Ultrashort Pulse Generation and Superradiance in FELs

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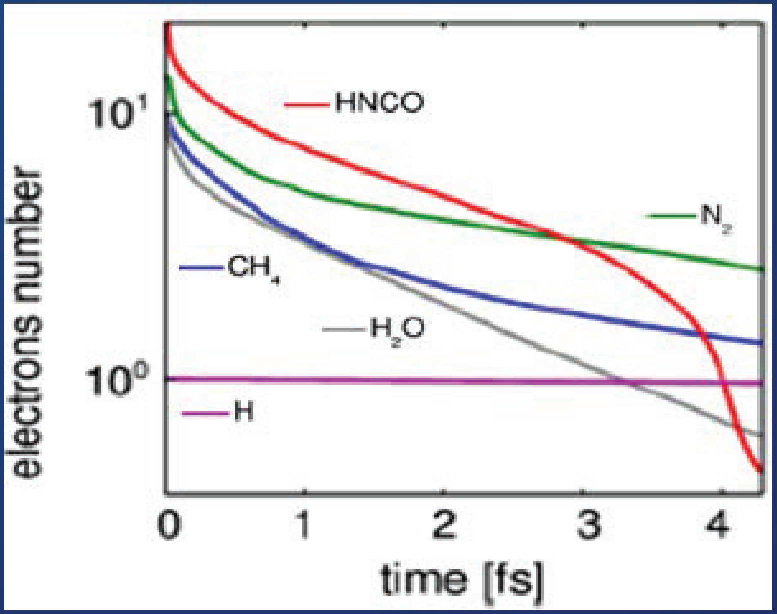
Outline

- Peak power and pulse duration limits in FEL amplifiers
- Methods to achieve single spike at saturation
- Saturation effects
  - Pulse shortening & power increase
  - Pulse splitting and tail formation after saturation
- Tail structure
  - FEL pulse splitting into head (L_+) and tail (L_-) modes after saturation
- Tail suppression

Motivation: Single-Shot Isolated-Molecule Imaging

- Key issues:
  - Time scale (sub-fs): Acquiring single shot images before radiation damage/Coulomb explosion of the sample takes place
  - Spatial resolution: Resolving the structure of proteins that cannot be crystallized in single-molecule level
  - High Intensity: **$1.3 \cdot 10^{11}$** photon/pulse at P=150 GW, λ=0.4 nm with $\sigma_{t\text{-}FWHM}$= 400 as
- Such conditions can be met by XFEL with peak power of multi-GW and sub-femtosecond temporal duration

Number of "bounded" electrons versus time of molecules illuminated by XFEL radiation with power P =150 GW and λ = 0.4 nm



A. Fratalocchi and G. Ruocco PRL 106, 105504 (2011)

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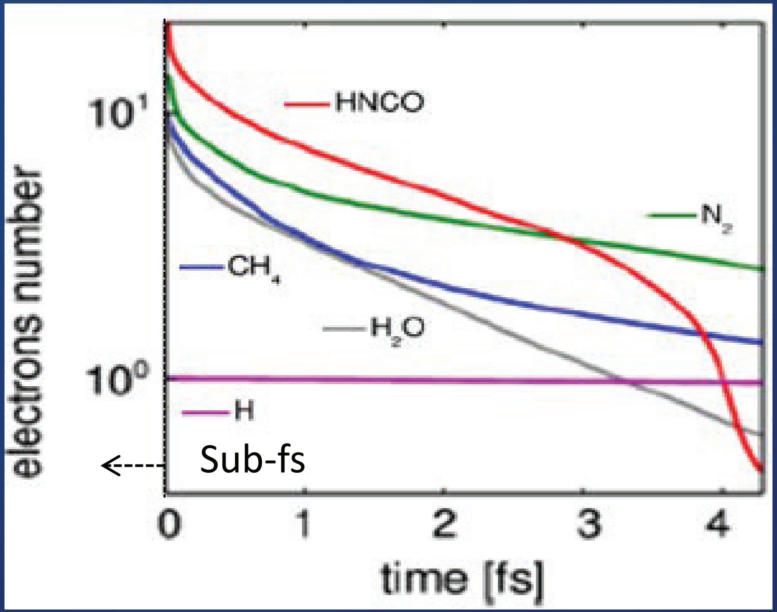

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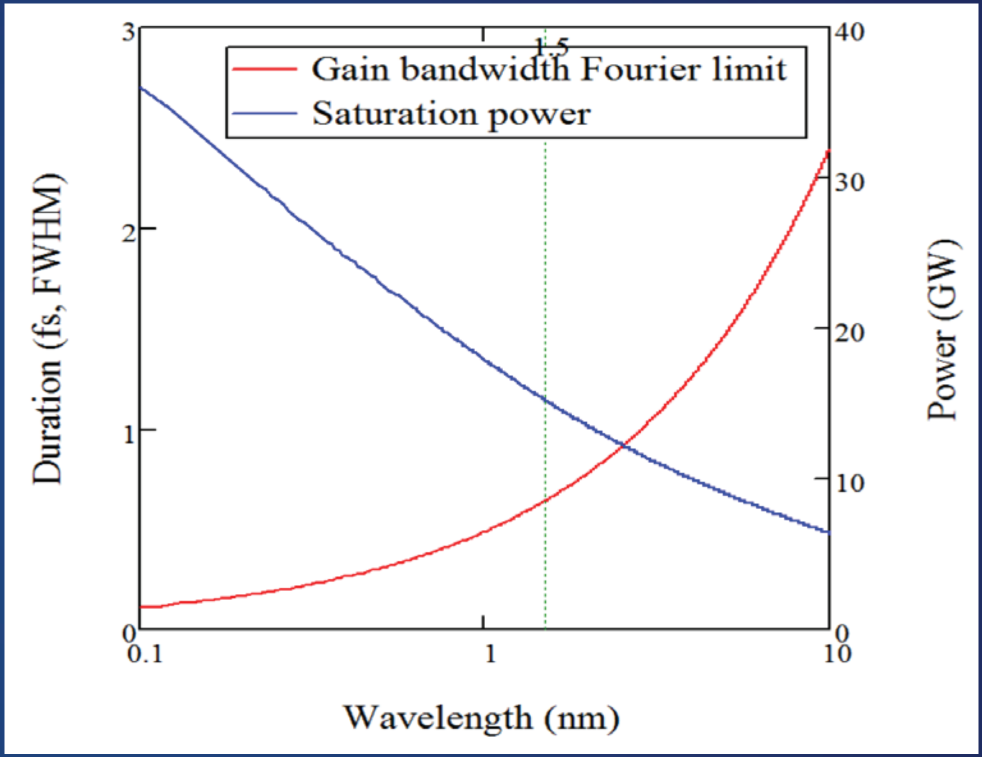
PRL 106, 105504 (2011)

Single spike:Peak Power and Pulse Duration Limits at FEL Saturation (no taper)

- Limit by saturation:
  - Power 20 to 40 GW at $\lambda = 0.1$ nm
- Limit by gain bandwidth
  - Pulse duration down to 100 as (FWHM)
- In order to meet the sub-fs –multi-GW (*tens of*) of peak power we get close to the gain bandwidth limit and to saturation
- It is possible to get to this condition



- Period 3.3 cm
- K = 3.5
- ε_n = 0.5 mm-mrad
- Reasonable assumptions of I_{pk} and β
- L. H. Yu, S. Krinsky, Phys. Rev. A. 35 3406-3422 (1987)
- M. Xie LINAC 1995

Methods to Achieve Single Spike at Saturation

- A few ways to trigger the formation of a single spike :
  - Short electron bunch single spike
    J. Rosenzweig et al, NIMA 593(2008)
  - Chirp + Taper
    200 as (FWHM) and 100 GW in λ~1Å (sim) **E. Saldin et al, PRST-AB 9, 050702 (2006)**
    E_{out} increases >10 times in single spike SASE at λ~ 540nm (exp) **L. Giannessi et al, PRL 106, 144801 (2011)**
  - Slotted foil
    Sub-fs 10GW x-ray pulse **P. Emma et al. PRL 92, 074801 (2004)**
  - Multi-foil + Electron Delay
    500as (FWHM) and 1TW at λ~1Å (sim) **E. Prat and S Reiche PRL 114, 244801 (2015)**
  - Fresh bunch self-seeding
    50 GW, 9 fs at 5.5keV **C. Emma et al, APL 110, 154101 (2017)**
  - Chirp + Taper + Fresh bunch self-seeding
    0.5TW and 260as (FWHM) at λ=1.5nm **S. Huang et al, PRAB 19, 080702 (2016)**
- When the short pulse reaches saturation -> superradiance

Saturation of the single spike

- When the peak power exceeds ρP_e

⬇

- Superradiance*
  - Modification of the pulse properties due to the electron longitudinal synchrotron oscillations.
  - Scaling relations**: $P_L \propto z^2, \;\; E_L \propto z^{3/2}, \;\; \sigma_t \propto z^{-1/2}$

*R. Bonifacio, B. W. J. Mc Neil, P. Pierini, PRA 40, 4467 (1989)
R. Bonifacio, L. De Salvo Souza, P. Pierini, N. Piovella, NIM A296, 358 (1990)

** see: L. Giannessi, P. Musumeci, S. Spampinati, JAP 98, 043110 (2005)

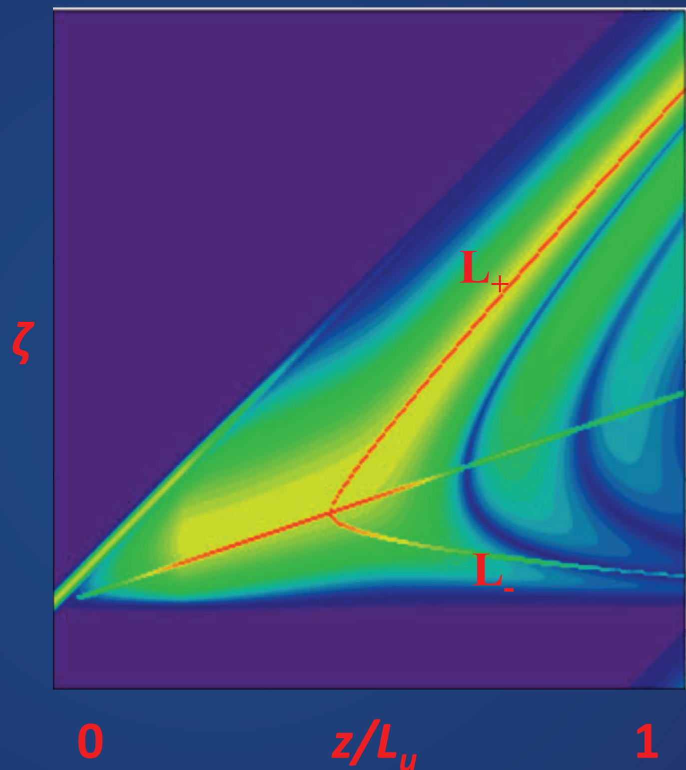
Experiments: Watanabe et al. PRL 98, 034802 (2007)
SPARC, Frascati: PRL 106, 144801 (2011) – PRL 108, 164801 (2012) – PRL 110, 044801 (2013)

MOVIE 1 AND MOVIE 2

What happens when single spike reaches saturation

Pulse Splitting and Tail Formation

- Local saturation condition is met
- P_{sr} exceeding saturation and increasing as $\propto z^2$
- σ_t shortening as $\propto z^{-1/2}$
- It is desired to get into the superradiance regime (indicated by L_+) with higher power and shorter pulse length
- Once getting into the saturation, the tail is formed
- The pulse length is determined by the structure between **L+ and L-,** both from the same origin of pulse splitting.



$\tau = z/L_u$

Longitudinal profile of the radiation field amplitude along the e- beam coordinate ζ as it propagates along the undulator with coordinate τ

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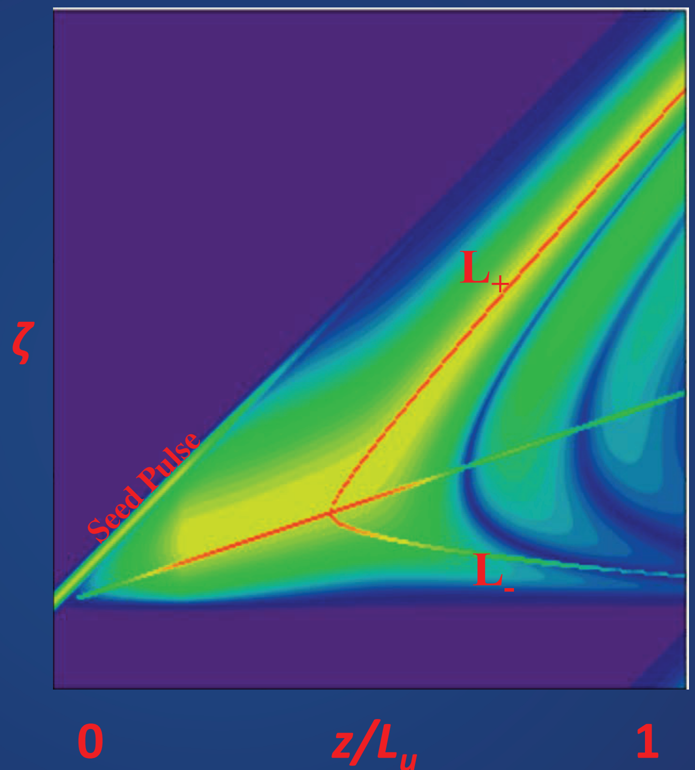

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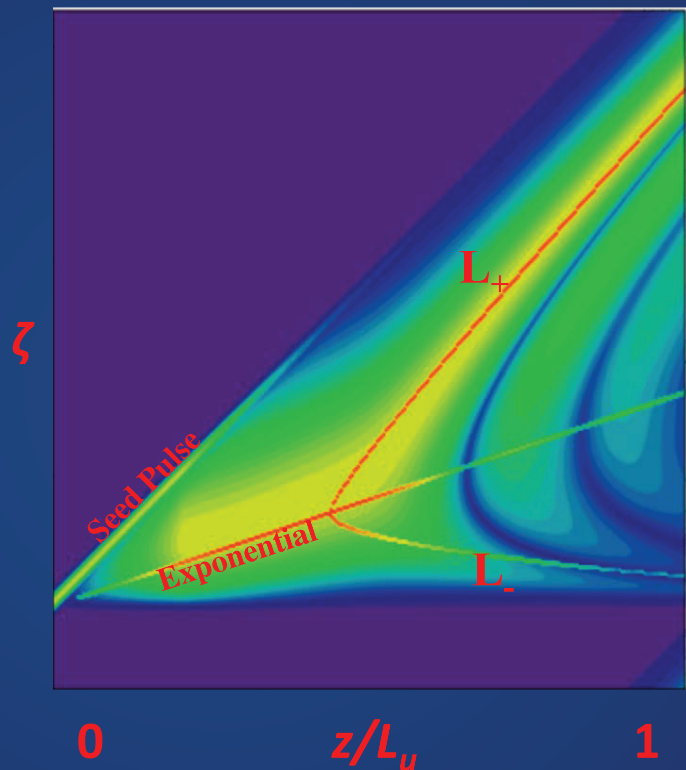

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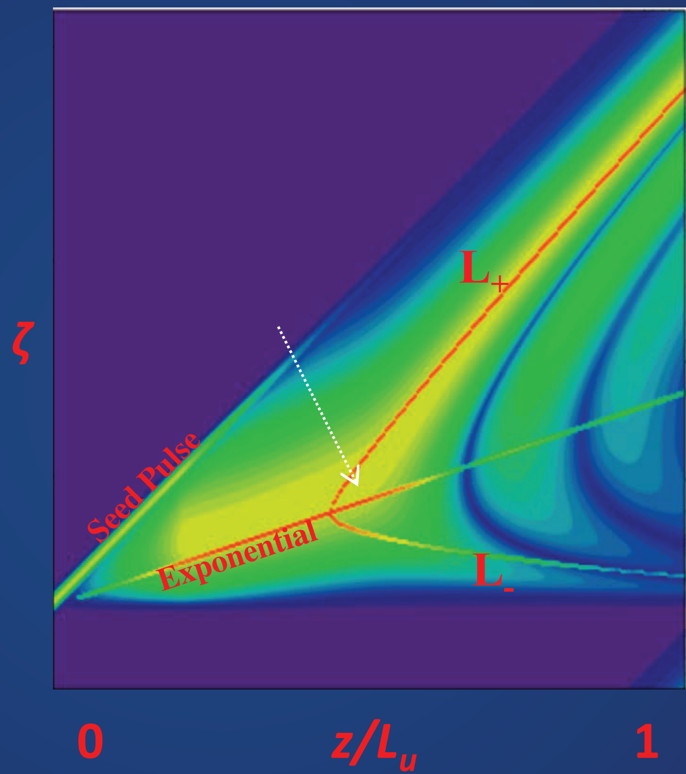

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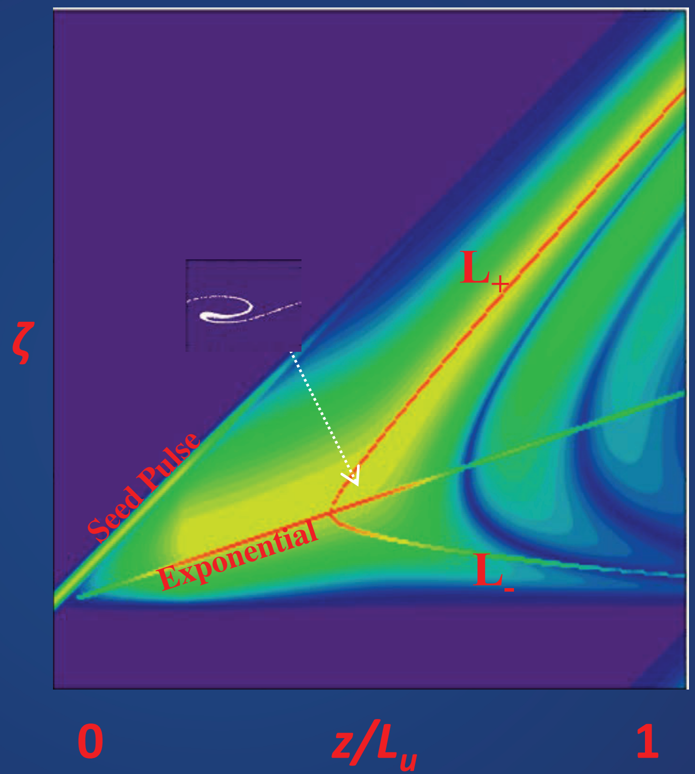

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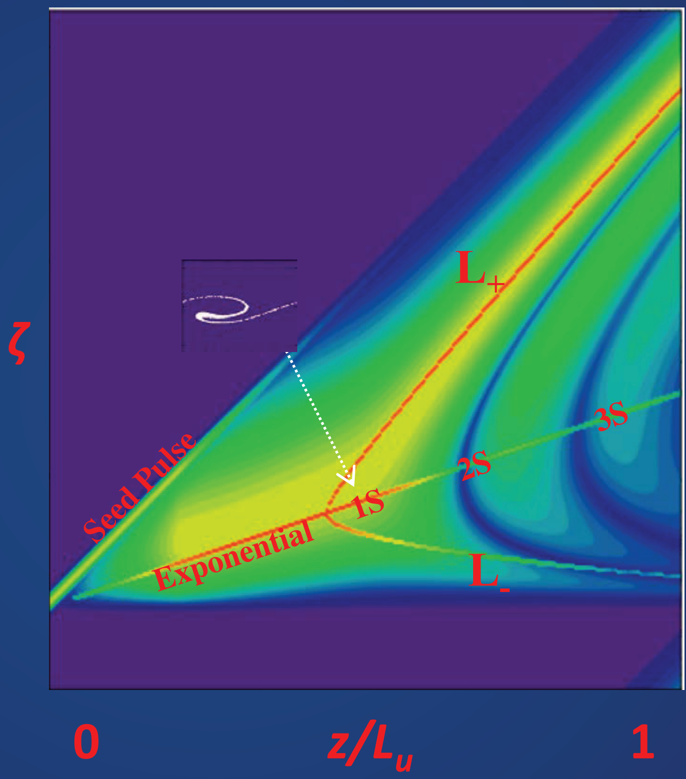

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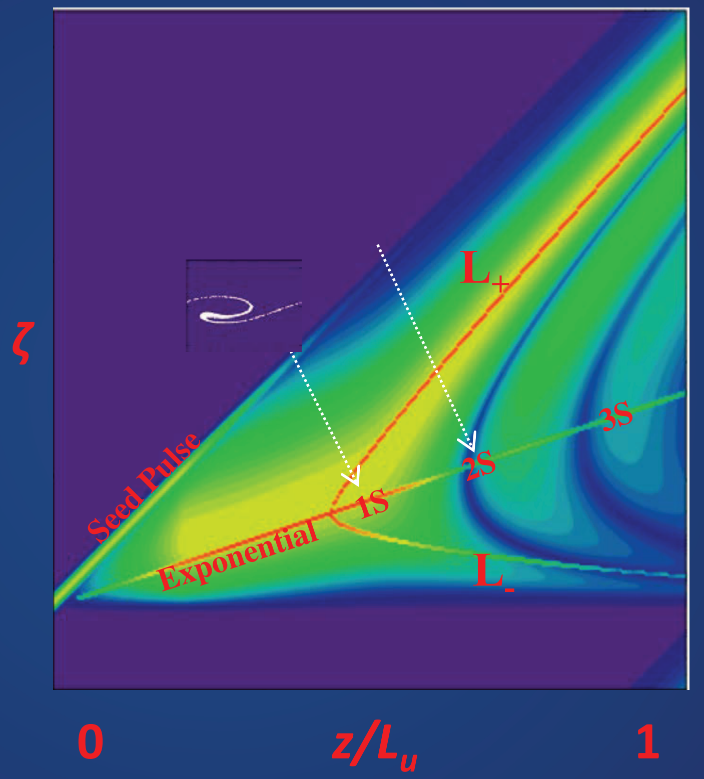

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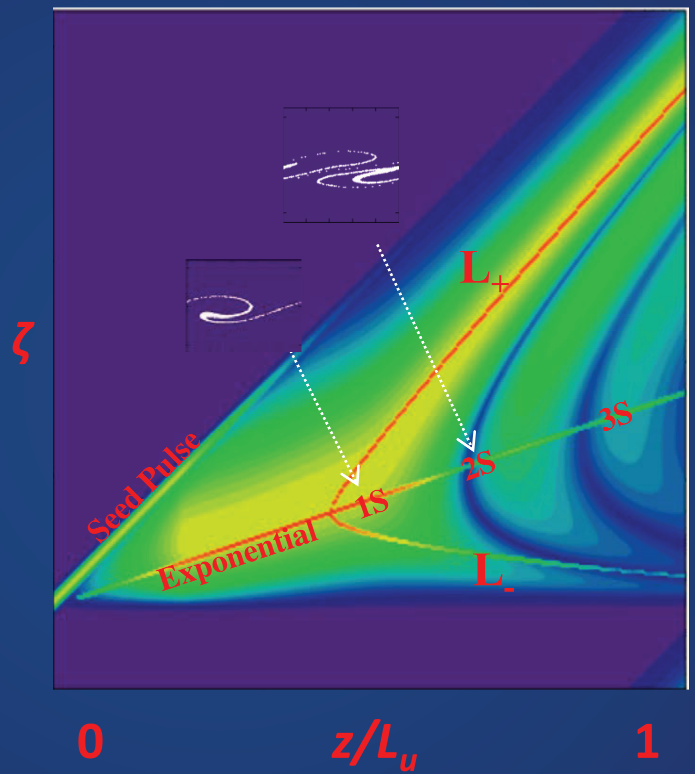

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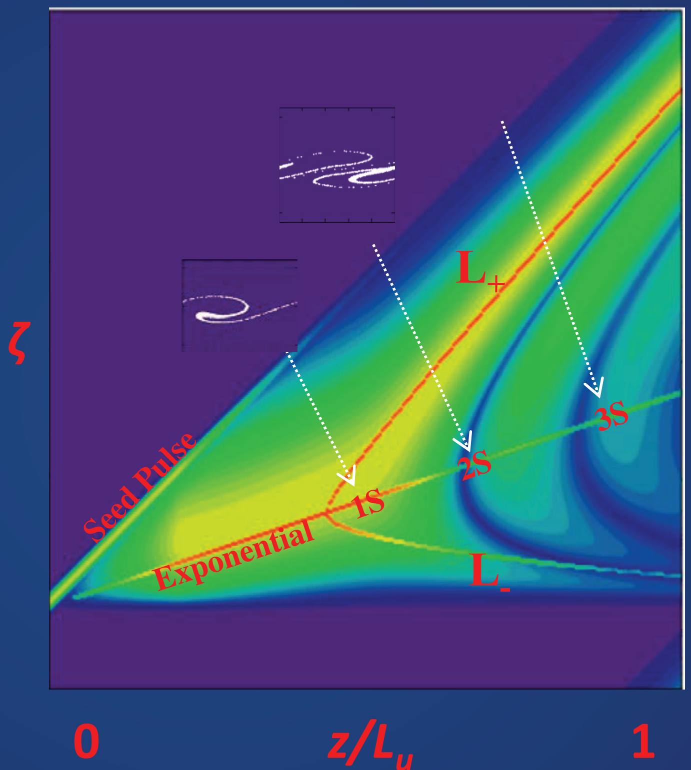

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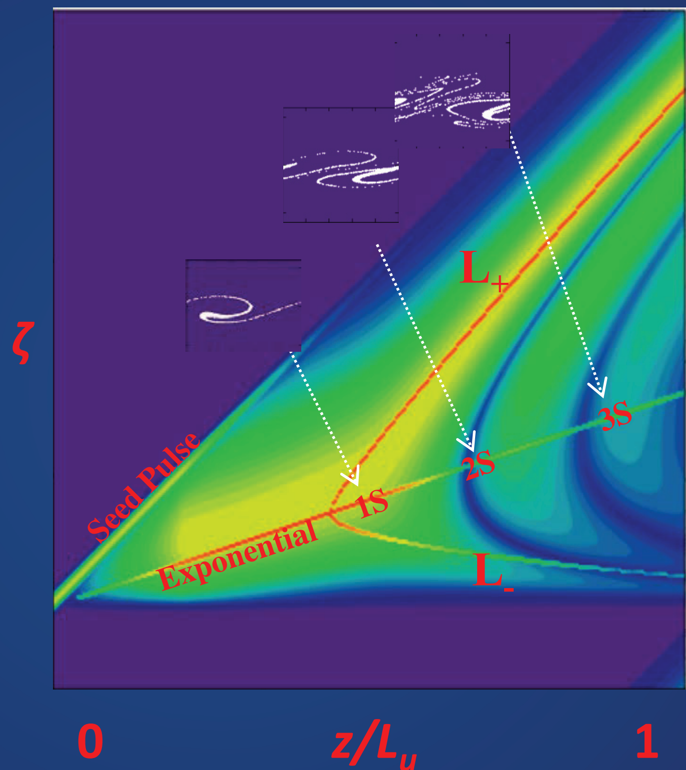

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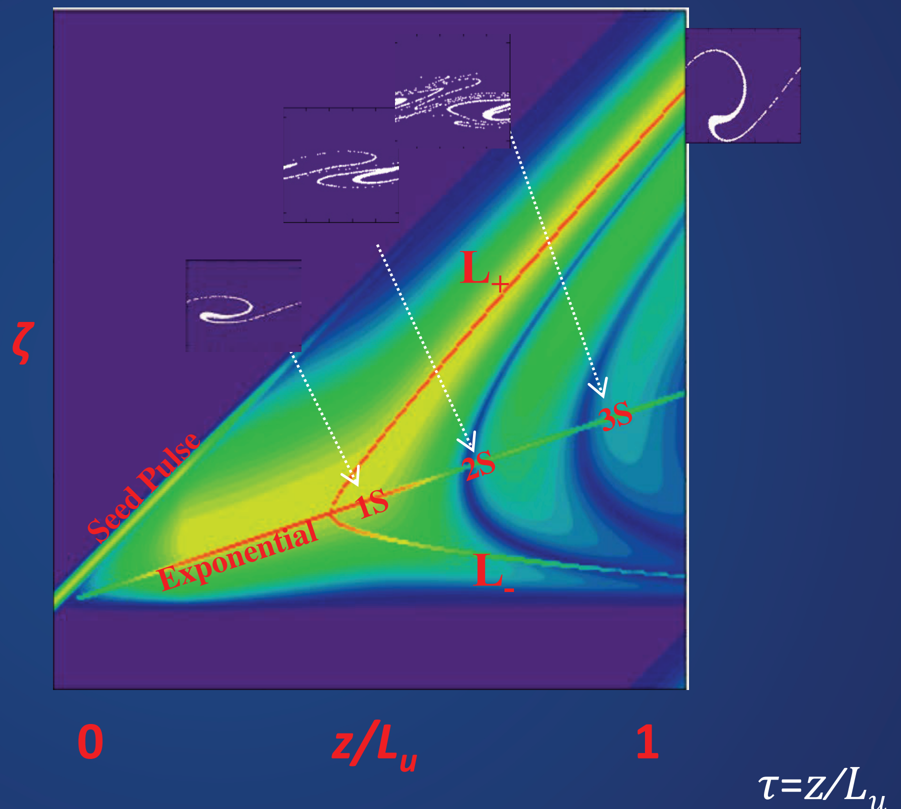

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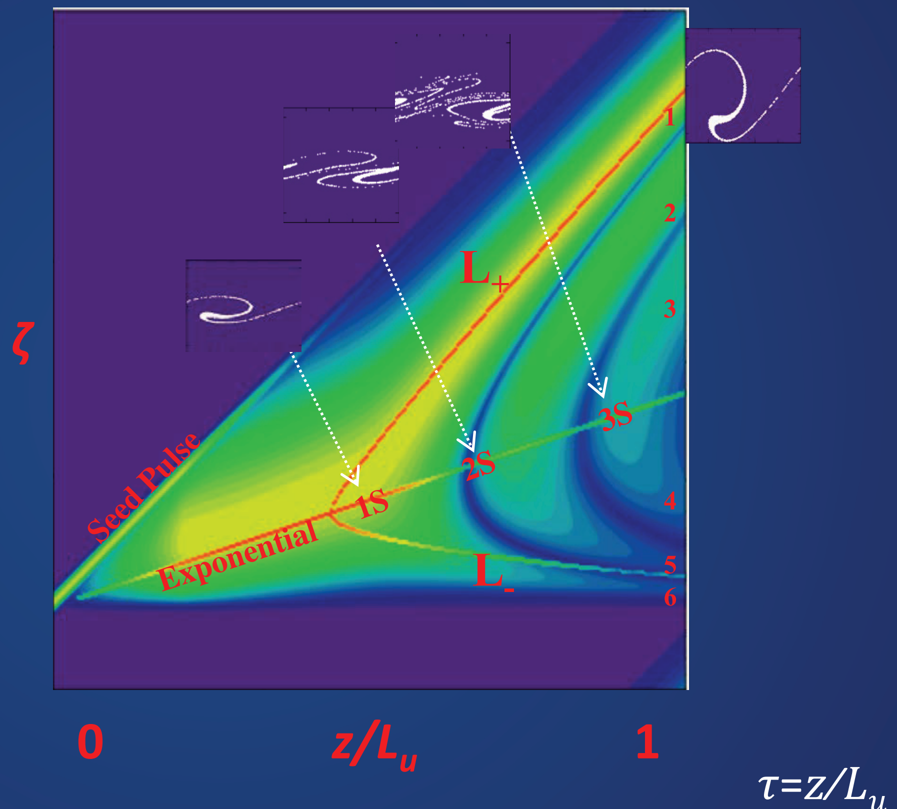

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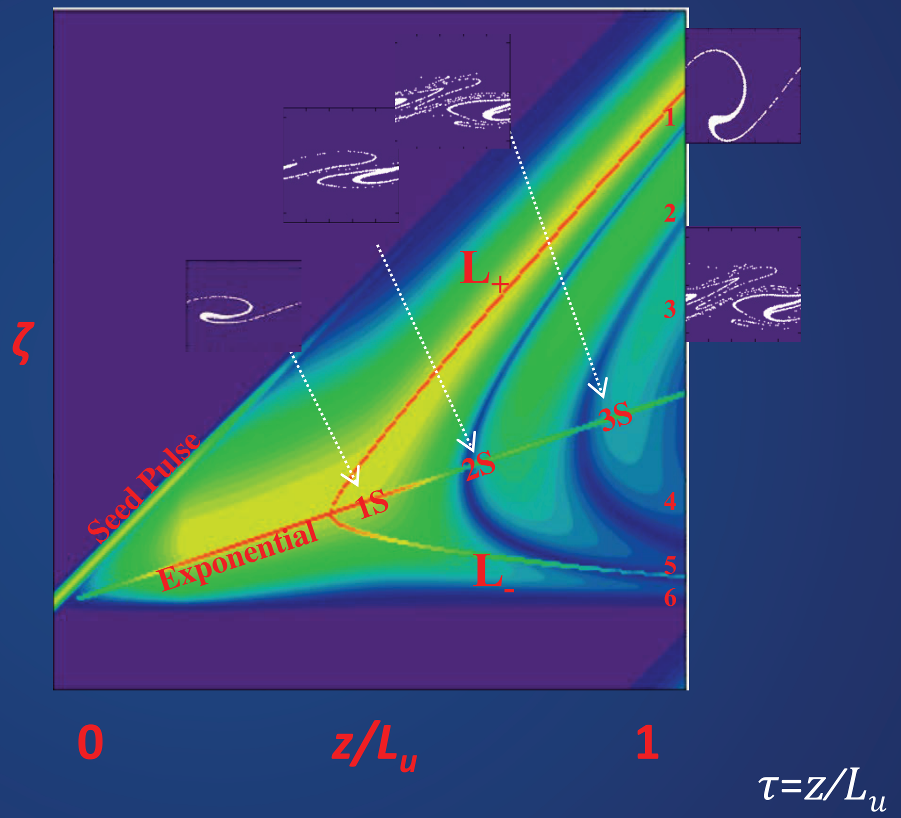

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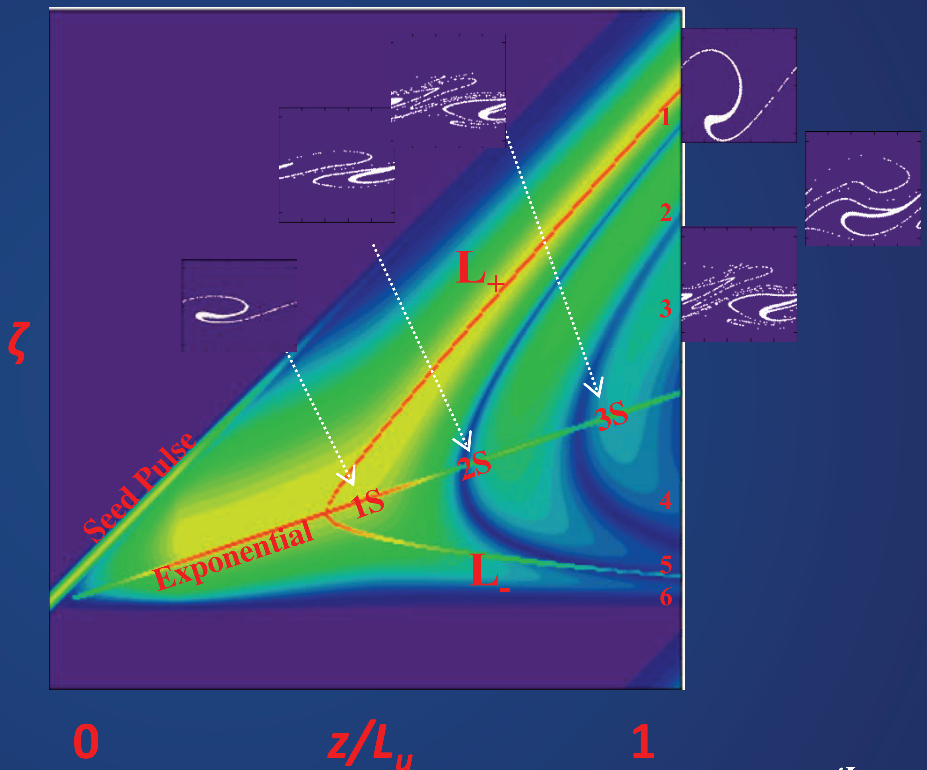

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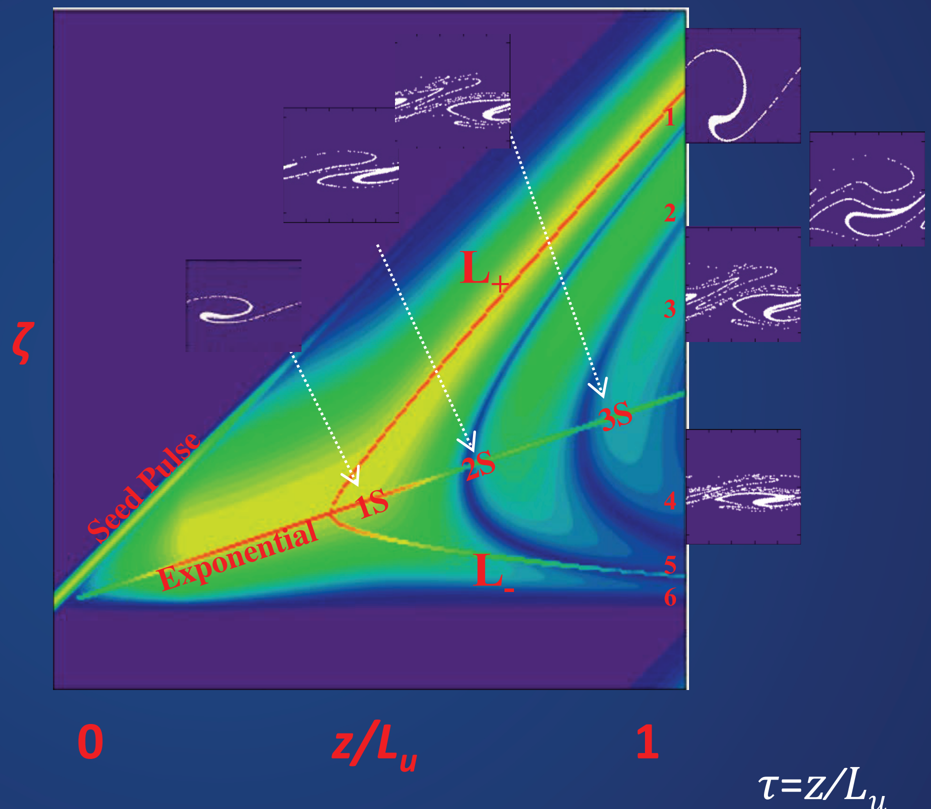

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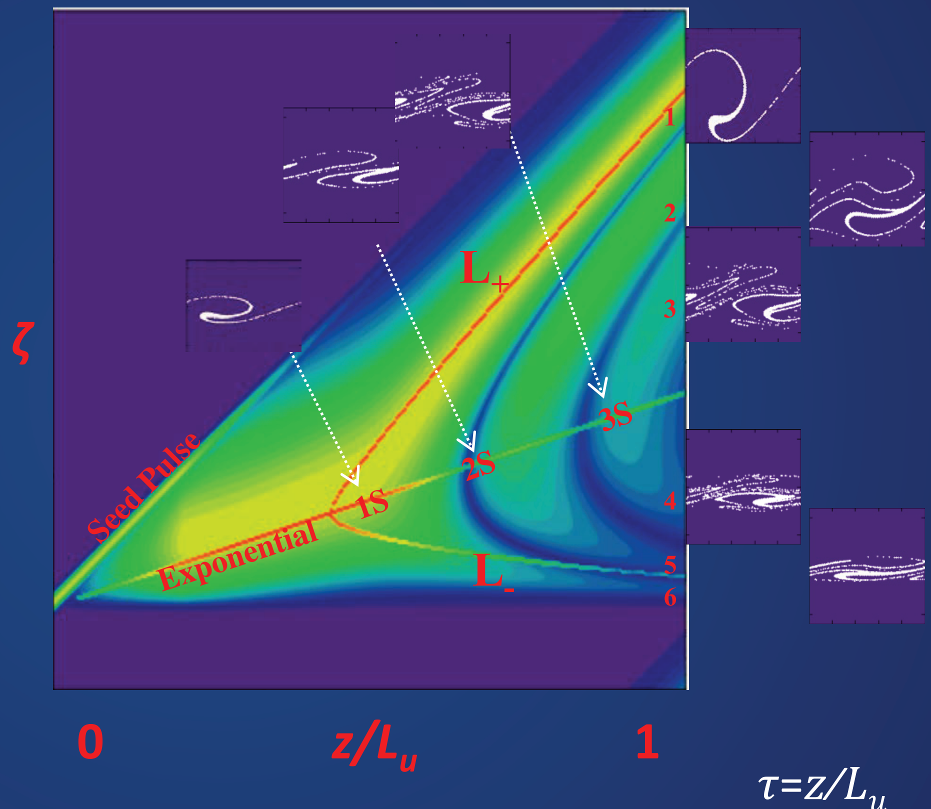

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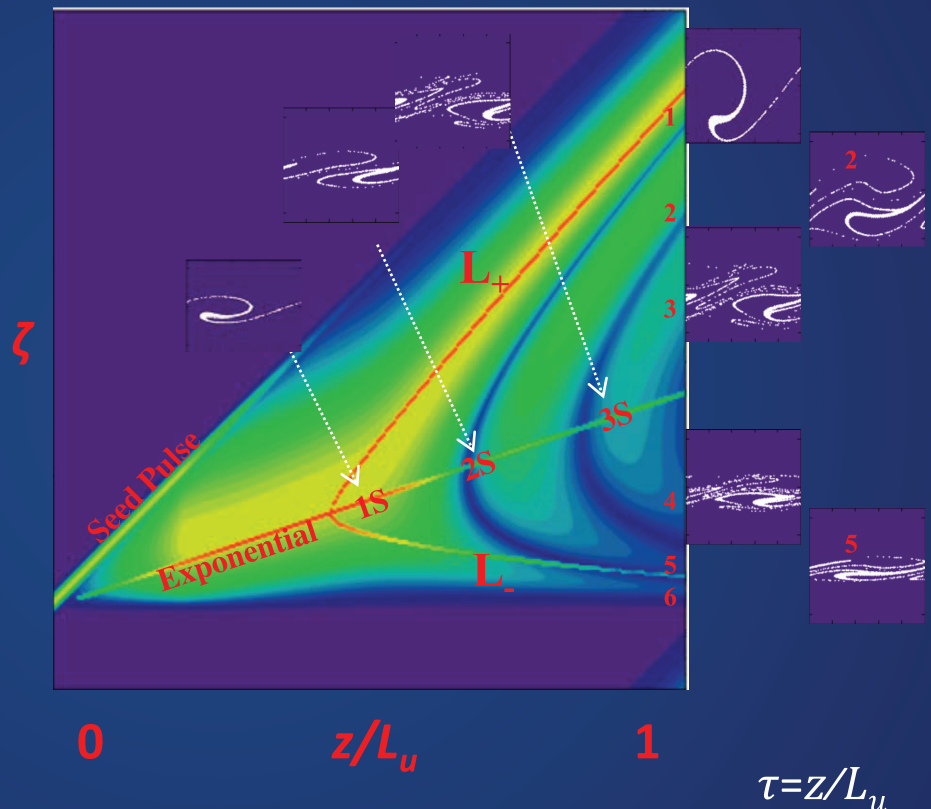

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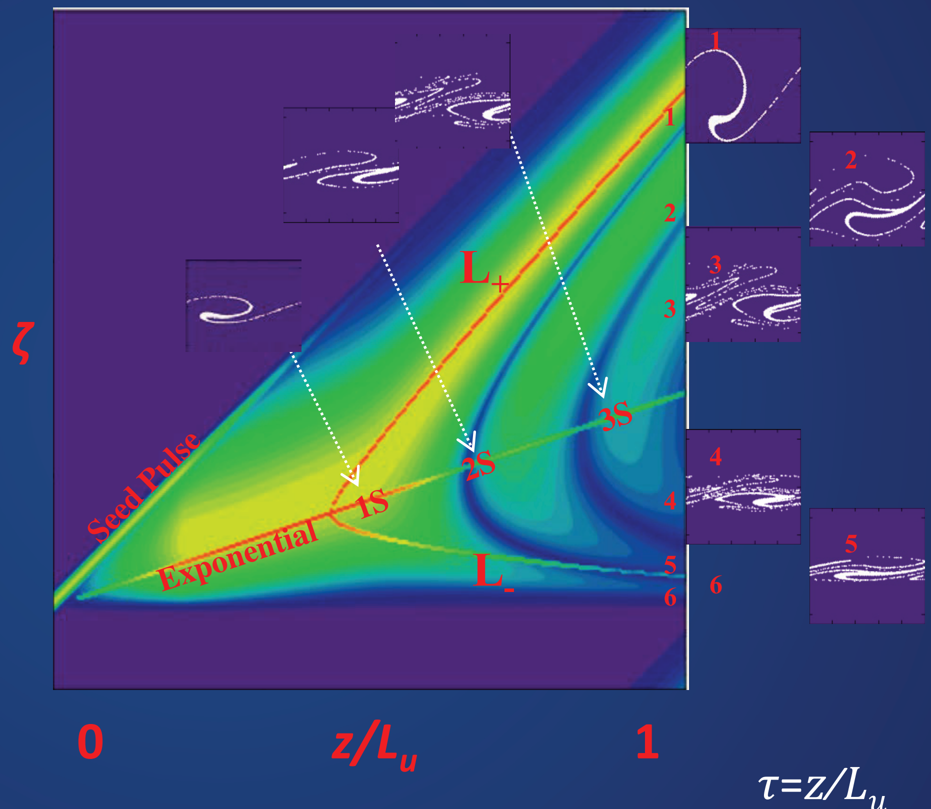

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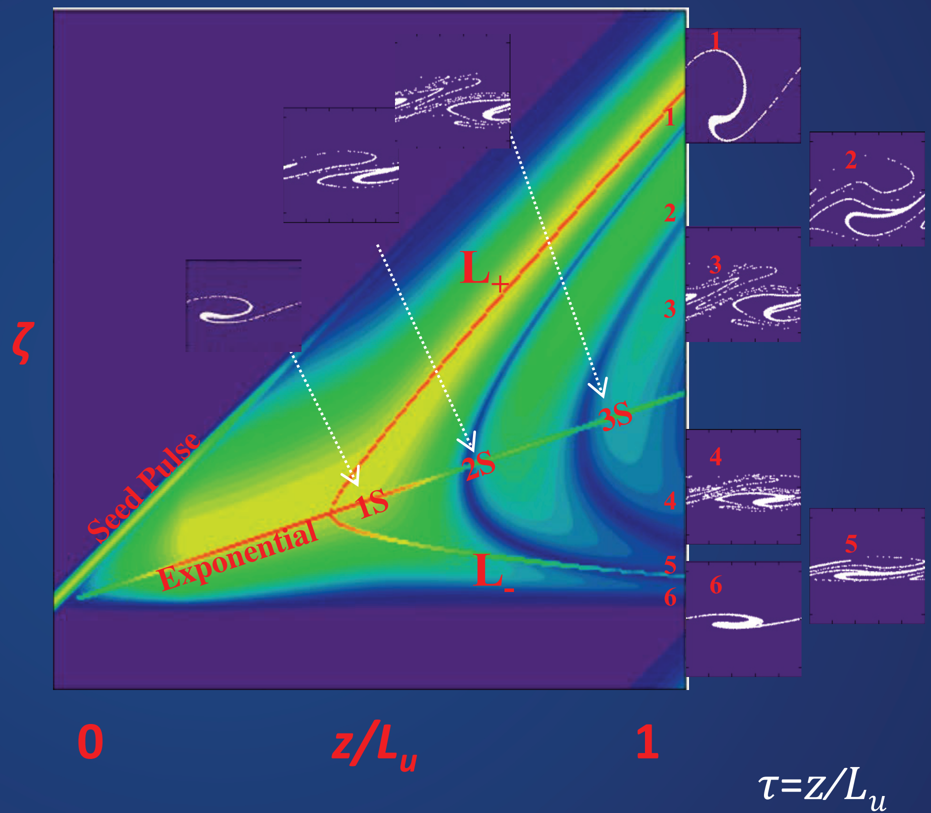

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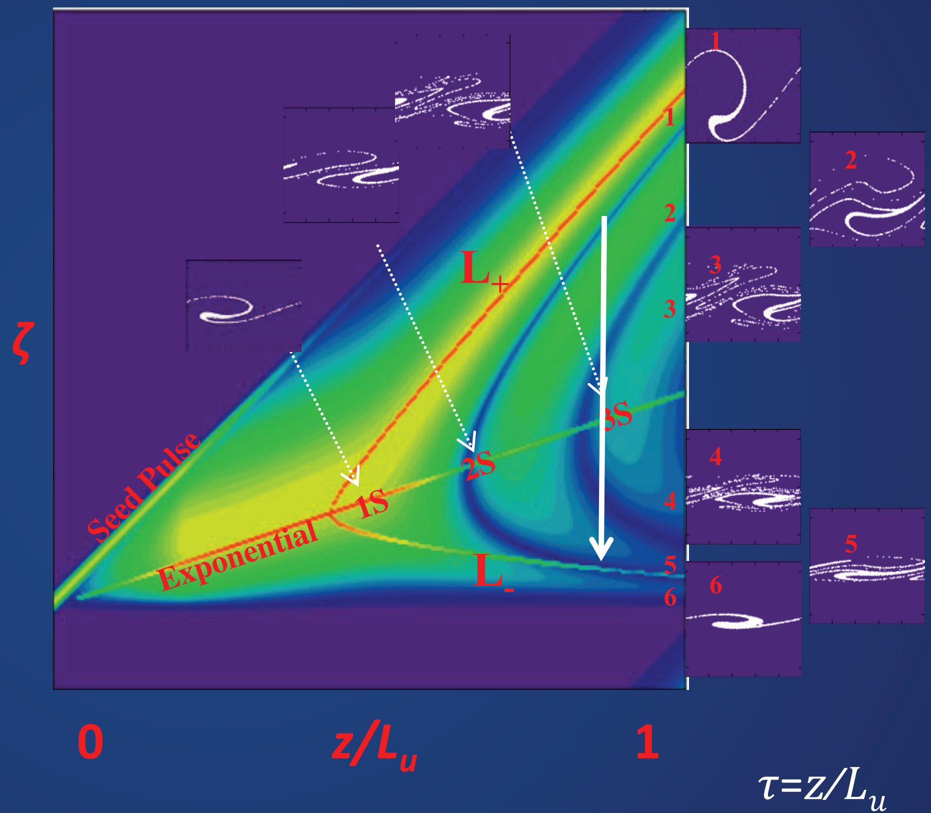

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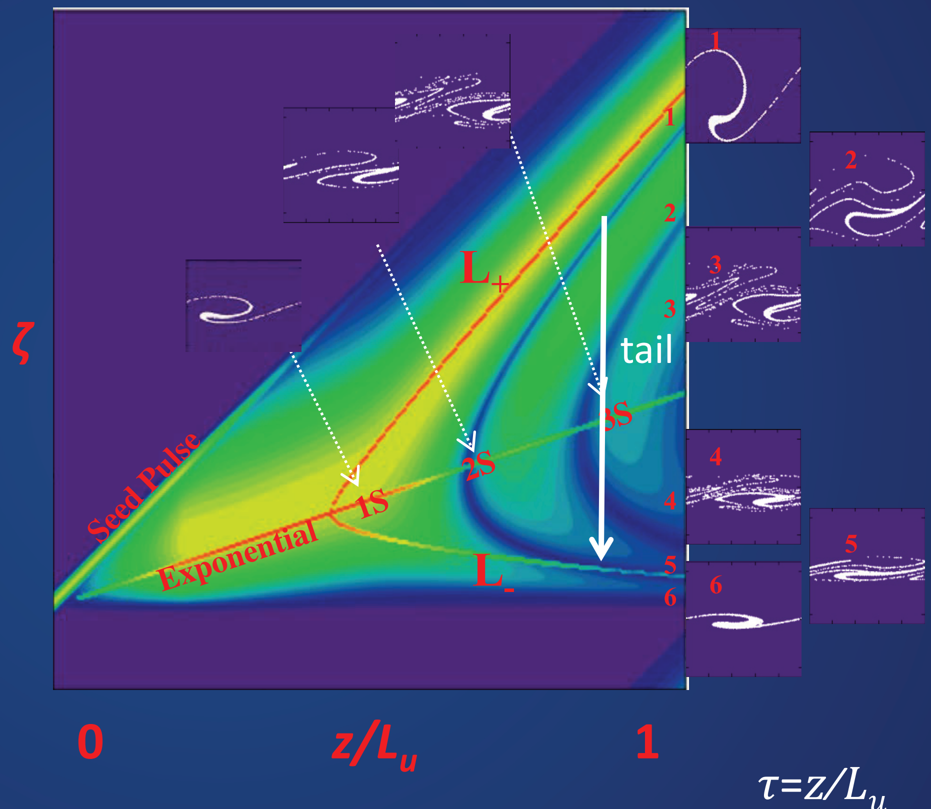

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Single electron FEL

Notes

- Pulse duration is determined by the slippage distance over ½ synchrotron period, i.e. ½ the Fourier limit of a pulse with bandwidth ρ

- Secondary peaks induced by residual bunching
- Peak amplitudes decaying with beam energy spread
- Phase shift of π between peaks
- Secondary peak in the tail, the trailing edge is still reaching saturation

- Peak propagation speed … see next

Peaks position

Condition for saturation $P(z) = P_0 \exp\left\{ -\frac{[\zeta - vz]}{2\sigma_\zeta^2} + \frac{z}{L_g} \right\} = P_s \simeq 1.6\,\rho_{fel} P_E$

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Peak velocity

$$v = \left\{ \begin{array}{c} v_e = \lambda_0/3\lambda_u \\ v_s = \lambda_0/\lambda_u \end{array} \right.$$

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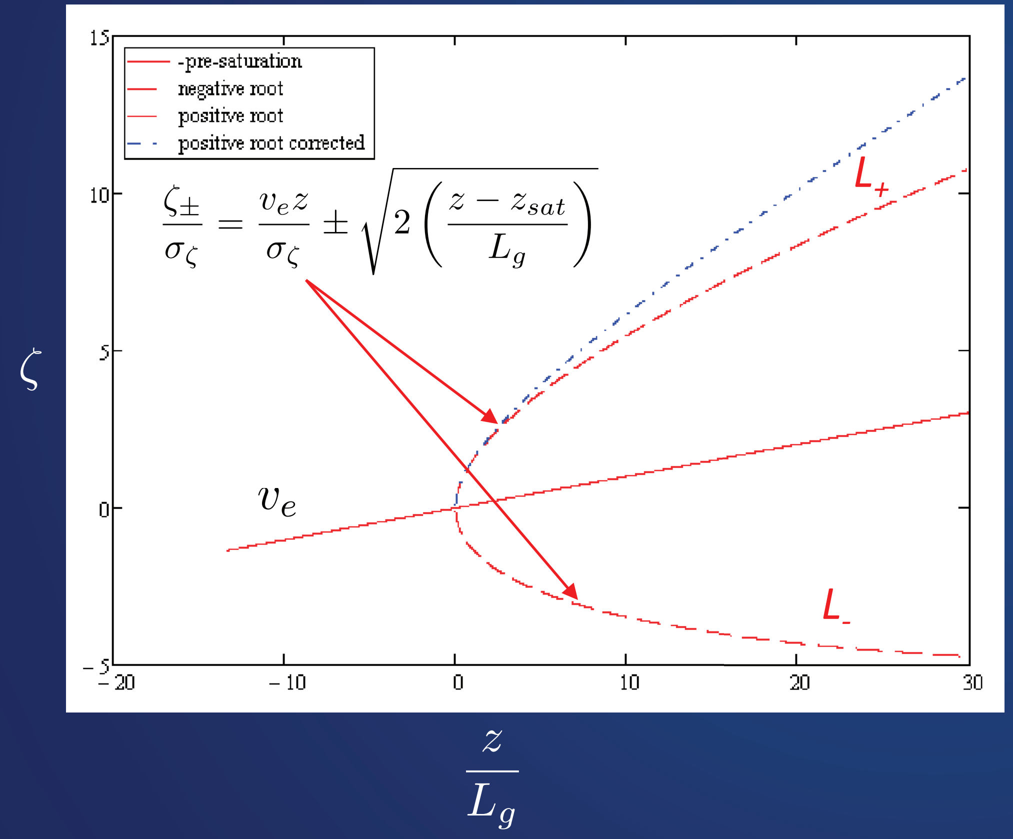
Two roots are plotted as solid lines indicated by L_+ and L_-



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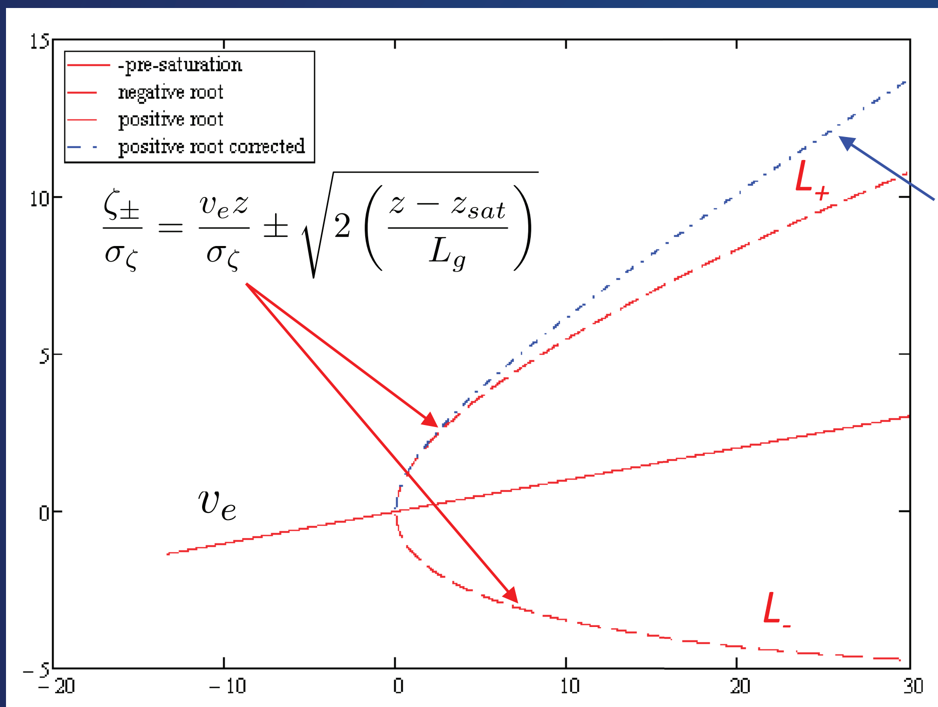


ζ

$\frac{z}{L_g}$

Peak velocity

$$v = \begin{cases} v_e = \lambda_0 / 3\lambda_u \\ v_s = \lambda_0 / \lambda_u \end{cases}$$

$$\frac{\zeta_+}{\sigma_\zeta} = \sqrt{\left(\frac{v_s z}{\sigma_\zeta}\right)^2 + 2\left(\frac{z - z_{sat}}{L_g}\right) + 2\frac{v_e z}{\sigma_\zeta}\sqrt{2\left(\frac{z - z_{sat}}{L_g}\right)}}$$

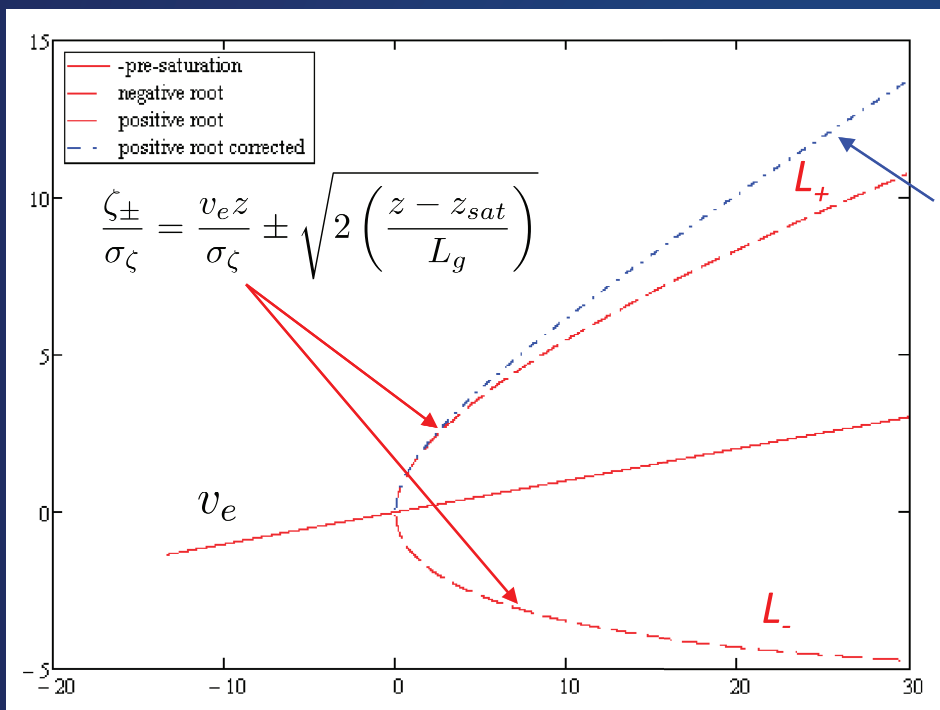
Corrected for saturation

Peaks position

Condition for saturation $P(z) = P_0 \exp\left\{ -\frac{[\zeta - vz]}{2\sigma_\zeta^2} + \frac{z}{L_g} \right\} = P_s \simeq 1.6\,\rho_{fel} P_E$

Two roots are plotted as solid lines indicated by L_+ and L_-

ζ



$\frac{z}{L_g}$

Peak velocity

$$v = \begin{cases} v_e = \lambda_0 / 3\lambda_u \\ v_s = \lambda_0 / \lambda_u \end{cases}$$

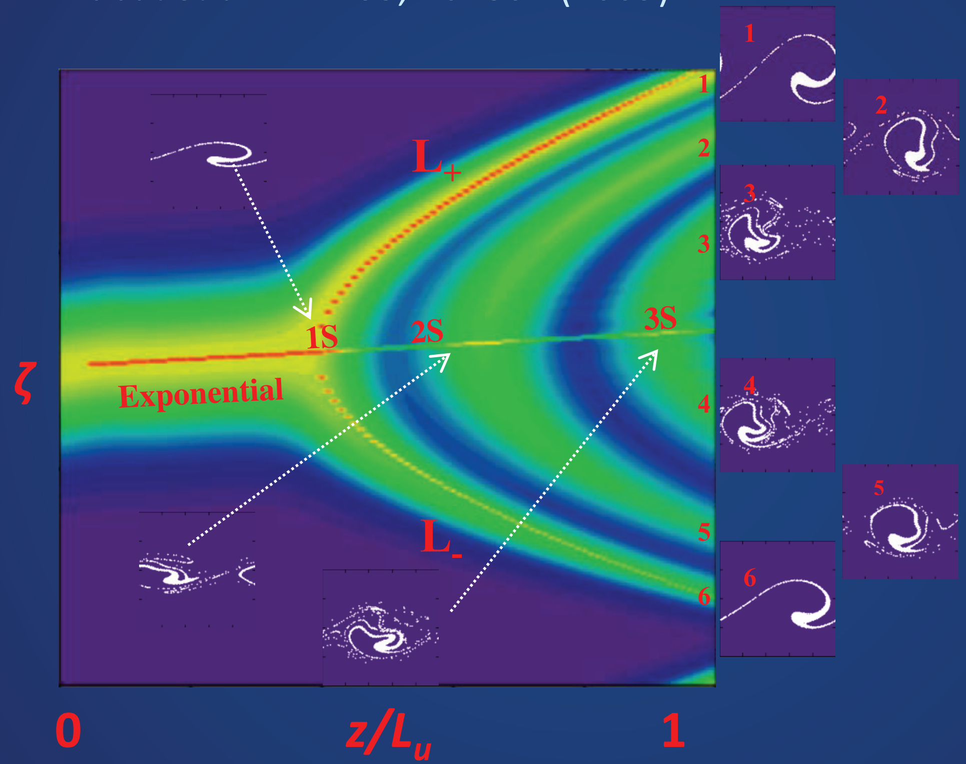
$$\frac{\zeta_+}{\sigma_\zeta} = \sqrt{\left(\frac{v_s z}{\sigma_\zeta}\right)^2 + 2\left(\frac{z - z_{sat}}{L_g}\right) + 2\frac{v_e z}{\sigma_\zeta}\sqrt{2\left(\frac{z - z_{sat}}{L_g}\right)}}$$

Corrected for saturation

Group velocity of the head mode is obtained by differentiating L_+ with respect to z

The correlation of the tail structure with the longitudinal phase space of the e-beam - Long seed, two symmetric roots

Pulse splitting in short wavelength seeded FEL
M. Labat *et al* PRL 103, 264801 (2009)

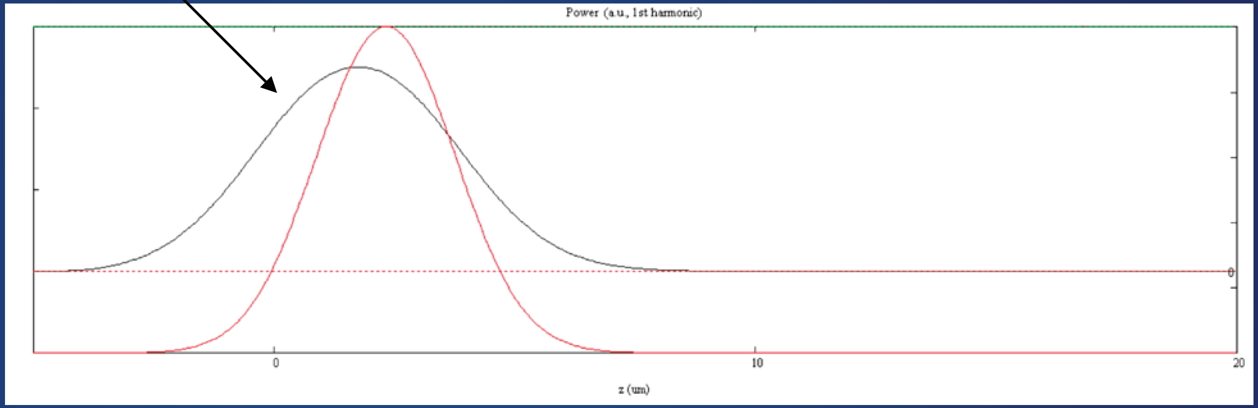


Length of the tail is given by $L_+ - L_-$

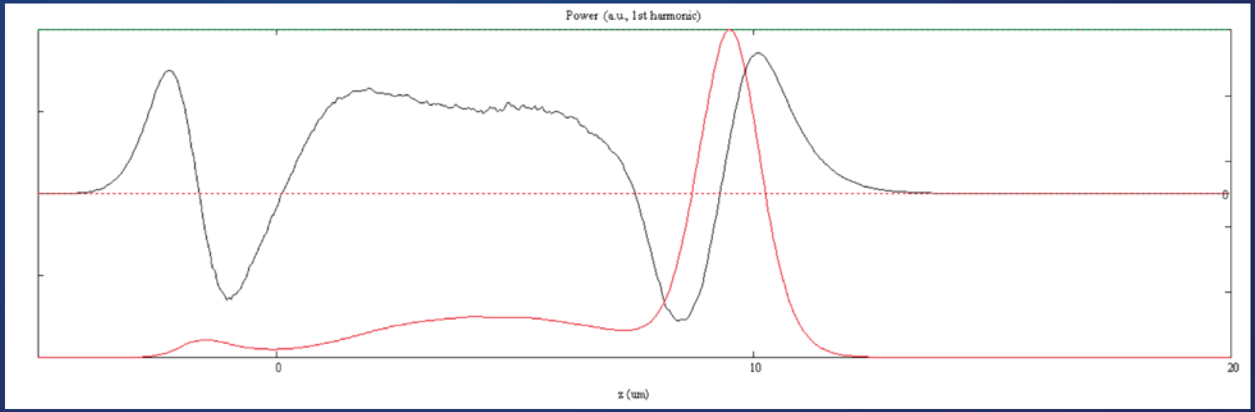
Local gain

Im. ref. Index

Exponential gain

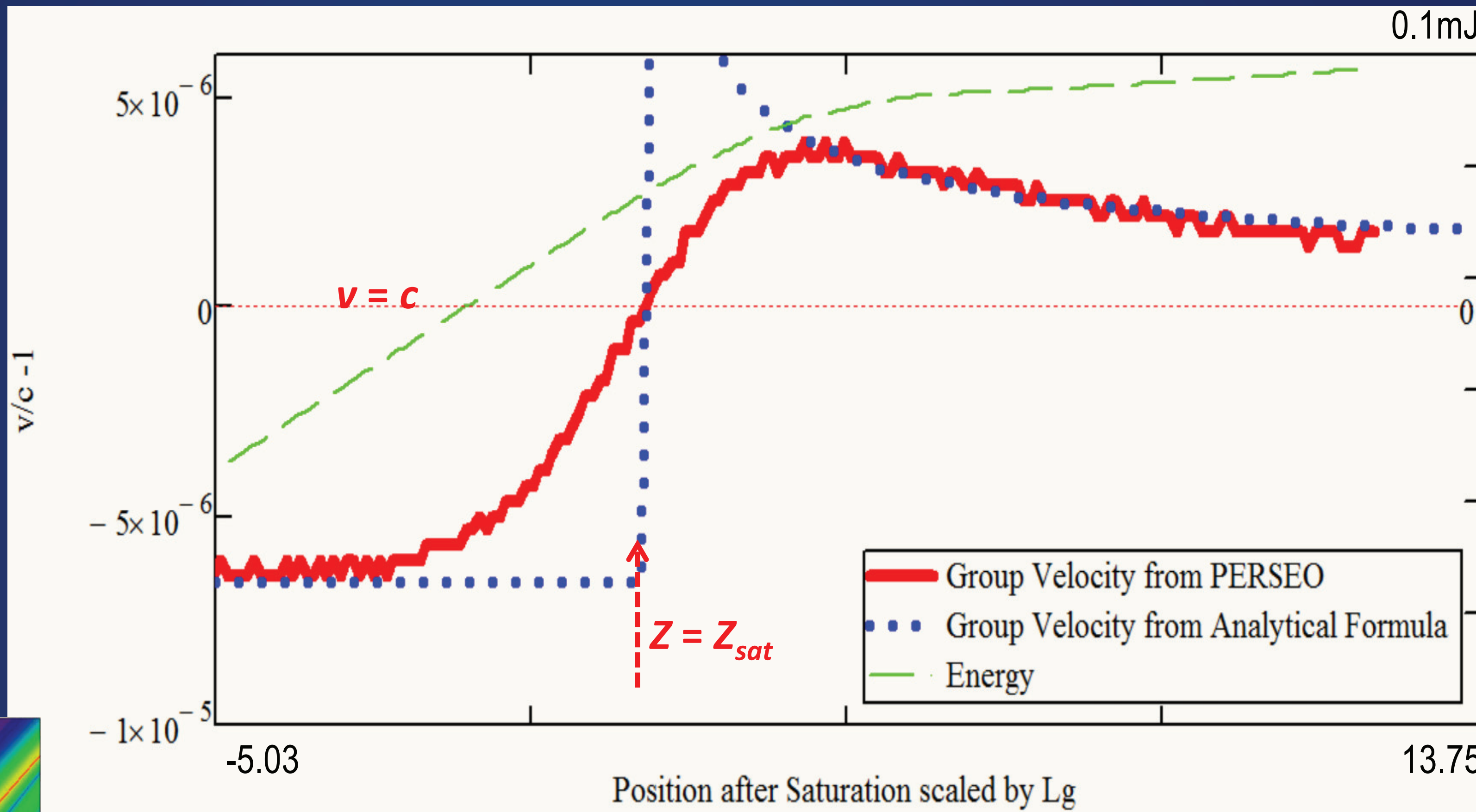


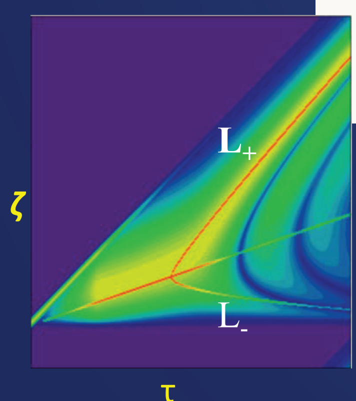
Superradiance



ζ

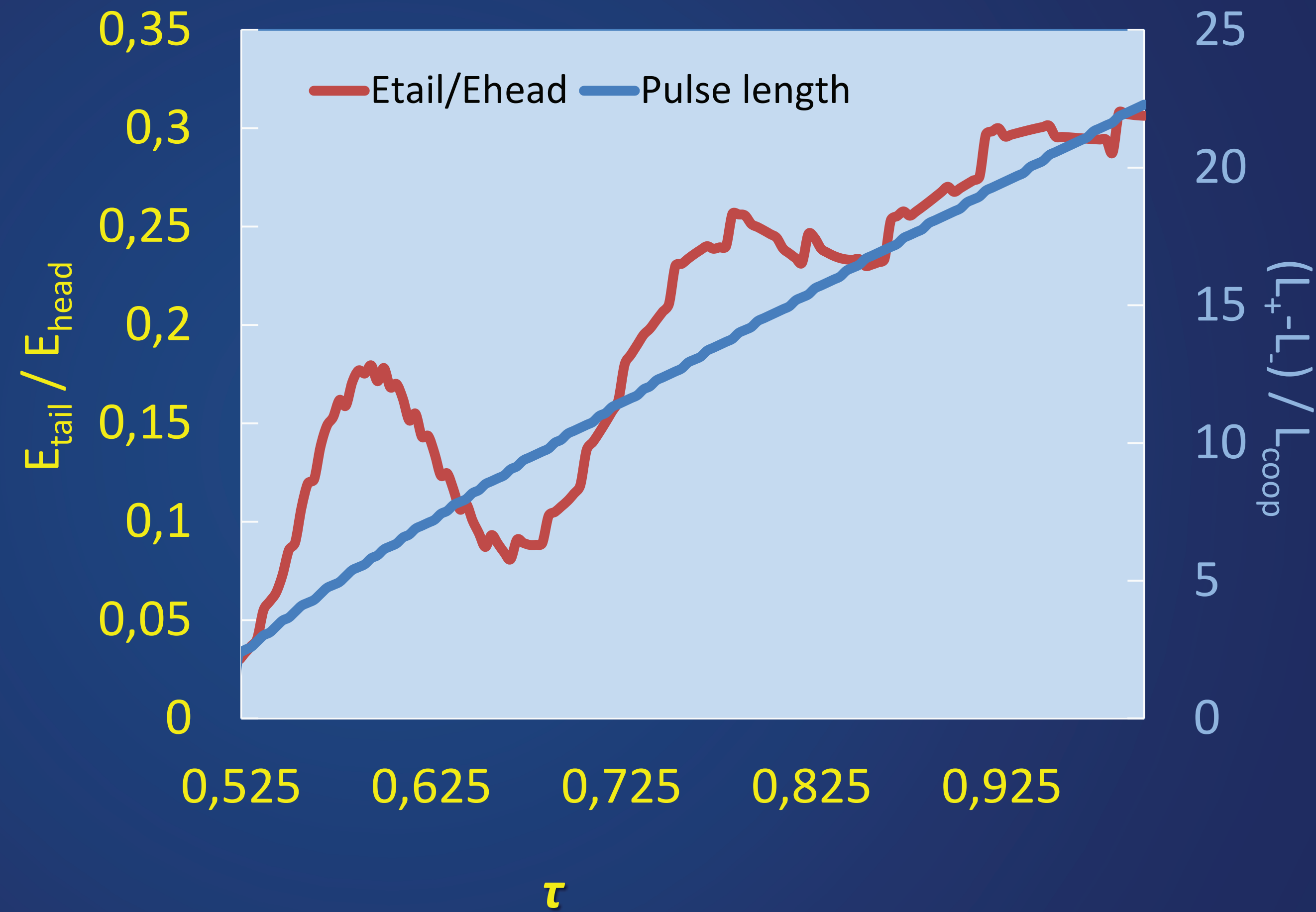
Head Peak Moving at Superluminal Speed

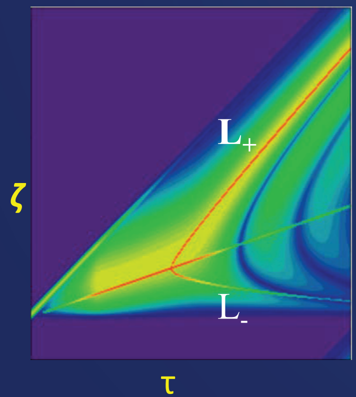




No causality violation, gain distortion, «information» is already distributed

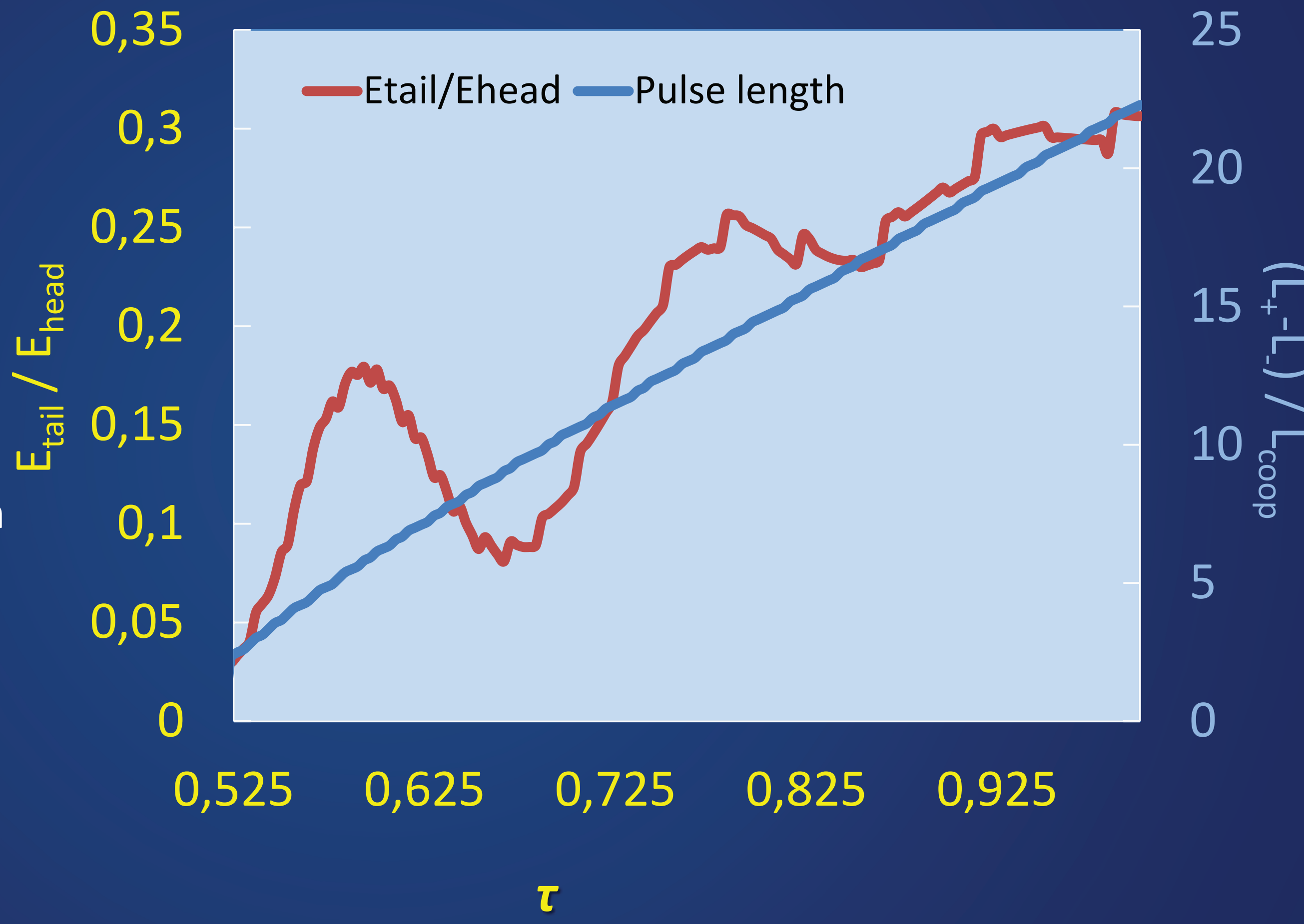
Tail after saturation: E_{tail} is ~30% of E_{main} and pulse is lengthening ~10 times

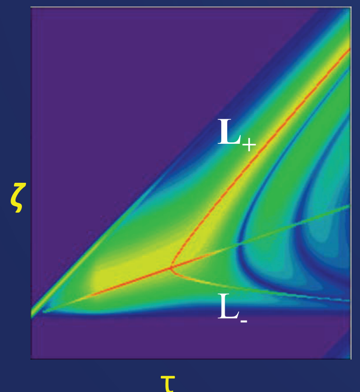




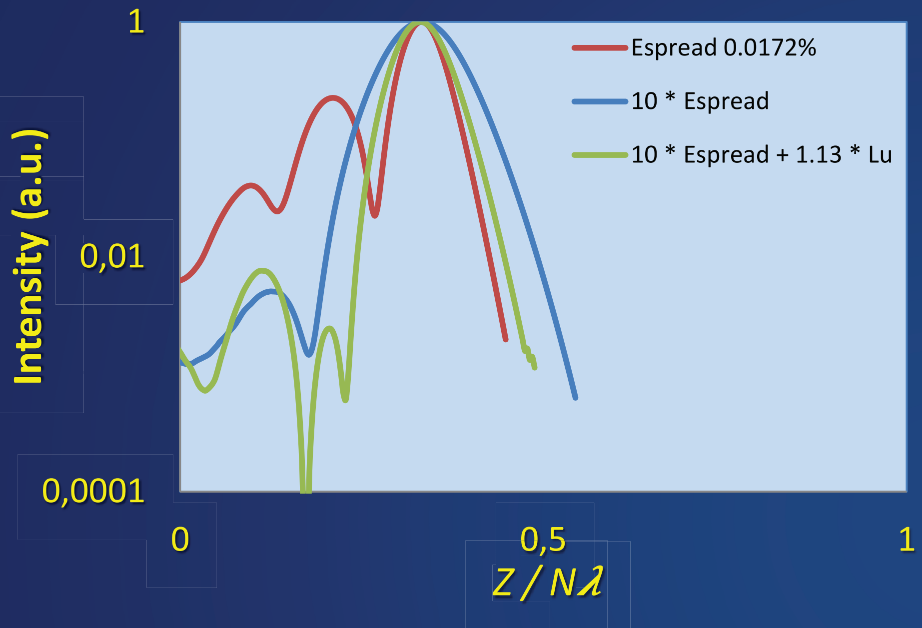
Tail after saturation: E_{tail} is ~30% of E_{main} and pulse is lengthening ~10 times

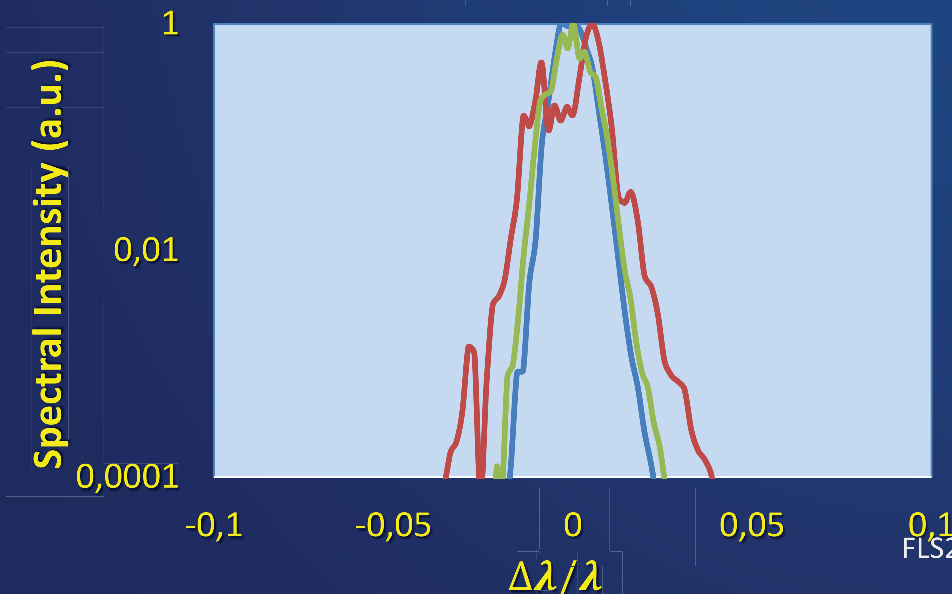
- Tail can have a significant amount of energy, ~30% of the main pulse
- Pulse length (L_+-L_-) gets longer ~10times
- The presence of the tail increases pulse duration and reduces the signal to noise ratio





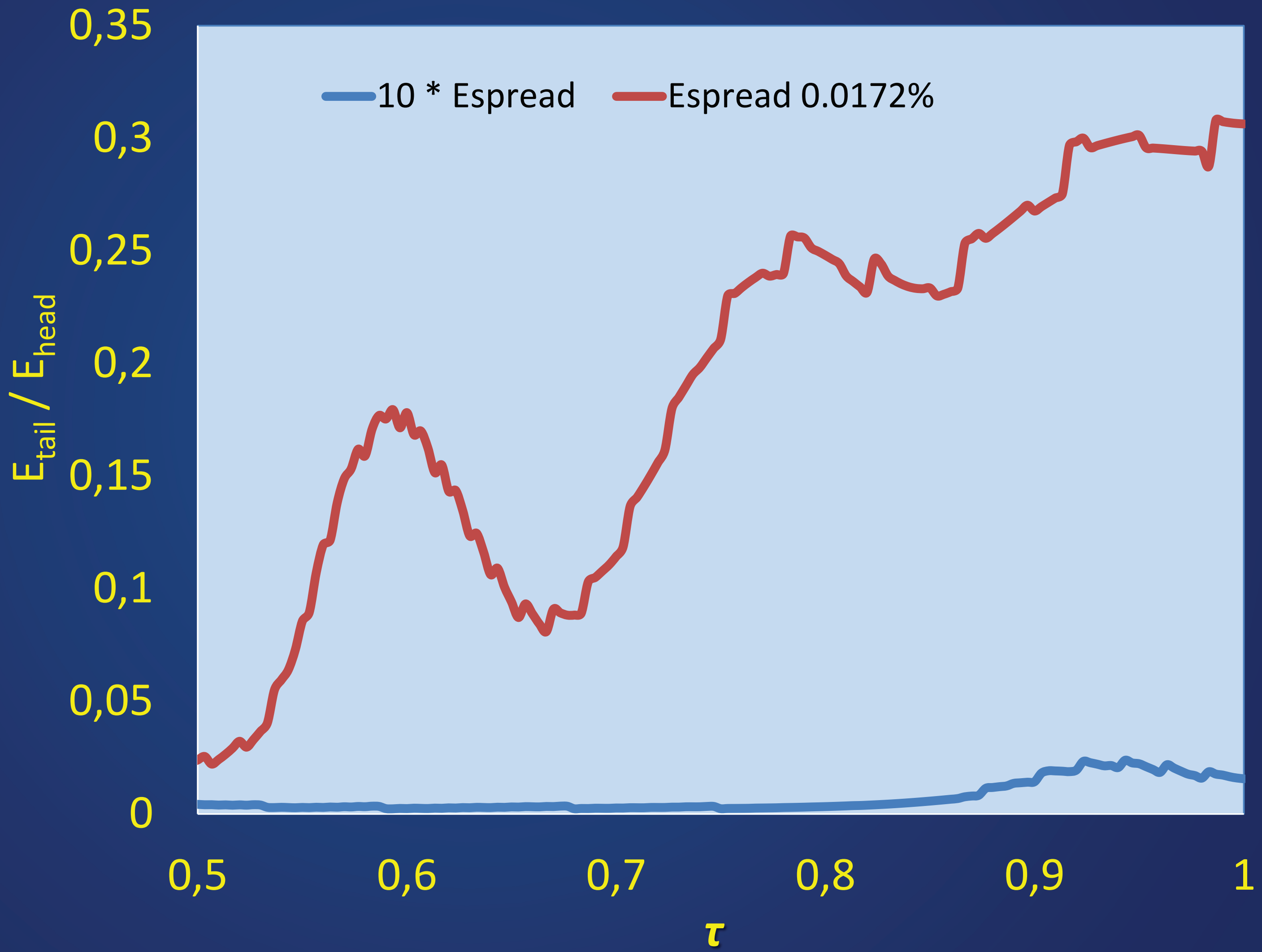
Suppress tail via increasing the energy spread

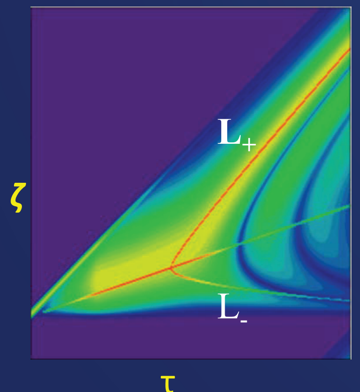




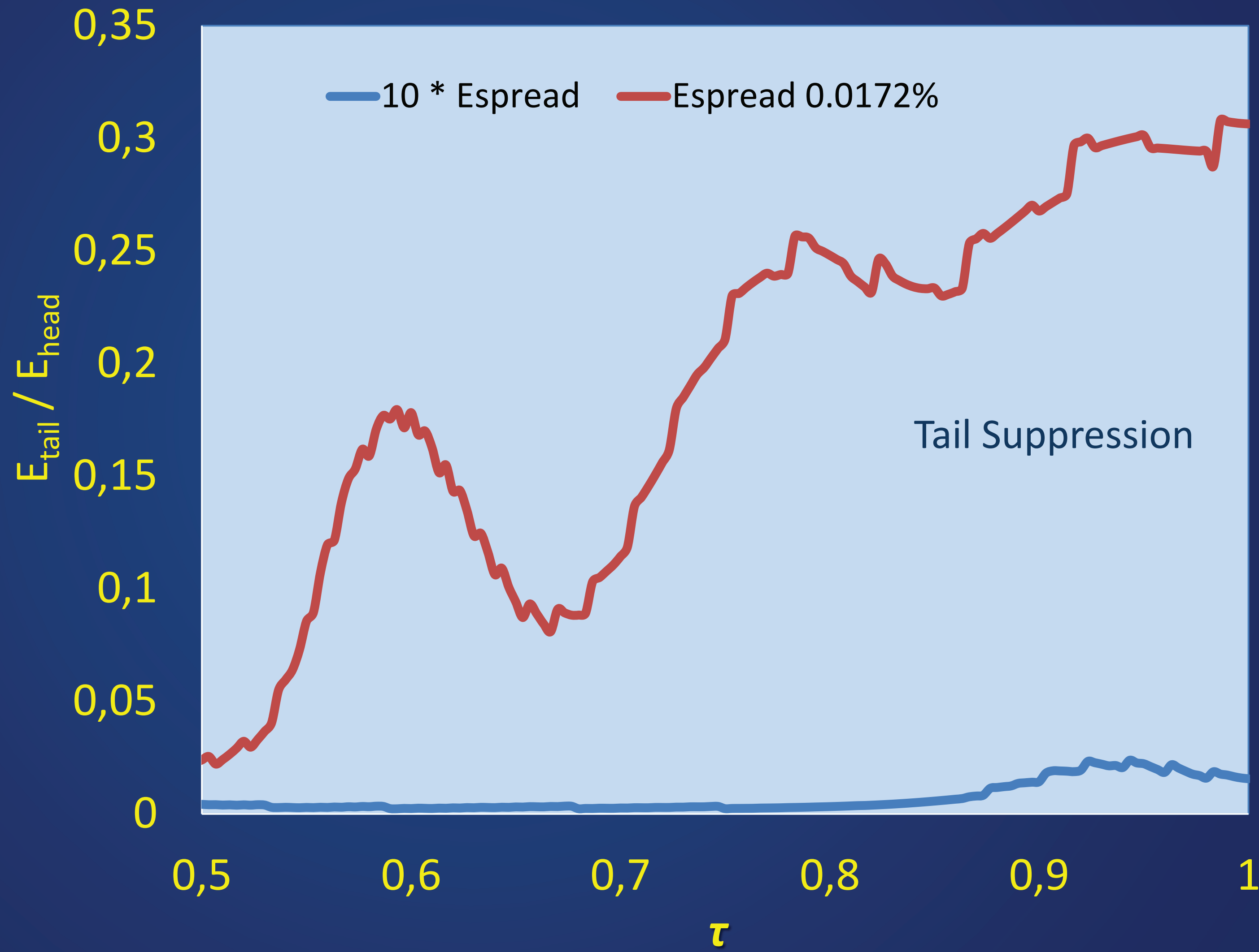
- The laser heater suppressing micro-bunching instability may be considered to increase the energy spread (σ_E/E) to suppress the tail to (< 1%) of the main pulse
- Time-bandwidth product (<0.7)
- A substantial reduction in the total pulse duration accompanied by an increase of the pulse longitudinal coherence
- Reduction in spectral broadening

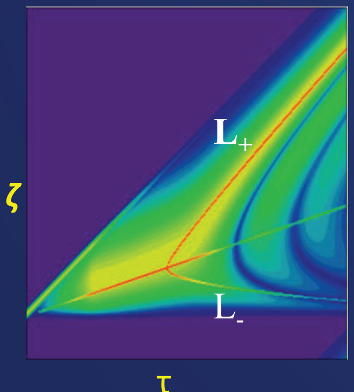
E_{tail}/E_{main} Reduction (~20 times) after Tail Suppression



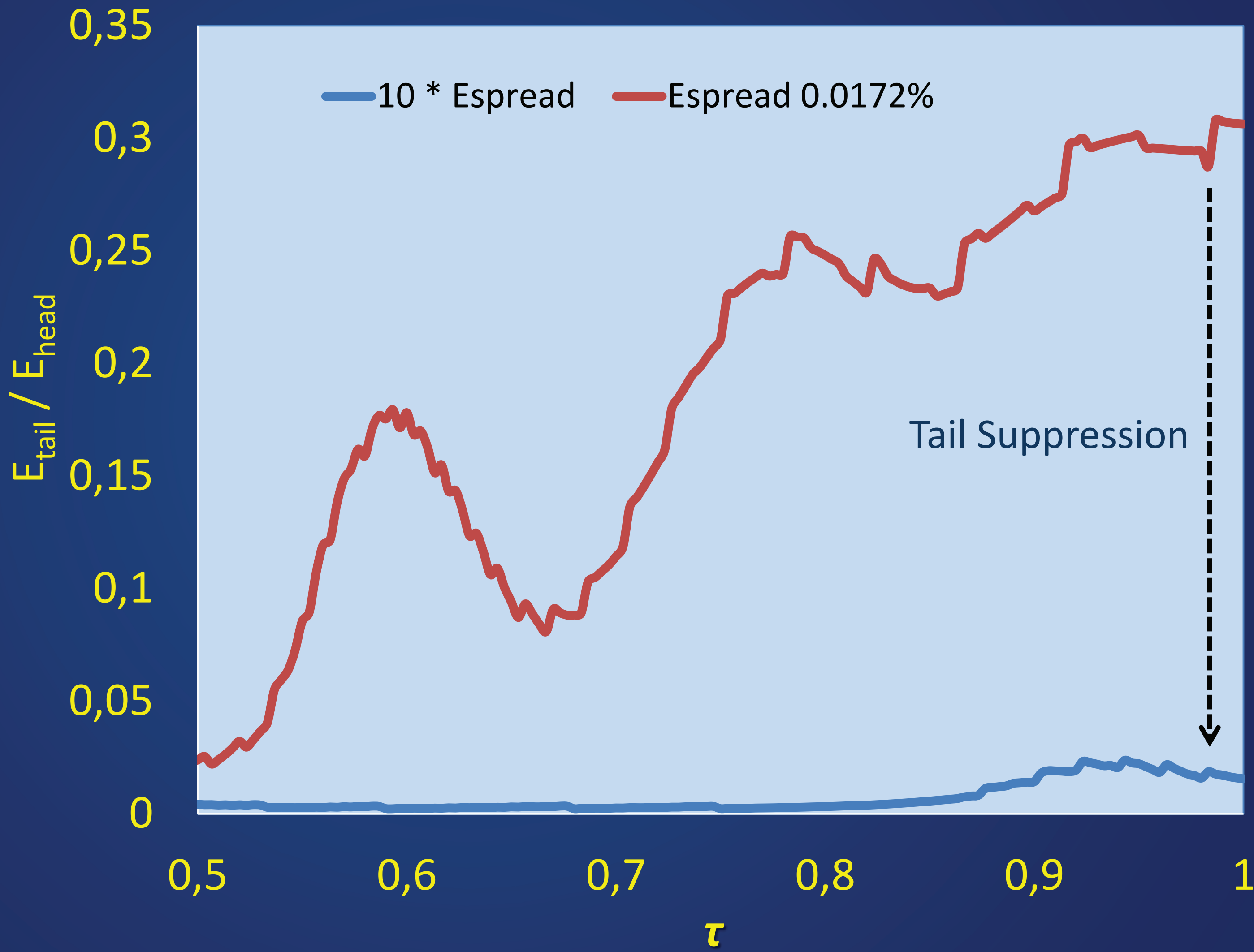


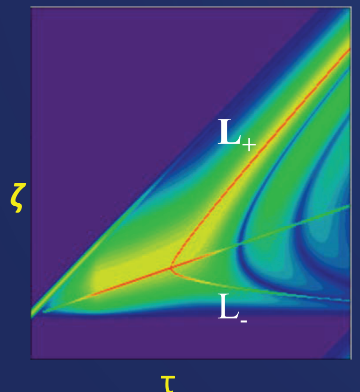
$^{E_{tail}}/_{E_{main}}$ Reduction (~20 times) after Tail Suppression



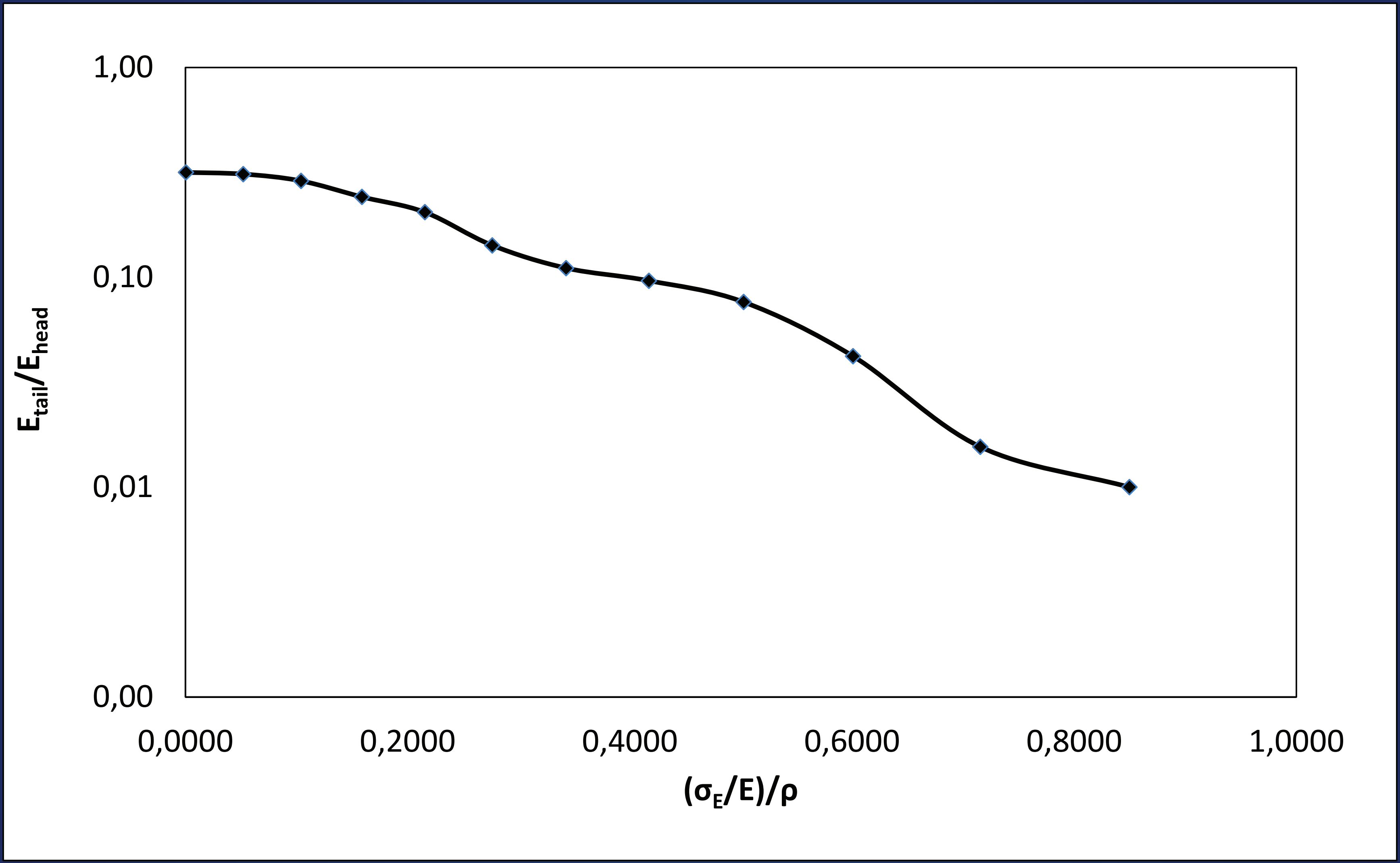


E_{tail}/E_{main} Reduction (~20 times) after Tail Suppression





$^{E_{tail}}/_{E_{main}}$ as a function of $(\sigma_E/E)/\rho$



Summary

- Time-resolved single-shot imaging of isolated molecules or non-periodic structures requires an XFEL with peak power at multi-GW level and sub-femtosecond temporal duration ➠**FEL operating in single spike - superradiant regime**

- When single spike reaches saturation, pulse splits and tail is formed. We studied this process in ideal conditions, ”flat” beam parameters, no taper

- Peak of **the pulse propagates at superluminal speed**
  The **tail is constituted by a train of pulses with both transverse and longitudinal coherence and decaying amplitudes**

- **Suppressing the tail to <1% of the main pulse,** can be achieved by inducing additional energy spread. Observed a factor of 10 reduction in the pulse duration and a factor of 20 reduction in E_{tail}/E_{main}