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Mixing and Turbulence: Are we there yet?

EXTREME FLUIDS

extremefluids.lanl.gov

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NNSA National Nuclear Security Administration

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We are developing predictive models for complex, multiphysics flows that can't be simulated directly.

Models
With the essential physics (often discovered through **experiments**)

→

Code implementation
With parameters set via **experiments**

→

Validation
With fundamental and complex **experiments**

Most turbulence at LANL does not fall into the idealized Kolmogorov 1941 (K41) conditions

Assumptions from K41:

- Gradual cascade from large to small scales, where the flow doesn't retain memory of how it started (initial conditions)
- Isotropy at small scales (statistics invariant to rotations of axes)
- Homogeneous (statistics invariant to translations of axes)

- **In transitional flows, large-scale mixing exists concurrently with small-scales**
- **Initial conditions are usually remembered**
- **Shock-driven mixing is transitional, inhomogeneous and anisotropic**
- **Variable-density flows can have homogeneity in the velocity fields but not the density fields**

How do we model these difficult flows?

The LANL Reynolds-Averaged Navier-Stokes (RANS) model is designed to distinguish between homogeneous and inhomogenous flows

LANL Turbulence Model Quantities are:

Reynolds stress, R_{ij} $\tilde{R}_{ij} = \overline{\rho u_i'' u_j''} / \bar{\rho}$ $u_i'' = u_i' - a_i$

Turbulent decay length scale, S_D

Turbulent transport length scale, S_T

Density specific-volume correlation, b $b = -\overline{\rho'(1/\rho)'}$

Turbulent mass flux, a_i $a_i \equiv -\overline{u_i''} = \overline{\rho' u_i'} / \bar{\rho}$

Schwarzkopf, Livescu, Baltzer, Gore, Ristorcelli, *Flow Turb. Combust.* (2016)

Variable-density and non-uniform mixing affect the stresses on the fluid

- Turbulent Mass Flux Transport (exact)

$$\frac{\partial(\bar{\rho}a_i)}{\partial t}+\left(\rho\tilde{u}_j a_i\right)_{,j}=b\left(\bar{P}_{,i}-\tilde{\tau}_{ki,k}\right)-\tilde{R}_{ik}\bar{\rho}_{,k}+\bar{\rho}\left(a_k a_i\right)_{,k}-\bar{\rho}a_k\bar{u}_{i,k}-\bar{\rho}\left(\frac{\overline{\rho' u_i' u_k'}}{\bar{\rho}}\right)_{,k}+\bar{\rho}\,\overline{v'\left(P'_{,i}-\tau'_{ki,k}\right)}$$

- Reynolds Stress (exact), R_{ik}

$$\frac{\partial(\bar{\rho}\tilde{R}_{ij})}{\partial t}+\underbrace{\frac{\partial}{dx_k}\left(\bar{\rho}\tilde{u}_k\tilde{R}_{ij}\right)}_{\text{Convection}}=\underbrace{a_i\frac{\partial\bar{P}}{\partial x_j}+a_j\frac{\partial\bar{P}}{\partial x_i}-\bar{\rho}\tilde{R}_{ik}\frac{\partial\tilde{u}_j}{\partial x_k}-\bar{\rho}\tilde{R}_{jk}\frac{\partial\tilde{u}_i}{\partial x_k}}_{\text{Production}}-a_i\frac{\partial\tilde{\tau}_{jk}}{\partial x_k}-a_j\frac{\partial\tilde{\tau}_{ik}}{\partial x_k}$$

$$\underbrace{\underbrace{-\frac{\partial}{\partial x_k}\overline{\rho u_i'' u_j'' u_k''}}_{\text{Turbulent Flux}}+\frac{\partial}{\partial x_k}\left(\overline{u_i''\tau_{jk}''}+\overline{u_j''\tau_{ik}''}\right)\underbrace{-\frac{\partial}{\partial x_j}\overline{u_i''P'}-\frac{\partial}{\partial x_i}\overline{u_j''P'}}_{\text{Pressure Flux}}}_{\text{Transport}}+\underbrace{\overline{P'\frac{\partial u_i''}{\partial x_j}}+\overline{P'\frac{\partial u_j''}{\partial x_i}}}_{\text{Pressure Strain}}\underbrace{-\overline{\tau_{jk}''\frac{\partial u_i''}{\partial x_k}}-\overline{\tau_{ik}''\frac{\partial u_j''}{\partial x_k}}}_{\text{Dissipation}}$$

Schwarzkopf, Livescu, Gore, Rauenzahn, Ristorcelli (2011) *J. Turbulence*

Models are chosen that reflect our best understanding of the physics

$$
\frac{\partial\left(\bar{\rho}\bar{R}_{ij}\right)}{\partial t}+\boxed{\left(\bar{\rho}\tilde{u}_k\bar{R}_{ij}\right)_{,k}}=\overbrace{\left[a_i\bar{P}_{,j}+a_j\bar{P}_{,i}\right]-\bar{\rho}\left[\bar{R}_{ik}\tilde{u}_{j,k}+\bar{R}_{jk}\tilde{u}_{i,k}\right]}^{\text{Production}} \quad (16)
$$

$$
+\underbrace{\frac{C_\mu}{\sigma_k}\left(\bar{\rho}S_T\sqrt{K}\bar{R}_{ij,k}\right)_{,k}}_{\text{Transport}}-\underbrace{C_{r3}\bar{\rho}\frac{\sqrt{K}}{S_D}\left(\bar{R}_{ij}-\frac{1}{3}\bar{R}_{kk}\delta_{ij}\right)}_{\text{Return to Isotropy}}
$$

$$
\overbrace{-C_{r1}\left[a_i\bar{P}_{,j}+a_j\bar{P}_{,i}\right]+C_{r2}\bar{\rho}\left[\bar{R}_{ik}\tilde{u}_{j,k}+\bar{R}_{jk}\tilde{u}_{i,k}\right]}^{\text{Rapid Distortion}}
$$

$$
\underbrace{-C_{r2}\frac{2}{3}\bar{\rho}\bar{R}_{mk}\tilde{u}_{m,k}\delta_{ij}+C_{r1}\frac{2}{3}a_k\bar{P}_{,k}\delta_{ij}}_{\text{Rapid Distortion}}-\underbrace{\bar{\rho}\frac{2}{3}\frac{K^{3/2}}{S_D}\delta_{ij}}_{\text{Dissipation}}
$$

Exact

Two length scales

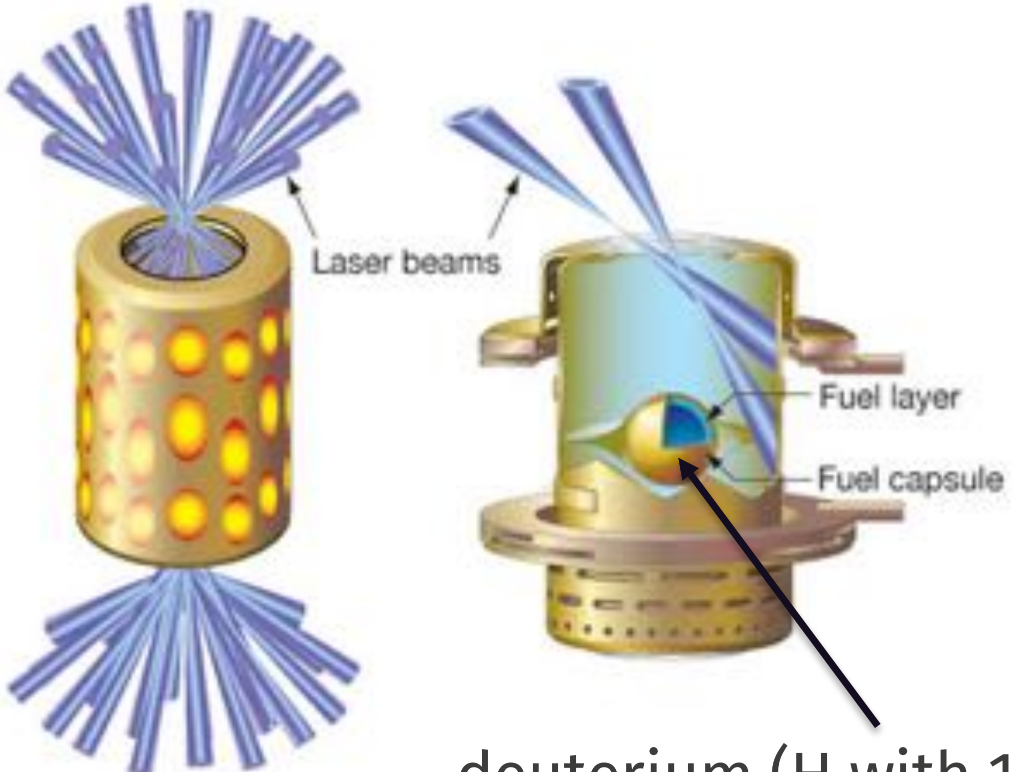
Assumptions:

- **Transport** is modeled as a **turbulent flux**. All other transport terms dropped or thought to be covered by this term.
- **Pressure strain** modeled with the isotropization of production model.
- **Dissipation** assumed isotropic.

What kind of flows require this complex modeling?

Inertial Confinement Fusion (ICF) at the National Ignition Facility (NIF)

192 Lasers: 500 trillion watts in 20 ns



deuterium (H with 1 neutron)
+ tritium (H with 2 neutrons)

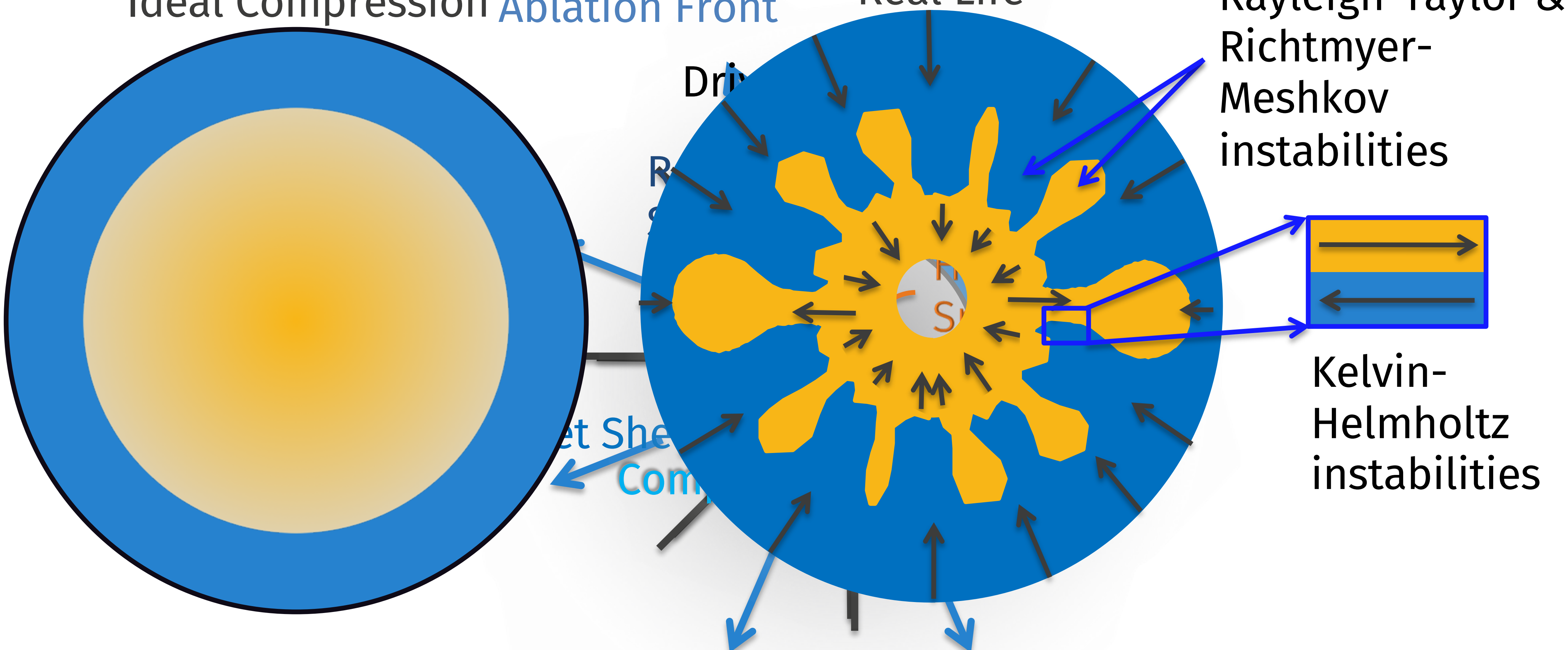
lasers.llnl.gov

NIF uses 192 laser beams to squeeze a tiny capsule to create ignition via fusion

Fuel capsule

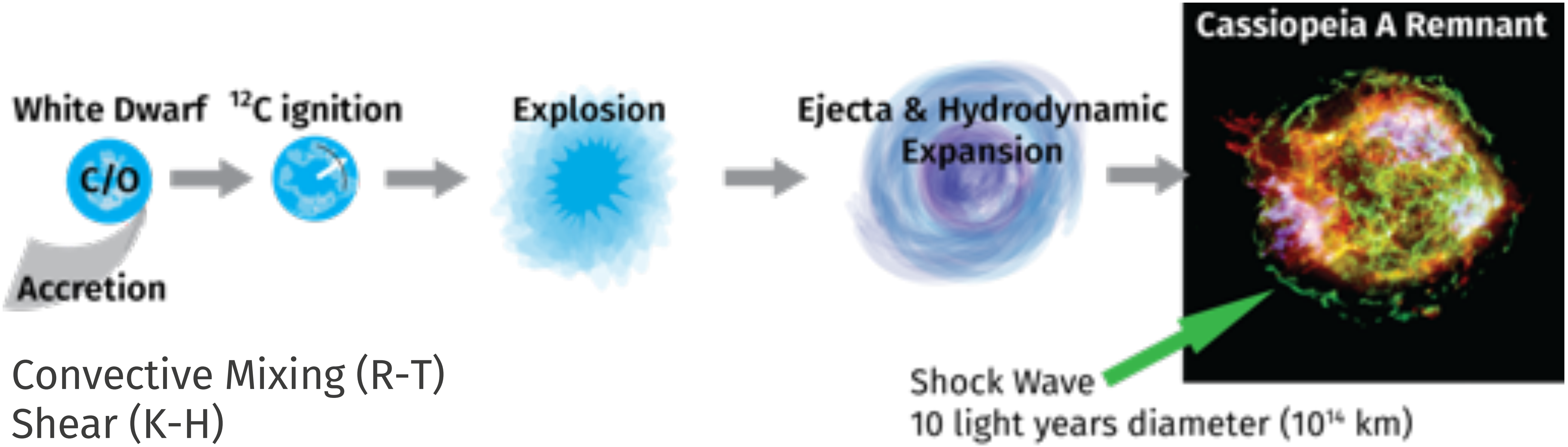
LLNL *Sci&Tech Review* (1999)

ICF capsules are compressed to form a hot spot, creating conditions for fusion



2-D and 3-D simulations can now account for instability growth that happens in these high energy density regimes. Can we predict the instabilities well enough to achieve ignition?

Type Ia supernovae are "standard candles" that help determine the age of the universe

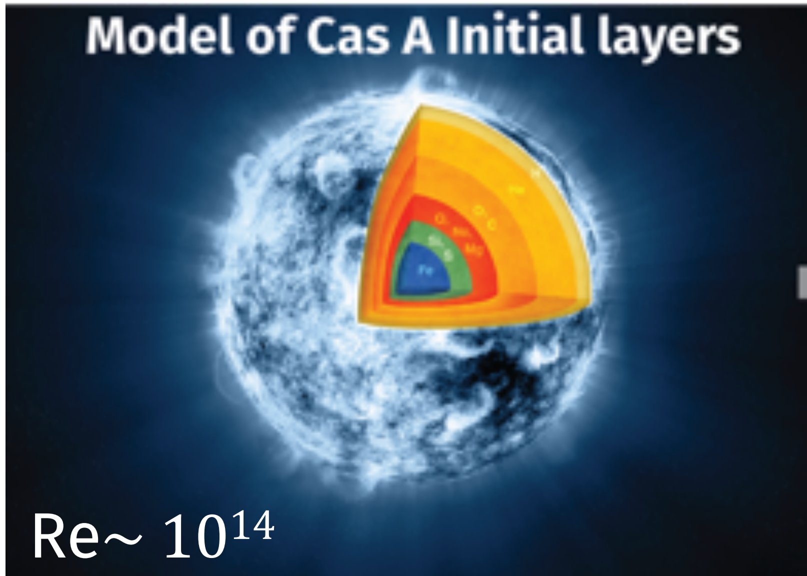


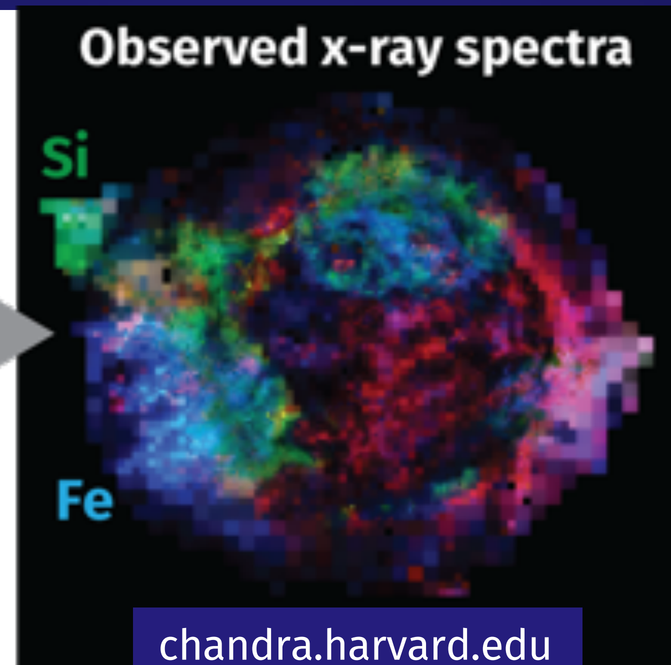
Convective Mixing (R-T)
Shear (K-H)
Shock-driven (R-M)

Instabilities are important in:
- Pre-ignition conditions
- Triggering ignition
- Final chemical structure

Image from NASA's Chandra X-Ray Observatory chandra.harvard.edu

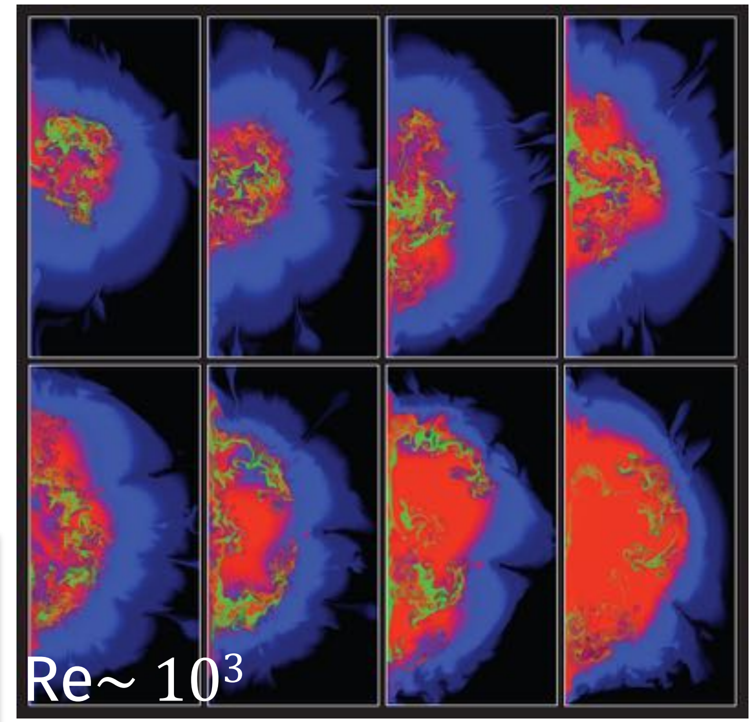
Initial Conditions affect the supernova's evolution. Turbulence models don't account for the ICs of the flow!





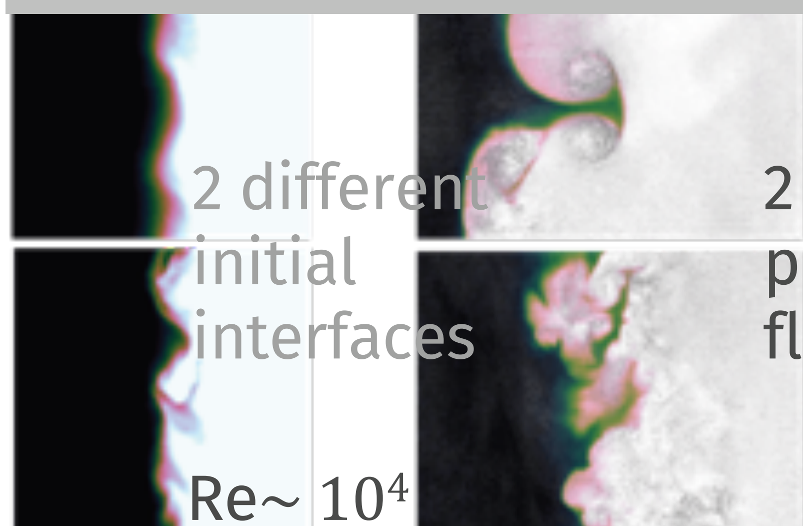
chandra.harvard.edu

Simulation of IC effects on chemical structure: 8 different ignition and detonation conditions 100 s after ignition



D Kasen *et al.* (2009) *Nature*

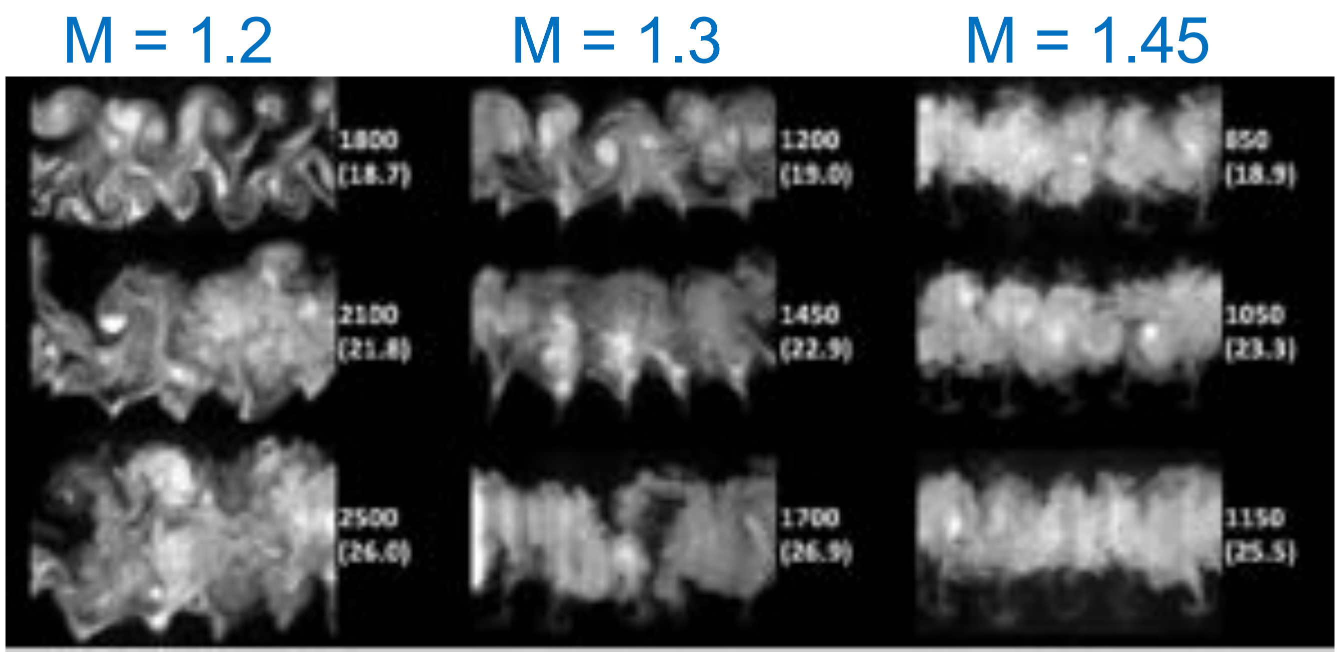
Laboratory-scale experiment

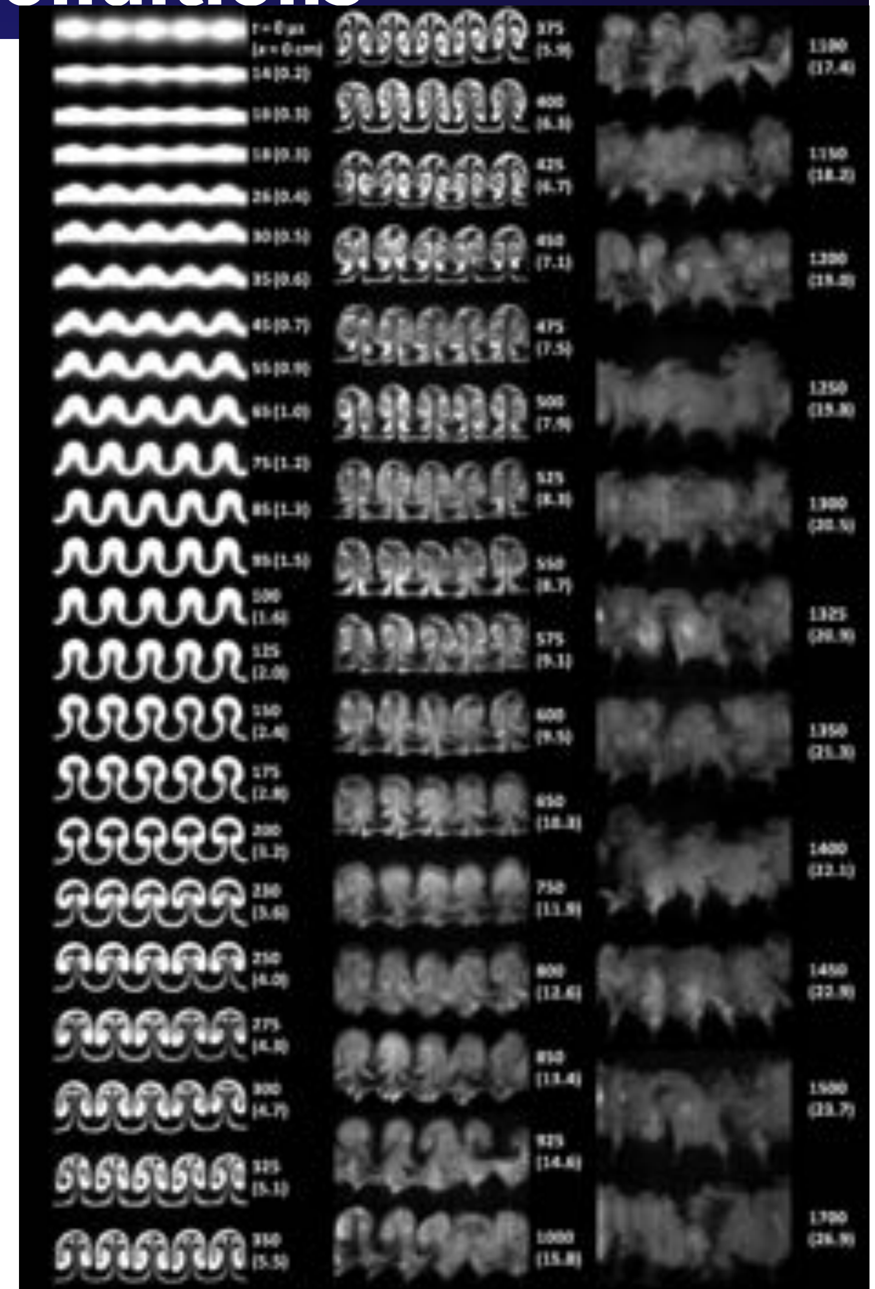


2 different post-shock flows

How do we simulate initial conditions effects?

Gas curtain experiments in a shock tube allow us to carefully control the initial and shock conditions





The nature of the mixing changes with Mach number, even after scaling time. How do we quantify these differences?

Orlicz, S. Balasubramanian, Prestridge (2013) *Phys. Fluids.*
Orlicz, S. Balasubramanian, Vorobieff, Prestridge (2015) *Phys. Fluids*

Reshocking the curtain speeds up mixing, yet sensitivity to initial conditions persists

$$At = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} = 0.6 \qquad M=1.2$$

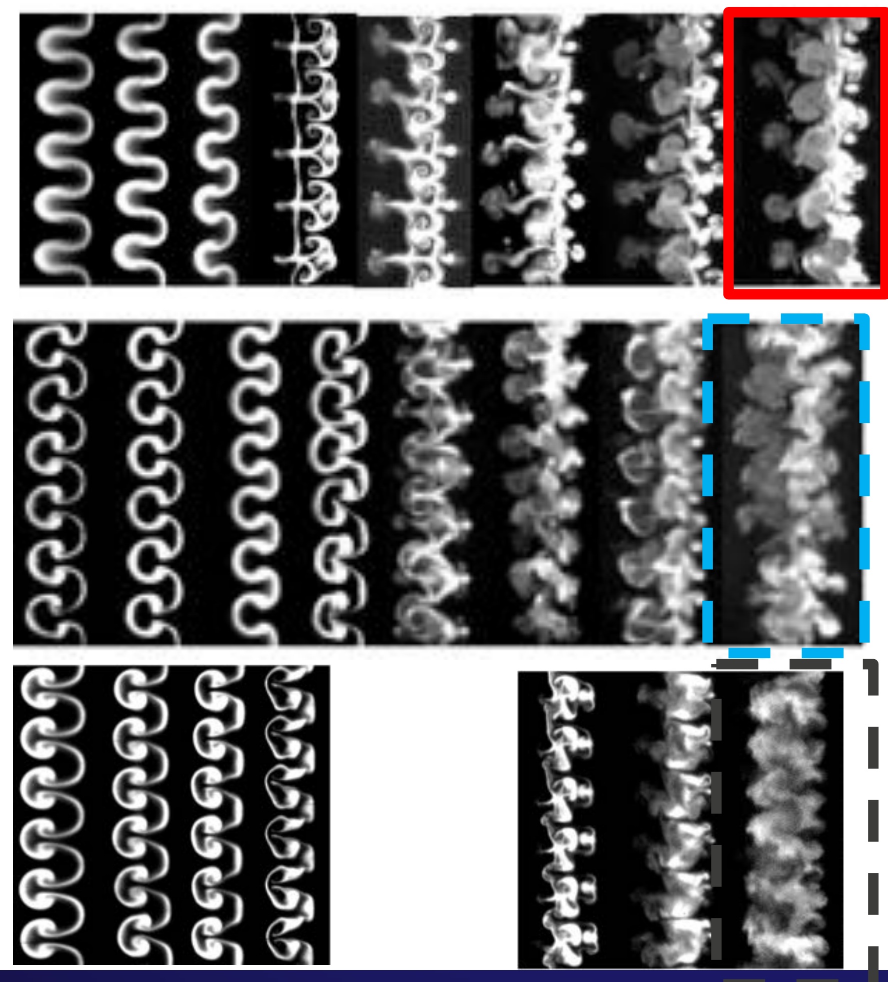
Reshock timing changes initial condition

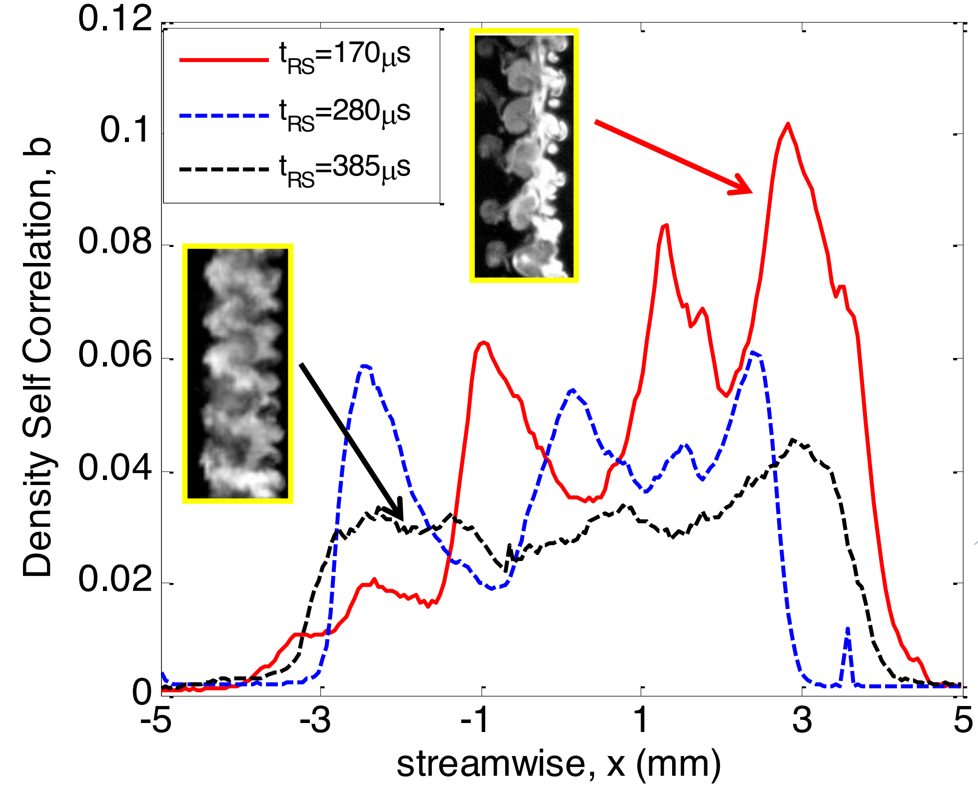
$\boxed{\eta_0 = \kappa_0 \delta_0}$

170μs
η_0 =15

280μs
η_0 = 18

385μs
η_0 = 35

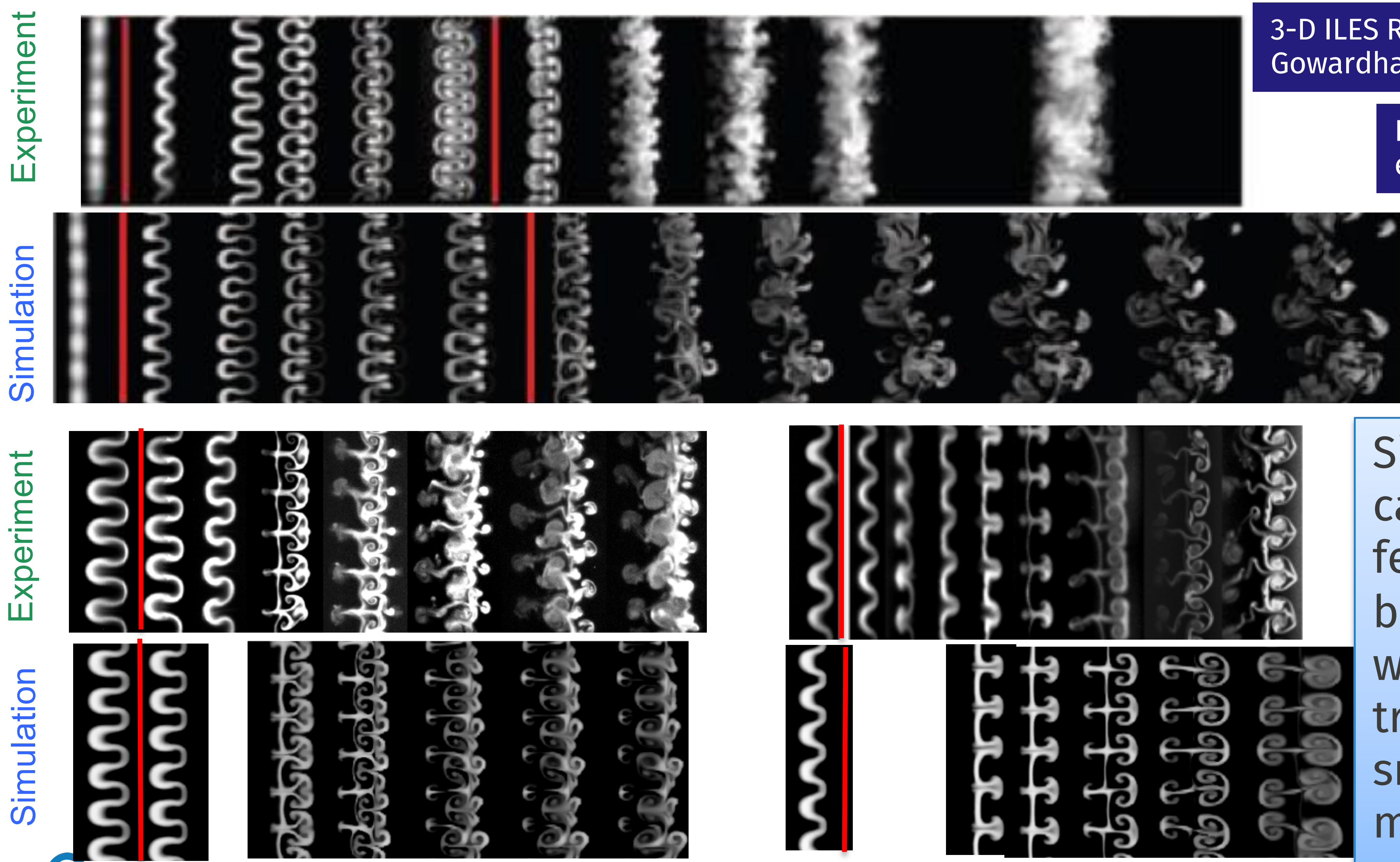




$$b = -\overline{\rho' \left(\frac{1}{\rho}\right)'}$$

Balasubramanian et al. (2012) *PoF*
Tomkins et al. (2013) *JFM*

Simulations can systematically show us how sensitive the flow is to initial conditions

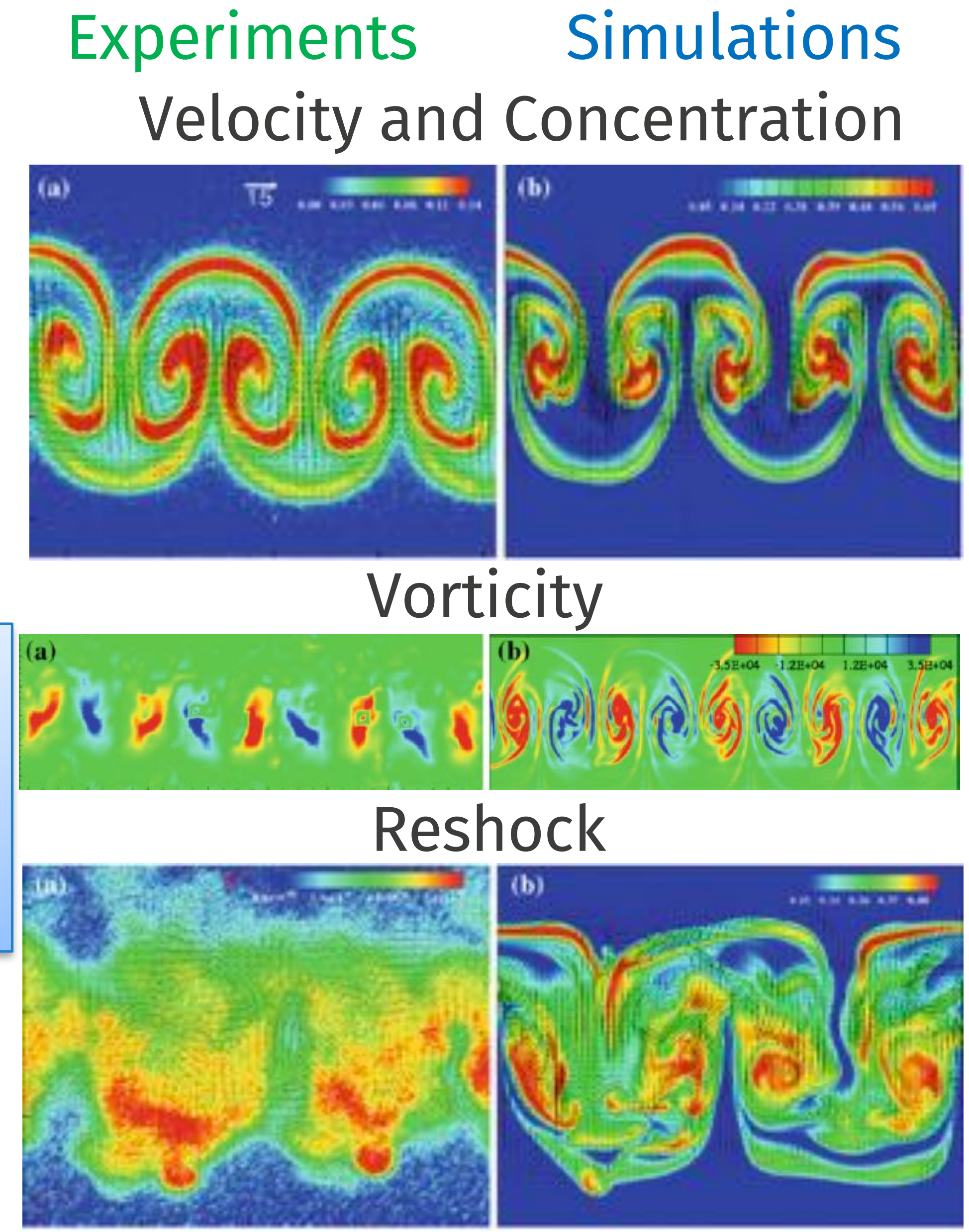


3-D ILES RAGE simulations
Gowardhan & Grinstein (2011) *JoT*

Experiments: Balakumar et al. (2008) *PoF*

Simulations capture large features well, but have trouble with mixing transition and smaller-scale mixing features

Collaborations with numerical physicists have driven the experimental conditions and measurements



Multispecies ILES simulations:

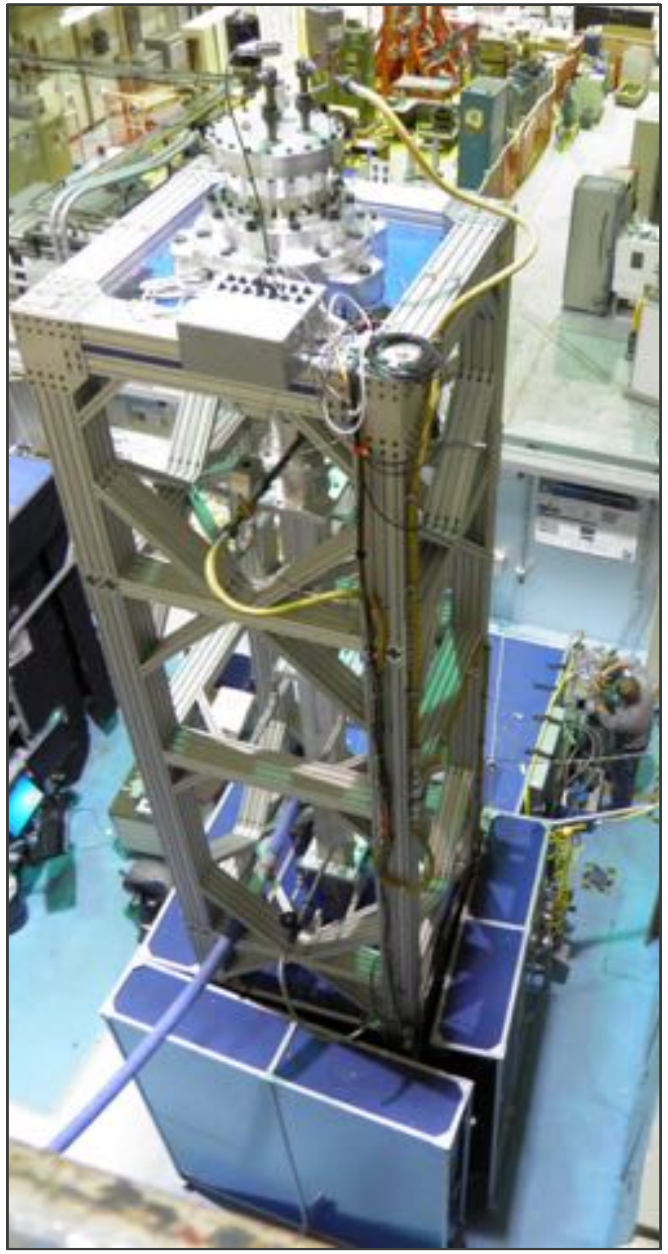
Good quantitative comparisons at large scales (e.g., peak vorticity, extent of mixing region).

Improvements/questions driven by validation:

- Always need higher resolution diagnostics!
- Mixing of 2 interfaces is difficult to understand
- Need IC parametric study

Shankar & Lele (2014) Shock Waves

We designed new experiments to study the effects of initial conditions and Mach number on shock-driven mixing



Vertical Shock Tube (VST)

Initial conditions
- Single interface, air/SF_6 (At=0.6)

Diagnostics
- Simultaneous PIV & Quantitative PLIF

Mach number
- 1.2<M<3

Powder Gun Shock Tube

Initial conditions
- Single interface, Xe/He (At=0.94)

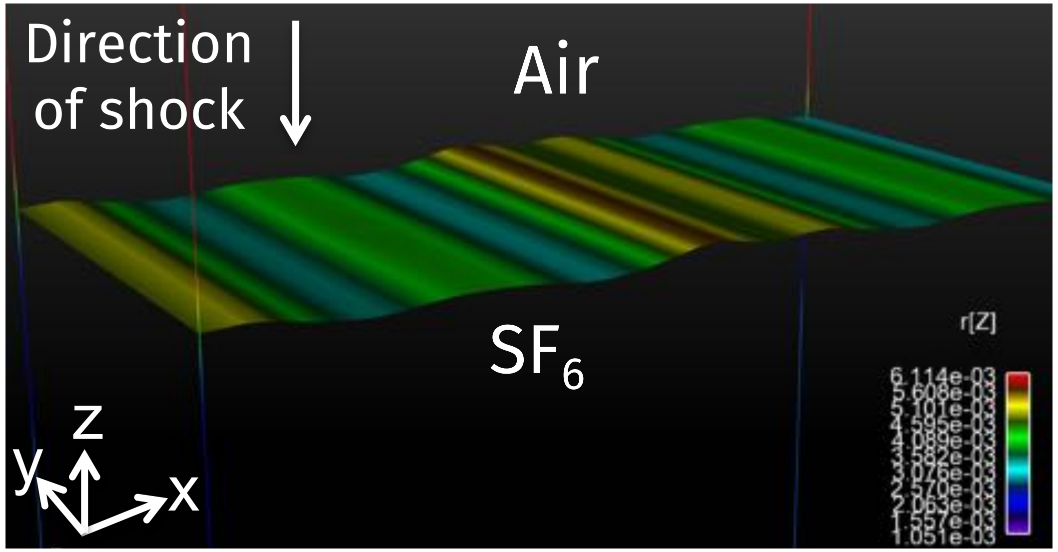
Diagnostics
- Proton Radiography (pRad)

Mach number
- M=8.8

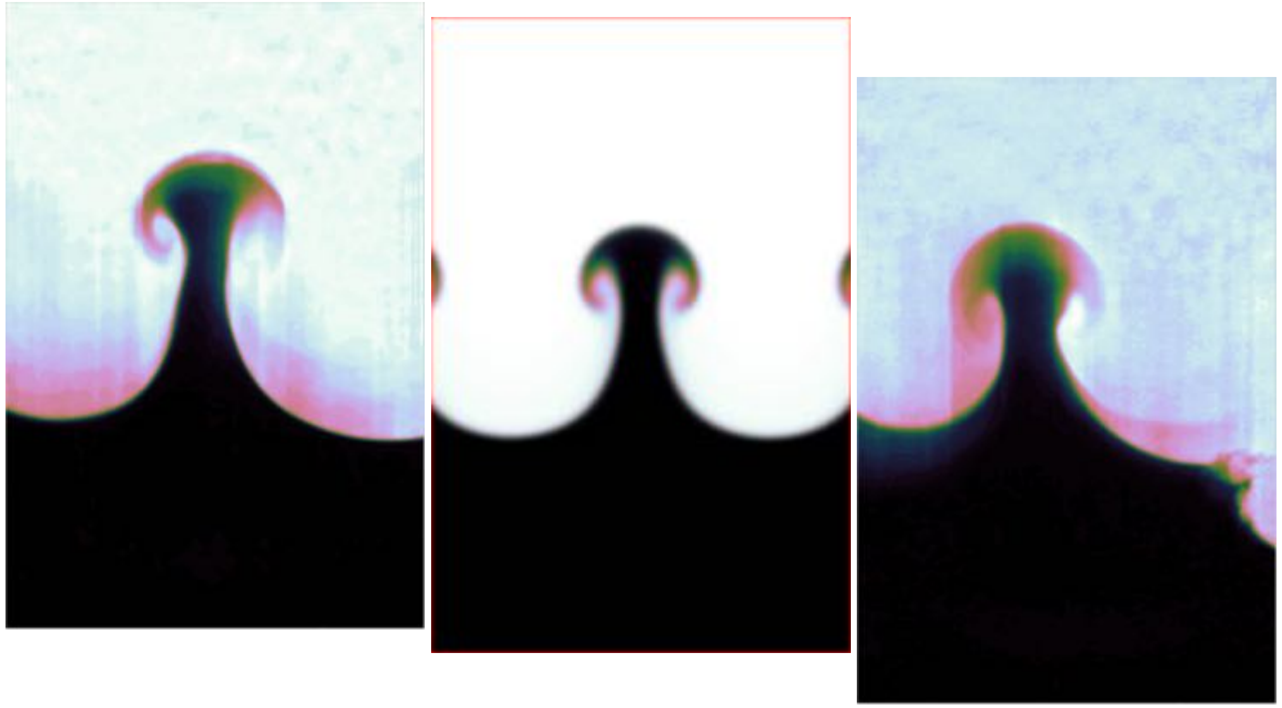
LES simulations of 2-D initial conditions capture large-scale ejections and vorticity

2D perturbations

- Modes in x-z plane



Experimental Initial Conditions used to develop simulation input

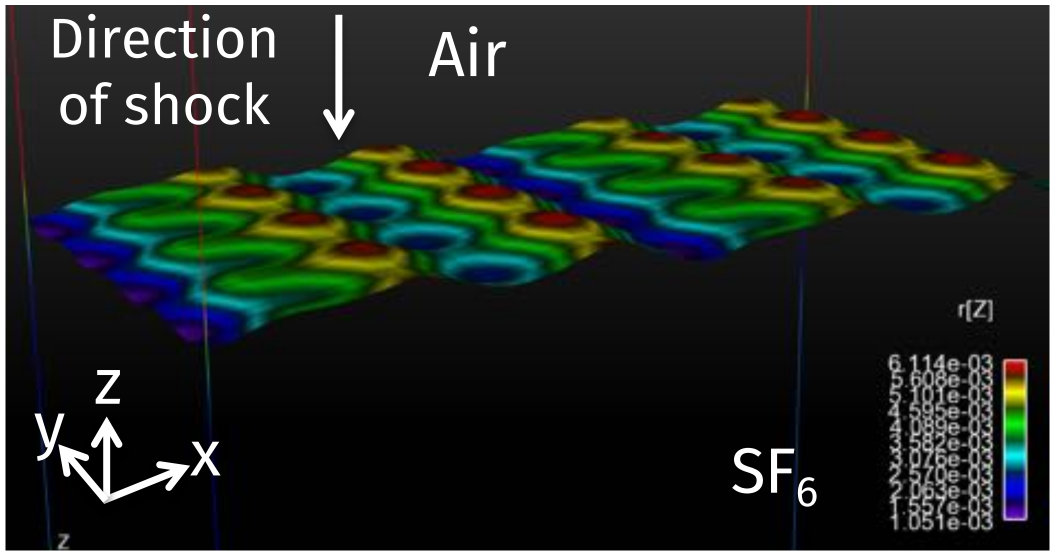


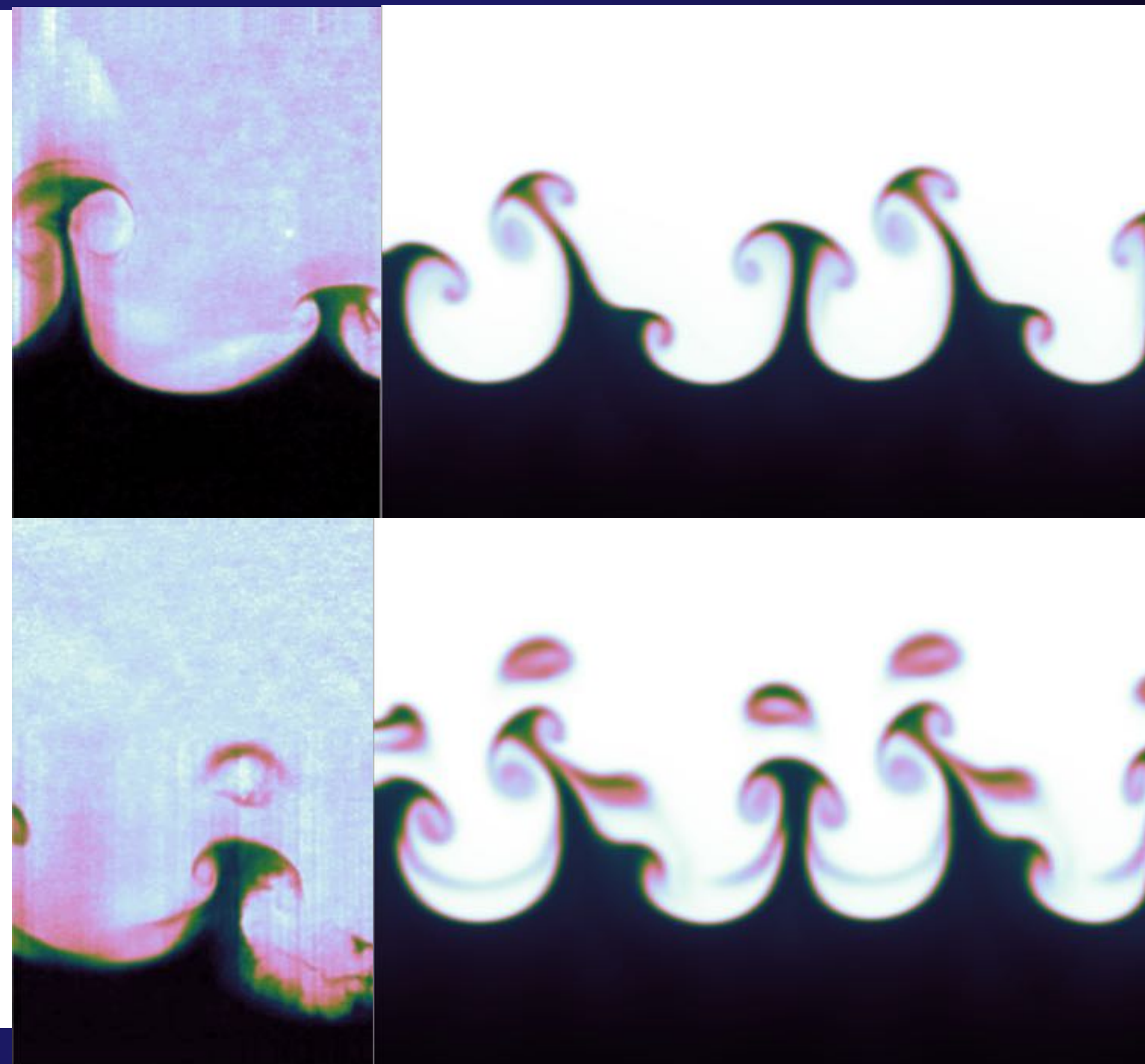
Simulations by Nick Denissen using Lagrangian code FLAG

3-D simulations help explain experimental observations

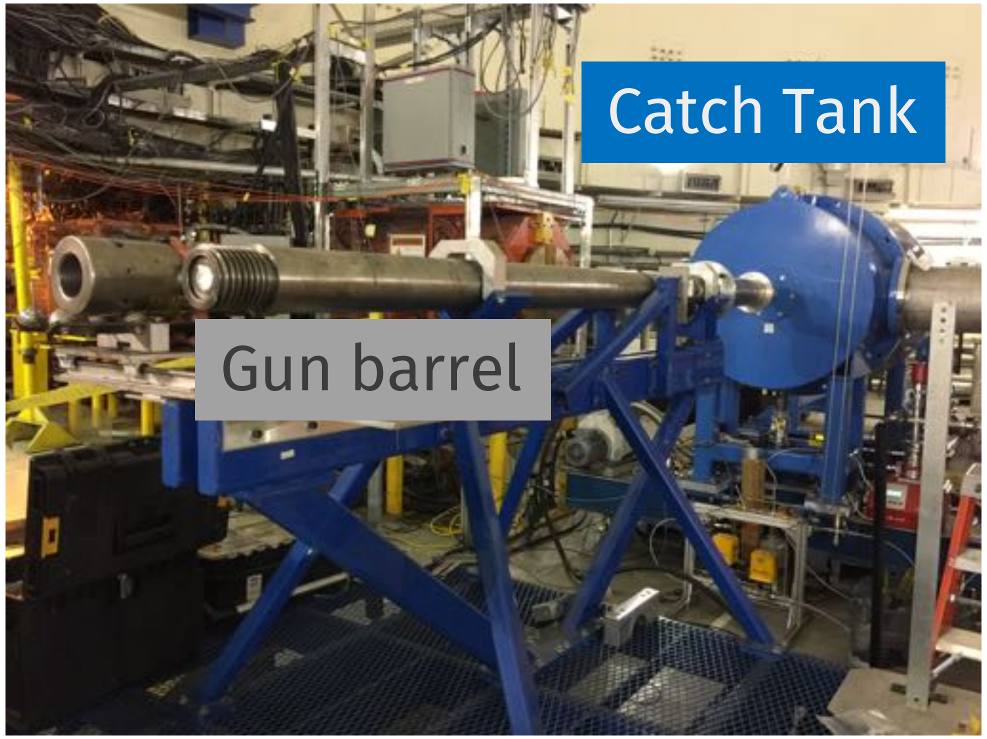
3D perturbations

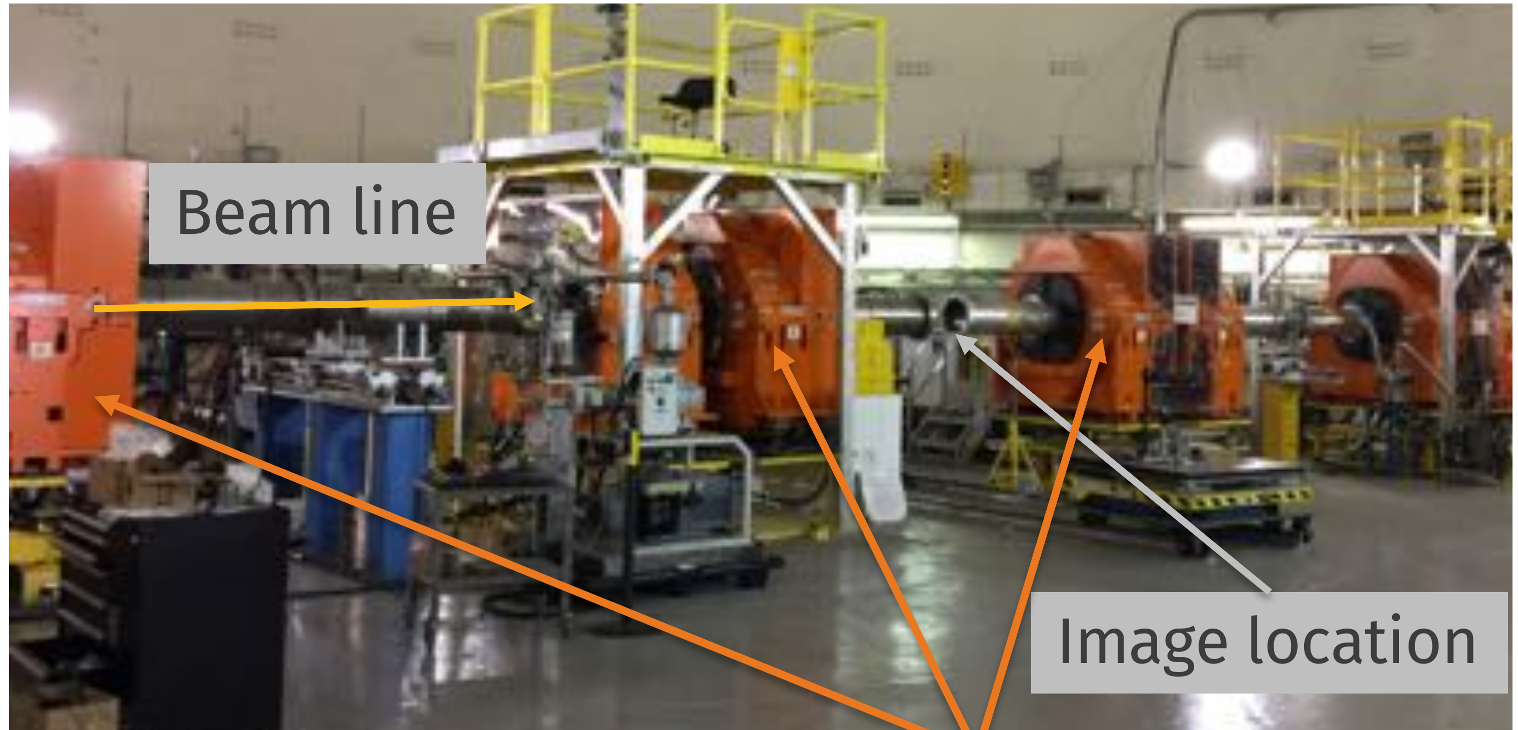
- Multi-mode in x-z plane
- Single-mode in y direction





The powder gun at LANL's proton radiography facility allows us to drive strong shocks into gases



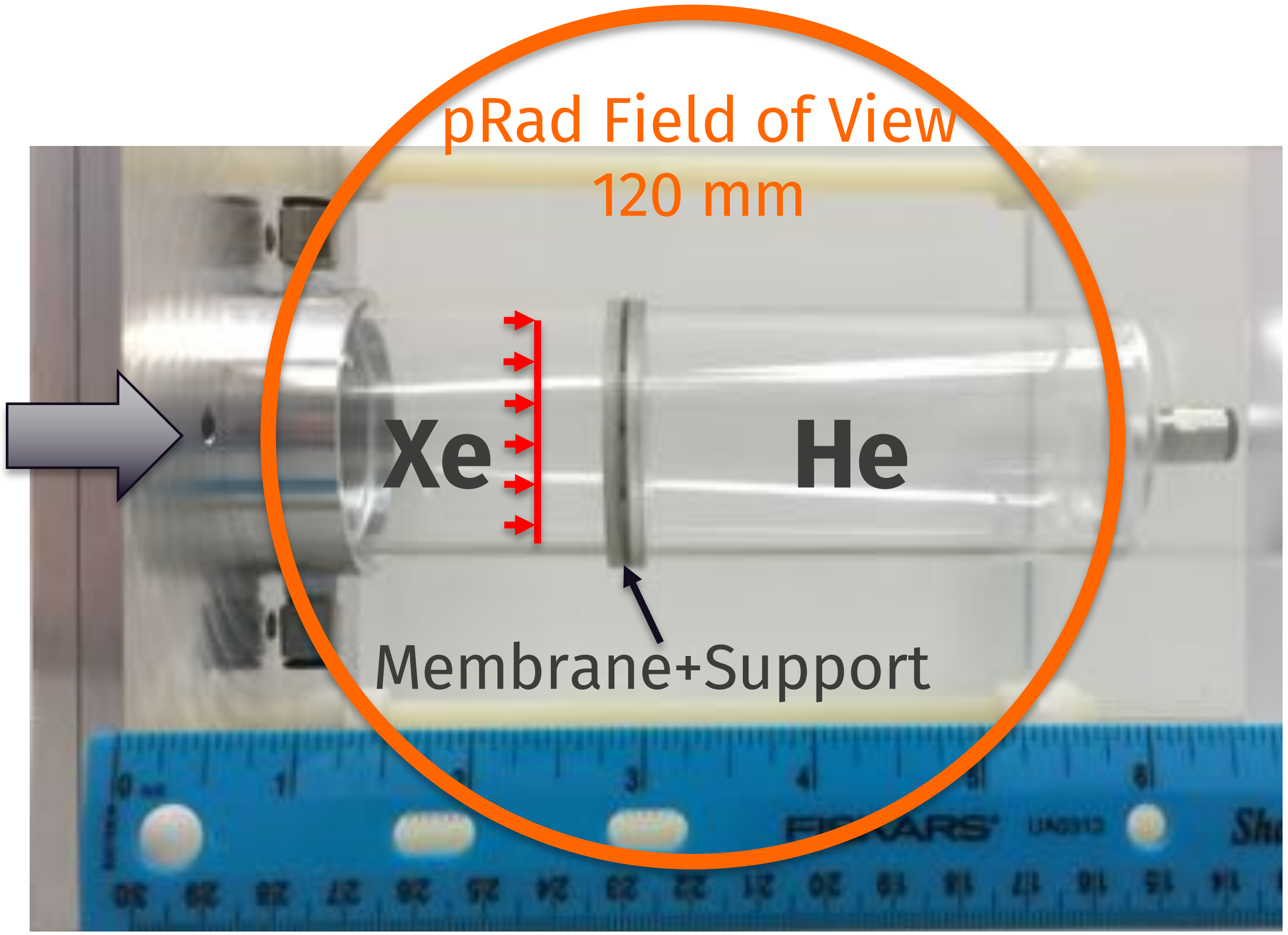


Magnetic lenses focus scattered protons

Proton Radiography:
21 dynamic images (up to 31)
50 ns minimum interframe timing
100 µm spatial resolution
Measurement of areal density

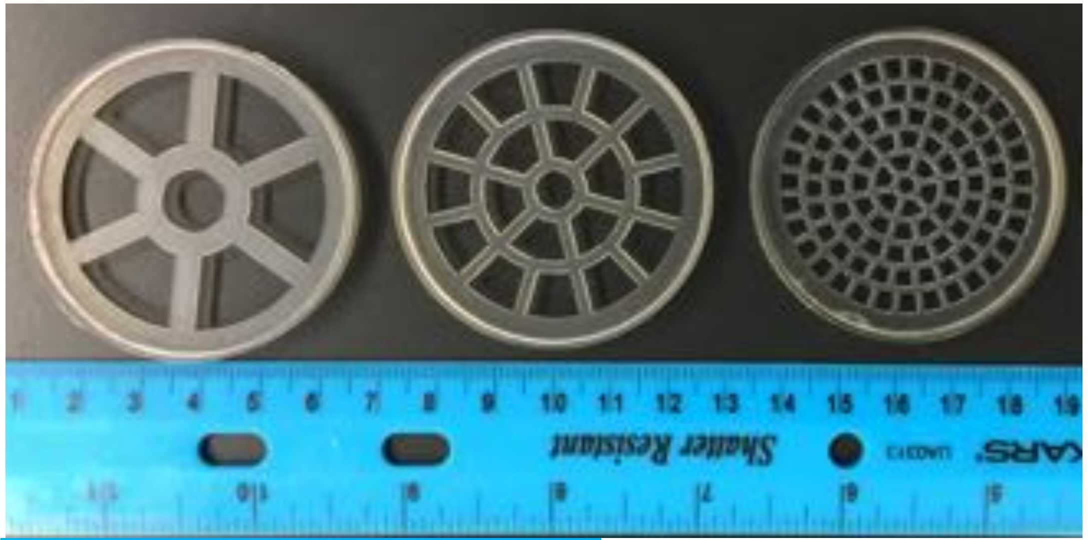
Test section designed to be impacted by gun projectile, and gases chosen to optimize radiography

Flow Conditions:
At=0.94 (xenon/helium)
Mach=8.8 in Xe



Initial Conditions set by membrane supports for each pRad shot

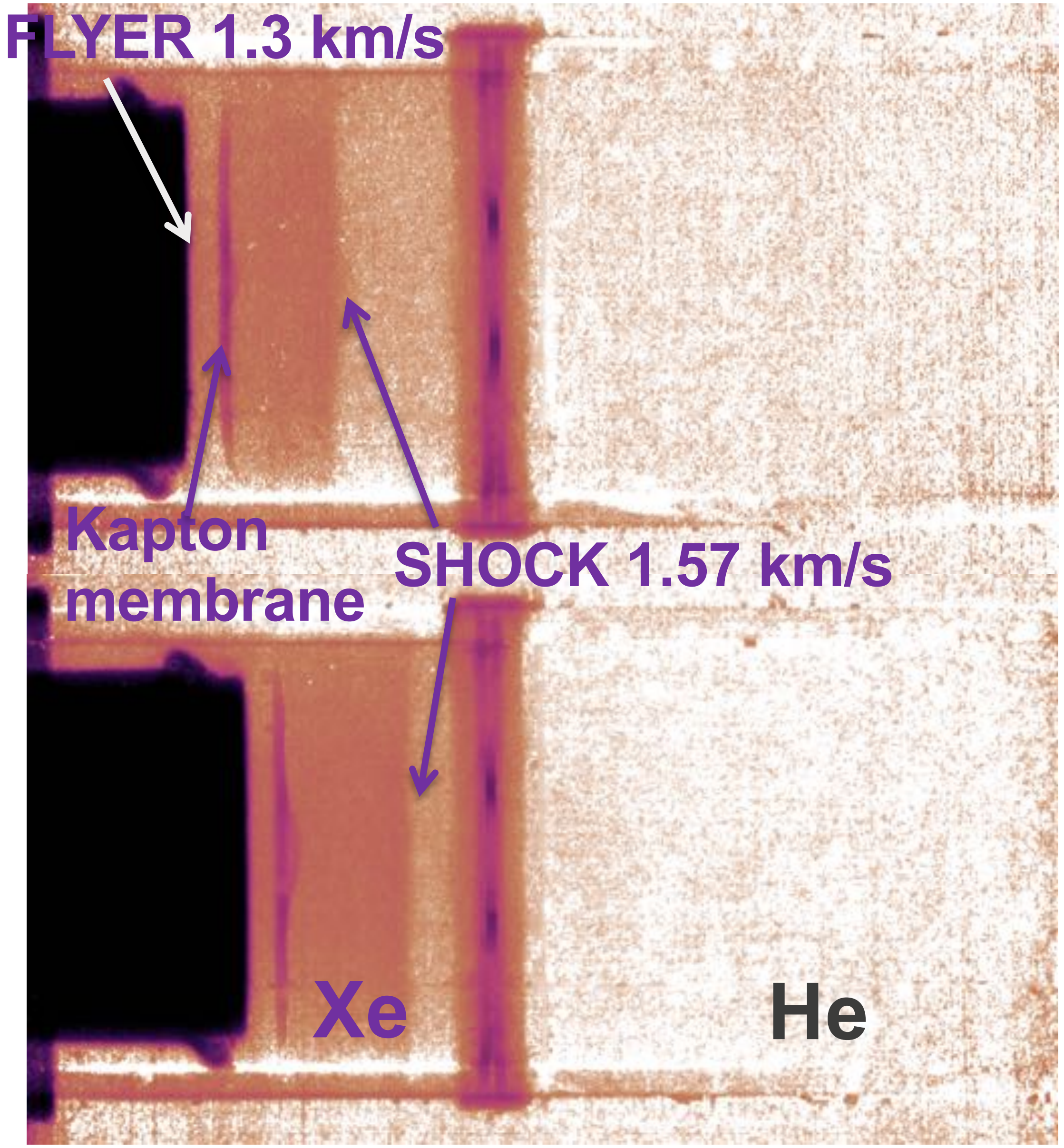
Shot # 680 679 677



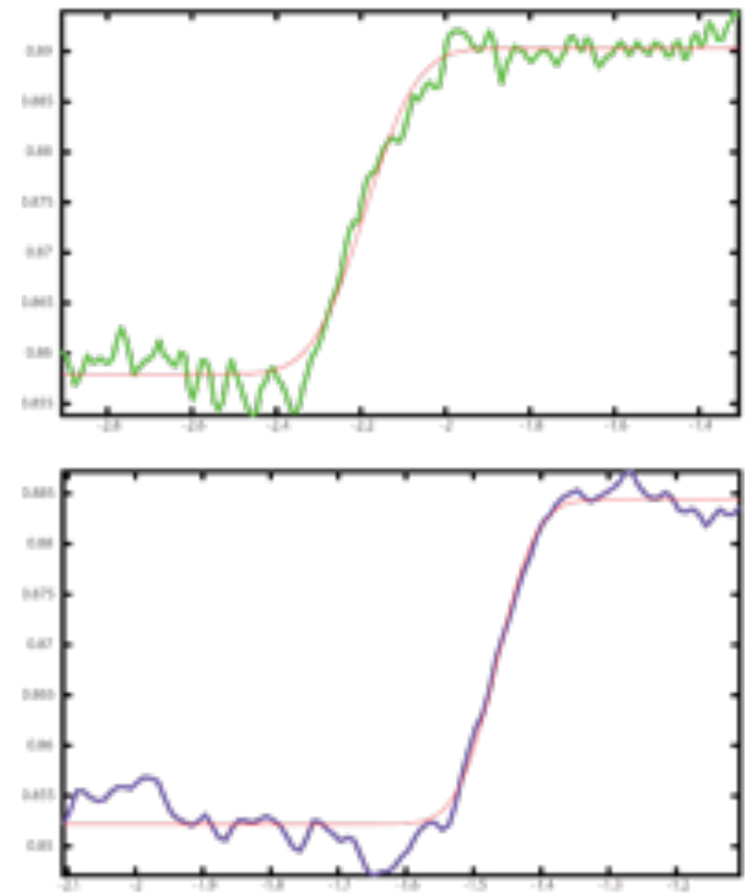
Aluminized Mylar membrane

Goal: Measure time-dependent growth of Xe-He turbulent mixing region

Proton Radiography (pRad) provides a movie of areal density of fast events



Transmission lineouts to determine shock position & speed



$$\frac{\rho_2}{\rho_1} = \frac{(\gamma + 1)\,\mathrm{M}^2}{2 + (\gamma - 1)\,\mathrm{M}^2}$$

$\gamma = 1.651$

$M = 8.78$

$$\frac{\rho_2}{\rho_1} = 3.92$$

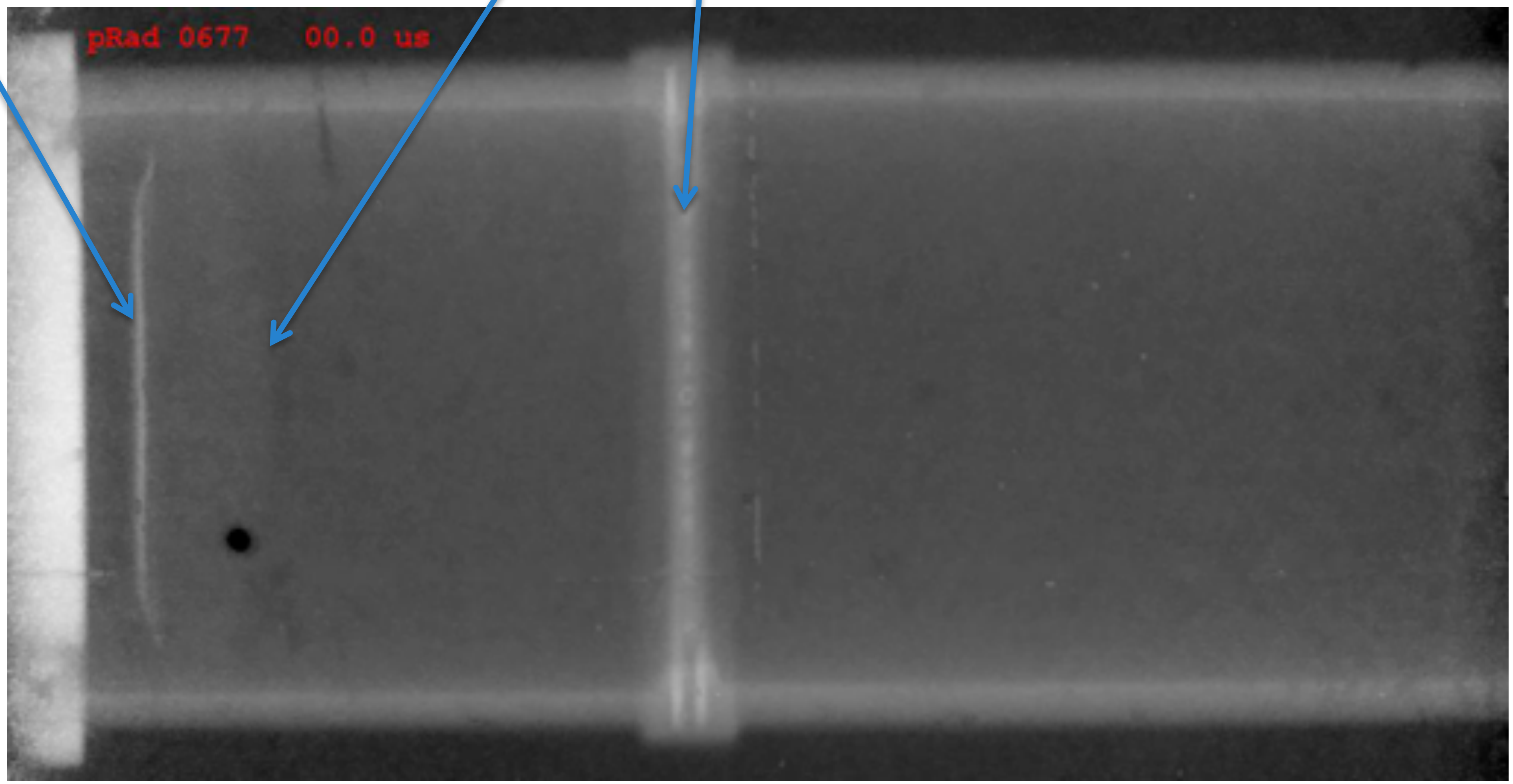
Δt = 5 μs. pRad pulse width=100 ns

Movie from pRad experiment with smallest initial perturbations

Kapton flying in front of projectile

Shock starting to form

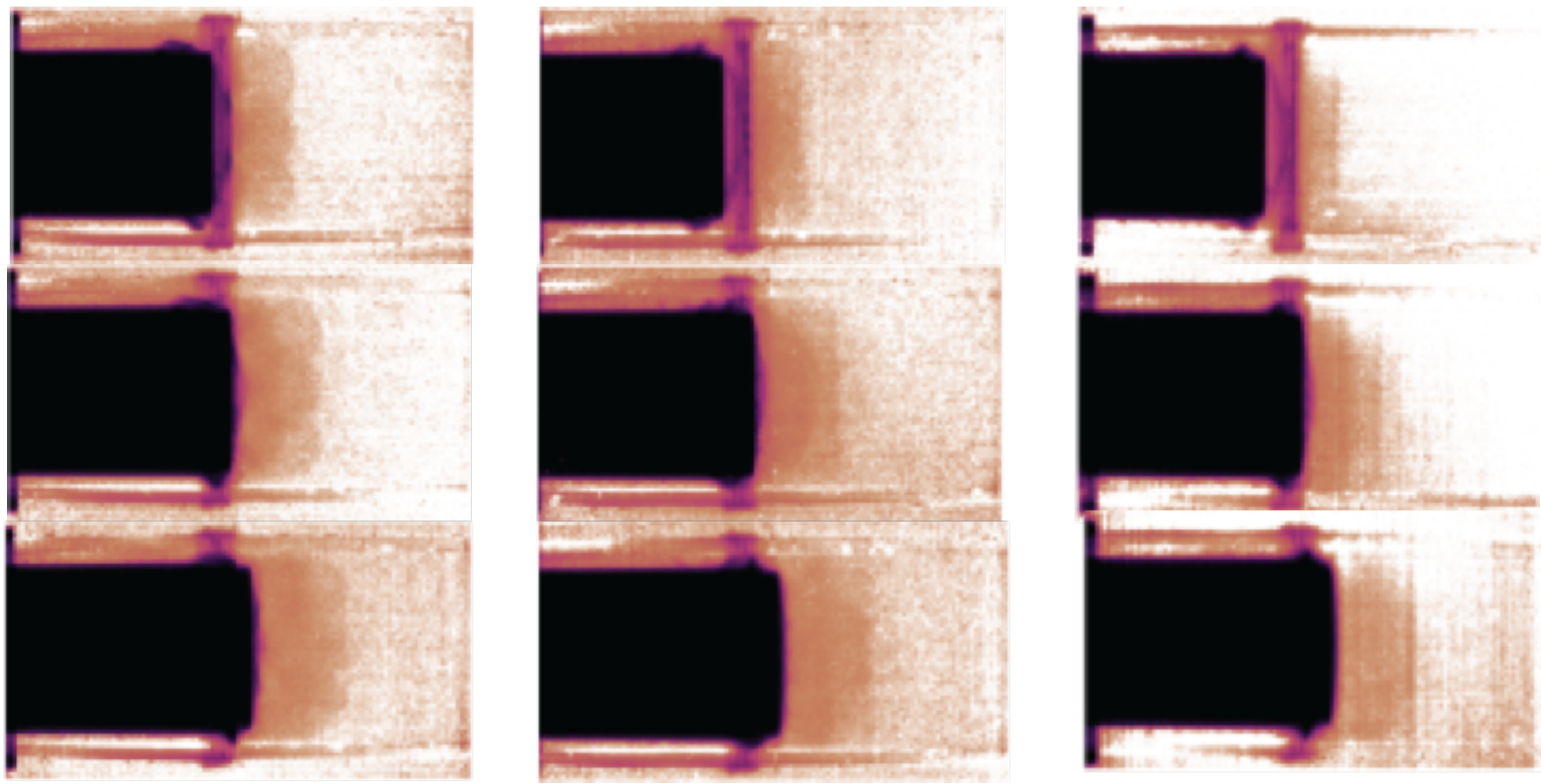
Mylar+Support



Xe

He

Experiments at Mach 8.8 reveal imprint of initial conditions over significant mixing times



11 µs | 10.5 µs

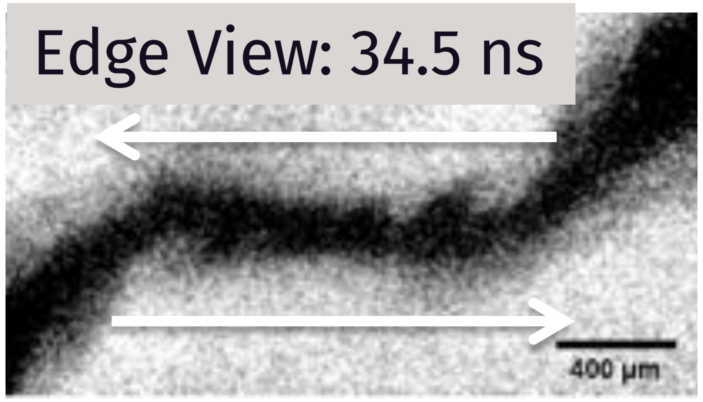
13 µs | 14 µs

17 µs | 17.5 µs

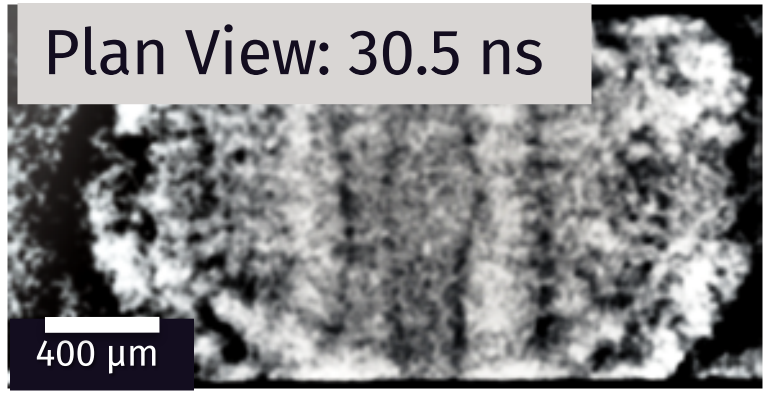
In multiphysics environments, variable-density mixing is important at critical times

Counter-shear of an Al foil turned into a plasma

Edge View: 34.5 ns

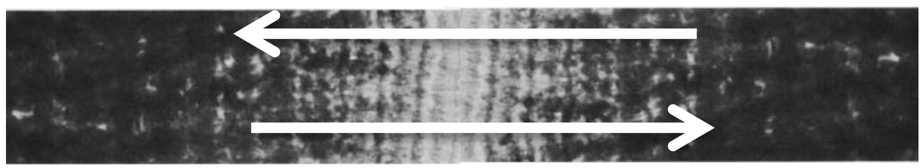


Plan View: 30.5 ns



Flippo et al (2016) *PRL*

Breidenthal (1981) *JFM*

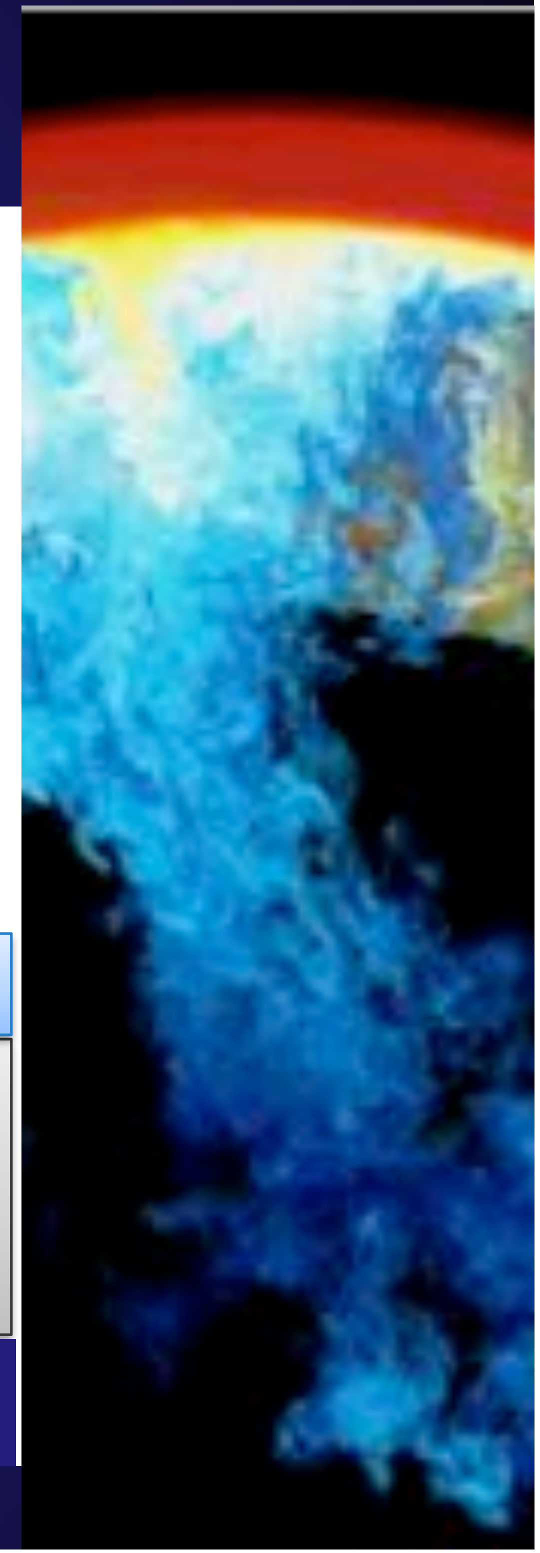


Variable-density jet mixing

Turbulent Mixing Tunnel
At=0.6

He-shell flash convection. Jet into ^{12}C He-burning layers leads to a regime of H-^{12}C combustion.
At≈0.6

Woodward, Herwig, Lin (2013) arXiv:1307.3821

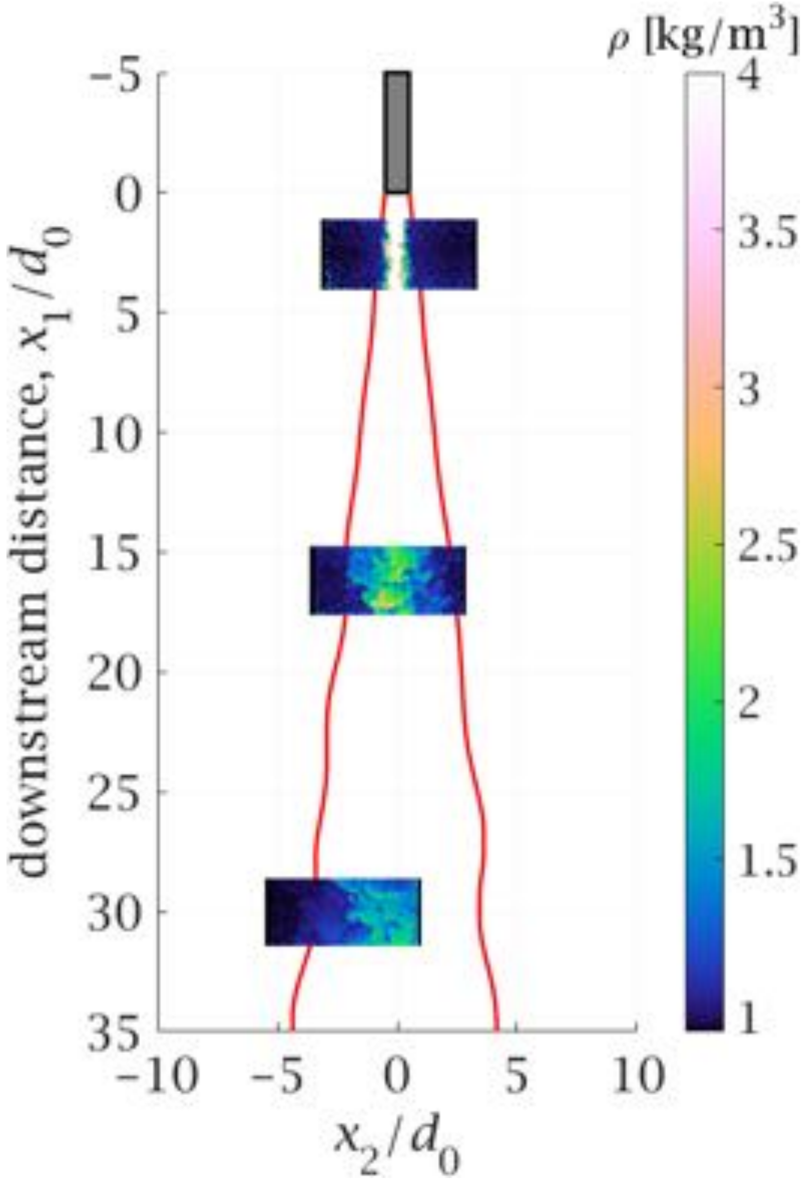


The Turbulent Mixing Tunnel is designed improve our understanding of subsonic variable-density mixing

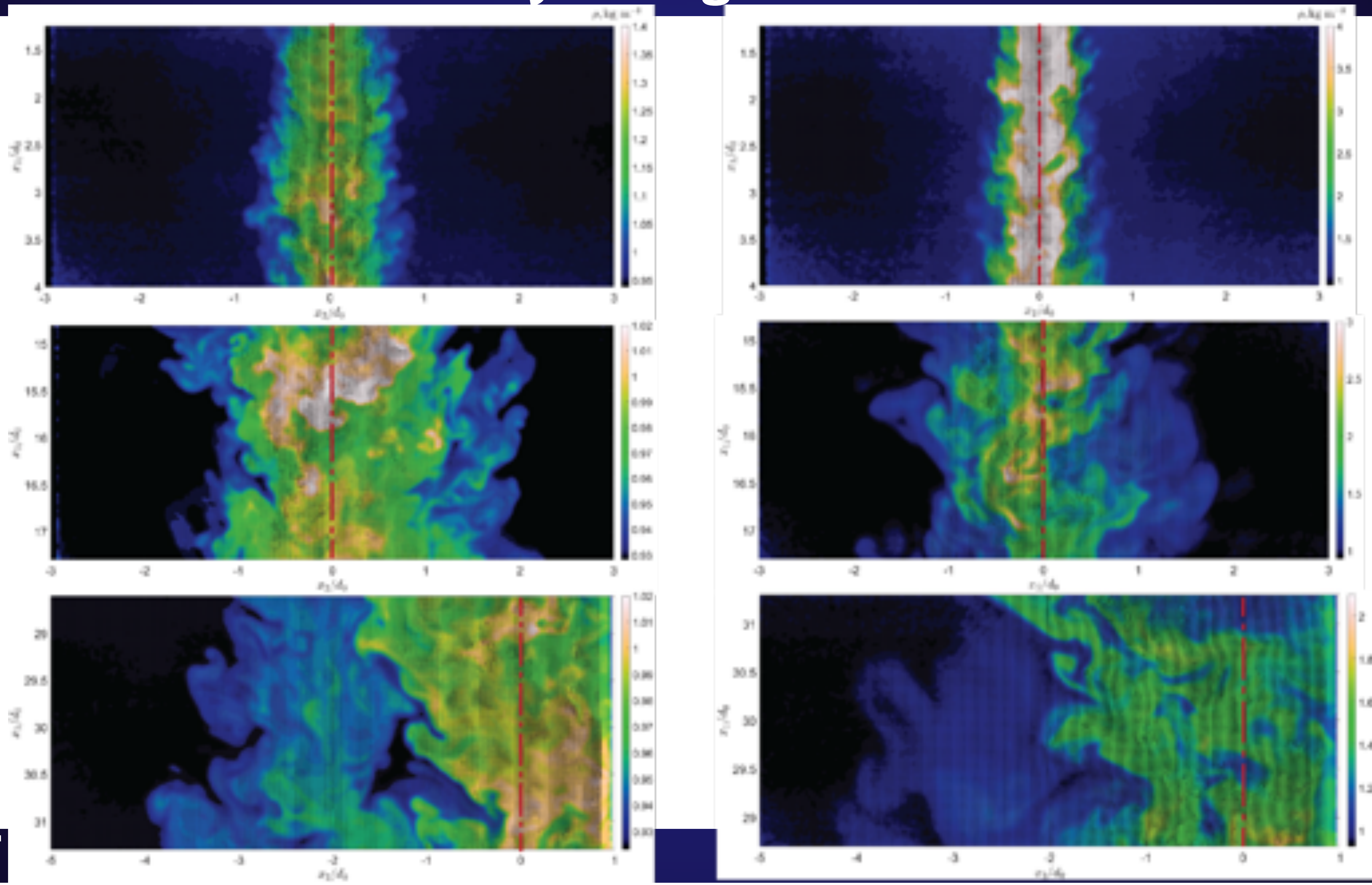
Measurements:
- 10,000 velocity & density fields of the flow per station

Jet conditions:
Re = 20,000
At = 0.1, 0.6
M = .09, .02

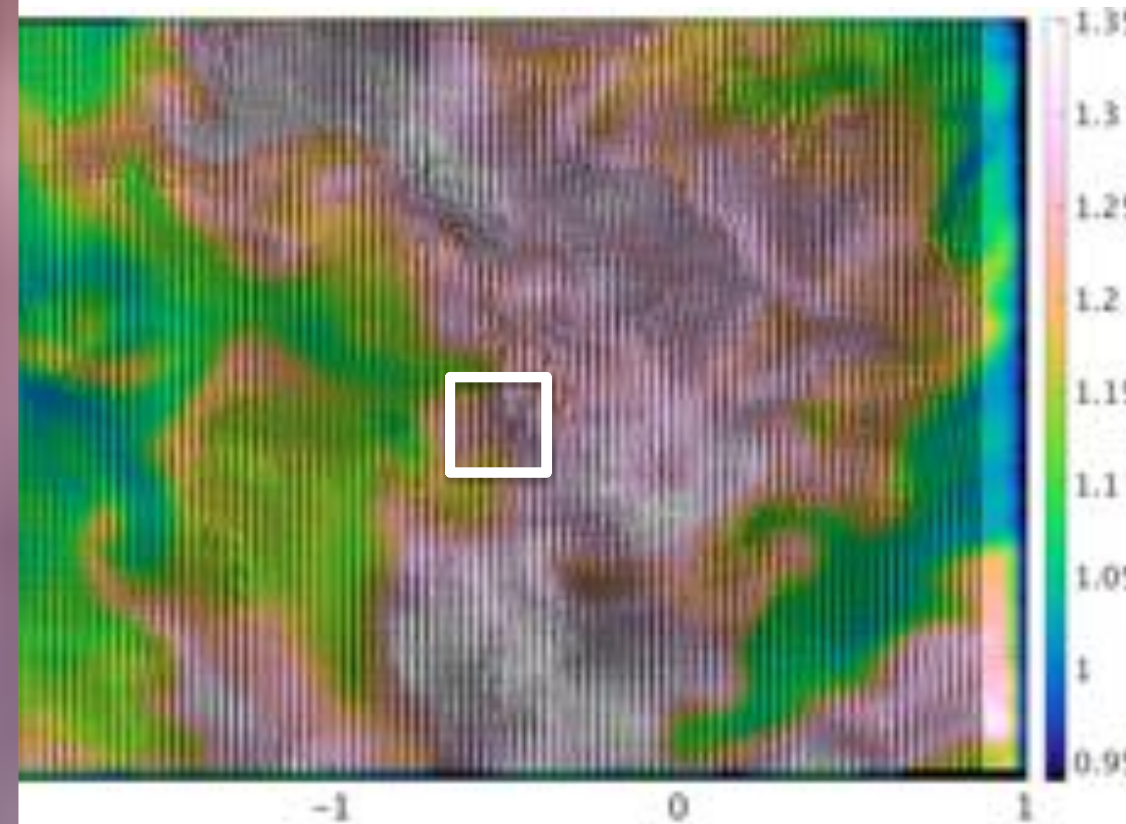
Open-circuit wind tunnel



Air & SF_6 jet turbulence can be compared in shear region and in momentum/buoyant regions



...velocity fields (PLIF/PIV)
...ations per field



Using experimental data, we can calculate quantities such as the turbulent kinetic energy, tke

Advection

$$C^{\tilde{k}} = -\Big[\frac{1}{r}\frac{\partial}{\partial r}(r\overline{\rho}\tilde{k}\tilde{u}_r) + \frac{\partial}{\partial z}(\overline{\rho}\tilde{k}\tilde{u}_z)\Big]$$

Production

$$P^{\tilde{k}} = -\overline{\rho}\Big[\frac{\partial \tilde{u}_r}{\partial r}\tilde{R}_{rr} + \Big(\frac{\partial \tilde{u}_r}{\partial z} + \frac{\partial \tilde{u}_z}{\partial r}\Big)\tilde{R}_{rz} + \frac{\tilde{u}_r}{r}\tilde{R}_{\theta\theta} + \frac{\partial \tilde{u}_z}{\partial z}\tilde{R}_{zz}\Big] + \Big[a_r\frac{\partial \overline{P}}{\partial r} + a_z\frac{\partial \overline{P}}{\partial z}\Big]$$

Transport

$$T^{\tilde{k}} = D^{\tilde{k}} + T_P^{\tilde{k}}$$

Turbulent Flux

$$D^{\tilde{k}} = -\frac{1}{2}\Big[\frac{1}{r}\tilde{R}_{rii} + \frac{\partial}{\partial r}\tilde{R}_{rii} + \frac{\partial}{\partial z}\tilde{R}_{zii}\Big]$$

Pressure Flux (Lumley Model)

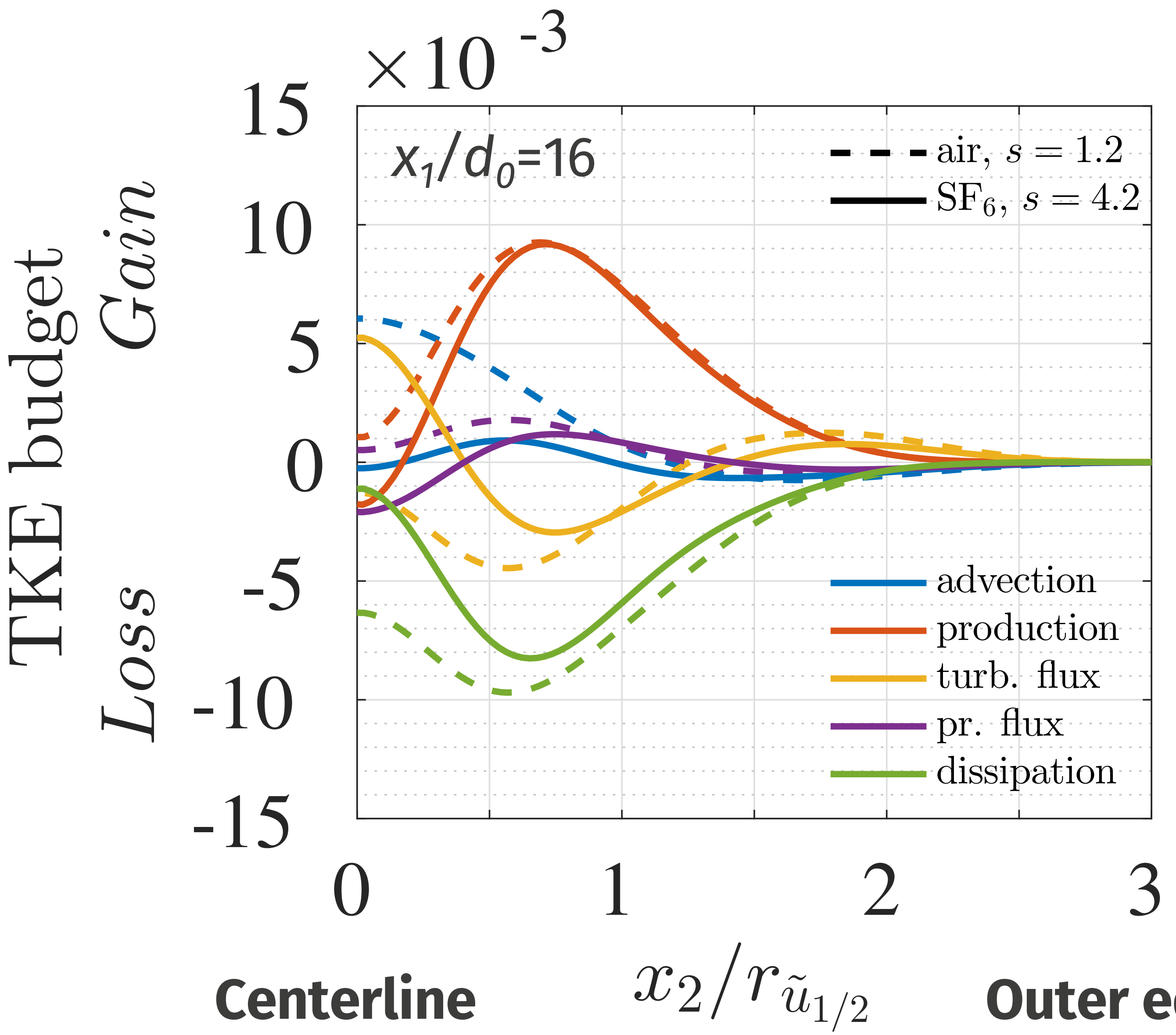
$$T_P^{\tilde{k}} \approx -\frac{2}{5}D^{\tilde{k}}$$

$$\epsilon^{\tilde{k}} \approx -\Big(C^{\tilde{k}} + P^{\tilde{k}} + D^{\tilde{k}} + T_P^{\tilde{k}}\Big)$$

Dissipation (calculated from balance of terms)

Charonko & Prestridge (2017) *JFM*

A comparison of the turbulent kinetic energy terms between the two jets shows spatial variations



Centerline **Outer edge of jet**

Air jet: **Higher advection**
SF_6 jet: **Negative production**
Positive Turbulent Flux

Negative production slows down total energy transfer compared to the Boussinesq (single density) case.

- Simulations will help us understand how this affects the jet behavior

What mechanisms are retarding the energy cascade in the dense jet?

Scale energy at two points: $$\overline{\delta q^2} = \overline{(\delta u_i)^2}$$

Constant density assumptions
i. High Re
ii. Local homogeneity
iii. Local isotropy

Constant density flows: $$\overline{\underline{u_i'^2}} + \overline{\underline{\underline{u_i'^2}}} - 2\overline{\underline{u_i'}\,\underline{\underline{u_i'}}}$$

Variable-density flows: $$\overline{\underline{\rho u_i''^2}} + \overline{\underline{\underline{\rho u_i''^2}}} - \boxed{2\left(\frac{1}{2}\overline{[\underline{\rho} + \underline{\underline{\rho}}]\,\underline{u_i''}\,\underline{\underline{u_i''}}}\right)}$$

Variable-density assumptions
i. Incompressible
ii. No shocks
iii. No magnetic field

Clark (2015), $R_{ij}(x_1,x_2)$

$$\overline{(\delta u_i'')^2_\rho} := \overline{(\underline{u_i''} - \underline{\underline{u_i''}})(\underline{\rho u_i''} - \underline{\underline{\rho u_i''}})}$$

What do the energy transfer terms mean physically?

Π – energy transfer due to local turbulent velocity fluctuations

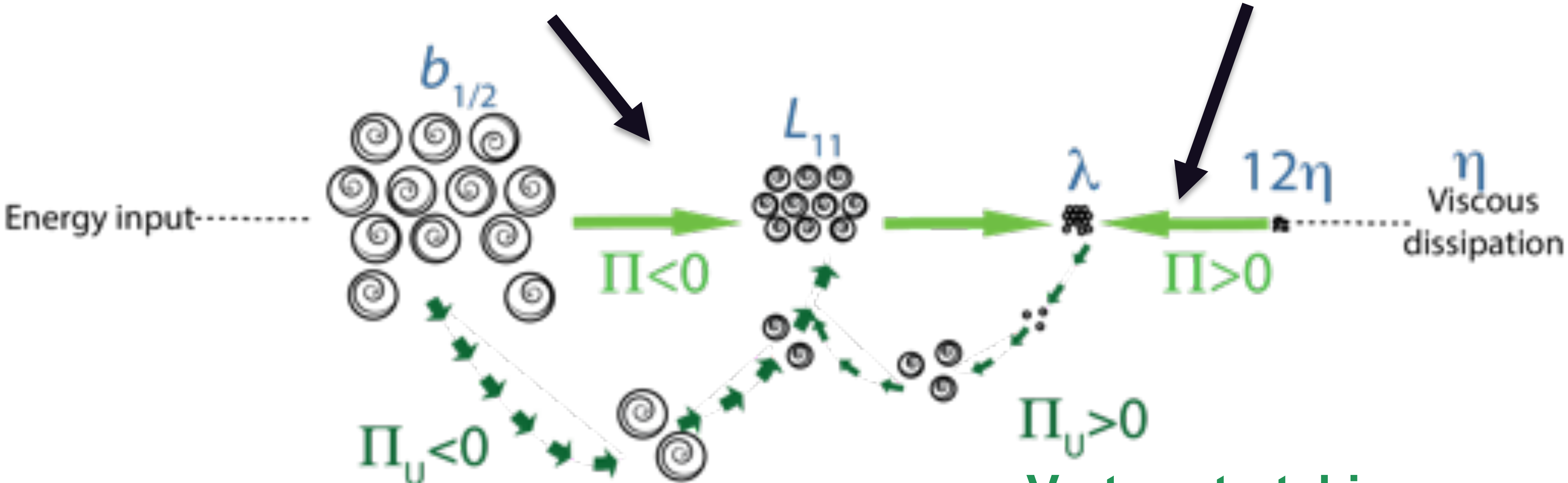
Π_U – energy transfer due to deformation of eddies by mean-flow gradients

$$\boxed{\Pi = \frac{\partial \delta u_k''\overline{(\delta u_i'')^2_\rho}}{\partial r_k}}$$

$$\boxed{\Pi_U = \frac{\partial \delta \widetilde{U}_k\overline{(\delta u_i'')^2_\rho}}{\partial r_k}}$$

Forward turbulent cascade

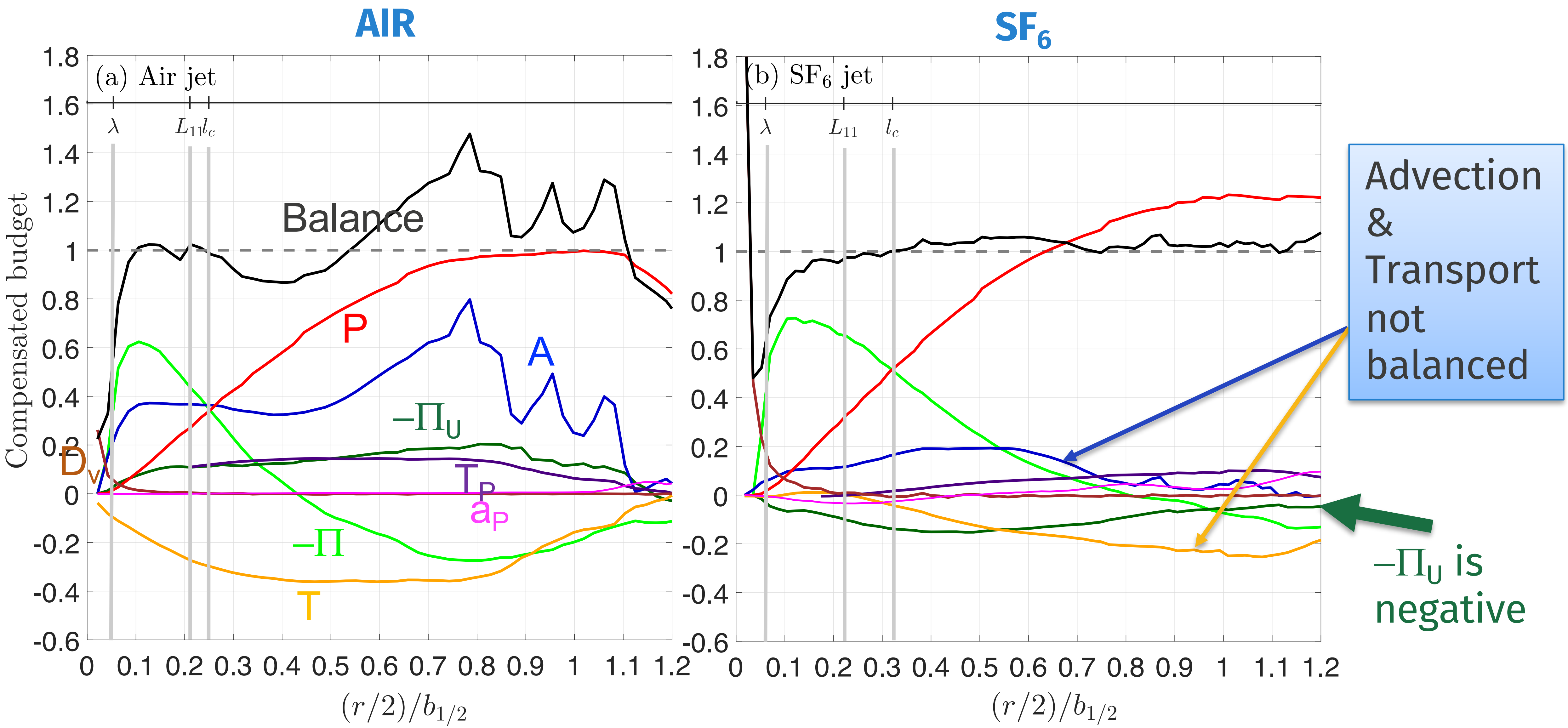
Backscatter



Vortex compression

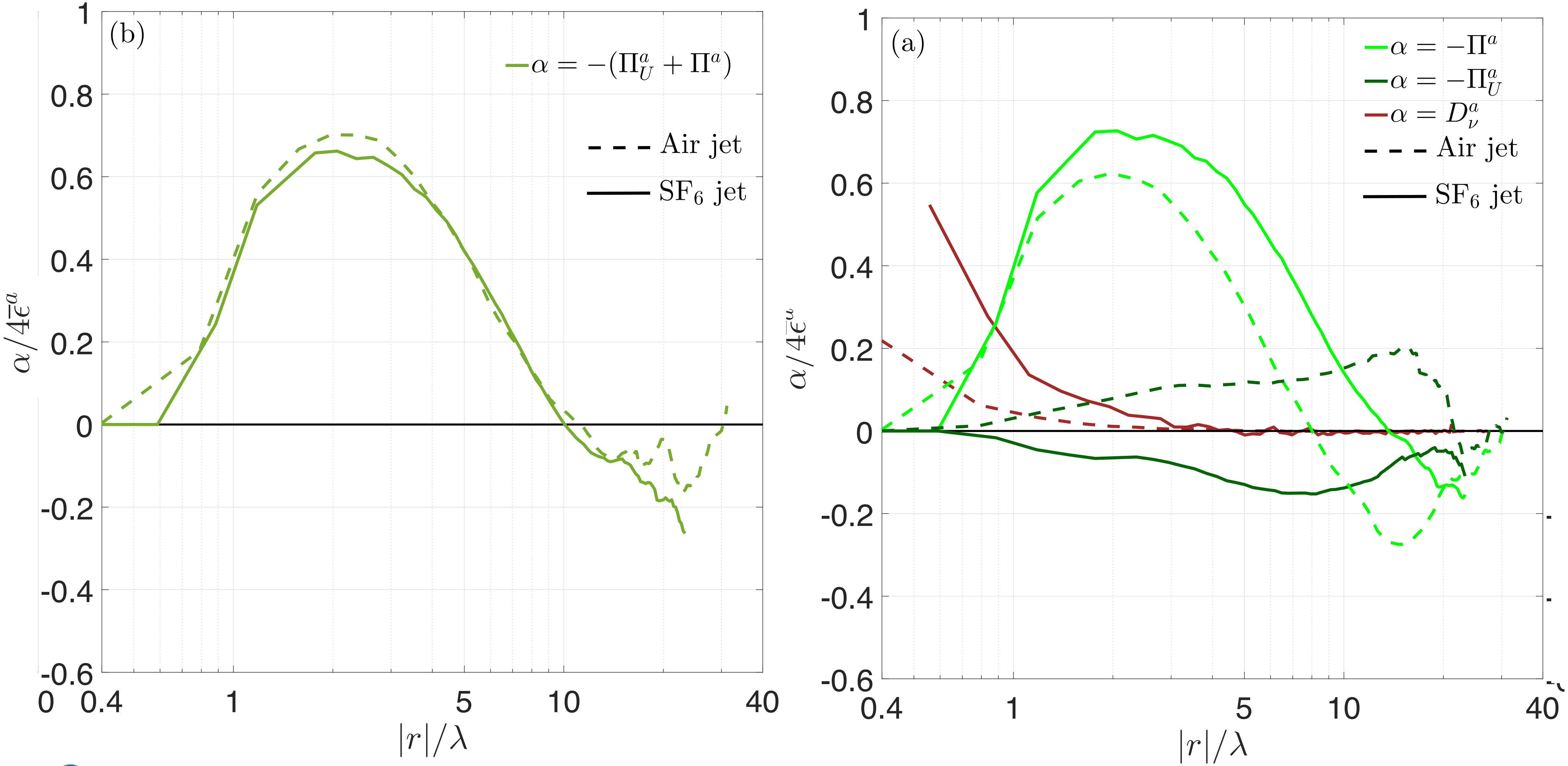
Vortex stretching

The scale-by-scale energy budgets (spherically averaged) show us differences between the two jets

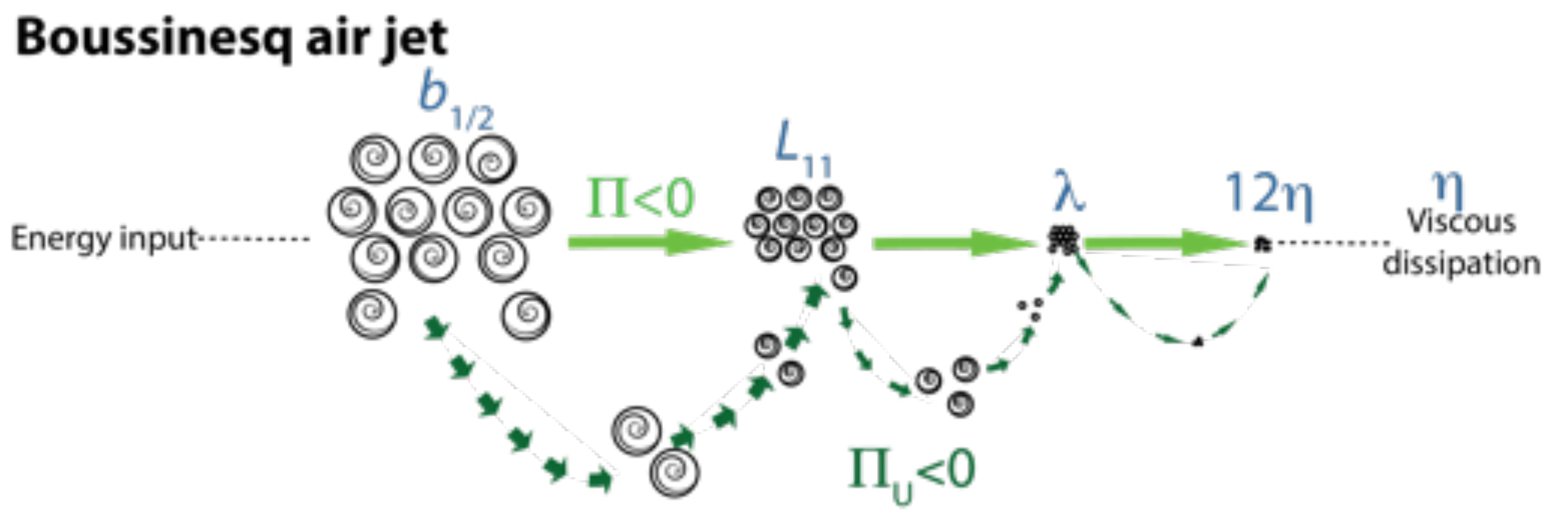


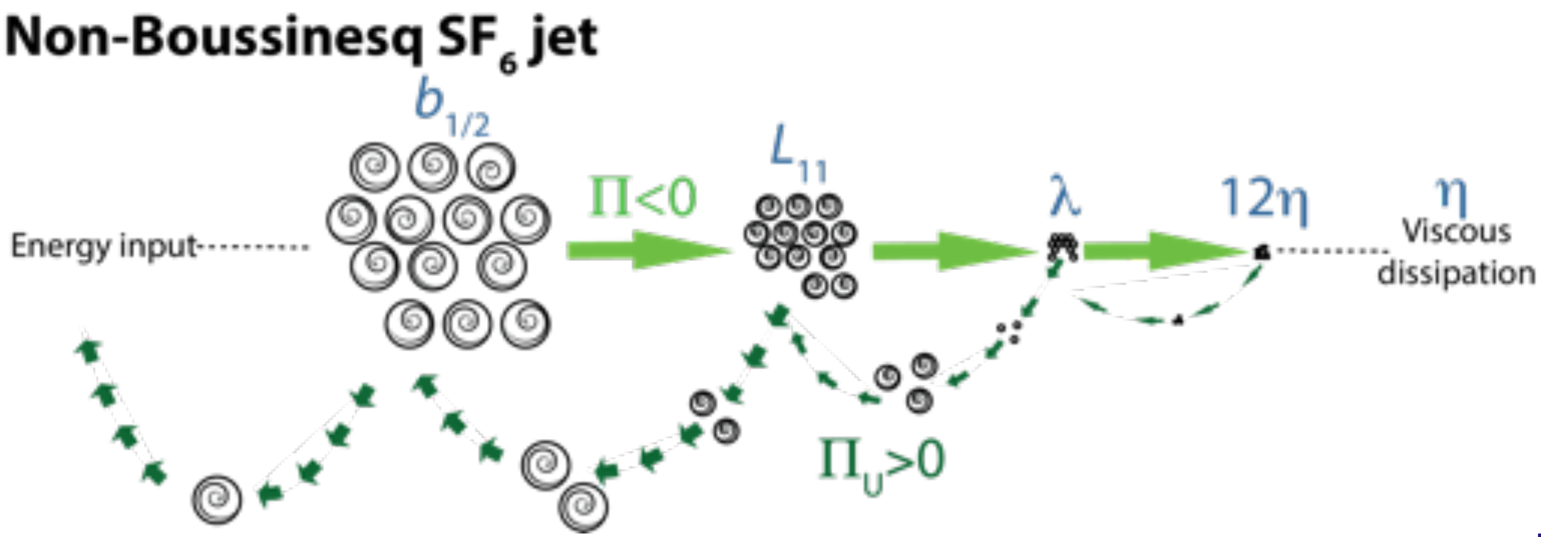
Production **Advection** **Turbulent Transport** **Pressure Transport** **Viscous diffusion** **Mass flux pressure**

The total energy transfer is similar in both jets, but the different mechanisms have modeling implications



SF_6 jet - Π_U (linear interscale energy transfer) strengthens the mean flow by deforming small eddies into larger ones





Boussinesq (air)

$$-(\Pi_U + \Pi) + P \approx \bar{\epsilon}$$

Production at large scales sets dissipation (the turbulent cascade)

Non-Boussinesq (SF_6)

$$-\Pi + P \approx \Pi_U + \bar{\epsilon}$$

Π_U causes energy to move from small to large scales

Lai, Charonko, Prestridge (2018) *JFM*

Exact and modeled terms can be compared using experimental data

$$
\frac{\partial\left(\bar{\rho}\tilde{R}_{ij}\right)}{\partial t}+\frac{\partial}{\partial x_k}\left(\bar{\rho}\tilde{u}_k\tilde{R}_{ij}\right)=\overbrace{a_i\frac{\partial\bar{P}}{\partial x_j}+a_j\frac{\partial\bar{P}}{\partial x_i}-\bar{\rho}\tilde{R}_{ik}\frac{\partial\tilde{u}_j}{\partial x_k}-\bar{\rho}\tilde{R}_{jk}\frac{\partial\tilde{u}_i}{\partial x_k}}^{\text{Production}}-a_i\frac{\partial\tilde{\tau}_{jk}}{x_k}-a_j\frac{\partial\tilde{\tau}_{ik}}{x_k}
$$

$$
\underbrace{-\frac{\partial}{\partial x_k}\overline{\rho u''_i u''_j u''_k}+\frac{\partial}{\partial x_k}\left(\overline{u''_i\tau''_{jk}}+\overline{u''_j\tau''_{ik}}\right)-\frac{\partial}{\partial x_j}\overline{u''_i P'}-\frac{\partial}{\partial x_i}\overline{u''_j P'}}_{\text{Transport}}
$$

$$
\underbrace{+\overline{P'\frac{\partial u''_i}{\partial x_j}}+\overline{P'\frac{\partial u''_j}{\partial x_i}}}_{\text{Pressure Strain}}\underbrace{-\overline{\tau''_{jk}\frac{\partial u''_i}{\partial x_k}}-\overline{\tau''_{ik}\frac{\partial u''_j}{\partial x_k}}}_{\text{Dissipation}}
$$

$$
\frac{\partial\left(\bar{\rho}\tilde{R}_{ij}\right)}{\partial t}+\left(\bar{\rho}\tilde{u}_k\tilde{R}_{ij}\right)_{,k}=\overbrace{\left[a_i\bar{P}_{,j}+a_j\bar{P}_{,i}\right]-\bar{\rho}\left[\tilde{R}_{ik}\tilde{u}_{j,k}+\tilde{R}_{jk}\tilde{u}_{i,k}\right]}^{\text{Production}} \tag{16}
$$

$$
\underbrace{+\frac{C_\mu}{\sigma_k}\left(\bar{\rho}S_T\sqrt{K}\tilde{R}_{ij,k}\right)_{,k}}_{\text{Transport}}\underbrace{-C_{r3}\bar{\rho}\frac{\sqrt{K}}{S_D}\left(\tilde{R}_{ij}-\frac{1}{3}\tilde{R}_{kk}\delta_{ij}\right)}_{\text{Return to Isotropy}}
$$

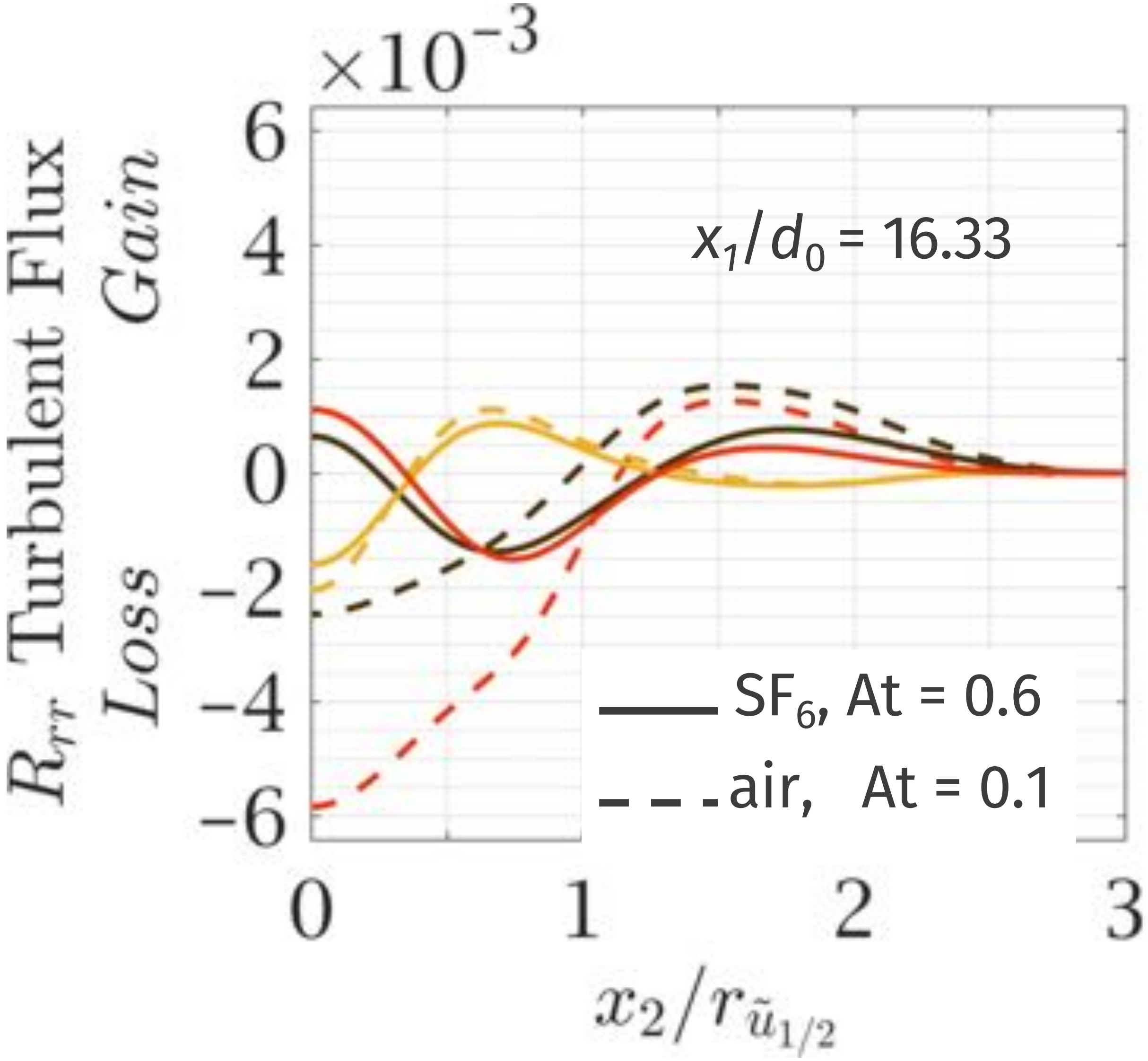
$$
\overbrace{-C_{r1}\left[a_i\bar{P}_{,j}+a_j\bar{P}_{,i}\right]+C_{r2}\bar{\rho}\left[\tilde{R}_{ik}\tilde{u}_{j,k}+\tilde{R}_{jk}\tilde{u}_{i,k}\right]}^{\text{Rapid Distortion}}
$$

$$
\underbrace{-C_{r2}\frac{2}{3}\bar{\rho}\tilde{R}_{mk}\tilde{u}_{m,k}\delta_{ij}+C_{r1}\frac{2}{3}a_k\bar{P}_{,k}\delta_{ij}}_{\text{Rapid Distortion}}\underbrace{-\bar{\rho}\frac{2}{3}\frac{K^{3/2}}{S_D}\delta_{ij}}_{\text{Dissipation}}
$$

- convection
- production
- turb. flux
- pr. flux
- dissipation
- pr. strain

- Formally, the modeled transport term corresponds only to the turbulent flux. Is it correct to lump in the pressure flux?
- The Pressure Strain was computed in the budgets from the balance, assuming isotropic dissipation

Transport: Pressure flux changes the shape (yellow lines)—can't lump pressure and turbulent flux together



Expt: $\boxed{T_{ij}^{\tilde{R}} = D_{ij}^{\tilde{R}}}$

$$\boxed{D_{ij}^{\tilde{R}} = -\frac{\partial}{\partial x_k}\overline{\rho u_i'' u_j'' u_k''}}$$

Expt: $\boxed{T_{ij}^{\tilde{R}} = \boxed{D_{ij}^{\tilde{R}}} + \boxed{\Pi_{ij}^{\tilde{R}}}}$

$$\boxed{\Pi_{ij}^{\tilde{R}} \approx \frac{2}{5}\bar{\rho}\left(\frac{\partial \widetilde{ku_i}}{\partial x_j} + \frac{\partial \widetilde{ku_j}}{\partial x_i}\right) \neq -\frac{2}{5}D_{ij}^{\tilde{R}}}$$

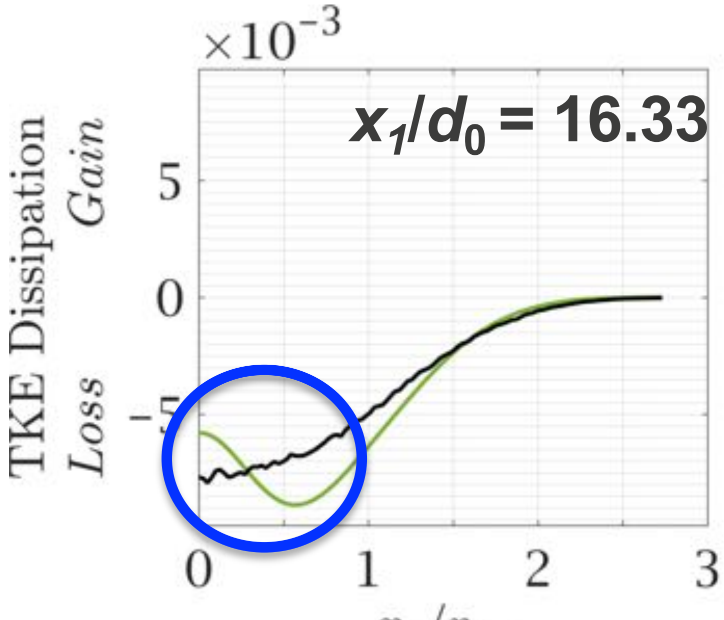
Model: $\boxed{T_{ij}^{\tilde{R}}(\varepsilon_{direct})}$

$$\boxed{T_{ij}^{\tilde{R}} = \boxed{D_{ij}^{\tilde{R}}} + \boxed{\Pi_{ij}^{\tilde{R}}} \approx \boxed{\frac{C_\mu}{\sigma_K}\left(\bar{\rho}S_T\sqrt{K}\tilde{R}_{ij,k}\right)_{,k}}}$$

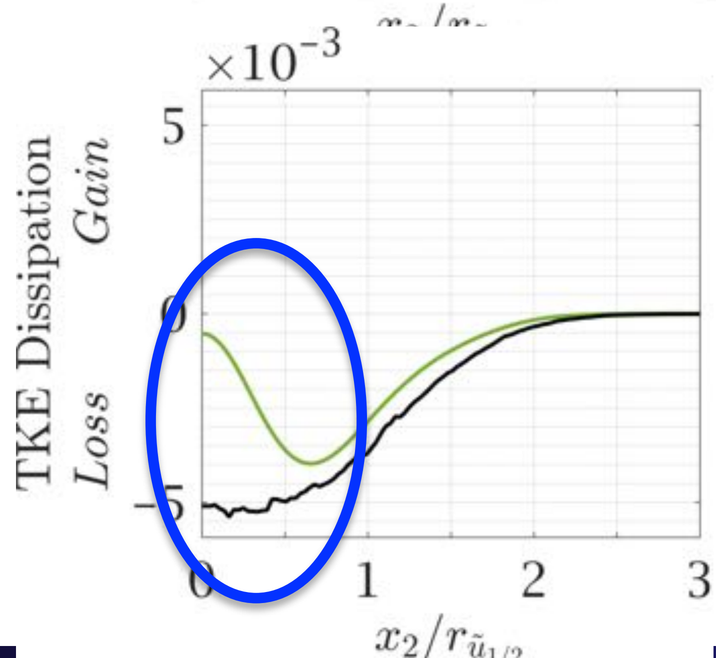
$C_\mu = 0.28$

The jet experiments are helping us identify potential modeling issues with variable-density flows

air
At=0.1
s =1.2



SF_6
At=0.6
s =4.2



t.k.e. dissipation

direct calculation $\varepsilon = -2\mu \overline{\frac{\partial u_i''}{\partial x_j}\frac{\partial u_i''}{\partial x_j}}$

energy balance $\varepsilon = -(C + P + D + \boxed{T_P})$

The **pressure flux** term in the **energy balance** is modeled from **turbulent flux**:

$$\boxed{T_P = -\frac{\partial}{\partial x_i}\overline{u_i'' P'} \approx} -\frac{2}{5}\boxed{\mathrm{D}}$$

Lumley's pressure flux model is not matching measured dissipation when density gradients are large

Lab-scale variable-density mixing experiments help us understand how to better model mixing

- What we know:
  - Mixing and turbulence applications require some sort of model for scales that aren't resolved in the simulations
  - Physical mechanisms—and the length scales at which they occur--are important to understand and model

- What we don't know:
  - How to best model pressure flux in variable-density flows!
  - How to incorporate initial conditions effects in shock-driven flows
  - How to incorporate energy transfer from small to large scales into subgrid models
  - How important all of these effects are for specific applications!