

Generation and x-ray diagnostic characterization of matter at extreme astrophysical conditions in the laboratory

P. Neumayer

EMMI Physics Days 2010

GSI, Darmstadt, Germany
November 4 - 5, 2010

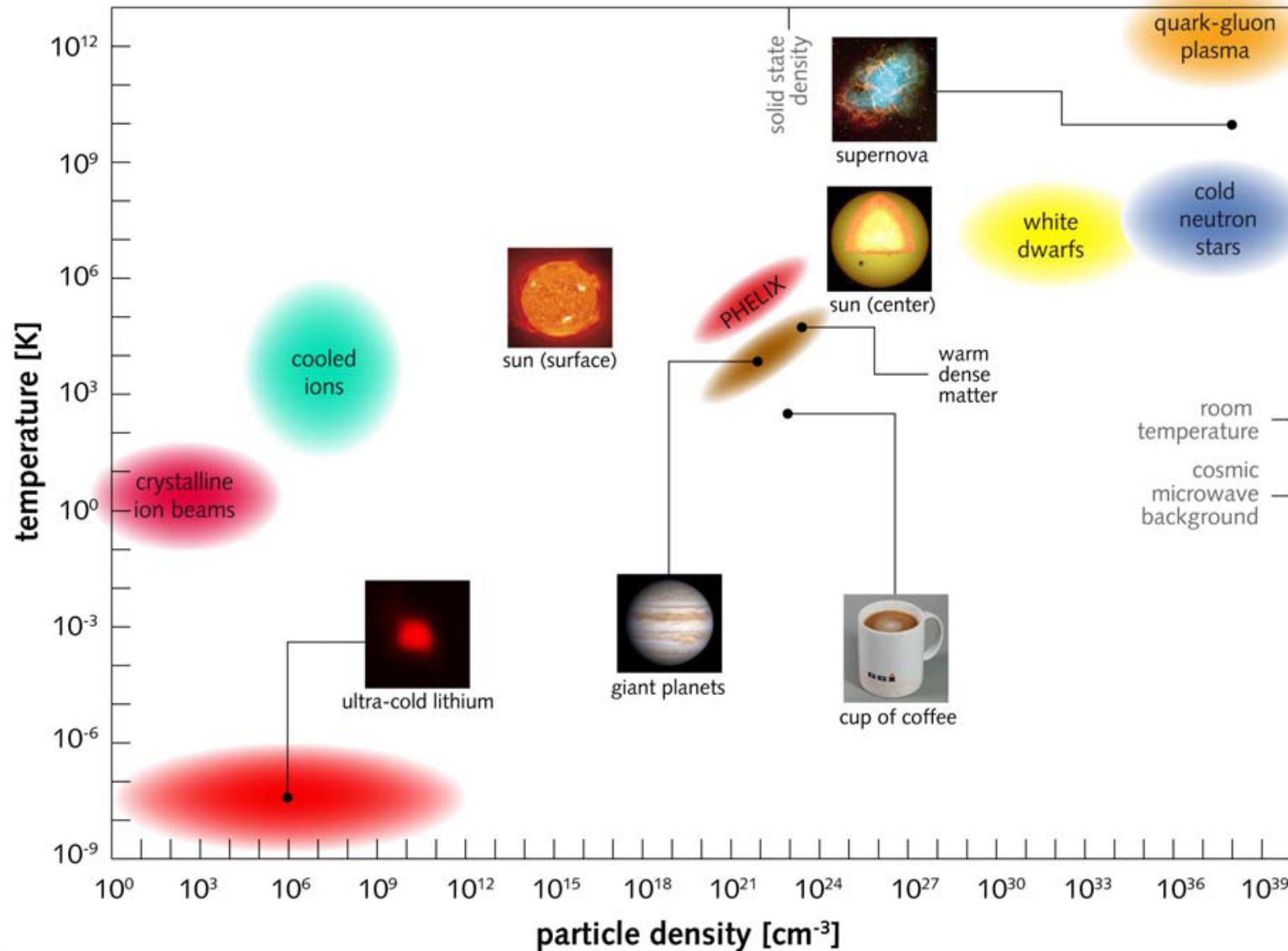


Extremes of Density and Temperature: Helmholtz Alliance "Cosmic Matter in the Laboratory"

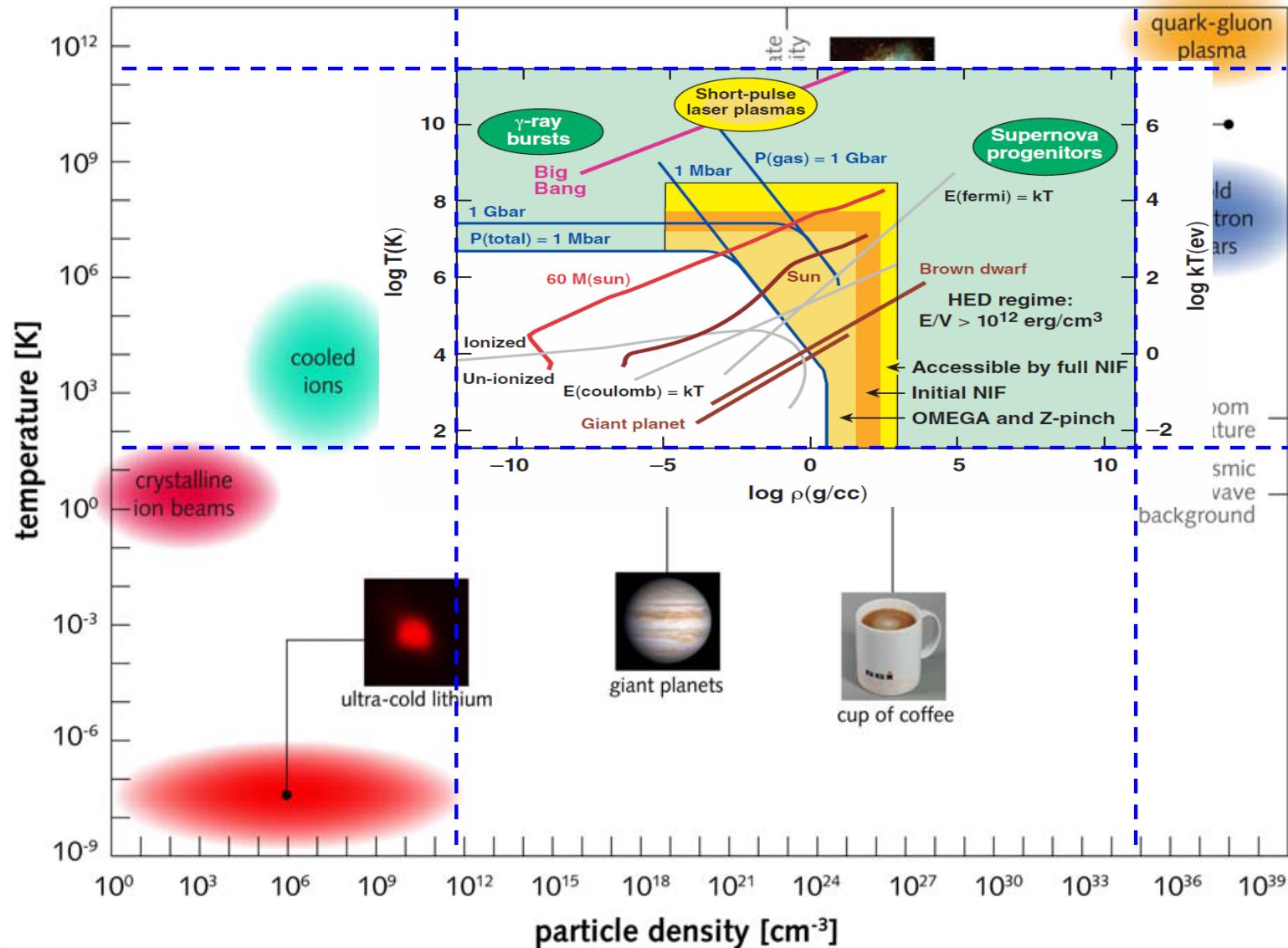


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Extremes of Density and Temperature: Helmholtz Alliance "Cosmic Matter in the Laboratory"

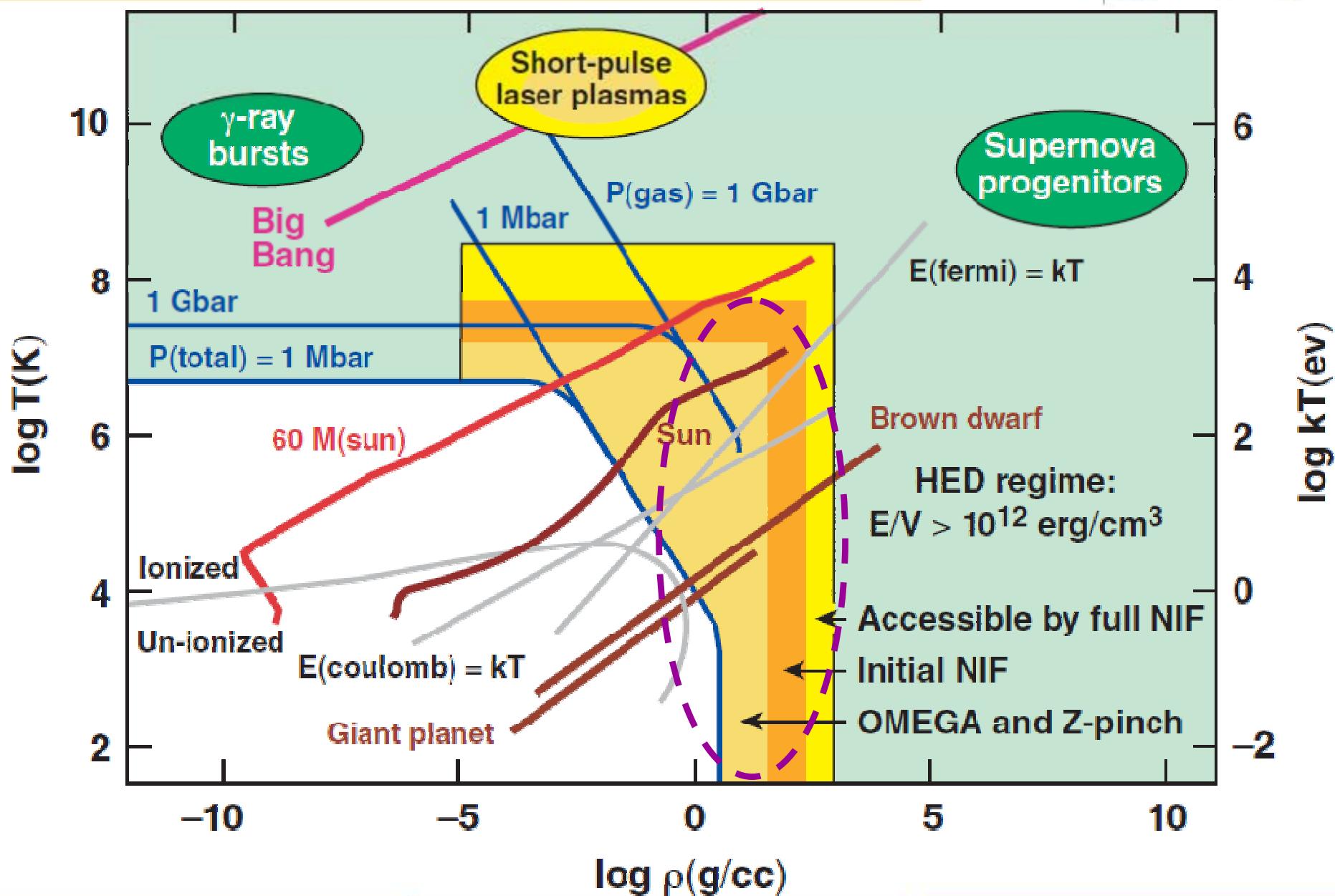


High energy density plasma physics

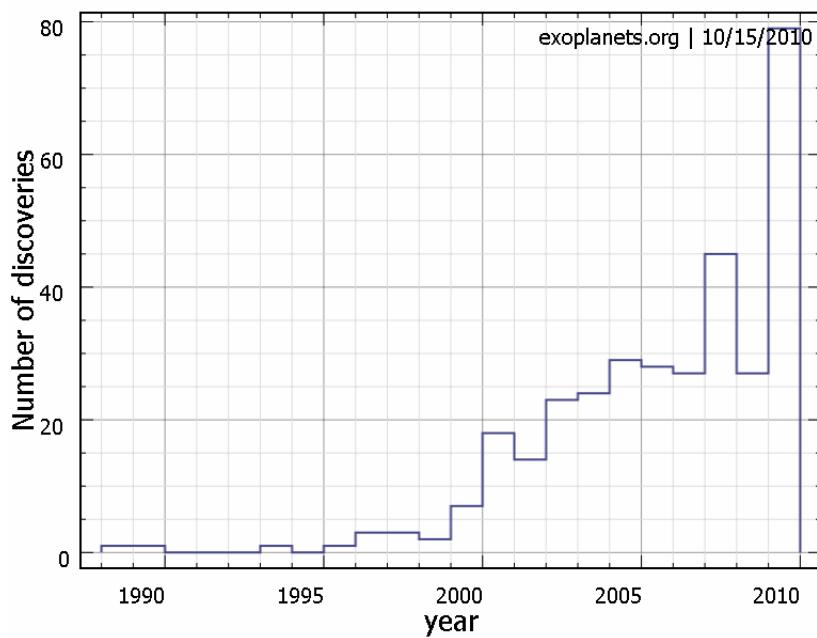


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Planetary science - Astrophysical observations



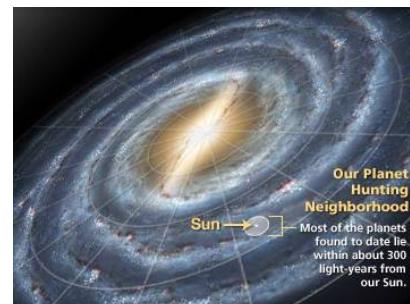
Precise data on planets within our solar system:

Radius, mass, angular velocity, gravitational moments, magnetic fields, surface temperature, chemical composition, ...

Exo-planets:

Nearly 500 planets outside our solar system, and counting...

M, a, R, ...



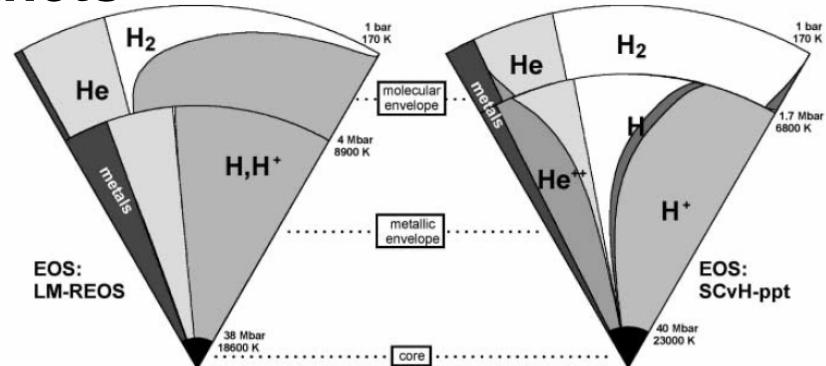
Advances in scientific computation and computing technology



Modeling of the interior structure in planets

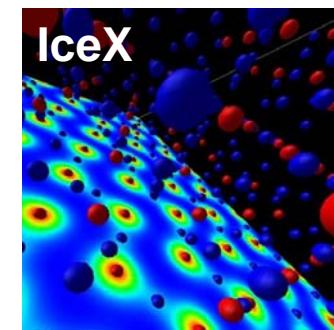
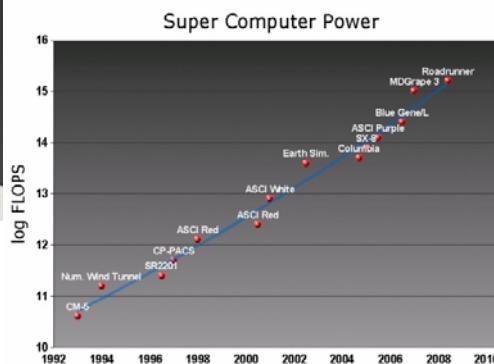
has to reproduce the observational data

- need equation-of-state over the entire parameter range



from Nettelmann *et al.*,
Astrophys. Journal, **683**, 1217 (2008)

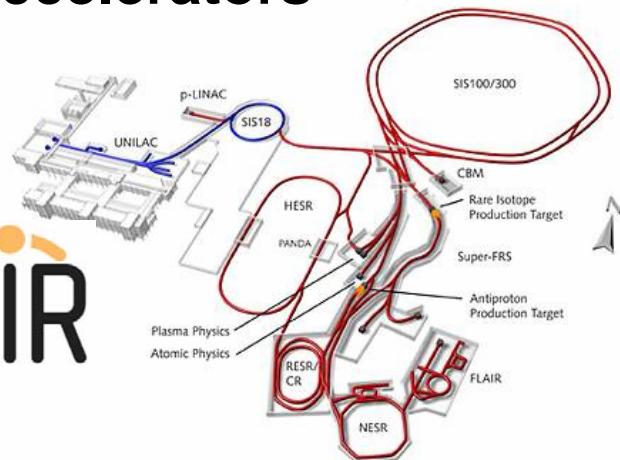
Large-scale computing allows ab-initio calculations of dense-matter properties



High-intensity drivers



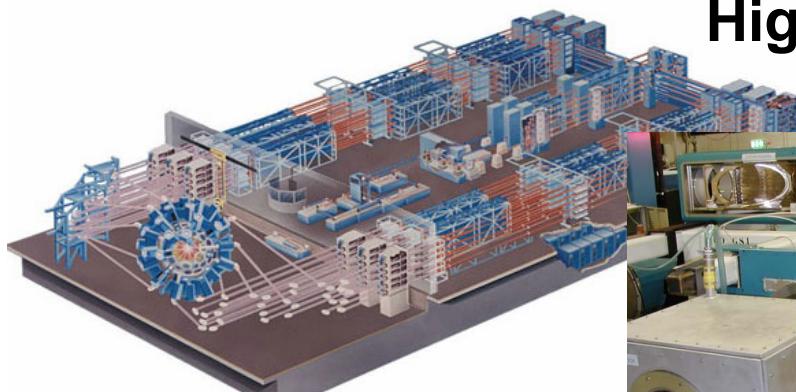
Intense pulse particle accelerators



X-Ray Free-Electron-Lasers



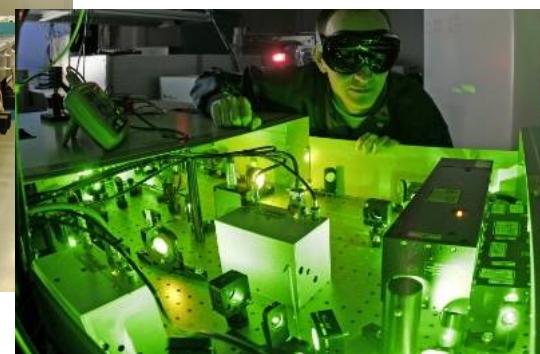
High-energy lasers



Omega (UR)

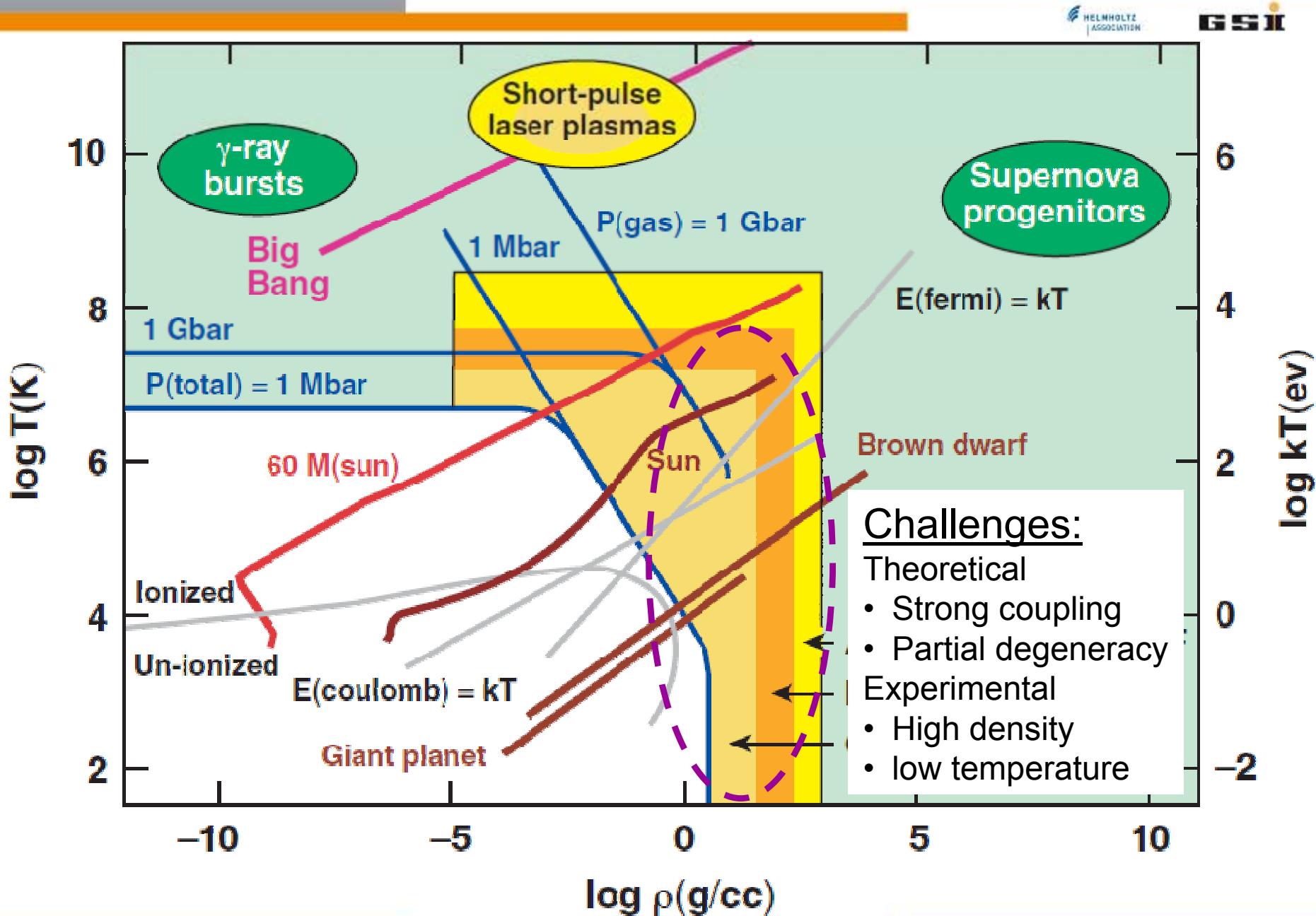


PHELIX (GSI)



DRACO (FZD)

We want to conduct experiments to test dense matter models, required for planetary structure calculations



Challenges:

Theoretical

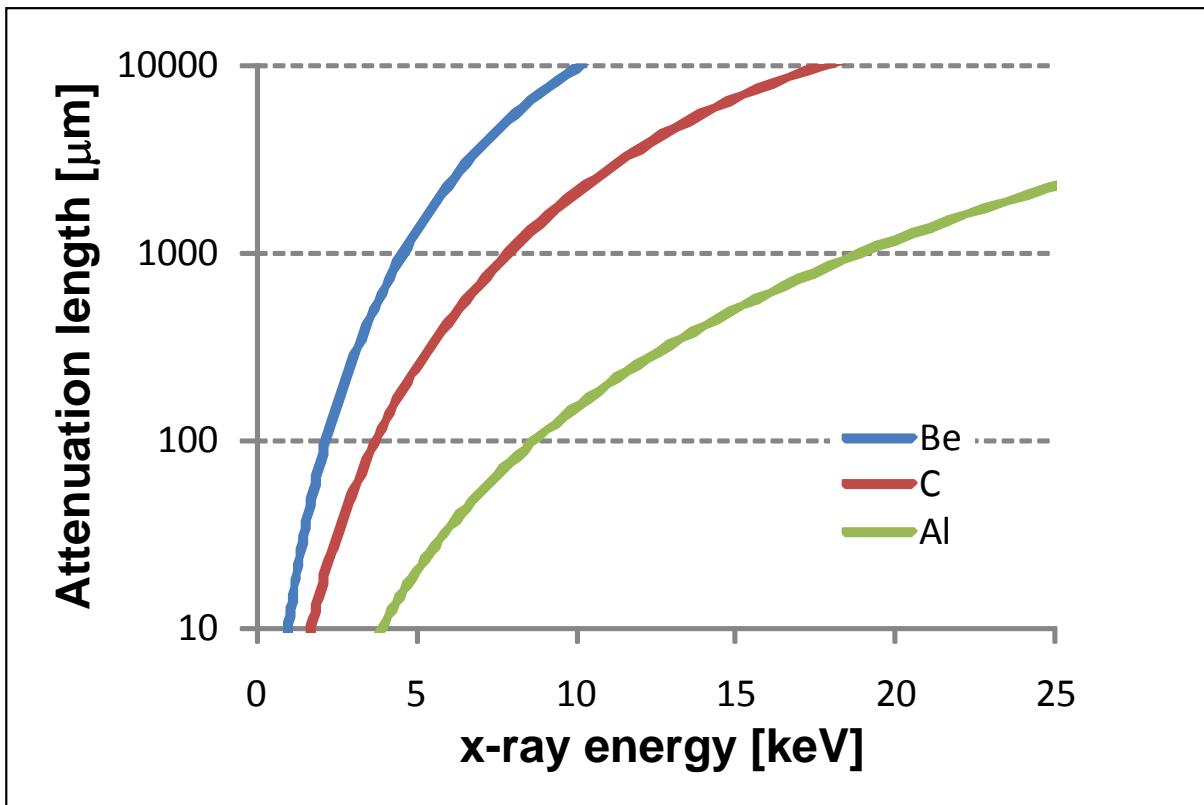
- Strong coupling
 - Partial degeneracy
- ### Experimental
- High density
 - low temperature

X-rays required to get information from inside



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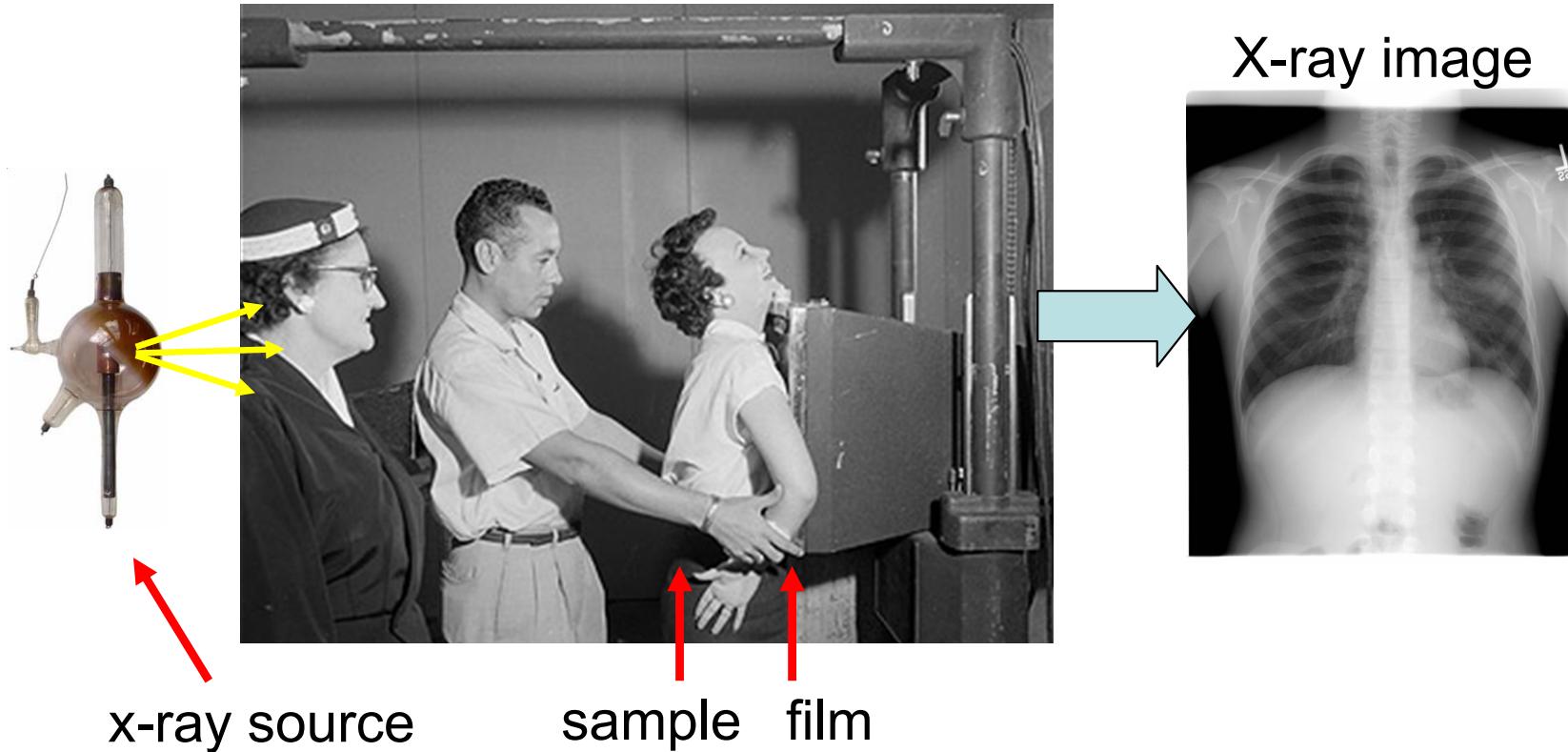


High density → multi-keV x-rays required
Low temperature → no keV x-rays emitted
→ Employ „active diagnostic“

X-rays radiography measures mass density



Typical experimental arrangement



Samples of HED matter in the laboratory do not hold still!

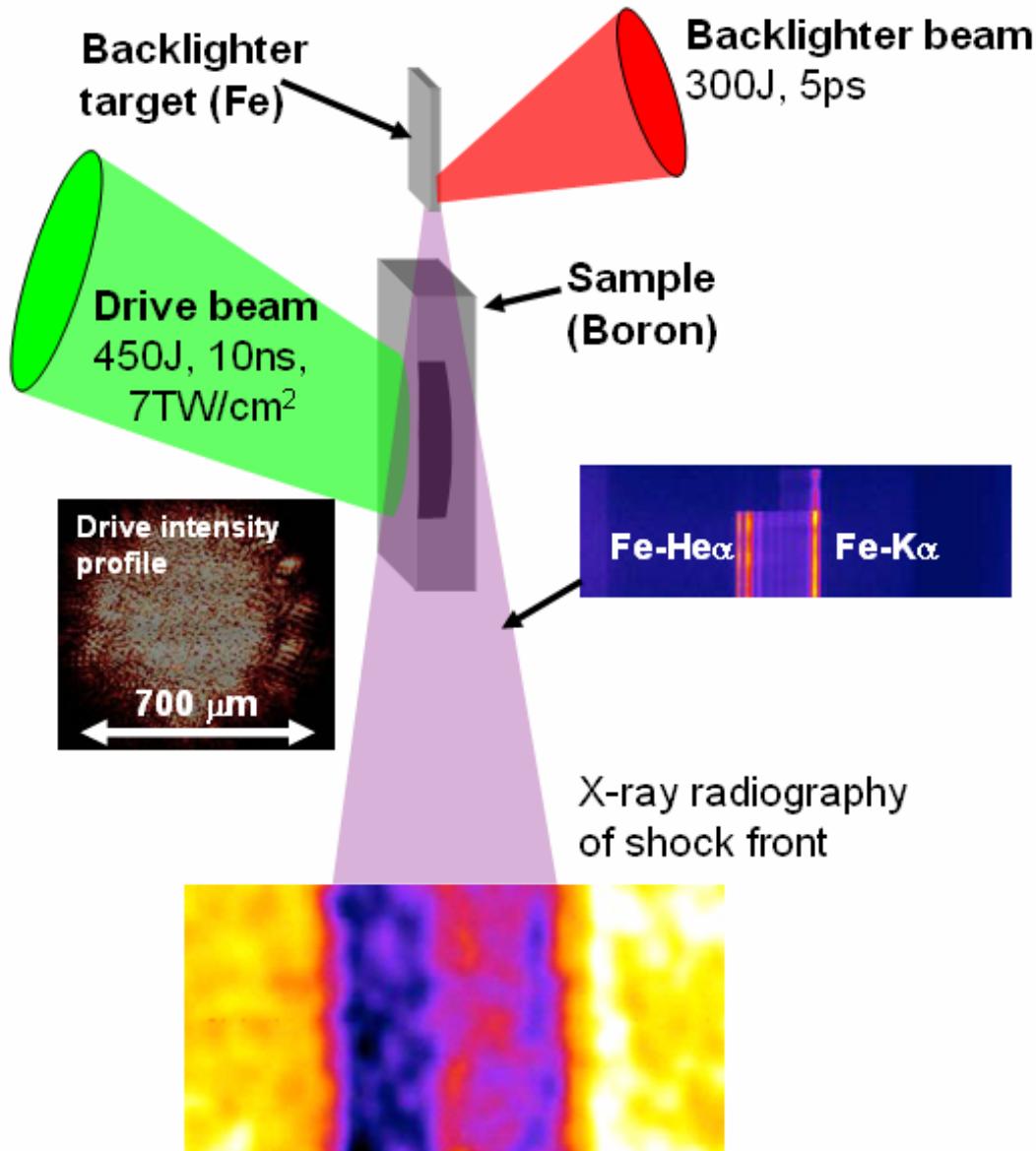
→ need a fast, bright source (typ. GW peak power in few ps)

X-ray radiography of a shock front

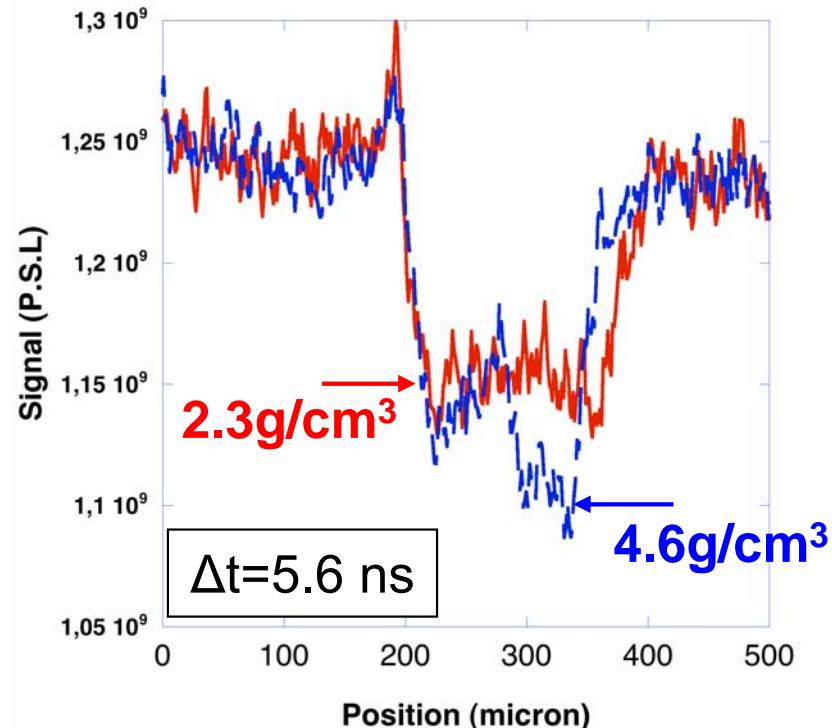


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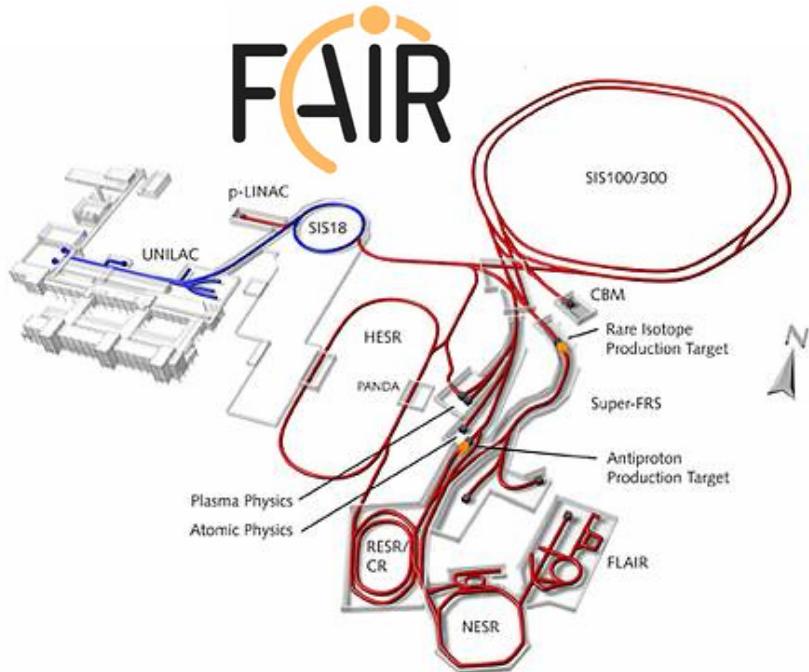


Careful calibration allows absolute density measurement

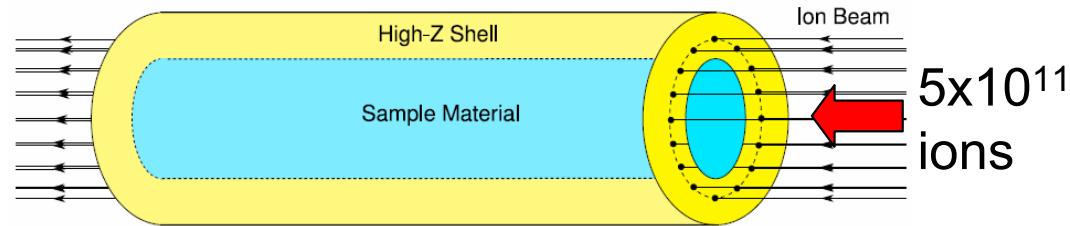


S. Le Pape et al., Phys. Plasmas 17, 056309 (2010)].

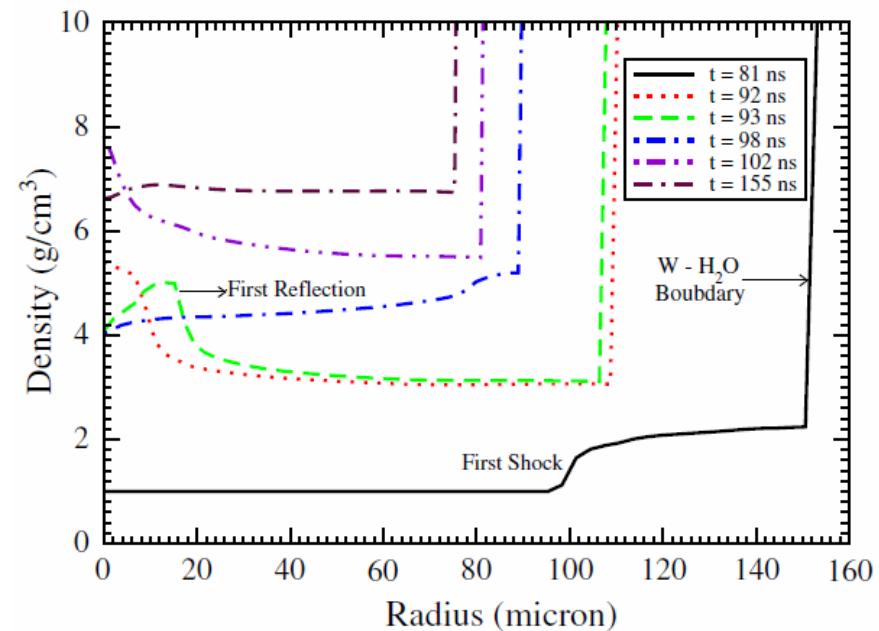
X-ray radiography: tool to follow hydrodynamical evolution of HED matter produced at FAIR



LAPLAS (LAboratory PLAnetary Science)



Multiple shock reflection increases density near-isentropically

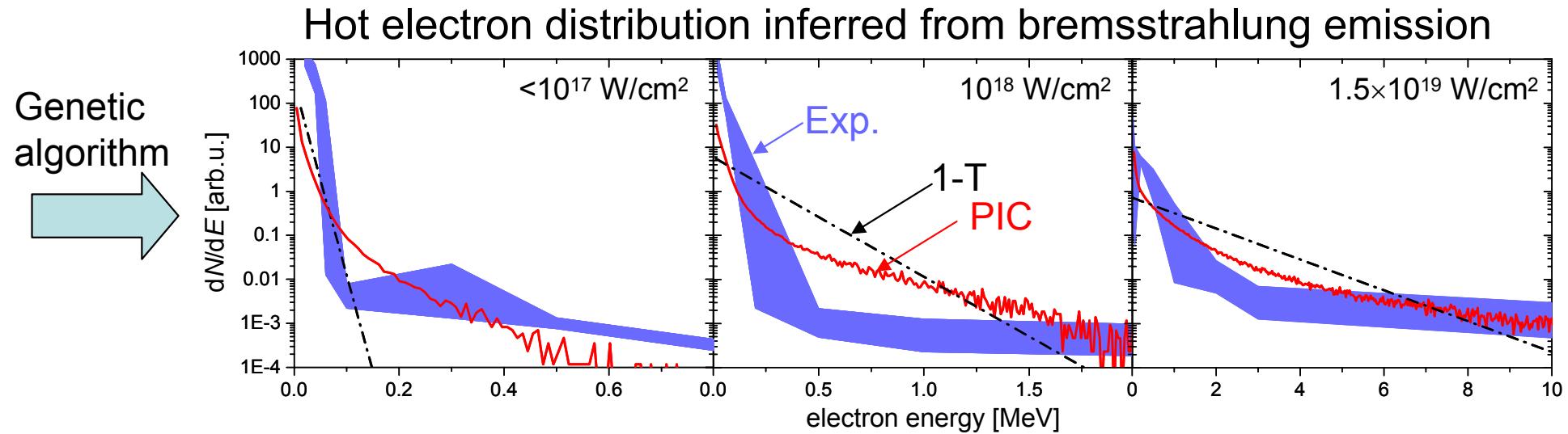
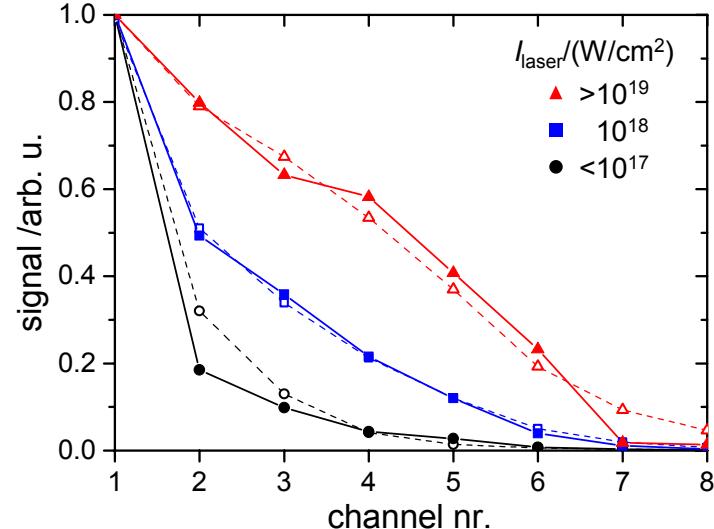
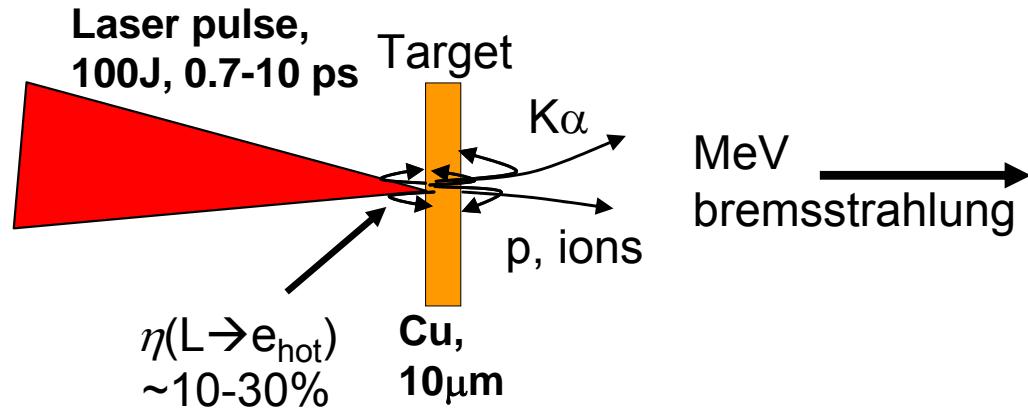


K-alpha backlighter optimization at PHELIX



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Hydro-calculations by An. Tauschwitz (EMMI) and M. Basko,
PIC calculations by P. Gibbon and A. Karmakar (EMMI)

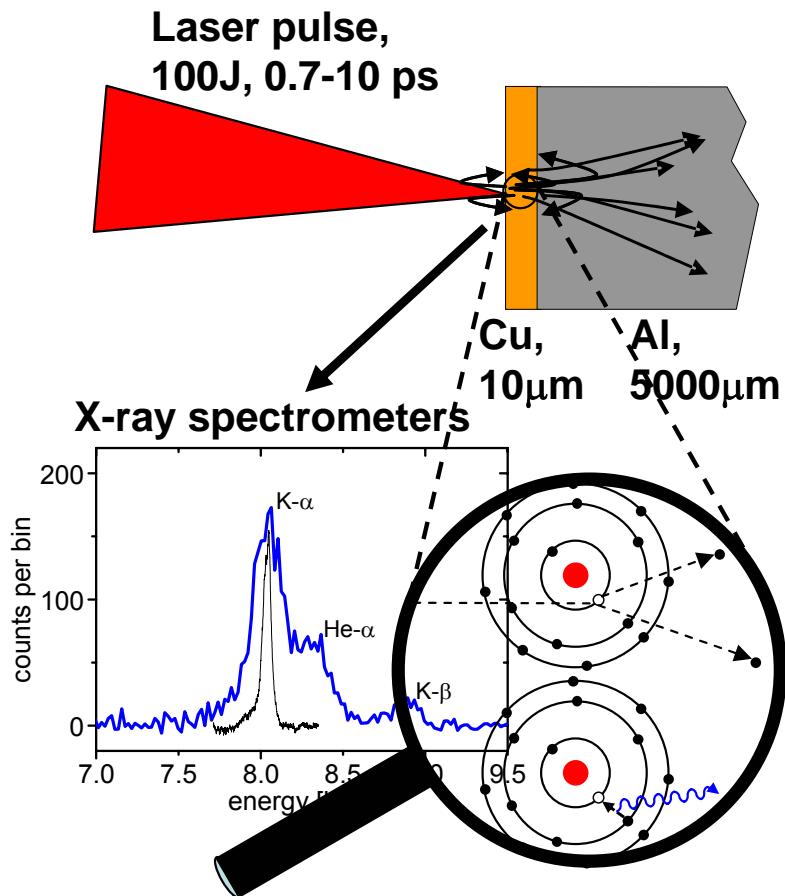
K-alpha backlighter optimization at PHELIX



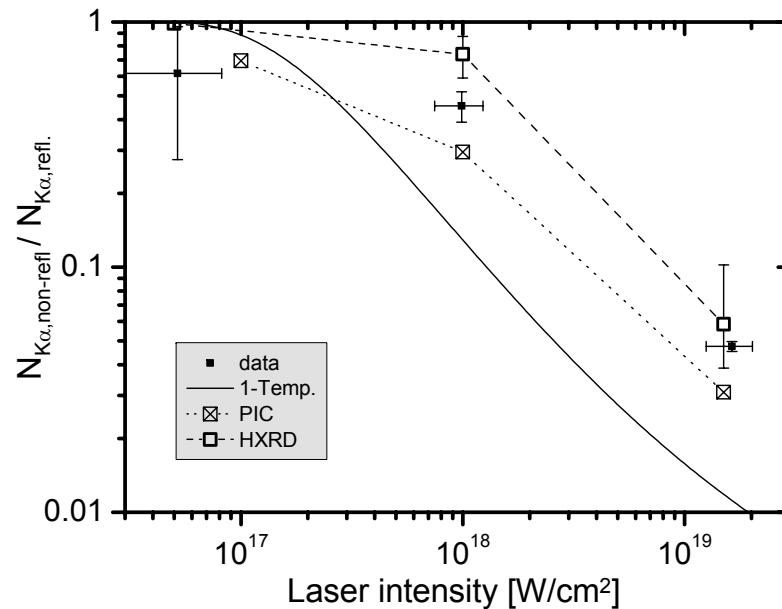
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Experimental setup



Modeling of the K-alpha yield



**Refluxing electrons can make up
>95% of the total K-alpha yield!**

Collaboration with PHELIX laser operations team: Implementation of 2-beam capability at PHELIX

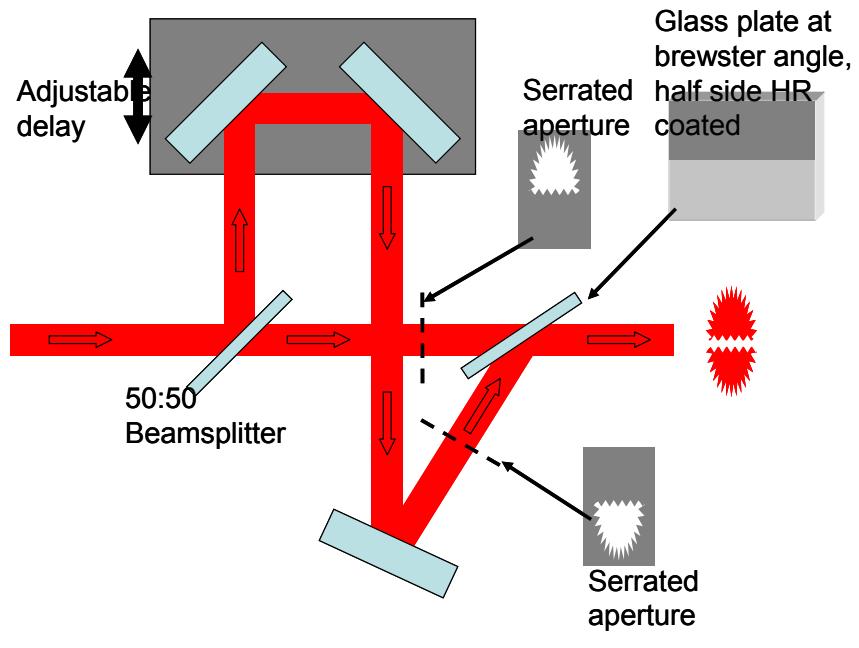


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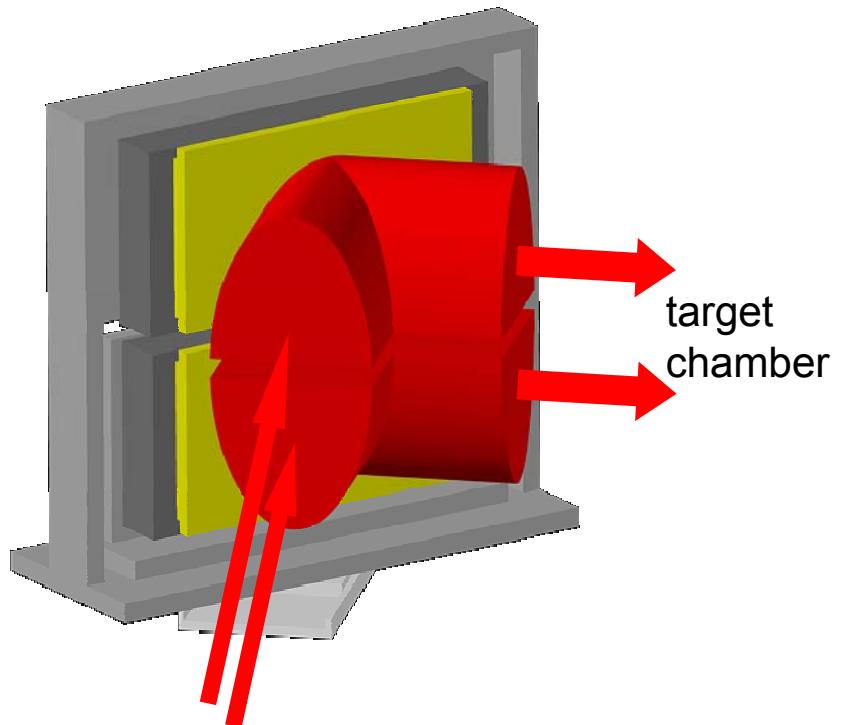
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Beam split&delay



Individual focusing of 2 full beams



Together with Prof. D. Batani, Univ. Milano: Proposal P046
Development of high-resolution x-ray radiography at PHELIX

Beams from PHELIX
laser pulse compressor

Having such bright x-ray sources...



... can we do more than (just) following hydrodynamic evolution and measure density?

Yes, we can!

X-ray Thomson Scattering

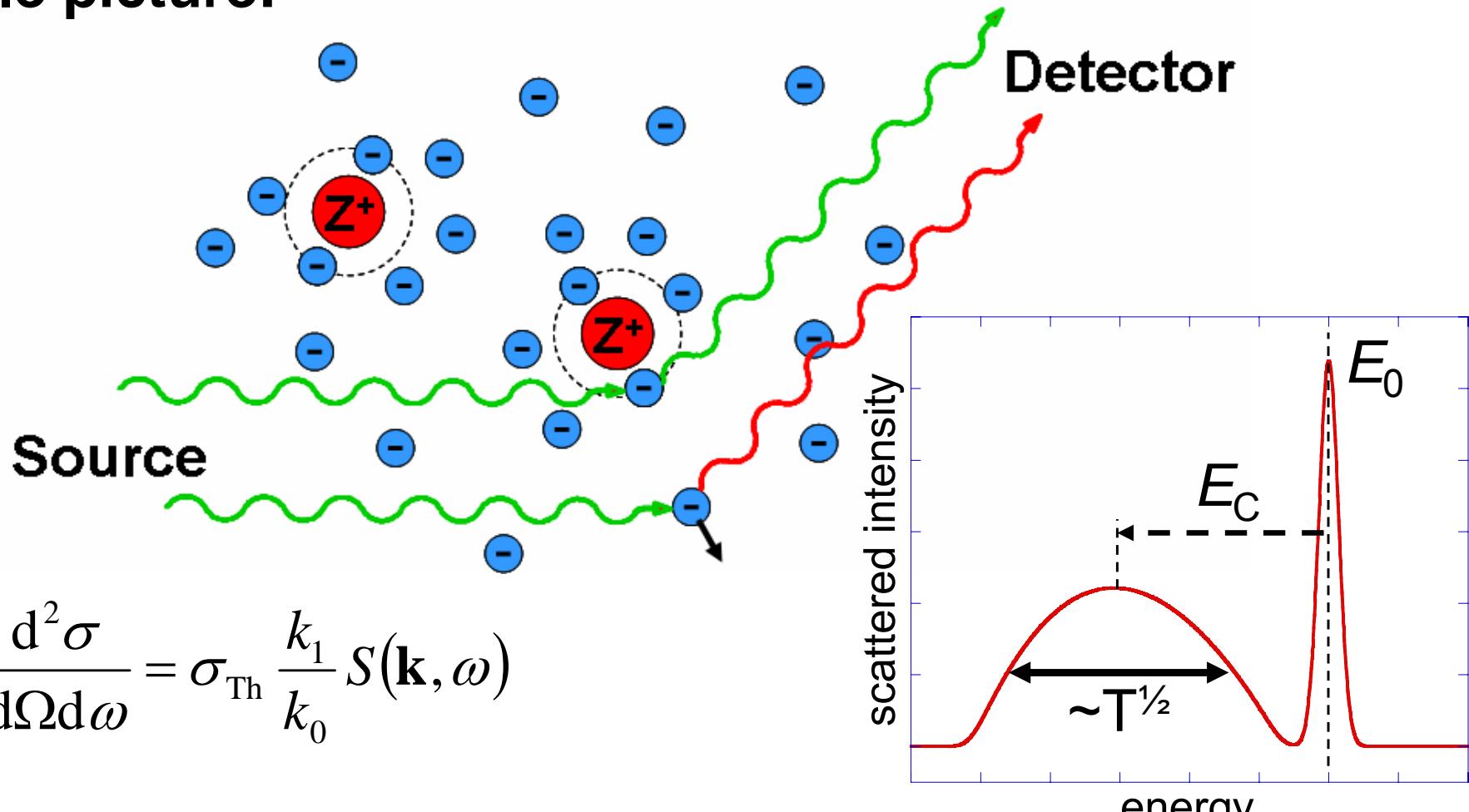
X-ray scattering as a diagnostic of plasmas at high-energy density



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Simple picture:



$$S(k, \omega) = |f_I(k) + q(k)|^2 S_{ii}(k, \omega) + Z_f S_{ee}^0(k, \omega) + Z_b \int \tilde{S}_{ce}(k, \omega - \omega') S_s(k, \omega') d\omega'$$

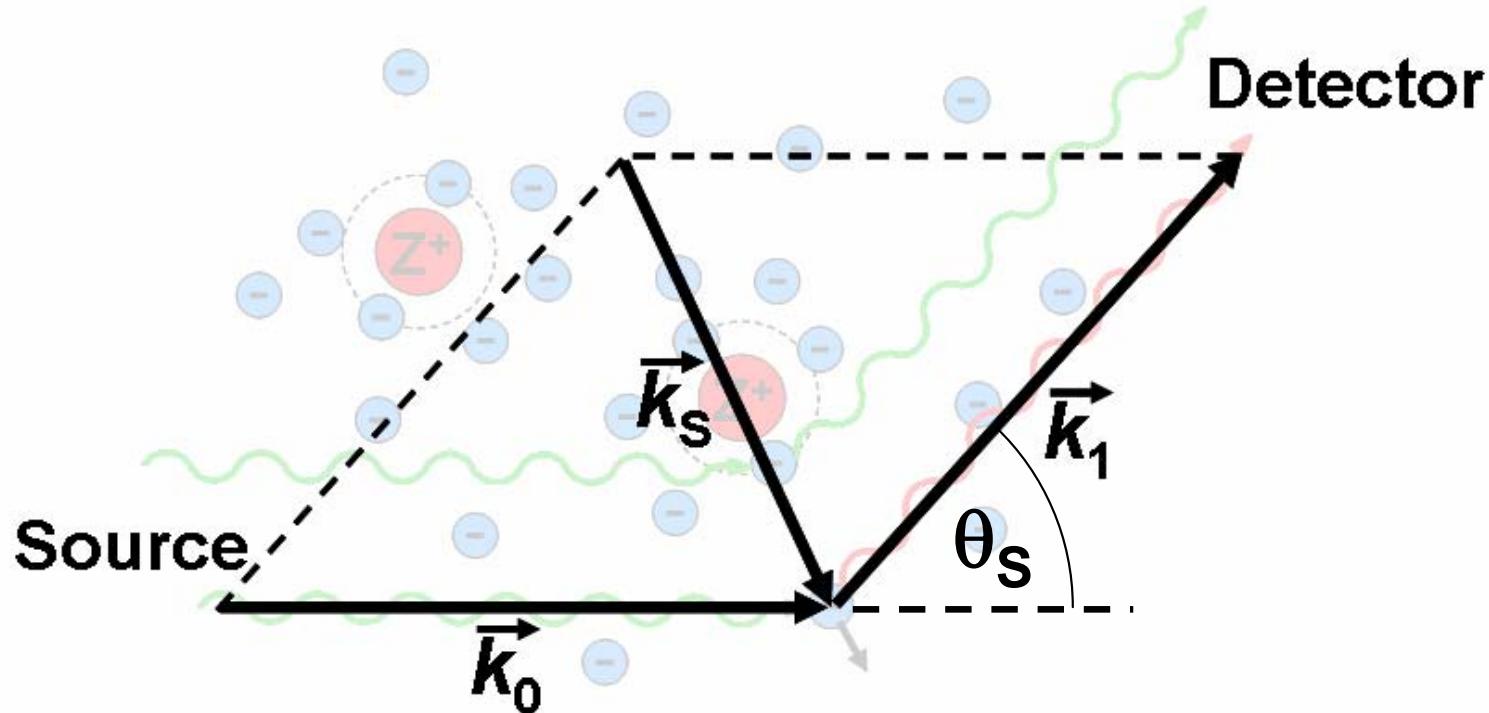
Ion feature Electron feature Bound-free

Scattering regime for electron structure factor S_{ee}



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$$\text{Scattering vector } |\mathbf{k}_s| = 4\pi E_0/hc \sin(\theta_s/2)$$

$1/k_s \ll \lambda_D$ → scattering on individual particles
→ electron motion → $f(E)$ ($\rightarrow T_e$ or T_F)

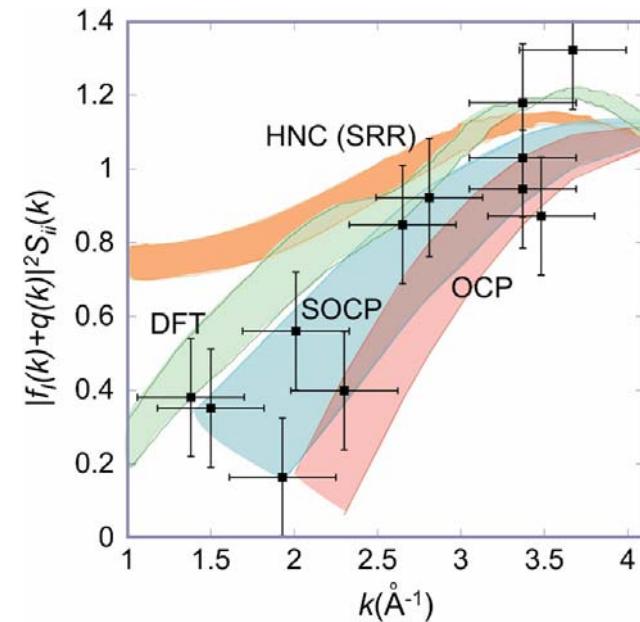
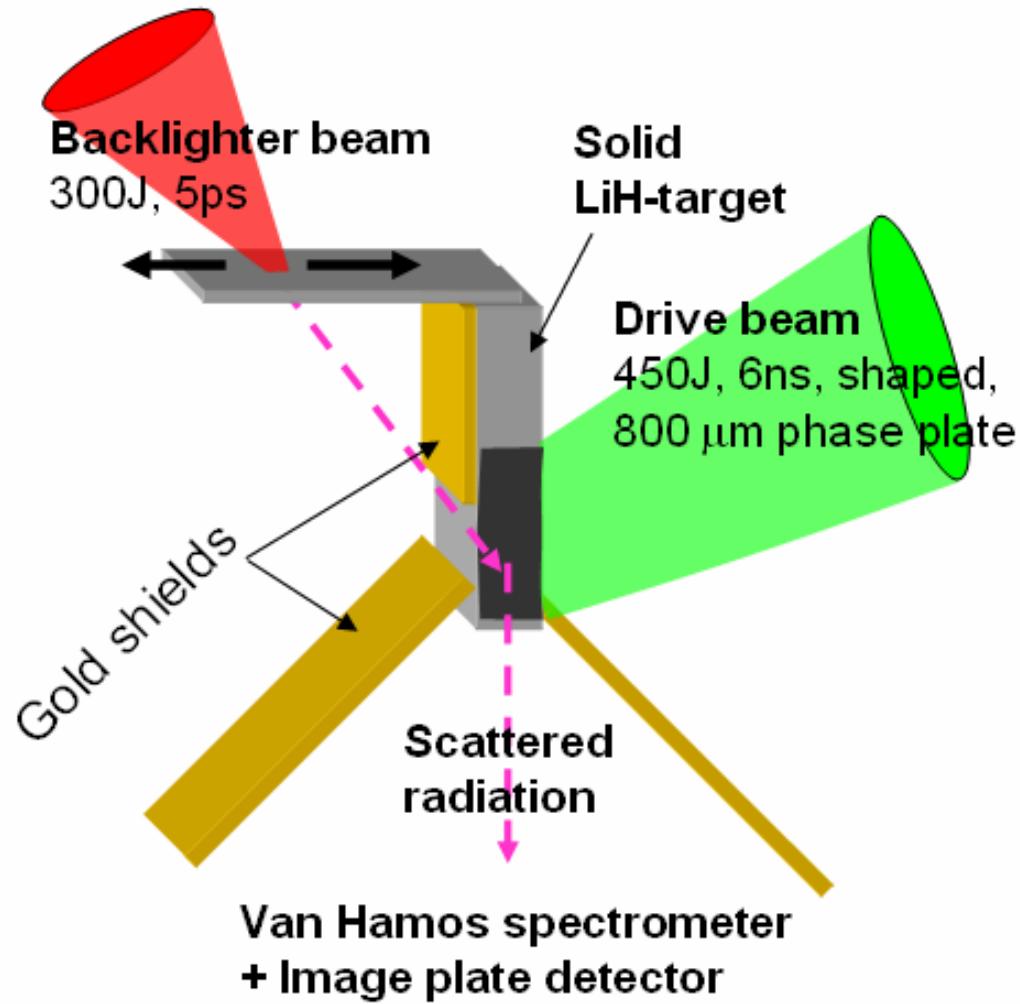
$1/k_s \gg \lambda_D$ → scattering on collective excitations ("plasmons") → n_e

XRTS on shock compressed matter to measure static structure factor: Test of dense matter models

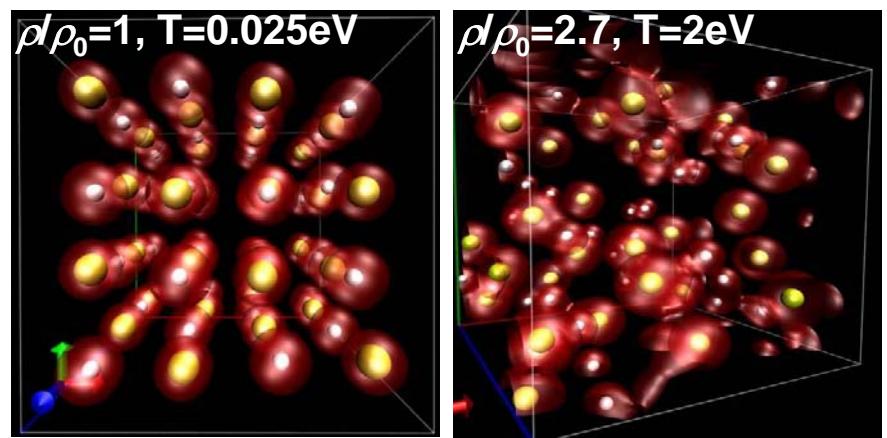


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FT-DFT-MD results

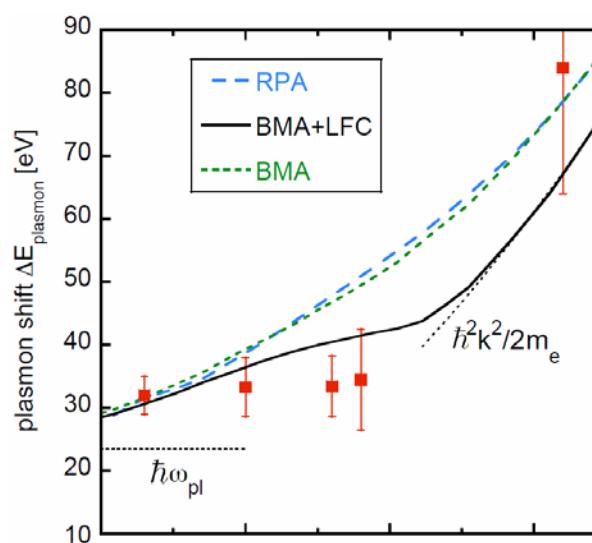
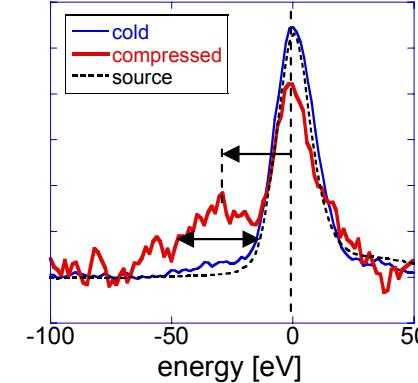
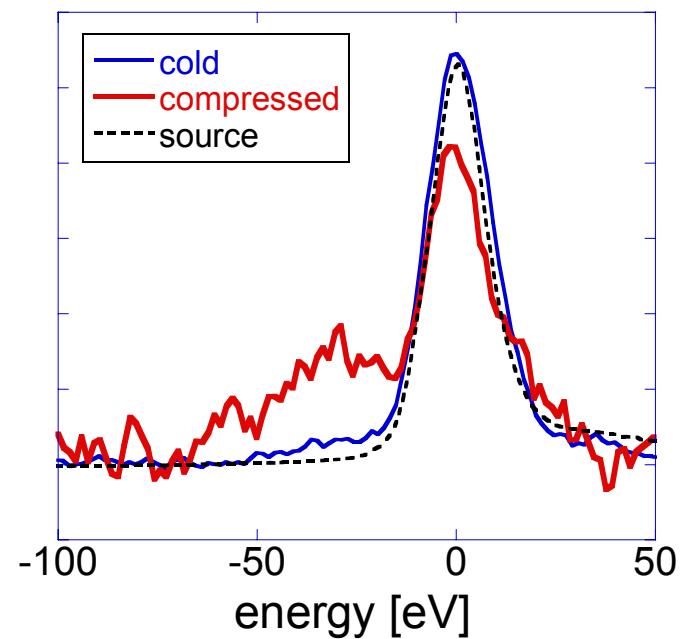
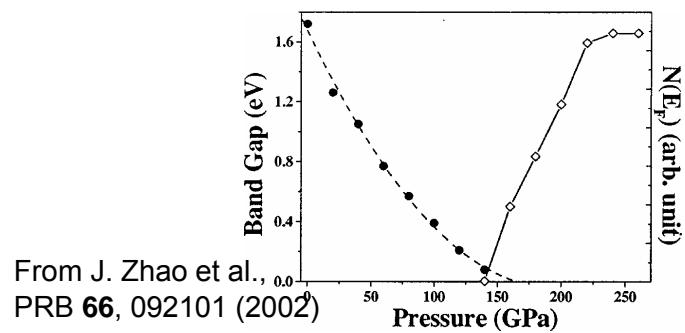


(B. Holst, R. Redmer, U-Rostock)

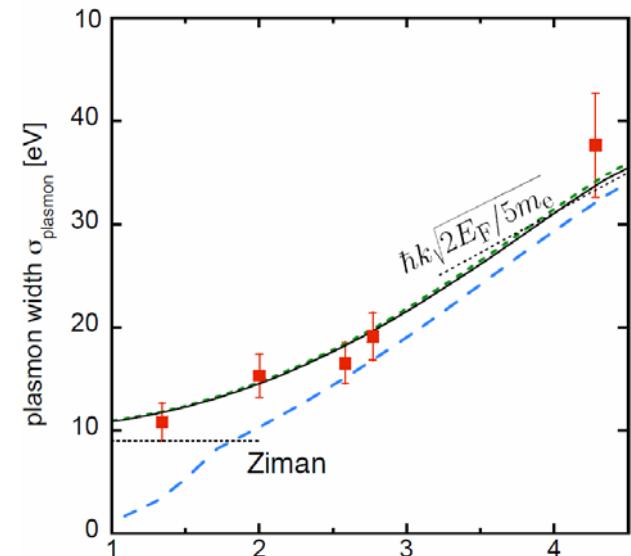
Insulator-metal transition and corrections to the electron response



Cold, solid B is an insulator
 >1.6 Mbar pressure → IMT → free electrons

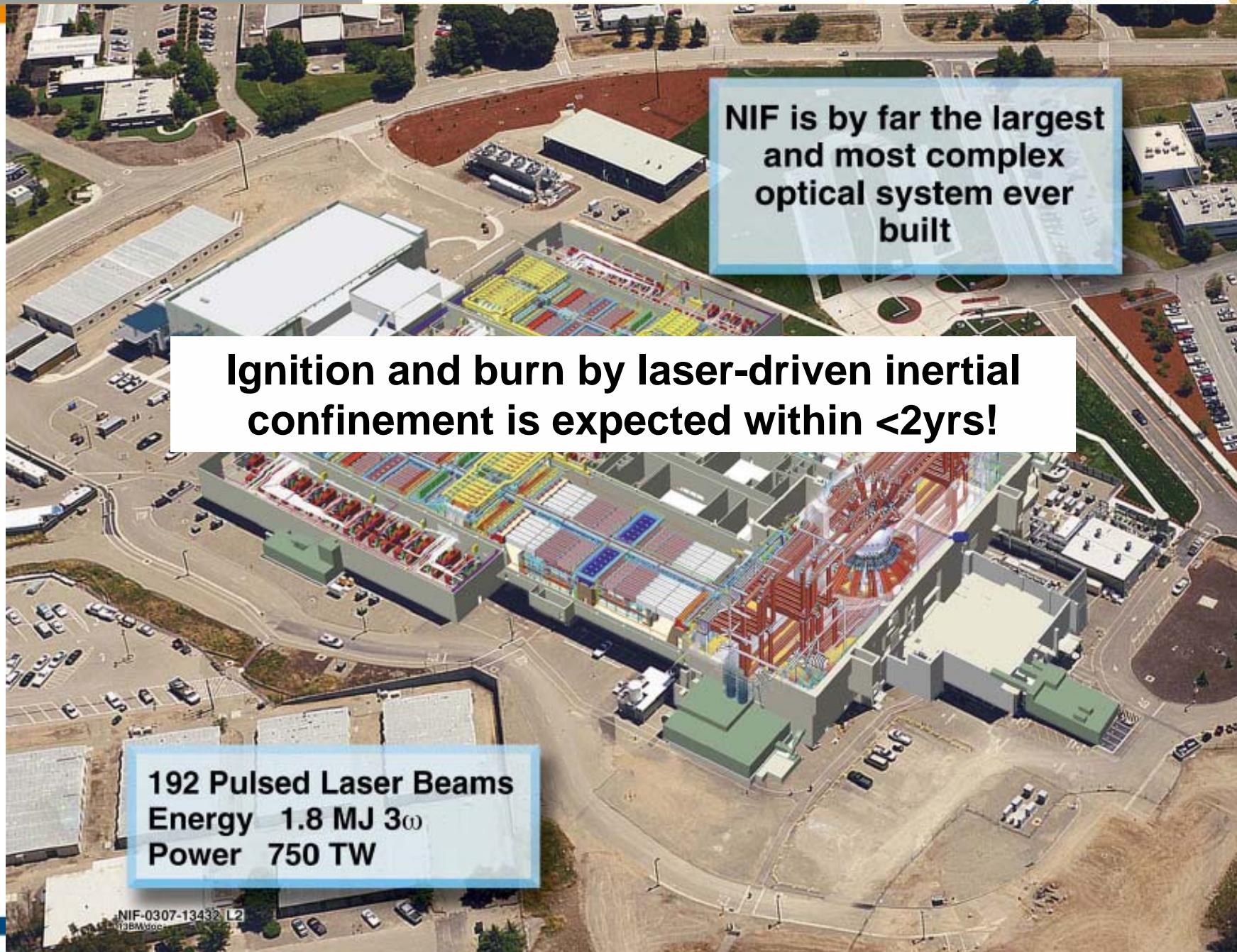


Strongly correlated electron gas
 → local field corrections

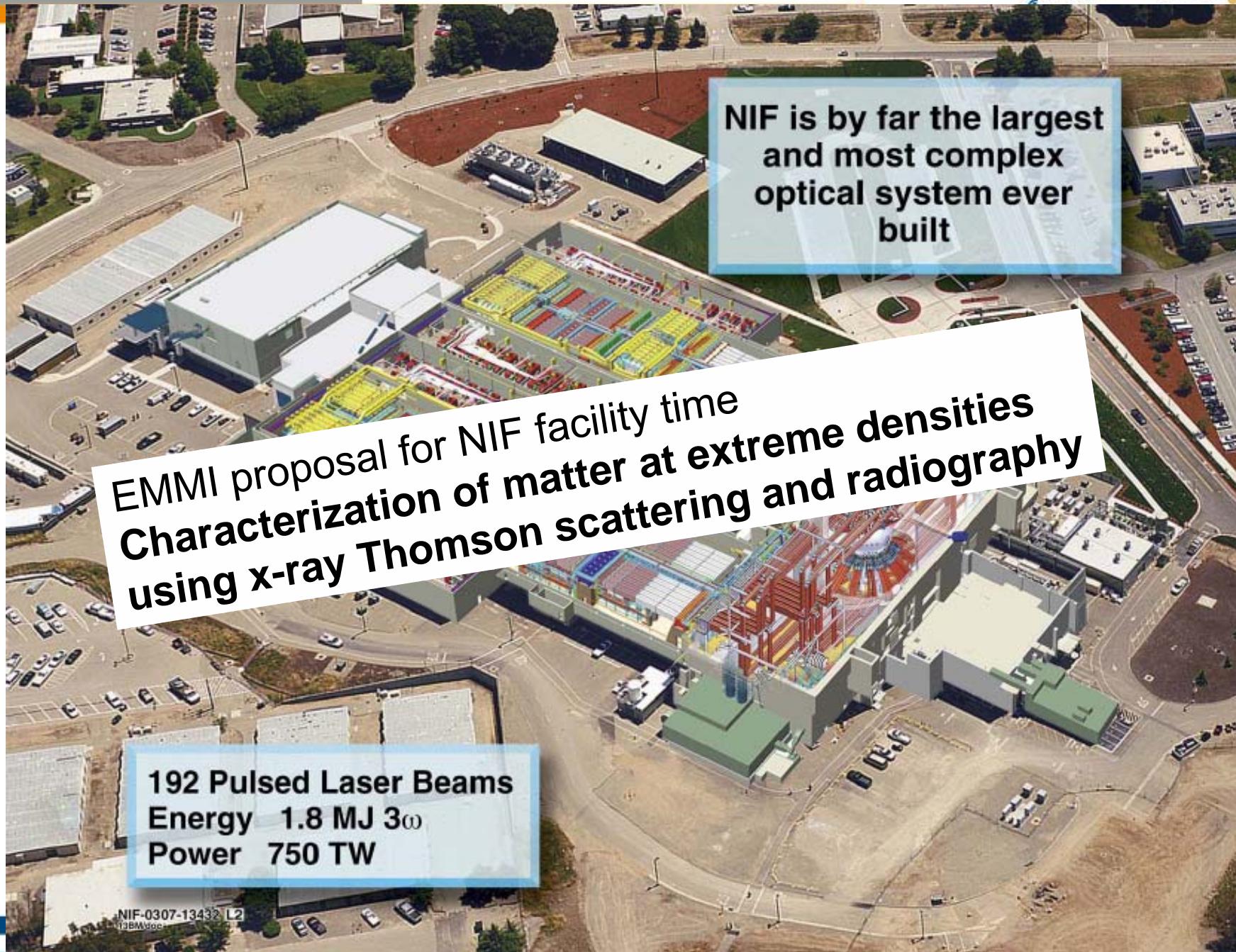


Plasmon damping due to
 e-i-collisions

The „National Ignition Facility“ (Livermore/CA, USA)



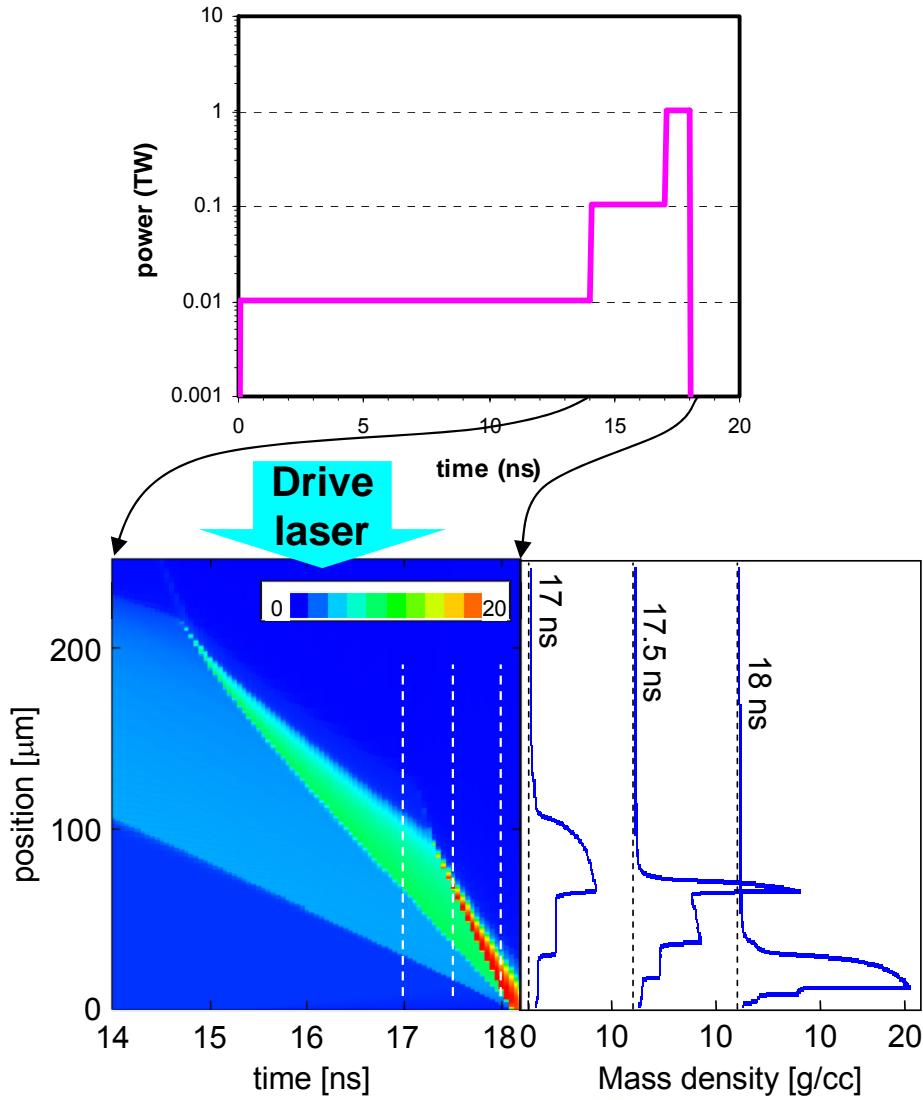
2009 call for proposals for fundamental high-energy-density science experiments at NIF in FY2010-2012



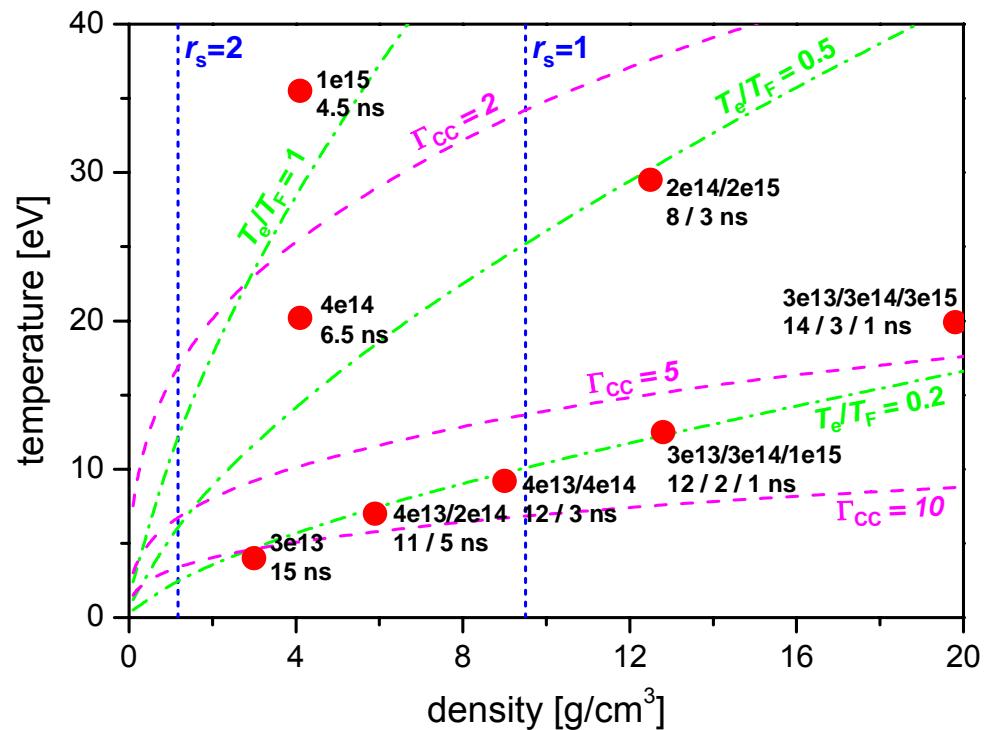
We will use NIF to compress matter extreme densities of >20x solid, while staying on low isentrope



Use NIF pulse shaping capability to launch multiple successive shocks



Rad-hydro calculations of multi-shock compression at NIF



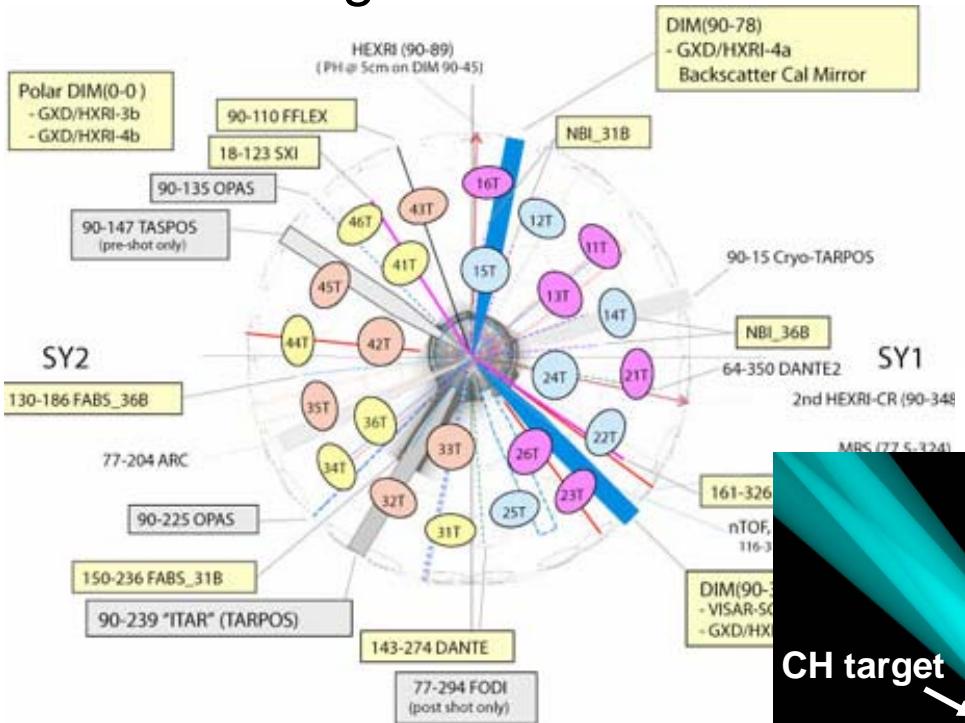
Multi-angle X-ray Thomson scattering and radiography characterize the compressed material



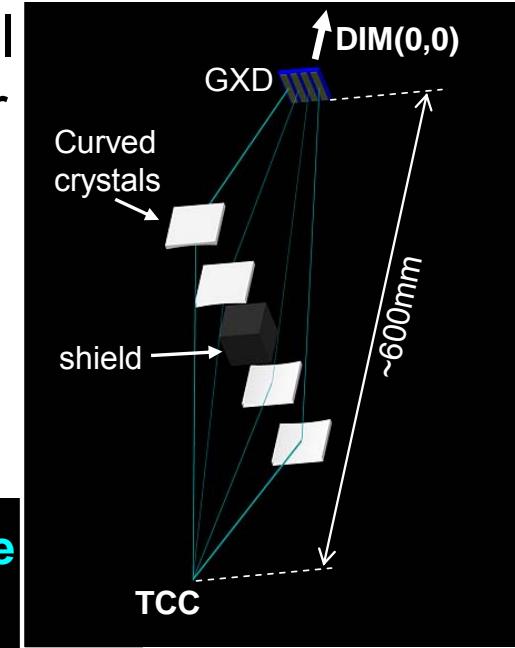
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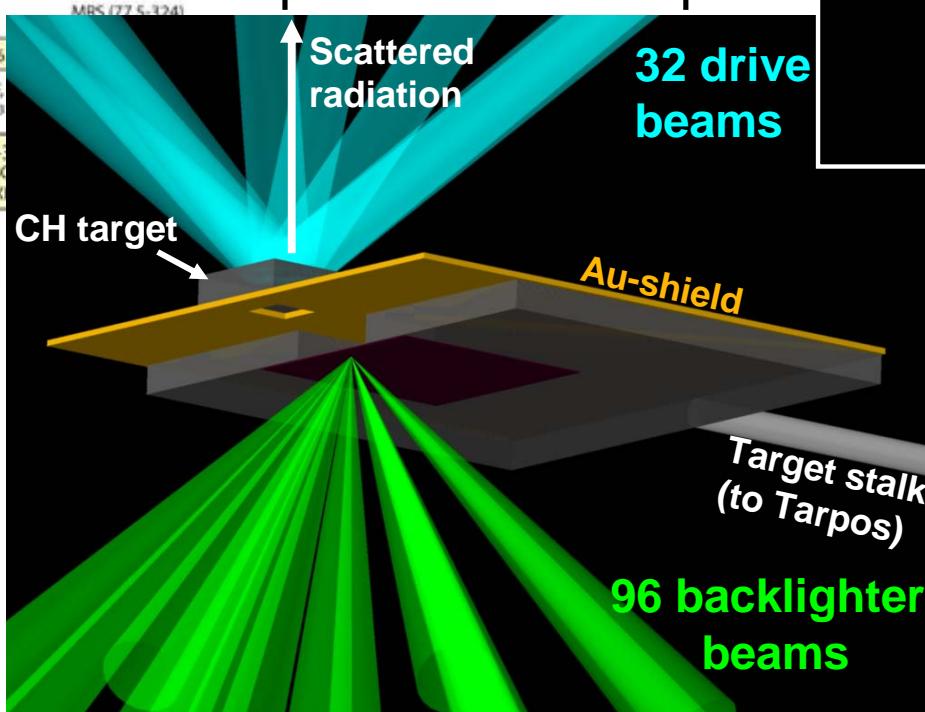
NIF target chamber



Multi-channel spectrometer design



Experimental setup

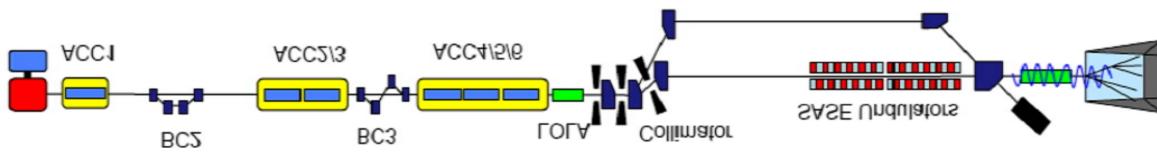


XRTS – the ideal x-ray source...

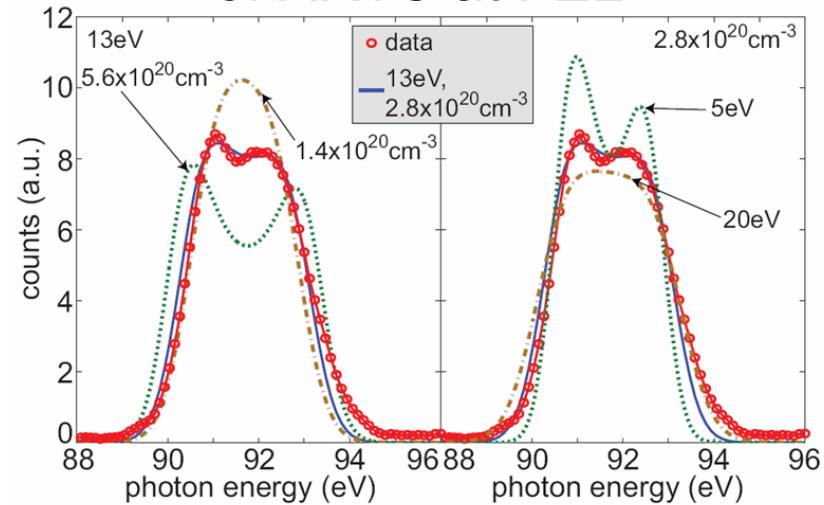


... are X-ray Free-Electron-Lasers (FEL)

- Well-collimated beam → can access large scale lengths
- $<\mu\text{m}$ focusability → can use small targets, gradients less severe
- Few 10fs pulse duration → can probe relaxation of non-equilibrium phenomena
- Small bandwidth → collisionality



At FLASH: First demonstration
of XRTS at FEL

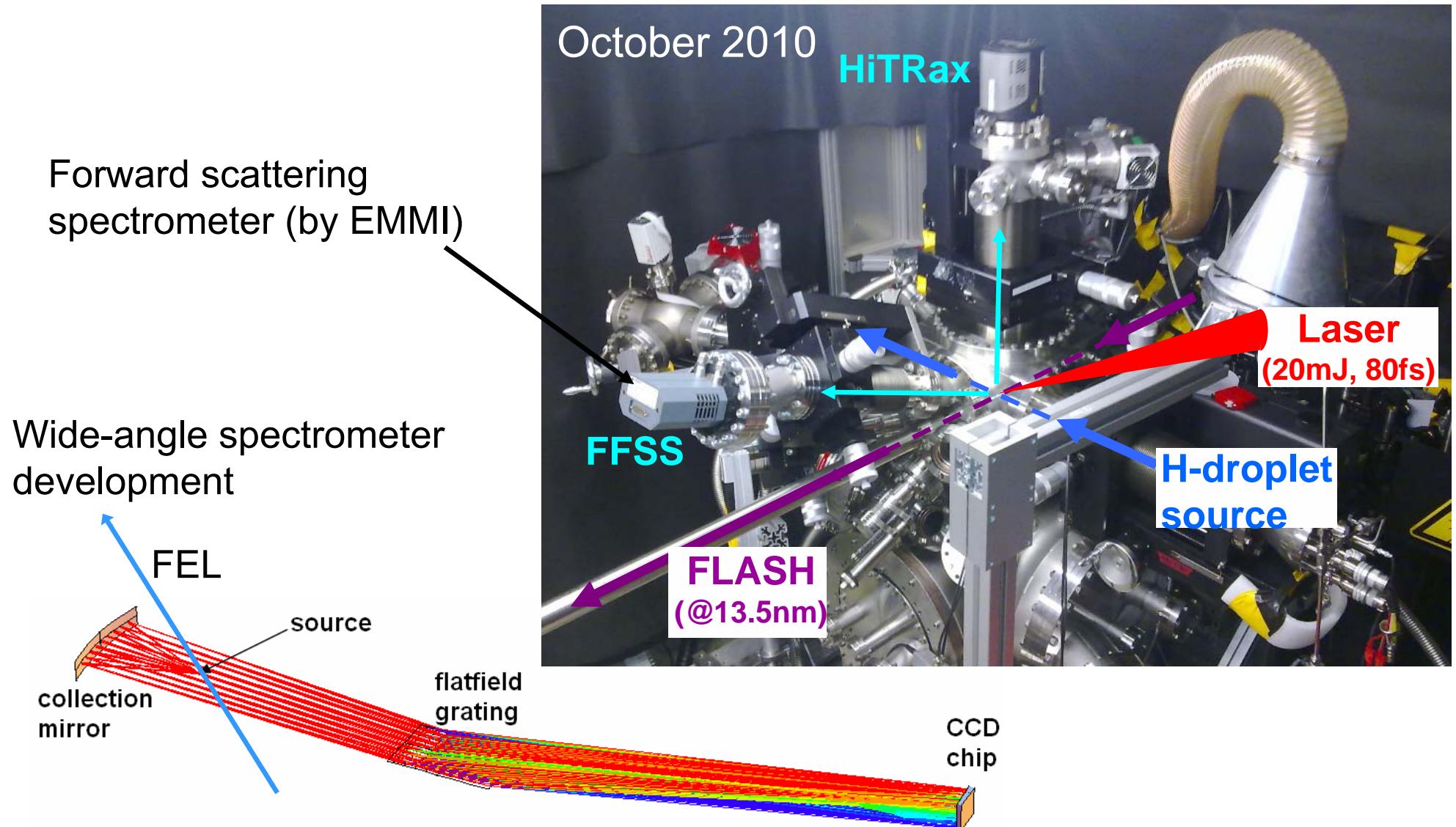


R. R. Fäustlin et al., PRL 104, 125002 (2010)

We have joined the FLASH-TS collaboration



October 2010: achieved laser-pump/FEL-probing

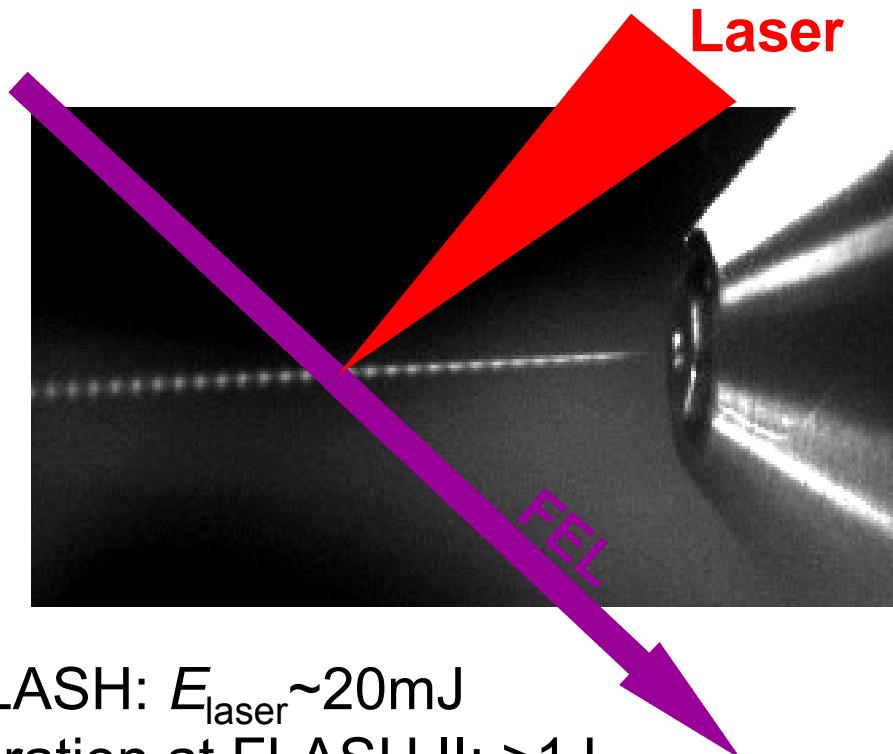


Our targets at FLASH: Laser-heated droplets



Liquid H₂-droplets

Droplet size: 20μm



- Currently at FLASH: $E_{\text{laser}} \sim 20\text{mJ}$
- Under consideration at FLASH II: $> 1\text{J}$
- At European XFEL: $E_{\text{short}} > 10\text{J}$

Droplets: „reduced-mass-target“
Model for laser-droplet heating
(refluxing!)

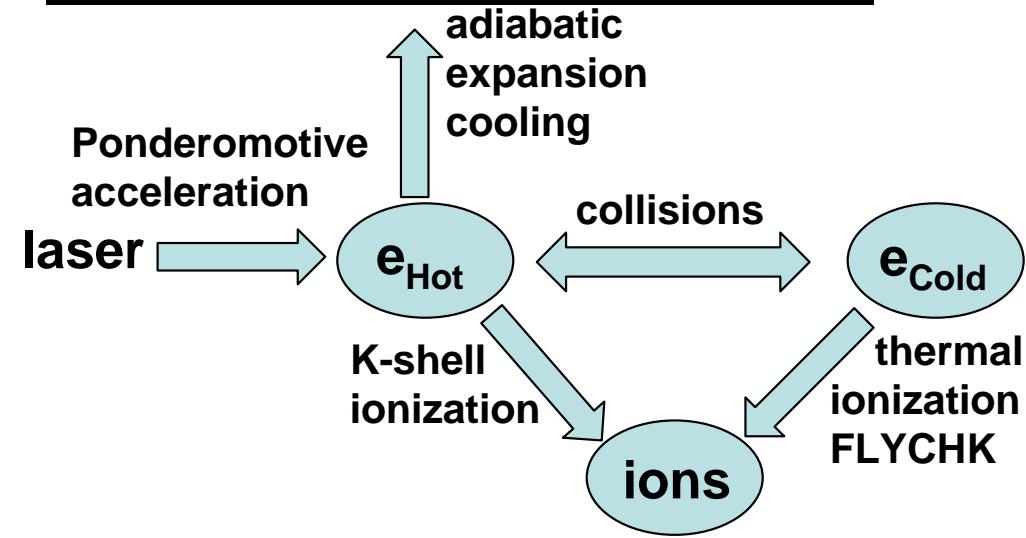
Where could we go with more laser energy



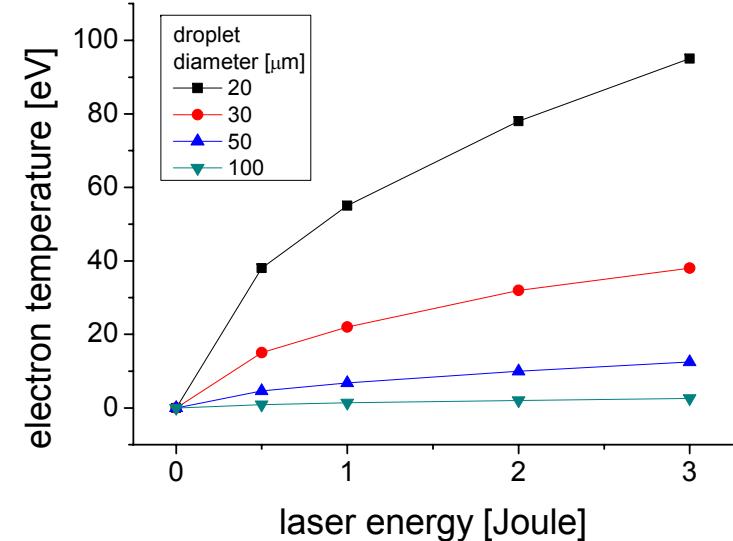
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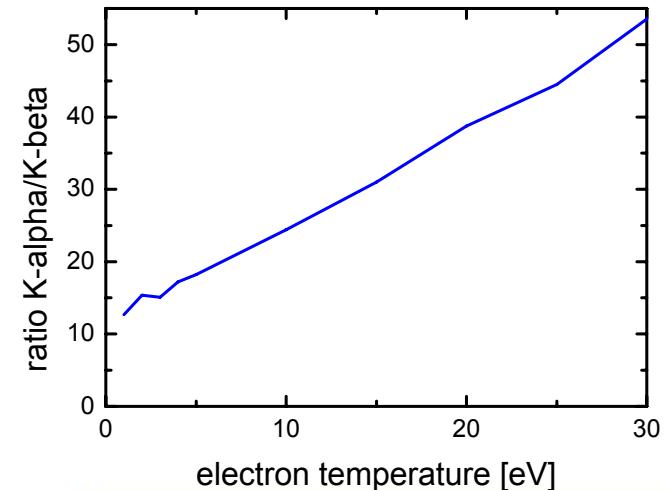
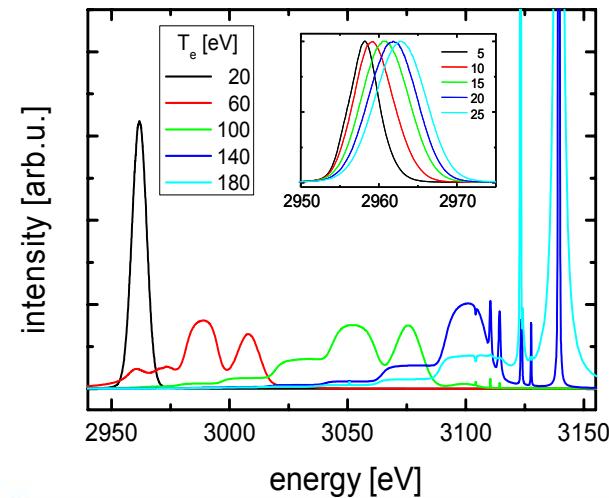
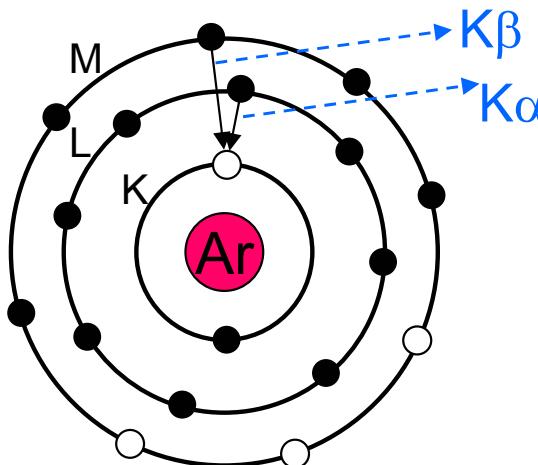
Two-temperature equilibration model



Model prediction for droplet heating



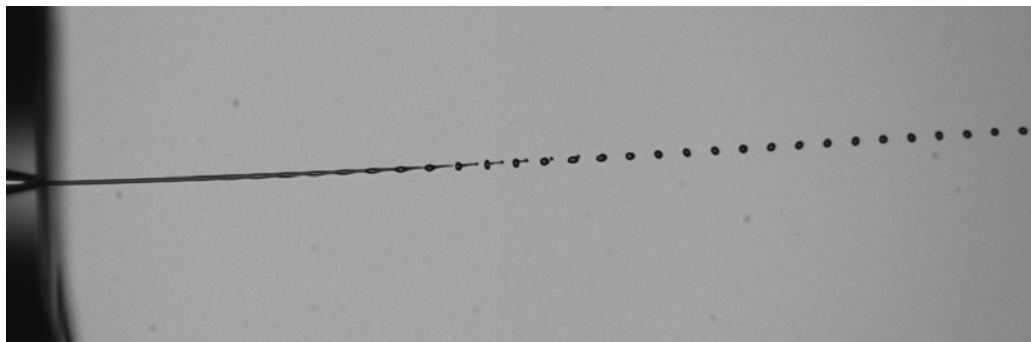
K-shell spectroscopy is suitable as a charge state/temperature diagnostic



Goal: heat droplet targets at PHELIX

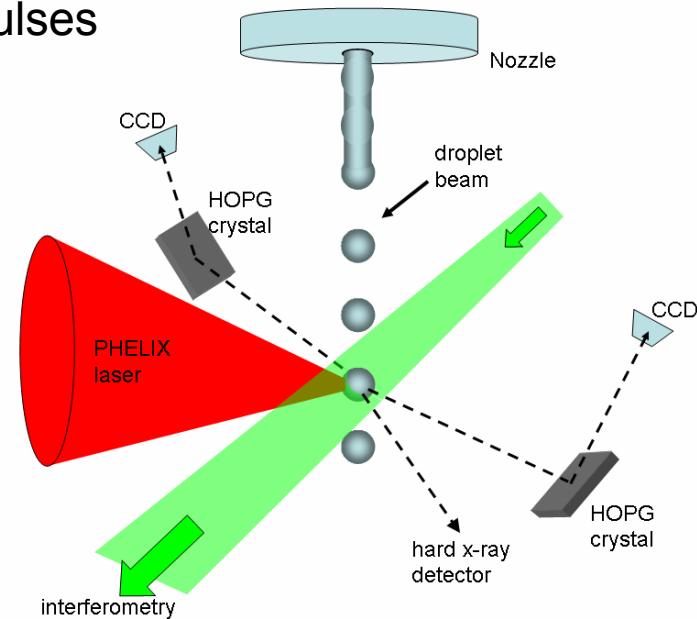


Collaboration with R. Grisenti, Helmholtz-Nachwuchsgruppe HeliJet (Univ. Frankfurt)



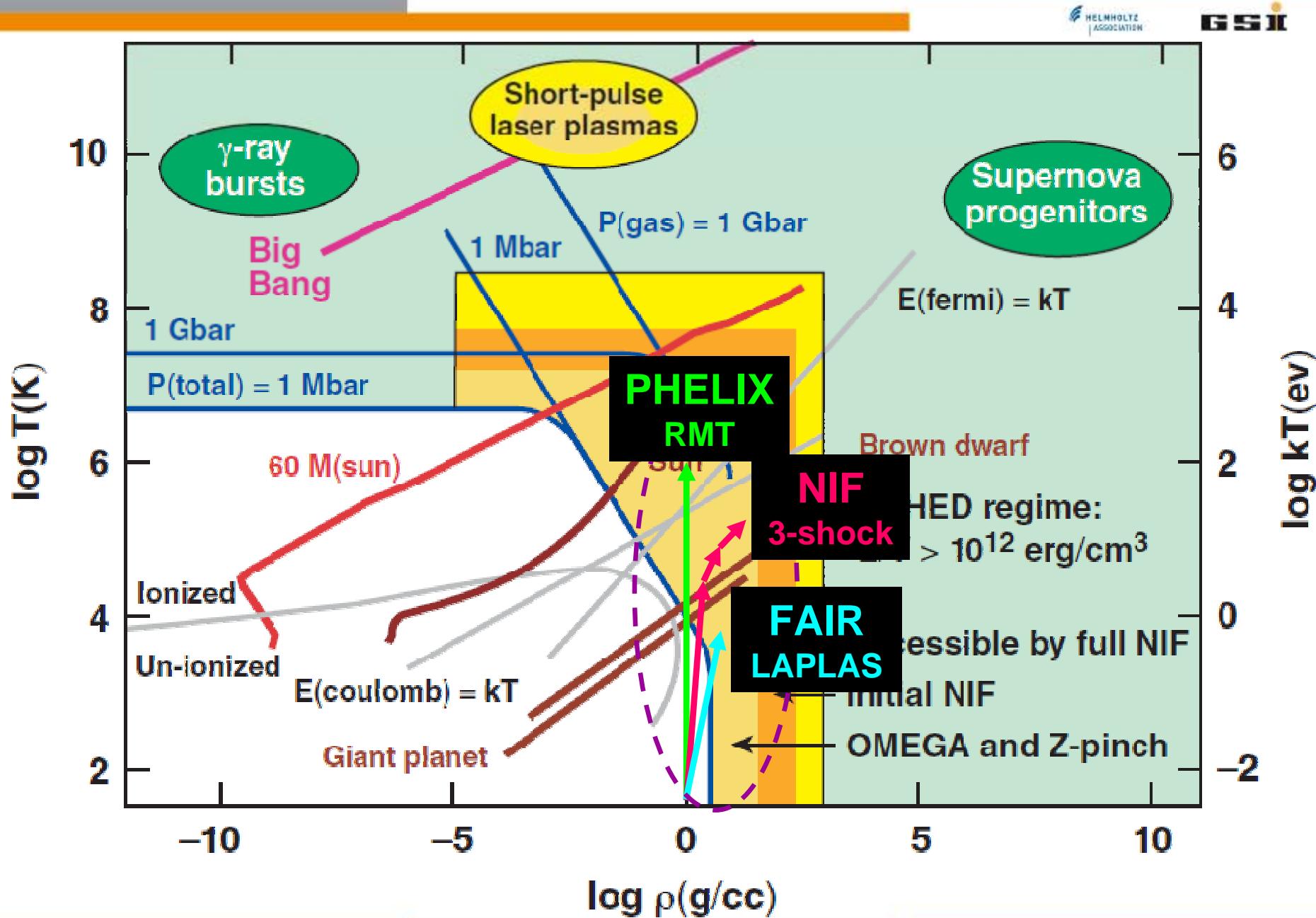
- Cryogenic liquid beam
- Triple-point chamber
- Piezo-excited Raleigh breakup

Proposal 035: Micro droplet targets irradiated with high-intensity laser pulses



S. Toleikis, M. Harmand (DESY), A. Kalinin, R. Costa Fraga, R. Grisenti (IKF, U-Frankfurt), A. Gumberidze, D. Hochhaus, B. Ecker, B. Aurand (EMMI/GSI), N. Winters, D. Winters, Th. Kühl (GSI), B. Zielbauer, T. Stöhlker (HI-Jena, GSI), J. Polz, M. Kaluza (IOQ, FSU Jena, HI-Jena)

Summary



Thank you for your attention!