2021 Dec 01

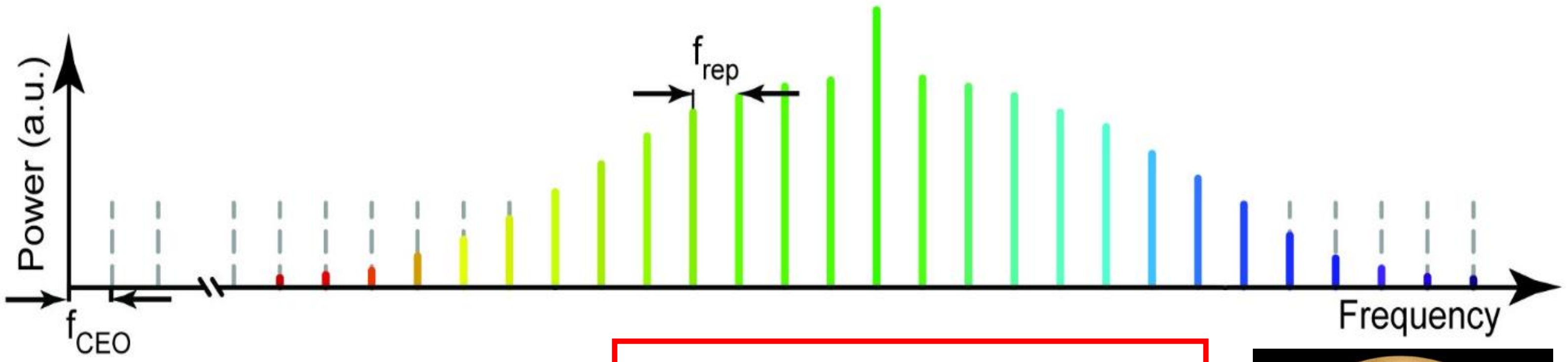
NLO #15

- **Supercontinua - what are they good for?**
  - **Frequency metrology**
  - **Optical spectroscopy**
  - **Short-pulse generation**
- **Numerical exploration of SC generation**
  - **Dispersion and SPM**
  - **Fundamental and higher order solitons**
  - **Dispersive wave**
  - **Soliton-self-frequency shift**
  - **Fission of higher order solitons**
  - **Normal dispersion**

Phase-coherent frequency measurement of visible light

- SI definition of time also defines optical frequency (and wavelength)
- Time-keeping / re-definition of the SI second
- Fundamental physics (Rydberg, Fine structure, Cosmological expansion, …)
- Precision spectroscopy

Frequency combs:



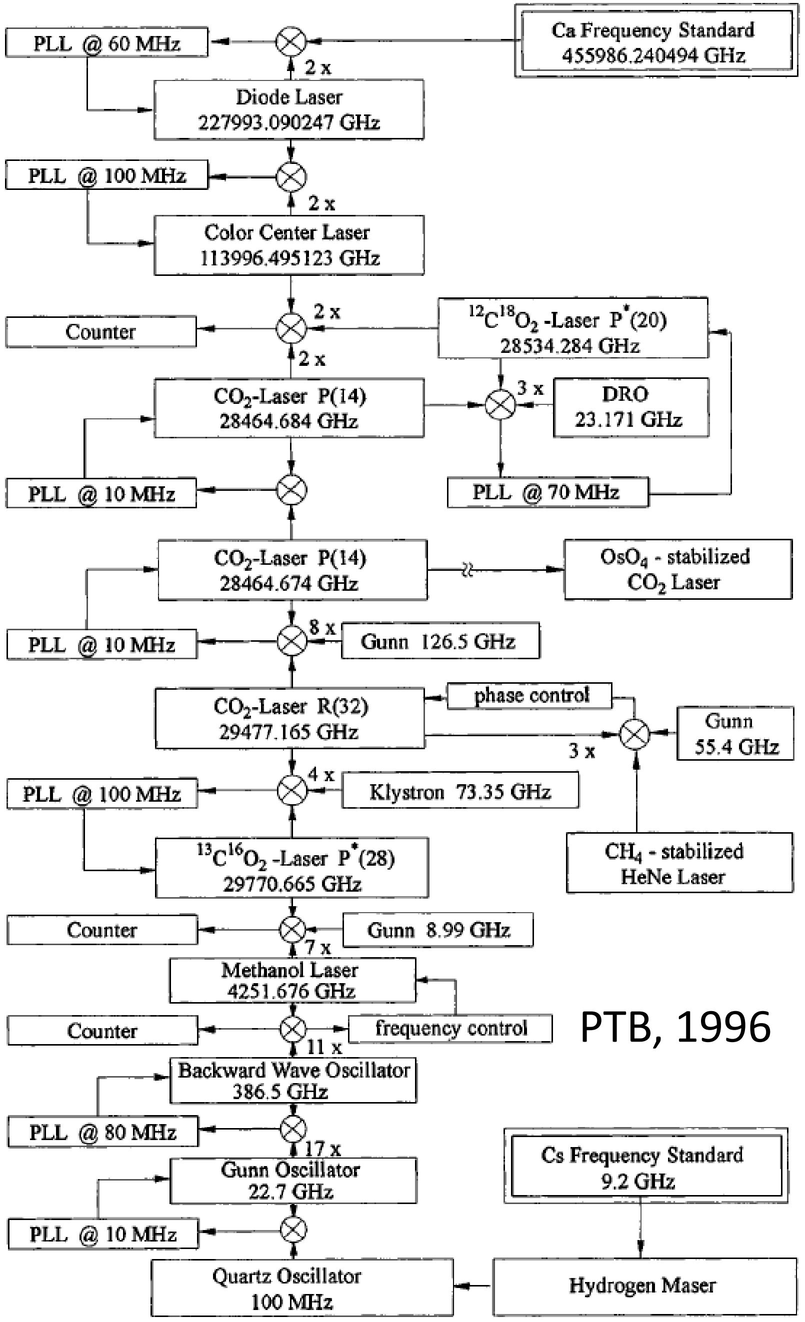
n^{th} Comb Line at

$$f_n = n \cdot f_{\text{rep}} + f_{\text{CEO}}$$

Repetition Rate / Mode Spacing

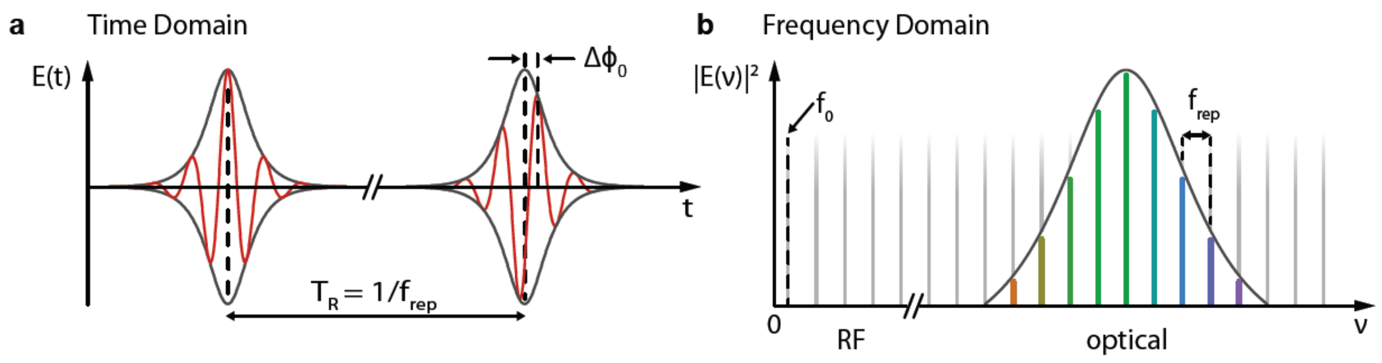
Carrier Envelope Offset Frequency

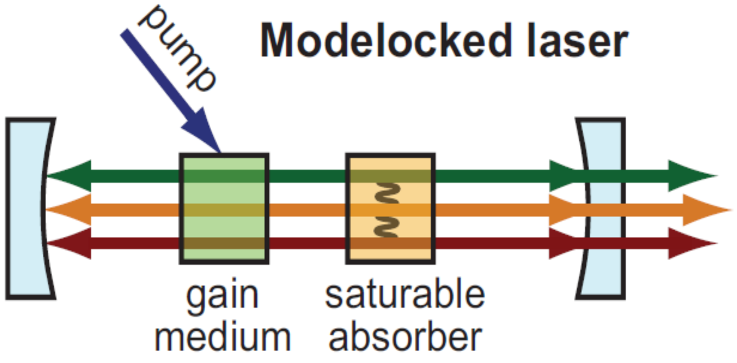
Nobel Prize 2005
J.L. Hall & T.W. Hänsch



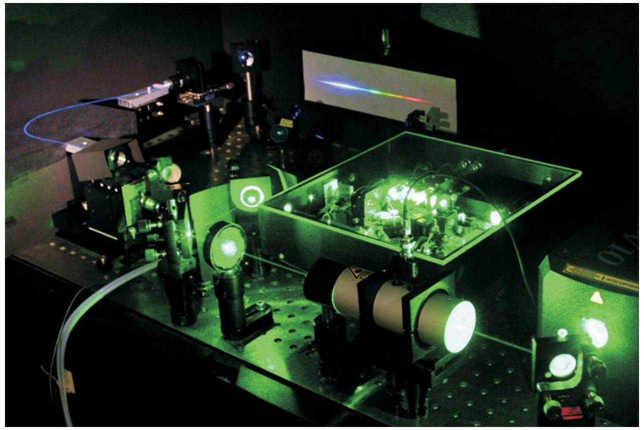
PTB, 1996

Self-referenced frequency combs

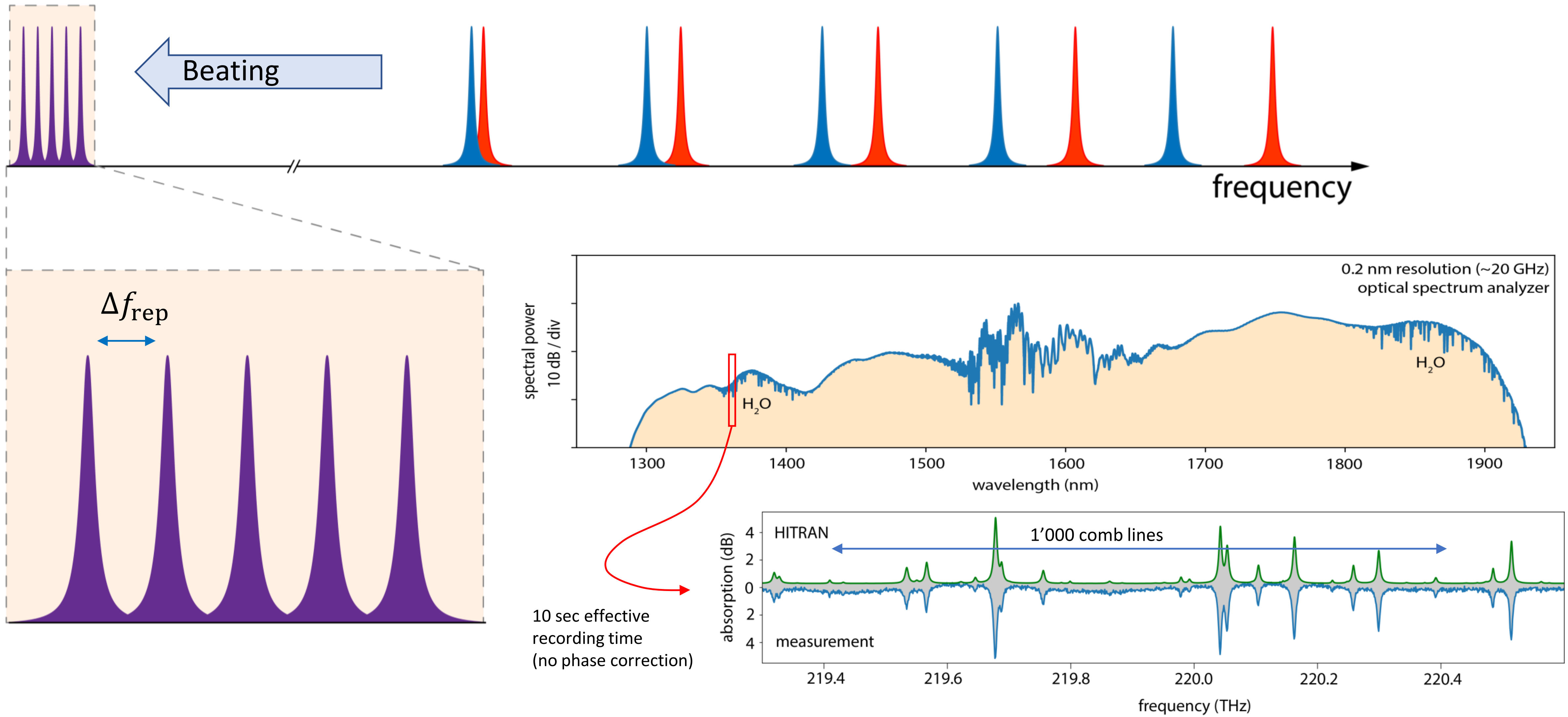




Only one of many examples:
Titanium:Sapphire Laser: typ. < 50 fs / 800 nm

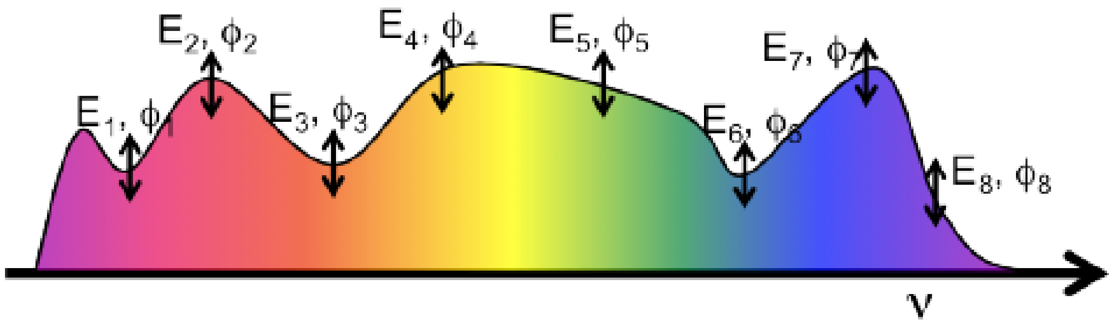


Dual comb spectroscopy



Synthesis of single- and sub-cycle optical pulses

Single cycle pulses



- Pump-probe spectroscopy

High-harmonic generation
(atto-second pulses)

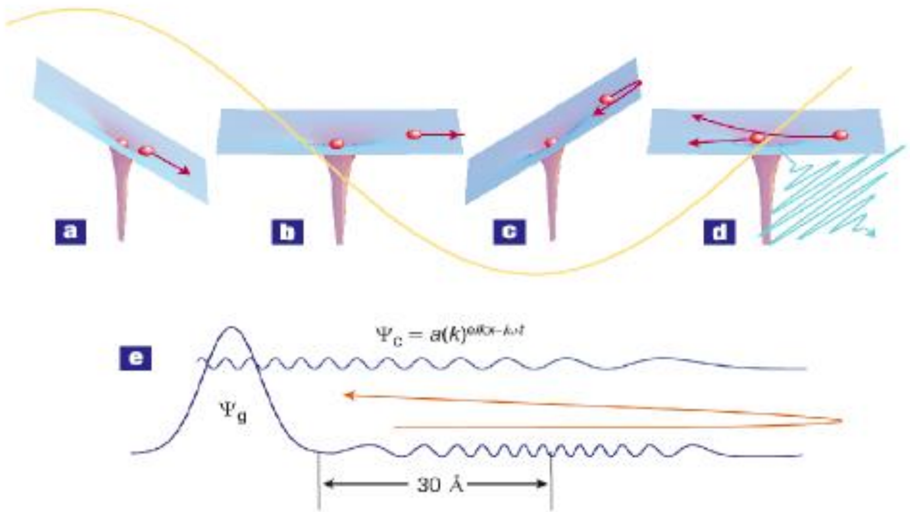


Figure from Corkum et al., Science **34**, 195, (2011)

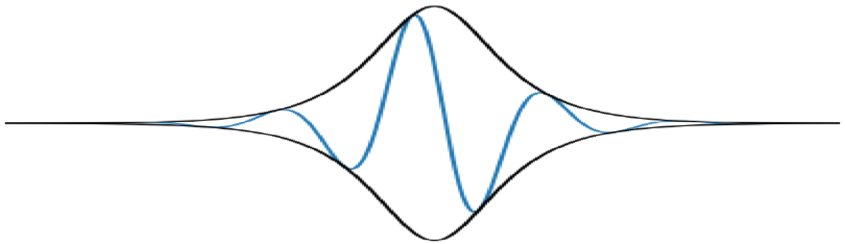
Reminder: GNLSE

loss — dispersion — nonlinearity [1/(W m)] — Incl. also dispersion of nonlinearity — Stimulated Raman scattering

$$\left(\frac{\partial}{\partial z} + \frac{\alpha}{2} - iD\right) A = i\gamma \left(1 + i\tau_{\text{shock}} \frac{\partial}{\partial \tau}\right) A(z,\tau) \int R(\tau')|A(z,\tau-\tau')|^2 \,\mathrm{d}\tau'$$

Temporal spreading — Solitons — SPM (XPM, FWM) — Shock-formation Self-steepening — Self-frequency shift (towards lower frequency)

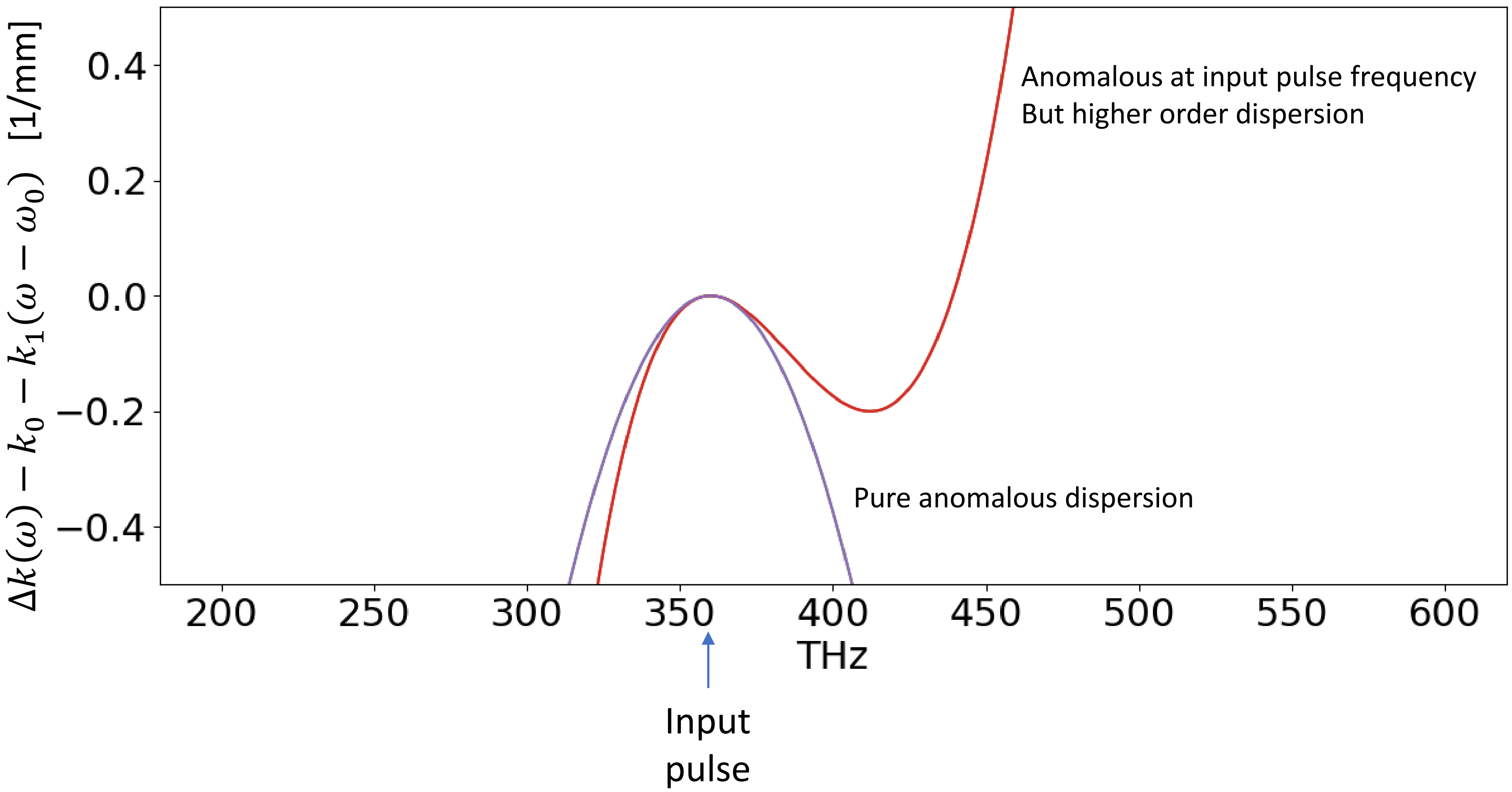
$k_2 > 0$: normal group velocity dispersion (GVD)
$k_2 < 0$: anomalous GVD → Solitons



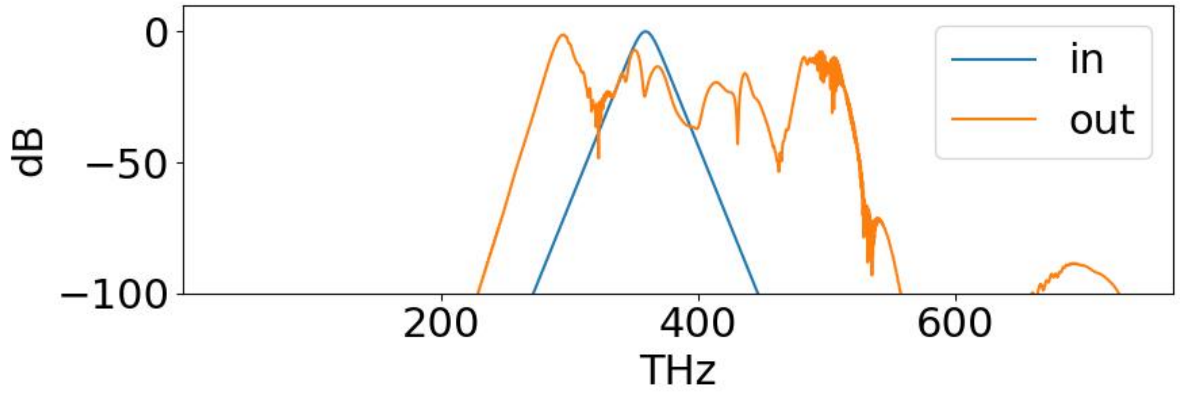
Equation valid down to the single-cycle regime

Dispersion

$$k(\omega) = k_0 + k_1\,(\omega - \omega_0) + \frac{1}{2}k_2(\omega - \omega_0)^2 + \ \dots$$

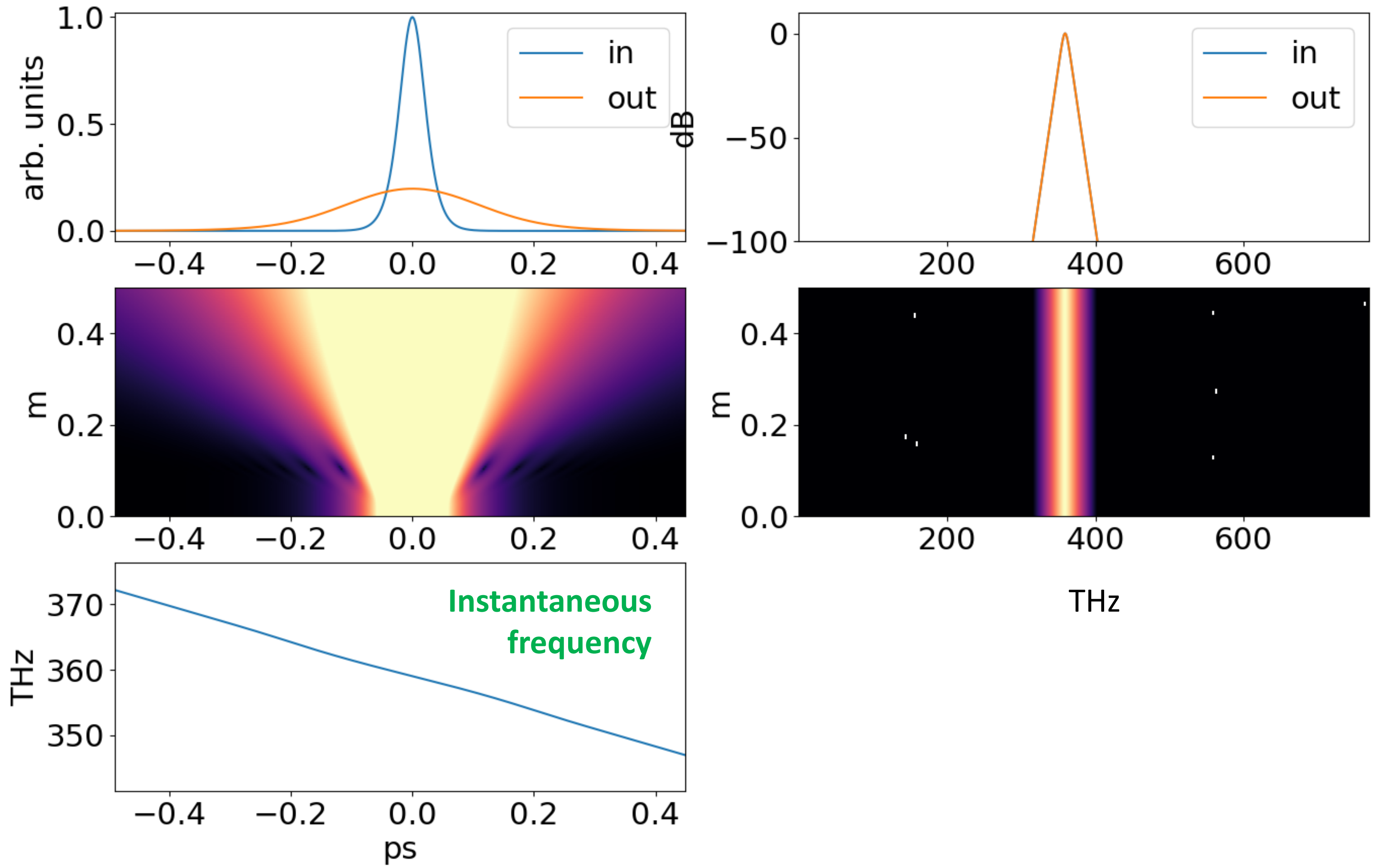


25 fs, 835 nm (360 THz), higher order dispersion, Raman, Self-steepening

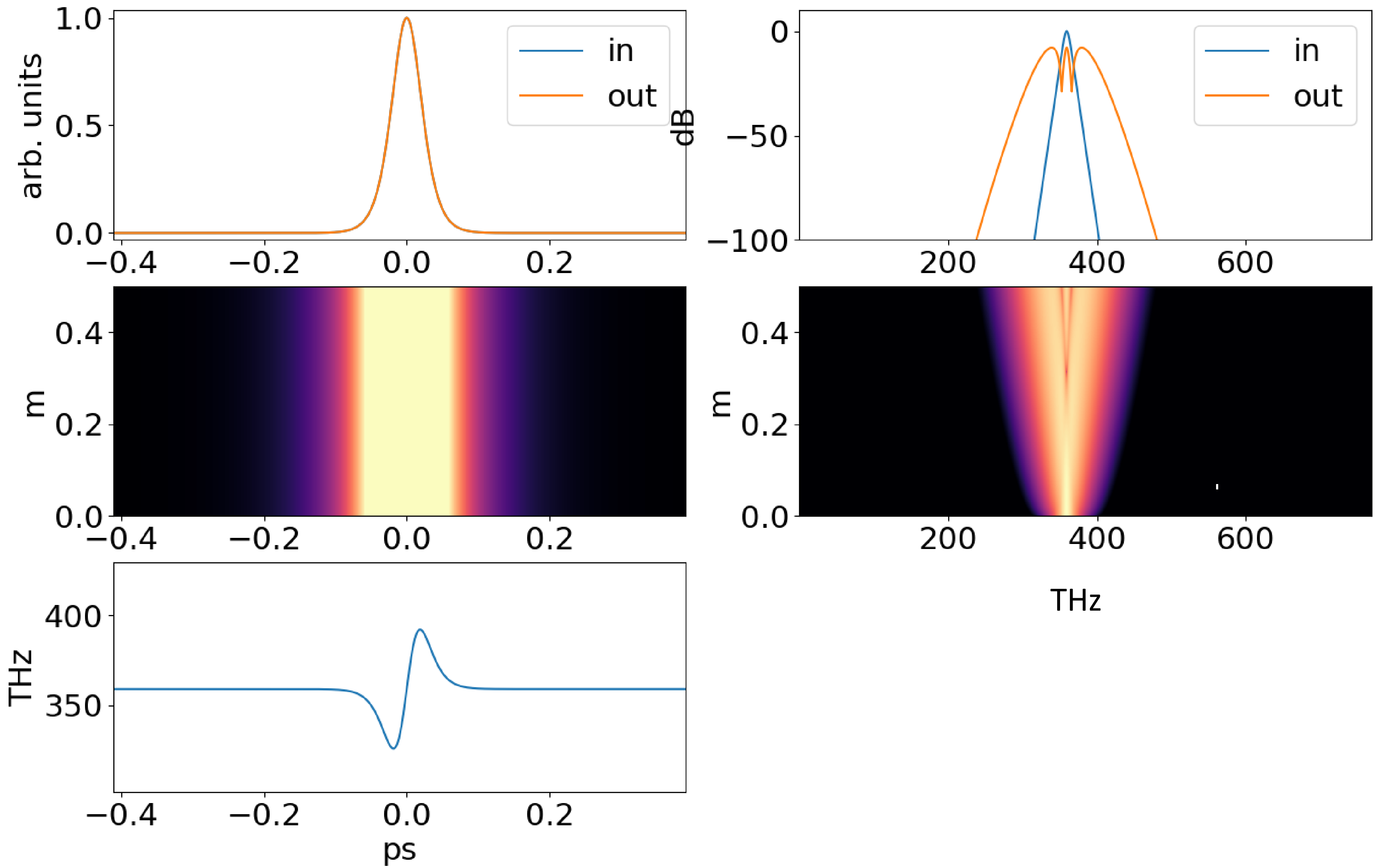


Can we understand this spectrum?

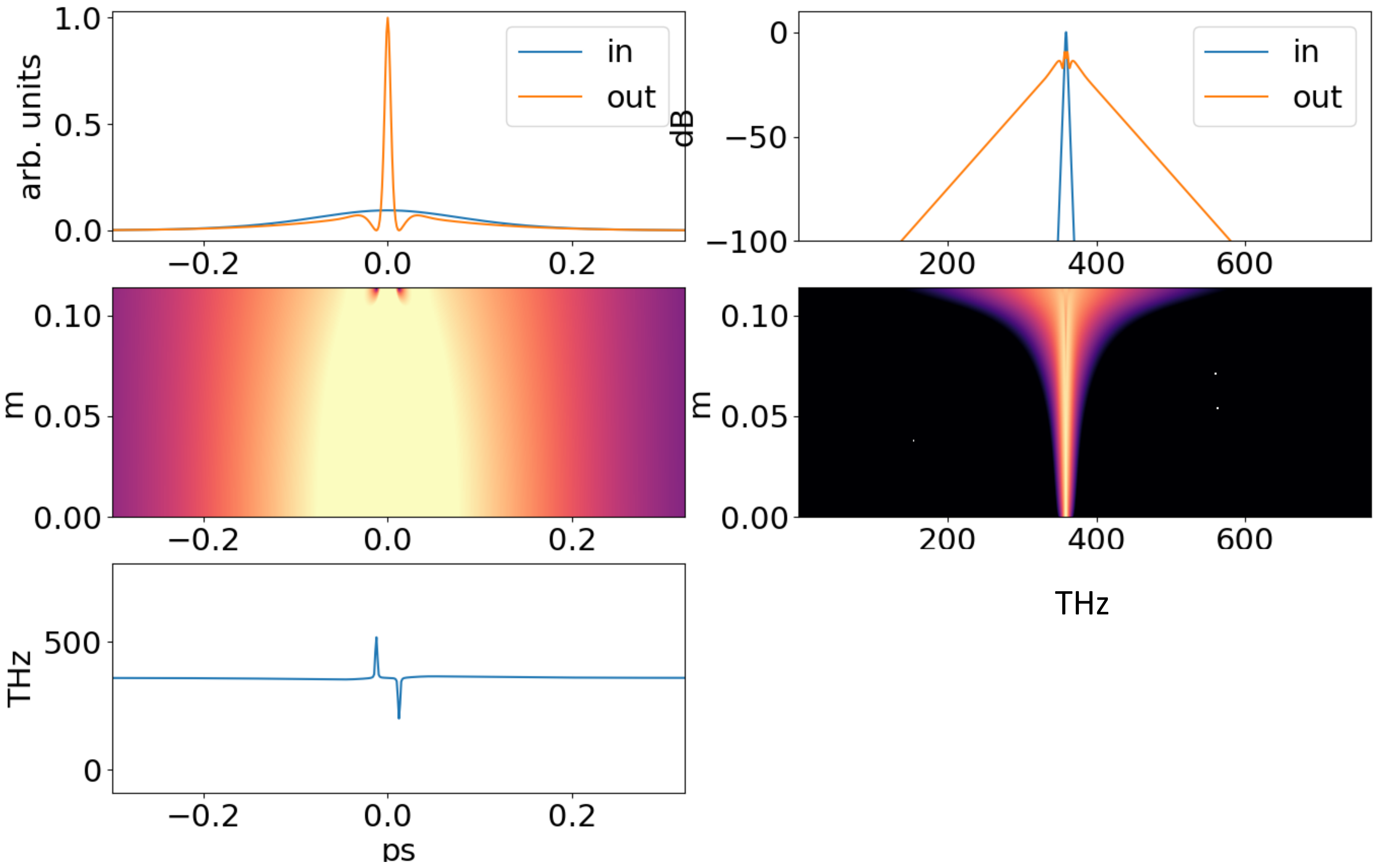
Dispersion: 50 fs, **no** higher order dispersion, **no** Raman, **no** self-steepening, **no** nonlinearity



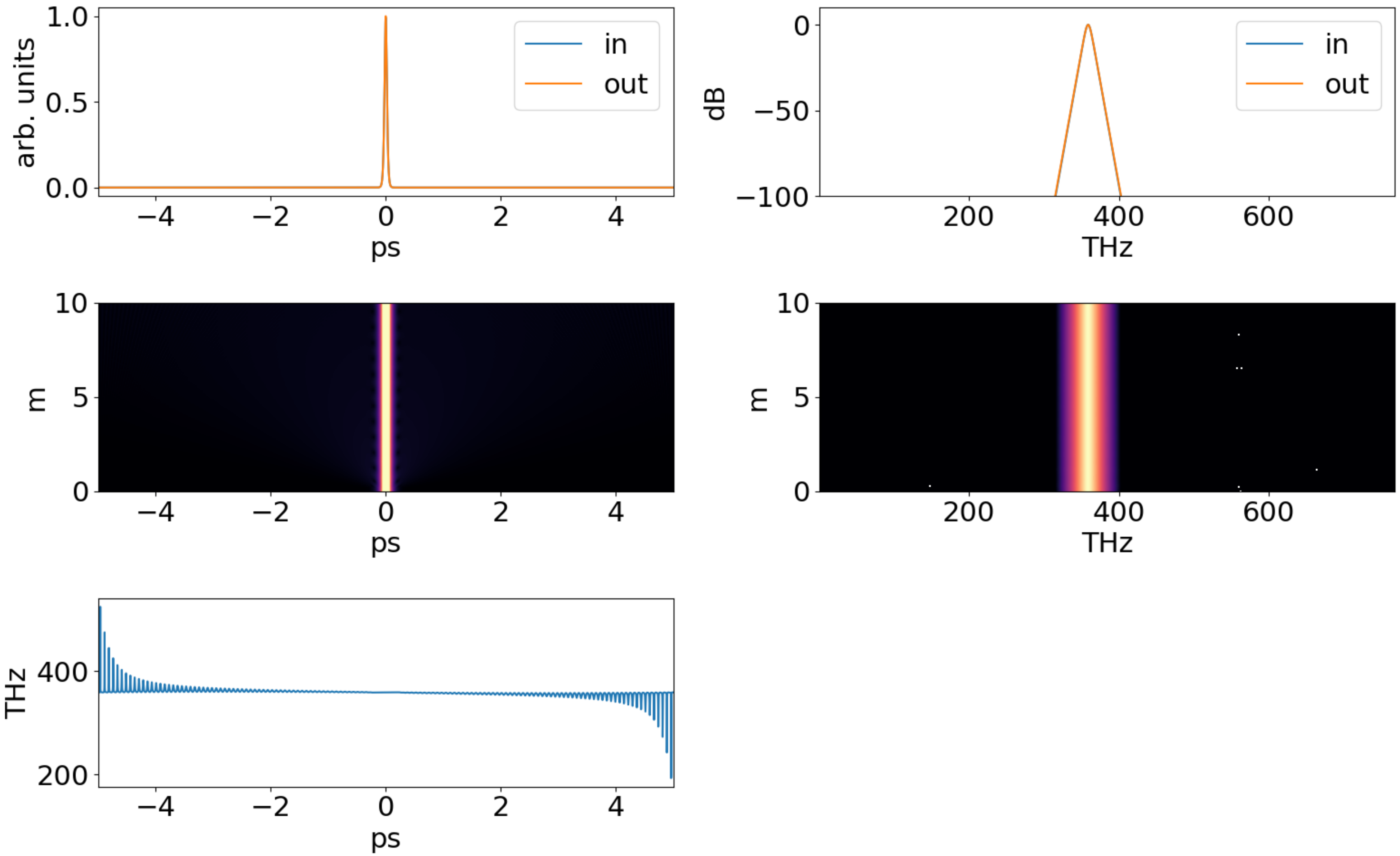
SPM: 50 fs, **no** dispersion, **no** Raman, **no** self-steepening



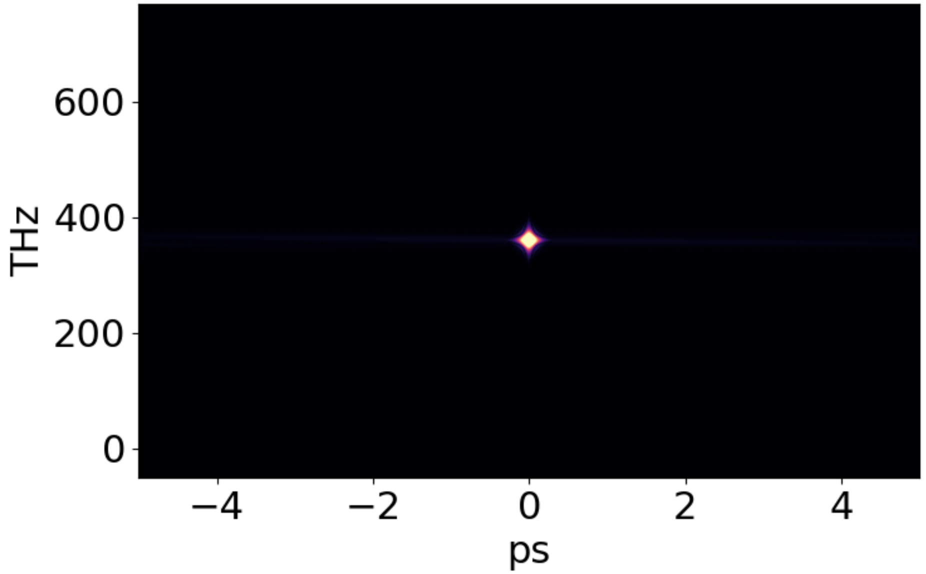
Pulse compression 200 fs, **no** dispersion, **no** Raman, **no** self-steepening

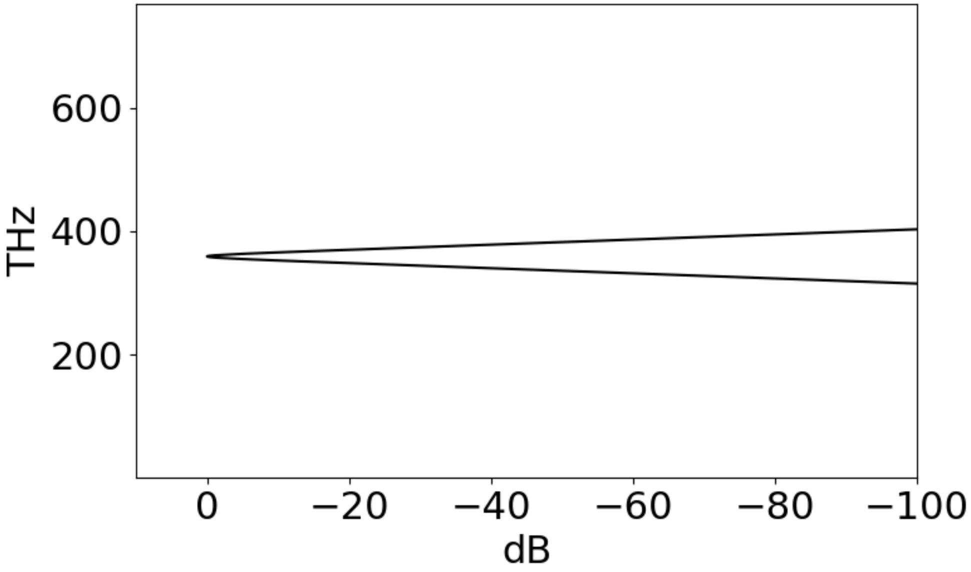


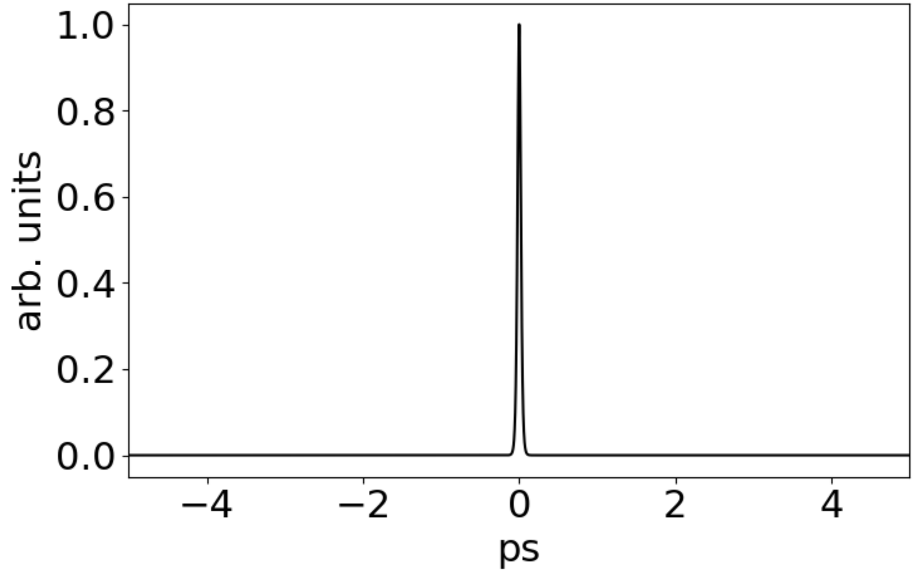
Fundamental soliton: 50 fs, **no** higher order dispersion, **no** Raman, **no** self-steepening



Spectrogram:

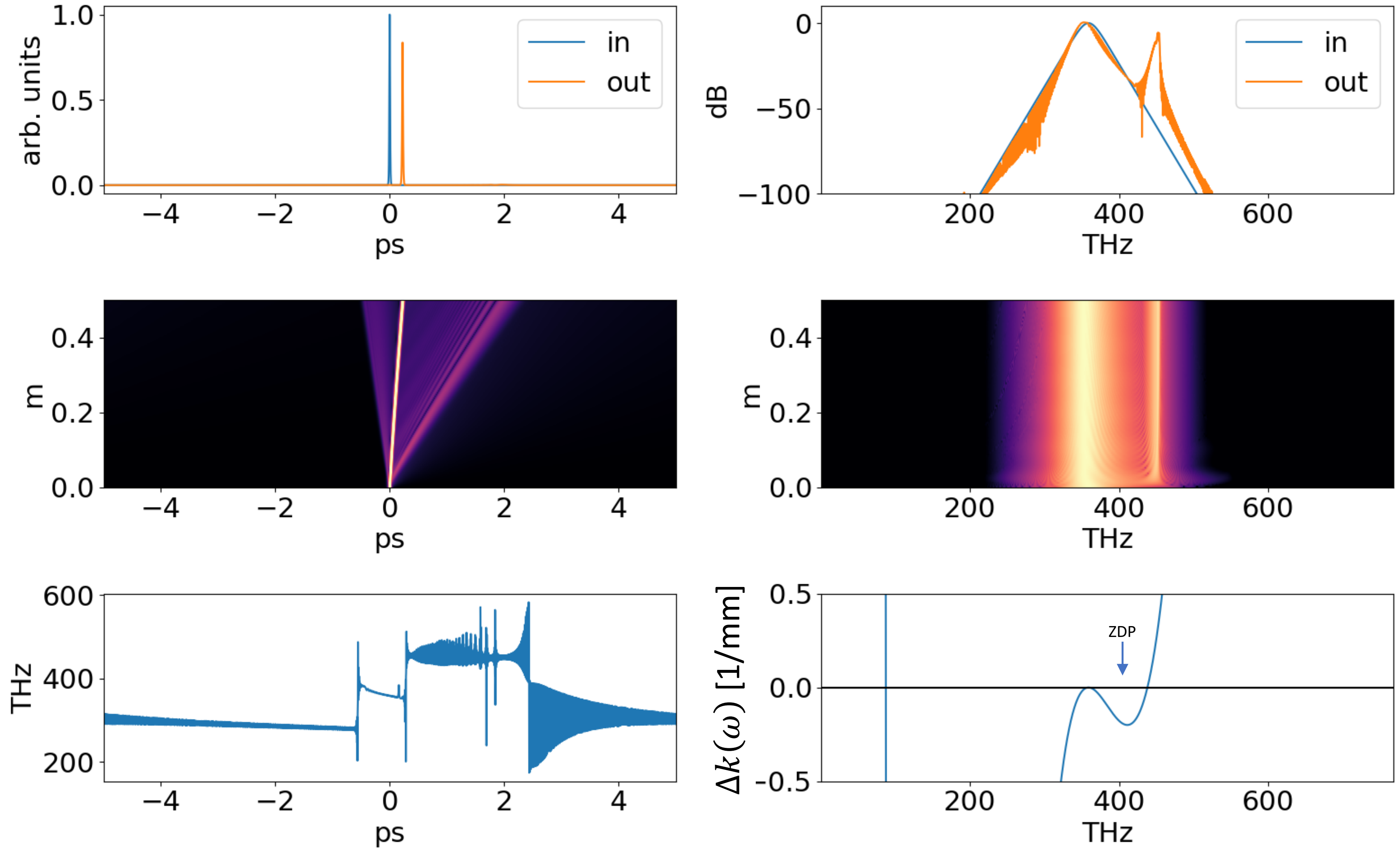




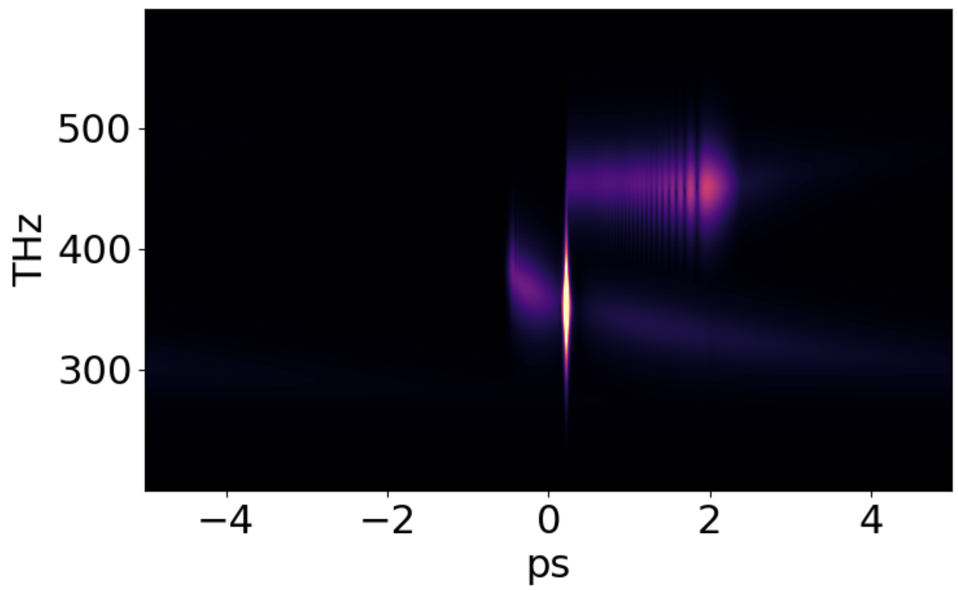


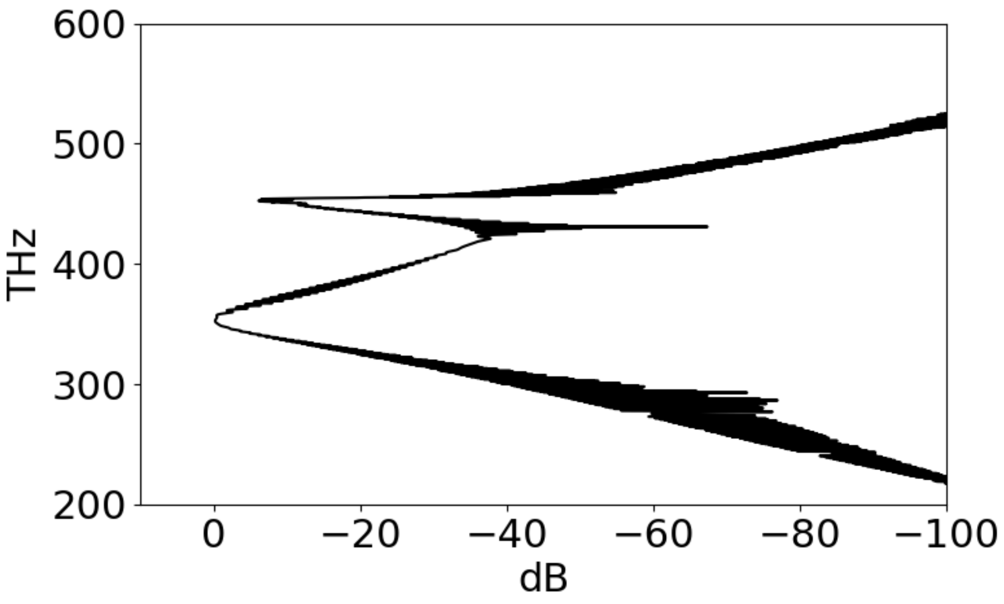
$$S(\omega, \tau) = \left| \int E(t) g(t - \tau)\, e^{-i\omega t}\, \mathrm{d}t \right|^2$$

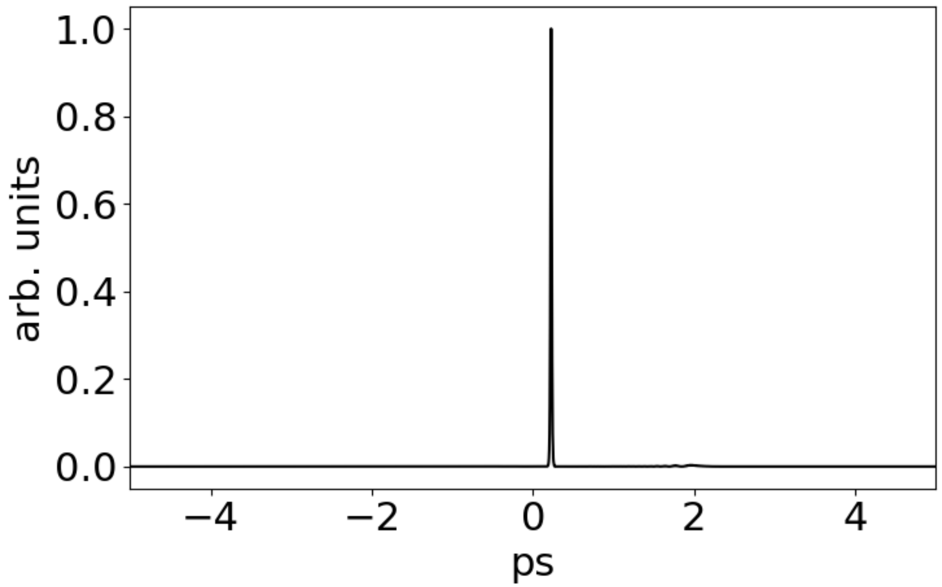
Fundamental Soliton: 15 fs, higher order dispersion, no Raman, no self-steepening



Spectrogram:

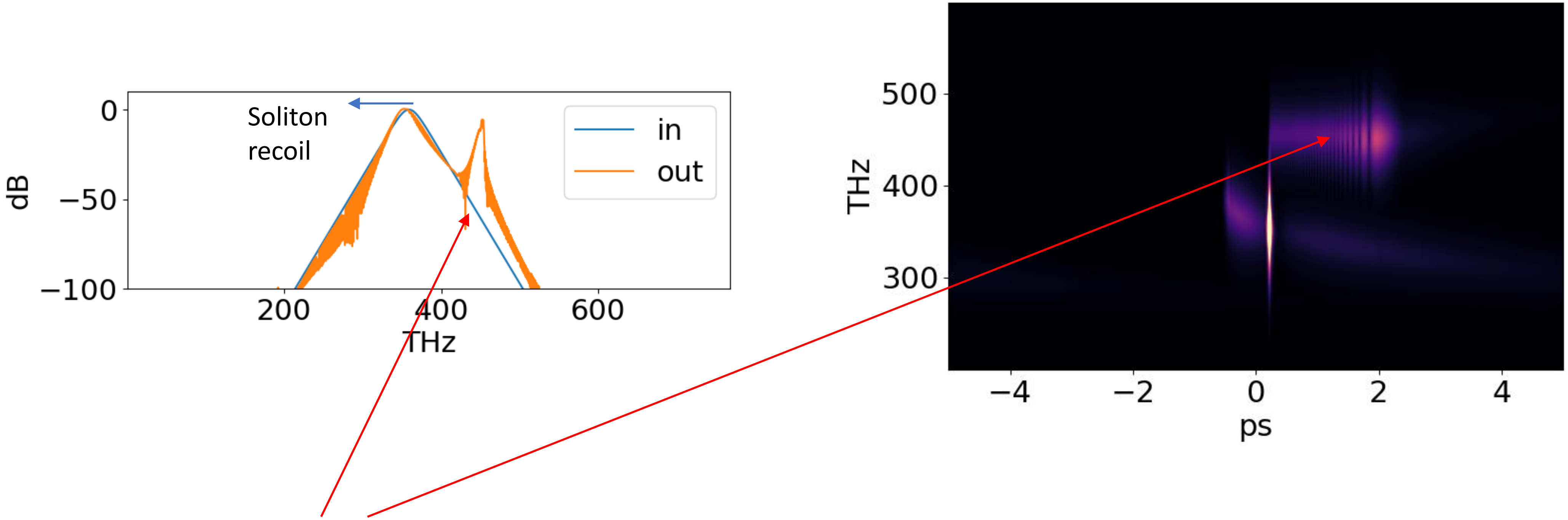






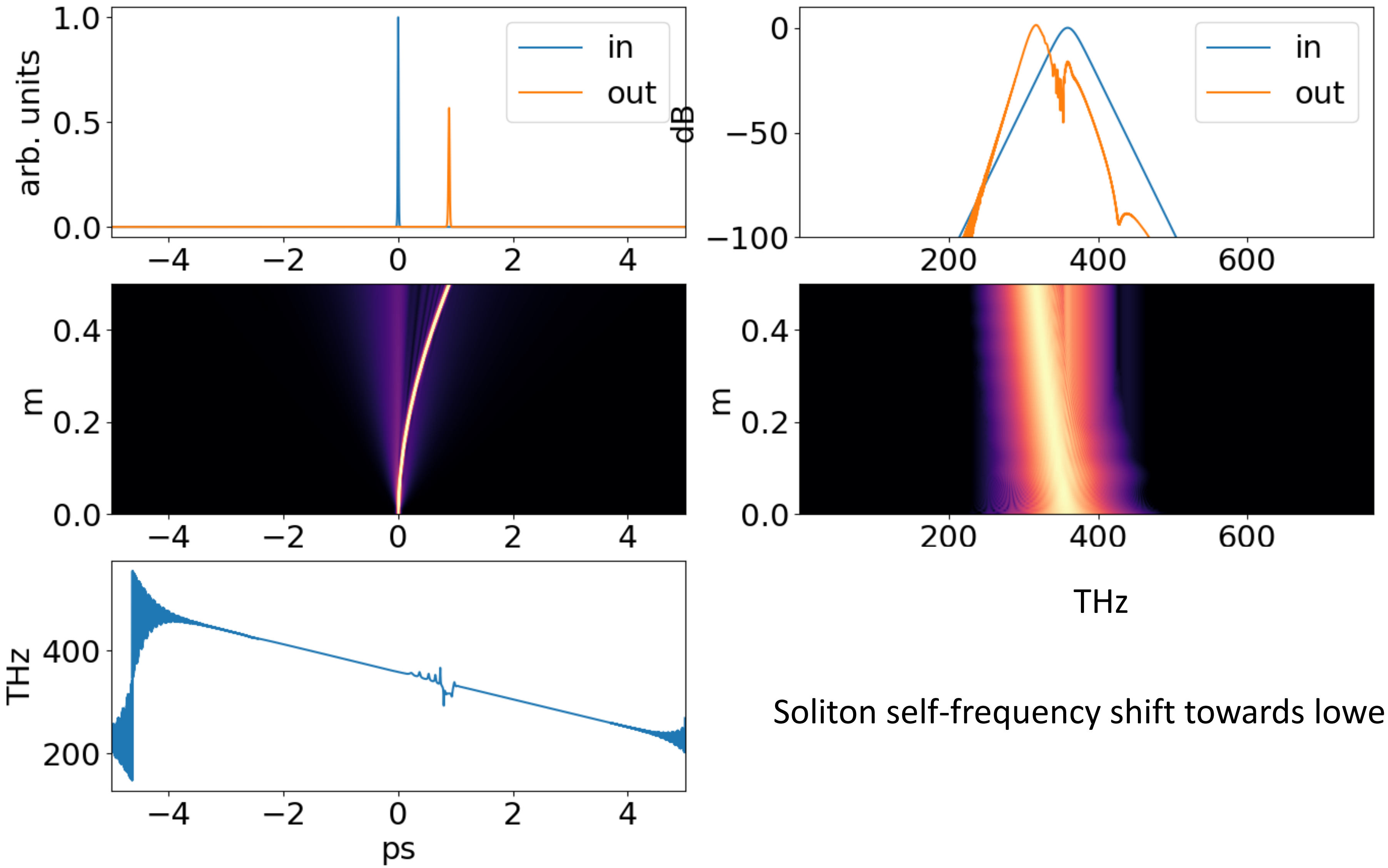
$$S(\omega,\tau) = \left| \int E(t) g(t-\tau)\, e^{-i\omega t} \; \mathrm{d}t \right|^2$$

Dispersive wave formation



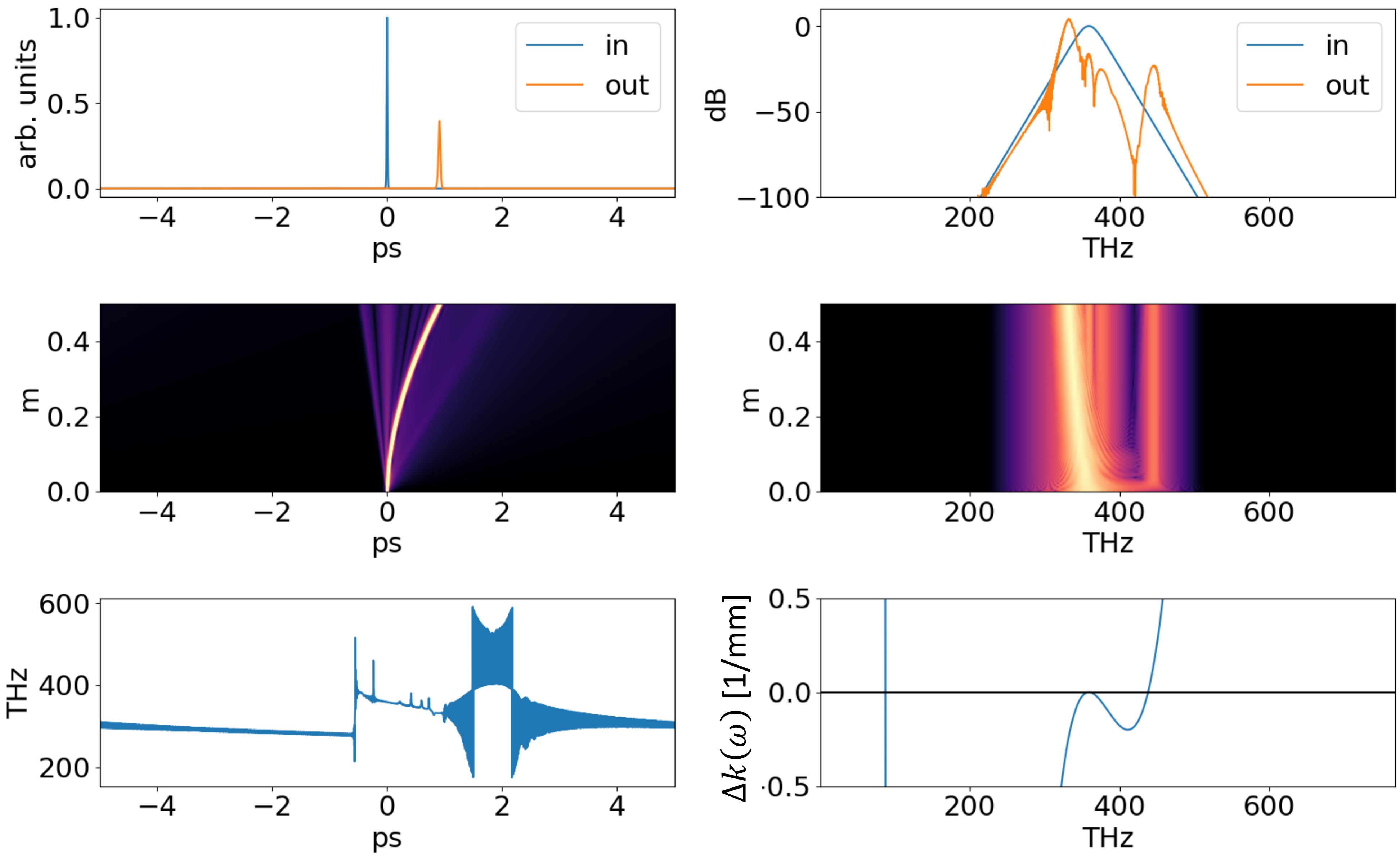
- A „**dispersive wave**“ is generated phase matched to the soliton across a zero-dispersion point (ZDP).
- The dispersive wave is not „solitonic“ and disperses into a temporal continuum.
- The soliton‘s center frequency is shifted away from the dispersive wave due to the „soliton recoil“ effect (energy conservation).

Fundamental Soliton: 15 fs, **no** higher order dispersion, **Raman**, **no** self-steepening

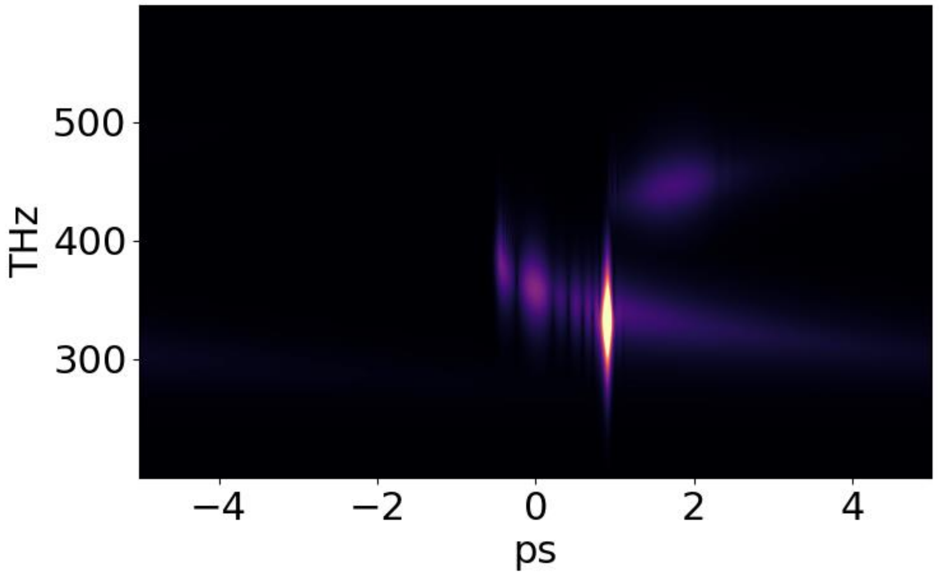


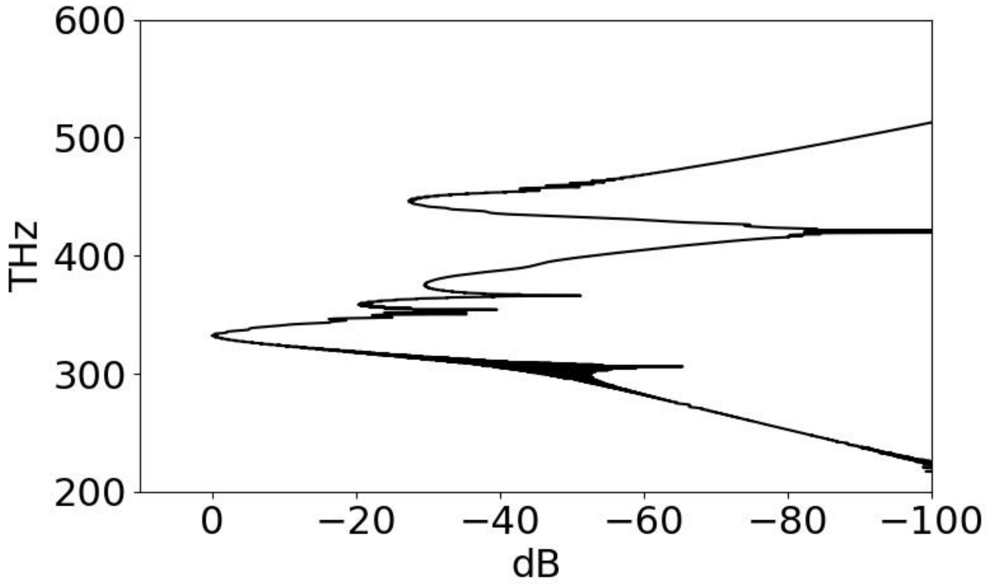
Soliton self-frequency shift towards lower frequency

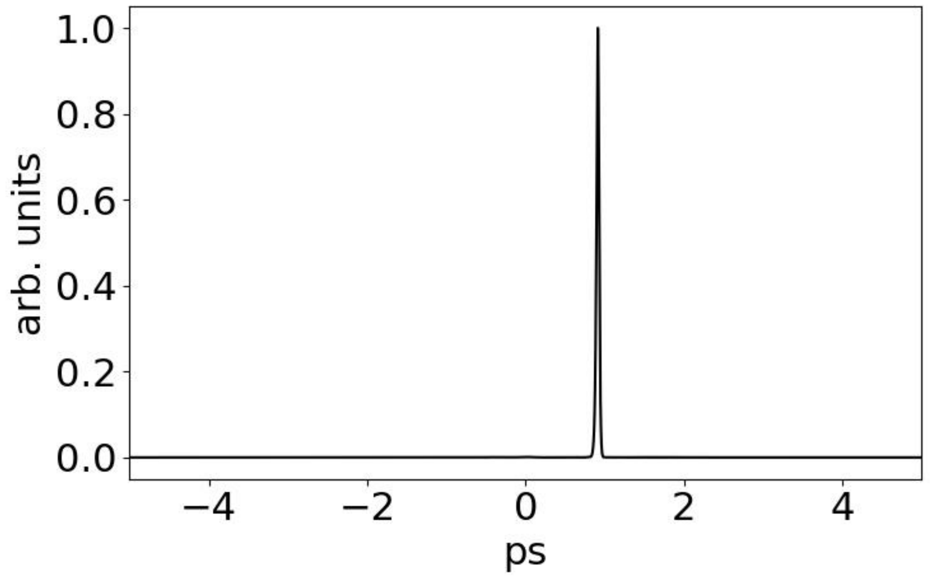
Fundamental Soliton: 15 fs, higher order dispersion, Raman, no self-steepening



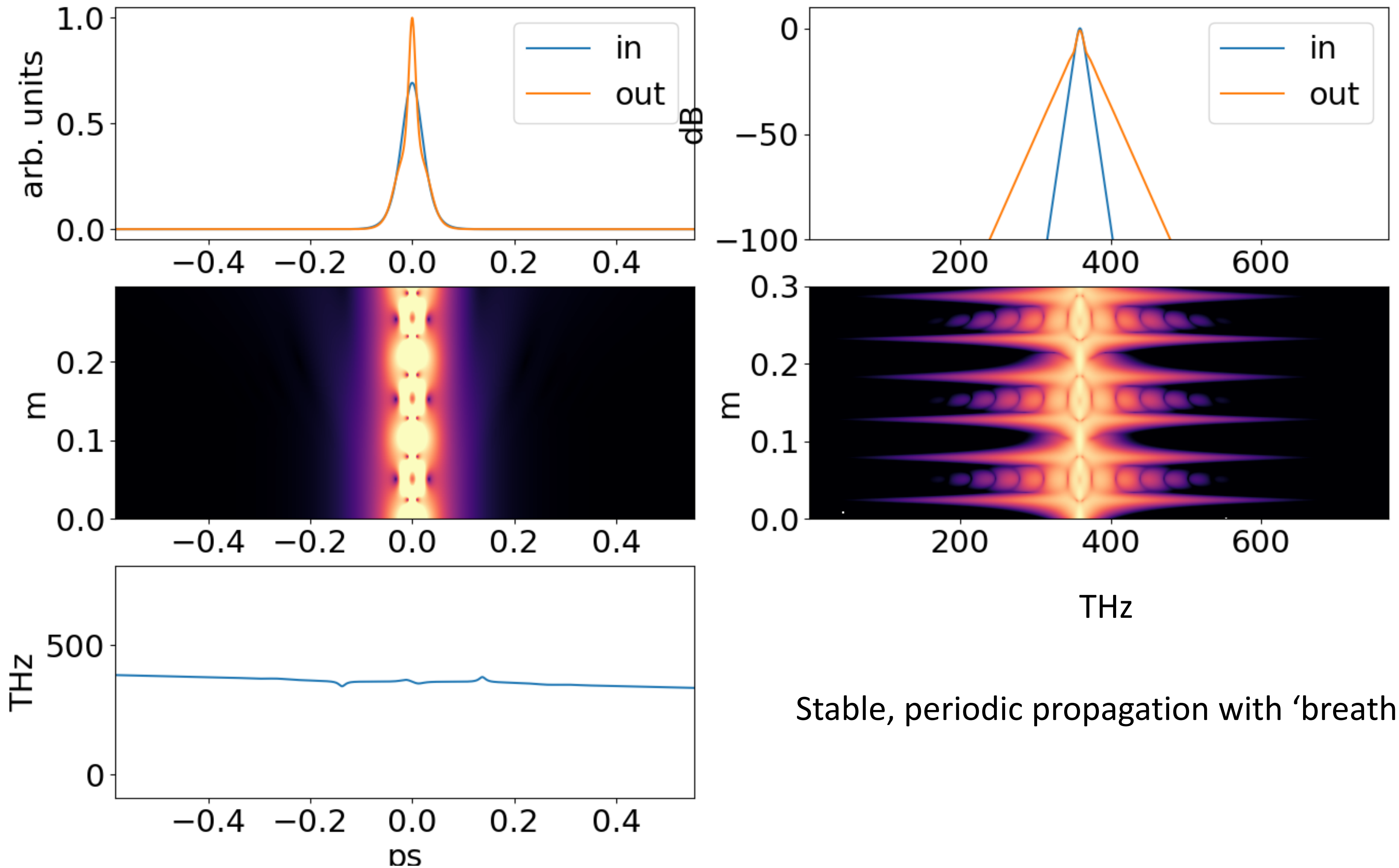
Spectrogram:





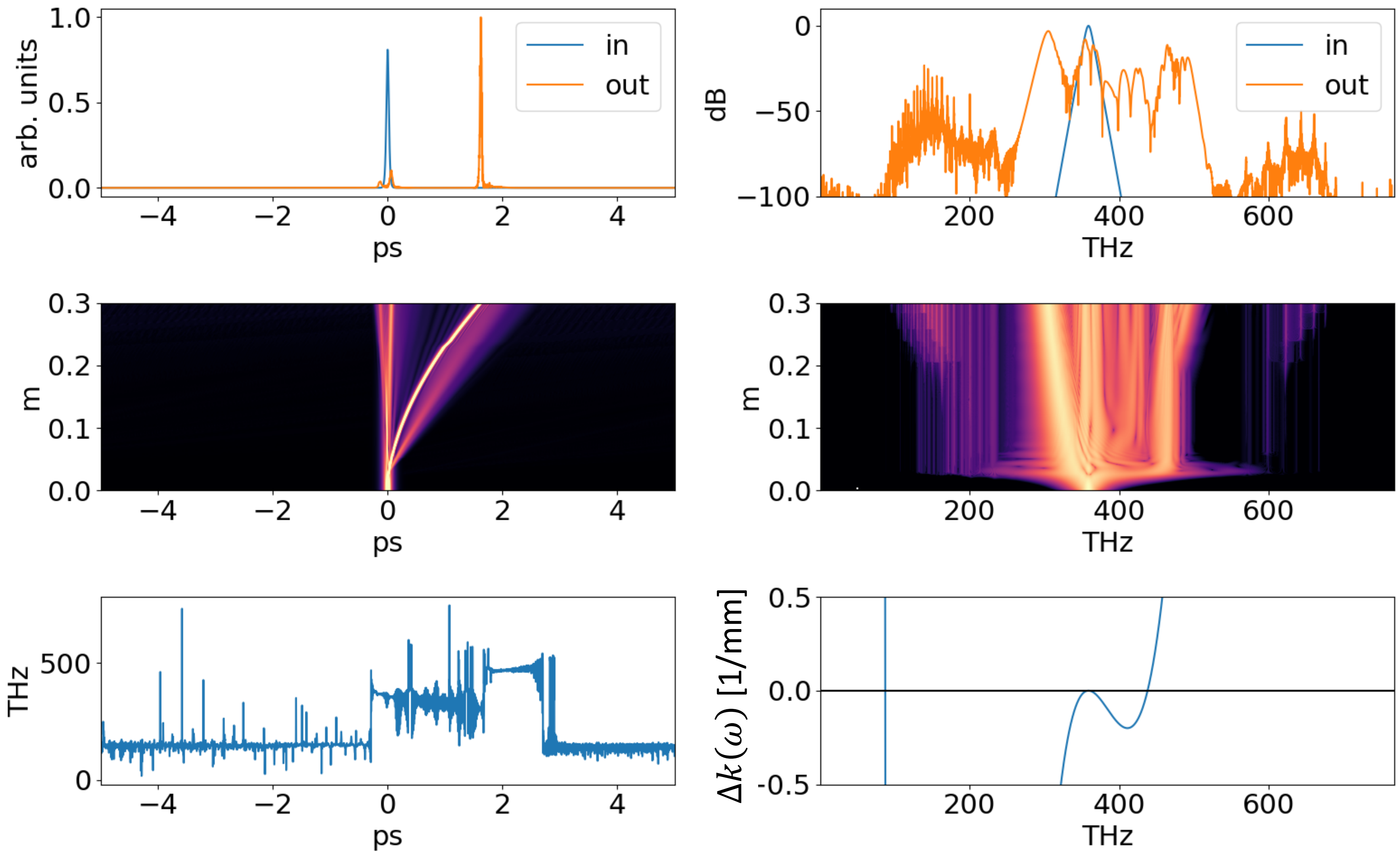


Order 3 Soliton: 50 fs, no higher order dispersion, no Raman, no self-steepening

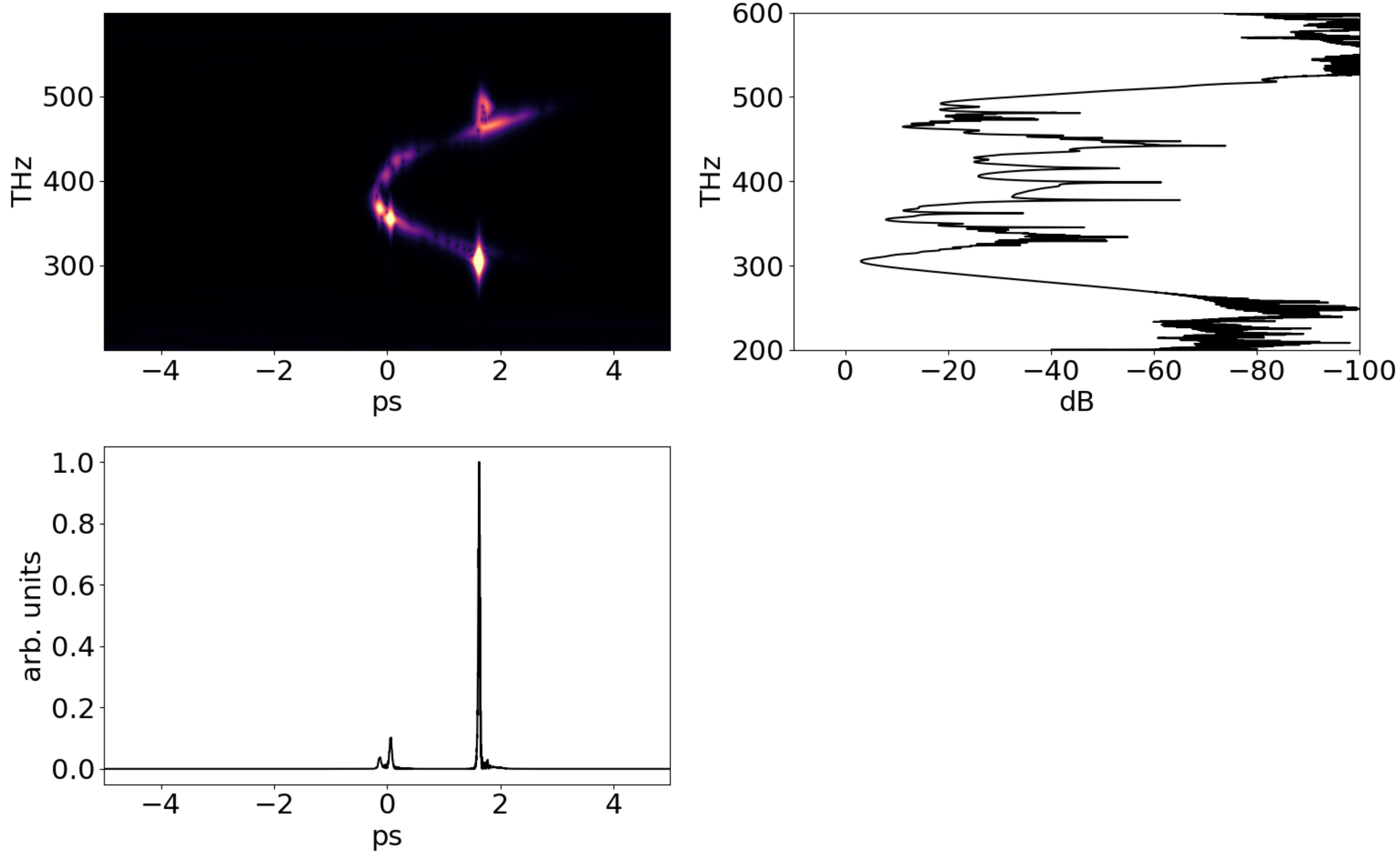


Stable, periodic propagation with ‘breathing’ pulses

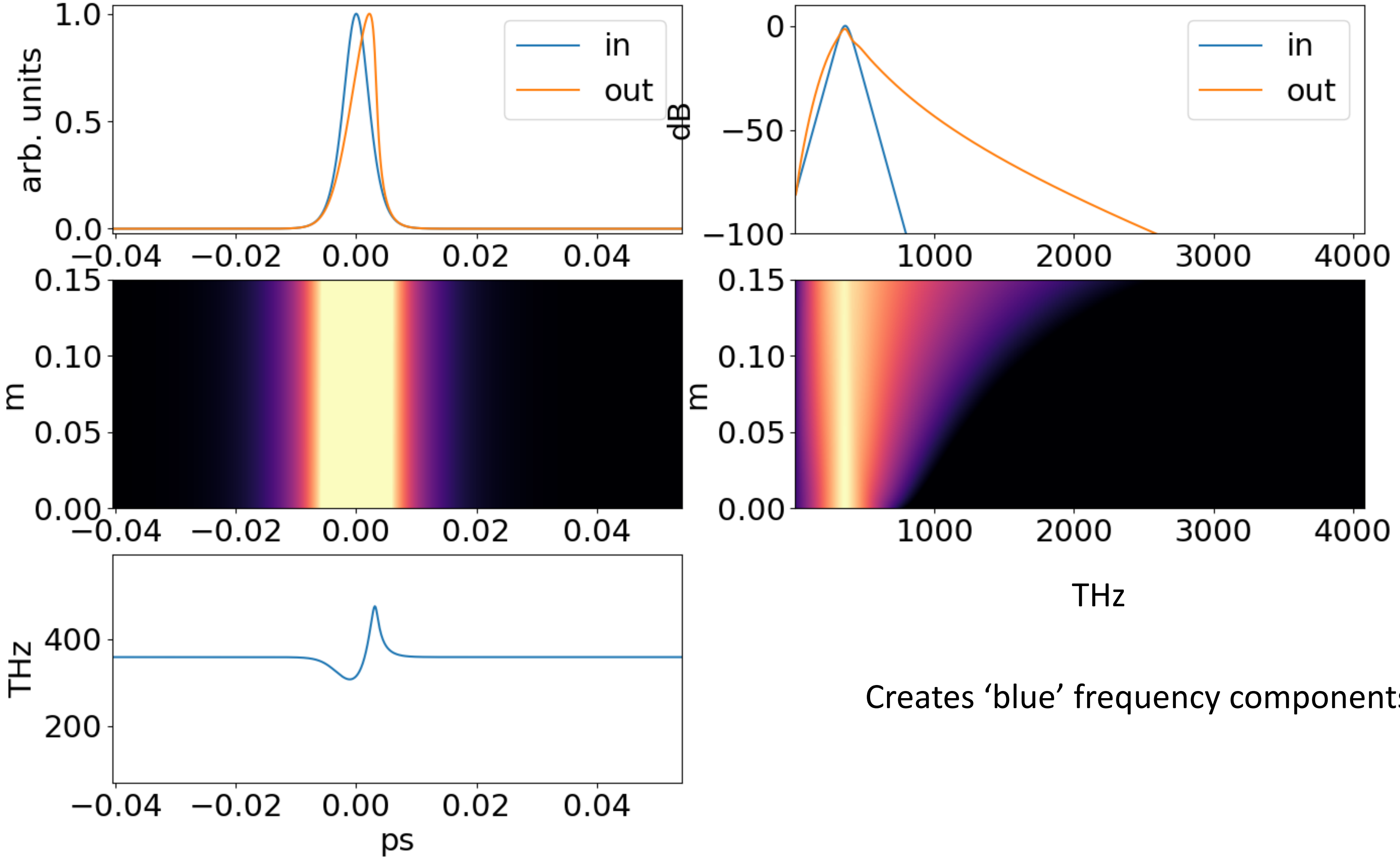
Order 3 Soliton: 50 fs, higher order dispersion, Raman, no self-steepening



Spectrogram:

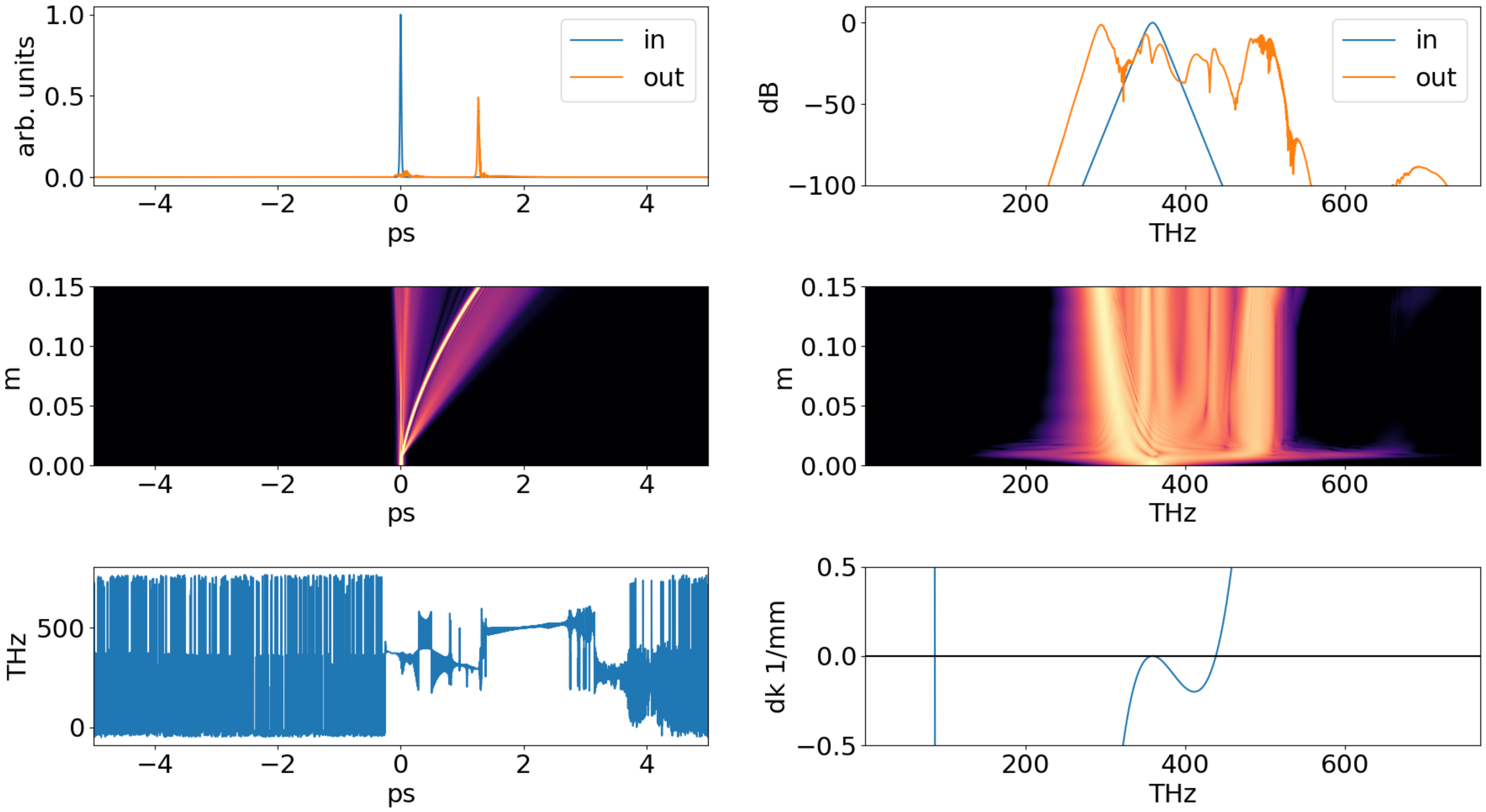


Shock-formation: 5 fs (10% of soliton energy), no higher order dispersion, no Raman, self-steepening

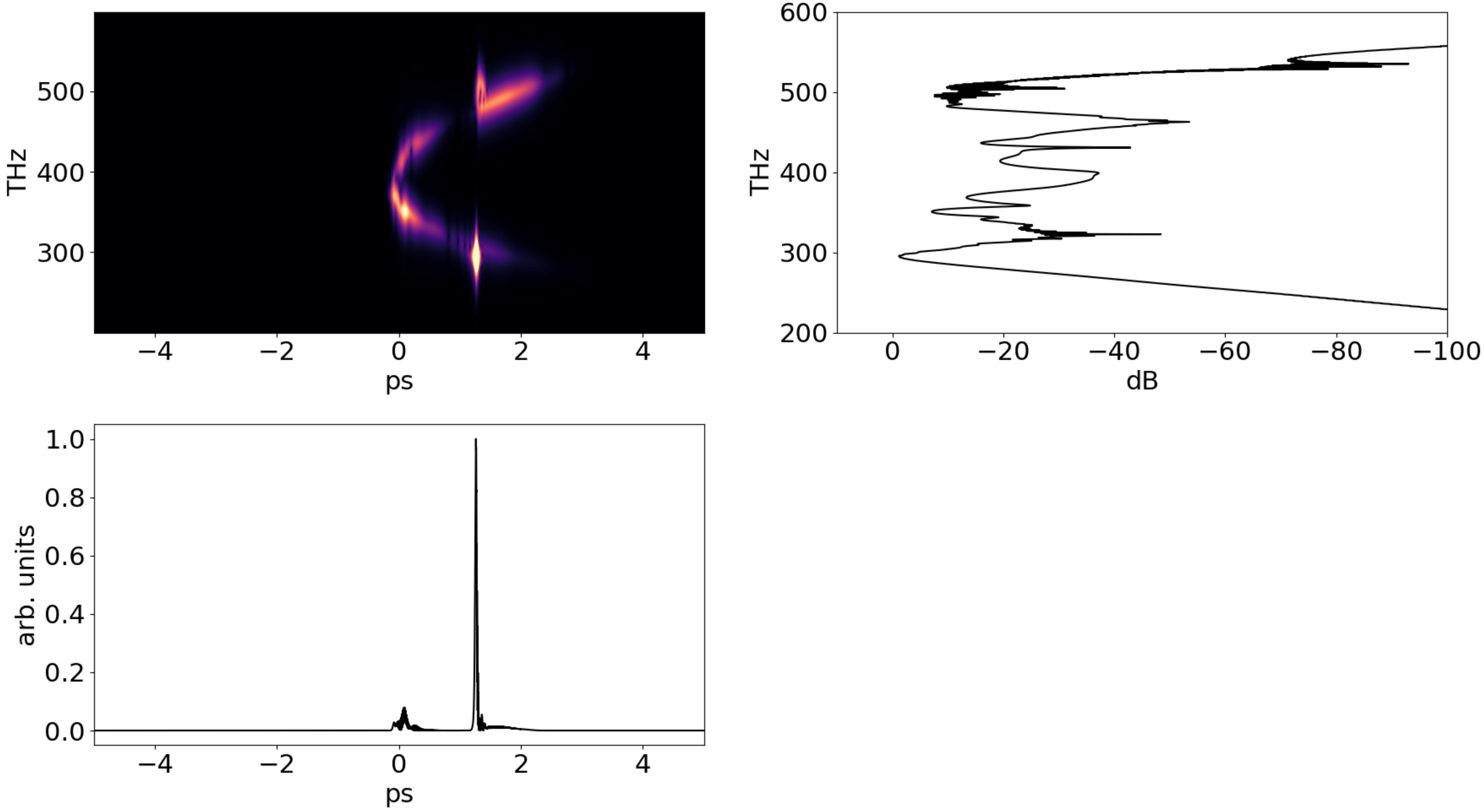


Creates ‘blue’ frequency components

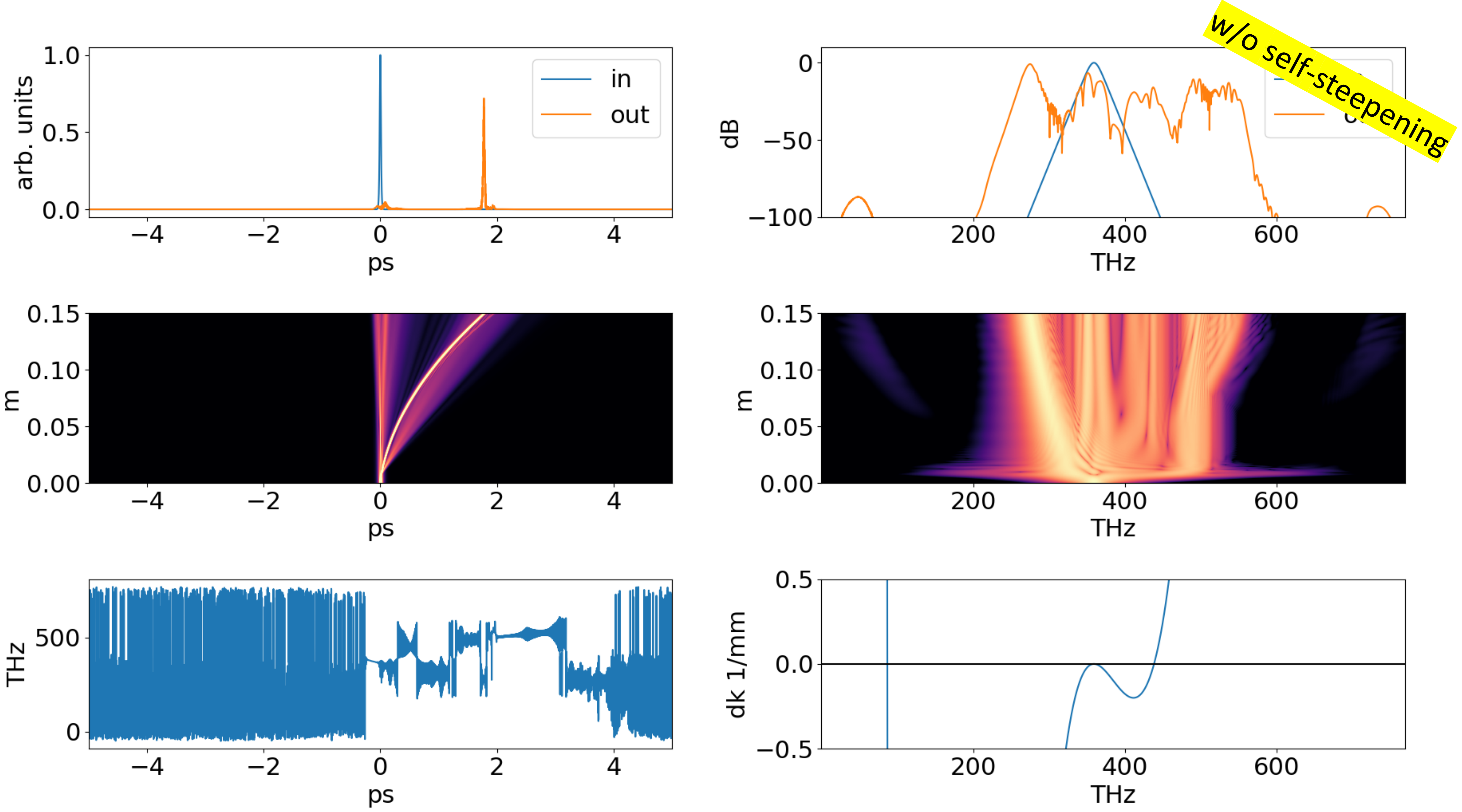
Order 3 Soliton: 25 fs, higher order dispersion, Raman, Self-steepening



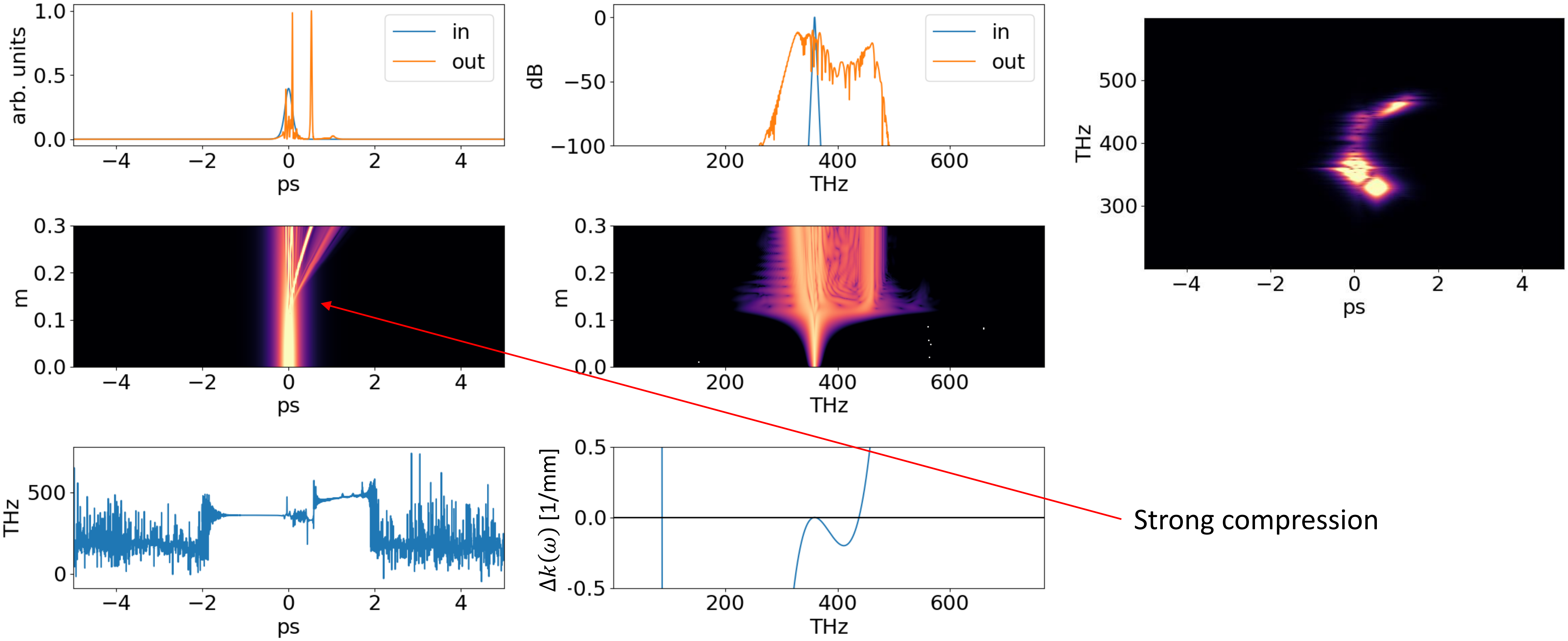
Spectrogram:



Order 3 Soliton: 25 fs, higher order dispersion, Raman, no self-steepening

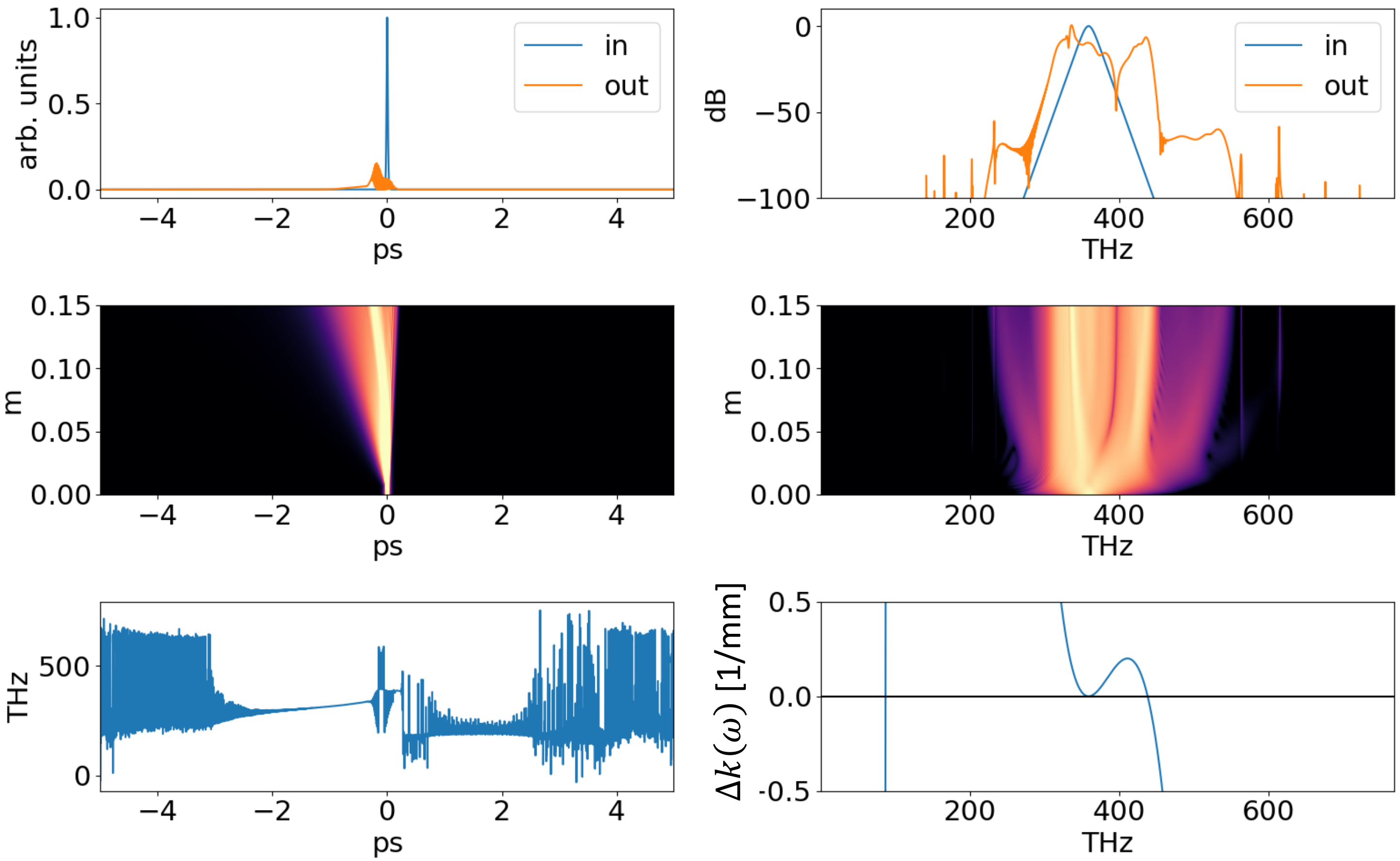


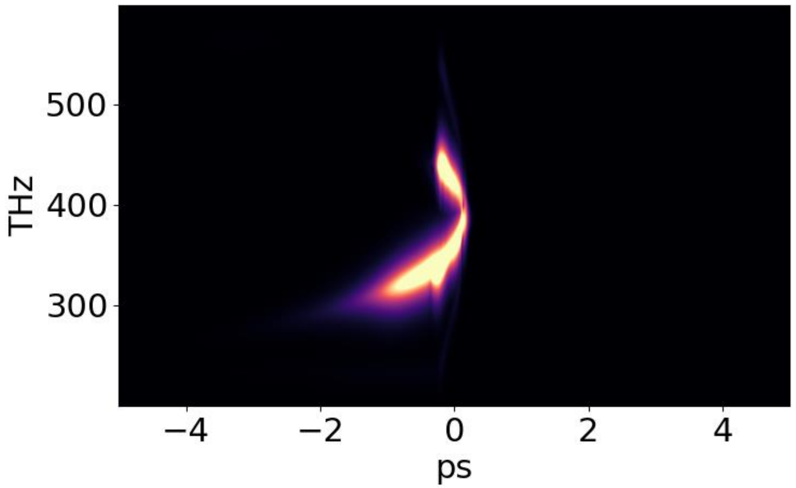
Long Pulse above soliton energy: 200 fs, higher order dispersion, Raman, Self-steepening



Equivalent to order 3 Soliton but normal GVD

15 fs, higher order dispersion, Raman, no self-steepening

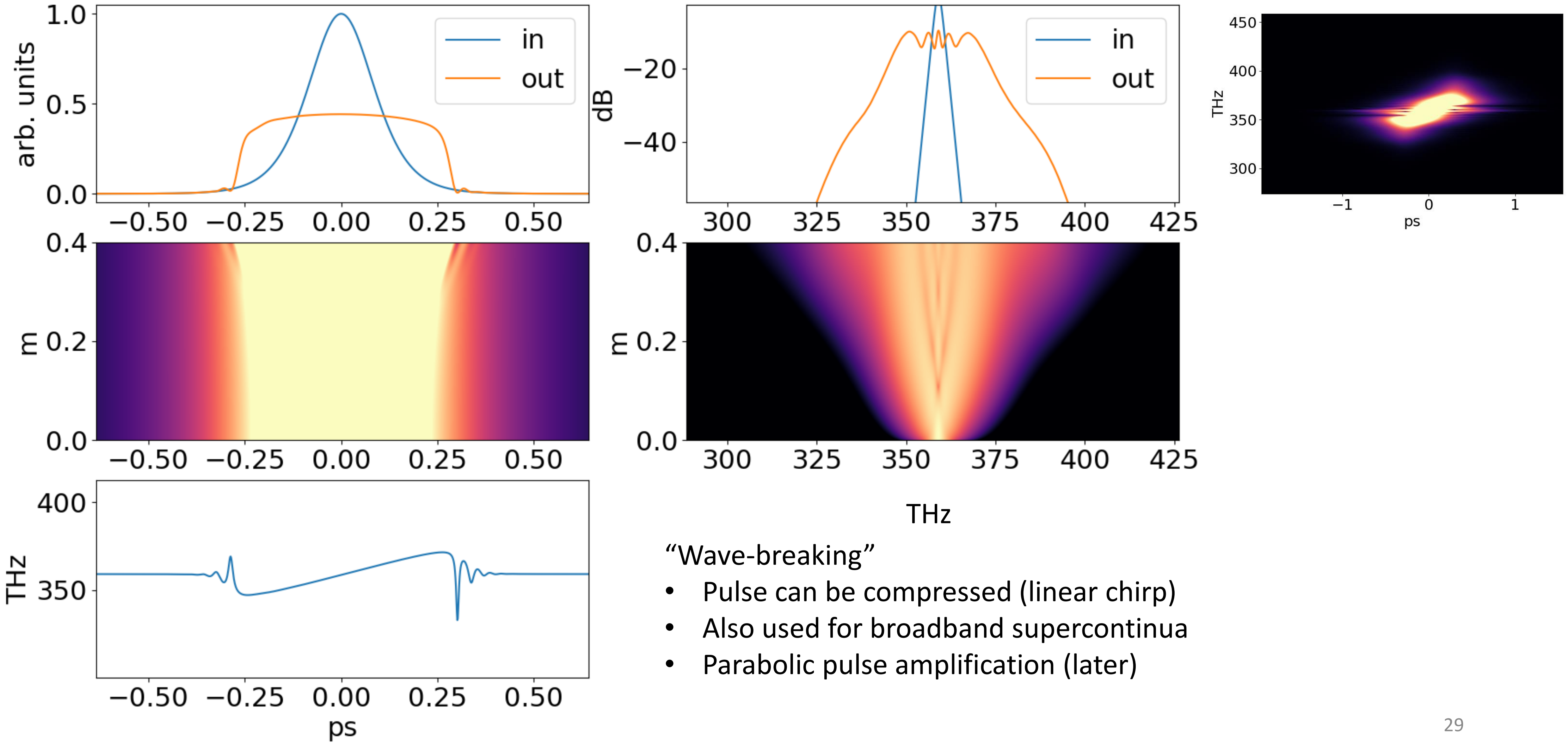




Spectrum is much narrower

Equivalent to order 3 Soliton but weak normal GVD

15 fs, no higher order dispersion, Raman, no self-steepening



“Wave-breaking”

- Pulse can be compressed (linear chirp)
- Also used for broadband supercontinua
- Parabolic pulse amplification (later)

Summary Supercontinuum Generation

Supercontinuum generation mostly <u>driven by solitons and related effects</u>:

- Soliton formation and compression (via SPM and dispersion/ higher-order solitons)
- Soliton fission (due to Raman and higher order dispersion)
- Soliton propagation, dispersive waves and some self-steepening
- Different mechanism for ps-pulses and continuous-wave pump (not generally coherent!)