Ion friction in strongly coupled plasmas

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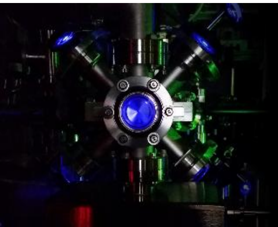


BYU Physics and Astronomy:
Inspiring learning

Special thanks…

- Ross Spencer (BYU)
- Michael Murillo (MSU)
- Scott Baalrud (Iowa)
- Tucker Sprenkle (BYU)
- Many undergraduate students and previous students who have contributed to the development of this work

Send feedback

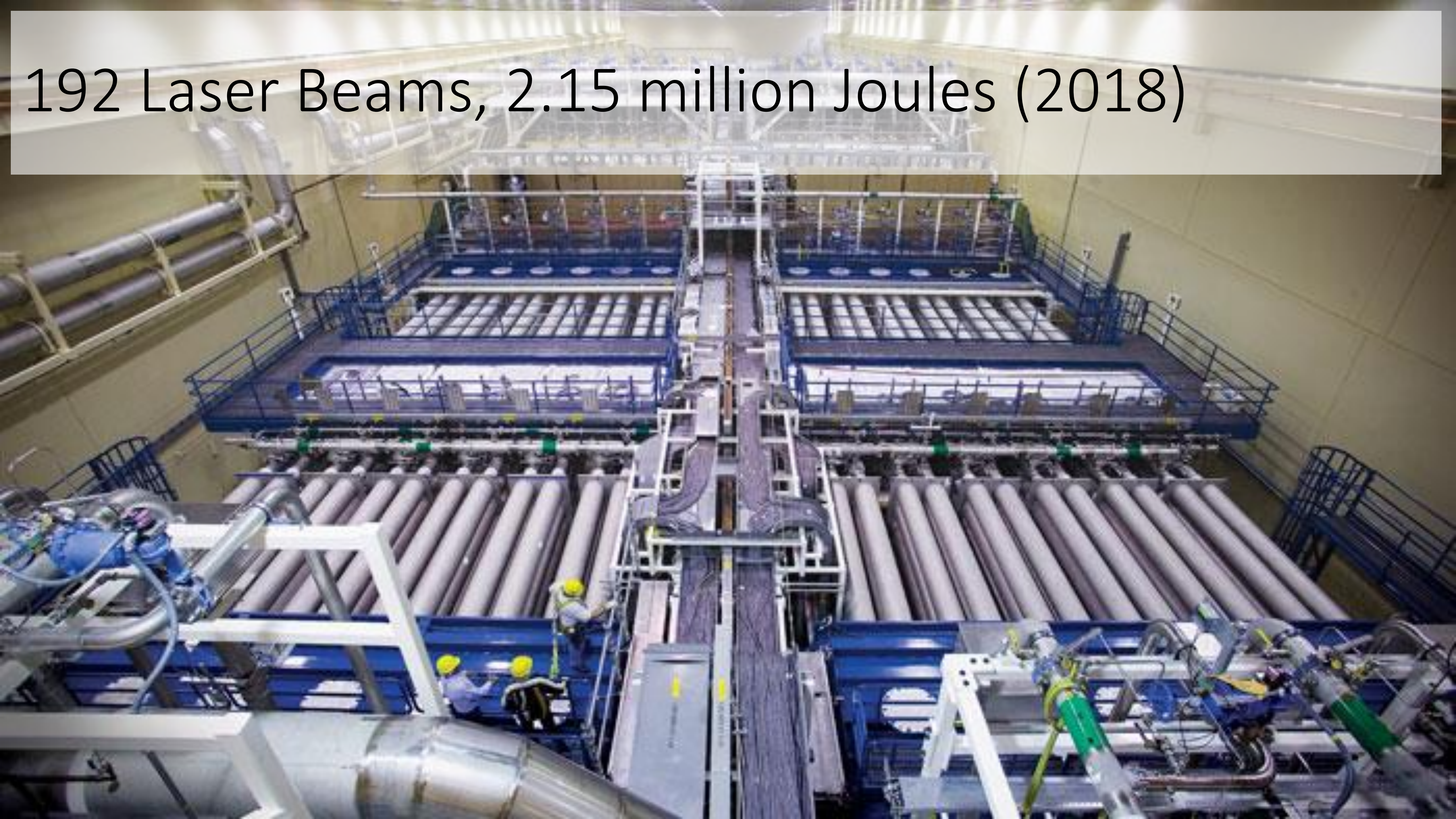
scott.bergeson@byu.edu

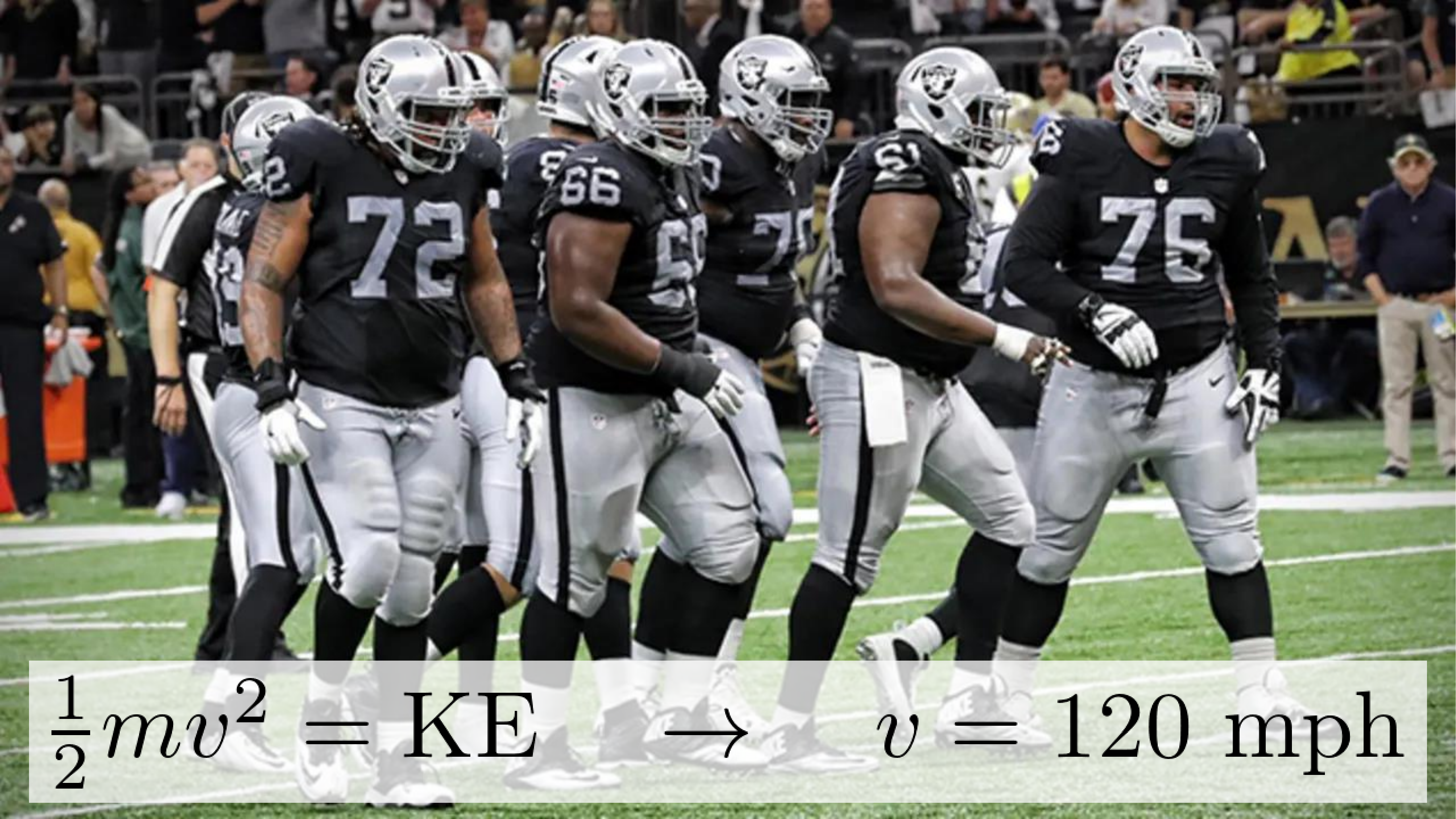
Crazy ideas, stupid things I say, potential future studies, previous work that you know about, relevance to ongoing research, uneducated or illogical statements, extensions of work I present, questions about experimental capabilities, etc.

I welcome your questions and impressions.

National Ignition Facility

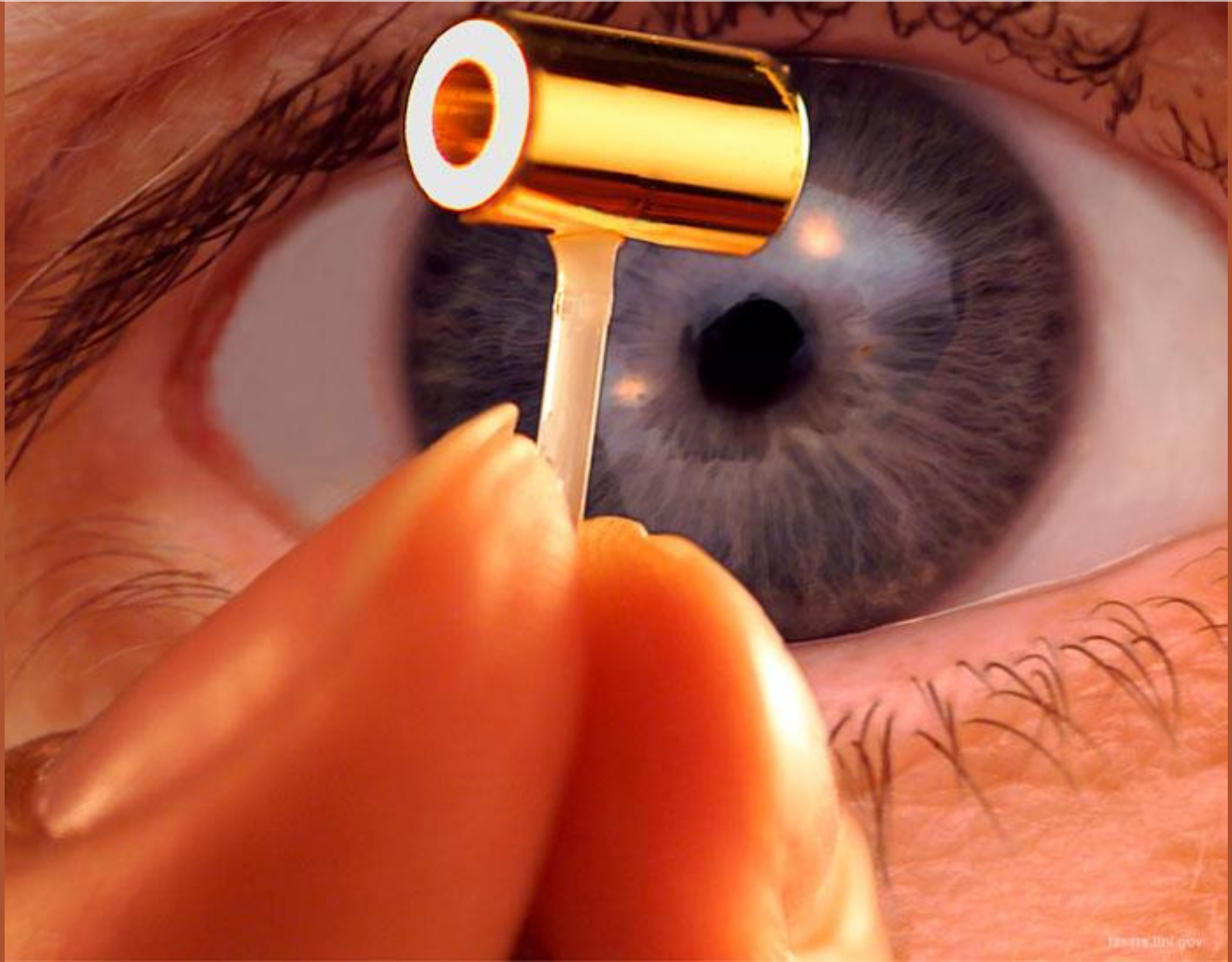
192 Laser Beams, 2.15 million Joules (2018)



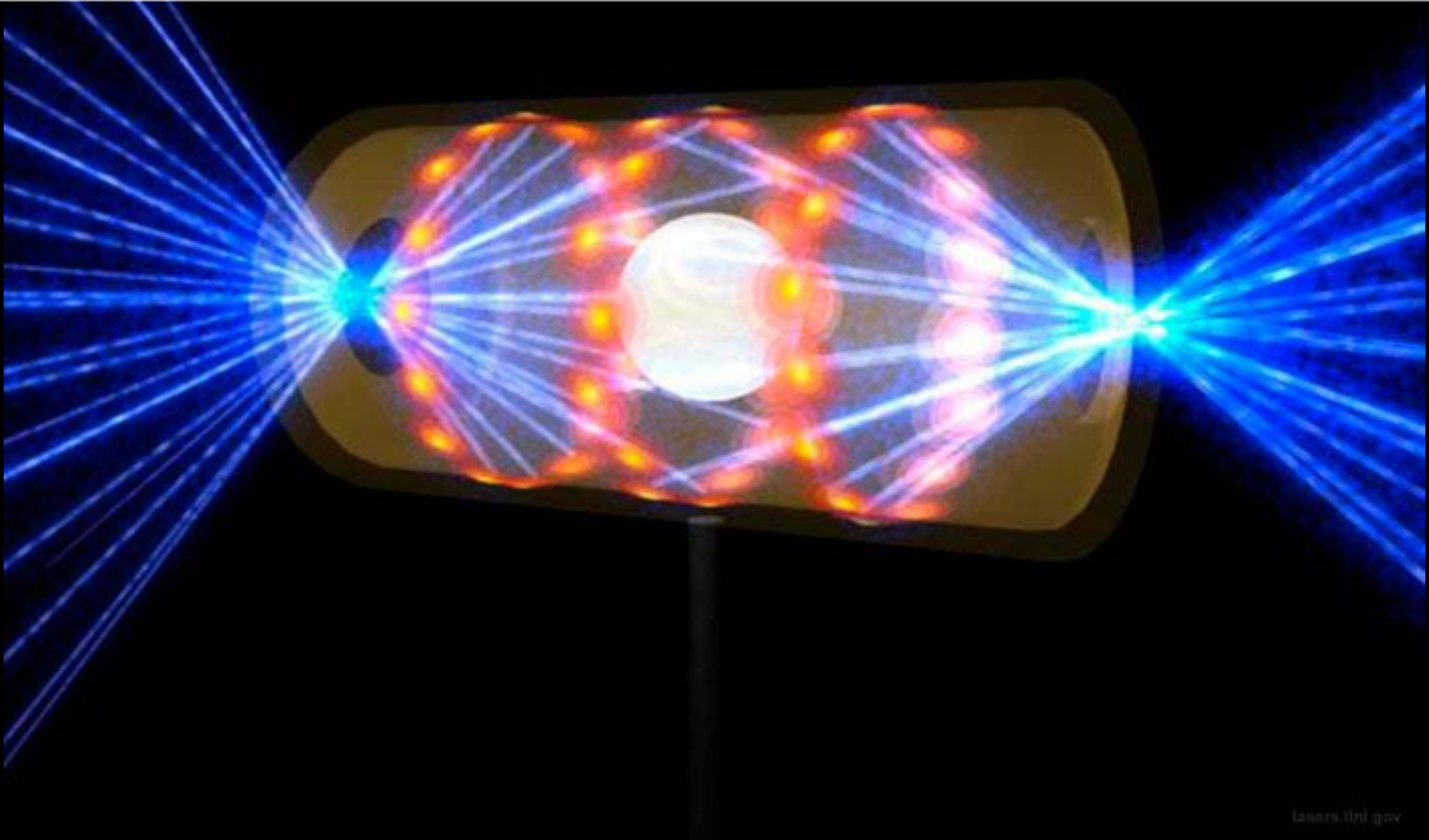


$$\frac{1}{2}mv^2 = \mathrm{KE} \quad \rightarrow \quad v = 120 \text{ mph}$$

Focused to a tiny spot



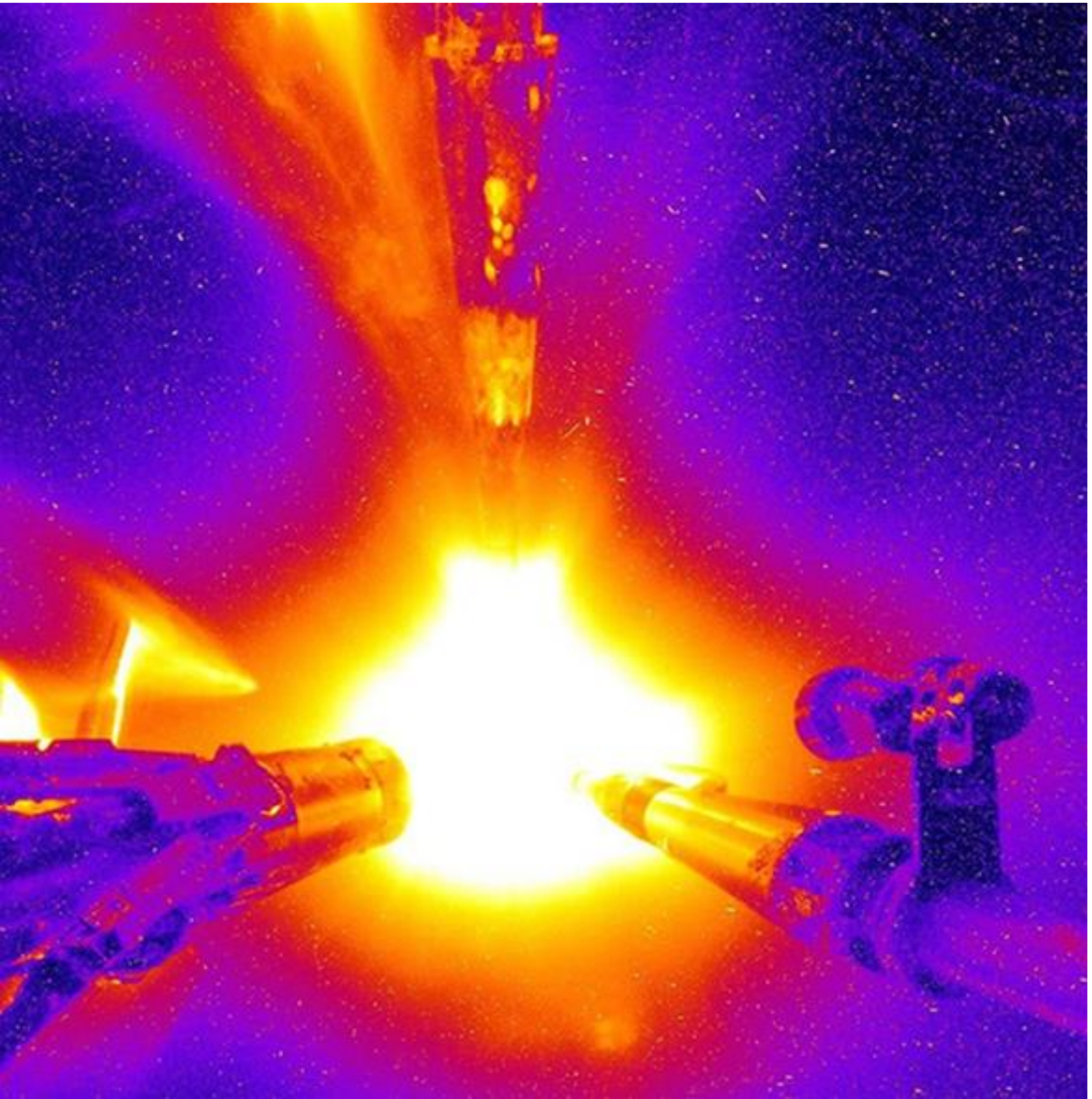
Driving nuclear fusion

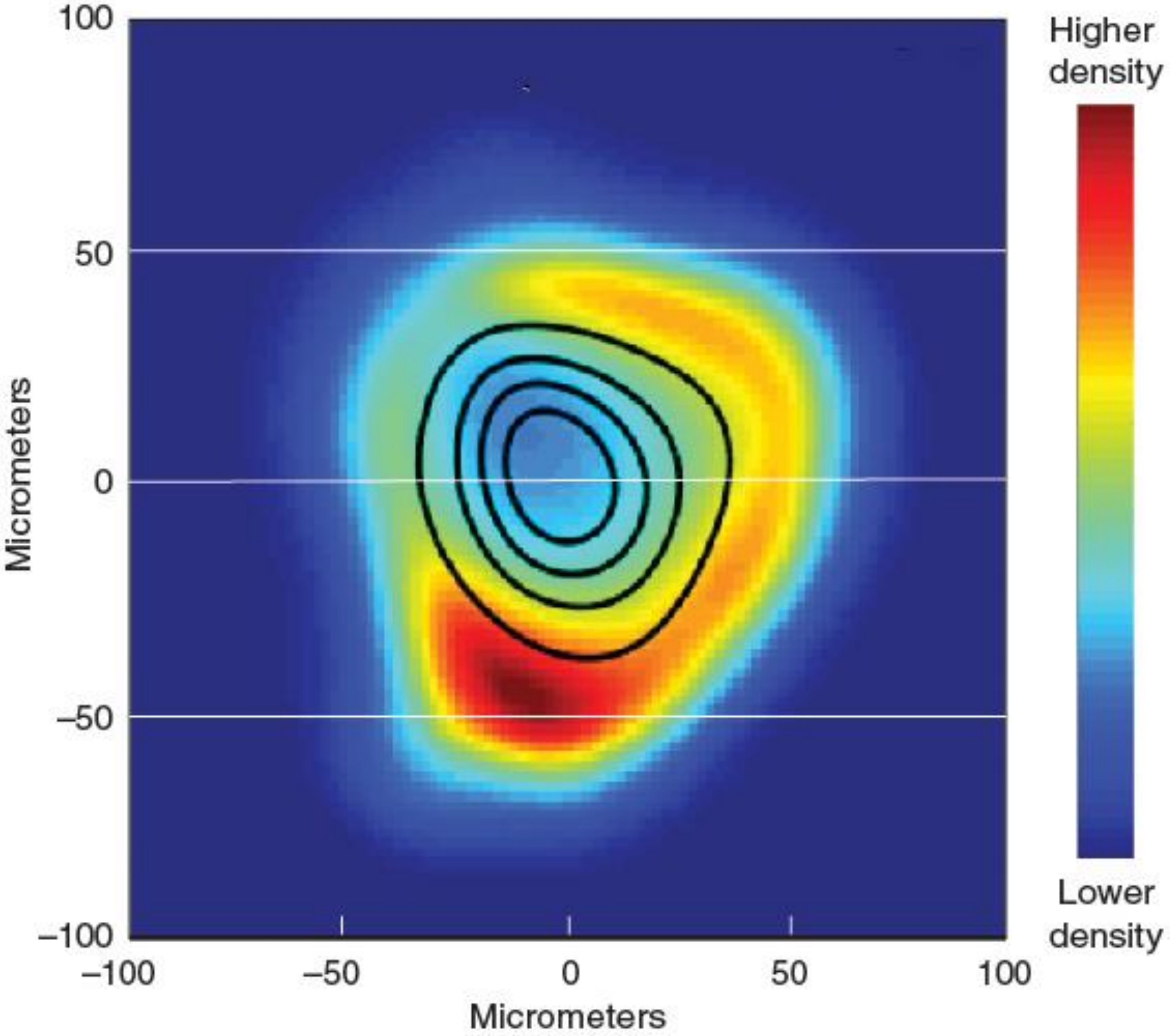


Dedicated 10 years ago, May 29, 2019

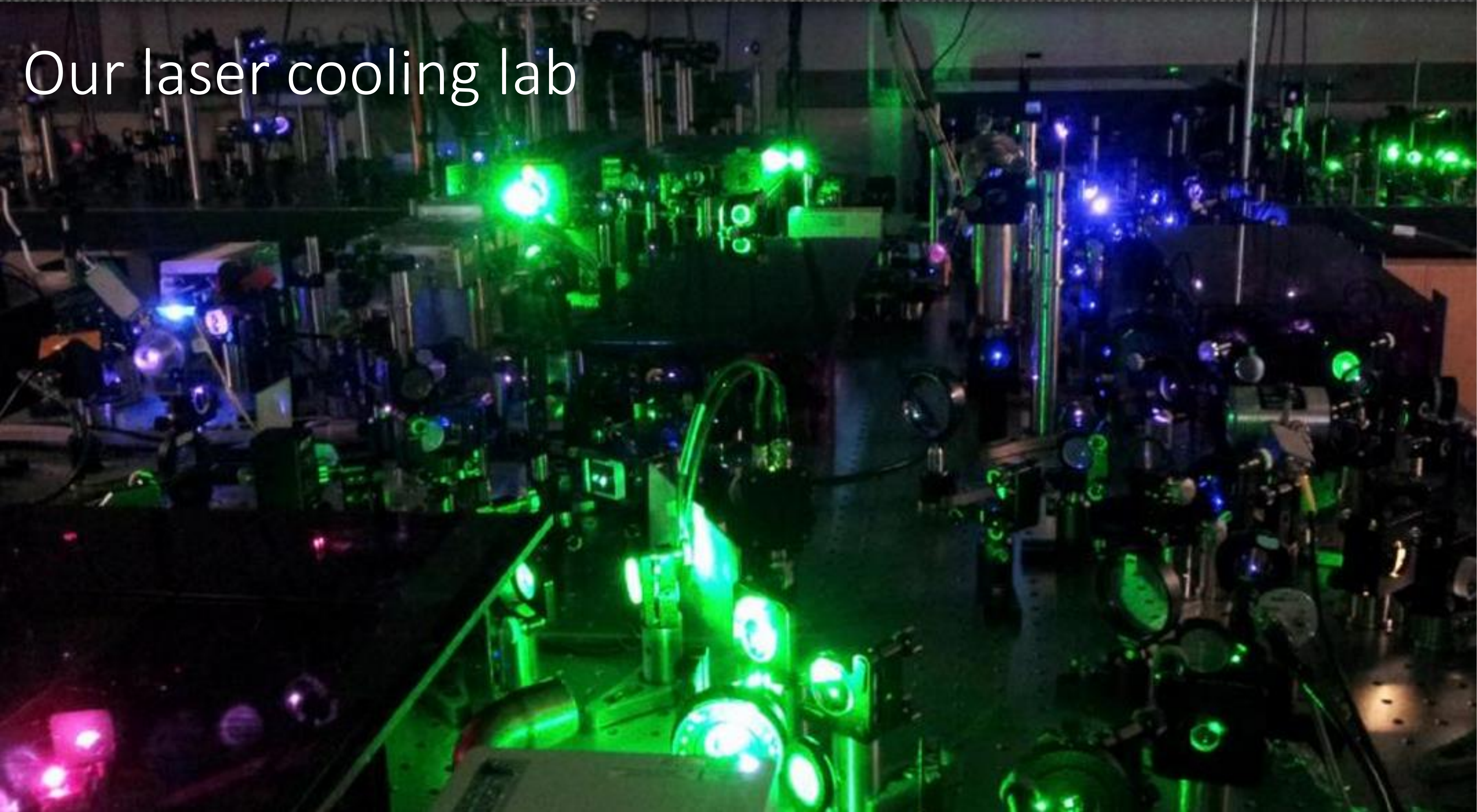
https://str.llnl.gov/2019-04/hurricane

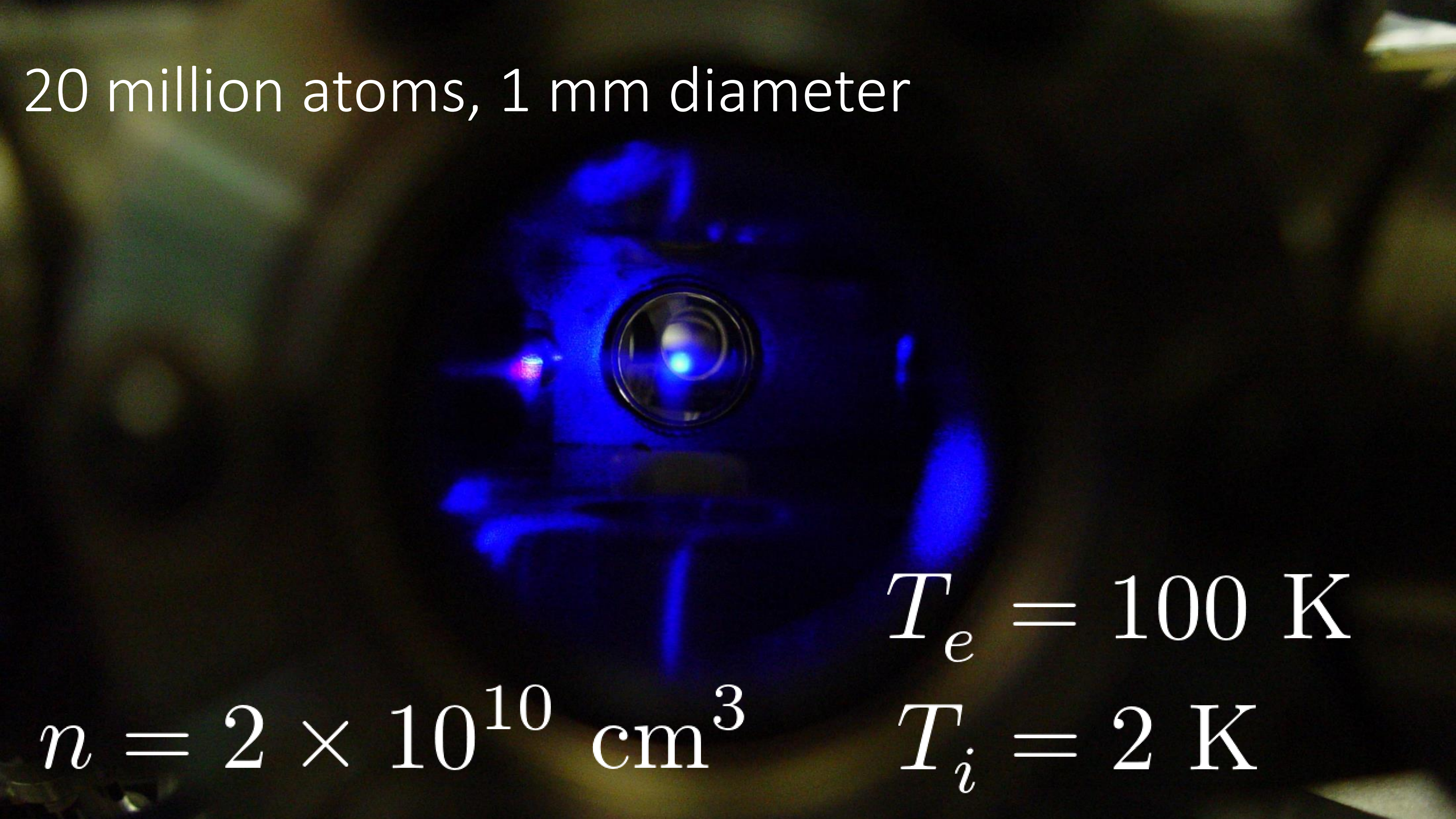
Closing in on Burning Plasma





Our laser cooling lab



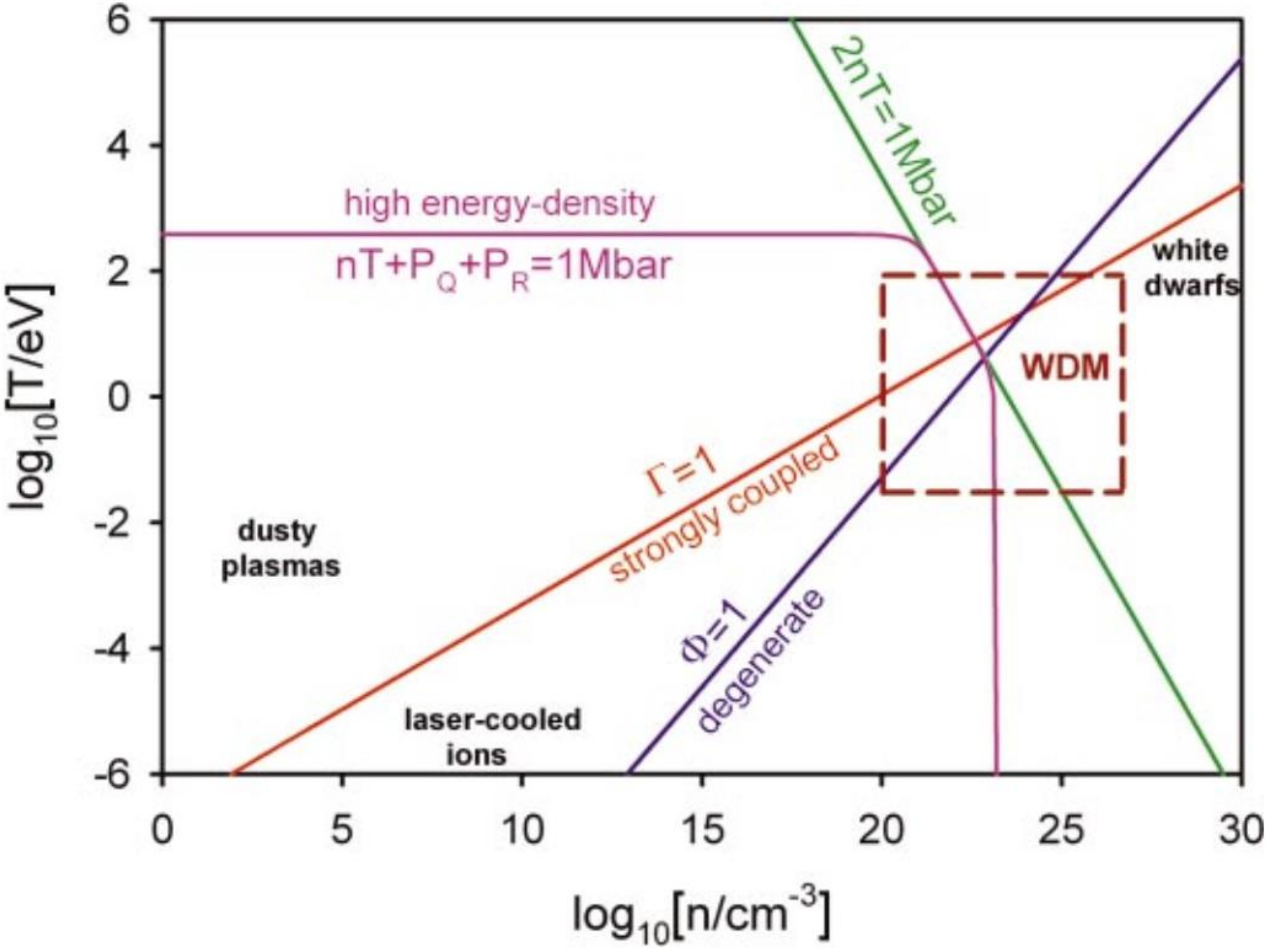

20 million atoms, 1 mm diameter
$T_e = 100\ \mathrm{K}$
$T_i = 2\ \mathrm{K}$
$n = 2 \times 10^{10}\ \mathrm{cm}^3$

One day a great big elephant and an itsy bitsy mouse went for a walk… Soon they came to a bridge [over a small stream]. And as they crossed the brook, the bridge trembled and shook under the weight of the elephant. “Gosh,” squeaked the mouse when they were on the other side of the stream, “Didn’t we make that bridge shake!”

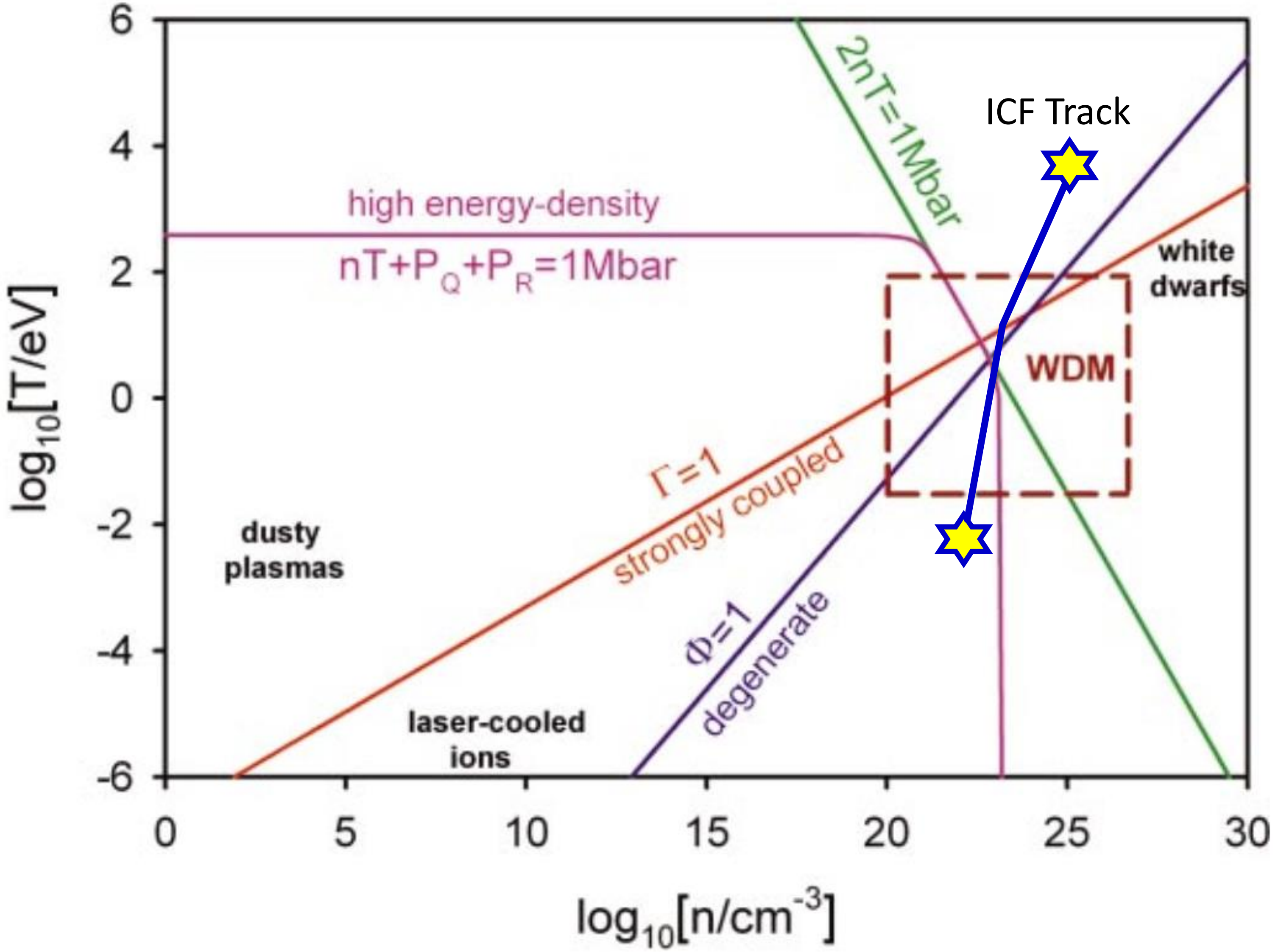
May 17, 1936, Cleveland (Ohio) Plain Dealer Newspaper, Funny Fables by Ed Kuekes

http://listserv.linguistlist.org/pipermail/ads-l/2014-October/134552.html

Strongly coupled Coulomb systems



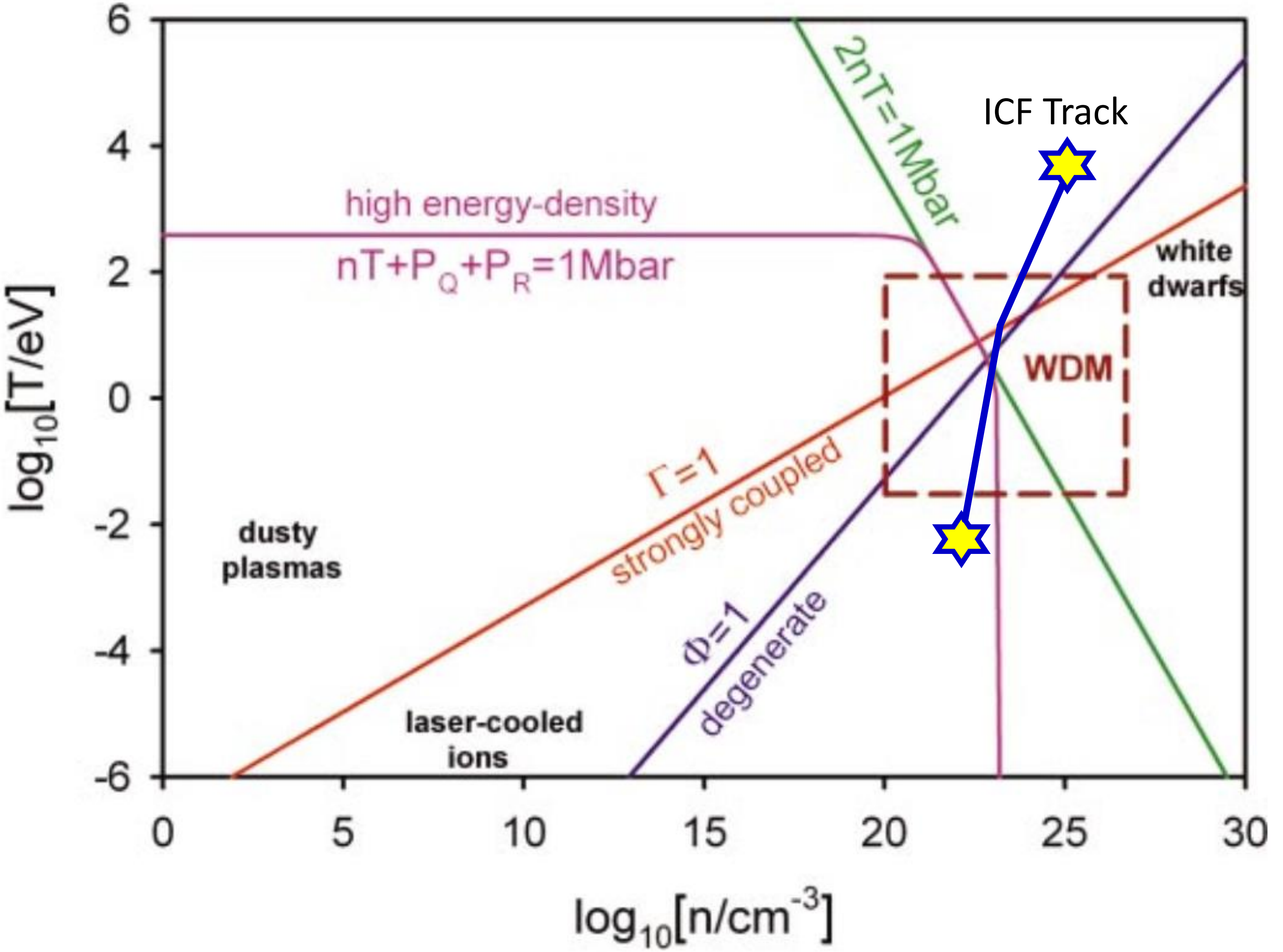
Strongly coupled Coulomb systems



Strongly coupled Coulomb systems

$$U = \frac{e^2}{4\pi\epsilon_0 a_{\mathrm{ws}}}$$

$$k_{\mathrm{B}}T$$

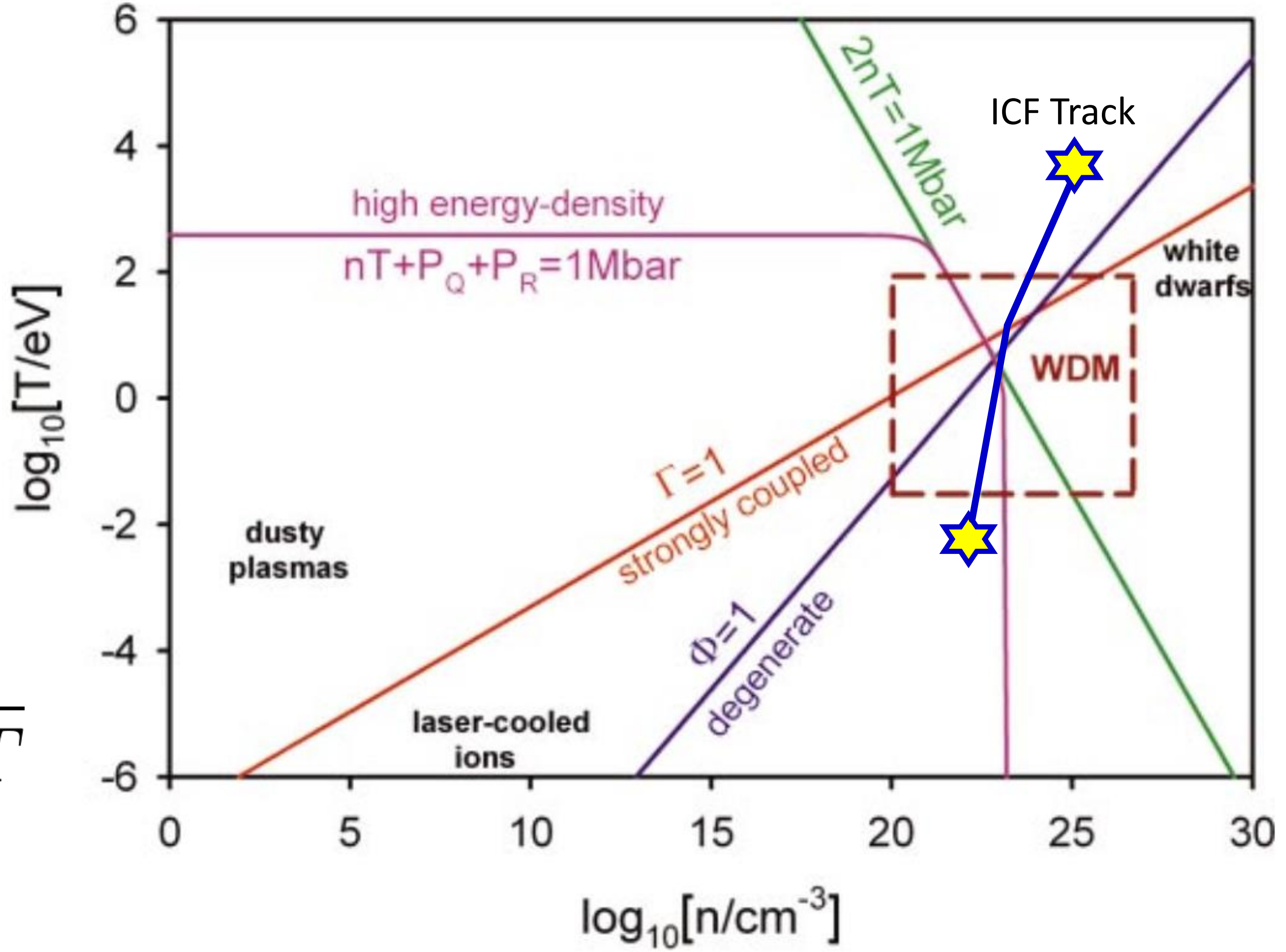


Strongly coupled Coulomb systems

$$\boxed{U = \frac{e^2}{4\pi\epsilon_0 a_{\text{ws}}}} \quad \boxed{k_{\text{B}}T}$$

A ratio of characteristic energies

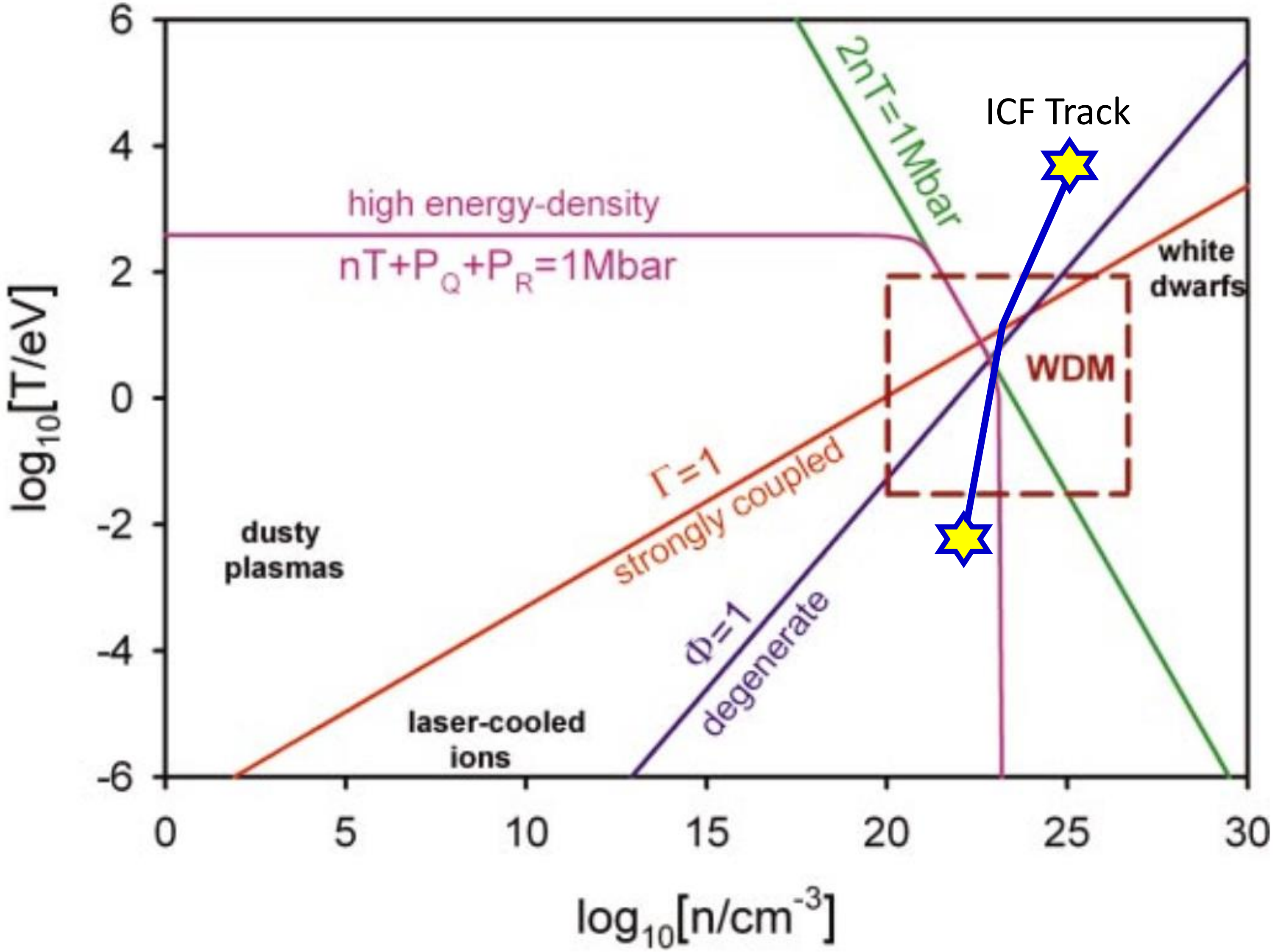
$$\Gamma = \frac{U}{k_{\text{B}}T} = \frac{e^2}{4\pi\epsilon_0 a_{\text{ws}}}\frac{1}{k_{\text{B}}T}$$



Strongly coupled Coulomb systems

$$r_0 = \frac{e^2}{4\pi\epsilon_0 k_\mathrm{B} T}$$

$$a_\mathrm{ws}$$



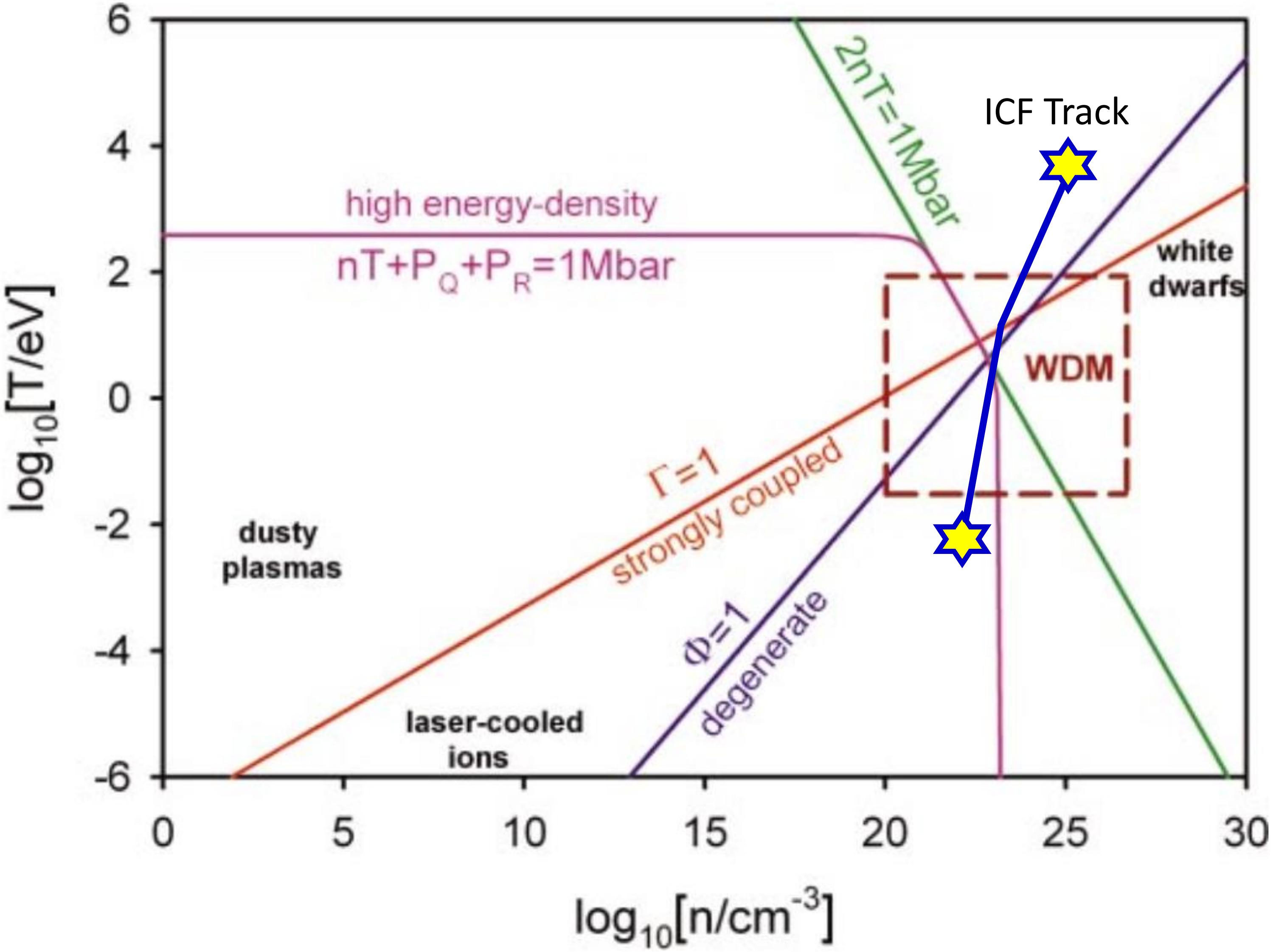
Strongly coupled Coulomb systems

$$r_0 = \frac{e^2}{4\pi\epsilon_0 k_B T}$$

$$a_{ws}$$

A ratio of characteristic lengths

$$\Gamma = \frac{r_0}{a_{ws}} = \frac{e^2}{4\pi\epsilon_0 a_{ws}} \frac{1}{k_B T}$$



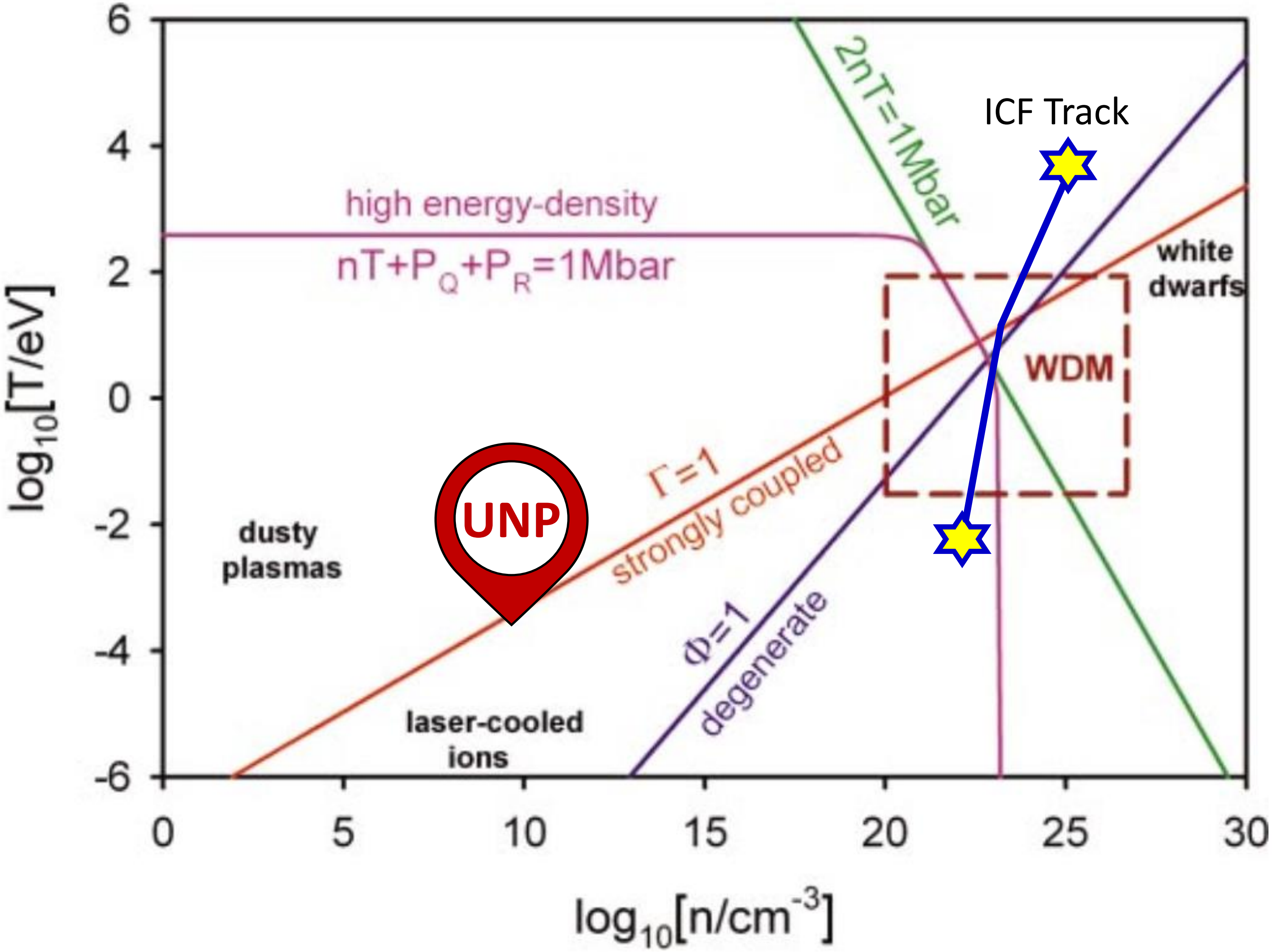
Strongly coupled Coulomb systems

$$r_0 = \frac{e^2}{4\pi\epsilon_0 k_B T}$$

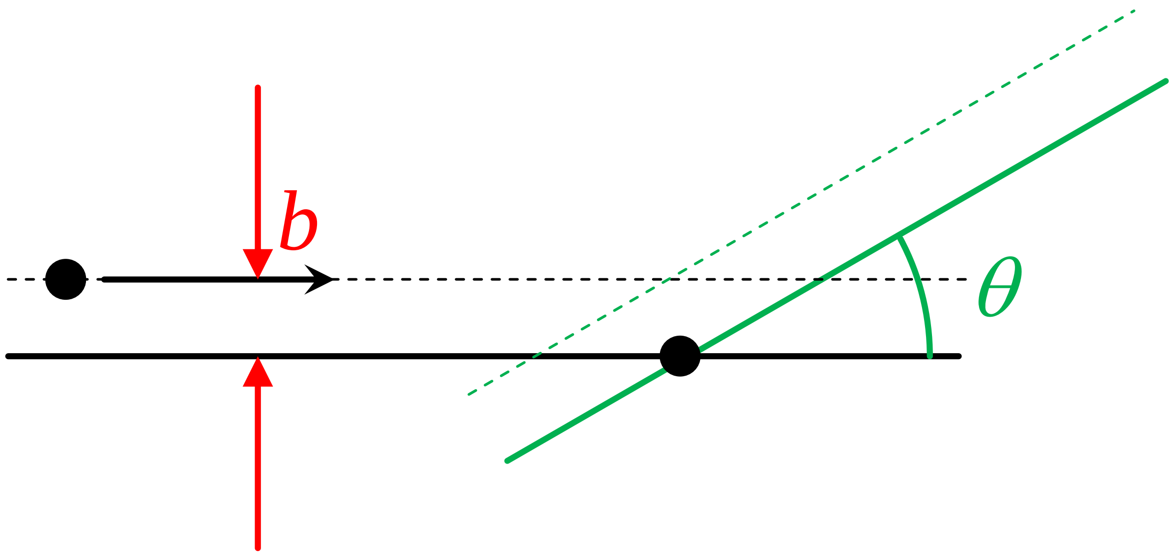
$$a_{ws}$$

A ratio of characteristic lengths

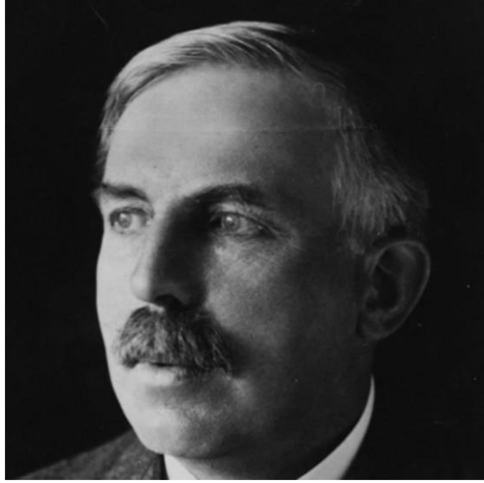
$$\Gamma = \frac{r_0}{a_{ws}} = \left(\frac{r_0^2}{3\lambda_D^2}\right)^{1/3}$$



Rutherford scattering



$$b = \frac{Z_1 Z_2 e^2}{4\pi\epsilon_0 m v_0^2} \cot(\theta/2)$$

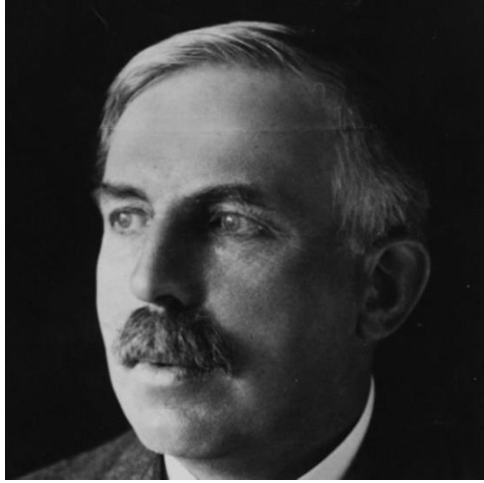


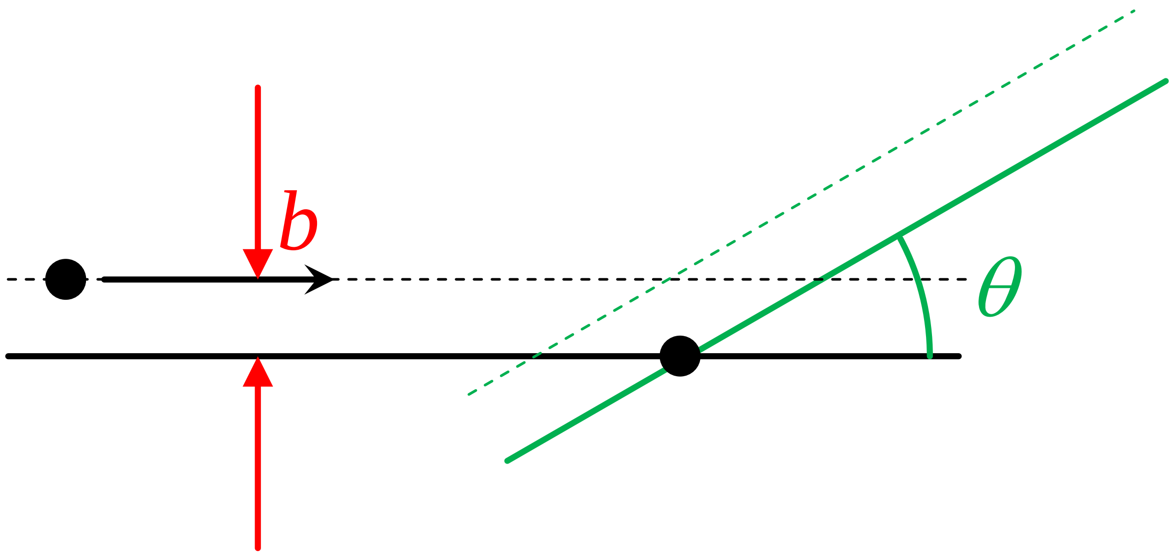
- We have the idea of "cross section"
  - An effective size of the scatterer
  - Allows us to write collision rates as

$$\gamma_{ee} = n\sigma v$$

  - Allows us to think about things like mean free path, scattering probability, etc.

Rutherford scattering





- The Coulomb cross section diverges

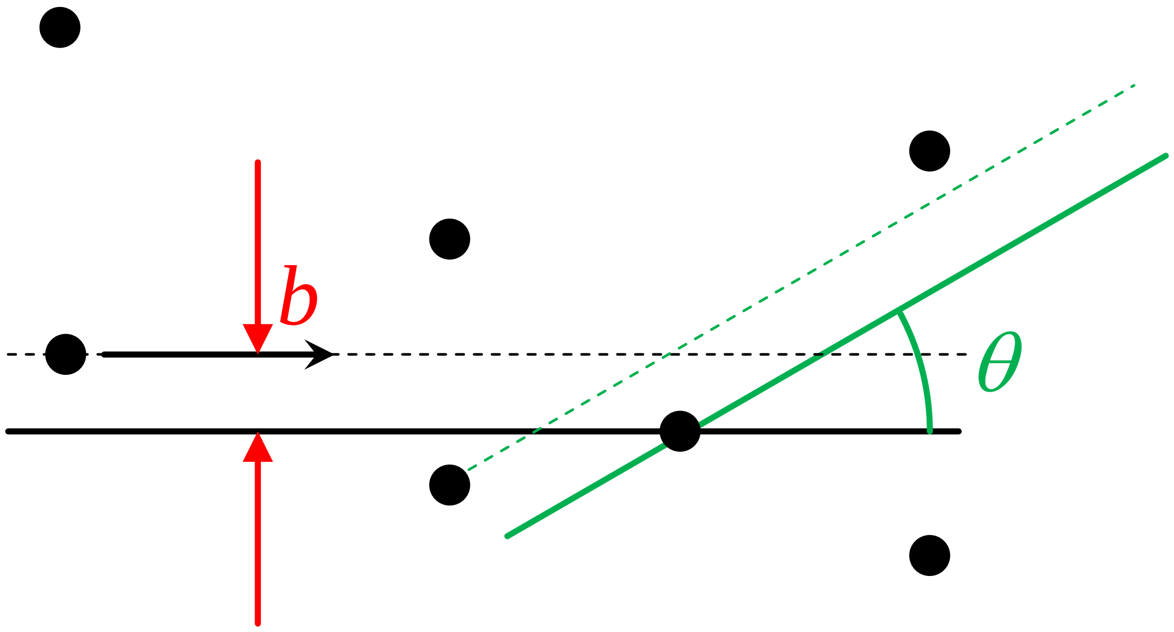
$$\frac{d\sigma}{d\Omega} = \left(\frac{Z_1 Z_2 e^2}{8\pi\epsilon_0 m v_0}\right)^2 \frac{1}{\sin^2(\theta/2)}$$

$$\sigma = 2\pi \int_0^{\pi} \frac{d\sigma}{d\Omega} \to \infty$$

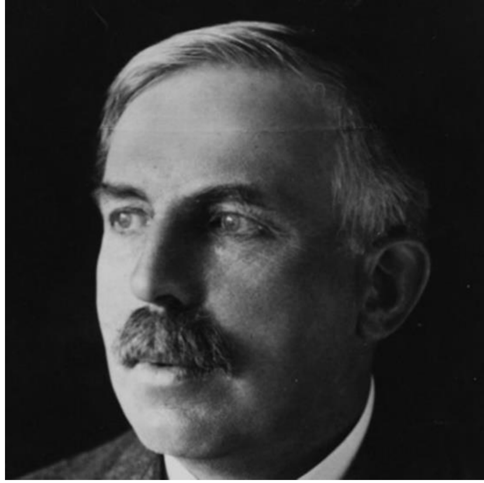
$$\sigma = 2\pi \int_{r_{\min}}^{r_{\max}} \frac{d\sigma}{d\Omega}$$

$$b = \frac{Z_1 Z_2 e^2}{4\pi\epsilon_0 m v_0^2} \cot(\theta/2)$$

Rutherford scattering



$$b = \frac{Z_1 Z_2 e^2}{4\pi\epsilon_0 m v_0^2}\cot(\theta/2)$$

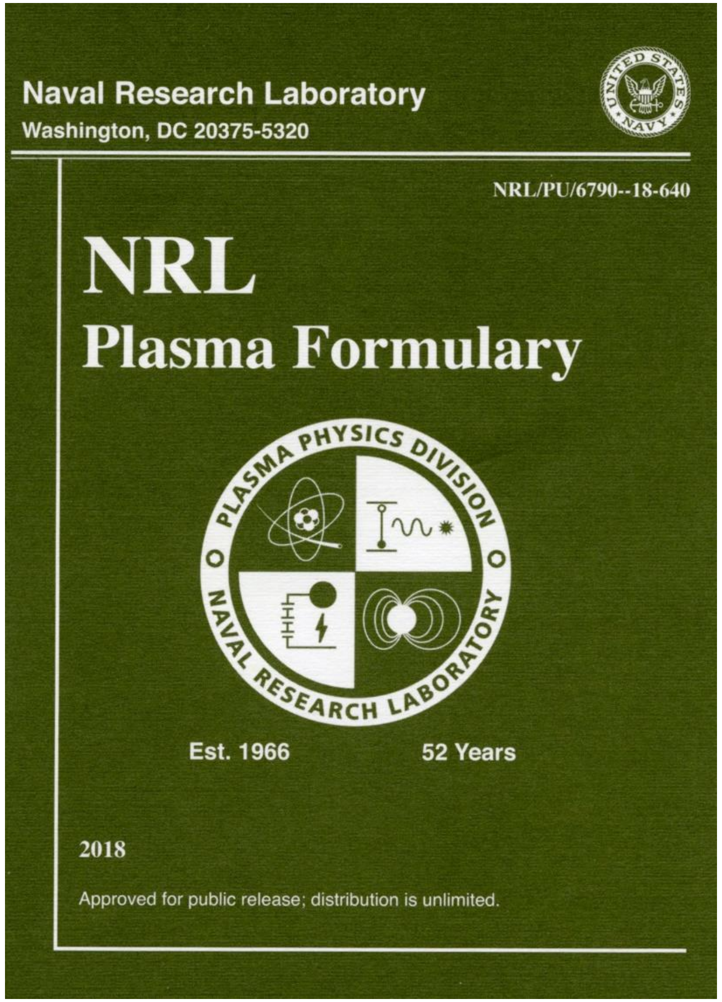


- And there are other particles to worry about

$$\gamma_{ee} = n\sigma v \ln\Lambda$$

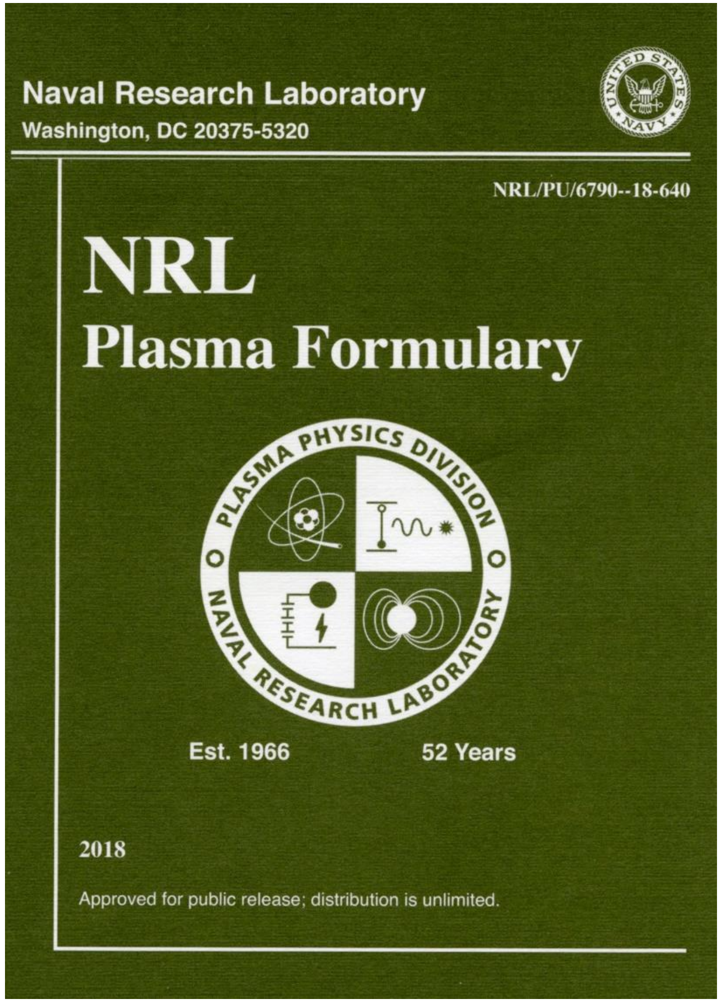
$$\ln\Lambda = \left(\frac{\lambda_D}{r_0}\right) = \frac{1}{2}\ln\left(\frac{1}{3\Gamma^3}\right)$$

$$\lambda_{ee} = \ln\Lambda = \left(\frac{\lambda_D}{r_0}\right) = \frac{1}{2}\ln\left(\frac{1}{3\Gamma^3}\right)$$



	Slow	Fast
Electron–electron		
$\nu_s^{e\|e}/n_e\lambda_{ee}$	$\approx 5.8\times10^{-6}T^{-3/2}$	$\longrightarrow 7.7\times10^{-6}\epsilon^{-3/2}$
$\nu_\perp^{e\|e}/n_e\lambda_{ee}$	$\approx 5.8\times10^{-6}T^{-1/2}\epsilon^{-1}$	$\longrightarrow 7.7\times10^{-6}\epsilon^{-3/2}$
$\nu_\parallel^{e\|e}/n_e\lambda_{ee}$	$\approx 2.9\times10^{-6}T^{-1/2}\epsilon^{-1}$	$\longrightarrow 3.9\times10^{-6}T\epsilon^{-5/2}$
Electron–ion		
$\nu_s^{e\|i}/n_iZ^2\lambda_{ei}$	$\approx 0.23\mu^{3/2}T^{-3/2}$	$\longrightarrow 3.9\times10^{-6}\epsilon^{-3/2}$
$\nu_\perp^{e\|i}/n_iZ^2\lambda_{ei}$	$\approx 2.5\times10^{-4}\mu^{1/2}T^{-1/2}\epsilon^{-1}$	$\longrightarrow 7.7\times10^{-6}\epsilon^{-3/2}$
$\nu_\parallel^{e\|i}/n_iZ^2\lambda_{ci}$	$\approx 1.2\times10^{-4}\mu^{1/2}T^{-1/2}\epsilon^{-1}$	$\longrightarrow 2.1\times10^{-9}\mu^{-1}T\epsilon^{-5/2}$
Ion–electron		
$\nu_s^{i\|e}/n_eZ^2\lambda_{ie}$	$\approx 1.6\times10^{-9}\mu^{-1}T^{-3/2}$	$\longrightarrow 1.7\times10^{-4}\mu^{1/2}\epsilon^{-3/2}$
$\nu_\perp^{i\|e}/n_eZ^2\lambda_{ie}$	$\approx 3.2\times10^{-9}\mu^{-1}T^{-1/2}\epsilon^{-1}$	$\longrightarrow 1.8\times10^{-7}\mu^{-1/2}\epsilon^{-3/2}$
$\nu_\parallel^{i\|e}/n_eZ^2\lambda_{ie}$	$\approx 1.6\times10^{-9}\mu^{-1}T^{-1/2}\epsilon^{-1}$	$\longrightarrow 1.7\times10^{-4}\mu^{1/2}T\epsilon^{-5/2}$
Ion–ion		
$\dfrac{\nu_s^{i\|i'}}{n_{i'}Z^2Z'^2\lambda_{ii'}}$	$\approx 6.8\times10^{-8}\dfrac{\mu'^{1/2}}{\mu}\left(1+\dfrac{\mu'}{\mu}\right)T^{-3/2}$	$\longrightarrow 9.0\times10^{-8}\left(\dfrac{1}{\mu}+\dfrac{1}{\mu'}\right)\dfrac{\mu^{1/2}}{\epsilon^{3/2}}$
$\dfrac{\nu_\perp^{i\|i'}}{n_{i'}Z^2Z'^2\lambda_{ii'}}$	$\approx 1.4\times10^{-7}\mu'^{1/2}\mu^{-1}T^{-1/2}\epsilon^{-1}$	$\longrightarrow 1.8\times10^{-7}\mu^{-1/2}\epsilon^{-3/2}$

$$\lambda_{ee} = \ln\Lambda = \left(\frac{\lambda_{\mathrm{D}}}{r_0}\right) = \frac{1}{2}\ln\left(\frac{1}{3\Gamma^3}\right)$$



Slow

Electron–electron

$$\nu_s^{e|e}/n_e\lambda_{ee} \approx 5.8\times10^{-6}T^{-3/2}$$
$$\nu_\perp^{e|e}/n_e\lambda_{ee} \approx 5.8\times10^{-6}T^{-1/2}\epsilon$$
$$\nu_\parallel^{e|e}/n_e\lambda_{ee} \approx 2.9\times10^{-6}T^{-1/2}\epsilon$$

Electron–ion

$$\nu_s^{e|i}/n_iZ^2\lambda_{ei} \approx 0.23\mu^{3/2}T^{-3/2}$$
$$\nu_\perp^{e|i}/n_iZ^2\lambda_{ei} \approx 2.5\times10^{-4}\mu^{1/2}T^{-}$$
$$\nu_\parallel^{e|i}/n_iZ^2\lambda_{ei} \approx 1.2\times10^{-4}\mu^{1/2}T^{-}$$

Ion–electron

$$\nu_s^{i|e}/n_eZ^2\lambda_{ie} \approx 1.6\times10^{-9}\mu^{-1}T^{-}$$
$$\nu_\perp^{i|e}/n_eZ^2\lambda_{ie} \approx 3.2\times10^{-9}\mu^{-1}T^{-}$$
$$\nu_\parallel^{i|e}/n_eZ^2\lambda_{ie} \approx 1.6\times10^{-9}\mu^{-1}T^{-}$$

Ion–ion

$$\frac{\nu_s^{i|i'}}{n_{i'}Z^2Z'^2\lambda_{ii'}} \approx 6.8\times10^{-8}\frac{\mu'^{1/2}}{\mu}\Big($$

$$\frac{\nu_\perp^{i|i'}}{n_{i'}Z^2Z'^2\lambda_{ii'}} \approx 1.4\times10^{-7}\mu'^{1/2}\mu^{-}$$

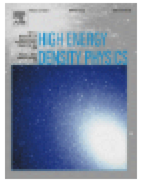
$$\Gamma \to 1$$

Evidence for Highly Charged Ion Coulomb Crystallization in Multicomponent Strongly Coupled Plasmas

L. Gruber, J. P. Holder, J. Steiger, B. R. Beck, H. E. DeWitt, J. Glassman, J. W. McDonald, D. A. Church, and D. Schneider
Phys. Rev. Lett. **86**, 636 – Published 22 January 2001

ELSEVIER

High Energy Density Physics
Volume 8, Issue 1, March 2012, Pages 105-131



Large-scale molecular dynamics simulations of dense plasmas: The Cimarron Project

Frank R. Graziani [a], Victor S. Batista [c], Lorin X. Benedict [a], John I. Castor [a], Hui Chen [a], Sophia N. Chen [a], Chris A. Fichtl [b], James N. Glosli [a], Paul E. Grabowski [b], Alexander T. Graf [a], Stefan P. Hau-Riege [a], Andrew U. Hazi [a], Saad A. Khairallah [a], Liam Krauss [a], A. Bruce Langdon [a], Richard A. London [a], Andreas Markmann [c], Michael S. Murillo [b] ... Heather D. Whitley [a]

Nuclear fusion in dense plasmas

Setsuo Ichimaru
Rev. Mod. Phys. **65**, 255 – Published 1 April 1993

Experimental Measurement of Self-Diffusion in a Strongly Coupled Plasma

T. S. Strickler, T. K. Langin, P. McQuillen, J. Daligault, and T. C. Killian
Phys. Rev. X **6**, 021021 – Published 17 May 2016

Measurement of Correlation-Enhanced Collision Rates

F. Anderegg, D. H. E. Dubin, T. M. O'Neil, and C. F. Driscoll
Phys. Rev. Lett. **102**, 185001 – Published 6 May 2009

Effective Potential Theory for Transport Coefficients across Coupling Regimes

Scott D. Baalrud and Jérôme Daligault
Phys. Rev. Lett. **110**, 235001 – Published 4 June 2013

Molecular dynamics simulations and generalized Lenard-Balescu calculations of electron-ion temperature equilibration in plasmas

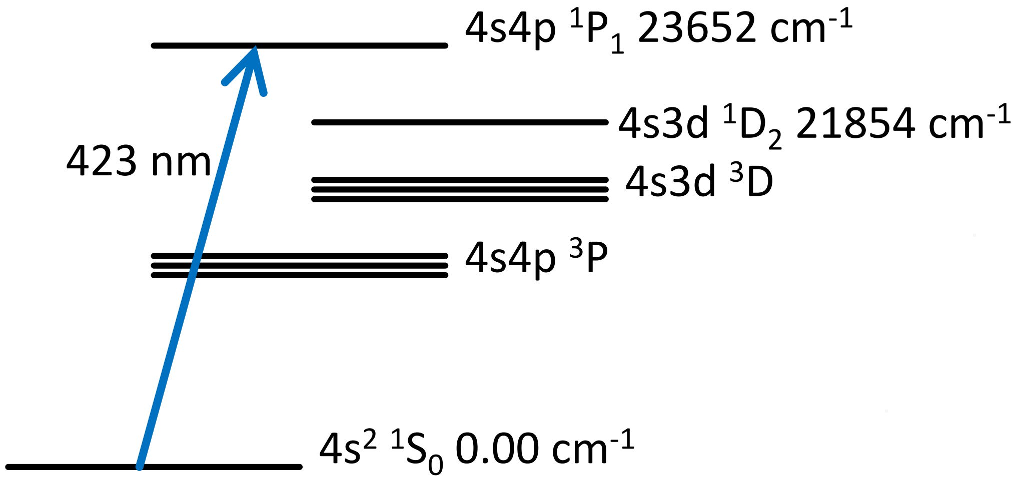
Lorin X. Benedict, Michael P. Surh, John I. Castor, Saad A. Khairallah, Heather D. Whitley, David F. Richards, James N. Glosli, Michael S. Murillo, Christian R. Scullard, Paul E. Grabowski, David Michta, and Frank R. Graziani
Phys. Rev. E **86**, 046406 – Published 25 October 2012

Let's design an experiment: Test lnΛ in the strongly-coupled regime

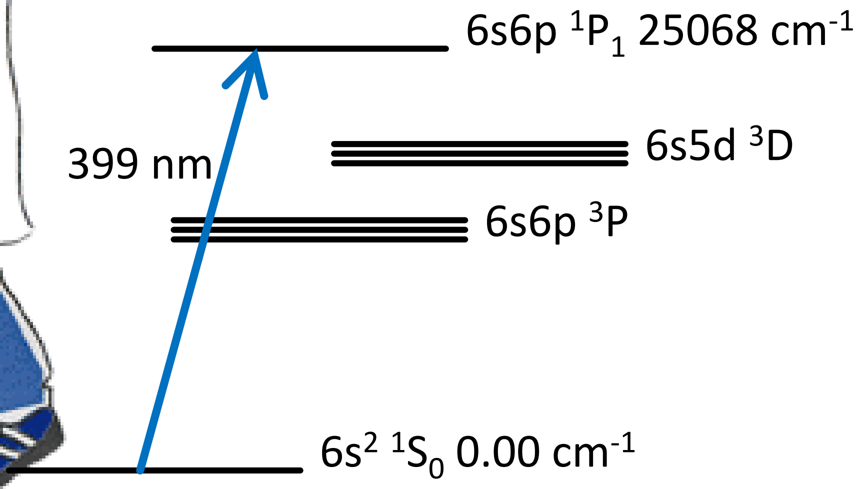
- Momentum transfer
- Γ = 2
- Yb^+ and Ca^+ (4:1 mass ratio)
- Use laser spectroscopy to measure the velocity distribution
- Simulate the experiment using a fluid code
- Use different formulations of the momentum transfer cross section
- Compare lab data and simulation data

Ultracold neutral plasmas

PRL 95, 235001 (2005)



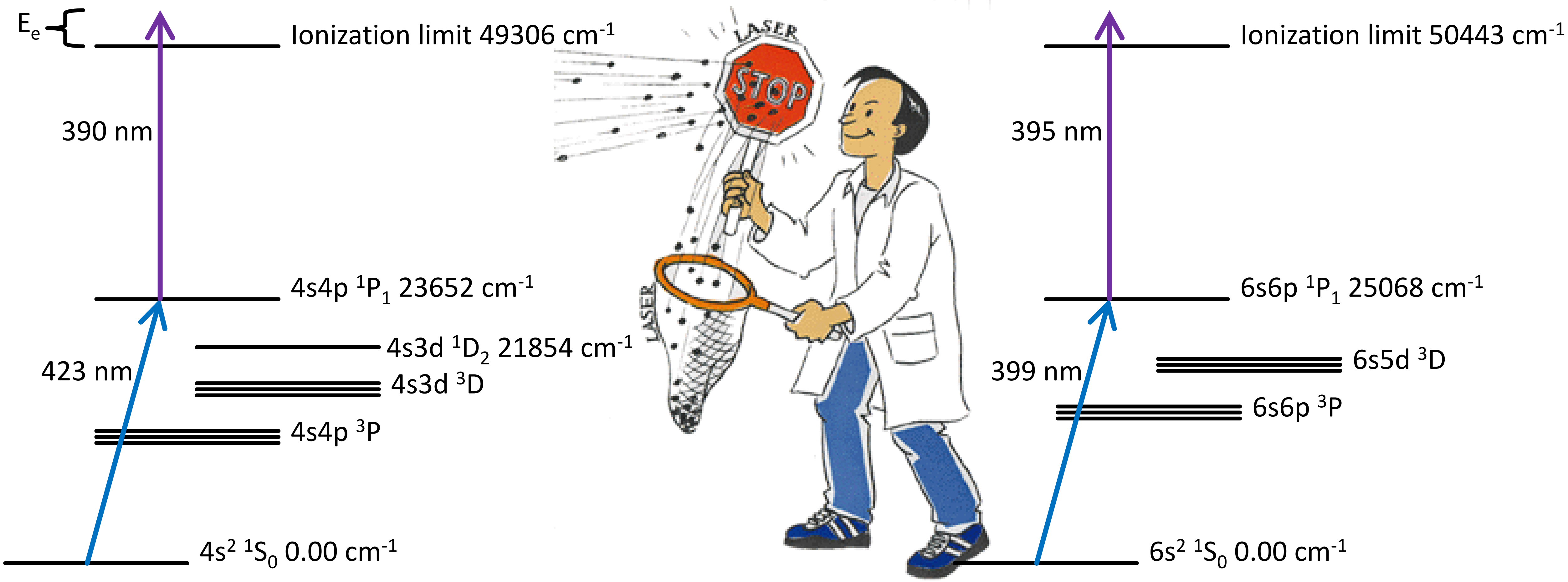
Neutral calcium



Neutral ytterbium

Ultracold neutral plasmas

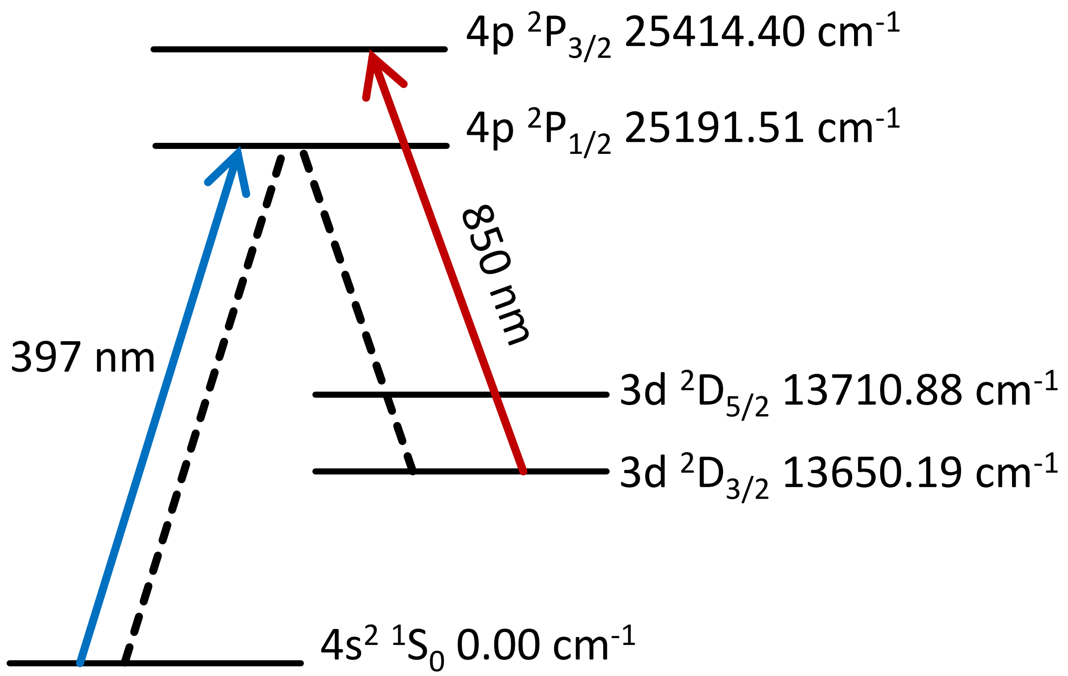
PRL 95, 235001 (2005)



Neutral calcium

Neutral ytterbium

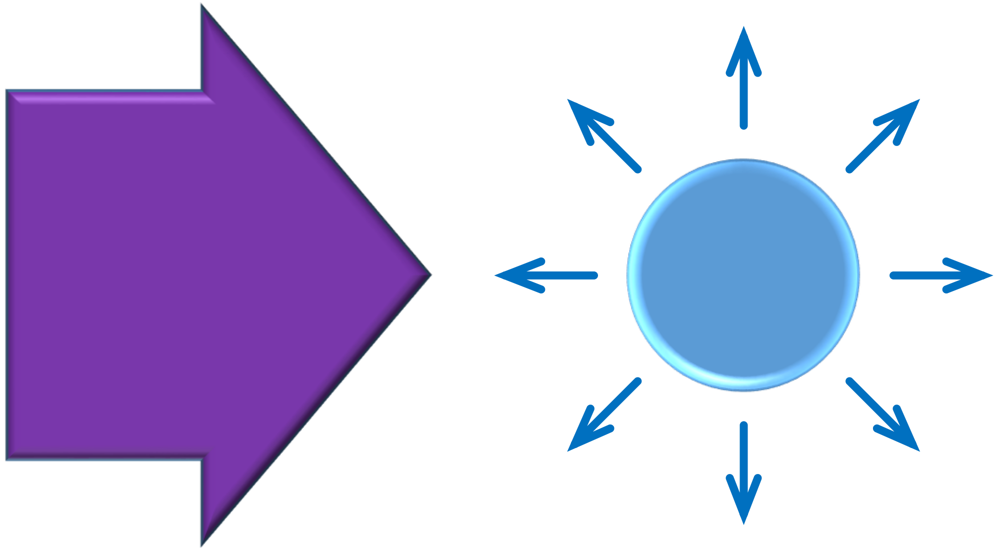
Laser-induced fluorescence



Singly-Ionized Calcium

- Trap neutral atoms in the MOT
- Resonantly photo-ionize the atoms to create a plasma
- Excite laser-induced fluorescence in the plasma ions

Laser-induced fluorescence

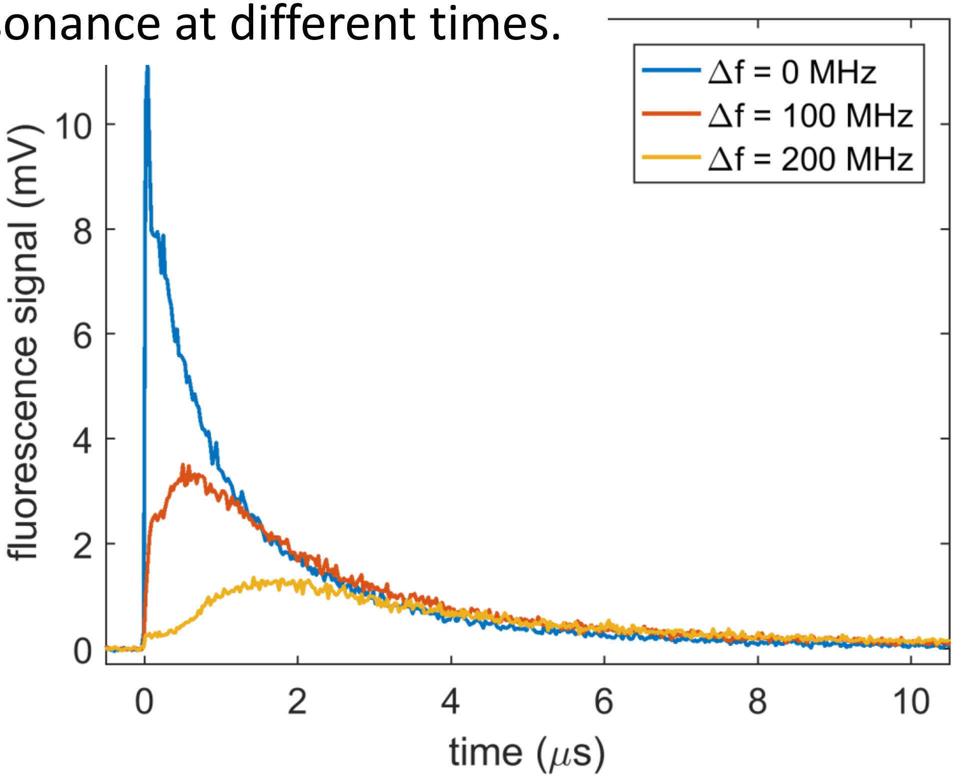


$$a = -\frac{k_{\mathrm{B}} T_e}{m_i} \frac{\nabla n(r,t)}{n(r,t)}$$

- Trap neutral atoms in the MOT
- Resonantly photo-ionize the atoms to create a plasma
- Excite laser-induced fluorescence in the plasma ions
- Measure fluorescence vs. time in repeated measurements at different laser frequencies

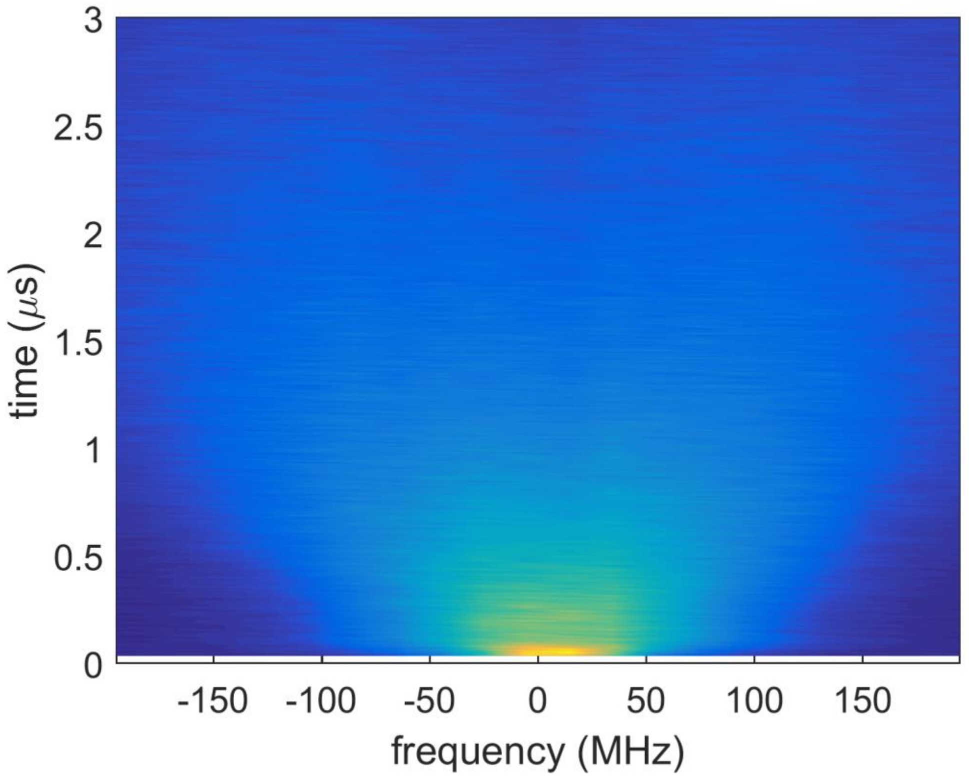
Laser-induced fluorescence

Signal is proportional to the number of ions Doppler-shifted into resonance at different times.



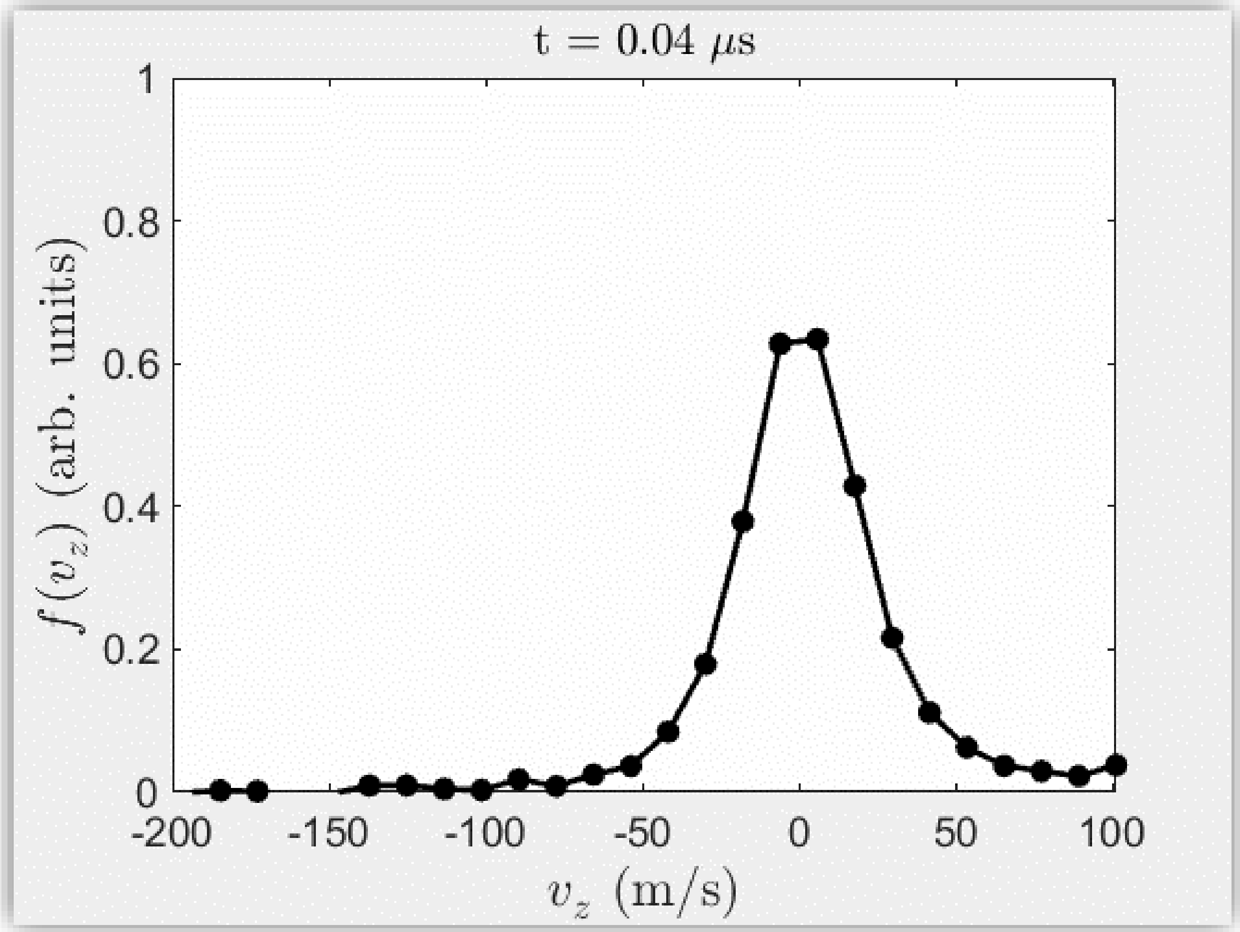
- Trap neutral atoms in the MOT
- Resonantly photo-ionize the atoms to create a plasma
- Excite laser-induced fluorescence in the plasma ions
- Measure fluorescence vs. time in repeated measurements at different laser frequencies
- Use Doppler-shift to map out ion velocity profile

Laser-induced fluorescence



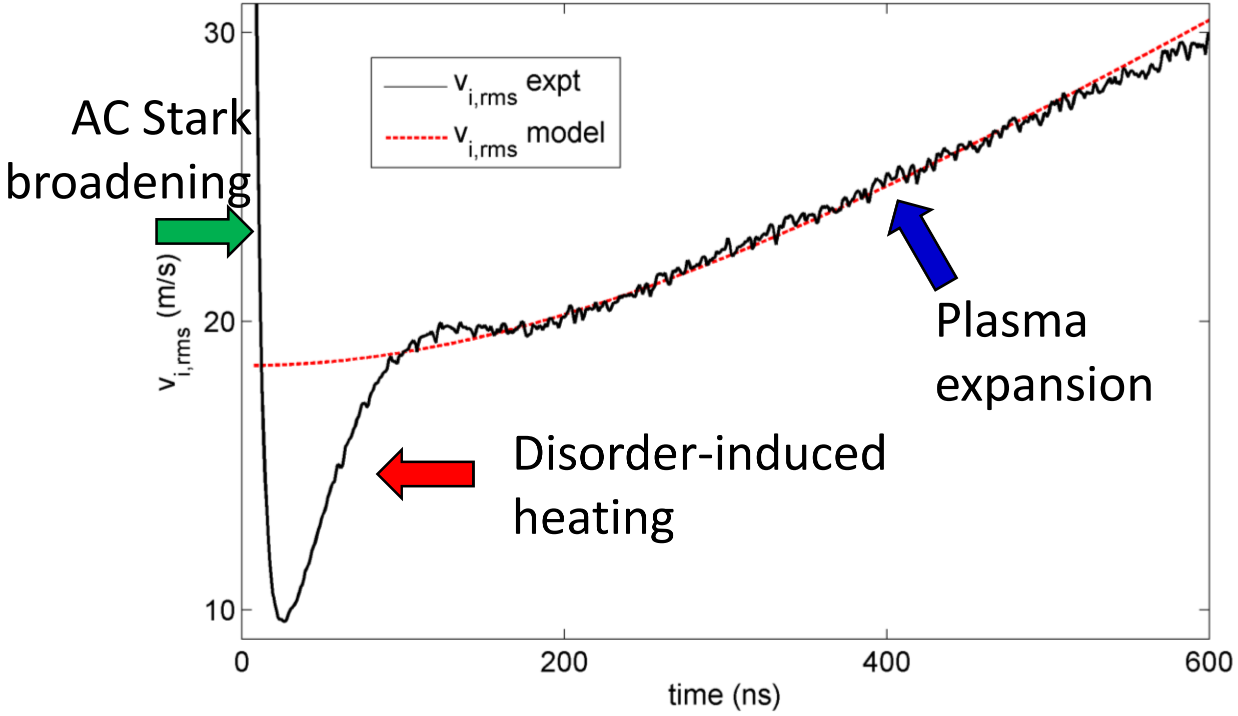
- Trap neutral atoms in the MOT
- Resonantly photo-ionize the atoms to create a plasma
- Excite laser-induced fluorescence in the plasma ions
- Measure fluorescence vs. time in repeated measurements at different laser frequencies
- Use Doppler-shift to map out ion velocity profile
- Horizontal cut

The velocity distribution broadens in time: A pure Ca plasma



The rms ion velocity

$$v_{\mathrm{i,rms}} = \sqrt{\frac{k_{\mathrm{B}}}{m_{\mathrm{i}}}\left[T_{\mathrm{i}}(0) + T_{\mathrm{e}}(0)\frac{t^2}{t^2+\tau^2}\right]}$$

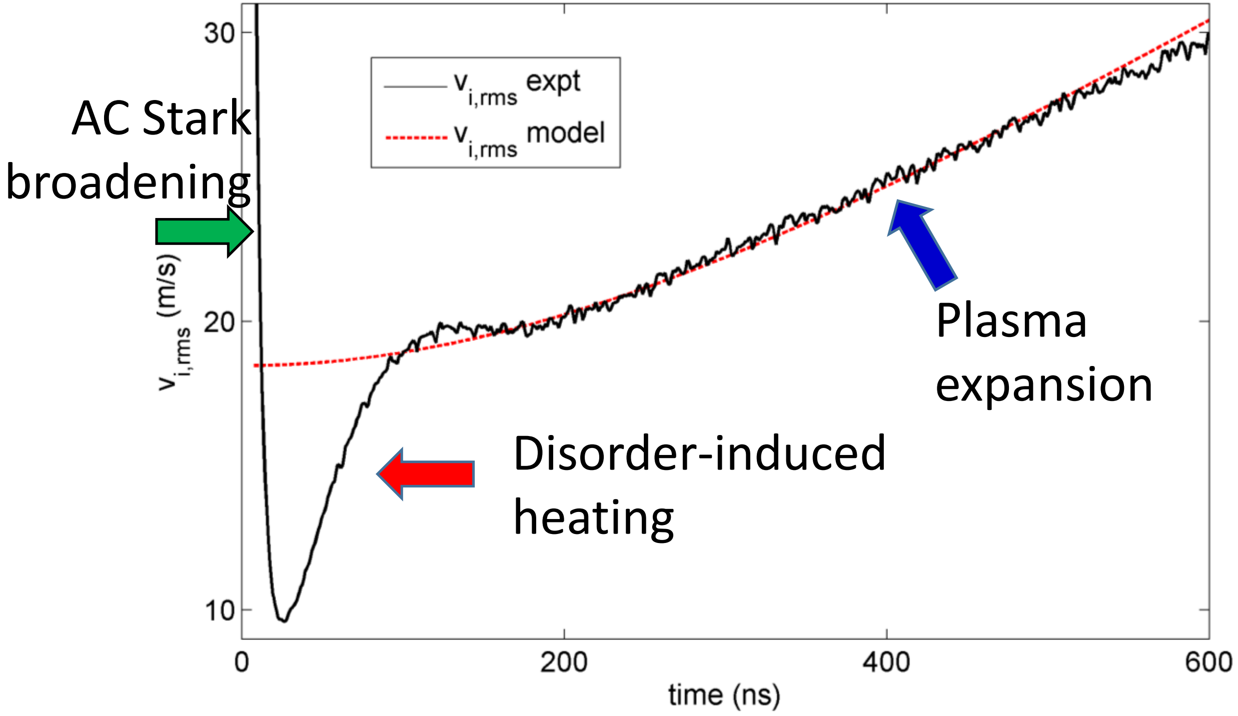


M. Lyon, S. D. Bergeson, and M. S. Murillo
Phys. Rev. E **87**, 033101 (2013)

Laha, et al., PRL 99, 115001 (2007)

The rms ion velocity

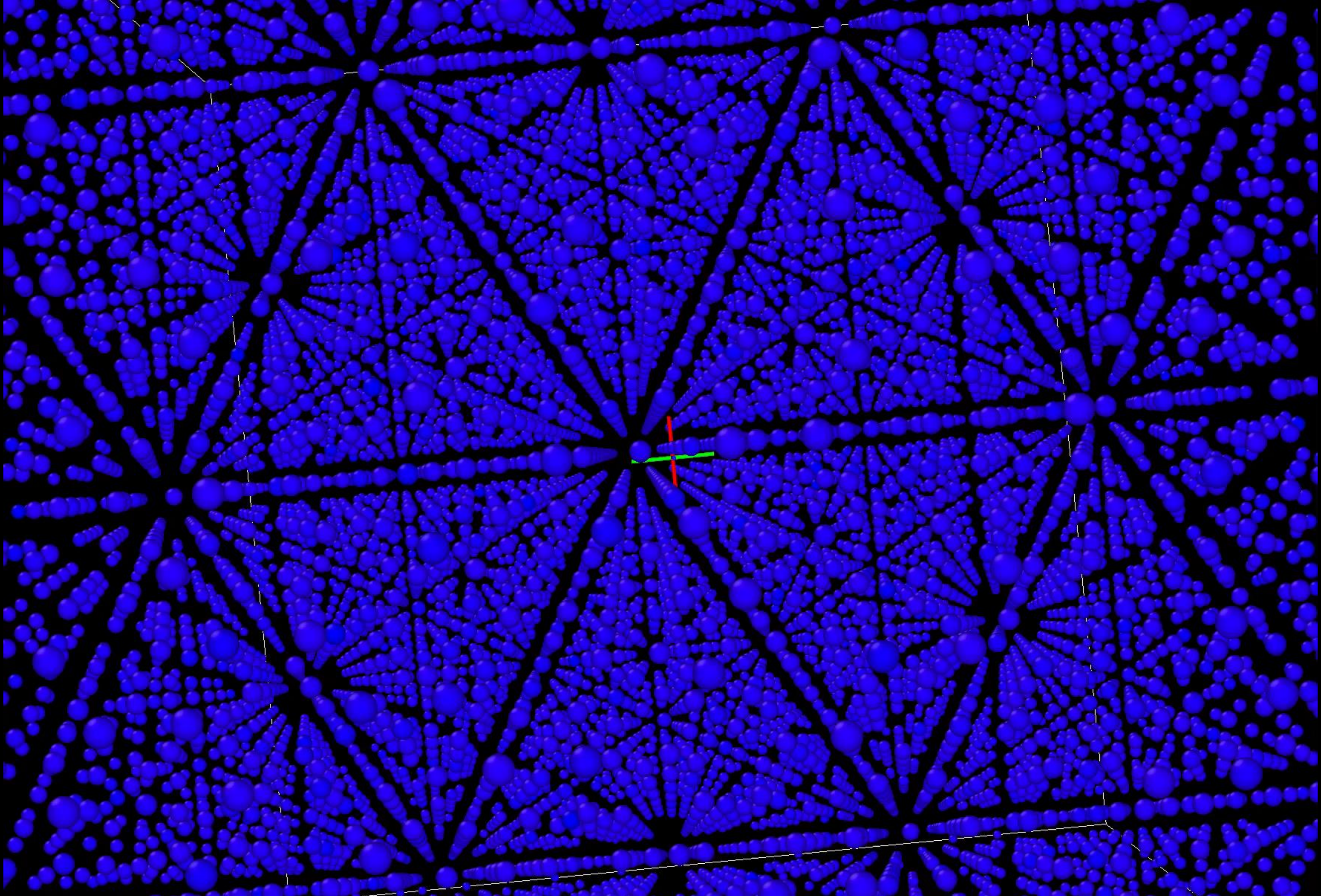
$$v_{\mathrm{i,rms}} = \sqrt{\frac{k_{\mathrm{B}}}{m_{\mathrm{i}}}\left[T_{\mathrm{i}}(0) + T_{\mathrm{e}}(0)\frac{t^2}{t^2+\tau^2}\right]}$$



- Atoms are initially randomly located in space
- Essentially zero atom-atom interaction
- Photoionization impulsively “hardens” the potential energy landscape
- Ions move to minimize their potential energy

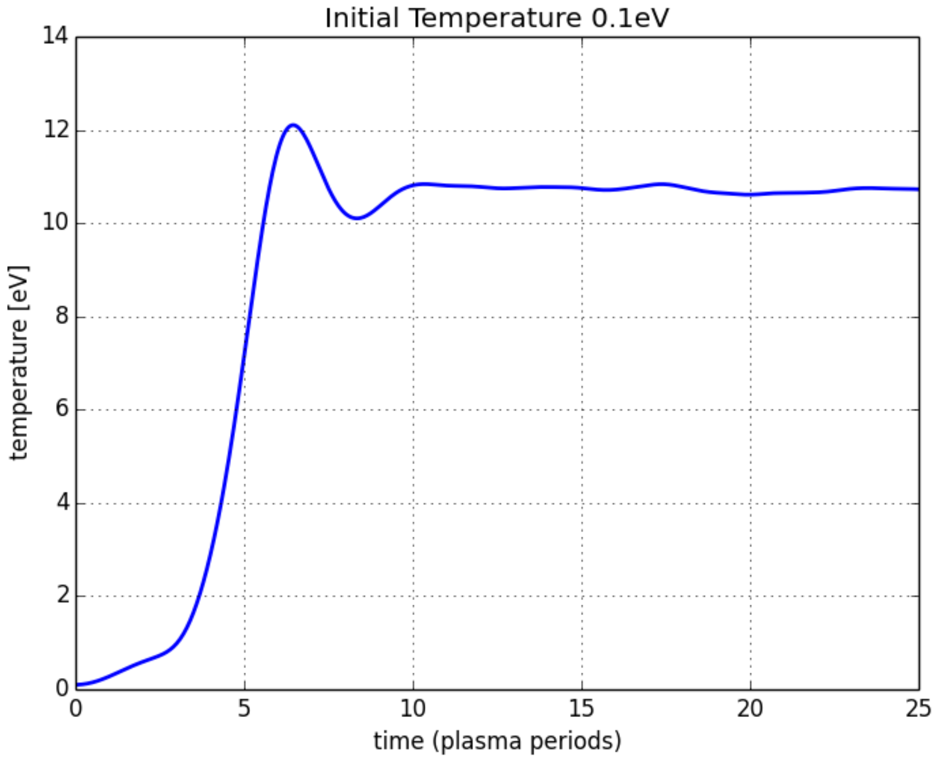
M. Lyon, S. D. Bergeson, and M. S. Murillo
Phys. Rev. E **87**, 033101 (2013)

Laha, et al., PRL 99, 115001 (2007)



CMH in graphite

- Final ion temperature is independent of initial conditions
- Ti = 11 eV
- Γ_{eff} around 10 to 15



Let's think about a new experiment: Yb^+ and Ca^+ in a dual-species UNP expansion

Let's suppose you had Yb^+ and Ca^+ in a plasma. What would happen to the Ca^+ velocity distribution as the plasma expands?

A. It will broaden more quickly because the heavy Yb ions will maintain a larger field gradient for a longer time.

B. It will uniformly broaden more slowly because of collisions with the heavier Yb+ ions.

C. The inner "core" of Ca+ ions will be held back (confinement) while the outer shell of Ca+ ions will be accelerated outwards more rapidly

$$T_i = 2\,\mathrm{K}$$
$$T_e = 100\,\mathrm{K}$$
$$n_0 = 10^{10}\,\mathrm{cm}^{-1}$$
$$w(0) = 0.3\,\mathrm{mm}$$
$$\gamma_{ii} = n\sigma v_{\mathrm{th}} = 4 \times 10^7\,\mathrm{s}^{-1}$$
$$\gamma_{ee} = 3 \times 10^7\,\mathrm{s}^{-1}$$
$$\tau_{\mathrm{exp}}^{-1} = 0.5 \times 10^6\,\mathrm{s}^{-1}$$

A 1D fluid code simulation

- Density, Temperature, and Radial fluid velocity for each species
  - Convection, adiabatic expansion, pressure acceleration, ambipolar field, interspecies friction, Joule heating
  - Assume ideal gas law EOS
- $F_{ss'}$ represents the friction force
- $Q_{ss'}$ represents frictional heating and temperature equilibration between species.
- Neglect:
  - viscosity
  - ion thermal conduction

$$\frac{\partial n_s}{\partial t} + u_s \frac{\partial n_s}{\partial r} = -n_s \nabla \cdot (u_s \hat{r})$$

$$\frac{\partial T_s}{\partial t} + u_s \frac{\partial T_s}{\partial r} = -\frac{2}{3} T_s \nabla \cdot (u_s \hat{r}) + \frac{2}{3 n_s k_B} Q_{ss'}$$

$$\frac{\partial u_s}{\partial t} + u_s \frac{\partial u_s}{\partial r} = -\frac{k_B}{n_s m_s} \frac{\partial n_s T_s}{\partial r} - \frac{k_B T_e}{n_s m_s} \frac{\partial n_s}{\partial r} + \frac{F_{ss'}}{m_s}$$

Effective potential kinetic theory for strongly coupled plasmas

AIP Conference Proceedings **1786**, 130001 (2016); https://doi.org/10.1063/1.4967627

Scott D. Baalrud[1] *and* Jérôme Daligault[2]

- Average the collision cross section over the two flowing Maxwellian velocity distributions to get a friction force

$$F_{ss'} = -\frac{16}{3}\frac{\sqrt{\pi}e^4 n_{s'}}{(4\pi\epsilon_0)^2 m_{ss'}\bar{v}_{ss'}^3}\,\Xi(\Delta\bar{V})(\mathbf{u_s} - \mathbf{u_{s'}})$$

$$\Xi(\Delta\bar{V}) = \frac{3}{16}\frac{1}{\Delta\bar{V}^3}\frac{1}{2}\int_0^\infty d\xi\,\xi^2\,\frac{\sigma_{ss'}^{(1)}(\xi)}{\sigma_0}\,\mathcal{X}$$

$$\mathcal{X} = (2\xi\Delta\bar{V} + 1)e^{-(\xi+\Delta\bar{V})^2} + (2\xi\Delta\bar{V} - 1)e^{-(\xi-\Delta\bar{V})^2}$$

Effective potential kinetic theory for strongly coupled plasmas

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Scott D. Baalrud[1] *and* Jérôme Daligault[2]

- Energy exchange and frictional heating

$$Q_{ss'} = -\frac{16\sqrt{\pi} n_s n_{s'} e^4 k_B}{(4\pi\epsilon_0)^2 m_s^2 \bar{v}_{ss'}^3} \tilde{\Xi}(\Delta\bar{V})(T_s - T_{s'}) - \frac{v_{Ts}^2}{\bar{v}_{ss'}^2} n_s \Delta\mathbf{V} \cdot \mathbf{F}^{ss'}$$

$$\tilde{\Xi}(\Delta\bar{V}) = \frac{1}{8\Delta\bar{V}} \int_0^\infty d\xi\, \xi^4 \frac{\sigma_{ss'}^{(1)}(\xi)}{\sigma_0} \left[e^{-(\xi-\Delta\bar{V})^2} - e^{-(\xi+\Delta\bar{V})^2} \right]$$

- The first momentum transfer cross section depends on the form of the ion-ion interaction potential

Molecular-Dynamics Simulations of Electron-Ion Temperature Relaxation in a Classical Coulomb Plasma

Guy Dimonte and Jerome Daligault
Phys. Rev. Lett. **101**, 135001 – Published 23 September 2008

- The generalized Coulomb logarithm calculation is challenging (for us)
- MD suggests

$$\ln\Lambda = \ln\left(1+\frac{C}{g}\right) \qquad g = \frac{e^2}{4\pi\epsilon_0}\frac{1}{\lambda_{De} k_{\mathrm{B}} T_e}$$

$$g = \frac{e^2}{4\pi\epsilon_0}\left[\lambda_D\left(\tfrac{1}{2}\,m_{ss'}\right)\left(\bar{v}^2_{ss'}+\tfrac{2}{3}\left|u_s-u_{s'}\right|^2\right)\right]^{-1}$$

- Liam G. Stanton and Michael S. Murillo, Phys. Rev. E **93**, 043203 (2016)

$$\frac{1}{\lambda_D^2} = \frac{1}{\lambda_e^2} + \sum_i \frac{1}{\lambda_i^2}\left(\frac{1}{1+(u_s-u_{s'})^2/v^2_{th,i}+3\Gamma_i}\right)$$

Ionic transport in high-energy-density matter

Liam G. Stanton and Michael S. Murillo
Phys. Rev. E **93**, 043203 – Published 8 April 2016

- Yukawa interaction

$$\sigma_{ij}^{(1)} = 2\pi\lambda^2\phi_1(w) \qquad \frac{1}{\lambda_D^2} = \frac{1}{\lambda_e^2} + \sum_i \frac{1}{\lambda_i^2}\left(\frac{1}{1 + (u_s - u_{s'})^2/v_{th,i}^2 + 3\Gamma_i}\right)$$

$$\phi_n(w) \approx \begin{cases} \phi_n^{\mathrm{SC}}(w), & w < 1 \\ \phi_n^{\mathrm{WC}}(w), & w > 1 \end{cases}$$

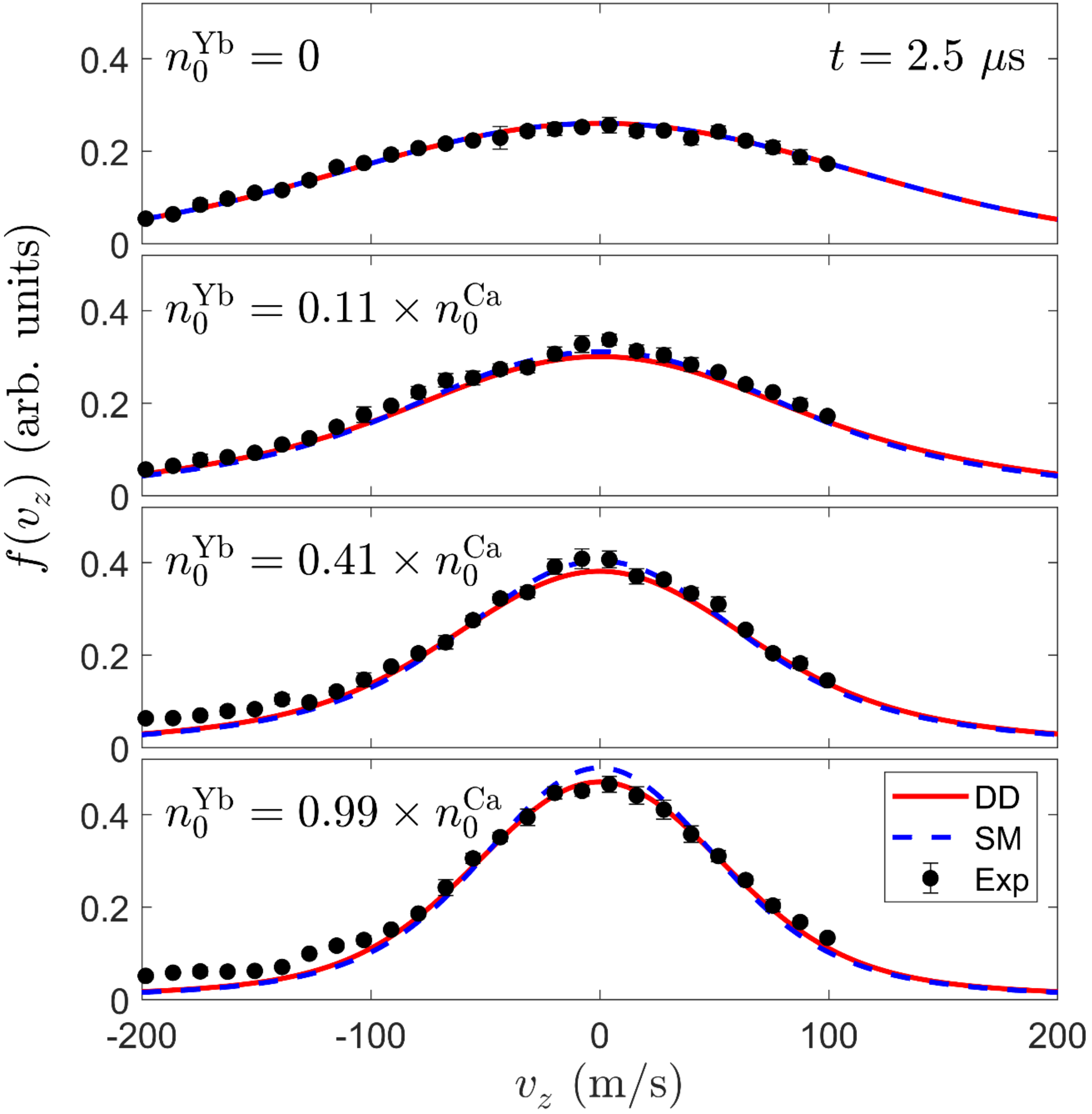
$$\phi_n^{\mathrm{SC}}(w) = \frac{c_0 + c_1 \ln(w) + c_2 \ln^2(y) + c_3 \ln^3(w)}{1 + c_4 \ln(w)}$$

$$\phi_n^{\mathrm{WC}}(w) = \frac{n}{2w^4} \ln(1 + w^2) P(w)$$

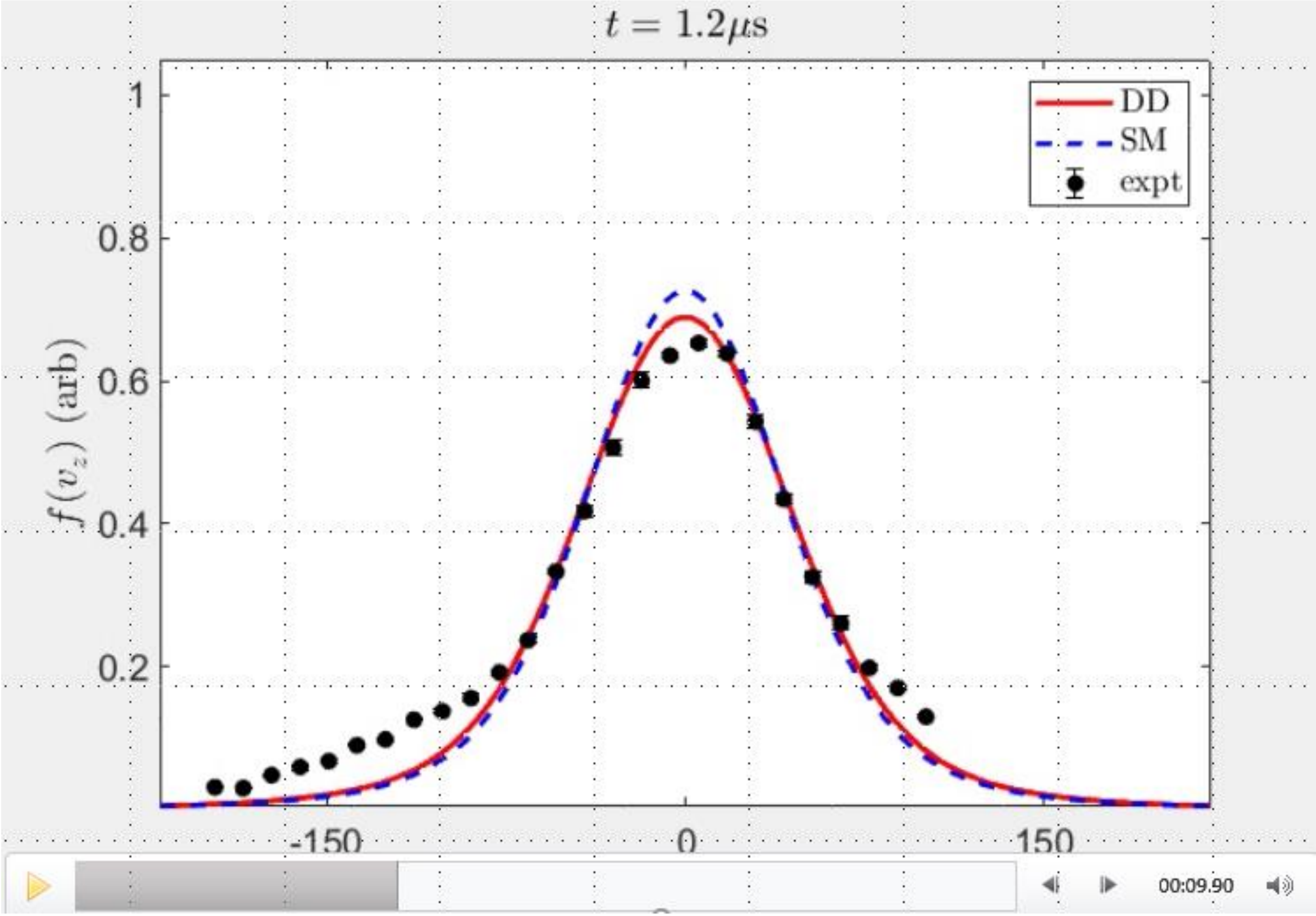
After 2.5 μs expansio with increasing Yb+

As the Yb^+ density increases…

- More Ca^+ ions are confined in the center of the plasma
- Greater Ca^+ acceleration in the wings of the distribution

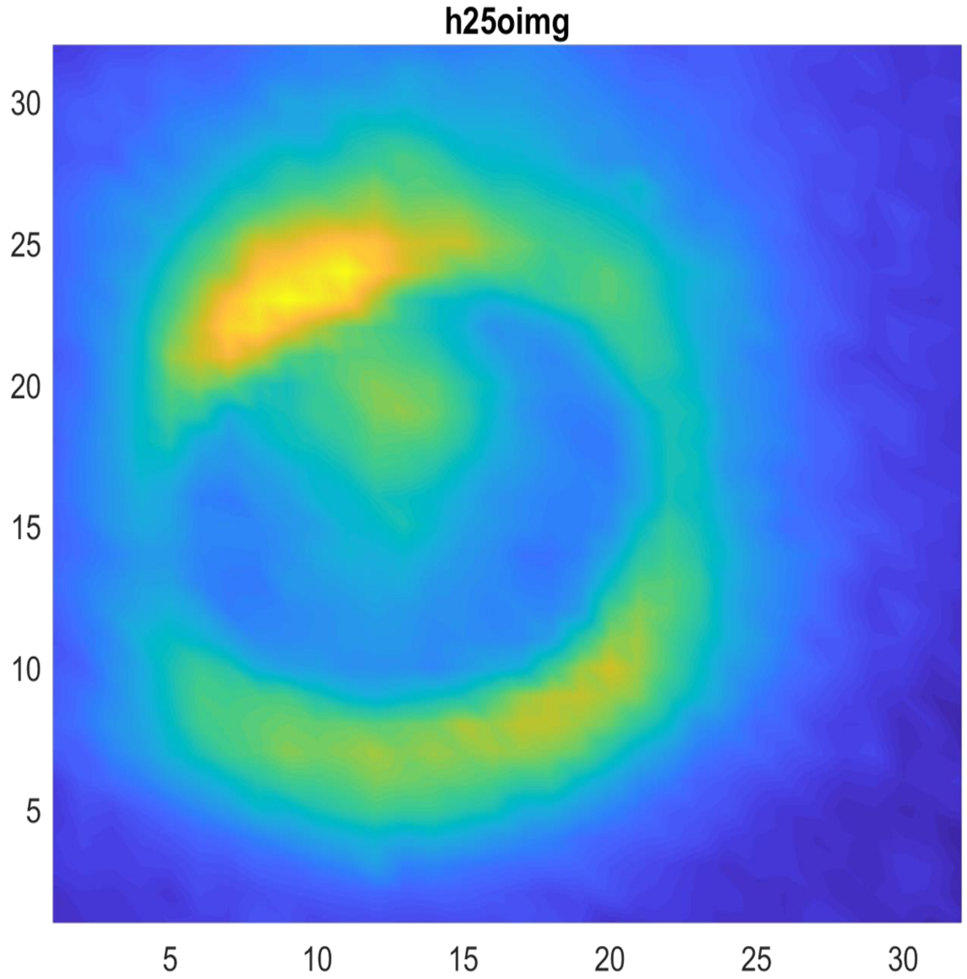


Velocity distribution: $n_0^{\mathrm{Yb}} = 0.99 \times n_0^{\mathrm{Ca}}$



A slice through the density distribution

- We recently developed the ability to measure a slice of the Ca^+ density distribution
- The plasma expands for a time
- We flash on a pulse of laser light
- Compile images over a range of laser frequency detunings
- Add images to get the ion density distribution



A slice through the density distribution

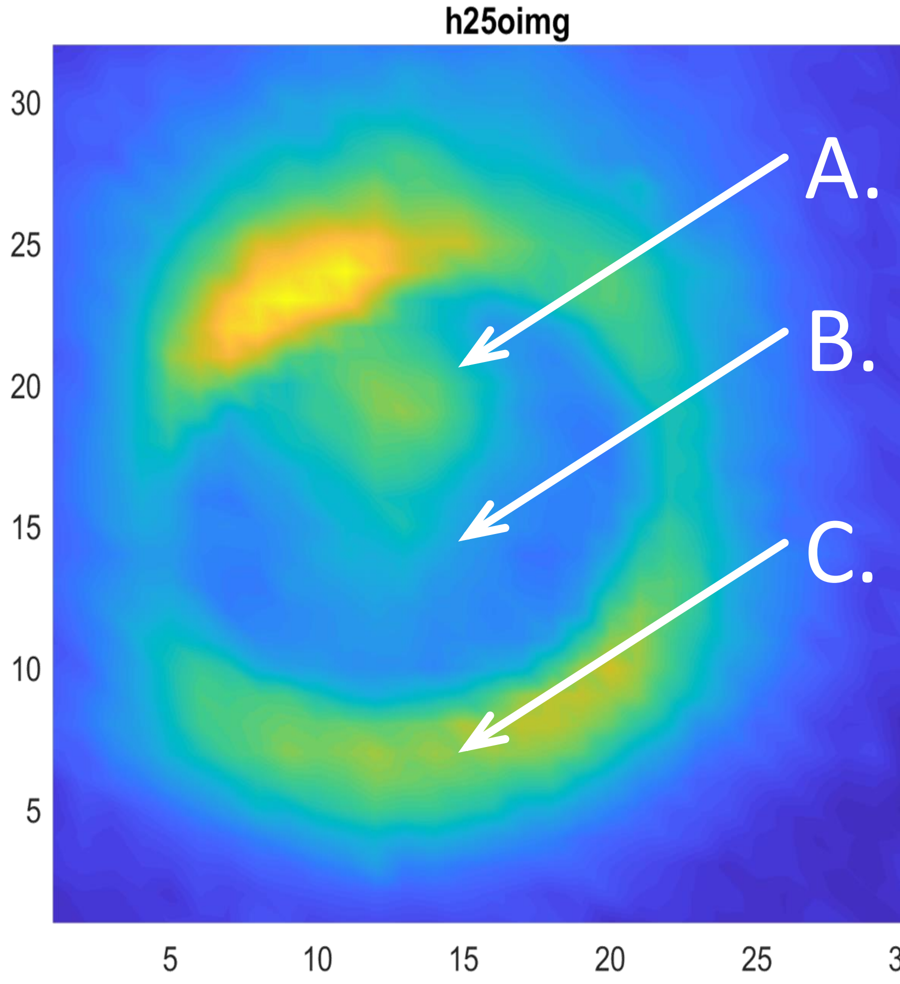
Consider a dual-species plasma expanding into the surrounding vacuum. After 5 μs, the Ca^+ spatial distribution clearly separates into two distinct spatial regions. Where will the ion temperature be the highest?

A.

B.

C.

D. Uniform everywhere



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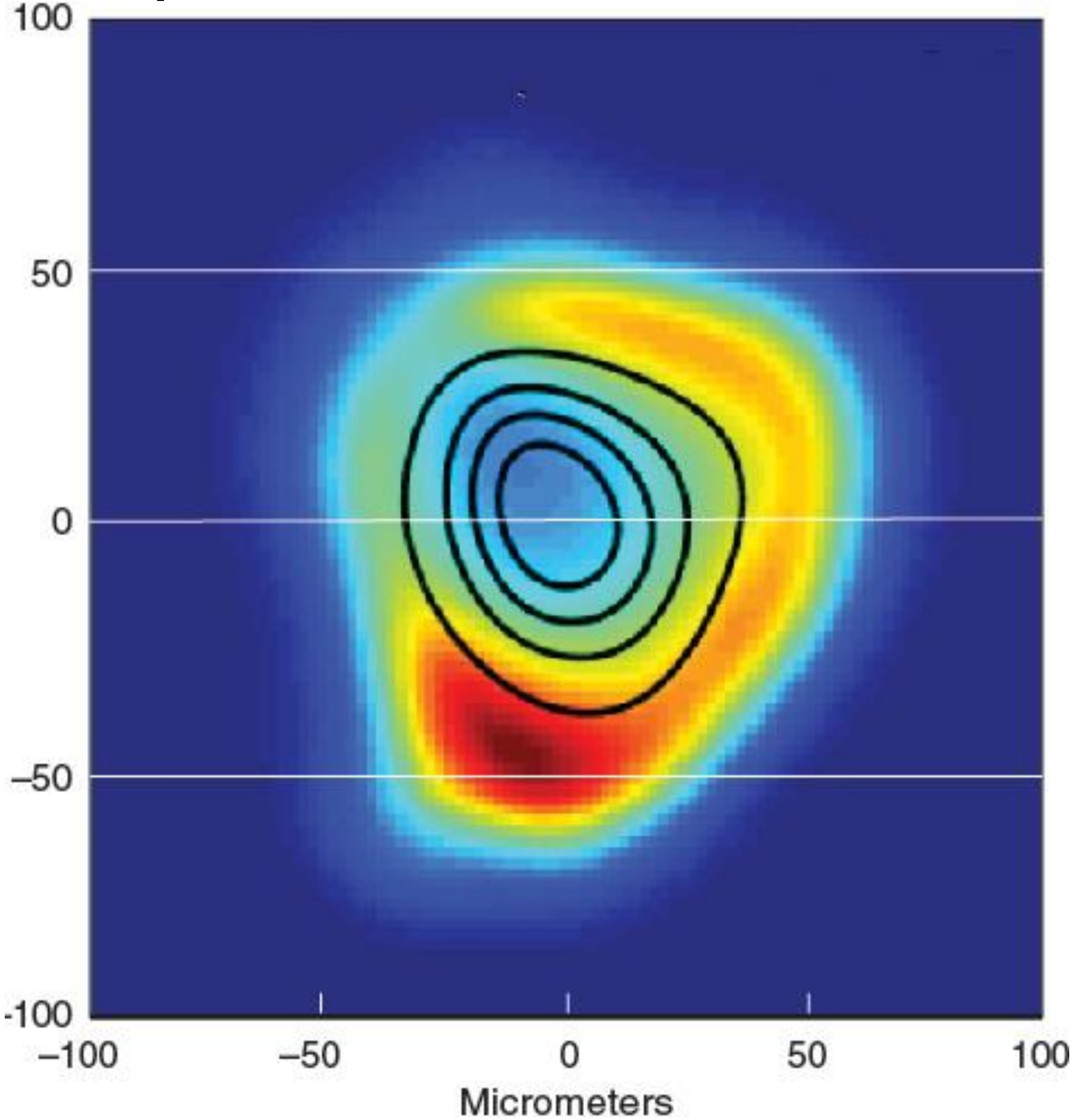

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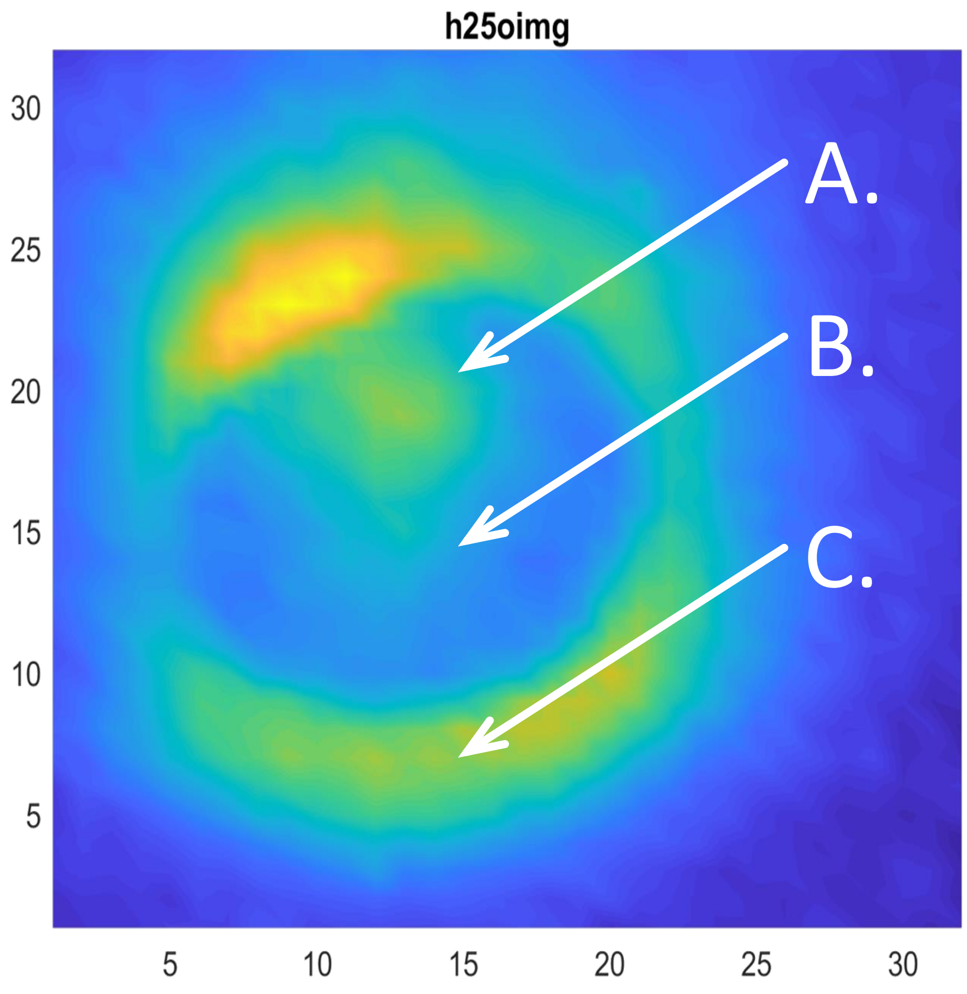
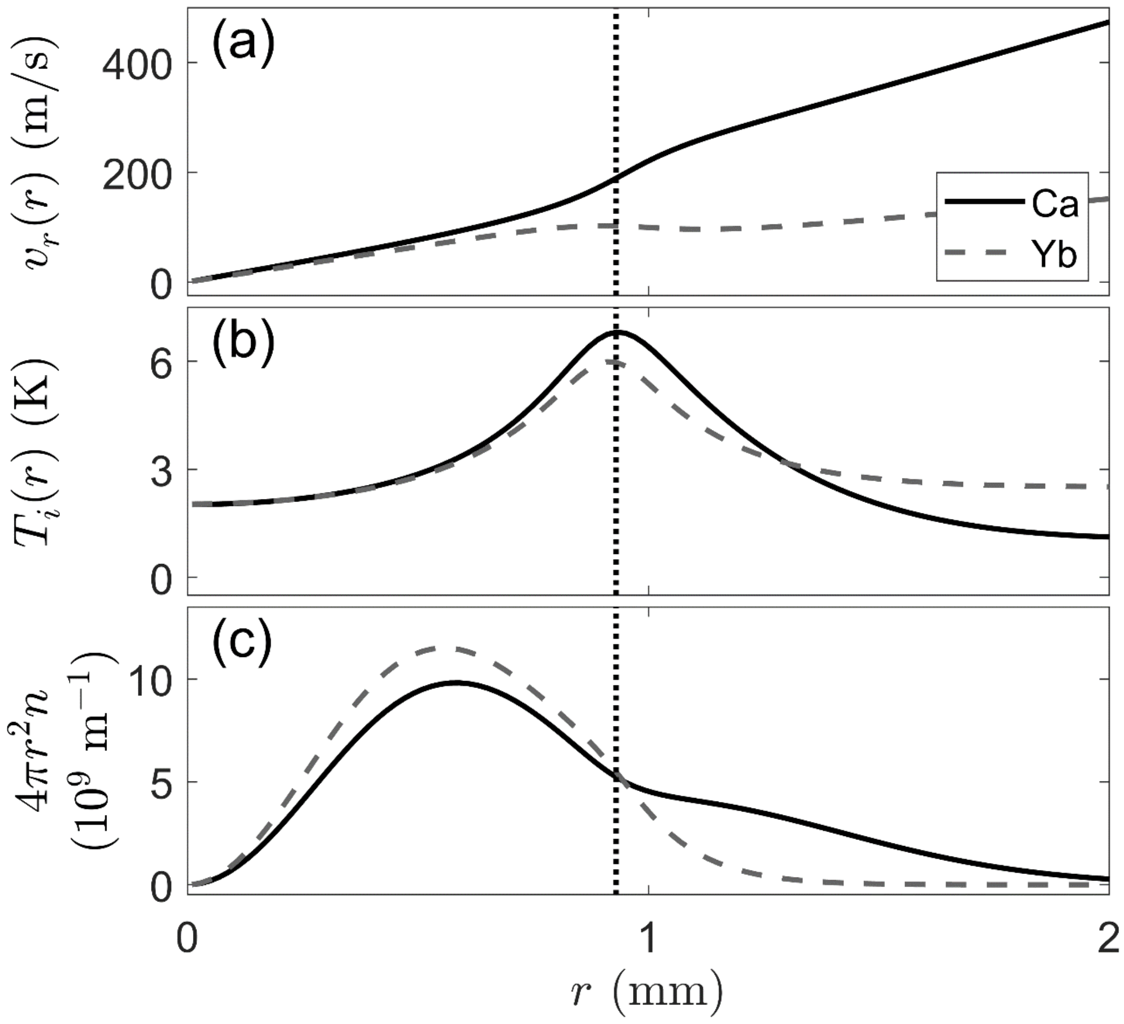


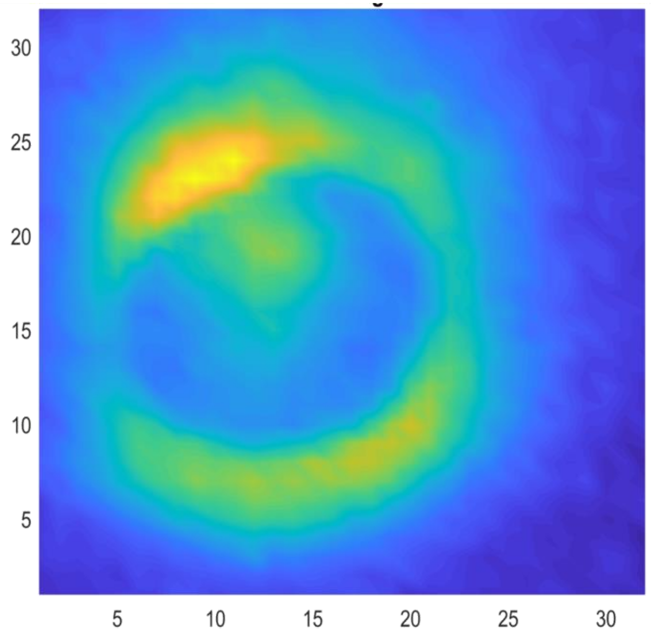
Simulation results qualitatively agree with experimental measurements

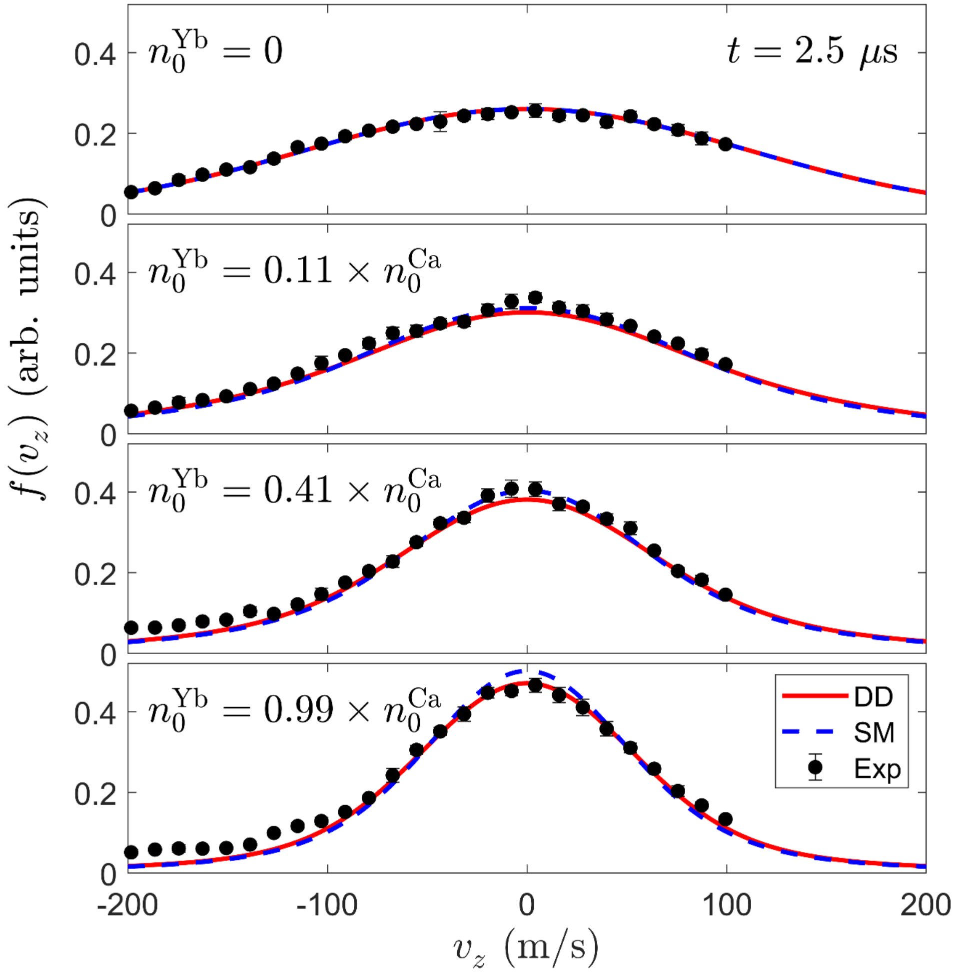
- The ion temperature is highest in the gap – heated by friction
- Inertial "confinement" of the Ca+ ions by the Yb+ ions
  - Confinement in phase space

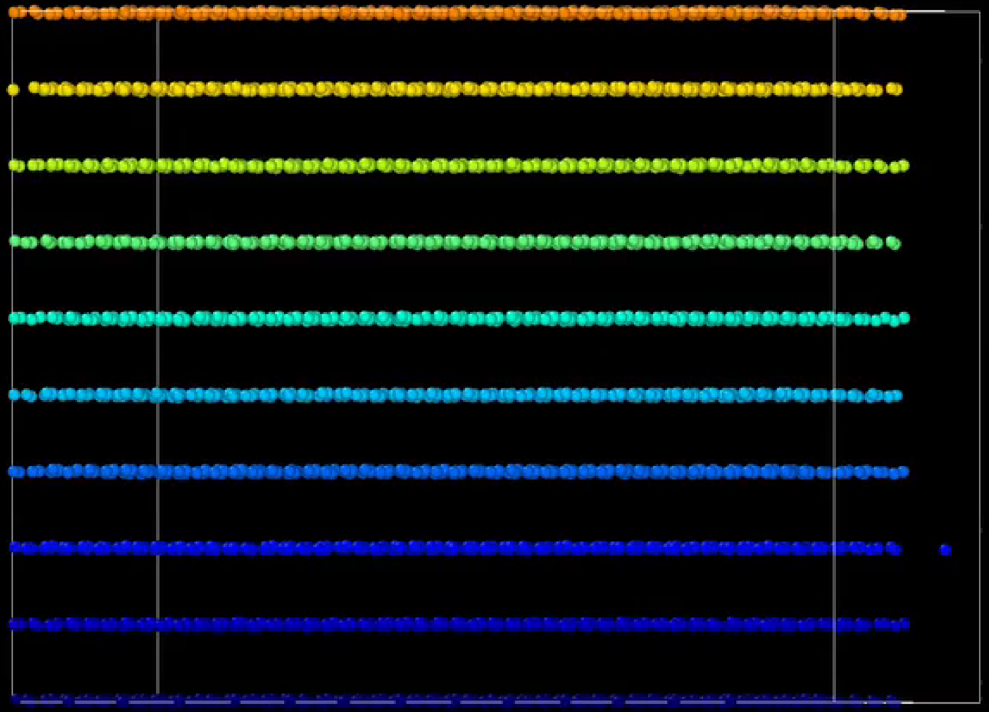


Summary

- Ultracold neutral plasmas as HEDP simulators
- Momentum transfer in strongly-coupled multi-species plasmas
- Phase space confinement in UNPs
- Potential for measuring transport properties in strongly-coupled systems







DIH in warm dense matter experiments

SCIENTIFIC REPORTS

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Evidence for a glassy state in strongly driven carbon

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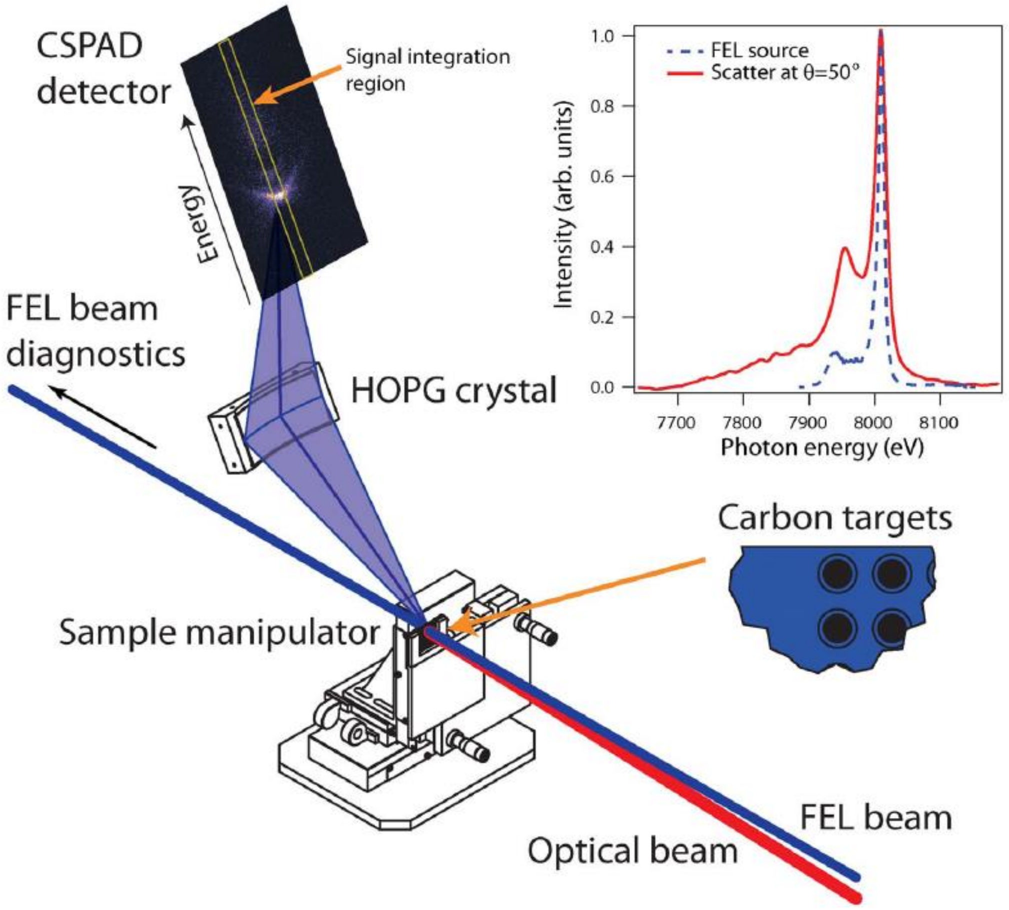
Strongly driven carbon

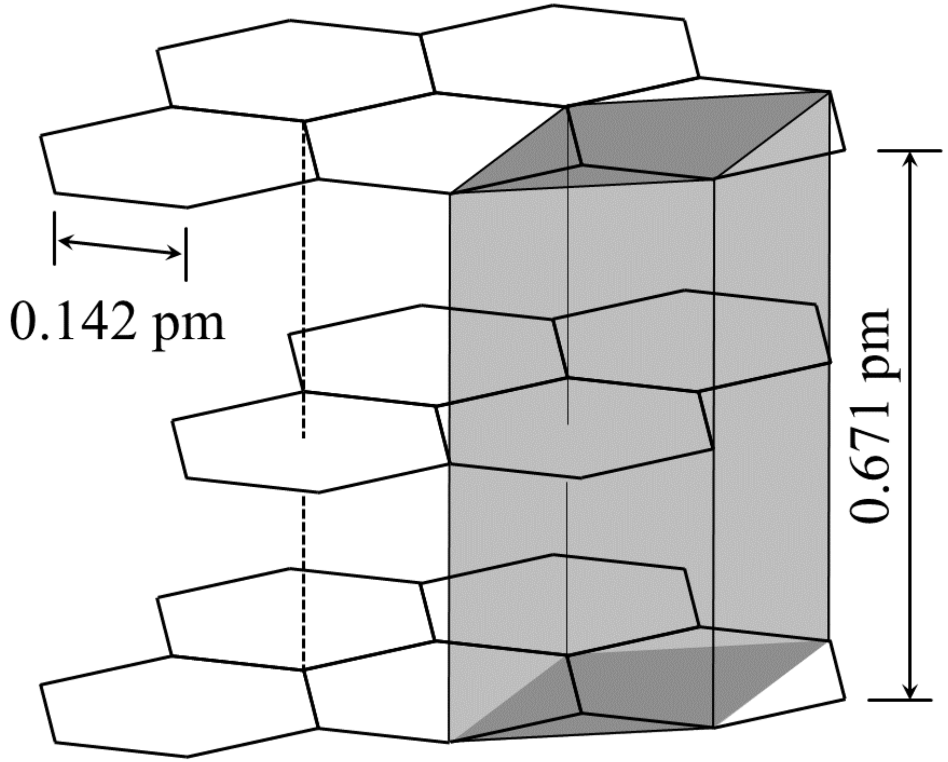


No crystallization observed

hydrodynamic times (typically tens of picoseconds), the dense plasma should have had enough time to evolve into a crystal, a process known as Wigner crystallization[12]. However, our measurements show no indication of a crystalline structure which points to a state where the ions are locked to a fluid-like structure by strong forces. Given the pump-probe difference used, this state exists much longer than typical nucleation models predict.

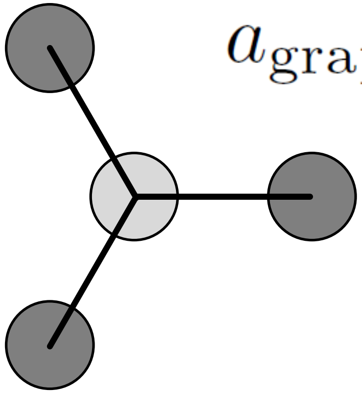
In order to test the possibility of a crystalline state, we infer $\Gamma \gtrsim 600$ at peak compression with $\rho \gtrsim 4.5\ \mathrm{g/cm^3}$ and $T \sim 5{,}000\ \mathrm{K}$ from the hydrodynamics simulations (see Figure 2). At such

CMH - crystallographic mismatch heating



A relatively simple calculation

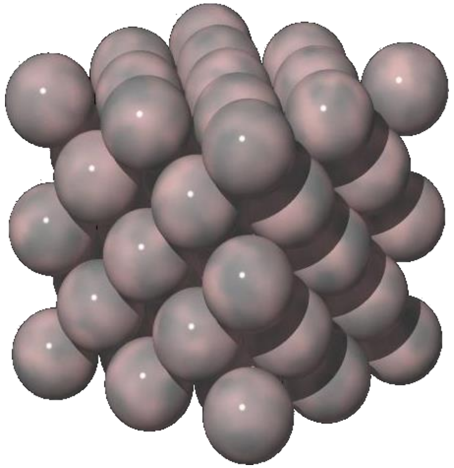
C^{4+} ions in graphite



$$a_{\text{graphite}} = 0.142 \text{ nm}$$
$$T_e = 60 \text{ eV}$$
$$n = 10^{29} \text{ m}^{-3}$$
$$Z = 4$$
$$\kappa = 1.5$$

$$U_i = \frac{Z^2 e^2}{4\pi\epsilon_0 a_i} \exp(-\kappa) = 36 \text{ eV}$$

C^{4+} ions in an FCC/HCP lattice



$$a_{\text{fcc}} = \frac{\ell}{\sqrt{2}}$$

$$n_{\text{fcc}} = \frac{4}{\ell^3}$$

$$U_f = \frac{Z^2 e^2}{4\pi\epsilon_0 a_{\text{fcc}}} \exp(-\kappa) = 23 \text{ eV}$$