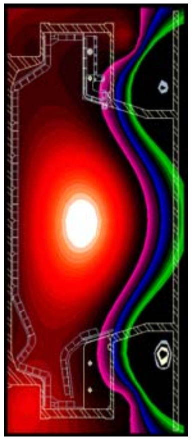
EDGE TURBULENCE AND TRANSPORT AS A POSSIBLE CAUSE OF THE TOKAMAK DENSITY LIMIT



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Cordoba, Spain
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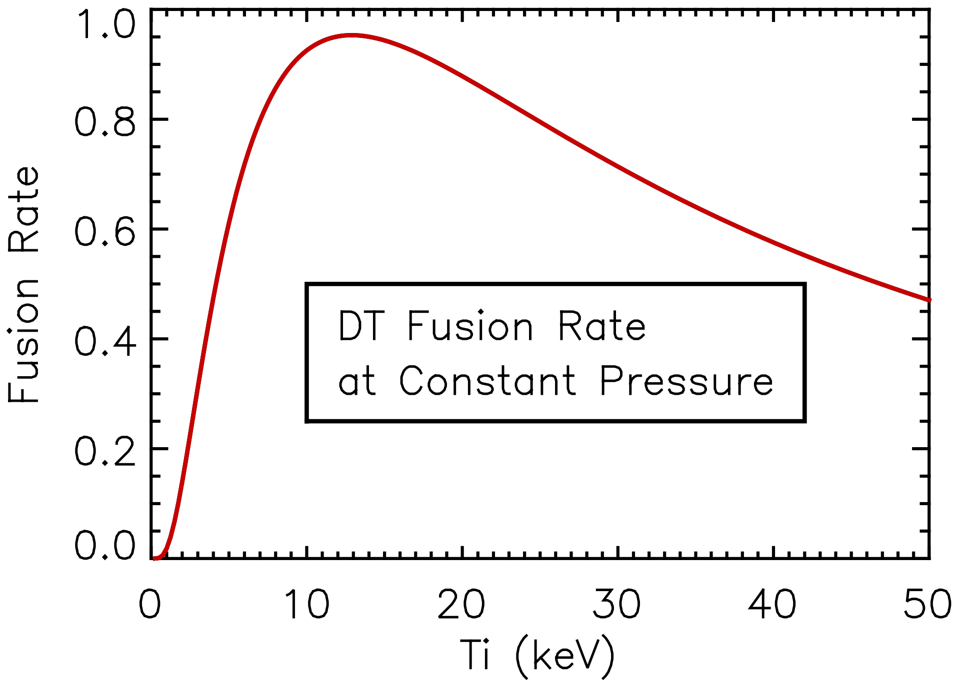
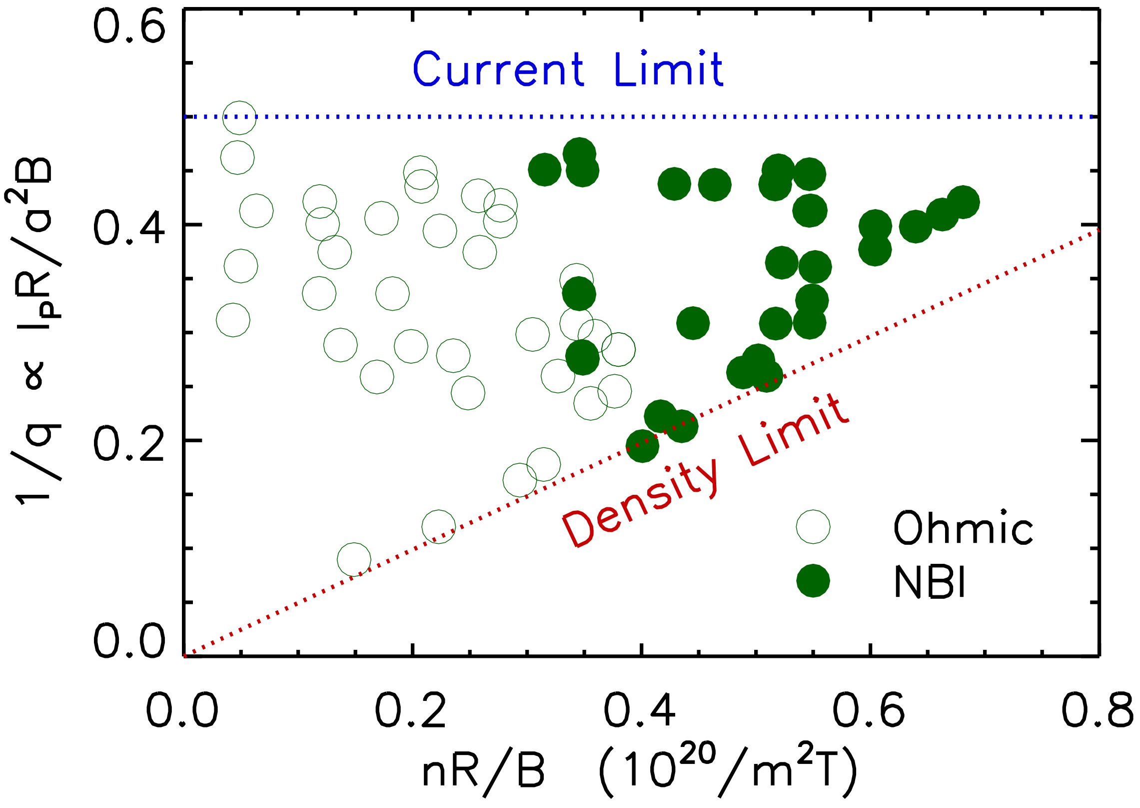
DENSITY LIMITS - AN IMPORTANT ISSUE FOR MAGNETIC FUSION



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

DENSITY LIMIT OFTEN 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)

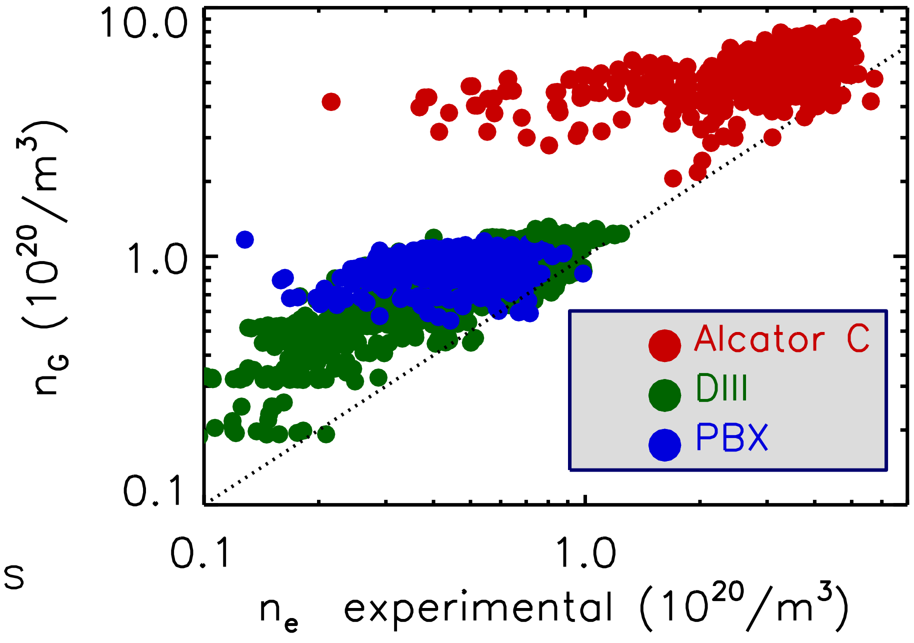
- $n_{LIM} \propto \frac{B}{qR} \approx \frac{I_P}{a^2}$ (Note absence of significant power scaling)

SCALING REFINED BY INCLUSION OF DATA FROM SHAPED TOKAMAKS

- Greenwald limit: $n_G = \frac{I_P}{\pi a^2}$

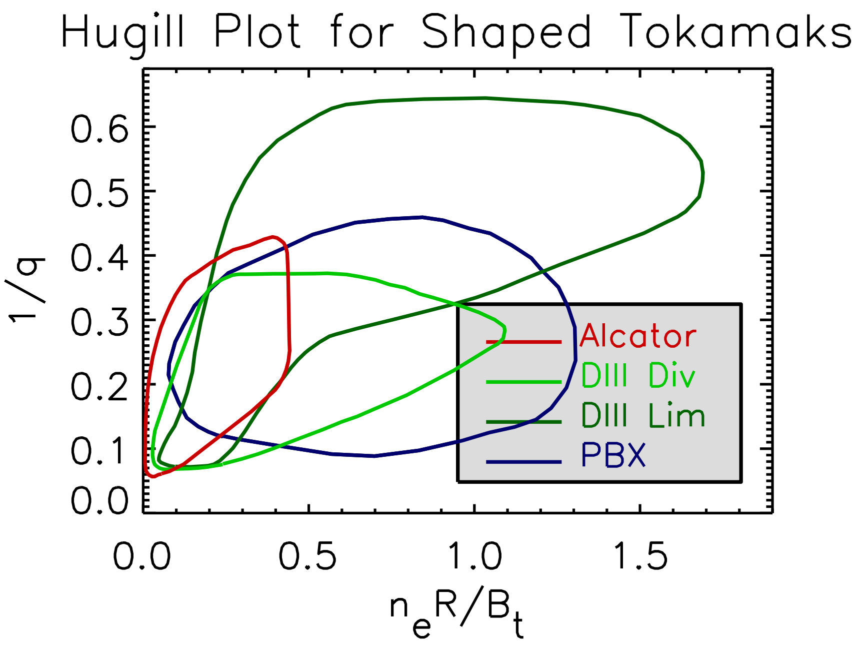
  (with n: $10^{20}/m^3$, I_P: MA, a: m)

- Identical to Hugill for circular plasmas



Differs significantly for shaped plasmas

Recent data from new machines roughly consistent (for flat density profiles)



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

- Scaling does an OK job
  - (Does empirical equation tell us anything about the physics?)

but

- Scaling variables are only proxies for the real physics dependences
- Covariance in data, may confuse 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 unroll cause and effect?
- How do we compute the density limit?

DENSITY LIMITS - THE PHYSICS PROBLEM

- What physics can limit the density?
  - Ideal MHD only cares about pressure (and current) not density
    - Temperature profile influences current profile
    - Resistive MHD can be important at low temperatures
  - Radiation cooling $P_{RAD} \propto n_e^2 f_Z R(T_e)$
  - Neutral shielding: fueling limits
  - Density or collisionality dependent transport $\Rightarrow$ edge cooling
- **No widely accepted first principles theory available**
- **Not even agreement on critical physics**

BASIC PHENOMENOLOGY OF DENSITY LIMIT

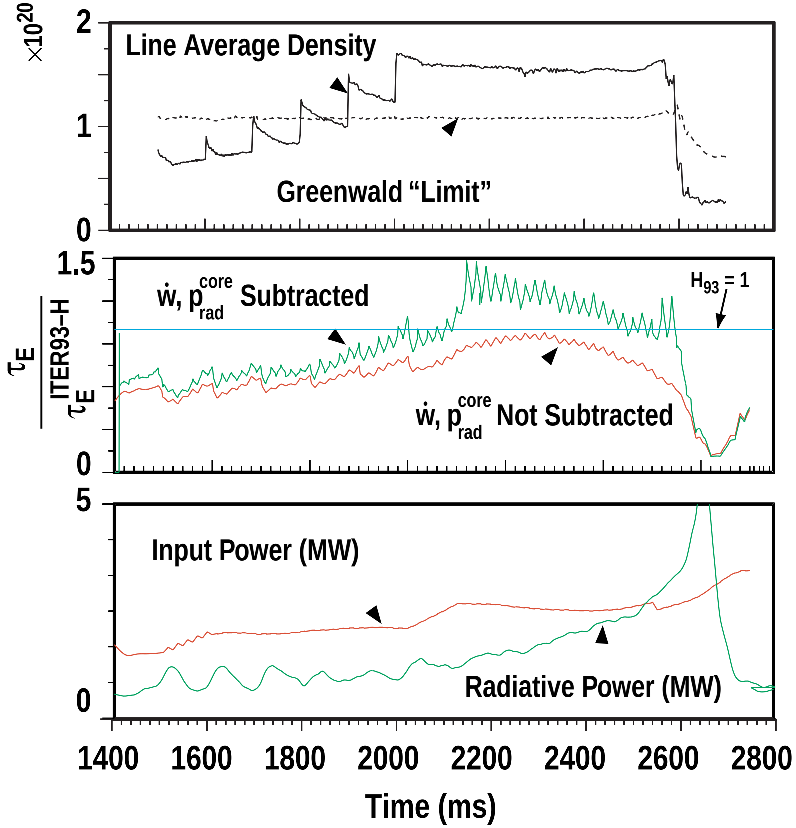
	Range of Normalized Densities (n/n_{LIMIT})
MARFEs	0.4-1
Divertor detachment	0.3-1
Drop in H-mode confinement	0.3-1
Change in ELM character	?
H/L transition	0.8-1
Poloidal detachment	0.7-1 (for clean plasmas)
MHD and Disruptions	~1

The density limit in tokamaks is apparently an edge limit

FURTHER EVIDENCE FOR AN EDGE DENSITY LIMIT

EXCEEDING THE EMPIRICAL LIMIT - PEAKED DENSITY PROFILES

- Particles in core apparently don't drive density limit



Density profiles not stiff

Peaked by core fueling, edge pumping, transport modification

(Maingi, Mahdavi 1997)

RADIATION POWER BALANCE - EDGE OR SCRAPE-OFF LAYER (SOL)

- **Motivation**
  - Very dirty plasmas don't reach high density
  - $P_{RAD} \propto n_e^2 f_Z R(T_e)$ - edge cooling
- **Choose physical phenomenon to model**
  - Global thermal collapse
  - Radiation condensation
  - Poloidal detachment
  - Divertor detachment
- Radiation dominated transport ⇒ MHD unstable pressure profiles
- **Solve coupled equations for energy, momentum, particle balance**

(+ Ad hoc assumptions; transport, n_{edge}/n_{core}*)*

ARE RADIATION MODELS SUFFICIENT?

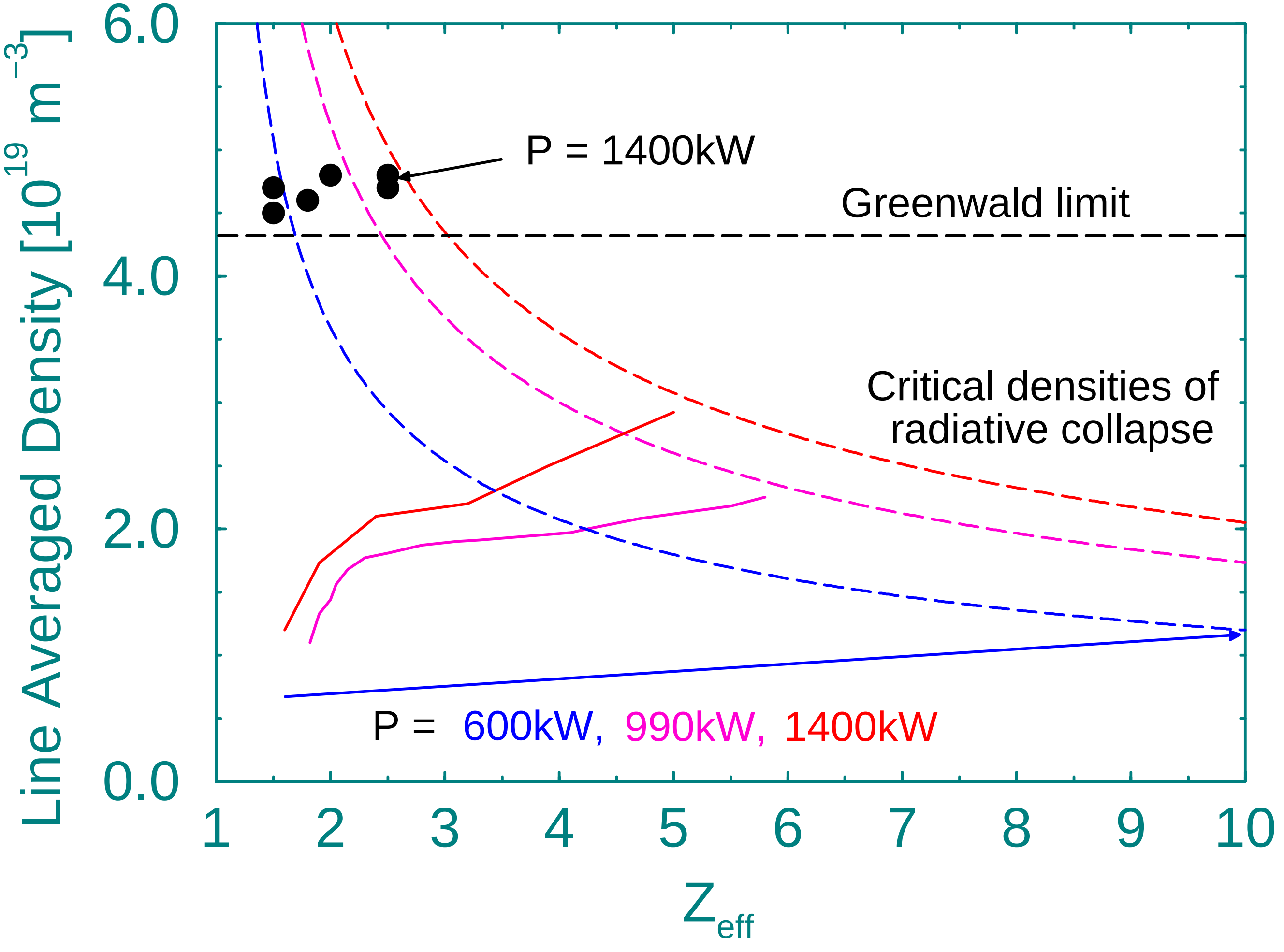
- **Problem with radiation models**
  - Power and impurity dependence too strong $\Rightarrow n_{LIM} \propto \sqrt{P_{IN} / (Z_{EFF} - 1)}$
  - Threshold mechanisms show up well below density limit
- Transport assumptions: ad hoc at best

- **Evidence for increased transport as cause of edge cooling**
- Transient transport experiments (Greenwald 1988, Marinak 1993)
- Fluctuation measurements (Brower 1991)
  - Detailed probe measurements in edge: observations of edge turbulence at high densities (LaBombard 2001)

- **Edge Simulations** (Rogers, Xu, Hallatschek, D'Ippolito)

BACK TO THE BEGINNING

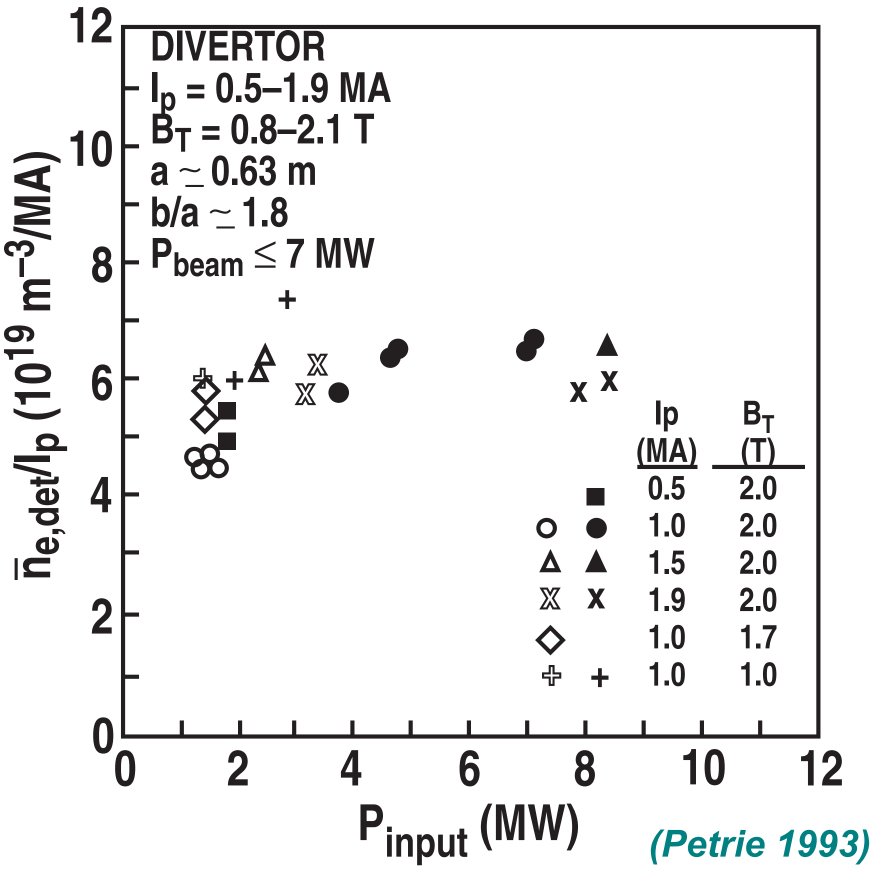
IMPURITIES ARE IMPORTANT …. BUT ONLY UP TO A POINT



- Below around Z_{EFF} ~ 2.5, drops out

(Rapp et al, 2000)

DENSITY LIMIT IN TOKAMAKS DOES NOT DEPEND STRONGLY ON INPUT POWER

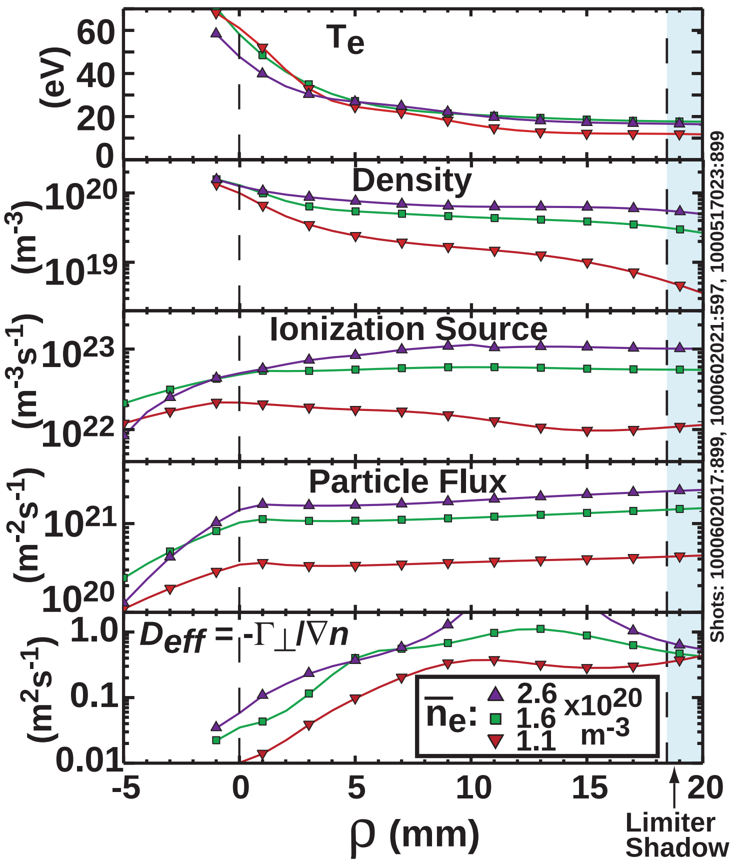


(Petrie 1993)

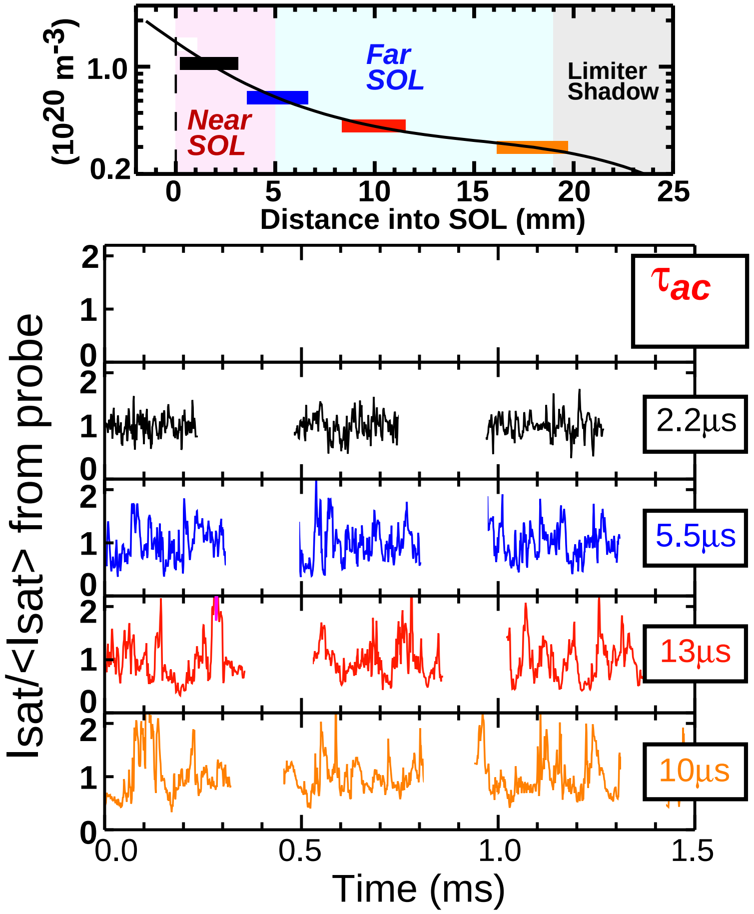
- Power dependence in low confinement mode (L-mode) varies from P^0 - $P^{0.25}$
- Role of neutral beam fueling and density peaking in power dependence is uncertain

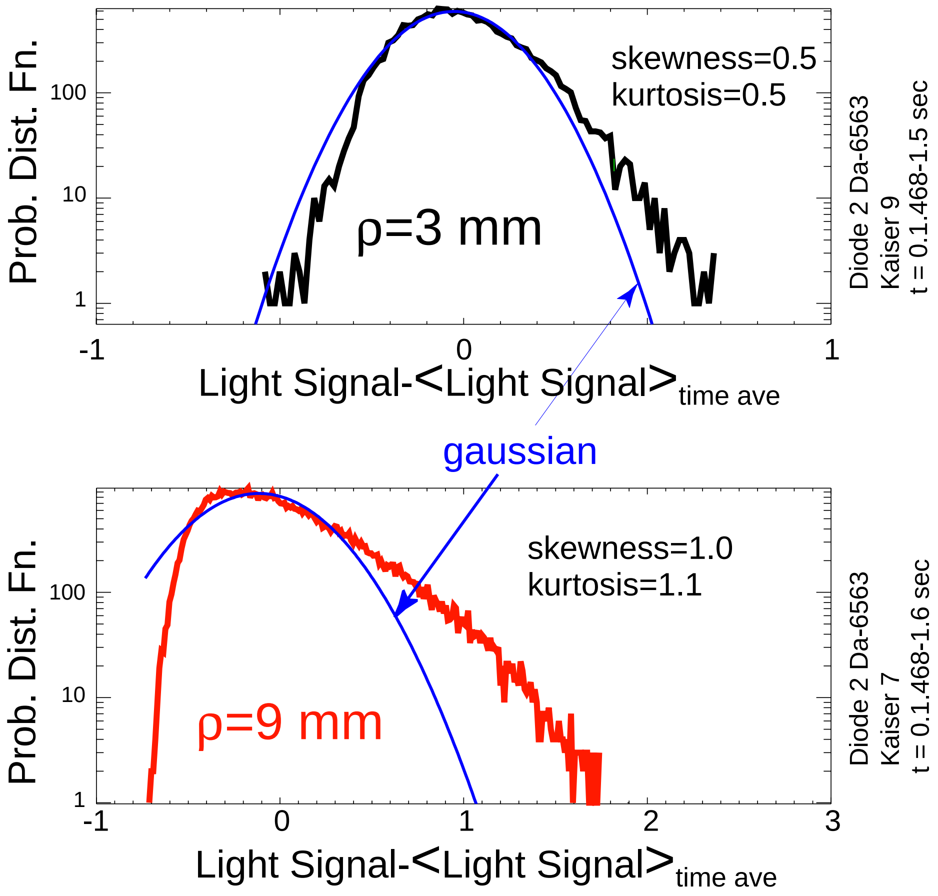
TURBULENT TRANSPORT IN EDGE INCREASES WITH COLLISIONALITY

- **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 in SOL



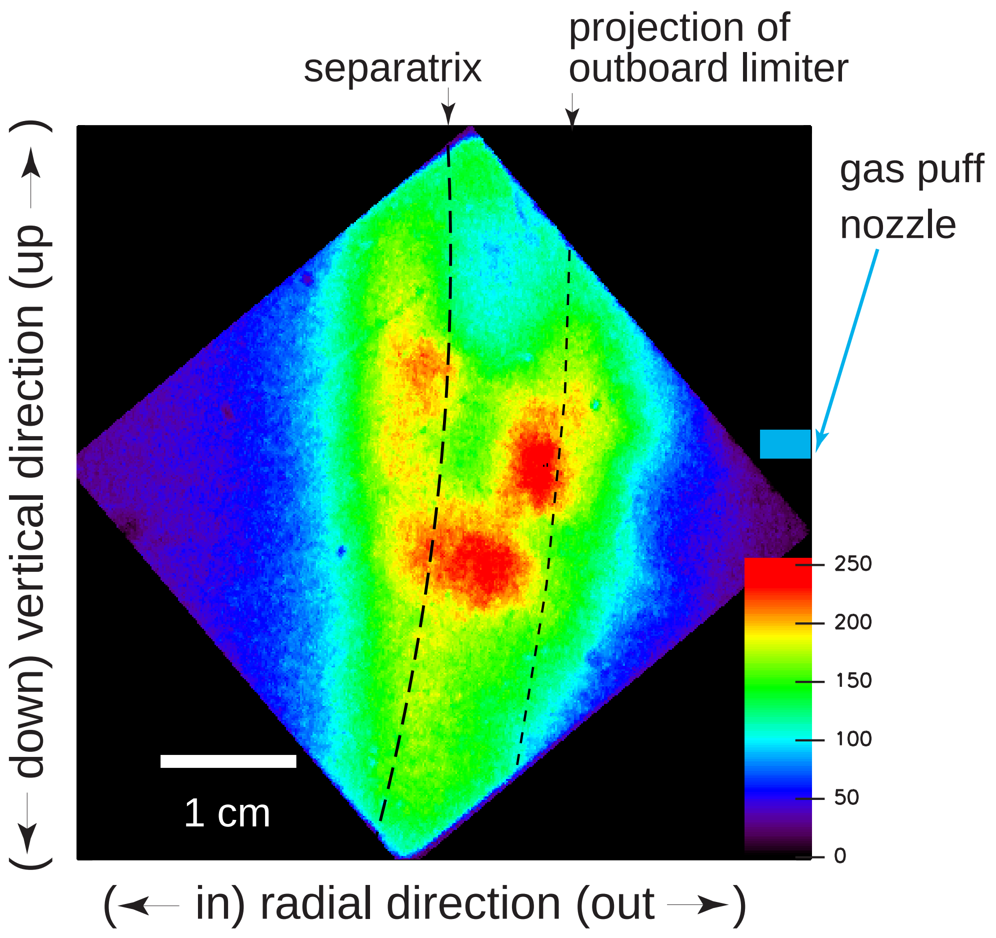


Normalized RMS fluctuation level & auto-correlation time of I_{sat} increase as distance into SOL increases

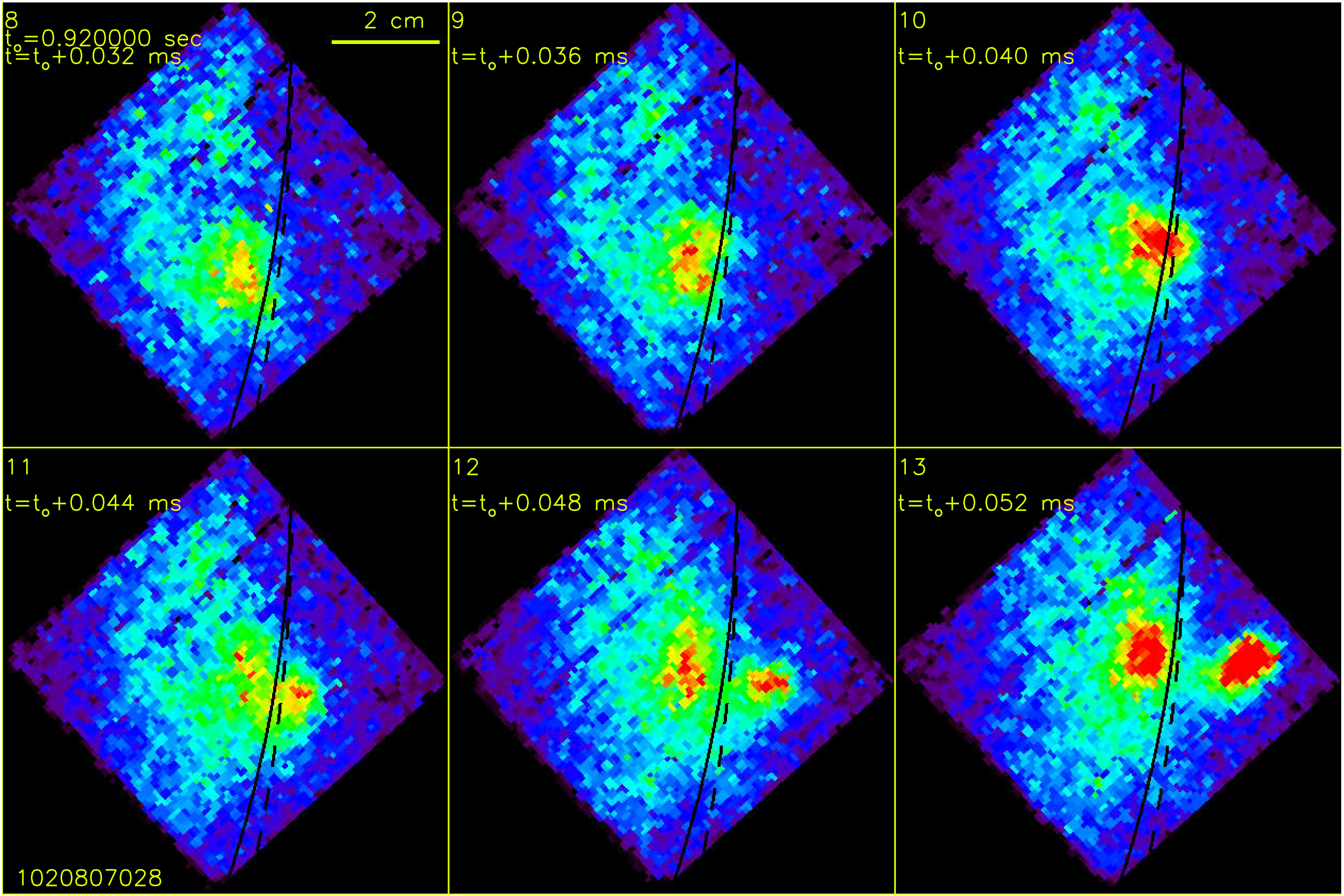
Probability distribution functions of emission get more skewed toward larger events, as distance into SOL increases

WE CAN VISUALIZE THE FAR-SOL FLUCTUATIONS - BLOBS

- Fast CCD camera images, 4 μsec framing time
- D_2 gas puff $\Rightarrow$ localization
- Large "blobs" dominate far-SOL
- Blobs move poloidally and radially
- Correlation length, correlation time, propagation velocity consistent with probe measurements

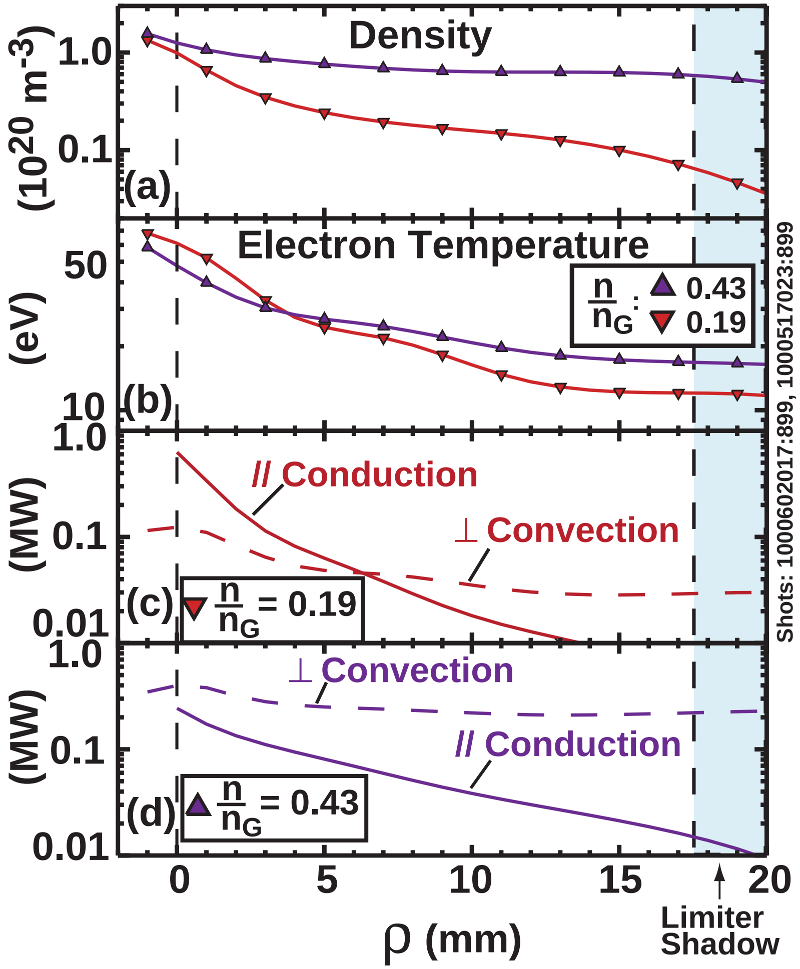


(Zweben, Terry 2001)


8
t_o=0.920000 sec
t=t_o+0.032 ms
2 cm
9
t=t_o+0.036 ms
10
t=t_o+0.040 ms
11
t=t_o+0.044 ms
1020807028
12
t=t_o+0.048 ms
13
t=t_o+0.052 ms

TURBULENCE DRIVEN CONVECTION CAN COMPETE WITH PARALLEL TRANSPORT

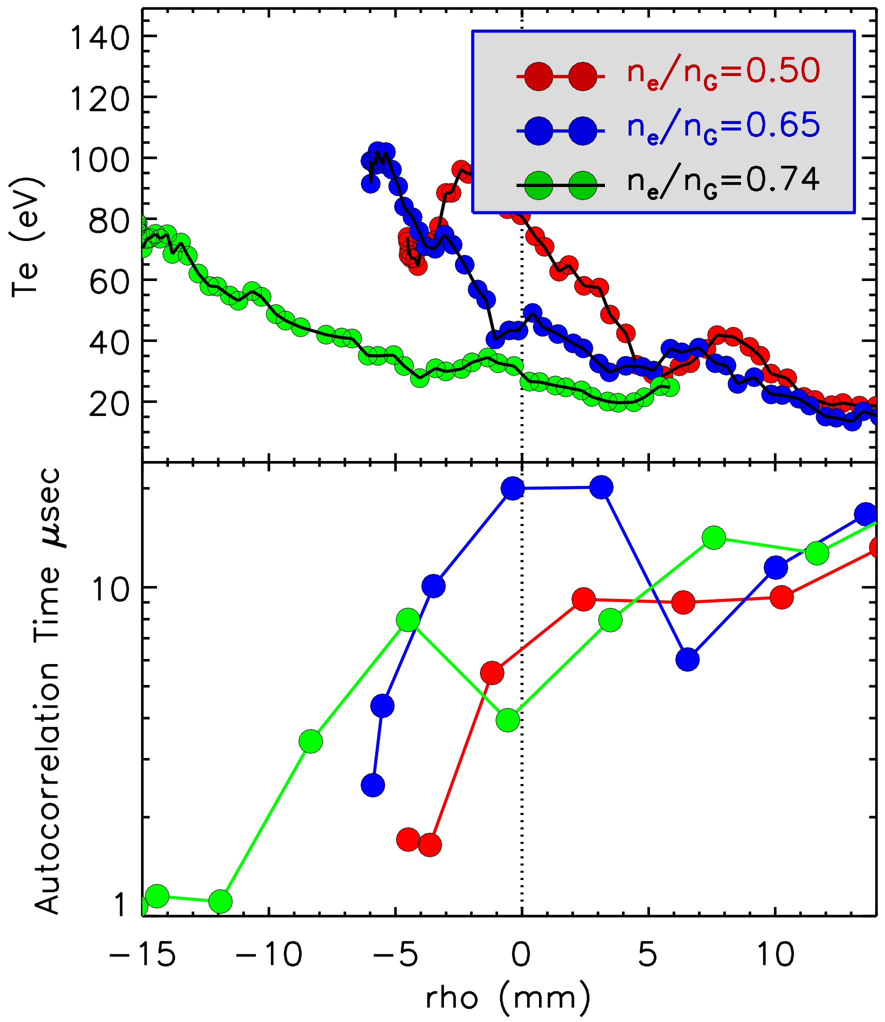
- In far SOL, cross-field transport overwhelms parallel transport
- As density is increased, region of large fluctuations and transport move inward toward separatrix
- Parallel transport ~$T_e^{7/2}$ is stable with respect to temperature perturbations
- Collisionality driven cross-field transport is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



(LaBombard 2000)

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

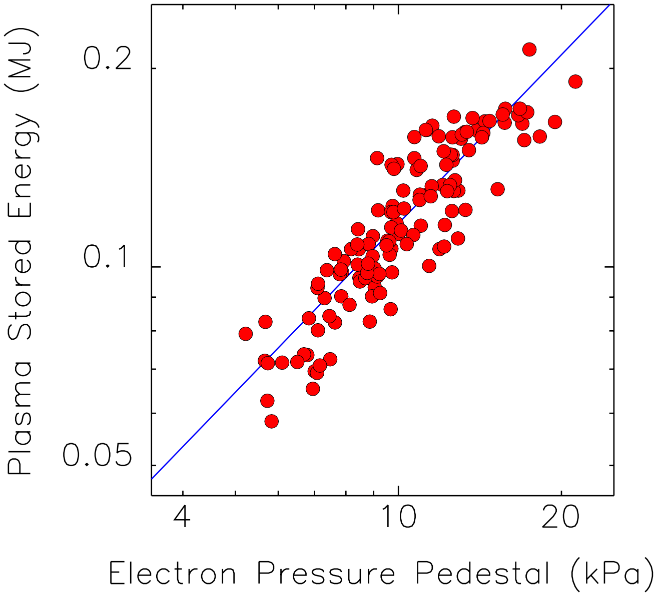
- Has the potential to explain range of density limit phenomena
- Fluctuations can cool edge, eliminate edge shear layer
- Once perpendicular transport dominates, stabilizing influence is lost
- Threshold condition? – need to understand interaction of turbulence and profiles



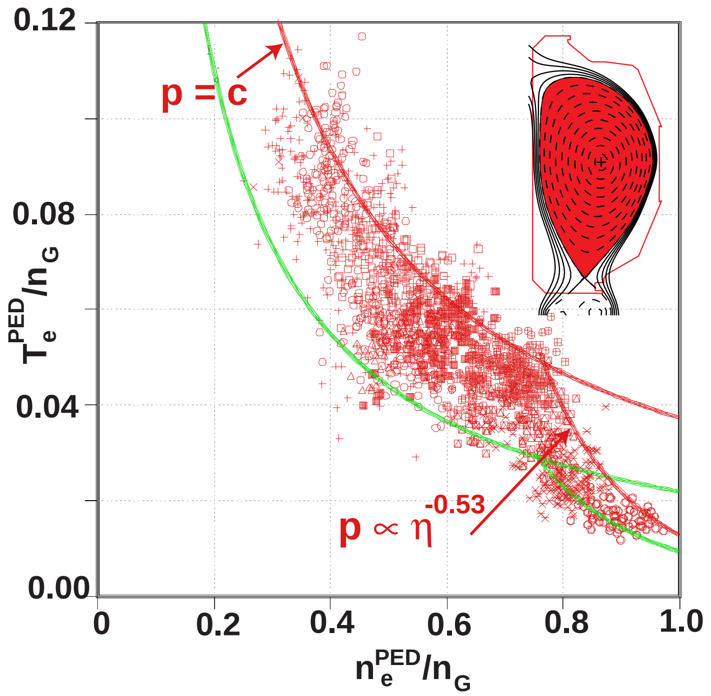
(LaBombard 2001)

THIS MODEL IS CONSISTENT WITH H-MODE CONFINEMENT DEGRADATION AND H/L TRANSITION

- $H \text{ and } \nabla T_{CORE} \propto T_{EDGE}$
- Constant edge pressure implies τ_E independent of density



(Greenwald, Hughes 1997)



(Osborne 2000)

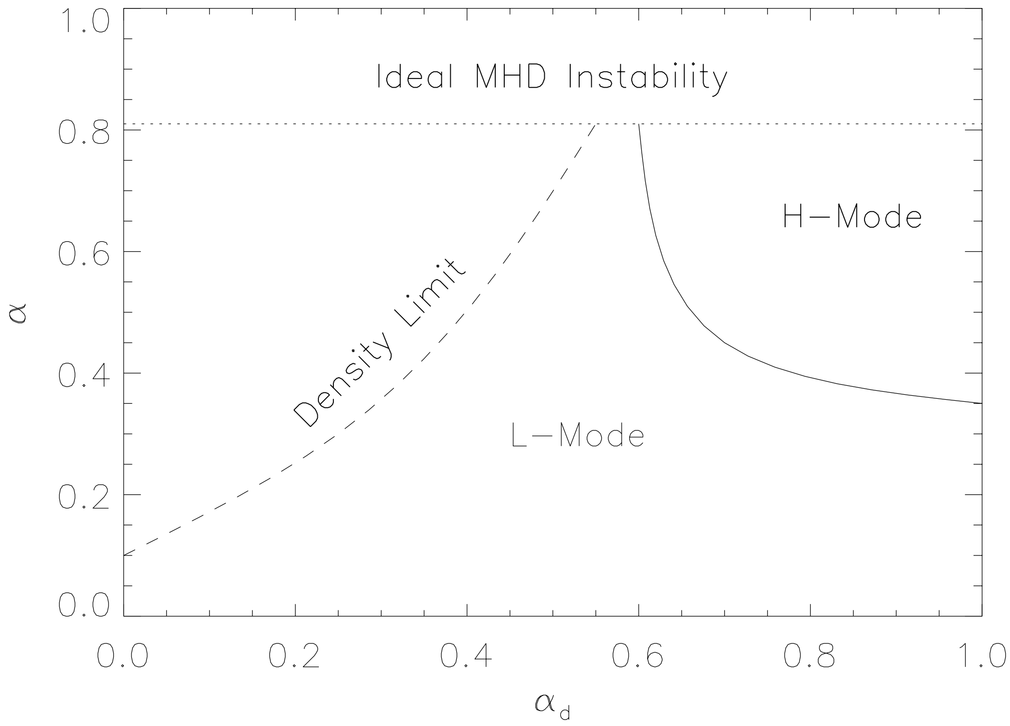
- Deterioration in edge confinement can be offset by internal transport barrier

SOME SUPPORT FROM EDGE TURBULENCE SIMULATIONS

- 3D gyro-fluid simulations have found regime of extremely high transport
- $\alpha = -Rq^2 d\beta / dr$
- $\alpha_D = \rho_s c_s t_0 / L_n L_0$

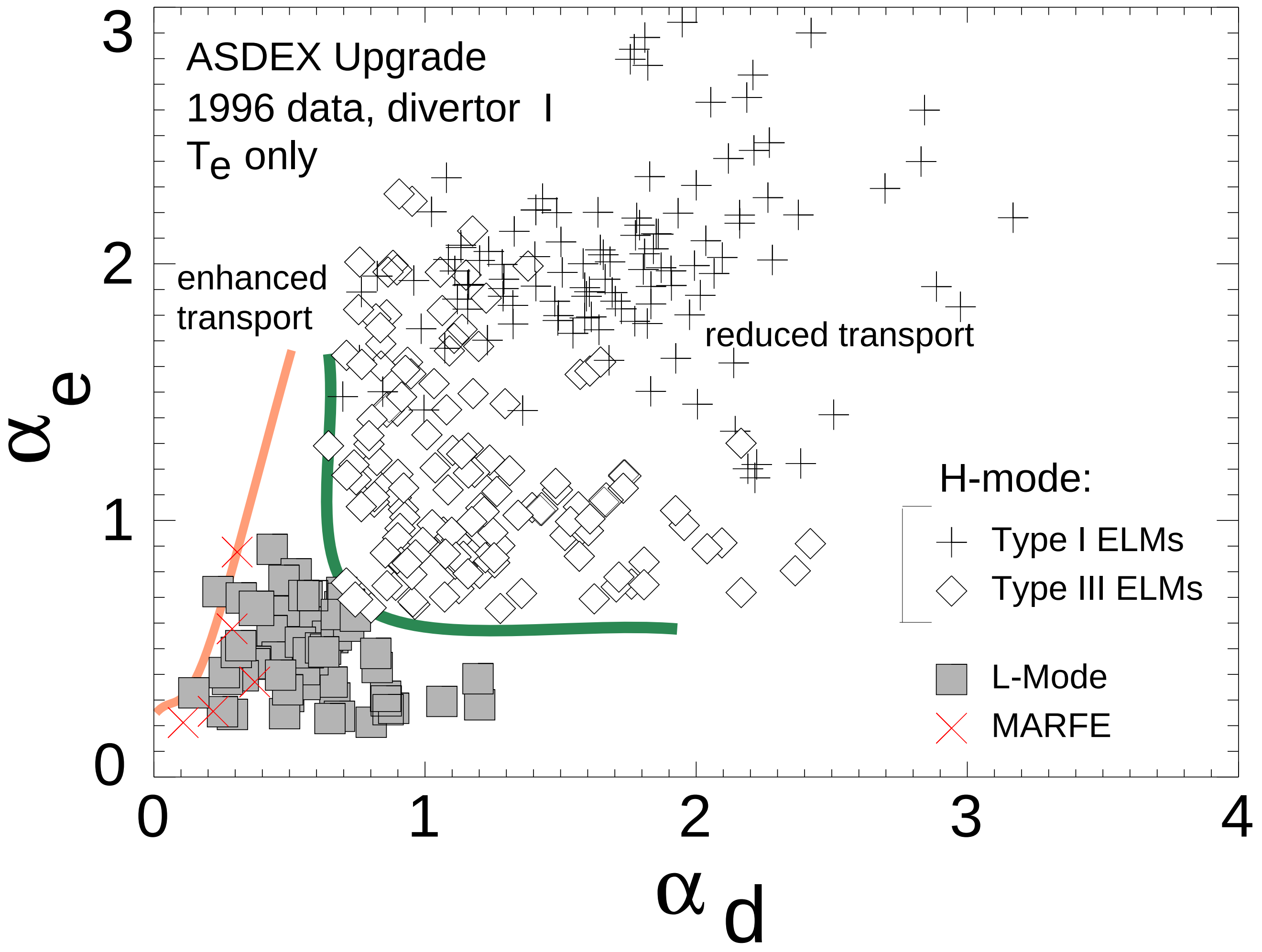
$$\propto \left(\frac{T^2}{nL_n} \right) \rightarrow \frac{\lambda}{L_n}$$

- 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

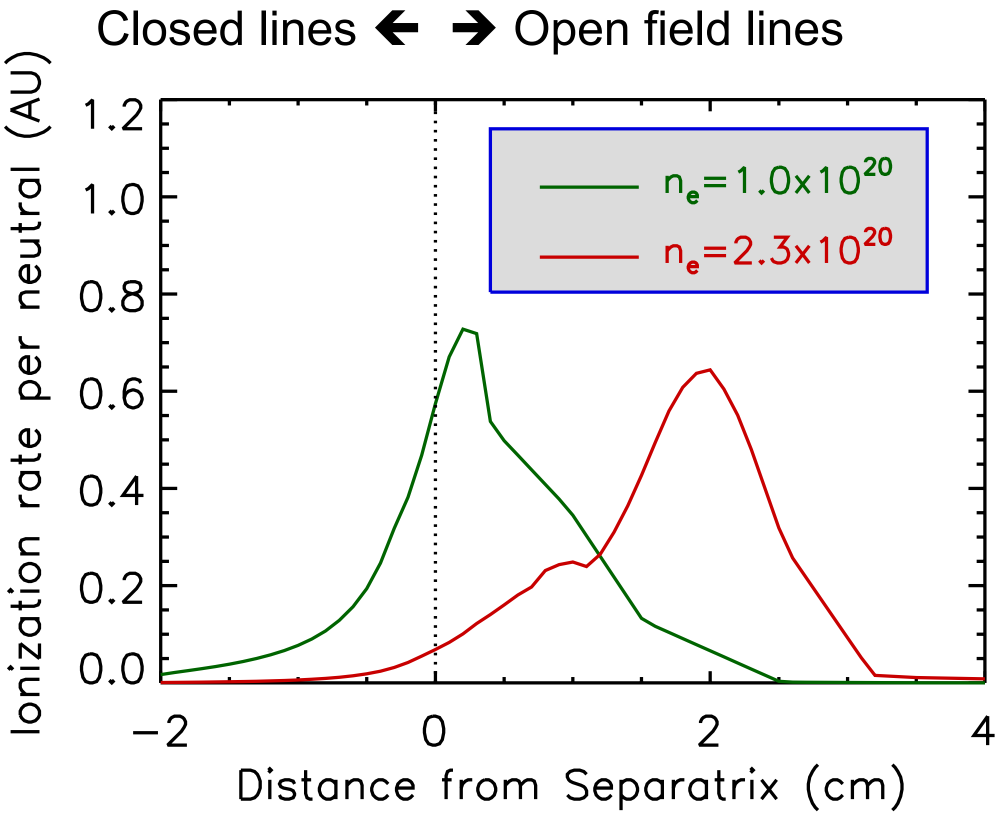


(Suttrop 1999)

MORE COMPLICATIONS - ROLE OF NEUTRALS IN THE DENSITY LIMIT?

- Self shielding - limits gas fueling
- Energy loss via ionization and charge exchange
- Source + particle transport. Sets edge gradient length ⇒unstable pressure profile
- Momentum transport.

  Flow damping from ion-neutral collisions.

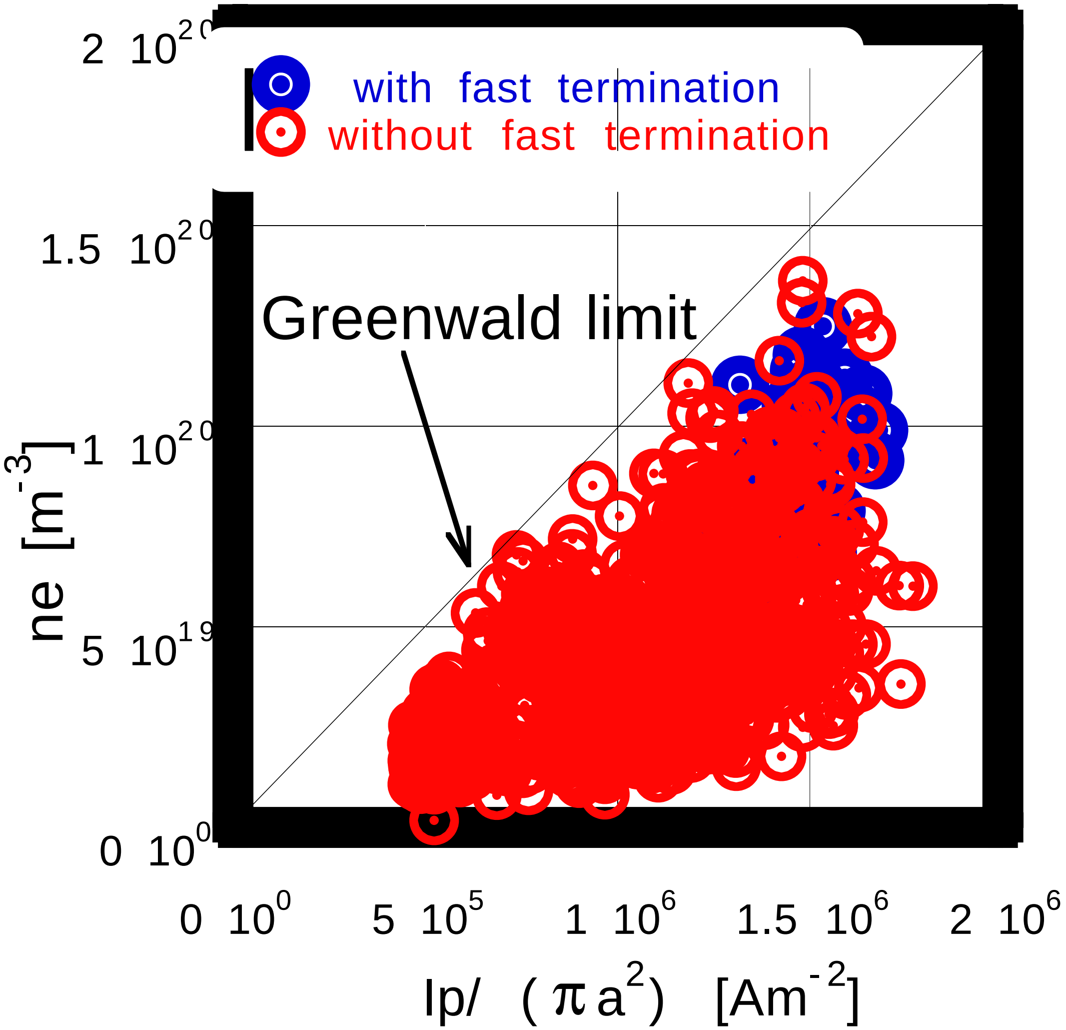


Relatively small increase in density leads to large reduction in ionization inside last closed flux surface

OTHER DEVICES? - DENSITY LIMITS IN REVERSED FIELD PINCH

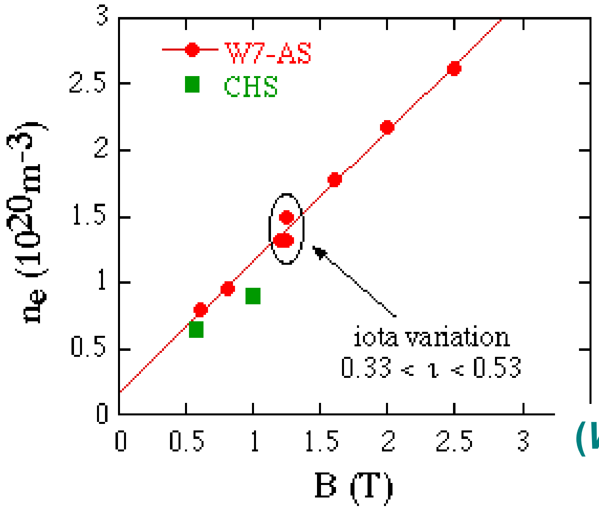
- RFP operating space characterized historically by I/N
- $\frac{I}{N} \propto \frac{n_G}{n}$
- Same scaling !
- Limit is quantitatively identical (!!)

(Bartiromo 2000)



STELLARATORS REACH SIMILAR DENSITIES BUT SHOW DIFFERENT DEPENDENCES

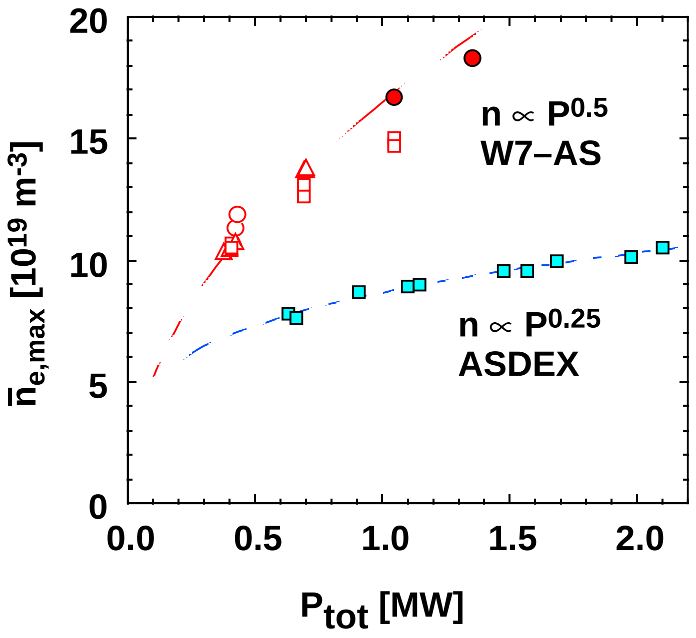
- Different scaling with power, size
- Shaping: B/qR vs I/a^2 scaling
- Scaling with ι = 1/q
- For machines with similar size and fields, stellarator will reach about twice the density of a tokamak



(Wagner 1997)

Power dependence of density limit

(Staebler 1992)



ASDEX: B_t = 2.1 T, $1/q_a$ = 0.34
W7-AS: B_t = 1.28 T, ι(a) = 0.33
both with boronized walls

ISSUES – THE DENSITY LIMIT AND THE NATURE OF EDGE TRANSPORT

- General question: Do we understand the important drives and saturation mechanisms?
- What is the role of open field lines and the separatrix?
- Creation and destruction of edge shear layer?
- Does model require that complex transport physics boil down to the "correct" form?
- Or is it robust with respect to details?
- Where does I_P (or B_P) dependence come from?
  - ExB
  - α_{MHD}
- Can we identify a reasonable threshold condition?

ISSUES – NATURE OF BLOBS, BALLISTIC TRANSPORT

- Are blobs fundamentally important or just a side effect?
  - Transition region is likely to be critical.
  - How are blobs shed?
- Do the blobs decouple the transport entirely from boundary conditions?
  - Profiles, gradients unimportant?
  - Is there an important role for ionization and fueling?

DISCUSSION - SUMMARY

- None of the proposed models are entirely satisfactory

- Radiation models consistent with some data, inconsistent with others
- Transport model far from point of making predictions
- Need to use self-consistent profiles, transport, power balance etc. for all models

- May need combination of turbulent transport and atomic mechanisms

- Physics strongly coupled – multiple feedback loops - cause and effects hard to untangle

- Can't expect analytic **form** of scaling laws to emerge from theory/simulation
- Transport studies need to be extended to other machines