

Self-phase modulation patterns in optical fibres

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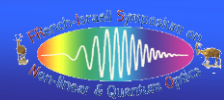
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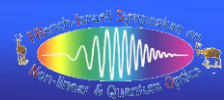


➤ Introduction

➤ Qualitative description of self-phase modulation and analytical guidelines

➤ Mitigation of self-phase modulation

➤ Conclusion

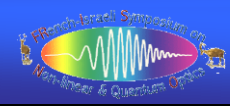


➤ Introduction

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Propagation in a nonlinear singlemode waveguide

NON-LINEARITY

velocity depends on the intensity

γ nonlinear Kerr coefficient

$$\gamma = \frac{n_2 \omega_0}{c A_{eff}}$$



Nonlinear Schrödinger equation (NLSE) governs the scalar propagation of light in a singlemode scalar optical waveguide.

$$i \frac{\partial \psi}{\partial z} = \frac{\beta_2}{2} \frac{\partial^2 \psi}{\partial t^2} - \gamma |\psi|^2 \psi$$

velocity depends on the frequency

β_2 2nd-order dispersion coefficient

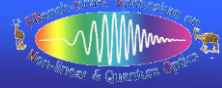
DISPERSION

Propagation in a nonlinear singlemode waveguide

- ➔ Nonlinear Schrödinger equation (NLSE) governs the scalar propagation of light in a singlemode scalar optical waveguide.

$$i \frac{\partial \psi}{\partial z} = \frac{\beta_2}{2} \frac{\partial^2 \psi}{\partial t^2} - \gamma |\psi|^2 \psi$$

- ➔ Optical fibers are a perfect testbed as it involves very low losses.
- ➔ The singlemode waveguide structure maintains the spatial profile unaffected.
- ➔ Nonlinearity can be observed with picosecond pulses of only a few Watt of peak power.



Propagation in the highly nonlinear regime

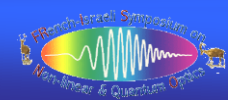
$$i \frac{\partial \psi}{\partial z} = \frac{\beta_2}{2} \frac{\partial^2 \psi}{\partial t^2} - \gamma |\psi|^2 \psi$$

➔ When nonlinearity strongly overcomes dispersive effects (i.e. for high peak power pulses or for long pulses), NLSE resumes to :

$$i \frac{\partial \psi}{\partial z} = -\gamma |\psi|^2 \psi$$

$$\psi(t, L) \simeq \psi(t, 0) \exp\left(i \gamma |\psi(t, 0)|^2 L\right)$$

➔ Kerr nonlinearity leads to the modulation of the temporal phase of a pulse propagating in a nonlinear waveguide : **SELF-PHASE MODULATION**.

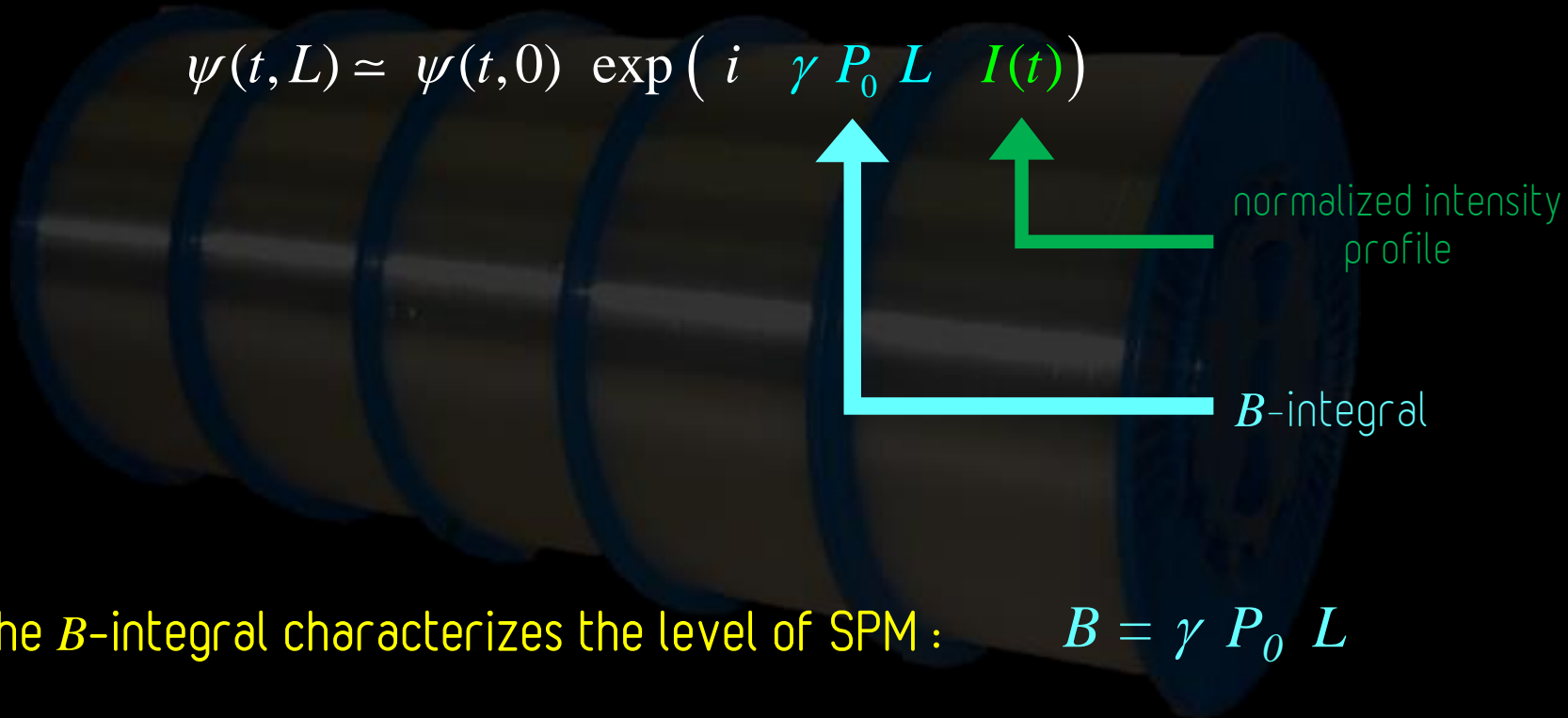


Self-phase modulation - B-integral

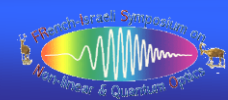
➔ Kerr nonlinearity leads to the modulation of the temporal phase of a pulse propagating in a nonlinear waveguide : **SELF-PHASE MODULATION**.

$$\psi(t, L) \simeq \psi(t, 0) \exp \left(i \gamma |\psi(t, 0)|^2 L \right)$$

$$\psi(t, L) \simeq \psi(t, 0) \exp \left(i \gamma P_0 L I(t) \right)$$



➔ The B -integral characterizes the level of SPM : $B = \gamma P_0 L$

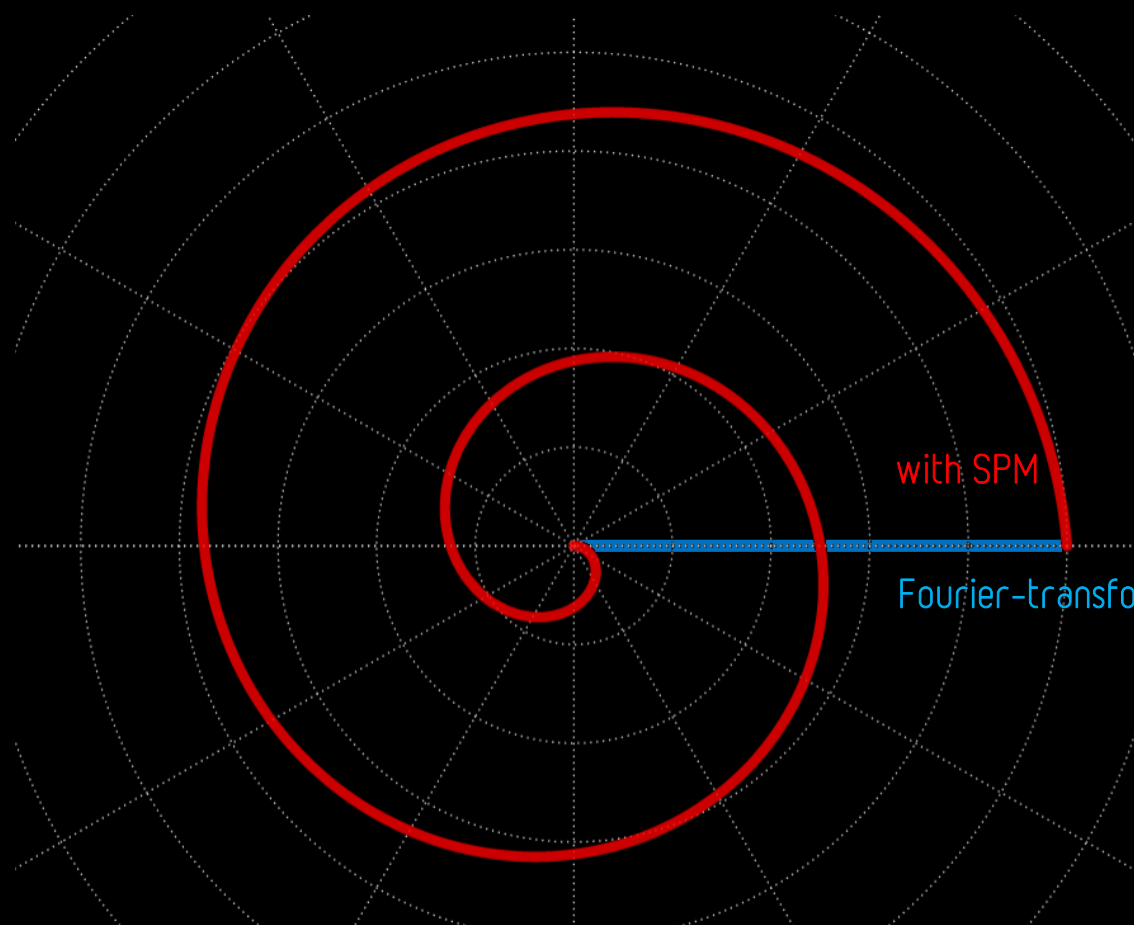


Self-phase modulation - polar plot



Kerr nonlinearity leads to the modulation of the temporal phase of a pulse propagating in a nonlinear waveguide : **SELF-PHASE MODULATION**.

$$\psi(t, L) \simeq \psi(t, 0) \exp(i B I(t))$$

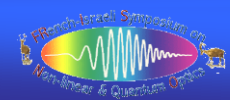


when a polar plot is used, a pulse is characterized by an Archimedean spiral

with SPM

Fourier-transform limited pulse

$B / 2\pi$ is the number of turns of the spiral

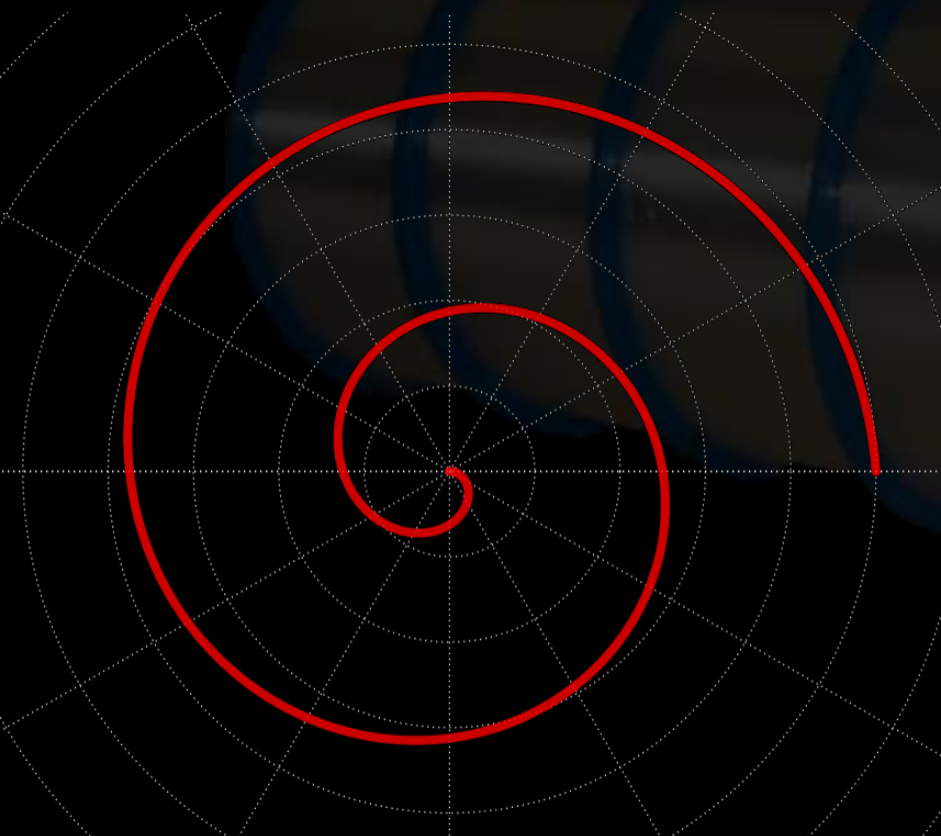


Self-phase modulation - polar plot



Kerr nonlinearity leads to the modulation of the temporal phase of a pulse propagating in a nonlinear waveguide : **SELF-PHASE MODULATION**.

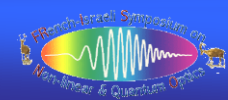
$$\psi(t, L) \simeq \psi(t, 0) \exp \left(i B I(t) \right)$$



Burgundy snail



6π B -integral



Self-phase modulation - Spectrum

- ➔ Kerr nonlinearity leads to the modulation of the temporal phase of a pulse propagating in a nonlinear waveguide : **SELF-PHASE MODULATION**.

$$\psi(t, L) \simeq \psi(t, 0) \exp(i B I(t))$$

- ➔ The phase modulation leads to a chirp : $\delta\omega(t, L) = -B \frac{\partial I}{\partial t}$

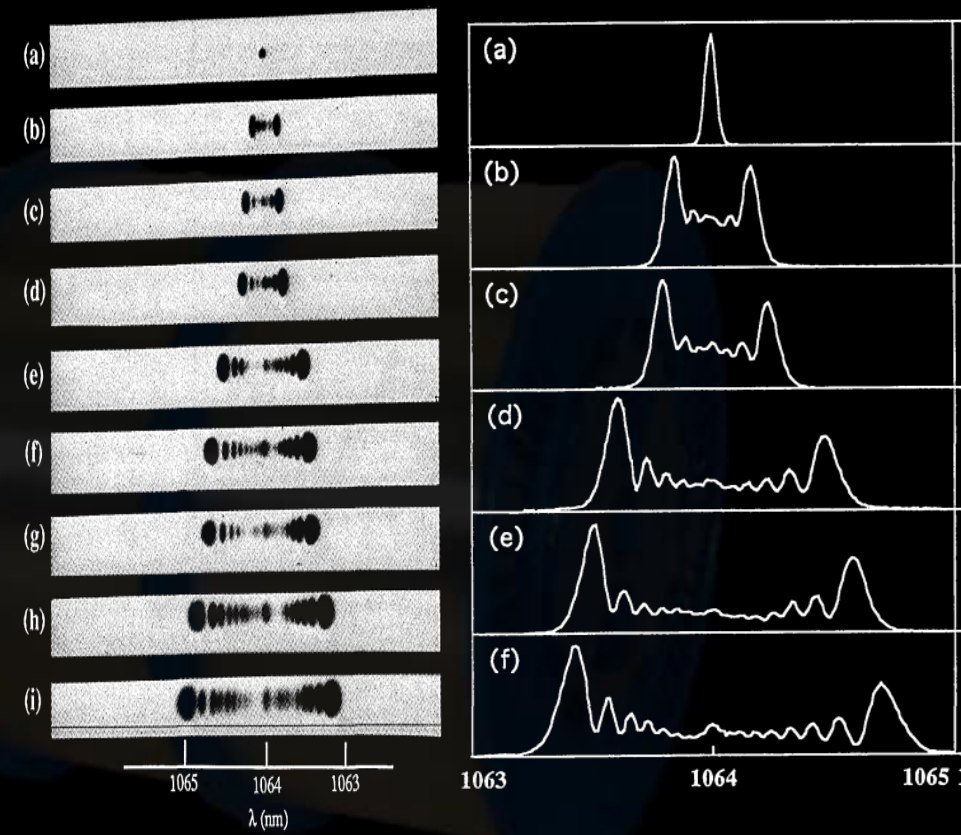
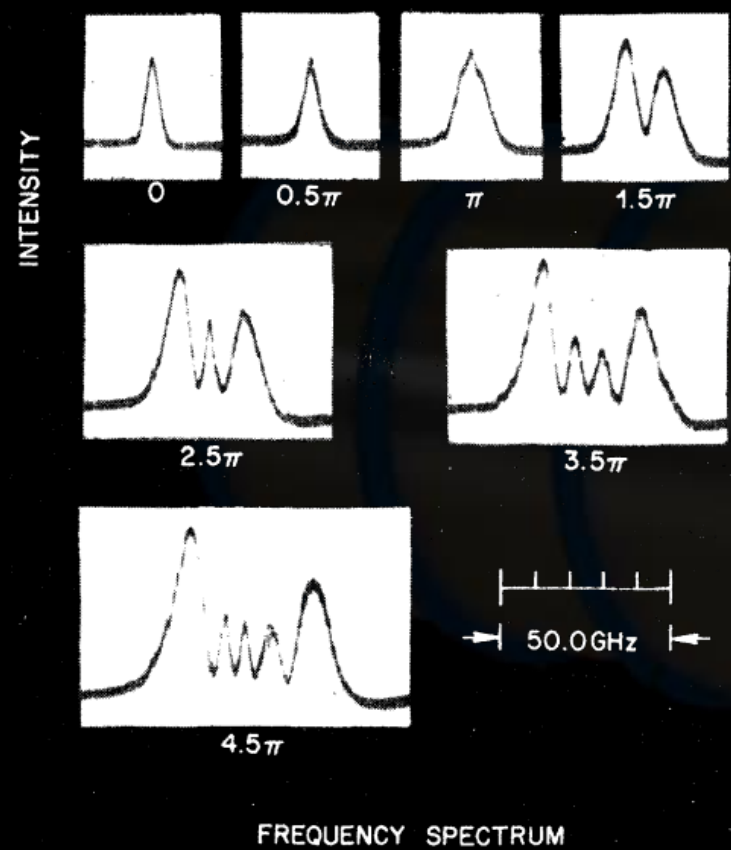
- ➔ The spectrum is affected :

$$S(\omega) = \left| \int_{-\infty}^{\infty} \psi(0, t) \exp(i B I(t)) \exp(i \omega t) dt \right|^2$$



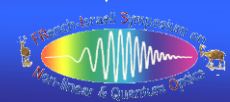
Examples of self-phase modulation

➤ The frequency chirp leads to the expansion of the spectrum with marked oscillations.



Stolen, R.H., Lin, C.:
 Phys. Rev. A 17(4), 1448-1453 (1978)

Wang, Q. Z., Liu Q. D., Liu D., Ho P. P., and Alfano R. R.,
 J. Opt. Soc. Am. B 11, 1084-1089 (1994).



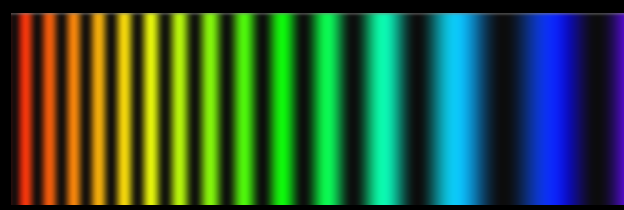
➤ Introduction

➤ Qualitative description of self-phase modulation and analytical guidelines

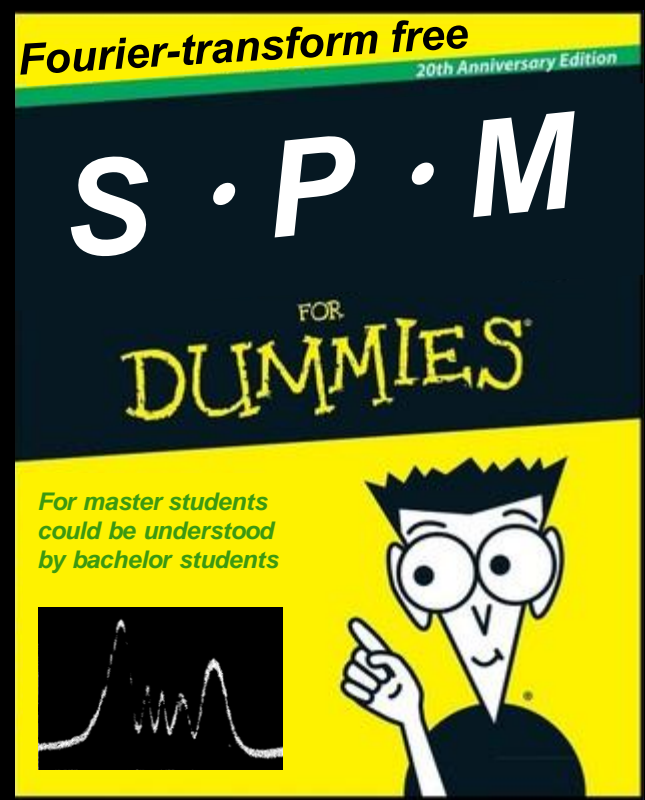
bachelor student

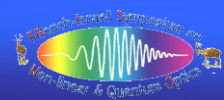


Hey, your SPM oscillations are what we observe in the experiment with a birefringent plate.

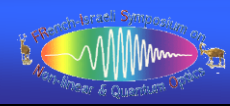


Bernard Brunhes. *Expérience sur les spectres cannelés.* J. Phys. Theor. Appl., 1891, 10 (1), pp.508- 512.



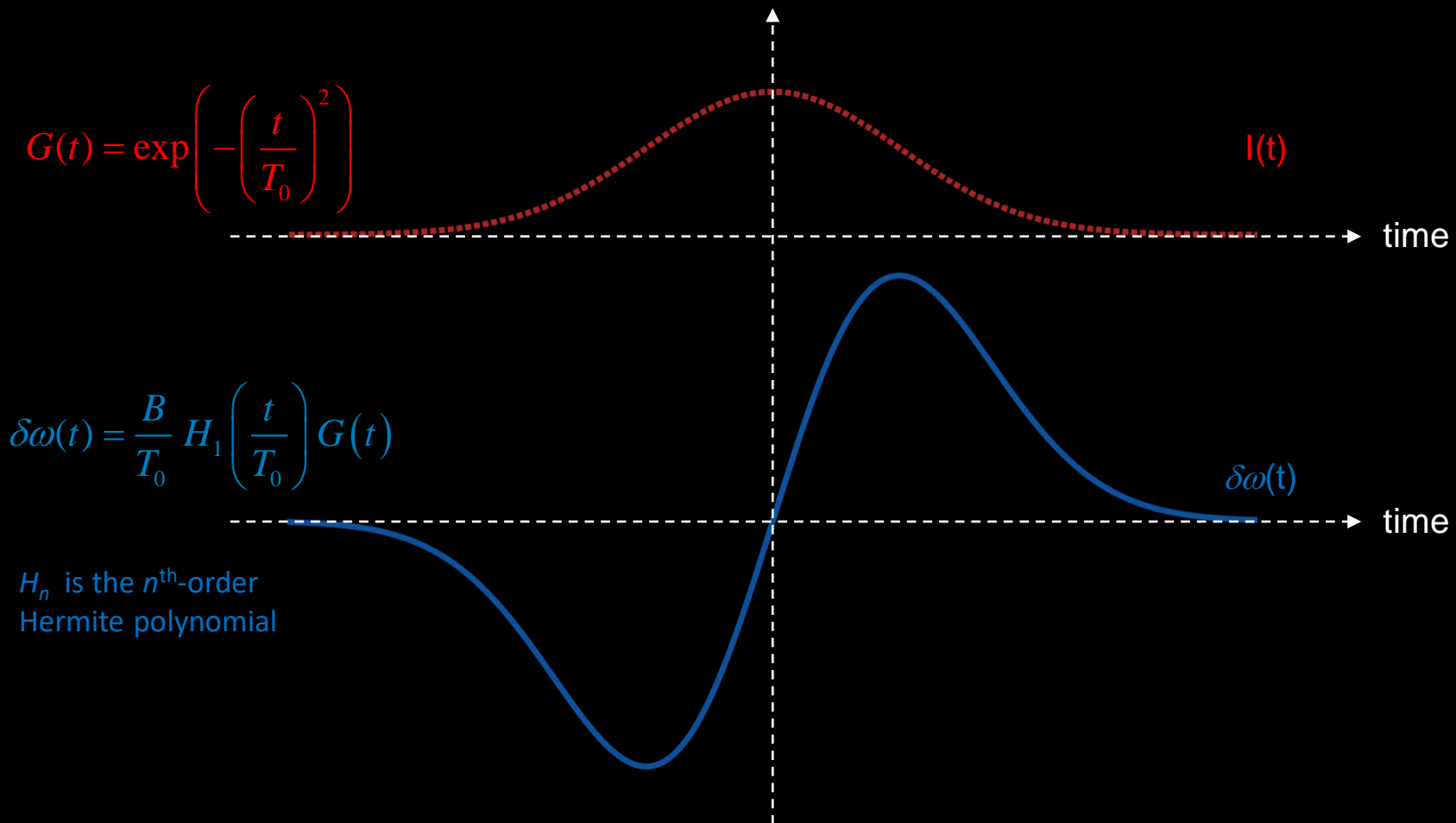


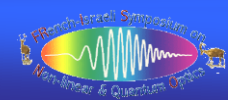
- Introduction
- Qualitative description of self-phase modulation and analytical guidelines
 - for initial Fourier-transform limited pulses
 - for initial linearly chirped pulses
- Cancelling self-phase modulation
- Conclusion



Self-phase modulation of a Gaussian pulse

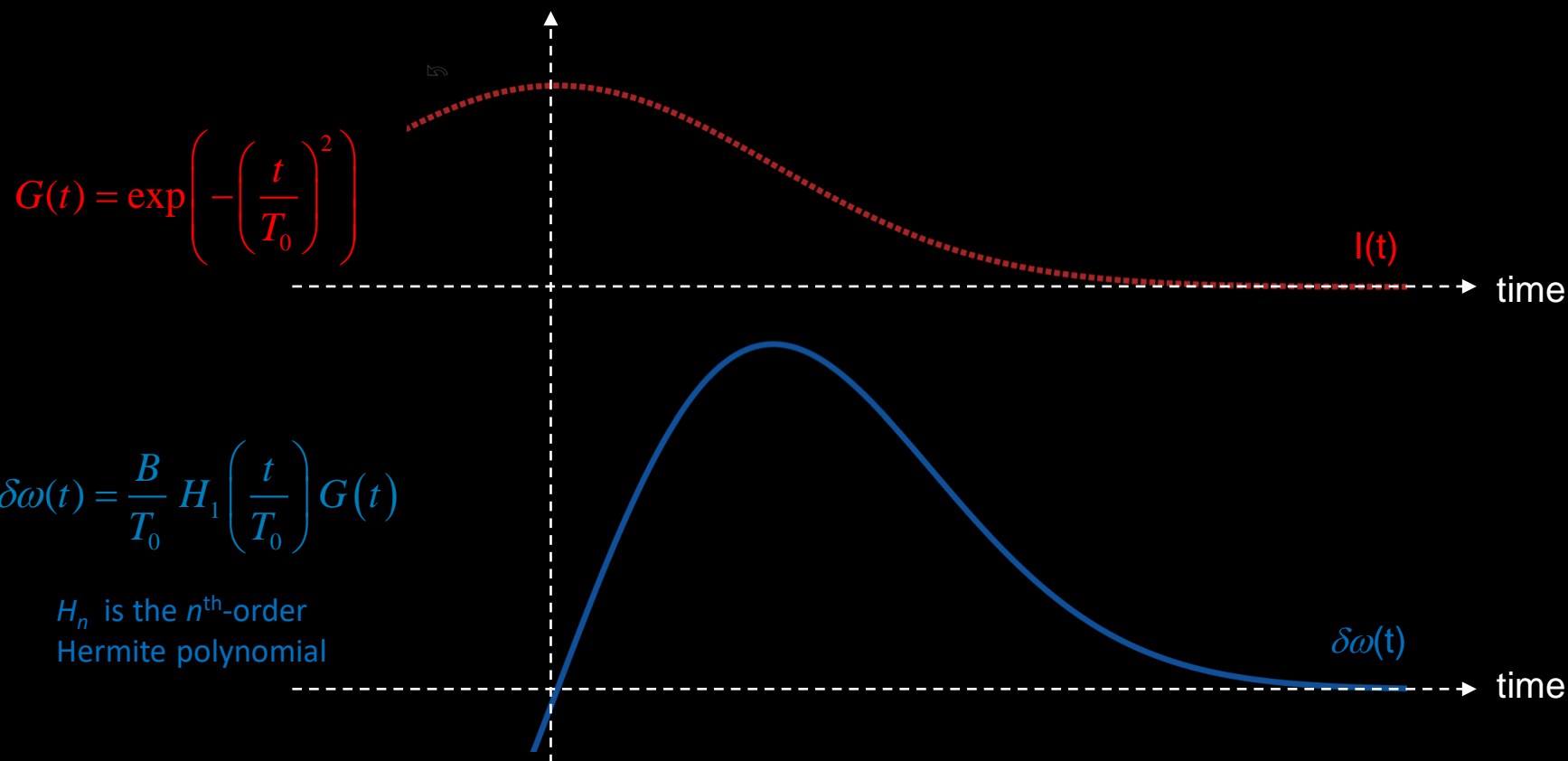
➤ Let us consider the case of a chirp-free Gaussian pulse.

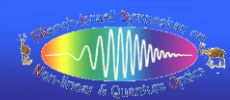




Self-phase modulation of a Gaussian pulse - Temporal chirp

➔ We can benefit from symmetry.





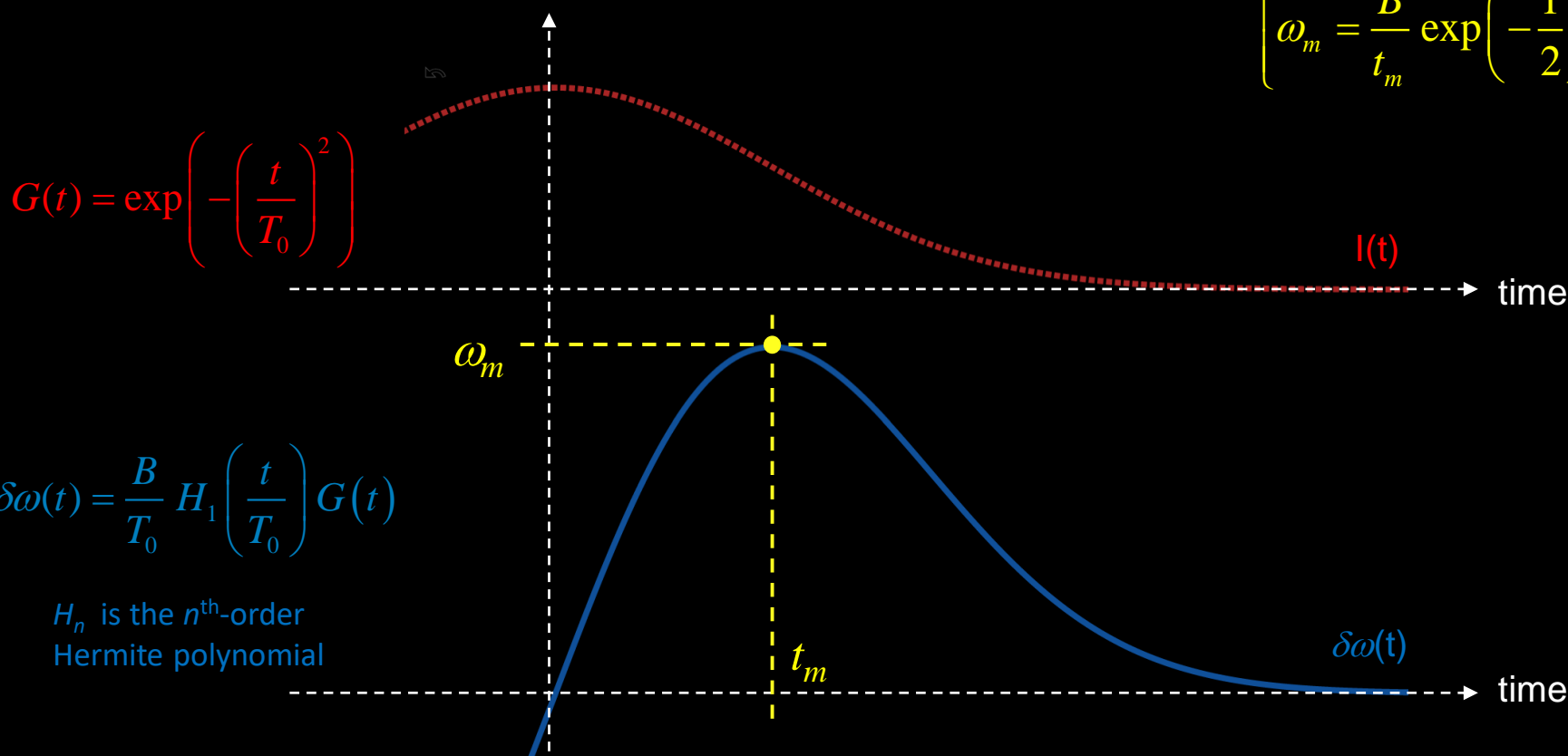
Self-phase modulation of a Gaussian pulse - Temporal chirp

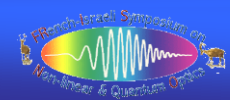
➔ The maxima of the chirp can be easily evaluated.

$$\frac{d\delta\omega(t)}{dt} = -\frac{B}{T_0^2} H_2\left(\frac{t}{T_0}\right) G(t) = 0$$

G. P. Agrawal, Nonlinear Fiber Optics, 2006.

$$\begin{cases} t_m = \frac{T_0}{\sqrt{2}} \\ \omega_m = \frac{B}{t_m} \exp\left(-\frac{1}{2}\right) \end{cases}$$

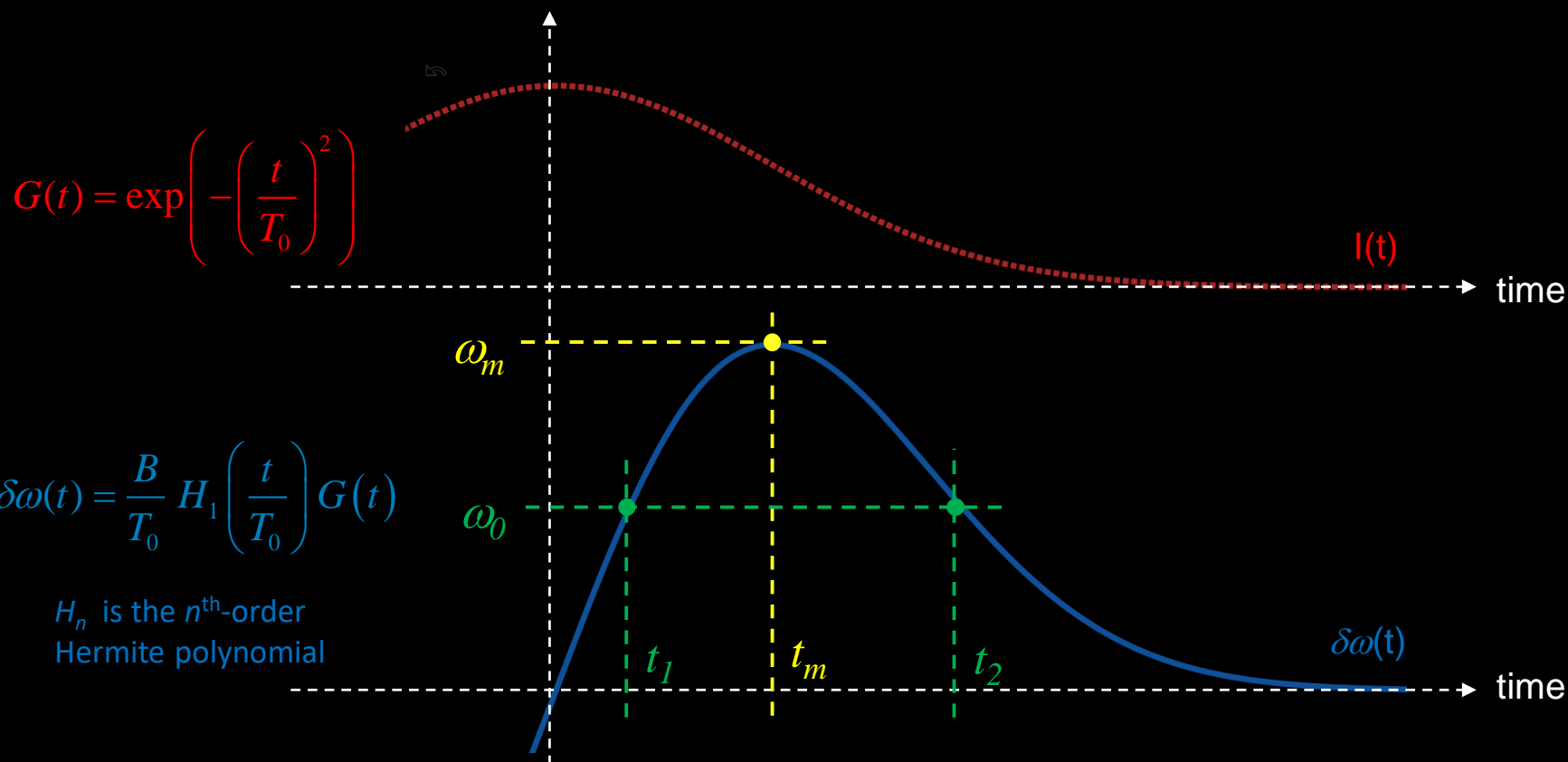


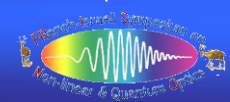


Self-phase modulation of a Gaussian pulse - Temporal chirp

➤ The same instantaneous frequency ω_0 exists at two different times t_1 and t_2 .

R. Cubeddu, R. Polloni, C. A. Sacchi, and O. Svelto, "Self-Phase Modulation and "Rocking" of Molecules in Trapped Filaments of Light with Picosecond Pulses," Physical Review A 2, 1955-1963 (1970).





Understanding of the interference

➔ The same instantaneous frequency ω_0 exists at two different times t_1 and t_2 .

W is the Lambert W function

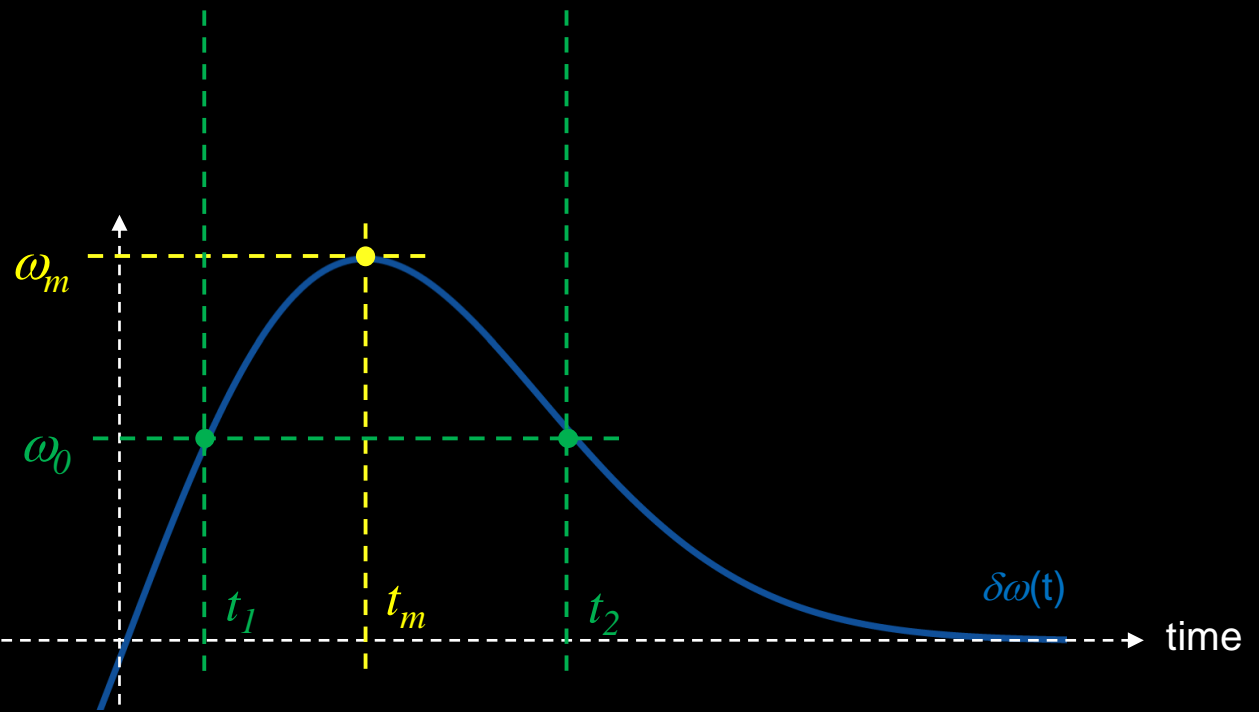


$$t_1 = t_m \sqrt{-W_0 \left(- \left(\frac{\omega_0}{\omega_m} \right)^2 e \right)}$$

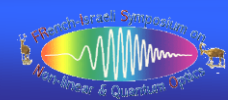
$$t_2 = t_m \sqrt{-W_{-1} \left(- \left(\frac{\omega_0}{\omega_m} \right)^2 e \right)}$$

$$\delta\omega(t) = \frac{B}{T_0} H_1 \left(\frac{t}{T_0} \right) G(t)$$

H_n is the n^{th} -order Hermite polynomial



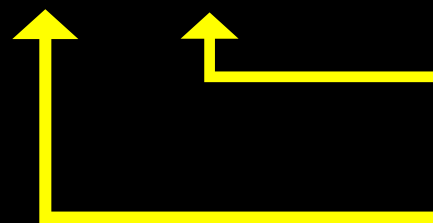
time



Understanding of the interference - phase difference

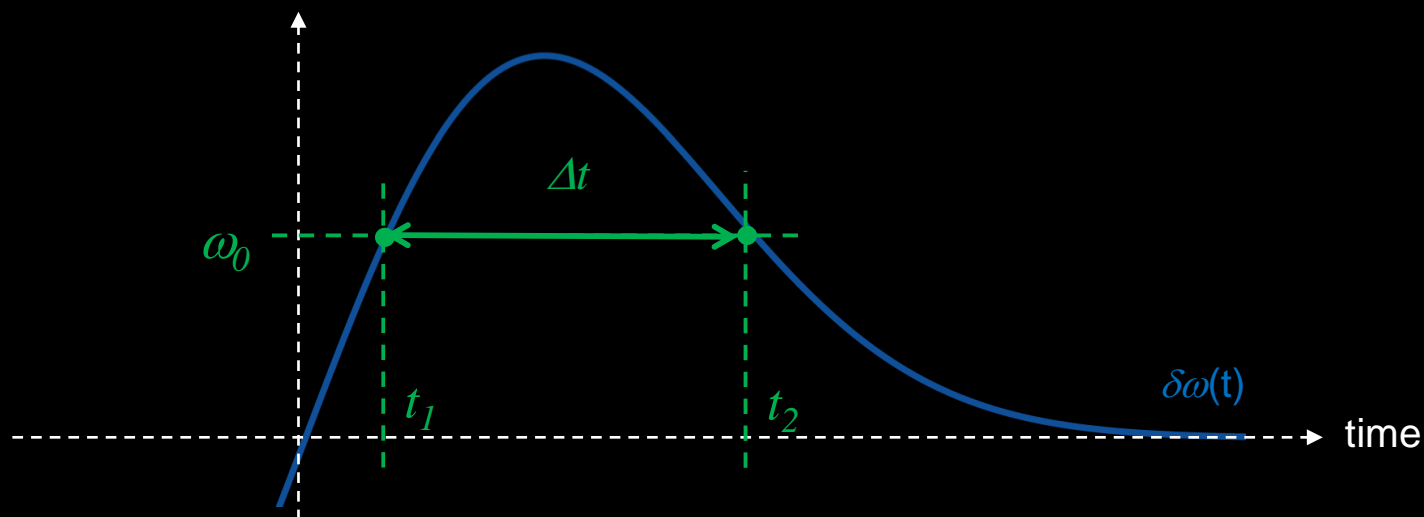
- The same instantaneous frequency ω_0 may exist at two instants t_1 and t_2 .
- An interference occurs between the two instants.
- We evaluate the phase difference $\Delta\varphi_T$ between the two times spaced by Δt .

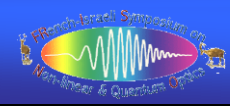
$$\Delta\varphi_T(\omega_0) = \Delta\varphi_D + \Delta\varphi_{NL}$$



nonlinear phase shift

linear phase shift

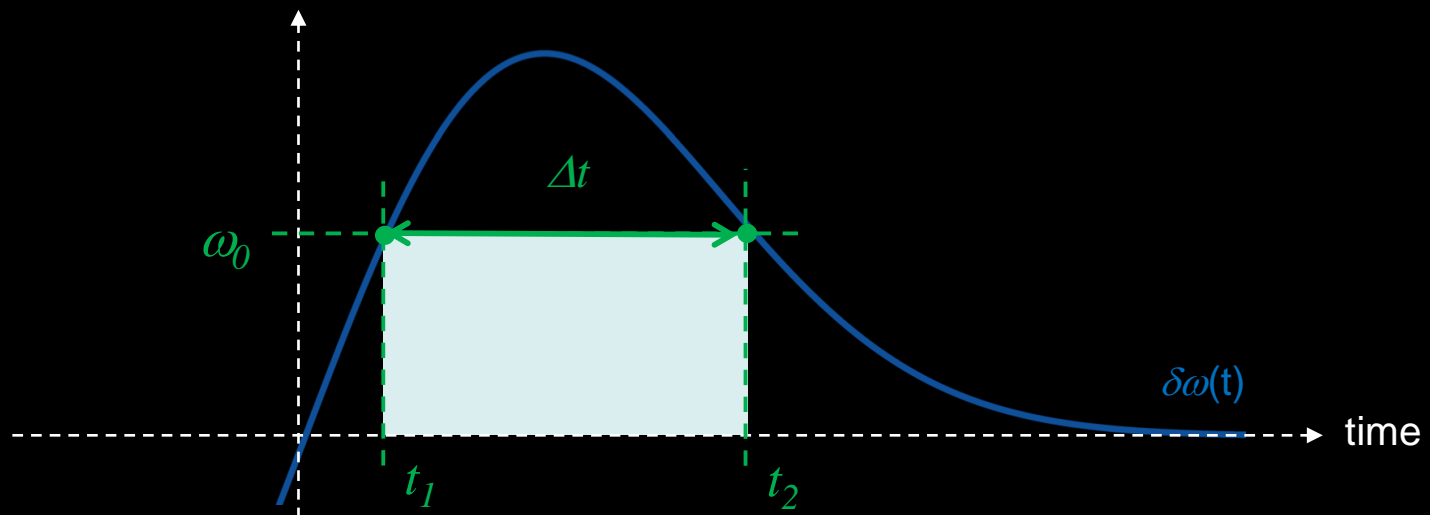


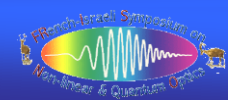


Understanding of the interference - linear phase contribution

$$\Delta\varphi_T(\omega_0) = \Delta\varphi_D + \Delta\varphi_{NL}$$

linear phase shift : $\Delta\varphi_D(\omega_0) = \omega_0 \Delta t$





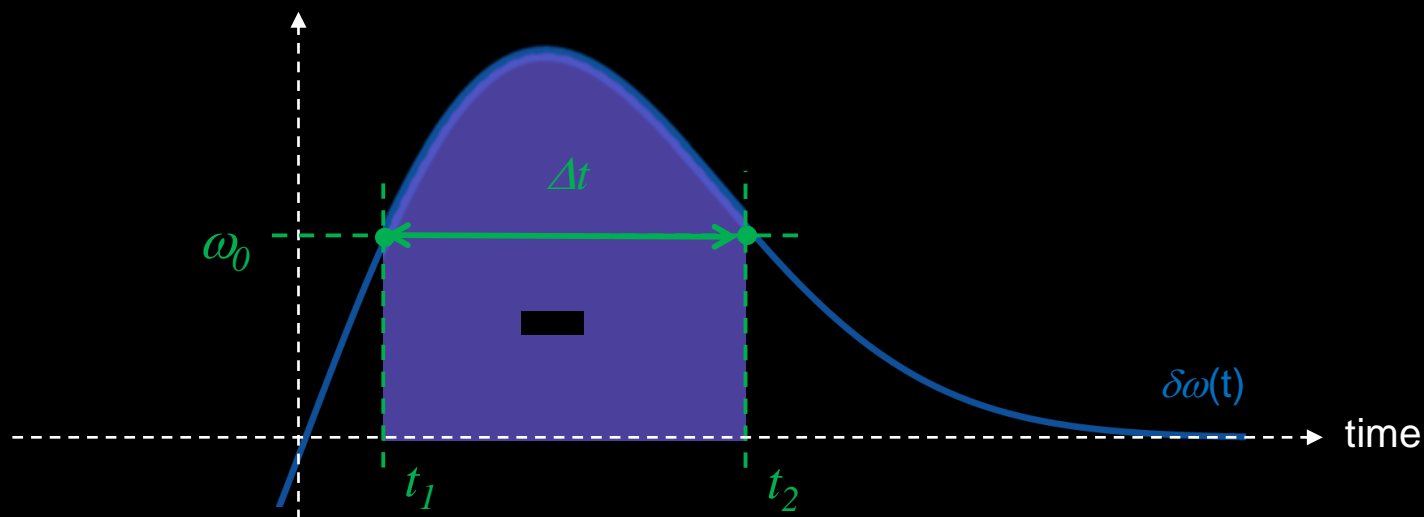
Understanding of the interference - nonlinear phase contribution

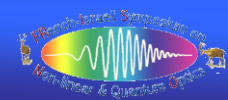
$$\Delta\varphi_T(\omega_0) = \Delta\varphi_D + \Delta\varphi_{NL}$$

linear phase shift : $\Delta\varphi_D(\omega_0) = \omega_0 \Delta t$

nonlinear phase shift : $\Delta\varphi_{NL}(\omega_0) = B [G(t_2) - G(t_1)]$

➡ $\Delta\varphi_{NL}$ increases with ω_0 from $-B$ up to 0 .





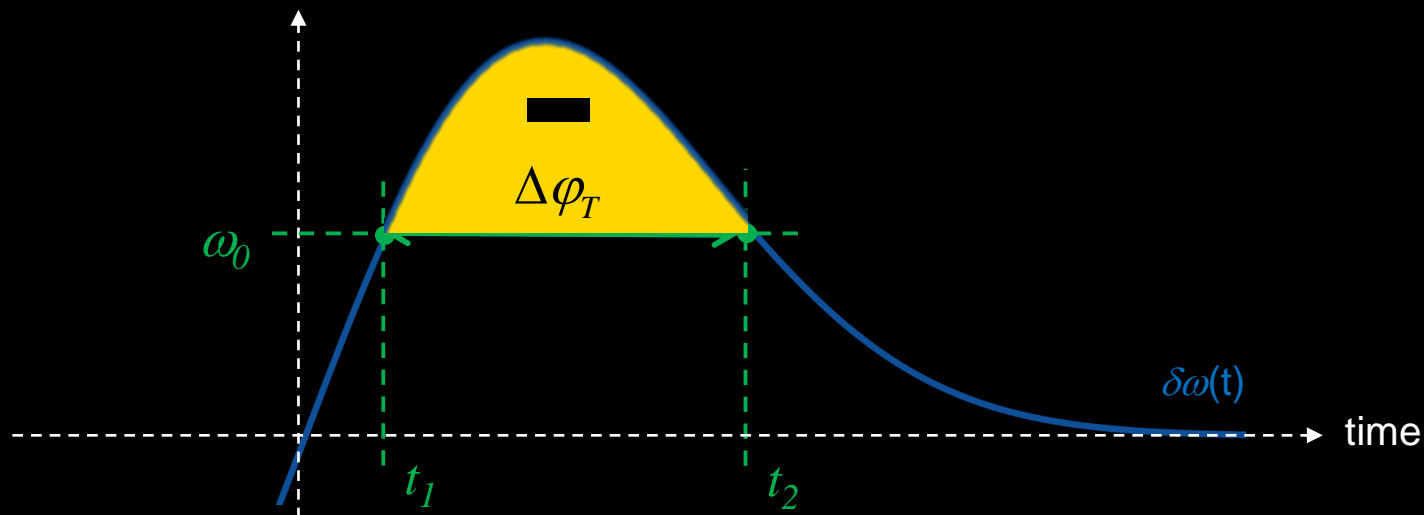
Understanding of the interference - total phase contribution

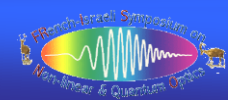
$$\Delta\varphi_T(\omega_0) = \Delta\varphi_D + \Delta\varphi_{NL}$$

linear phase shift : $\Delta\varphi_D(\omega_0) = \omega_0 \Delta t$

nonlinear phase shift : $\Delta\varphi_{NL}(\omega_0) = B [G(t_2) - G(t_1)]$

➡ $\Delta\varphi_T$ increases with ω_0 from $-B$ up to 0 .



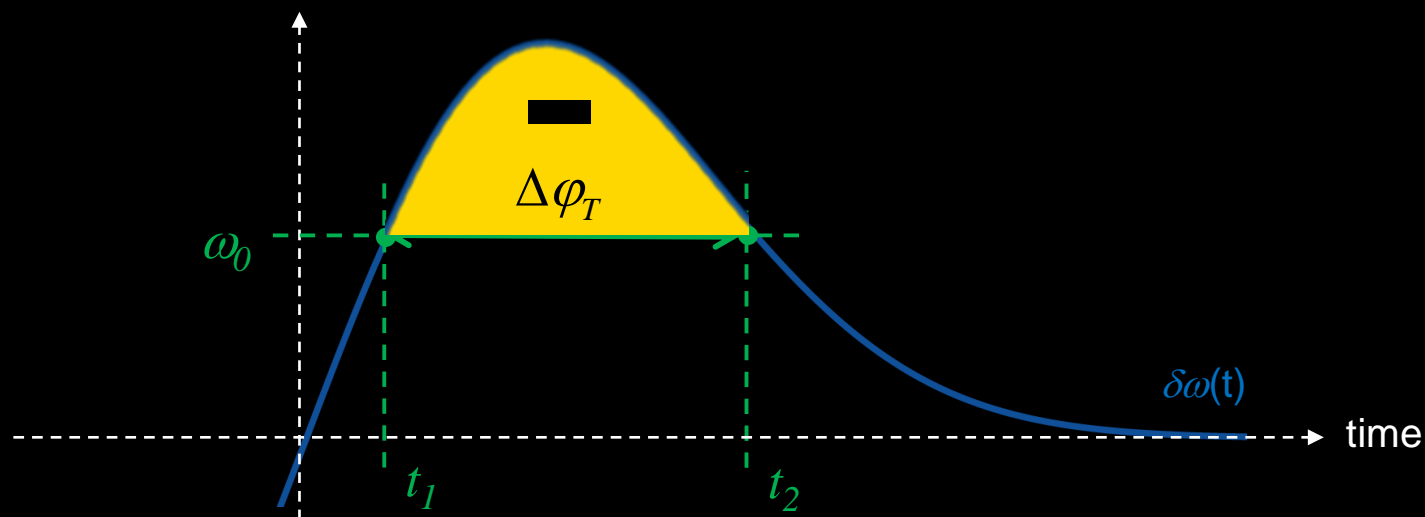


Constructive and destructive interferences

$$\Delta\varphi_T(\omega_0) = \Delta\varphi_D + \Delta\varphi_{NL}$$

destructive interference : $\Delta\varphi_T = (2m+1)\pi - \frac{\pi}{2}$

constructive interference : $\Delta\varphi_T = 2m\pi - \frac{\pi}{2}$



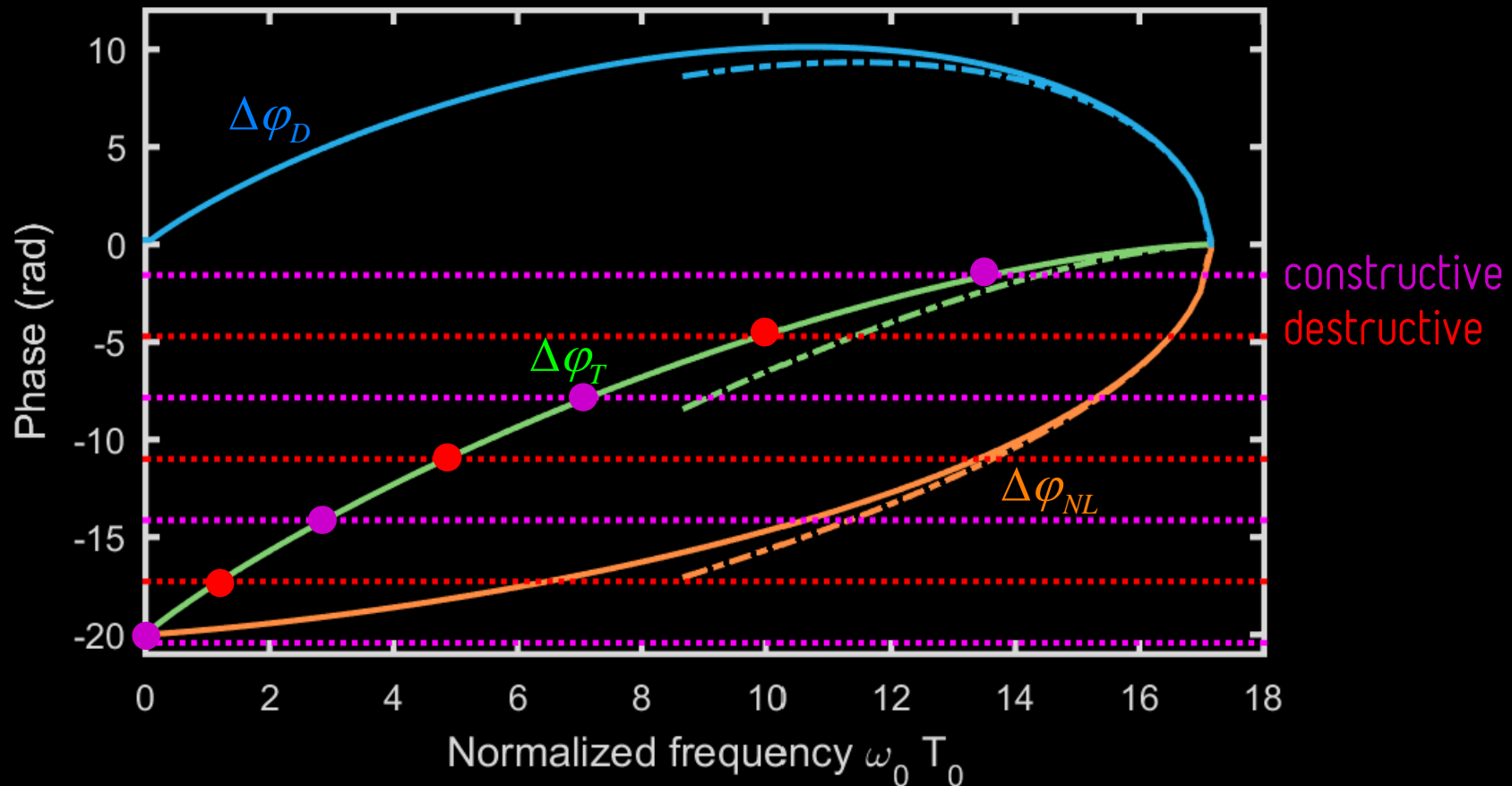


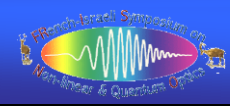
Constructive and destructive interferences

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destructive : $\Delta\varphi_T = (2m+1)\pi - \frac{\pi}{2}$

constructive : $\Delta\varphi_T = 2m\pi - \frac{\pi}{2}$

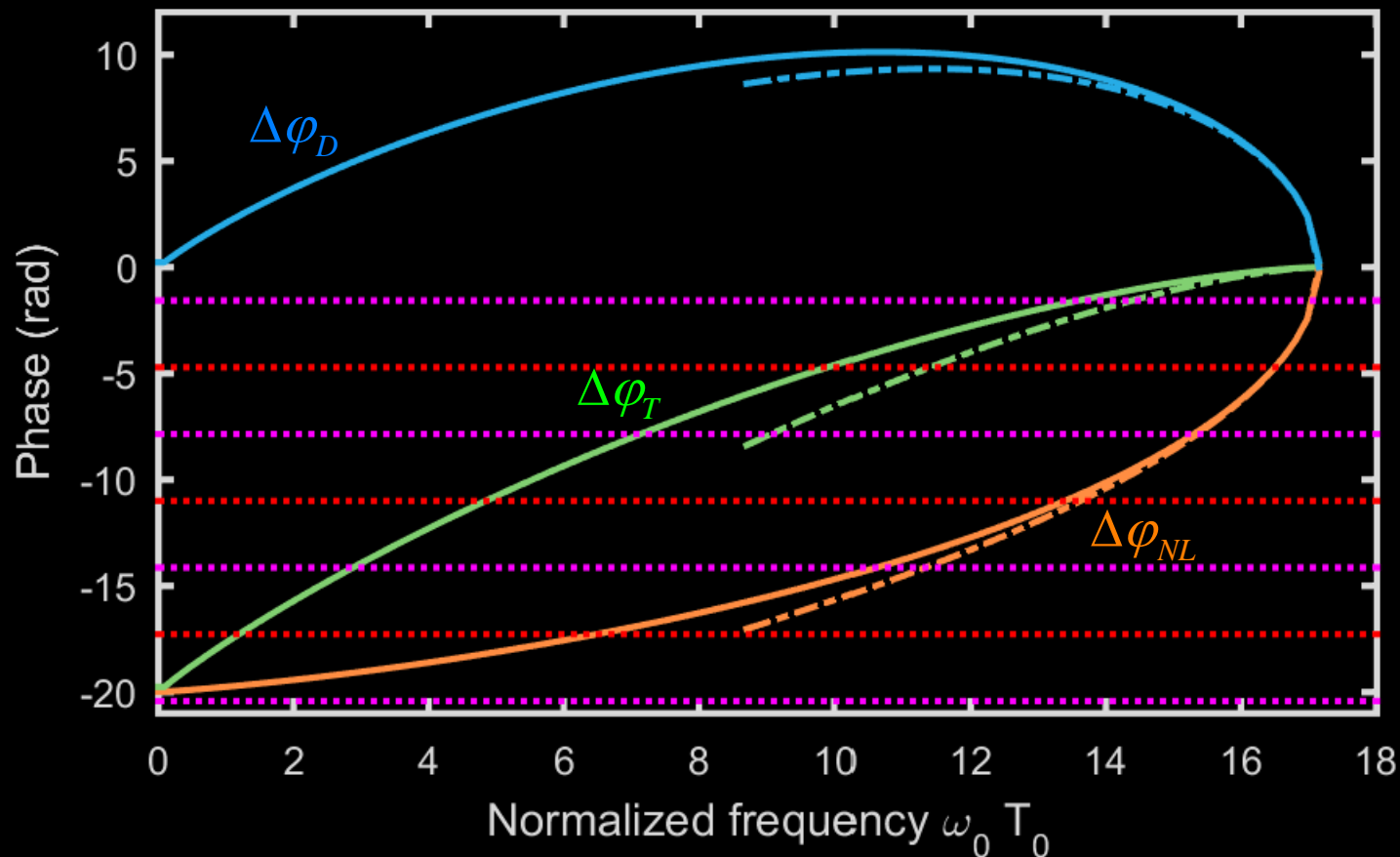


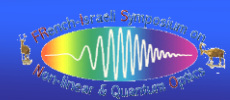


Interference pattern

$$\Delta\varphi_T(\omega_0) = \Delta\varphi_D + \Delta\varphi_{NL}$$

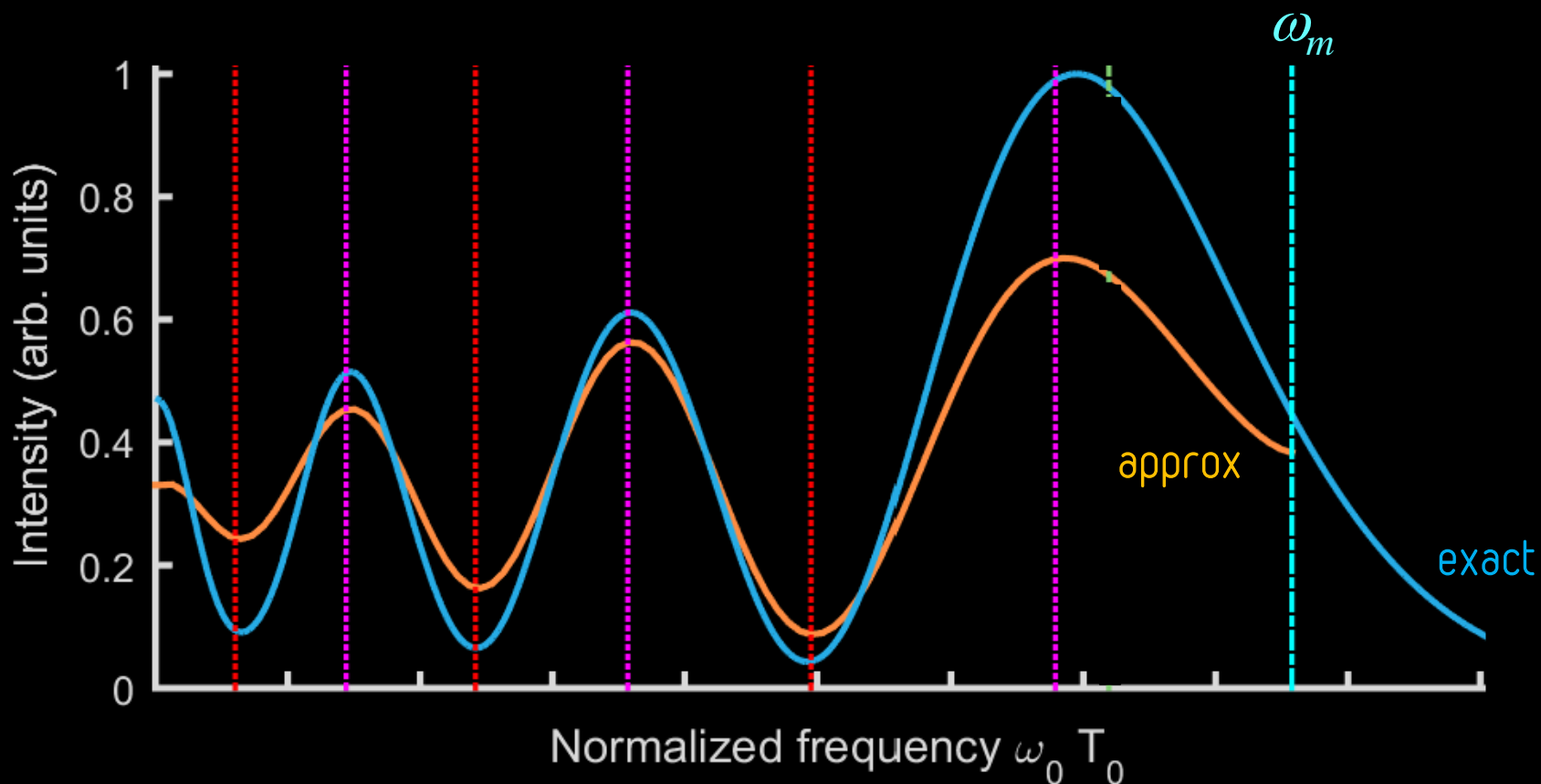
$$I(\omega_0) = G(t_1) + G(t_2) + 2\sqrt{G(t_1)G(t_2)} \cos\left(\Delta\varphi_T(\omega_0) + \frac{\pi}{2}\right)$$

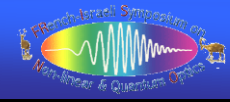




Interference pattern

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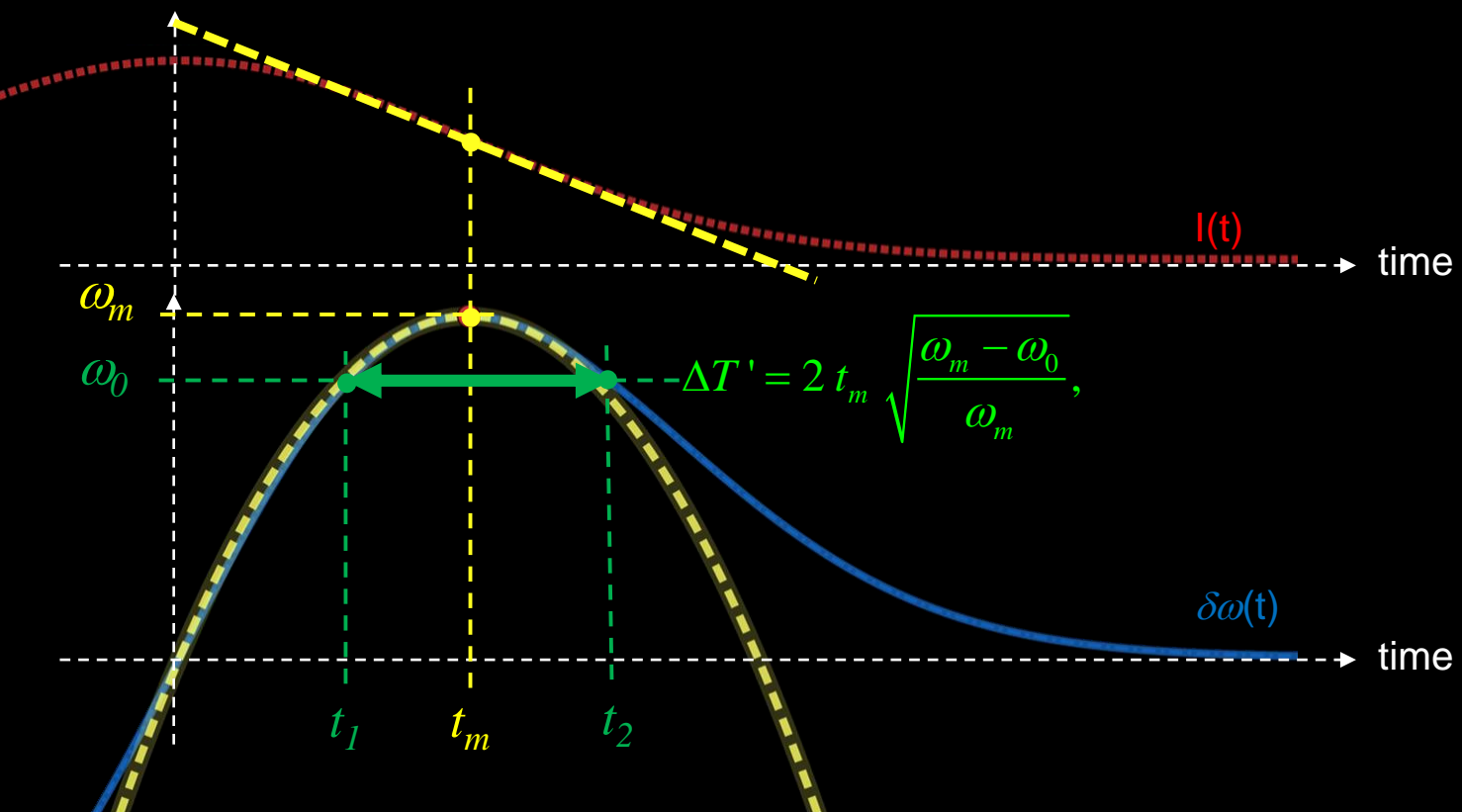


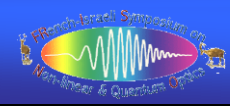


Simplified model

➔ A simplified model can be developed.

$$\begin{cases} \Delta\varphi'_D = \omega_0 \Delta T' \\ \Delta\varphi'_{NL} = -\omega_m \Delta T' \end{cases}$$

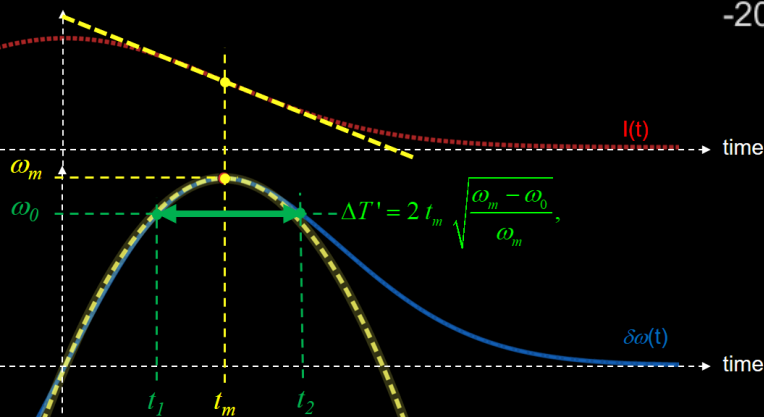
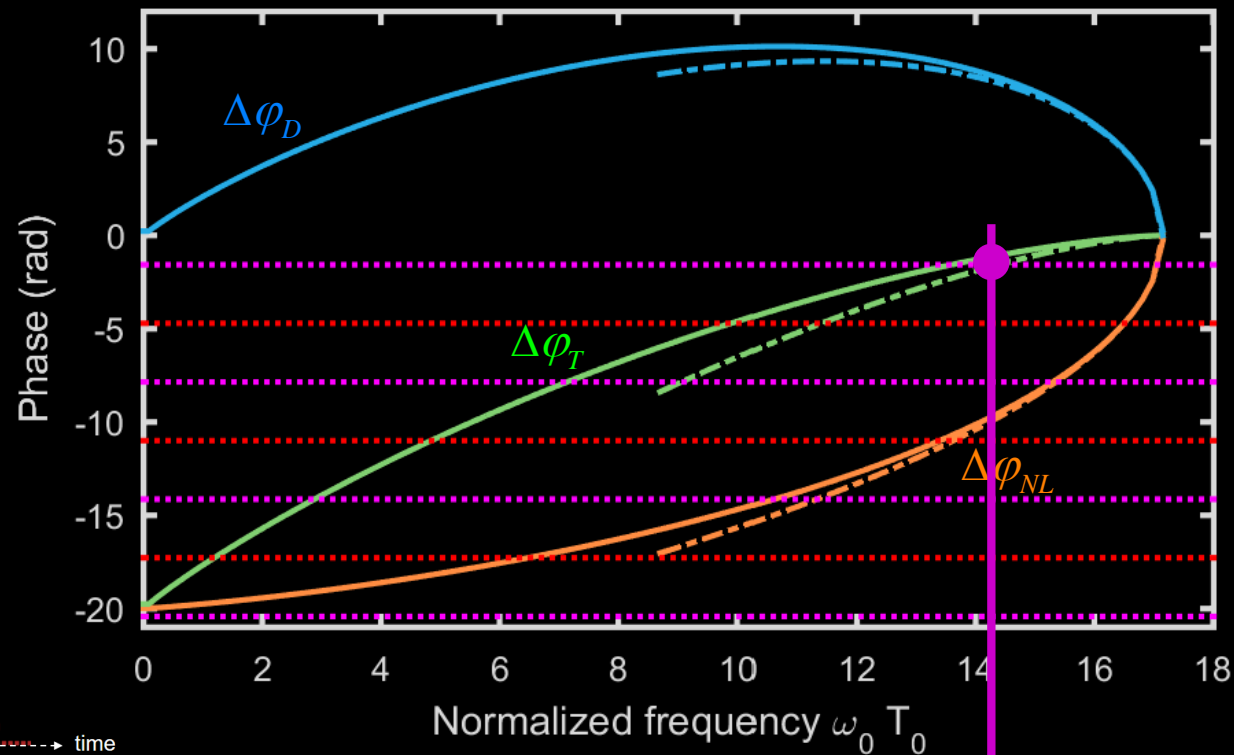




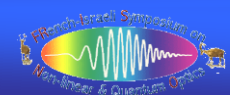
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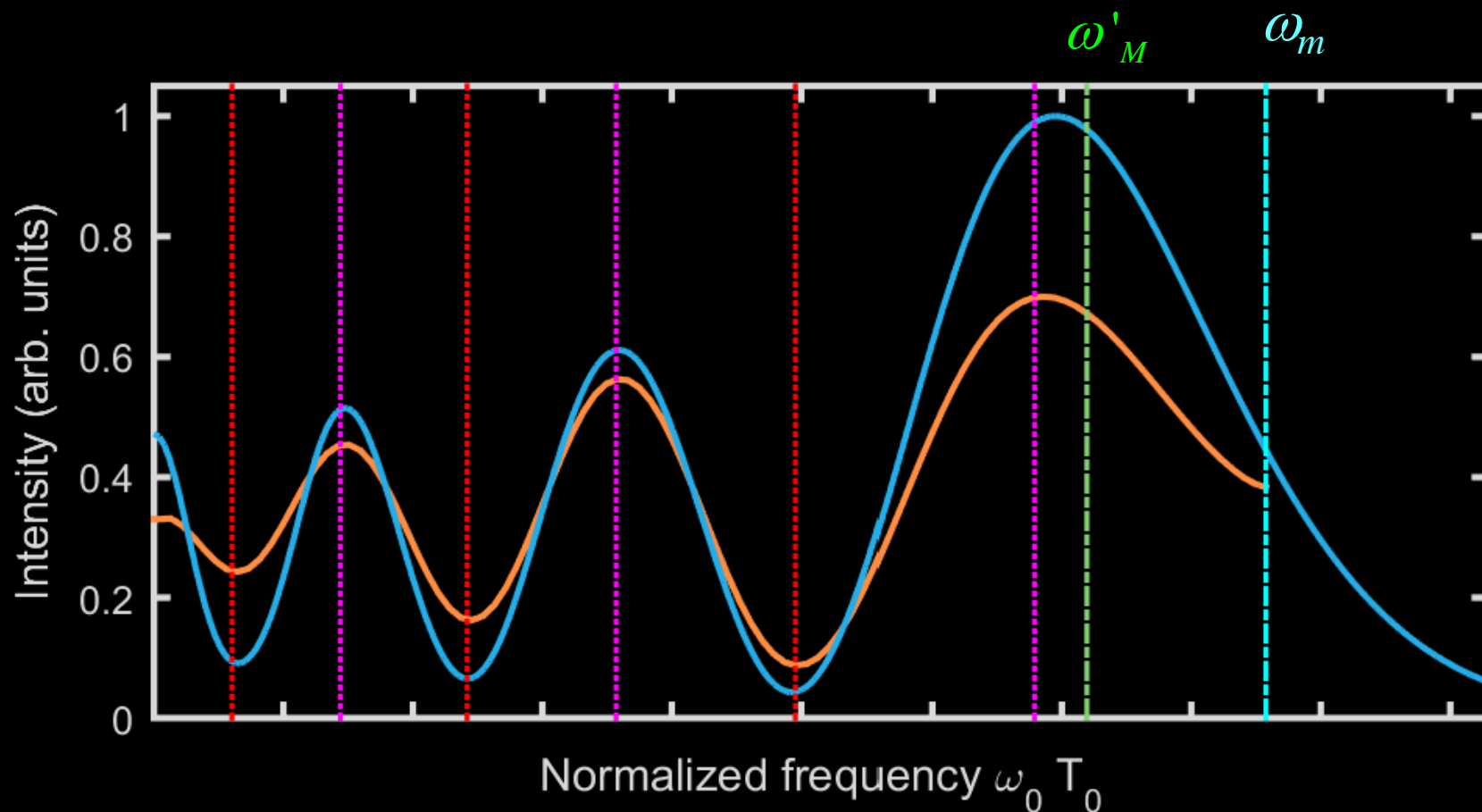


$$\omega'_M \simeq \omega_m \left(1 - 1.84 B^{-\frac{2}{3}} \right)$$

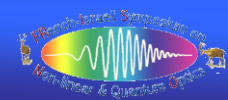


Simplified model

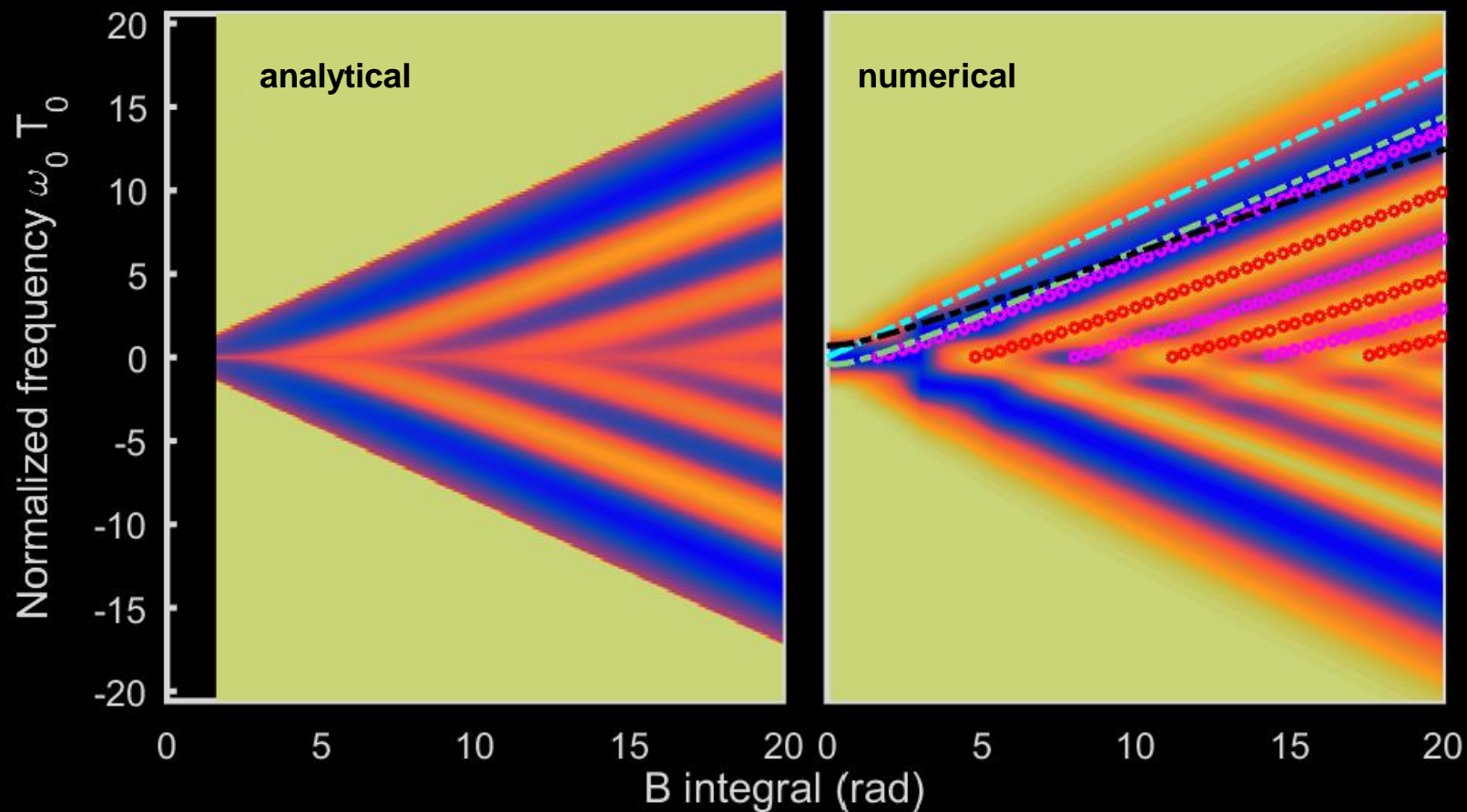
$$\omega'_M \approx \omega_m \left(1 - 1.84 B^{-\frac{2}{3}} \right).$$



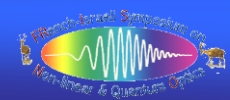
➡ The simplified approach provides a pretty good estimate of the spectral extend.



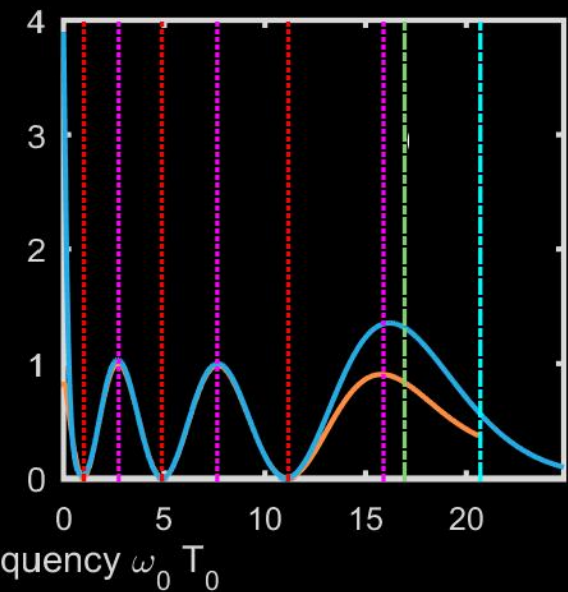
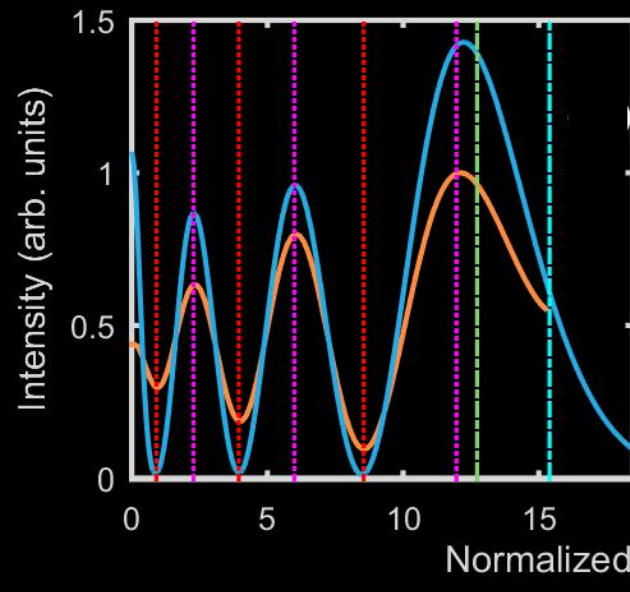
SPM spectrum



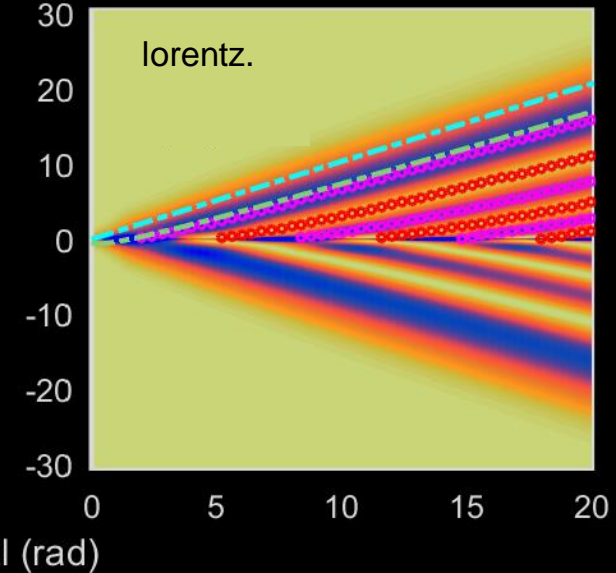
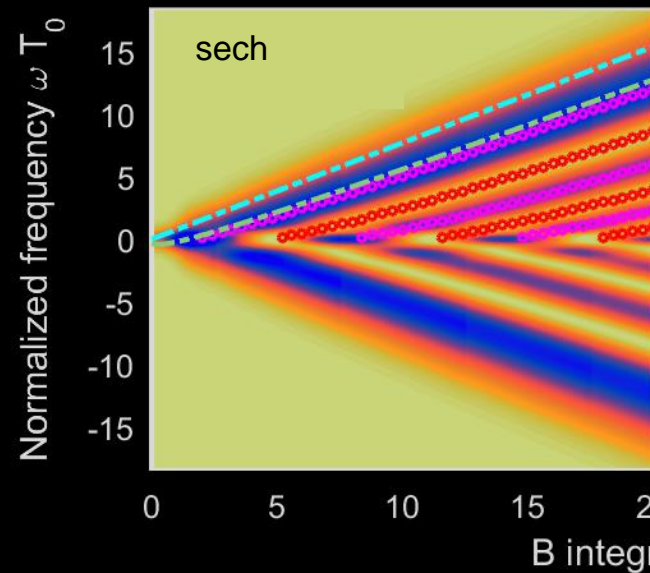
➡ The approach is in agreement with the numerical simulations.

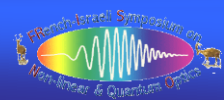


SPM spectrum of other pulse shapes

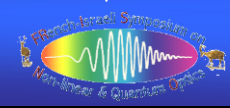


The approach can be extended to other pulse shapes.





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 - for Fourier-transform limited pulses
 - for linearly chirped pulses
- Cancelling self-phase modulation
- Conclusion



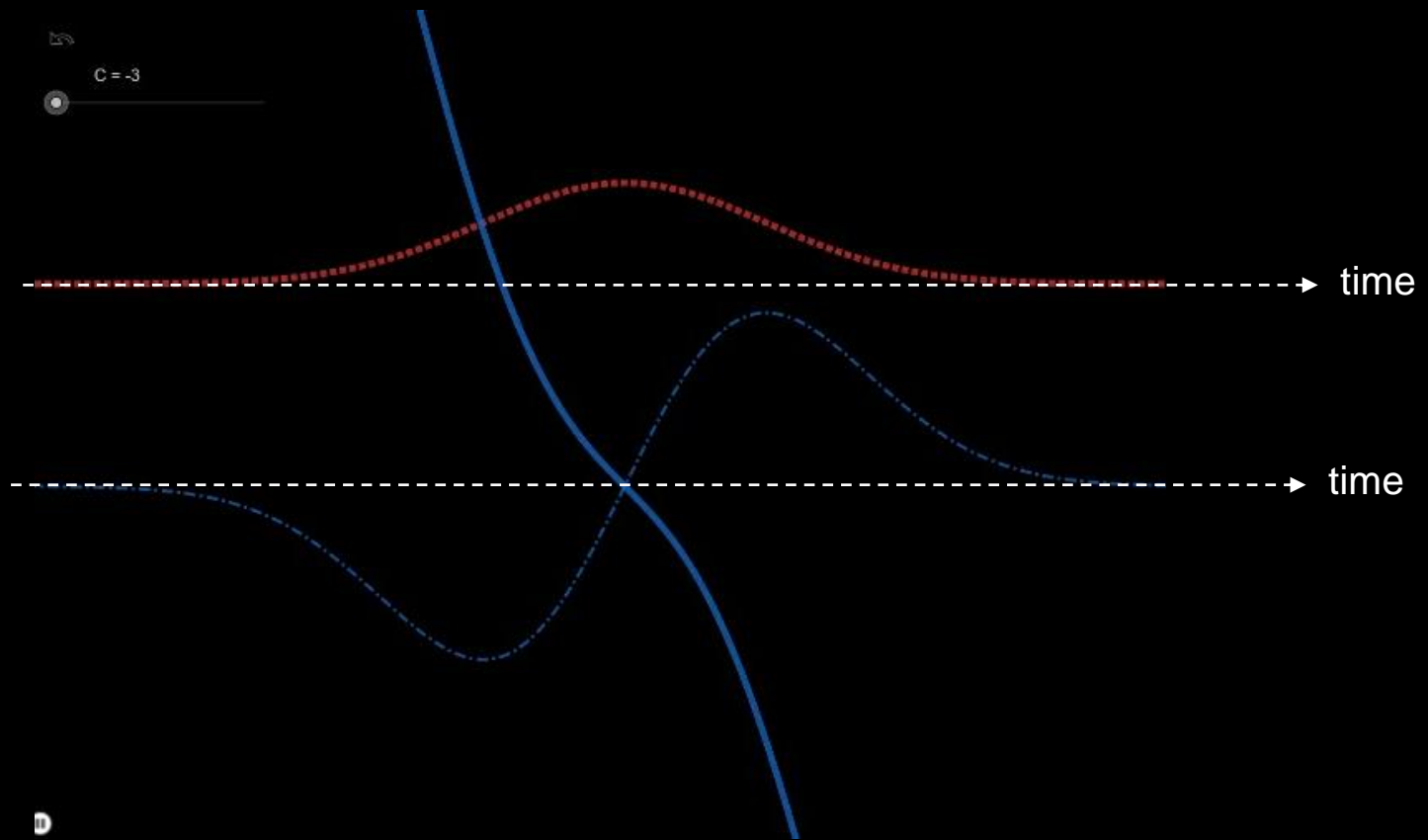
SPM chirp of a linearly chirped Gaussian pulse

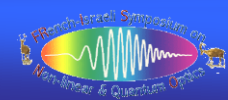
➔ We now consider a Gaussian pulse with an initial linear chirp.

$$\psi(t,0) = \sqrt{P_0} \sqrt{G(t)} \exp\left(-C t^2 / (2T_0^2)\right)$$

➔ The resulting chirp is :

$$\delta\omega(t) = \frac{1}{T_0} H_1\left(\frac{t}{T_0}\right) \left(B G(t) + \frac{C}{2} \right)$$

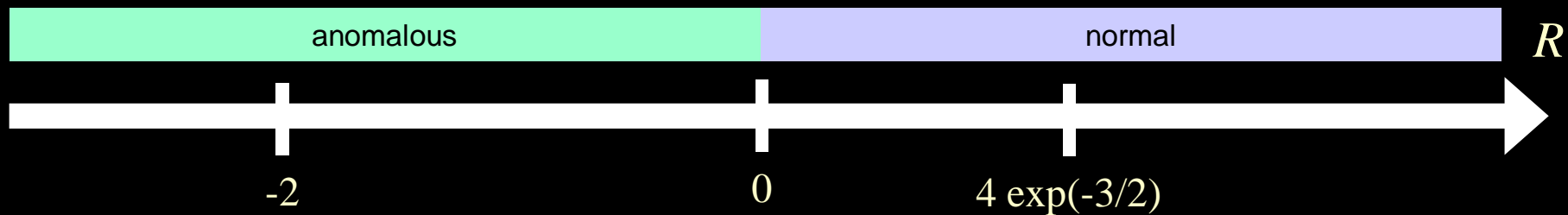




SPM chirp of a linearly chirped Gaussian pulse

➔ The resulting chirp is :
$$\delta\omega(t) = \frac{1}{T_0} H_1\left(\frac{t}{T_0}\right) \left(B G(t) + \frac{C}{2} \right)$$

➔ The ratio R will be crucial : $R = C/B$

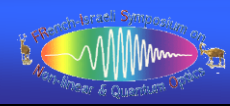


no extrema

2 extremas

4 extremas

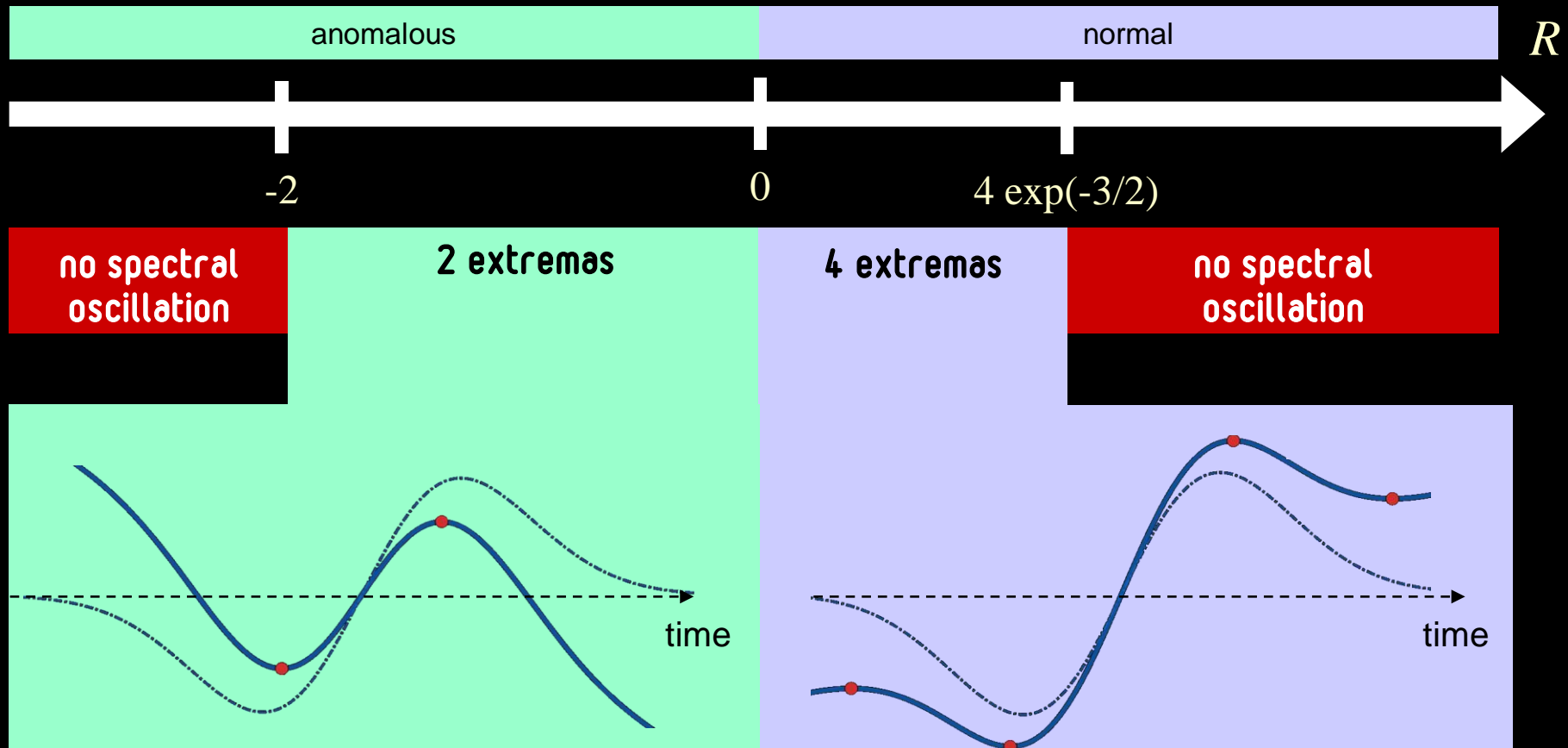
no extrema

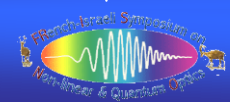


SPM chirp of a linearly chirped Gaussian pulse

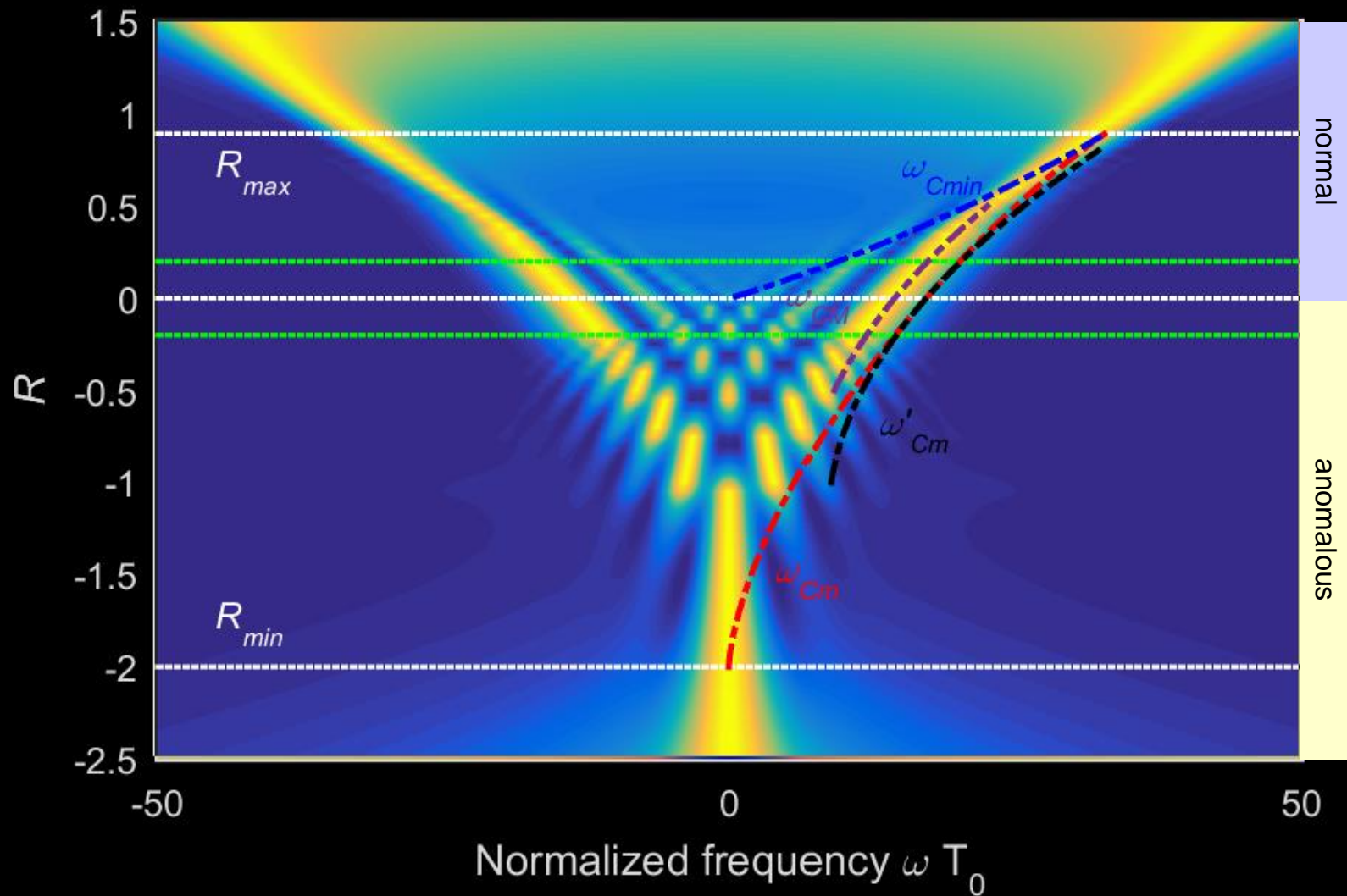
➔ The resulting chirp is :
$$\delta\omega(t) = \frac{1}{T_0} H_1\left(\frac{t}{T_0}\right) \left(B G(t) + \frac{C}{2} \right)$$

➔ The ratio R will be crucial : $R = C/B$

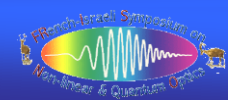




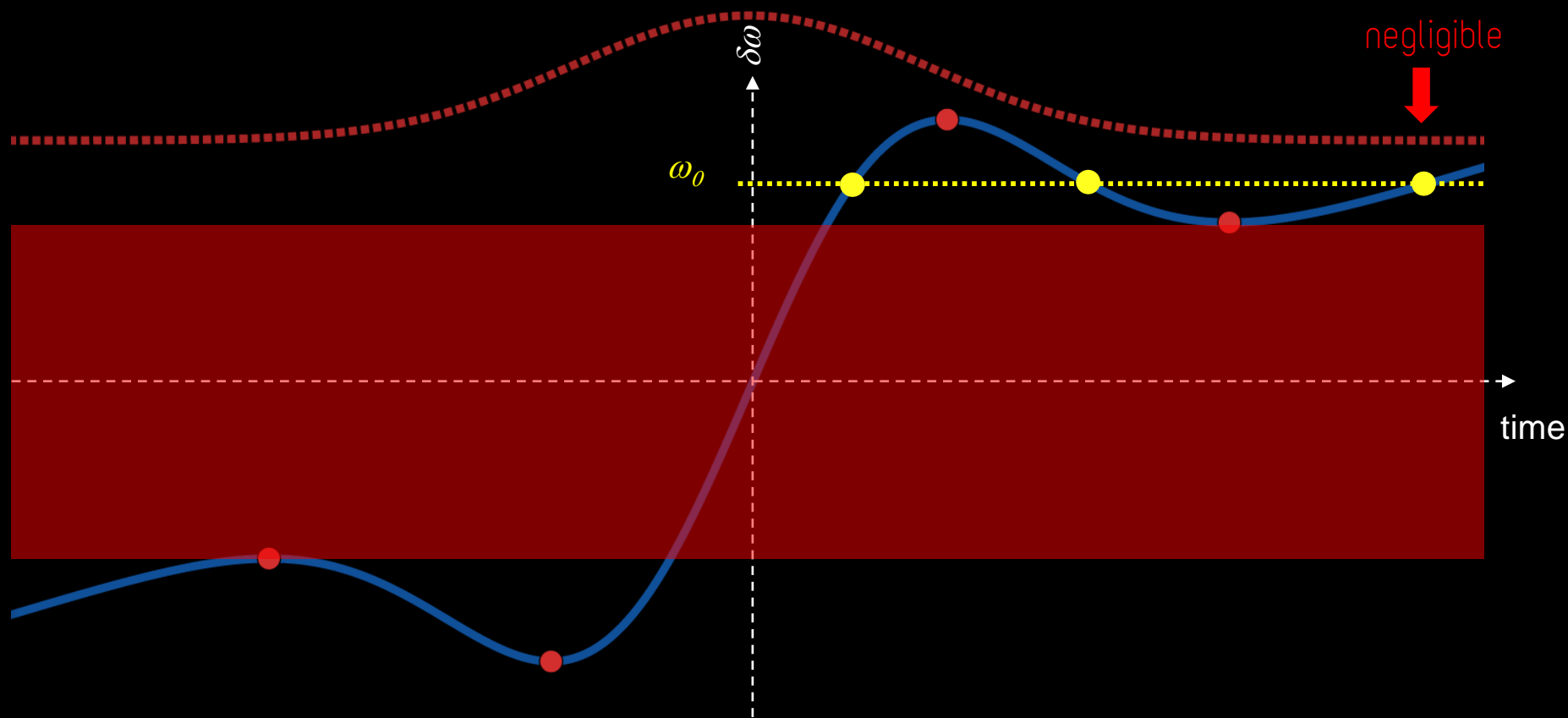
SPM spectrum of linearly chirped Gaussian pulses



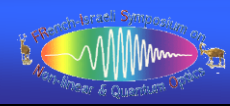
➡ The spectral shape is strongly affected by R .



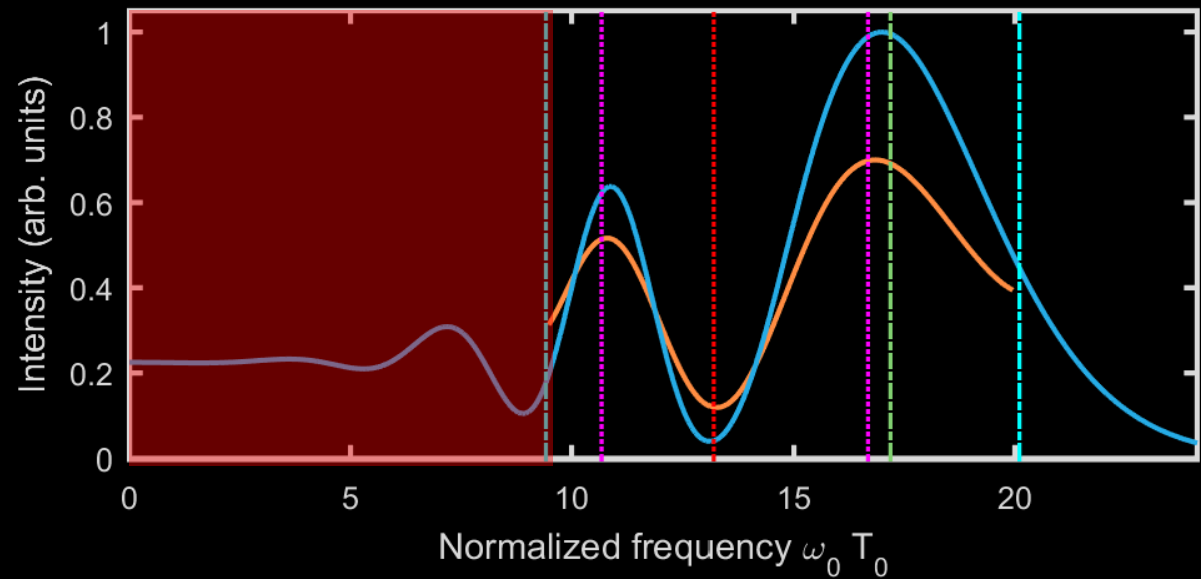
Interference pattern for linearly chirped pulses (normal case)



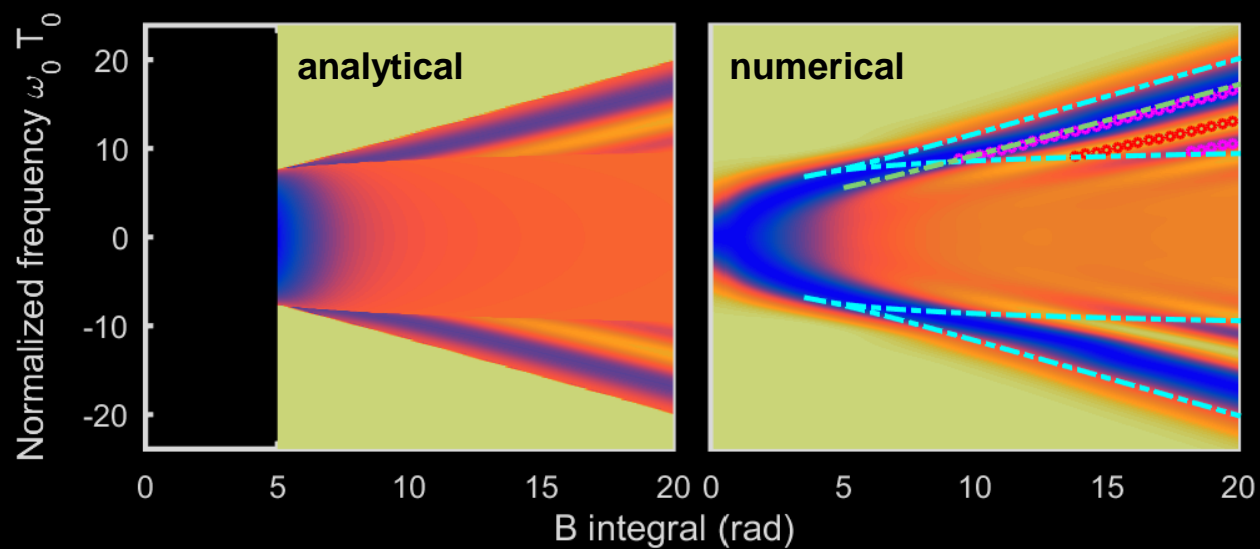
- No spectral interference are observed in the central part of the spectrum.
- The same instantaneous frequency appears at three different times.

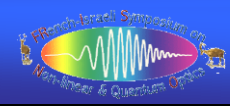


Interference pattern for linearly chirped pulses (normal case)

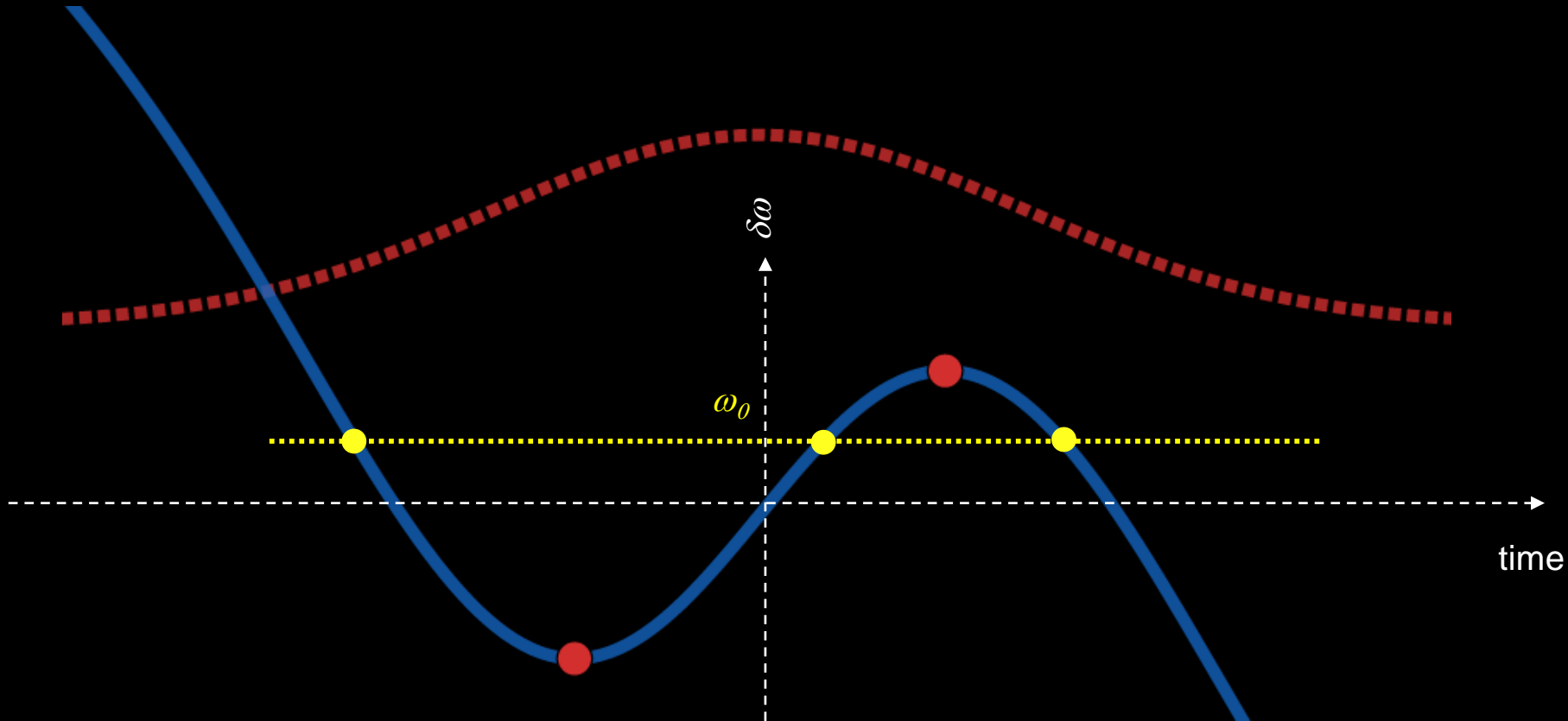


➡ a two-wave model qualitatively reproduces the spectral pattern.

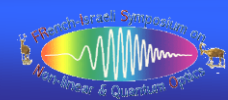




Interference pattern for linearly chirped pulses (anomalous case)

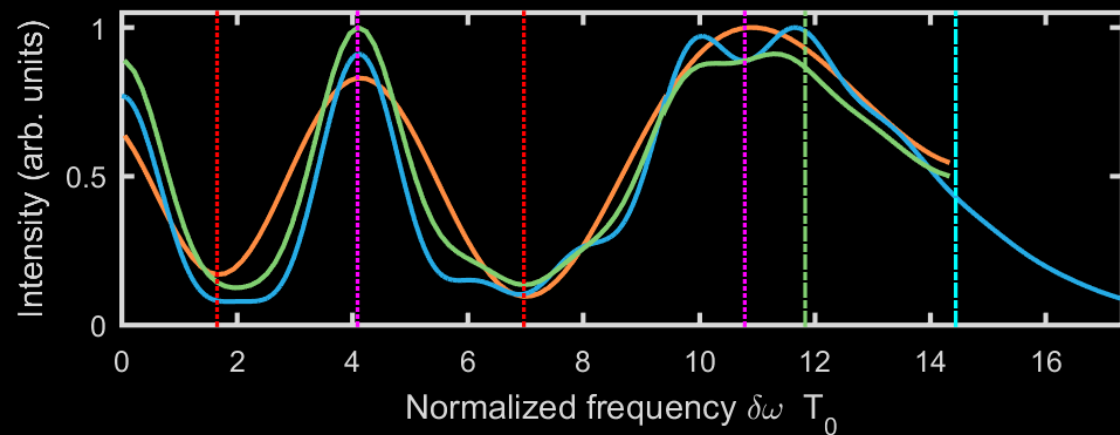


The same instantaneous frequency appears at three different times with non negligible energy.

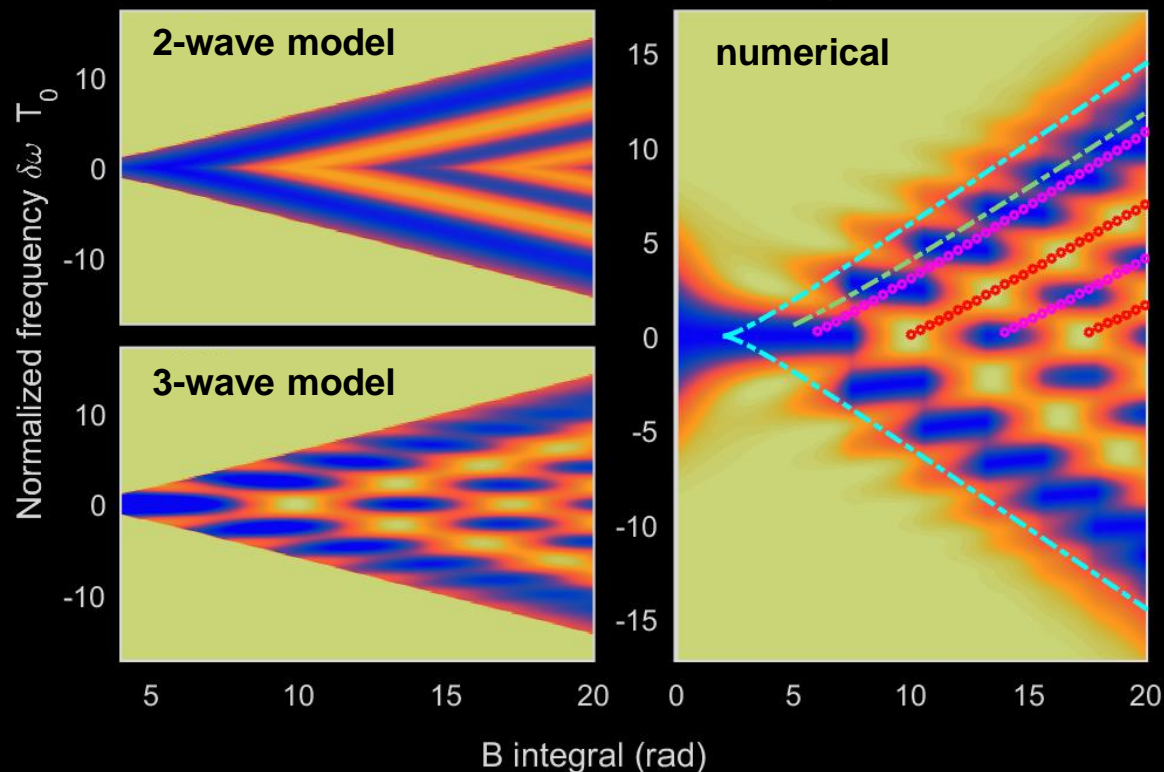


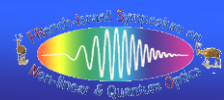
Interference pattern for linearly chirped pulses (anomalous case)

➔ A two-wave interference process does not reproduce the details of the spectrum.



➔ A three-wave interference model is required.



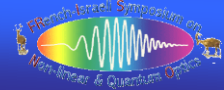


➤ Introduction

➤ Qualitative description of self-phase modulation and analytical guidelines

➤ Mitigation of self-phase modulation

➤ Conclusion



Applications of self-phase modulation in fibers

➤ Plethora of applications based on SPM have already been demonstrated :

✓ Ultrashort pulse generation

T. Gustafson, P. Kelly, and R. Fisher, "Subpicosecond pulse generation using the optical Kerr effect," IEEE J. Quantum Electron. 5, 325 (1969).

W. J. Tomlinson, R. H. Stolen, and C. V. Shank, "Compression of optical pulses chirped by self-phase modulation in fibers," J. Opt. Soc. Am. B 1, 139-149 (1984).

✓ Wavelength-multiplexed sources

Z. Yusoff, P. Petropoulos, F. Furuşawa, T. M. Monro, and D. J. Richardson, "A 36-channel x 10-GHz spectrally sliced pulse source based on supercontinuum generation in normally dispersive highly nonlinear holey fiber," IEEE Photon. Technol. Lett. 15, 1689-1691 (2003).

✓ Contrast enhancement of pulses

H.-Y. Chung, W. Liu, Q. Cao, L. Song, F. X. Kärtner, and G. Chang, "Megawatt peak power tunable femtosecond source based on self-phase modulation enabled spectral selection," Opt. Express 26, 3684-3695 (2018)

✓ Ultrafast optical processing

C. Finot and J. Fatome, "All-optical fiber-based ultrafast amplitude jitter magnifier," Opt. Express 18, 18697-18702 (2010).

C. Finot and J. Fatome, "Experimental demonstration of an ultrafast all-optical bit-error indicating scheme," Microw. Opt. Technol. Lett. 53, 392-395 (2010).

✓ Characterization of optical pulses

C. Lin and T. Gustafson, "Optical pulsewidth measurement using selfphase modulation," IEEE J. Quantum Electron. 8, 429-430 (1972).

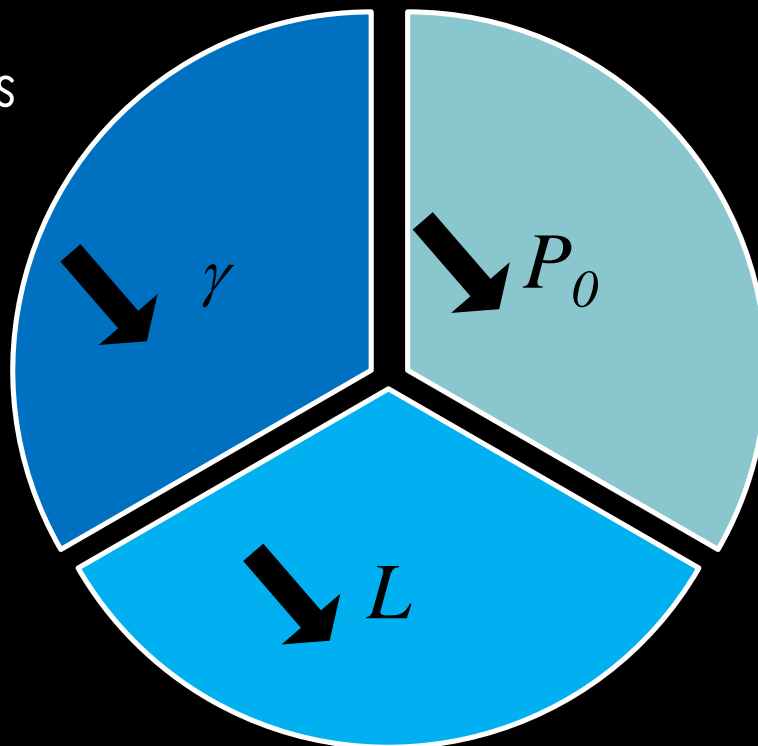
✓ Spectral compression

Mitigation of self-phase modulation: reducing B

➤ One strategy is to reduce the B -integral.

$$B = \gamma P_0 L$$

Large Mode Area fibers
Hollow core fibers

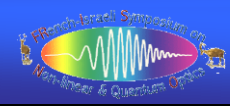


Chirped Pulse
Amplification

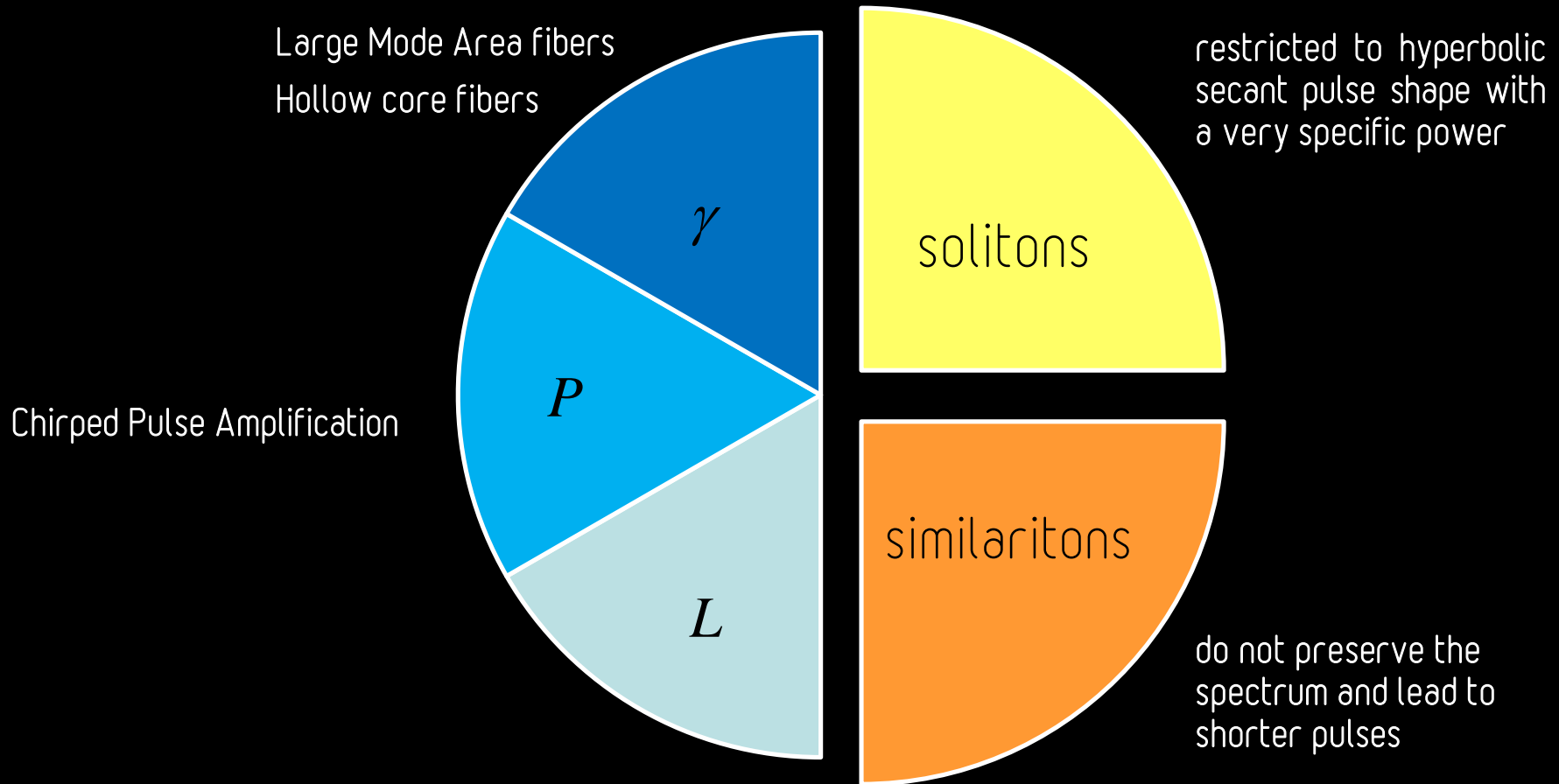
Ma, X., Zhu, C., Hu, I.N., Kaplan, A., Galvanauskas, A.: *Opt. Express* 22(8), 9206–9219 (2014).

Michieletto, M., et al.: *Hollow-core fibers for high power pulse delivery*. *Opt. Express* 24(7), 7103–7119 (2016).

Strickland, D., Mourou, G.: *Compression of amplified chirped optical pulses*. *Opt. Commun.* 56, 219–221 (1985)

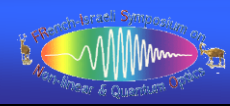


Mitigation of self-phase modulation: nonlinear structures

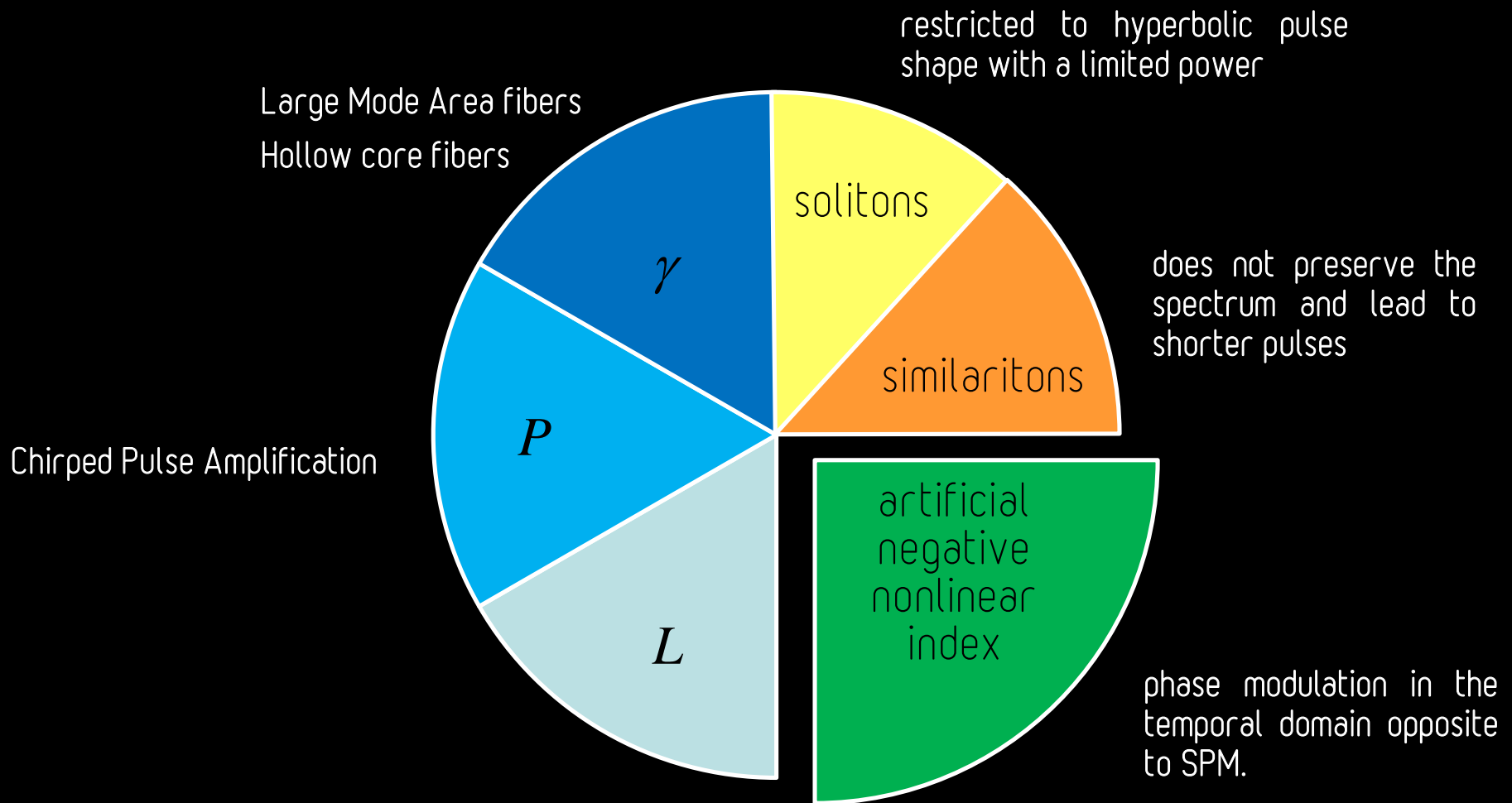


Hasegawa, A., Tappert, F.: *Transmission of stationary nonlinear optical pulses in dispersive dielectric fibers.*
Appl. Phys. Lett. 23, 171-172 (1973)

Finot, C., Dudley, J.M., Kibler, B., Richardson, D.J., Millot, G.: *Optical parabolic pulse generation and applications.*
IEEE J. Quantum Electron. 45(11), 1482-1489 (2009)

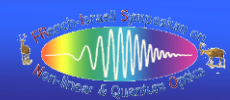


Mitigation of self-phase modulation: negative nonlinear index



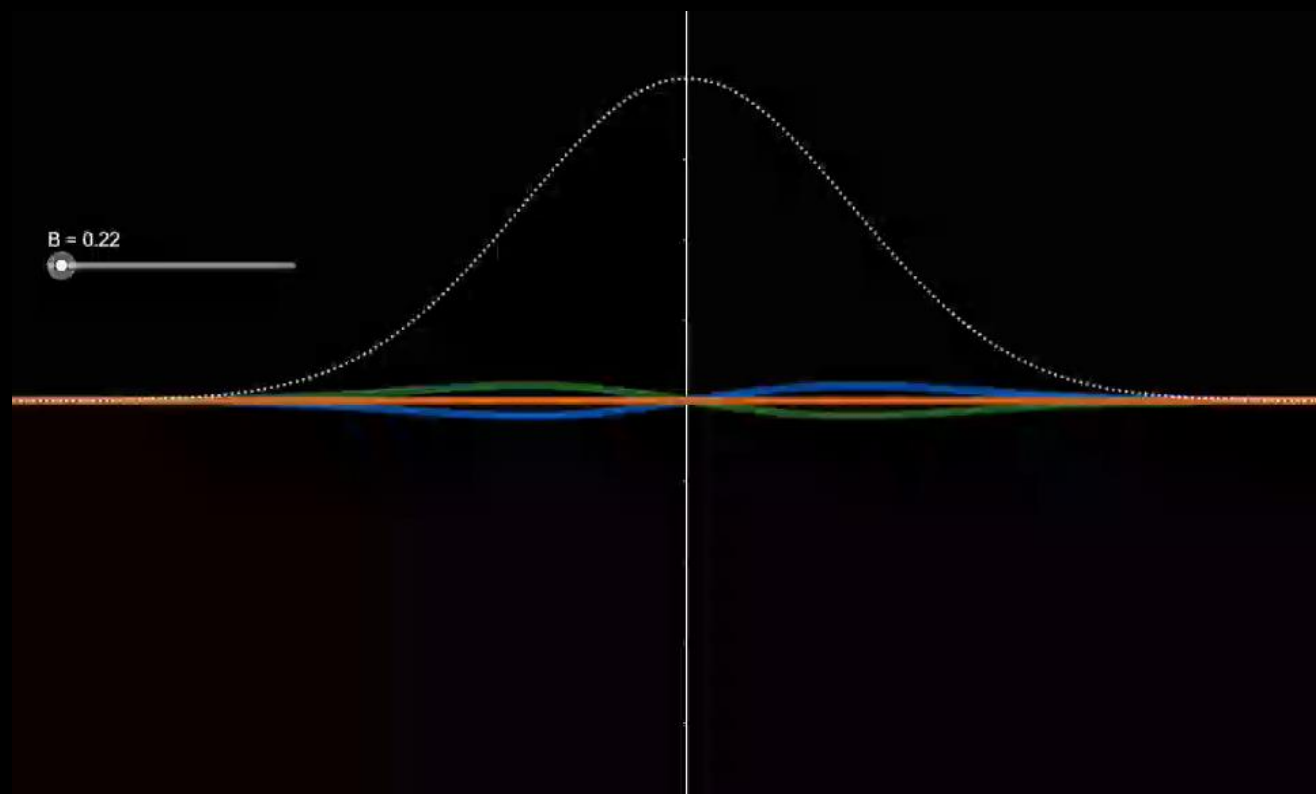
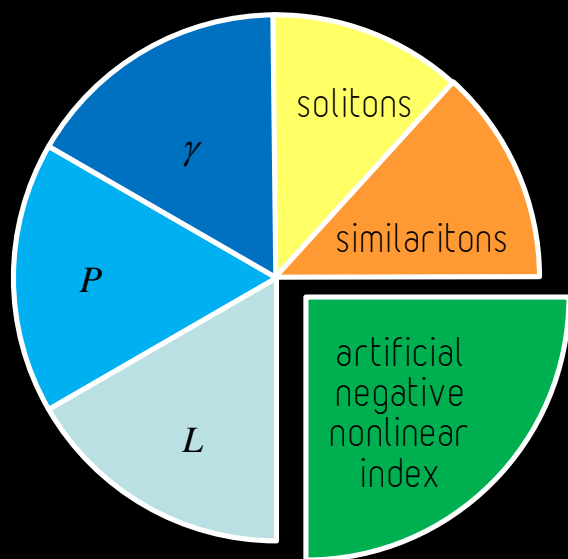
Xu, C., Mollenauer, L., Liu, X.: *Compensation of nonlinear self-phase modulation with phase modulators*. Electron. Lett. 38(24), 1578-1579 (2002).

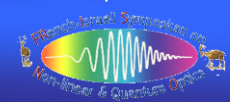
Ulmer, T., Roth, J.M., Minch, J.R., Chang, J., Moores, J.D., Nowak, G., Walther, F.G.: *Mitigation of self-phase modulation in high-peak-power lasercom systems*. In: Lasers Congress 2016, Boston, Massachusetts.



Mitigation of self-phase modulation : negative nonlinear index

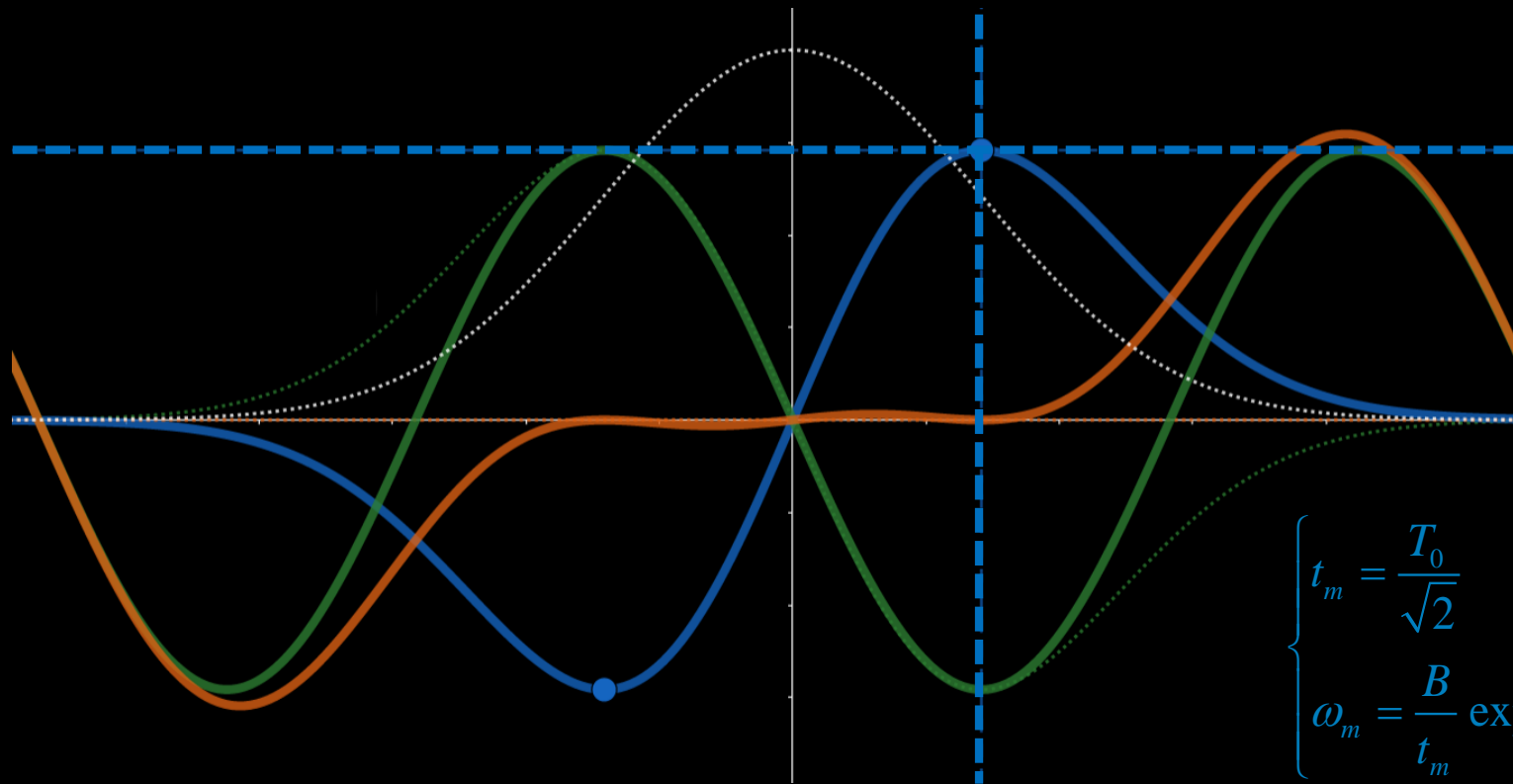
➔ Using an external phase modulation to imprint the opposite chirp in the temporal domain enables the SPM cancellation.





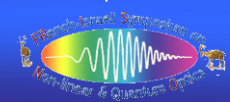
Mitigation with a single harmonics?

➤ Can be mitigation be also efficient if a simple sinusoidal wave is used ?



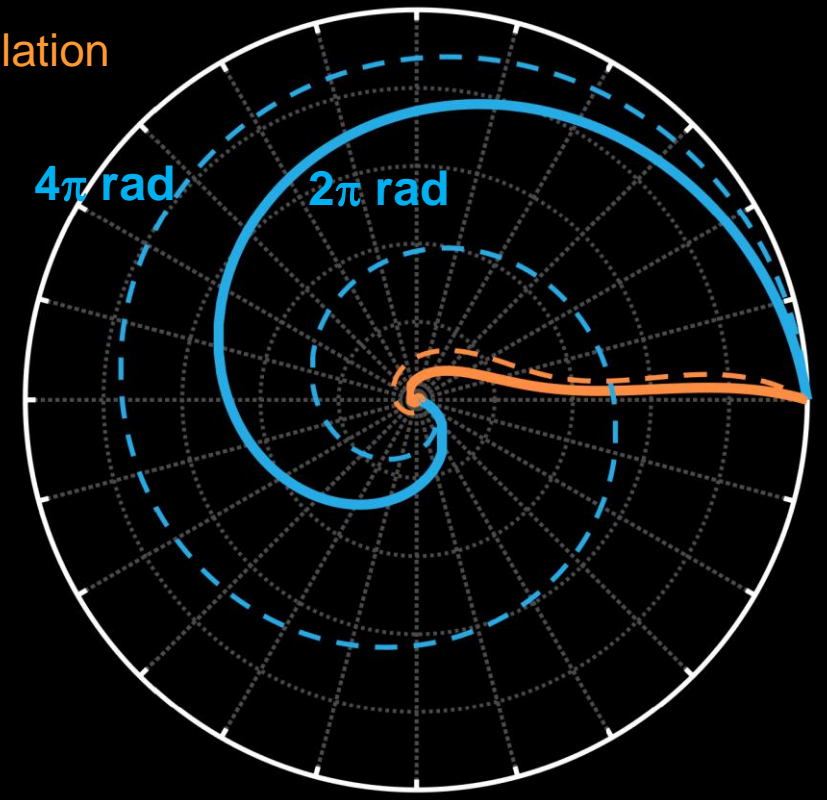
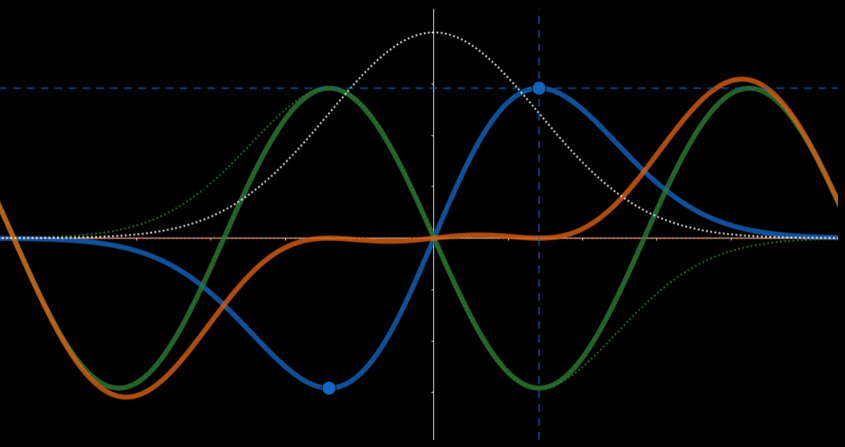
➤ The SPM-induced chirp is canceled over most of the central part of the pulse.

➤ The amplitude and frequency of the sinusoidal modulation are derived from the value and position of the maximum chirp.

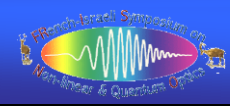


Numerical simulations for a Gaussian pulse: chirp cancellation

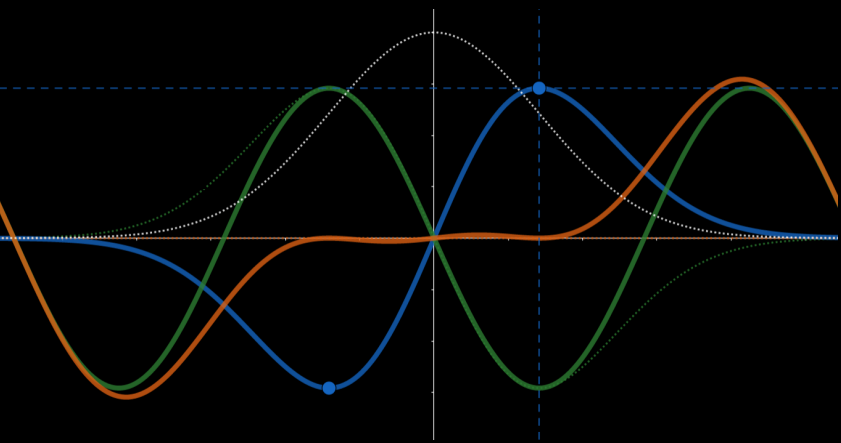
SPM alone
with external phase modulation



➡ The SPM-induced chirp is canceled over most of the central part of the pulse.

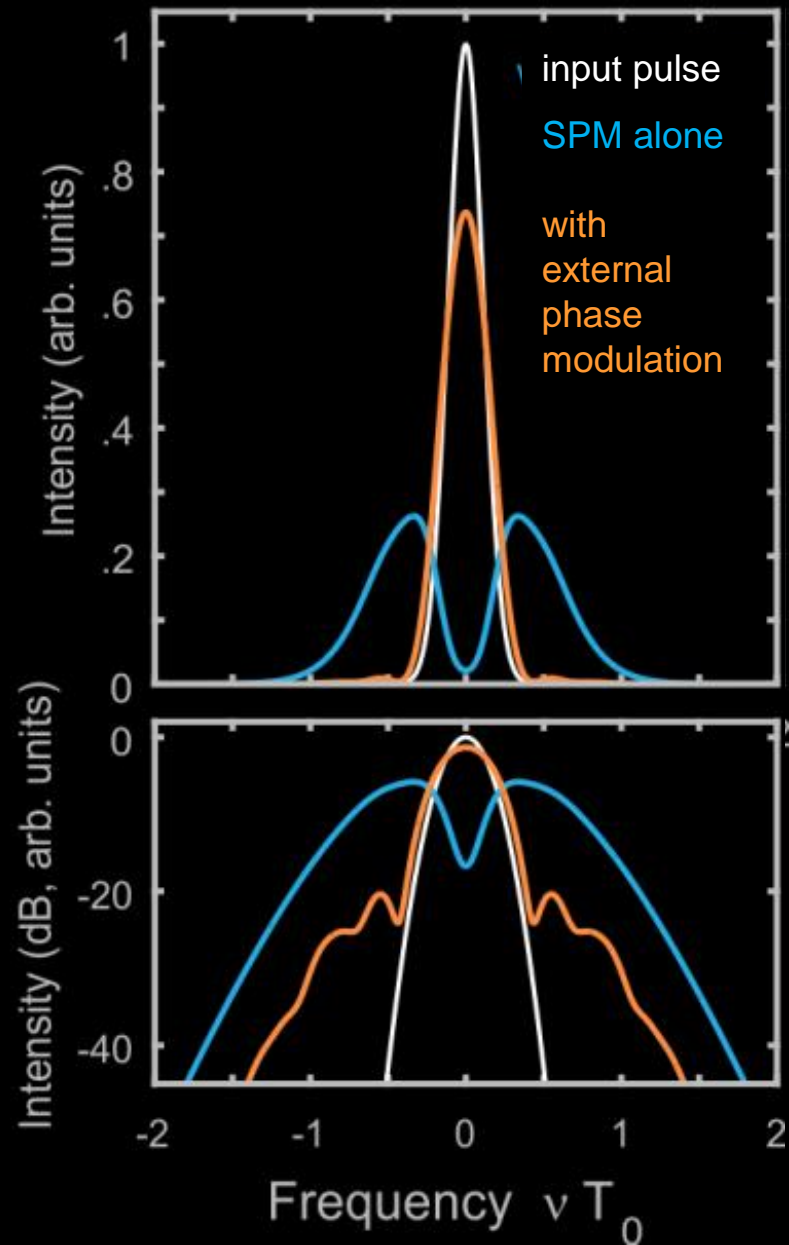


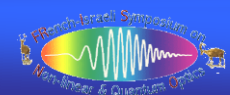
Numerical simulations for a Gaussian pulse: spectral broadening



➡ The spectral broadening is canceled.

➡ Some low-level wings exist.





Numerical simulations for a Gaussian pulse: spectral broadening

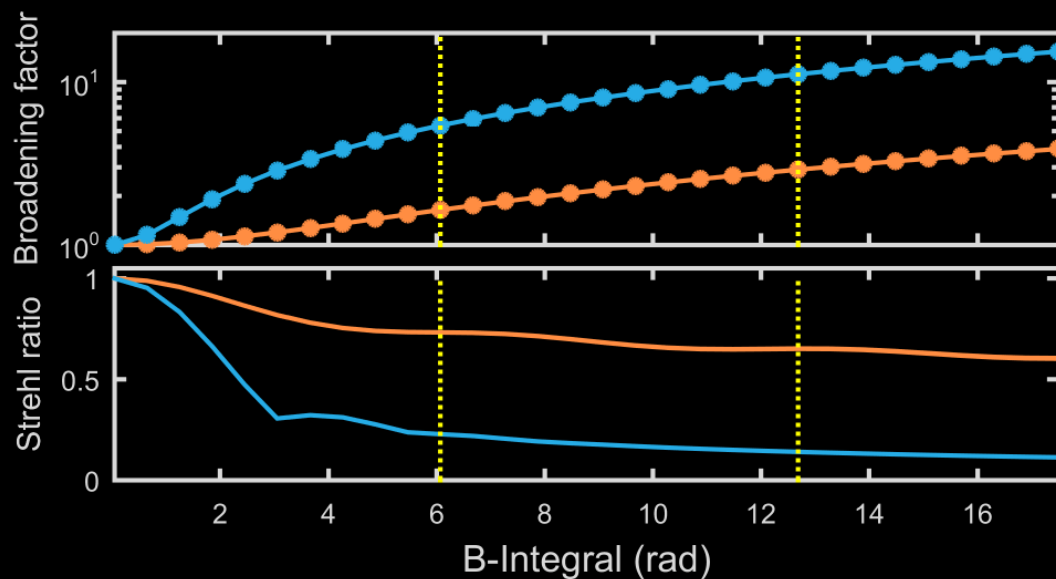
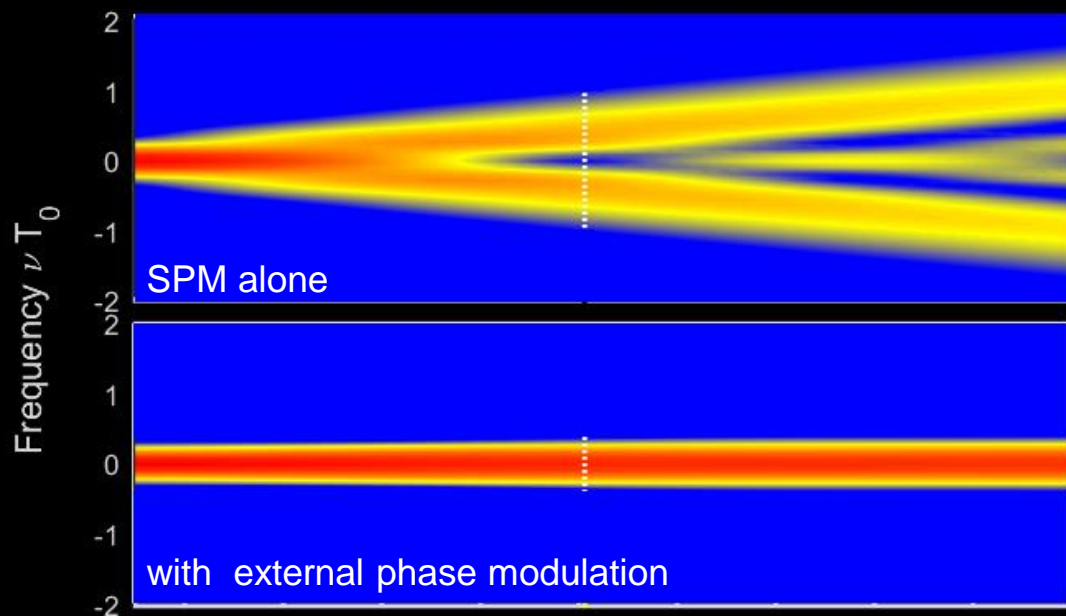
➔ The changes in the spectrum are canceled.

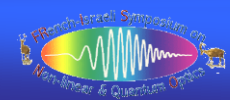
➔ The rms spectral broadening is reduced by a factor 4.

$$\frac{\sigma_{\omega}}{\sigma_{\omega 0}} \approx 0.8774 \cdot B \quad \text{SPM alone}$$

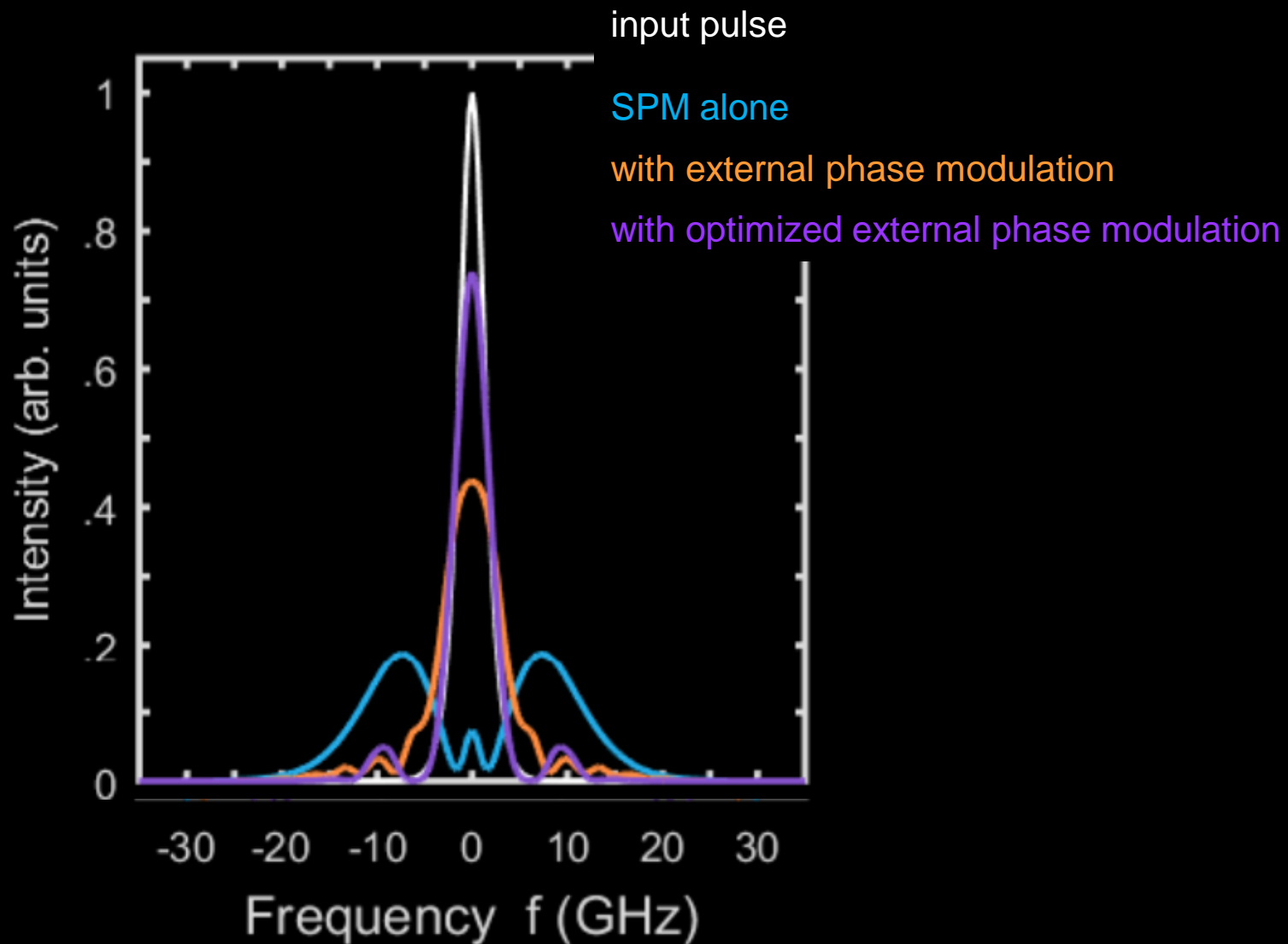
$$\frac{\sigma_{\omega C}}{\sigma_{\omega 0}} \approx 0.2146 \cdot B \quad \text{with external phase modulation}$$

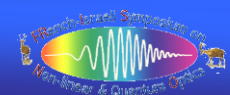
➔ The Strehl ratio is highly improved.



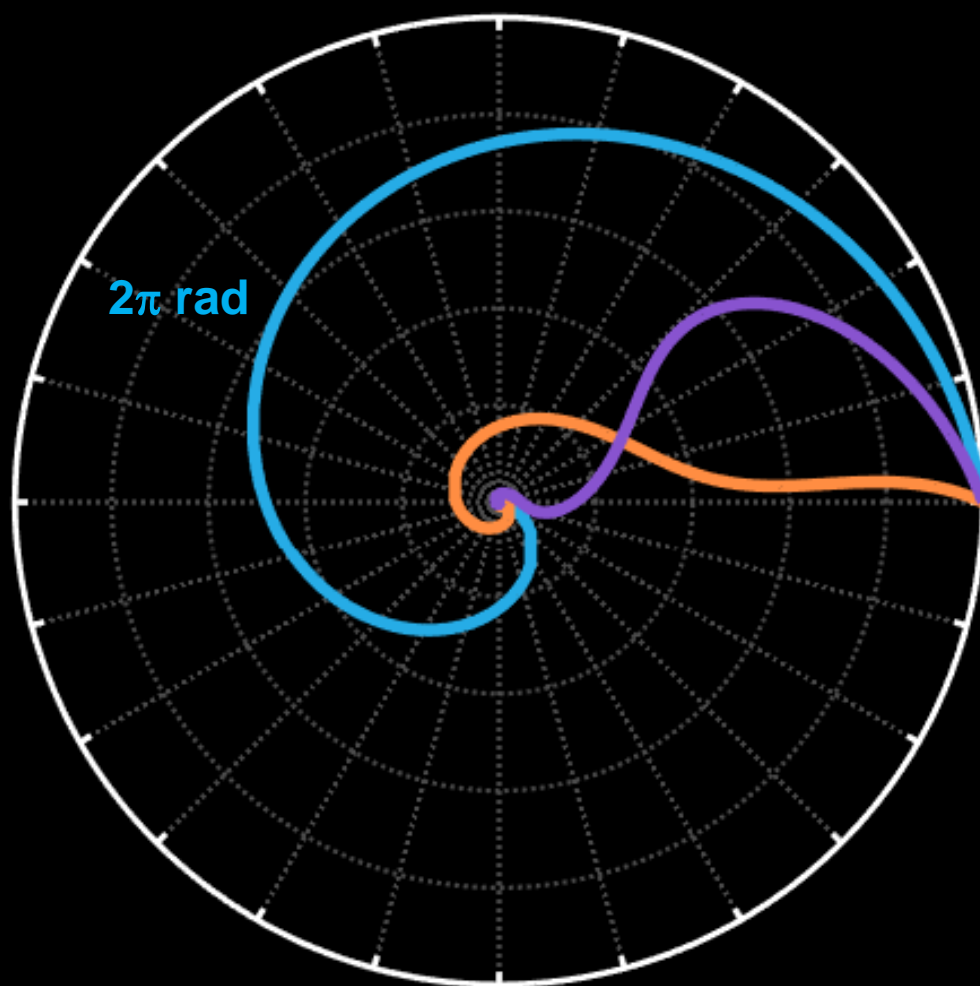


Numerical simulations for a hyperbolic secant pulse





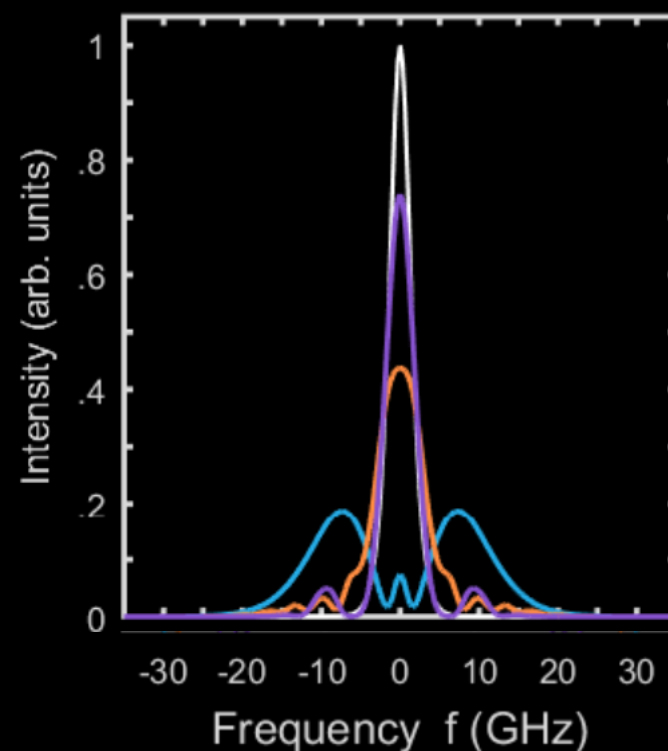
Numerical simulations for a hyperbolic secant pulse



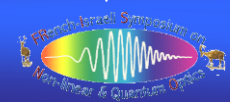
SPM alone

with external phase modulation

with optimized phase modulation



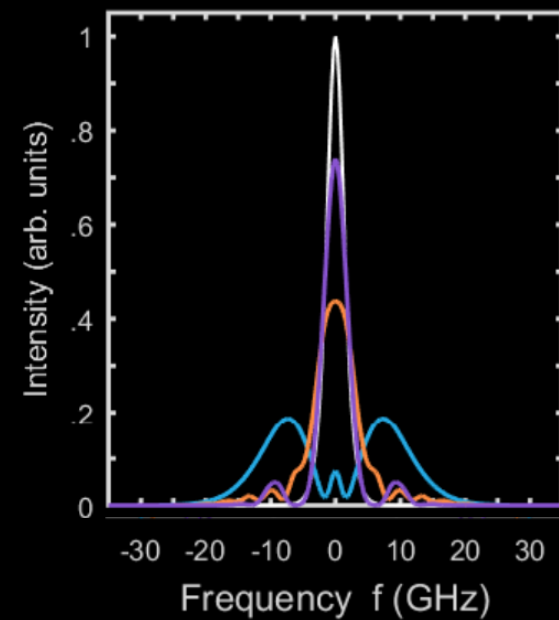
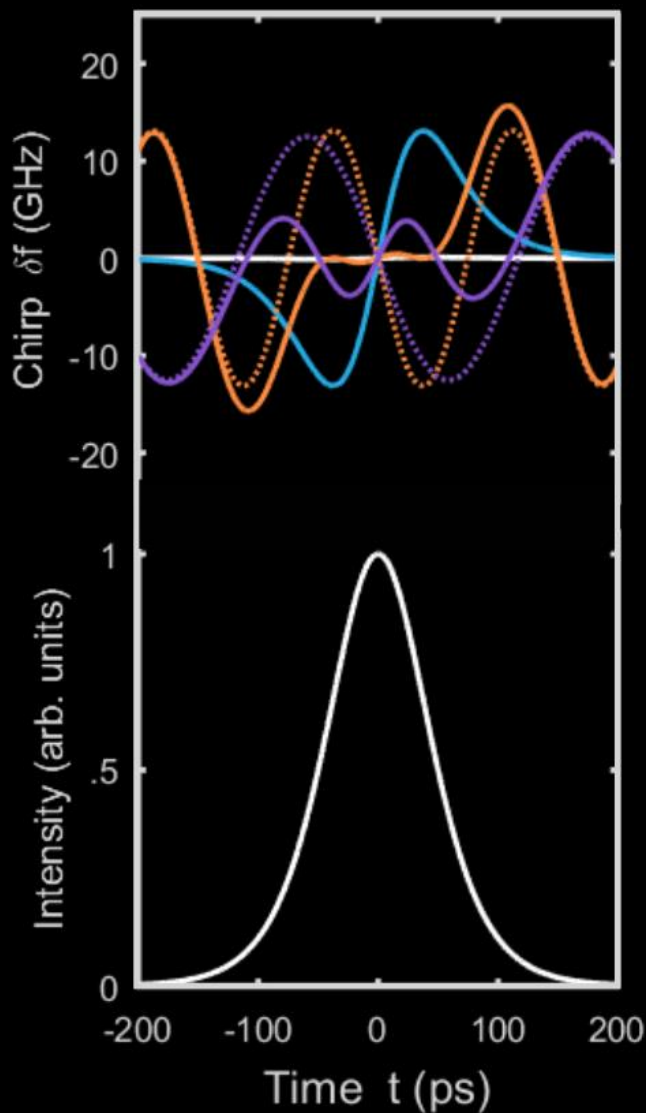
➡ The interference process enhances the central part of the spectrum.



Numerical simulations for a hyperbolic secant pulse

➡ The previous strategy works and leads to flat chirp.

➡ The performance can be enhanced by slightly tuned parameters.



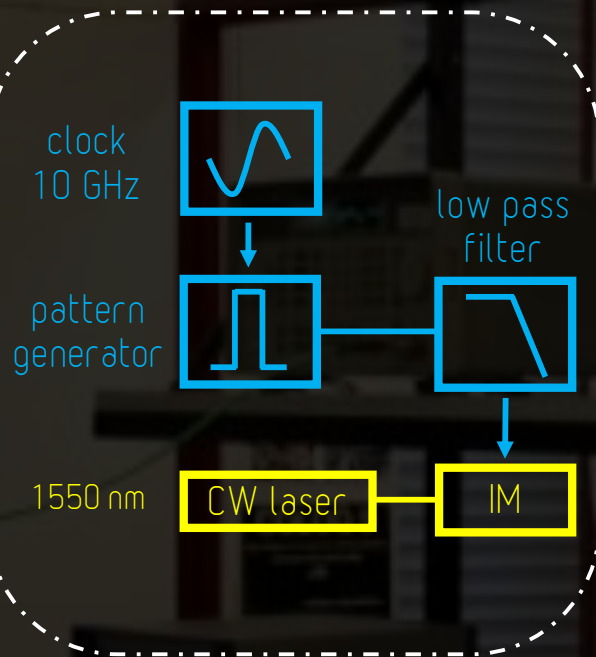
input pulse

SPM alone

with external phase modulation

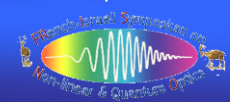
with optimized phase modulation

Experimental setup

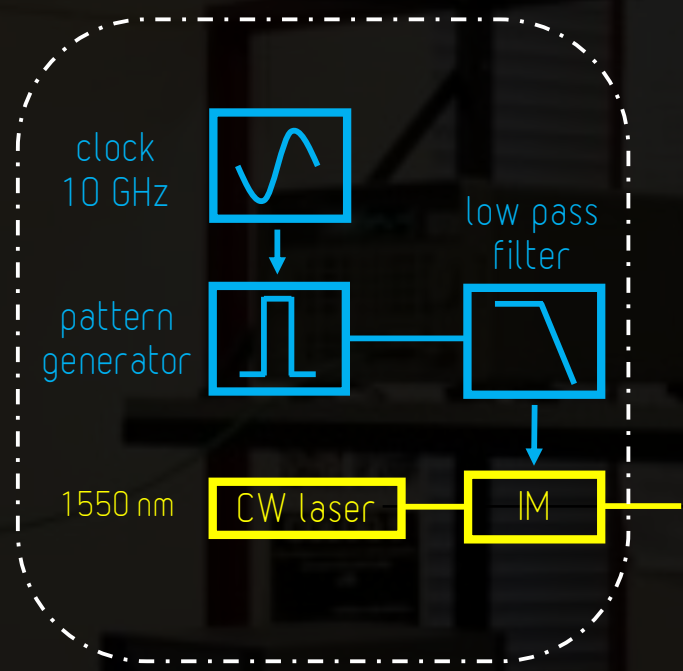


PULSE GENERATION
OF GAUSSIAN-LIKE PULSES

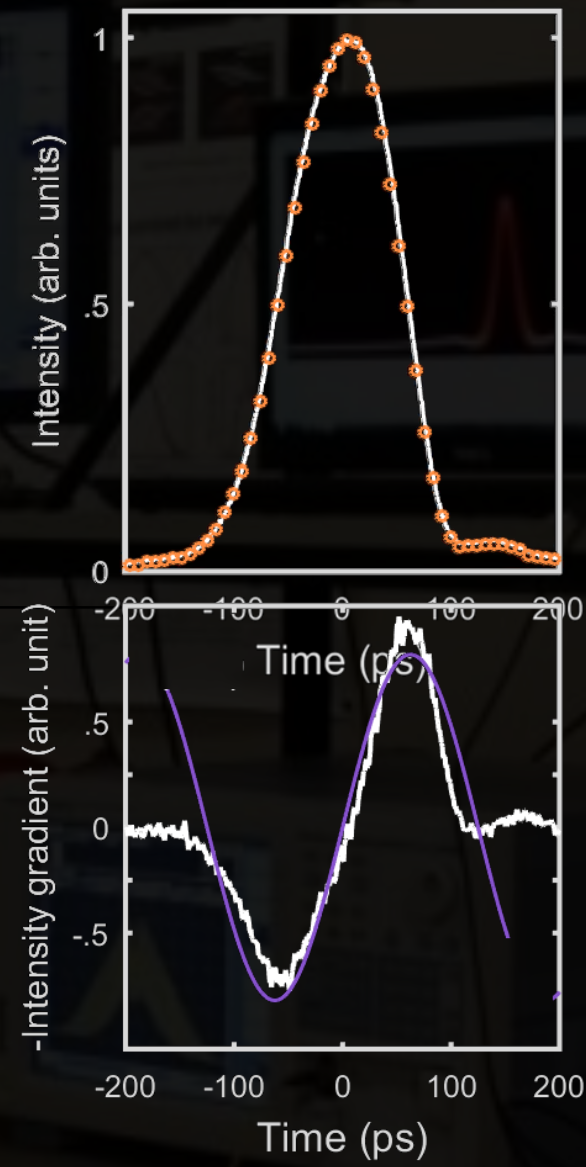
➡ The all-fibered device is made of commercially available components.



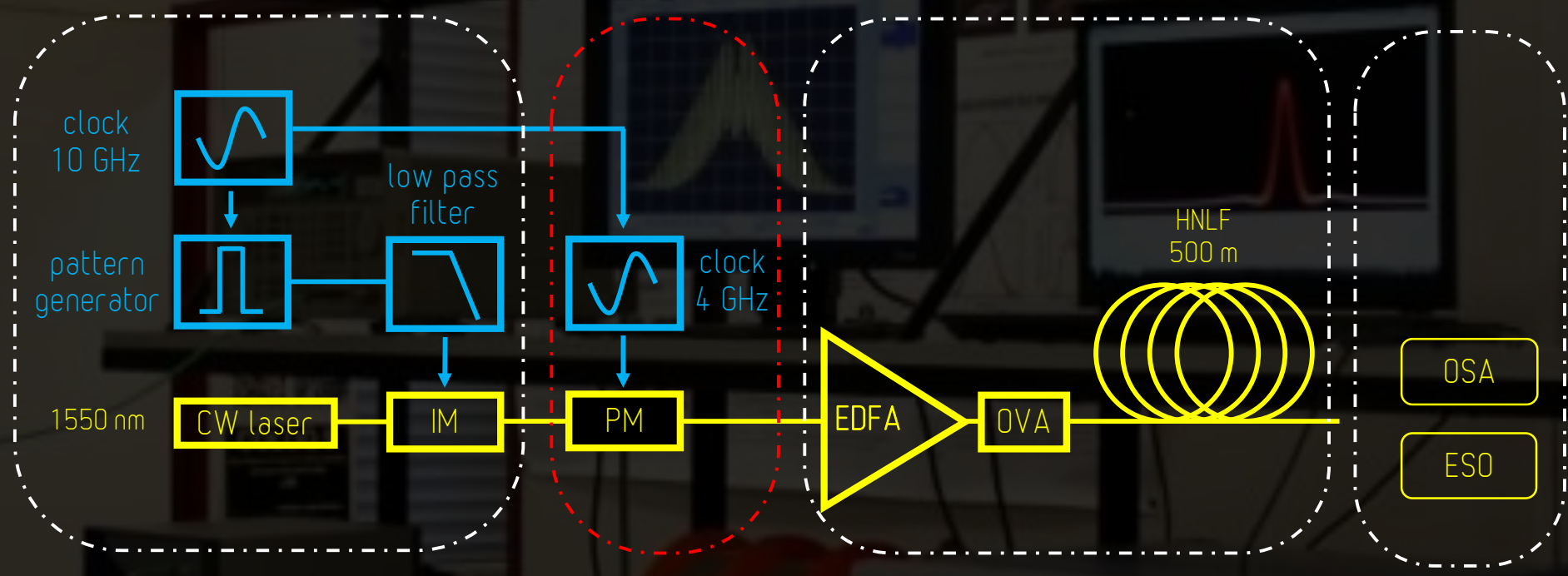
Experimental setup - Input pulses



PULSE GENERATION OF GAUSSIAN-LIKE PULSES



Experimental setup



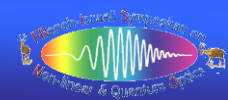
PULSE GENERATION OF GAUSSIAN-LIKE PULSES

SPM MITIGATION

SPM

MEASUREMENTS

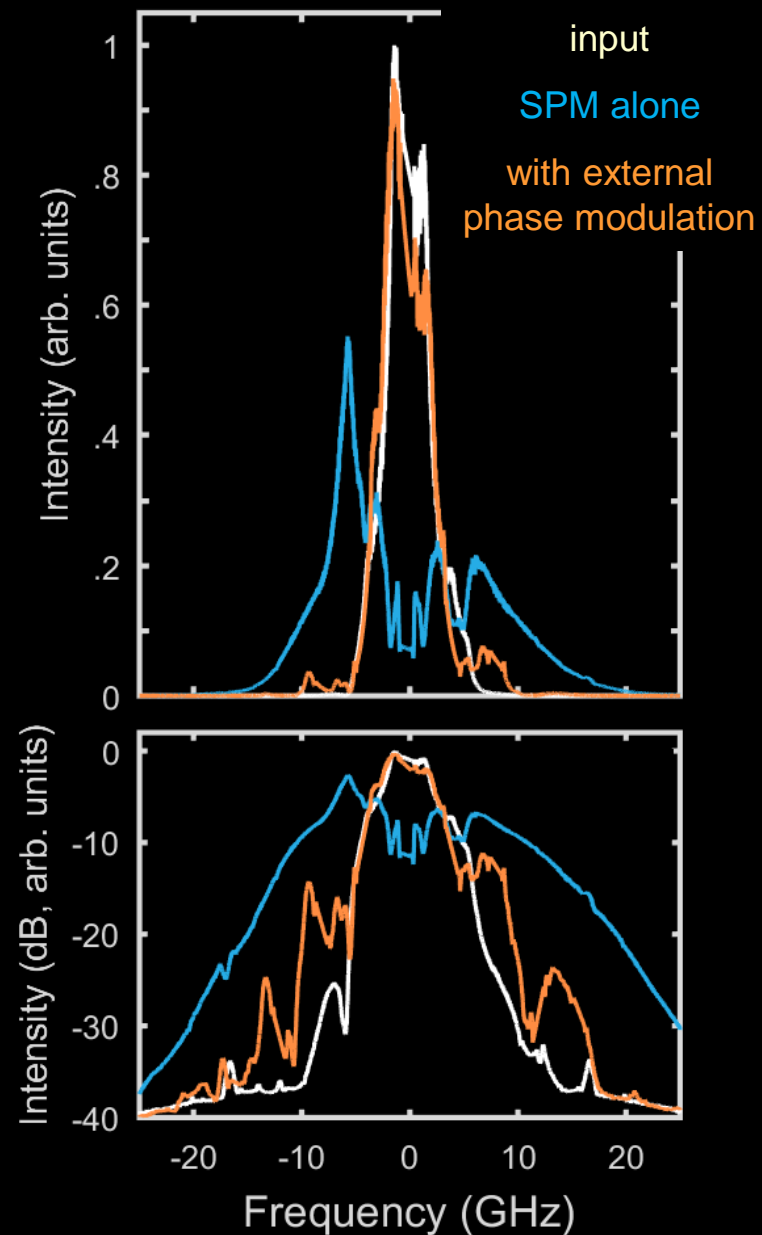
➡ The all-fibered device is made of commercially available components.

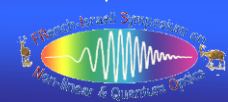


Experimental results 1 - passive configuration

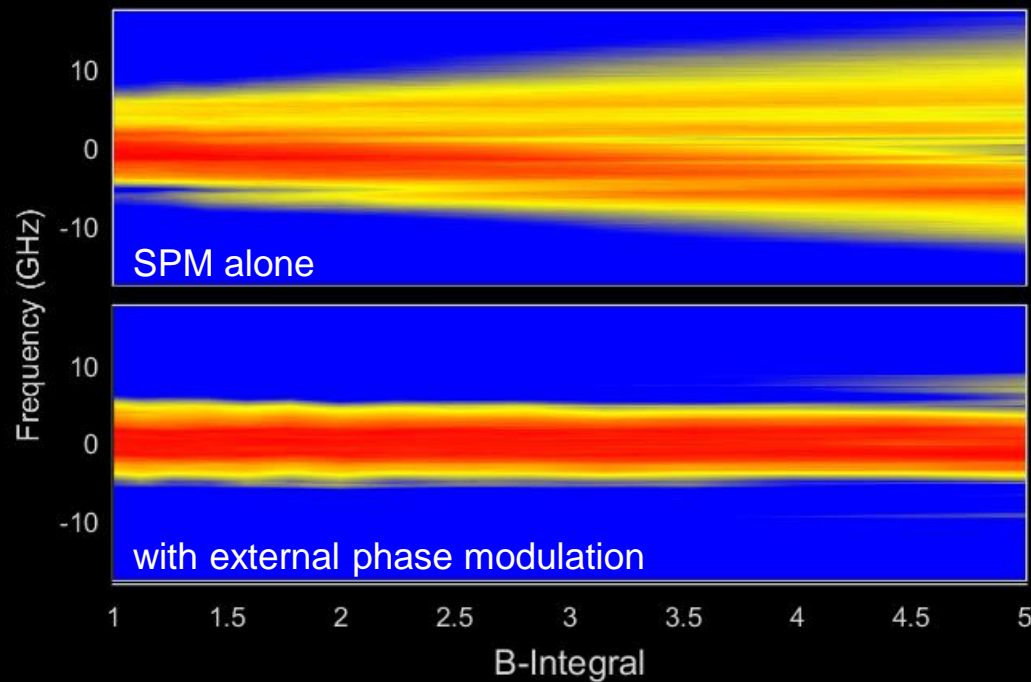
➤ The spectral width of the pulse is restored.

➤ The SPM-cancellation is partial in the wings.

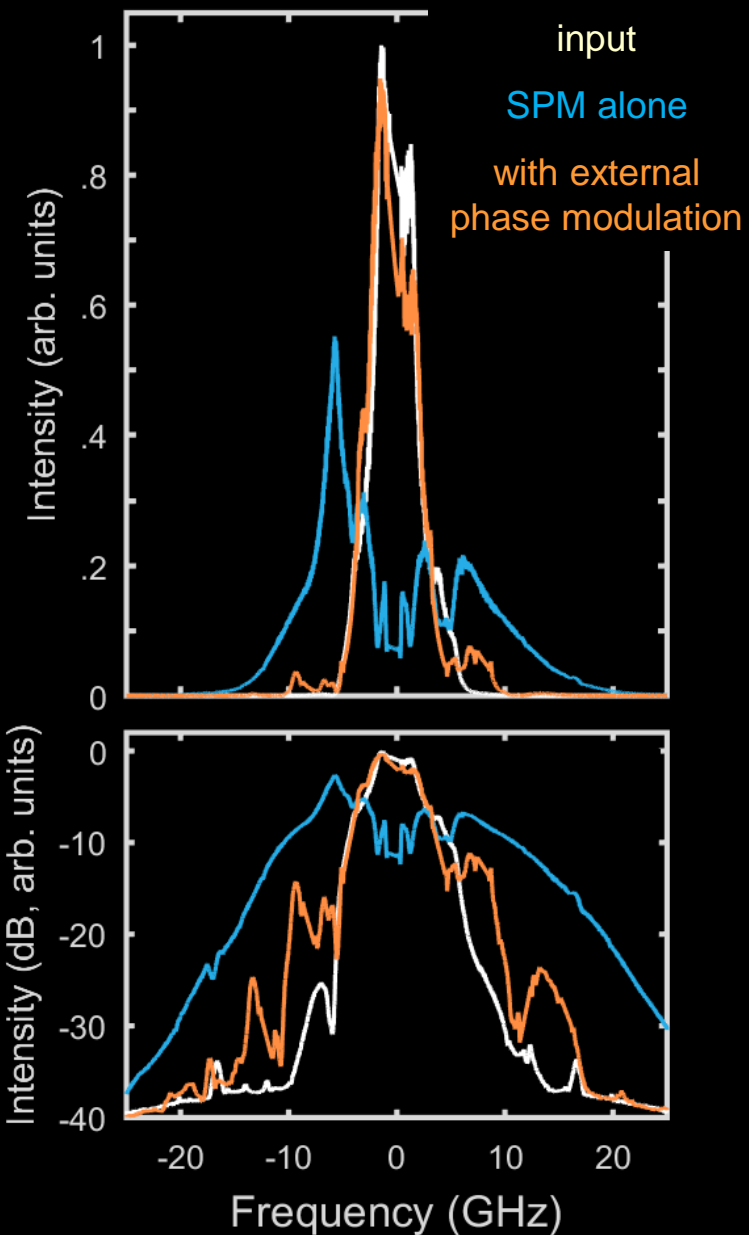


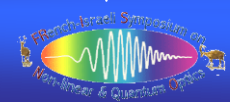


Experimental results 1 - passive configuration

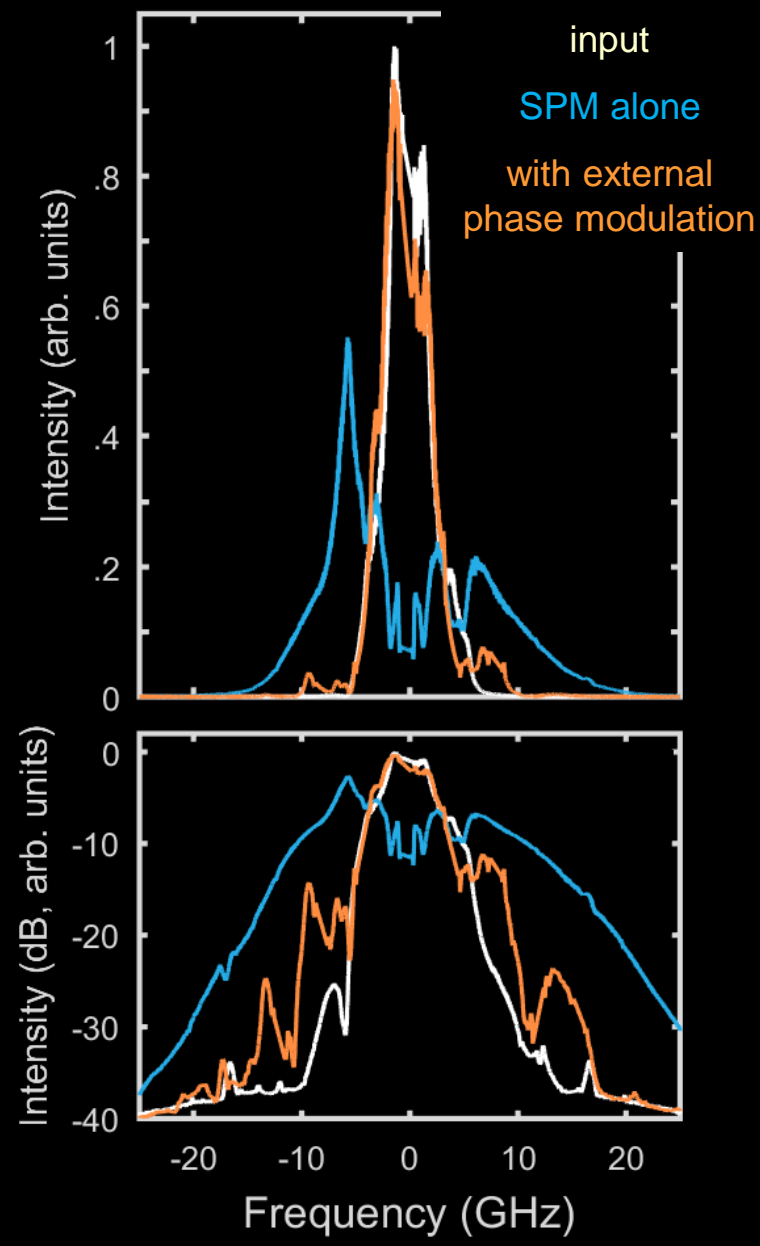
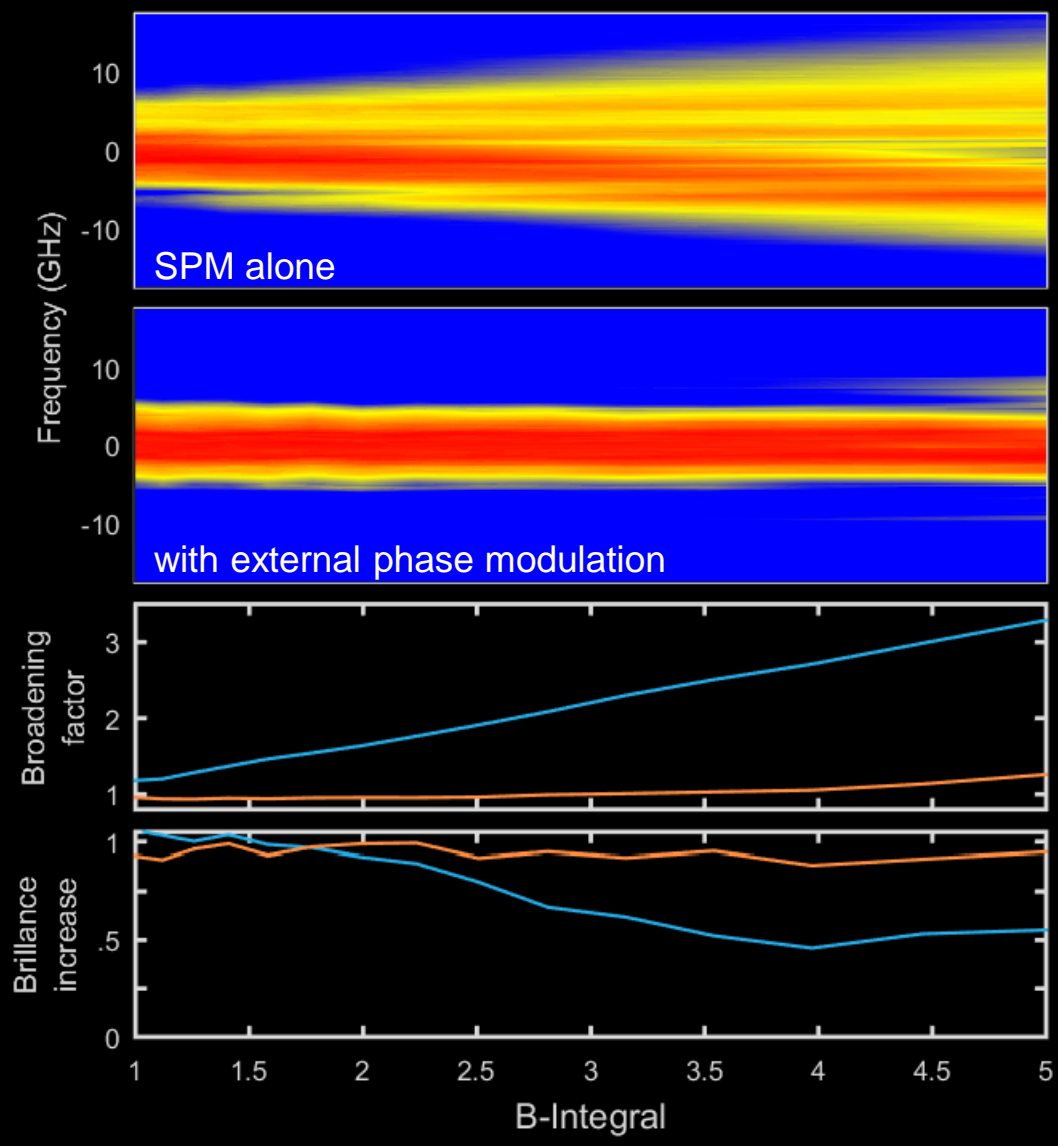


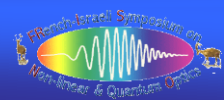
We have checked the validity of the mitigation process up to $B = 5$ rads.





Experimental results 1 - passive configuration





➤ Introduction

➤ Qualitative description of self-phase modulation and analytical guidelines

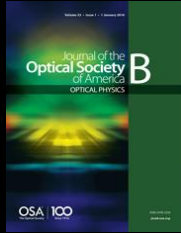
➤ Mitigation of self-phase modulation

➤ Conclusion

Conclusions

- Self-phase modulation can be understood and qualitatively described as a spectral interference process. Positions of the minima and maxima can be accurately derived.
- Simplified models can estimate the frequency of the outlying peaks.
- A linear chirped pulse may require to include a third wave in the interference process in order to correctly describe the pattern.
- A nice exercise for master students. Method can be simply extrapolated to other cases.
- SPM can be mitigated using a simple sinusoidal phase modulation.
- Parameters of the phase modulation may have to be adjusted for optimum mitigation.
- Short pulses can be handled and dispersion is not a problem.

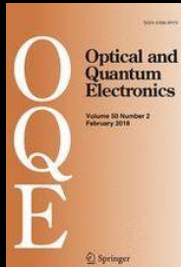
Conclusion - *If you want to know more about this ...*



Sonia Boscolo, Frédéric Chaussard and Christophe Finot.
"Simple guidelines to predict self-phase modulation patterns."
 Journal of the Optical Society of America B 35, 3143 (2018)



Frederic Audo, Sonia Boscolo, Julien Fatome, Bertrand Kibler, and Christophe Finot.
"Nonlinear spectrum broadening cancellation by sinusoidal phase modulation."
 Optics Letters 42, 2902 (2017)



Sonia Boscolo, Frédéric Audo, Christophe Finot.
« Impact of initial pulse characteristics on the mitigation of self-phase modulation by sinusoidally time varying phase ».
 Optical and Quantum Electronics, 50, 62 (2018)



Sonia Boscolo, Levon Mouradian, Christophe Finot.
Enhanced nonlinear spectral compression in fibre by external sinusoidal phase modulation
 Journal of Optics, 10, 18, (2016)