Quantification of normal and oblique shock-driven phase interaction and transition to turbulence in media with multiscale density interfaces

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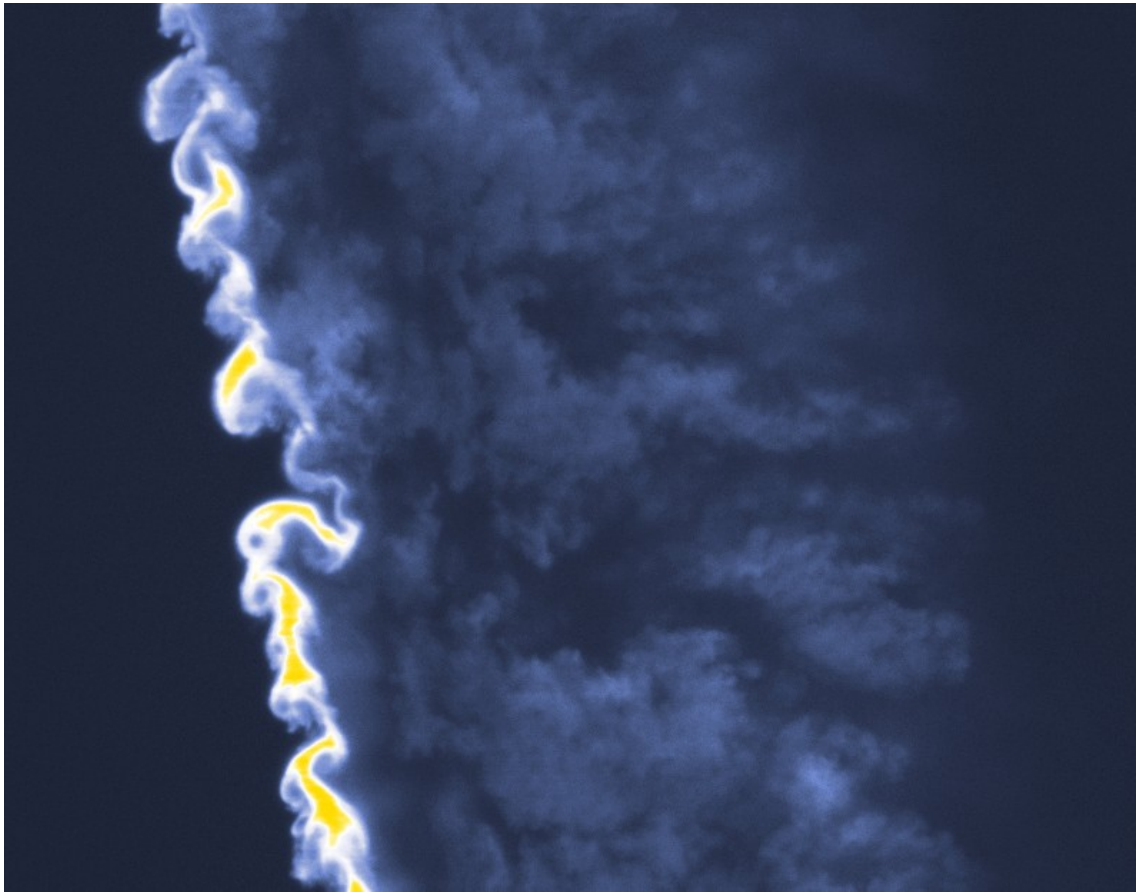
- Setup and flow visualization
- Historic digression: spectra and structure functions
- Mixing studies



Driver Section
Gas and droplet injection
Driven
Camera
Control Console
Test Section
Visualization lasers
Run-off

Test section schematic

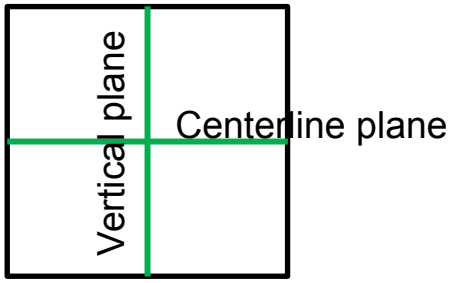
- Experimental parameters
  - Mach number *M*
  - Atwood number *A*

$$A = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$$

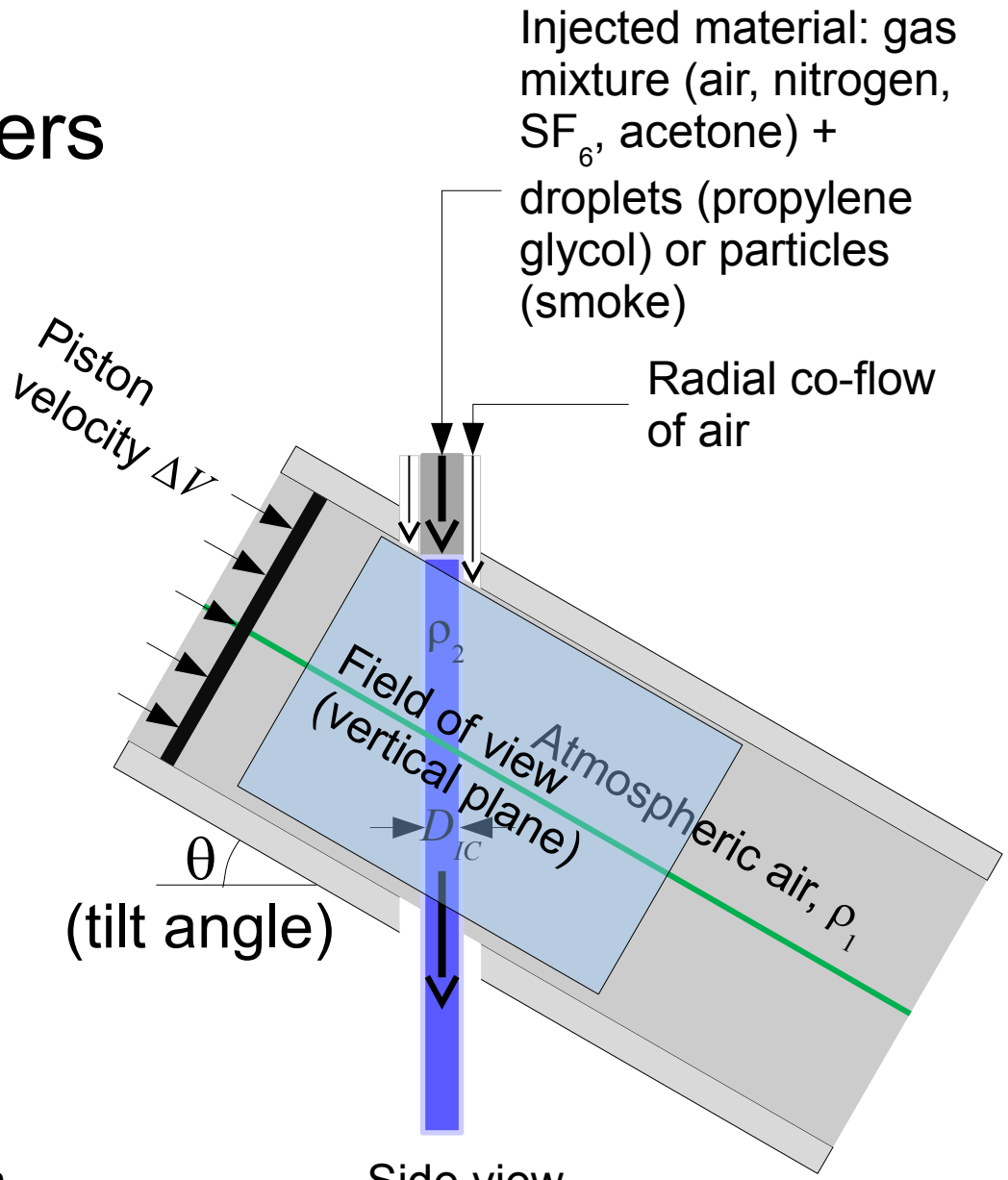
  - Dimensionless time τ

$$\tau = \frac{2\pi}{D_{IC}} A \Delta V t$$

- Two imaging planes



View of cross-section from downstream

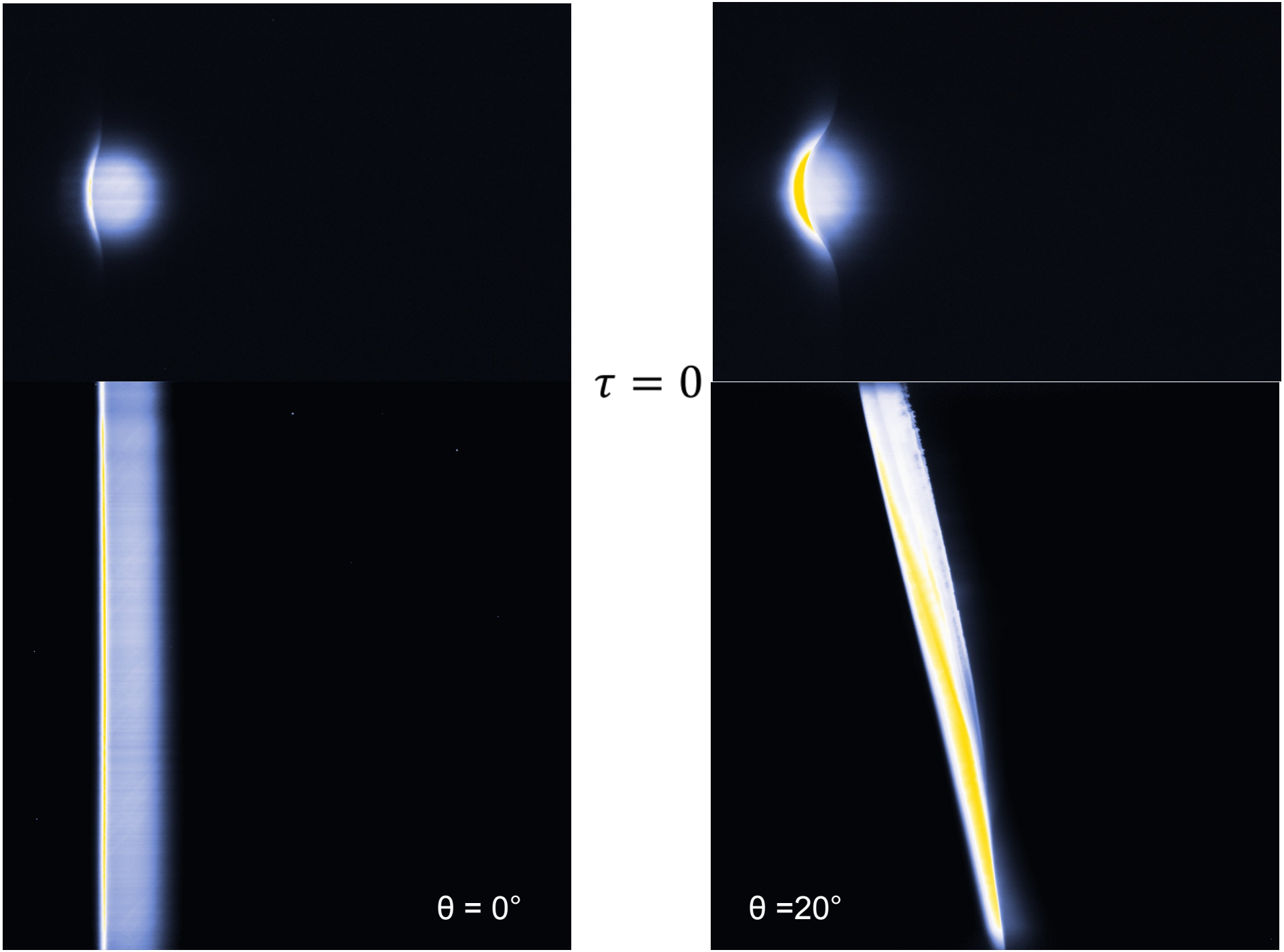


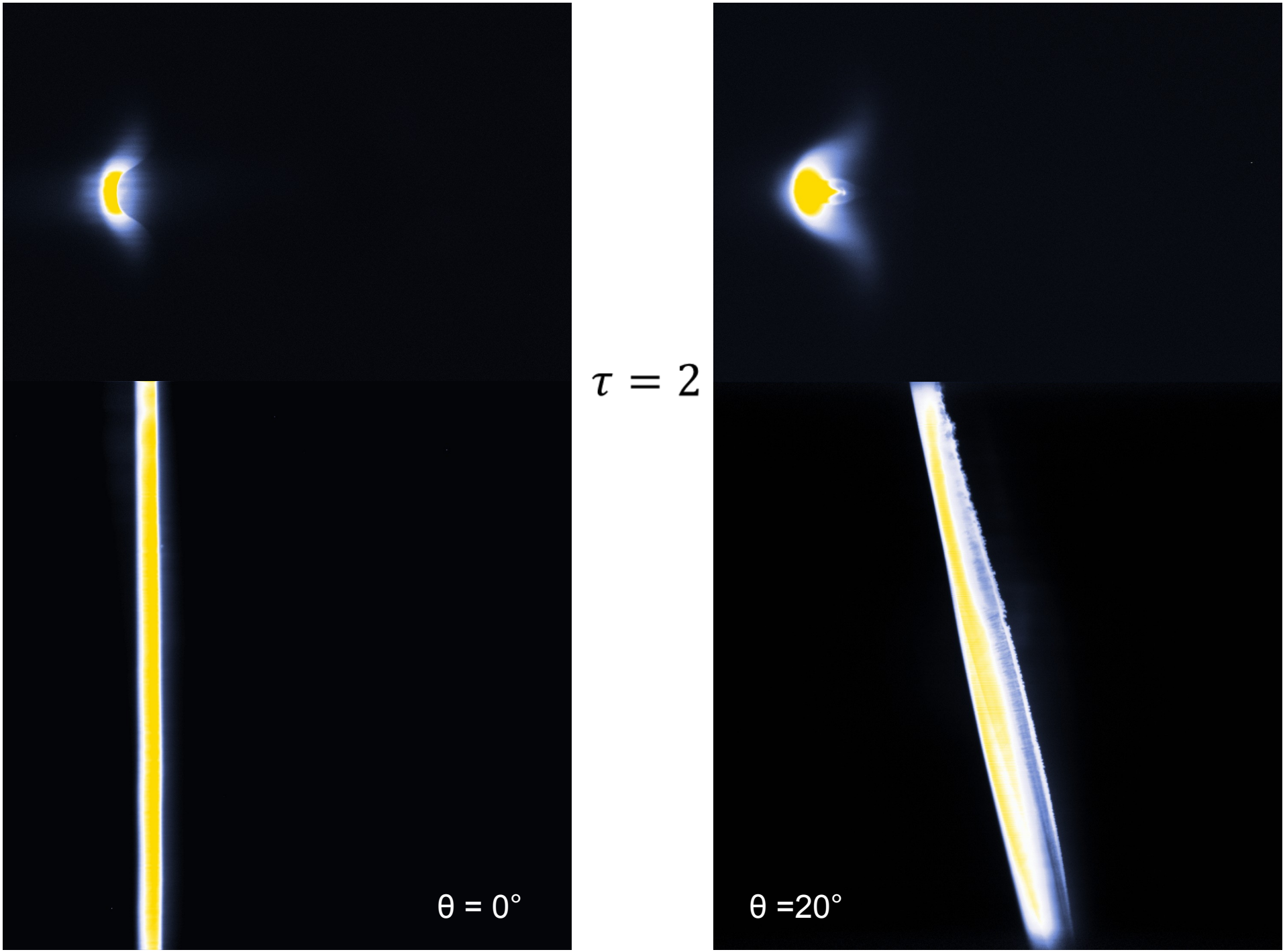
Side view

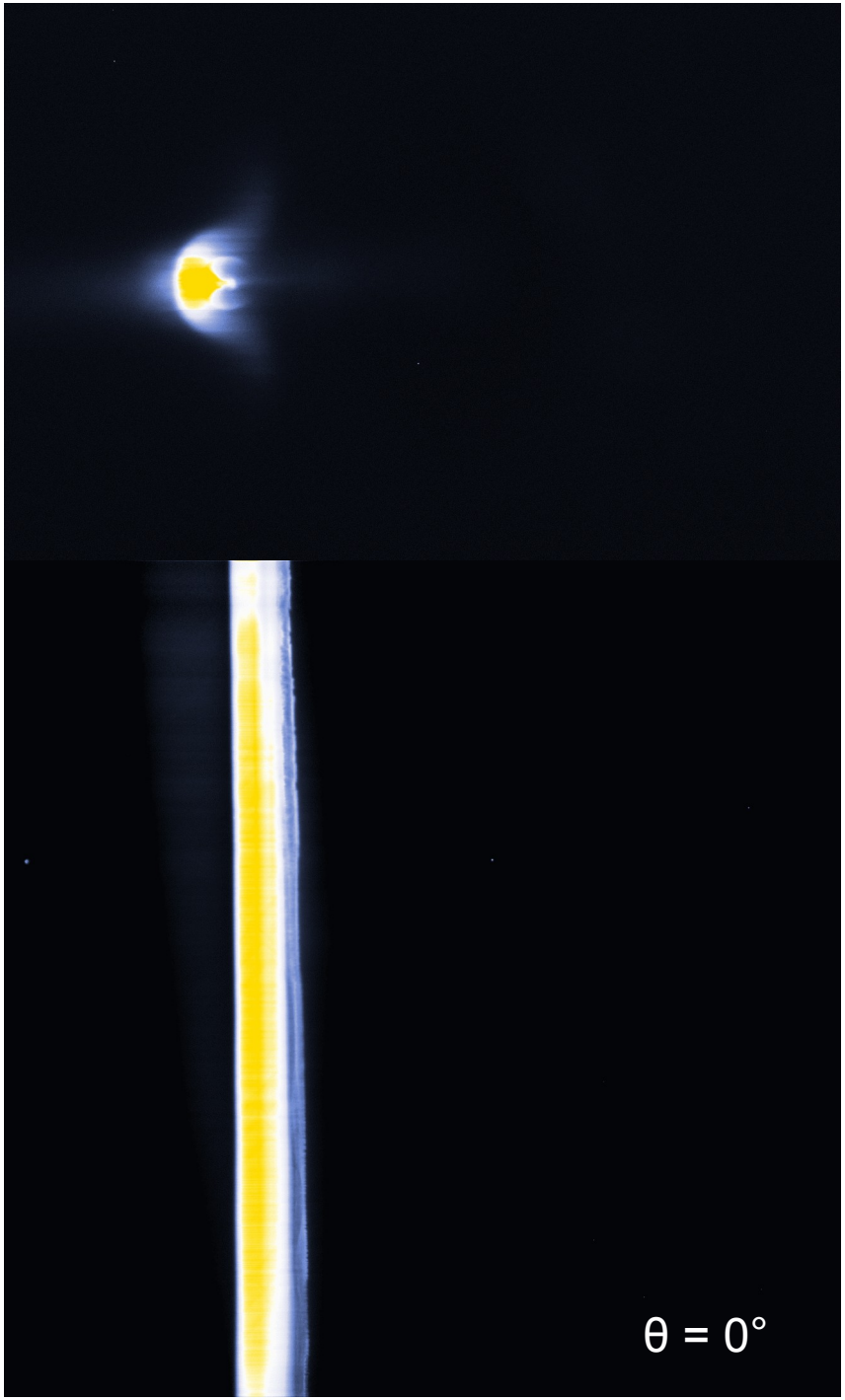
A wee image sequence

Planar ($\theta = 0$) vs. oblique ($\theta = 20°$) shock,
$M = 2$, $A = 0.6$

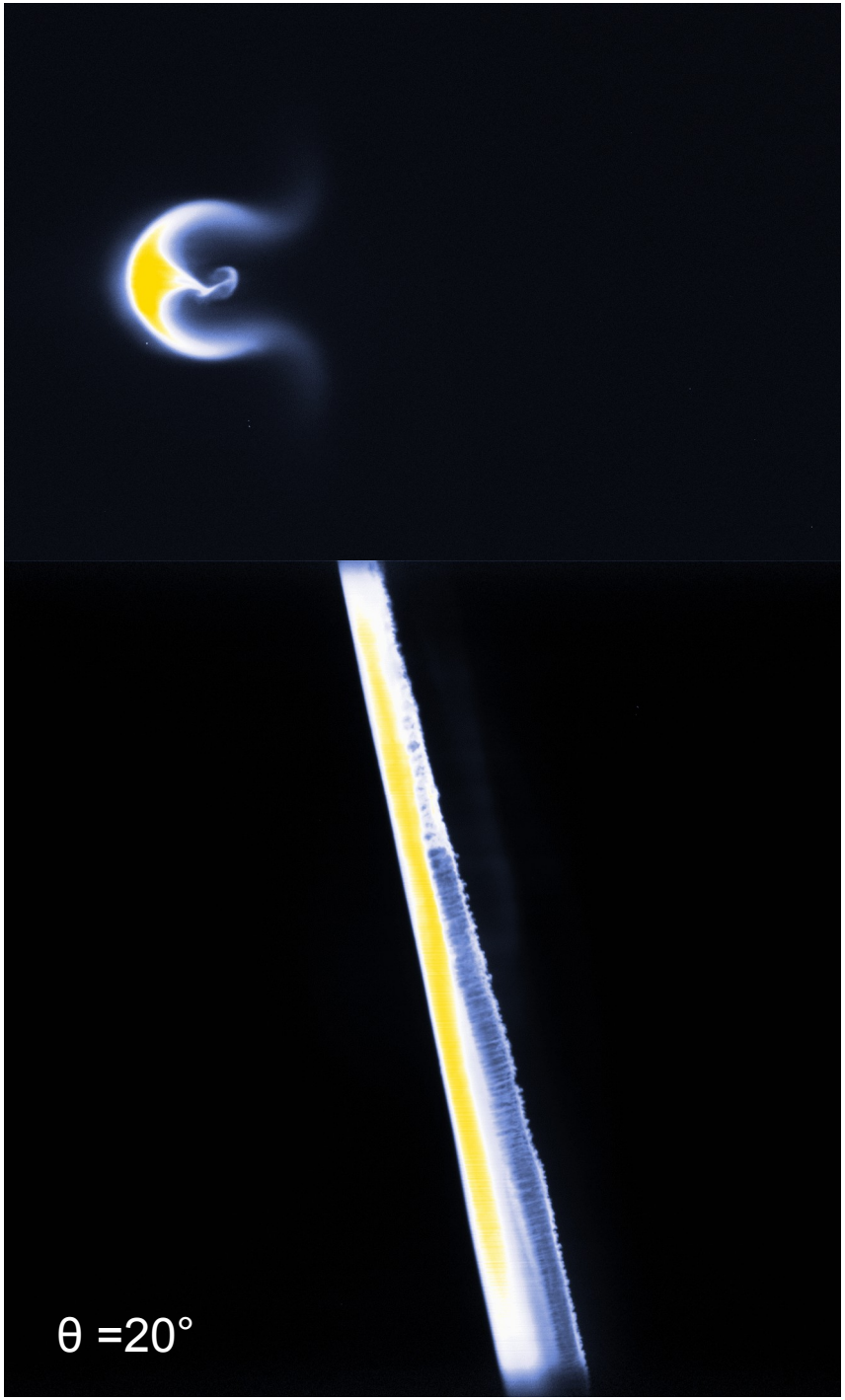
Visualization:
planar laser-induced fluorescence in acetone tagging SF_6

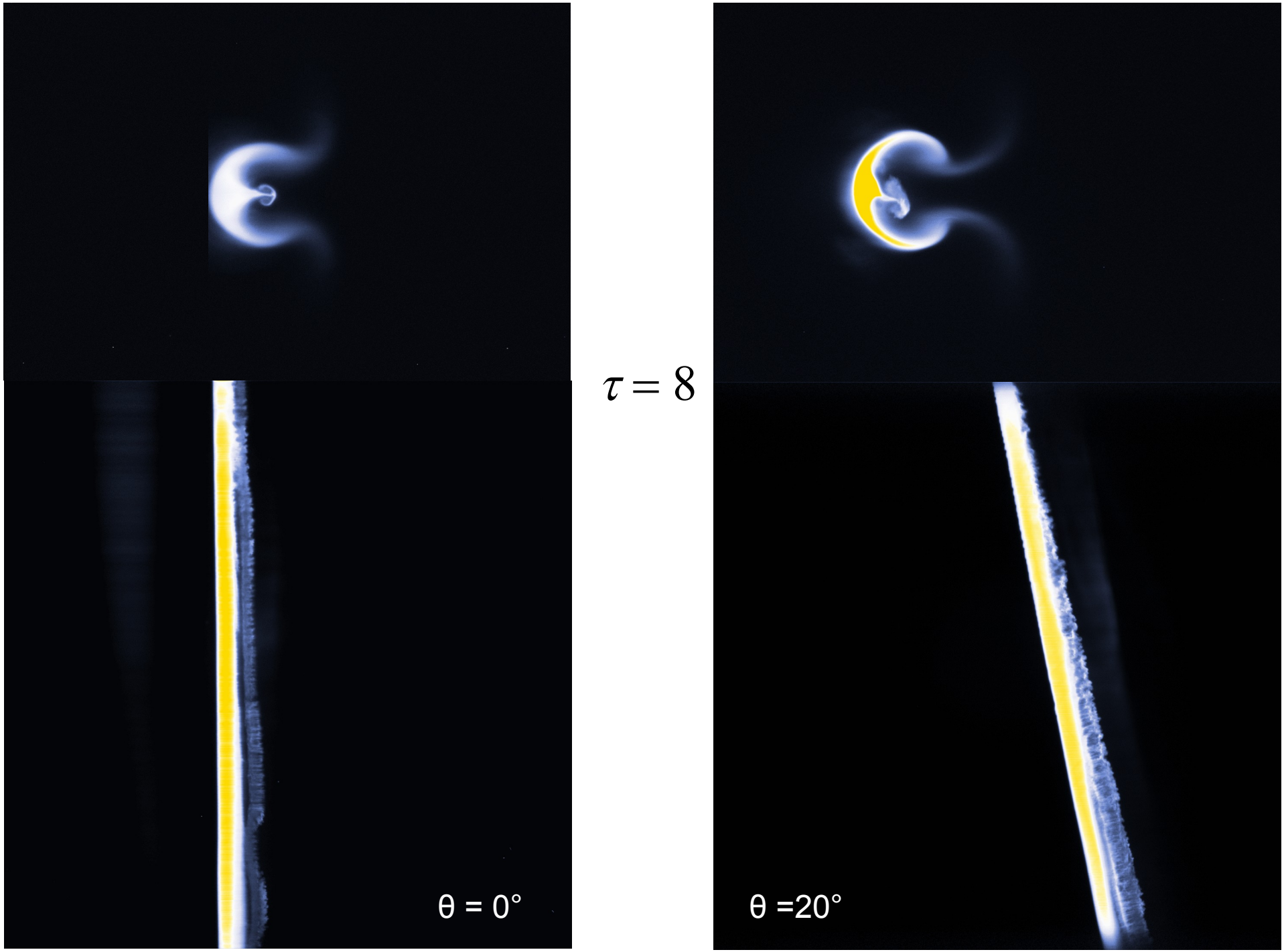

$\tau = 0$
θ = 0°
θ =20°

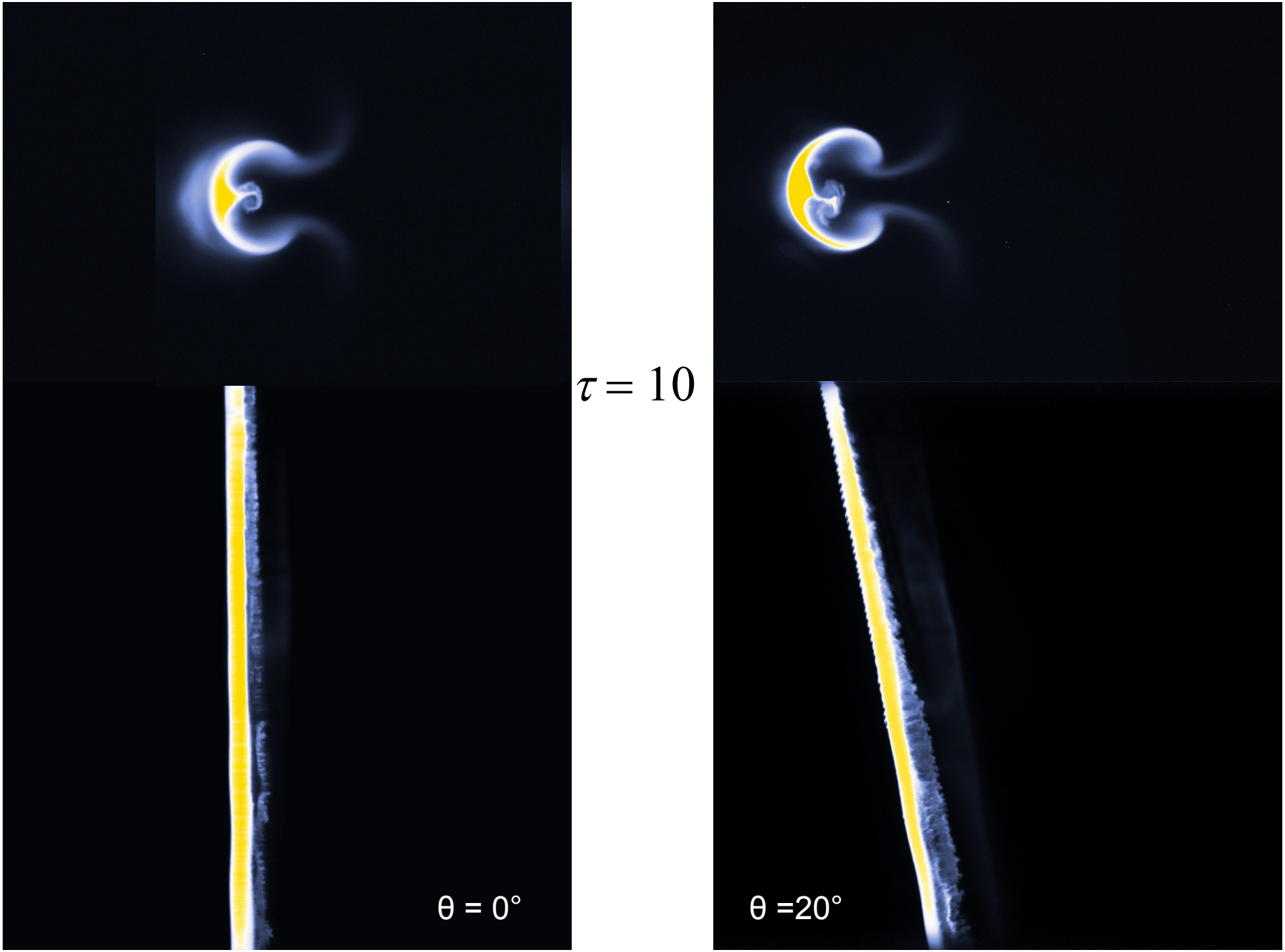

$\tau = 2$
θ = 0°
θ =20°

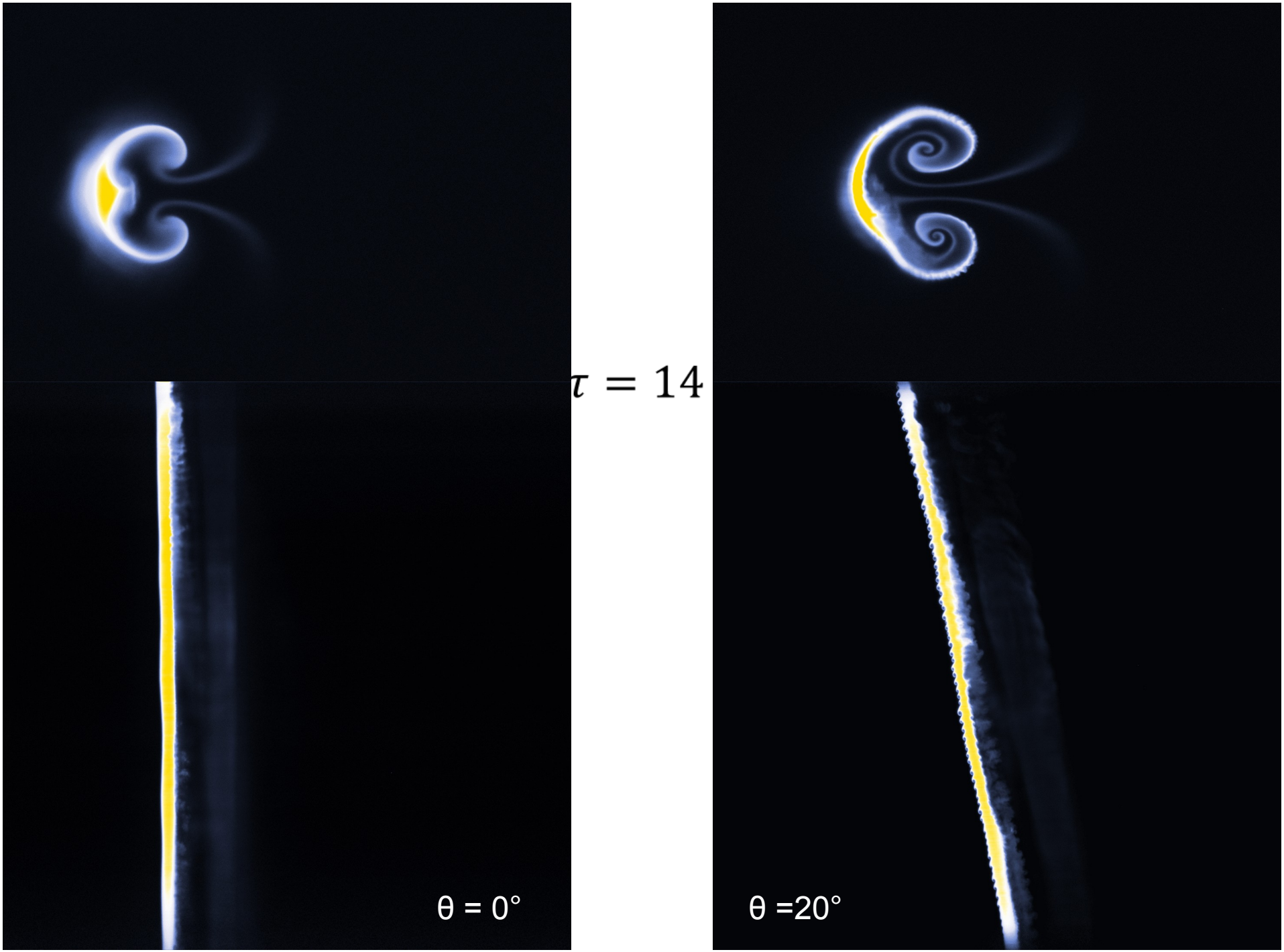


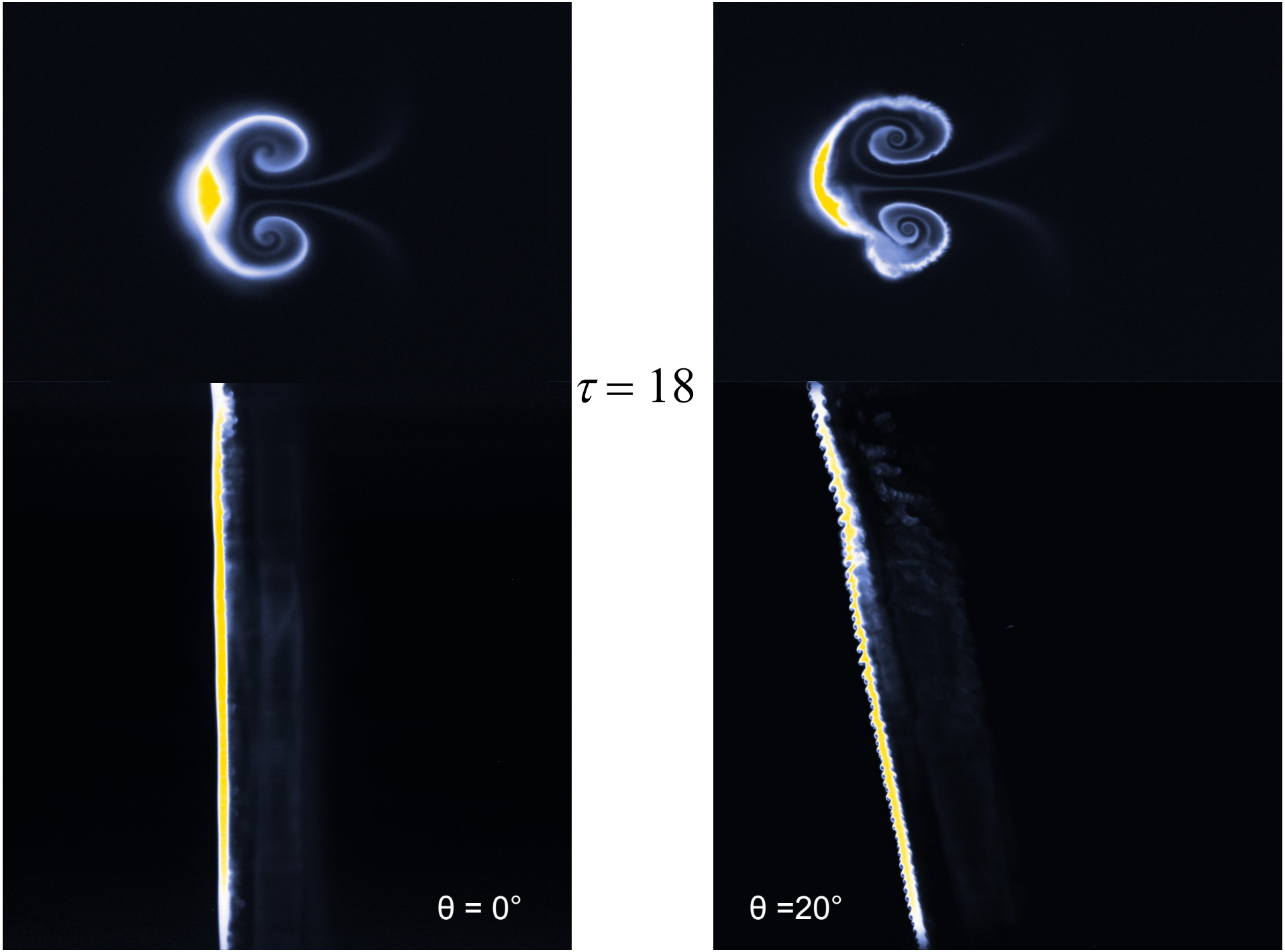
$\tau = 4$

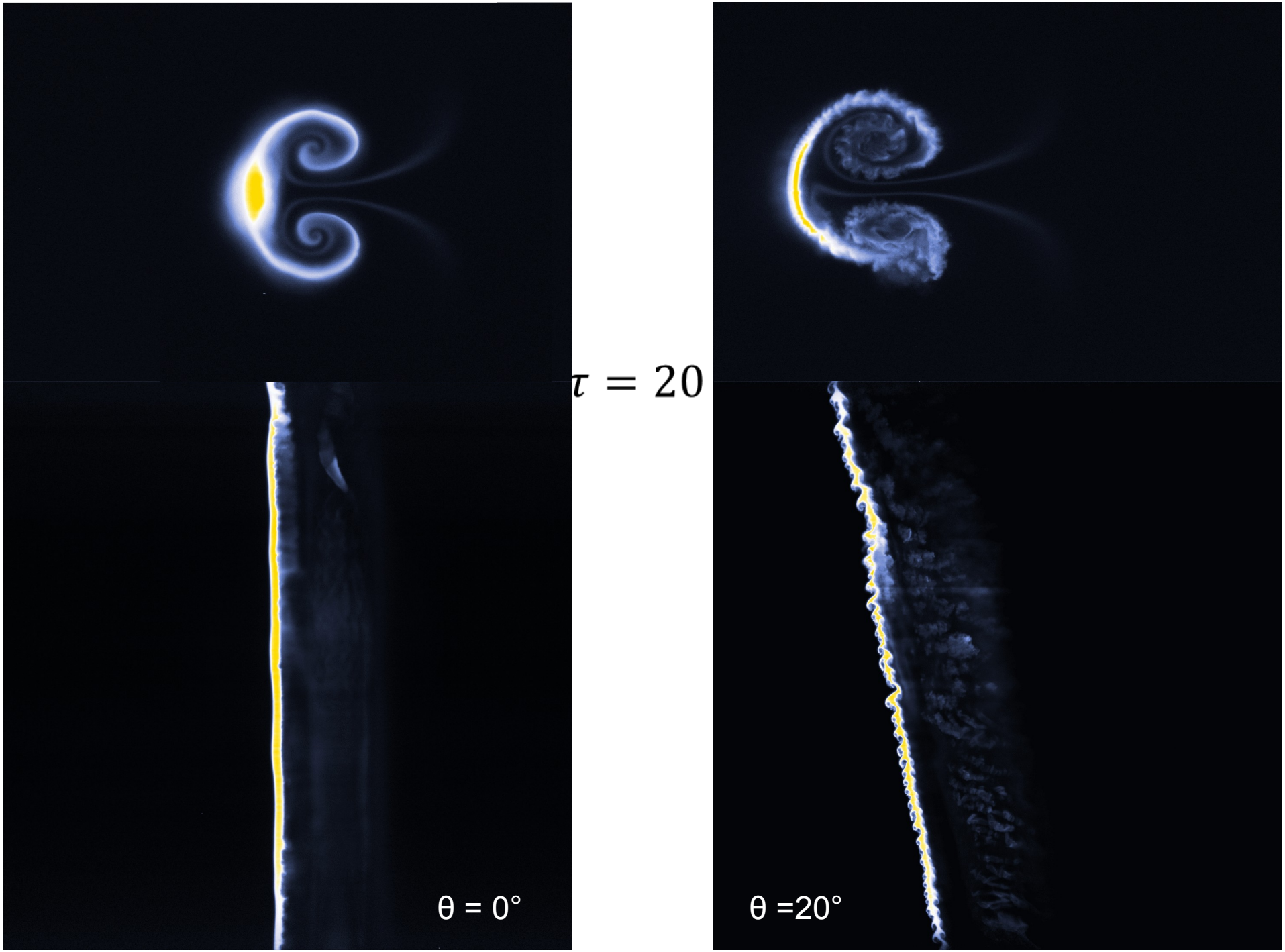


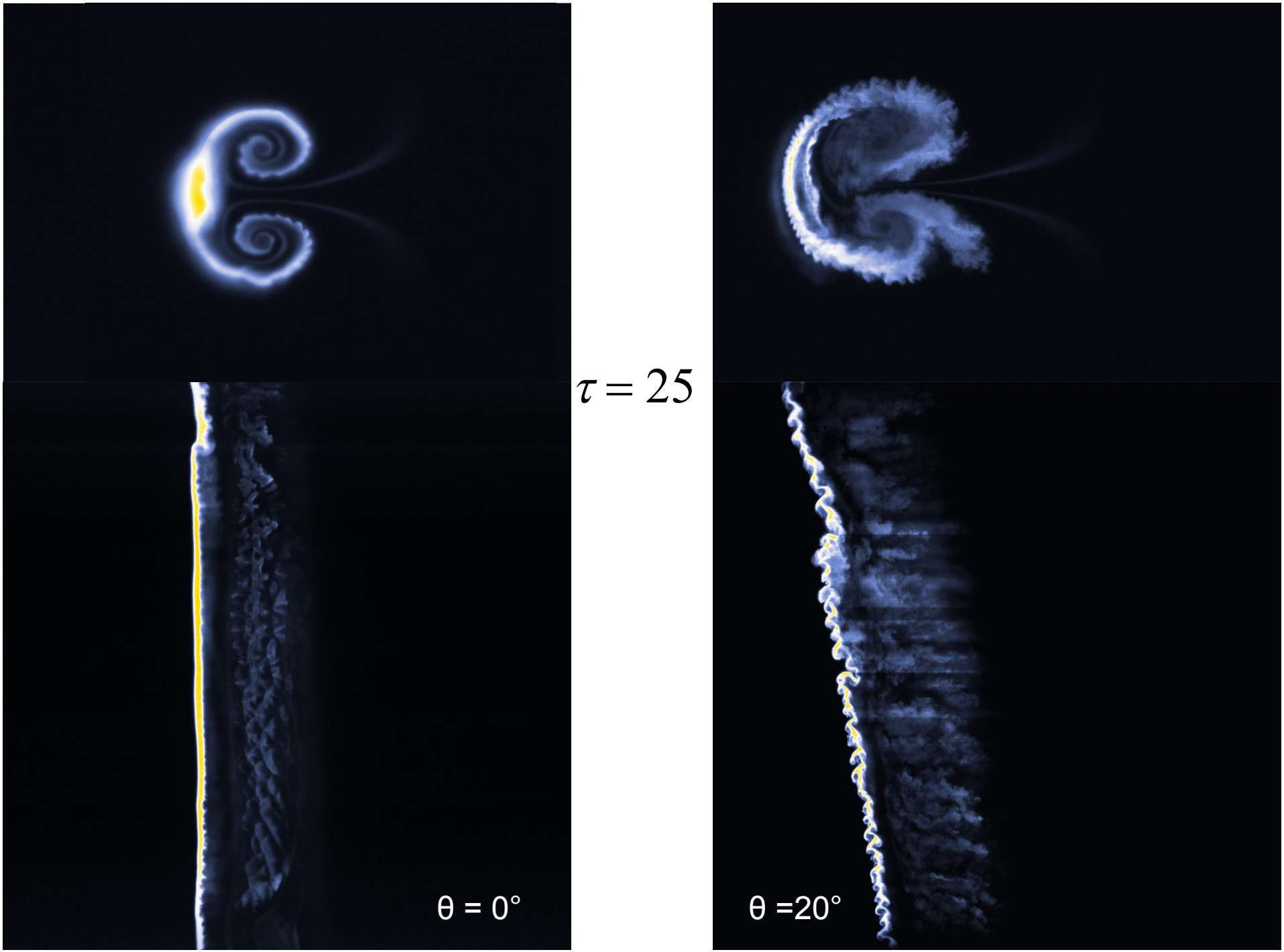

$\tau = 8$
θ = 0°
θ =20°

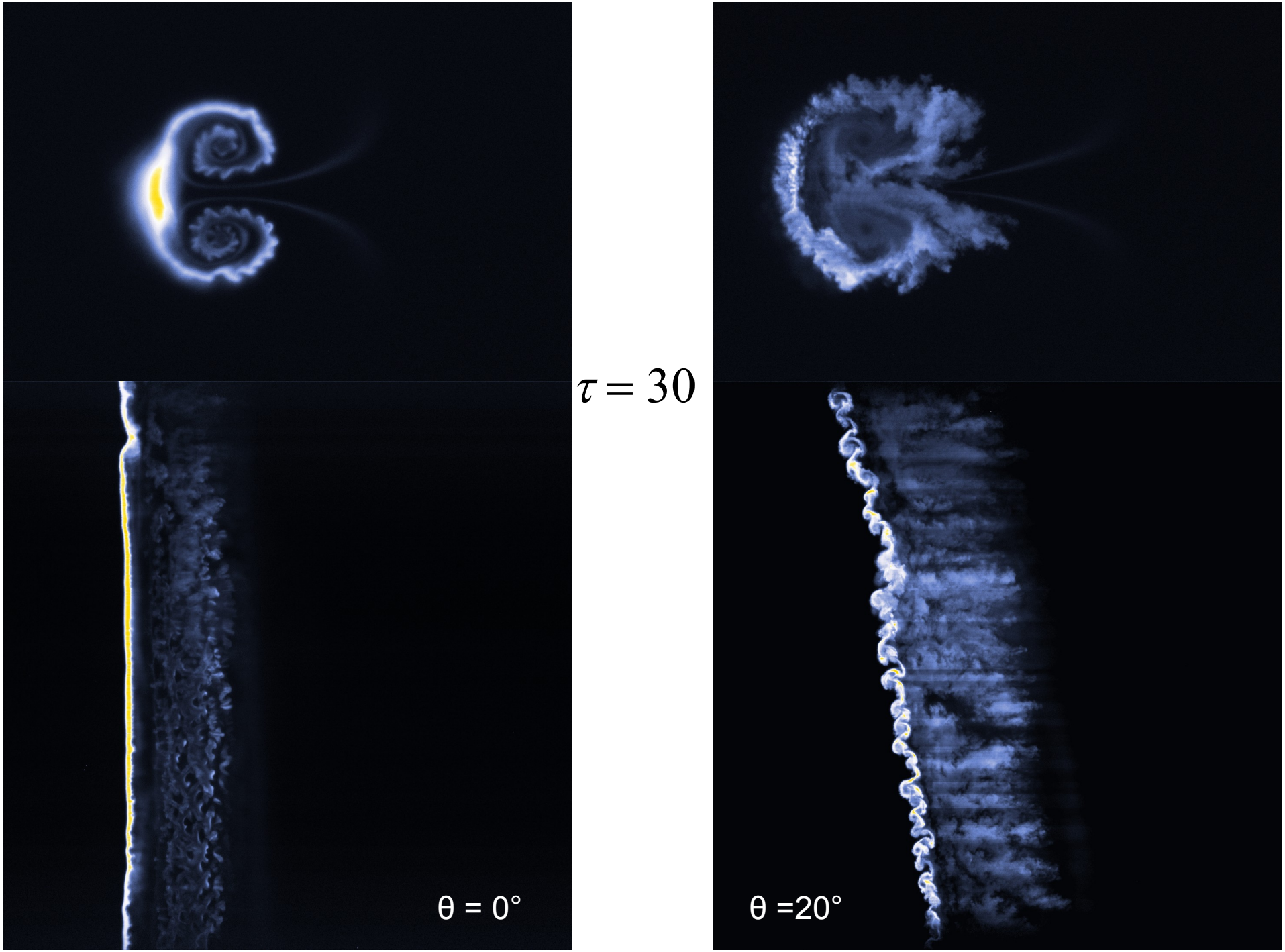

$\tau = 10$
θ = 0°
θ =20°

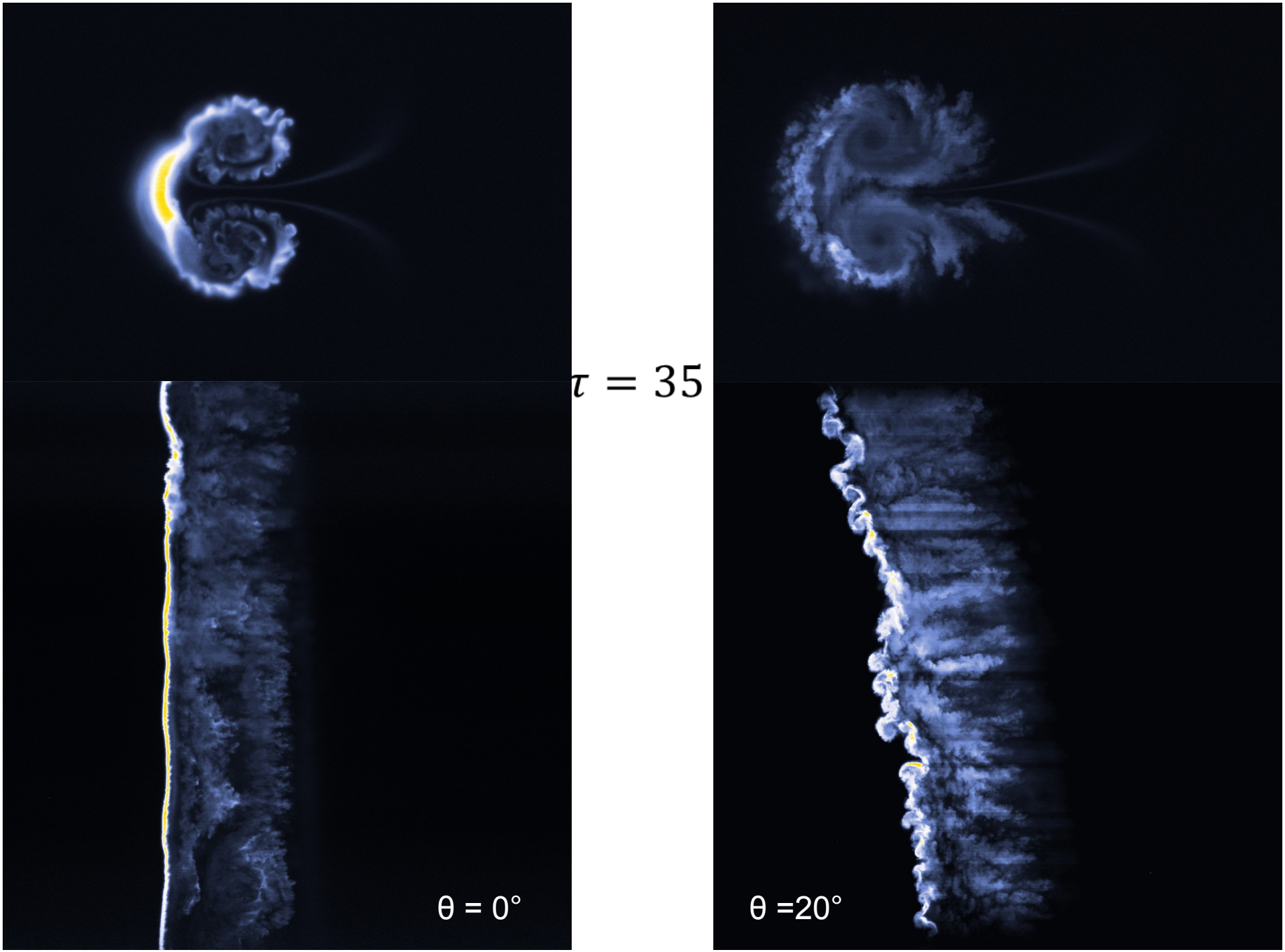

$\tau = 14$
θ = 0°
θ =20°

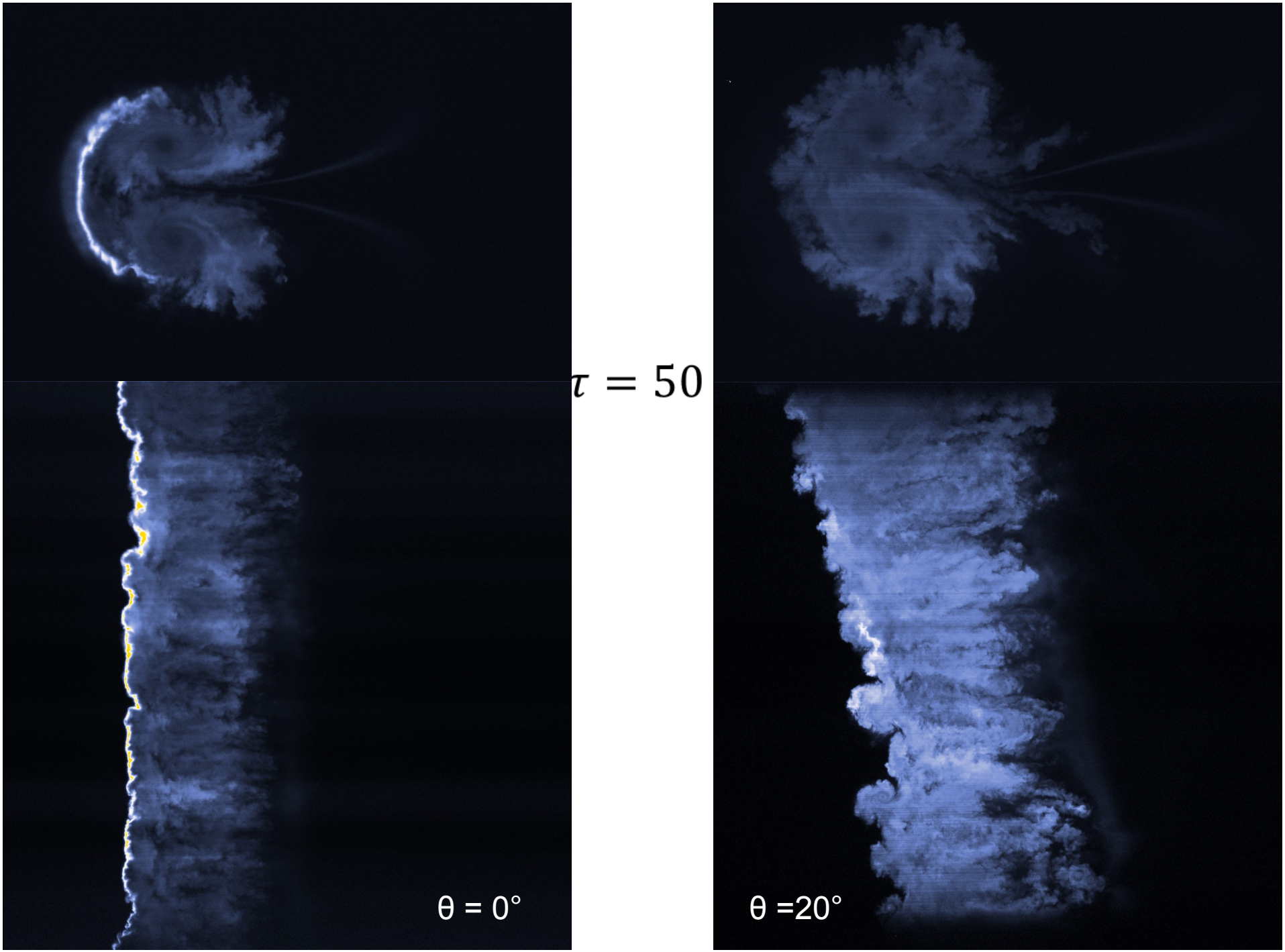

$\tau = 18$
θ = 0°
θ =20°

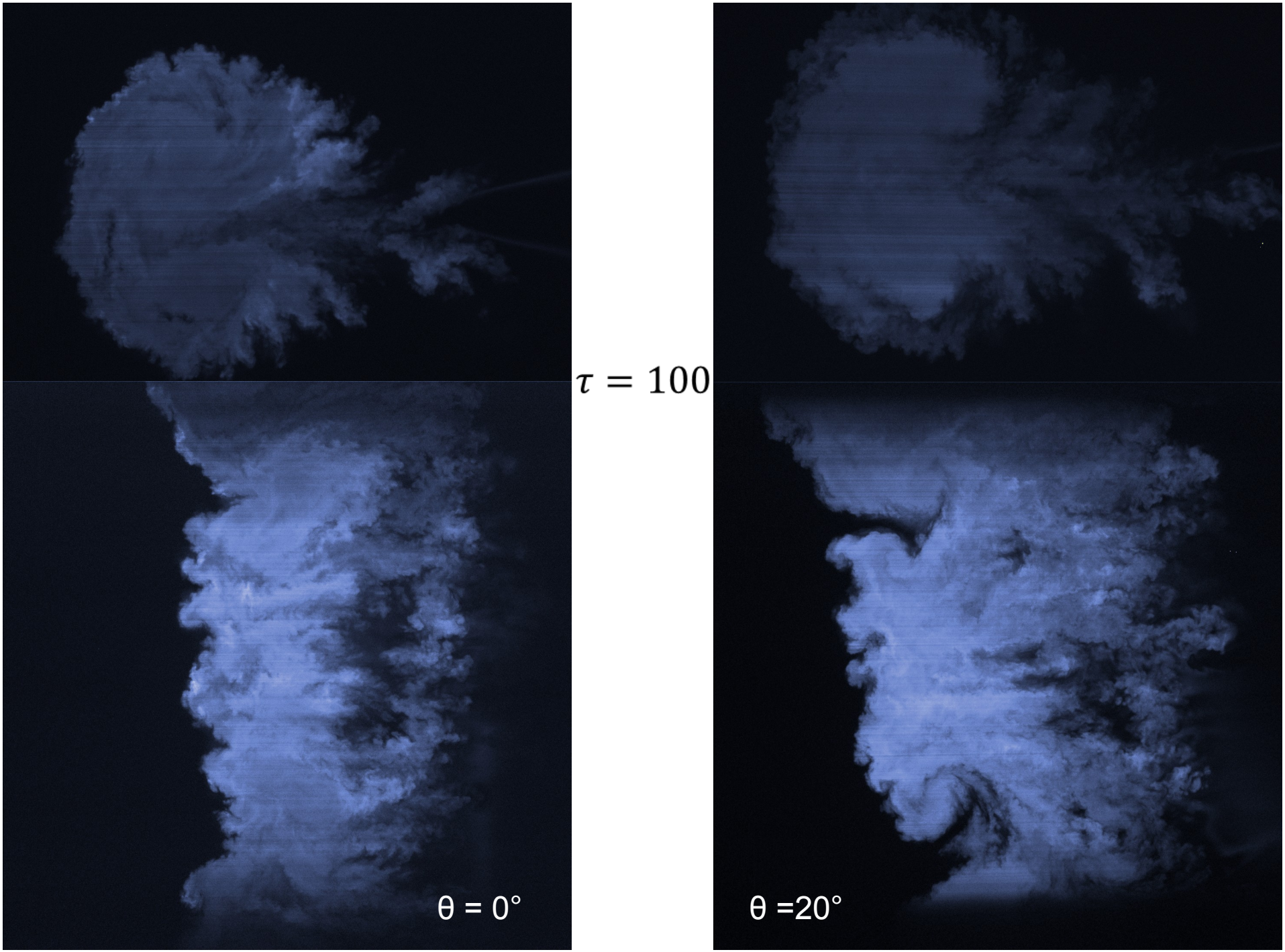

$\tau = 20$
θ = 0°
θ =20°


$\tau = 25$
θ = 0°
θ =20°


$\tau = 30$
θ = 0°
θ =20°


$\tau = 35$
θ = 0°
θ =20°


$\tau = 50$
θ = 0°
θ =20°


$\tau = 100$
θ = 0°
θ =20°

Historical digression

- ~~Kolmogorov 41~~ 5/3 law

Wavenumber
In Fourier space

$$E(k) = C\,\varepsilon^{2/3}\,k^{-5/3}$$

Energy spectrum of
turbulent velocity field

Energy dissipation rate

- True origin of 5/3 law: Kolmogorov and Obukhov, 1962
- The real Kolmogorov 41 law

n^{th} order velocity
structure function
(n = 2 ~ kinetic energy)

$$\left\langle \left[\delta \boldsymbol{u}(r) \right]^n \right\rangle = C_n \varepsilon^{n/3} r^{n/3}$$

2/3 law
(n = 2)

$$\delta \boldsymbol{u}(r) = \boldsymbol{u}(\boldsymbol{x}) - \boldsymbol{u}(\boldsymbol{x}+\boldsymbol{r})$$

When are the 2/3 law and 5/3 law equivalent?

- Locally isotropic turbulence
- Injection scale $L \to \infty$
- Kolmogorov microscale $\eta \to 0$
- (less restrictive formulation – for any locally isotropic turbulence where velocity second-order structure functions scale as $r^{2/3}$)

  (Monin & Yaglom, *Statistical Hydromechanics* Vol. 2)

Spectra and structure functions for passive scalars

- Corrsin – spectrum of temperature fluctuations in isotropic, etc. turbulent flow

$$\psi(k_x) = C_\theta \langle \epsilon \rangle^{-1/3} \langle \xi \rangle k_x^{-5/3}$$

- Can be generalized to any diffusive passive scalar and even to reacting component
- Can be expressed in terms of structure function (caveats from previous slide apply)

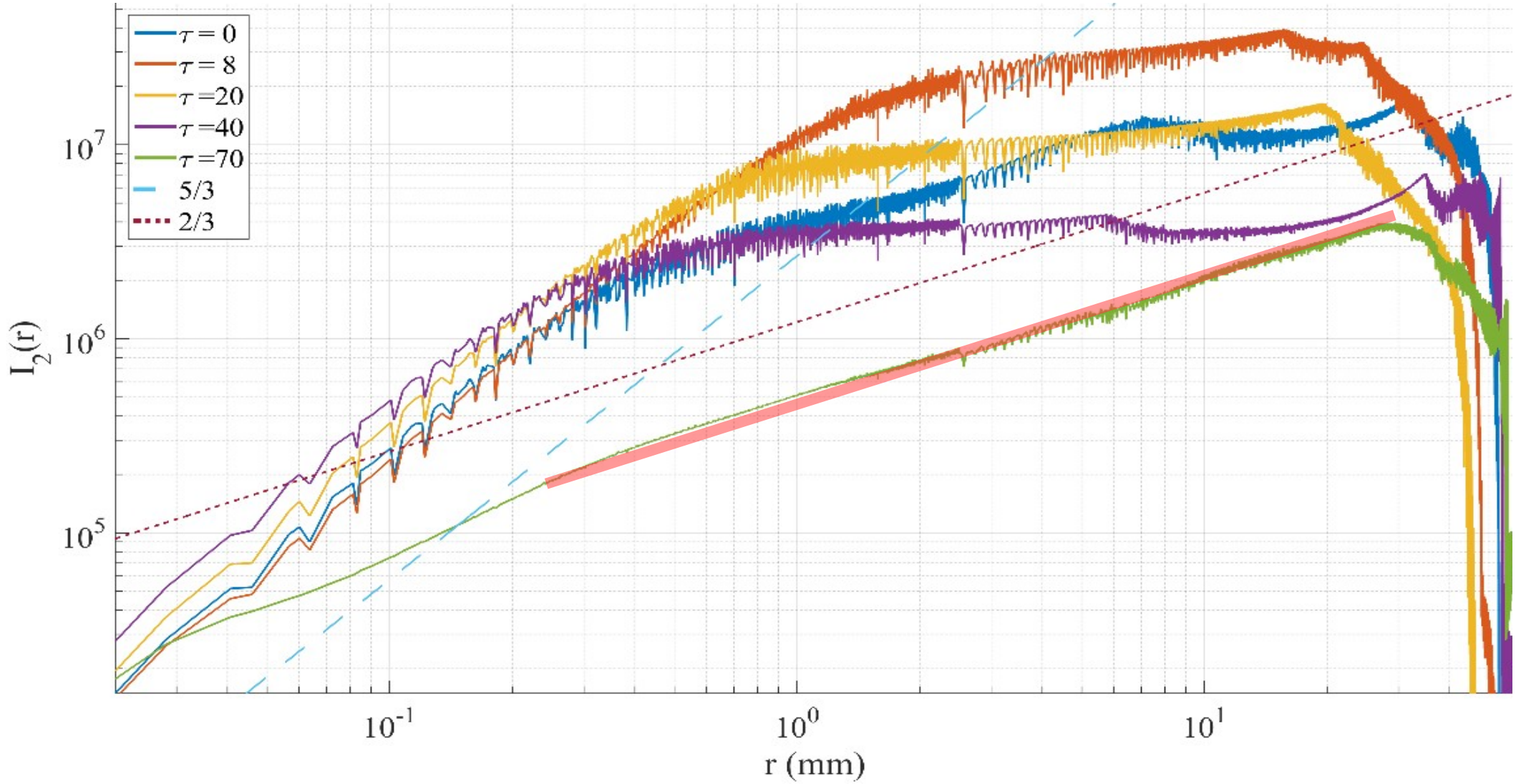
$$D_{\theta\theta}(r) = C_\theta \bar{N} \varepsilon^{-1/3} r^{2/3}$$

Equation 22.12, Monin & Yaglom, Vol. 2

Also too 2/3 law

Plot of $I_2(r) = \left\langle \left[I(x) - I(x+r) \right]^2 \right\rangle$

(second-order structure function of fluorescence intensity, vertical plane)



Plot of $I_2(r) = \left\langle \left[I(x) - I(x+r) \right]^2 \right\rangle$

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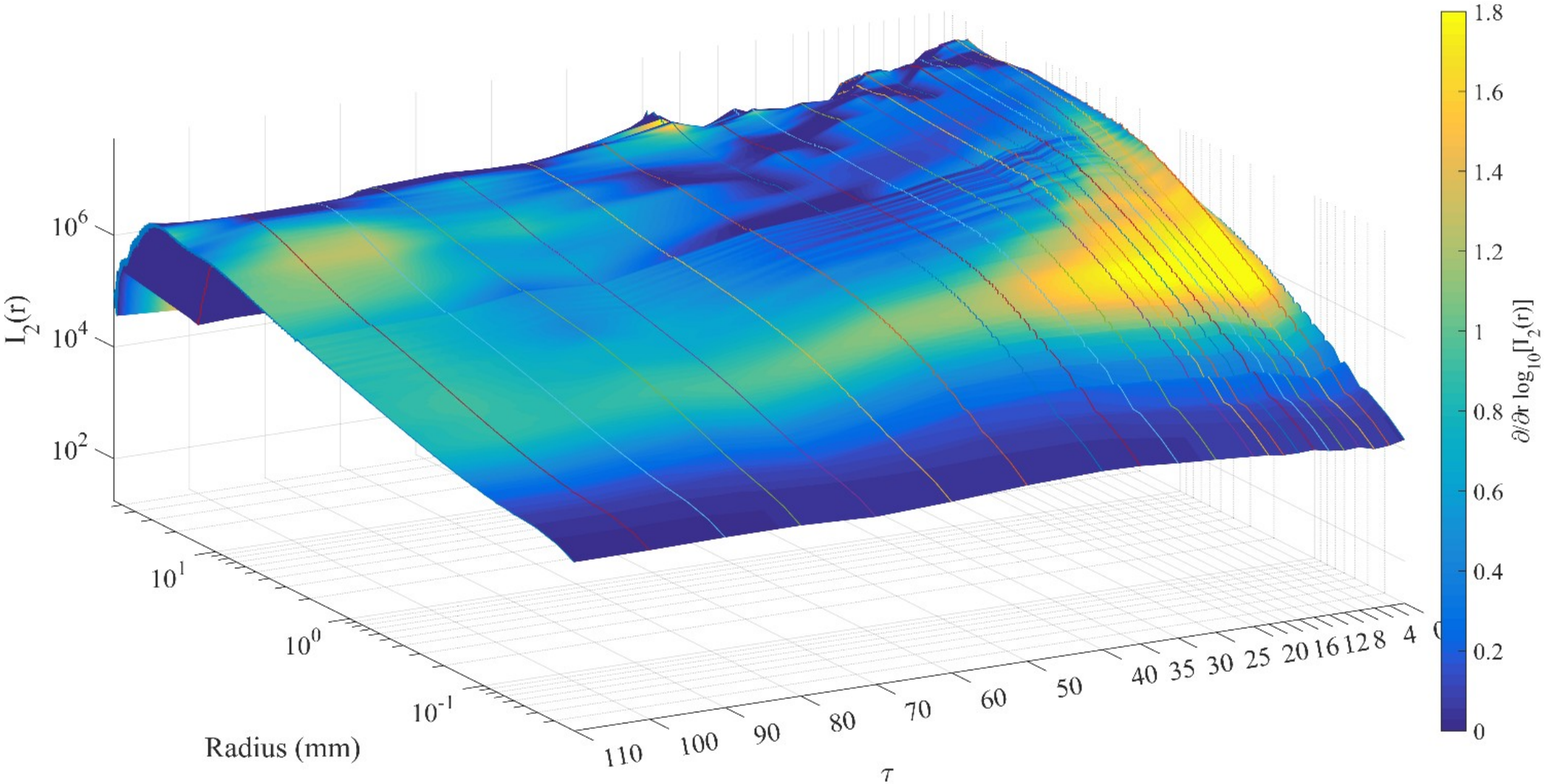
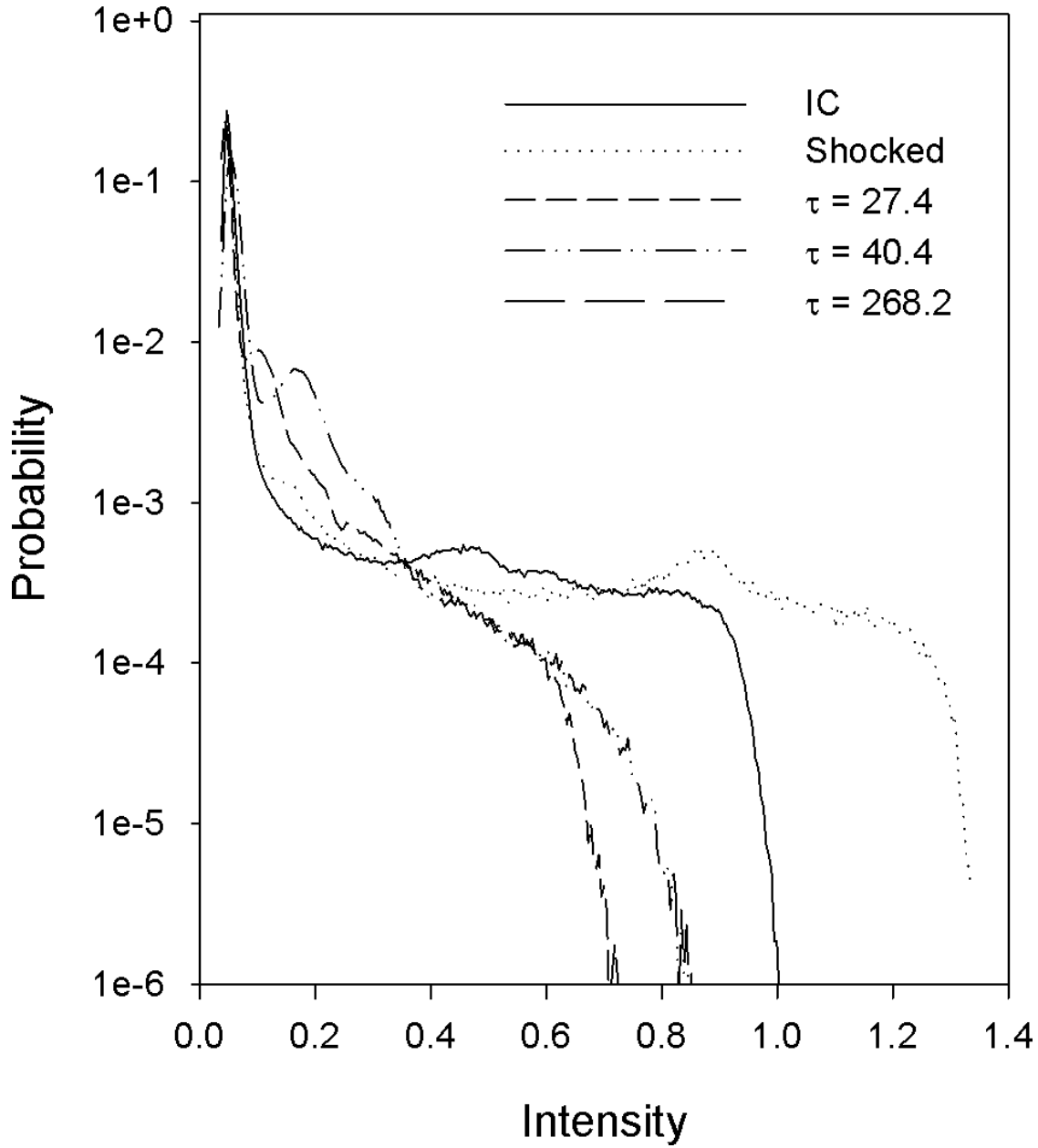


Intensity histogram evolution

- M = 1.7, vertical plane
- Early-time fluorescence intensity distribution – bimodal (bright column material, dark air)
- At late times, bright peak fades due to mixing

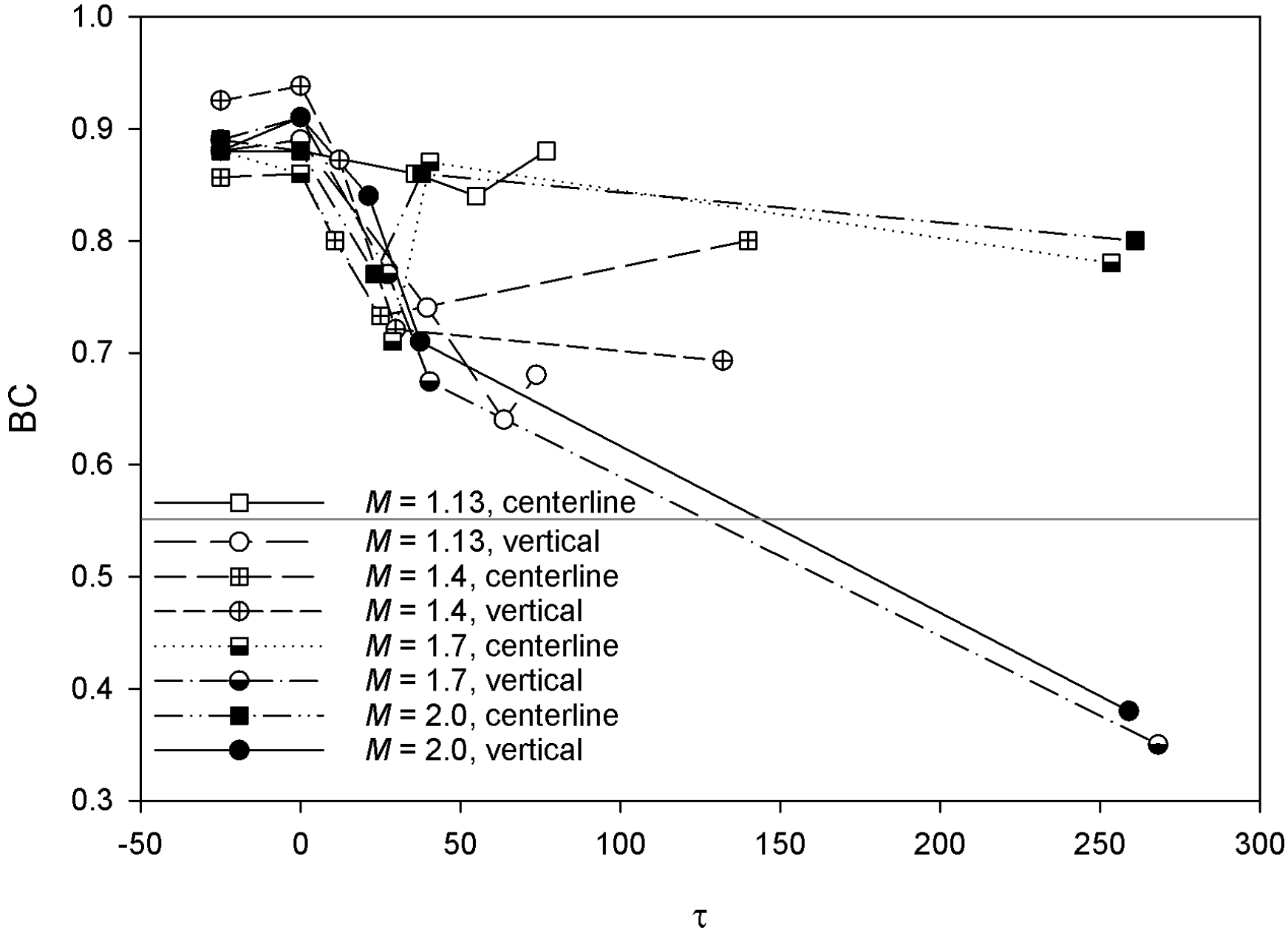


Bimodality criterion

$$BC = \frac{m_3^2 + 1}{m_4 + 3\frac{(n-1)^2}{(n-2)(n-3)}}$$

- Proposed by Warren Sarle
- n – distribution size
- m_3 – skewness (3rd moment)
- m_4 – excess kurtosis (4th moment)
- For a uniform distribution, BC = 5/9
- Higher values suggest bimodality, lower - unimodality

Bimodality criterion (cont.)



Summary

- Shock-driven mixing flow manifests scalar scaling consistent with classical turbulence theory predictions
- Emergence of 2/3 power-law scaling in terms of dimensionless time τ is…
  - Accelerated for oblique shock (compared to planar)
  - Accelerated by increased Atwood number
  - Weakly dependent on Mach number
  - Consistent in time with mixing transition based on histogram data

Recent publications (2015)

T. Bernard, C.R. Truman, P. Vorobieff, C. Corbin, P.J. Wayne, G. Kuehner, M. Anderson, and S. Kumar, “Observation of the Development of Secondary Features in a Richtmyer–Meshkov Instability Driven Flow,” ASME Journal of Fluids Engineering Vol. 137 No. 1 (2015), art. no. 011206.

P. Wayne, D. Olmstead, P. Vorobieff, C.R. Truman, and S. Kumar, “Oblique shock interaction with a cylindrical density interface,” Computational Methods in Multiphase Flow VIII, editors: C.A. Brebbia, P. Vorobieff, J.L. Muñoz-Cobo, WIT Press, Southampton, UK (2015), pp. 161-170.

D. Olmstead, C.R. Truman, P. Wayne, and P. Vorobieff, “Effects of inclination angle on a shock-accelerated heavy gas colum,” Computational Methods in Multiphase Flow VIII, editors: C.A. Brebbia, P. Vorobieff . J.L. Muñoz-Cobo, WIT Press, Southampton, UK (2015), pp. 171-180.

M. Anderson, P. Vorobieff, C.R. Truman, C. Corbin, G. Kuehner, P. Wayne, J. Conroy, R. White, and S. Kumar, “An experimental and numerical study of shock interaction with a gas column seeded with droplets,” Shock Waves Vol. 25 No. 2 (2015), pp. 107-125.

C. Corbin, P. Vorobieff, P. Wayne, T. Bernard, C.R. Truman, and S. Kumar, “Experimental Studies of Shock Interactions with a Multiphase Medium,” 29th International Symposium on Shock Waves, editors: R. Bonazza, D. Ranjan, Vol. 2 (2015), pp. 1553-1558.

P. Wayne, D. Olmstead, C.R. Truman, P. Vorobieff, and S. Kumar, "Oblique Shock Interaction with a Laminar Cylindrical Jet," to appear, AIP Proceedings, 2016.

(names of student authors underlined)