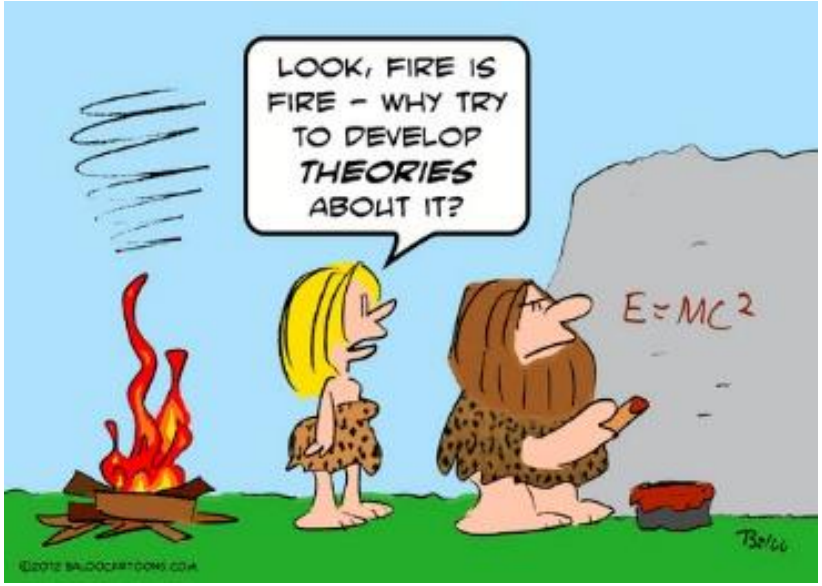
Wildfire modelling: the CFD approach

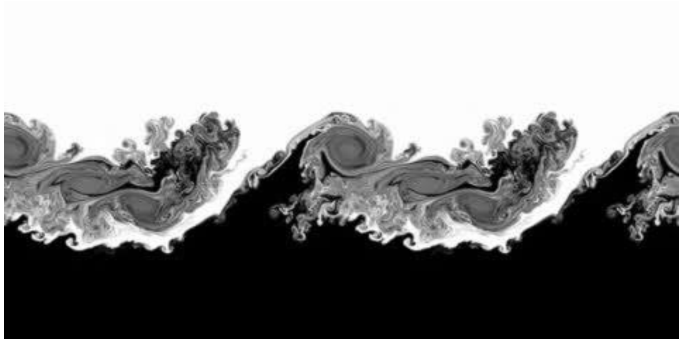
Dominique MORVAN
Aix-Marseille Université

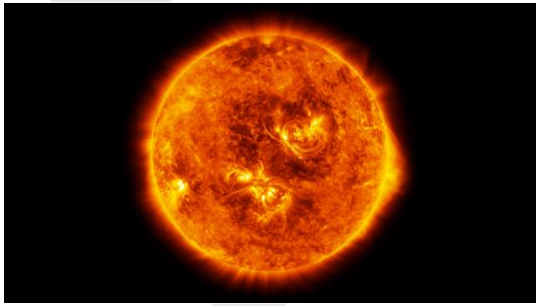


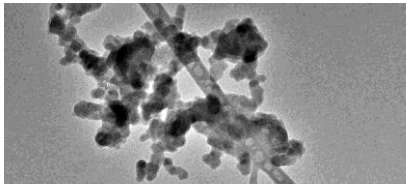
Some general recommandations in CFD modelling

- **Evaluate even coarsly the characteristic length and time scales of the problem**
- **The mesh size must not be defined arbritray but from physic based considerations**
- **Simplify as possible the problem (2D/3D, compressible/incompressible flow …)**
- **Turbulence, Combustion, Radiation models ?**
- **Use adapted numerical scheme avoiding numerical dissipation and a certain guaranty of stability (with a flux-limiter strategy, TVD, Ultra-Sharp …)**
- **If possible (highly recommanded) compare some numerical results with experimental data**
- **Evoid the use of the following expression « Our model is validated … »**
- **Consider that « All models are wrong but someones are usefull »**

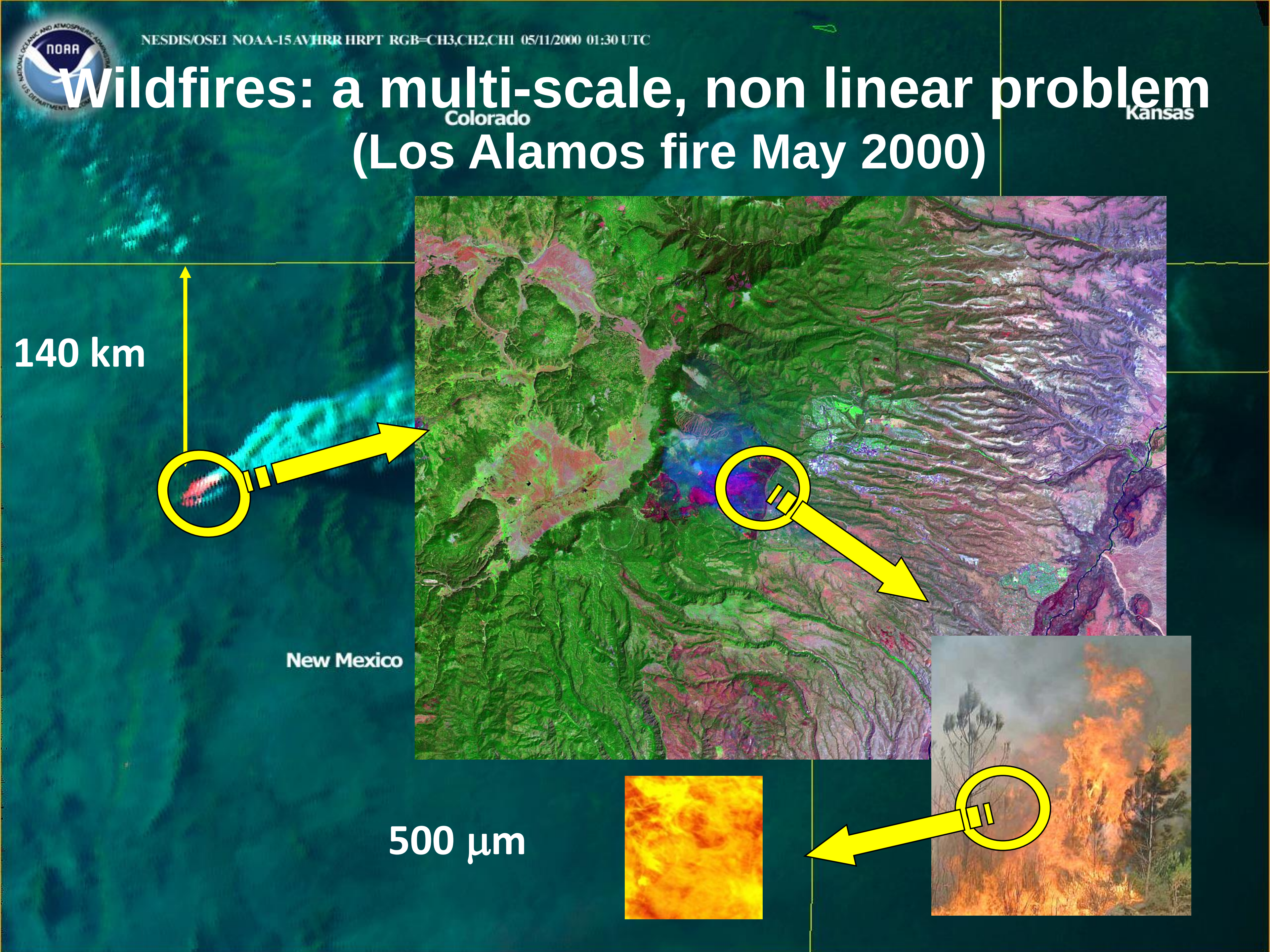
Physical phenomena governing wildfires



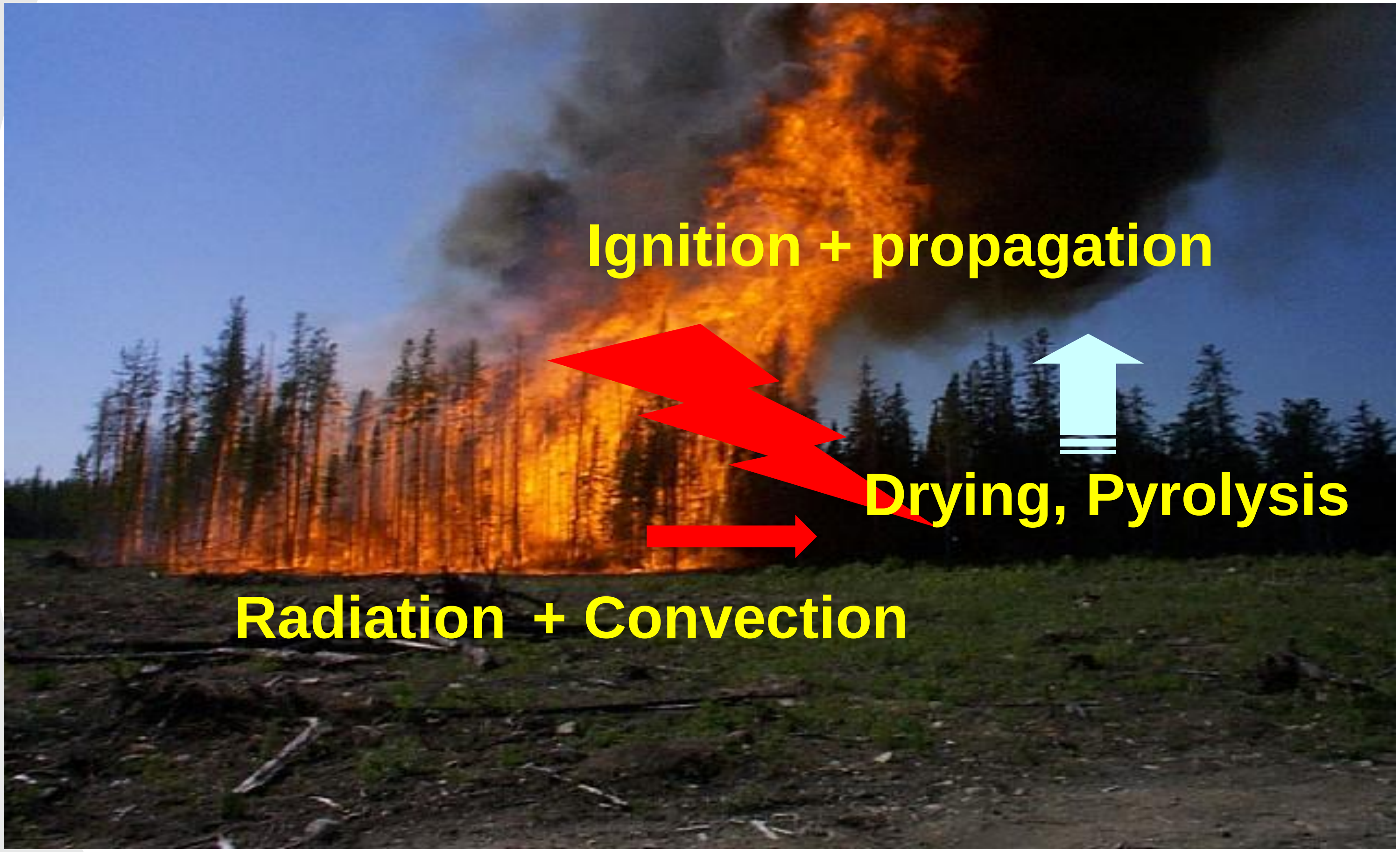




Wildfires: a multi-scale, non linear problem
(Los Alamos fire May 2000)

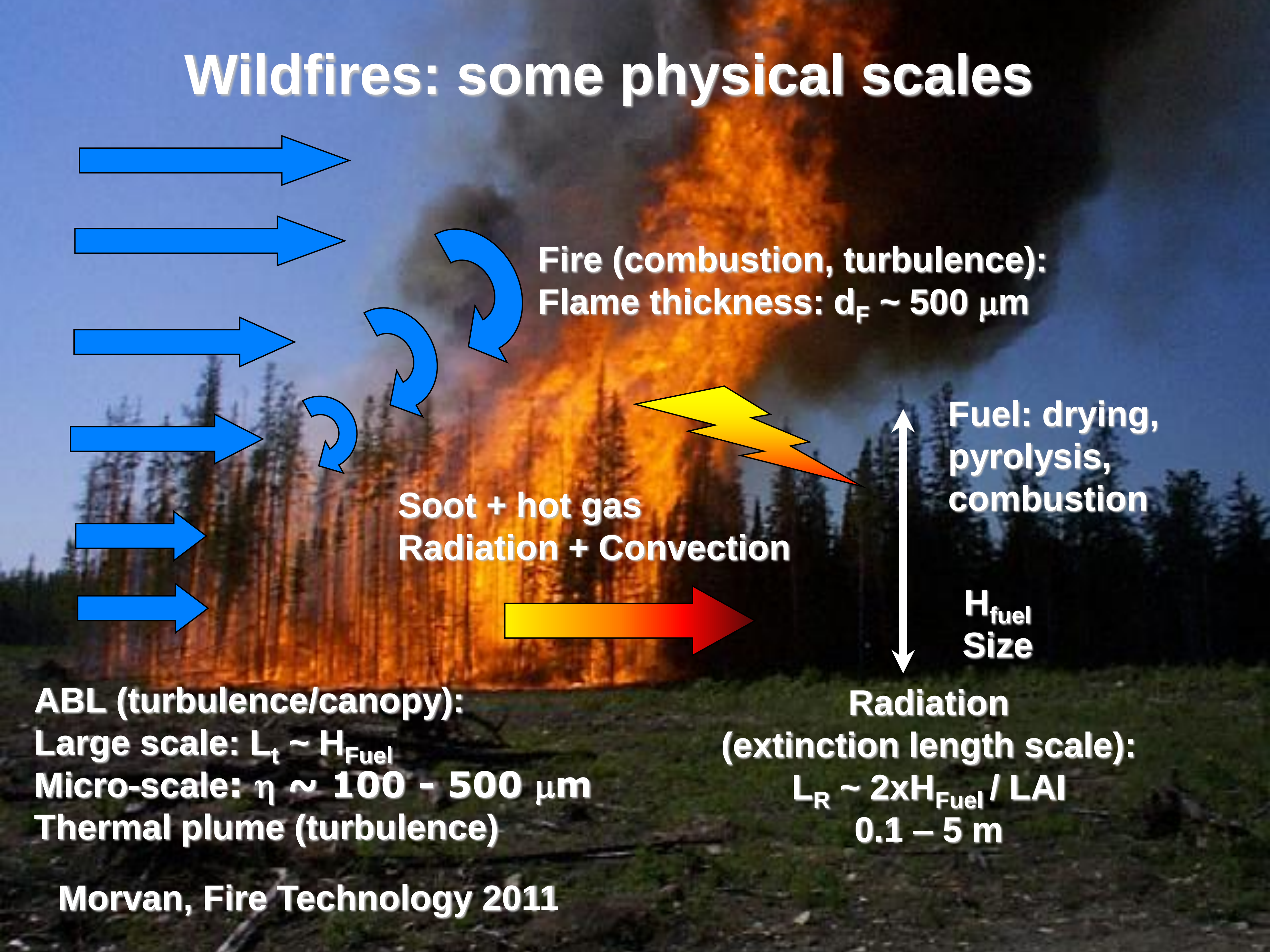


Heat transfer mechanisms governing fire behaviour



Another mechanism of fire propagation: firebrands

Travelling distance by brands; few kms !
Brands are the main source of vulnerability of houses located in WUI.


Wildfires: some physical scales
Fire (combustion, turbulence):
Flame thickness: d_F ~ 500 μm
Fuel: drying, pyrolysis, combustion
Soot + hot gas
Radiation + Convection
H_{fuel}
Size
ABL (turbulence/canopy):
Large scale: $L_t \sim H_{Fuel}$
Micro-scale: η ~ 100 - 500 μm
Thermal plume (turbulence)
Radiation
(extinction length scale):
$L_R \sim 2xH_{Fuel}$ / LAI
0.1 – 5 m
Morvan, Fire Technology 2011

Wildfires modeling (Weber 1991, Sullivan 2009 …)

- **Statistical models (empirical),**

  Mc Arthur (1966) $R=f(f_i)$

- **Semi-empiririical models,**

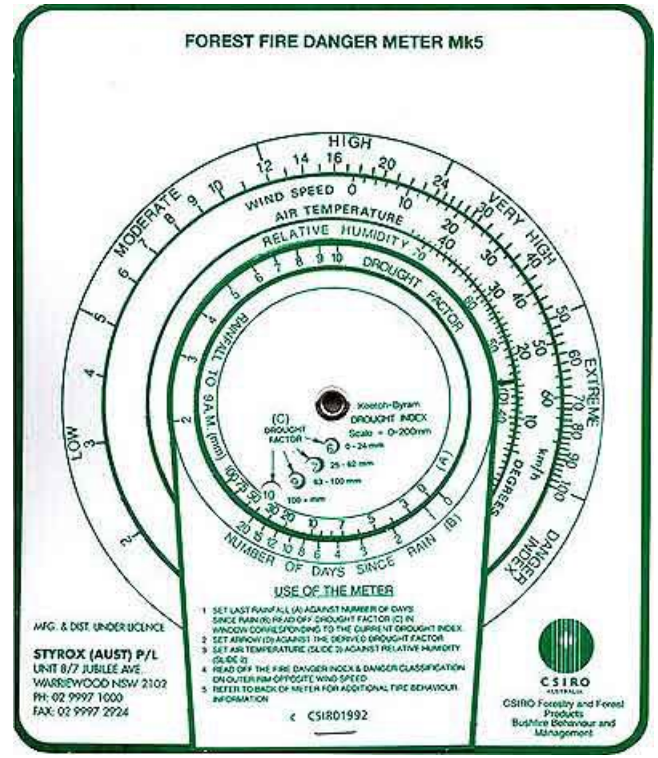
  Rothermel (1972) $R= \xi \, I_r / \rho \, \Delta h_i$

- **Physical models (radiative, full physics),**

  Albini (1985), De Mestre (1989),
  Balbi, Santoni & al (1998), Siméoni & al (2001),
  Chatelon, Rossi, Marcelli & al (2010)

  Grishin (1985), Larini, Morvan, Porterie & al (1996)
  Clark & al (1996), Lin & al (1997),
  Sero-Guillaume & al (2002), Rehm & al (2003), Mandel & al (2004), Mell & al (2005), Mahalingam (2008), Filippi & al (2009), Rochoux & al (2013) …

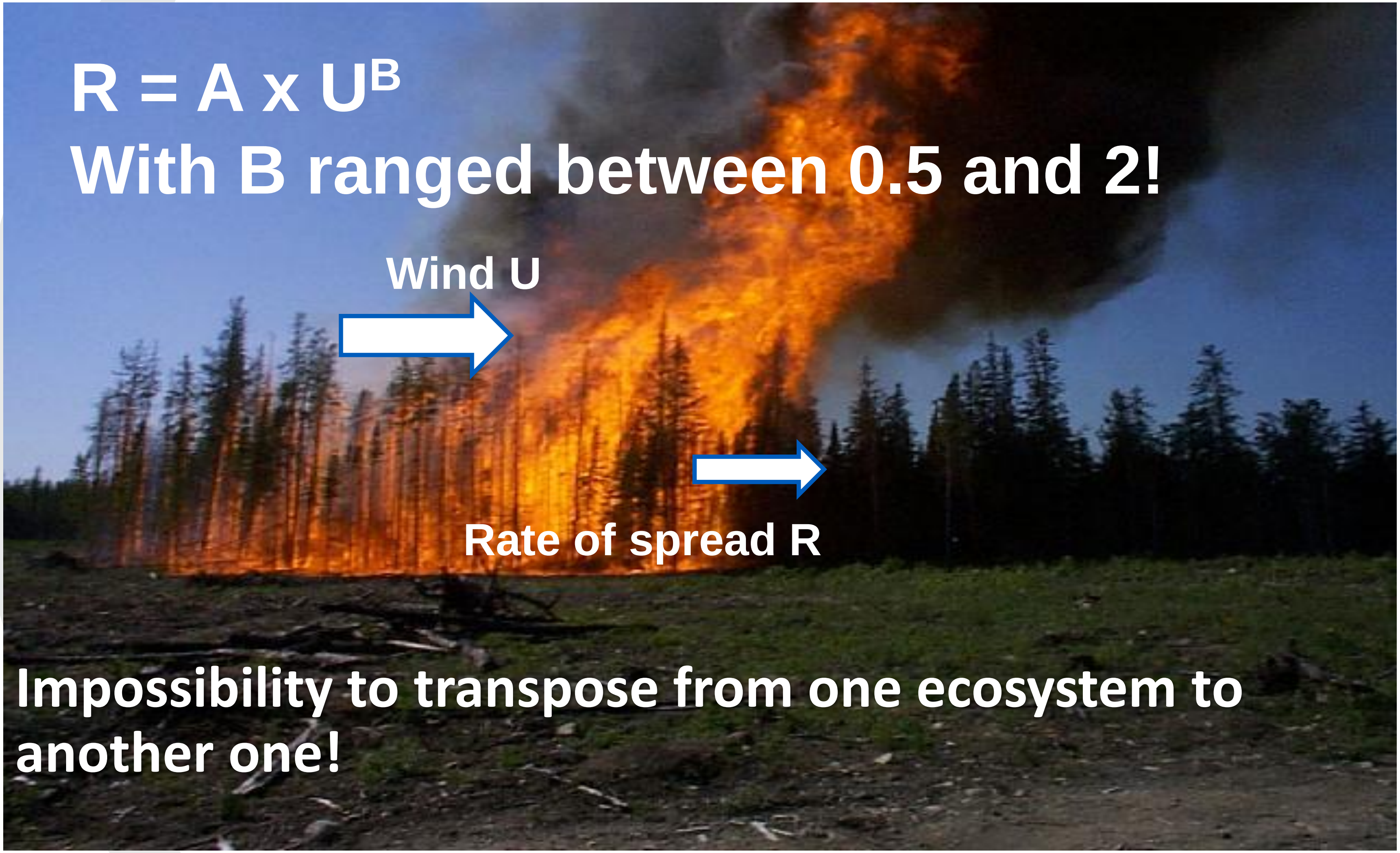
Empirical wildfire model (McArthur 1966 …)



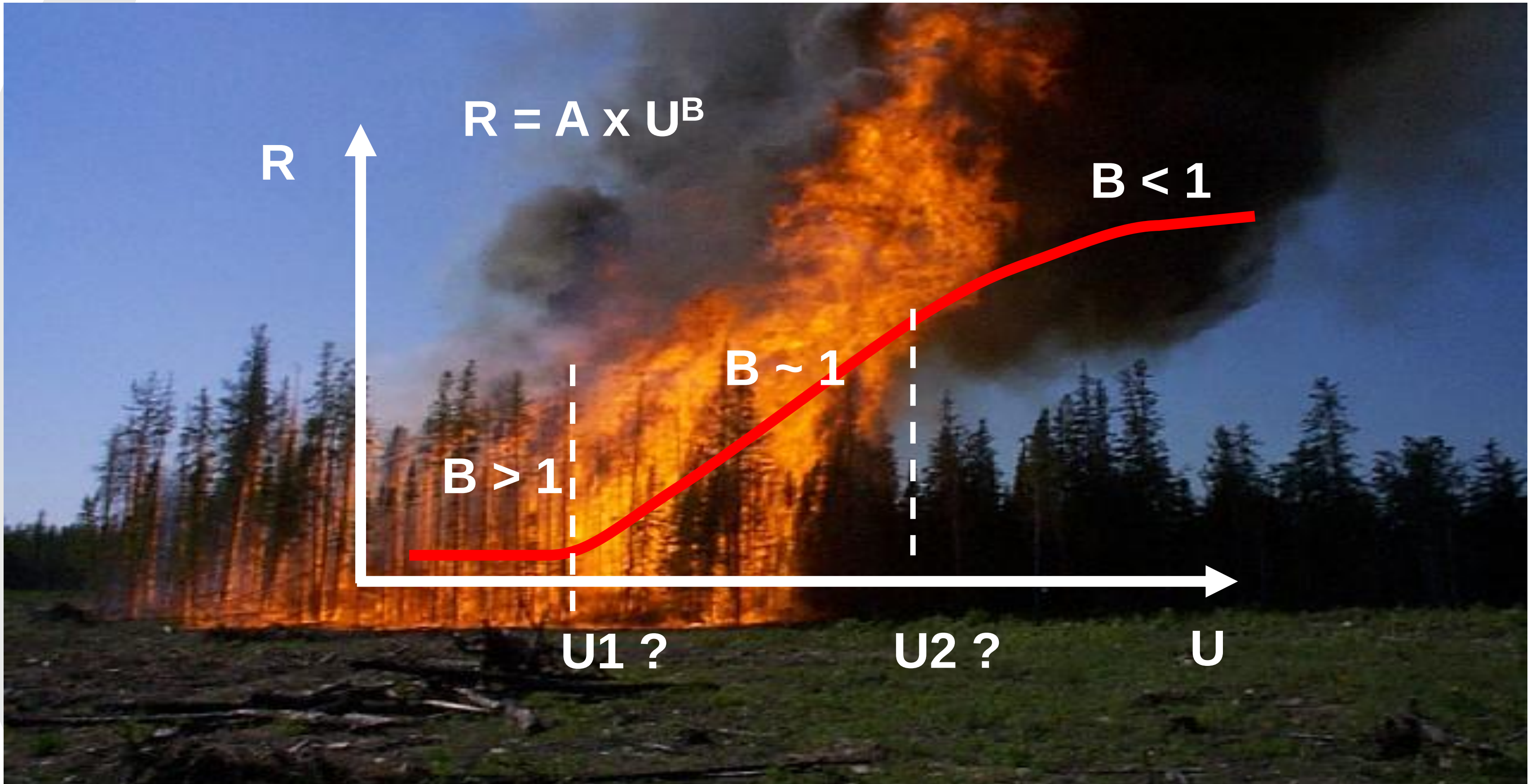
Experimental fires → Risk index

Risk index = f (Air T° and humidity, Drought factor, Wind speed, Last rainfall)

Wildfire physics: example of the relationship rate of spread versus wind speed from empirival approach.



Rate of spread versus wind speed: the impossible extrapolation.



A = f(Fuel, FMC, slope, LAD…)
B = g(regime of propagation …)

Semi-empirical 1972 Rothermel's model (BEHAVE, FARSITE)

$$R = \xi \; Ir \; / \; (\rho_s \; \alpha_s \; \Delta hi) \; (1 + \phi_w + \phi_s), \; \xi = f(\sigma_s)$$

$\rho_s \; \alpha_s$: Fuel density and fuel volume fraction

Ir : Heat of combustion

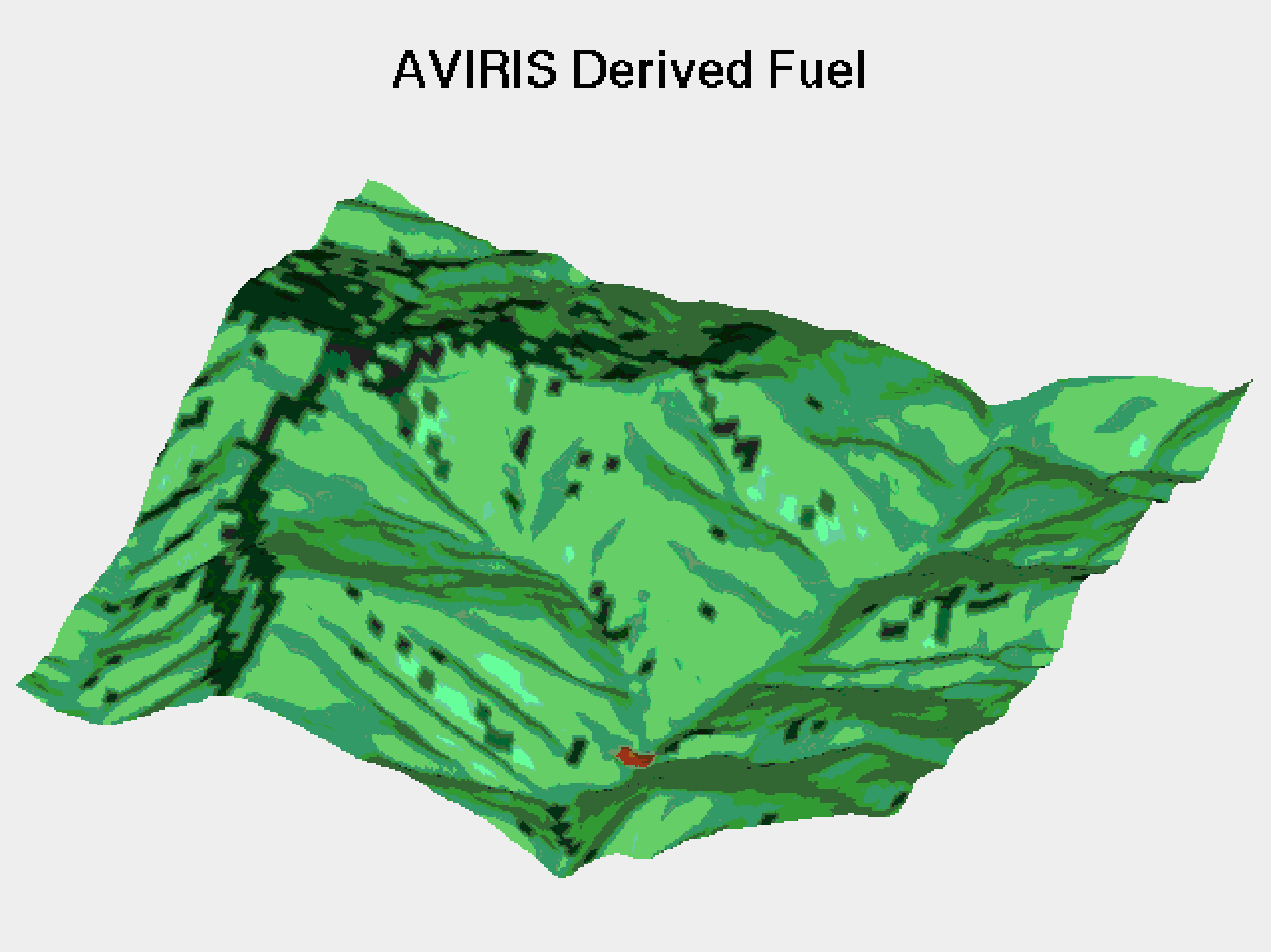
$\Delta hi = C_p \, [T_i - T_a]$ Enthalpy of ignition

σ_s : Surface area / Volume ratio of solid fuel particles

ϕ_w ; ϕ_s : wind and slope factor

Malibu fire (22/10/1996)

Firetec simulation (LANL)



Malibu fire: semi-empirical model versus physical model

Time necessary to burn 50 ha from the canyon to the top of the hill (real time =10 minutes)

Effect of … to evaluate the wind	Slope	Fire	Time
Farsite (Rothermel)			180 min.
Hygrad + Rothermel	X		20 min.
Firetec	X	X	10 min.

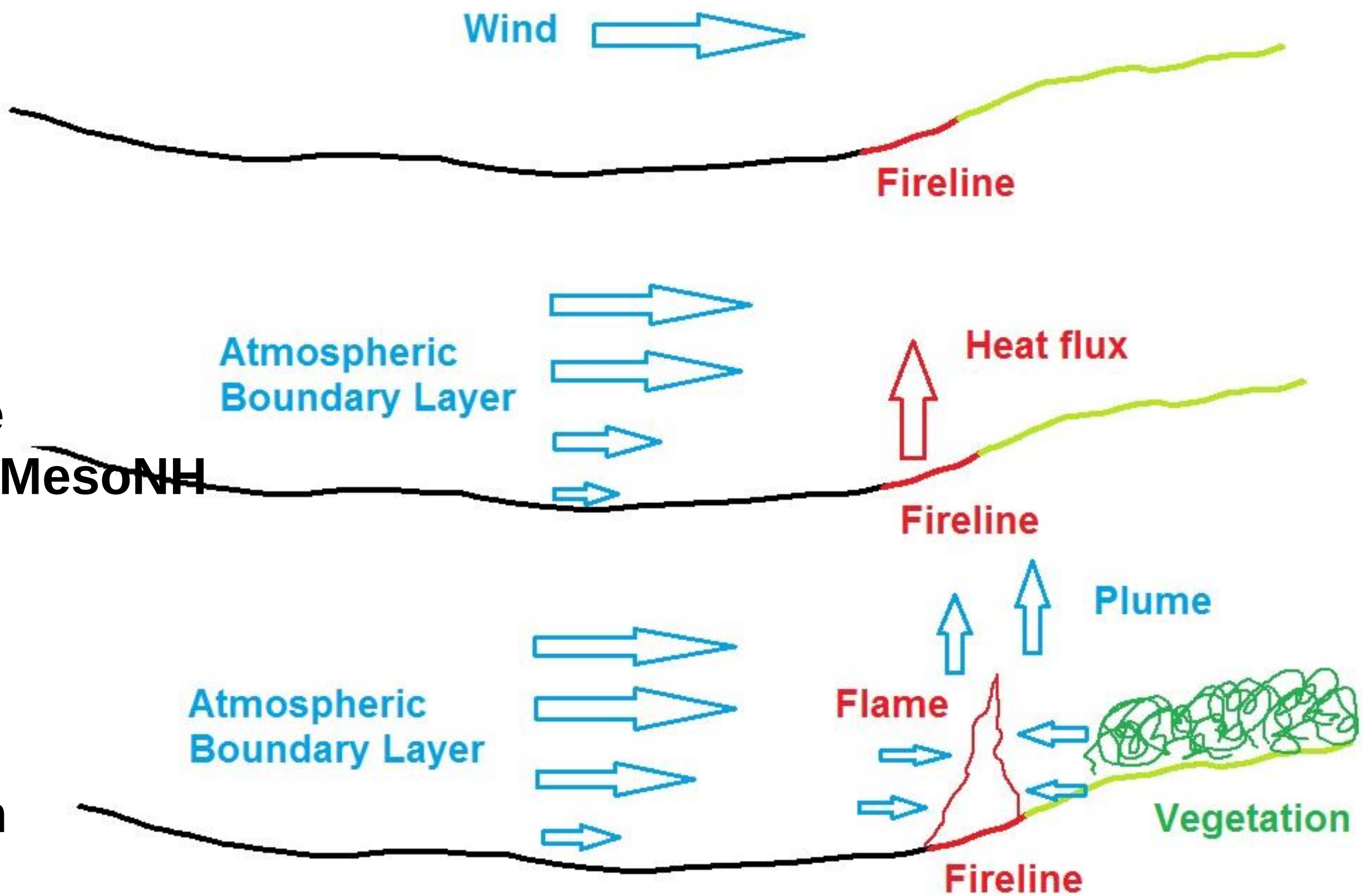
Hierarchy of wildfire models from semi-empirical model (top), to coupled meso-scale atmospheric-fire (middle), to fully physical model (bottom)

FlamMap

WRF Fire
ForeFire/MesoNH

FireTec

FDS
FireFoam
FireStar



How simulate the behaviour of wildfires using a “fully” physical model ?

Physical phenomena

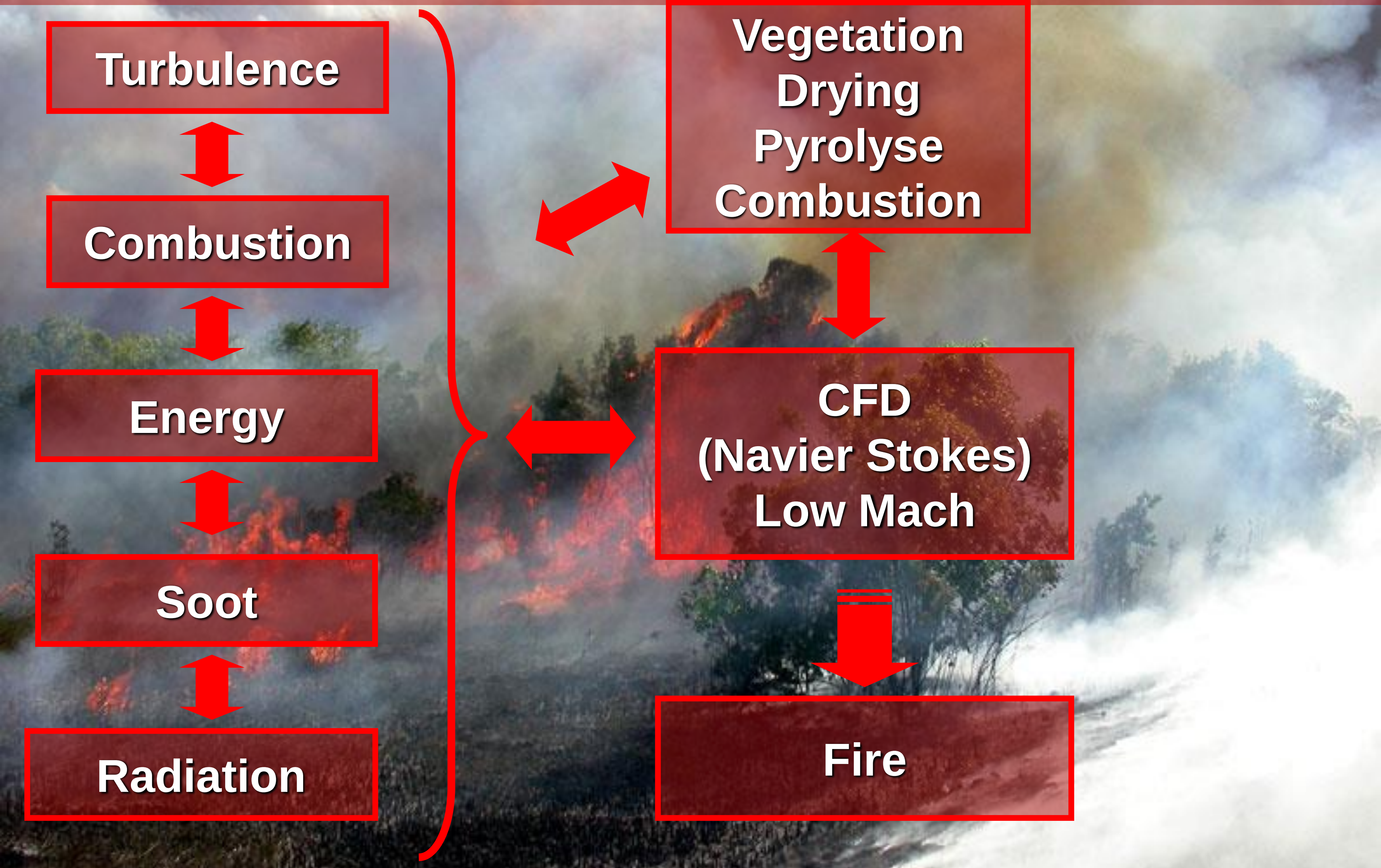
Compressible flow
Reactive flow
Turbulent flow
Radiation
Solid/Gas interface

Solid fuel degradation

Scales

Wind speed
Flame thickness
Turbulent structures
Extinction length
Vegetation

Simulating wildfire behaviour using a physical model : multiphase approach

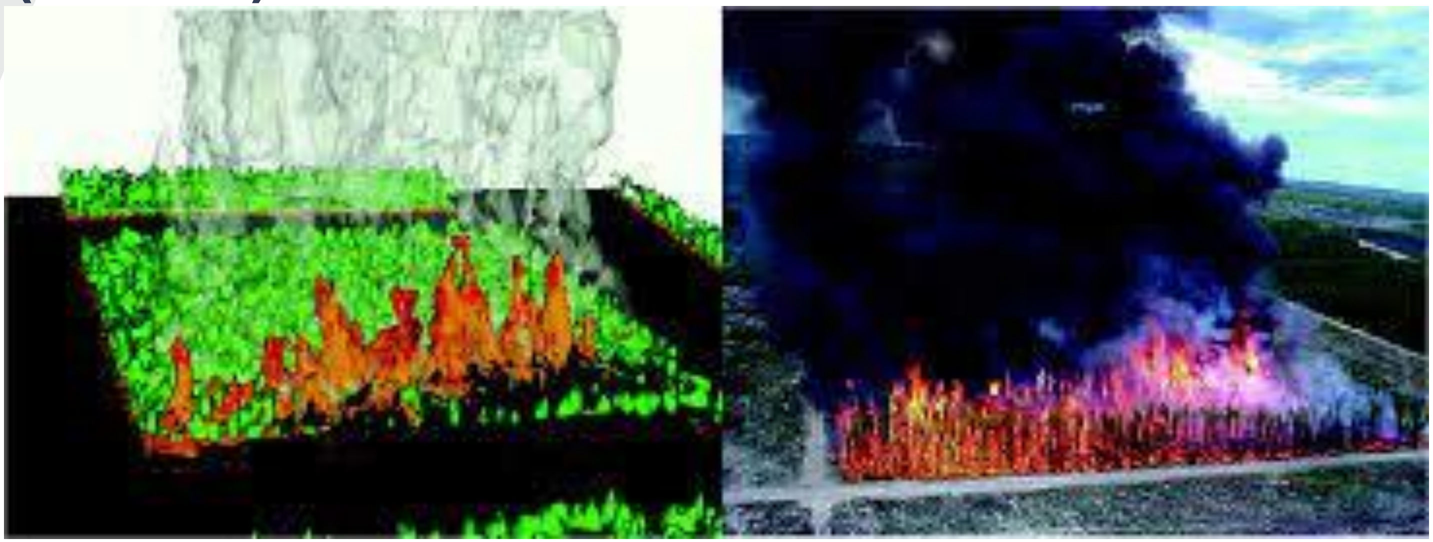


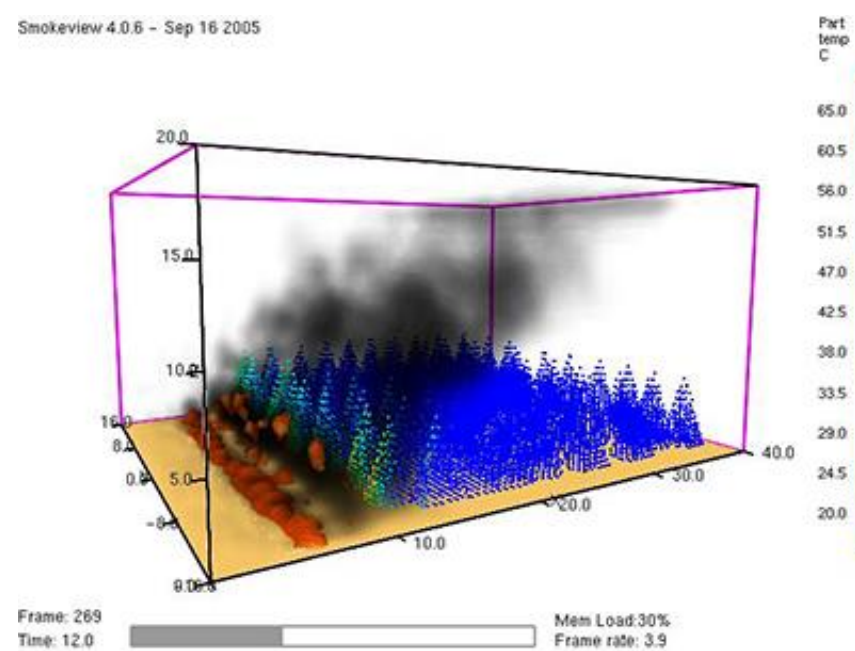
Some wildfire fully physical models

	Time integration	Low Mach	Turbulence	TRI model	Combustion model	Multi phase	Lab scale	Large scale
FIRESTAR	Implicite	Yes	LES	Yes	Yes	Yes	Yes	Yes (**)
FDS	Explicite	Yes	LES	No (*)	Yes	Yes	Yes	Yes
FIRETEC	Explicite	No	LES	No (*)	No (***)	Yes	No	Yes
FIREFOAM	Implicite	Yes	LES	Yes	Yes	No	Yes	Yes (**)

(*) Prescribed global radiant model
(**) < 500 m
(***) Degradation of the vegetation and heat release occur in one single cell

Results obtained for crown fires using Firetec and FDS (ICFME) …





Compressible flow: low Mach number approximation (non reactive flow, ideal gas)

Compressible Navier-Stokes equations

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho\, U_j}{\partial x_j} = 0$$

$$\frac{\partial \rho U_i}{\partial t} + \frac{\partial \rho U_j U_i}{\partial x_j} = \frac{\partial \overline{\sigma_{ij}}}{\partial x_j} + \rho f_i$$

$$\frac{p}{\rho} = \frac{R\,T}{M}$$

$$\frac{\Delta p}{p} = O(Mach^2) \quad \mathrm{Mach} = \frac{U}{a} \qquad a: sound\ speed\ in\ air\ (\sim 340\ m\ s^{-1})$$

$$\mathrm{U} = 50\ \mathrm{km/h} = 14\ \mathrm{m/s} \ \rightarrow Mach = 0.04 \ \rightarrow \frac{\Delta p}{p} = 0.0016\ (160\ \mathrm{pa})$$

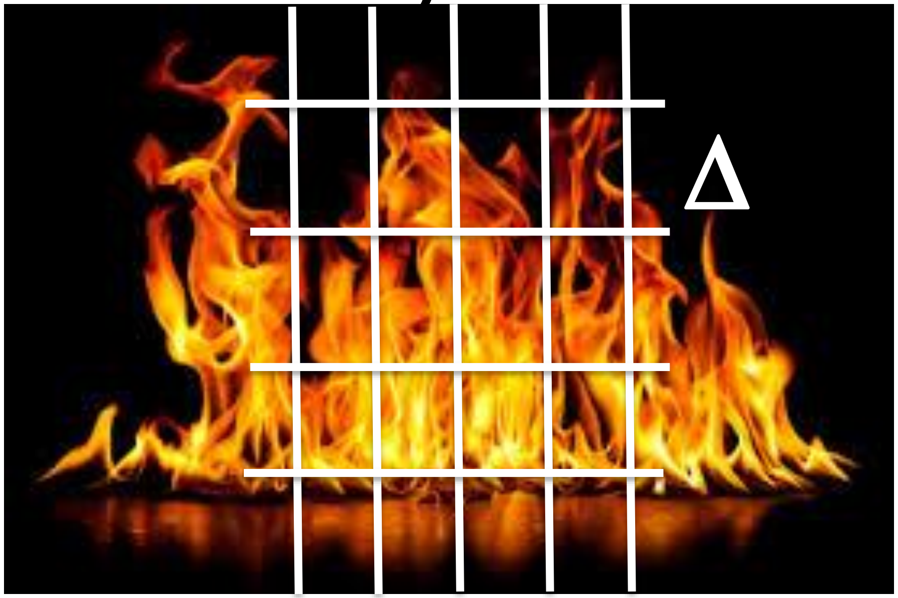
$$p = \hat{P} + p' \rightarrow \frac{\hat{P}}{\rho} = \frac{R\,T}{M}\ (\text{in open domain } \hat{P} = \text{cte} = 10^5\ pa)$$

Compressible flow: low Mach number approximation
CFL stability criteria (numerical simulation)

$$\frac{V\,\delta t}{\Delta} < C$$

Explicit scheme: $\mathrm{C} < 1$

Implicit scheme: $\mathrm{C} > 1$



Full compressible

$\mathrm{V} = \max(U, a)$

Low Mach number

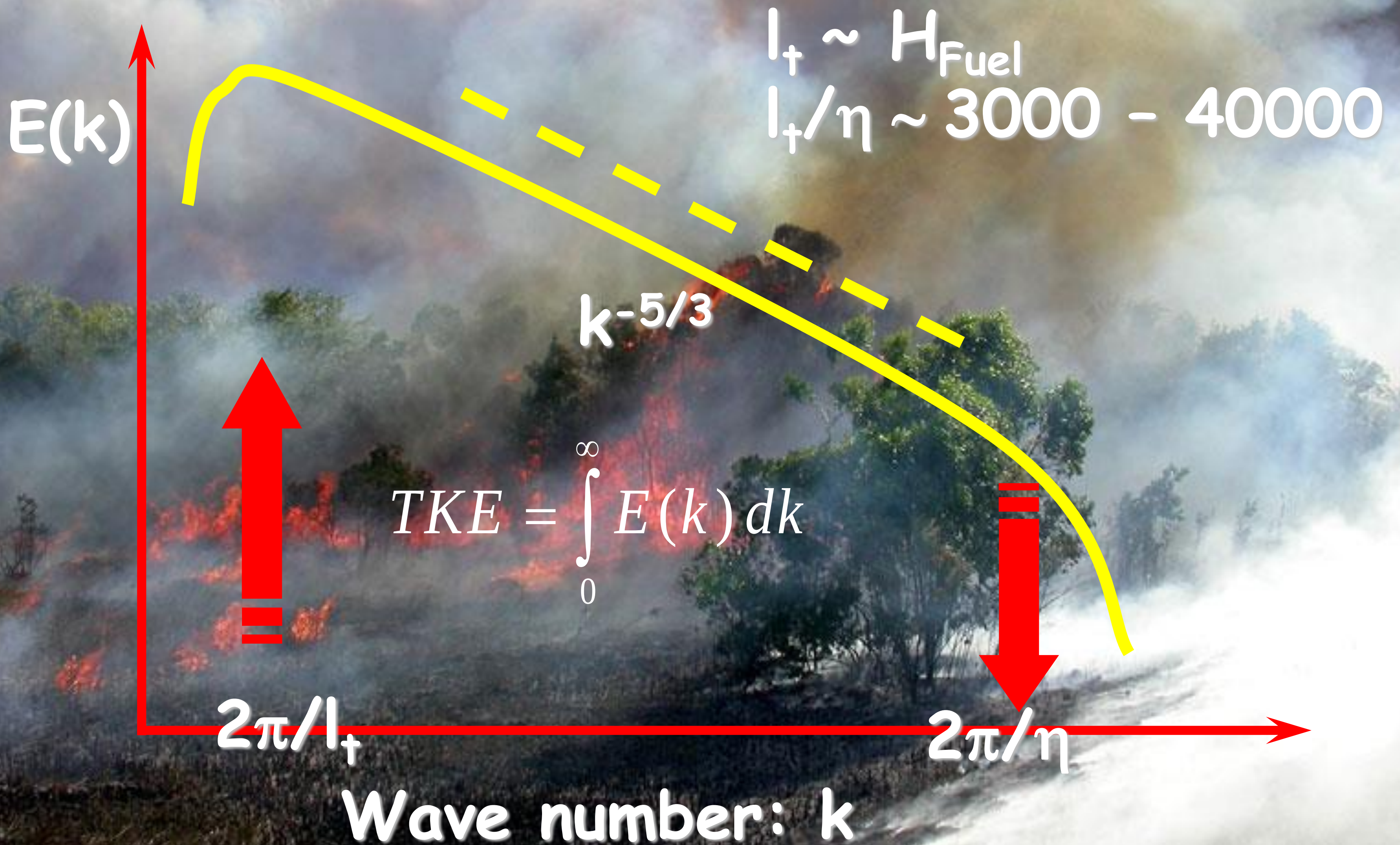
$\mathrm{V} = \mathrm{U}$

δt : time step

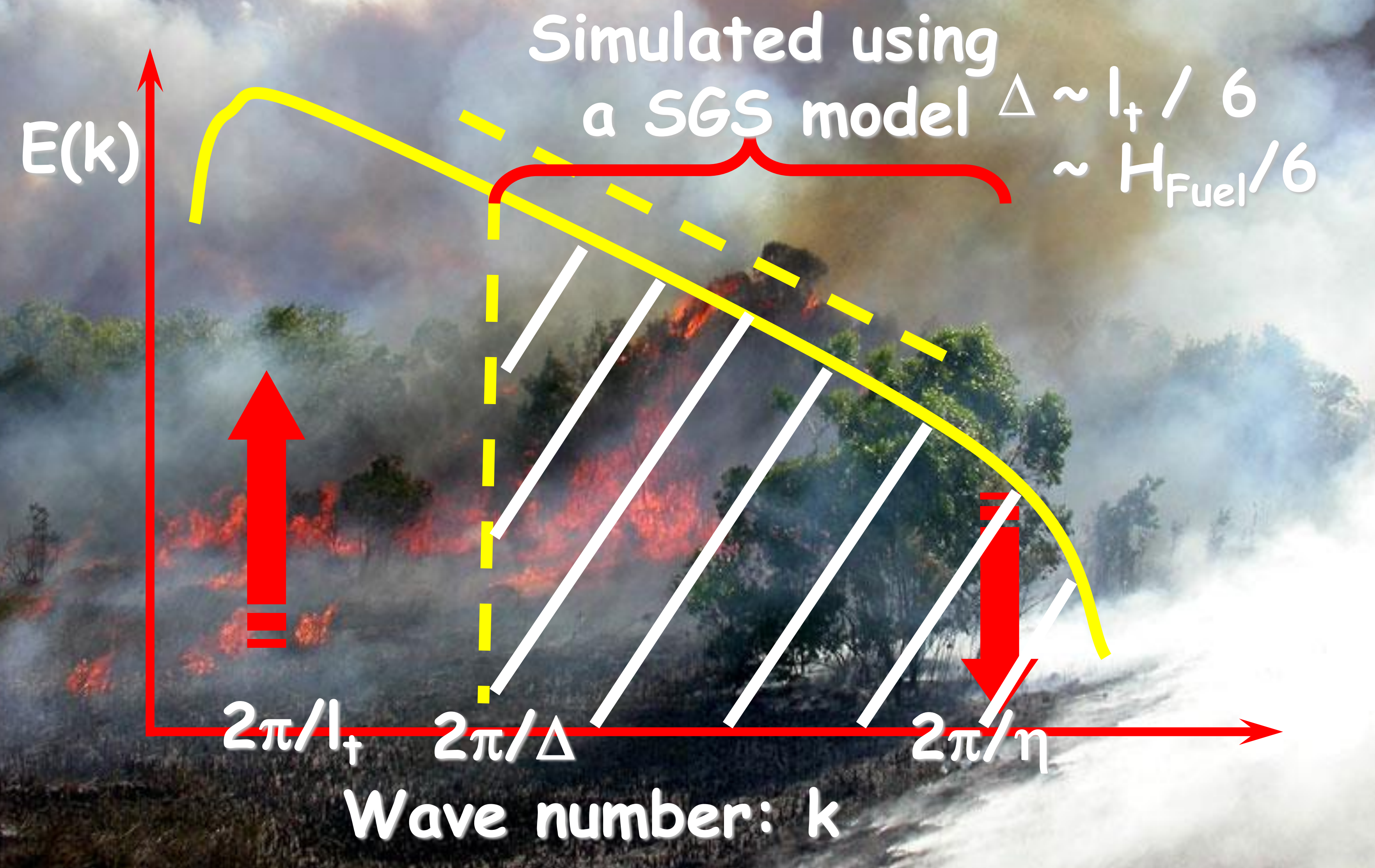
Δ : mesh size

The low Mach number approximation allows theoretically to reduce the time step by a factor equal to 1/Mach

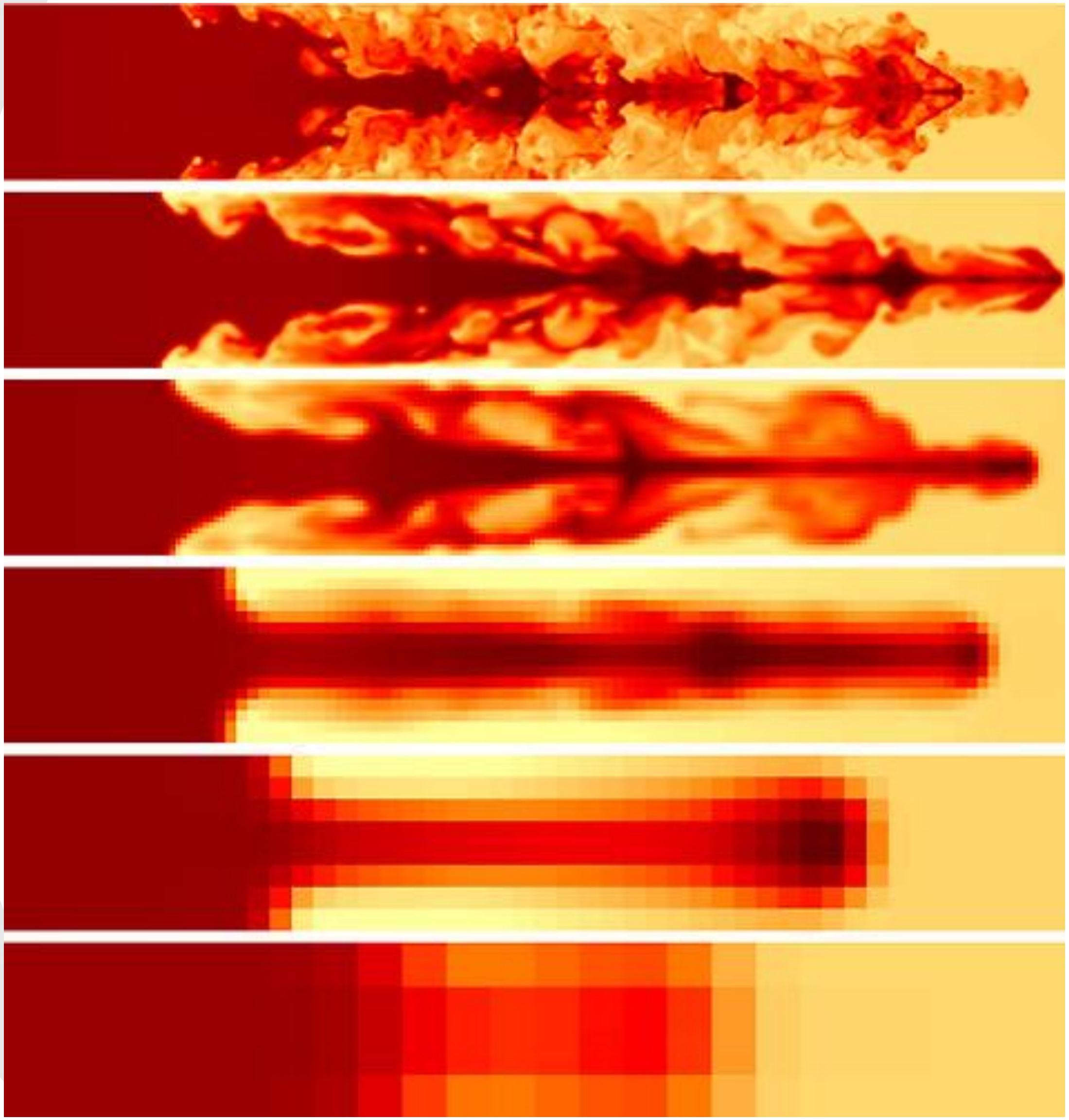
Some results from the classical homogeneous theory (Kolmogorov 1941)



Some results from the classical homogeneous theory (Kolmogorov 1941): turbulence modelling



Turbulence modelling



DNS

LES

RANS

Turbulence modelling, Reynolds decomposition

$$U_i = \overline{U_i} + U_i' \quad \text{with } \overline{U_i} = \frac{1}{T}\int_t^{t+T} U_i(t)\, dt$$

Instantaneous momentum equation (isotherm, incompressible flow)

$$\frac{\partial \rho U_i}{\partial t} + \frac{\partial \rho U_j U_i}{\partial x_j} = \frac{\partial \sigma_{ij}}{\partial x_j} + f_i$$

Average momentum equation

$$\frac{\partial \rho \overline{U_i}}{\partial t} + \frac{\partial \rho \overline{U_j U_i}}{\partial x_j} = \frac{\partial \overline{\sigma_{ij}}}{\partial x_j} + \overline{f_i} - \underbrace{\frac{\partial \rho \overline{U_j' U_i'}}{\partial x_j}}$$

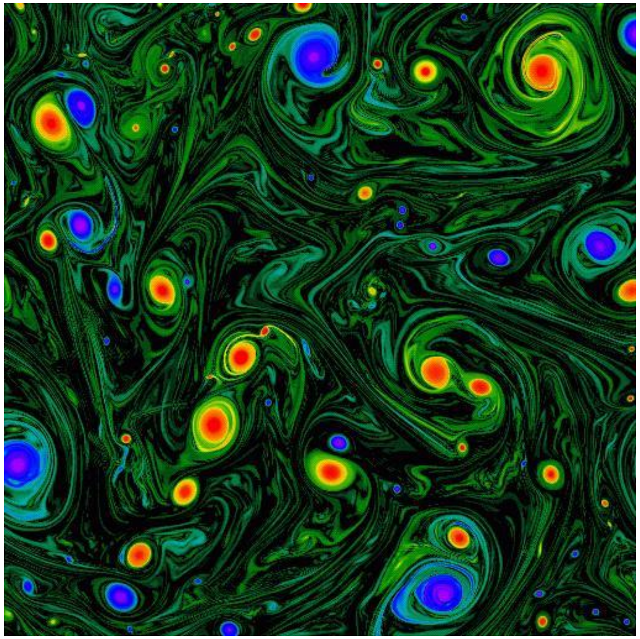
Additional terms → turbulence model

Lot of turbulence models are based on the concept of eddy viscosity, associate to the idea that the turbulent structures are isotropic (assumption only verified for small turbulent structures and not for large scale turbulent structures)

$$\overline{U_j' U_i'} = \frac{2}{3} K \delta_{ij} - \mu_T \left(\frac{\partial \overline{U_i}}{\partial x_j} + \frac{\partial \overline{U_j}}{\partial x_i} \right) \text{ with } \mu_T = \rho L^2 \left| \frac{\partial \overline{U_i}}{\partial x_j} + \frac{\partial \overline{U_j}}{\partial x_i} \right|$$

Turbulence model, K-ε model

Eddy viscosity, effective viscosity



$$\mu_{eff} = \mu + \mu_T \quad with\ \mu_T = \rho\, C_\mu\, \frac{K^2}{\epsilon}$$

$$\overline{\sigma_{ij}} = -\left(p + \frac{2}{3}\,K\right)\delta_{ij} + \mu_{eff}\left(\frac{\partial \overline{U_i}}{\partial x_j} + \frac{\partial \overline{U_j}}{\partial x_i}\right)$$

$$\frac{D\rho\overline{U_i}}{Dt} = \frac{\partial \overline{\sigma_{ij}}}{\partial x_j}$$

$$\frac{D\rho K}{Dt} = \frac{\partial}{\partial x_j}\left[\frac{\mu_{eff}}{\sigma_K}\frac{\partial K}{\partial x_j}\right] + \rho P - \rho\epsilon$$

$$\frac{D\rho\epsilon}{Dt} = \frac{\partial}{\partial x_j}\left[\frac{\mu_{eff}}{\sigma_\epsilon}\frac{\partial \epsilon}{\partial x_j}\right] + \rho\, C_{\epsilon 1}\frac{P}{T} - \rho\,(C_{\epsilon 2} + R)\frac{\epsilon}{T}$$

T: characteristic time of the turbulence

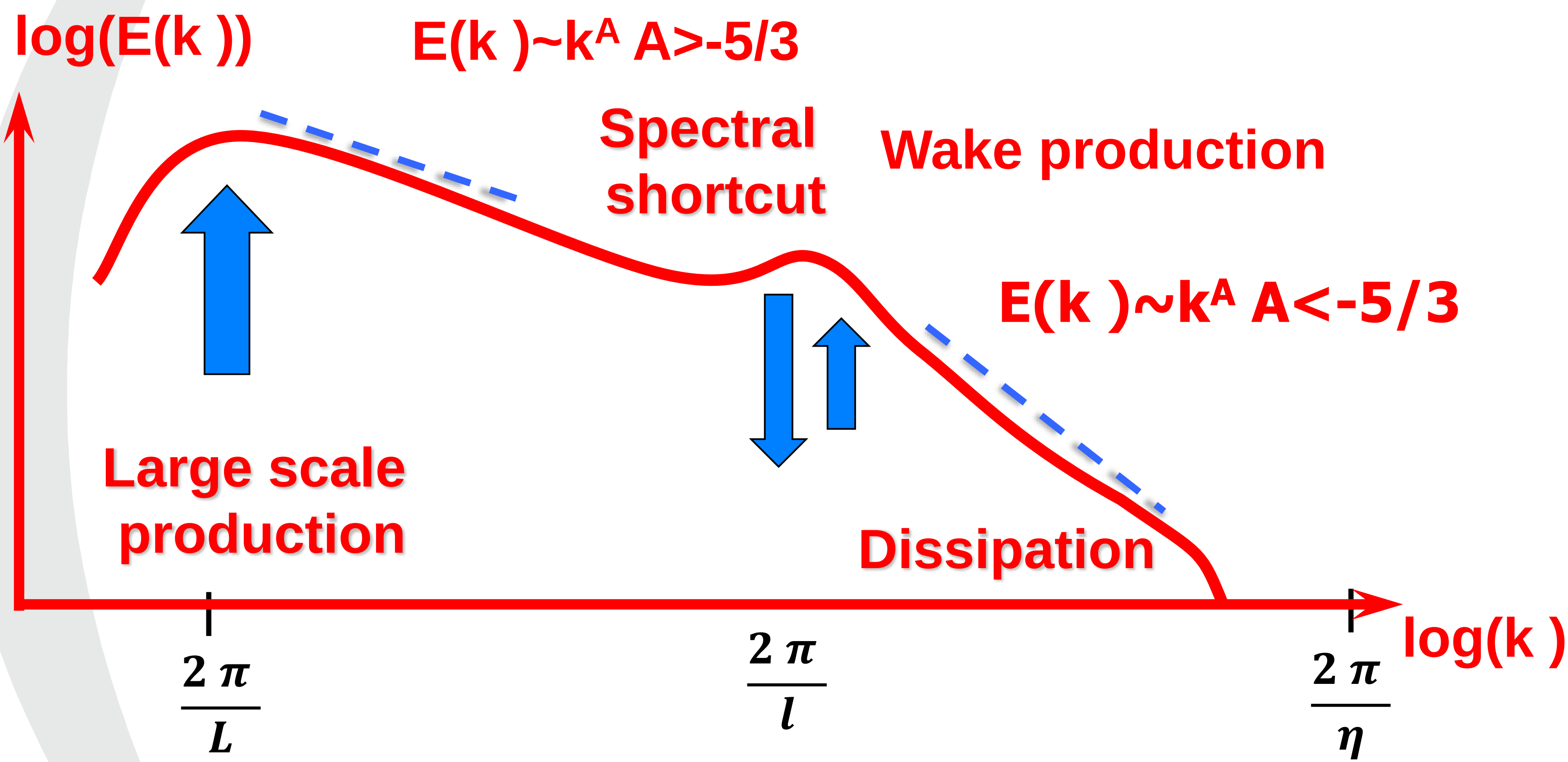
$$T = \max(\tau, C_T\,\tau_\eta) \quad \tau = \frac{K}{\epsilon} \quad \tau_\eta = \left(\frac{\nu}{\epsilon}\right)^{1/2}$$

Turbulence modeling: how evaluate the turbulence integral length scale l_t?

Two sources of production of turbulence:

- **The shear flow between the vegetation and the boundary layer flow**
- **The buoyancy between the hot gas in the plume and the ambient air**

Canopy/ABL interaction
Turbulence kinetic energy spectra



E.G. Patton, J.J. Finnigan 2013

ABL/canopy interaction (Finnigan 2000)

- **Dense canopy (C_DxLAI > 0.1) mixing layer flow**
- **Sparse canopy: boundary layer flow**

$$LAD = \frac{\alpha_S \, \sigma_S}{2}$$

$$LAI = \int_0^H LAD(z)\,dz$$

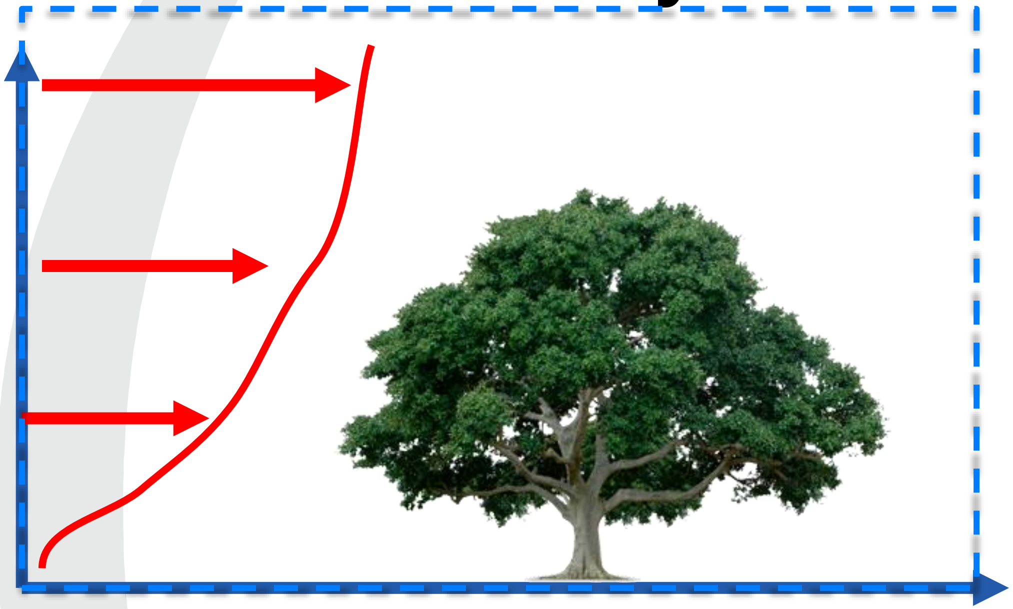
surface layer
logarithmic zone

2 or 3 x H

roughness layer (KH instability)

H

ABL/canopy interaction: how evaluating the force induced by the tree upon the air flow?

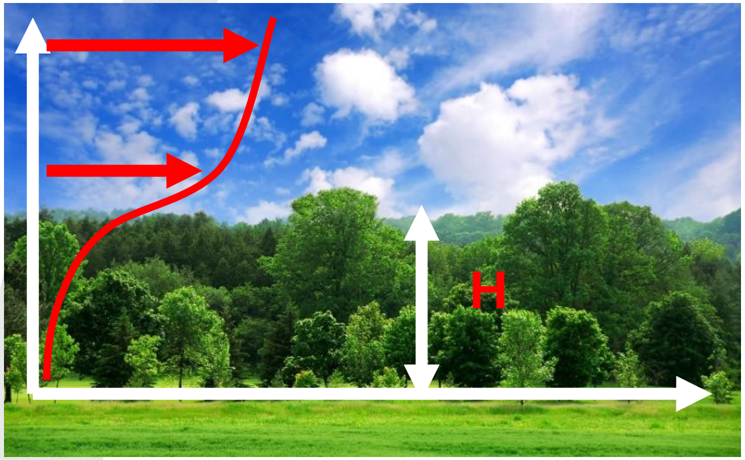


$$\int_S \rho \left(\vec{U}.\vec{n}\right) \vec{U}\, dS = \sum \overrightarrow{F_{ex}}$$

$$\rho\left(\vec{U}.\vec{\nabla}\right)\vec{U} = \overrightarrow{F_V} + \mathrm{Div}\,\bar{\bar{\sigma}} - \rho\, C_D\, LAD\, \|U\|\, \vec{U}$$

Integrating the stress forces along the interface air/tree?
Problem: the fractal nature of this interface
Solution global balance + considering the tree (leaves, twigs, branches…) as a sparce porous media
Drag force with a drag coefficient defined from the Leaf Area Density (LAD)

ABL/canopy interaction



Leaf Area Density (LAD)

$$\frac{\alpha_k \, \sigma_k}{2} = \mathrm{LAD}$$

$$\frac{D\rho U}{Dt} = \mathrm{Div}\, \bar{\bar{\sigma}} - \underbrace{\sum_k \rho \, C_D \frac{\alpha_k \, \sigma_k}{2} \, \|U\| \, \mathrm{U}}_{\text{Drag force}}$$

Leaf Area Density (m^2/m^3)
Similitude parameter LAI (Leaf Area Index)

$$\mathrm{LAI} = \int_0^H LAD(z)\, dz$$

Aix*Marseille université Initiative d'excellence

Turbulence model, ABL/canopy interaction

Leaf Area Density (LAD)

$$\frac{\alpha_k \, \sigma_k}{2} = \mathrm{LAD}$$

$$\frac{D\rho U}{Dt} = \mathrm{Div}\, \bar{\bar{\sigma}} - \underbrace{\textstyle\sum_k \rho \, C_D \frac{\alpha_k \, \sigma_k}{2} \, \|U\| \, \mathrm{U}}$$

$$\frac{D\rho K}{Dt} = \frac{\partial}{\partial x_j}\left[\frac{\mu_{eff}}{\sigma_K}\frac{\partial K}{\partial x_j}\right] + \rho P - \rho\epsilon + \underbrace{\sum_k \rho \, C_D \frac{\alpha_k \, \sigma_k}{2}\left[U^3 - 4UK\right]}$$

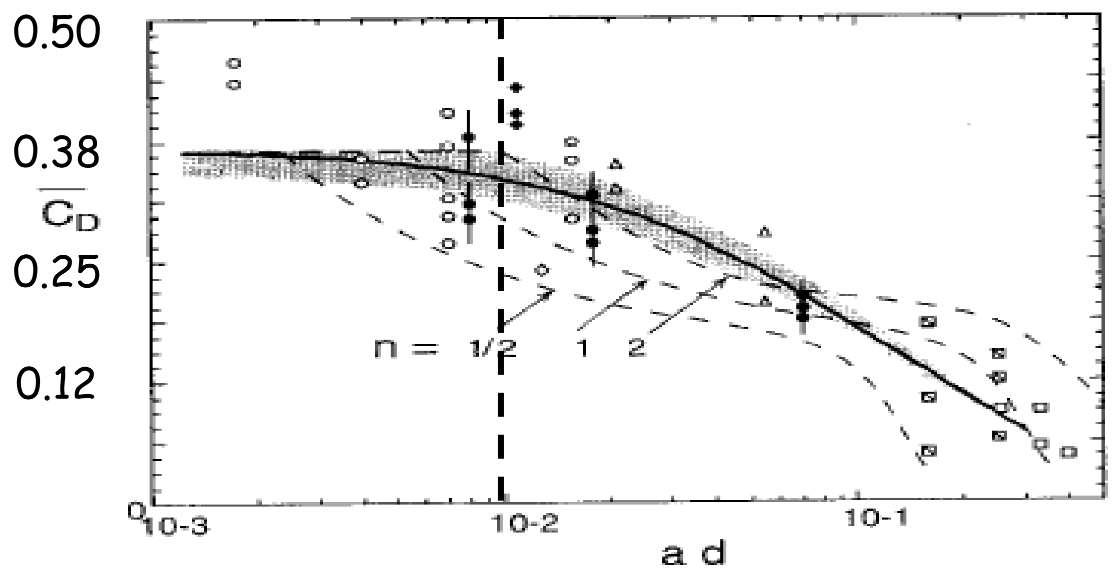
$$\frac{D\rho\epsilon}{Dt} = \frac{\partial}{\partial x_j}\left[\frac{\mu_{eff}}{\sigma_\epsilon}\frac{\partial \epsilon}{\partial x_j}\right] + \rho \, C_{\epsilon 1}\frac{P}{T} - \rho \, (C_{\epsilon 2} + R)\frac{\epsilon}{T} + \underbrace{\sum_k \rho \, C_D \frac{\alpha_k \, \sigma_k}{2}\left[\frac{3\epsilon}{2\,K}U^3 - 6U\epsilon\right]}$$

$$T = \max(\tau, C_T \, \tau_\eta) \quad \tau = \frac{K}{\epsilon} \quad \tau_\eta = \left(\frac{\nu}{\epsilon}\right)^{1/2}$$ **(Integral and Kolmogorov time scale C_T=6)**

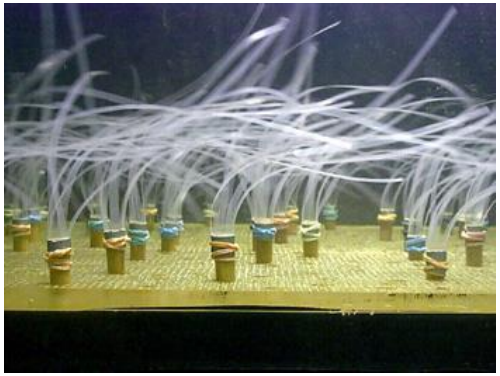
Additionnal terms resulting from the flow/vegetation interaction (micro-wake) ! C_d ~ 0.1-0.4 (typical value)

Drag coefficient in seagrass (experiments)

(C_D defined using LAD (Leaf Area Density) as a reference surface)



$$ad = \frac{4\,\alpha_S}{\pi}$$



- If ad < 0.01 $< C_D > = C_D (R_e)$ (~ single particule)
- If ad > 0.01 $< C_D > = f(ad)$ (wake interaction)
- Typical value: ad ~ α_s ~ 10^{-3}- 10^{-2} → $C_D = 0.38$

(Water Resources Research Vol.35(2) pp.479-489 (1999), H.M. Nepf)

Effect of atmospheric stratification upon fire dynamics.

$$R_i = \frac{N^2}{\left(\frac{du}{dz}\right)^2}$$

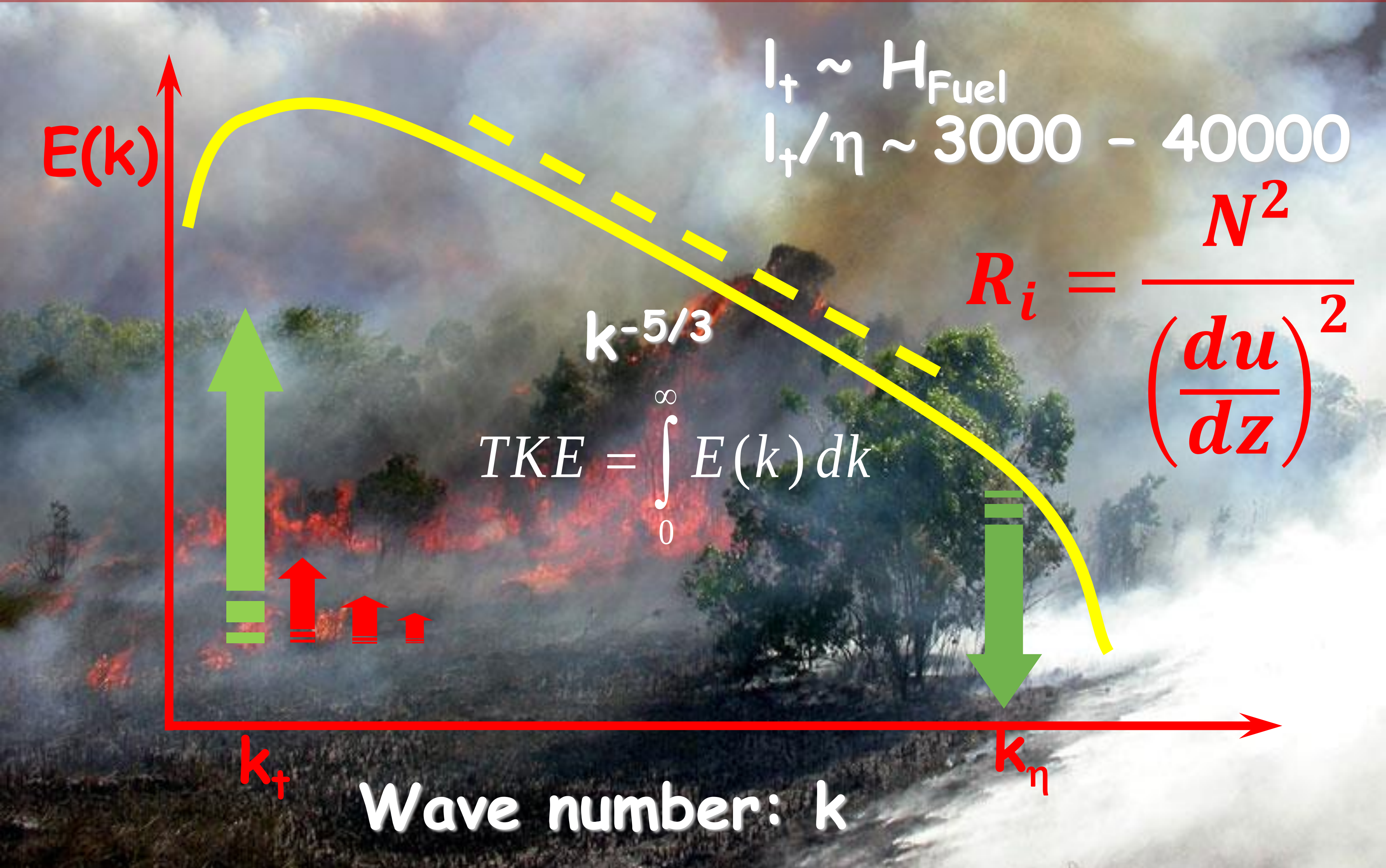
Effect of atmospheric stratification (stability) upon the fire dynamics, thermal plume, aerosols transport, turbulence …

N: Brunt-Väisälä frequency

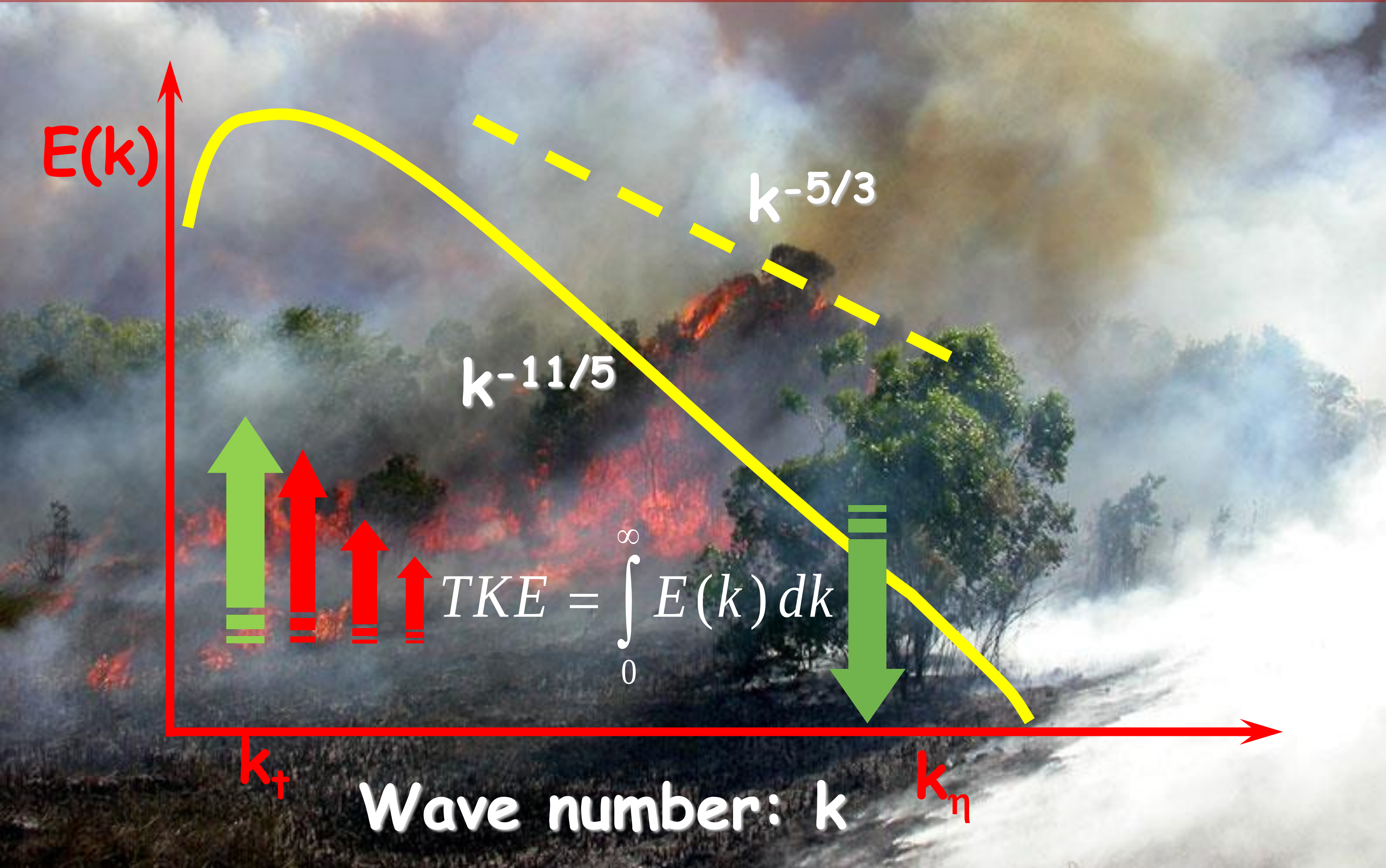
$$N^2 = \frac{g}{\rho_\theta}\left|\frac{d\rho_\theta}{dz}\right|$$

$$\rho_\theta = \rho\left(\frac{p}{p_0}\right)^\gamma$$

Weak gravity flow (Kolmogorov): Ri <<1

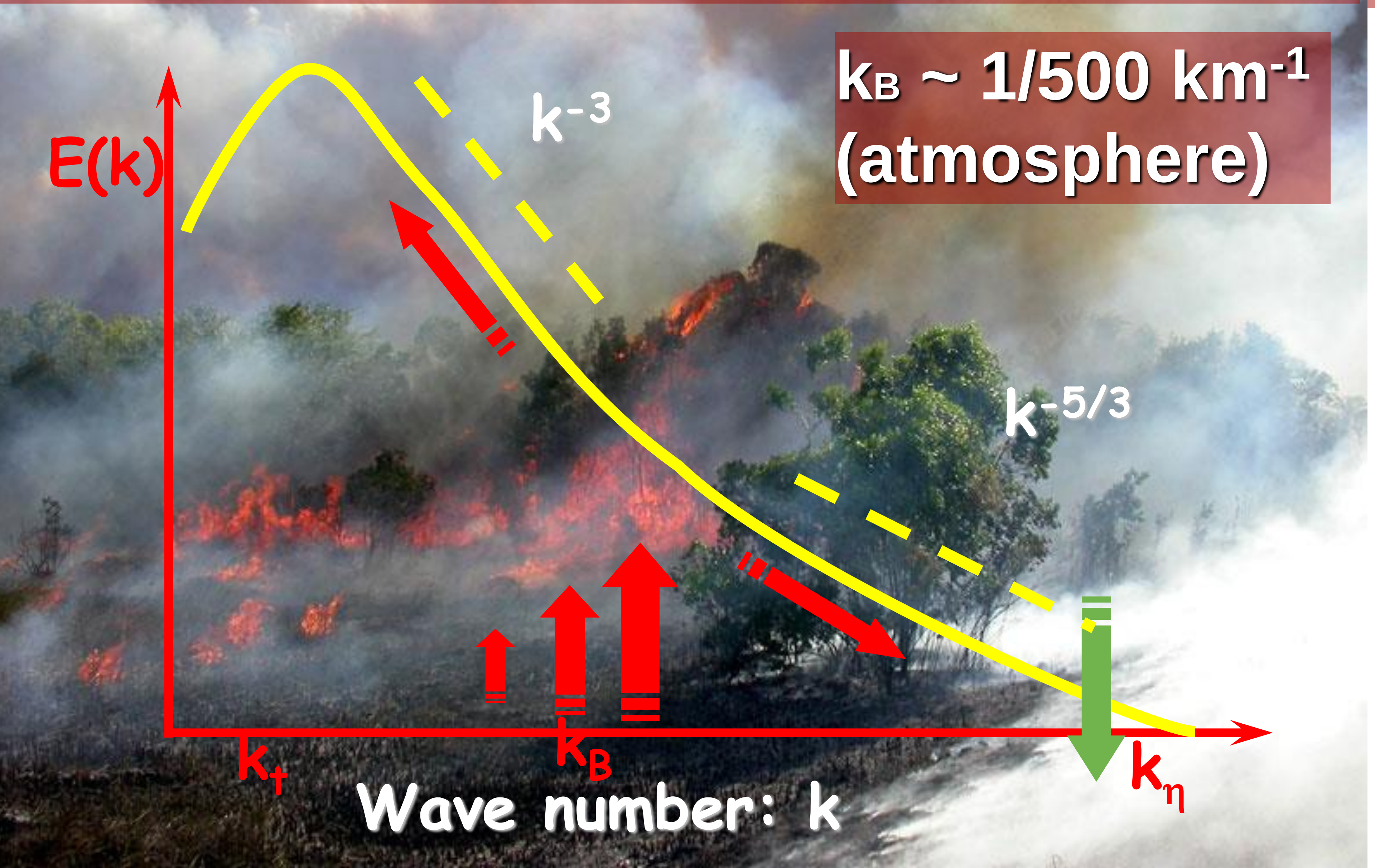


Moderate gravity flow (Bolgiano-Obukhov): Ri ~1

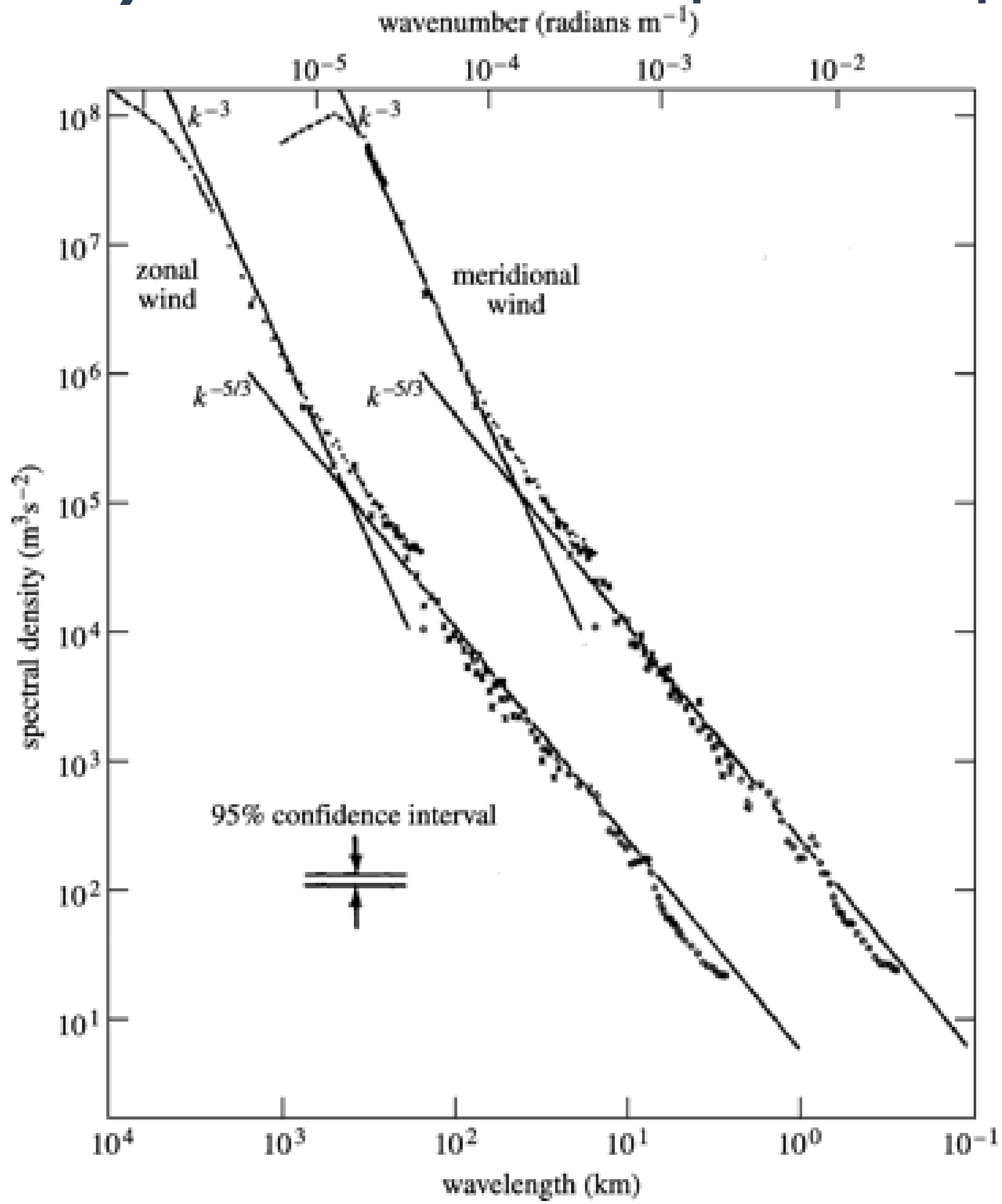


Strong gravity flow: Ri >>1 (Bolgiano scaling) $k_B \sim (\beta\ g)^{3/2}\ \varepsilon^{-5/4}\ \varepsilon_T^{3/4}$

$k_B \sim 1/500\ km^{-1}$ (atmosphere)



Turbulence kinetic energy spectra (atmospheric data, GASP) GASP: Global Atmospheric Sampling Program (NASA)



Transport equation of chemical species (α)

For each species α: $$\frac{\partial}{\partial t}(g_\alpha \rho_\alpha) + \frac{\partial}{\partial x_j}\left(g_\alpha \rho_\alpha u_j^\alpha\right) = \dot{\omega}_\alpha$$

Average density and velocity: $$\rho = \sum_\alpha g_\alpha \rho_\alpha \qquad \rho u_j = \sum_\alpha g_\alpha \rho_\alpha u_j^\alpha$$

Mass fraction: $$\rho Y_\alpha = g_\alpha \rho_\alpha$$

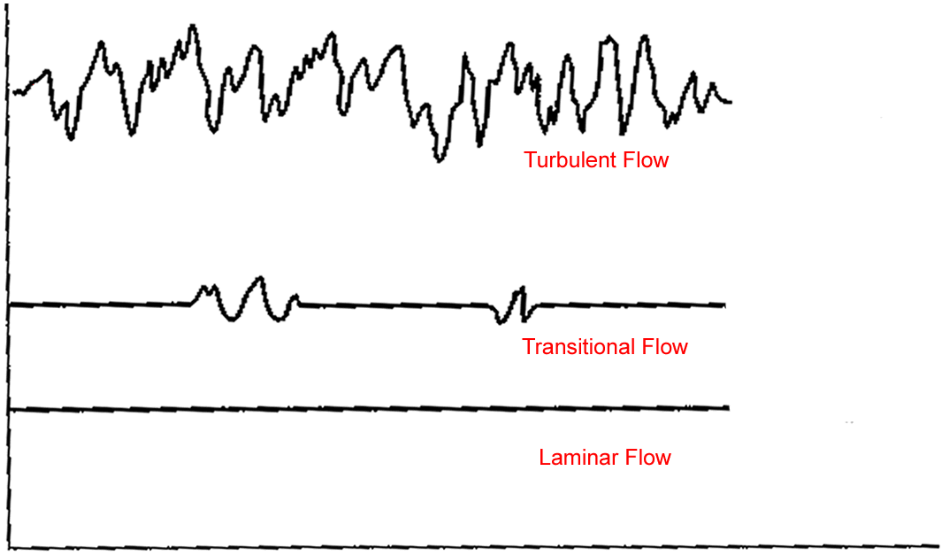
$$\frac{\partial}{\partial t}(\rho Y_\alpha) + \frac{\partial}{\partial x_j}(\rho Y_\alpha u_j) = \dot{\omega}_\alpha - \frac{\partial}{\partial x_j}\left(\rho Y_\alpha \left(u_j^\alpha - u_j\right)\right)$$

Diffusion velocity: $$-Y_\alpha\left(u_j^\alpha - u_j\right) = D_\alpha \frac{\partial Y_\alpha}{\partial x_j}$$

$$\frac{\partial}{\partial t}(\rho Y_\alpha) + \frac{\partial}{\partial x_j}(\rho Y_\alpha u_j) = \frac{\partial}{\partial x_j}\left(\rho D_\alpha \frac{\partial Y_\alpha}{\partial x_j}\right) + \dot{\omega}_\alpha$$

Laminar/turbulent flame

Velocity or temperature signals



Combustion, Arrhenius law, turbulence

Fire:
Turbulent flame
Soot particules
Chemistry
Radiation
Coupling
combustion/turbulence
radiation/turbulence

$$Fuel + \nu\, O_2 \rightarrow (1+\nu)\, Produits$$

Reaction rate:

$$\dot{\omega}_{Fuel} = f(Y_{Fuel}, Y_{O2}, T) = -\, k_0\, Y_{Fuel}^{a}\, Y_{O2}^{b}\, T^{c} exp\left(-\frac{E}{R\,T}\right)$$

$\overline{\dot{\omega}_{Fuel}} = f(\overline{Y_{Fuel}}, \overline{Y_{O2}}, \bar{T})$? No because $\frac{\sqrt{\overline{T'^2}}}{\bar{T}} \gg 1$

Average reaction rate: example of a point located in the intermitent zone (50%: T = 500 K; 50%: T =2000 K)

$$k(T) = k_0\, exp\left(-\frac{E}{R\,T}\right) \quad \frac{E}{T} = 20\,000K\ (typical\ value)$$

$$PDF(T) = \frac{1}{2}\left(\delta(T - T_1) + \delta(T - T_2)\right)$$

T_1=500 K and $T_2 = 2000\ K$

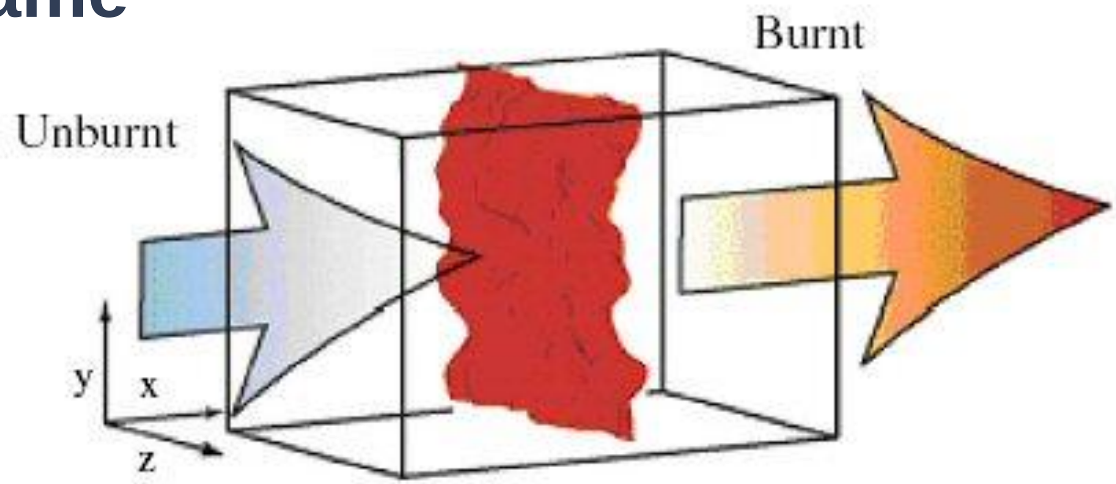
$$\bar{k}(T) = \int PDF(T)\ k(T)\, dT = \frac{1}{2}\, k_0 \left(exp\left(-\frac{E}{R\,T_1}\right) + exp\left(-\frac{E}{R\ T_2}\right)\right)$$

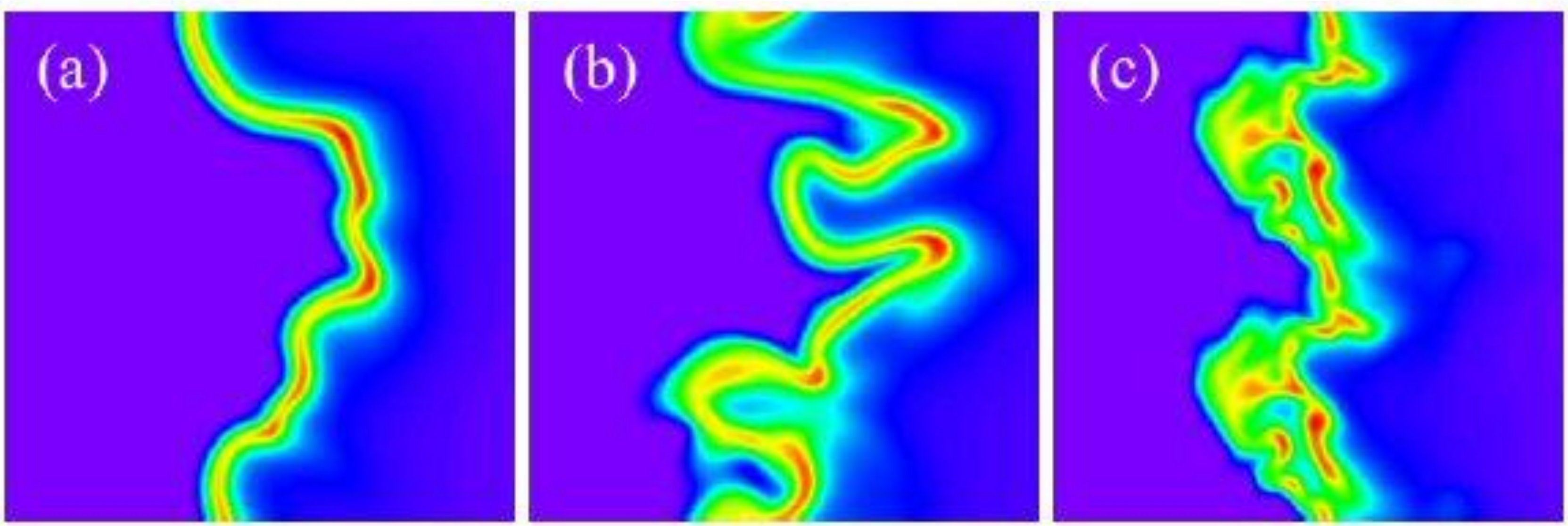
$$k(\bar{T}) = \ k_0\, exp\left(-\frac{2\,E}{R\,(T_1 + T_2)}\right)$$

$$\frac{k(\bar{T})}{\bar{k}(T)} = 0.005$$

$$\overline{\dot{\omega}}_{Fuel} \neq f(\bar{T}, \overline{Y_{Fuel}}, \overline{Y_{O2}})$$

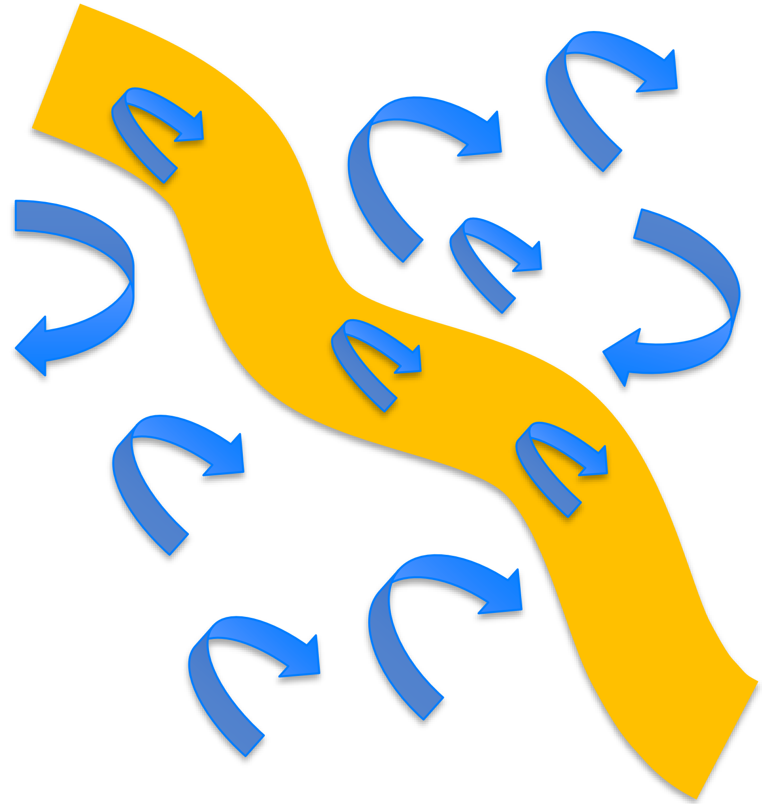
Turbulent flame: the example of a stabilized premixed flame





U'/S_L : 0.85 1.70 3.38

Turbulent flame in fires



Reaction rate (EDC type model):

$$\overline{\dot{\omega}_{Fuel}} = \frac{\overline{\rho}}{\tau} \min\left(\widetilde{Y_{Fuel}}, \frac{\widetilde{Y_{O2}}}{\nu}\right) \quad (kg\, m^{-3} s^{-1})$$

Temperature fluctuations in a turbulent flame

Average flame

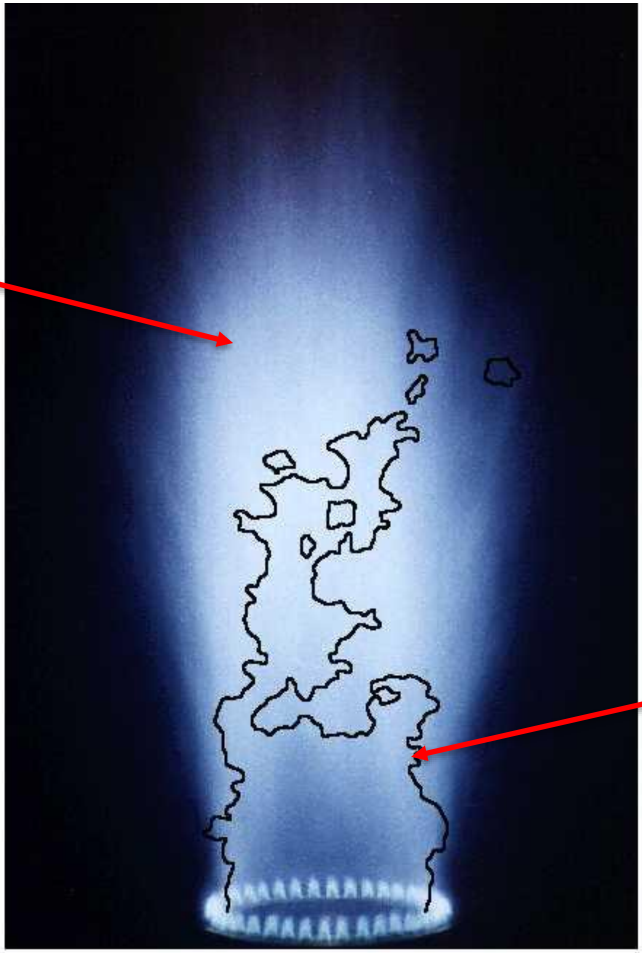


Figure 1. Superposition of a time-averaged photograph of the flame (1/50th sec) and an instantaneous (10^{-4} sec) flame contour obtained from a tomographic cut. The ring of pilot flames is visible. Mean flow velocity : 12 m/s, Equivalence ratio : 0.75.

$$\frac{\sqrt{\overline{T'^2}}}{\bar{T}} \gg 1$$

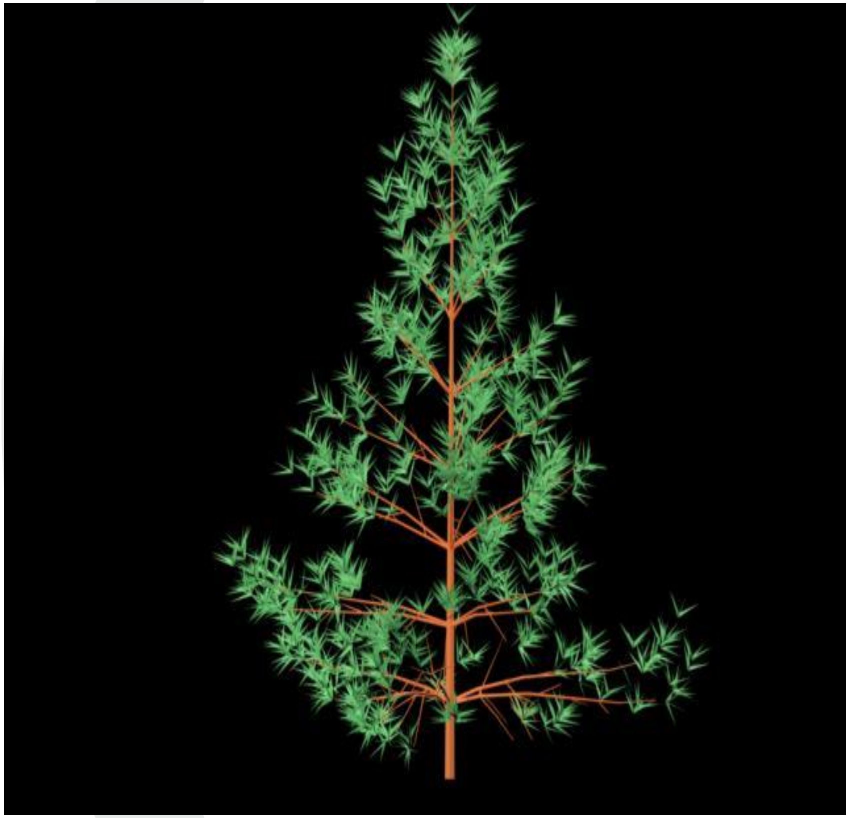
Instantaneous flame

How describing a vegetation layer ?

Physical properties

- **Density**
- **Volume fraction**
- **Surface Area/Volume (SA/V)**
- **Fuel moisture content (FMC)**

Solid fuel classification

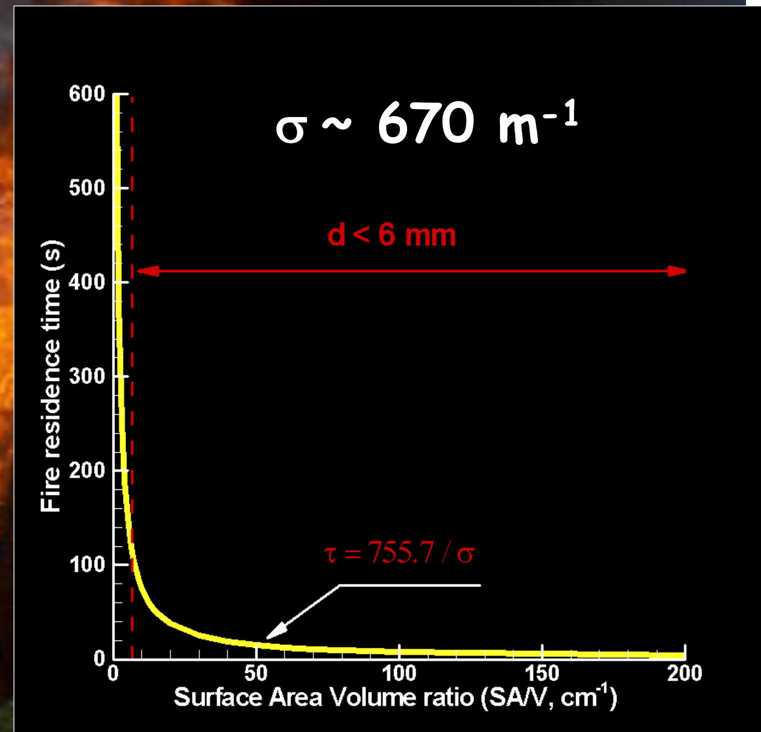


Equilibrium time (FMC/Air):

- **1H** ϕ : **0-0.64 cm**
- **10H** ϕ : **0.64-2.54 cm**
- **100H** ϕ : **2.54-7.62 cm**

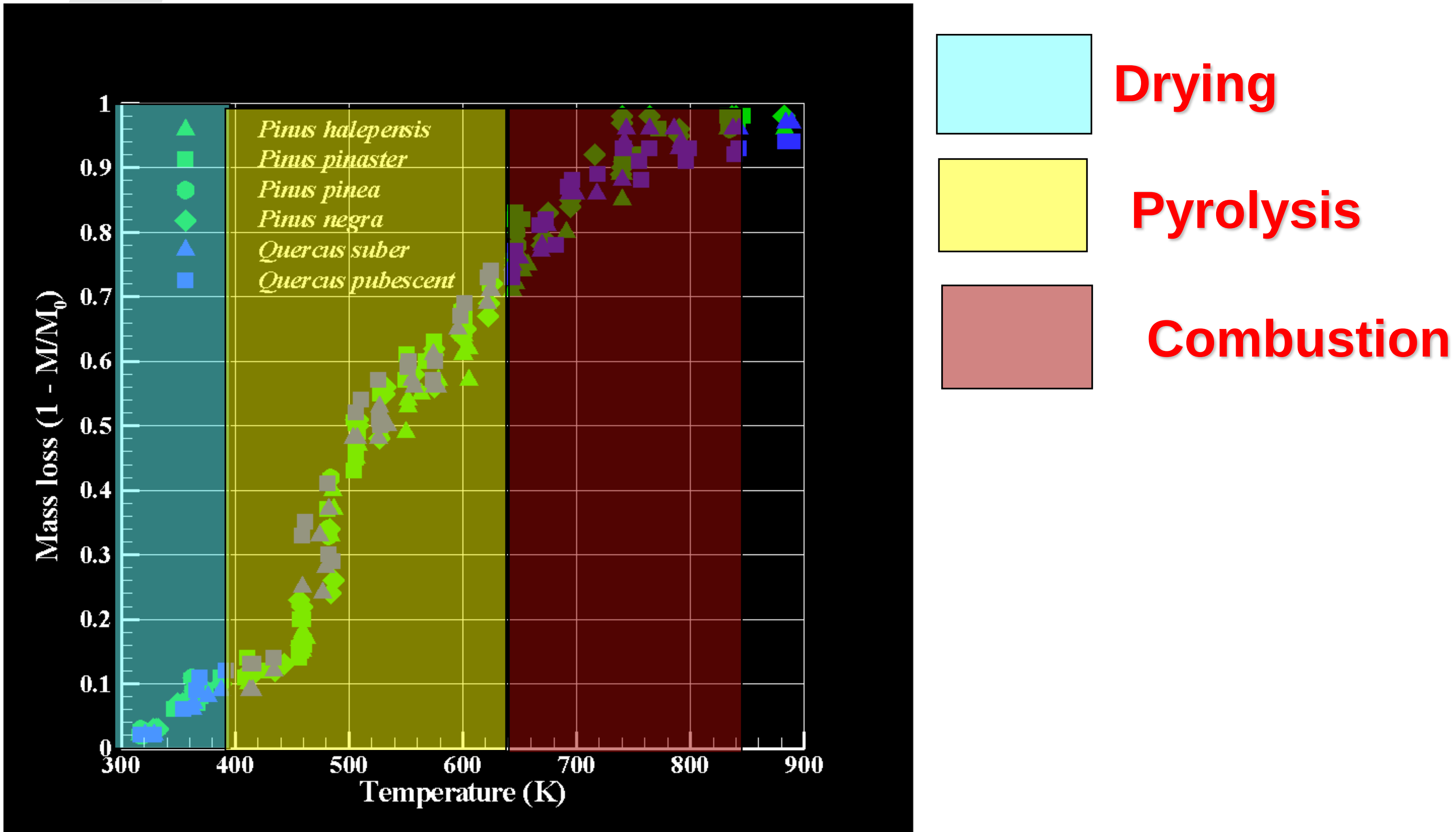
Fire residence time

$$\tau = \frac{L}{R}$$

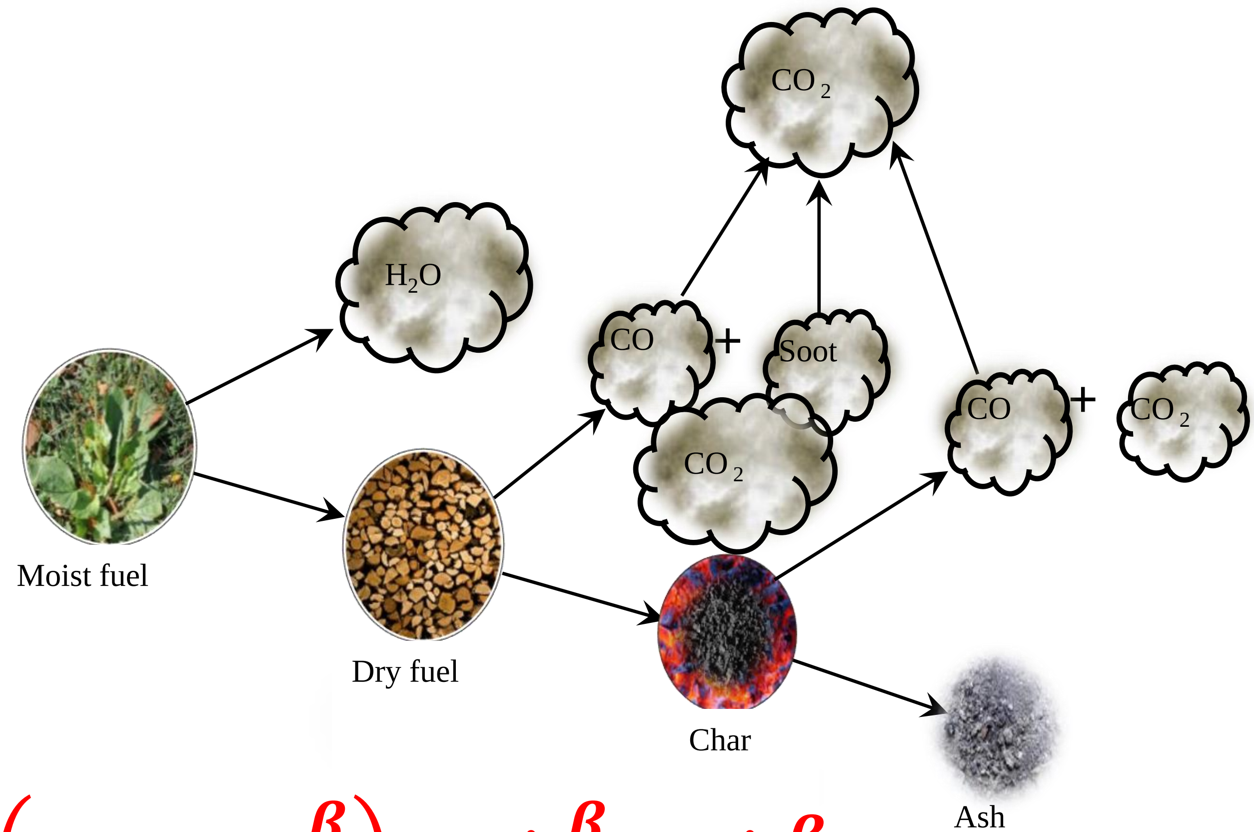


σ (m^{-1})	600	2000	5000	10000	20000
τ (s)	125	37	15	7	3

Thermal analysis of Mediteranean vegetation samples (INRA-Avignon)



Solid fuel degradation model



$$\frac{d}{dt}\left(\alpha_s\,\rho_s\,Y_s^{\beta}\right) = \dot{\omega}_{+}^{\beta} - \dot{\omega}_{-}^{\beta}$$

$$Y_s^{\beta} = Y_s^{H2O},\ \ Y_s^{Dry}, Y_S^{Char}, Y_S^{Ash}$$

Extinction length scale: typical values

Fuel	Boreal forest	Grass	Med. forest	Med. shrubs
δ_R (m)	4.75	0.15-0.5	0.25	0.15

Fuel	Pine needles	Shrubland (Galice)
δ_R (m)	0.025	0.015

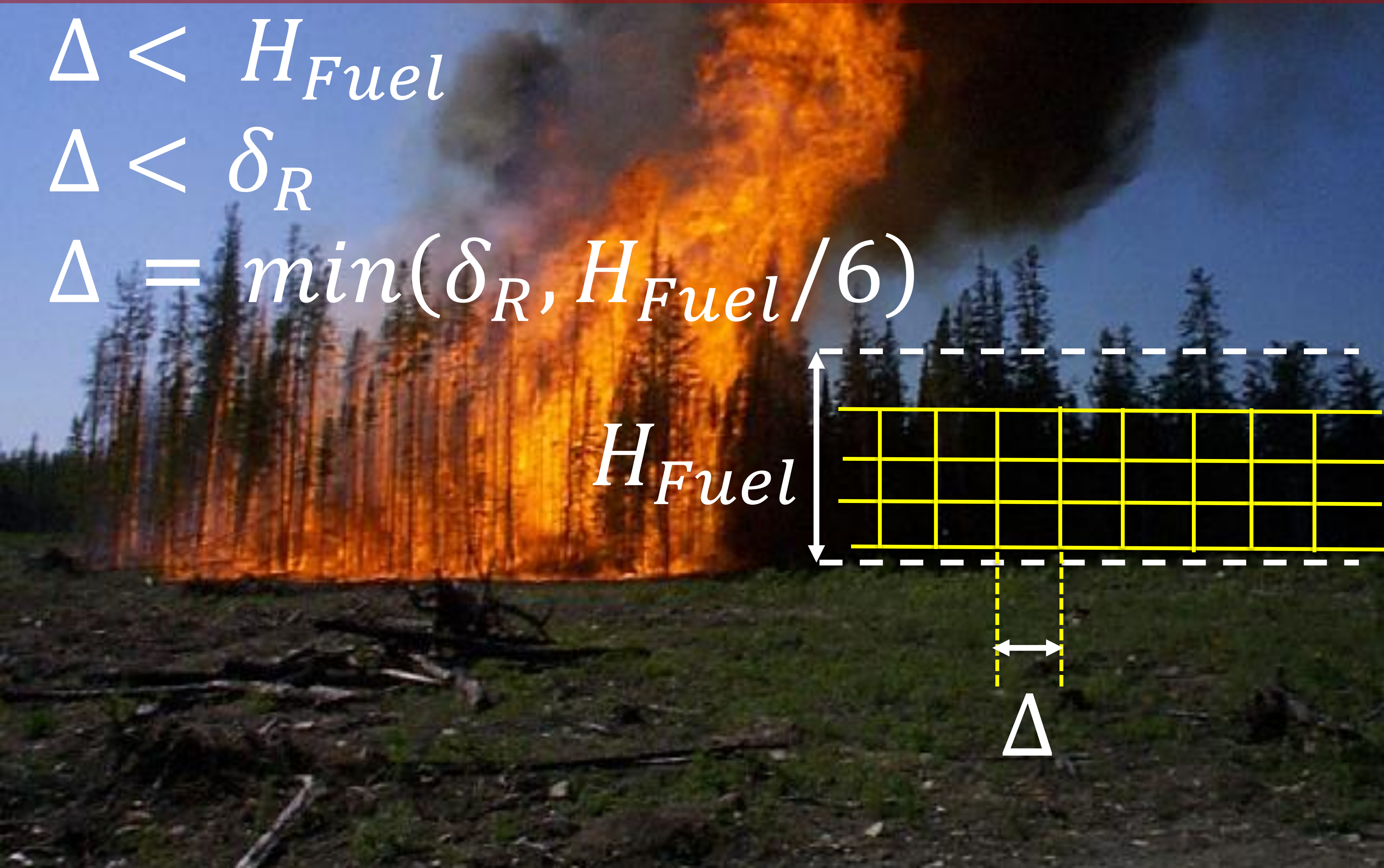
$$\Delta \approx \delta_R = \frac{2}{LAD}$$

Numerical simulation of the propagation of a wildland fire: grid dimension criterium

$$\Delta < H_{Fuel}$$

$$\Delta < \delta_R$$

$$\Delta = min(\delta_R, H_{Fuel}/6)$$



Transport equations in the gas phase

$$\frac{D\bar{\rho}}{Dt} = \sum_{\beta} \dot{\omega}^{\beta}$$

$$\frac{D\bar{\rho}\tilde{u}_i}{Dt} = \cdots - \rho C_D \, LAD \, \|\tilde{U}\| \, \tilde{u}_i$$

$$\frac{D\bar{\rho}K}{Dt} = \ \ldots - 2\, \bar{\rho}\, C_D \, LAD \, \|\tilde{U}\| \, K$$

$$\frac{D\bar{\rho}\tilde{h}}{Dt} = \cdots + Q_S$$

$$\frac{D\bar{\rho}\widetilde{Y_\alpha}}{Dt} = \cdots + \dot{M}_\alpha$$

Radiation transfer equation + TRI

Optically Thin Fluctuation Approximation (OTFA)

P.J. Coelho Prog. Energ. & Combust. Science (2007)

(neglecting the scaterring)

$$\frac{dI_\nu}{ds} = K_\nu (I_{B\nu} - I_\nu)$$

$$\frac{d\bar{I}_\nu}{ds} \approx K_\nu(\bar{T}) I_{B\nu}(\bar{T}) \left[1 + 6\,\frac{\overline{T'^2}}{\bar{T}^2} + 4\,\frac{\overline{T'^2}}{\bar{K}\,\bar{T}}\,\frac{\partial K_\nu}{\partial T}\bigg|_{\bar{T}}\right] - K_\nu(\bar{T})\,\bar{I}_\nu$$

OTFA theoretical domain of validity: $K_\nu \times l_t \ll 1$

$$\frac{\left(\overline{I'^2}\right)^{1/2}}{\bar{I}} \approx 20\%\ to\ 500\%$$

Radiation transfer equation + TRI
Optically Thin Fluctuation Approximation (OTFA)
P.J. Coelho Prog. Energ. & Combust. Science (2007)

$$\frac{d\alpha_g \bar{I}}{ds} = \alpha_g \left(\frac{\sigma \overline{KT^4}}{\pi} - \overline{\sigma_a} \bar{I} \right) + \sum \left[\frac{LAD}{2} \left(\frac{\sigma T_s^4}{\pi} - \bar{I} \right) \right]$$

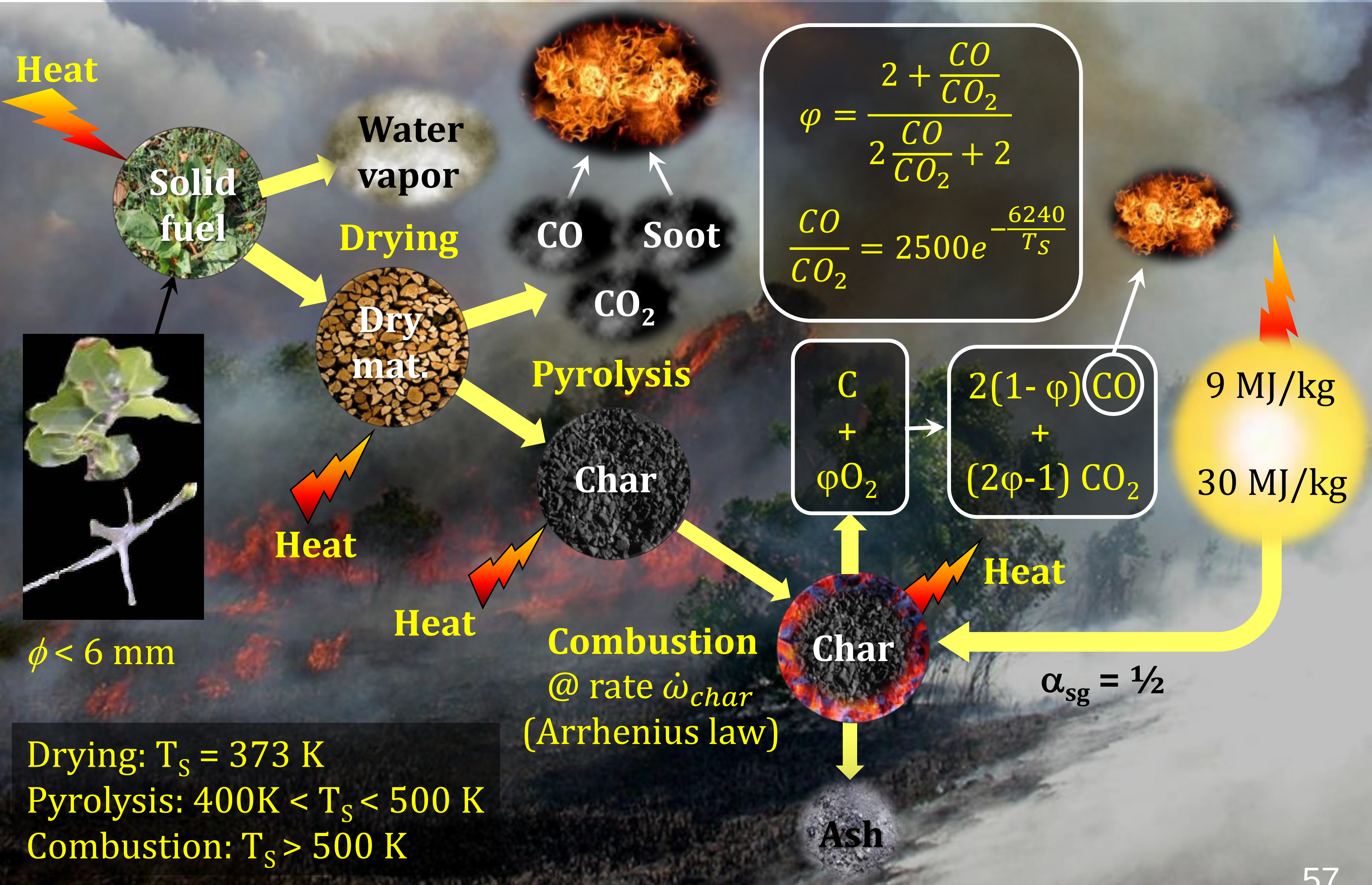
$$\overline{KT^4} \approx \bar{K}\bar{T}^4 \left[1 + 6 \frac{\overline{T'^2}}{\bar{T}^2} + 4 \frac{\overline{T'^2}}{\bar{K}\,\bar{T}} \left. \frac{\partial K}{\partial T} \right|_{\bar{T}} \right]$$

$$K = K_{Pro} + K_{Soot} = 0.1\, X_{Pro} + 1862\, f_v\, T$$

FireStar3D Model

- ❑ **Fluid Mixture**
  - ➢ Low Mach number formulation (Navier-Stokes equations)
  - ➢ Turbulence: k-ε and LES approaches
  - ➢ Heat Transfer: Enthalpy formulation + Radiation (RTE)
  - ➢ Species: Transport + Combustion in fluid phase (EDC model)
  - ➢ Soot: Transport equation + Oxidation
- ❑ **Solid Particles**
  - ➢ Drying, Pyrolysis & Combustion models
  - ➢ Mass, energy and particle size balances
- ❑ **Fluid Mixture/Solid coupling**
  - ➢ Aerodynamics (porous media)
  - ➢ Heat transfer
  - ➢ Species exchange

Solid Fuel Combustion Model



Fluid-Phase Model

- $$\frac{D\bar{\rho}}{Dt} = \sum_{m}\sum_{\alpha}\dot{M}_{\alpha}^{m}$$

- $$\frac{D(\bar{\rho}\bar{u}_i)}{Dt} = -\frac{\partial \bar{P}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\bar{\mu}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} - \frac{2}{3}\frac{\partial \bar{u}_l}{\partial x_l}\delta_{ij}\right)\right] - \frac{\partial}{\partial x_j}\left(\overline{\rho u_i' u_j'}\right) + (\bar{\rho} - \bar{\rho}_0)g_i - \sum_{m} F_{Di}^{m}$$

- $$\frac{D(\bar{\rho}\bar{h})}{Dt} = \frac{\partial}{\partial x_j}\left(\frac{\bar{\mu}}{Pr}\frac{\partial \bar{T}}{\partial x_j}\right) - \frac{\partial}{\partial x_j}\left(\overline{\rho u_j' h'}\right) + \frac{d\bar{P}_{th}}{dt} + (1 - \alpha_{SG})\Delta h_{Char}\sum_{m}\dot{\omega}_{Char}^{m} + \sum_{m}\sum_{\alpha}\dot{M}_{\alpha}^{m}\bar{h}_{\alpha}^{m} - \sum_{m}\dot{Q}_{S,Conv}^{m} + \alpha_G\sigma_G\left(J - 4\sigma\bar{T}^4\right)$$

- $$\frac{D(\bar{\rho}\bar{Y}_\alpha)}{Dt} = \frac{\partial}{\partial x_j}\left(\frac{\bar{\mu}}{Sc}\frac{\partial \bar{Y}_\alpha}{\partial x_j}\right) - \frac{\partial}{\partial x_j}\left(\overline{\rho u_j' Y_\alpha'}\right) + \bar{\dot{\omega}}_\alpha + \sum_{m}\dot{M}_{\alpha}^{m}$$

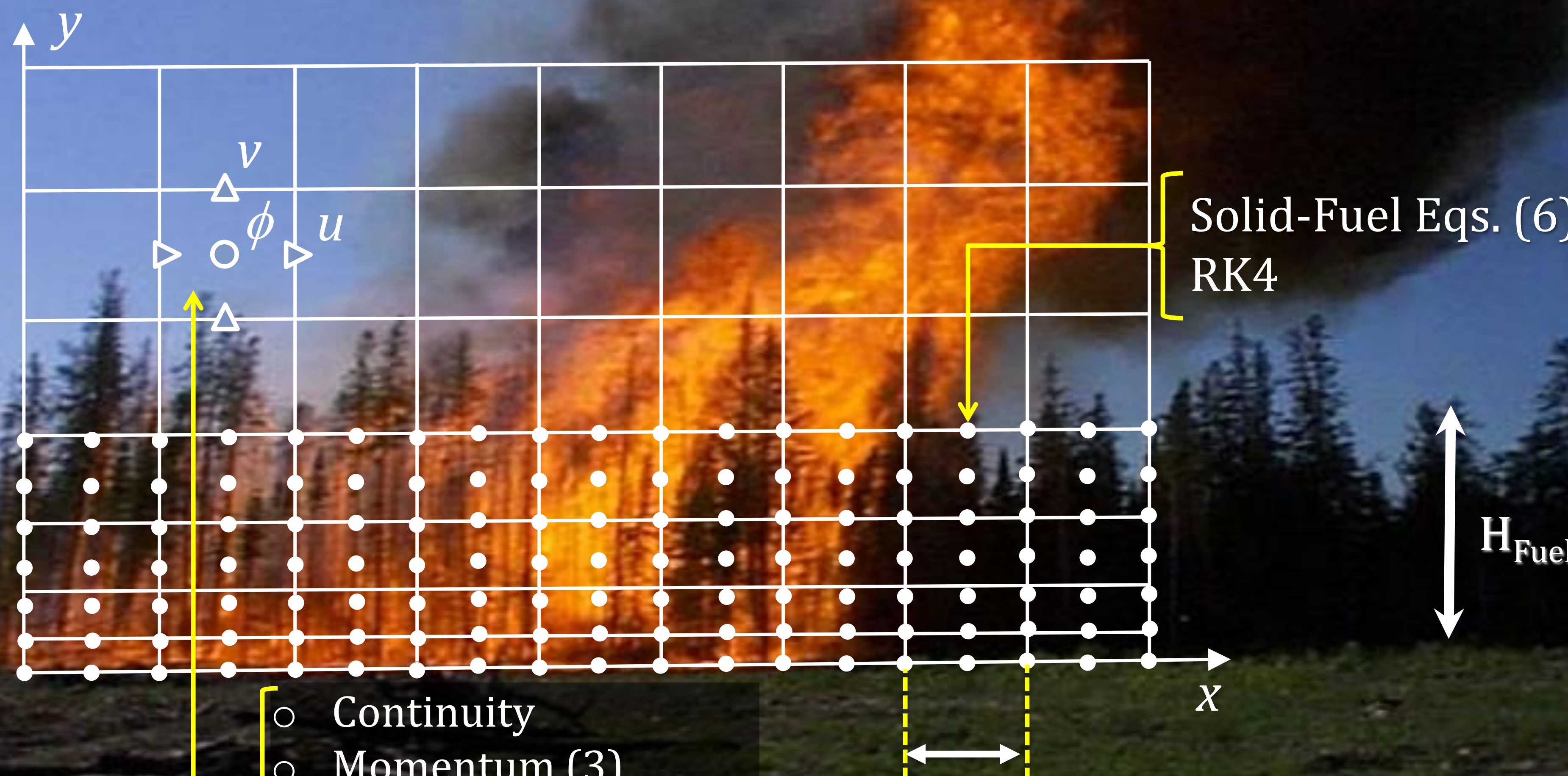
- Ideal Gas Equation

Morvan *et al.* (2001, 2004, 2008, 2009, 2018)

Numerical Approach

- **Formulation**
  - Fully Implicit (Non-conditional temporal stability)
  - Segregated Formulation (PISO algorithm)
- **Numerical Method**
  - Finite Volume Method on Cartesian non-uniform grid
  - ~ 3rd order space accuracy (QUICK scheme)
  - 3rd order time precision with Adaptive time-stepping
- **Radiation:** Discrete Ordinate Method (DOM)- S8
- **Parallel Computing:** OpenMP directives

Fluid-Phase and Solid-Phase Meshes



$$\Delta = min(\delta_R, H_{Fuel}/6)$$

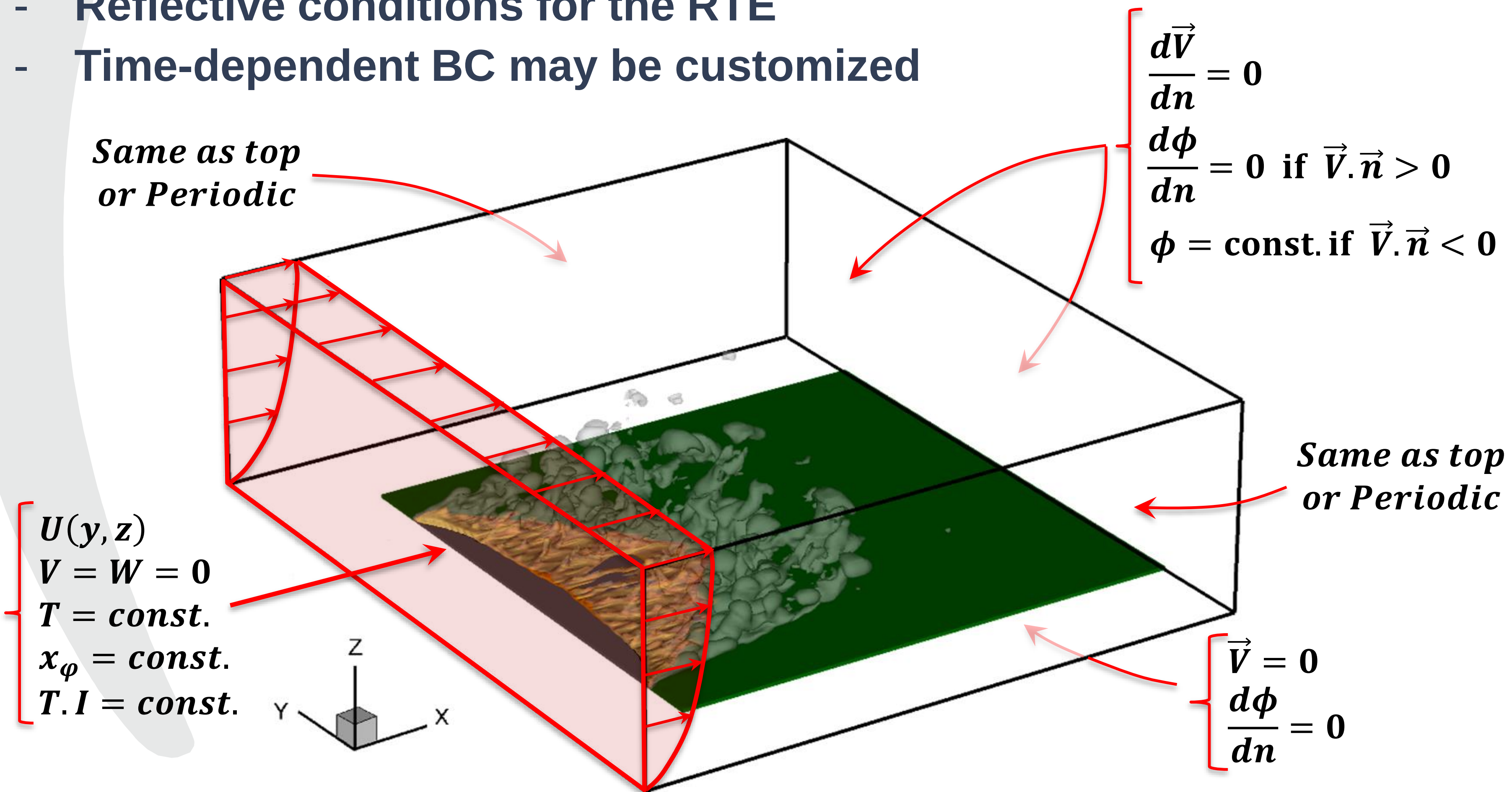
- Continuity
- Momentum (3)
- Energy
- Species (4)
- Turbulence (1 or 2)
- Soot
- Radiation (DOM)

$$\delta_R = \frac{4}{\alpha_s \, \sigma_s}$$

$\delta_R \sim 0.01$ m - 5 m

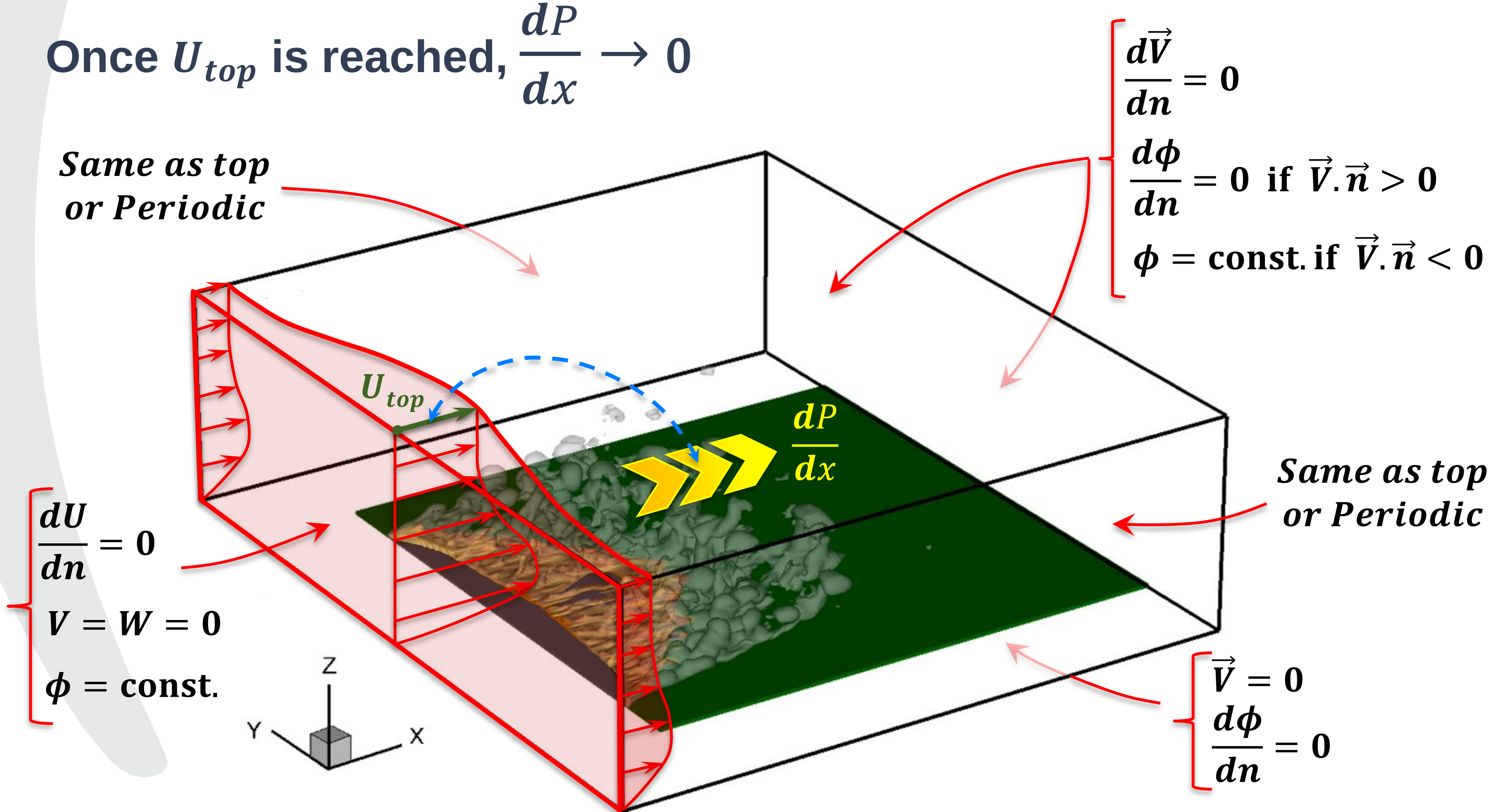
Firestar3D: Boundary conditions

- Dirichlet (imposed ϕ profiles) or Neumann $\left(\frac{d\phi}{dn} = const.\right)$
- Periodic conditions in any direction
- Reflective conditions for the RTE
- Time-dependent BC may be customized



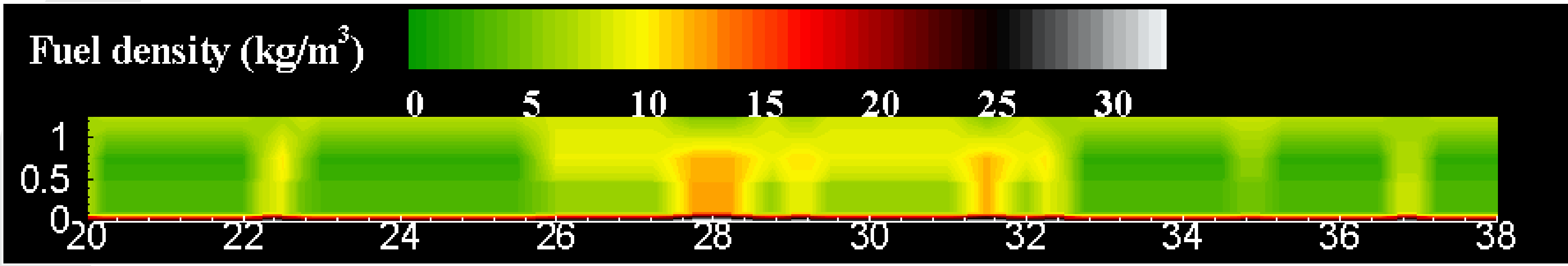
Firestar3D: Fire can creates its own wind

- A pressure gradient is applied to impose U_{top} $\quad \frac{dP^*}{dx} = \frac{\rho U^*}{dt}\left(1 - \frac{U^*}{U_{top}}\right)$
- The code determines velocity distribution at inlet
- Once U_{top} is reached, $\frac{dP}{dx} \rightarrow 0$



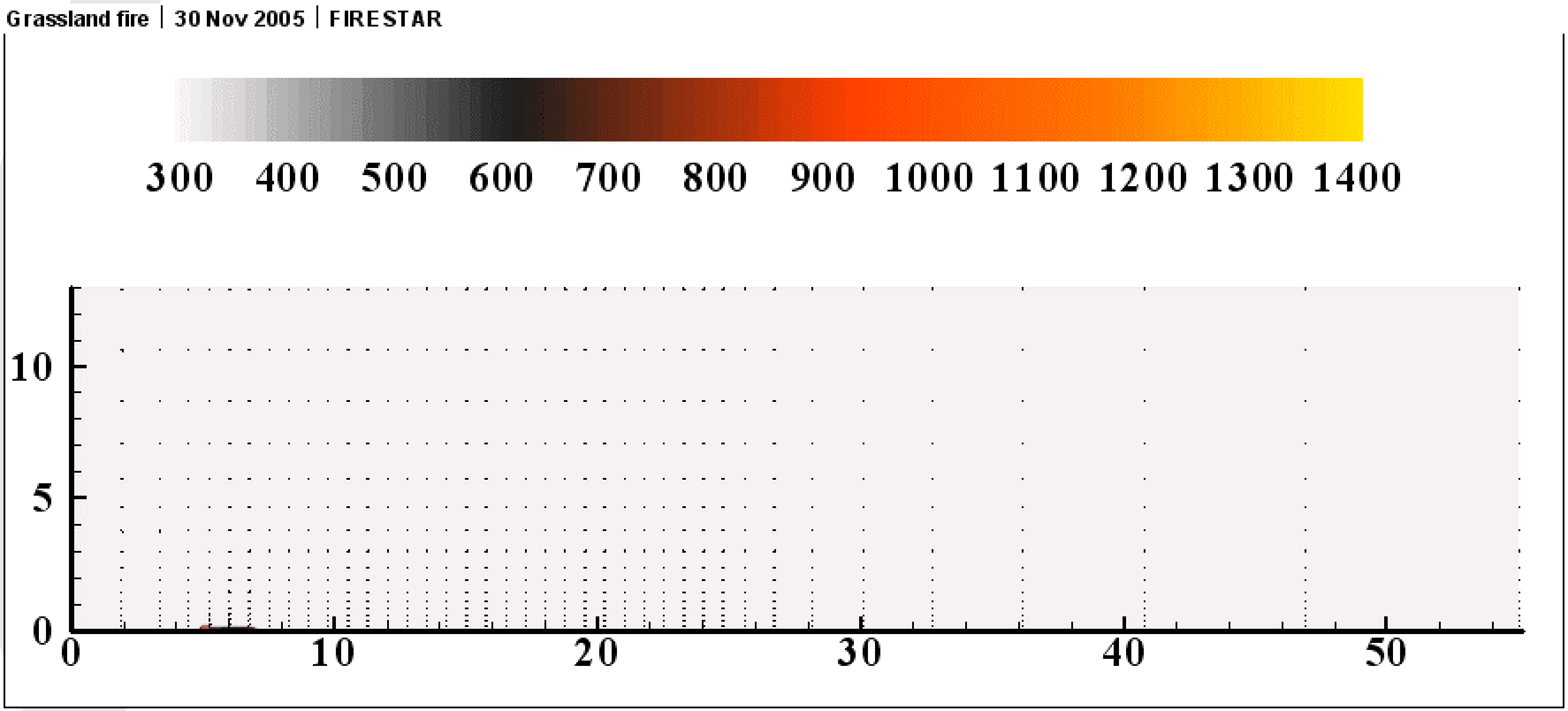
Experimental fire in shrubland
(EU Firestar project,Galicia-Spain)

Experimental fire in shrubland
(EU Firestar project,Galicia-Spain)



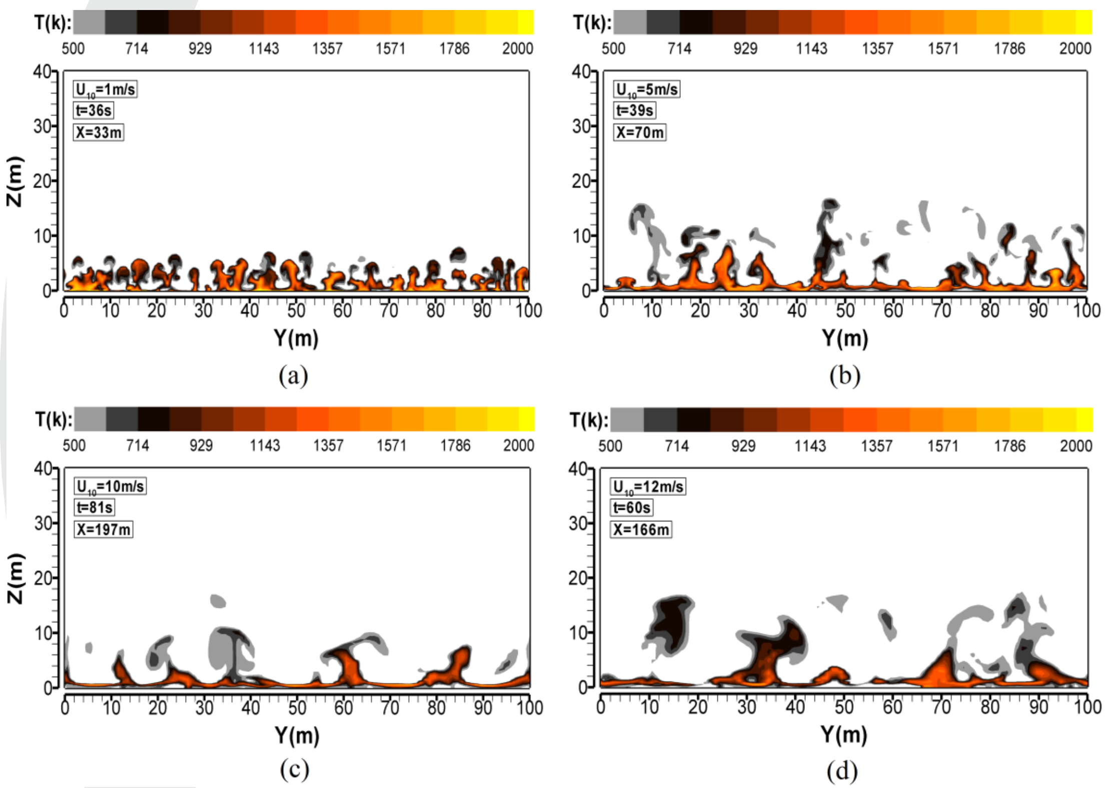
- **Fuel: *Ulex (Europaeus, Minor)* (ajoncs)**
- **Fuel Families = 14**
- **FMC:**
  108-150 % (living), 10-32% (dead)
- **Fuel depth = 1.25 m,**
- **Wind: 5.7 m/s (z=10 m),**
- **Slope : 5°**

Experimental fire *(EU Firestar project,Galicia-Spain)*



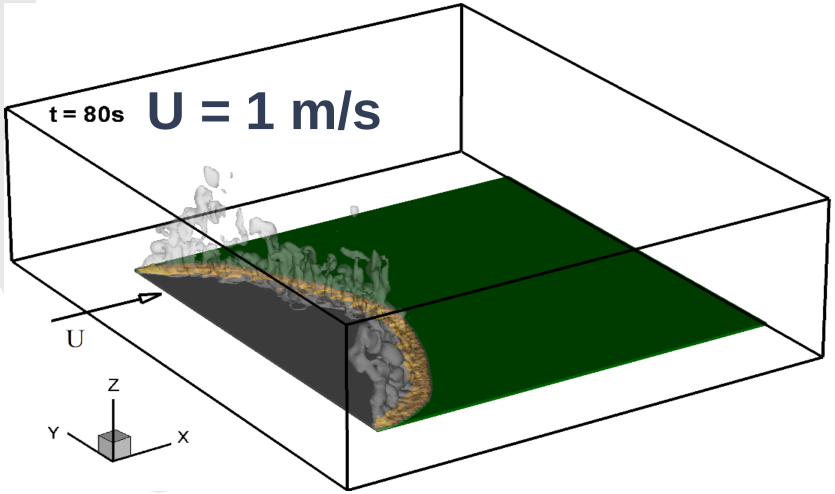
- **Experiment: ROS = 0.273 m/s**
- **Simulation : ROS = 0.248 m/s**

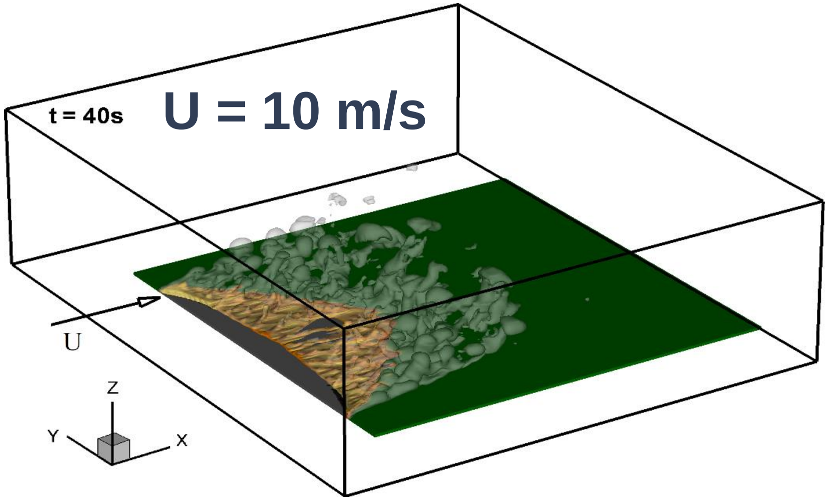
Why performing 3D simulations ? Because of the 3D structuration of the fire front ?



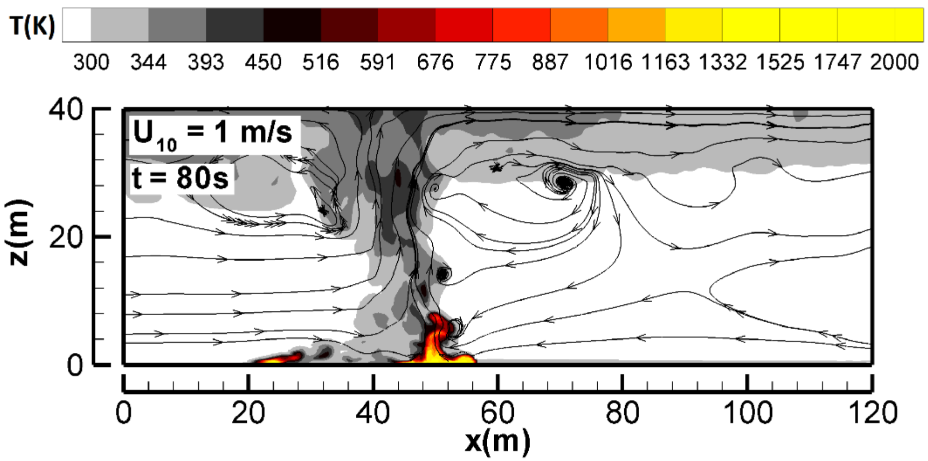
Consequence: in some situations the wind flow can cross the fire front, affecting a lot the wind/fire interaction, this event cannot be reproduced in 2D !

Numerical simulations of grassland fires

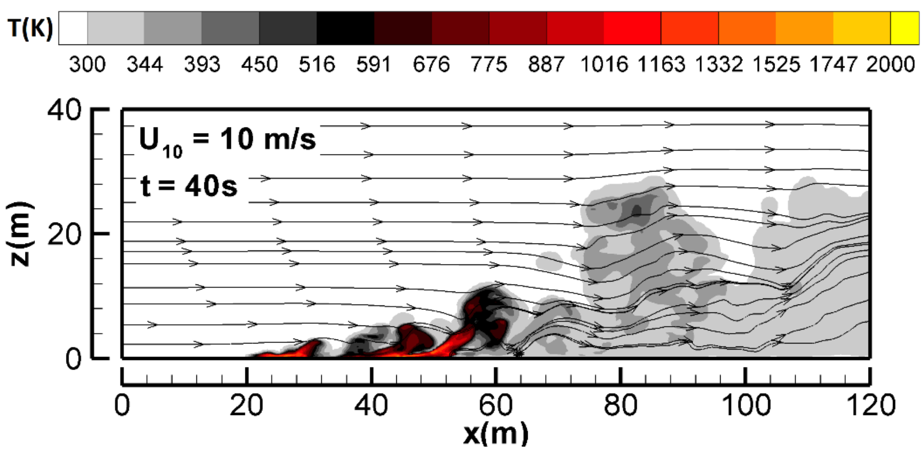




Numerical simulations of grassland fires

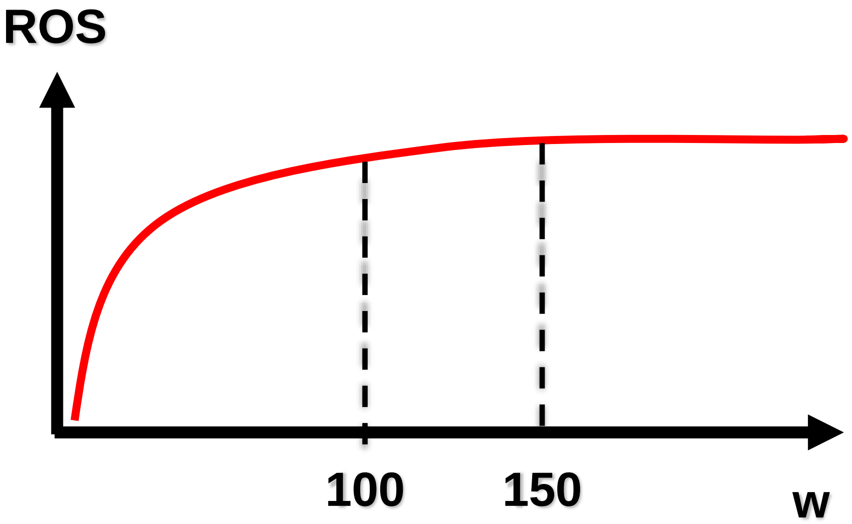


U = 1 m/s
(plume dominated)



U = 10 m/s
(wind driven)

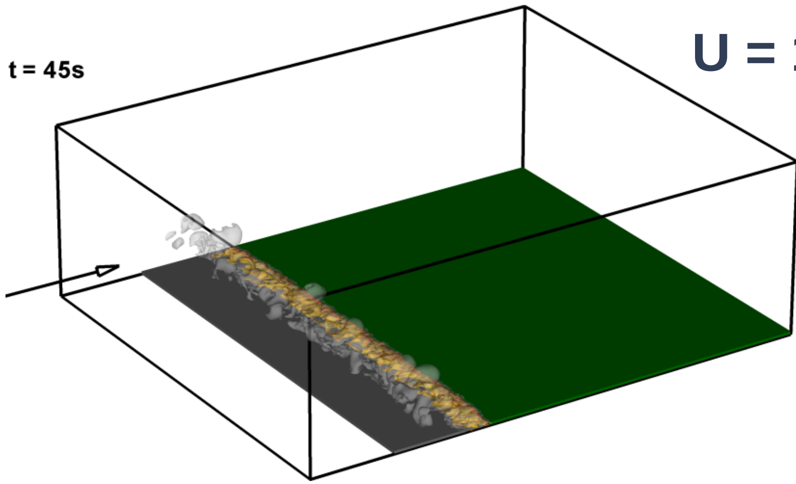
Grassland fire: rate of spread (ROS) vs ignition line width (w) (border effect)



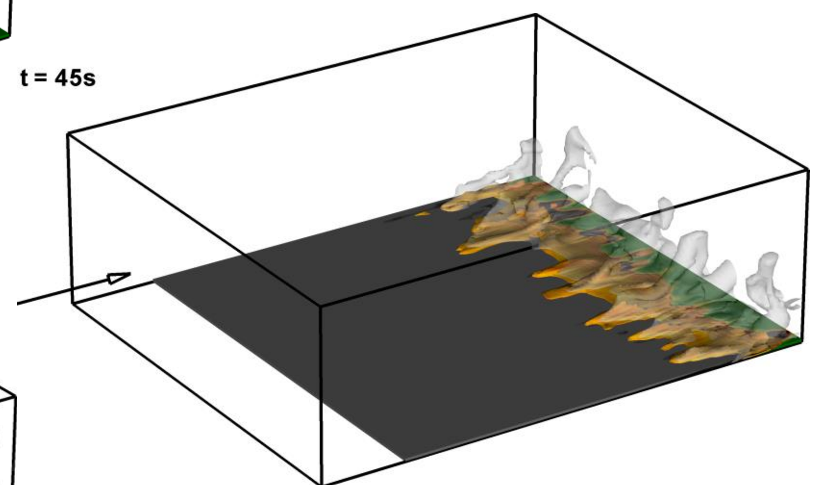
Cheney and Gould IJWF 1995

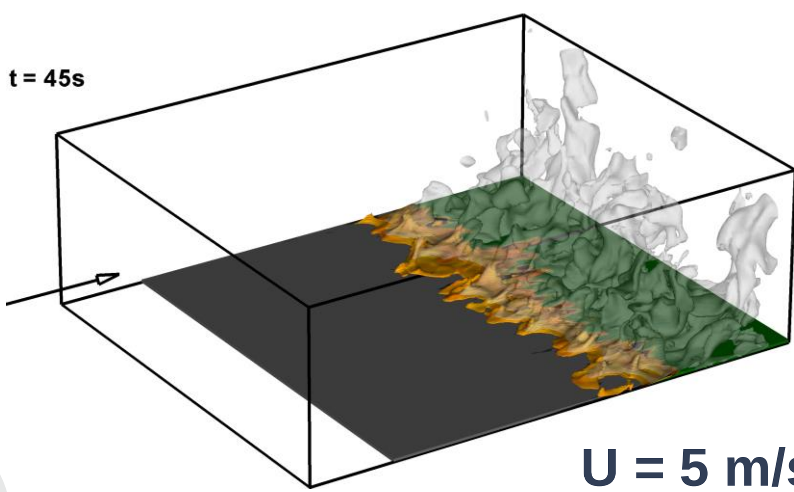
Numerical simulations of grassland fires (with periodic lateral boundary conditions)

U = 1 m/s



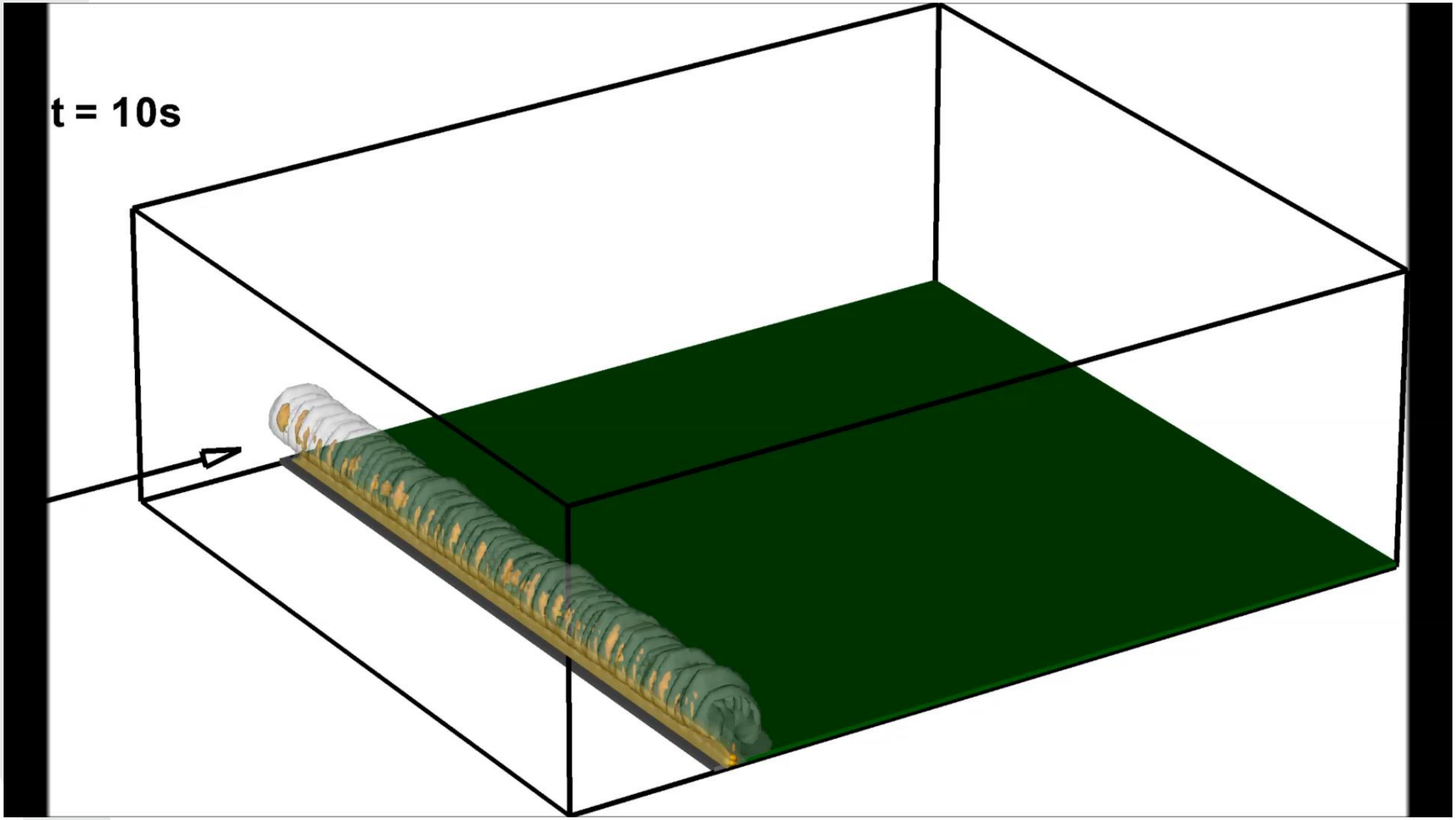
U = 10 m/s



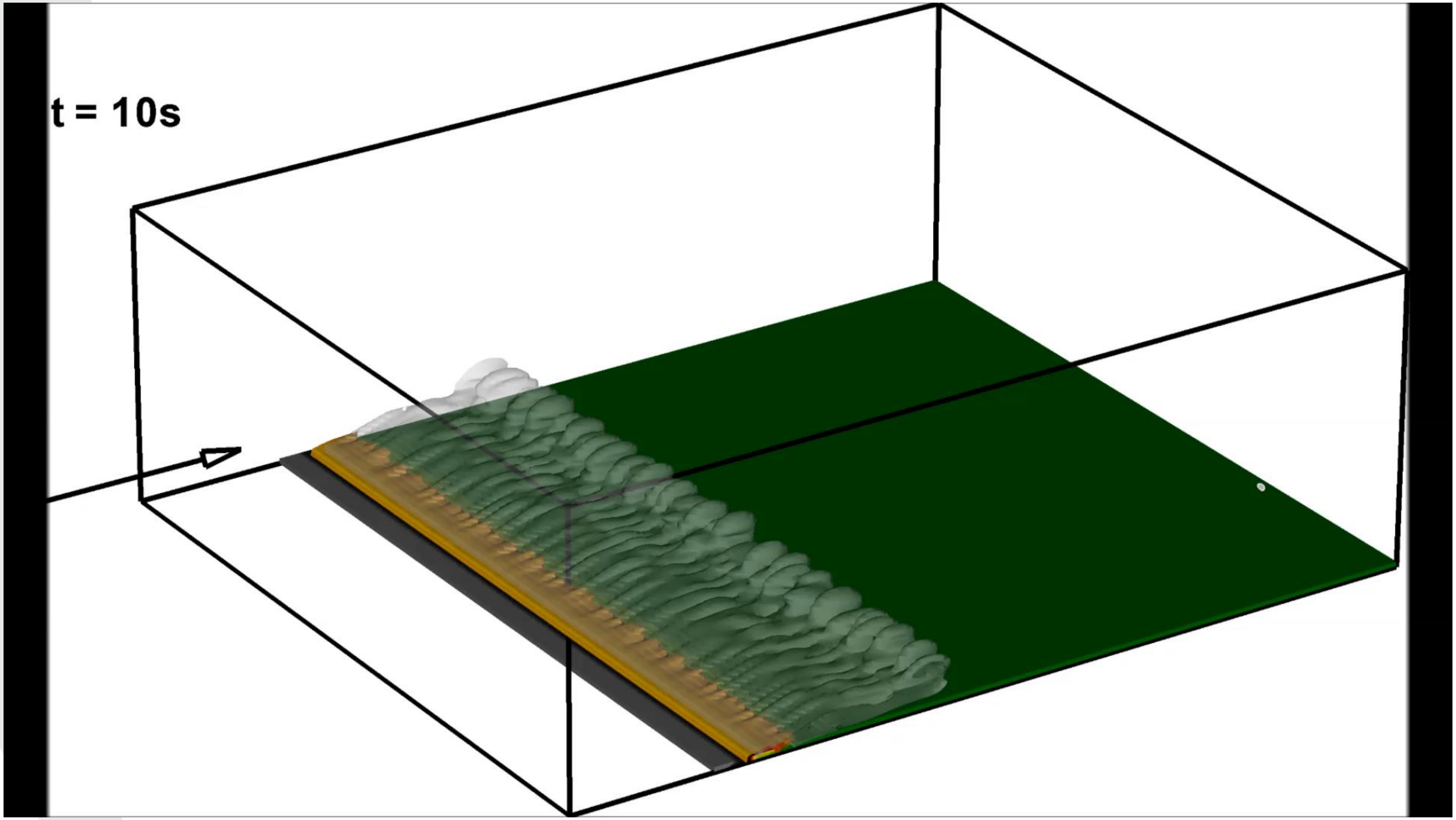


U = 5 m/s

Numerical simulation of grassland fire (with periodic BC) U = 1 m/s

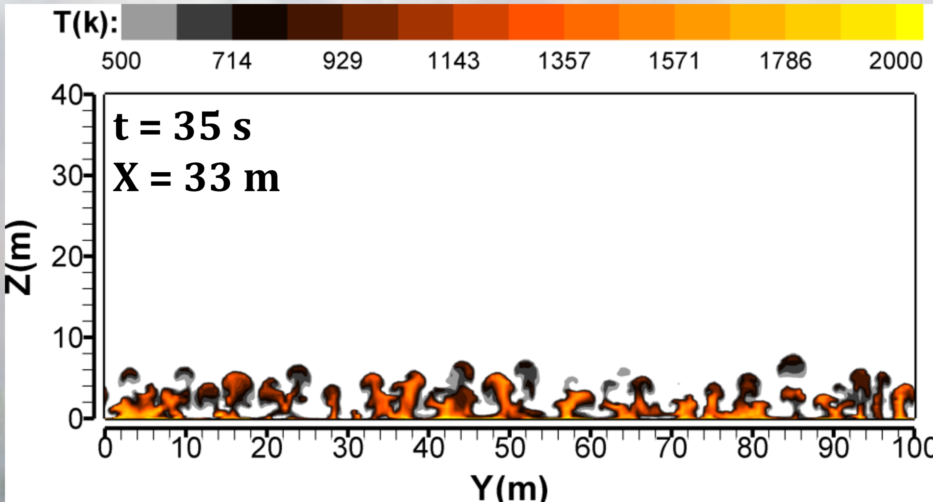


Numerical simulation of grassland fire (with periodic BC) U = 10 m/s

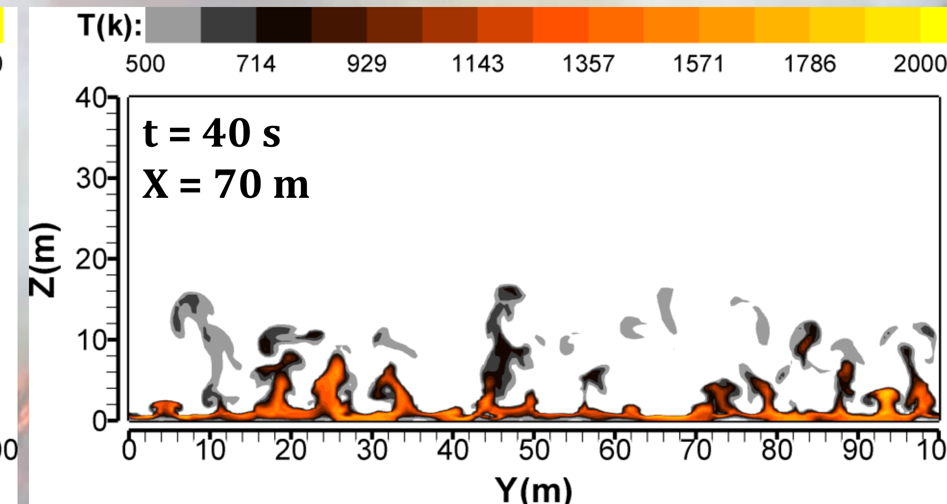


Flames Patterns ↔ Wind Speed

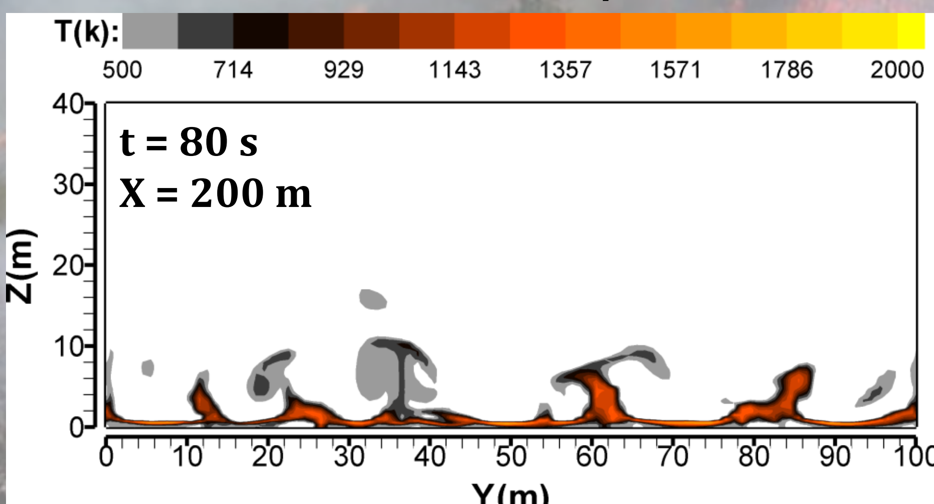
$U = 1$ m/s



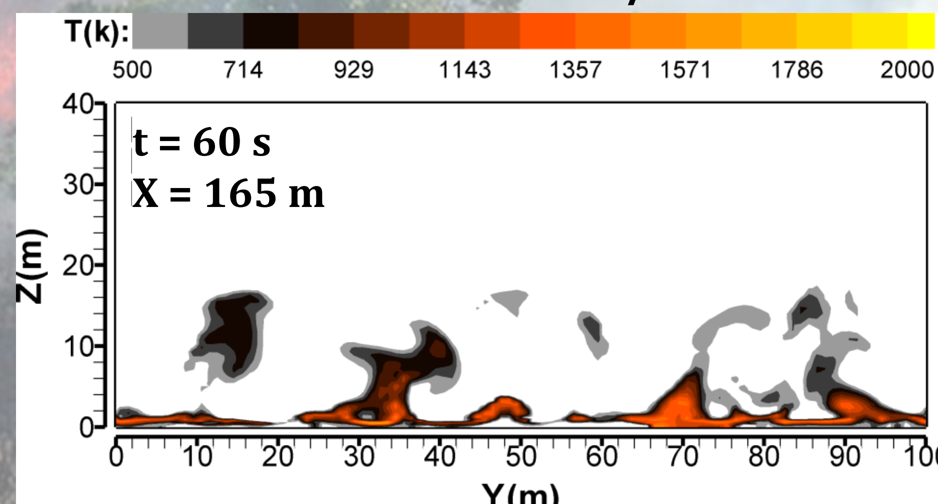
$U = 5$ m/s



$U = 10$ m/s

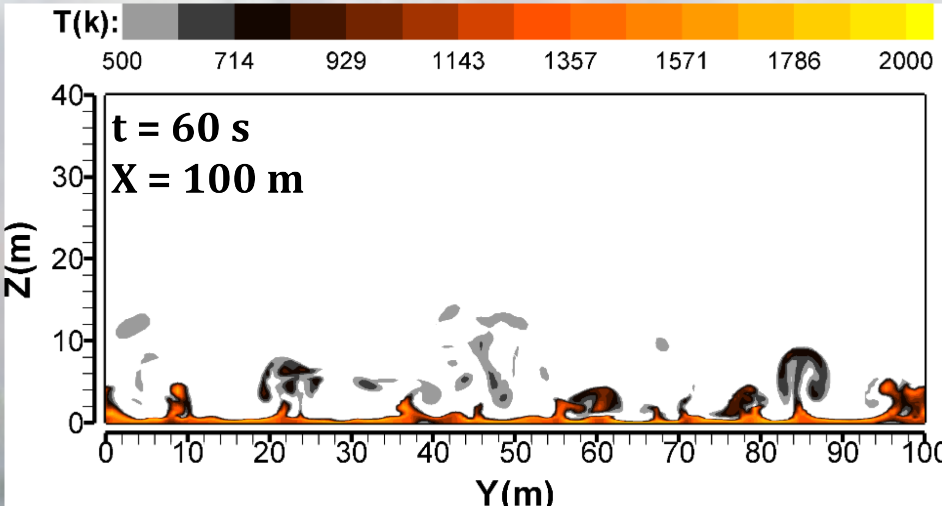


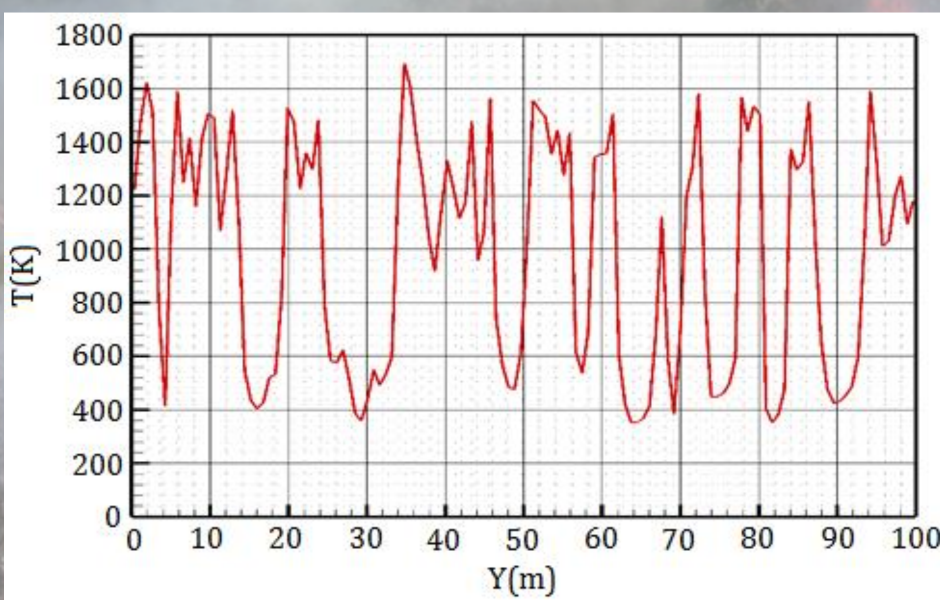
$U = 12$ m/s



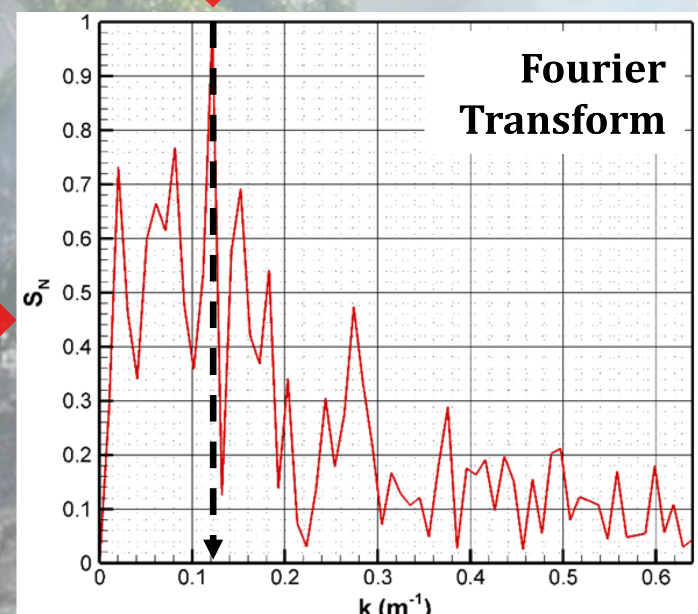
Wavelength of Coherent Structures (Plumes)

U **= 5 m/s**

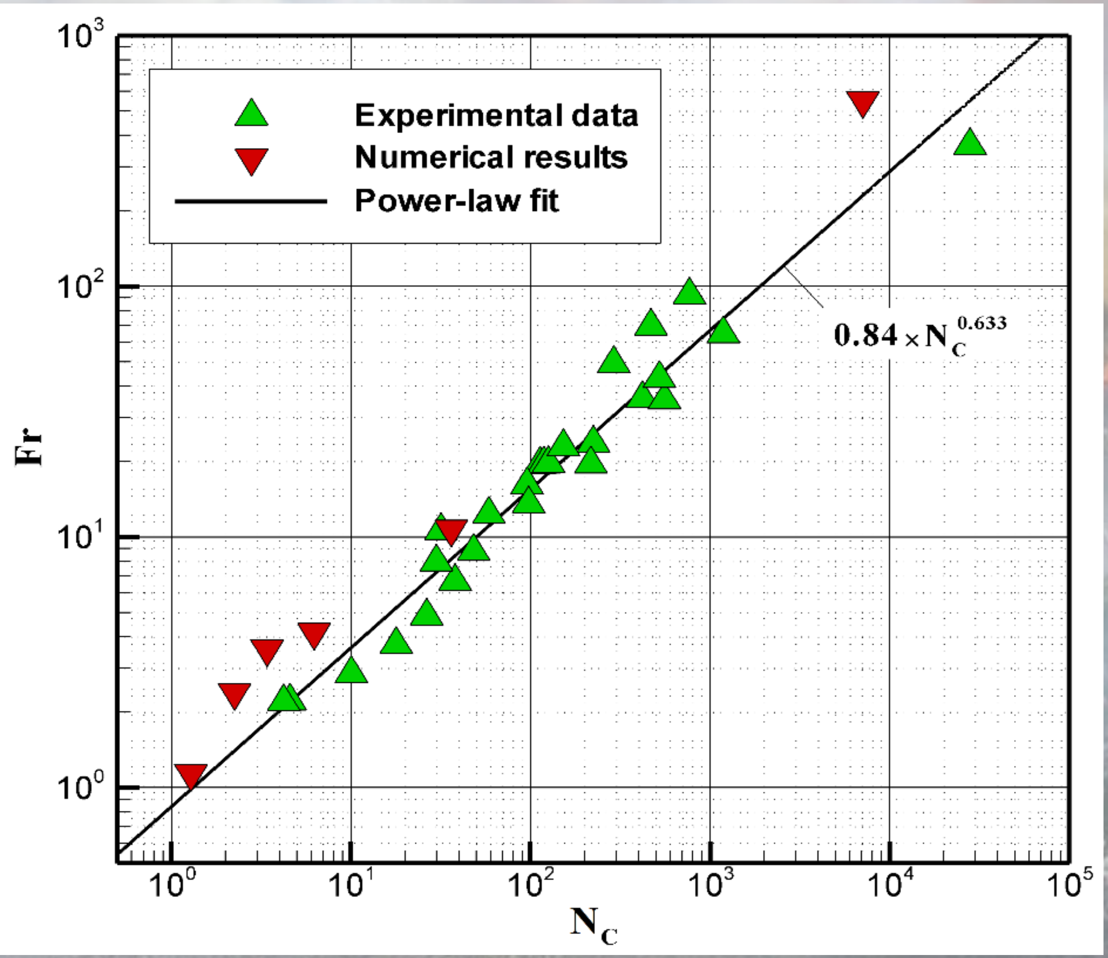




Wave number
k = 0.12 m^{-1}



Wavelength of Coherent Structures (Plumes)

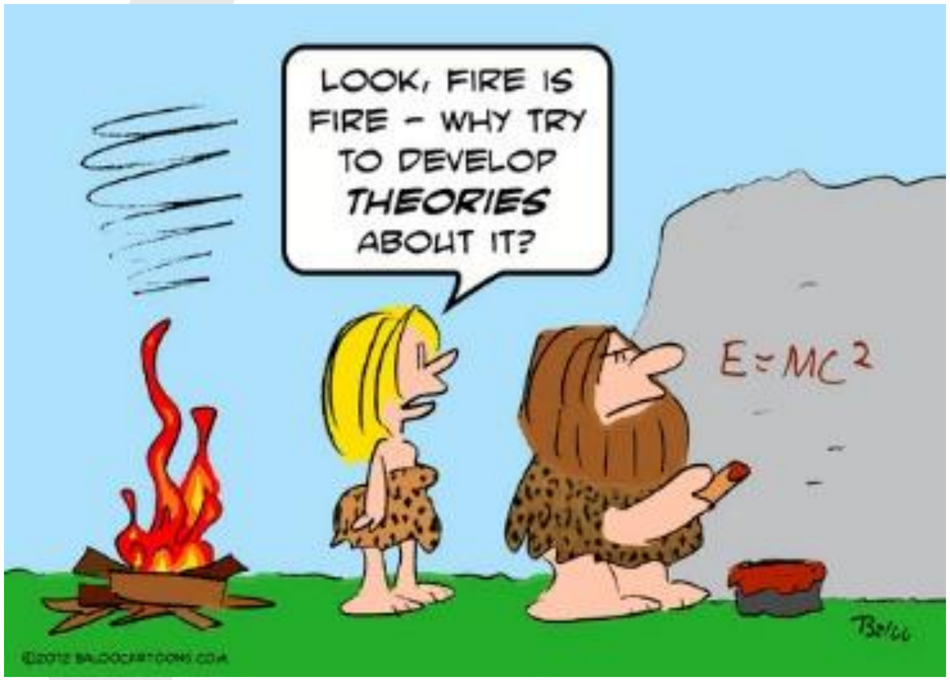


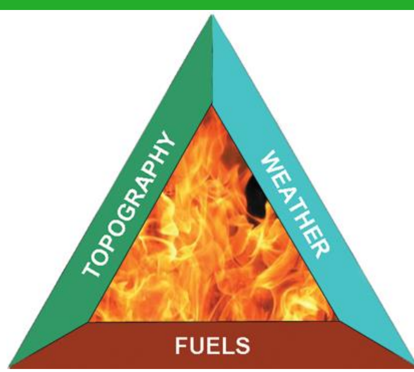
$$F_r = \frac{g\,\lambda}{(U_{10} - ROS)^2}$$

$$N_C = \frac{2\,g\,I}{\varrho_0\,C_{p0}\,T_0 (U_{10} - ROS)^3}$$

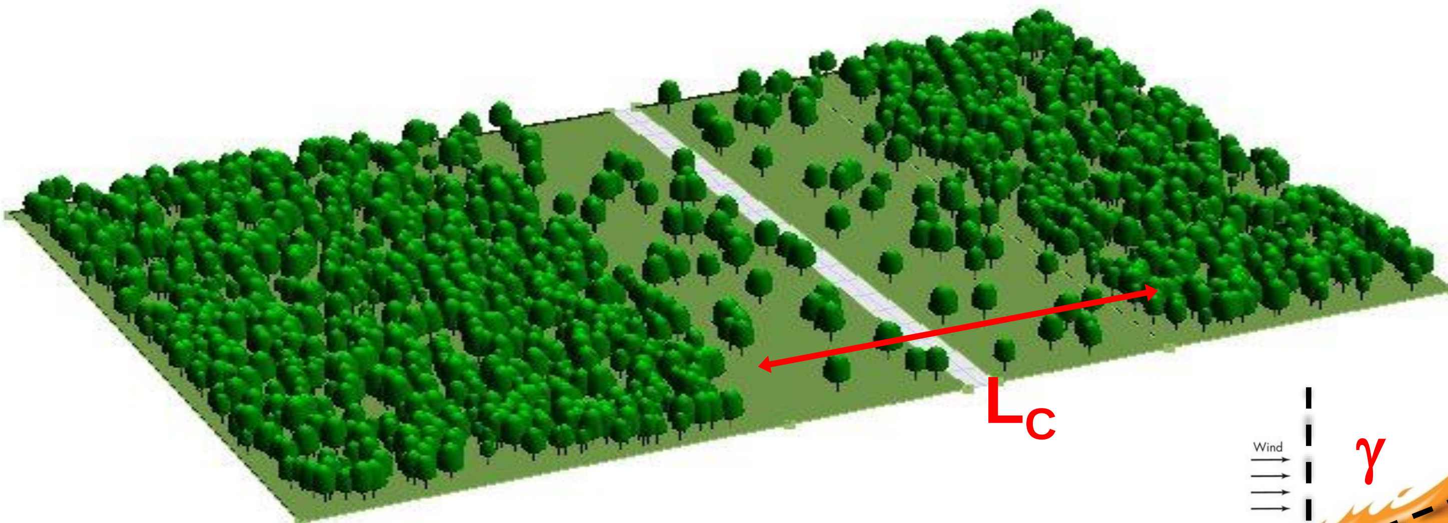
Exp. Data: Finney *et al.*, 2013

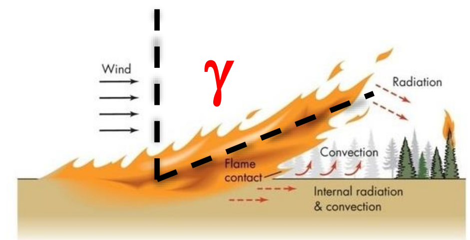
Fire safety engineering applied to wildfire: how design a fuel break ?





How design a fuel break: some empirical formula





$$L_C \geq \frac{LAI \times D_{Fire}}{2} \quad \text{(Emmons 1964)}$$

$$L_C \geq 4 \times H_{Flame} \quad \text{(Butler, Cohen 1998)}$$

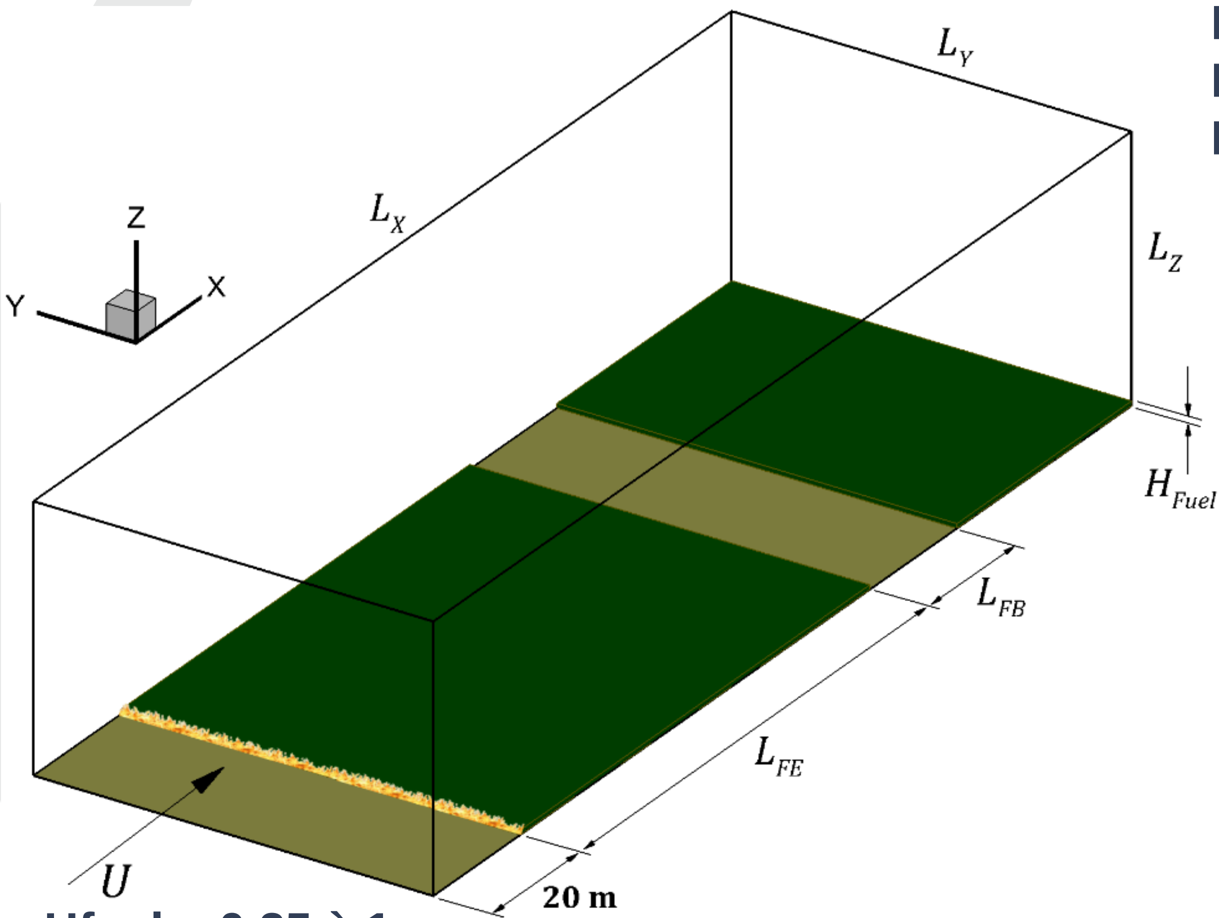
$$L_C \geq L_F \left[\frac{\cos\gamma \left(\left(\varepsilon\tau\sigma T_F^4\right)^2 - 4Q_R^2 \right)^{1/2}}{2Q_R} + \sin\gamma \right]$$

(Rossi, Simeoni, Moretti, Leroy-Cancellieri 2011)

Some critical heat fluxes

Exposure without risk (skin)	1 kW/m^2
Firefighter	7 kW/m^2
Skin, 3 s exposure (pain)	10.4 kW/m^2
Skin 5 s exposure (2nd degree burning)	16 kW/m^2
Wood 60 s exposure (ignition)	31 kW/m^2

Numerical simulation of fire front behaviour in the vincinity of a fuel break

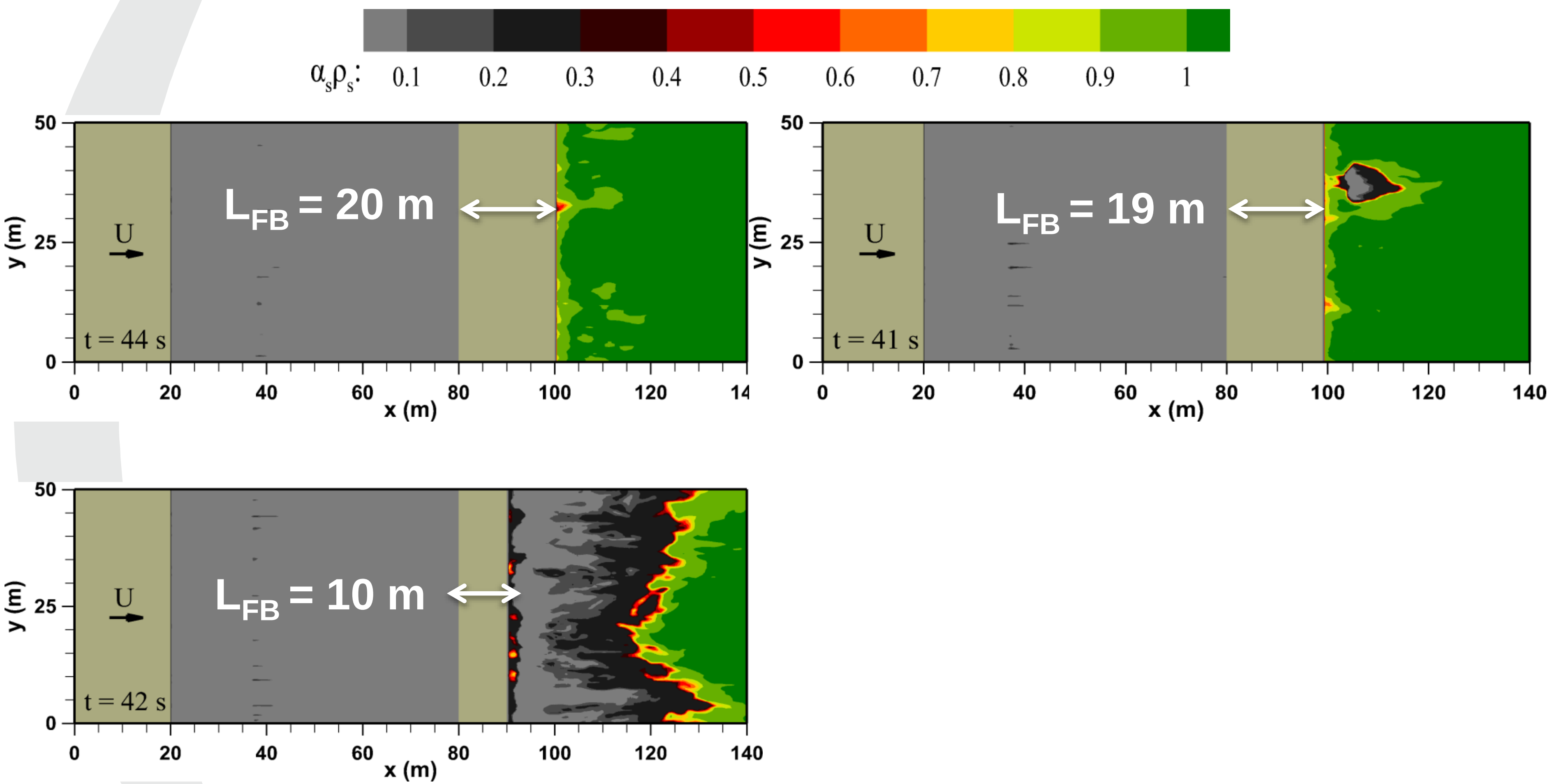


Lx = 140 à 200 m
Ly = 50 à 80 m
Lz = 40 m

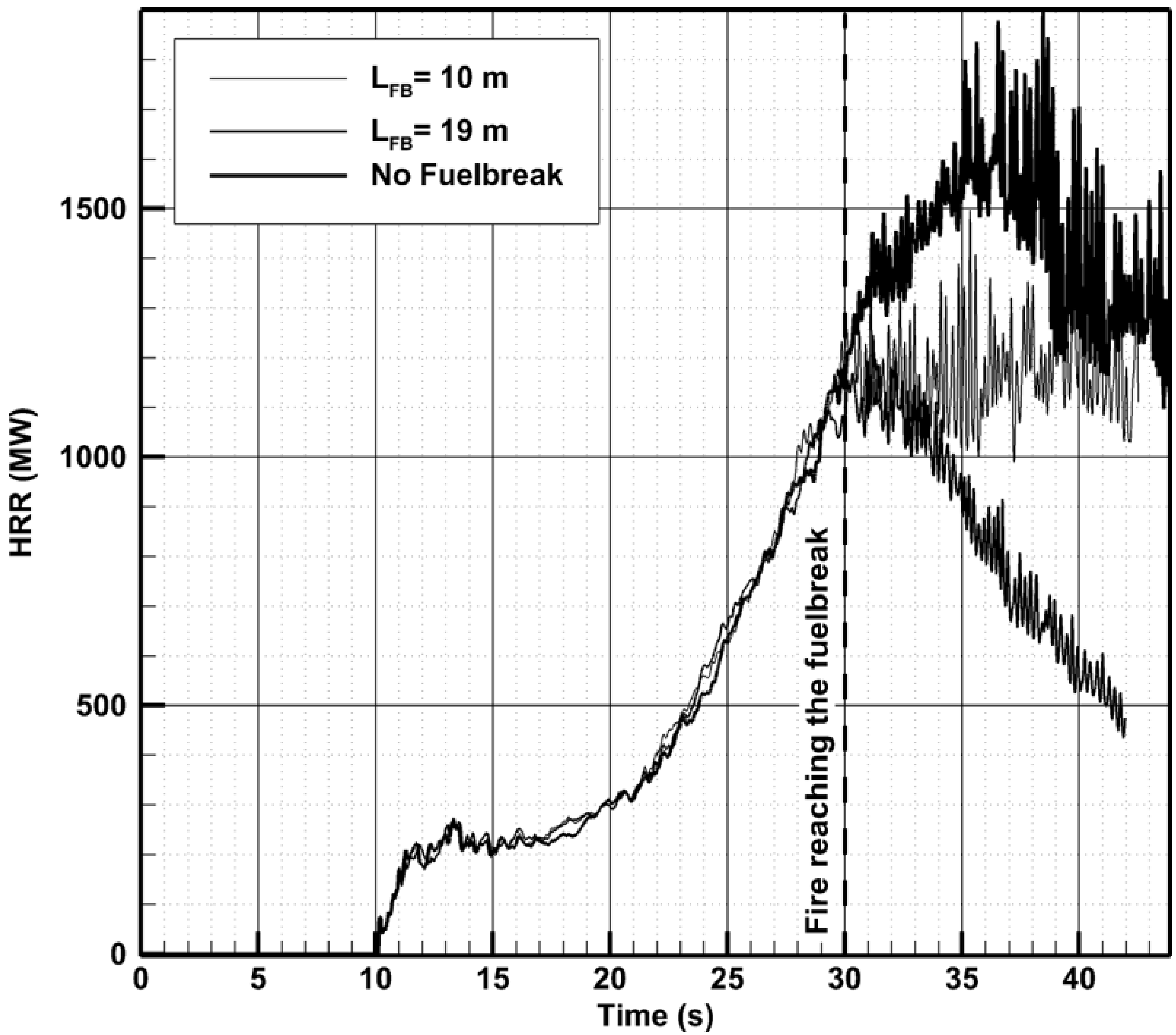
Grassland:
Fuel load = 0.25 à 1 kg/m^2
FMC = 5%

Hfuel = 0.25 à 1 m
U1 = 3 à 14 m/s
Nc = 0.4 à 50 (24 simulations)

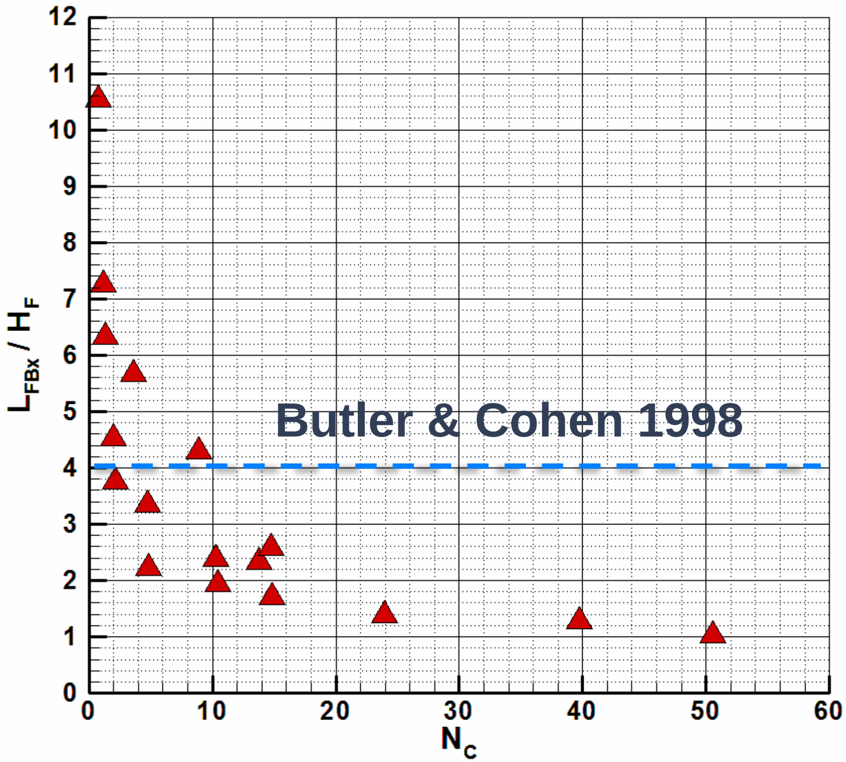
With a fuel break : U_1 = 8 m/s, w = 0.5 kg/m^2, Nc = 4.2, L_{FB} = 20, 19 et 10 m

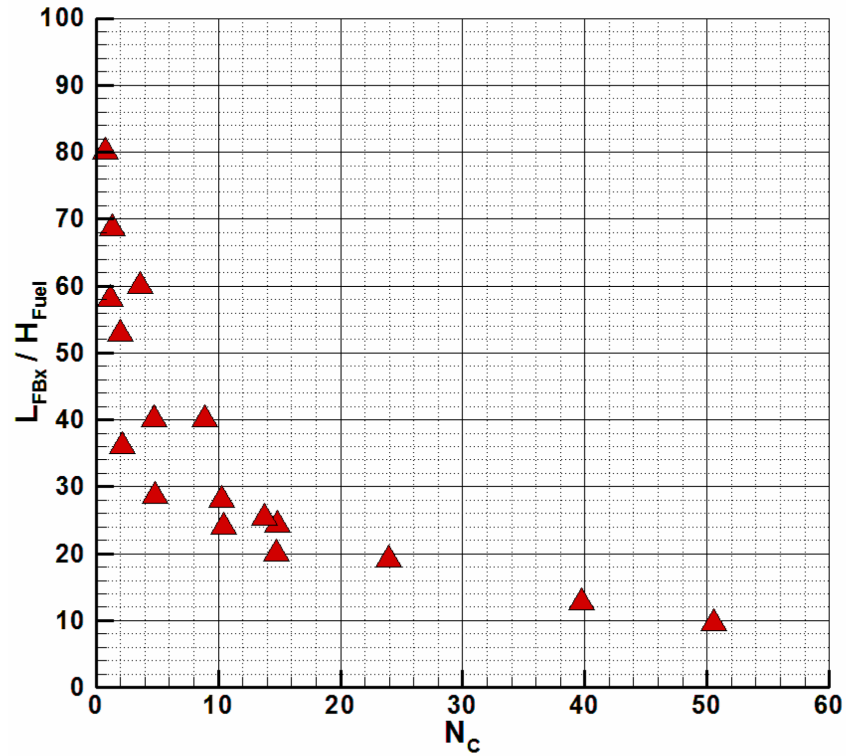


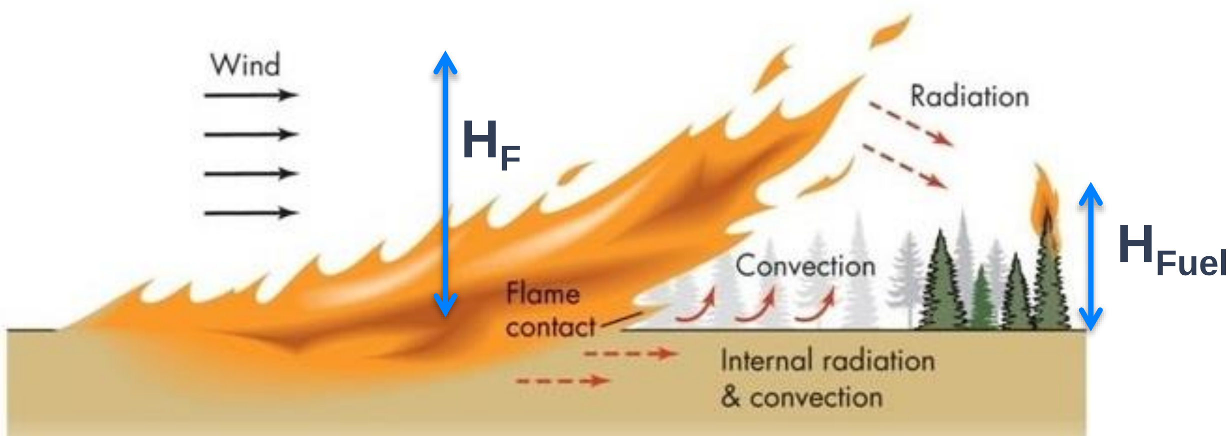
Heat release rate (HRR):
U_1 = 8 m/s, w = 0.5 kg/m^2, Nc = 4.2, L_{FB} = 20, 19 et 10 m



Optimal fuel break width vs Byram's convective number (N_C)







Conclusions (I)

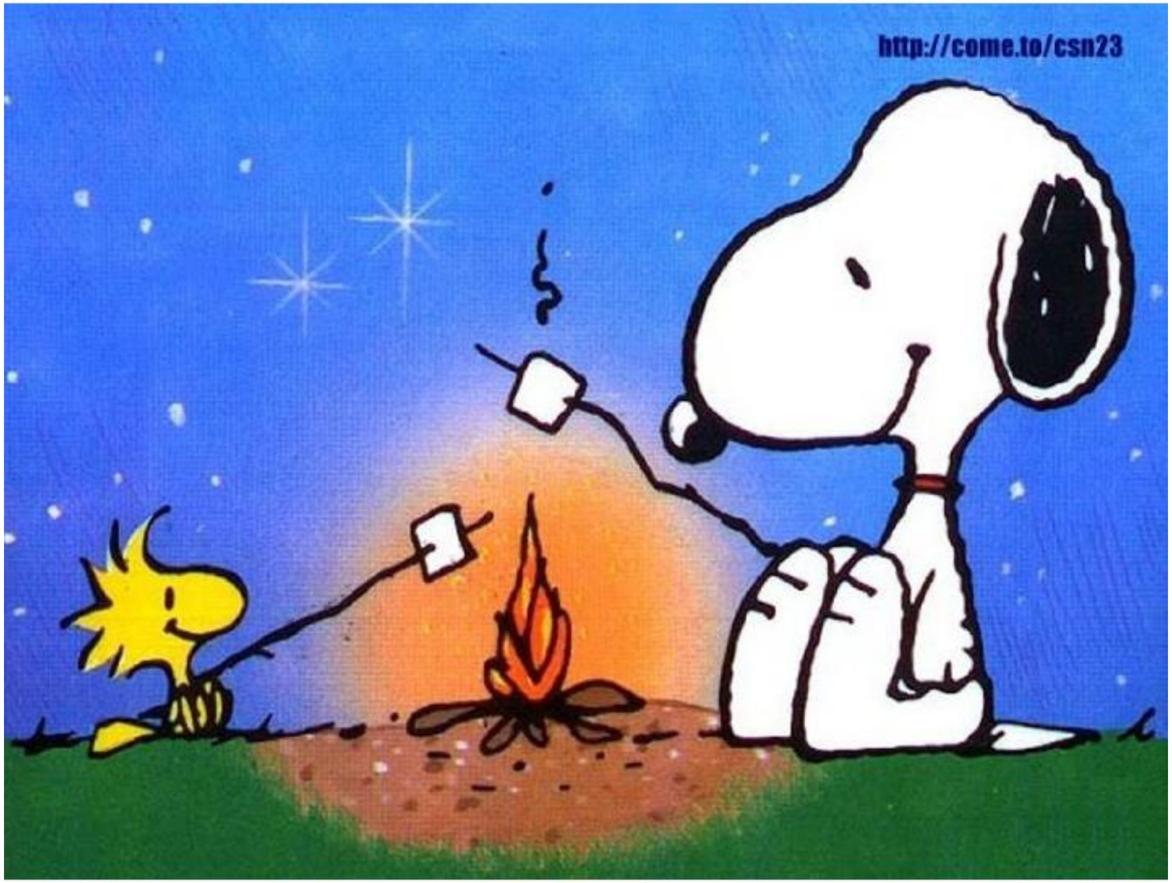
- As a complementary approach to experimental fires CFD modeling can contribute in the understanding of wildfires behaviour.
- CFD wildfire modeling regroups various level of description in order to reproduce fires at different scales (from < 500 m to >> 1km)
- At a quite large scale, a simple coupling between an atmospheric mesoscale model with a simplied fire propagation model is sufficient to forecast the trajectory of the thermal plume associated to the development of a wildfire (air quality, airport activity …).
- At a more local scale, a detailed CFD approach can contribute to the understanding of wildfires behaviour, especially the effects of slope, wind and other physical parameters upon the fire front dynamic, the identification of regimes of propagation (wind driven, plume dominated, slope driven …) …
- As a postfire or a fire safety analysis CFD tools can contribute to understand some critical phenomena occuring during fire fighting operations or help to the design of fire safety layout (fuelbreak …)

Conclusions (II)

- Correctly define the objectives of the numerical study,
- Don’t forget the state of the art of CFD modeling (mesh design, numerical scheme, convergence monitoring …),
- Computational effeciency needs also by a great attention on physical models (low Mach number approximation, turbulence and combustion modeling, heat transfer modeling, boundary conditions, size of the computational domain …)
- Don’t limit the analysis to few numerical results, exploring the trends …
- As possible, comparing with experimental data,
- Don’t forget that a model is not the full reality, keep in mind the limitations, no model can be considered as validated (this qualification must be bannied to all scientific report).
- To generalize and compare numerical/experimental results, dimensional analysis can be a good option (Byram’s convective number, Froude number, Leaf Area Index …)
- Round trip between CFD fire models and simplified physical models can be very often useful.

Aix*Marseille université
Initiative d'excellence

Thank you for your attention.



Time integration: explicit / implicit?

$$\frac{\partial \rho\phi}{\partial t} = F(t, \phi \ldots)$$

Euler explicit:

$$\frac{(\rho\phi)^{n+1} - (\rho\phi)^{n}}{\delta t} = F(\phi \ldots)\Big|_{n}$$

Euler implicit:

$$\frac{(\rho\phi)^{n+1} - (\rho\phi)^{n}}{\delta t} = F(\phi \ldots)\Big|_{n+1}$$

Stability criterium

$$\boldsymbol{CFL = \frac{U\,\delta t}{\delta h} < 1}$$

$$\boldsymbol{CFL = \frac{U\,\delta t}{\delta h} < C_{Max}}$$

$$\boldsymbol{C_{Max} > 1}$$

Some words on numerical diffusion

Exact equation:

$$\rho u \frac{\partial \phi}{\partial x} = \Gamma \frac{\partial^2 \phi}{\partial x^2}$$

Equation modélisée :

Convective part:
Second order scheme:

$$\rho u \frac{\partial \phi}{\partial x} = \Gamma \frac{\partial^2 \phi}{\partial x^2} + O(\delta h^2)$$

First order scheme:

$$\rho u \frac{\partial \phi}{\partial x} = \left(\Gamma + \frac{\rho u \delta h}{2} \right) \frac{\partial^2 \phi}{\partial x^2} + O(\delta h^2)$$

$$P_e = \rho \frac{u \delta h}{\Gamma}$$ (Péclet mesh number)

Some words on numerical diffusion

Second order centred scheme:

$$\rho u\left(\frac{\phi_{i+1}-\phi_{i-1}}{2\delta h}\right)=\Gamma\frac{\phi_{i+1}+\phi_{i-1}-2\phi_i}{\delta h^2}$$

First order upwind scheme:

$$\rho u\left(\frac{\phi_i-\phi_{i-1}}{\delta h}\right)=\Gamma\frac{\phi_{i+1}+\phi_{i-1}-2\phi_i}{\delta h^2}$$

Some words on numerical diffusion

$$\phi_{i+1} = \phi_i + \left.\frac{\partial \phi}{\partial x}\right|_i \delta h + \left.\frac{\partial^2 \phi}{\partial x^2}\right|_i \frac{\delta h^2}{2} + \left.\frac{\partial^3 \phi}{\partial x^3}\right|_i \frac{\delta h^3}{6} + O\left(\delta h^4\right)$$

$$\phi_{i-1} = \phi_i - \left.\frac{\partial \phi}{\partial x}\right|_i \delta h + \left.\frac{\partial^2 \phi}{\partial x^2}\right|_i \frac{\delta h^2}{2} - \left.\frac{\partial^3 \phi}{\partial x^3}\right|_i \frac{\delta h^3}{6} + O\left(\delta h^4\right)$$

Some words on numerical diffusion

$$\frac{\phi_{i+1}-\phi_{i-1}}{2\delta h}=\left.\frac{\partial\phi}{\partial x}\right|_i+\left.\frac{\partial^3\phi}{\partial x^3}\right|_i\frac{\delta h^2}{2}+\dots$$

$$\frac{\phi_i-\phi_{i-1}}{\delta h}=\left.\frac{\partial\phi}{\partial x}\right|_i-\left.\frac{\partial^2\phi}{\partial x^2}\right|_i\frac{\delta h}{2}+\dots$$

$$\frac{\phi_{i+1}+\phi_{i-1}-2\phi_i}{\delta h^2}=\left.\frac{\partial^2\phi}{\partial x^2}\right|_i+\left.\frac{\partial^4\phi}{\partial x^4}\right|_i\frac{\delta h^2}{12}+\dots$$

Some words on numerical diffusion

<u>Schéma centré du 2nd ordre:</u>

$$\rho u \frac{\partial \phi}{\partial x} = \Gamma \frac{\partial^2 \phi}{\partial x^2} + O(\delta h^2)$$

<u>Schéma décentré du 1er ordre:</u>

$$\rho u \frac{\partial \phi}{\partial x} = \left(\Gamma + \frac{\rho u \delta h}{2} \right) \frac{\partial^2 \phi}{\partial x^2} + O(\delta h^2)$$