Architectural Acoustics

7LS8M0

Room Acoustics

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Introduction
Room Acoustics

"Acoustics: An Introduction", Kuttruff (Taylor and Francis, 2007)

Detailed information:

Sound in closed spaces	Chapter 9
Room acoustics	Chapter 13

Introduction

'Room Acoustics' in closed spaces

Small rooms ⟷ Large rooms/halls

Small rooms	Large rooms/halls
Listening rooms	Concert halls
Sound studios	Theaters
Recording studios	Auditoriums
Audiometry rooms	Lecture halls

Introduction

'Room Acoustics' in closed spaces

Small rooms	⟷	Large rooms/halls
Listening rooms		Concert halls
Sound studios		Theaters
Recording studios		Auditoriums
Audiometry rooms		Lecture halls

Introduction

'Room Acoustics' in closed spaces

- Music transfer
- Speech transfer
- Sound assessment
- Measurements

Introduction

'Room Acoustics' in closed spaces

Small rooms ⟷ Large rooms/halls

'Large room condition':

$$f > f_s = 2000\sqrt{\frac{T}{V}}$$

(f_s = Schroeder frequency)

$V = 25\ m^3$
$T = 1\ s$
$f_s = 400\ Hz$

$V = 13000\ m^3$
$T = 2\ s$
$f_s = 25\ Hz$

Introduction

'Room Acoustics' in small rooms

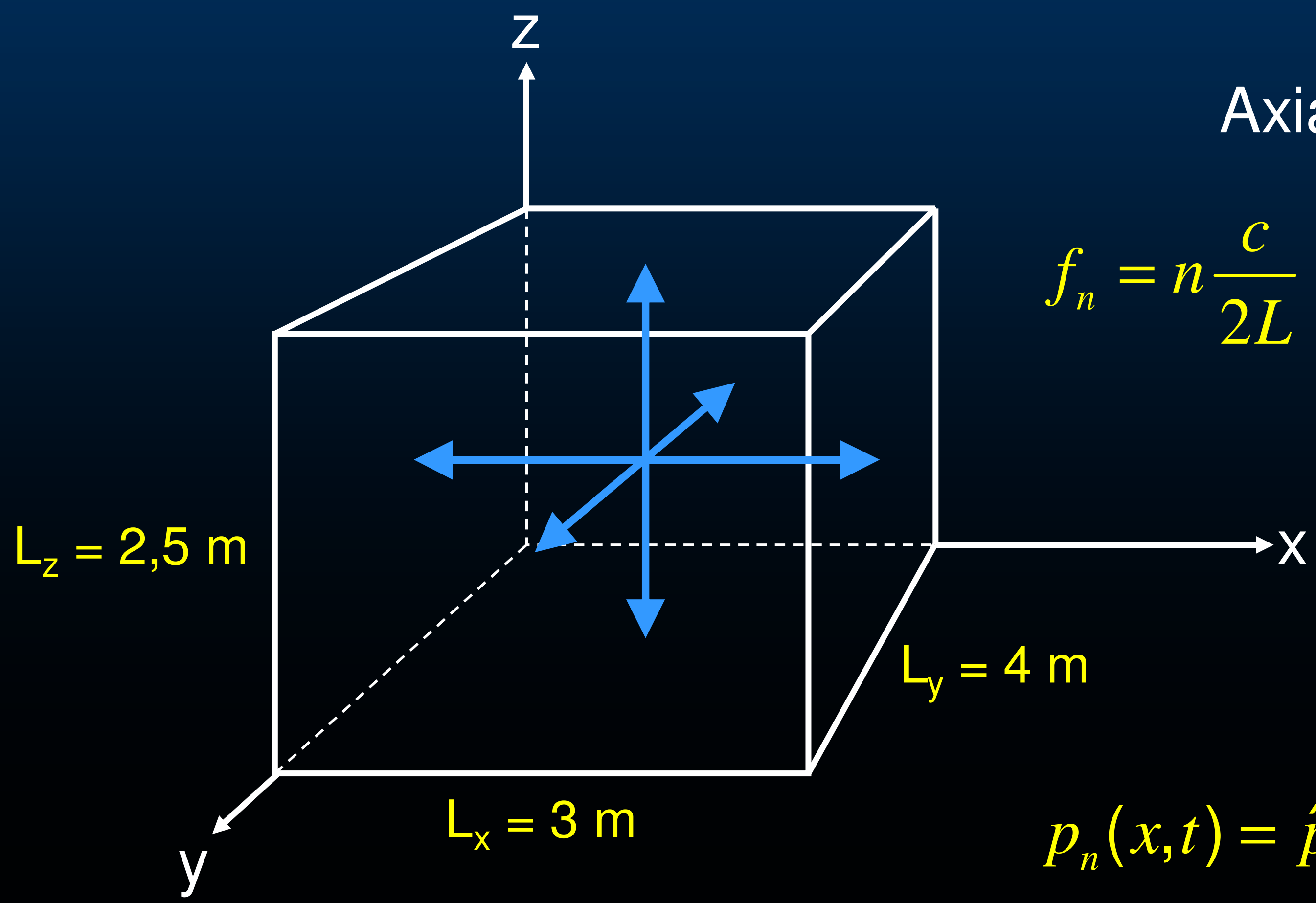
$V = 3 \times 4 \times 2{,}5 = 25\ m^3$

$T = 1\ s$

$f_s = 400\ Hz$

‘Small’ Rooms

Normal modes in small (rectangular) rooms



Axial modes:

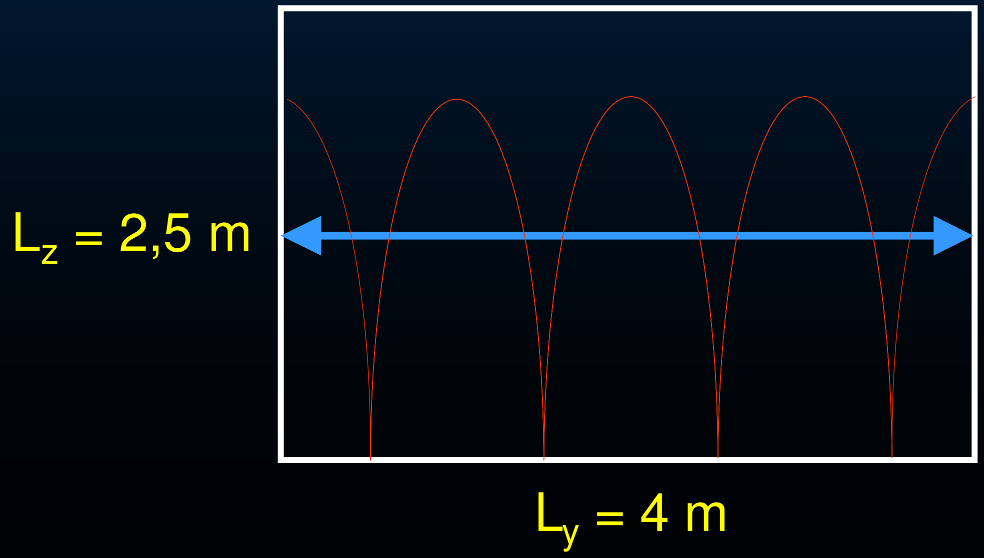
$$f_n = n\frac{c}{2L} \qquad (n = 0, 1, 2, \ldots)$$

$$p_n(x,t) = \hat{p}\cos\left(\frac{n\pi x}{L}\right)e^{j\omega_n t}$$

‘Small’ Rooms

Normal modes in small (rectangular) rooms

Axial mode:



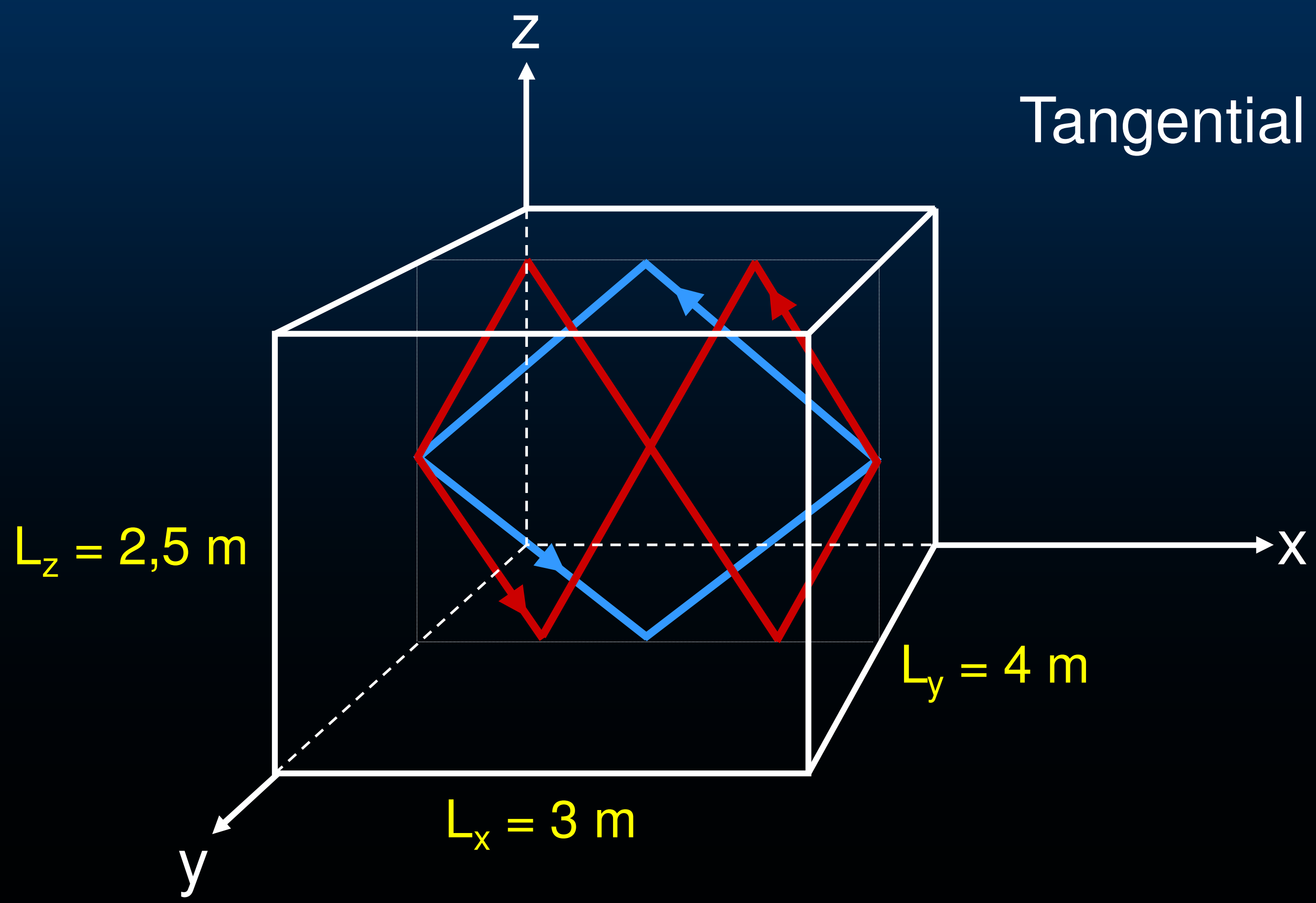
$$f_4 = 4\frac{c}{2L} \quad (m = 4)$$

$$p_4(y,t) = \hat{p}\cos\left(\frac{4\pi y}{L}\right)e^{j\omega_4 t}$$

‘Small’ Rooms

Normal modes in small (rectangular) rooms

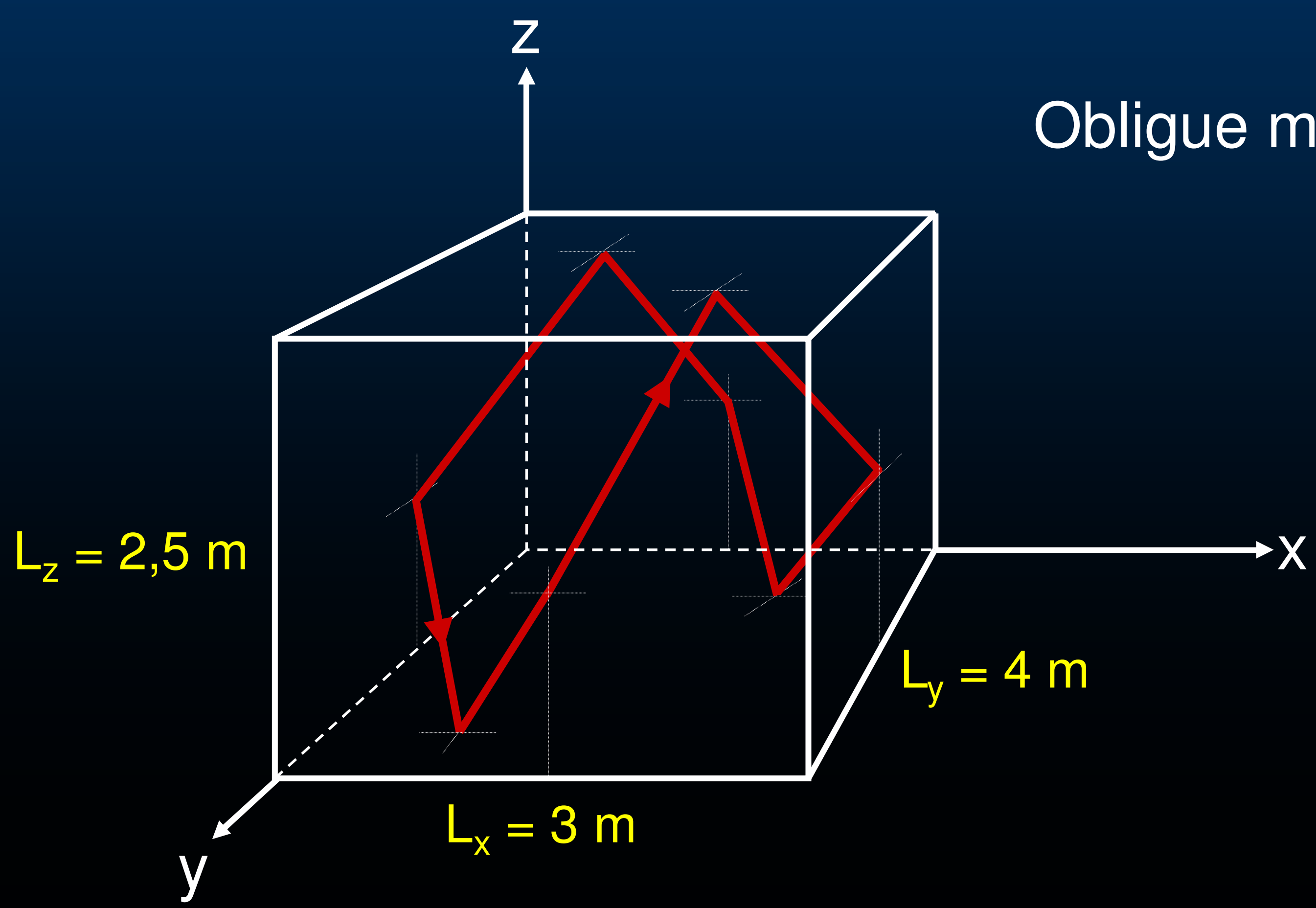
Tangential modes:



‘Small’ Rooms

Normal modes in small (rectangular) rooms

Oblique mode(s):

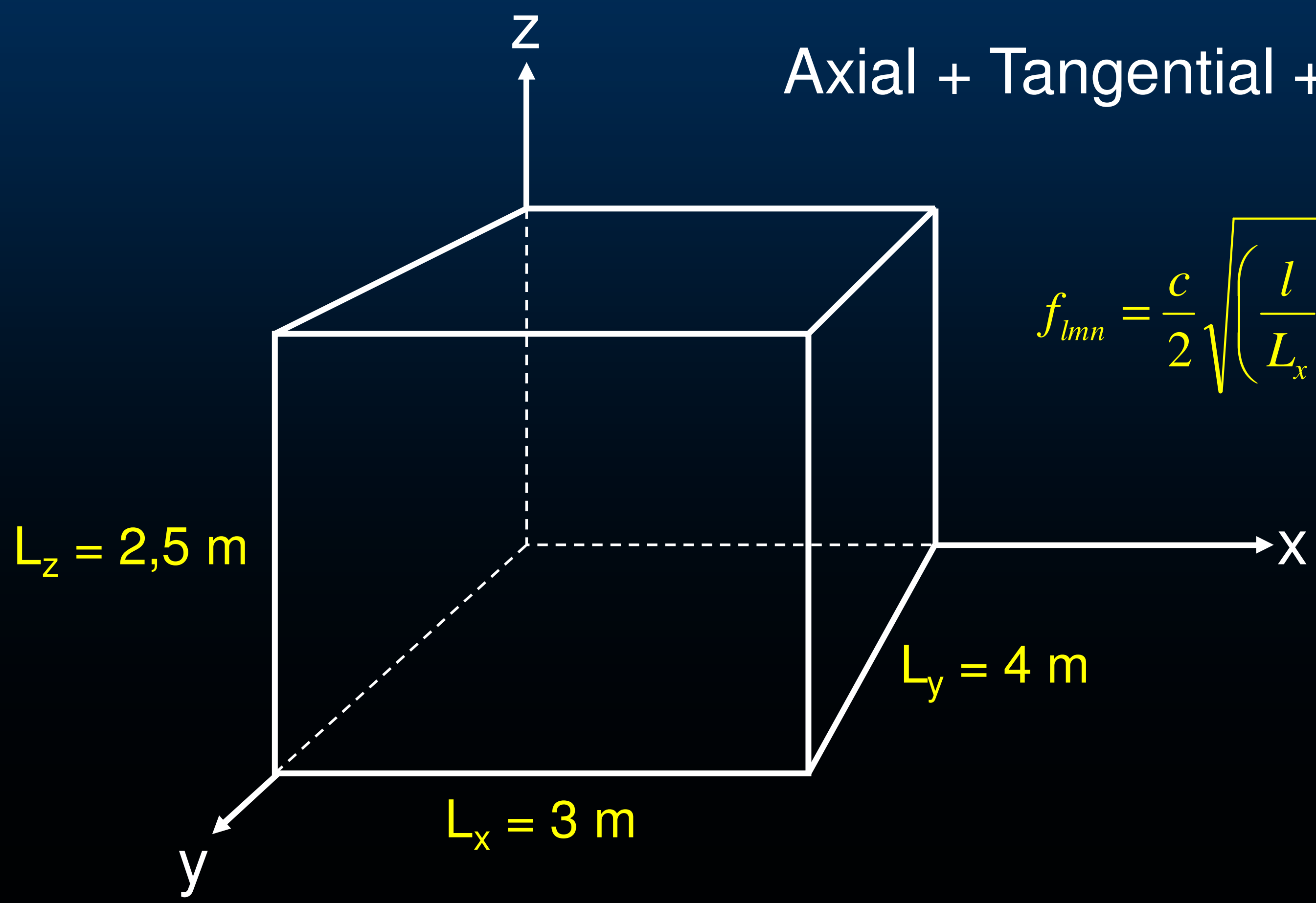


'Small' Rooms

Normal modes in small (rectangular) rooms

Axial + Tangential + Oblique:

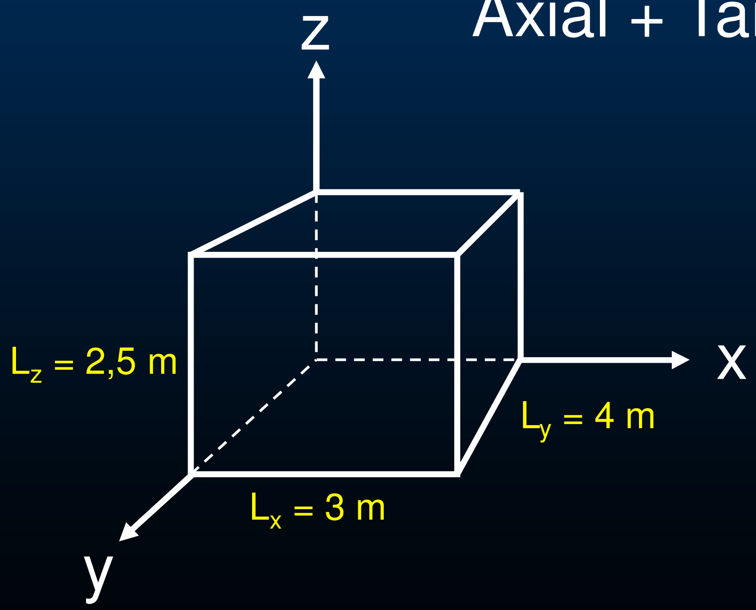
$$f_{lmn} = \frac{c}{2}\sqrt{\left(\frac{l}{L_x}\right)^2 + \left(\frac{m}{L_y}\right)^2 + \left(\frac{n}{L_z}\right)^2}$$



‘Small’ Rooms

Normal modes in small (rectangular) rooms

Axial + Tangential + Obligue:



$$f_{lmn} = \frac{c}{2}\sqrt{\left(\frac{l}{L_x}\right)^2 + \left(\frac{m}{L_y}\right)^2 + \left(\frac{n}{L_z}\right)^2}$$

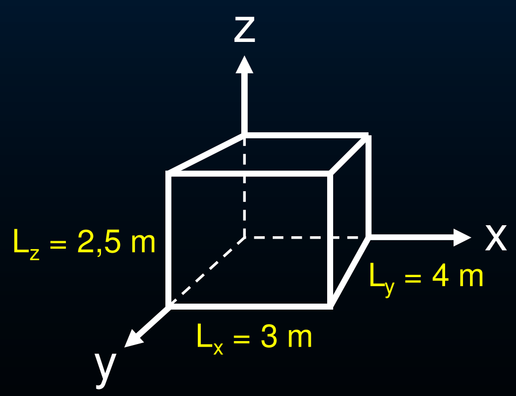
$$p_{lmn}(x, y, z, t) = \hat{p}\cos\left(\frac{l\pi x}{L_x}\right)^2 \cos\left(\frac{m\pi y}{L_y}\right)^2 \cos\left(\frac{n\pi z}{L_z}\right)^2 \cdot e^{j\omega_{lmn}t}$$

‘Small’ Rooms

Normal modes in small (rectangular) rooms

Axial + Tangential + Obligue:

http://amroc.andymel.eu/



1	42.9	0-1-0	ax	11	114.3	2-0-0	ax
2	57.2	1-0-0	ax	12	122.1	2-1-0	tan
3	68.6	0-0-1	ax	13	123.8	1-2-1	obl
4	71.5	1-1-0	tan	14	128.6	0-3-0	ax
5	80.9	0-1-1	tan	15	133.3	2-0-1	tan
6	85.8	0-2-0	ax	16	137.2	0-0-2	ax
7	89.3	1-0-1	tan	17	140.1	2-1-1	obl
8	99.1	1-1-1	obl	18	140.8	1-3-0	tan
9	103.1	1-2-0	tan	19	142.9	2-2-0	tan
10	109.8	0-2-1	tan	20	143.7	0-1-2	tan

'Small' Rooms
Literature

Bolt	(1946)	1 : 1.25 : 1.6
Louden	(1971)	1 : 1.4 : 1.9
Gilford	(1979)	stronger weighting axial modes
Bonello	(1981)	increasing number of modes over 1/3 octave bands
Walker	(1996)	$1.1L_y \le \frac{L_x}{L_z} \le \frac{4.5L_y}{L_z} - 4$

$$L_x < 3L_z$$

$$L_y < 3L_z$$

Cox and D'Antonio (2000) flattest possible modal frequency response

‘Small’ Rooms
Literature

[1] R.H.Bolt. Note on the normal frequency statistics in rectangular rooms. J.Acoust.Soc.Am. 18(1) 130-133. (1946).

[2] M M Louden. Dimension ratios of rectangular rooms with good Distribution of eigentones. Acustica. 24. 101-104 (1971).

[3] C.L.S.Gilford. The acoustic design of talk studios and listening rooms. J.Audio.Eng.Soc. 27. 17-31. (1979).

[4] O. J. Bonello. A New Criterion for the Distribution of Normal Room Modes. JAES Volume 29 Issue 9 pp. 597-606; (1981).

[5] R. Walker. Optimum Dimension Ratios for Small Rooms. Preprint 4191. 100th Convention of the AES. (5/1996).

[6] Trevor J Cox and Peter D'Antonio. Determining Optimum Room Dimensionsfor Critical Listening Environments: A New Methodology. Proc 110th Convention AES. paper 5353 (2000)

Acoustics Design

Dimension: volume

hall function
- concert hall
- cinema
- etc.

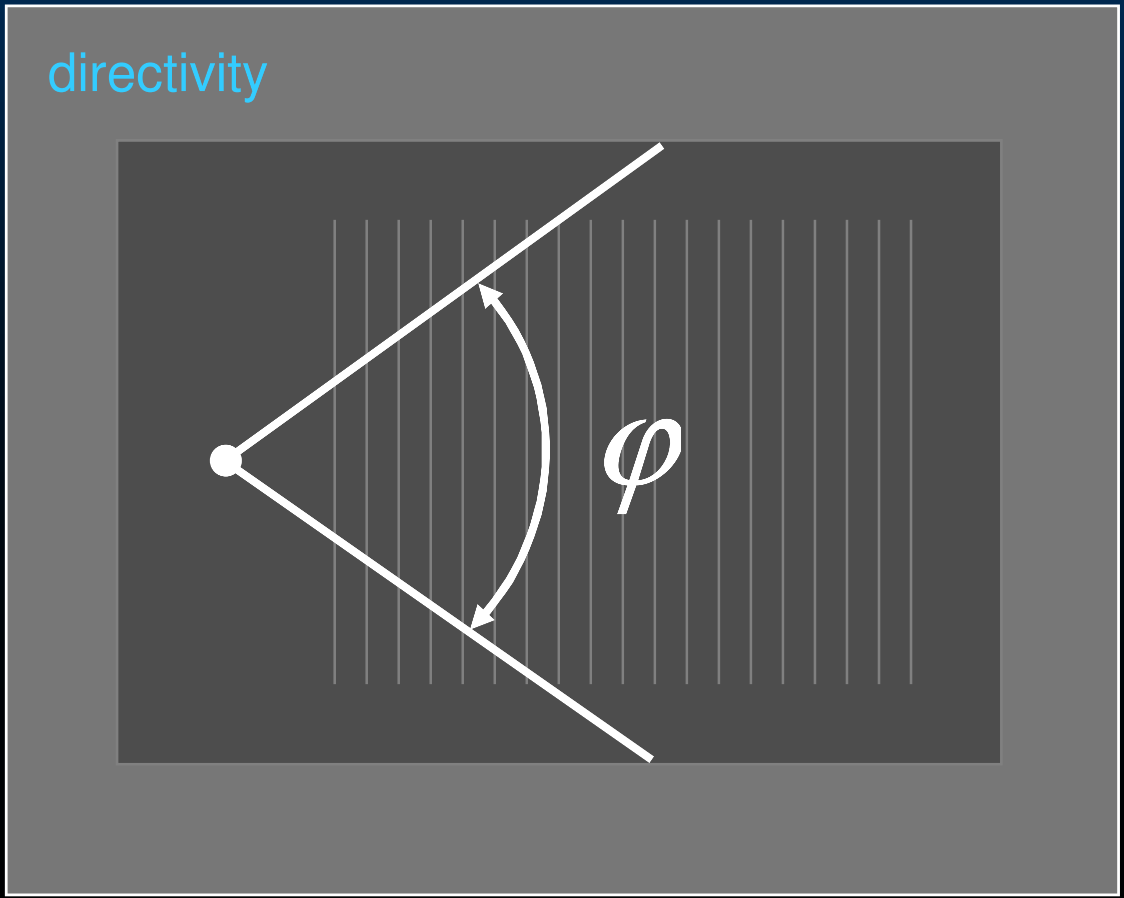
m^3/pp

# of persons

volume

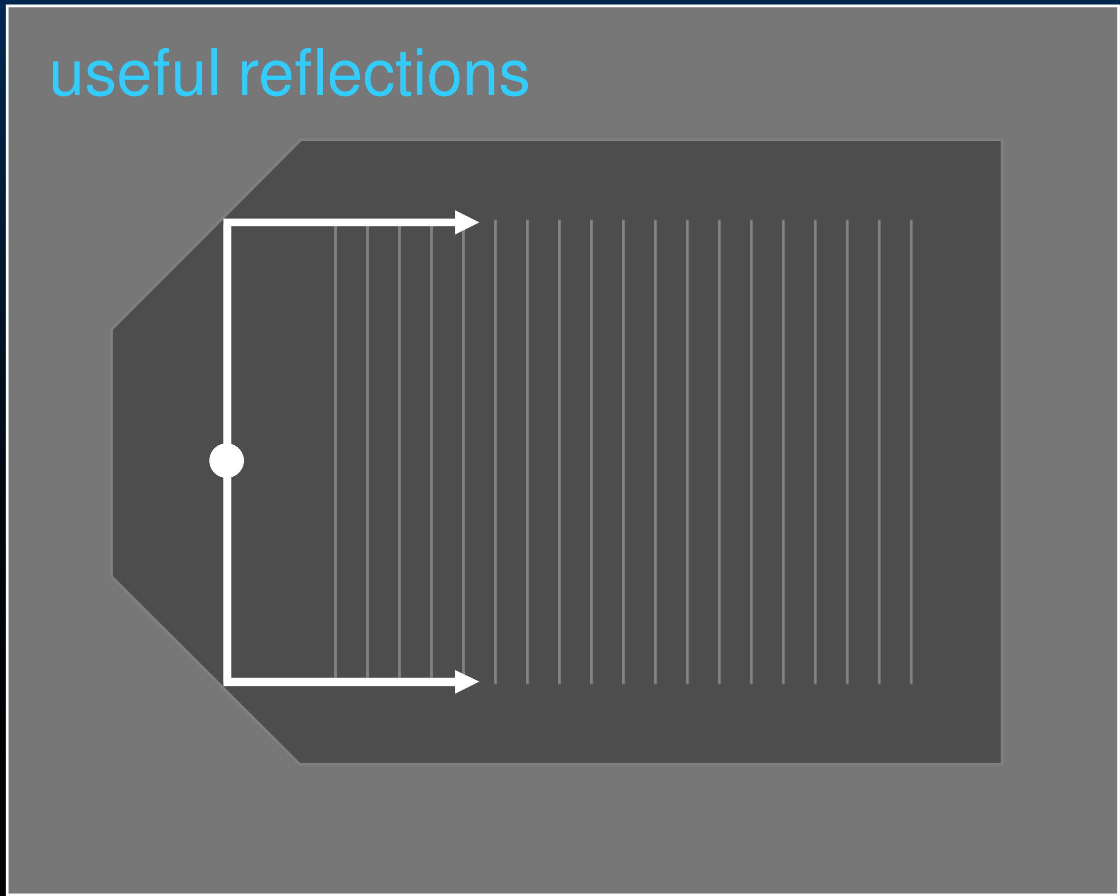
Acoustics Design

Shape/dimensions

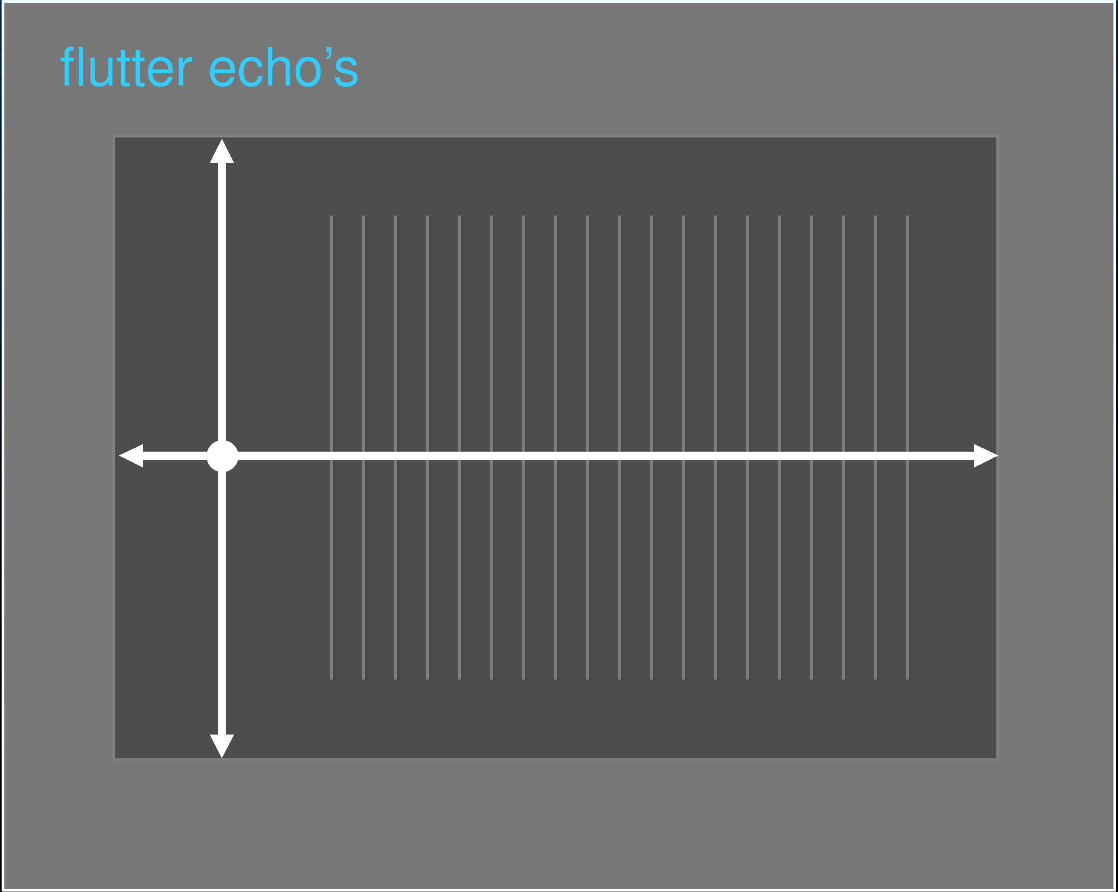


Acoustics Design

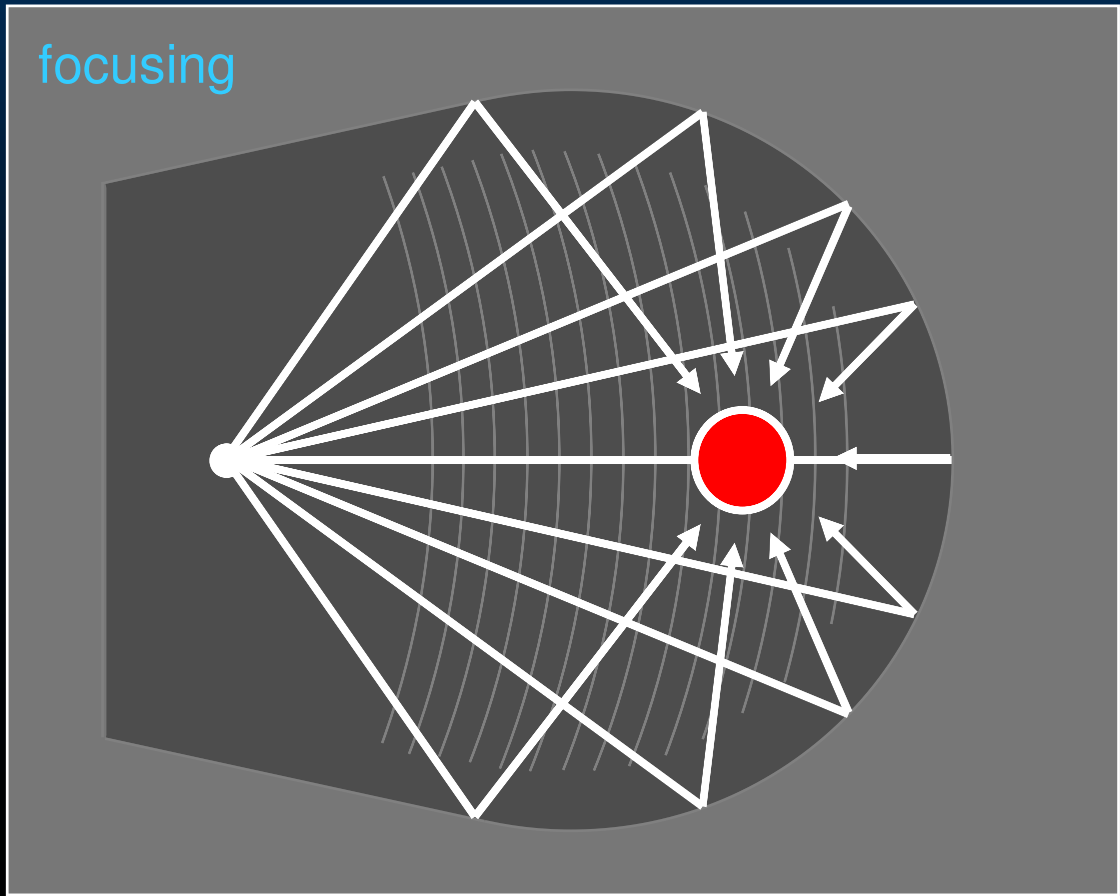
Shape/dimensions



Acoustics Design
Shape/dimensions

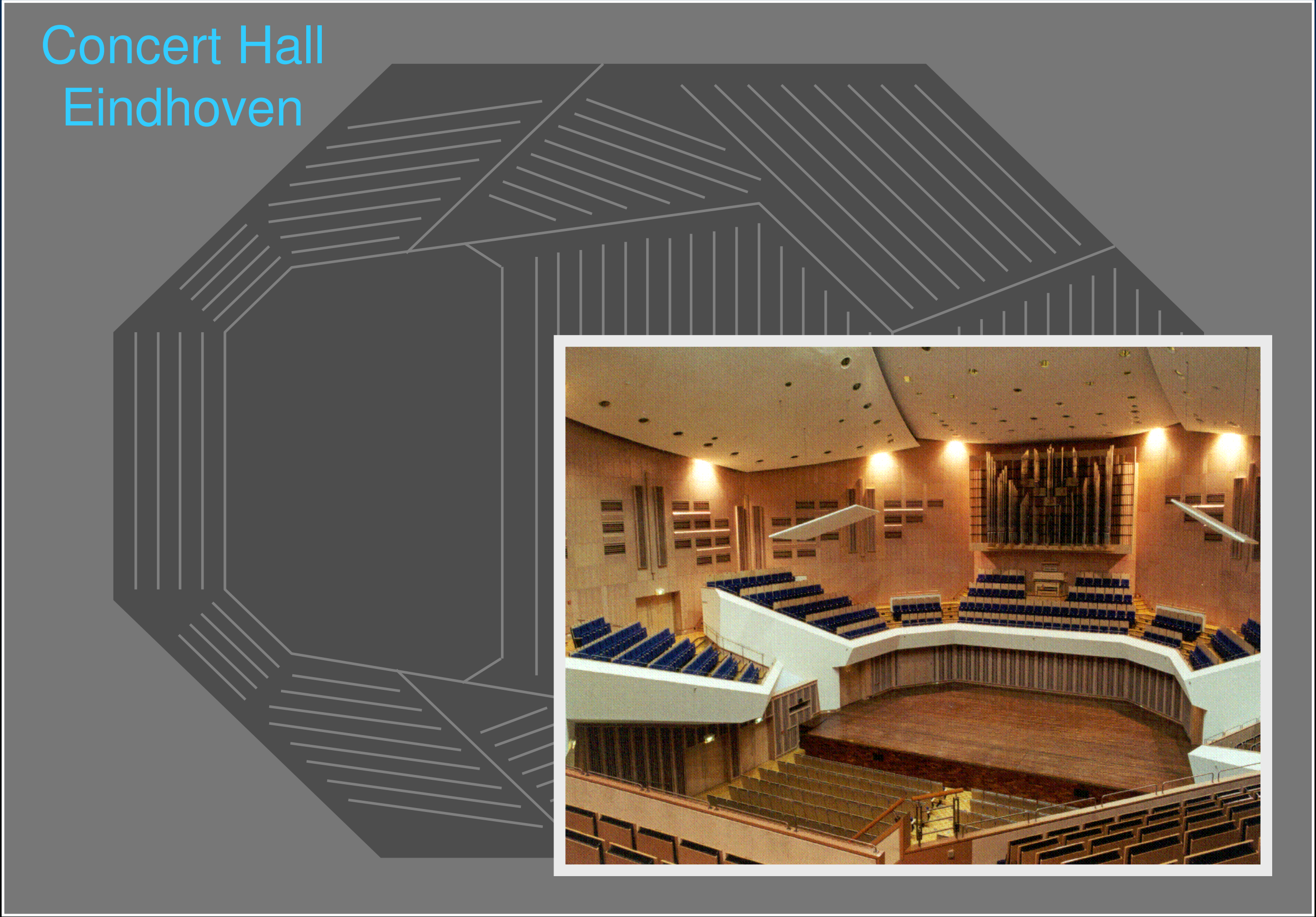


Acoustics Design
Shape/dimensions



Acoustics Design

Shape/dimensions



Acoustics Design

Direct sound field: theoretical free field

$$I_{dir} = \frac{p_{eff}^2}{\rho c} \qquad \mathbf{W} = \frac{\mathbf{p}_{\mathbf{eff}}^2}{\rho \mathbf{c}} \cdot 4\pi \mathbf{r}^2$$

$$\mathbf{L_p = 10 \cdot lg\left(\frac{p_{eff}^2}{p_0^2}\right) = 10 \cdot lg\left(\frac{W\rho c}{p_0^2 4\pi r^2}\right)}$$

$$\mathbf{L_p = 10 \cdot lg\left(\frac{W}{W_0}\right) + 10 \cdot lg\left(\frac{1}{4\pi r^2}\right) + \underbrace{10 \cdot lg\left(\frac{W_0 \rho c}{p_0^2}\right)}_{\approx 10 \cdot lg(1) = 0}}$$

$$\boxed{L_p = L_w + 10 \cdot \lg\left(\frac{1}{4\pi r^2}\right)} \quad [\mathrm{dB}]$$

Intermezzo

Acoustics Design

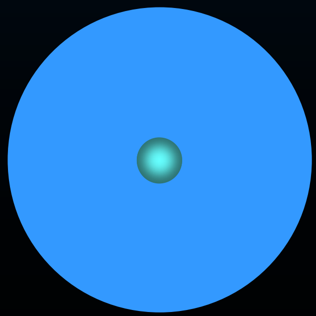
Shape (intermezzo)

$$L_p = L_w + 10 \cdot \lg\left(\frac{Q}{4\pi r^2}\right)$$

Q = directivity factor

sound source in free field:

- 1/1 sphere
- Q = 1
- + 0 dB



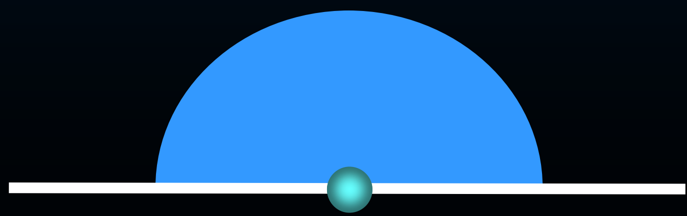
Acoustics Design
Shape (intermezzo)

$$L_p = L_w + 10 \cdot \lg\left(\frac{Q}{4\pi r^2}\right)$$

Q = directivity factor

<u>sound source on hard surface:</u>

- 1/2 sphere
- Q = 2
- + 3 dB



Intermezzo

Acoustics Design

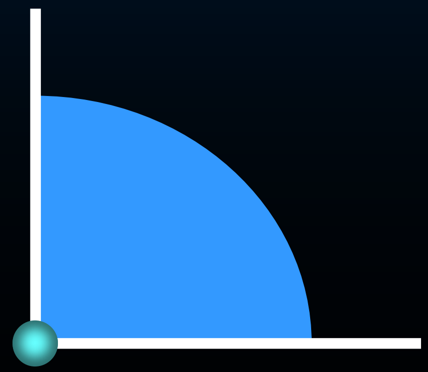
Shape (intermezzo)

$$L_p = L_w + 10 \cdot \lg\left(\frac{Q}{4\pi r^2}\right)$$

Q = directivity factor

<u>sound source in 2 surface corner:</u>

- 1/4 sphere
- Q = 4
- + 6 dB



Intermezzo

Acoustics Design

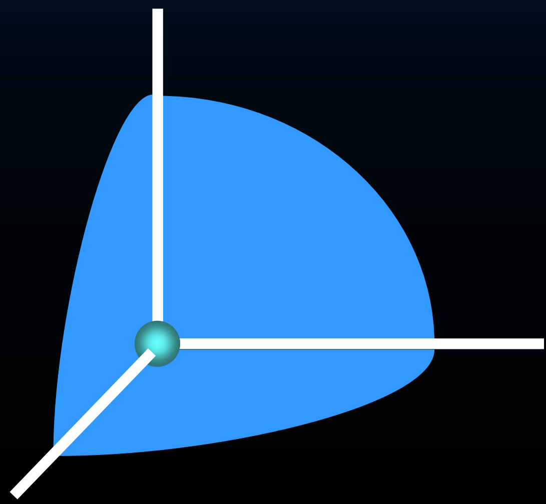
Shape (intermezzo)

$$L_p = L_w + 10 \cdot \lg\left(\frac{Q}{4\pi r^2}\right)$$

Q = directivity factor

<u>sound source in 3 surface corner:</u>

- 1/8 sphere
- Q = 8
- + 9 dB



Acoustics Design

Shape (intermezzo)

$$Q = Q_s \cdot Q_r$$

$$L_p = L_w + 10 \cdot \lg\left(\frac{Q_s \cdot Q_r}{4\pi r^2}\right)$$

$$Q \quad \textit{directivity factor}\ [-]$$

$$q = 10\lg Q \quad \textit{directivity index}\ [dB]$$

Sound Field

Diffuse sound field: theoretical reverberant field

$$I = \frac{p_{eff}^2}{4\rho c} \qquad W = I \cdot A \qquad W = \frac{p_{eff}^2}{4\rho c} \cdot A$$

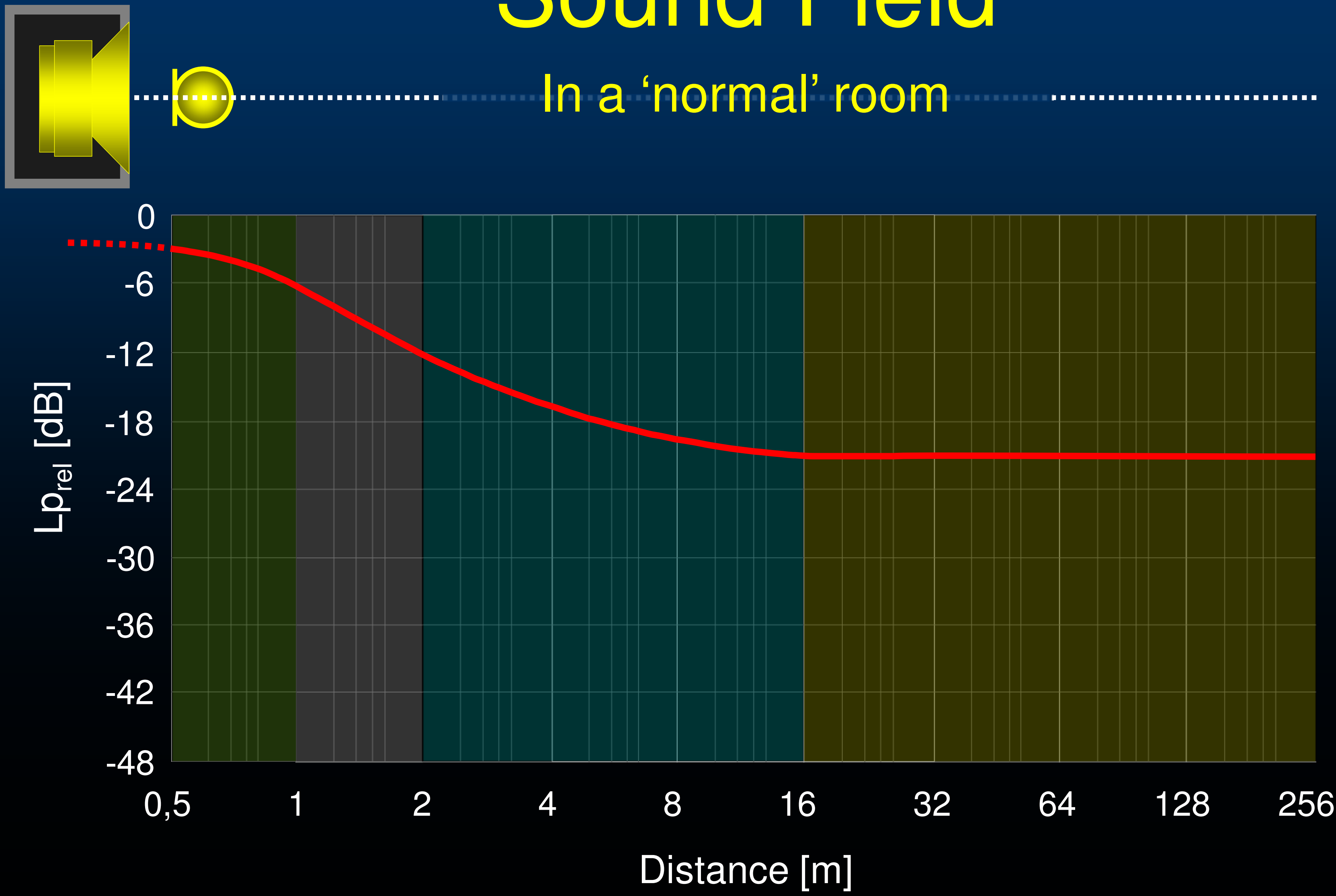
$$L_p = 10 \cdot \lg\left(\frac{p_{eff}^2}{p_0^2}\right) = 10 \cdot \lg\left(\frac{W \cdot 4 \cdot \rho \cdot c}{A \cdot 4 \cdot p_0^2}\right)$$

$$L_p = 10 \cdot \lg\left(\frac{W}{W_0}\right) + 10 \cdot \lg\left(\frac{W_0 \cdot 4 \cdot \rho \cdot c}{A \cdot 4 \cdot 10^{-10}}\right)$$

$$\boxed{L_p = L_w + 10 \cdot \lg\left(\frac{4}{A}\right)} \quad [\mathrm{dB}]$$

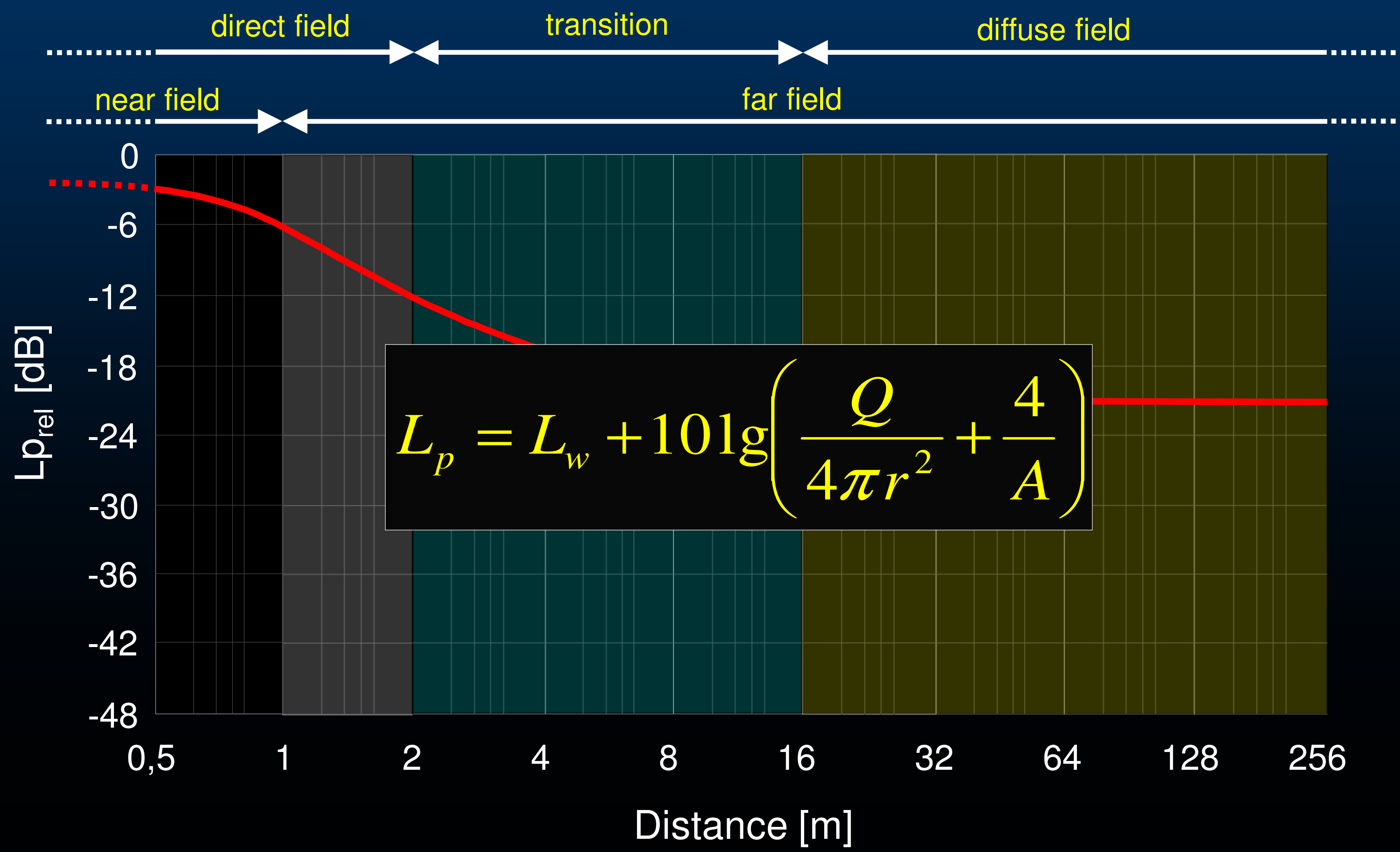
Sound Field

In a ‘normal’ room



Intermezzo

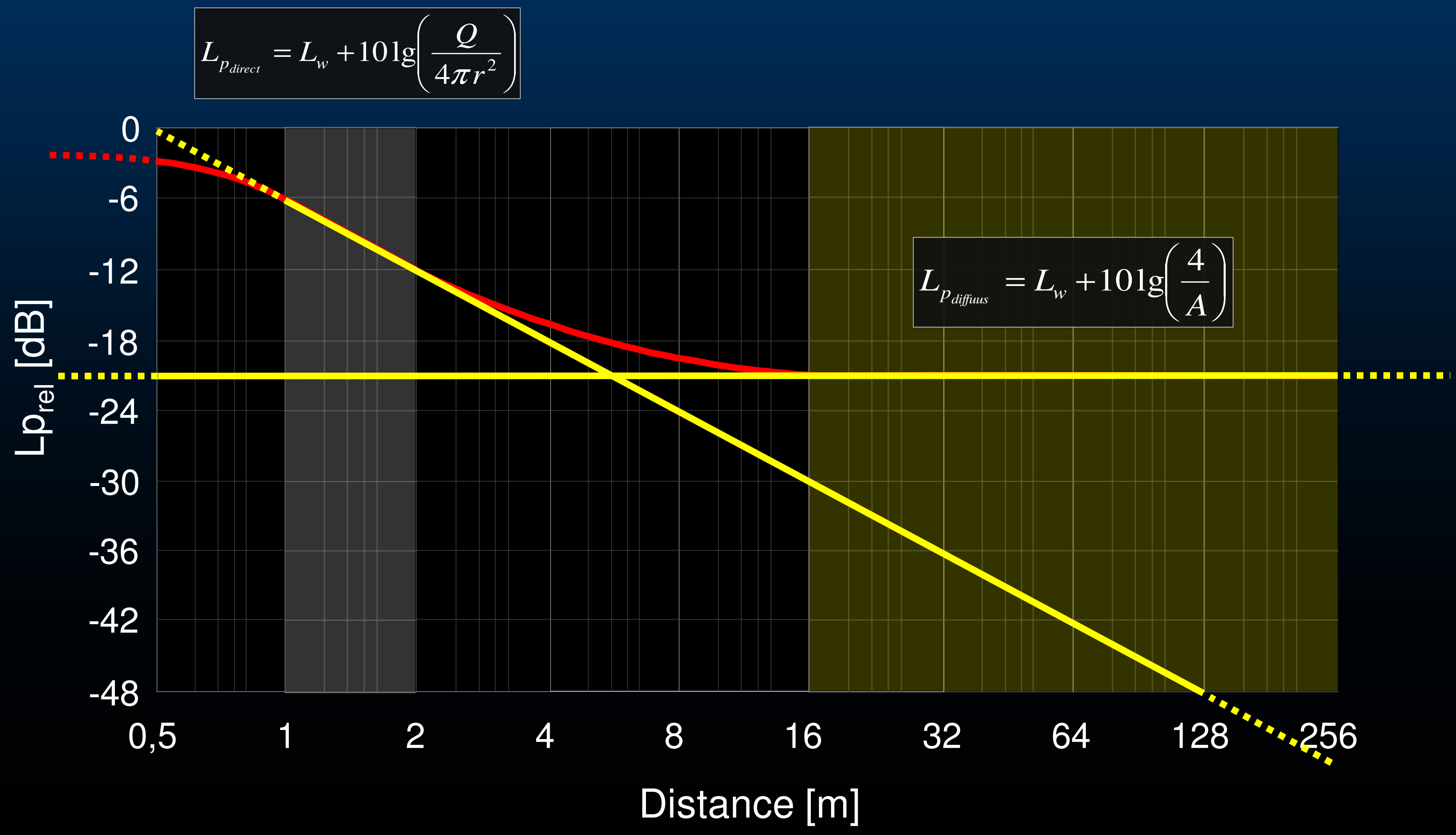
Sound Field



$$L_p = L_w + 10\lg\left(\frac{Q}{4\pi r^2} + \frac{4}{A}\right)$$

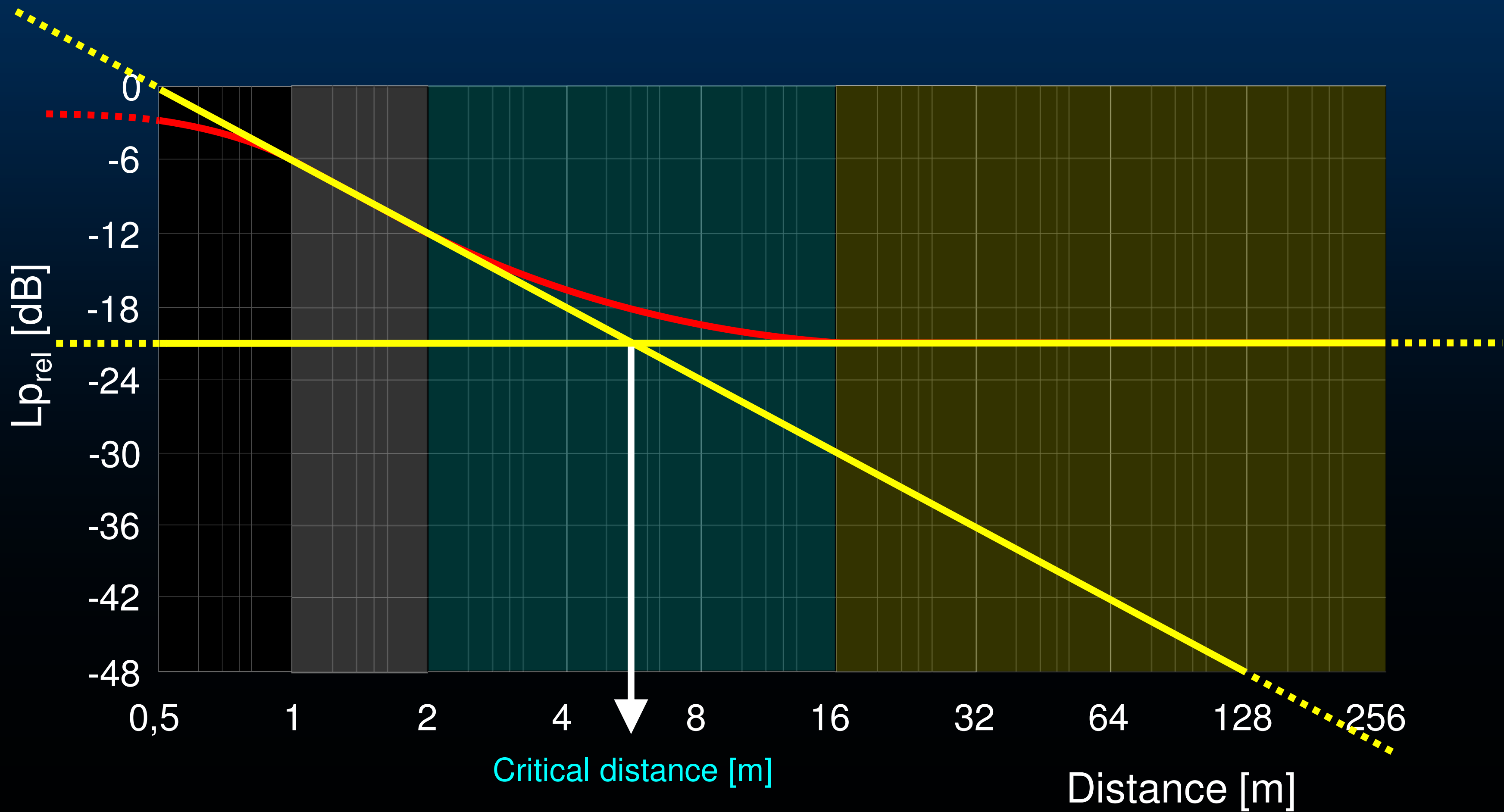
Sound Field

Intermezzo



Sound Field

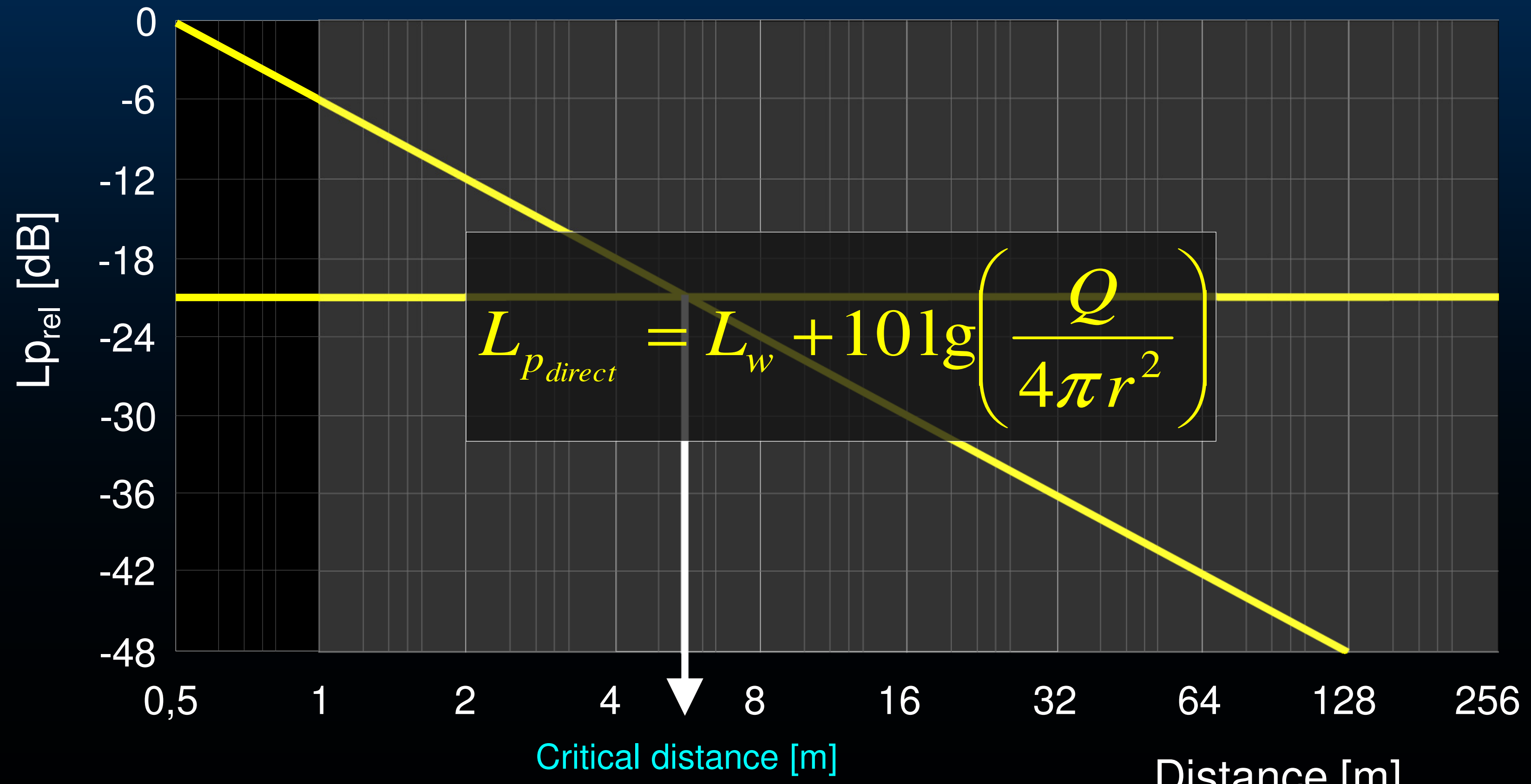
Intermezzo



Intermezzo

Sound Field

Anechoic room / Reflection free room

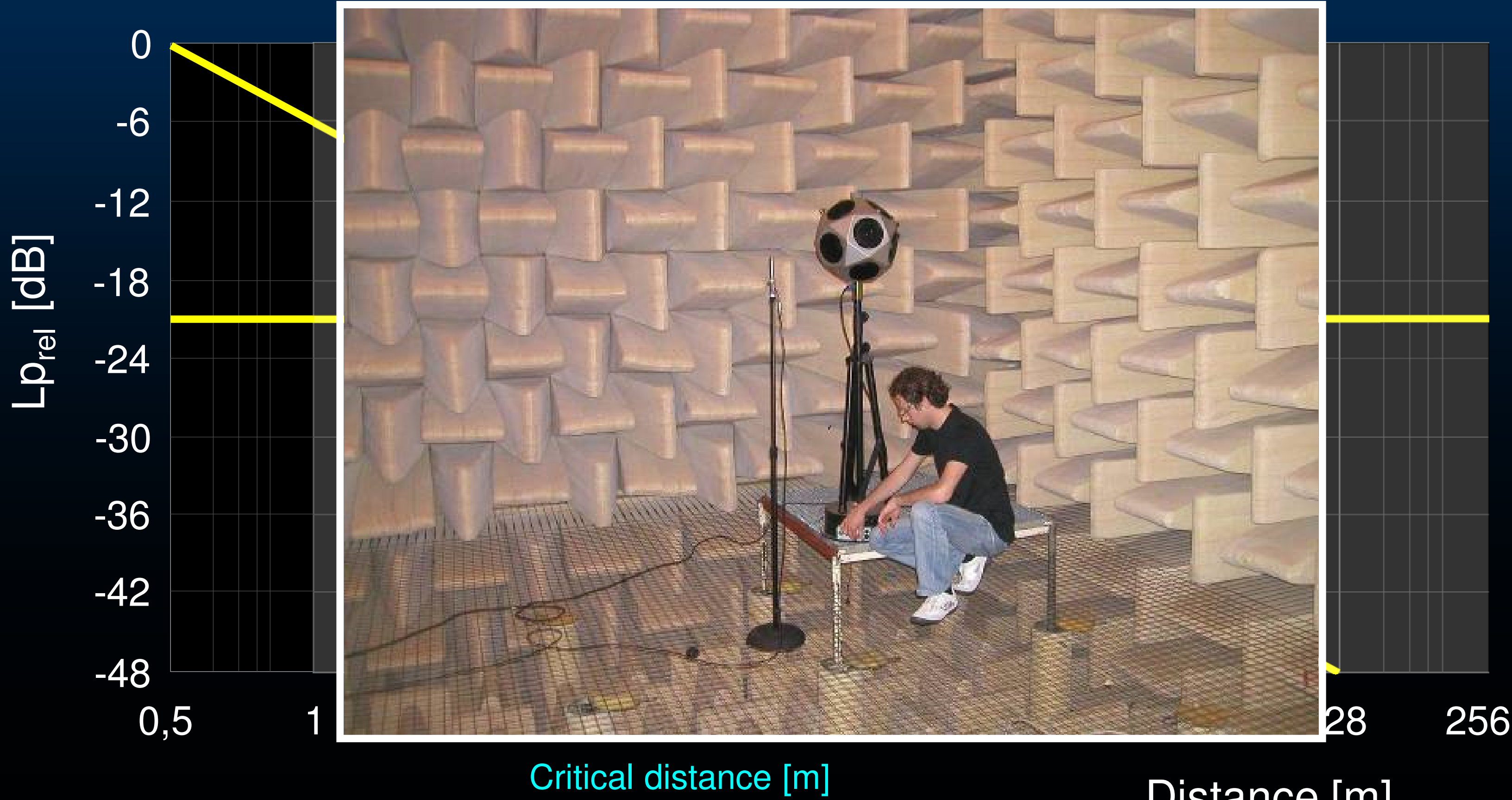


$$L_{p_{direct}} = L_w + 10\lg\left(\frac{Q}{4\pi r^2}\right)$$

Intermezzo

Sound Field

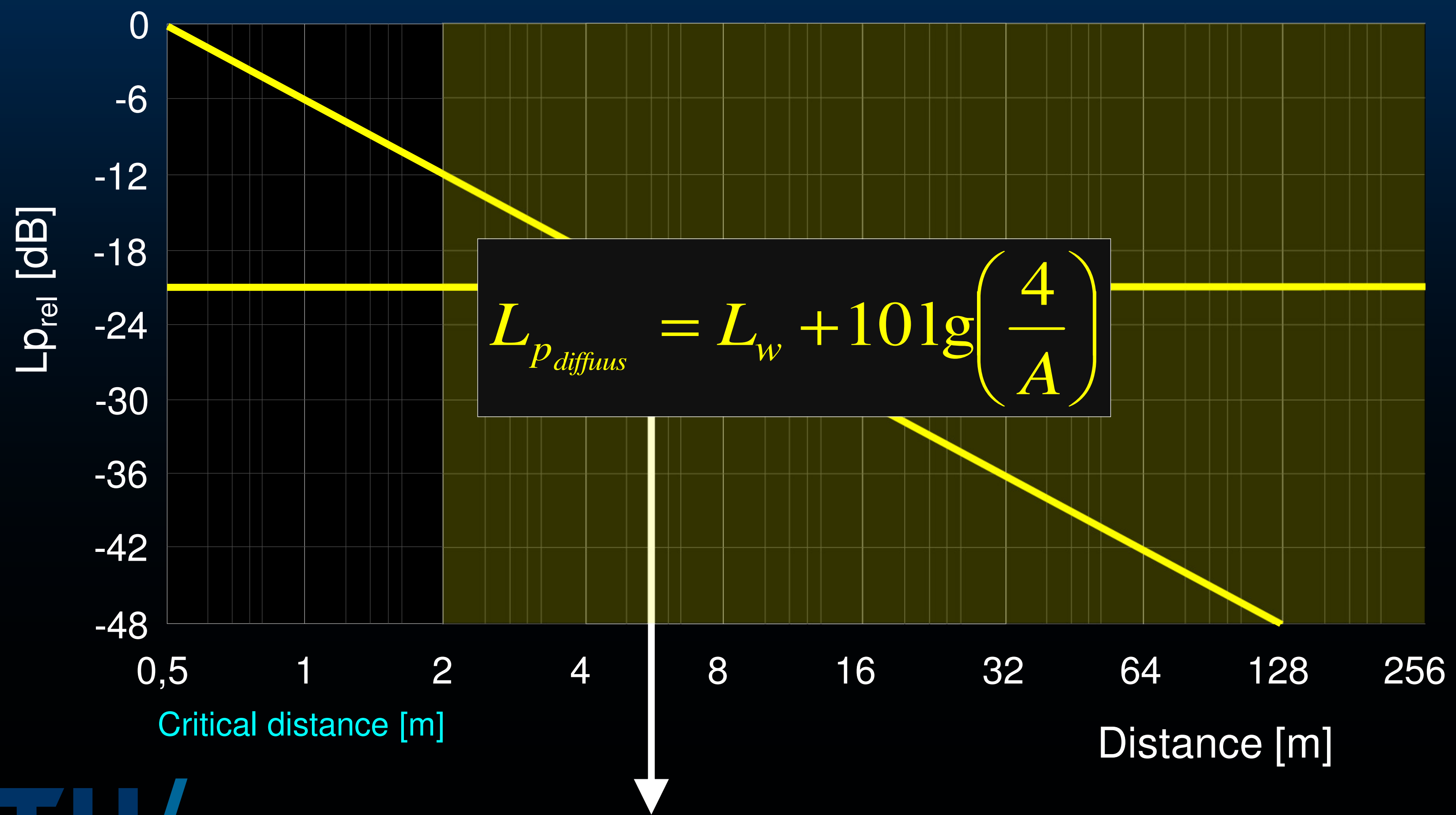
Anechoic room / Reflection free room



Intermezzo

Sound Field

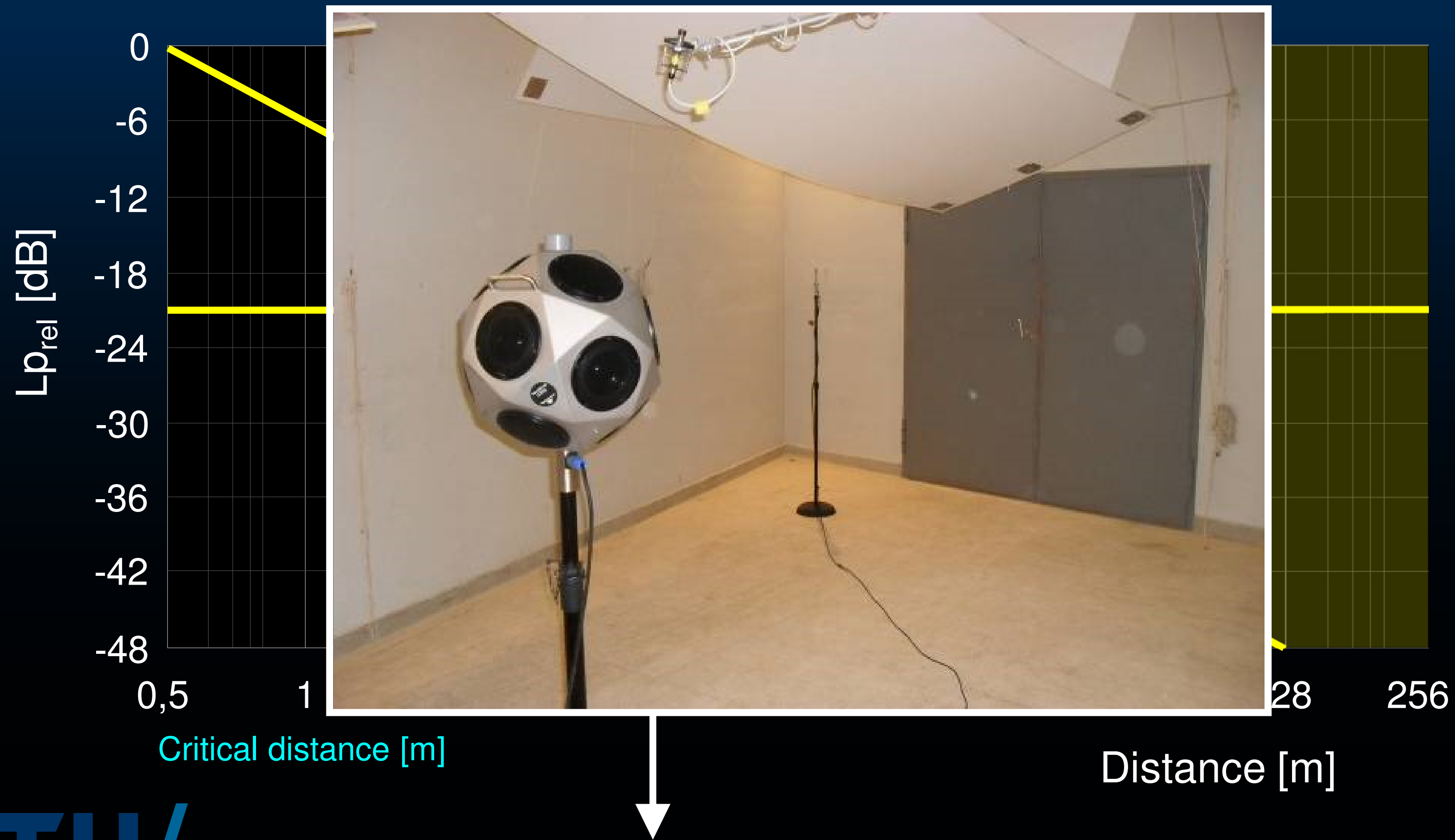
Reverberation room



Intermezzo

Sound Field

Reverberation room



Sound Field

Direct field / Diffuse field

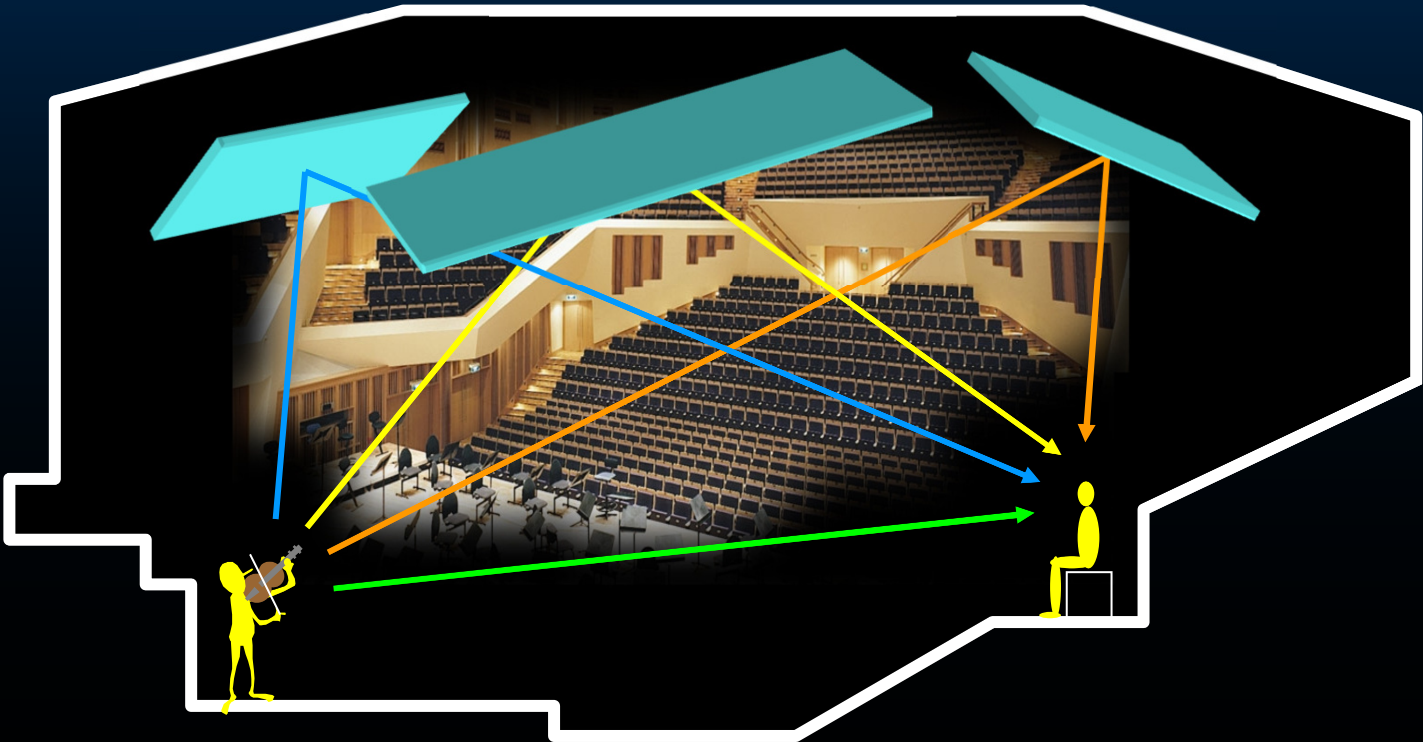
direct field $$L_{p_{direct}} = L_w + 10\lg\left(\frac{Q}{4\pi r^2}\right)$$

diffuse veld $$L_{p_{diffuus}} = L_w + 10\lg\left(\frac{4}{A}\right)$$

dir. + diff. field $$L_{p_{dir+diff}} = L_w + 10\lg\left(\frac{Q}{4\pi r^2} + \frac{4}{A}\right)$$

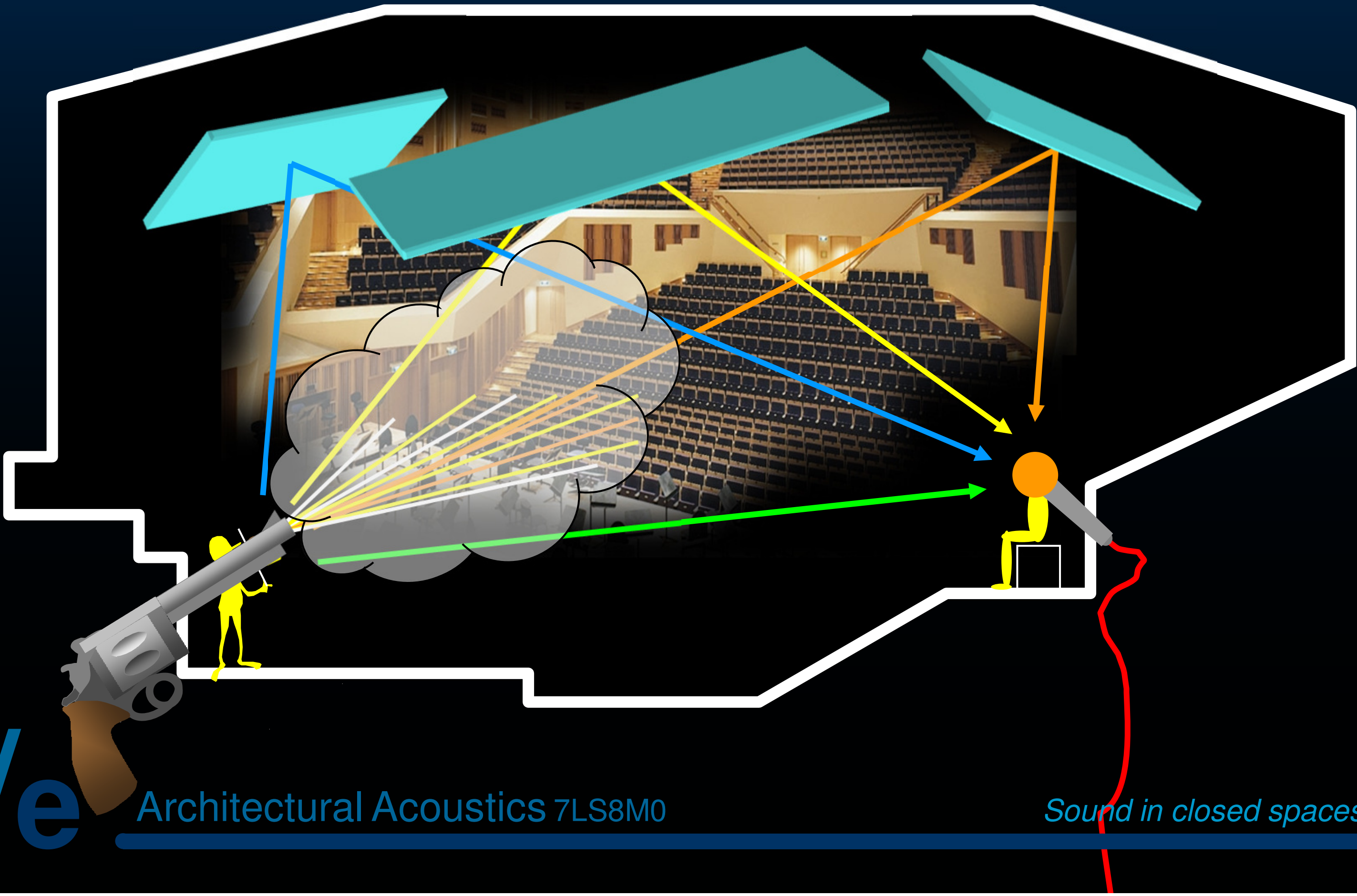
Critical distance $$L_{p_{dir}} = L_{p_{diff}} \Rightarrow r_k = \sqrt{\frac{QA}{16\pi}}$$

Room Acoustics
Concert hall



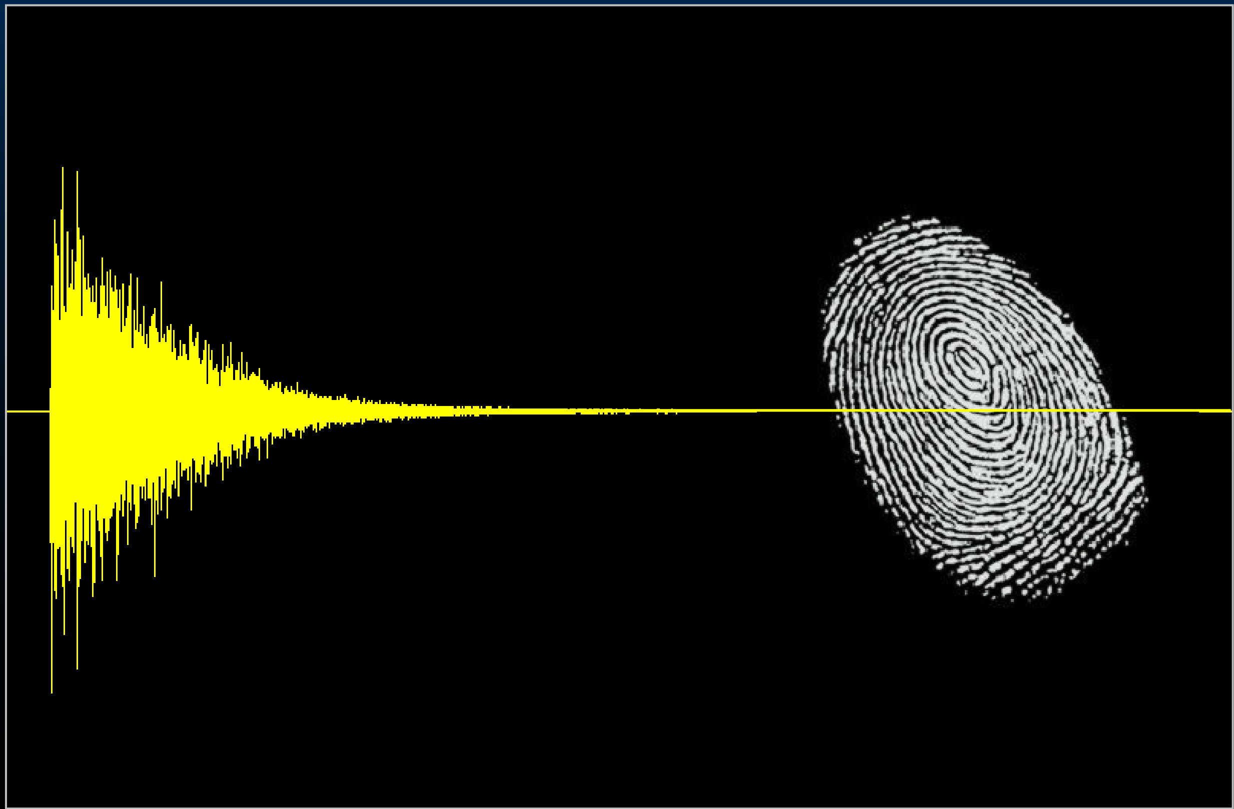
Room Acoustics

Concert hall



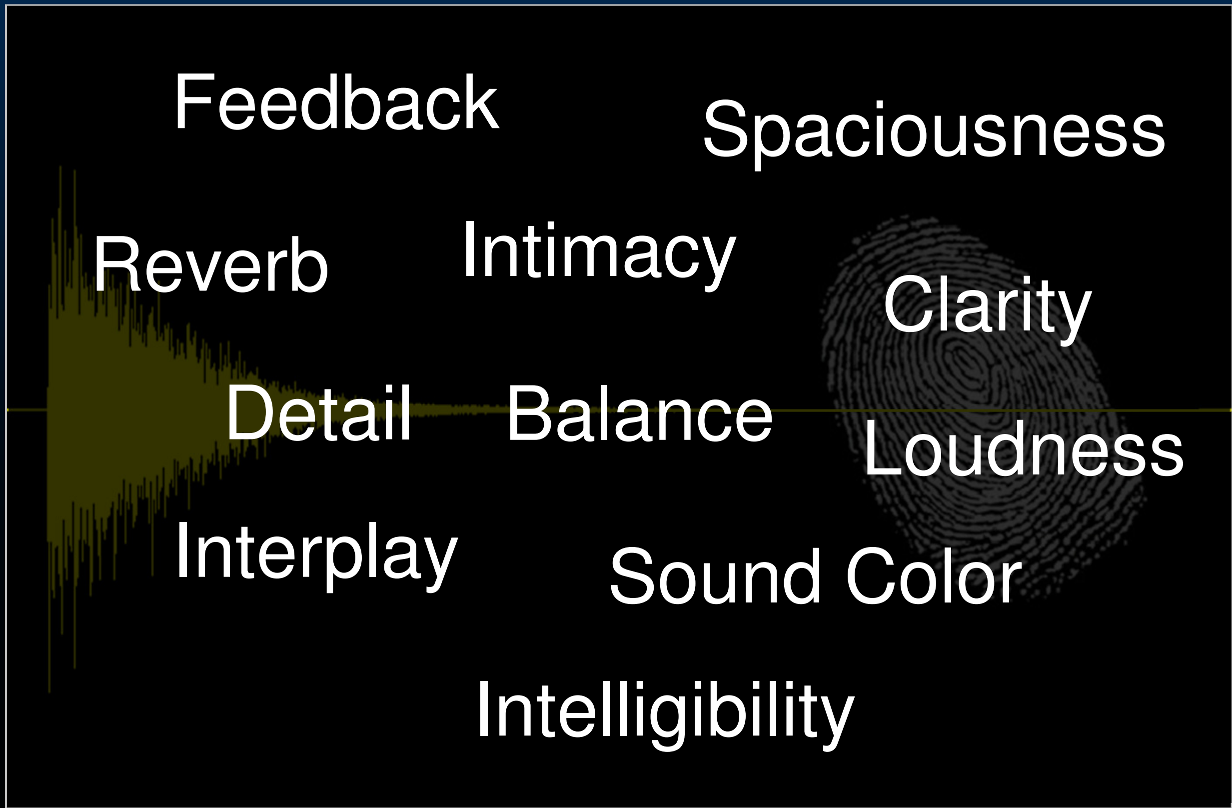
Room Acoustics

Fingerprint(s) of the hall

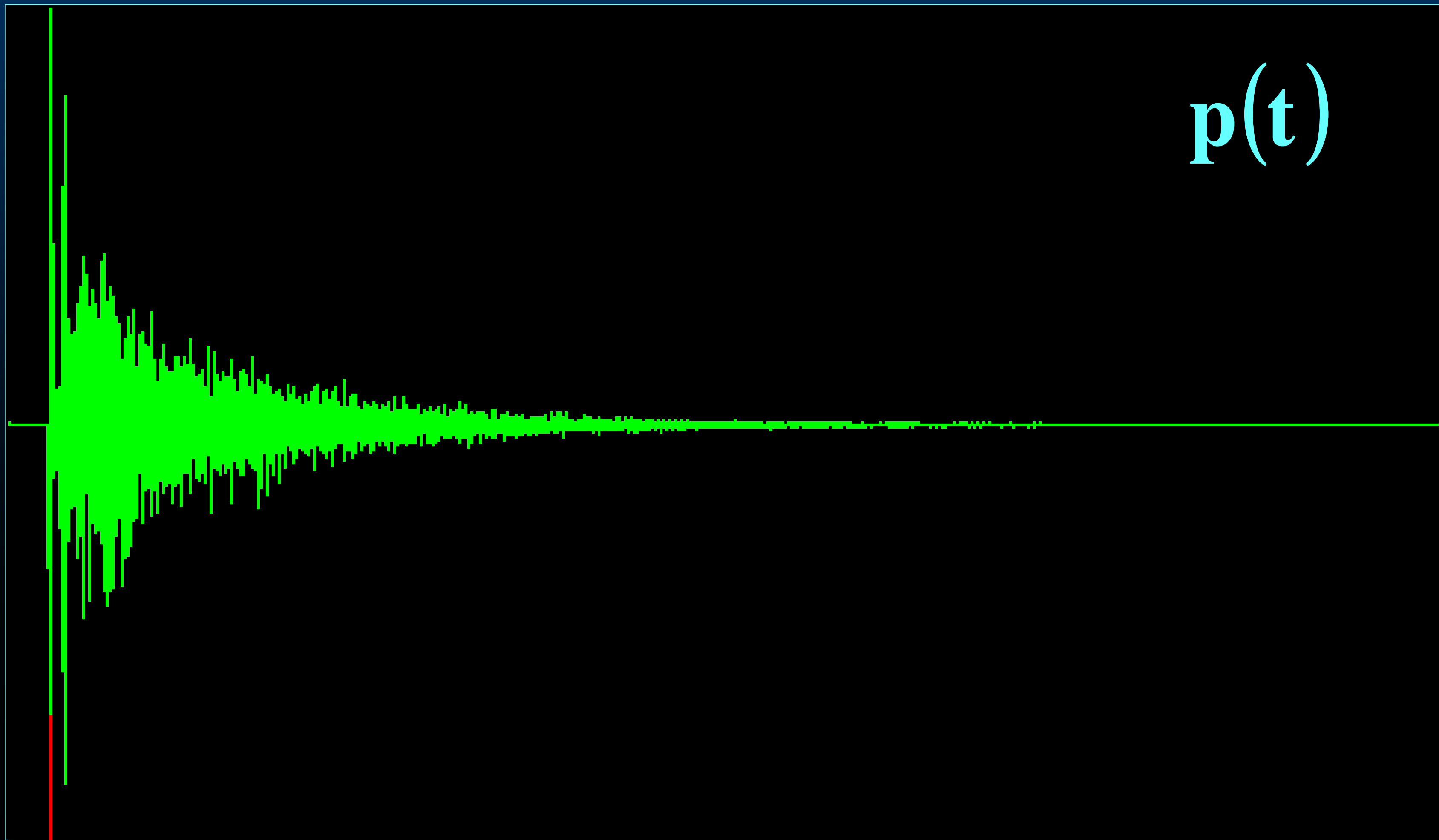


Room Acoustics

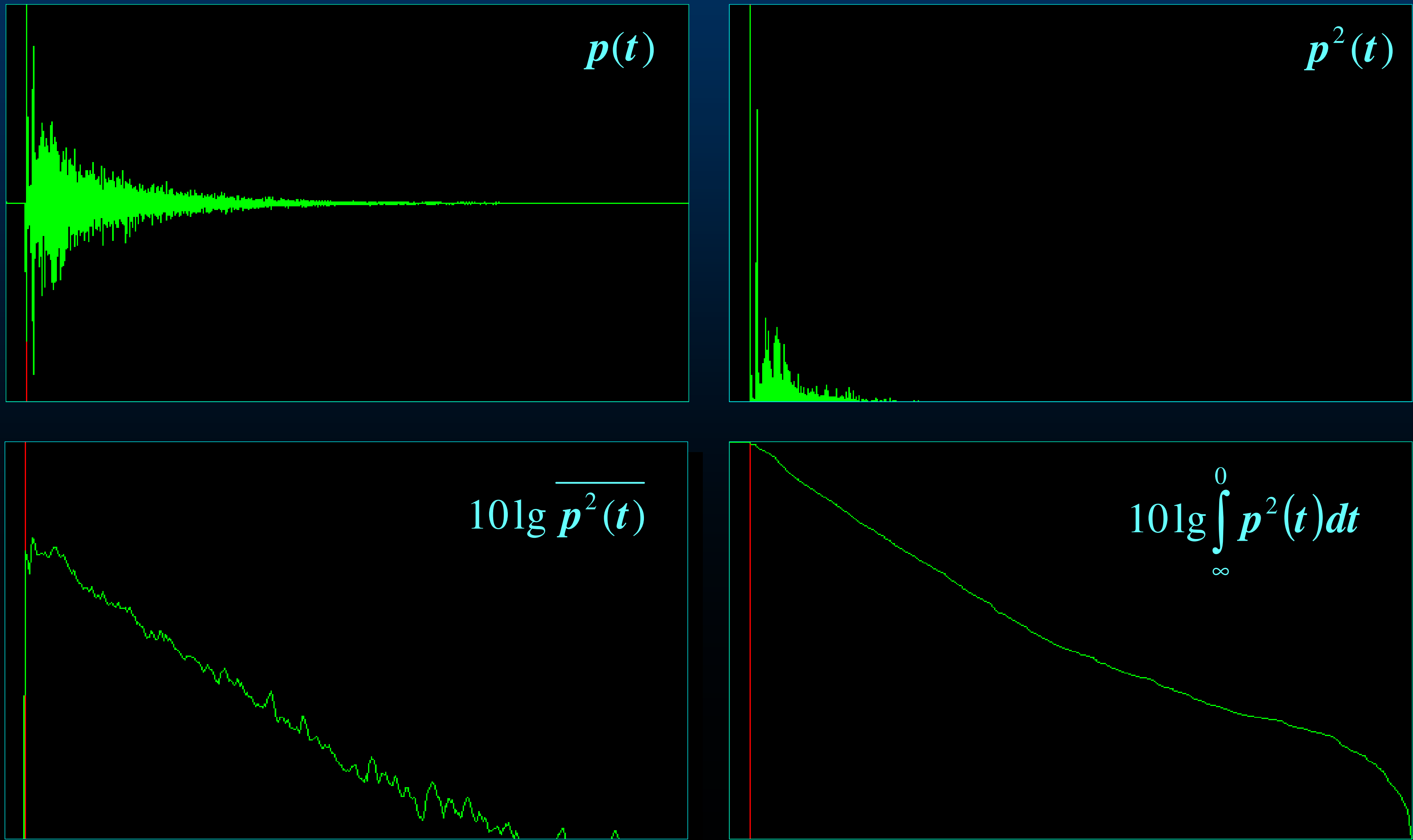
Subjective room acoustical parameters



Room Impulse Response (RIR)

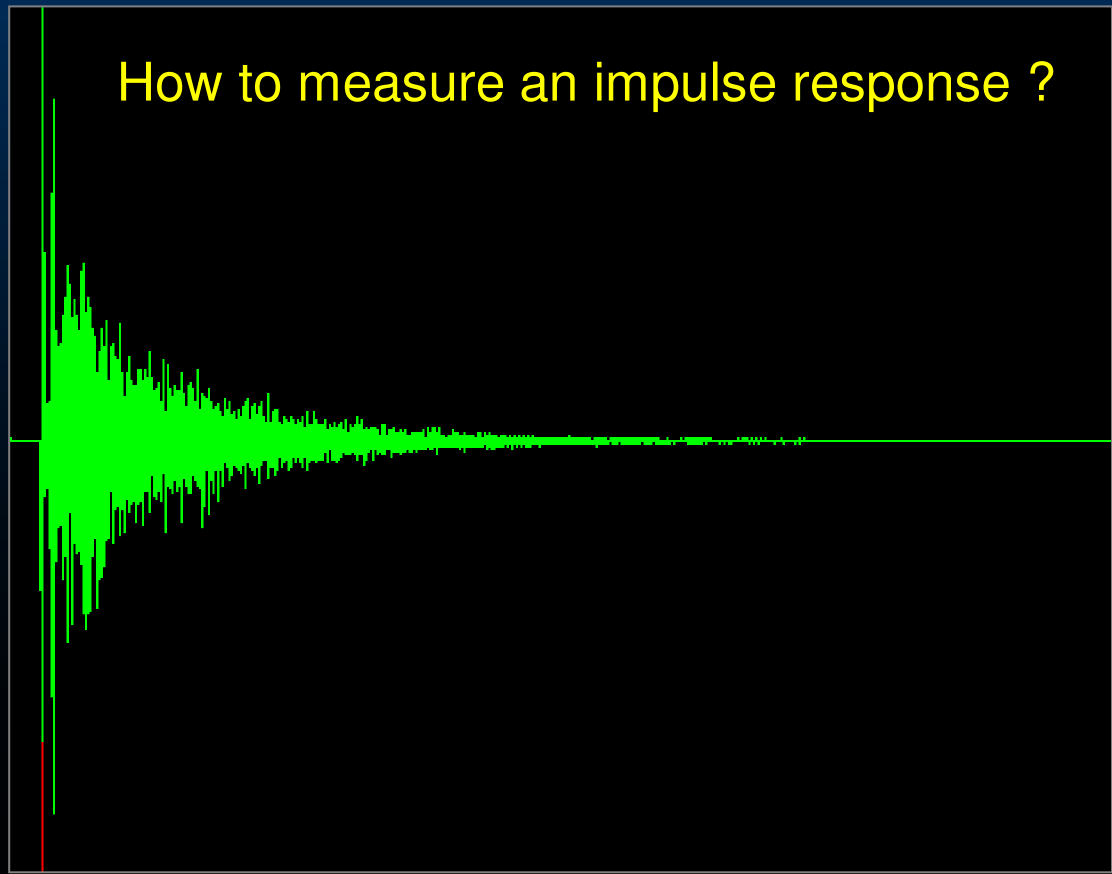


Time-domain



IR Measurement

- External
  - Impuls
- Internal
  - MLS
  - lin Sweep
  - e-Sweep



IR Measurement

- External
  - Impuls
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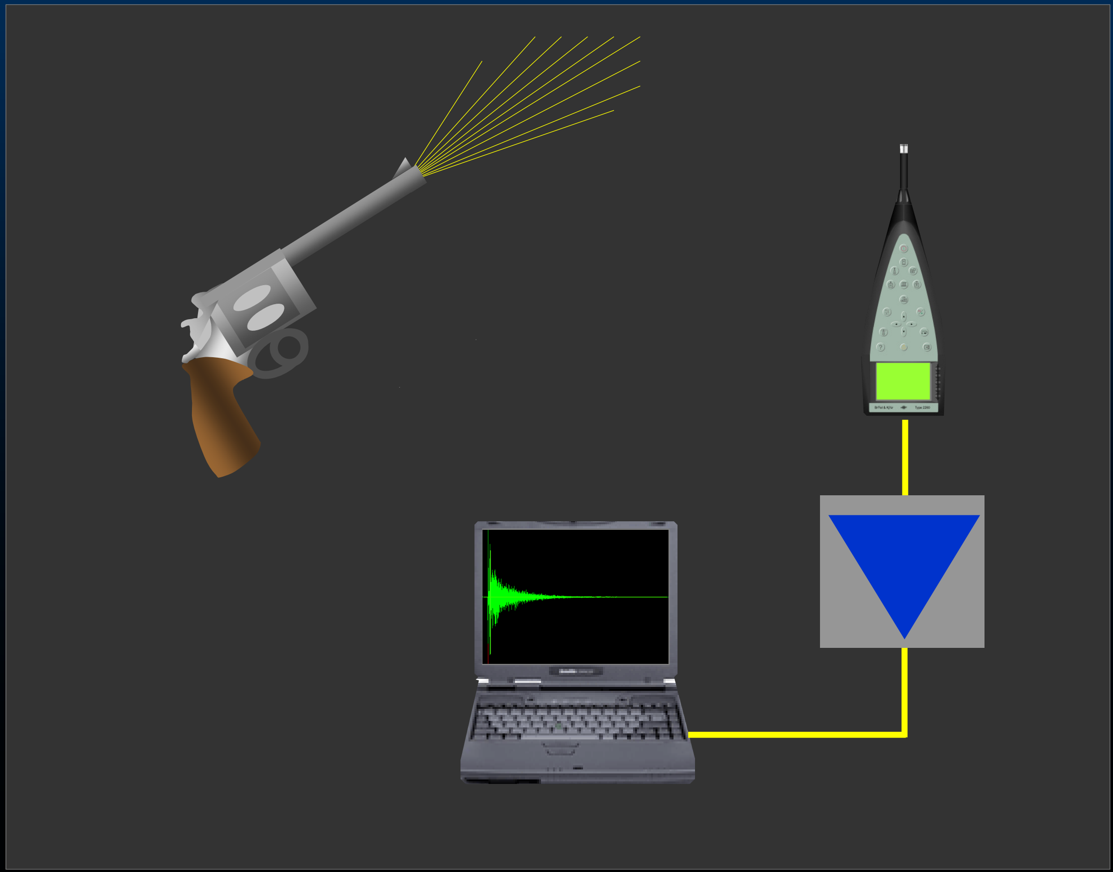
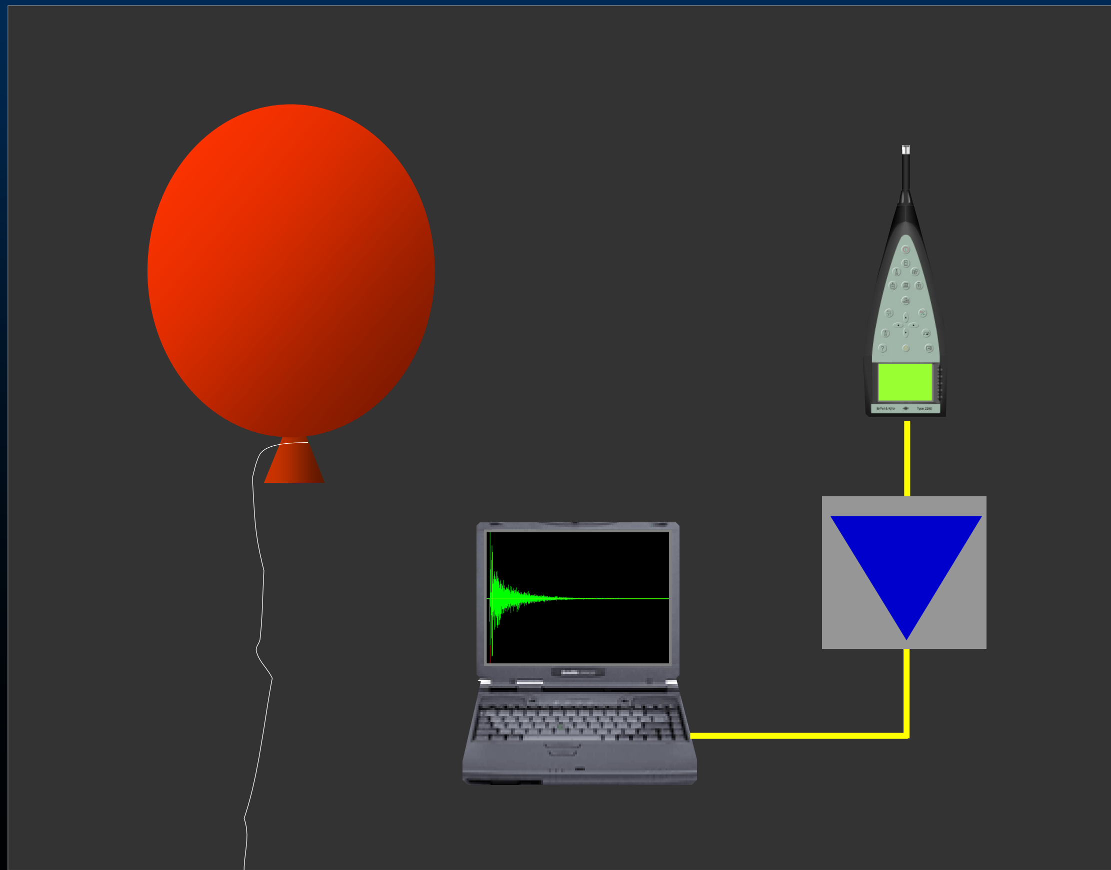
  - e-Sweep



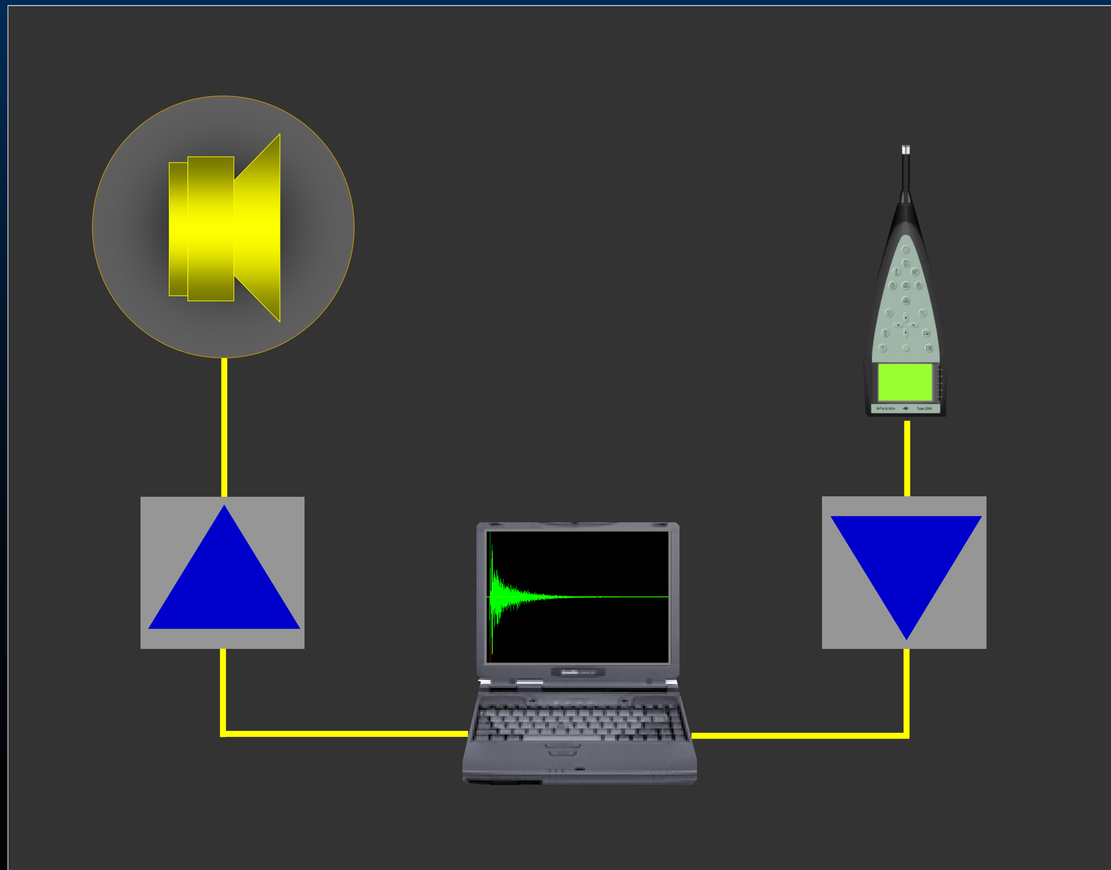
IR Measurement

- External
  - Impuls
- Internal
  - MLS
  - lin Sweep
  - e-Sweep



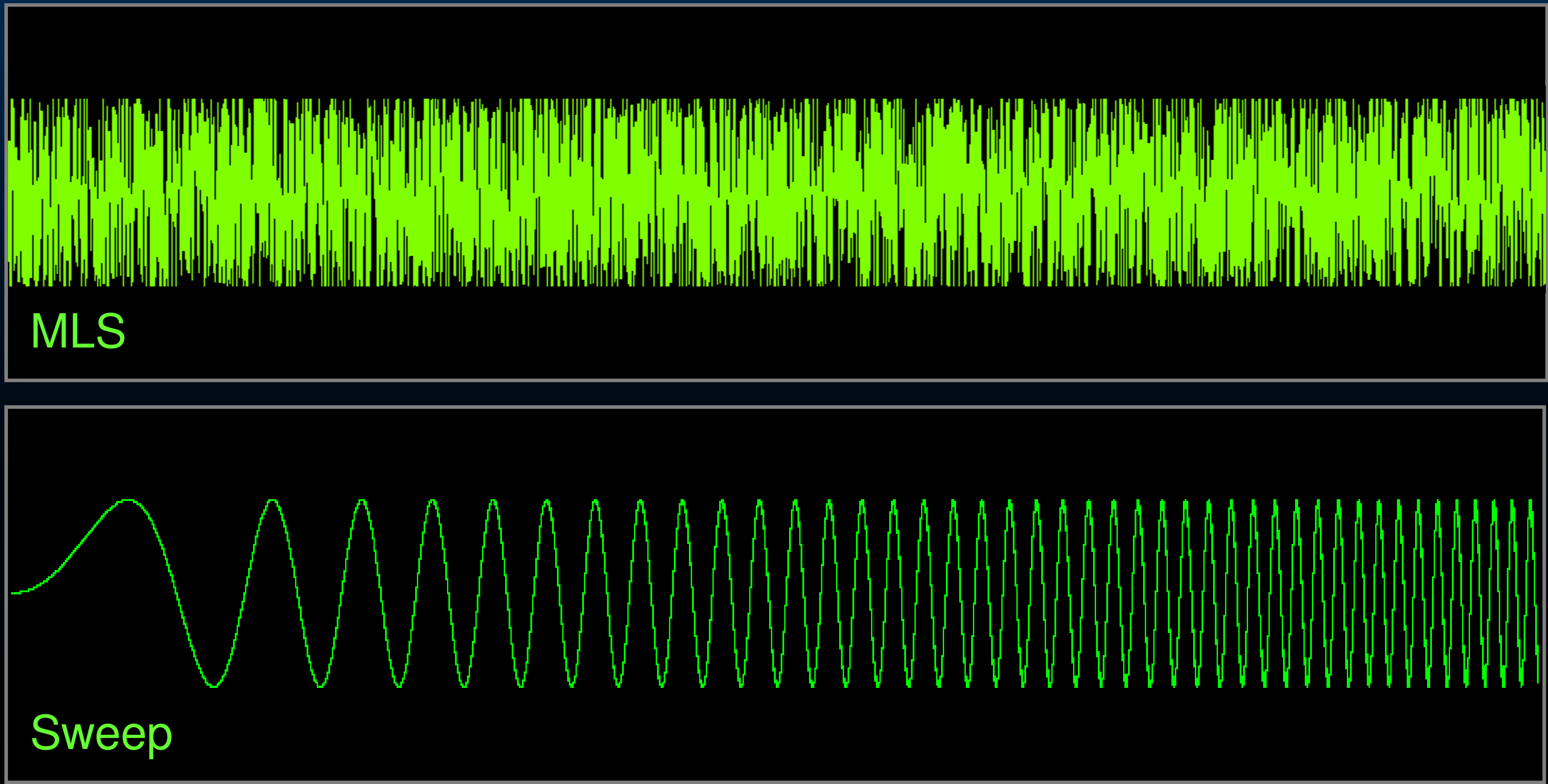
IR Measurement

- External
  - Impuls
- Internal
  - MLS
  - lin Sweep
  - e-Sweep



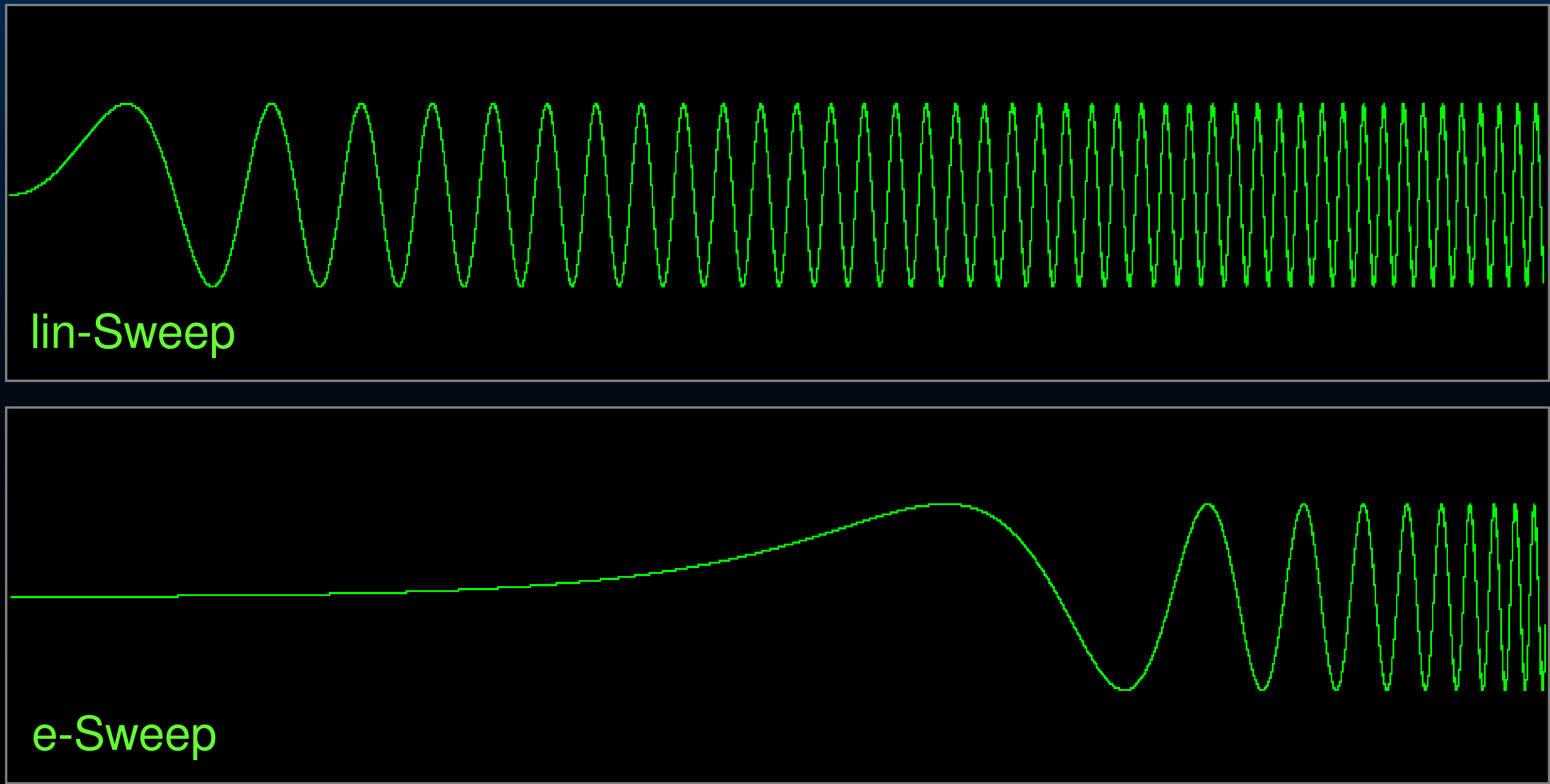
IR Measurement

MLS versus Sweep



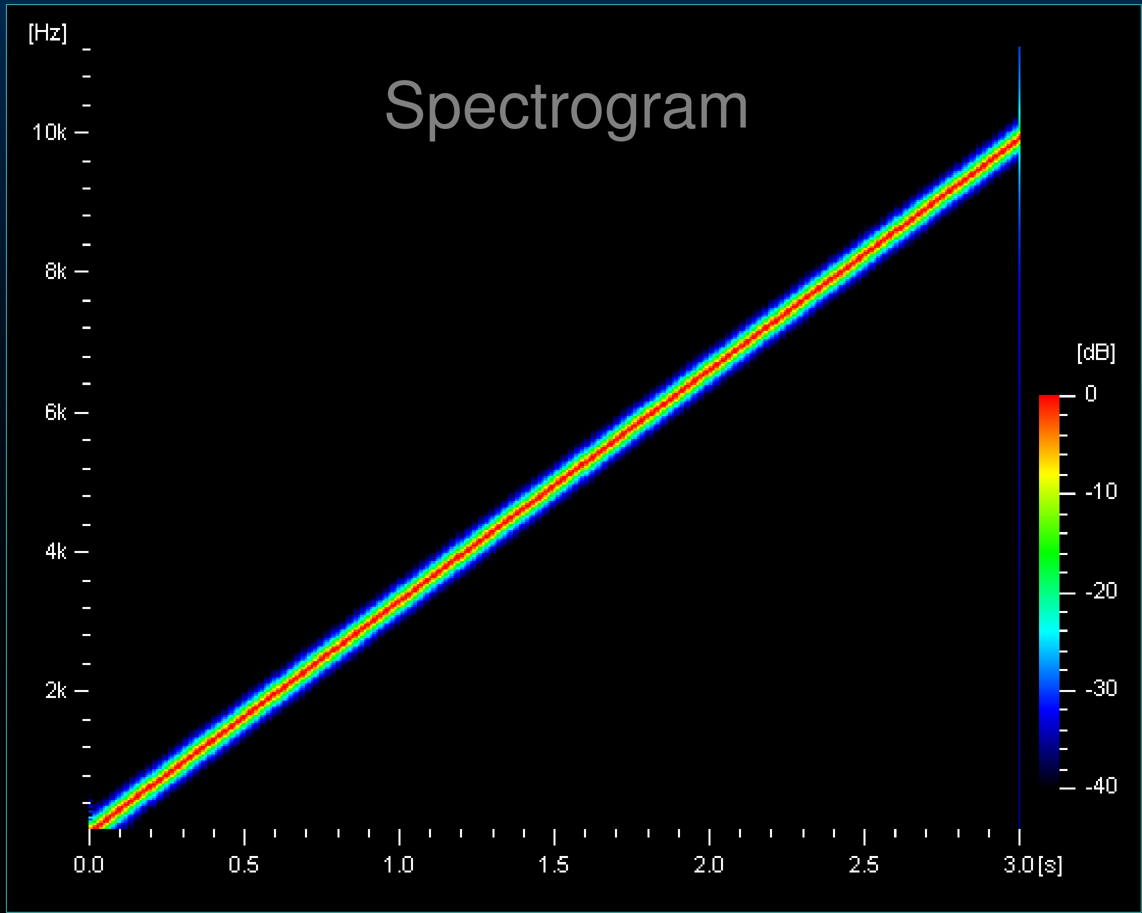
IR Measurement

e-Sweep versus lin-Sweep



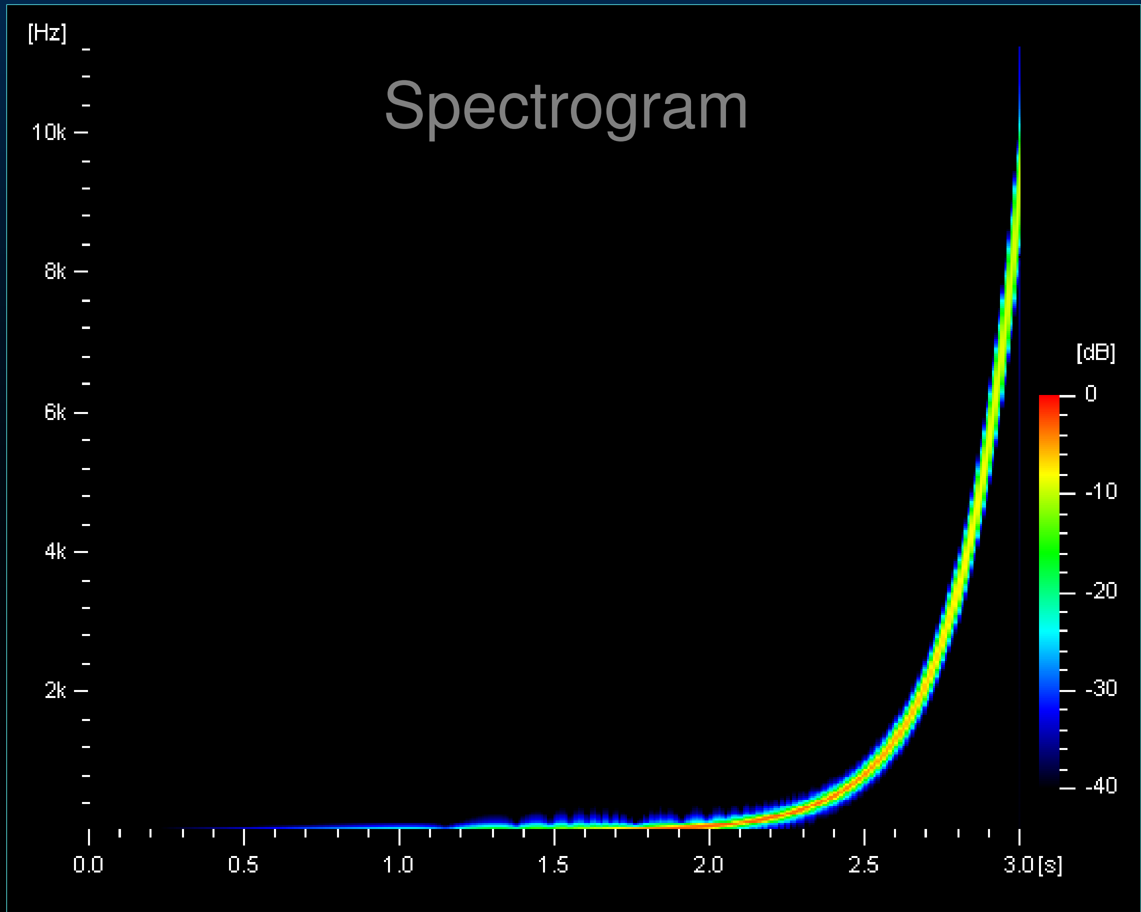
IR Measurement

e-Sweep versus lin-Sweep

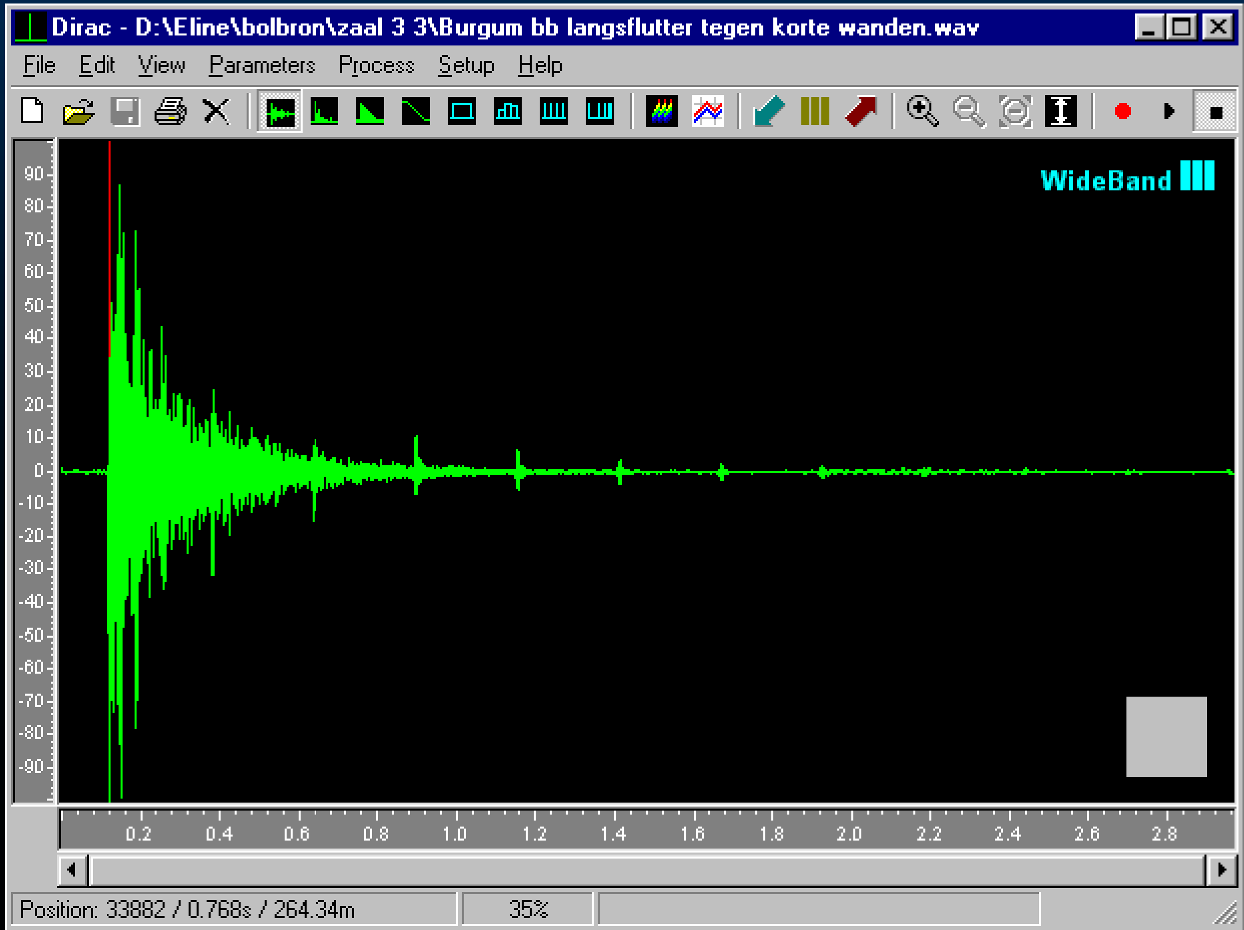


IR Measurement

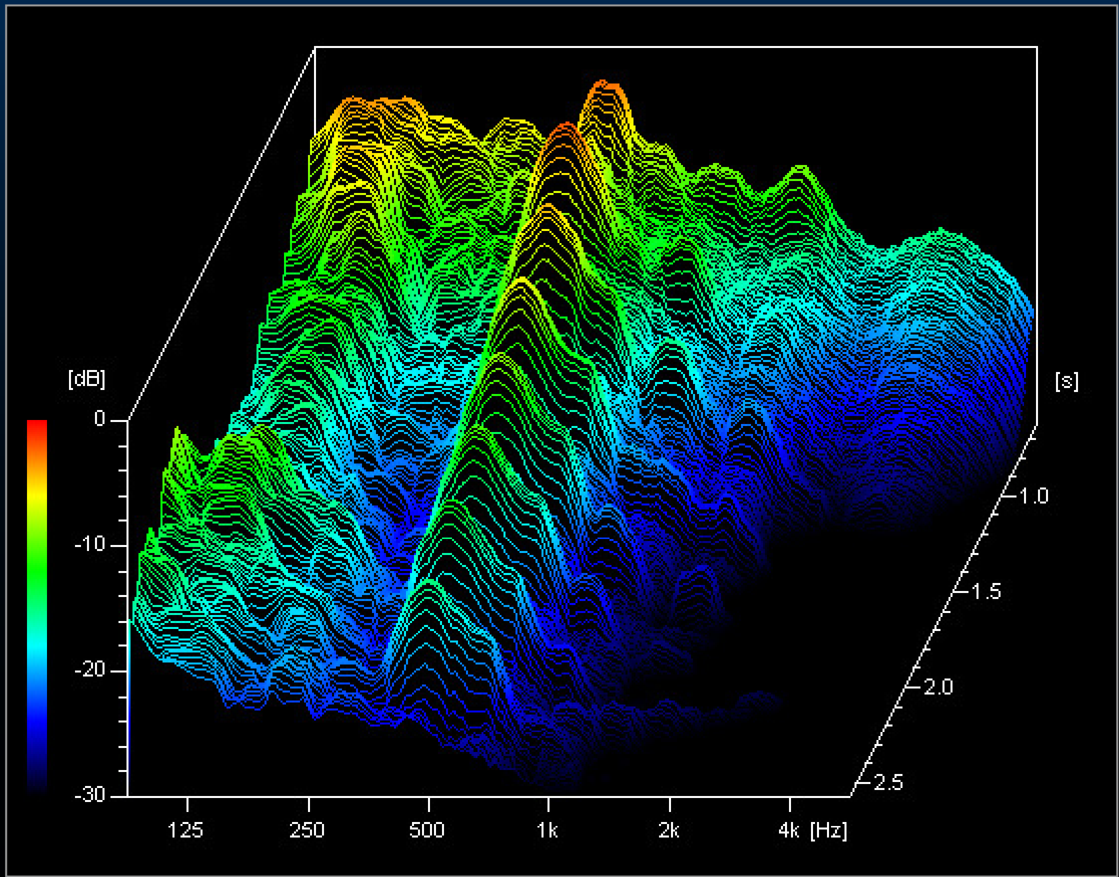
e-Sweep versus lin-Sweep



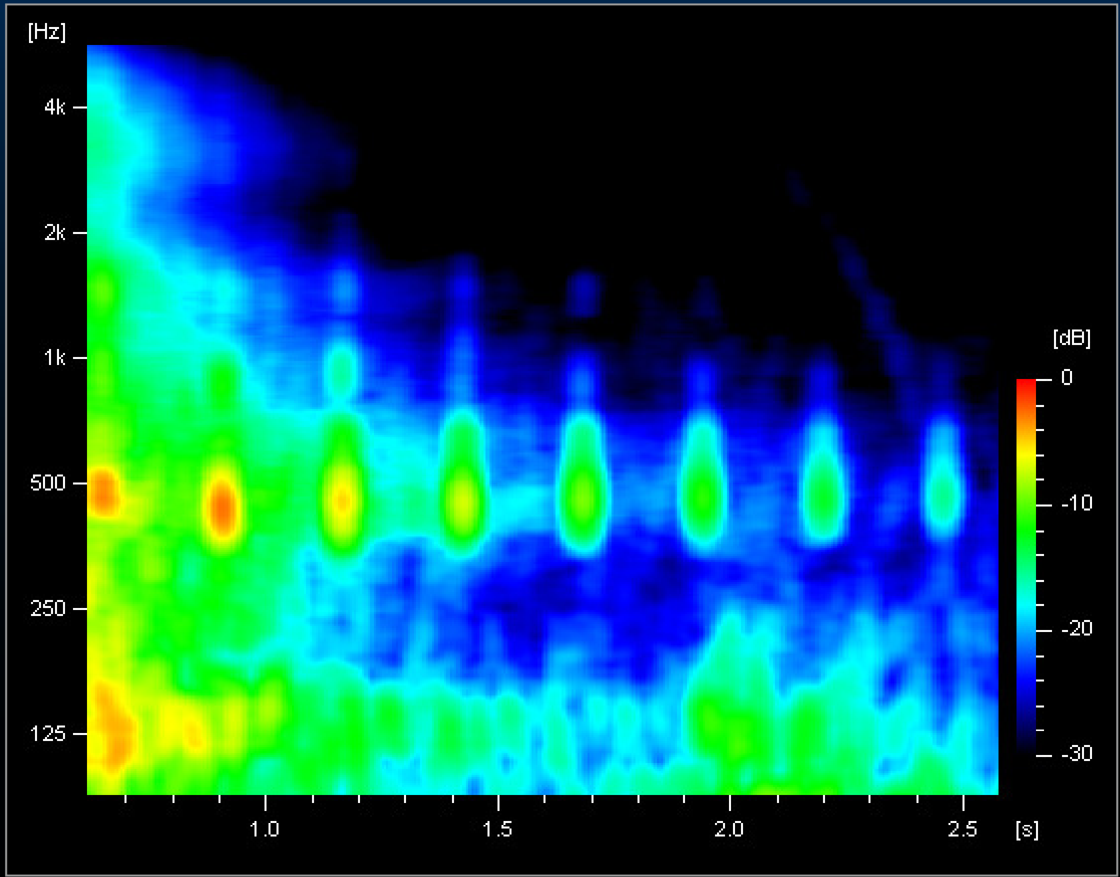
IR Measurement
flutter in sporthal



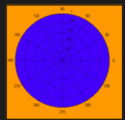
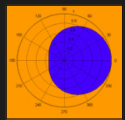
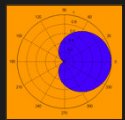
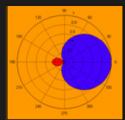
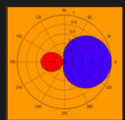
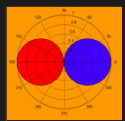
IR Measurement
waterfall plot



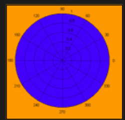
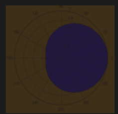
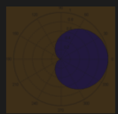
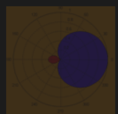
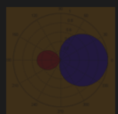
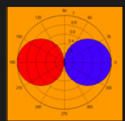
IR Measurement
spectrogram



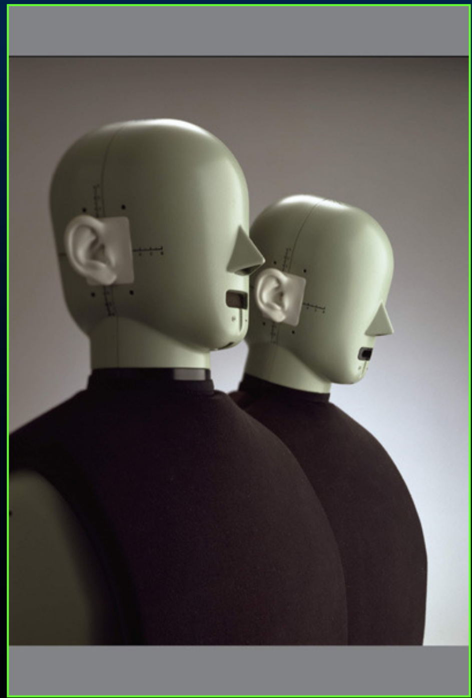
Microphones

	B	Microphone type	Application
	0	Omnidirectional	Measurement!
	0,37	Hypocardioid	
	0,5	Cardioid	
	0,63	Hypercardioid	
	0,75	Supercardioid	
	1,0	Bidirectional	Measurement!

Microphones

	B	Microphone type	Application
	0	Omnidirectional	Measurement!
	0,37	Hypocardioid	
	0,5	Cardioid	
	0,63	Hypercardioid	
	0,75	Supercardioid	
	1,0	Bidirectional	Measurement!

Microphones



Parameters

Room
ISO 3382

Parameter	Unit
G	[dB]
EDT	[s]
T_{20}	[s]
T_{30}	[s]
C_{80}	[dB]
D_{50}	--
T_S	[ms]
LF	--
LFC	--
IACC	--

Stage
Gade

Parameter	Unit
ST early	[dB]
ST late	[dB]
ST total	[dB]

Quality

Parameter	Unit
INR	[dB]
SNR	[dB]
cc	--

Reflection

Parameter	Unit
RI	--
Q_w	--

Speech
ISO 60268-16

Parameter	Unit
STI	--
STI male	--
STI female	--
STITEL	--
RASTI	--
ALC	[%]

Level

Parameter	Unit
Grel	[dB]
Magnitude	--
SPL	[dB]

Roomacoustic Parameters

(ISO 3382)

- G [dB]
- EDT [s]
- T_{20} [s]
- T_{30} [s]
- C_{80} [dB]
- D_{50} --
- T_s [ms]
- LF --
- LFC --
- IACC --

Strength G

- G [dB]
- EDT [s]
- T20 [s]
- T30 [s]
- C80 [dB]
- D50 --
- Ts [ms]
- LF --
- LFC --
- IACC --

$$G = L_p - L_W + 31\,[dB]$$

$$G = L_p - L_{p(10m\,dir)}[dB]$$

1

Strength G

- G [dB]
- EDT [s]
- T_{20} [s]
- T_{30} [s]
- C_{80} [dB]
- D_{50} --
- Ts [ms]
- LF --
- LFC --
- IACC --

$$G = 10\lg \frac{\int_0^\infty p^2(t)\,dt}{\int_0^\infty p_{10,dir}{}^2(t)\,dt}\,[dB]$$

2

Intermezzo

Reverberation Time T_{60}

Sabins decay formula

- G [dB]
- EDT [s]
- T20 [s]
- T30 [s]
- C80 [dB]
- D50 --
- Ts [ms]
- LF --
- LFC --
- IACC --

$$w(t) = w_0 e^{\frac{-cAt}{4V}} \quad for\ t > 0$$

$$T = \frac{24 \ln 10}{c} \cdot \frac{V}{A}$$

$$T = 0.163 \frac{V}{A} \qquad T = \frac{V}{6A}$$

Intermezzo

Reverberation Time T_{60}

Eyring's formula

- G [dB]
- EDT [s]
- T20 [s]
- T30 [s]
- C80 [dB]
- D50 --
- Ts [ms]
- LF --
- LFC --
- IACC --

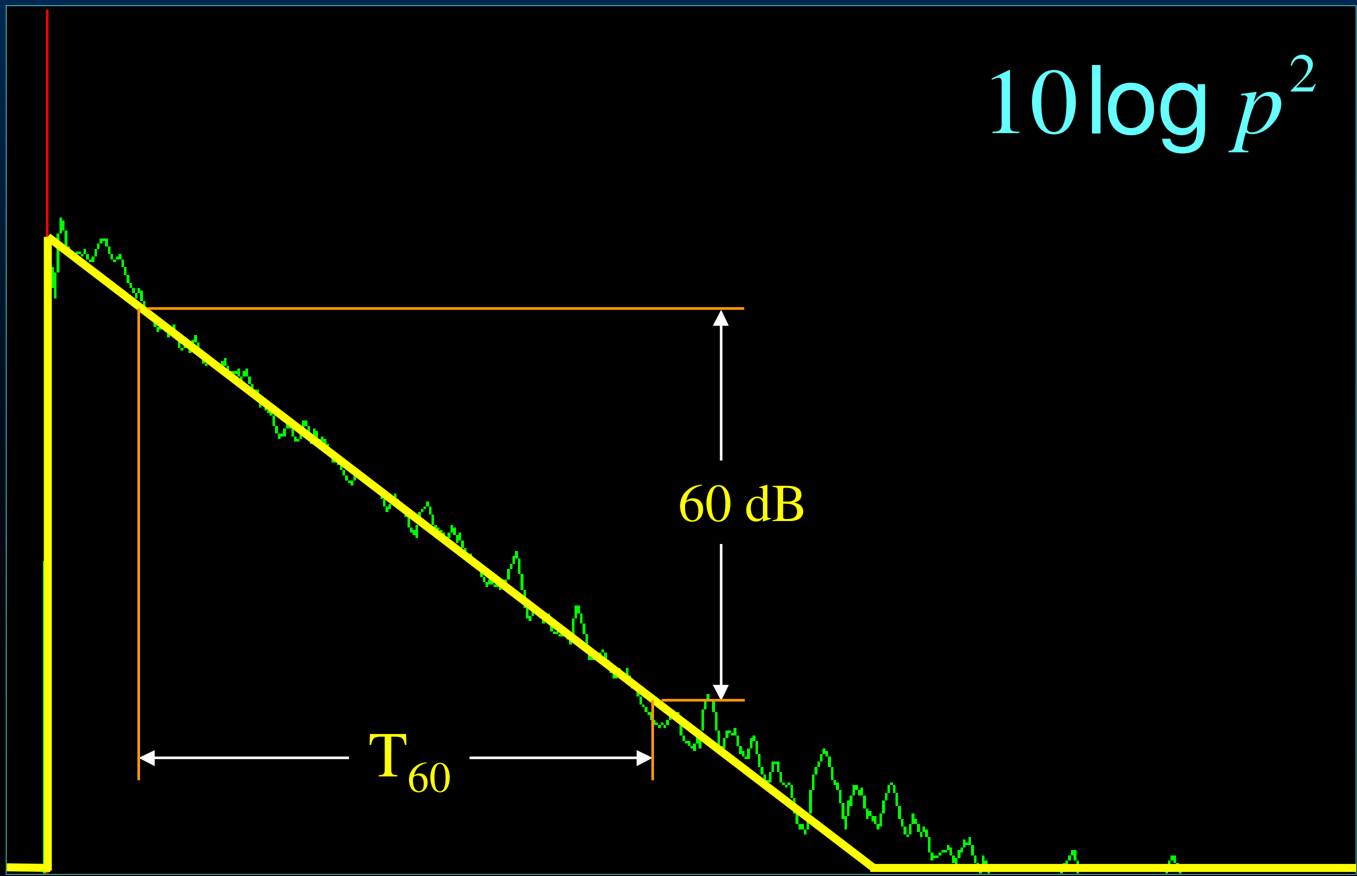
$$w(t) = w_0 e^{\frac{-cSt}{4V}\ln(1-\overline{\alpha}) - mct}$$

$$T = 0.163 \frac{V}{4mV - S\ln(1-\overline{\alpha})}$$

$$for\, \alpha << 1 \quad \ln(1-\overline{\alpha}) \approx -\overline{\alpha} \rightarrow Sabin$$

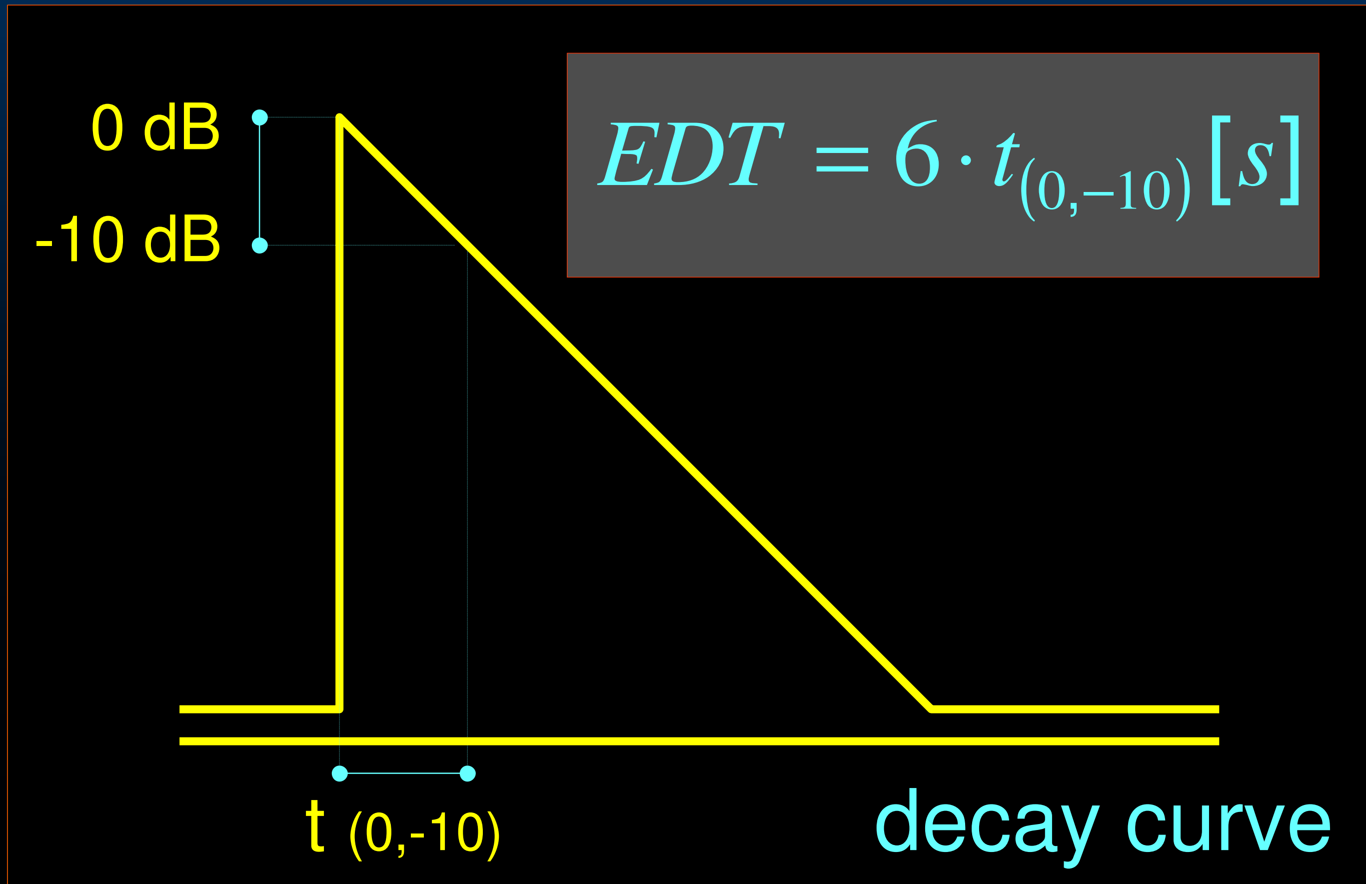
Reverberation Time T_{60}

- G [dB]
- EDT [s]
- T20 [s]
- T30 [s]
- C80 [dB]
- D50 --
- Ts [ms]
- LF --
- LFC --
- IACC --



Early Decay Time EDT

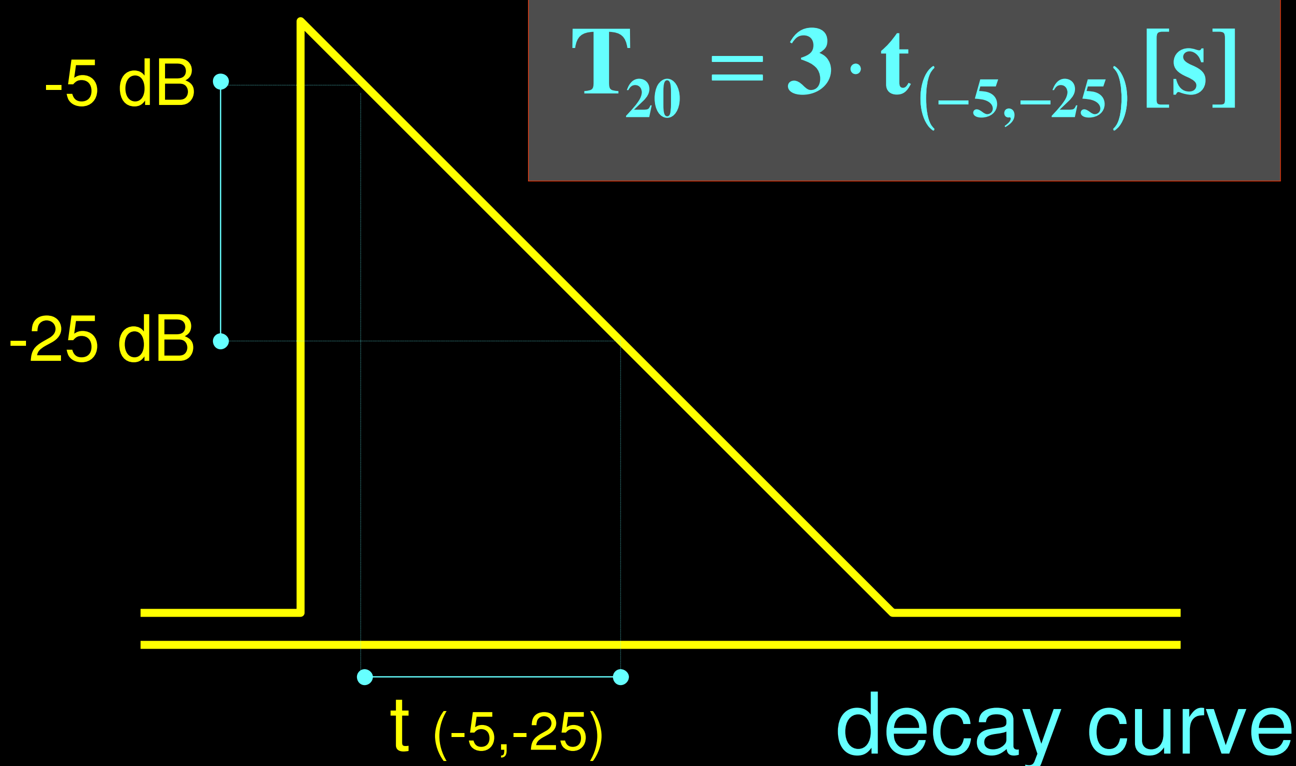
☐	G	[dB]
☑	EDT	[s]
☐	T_{20}	[s]
☐	T_{30}	[s]
☐	C_{80}	[dB]
☐	D_{50}	--
☐	Ts	[ms]
☐	LF	--
☐	LFC	--
☐	IACC	--



$$EDT = 6 \cdot t_{(0,-10)}\,[s]$$

Reverberation Time T20

- G [dB]
- EDT [s]
- ✓ T20 [s]
- T30 [s]
- C80 [dB]
- D50 --
- Ts [ms]
- LF --
- LFC --
- IACC --

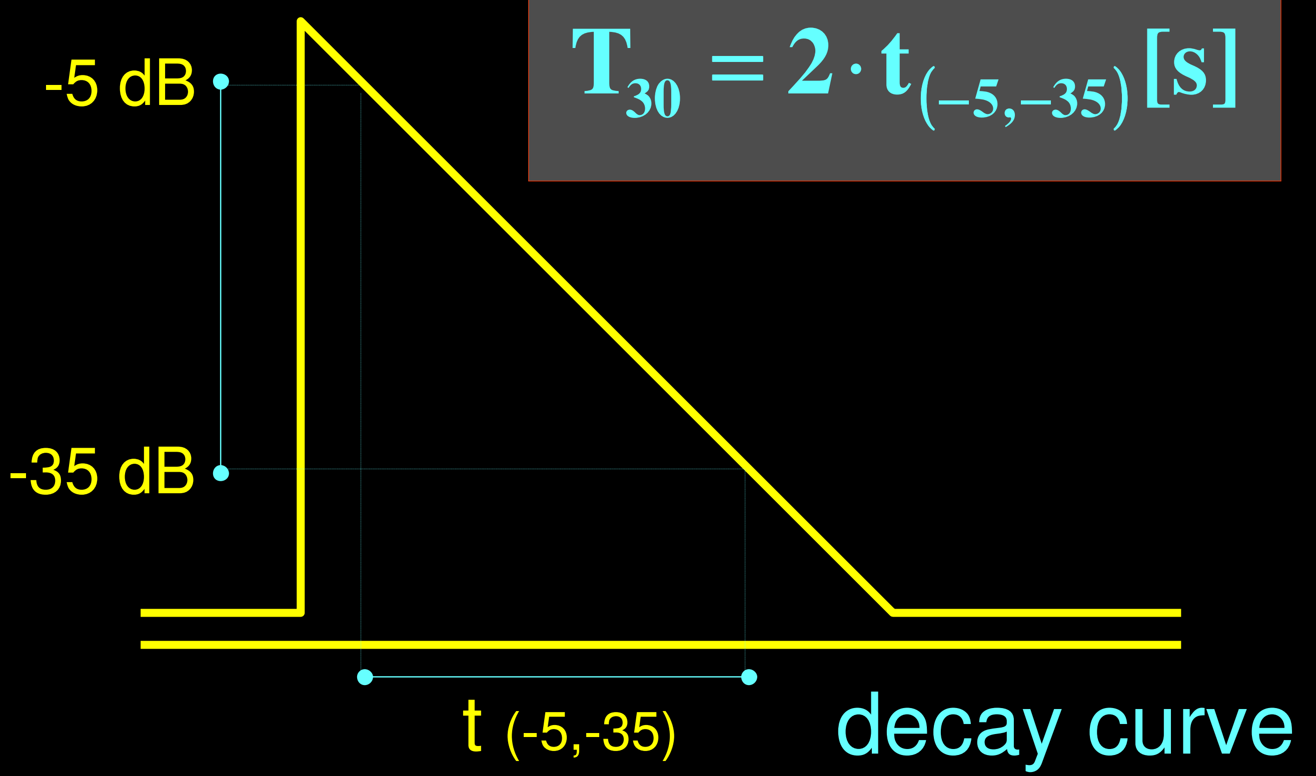


$$T_{20} = 3 \cdot t_{(-5,-25)} \, [s]$$

Reverberation Time T30

☐	G	[dB]
☐	EDT	[s]
☐	T20	[s]
√	T30	[s]
☐	C80	[dB]
☐	D50	--
☐	Ts	[ms]
☐	LF	--
☐	LFC	--
☐	IACC	--

$$T_{30} = 2 \cdot t_{(-5,-35)} \, [s]$$

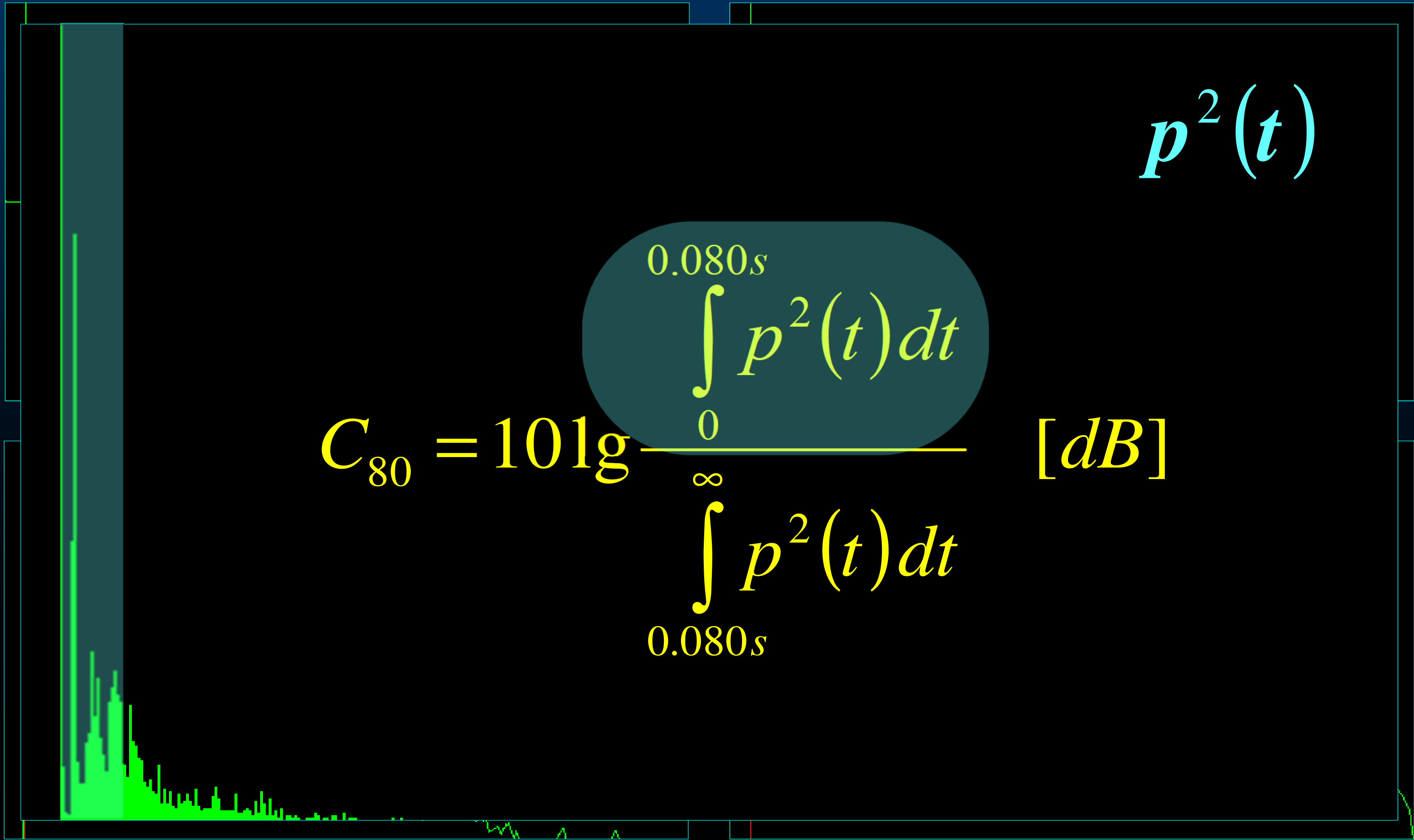


Clarity C80

- G [dB]
- EDT [s]
- T20 [s]
- T30 [s]
- C80 [dB]
- D50 --
- Ts [ms]
- LF --
- LFC --
- IACC --

$$C_{80} = 10 \lg \frac{\int_{0}^{0.080s} p^2(t)\,dt}{\int_{0.080s}^{\infty} p^2(t)\,dt} \quad [dB]$$

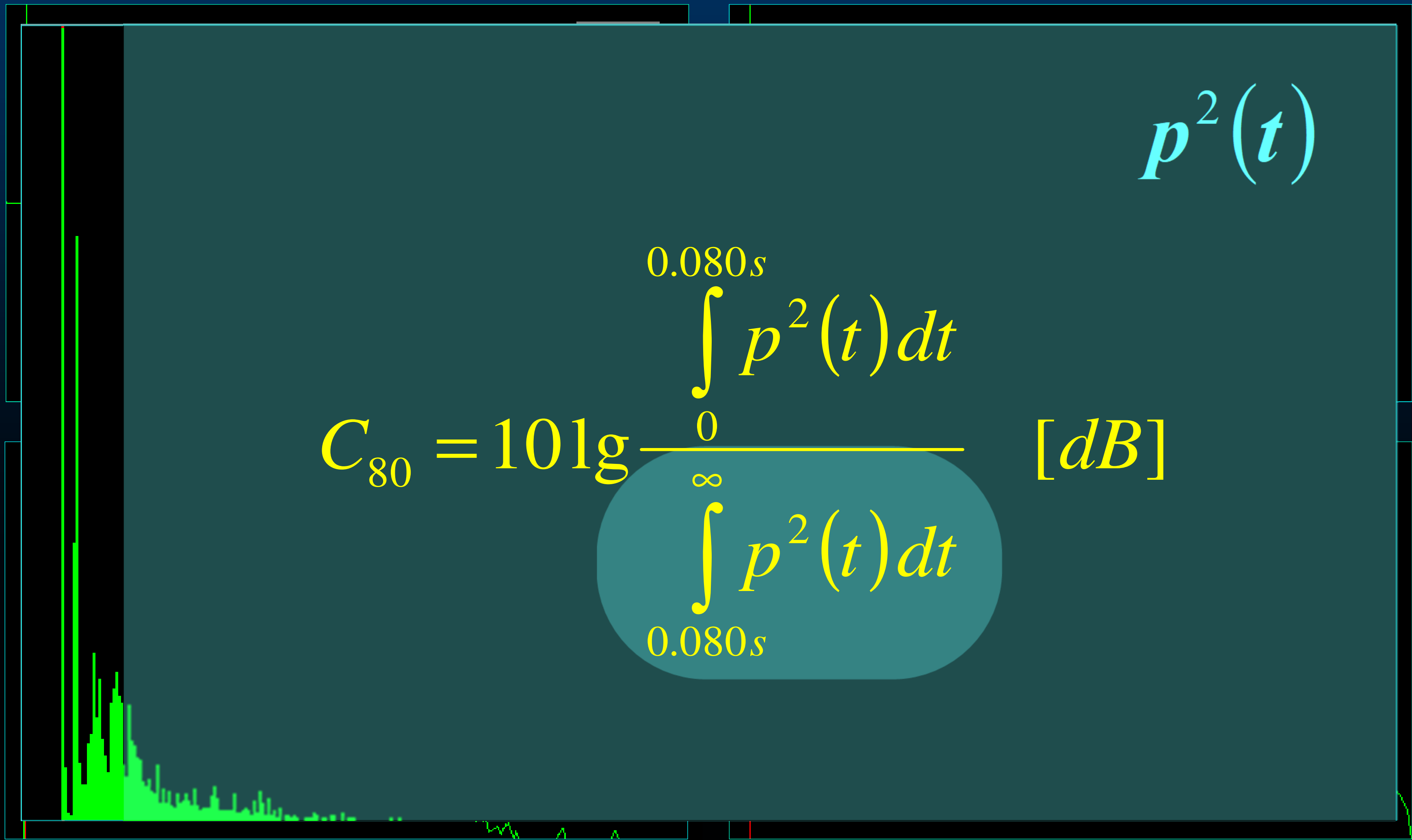
Clarity C80



$$p^2(t)$$

$$C_{80} = 10\lg \frac{\int_0^{0.080s} p^2(t)\,dt}{\int_{0.080s}^{\infty} p^2(t)\,dt} \quad [dB]$$

Clarity C80



$$p^2(t)$$

$$C_{80} = 10\lg \frac{\int_0^{0.080s} p^2(t)\,dt}{\int_{0.080s}^{\infty} p^2(t)\,dt} \quad [dB]$$

Definition D50

- G [dB]
- EDT [s]
- T20 [s]
- T30 [s]
- C80 [dB]
- D50 --
- Ts [ms]
- LF --
- LFC --
- IACC --

$$D_{50} = \frac{\int_0^{0.050s} p^2(t)\,dt}{\int_0^{\infty} p^2(t)\,dt} \qquad [-]$$

Centre Time

- G [dB]
- EDT [s]
- T20 [s]
- T30 [s]
- C80 [dB]
- D50 --
- Ts [ms]
- LF --
- LFC --
- IACC --

$$T_S = \frac{\int_0^\infty t \cdot p^2(t)\,dt}{\int_0^\infty p^2(t)\,dt} \quad [s]$$

Early Lateral Energy LF

- G [dB]
- EDT [s]
- T_{20} [s]
- T_{30} [s]
- C_{80} [dB]
- D_{50} --
- Ts [ms]
- LF --
- LFC --
- IACC --

$$LF = \frac{\int_{0}^{0.080s} p_{\oplus}^{2}(t)\,dt}{\int_{0}^{0.080s} p_{\oplus}^{2}(t)\,dt} \quad [-]$$

Early Lateral Energy LFC

- G [dB]
- EDT [s]
- T20 [s]
- T30 [s]
- C80 [dB]
- D50 --
- Ts [ms]
- LF --
- √ LFC --
- IACC --

$$LFC = \frac{\int_{0.005s}^{0.080s} \left| p_L(t) \cdot p(t) \right| dt}{\int_{0}^{0.080s} p^2(t)\, dt} \left[-\right]$$

Inter Aural Cross Correlation
IACC

- G [dB]
- EDT [s]
- T_{20} [s]
- T_{30} [s]
- C_{80} [dB]
- D_{50} --
- Ts [ms]
- LF --
- LFC --
- ✓ IACC --
- STI --

$$\mathrm{IACF}_{t1,t2} = \frac{\int_{t1}^{t2} \left| p_L(t) \cdot p_R(t+\tau) \right| dt}{\sqrt{\int_{t1}^{t2} p_L^{\,2}(t)\,dt \cdot \int_{t1}^{t2} p_R^{\,2}(t)\,dt}}$$

$$\mathrm{IACC}_{t1,t2} = \max \left| \mathrm{IACF}_{t1,t2}(\tau) \right| \quad \begin{matrix} \tau > -1\,\mathrm{ms} \\ \tau < +1\,\mathrm{ms} \end{matrix}$$

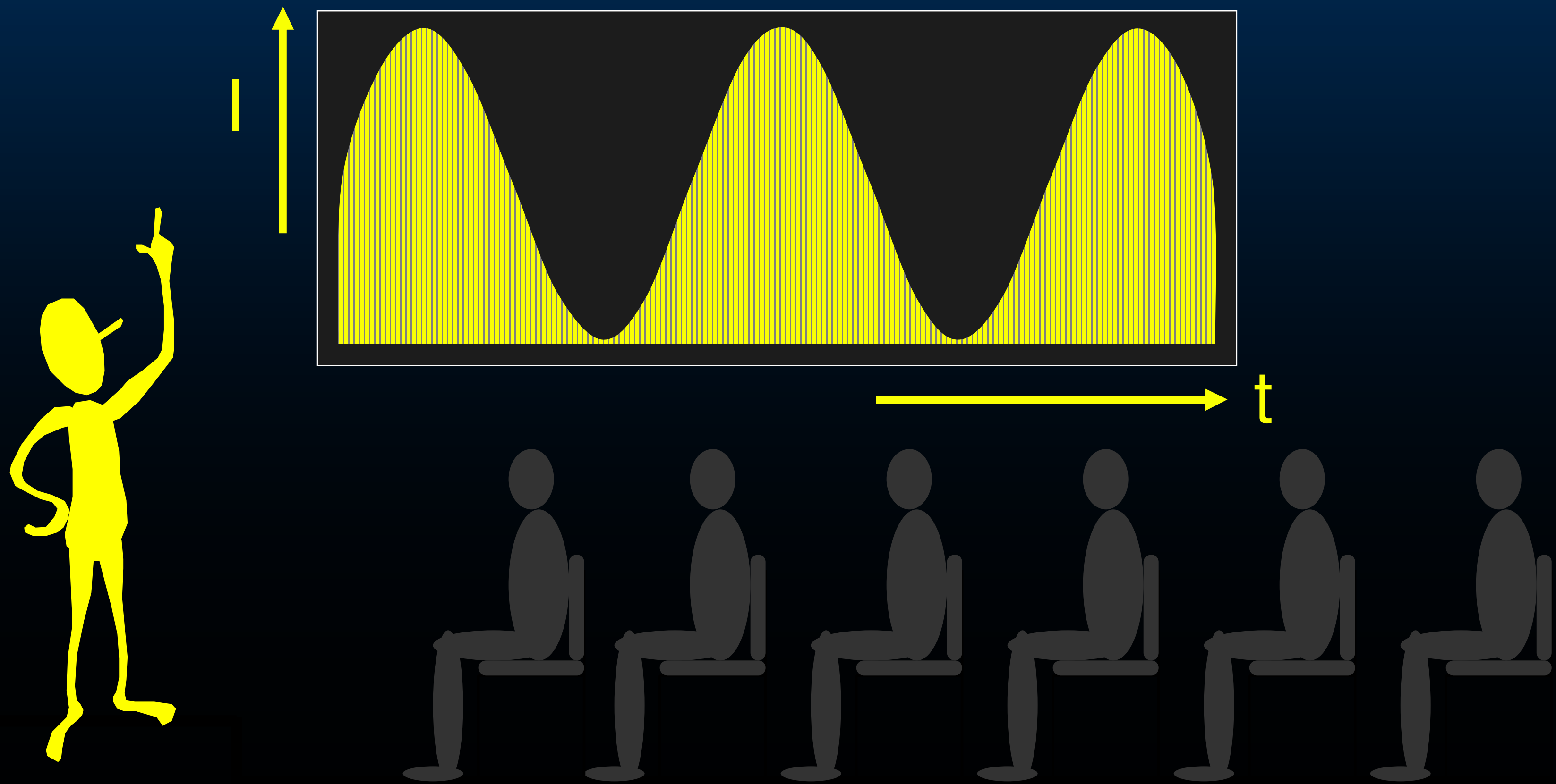
Speech Intelligibility

- G [dB]
- EDT [s]
- T20 [s]
- T30 [s]
- C80 [dB]
- D50 --
- Ts [ms]
- LF --
- LFC --
- IACC --
- ✓ STI --

$$m(F)=\frac{\int_{-\infty}^{\infty} p^2(t)\cdot e^{-j2\pi Ft}\,dt}{\int_{-\infty}^{\infty} p^2(t)\,dt}\,[-]$$

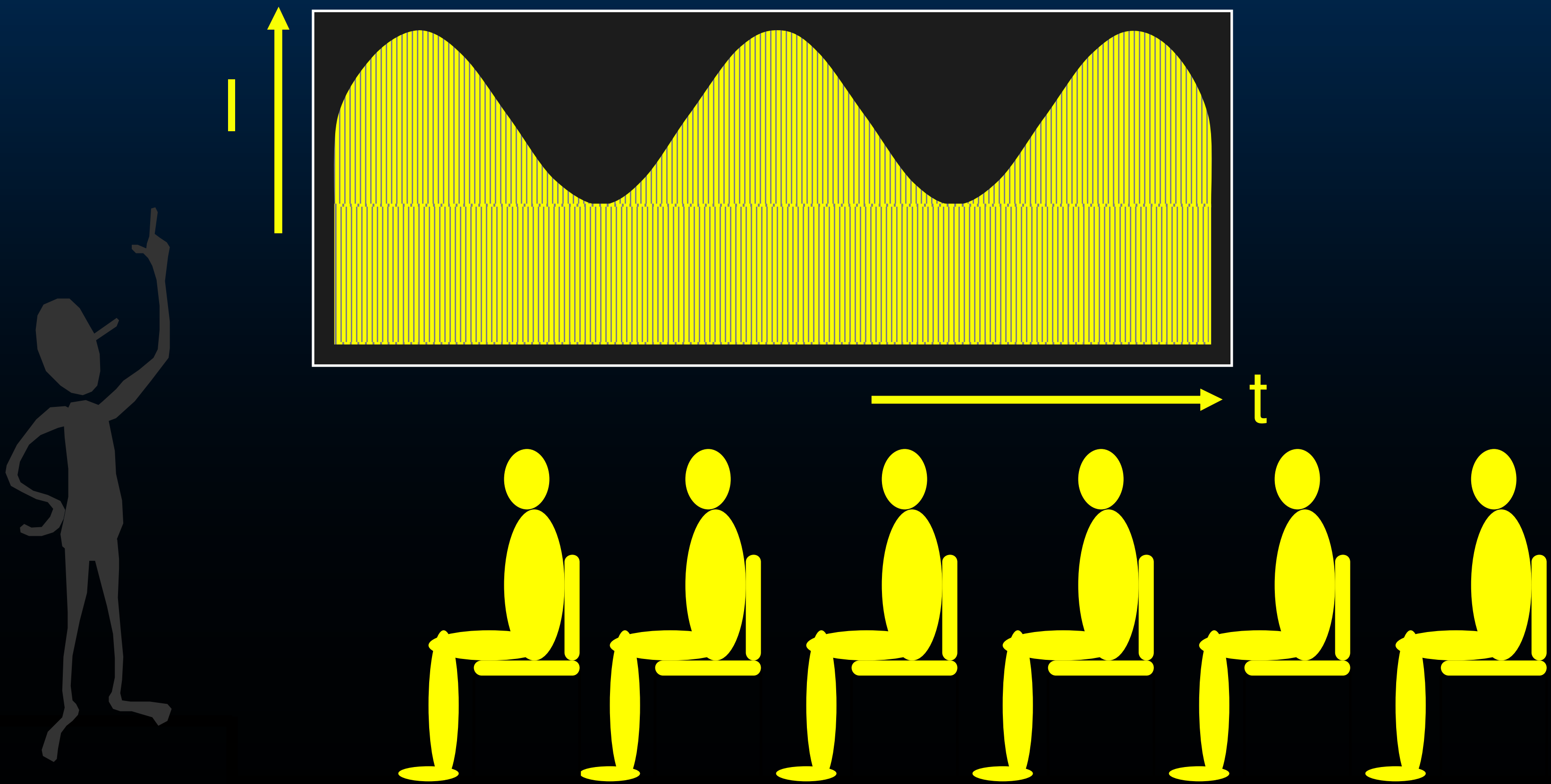
Speech Transmission Index

Signal modulation reduction



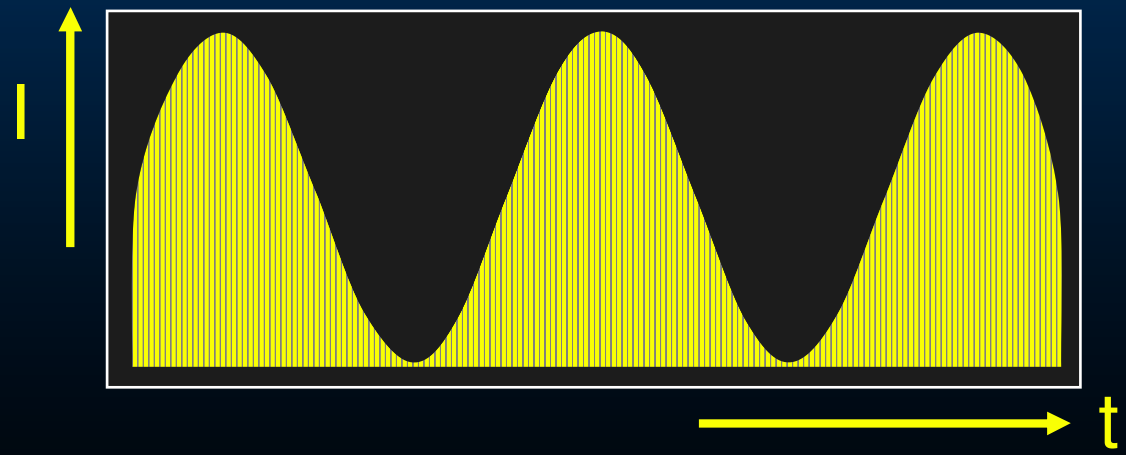
Speech Transmission Index

Signal modulation reduction



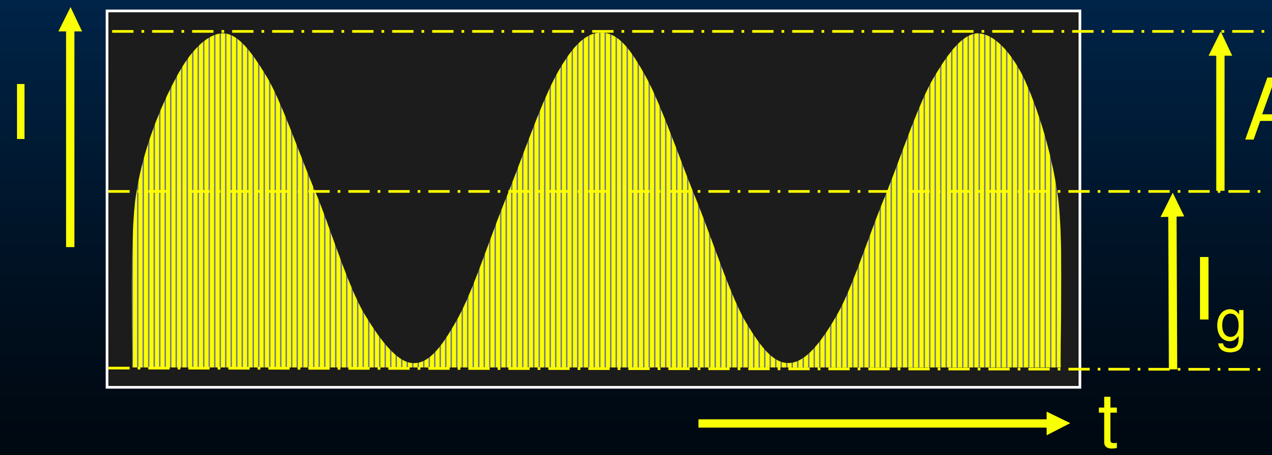
Speech Transmission Index

Modulation reduction



Speech Transmission Index

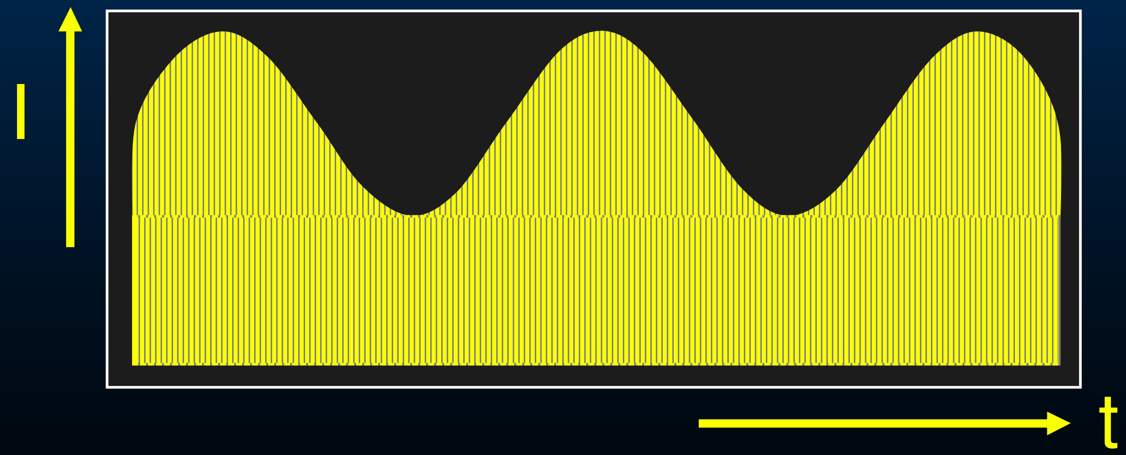
Modulation reduction



$$m = \frac{A}{I_g} = 1$$

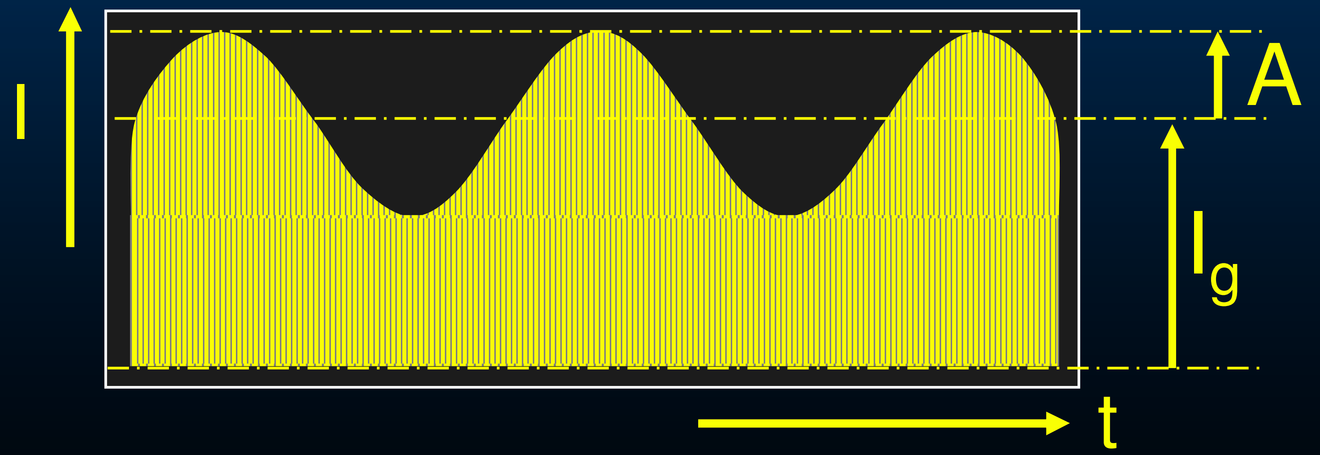
Speech Transmission Index

Modulation reduction



Speech Transmission Index

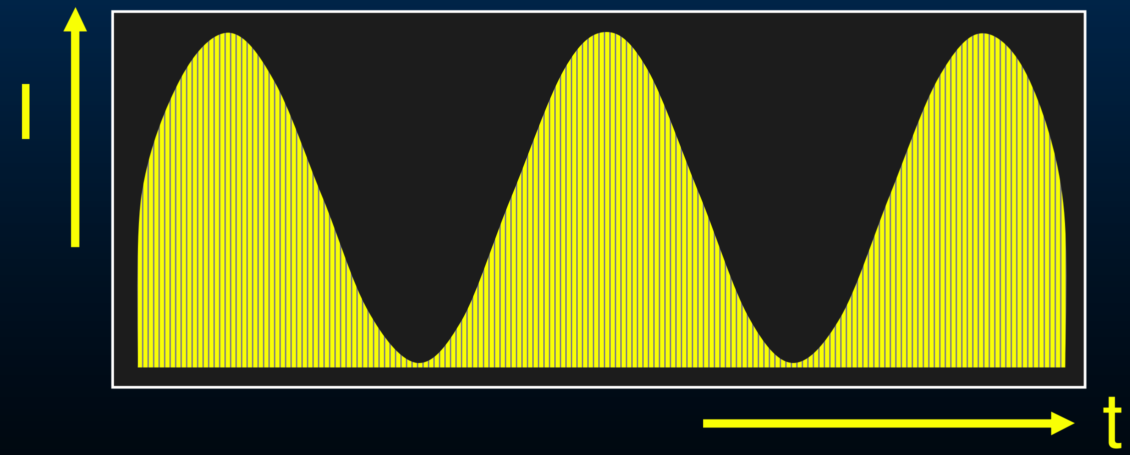
Modulation reduction



$$m = \frac{A}{I_g} < 1$$

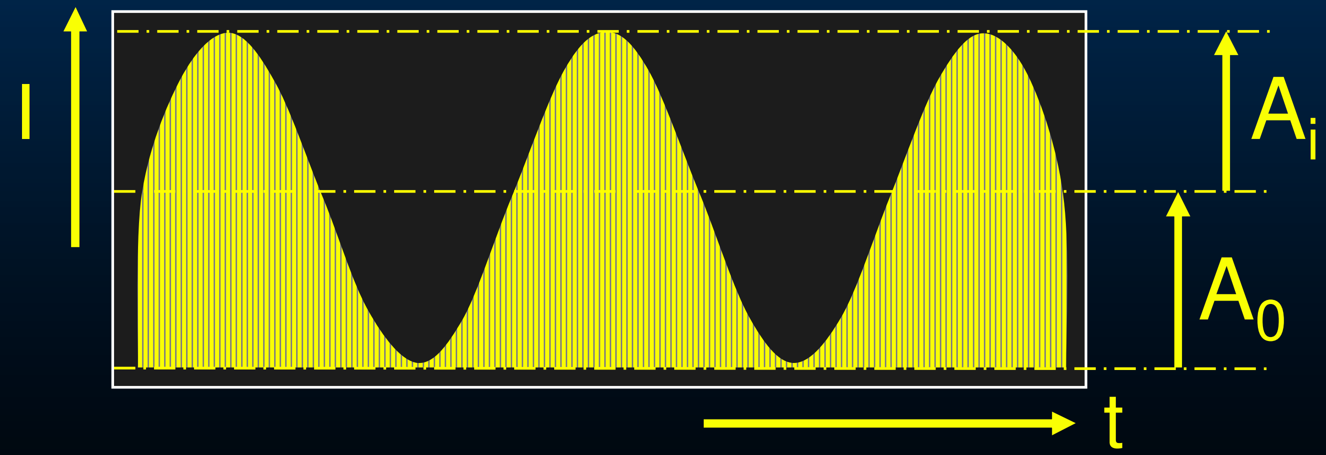
Speech Transmission Index

Modulation reduction



Speech Transmission Index

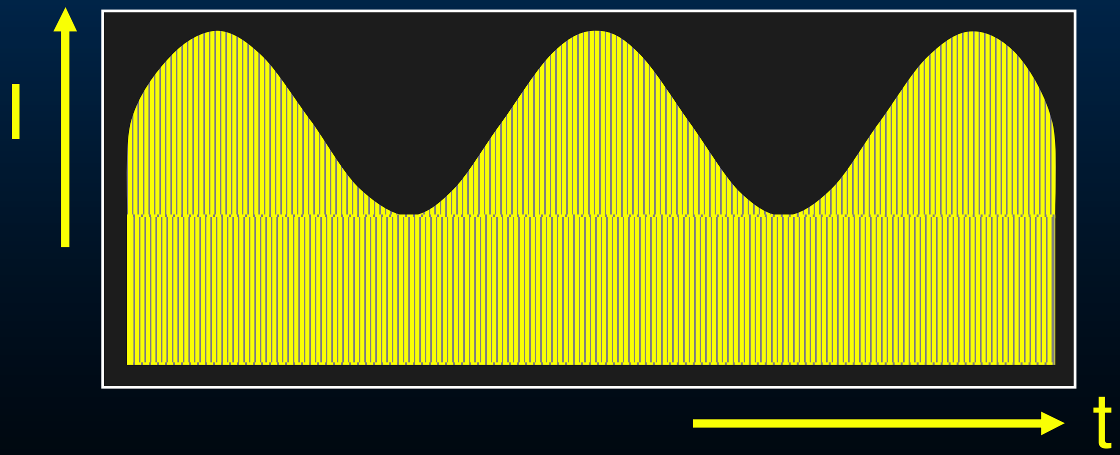
Modulation reduction



$$m = \frac{A_i}{A_0} = 1$$

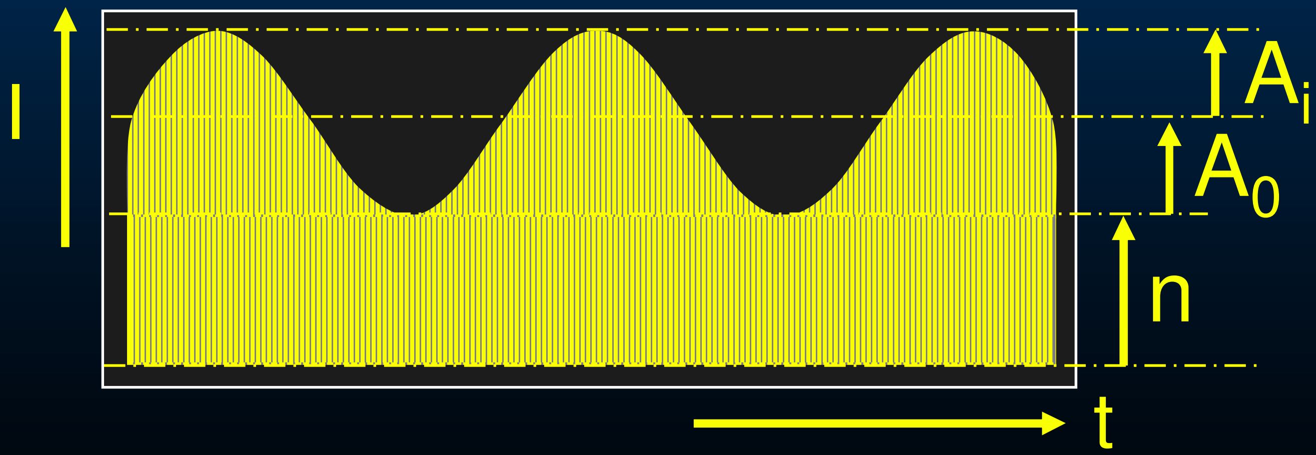
Speech Transmission Index

Modulation reduction



Speech Transmission Index

Modulation reduction

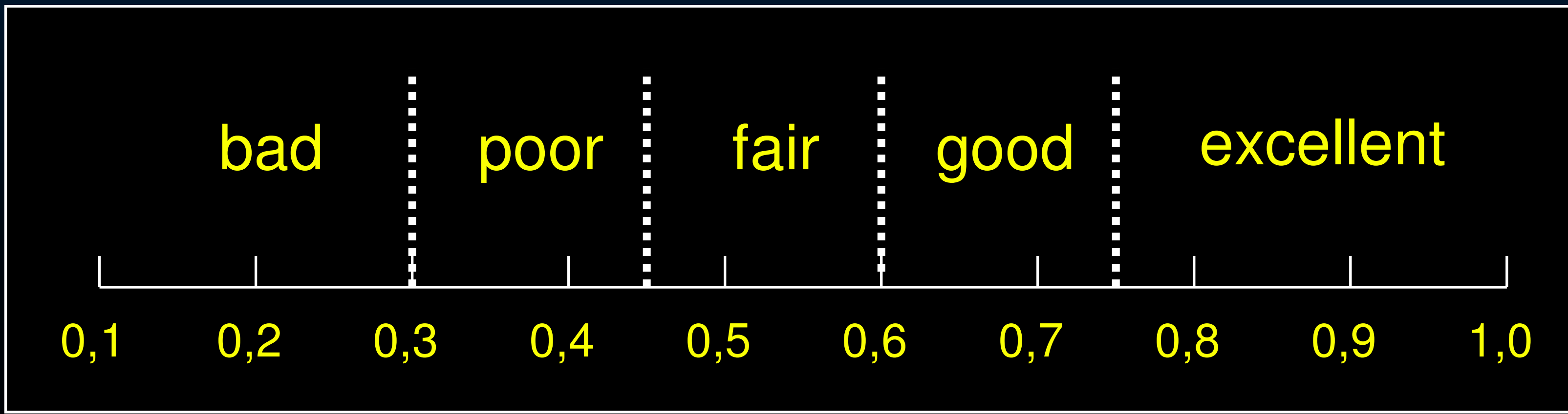


$$m = \frac{A_i}{A_0 + n} < 1$$

Speech Intelligibility

Speech Transmission Index: STI

$$0 < STI < 1$$



$$m(F) = \frac{\int_{-\infty}^{\infty} p^2(t) \cdot e^{-j2\pi F t} dt}{\int_{-\infty}^{\infty} p^2(t) dt} [-]$$