On the Physics of the L/H Transition

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Outline

- **Physical (Parameter) Situation**

  — steep gradients, not so fast electron/Alfvén transit frequencies

- **Turbulence**

  — energetics, drift/Alfvén wave foundation, ion grad-T

  — nonlinear scales (spectrum controlled by range with no linear role)

- **Flows**

  — energetics, neoclassical balances, forcing by turbulence, ion grad-T

- **L/H Transition and why we all blew it**

  — lots of insight in the 1995-7 data we should still face

  — parameter scalings in turbulence computations

  — effect of nonlinear scales $\rightarrow$ beta scaling incompatible with experiments

Parameter Situation in the Edge

- meanings of steep gradients — parallel dynamics

$$\frac{qR}{L_T} > \sqrt{\frac{M_D}{m_e}}, \sqrt{\frac{1}{\beta_e}} \qquad \Longrightarrow \qquad \frac{c_s}{L_T} > \frac{v_A}{qR} \qquad \frac{c_s}{L_T} > \frac{V_e}{qR}$$

- meanings of steep gradients — drift dynamics (drift wave vorticity $\omega_t \sim \omega_*$)

$$\frac{\rho_s}{L_T} > \frac{L_T}{R} > \frac{L_T}{qR} \qquad \Longrightarrow \qquad \text{vorticity} \gg \text{bounce/sound in entire spectrum}$$

- disparate scale lengths — besides R/L_T of several tens we have

$$\frac{a}{L_T} \gtrsim 10 \qquad \text{not} \qquad \frac{a}{L_T} \gtrsim 1$$

- hence $qR > R > a \gg L_T \gg \rho_s$ also (consider trapping) $\sqrt{2\epsilon} \sim 1$

parameters affecting electron responses

- typical situation: Alfvén/electron transit, collision, and drift frequencies comparable
- drift frequency is $c_s/L_\perp$, spectral range of main interest is $10^{-2} < k_y\rho_s < 1$
- steep gradient

$$\hat{\mu} \equiv \frac{m_e}{M_D}\left(\frac{qR}{L_\perp}\right)^2 = \left(\frac{c_s/L_\perp}{V_e/qR}\right)^2 \sim 10$$

- collisional

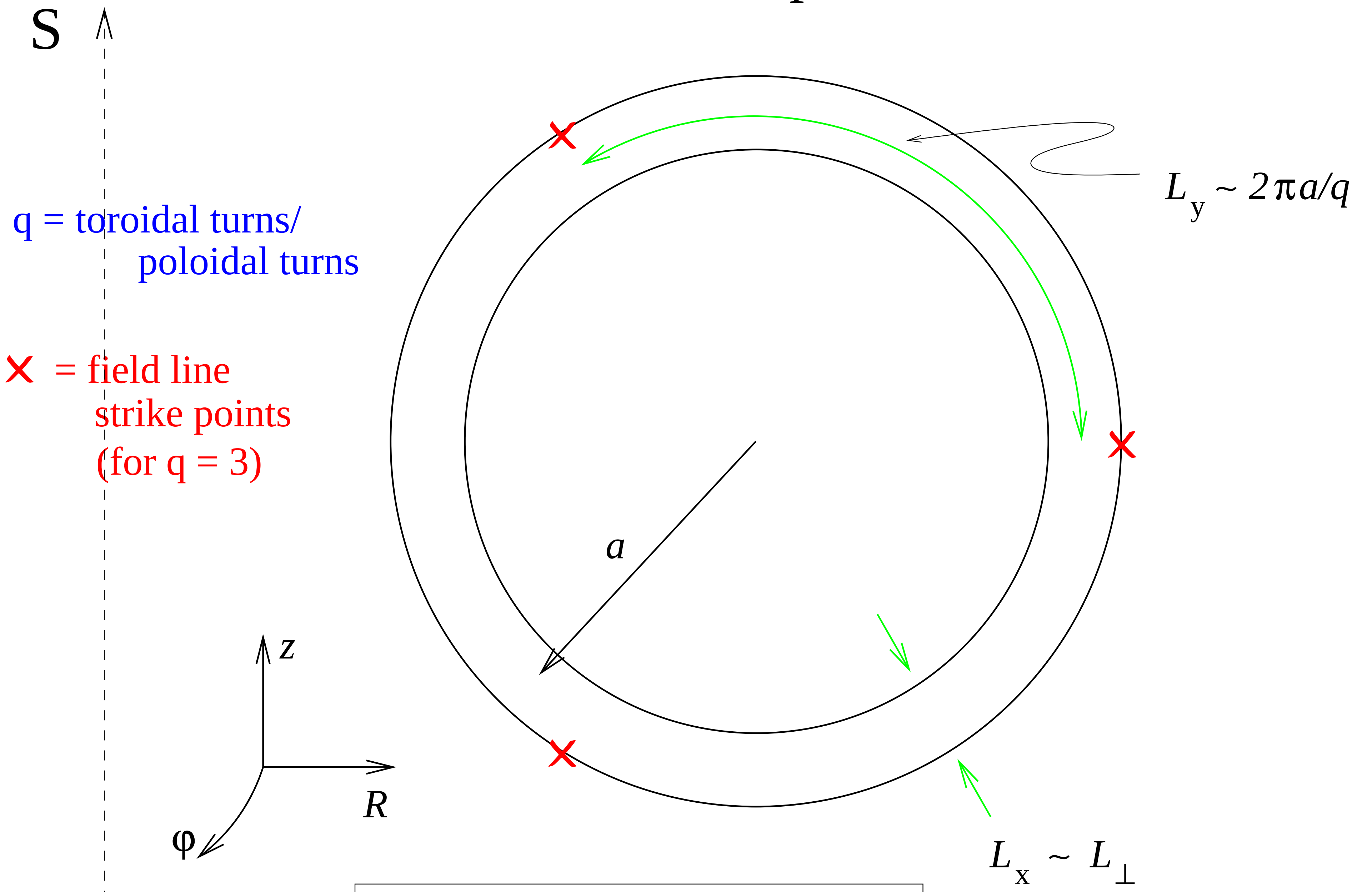
$$C \equiv \frac{0.51\nu_e}{c_s/L_\perp}\frac{m_e}{M_D}\left(\frac{qR}{L_\perp}\right)^2 = 0.51\frac{\nu_e\, c_s/L_\perp}{(V_e/qR)^2} > 1$$

- electromagnetic

$$\hat{\beta} \equiv \frac{4\pi p_e}{B^2}\left(\frac{qR}{L_\perp}\right)^2 = \left(\frac{c_s/L_\perp}{v_A/qR}\right)^2 > 1$$

- these mean drift wave physics trumps instabilities $(\omega_t \sim \omega_* > \gamma_L)$

Computational Domain



large aspect ratio: $L_y >> L_x$

extreme anisotropy of edge domain

- in perp plane $L_x \lesssim L_T$ while $L_y = 2\pi a/q$

- definition of long wavelength component (part forced to be anisotropic)

$$k_y L_T < \pi \qquad \text{viz.} \qquad k_y \rho_s < \pi \frac{\rho_s}{L_T} \lesssim 0.1$$

- drift wave turbulence range (ω_* is diamagnetic, γ_I is ideal interchange)

$$k_y \quad \text{for which} \quad \omega_t > \gamma_I \qquad \text{where} \qquad \omega_t \sim \omega_* = k_y \rho_s \frac{c_s}{L_T} \quad \text{and} \quad \gamma_I = c_s \sqrt{\frac{2}{L_T R}}$$

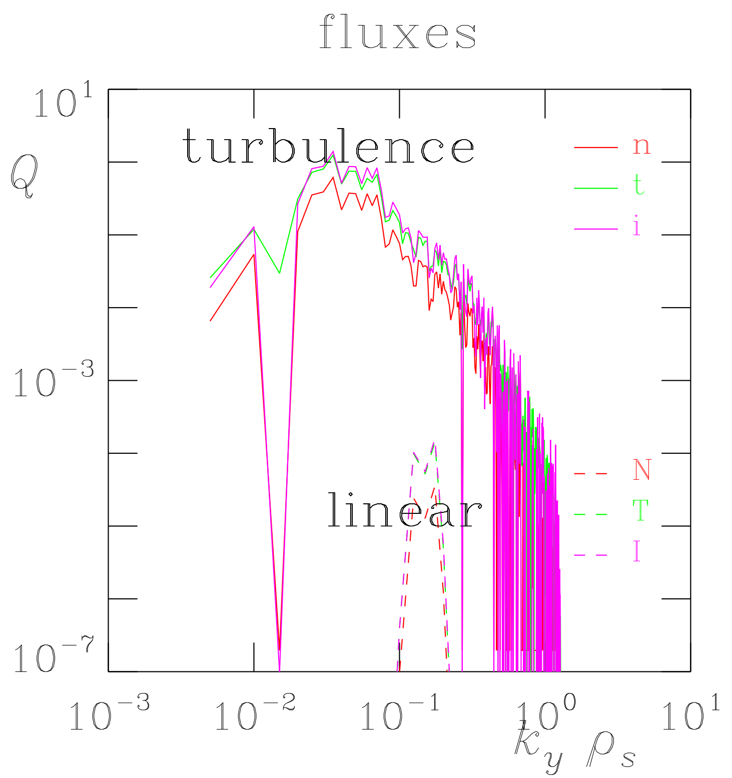
- in practice toroidicity (curvature) induced instabilities have $\gamma_L \sim 0.3$ to $0.5\,\gamma_I$

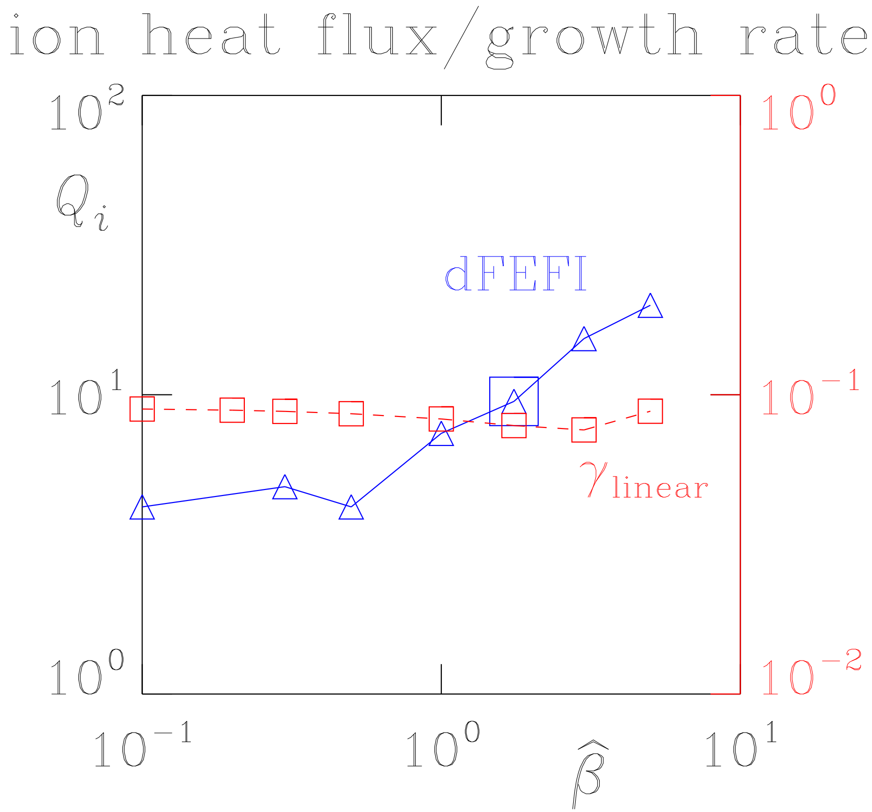
- nonlinear situation: drift wave turbulence $k_y \rho_s > 0.1$
  ◦ but with *nonlinearly driven* long-wave MHD component

- main beta effect: weaker *Alfvén damping* of the MHD component
  ◦ hence stronger, longer-wave turbulence overall

extreme nonlinearity in gyrokinetic edge turbulence

- delta-FEFI L-mode base case ($T = 100\,\mathrm{eV}$): spectra and scaling





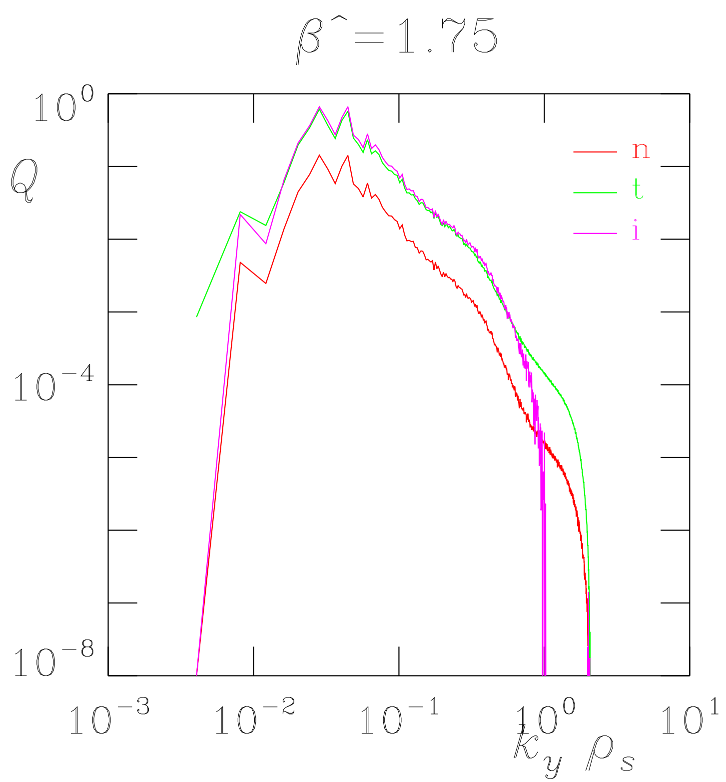
- nonlinear shift almost one order of magnitude

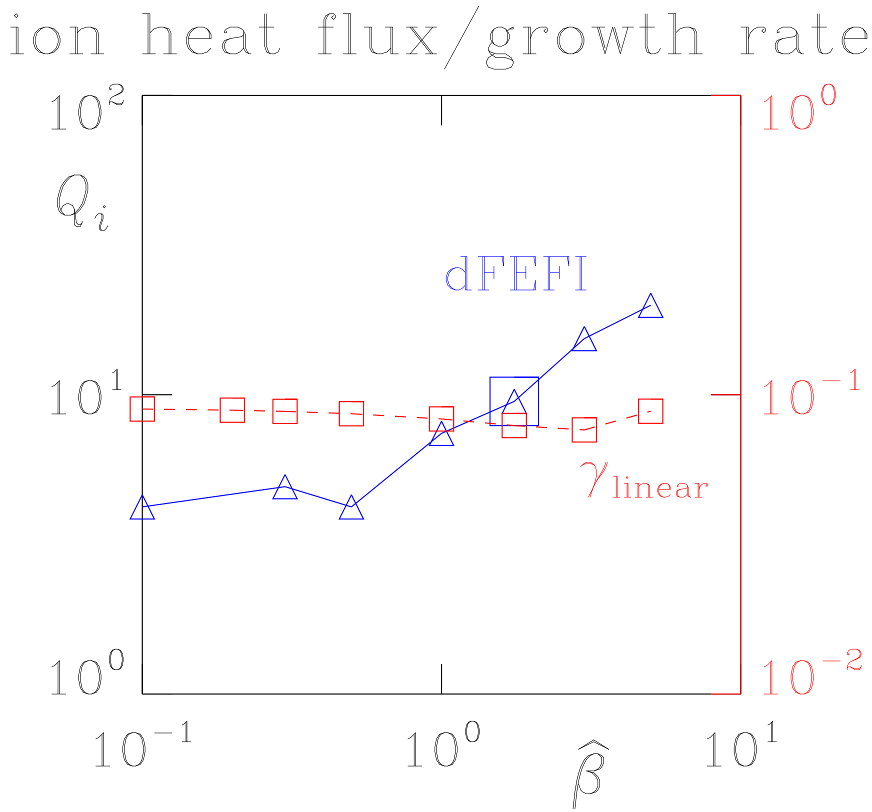
- edge turbulence necessarily involves MHD scales – full flux surface runs needed (2010)

- resulting scaling determined by nonlinear transfer
  - MHD scales weakly driven, but also weakly damped

same picture, turbulent flux time averaged

- delta-FEFI L-mode base case ($T = 100\,\mathrm{eV}$): spectra and scaling





- time average smooths out low-$k_\perp$ dropouts

- full flux surface ($64 \times 1500\rho_s$)
  - ∘ long-wave part involved, also: **medium-wave statistics**

what determines the edge?

- mainly, the first of the conditions: $\hat{\mu} > 1$
- consider the boundary, $\hat{\mu} = 1$

$$\frac{m_e}{M_D}\left(\frac{qR}{L_\perp}\right)^2 = 1$$

- solve this for the profile scale length

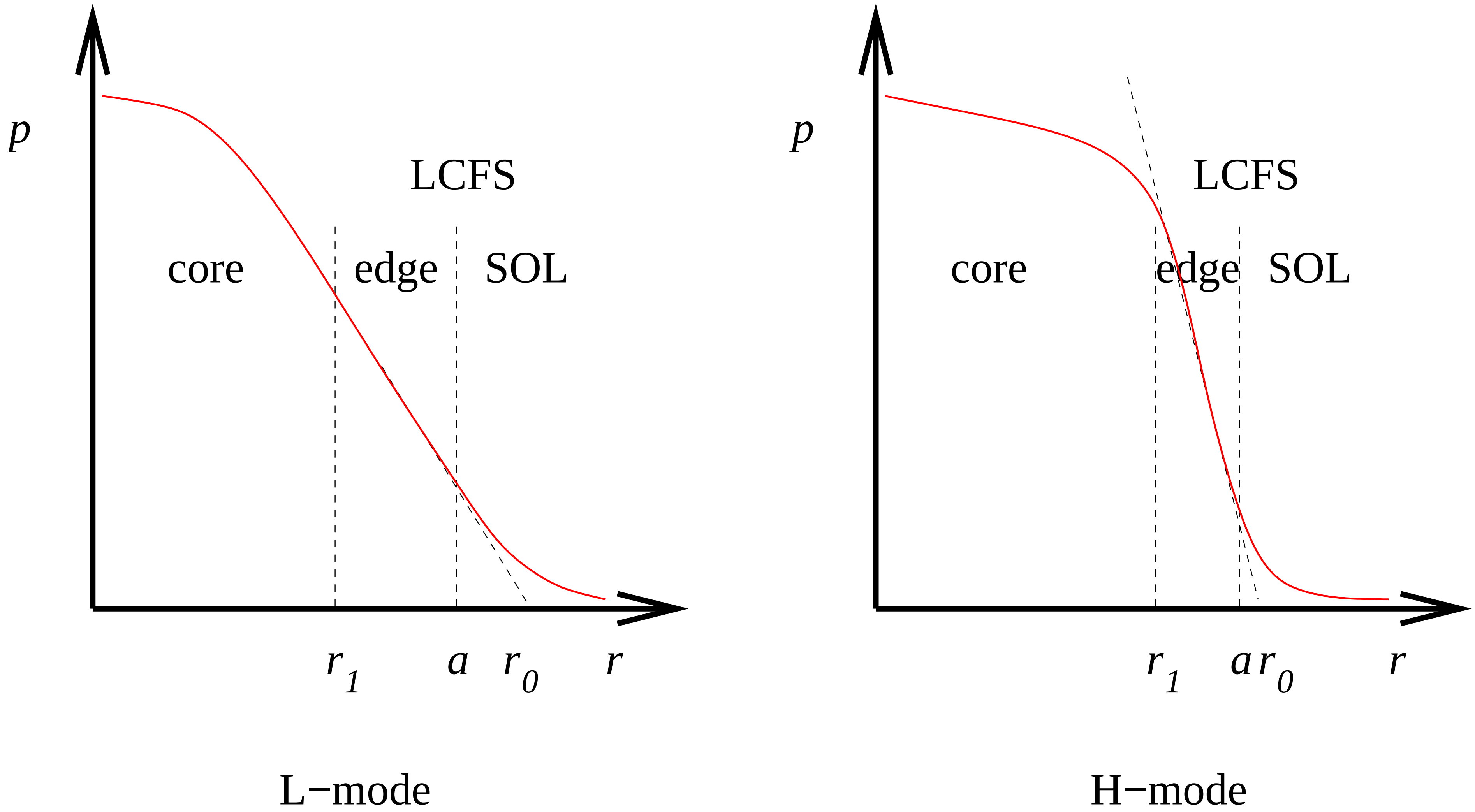
$$L_\perp = \sqrt{m_e/M_D}\, qR$$

- for linear profile gradients this is typically about 8 cm
  - ◦ and it holds over about the last 4 cm within the LCFS

if a pedestal exists, the top is the edge/core boundary

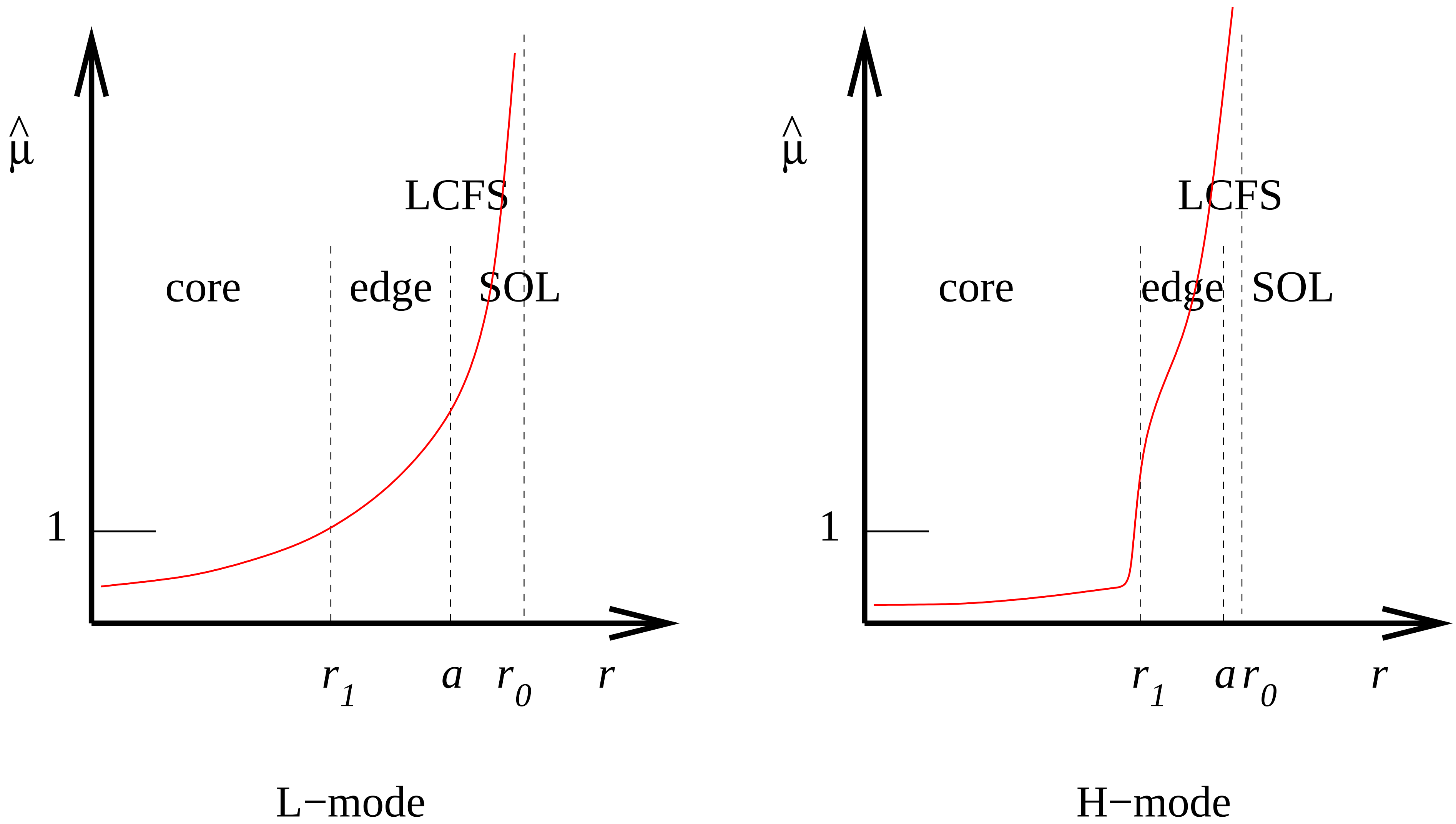
Edge Layer Extent

$\hat{\mu} = 1$ at $r = r_1$

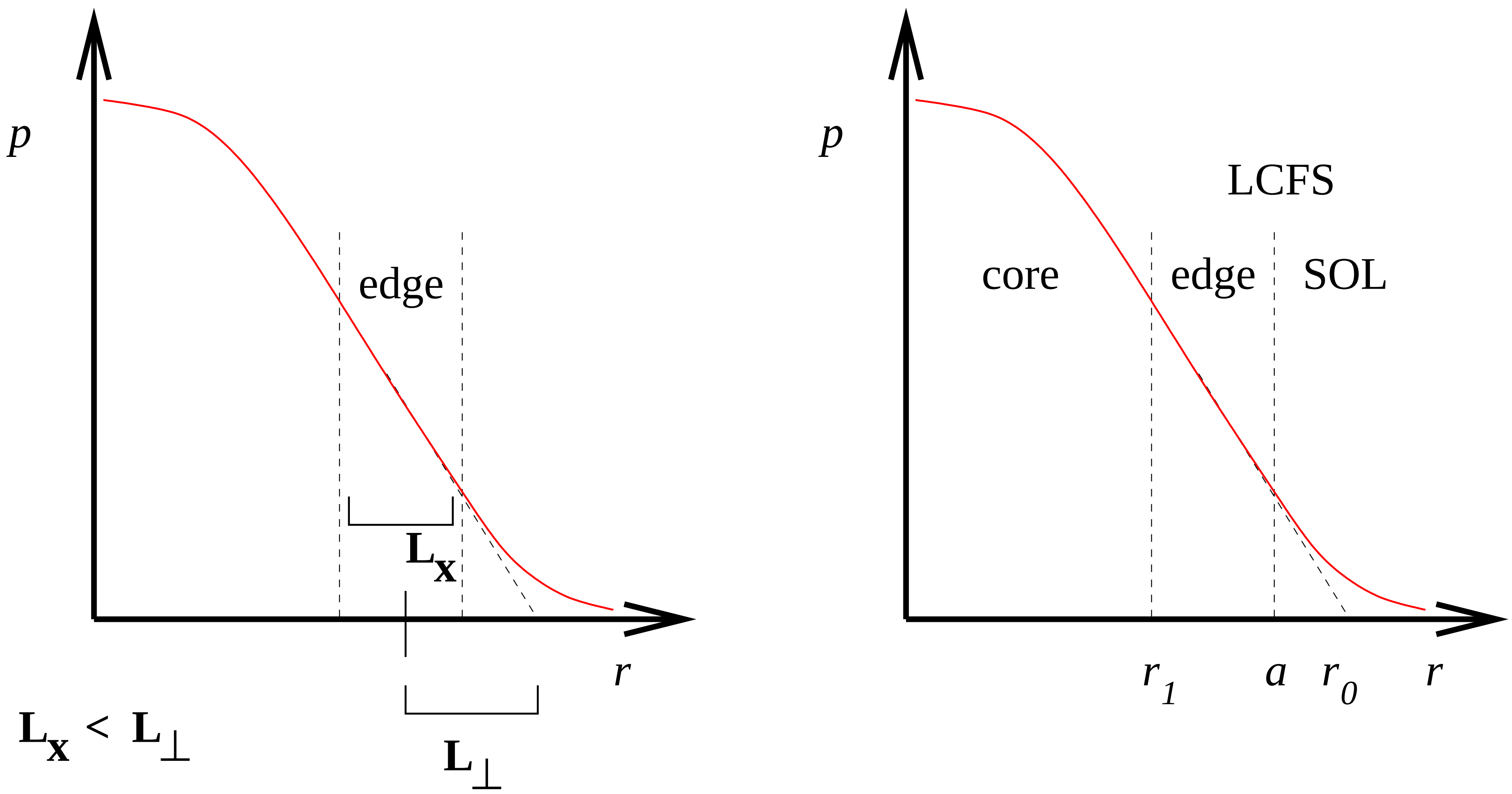


Edge Layer Extent

$\hat{\mu} = 1 \text{ at } r = r_1$



Edge Turbulence Computation Arrangement



Turbulence Properties

- it's really turbulence: no coherent relation between any degrees of freedom
- drift wave turbulence underlies edge turbulence, with special properties ...
- energy transfer goes both ways and it is a cascade
- it is also a *turbulent* cascade
- result of dual energy cascade:

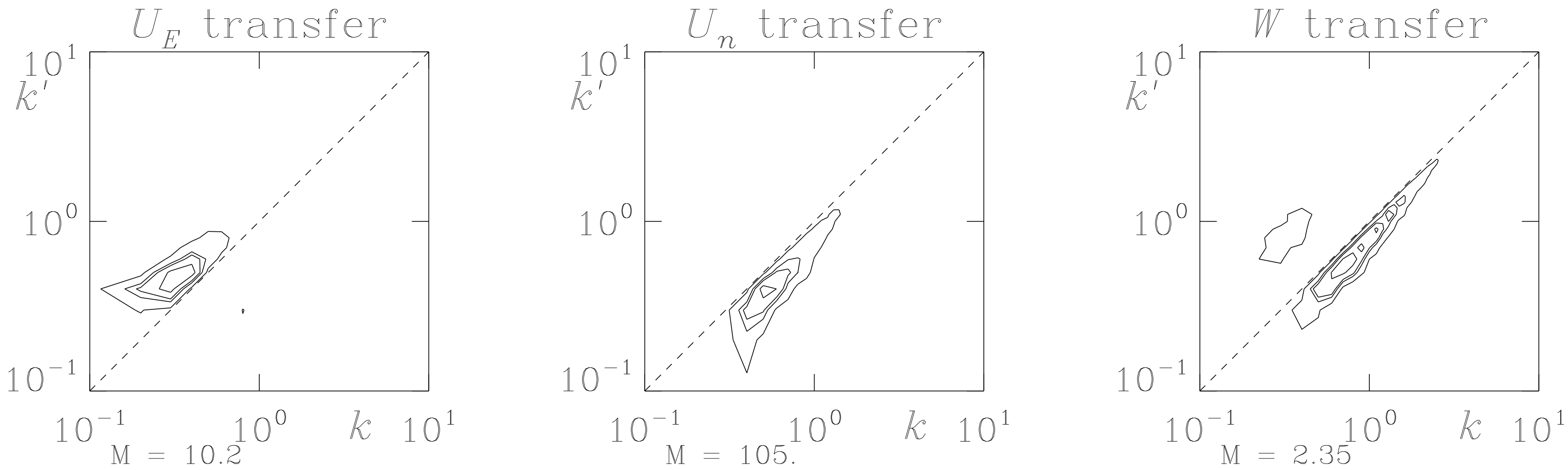
$$\text{eddy vorticity} \quad > \quad \text{drive rate}$$

- consequence: linear eigenmodes don't form, linear scaling does not persist
- we find out these things by measuring nonlinear energy transfer
  ◦ direct statistical diagnosis in the simulation, not in a cartoon of it
- the linear versus nonlinear part comes from direct quantitative comparison
  ◦ energy transfer and drive rates in linear terms, in linear and turbulent phases

energy transfer spectra

(Camargo, Scott, Biskamp, PoP 1995)

- ExB and δf free energy, and mean squared vorticity

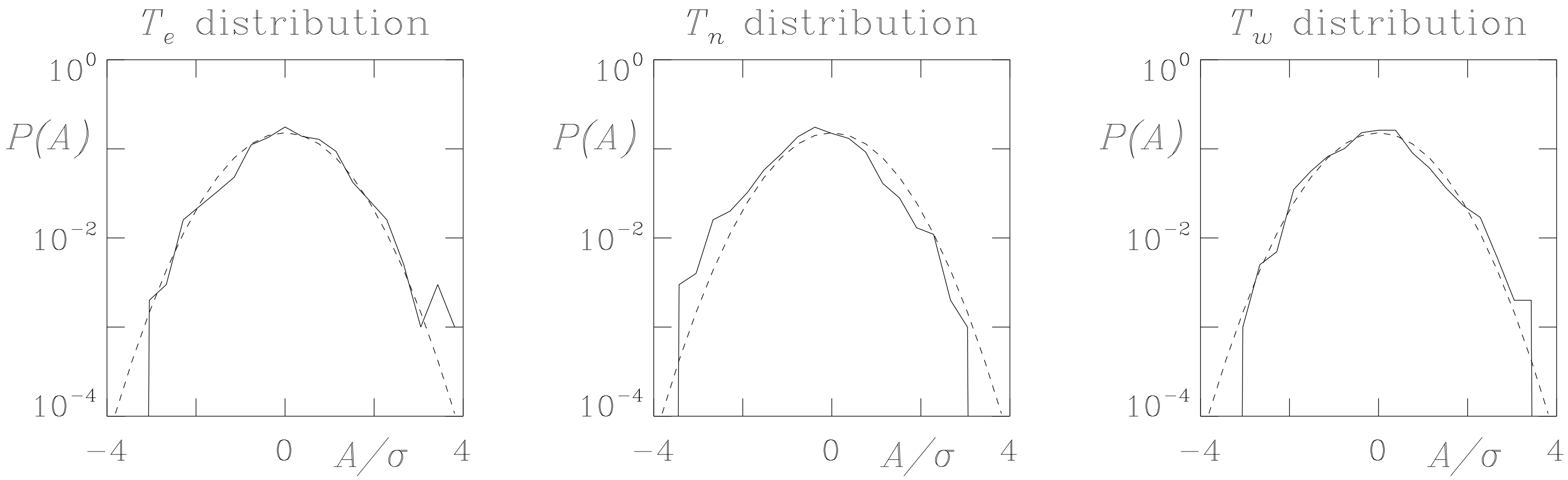


- transfer is from k' to k, shown where positive
- direct cascade for U_n and W, ... inverse cascade for U_E
- cascade dynamics not changed by linear forcing
- this is the indication that the transfer is a local cascade: it's mostly $1/2 < k'/k < 2$

energy transfer statistics

(should have been in B Scott, New J Phys 2002, but wasn't)

- transfer (ExB, δf, vorticity) from $k_y \rho_s \sim 0.5$ to 0.3 in drift Alfvén turbulence

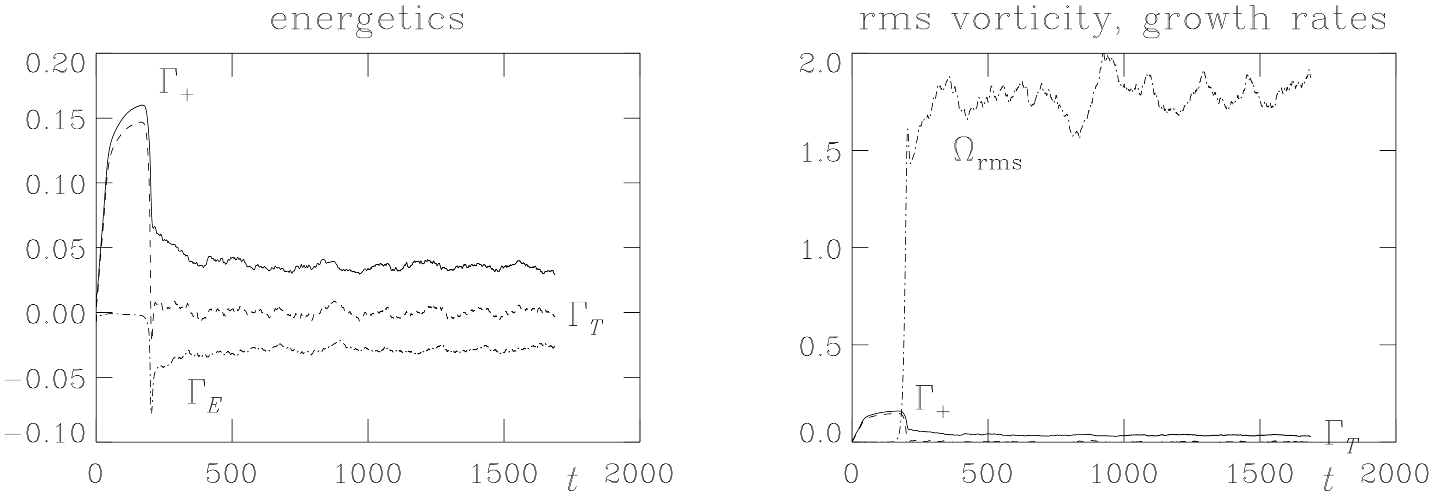


M/σ values: 0.103 -0.255 -0.0504

- Gaussian PDF shape, std dev (σ) always much larger than mean (M)
- this is the indication that the cascade is turbulent

linear to nonlinear (turbulence) transition

(B Scott, Phys Plasmas June 2005)



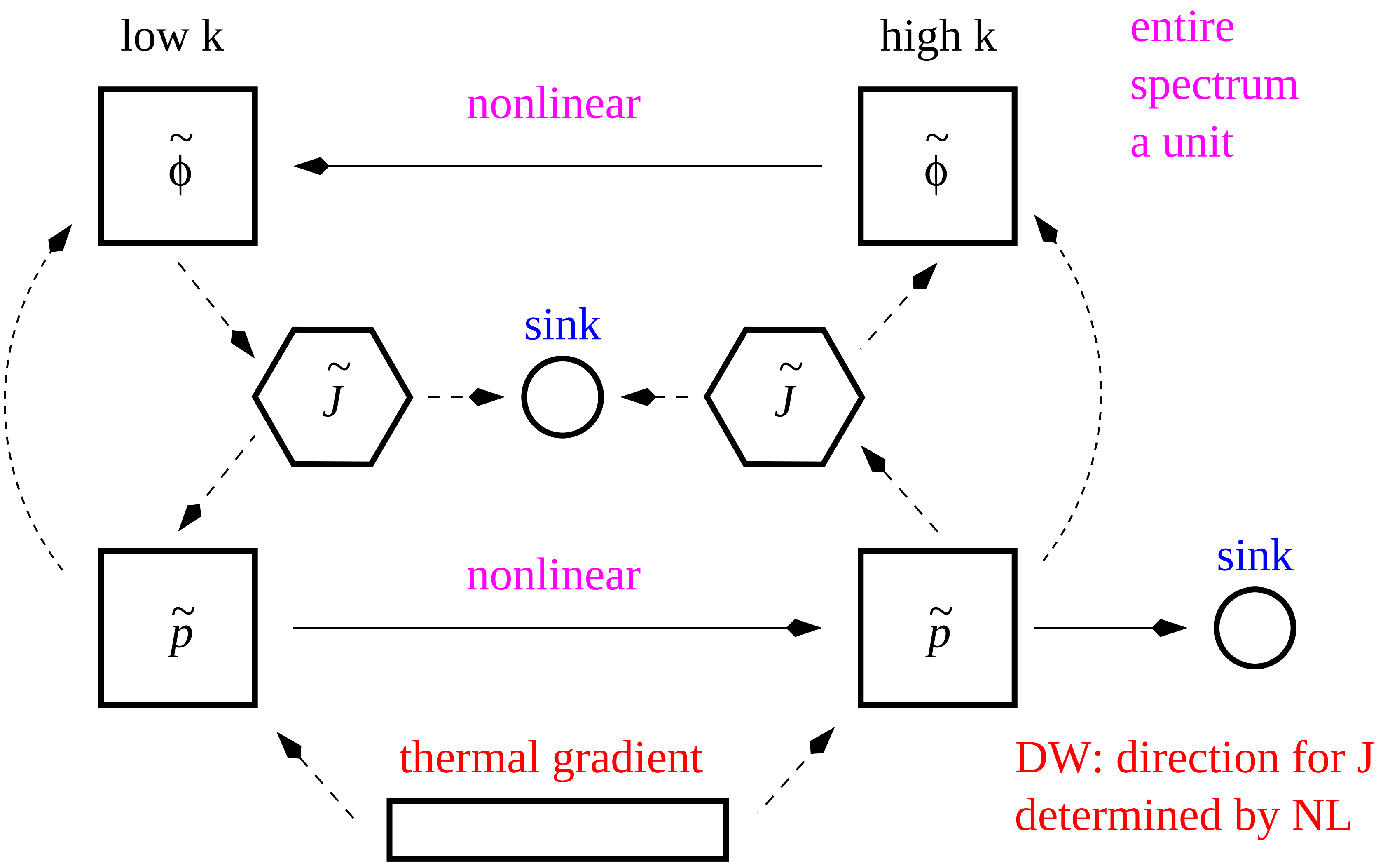
- linear: where growth rate (Γ_T) is near maximum (which defines the linear value γ_L)

- saturation: where Γ_T hits zero

- turbulence: at late times, $\Gamma_T \approx 0$ and the drive rate Γ_+ is smaller than γ_L
  ◦ lots of energy is in stable modes, maintained by the turbulence

- RMS vorticity is much larger than γ_L or Γ_+

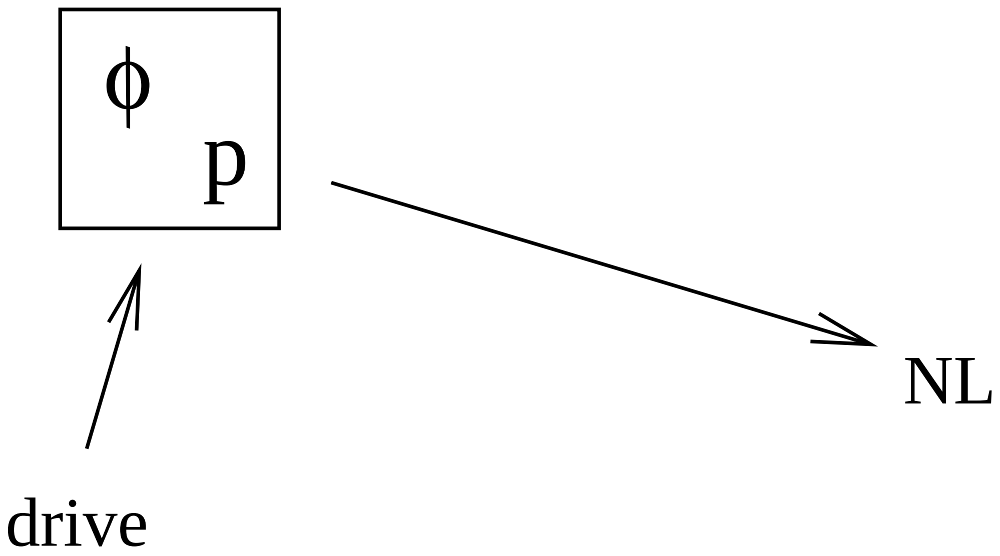
Energy Transfer: electromagnetic turbulence



(B Scott Phys Fluids B 1992, Plasma Phys Contr Fusion 1997)

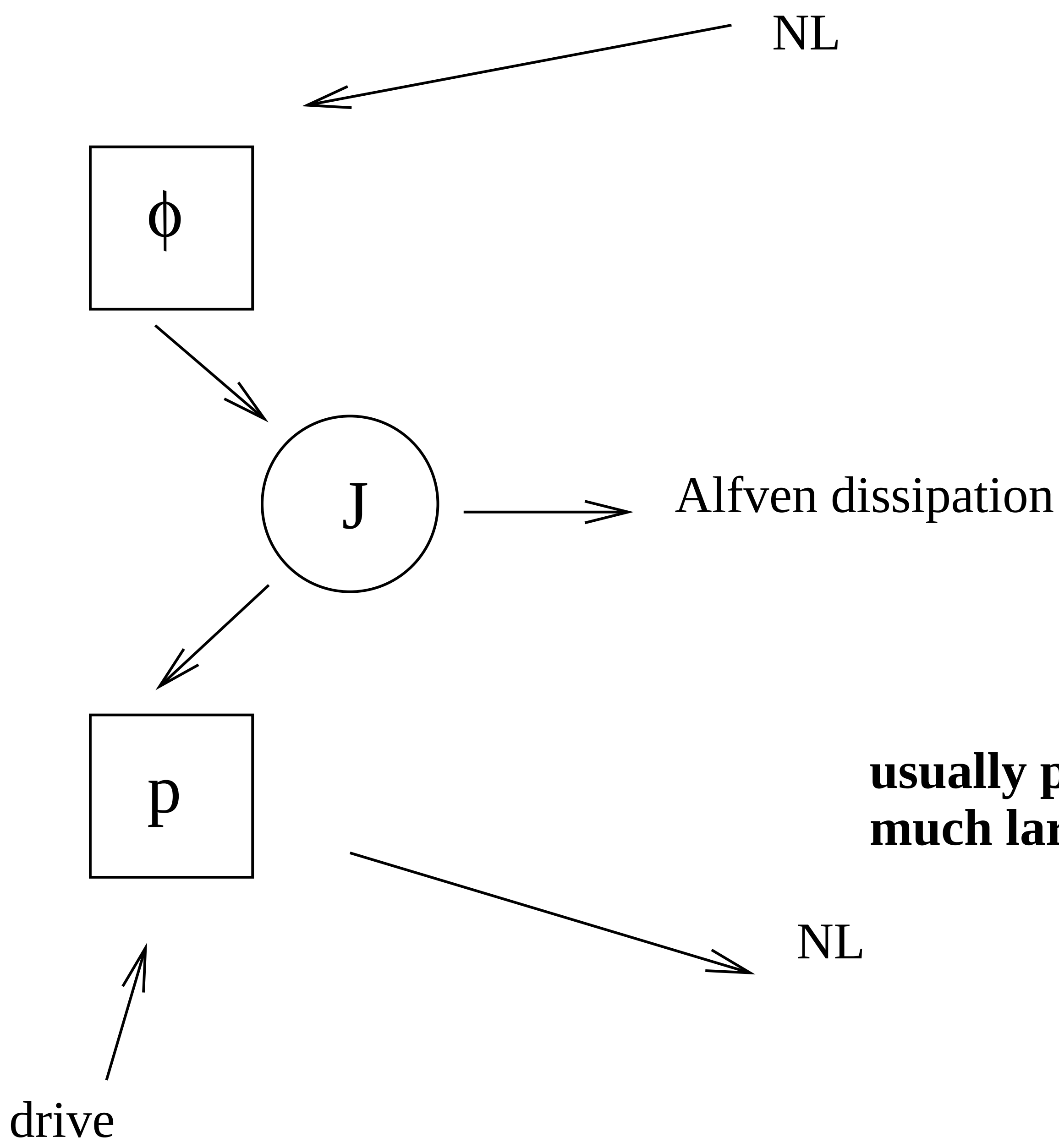
(S Camargo et al Phys Plasmas 1995 and 1996)

Simple model of instability−driven strong turbulence



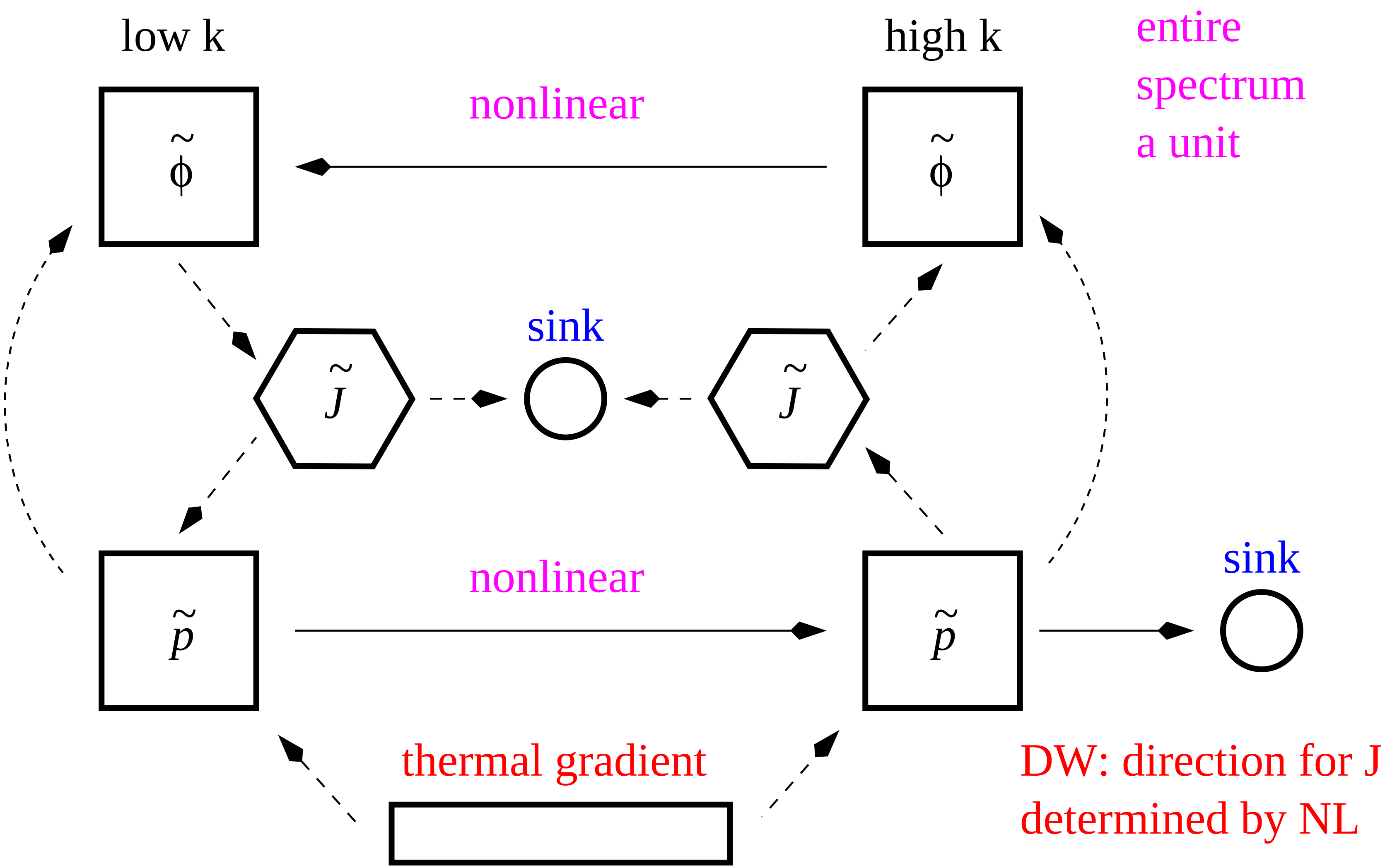
always produces equality between linear drive and rms vorticity

Long wavelength side of drift−wave energetics



usually produces rms vorticity much larger than linear drive

Energy Transfer: electromagnetic turbulence



(B Scott Phys Fluids B 1992, Plasma Phys Contr Fusion 1997)

(S Camargo et al Phys Plasmas 1995 and 1996)

Zonal Flow Dynamics in Toroidal Geometry

- ExB flow is compressible in toroidal geometry (variation of B)
  ◦ generation of sidebands $\langle \widetilde{p}_e \sin\theta \rangle$ from zonal $\left\langle \widetilde{\phi} \right\rangle$

- turb/ZF energy transfer is Reynolds stress $\times$ vorticity
  ◦ loss channels provided by Maxwell stress, geodesic coupling

$$- \left\langle \widetilde{\phi} \right\rangle \frac{\partial}{\partial t} \left\langle \widetilde{\Omega} \right\rangle = \left\langle \widetilde{\phi} \right\rangle \frac{\partial^2}{\partial x^2} \langle \widetilde{v}_E^x \widetilde{v}_E^y \rangle - \left\langle \widetilde{\phi} \right\rangle \frac{\partial^2}{\partial x^2} \hat{\beta}^{-1} \left\langle \widetilde{b}^x \widetilde{b}^y \right\rangle + \left\langle \widetilde{\phi} \right\rangle \omega_B \frac{\partial}{\partial x} \langle \widetilde{p}_e \sin\theta \rangle$$

- in MHD this gives a ZF, geodesic curv, sound waves coupling path

- in GENERAL the Alfvén dynamics enters ($\nabla_\parallel \widetilde{p}_e$ interacting with $\nabla_\parallel \widetilde{J}_\parallel$)

- ZF can now saturate:
  ◦ finite turbulence and Reynolds stress drive
  ◦ geodesic transfer to pressure sideband
  ◦ adiabatic transfer to global Alfvén oscillation
  ◦ resitive damping

- zonal evolution equations

$$\frac{\partial}{\partial t}\left\langle\widetilde{\Omega}\right\rangle = -\frac{\partial^2}{\partial x^2}\left\langle\widetilde{v}_E^x\widetilde{v}_E^y\right\rangle + \frac{1}{\hat{\beta}}\frac{\partial^2}{\partial x^2}\left\langle\widetilde{b}^x\widetilde{b}^y\right\rangle - \omega_B\frac{\partial}{\partial x}\left\langle\widetilde{p}_e\sin\theta\right\rangle$$

$$\frac{\partial}{\partial t}\left\langle\widetilde{p}_e\right\rangle = -\frac{\partial}{\partial x}\left\langle\left(\widetilde{p}_e\widetilde{v}_E^x + \widetilde{u}_\parallel\widetilde{b}^x\right)\right\rangle - \omega_B\frac{\partial}{\partial x}\left\langle\sin\theta\left(\widetilde{p}_e - \widetilde{\phi}\right)\right\rangle$$

- sideband evolution equations (finite m_e and $\cos 2\theta$ neglected)

$$\frac{\partial}{\partial t}\left\langle\widetilde{\Omega}\sin\theta\right\rangle = -\frac{\partial^2}{\partial x^2}\left\langle\widetilde{v}_E^x\widetilde{v}_E^y\sin\theta\right\rangle + \frac{\partial^2}{\partial x^2}\frac{1}{\hat{\beta}}\left\langle\widetilde{b}^x\widetilde{b}^y\sin\theta\right\rangle - \left\langle\widetilde{J}_\parallel\cos\theta\right\rangle - \frac{\omega_B}{2}\left\langle\frac{\partial\widetilde{p}_e}{\partial x}\right\rangle$$

$$\frac{\partial}{\partial t}\left\langle\hat{\beta}\widetilde{A}_\parallel\cos\theta\right\rangle = \left\langle\cos\theta\,\widetilde{b}^x\frac{\partial\widetilde{h}_e}{\partial x}\right\rangle + \left\langle\left(\widetilde{p}_e - \widetilde{\phi}\right)\sin\theta\right\rangle - C\left\langle\widetilde{J}_\parallel\cos\theta\right\rangle$$

$$\frac{\partial}{\partial t}\left\langle\widetilde{p}_e\sin\theta\right\rangle = -\frac{\partial}{\partial x}\left\langle\left(\widetilde{p}_e\widetilde{v}_E^x + \widetilde{u}_\parallel\widetilde{b}^x\right)\sin\theta\right\rangle + \left\langle\widetilde{u}_\parallel\cos\theta\right\rangle - \frac{\omega_B}{2}\left\langle\left(\frac{\partial\widetilde{p}_e}{\partial x} - \widetilde{v}_E^y\right)\right\rangle$$

$$\hat{\epsilon}\frac{\partial}{\partial t}\left\langle\widetilde{u}_\parallel\cos\theta\right\rangle = -\frac{\partial}{\partial x}\left\langle\hat{\epsilon}\widetilde{u}_\parallel\widetilde{v}_E^x\cos\theta\right\rangle - \left\langle\cos\theta\,\widetilde{b}^x\left(\frac{\partial\widetilde{p}_e}{\partial x}\right)\right\rangle - \left\langle\widetilde{p}_e\sin\theta\right\rangle - \mu_\parallel\left\langle\widetilde{u}_\parallel\cos\theta\right\rangle$$

Zonal Flow and Sideband Energetics (simplified)

- zonal flow energy (braces: mesoscale radial average)

$$\frac{\partial}{\partial t}\left\{\frac{1}{2}\left\langle\widetilde{v}_E^y\right\rangle^2\right\} = \left\{\left\langle\widetilde{\Omega}\right\rangle\left\langle\widetilde{v}_E^x\widetilde{v}_E^y\right\rangle\right\} - \omega_B\left\{\left\langle\widetilde{p}_e\sin\theta\right\rangle\left\langle\widetilde{v}_E^y\right\rangle\right\}$$

- the sideband (geodesic, sound wave, and global Alfvén oscillations) system

$$\begin{aligned}\frac{\partial}{\partial t}\left\{\left\langle\widetilde{p}_e\sin\theta\right\rangle^2\right\} = {} & 2\left\{\left\langle\frac{\partial\widetilde{p}_e}{\partial x}\sin\theta\right\rangle\left\langle Q^x\sin\theta\right\rangle\right\} + \omega_B\left\{\left\langle\widetilde{p}_e\sin\theta\right\rangle\left\langle\widetilde{v}_E^y\right\rangle\right\} \\ & + 2\left\{\left\langle\widetilde{p}_e\sin\theta\right\rangle\left\langle\widetilde{u}_\parallel\cos\theta\right\rangle\right\} \\ & - \omega_B\left\{\left\langle\widetilde{p}_e\sin\theta\right\rangle\left\langle\frac{\partial\widetilde{p}_e}{\partial x}\right\rangle\right\} - 2\left\{\left\langle\widetilde{p}_e\sin\theta\right\rangle\left\langle\widetilde{J}_\parallel\cos\theta\right\rangle\right\}\end{aligned}$$

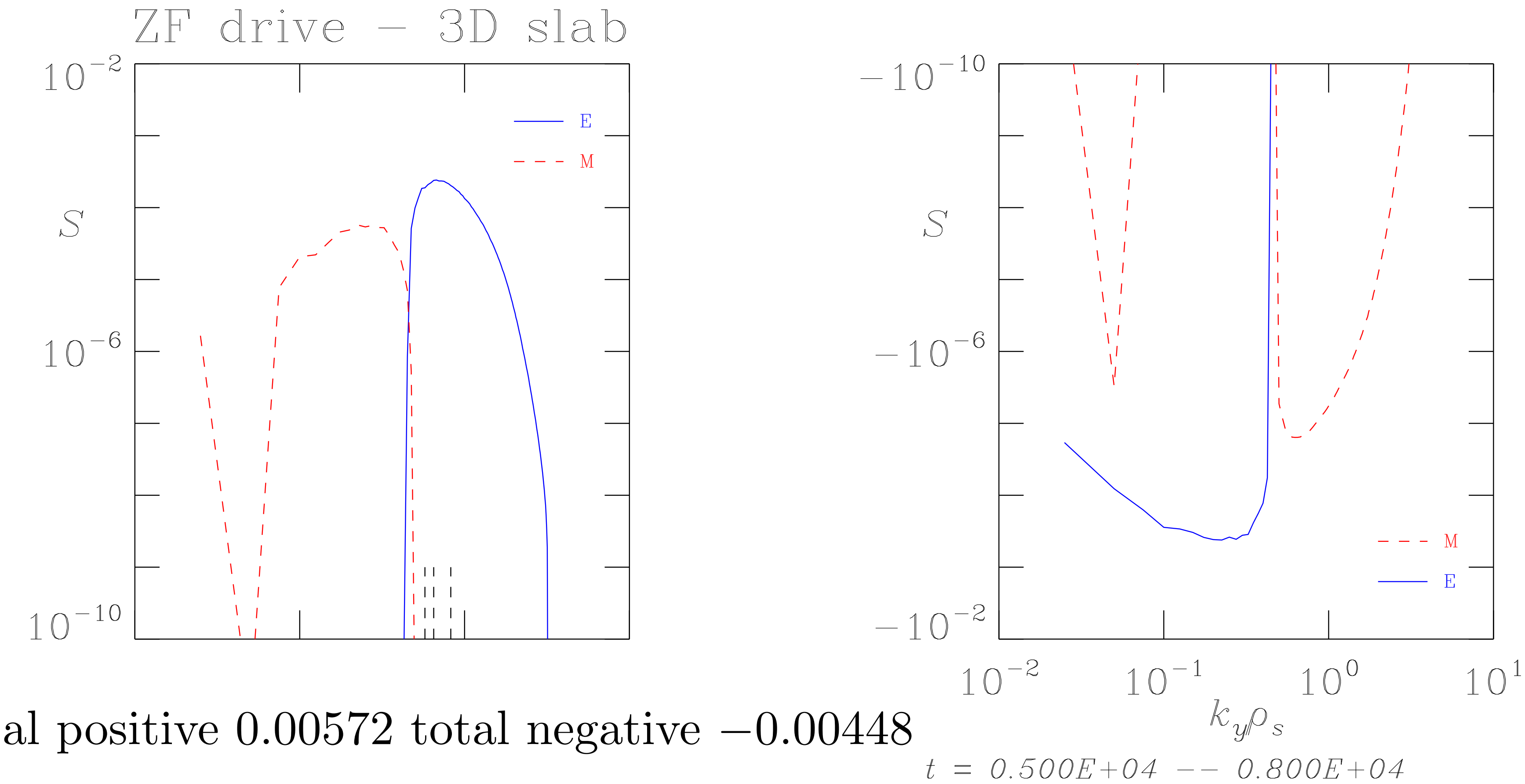
(energy equations for current, parallel velocity, and vorticity sidebands)

- the thermal reservoir (background pressure)

$$\frac{\partial}{\partial t}\left\{\frac{1}{2}\left\langle\widetilde{p}_e\right\rangle^2\right\} = \left\{\left\langle\frac{\partial\widetilde{p}_e}{\partial x}\right\rangle\left\langle Q^x\right\rangle\right\} - \omega_B\left\{\left\langle(\widetilde{\phi}-\widetilde{p}_e)\sin\theta\right\rangle\left\langle\frac{\partial\widetilde{p}_e}{\partial x}\right\rangle\right\}$$

Reynolds Stress Saturation Balance in 3D Slab

nominal case with wcv = 0,   run to t = 8000

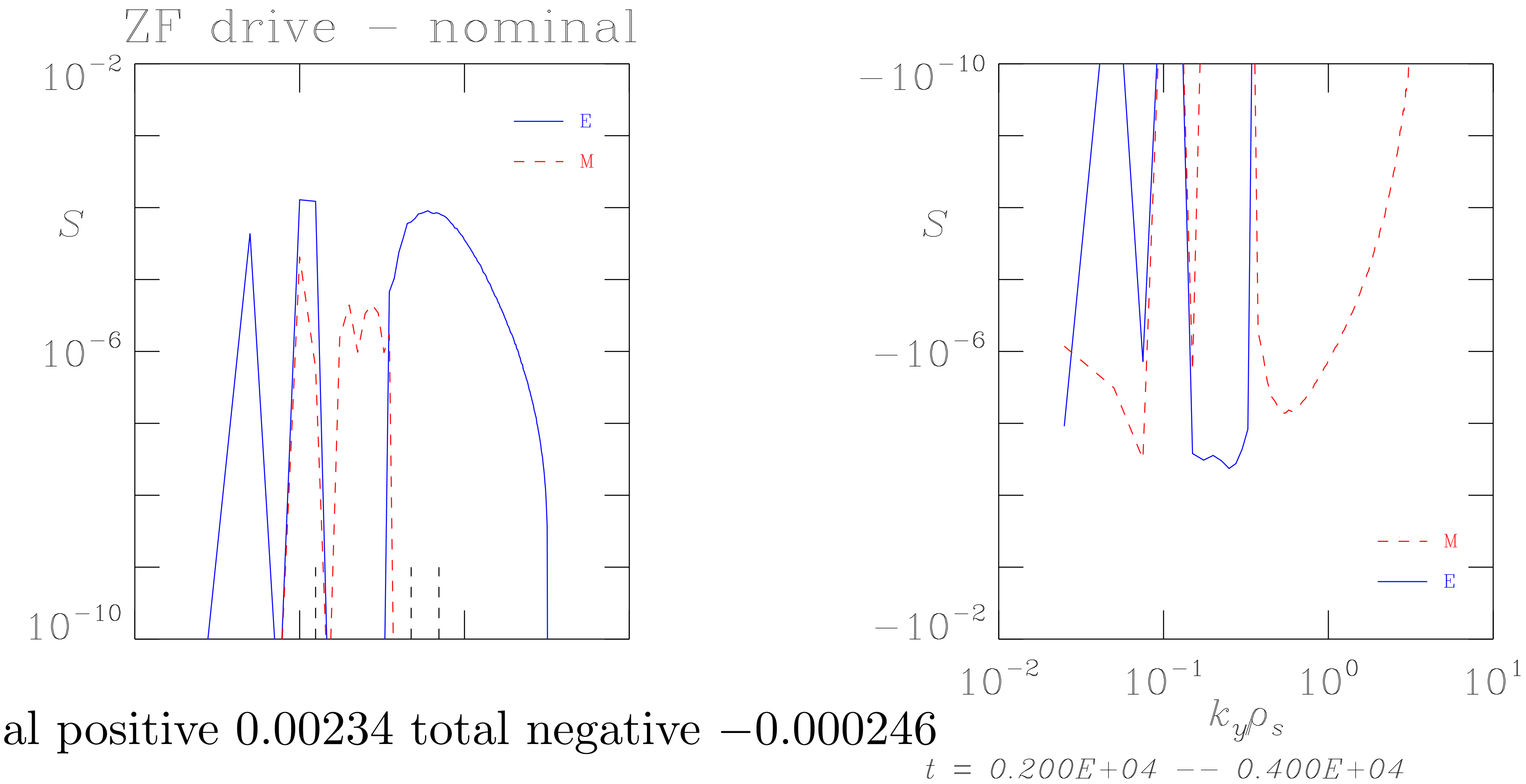


- R_E: total positive 0.00572 total negative −0.00448
- R_M: total positive 0.000569 total negative −0.000292

ZF saturation is RS balance as in 2D

Reynolds Stress Saturation Balance in 3D Torus

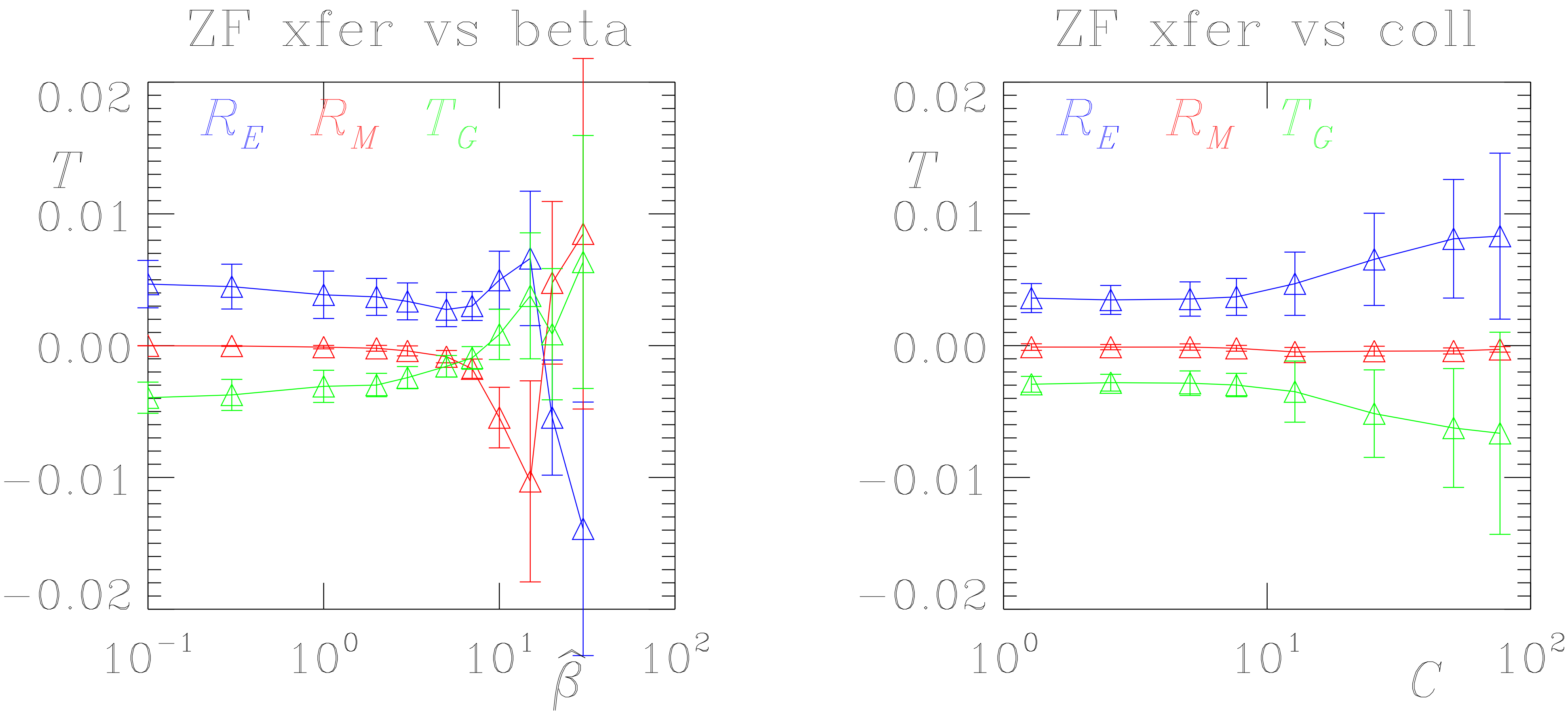
nominal case



- R_E: total positive 0.00234 total negative −0.000246
- R_M: total positive 0.0000424 total negative −0.000152

Reynolds stress remains strongly positive, Maxwell stress weak

ZF Statistical Equilibrium Scaling



- R_M assumes major role in MHD regime (transition to ideal ballooning)

drift wave (turbulence) and MHD (possibly in ELMs) regimes fundamentally different

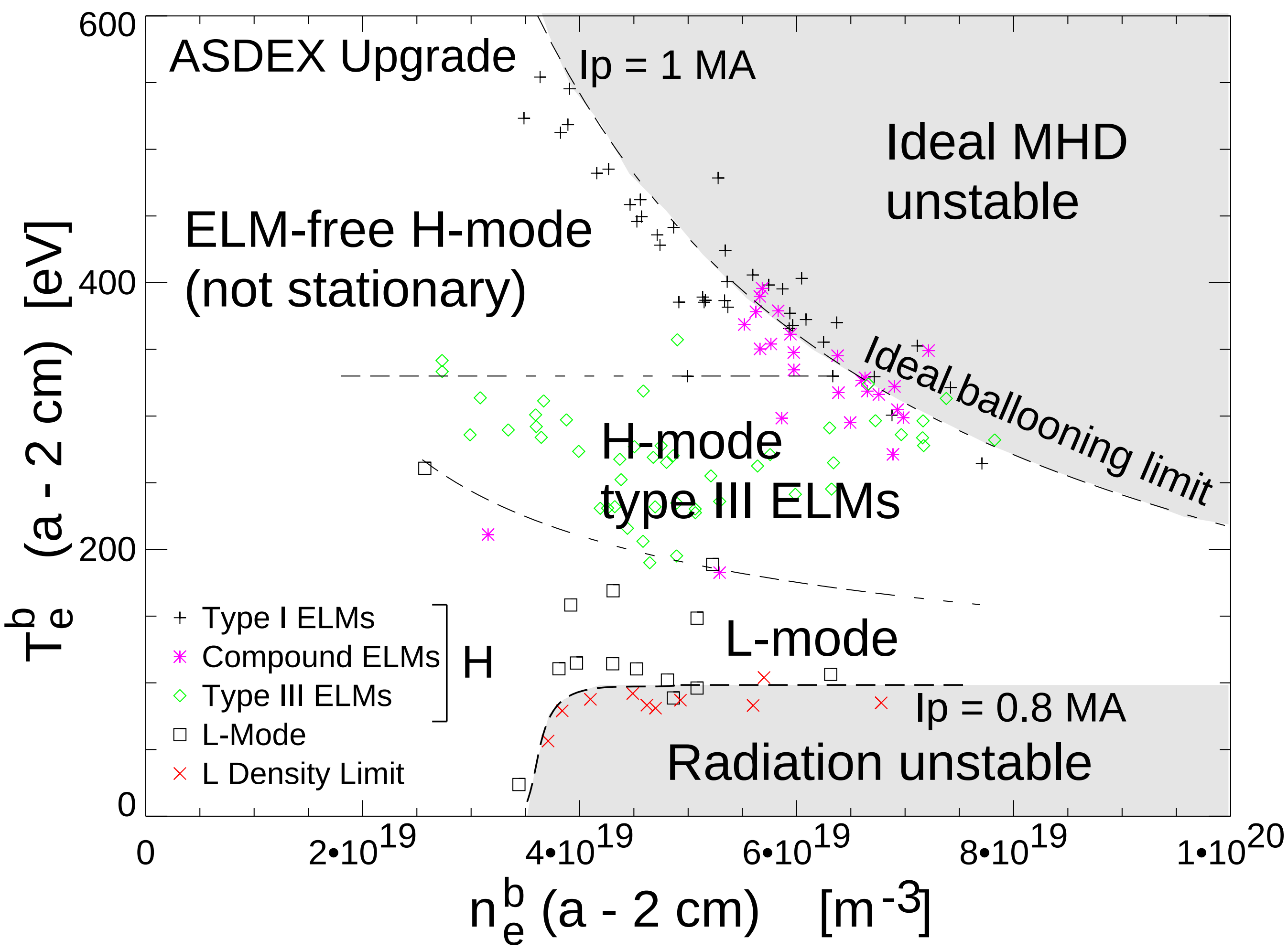
references for ZF drive mechanisms

- we're interested in things other than Reynolds Stress:

K Hallatschek and Biskamp, Phys Rev Lett 2001
V Naulin New J Phys 2002, et al, Phys Plasmas 2005
B Scott, Phys Letters A 2003 New J Phys 2005
N Miyato et al, Phys Plasmas 2004
M Ramisch et al, New J Phys 2003

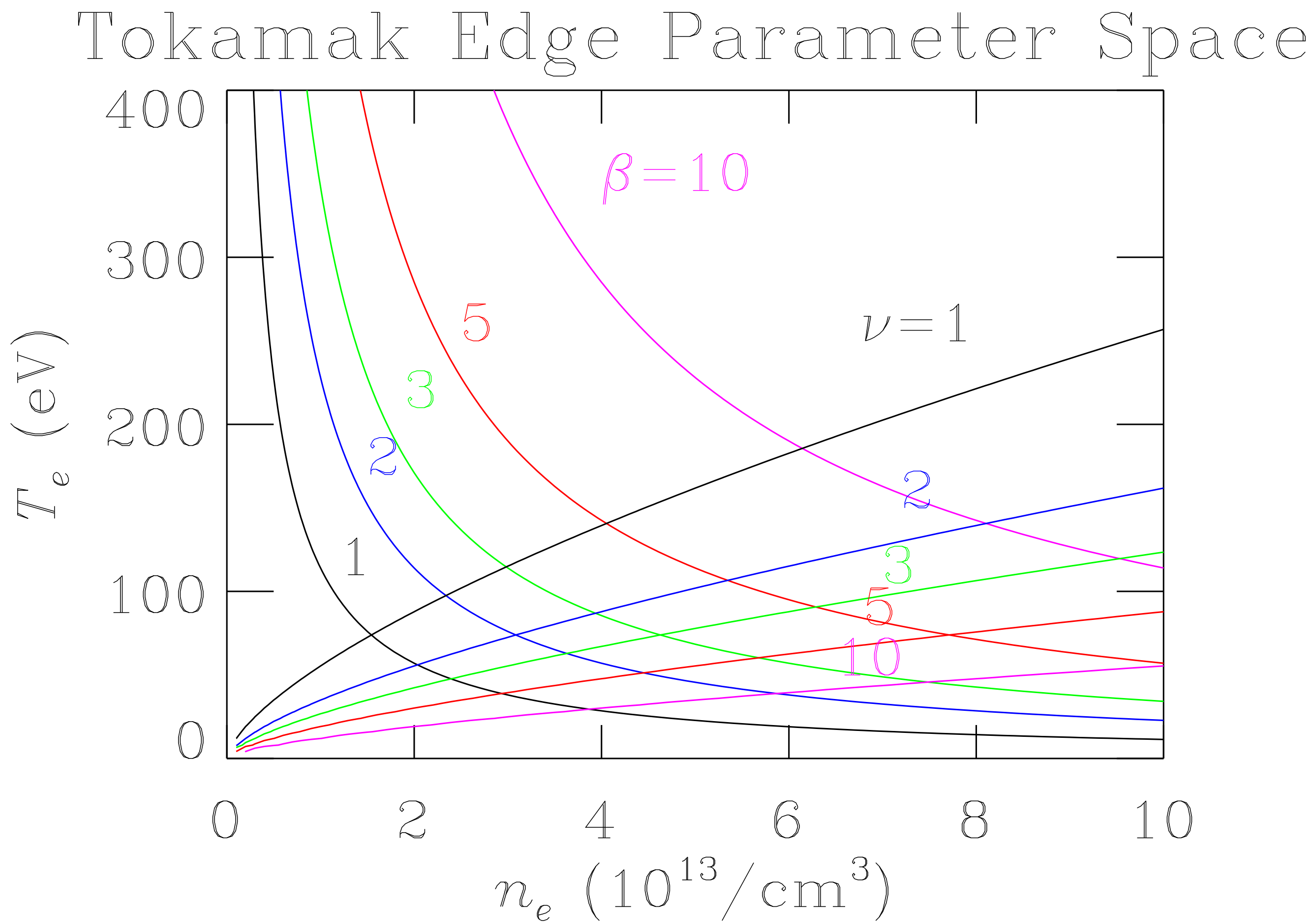
L/H transition – Experimental Parameters

(W Suttrop, M Kaufmann *et al*, PPCF 1997)

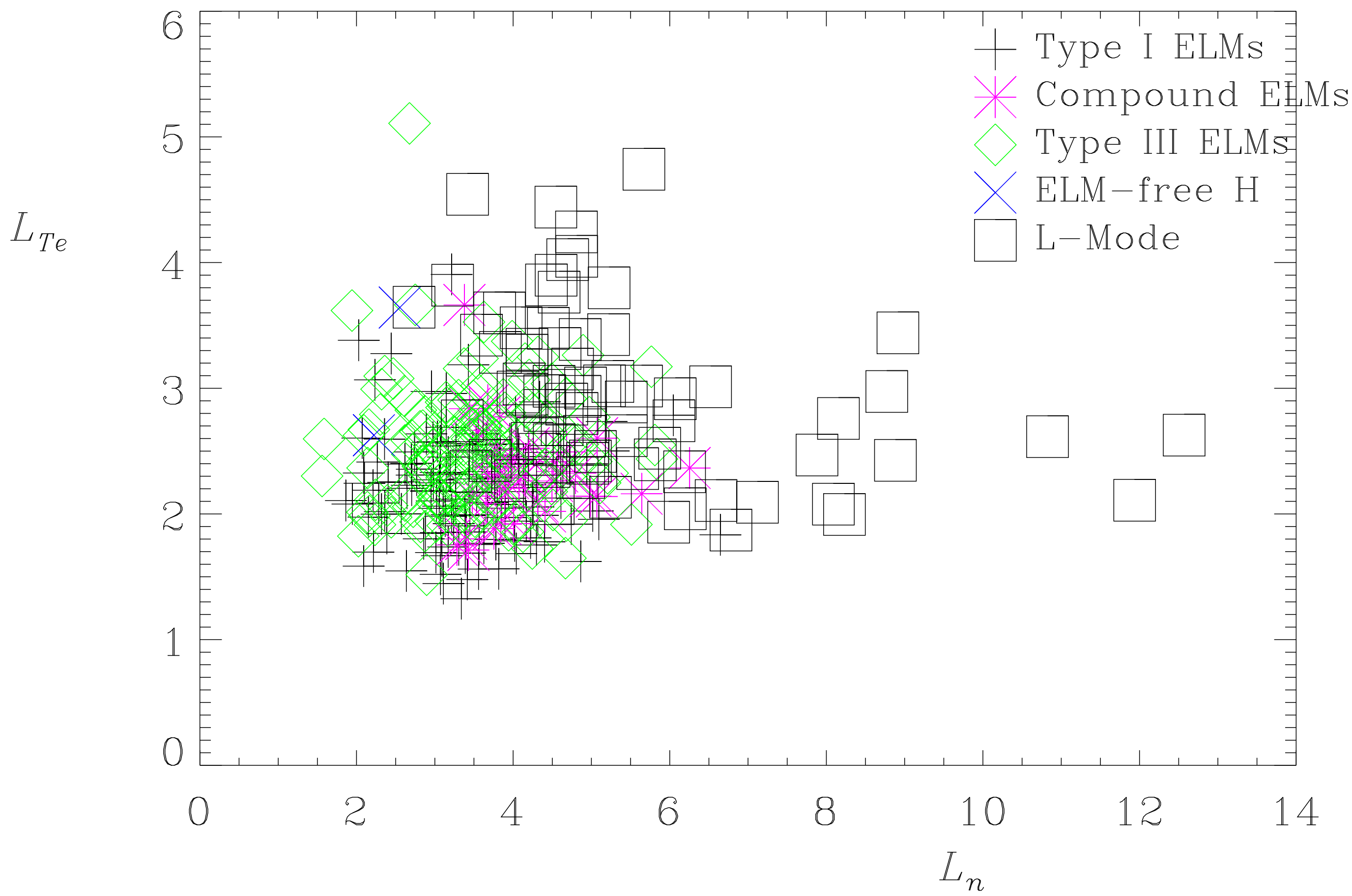


normalised parameters

(B Scott, PPCF 1997)

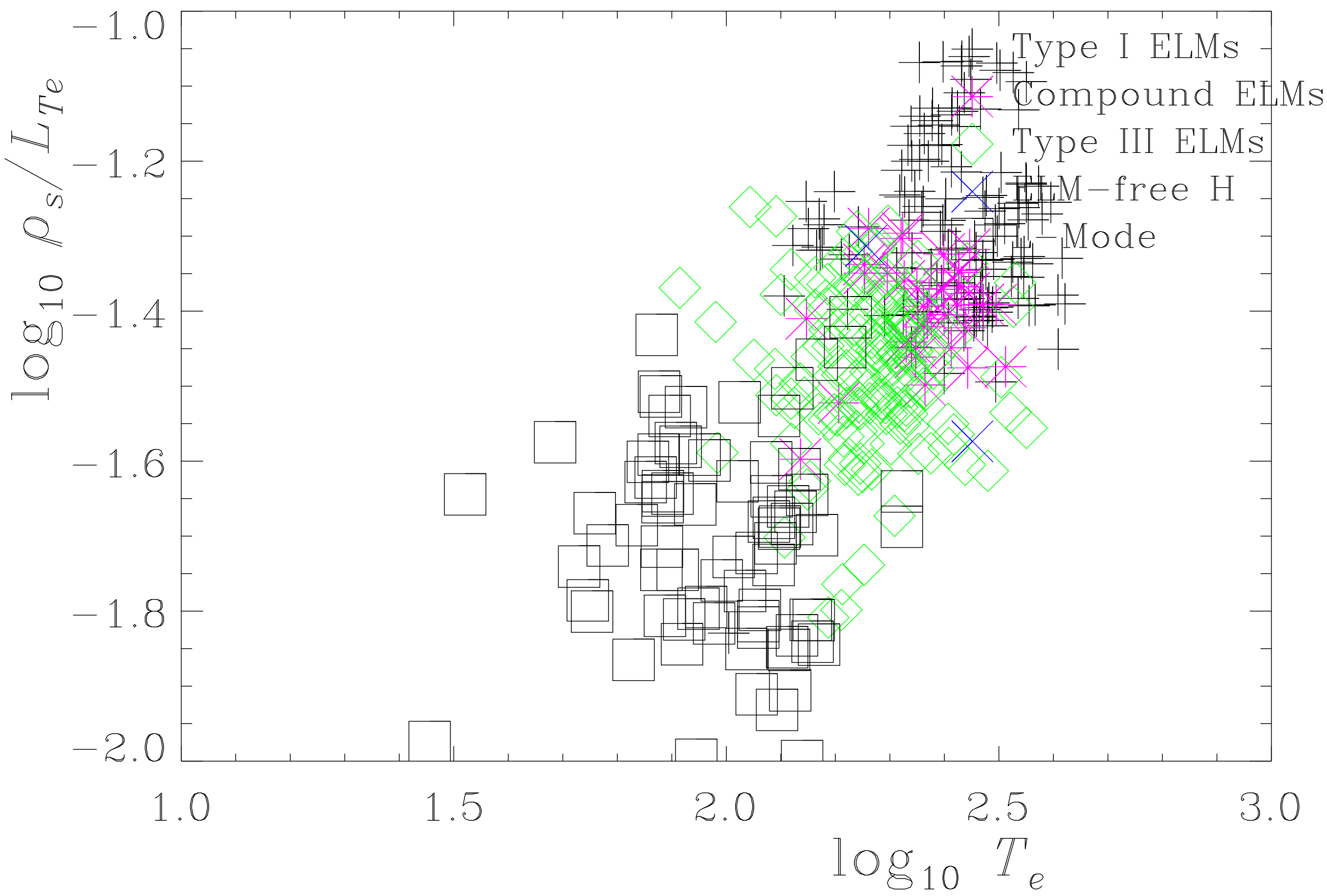


gradients across transition



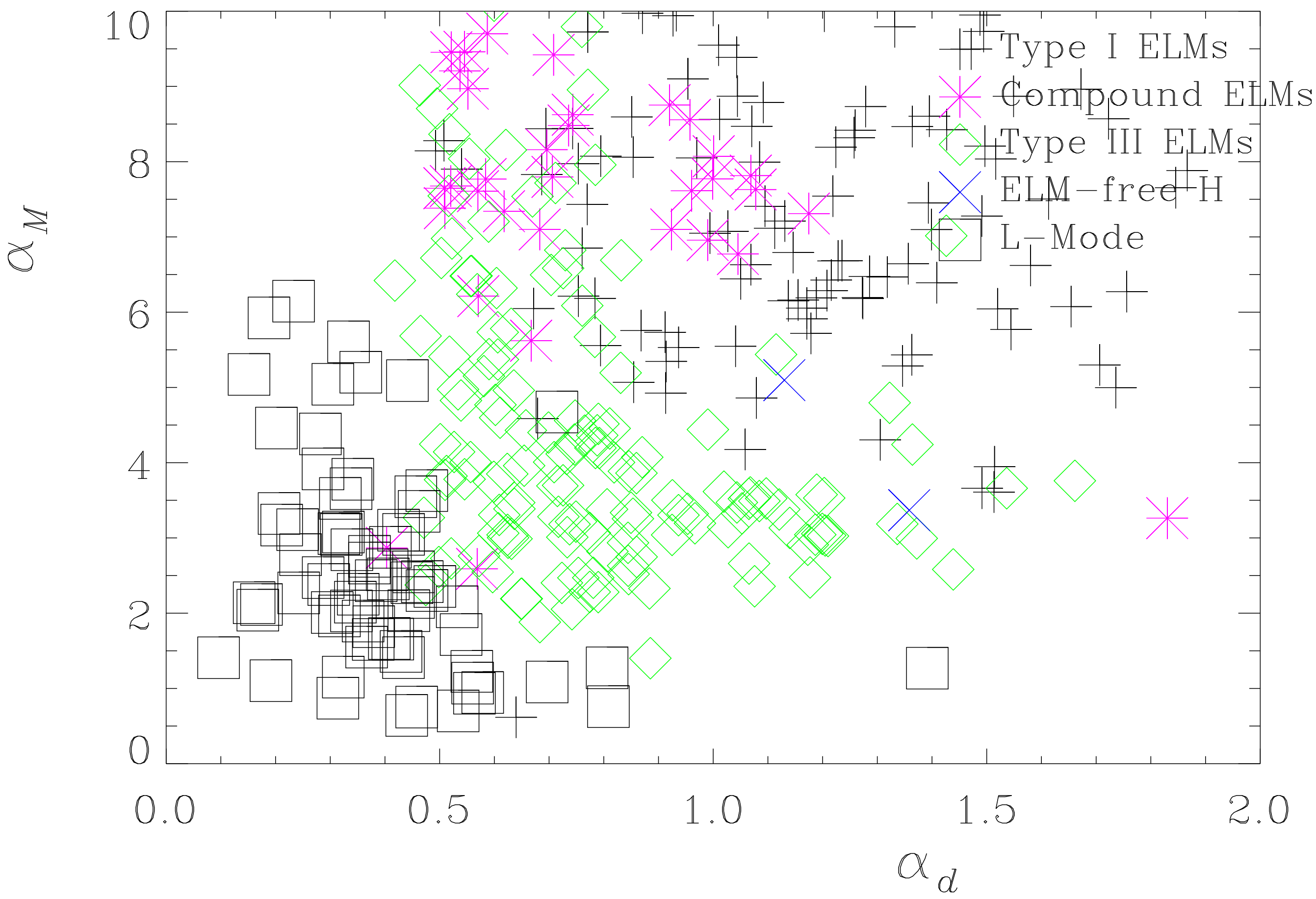
- T_e-profile steepest and nearly self similar: **weak scale ratio changes**
  ◦ newer data: changes in T_i-profile (affects flows, not basics of turbulence)

effective rho star



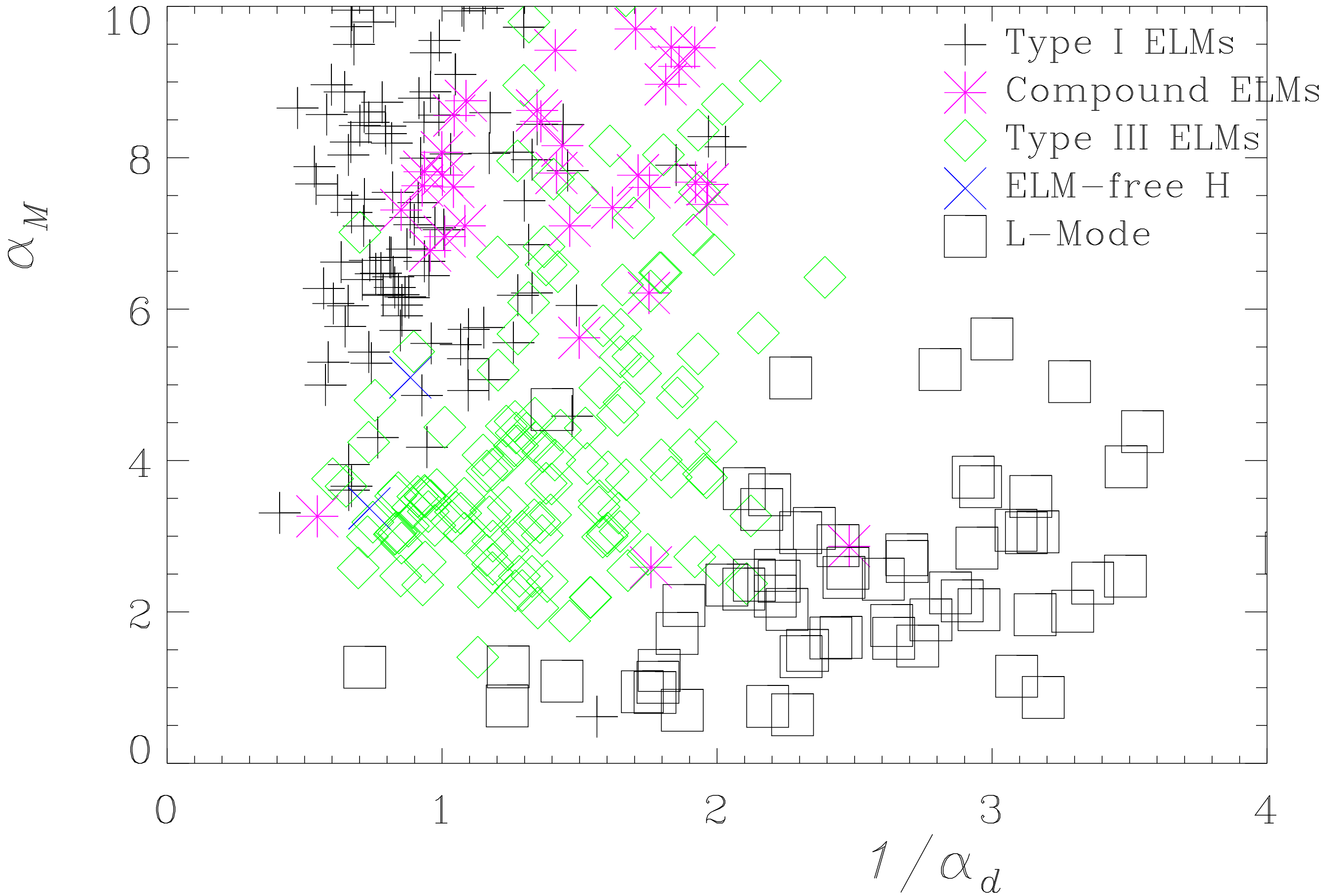
- key point: very limited allowed domain size $L_x \sim L_T \ll 100\rho_s$
  - violated in many computations

Drake's drift-resistive ballooning parameters



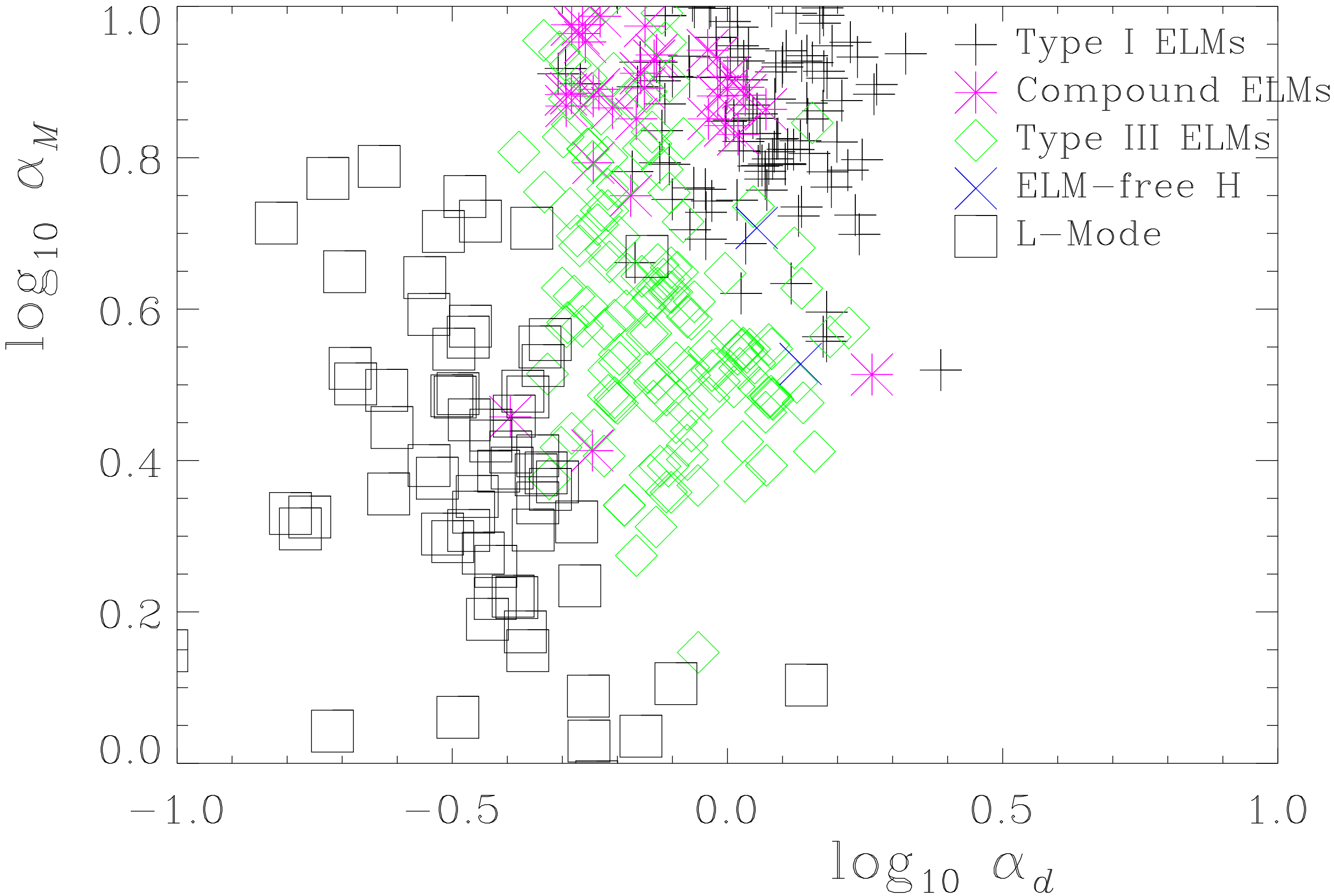
- apparent boundaries in α (L/H) and α_d (density limit)
  - ◦ effect of reciprocal SQRT in collisionality ($\alpha_d \sim C^{-1/2}$)
  - ◦ following slides: various representations

reciprocal α_d



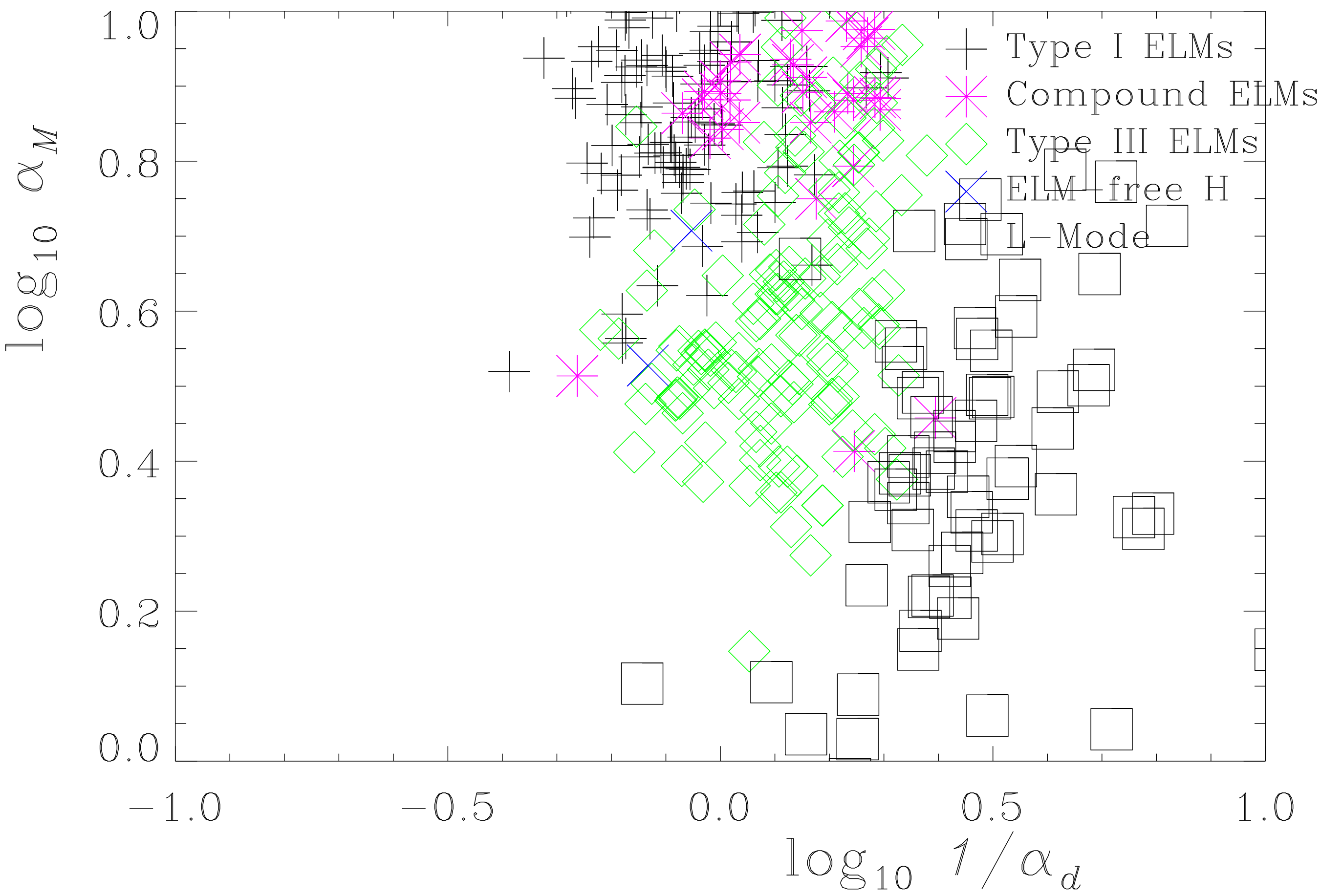
- the α_d limit is slightly less sharp

log version α–α_d



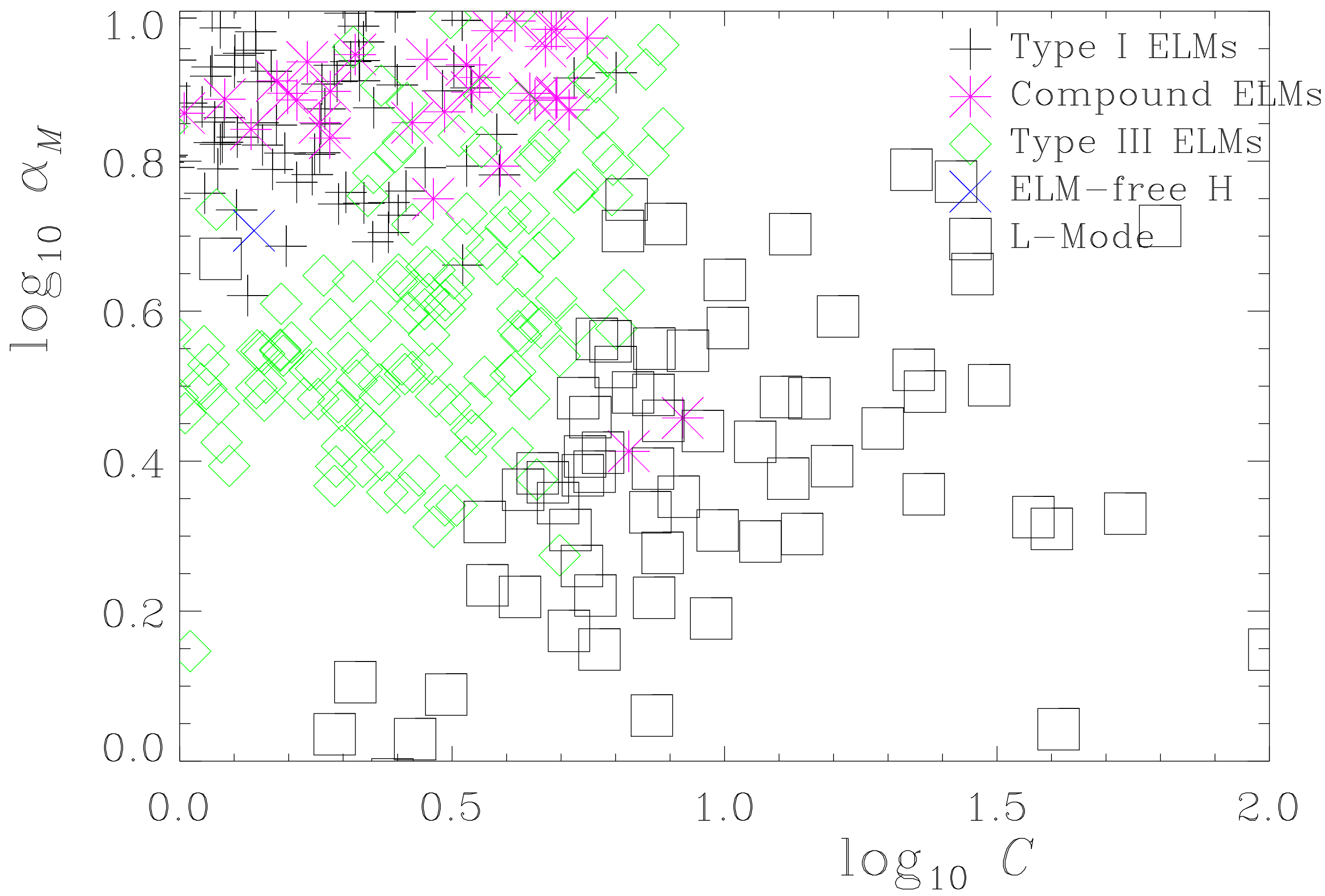
- as a scaling it appears like many others

log version with reciprocal α_d



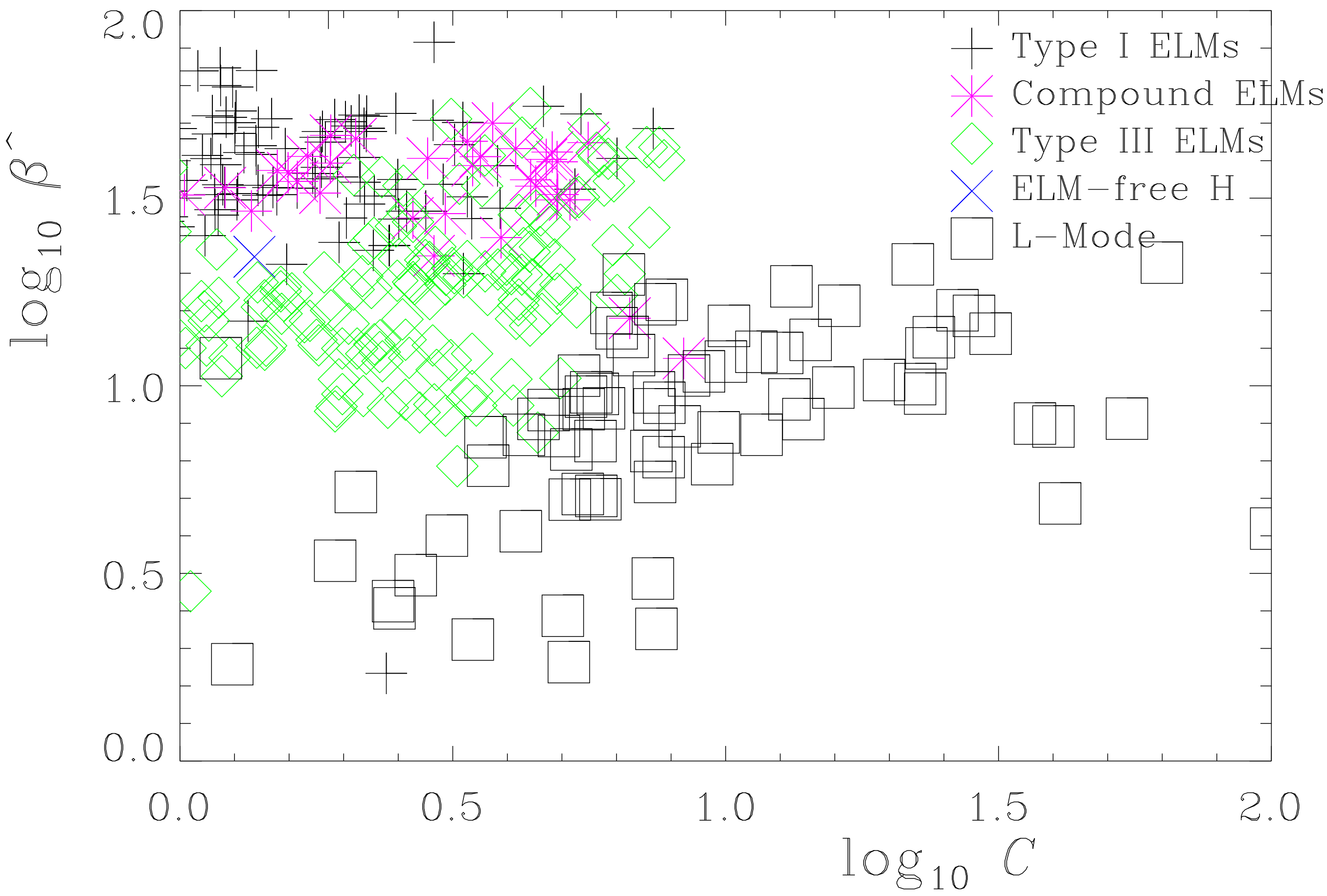
- this is a little joke :-)

collisionality and alpha



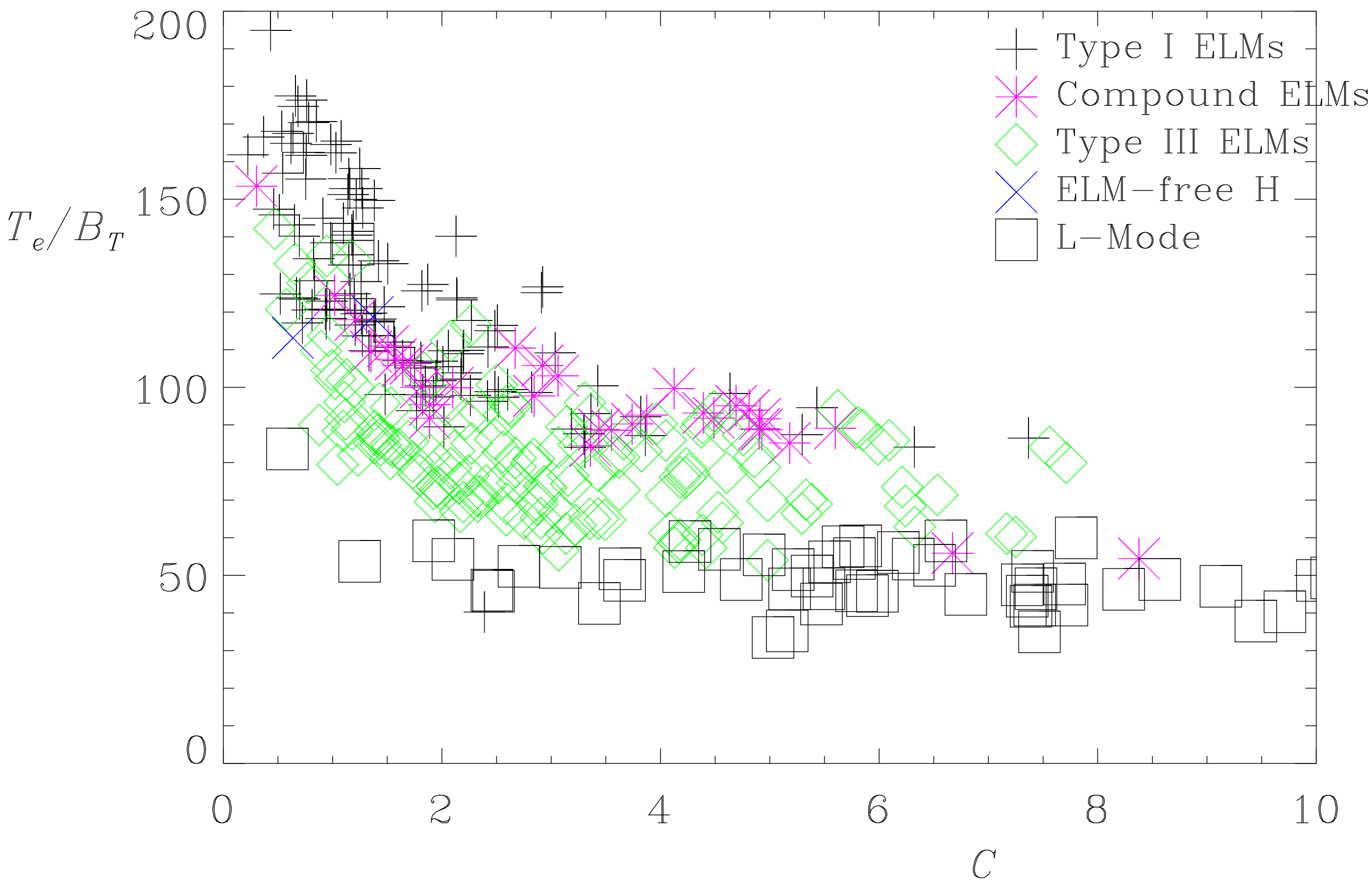
- about the same

collisionality and inductivity (beta-hat)



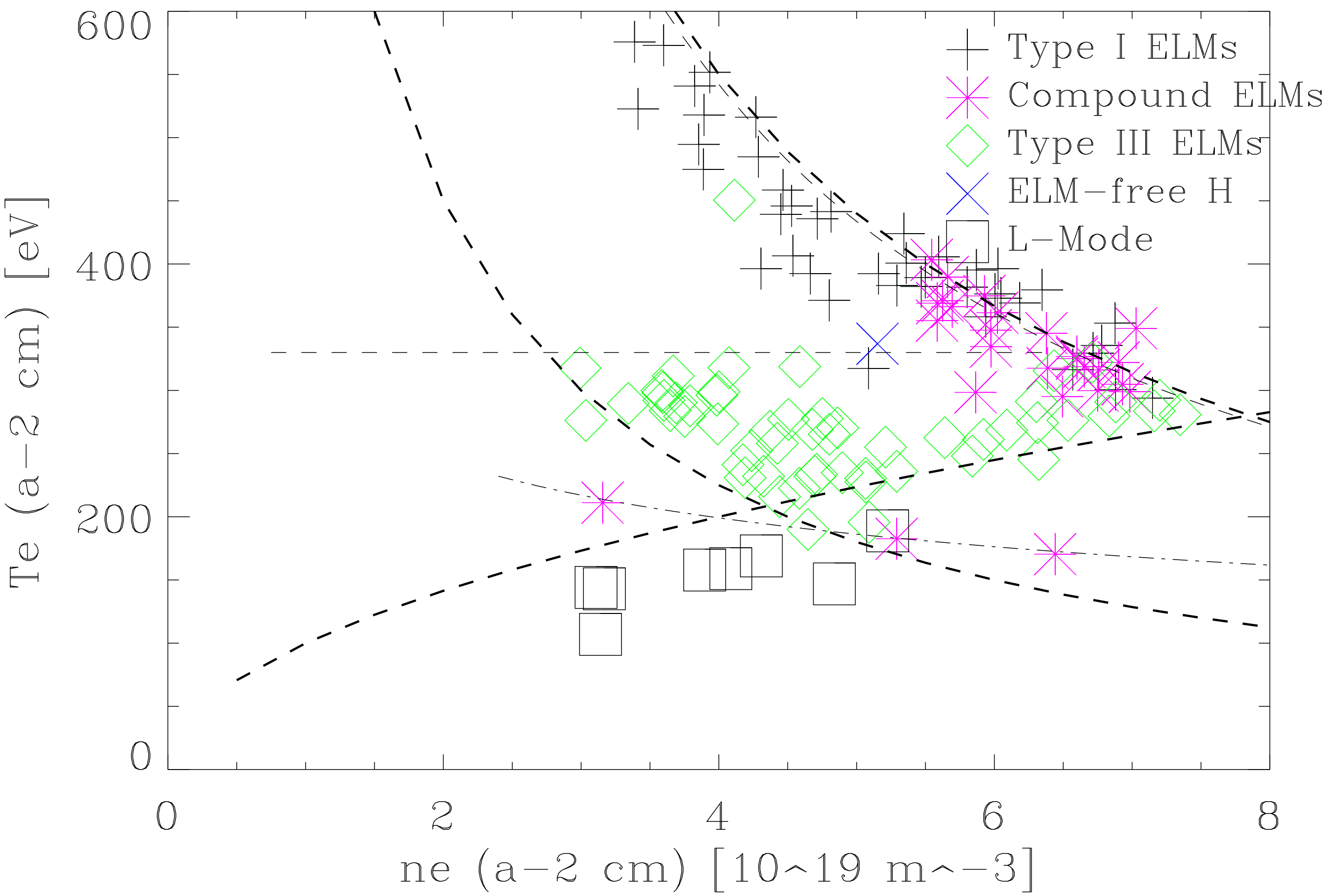
- also about the same – **now no role for resistive ballooning**

temperature and magnetic field



- Alex Chankin's analysis of JET results, also fits these data reasonably

operational diagram again



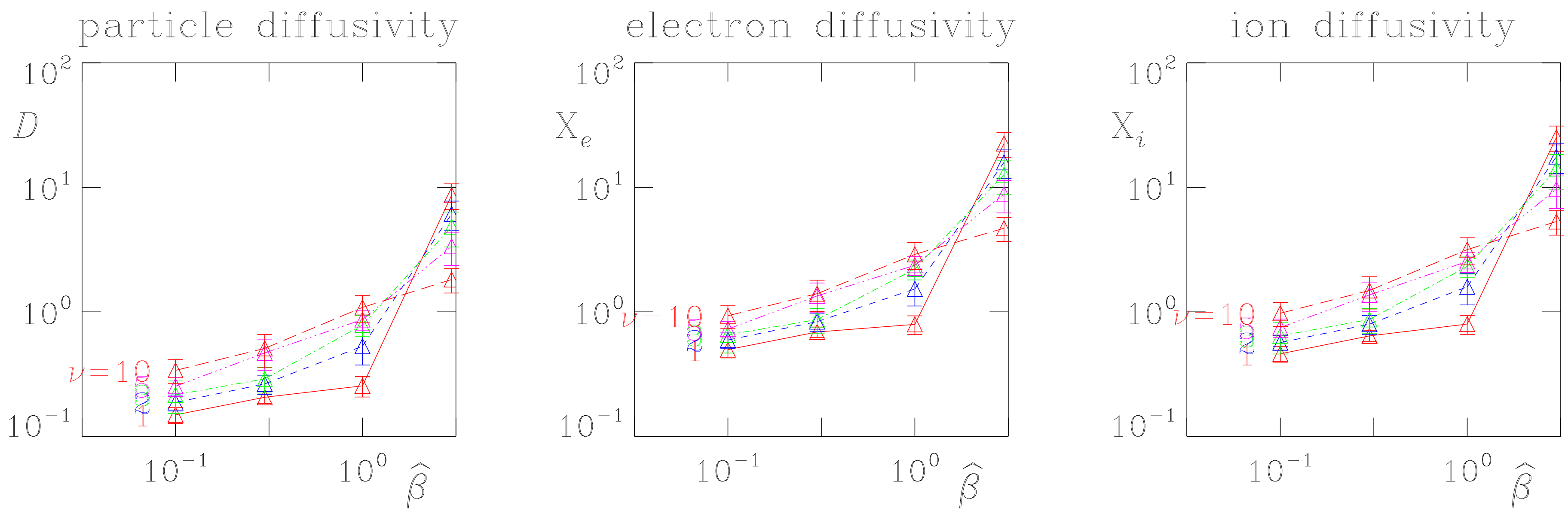
- simple lines of constant n_eT_e (beta) and n_e/T_e^2 (coll) drawn
  - ◦ obvious role for these parameters, but . . . (see below)

the data are equivocal

- many stories were made based on one or the other person's model
- however, the data do not distinguish among these models
- newer data (last 5 years of AUG and competitors): better but not enough of it
  - flow shear
  - flow structure (jet versus shear layer)
  - switching B, in and out of H mode
  - ion temperature information
  - flows versus force balance
  - questions against neoclassical equilibrium
  - causality (IMHO very problematic, people are still too fast with stories)
- always note: neoclassical **balances** not neoclassical theory's **textbook equilibrium**

computed transport

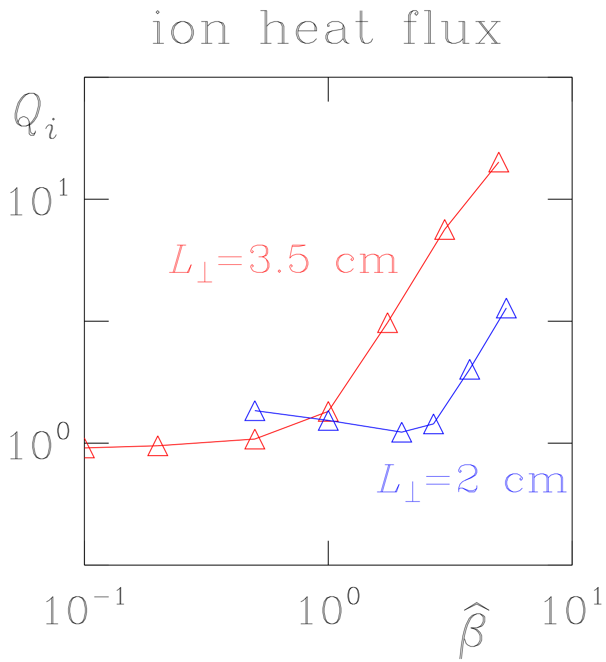
(B Scott, New J Phys 2002)

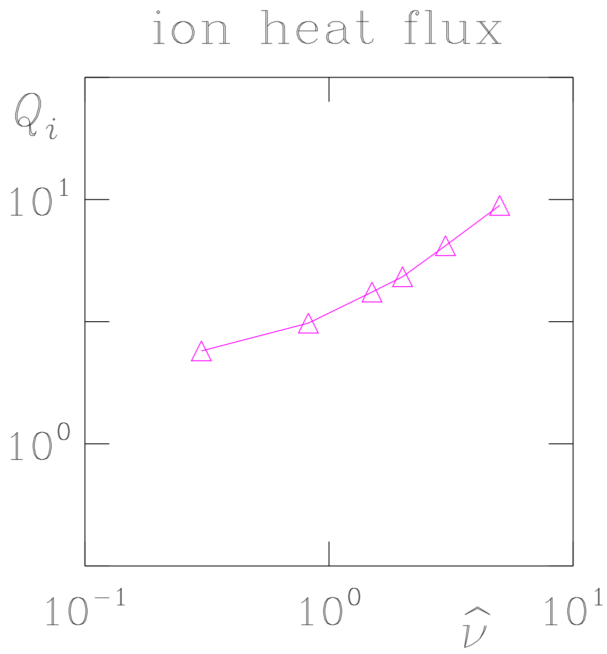


rising trend with beta for any relevant collisionality

gyrofluid computed transport

(B Scott, PPCF 2007)



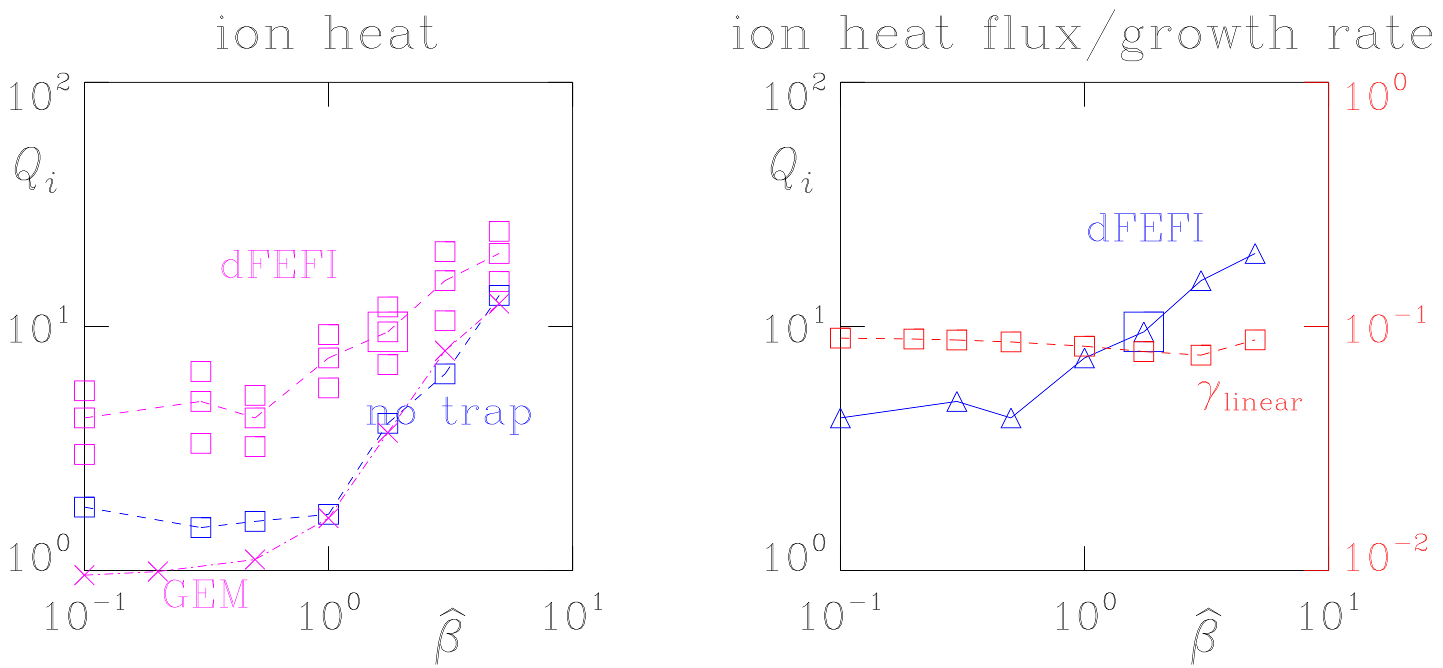


- rising trend with both beta and collisionality
  - two choices of $L_\perp$ indicates beta follows alpha (MHD)

- phys units: multiply Q_i by $(\hat{\beta}/1.75)^{3/2}$ or $(C/3.11)^{-1/2}$
  - nominal case: gyro-Bohm diffusivity is $\rho_s^2 c_s/L_\perp = 0.66\,\mathrm{m}^2/\mathrm{sec}$

gyrokinetic computed transport

(B Scott, Contrib Plasma Phys 2010)

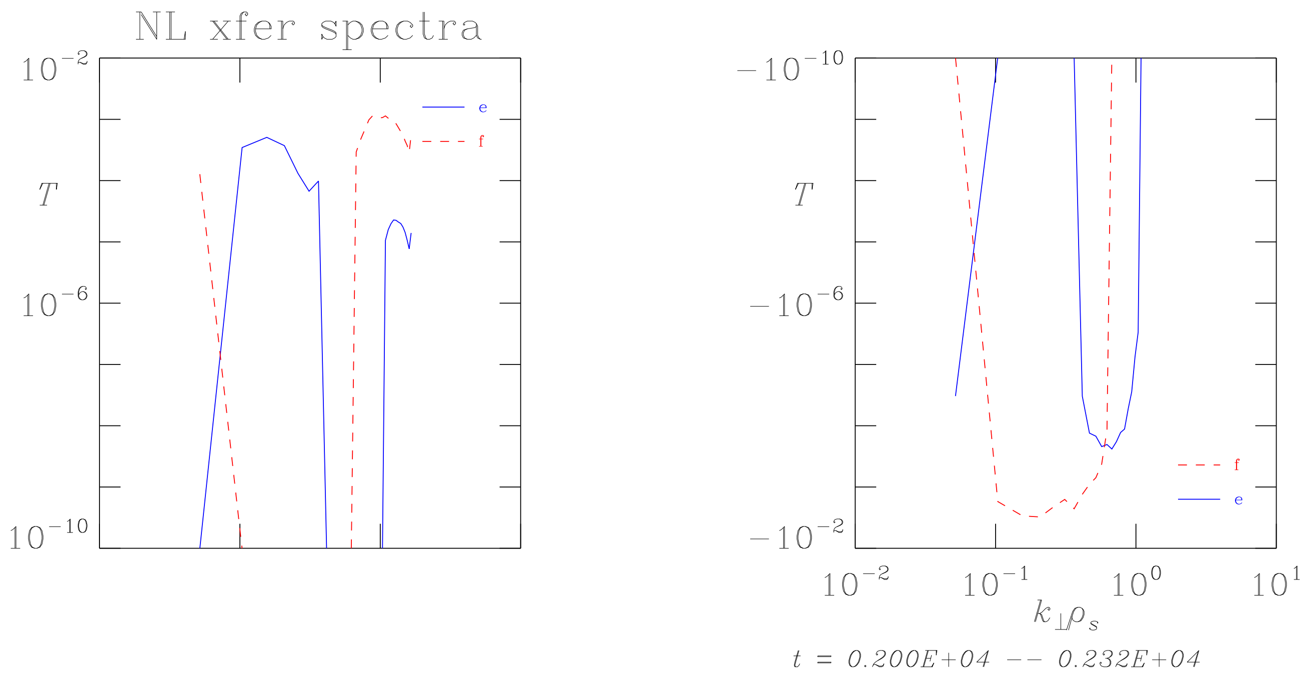


- all models show a rising trend with beta

- basic nonlinearity: qualitative disagreement with linear scaling
  - next slide: nonlinear drive of long wavelength MHD component

gyrokinetic energy transfer

(B Scott, Contrib Plasma Phys 2010)



- log-log: positive and negative values plotted separately
- ExB transfer positive at long wavelength; delta-f opposite
- same qualitative behaviour as in the simplest (HW) drift wave models

references for turbulence transport trends

- we're interested in things other than linear modes or resistive MHD

  B Scott, PPCF 1997,-8,2007, Phys Pl 2000,-5 New J Phys 2002, CPP 2010

  V Naulin et al, Phys Plasmas 2003, Phys Letters A 2004

  S Niedner et al, PPCF 2002

  S Korsholm et al, Phys Plasmas 1999

- the main L/H results that didn't stand

  B Scott, JF Drake, different papers in IAEA 1996

  B Rogers and JF Drake, PRL 1997, Phys Plasmas 1998

- pedestal attempt, very uncertain about what was done with profiles
  - were they included in the curvature terms?

  X Xu et al, Phys Plasmas 2000

- main transport trend issues: box size and aspect ratio

- main pedestal issue:

  if you initialise a pedestal in a delta-f model, it straightens out

Things to Remember

- the edge is harder than anyone ever thought (turbulence, "equilibrium")
  - all aspects are strongly nonlinear; mutual self consistency is paramount

- no model or code is adequate to the L/H transition to date
  - many claims which ignore even the experiment (majority of data)

- turbulence: underlain by self sustained drift wave turbulence
  - linear scaling, ballooning, secondaries, resistive MHD all qualitatively inadequate
  - nonlinear conservative processes dominate: computation must show good energetics

- flows (both ExB and parallel): probably decided by equilibrium processes
  - local Reynolds stress effectively trumped even when it is present

- L-H transition: well known data in Edge Operation Diagram
  - trigger mechanism should not depend on pre-existing model pedestal
  - MHD component must be faced even though an MHD model is not adequate
  - mechanism is probably not local; not yet decided if it is kinetic

- gyrokinetic study of equilibrium flows is very relevant
  - neoclassical process, not "neoclassical theory"

Edge Core Transition Studies

- model: GEM, 12 flux tubes, spaced at normalised volume radius values

$$r_a = \{\ 0.11 \quad 0.23 \quad 0.33 \quad 0.42 \quad 0.50 \quad 0.58 \quad 0.65 \quad 0.72 \quad 0.79 \quad 0.85 \quad 0.91 \quad 0.97\ \}$$

- $T_{e,i}$ and $\nabla T_{e,i}$ adjusted to get flux times sfc $\approx$ given input power profile
  - ◦ species done separate or together with $T_i = T_e$
  - ◦ it is an optimisation scheme, not a transport model

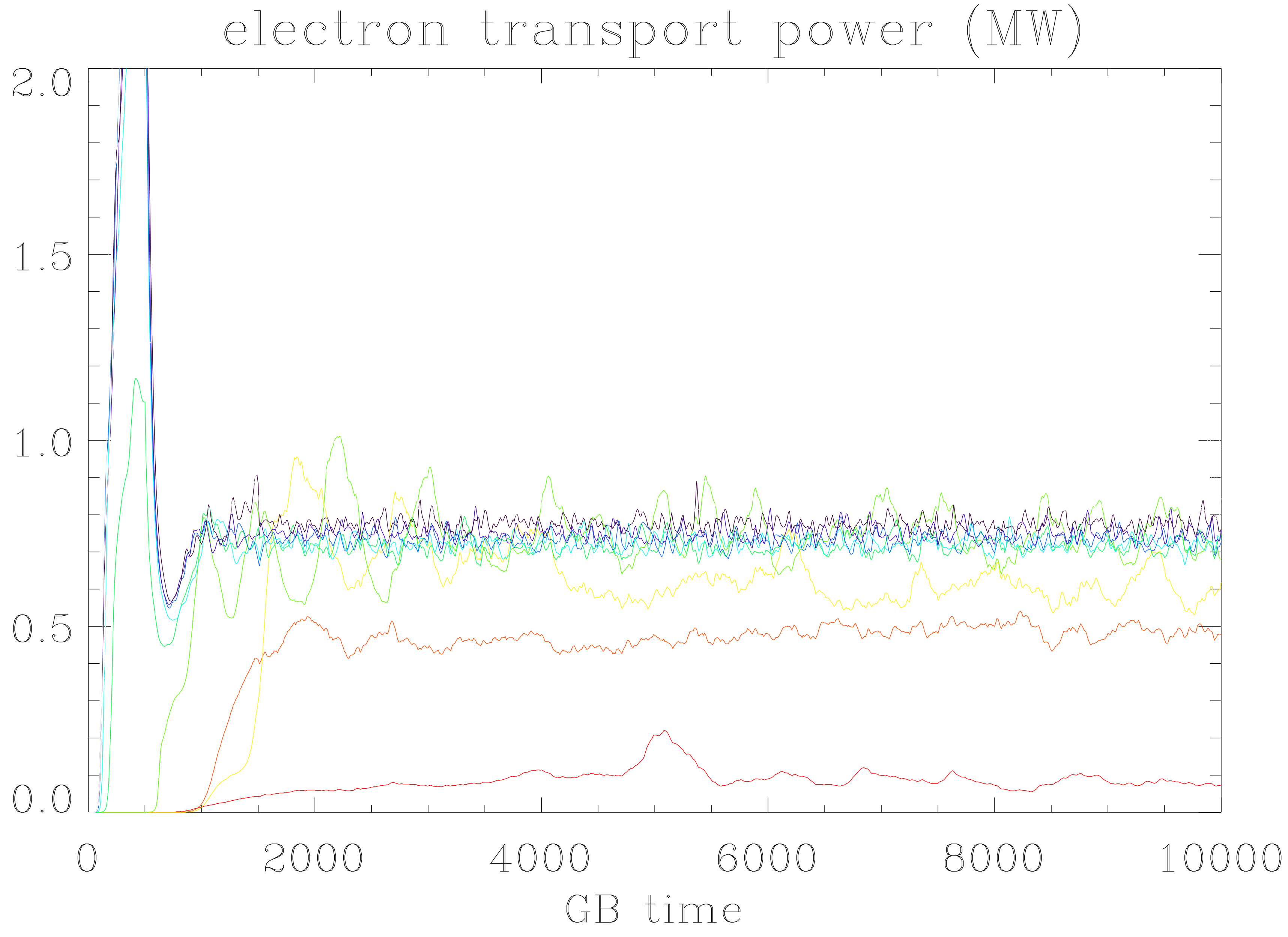
- GEM is formulated for all parameters, but lacks trapped electrons
  - ◦ physics is found to stay in EM/NL ITG plus MHD regime anyway

- model is AUG-sized, profiles for q, n_e, $T_{e,i}$, $P_{e,i}$ given, with LCFS values fixed

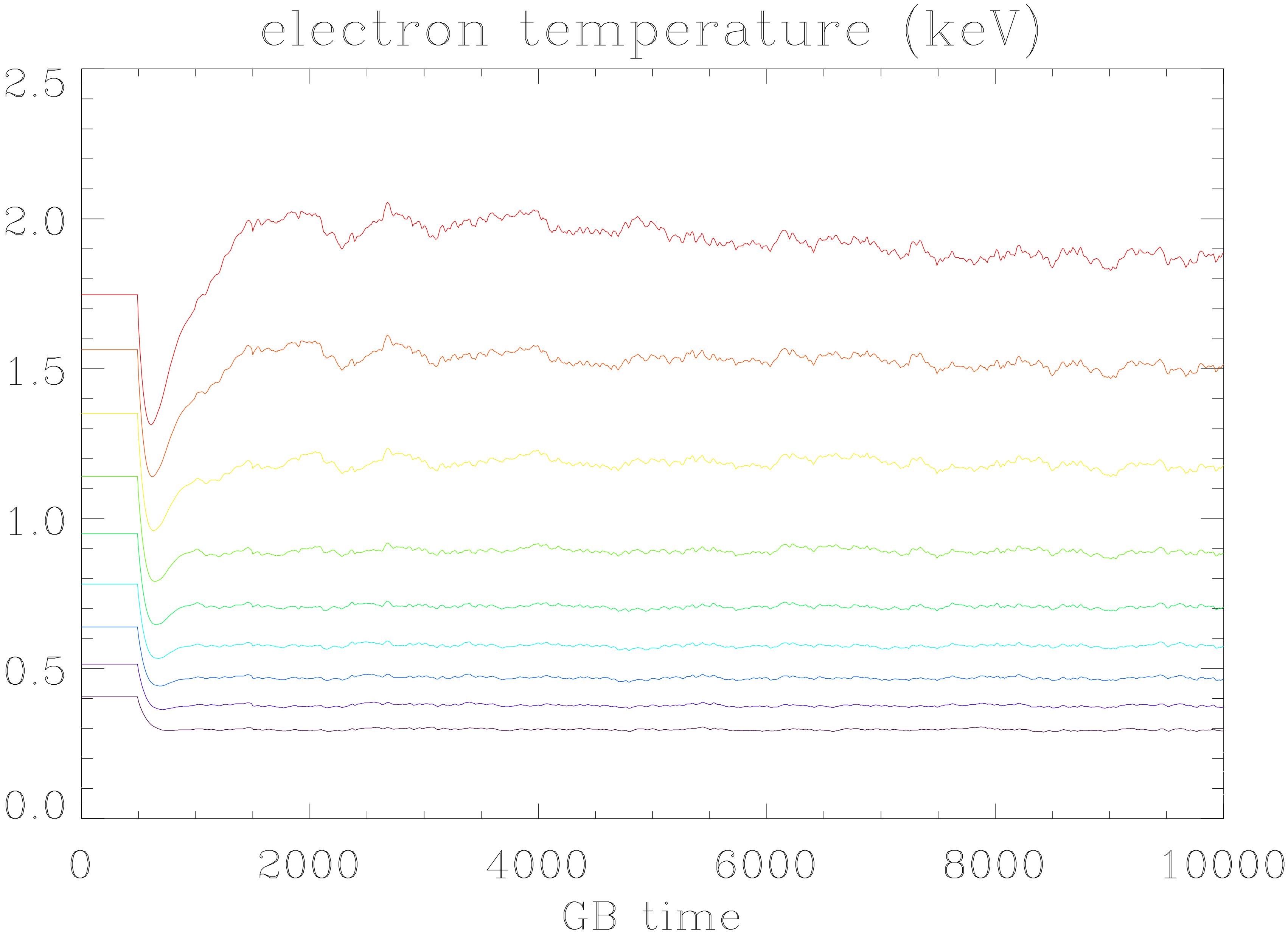
- time traces and profiles are shown for standard case
  - ◦ species-separate 1 MW power each or 2 MW together

- GEM: B Scott Phys Plasmas 12 (2005) 102307 and PPCF 48 (2006) B277

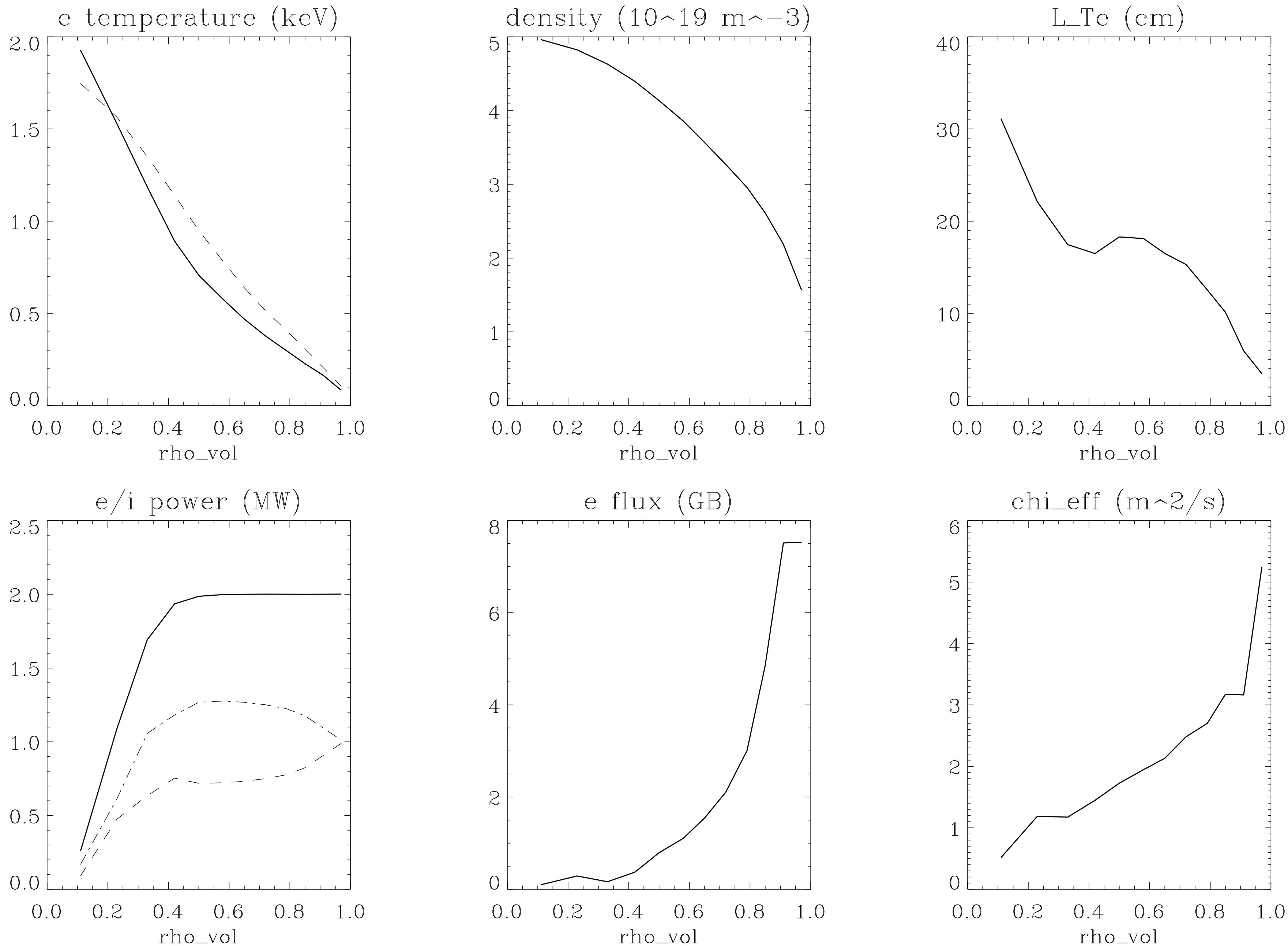
2 MW power together



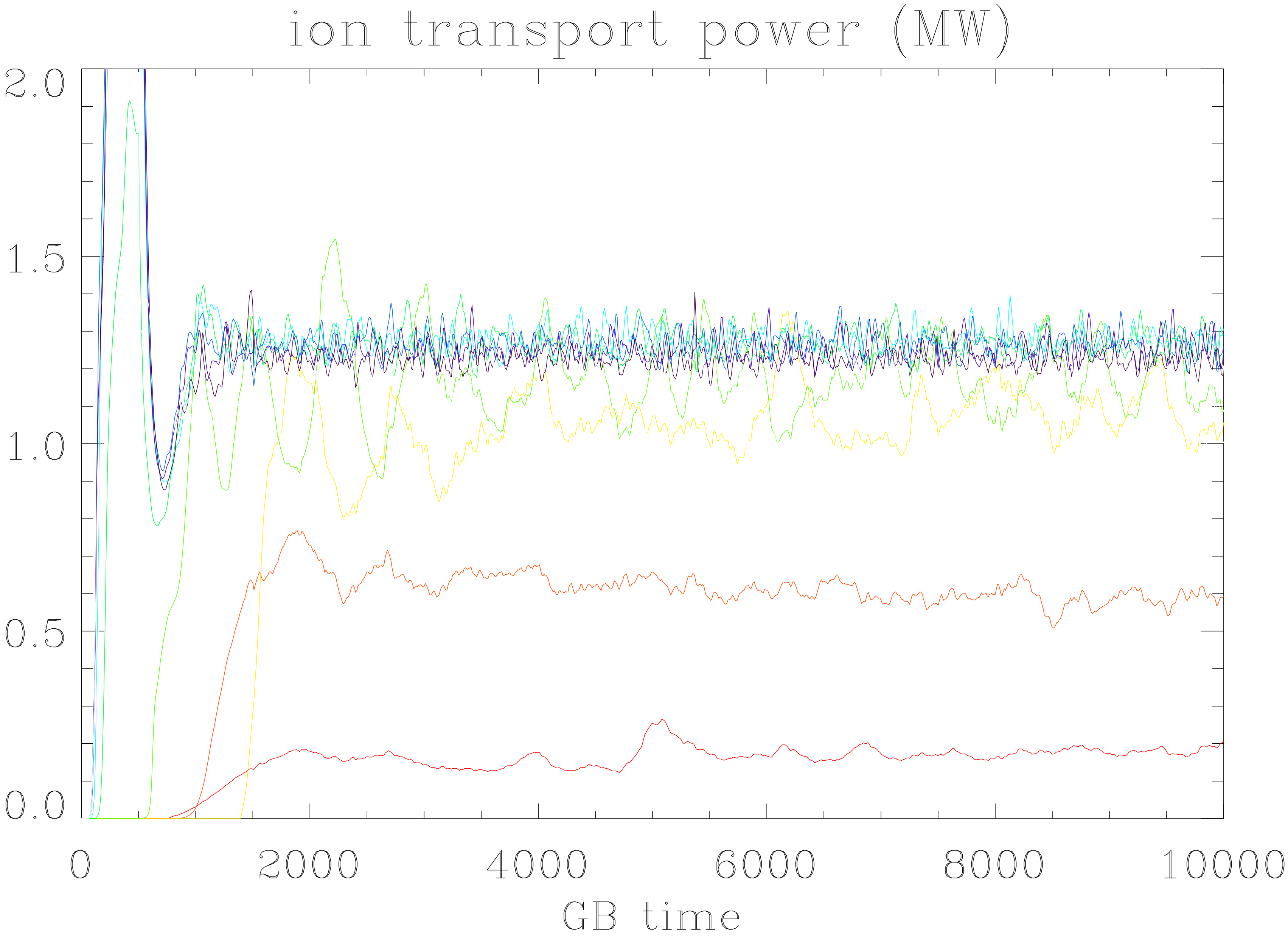
2 MW power together



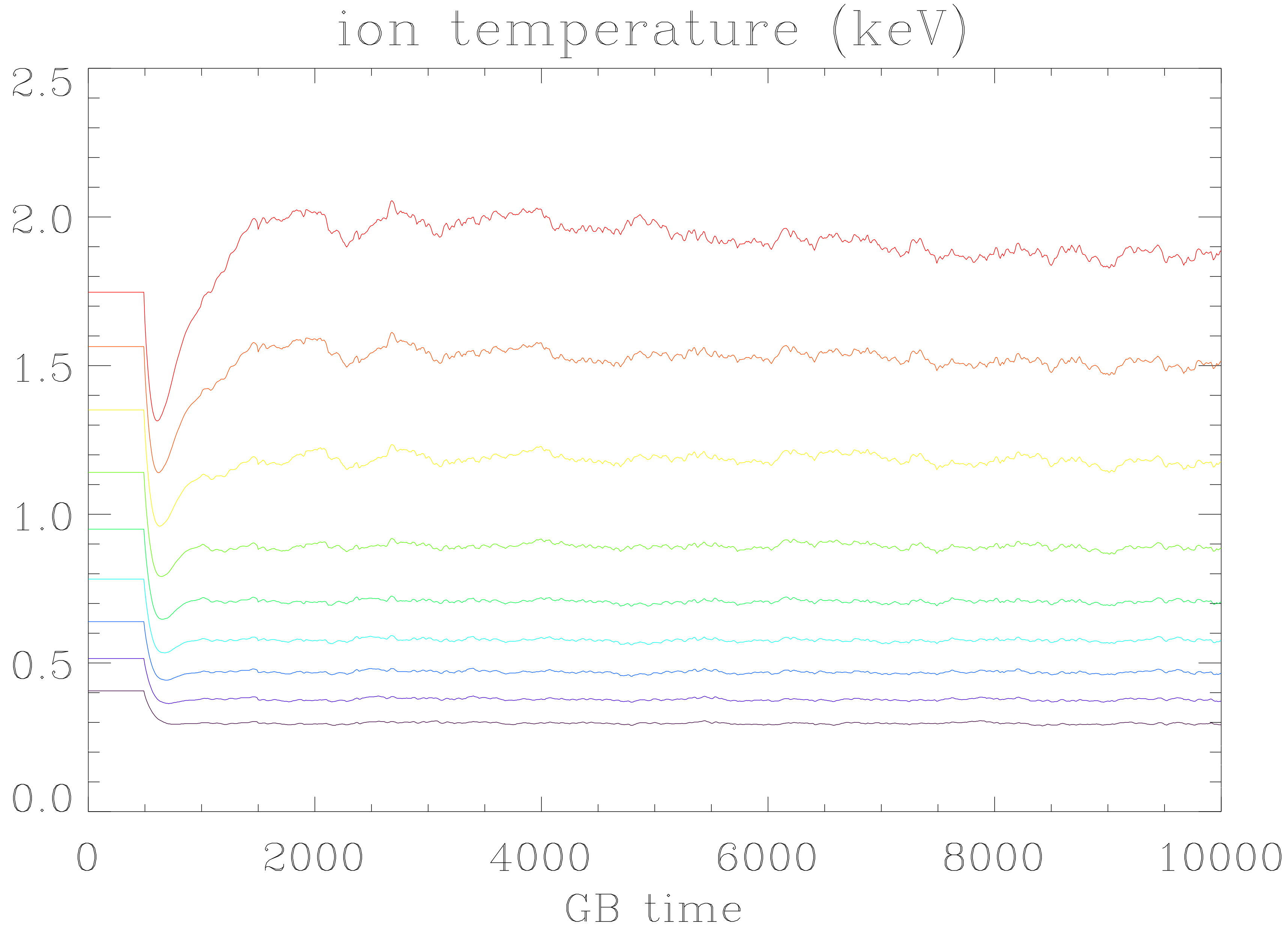
2 MW power together



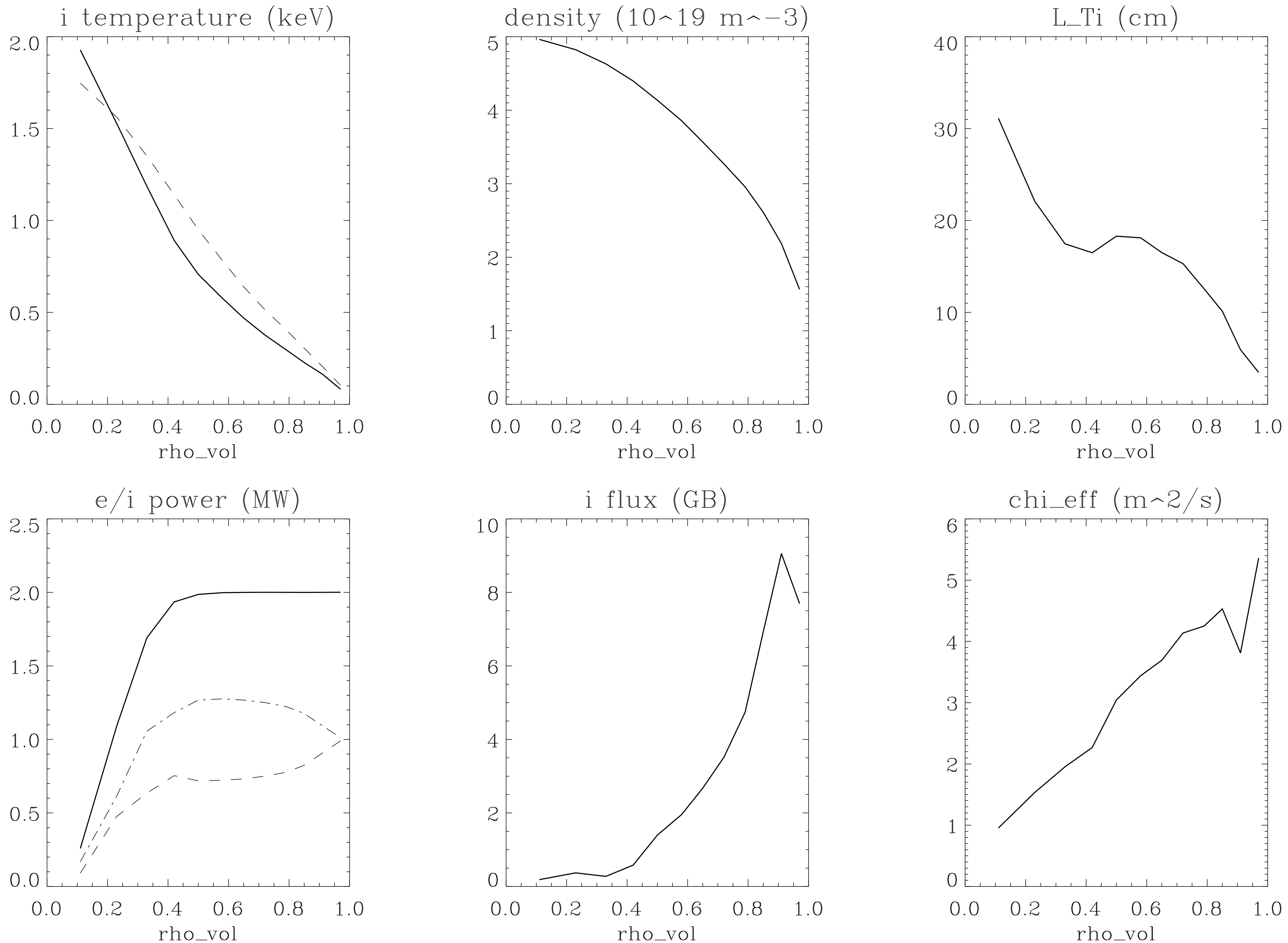
2 MW power together



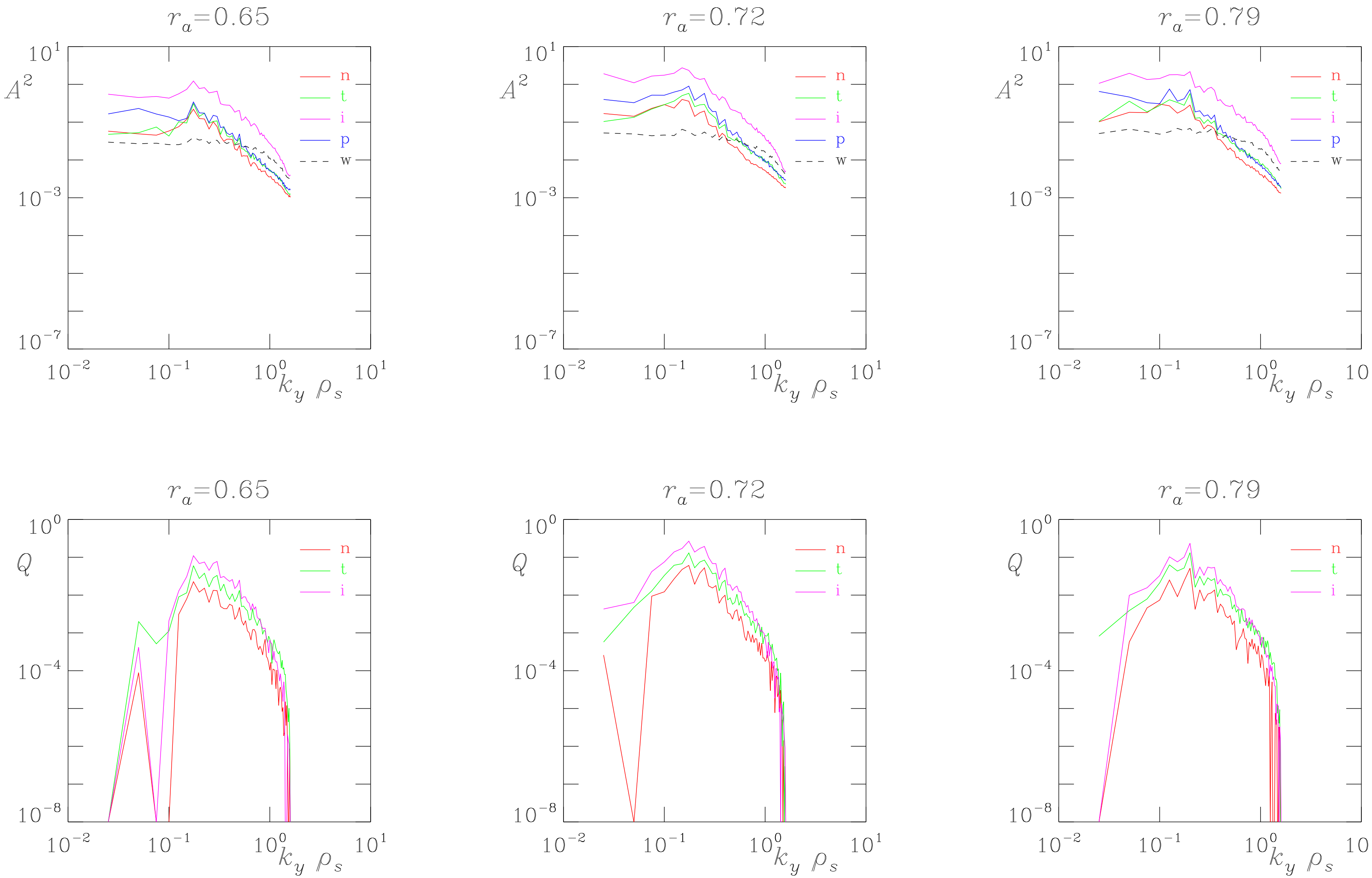
2 MW power together



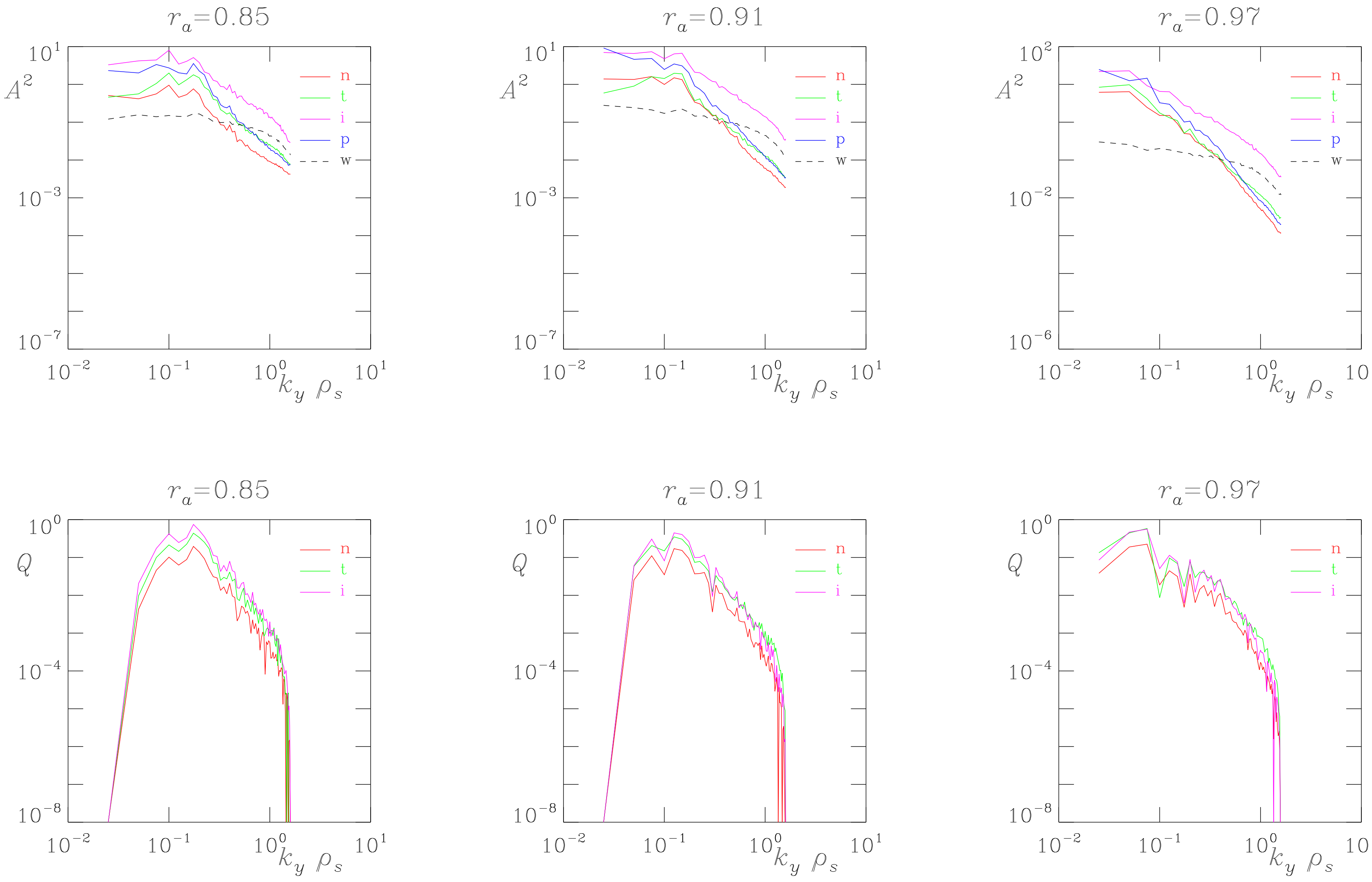
2 MW power together



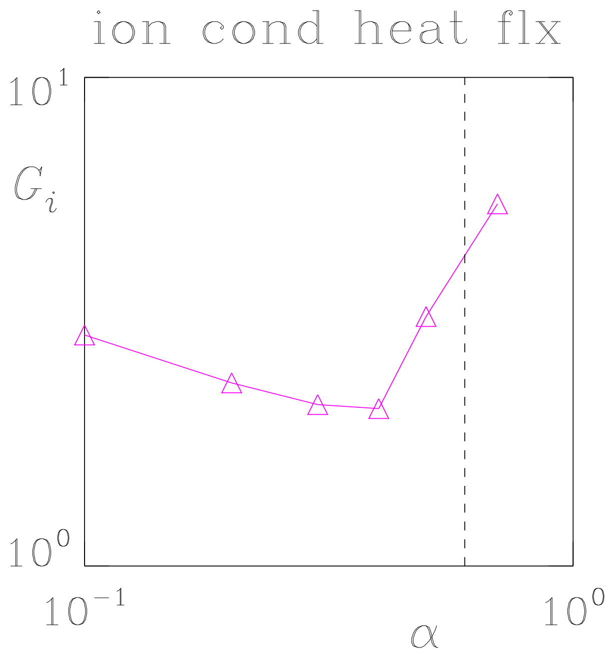
Amplitude and Flux Spectra Coreward

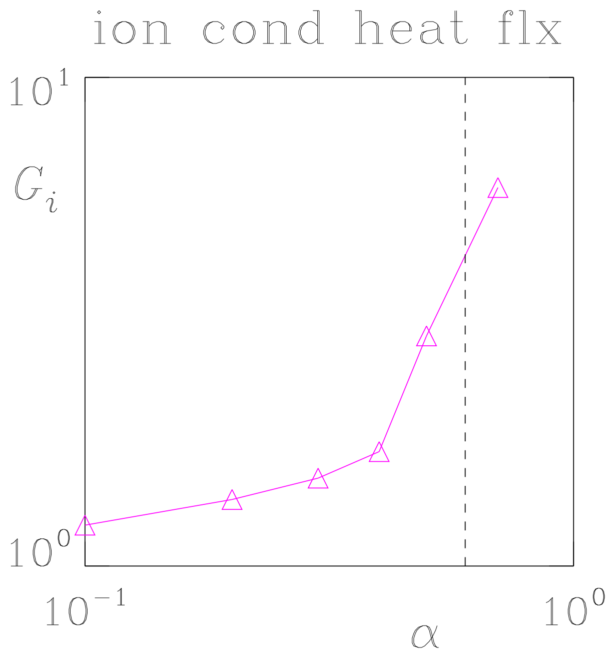


Amplitude and Flux Spectra Edgeward



gyrofluid computed transport, Drake's cases





- normalised units (gyro-Bohm, left), physical units (SI, right)
- the $\alpha = 0.6$ line is the L-H transition expected by the model

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