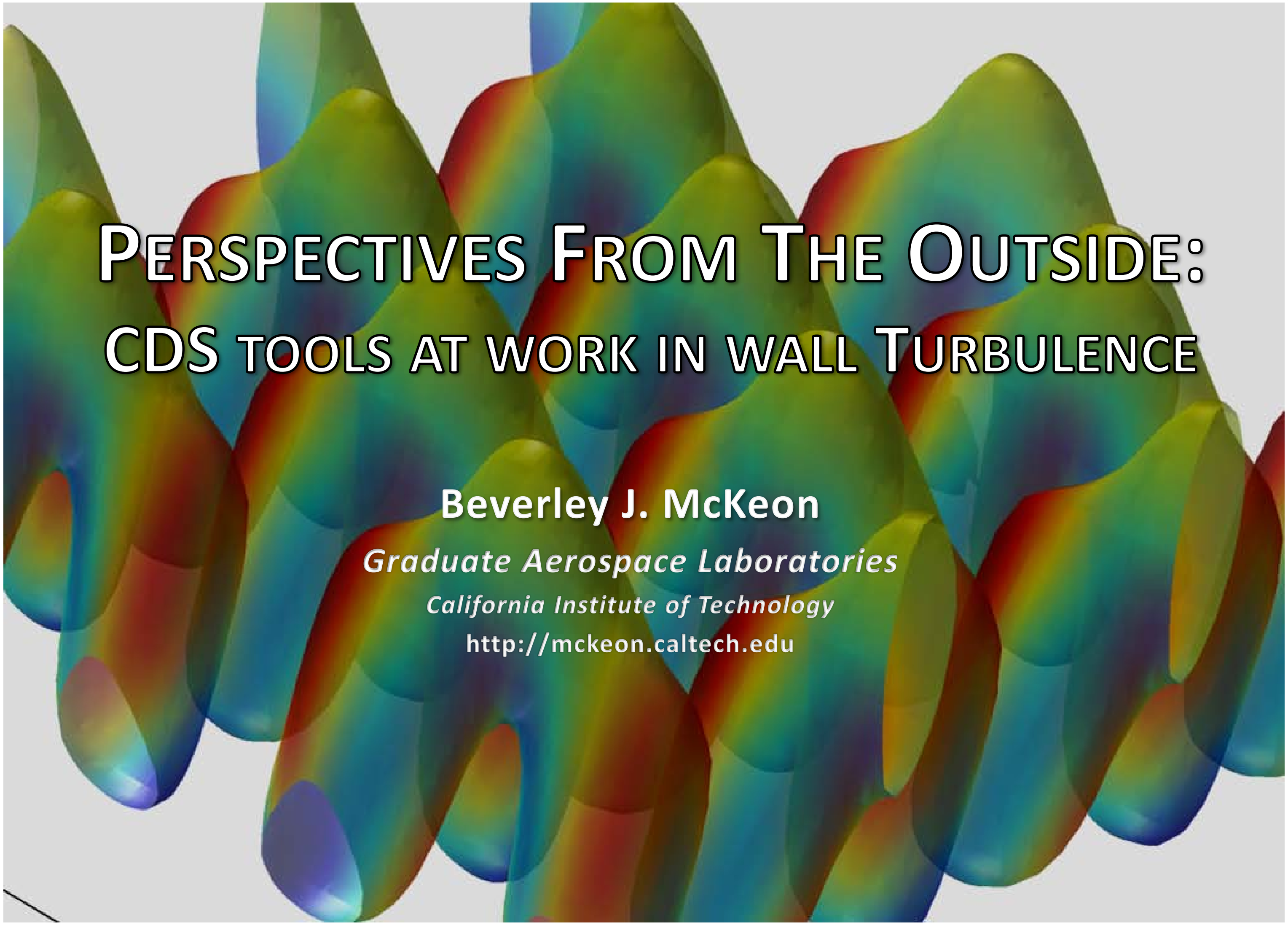

Perspectives From The Outside: CDS tools at work in wall Turbulence

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CDS TOOLS AT WORK IN WALL TURBULENCE

Why do we care about wall turbulence?

How do CDS tools help?

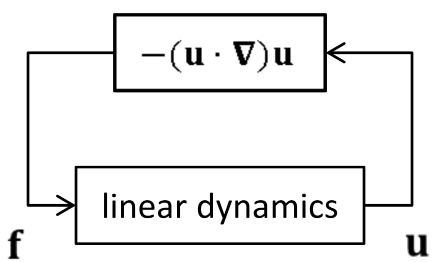
ROBUSTNESS

STRUCTURE

AMPLIFICATION

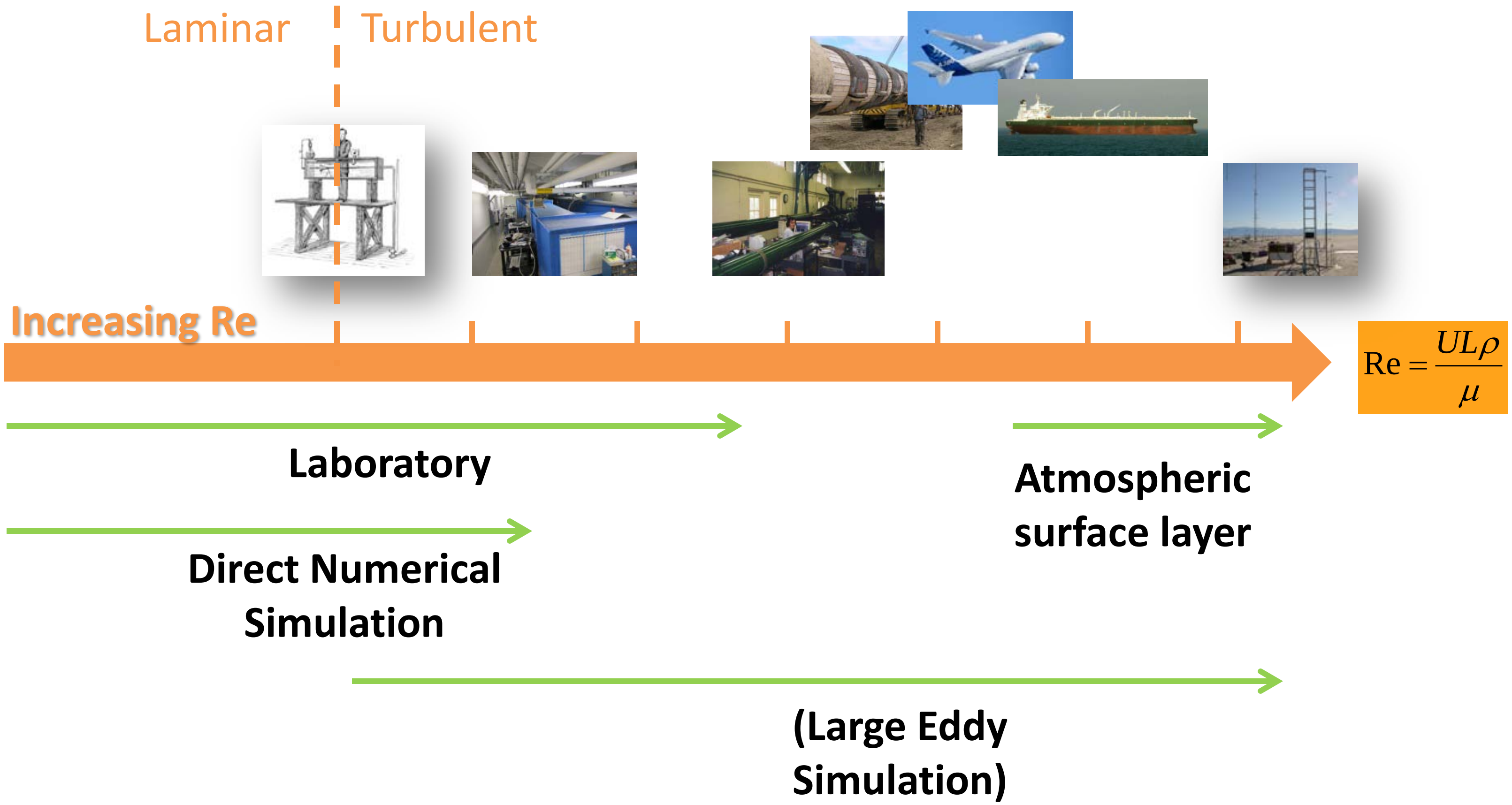
REPEATING PATTERNS

Input-output model fully-consistent with Navier-Stokes equations

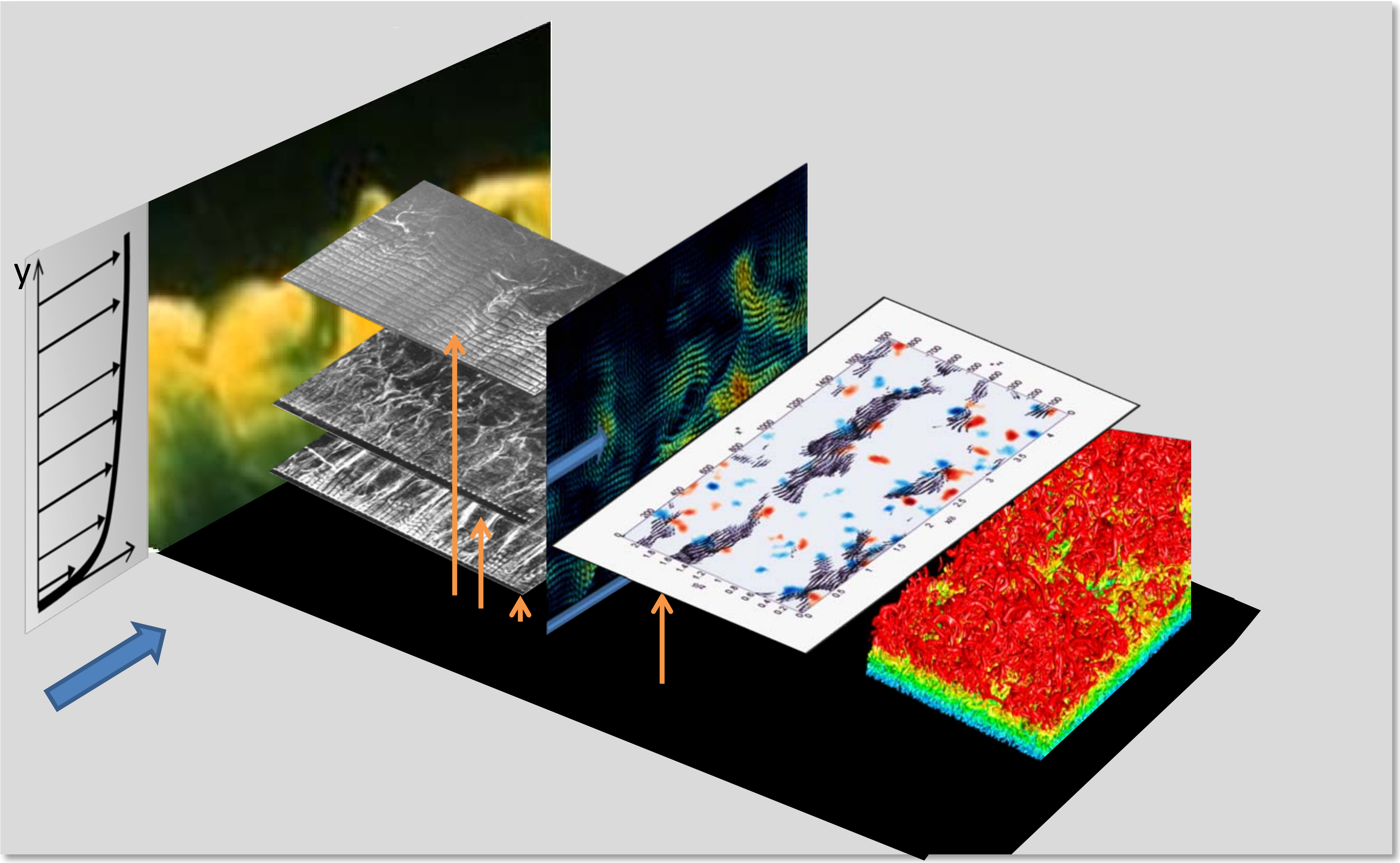


Outlook: the power of CDS tools

WHY DO WE CARE ABOUT WALL TURBULENCE?



TOWARDS THE BUILDING BLOCKS OF TURBULENCE



von Karman (1930)
Millikan (1938)
Coles (1952)

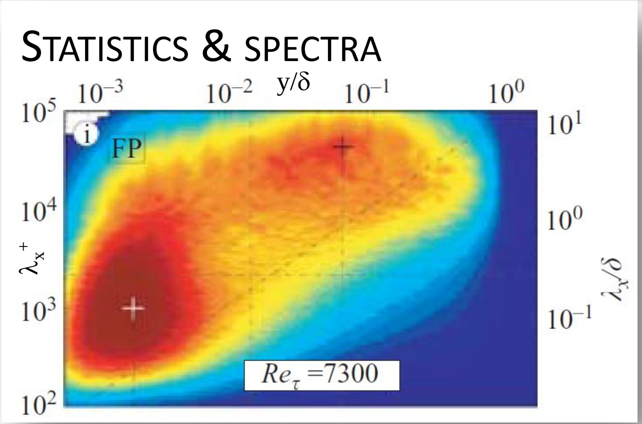
Gad-el-Hak
http://efluids.com

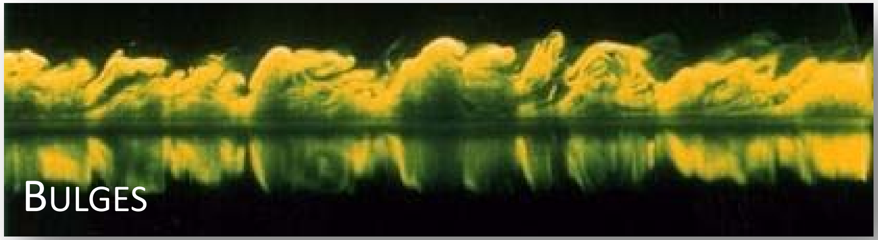
Kline, Reynolds, Schraub & Runstadler
J. Fluid Mechanics (1967)

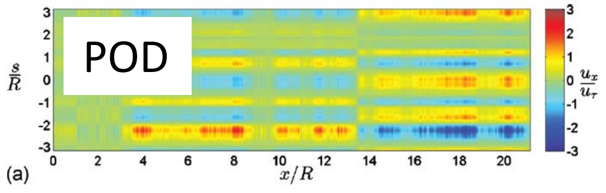
LeHew, Guala & McKeon
Expts. in Fluids (2011)

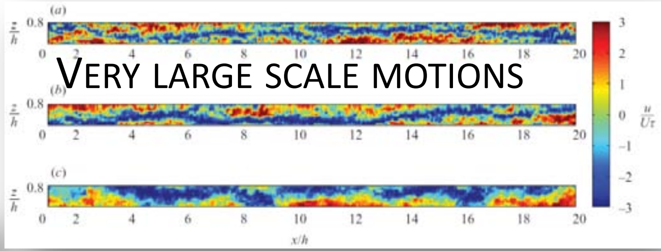
Wu & Moin
http://ctr.stanford.edu

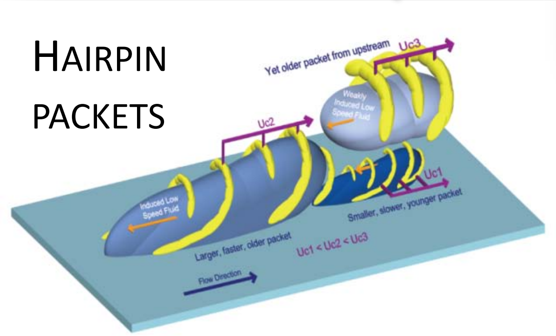
Towards the building blocks of turbulence

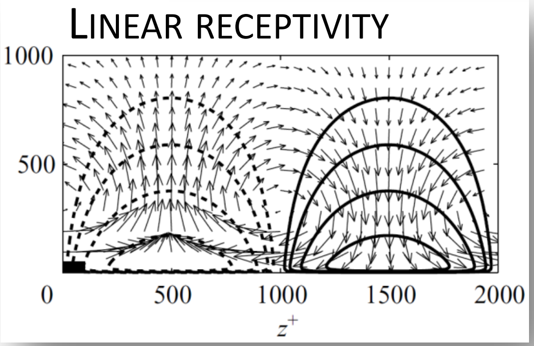












"So, actually the elephant has all the features you mentioned…"

Credits, CW from top left
Hutchins & Marusic
Gad-el-Hak
Hellstroem, Sinha & Smits
Monty, Stewart, Williams & Chong
Adrian, Meinhart & Tomkins
Del Alamo & Jimenez

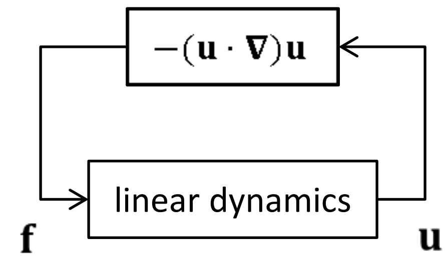
THEORETICAL BASIS: RESOLVENT FORMULATION

McKeon & Sharma, J. Fluid Mech., 2010

Navier-Stokes (NSE) and continuity equations, $\mathbf{u} = [u, v, w]^T$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\boldsymbol{\nabla})U + (U\cdot\boldsymbol{\nabla})\mathbf{u} + \boldsymbol{\nabla} p - \frac{1}{Re}\boldsymbol{\nabla}^2\mathbf{u} = \overbrace{-(\mathbf{u}\cdot\boldsymbol{\nabla})\mathbf{u}}^{\mathbf{f}}$$

$$\boldsymbol{\nabla}\cdot\mathbf{u} = 0$$



Fully developed turbulent pipe or channel flow:

homogeneous in (x, θ) or (x, z), stationary in t $\rightarrow$ Fourier transform $\mathbf{k} = (k, n, \omega)$ or $(\kappa_x, \kappa_z, \omega)$

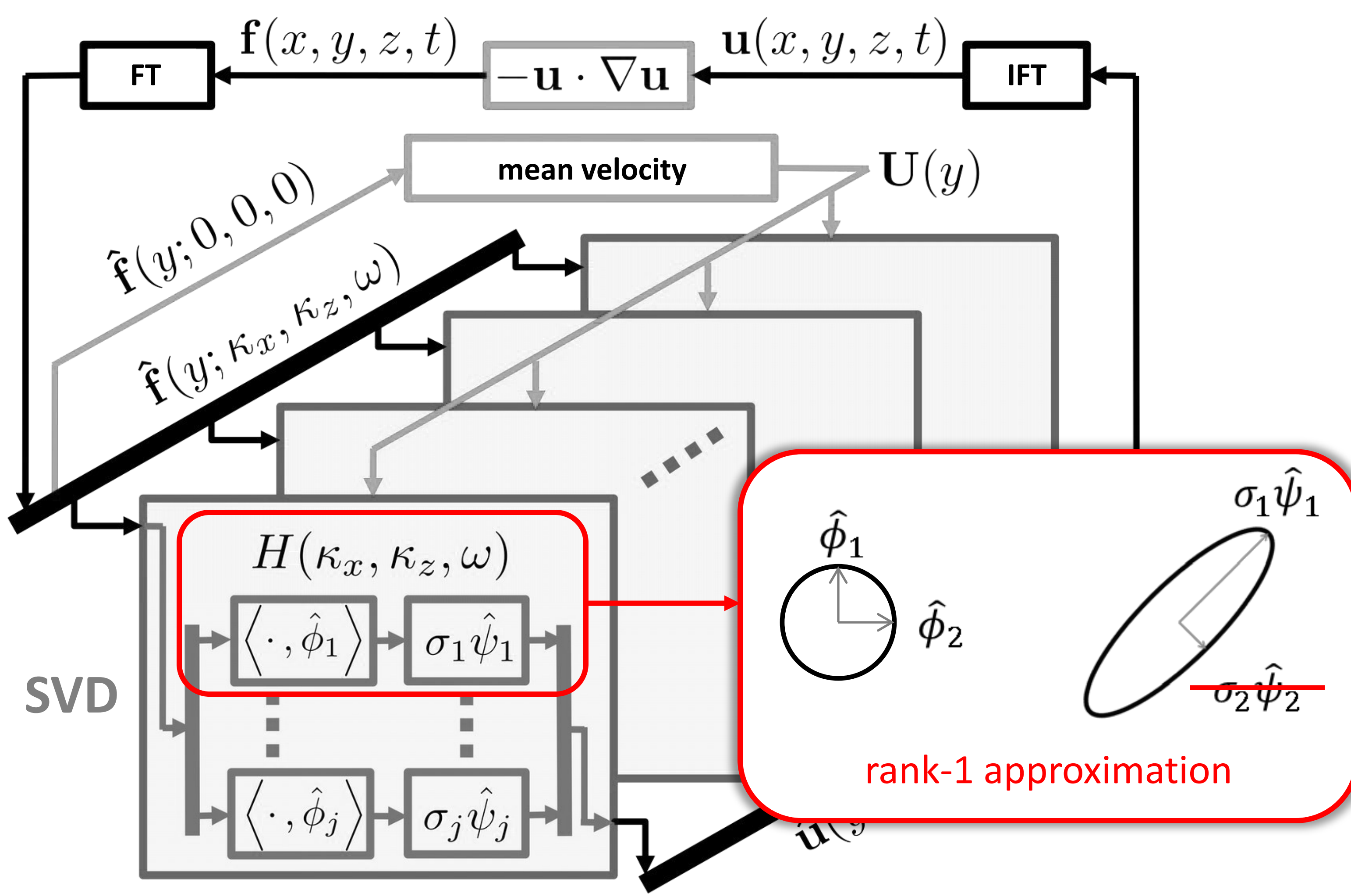
$$\begin{bmatrix}\mathbf{u}_\mathbf{k}\\ p_\mathbf{k}\end{bmatrix} = \left(-i\omega\begin{bmatrix}\mathbf{I} & 0\\ 0 & 0\end{bmatrix} - \begin{bmatrix}\mathcal{L}_\mathbf{k}(\mathbf{k}, U, Re) & -\boldsymbol{\nabla}_\mathbf{k}\\ \boldsymbol{\nabla}_\mathbf{k}^T & 0\end{bmatrix}\right)^{-1}\mathbf{f}_\mathbf{k}$$

$$\therefore \begin{bmatrix}\mathbf{u}_\mathbf{k}\\ p_\mathbf{k}\end{bmatrix} = H_\mathbf{k}\mathbf{f}_\mathbf{k}$$

$H_\mathbf{k}$ is the resolvent

GAIN-BASED DECOMPOSITION

McKeon & Sharma, J. Fluid Mech., 2010
Moarref, Sharma, Tropp & McKeon, J. Fluid Mech., 2013



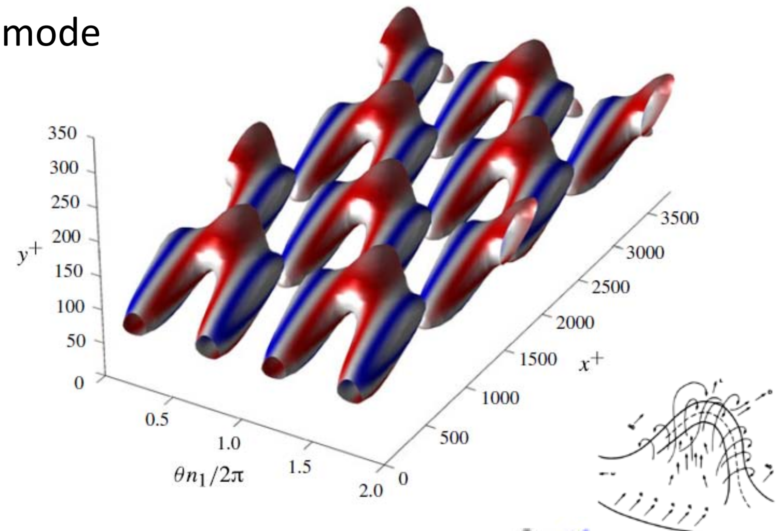
PREDICTIONS BASED ON RANK-1 RESOLVENT ANALYSIS

Sharma & McKeon, J. Fluid Mech., 2013

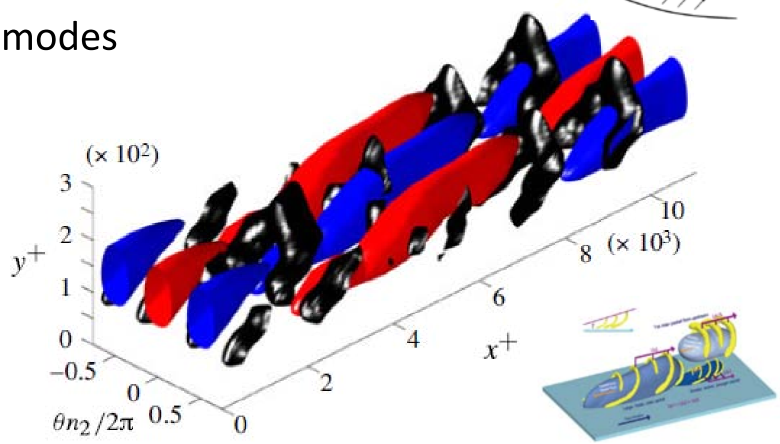
Moarref, Sharma, Tropp & McKeon, J. Fluid Mech., 2013

Coherent structure

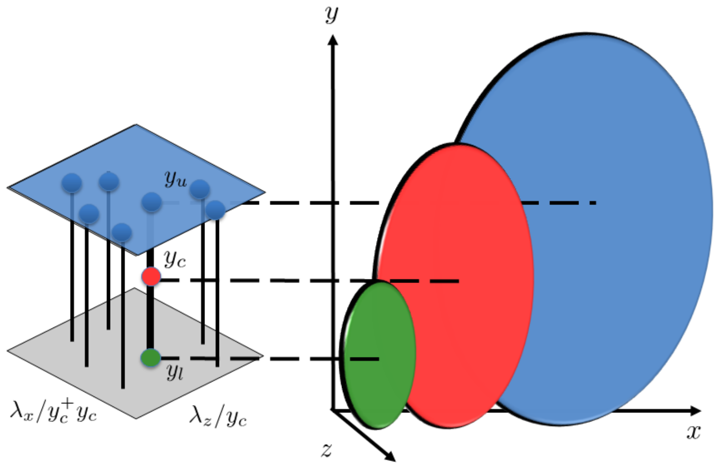
1 mode

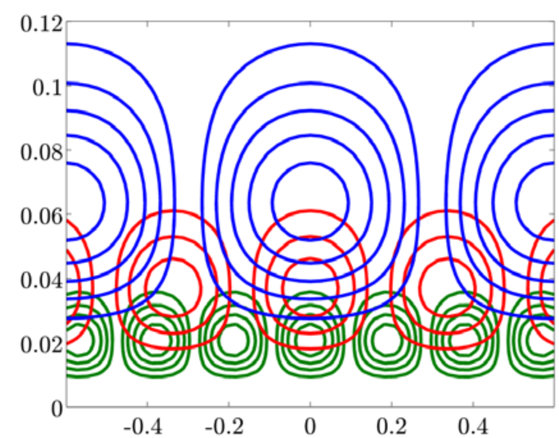


2 modes



Geometrical self-similarity



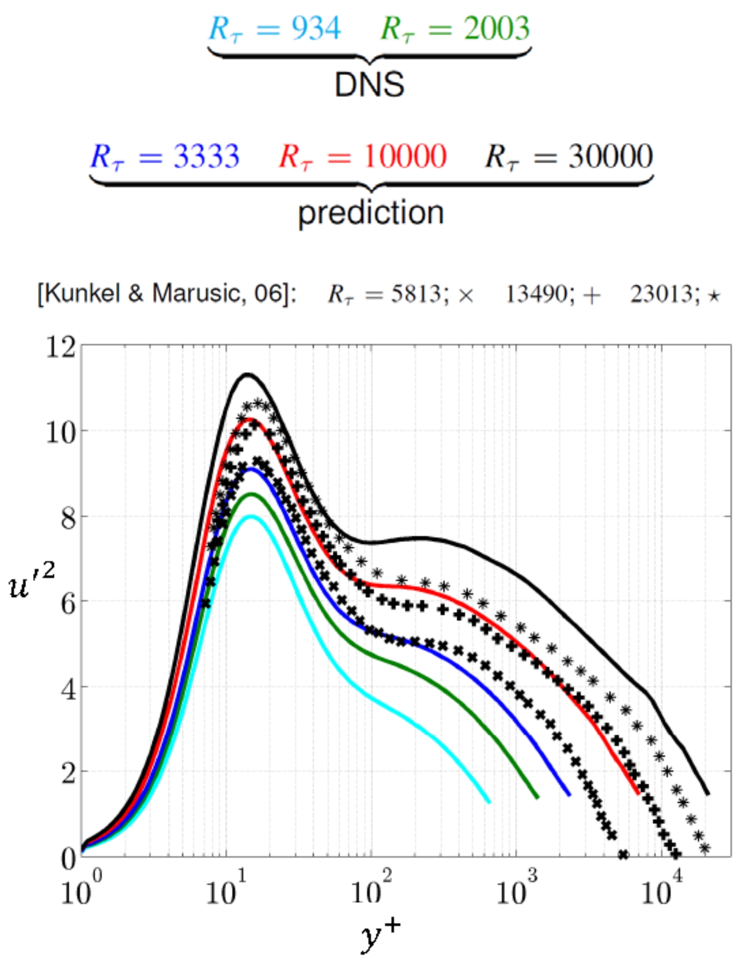


How much of an order reduction?

Moarref, Sharma, Tropp & McKeon, J. Fluid Mech., 2013

Moarref, Jovanovic, Sharma, Tropp & McKeon, Phys. Fluids, 2014

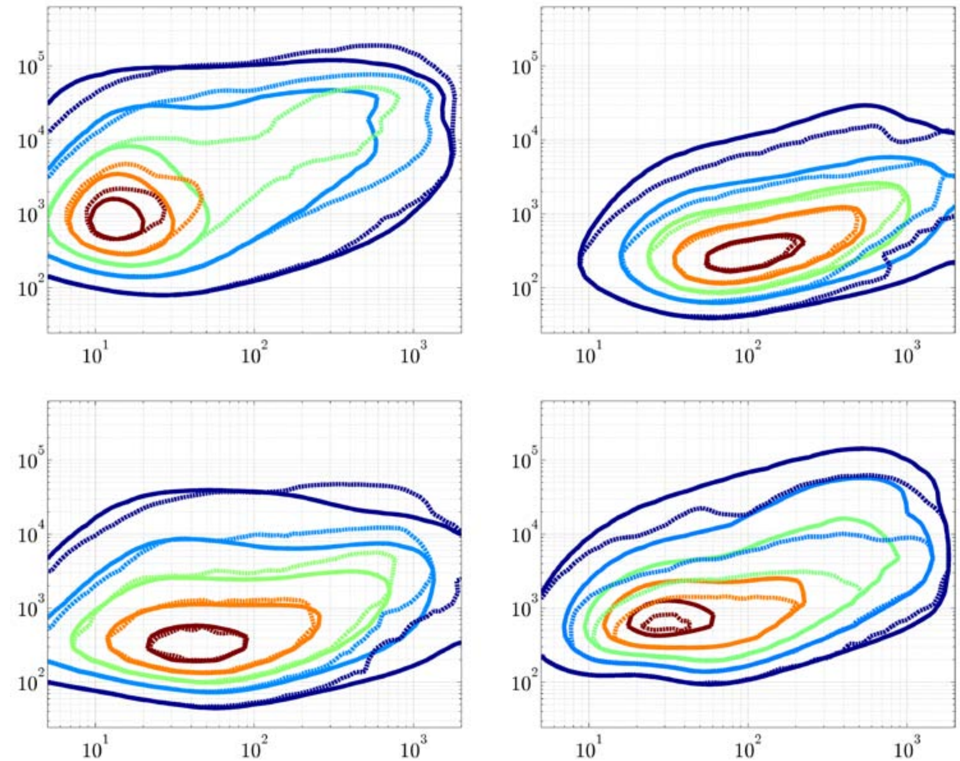
Statistics



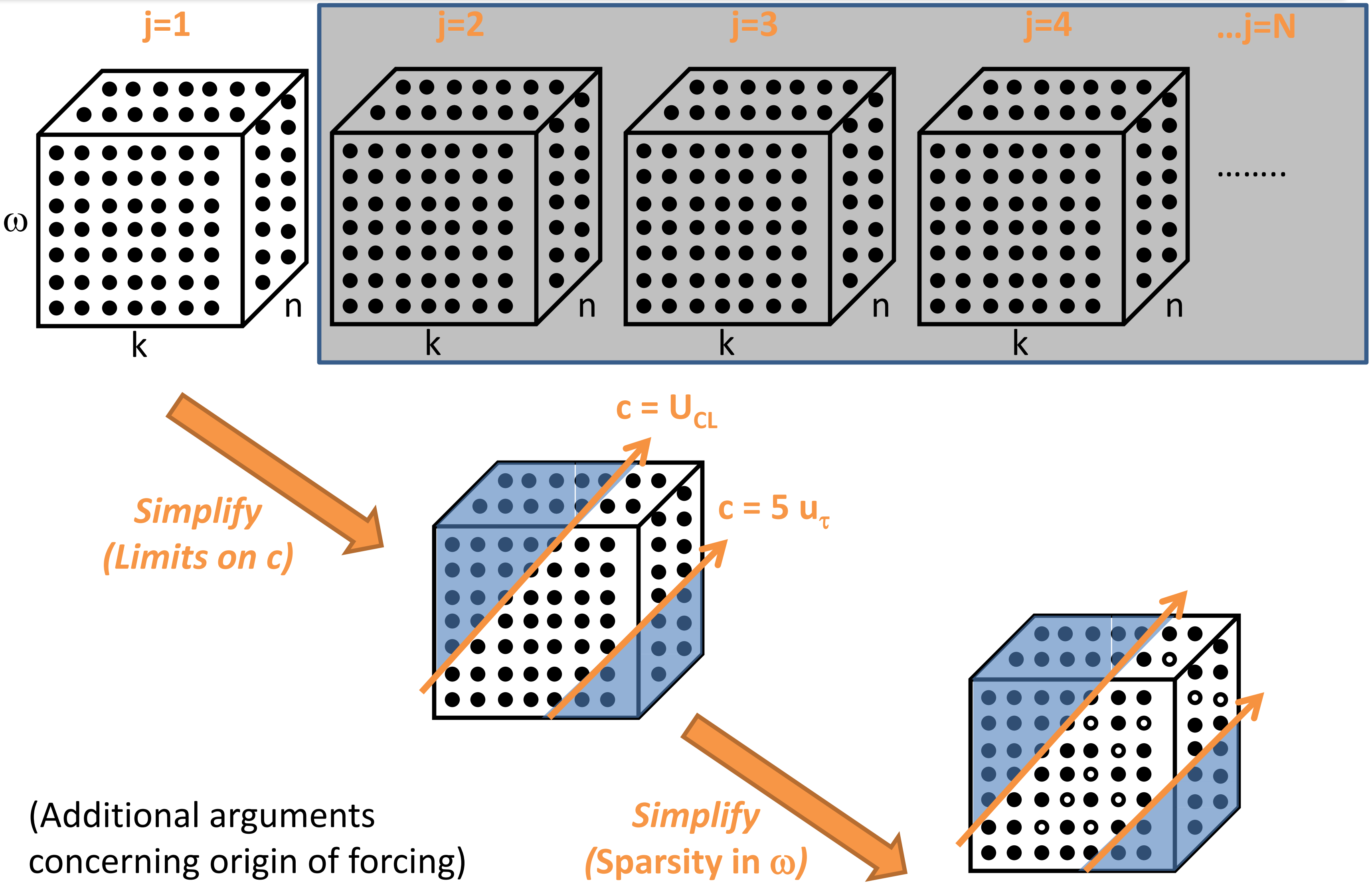
Spectra

Non-convex problem but possible to find global optimum

12 modes, same spatial discretization - 10^3 reduction in degrees of freedom



REPRESENTATION OF THE VELOCITY (& P) FIELD

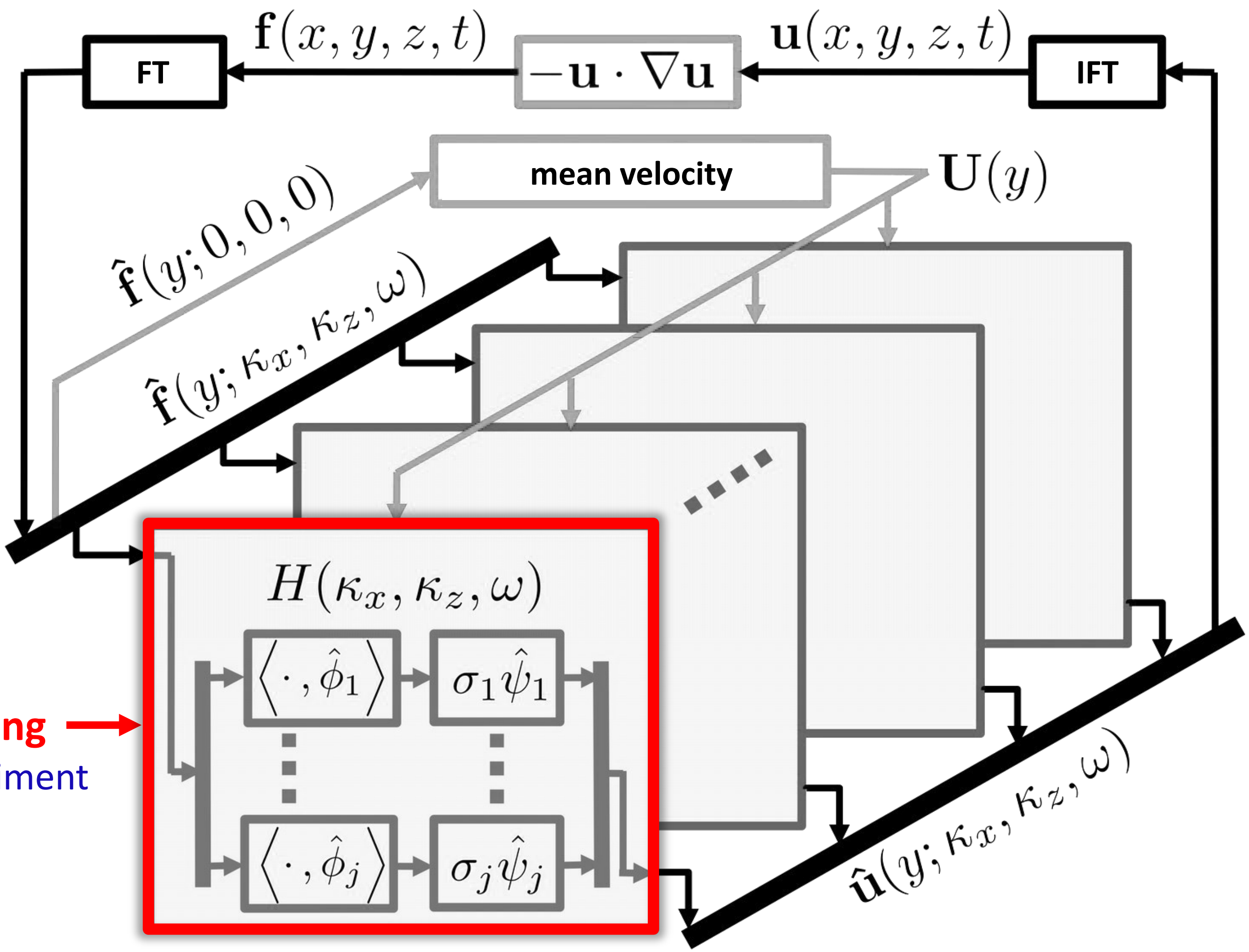


(Additional arguments concerning origin of forcing)

Bourguignon, Sharma, Tropp & McKeon, Phys. Fluids, 2014
Moarref, Sharma, Tropp & McKeon, J. Fluid Mech. 2013

Mode excitement in experiment and DNS

Sharma et al., AIAA, 2014

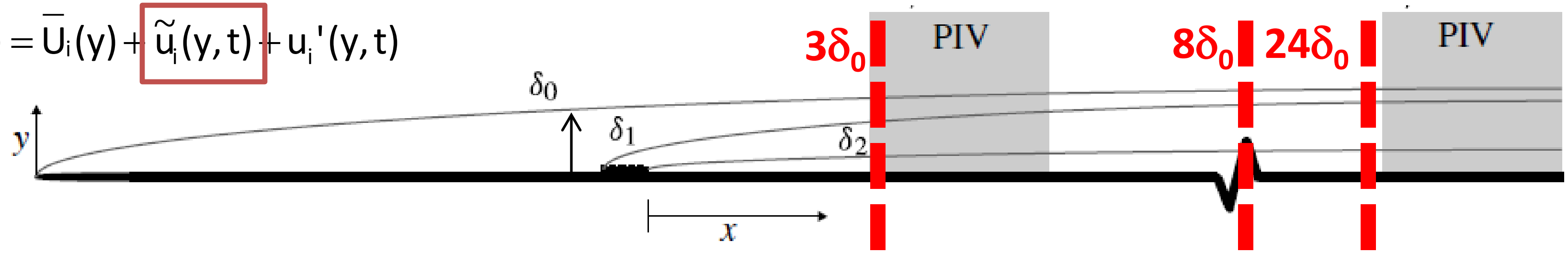


External forcing

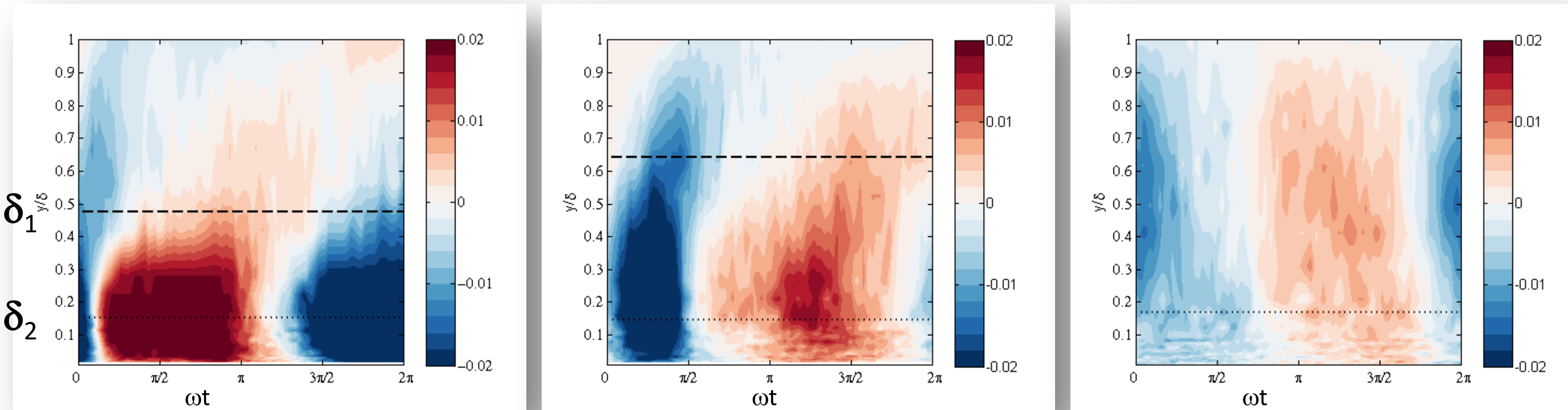
DNS and experiment

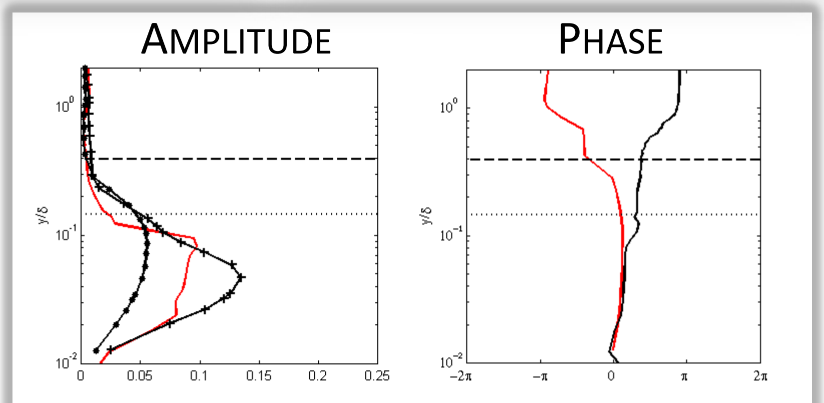
INJECTION OF A SYNTHETIC LARGE SCALE, $\tilde{u}_i$

$$u_i(y,t) = \bar{U}_i(y) + \boxed{\tilde{u}_i(y,t)} + u_i'(y,t)$$



$\tilde{u}(y, \omega t)$ δ_1 δ_2

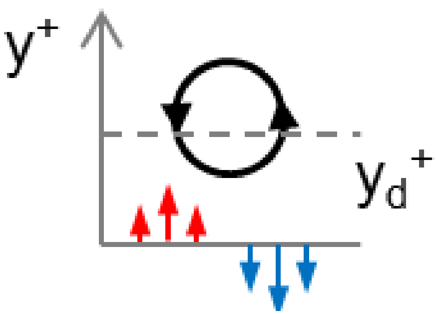




Jacobi & McKeon, J. Fluid Mech., 2010
Duvvuri & McKeon, AIAA 2014

TOWARDS CONTROL: OPPOSITION CONTROL

Luhar, Sharma & McKeon, J. Fluid Mech., 2014



Opposition control:

Choi, Moin & Kim, *J. Fluid Mech., 1994*

$$v_{\mathbf{k}}(0) = -v_{\mathbf{k}}(y_d^+)$$

More general:

$$v_{\mathbf{k}}(0) = A\, v_{\mathbf{k}}(y_d^+)$$

A can be complex to account for phase difference between sensing and actuation

Mode resembling energetic NW-cycle

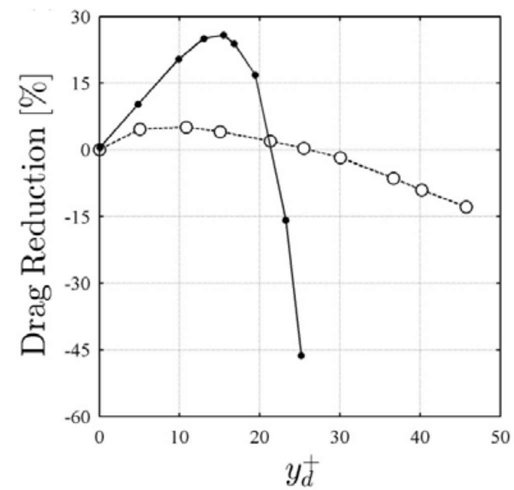
$(\lambda_x^+, \lambda_\theta^+, c^+) \approx (1100{,}110{,}11)$ at $R^+ = 1800$

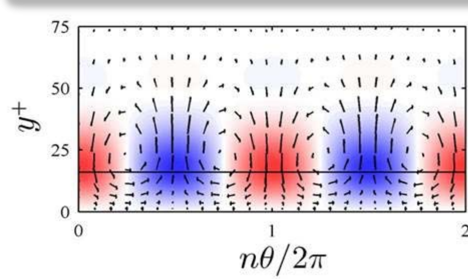
null case

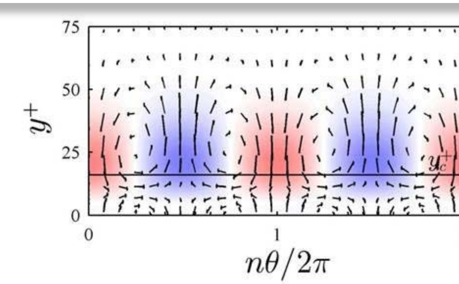
control $\rightarrow$ $\sigma_c/\sigma_0 = 0.6$

Turbulent pipe flow, $R^+ = 180$

Rank-1
Broadband forcing
No feedback to U







Conclusions

Systems approach to wall turbulence via resolvent analysis

Nonlinearity retained (and supports mean velocity profile)
Provides basis for coherence in y (using laptop-scale computational power)
Resolvent appears to be ***low-rank*** and ***sparse***

Low-rank (rank-1) model captures significant features of v and p fields

Insight into scaling behavior from resolvent
Geometrical self-similar behavior admitted
Identification of building blocks of coherent structure

Interaction with resolvent possible in the laboratory

Demonstration of mode excitation from the wall ("designer turbulence")

Deconstruction of (opposition) control

Control leads to singular value suppression
Optimized control based on mode scaling possible

Outlook

Robustness harnessed for modeling and manipulation of wall turbulence

Opportunities for further use of CDS/ACM tools for prediction and implementation of practical control

Challenges remain

Close the loop (self-similarity helps, start with exact solutions)

Limitations on practical spatial and temporal actuation/sensing resolution

THIS IS A FRONTIER: old tools don't work

CDS tools open doors to new and efficient ways to illuminate an old problem

Anyone who claims to fully understand wall turbulence…