PhD Aerospace Engineering UC3M
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MIXING DYNAMICS IN TURBULENT FLOWS WITH HIGH-DENSITY RATIOS

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Motivation

APPLICATIONS

- **Hydrogen Propulsion**: Explosion risk assesment
- **Chemical Manufacturing:** Reaction control
- **Environmental Protection:** Toxic exposure limits

Mixing in turbulent flows is notoriously **difficult to predict** due to extreme fluctuations and highly variable mixing rates. Rather than focusing on averages, this research models the **maximum of the scalar**.

The advantage is that by defining this upper limit, we can determine if a safety threshold will be crossed; if the critical limit is above the predicted maximum, the probability of an incident is mathematically zero.

State of the Art

- **1922** — Taylor's fundamental length and time scales [1]
- **1941** — Energy Decay Spectrum $k^{-5/3}$ [2]
- **1959** — Spectral & Intermitency theories [3]
- **1976** — PDFs and spectral relaxation [4]
- **1993** — Anomalous scaling of advected passive scalar [5]
- **Now** — High-resolution DNS [6]

LIMITATIONS OF CURRENT MODELS

- Statistical models **fail to capture transient extremes.**
- DNS give precise statistics but are **computationally very expensive**
- Most studies focus on steady-state mixing and **not transient**

Objectives

- Construct an extensive **database** describing the statistics of the transient mixing of scalar in turbulence
- Characterization of transient **mixing dynamics** in terms of flow patterns
- Construct **statistical models** that provide theoretical explanations and predict statistics of transient mixing depending on the initial distribution of scalar

Methodology

DNS in GPUs CUDA-based solver using parallel computing → Massive Ensembles of simulations → Statistical analysis of mixing → Theoretic measure for predictability and modelling

EQUATIONS

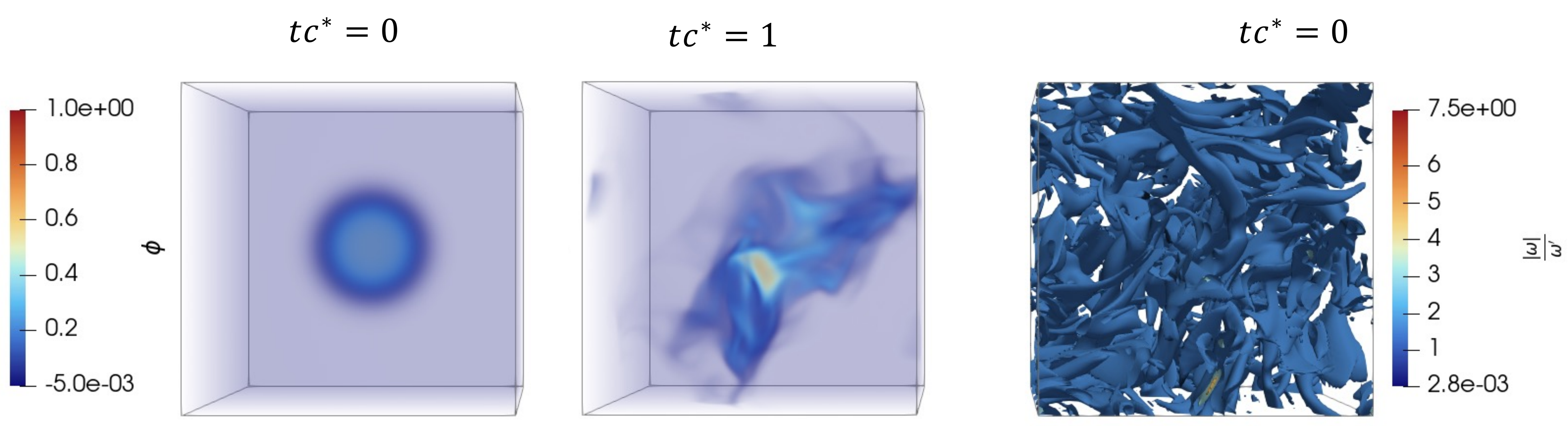
Mass conservation : $\nabla \cdot \boldsymbol{u} = 0$

Momentum conservation: $\dfrac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{\omega} \times \boldsymbol{u} = -\dfrac{1}{\rho}\nabla p + \nu \nabla^2 \boldsymbol{u} + \boldsymbol{cf}$

Fick's law: $\dfrac{\partial \phi}{\partial t} + \boldsymbol{u} \cdot \nabla \phi = D \nabla^2 \phi$

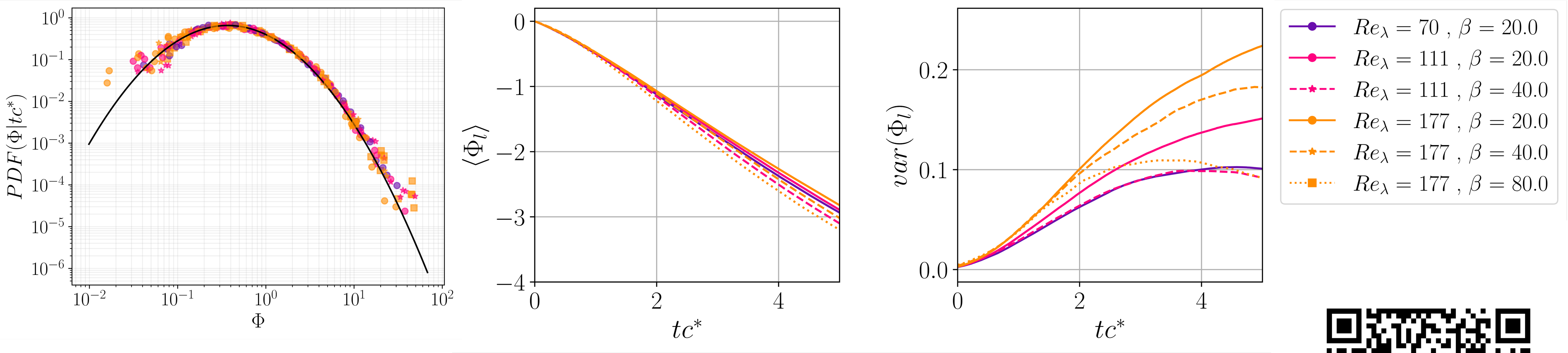
$\boldsymbol{u} \equiv$ *velocity vector*
$\boldsymbol{\omega} \equiv$ *vorticity vector*
$p \equiv$ *pressure*
$\rho \equiv$ *density*
$\nu \equiv$ *kinematic viscosity*
$\boldsymbol{cf} \equiv$ *adaptive force to sustain turbulence*
$\phi \equiv$ *scalar mass fraction*
$D \equiv$ *scalar diffusivity*

- Initial condition of scalar: **Gaussian sphere of radius r_0**
- Mixing depends on Re_λ & $\beta = r_0/\eta$ (initial scalar size in Kolmogorov units)



- To account for the scalar size, time is non-dimensionalised with the inertial scalar time and a correction τ_0 is substracted to account for the time required to break the Gaussian : $tc^* = \frac{t - \tau_0}{t_i}$

Preliminary Research/Results



Probability Density Function of $\Phi = \max(\phi)$ standarized at $tc^*[1.5, 2, 2.5, 3, 3.5, 4]$ follow a lognormal distribution → Analyse statistics of $\Phi_l = Ln(\Phi)$

- The lognormal median shows an excellent collapse across all cases with scaling behaviour suggesting the presence of intermitency.
- The lognormal variance fails to collapse → dependence on Re_λ and β

SCALAR MIXING & TURBULENT FLOW VIDEOS:

[1] *Taylor, G. I. (1922). Diffusion by continuous movements. Proc. London Math. Soc., 2(1), 196-212.*
[2] *Andrei Nikolaevich Kolmogorov, V. Levin, Julian Charles Roland Hunt, Owen Martin Phillips, David Williams; Dissipation of energy in the locally isotropic turbulence. Proc. A 1 July 1991; 434 (1890): 15–17.*
[3] *Batchelor, G. K. (1959). Small-scale variation of convected quantities like temperature in turbulent fluid Part 1. General discussion and the case of small cond. J. Fluid Mech., 5(1), 113-133. (4), 437-450.*
[4] *Dopazo, C. (1976). A probabilistic approach to turbulent flame theory. Acta Astronautica, 3(9-10), 853-878.*
[5] *Kraichnan, R. H. (1994). Anomalous scaling of a randomly advected passive scalar. Phys. Rev. Lett., 72(7), 1016-1019.*
[6] *Schumacher, J., Sreenivasan, K. R., & Yeung, P. K. (2005). Very fine structures in scalar mixing. Journal of Fluid Mechanics, 531, 113–122.*

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FLOWERS CFD LAB

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