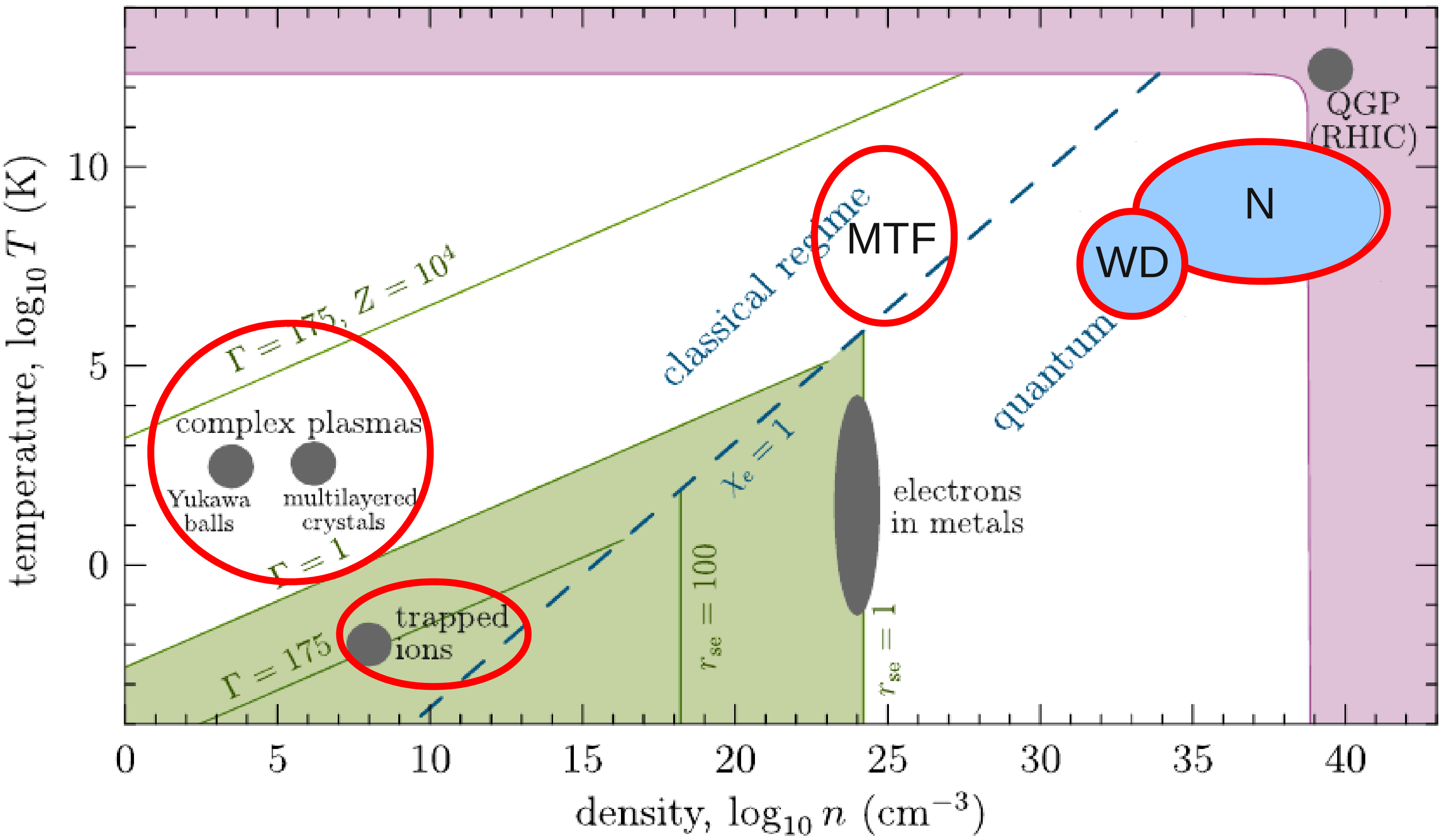
Questions

1. Experimental verification in real complex (dusty) plasmas?

2. Use of dusty plasmas as test system for magnetized correlated plasmas?

Magnetized strongly coupled Coulomb systems

Universality: plasmas with **same Gamma and beta** have same properties (equilibrium, OCP)



WD: White dwarfs

N: Neutron stars

MTF: magnetized target fusion

Coupling parameter

$$\Gamma = Q^2/(4\pi\epsilon_0 a k_B T)$$

Magnetic field strength

$$\beta = \omega_c/\omega_0$$

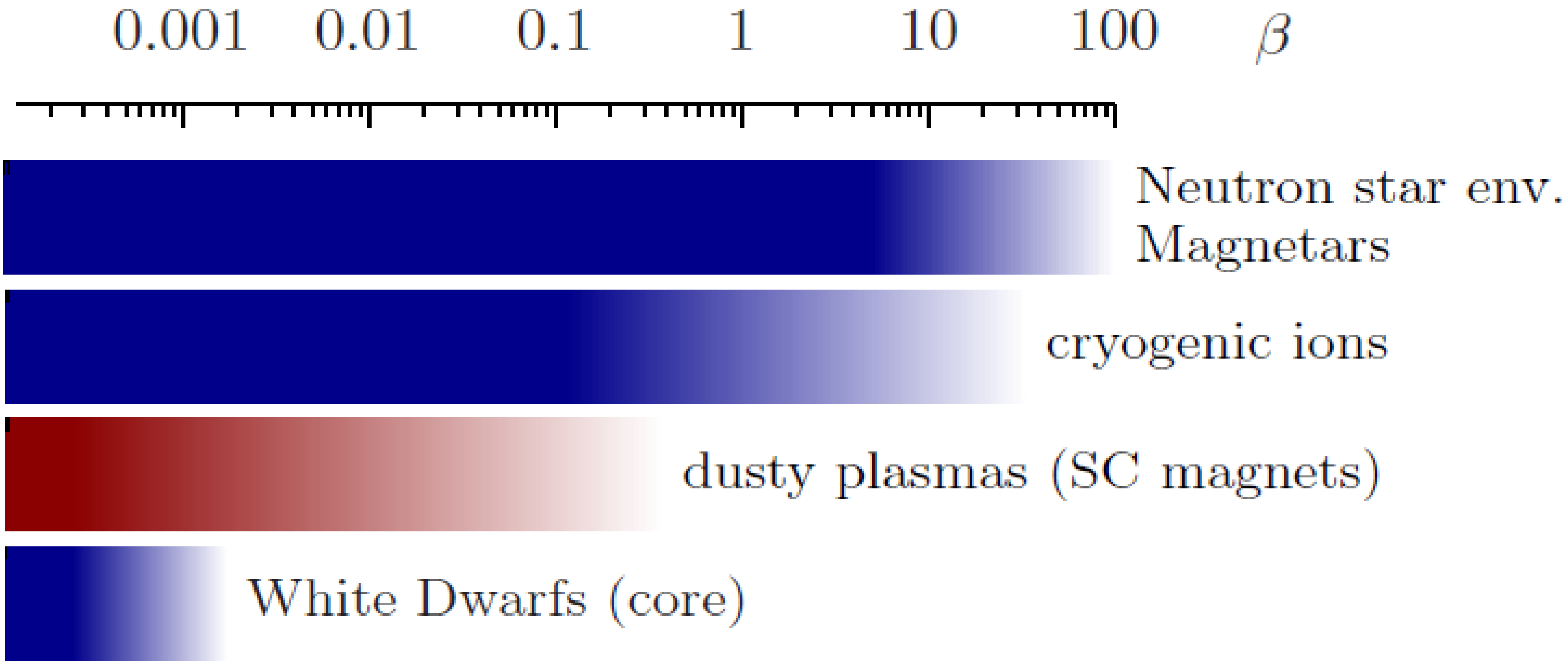
$$\delta = r_L/a \propto 1/\Gamma^{0.5}$$

Magnetization of strongly coupled plasmas

$$\beta = \frac{\omega_c}{\omega_p} = B\sqrt{\frac{\epsilon_0}{\rho}} \approx 3 \cdot 10^{-6}\frac{B\,[\mathrm{T}]}{\sqrt{\rho\,[\mathrm{kg\ m^{-3}}]}}$$

Mass density

$$\rho = mn$$



Complex plasma in a magnetic field

Dusty plasma experiments with superconducting magnets:

Recent results: G. Morfill (Garching), A. Piel (Kiel)
New devices: E. Thomas (Auburn)...

Fully magnetized electrons, partially magnetized ions

But: dust un-magnetized because of large particle mass

$$\beta = \frac{\omega_c}{\omega_p} = B\sqrt{\frac{\epsilon_0}{\rho}} \approx 3 \cdot 10^{-6} \frac{B\,[\mathrm{T}]}{\sqrt{\rho\,[\mathrm{kg\ m^{-3}}]}}$$

Mass density
$\rho = mn$

Examples (4T):

$$d = 20\,\mu m\,, \rho = 1200\,kgm^{-3} \rightarrow \beta = 3 \cdot 10^{-5}$$

$$d = 100\,nm\,, \rho = 4 \cdot 10^{-8}\,kgm^{-3} \rightarrow \beta = 0.06, (but: no\ optical\ diagnostics)$$

Magnetizing a complex plasma without a magnetic field

Dust particles set into rotation by rotating neutral gas $\boldsymbol{u}(\boldsymbol{r}) = (\Omega\, \hat{e}_z) \times \boldsymbol{r}.$

Confinement potential: $V(\rho, z) = \frac{m}{2}\left(\omega_\perp^2 \rho^2 + \omega_z^2 z^2\right)$

$$m\ddot{\boldsymbol{r}}_i = -\nabla_i V(\rho_i, z_i) + \sum_{j\neq i}^{N} \boldsymbol{F}_{ij}^{\mathrm{int}} - \nu m\left[\dot{\boldsymbol{r}}_i - \boldsymbol{u}(\boldsymbol{r}_i)\right] + \boldsymbol{f}_i$$

H. Kählert, J. Carstensen, M. Bonitz, H Löwen, F. Greiner, and A. Piel., PRL **109**, 155003 (2012).

Magnetizing a complex plasma without a magnetic field

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$$m\ddot{\boldsymbol{r}}_i = -\nabla_i V(\rho_i, z_i) + \sum_{j\neq i}^{N} \boldsymbol{F}_{ij}^{\mathrm{int}} - \nu m\left[\dot{\boldsymbol{r}}_i - \boldsymbol{u}(\boldsymbol{r}_i)\right] + \boldsymbol{f}_i$$

Transform to frame rotating with the neutral gas

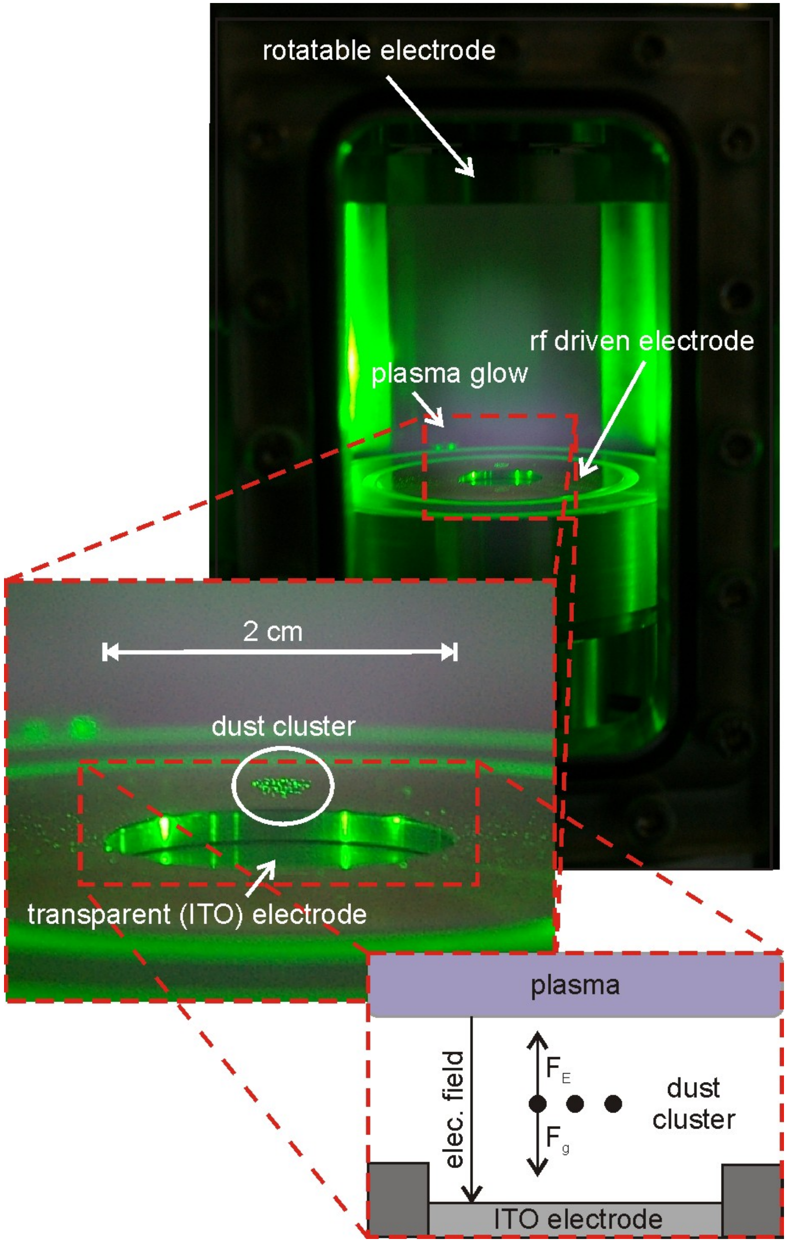
$$m\ddot{\bar{\boldsymbol{r}}}_i = -\bar{\nabla}_i\bar{V}(\bar{\rho}_i, \bar{z}_i) + \sum_{j\neq i}^{N} \bar{\boldsymbol{F}}_{ij}^{\mathrm{int}} + \bar{\boldsymbol{F}}_{\mathrm{Cor}}(\dot{\bar{\boldsymbol{r}}}_i) - \nu m\dot{\bar{\boldsymbol{r}}}_i + \bar{\boldsymbol{f}}_i,$$

$$\bar{\boldsymbol{F}}_{\mathrm{Cor}}(\dot{\bar{\boldsymbol{r}}}) = m\dot{\bar{\boldsymbol{r}}} \times (2\,\Omega\,\hat{e}_z)$$

Coriolis force equivalent to Lorentz force:

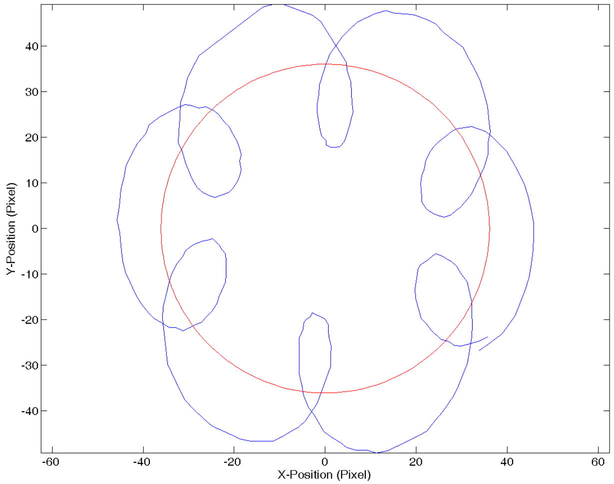
$$B_{\mathrm{eff}} = (2m\Omega/Q)\hat{e}_z$$

Experimental verification



P=0.4Pa, Argon, Ω=0...30 Hz
2D dust cluster

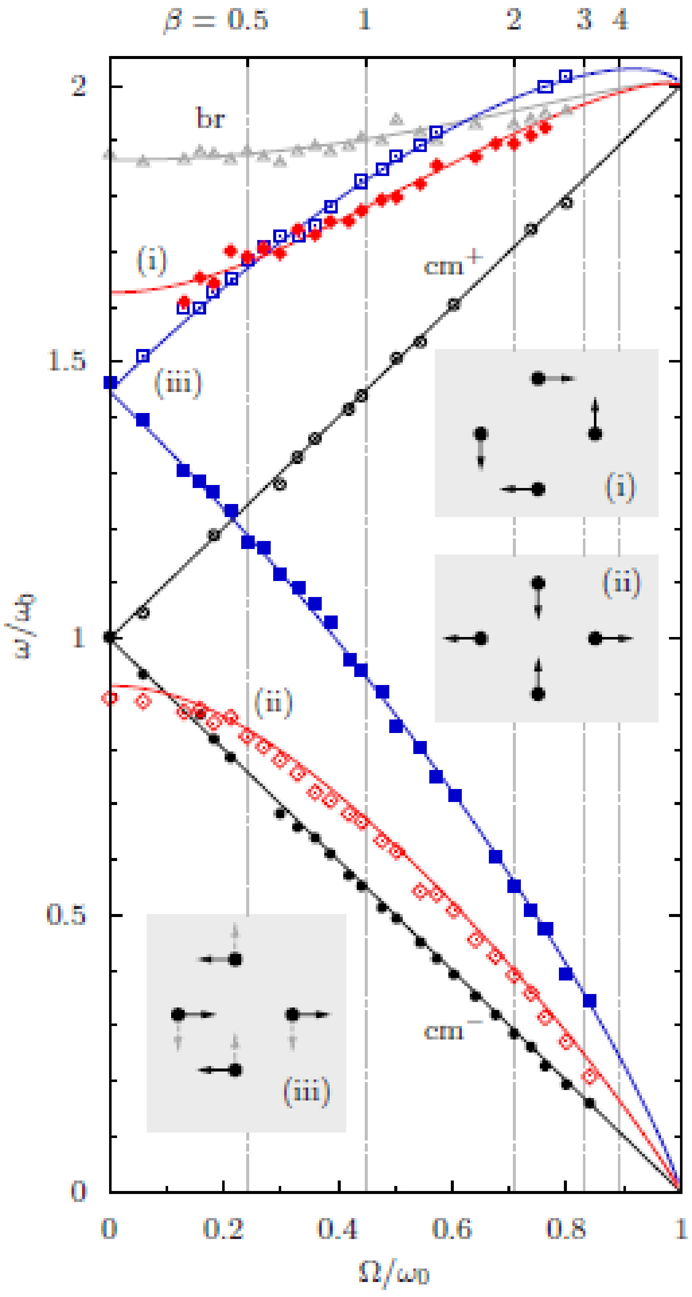
Typical trajectory (rest frame)



Kählert et al., PRL **109**, 155003 (2012).

Experiment: J. Carstensen

Theory-Experiment comparison



Video camera diagnostics
Particles with d=21.8μm in horizontal plane

7 (of 8) Normal modes of 4 particles
for different rotation speeds

Symbols: experiment
Lines: theory

→ easily reach β=3
equivalent B-field (without rotation): 100,000T!

Kählert et al., PRL **109**, 155003 (2012)

Extension to macroscopic 2D systems:
M. Bonitz, H. Kählert, T. Ott, and H. Löwen,
Plasma Sources Sci.Technol. **22**, 015007 (2013)

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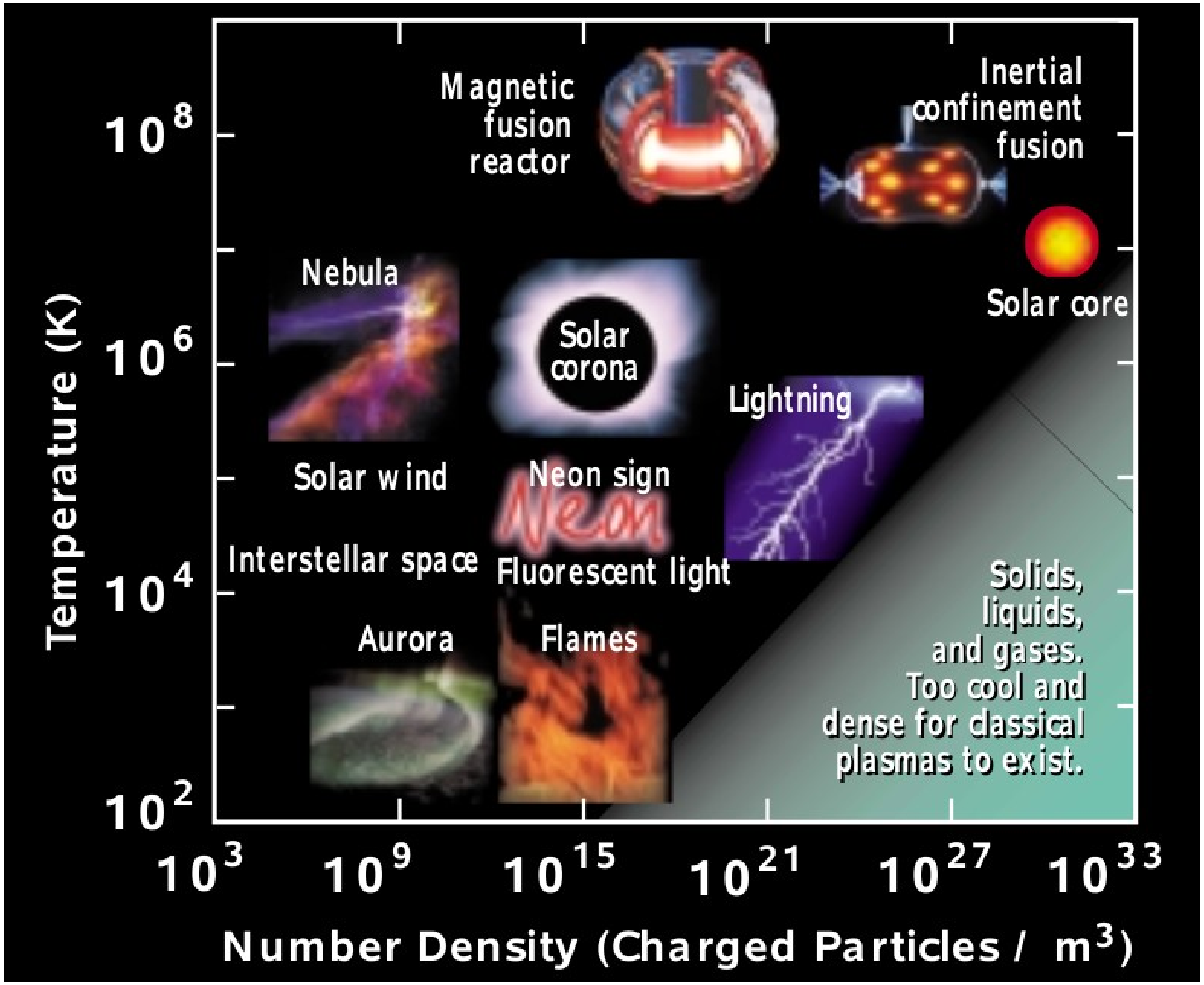
Quantum plasmas in the Universe and in the Lab



Dense space plasmas:

- Cores of giant planets
- dwarf stars
- neutron stars

Dense laboratory plasmas:
- laser plasmas
- ion beam produced plasmas
- Inertial confinement fusion

From Contemporary physics education project 2010 (NSF, DOE sponsored)

http://www.cpepphysics.org/fusion.html

Correlations of quantum plasmas

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

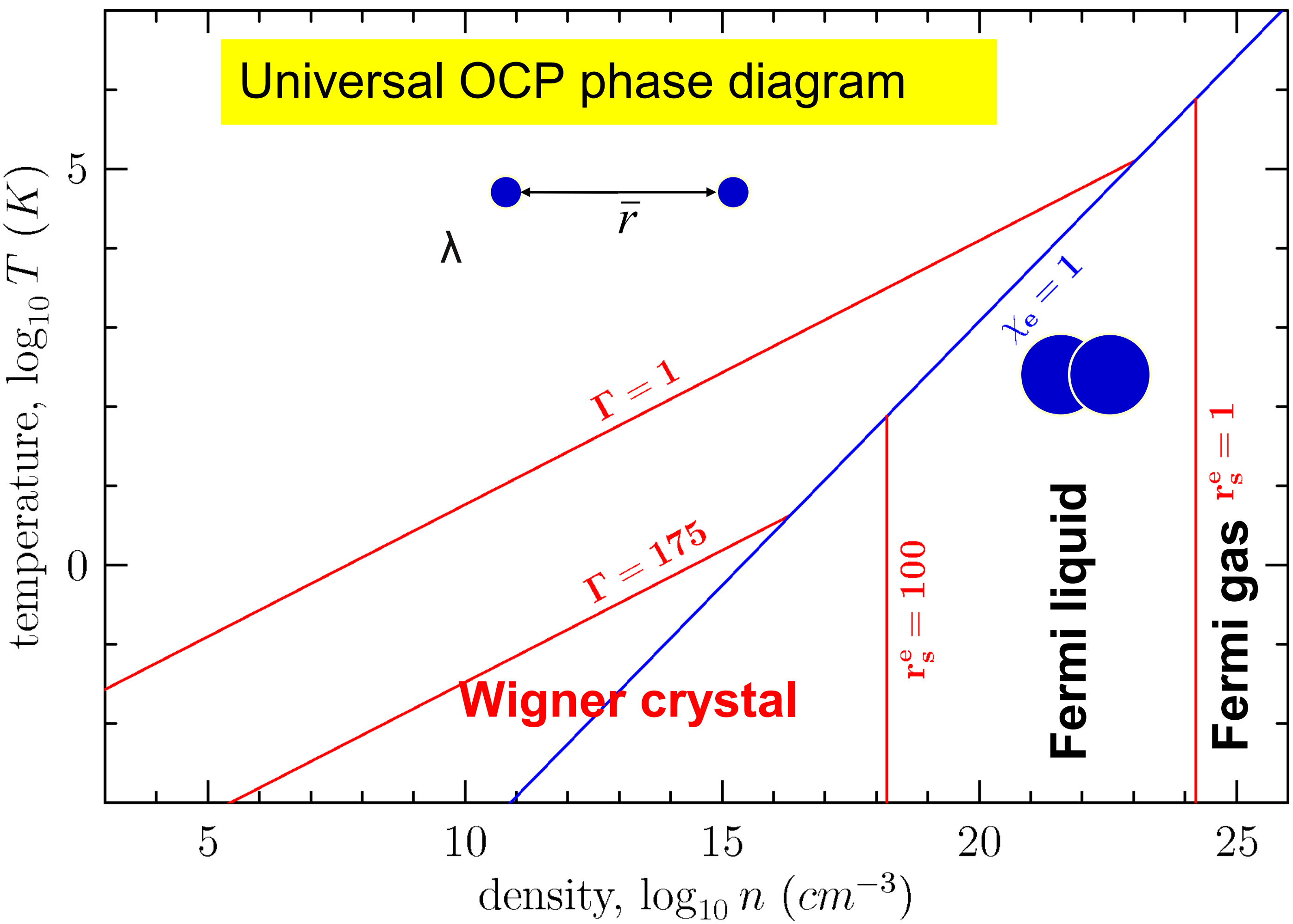
$$\Gamma^Q = \frac{|\langle U \rangle|}{\langle E_{KIN} \rangle} \sim \frac{e^2}{E_F\, \bar{r}} \propto \frac{e^2 n^{1/3}}{n^{2/3}} \propto n^{-1/3}$$

Quantum degeneracy

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

DeBroglie
wave length

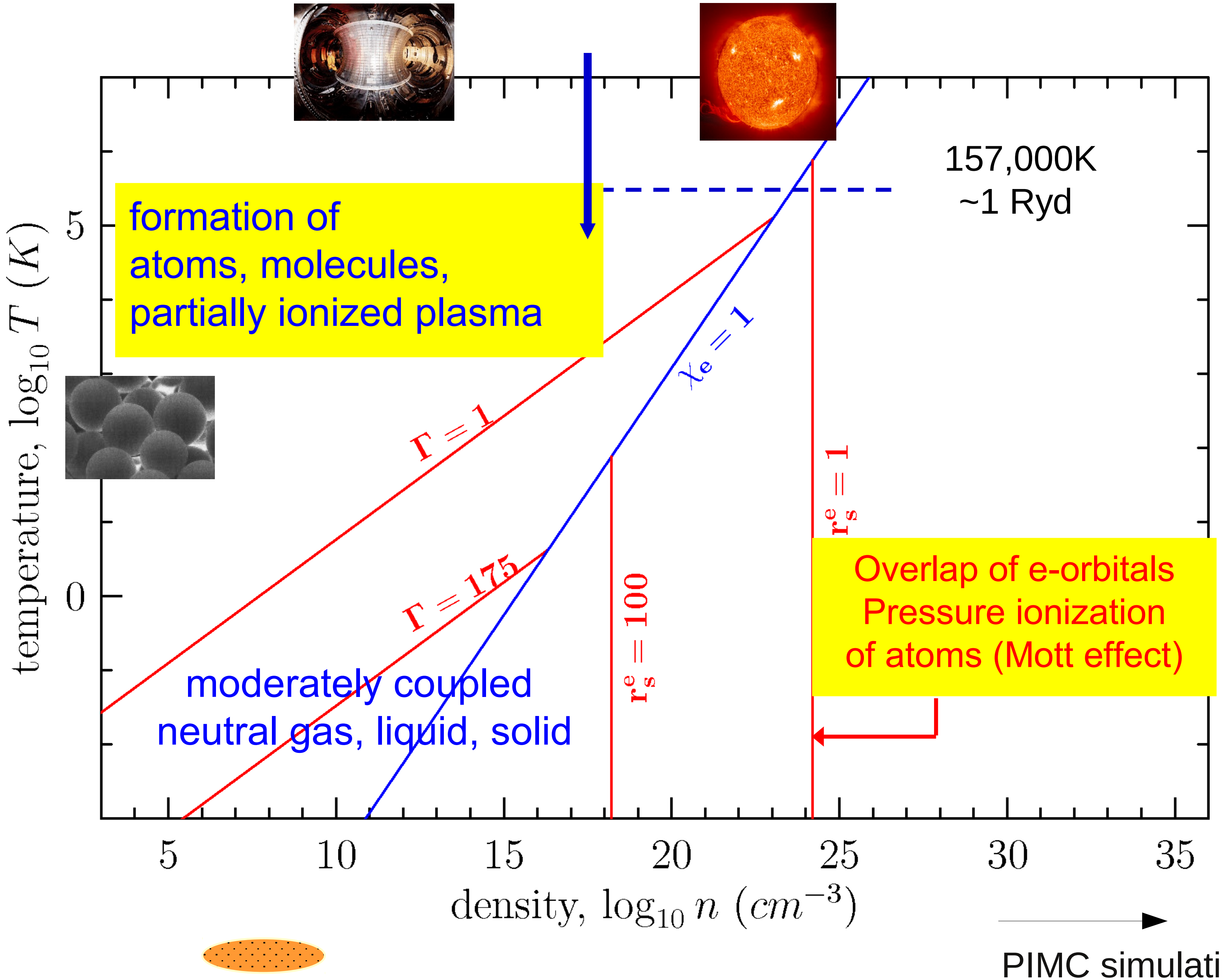
$$\lambda = h / \sqrt{2\pi m k_B T}$$



$r_s^{cr} \approx 100/37\ (3D/2D)$

Ceperley et al.,
A. Filinov, MB

Partially ionized 2-comp. plasma



formation of
atoms, molecules,
partially ionized plasma

157,000K
~1 Ryd

Overlap of e-orbitals
Pressure ionization
of atoms (Mott effect)

moderately coupled
neutral gas, liquid, solid

PIMC simulations

Partially ionized dense plasma

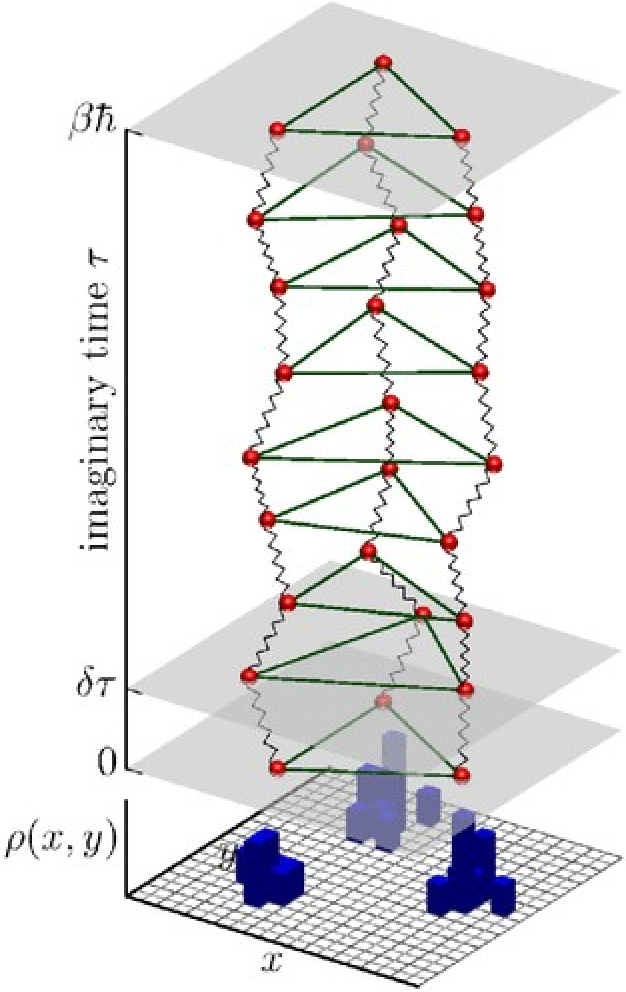
Need **„chemical“ composition** of plasma: fraction of free and bound electrons

Equilibrium: **mass action law** (Saha equation),
including correlation and quantum effects, Mott effect

→ chemical models break down

Alternative: first principle simulations: Path integral quantum Monte Carlo

Illustration of PIMC



animation

PIMC simulations
of dense hydrogen

Computer lab, text books:

„Introduction to Computational Methods for Many-Body Physics“, Rinton Press 2006
„Introduction to Complex Plasmas“, Springer 2010

Ultra-dense fully ionized two-component plasma

$$\chi_a = n_a \Lambda_a^3 \sim \frac{n_a}{m_a^{3/2}}$$

$$r_{sa} = \bar{r}_a / a_{Ba} \sim \bar{r}_a m_a Z_a^2$$

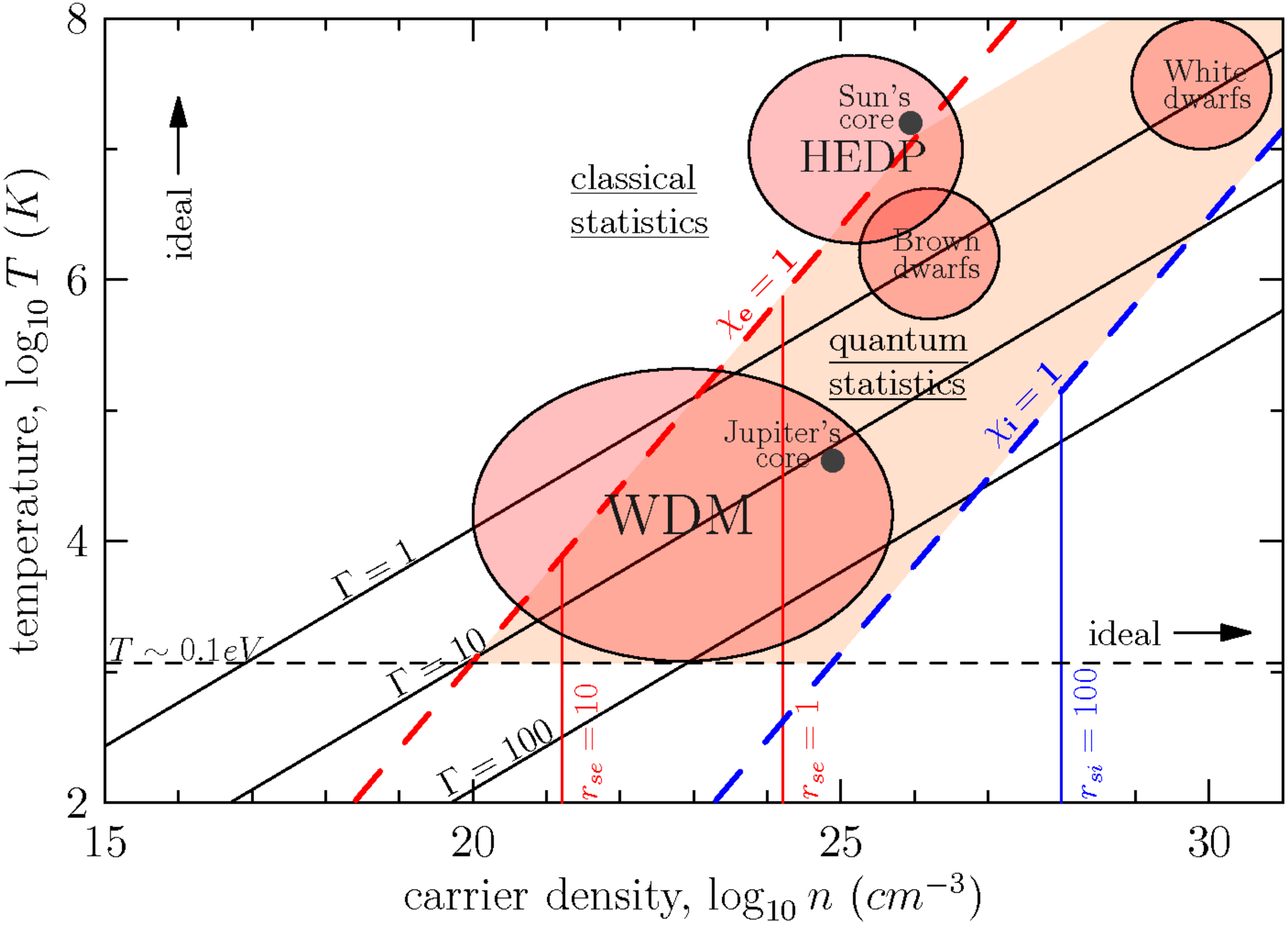
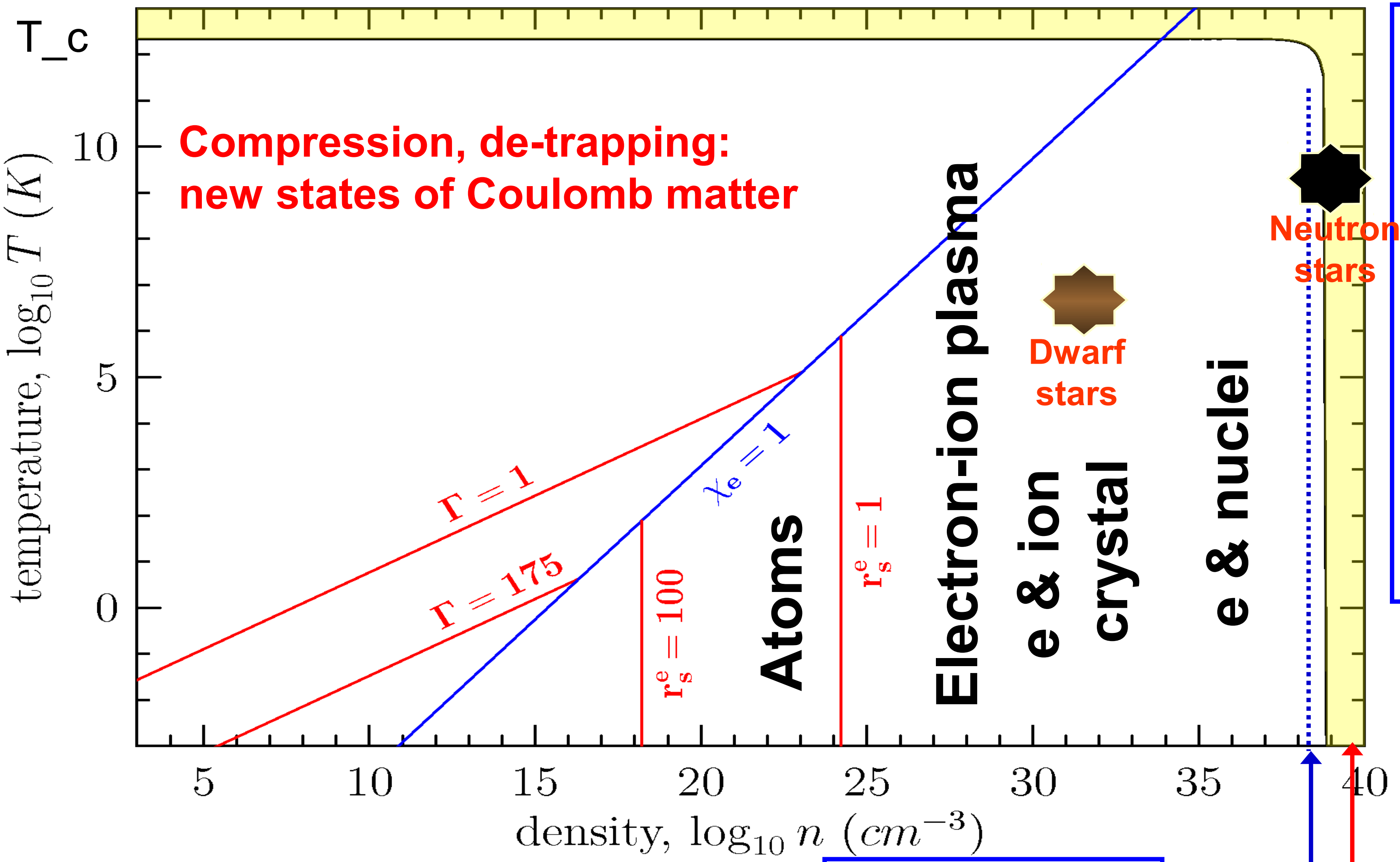


figure:
Hydrogen

WDM: „warm dense matter“, **HEDP**: high energy density plasmas

MB, V. Filinov, V. Fortov, P. Levashov, and H. H. Fehske, PRL ***95****, 235006 (2005)*

From atomic nuclei to quarks



Compression, de-trapping: new states of Coulomb matter

(e & protons &) neutrons

Quark-gluon plasma

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

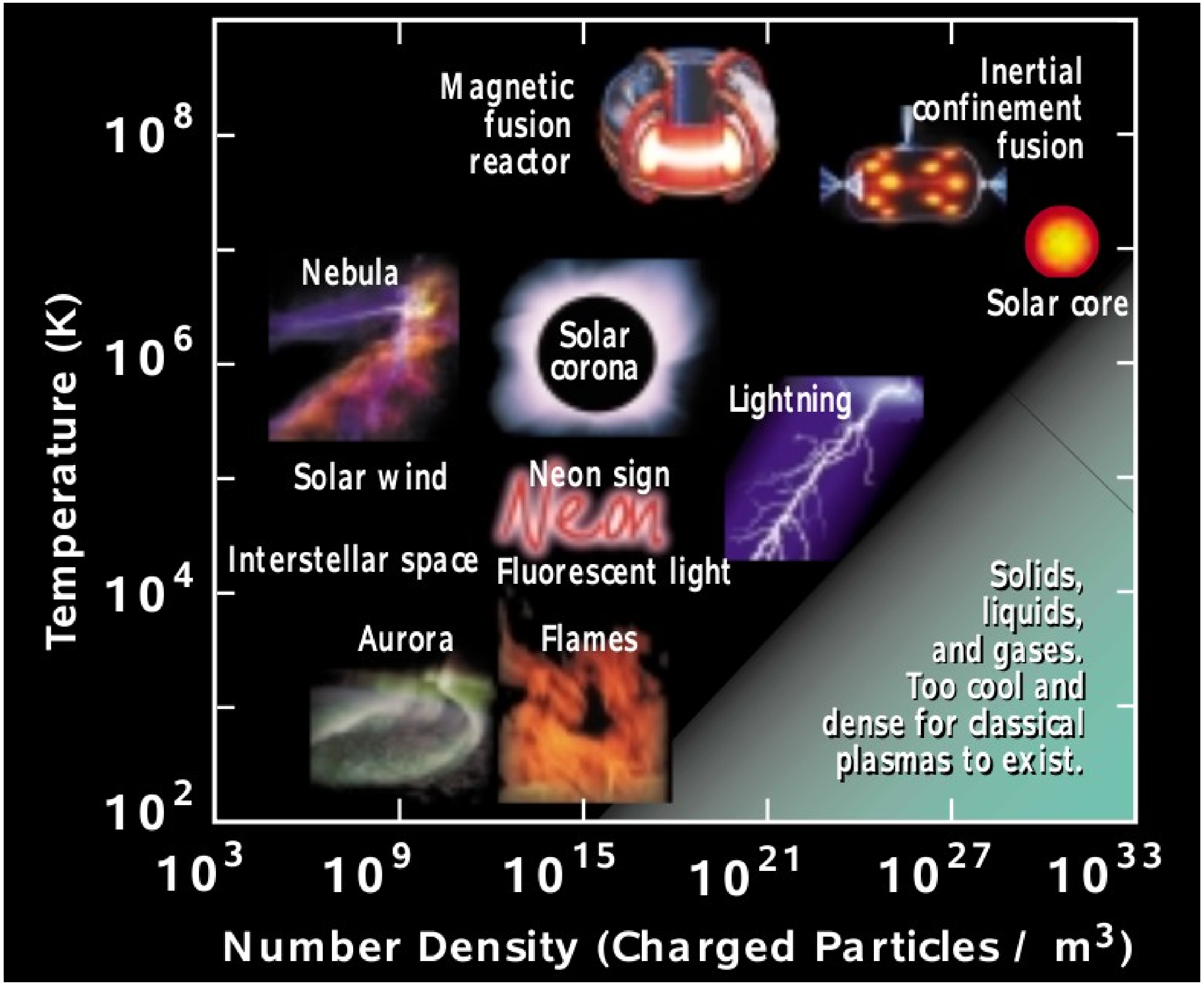
$$T_C = 175\,MeV$$

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

deconfinement

$$(5 \ldots 10)\rho_N$$

Quantum plasmas in the Universe and in the Lab



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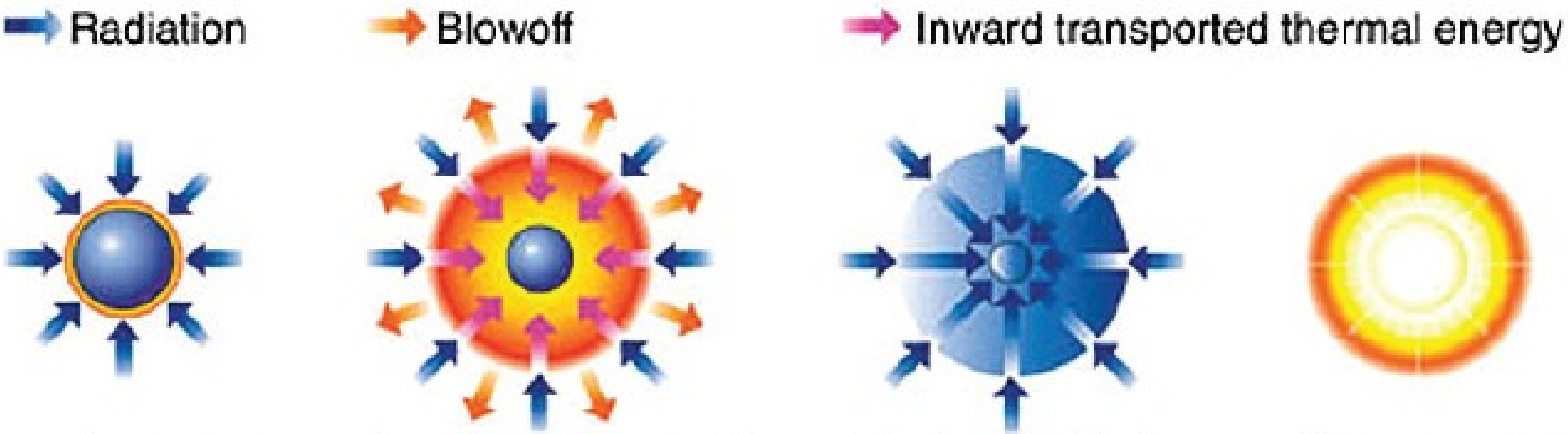
- Inertial confinement fusion

From Contemporary physics education project 2010 (NSF, DOE sponsored)

http://www.cpepphysics.org/fusion.html

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.

Failure of NIF

ScienceInsider, News Reports 12 December 2012

Agency Tells Congress That NIF Is Not Working
by Daniel Clery

Ignition scheduled by Oct 1 2012, but campaign unsuccessful

"At present, it is too early to assess whether or not ignition can be achieved at the National Ignition Facility," wrote Thomas P. D'Agostino, administrator of the National Nuclear Security Administration (NNSA) in a report requested by Congress that was submitted last week....

...Although the laser itself, the diagnostic instruments, and the target fabrication have all met or exceeded specifications, the physics of the implosions was unexpected. "Experimental data demonstrate that the **physics underlying ignition implosions are not predicted accurately by the simulation codes** that were used to design ignition targets and to predict their performance," the report says.

New theoretical / simulation efforts in dense quantum plasmas needed

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National Research Council, Report, Feb 20 2103

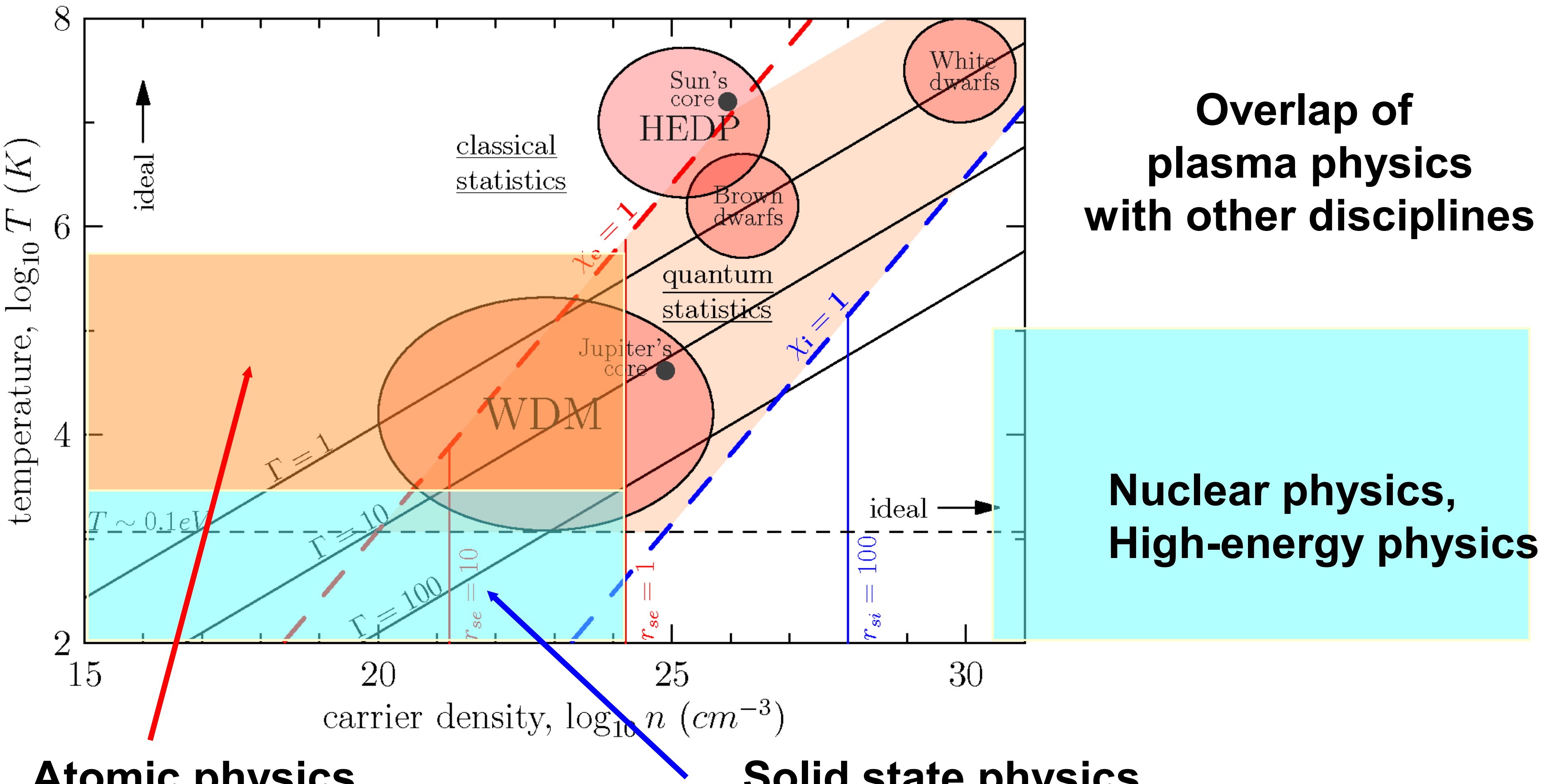
Realistic dense quantum plasmas

Required: selfconsistent account of

1. Many-component system (mass-asymmetric)
2. Quantum degeneracy of light component (electrons)
3. Bound states of electrons and ions
4. Strong ion coupling
5. Strong magnetic field
6. Nonequilibrium:
   - streaming plasmas, ion beams
   - laser pulse or FEL excitation etc.

Current status: no solution of the quantum many-body problem
Theoretical concepts for limiting cases
Accurate computer simulations in TD equilibrium

Theoretical concepts for dense quantum plasmas



Overlap of plasma physics with other disciplines

Nuclear physics, High-energy physics

Atomic physics

- atoms, molecules
- ionization/recombination

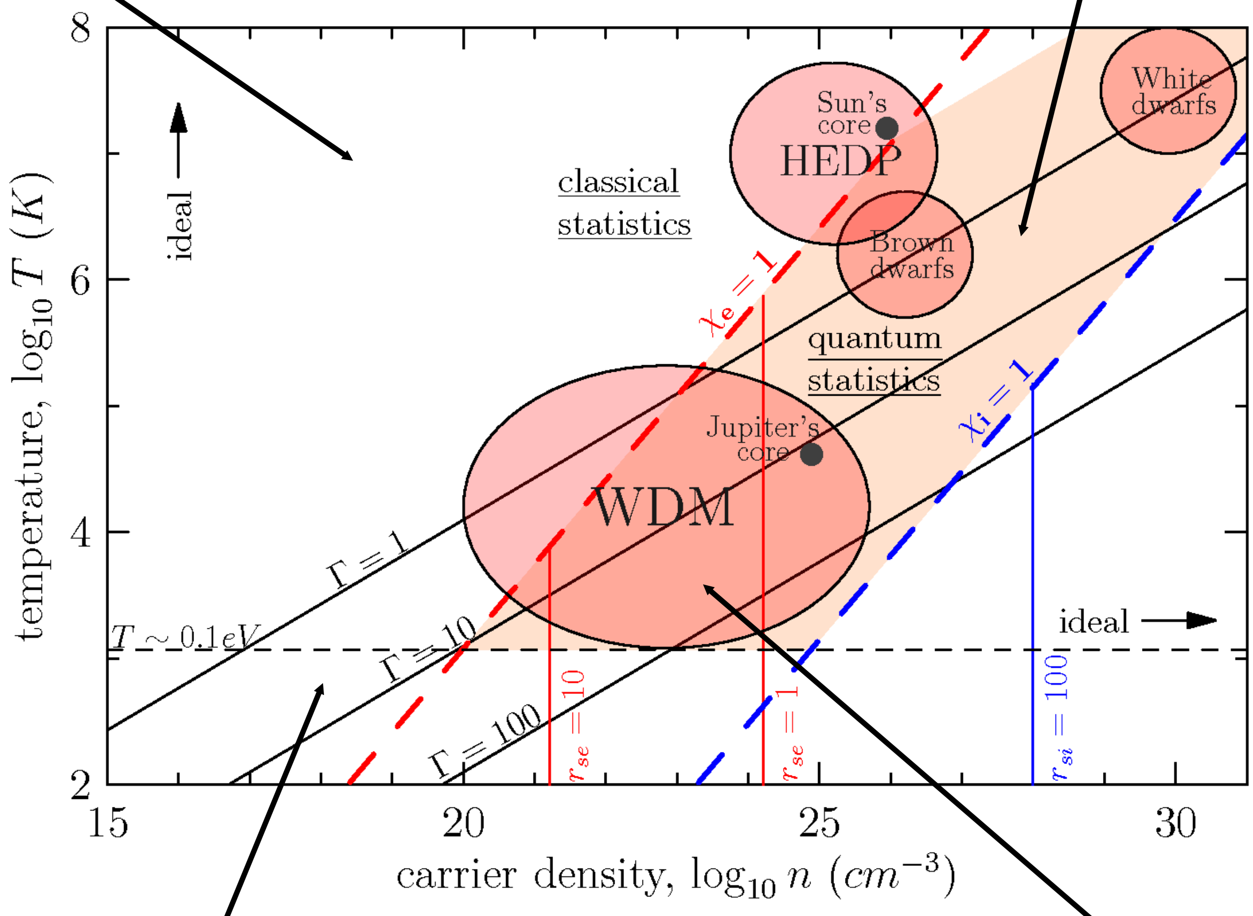
Solid state physics

- molecular/atomic crystal
- targets for laser ionization

Regimes of equilibrium plasmas

I. weakly nonideal plasma,
perturbation theory

IV. strongly coupled classical ions,
nearly ideal quantum electrons



Coupling grows with ion charge!

figure:
Hydrogen

II. strongly coupled classical OCP

III. partially ionized plasma

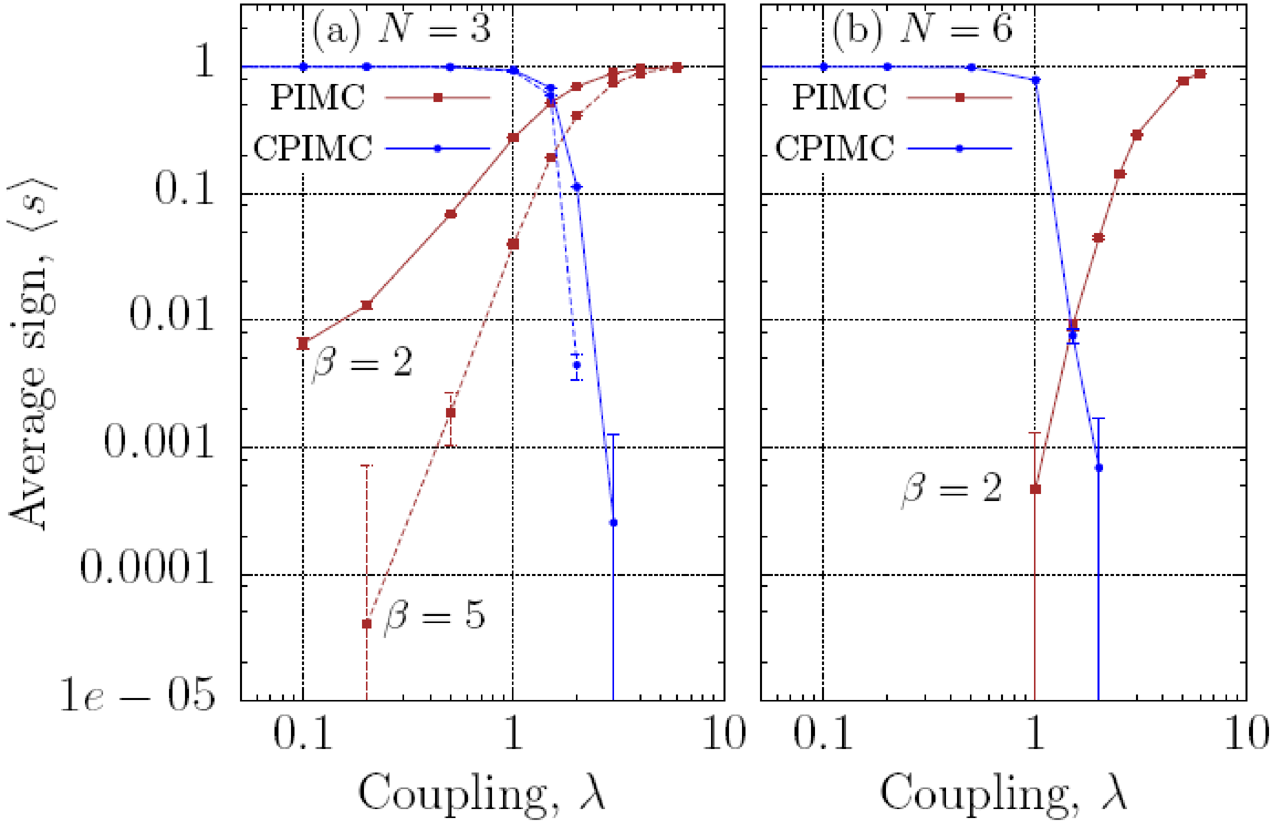
Theory of dense plasmas: Methods

	Classical Systems	Quantum Systems
Theory	-Density functional theory -Fluid theory	-Density operator theory -Nonequilibrium Greens functions
1st principle simulations	-MC -MD -Langevin MD -Kinetic MC	-PIMC, CPIMC -QMD -DFT -TDSE, TDCI, MCTDHF -NEGF

Configuration PIMC

Fighting the fermion sign problem (NP hard)

New PIMC approach (CPIMC):
Exact for weak coupling
Complementary to standard PIMC



T. Schoof, MB, A. Filinov, D. Hochstuhl and J.W. Dufty, Contrib. Plasma Phys. ***51****, 687 (2011)*
T. Schoof, Diplomarbeit, Uni Kiel 2011

Strongly correlated classical ions & weakly coupled quantum electrons

Dynamics, Transport → new multi-scale approach*:

- ions treated exactly (MD)
- electrons give rise to *dynamically screened* ion pair potential, includes quantum dielectric function with correlations (Mermin DF) and external field effects
- includes nonequilibrium effects, such as wakes

$$\phi_{ij}(\vec{r}_i - \vec{r}_j) = \int d^3\vec{k}\, \frac{Z^2 e^2}{(2\pi)^2 k^2} \frac{e^{i\vec{k}\cdot(\vec{r}_i - \vec{r}_j)}}{\varepsilon(\vec{k}, -\vec{k}\cdot\vec{v}_0)}$$

Similar concept: „Kinetic theory MD“ (F. Graziani, LLNL 2011)

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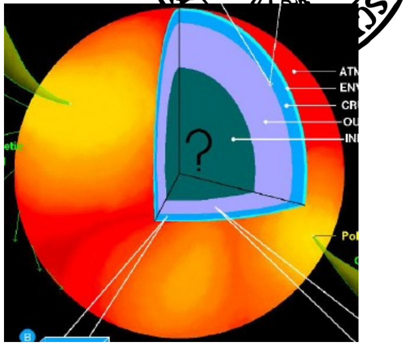
*P. Ludwig, MB, H. Kählert, and J.W. Dufty, J. Phys. Conf. Series **220**, 012003 (2010)*

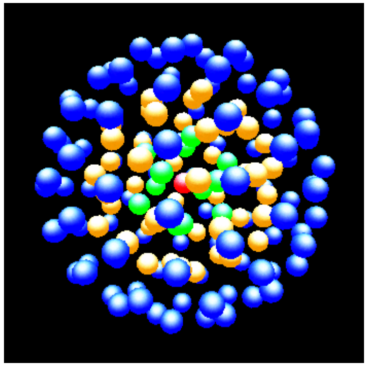
Correlated dielectric function: *N.H. Kwong, and MB, Phys. Rev. Lett.* ***84****, 1768 (2000)*

Conclusions

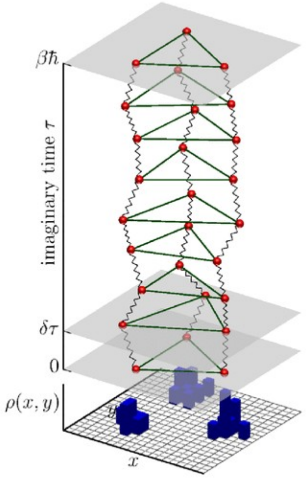


Strongly correlated plasmas
fluid and crystal structures

Complex plasmas
room temperature, direct optical diagnostics
prototype for correlated plasmas



Magnetized strongly coupled plasmas
reduced transport
realized in complex plasmas without magnetic field



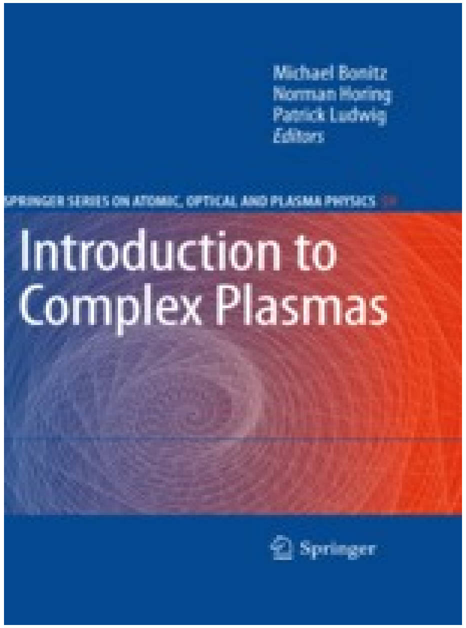
Dense quantum plasmas
Partial ionization
First principle PIMC simulations
Multiscale simulations for electrons and ions

Review: Bonitz, Henning, Block, Rep. Prog. Phys.**73**, 066501 (2010)
Further information: www.theo-physik.uni-kiel.de/~bonitz

Complex plasmas - outlook

Diagnostics with unprecedented single-particle resolution
→ Unique opportunities for comparison experiment – simulation - theory

- **Fundamental properties, interaction**
  beyond linear response
- **Many-particle properties:**
  phase diagram
  collective oscillation spectrum
- **Magnetic field effects:**
  competition of correlations and magnetization
  shear instabilities
- **Technological applications:**
  nanoparticle growth in magnetron discharge
  nanocomposite formation


Michael Bonitz
Norman Horing
Patrick Ludwig
Editors

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Review: Bonitz, Henning, Block, Rep. Prog. Phys.**73**, 066501 (2010)
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