Progress in strongly correlated Coulomb systems

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Coulomb systems

charged particles: electrons, ions, holes, positrons, quarks* ...

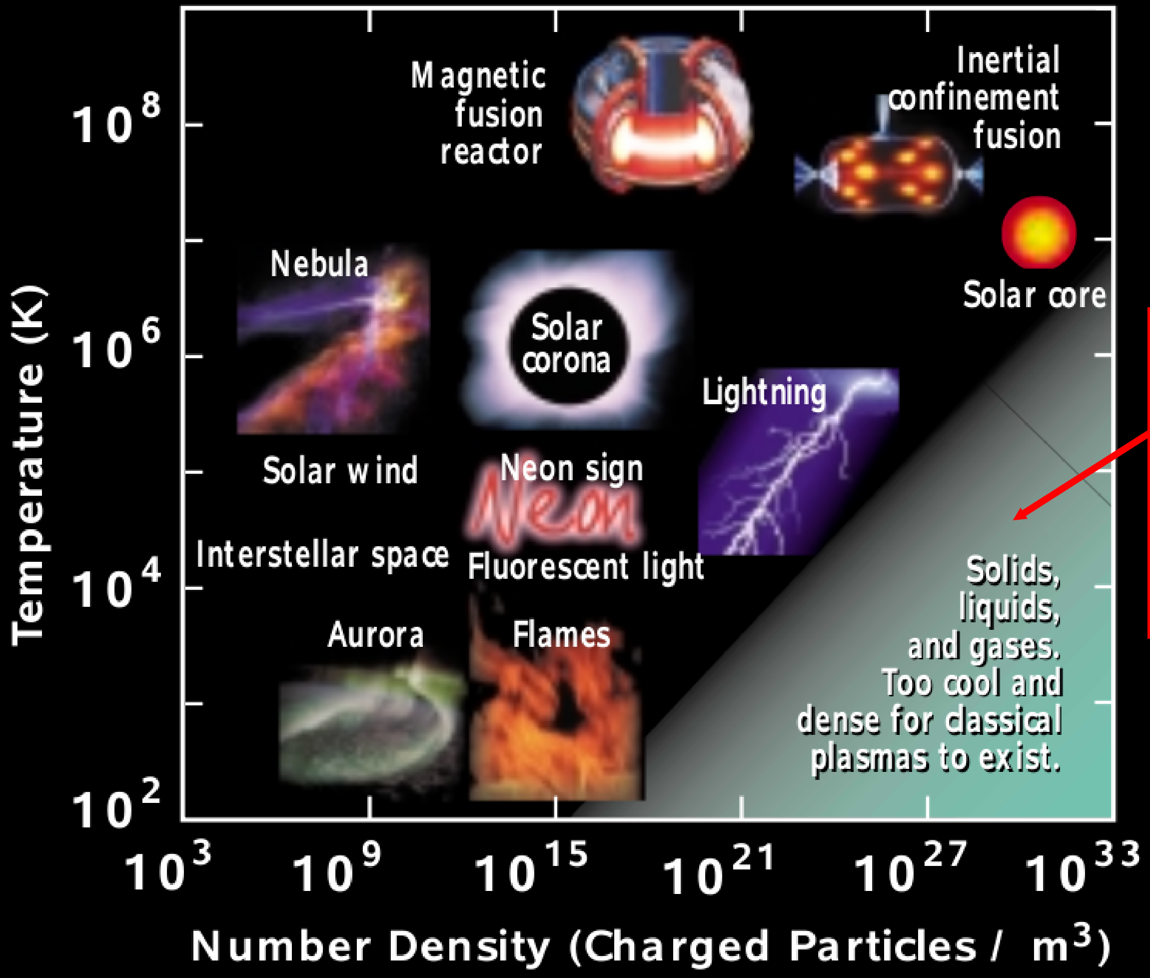
Behavior dominated by Coulomb interaction $U(r) = q^2/r$

This interaction is strong and long range!

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

also: Plasma of *magnetic* charges (monopoles) in spin ice:
MB, Nature Physics ***7,*** *192 (2011)*

Occurences of plasmas*



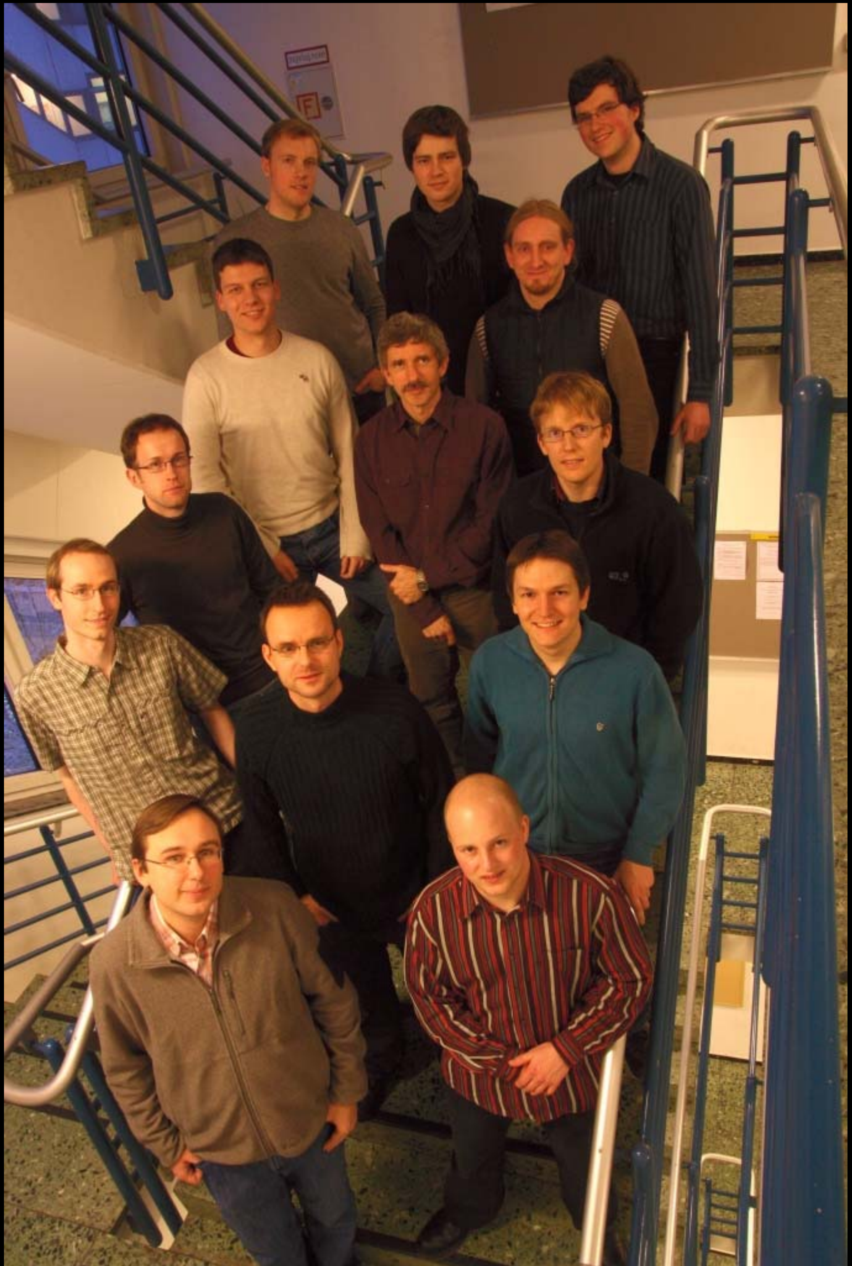
„unusual plasmas“

- astrophysical objects
- laser compression

new states of matter

*Contemporary Physics Education Project, http://www.cpepweb.org/

Acknowledgements 1: Group



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C | A | U

Collaborations

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DFG

DAAD

TR 24 complex plasmas

Bundesministerium für Bildung und Forschung

U.S. DEPARTMENT OF ENERGY

National Science Foundation WHERE DISCOVERIES BEGIN

Contents

1. **Overview: strongly correlated plasmas**
    1.1 One-component plasma (OCP) in TD equilibrium
    1.2 Two-component plasma: partial ionization, compact stars, dense laboratory plasmas

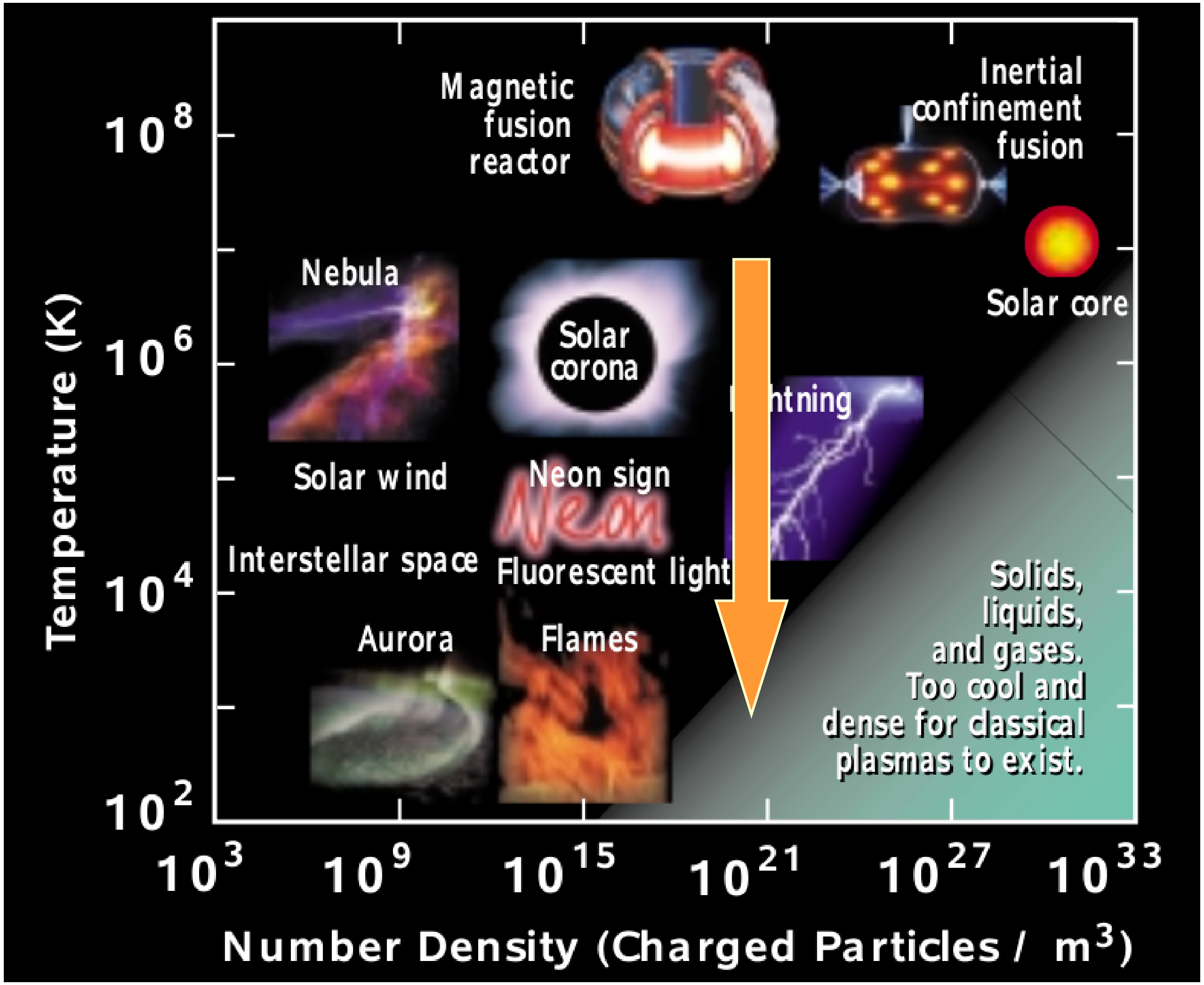
2. **Theory of strongly correlated plasmas**
    2.1 First-principle equilibrium simulations
    2.2 Dense plasmas in nonequilibrium:
        - laser plasmas
        - photoionization

3. **Outlook:** Multiscale simulations of dense plasmas

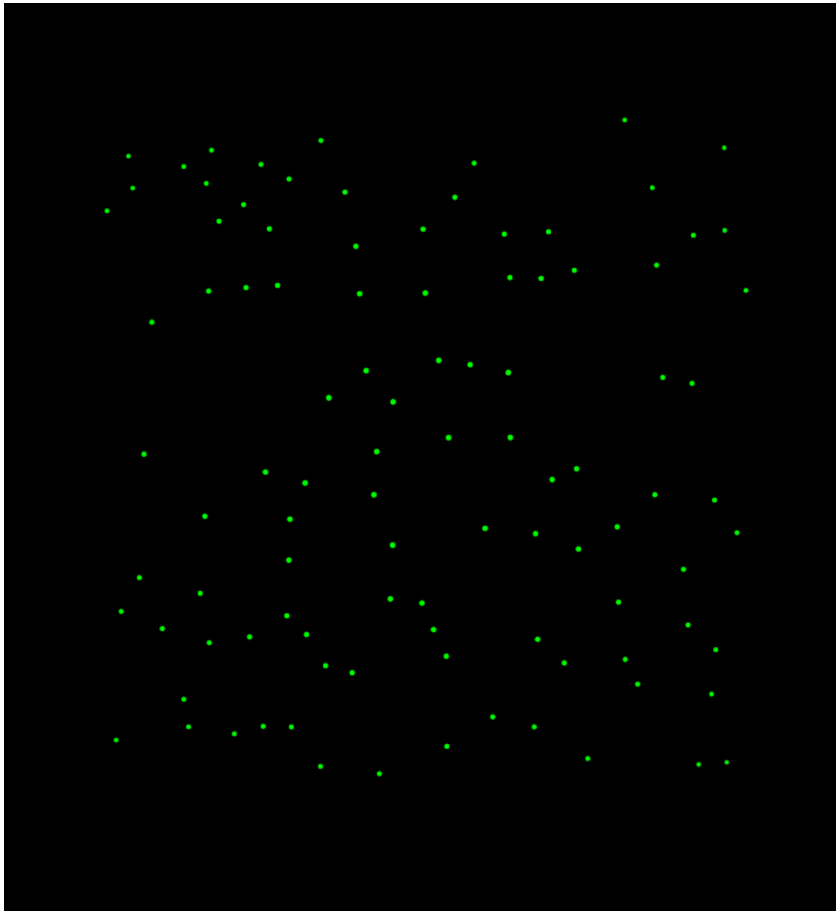
One-component plasma model

- OCP: charged particles in neutralizing background (jellium)

1. Equilibrate
2. cool



Thermodynamics of OCP



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

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).

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

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

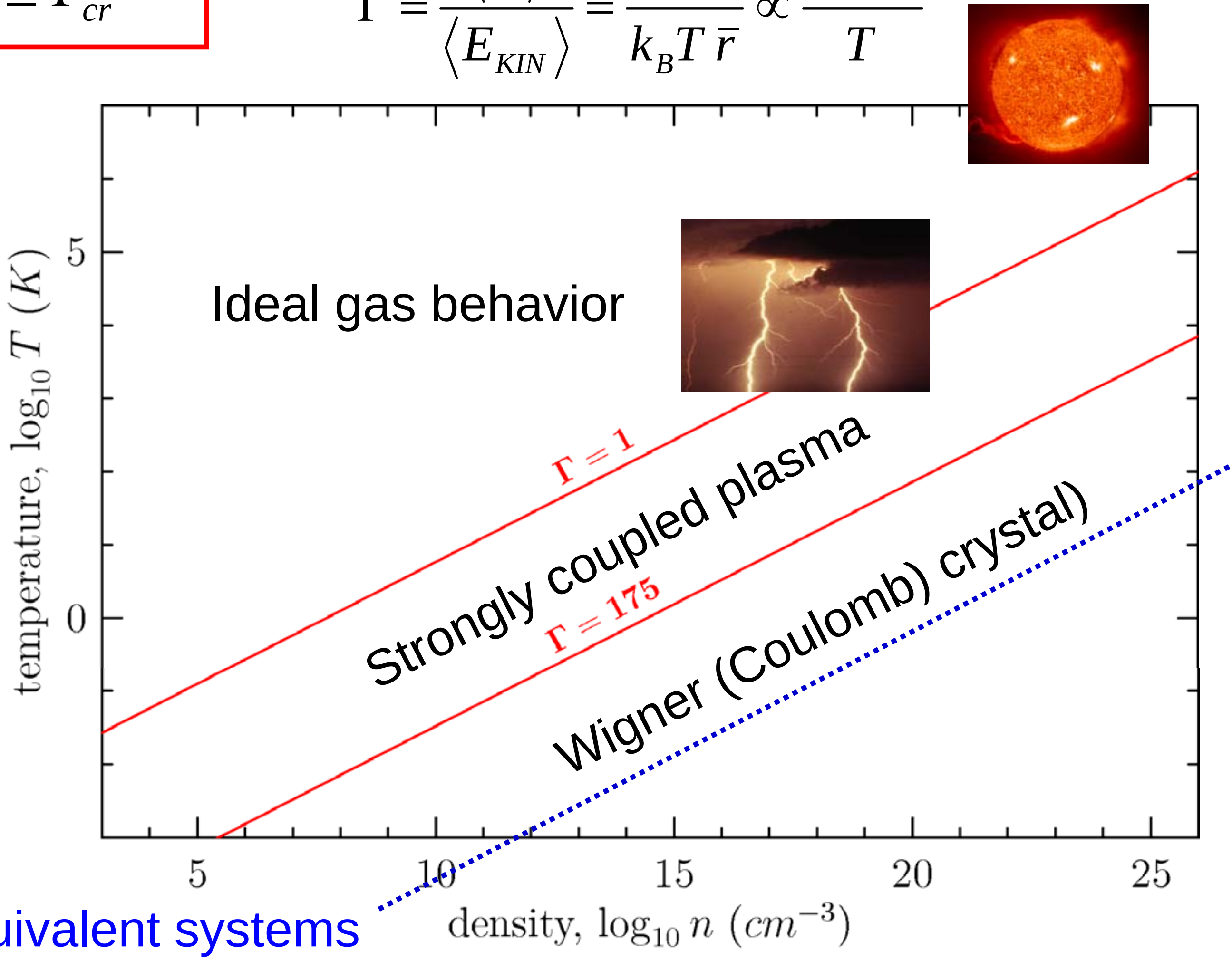
Plasma crystals in the laboratory

Need: $\Gamma \geq \Gamma_{cr}$

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

Ways to achieve:

1. cooling

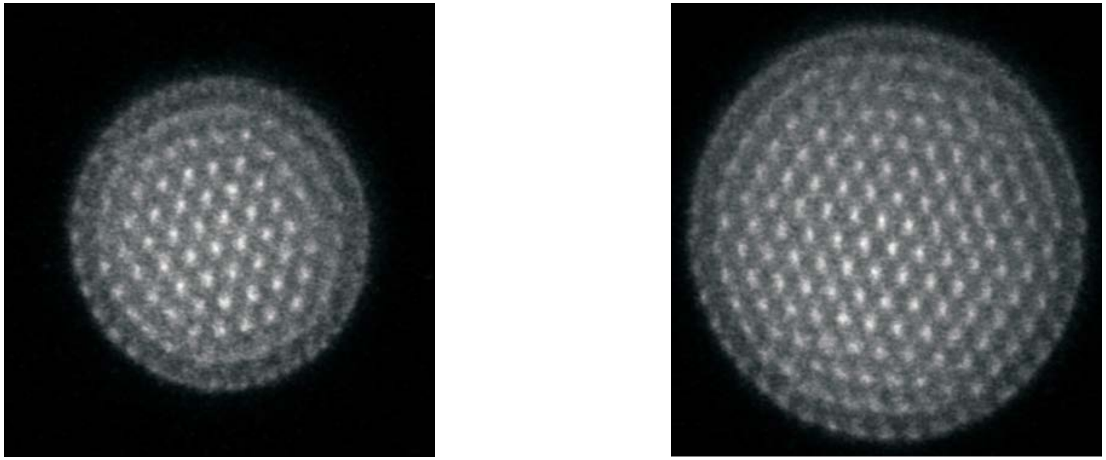


Physically equivalent systems

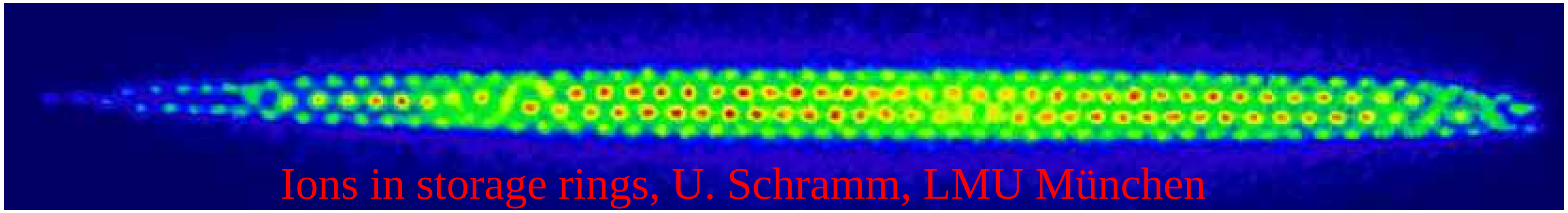
Ion crystals in traps

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

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



Drewsen



Ions in storage rings, U. Schramm, LMU München

Problem: strong correlations require ultra-low temperatures (mK)

Correlated plasmas – approach 2

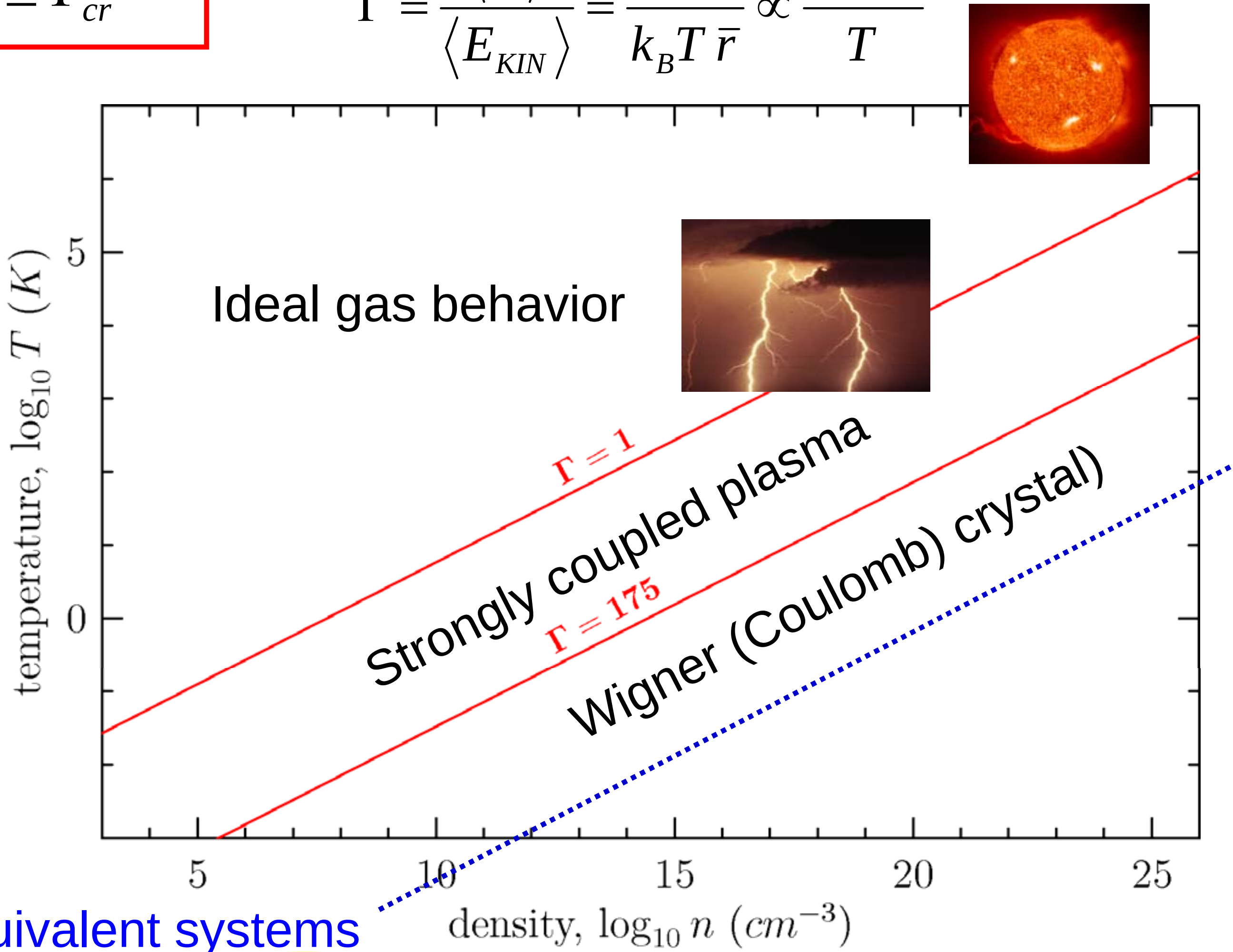
Need: $\Gamma \geq \Gamma_{cr}$

$$\Gamma = \frac{|\langle U \rangle|}{\langle E_{KIN} \rangle} = \frac{e^2}{k_B T \bar{r}} \propto \frac{e^2 n^{1/3}}{T}$$

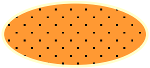
Ways to achieve:

1. cooling

2. Charge increase



Physically equivalent systems



Trapped ions

Strongly correlated plasmas

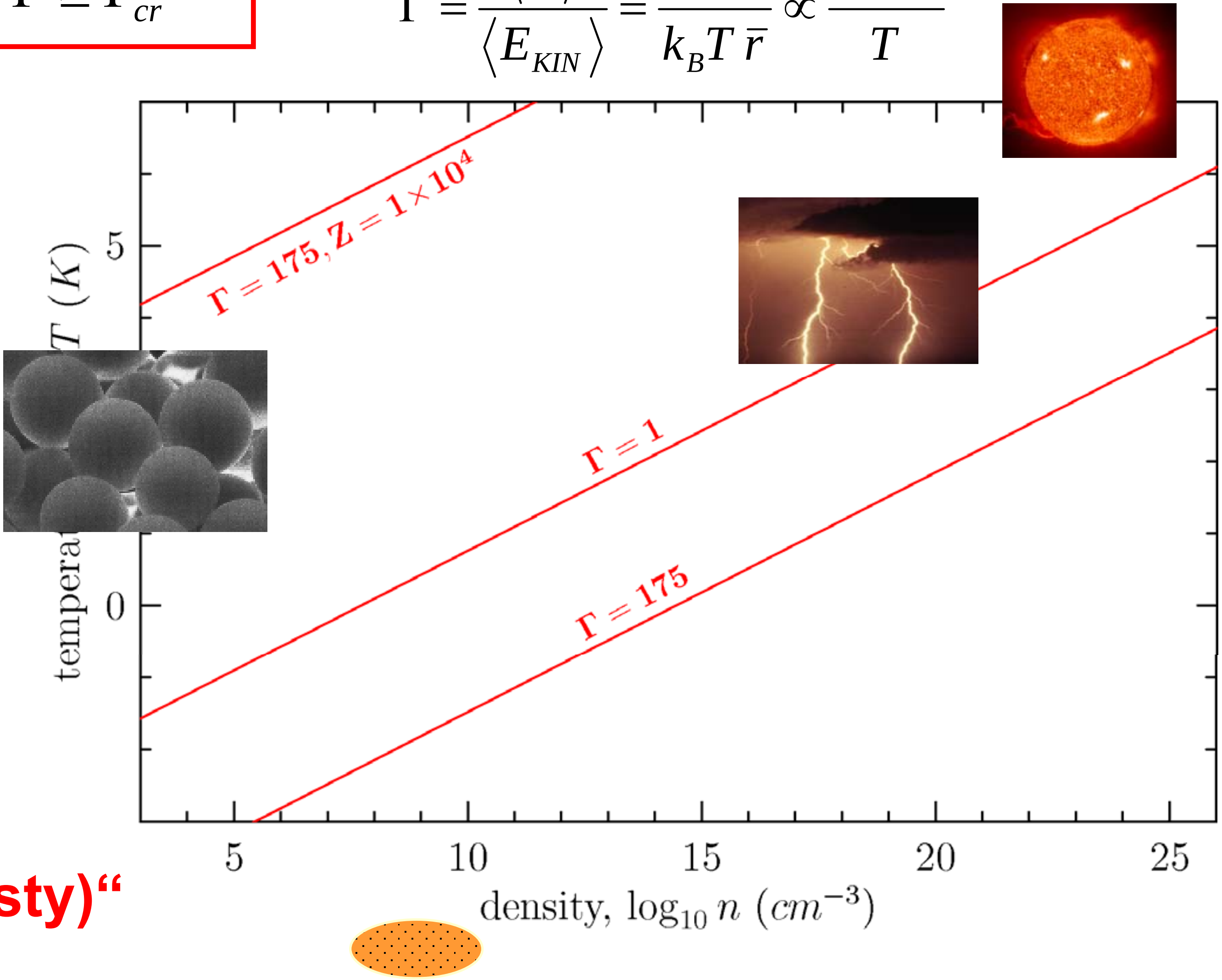
Need: $\Gamma \geq \Gamma_{cr}$

$$\Gamma = \frac{|\langle U \rangle|}{\langle E_{KIN} \rangle} = \frac{e^2}{k_B T \bar{r}} \propto \frac{e^2 n^{1/3}}{T}$$

Ways to achieve:

1. cooling

2. Charge increase



„Complex (dusty)“ plasma

Complex (dusty) plasmas*

Experimental realization: 1994
Strongly correlated liquid and crystalline plasmas
Phase transitions

- prototype system to study charged particle correlations
- (virtually) exact computer simulations possible
- perfectly suited for development of theoretical concepts

→ Major progress in our understanding of strongly coupled Coulomb systems

Transregio-SFB „Fundamentals of complex plasmas“
Greifswald/Kiel

DFG

TR 24 complex plasmas

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*M.B., C. Henning, D. Block, *Rep. Prog. Phys.* ***73***, *066501 (2010)*

„Introduction to Complex Plasmas“, MB, N. Horing and P. Ludwig (eds.), Springer 2010

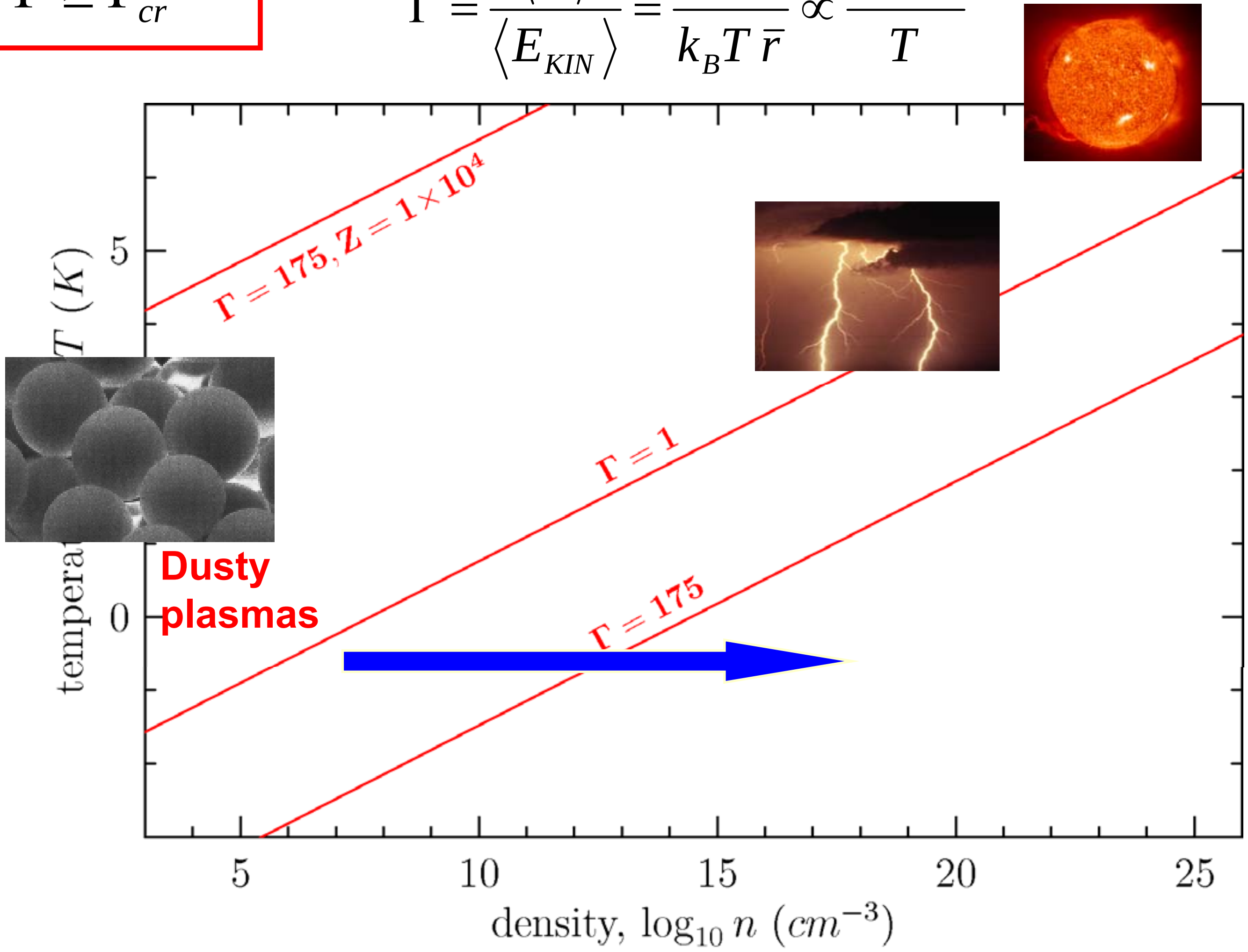
Correlated plasmas by compression

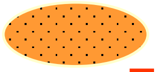
Need: $\Gamma \geq \Gamma_{cr}$

$$\Gamma = \frac{|\langle U \rangle|}{\langle E_{KIN} \rangle} = \frac{e^2}{k_B T \bar{r}} \propto \frac{e^2 n^{1/3}}{T}$$

Ways to achieve:

1. cooling
2. Charge increase
3. **compression**

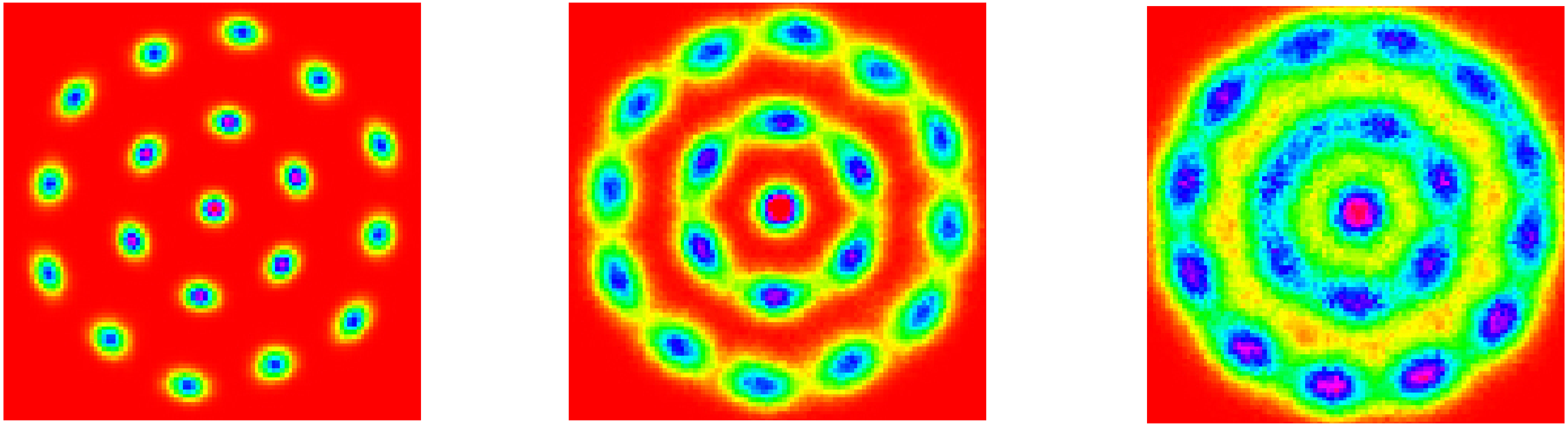




Trapped ions

Mesoscopic Coulomb crystal („artificial atom“*)

compression →



Density increase → quantum („cold“) melting of „crystal“, despite increase of coupling parameter Gamma! Why?

$$\hat{H} = -\sum_{i=1}^{N} \frac{\hbar^2 \nabla_i^2}{2m_i^*} + \sum_{i=1}^{N} \frac{m_i^* \omega_0^2 r_i^2}{2} + \sum_{i<j}^{N} \frac{e^2}{\epsilon_b |\mathbf{r}_i - \mathbf{r}_j|}$$

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*R.C. Ashoori, Nature **379**, 413 (1996)

*A.Filinov, MB, Yu. Lozovik, PRL **86**, 3851 (2001)*

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

Correlations of quantum plasmas

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

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

Quantum degeneracy

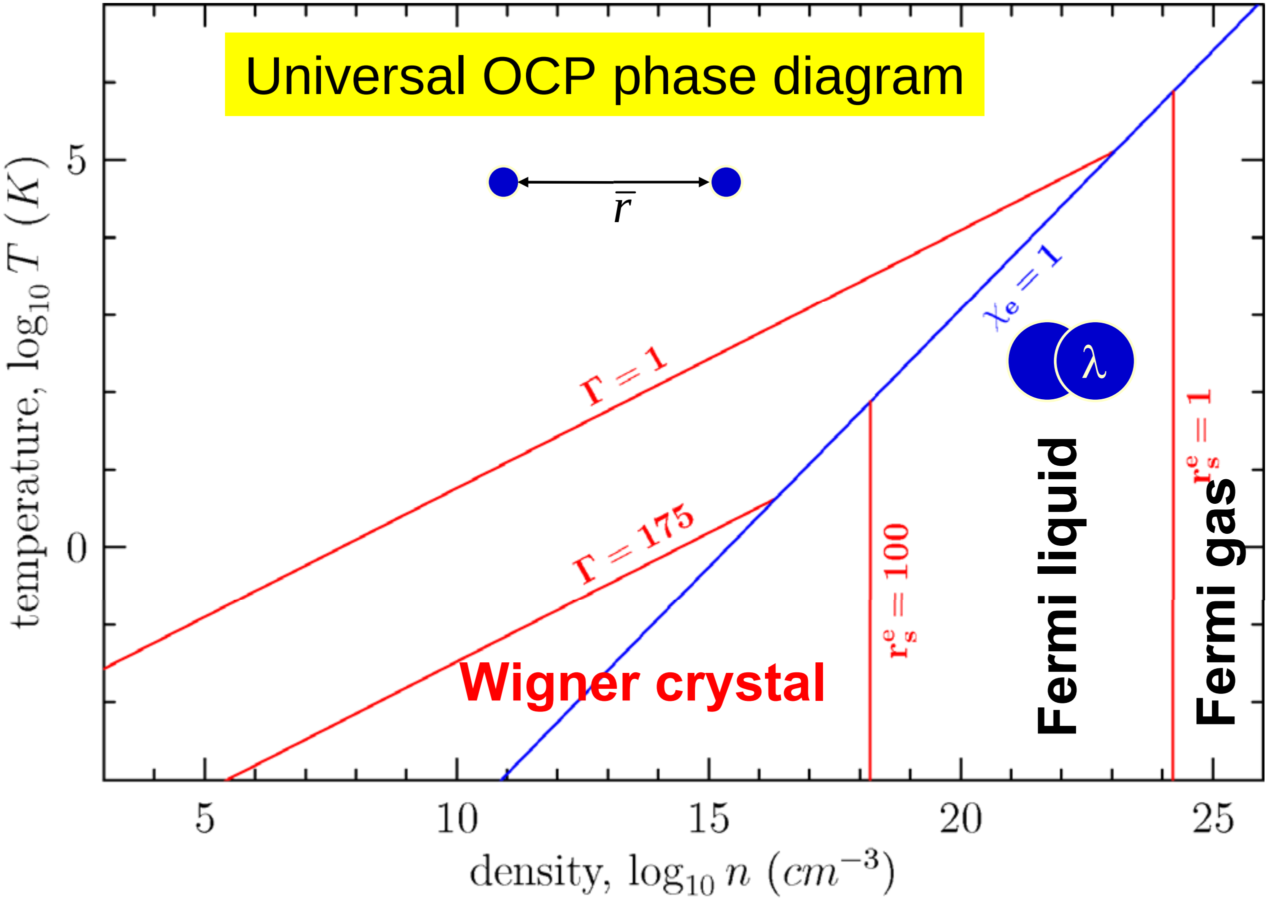
$\chi = n\lambda^3$

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



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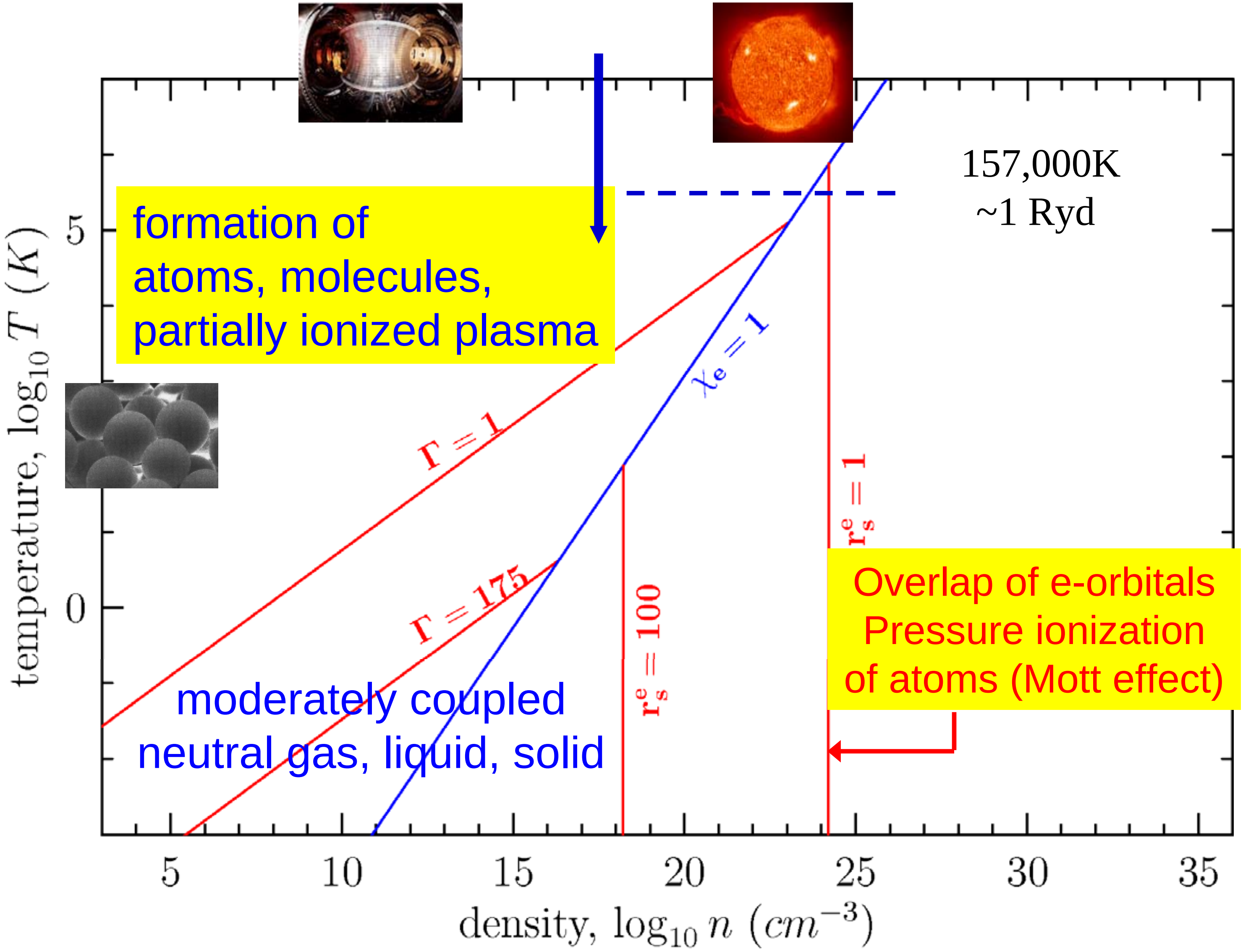
     - photoionization

3. **Outlook:** Multiscale simulations of dense plasmas

Partially ionized 2-comp. plasma

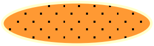


formation of
atoms, molecules,
partially ionized plasma

157,000K
~1 Ryd

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

moderately coupled
neutral gas, liquid, solid



Ultra-dense fully ionized two-component plasma

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

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

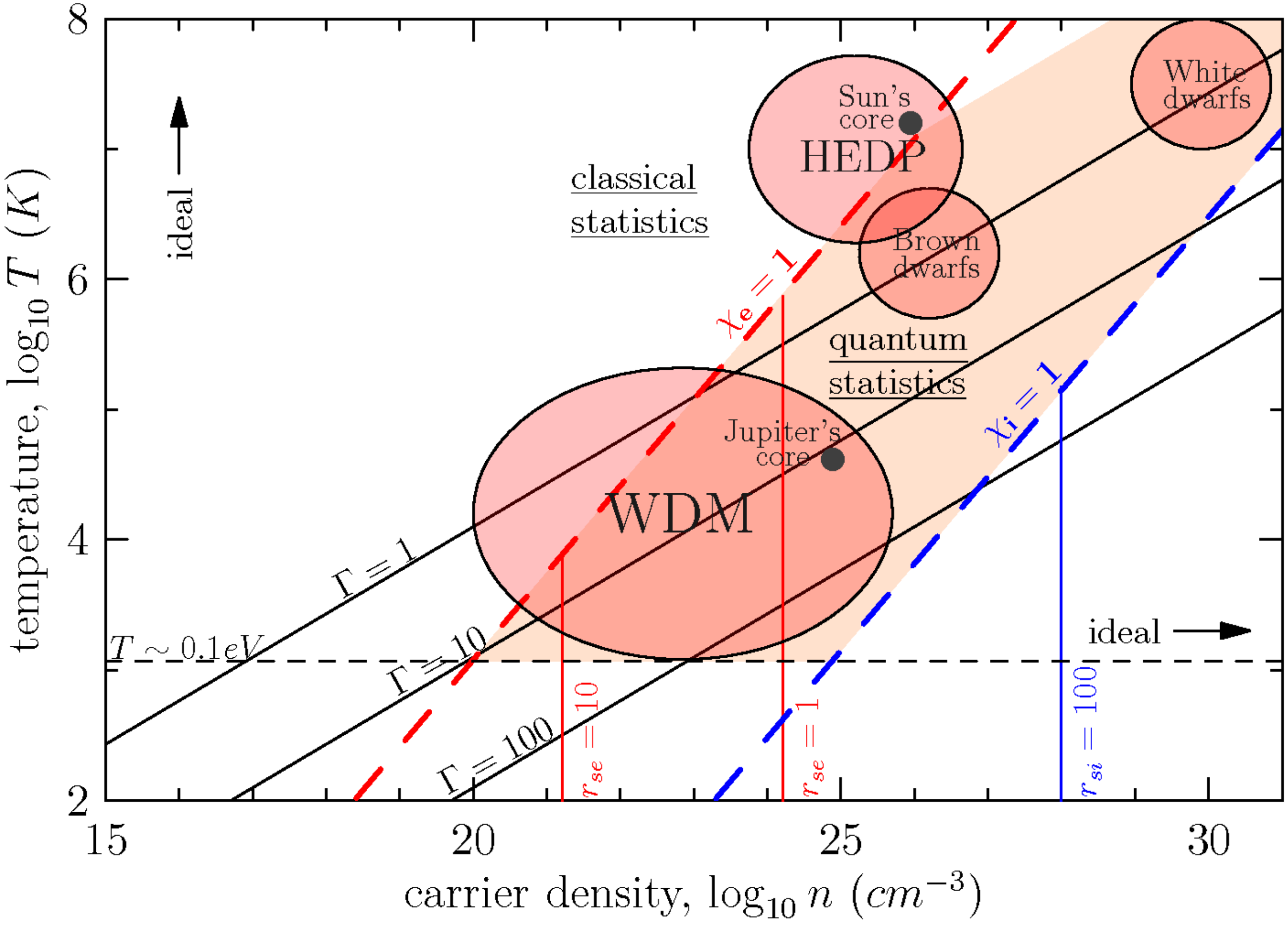
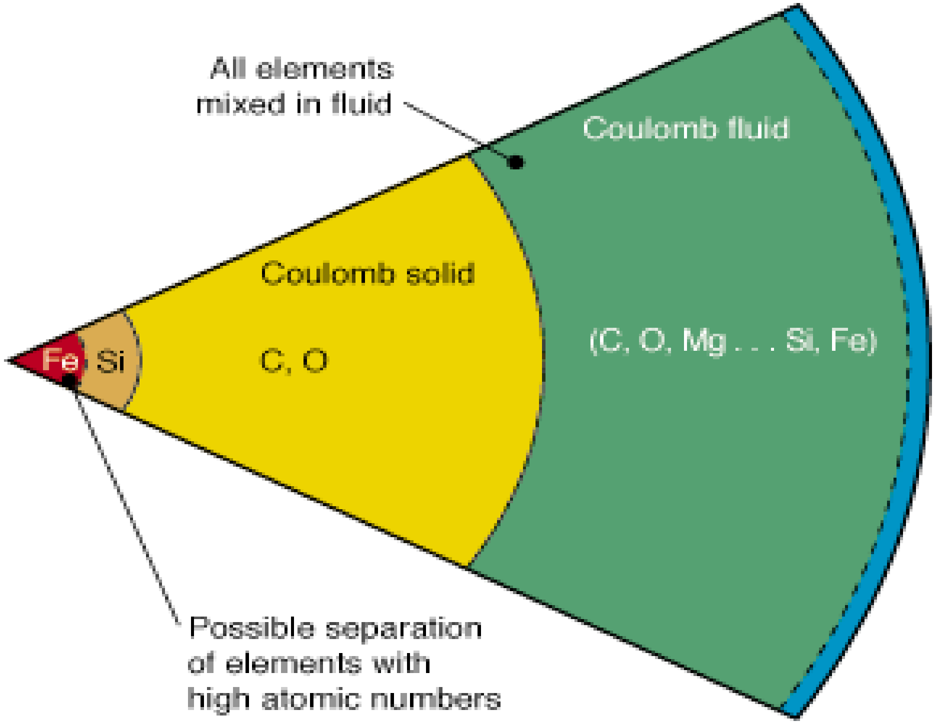


figure:
Hydrogen

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

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

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.

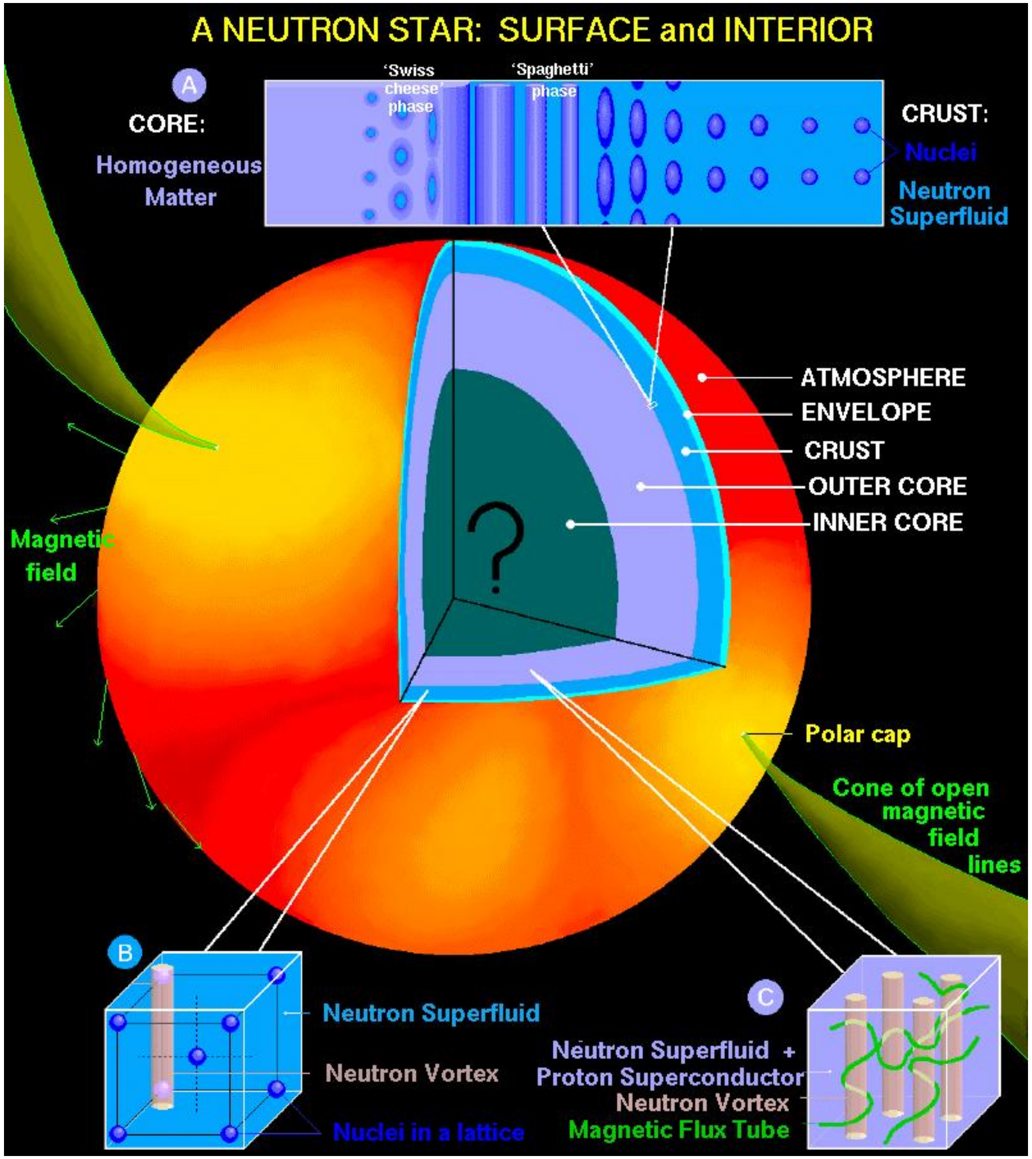
D. Schneider, LLNL

Size ~ our Earth
Mass ~ our Sun
→density:

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

- classical fluid and crystal (**carbon, oxygen nuclei**) in „**quantum** sea“ of **nearly ideal electrons**
- Many observations

Neutron star



Crust: crystal and quantum fluid of Fe-nuclei

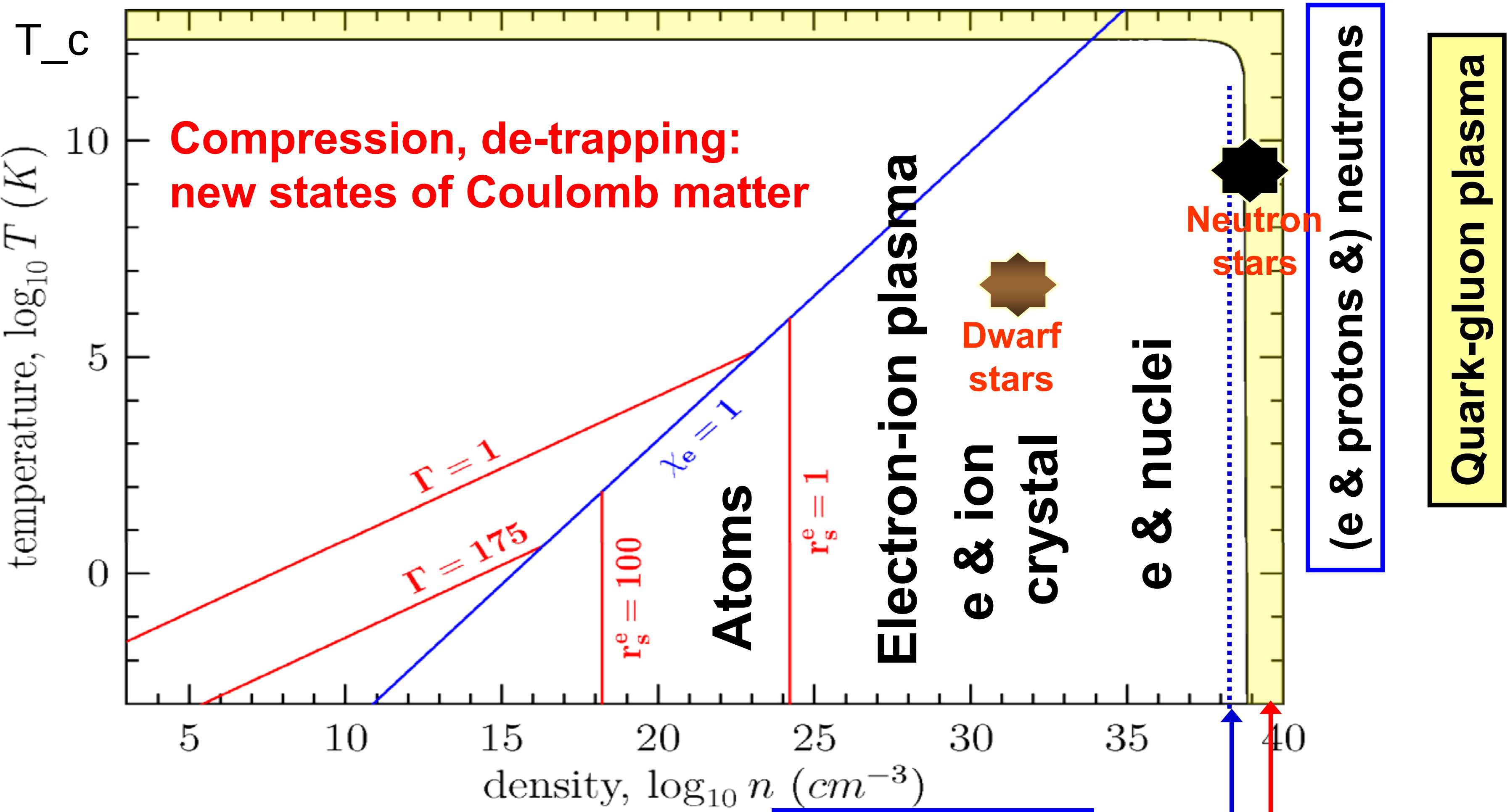
in „quantum sea“ of electrons

Radius ~ 10km
Mass ~ our Sun

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

Source: Coleman, UMD

From atomic nuclei to quarks



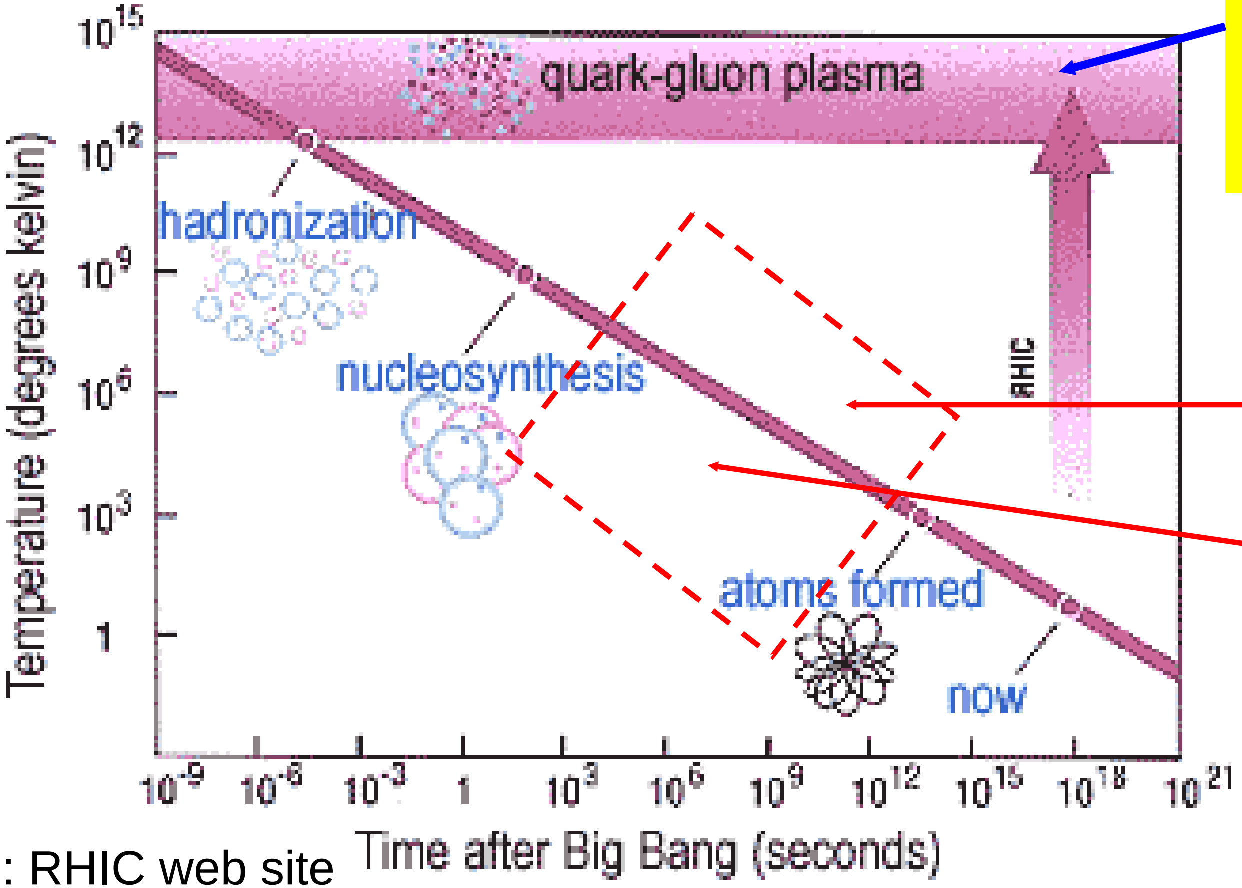
$$1\,fm = 10^{-13}\,cm$$

$$T_C = 175\,MeV$$

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

deconfinement $(5 \ldots 10)\rho_N$

Big bang: trapping of charged matter



Plasma with color Coulomb interaction, moderately coupled*

partially ionized plasma, ion recombination

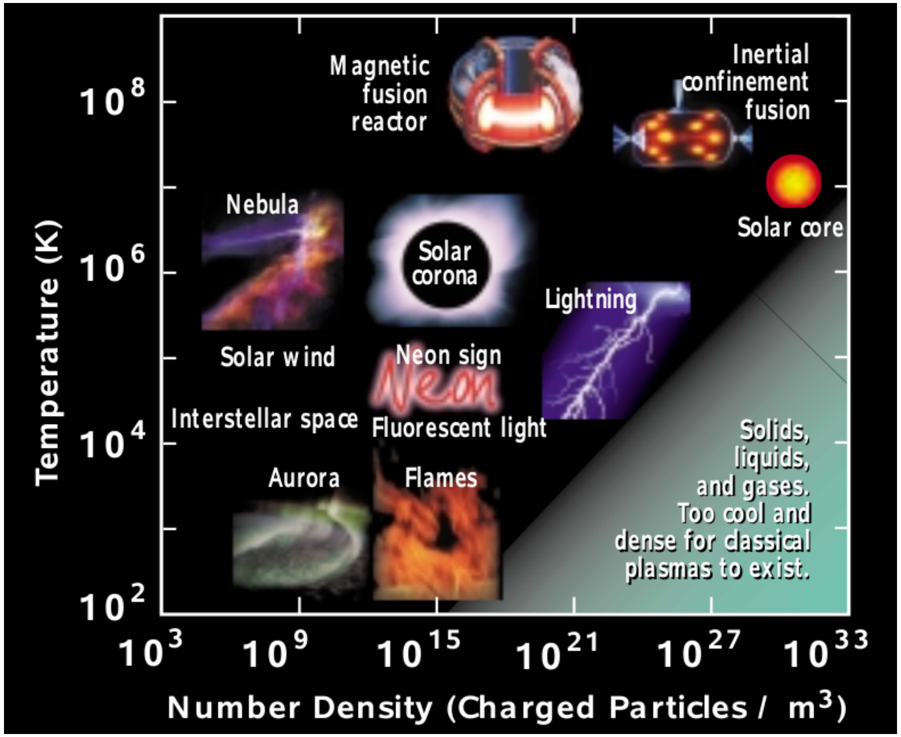
liquid or crystal of nuclei, ions

Source: RHIC web site

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

**V. Filinov, MB, Y.B. Ivanov, P.R. Levashov, and V.E. Fortov,*
Contrib. Plasma Phys. ***49****, 536 (2009) and* ***51****, 322 (2011); Phys. Particles and Nuclei Lett. (2011)*

Summary 1: „white corner“



Dense Coulomb systems

- Universal plasma properties
  (scaling from one plasma to another)
- Exciting forms of matter
- Fundamental questions:
  Early universe,
  dense astrophysical objects

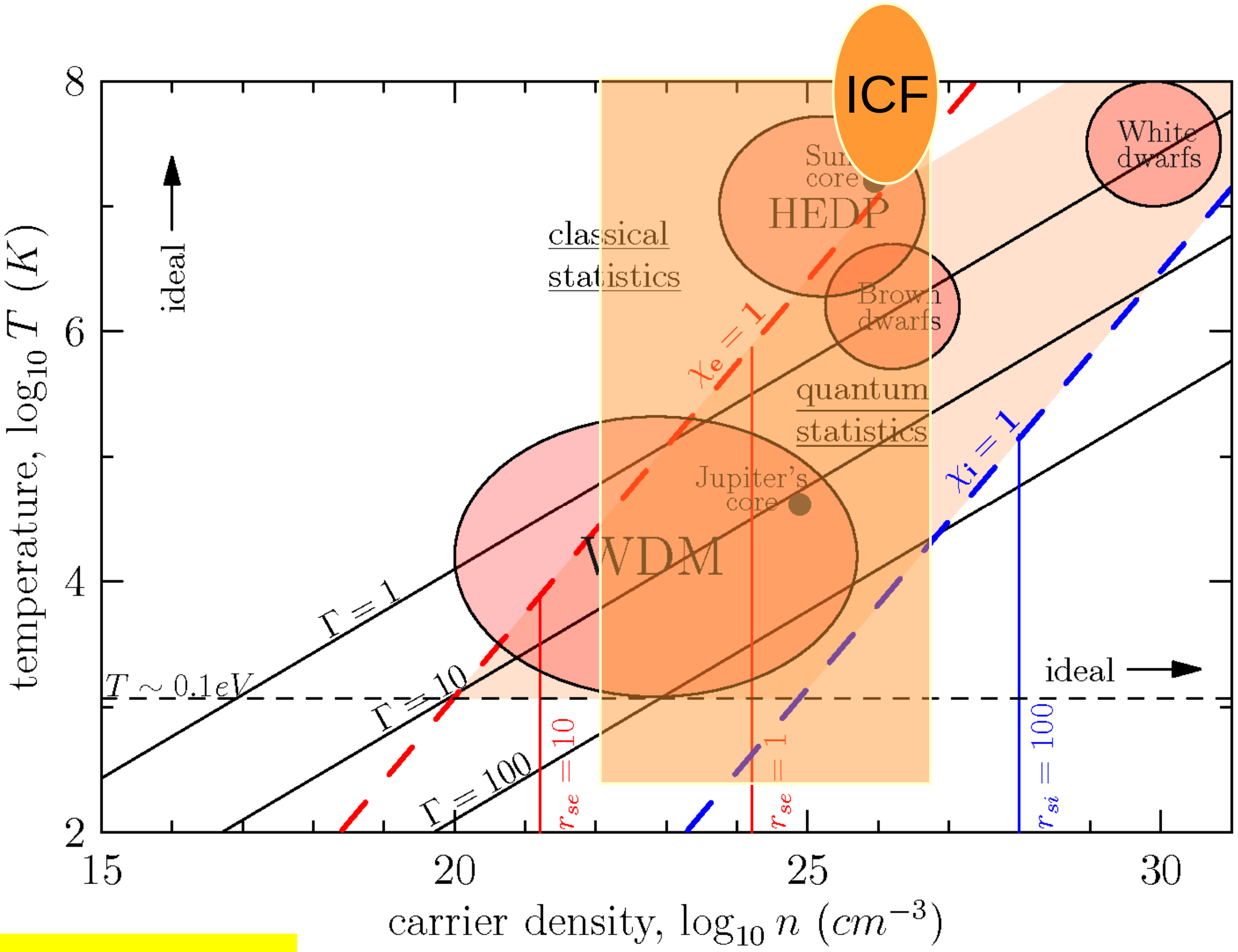
Realization in laboratory experiments?
Technological applications?
Theoretical plasma physics concepts?

Dense plasmas in the laboratory

Shock compression
Z-pinch

Lasers: Omega,
Vulcan, Jupiter…
NIF (LLNL)
ELI (Europe)
…

Ion beams:
(NDCX_II, FAIR…)

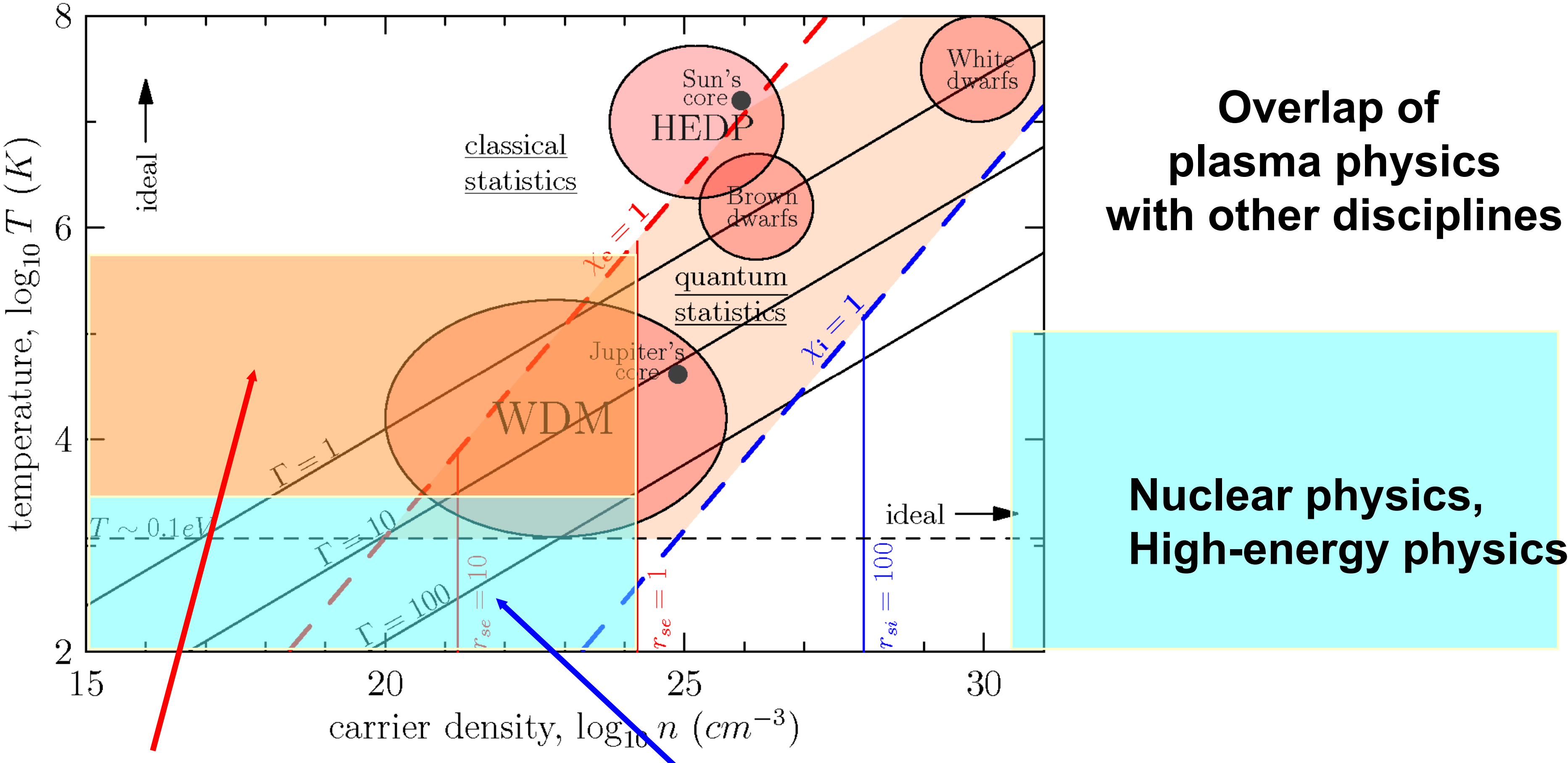


Tremendeous progress in the next 10 years!

ICF: Inertial confinement fusion

Contents

Theoretical concepts for dense plasmas



Overlap of plasma physics with other disciplines

Nuclear physics, High-energy physics

Atomic physics

- atoms, molecules
- ionization/recombination

Solid state physics

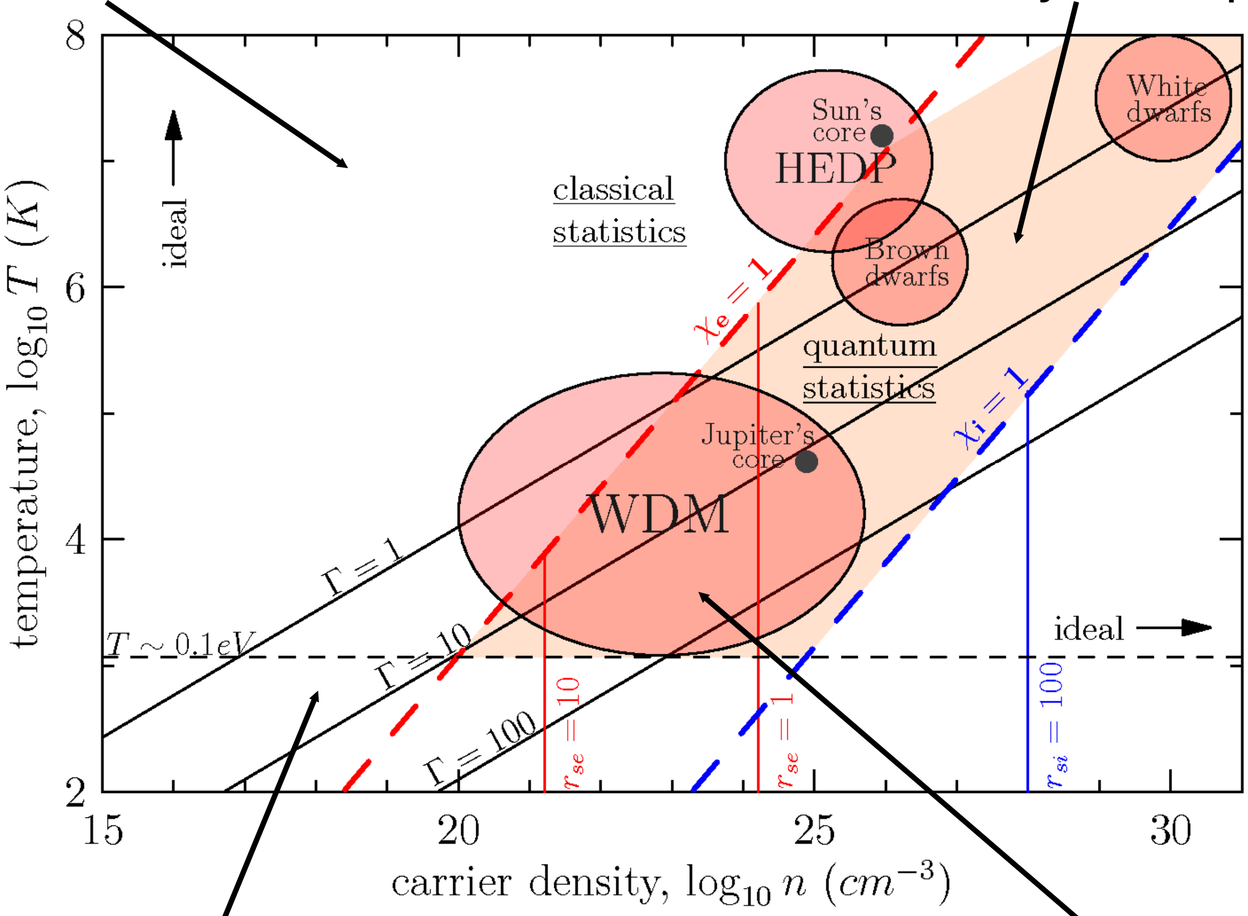
- molecular/atomic crystal
- targets for laser ionization

M. Bonitz, „Progress in correlated Coulomb systems“, Dornburg, 1.6. 2011

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

II. Strongly correlated classical OCP

1. **Spatially confined complex plasmas: plasma liquids, crystals („Yukawa balls“)**, close collaboration with experiments

→ **first-principle MC and MD simulations**:

- shell structure, metastable states
- determination of effective pair interaction
- plasma excitations, normal modes
- melting behavior, crystallization dynamics
- laser excitation and heating of plasma

Selected publications:

*Ludwig et al., PRE **71**, 046403 (2005)*
*MB et al., PRL **96**, 075001 (2006)*
*Block et al., Plasma Phys. Control. Fusion **49**, B109 (2007)*
*Böning et al., PRL **100**, 113401 (2008)*
*Henning et al. PRL **101**, 045002 (2008)*
*Block et al., Phys. Plasmas **15**, 040701 (2008)*
*Käding et al., Phys. Plasmas **15**, 073710 (2008)*
*Baumgartner et al., New J. Phys. **10**, 093019 (2008)*
*Kählert, MB, PRL **104**, 015001 (2010)*
*MB et al., Rep. Prog. Phys. **73**, 066501 (2010)*

II. Strongly correlated classical OCP

2. Spatially confined complex plasmas: plasma liquids and crystals, „Yukawa balls“,

→ **Analytical theory**: benchmark tests with experiments and simulations

- statistical theory of metastable states
- average density profile (mean field plus LDA)
- shell structure (HNC plus bridge terms)
- collective excitations, normal modes

Selected publications:	*Henning et al., PRE **74**, 056403 (2006)*
	*Henning et al., PRE **76**, 036404 (2007)*
	*Kählert et al., PRE **78**, 036408 (2008)*
	*Wrighton et al., PRE **80**, 066405 (2009)*
	*Kählert, MB., PRE **82**, 036407 (2010)*
	*Kählert, MB, PRE **83**, 056401 (2011)*

II. Strongly correlated classical OCP

3. Strongly coupled macroscopic 2D and 3D plasmas

→ **first-principle MD and Langevin simulations:**

- transport properties: diffusion, anomalous diffusion
- normal mode spectra, dynamic structure factor
- strongly coupled plasma in strong magnetic field
- transport, diffusion in strong B-field

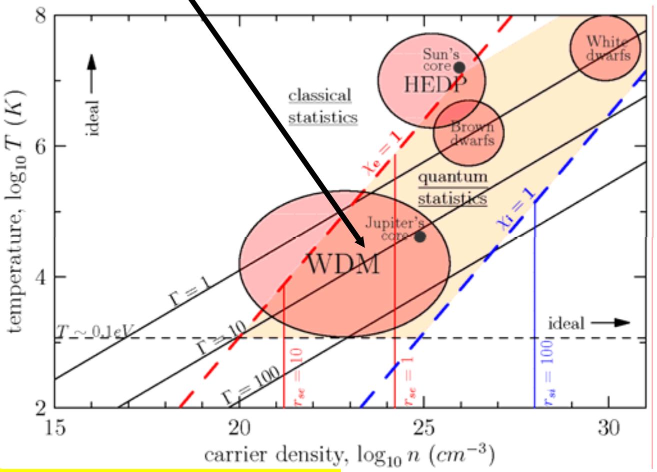
Basic understanding of correlations in classical equilibrium plasmas

Selected publications:

*Ott et al., PRE **78**, 026409 (2008)*
*Ott et al., PRL **103**, 099501 (2009)*
*Ott, MB, PRL **103**, 195001 (2009)*
*Ott, MB, Contrib. Plasma Phys. **49**, 760 (2009)*
*MB et al., PRL **105**, 055002 (2010)*
*Ott et al., PRE **83**, 046503 (2011)*
Ott et al., IEEE-TPS in press (2011)

III. Partially ionized dense plasma

Examples: - laser plasmas
- ion beam compressed plasmas
- ionization of solid targets
- plasmas containing highly charged ions

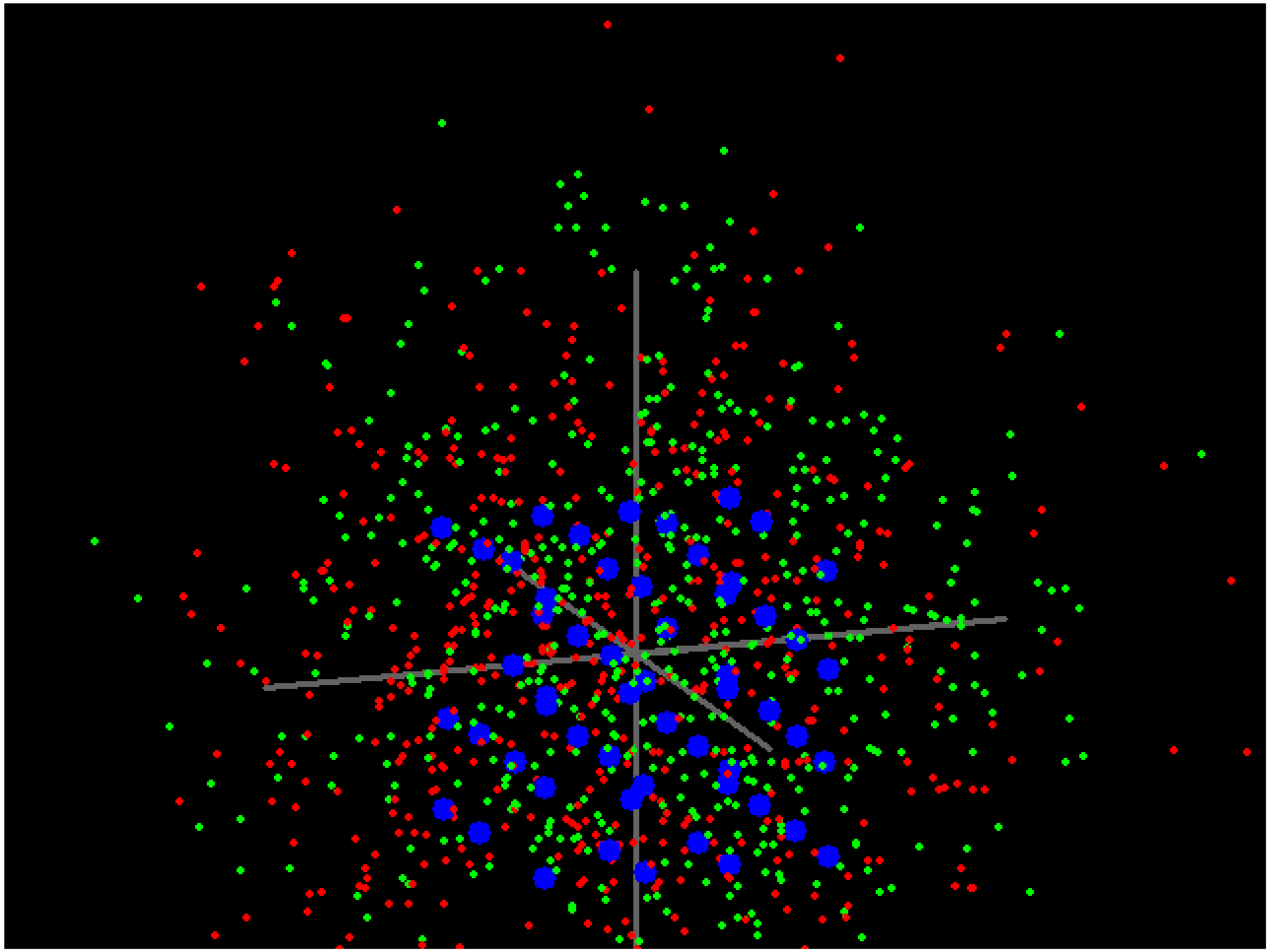


First-principle path integral Monte Carlo simulations*: include
- strong Coulomb correlations
- quantum and spin effects of electrons
- Rigorous treatment of bound state formation (no artificial subdivision in free and bound particles)

*V. Filinov, MB, V. Fortov et al., Plasma Phys. Control. Fusion **43**, 743 (2001);
JETP Letters **72**, 361 (2000), JETP Letters **74**, 384 (2001);
MB, V. Filinov et al., PRL **95**, 235006 (2005), JPA **39**, 4717 (2006), PRE **75**, 036401 (2007)

Proton crystallization in dense Hydrogen

$T = 10{,}000$ K, $n = 3 \cdot 10^{25}$ cm^{-3}, $\rho = 50.2$ g/cm^3



● - proton

● - electron ↑

● - electron ↓

1st-principle Path integral Monte Carlo simulation

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

Quantum *TCP* Coulomb crystals

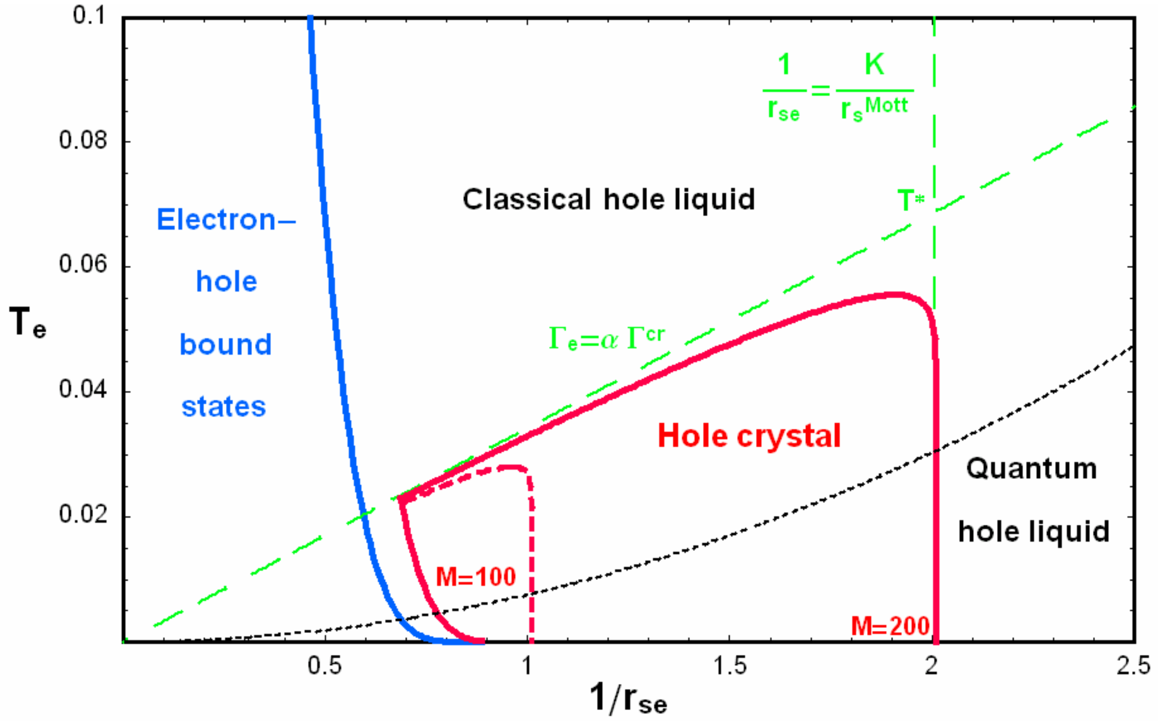
mass, charge and temperature asymmetry $M = \frac{m_h}{m_e},\ Z = \frac{q_h}{q_e},\ \Theta = \frac{T_e}{T_h}$

Analytical Results:

- Finite density range: $n^{Mott} \le n_e \le \left(\frac{M+1}{M^{cr}+1}\right)^3 n^{Mott}$
- Critical mass ratio: $M \ge M^{cr}(T_e) = \frac{r_s^{cr}}{Z^{4/3}\, r_s^{Mott}(T_e)} - 1$
- Maximum temperature: $\frac{k_B T_e}{E_B} = 4\frac{Z^2\,\Theta(M+1)}{\Gamma^{cr}\, r_s^{cr}}$

Phase diagram of ion (hole) crystal

$$K = \frac{M+1}{M^{cr}+1}$$



$$\alpha = \frac{1}{Z^2 \Theta}$$

$$T_e = \frac{3}{2} \frac{kT}{E_R}$$

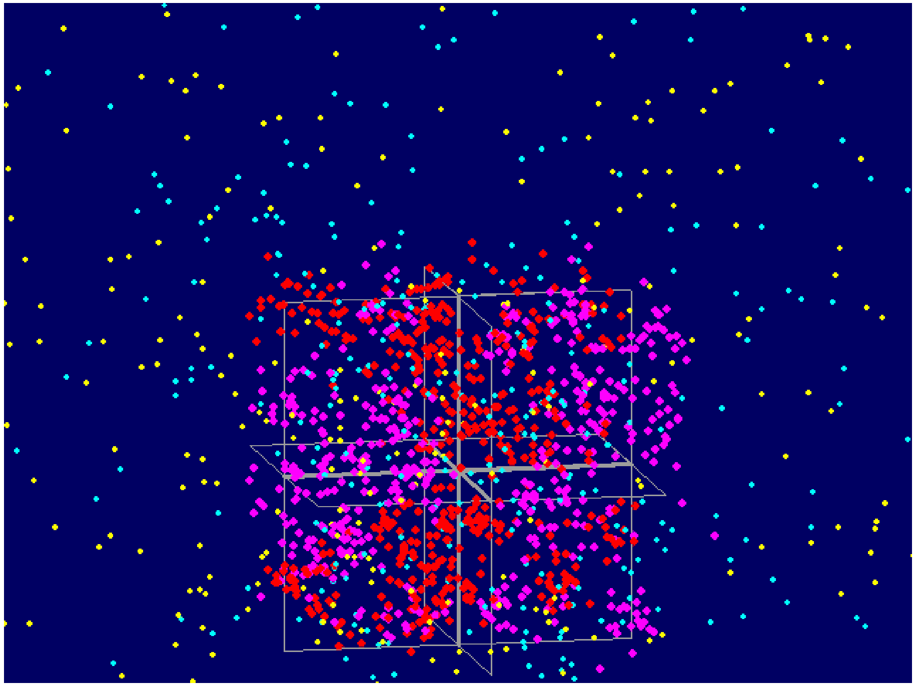
$$\frac{1}{r_{se}} = \frac{a_B}{\bar{r}_e} \propto n^{1/3}$$

- for Z=1 (e.g. electron-hole plasma): $M^{cr} = 83\,(3D),\ 60\,(2D)$

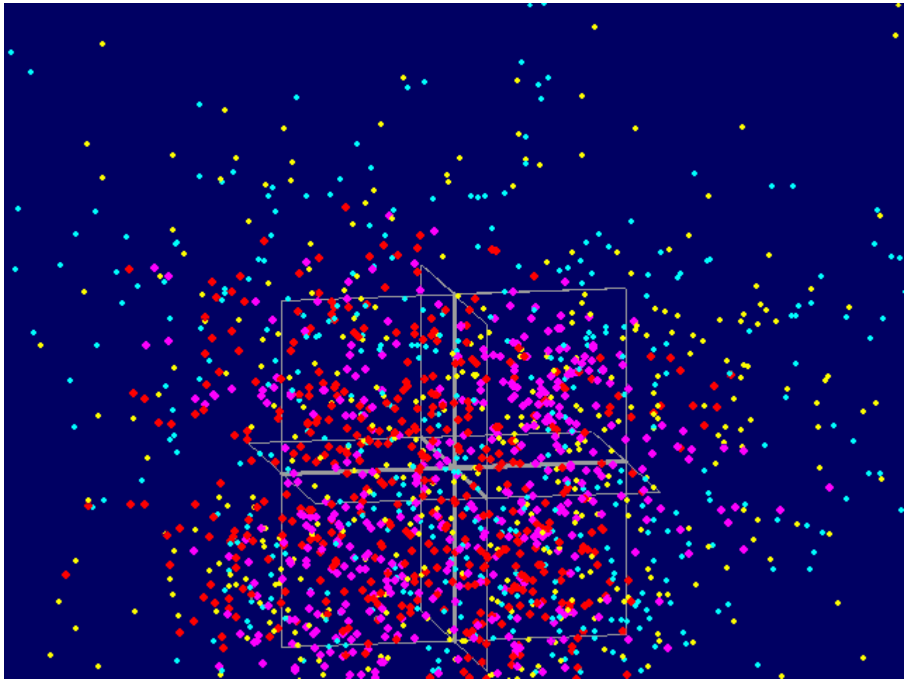
Bonitz, Filinov, Fortov, Levashov, and Fehske, Phys. Rev. Lett. ***95,*** *235006 (2005)*

Quantum melting of ion crystal

Reduce ion mass to M=25 and M=5
to simulate density increase



Ion liquid



Ion gas

$$\chi = n\Lambda^3 \sim \frac{n}{m^{3/2}}$$

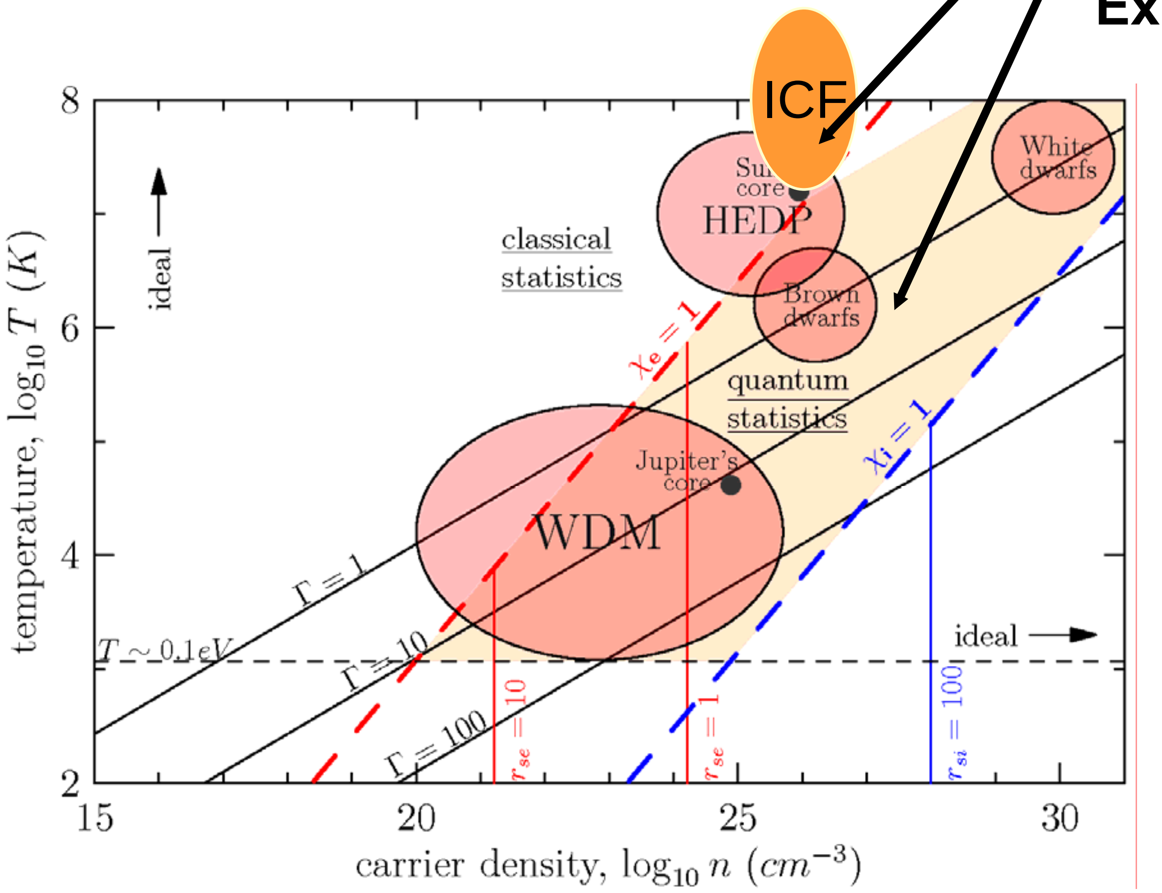
TCP Coulomb crystals

	$n_{\min}[cm^{-3}]$	$n_{\max}[cm^{-3}]$	$T_{\max}[K]$
C^{6+} Ions (white dwarfs)	$2 \cdot 10^{26}$	$3.6 \cdot 10^{33}$	10^{9}
Protons (hydrogen)	$5 \cdot 10^{24}$	$1.0 \cdot 10^{28}$	66,000

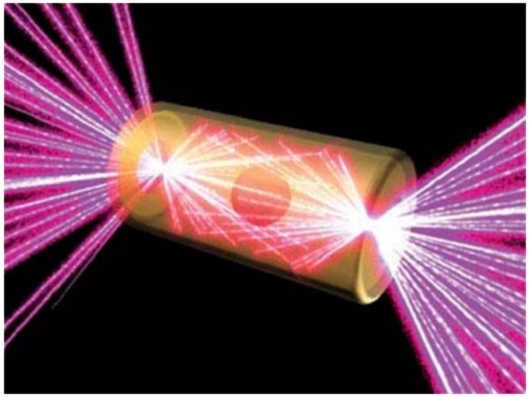
Laser or ion beam compression experiments?

Bonitz, Filinov, Fortov, Levashov, and Fehske, Phys. Rev. Lett. ***95,*** *235006 (2005)*

IV. Strongly correlated classical ions & weakly coupled quantum electrons



Examples: - laser compression
- inertial confinement fusion (ICF):



Source: NIF web page, LLNL

$$\rho \propto 10^3 gcm^{-3},\ T = 10^3 ... 10^5 eV$$

IV. Strongly correlated classical ions & weakly coupled quantum electrons

Thermodynamics: quantum Monte Carlo, quantum MD

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)

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)*

Contents

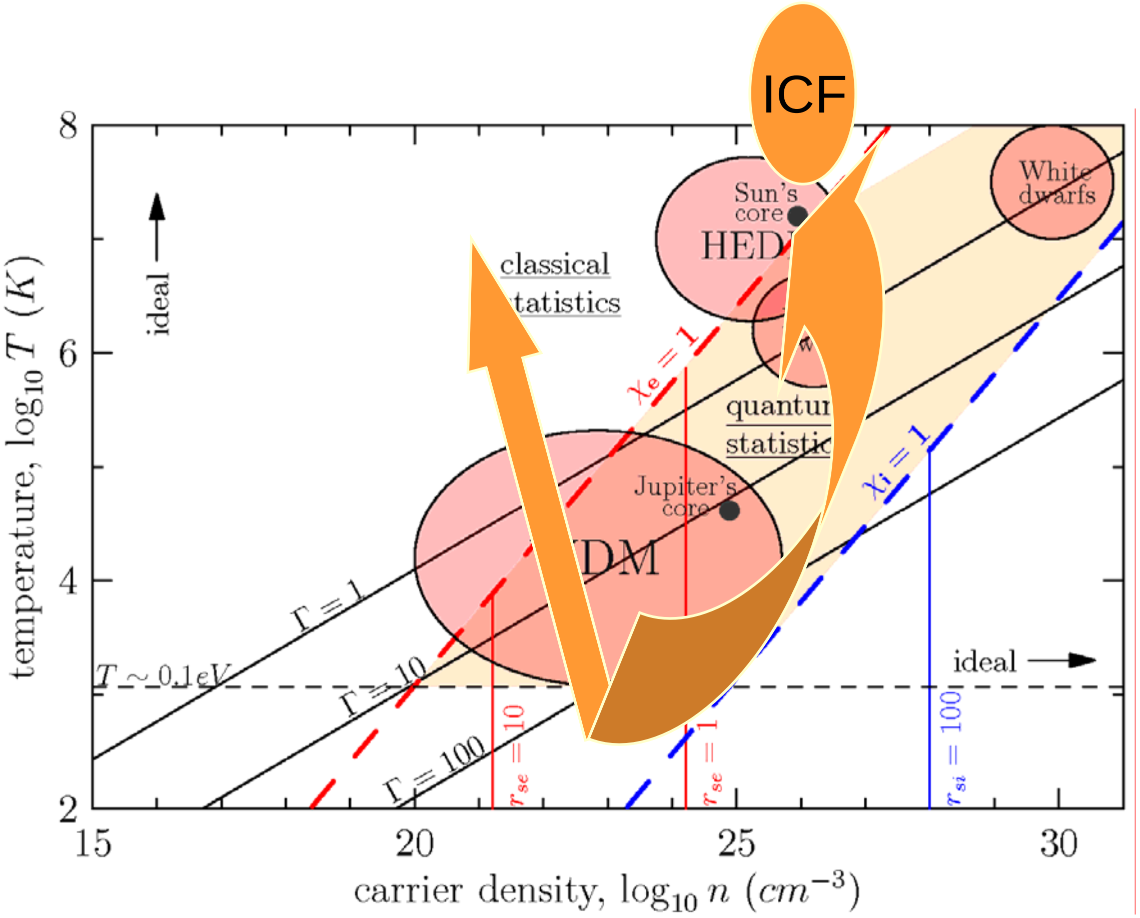
1. **Overview: strongly correlated plasmas**
   1.1 One-component plasma (OCP) in TD equilibrium
   1.2 Two-component plasma: partial ionization, compact stars, dense laboratory plasmas

2. **Theory of strongly correlated plasmas**
   2.1 First-principle equilibrium simulations
   2.2 Dense plasmas in nonequilibrium:
      - laser plasmas
      - photoionization

3. **Outlook:** Multiscale simulations of dense plasmas

Dense plasmas in nonequilibrium

Examples: 1. interaction of strong laser pulse with plasma
2. ionization of atoms, solid targets



excitation out
of equilibrium
and relaxation
→ kinetic theory

Dense plasmas in nonequilibrium

Challenge:

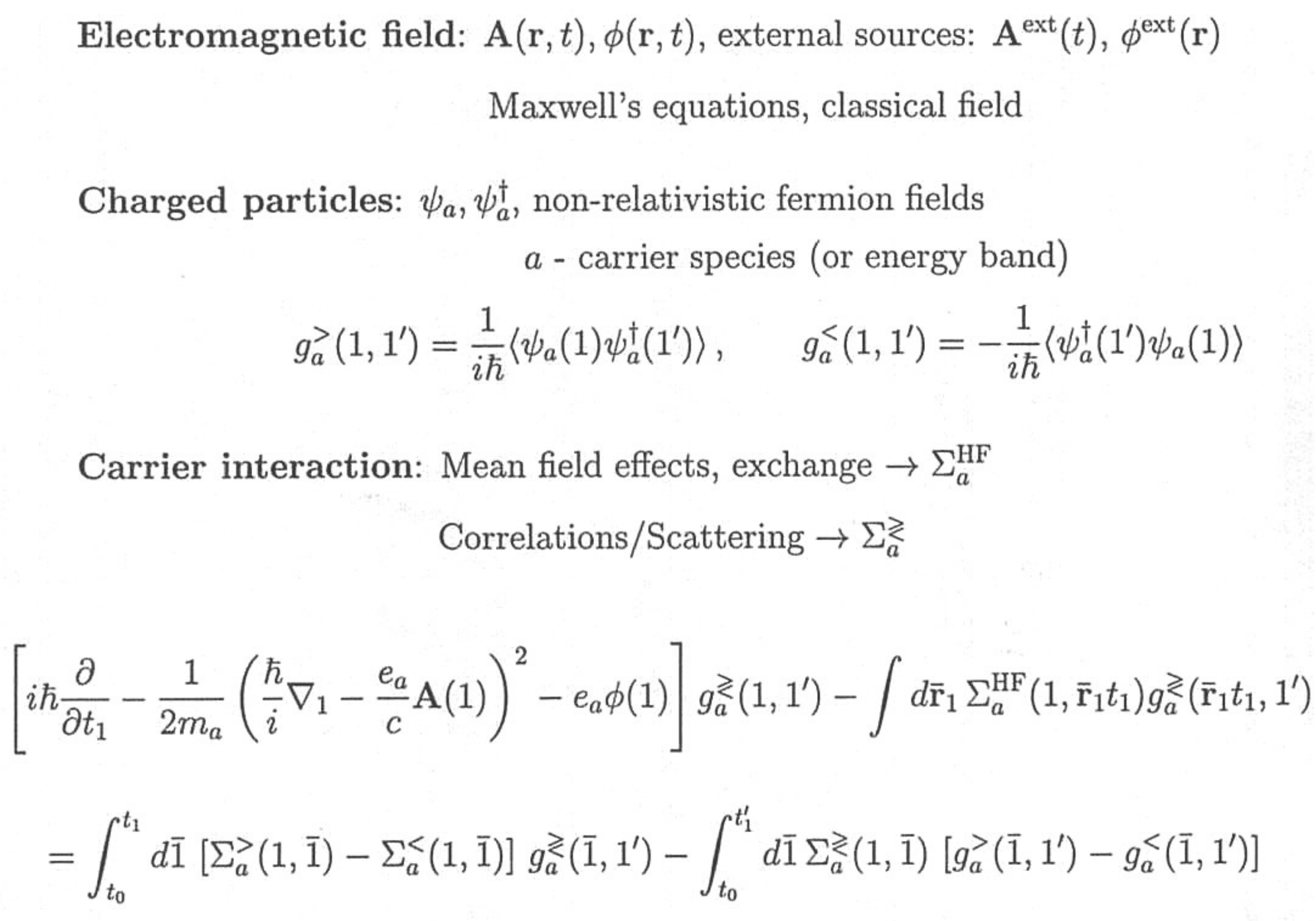
1. thermalization requires collisions (beyond mean field, PIC)
2. collisions are modified by strong field
3. collisions have finite duration, comparable with pulse width, period
   → nonlinear effects, photon absorption, harmonics generation
4. have to treat free and bound electrons (atoms), ionization
5. need to include quantum and spin effects of elctrons, atoms

→ Requires to go beyond standard Boltzmann-type equations
→ Development of generalized quantum kinetic theory:

- *M. Bonitz, „Quantum Kinetic Theory", Teubner, Stuttgart, Leipzig (1998*)
- extension to gauge-invariant theory of field-matter interaction:

D. Kremp T. Bornath, MB, and M. Schlanges, Phys. Rev. E ***60****, 4725 (1999)*
H. Haberland, MB, and D. Kremp, Phys. Rev. E ***64****, 026405 (2001)*

Quantum kinetic theory*



Electromagnetic field: $\mathbf{A}(\mathbf{r},t), \phi(\mathbf{r},t)$, external sources: $\mathbf{A}^{\rm ext}(t)$, $\phi^{\rm ext}(\mathbf{r})$

Maxwell's equations, classical field

Charged particles: $\psi_a, \psi_a^\dagger$, non-relativistic fermion fields

a - carrier species (or energy band)

$$g_a^>(1,1') = \frac{1}{i\hbar}\langle\psi_a(1)\psi_a^\dagger(1')\rangle\,, \qquad g_a^<(1,1') = -\frac{1}{i\hbar}\langle\psi_a^\dagger(1')\psi_a(1)\rangle$$

Carrier interaction: Mean field effects, exchange $\rightarrow \Sigma_a^{\rm HF}$

Correlations/Scattering $\rightarrow \Sigma_a^{\gtrless}$

$$\left[i\hbar\frac{\partial}{\partial t_1} - \frac{1}{2m_a}\left(\frac{\hbar}{i}\nabla_1 - \frac{e_a}{c}\mathbf{A}(1)\right)^2 - e_a\phi(1)\right] g_a^{\gtrless}(1,1') - \int d\bar{\mathbf{r}}_1\,\Sigma_a^{\rm HF}(1,\bar{\mathbf{r}}_1 t_1)\,g_a^{\gtrless}(\bar{\mathbf{r}}_1 t_1, 1')$$

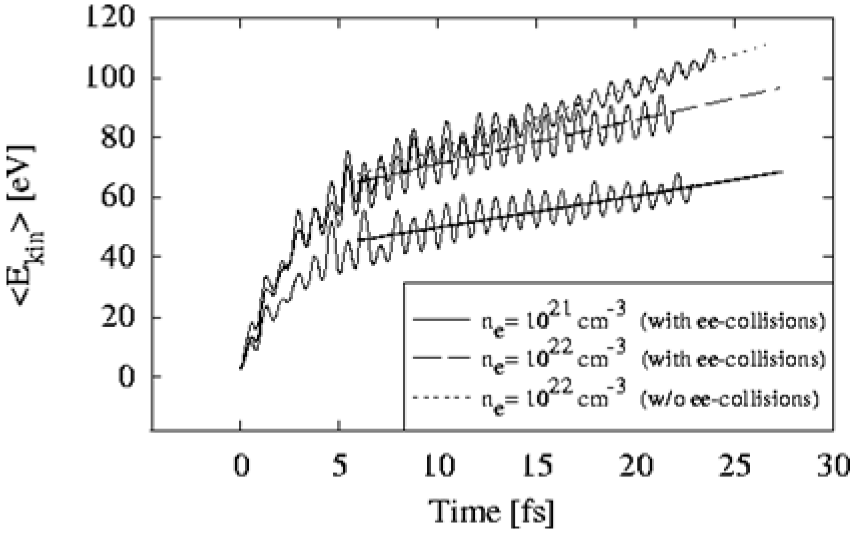
$$= \int_{t_0}^{t_1} d\bar{1}\,[\Sigma_a^>(1,\bar{1}) - \Sigma_a^<(1,\bar{1})]\; g_a^{\gtrless}(\bar{1},1') - \int_{t_0}^{t_1'} d\bar{1}\,\Sigma_a^{\gtrless}(1,\bar{1})\;[g_a^>(\bar{1},1') - g_a^<(\bar{1},1')]$$

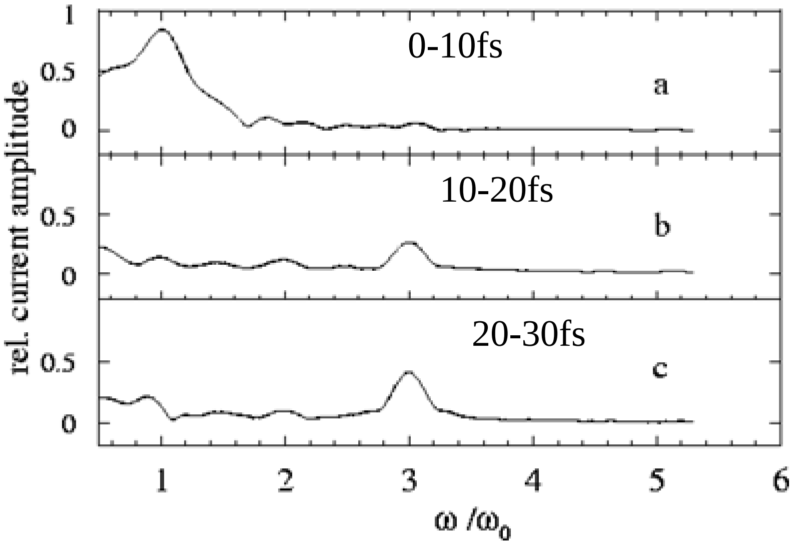
•M. Bonitz, „Quantum Kinetic Theory“, Teubner 1998
„Introduction to Computational Methods for Many-Body Physics“, MB and D. Semkat (eds.), Rinton 2006
*N.H. Kwong, and MB, Phys. Rev. Lett. **84**, 1768 (2000)*

Collisional heating of laser plasmas

Plasma heating due to e-i collisions in strong field (inverse bremsstrahlung)

Nonlinear current spectrum: femtosecond time resolution





Fully ionized hydrogen plasma, monochromatic laser pulse $I = 10^{14} Wcm^{-2}$

Also developed: quantum kinetic theory for partially ionized plasma*

*H. Haberland, MB, and D. Kremp, Phys. Rev. E **64**, 026405 (2001)*

**Semkat et al., J. Phys. Conf. Ser. 2005 and 2006*

Dynamics of strong field ionization

Examples: - interaction of strong uv…x-ray pulse with atoms, molecules:
e.g. laser harmonics or FEL radiation*
- inner shell ionization, „hollow atoms“, Auger processes
- many-electron dynamics on (sub-)femtosecond scale

Theoretical approaches:

1.) time-dependent Schrödinger equation (TDSE, TDCI)
2.) time-dependent Hartree-Fock (TDHF)
3.) nonequilibrium Green‘s functions (NEGF), quantum kinetic theory
4.) Multiconfiguration time-dependent Hartree-Fock (MCTDHF)

Problems: - 1. and 4.: exponential scaling with electron number
- 2. pure mean field, no e-e correlations
- 3. includes correlations, but memory-expensive
→ required: combinations of methods, hybrid approaches

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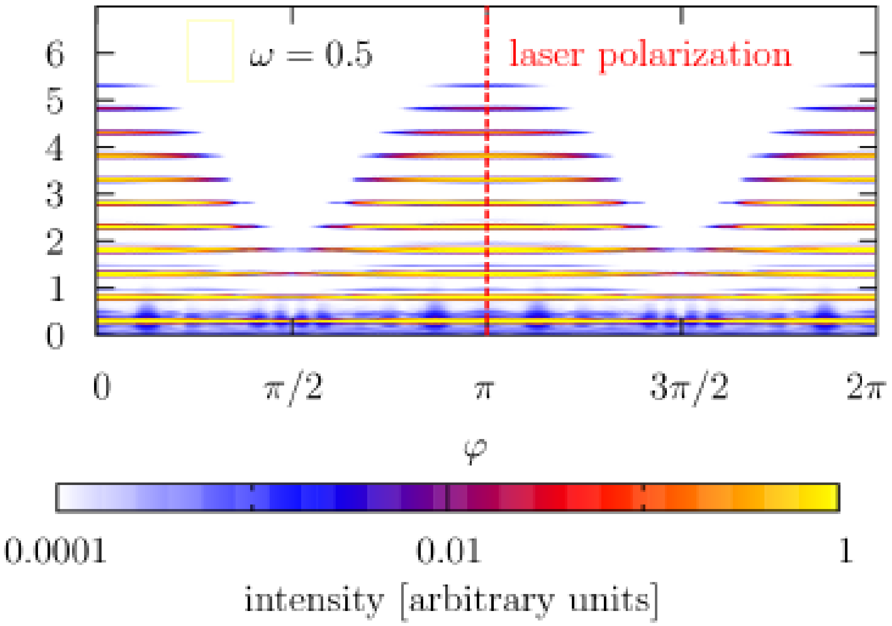
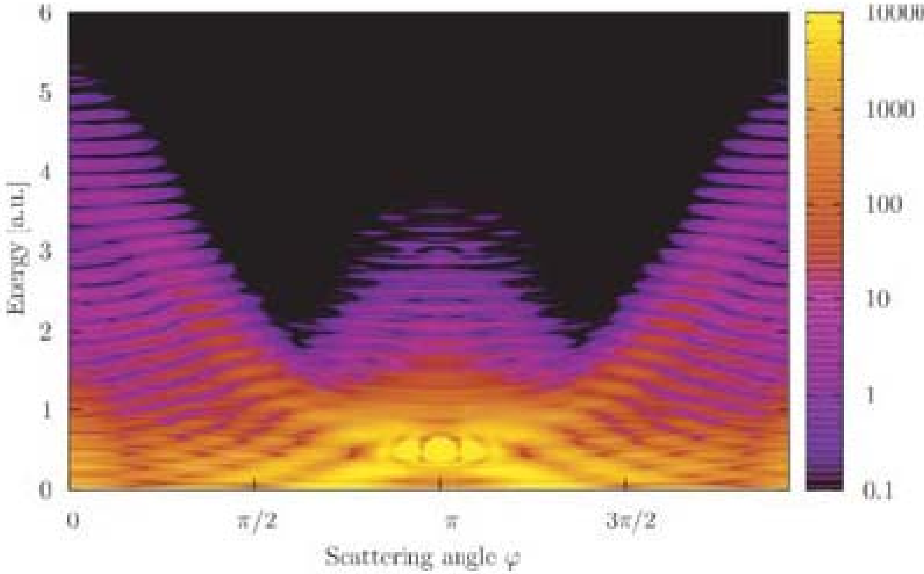
*Collaboration with M. Drescher (DESY), BMBF-Verbund „Flash“

Matter in strong UV field: solution of TDSE

1. **Photoionization**, energy spectrum in strong field, om=0.5, E_0=0.1



3. Electron spectrum: **e-i scattering** in strong field, om=0.2, E_0=0.2, k_0=1



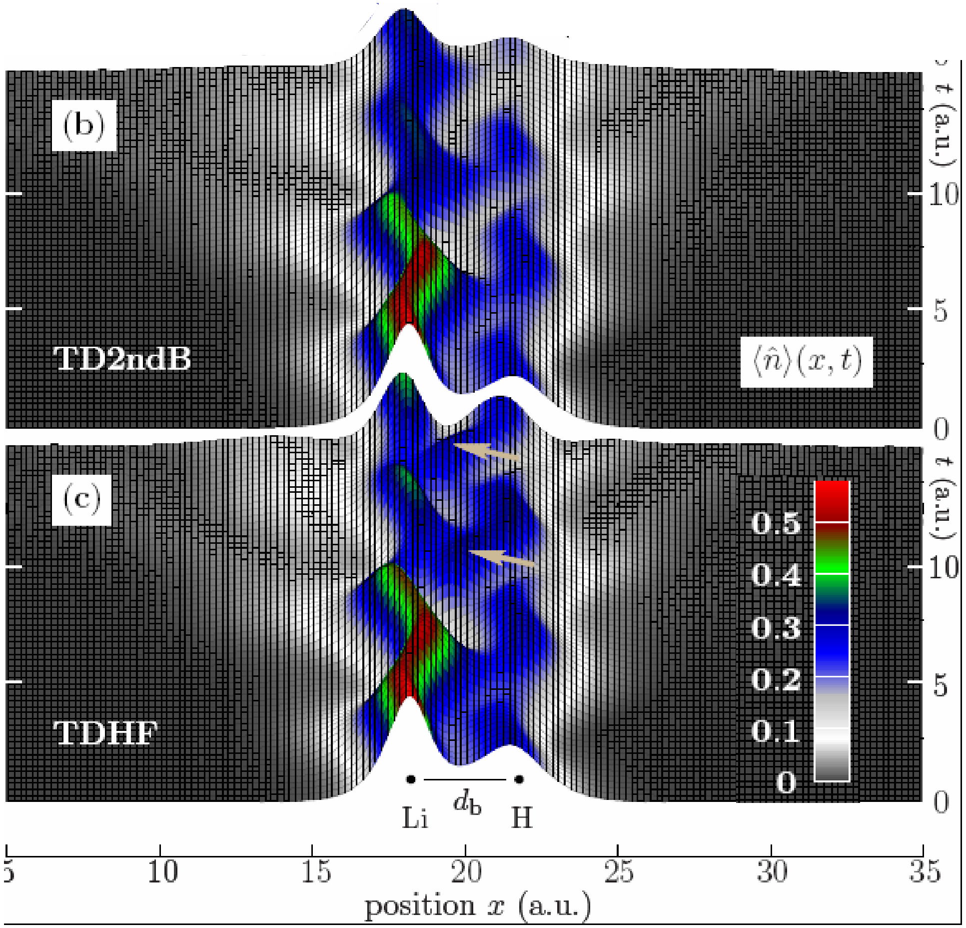
atomic units

2. t-resolved **photoemission of solids***

Angle and energy resolved spectrum

S. Bauch, and MB, Phys. Rev. A ***78****, 043403 (2008); Contrib. Plasma Phys.* ***49****, 558 (2009)*
S. Bauch et al., Europ. Phys. Lett. ***91****, 53001 (2010)*
** E. Krasovskii, and MB, Phys. Rev. Lett.* ***99****, 247601 (2007); Phys. Rev. A* ***80****, 053421 (2009)*

Atoms and molecules in strong field



Attosecond dynamics of electron density (excitation, ionization)

4-electron molecule LiH
Short-pulse laser excitation

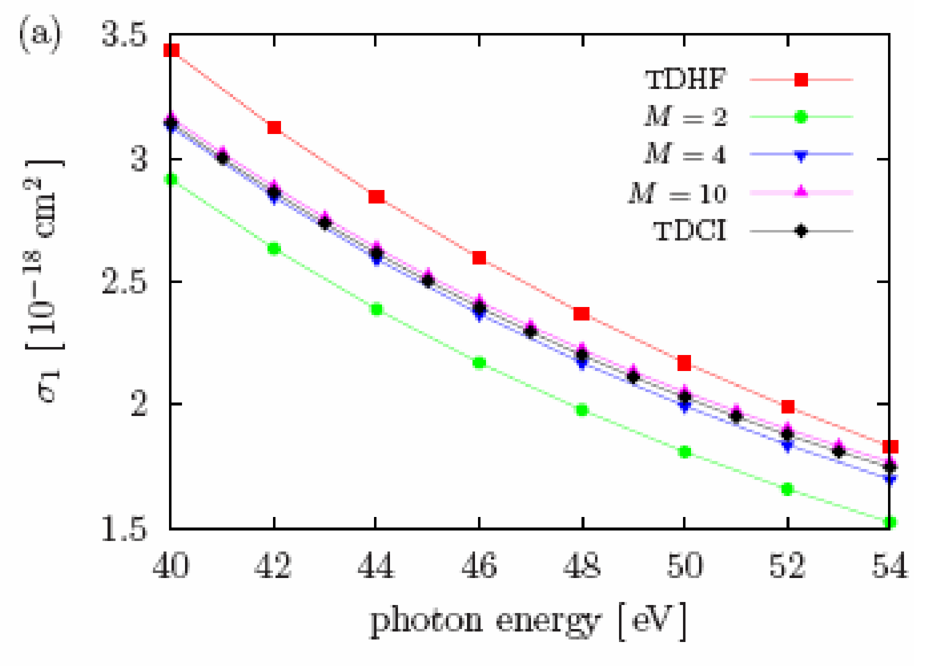
NEGF (b, with e-e correlations) vs. TDHF (c, no correlations)

Inhomogeneous system treated via FEDVR basis. 1d model

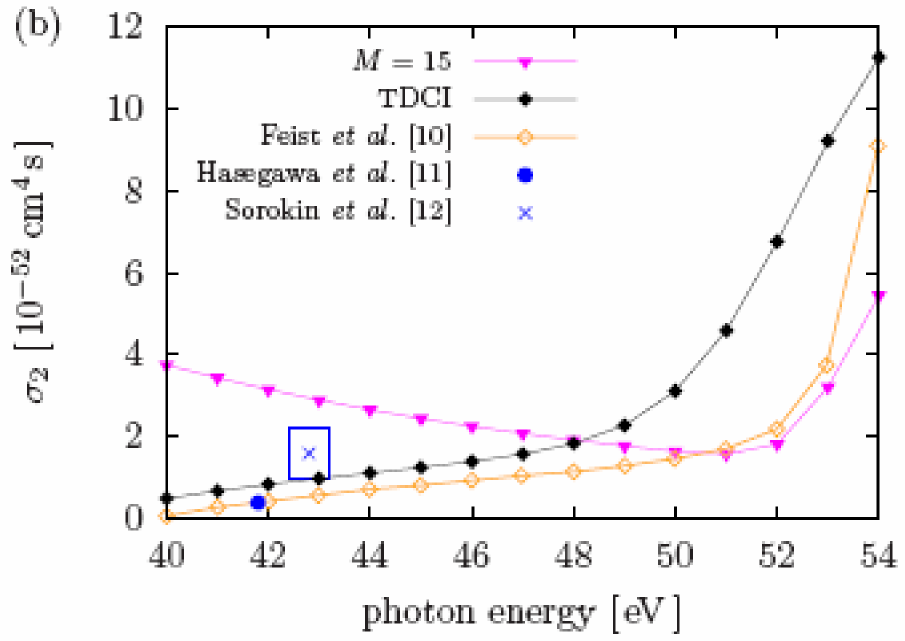
M. Bonitz et al., Contrib. Plasma Phys. ***50****, 54(2010)*
K. Balzer, S. Bauch, and MB, PRA ***81****, 022510 (2010)*
K. Balzer, S. Bauch, and MB, PRA ***82****, 033427 (2010)*

Two-photon ionization cross sections

Single ionization cross section



Double ionization cross section



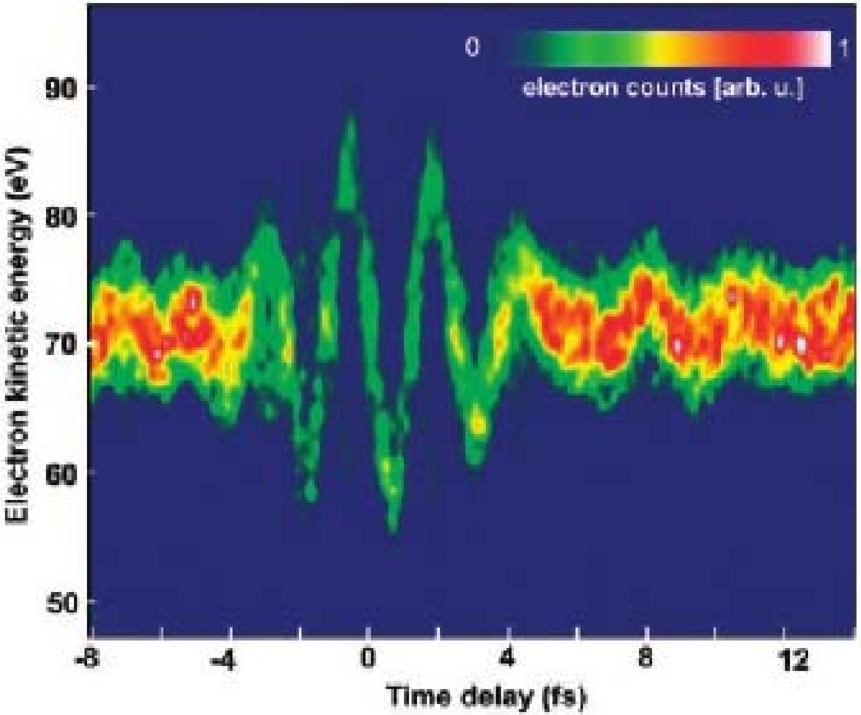
$$I = 10^{13} Wcm^{-2}$$

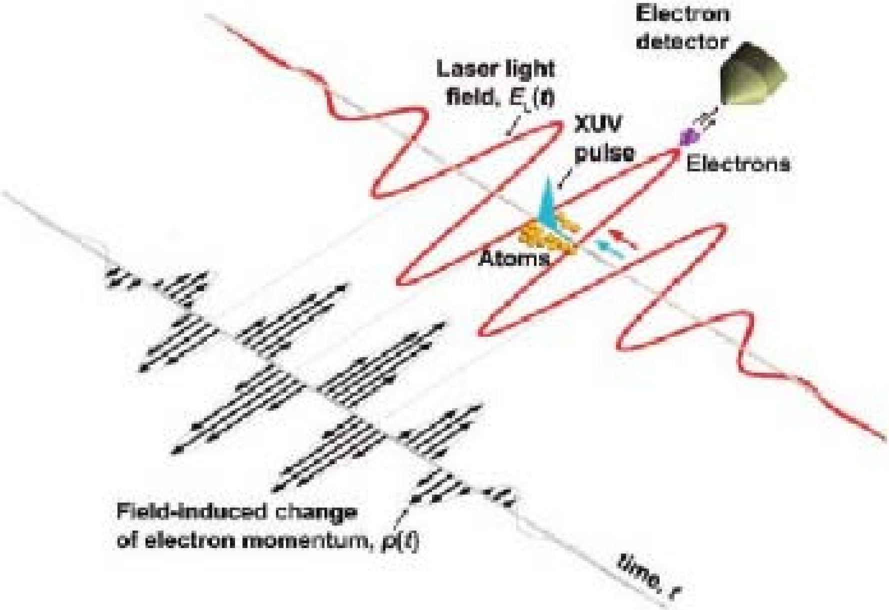
MCTDHF **full 3D Helium**, radial FEDVR basis, different M, vs. exact results (TDCI) and experiments (symbols)

D. Hochstuhl, and MB, J. Chem. Phys. ***134****, 084106 (2011)*

Simulation of as-streaking experiments

Goal: angle, energy and time-resolved spectrum





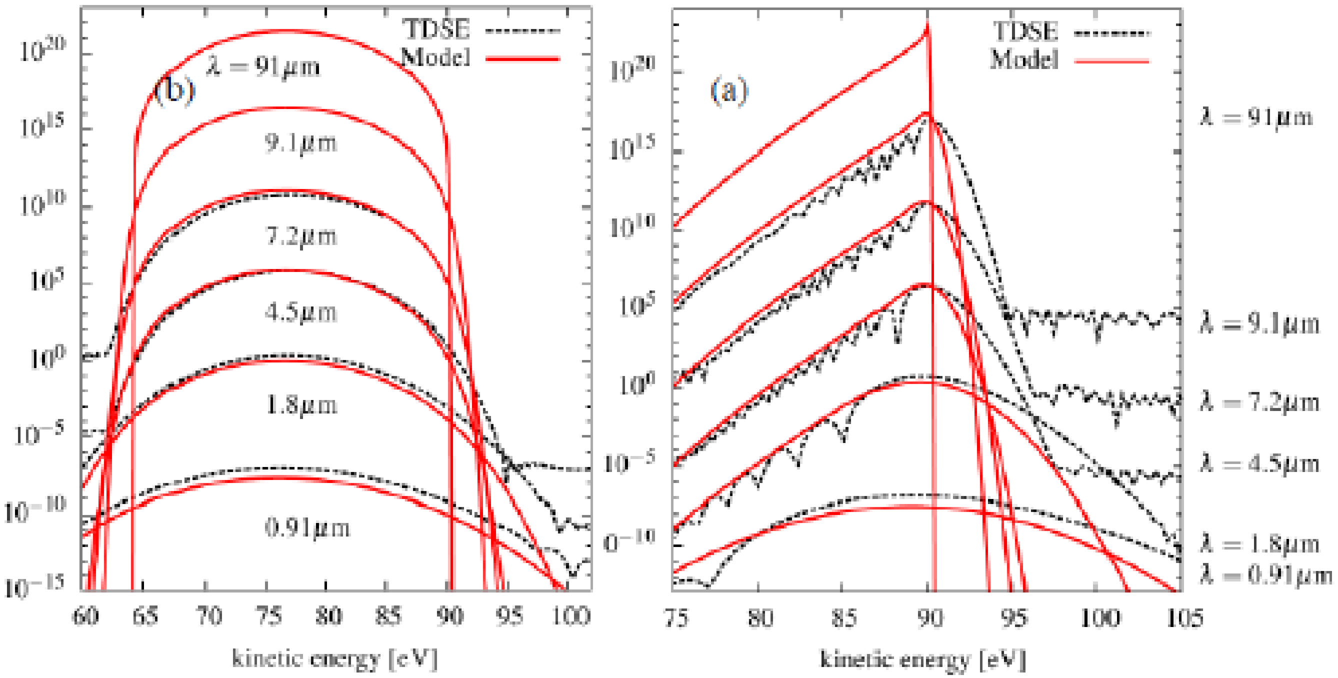
xuv/ir pump-probe measurement

Goulielmakis et al., Science **305**, 1267 (2004)

Simulation of THz-streak camera*

Extension to FEL radiation: xuv (5…60 fs pulses) + THz pulse

A=0 A=max



Solution of TDSE compared to semiclassical model**

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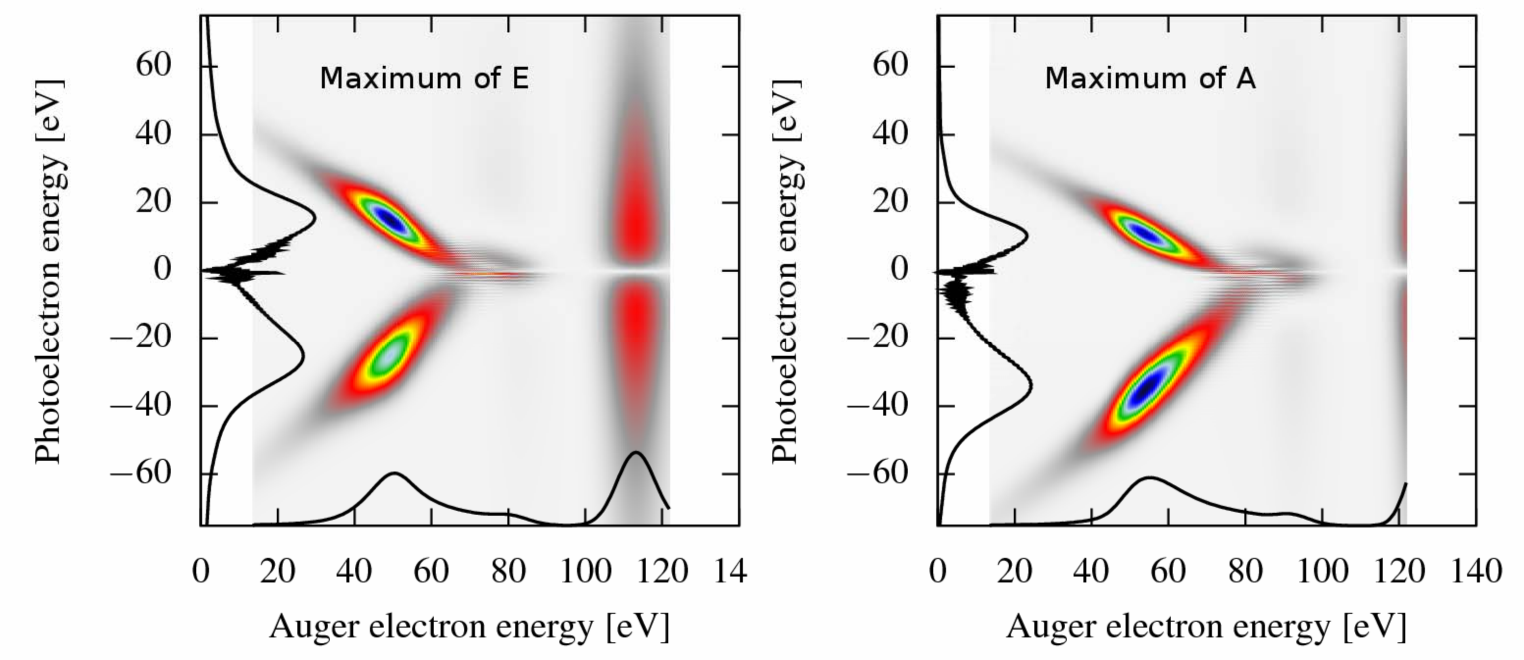
*Frühling et al., Nature Photonics **3**, 523 (2009)

*** E. Krasovskii, and MB, Phys. Rev. Lett.* ***99****, 247601 (2007); Phys. Rev. A* ***80****, 053421 (2009)*
U. Frühling, S. Bauch, M. Drescher, and MB, to be published

Correlated electron dynamics*

- UV…x-rays: Ionization of inner shell electrons, Auger processes
- e-e, e-i coincidence experiments, e.g. Coltrims

→ diagnostics of laser pulse shape, sub-fs resolution of inneratomic electron dynamics, diagnostics of surrounding plasma



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*S. Bauch et al., Europ. Phys. Lett. **91**, 53001 (2010)

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      - photoionization

3. Outlook: Multiscale simulations of dense plasmas

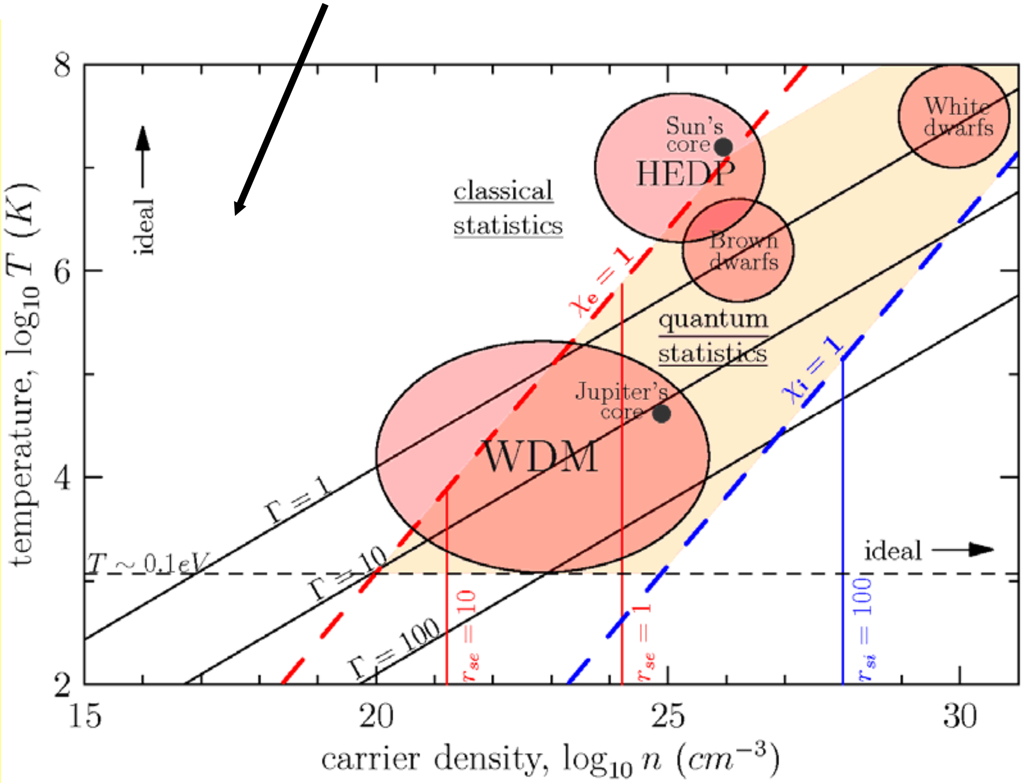
Correlations in relativistic plasmas

Relativistic PIC simulations: mean field

I. weakly nonideal plasma

Correlation and quantum effects:

- e-i scattering effects in EMF
  (inverse bremsstrahlung [1,2])
- inner shell ionization,
  highly charged ions [3]
- pair creation in strong AC field,
  Gies et al.
  but: modification by quantum &
  plasma effects [1,4]



[1] *M. Bonitz, „Quantum Kinetic Theory"*
[2] *D. Kremp et al., Phys. Rev. E* ***60****, 4725 (1999); MB et al. Contrib. Plasma Phys.* ***39****, 329 (1999)*
[3] *D. Hochstuhl, and MB, J. Chem. Phys.* ***134****, 084106 (2011)*
[4] *S. Smolyanski, MB et al. (2007-2010,* Schwinger vs. Landau-Zener tunneling*)*

Dense plasma simulations: perspectives

Towards multi-scale simulations from first principles:

1. Effective static i-i, e-i quantum pair potentials from equilibrium QMC
   Improvement of PIMC, dynamic and transport properties

2. First-principle ion MD with dynamically screened potentials
   Inclusion of nonequilibrium electrons, field effects

3. Combination of ion dynamics with electron quantum kinetics:
   TDHF, quantum kinetic equation or NEGF

4. Inclusion of inelastic processes in partially ionized plasmas:
   - ionization and recombination of atoms and (highly charged) ions
   - radiative processes

5. Modification of atomic processes by plasma and field

Multi-scale simulations for dense plasmas (1)

EM field

Input: f_e

Electrons

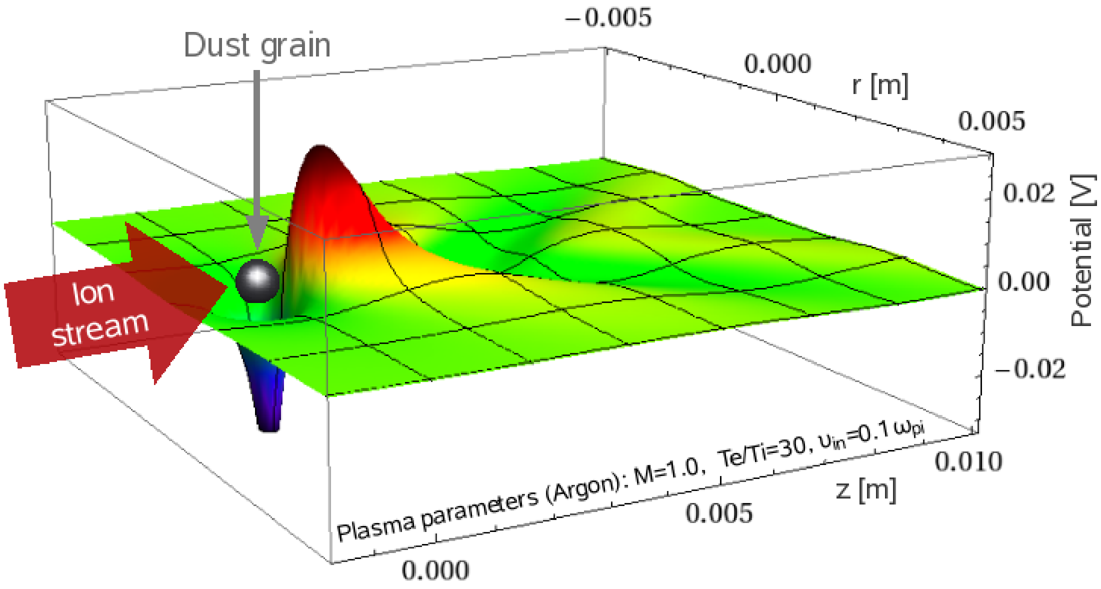
Ions

MD

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

Ion dynamics dynamically screened by nonequilibrium quantum electrons

Examples: - laser compression
- inertial confinement fusion: $\rho \propto 10^3 gcm^{-3},\ T = 10^3 ... 10^5 eV$



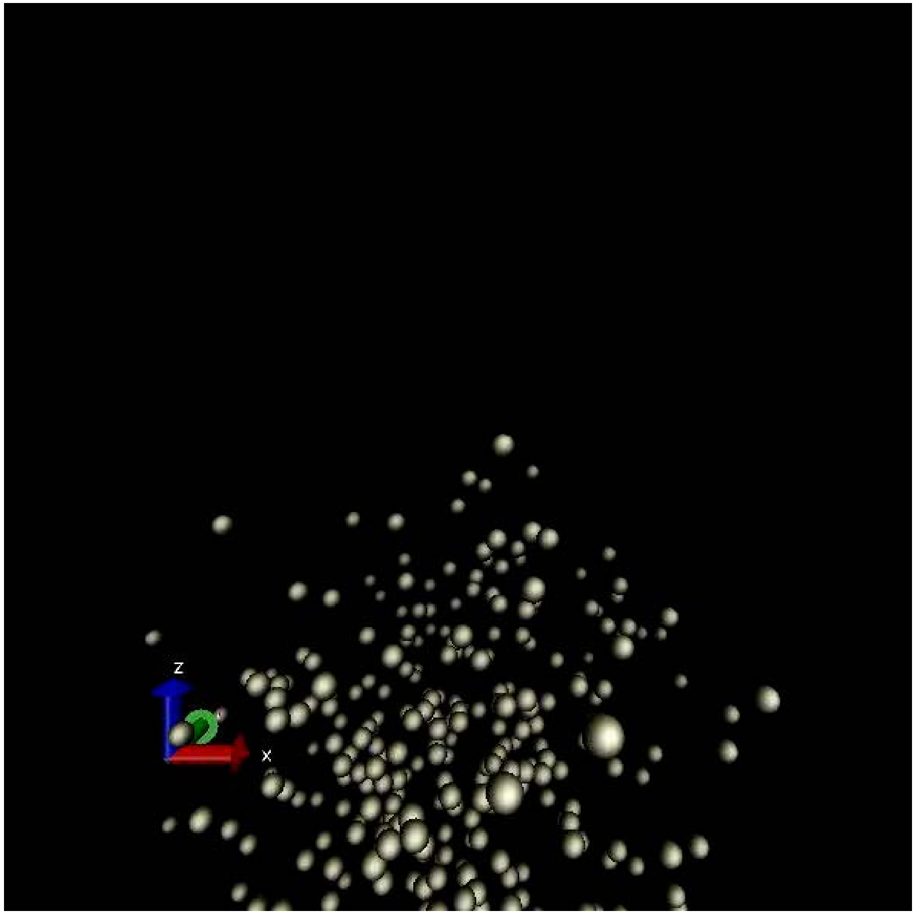
Electrons:
Mermin dielectric function (Lindhard plus collisions)

Test system:
dust in streaming e-i plasma (experiments)

Wake field *attraction* of equally charged particles

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

Strongly correlated heavy particles in streaming flow of light particle



Test system:
300 heavy particles

Plasma flow
downward, M=0.8

Non-hamiltonian system,
collective modes,
instabilities

MD Simulation:
Patrick Ludwig

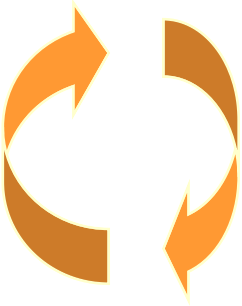
*P. Ludwig, MB, H. Kählert, and J.W. Dufty, J. Phys. Conf. Series **220**, 012003 (2010),*
P. Ludwig, W. Miloch, and MB, to be published

Multi-scale simulations for dense plasmas (2)

EM field

f_e(t) from
kinetic equation

Electrons



potential

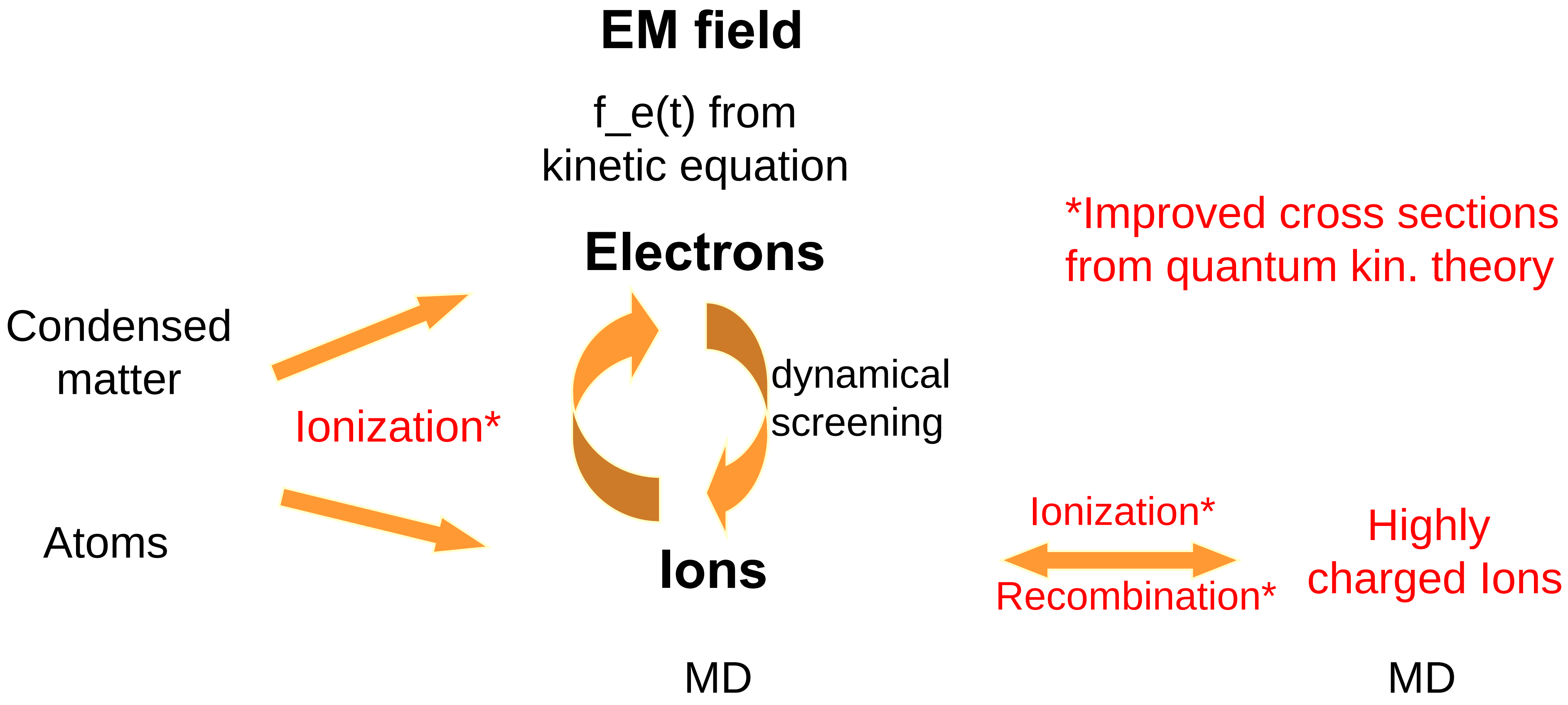
dynamical
screening

Ions

MD

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

Multi-scale simulations for dense plasmas (3)



EM field

f_e(t) from
kinetic equation

Electrons

Condensed
matter

Ionization*

Atoms

dynamical
screening

Ions

MD

*Improved cross sections
from quantum kin. theory

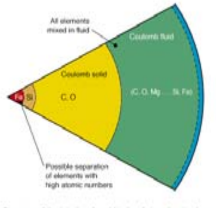
Ionization*

Recombination*

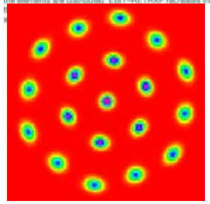
Highly
charged Ions

MD

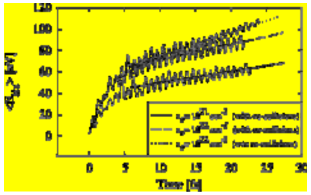
Summary

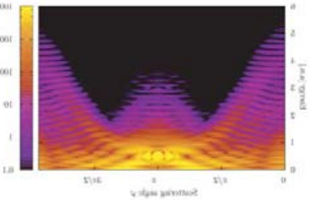


Structure of the interior of a white dwarf star, showing how the elements are distributed. EBIT–RETRAP recreates the

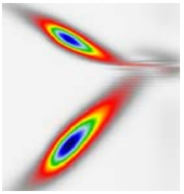


1. **Correlated plasmas: new states of matter**
   - compact stars, quark-gluon plasma,
   - lasers and ion beams: WDM, HEDP, ICF





2. **Theory of strongly correlated plasmas**
   - First-principle equilibrium simulations: QMC, QMD
   - nonequilibrium: quantum kinetic theory
   - atomic ionization dynamics

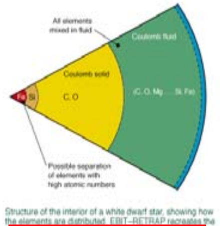


3. **Outlook**
   - Correlations, quantum effects in relativistic plasmas
   - Multiscale simulations of dense plasmas

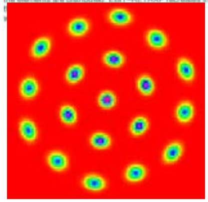
M. Bonitz, „Progress in correlated Coulomb systems“, Dornburg, 1.6. 2011

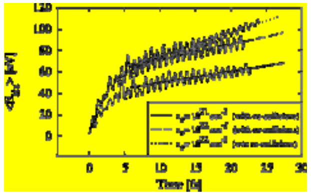
Thank you

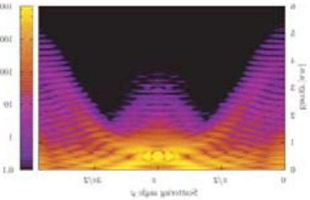
good luck Helmholtz institute Jena!

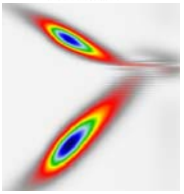


Structure of the interior of a white dwarf star, showing how the elements are distributed. EBIT–RETRAP recreates the









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

APS/DPP meeting 2011: mini-symposium
„quantum plasmas in nonequilibrium“

Network: „time-dependent many-body systems
out of equilibrium“