Evgenii Kuznetsov - 70
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Nonlocal effects in transport: The role of turbulence energy

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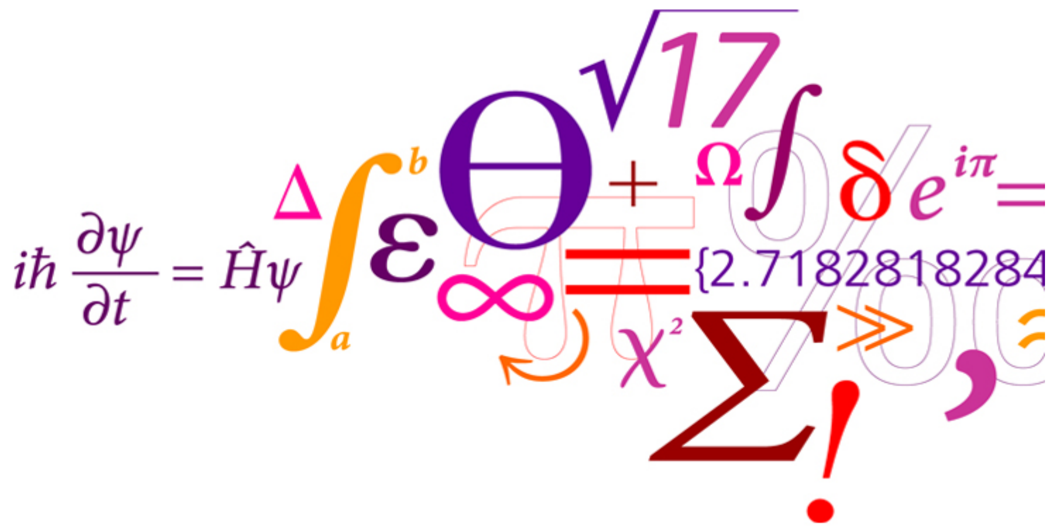

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Department of Physics

Outline

- Turbulence spreading
- Effects on anomalous turbulent transport
    - nonlocality
    - up-gradient transport
- 1D transport model (TSTM) accounting for turbulence spreading and relation to critical gradient model (CGM)
- Comparison with “simple” 2D interchange turbulence simulation
- Applying the TSTM to JET experiment with heat modulation and fast heat pulse propagation
- Inclusion of momentum transport: Spontaneous spin up and rotation reversal

Local Transport Models

Quasi-linear approach and mixing length theory [Kadomtsev 1965]:

Balance the linear growth of instability, γ, against *D*, the "*turbulent diffusion*"

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

k is a "typical" perpendicular wave number of the turbulence (Drift-wave type…).
More refined versions look at turbulent spectra and include off-diagonal terms (f.x., Weiland transport model, GLF….).

Transport depends on local variables and gradients!

Gyro Bohm scaling:

$$\chi \sim (T_e / eB)\, \rho_I\, a$$

Petty, PRL, 1995

Pedestal buildup after LH transition, f.x. does not influence transport analysis in turbulent core!

What do we mean by.....

- Non-local
  - Transport at location R is **not** a function of gradients, temperature, density etc. **AT** location R
  - Water flow downstream does not always depend on local conditions....

- Non-diffusive
  - Relation gradient-flux is broken
  - Non-locality ONE possible reason

Local Transport models

Successful approach, which works mostly.

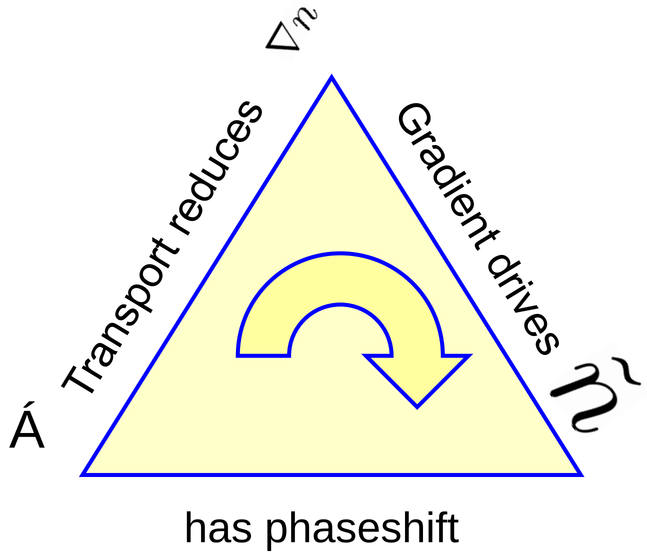
Motivates use of local turbulence simulations (flux-tube codes, periodic boundaries in radial direction etc) to calculate transport.

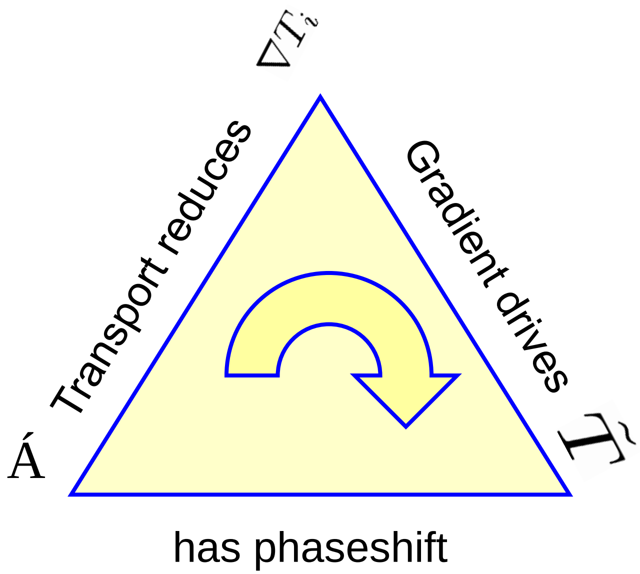
Local turbulent transport models do not account for:

- up-gradient transport of quantity driving turbulence
- variation in speed of transport events
- broken Gyro-Bohm scaling

Burrell, PPCF 48, 2006

Transport





Free energy in gradient drives turbulent flux. Gradient is reduced towards the critical one.

Ex**B**-velocity fluctuations lead to transport, with appropiate phase shifts in density and temperature

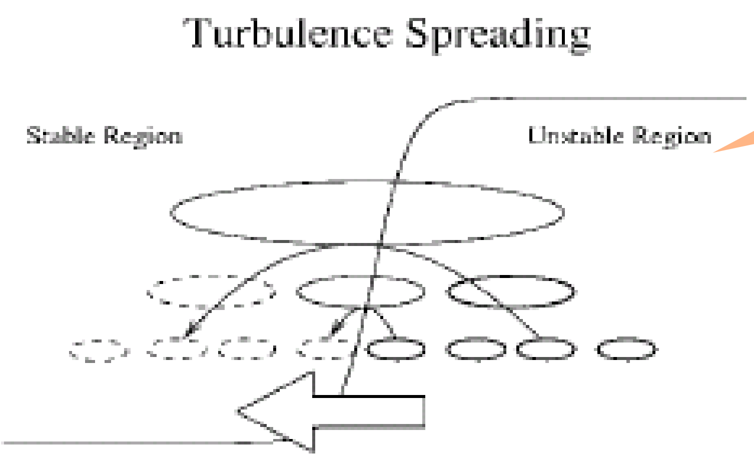
Turbulent density flux:

$\Gamma = \langle \tilde{n}\, \boldsymbol{v}_{ExB} \rangle$

Turbulence Spreading

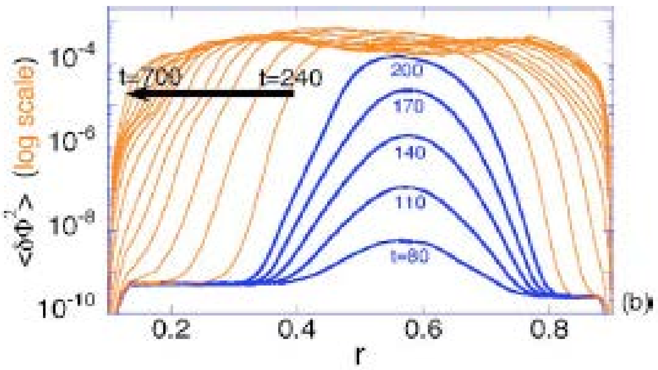
The turbulence energy is a transported quantity in itself: it will spread from unstable regions of generation into stable regions.

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 configuration space from unstable region into stable region

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



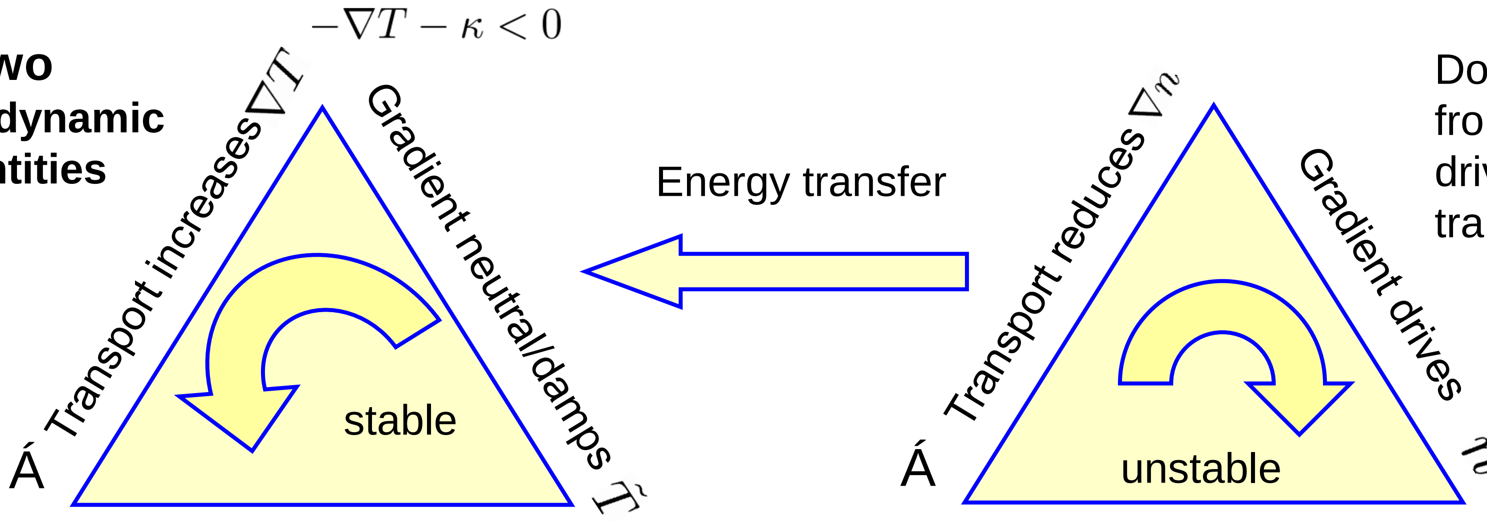
Gyrokinetic simulations

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

We propose: Turbulence energy is an active thermodynamical quantity in itself

Upgradient transport role of turbulence

Two thermodynamic quantities

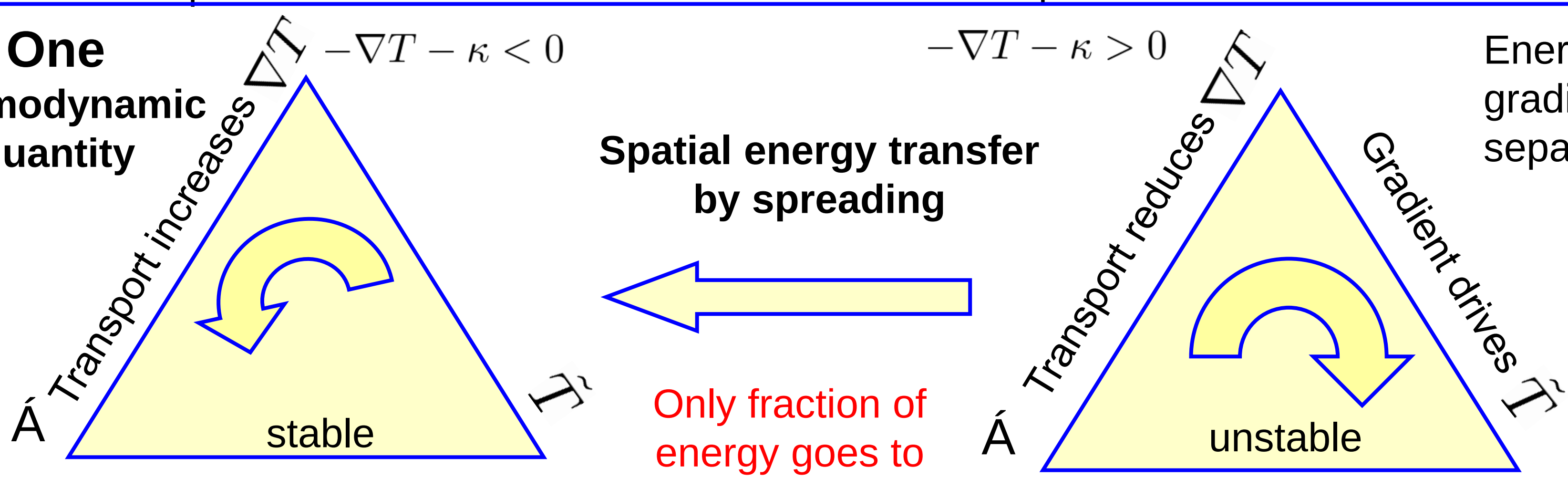


stable mode
phaseshift < 0

unstable mode
phaseshift > 0

Dominant energy input from second gradient can drive upgradient transport

One thermodynamic quantity



stable mode
phaseshift

Only fraction of energy goes to upgradient transport

unstable mode
phaseshift

Energy input by gradient at spatially separated location.

Motivation for TS Models

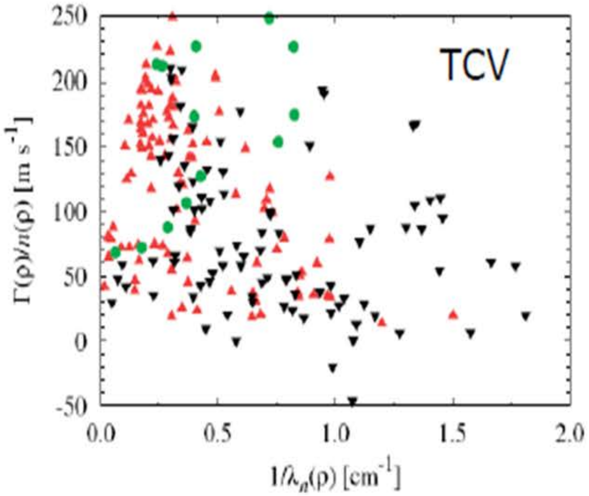
- Turbulence spreading accounts for nonlocal effects: turbulence is generated in different region than transport occurs.
- Breaks relationship between gradients and fluxes (Ficks law)
- Includes up-gradient transport of turbulence driving component

Turbulence spreading works in basically two ways:

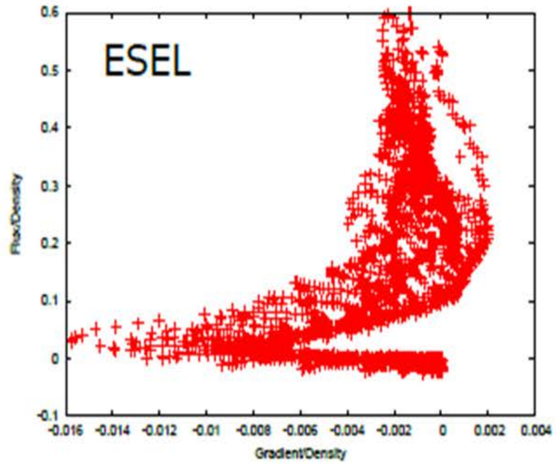
1. The turbulence spreading can increase transport towards the critical gradient in stable regions, works as thermodynamically active component, not just as local parameter.
2. Transport can depend on changes to the system spatially afar.

Test the simplemost model for these effects

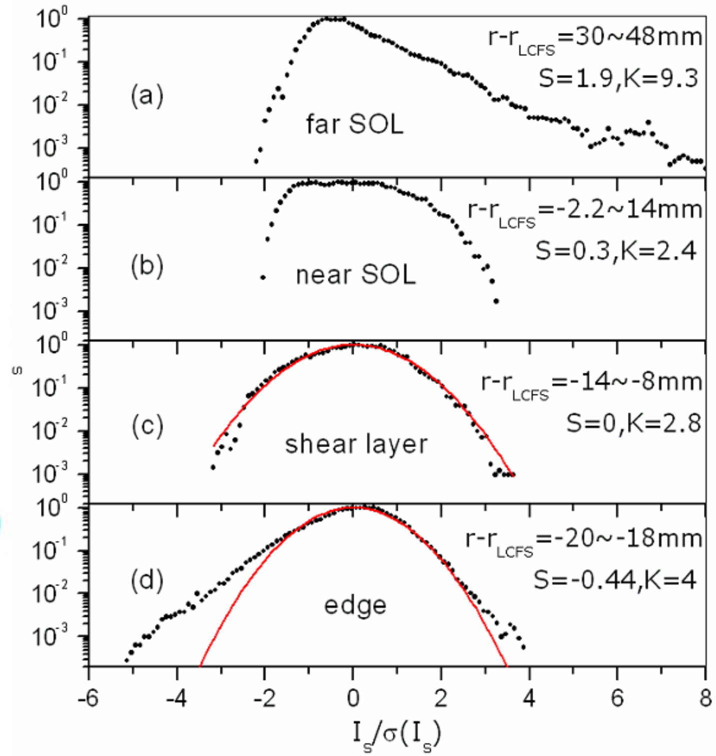
Transport in the SOL: Nonlocal, non Fickian, universal (ESEL simulation/JET/TCV data)



Garcia *et al.*, J. Nucl. Mater. 263-265, 575 (2007)



Naulin, J. Nucl. Mater. 263-265, 24 (2007), (PSI 2006)



Transport modelling: linear combination of effective convection and diffusion

$$\Gamma = nV_{\text{eff}} - D_{\text{eff}}\frac{\partial n}{\partial r} \quad \Rightarrow \quad \frac{\Gamma}{n} = V_{\text{eff}} - D_{\text{eff}}\frac{1}{n}\frac{\partial n}{\partial r}.$$

- Flux in SOL does not depend on local gradients
- Ficks law does not apply
- Structures/turbulence generated at LCFS (Xu et al. NF 2009): Turbulent structures spread from this location through SOL:

Parameters set at LCFS/Pedestal

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:

$$\partial_t T = -\nabla \cdot q_h + \frac{3}{2}\nabla \cdot \left(\chi_0 T^{5/2} q^{3/2} \nabla \log T\right) + S(r)$$

$$\partial_t E = \frac{1}{r}\partial_r r \left[D_0 E \partial_r E\right] + \gamma E - \beta E^3$$

Fisher–Kolmogorov–Petrovskii–Piskunov (FK) type equation,

Growth rate $\boxed{\gamma = \lambda\sqrt{-\nabla T - \kappa},}$ with λ a free parameter

Heat flux $g_h = \left\langle \tilde{T} v_r \right\rangle$ with $E \sim V_r^2$

Cross coherence $\xi \propto \tanh\gamma$

$$q_h = \xi\sqrt{< T^2 >< V_r^2 >}\; T \sim C\sqrt{E}$$

$q_h > 0$ for $\gamma > 0$

$q_h < 0$ for $\gamma < 0$

$$q_h = C\tanh(\gamma)ET$$

Upgradient transport for damped modes!

No effects of turbulence spectra taken into account. Just a simple starting point for a model...

Test of TSTM vs. DNS

Use a 2D interchange model for testing the TSTM:

$$\partial_t \omega + \vec{V} \cdot \nabla \omega + \mathcal{K}(T) = \mu_\omega \nabla^2 \omega \quad (1)$$

$$\partial_t T + \vec{V} \cdot \nabla T + T\mathcal{K}(\phi)\mathcal{K}(T) = \mu_T \nabla^2 T \quad (2)$$

is the vorticity ($\omega = \nabla^2 \phi$) perpendicular to the (x; y)-plane

Contains curvature for energy exchange,

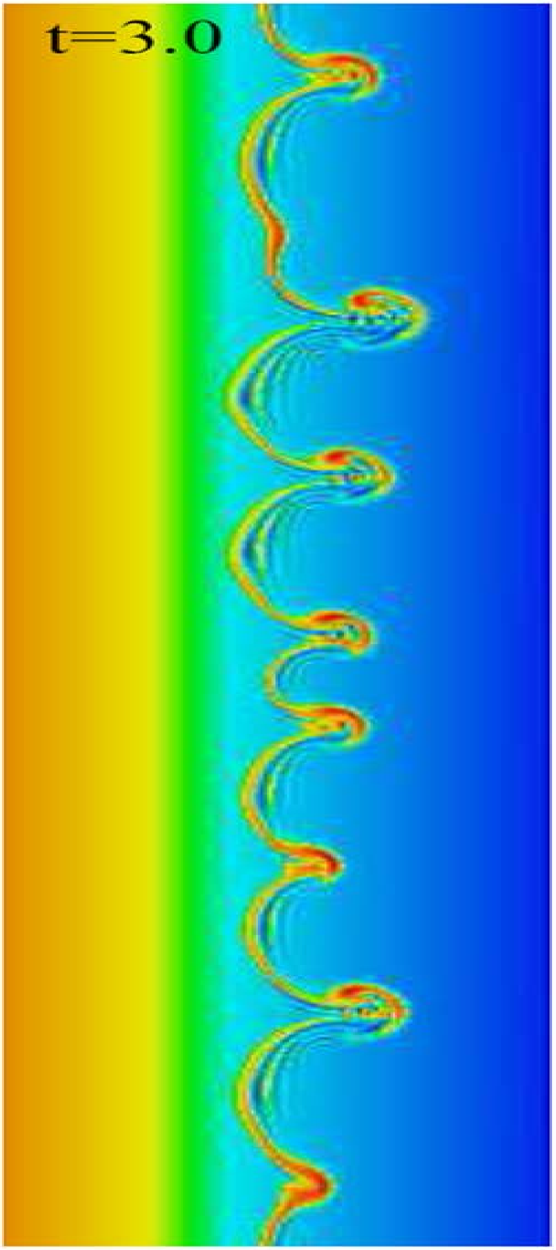
heat source

threshold for instability, due to curvature.

T is a proxy for temperature or density.

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

2D-Evolution



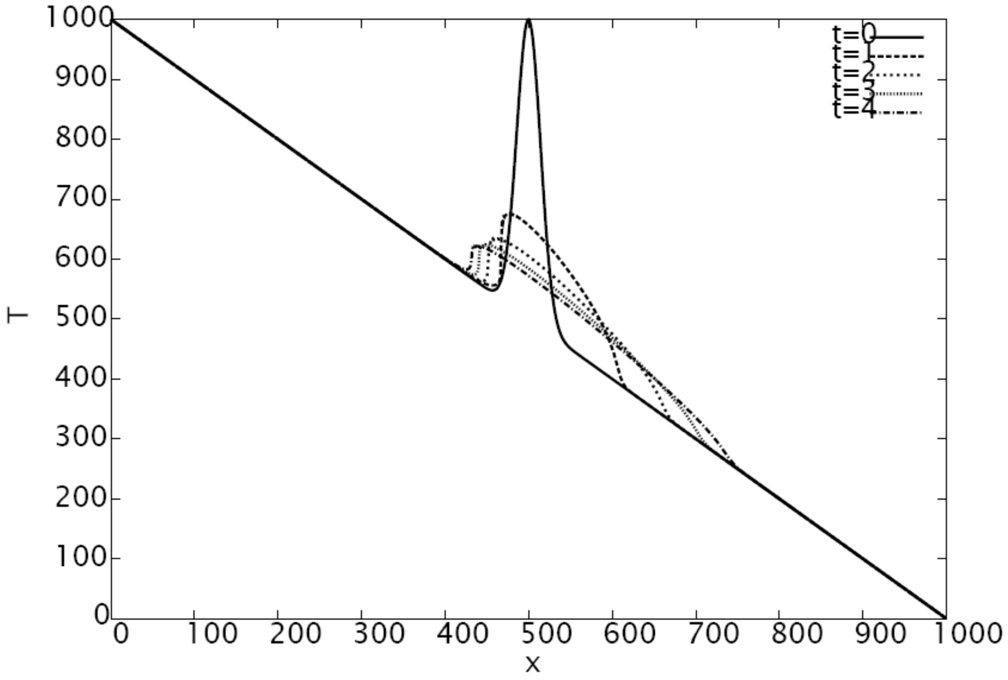
Initialize pulse on a subcritical background gradient.

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

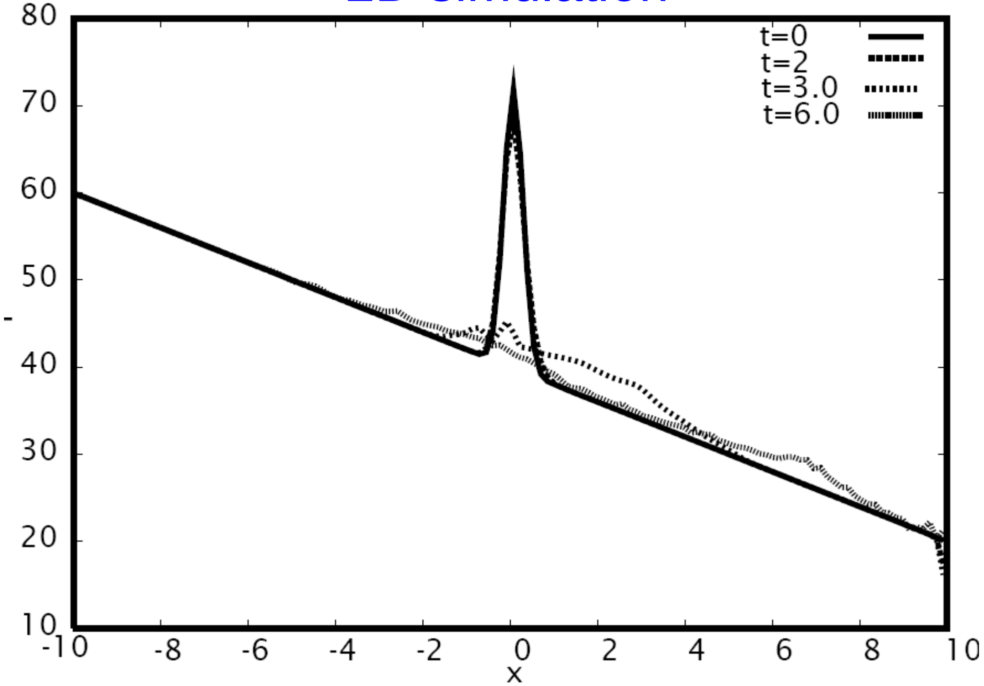
However, the mean profile appears to be well described by the 1D transport model!

Evolution of Temperature Peak

TSTM



2D simulation

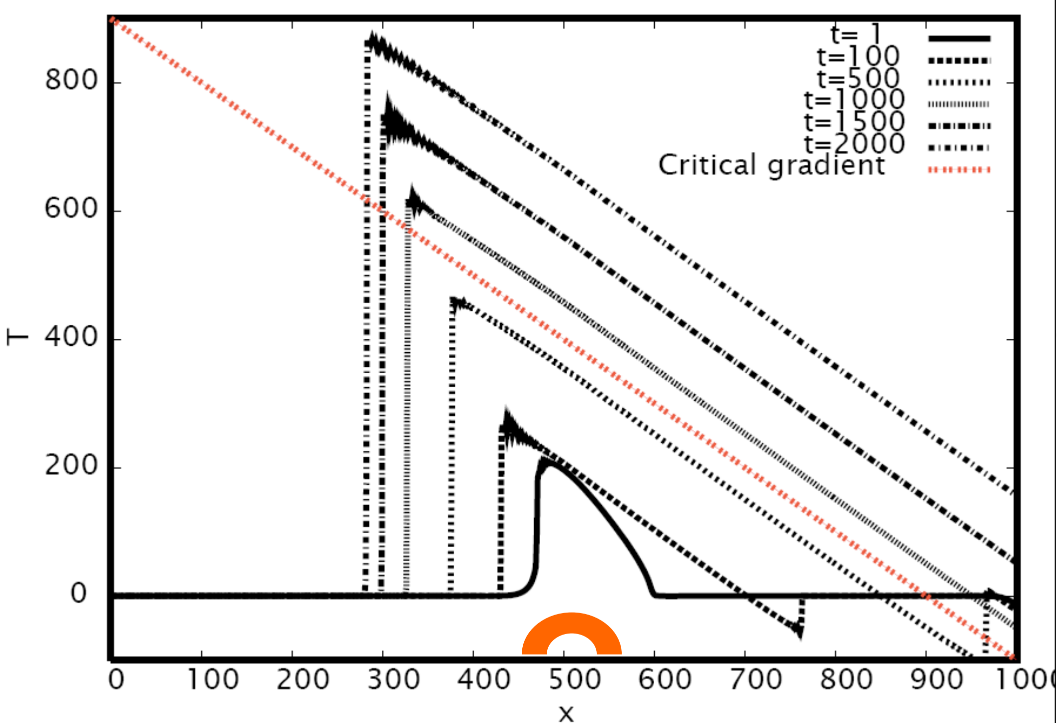


Heat Pulse initialized on a subcritical background gradient.

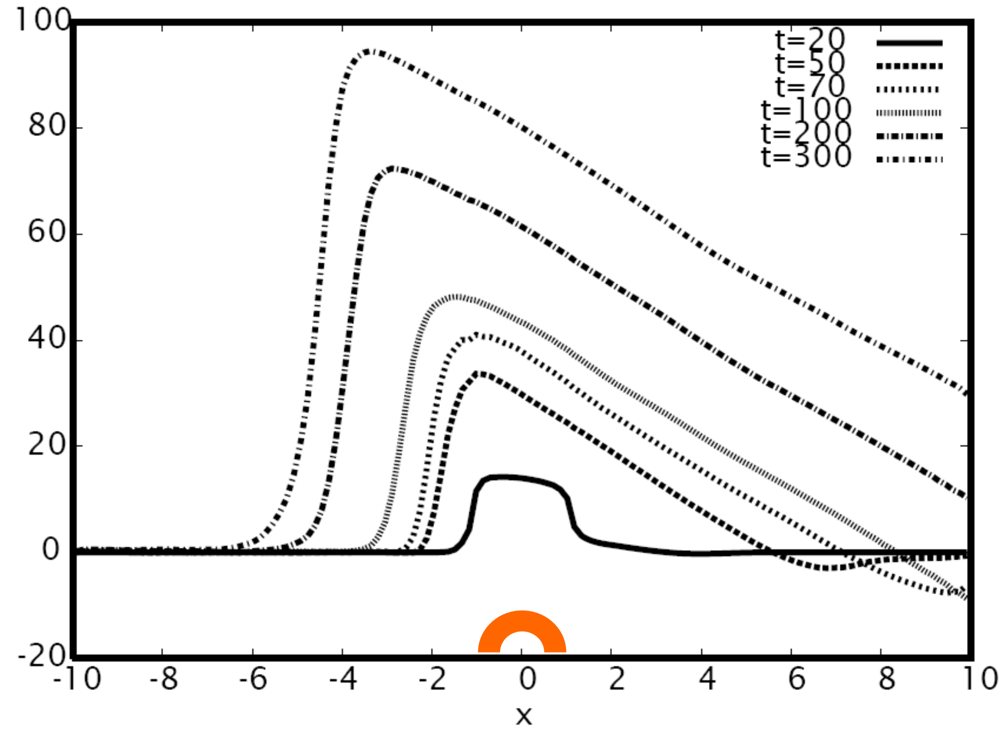
Up-gradient transport as well as front propagation visible

Profile Evolution

TSTM



2d simulation



Evolution of profiles: location of source indicated

The profile evolves toward "marginally stable" profile

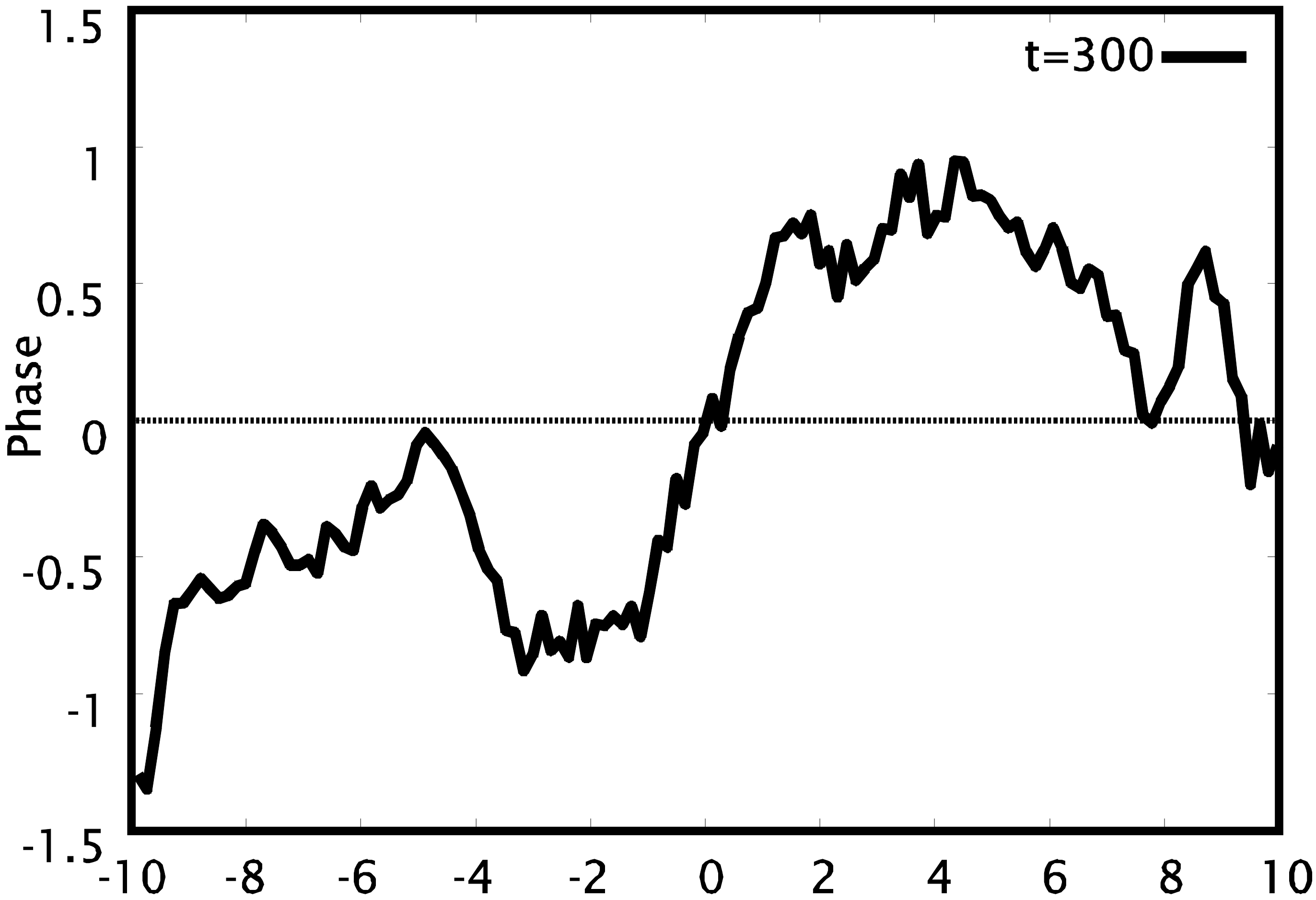
Where does the energy come from?

- 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

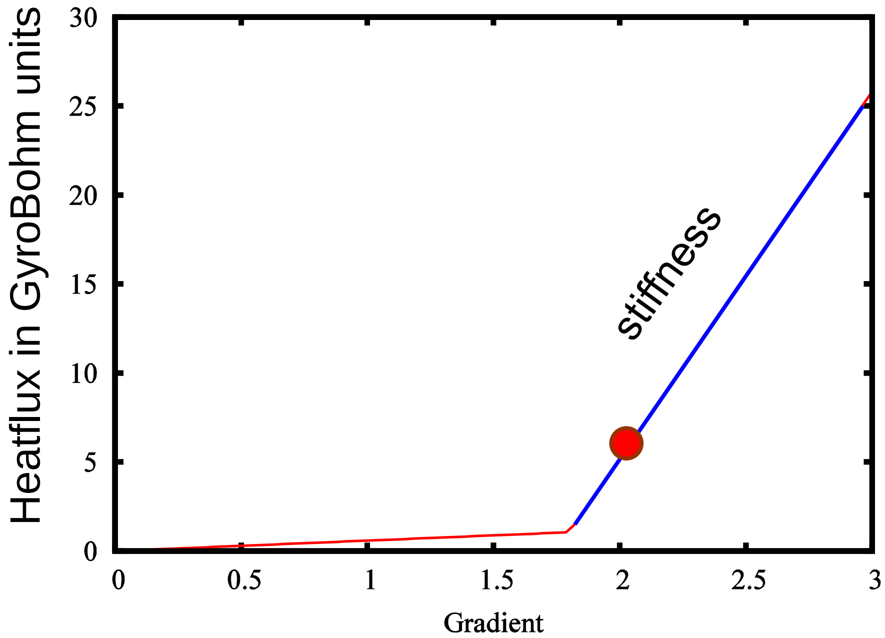
Locality and non-locality: TSTM and CGM

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)

$$\partial_t T = \frac{3}{2}\nabla\cdot q^{3/2}T^{5/2}\left[\chi_s\left(\frac{-R\nabla T}{T}-\kappa_c\right)_H+\chi_0\right]\frac{\nabla T}{T}$$

In this local model the response of the system to changes in the heatflux is given by ξ_0, and after onset of instability at $-R\nabla T/T-\kappa_c=0$ the stiffnessfactor χ_s (relative to Gyro Bohm scaling).



Dynamics happens on this trajectory in Flux/Gradient space.

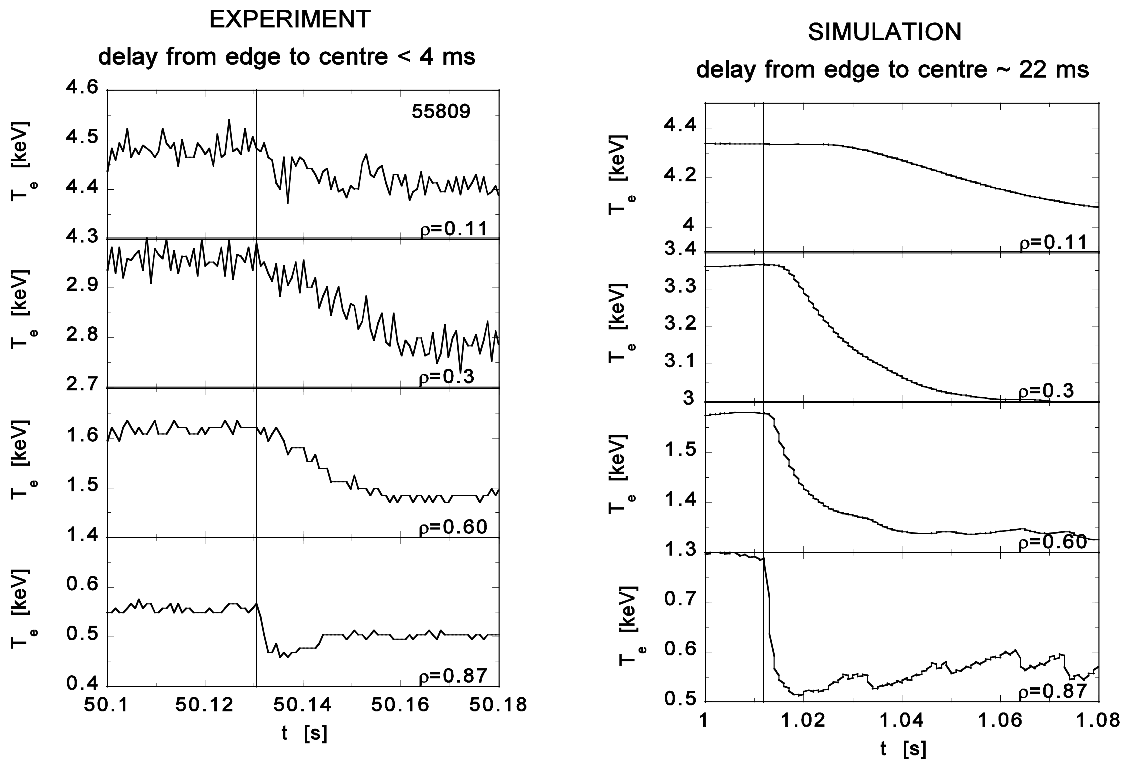
Determined by local properties.

Stiffness determines speed of perturbations

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



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

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!

CGM Results

Result:

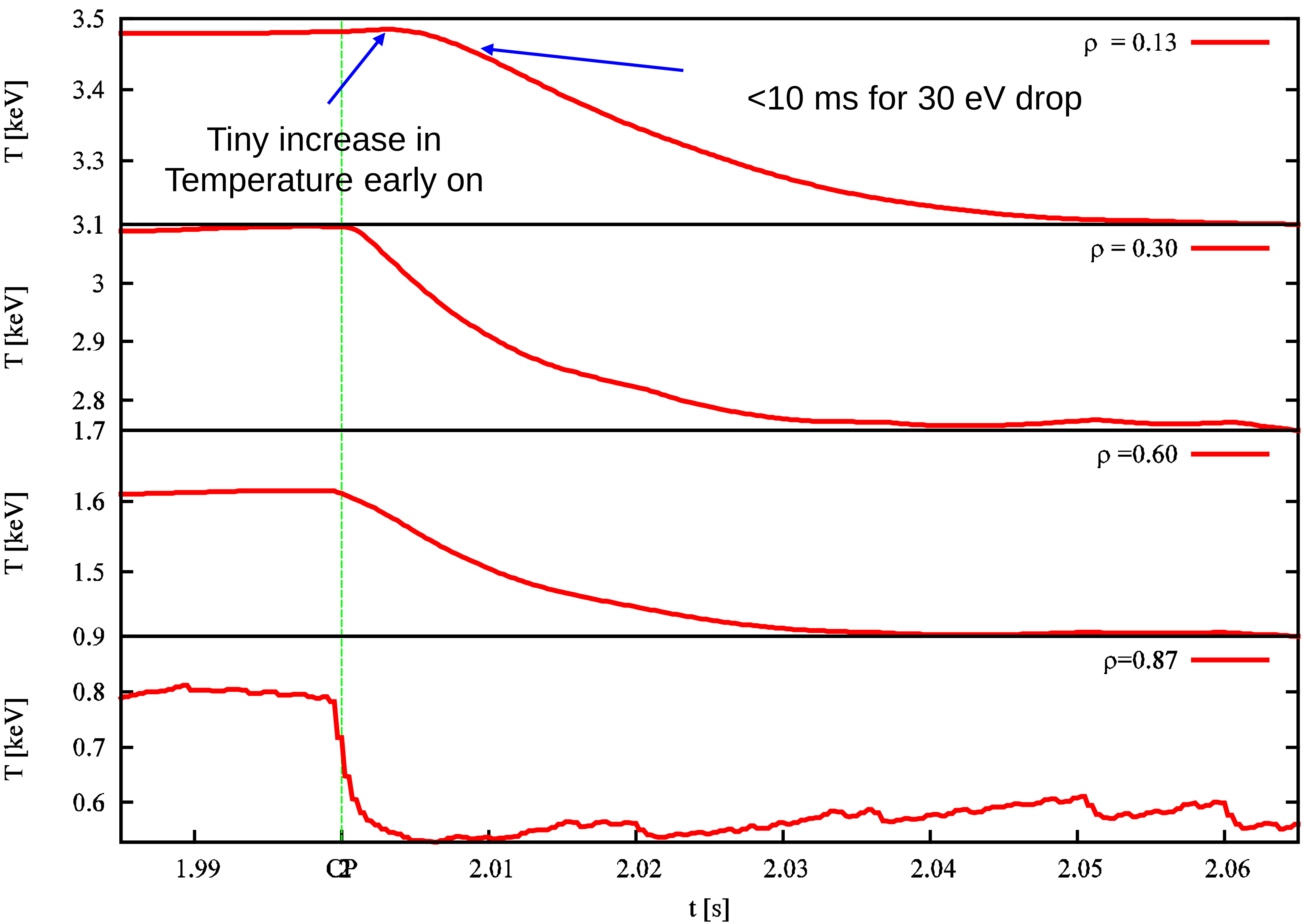
ρ>0.3: the plasma is unstable, has a high degree of stiffness and both modulation and fast perturbation propagates fast, but at same speed

ρ<0.3: the plasma is below threshold, the stiffness is lower, consequently the heat wave slows down and is damped. The CGM captures this behaviour. In the experiment, however,

The cold pulse travels faster.

Incompatible with local transport models!

Cold pulse in TSTM



Cold pulse after 8ms for

parameters

From modulation experiment!

Turbulence spreading transport model, with momentum

$$\frac{\partial I}{\partial t} = \nabla \cdot [D_0 I \, \nabla I] + \gamma I - \left(\beta I^2\right) I, \quad (1)$$

$$\frac{\partial T}{\partial t} = -\nabla \cdot (\vec{q} + \chi_0 \nabla T) + S(r), \quad (2)$$

$$\frac{\partial M}{\partial t} = \nabla \cdot [D_M \nabla M + V_{Pinch} M + \mathcal{R}], \quad (3)$$

I: turbulence intensity, generated by instability with critical gradient, growth rate γ

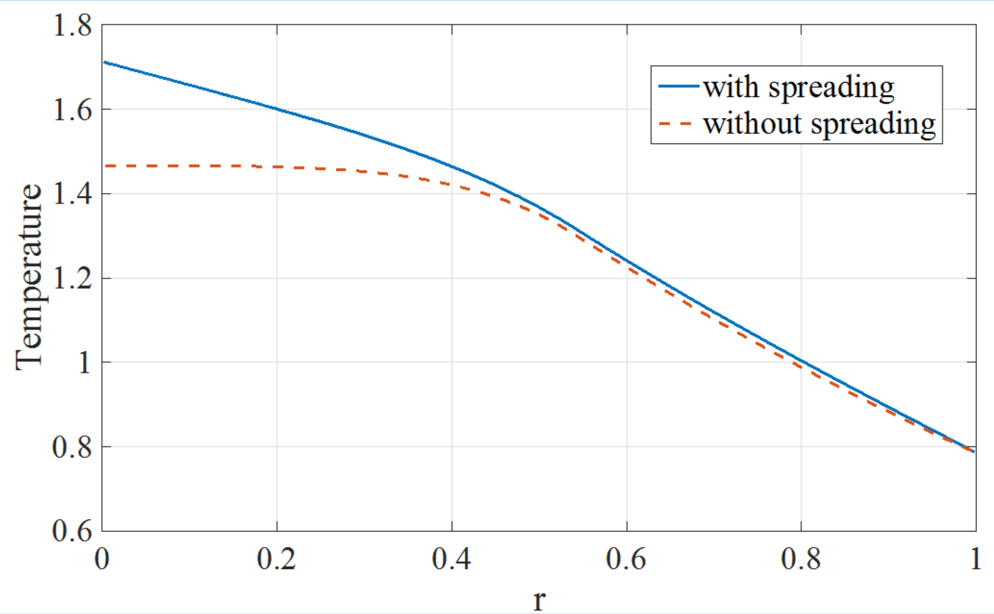
T: temperature, heatflux *q* proportional to *T*I* tanh*(γ),* source *S(r)*

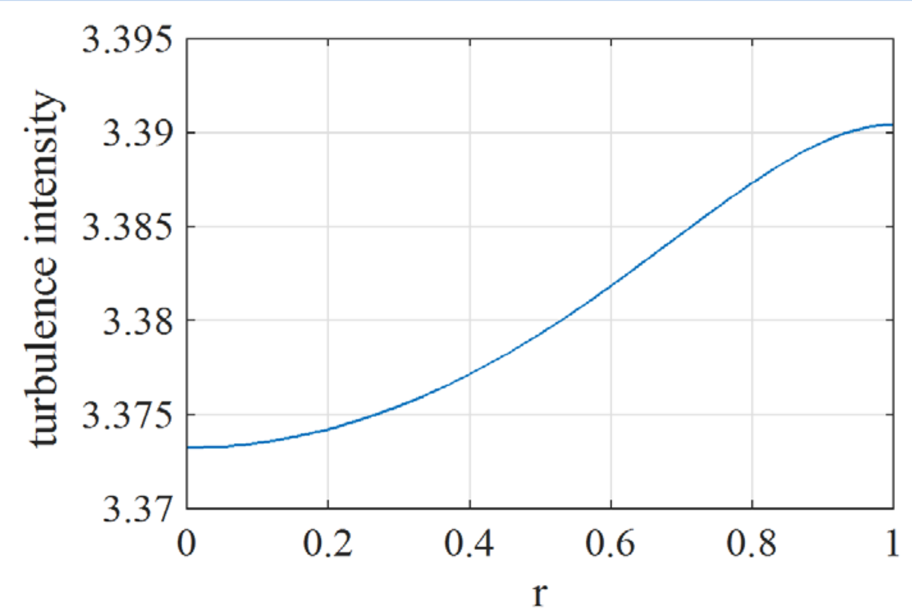
M: momentum,

R: residual stress proportional to ∇I *(Hahm et al. PPCF (2004))*

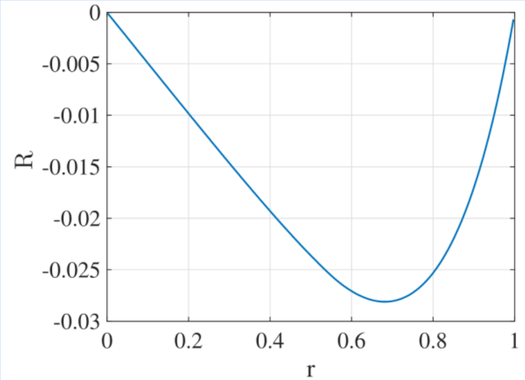
Hariri et al. PoP ***23, 052512*** *(2016);*

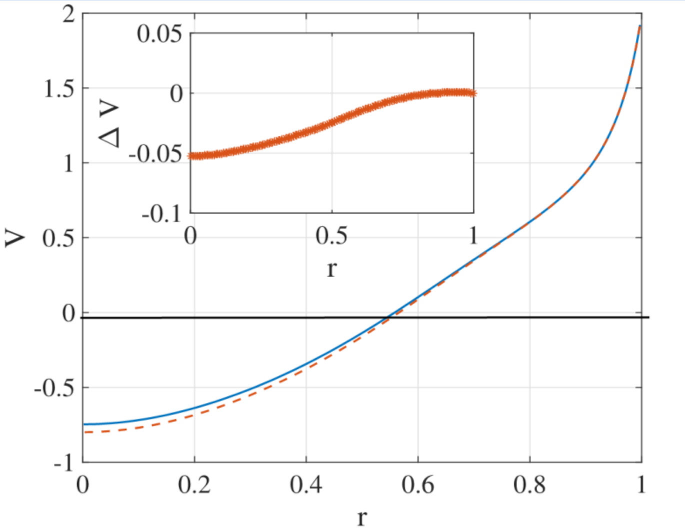
Steady State





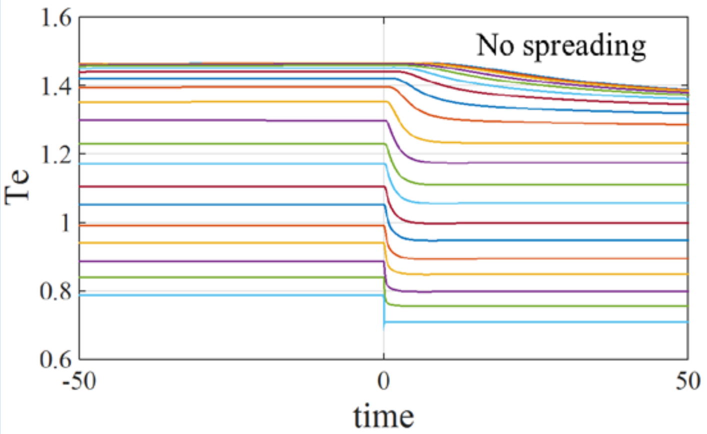
A gradient in the turbulence intensity profile
I creates residual stress R and thus a finite momentum flux,
leading to plasma spin-up without momentum source

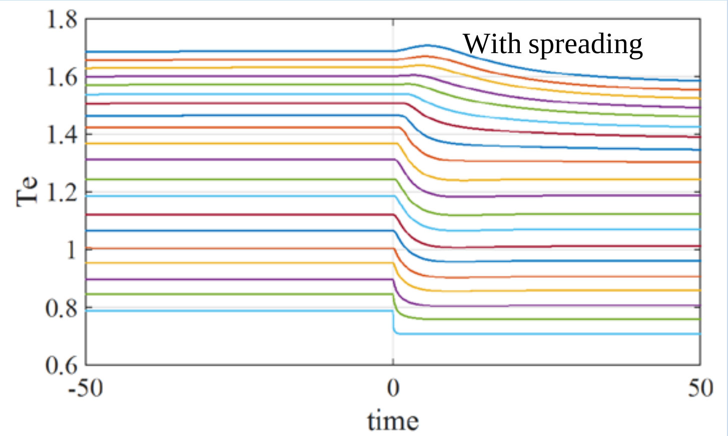




Dynamical properties

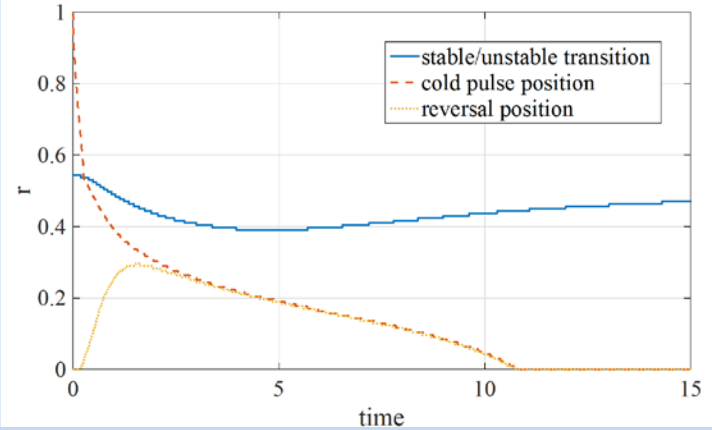
Cold pulse leads to temperature increase in the plasma core while in the absence of spreading no reversal is observed.



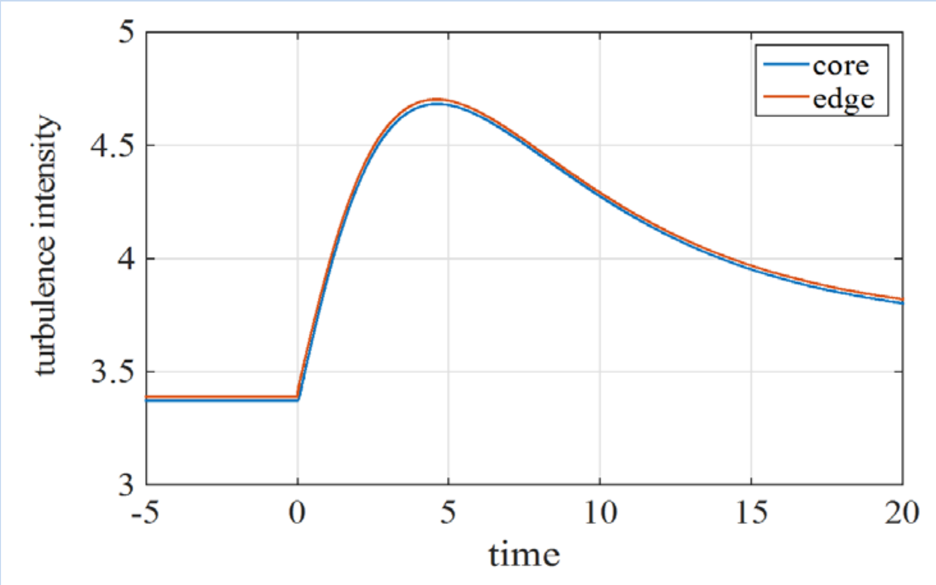


The radial position of the transition from stable to unstable plasma over time showing an extreme fast propagation of the cold pulse.

The reversal of the cold pulse is an effect spreading from r = 0 and meeting the cold pulse front.

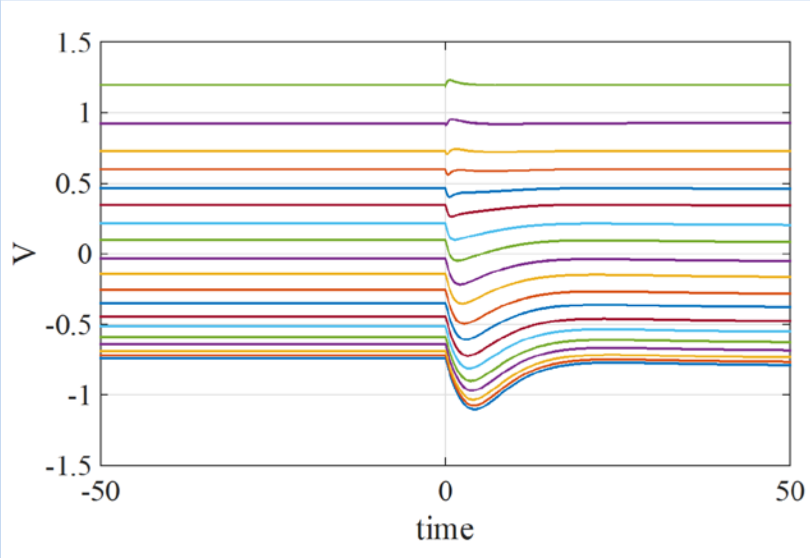


Cold pulse impact on velocity profile

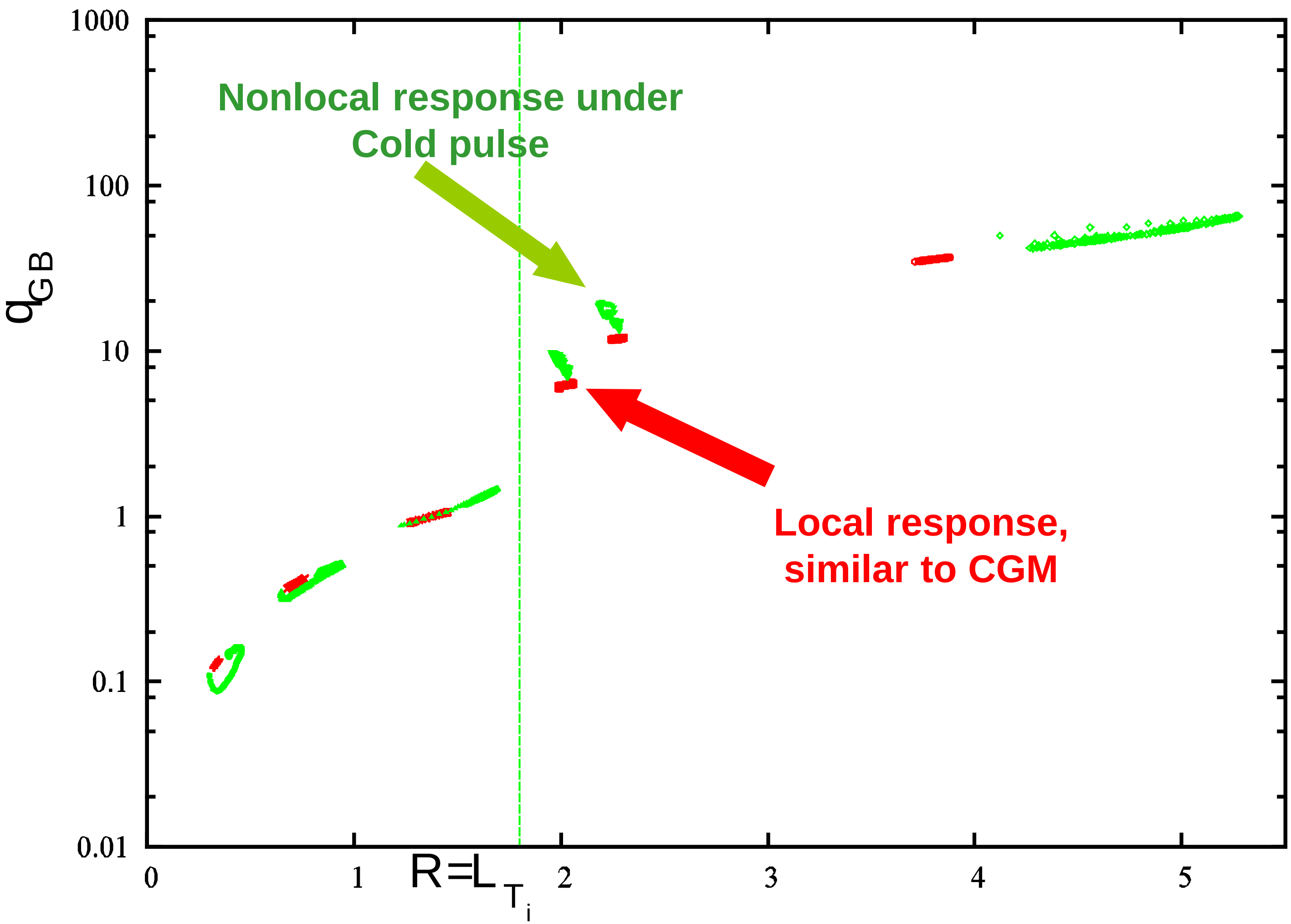


The core response in the turbulence intensity starts immediately after the cold pulse is initiated. This shows an extremely fast response of the turbulence intensity to edge cooling.

We observe a reversal of the polarity in the changes of the velocity profile due to the residual stress being a redistribution of momentum, but not a net source.



Nonlocal response of TSTM



- 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 in 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.

Hariri et al. PoP (2016); Naulin et al. PoP (2005)

Conclusion

- Turbulent spreading is important in many systems – in plasmas often observed, also in turbulence simulations, incl. gyro-kinetic simulations
- Turbulence spreading introduces “non-locality”
- Up-gradient transport even with **one** thermodynamically quantity: **turbulence energy** plays a role
- TSTM compares well with direct simulations
- Slow modulation as well as fast pulse propagation
- Explains observations inversion of cold pulse
- Explains rotation reversal observed in non saturated L mode
- Predicts rotation profile reversal under cold pulse. Test!
- A **first step** towards nonlocal transport models