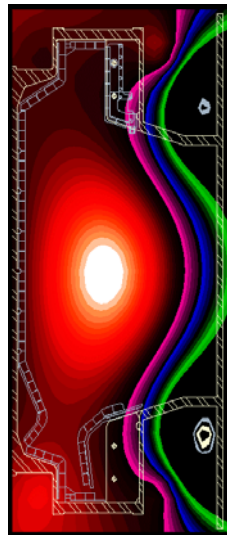

Turbulence, Transport and the Density Limit in Magnetic Fusion Experiments

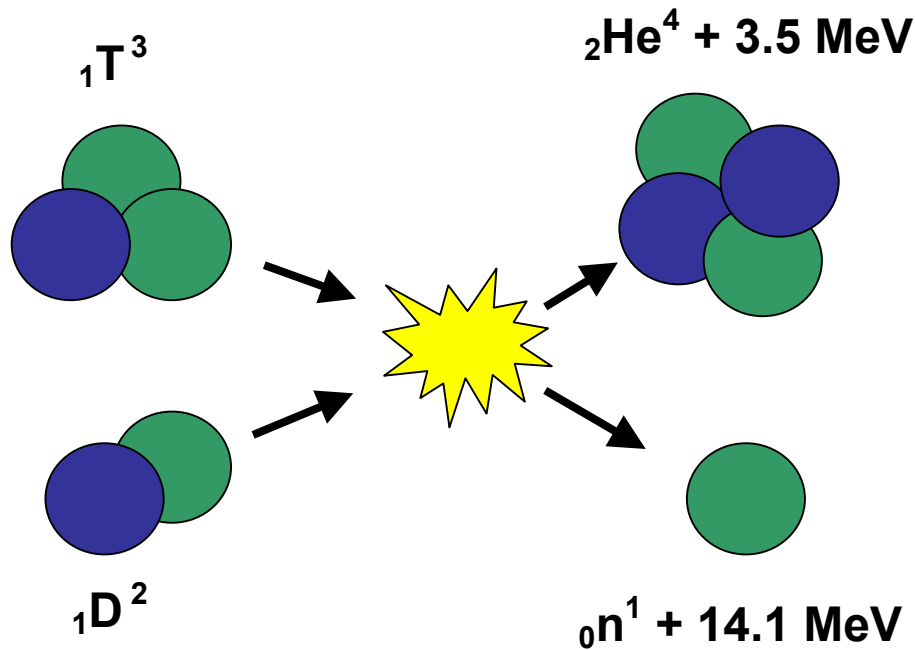
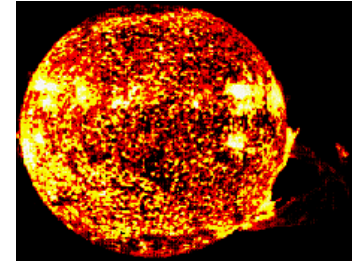


Martin Greenwald - MIT Plasma Science and Fusion Center
Dartmouth College, May 2, 2003

OUTLINE

- **INTRODUCTION TO FUSION AND MAGNETIC CONFINEMENT**
- **THE DENSITY LIMIT PROBLEM**
- **INTERLUDE ON TRANSPORT AND TURBULENCE**
- **TOWARDS AN EXPLANATION OF THE LIMIT**

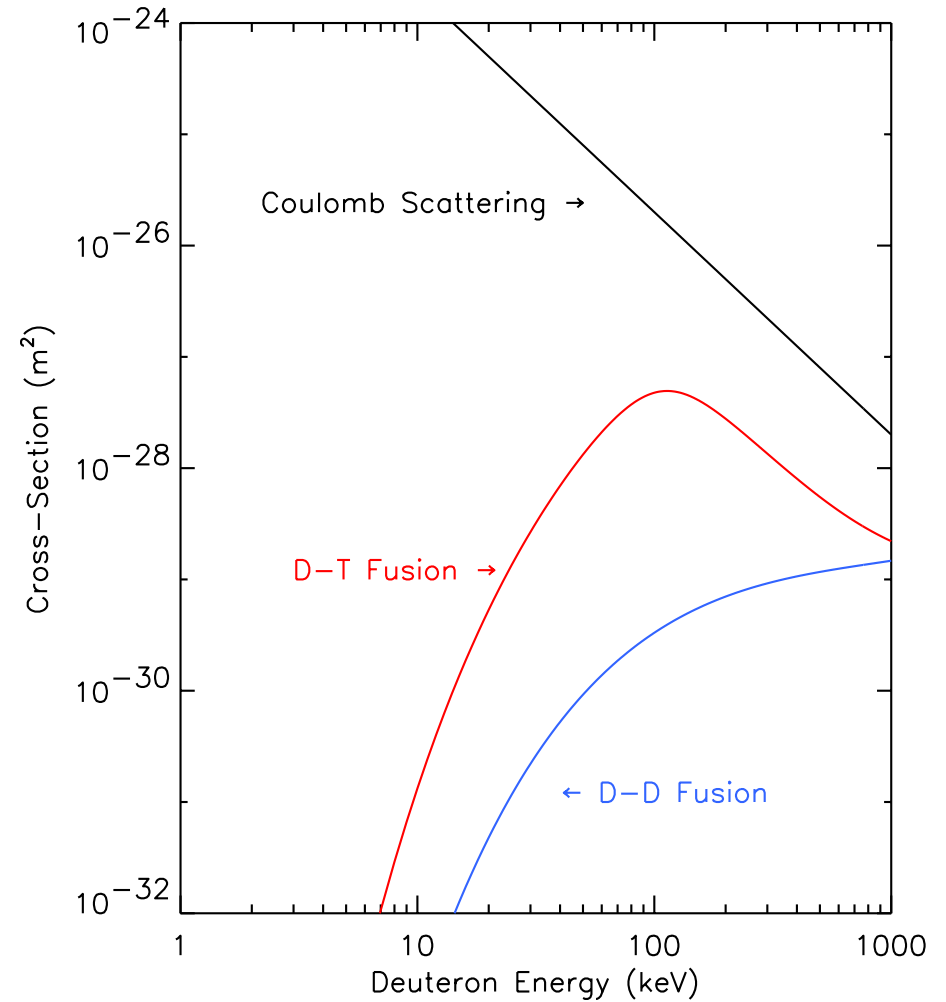
THE FUSION REACTION POWERS THE STARS AND PRODUCES THE ELEMENTS OF THE PERIODIC TABLE



- For 50 years, scientists and engineers at laboratories around the world have been working to exploit the fusion reaction as a practical energy
- The promise is for an environmentally friendly method for generating electricity with an inexhaustible fuel supply.

THE CURVES OF THE FUSION REACTION AND FOR ELASTIC SCATTERING LEAD US DIRECTLY TO THE STUDY OF **CONFINED PLASMAS**

- Even at the optimum energy, the nuclei are much more likely to scatter elastically than to fuse
- Nuclei must be confined for many interaction times.
- Multiple scatterings thermalize the constituent particles.
- At the energies involved (10-100 keV), matter becomes fully ionized \Rightarrow **plasma**.

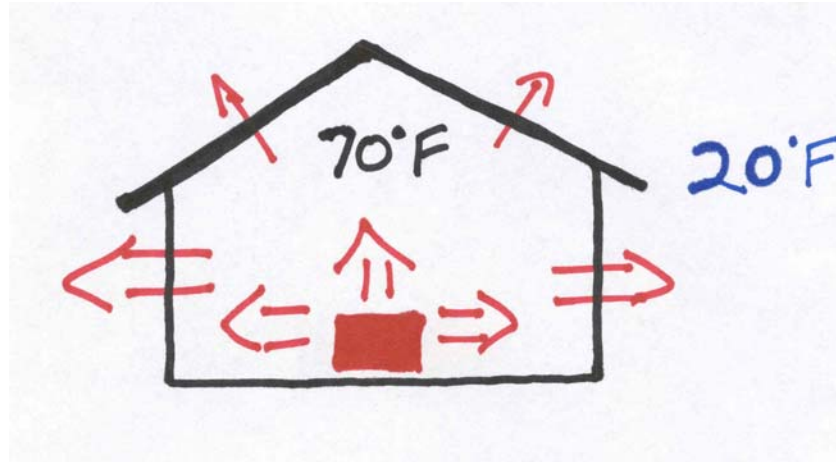


90% OF THE (VISIBLE) UNIVERSE IS MADE OF PLASMA



WHAT PRECISELY DO WE MEAN BY THE TERM “CONFINEMENT” ?

An analogy for fusion energy: Heating a building



$$\tau_E (\text{sec}) \equiv \frac{\text{Total stored energy (Joules)}}{\text{Heating rate (Watts)}}$$

- Our goal is to get to the required temperature with the least amount of heating power.

HOW DO WE DO IT?

1 Gravitational Confinement

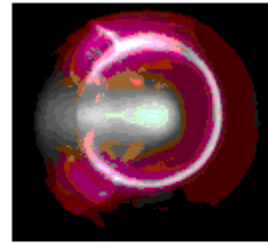
- In a dense gravitational well, even fast particles are trapped
- Works well for stars
- (Who can afford to build a star?)

2 Inertial Confinement

- Heat and compress plasma to ignition plasma before constituents fly apart.
- Works for the H-bomb
- "Micro" explosions to be tested with NIF (Defense Program)

3 Magnetic Confinement

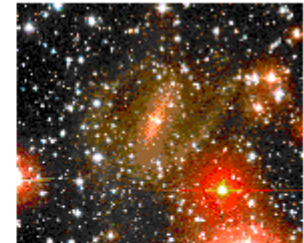
- Takes advantage of the motion of charged particles in a magnetic field



Magnetic
Confinement



Inertial
Confinement



Gravity

MAGNETIC CONFINEMENT

Gyro-radius

$$\rho = \frac{mV_{\perp}c}{qB} \propto \frac{\sqrt{mT}}{B}$$

Gyro-frequency, $\omega_c = \frac{eB}{mc}$

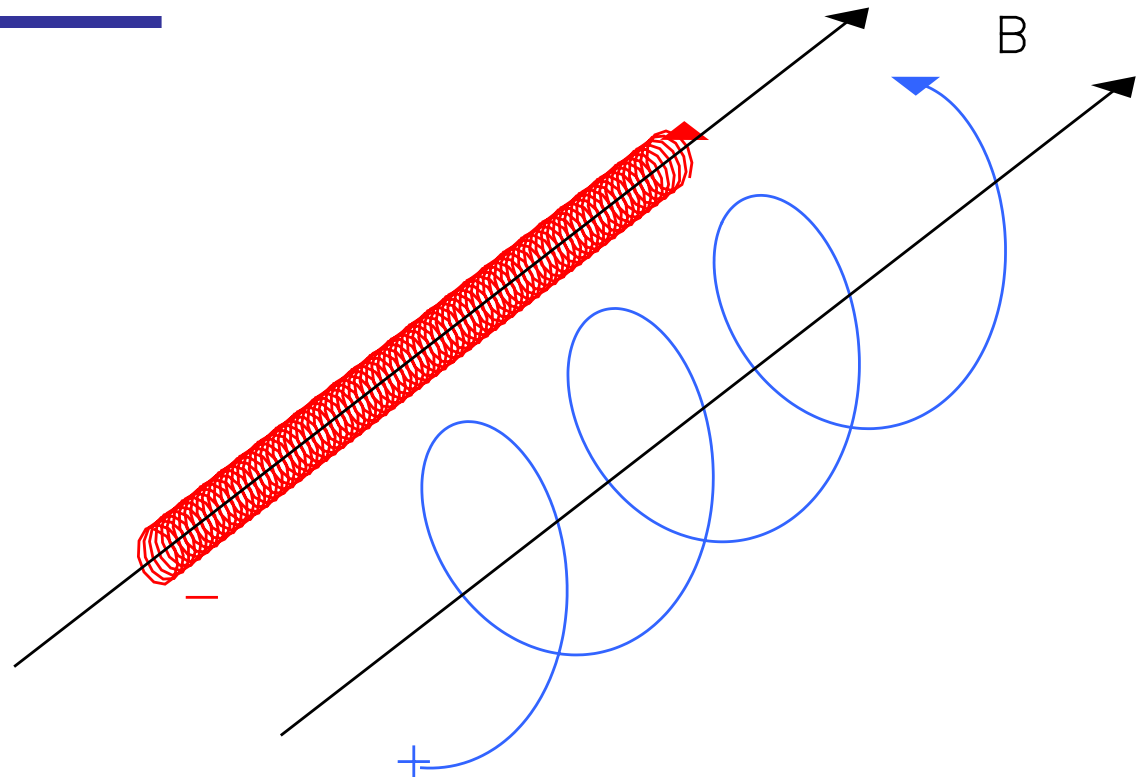
At $B = 5\text{T}$, $T = 10\text{keV}$

$\rho_e = 0.067\text{ mm}$

$\rho_i = 2.9\text{ mm}$

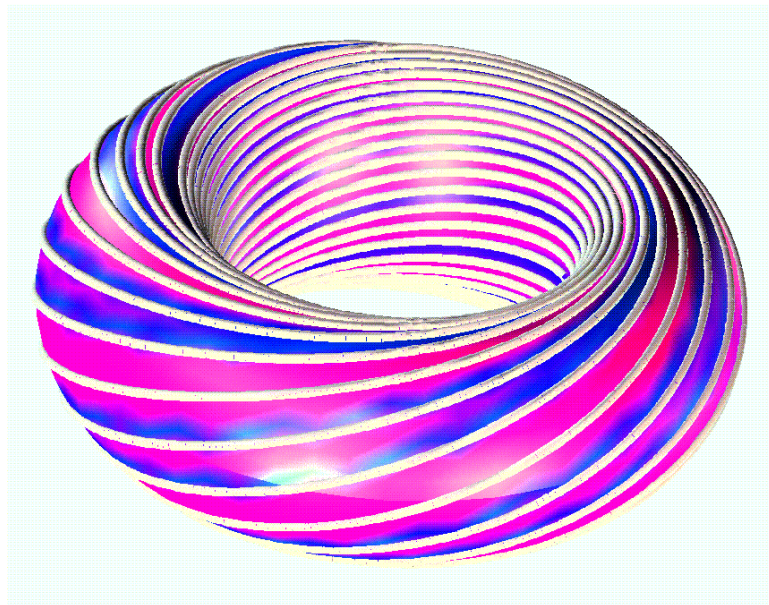
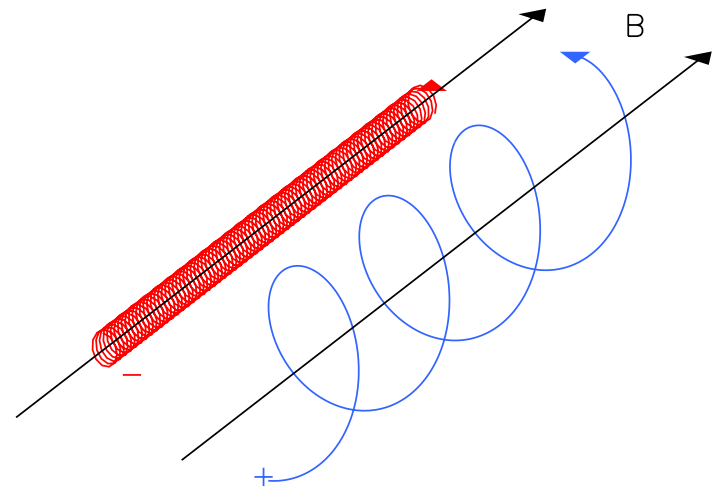
$\omega_e = 8.8 \times 10^{11}\text{ rad/sec}$

$\omega_i = 4.8 \times 10^8\text{ rad/sec}$



Ionized particles are deflected by the Lorentz force and bent into circular orbits.

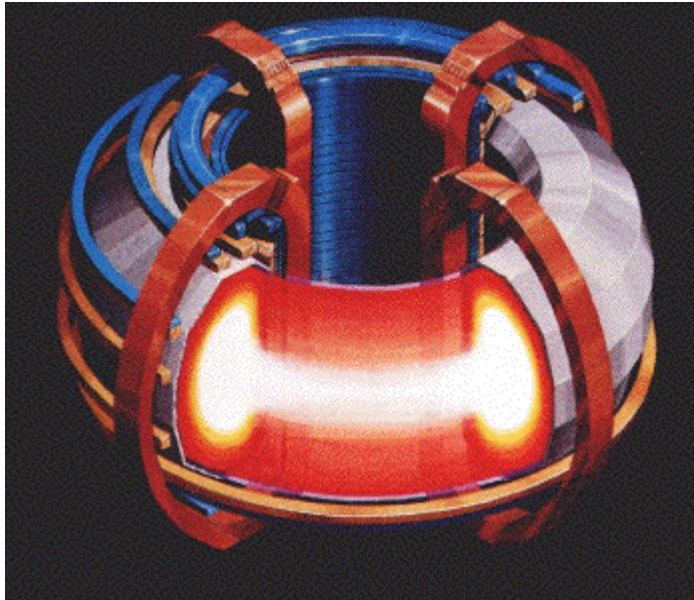
IN THE SIMPLE EXAMPLE SHOWN,
THERE IS NO CONFINEMENT **AT ALL**
PARALLEL TO THE MAGNETIC FIELD.



- For a practical device, the end losses must be eliminated

Voila! Eliminate the ends.

MOST FUSION EXPERIMENTS START HERE: WITH TOROIDAL PLASMAS.

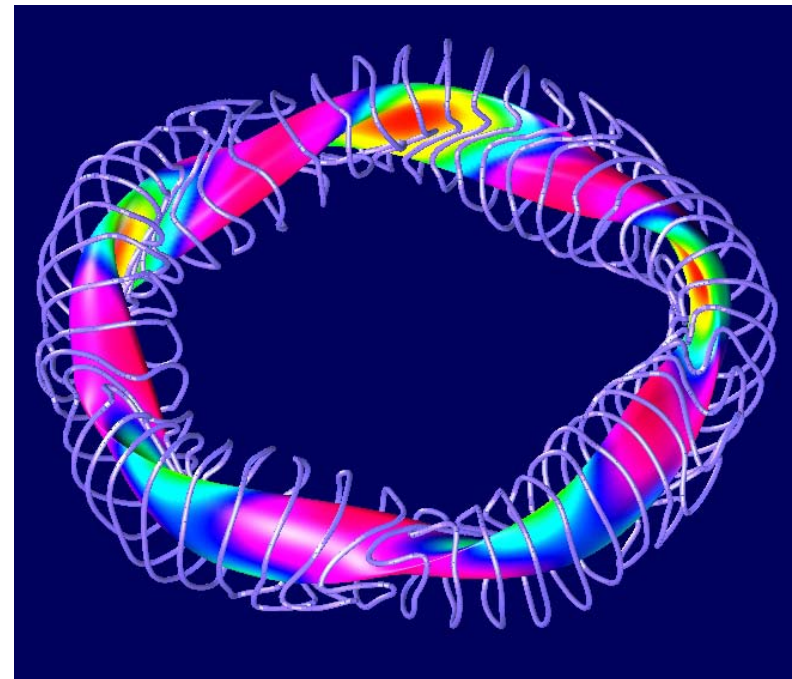


Tokamak

*(toroidalnaya kamera
magitnaya katushka)*

Stellarator - Wendelstein 7AX

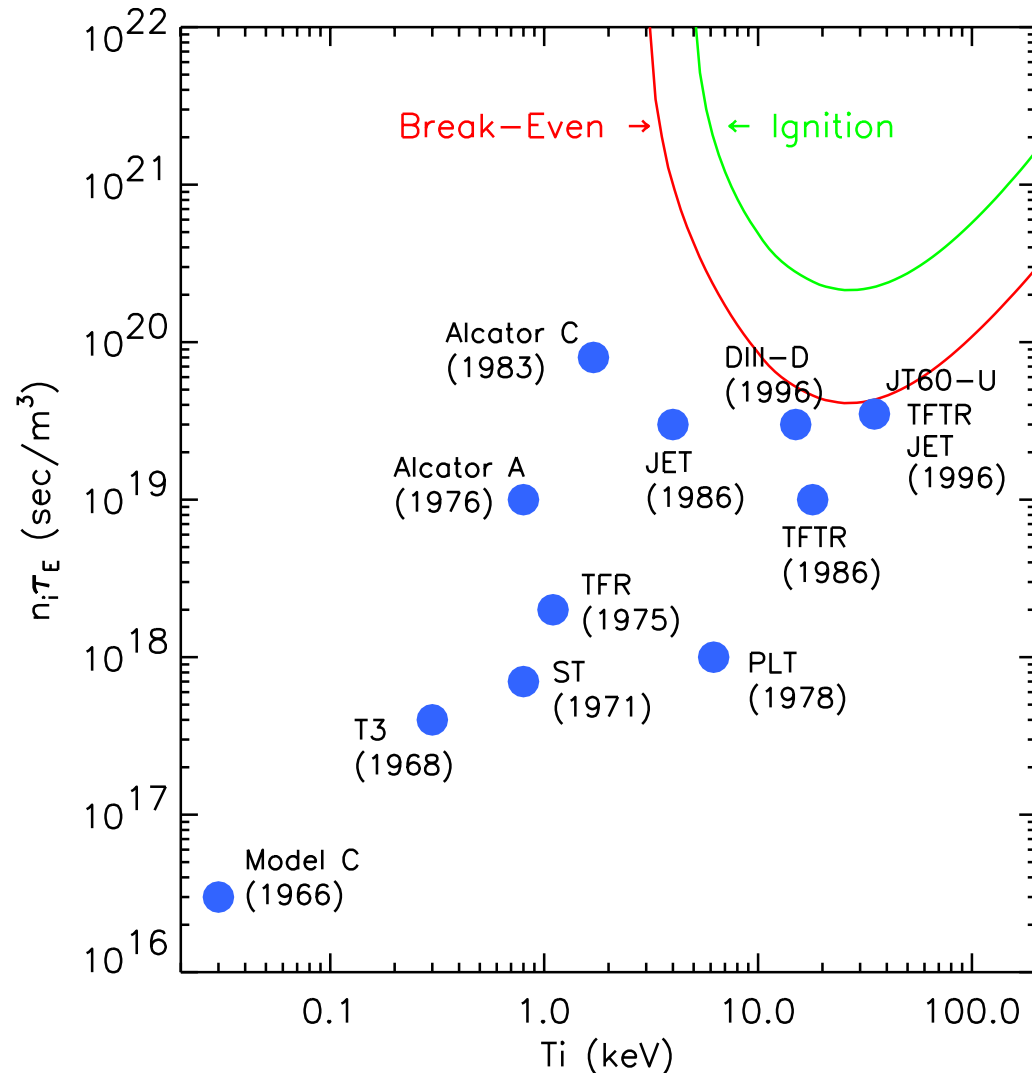
*(Under construction in
Greifswald Germany)*



- In toroidal devices, plasma is confined by *Poloidal* magnetic fields

DESPITE THE CHALLENGES, PROGRESS HAS BEEN SIGNIFICANT

- Over the last 35 years fusion yield has increased by about 10^7 . **A doubling time of about 18 months!**
- We have roughly another factor of 100 in performance to go.
- We also need to go from pulses to steady state.

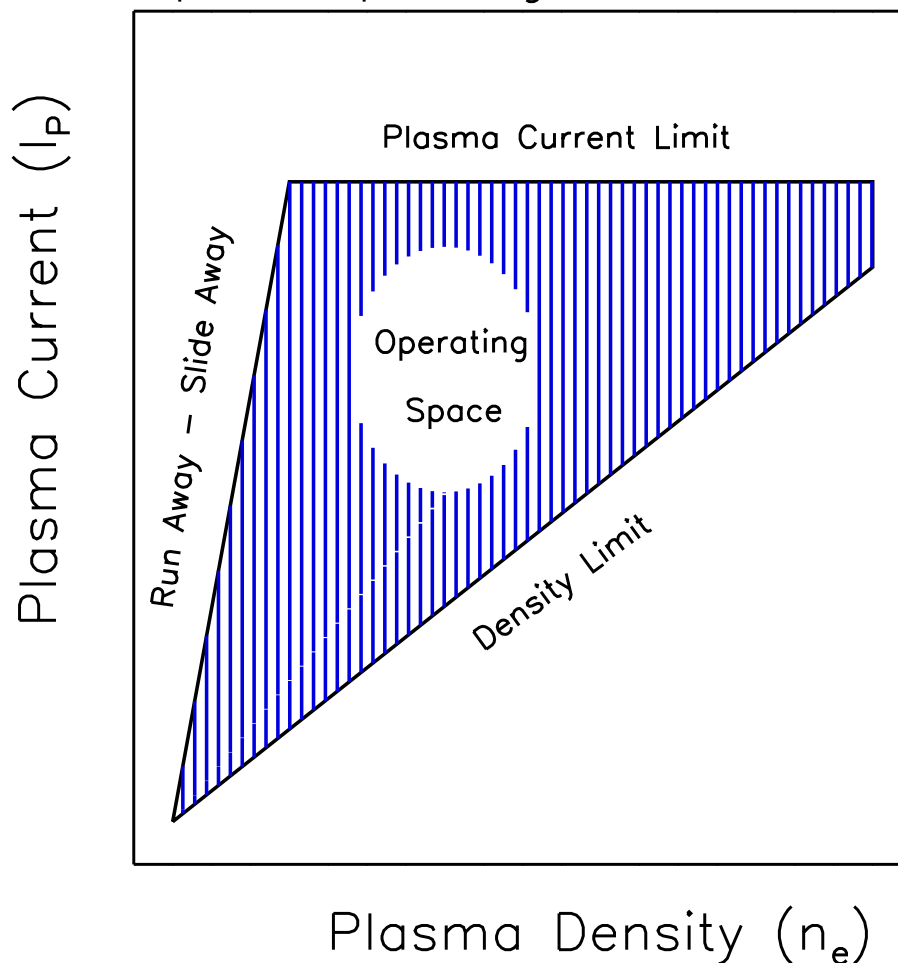


The Density Limit Problem

OPERATIONAL LIMITS

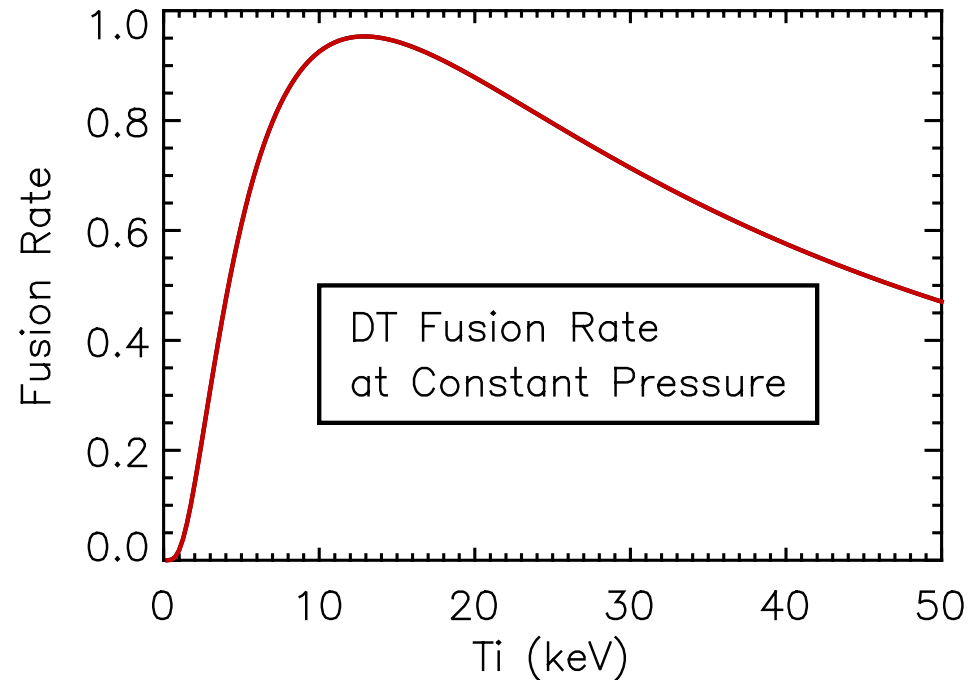
- Magnetic confinement devices don't operate at arbitrary plasma parameters
- There are well established, **distinct** limits on plasma **pressure, current, and density**
- Understanding these limits and their implications has always been an active area of research

Example – Operating Limits in Tokamak



DENSITY LIMITS - AN IMPORTANT ISSUE FOR MAGNETIC FUSION

- $R_{DT} \propto n^2 \langle \sigma v \rangle$
- Plasma pressure limited by MHD stability
- At fixed pressure, there is an optimum temperature \Rightarrow optimum density
- **No guarantee that this density is achievable in any given device**
- Critical issue for conventional tokamak reactor

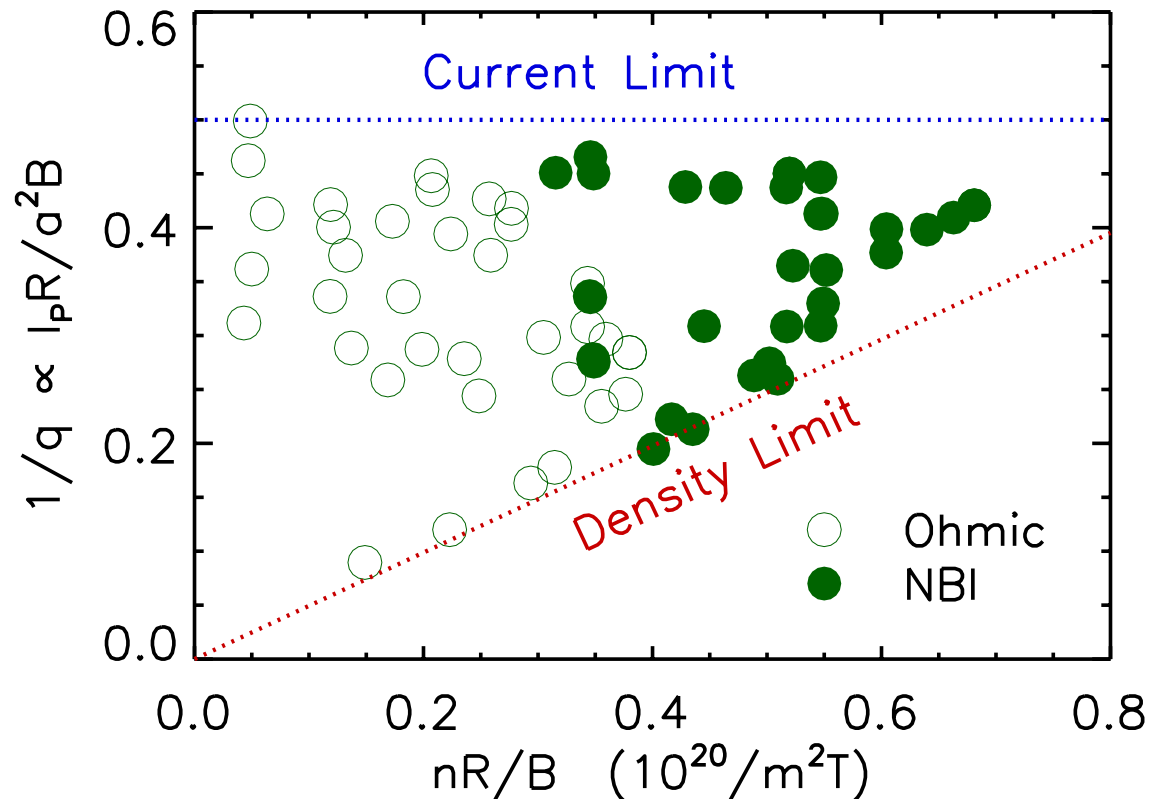


IN TOKAMAKS, THE DENSITY LIMIT ULTIMATELY MANIFESTS ITSELF AS A DISRUPTION

- General agreement on final scenario
- Current profile shrinkage \Rightarrow MHD instability \Rightarrow disruption
- Disruption is sudden (and violent) termination of discharge
- Thermal and magnetic energy released in a disruption can cause significant damage.
- Critical questions involve the evolution to the point where the current profile collapses – edge cooling
- What is the essential physics of the bifurcation or catastrophe

DENSITY LIMIT FIRST CHARACTERIZED BY EMPIRICAL SCALING

- First motivated by observation that impure plasmas disrupted at lower densities
- Murakami limit (1976)
 $B_T / R \propto j_0 \approx P_{Ohmic}$
- Hugill plot ~ 1978
- Leading dependence is with plasma current density

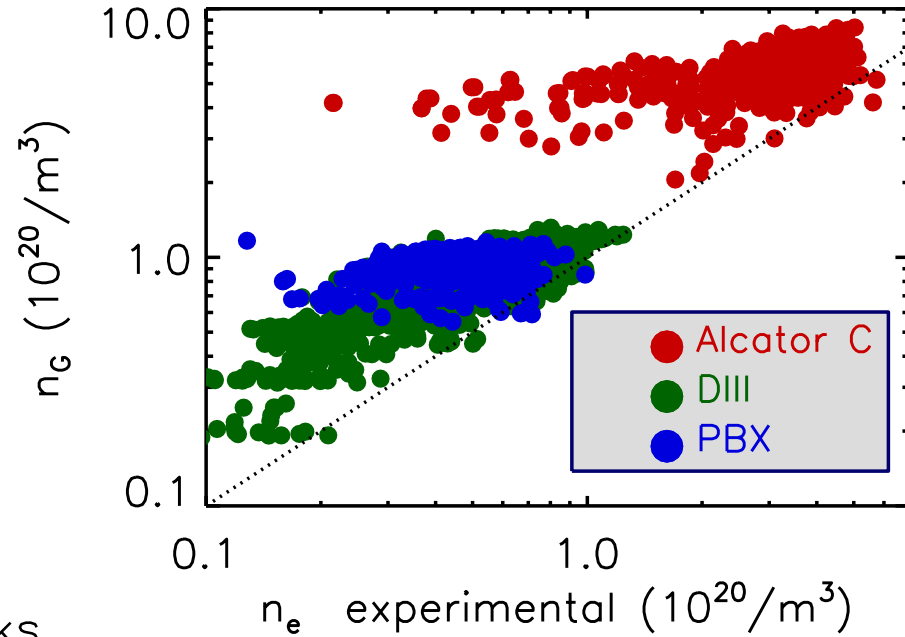


(Axon 1980)

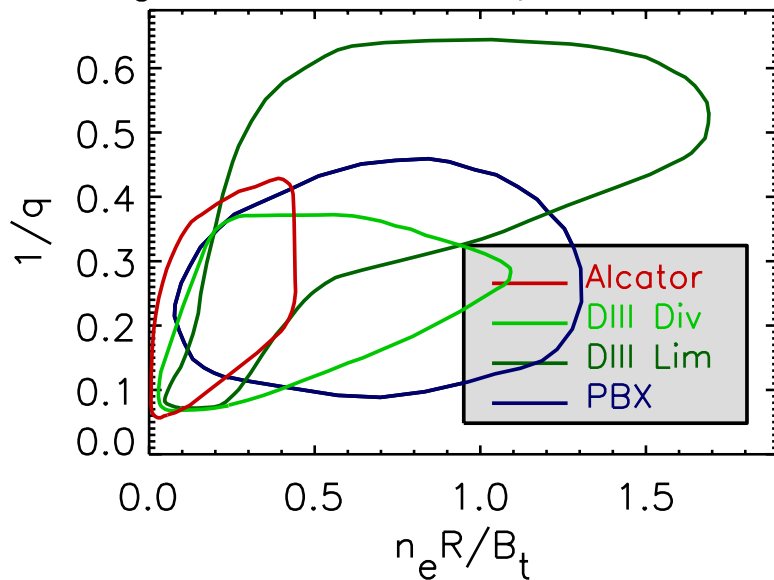
- $n_{LIM} \propto \frac{B}{qR} \approx \frac{I_P}{a^2}$ (Note absence of significant power scaling)

SCALING REFINED BY INCLUSION OF DATA FROM SHAPED TOKAMAKS

- Greenwald limit: $n_G = \frac{I_P}{\pi a^2}$
(with n : $10^{20}/\text{m}^3$, I_P : MA, a : m)



Hugill Plot for Shaped Tokamaks



Identical to Hugill for circular plasmas

Differs significantly for shaped plasmas

GLOBAL SCALING BY ITSELF IS AN INSUFFICIENT FOUNDATION FOR PREDICTING THE PERFORMANCE OF FUTURE MACHINES

- Scaling does an OK job,
but
- Covariance in data, may hide dependences (I_P and P_{IN} for example)
- Misses important local physics - **density profiles**
- **Need verified, first principles model**

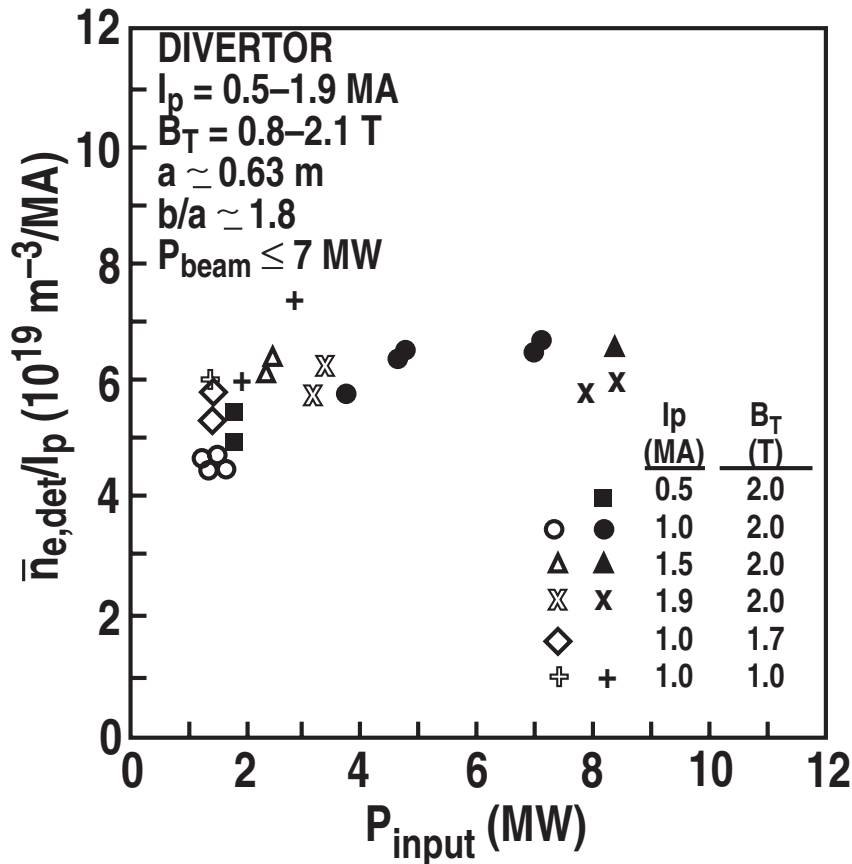
Big questions

- Where does the catastrophe come from?
- How do we compute the density limit?

DENSITY LIMITS - THE PHYSICS PROBLEM

- Operational limits normally set by MHD
 - Ideal MHD only cares about pressure (and current) not density
- What physics can lead to edge cooling and ultimately limit the density?
 - Neutrals – fueling and power balance
 - Radiation cooling $P_{RAD} \propto n_e^2 f_Z R(T_e)$
 - Density or collisionality dependent transport
- **No widely accepted first principles theory available**
- **Not even agreement on critical physics**

RADIATION/POWER BALANCE THEORIES HAVE DOMINATED HISTORICALLY – HOWEVER....



- There is significant evidence that this approach is not sufficient
- Experimentally power dependence varies from P^0 - $P^{0.25}$
- Limit does not depend strongly on plasma purity.

(Petrie 1993)

Transport and Turbulence

COLLISIONS DRIVE DIFFUSION - HEAT CONDUCTION

- Elastic collisions cause particles to move off field lines; energy is transferred (transported) in these collisions too.
- The process resembles a random walk with a step of size Δx taken every Δt seconds

$$\text{Diffusion Coefficient} \equiv D = \frac{\Delta x^2}{\Delta t}$$

$$\Delta t = \frac{1}{\nu}; \quad \nu \equiv \text{collision frequency}$$

- Characteristic relaxation time for a

diffusive process, $\tau \propto \frac{L^2}{D}$

**For a magnetic fusion
plasma:**

$$\Delta x = \rho_i$$

$$D \sim 10^{-3} \text{ m}^2/\text{sec}$$

So for L = plasma radius

~ 1 meter,

$$\tau \sim 1000 \text{ sec}$$

(more than good enough)

PARTICLE ORBITS ARE MORE COMPLICATED IN A TOROIDAL SYSTEM

Ions and electrons drift off of magnetic field lines due to:

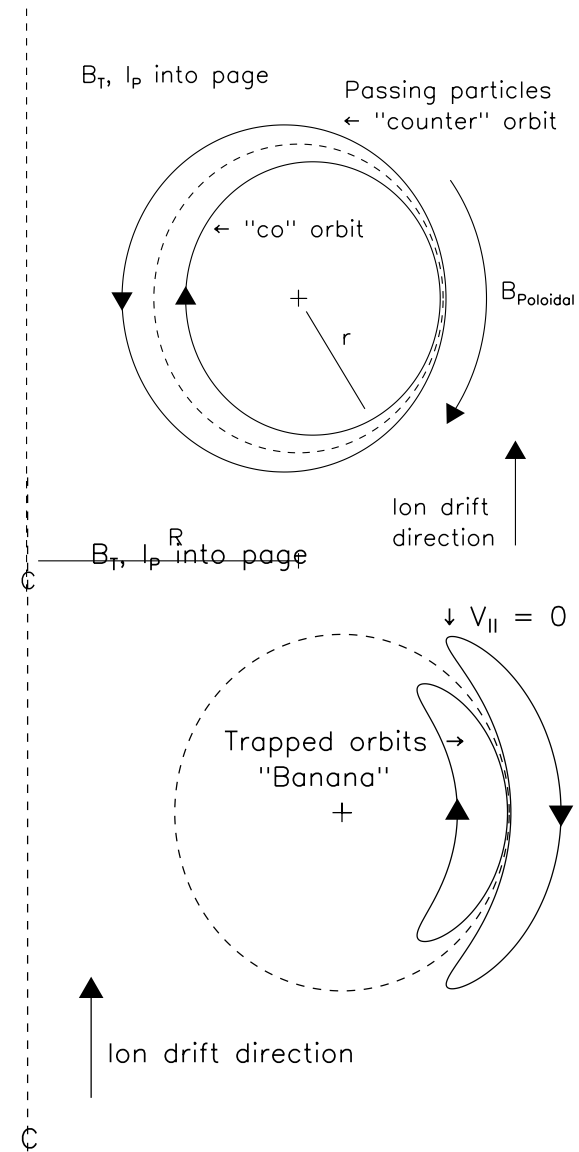
Magnetic Field Curvature

$$V_D = \frac{mV_{\parallel}^2}{qBR}$$

Magnetic Field Gradients

$$V_D = \frac{mV_{\perp}^2}{qB^2} \nabla B$$

Electric Fields $V_D = \frac{\mathbf{E} \times \mathbf{B}}{B^2}$



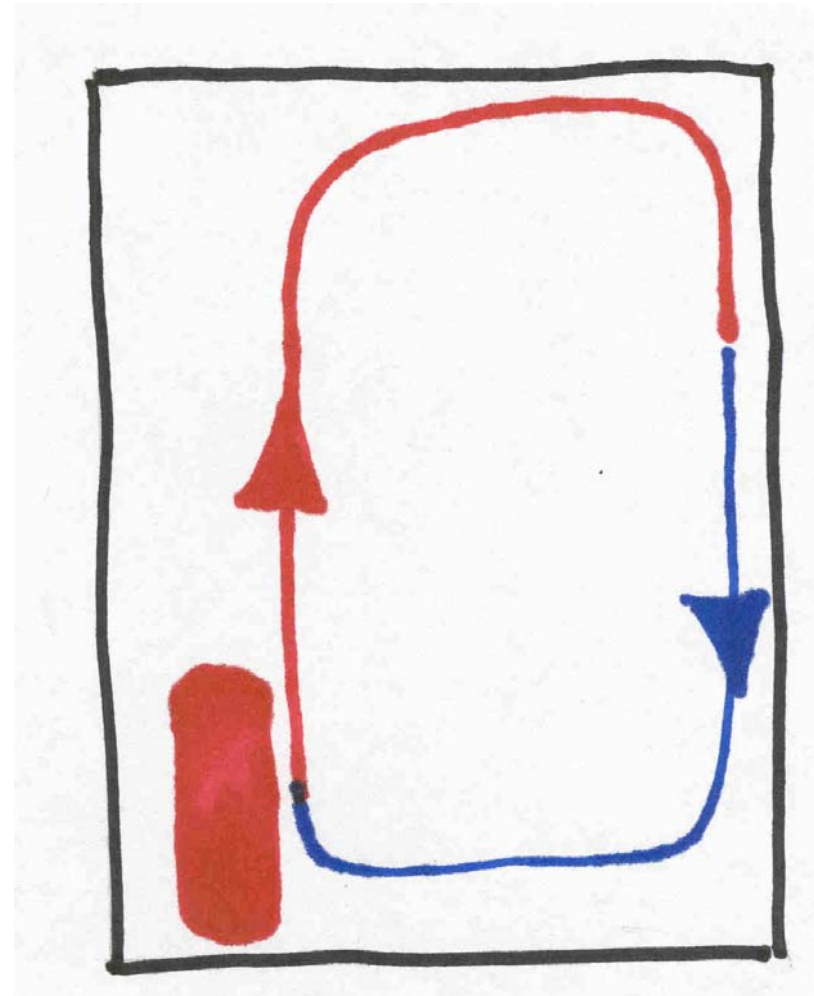
Classical (Collisional) vs Anomalous Transport

- We could live easily with classical conductive losses, **even with the toroidal effects.**
- For a plasma about 2 meters in diameter:
- $D \sim 5 \times 10^{-2} \text{ m}^2/\text{sec}$
- $\tau \sim 20 \text{ sec}$ (still more than enough)

- **In experiments, losses are typically much higher.**
- The search for source of these anomalous losses has been an important part of controlled fusion research .
- It presents one of the most challenging problems of classical physics.
- To begin, consider the difference between conduction and convection.

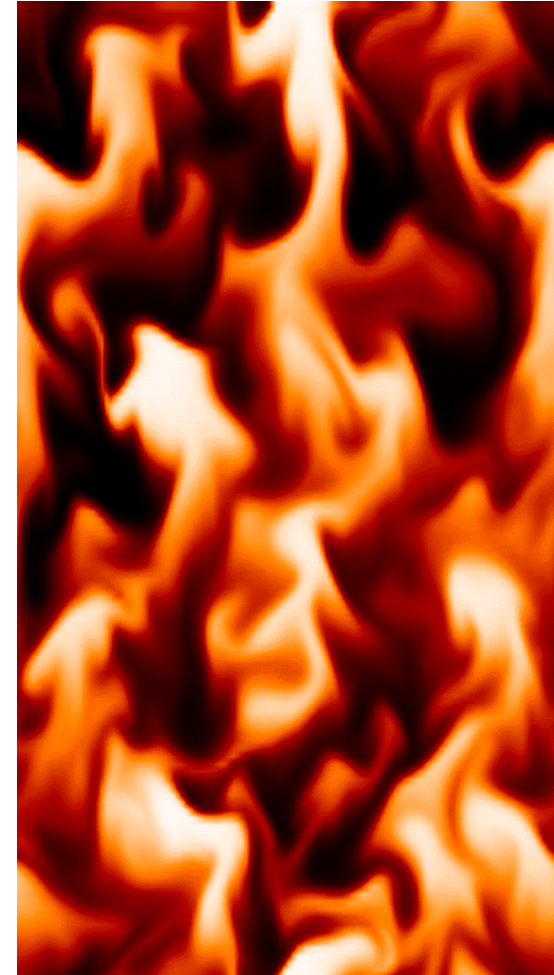
CONVECTION – Usually Dominates Heat Transfer in Fluids

- Air is a very poor conductor of heat
- Theoretically it is 4 orders of magnitude worse than typical solids.
- So why do we wear coats, why insulate our houses???
- The **only** purpose of insulation (down/fiberglass) is to break up convection currents
- To make the convection process less efficient at



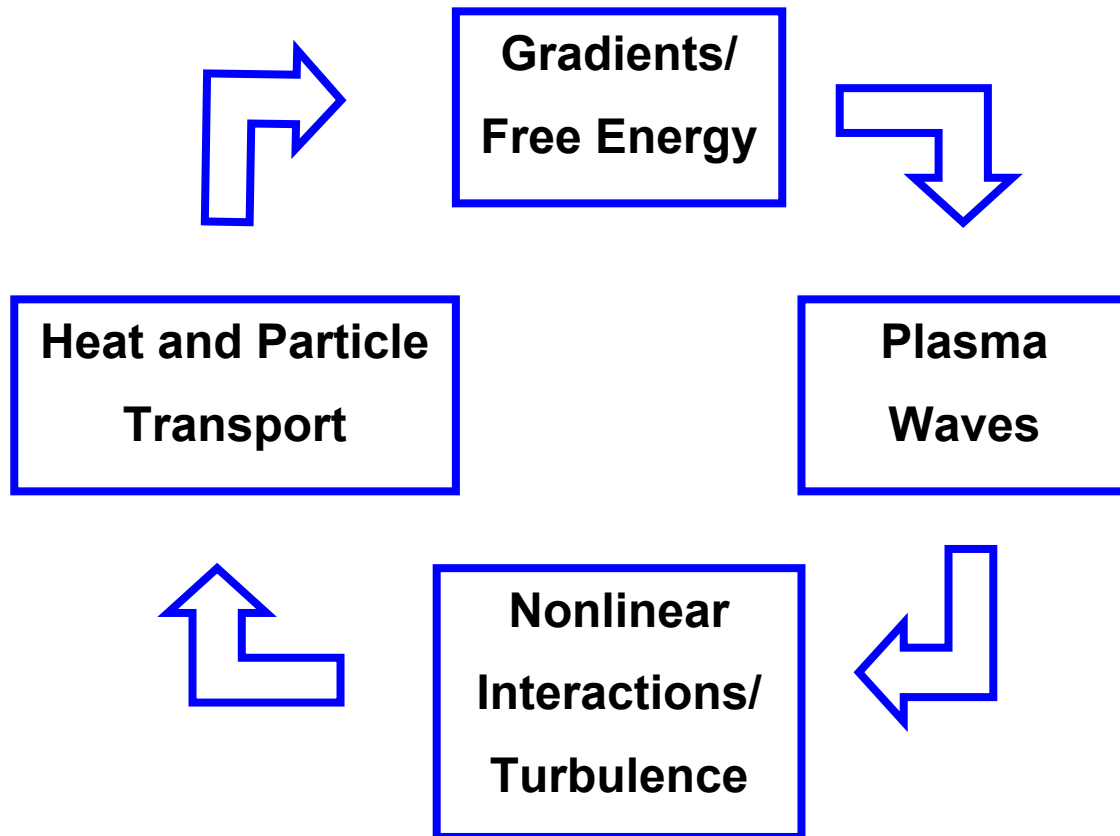
WHERE DOES CONVECTION COME FROM IN PLASMAS?

- Plasmas support all sorts of wave motion
- The system is far from thermodynamic equilibrium (strong gradients)
- Waves grow by tapping free energy in temperature and density gradients
- As they grow, the waves modify the plasma (non-linear physics - compare to waves breaking at the shore)
- Waves evolve and interact with plasma particles, transporting energy and particles.



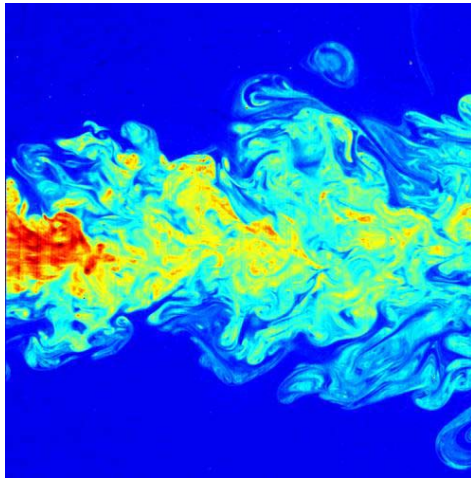
(Rogers 2000)

PROFILES AND CONVECTIVE TRANSPORT EVOLVE SELF-CONSISTENTLY



TURBULENCE

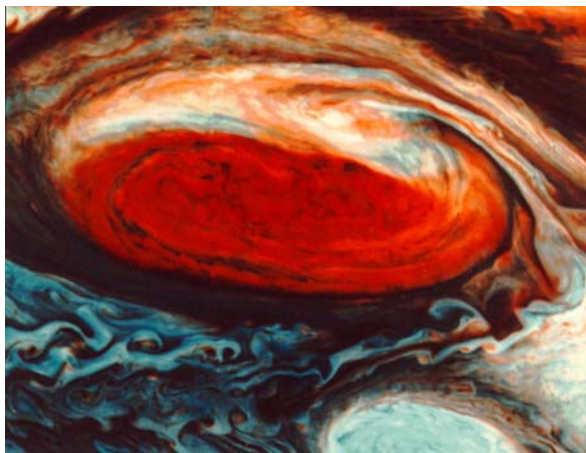
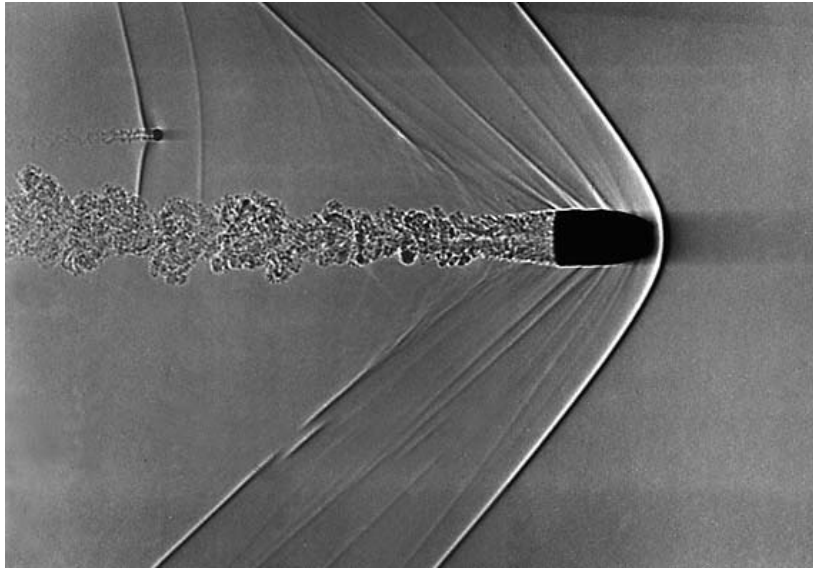
- Turbulence is a ubiquitous phenomenon in nature.
- It is generated as a spontaneous way of releasing the free energy associated with gradients.
- As waves grow, they modify the medium in which they propagate
- This non-linear interaction leads to “chaotic” behavior, turbulence
- It breaks the symmetry of the physical system and involves multiple time and space scales..



**Turbulence is a
Grand challenge
of physics**

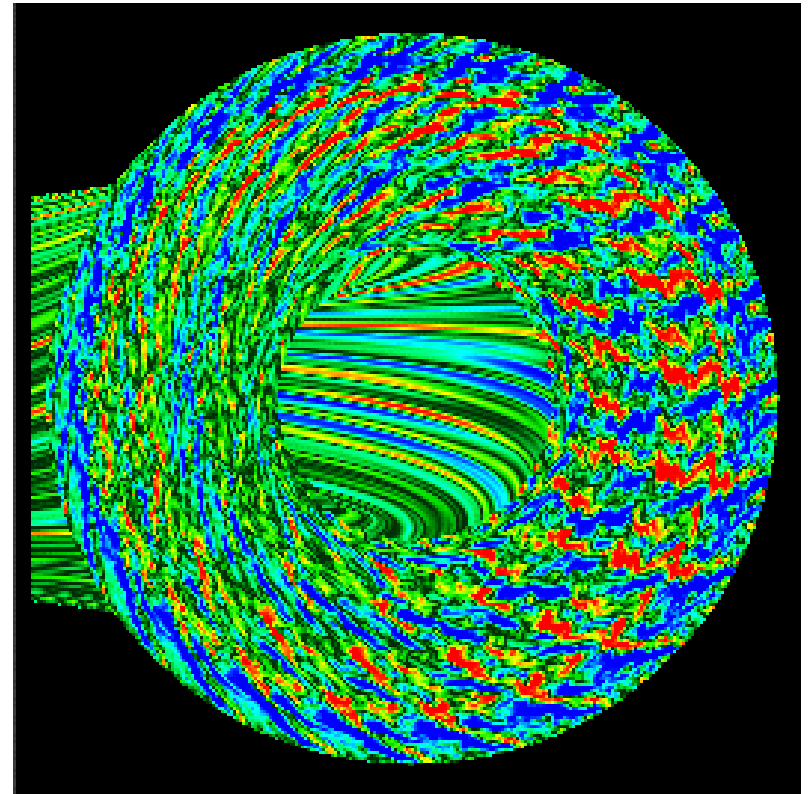


TURBULENCE OCCURS OVER A WIDE RANGE OF SCALES



PLASMA TURBULENCE AND TRANSPORT CAN BE SIMULATED BY LARGE COMPUTER CODES

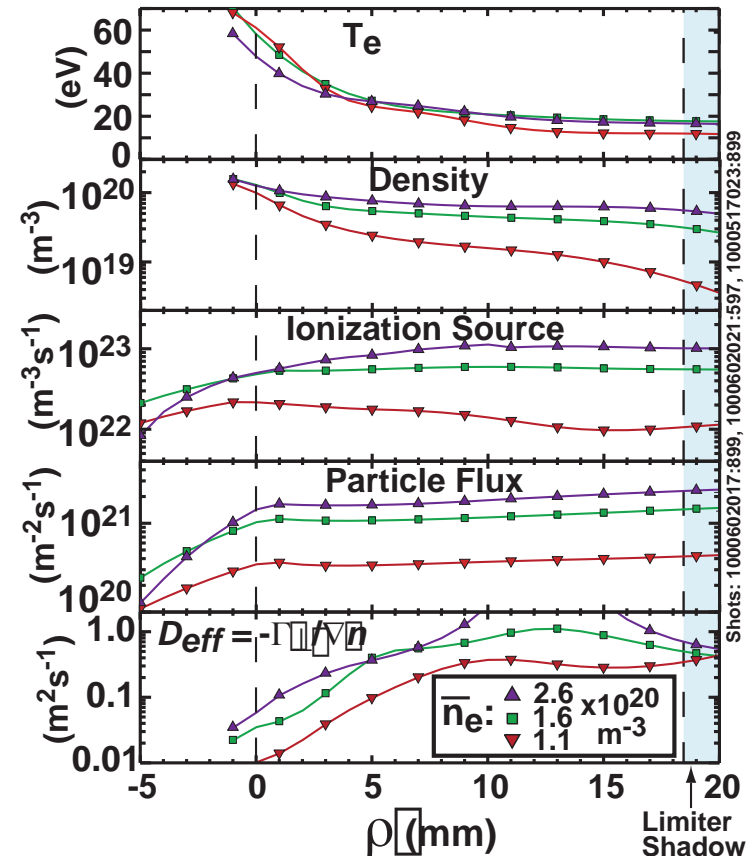
- Plasmas can be described with a set of fluid equations (MHD) plus Maxwell's equations
- Or with a full “kinetic” treatment which looks at the evolution of the system in six dimensional “phase space” (position + velocity)
- In magnetized plasmas, turbulence features are small in cross section, but extend along the magnetic field lines



**Towards an
Explanation of the Limit**

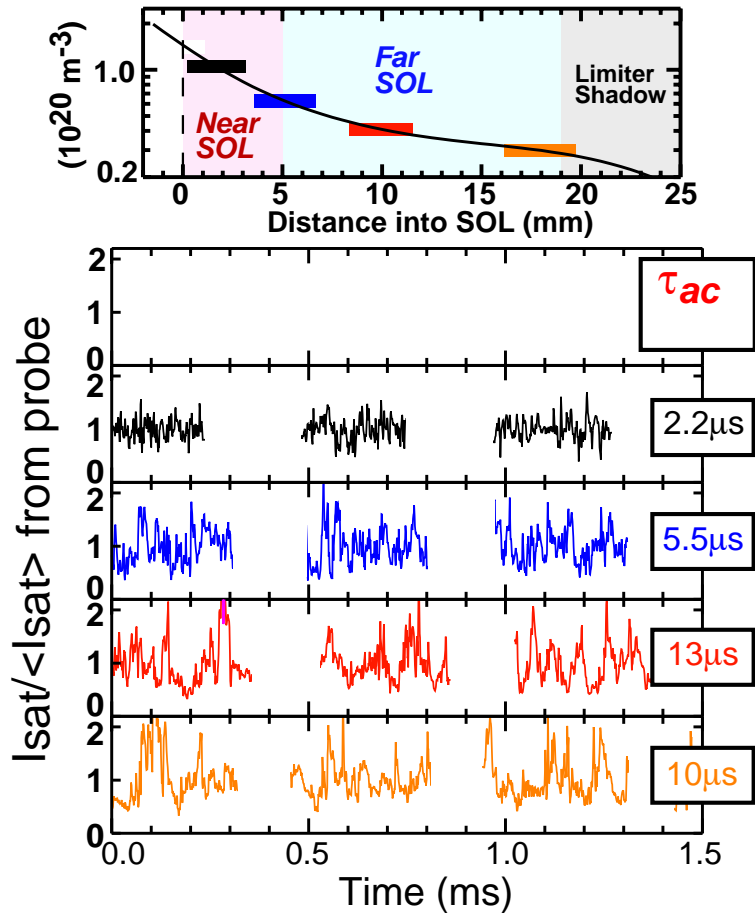
TURBULENT TRANSPORT IN EDGE INCREASES WITH COLLISIONALITY

- Two regimes observed in scrape-off layer (SOL)
 - Near-SOL: steep gradients
 - Far-SOL: flat profiles
- Particle flux and transport
 - Near-SOL: cross-field transport low
 - Far-SOL: cross-field transport high
- Fluctuation changes character
 - Near-SOL: low amplitude, short correlation times and lengths
 - Far-SOL: large amplitude, bursty, long correlation times

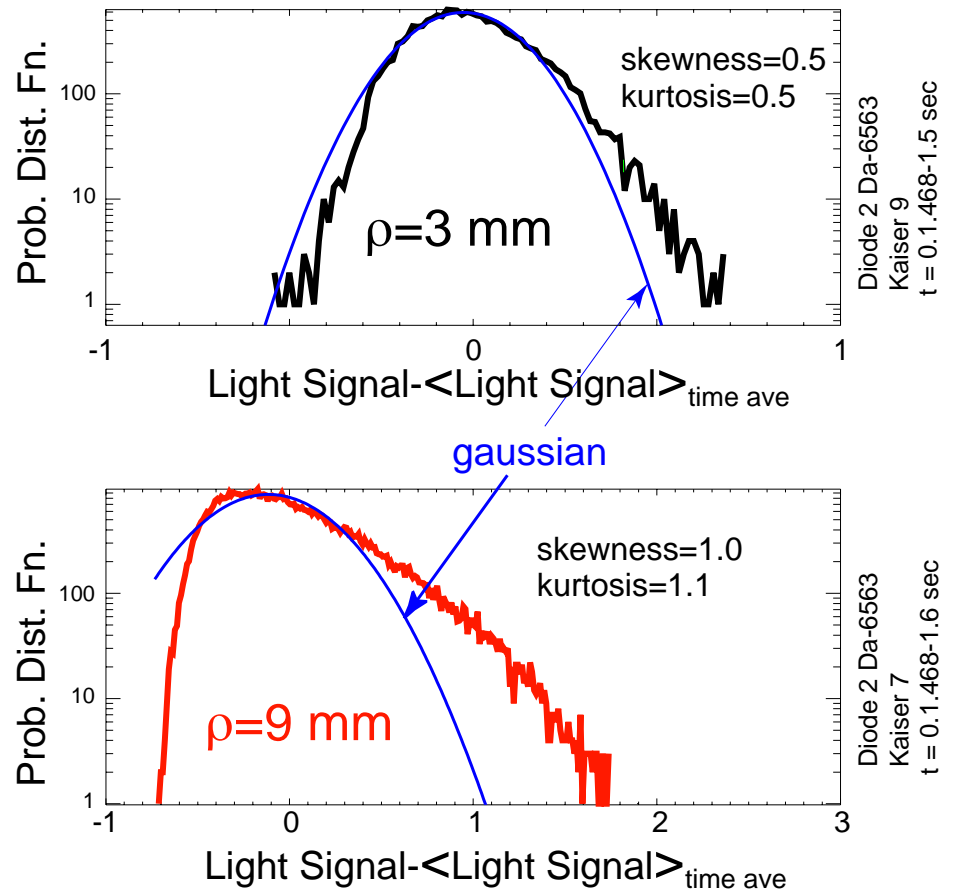


"Bursty" Transport Dominates in SOL

"bursty" transport in SOL



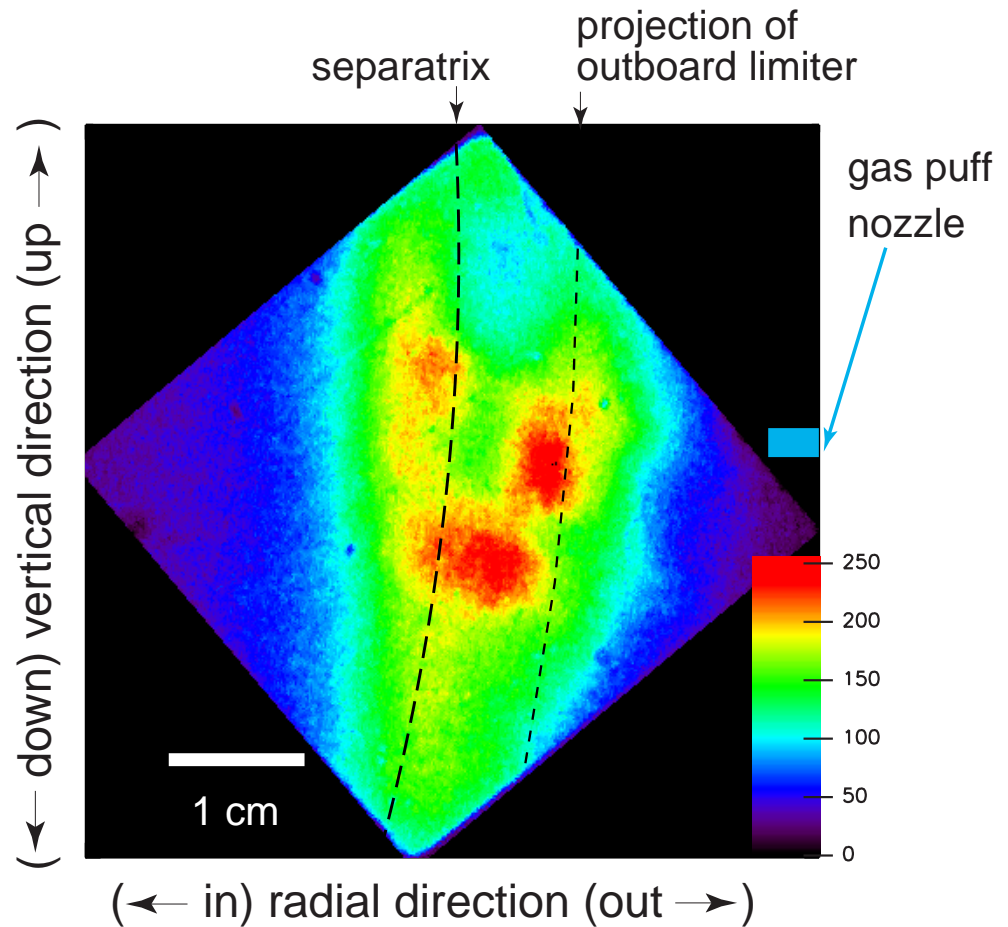
Normalized RMS fluctuation level & auto-correlation time of I_{sat} increase as distance into SOL increases



Probability distribution functions of emission get **more skewed** toward larger events, as distance into SOL increases

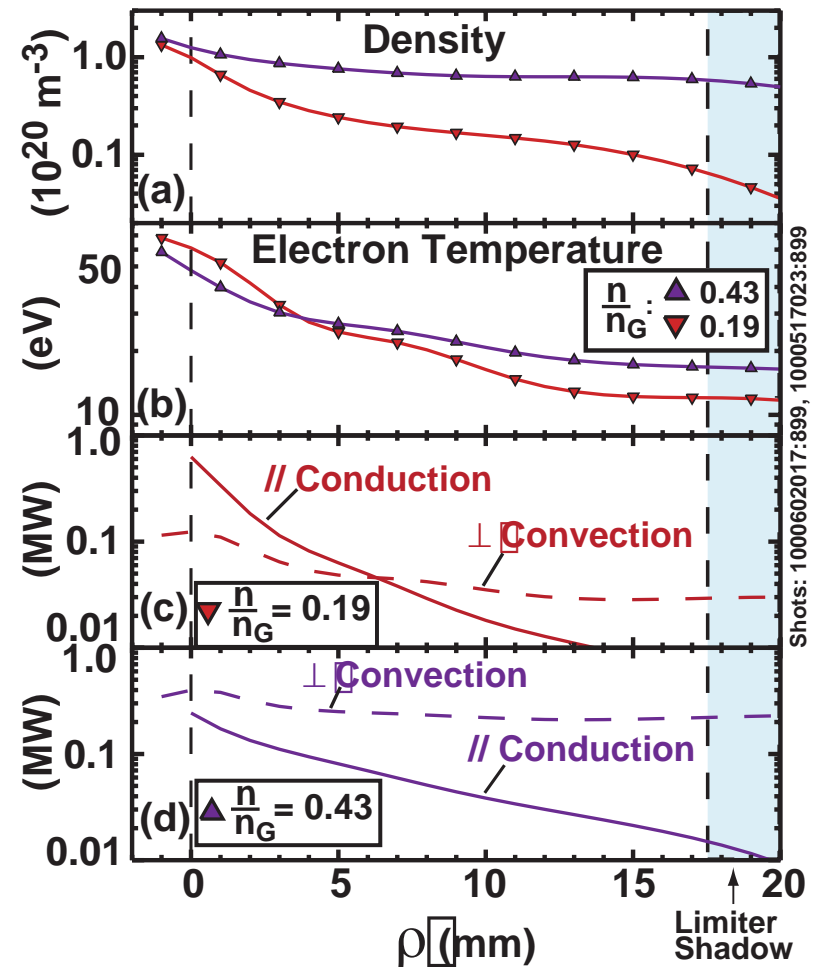
WE CAN VISUALIZE THE FAR-SOL FLUCTUATIONS - BLOBS

- Fast CCD camera images, 4 μ sec framing time
- D₂ gas puff \Rightarrow localization
- Large "blobs" dominate far-SOL
- Blobs move poloidally and radially
- Correlation length, correlation time, propagation velocity consistent with probe measurements



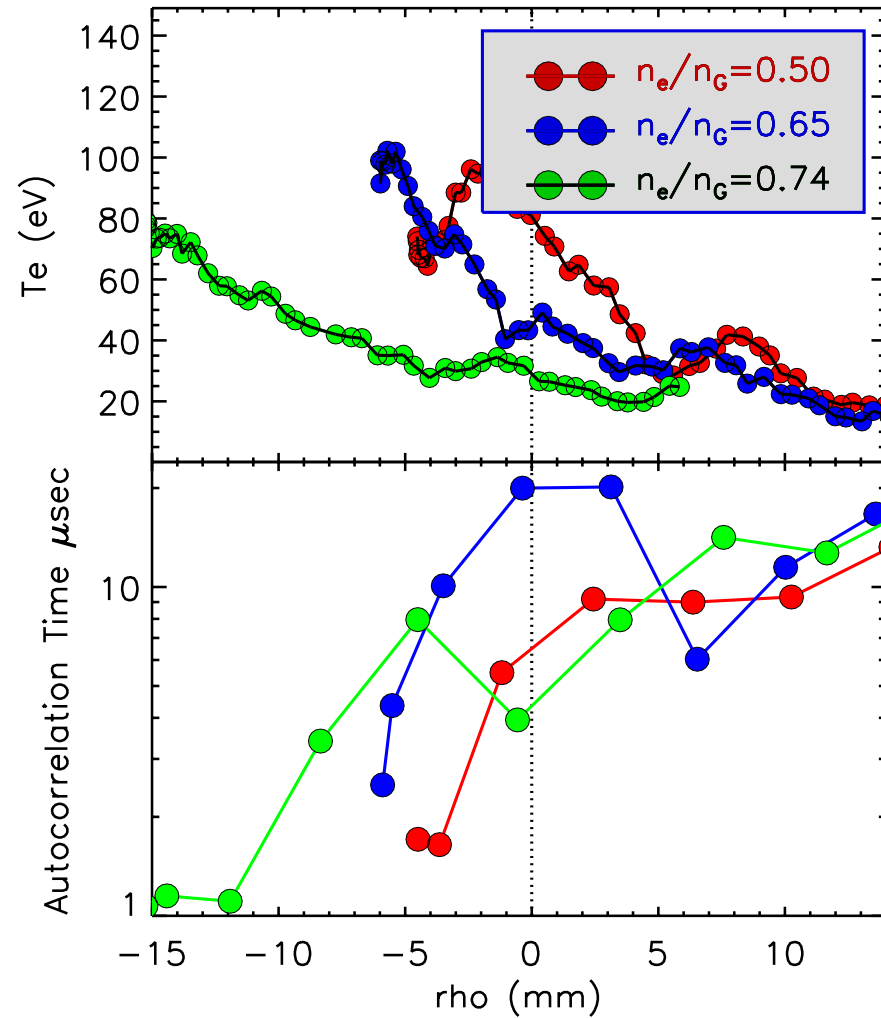
TURBULENCE DRIVEN CONVECTION CAN COMPETE WITH PARALLEL TRANSPORT

- In far SOL, cross-field transport overwhelms parallel transport
- As density is increased, region of large fluctuations and transport move inward toward separatrix
- Parallel transport $\sim T_e^{7/2}$ is stable with respect to temperature perturbations
- Collisionality driven cross-field transport is unstable



AS THE DENSITY LIMIT IS APPROACHED, HIGH TRANSPORT REGIME CROSSES SEPARATRIX AND MOVES INTO MAIN PLASMA

- Has the potential to explain range of density limit phenomena
- Fluctuations can cool edge, eliminate edge shear layer
- Once perpendicular transport dominates, stabilizing influence is lost
- Threshold condition? – need to understand interaction of turbulence and profiles



SOME SUPPORT FROM EDGE TURBULENCE SIMULATIONS

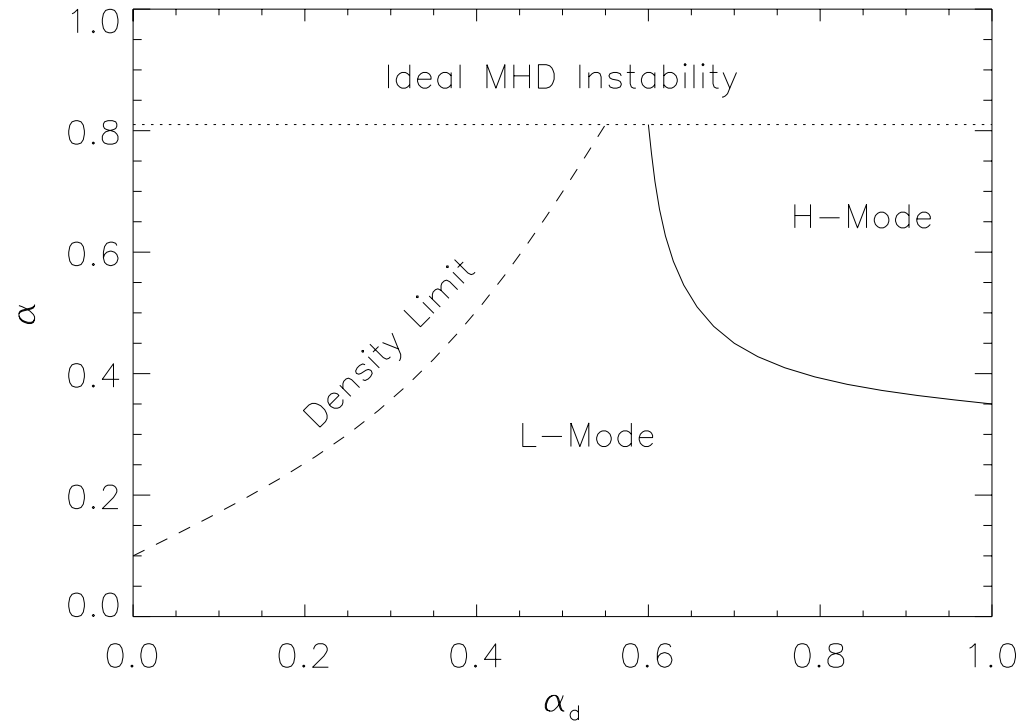
- 3D gyro-fluid simulations have found regime of extremely high transport

- $\alpha = -Rq^2 d\beta / dr$

- $\alpha_D = \rho_s c_s t_0 / L_n L_0$

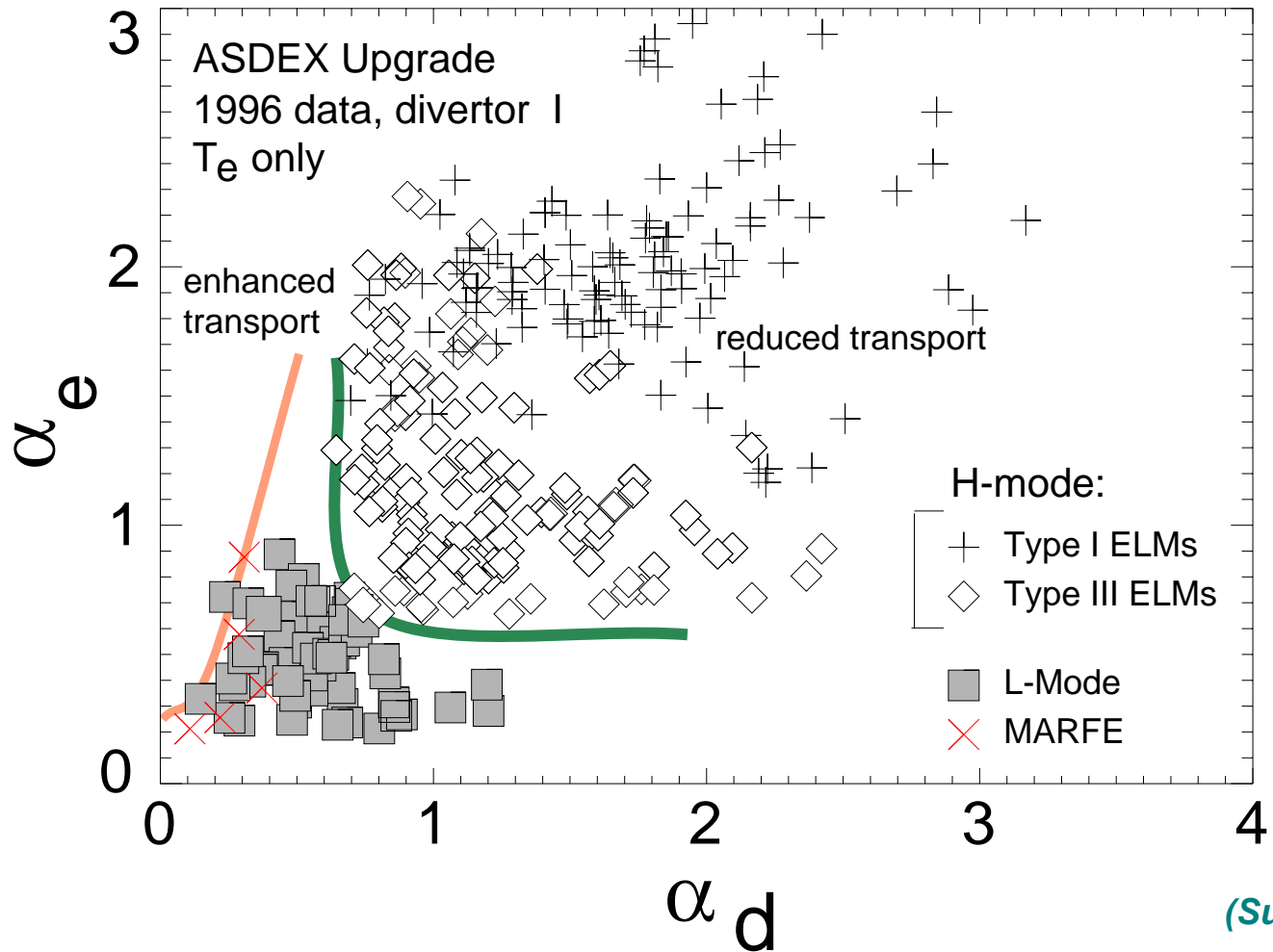
$$\propto \left(\frac{T^2}{nL_n} \right) \rightarrow \frac{\lambda}{L_n}$$

- Region of ultra-high transport consistent with high density, low temperature
- Similar results from Xu, Hallatschek
- No quantitative predictions yet
- Unfortunately models for edge turbulence are incomplete

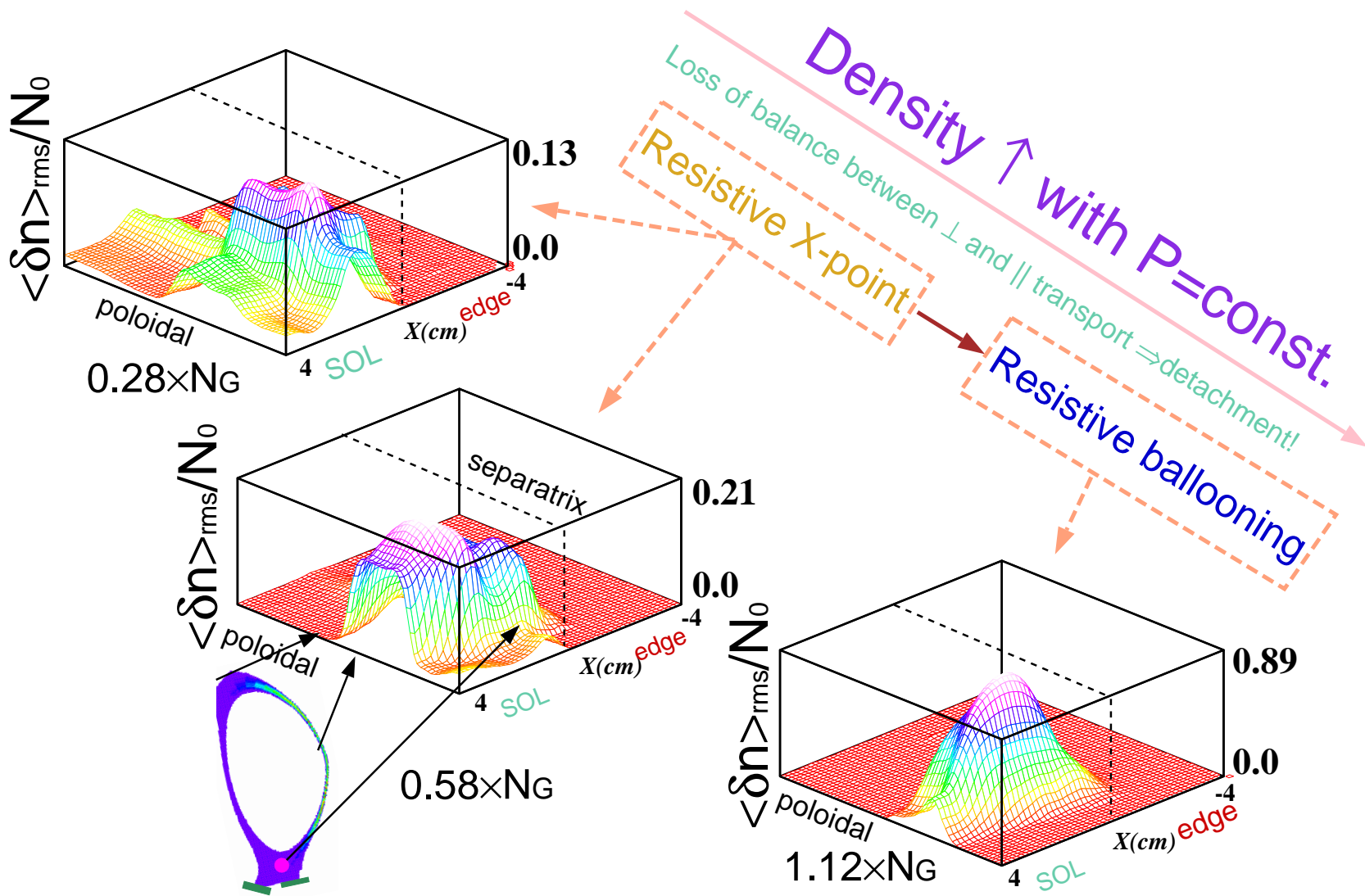


(Rogers, Drake 1998)

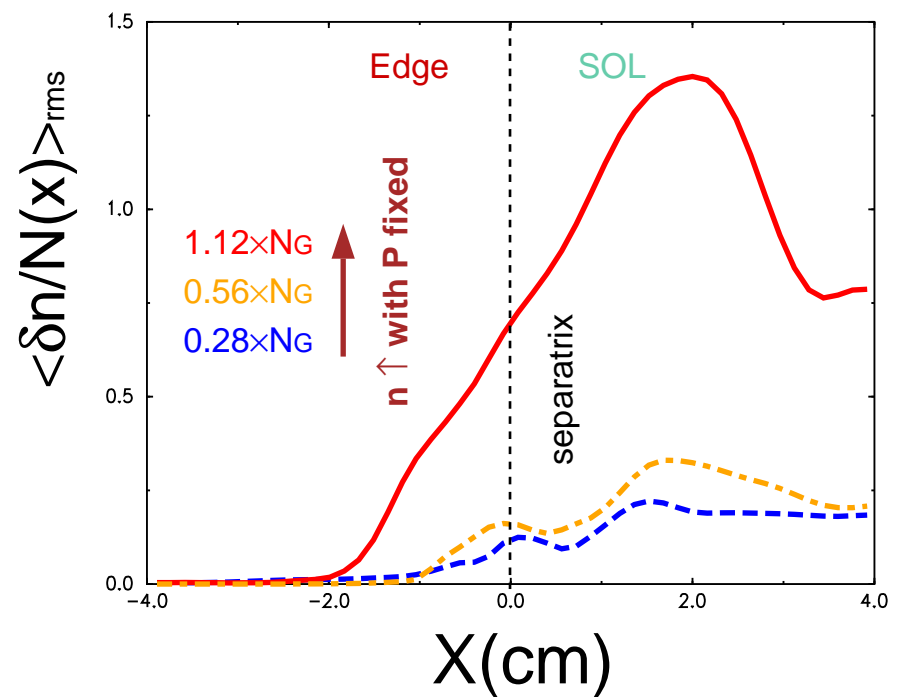
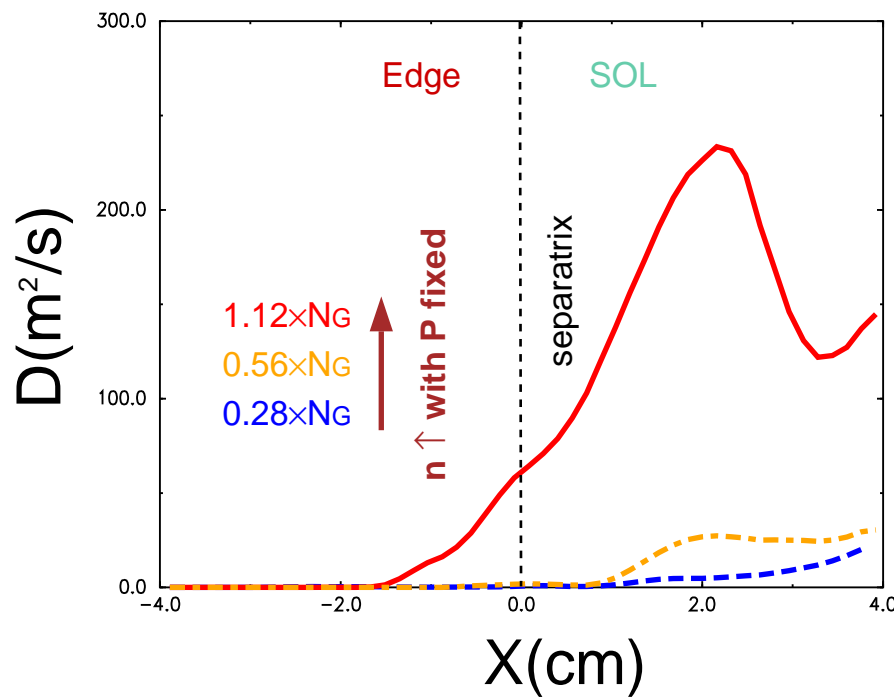
EXPERIMENTAL SUPPORT FOR TURBULENCE MODEL



Density Limit: High collisionality \Rightarrow fluctuation level/transport \uparrow and parallel correlation length \downarrow



Turbulent fluctuation levels and transport in boundary increase with collisionality



👉 The region of high diffusivity extends inward.

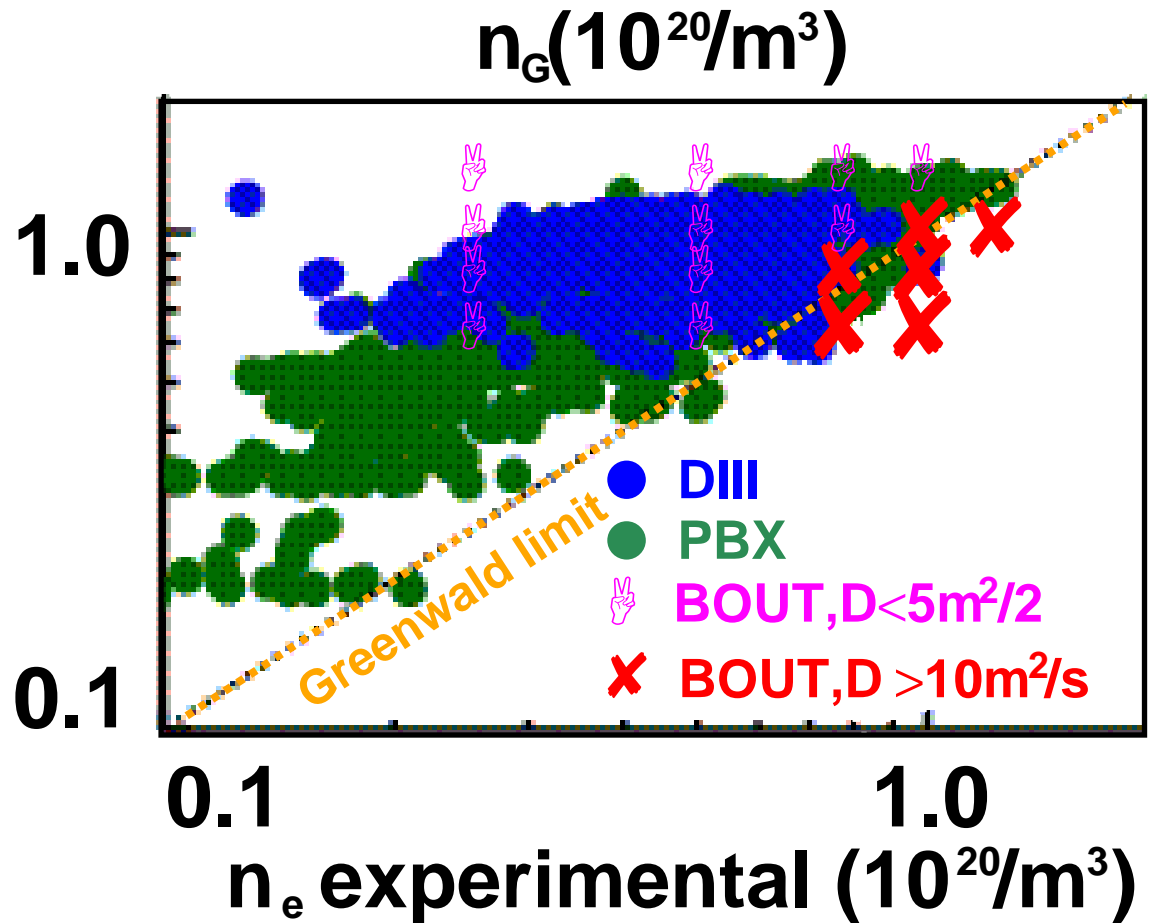
👉 $D \uparrow$ as $n \uparrow$, but D exhibits a discontinuous behavior
⇒ a catastrophic boundary is crossed

Large transport boundary vs current and density is consistent with expt. operational limits



- ➡ q is held fix while I_p changes
- ➡ P is held fix while n changes
- ➡ Transport coefficient at LCFS
- ➡ Large transport leads to a collapse of edge plasma

Greenwald Limit: $N_G = \frac{I_p}{\pi a^2}$
 (with n : $10^{20}/m^3$, I_p : MA, a :m)



SUMMARY

- “Standard” models for density limit based on radiation and power balance seem to fail experimental tests
- A new approach based on turbulence driven transport is showing promise.
- This model is far from the point of making predictions
- **Need to use self-consistent profiles, transport, power balance etc.**
- May need combination of turbulent transport and atomic mechanisms
- Must simultaneously obey power and particle balance
- **Physics strongly coupled – multiple feedback loops - cause and effects will be hard to untangle.**