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SOLITONS, COLLAPSES AND TURBULENCE
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Turbulence Spreading and Nonlocal Transport in Magnetized Plasmas

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Outline

-- Definition of turbulence spreading, TS

-- Motivation: how does TS influence anomalous turbulent transport

-- 1D transport model (TSTM) accounting for turbulence spreading and relation to critical gradient model (CGM)

-- Comparison with a “simple” turbulence simulation: 2D interchange model

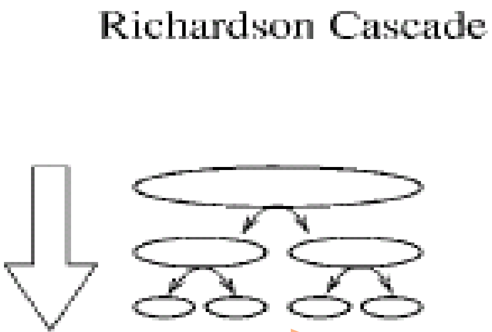
-- Applying the TSTM to perturbative transport experiment in tokamak plasmas: heat modulation and fast heat pulse propagation in JET.

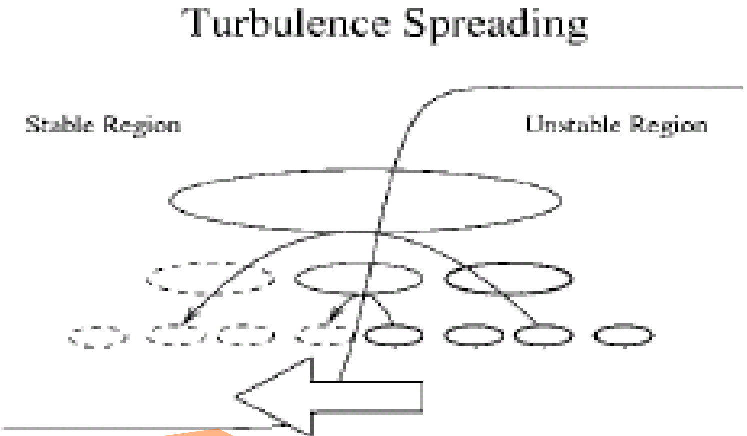
-- Non-locality in transport models

Turbulence Spreading

The turbulence energy itself is a transported quantity: it will spread from unstable regions of generation into stable regions.

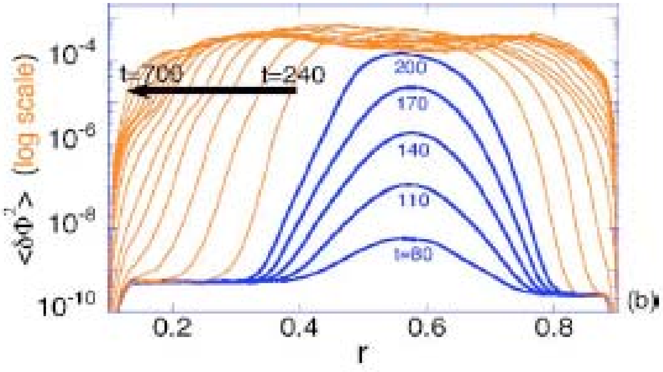
Plasma Turbulence: Garbet *et al,* NF **34**, 963 (1994); Gürcan, Diamond, Hahm, PoP, **13**, 052306 (2006); **14**, 055902 (2007); Garbet *et al.* PoP **14,** 122305 (2007)





Spreading in k-space, from “unstable” k to “stable” k

Spreading in configuration space from unstable region into stable region



Gyrokinetic simulations

Wang *et al. PoP* **14**, 072306 (2007)

Turbulent spreading well-known in fluid turbulence: turbulent overshoot, penetration

Local Transport Models

Quasi-linear approach and mixing length theory [Kadomtsev 1965]: Balance the linear growth of instability, γ, against *D*, the "*turbulent diffusion*"

$$D \propto \frac{\gamma}{k^2}$$

k is a "typical" perpendicular wave number of the turbulence.

More refined versions look at turbulent spectra and include off-diagonal terms.

Transport depends on local variables and gradients!

Successful approach, but drawbacks:

Local transport models do not account for:

- Up-gradient transport
- burstiness
- avalanches
- fast transport events

All observed effects!

Motivation for TSTM

- Turbulence spreading accounts for nonlocal effects: turbulence spreads into stable regions and give rise to transport there
- Includes naturally up-gradient transport
- May account for avalanche and bursty transport
- Non-diffusive effects: breaks relationship between gradients and fluxes (Ficks law)

Note: Turbulence spreading may work in basically two ways:

1. The turbulence spreading takes the stability boundary with it implying enhanced turbulence and transport in the “new” region
2. The turbulence penetrates into a stable region where the modes are damped, implying different transport characteristics as, e.g., up-gradient transport

Turbulence Spreading Transport Model (TSTM)

1D turbulent transport model of heat in the core (density profile fixed and flat), accounting for spreading of turbulence into stable regions:

$$\frac{\partial E}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r} r\left[D_0 E \frac{\partial}{\partial r} E\right] + \gamma E - (\gamma_0 + \beta E^2)E,$$

⇨ Turbulent energy, growth, saturation and spreading D_0 const.

$$\frac{\partial T}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r} r q + \chi_0 \frac{1}{r}\frac{\partial}{\partial r} r \frac{\partial}{\partial r} T + S(r)$$

⇨ Temperature transport

Growth rate: $\gamma = \lambda\left[\kappa_T - \kappa_c\right]$; λ: free parameter; $\kappa_T \equiv |\partial_r T|/T$, κ_c: critical.

The heat flux: $q = \left\langle \tilde{T} v_r \right\rangle$, $E \approx \left\langle v_r^2 \right\rangle$. cross coherence $\xi \propto \gamma$ between $\tilde{T}$ and v_r:

⇨ $q = \xi \sqrt{\left\langle \tilde{T}^2 \right\rangle \left\langle v_r^2 \right\rangle}$, $\tilde{T}/T = C\sqrt{E}$, i.e., and $\left\langle \tilde{T}^2 \right\rangle = C^2 \left\langle E \right\rangle \left\langle T^2 \right\rangle$,

$\underline{q = C\gamma E T = C\lambda E T\left[\kappa_T - \kappa_c\right].}$ $q < 0$ for $\kappa < \kappa_c$: ⇨ Upgradient transport !

Stable modes!

Simple model to demonstrate the effect!

TSTM vs. Turbulence Simulations

Use a simple 2D interchange model for testing the TSTM:

$$\partial_t \Omega + \vec{v} \cdot \nabla \Omega + \mathcal{K}(T) = \mu_\omega \nabla^2 \Omega$$

$$\partial_t T + \vec{v} \cdot \nabla T - T\mathcal{K}(\phi) + \mathcal{K}(T) = \mu_T \nabla^2 T + S(T)$$

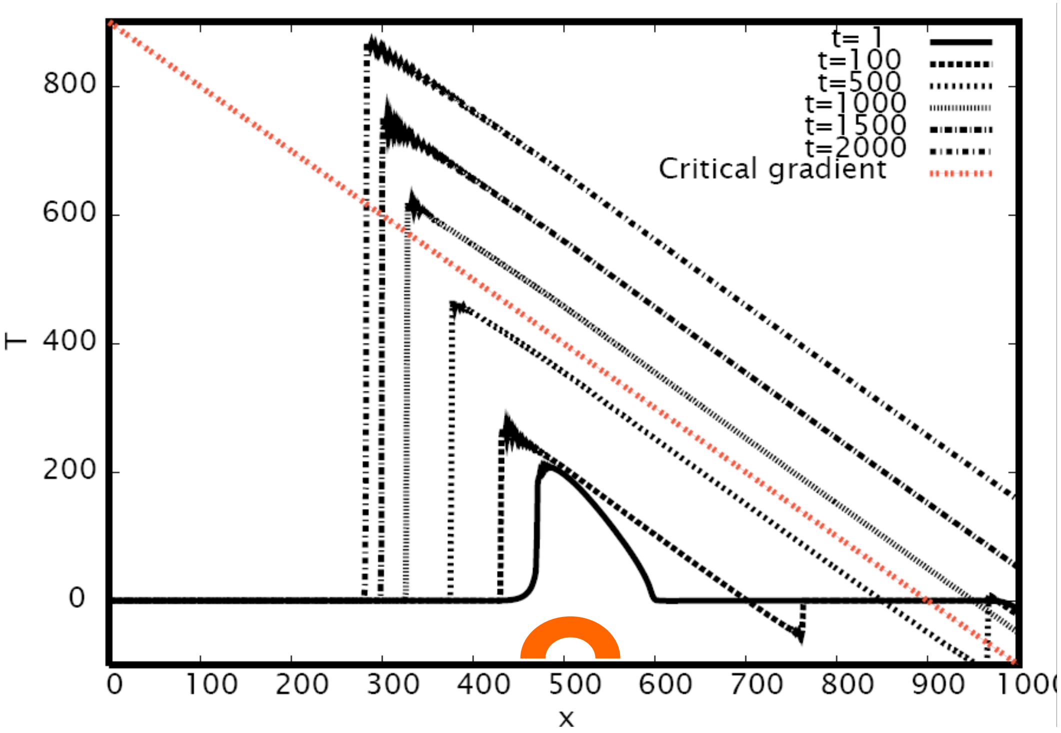
Ω is the vorticity $(\Omega = \nabla^2 \phi)$ perpendicular to the (x, y)-plane

Contains curvature as drive, heat source and exhibits threshold for instability. T is a proxy for temperature or density.

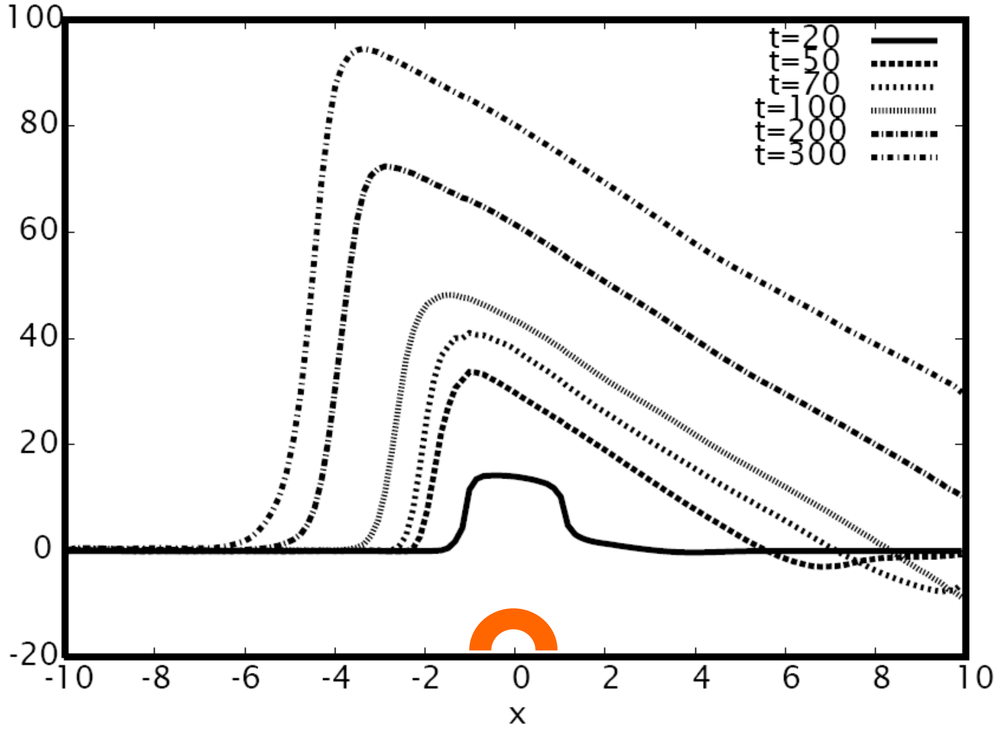
Naulin *et al* Phys Plasma 12, 122306 (2005)

Profile Evolution

TSTM



2d simulation



Evolution of profiles: location of source indicated

The profile evolves toward “marginally stable” profile

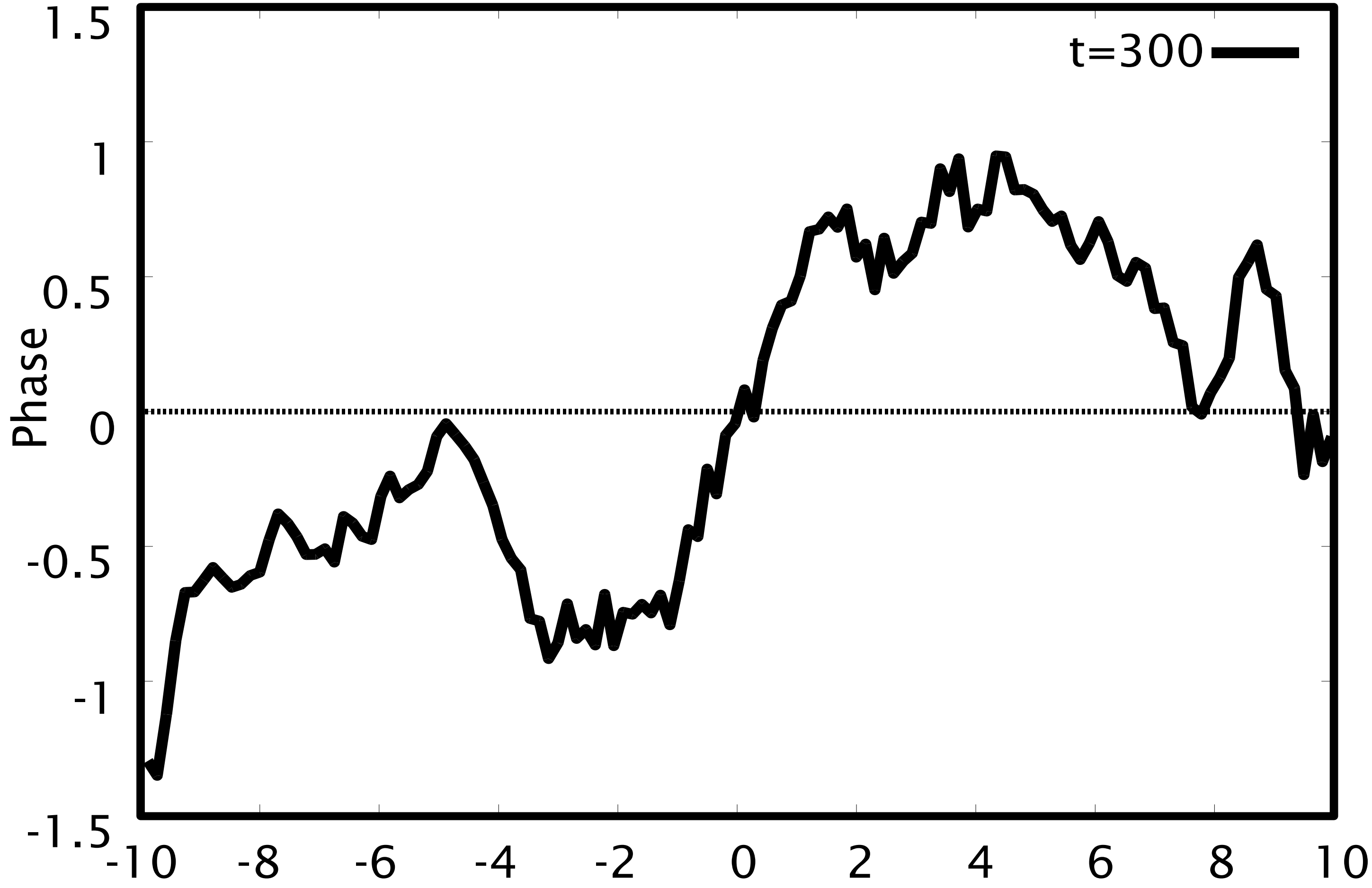
Up-gradient Transport

Where does the energy come from?

- Gradient is a drive for turbulence.
- The energy input into turbulence (growth-rate) is connected with positive flux (phase relation between fluctuations).
- Turbulence is damped in stable regions.
- Turbulent energy is exhausted not in dissipative effects, but in reversal of transport direction (phases between fluctuations)
- Role of stable modes!!!! (which are ignored in traditional turbulent transport models)

Stable modes have different phase relationship between turbulence and the transported quantity than unstable ones!

Phase Relation

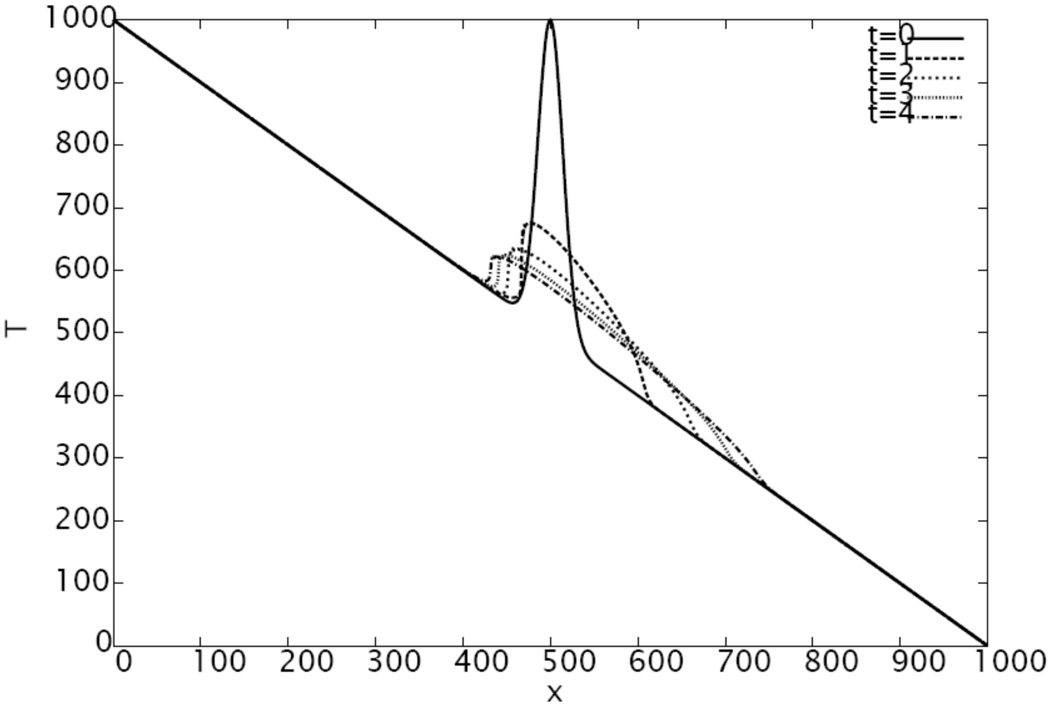


Average phase between temperature and radial velocity fluctuations

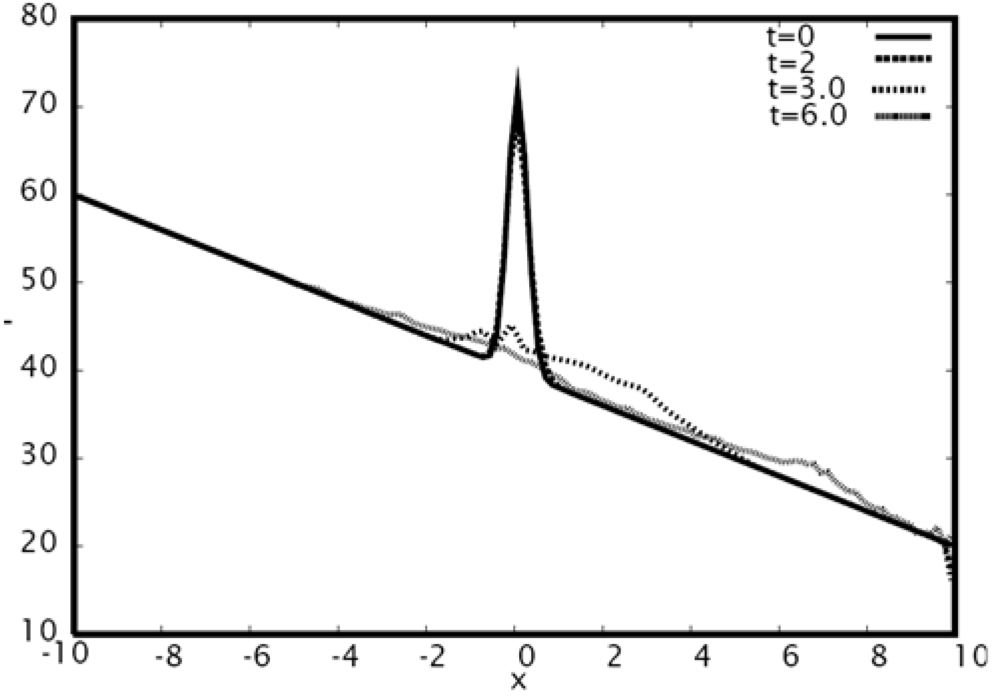
Note: sign of $\Gamma(=\left\langle \tilde{T} v_r \right\rangle)$ is determined by sign of phase between T and v_r

Evolution of Temperature Peak

TSTM



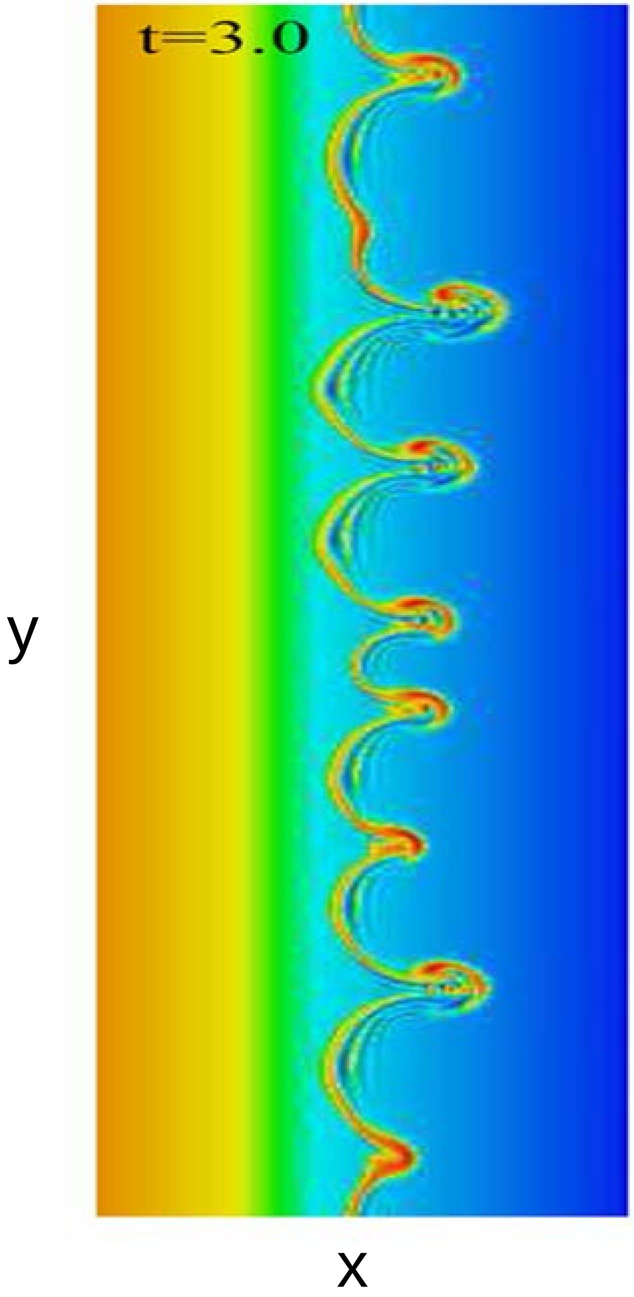
2D simulation



Heat Pulse initialized on a subcritical background gradient.

Up-gradient transport as well as front propagation visible

2D-Evolution



Initialize pulse on a subcritical background gradient.

Instability develops into mushroom like structures, clearly neither local nor diffusive transport...

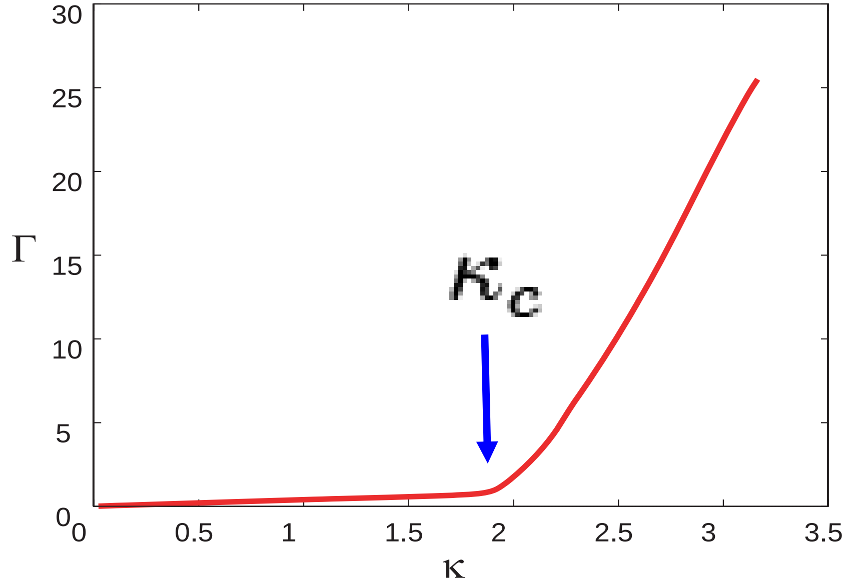
However, the mean profile appears to be well described by the 1D transport model!

TSTM and CGM

$$\begin{aligned}\frac{\partial E}{\partial t} &= \frac{1}{r}\frac{\partial}{\partial r} r\left[D_0 E \frac{\partial}{\partial r} E\right] + \gamma E - (\gamma_0 + \beta E^2)E, \\ \frac{\partial T}{\partial t} &= -\frac{1}{r}\frac{\partial}{\partial r} r q + \chi_0 \frac{1}{r}\frac{\partial}{\partial r} r \frac{\partial}{\partial r} T + S(r)\end{aligned}$$

$D_0 = 0$ Critical Gradient Transport model. → $q_t = C\frac{\lambda^{3/2}}{\beta^{1/2}} T\left[\kappa_T - \kappa_c\right]^{3/2} H\left[\kappa_T - \kappa_c\right] - \chi_0 \partial_r T$

The model then reduce to the standard critical gradient model, CGM, widely used in describing perturbative transport experiments



Imbeaux *et al.* PPCF 43, 1503 (2001)

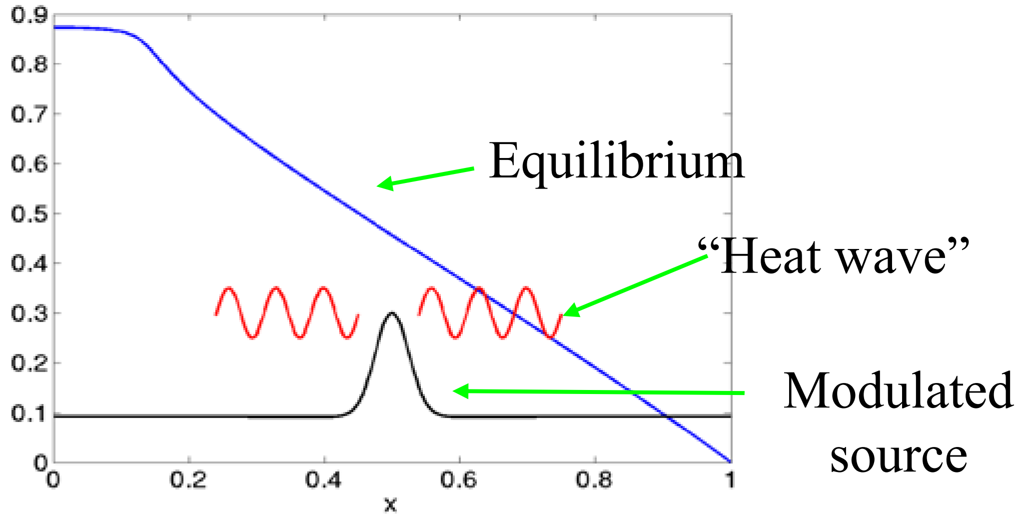
Mantica & Ryter, C.R. Physique 7, 634 (2006)

The Flux-Gradient space: dynamics governed by the trajectory.

Determined by local properties.

Heat Modulation

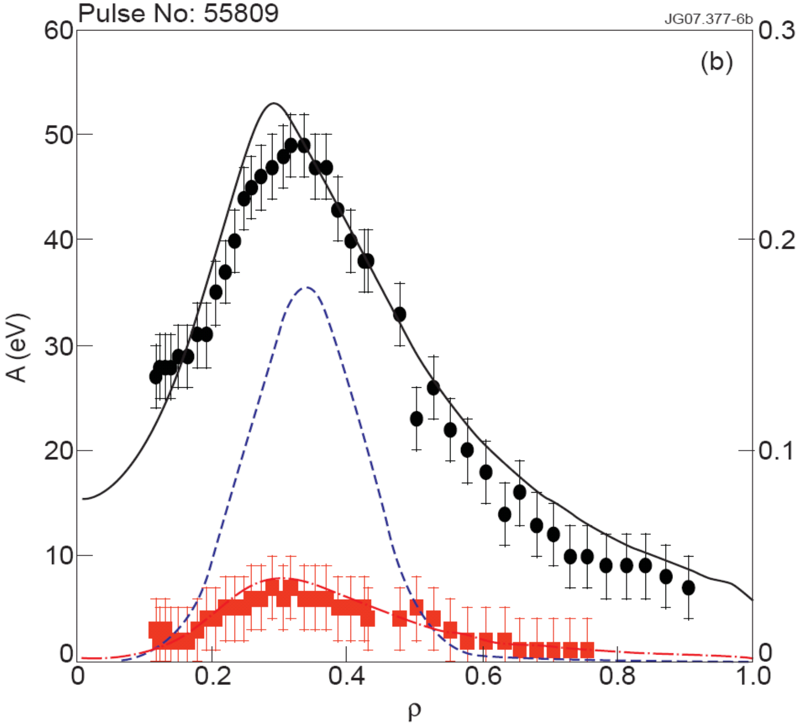
Modulation of T_e by off-axis ICH in JET

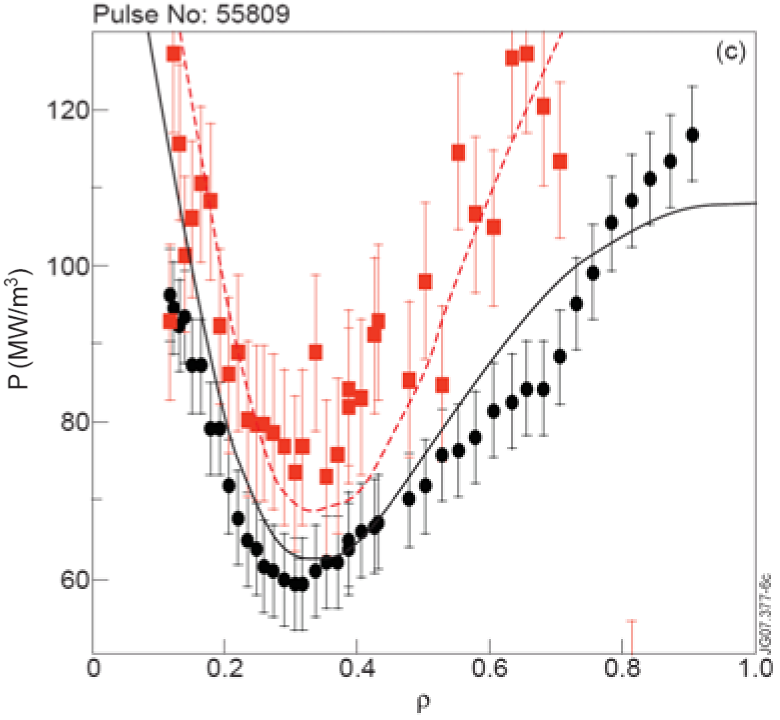


Equilibrium

“Heat wave”

Modulated source



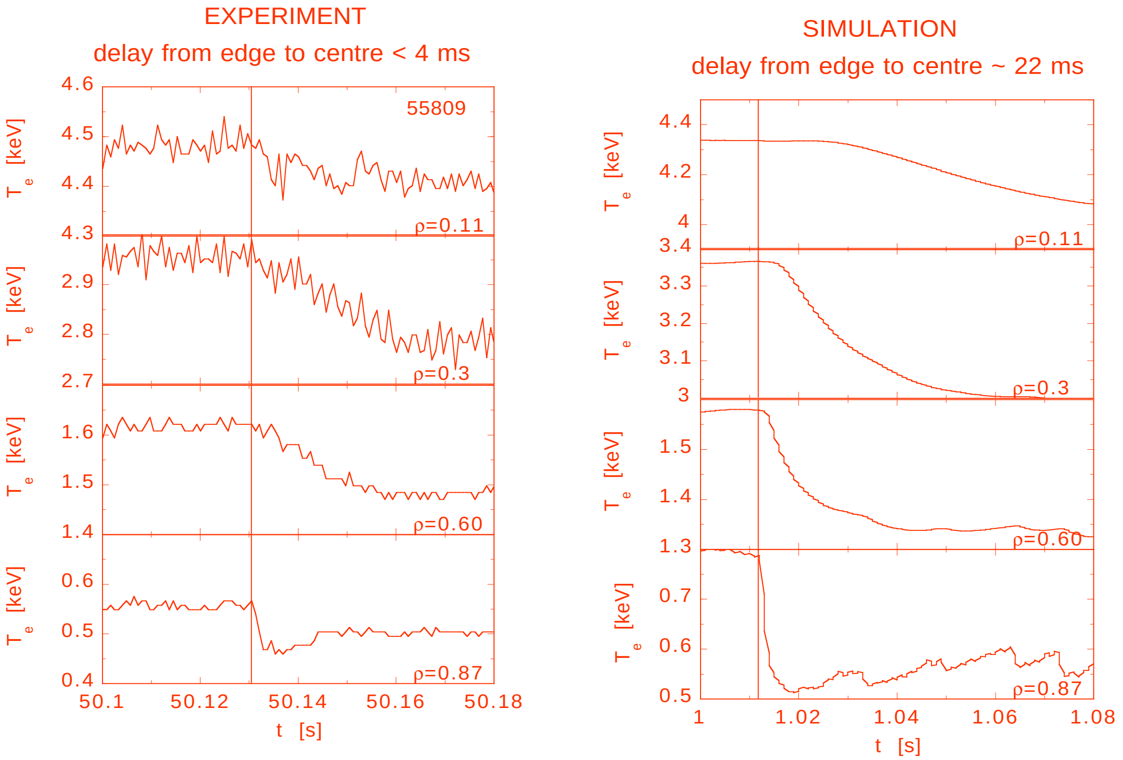


Fine agreement with CGM

Transient Transport Events

Application to transient transport events in JET: Fast propagation of cold pulse

P. Mantica et al., (Proc. 19thIAEA Conf. Lyon, 2002) EX/P1-04, IAEA 2002



Transient cold pulse, initiated by local cooling at the edge

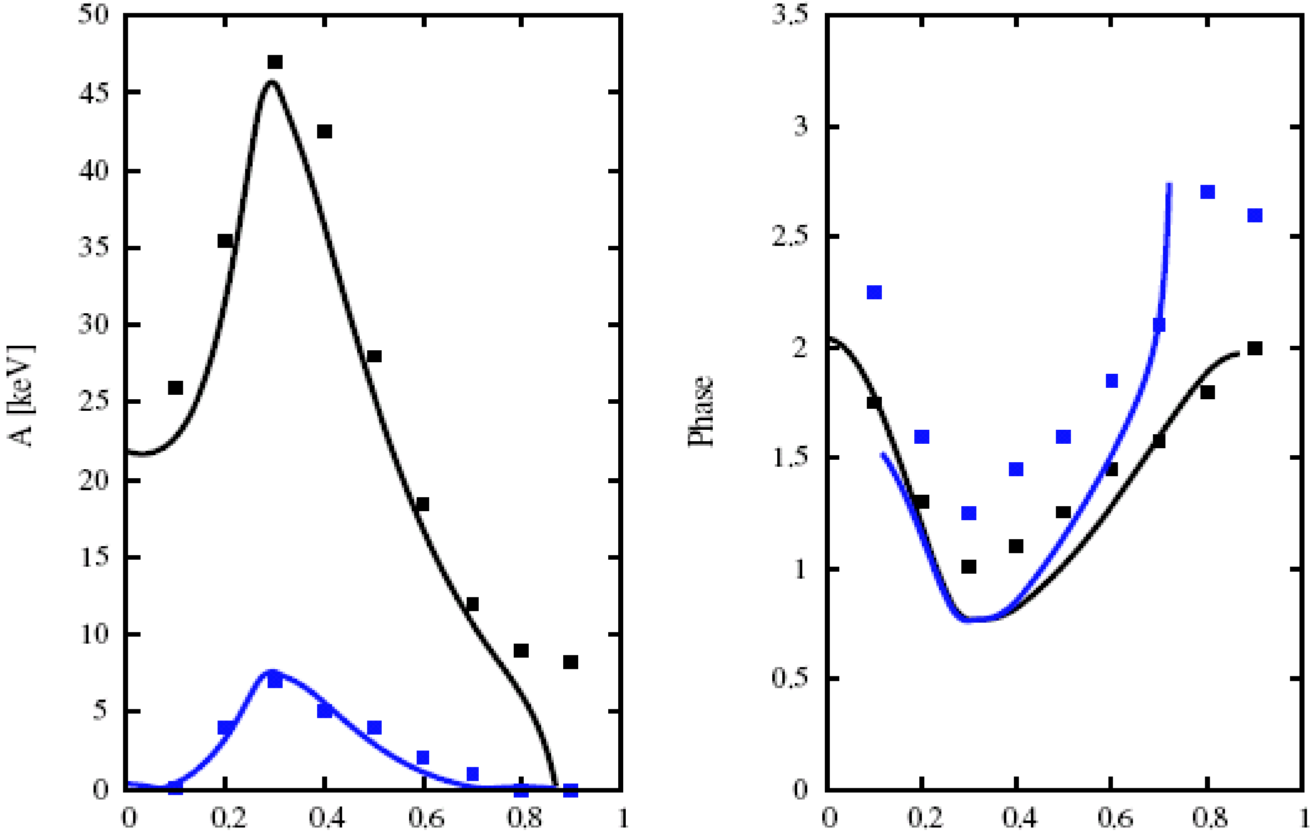
The pulse propagates much faster than heat modulation, which was well described by a “standard” critical gradient model, CGM.

Challenge: explain both effects within the same model!

Incompatible with local transport models!

Cold pulse experiment, JET # 55809; CGM simulation with coefficients fitting heat modulation experiment, too slow for cold pulse.

Results from TSTM: Heat Modulation

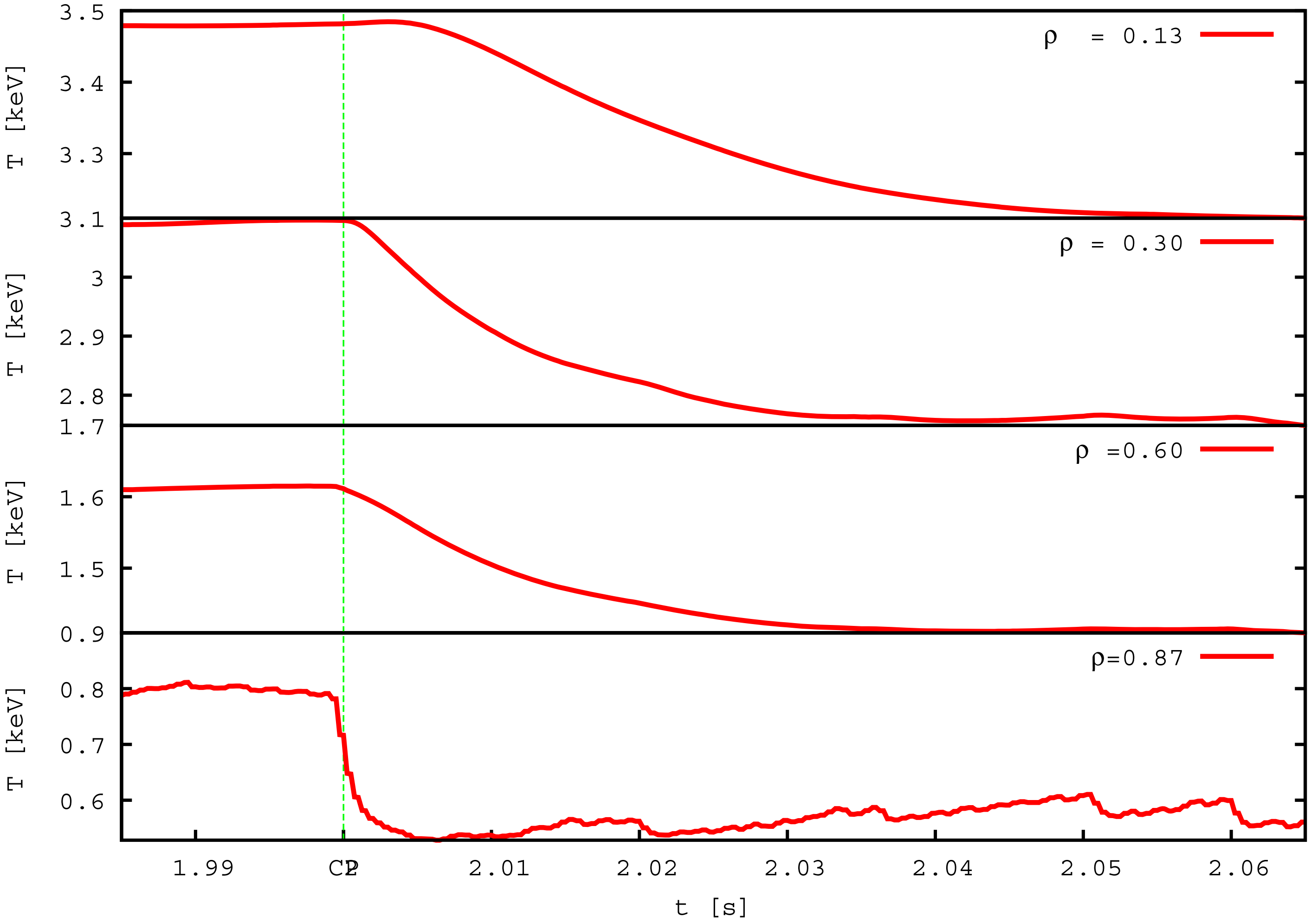


Lines from TSTM

Points from experimensts

TSTM results matches the amplitudes and phases of the first harmonic and third harmonic of the “heat wave”

TSTM Cold Pulse Propagation



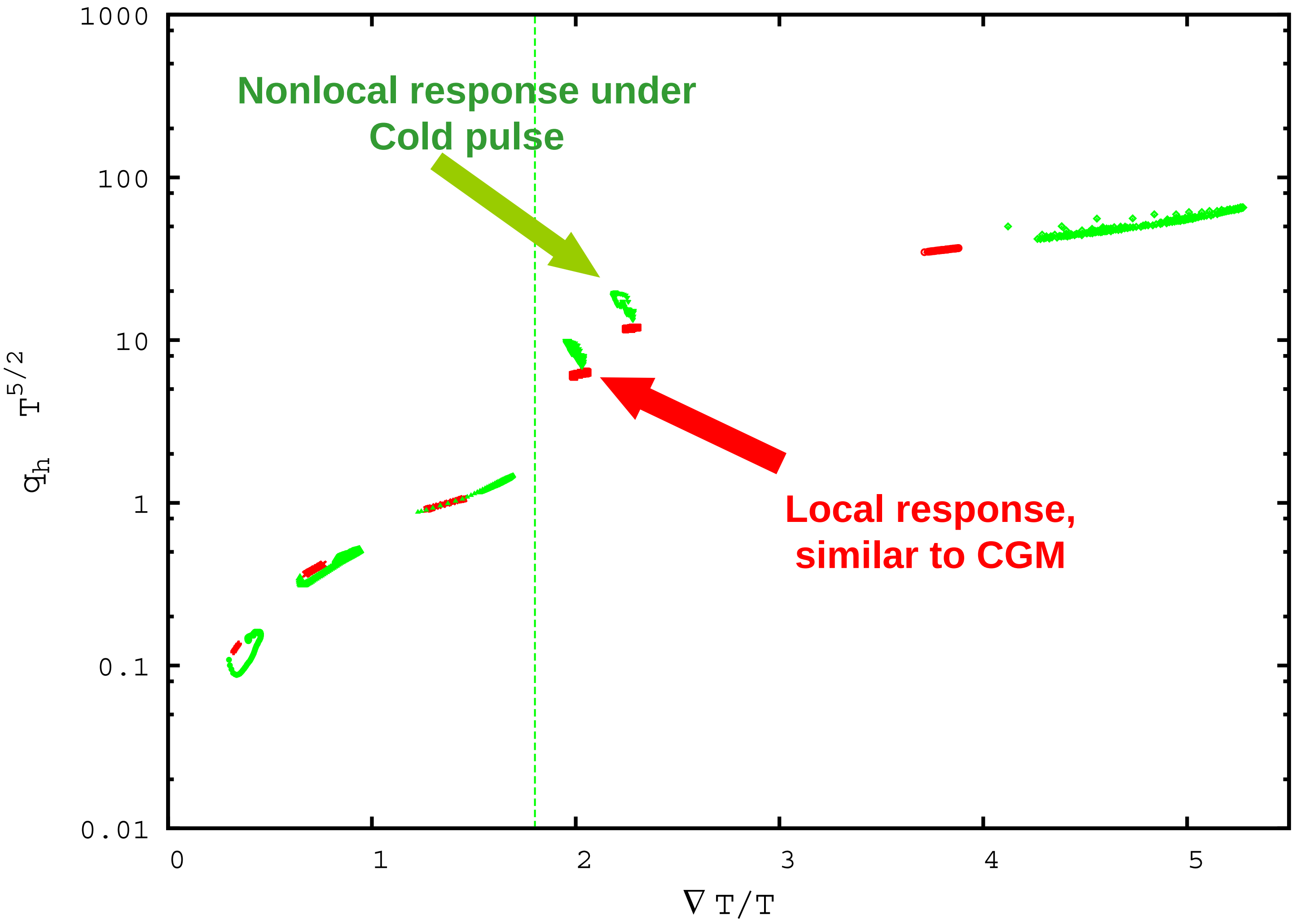
Cold pulse at center in < 8ms for

same parameters

as modulation experiment!

TSTM modelling of cold pulse propagation

Nonlocal Response of TSTM



Nonlocal response under Cold pulse

Local response, similar to CGM

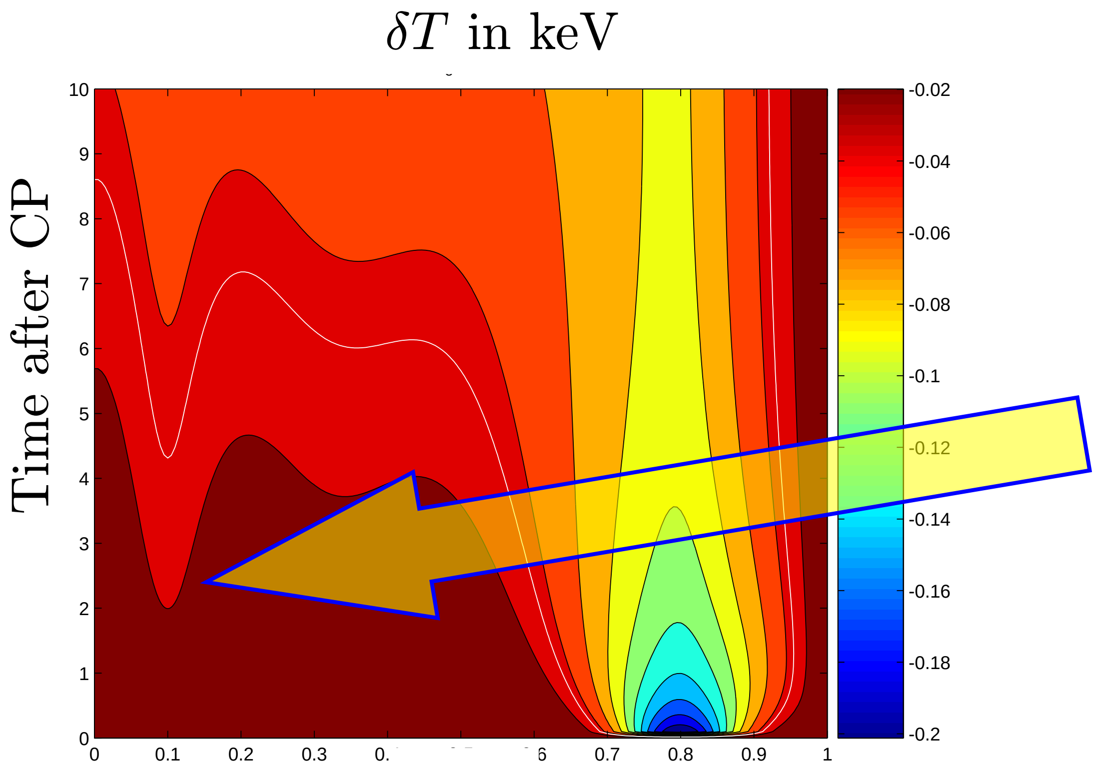
- Clear nonlocal response for cold pulse: Significant increase of flux at constant gradient!
- Effect due to increase of turbulence amplitude from cold pulse perturbation.
- In stable region response is negative as increase turbulence drives upgradient transport!

Local response of TSTM is seen in Flux/Gradient trajectories. **Modulation** and **Cold Pulse** at six fixed radial positions. Note logarithmic scale.

Fractional Diffusion

Nonlocality can be included f.x. by fractional diffusion model

del-Castillo-Negrette et al. Nucl. Fus, **48**, 075009 2008



Nonlocal trigger of transport in fractional diffusion model

Conclusions

- Turbulent spreading is important in many systems – in plasmas often observed, in turbulence simulations and experiments
- Turbulence spreading introduces “non-locality”
- Up-gradient transport of quantity driving the instability
- TSTM compares well with direct turbulence simulations
- TSTM compares well with heat modulation and fast pulse propagation experiments
- May explain inversion of cold pulse observed in particular cases, i.e., cooling at the edge leads to a temperature increse in the center
- A first step to include more complicated transport processes into “simple” models