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The Measurement of Dissipation in Turbulent Flames: A Major Challenge for Laser Diagnostics

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Guanghua Wang, Philip Varghese, Rob Barlow
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Publications

Wang, Clemens, Barlow, Varghese, “A System Model for Assessing Scalar Dissipation Measurement Accuracy in Turbulent Flows,” *Measurement Science and Technology*, 2007

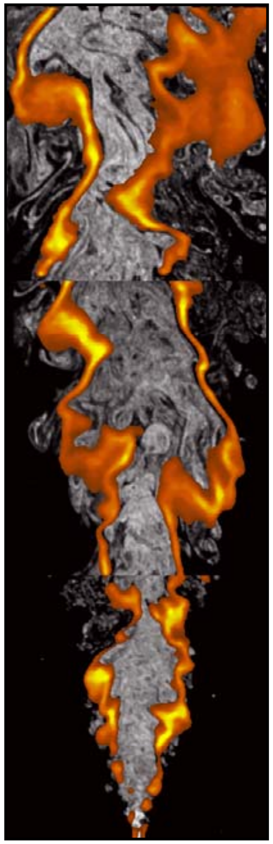
Wang, Clemens, Varghese, Barlow, "Turbulent Time Scales in a Nonpremixed Turbulent Jet Flame by Using High-Repetition Rate Thermometry," *Combustion and Flame*, 2007

Wang, Barlow, Clemens, "Quantification of Resolution and Noise Effects on Thermal Dissipation Measurements in Turbulent Non-premixed Jet Flames," *Proceedings of the Combustion Institute*, Vol., 2007

Wang, Clemens and Varghese, "High-Repetition Rate Measurements of Temperature and Thermal Dissipation in a Nonpremixed Turbulent Jet Flame," *Proceedings of the Combustion Institute*, 2005

Motivation for Measuring Dissipation Rate

- Dissipation in Turbulent Nonpremixed Combustion
  - Nonpremixed flame structure strongly tied to underlying scalar dissipation rate
    - In fast chemistry limit the reaction rate is proportional to scalar dissipation rate
    - For finite rate chemistry the scalar dissipation affects the degree of nonequilibrium
  - Thermal dissipation may be used as a surrogate for scalar dissipation
  - Kinetic energy dissipation important for modeling and understanding flame physics
  - Very little is known of the dissipative structure of turbulent flames



Characteristics of Dissipation Fluctuations

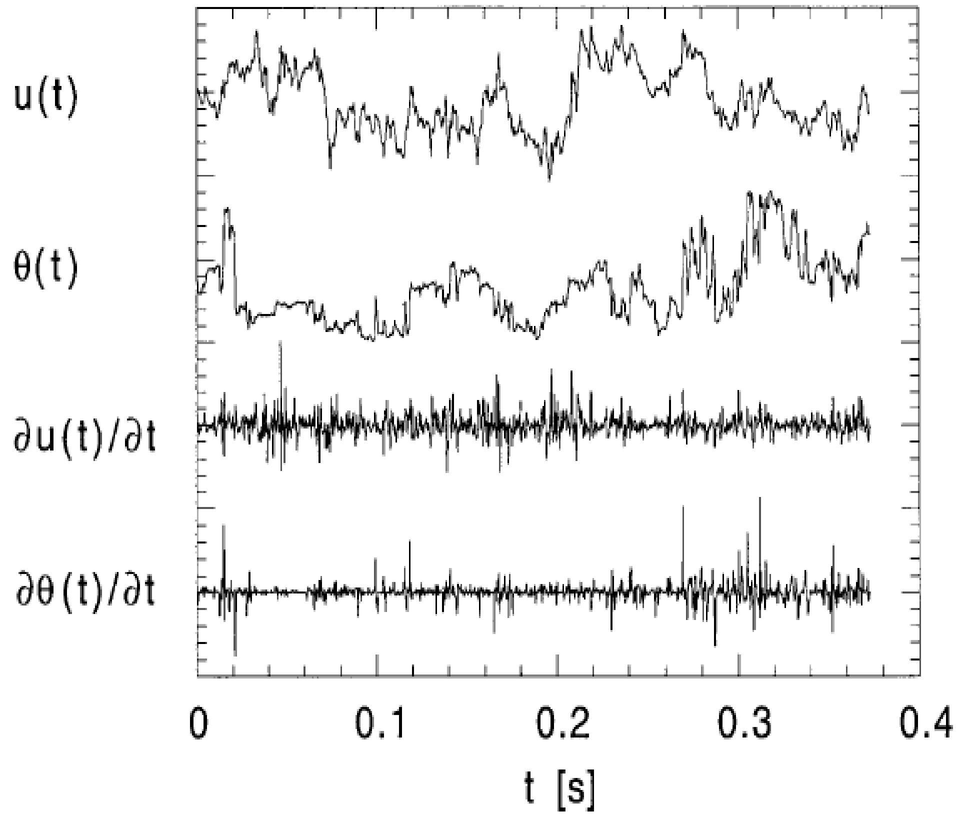
Kinetic energy Dissipation rate

$$\varepsilon = \frac{\nu}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

$$= 2\nu \mathbf{s} : \mathbf{s}$$

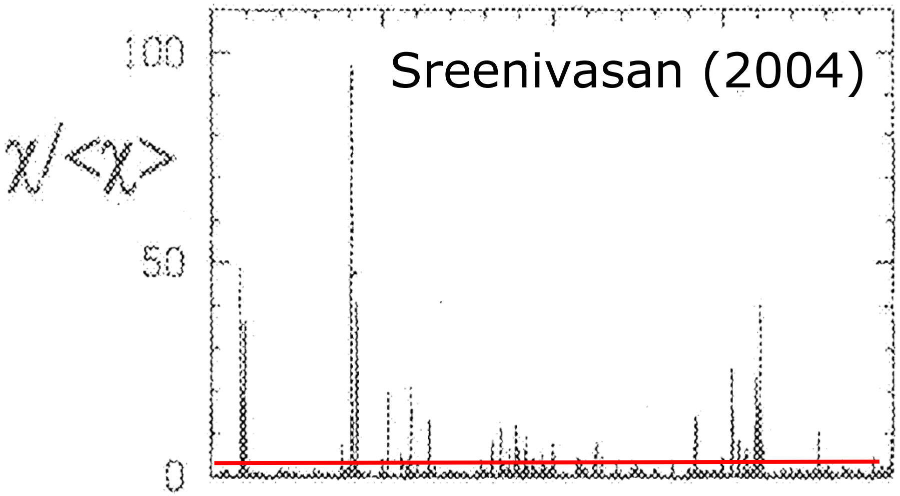
Scalar energy dissipation rate

$$\chi = 2D(\nabla \xi \cdot \nabla \xi)$$

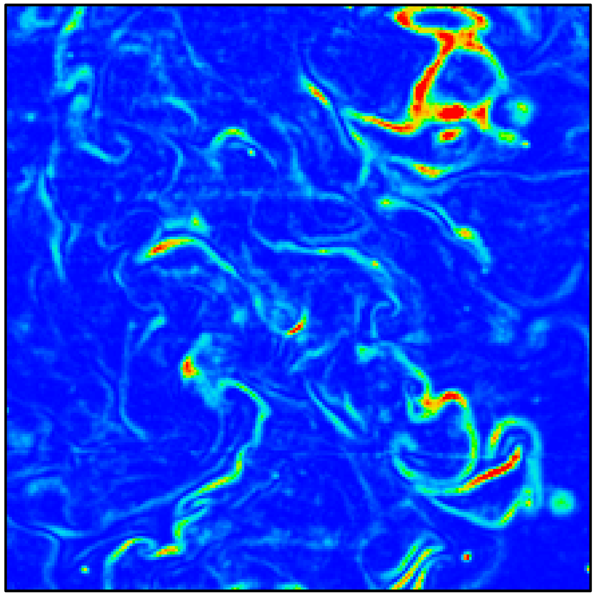


Mydlarski & Warhaft (1998)

Characteristics of Dissipation Fluctuations



Su & Clemens (2002)



- Instantaneous dissipation is much larger than the mean
- Measurements of mean dissipation important in turbulence modeling

Dissipative Scales

- Dissipation is important only at the smallest scales where gradients are largest
- Kolmogorov (1941)

Kolmogorov scale: $\eta \equiv \left(\nu^3/\bar{\varepsilon}\right)^{1/4}$ *← Finest scale in velocity field (Finest scale eddy?)*

- Batchelor (1959) scale - Sc » 1

(Sc = ν / D, where D is the mass diffusivity)

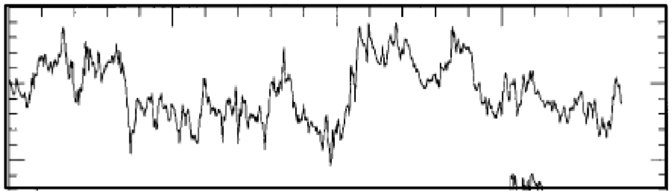
Batchelor scale: $\lambda_B = \eta Sc^{-1/2}$ *← Finest scale in concentration field*

- Obukhov-Corsin scale - Sc < 1

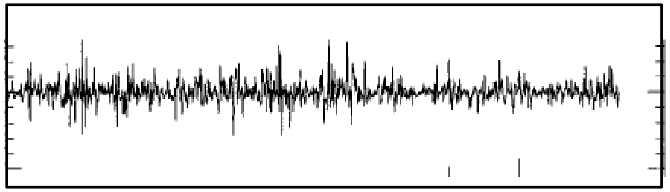
Obukhov-Corsin: $\lambda_{OC} = \eta Sc^{-3/4}$

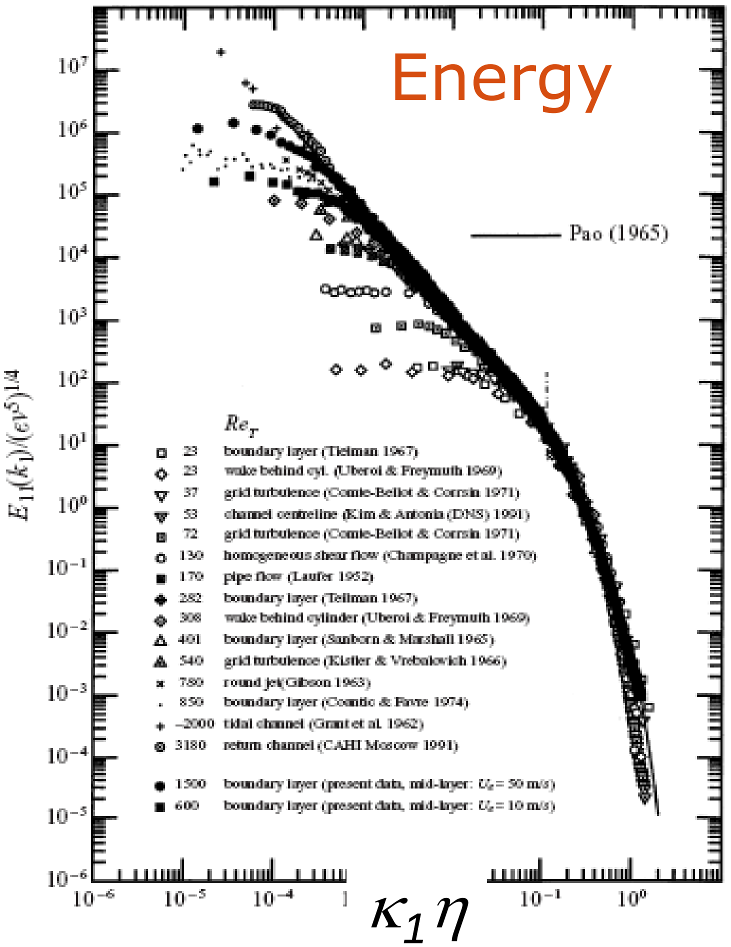
Energy Spectra of *u'(t)* and *∂u'/∂t*

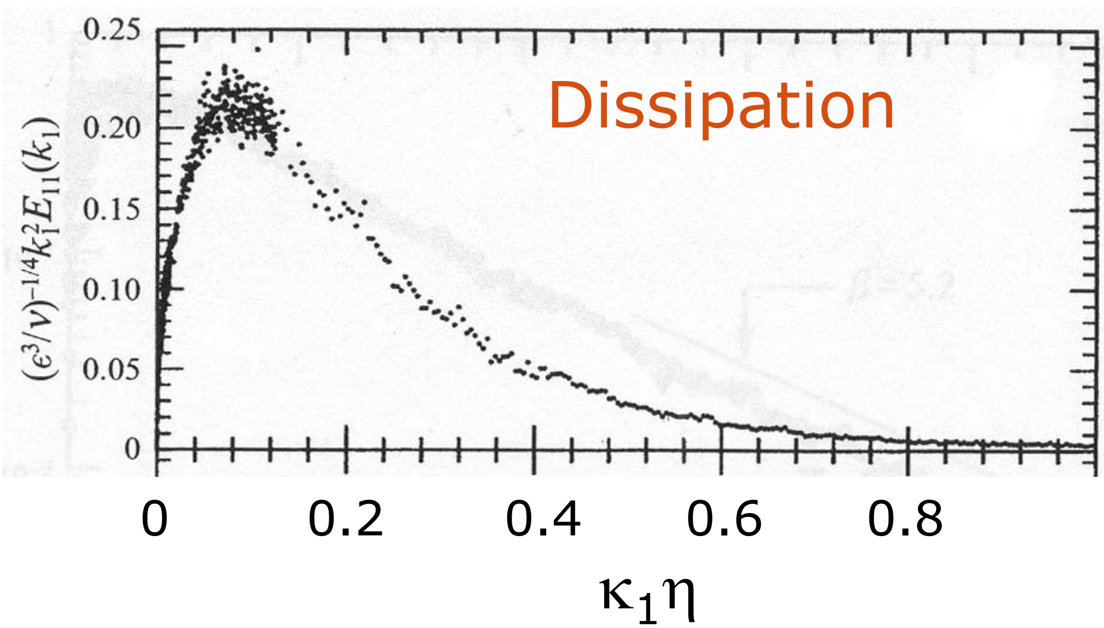
u(t)



∂u(t)/∂t







Peak of dissipation at $\kappa_1\eta \approx 0.1$

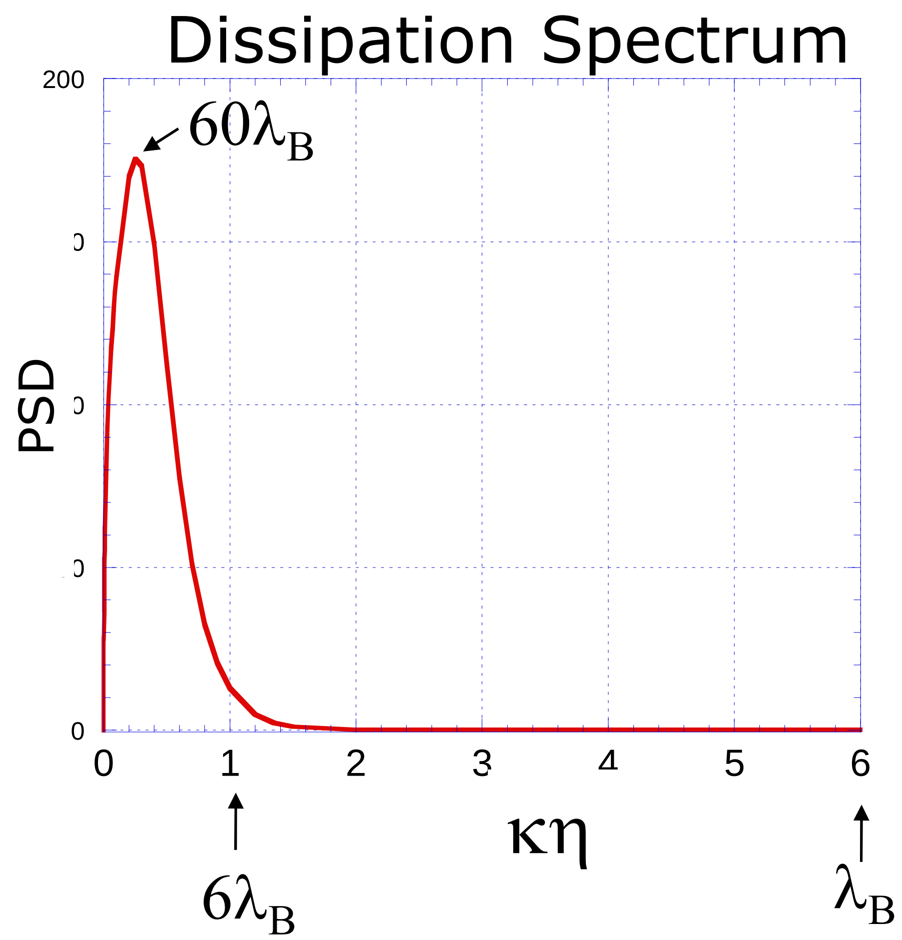
Saddoughi & Veeravalli (1994)

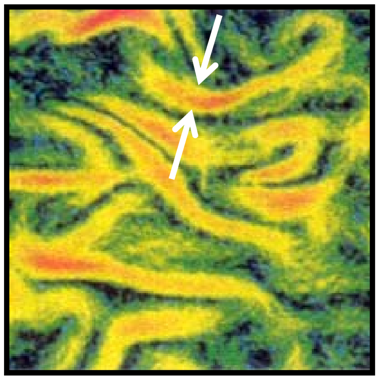
Spectral Cutoff Frequencies

- Batchelor Frequencies:

$$\kappa_B \equiv \frac{1}{\lambda_B} \qquad f_B \equiv \frac{\bar{U}}{2\pi\lambda_B}$$

- Typically data are filtered to f_B and sampled at 2 f_B
- Both Batchelor frequencies correspond to a physical lengthscale of $\lambda = 6\lambda_B$

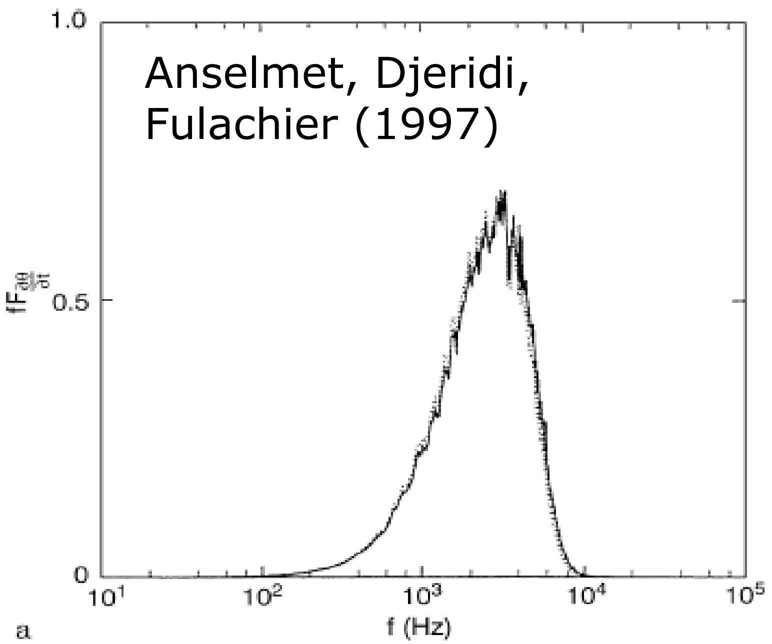


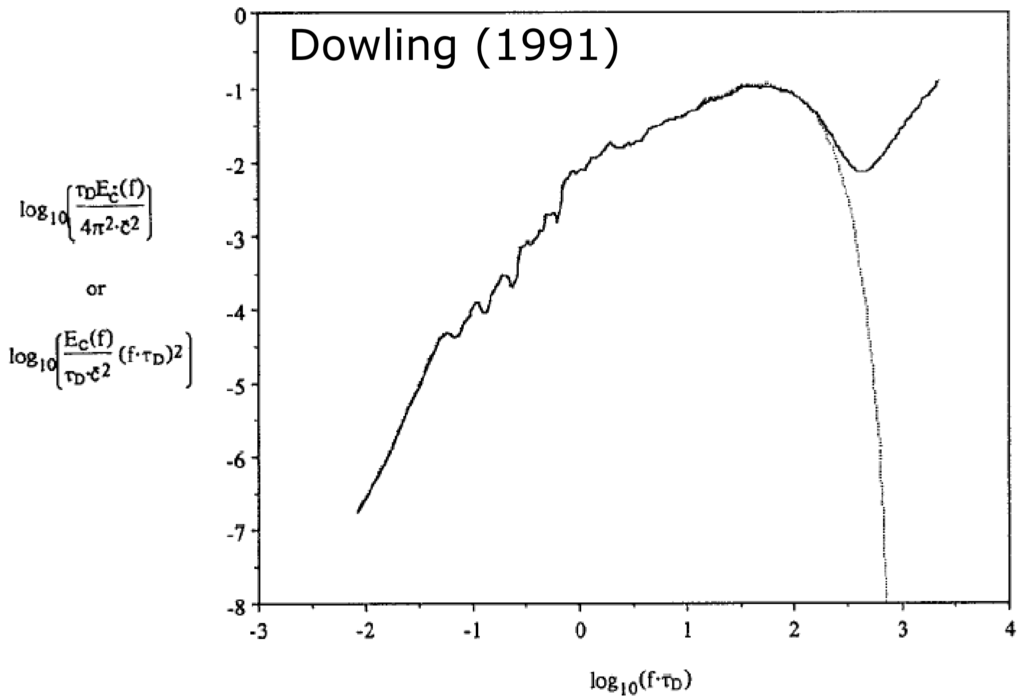


κ_B and f_B correspond to λ_D defined by Buch & Dahm (1998)

The Problem of Noise

Comparison of Dissipation Spectra





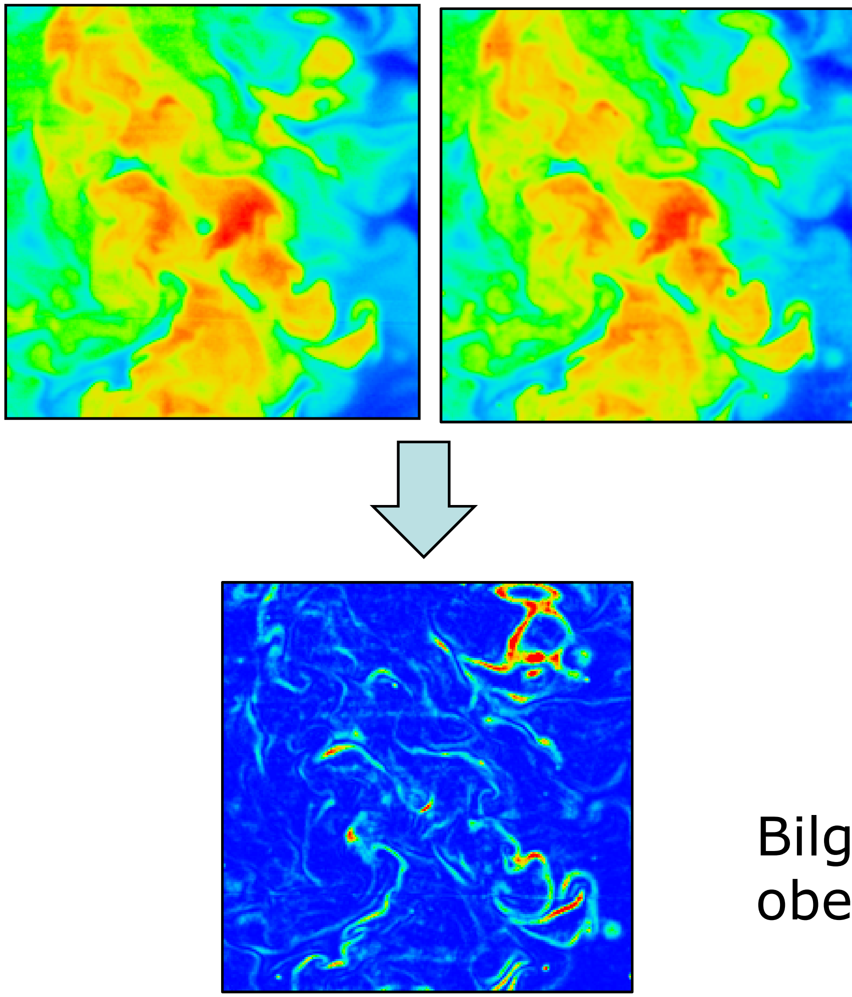
Cold-wire dissipation spectrum computed without filtering

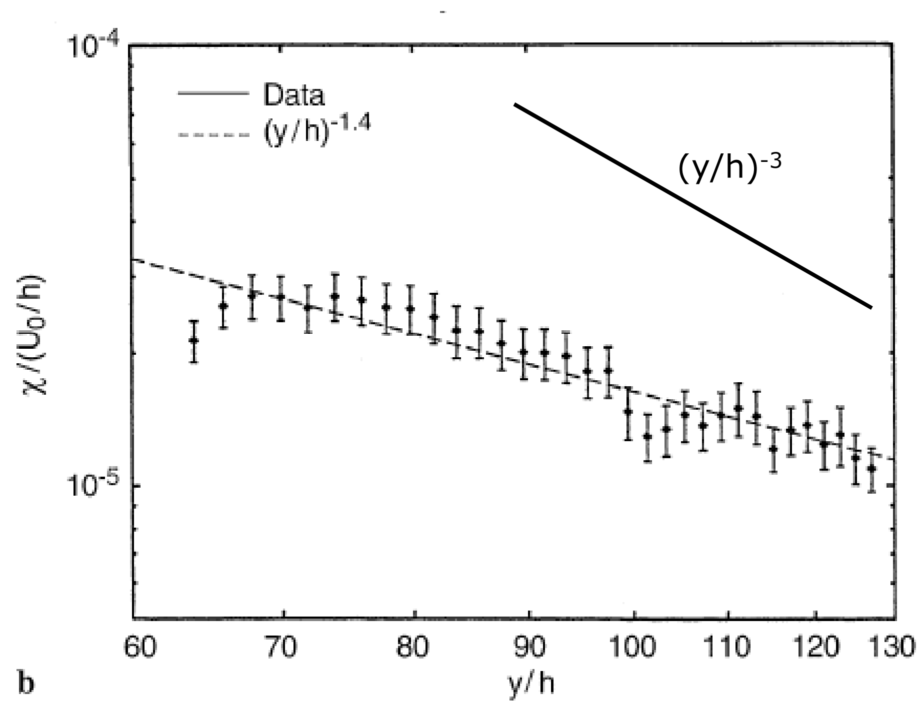
Non-reacting flow Rayleigh scattering (20W laser, ethylene)

Resolution Requirements for Mean Dissipation

- Wyngaard (1971) ; Antonia & Mi (1993): 2-3η
- George and Hussein (1991): $<1\eta$
- Ewing, Hussein, George (1995): 3η
- Anselmet, Djeridi, Fulachier (1997): 3 to 6η
- Buch & Dahm (1998): The smallest turbulent structures are of order 6η
- Su & Clemens (2002): The smallest turbulent structures are of order 7η

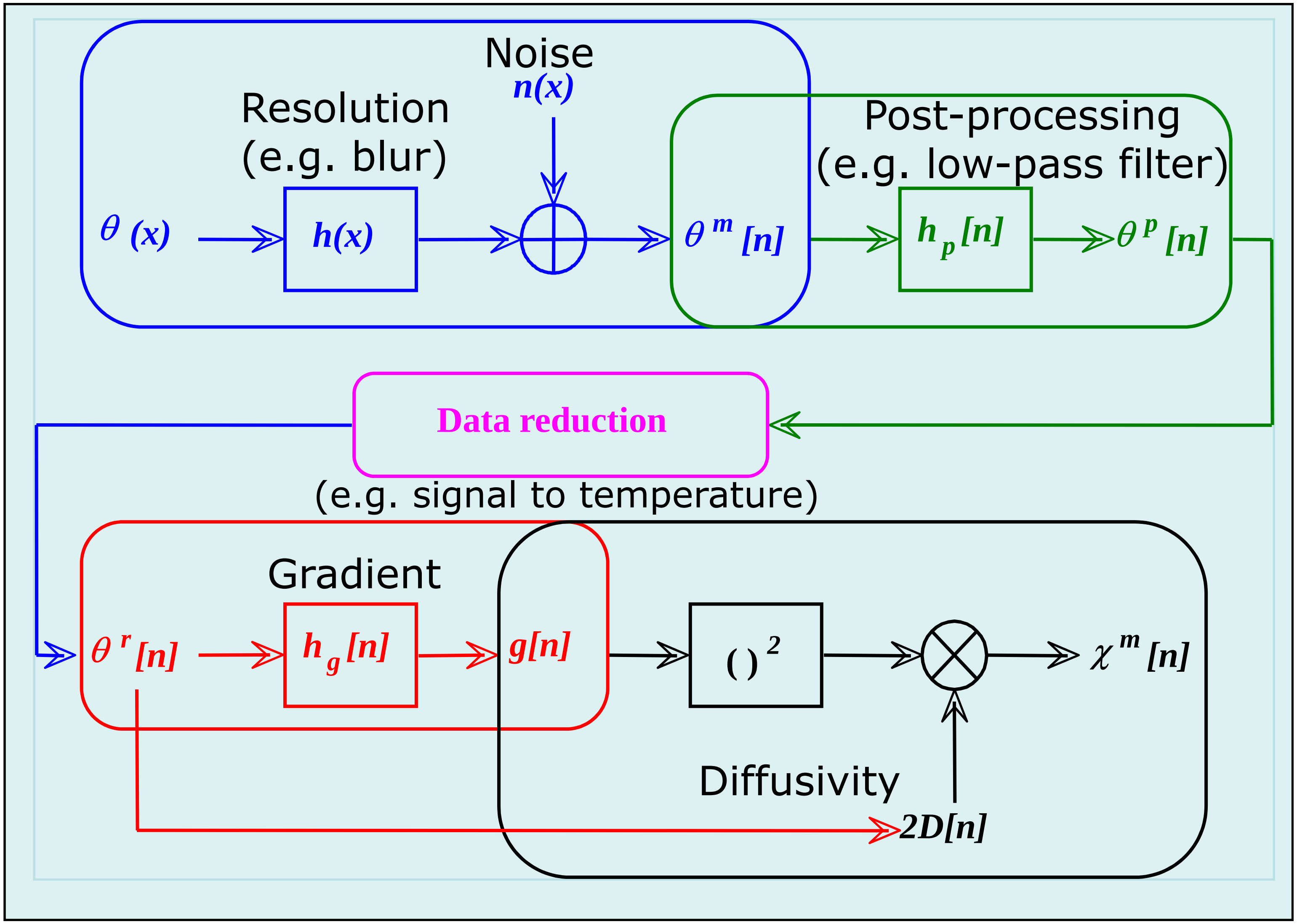
Mean Scalar Dissipation: Su & Clemens (1999)





Bilger (2004): Measurements should obey global conservation

Measurement System Model



Wang, Clemens, Barlow, Varghese, MST 2007

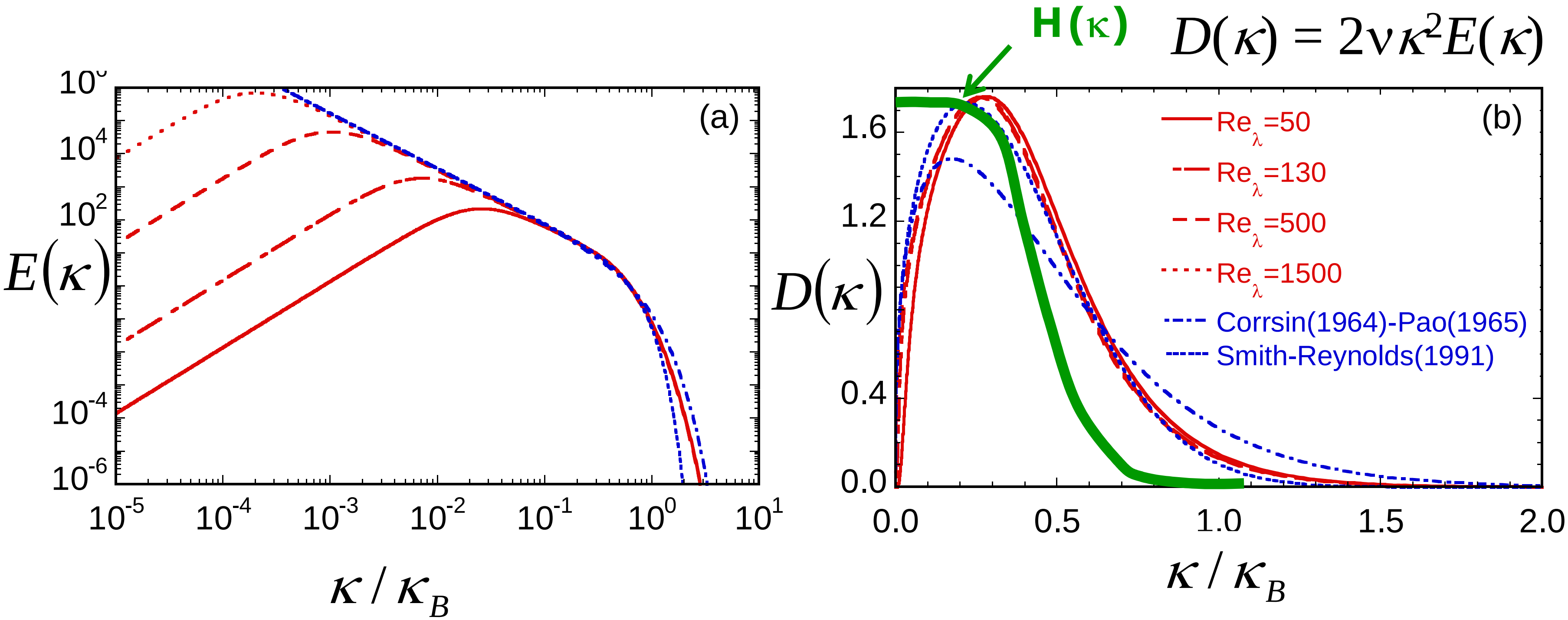
Measurement System Model

For 1D linear operations, these sub-models can be characterized as:

$\theta_m = h_r * \theta + n$	Measurement with additive noise
$\theta_p = h_p * \theta_m$	Post-processing
$\theta_p \rightarrow \theta_d$	Data-reduction
$g_m = h_g * \theta_d$	Gradient
$\chi = 2D \mid g_m \mid^2$	Dissipation

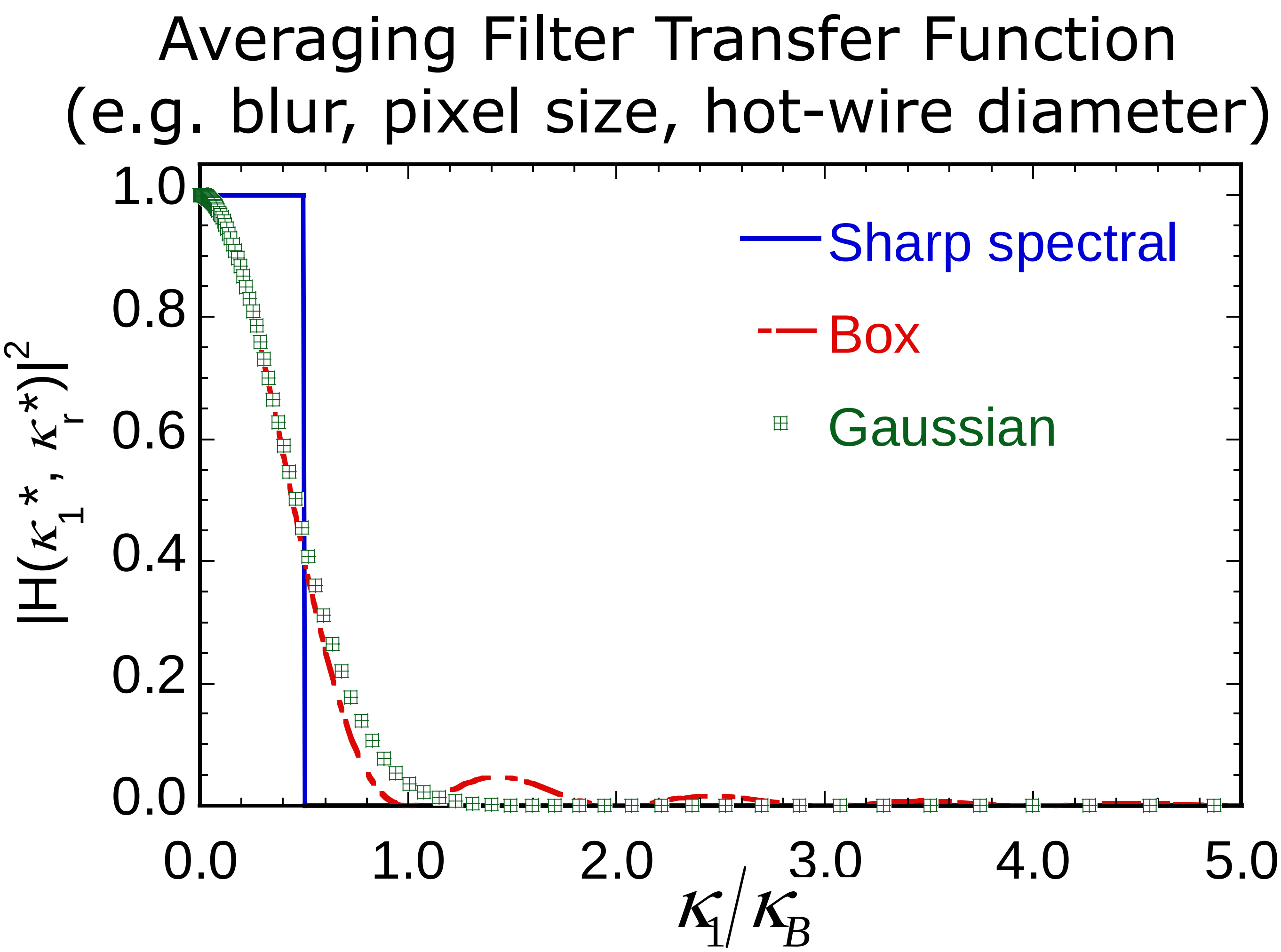
Measurement System Model

- Model resolution and noise effects on turbulence by using Pope's (2000) model spectrum



- Similar to probe resolution studies by Wyngaard (1971); Ewing, George, Hussein (1995)

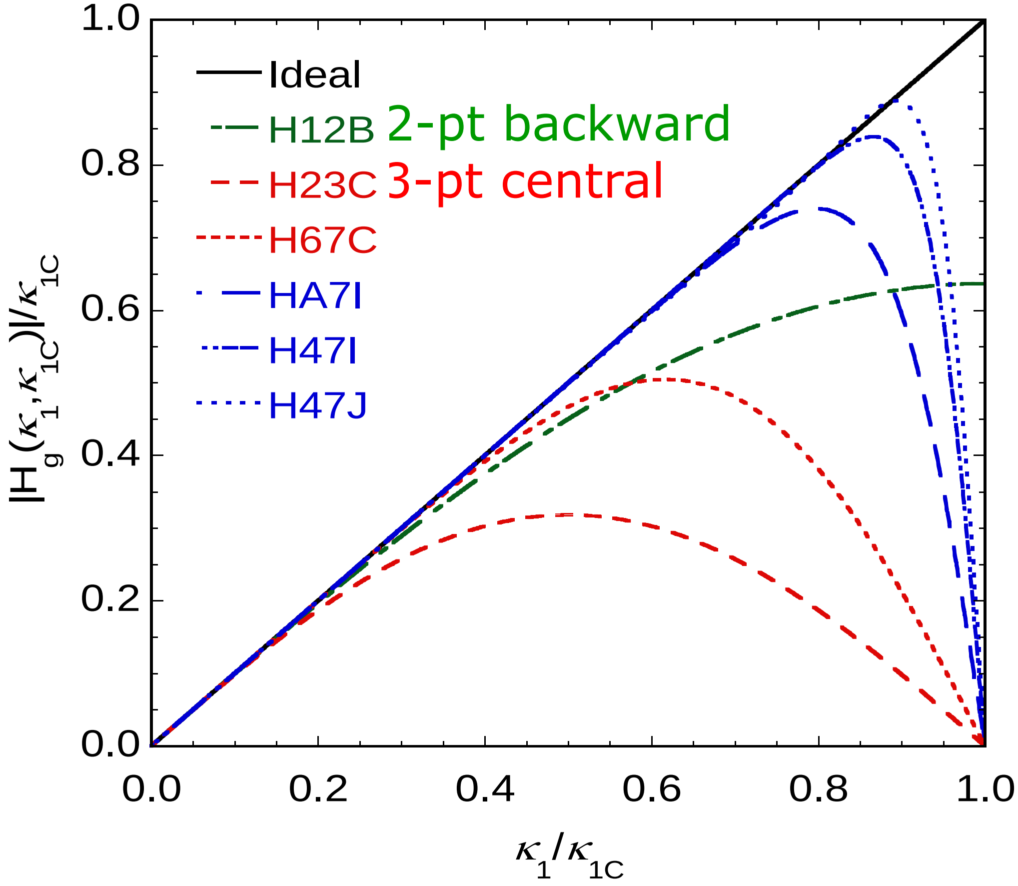
Spatial Averaging Effect



Cutoff wavenumber of the filter: $\kappa_r = 0.5\kappa_B$

Effect of Gradient Stencil

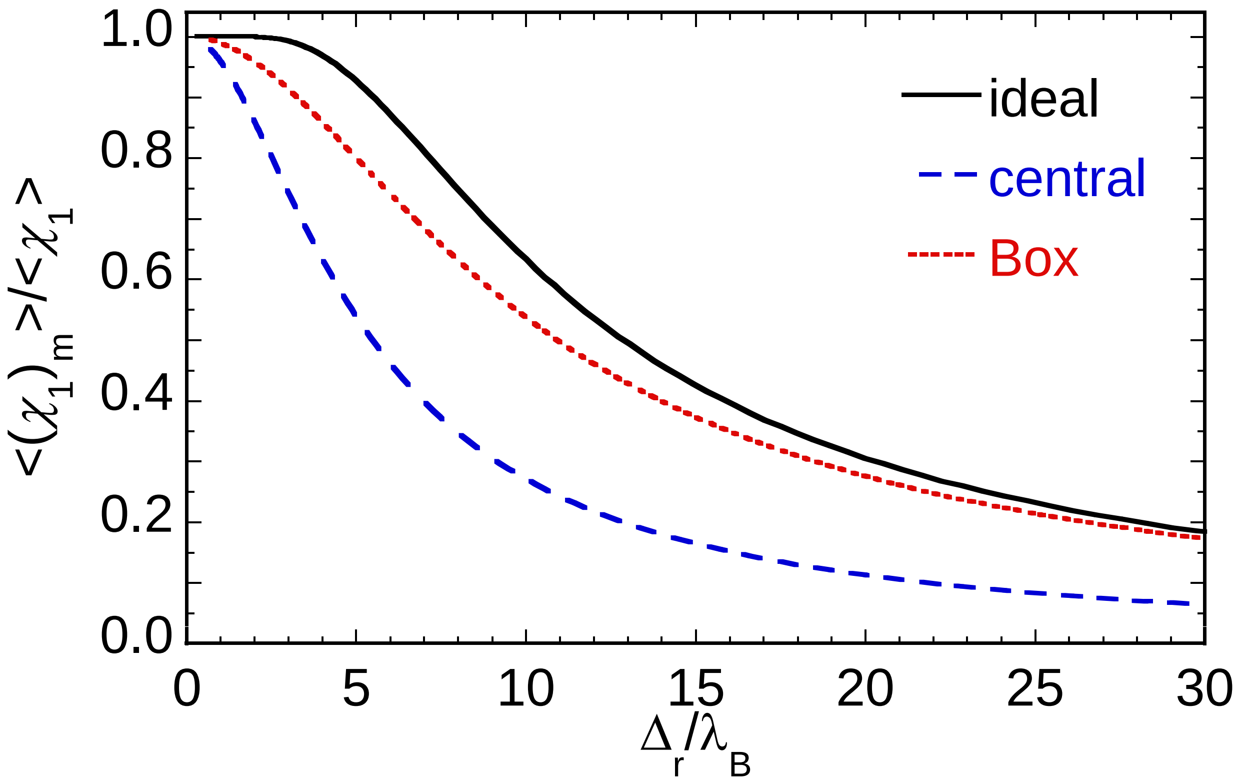
- Resolving efficiency of the gradient stencil



  - Severe attenuation with central difference
  - Better performance with high order Padé scheme

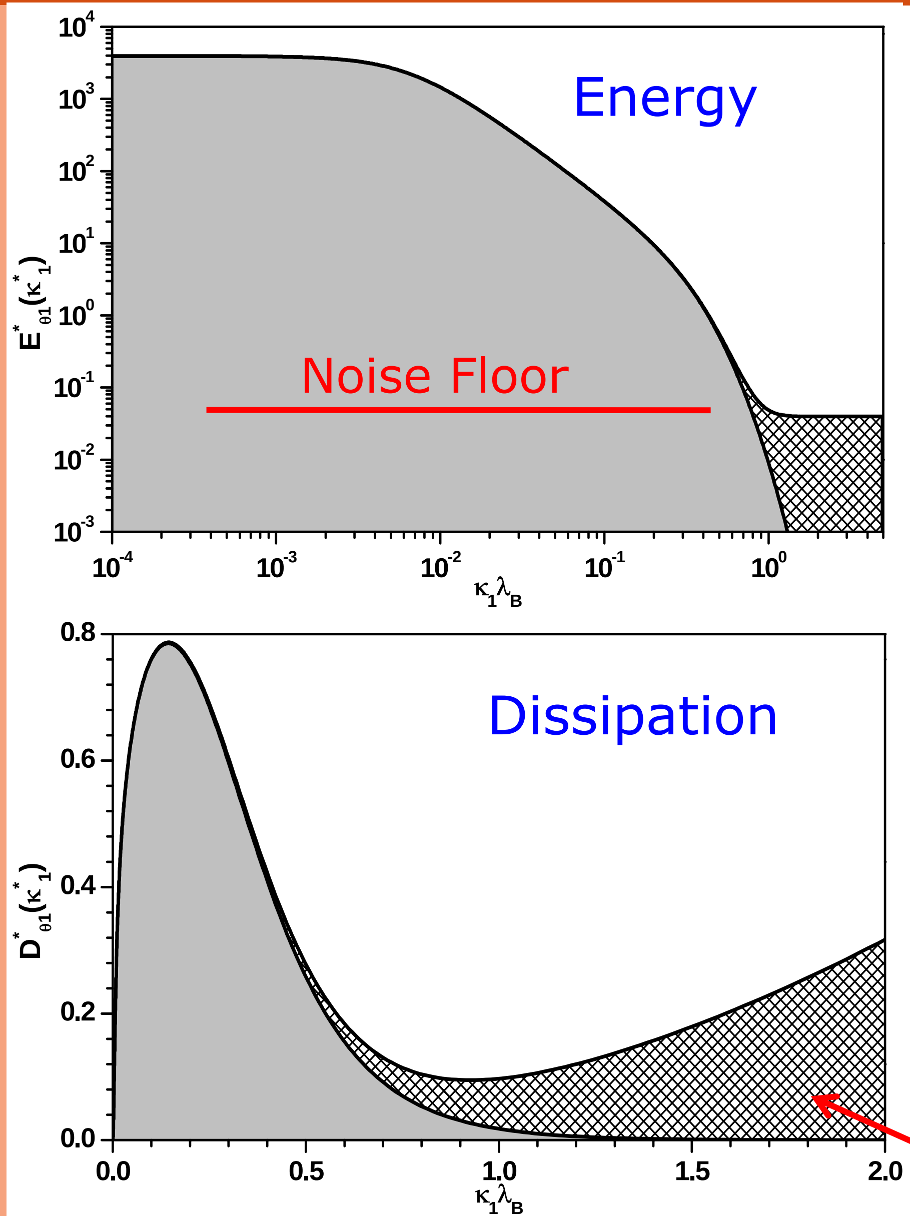
Resolution + Gradient Stencil Effect

- Perfect (spectrally sharp) filters don't show resolution error until filter width about $5\lambda_B$
- Box filter: averages over box width Δ_r



- 2^{nd} Order central difference (sampled at twice cutoff κ_B)
- All techniques attempting to measure same physical scale but have different resolution requirements to do so

Effect of Noise on Spectra



- Energy spectrum with noise floor

$$\left[E_1(\kappa_1)\right]_m = E_1(\kappa_1) + NF$$

- Dissipation spectrum

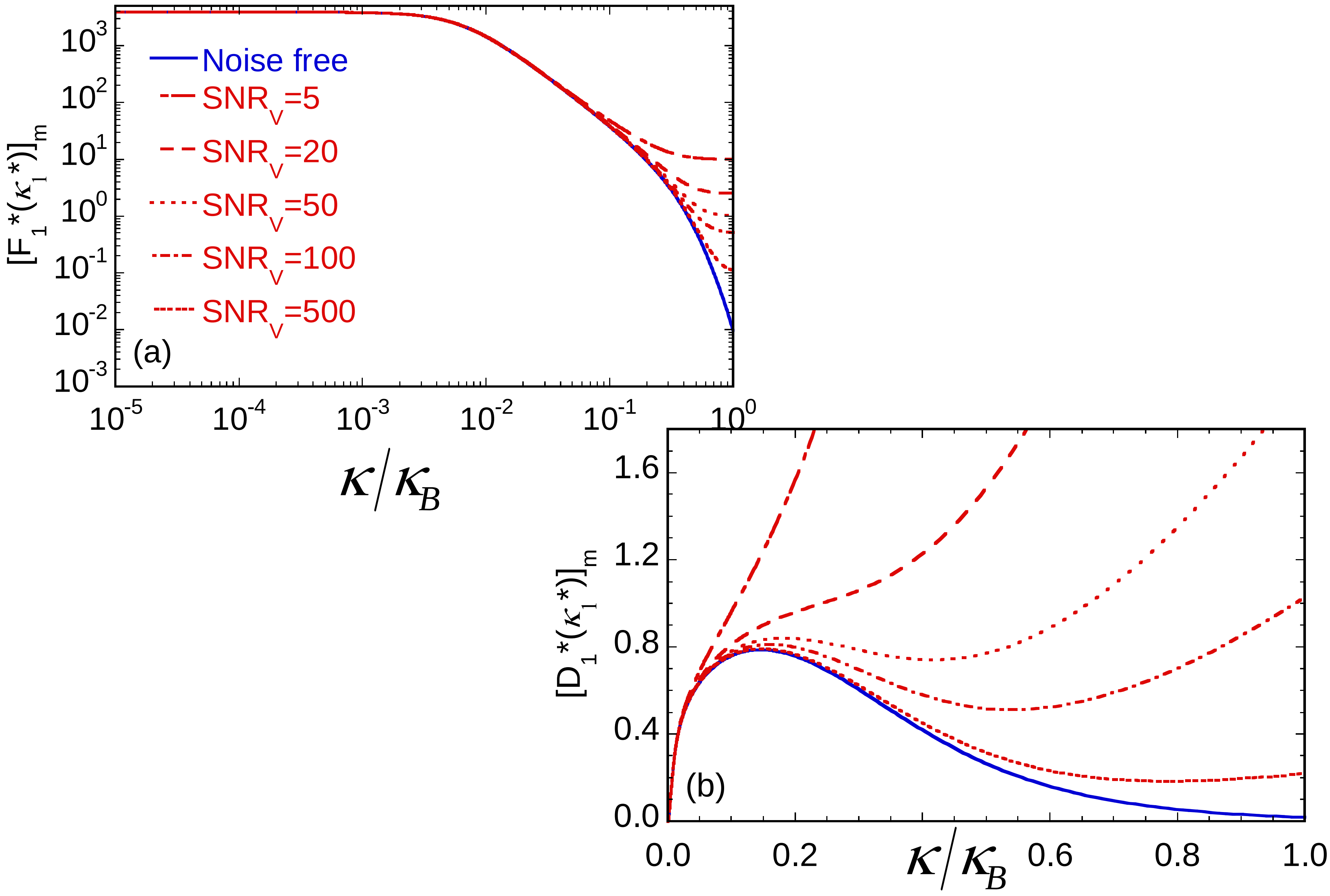
$\Rightarrow$ noise floor amplified when oversampled

$$\left[D_1(\kappa_1)\right]_m = 2D\,\kappa_1^2\left[E_1(\kappa_1) + NF\right]$$

- Flames measurements are virtually always in this regime

Apparent dissipation

Effect of Resolution and Noise



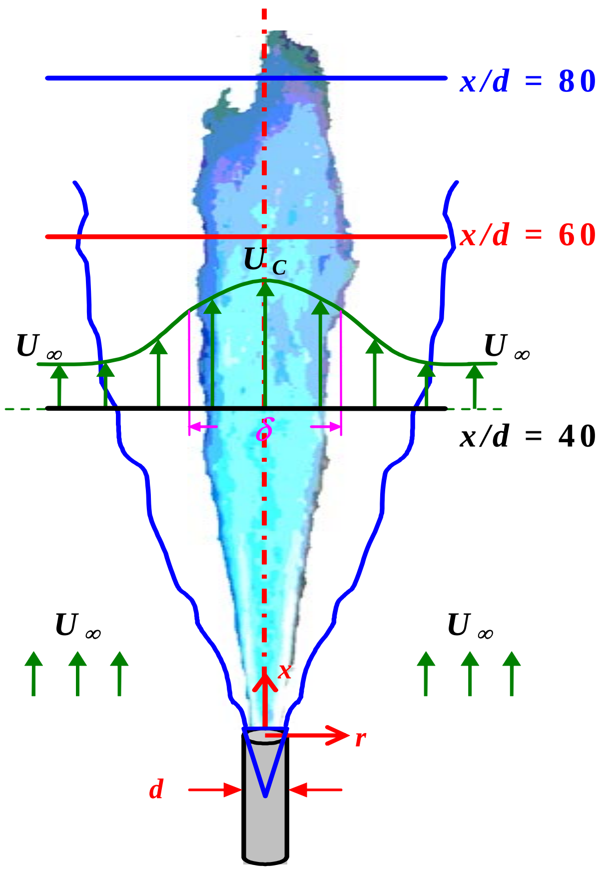
Time-Resolved Thermal Dissipation in Turbulent Nonpremixed Jet Flames

Thermal Dissipation

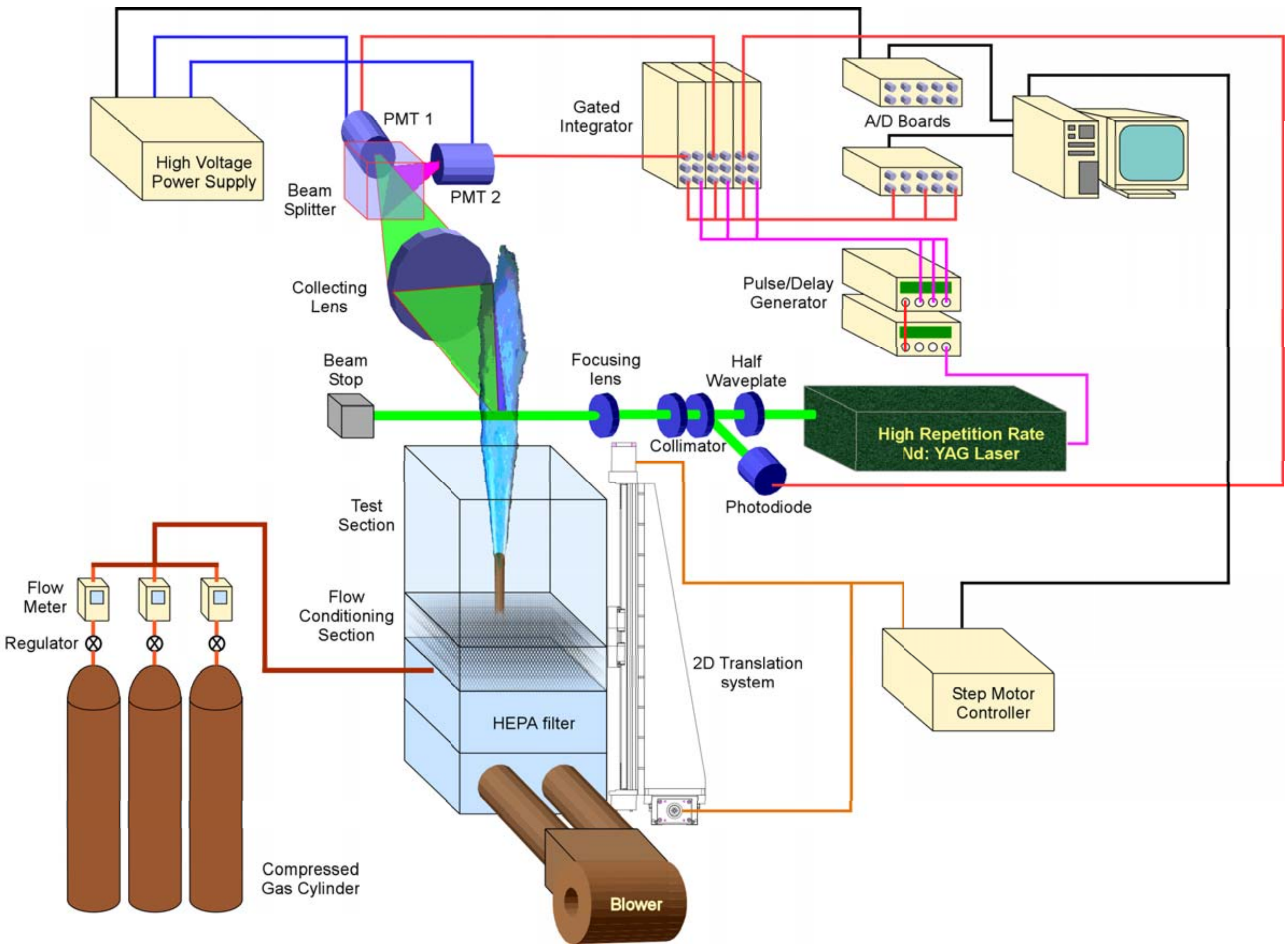
- It is difficult to make accurate mixture fraction dissipation measurements in flames
  - Instead use thermal dissipation as a surrogate for obtaining information about
    - Higher signals for Rayleigh scattering *vs.* Raman
      - Can get time-resolved data!
    - Obtain basic information about turbulence characteristics (frequencies, length-scales, etc.)
    - Obtain estimates of resolution requirements valid for scalar dissipation

Experiment

- Two-point-redundant high-repetition rate laser Rayleigh system
  - High average power (72 W) Nd:YAG laser at 532nm
  - 10 kHz repetition rate
  - Spatial resolution 300 μm, beam diameter, slit width, separation
  - SNR ~ 65 for air at room temperature
- Fuel
  - 22.1% CH_4, 33.2% H_2 and 44.7% N_2
  - TNF workshop simple jet flame (DLR_A)
    - Bergmann et al. (1998)
    - Meier et al. (2000)
    - Schneider et al. (2003)
  - Const effective Rayleigh cross-section (±3%)
- Conditions
  - Coflowing, nonpremixed jet flame
  - Re_d = 15,200
  - f_S = 10 kHz, sampling time period = 6 s



High-Repetition Rate Rayleigh Scattering Setup



Temperature and Dissipation Calculations

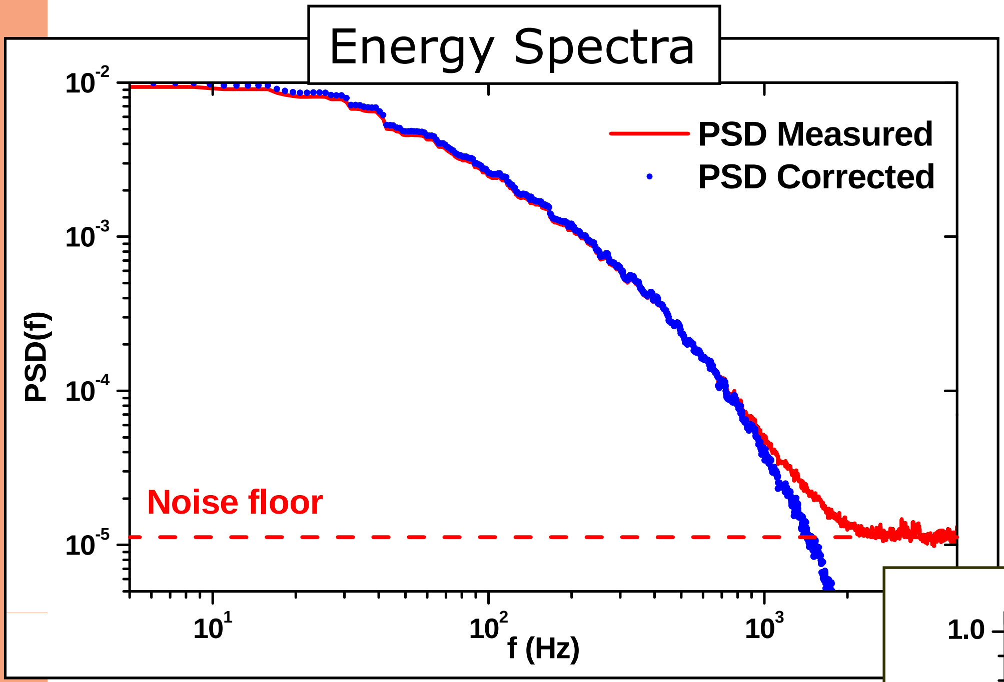
- Temperature: $$T = \frac{I_{R,ref} T_{ref}}{I_R} = \frac{C}{I_R}$$

  $I_{R,ref}$ is the reference Rayleigh signal from air at room temperature (T_{ref}), I_R is the Rayleigh signal

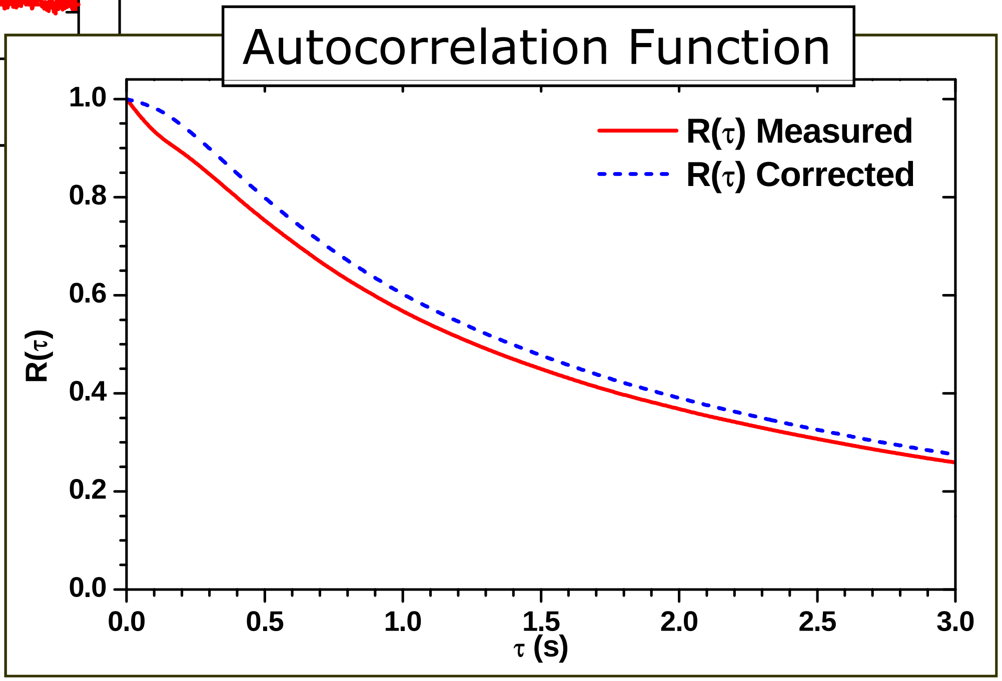
- Thermal dissipation rate (inferred by using Taylor's hypothesis)

$$\chi_{T,x} = 2\alpha U^{-2} \left(\partial T / \partial t \right)^2$$

Energy Spectra Correction



- Gaskey et al. (1990)
- Miller and Dimotakis (1996)
- Renfro et al. (1999, 2000)



Centerline Turbulent Time Scales

- Outer time scale:

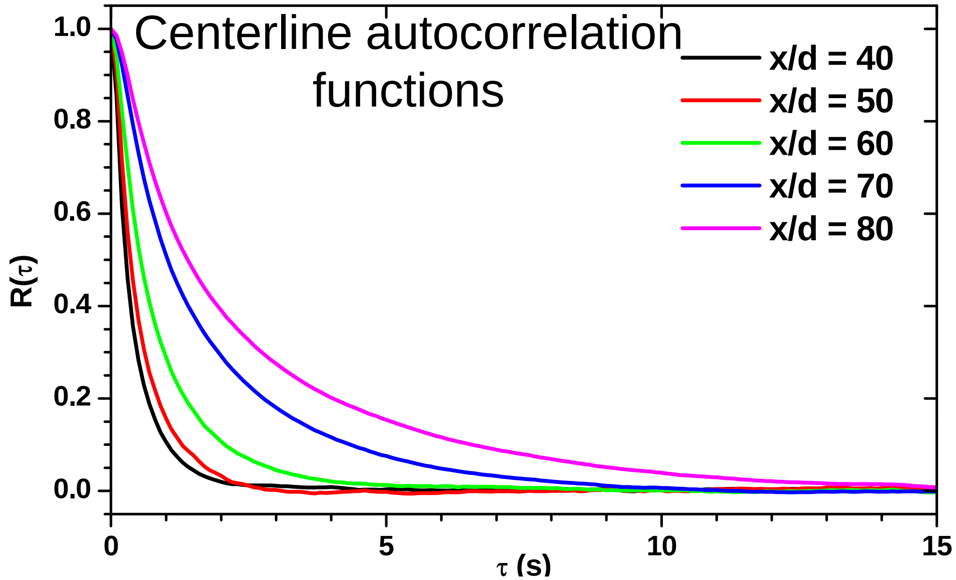
$$\tau_\delta = \delta / U_C$$

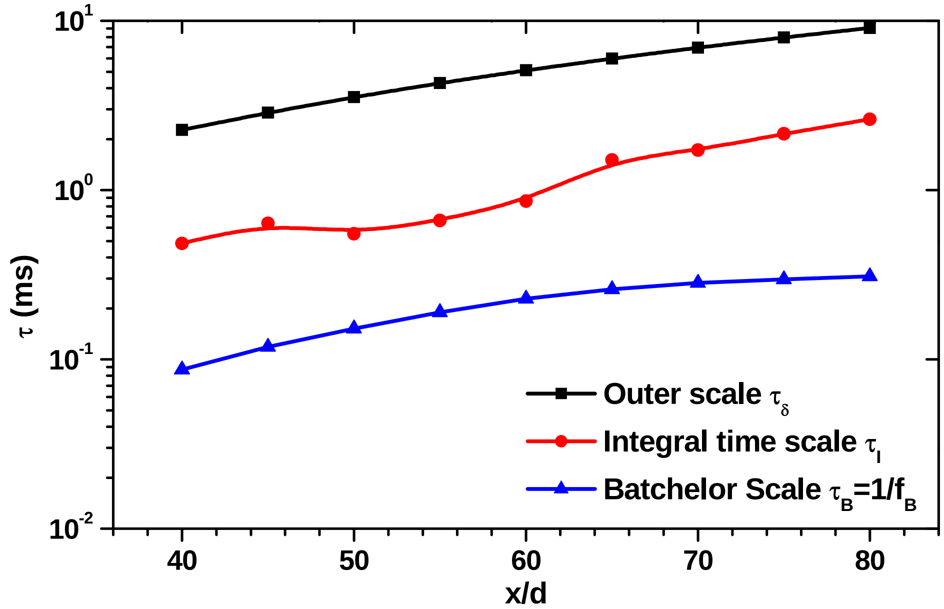
- Integral time scale:

$$\tau_I = \int_0^\infty R_{T'^*}(\tau) d\tau$$

- Batchelor time scale:

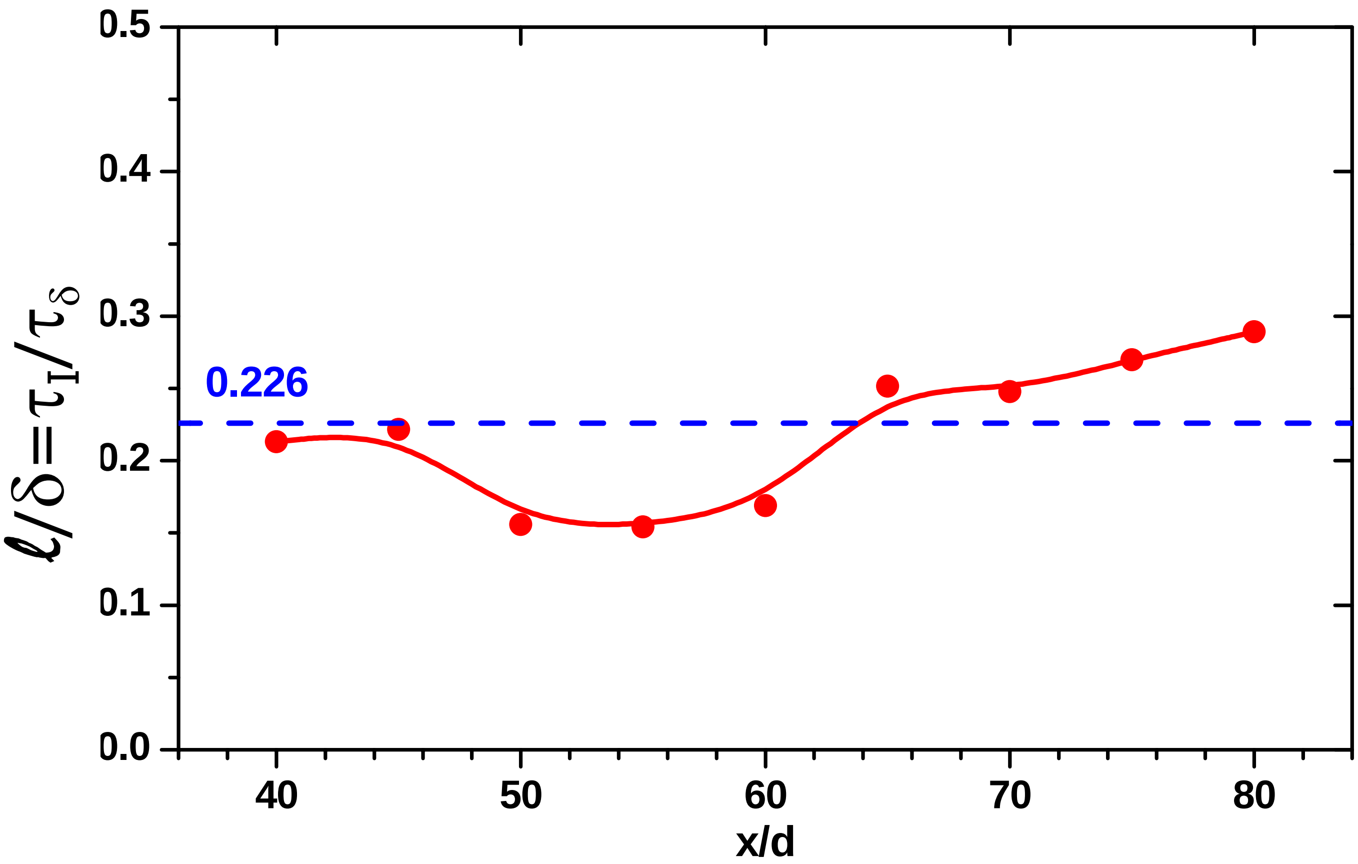
$$\tau_B = 1/ f_B$$





Centerline outer, integral and Batchelor time scales

Ratio of Outer Scales along Centerline

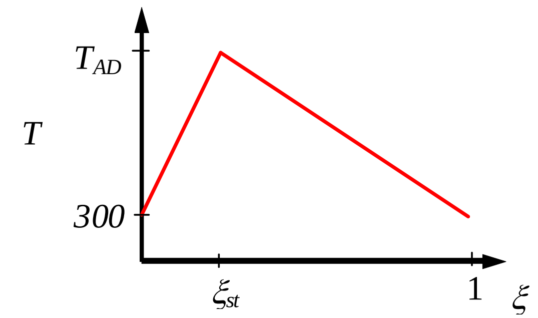


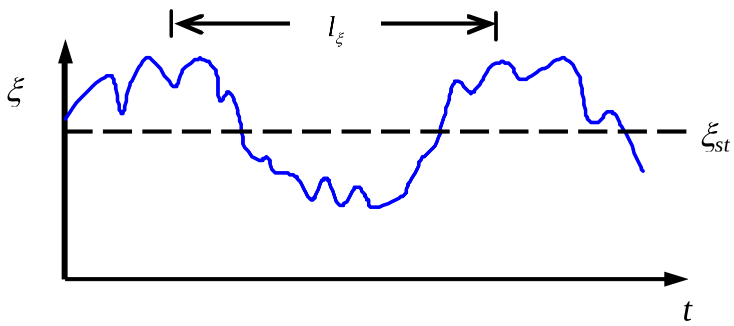
Nonreacting axisymmetric jet
(Wygnanski & Fiedler, 1969):

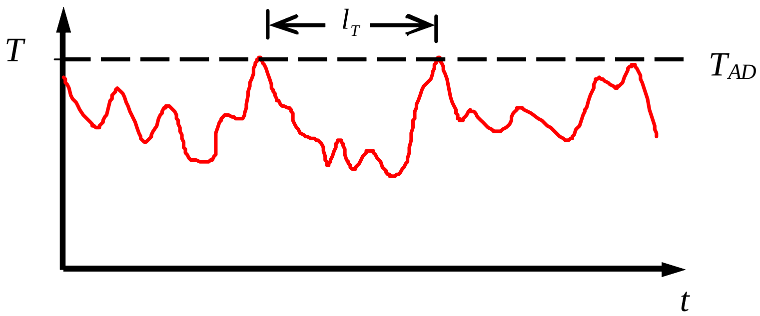
$$l/\delta = \tau_I/\tau_\delta = 0.226$$

Why the dip near the flame tip?

- Why is there a dip in the integral scale near the flame tip?
- Similar effect seen by Renfro et al. (2002) with OH time-series
- Caused by state relationship between temperature and mixture fraction
- Shows that temperature fluctuations will exhibit smaller length scales than mixture fraction
- Shown empirically by Wang, Karpetis, Barlow (2007)







Corrected Energy and Dissipation Spectra

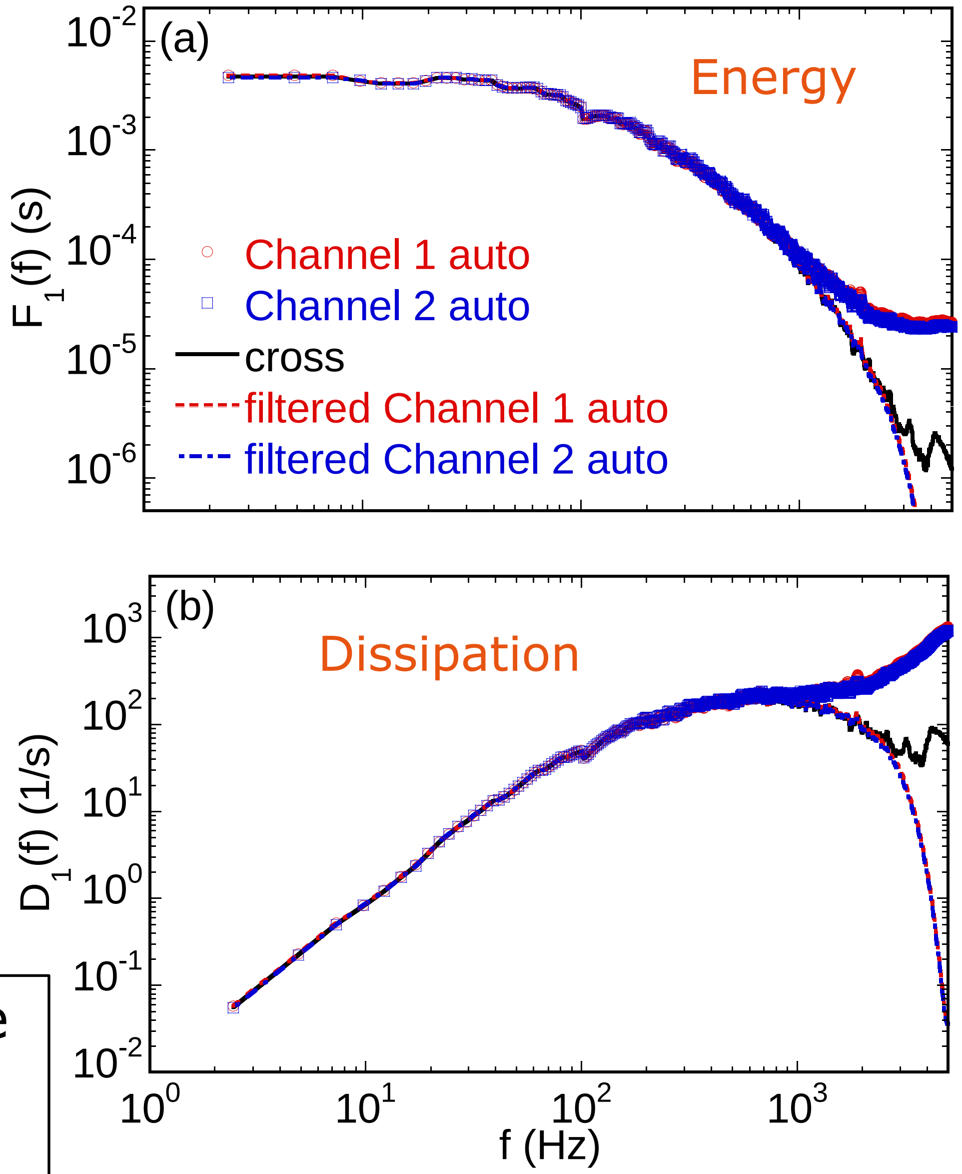
PSDs computed by:

- auto-correlation (single-probe)
- cross-correlation of two-point redundant (Panda & Seasholz, 2002)
- low-pass filtering

$$R_m^{XY} = \langle T_1' * T_2' \rangle + \langle n_1' * n_2' \rangle$$

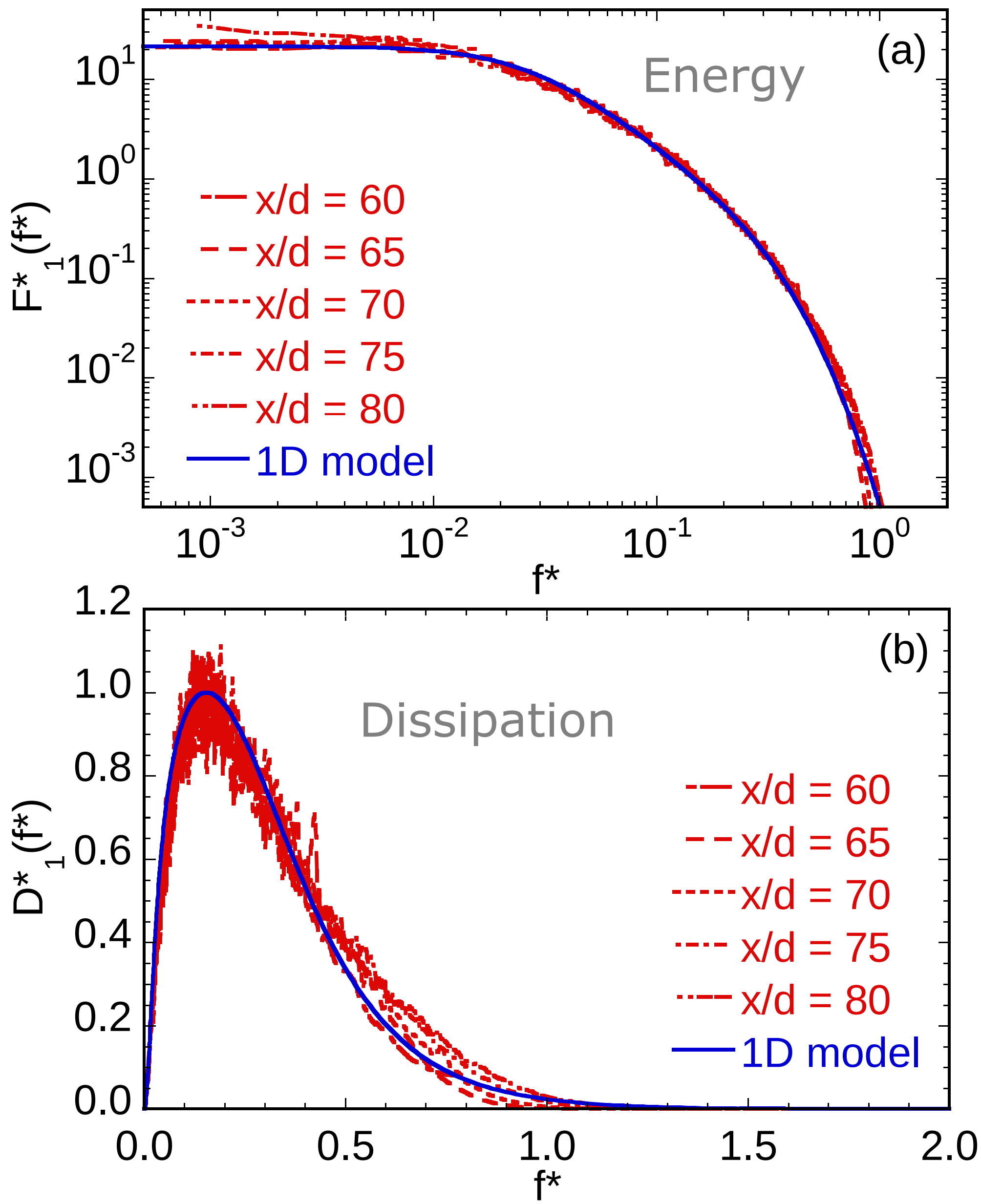
$$= \langle T_1' * T_1' \rangle \approx R^{XX}$$

Noise is averaged out and true autocorrelation function is recovered

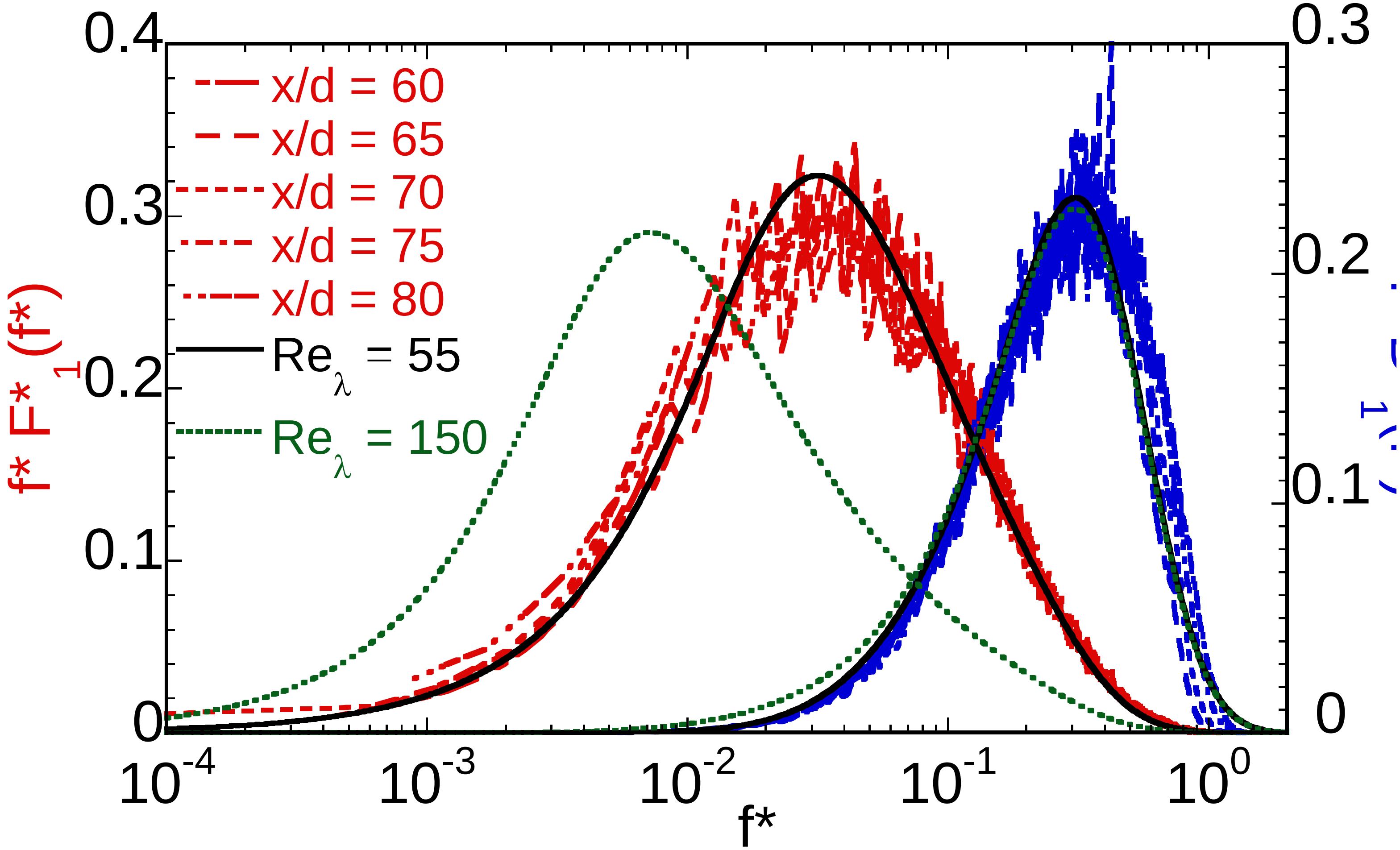


Corrected Energy and Dissipation Spectra

- Spectra computed with:
  - Cross-correlation
  - Filtering with specially designed FIR filter to match rolloff of model spectrum
- Importantly, the peak and some rolloff of dissipation spectrum is seen
- Need the model spectrum to guide filtering



Corrected Dissipation Spectra, Re_d=15,000



Overlapping spectra indicate strong coupling between energy producing and dissipation scales

- May be problematic for models that require independence of dissipation scales

Conclusions

- Dissipation affected by interaction among spatial averaging, discrete sampling, gradient-filter and noise
- Many previous measurements in flames incompletely quantify these effects and are therefore suspect
- Our system model helps us to understand these effects and enables meaningful measurement of dissipation