# STUD Pulses for Shock Ignition and LPI Control

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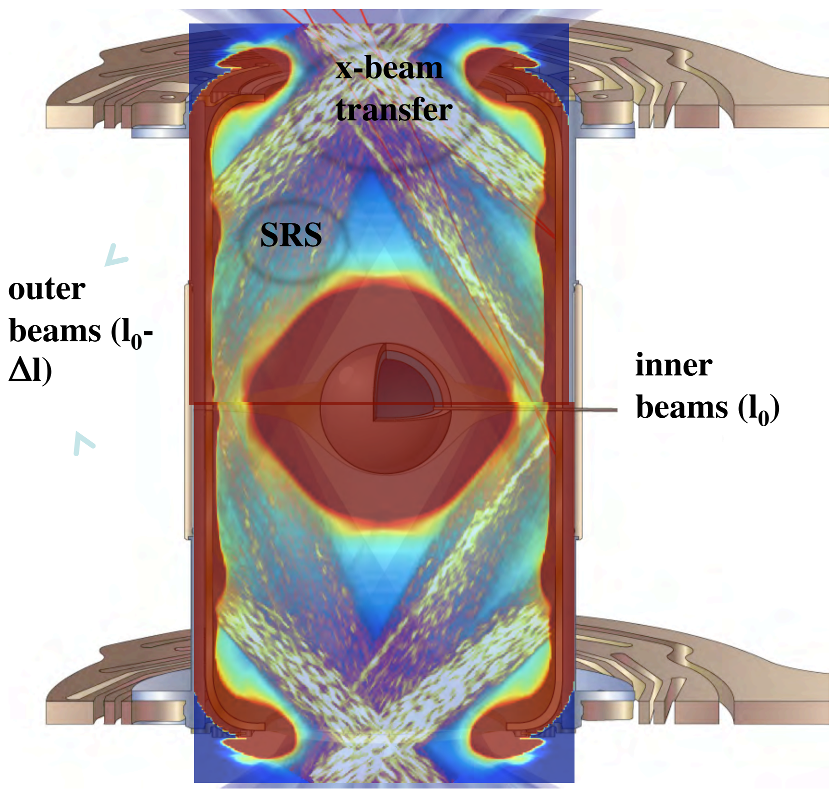
$\omega_{pe}^2 = \frac{4\pi n_e e^2}{m_e}$ $\frac{e^2}{\hbar c} = \frac{1}{137}$

# Adequate Control of Laser-Plasma Instabilities is Required to Achieve Indirect-Drive Ignition




- Energy coupling should be > 90% to achieve required $T_{rad}$

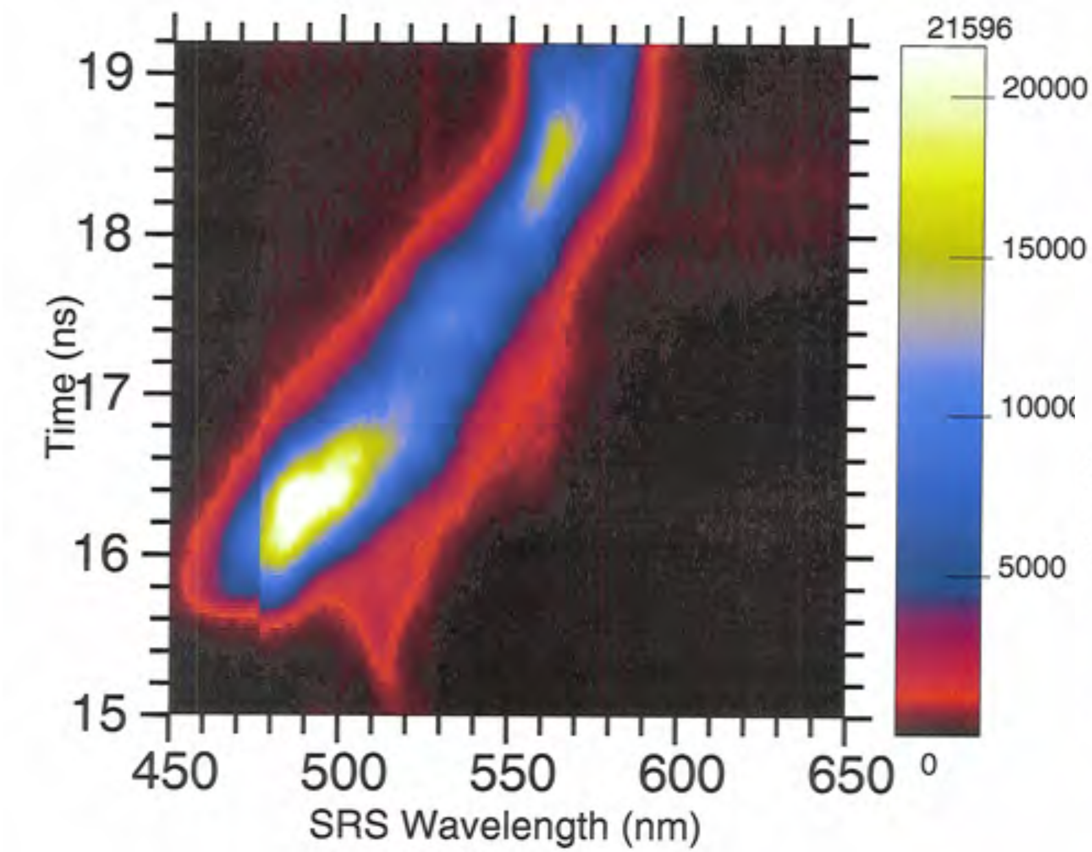
- Implosion symmetry requires controlled power balance between “inner” and “outer” beams (x-ray flux on equator vs. poles)

- low capsule preheat ($T_{hot}$, $f_{hot}$)

- these requirements translate to control of SBS, SRS, $2\omega_p$, filamentation, beam-steering, cross-beam energy transfer

# SRS Spectra from the Inner Cone Beams on the NIF Show Alarming Levels With Unpredicted Features

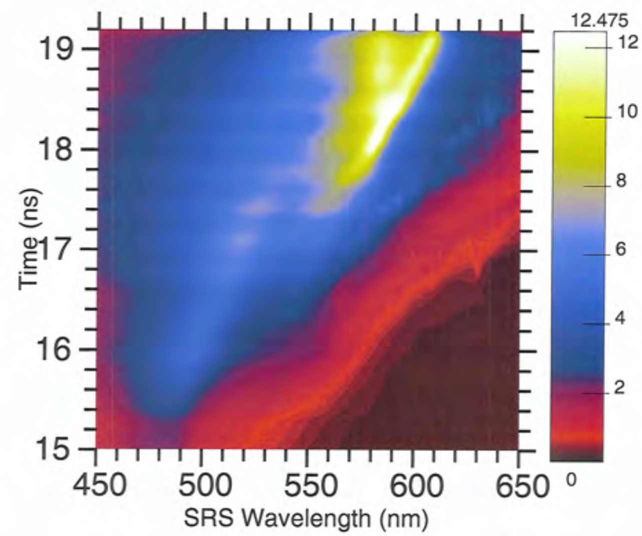
N091204 “1MJ shot”




Measured streaked spectrometer data

The SRS reflectivity at these high intensities is alarmingly high: > 40%

Single beam SRS Gain spectrum from LIP



# Most Prominent LPI Processes Are: SRS, SBS, $2\omega_p$, Filamentation

SRS $\boxed{\mathbf{EMW \rightarrow EMW + EPW}}$ $T_{rad}$, symmetry, preheat

Very dangerous Instability for indirect drive ICF. Did in the Shiva Laser at 1 $\mu$m back in the 70's. Almost equal amounts of hot e- generation and Backscattering

SBS $\boxed{\mathbf{EMW \rightarrow EMW + IAW}}$ $T_{rad}$, symmetry

Very dangerous Instability for indirect drive. Almost all the energy goes to the scattered light wave. Velocity gradients can potentially tame it.

$2\omega_p$ $\boxed{\mathbf{EMW \rightarrow EPW + EPW}}$ preheat

Very dangerous instability for direct drive. It has the lowest intensity threshold, all the energy goes to coherent high frequency oscillations of the plasma and then perhaps to IAWs but with preheat getting you first.

FIL Breakup of the laser light into dancing filaments. Really a 4 wave process including both Stokes and Anti-Stokes components interacting with a degenerate zero frequency IAW. Related to Self-Focusing in classical NLO. symmetry

# Direct Drive w or w/o Shock Ignition Also Requires LPI Control

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- If we do not keep the growth of parametric instabilities under strict control during the main pulse, then the hot electron preheat will make the final shock have dubious prospects.

- Worry about SRS and $2\omega_p$ as the two most likely hot electron generating instabilities via their plasma waves daughter waves.

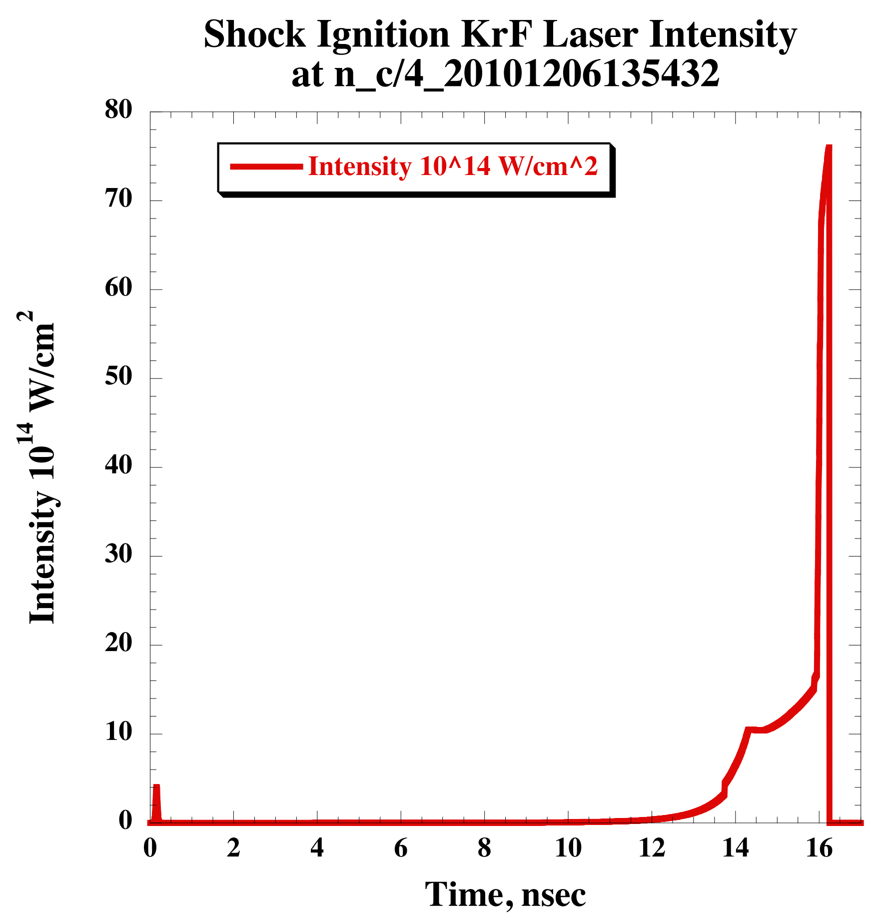
- Worry about the physics of multiple of massively overlapping beams, hot spots overlapping, triggering each other's instabilities, nonlocal influences in space, mediated by hot electrons, secondary instabilities, SRS/SBS anti-correlation, ...

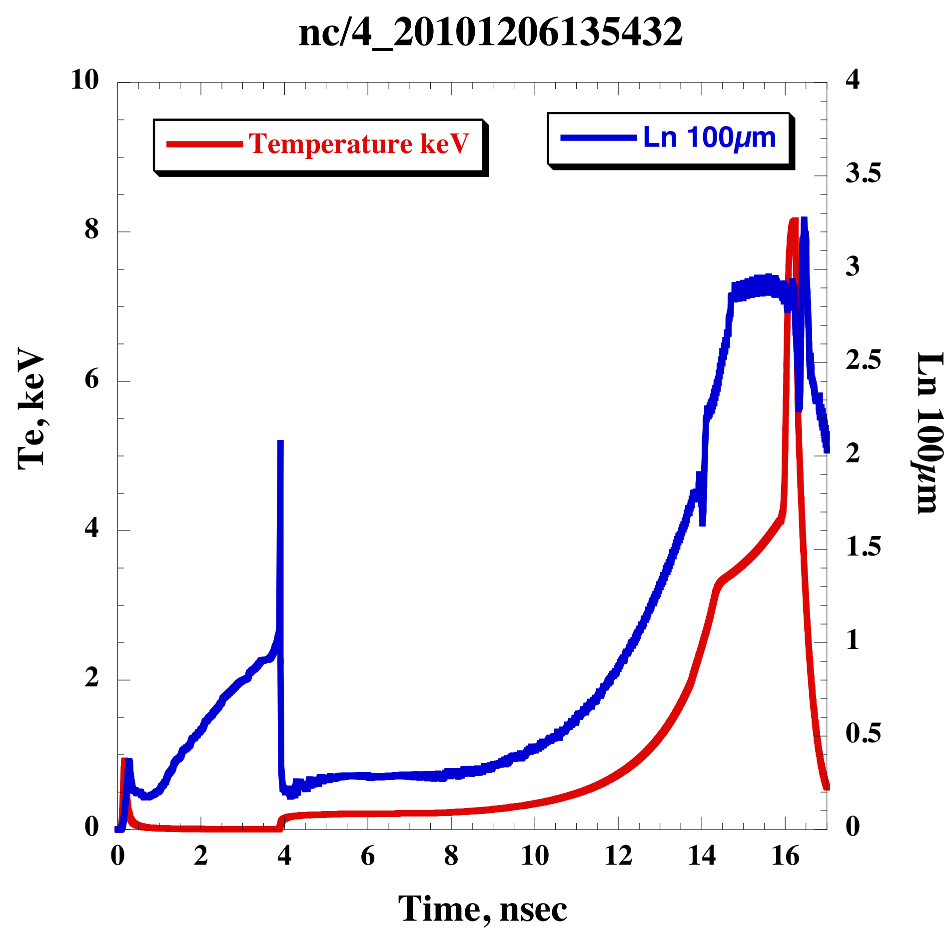
- This is not your grandfather's LPI scenario.

- For shock ignition, need to convert the right distribution of hot $e^-$s into a sharp heat front that becomes that last shock, quickly assembled. Designing this is a wonderful challenge of our knowledge of LPI physics.

- What wavelength to use for the last shock, what pulse shape, what intensity regime, all remain open and exciting questions.

# Typical Shock Ignition Parameters and Profiles



# Outline

- **STUD pulses:** Spike Trains of Uneven Duration and Delay for the control of LPI in DD, ID, SI, Green driven ICF, etc.

- STUD pulses are designed laser pulse shapes that adaptively mitigate LPI as plasma conditions change.

- A theoretical model that contains the essential elements of this new approach including the role played by Gaussian random fields and hot spot recurrence time estimates.

- Numerical simulations of SBS in structured beams comparing Continuous RPP pulses to highly modulated STUD and pseudo STUD pulses with or without pump depletion. In Pseudo-STUD pulses, the pulse is modulated in time just as in a STUD pulse but the speckle patterns are not changed in between successive spikes.

- Note the cumulative effect of stationary and repeatedly driven IAWs or EPWs in RPP or SSD beams is eliminated in STUD pulses since the hot spots move around randomly from spike to spike and don’t come back to the same locations before the plasma modes are damped if $t_{recur} > t_{damp} > t_{spike} > t_{growth}$.

# A New Approach to LPI Control

- Instead of just phase control (in space-time) through masks and electro-optic modulators, or the all purpose PS solution, it is worth exploring the intentional variation of the amplitude and duration of short bursts of laser light ==> **STUD pulses**: Spike Train of Uneven Duration or Delay.

- Use **variable width spikes** to last 4-8 growth times of the most unstable mode to be avoided, and then shut off the pump long enough to disallow self-organization of plasma into coherent large amplitude waves which can then do real damage, and then repeat.

- Divide and conquer the laser's propensity to whip the entire plasma up into a coherent pump driven LPI haven. **Start and stop the interaction processes to avoid cumulative damage**. Three main reasons you win with STUD pulses: Don't allow growth in entire hot spot, avoid hitting the same driven wave by the same or similar hot spot over and over again, damp the wave between recurrence of hot spots to the same location as previously driven waves.

# Three Physical Mechanisms Are Primarily Responsible for Producing Unprecedented Control of Laser-Plasma Instability with STUD Pulses
## (Pump Depletion PD or NPD, Self Focusing SF or NSF)

- By **turning the pump on and off** on a time scale short compared to the hot spot traversal time, get lower gains per hot spot. (STUD and Pseudo-STUD, SDL and WDL)

- By turning the **laser off roughly half the time**, you allow time in between spikes for the driven EPWs or IAWs to damp. No damping effect exists in the Rosenbluth Gain model of parametric amplification in an inhomogeneous linear profile plasma for a continuous pulse. (STUD and Pseudo-STUD, SDL only)

- By **scrambling the hot spots around in space between spikes**, break the repeated growth of locally driven EPWs and IAWs when the pump is on at the same place all the time. Recurrence time being long wins. (STUD, SDL mostly)

# Highlights of What Lies Ahead with Designed STUD Pulses, All Absent in Present Illumination Schemes

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- **STUD pulses**: **Spike Trains of Uneven Duration and Delay** may help **control LPI once and for all** in DD, ID, SI, Green driven ICF, hotter holraums.
- Can we systematically avoid absolute instabilities (no coherent feedback allowed)?
- Can we limit or halt the growth of convective instabilities?
- Can we take advantage of plasma wave damping even in inhomogeneous plasmas (beat the MNR model oddity that damping never affects gain even in the SDL)?
- Can we take advantage of the dancing beamlets scenario of plasma induced laser incoherence generation in order to decorrelate successive spikes in a STUD pulse?
- **STUD pulses allow Green Laser use for Indirect Drive.**
- **Allow LEH LPI Control (turn on, or switch off) for Indirect Drive.**
- **Allow Overlapping Beam LPI Catastrophe** to be averted in direct drive.
- Allow restraining hot electron generation at first for Fast or Shock ignition and hot electron unleashing at the end of a **Shock Ignition** pulse.
- Allow hotter hohlraums, thicker ablators, solve the ablator-fuel mix problem.

# STUD Pulses Address Overlapping Beam and Beam Crossing Problems that Adversely Impact ICF and IFE

- By **interleaving inner and outer cone beams** in time, with STUD pulses where the spikes do not overlap in time, we control the crossing beam interactions at the LEH which has its own logic in conventional long pulse, illumination schemes.

- By **randomly offsetting the STUD pulses in *different* overlapping beams** in DD ICF, we drastically reduce the possibility of symmetric mutually driven modes by reducing that symmetry by a factor as large as a square root of N, where N is the number of overlapping beams.

- From $\exp[N\,\gamma_0\,\Delta t]$ to $N/2 * \exp[2\,\gamma_0\,\Delta t]$ is an increase in control that is substantial. Since N can be 1000 or more, $\ln[N] / N$ can be smaller than 0.007: **OPT FOR INCOHERENT ADDITION of ELEMENTARY GROWTH SPURTS.**

- The option to consider **Green** or **Red** lasers for IFE and ICF become possible.

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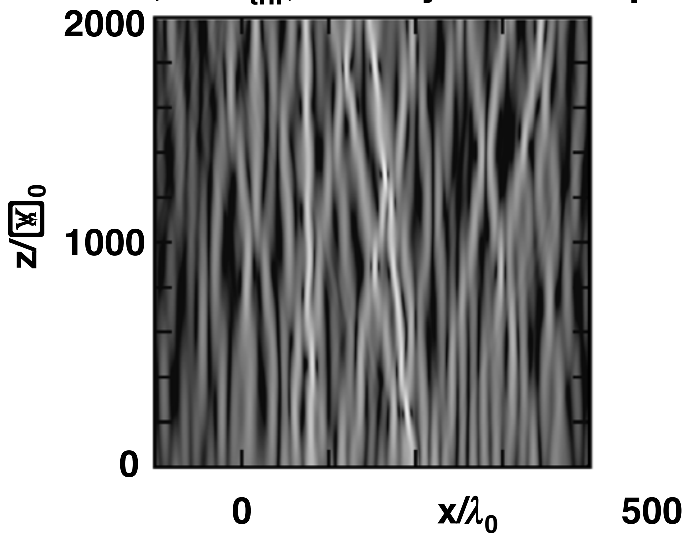
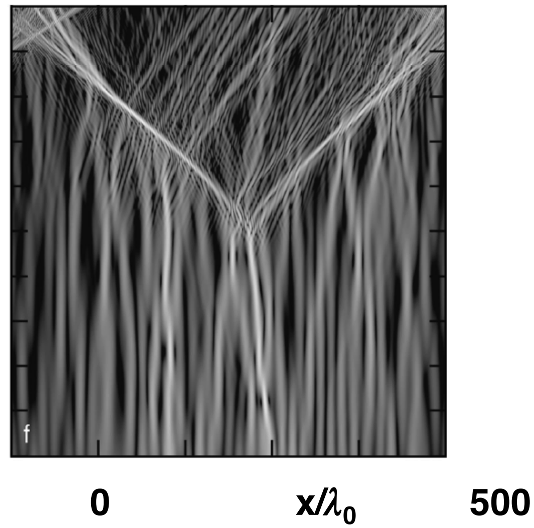
# Understanding the Coherent and Incoherent Interactions between Multiple Crossing laser Beams Is an Outstanding Challenge in NLO

**Single beam, $I < I_{thr}$, steady state response**

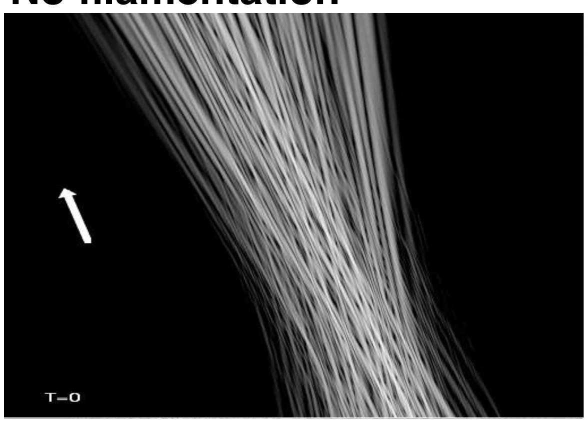



**$I > I_{thr}$, nonstationarity & "dancing beamlets" are unavoidable**

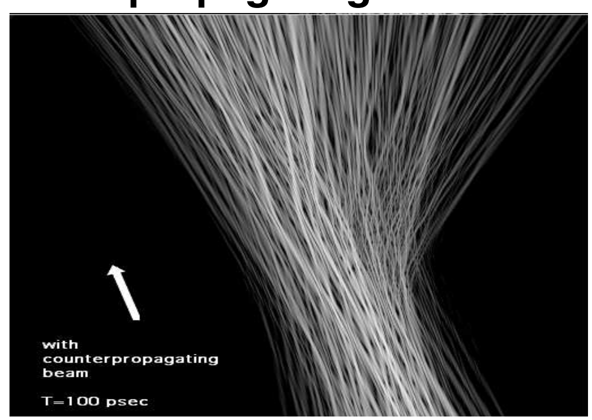



**Dancing Beamlets**

**$I < I_{thr}$, single-beam simulation**
**No filamentation**




**$I < I_{thr}$, non-resonant, lower amplitude counterpropagating beam seeds enhanced scatter**




**Schmitt & Afeyan, PoP 5, 503 (1998)**

- **Filamentation strongly affects the initiation and evolution of SRS and SBS backscatter as well as beam pointing.**

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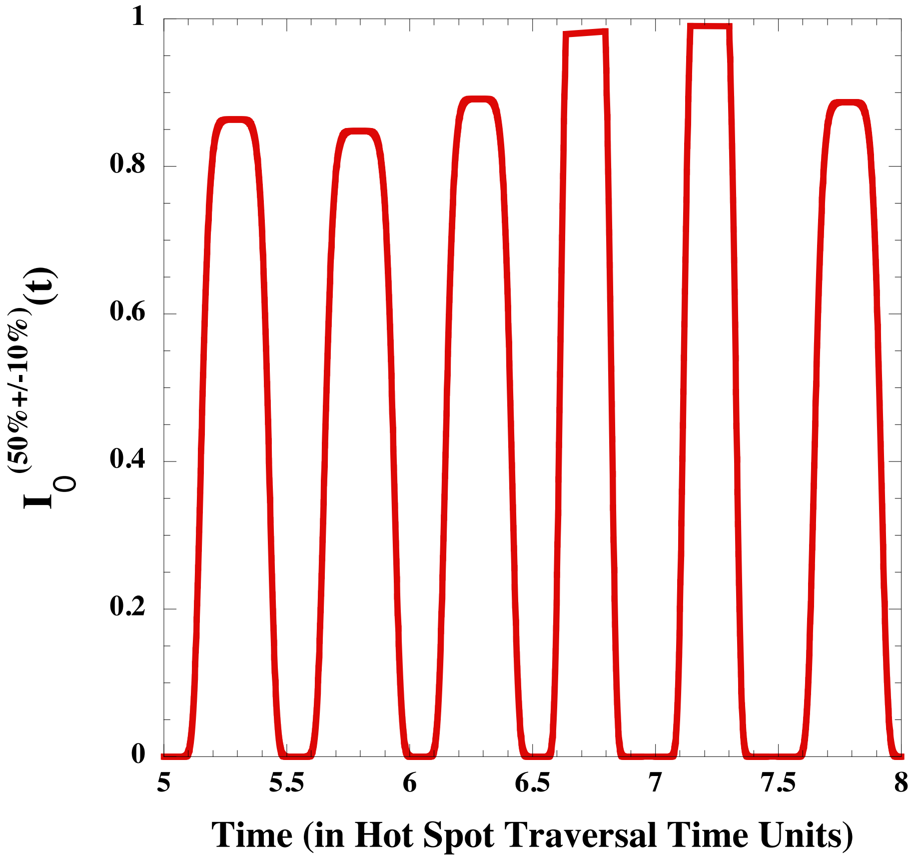
# What Do STUD Pulses Look Like?

$$I_0(t) = \sum_{n=1}^{N_{SPIKES}} I_0^{(n)} \exp - \left[ \frac{\left(t - t_c^n\right)}{\left(t_W^n / 2\right)} \right]^{2\sigma_n}$$

$$I_o^{(n)} \times t_{width}^{on(n)} = I_o^{(n+1)} \times t_{width}^{on(n+1)}; \quad \forall n$$

$$t_{width}^{on(n)} + t_{width}^{off(n)} = t_{width}^{on(n+1)} + t_{width}^{off(n+1)}; \quad \forall n$$

STUD Pulse Shape 10% Random Modulation of a 50% Duty Cycle

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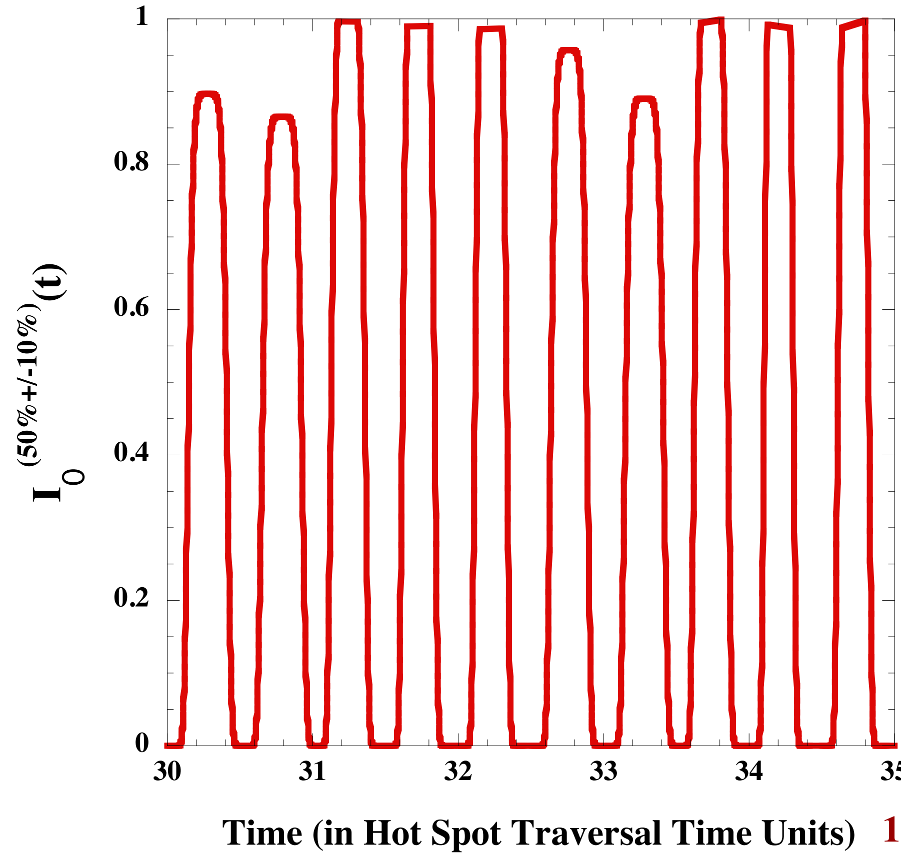

# What Do STUD Pulses Typically Look Like?

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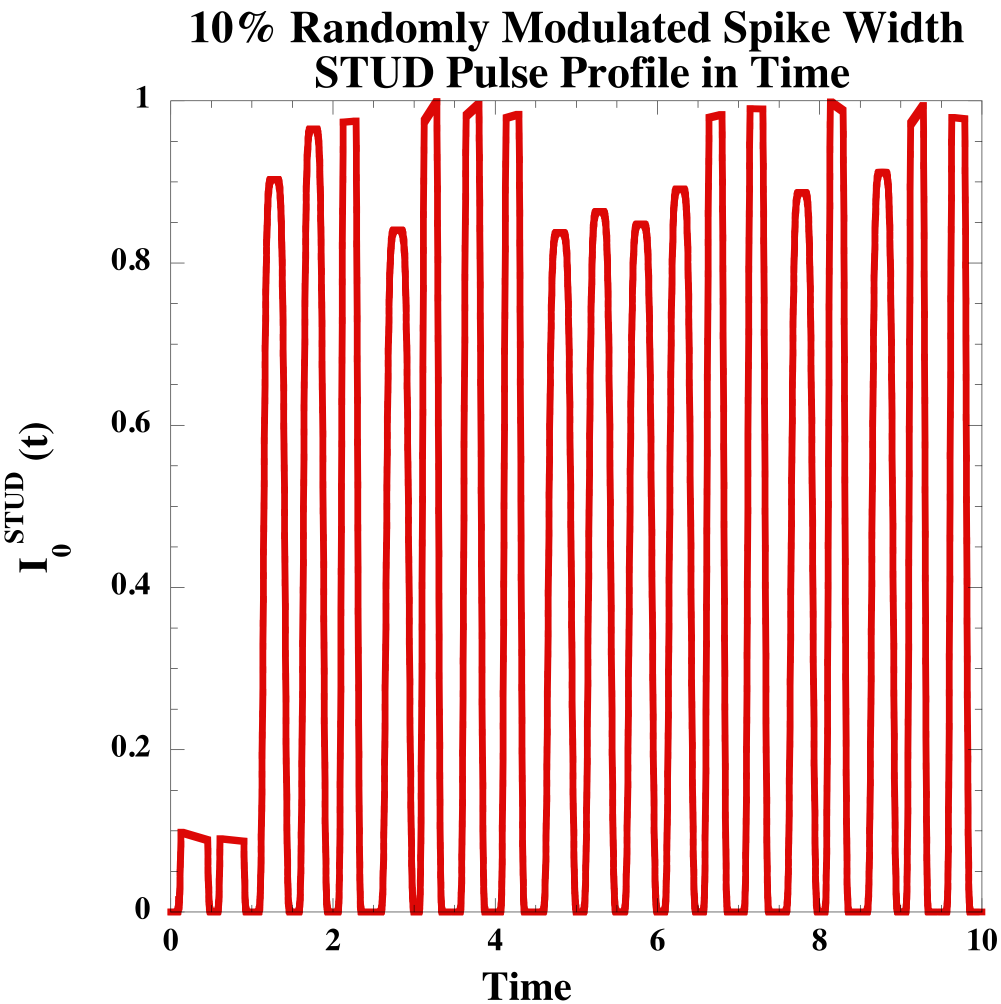
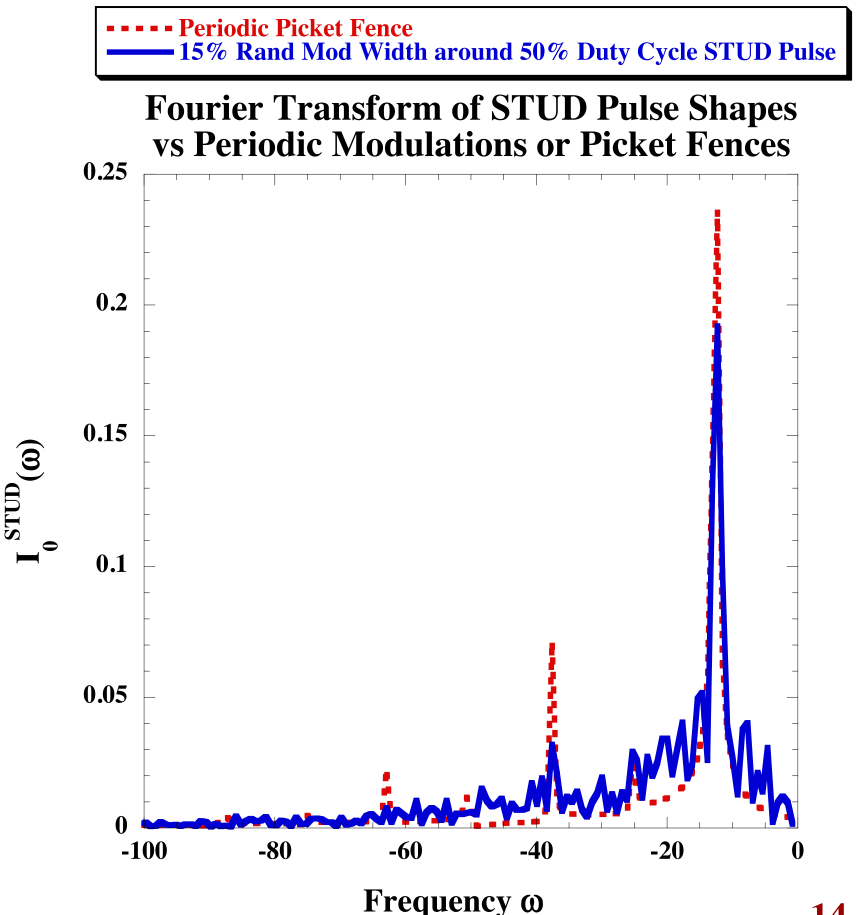
$$I_0(t) = \sum_{n=1}^{N_{SPIKES}} I_0^{(n)} \exp - \left[ \frac{\left(t - t_c^n\right)}{\left(t_W^n/2\right)} \right]^{2\sigma_n}$$

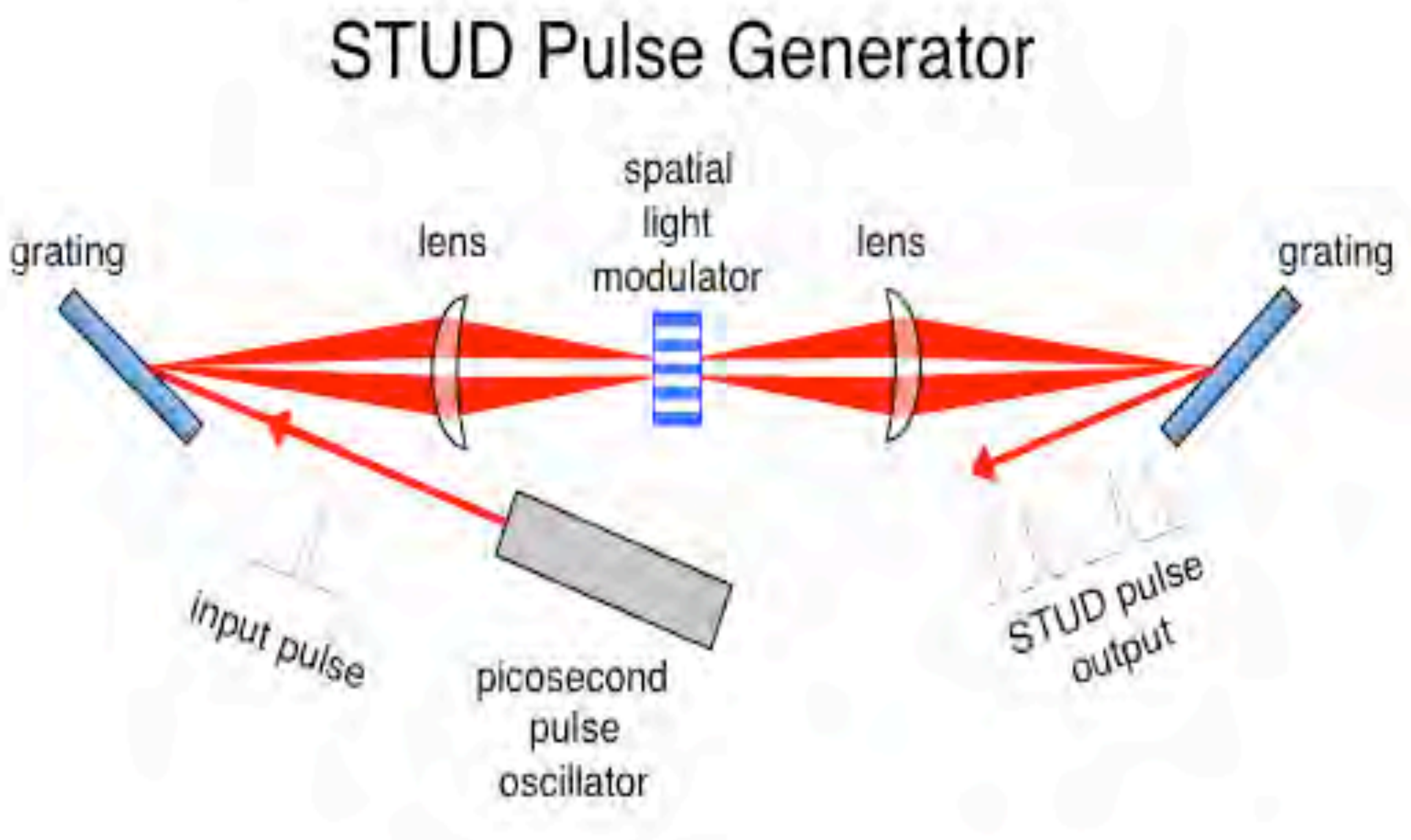
$$I_o^{(n)} \times t_{width}^{on(n)} = I_o^{(n+1)} \times t_{width}^{on(n+1)}; \quad \forall n$$

$$t_{width}^{on(n)} + t_{width}^{off(n)} = t_{width}^{on(n+1)} + t_{width}^{off(n+1)}; \quad \forall n$$



# How Do We Generate STUD Pulses? 4*f* or 6*f* System of USP Laser




Wiener, *Ultrafast Optics*, 2009

# SRS and SBS in the Strong Damping Limit Driven by STUD Pulses: An Analytically Solvable Nonlinear Model

$$\bar{L}_1 a_1 = \left( \frac{\partial}{\partial t} + V_1 \frac{\partial}{\partial z} + i\, \beta_1\, \nabla_\perp^2 + \nu_1 - \frac{|\gamma_0|^2 |a_0|^2}{\bar{\nu}_2} \right) a_1 = \frac{\gamma_0 a_0 e^{i\varphi}}{\bar{\nu}_2} S_2^* + S_1$$

$$\bar{L}_0 a_0 = \left( \frac{\partial}{\partial t} - V_0 \frac{\partial}{\partial z} - i\, \beta_2\, \nabla_\perp^2 + \nu_0 - \frac{|\gamma_0|^2 |a_1|^2}{\bar{\nu}_2} \right) a_0 = \frac{\gamma_0^* a_1 e^{-i\varphi}}{\bar{\nu}_2} S_2 + S_0$$

$$\bar{\nu}_2 = \nu_2 - i\, V_2 \left[ k_0(z) - k_1(z) - k_2(z) \right]$$

Transform into a frame moving with the STUD pulse SPIKES and do integration over pulses as integrals over space (z).

$$S_0(z,t;x_\perp) = \sum_{i=1}^{N_{HS}} f_z\left( \frac{z - z_{C,i}}{z_{W,i}} \right) \sum_{j=1}^{N_{spikes}} S_{0,j}^{(i)}\left( \frac{t - t_{C,j}}{t_{W,j}} \right)$$

Then average over transverse distributions which reflect the hot spot exponential statistics.

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# The Gain Exponent of SRS or SBS in the Strong Damping Limit is Made Up of Individual Elements of this Form

$$\mathbf{L}_{HS}\left(8 f^2 \lambda_0\right) : \mathbf{L}_{INT}\left(\frac{\nu_2}{V_1 \kappa'}\right) : \mathbf{L}_{Spike(i)}\left(V_1 \tau_{Spike(i)}\right)$$

The smallest of these three lengths will dictate the individual HS's contribution to the overall gain during each spike of a STUD pulse train of spikes.

$$\tilde{G}^{(i)}(z) = \left[\frac{\left|\gamma_0\right|^2_{MAX} \left|a_0^{(i)}\right|^2}{V_1^2 \kappa'}\right] \times \left[\mathrm{Tan}^{-1}\left[\frac{\left(z - z_{PPMP}\right)}{L_{INT}}\right] - \mathrm{Tan}^{-1}\left[\frac{\left(z_R - z_{PPMP}\right)}{L_{INT}}\right]\right]$$

$$\tilde{G}^{(i)}(z)\Big|_{\text{Largest Possible Gain}} = \pi \left[\frac{\left|\gamma_0\right|^2_{MAX} \left|a_0^{(i)}\right|^2}{V_1^2 \kappa'}\right]$$

$$\tilde{G}^{(i)}(z)\Big|_{\text{small Gain}} = \left[\frac{\left|\gamma_0\right|^2_{MAX} \left|a_0^{(i)}\right|^2}{V_1 \nu_2}\right] \times \left|\left(z - z_R\right)\right|$$

$$S_0\left(z, t; x_\perp\right) = \sum_{i=1}^{N_{HS}} f_z\left(\frac{z - z_{C,i}}{z_{W,i}}\right) \sum_{j=1}^{N_{spikes}} S_{0,j}^{(i)}\left(\frac{t - t_{C,j}}{t_{W,j}}\right)$$

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# A Hierarchy of Scales and Models Exist to Capture the Physics of SBS or SRS at Higher and Higher Intensities

- WDL: $\nu_{IAW} / \gamma_0 << 1$ ➔ G ~ $\gamma_0^2/\kappa' V_1 V_2$ but also, the possibility of an absolute instability
- SDL: $\nu_{IAW} / \gamma_0 >> 1$ ➔ G ~ $\gamma_0^2 / \kappa' V_1 V_2$ without absolute instabilities.
- WCL: $\gamma_0/\omega_{IAW} << 1$ ➔ G ~ $\gamma_0^2/\kappa' V_1 V_2$ easy to violate in hot spots.
- SCL: $\gamma_0/\omega_{IAW} >> 1$ ➔ G ~ $\gamma_0^{2/3}$ + laser intensity dependent IAW frequency shifts. Multiple resonances in an inhomogeneous flow profile.
- PD or w/o PD: Clamp Gain to Reflectivity < 1 values or arbitrarily large growth or need to model IAW nonlinearity.
- SF or w/o SF: SCL & FIL in nonuniform flow interesting nonstationarity results: No longer GRF. Prominent tails develop. New regimes of statistical behavior.
- Single Beam vs Overlapped Beams. Easy to get off the GRF reservation.

# What Do Structured or Speckled RPP/ DPP/CPP Laser Beams Look Like?

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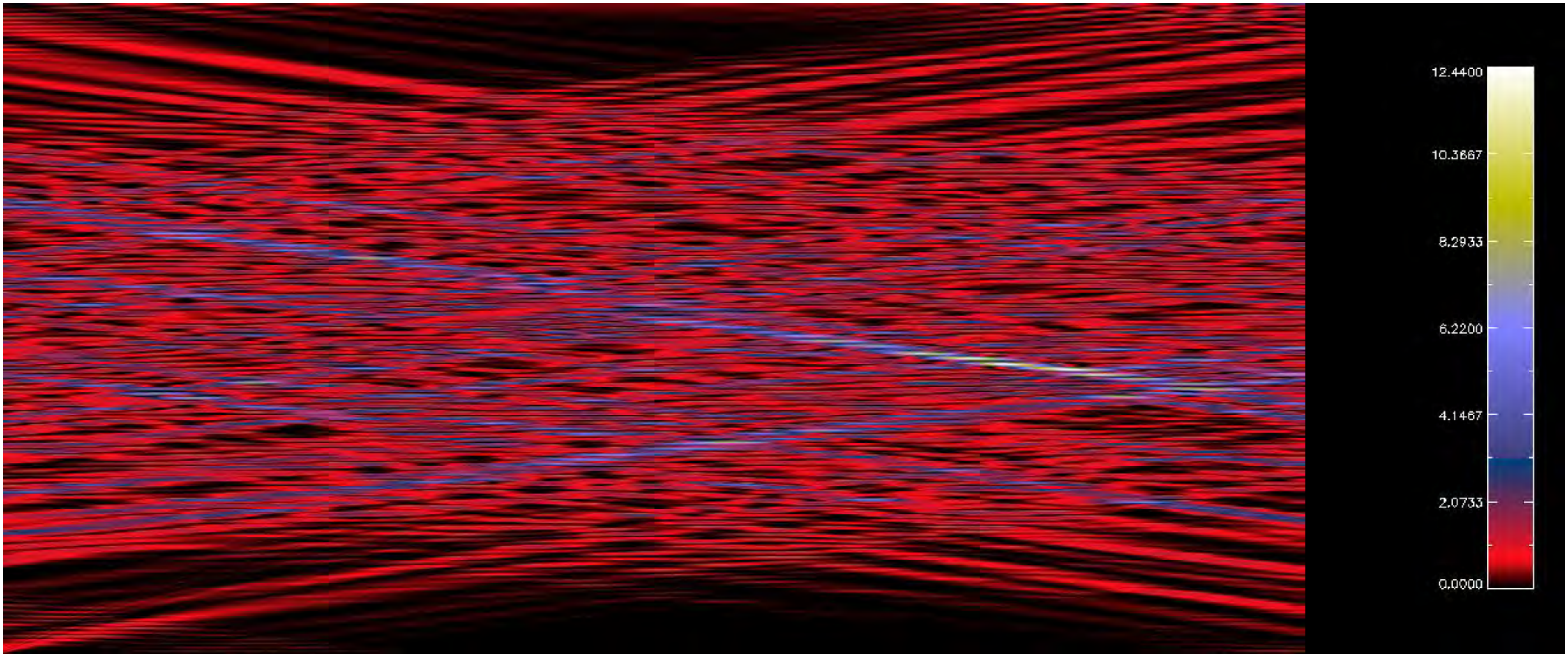
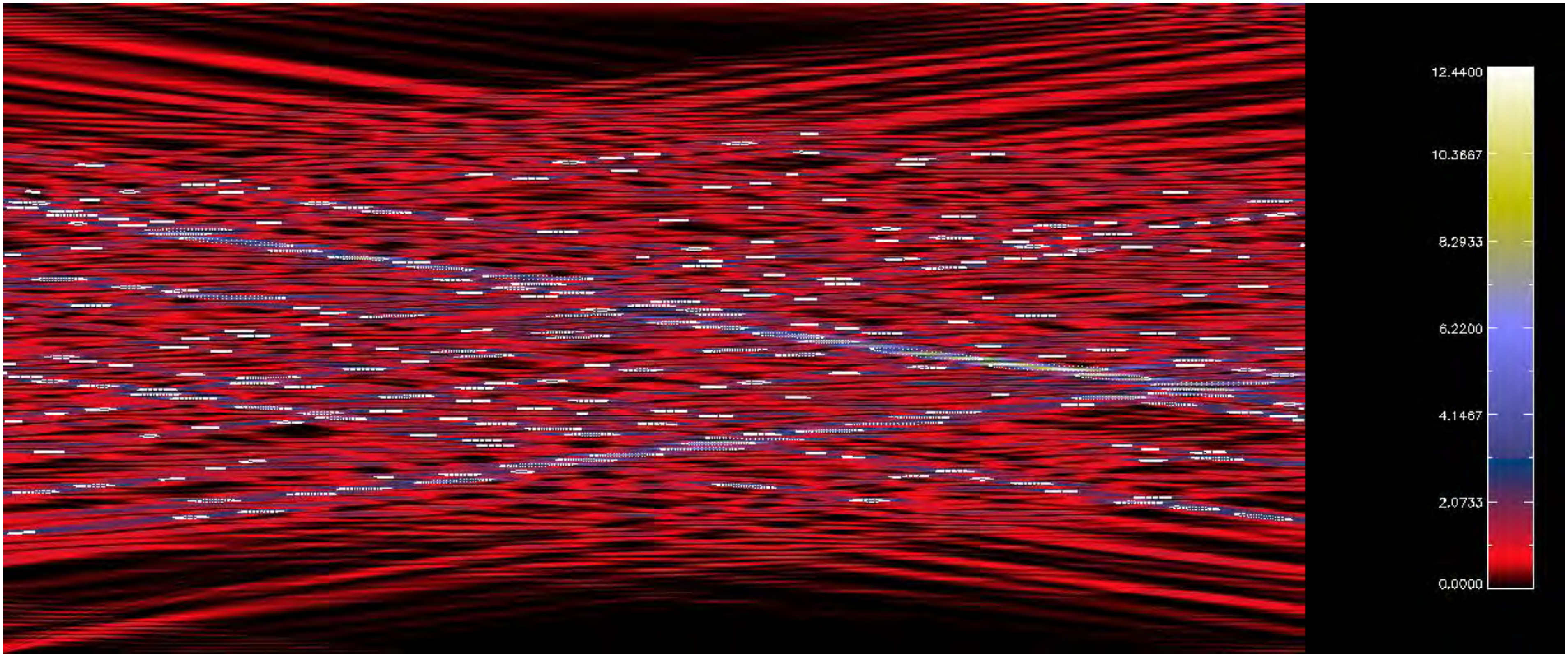
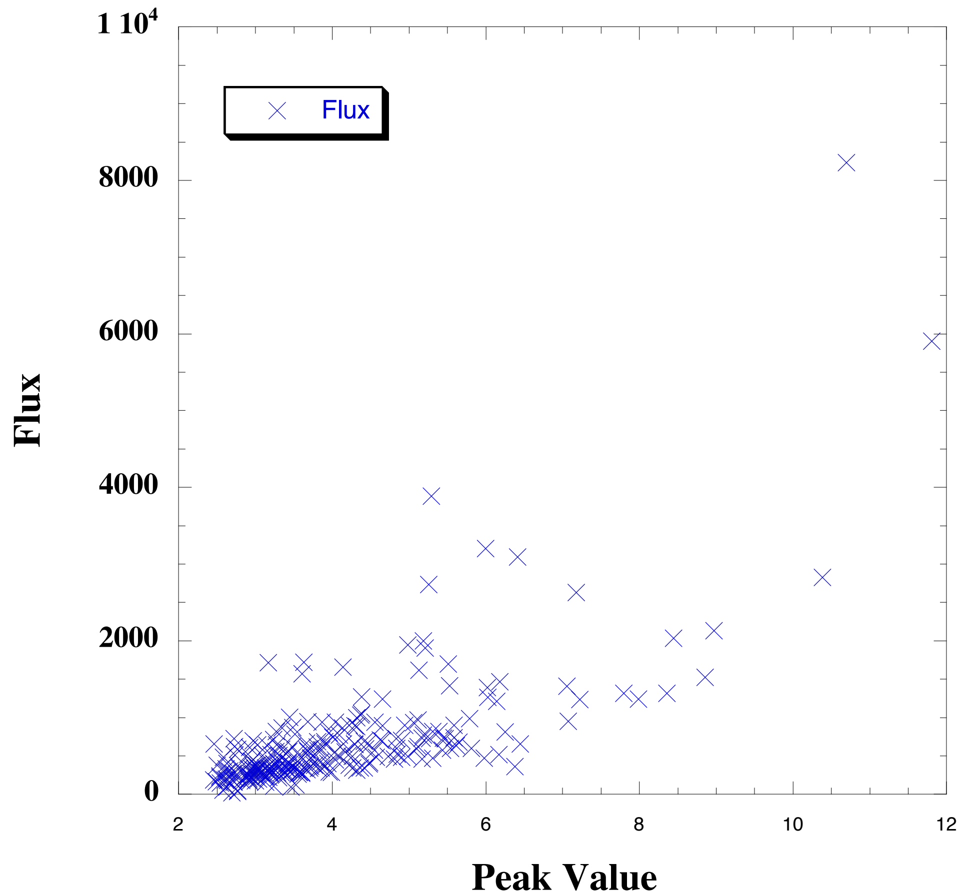


# We Can Detect the Hot Spots and Classify Their Properties

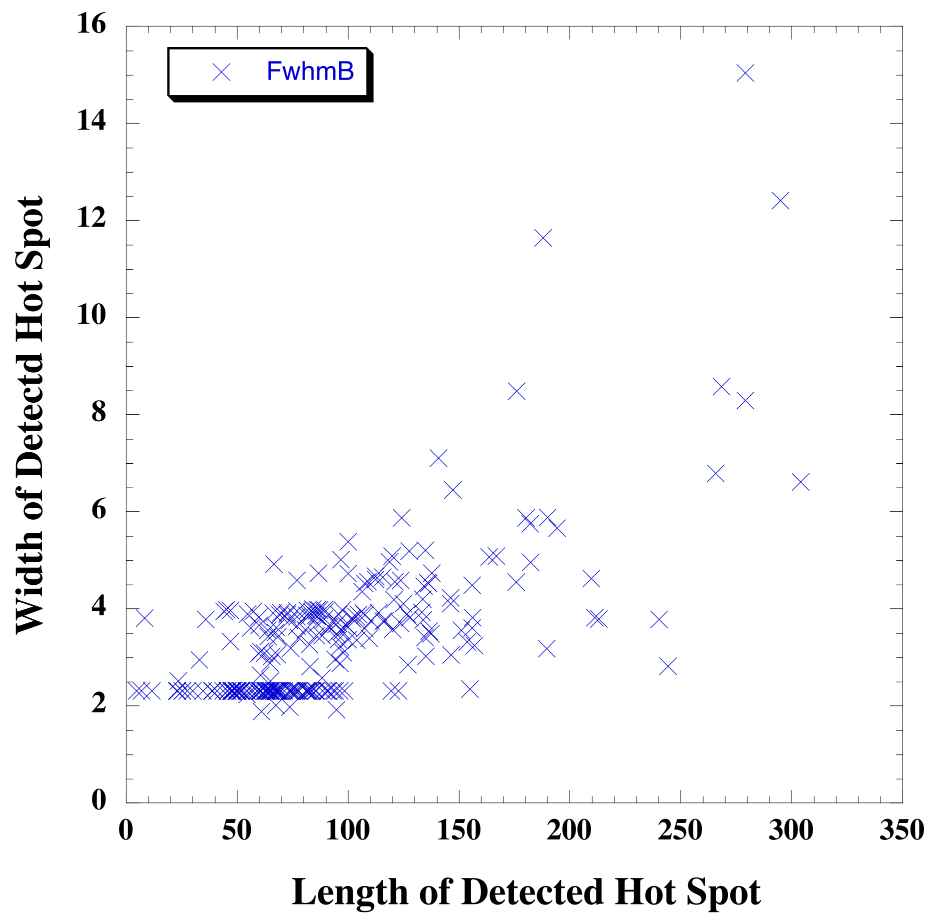


# Once You Detect the Hot Spots You Can Classify Their Properties

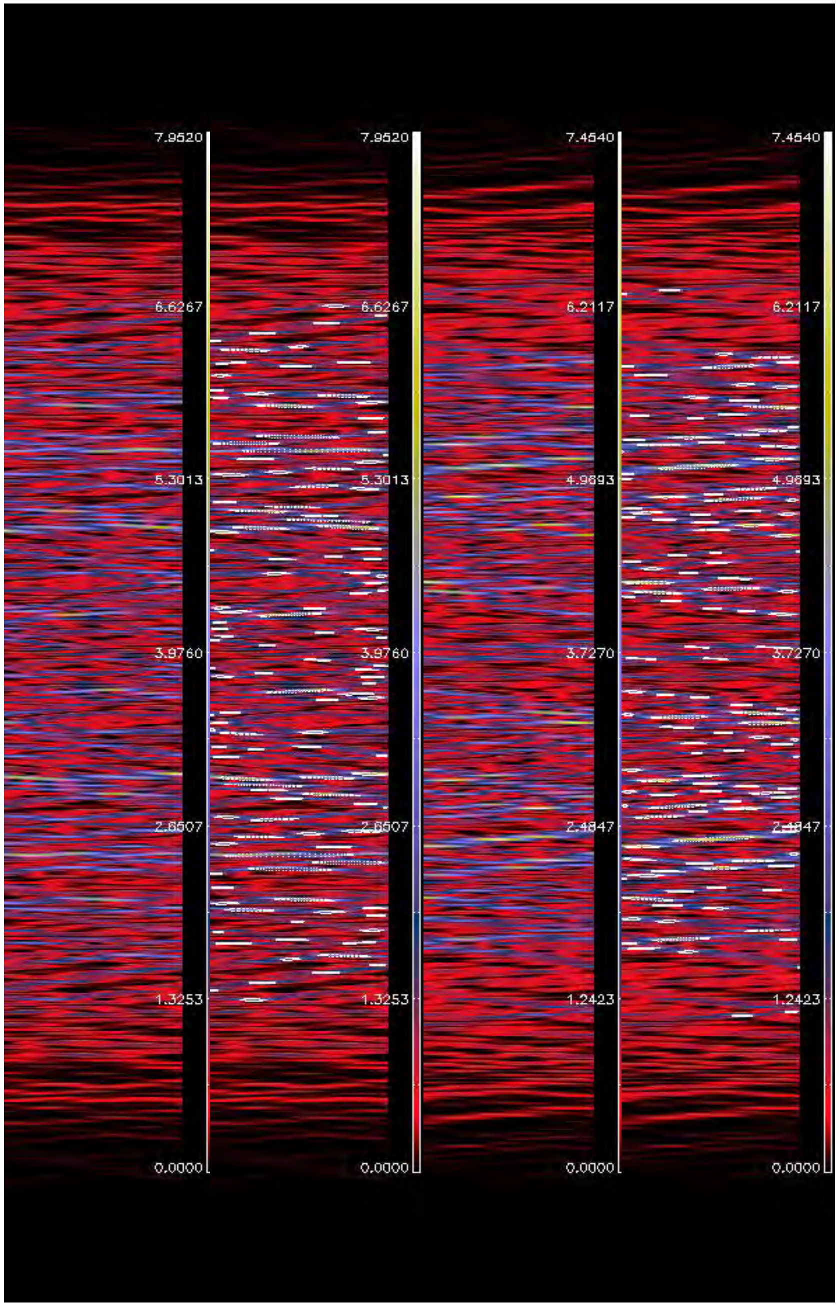
Integrated Fluxes in Each Detected Hot Spot

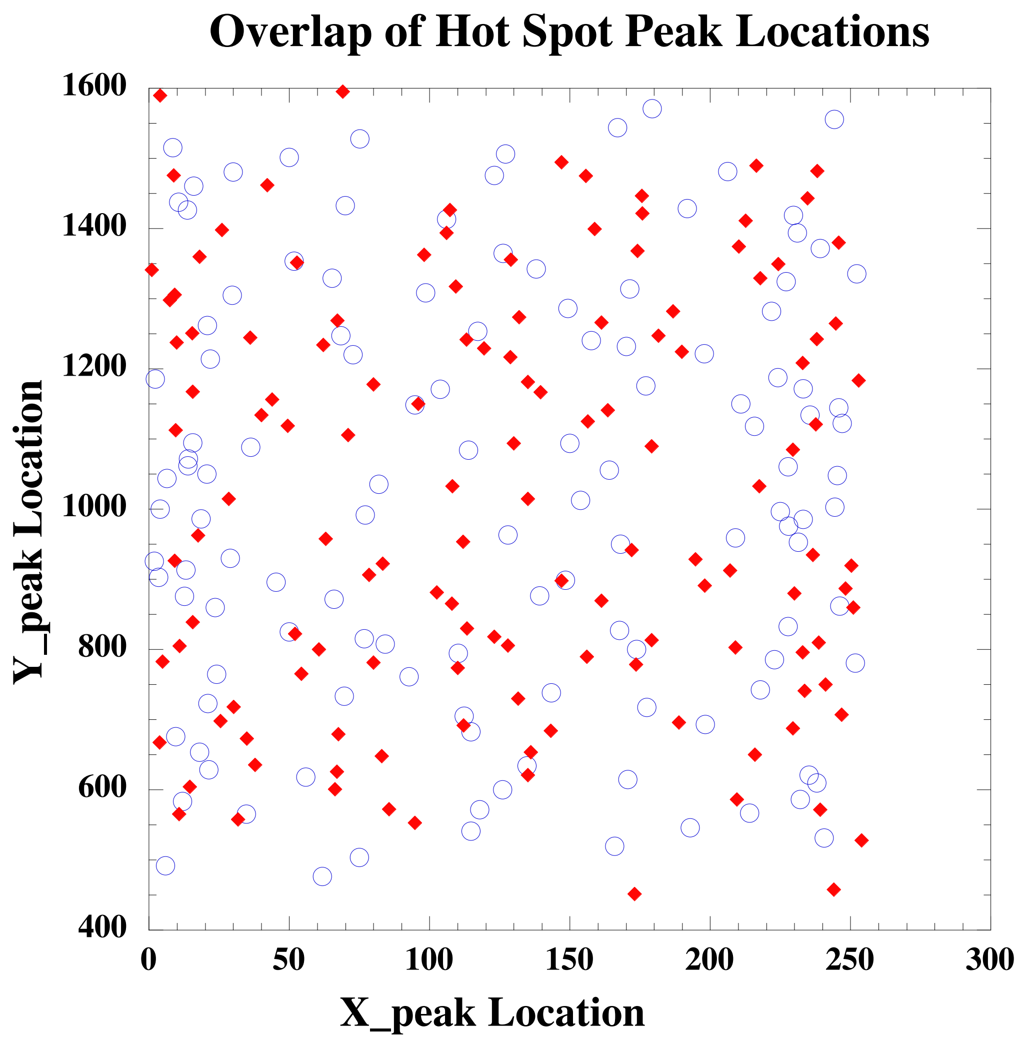



Classification of Hot Spot Statistics

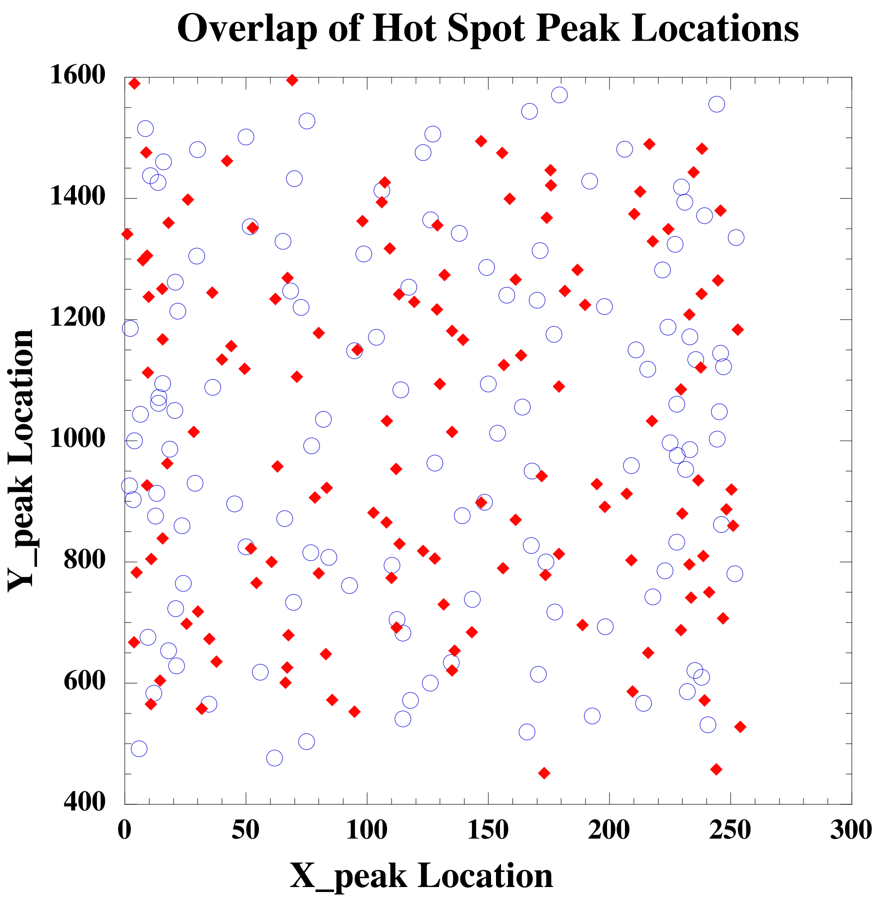


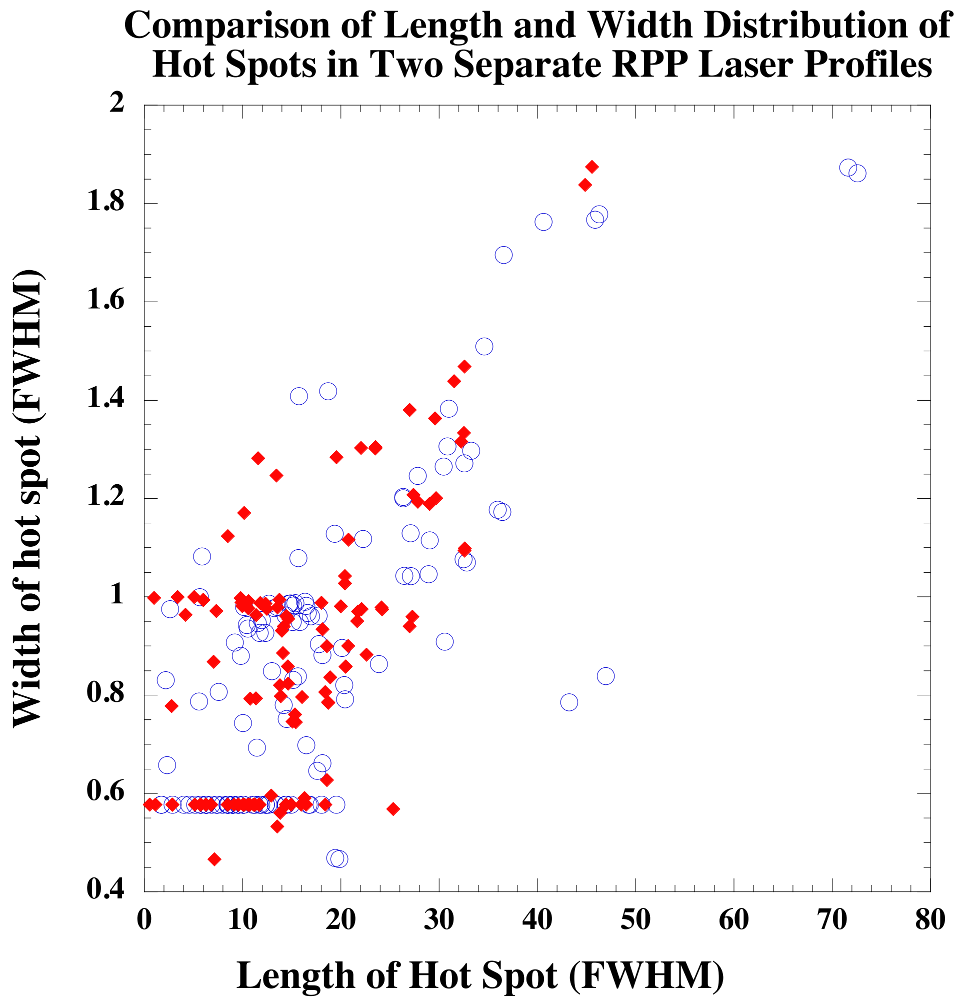
# Two Realizations of Sections of f/20 Beams



# Statistical Properties of Two Independent Realizations of RPP f/20 Beams



# The Number of Hot spots Whose Peak Intensity is Greater than u Is Estimated for a Complex Gaussian Random Field with a Gaussian Covariance Matrix to Be:

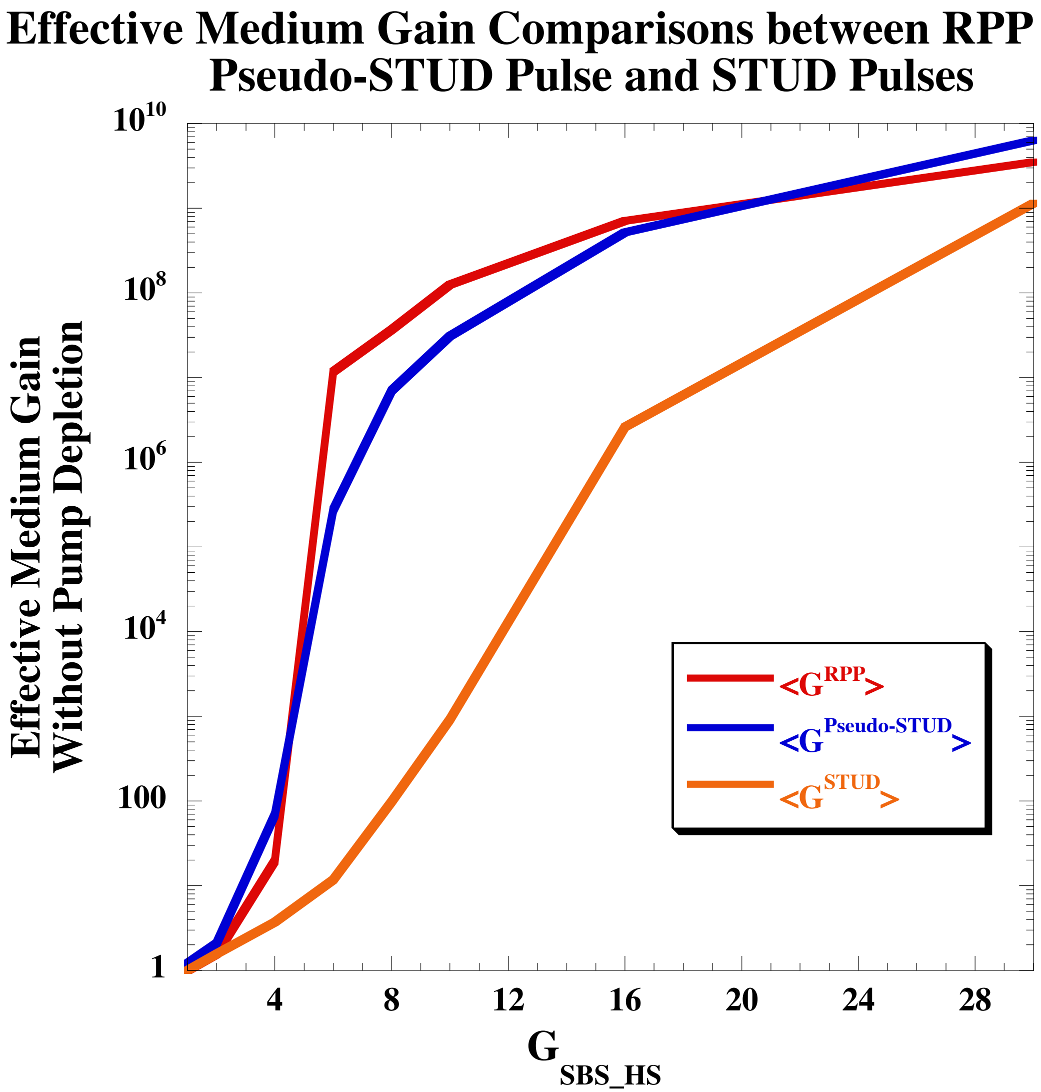
**Rice's Lemma:** $M_u^V = \int_V \delta[\nabla A(\mathbf{x})] \; \mathbf{1}_{A(\mathbf{x})\geq u} \; |\det \nabla\nabla A(\mathbf{x})| \; \mathbf{1}_{\nabla\nabla A(\mathbf{x})<0} \, d\mathbf{x}$

$$\langle M_u^{3D} \rangle = \frac{\pi^{3/2}\sqrt{5}\, V_{tot}}{27\,\rho_c^2\, z_c}\left[\left(\frac{u}{I_0}\right)^{3/2} - \frac{3}{10}\left(\frac{u}{I_0}\right)^{1/2}\right]\exp\left[-{}^{u}\!/_{I_0}\right]$$

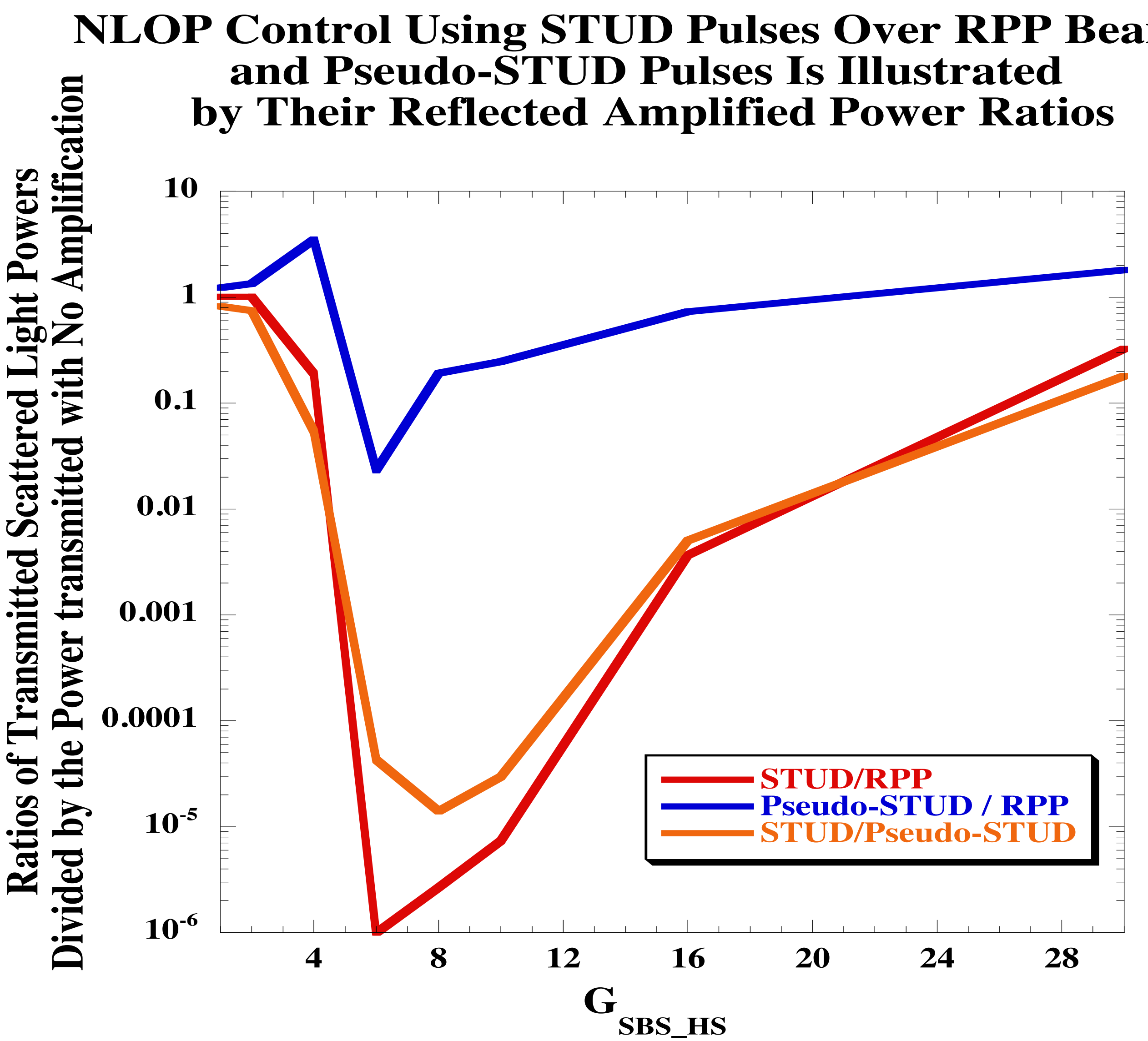
$$\langle M_u^{3D} \rangle \approx 56 \times L_{Beam,\mu m} \approx 56{,}000 \text{ per mm}$$

$$\mathrm{R} \propto \int_{N(m)}^{\infty} d\langle M_u \rangle \int_0^{\infty} dz_c \, \exp[\alpha\, u\, z_c] \times u \times \mathbf{P}_u(z_c)$$

# SBS Normalized Effective Gain Exponent $\langle G^{SBS} \rangle_{Norm}$ for RPP Beams, STUD and Pseudo-STUD Pulses in the Strong Damping Limit, f/8, vs G_SBS_HS: No PD (Picket Fence)



# Ratios of Effective Gain Exponents $\langle G^{SBS} \rangle_{Norm}$ in the Strong Damping Limit, f/8, vs G_SBS_HS: STUD/RPP, Pseudo-STUD/RPP & STUD / Pseudo-STUD (NPD) (Picket Fence)



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# Summary: Use STUD Pulses

- **STUD pulses** allow optimal LPI control and design flexibility.
- Exponential growth and uncontrolled behavior is mitigated by modulating the incident laser in time with new **design principles** derived and illustrated.
- The relative durations of **growth**, **damping** and **hot spot recurrence** time determine the likelihood of success. This opens up a wide design/control space to explore for each **ICF** target design or each **HEDLP** application setting.
- The march back to **GREEN ICF & IFE** can be contemplated in earnest. It is not as perilous or as daunting a prospect as it seemed in the past.
- Keeping NLO processes linear (tamed) and then letting them run wild (at the end of the pulse for **Shock Ignition**) by using staggered and then overlapped STUD pulses makes the success of FI or SI far more likely.

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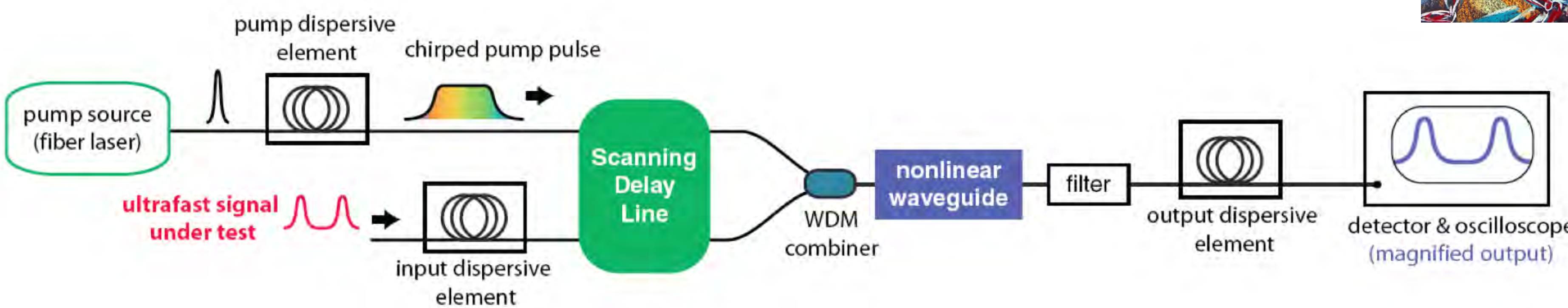
# 3 Major Experimental Tools Are Needed in Order to Explore the Effectiveness of and to Optimize STUD Pulses in the Green

- Need **ps time scale Thomson Scattering** capability
- Need **ps time scale backscatter streaked spectrometry**
- **TIME LENSES will allow STUD pulse design at longer time scales compressed down to psecs AND the dilation of Raman and Brillouin scattered signals so that an instrument with 50-100 psecs time resolution is enough.**
- **Need a tunable short pulse OPO** for pump-probe experiments where small signal gain can be measured once STUD pulses control the instability and direct measurements of the plasma distribution function become possible.

# How Do Time Lenses Work?




Schematic diagram showing the concept of temporal magnification, or "Time-Lens", using **nonlinear optical mixing in a waveguide**. The scanning delay line allows a delay between the measurement window and the input pulse. The measurement window is as large as 200-ps, with <1-ps resolution on a single shot. The nonlinear wave guide mixes the linearly chirped pulse with the input pulse, encoding the time-dependence of the input pulse on the chirped pulse. The input pulse is filtered out, and the **encoded chirped pulse stretches out in time via linear dispersion in a long fiber**. The stretched pulse is then measured using a conventional oscilloscope. Temporal magnification up to M=500 have been reported.


"**High-speed optical sampling using a silicon-chip temporal magnifier**,"
R. Salem, M.A. Foster, A.C. Turner-Foster, D.F. Geraghty, M. Lipson,
A.L. Gaeta, *Optics Express* **17,** 4324 (2009)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