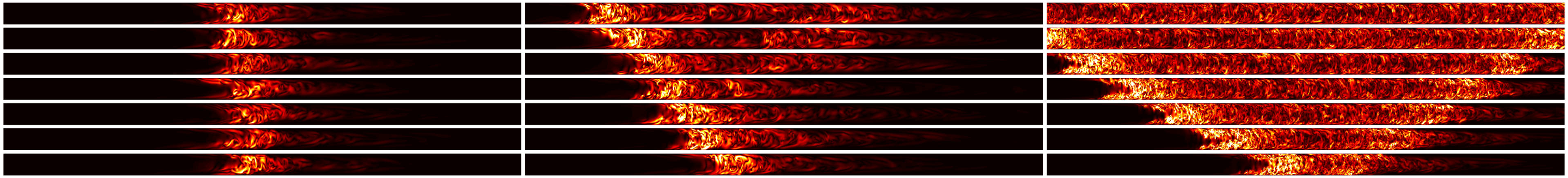
Physics and modeling of laminar-turbulent interfaces in pipe flow

Marc Avila



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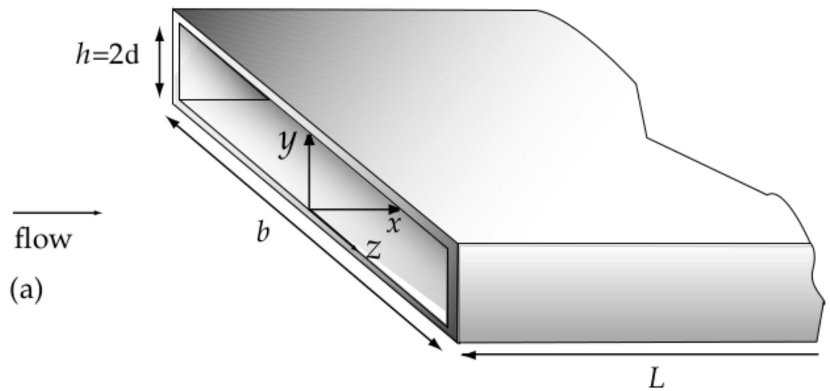
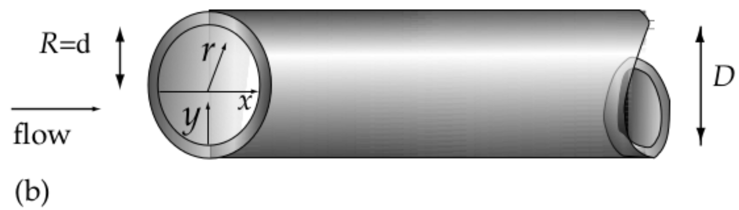
Why pipe flow?

Channel flow

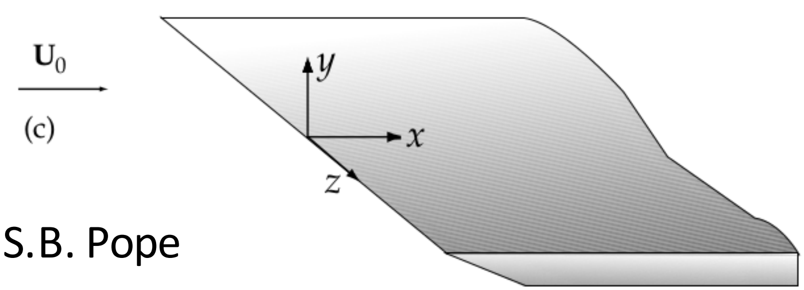


Pipe flow



Span-wise periodic
Quasi 1D

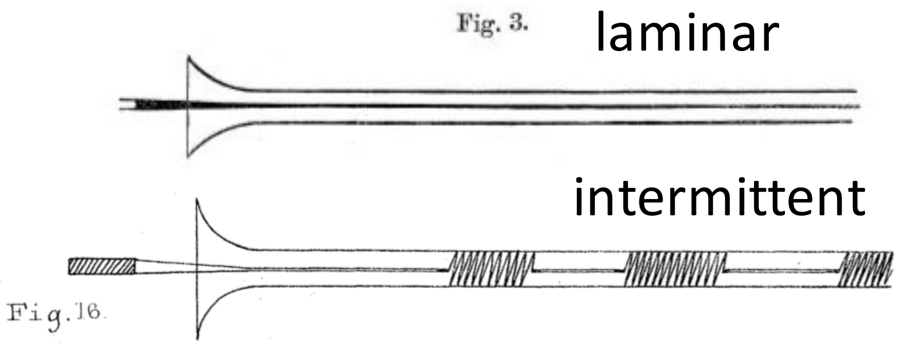
Boundary layer flow



TURBULENT FLOWS, by S.B. Pope

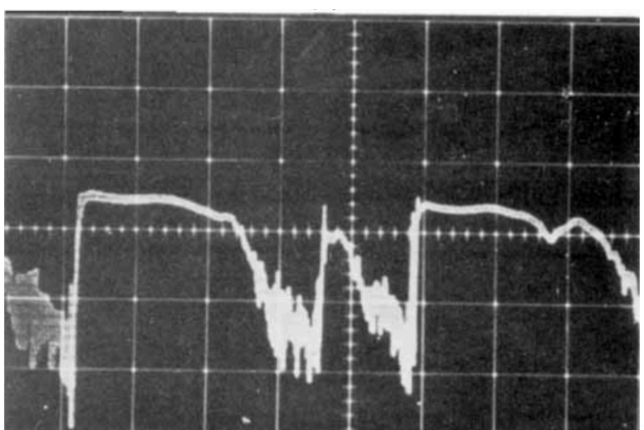
Transitional pipe flow

Reynolds *PTRSL* 1883

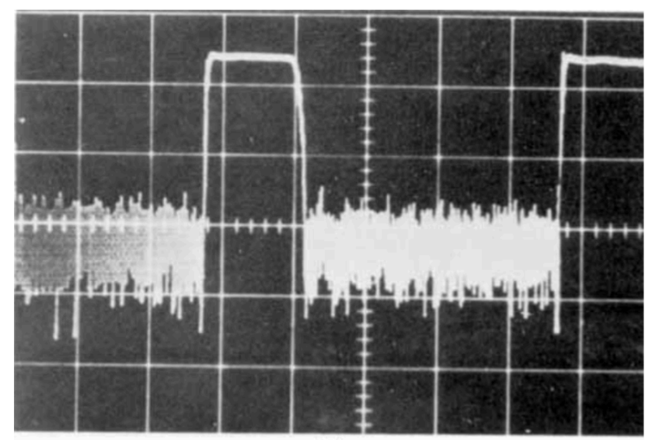


Wygnanski & Champagne *JFM* 1973: obstacle at inlet

Re=2400 Spatio-temporal intermittency

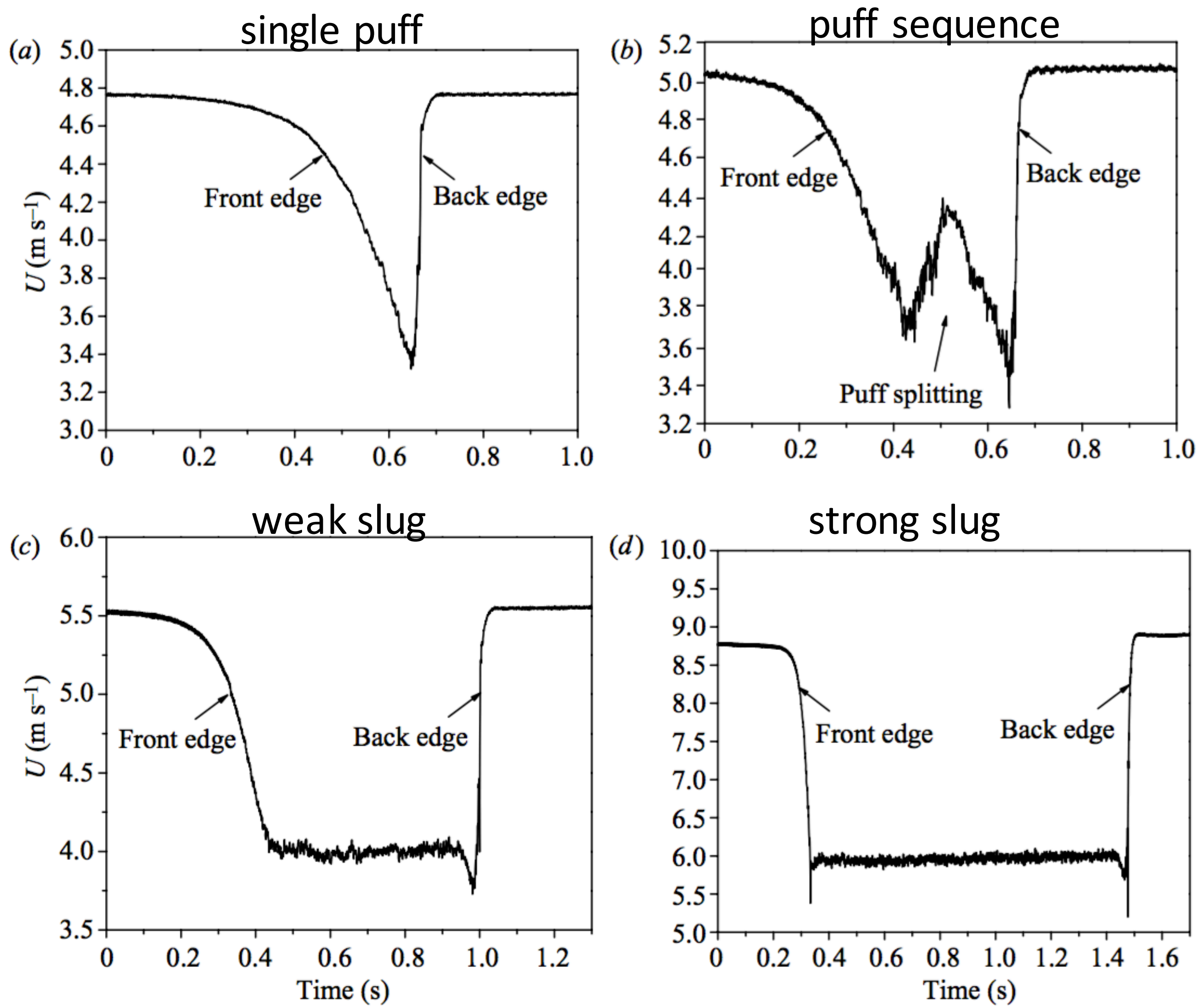


Re=4200 Slug sequence



Laminar-turbulent fronts

Re~2100 Re~2300

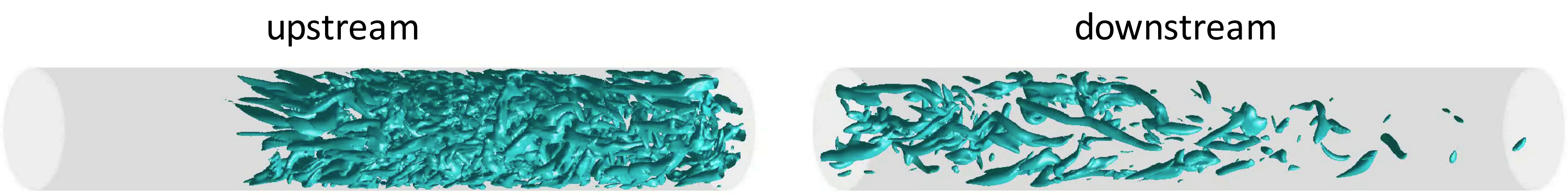


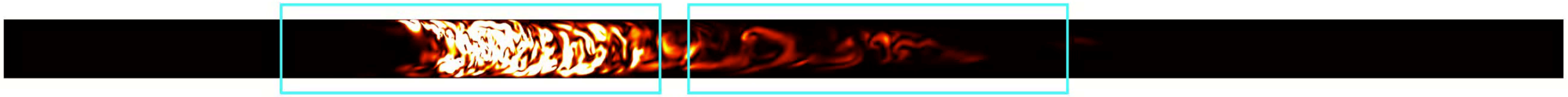
Re~3000 Re~4100

Nishi *et al., JFM* 2008: controlled (pulsed) disturbance

DNS: weak slug

Re=2600, weak downstream front

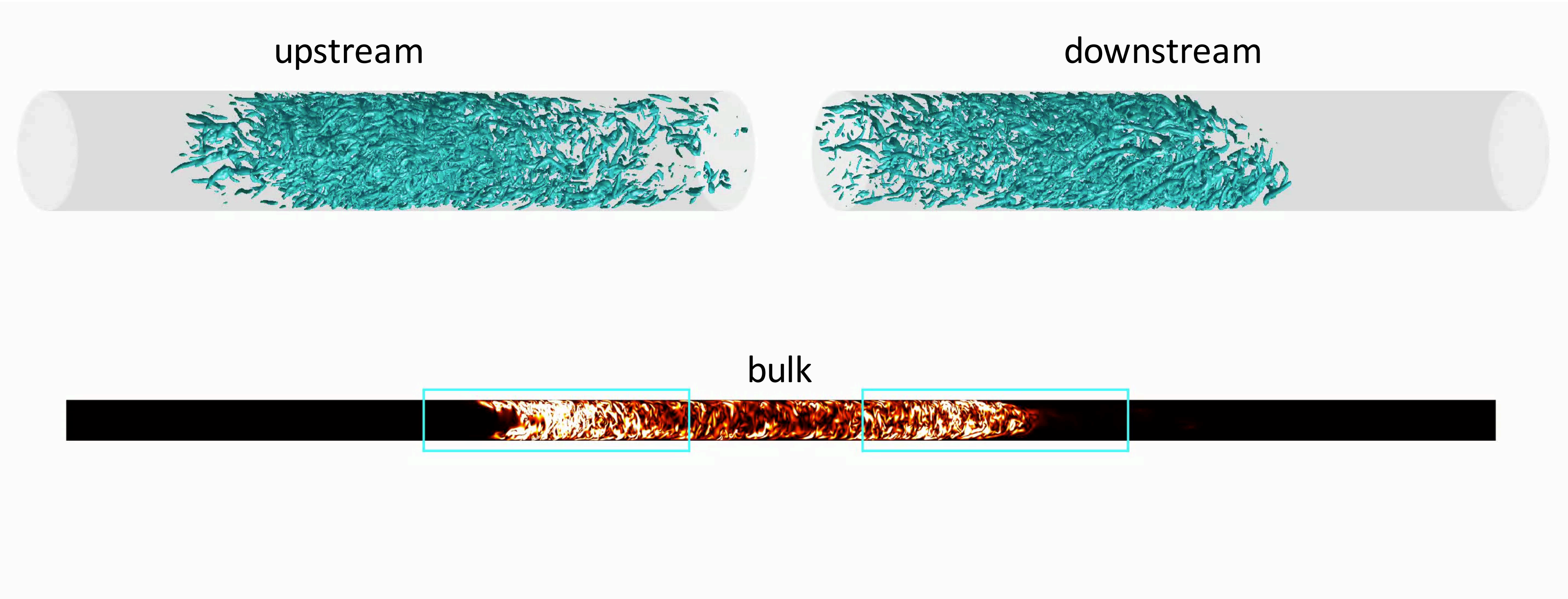




Song *et al.*, JFM (in press)

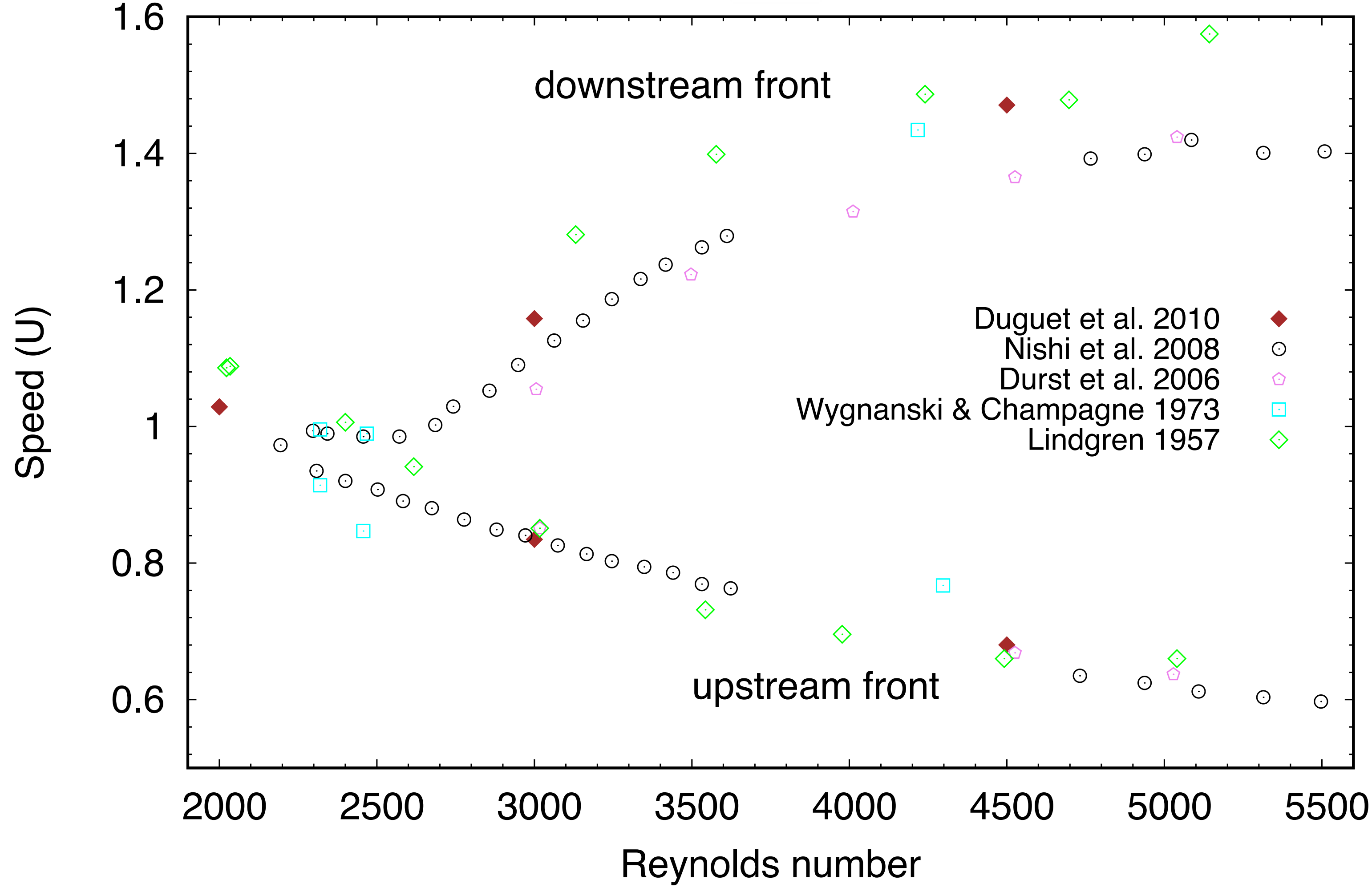
DNS: strong slug

Re=5000, strong downstream front

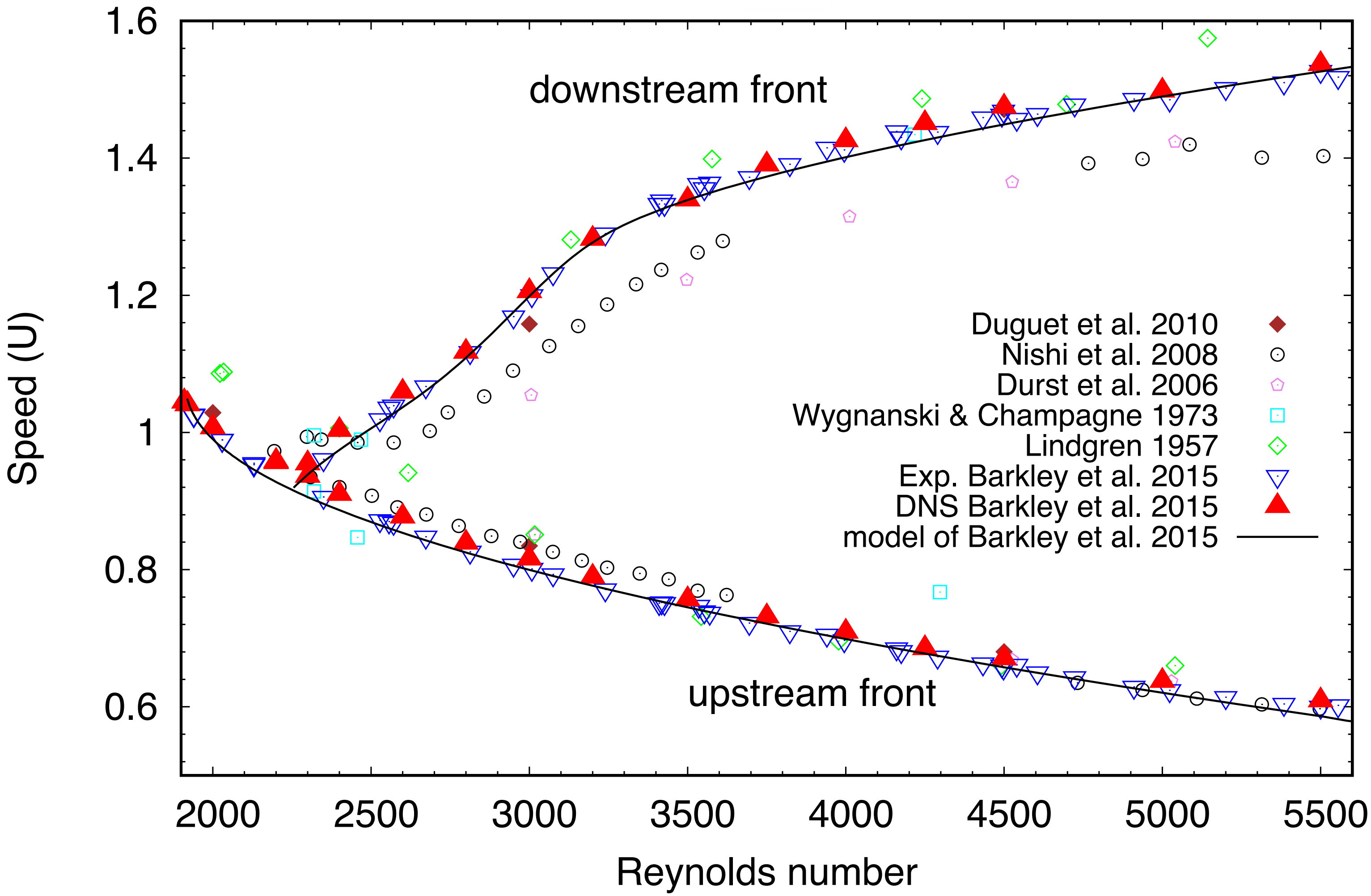


Song *et al.*, JFM (in press)

Front speeds



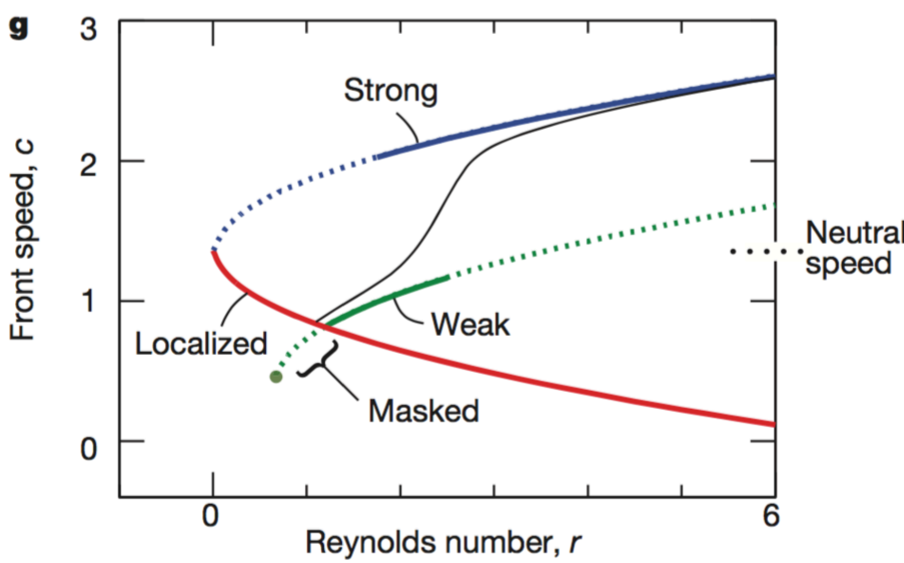
Front speeds

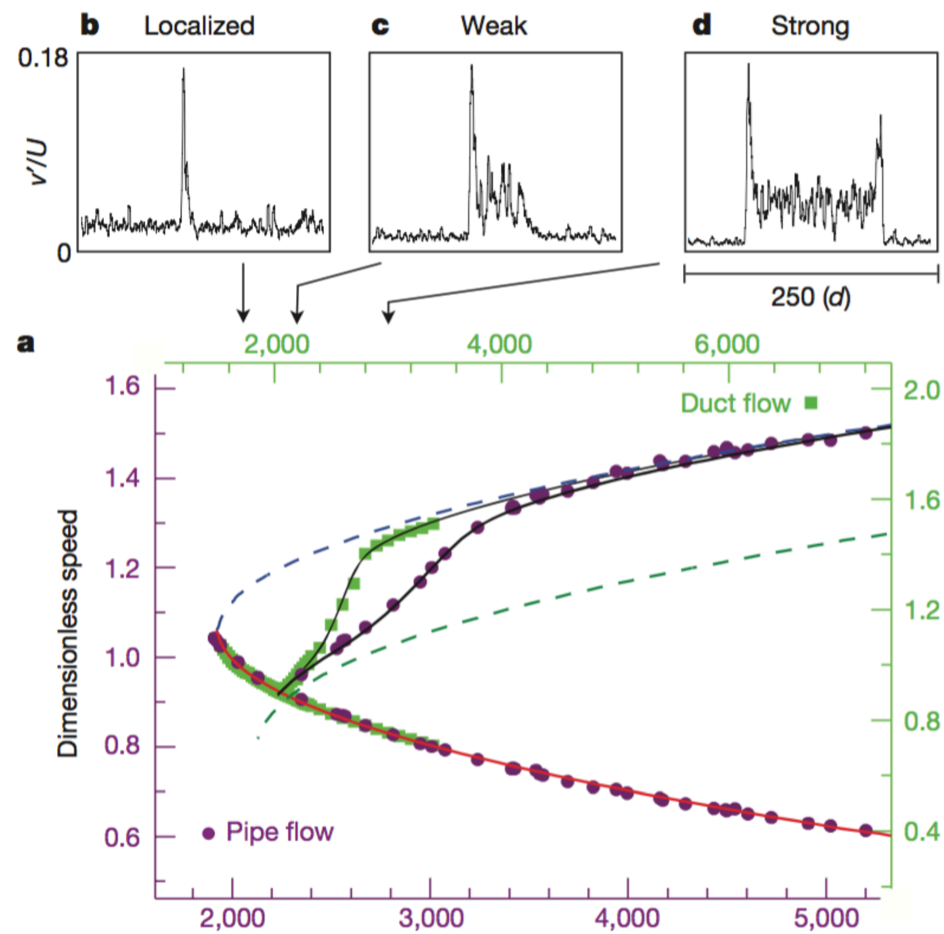


The rise of fully turbulent flow

u: centerline velocity
q: turbulence intensity

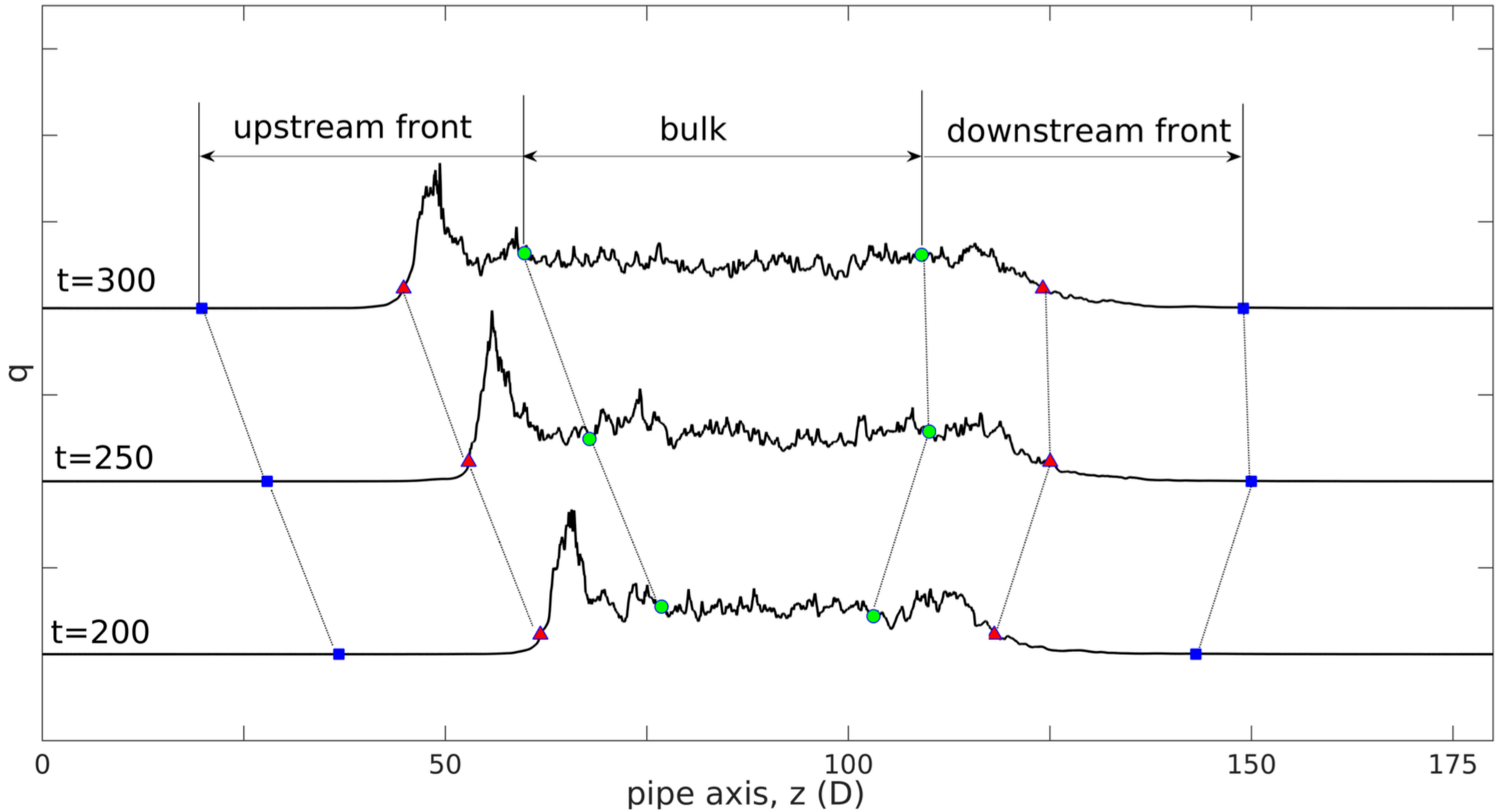
$$u_t + u u_x = \epsilon g(q, u)$$
$$q_t + (u - \zeta) q_x = f(q, u) + D q_{xx}$$





Barkley e*t al., Nature* 2015; Barkley *JFM* 2016

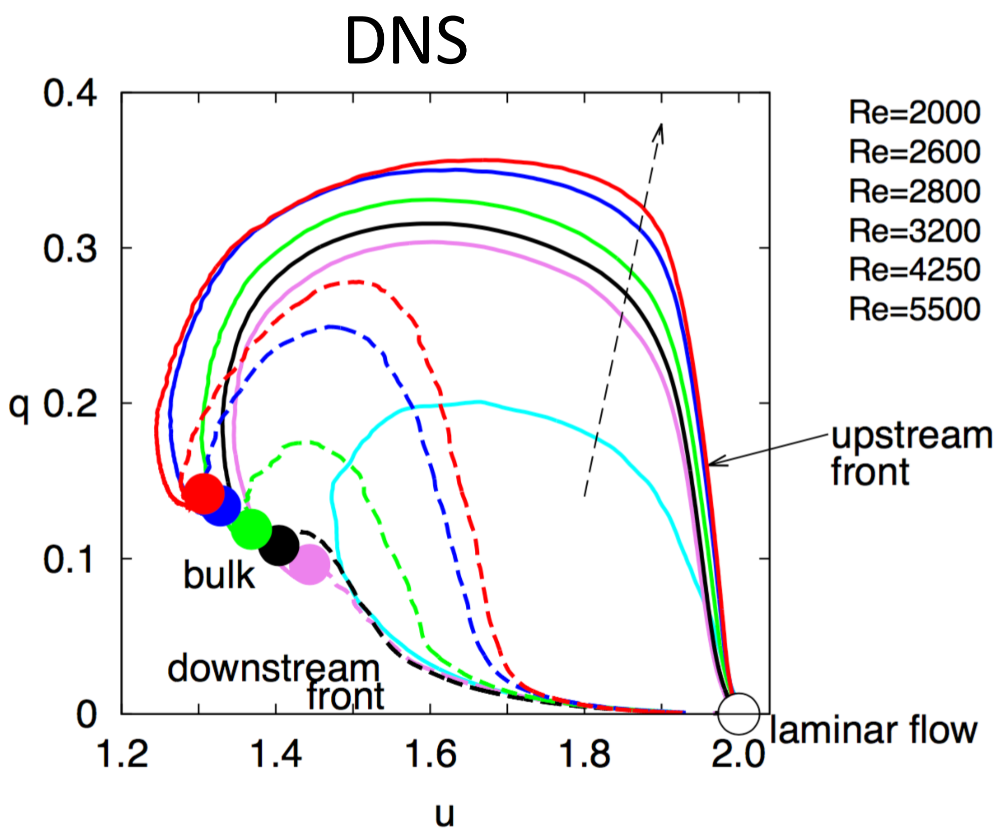
Front definitions

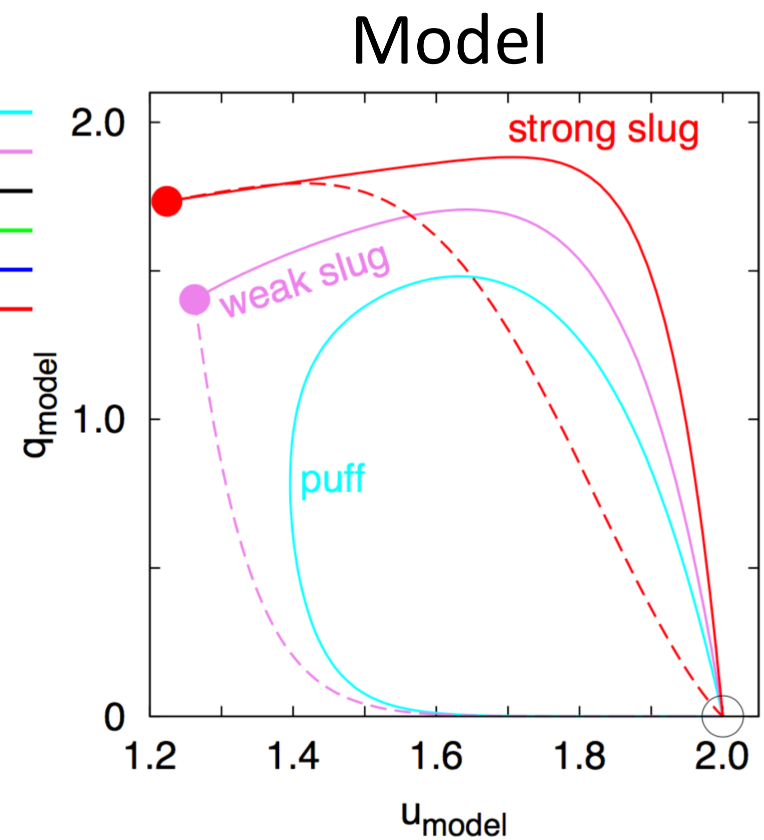


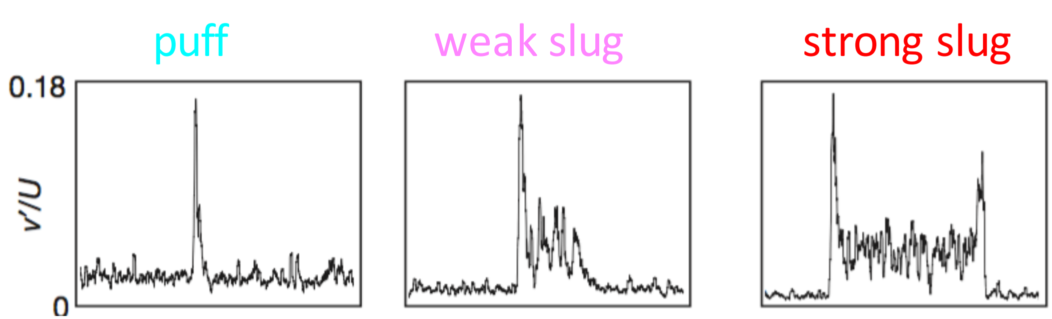
$$q(z) := \sqrt{\int\int (u_r^2 + u_\theta^2) r dr d\theta}$$

Song *et al.*, JFM (in press)

Front structure in (*u*,*q*)-space

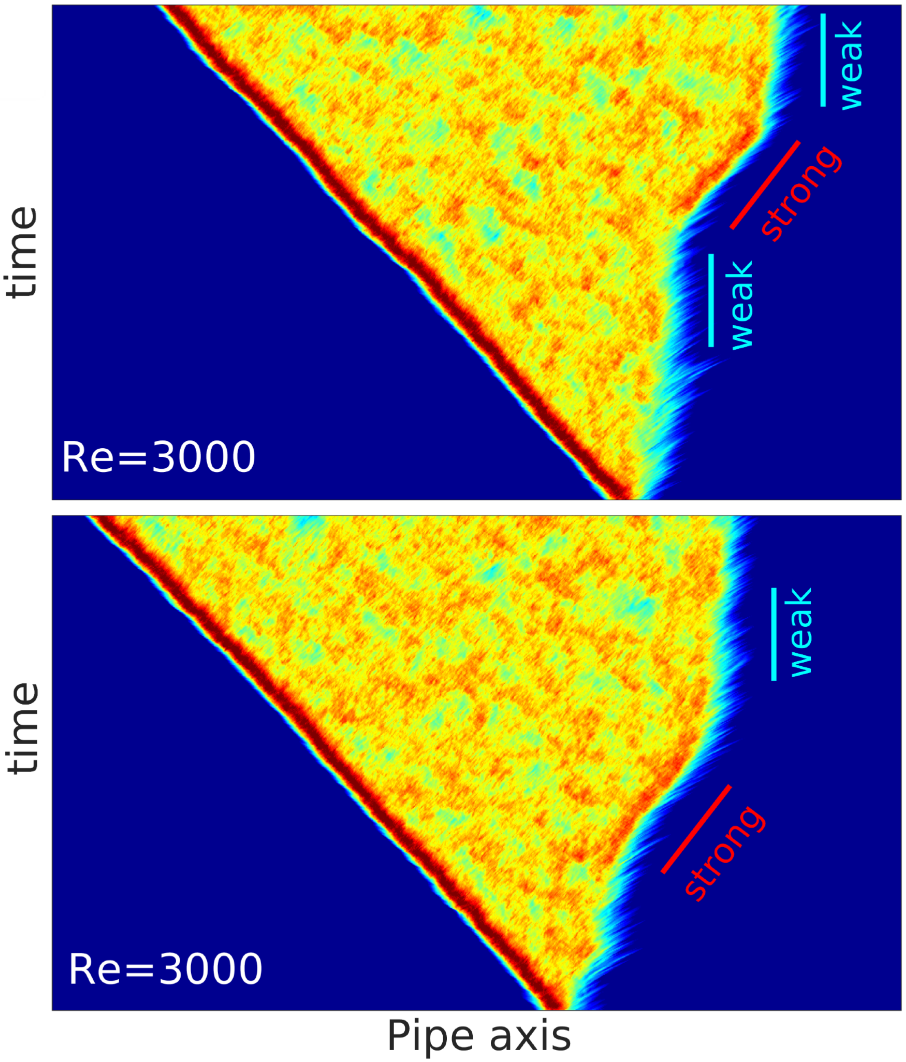


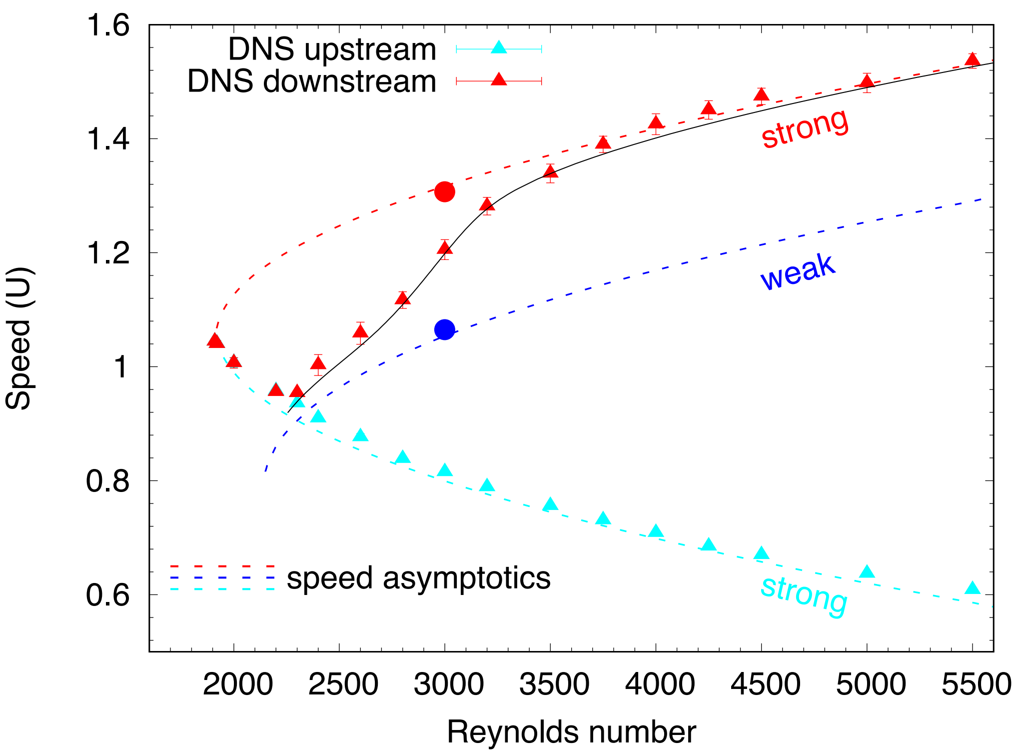




Song *et al.*, JFM (in press)

Front switching





Song *et al.*, JFM (in press)

Turbulent kinetic energy equation

- Turbulent kinetic energy: $k = \frac{1}{2}\overline{\boldsymbol{u}' \cdot \boldsymbol{u}'}$

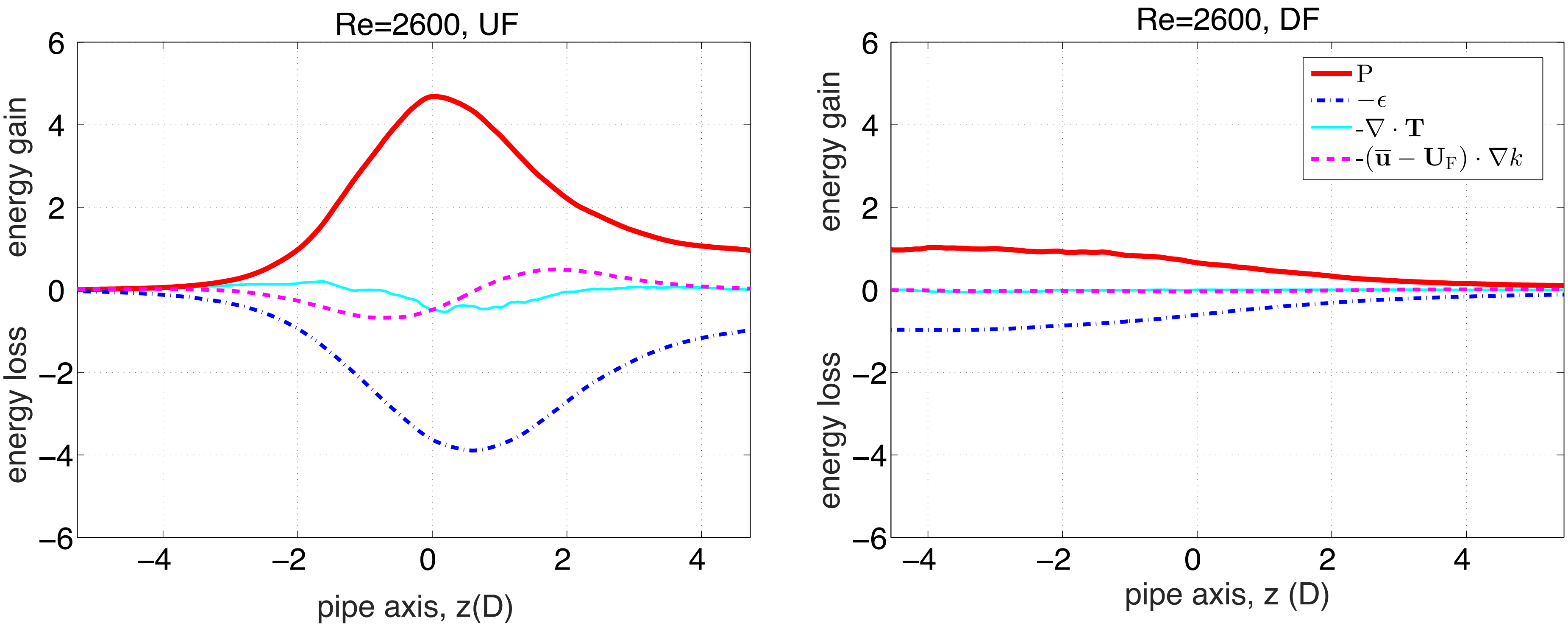
$$\frac{\bar{\mathrm{D}}k}{\bar{\mathrm{D}}t} + \nabla \cdot \boldsymbol{T} = P - \epsilon$$

- Co-moving with the front:

$$\frac{\partial k}{\partial t} = P - \epsilon - (\bar{\boldsymbol{u}} - \boldsymbol{U}_{\mathrm{F}}) \cdot \nabla k - \nabla \cdot \boldsymbol{T} = 0$$

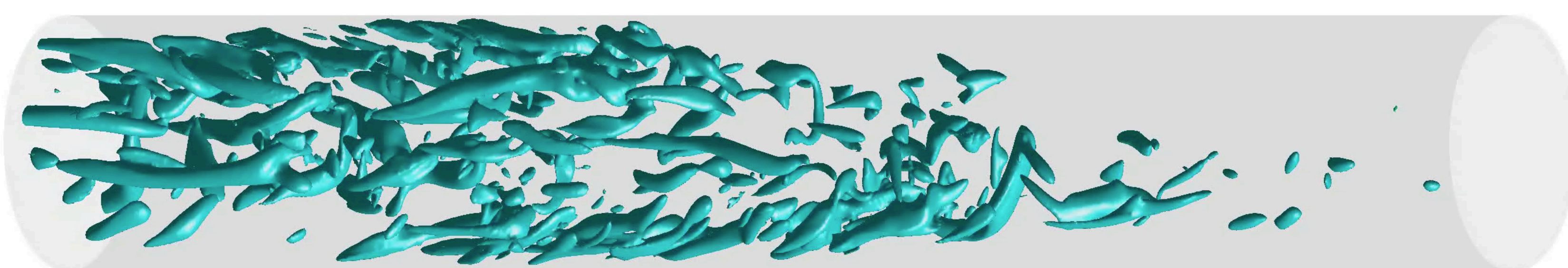
Song *et al.*, JFM (in press)

Kinetic-energy budget at Re=2600



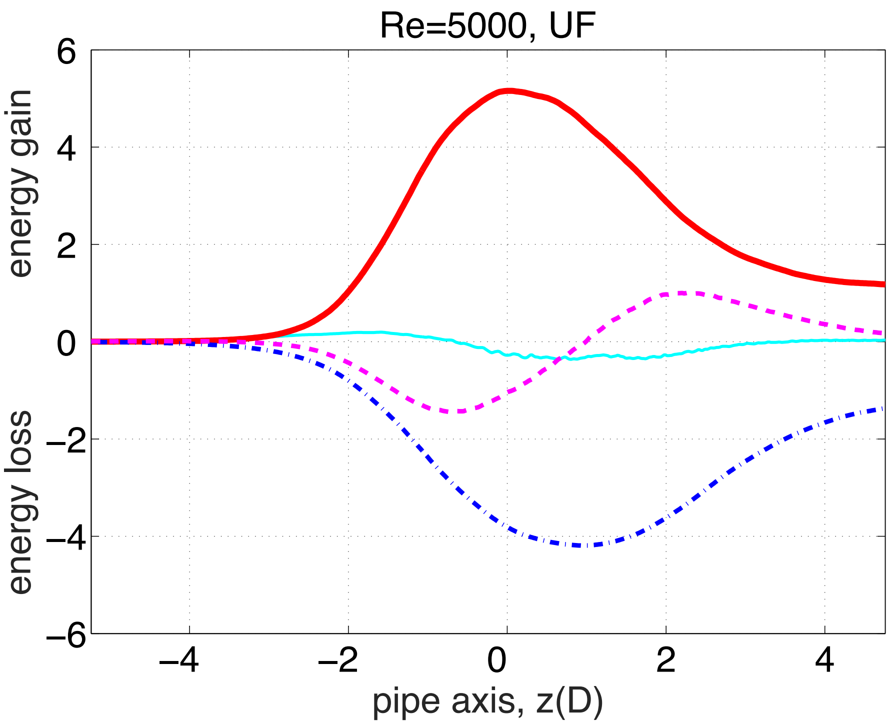
DF

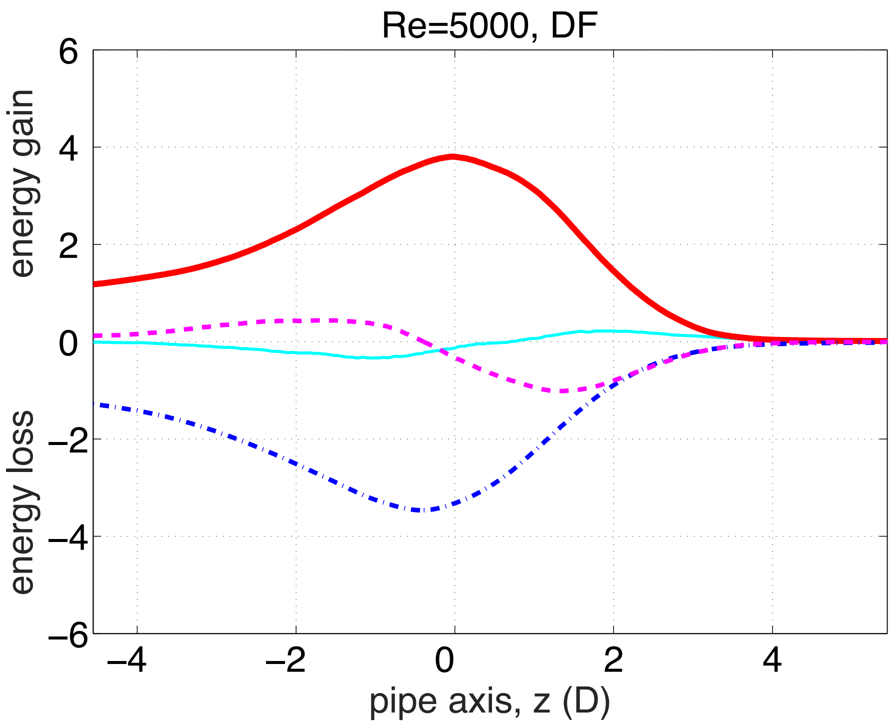
advection

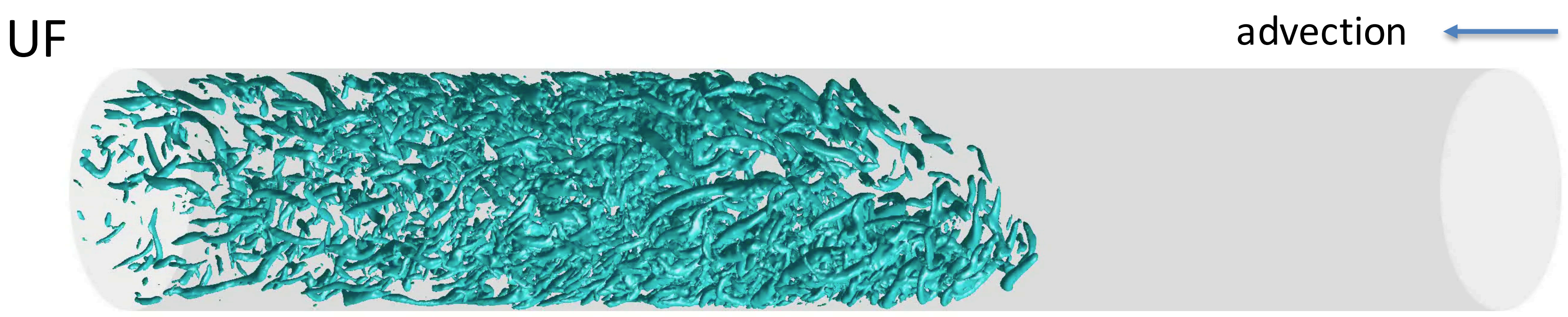


Song *et al.*, JFM (in press)

Kinetic-energy budget at Re=5000





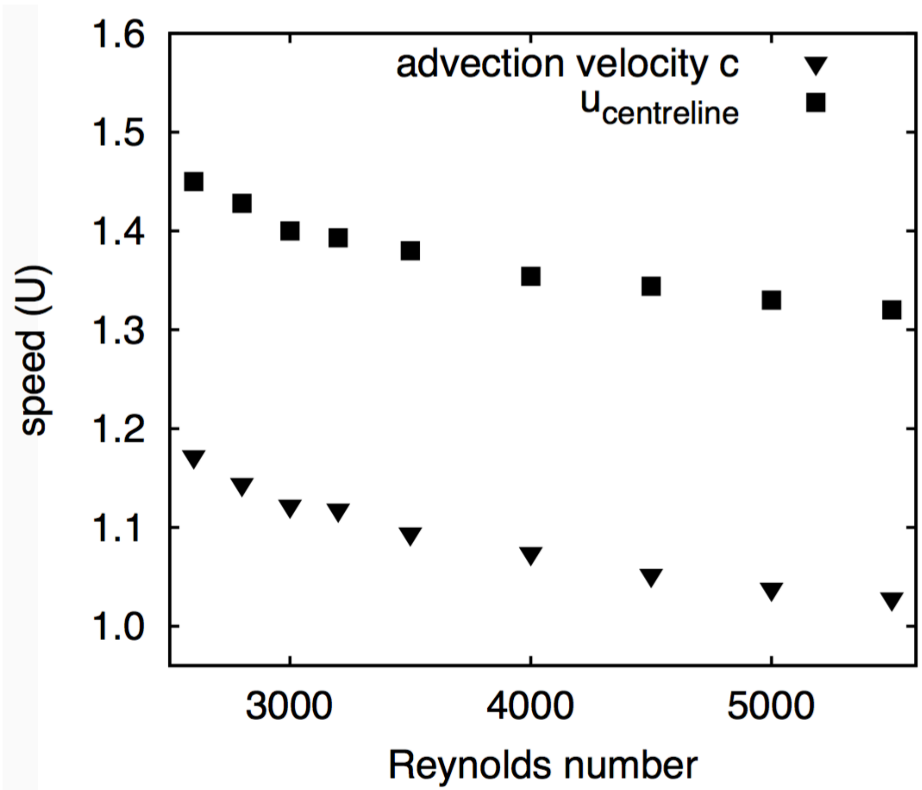


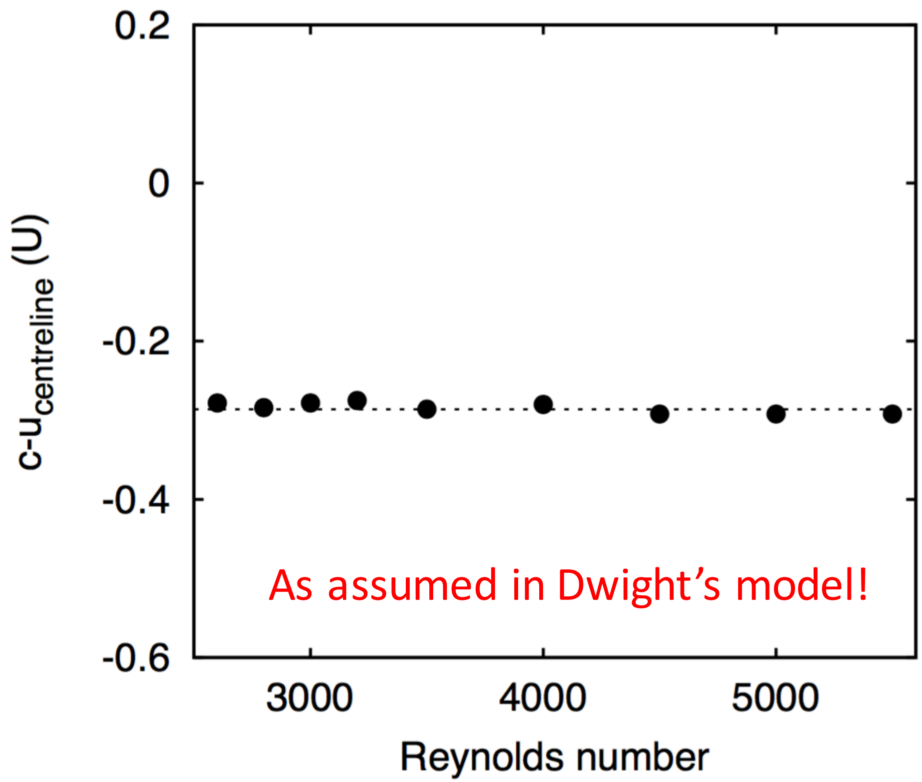
Song *et al.*, JFM (in press)

Mean turbulent advection speed

$$c = -\frac{< \partial_z \boldsymbol{u}(r,\theta,z,t) \cdot \boldsymbol{f}(\boldsymbol{u}(r,\theta,z,t),p,t) >}{\|\partial_z \boldsymbol{u}(r,\theta,z,t)\|^2}$$

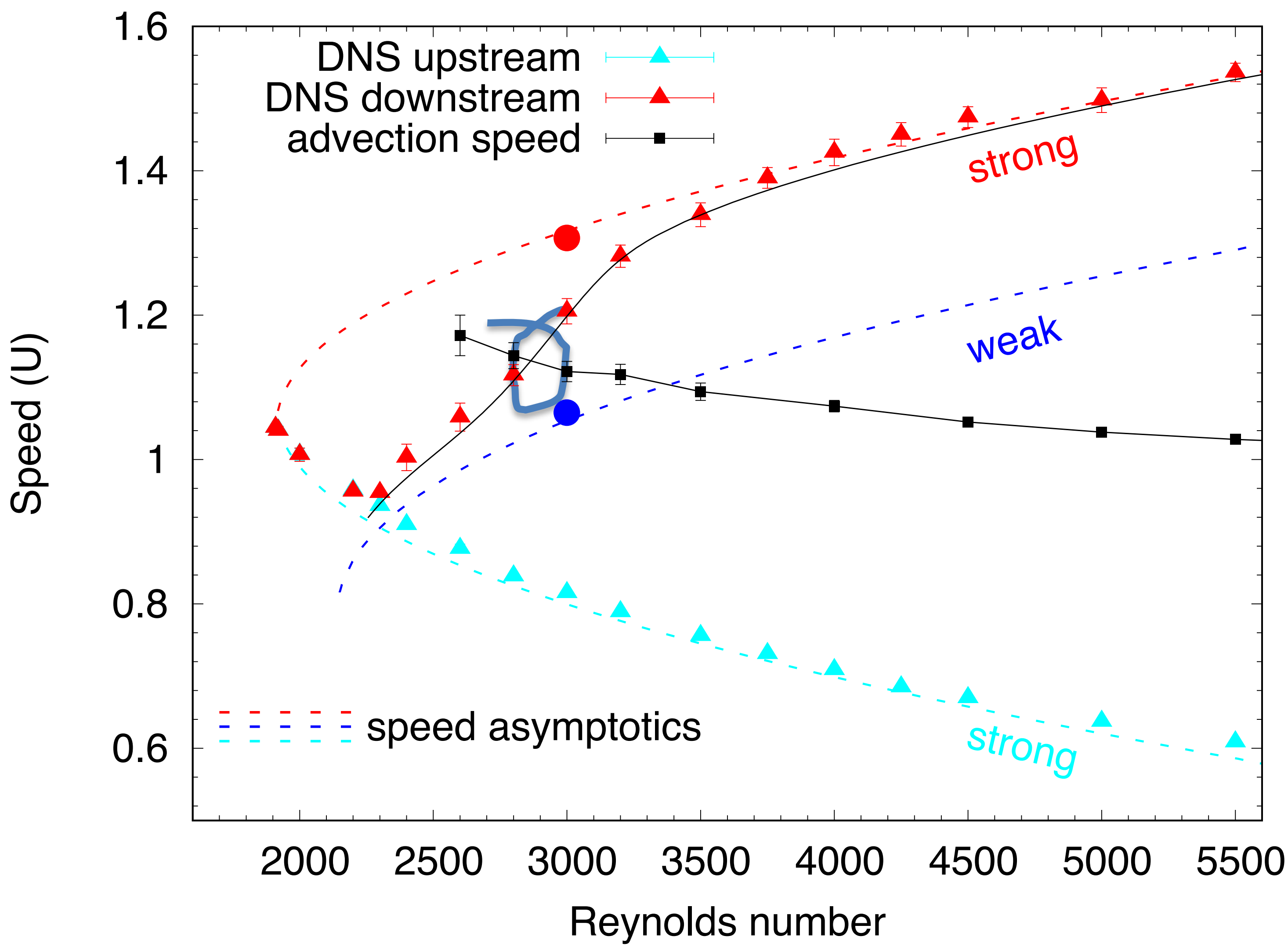
Kreilos, Zammert & Eckhardt, JFM 2014



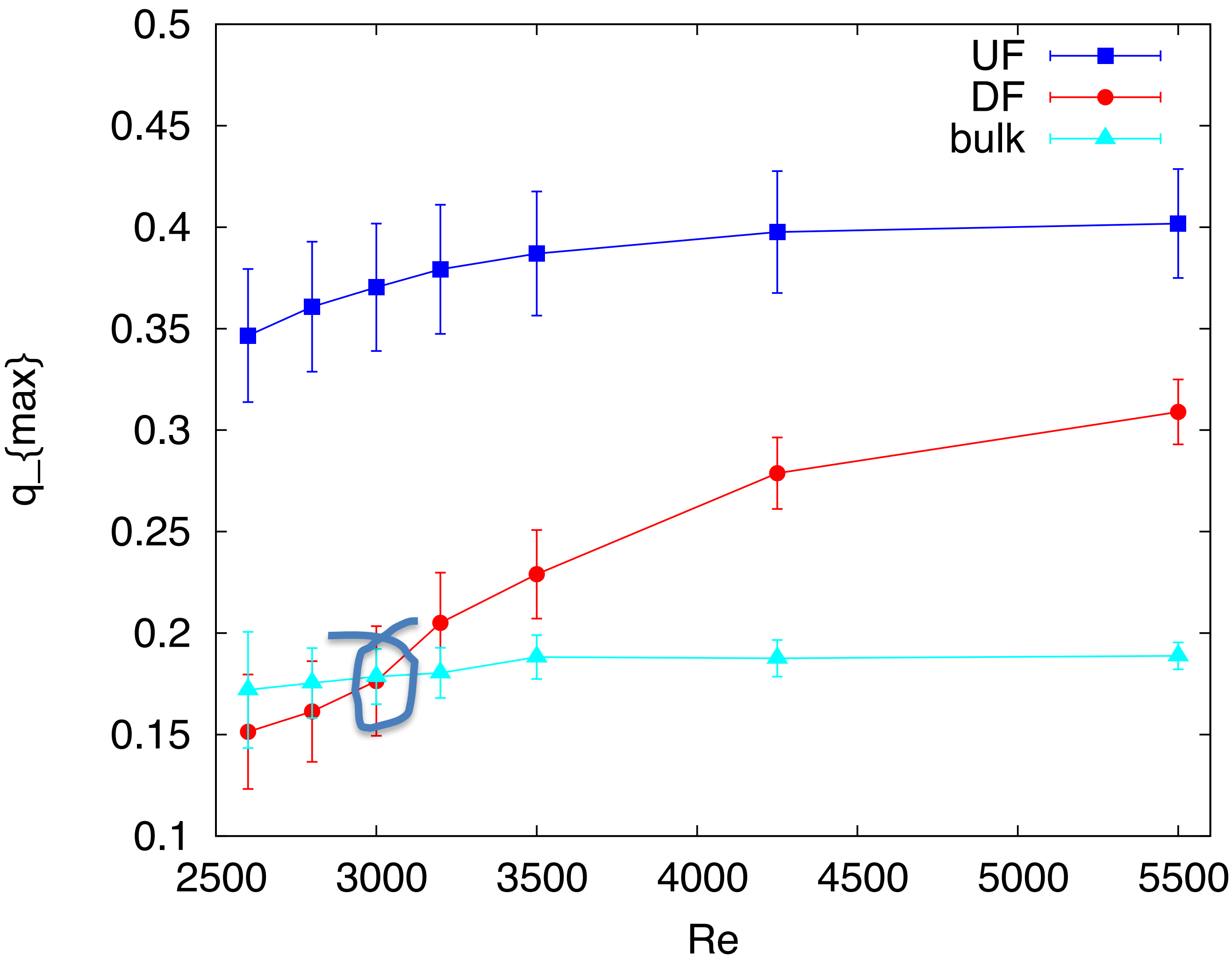


Song *et al.*, JFM (in press)

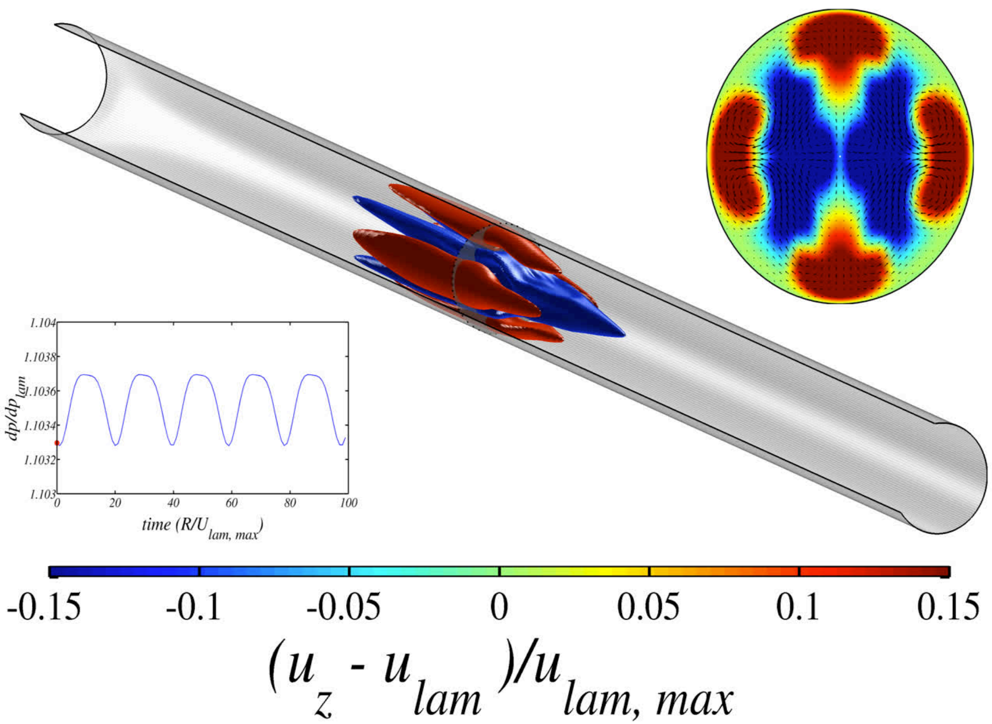
Crossover weak to strong fronts



Crossover weak to strong fronts



Fronts and ECS: localized RPO



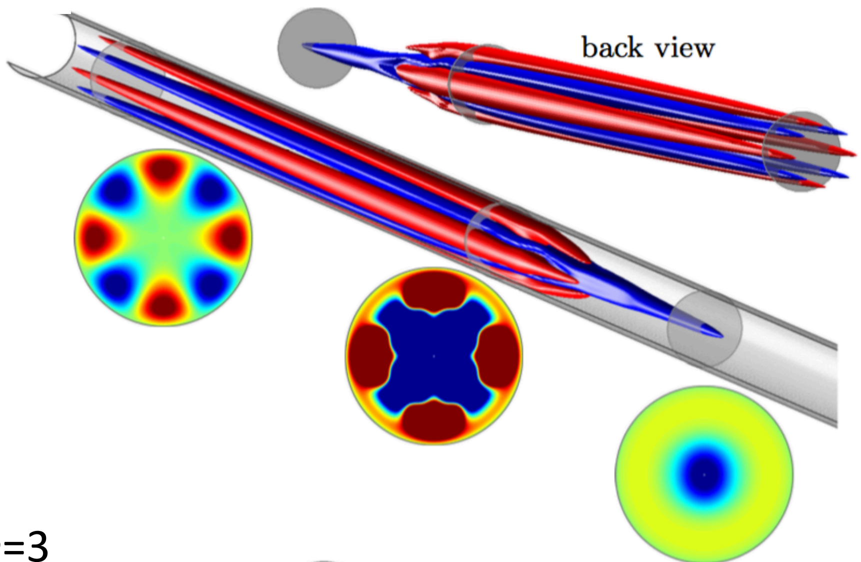
RPO* → torus → chaos → transient chaos → spatio-temporal chaos

Avila *et al., PRL* 2013
Ritter *et al., NJP* 2016

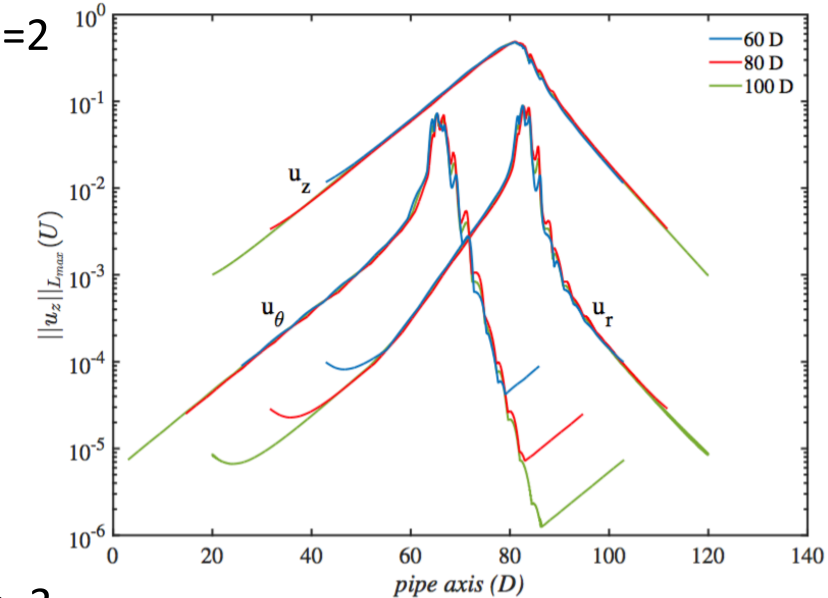
* Sub-harmonic bifurcation from TW: Chantry *et al., PRL* 2014

Exponential localization

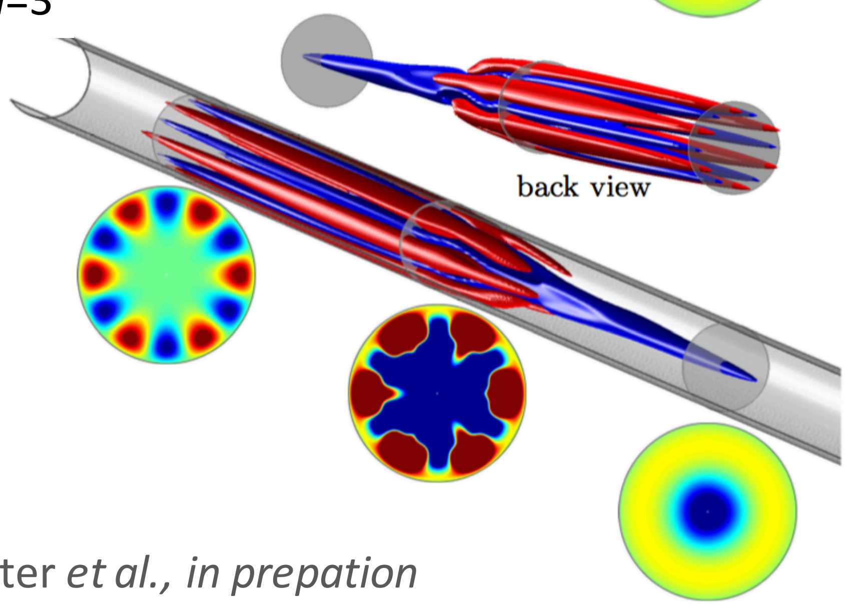
m=2



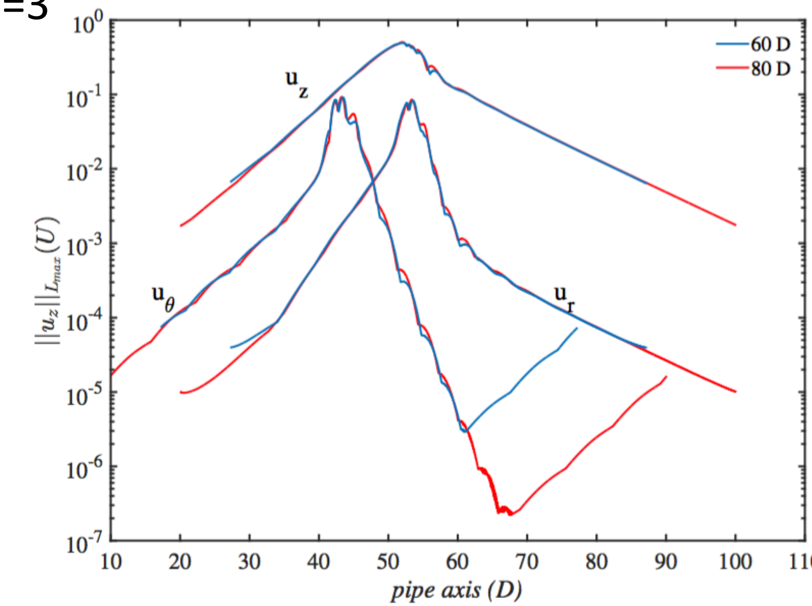
m=2



m=3



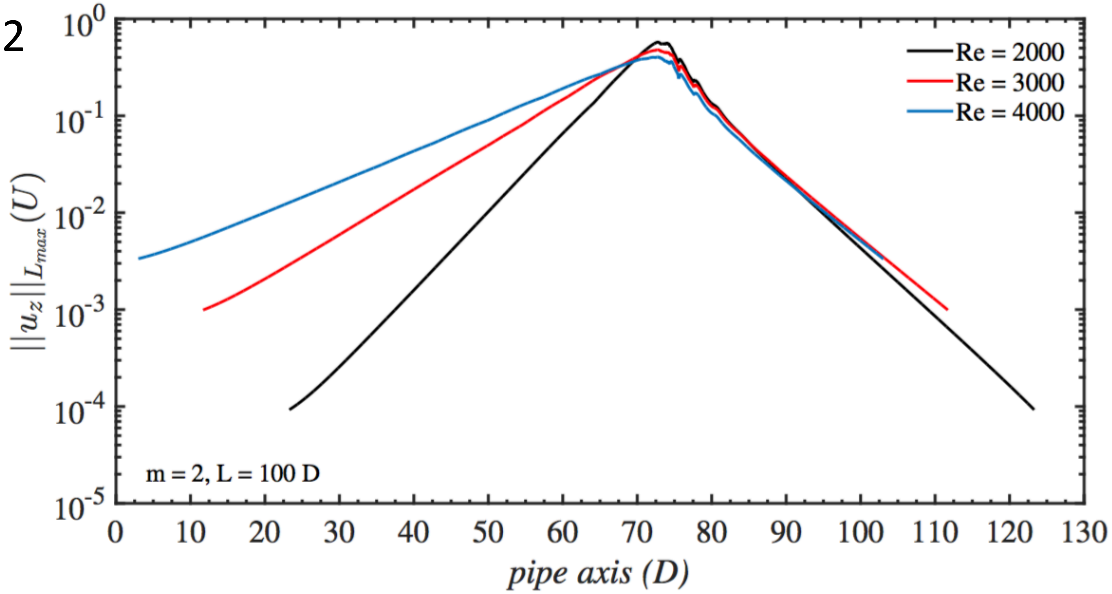
m=3



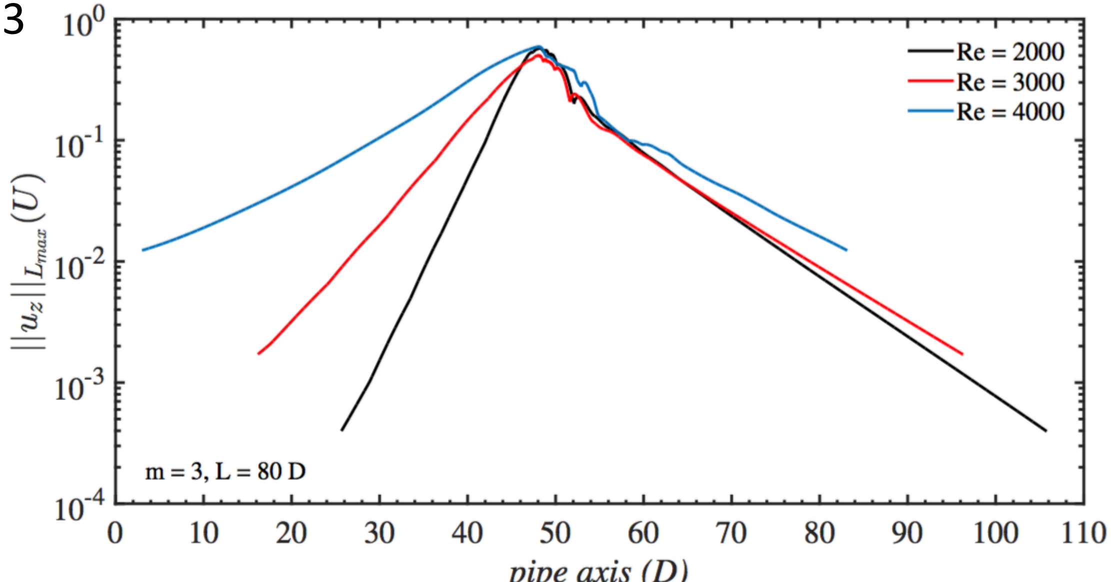
Ritter *et al., in prepation*

Localization: Re-dependence

m=2

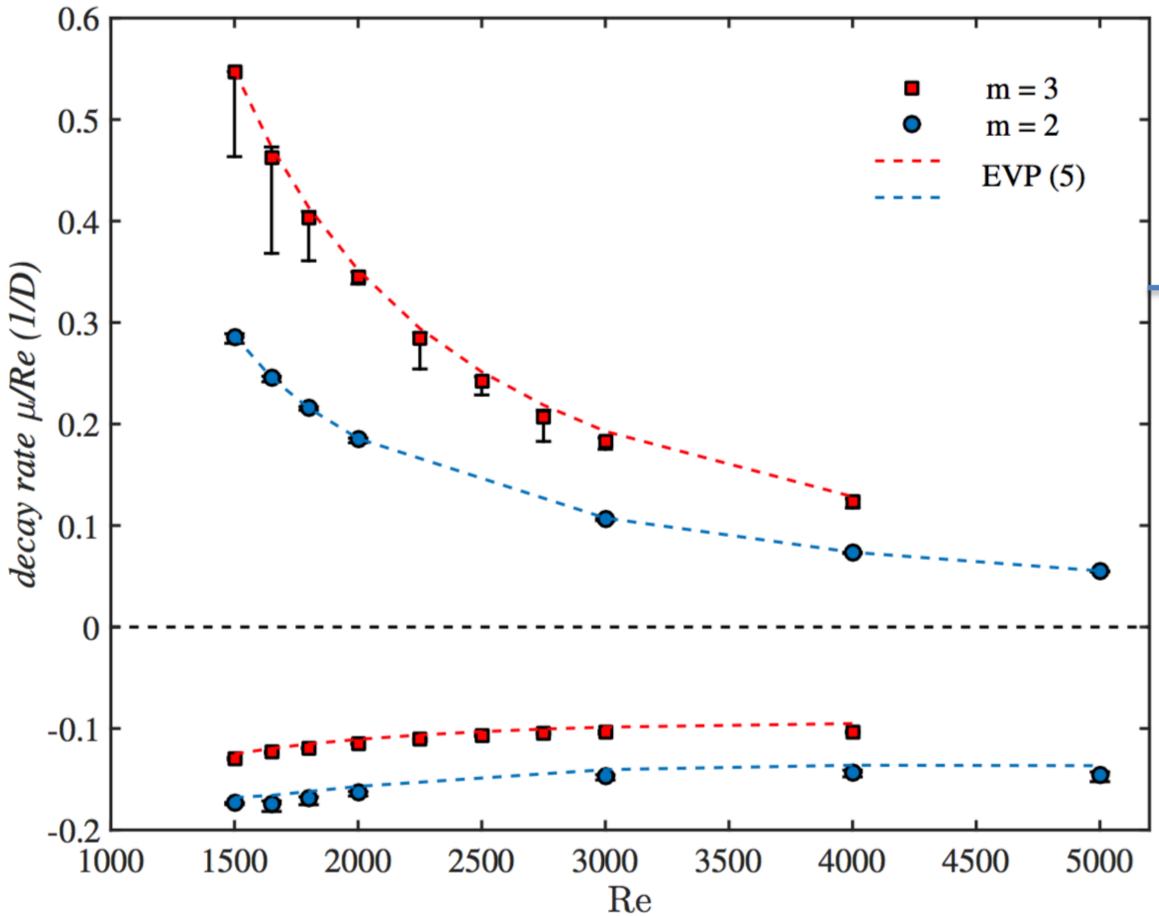


m=3



Ritter *et al., in prepation*

Model vs. ECS

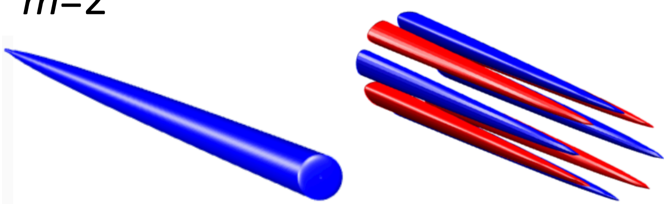


$$\boldsymbol{u} = \tilde{\boldsymbol{u}}(r)\exp\left[im\theta + \frac{\mu}{\mathrm{Re}}(z - ct)\right]$$

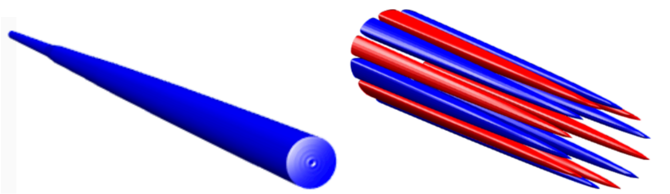
$$p = \tilde{p}(r)\exp\left[im\theta + \frac{\mu}{\mathrm{Re}}(z - ct)\right]$$

→ Quadratic eigenvalue problem

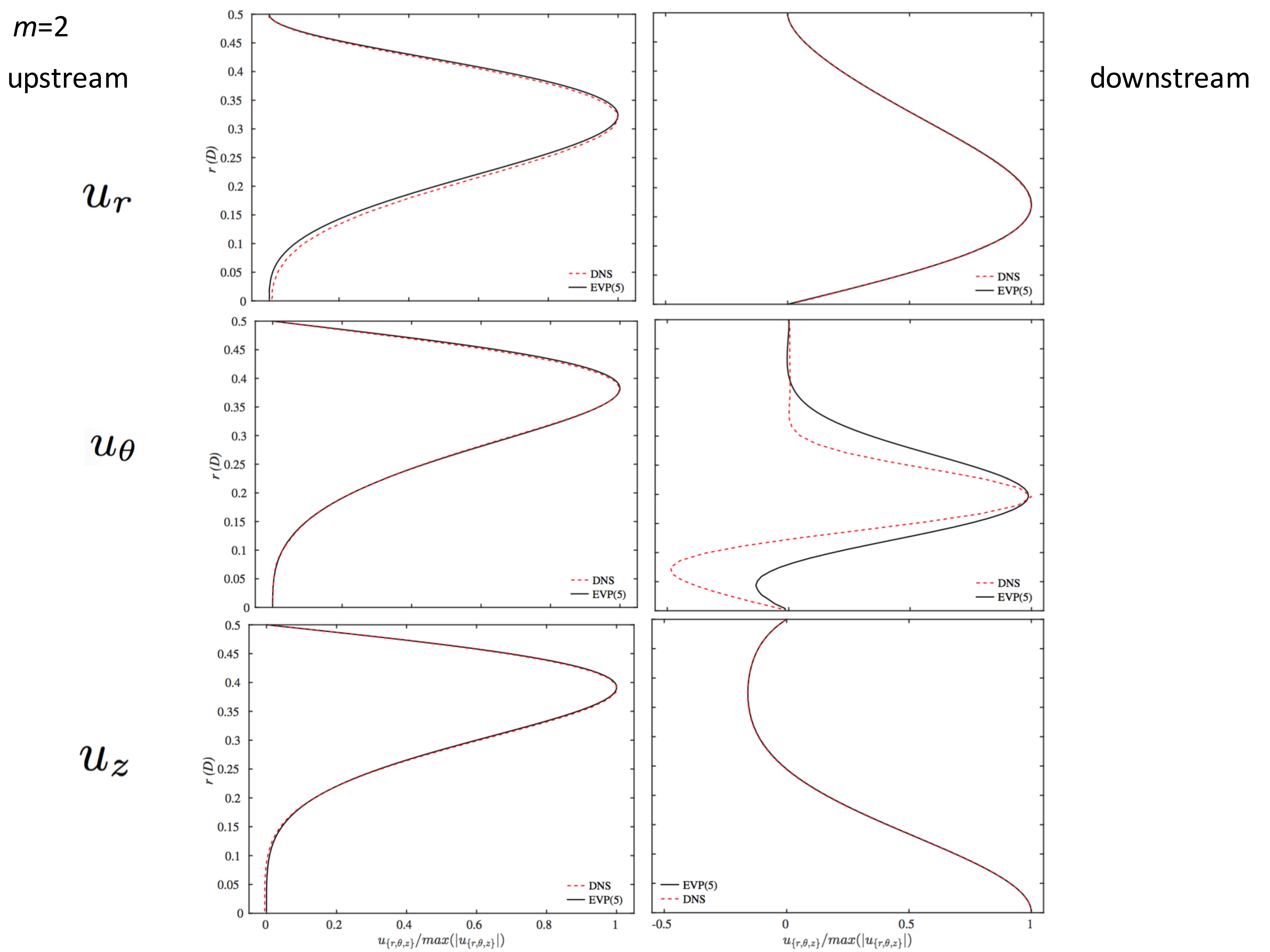
m=2



m=3

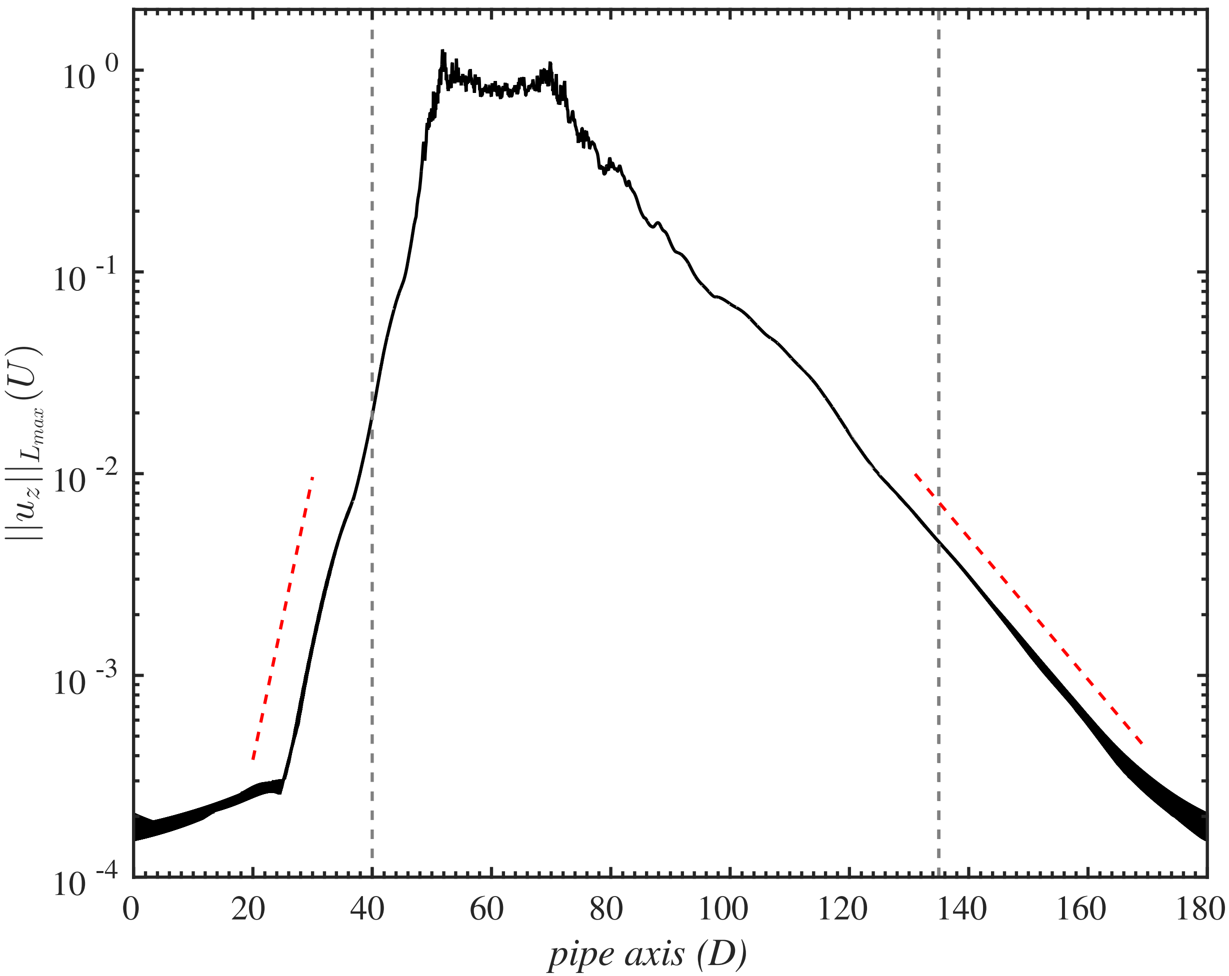


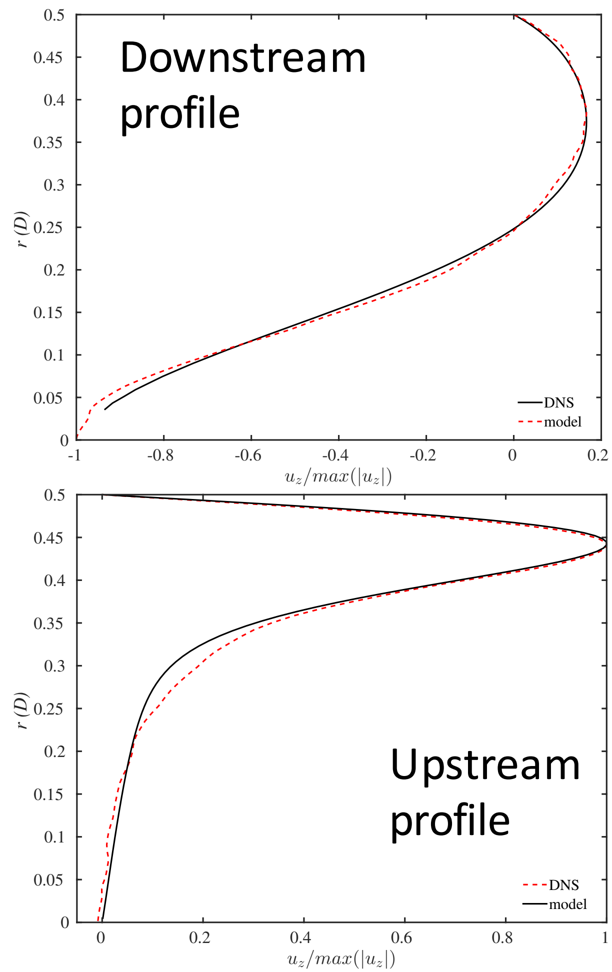
Ritter *et al., in prepation*



m=2
upstream
downstream
u_r
u_θ
u_z
r (D)
DNS
EVP(5)
$u_{\{r,\theta,z\}}/max(|u_{\{r,\theta,z\}}|)$

Modeling fronts with linear model





Conclusions

- 1D-modeling (ARD) describes dynamics of interfaces

  Barkley, Song, Mukund, Lemoult, Avila & Hof, *Nature* 2015

- Weak/strong fronts are physically distinct:
  - Weak: relaminarization at near (local) equilibrium
  - Strong: peak in production with delayed dissipation
  - Key role of mean advection speed of turbulence

  Song, Barkley, Hof & Avila, *JFM* 2017 (in press)

- Fronts of ECS:

  Ritter, Zammert, Eckhardt & Avila, in preparation

Further reading: Holzner, Song, Avila & Hof, *JFM* 2013:
"Lagrangian approach to laminar–turbulent interfaces in transitional pipe flow"