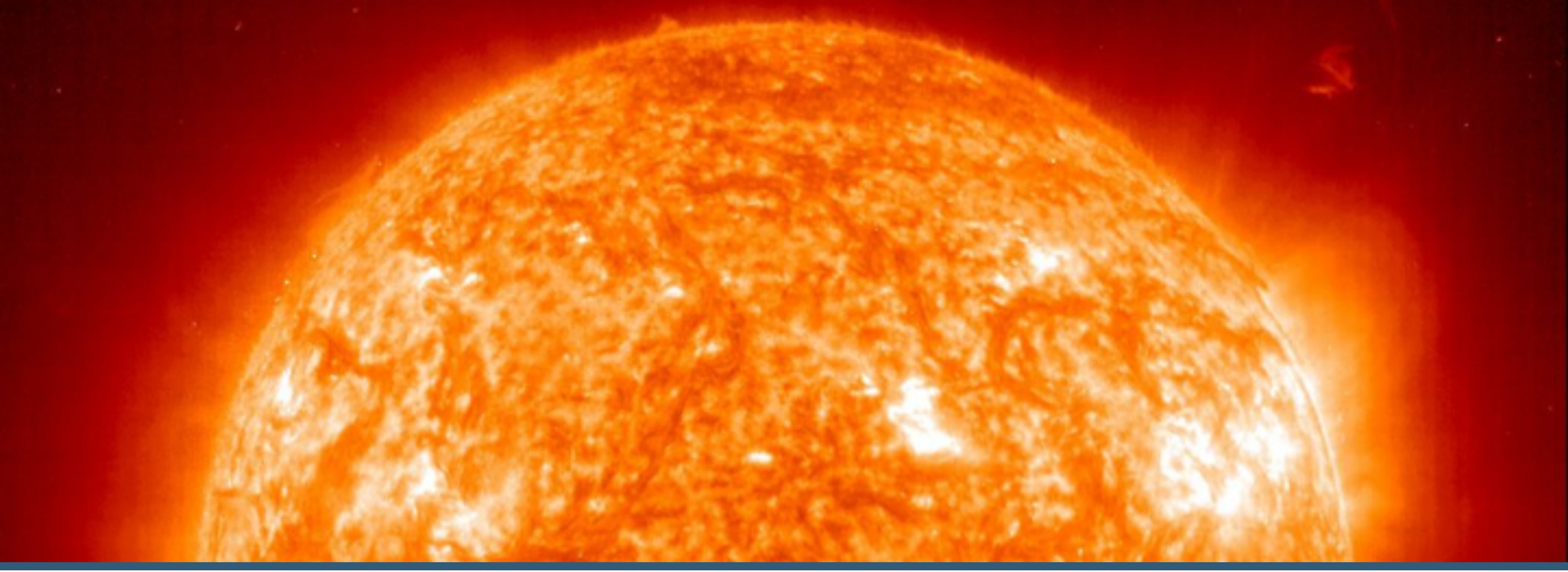


Introduction to the SULI One Week Course and to Plasma Physics

2019 SULI One Week Course

PPPL

Arturo Dominguez

Senior Program Leader, Science Education Department

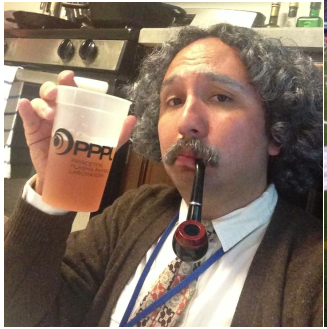
First, a bit about myself

- From Bogotá, Colombia
- Started studying physics at the National University of Colombia at Bogota.

- Did my graduate work at MIT, in Boston on **fusion plasmas** (GO BEAVERS!)

- Transferred to University of Texas at Austin where I finished undergrad (HOOK’EM HORNS!)

- Now I’m at the Princeton Plasma Physics Lab (GO TIGERS!)`



Second, a bit about yourselves

Second, a bit about yourselves

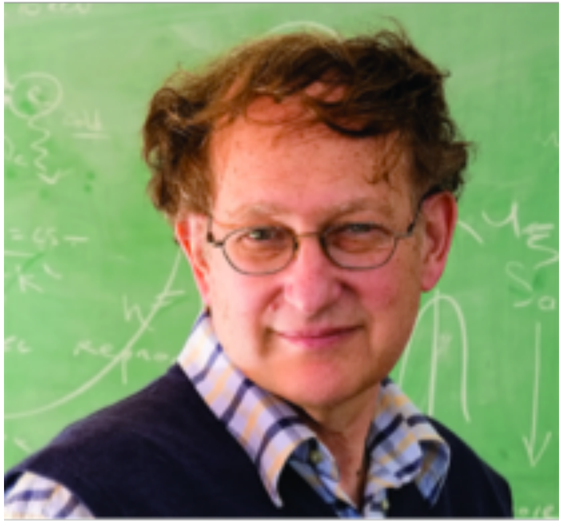
- Science Undergraduate Laboratory Internship Program (SULI). This is a DOE sponsored undergraduate internship.
- Of the SULI students, some are staying at PPPL and some are going to General Atomics (GA) in San Diego.
- Community College Interns (CCI), also a DOE run program.
- Princeton Environmental Institute (PEI) internship program.
- Princeton University Tokyo Exchange Program (PUTEP)
- Alabama EPSCoR
- Engineering Apprenticeship
- High School interns, independent interns, and visitors (some PPPL staff/students?)

Second, a bit about yourselves

WELCOME!!

The SULI One Week Course

- Originally started in 1993 by Prof. Nat Fisch as part of the National Undergraduate Fellowship (NUF).

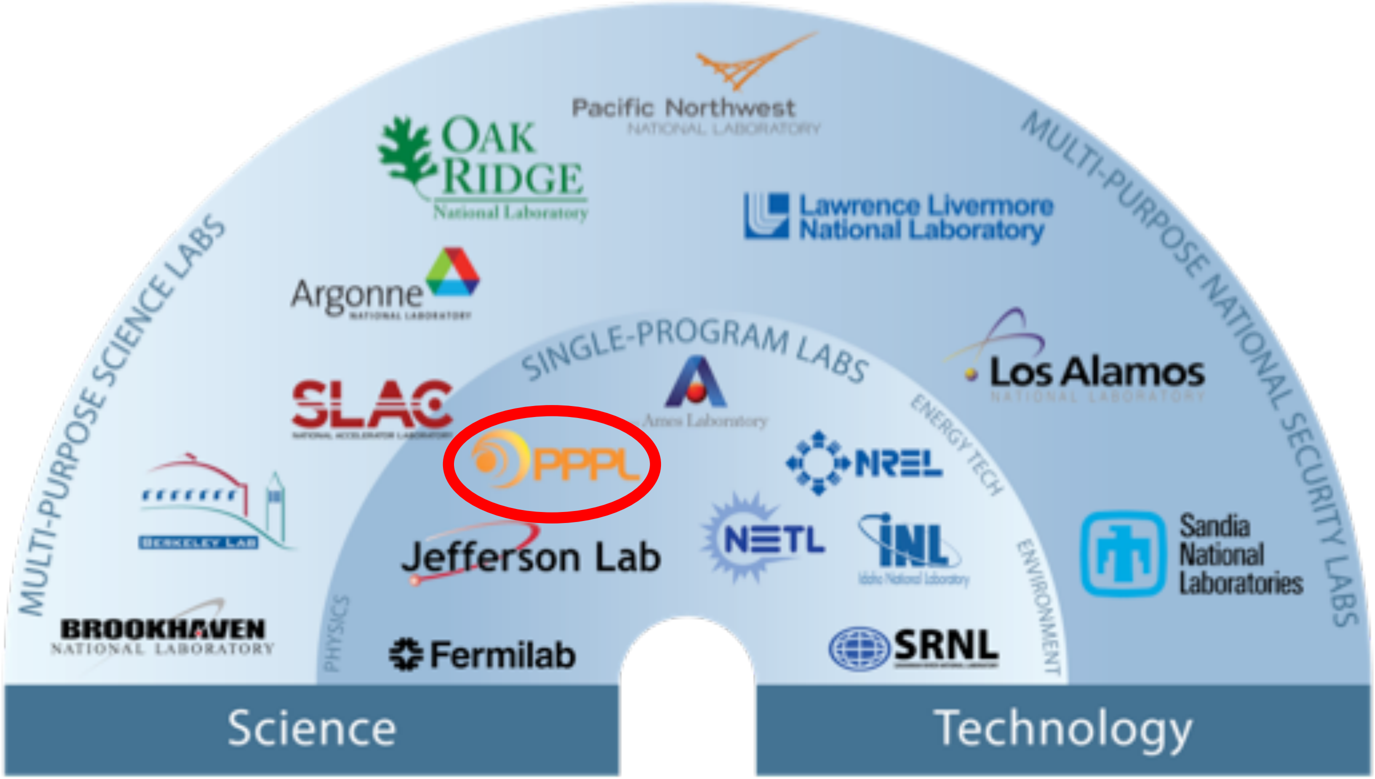


The SULI One Week Course

- This week will feature:
  - 15 lectures on different plasma physics/engineering topics
  - Tour of the lab
  - Experimental session
  - HW sessions where you will review the HW sets with a graduate student (COME PREPARED WITH QUESTIONS)

- All lectures are streamed live and the slides can be found at: https://suli.pppl.gov/2019/course/

PPPL is one of 17 Department of Energy national laboratories

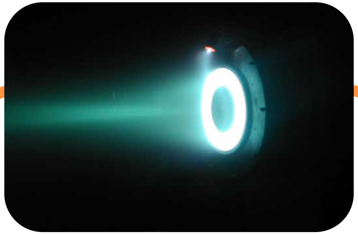


PPPL

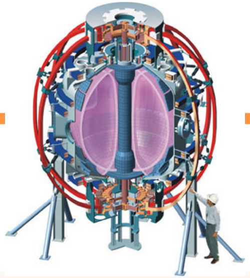
- Approximately 450 employees
- 90 acres
- Operated by Princeton U.

- Approximately 450 employees
- 90 acres
- Operated by Princeton U.

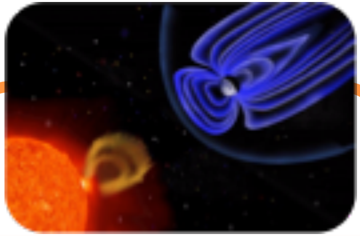
At PPPL we study plasmas at all scales.



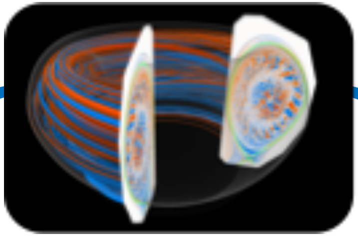
Low Temperature Plasmas



Fusion



Astrophysical Plasmas



Theory and Simulation

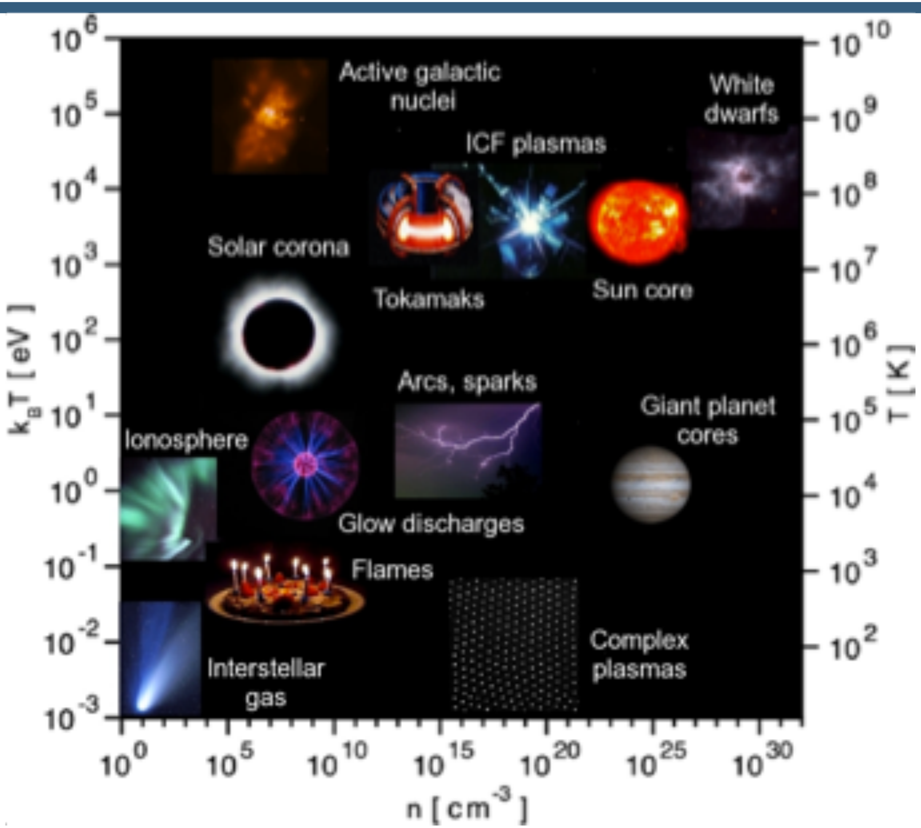
Experiments

Engineering / Technology

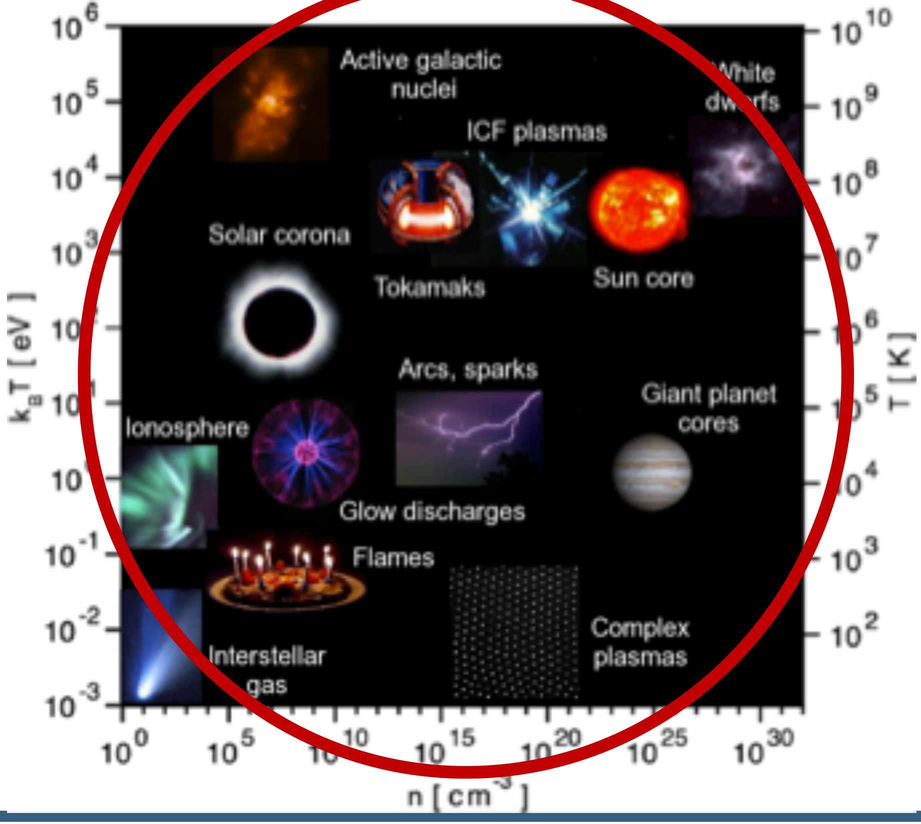
Plasma is a rich and varied field of study

- **Plasma is the 4th state of matter:** It is qualitatively different than gas due to its collective behavior, particularly its interactions with E&M fields.

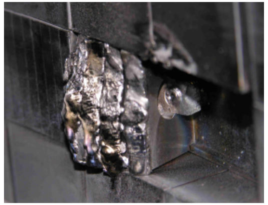
- **Plasmas cover a wide range of densities and temperatures** This makes the field rich in scope



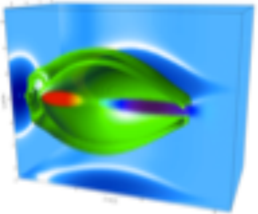
What will we be studying this week?



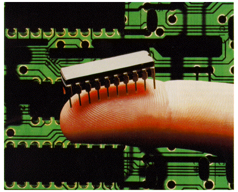
+



Plasma/Materials



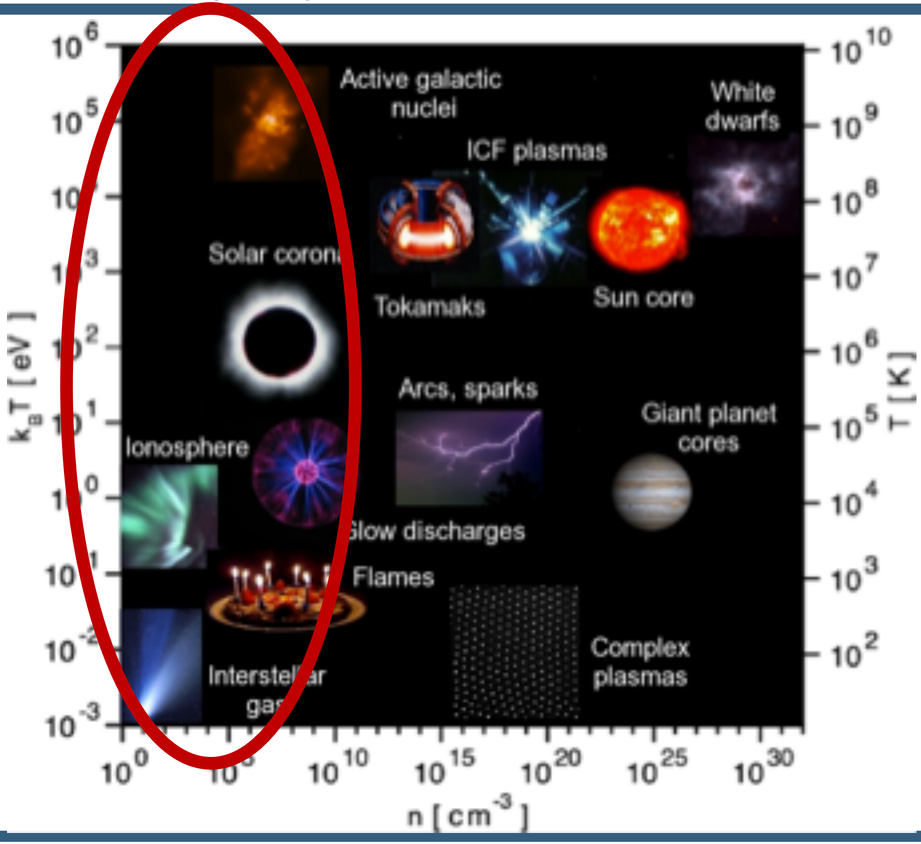
Plasma/Lasers



Plasma in industry

...

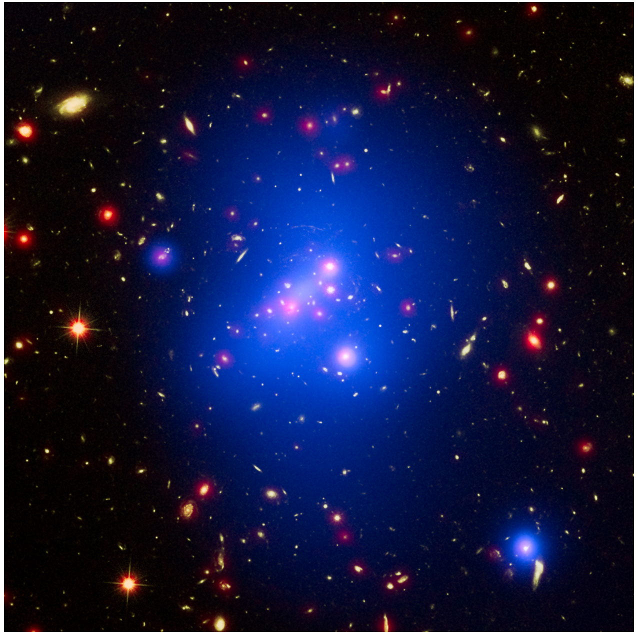
Astrophysical Plasmas



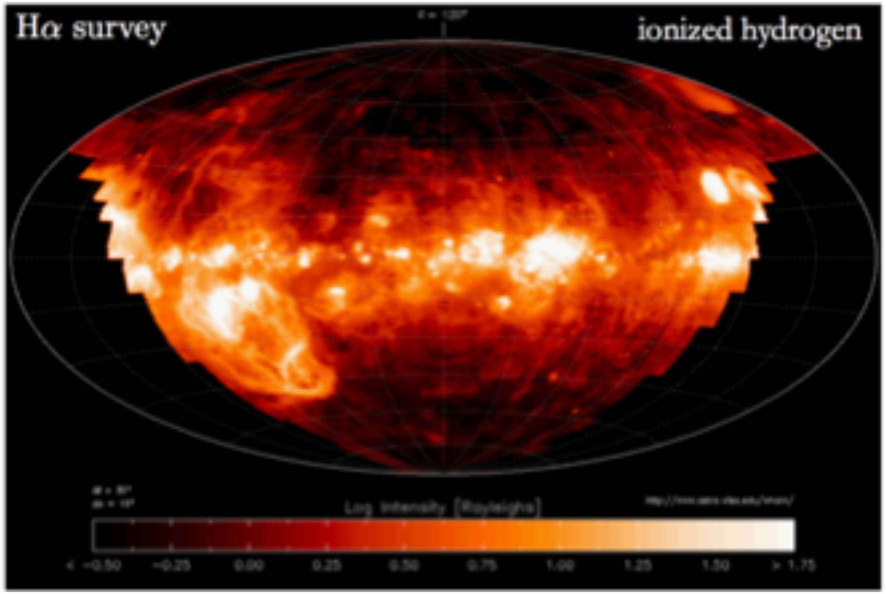
Prof. Matt Kunz
Astrophysical Plasmas

Dr. Will Fox
Magnetic Reconnection

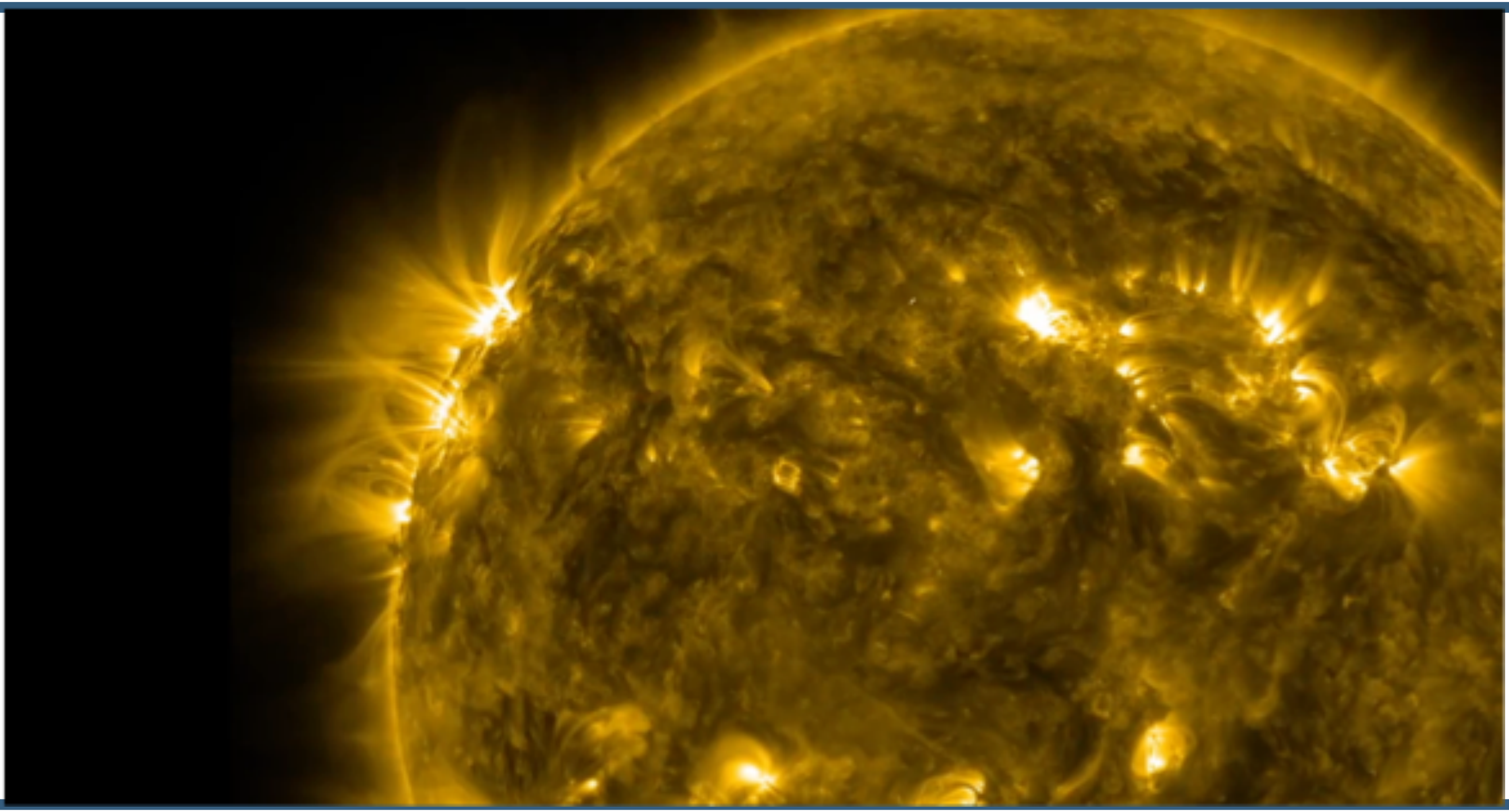
Astrophysical Plasmas



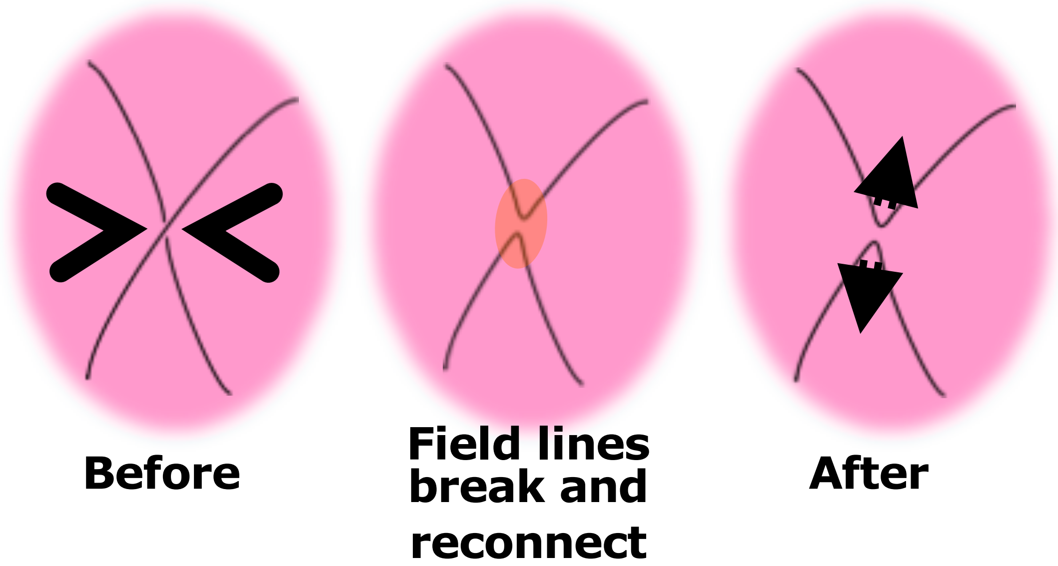
Galaxy cluster IDCS J1426 is located 10 billion light-years from Earth



A little closer to home

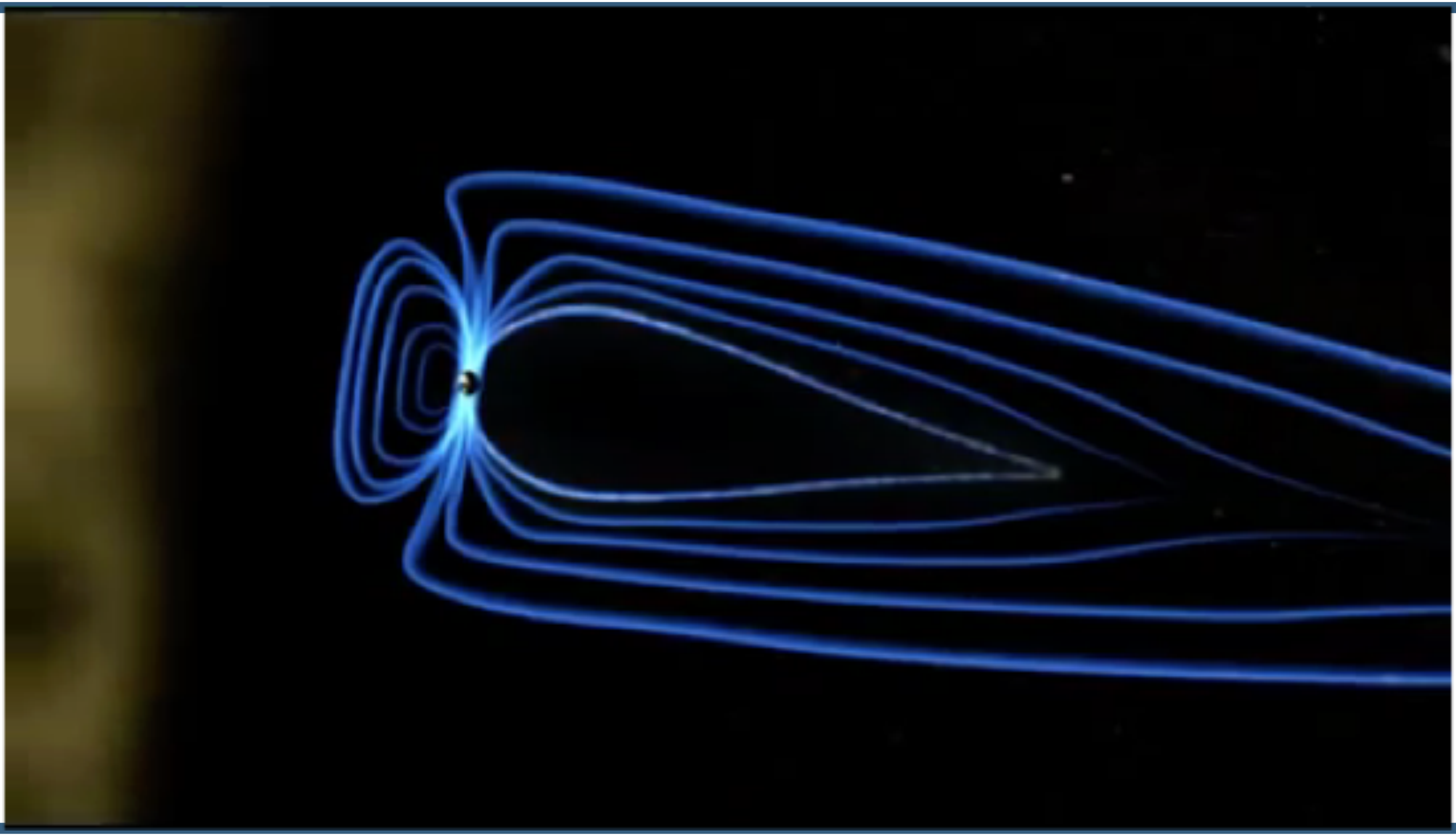


Magnetic reconnection is a big field of research

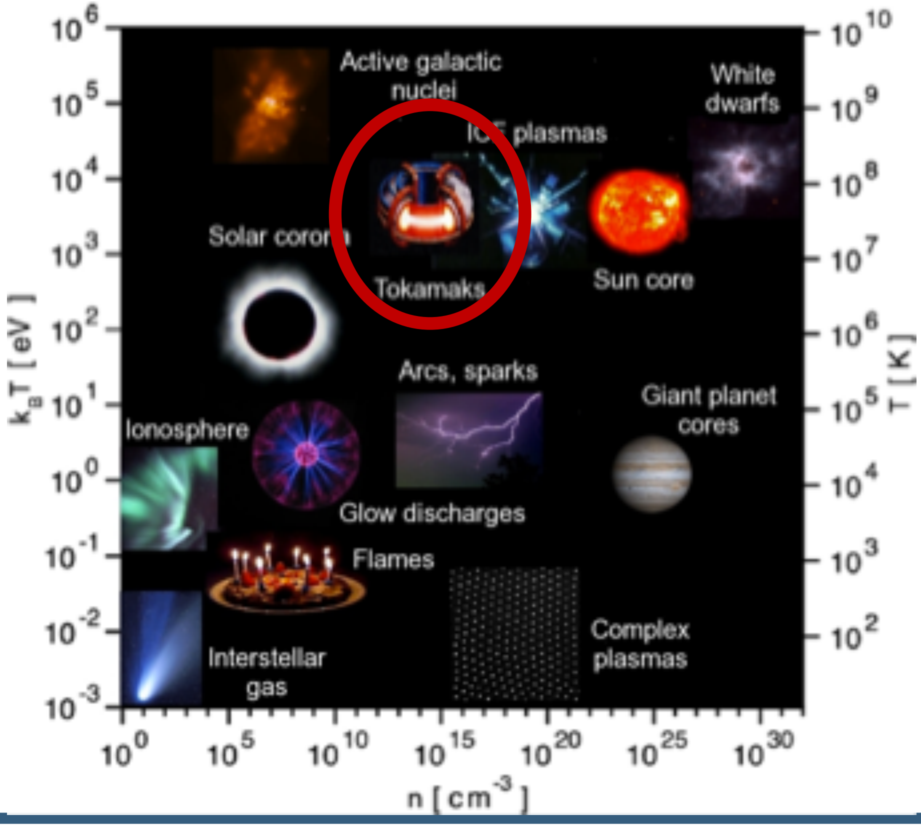


- **Topological rearrangement of the plasma** → breaks the "frozen in" condition on the magnetic field
- **Converts some magnetic field energy into particle energy** → the plasma charges a "toll" to the magnetic field

Reconnection in our magnetosphere



Magnetic Fusion Plasmas



Director Steven Cowley
Introduction to Magnetic Fusion

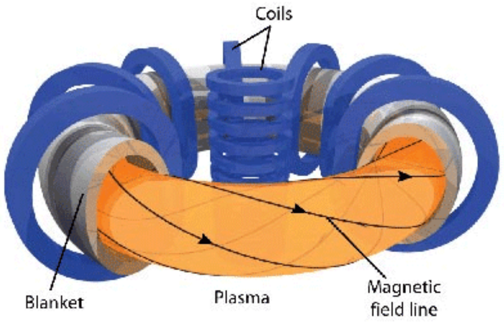
Prof. Michael Maurer
Introduction to Stellarators

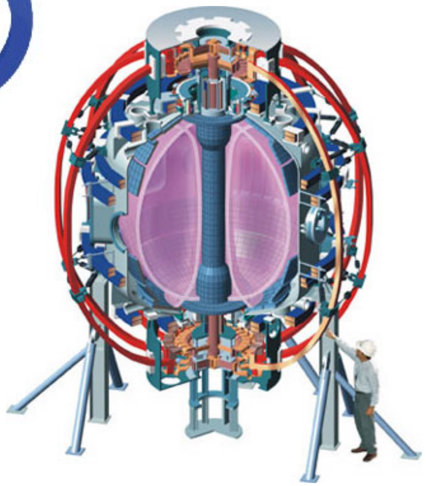
Prof. Dan Andruczyk
Plasma-Materials Interaction

www.phdcomics.com/tv

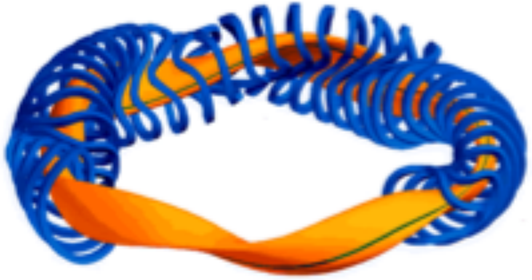
The two main configurations of magnetic confinement devices

Tokamak

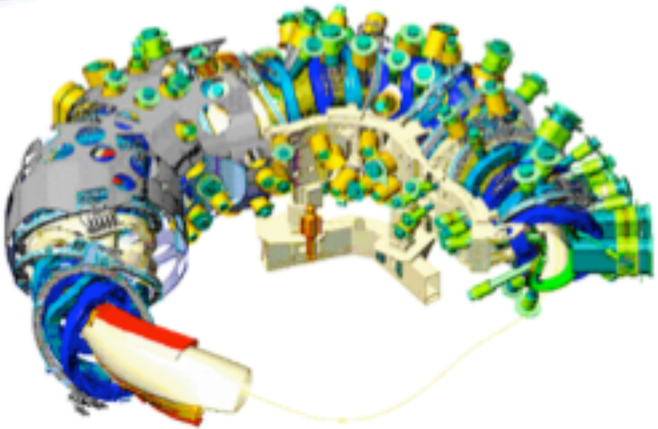




NSTXU @ PPPL



Stellarator



W7X @ Max-Planck / Germany

We, at PPPPL, are proud of the Stellarator…we invented it! (Lyman Spitzer did)

Inventor or the Stellerator

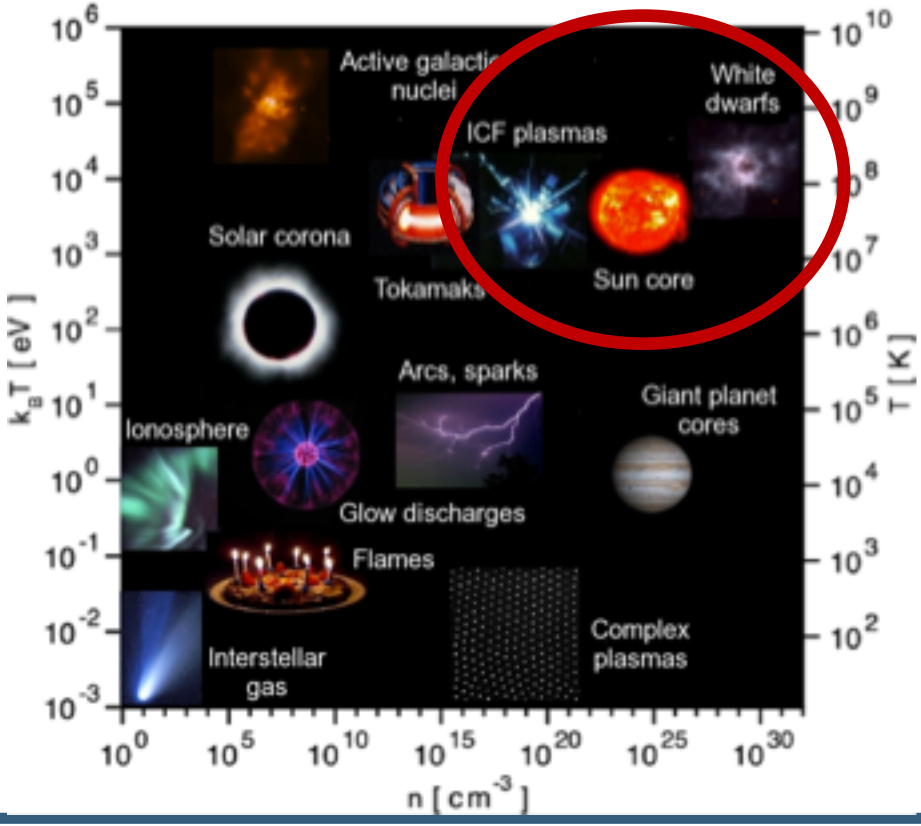
Founder of the lab

“Figure 8” Stellarator

Made countless advances in plasma physics (his name is everywhere)

Proposed telescopes in outer space (hence the Spitzer Space Telescope)

High Energy Density Plasmas



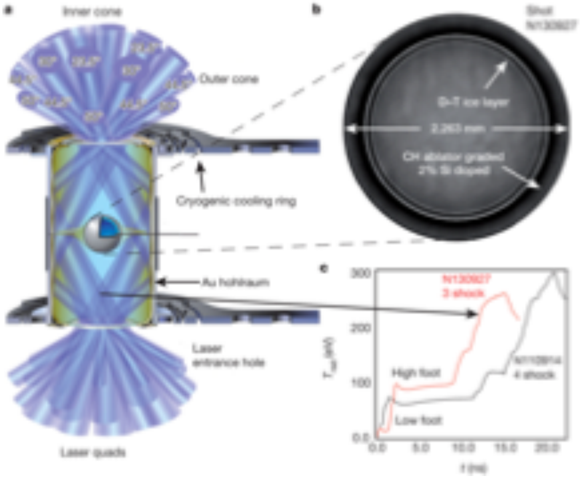
Dr. Tammy Ma

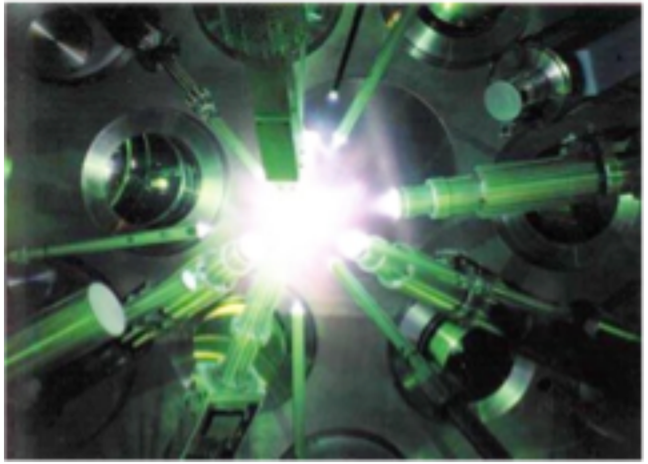
Introduction to Inertial Confinement Fusion

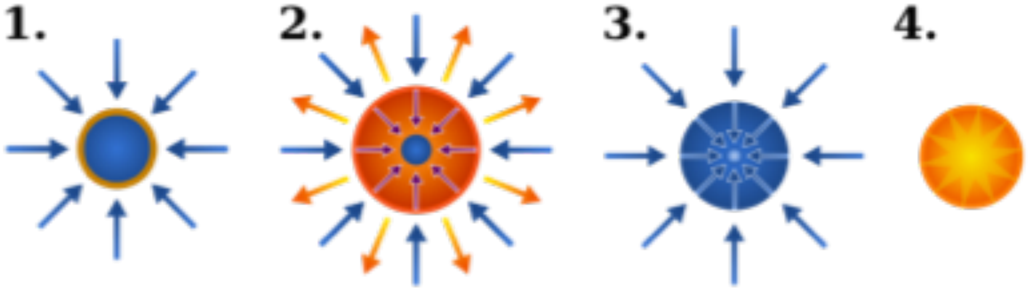
Dr. Cameron Geddes

Introduction to Wakefield Acceleration

Another way to create fusion conditions

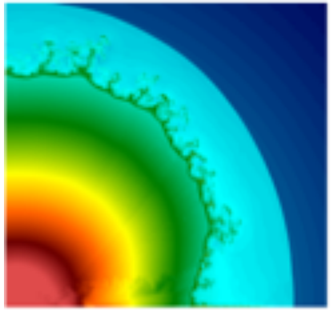


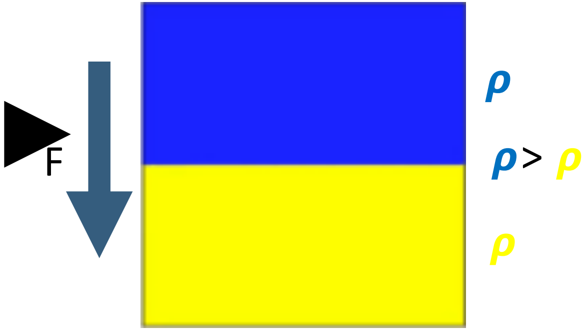




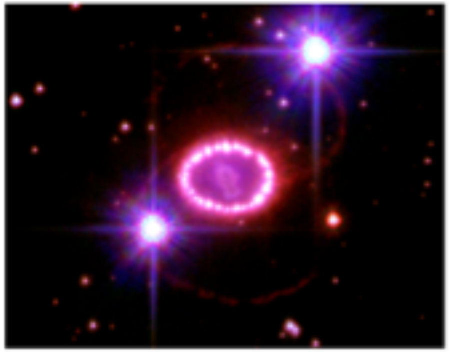
High energy density plasmas can model astrophysical phenomena

Raileigh-Taylor Instability



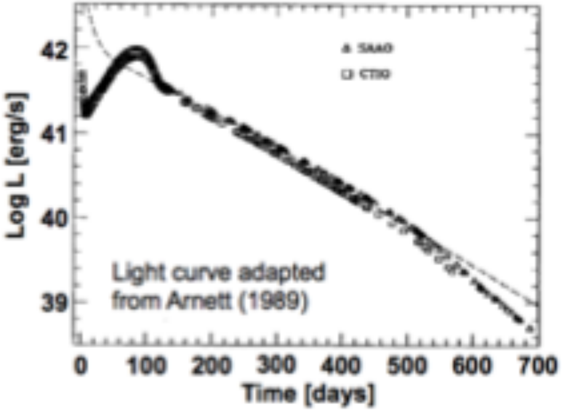


SN1987A, Hubble Space Telescope



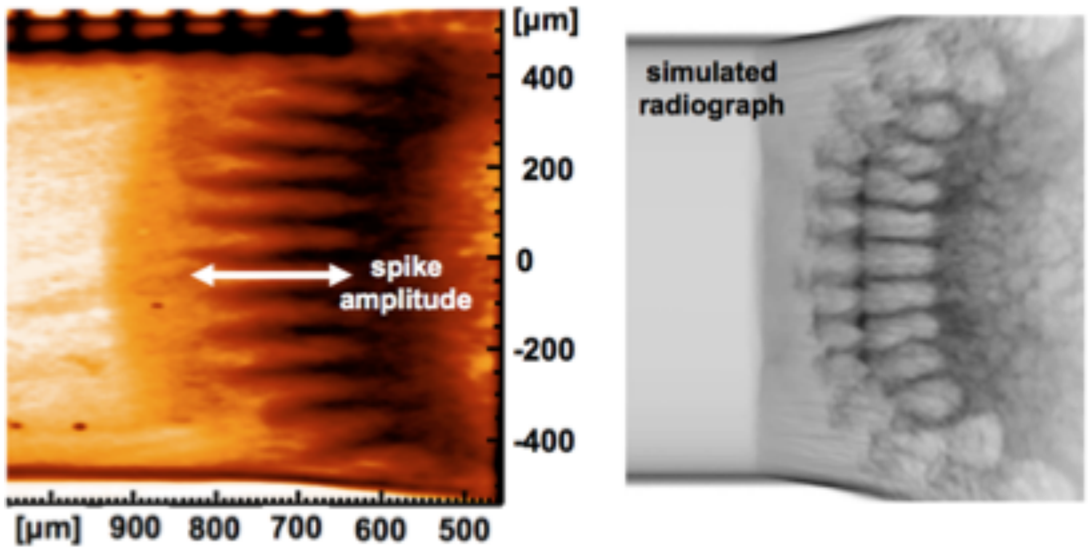
Can mixing in supernovae be investigated in the lab?

- Core-collapse supernova of a bluegiant
- Light curve data suggested* 'mixing' between stellar layers



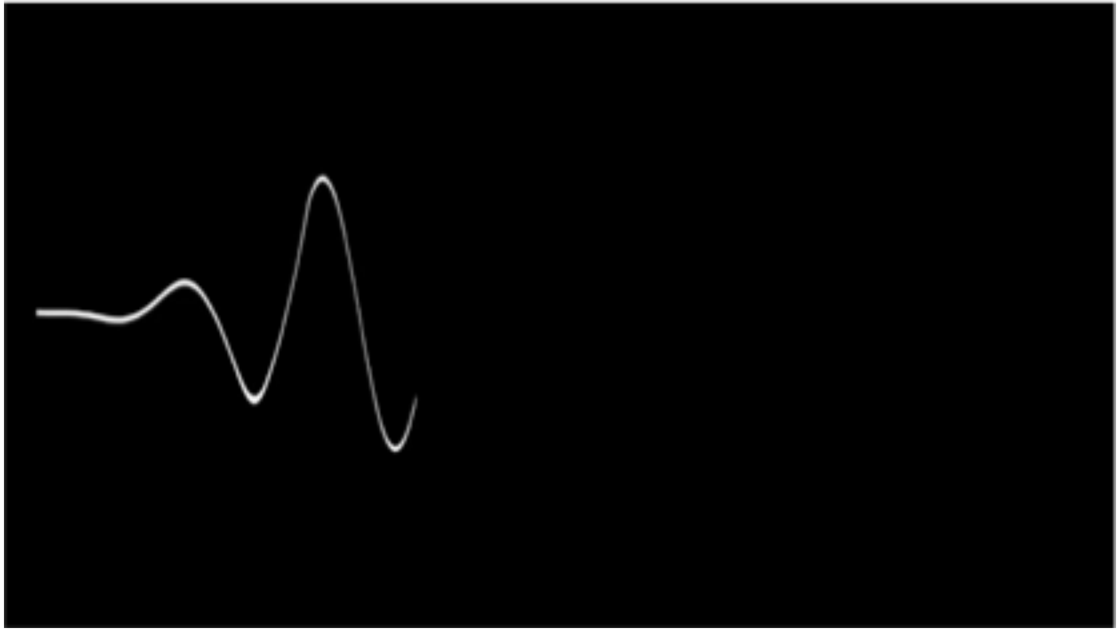
High energy density plasmas can model astrophysical phenomena

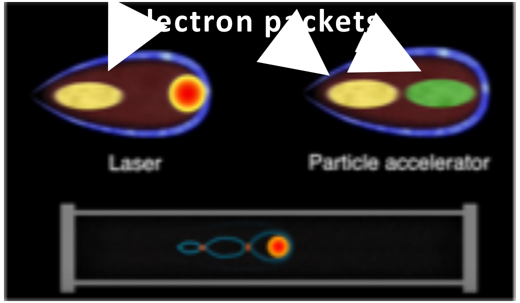
Laser/plasma experiments at Omega facility
to simulate the RTI observed in in the supernova collapse



Dr. Mario Manuel, 2018 SULI talk

Laser/plasma interactions can help create smaller accelerators

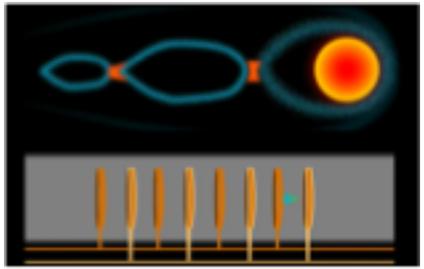




1.2m

=

~1km



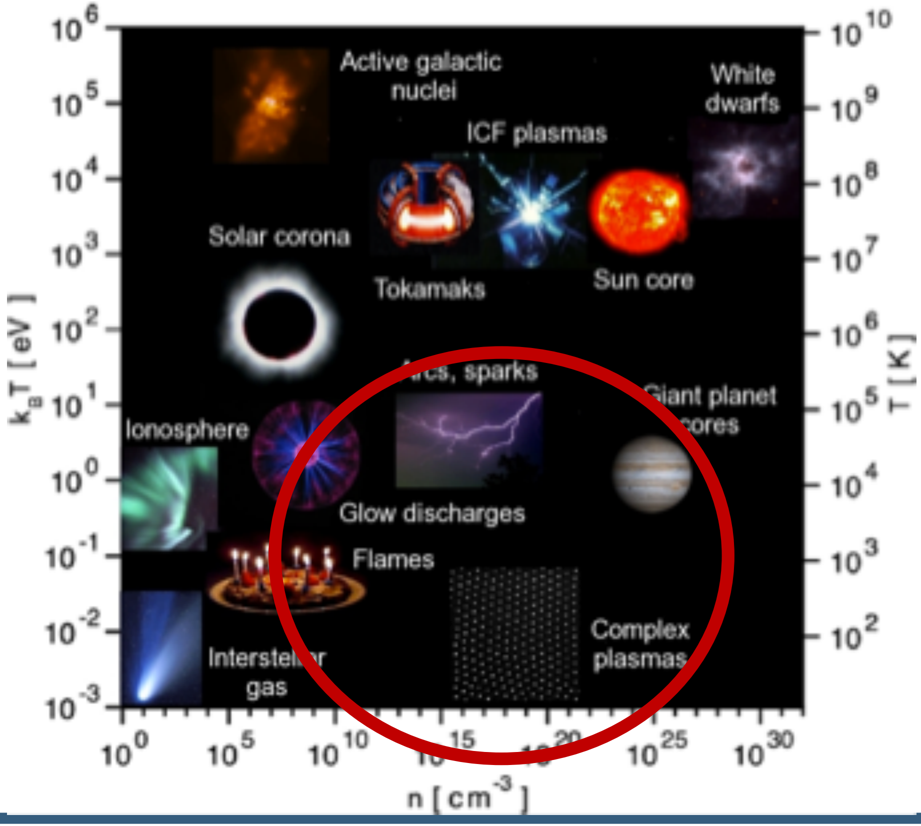
Wakefield Accelerators: The Future of Particle Colliders? - Deep Dive 1

108,319 views

The Thought Emporium

Published on Feb 26, 2018

Low Temperature and Complex Plasmas

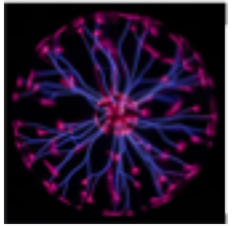


Prof. Jose Lopez
Low Temperature Plasmas

Prof. Edward Thomas
Complex Plasmas

An aside on temperatures

1ev = 10,000K (11,600, but whatever)

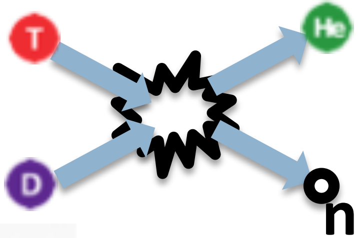


~1eV

13.6eV

~1keV

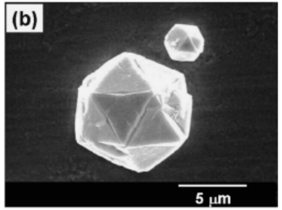
~10keV



~10MeV

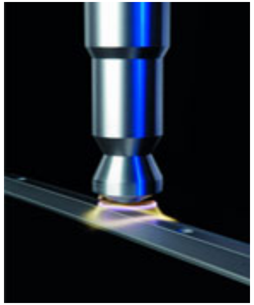
There are MANY applications for low temperature plasmas

Material Synthesis



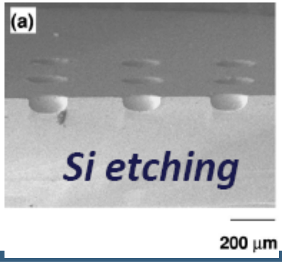
Plasma display

Surface Treatment



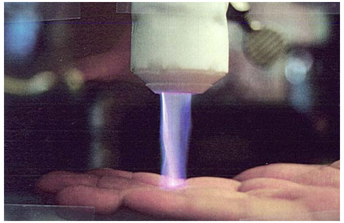
Lighting

Material processing

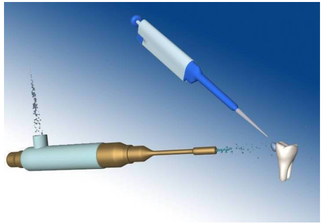


Ozone generation
for water cleaning

Bio-application

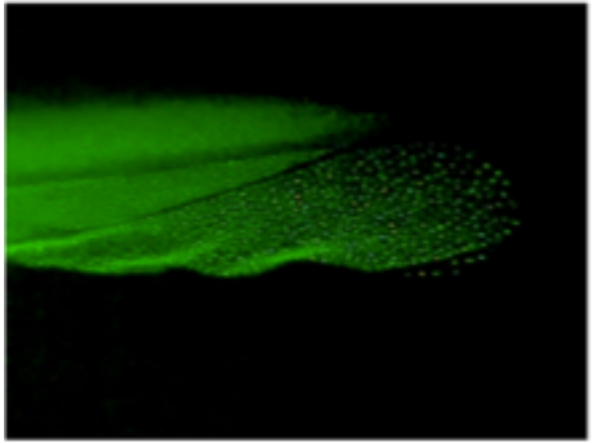


Dental application

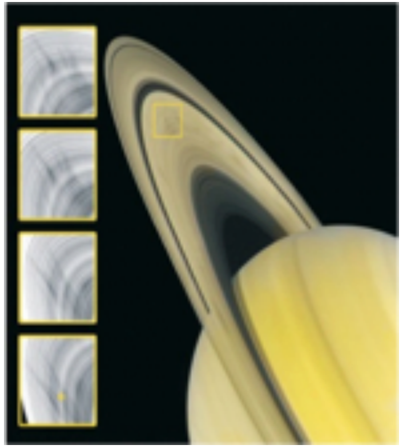


Complex Plasmas

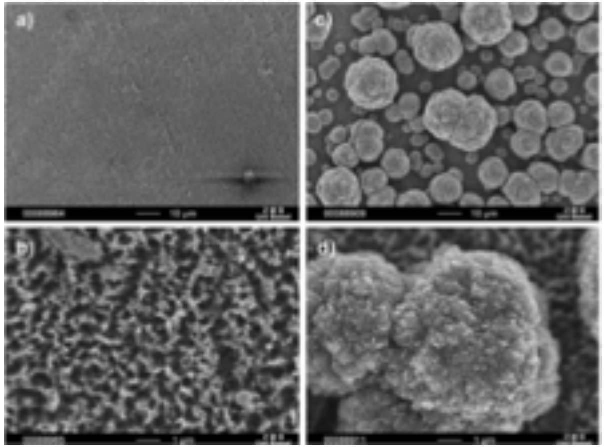
Complex/Dusty plasmas = electrons + ions + neutrals + **charged microparticles (dust)**



Lab dusty plasma

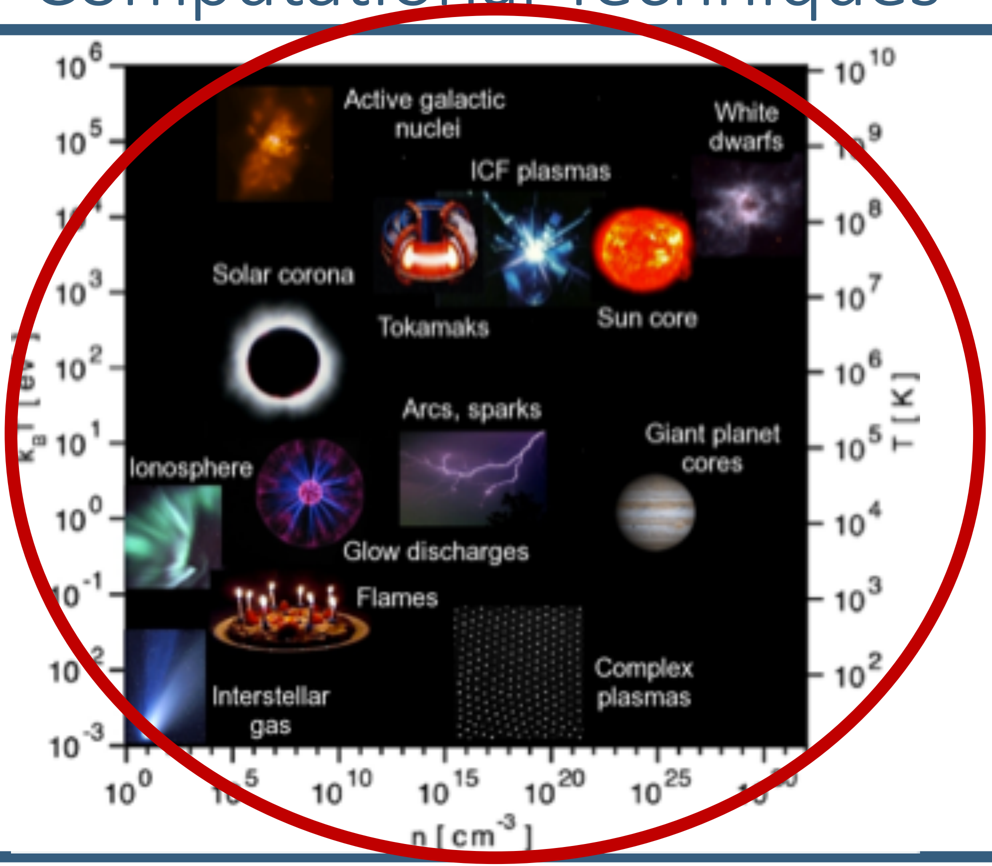


Dusty plasma
In our solar system



Dusty plasma
In fusion devices

Computational Techniques



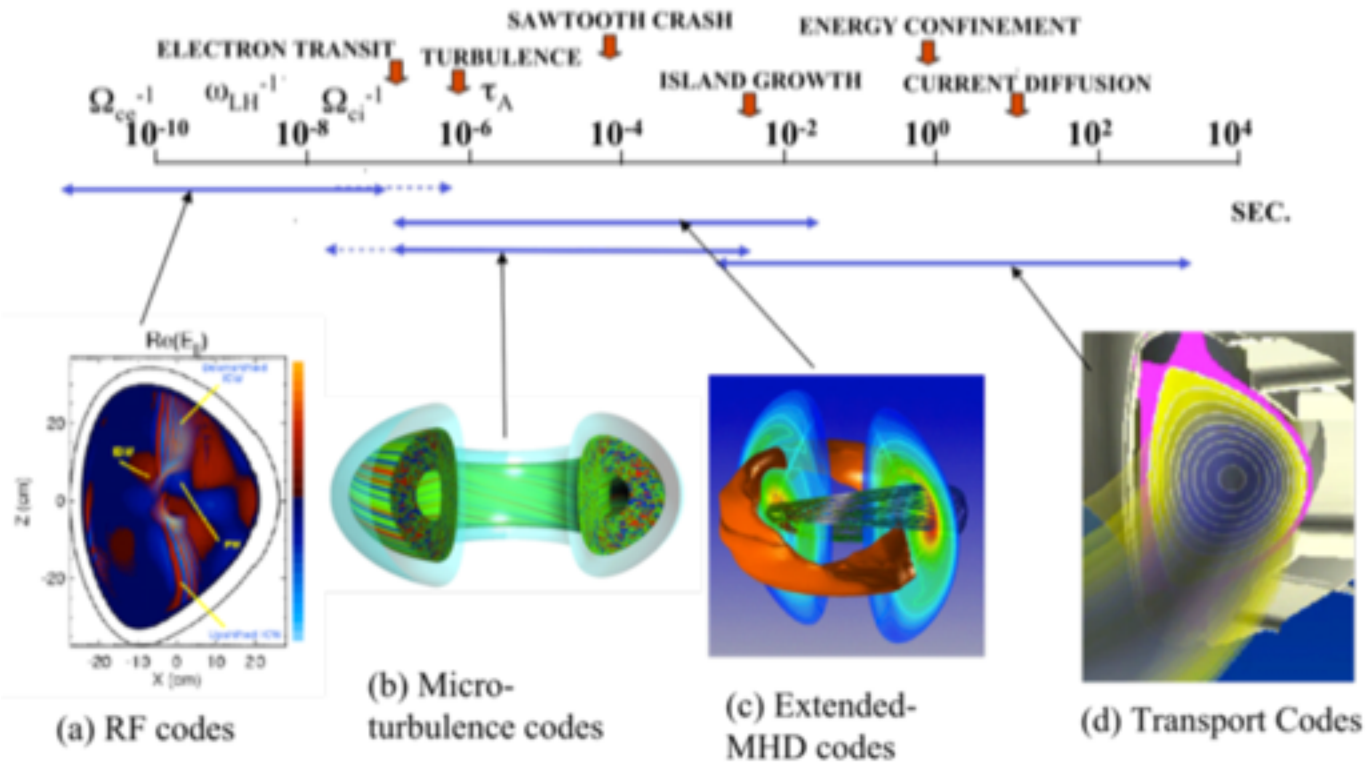
Dr. Matt Landreman

Computational Plasma Physics

The complexity of the systems lead to the need for simulations

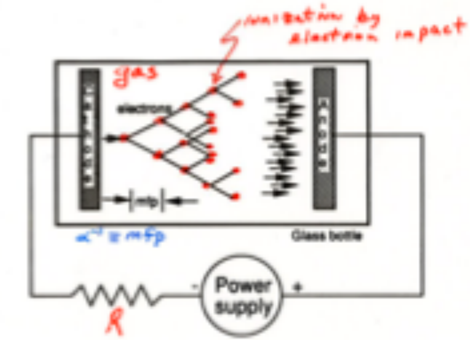
- In a typical lab plasma, N~1E20
- Every charged particle creates an E and B everywhere in space
- Every charged particle is subject to q(E+vxB) forces from every other particle (plus from external sources)
- **The problem becomes analytically intractable very quickly**

Time/length scales span many decades

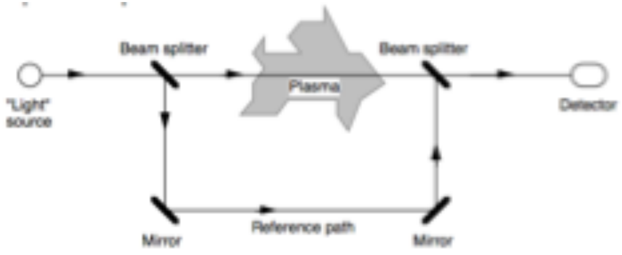


Experimental techniques

Paschen's Law



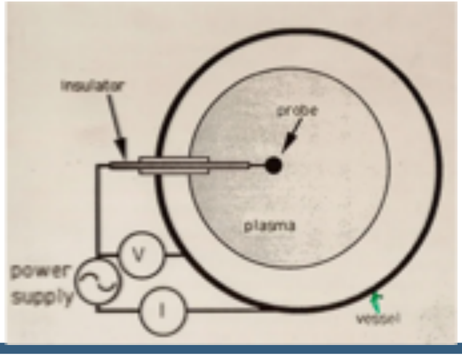
Interferometry



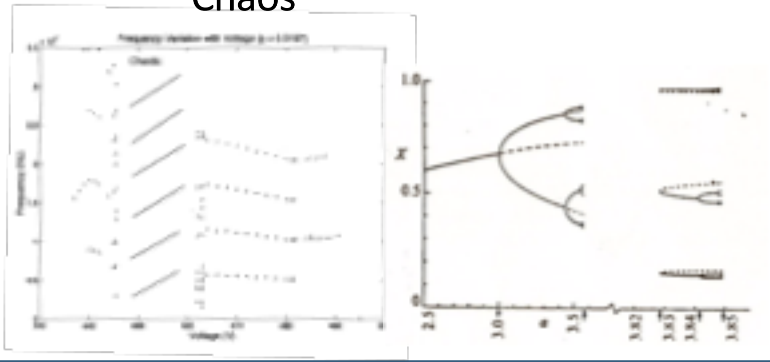
Prof. Sam Cohen

Experimental Methods

Langmuir Probes

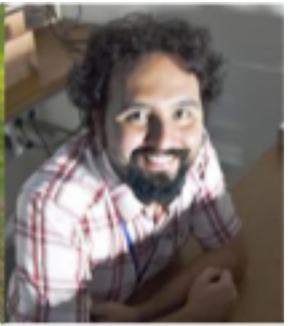


Chaos



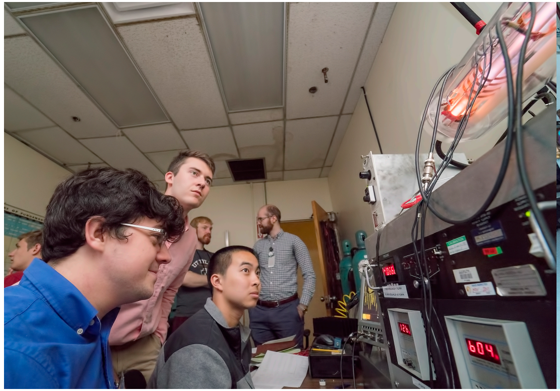
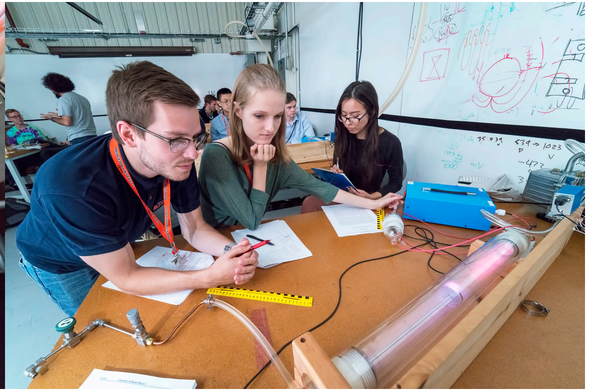
Experimental Session





Paschen’s Law
Interferometry

Langmuir Probes
Chaos

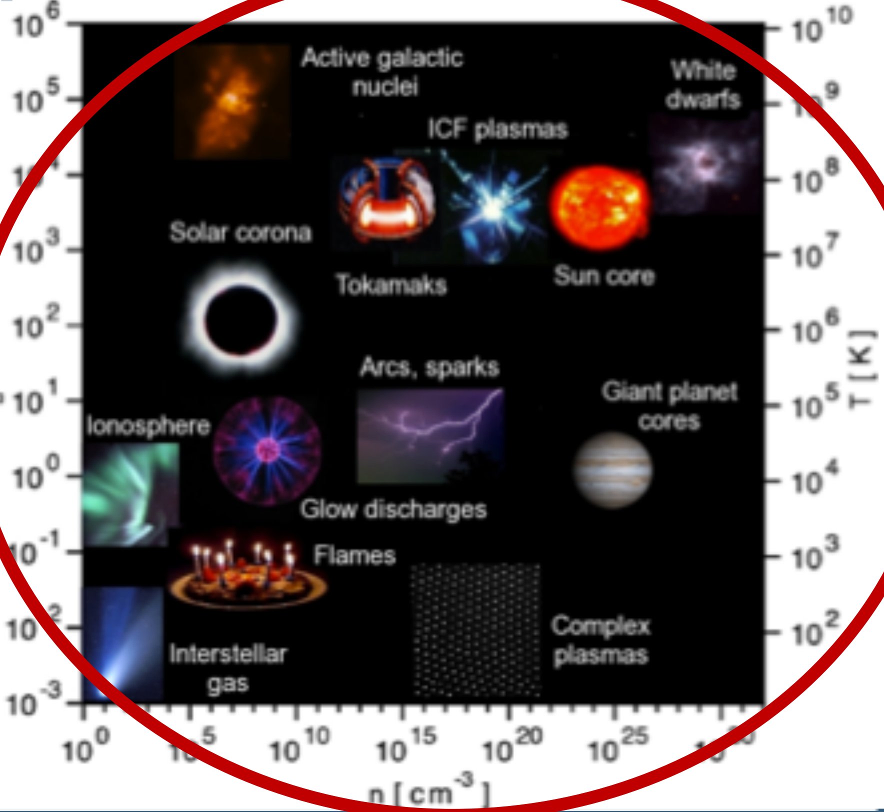
Experimental Session

Group A		Group B		Group C	
Group A1 (Grad lab)	**Group A2 (SciEd lab)**	**Group B1 (Grad Lab)**	**Group B2 (SciEd lab)**	**Group C1 (SciEd lab)**	**Group C2 (SciEd lab)**
Barbara Garcia	Marco Andres Miller	Paul Simmerling	Ryan Golant	Demetrius McAtee	Chandler Cotton
Gabriel Antonio Gonzalez Jusino	Colin Myrick	Katrina Teo	Shun Kamiya	Jacob Paiste	Julio Ocana Ortiz
Andrew Herschberg	Samantha Ann Pereira	Mikayla Washington	Keisuke Kanda	Allison Price	Arie Henderson
Natalie Cannon	Esha Rao	Anna Martha Wolz	Shinichiro Kojima	Shannon Baeske	Jack Robertson
Carlos Andre Catalano	Luquant Singh	Laura Natalia Zaidenberg	Hibiki Yamazaki	Marisa Thompson	Reece Frederick
Matthew Barber	Marion Elizabeth Smedberg	Ish Kaul	Kota Yanagihar	Chigozie Chinakwe	Shakina Hogan
Loukas Carayannopoulos	Jace Christian Waybright	Andrew Christopher Hernandez	*Rob Goldston PEI student*	Robert Galvez	Laura Bentivegna
James LeCompte	Eric Wolf	Trace Johnson	Andrew Brown	Taylor Shead	Chris Barber
Cristian Arens	Oleksandr Redin Yardas	Kai Torrens	Joshua Latham		
Ben Alessio	Courtney L Johnson	Andy Brown	Joshua James Luoma		
Michaela Hennebury	Ryan Arbon	Alexander Liu	Stephen Yan		
Adeline Hennebury	Promise Oluwagbope Adebayo-Ige	Daniel Thomas	Cole Alexander Love-Baker		
	Landon David Bevier		Kellin Murphy		
	Jamal Johnson		Le Viet Nguyen		
	Justin Cohen		Wyatt Pauley		
	Henry Fetsch		James Robinson		

Tour of PPPL

Dr. Erik Gilson

Plasma Physics Fundamentals



Dr. Cami Collins
Single Particle Motion

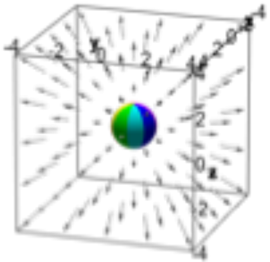
Dr. Carlos Paz-Soldan
Fluid Theory and MHD

Dr. Steffi Diem
Plasma Waves and Turbulence

First, a little reminder of vector calculus

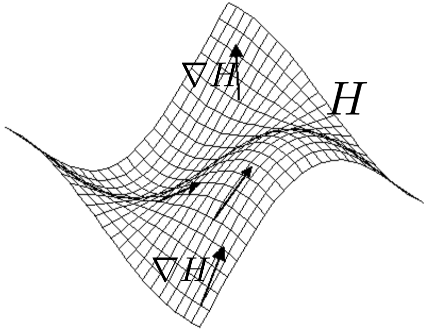
Divergence

$$\nabla \cdot \vec{V} > 0$$



$$\nabla H$$

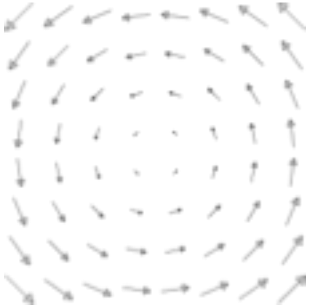
Gradient



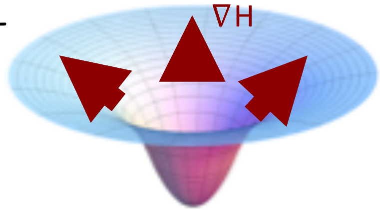
Curl

$$\nabla \times \vec{V} \neq 0$$

$\odot$



H

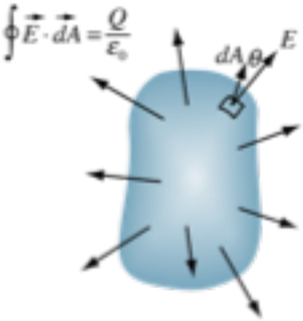


Laplacian

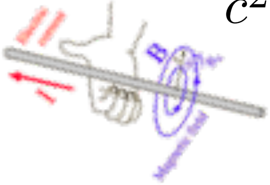
$$\nabla \cdot (\nabla H) = \nabla^2 H > 0$$

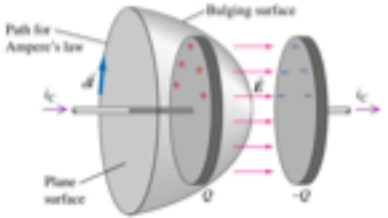
Gospel according to Maxwell

$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$

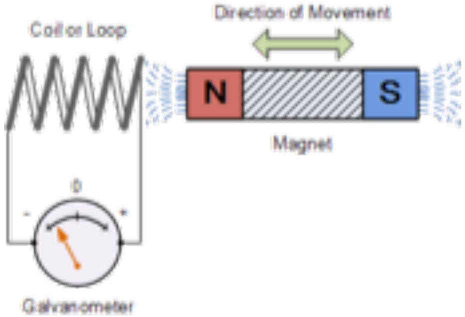


$$\nabla \times \vec{B} = \mu_0 \vec{J} + \frac{1}{c^2}\frac{d\vec{E}}{dt}$$

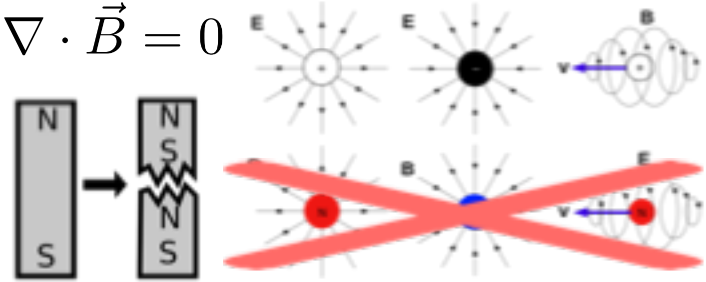




$$\nabla \times \vec{E} = -\frac{d\vec{B}}{dt}$$



$$\nabla \cdot \vec{B} = 0$$



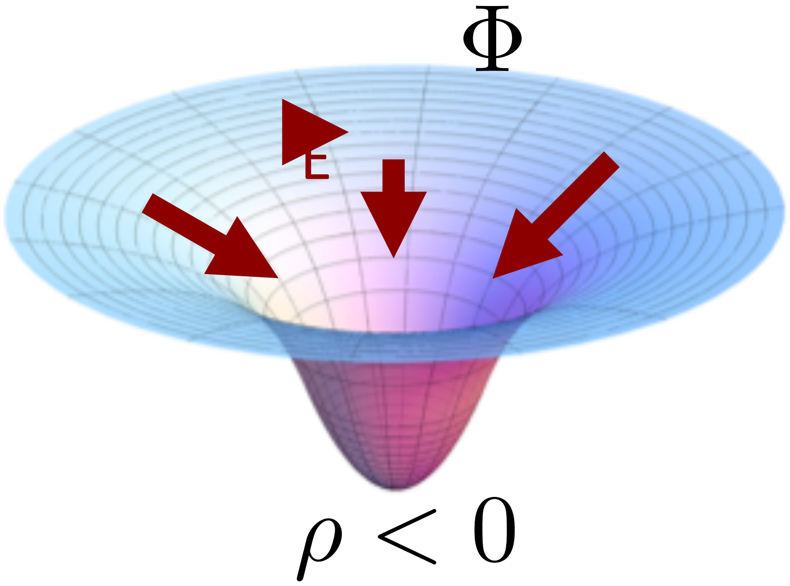
Electric potential and Poisson's equation

$$\vec{E} = -\nabla\Phi$$

$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$

$$\nabla \cdot (-\nabla\Phi) = \frac{\rho}{\epsilon_0}$$

$$\nabla^2\Phi = -\frac{\rho}{\epsilon_0}$$



Potential energy of a charge in an electric potential = $q\Phi$

Saha's equation tells you the degree of ionization

Ionization energy

$$\frac{n_i}{n_n} \approx 2.4 \times 10^{21} \frac{T^{3/2}}{n_i} e^{-U_i/k_B T}$$

Degree of ionization

For nitrogen at standard temperature and pressure (STP):

$$\frac{n_i}{n_n} \approx 10^{-122}$$

At STP, most of what's around us is neutral

Comparison between electric/gravitational forces

The electric and gravitational forces exerted on m_1 by m_2 are:

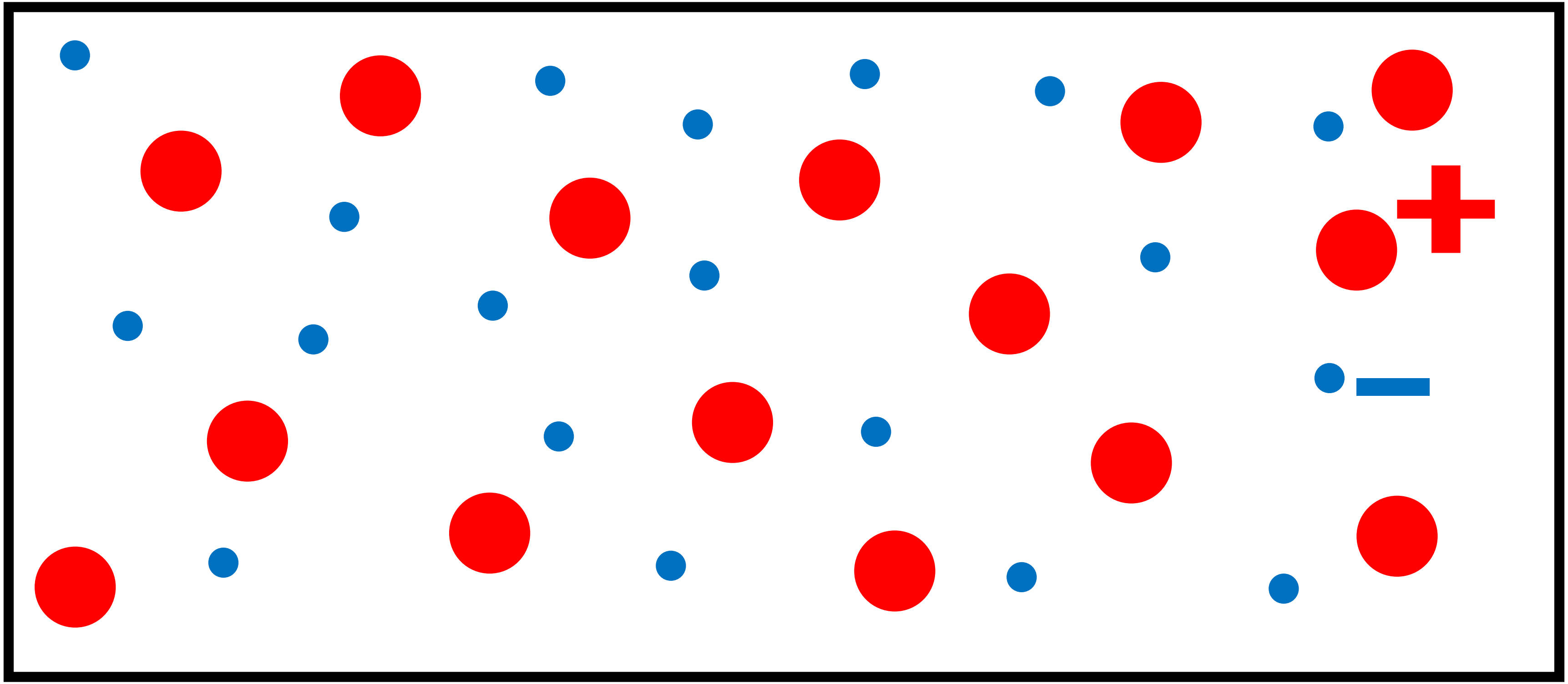
$$m_1 \vec{a} = \Sigma \vec{F} = \vec{F}_G + \vec{F}_E = \left[-\frac{G m_1 m_2}{r_{1,2}^2} + \frac{q_1 q_2}{4\pi\epsilon_0 r_{1,2}^2} \right] \hat{r}$$

Assuming one is an ionized deuterium atom and the other is an electron:

$$\frac{F_E}{F_G} = 1.1 \times 10^{39}$$

Gravity is irrelevant for lab plasmas (but not for astrophysical ones)

Even though it's (partially/fully) ionized, plasma equilibrium is quasi-neutral



We start with a thought experiment where we disturb this quasi-neutrality