How to measure femtosecond laser pulses

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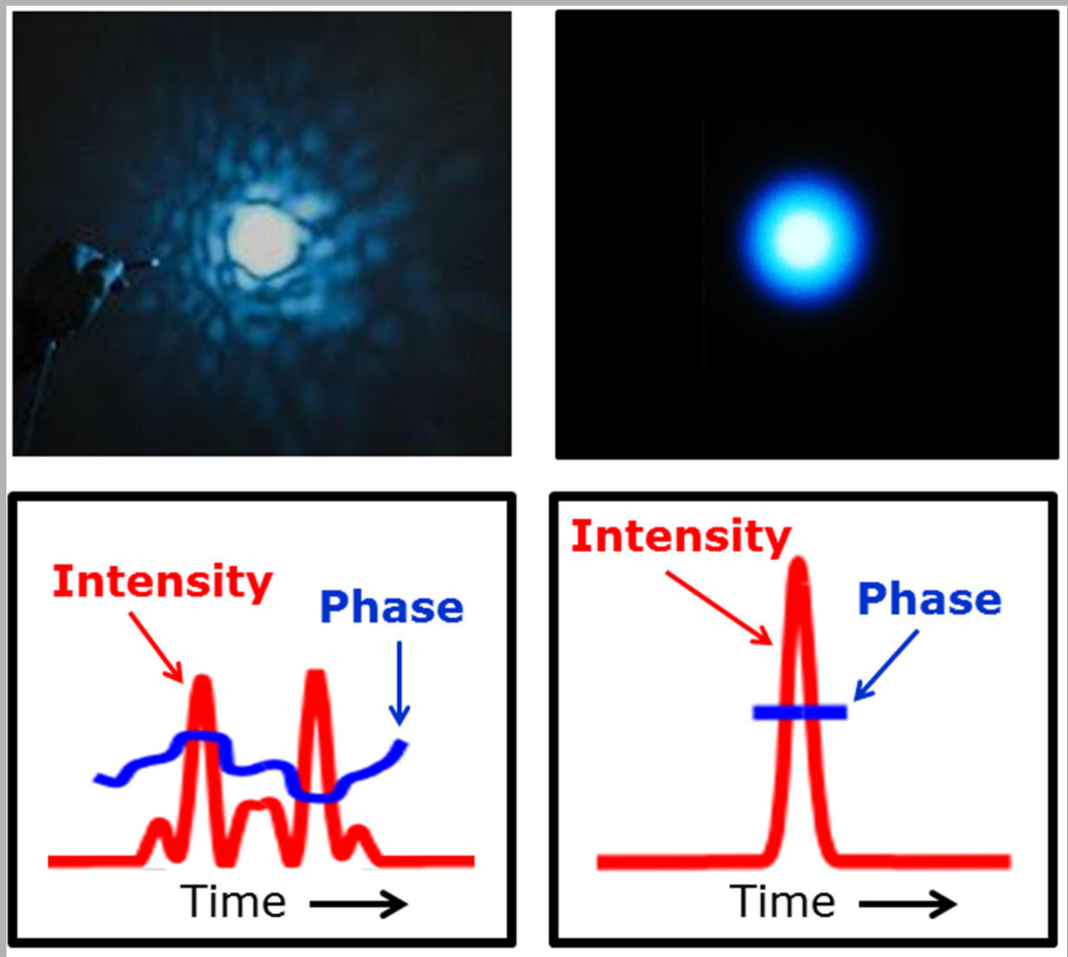
Swamp Optics

Temporal distortion in pulses



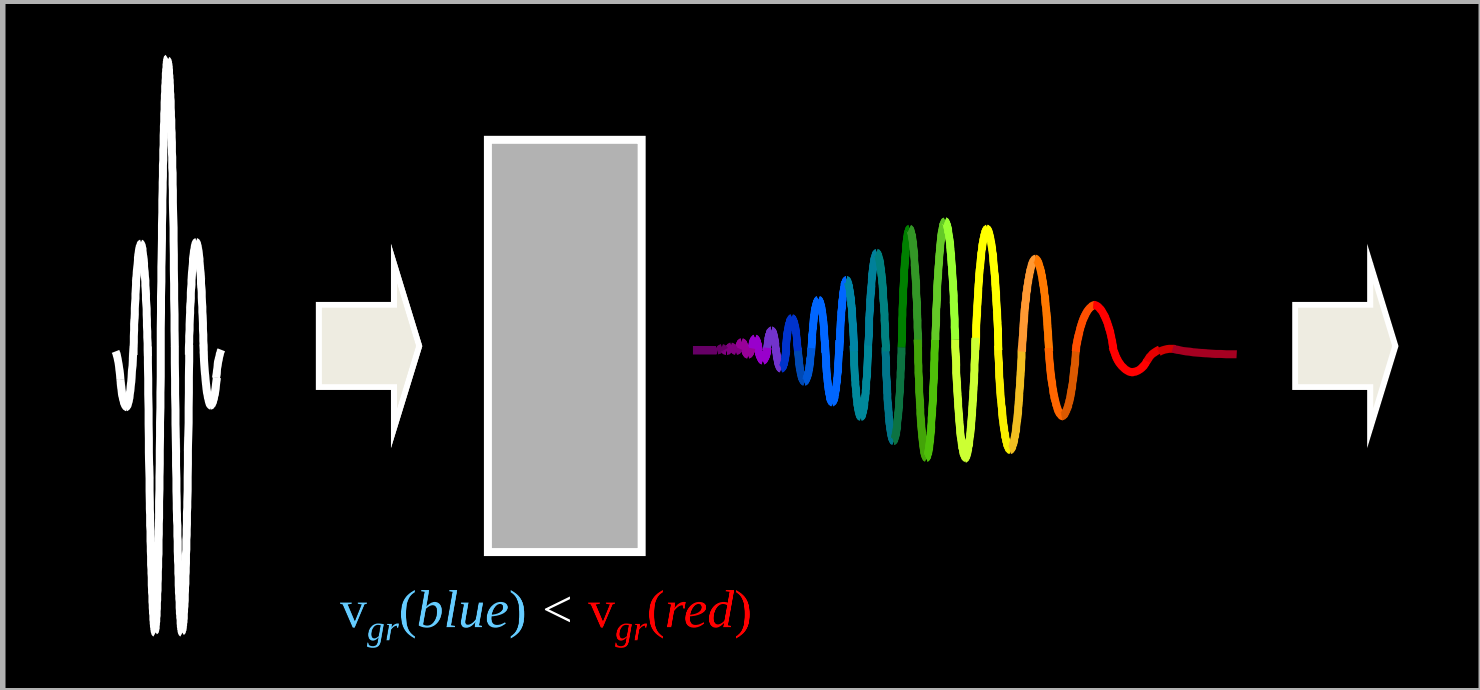
-.After the development of the lasers, researchers realized that the lasers were not very useful if their beam spatial quality was poor. And it was. Variations in the light intensity from place to place in the beam made experiments noisy and applications unreliable.

-. After developing short pulse laser system, they learned that unstructured pulse shapes in *time* are equally important for the same reasons.

Top left: Photograph of a complex, poor-quality laser beam. Top right: Photograph of a simple, high-quality laser beam, which is much more useful. Bottom left: Plot of the intensity and phase vs. time of a complex, poor-quality laser pulse. Bottom right: Plot of the intensity and phase vs. time of a simple, high-quality laser pulse, which is also much more useful. (Beam images from Molecular Imaging Center, UC Berkeley.)

The effect of group velocity dispersion

GVD means that the group velocity will be different for different wavelengths in the pulse.



Because ultrashort pulses have such large bandwidths, GVD is a bigger issue than for cw light.

Experimental continuum spectrum in a fiber due to the nonlinear processes

- Continua created by propagating 500-fs 625nm pulses through 39cm of single-mode fiber.

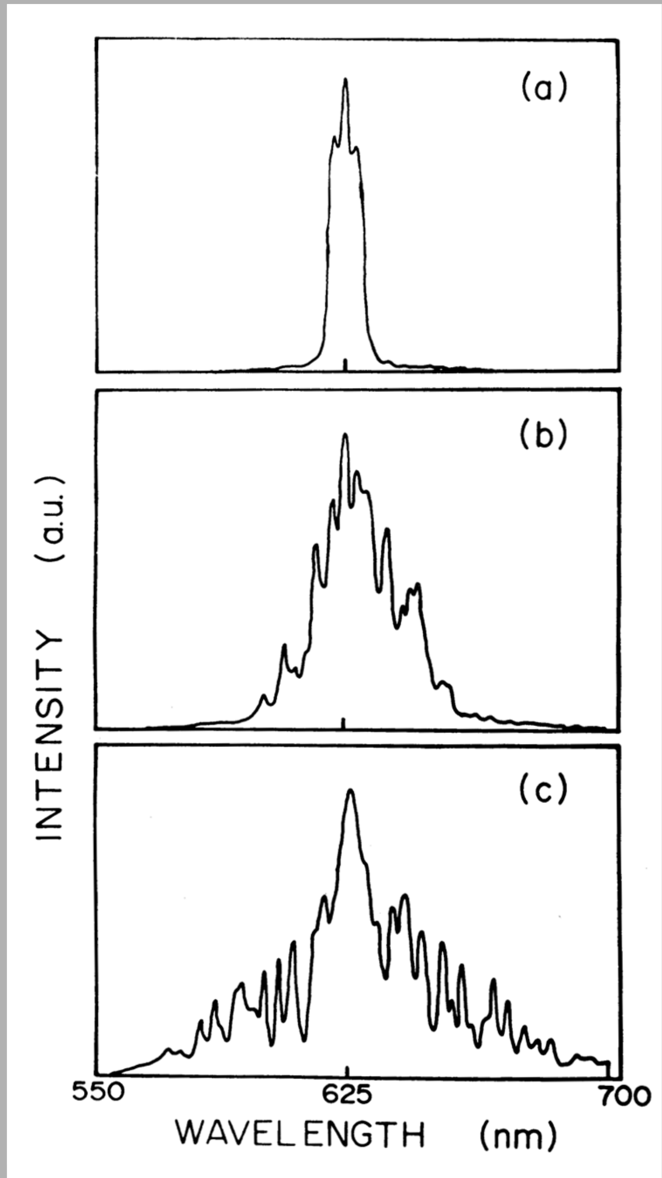
The Supercontinuum Laser Source, Alfano, ed.

Broadest spectrum occurs for highest energy.

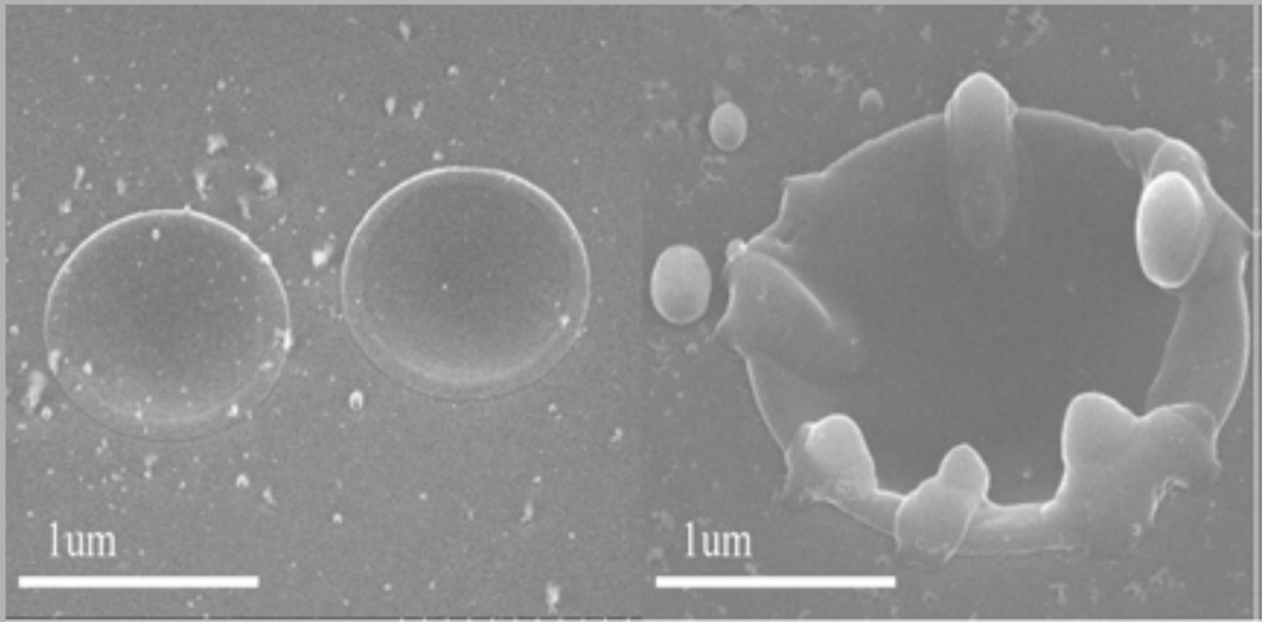
Low Energy

Medium Energy

High Energy



Micromachining process with distorted pulses



Femtosecond laser pulse-induced ablation of a silicon wafer surface using an undistorted pulse (left) and a chirped pulse (right).

The Dilemma

In order to measure
an event in time,
you need a *shorter* one.

To study this event, you need a strobe light pulse that's shorter.

Photograph taken by Harold Edgerton, MIT

But then, to measure the strobe light pulse,
you need a detector whose response time is even shorter.

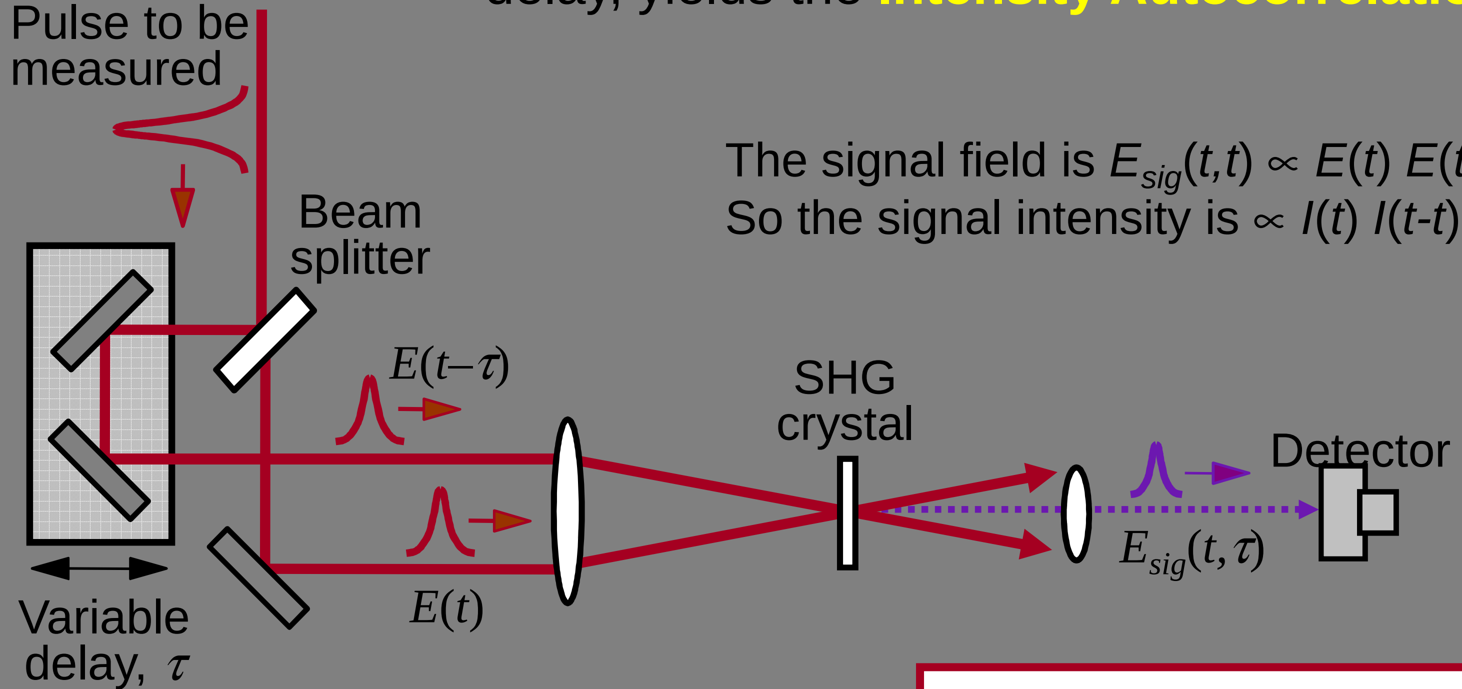
And so on…

So, now, how do you measure the *shortest* event?

Pulse Measurement in the time domain:

The Intensity Autocorrelator

Crossing beams in a nonlinear-optical crystal, varying the delay between them, and measuring the signal pulse energy vs. delay, yields the **Intensity Autocorrelation, $A^{(2)}(\tau)$**.



The signal field is $E_{sig}(t,t) \propto E(t)\, E(t-t)$.
So the signal intensity is $\propto I(t)\, I(t-t)$

The Intensity Autocorrelation:

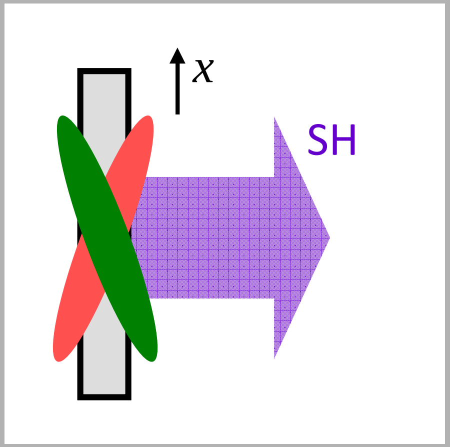
$$A^{(2)}(\tau) \equiv \int_{-\infty}^{\infty} I(t)\, I(t-\tau)\, dt$$

Single-shot FROG

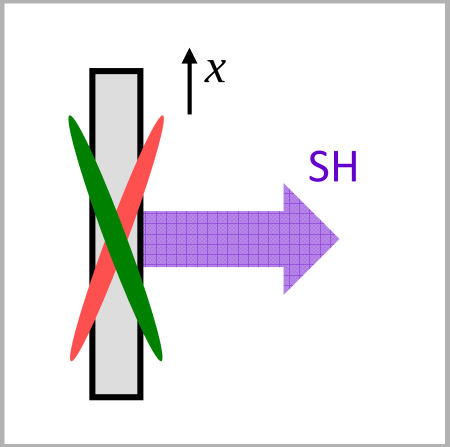
Crossing beams at an angle also maps delay onto transverse position.

$$\tau(x) = 2(x/c)\sin(\theta/2) \approx x\theta/c$$

Long pulse



Short pulse

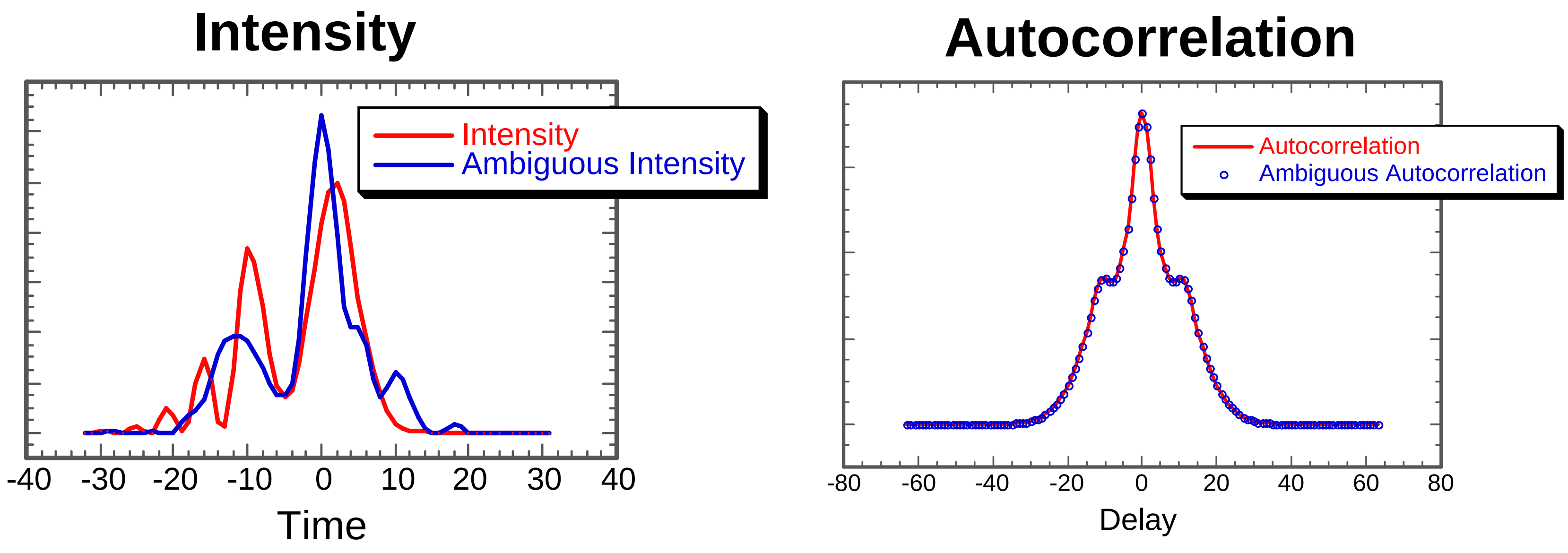


Use a large beam and a large beam crossing angle to achieve the desired range of delays. Then image the crystal onto a camera.

So single-shot SHG FROG has no geometrical smearing!

Autocorrelations of more complex intensities

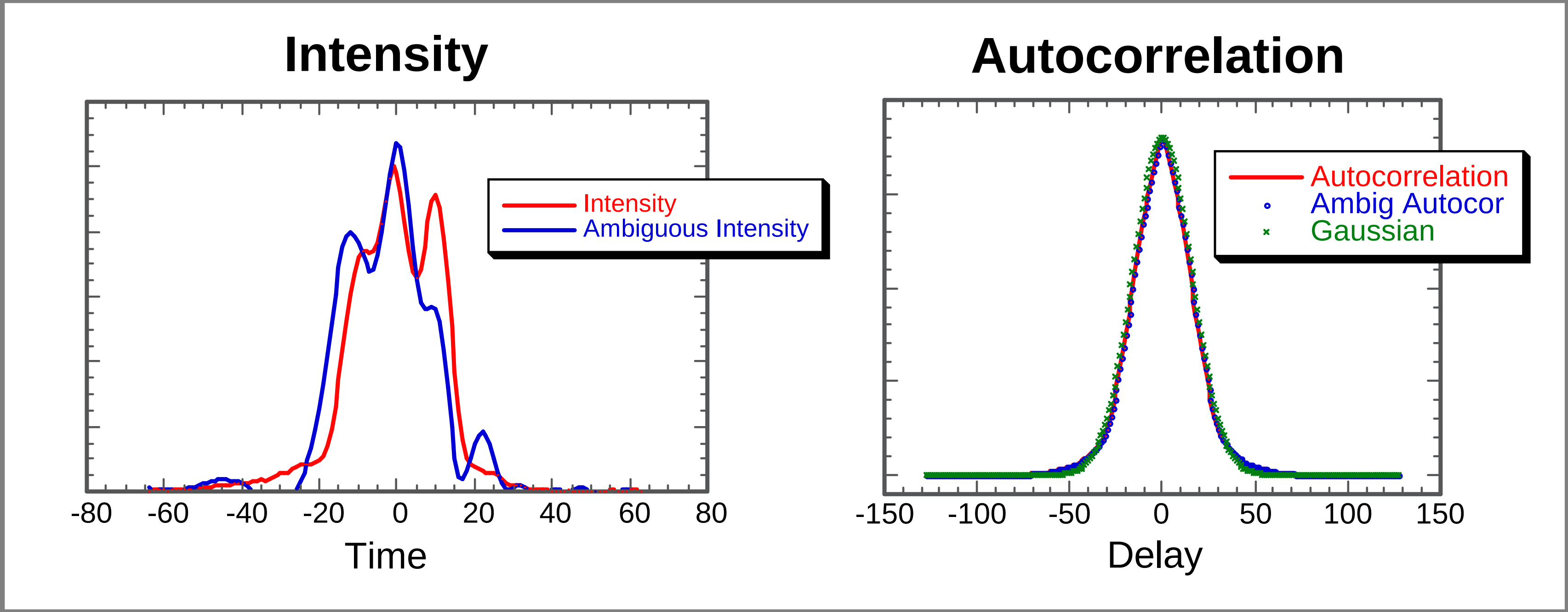
Autocorrelations nearly always have considerably less structure than the corresponding intensity.



An autocorrelation typically corresponds to many different intensities. Thus the autocorrelation does not uniquely determine the intensity.

Even simple autocorrelations have ambiguities.

Ambiguities are different pulses with the same measured trace.

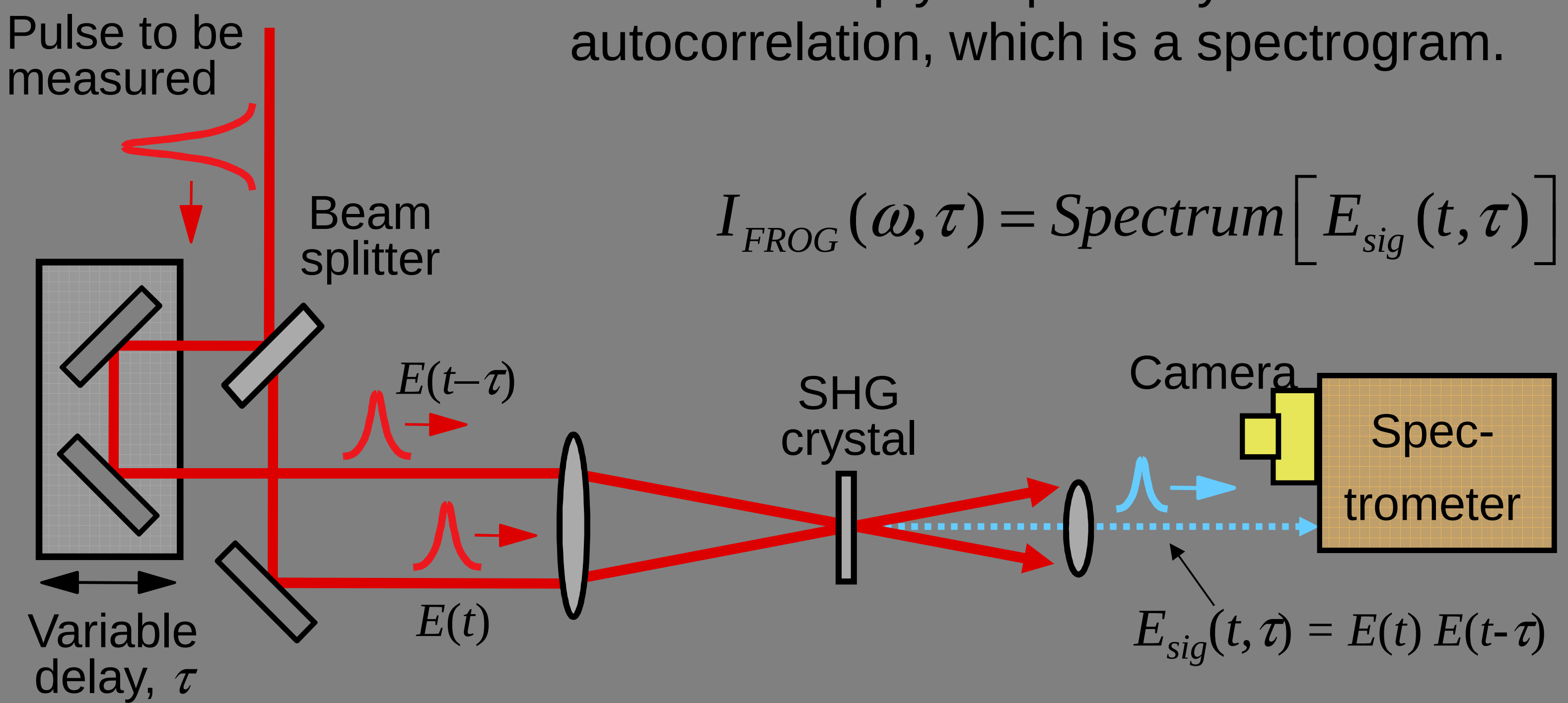


Autocorrelation yields only a rough measure of the pulse width (± ~30%).

Frequency-Resolved Optical Gating (FROG)

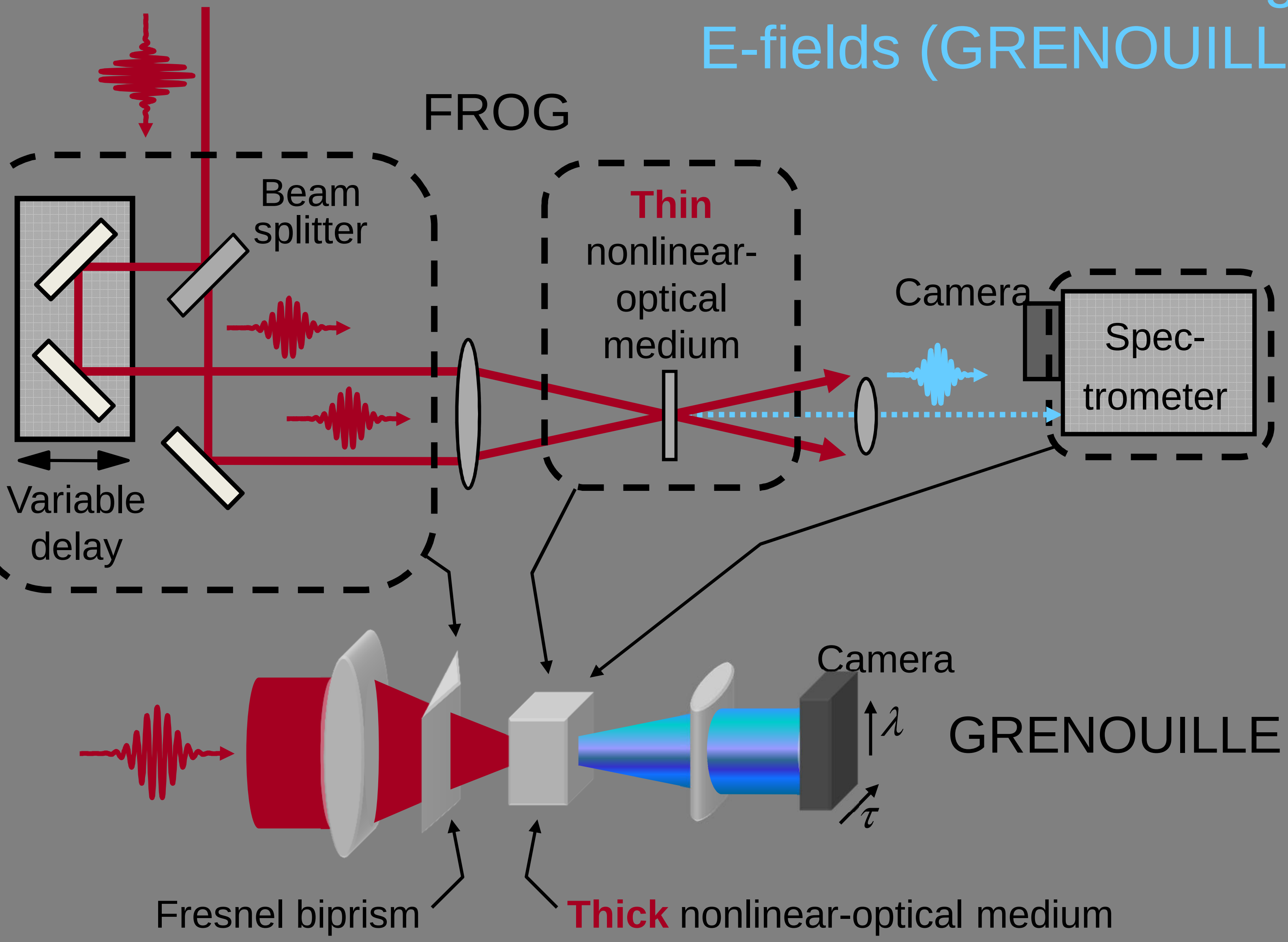
FROG is simply a spectrally resolved autocorrelation, which is a spectrogram.

$$I_{FROG}(\omega,\tau) = Spectrum\left[E_{sig}(t,\tau)\right]$$



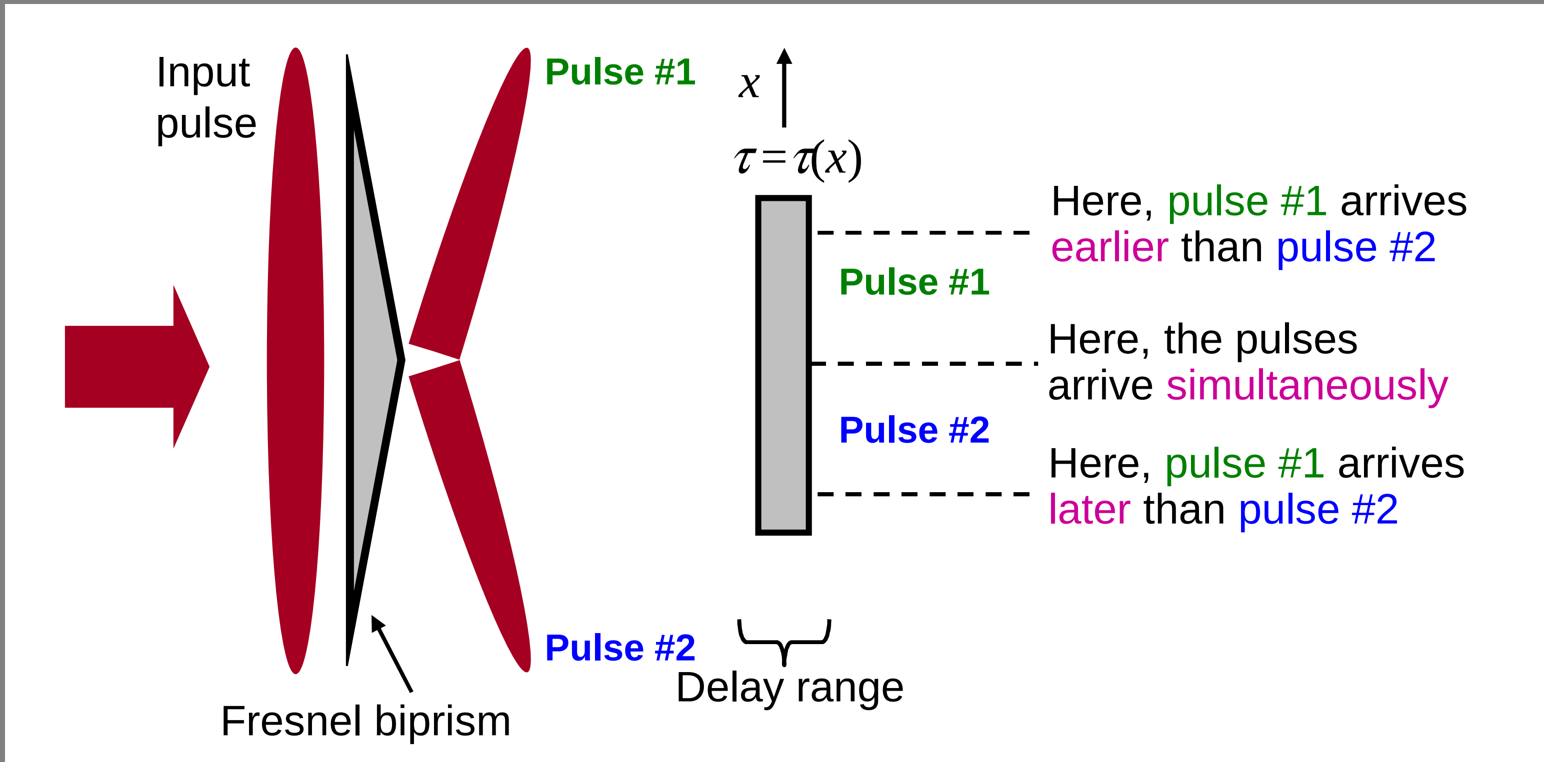
FROG can use any fast nonlinear-optical process. SHG FROG is the most sensitive version. When using SHG, however, the trace is always symmetrical with respect to delay, yielding an ambiguity in the direction of time.

GRating-Eliminated No-nonsense Observation of Ultrafast Incident Laser Light E-fields (GRENOUILLE)



The Fresnel biprism

Crossing beams at a large angle maps delay onto transverse position.

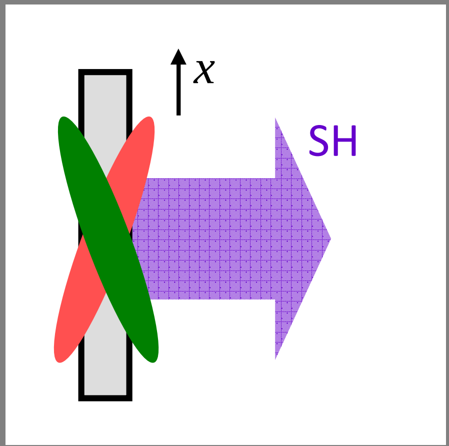


This yields an **alignment-free single-shot** measurement of a pulse.

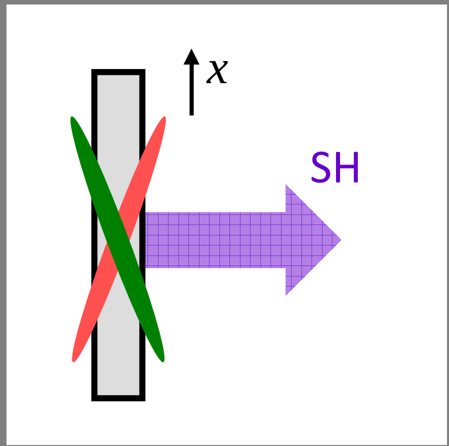
The Fresnel biprism

Crossing beams at a large angle maps delay onto transverse position.

Long pulse



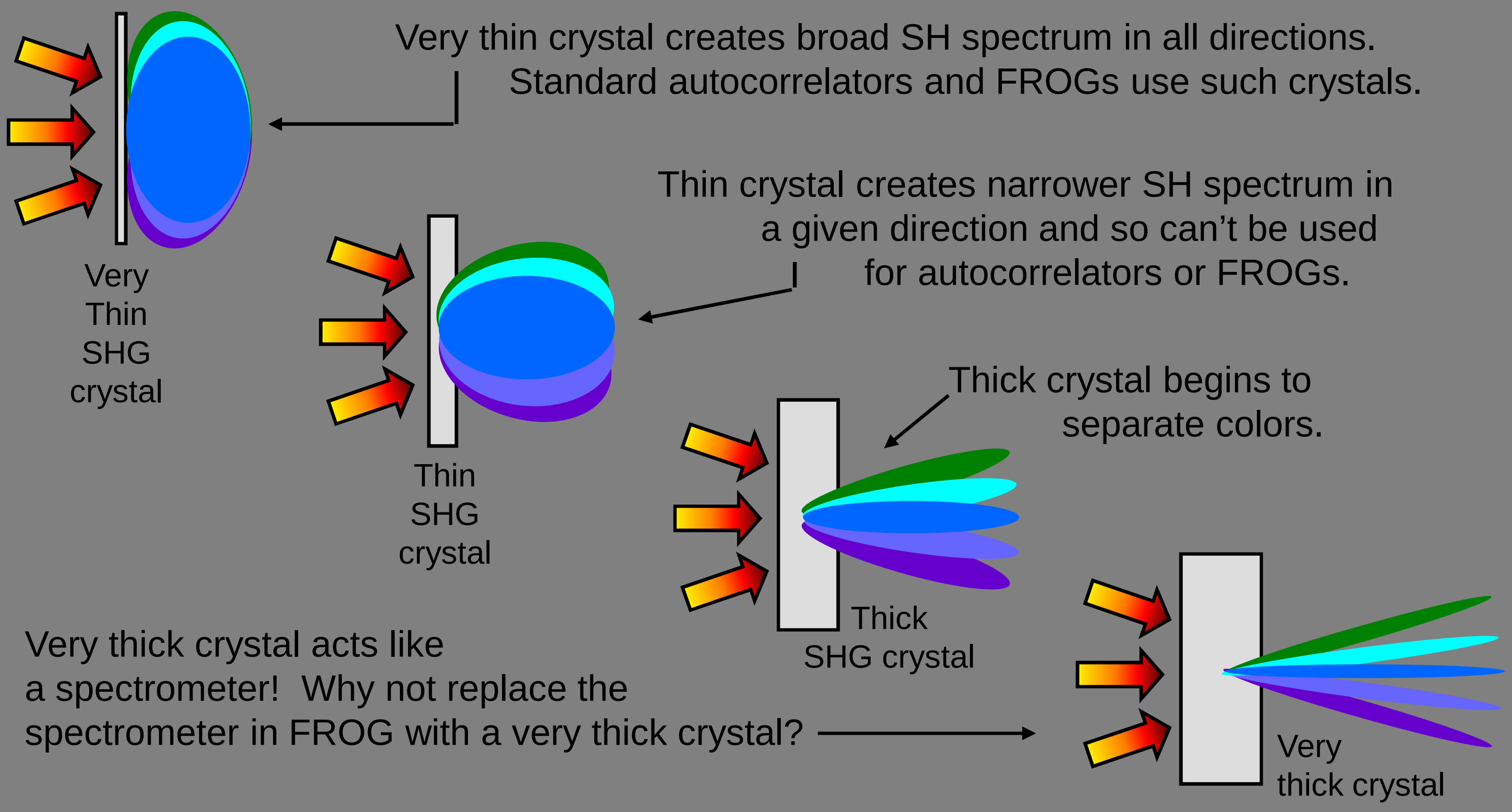
Short pulse



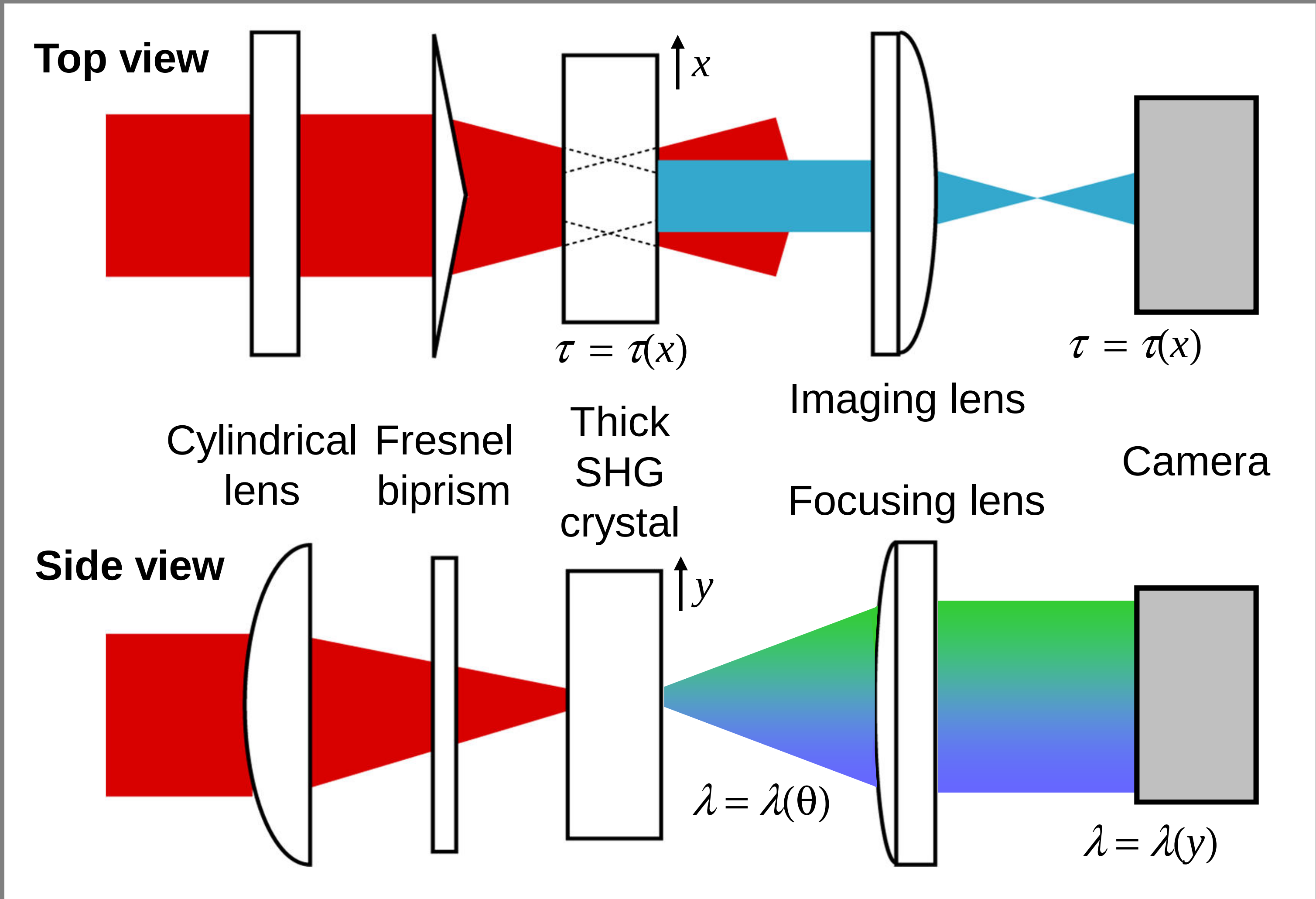
This yields an **alignment-free single-shot** measurement of a pulse.

The thick crystal

Suppose broadband light with a large divergence angle impinges on an SHG crystal. The SH generated depends on the angle. And the angular width of the SH beam created varies inversely with the crystal thickness.



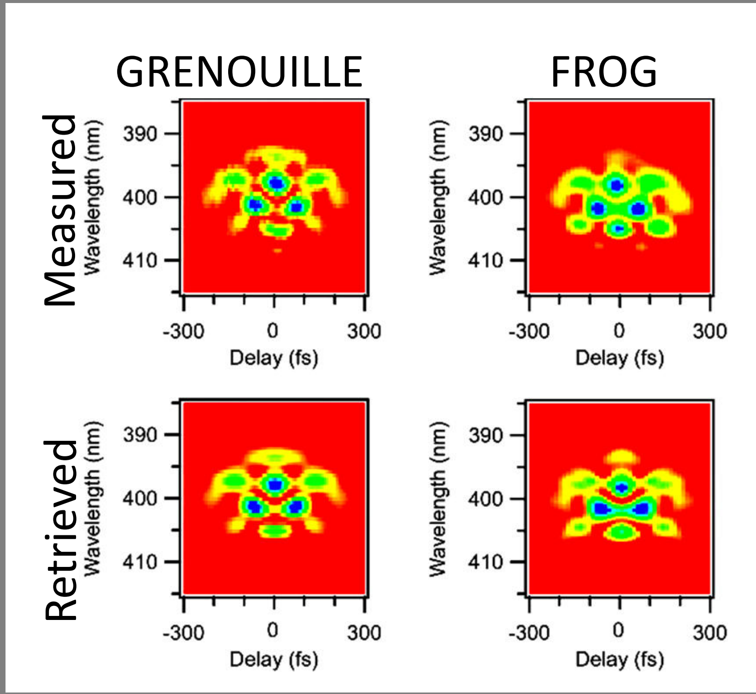
GRENOUILLE beam geometry



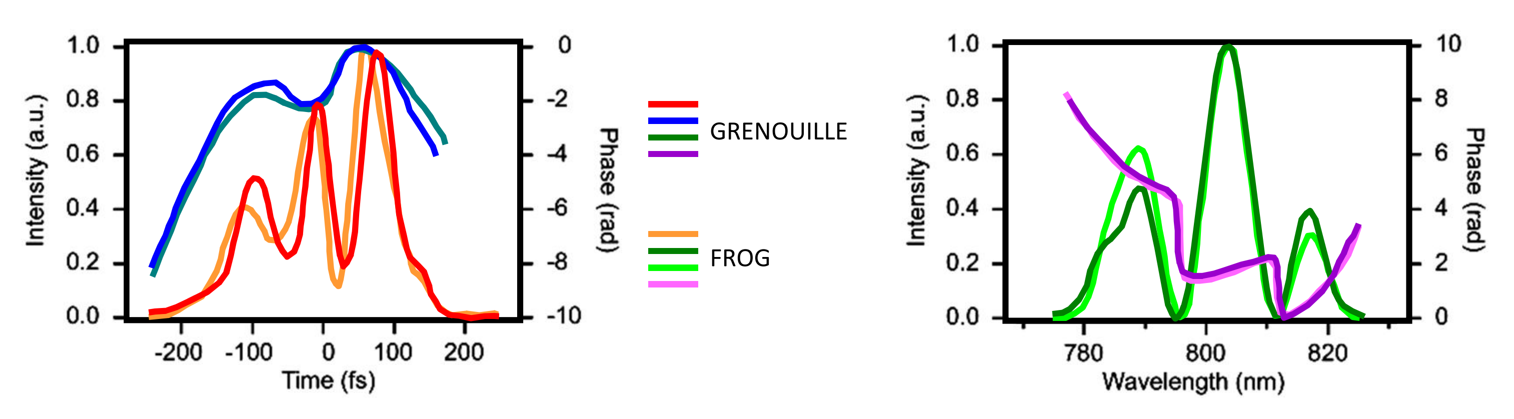
GRENOUILLE is a complete single-shot FROG, but is more sensitive.
It uses the standard FROG algorithm.

GRENOUILLE measurements

GRENOUILLE measurements agree with tried-and-true FROG measurements of the same pulse:



Retrieved pulse in the time and frequency domains



The maximum delay is ~6ps.

Limitations of SHG in Pulse Measurements

-The SHG crystals do not phase-match in the UV (the cutoff wavelengths are 532 nm for KDP and 410 nm for BBO).

-The crystal needs to be extremely thin to have large enough phase-matching bandwidth, when measuring very short pulses.

-Most nonlinear materials start to absorb heavily in the UV, causing significant absorption of the SH signal.

Third-order nonlinearities can be used to measure UV pulses

- **Polarization Gate (PG) FROG**: Requires high quality polarizers, which are difficult to find in the UV. Polarizers are also thick materials causing significant GVD.

- **Self Diffraction (SD) FROG**: This process is phase-mismatched, requiring very thin medium, which in turn limits the sensitivity.

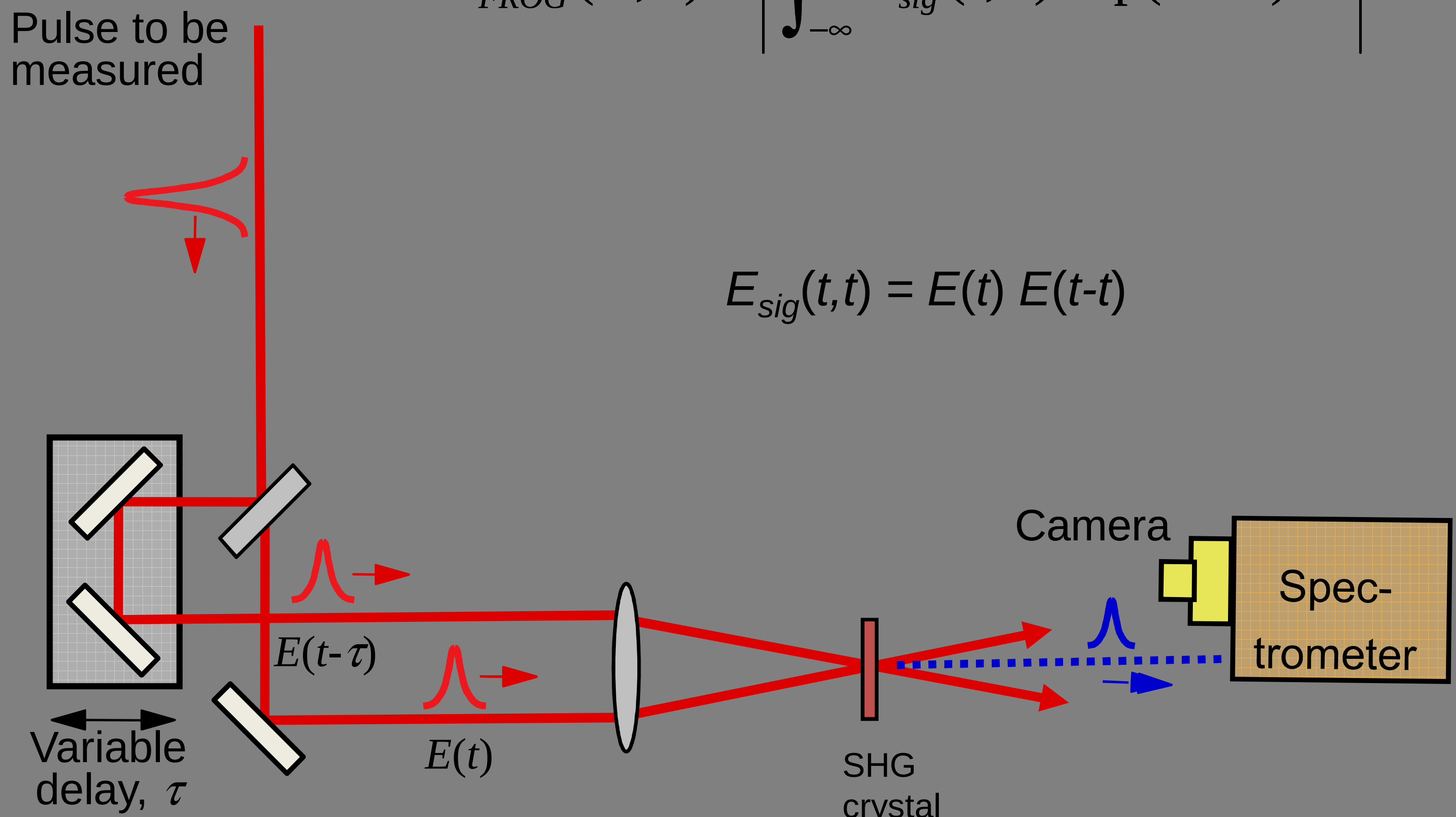
- **Transient Gating (TG) FROG**: This process can be automatically phase-matched! Thick materials can be used to increase the sensitivity.

TG FROG can be a good candidate to measure ultrashort pulses over a very broad range of wavelengths, including the UV!

SHG FROG and TG-FROG

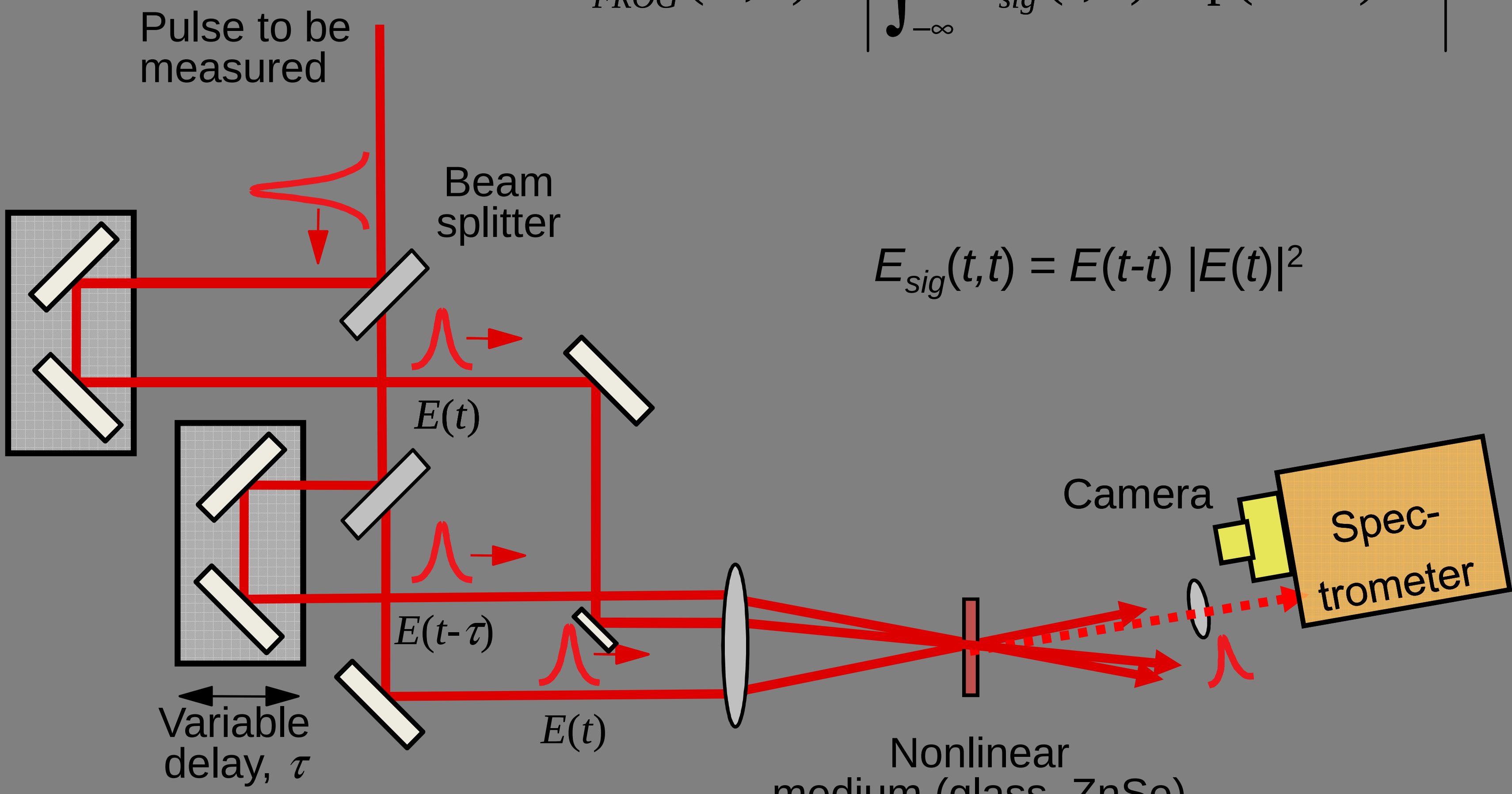
$$I_{FROG}(\omega,\tau) = \left| \int_{-\infty}^{\infty} E_{sig}(t,\tau) \exp(-i\omega t)\, dt \right|^2$$

$$E_{sig}(t,t) = E(t)\ E(t\text{-}t)$$



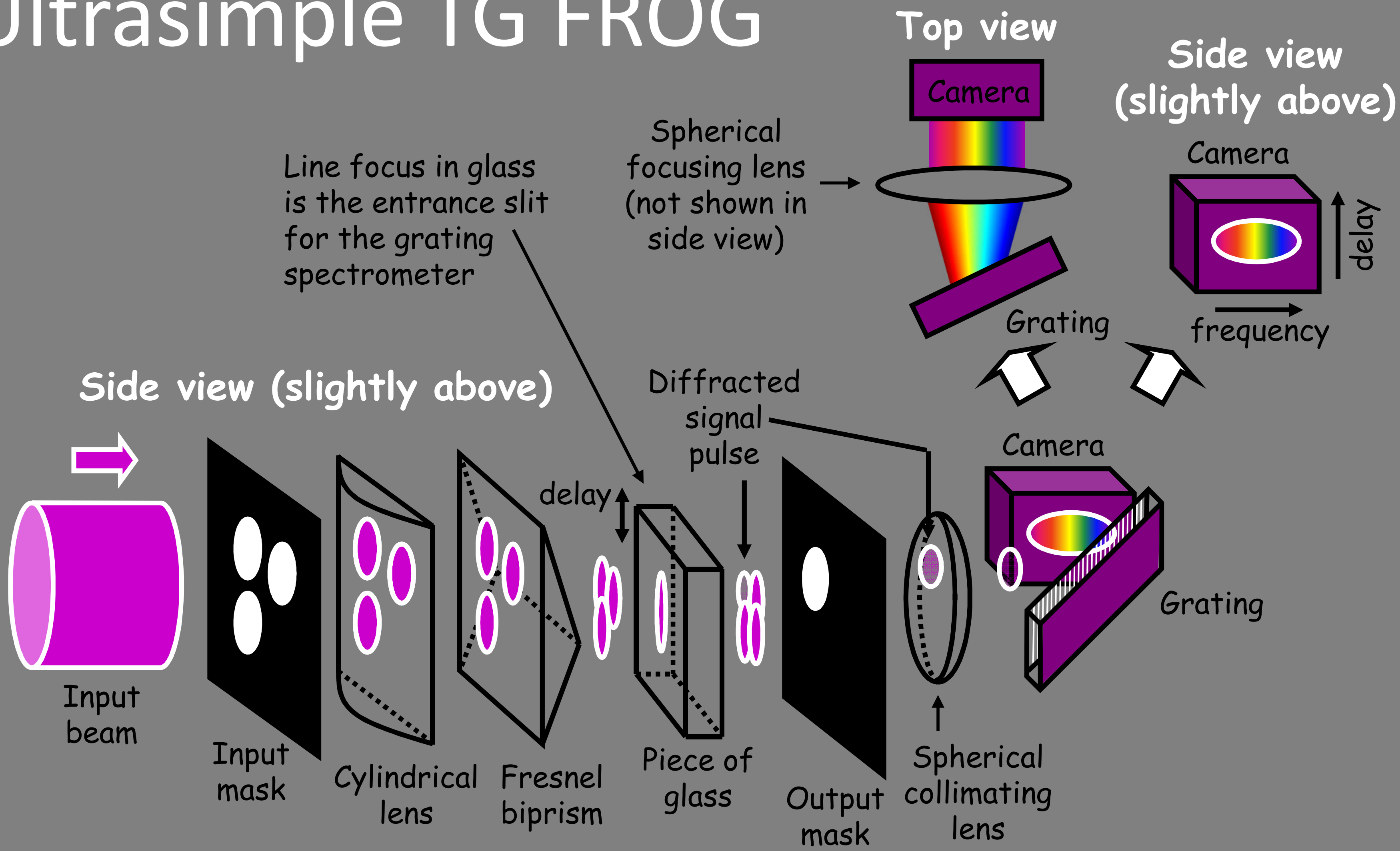
SHG FROG and TG-FROG

$$I_{FROG}(\omega,\tau) = \left| \int_{-\infty}^{\infty} E_{sig}(t,\tau)\exp(-i\omega t)\,dt \right|^2$$



$$E_{sig}(t,t) = E(t\text{-}t)\ |E(t)|^2$$

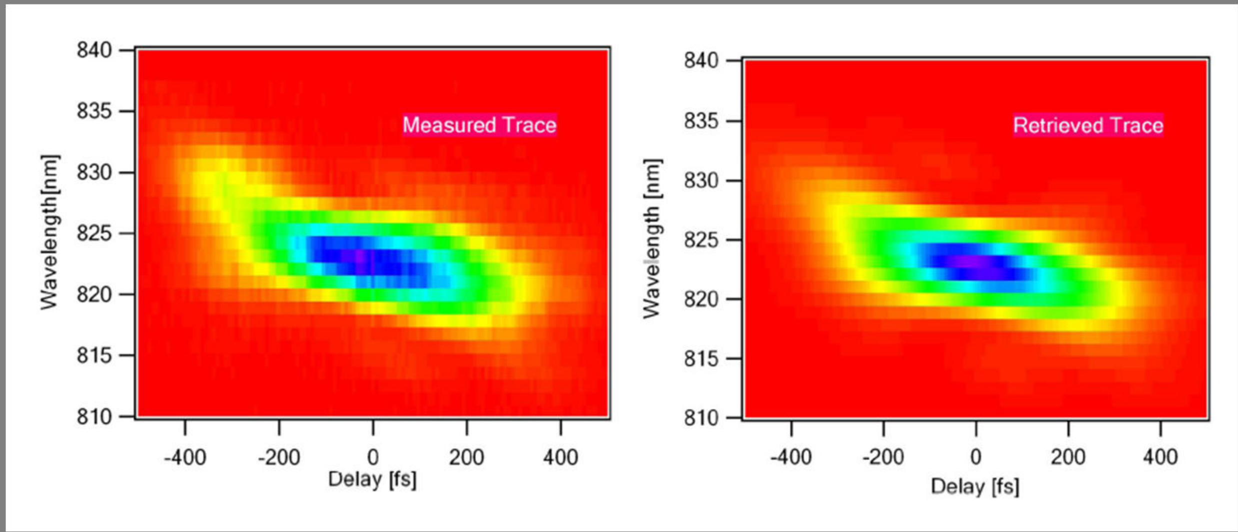
Ultrasimple TG FROG



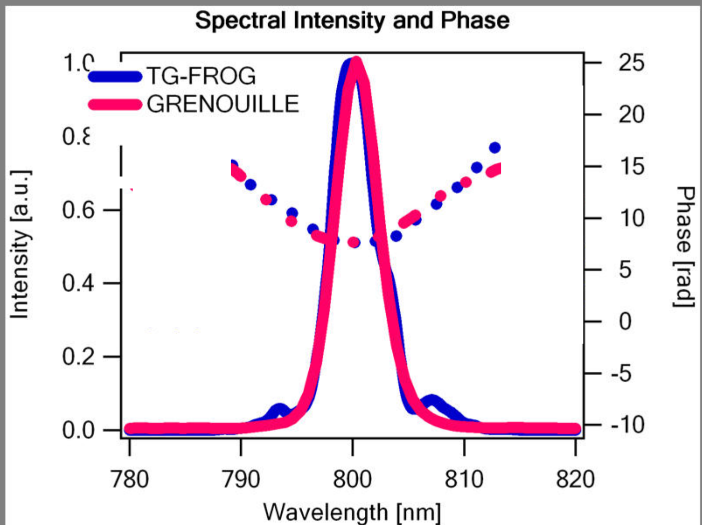
The simple input mask splits three replicas from input beam, and the output mask isolates the signal from the three beams.

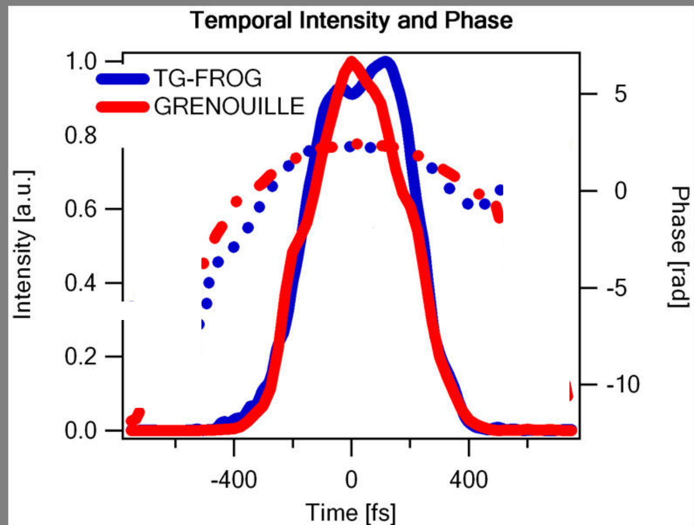
The home brew spectrometer makes the device simpler.

Testing the ultrasimple TG FROG



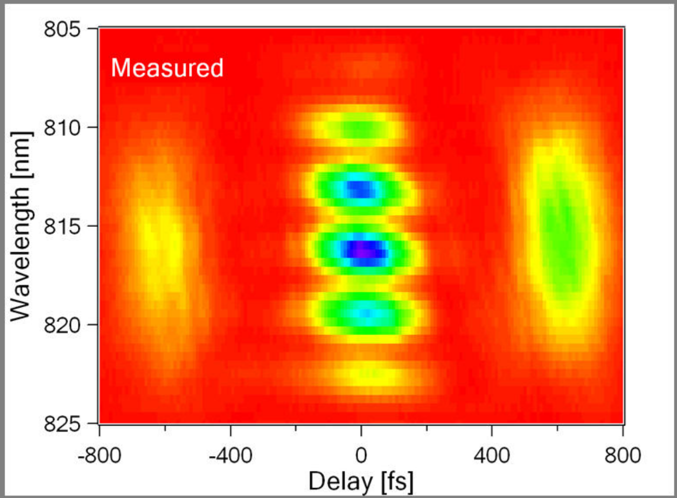
1-kHz-rep-rate 800-nm regenerative Ti:Sapphire amplifier

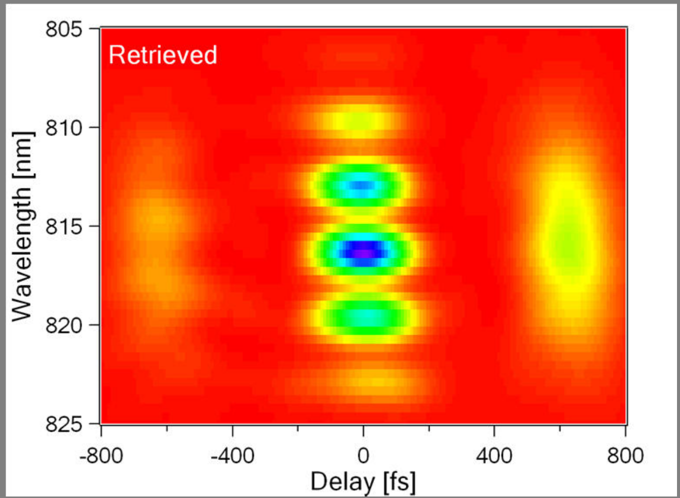


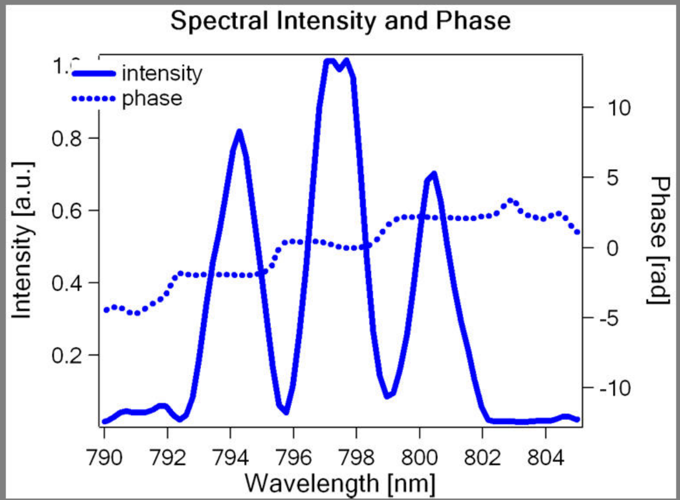


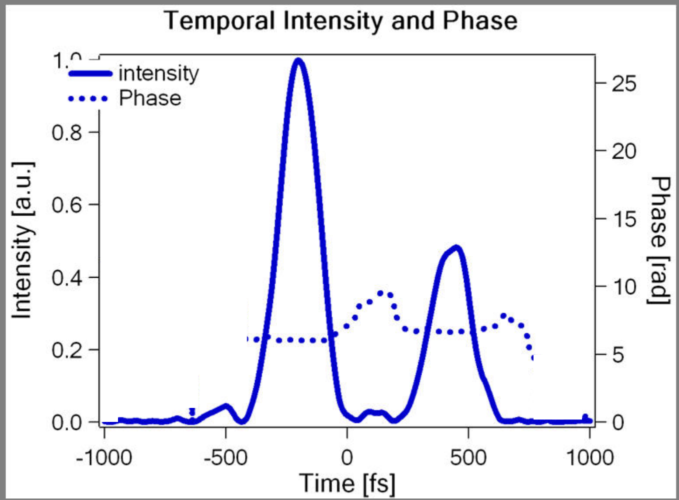
- TG-FROG: 420fs and 4.58nm
- GRENOUILLE: 406fs and 4.61nm

TG FROG measurement of a double pulse

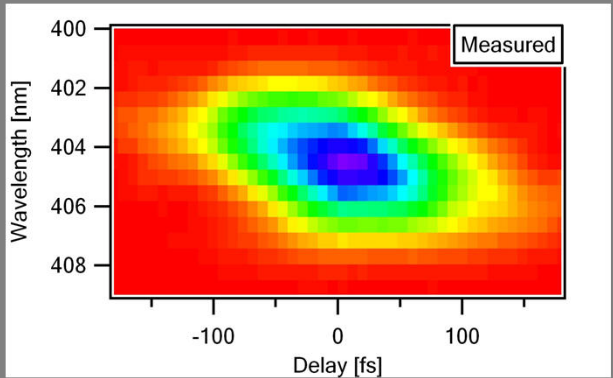


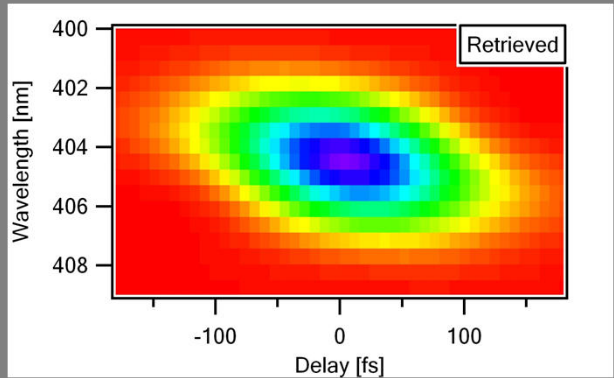




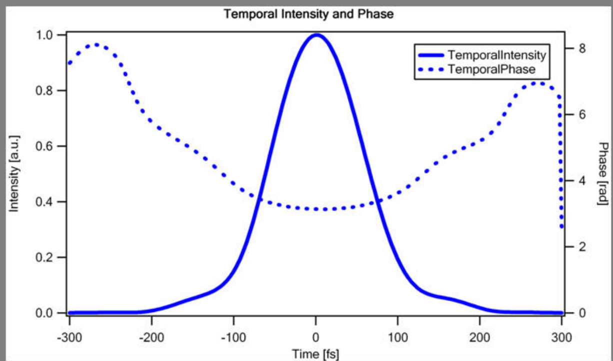


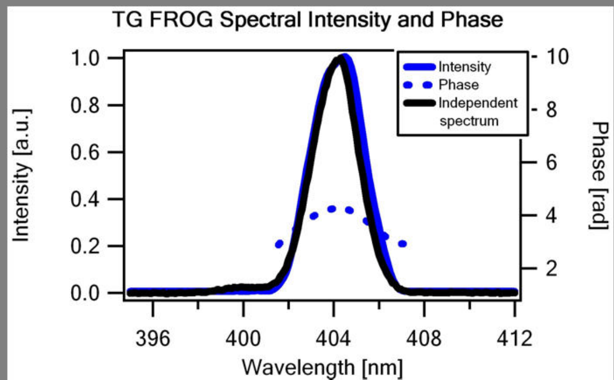
TG FROG measurement for 400nm





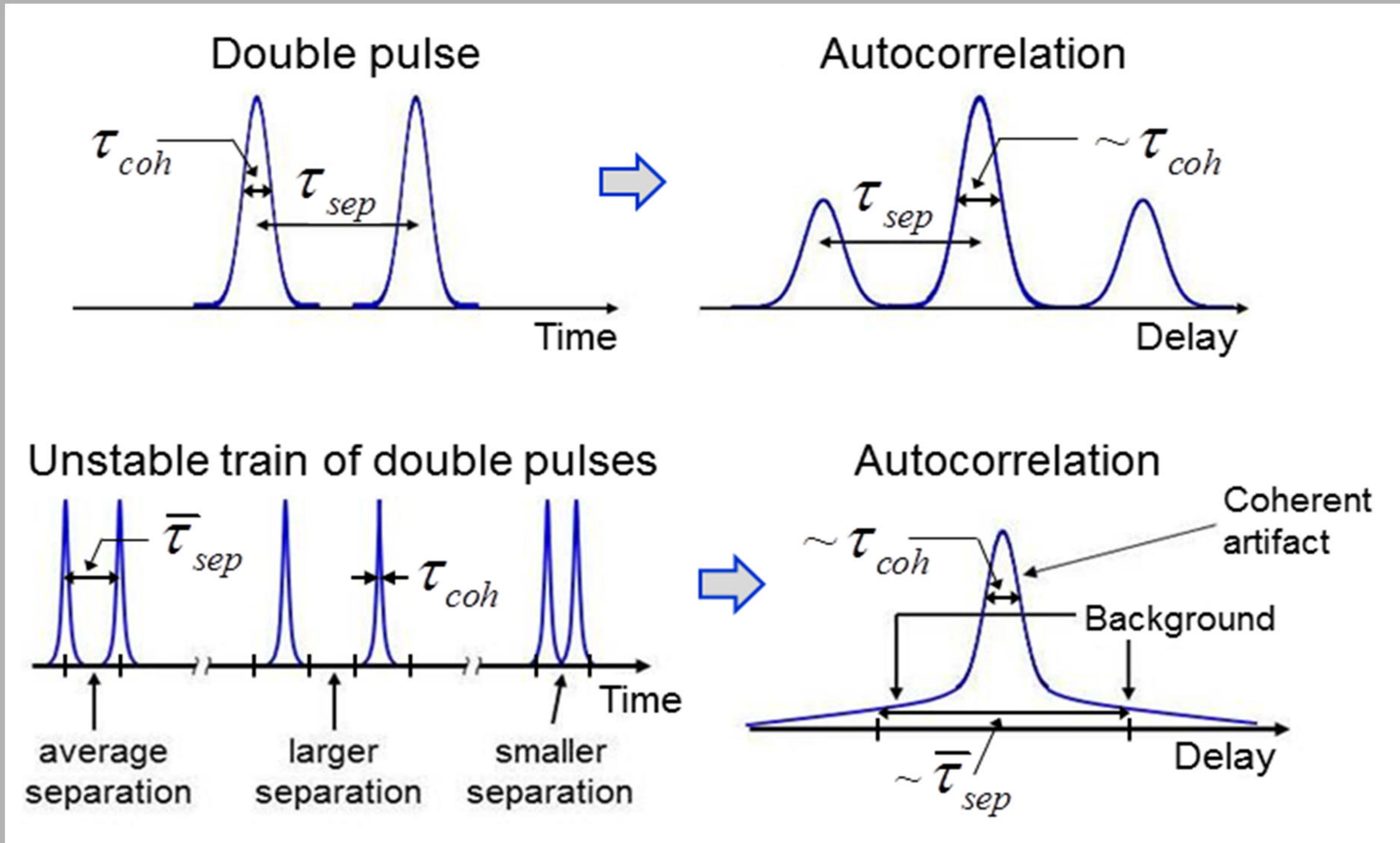
Using 500micron BBO
Regen Power: 520mW
400nm Power: 85mW
Efficiency: 16.3%
130fs 2.57nm Pulse
FROG error: 0.4%



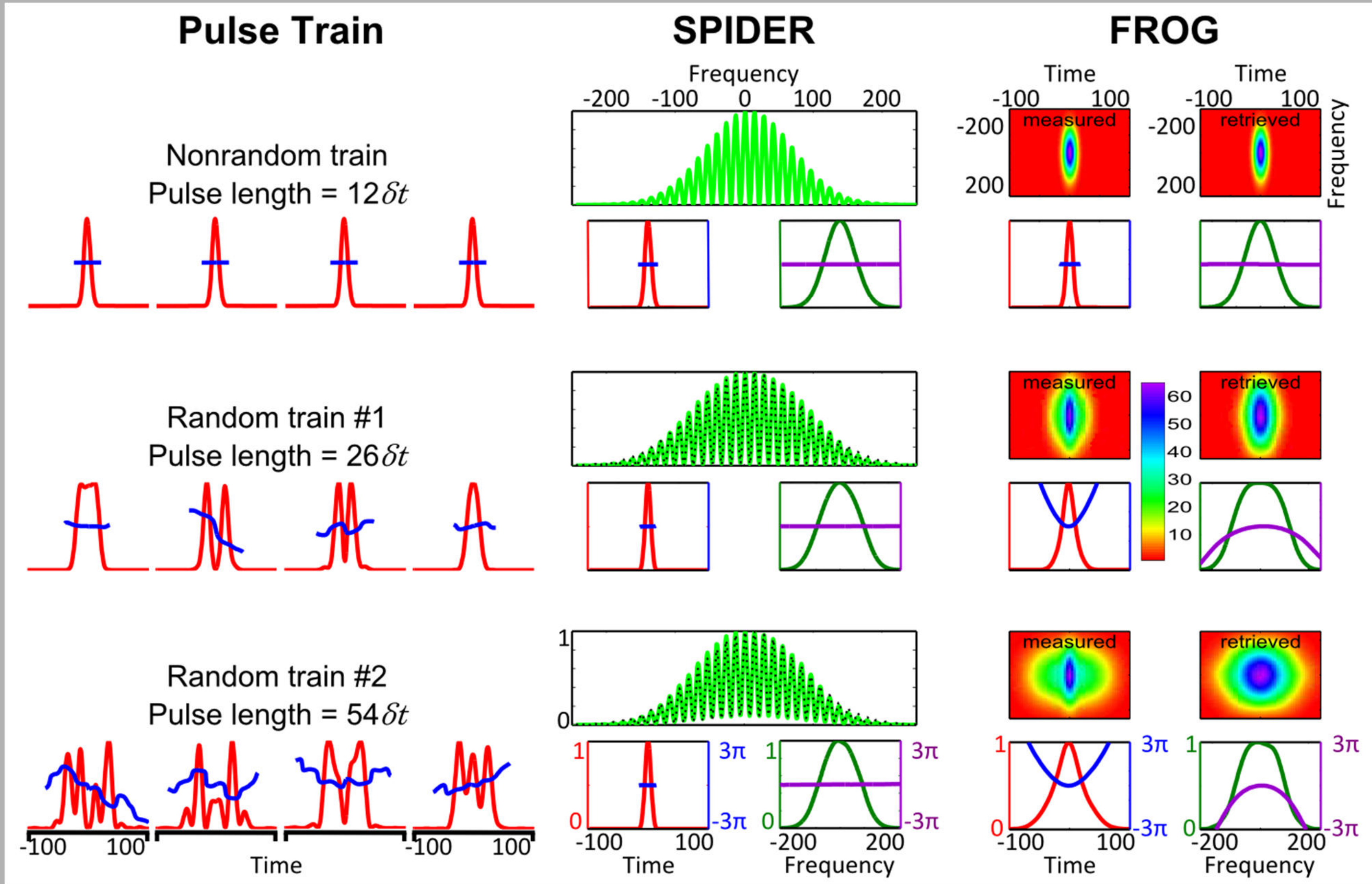


Coherent Artifact in Autocorrelation

In a multi-shot autocorrelation of variably spaced double pulses, the background, not the coherent artifact, yields the correct pulse length.



Simulation for multi-shot SPIDER and SHG FROG



Simulation conclusions

Both techniques work well for the nonrandom pulse train.

For all three pulse trains, SPIDER retrieves **only** the nonrandom (coherent) pulse component, **12*dt* long**, and exhibits **decreasing fringe visibility** (100%, 98%, and 90%, respectively).

Multi-shot SPIDER measures **only** the **coherent artifact** and does not see the full pulse. Reduced fringe visibility indicates this but could also be due to device misalignment. Worse, even a 98% fringe visibility corresponds to an under-estimate of the pulse length by more than a factor of 2.

SPIDER gives no indication of the correct pulse length.

FROG also does not see the pulse structure, but it does yield the correct durations.

Also, for unstable pulse trains, FROG shows a **large disagreement between measured and retrieved traces** and **a large rms difference (G error).**

Analytical SPIDER calculation

$$S_{SPIDER} \propto \left\langle \left| E(\omega) + E(\omega+\delta\omega)\exp(i\omega T) + E_{rand}(\omega) + E_{rand}(\omega+\delta\omega)\exp(i\omega T) \right|^2 \right\rangle$$

$$\begin{aligned} S_{SPIDER} \propto \Big\langle & \left|E(\omega)\right|^2 + \left|E(\omega+\delta\omega)\right|^2 + \left|E_{rand}(\omega)\right|^2 + \left|E_{rand}(\omega+\delta\omega)\right|^2 + \\ & 2\,\mathrm{Re}\{E^*(\omega)E(\omega+\delta\omega)\exp(i\omega T)\} + 2\,\mathrm{Re}\{E^*(\omega)E_{rand}(\omega)\} + \\ & 2\,\mathrm{Re}\{E^*(\omega)E_{rand}(\omega+\delta\omega)\exp(i\omega T)\} + 2\,\mathrm{Re}\{E^*(\omega+\delta\omega)\exp(-i\omega T)E_{rand}(\omega)\} + \\ & 2\,\mathrm{Re}\{E^*(\omega+\delta\omega)E_{rand}(\omega+\delta\omega)\} + 2\,\mathrm{Re}\{E^*_{rand}(\omega)E_{rand}(\omega+\delta\omega)\exp(i\omega T)\} \Big\rangle \end{aligned}$$

Any term containing only one random field will sum to zero in the average over many pulses due to zeroth-order phase variations.

$$\begin{aligned} S_{SPIDER} \propto \Big\langle & \left|E(\omega)\right|^2 + \left|E(\omega+\delta\omega)\right|^2 + \left|E_{rand}(\omega)\right|^2 + \left|E_{rand}(\omega+\delta\omega)\right|^2 + \\ & 2\,\mathrm{Re}\{E^*(\omega)E(\omega+\delta\omega)\exp(i\omega T) + E^*_{rand}(\omega)E_{rand}(\omega+\delta\omega)\exp(i\omega T)\} \Big\rangle \end{aligned}$$

Expressing in terms of the spectra, $S(\omega)$ and $S_{rand}(\omega)$, and the spectral phases, $\varphi(\omega)$ and $\varphi_{rand}(\omega)$:

$$
\begin{aligned}
S_{SPIDER} = {} & S(\omega) + S(\omega+\delta\omega) + \langle S_{rand}(\omega)\rangle + \langle S_{rand}(\omega+\delta\omega)\rangle + \\
& 2\sqrt{S(\omega)}\sqrt{S(\omega+\delta\omega)}\cos[\varphi(\omega+\delta\omega) - \varphi(\omega) + \omega T] + \\
& 2\left\langle \sqrt{S_{rand}(\omega)}\sqrt{S_{rand}(\omega+\delta\omega)}\cos[\varphi_{rand}(\omega+\delta\omega) - \varphi_{rand}(\omega) + \omega T]\right\rangle
\end{aligned}
$$

Rewriting in terms of the group delay vs. frequency for the two pulse components, $\tau(\omega) = d\varphi/d\omega$ and $\tau_{rand}(\omega) = d\varphi_{rand}/d\omega$:

$$
\begin{aligned}
S_{SPIDER} = {} & S(\omega) + S(\omega+\delta\omega) + \langle S_{rand}(\omega)\rangle + \langle S_{rand}(\omega+\delta\omega)\rangle + \\
& 2\sqrt{S(\omega)}\sqrt{S(\omega+\delta\omega)}\cos[\delta\omega\ \tau(\omega) + \omega T] + \\
& 2\left\langle \sqrt{S_{rand}(\omega)}\sqrt{S_{rand}(\omega+\delta\omega)}\cos[\delta\omega\ \tau_{rand}(\omega) + \omega T]\right\rangle
\end{aligned}
$$

Sum of spectra

SPIDER fringe term for the nonrandom component

SPIDER fringe term for the random component (goes to zero for variations in pulse arrival time of $>2\pi/\delta\omega$)