~~Edge~~ Core Turbulence in tokamak plasmas experiments:

Diagnostics

Reflectometry, Beam Emission Spectroscopy, EM wave scattering

Scaling laws

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TORE SUPRA

Association Euratom-Cea

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overview

- Introduction/Motivation
  - Fluctuations measurements required for validating transport models and predictions
  - Which measurements are available in the plasma core? (selected):
    - ✓ *Reflectometry, Beam Emission Spectroscopy, EM wave scattering*

- Scaling laws of turbulence and transport
  - Introduce dimensionless parameters: $\rho_{L,}$ β…

- Identification of turbulence scales and times
  - Large scales dominate, linked with Larmor radius
  - Role of small scales
    - wave number spectrum shape

- Identification of structures

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Evaluation of fluctuation induced transport

- **Extensively studied at the edge**

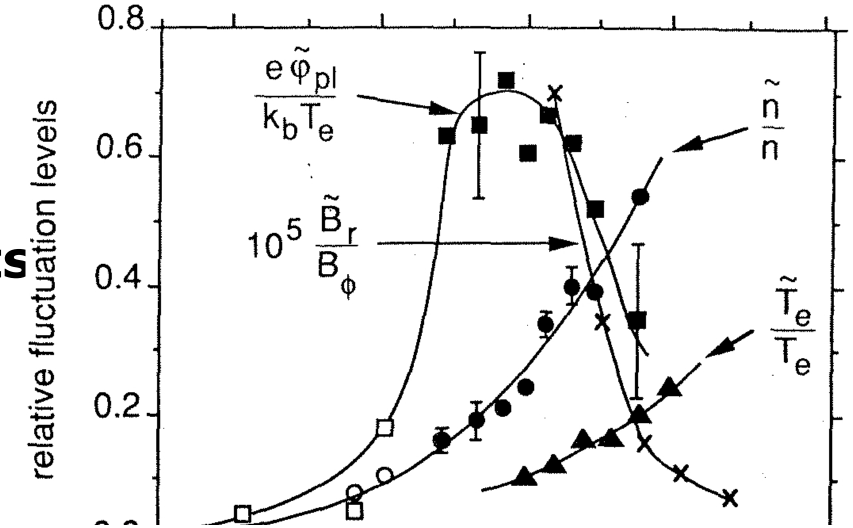
Turbulent flux can be directly evaluated from probes measurements

$\Gamma_e = \langle \tilde{n}\, v_r \rangle = \langle \tilde{n}\, \delta E_\theta \rangle / B$

fluctuating E $\Rightarrow \Phi$

$\Rightarrow$ ExB drift velocity $v_E = \dfrac{B \times \nabla\phi}{B^2}$

$Q_e = T \langle \tilde{n}\, v_r \rangle + n \langle \delta T\, v_r \rangle$



Fluctuations are:

mainly electrostatic [Ritz89, Wootton90, .

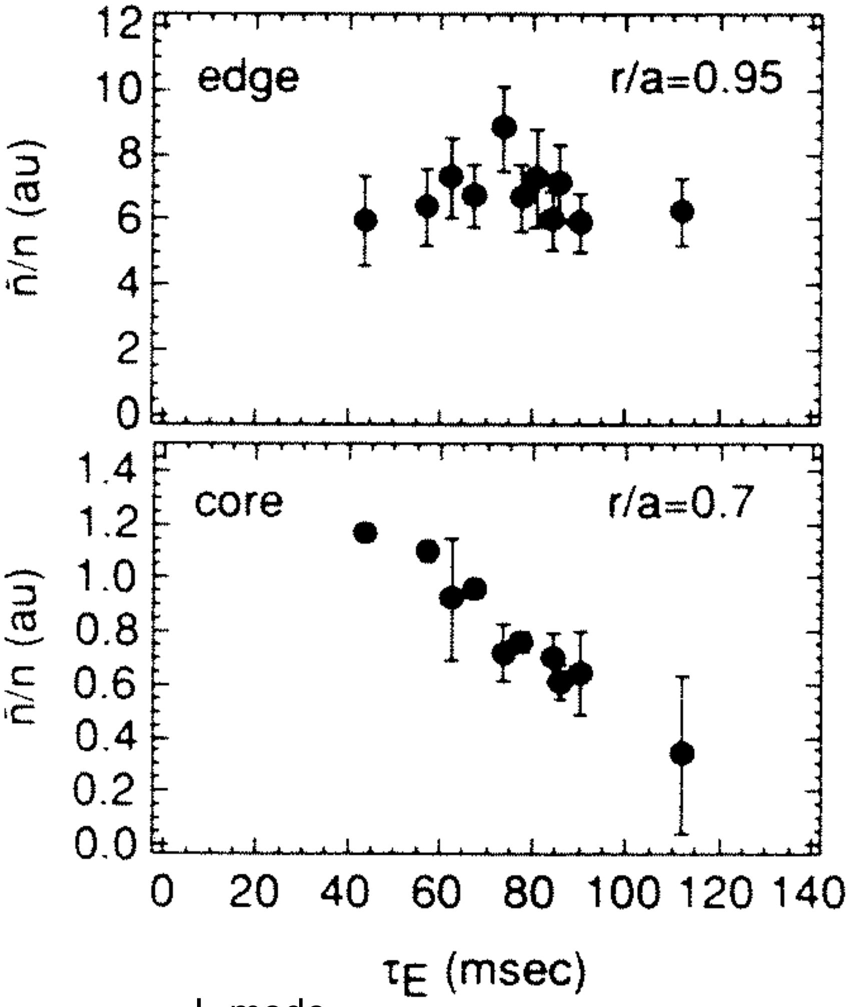
highly intermittent [Boedo01, Graves05 …,

Spatial structure studied by probes, fast imaging…

Contour plot potential fluctuations *Jenko PoP*

Measurements are more difficult in the core: no direct evaluation of the turbulent flux

direct correlation of confinement performance with turbulence level



L-mode

Global confinement scales with

core turbulence level

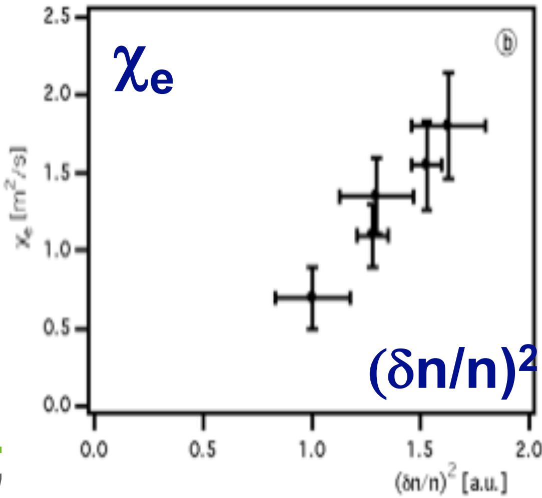
*Equipe **TFR** & A. Truc, NF (1986)*

Brower NF (1987) TEXT

*Paul et al, PoF (1992) **TFTR***   *R=2.5m, a=0.89m*

Durst et al, PRL (1993)

Local confinement also scales with turbulence level



Tore Supra

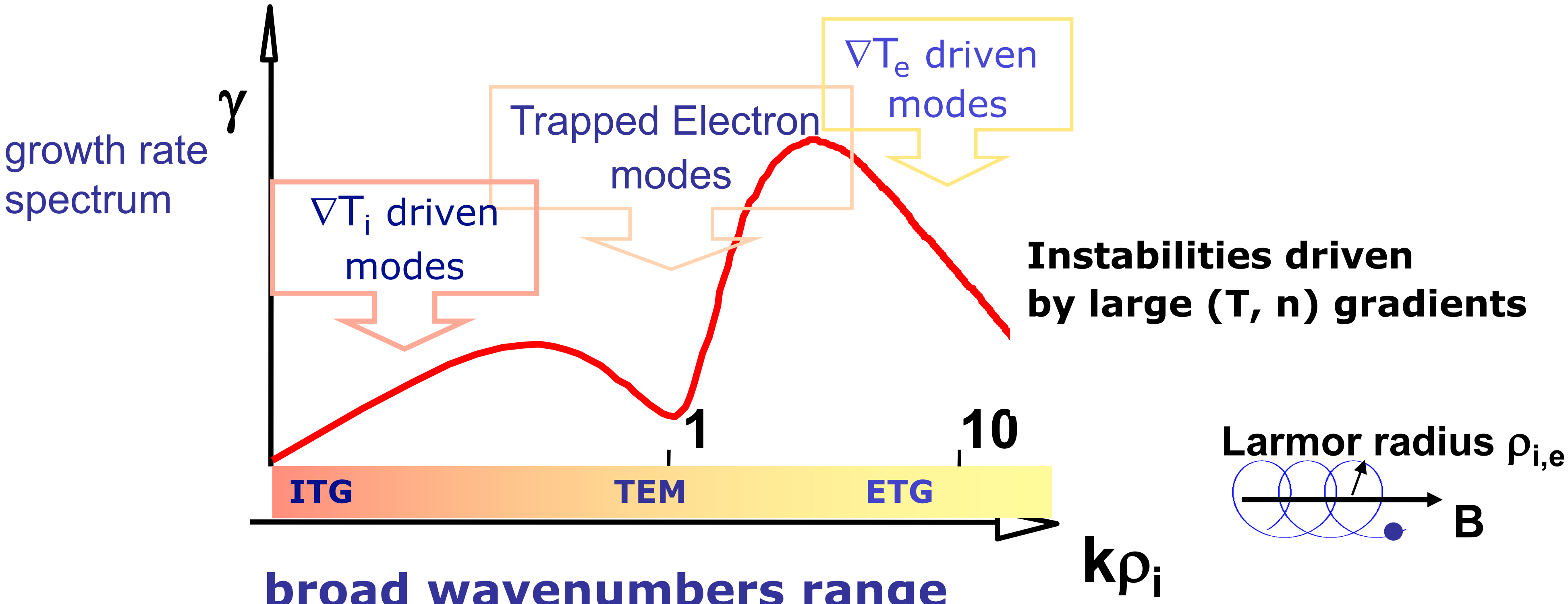
R=2.4m, a=0.7m

Laviron et al., IAEA (1996)

Zou et al., PRL (1995)

Hoang et al, Nuc. Fus. (1998)

Identifying Turbulence Scales is crucial for understanding anomalous transport

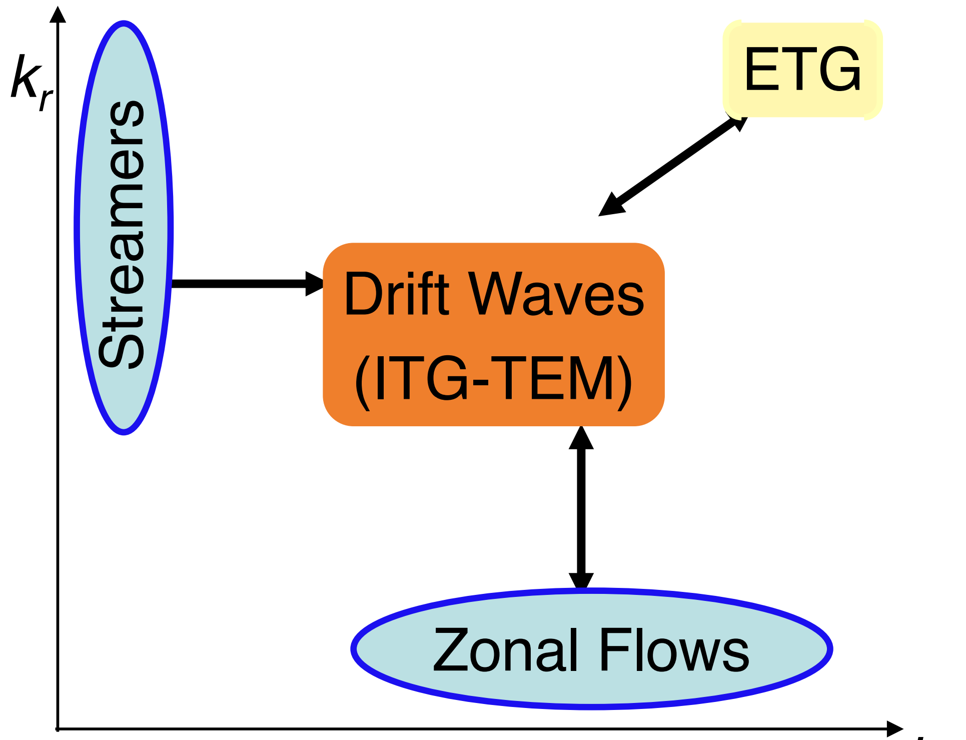


broad wavenumbers range

- Ionic vs Electronic Transport : role of small scales?
  - *Stallard PoP 99, Hoang PoP 03*

Broad range of scales and variety of interaction mechanisms

- Radial /poloidal scales
  - Large sheared flows
  - Streamers & meso scale transport
  - small scales



Requires active methods using wave or beam probing, to get spectral/spatial resolution

Fluctuation measurements →	at low k	medium to high k
	Correlation techniques: BES, reflectometry	Scattering diagnostics: laser, micro-waves

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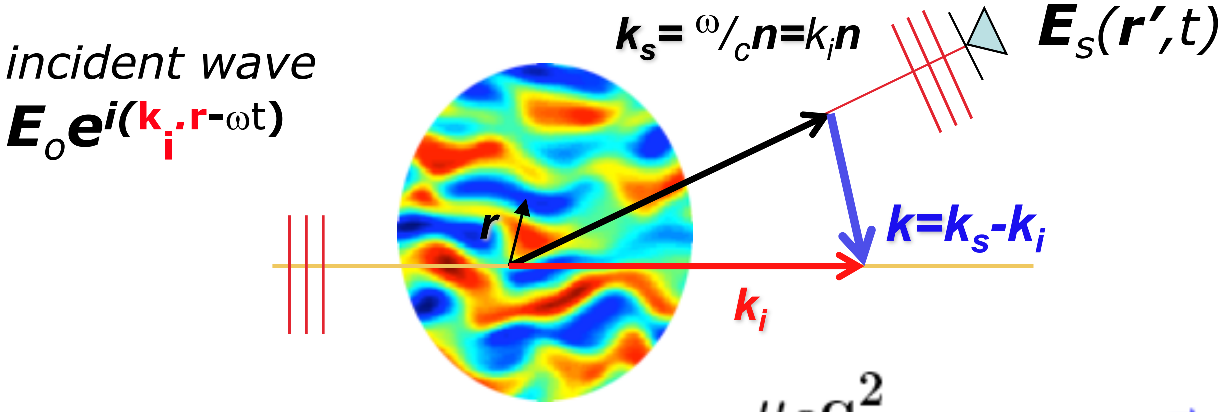
EM wave scattering for detecting turbulent structures and their movement: basic principle



radiation from accelerated electrons (oscillating dipoles)

far field approximation

Phase related to scatterer position

$$E_s(r',t) = \frac{\mu_0 q^2}{4\pi m}\{\vec{n}\times\vec{n}\times\vec{E}_0\}\, e^{-i\omega t}\,\frac{e^{ik_iR}}{R}\sum_r e^{i(\vec{k}_i-\frac{\omega}{c}\vec{n}).\vec{r}}$$

Spatial Fourier analysis of fluctuations $\tilde{n}(\mathbf{k},t)$
with selected wave number $k=k_s-k_i$ *(Bragg selection rule)*

$$i_k(t) \propto \int_V \tilde{n}(\mathbf{r},t)\; e^{i\mathbf{k}.\mathbf{r}} d\mathbf{r}$$

explore	**spatial scales** $1/k$
	temporal scales
determine	**turbulence intensity**
	dynamics from Doppler effect

3D k-spectrum of the density fluctuations at k

$E(k) \equiv k^{D-1} S(k)$

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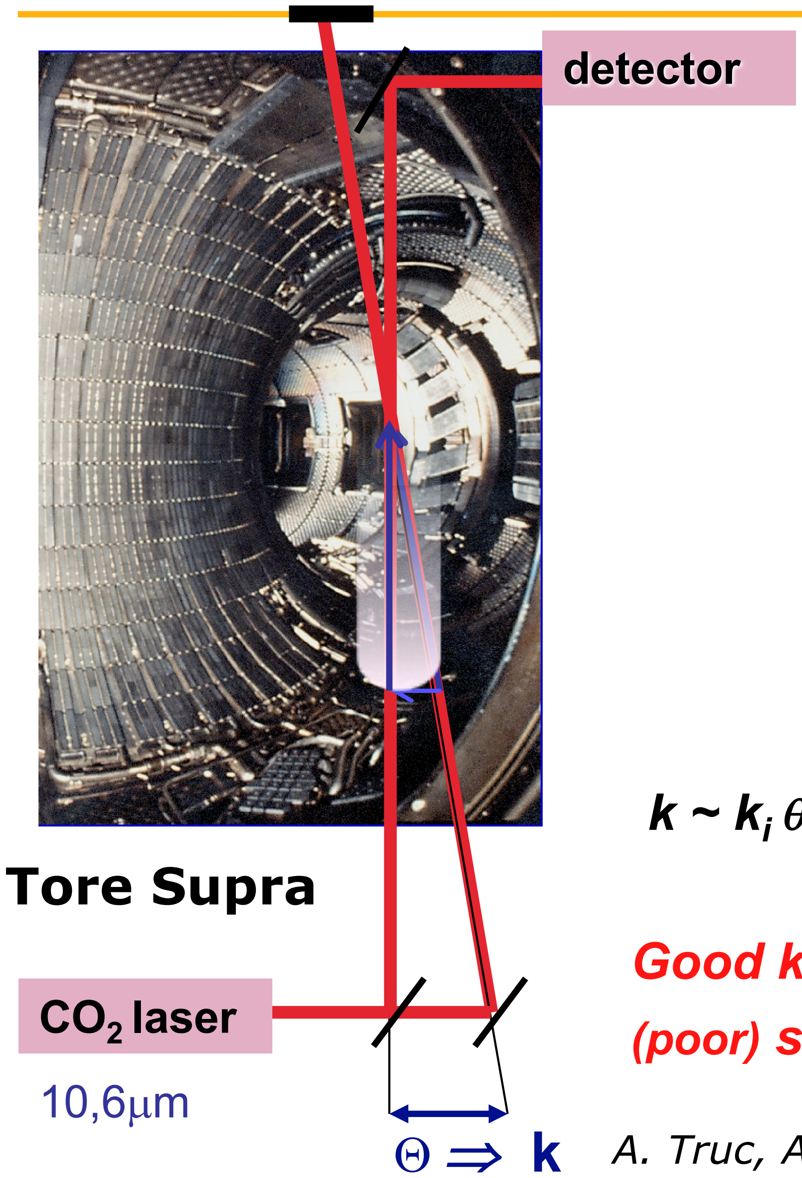
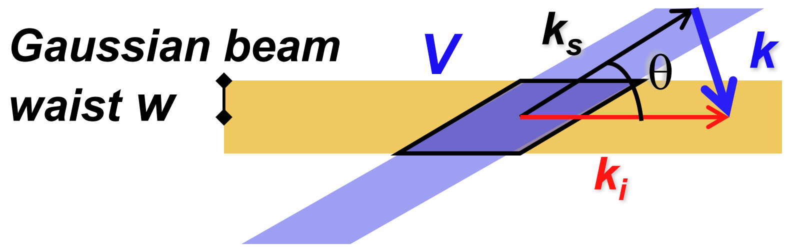
EM wave scattering for detecting turbulent structures and their movement: *Different scattering geometries*



Spatial Fourier analysis
of fluctuations $\tilde{n}(\mathbf{k},t)$
with selected wave number $\mathbf{k}=\mathbf{k}_i-\mathbf{k}_s$

Forward scattering



$k \sim k_i\,\theta$ for *small* θ $\quad k_i=2\pi/\lambda_i$ *IR / FIR sources*

ATC, TFR, TEXT, Tore Supra, DIIID

Good k resolution $\Delta k=2/w$

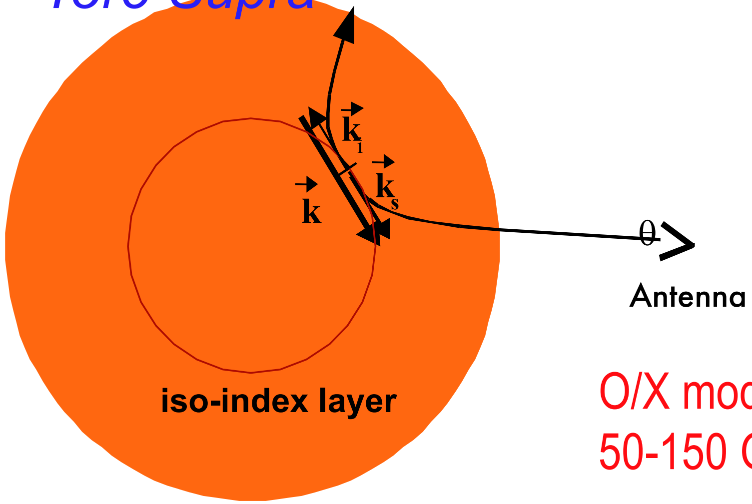
(poor) spatial localization: *transverse* w

longitudinal w/θ

A. Truc, A. Quéméneur, P. Hennequin &al, RSI92

EM wave scattering for detecting turbulent structures and their movement: *Different scattering geometries*

Doppler reflectometry
Tore Supra



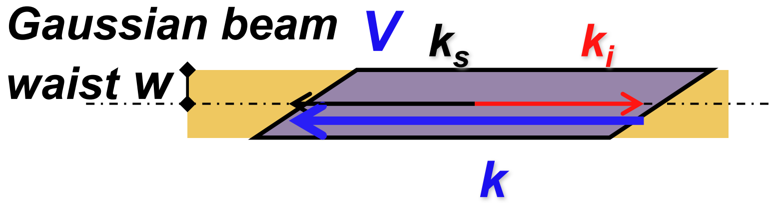
O/X mode
50-150 GHz

Probing frequency range of reflectometry
Backscattering localised at the cut-off
Oblique incidence selects $k_{\theta,c}$ at the cut-off

T. Rhodes, Peebles, APS 04, PHP07
P. Hennequin, C. Honoré, A. Truc et al, RSI (2004)

Spatial Fourier analysis
of fluctuations $\tilde{n}(\mathbf{k},t)$
with selected wave number $\boldsymbol{k=k_i-k_s}$

back scattering



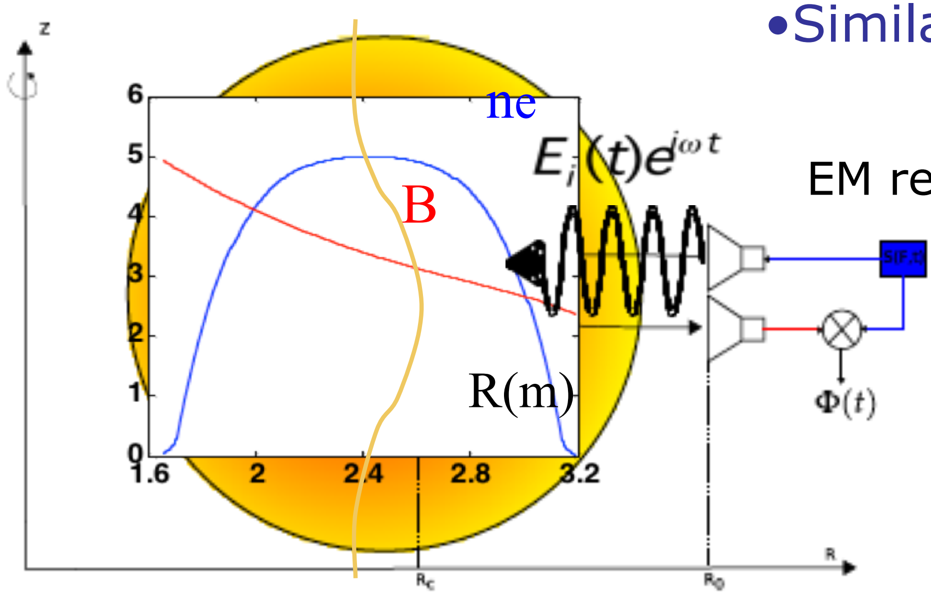
***k* ~ -2 *k*$_i$** *μwave sources*
DIIID, W7AS, Asdex, Tore Supra

k resolution **Δ*k*=2/*w***

spatial : *transverse **w** /*
***no** longitudinal localization*

Except using resonance and cut-off

Localised measurement using reflectometry

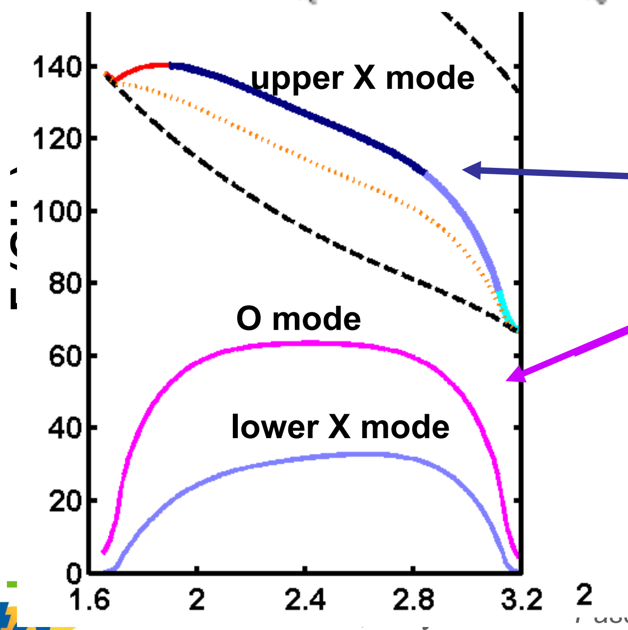


- Similar to radar ⇐ Plasma good reflector (*ionosphere…*)

EM reflected at the cut-off $E_r(t) = A(r,t)e^{i(\omega t - \Phi(t))}$

- phase (or time of flight) from propagation in dispersive medium

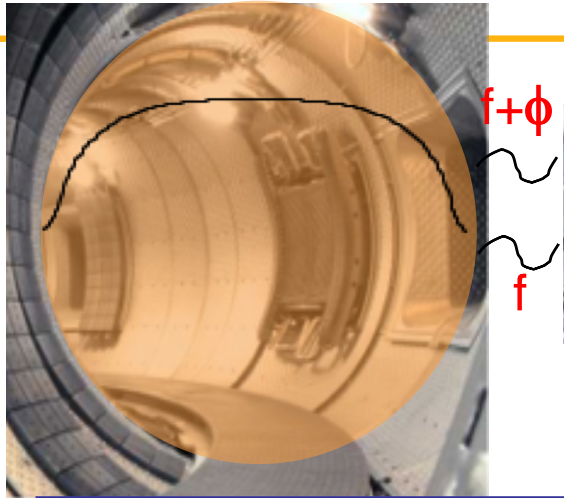
$$\phi = \frac{4\pi}{c} \cdot f \cdot \int_{x=0}^{x=r_c} N(r,t)\,dr - \frac{\pi}{2}$$

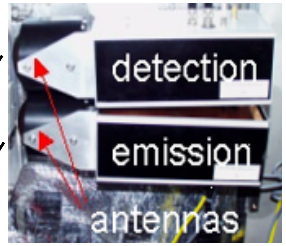


X-Mode (E ⊥ B_0) $\frac{1}{2}\left(f_{ce} \pm \sqrt{f_{ce}^2 + 4 f_p^2} \right)^{0.5}$

O-Mode (E // B_0) $f_p = \frac{1}{2\pi}\left(\frac{ne^2}{\varepsilon_0 m_e}\right)$

Localised measurement using reflectometry





$\varphi >> 2\pi$, φ difficult to measure

⇓

Tore Supra:

$$\frac{\partial \phi_p}{\partial t} = \frac{4\pi}{c}\left(\frac{\partial f}{\partial t}\right)\int_{x=0}^{r_{co}} N(r,f,t)dr + \frac{4\pi}{c} f \frac{\partial}{\partial t}\left(\int_{x=0}^{r_{co}} N(r,f,t)dr\right)$$

profile measurement

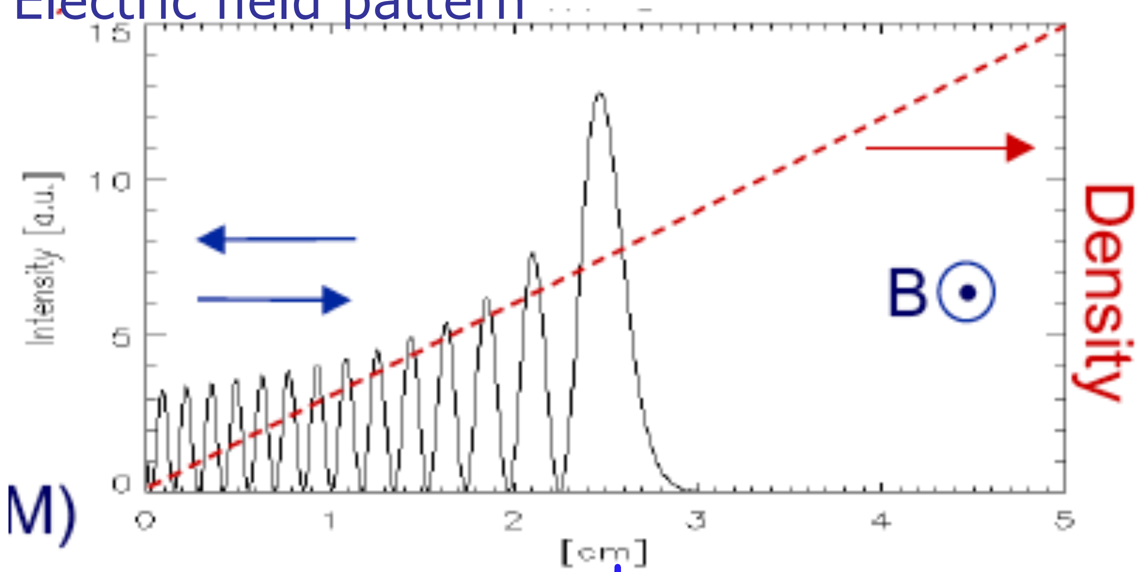
$\frac{\partial f}{\partial t} \sim 1GHz/\mu s$ *δn negligeable*

- fluctuations measurement
- *$f = C^{ste}$, $\delta\varphi \sim \delta n$* ***along the path***

3 fast swept X mode 50-150 GHz **+** fixed frequency (105-155 GHz) for core fluctuations

Localised measurement using reflectometry

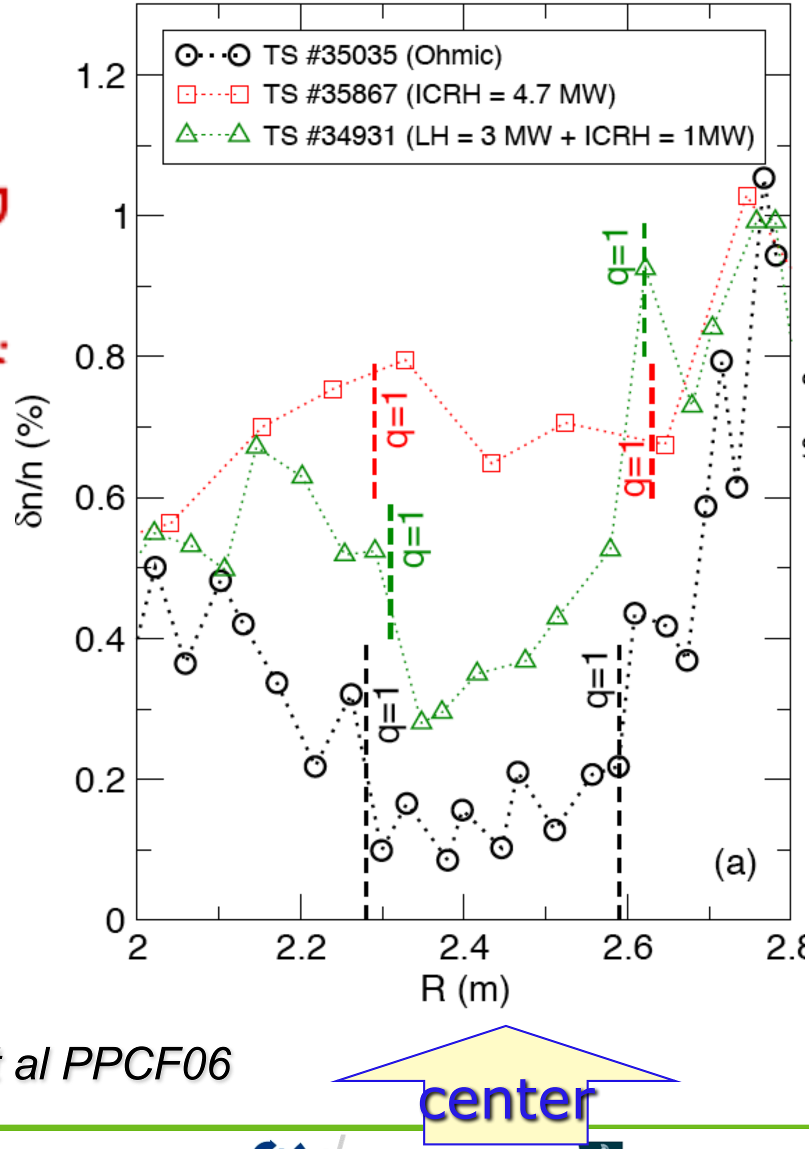
Electric field pattern



$$\lambda_{AIRY} = \left(\lambda_o^2 L_n\right)^{1/3}$$

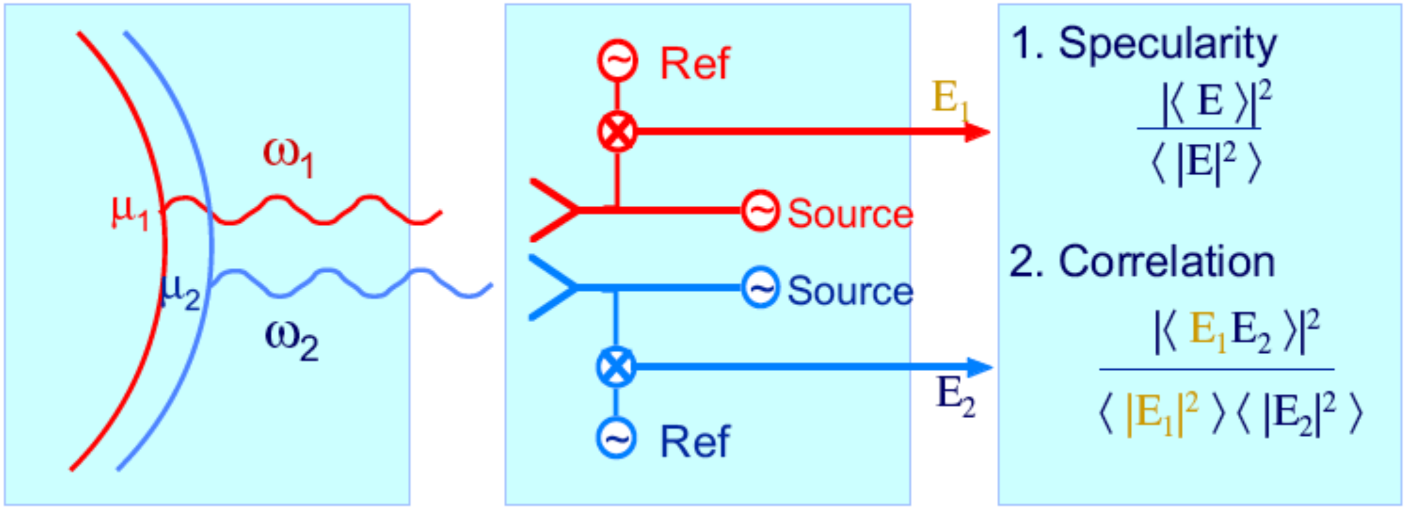
- Large scale fluctuation

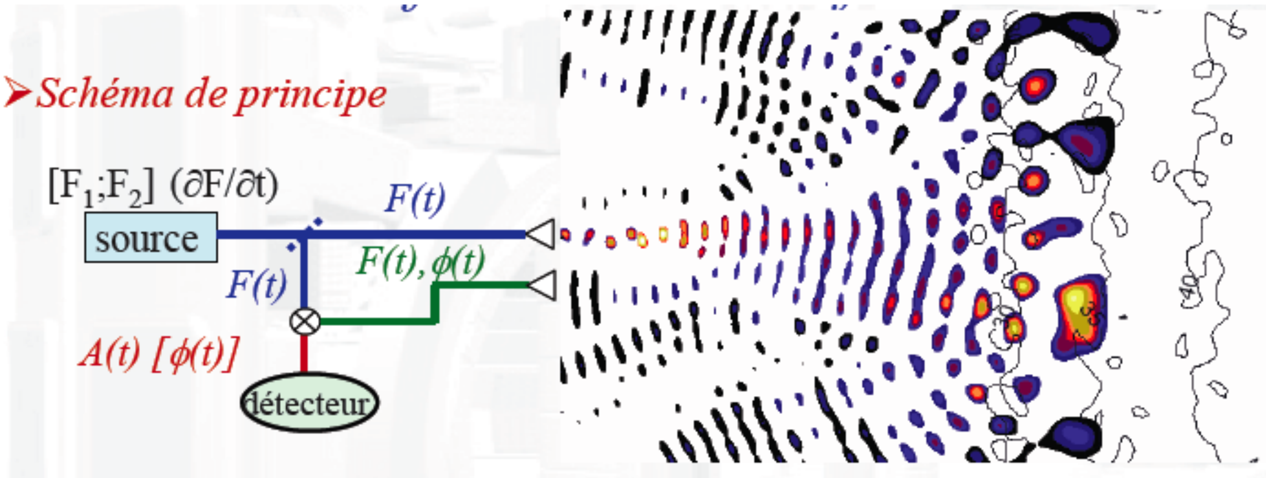
  k <3 cm^{-1}
- High sensitivity



Sabot et al PPCF06

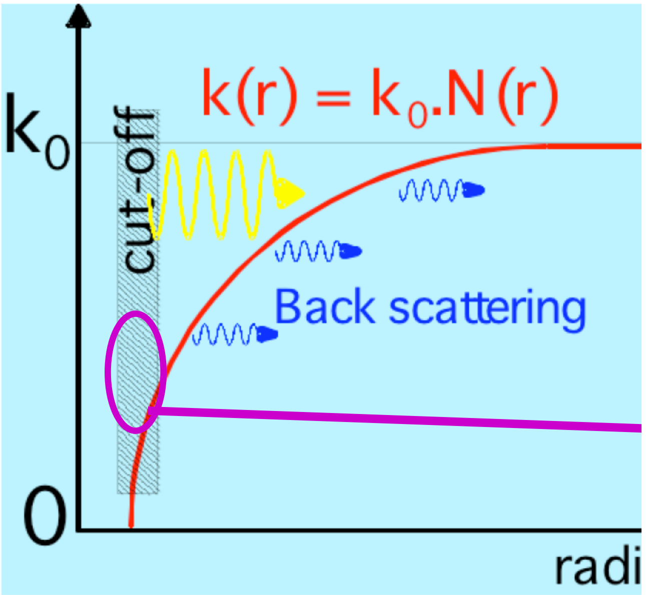
Correlation lengths measurement using reflectometry



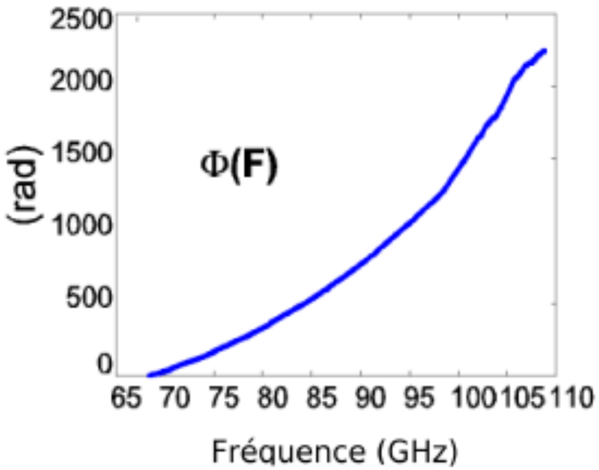


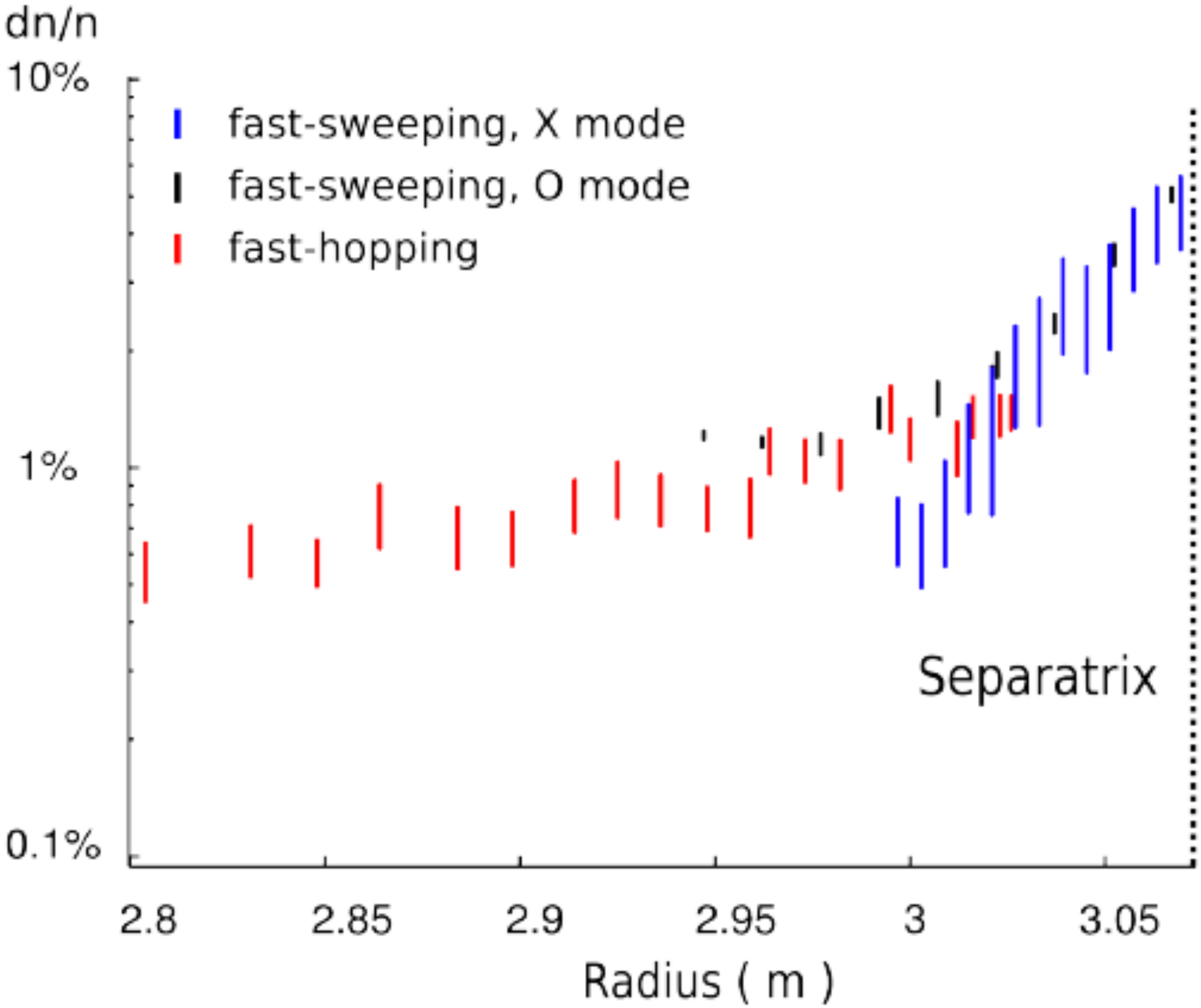
But non linear effects at large fluctuation level affect spatial resolution

Reflectometry signal propagation in a turbulent plasma



Signal mesuré : $A(t)e^{i\Phi(t)}$





Gerbaud *et al*, Rev. Sci. Instrum. 77, 10E928 (2006)

Rayon (m)

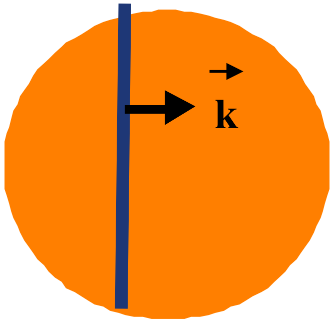
1 10 100

k (cm-1)

CHNIQUE

spatial and spectral information from EM wave probing

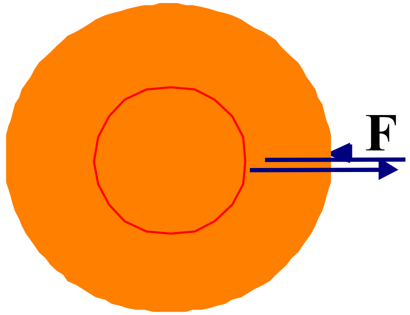
Coherent scattering



$3 < k < 20$ cm^{-1}
$\Delta k = 0{,}7$ cm^{-1}
large volume
- crossing access

⇒ $k\rho_i$ ~0.5 to 3

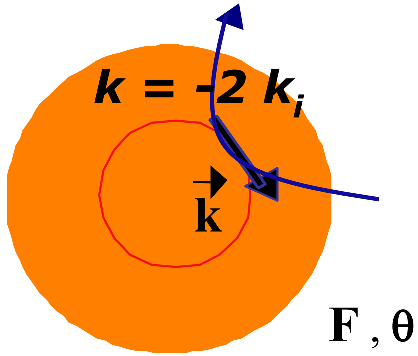
Reflectometry



integrated k
between 0 and 1 cm^{-1}
good localization
- no k resolution

⇒ $k\rho_i$ ~0.1

Backscattering



$4 < k < 30$ cm^{-1}
$\Delta k = 2$ cm^{-1}
good localization
+ poloidal rotation
- ray tracing

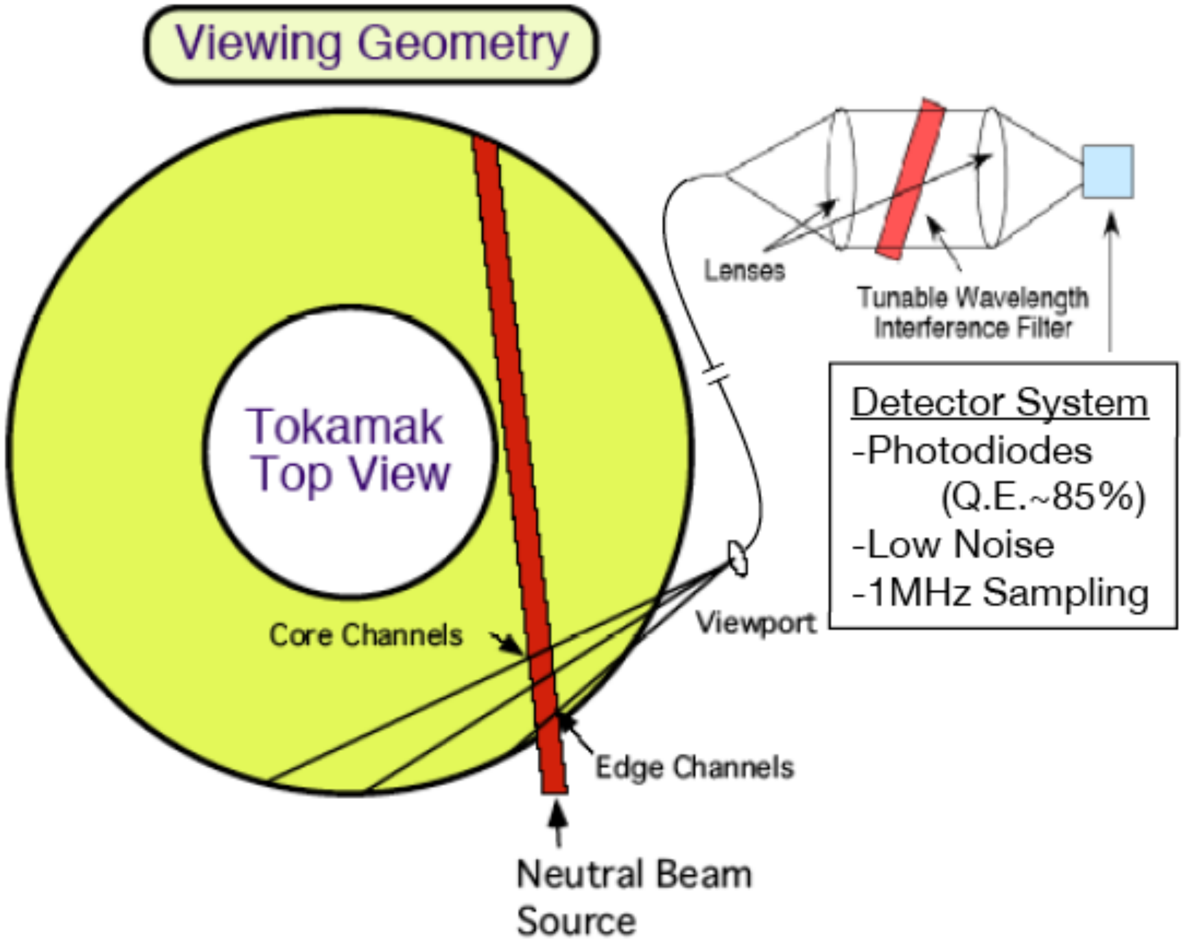
⇒ $k\rho_i$ ~0.5 to 4

P. Hennequin, C. Honoré, A. Truc et al, RSI (2004)

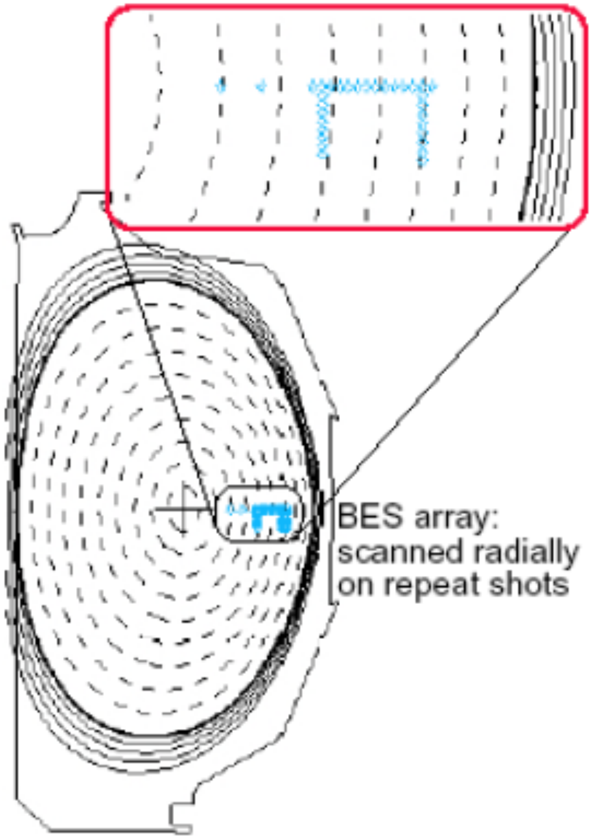
Beam Emission Spectroscopy(BES) Diagnostic Measures Long-Wavelength Density Fluctuations

- Measures collisionally excited, Doppler shifted, neutral beam fluorescence

$$D^o + e,i \quad (D^o)^{*} + \gamma(n = 3 \quad 2,\ \lambda_o = 656.1 nm)$$



Poloidal Cross Section

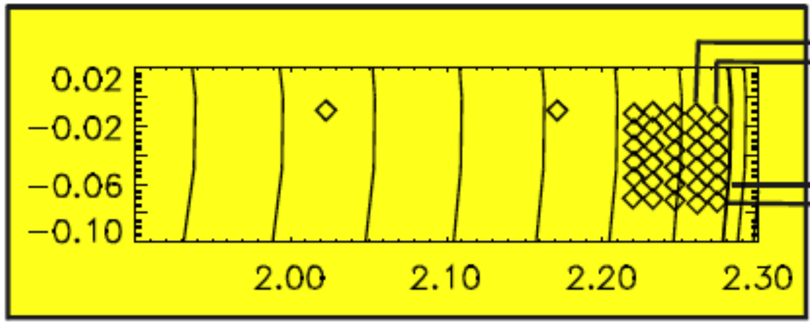


Fonck PRL93 (TFTR), McKee RSI 99, NF01, PPCF03

Fluctuation level and dynamics, correlation lengths, velocity field can be extracted

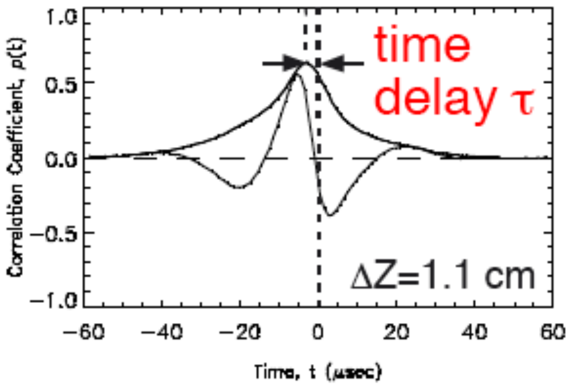
$\tilde{v}_r$, $\tilde{v}_\theta$ Obtained from $\tilde{n}(t)$ via Time Delay Estimation

Poloidal Cross Section of Tokamak



Two radial $\tilde{n}(t)$ channels --> $\tilde{v}$

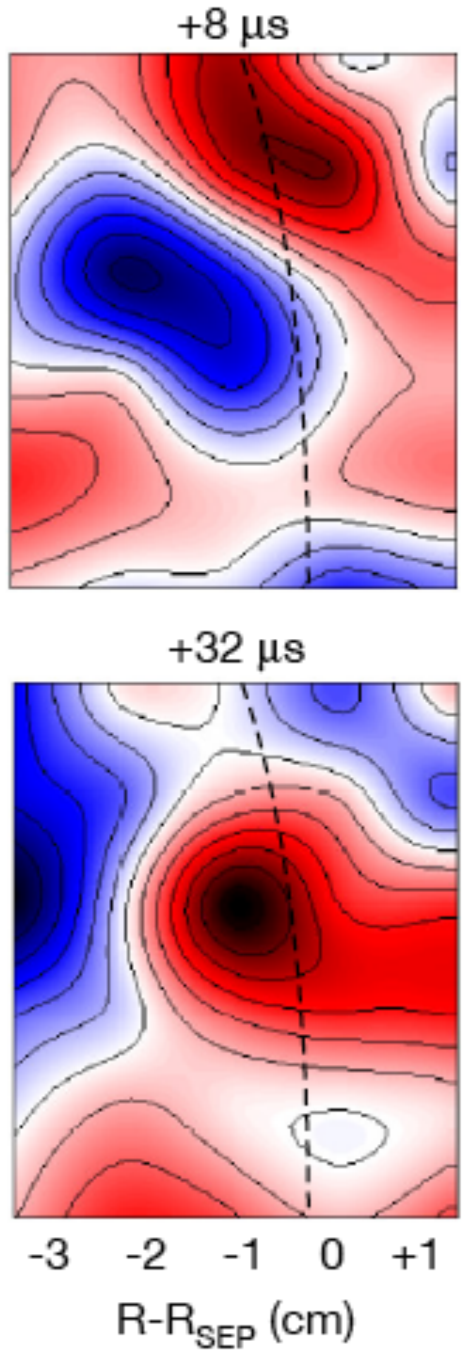
Two poloidal $\tilde{n}(t)$ channels -->



- We observe turbulent eddies moving past our view:

$$\tilde{v}_z(t) = \frac{\Delta z}{\tilde{\tau}(t)}$$ ← delay between two observation points

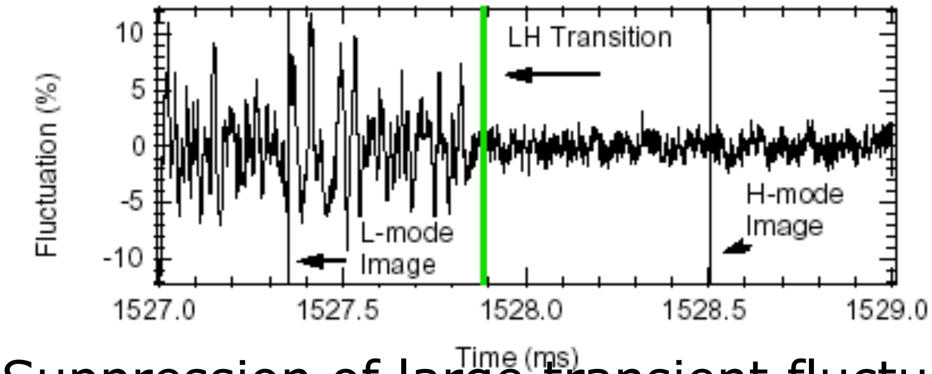
McKee RSI 99, NF01, PPCF03



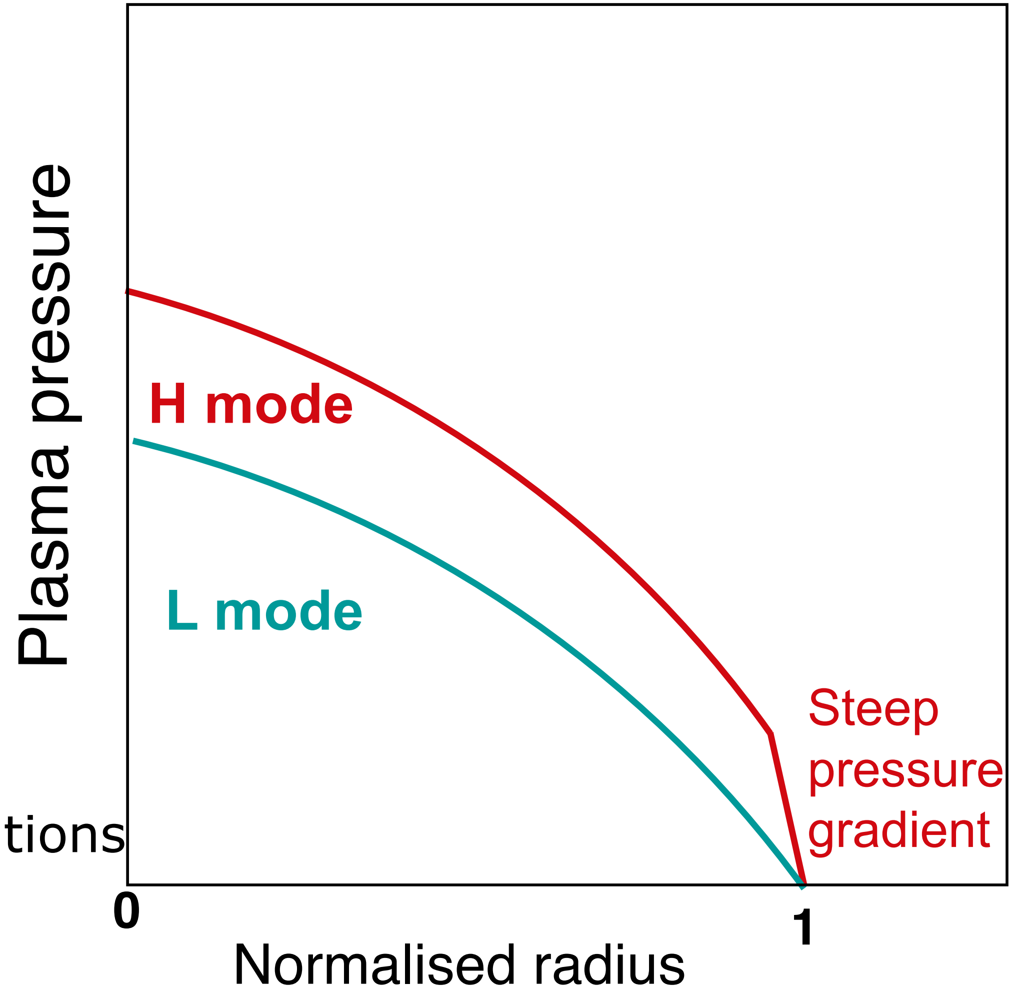
Turbulence monitoring during confinement regime bifurcation

- **L to H mode transition**
- **⇒pedestal formation**

DIIID beam emission spectroscopy

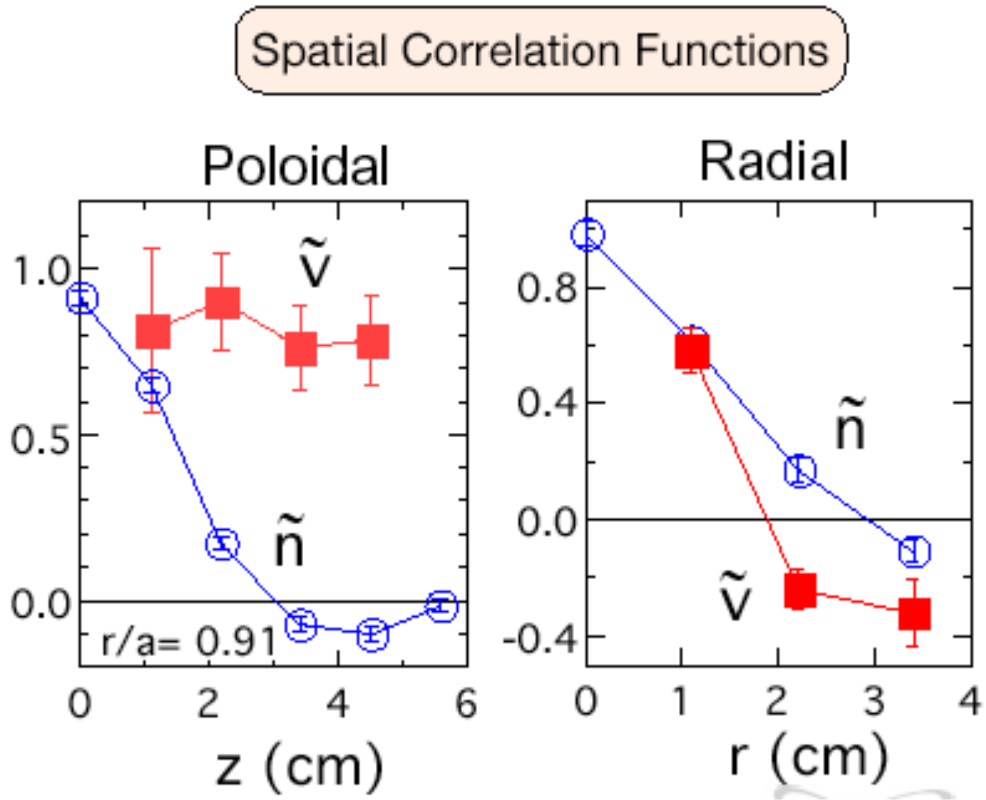


Suppression of large transient fluctuations at the L-H transition



TFTR, JET, JT60, AUG,TEXTOR .. observed by reflectometry, phase contrast imaging, Langmuir probes

Coherent velocity oscillation indicates radially localised, poloidaly uniform shear flow

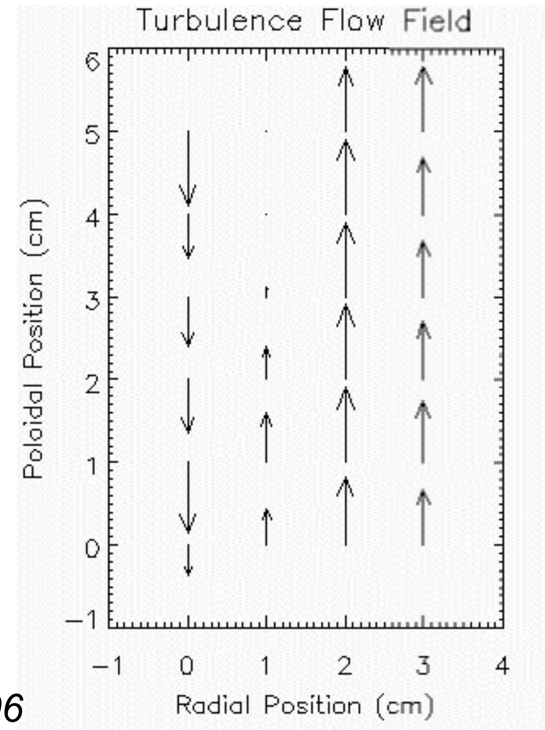


Consistent with expected features of a **Geodesic Acoustic Mode**

f~10-20 kHz

Poloidally extended

Radially narrow



Jakubowski, PRL2002
McKee, PoP 2002

Also observed with Doppler reflectometry Conway PPCF06

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Dimensionless scaling laws predict transport in next step devices and test transport models

Similarity principle [X. Garbet]

extensively used in fluids

In plasmas *B.B.Kadomtsev, J. Connor*

Assumes a limited number of dimensionless parameters governs the physics

$B\tau_E = F(\rho_*, \beta, \nu_*)$

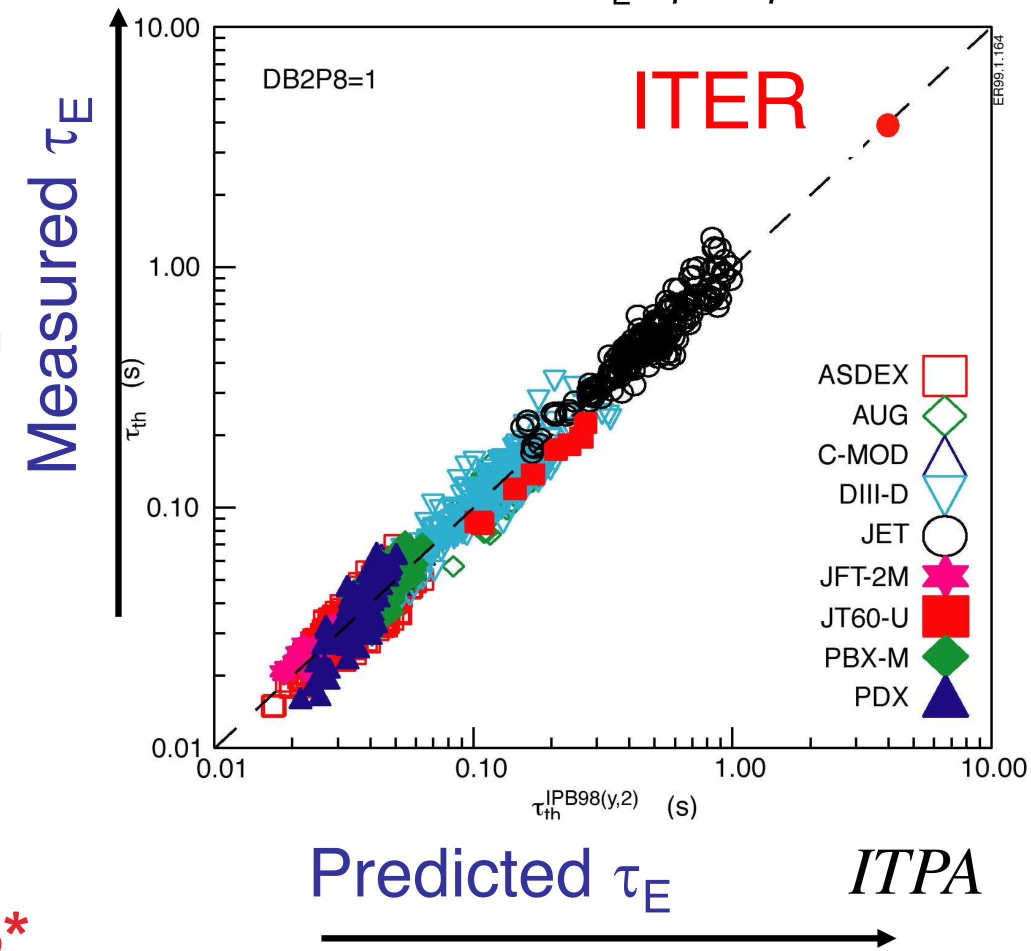
$\rho_* = \rho_s / a$: normalised gyroradius

$\nu_* = \nu_c\, a / v_{th}$: collisionality

$\beta = P_0\, 2\mu_o / (B_0^2)$: beta

△ largest extrapolation for ρ^*

$B\tau_E = \rho_*^{-2.7} \beta^{-0.9} \nu_*^{-0.01}$



ITPA

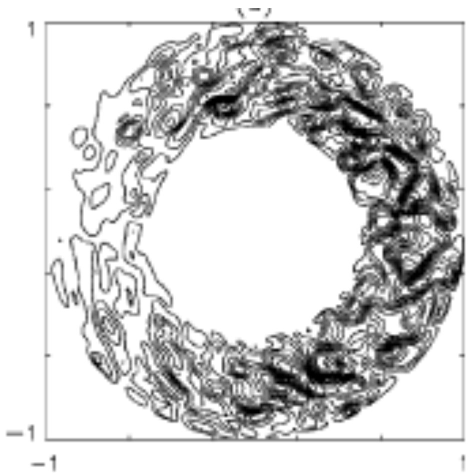
ρ* scaling crucial to large machines extrapolation

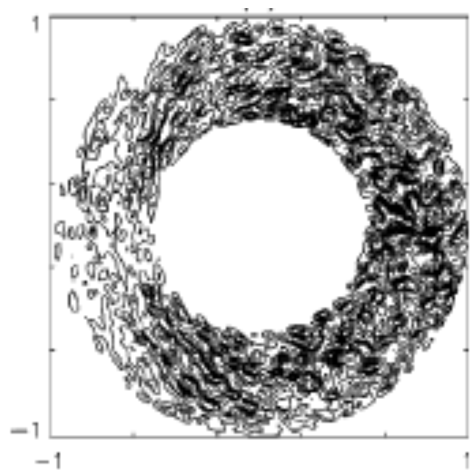
- Is the scaling with the size (ρ*) favourable or unfavourable?

$$\chi_T = \frac{T}{eB}[\rho *]^\alpha \quad \begin{cases} \alpha = 0 : \text{Bohm} \\ \alpha = 1 : \text{gyroBohm} \end{cases}$$

  - Transport studies: different behaviour for Ions and Electrons *[Petty 97 Baker NF 2000]*
  - Simulations favour gyro-Bohm scaling *[Manfredi & Ottaviani PRL97, Lin PRL 2002]*

ρ*=1/50





ρ*=1/100

How fluctuation characteristics scale with ρ_L?

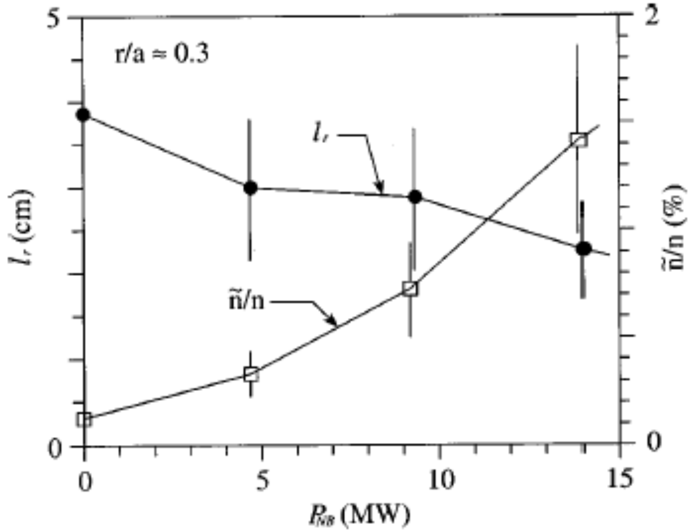
Fluctuations characteristic scales $\lambda_c \sim \rho_L$
times $\tau_c \sim a/c_s$ $\rightarrow$ $\mathbf{D \sim \lambda_c^2 / \tau_c \sim \rho_L^2 c_s/a \equiv \rho^* T/eB}$

$D \sim \rho^* D_B \rightarrow$ Local turbulent transport theories predict **gyro-Bohm transport scaling**

- Mixing length estimate:

$\nabla \tilde{n} \equiv \nabla n_{eq} \Rightarrow k_\perp \tilde{n} \equiv n / L_n$

$\tilde{n} / n \equiv \rho_L / L_n$



- Observed in early experiments
- Less clear, in improved confinement regimes

[Mazzucato PRL93]

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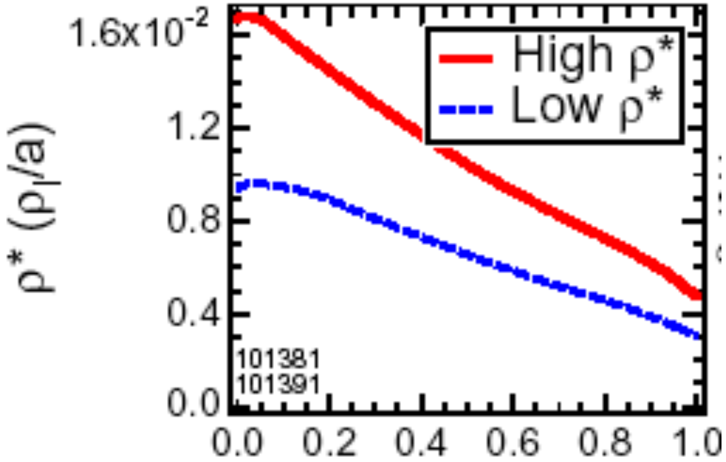
Dedicated experiments for ρ_i scaling on DIIID

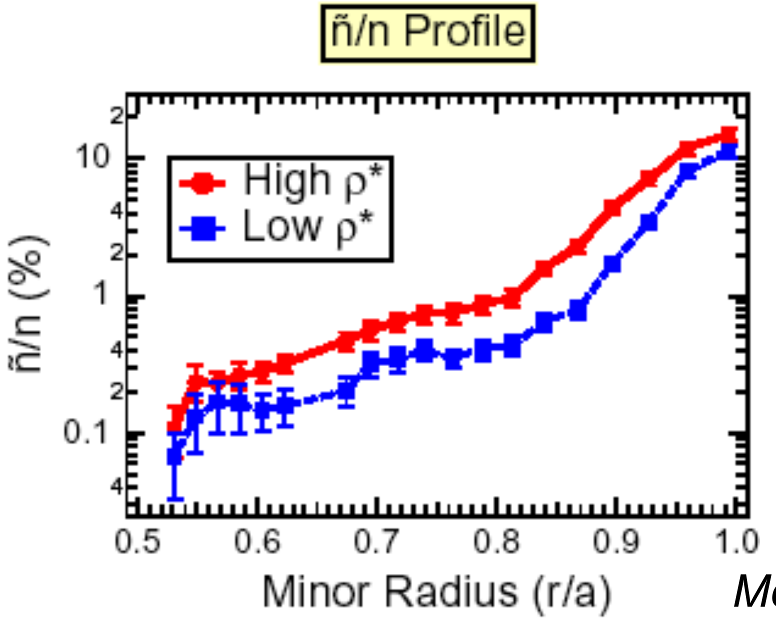
R=1.7, a=.6m

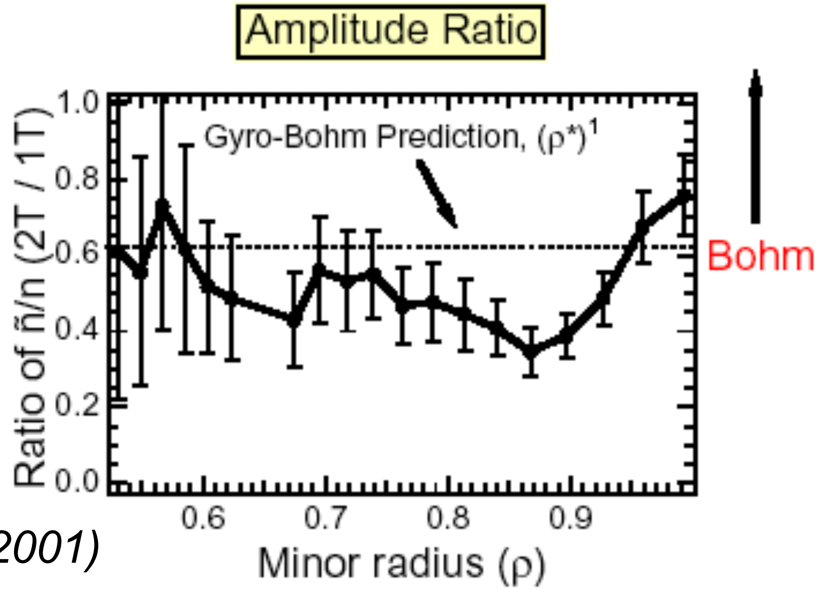


Similar discharges in β, ν, T_e/T_i, q
differ only in ρ_i : varied by 1.6 (B scan)

ñ measured by Beam Emission Spectroscopy
$k < 3\ cm^{-1}$ $\quad$ $0.6 < r/a < 1$

Close to gyro-Bohm prediction ñ /n ~ ρ_i





McKee, Nuc Fus (2001)

Fluctuation level scaling with ρ_i on Tore Supra

Similar discharges

ρ_i varied by 1.4 / B scan and gas

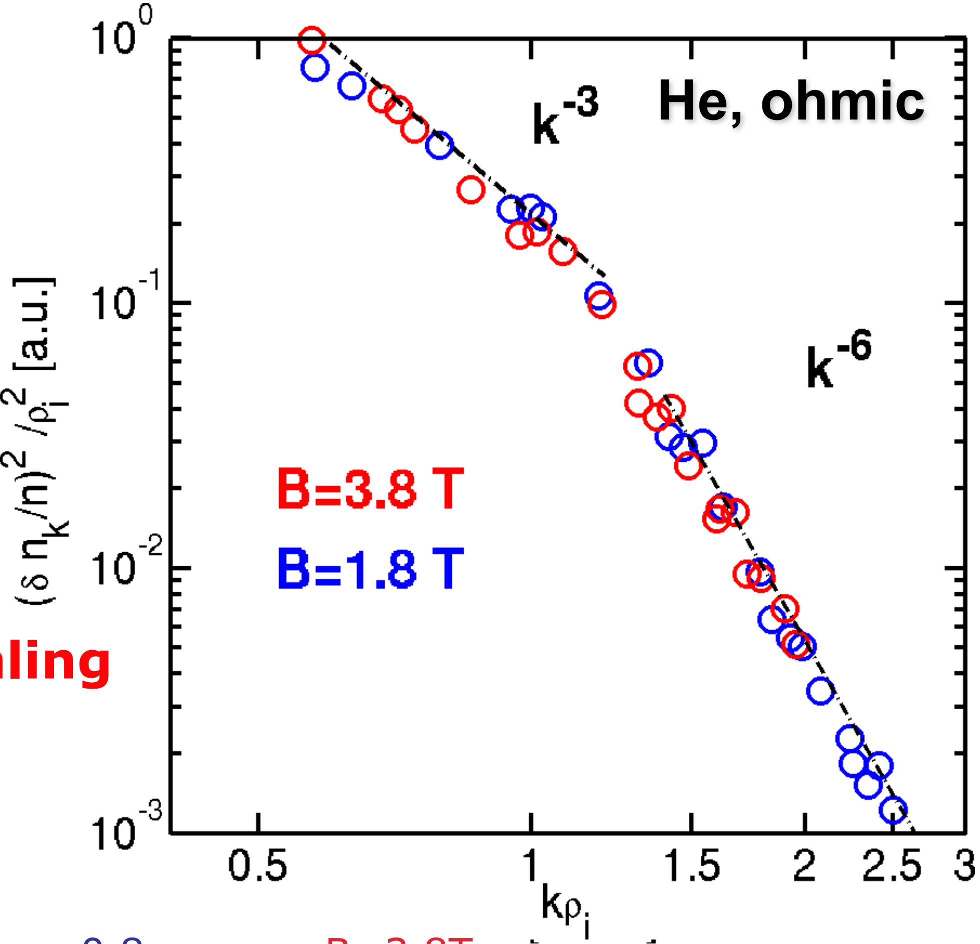
$\tilde{n} / n \equiv \rho^* F(k \rho_i, \nu^*, \beta)$

Zou et al, EPS97

$\Rightarrow (\delta n_k / n)^2 / \rho_i^2$ vs $k \rho_i$

Consistent with gyro-Bohm scaling

$\tilde{n}$ Measured by laser scattering



$\rho_i \sim 0.8$ mm $\pm .2$ B=3.8T

1.05 mm $\pm .2$ B=1.8T

Hennequin et al, PPCF04

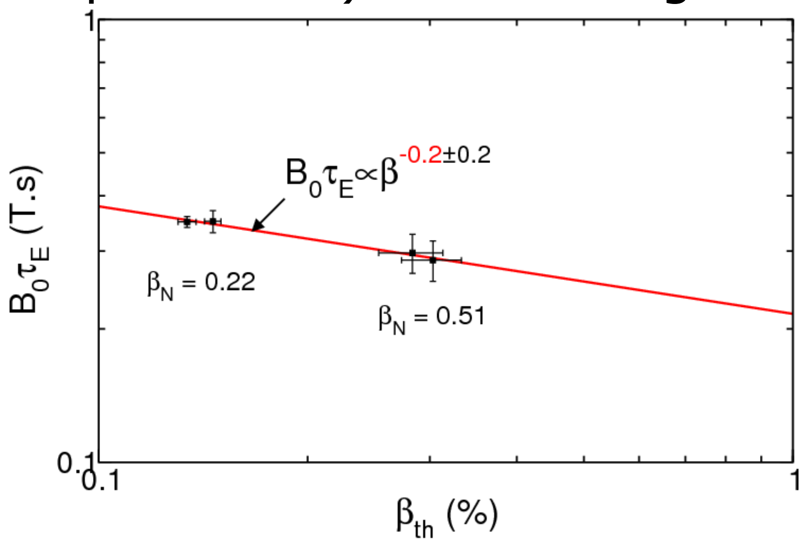
weak dependance of turbulence and transport with β on Tore Supra

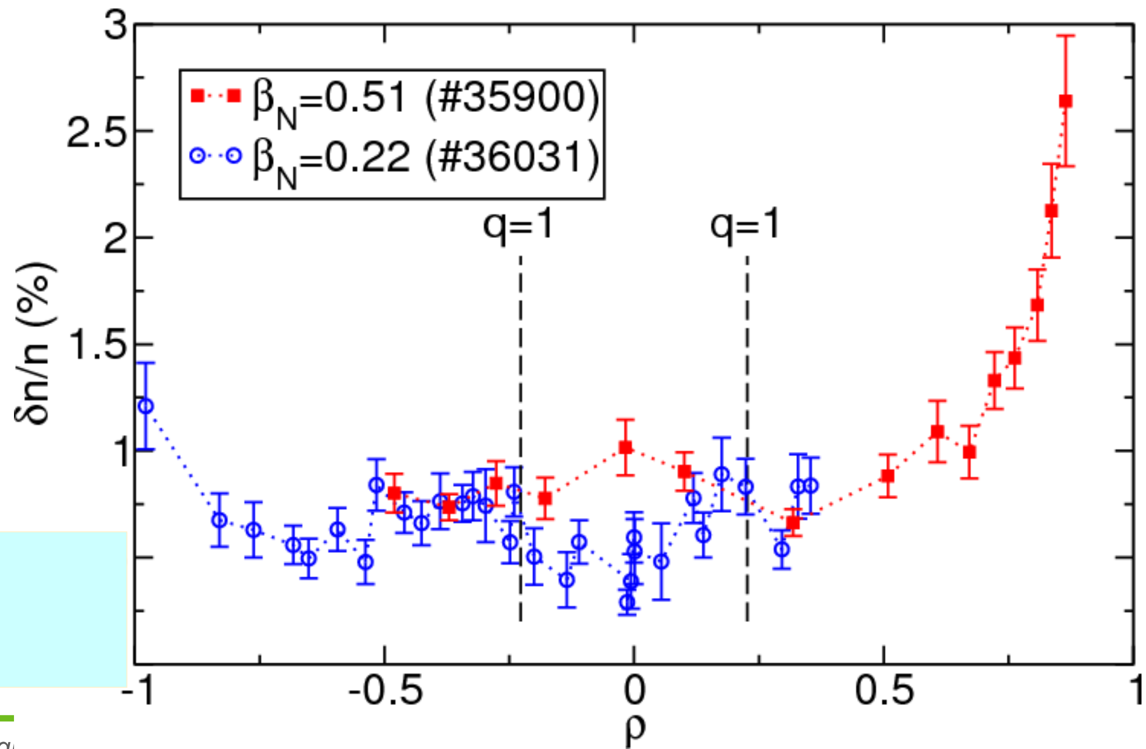
•ITER H-mode dimensionless scaling law predicts **degradation with β**

$$B_0\tau_E^H \propto \rho_*^{-2,70}\beta^{-0,90}\nu_*^{-0,01}M^{0,96}q^{-3,0}\epsilon^{0,73}\kappa^{2,3}$$

- **but** weak dependence observed on JET and DIII-D $\propto\beta^{0.0\pm0.1}$ (dedicated similarity experiments) while strong on JT-60U

- **β scaling in L mode in TS**
- β x2 profile
- similar profile ρ*, ν*





weak τ_E degradation / no change in δn

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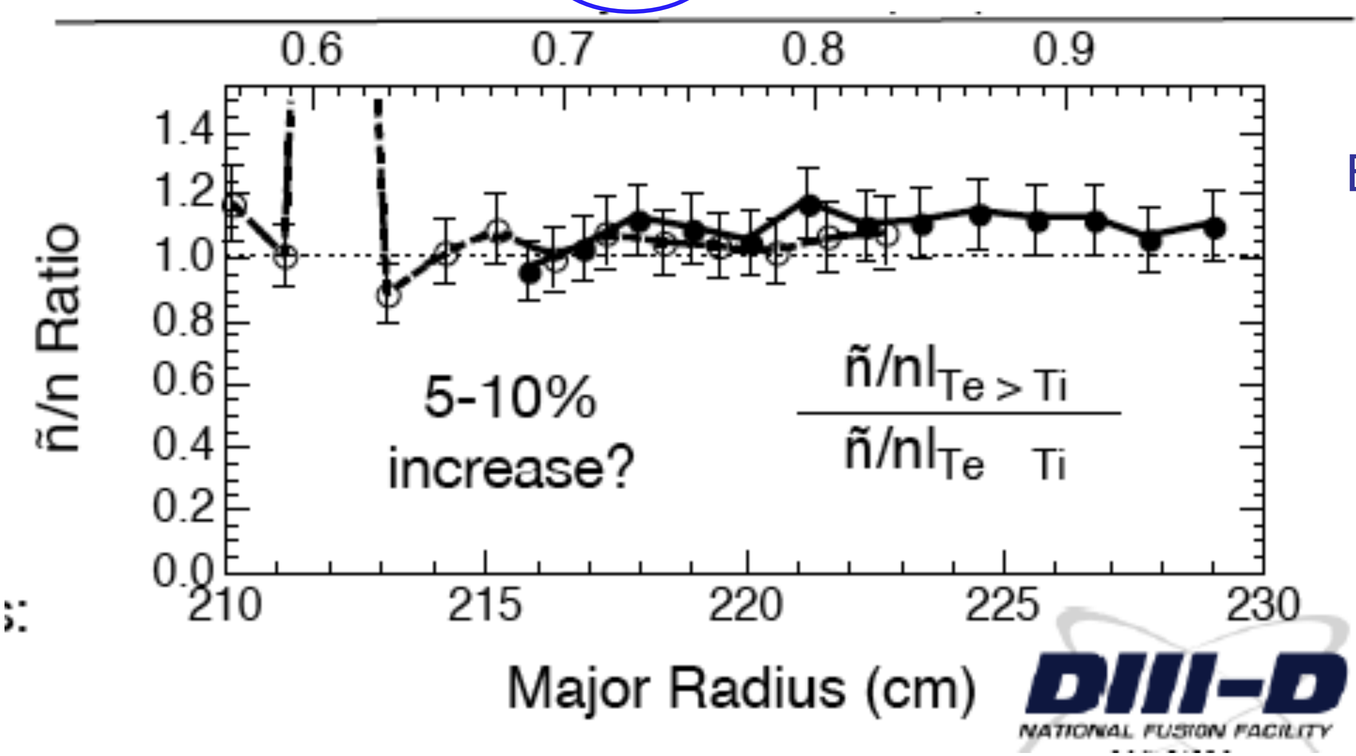
further experiments to explore non- dimensional parameters dependence

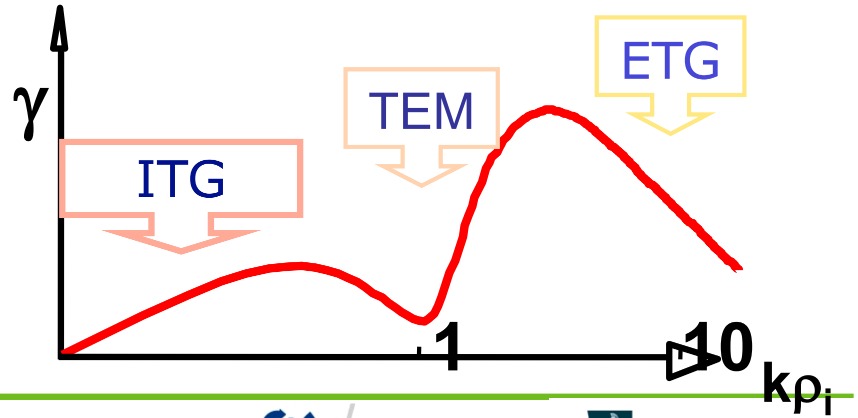
- β dependence still controversial
- Attempts on DIIID, BES lack of sensitivity
- On going ν*, Te/Ti, q scaling on several machines



But increase of transport

outline

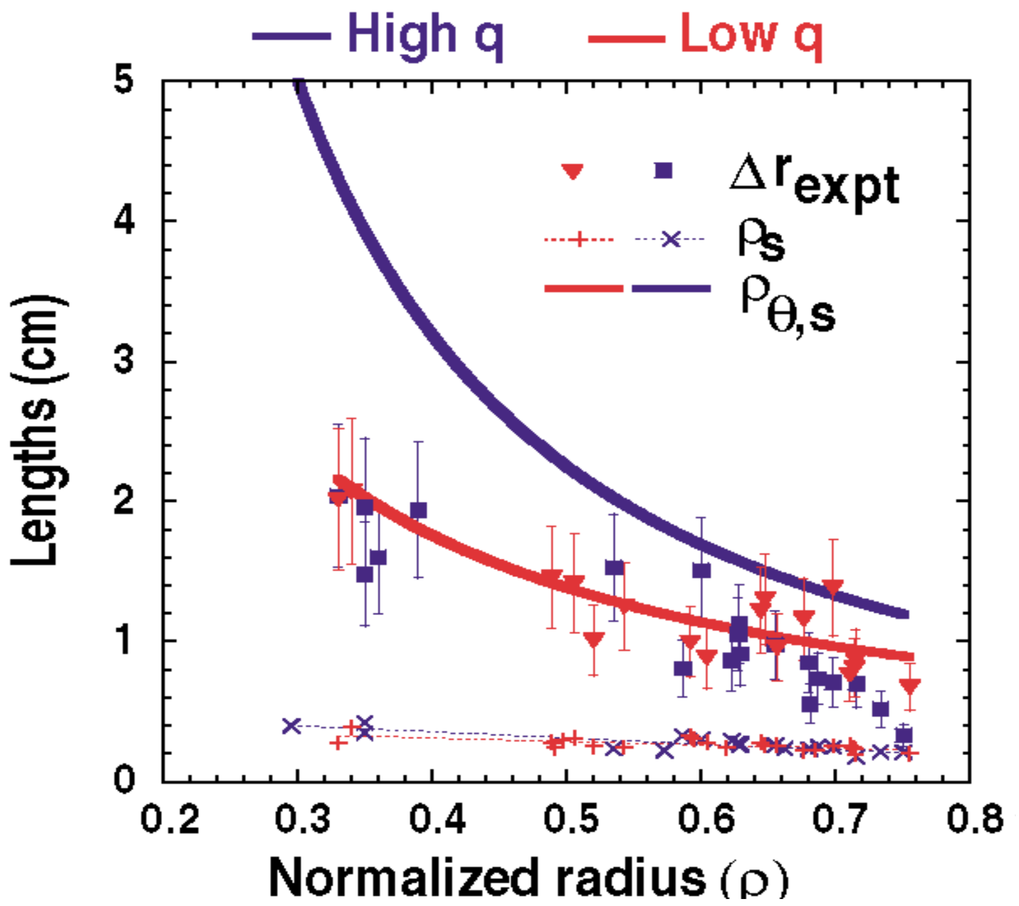
- Introduction/Motivation
  - Fluctuations measurements required for validating transport models and predictions
  - Which measurements are available in the plasma core? (selected):
    - ✓ *Reflectometry, Beam Emission Spectroscopy, EM wave scattering*
- Scaling laws of turbulence and transport
  - Introduce dimensionless parameters: $\rho_{L,}$ β…
- Identification of turbulence scales and times
  - Large scales dominate, linked with Larmor radius
  - Role of small scales
    - wave number spectrum shape



- Identification of structures

Radial correlation lengths scale with ρ_i

•Measured by correlation reflectometry



JET, TFTR, T10, NSTX

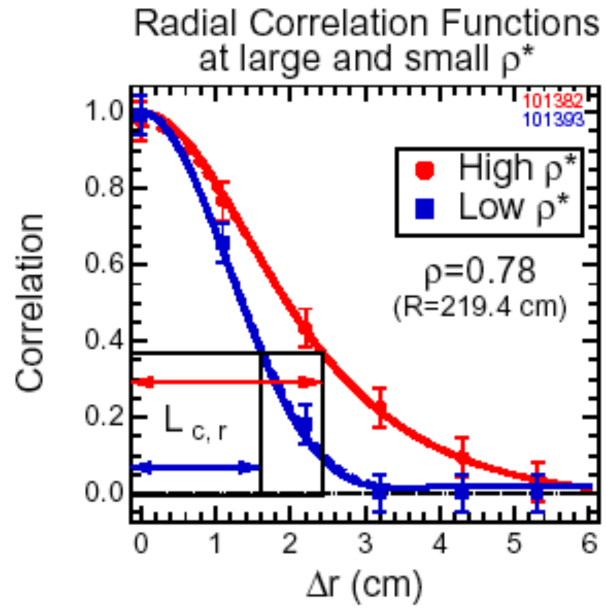
⇒ In the range **$L_c \sim 5 - 10\ \rho_s$**

Rhodes et al., EPS 00

• Little dependence on *q*

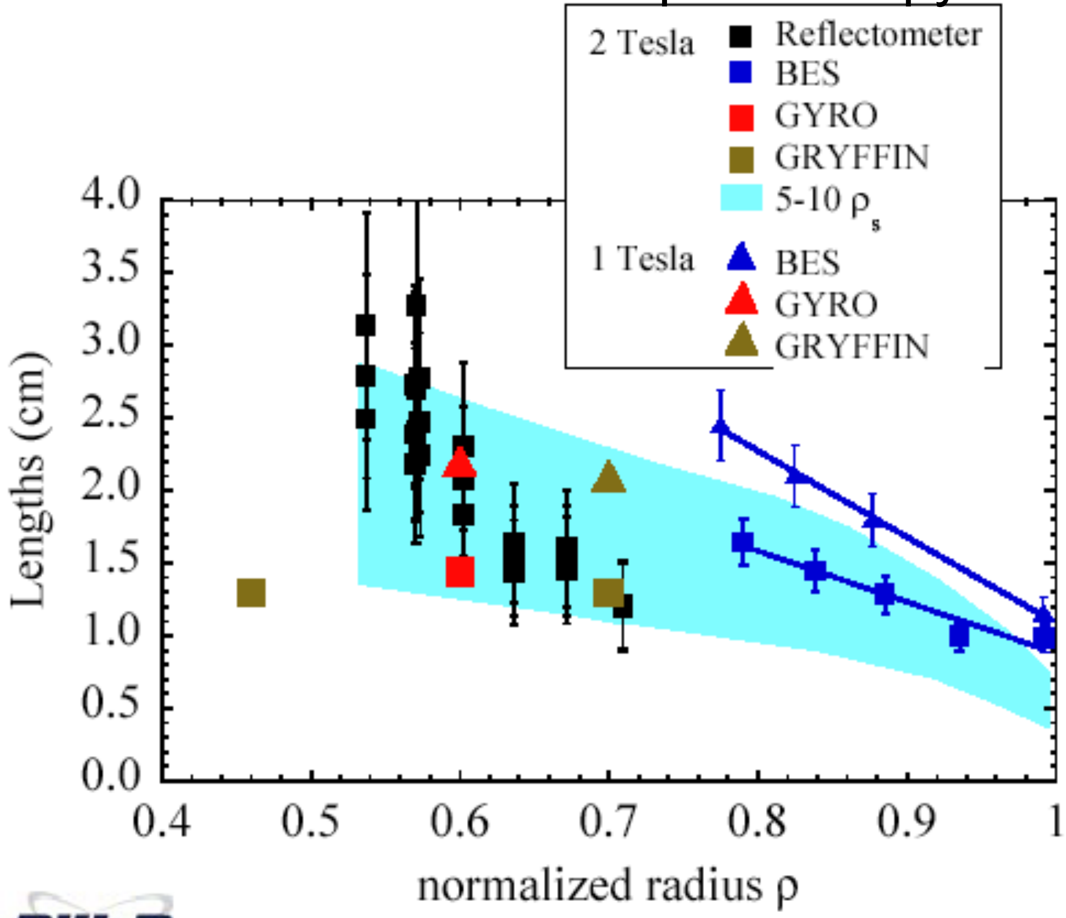
-> **ρ_s, not ρ_θ**

• *consistent with BES scaling with* ρ_i



Radial correlation lengths scale with ρ_i

•Measured by correlation reflectometry and Beam Emission Spectroscopy



17

$\Rightarrow$ In the range **$L_c \sim 5 - 10\ \rho_s$**

Rhodes et al., EPS 00, PoP02

• different radial positions

• Consistency between measurements and simulations gyro-fluid and gyro-kinetic predictions

$\Rightarrow$ radial scale lengths scale with ρ^*

$\Rightarrow$broken by flow shearing

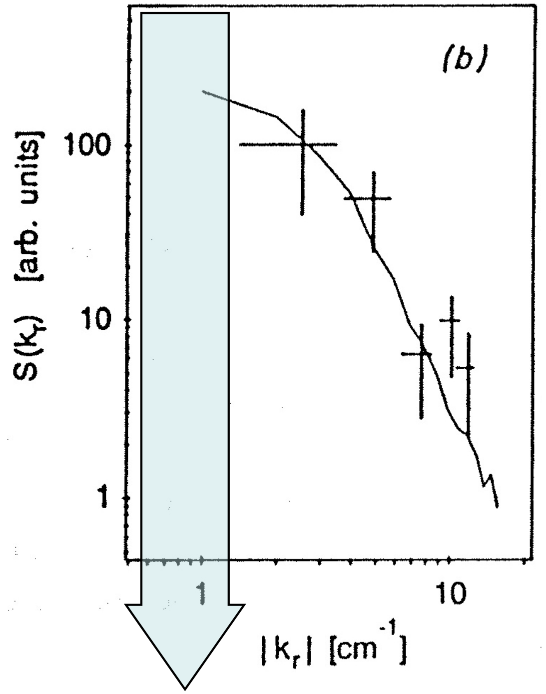
JET, TFTR, T10, NSTX

Fluctuations are mainly at low *k*

- early scattering measurements $\Rightarrow k\rho_i < 1$

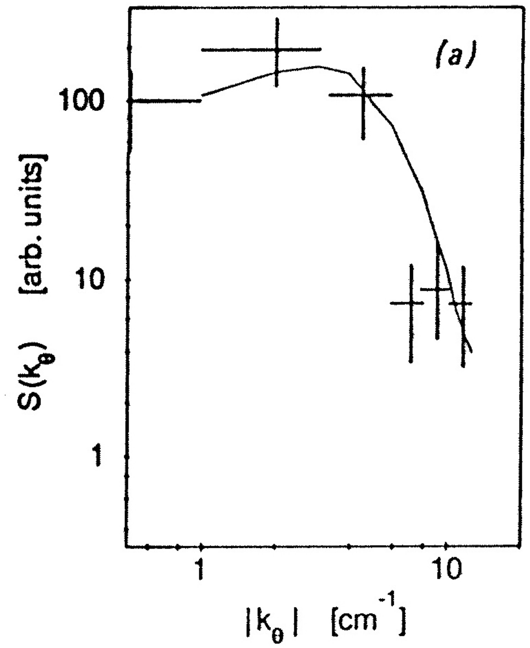
ATC, PLT, TFR, TCA (PCI)…

- asymmetry in the perpendicular plane k_r , k_θ



TEXT

Brower 85, Ritz 87



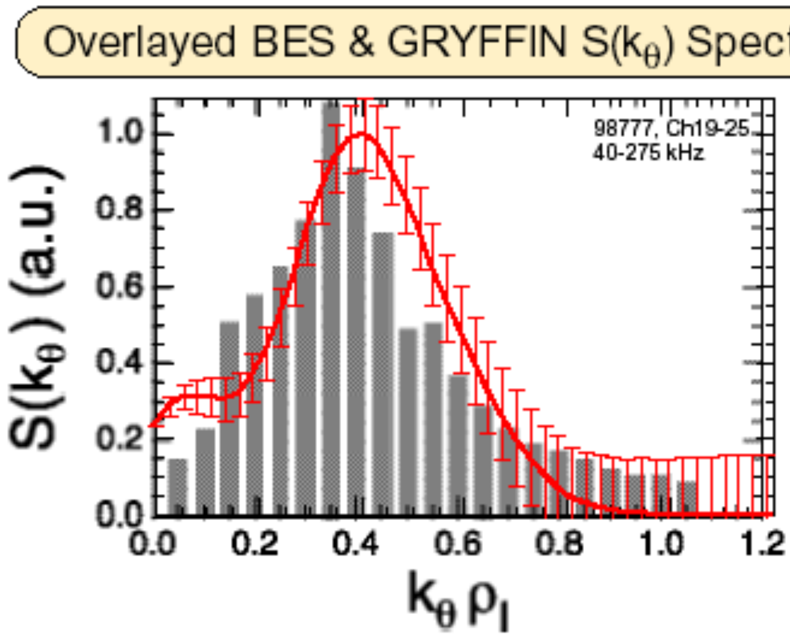
local measurements developed for reaching long scales:
Reflectometry, beam emission spectroscopy…

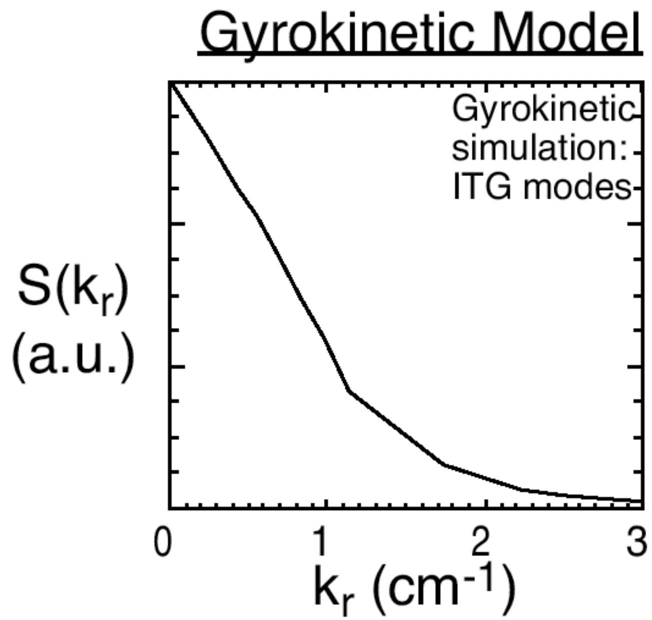
Structure of Fluctuations at low *k*

asymmetry of eddy structure in the poloidal plane at low *k*

$k_\theta \rho_i \sim 0.3$ $k_r \rho_i \sim 0.1$

DI





TFTR

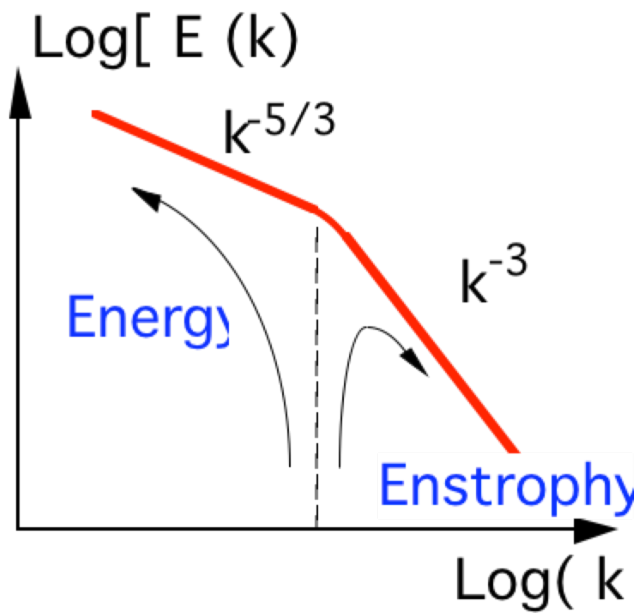
McKee NF 2001
Ross PoP 2002

Fonck et al, PRL 1993
Parker et al, PRL1993

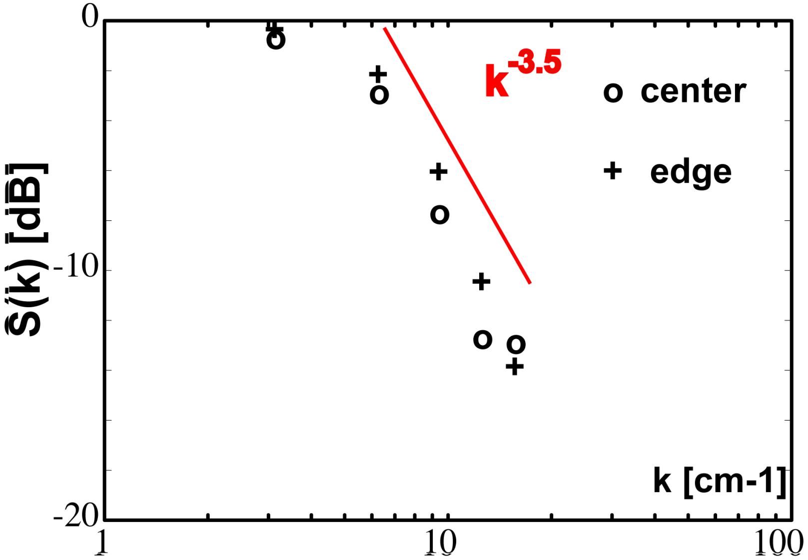
Agreement with numerical simulations

Wave number spectrum characterizes non-linear interaction between modes

- 3D Fluid Turbulence:
  - Kolmogorov direct energy cascade
    Kinetic Energy $E(k)=<v_k^2> \sim k^{-5/3}$
- 2D Fluid turbulence:
  - Inverse energy cascade leads to the formation of large scale structures (streamers/zonal flows)
- Magnetized plasma turbulence:
  - strong anisotropy induced by large B $\Rightarrow$ 2D.
  - 1 field isotropic 2D simplified picture
  - inertial range



Spectral power law in the medium *k* range



- In the range 3 < k < 15 cm $^{-1}$

  power law $S_n(k) \sim k^{-a} \rightarrow a \sim 3.5 \pm 0.5$

  Measured by CO_2 scattering
  F. Gervais et al., EPS92

- spectral index $a \sim 4 \pm 1$ for most experiments

- Simulations

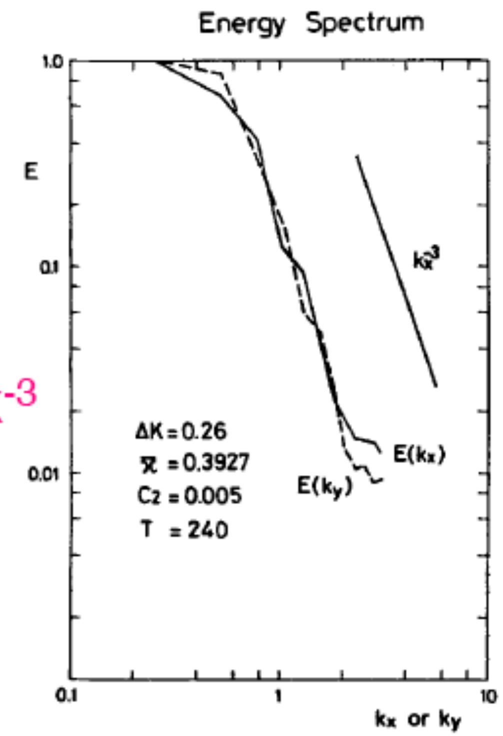
  $S_E(k) \sim k^{-a} \rightarrow a \sim 3$

  Hasegawa Wakatani PRL83

  $E_k(k) = 1/2(n_k^2 + k^2\varphi_k^2) \propto k^{-3}$

Inverse cascade:
mode condensation at low *k*

Horton RMP99
Scott, Jenko PoP99

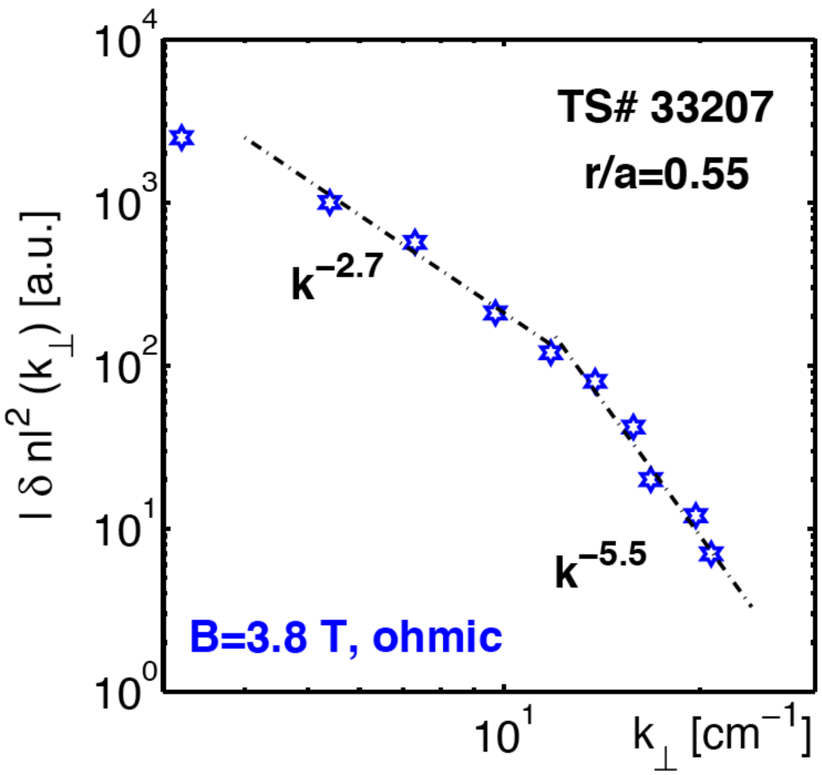


Transition in the *k*-spectrum at high *k*

in ohmic and L mode

- Usual power law
  - $S(k) \sim k^{-3\pm 0.5}$ for $k < 10\ cm^{-1}$
- Fast decrease at higher *k*:
  - $S(k) \sim k^{-6\pm 1}$

Doppler reflectometry



Hennequin et al, Nuc Fus 2006

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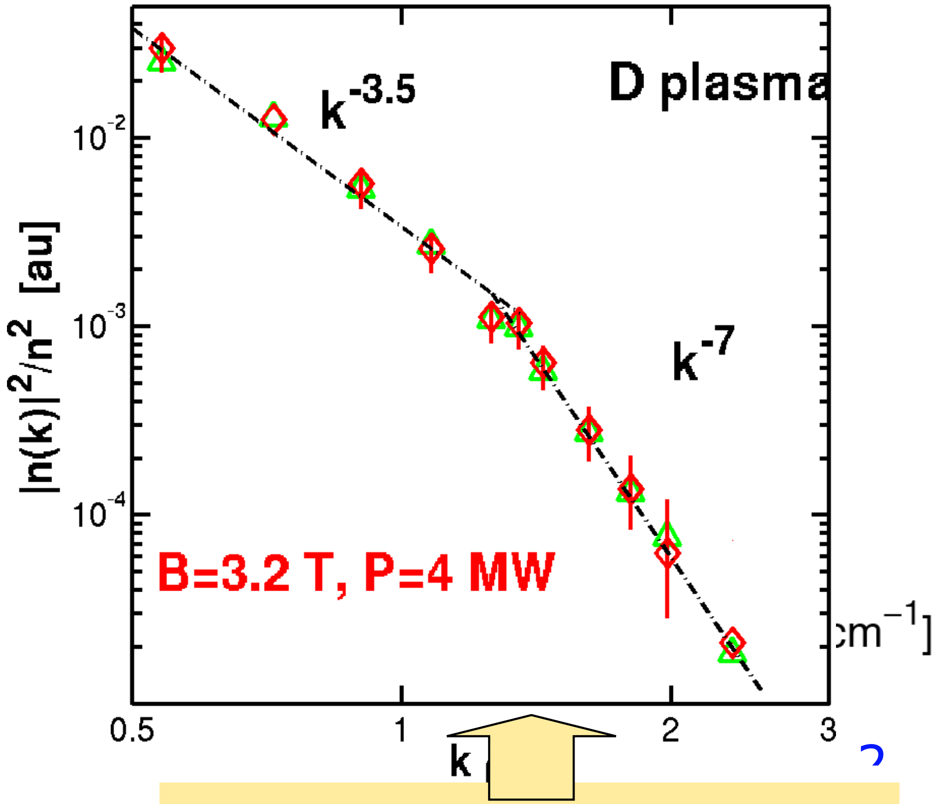
Transition in the *k*-spectrum at high *k*

in ohmic and L mode

- Usual power law
  - $S(k) \sim k^{-3 \pm 0.5}$ for $k < 10\ cm^{-1}$
- Fast decrease at higher *k*:
  - $S(k) \sim k^{-6 \pm 1}$
- Transition linked with Larmor radius
- No high *k* component visible
  in the *k* and *f* range of measurement
- Similar to previous results with CO_2 laser scattering experiment on Tore Supra *Hennequin PPCF04*

laser scattering



$1 < k\ \rho_i < 2$ at the transition

ITG TEM ETG

- Very Low Fluctuation Level in the high *k* range:
  - ETG expected in this range: account for transport ?

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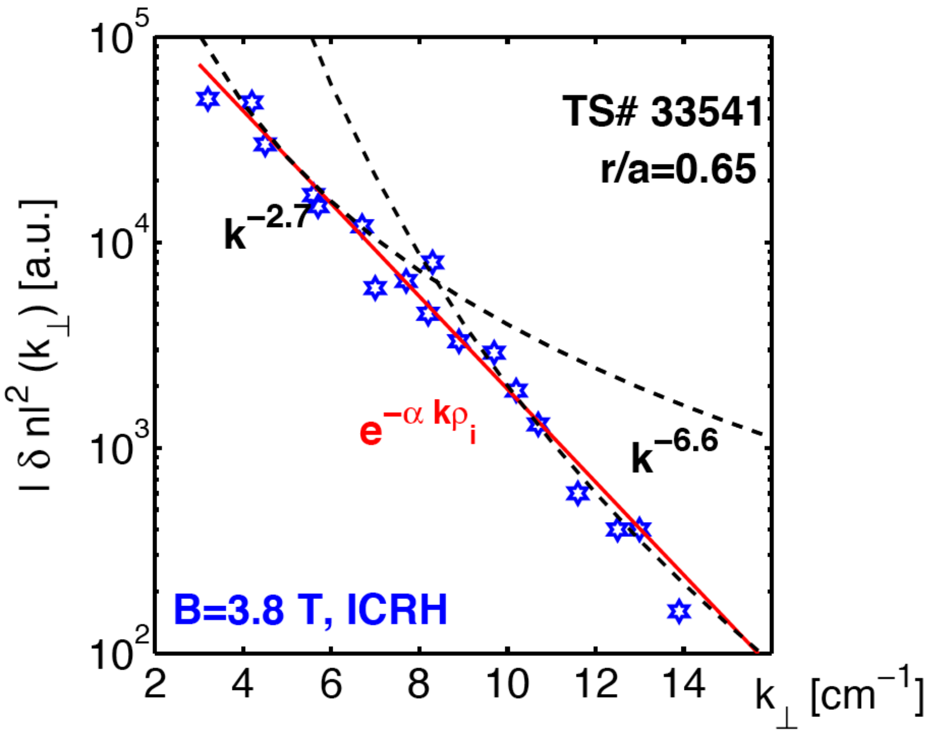
Transition in the *k*-spectrum : evidence of a characteristic scale?

- Similar to 2D turbulence ?
  - direct and inverse cascade
  - but ≠slopes and k_c at the transition

- $S(k) \sim e^{-k\lambda_c}$ better than usual power law
  - $S(k) \sim e^{-4k\rho_i}$

laser scattering



Transition in the *k*-spectrum : evidence of a characteristic scale?

- Similar to 2D turbulence ?
  - direct and inverse cascade
  - but ≠slopes and k_c at the transition

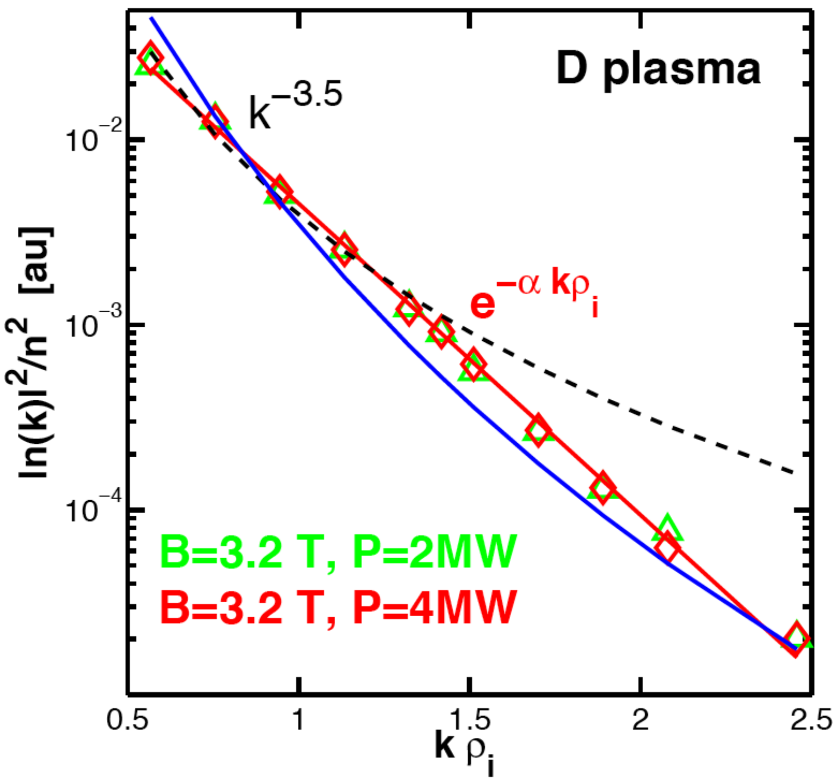
- $S(k) \sim e^{-k\lambda_c}$ better than usual power law
  - $S(k) \sim e^{-4k\rho_i}$

- No inertial range? Scale separability
- Change in the nature of turbulence ?
- NL interaction DW-ETG?
- Finite Larmor radius effect ? $k\rho_i > 1$

Hasegawa-Mima, Horton

$$S(k) \sim \frac{k^{-3}}{(1+k^2\rho^2)^2}$$

laser scattering



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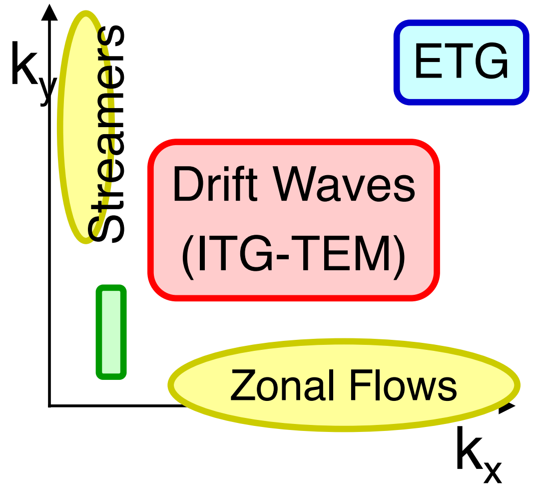
sommaire

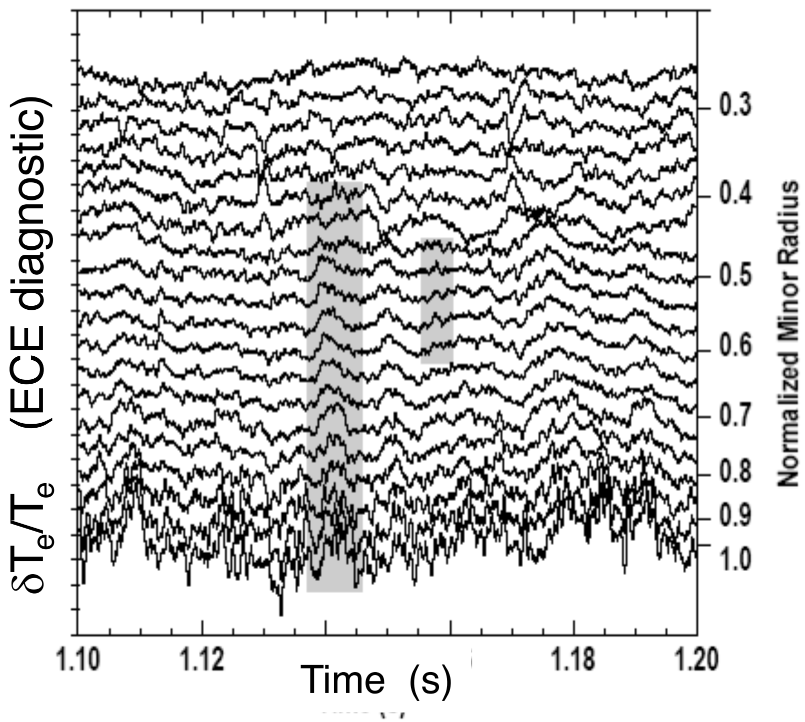
- Introduction/Motivation
  - transport turbulent valider les prédictions
  - quelles mesures dans le cœur du plasma
- Identification des échelles de la turbulence
  - Domination des grandes échelles et lien avec le
  - Rôle des petites échelles et lien avec le rayon c
    - Transition dans le spectre en k?
- Lois de similitude du transport et de la turbule
  - Paramètres sans dimension $\rho_{L,}$ β
  - Fluctuation level scaling with gyroradius ρ_L
- Identification et rôle des structures dans le transport

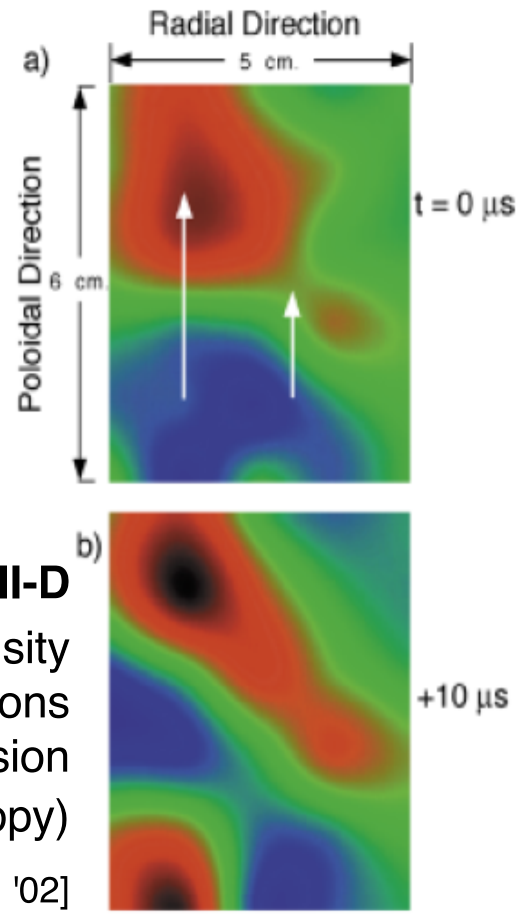


Avalanches & turbulence spreading

- Avalanches = fast ($\tau << \lambda^2/\chi$) transport
  on large radial scale ($\lambda >> \lambda_{corr}$)
- streamers and blobs observed in the edge

DIII-D [Politzer '00]





DIII-D

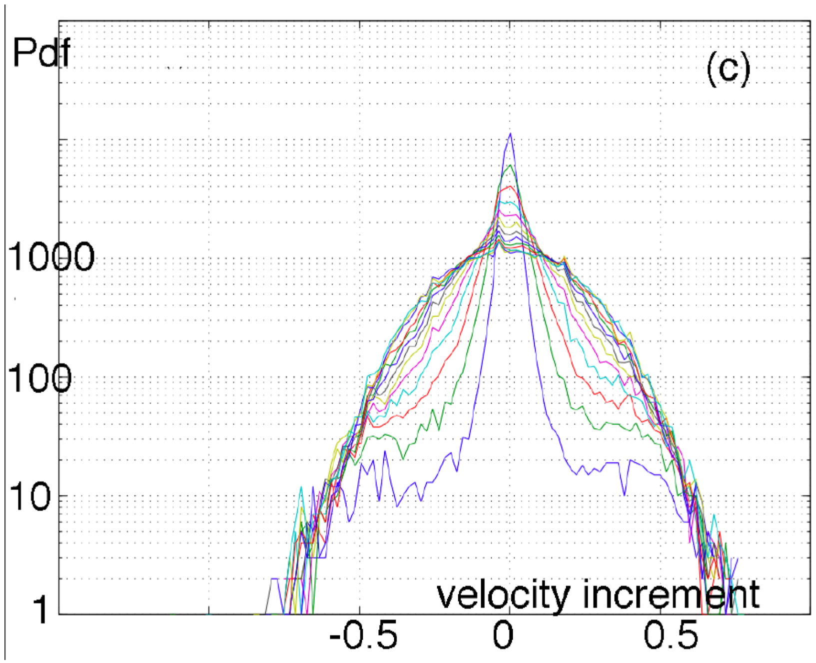
Density fluctuations (Beam Emission Spectroscopy)

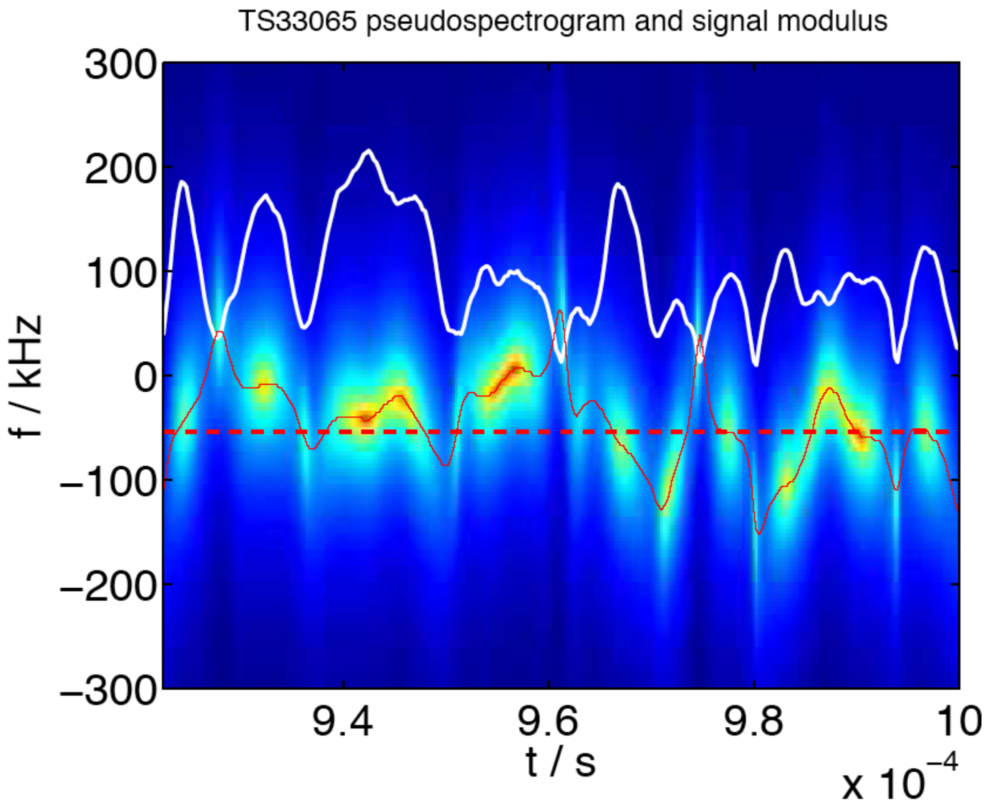
[McKee '02]

Identification and dynamics of structures

- Fluctuations as plasma movement tracers
- *Parametric Method ≠ Fourier for instantaneous velocity mesurement*

Velocity Histogram identical to Doppler spectrum





- Mixing and transport from Lagrangian velocity correlation function
- Structure functions and velocity increments

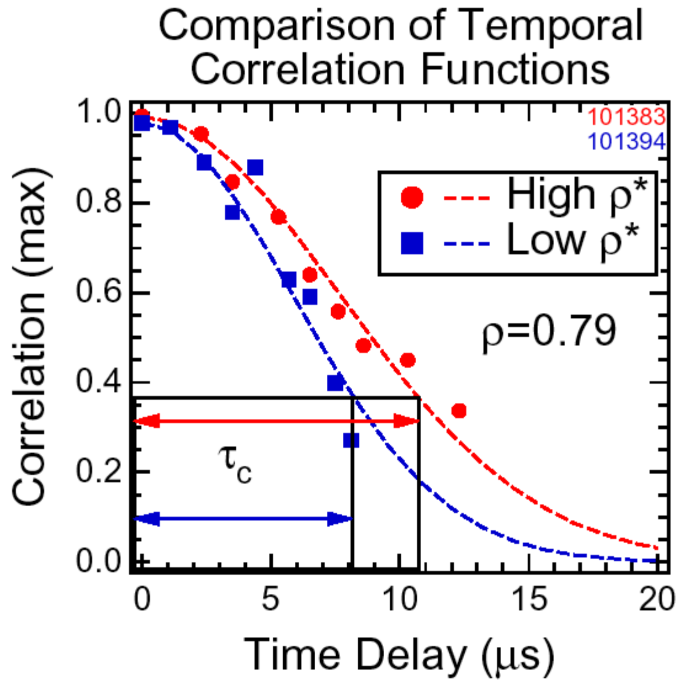
- Introduction/Motivation
  - How can turbulence measurements help to validate predictions?
- Similarity analysis to investigate Bohm/gyro-Bohm behaviour
  - Fluctuation level scaling with gyroradius ρ_L
- How are governed the turbulent scales?
  - Large scales scaling with gyroradius
  - *k* spectra: transition at small scales ?
  - Correlation time scaling with transit time a/c_s

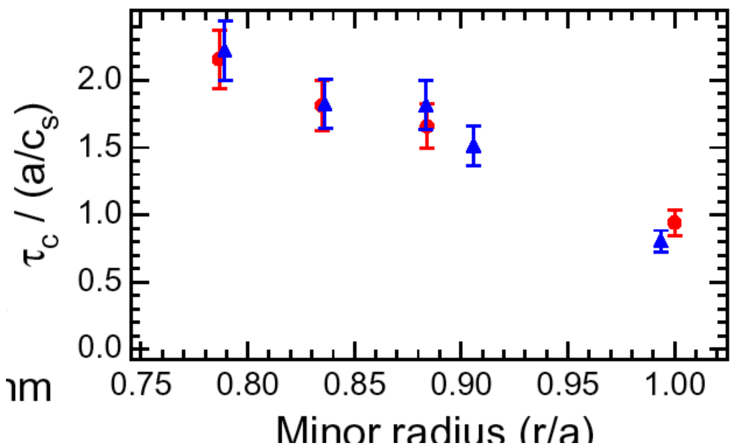
Correlation time scales with transit time a/c_s

- Dedicated DIIID similar discharges with ρ_i scan

➢ Consistent with a gyro-Bohm like scaling

McKee, Nuc Fus (2001)





Correlation time scales with transit time a/c_s

- Dedicated DIIID similar discharges with ρ_i scan

➢ Consistent with a gyro-Bohm like scaling

McKee, Nuc Fus (2001)

- Tore Supra B scan experiments

  Hennequin EPS04

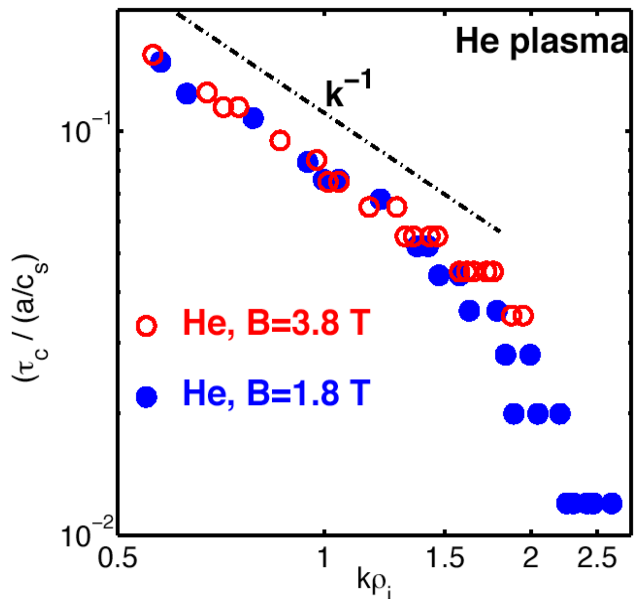
- Signal auto-correlation time : $\tau_c \equiv k^{-1}$

  $\tau_c \equiv$ eddy turnover time

  – Kolmogorov $\tau_c \equiv k^{-2/3}$

  – Sweeping of small scales by large scales

  [Kraichnan 58, 65]



Concluding remarks

- Needs for turbulent transport direct evaluation in the core

Correlated multi-field measurement **$\tilde{n}$, v_r , ϕ , δT**

few tokamak equipped with complementary diagnostics:

Reflectometry	**$\tilde{n}$**	small *k*	n profile, B dependant
Scattering	**$\tilde{n}$, v_θ**	med to high *k*	spatial localisation
cross polarisation scattering	**$\tilde{n}$, δB**	med to high *k*	access
beam emission spectroscopy	**$\tilde{n}$, v_r , v_θ**	small *k*	neutral beam
phase contrast imaging	**$\tilde{n}$**	small to med *k*	chord average
ECE	**δT**	small *k* long time	integration, statistics
heavy ion beam probe	**$\tilde{n}$, ϕ , δT, j**	"	access

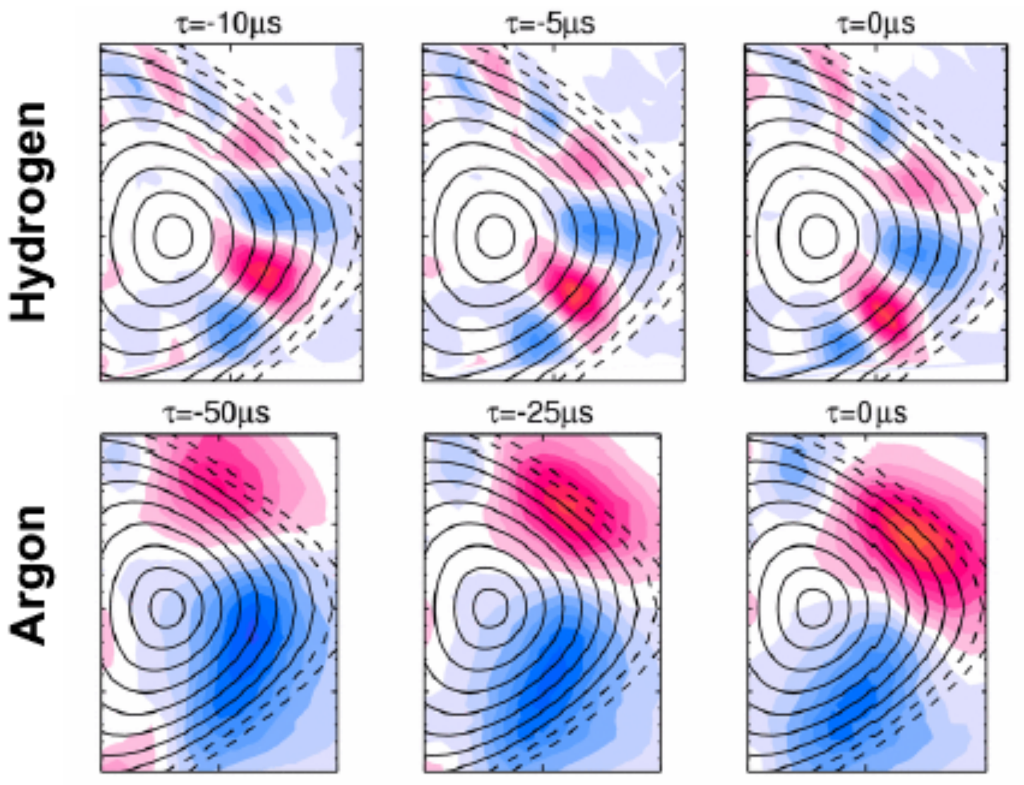
- Still Investigate stabilisation/regulation mechanisms

  Correlate fluctuation level, eddy size, phase and confinement

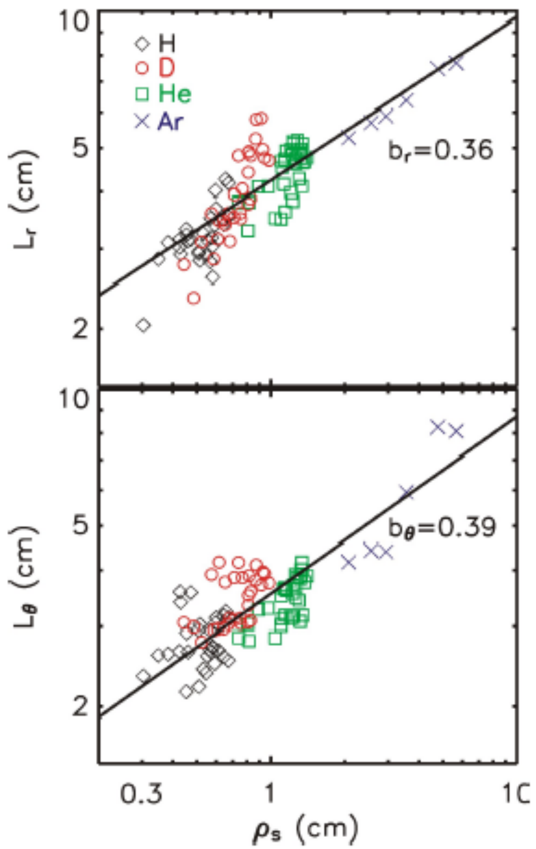
- Structures and their impact on transport

Eddy size scaling with ρ_s

Perpendicular structure of density perturbation



- measured by Langmuir probes array
- ρ_s changed by 10 by changing gaz



Torsatron TJ-K, *Stroth, U-Kiel*

•$L_c \equiv \rho_s^{1/3}$
≠Gyro-Bohm

Rétro-diffusion Doppler dans Tore Supra

P. Hennequin, C. Honoré, A. Truc, A. Quéméneur &al, RSI04

Faisceau μ-onde