Déstabilisation par un processus d'advection dans un laser: défauts spectro−temporels et structures induites par bruit

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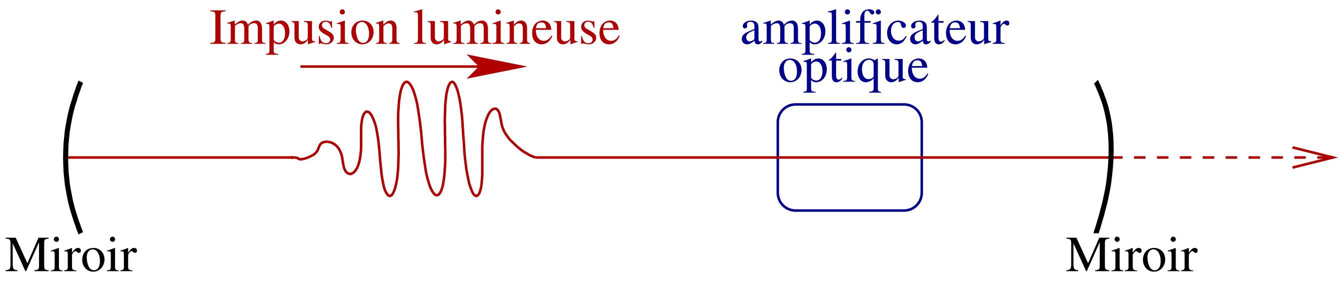


1. Le laser à électrons libres:

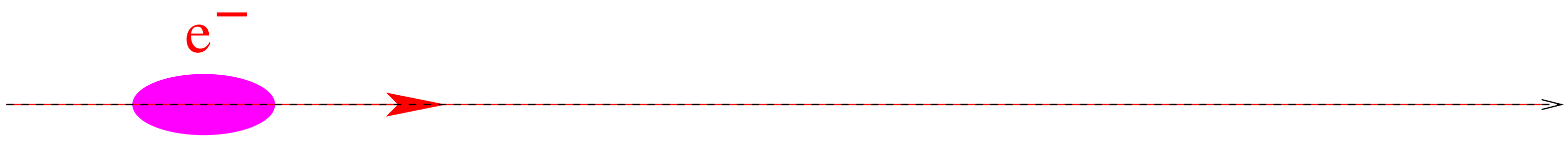
aspect physique → expérience et modèle

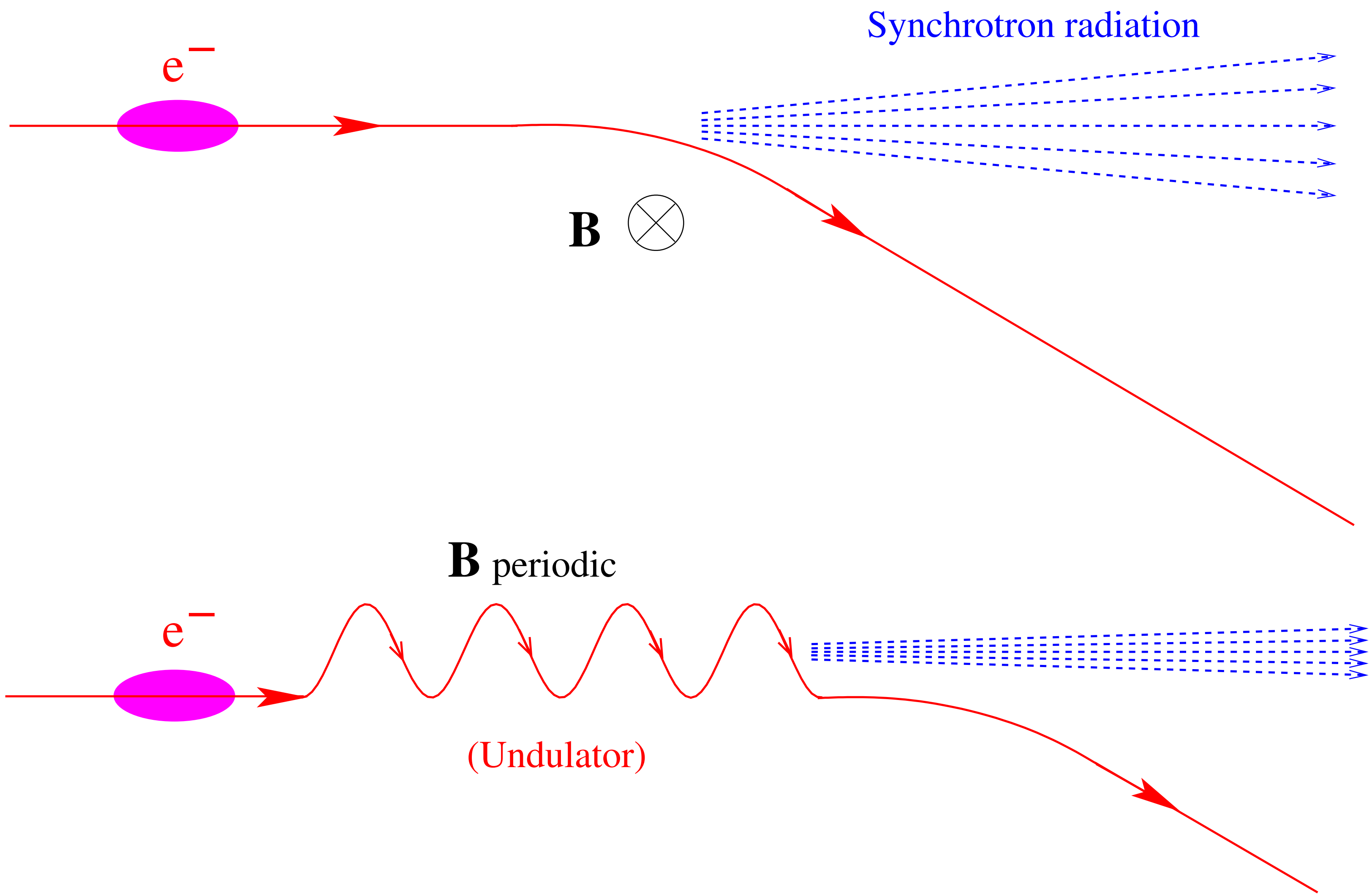
aspect "dynamique" → système du type "advection−diffusion" à 1d + saturation globale

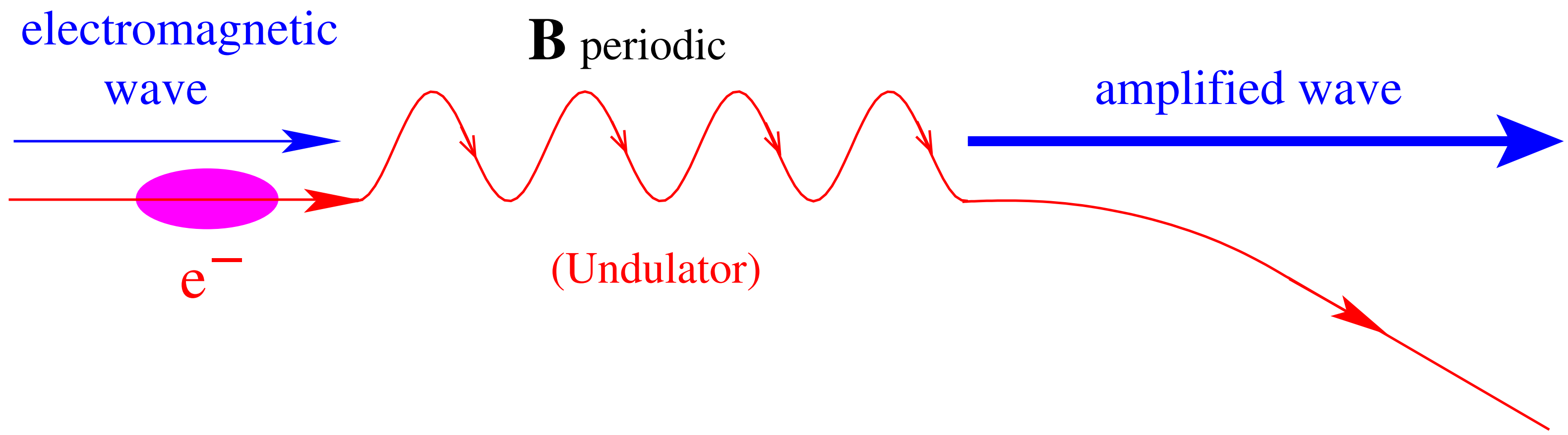
2. Résultats (quoi de neuf?) → dynamique spectro−temporelle

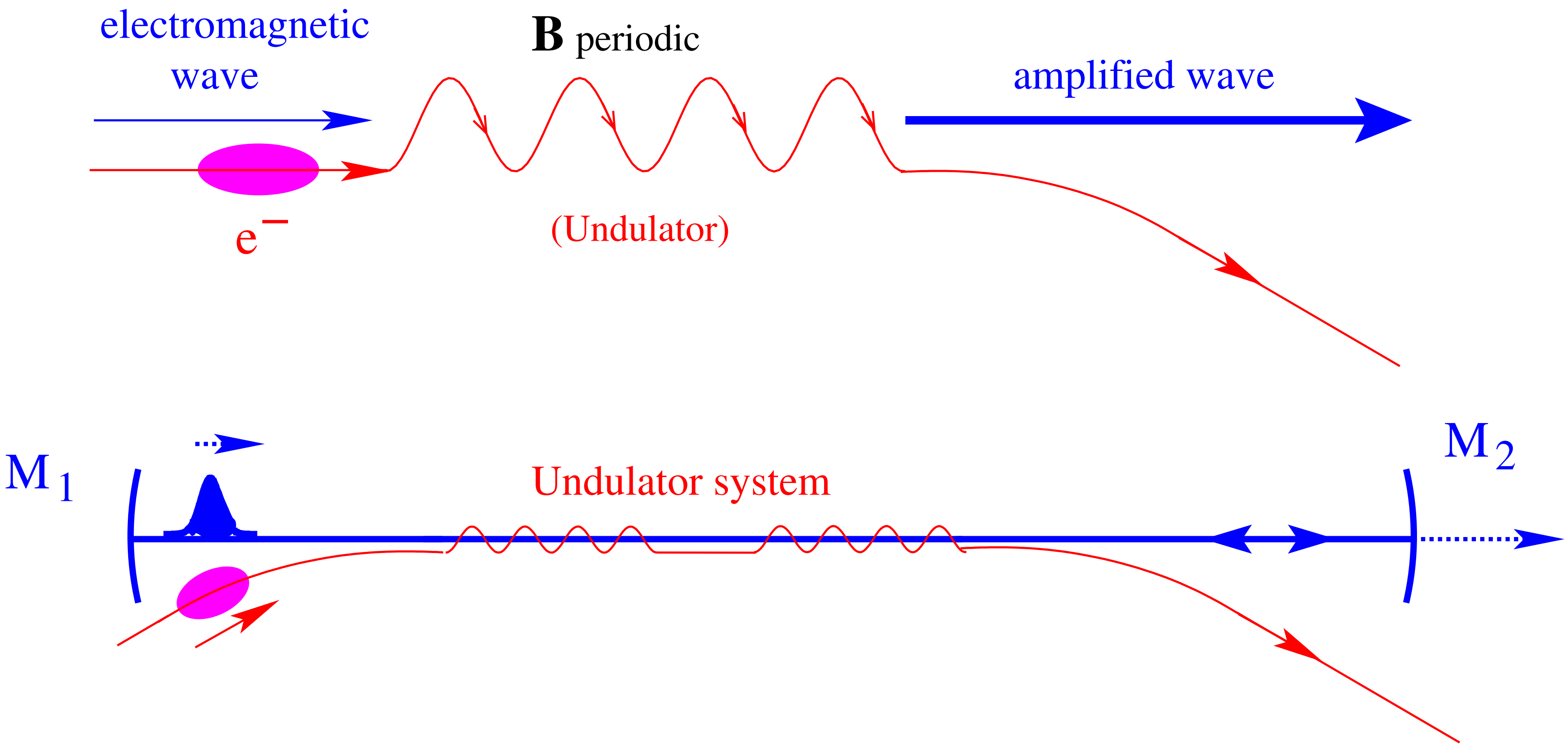
→ saturation globale vs saturation locale

3. Quels phénomènes retrouve t−on dans des équations de Ginzburg−Landau élémentaires?


e^-


Synchrotron radiation
e⁻
B
e⁻
B periodic
(Undulator)


electromagnetic
wave
B periodic
amplified wave
e⁻
(Undulator)



Free–electron laser (FEL):

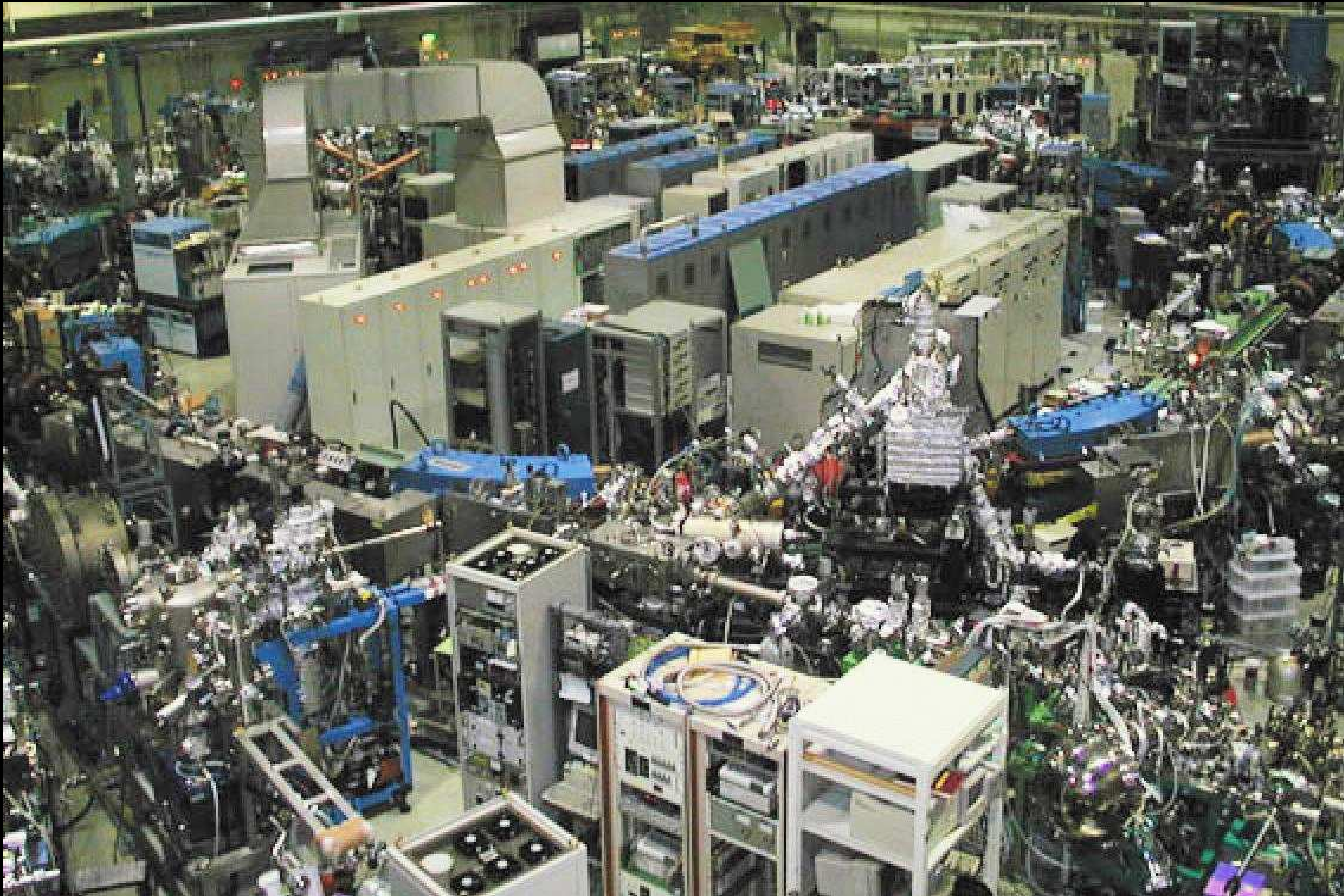
– tunable

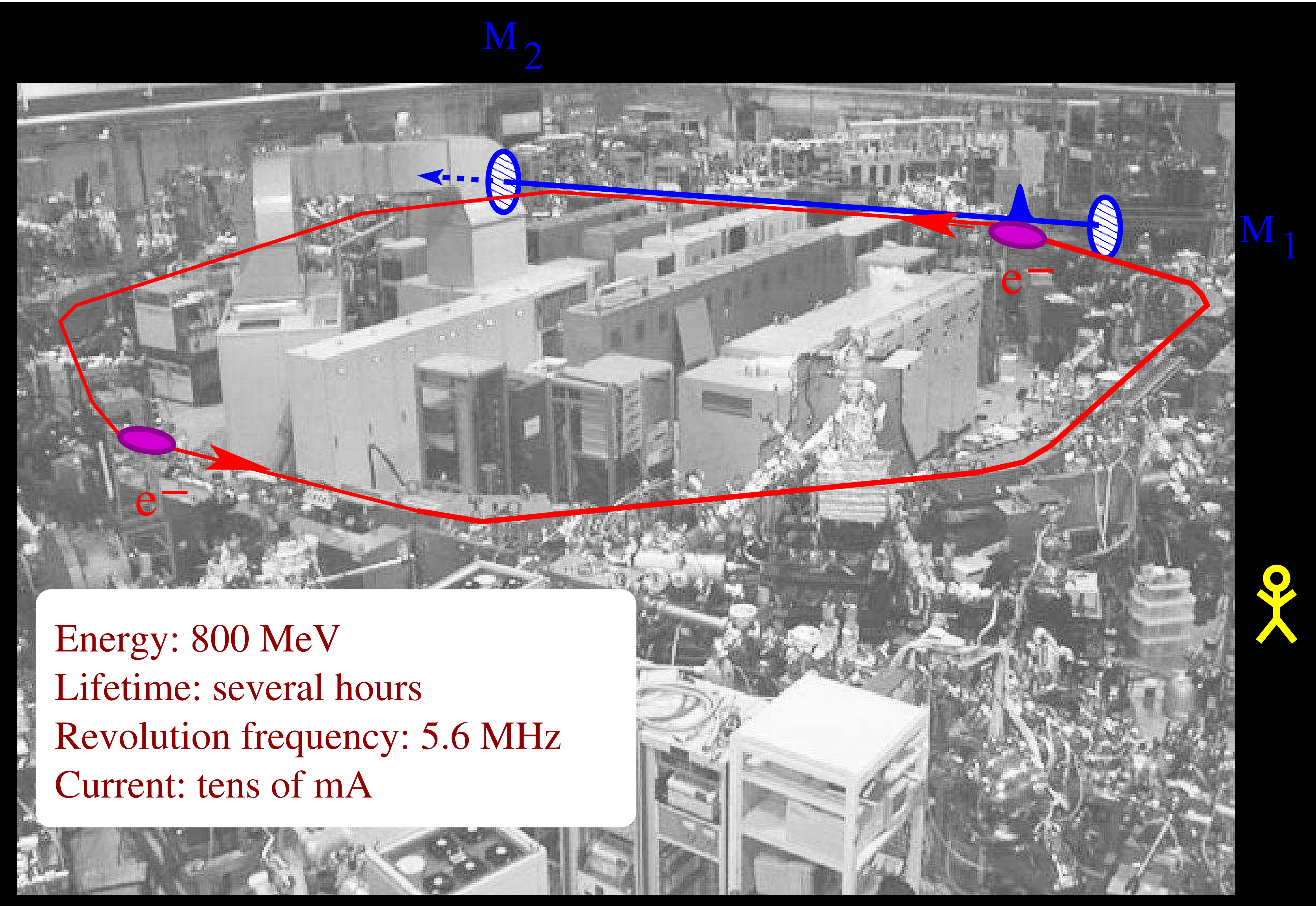
– far infrared to UV (and X...)

Super–ACO (LURE, Orsay, France) ⟶ UV (350 nm)

UVSOR (IMS, Okazaki, Japan) ⟶ UV (250 nm), visible (520 nm), etc

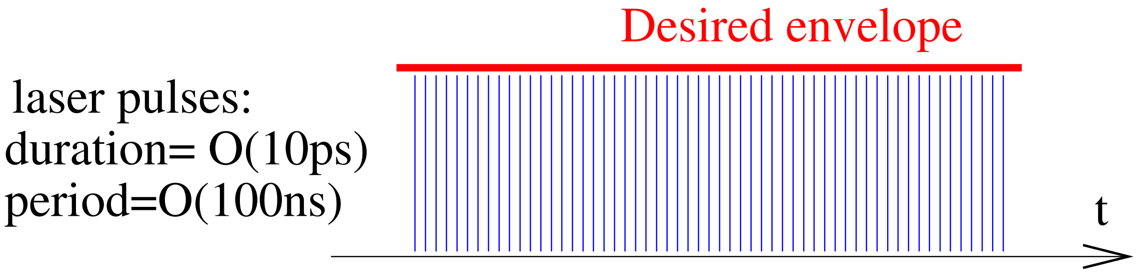
UVSOR storage ring (IMS, Okazaki)

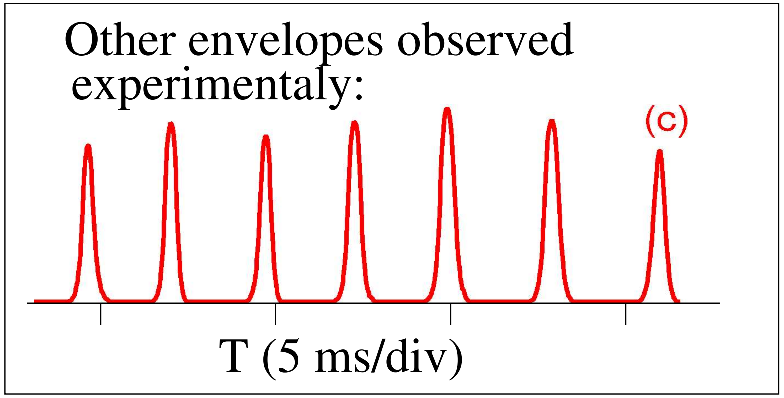


M 2
M 1
e−
e−
Energy: 800 MeV
Lifetime: several hours
Revolution frequency: 5.6 MHz
Current: tens of mA

Stability issues vs frequency mismatch

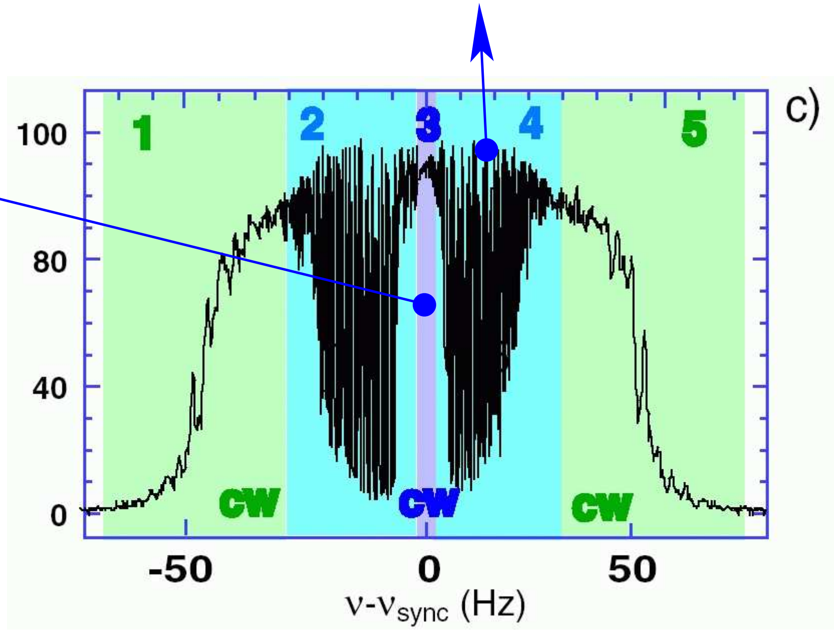
1) Envelope of the pulse train

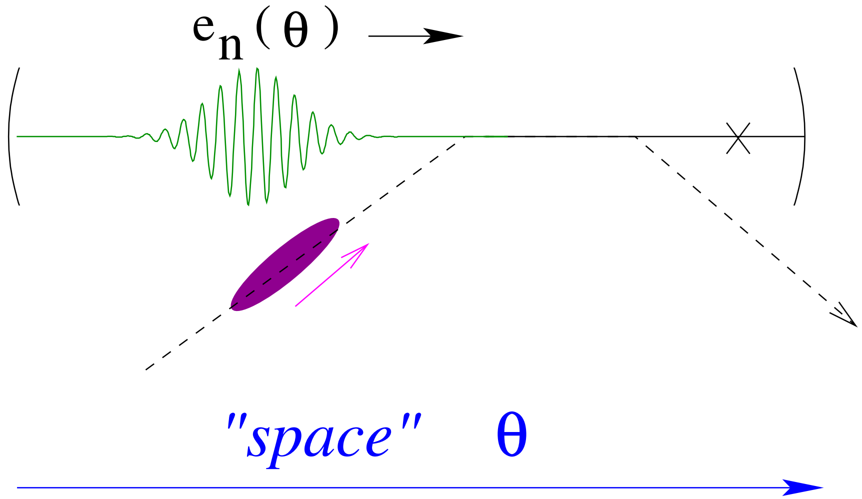




2) Internal structure of the picosecond pulses ?

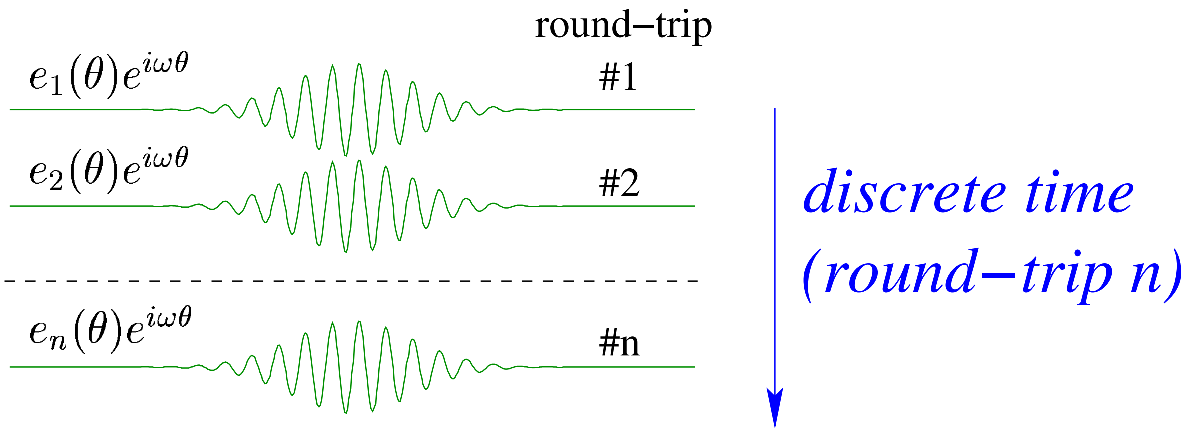
(this talk)



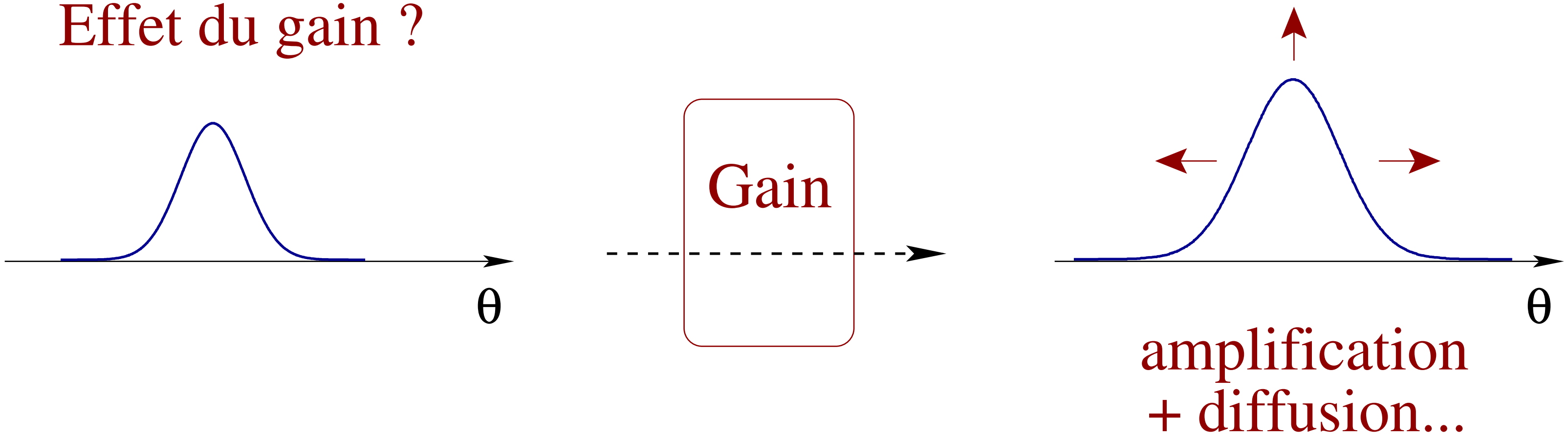


– at each round-trip:

$$e_n(\theta) \xrightarrow{\text{loss, gain}} e_{n+1}(\theta)$$

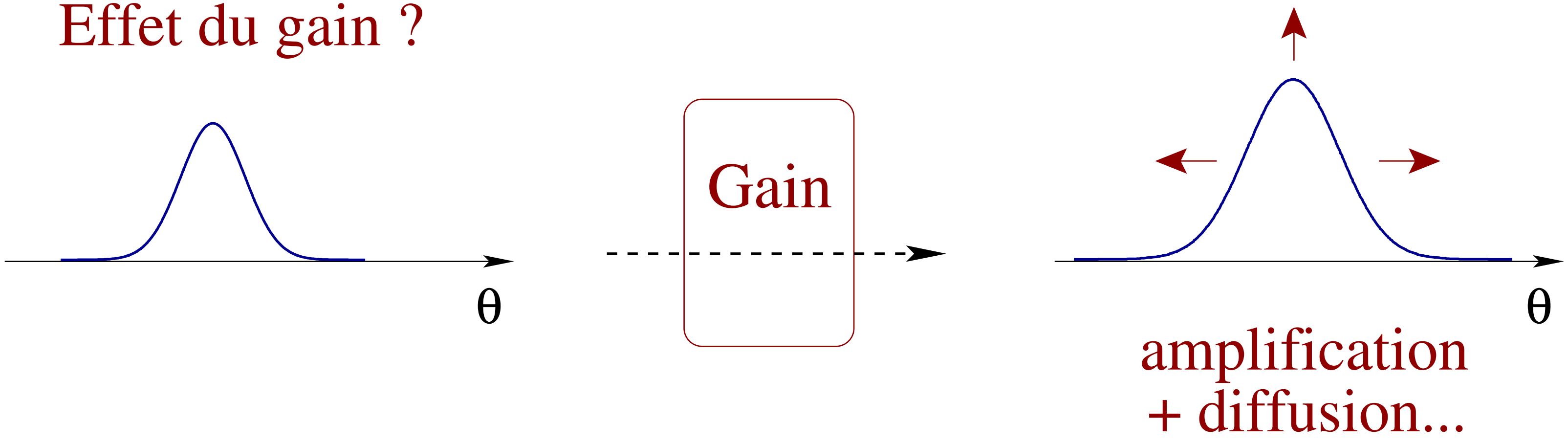


Effet du gain ?



$$e(\theta) \longrightarrow L \otimes e(\theta) = G_0 \times (e + e_{\theta\theta})$$

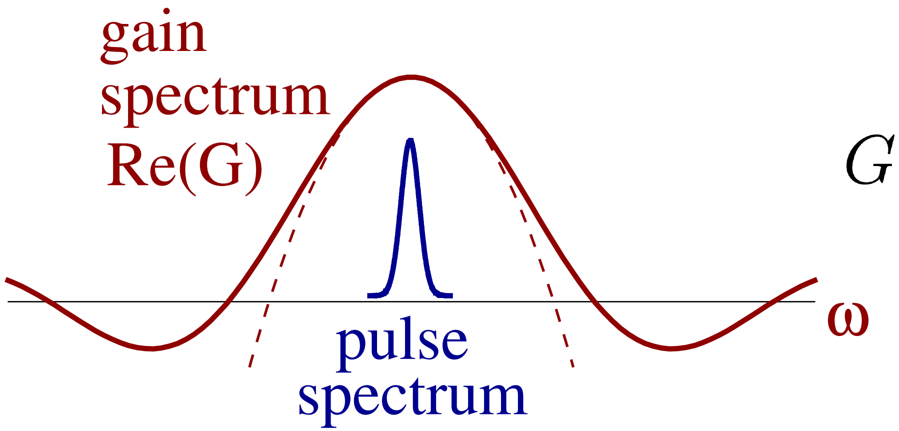
Effet du gain ?



$e(\theta) \longrightarrow L \otimes e(\theta) = G_0 \times (e + e_{\theta\theta})$

TF $\Downarrow \Uparrow$ $\qquad\qquad\qquad \Downarrow \Uparrow$

$\tilde{e}(\omega) \longrightarrow G(\omega)\tilde{e}(\omega)$



$$G(\omega) = G(0) + G'(0)\omega + G''(0)\omega^2 + \dots$$

$$L = G_0\,(1 + \partial_\theta + \partial_{\theta\theta} + \dots)$$

Final step: continuous limit: Map –> PDE

Pulse shape $e(\theta, T)$

$$e_T + ve_\theta = -e + Gf(\theta)\left[e + e_{\theta\theta}\right] + \sqrt{\eta}\xi$$

T= round–trips

frequency mismatch

losses

Gain variable

bunch shape (gaussian)

Gain depends only on slow time T

$$G = \text{ decreasing function of temperature } \sigma^2$$

$$\frac{d\sigma^2(T)}{dT} = -\frac{1}{T_s}\left(1 - \sigma^2 + \int_0^L |e(\theta, T|^2 d\theta\right)$$

Gain saturation depends on overall power *competition between*

advection | *diffusion*

$$e_T + ve_\theta = -e + g(T)f(\theta)(e + e_{\theta\theta}) + \sqrt{\eta}\xi,$$

v large: $v > v_{cv}$

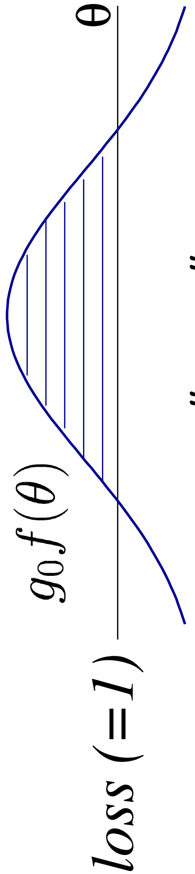
transient growth

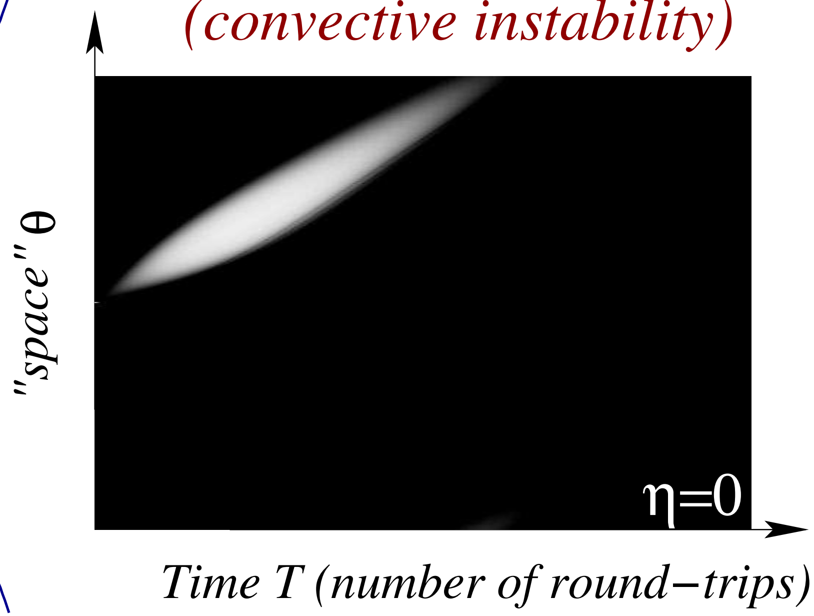
e=0 is globally stable

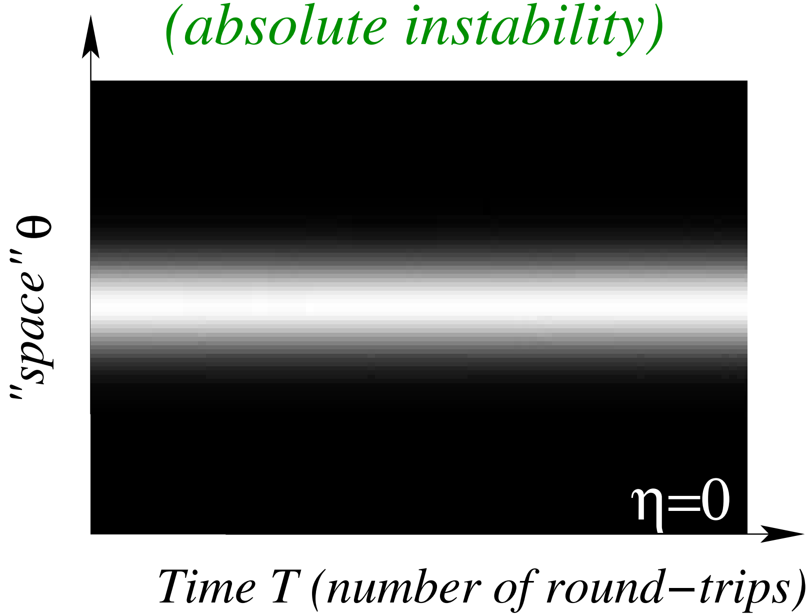
(convective instability)

v not too large: $v < v_{cv}$

(absolute instability)







$$v_{cv} = 2\sqrt{g_0(g_0 - 1)}$$

Basic concepts: see eg Huerre and Monkewitz, Ann. Fluid Mech. 22, 473 (1990), *competition between*

advection — *diffusion*

$$e_T + \boxed{v e_\theta} = -e + g(T)f(\theta)(e + \boxed{e_{\theta\theta}}) + \sqrt{\eta}\xi,$$

v large: $v > v_{cv}$

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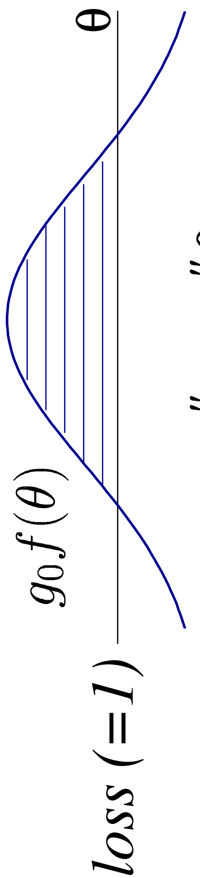
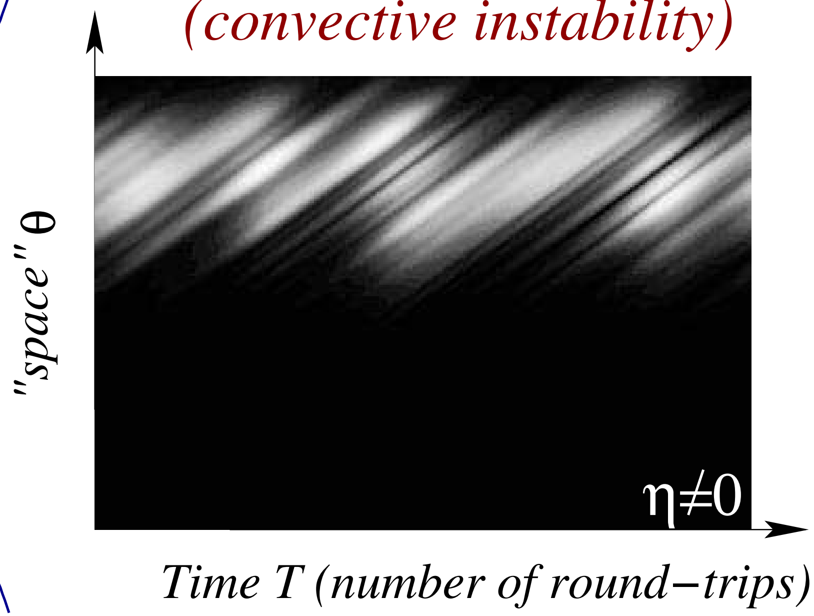
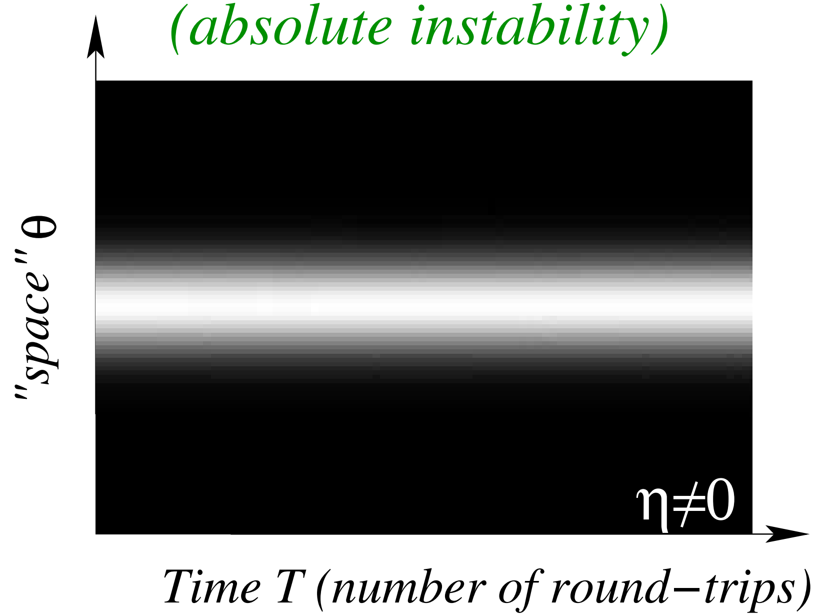


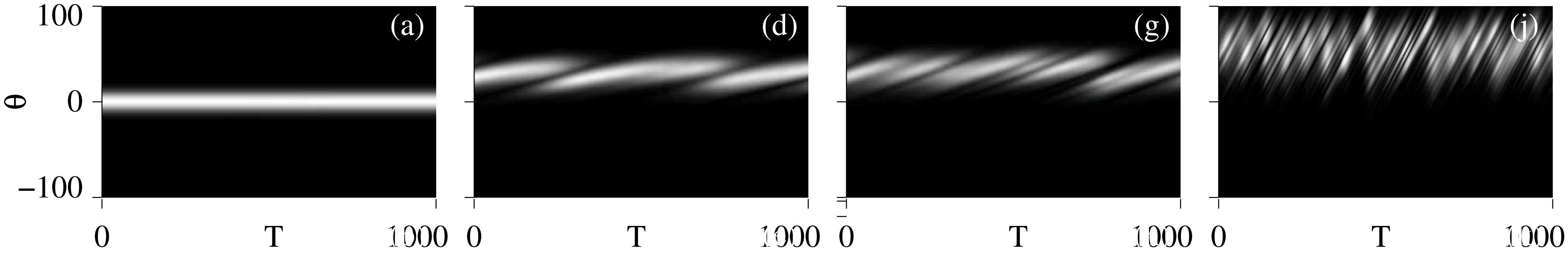




Transient growth known in mode locked lasers:
Kartner et al. PRL 82, 4428 (1999)
Morgner & Mitschke, PRE58, 187 (1999)

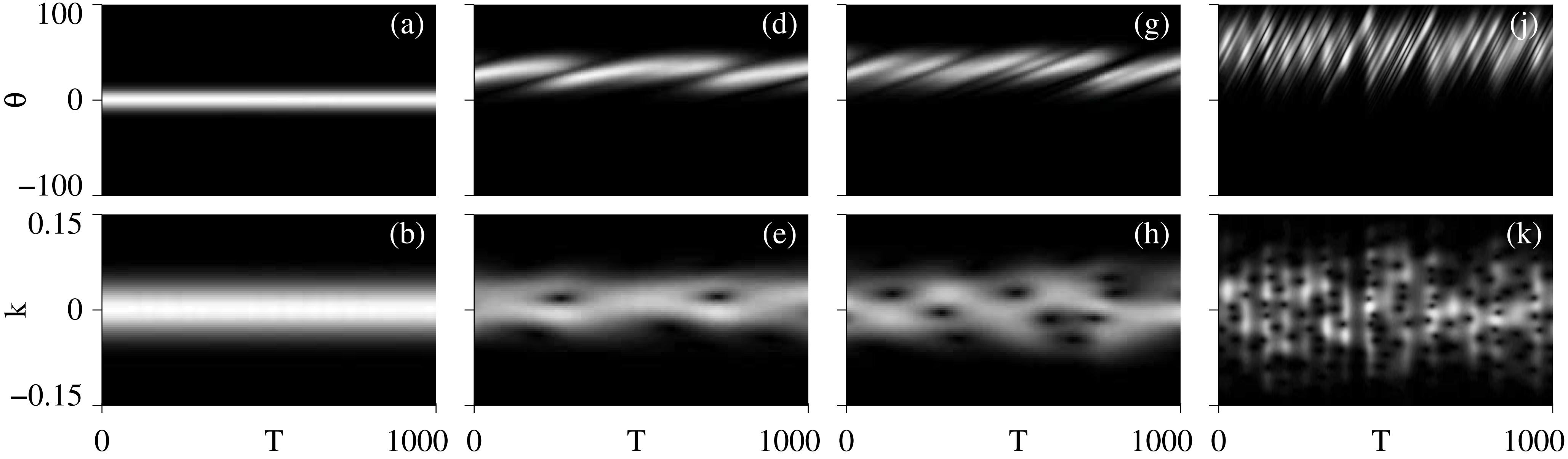
Basic concepts on cv instabilities: see eg Sturrock, Phys. Rev. 5, 488 (1958)
Huerre and Monkewitz, Ann. Fluid Mech. 22, 473 (1990),
Cossu & Chomaz PRL 78, 4387 (1997)
Fluid ex.(Hele−Shaw cell) PRL 82, 1442 (1999)

Numerical results

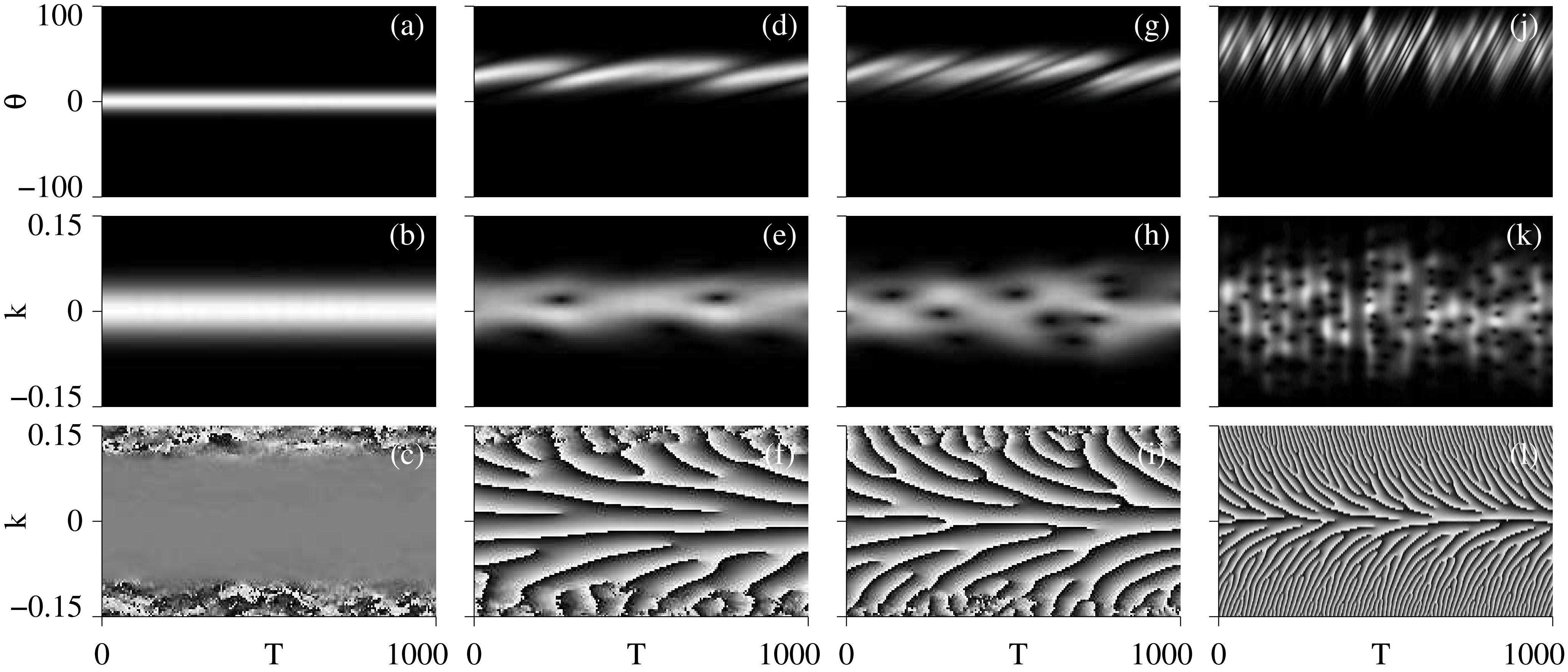


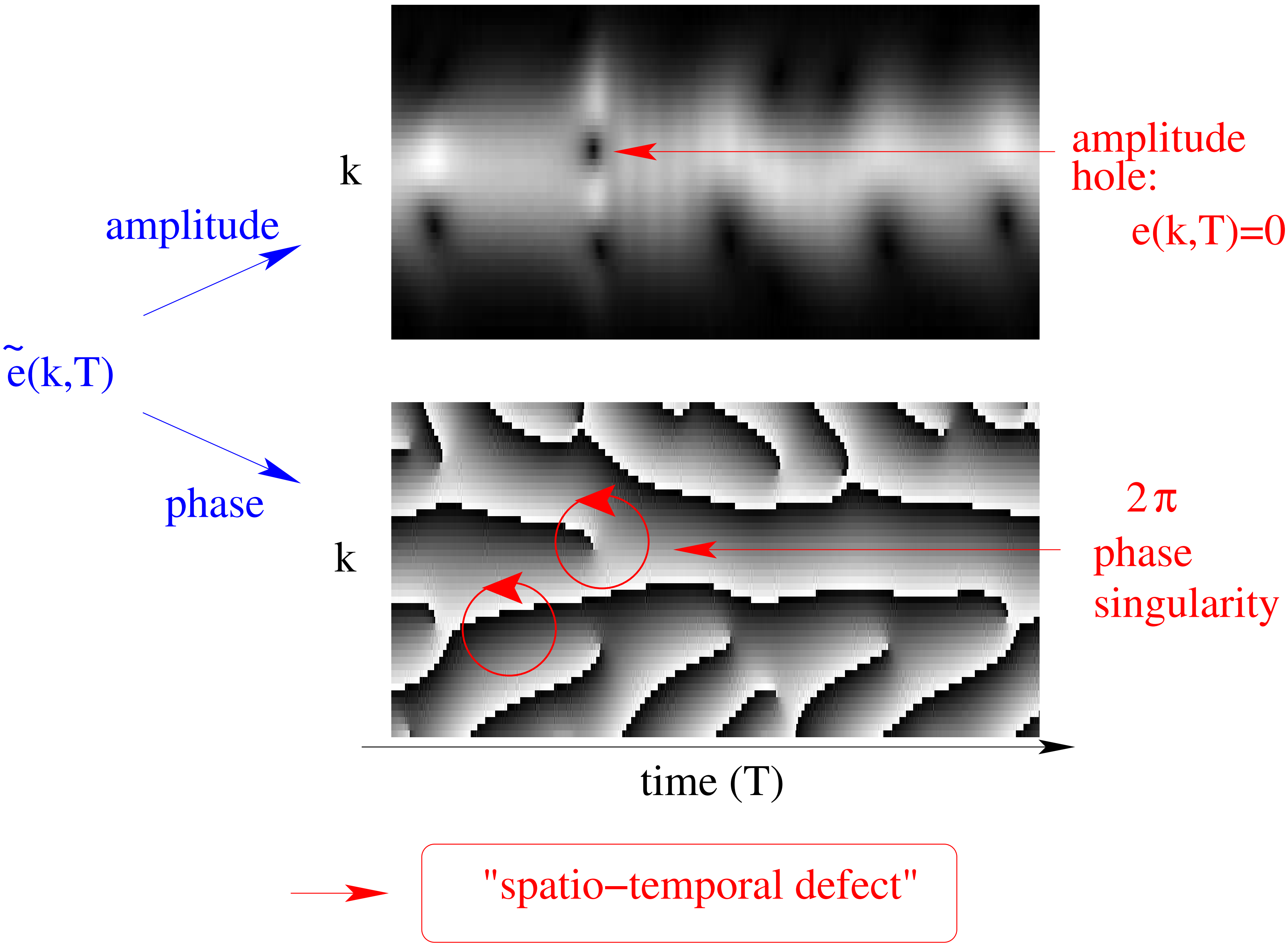
Frequency mismatch: v=0 v=0.5 v=0.7 v=3.4

Numerical results

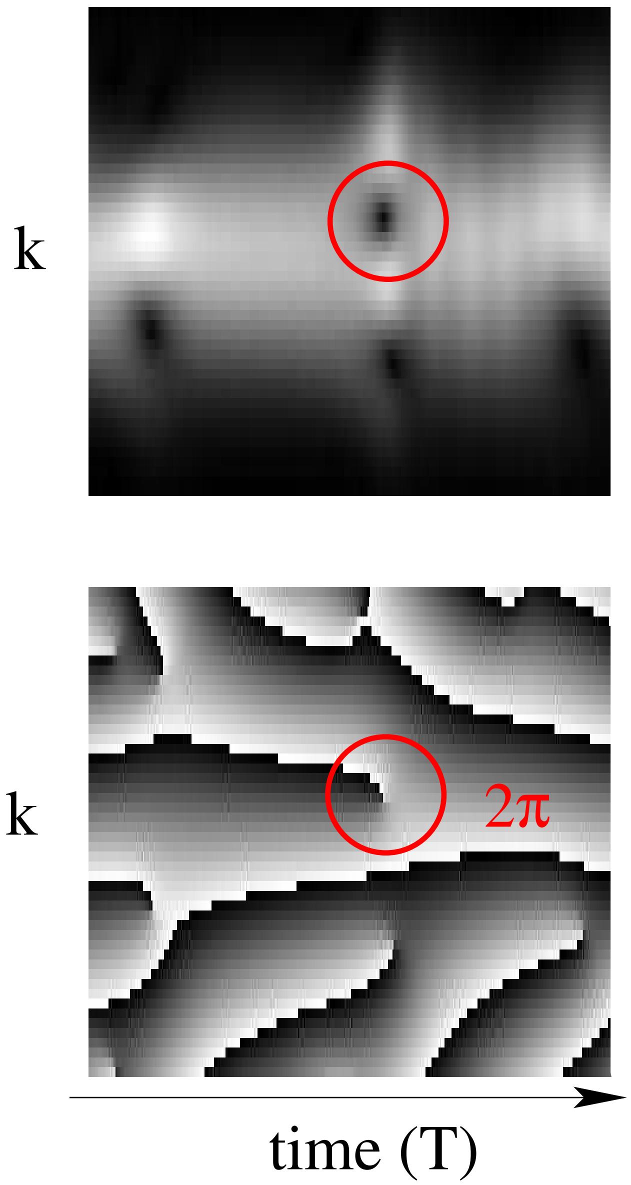


Numerical results





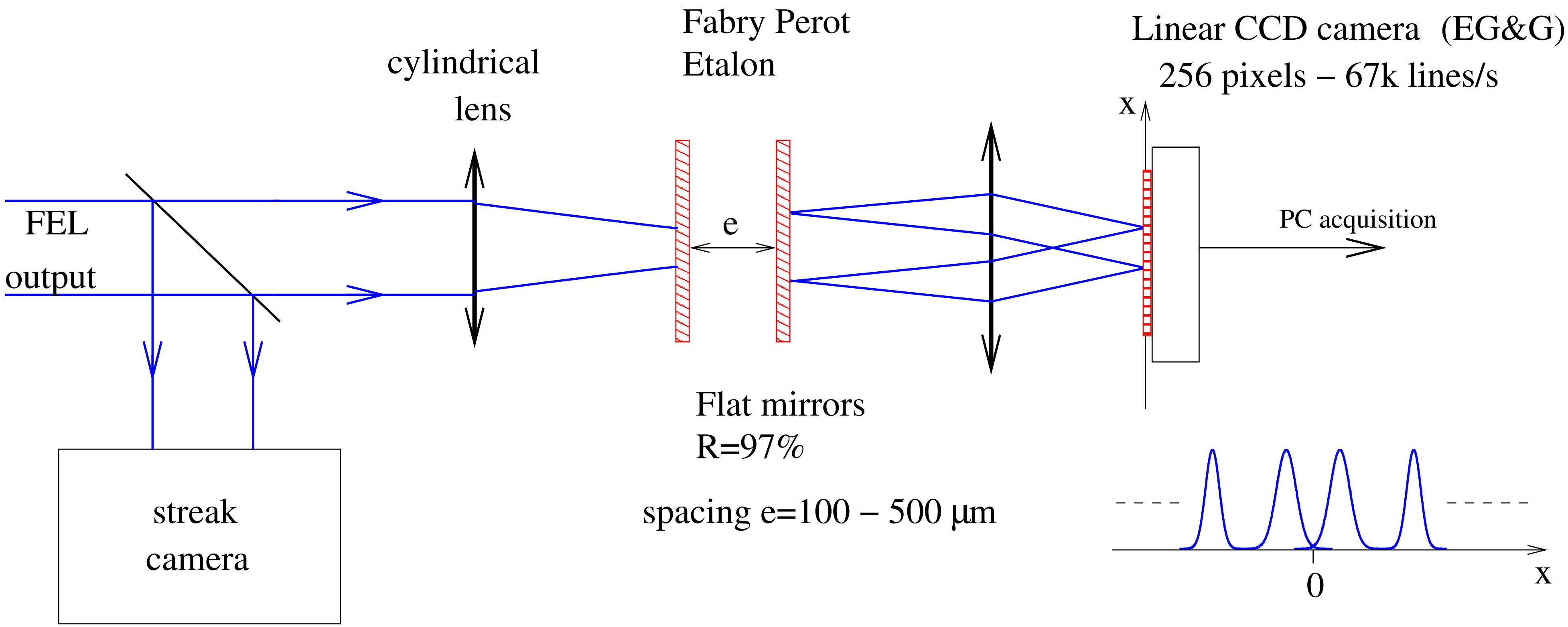
amplitude
k
amplitude hole:
e(k,T)=0
ẽ(k,T)
phase
k
2π
phase singularity
time (T)
"spatio–temporal defect"



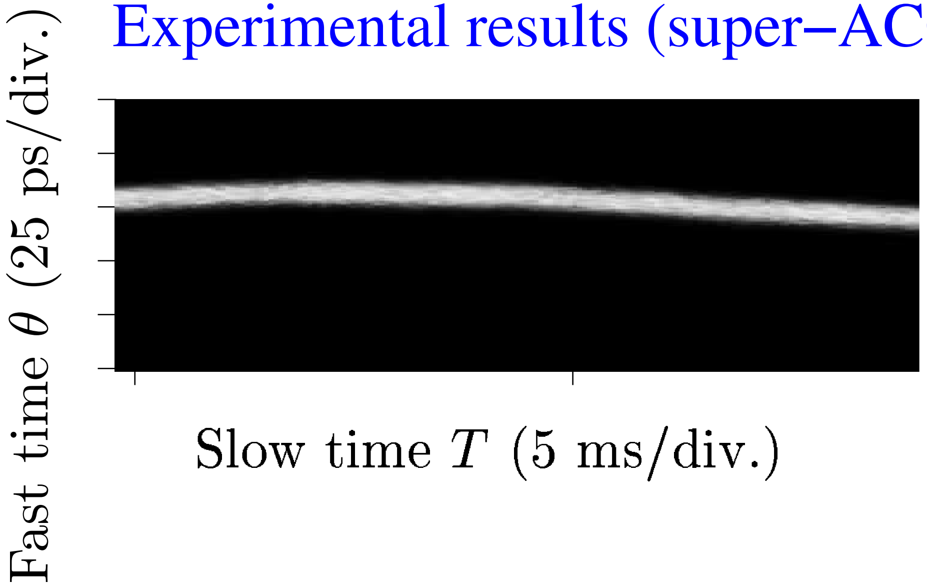
Questions:

- Experimentally realistic ?
- insights on the "origin" of these holes ?

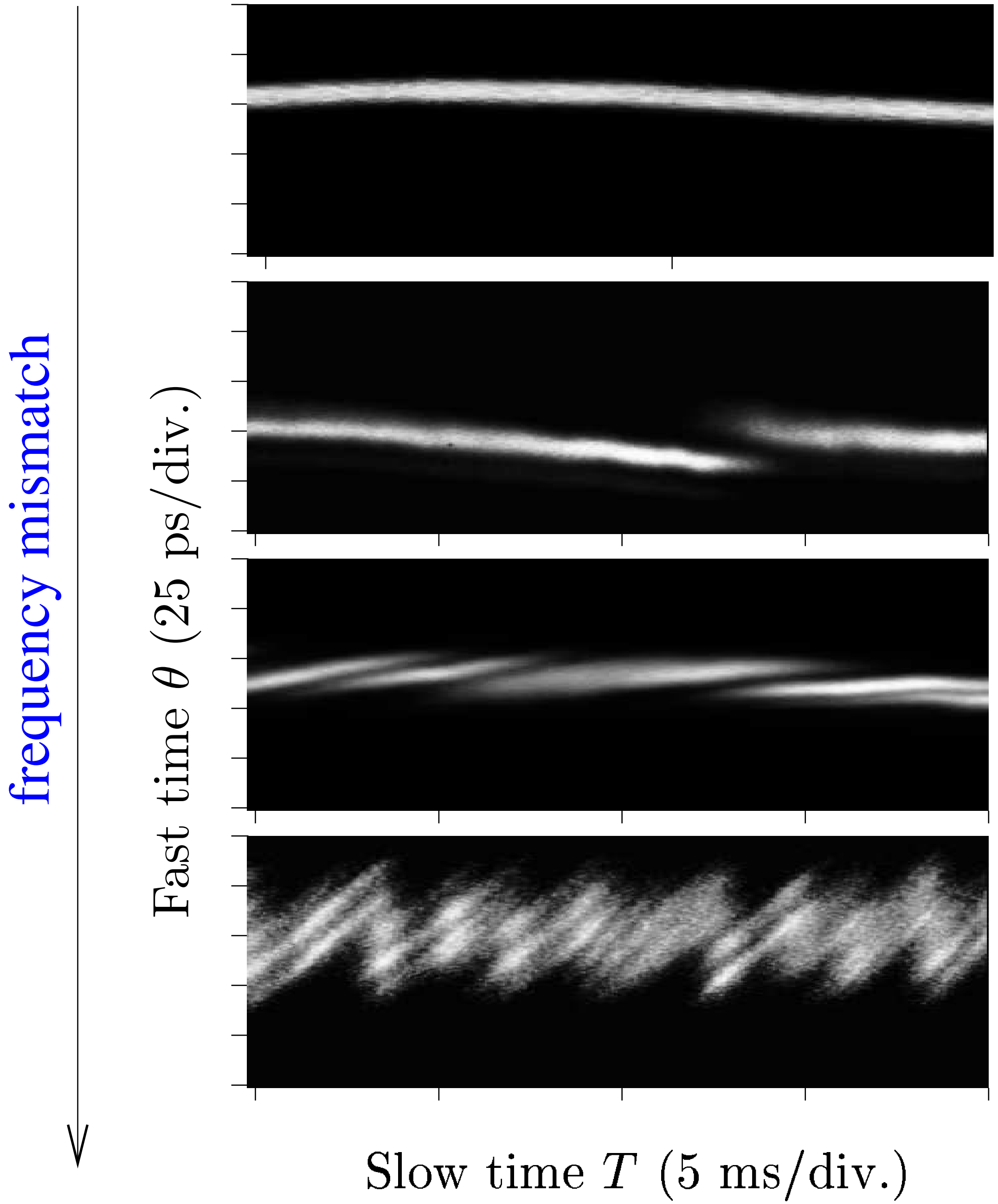
Real–time spectrum analyzer

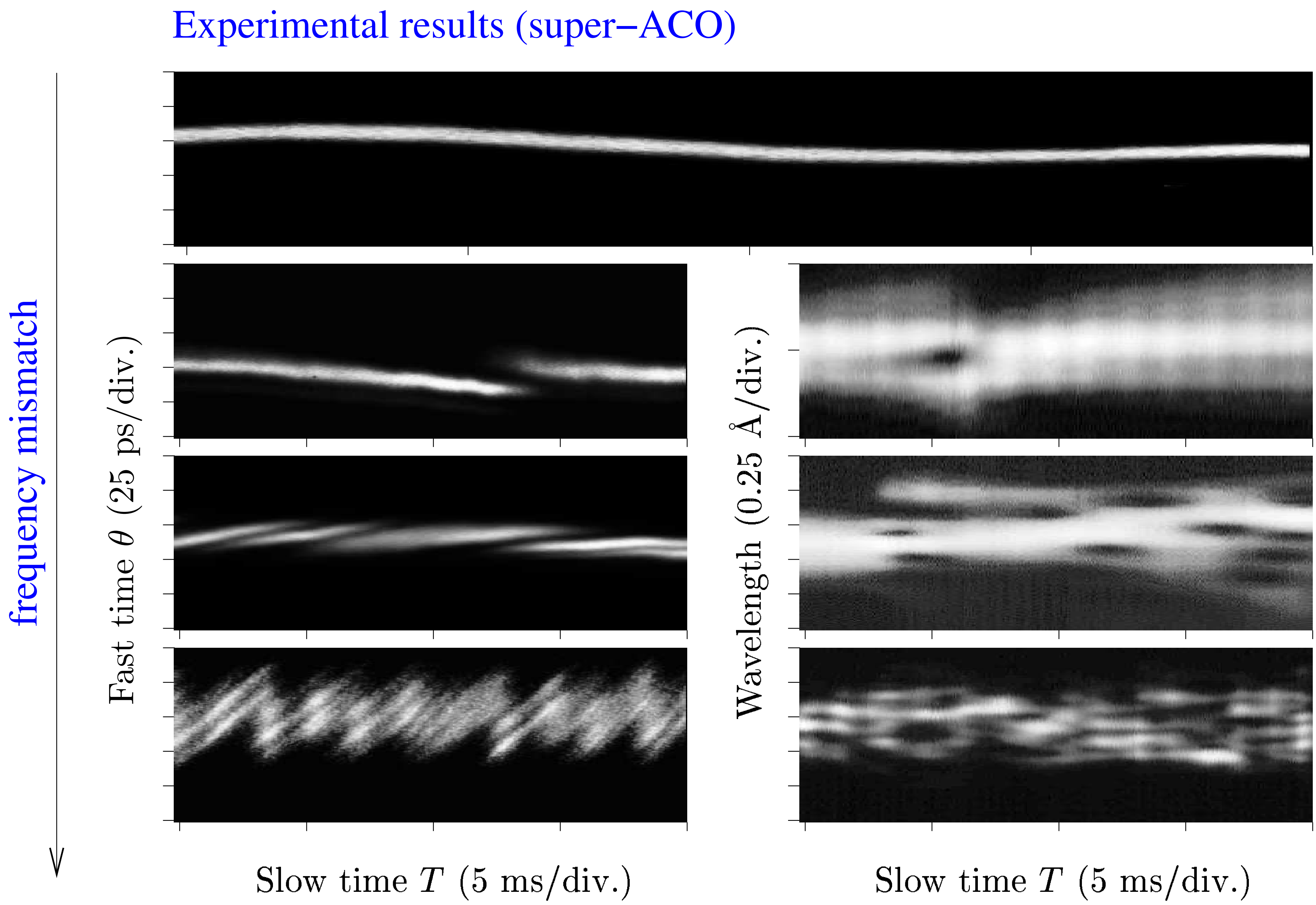


Experimental results (super–ACO)



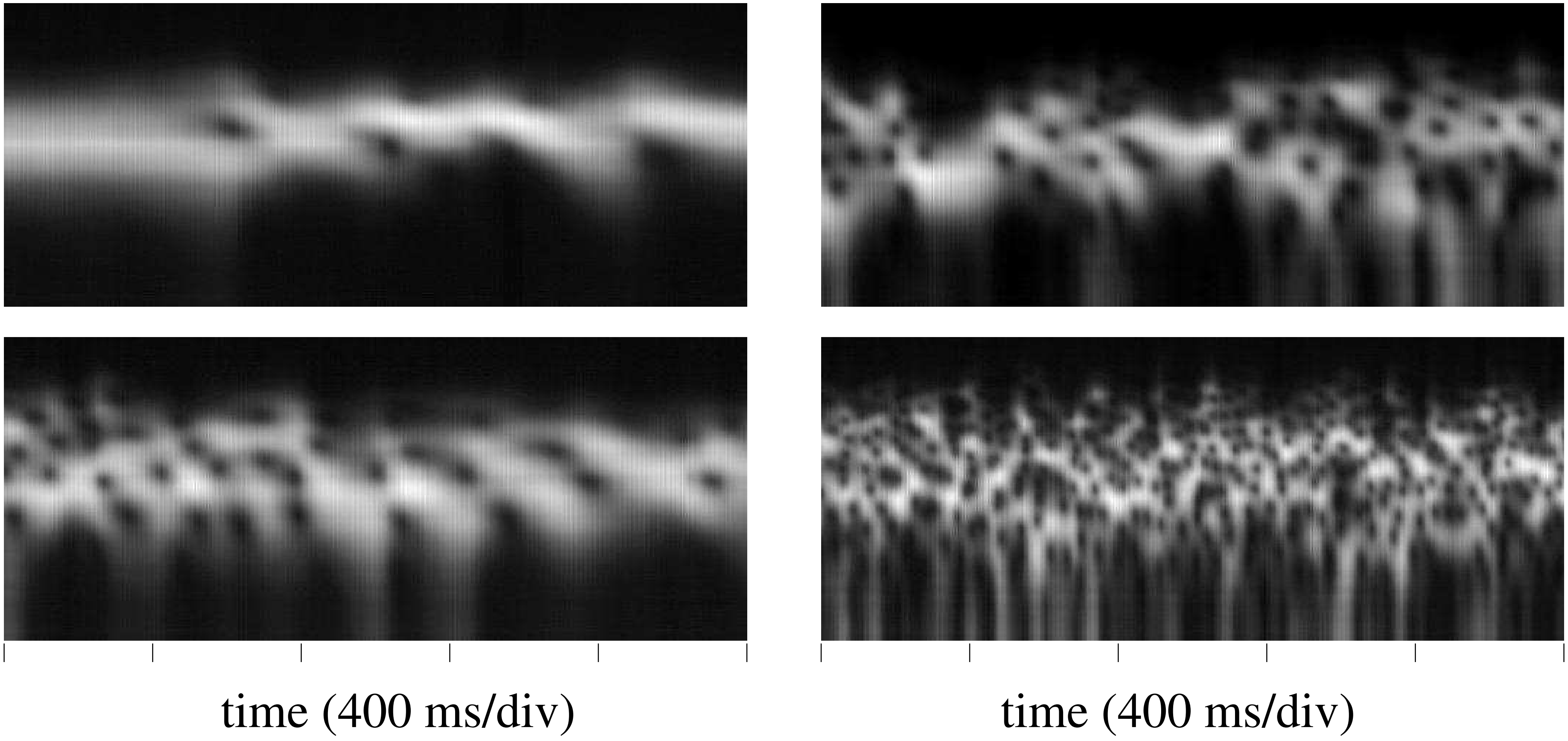
Experimental results (super−ACO)





Experimental results (super–ACO)
frequency mismatch
Fast time θ (25 ps/div.)
Wavelength (0.25 Å/div.)
Slow time T (5 ms/div.)
Slow time T (5 ms/div.)

Optical spectrum versus time: Recent results at UVSOR (IMS, Japan)



Nonlinear dynamics point of view: Minimum dynamical ingredients?

Part of this specific model is necessary for the instability, part is NOT

$$e_T + ve_\theta = -e + g(T)f(\theta)(e + e_{\theta\theta}) + \eta\xi, \tag{1}$$

$$g(T) = \frac{A}{\sigma^2(T)} \exp\left[-(\sigma^2(T) - 1)/2\right] \tag{2}$$

$$\text{with } \frac{d\sigma^2}{dT} = \gamma\left(1 - \sigma^2 + \int_0^L |e(\theta, T)|^2 d\theta\right). \tag{3}$$

- laser pulse length $\ll$ bunch length: Taylor expansion of $f(\theta)$
- identification of slowest timescales? Usually γ (e.g., macropulse instabilities). Here?

"Minimal" equations ?

A Ginzburg-Landau equation with

- global coupling
- a slowly-varying parameter

$$e_T + v e_z = e_{zz} + R\left[1 - (\epsilon z)^2\right] e - e\int_{-\infty}^{+\infty} |e|^2 dz + \eta\xi$$

or $-|e|^2 e$

convection

(Global or local coupling)

"Minimal" equations ?

A Ginzburg-Landau equation with

- global coupling
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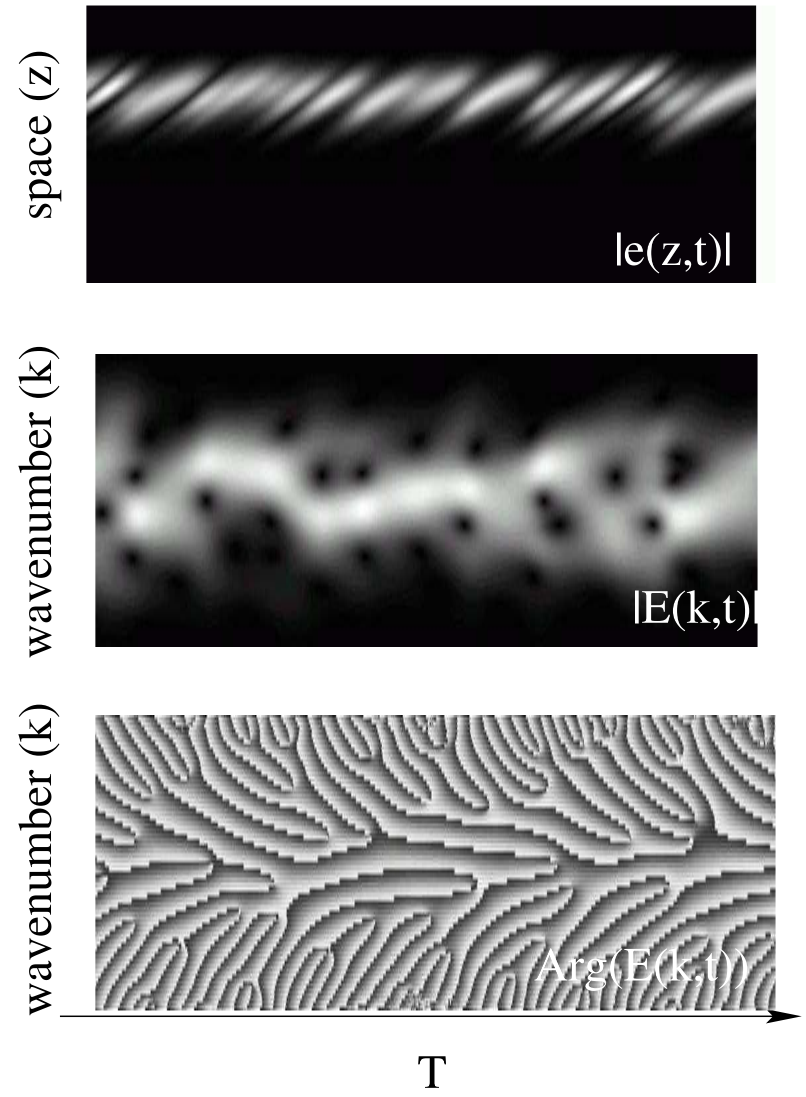
$$e_T + v e_z = e_{zz} + R\left[1 - (\epsilon z)^2\right] e - e \int_{-\infty}^{+\infty} |e|^2 dz + \eta\xi$$

or $-|e|^2 e$

convection

(Global or local coupling)

ex. with global coupling



Mechanism ? (GL+global coupling)

A Ginzburg-Landau equation with

- global coupling
- a slowly-varying parameter

$$e_T + v e_z = e_{zz} + R\left[1 - (\epsilon z)^2\right] e - e \int_{-\infty}^{+\infty} |e|^2 dz + \eta\xi$$

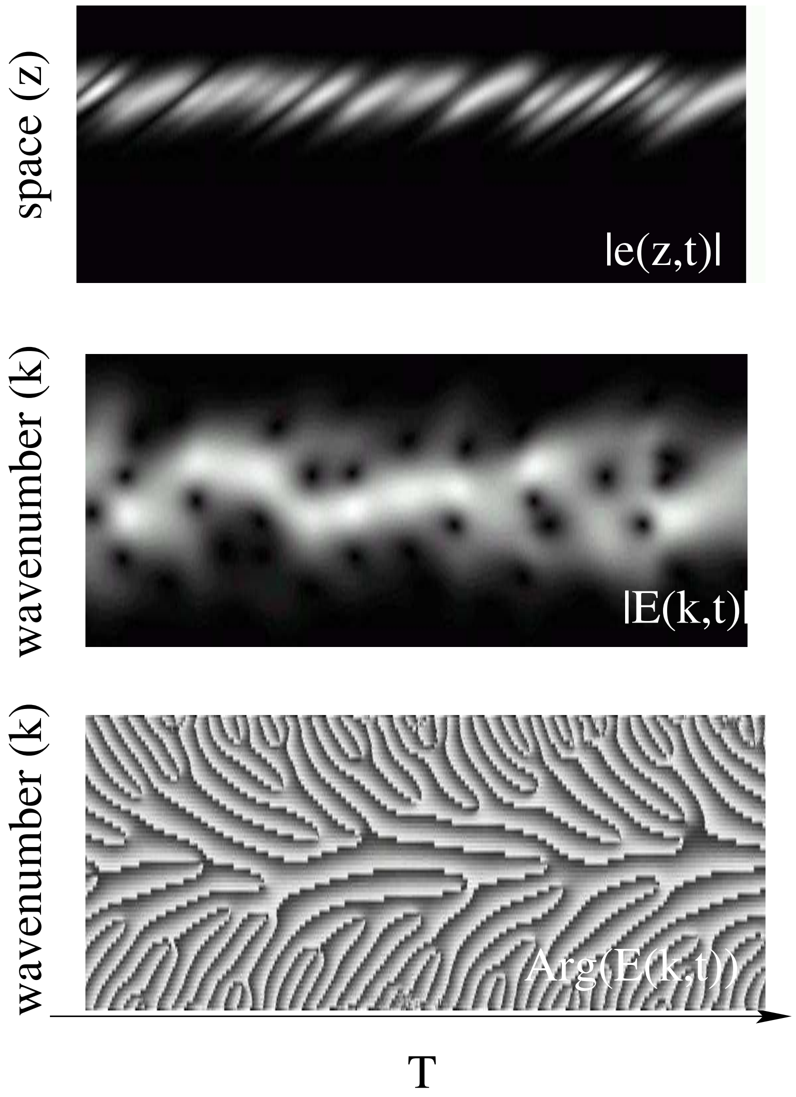
In Fourier space:

$$E_T = \epsilon^2 E_{kk} + RE - (ivk + k^2)E - E \int_{-\infty}^{+\infty} |E|^2 dk + \eta\xi$$

Diffusion

Non–uniformities of control parameters

Global coupling



Open question: links with the "Riecke and Paap instability? Riecke and Paap, PRL 59, 2570 (1987)

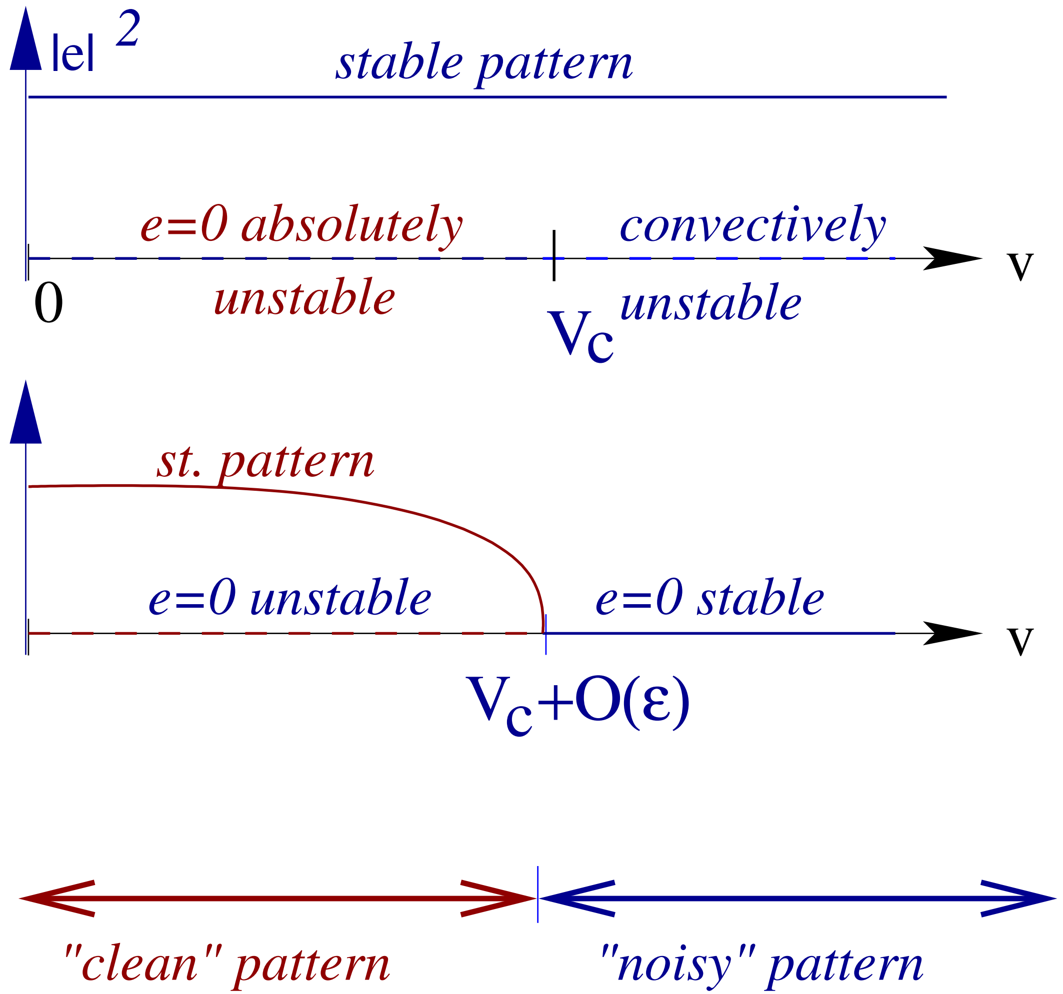
Differences between global and local couplings? –> (1) local

$$e_T + v e_z = e_{zz} + R\left[1 - (\epsilon z)^2\right] e - |e|^2 e + \eta\xi$$

infinite medium (ε=0)

finite medium (ε≠0)

finite medium +noise



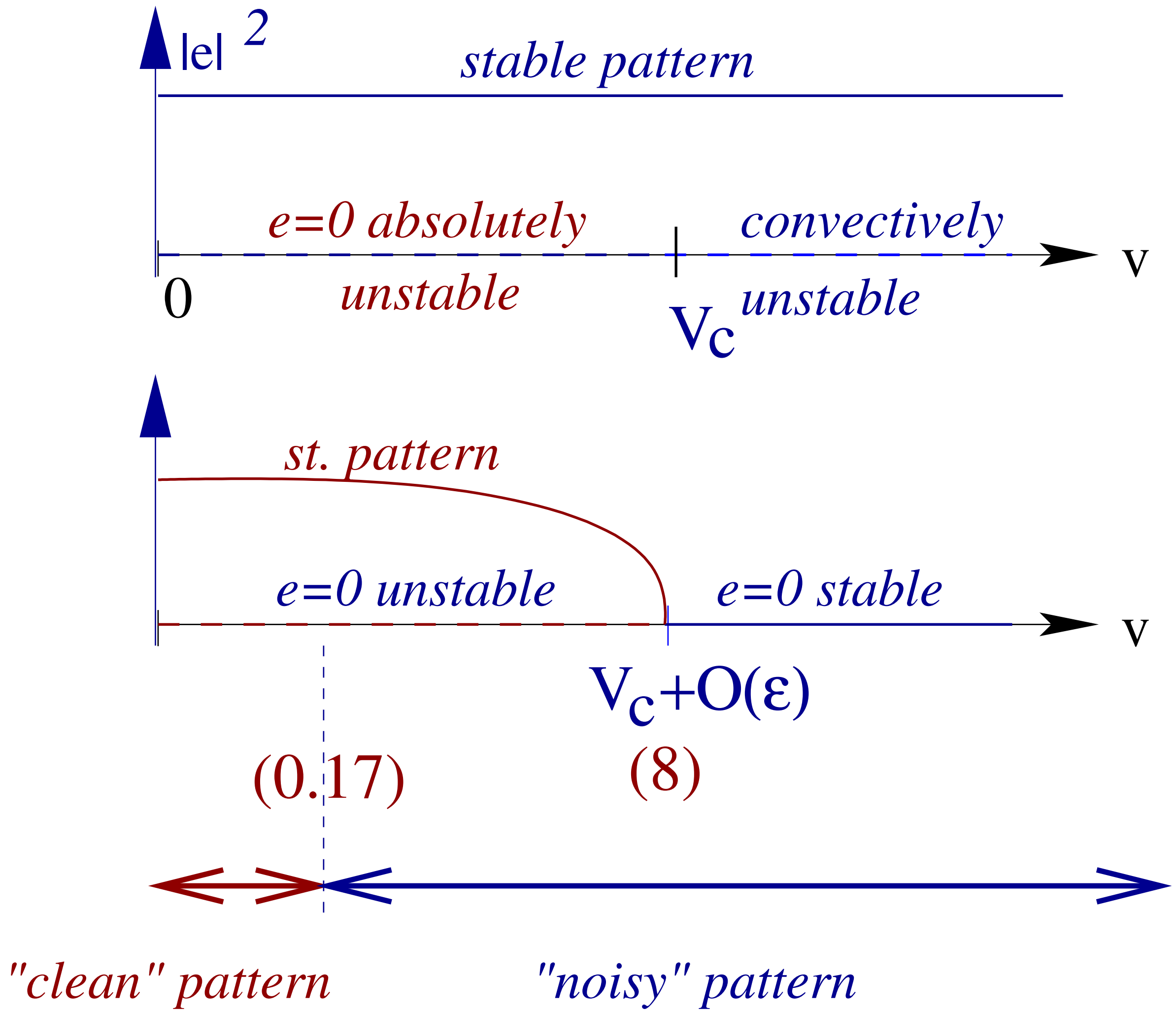
Differences between global and local couplings? –> (2) global

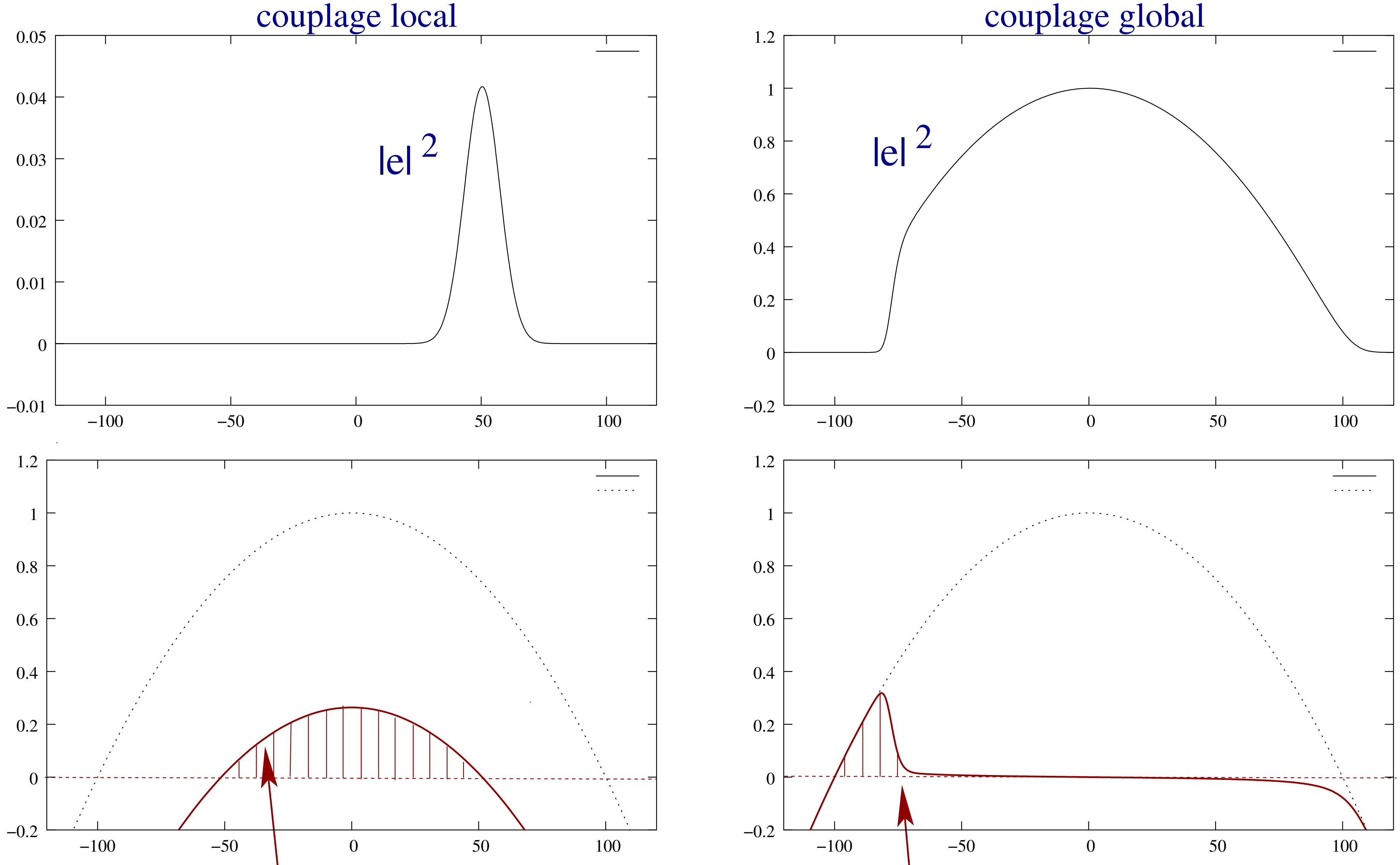
$$e_T + v e_z = e_{zz} + R\left[1 - (\epsilon z)^2\right] e - e \int_{-\infty}^{+\infty} |e|^2 dz + \eta \xi$$

infinite medium (ε=0)

finite medium (ε≠0)

finite medium +noise





$$e_T + v e_z = e_{zz} + \left(R\left[1 - (\epsilon z)^2\right] - \int_{-\infty}^{+\infty} |e|^2 dz\right) e$$

$$e_T + v e_z = e_{zz} + \left(R\left[1 - (\epsilon z)^2\right] - |e|^2\right) e$$

Conclusion

* Laser à électrons libres = système avec advection + saturation globale
* Transition lorsque v augmente –> trous spectro–temporels
  –> idem pour Ginzburg–Landau avec couplage local ou global

Bielawski, Szwaj, Bruni, Garzella, Orlandi, Couprie, PRL 95, 034801 (2005)

For other issues (FEL control), see:

Bielawski, Bruni, Garzella, Orlandi, Couprie, PRE, 69, R045502 (2004)

Conclusion

* Laser à électrons libres = système avec advection + saturation globale

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–> idem pour Ginzburg–Landau avec couplage local ou global

couplage global

Distinction entre:

– Domaines convectif/absolu
– Structures entretenues par le bruit
– Structures bruyantes

➤ *poster RNL*

Bielawski, Szwaj, Bruni, Garzella, Orlandi, Couprie, PRL 95, 034801 (2005)

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$$e_T + v e_z = e_{zz} + R\left[1-(\epsilon z)^2\right] e \quad - \quad e\int_{-\infty}^{+\infty} |e|^2 dz + \eta\xi$$

$$\text{- - - - - - - - - - - - - - - - - - - -} \quad - \quad |e|^2 e$$