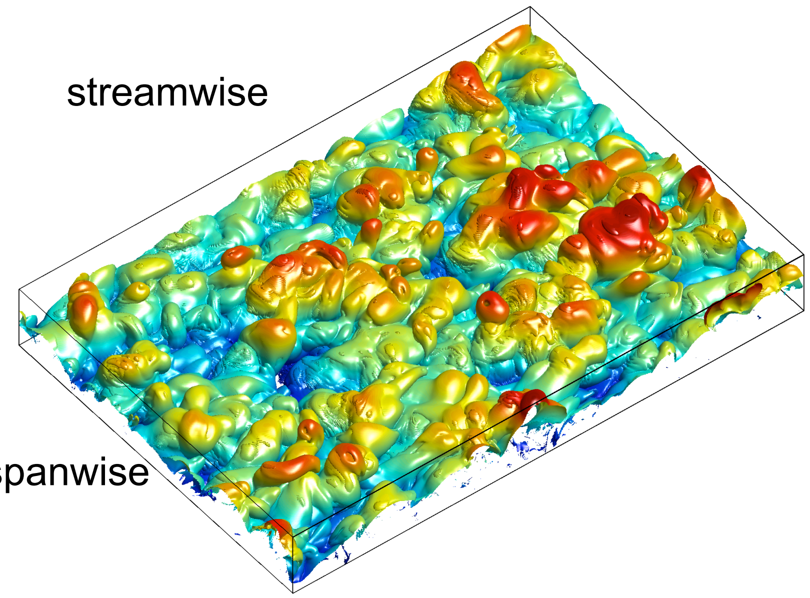
Lagrangian behaviour and enstropy evolution of fluid particles near the turbulent / non-turbulent interface of a turbulent boundary layer



T/NT interface
$Re_\tau = 600$

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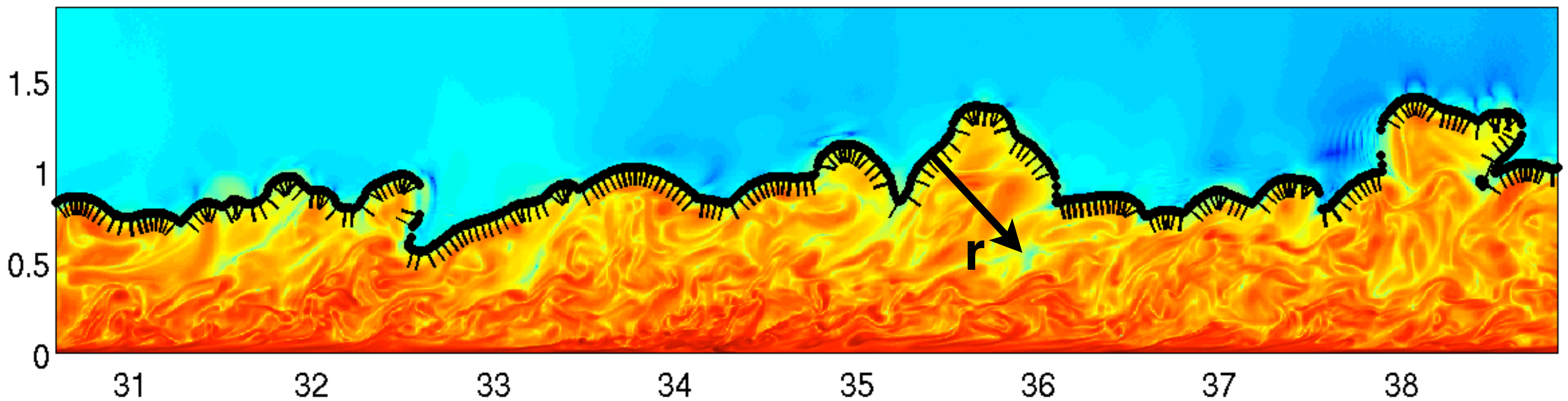
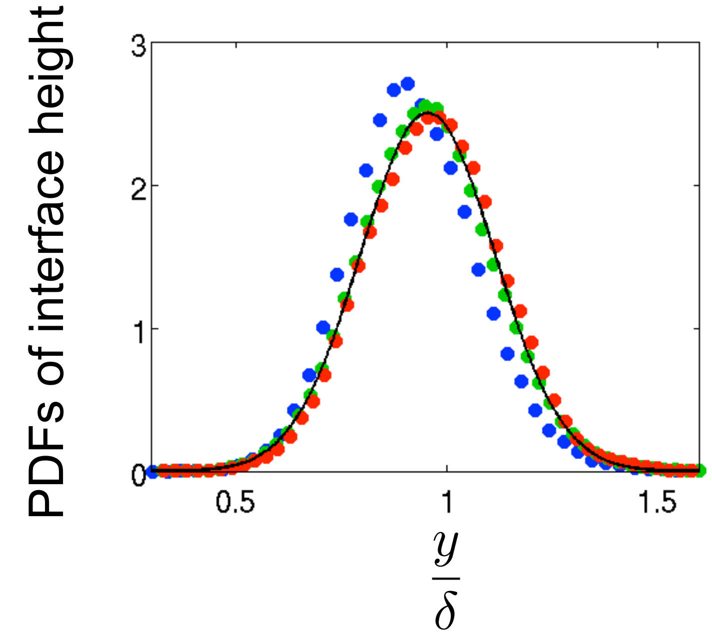
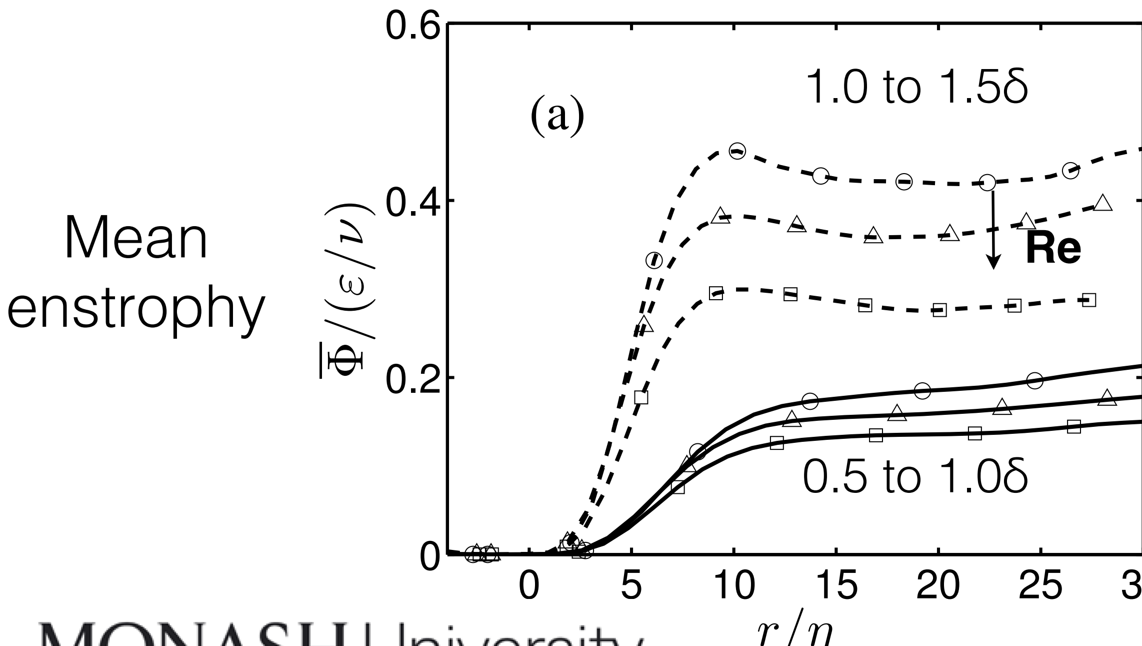
Recent work - Y. Mizuno, O. Amili, J. Soria

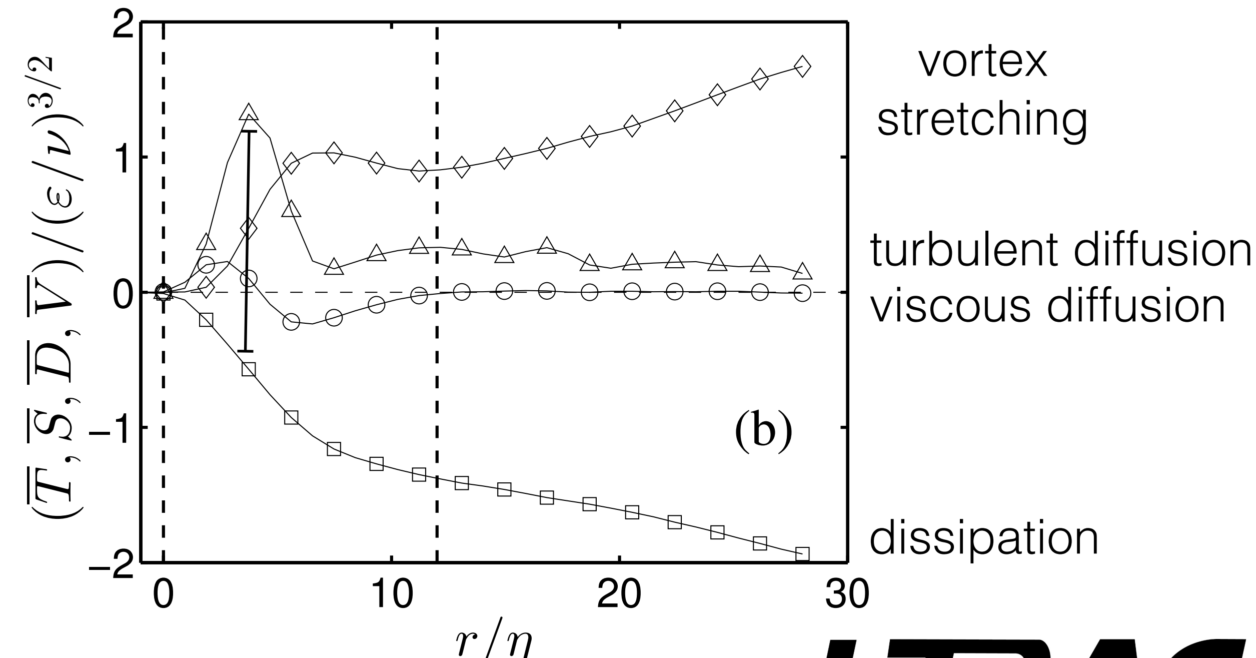


(color: enstrophy field, black dots: interface position, black lines: *r*)



- Examined statistics about the interface:
  - position, intermittency factor, velocity, enstrophy
- Contribution of terms in the vorticity evolution equation to the advancement of the interface





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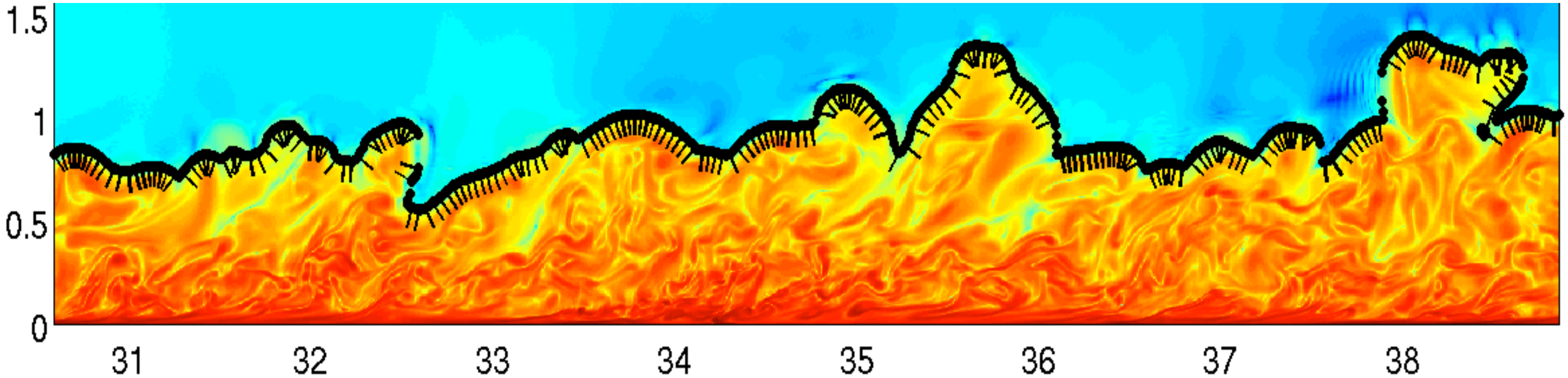
Open Questions:

- What is the dynamical process by which irrotational fluid particles are entrained across the interface and gain enstrophy?
- Can we identify a structure, topology and time-scale associated with this process?
- What is the best means of investigating evolution associated with the T/NT interface?
  1. Compute Lagrangian evolution of VGT invariants



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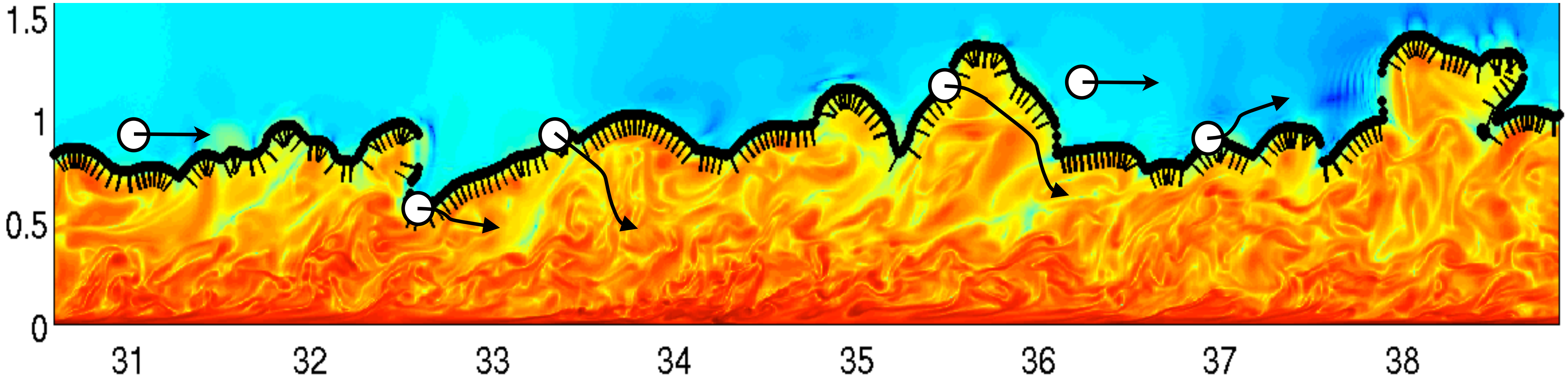
  1. Compute Lagrangian evolution of VGT invariants
  2. Track fluid particles across the interface



(color: enstrophy field, black dots: interface position, black lines: *r*)

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Flow Topology

- Represent the topology of the T/NT interface in terms of critical point theory (Chong, Perry and Cantwell, 1990)

$$A_{ij} = \partial u_i / \partial x_j$$

$$\lambda_i^3 + P_A \lambda_i^2 + Q_A \lambda_i + R_A = 0$$

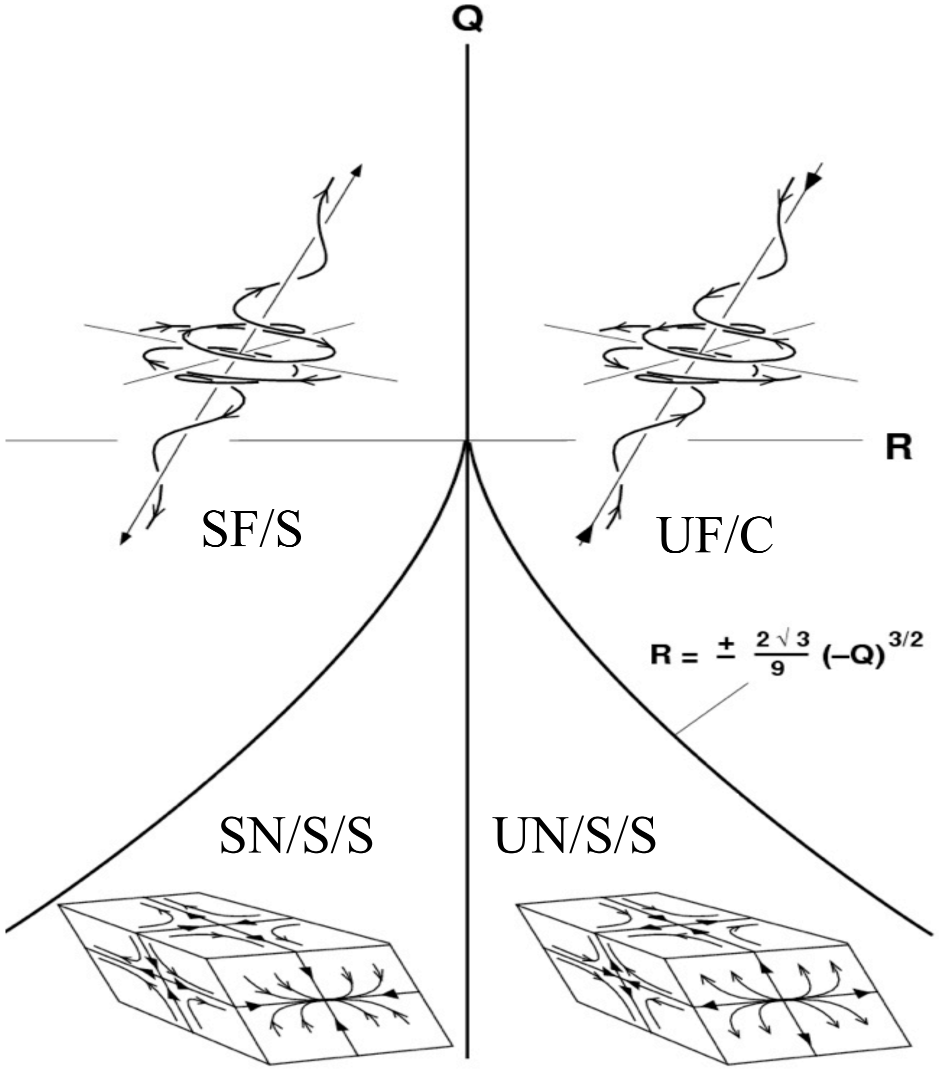
$$Q_A = -\tfrac{1}{2} A_{ij} A_{ji},$$
$$R_A = -\tfrac{1}{3} A_{ij} A_{jk} A_{ki}$$

$$A_{ij} = S_{ij} + W_{ij}$$

$$Q_S \propto \epsilon$$

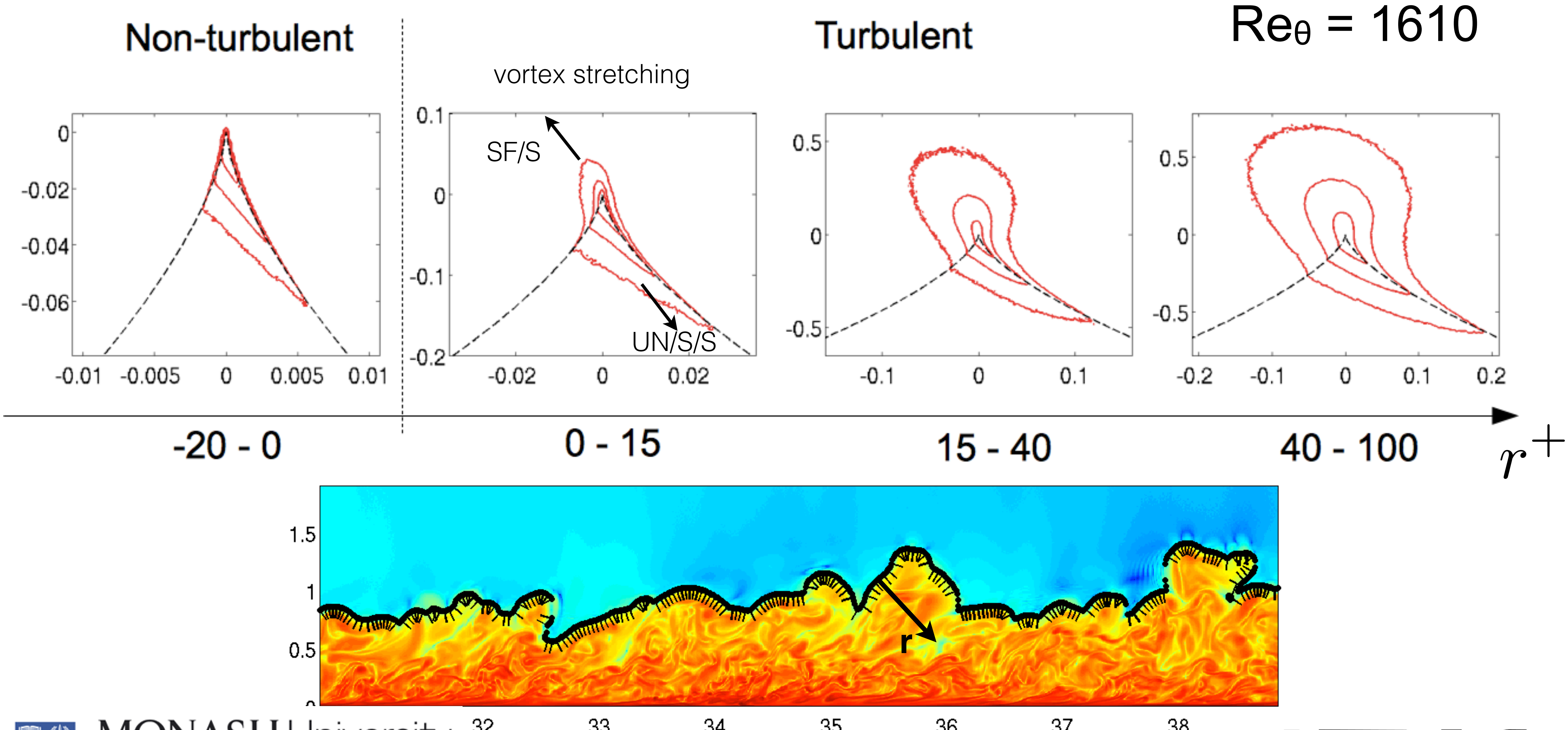
$$Q_W \propto \omega \cdot \omega$$

Incompressible flow $P_A = 0$
(Chong et al. 1990, Soria et al. 1994)



JPDF of Q,R invariant across interface of a Jet

- JPDF of Q_A and R_A
  - ➡ similar to da Silva & Pereira (2008) at the interface of jet



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Topological Evolution

- Represent the Lagrangian evolution of the flow in terms of the change in flow topology (Cantwell, 1992)
- Trace position in Qa, Ra plane as function of time - Lagrangian tracking
- Evaluate RHS of Navier-Stokes and Compute change in DQ_A/Dt, DR_A/Dt conditional on Q_A,R_A

$$\frac{\mathrm{D}Q_A}{\mathrm{D}t} = -3R_A - A_{ik}H_{ki}$$

$$\frac{\mathrm{D}R_A}{\mathrm{D}t} = \frac{2}{3}Q_A^2 - A_{in}A_{nm}H_{mi}$$

$$H_{ij} = -\left(\frac{\partial^2 p}{\partial x_i \partial x_j} - \frac{\partial^2 p}{\partial x_k \partial x_k}\frac{\delta_{ij}}{3}\right) + \nu\frac{\partial^2 A_{ij}}{\partial x_k \partial x_k}$$

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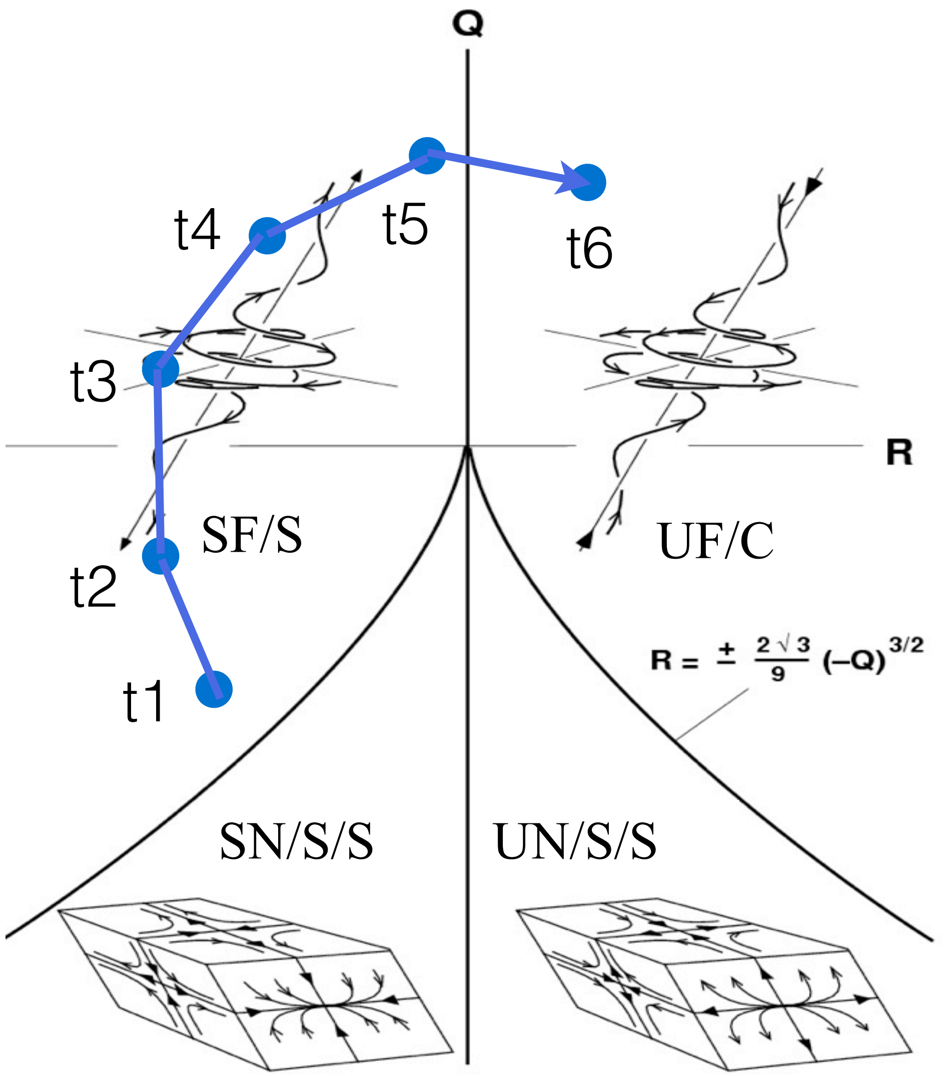

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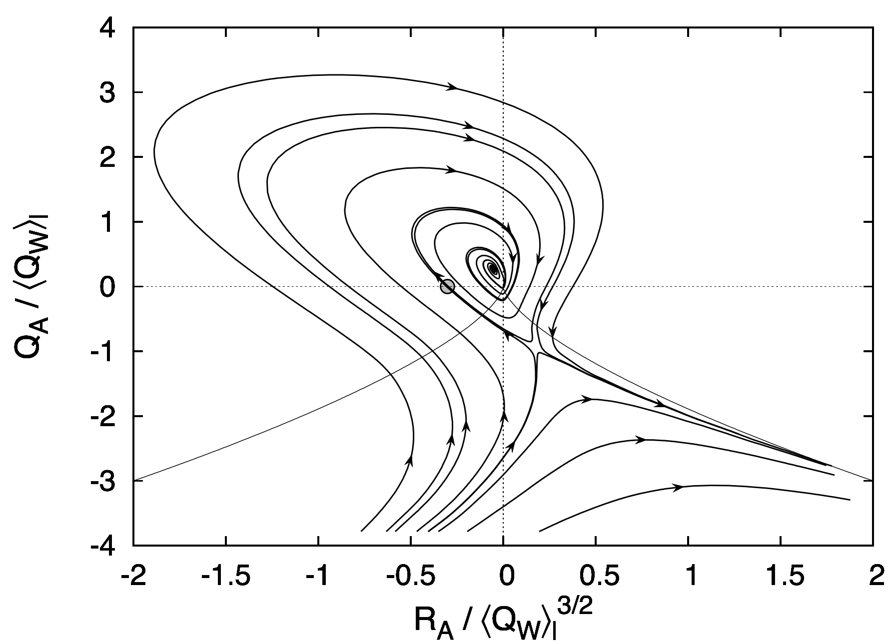
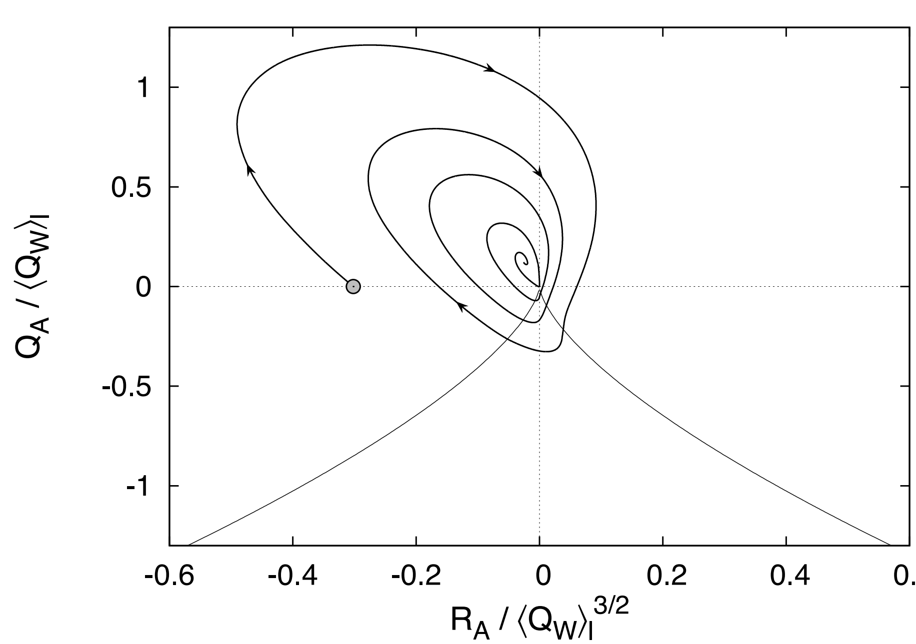
Conditional Mean Trajectories

- Mean time-scale associated with spiraling evolution
  - time-scale of 'periodic' evolution of flow topology

Region	$t/\langle Q_W \rangle_l^{1/2}$	$t/(\nu/u_\tau^2)$	$t/(\delta/U_e)$	$t/(\nu/\langle\epsilon\rangle_l)^{1/2}$	$t/(\delta/u_{rms})$
Viscous layer	36.5	67.9	2.10	73.2	0.259
Buffer layer	34.5	151	4.65	69.9	0.575
Log and wake	22.4	658	20.3	45.9	2.51

TBL at Re_θ = 730 to 1954 (Atkinson et al. 2012)





log and wake region of TBL at Re_θ = 730 to 1954 (Atkinson et al. 2012)

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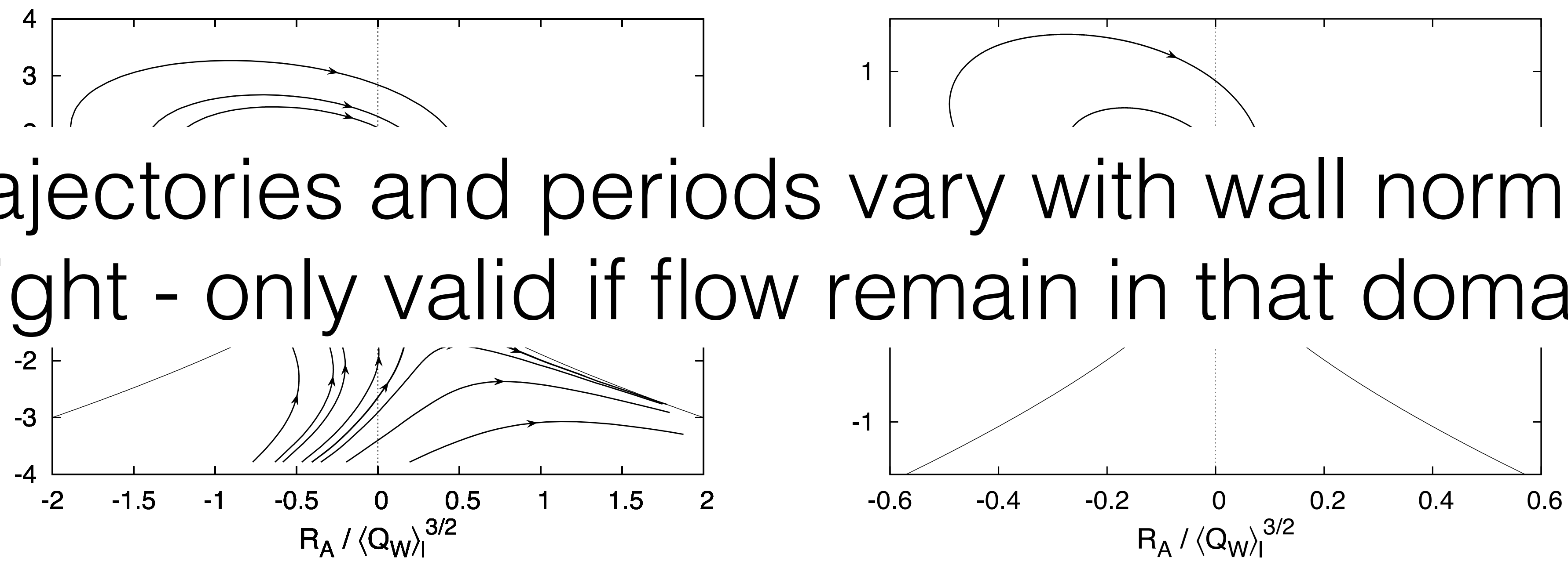


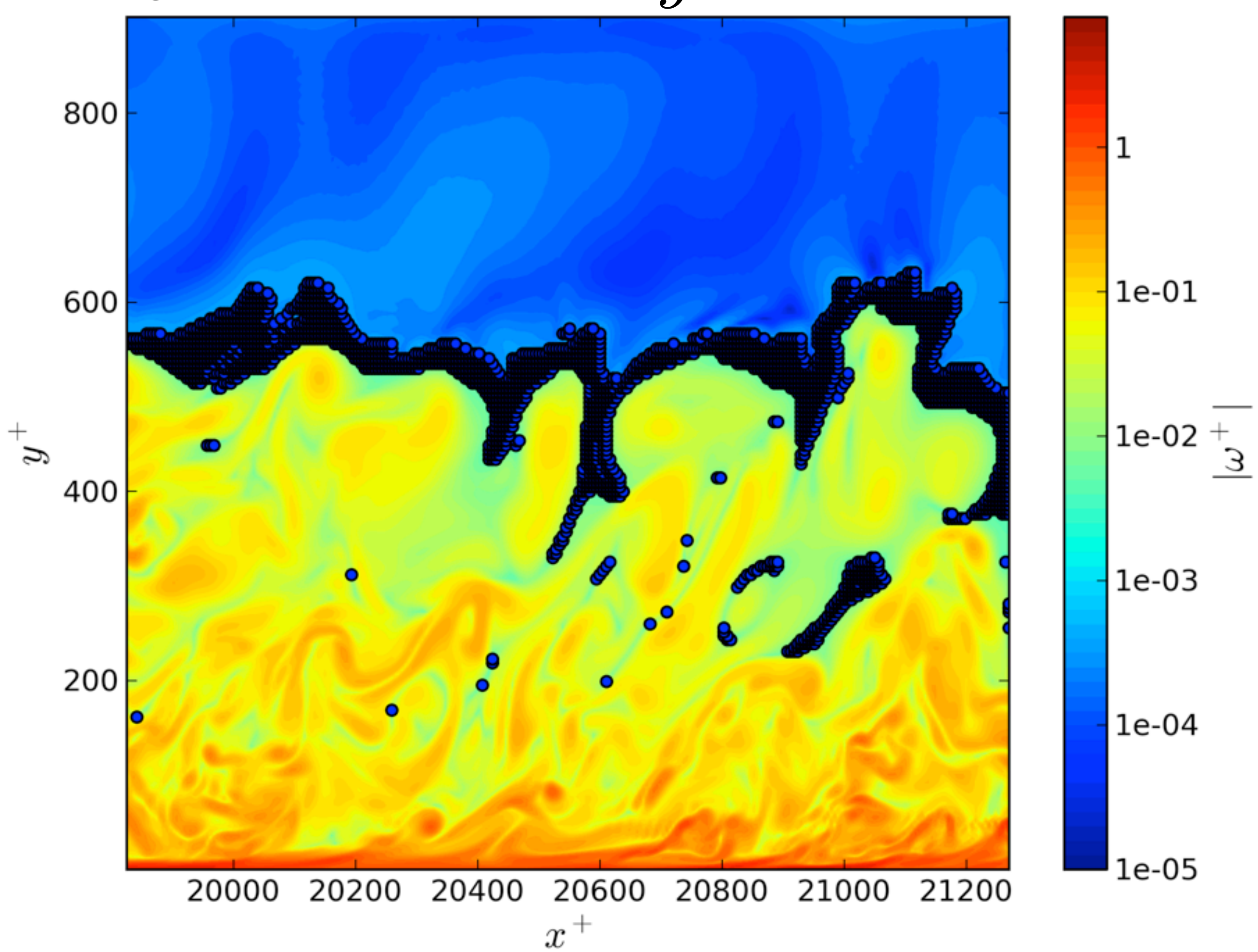
Trajectories and periods vary with wall normal height - only valid if flow remain in that domain

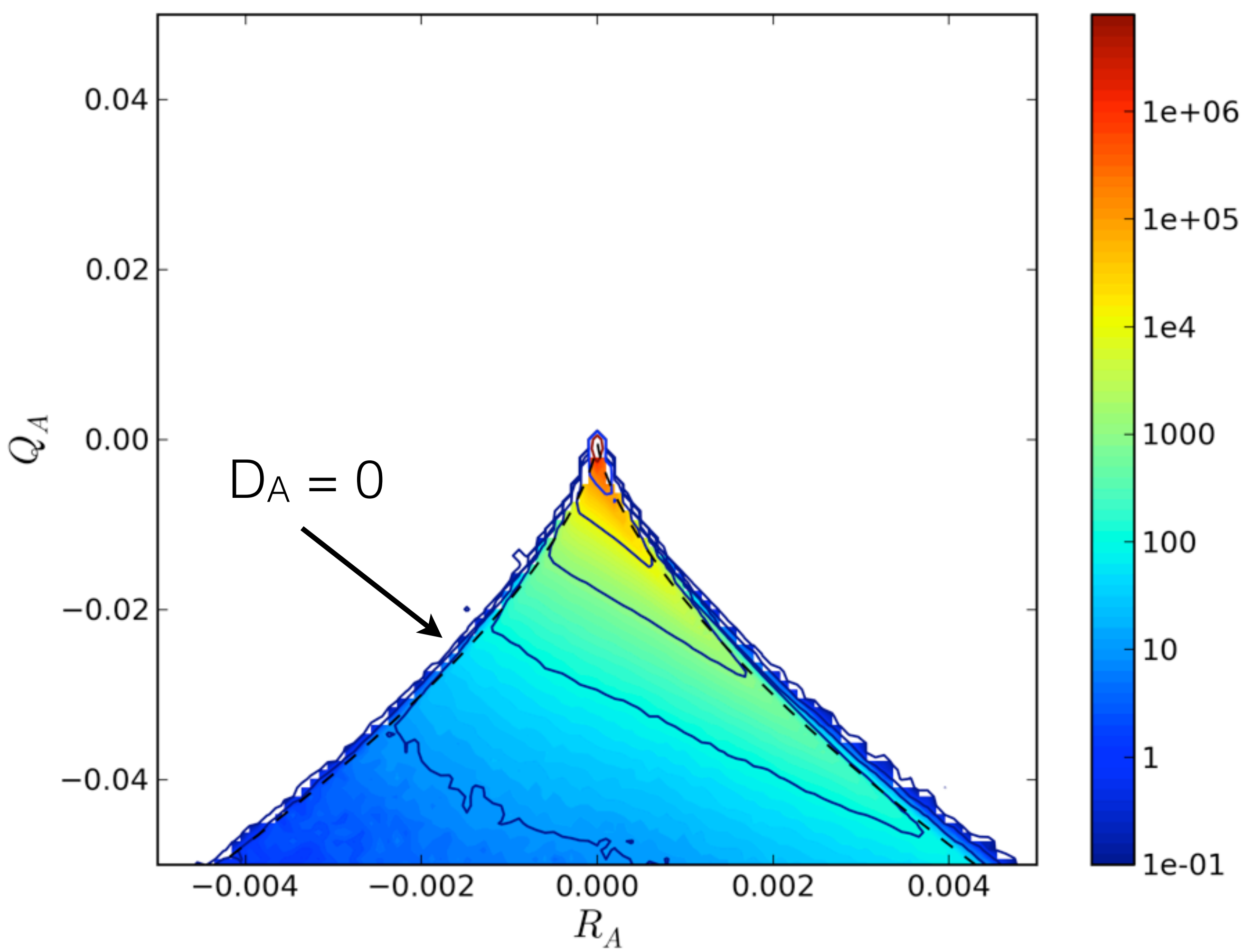
log and wake region of TBL at Re_θ = 730 to 1954 (Atkinson et al. 2012)

Identifying the T/NT interface

- Interface based on vorticity threshold 0.01 to 0.1$|\omega^+|(\delta^+)^{-1/2}$ (Borrell et al.)
- DNS TBL Re_τ ~ 600 (Mizuno et al.) 18 fields

$$\overline{y^+} = 524 \quad \sigma_{y^+} = 101$$





Conditional mean trajectories at T/NT interface

- Interface based on vorticity threshold 0.01 to $0.1|\omega^+|(\delta^+)^{-1/2}$ (Borrell et al.)
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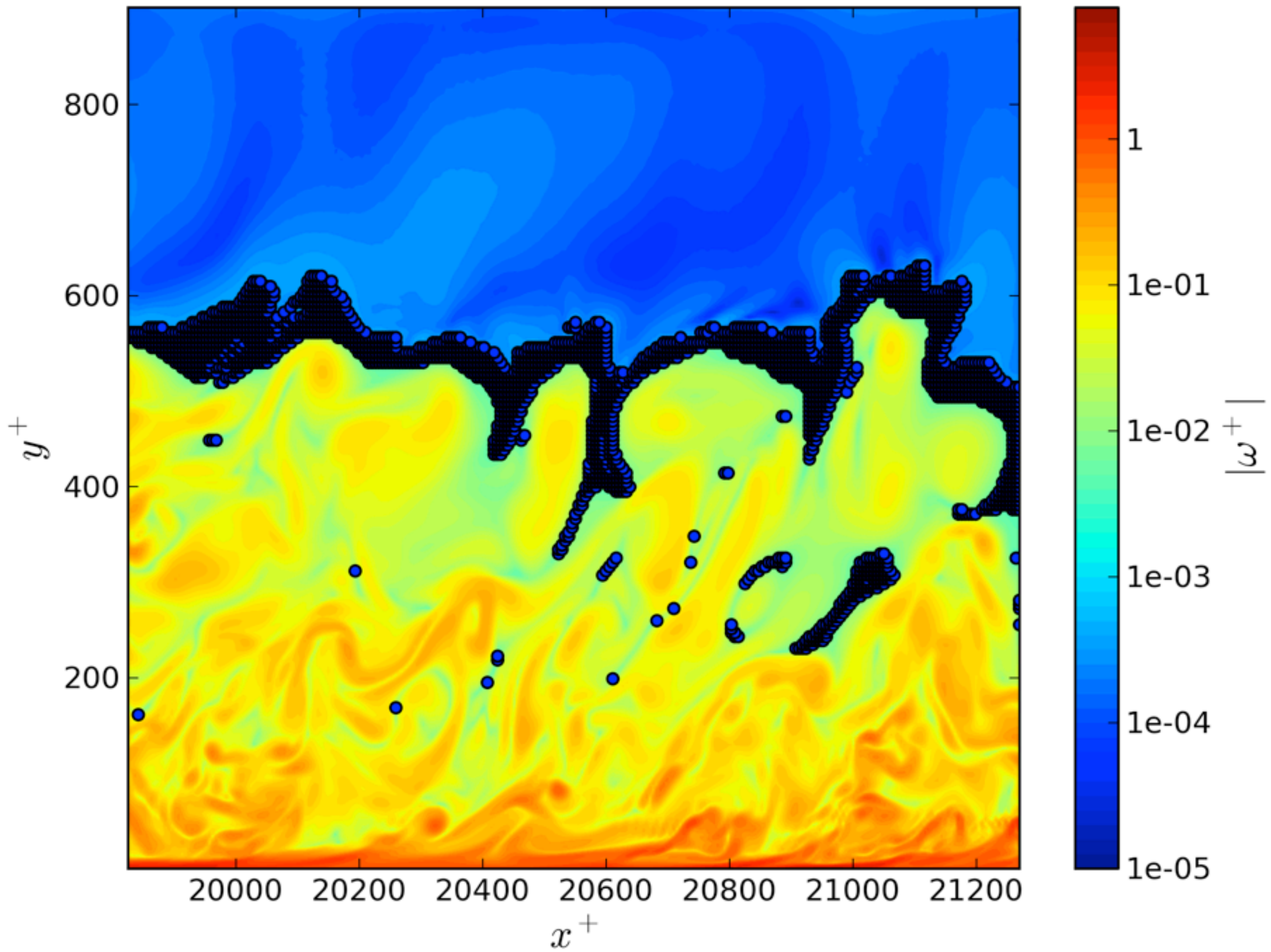

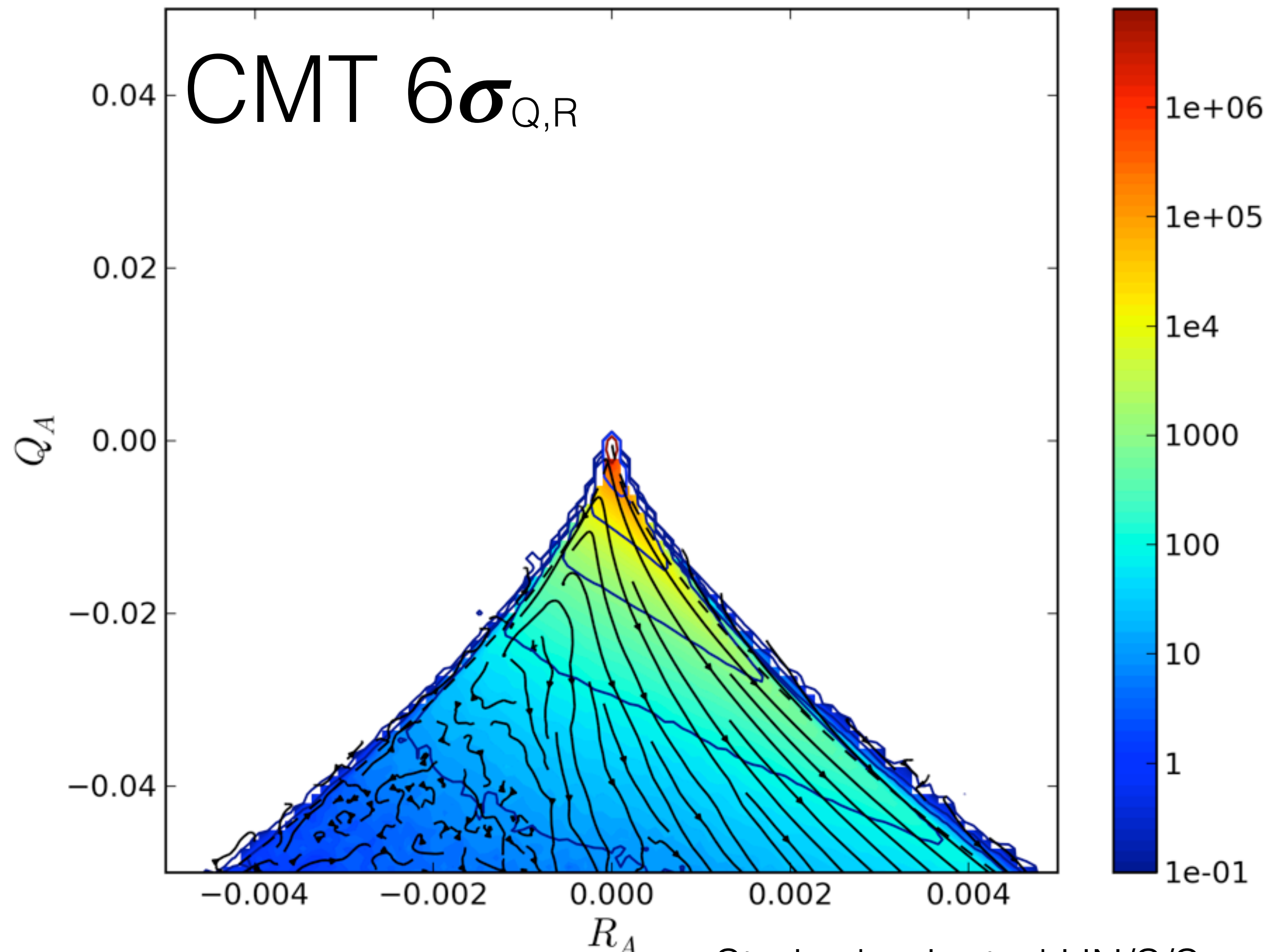

Strain dominated UN/S/S

Conditional mean trajectories at T/NT interface

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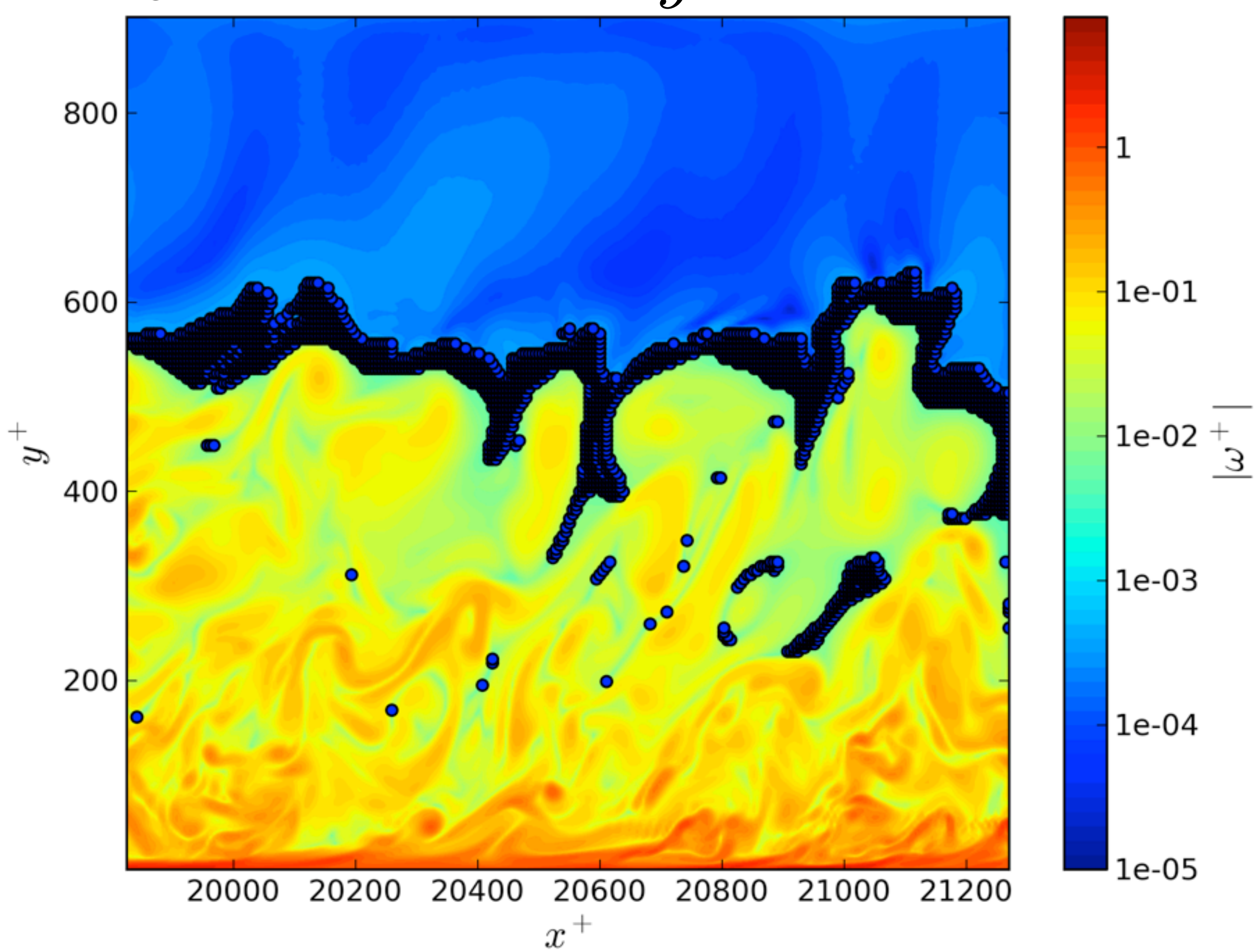

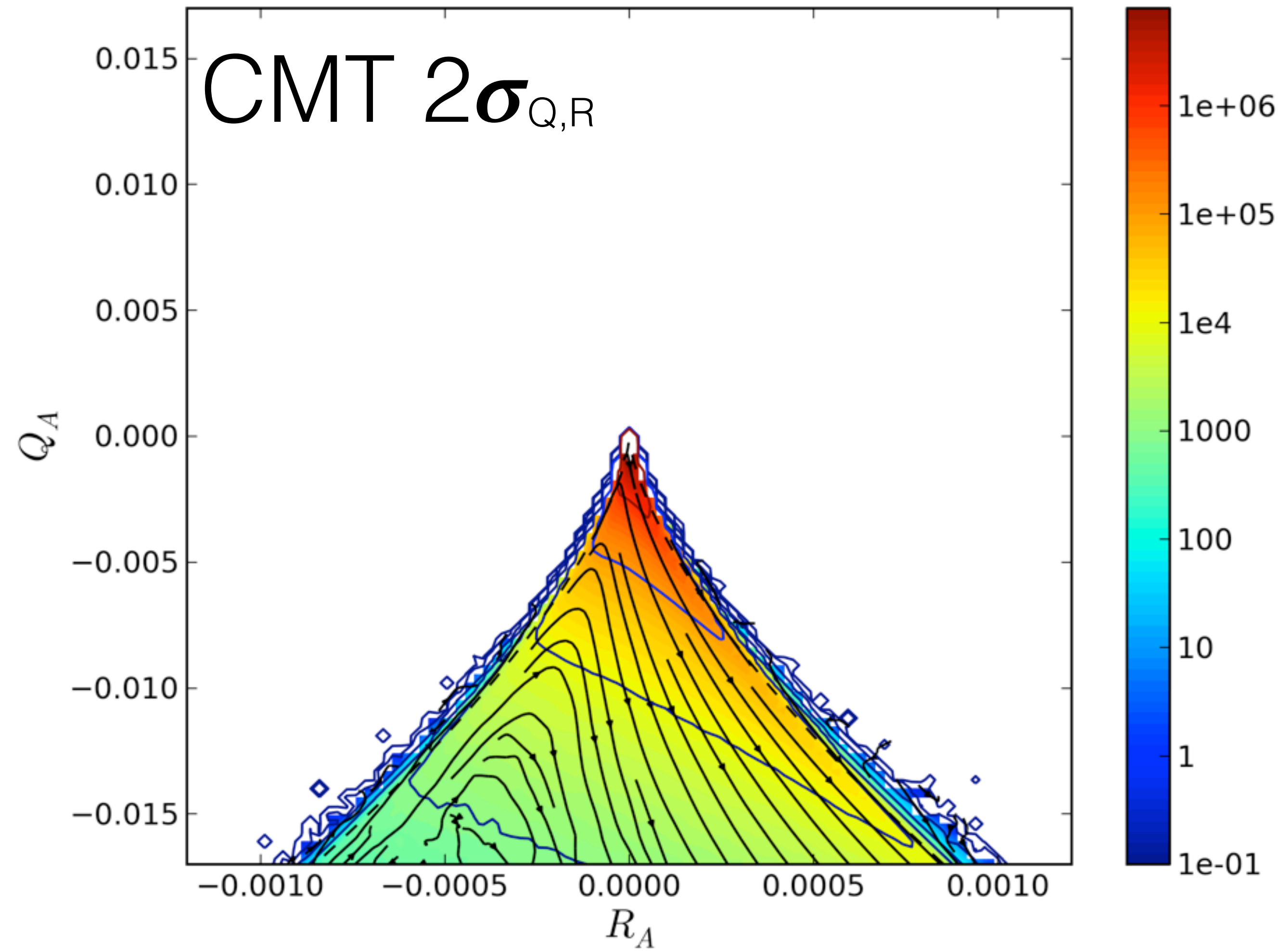

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Conditional mean trajectories at T/NT interface

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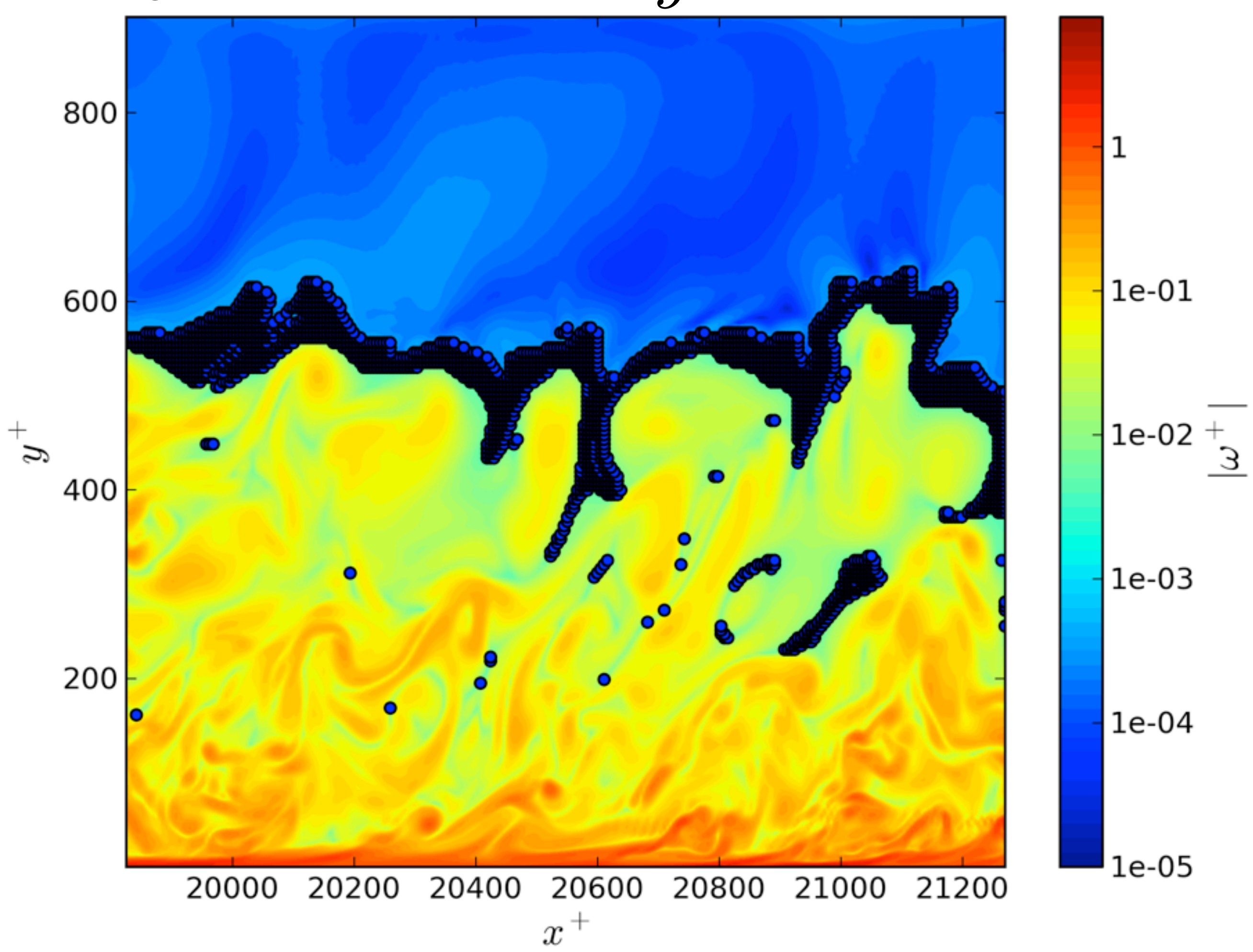

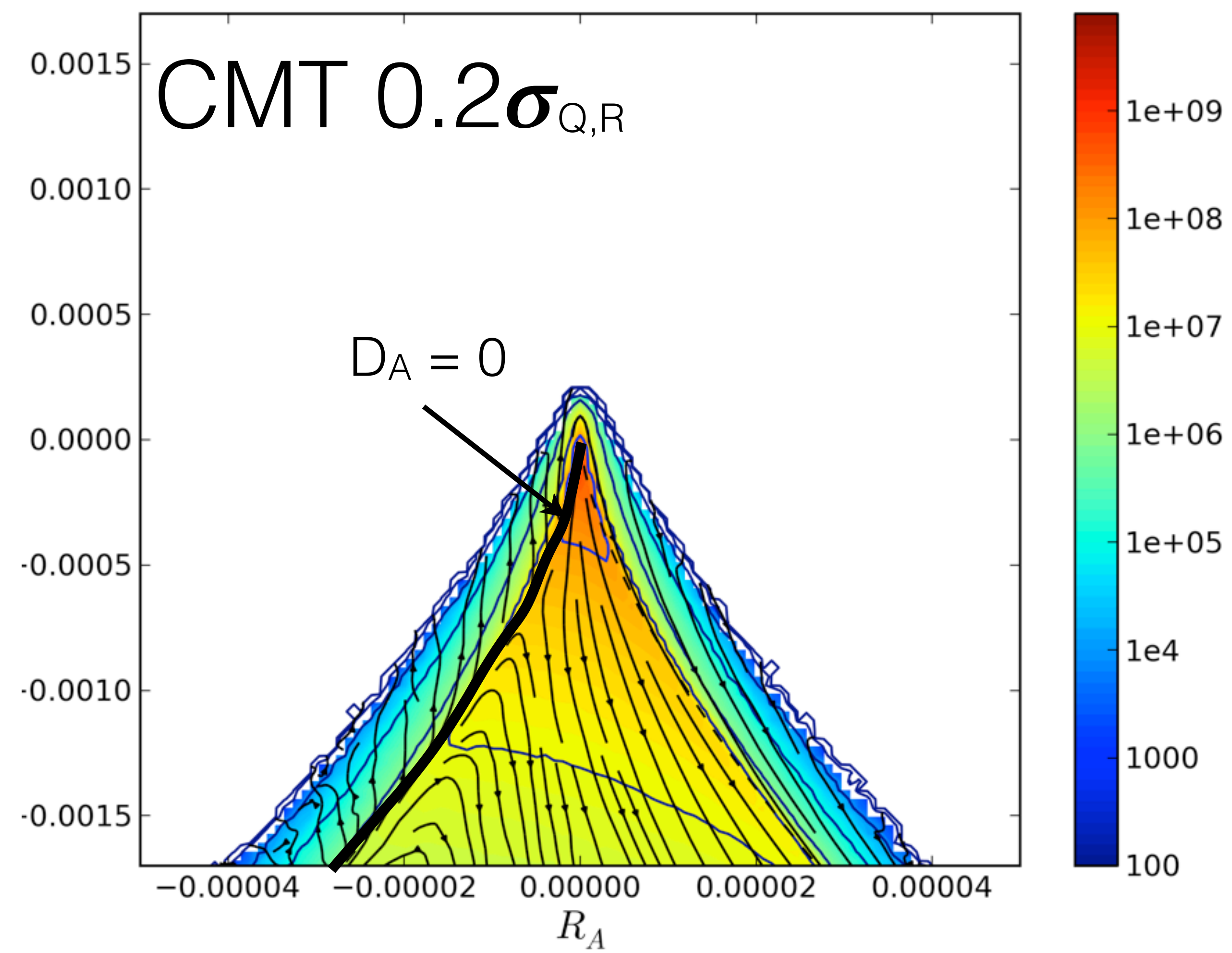

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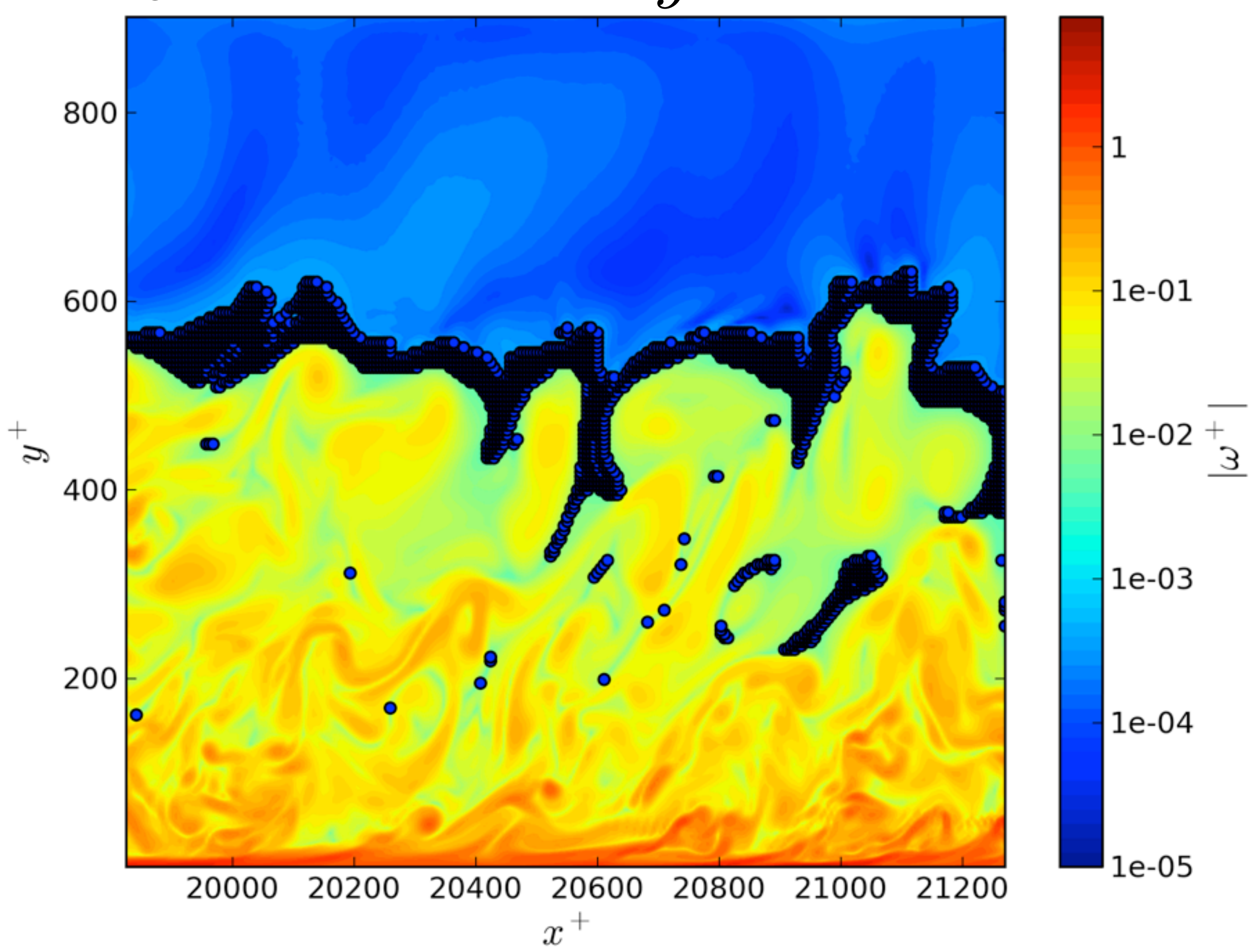

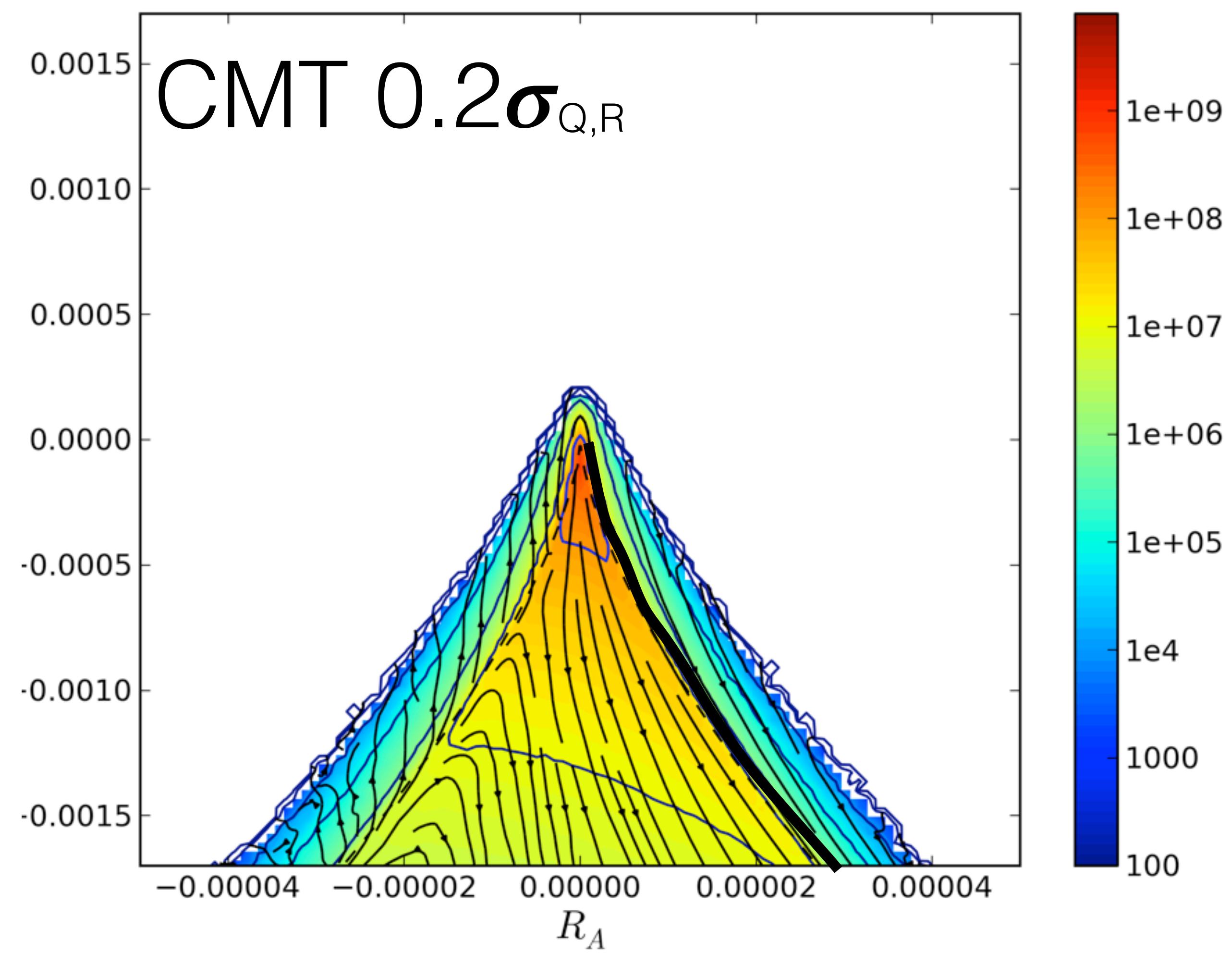

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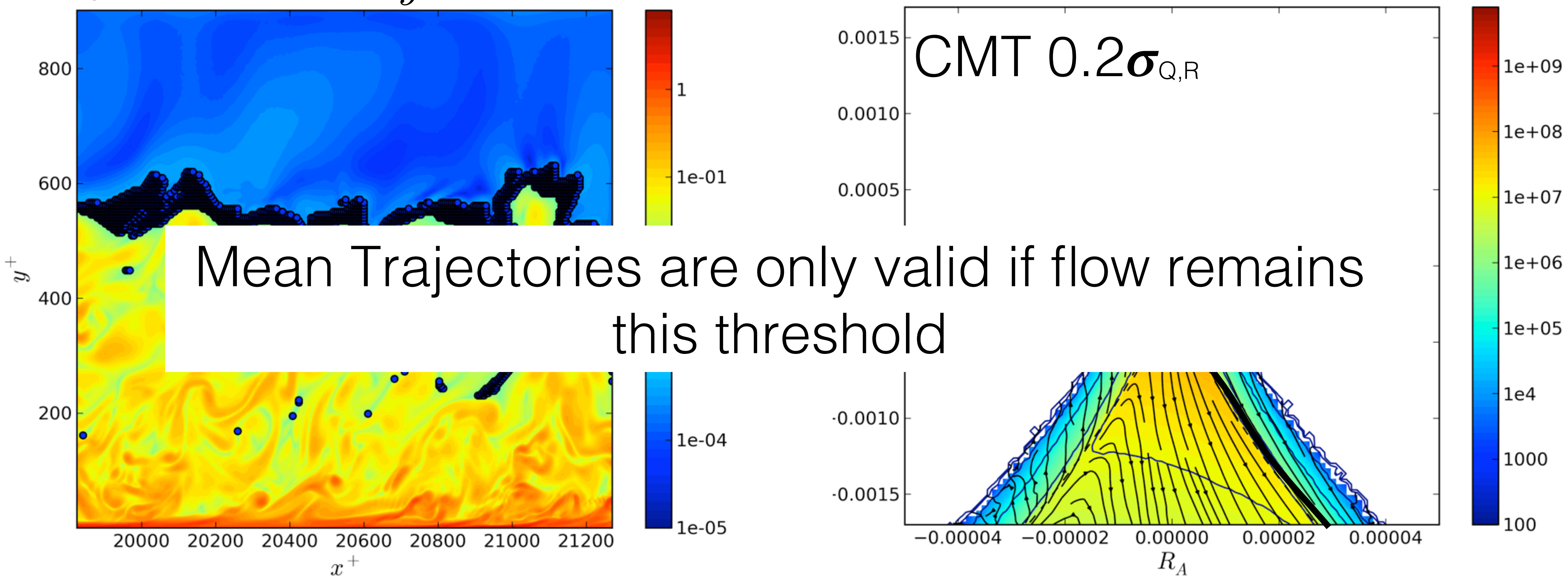

Mean Trajectories are only valid if flow remains this threshold

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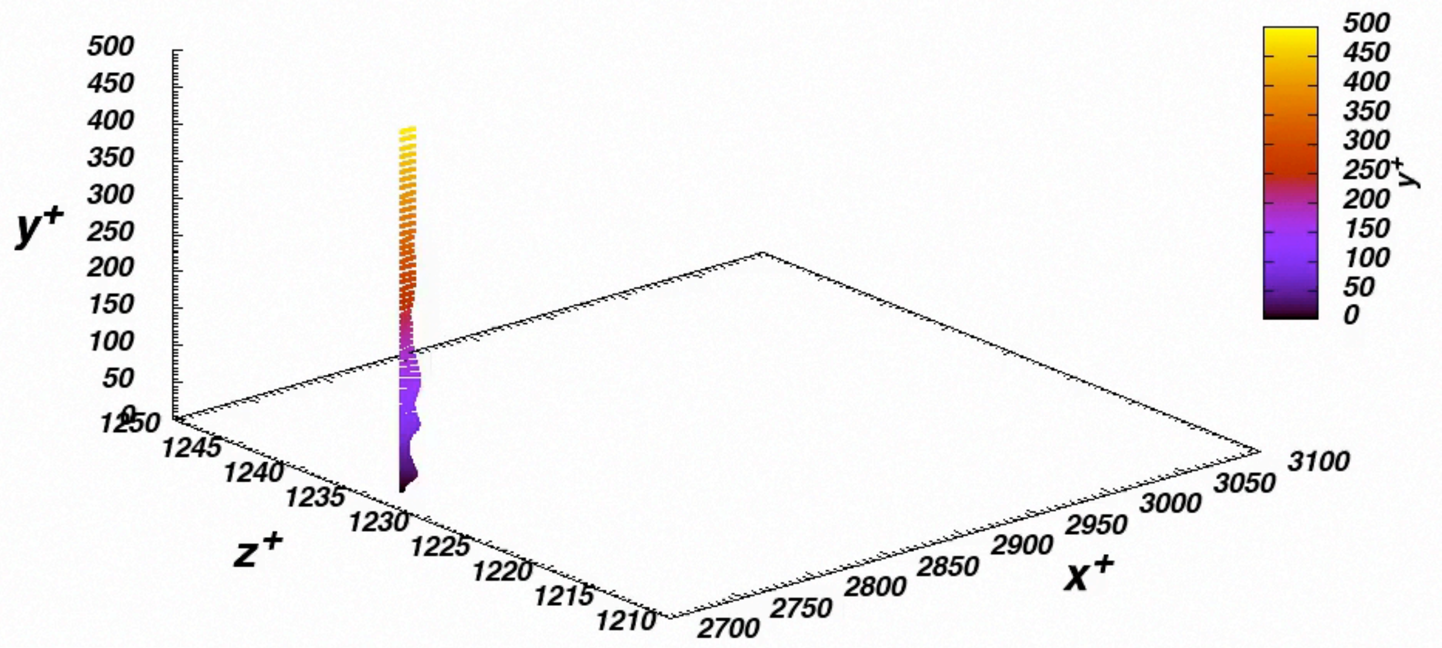
Fluid Particle Tracking

- Turbulent boundary layer DNS (Simens et al 2009, Sillero et al. 2011)

Re_τ	$(L_x, L_y, L_z)/\delta$	$\Delta x^+, \Delta y^+, \Delta z^+$	N_x, N_y, N_z	$Particles$
$137 - 800$	$20.7 \times 15.7 \times 55.4$	$13.6 \times 0.18 \times 12.5$	$4097 \times 315 \times 1024$	2.5 x 10^6

- Cubic Hermite spline interpolation
- track every Δt+ =0.12 RK3 time step, CFL=0.4



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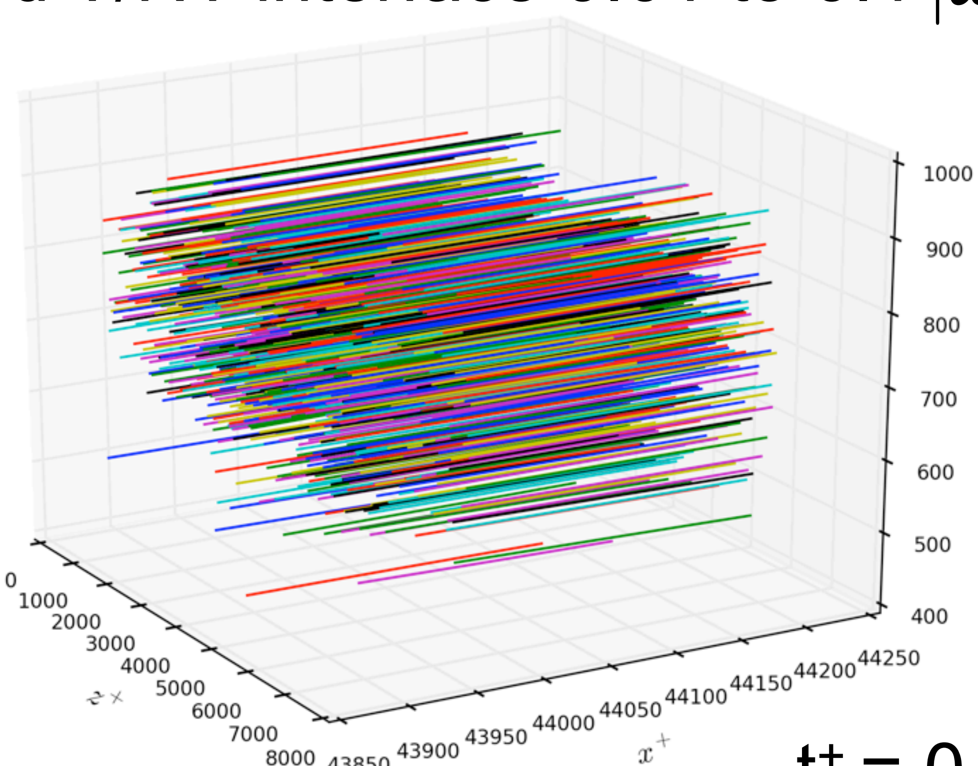
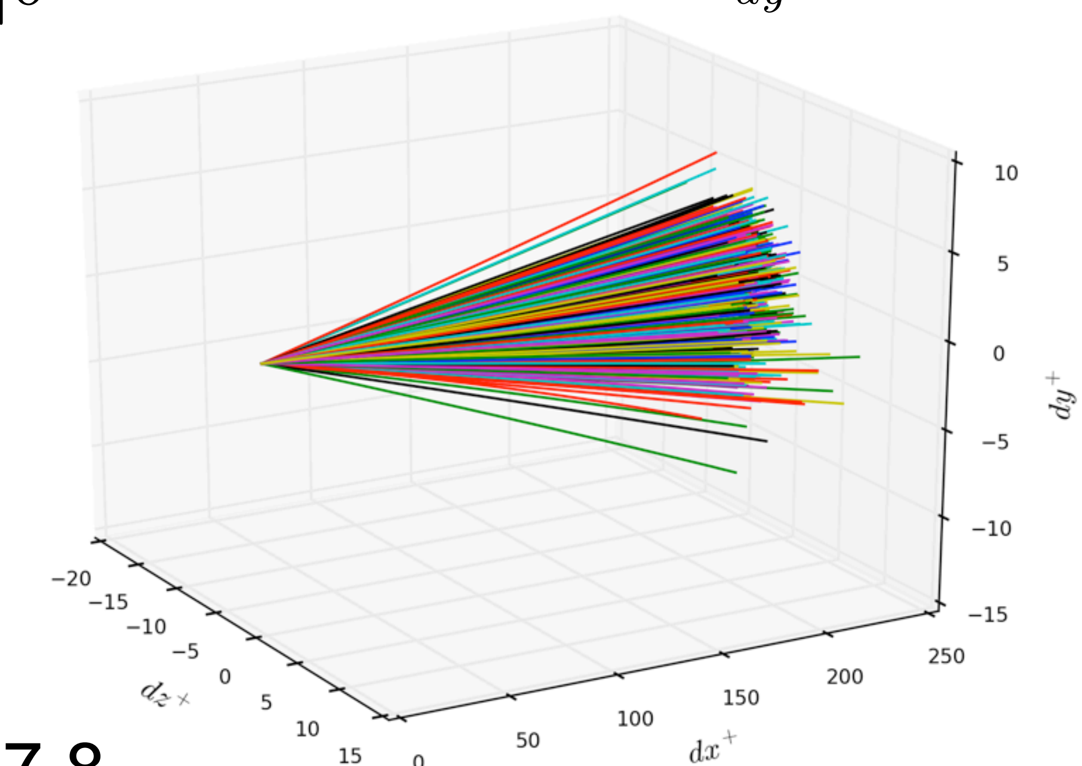
- Seed T/NT interface 0.01 to 0.1 $|\omega_0^+|\delta^+$

$$\overline{dy^+} = -0.75$$

$$\sigma_{dy^+} = 2.6$$





t^+ = 0 to 7.8

2000 particles

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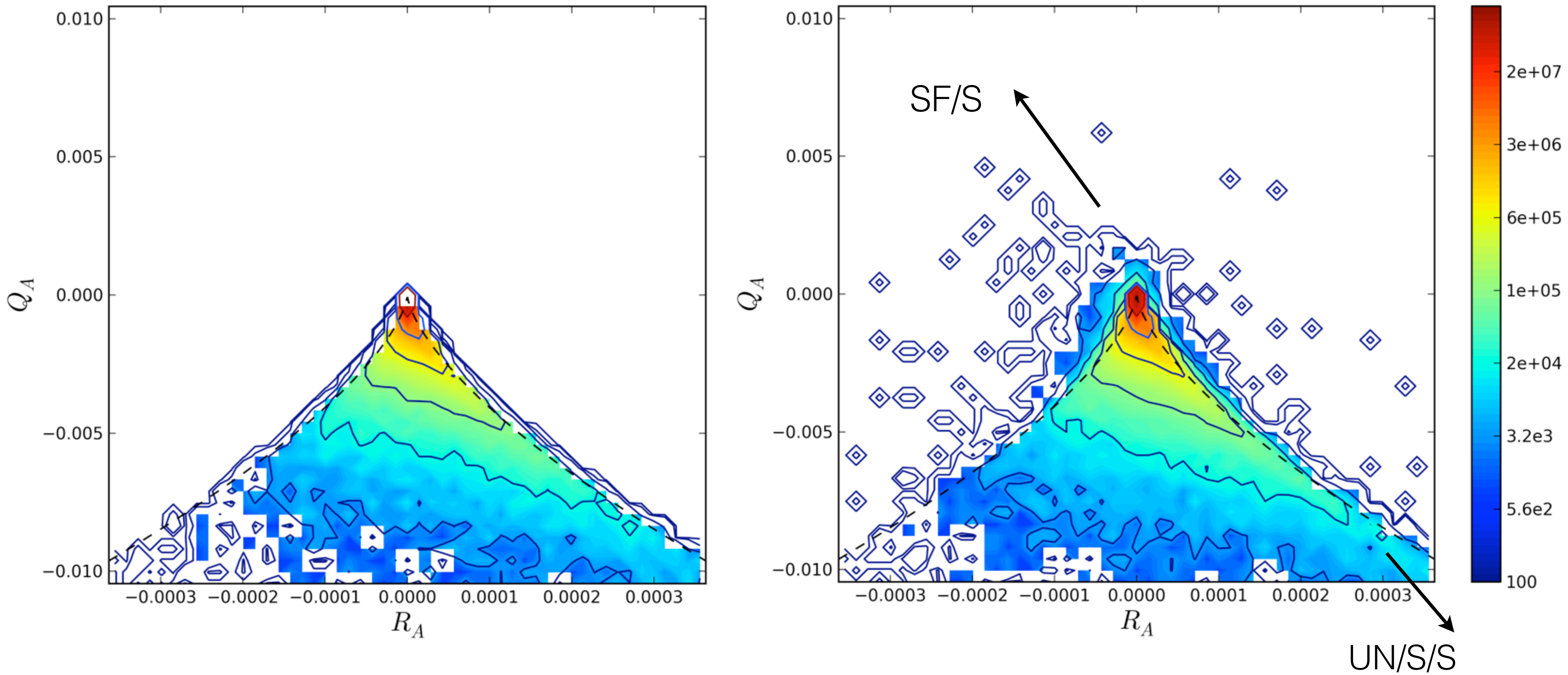
Change in Flow topology at particle positions

- Calculate JPDF at tracked fluid particle locations
- Topologies as fluid moves past T/NT interface



$t^+ = 0$ $t^+ = 7.8$

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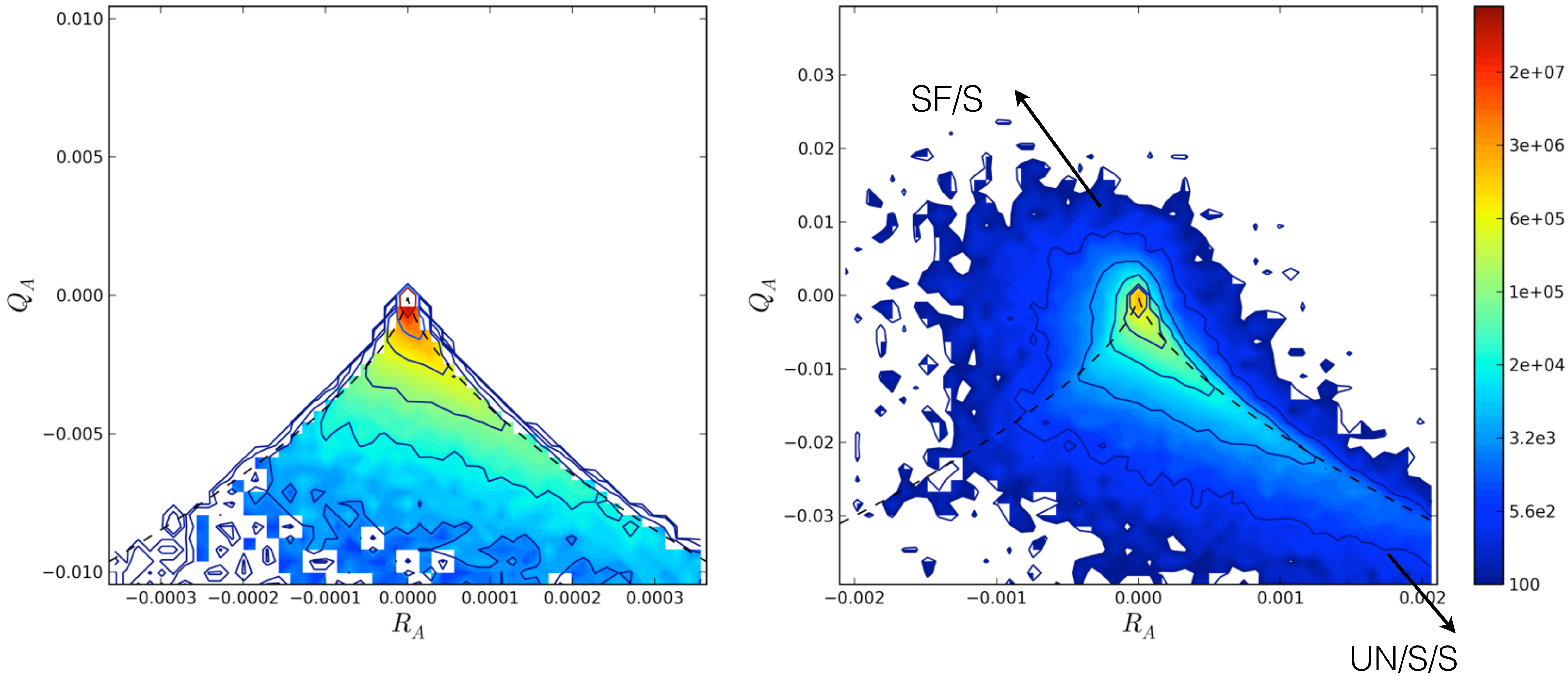

$t^+ = 0$

$t^+ = 38$

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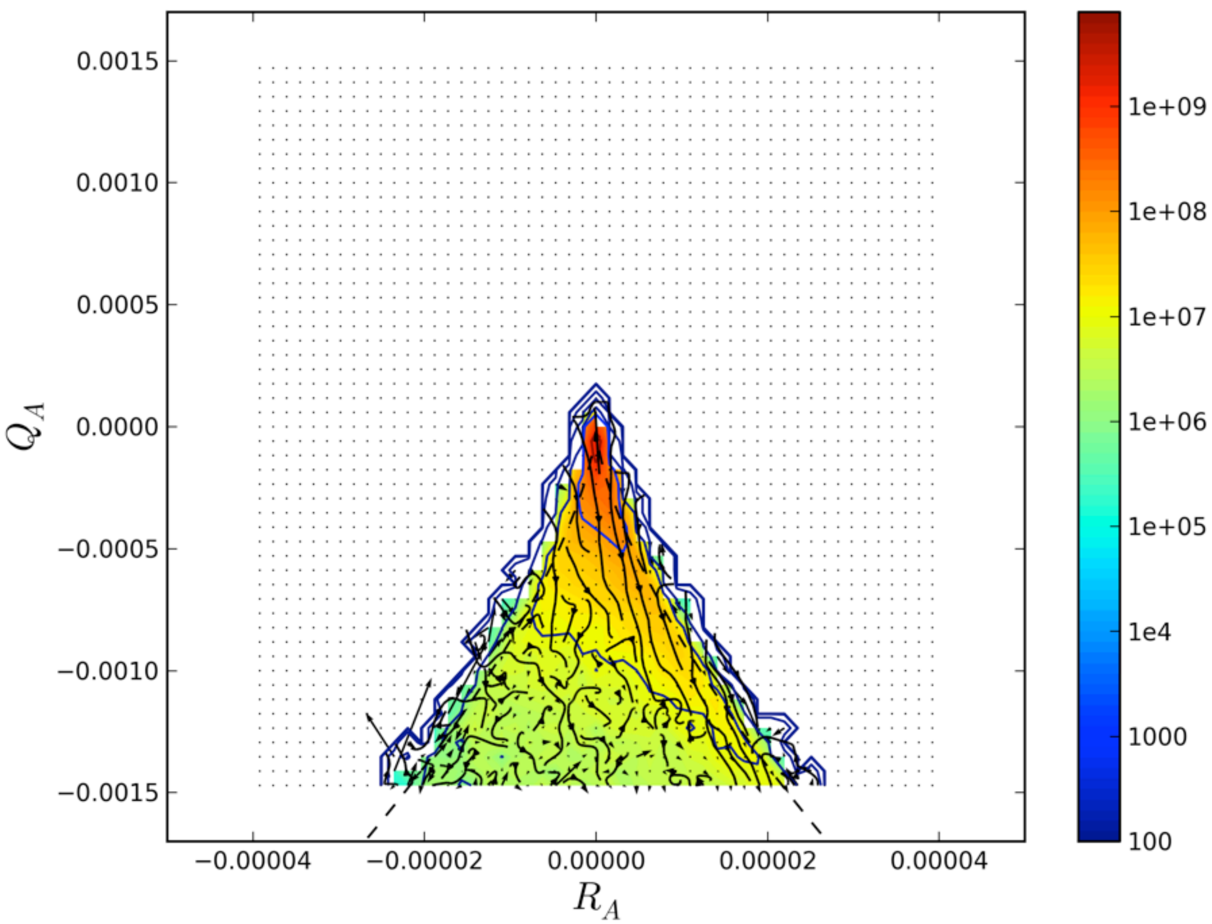
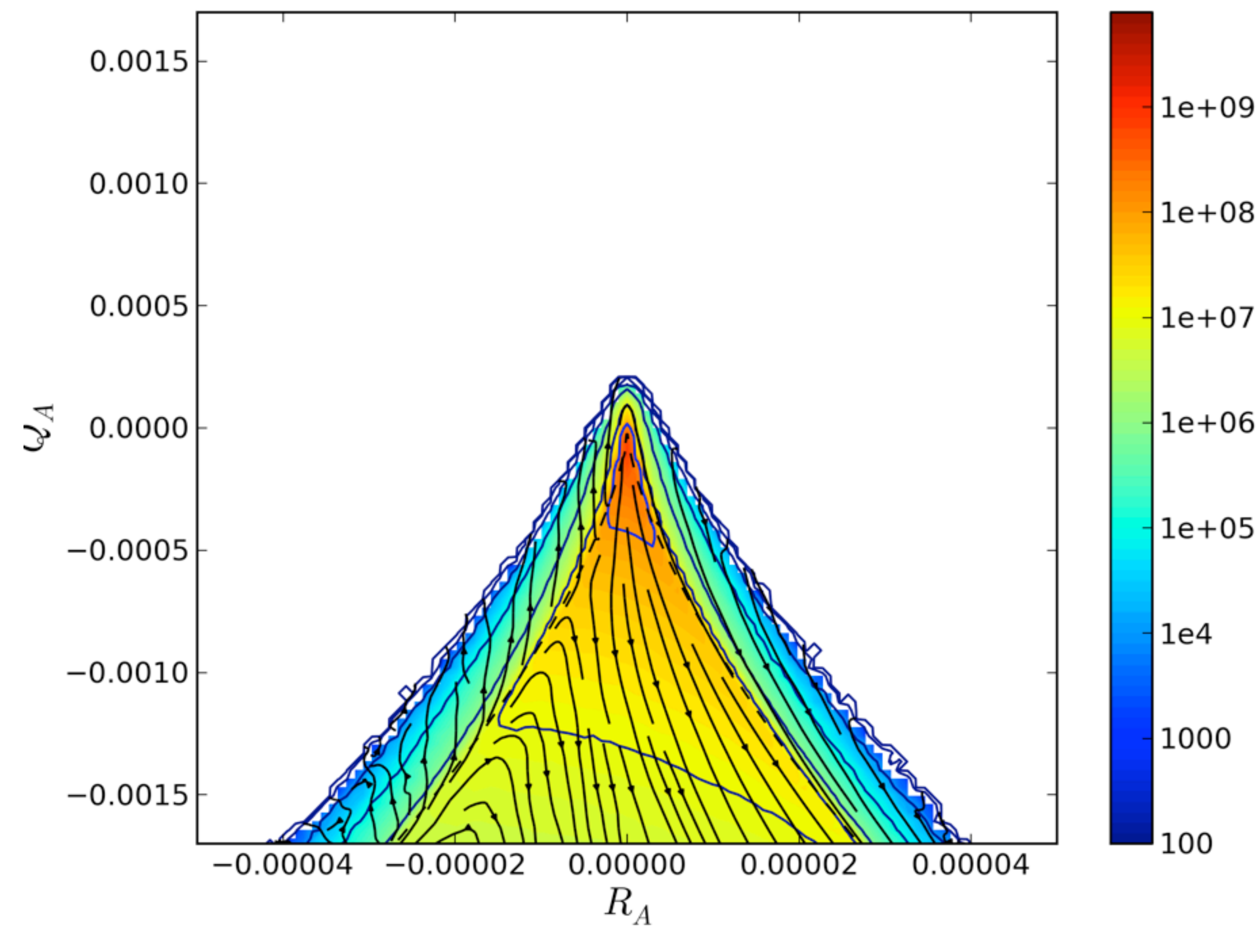
Conditional mean trajectories for particles

- trajectories in Q,R plane



CMT t^+ = 0 to 0.12



CMT at interface

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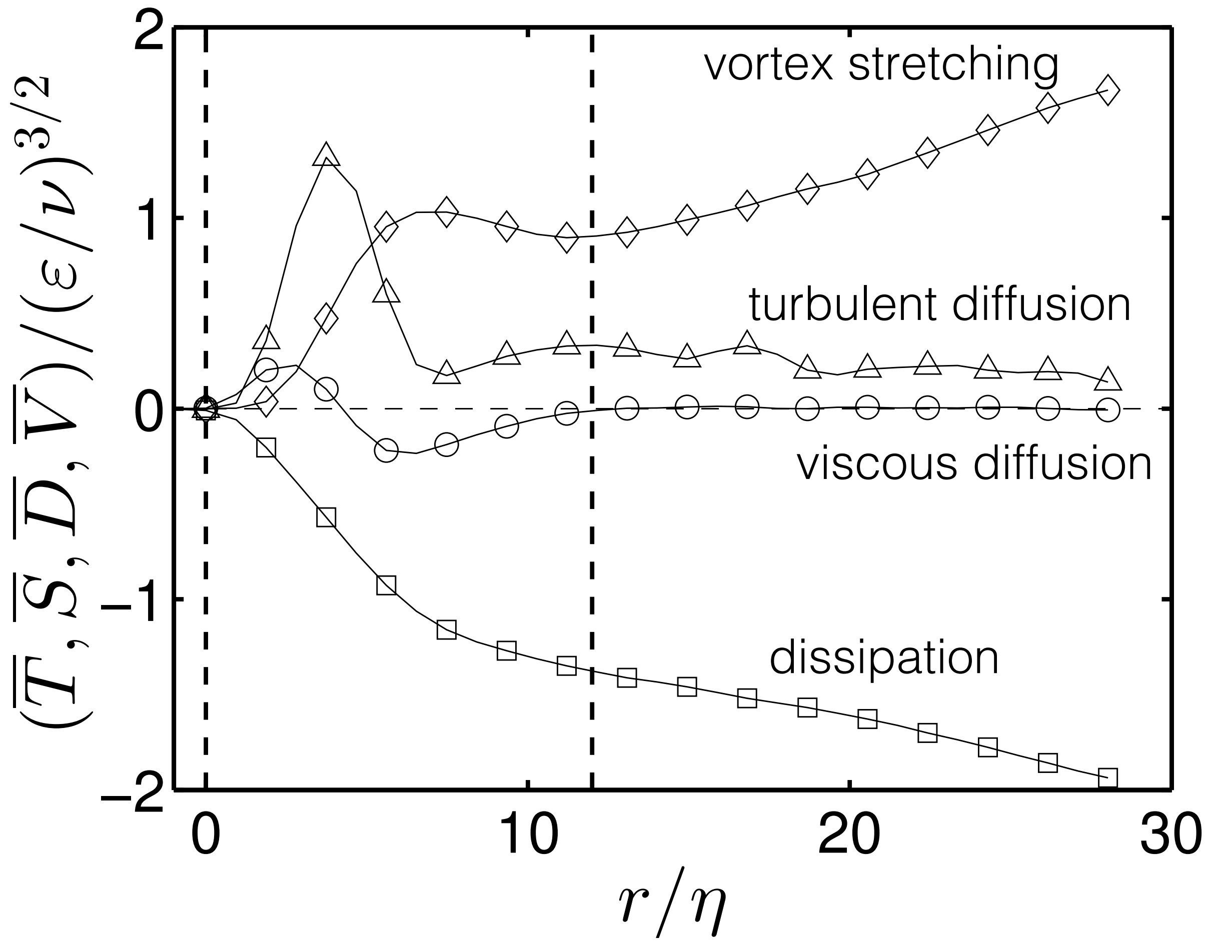
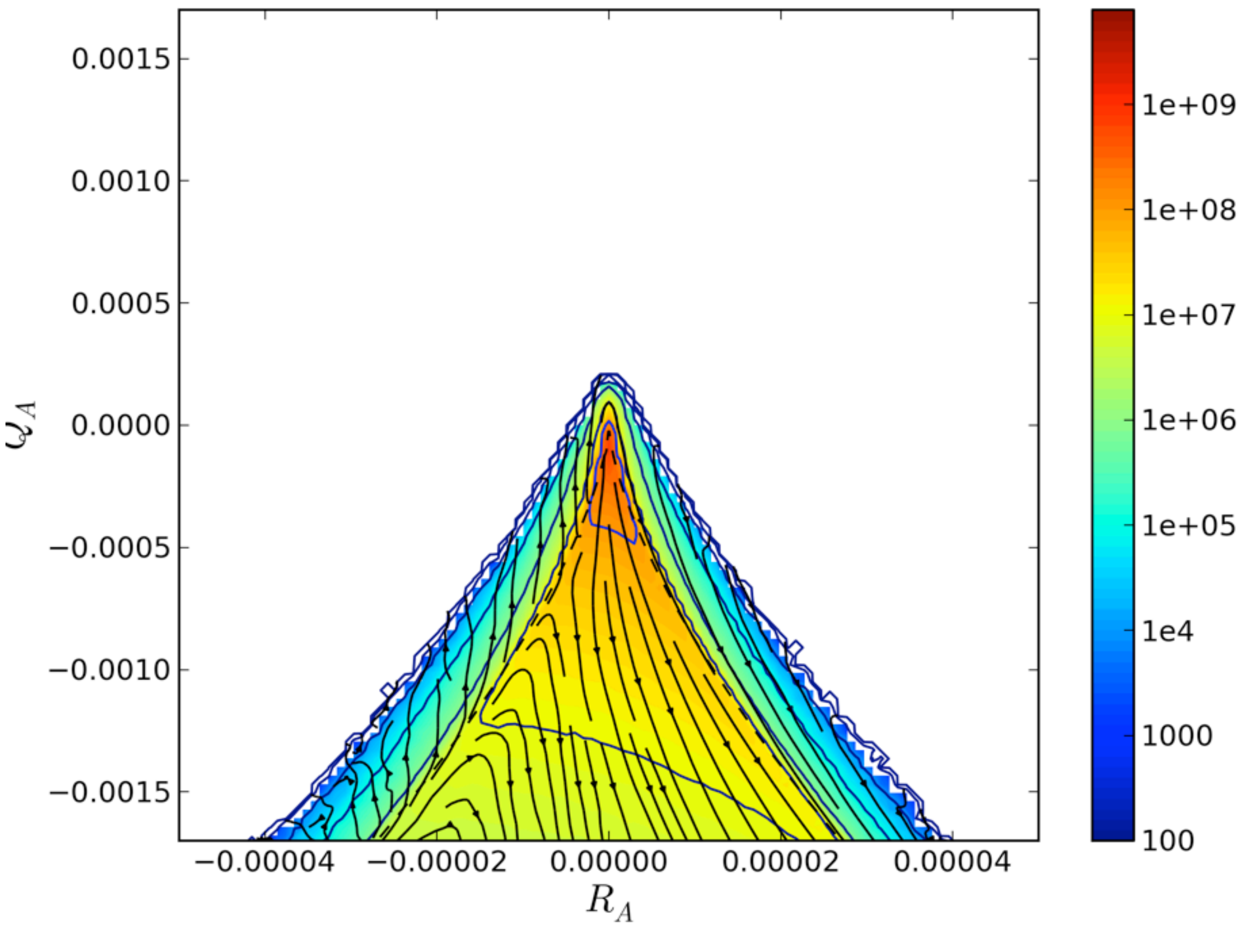
Change in Flow topology for individual particles

- Trajectories are consistent with vorticity evolution equation





CMT at interface

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Summary

- Used critical point theory invariants of the VGT to investigate topological evolution of the flow in the vicinity of the T/NT interface
- Conditional mean trajectories from RHS of N.S at the interface
  - ➡ indicates strong attraction towards UN/S/S for most locations
  - ➡ Gain in enstrophy is associated fluid in region of weak gradients moving to regions of SF/S
- Particle trajectories show nett entrainment and similar changes in topology as predicted by CMTs
- Remains to examine correlation between increased enstrophy, velocity, position - further explore particle statistics

Thank you for your attention

The Australian and European Research Councils are acknowledged for their financial support