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Modal analysis of reacting JICF using direct numerical simulations

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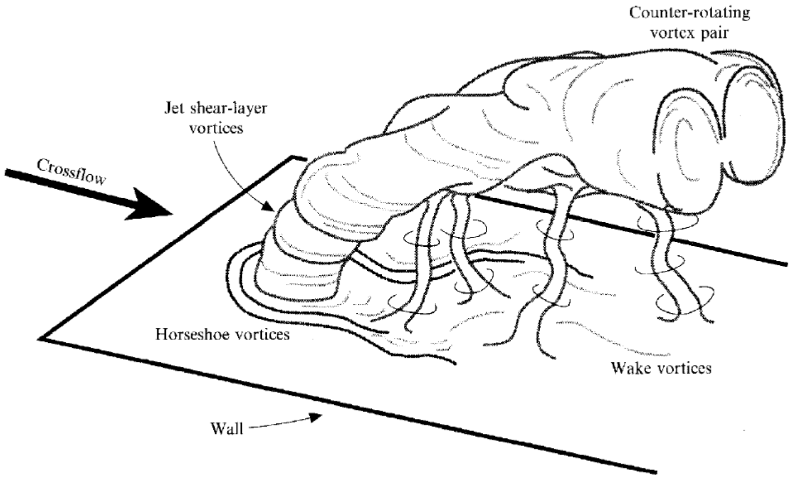
Jet in Cross Flow

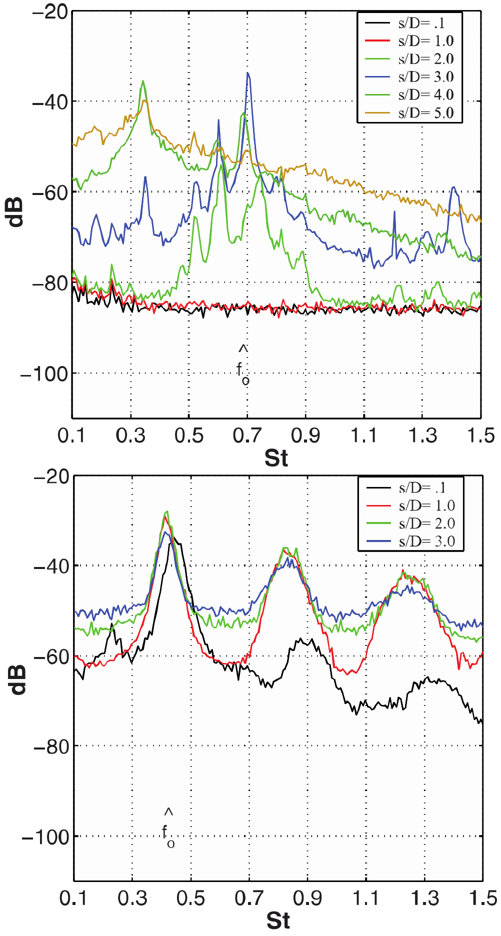
- Relevant in many practical combustion systems:
  - Stationary/aviation gas turbines
  - Furnaces, boilers
- Complex 3D flow structures spanning a broad range of scales.
- Dynamics of flow structures have direct bearing on mixing.



Fric & Roshko 1994, *J. Flu. Mech.*, **279**

Transverse jet instability modes

- Convectively unstable:
  - modes/frequencies evolve spatially
  - sensitive to external forcing (can amplify)
  - undesirable for thermo-acoustic instability
- Globally unstable:
  - single, spatially uniform, frequency
  - insensitive to moderate external forcing
  - can “lock-in” to high amplitude forcing
- In reacting systems heat release an additional factor. Important implications for thermo-acoustic instability.

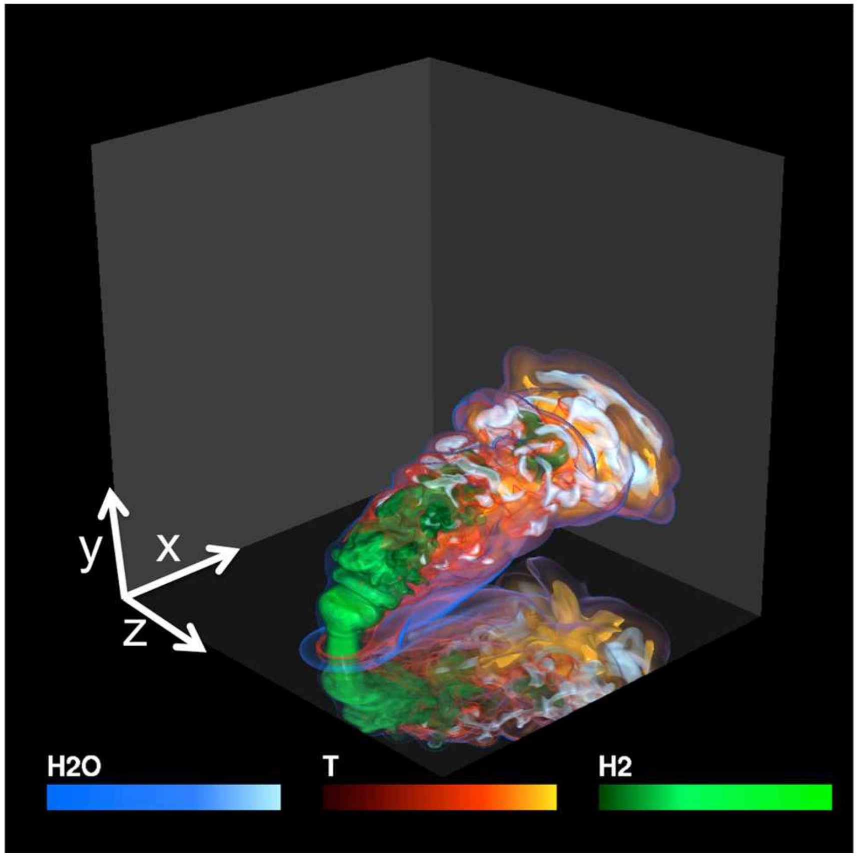


Ann R. Karagozian, 2014, *Phys. Fluids*, **26**

Motivation and Objectives

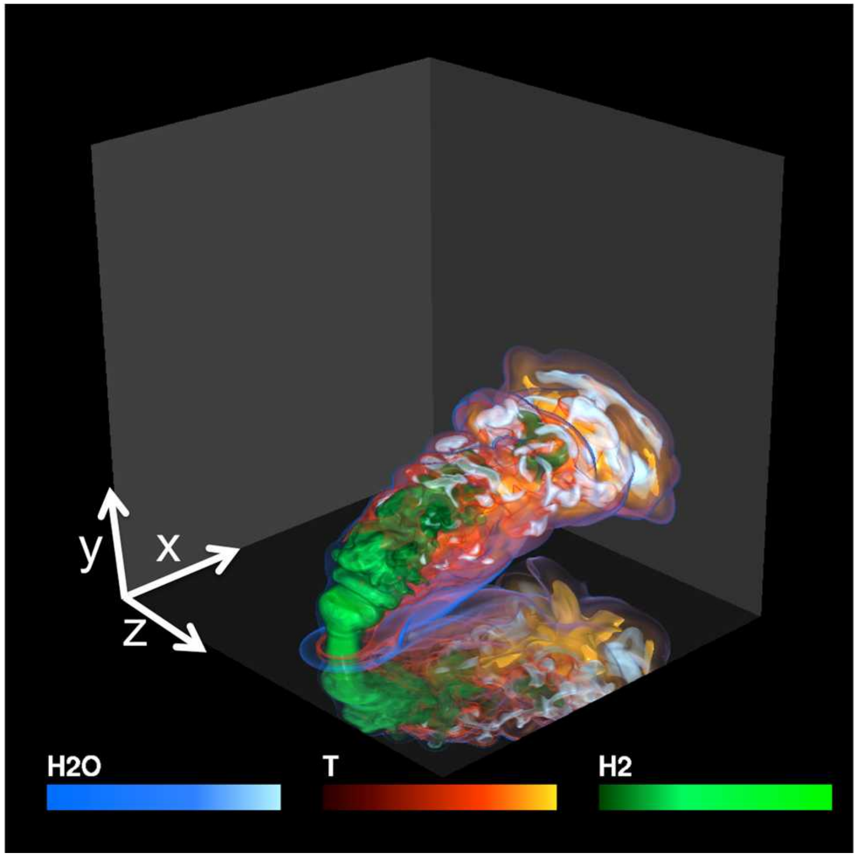
- Fuel jet in turbulent cross flow of hot vitiated combustion products:
  - Secondary fuel injection in staged combustion
  - Thermo-acoustic instability is a concern
- Study near field jet dynamics:
  - What are the dominant modes (shapes/frequencies)?
  - What influence does chemical reaction have?
- Employ Dynamic Modal Decomposition (DMD) on 3D DNS data.
- Joint experiment-DNS investigation to study flame structure (Talk in session CP5 (4/6) by Lyra et al.)

DNS physical parameters



- Fuel jet (70% H_2/30% He):
  - d = 1.5 mm, U_j = 291 m/s, T_j = 407 K, Re_j ~ 2,400.
- Crossflow (lean CH_4 products):
  - U_∞ = 59 m/s, T_∞ = 1,640 K, Re_∞ ~ 10,000.
- Jet-to-crossflow density ratio, ***S=0.37.***
- momentum flux ratio, ***J=9.***
- Detailed H_2/C1 chemistry: 13 species/35 reactions (Li et al. 2004).
- Two simulations, “inert” and reacting, under identical conditions.

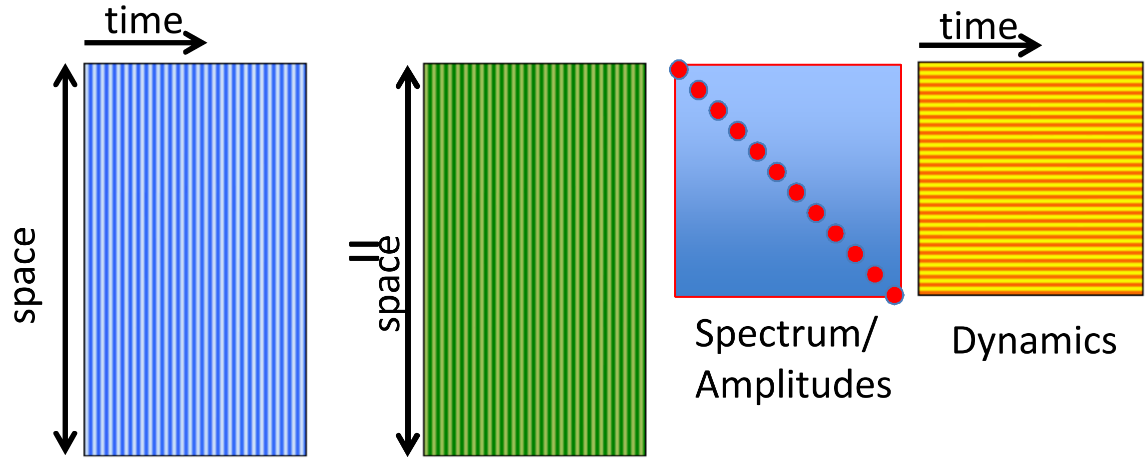
DNS numerical parameters



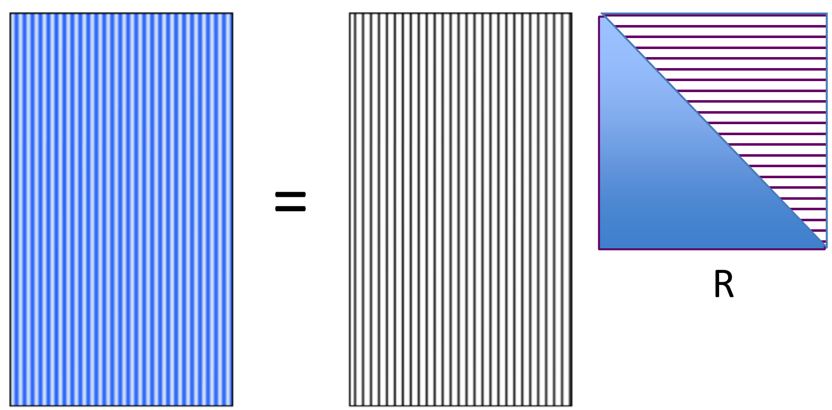
- Cubic domain 30d x 30d x 30d.
- Uniform grid about 10d around the jet, gradually coarser away.
- Grid size:
  - 44 microns in inert case, resolves near wall region.
  - 18 microns in reacting case, resolves the reacting layers.
- Grid count 0.16 x 10^9 (inert) and 4.7 x 10^9 (reacting).
- DNS with S3D: high order explicit finite difference compressible solver.
- Data over 2 flow through times analyzed.

Basis of Data-decomposition techniques

- Basis of most data-driven decomposition, an SVD of the data-matrix:



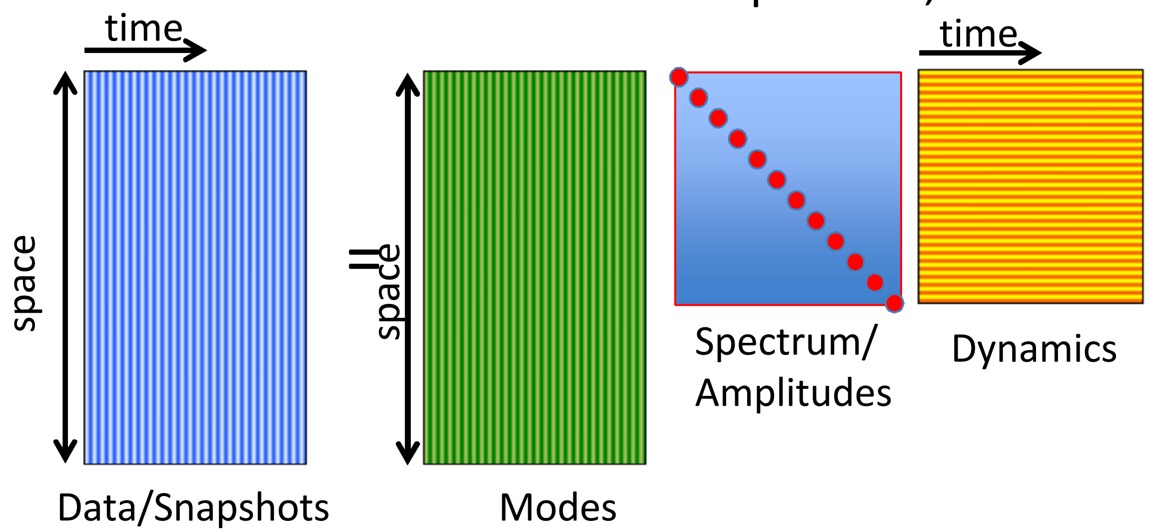
- These decompositions (POD, DMD, etc), are made possible by an initial QR-factorization:



✓ Q is an orthogonal matrix
✓ R is an upper-triangular matrix

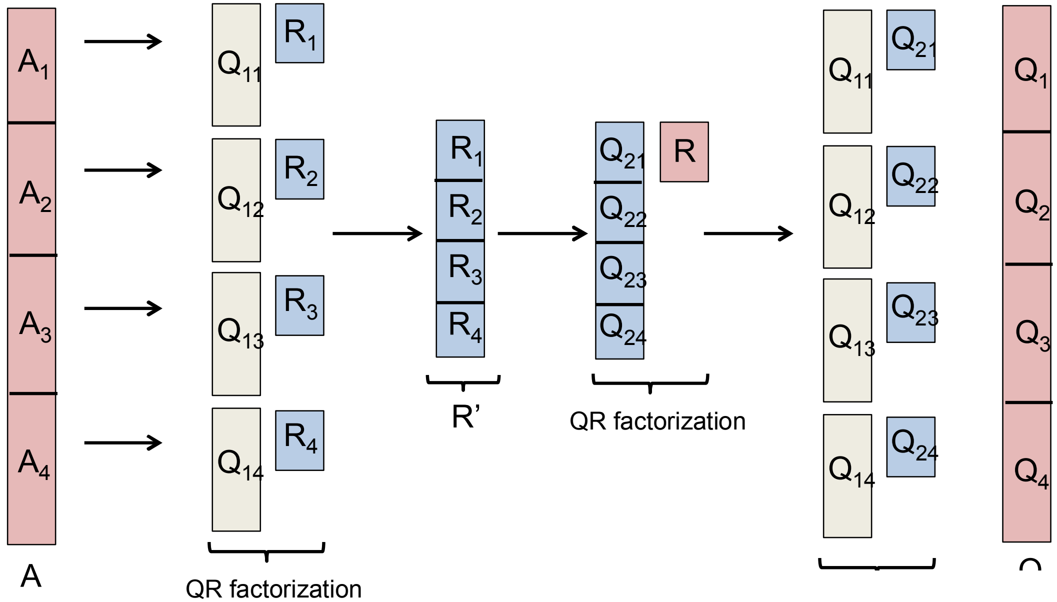
Large numerical and experimental data

- Basis of most data-driven decomposition, an SVD of the data-matrix:



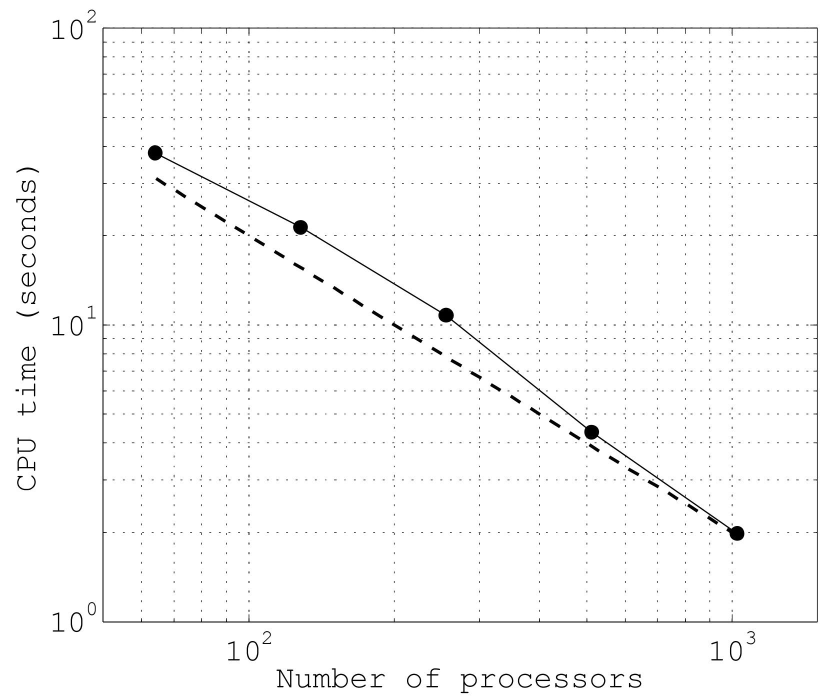
- These decompositions (POD, DMD, etc), are made possible by an initial QR-factorization.
- As the size of the data-matrix increases:
  - ✓ Lack of memory on a single processor to perform decomposition
  - ✓ Parallel version of the QR-decomposition exists:
    - ➢ Trilinos, ScaLAPCK, etc.
    - ➢ No added library
    - ➢ Can easily be integrated in the code
    - ➢ Allow on the fly calculations

Parallel algorithm



- The algorithm is based on the TSQR-factorization proposed by Benson et al. (2013) for MapReduce environments.

- Agreeable scaling on HPC environments (Sayadi *et al.* 2014):

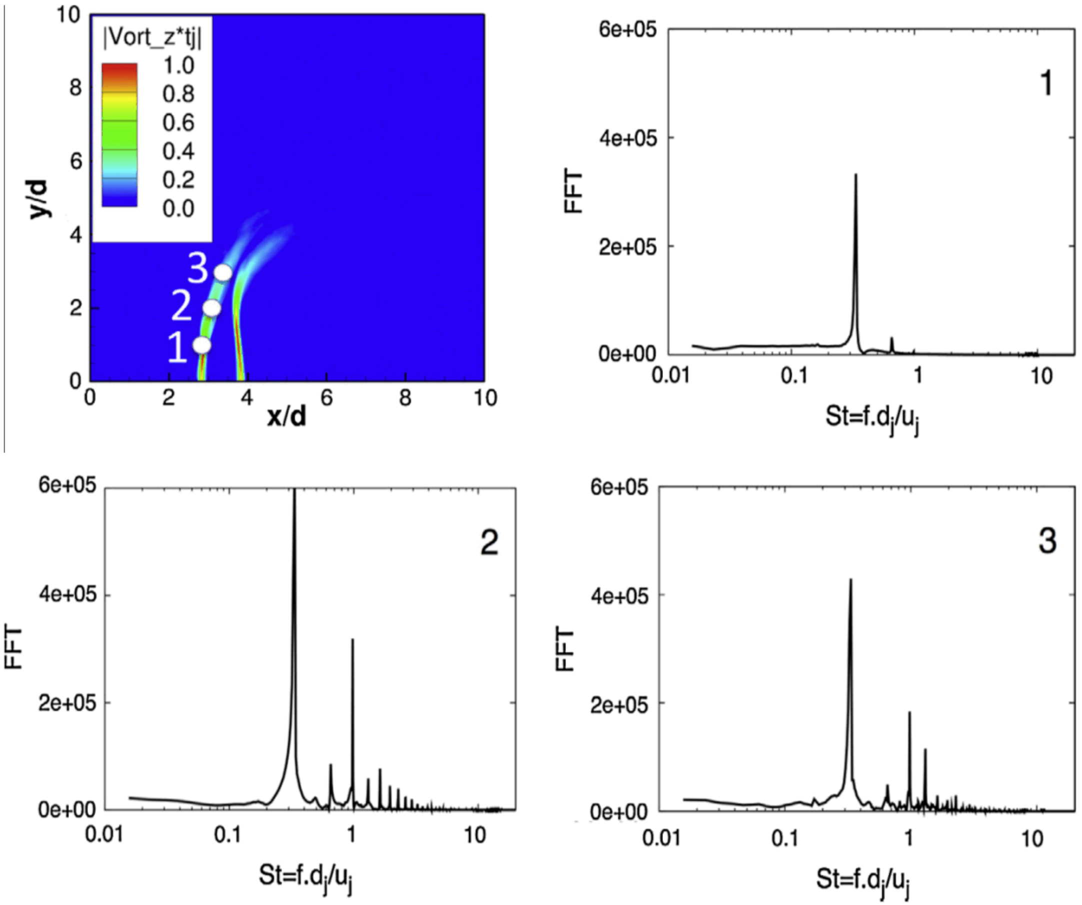


DMD methodology

- Focus on a cubic subdomain (3d x 3d x 3d) close to the jet exit.
- Perform the analysis in parallel to extract modes of three velocity components together.
- Apply the sparsity promoting algorithm to pick the relevant modes of interest.
- Compare with frequencies from probes.
- Apply the transformation velocity $\rightarrow$ Q criterion for the selected mode to examine shape.

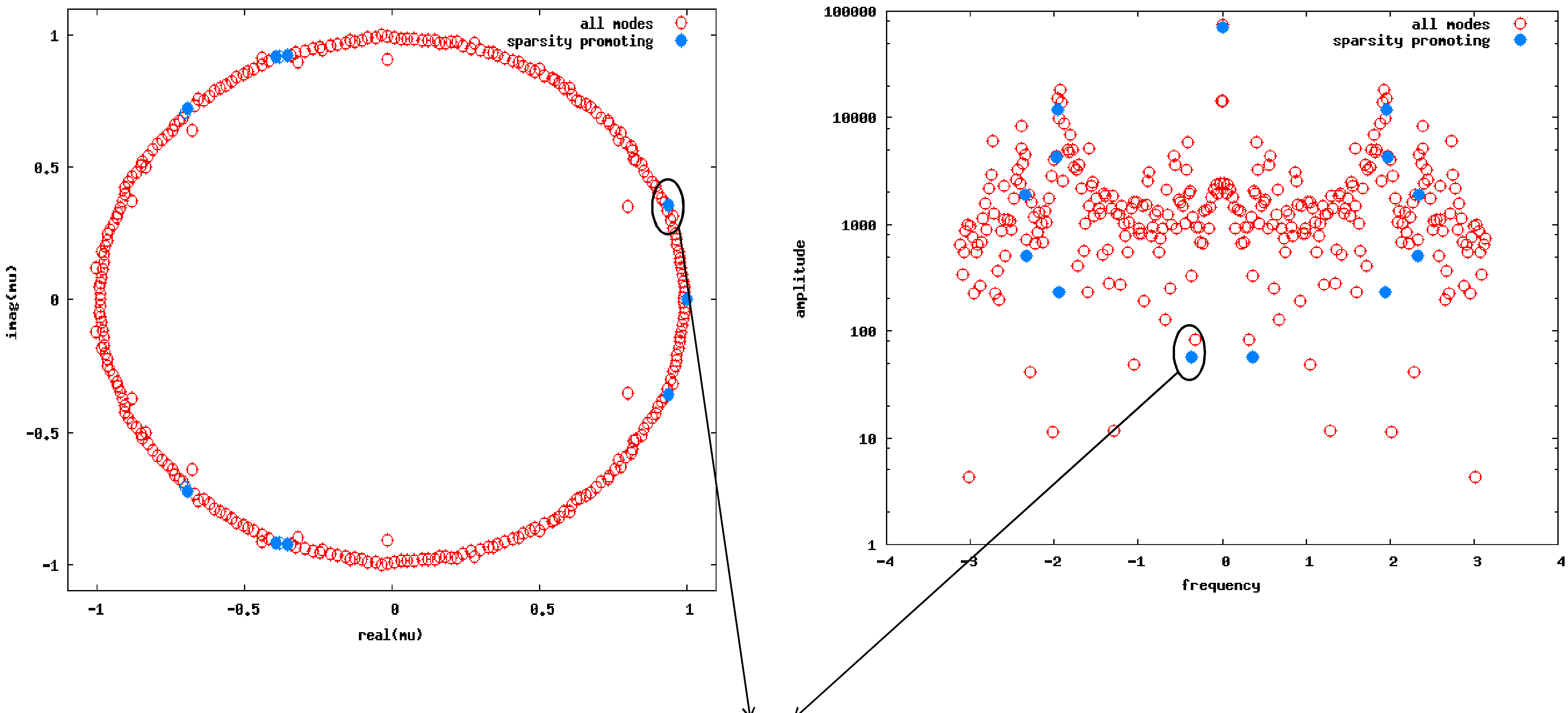
Relevant mode

- 3 probes placed in DNS
- Spectra from time-continuous data.
- Dominant mode has St ~0.37.



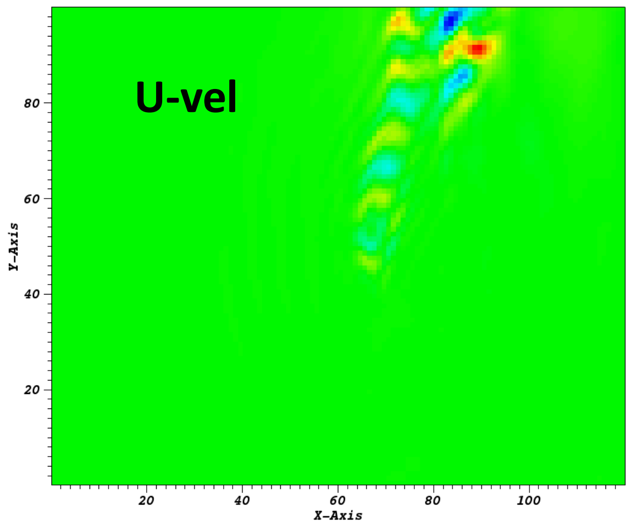
Results – Inert DNS

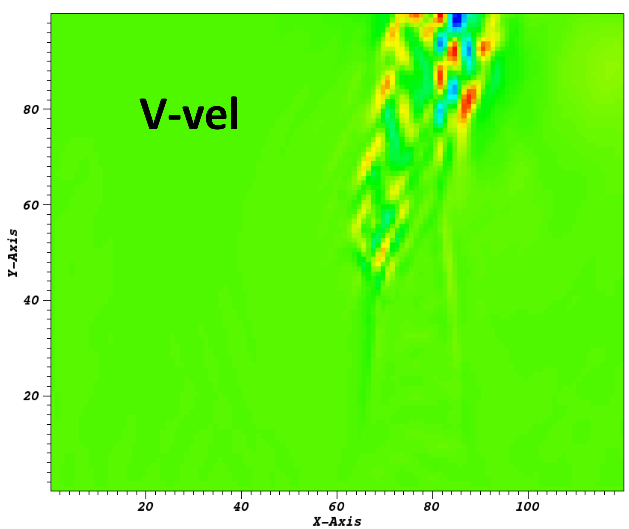
The frequency of the DMD mode agrees well.



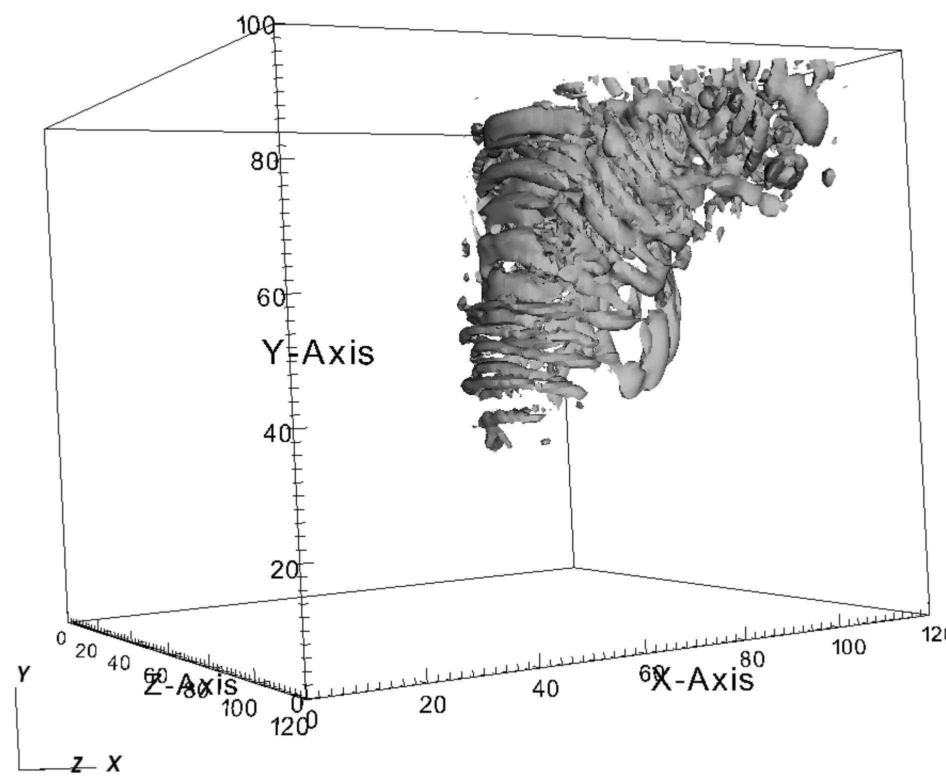
Relevant mode, St = 0.37

Relevant mode - Shape



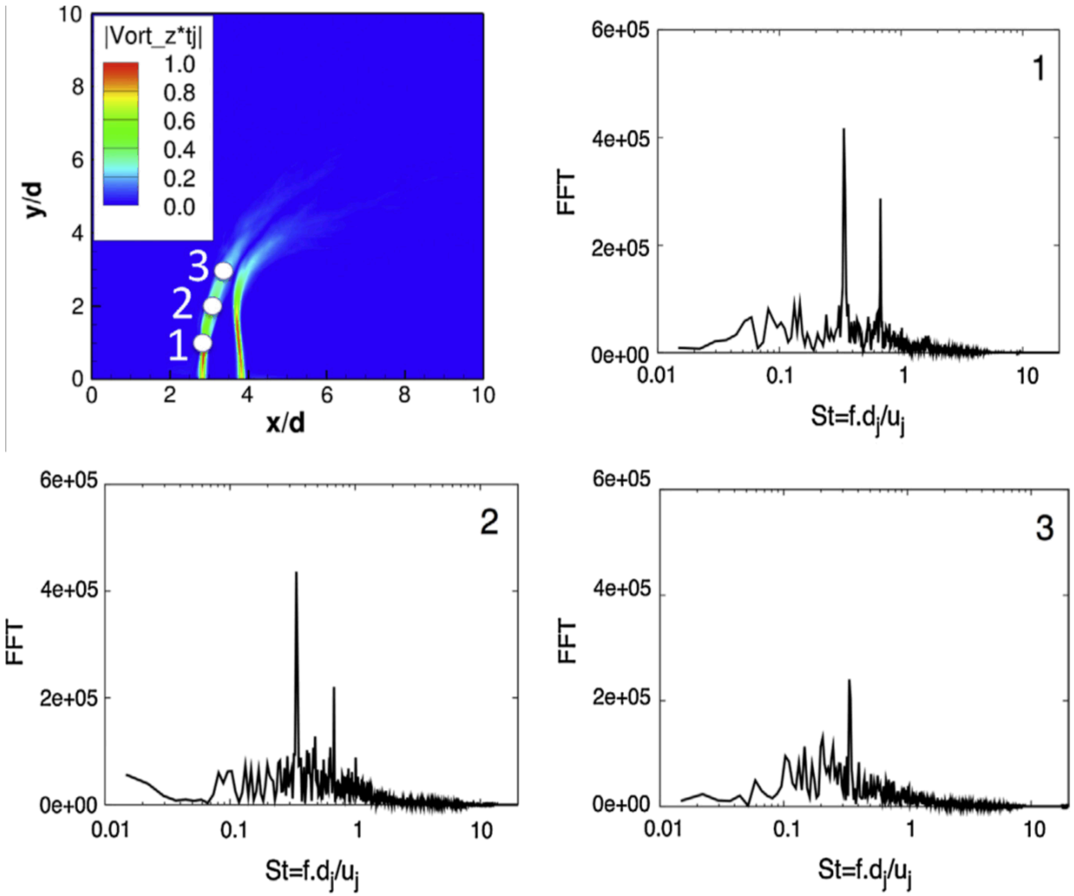


Iso-surface of Q



Relevant mode

- The probes in reacting DNS give qualitatively different spectra
- Two modes dominant closest: St = 0.3, 0.6
- Reacting case convectively unstable??



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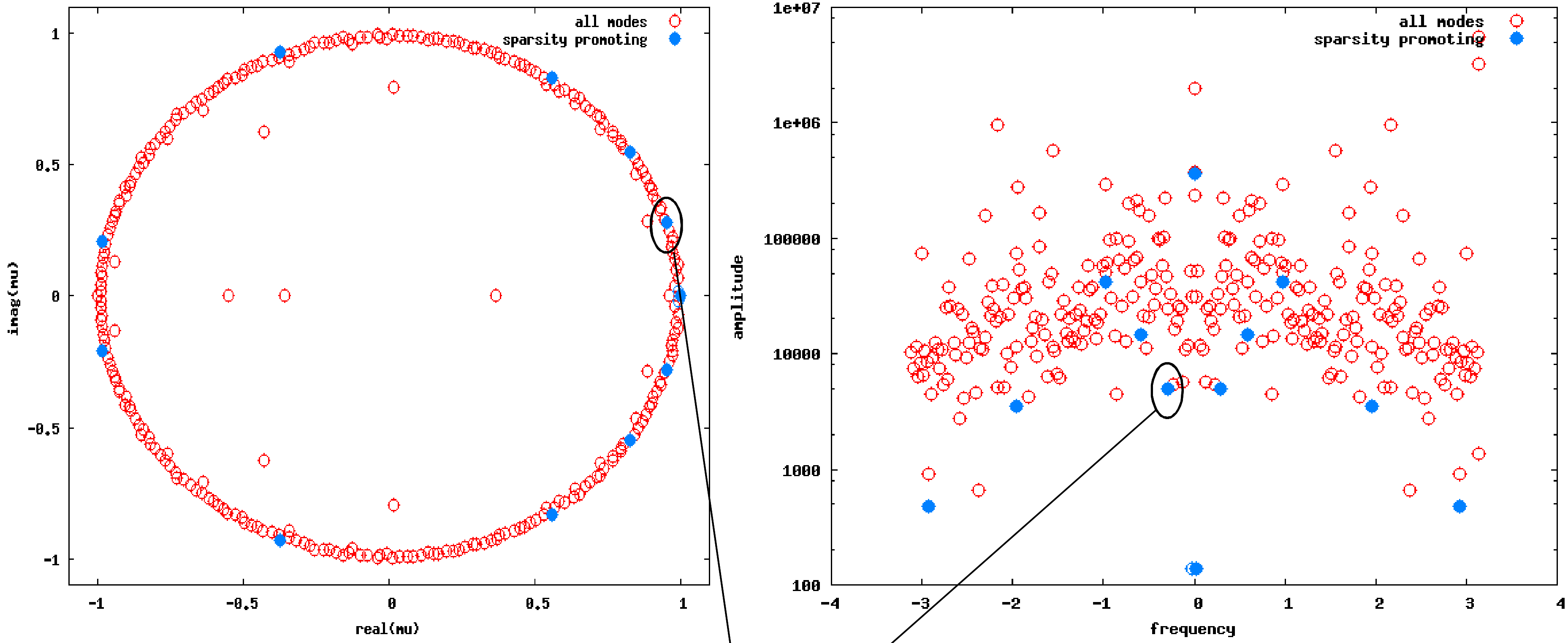
Results – Reacting DNS

The DMD appears to be picking the second mode.



You can manually pick ST = 0.3, we are not restricted to the sparsity-promoting algorithm!

Relevant mode, St = 0.6

Relevant mode - Shape