Animating Fire with Sound

Jeff Chadwick and Doug James

Cornell University

[Nguyen et al. 2002]

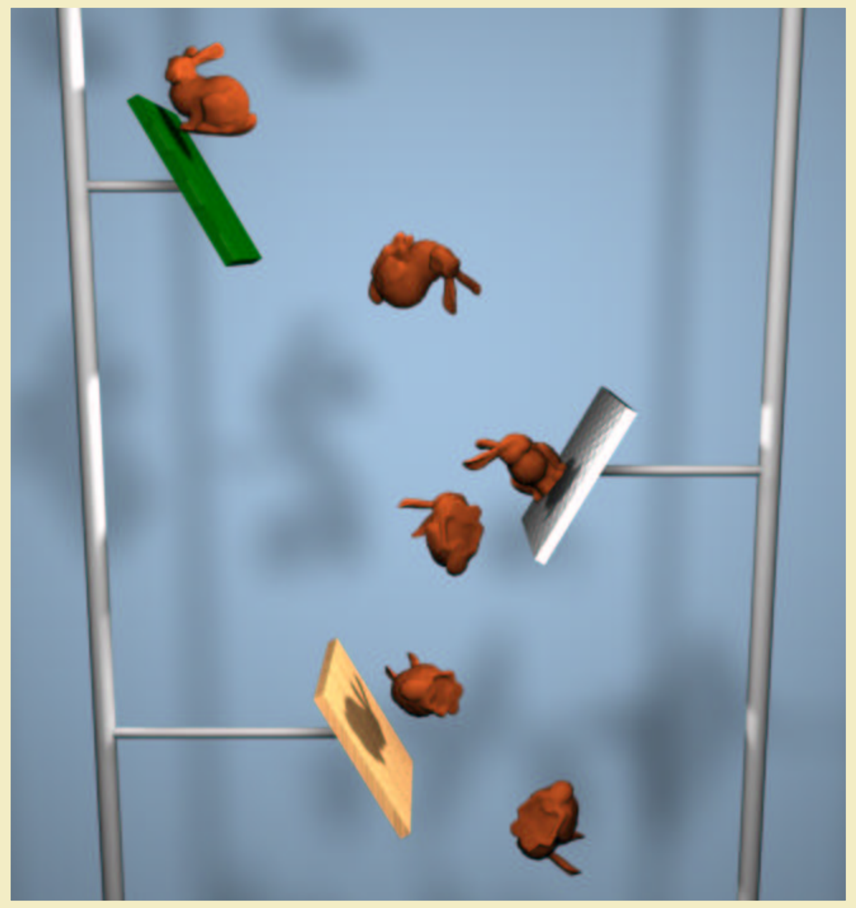
[Hong et al. 2007]

[Feldman et al. 2003]

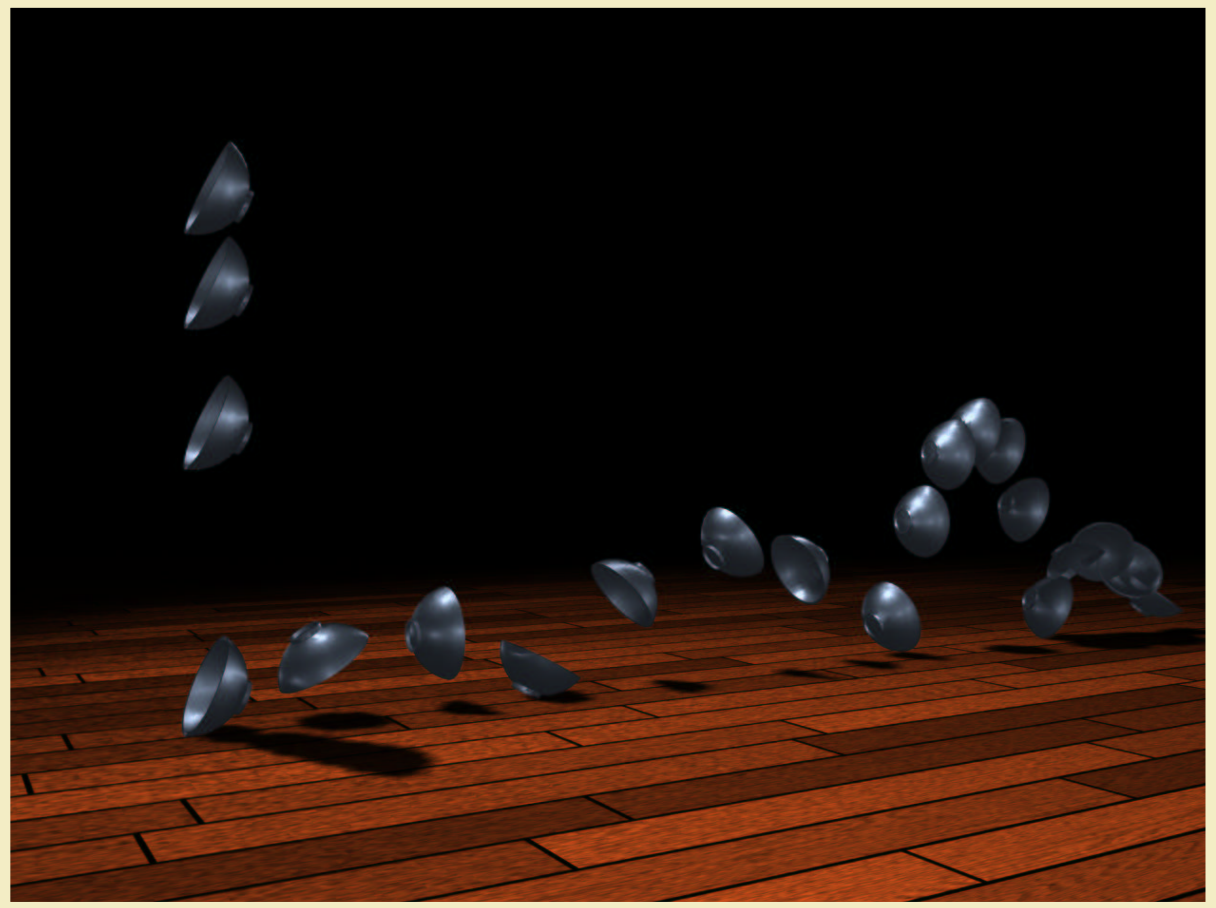
[Horvath and Geiger 2009]

Sound Synthesis

[van den Doel et al. 2001]

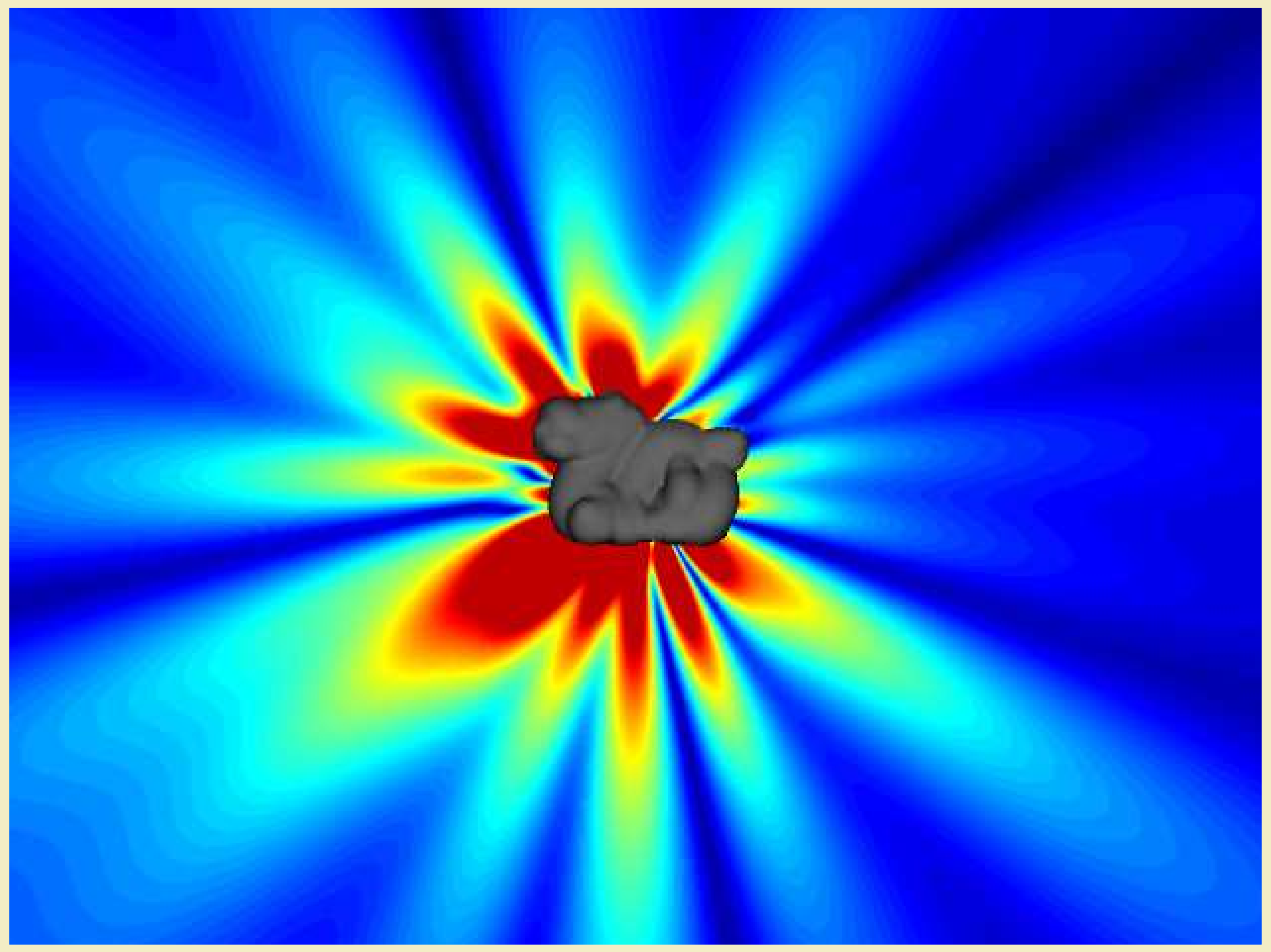


[O'Brien et al. 2002]

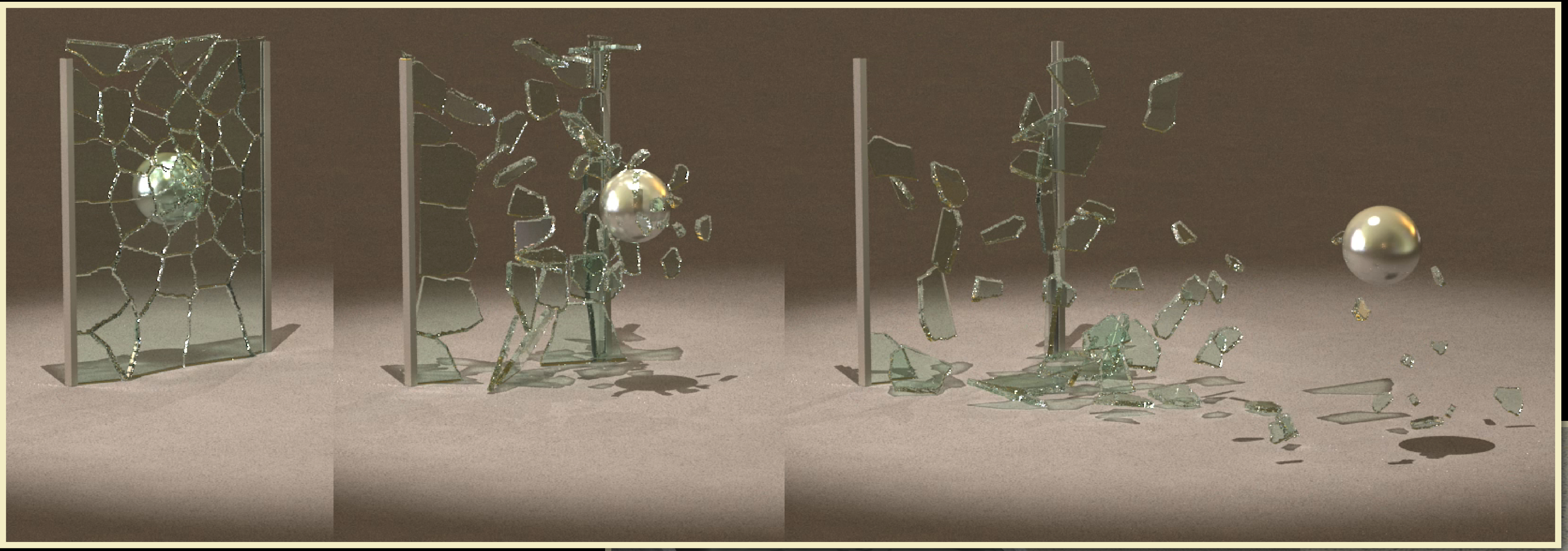


[O'Brien et al. 2001]

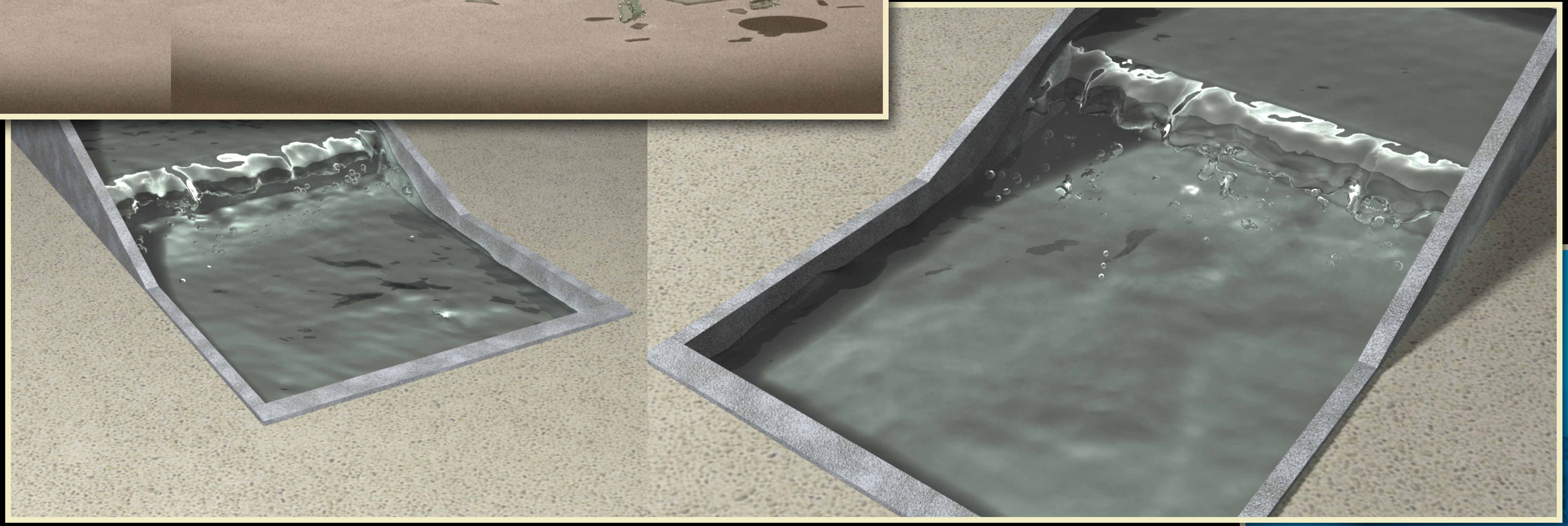
[Bonneel et al. 2008]



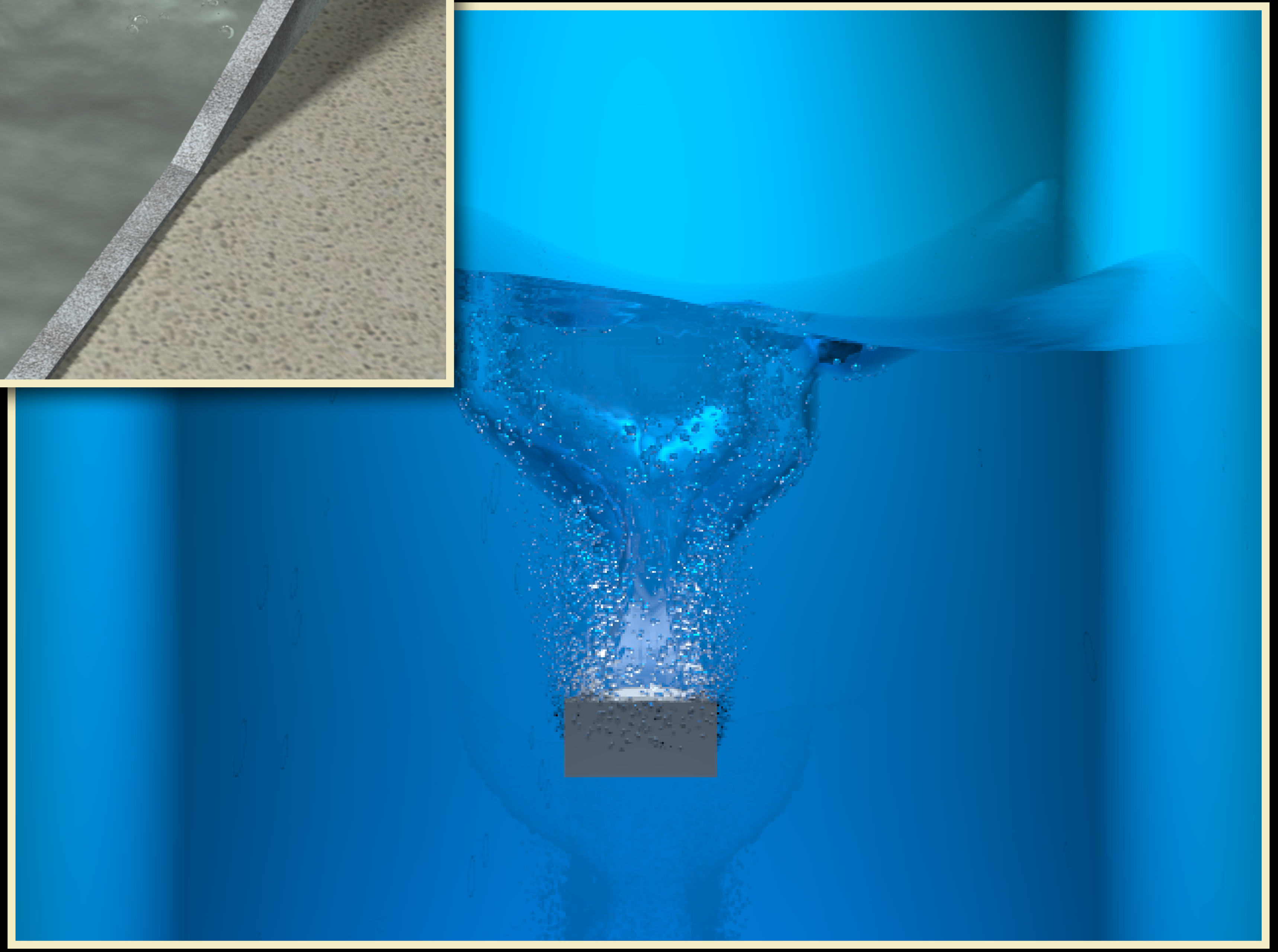
[James et al. 2006]



[Zheng and James 2010]



[Zheng and James 2009]

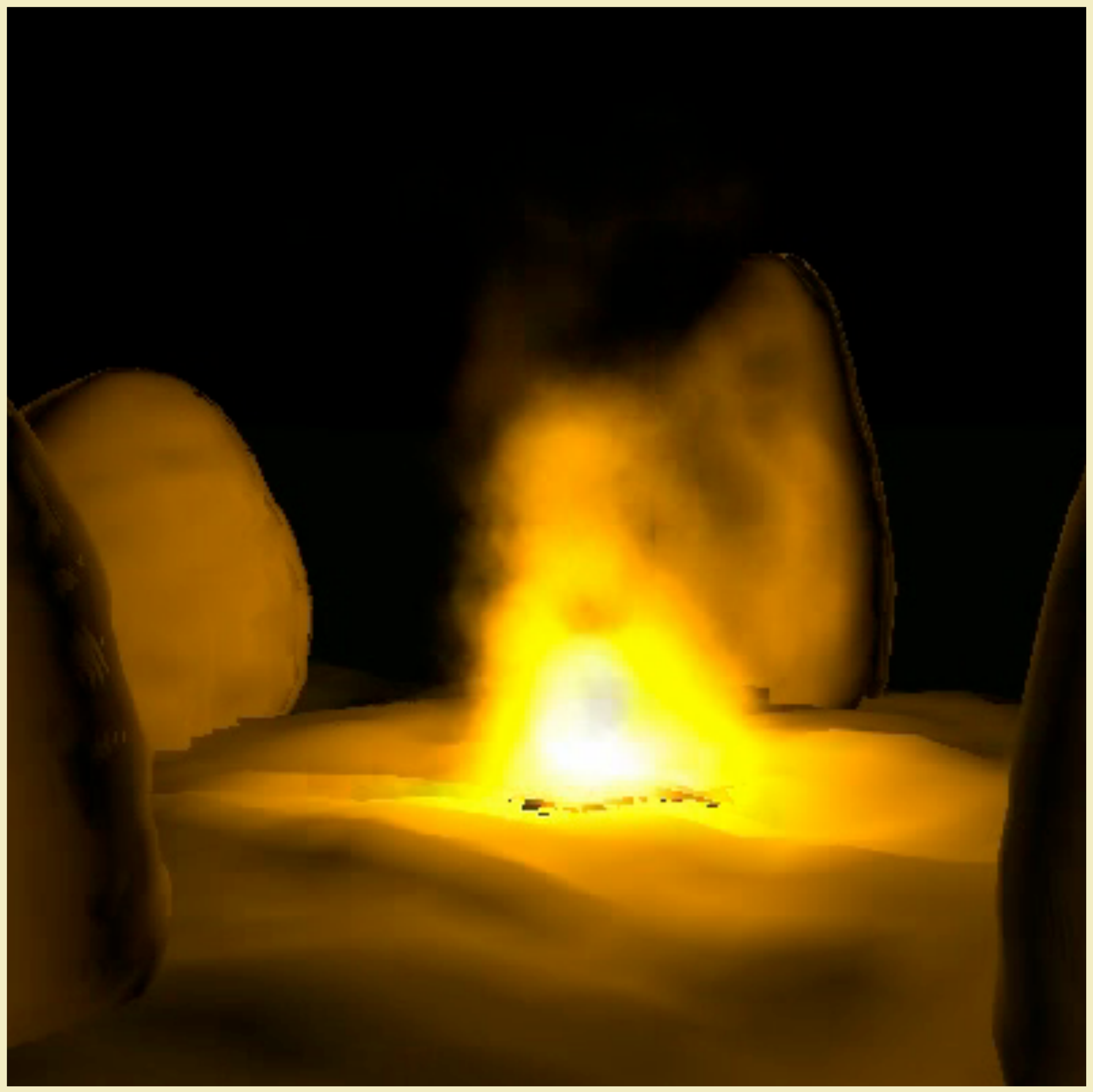


[Moss et al. 2010]

Sound Synthesis

Aerodynamic Sound

[Dobashi et al. 2003]



[Dobashi et al. 2004]

[Nguyen et al. 2002]

[Hong et al. 2007]

[Feldman et al. 2003]

[Horvath and Geiger 2009]

Preview

Background

- Combustion sound components [Chrighton et al. 1992; Poinsot and Veynante 2005]
  - Aerodynamic noise (eg. [Dobashi et al. 2003])
    - Resulting from turbulent flow
  - “Direct combustion noise”
    - Produced by density fluctuations resulting from heat release
    - Dominant source of combustion sound [Ihme et al. 2009]

Background

Combustion heat release rate

- Combustion sound wave equation

$$\frac{1}{c_0^2}\frac{\partial^2 p}{\partial t^2} - \nabla^2 p = -C\frac{\partial \boxed{q}}{\partial t}$$

- Convert to integral equation

$$p(\mathbf{x}, t) = \frac{C}{4\pi}\frac{\partial}{\partial t}\int_{\mathbb{R}^3}\frac{1}{r} q\left(\mathbf{y}, t - r/c_0\right) d^3\mathbf{y}$$

$$sound \approx \frac{d}{dt}\boxed{\int_{\mathbb{R}^3} q(\mathbf{y}, t) d^3\mathbf{y}}$$

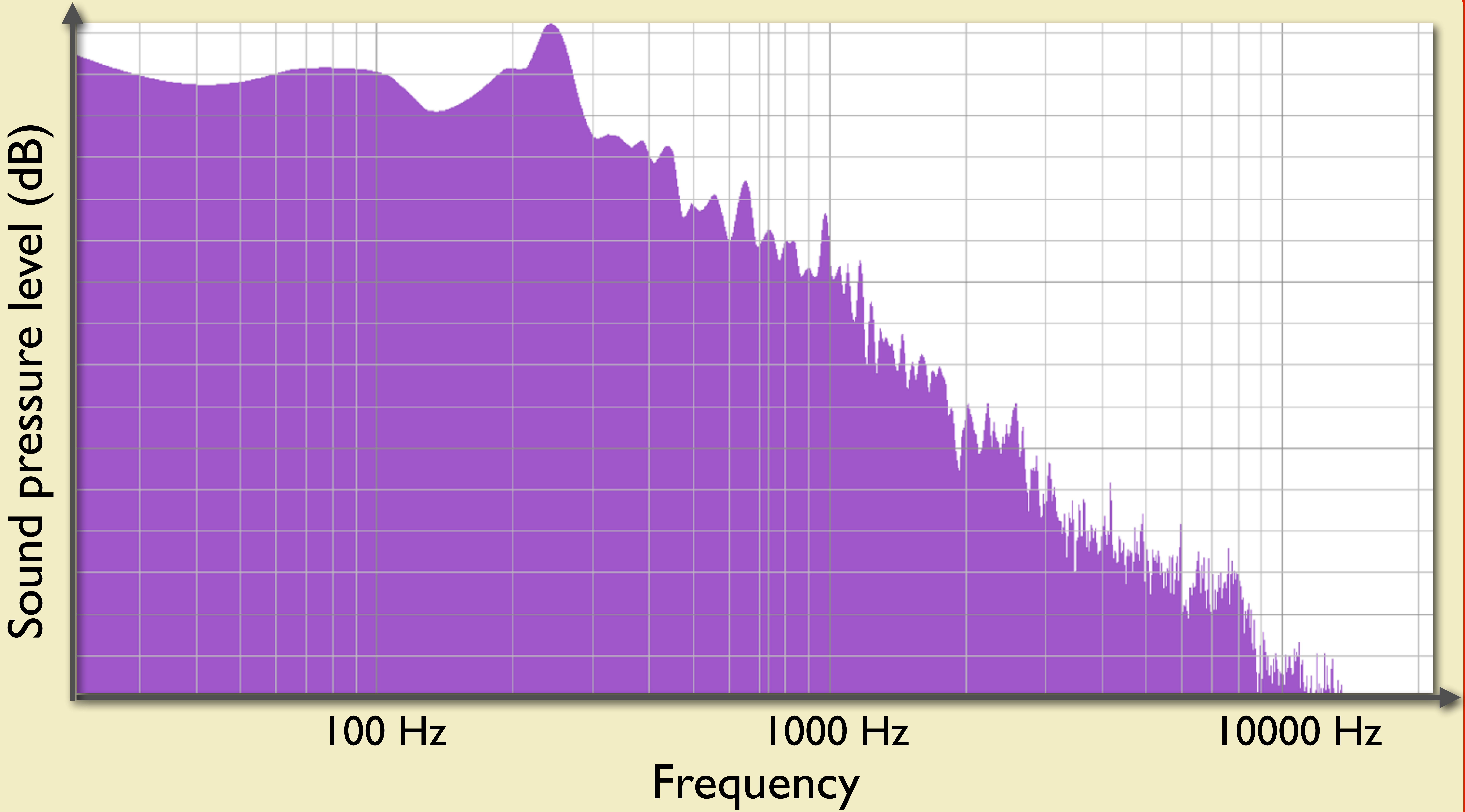
Background

$$sound \approx \frac{d}{dt} \int_{\mathbb{R}^3} q(\mathbf{y}, t) d^3\mathbf{y}$$

- **Problem:** Flame solvers from the graphics community do not realistically model heat release
  - Heat release modeled artistically, via simple functions, etc.
  - **Goal:** express heat release in terms of quantities we have access to

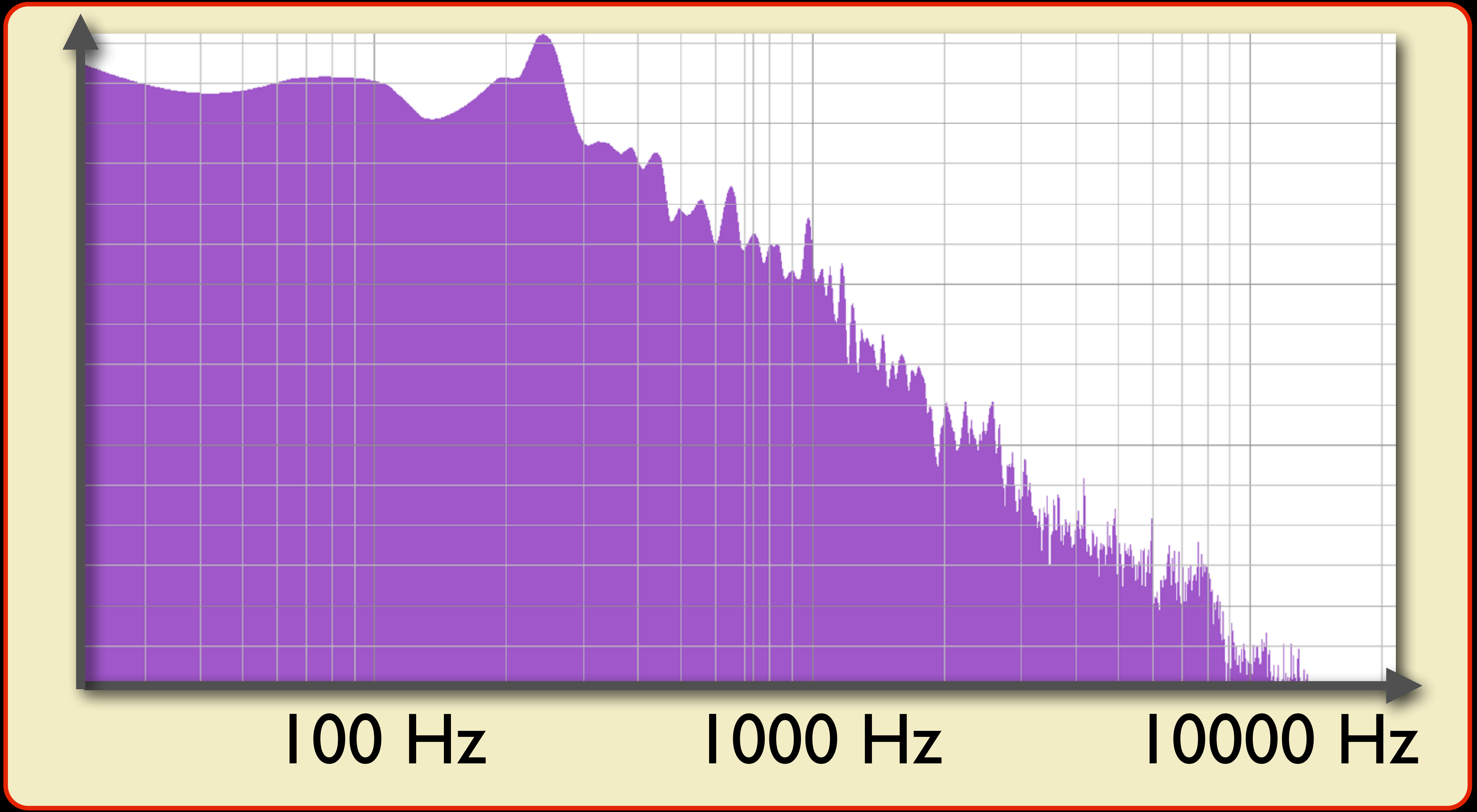
Flame Recording

1/10th speed


Sound pressure level (dB)
100 Hz
1000 Hz
10000 Hz
Frequency

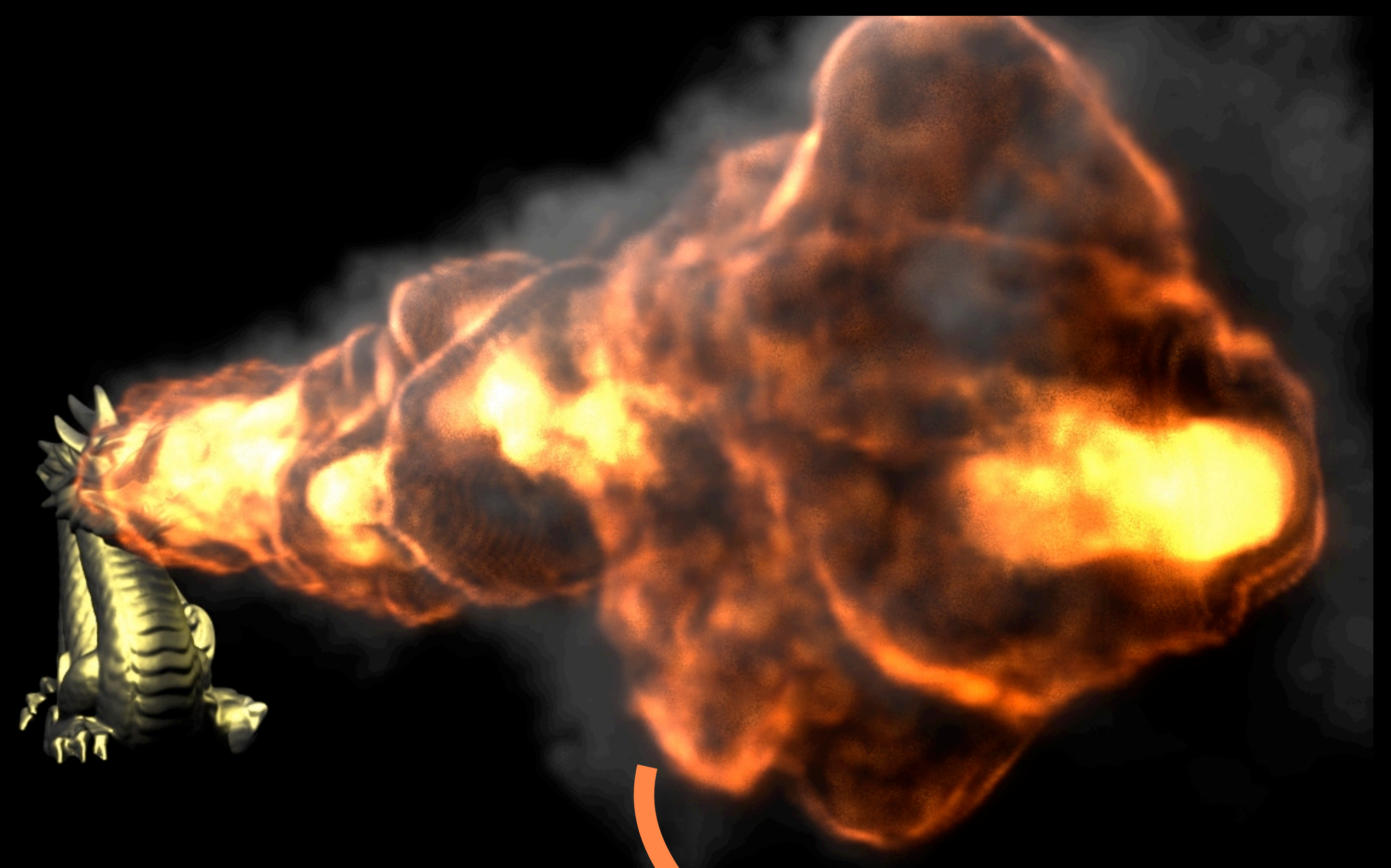
Problem Statement

- Time stepping 3D fluid simulation to resolve all frequency content impractical

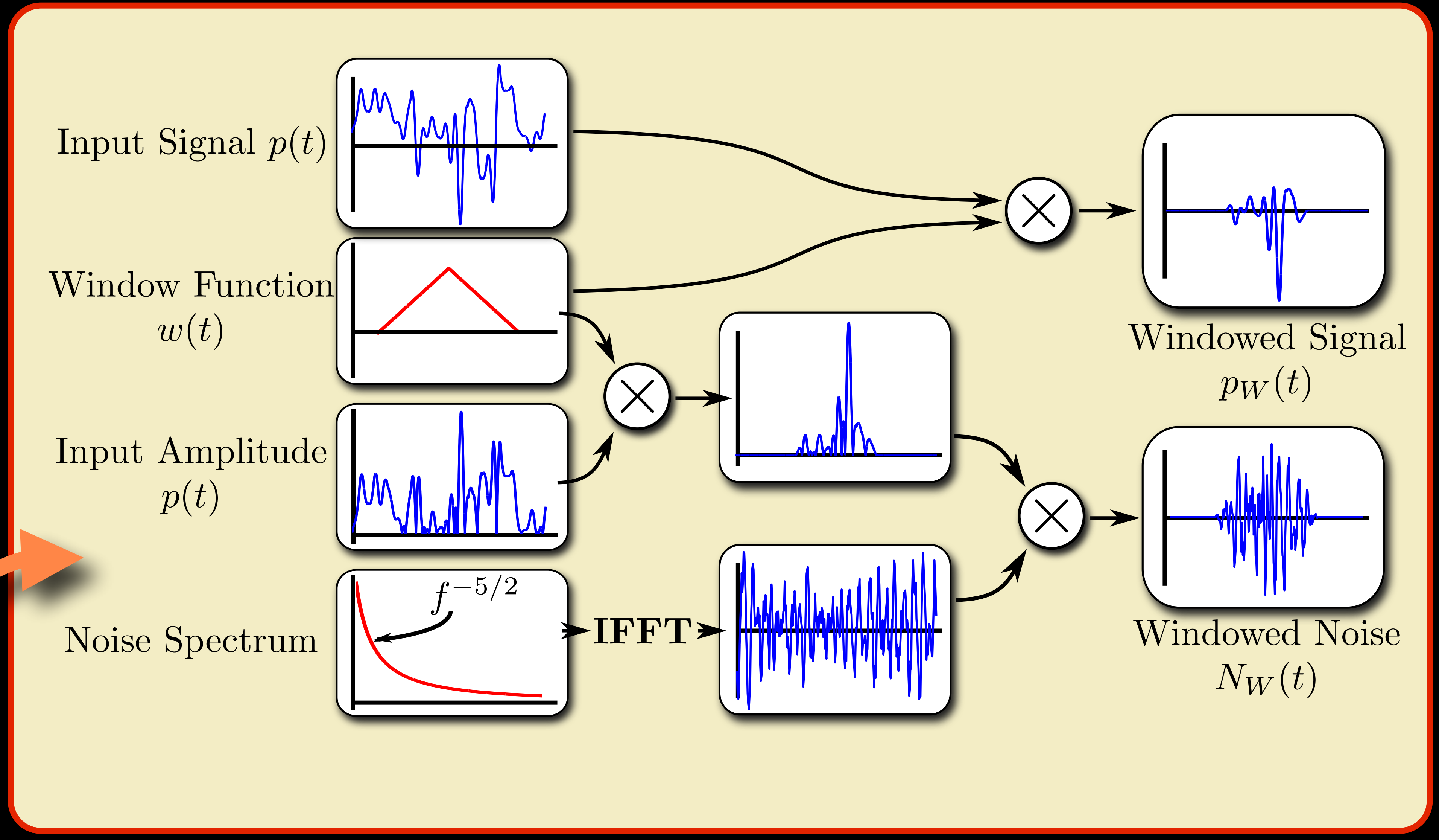


- Flame solvers used in the graphics community do not model complex combustion chemistry
  - Increasing temporal resolution would not be effective

Overview

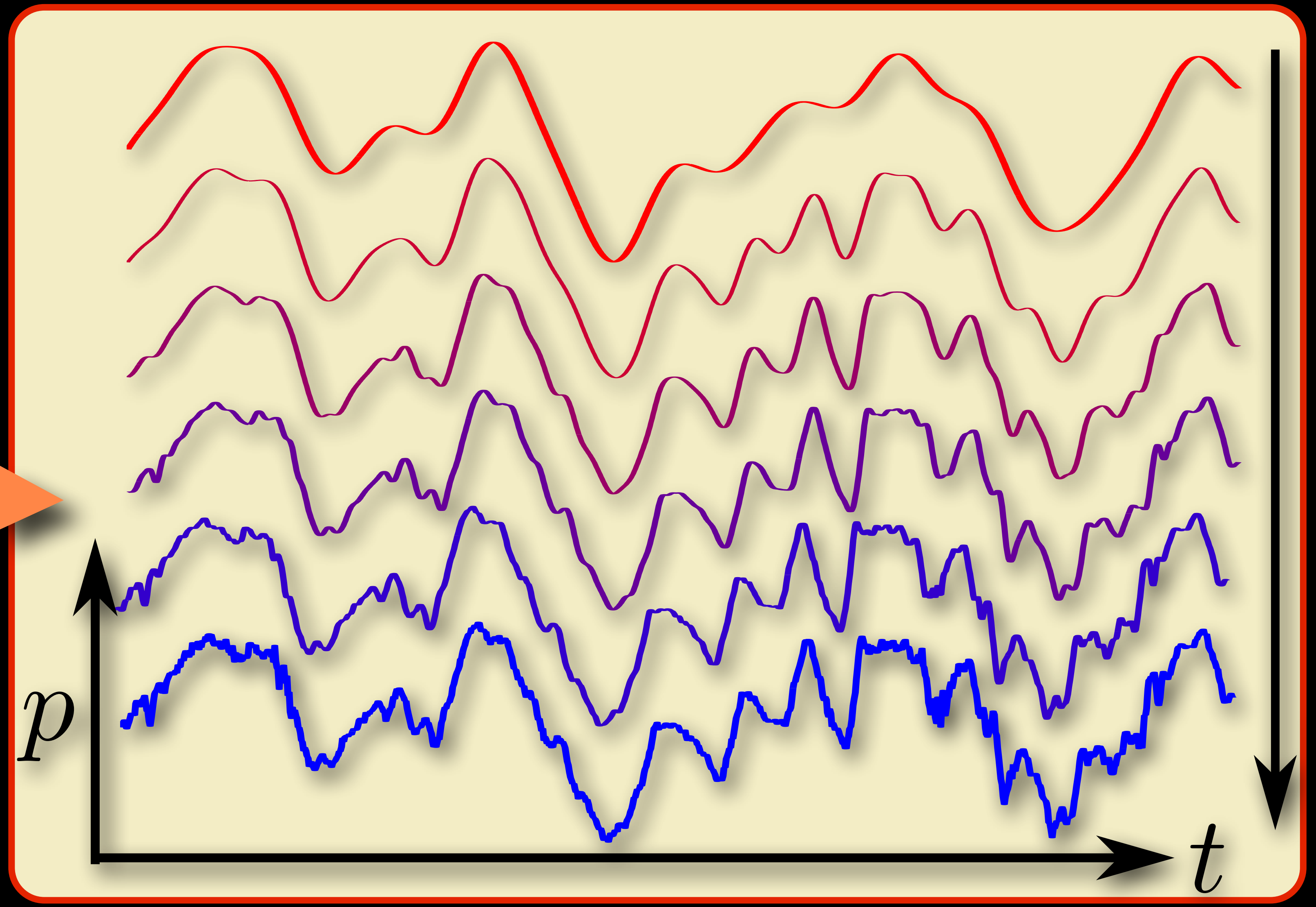


Spectral Bandwidth Extension



OR

Sound Texture Synthesis



Low-frequency Sound Model

Low-frequency Sound Model

$$sound \approx \frac{d}{dt} \int_{\mathbb{R}^3} q(\mathbf{y}, t) d^3\mathbf{y}$$

- **Problem:** Flame solvers from the graphics community do not realistically model heat release
  - Heat release modeled artistically, via simple functions, etc.
  - **Goal:** express heat release in terms of quantities we have access to

Low-frequency Sound Model

Modeling Heat Release

- Premixed flame assumption:
  - Reactants mixed prior to combustion
  - Combustion occurs rapidly when ignition temperature is reached
  - **Result:** heat release confined to “flame front” separating burnt and unburnt gasses

Low-frequency Sound Model

Modeling Heat Release

$$sound \approx \frac{d}{dt}\int_{\mathbb{R}^3} q(\mathbf{y},t)d^3\mathbf{y}$$

$$sound \approx \frac{d}{dt}\int_{S(t)} q\ dS$$

Low-frequency Sound Model

Modeling Heat Release

- Approximate heat release with velocity flux [Strahle 1972; Clavin and Siggia 1991; Chrighton et al. 1992]

$$sound \approx \frac{d}{dt}\int_{S(t)} q\,dS \approx \frac{d}{dt}\int_{S(t)} \mathbf{u}\cdot\mathbf{n}\,dS$$

Low-frequency Sound Model

Flame Front Surface

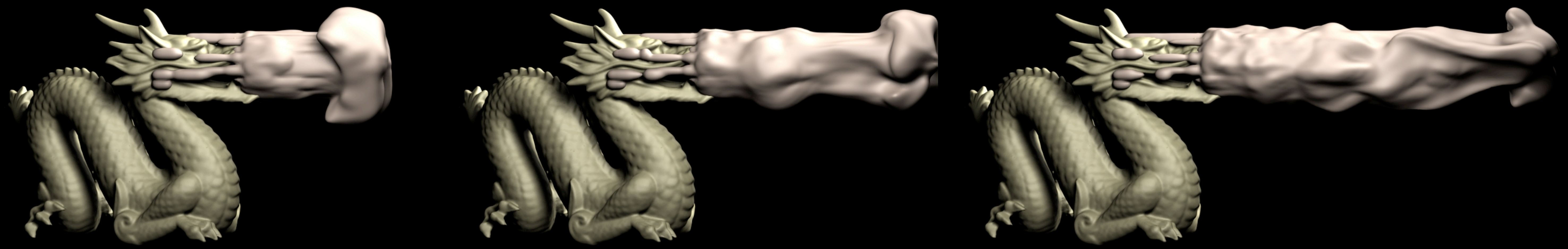
$$sound \approx \frac{d}{dt} \int_{S(t)} \mathbf{u} \cdot \mathbf{n} \, dS$$

- "Blue core" flame solvers [Nguyen et al. 2002; Hong et al. 2007]
  - Explicitly model flame front surface level set
- Other solvers which explicitly model fuel (eg. Houdini's *Pyro FX* solver)
  - Track rate at which fuel is consumed at each voxel and build an iso-surface

Low-frequency Sound Model

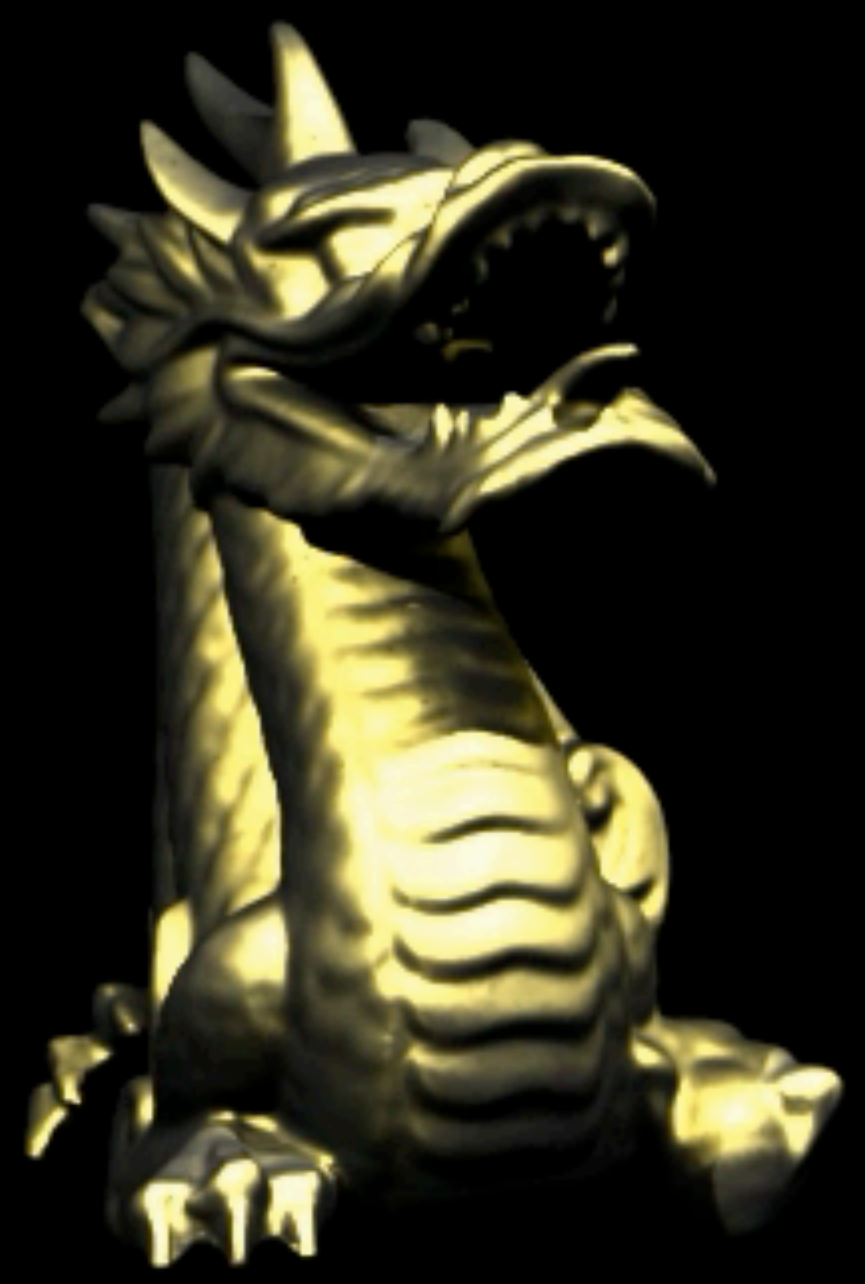
Results

$$sound \approx \frac{d}{dt}\boxed{\int_{S(t)} \mathbf{u}\cdot\mathbf{n}\, dS} = \frac{d}{dt}\boxed{I(t)}$$

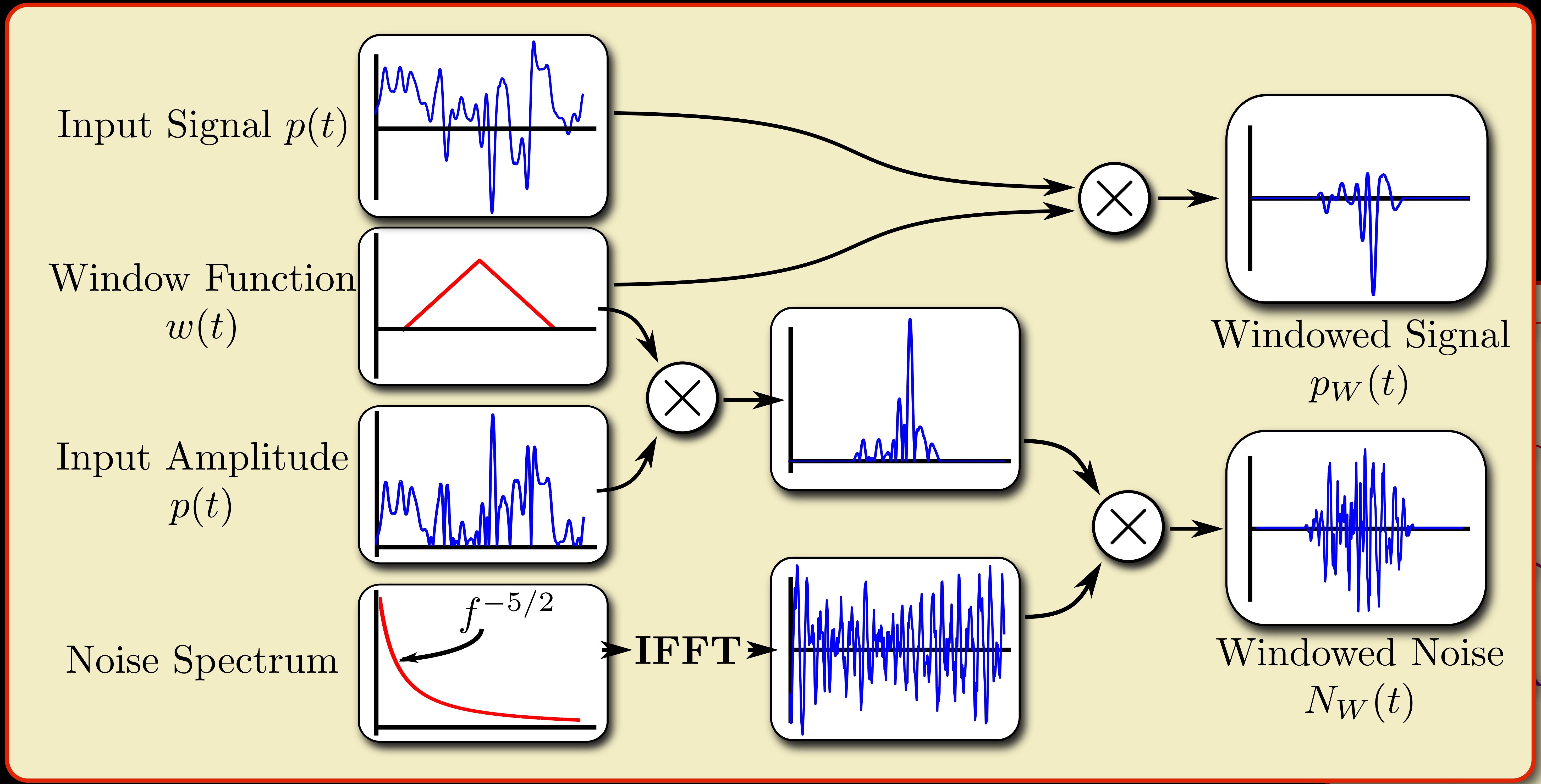


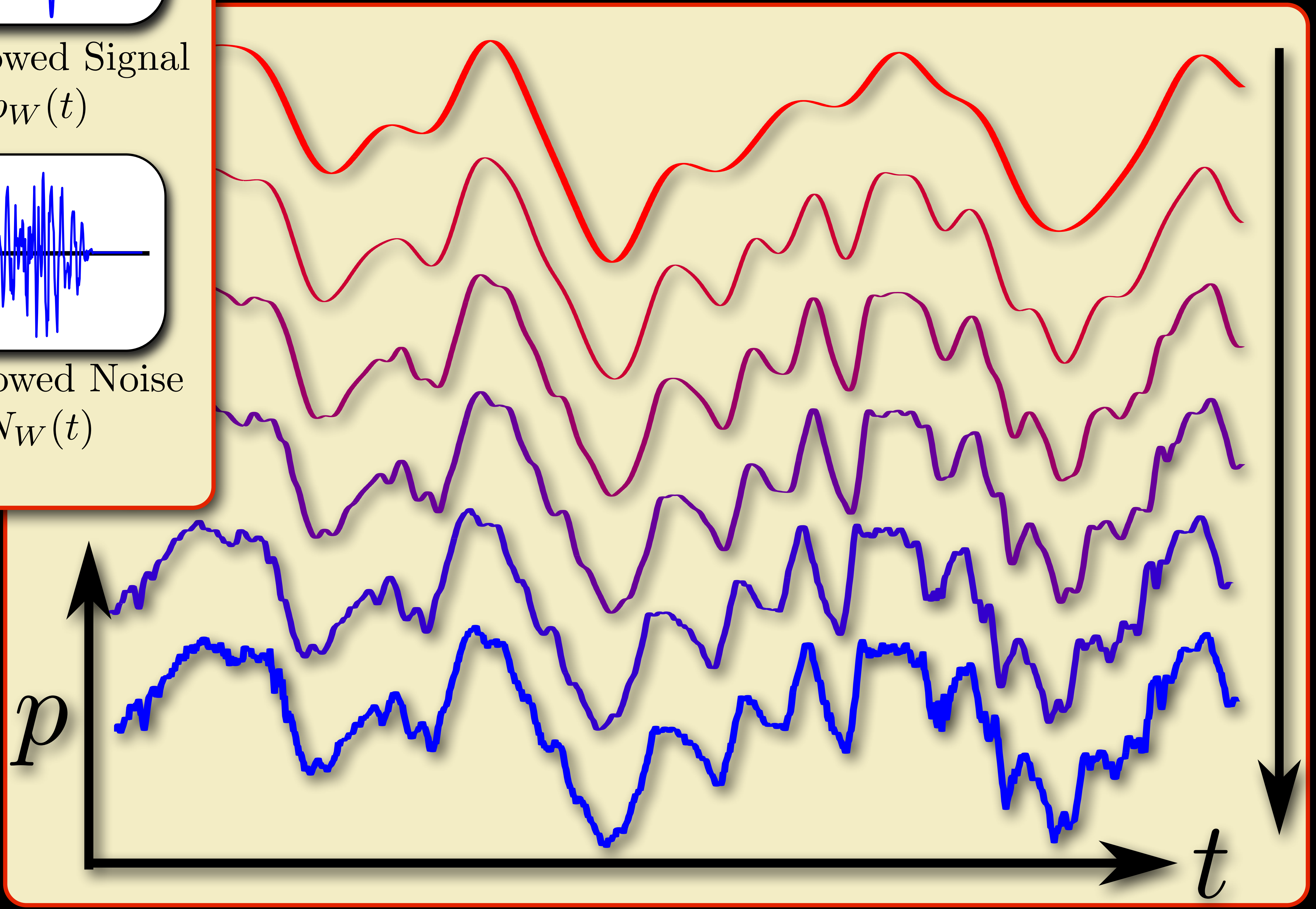
Compute $I(t_0), \quad I(t_1), \quad I(t_2), \ldots$

Simulation time steps



Synthesizing High-Frequency Sound

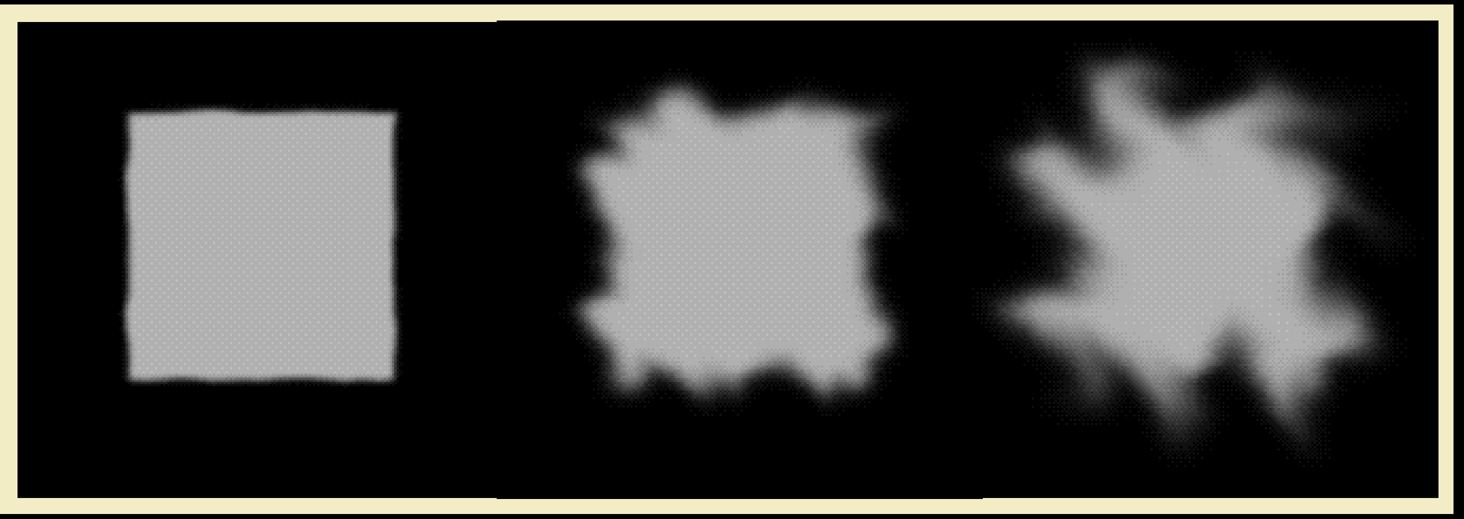




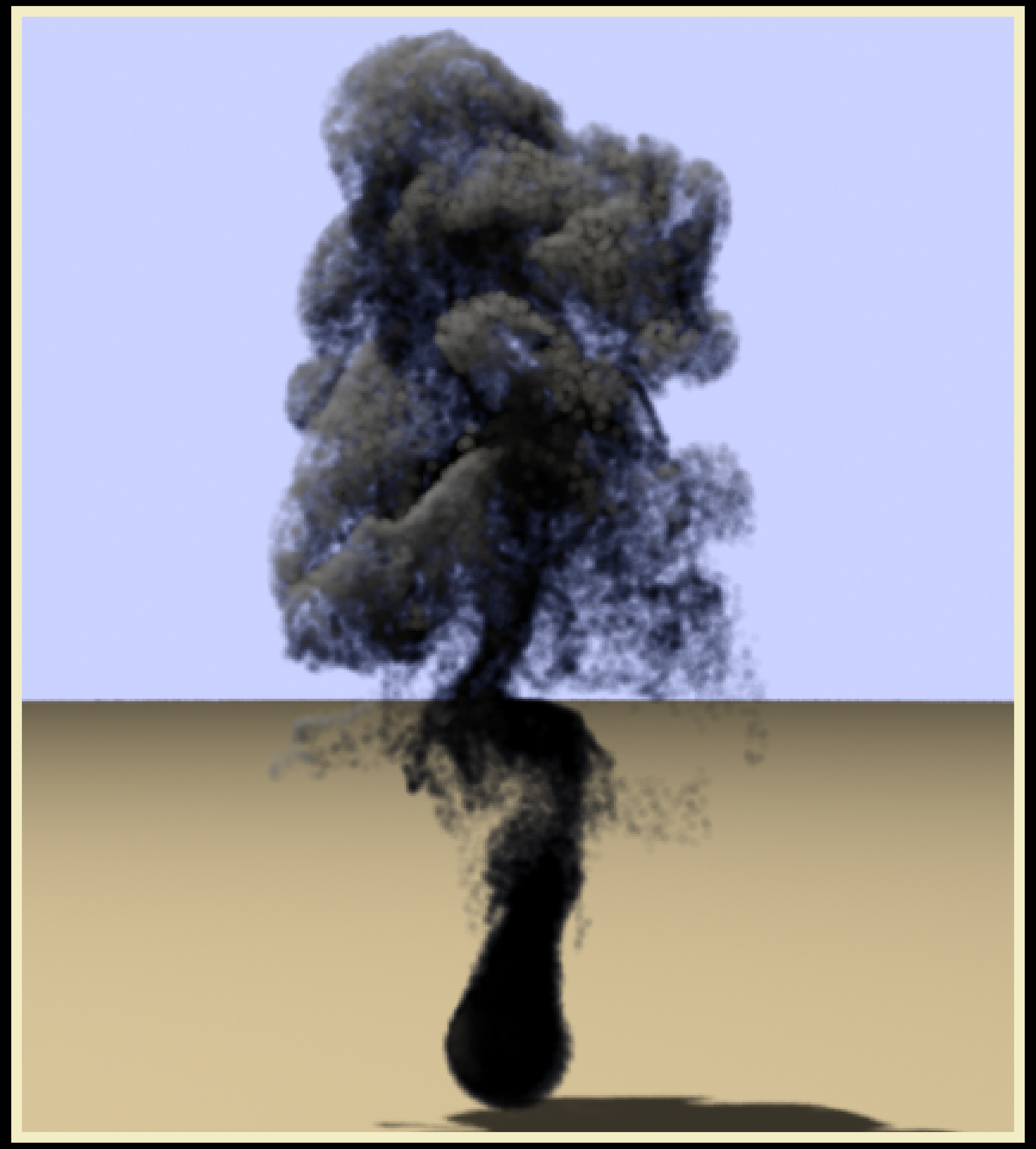
Bandwidth Extension

Summary

- **Idea:** synthesize noise with physically plausible spectrum to introduce high frequency content
- Similar to fluid velocity turbulence ideas, eg.



[Stam and Fiume 1993]



[Schechter and Bridson 2008]

[Kim et al. 2008]

Bandwidth Extension

Summary

- Numerous studies have examined spectral behaviour of combustion sound, eg. [Abugov and Obrezkov, 1978; Clavin and Siggia, 1991]

$$k^{-\frac{5}{3}}$$

Kolmogorov velocity spectrum

$$\longrightarrow$$

$$f^{-\frac{5}{2}}$$

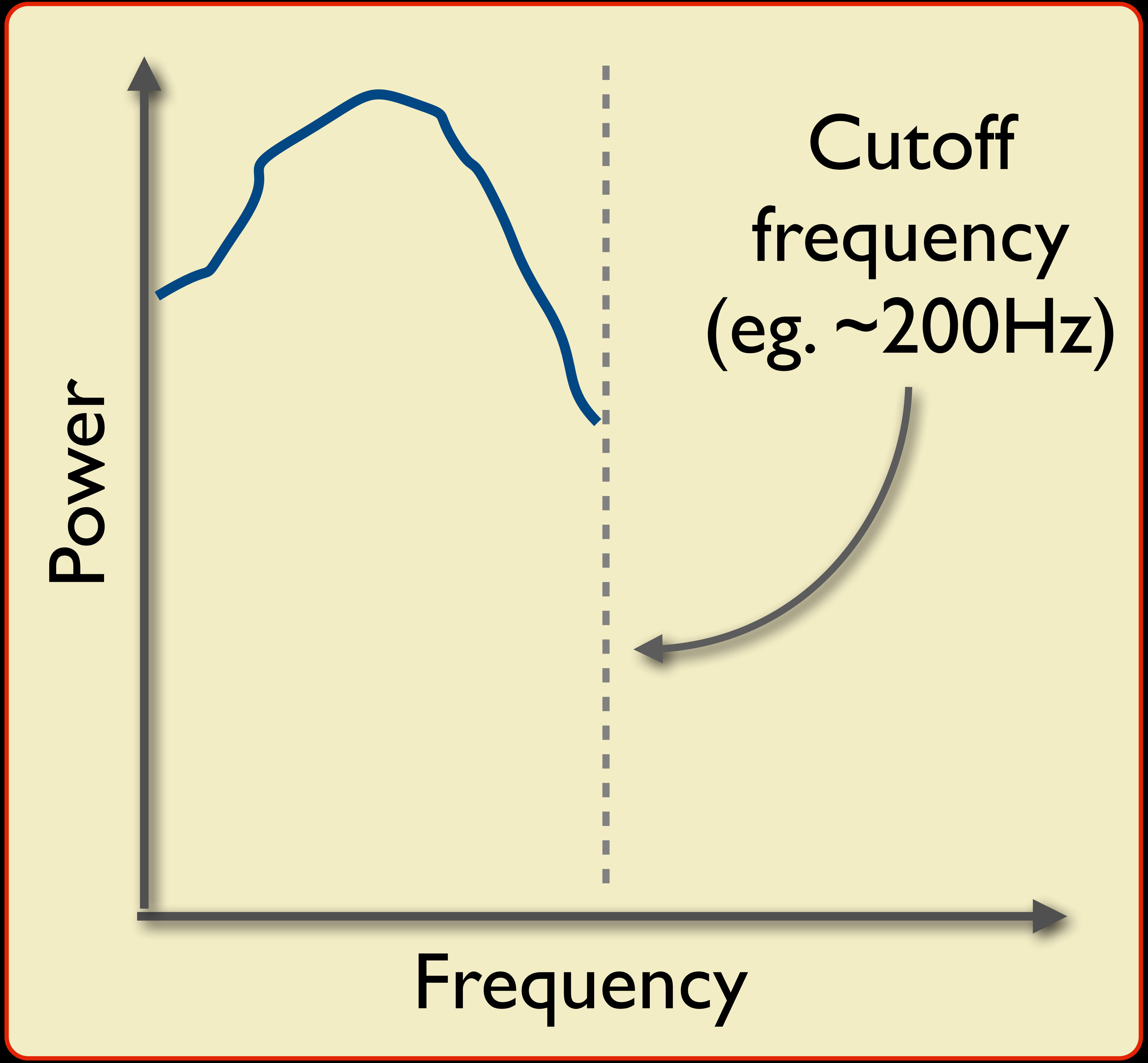
Power law sound spectrum

- Similar results from experimental studies [Rajaram and Lieuwen, 2009]

$$f^{-\alpha}, \quad 2.2 \lesssim \alpha \lesssim 3.7$$

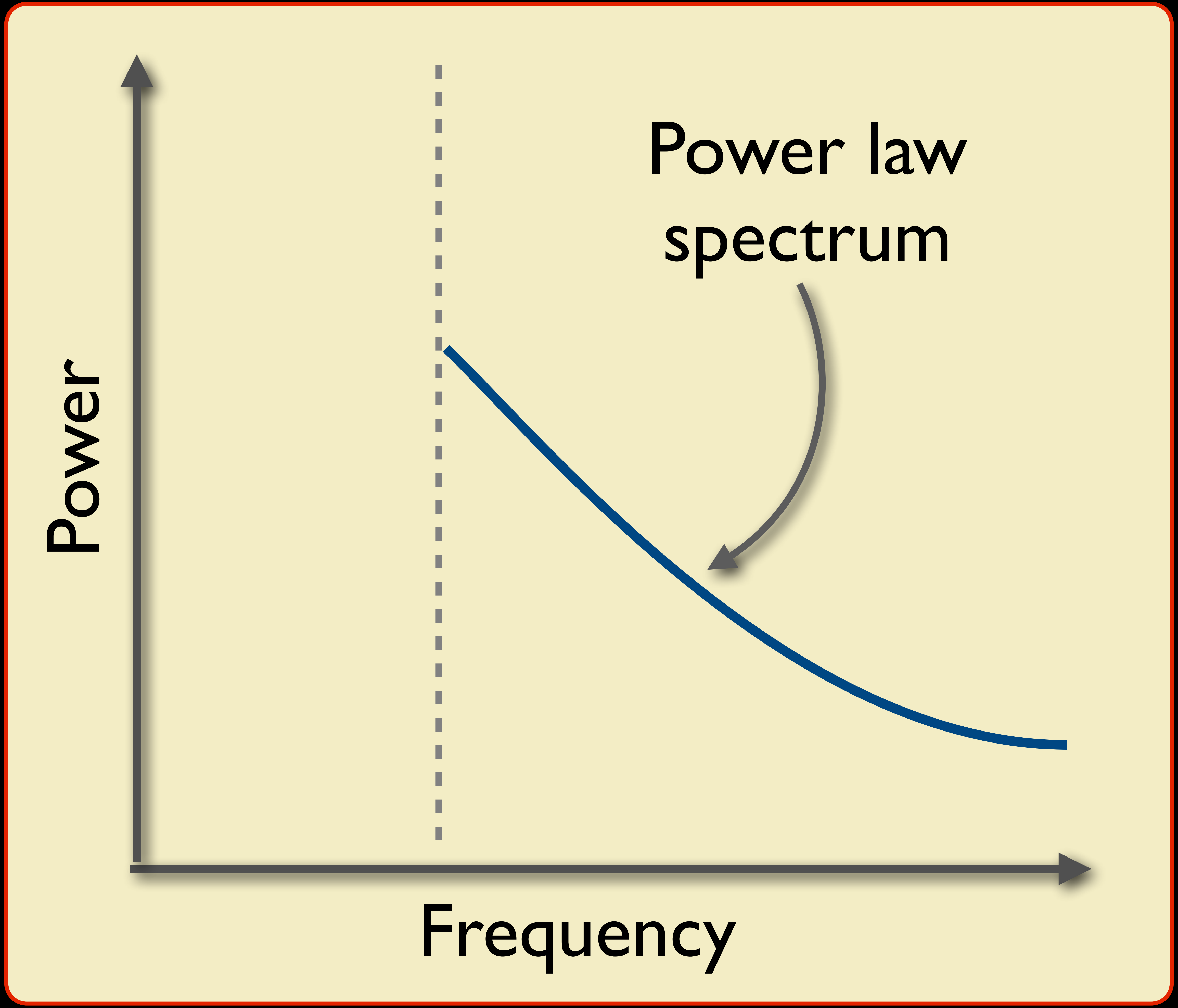
Bandwidth Extension

Summary



Low-frequency sound

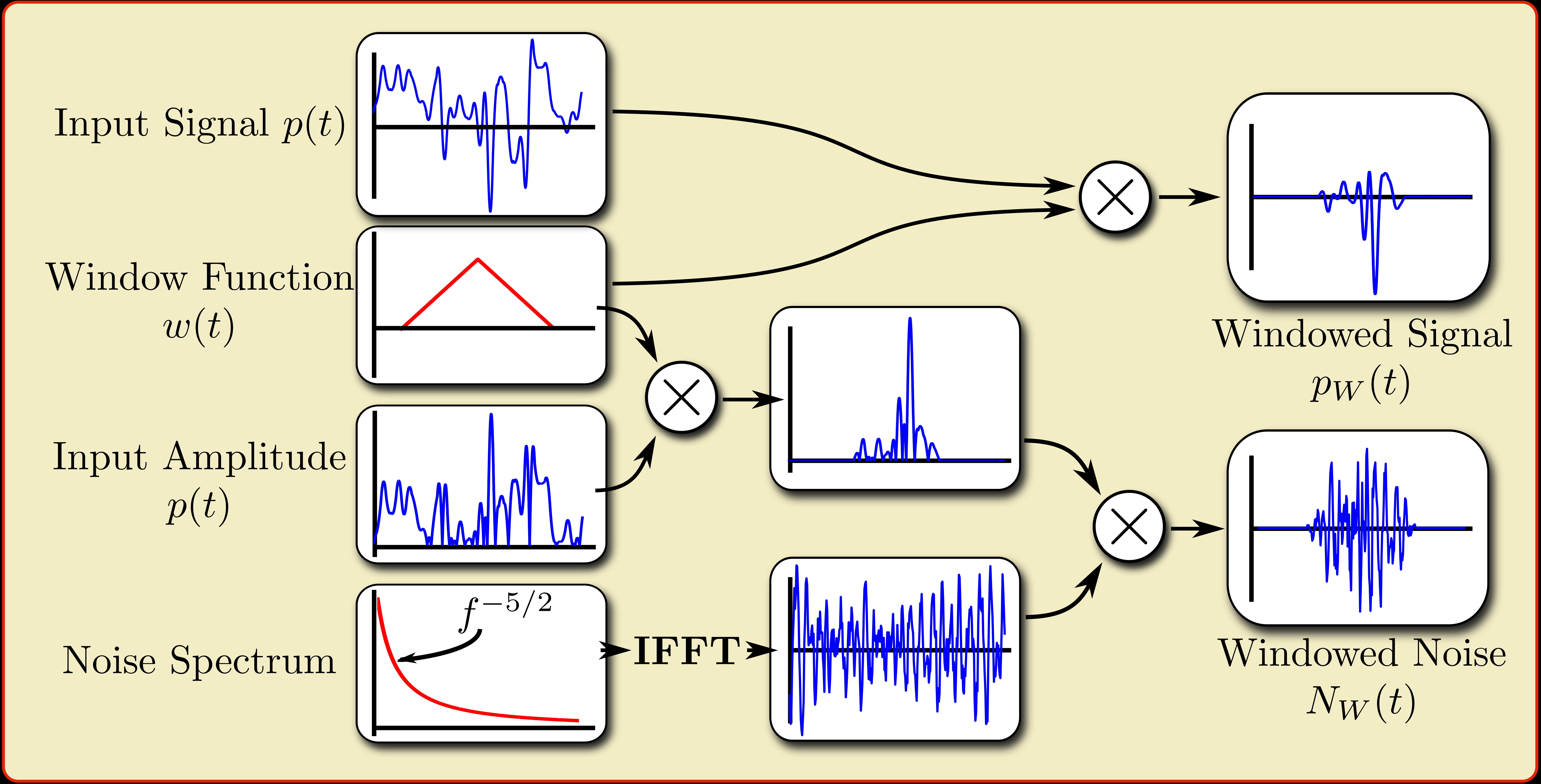
+

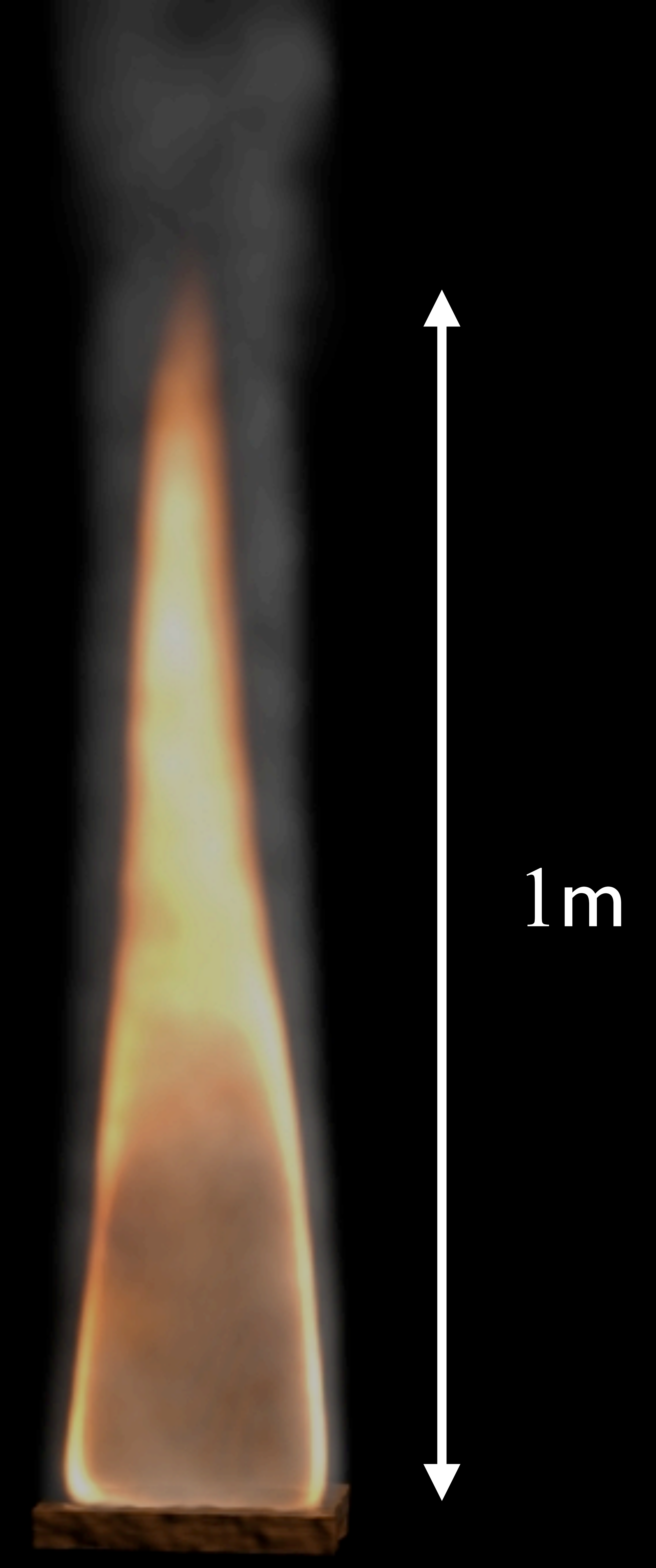


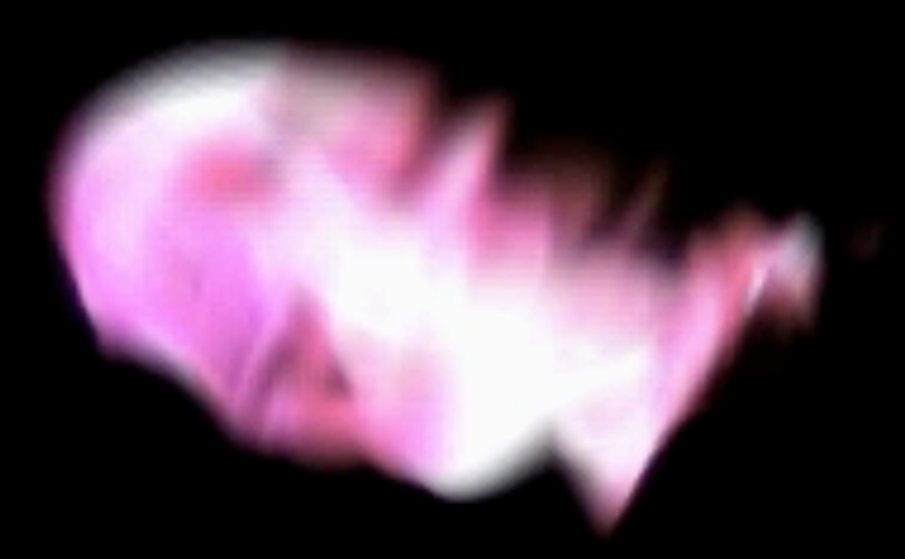
Synthetic high-frequency content

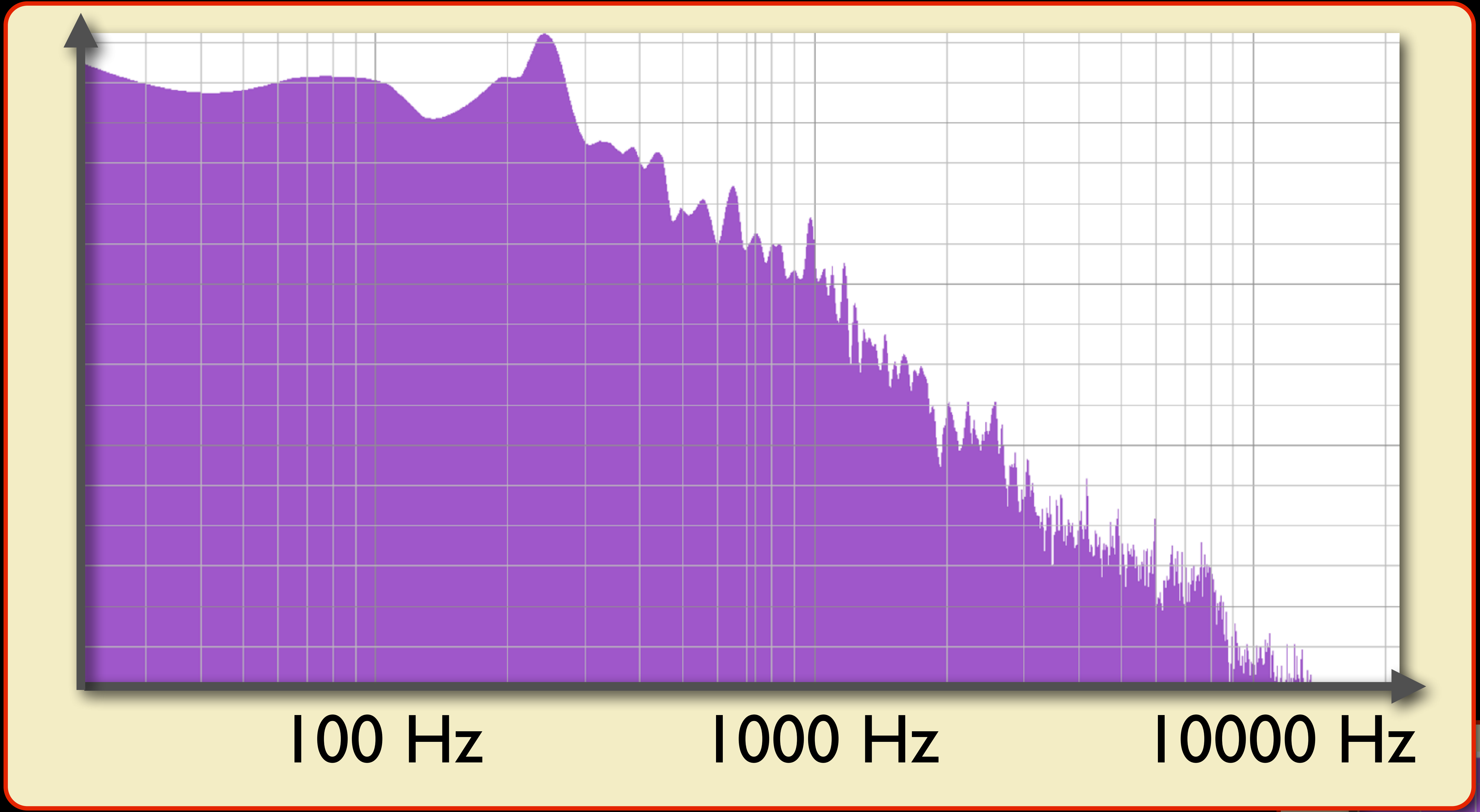
Bandwidth Extension

Results



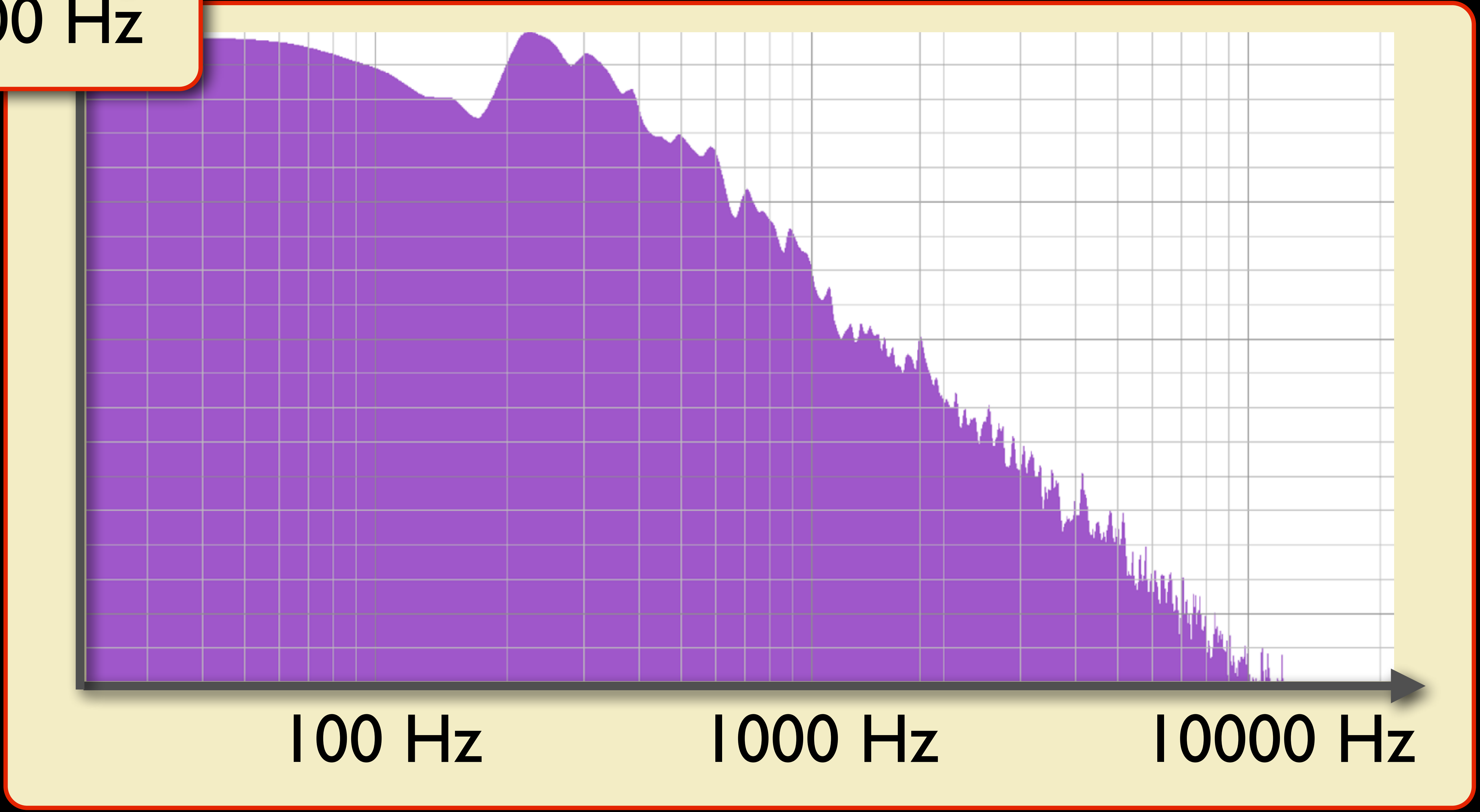

1m





Real spectrum

Synthesized spectrum



Sound Texture Synthesis

Motivation

- Noise-based bandwidth extension introduces higher frequencies
  - Missing temporal structure present in real flame sounds
  - No “style control”
- **Idea:** Using low-frequency results as a guide, introduce high-frequency detail based on recorded flame sounds

Sound Texture Synthesis

Introduction

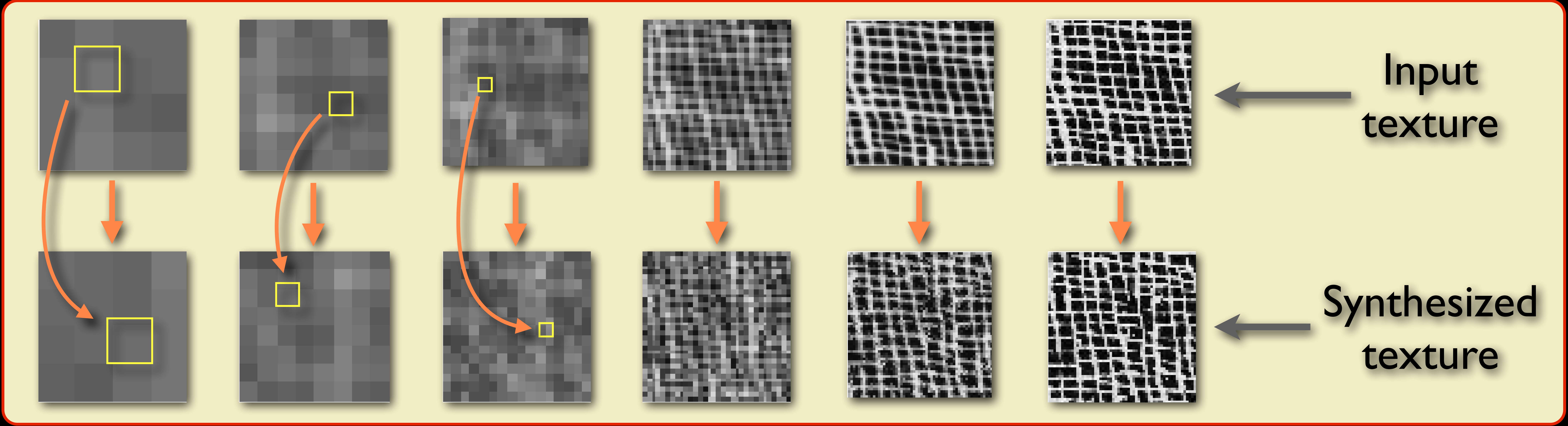
- Related work for image textures; [Heeger and Bergen 1995; Efros and Leung 1999; Wei and Levoy 2000; Efros and Freeman 2001] (and many others)

- Sound texture synthesis: [Dubnov et al. 2002; Strobl et al. 2006; McDermott et al 2009; Marelli et al. 2010]

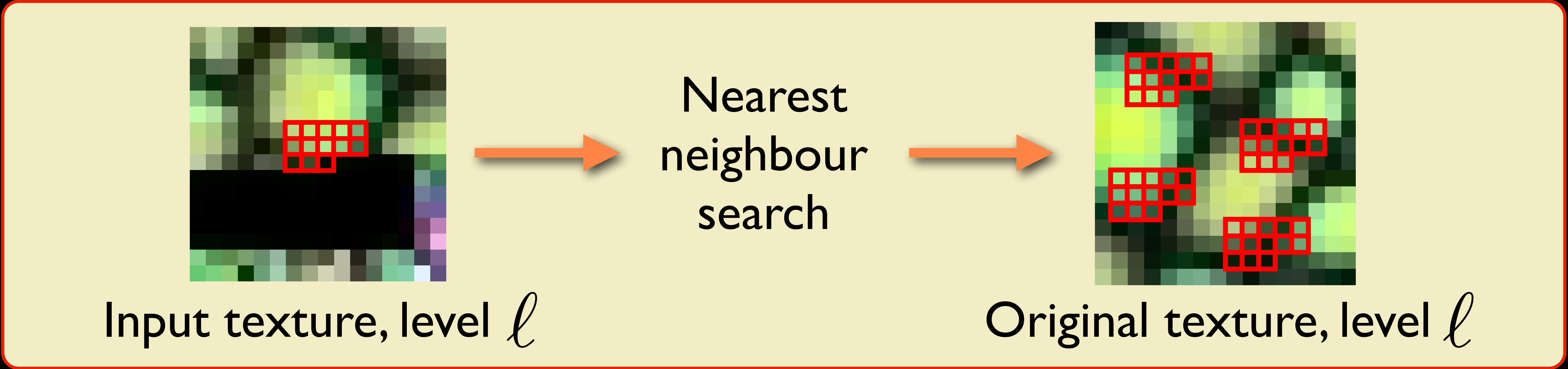
- We use image texture synthesis techniques of [Wei and Levoy 2000]

Texture Synthesis Basics

[Wei and Levoy 2000]



Images from [Wei 1999]

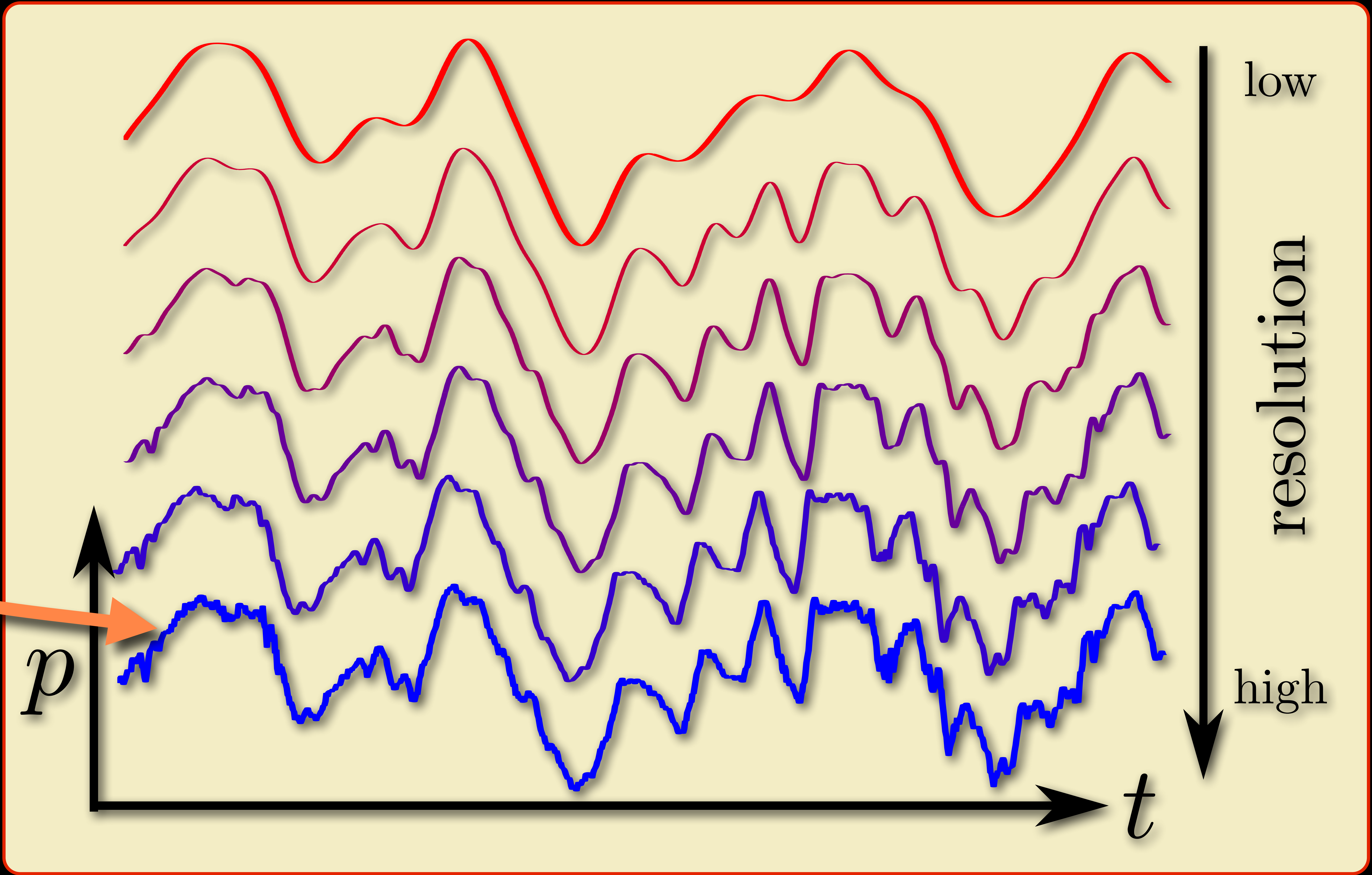


Images from [Wei and Levoy 2000]

Sound Texture Synthesis

Feature Training

Training sound (eg. recorded flame sound)

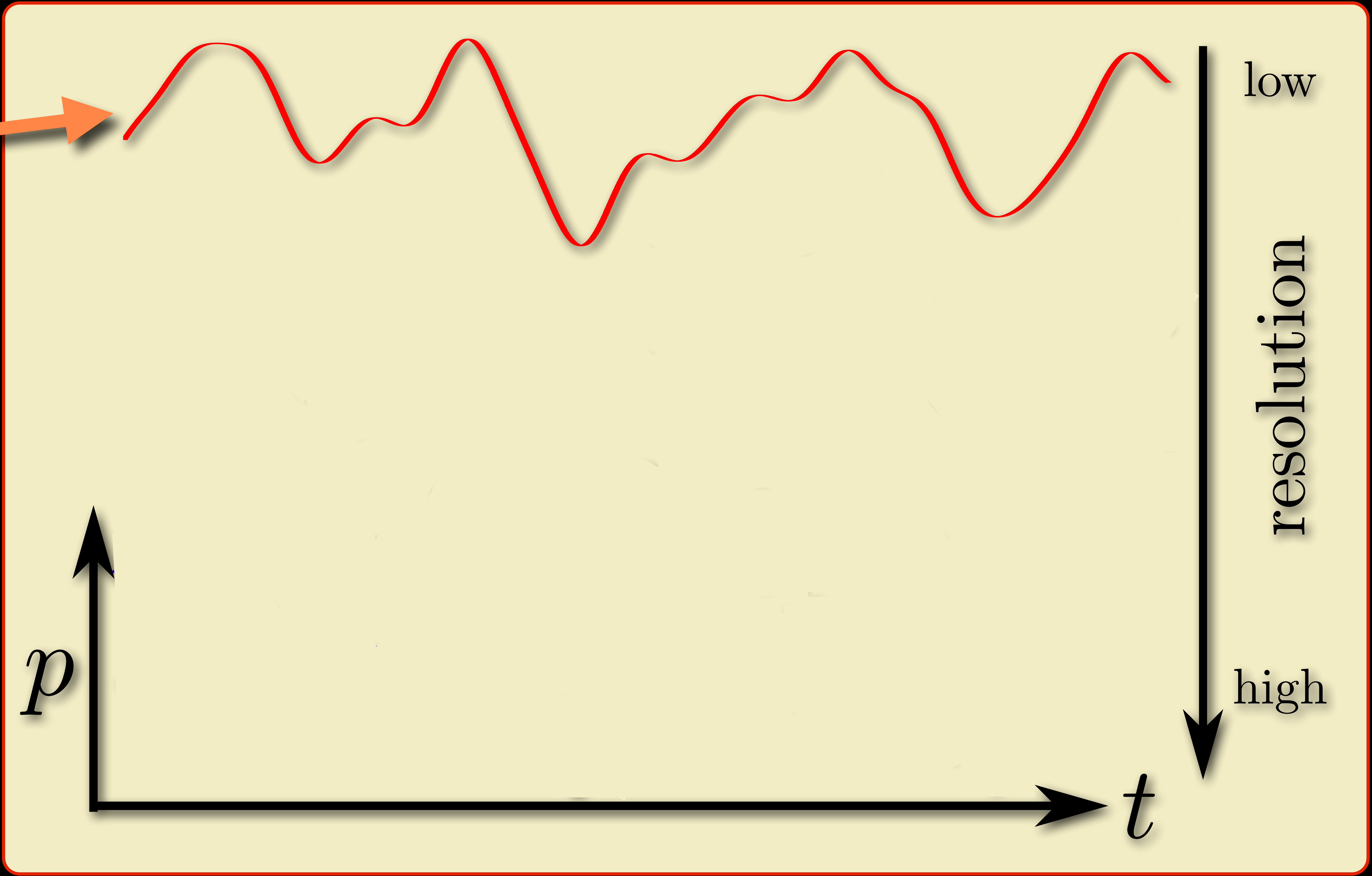


1D Gaussian pyramid

Sound Texture Synthesis

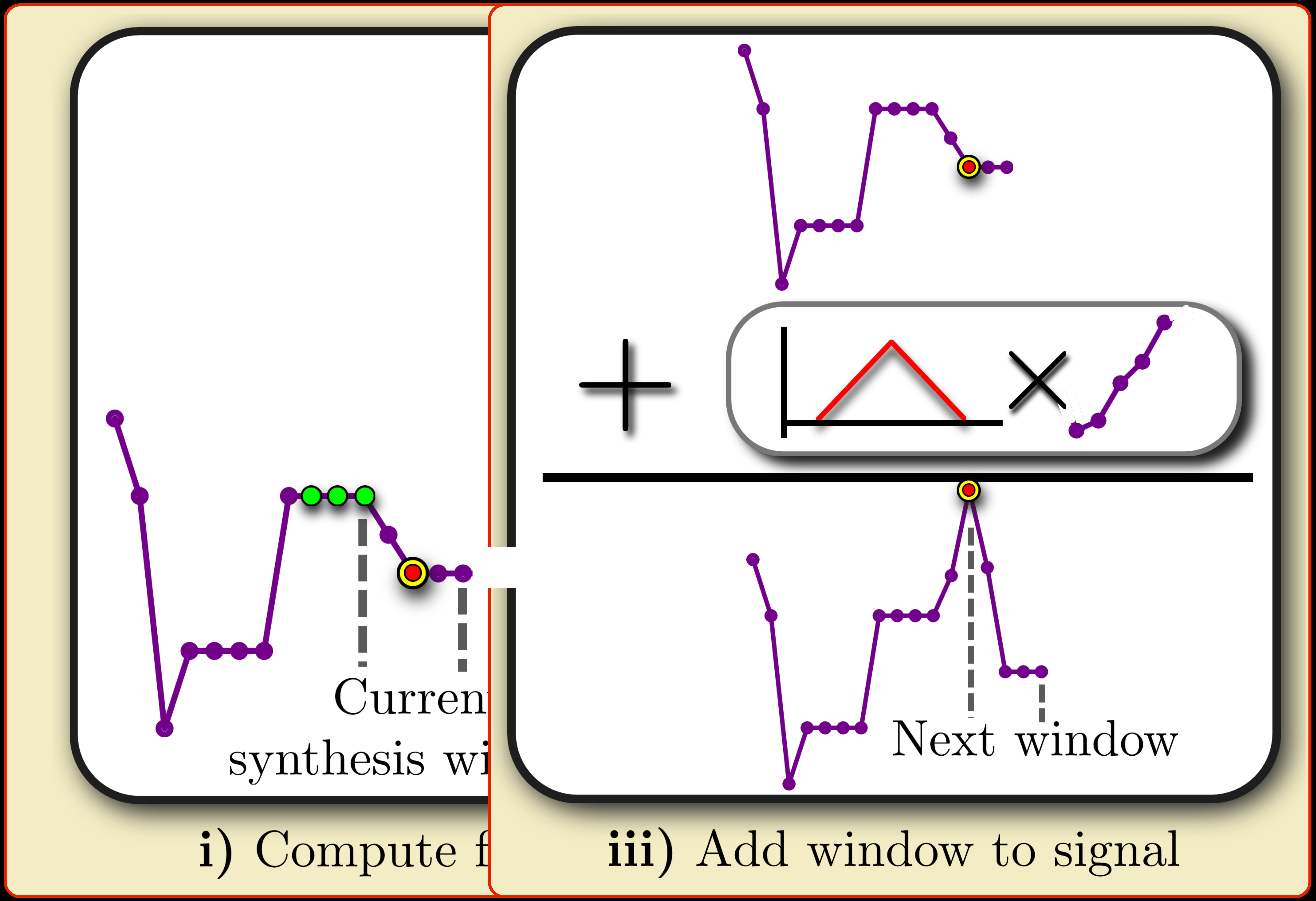
Low to High Frequency Synthesis

Physically based low frequency sound



1D Gaussian pyramid

Sound Texture Synthesis: Signal Synthesis



Style Control

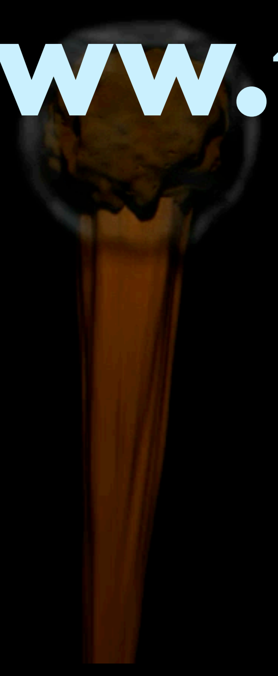
Torch

Torch length: 70cm

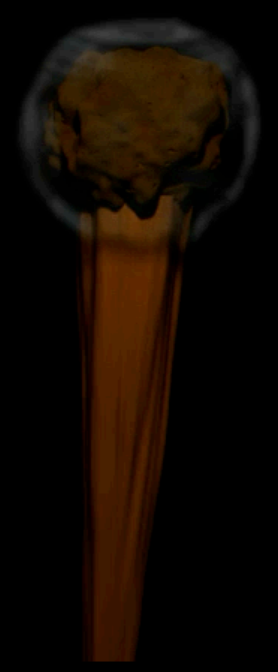
Simulated with: Houdini fire solver (blue core model with detonation shock dynamics [Nguyen et al. 2002; Hong et al. 2007])

Training clips taken from *Ultimate Fire* sound library

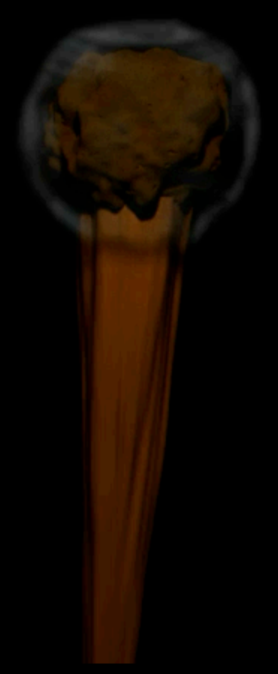
http://www.therecordist.com



Training clip #1



Training clip #2



Training clip #3

Sound Texture Synthesis
Results

Dragon

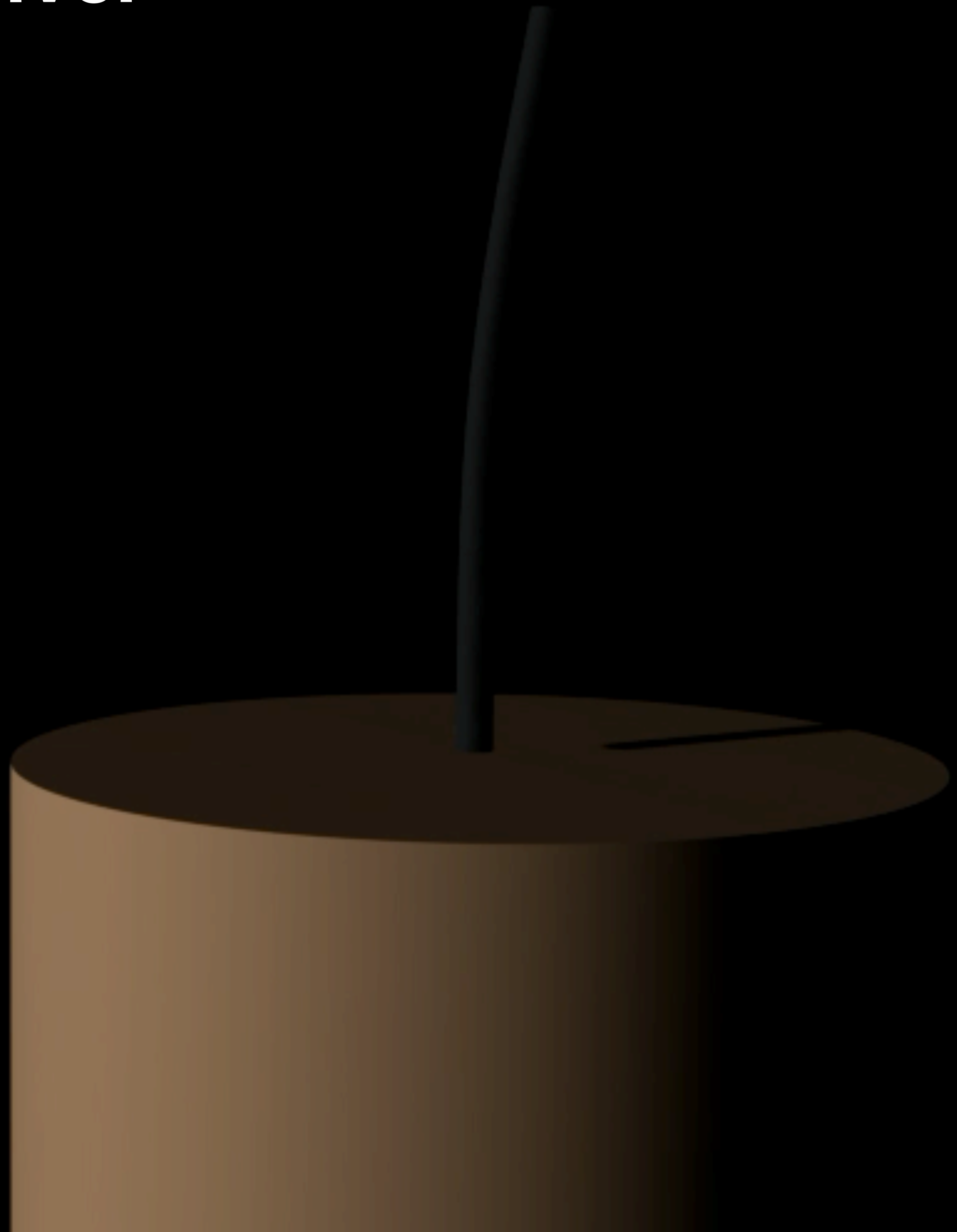
Dragon height: 1.15m

Simulated with: Houdini *Pyro FX* solver

Candle

Wick height: 4cm

Simulated with: Houdini *Pyro FX* solver



Burning Brick

Brick width: 20cm

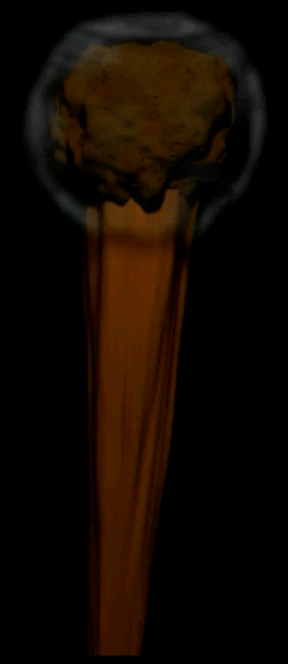
Simulated with: Houdini *Pyro FX* solver

Flame Jet

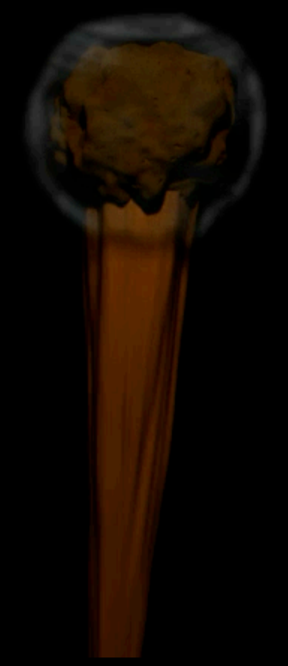
Domain size: 1.5m x 1.4m x 0.7m

Simulated with: Houdini *Pyro FX* solver

Physically based low-frequency sound



Bandwidth extension



Sound texture synthesis

Limitations and Future Work

- Spatialization
- Hybrid synthesis of other phenomena
  - Low-frequency physics-based model w/ high-frequency detail synthesis
- Integrating physically based model with fast, parallel hardware

Acknowledgements

Webpage **(with code)** http://www.cs.cornell.edu/~chadwick/fire

Renderer Side Effects Software's *Mantra*

Support

Side Effects Software (for *Houdini* 3D animation tools and *Mantra* renderer)
The National Science Foundation (HCC-0905506)
The Natural Sciences and Engineering Research Council of Canada
The Alfred P. Sloan Foundation
The John Simon Guggenheim Memorial Foundation
Intel (Intel Science and Technology Center for Visual Computing)
Pixar
Autodesk
Vision Research

Simulation/Timing data

Simulation times: ~2-3 hours
Iso-surface construction times: ~10s per time step

Scene	Domain size (m)	Domain resolution (voxels)	Animation length (s)	Bandwidth extension time (s)	Sound texture synthesis time (s)
Burning brick	2.0x1.7x0.9	180x151x78	5	64	20
Candle	0.15x0.15x0.12	115x120x96	6	151	86
Dragon	4.1x2.9x2.1	200x142x102	9	223	56
Flame jet	1.5x1.4x0.69	140x134x65	10	256	54
Torch	1.5x1.4x1.8	104x100x128	5	63	41