Massively Parallel Vortex Particle Simulations of Aircraft Wakes

Philippe Chatelain

with : M. Bergdorf, D. Rossinelli, P. Koumoutsakos
and A. Curioni (IBM Research)

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Outline

- Motivation
- Vortex Particle Method
- Medium Wavelength Instability
- Optimization of Wake Decay
- Conclusions

Motivation

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- **COMPUTATION**
  - Massively Parallel Simulations Using Particles
    - IBM/BG: Distributed memory (10^4 - 10^5 CPUS), with low RAM per node
    - Achieve sustained *O*(Tflops) performance

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- **PHYSICS**
  - Optimization of aircraft wake decay
    - aircraft & lift devices design
  - High Reynolds DNS
    - Capture accurate decay of vortical flows
    - Physical insight - Basis for turbulent models

Vortex Particle Method

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- **GOVERNING EQUATIONS**
  - Navier-Stokes, incompressible

$$\begin{aligned} \nabla \cdot \mathbf{u} &= 0 \\ \frac{D\mathbf{u}}{Dt} &= -\frac{1}{\rho}\nabla p + \nu \Delta \mathbf{u} \end{aligned}$$

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- **EVOLUTION EQUATIONS**

$$\begin{aligned} \frac{d\mathbf{x}_p}{dt} &= \mathbf{u}(\mathbf{x}_p) \\ \frac{d\boldsymbol{\alpha}_p}{dt} &= \left((\boldsymbol{\omega} \cdot \nabla)\mathbf{u}(\mathbf{x}_p) + \nu \nabla^2 \boldsymbol{\omega}(\mathbf{x}_p)\right) V_p \end{aligned}$$

Vortex Particle Method

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- Particle methods ARE NOT MESH-FREE

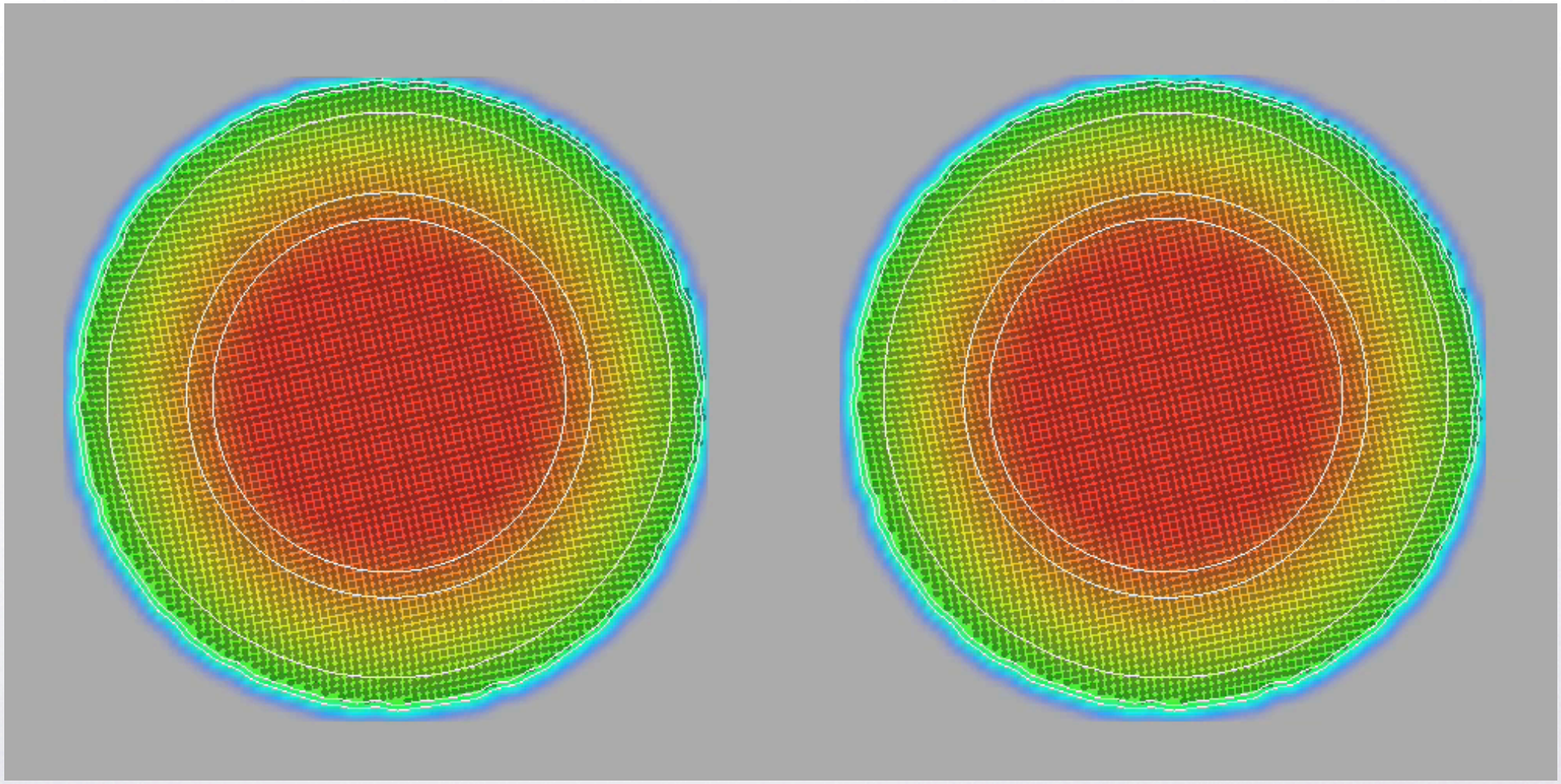
Vortex Particle Method

- ACCURATE Particle methods ARE NOT MESH-FREE

  ➡ Particle distortion = loss of convergence

$$\frac{D\Gamma_p}{Dt} = 0$$

Euler Equations (2D : u−w) for an incompressible evolution of an axi-symmetric vortex patch



Remeshed Particle Methods

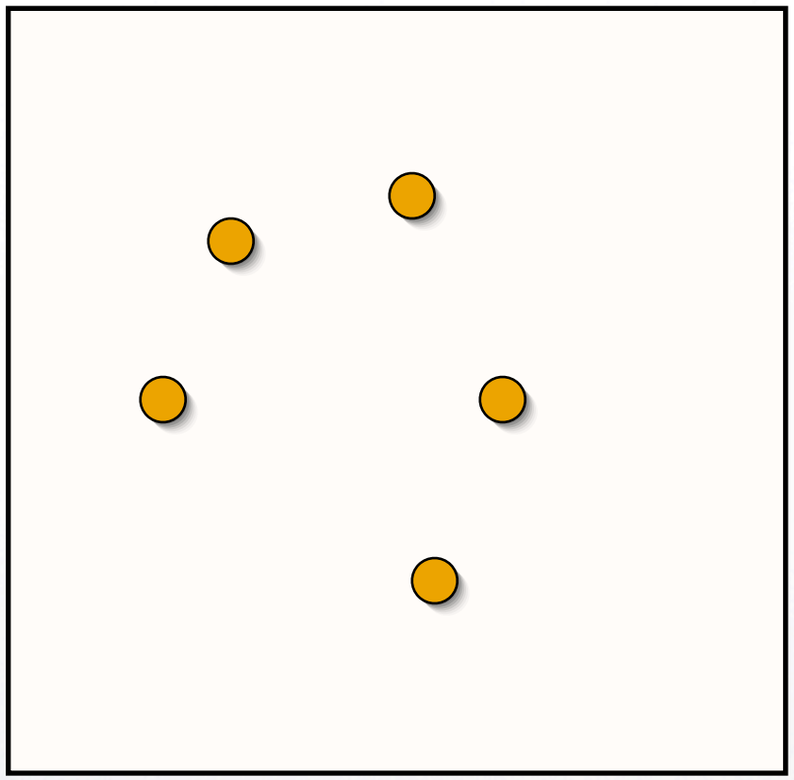
$$Q_p^{\text{new}} = \sum_{p'} Q_{p'} M(j\,h - x_{p'})$$

Interpolation Kernel $M(x)$

- **Moment** conserving
- Tensorial Product of 1D kernels

Remeshed Particle Methods

- *Remesh* : reinitialize particles onto regular locations



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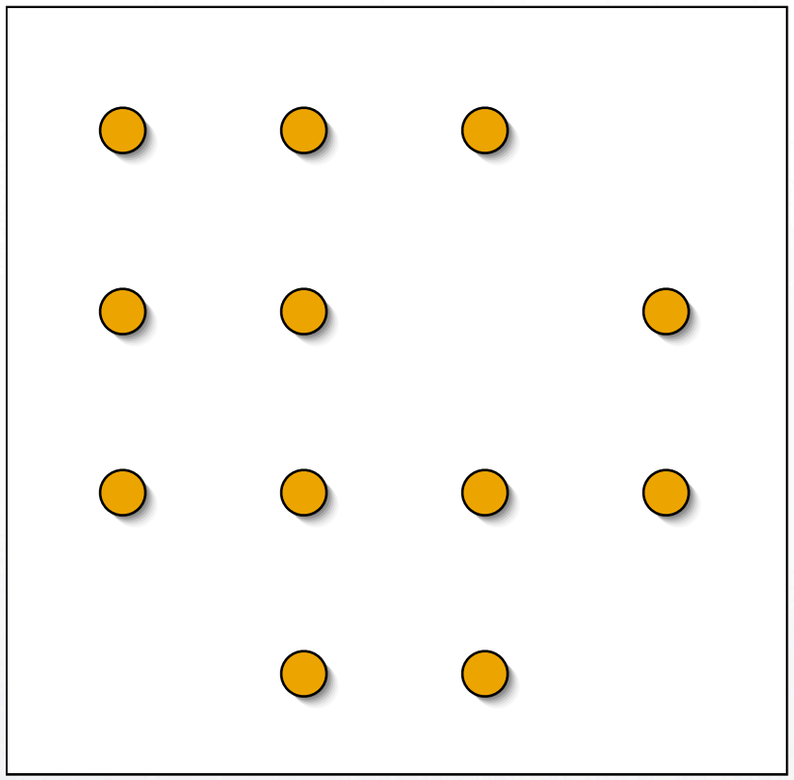

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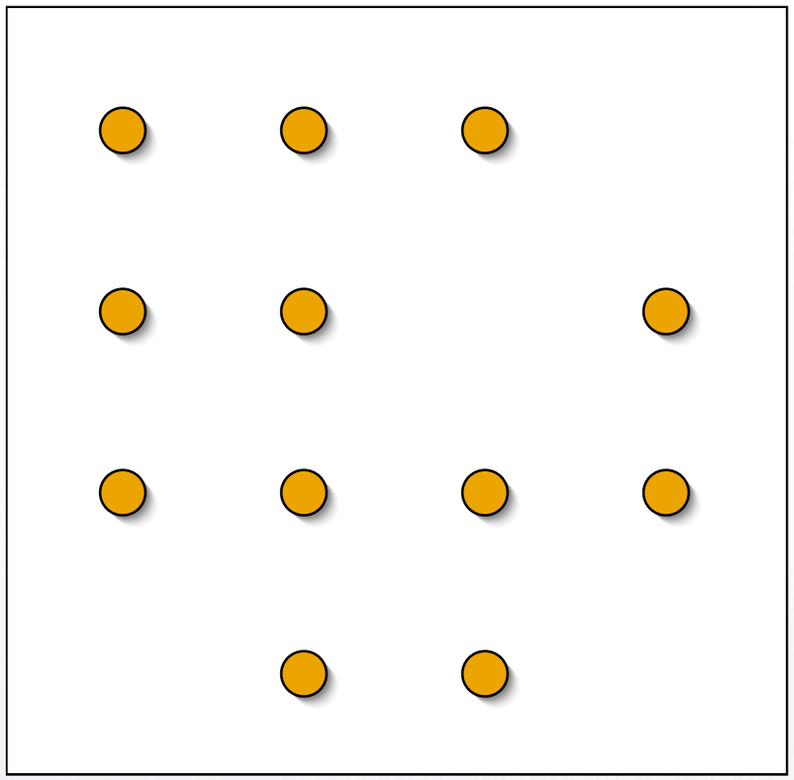

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- Mesh also used for the efficient computation of **Right-Hand Side**

Vortex particle method

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- Hybrid scheme
  - Mesh: **RHS** evaluations

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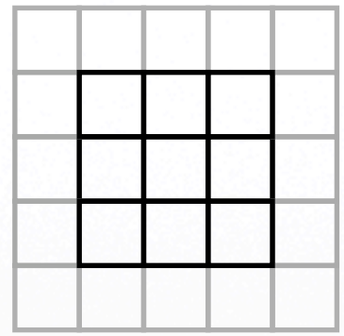
    - Differential operators (F.D.)
    - Fast Poisson solver (Fourier)



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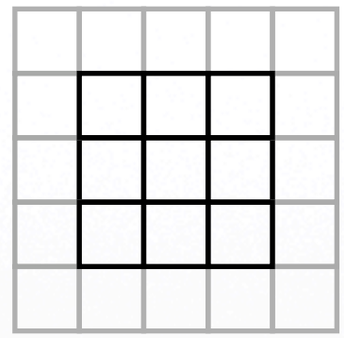

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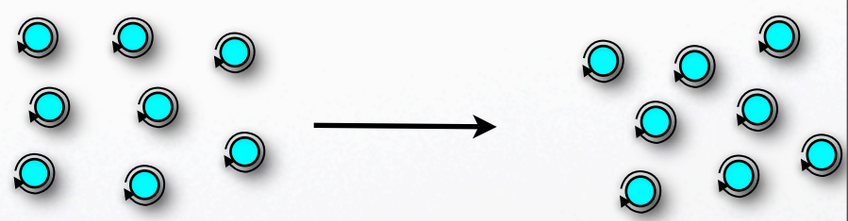

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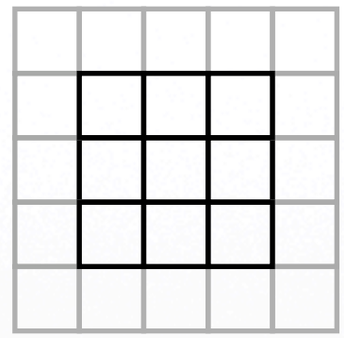

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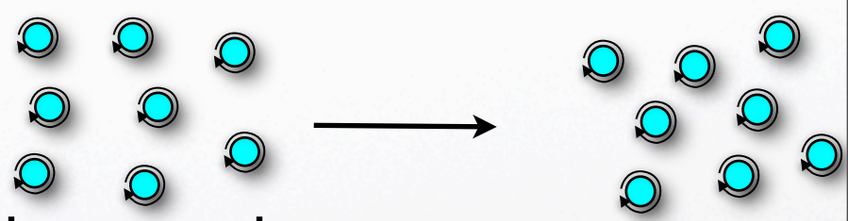
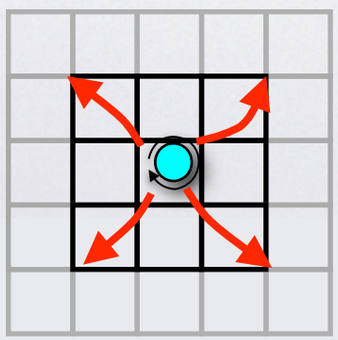


  - Particles and Mesh communicate through **interpolation**



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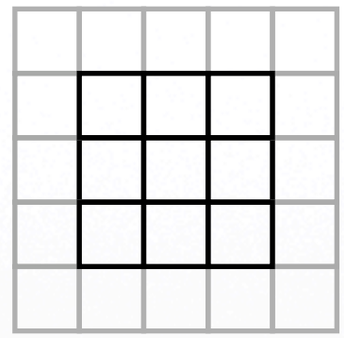

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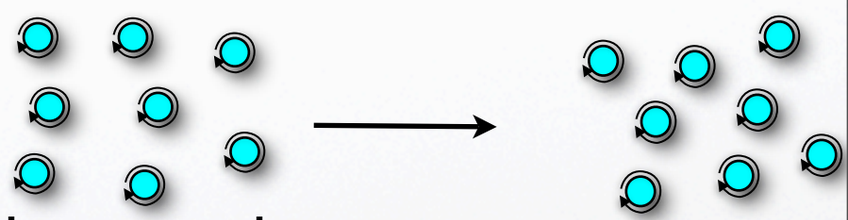

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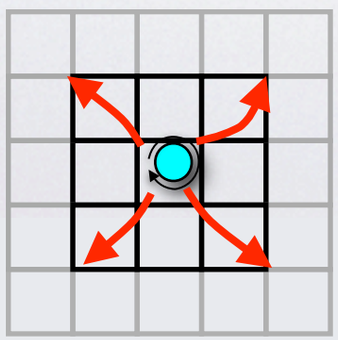

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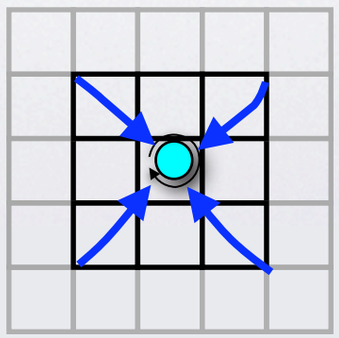

$$\begin{matrix}\mathbf{u}_{ij}\\ (\boldsymbol{\omega}\cdot\nabla)\mathbf{u}_{ij}\\ \Delta\boldsymbol{\omega}_{ij}\end{matrix} \rightarrow \begin{matrix}\mathbf{u}_{p}\\ (\boldsymbol{\omega}\cdot\nabla)\mathbf{u}_{p}\\ \Delta\boldsymbol{\omega}_{p}\end{matrix}$$

Implementation

www.cse-lab.ethz.ch/software.html

- Code is client of the **PPM** library

Sbalzarini et al, JCP 2006

- **P**arallel **P**article **M**esh Library (Fortran 90, MPI)
- Client and library *tuned* for BG/L

Chatelain et al, CMAME 2008

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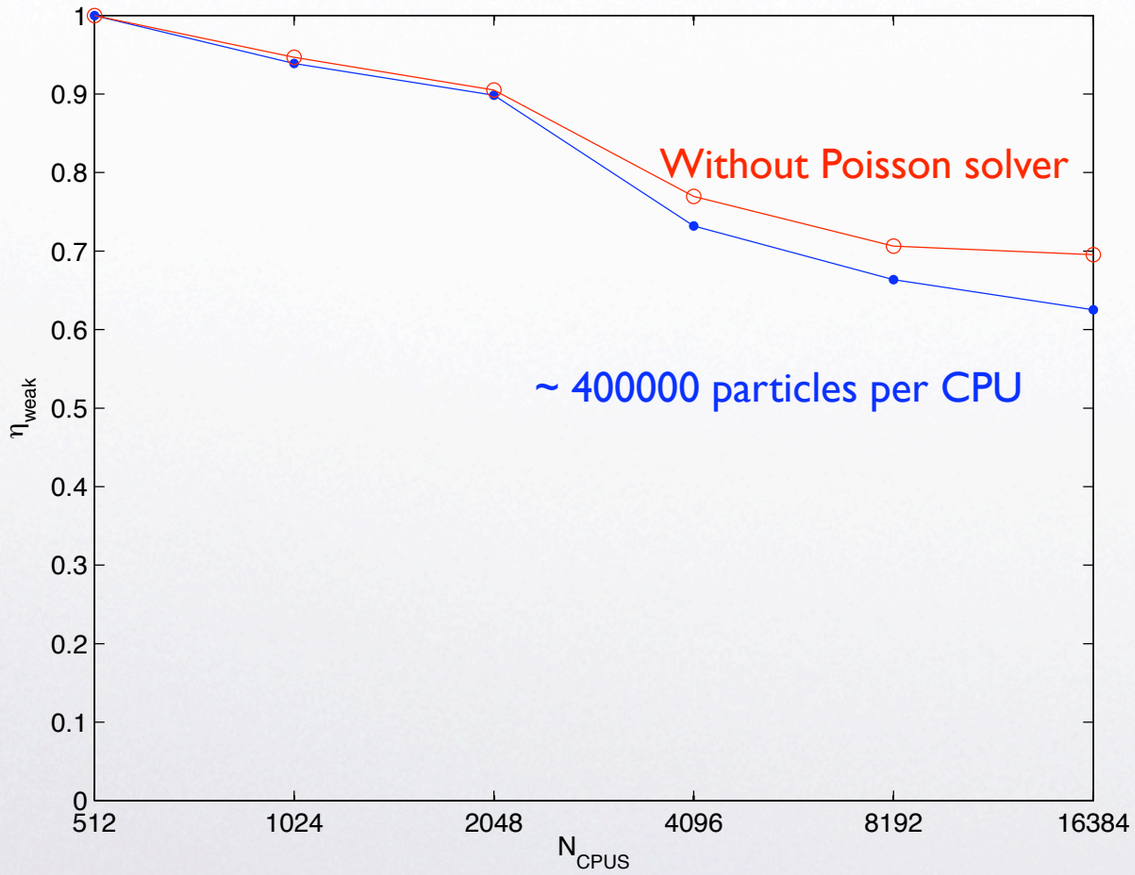

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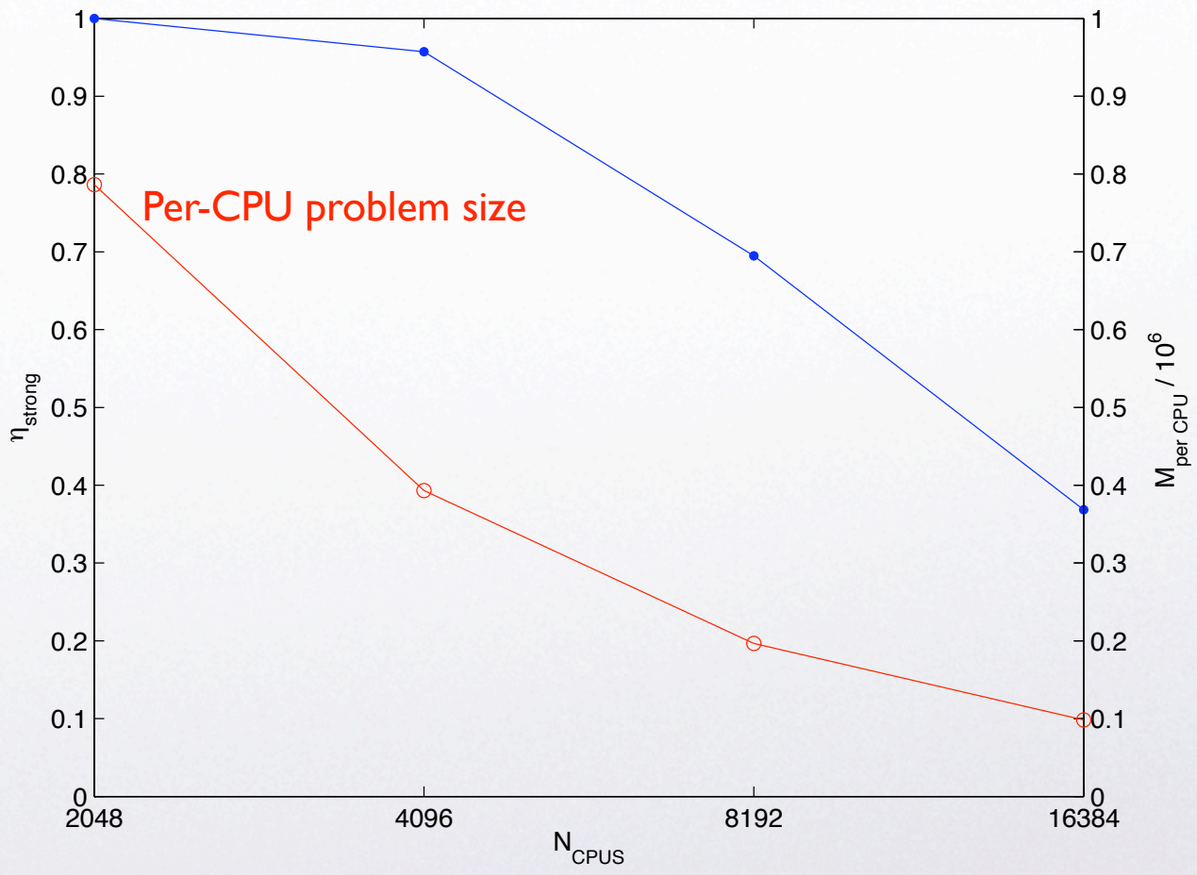

PPMers: I. Sbalzarini, J. Walther, M.Bergdorf, P. Chatelain, S. Hieber, E. Kotsalis, P. Koumoutsakos, F. Milde, M. Quack, B. Hejazi Alhosseini

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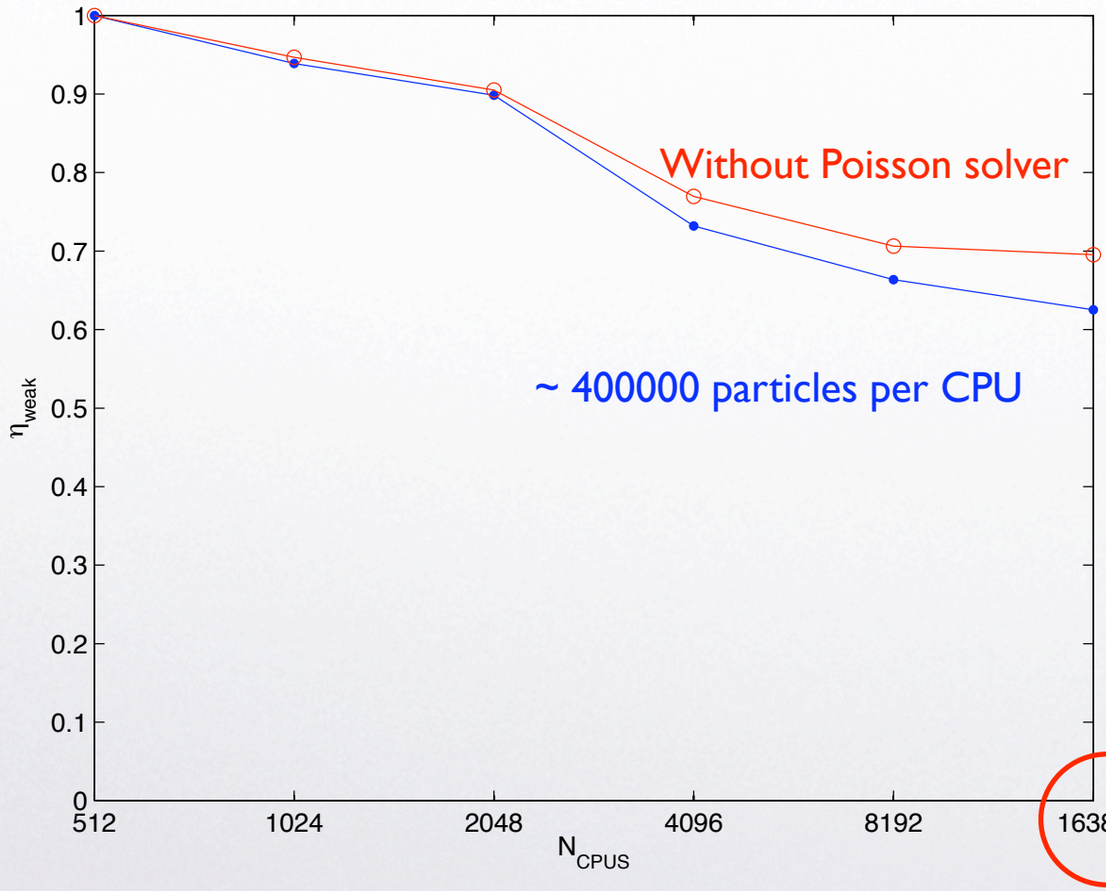

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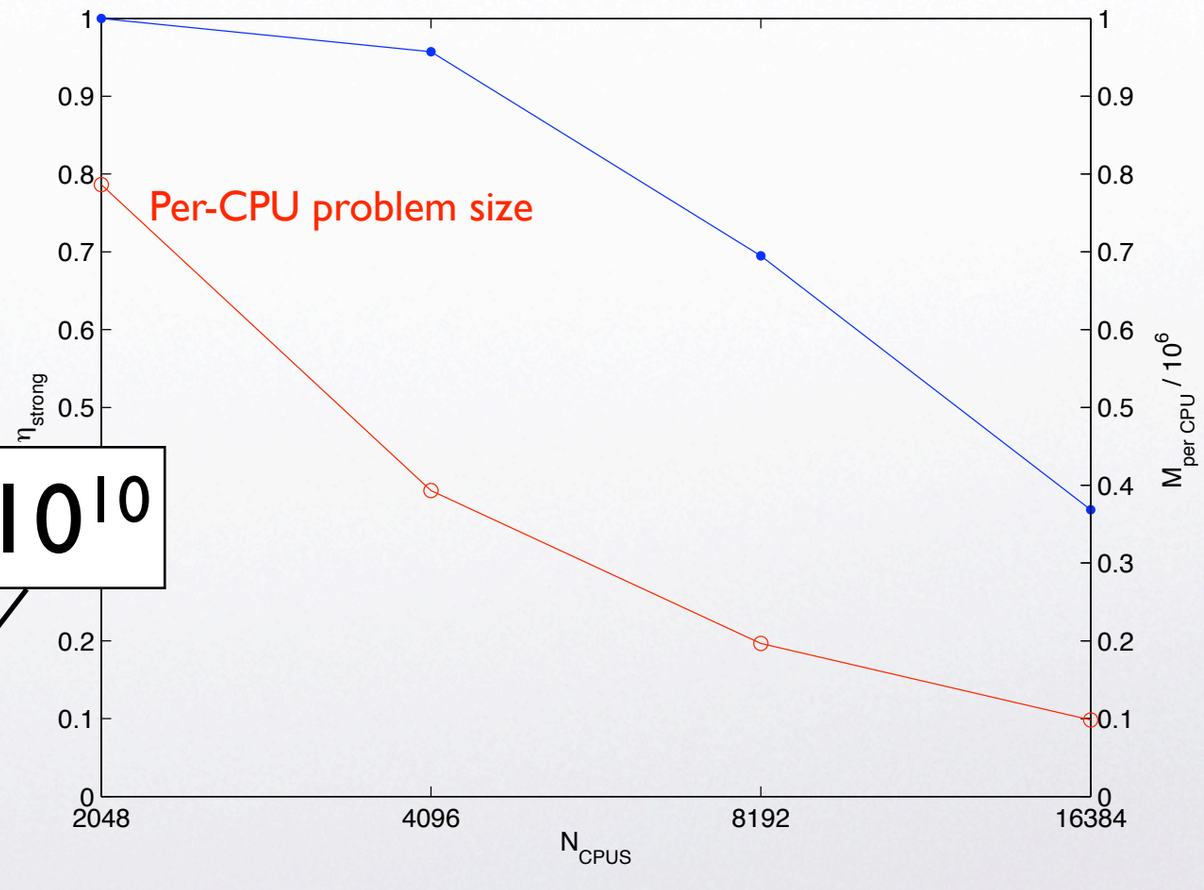

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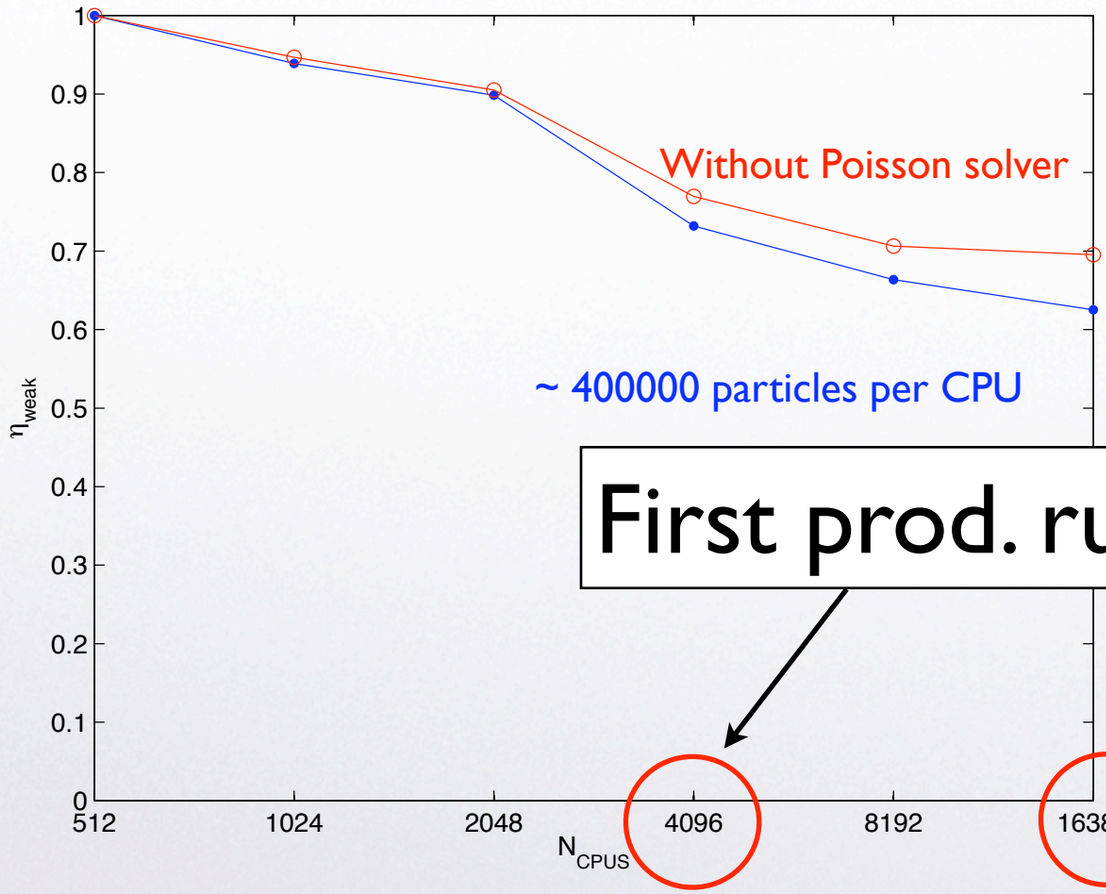

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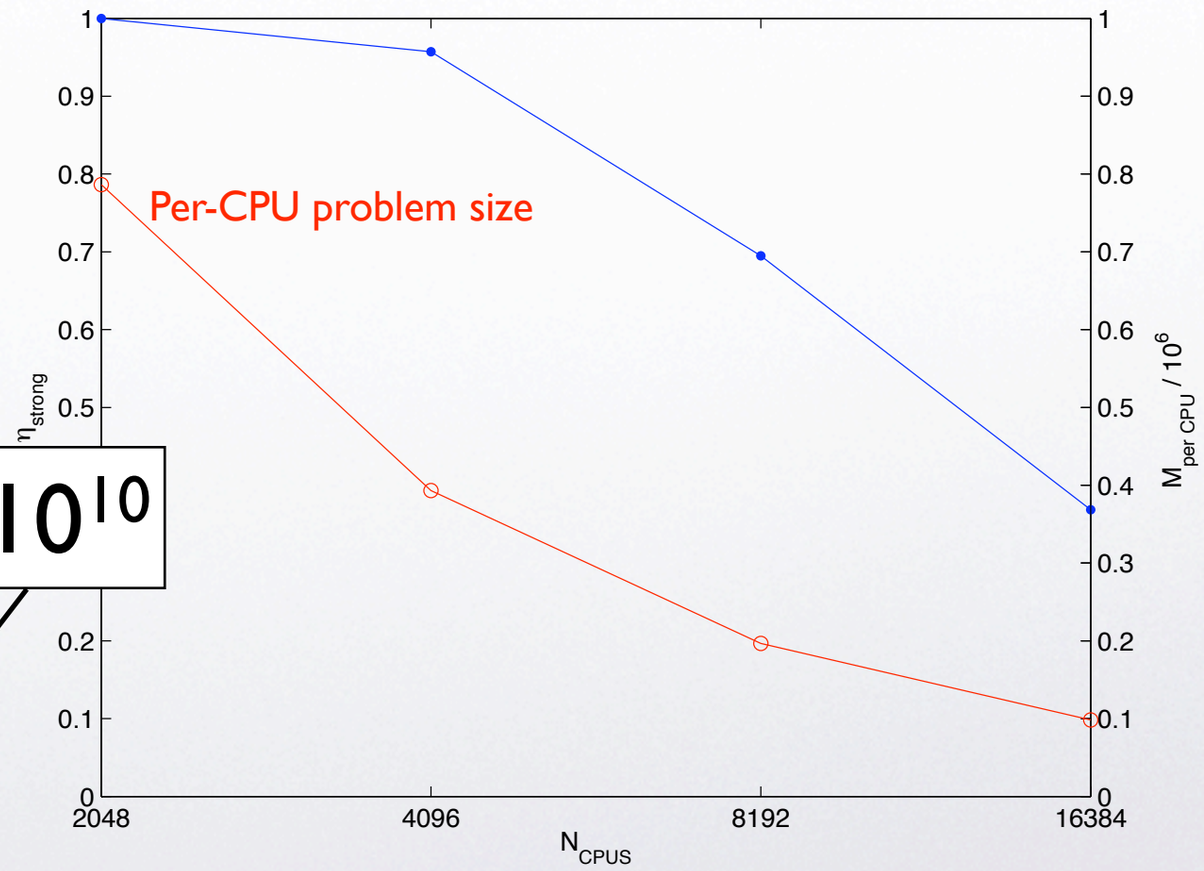

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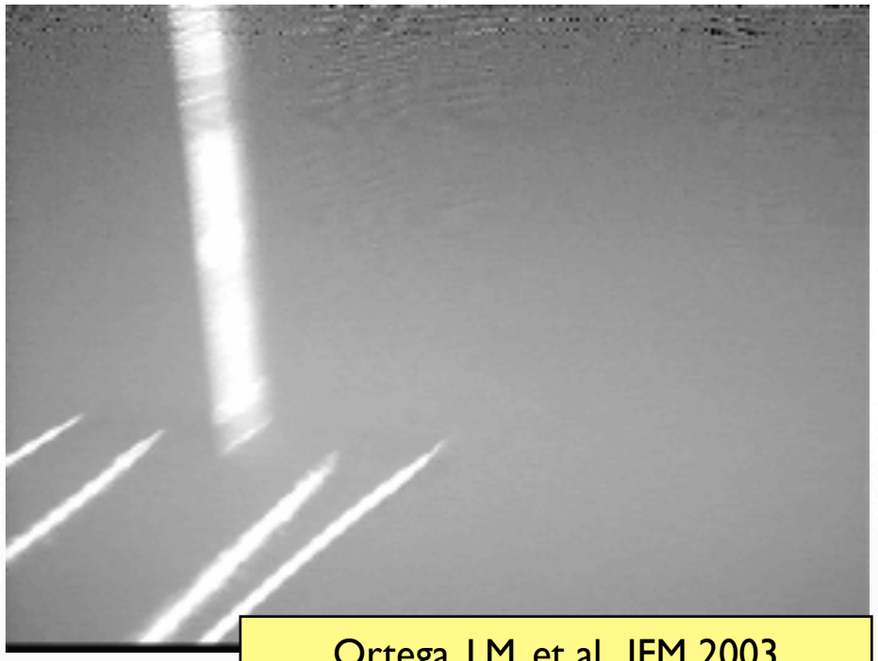
- Long domain
- Periodic in all directions
- Initiation by ambient noise



Ortega, J.M. et al., JFM 2003

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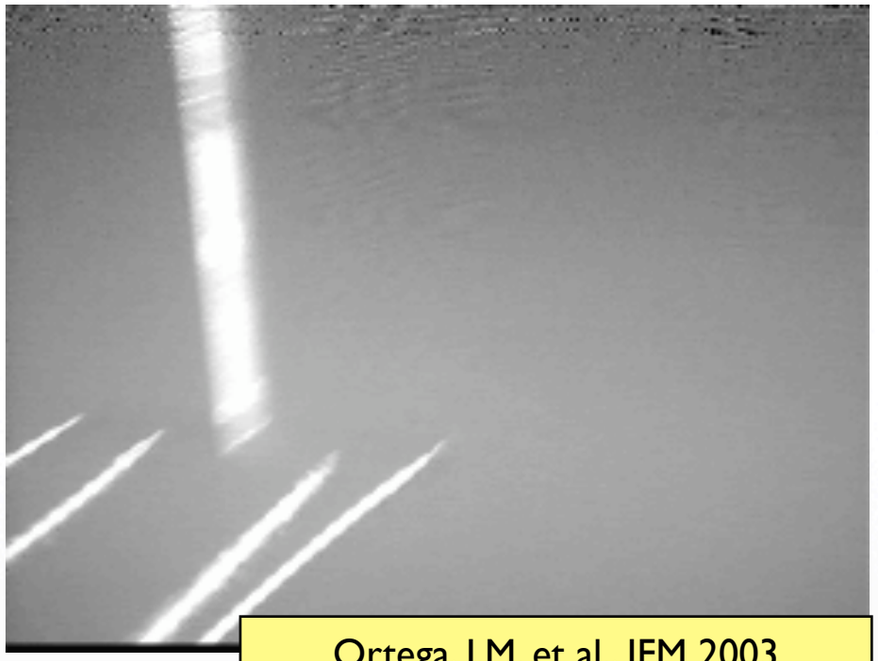

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Physical parameters

- Re_Γ = 6,000
- Circulation ratio Γ_2/Γ_1 = -0.35
- Span ratio b_2/b_1 = 0.5
- Domain $L_x = 10\ b_1$
- Time = 0.35
- Ambient white noise u_{RMS}= 0.5%

Numerical parameters

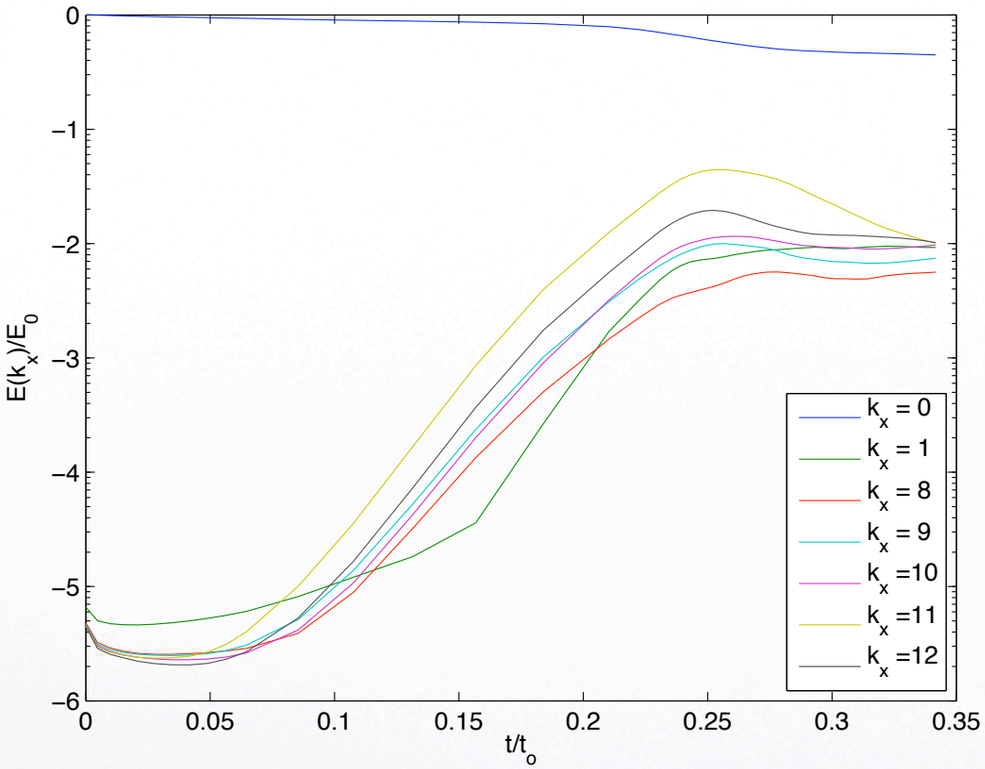
- ~1.6 10^9 particles
- 1024 x 768 x 2,048 grid
- 10,000 time steps
- RK3 Low-storage
- 4th order FD

CPU parameters

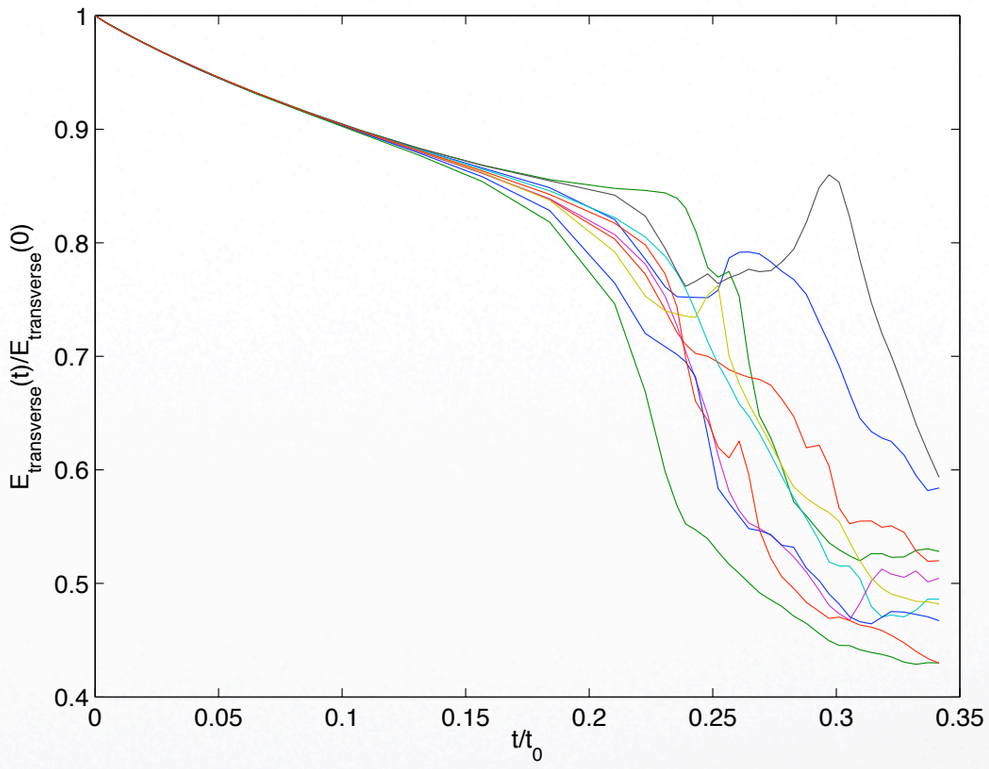
- IBM BlueGene/L
- 4096 CPUS
- 100 hours

Medium Wavelength Instability

- Spectra



- Cross-flow energy



  - Mode $\lambda/b_1 = 0.86 - 0.943$
    - Experimental $\lambda/b_1 = 0.9 - 1.3$
  - Bursts when Ω-loop feet come together
- Visualization: volume rendering of $|\omega|$

Rossinelli D. et al., SIGGRAPH08

Instability : **Linear phase** t=0.21

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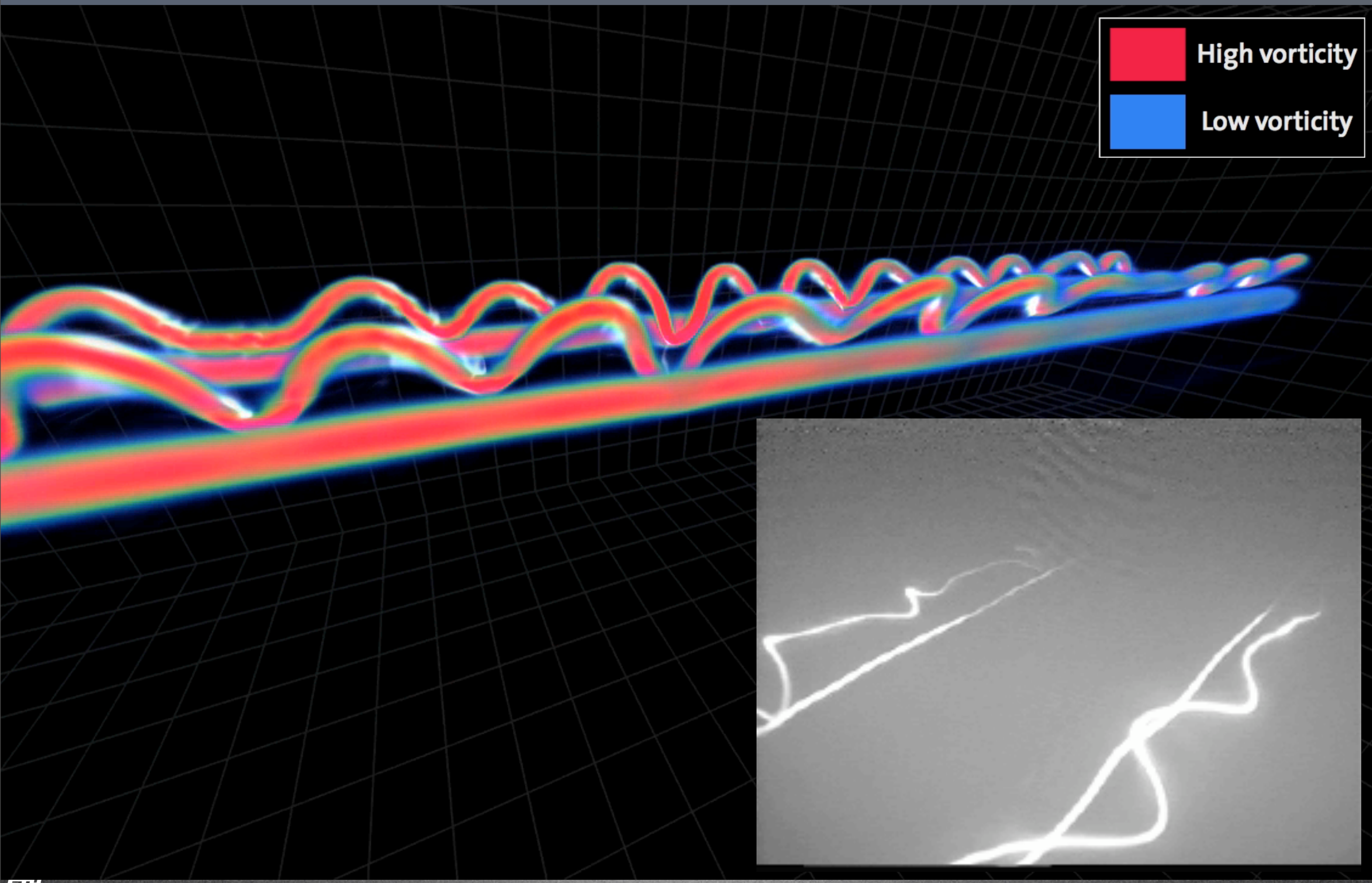
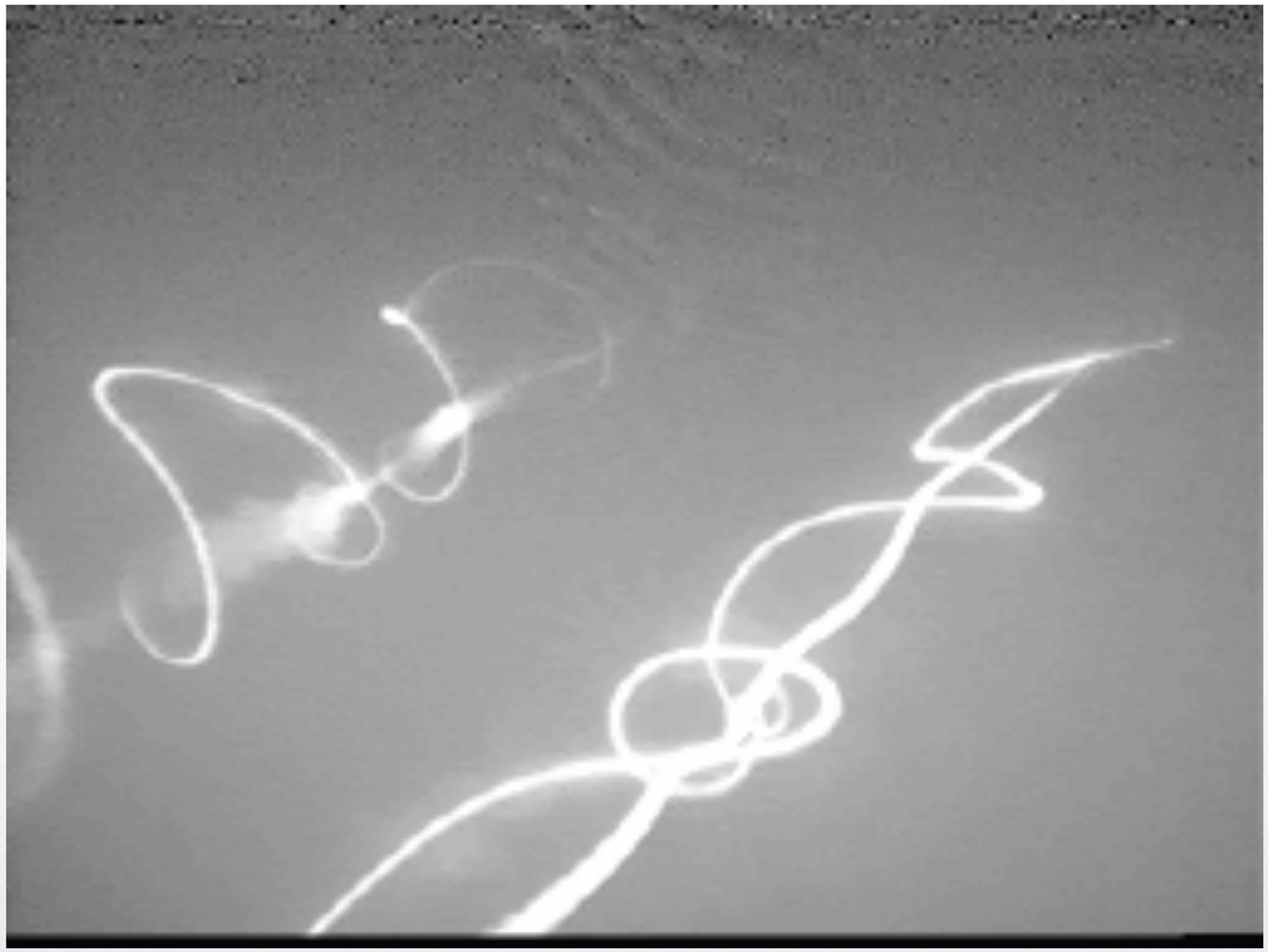


Instability : **Reconnections** t=0.25



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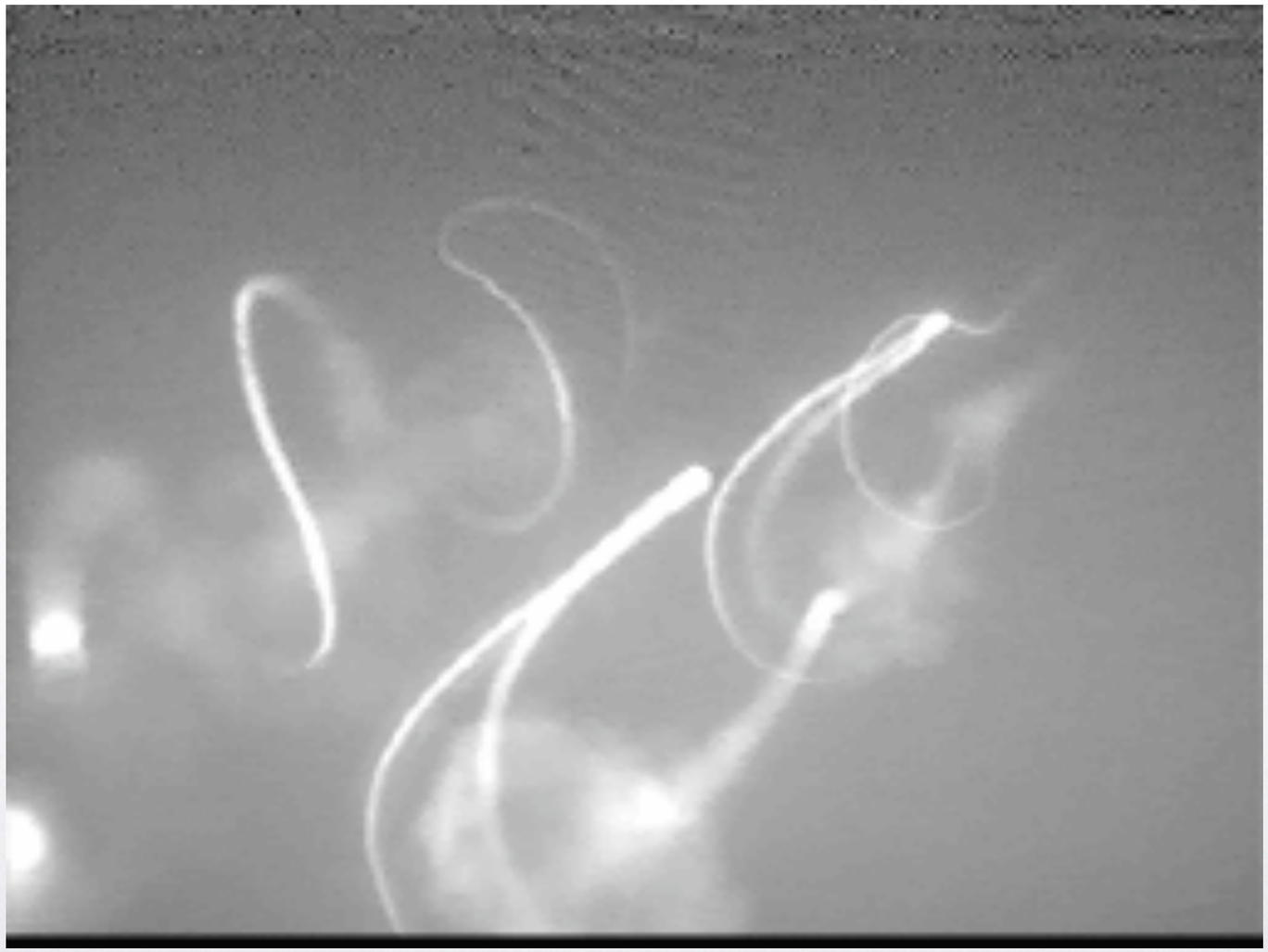
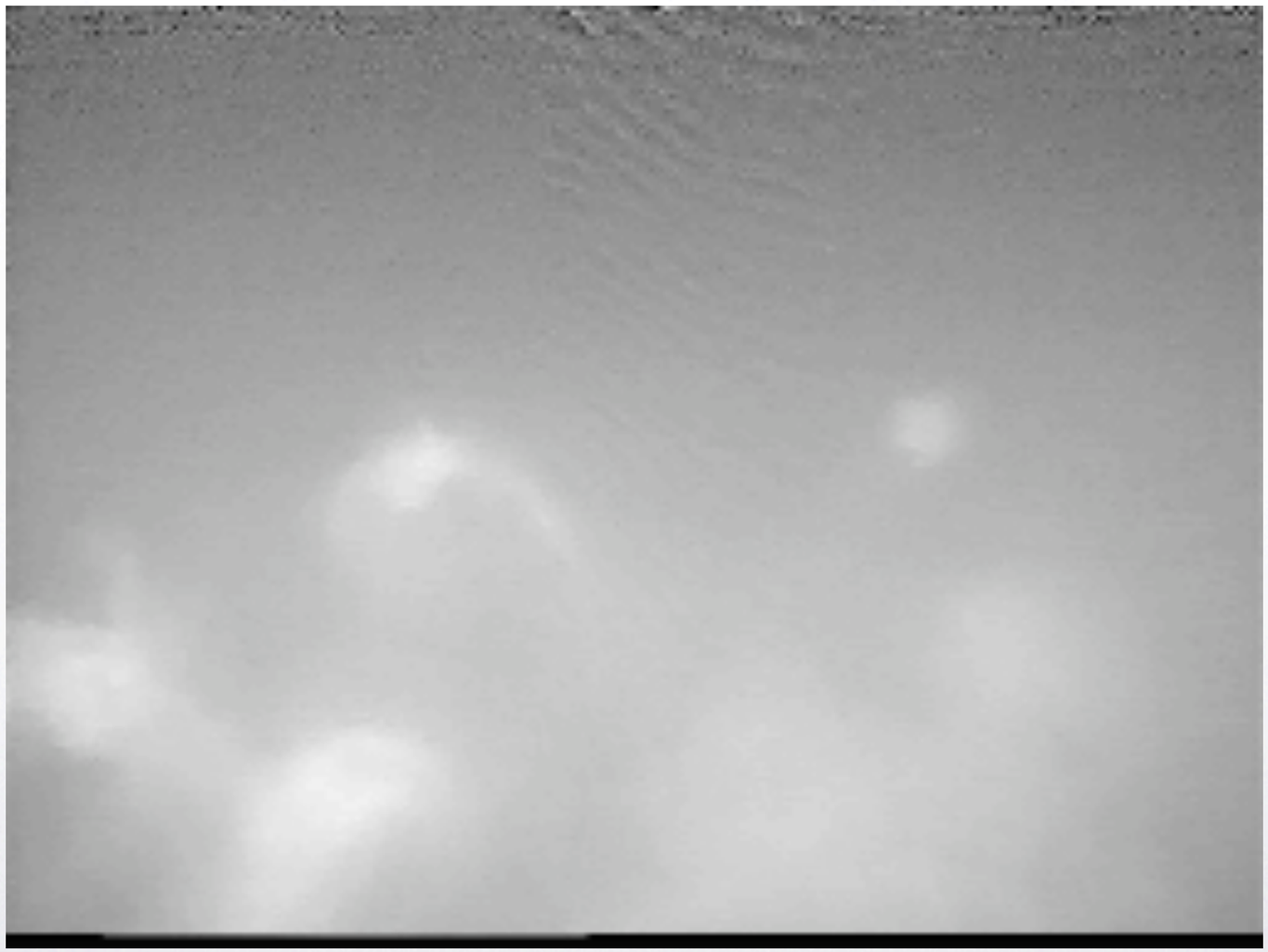


Instability: **Propagation** t=0.27

Instability: Decay t=0.35



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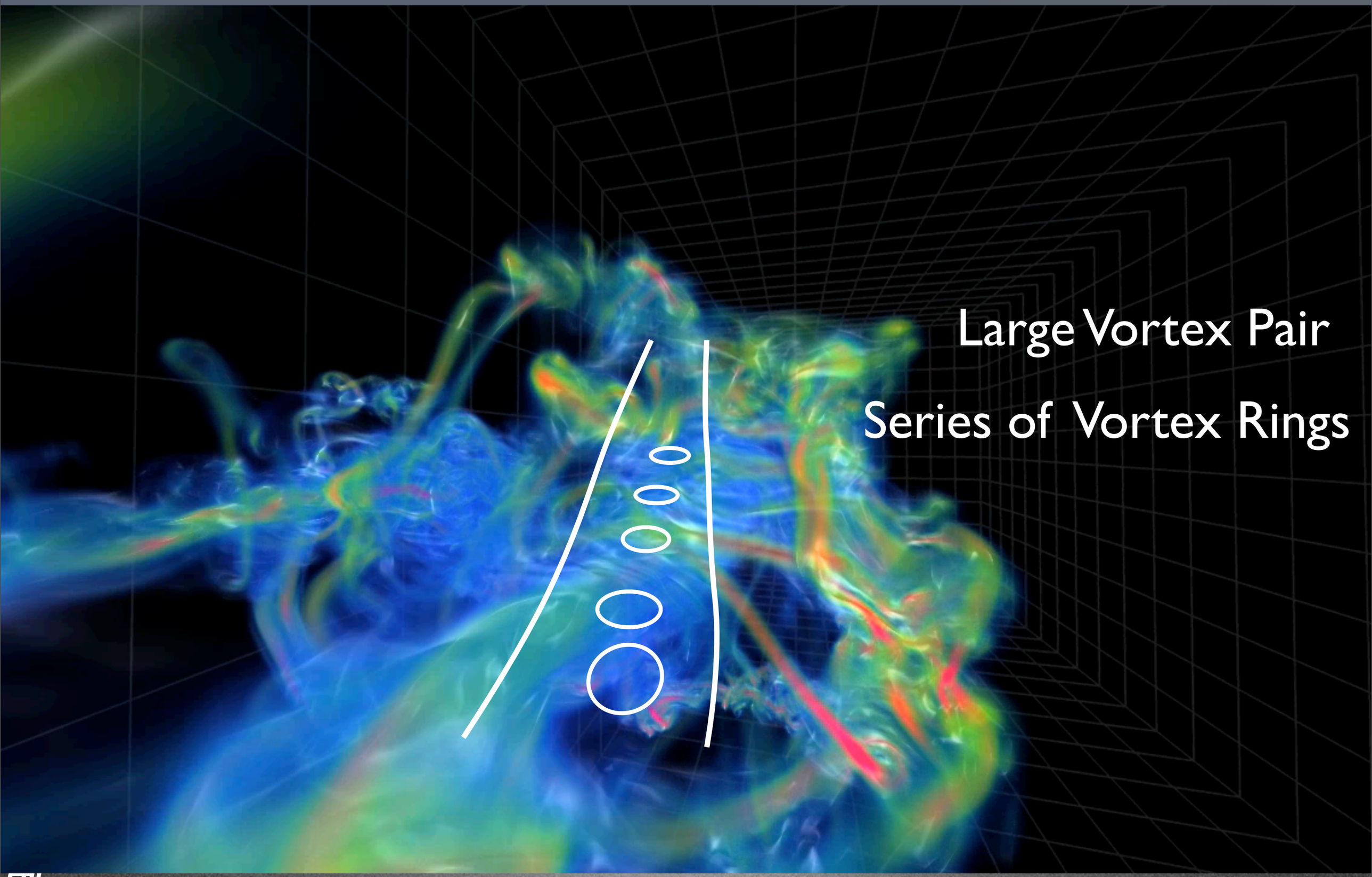

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- Given, e.g.
  - a range in trim
  - active device perturbations

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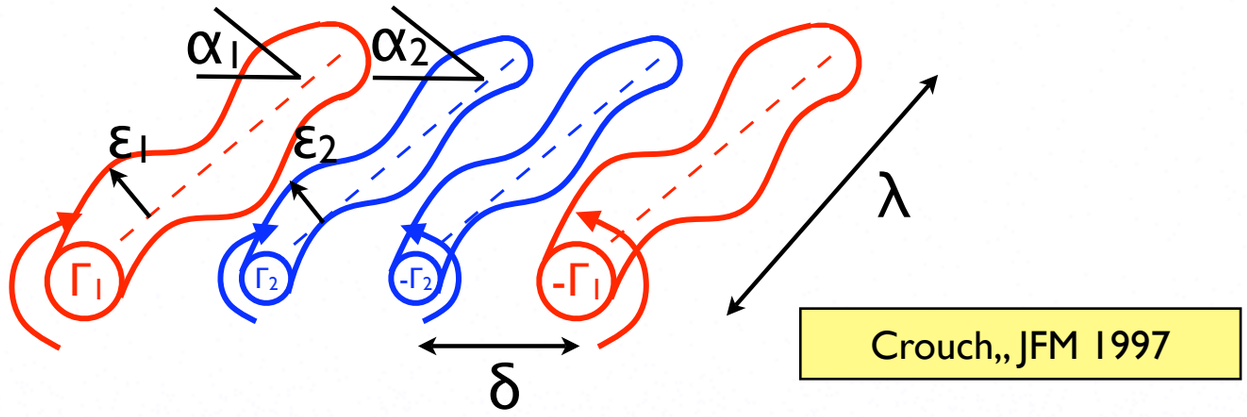
- Configuration
  - Co-rotating pairs
  - Re = 2500



Crouch,, JFM 1997

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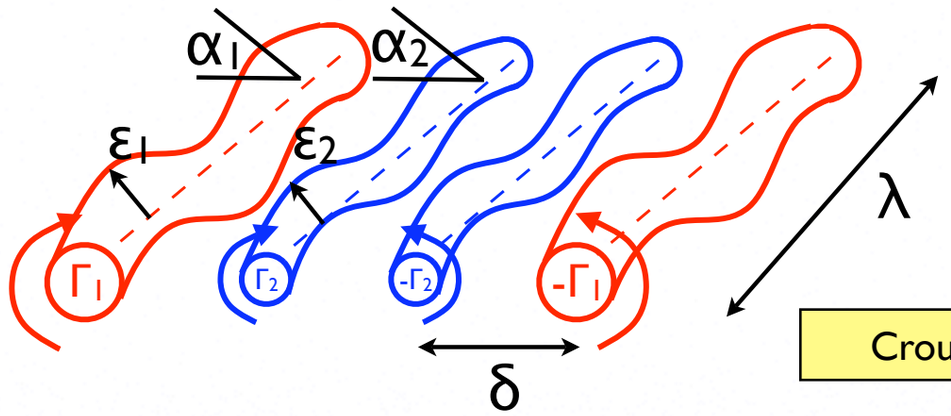

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- Problem: minimize **objective function**

$$f_{\text{decay}} = \frac{\int_0^T E(t)\,dt}{E(0)T} \qquad (\mathsf{T} = 4)$$

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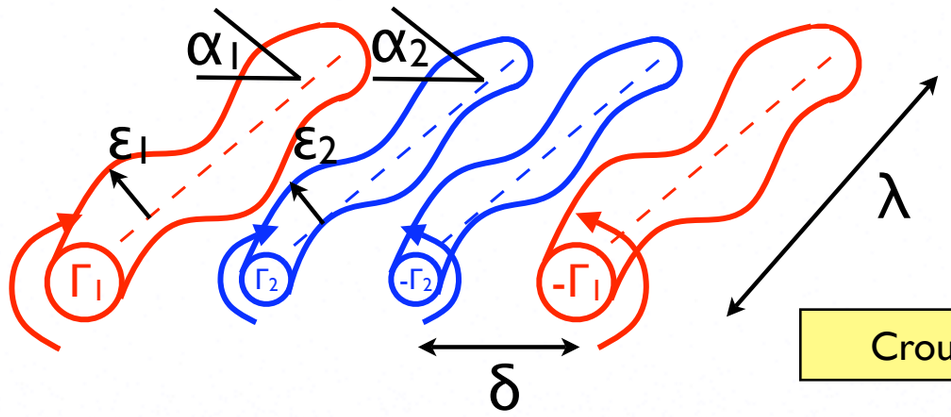

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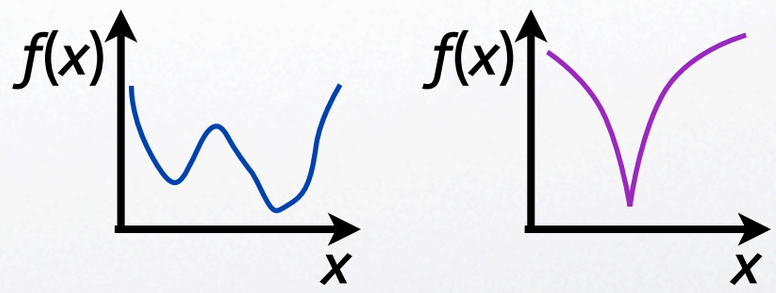
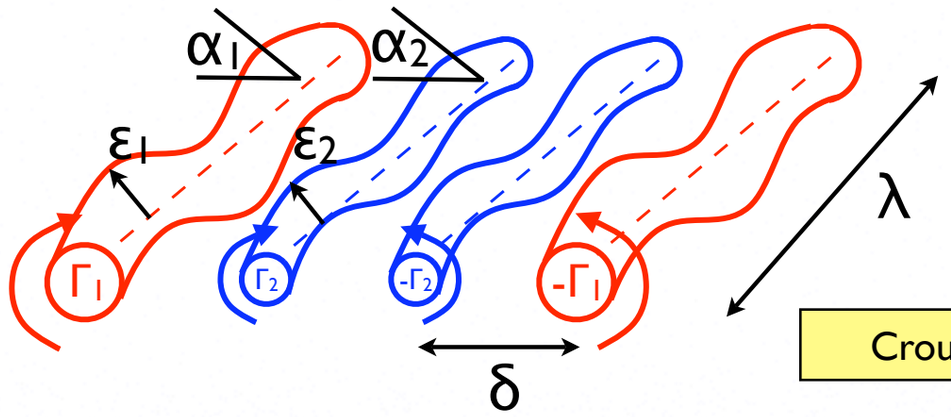
$$f_{\text{decay}} = \frac{\int_0^T E(t)\,dt}{E(0)T} \qquad (\mathsf{T} = 4)$$

- Challenges
  - f can be multi-modal, non-convex, etc.
  - ∇f not readily available
  - evaluation of f is **expensive**



Optimization of Vortex Decay

- Configuration
  - Co-rotating pairs
  - Re = 2500



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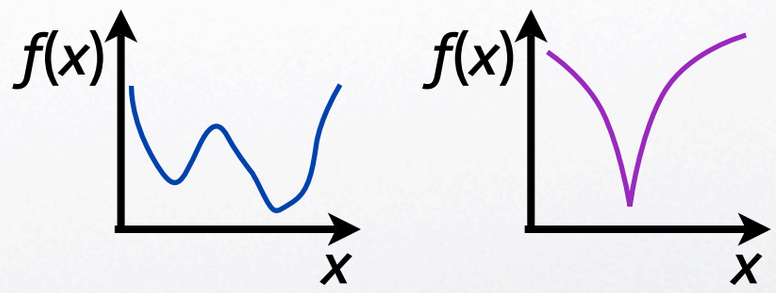
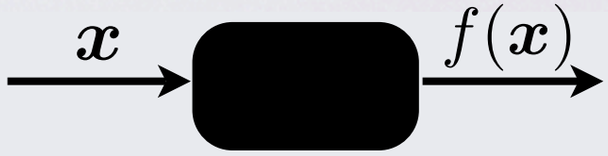


- Approach
  - Evolutionary Optimization
  - Prior knowledge encoded in parametrization

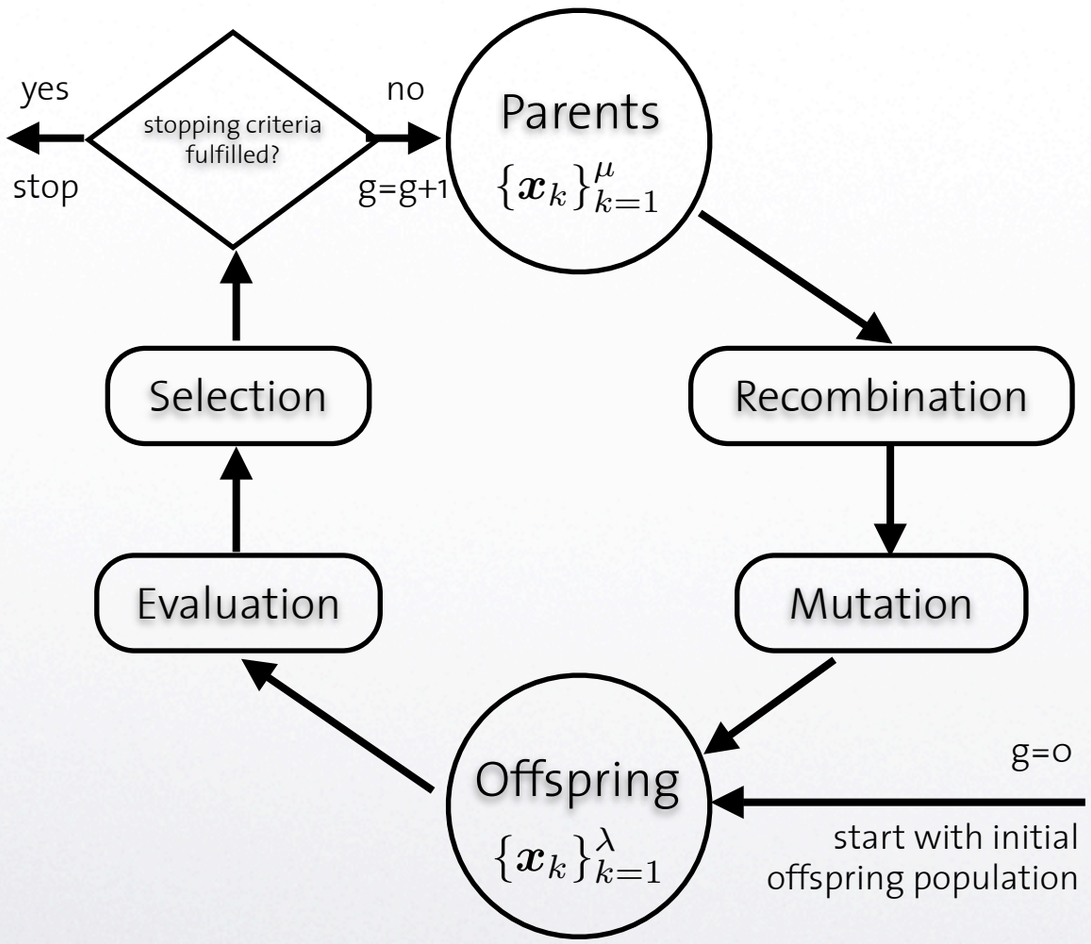


Optimization of Vortex Decay

Evolutionary Algorithms (EAs)

- **iterative methods** operating with **populations** of candidate solutions
- Here : Covariance Matrix Adaptation - ES

Hansen et al., Evol. Comput. 2003



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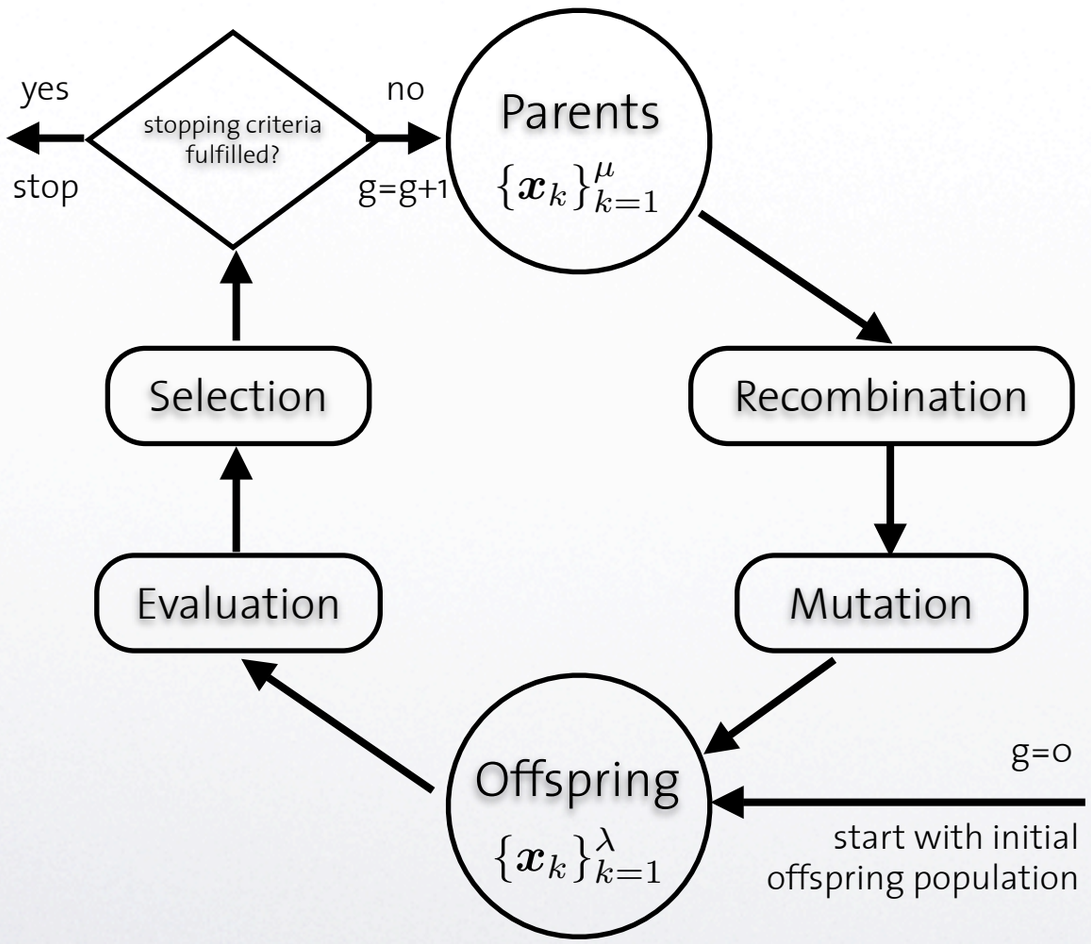

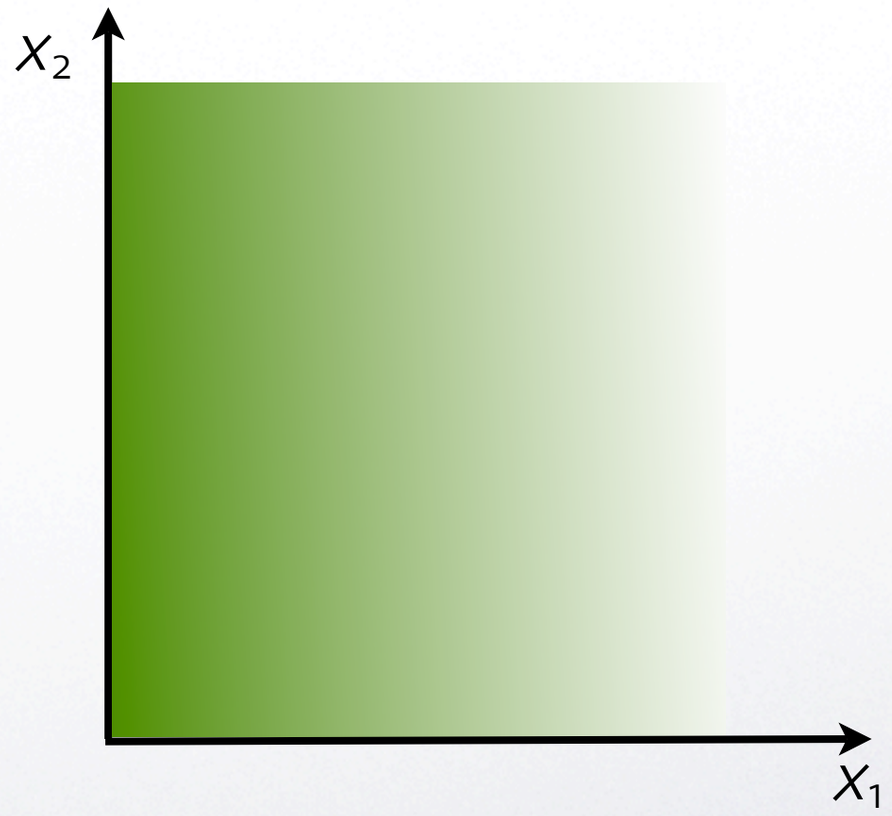

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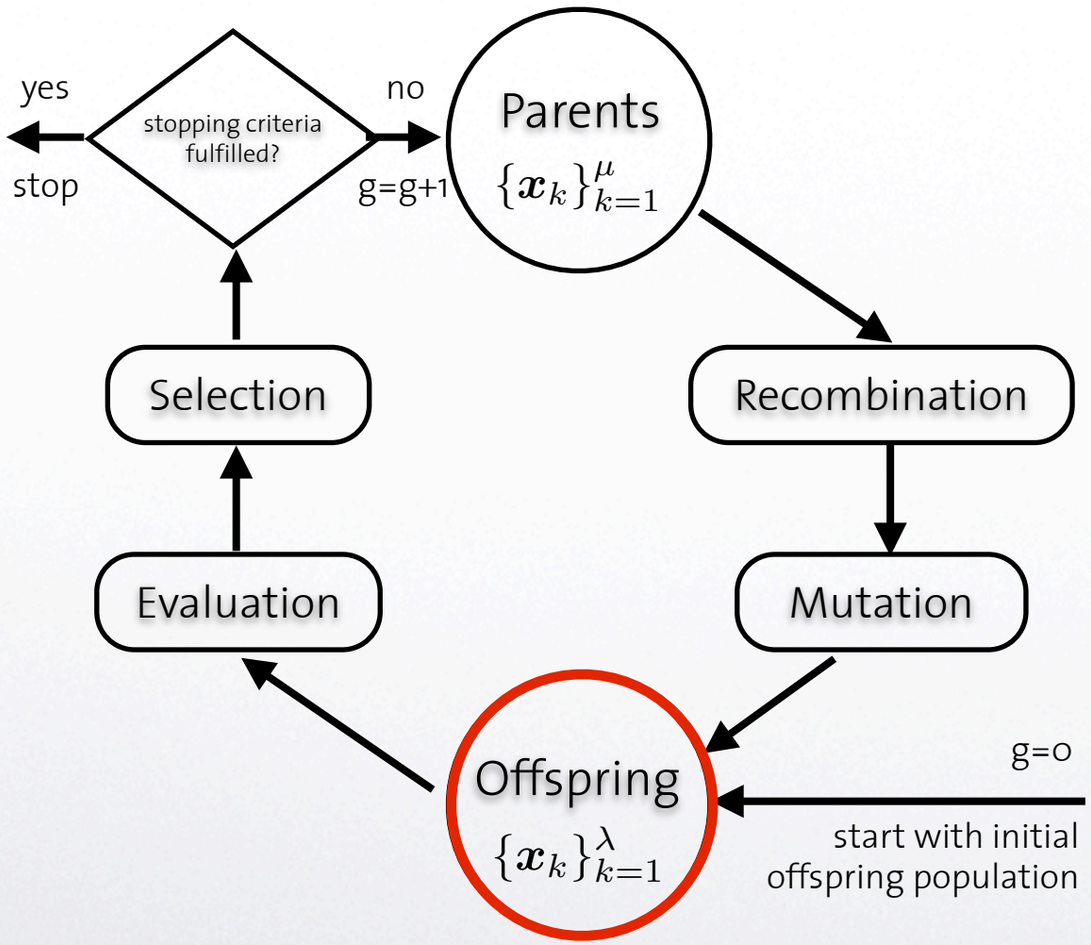

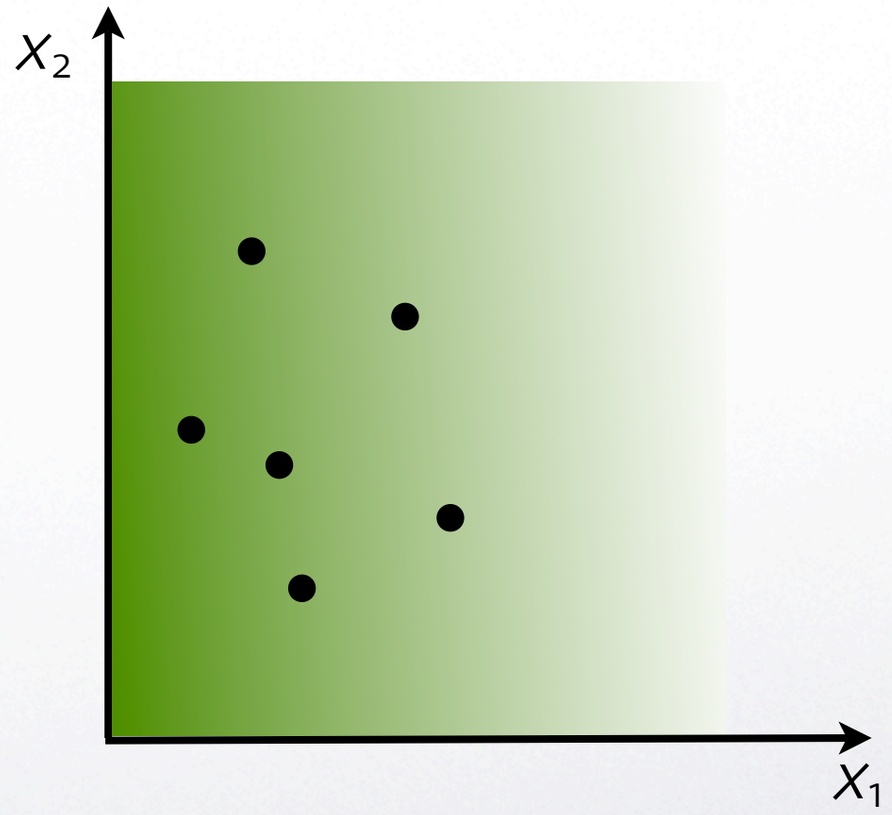

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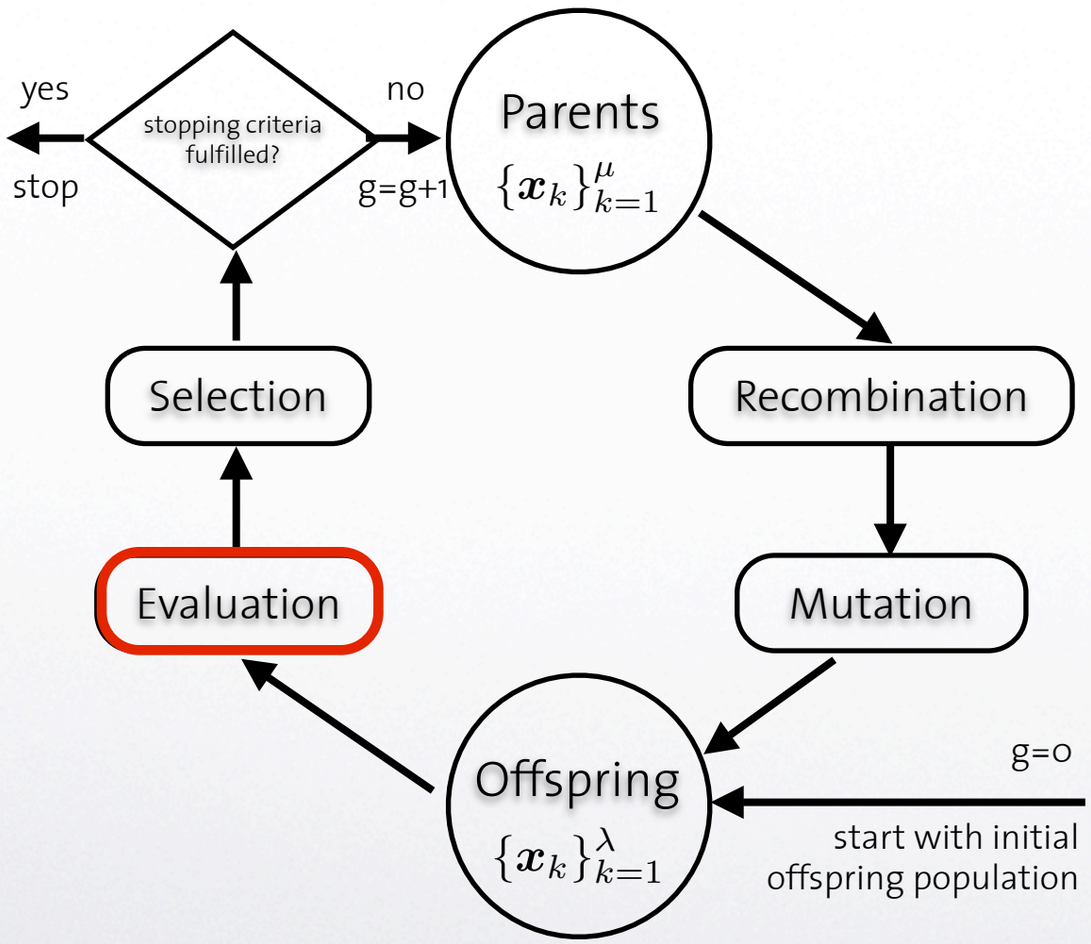

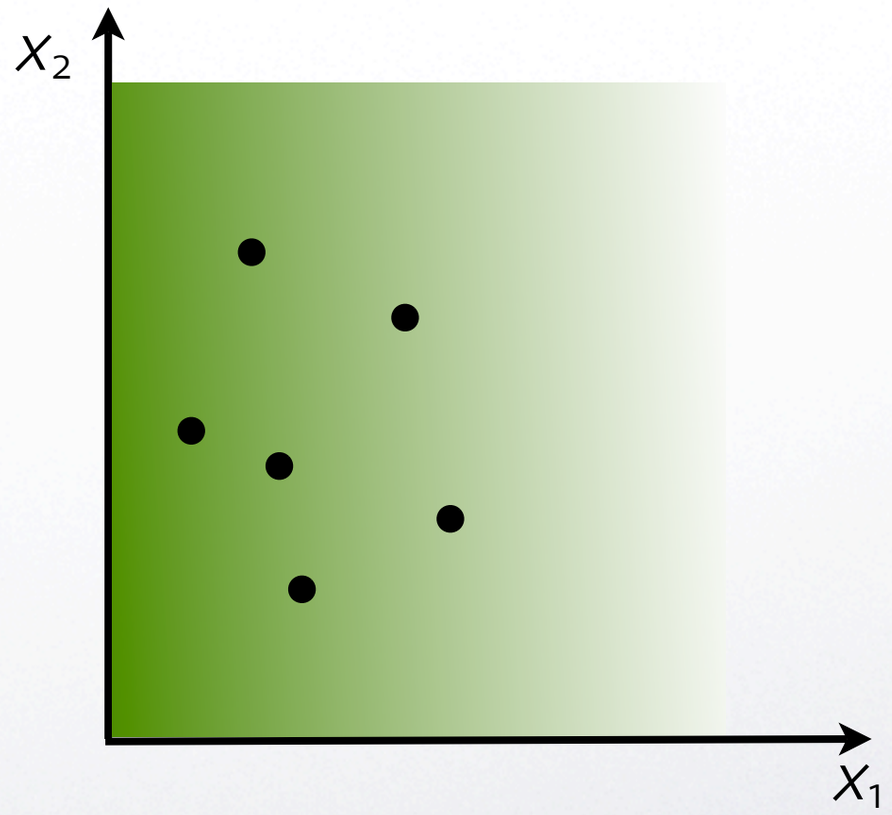

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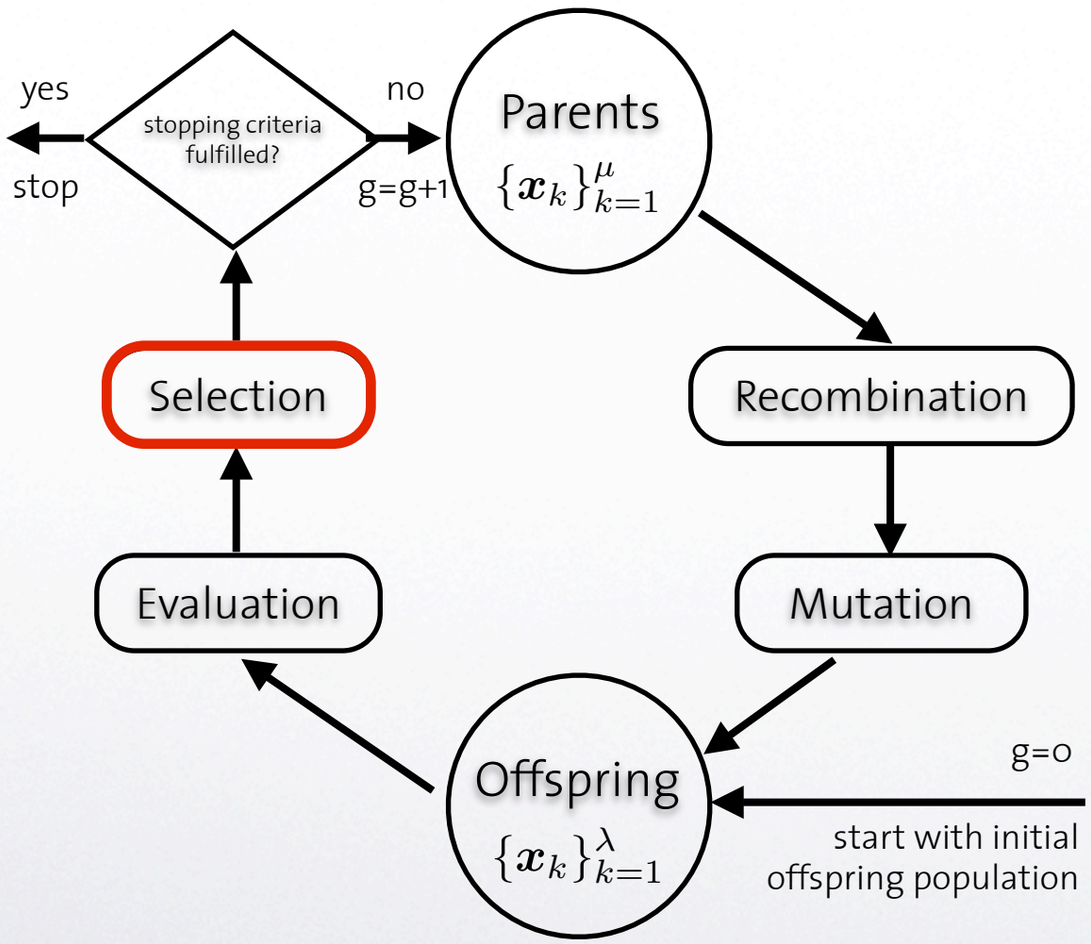

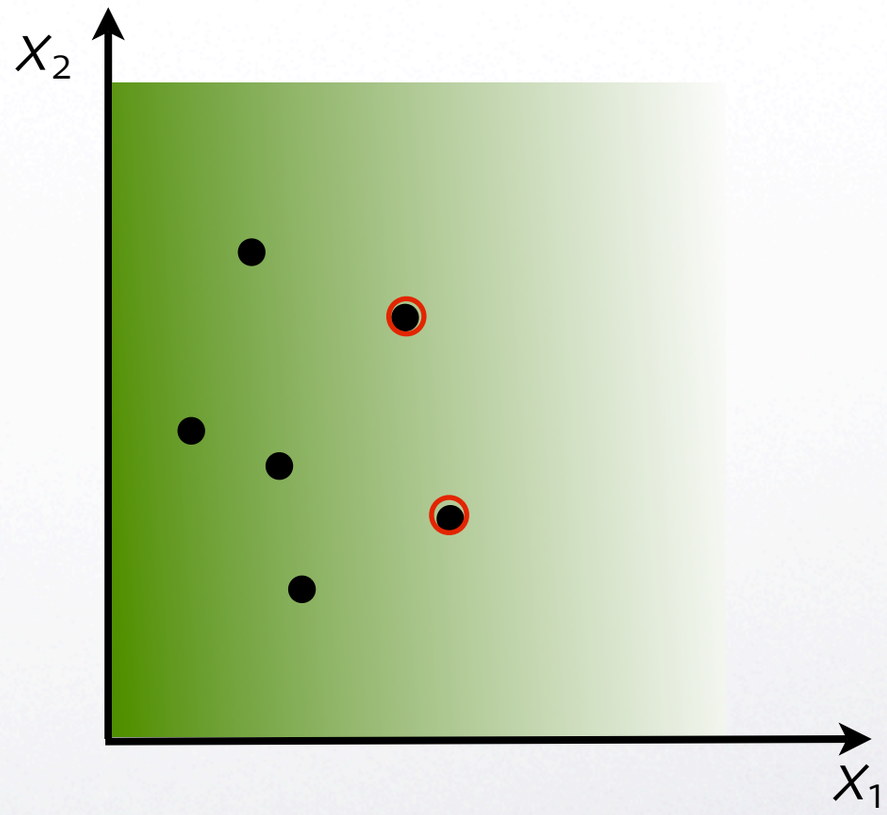

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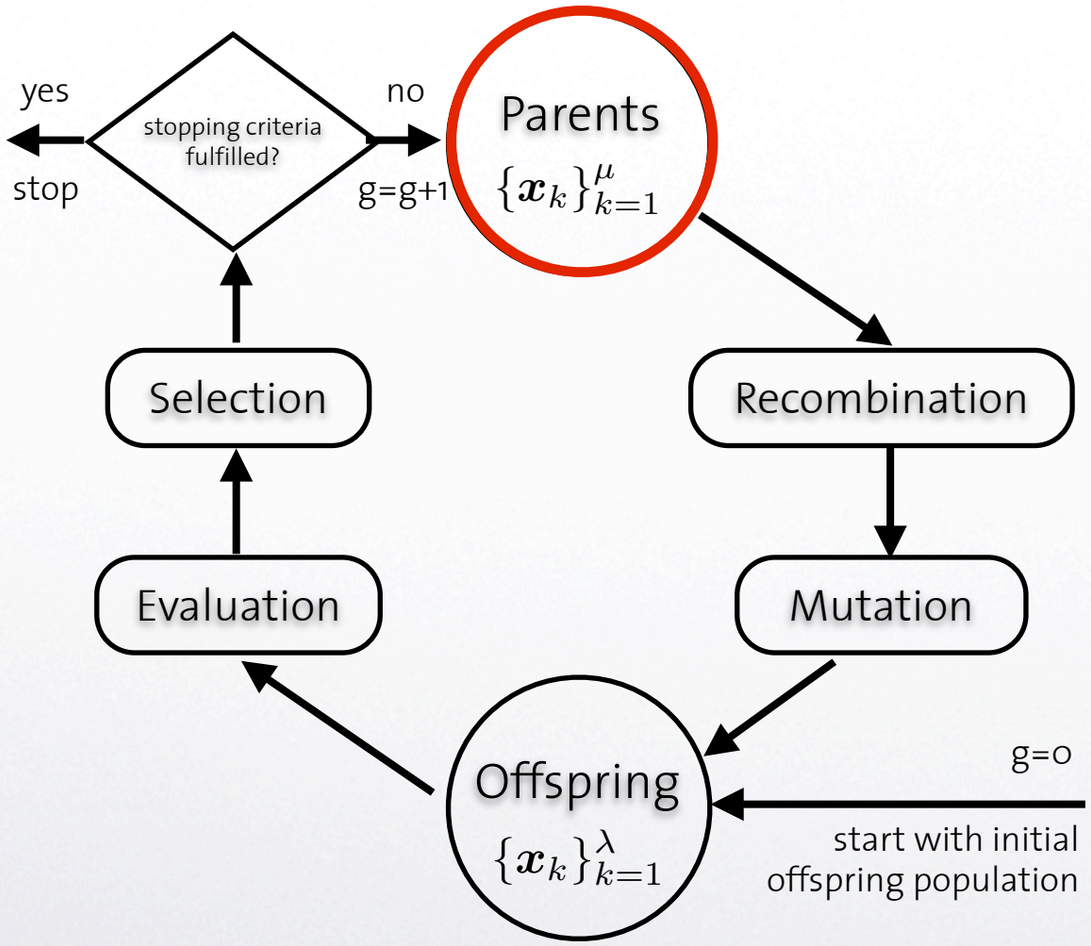

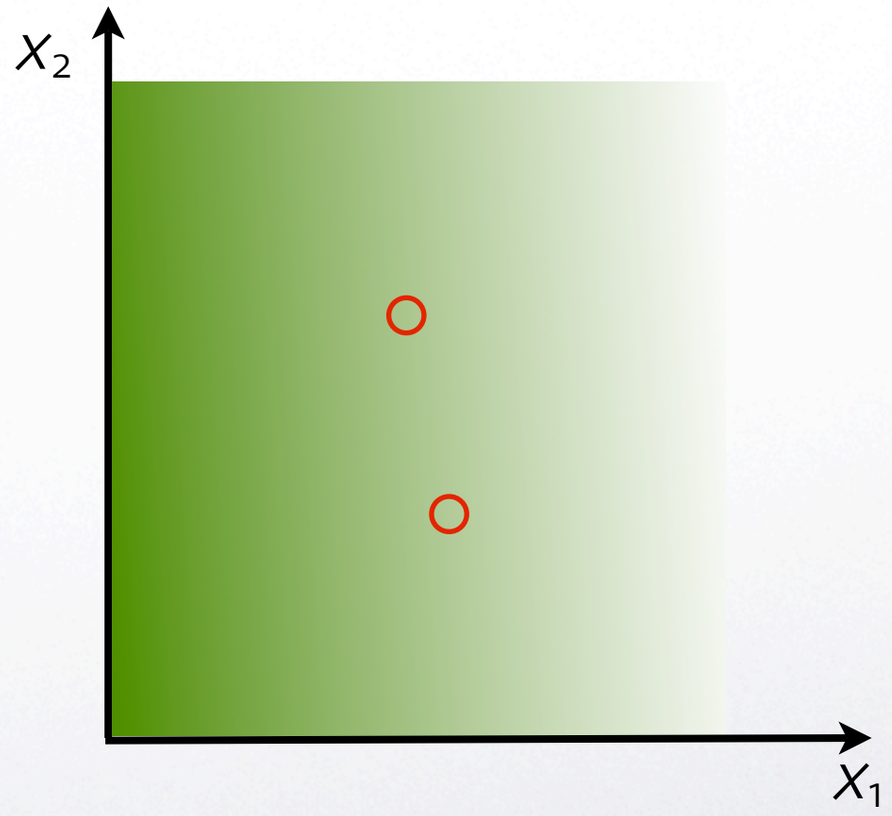

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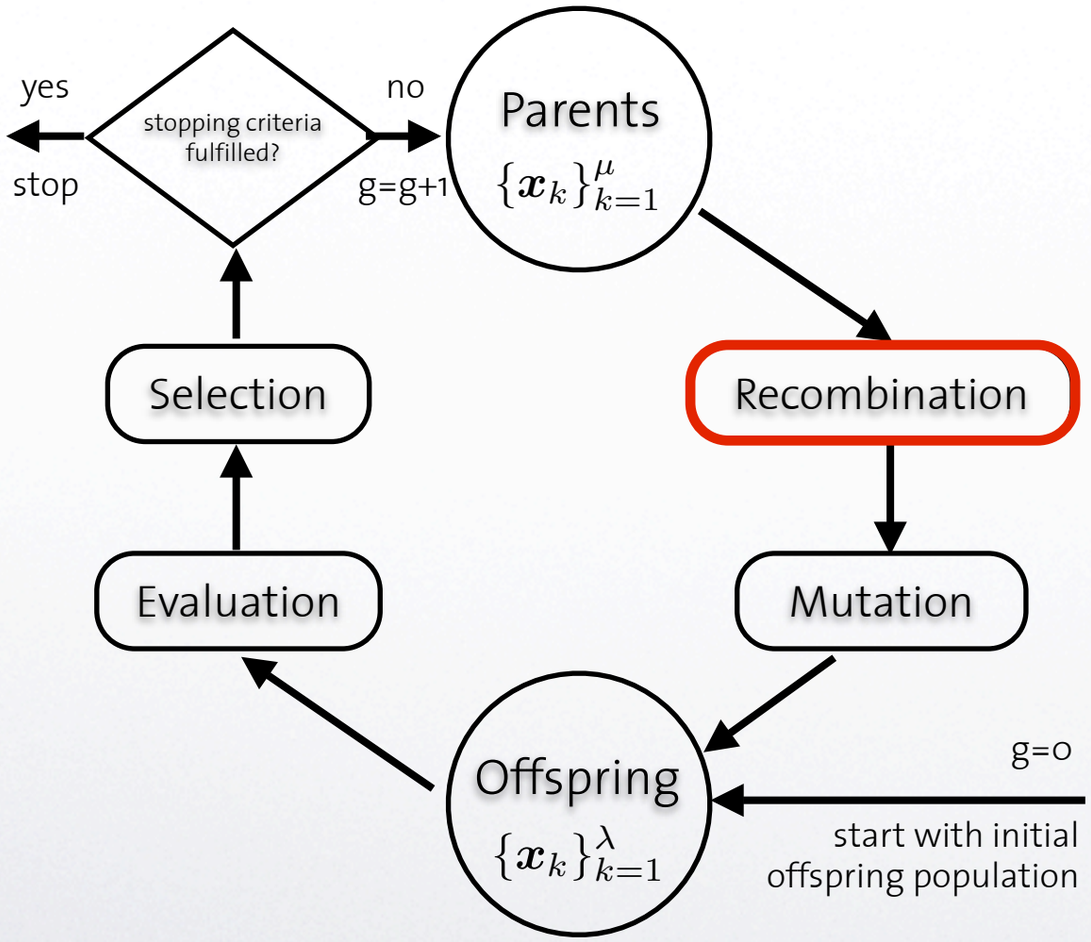

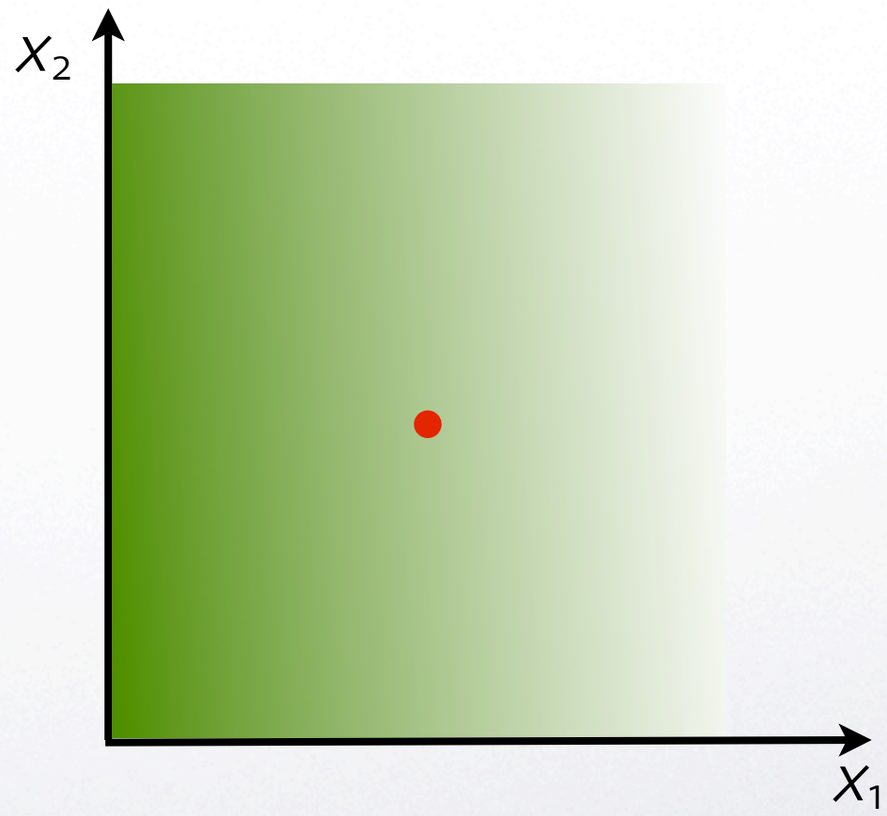

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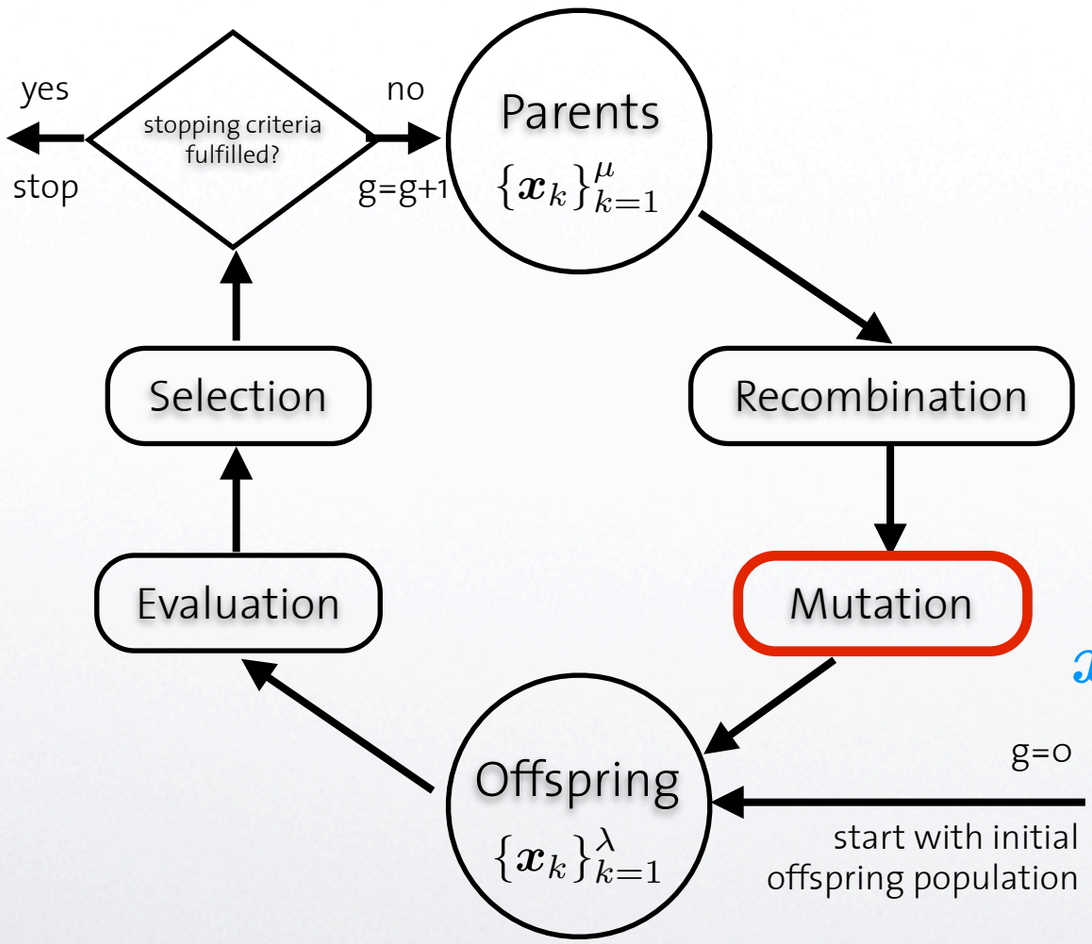
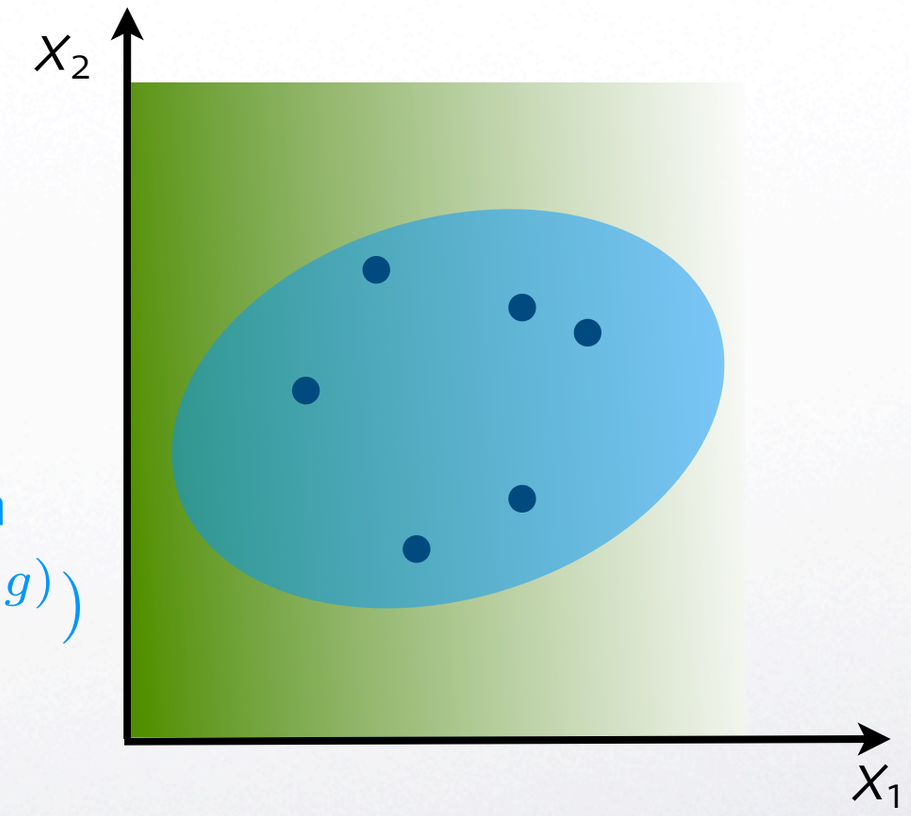


Probability distribution

$$\boldsymbol{x}_k \sim P(\boldsymbol{\theta}^{(g)})$$



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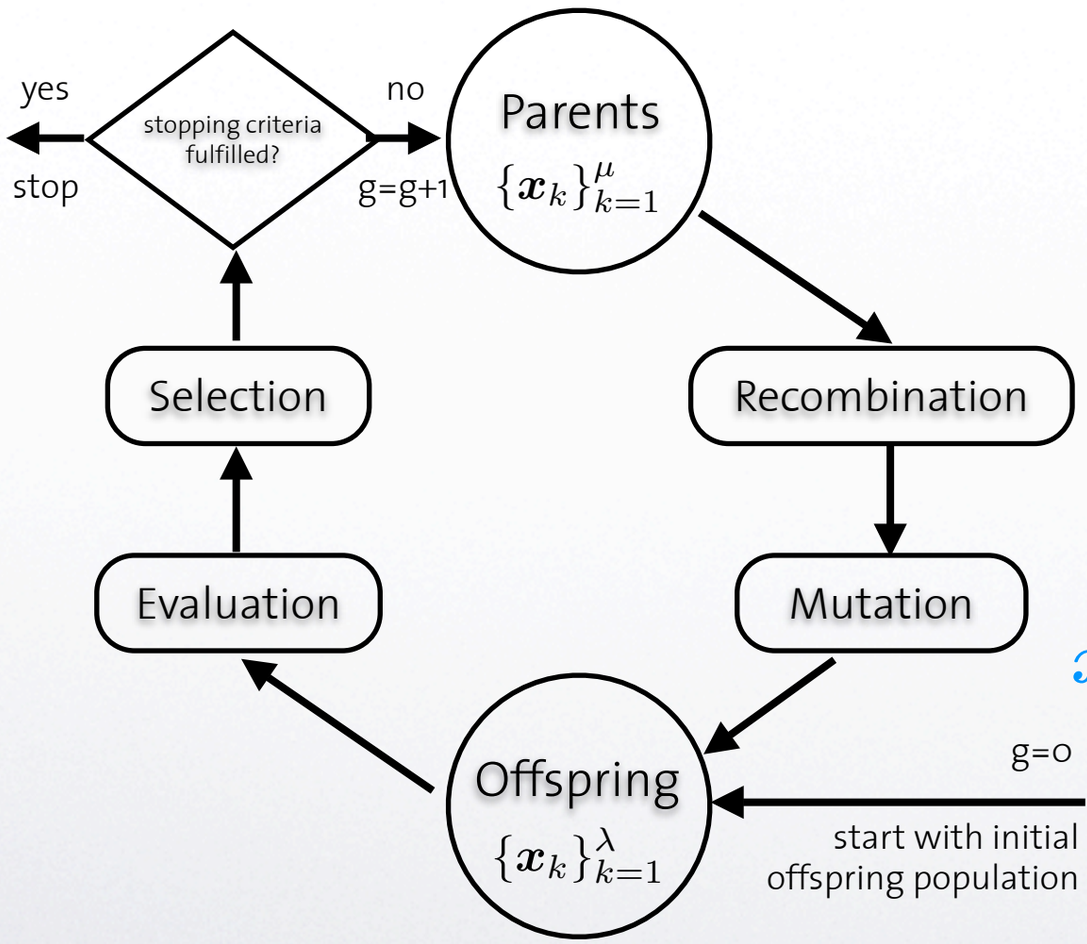

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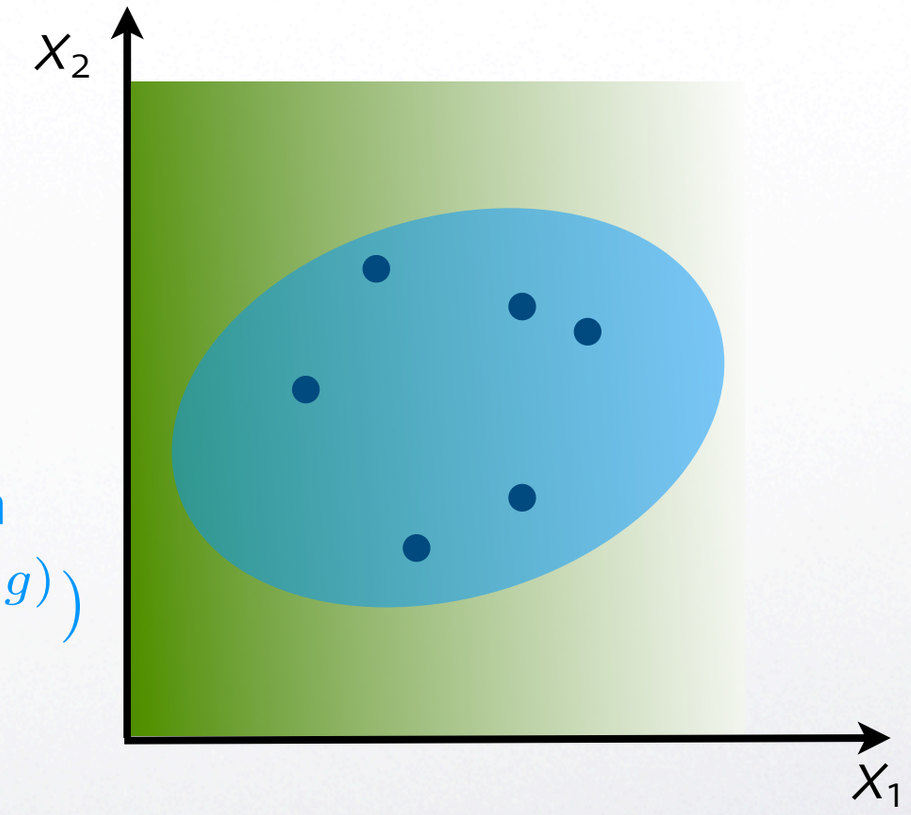

- popular because of their flexibility and **robustness**

Optimization of Vortex Decay

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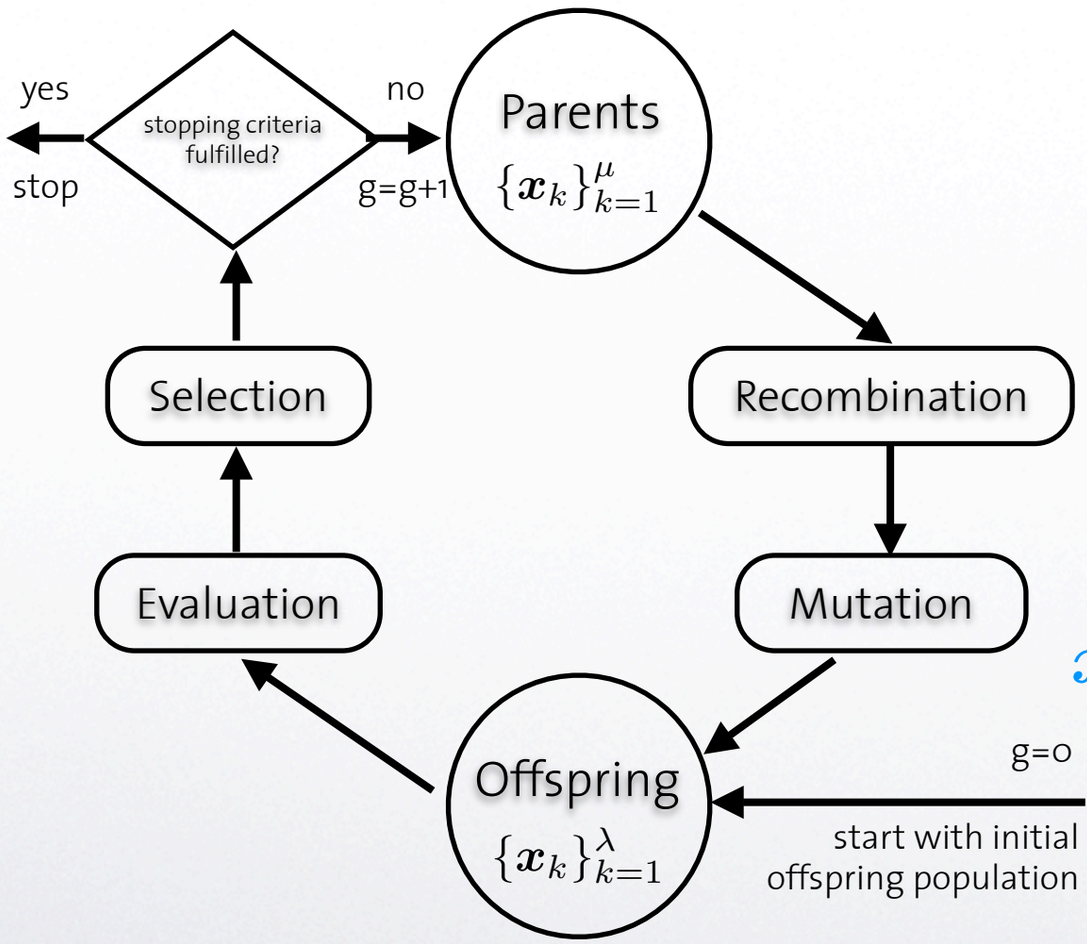

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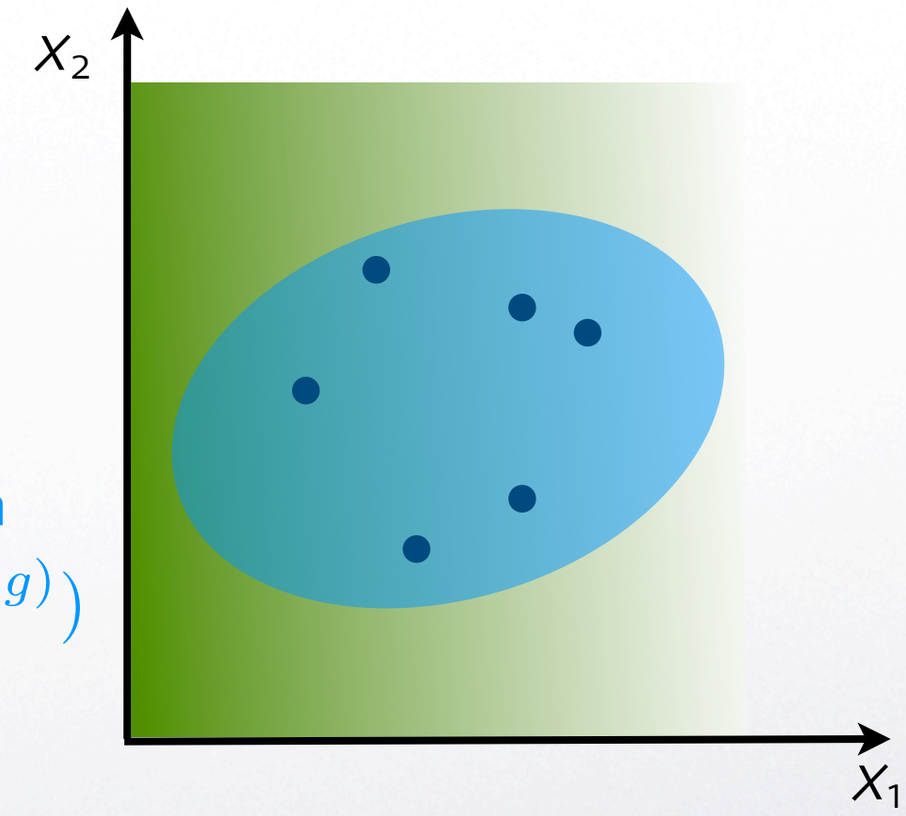


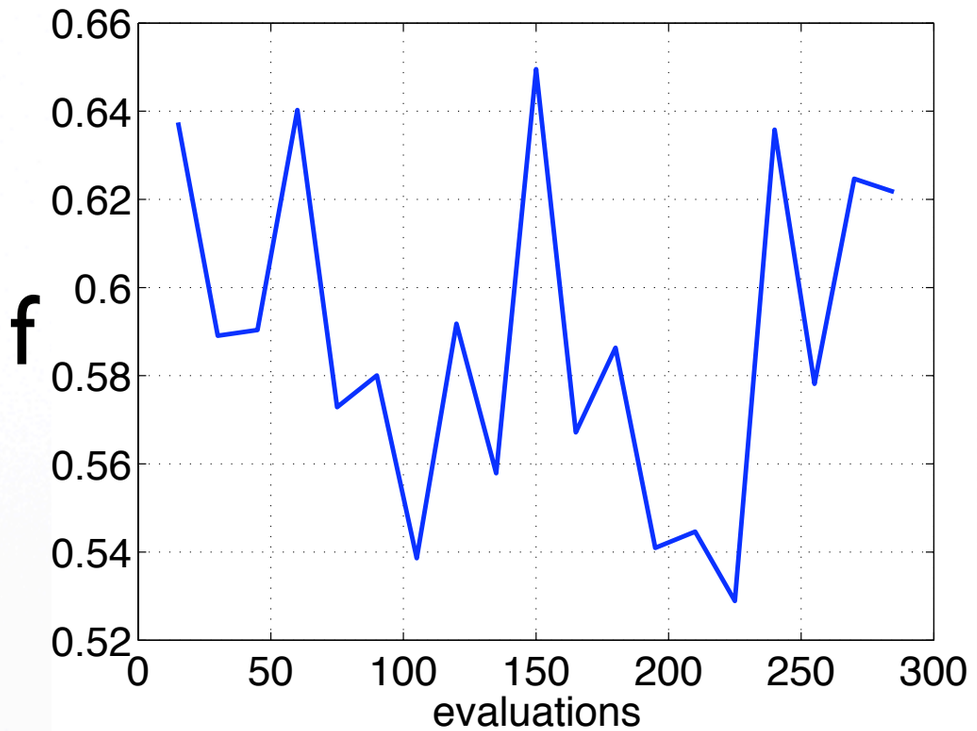
- popular because of their flexibility and **robustness**
- main **disadvantage**: Need **large number of objective function evaluations**

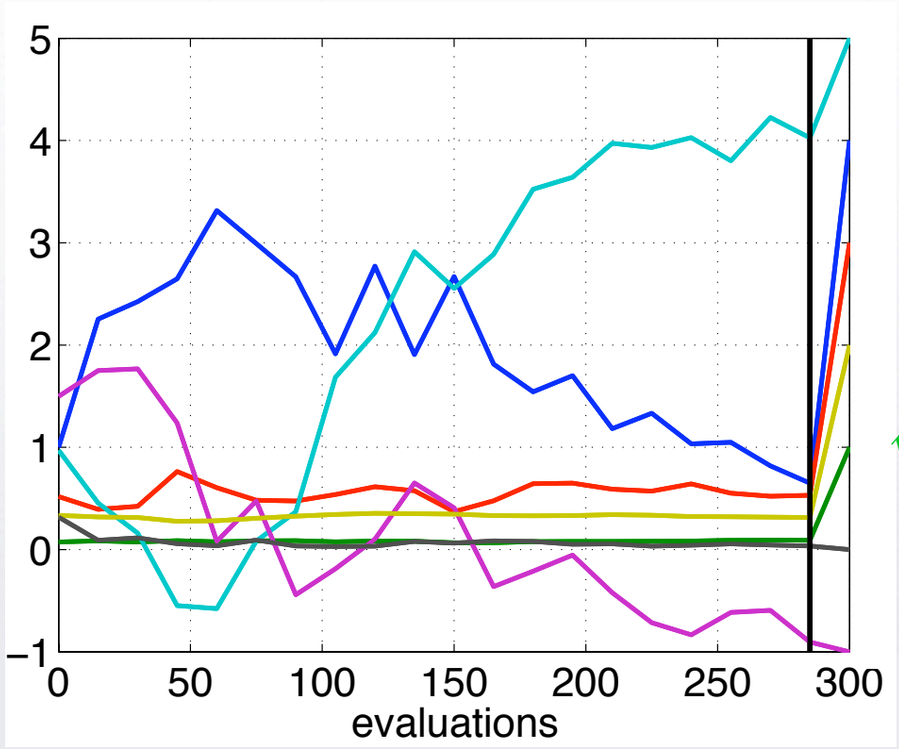
Optimization of Vortex Decay

$$f$$

Optimization of Vortex Decay

- PRESENT
  - After sweep toward large λ, moves toward smaller values
  - Convergence





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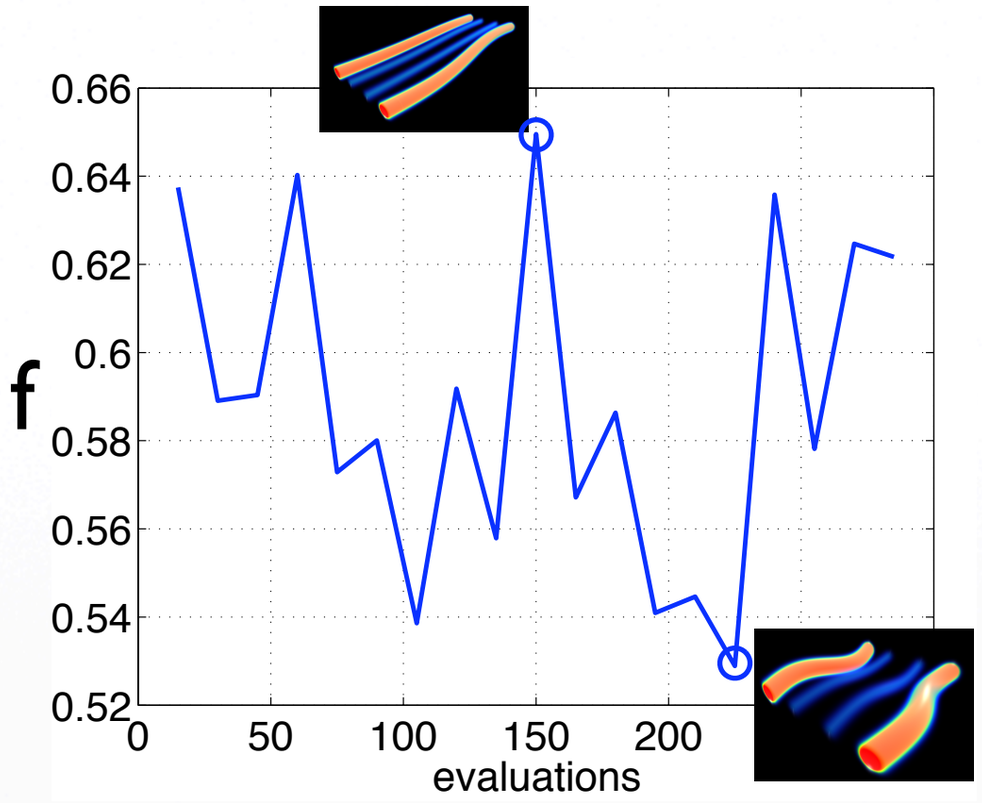

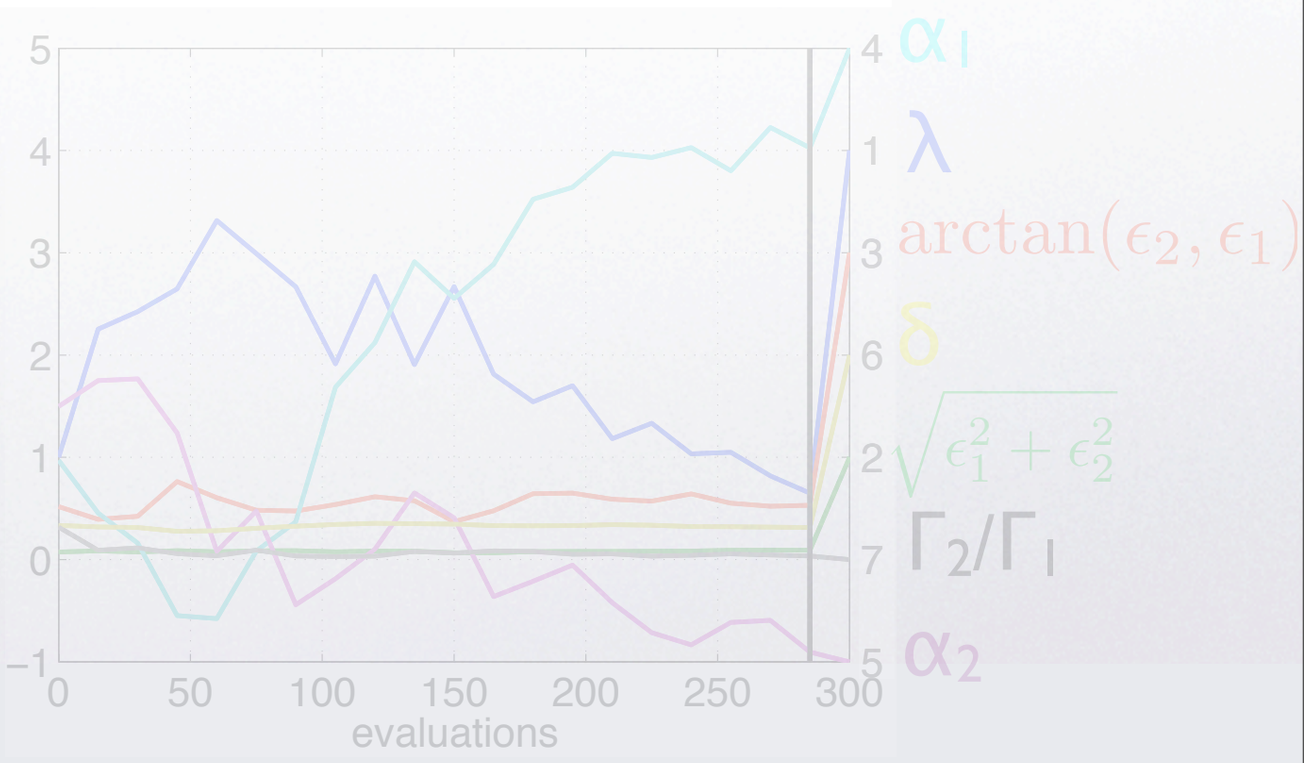

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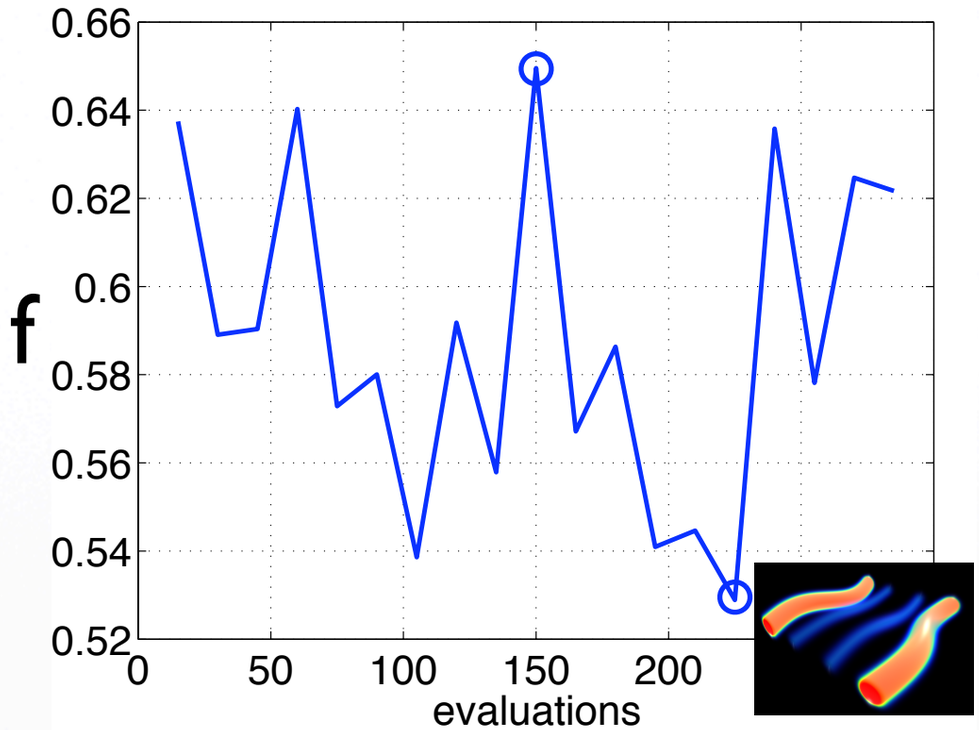

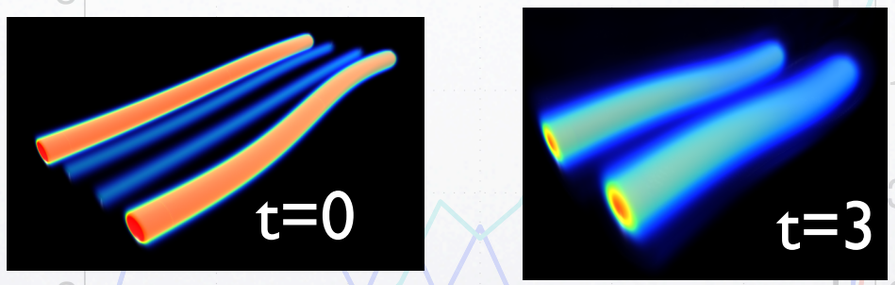

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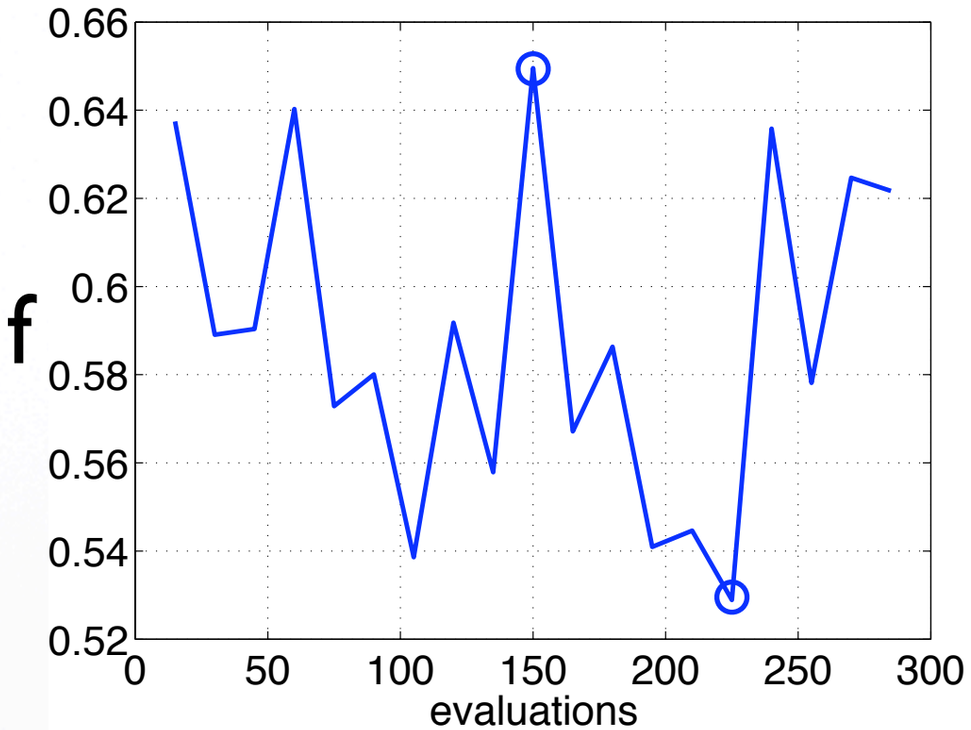
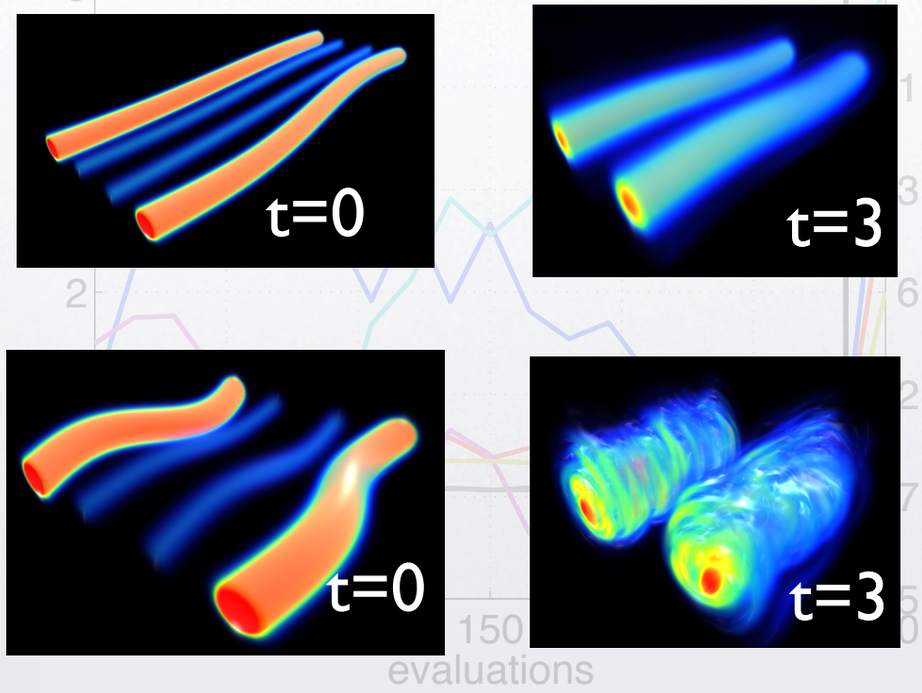
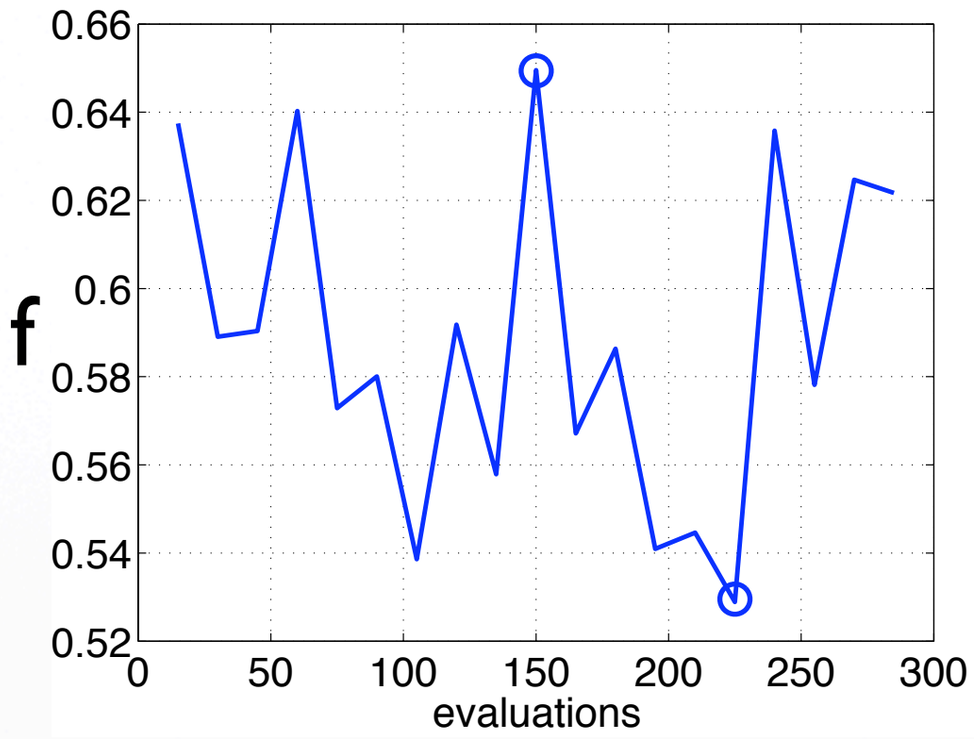
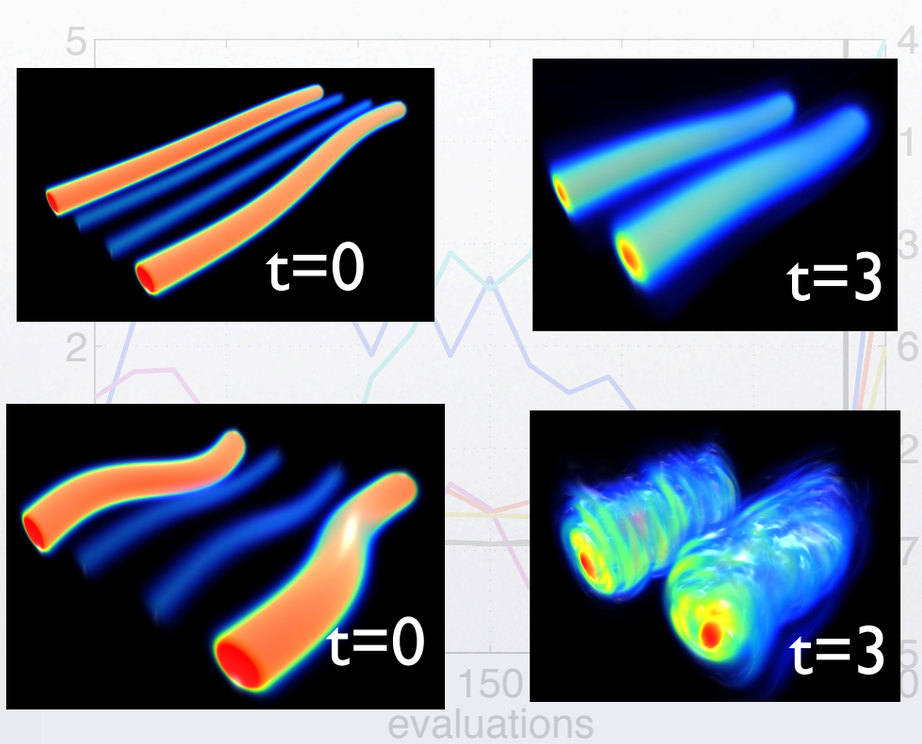




Optimization of Vortex Decay

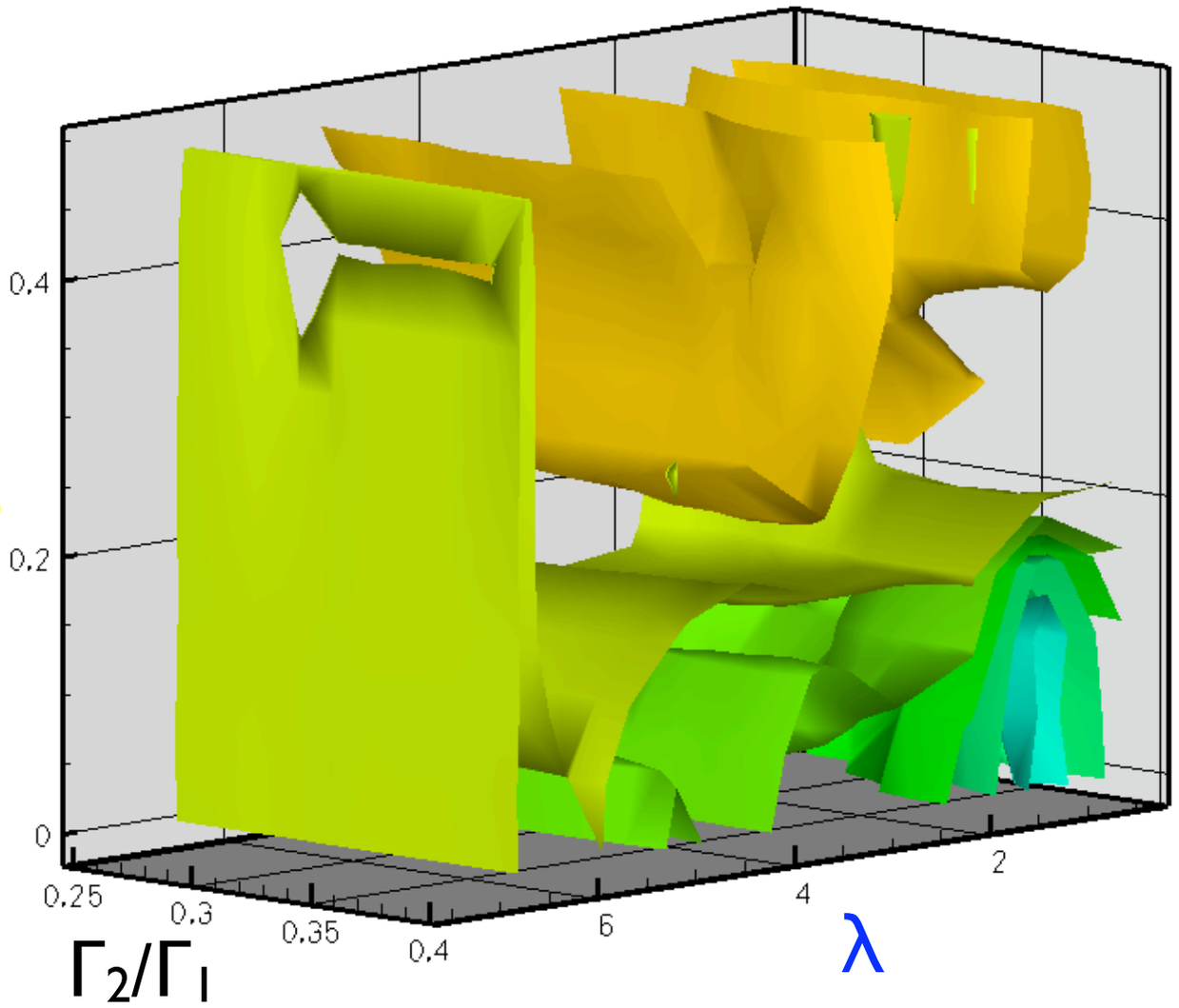
- PRESENT
  - After sweep toward large λ, moves toward smaller values
  - Convergence
- PROBLEMS
  - Resolution of Optimized Flows ?
  - Synchronize Optimization and Numerics





Optimization of Vortex Decay

- FUNCTION LANDSCAPE
  - in (λ,δ,Γ) hyperplane
  - Multi-modality
  - Effect of numerics?



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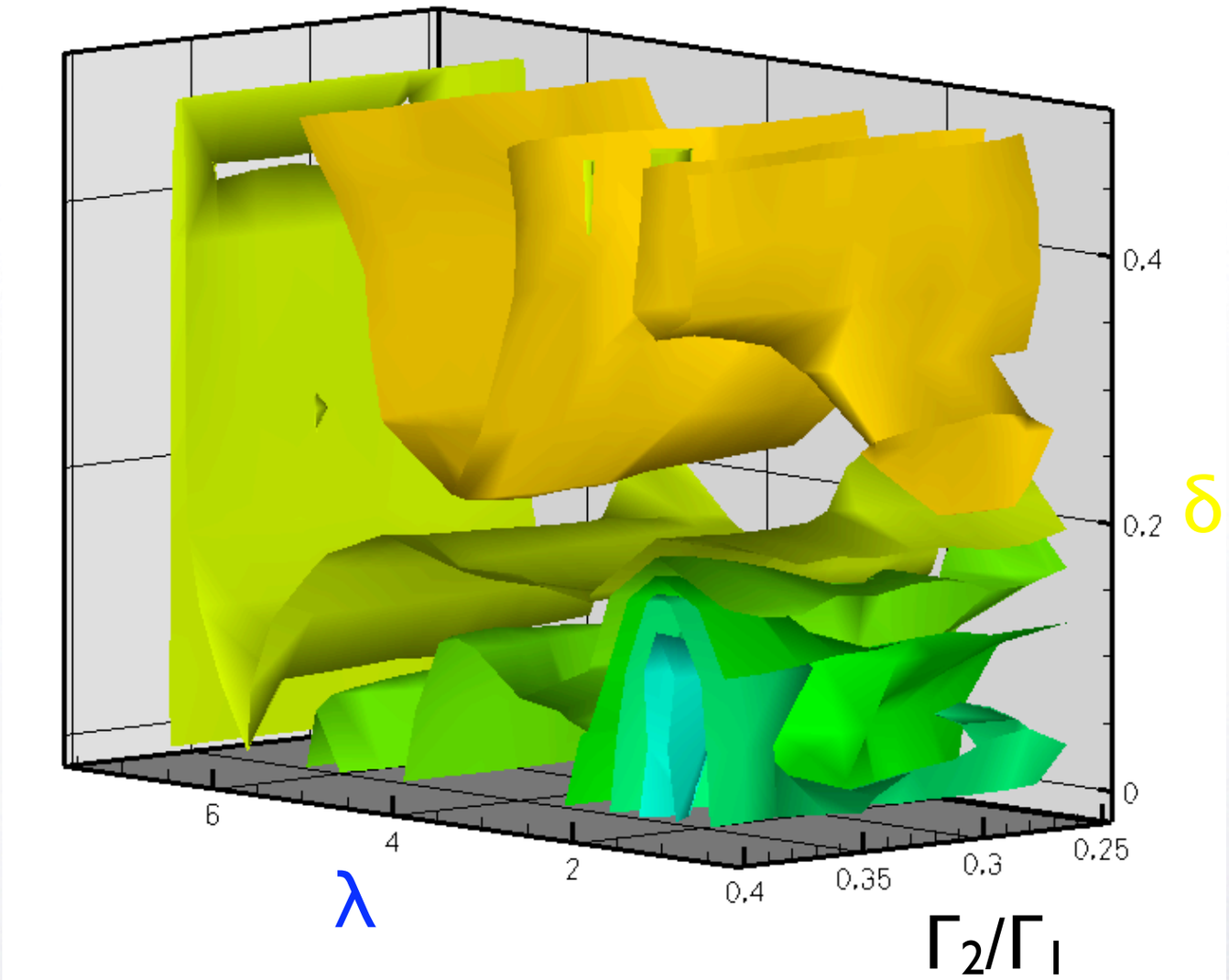

Ongoing work

- Development
  - Bigger, *faster*:
    Mixed MPI/SMP implementation of library
    - multicore machines: BlueGene/P
  - Smarter:
    Unbounded boundary conditions
  - More physical:
    Non-periodic streamwise boundary conditions
    - spatially developing wake

Conclusions

- Implementation of Vortex Particle Method on massively parallel architecture
  - Scalability
- Large-scale High Re DNS
- Coupling of DNS code with Evolutionary Strategy: Optimization of wake decay

Acknowledgements

M. Bergdorf
D. Rossinelli
S. Kern
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Swiss Super-Computing Center