

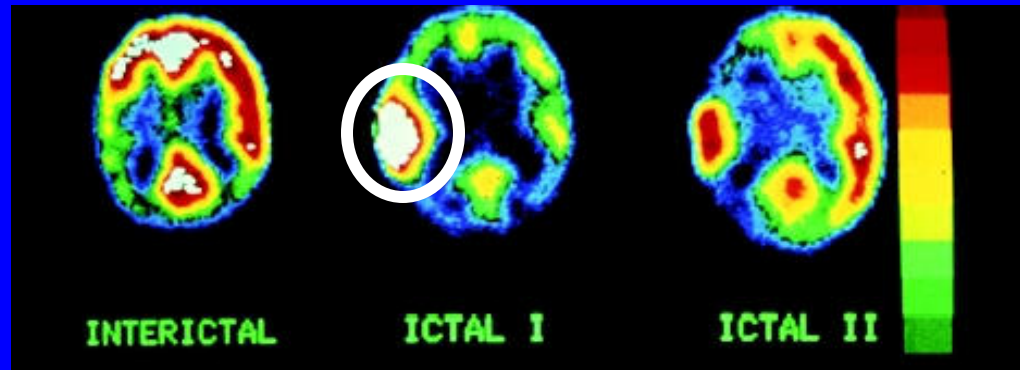
# **A Micro-power EEG Acquisition SoC with Integrated Seizure Detection Processor for Continuous Patient Monitoring**

**Naveen Verma, Ali Shoeb, John Gutttag, and  
Anantha Chandrakasan**

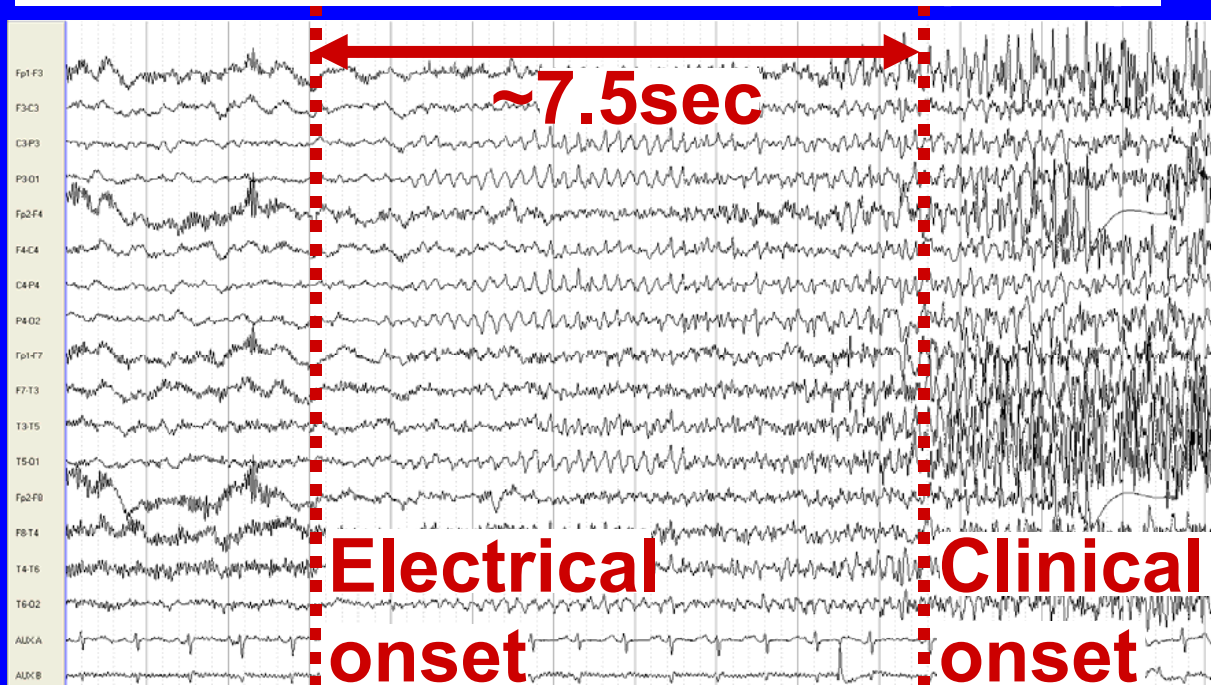
***Massachusetts Institute of Technology***

**2009 Symposium on VLSI Circuits**

# Epilepsy



## On-scalp Field Potentials (EEG):



## Electrical Onset:

- Abnormal EEG observed at scalp

## Clinical Onset:

- Convulsions cause muscle artifacts

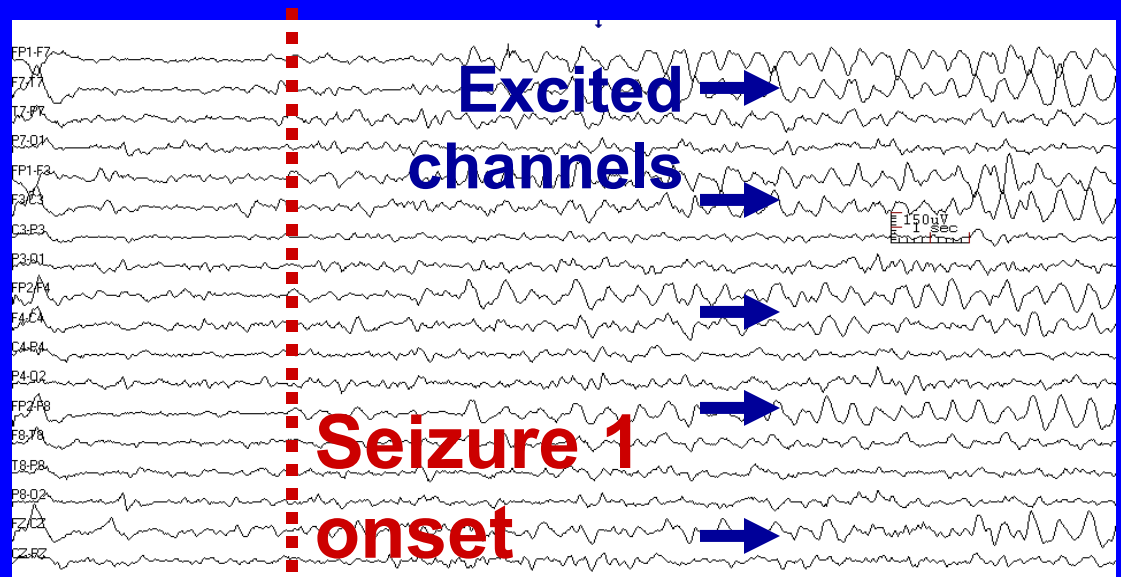
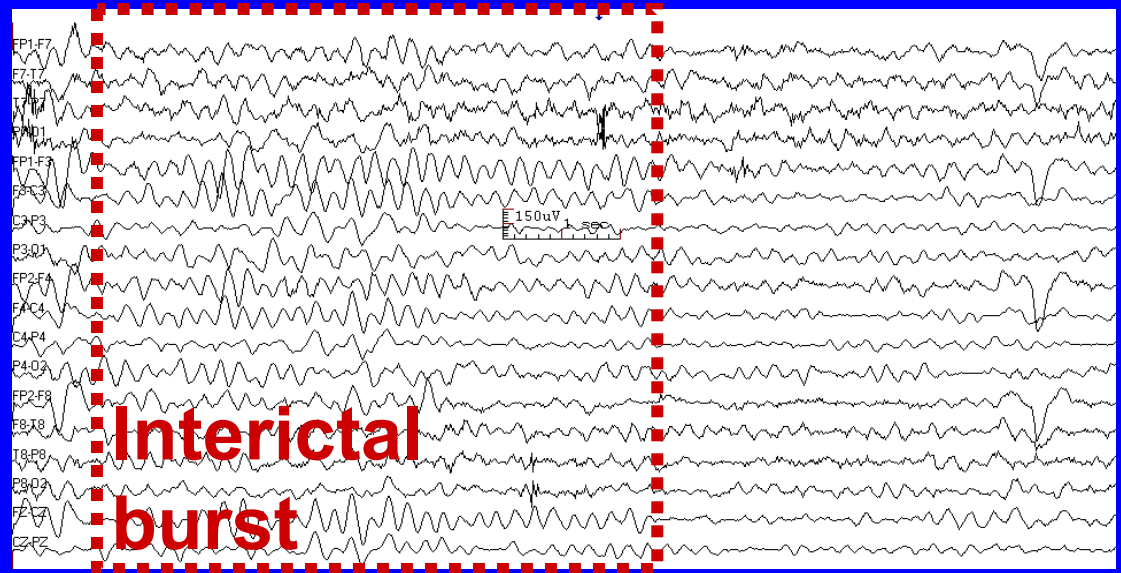
# Outline

- **Seizure detection algorithm**
- **Patient monitoring system approach**
- **Sensing and processing hardware**
  - **Instrumentation amplifier**
  - **ADC**
  - **Feature extraction processor**
- **System tests**

# Need for Patient-Specific Learning

Patient A:

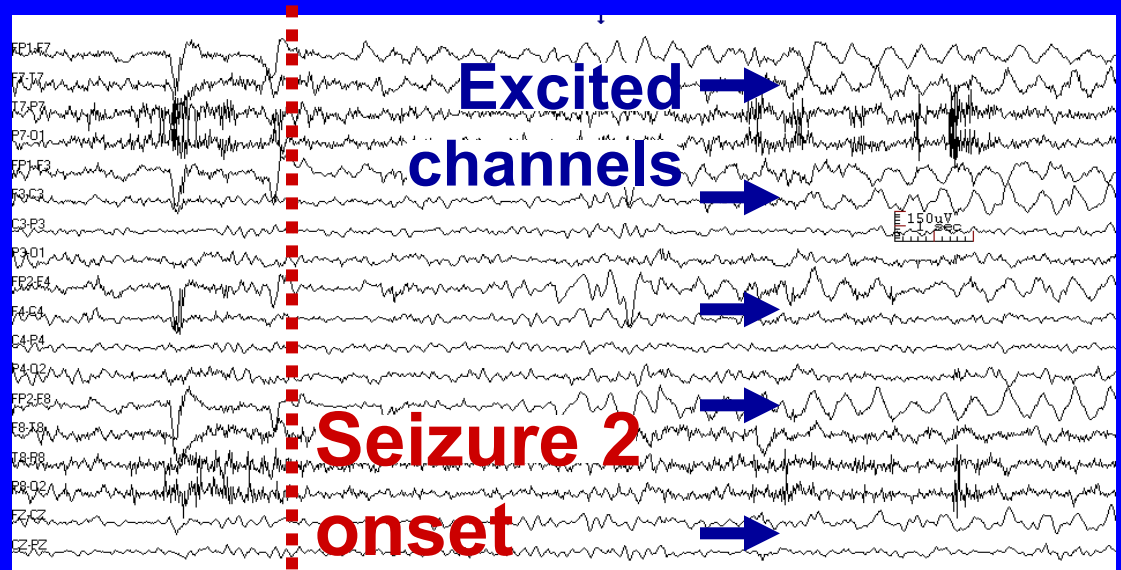
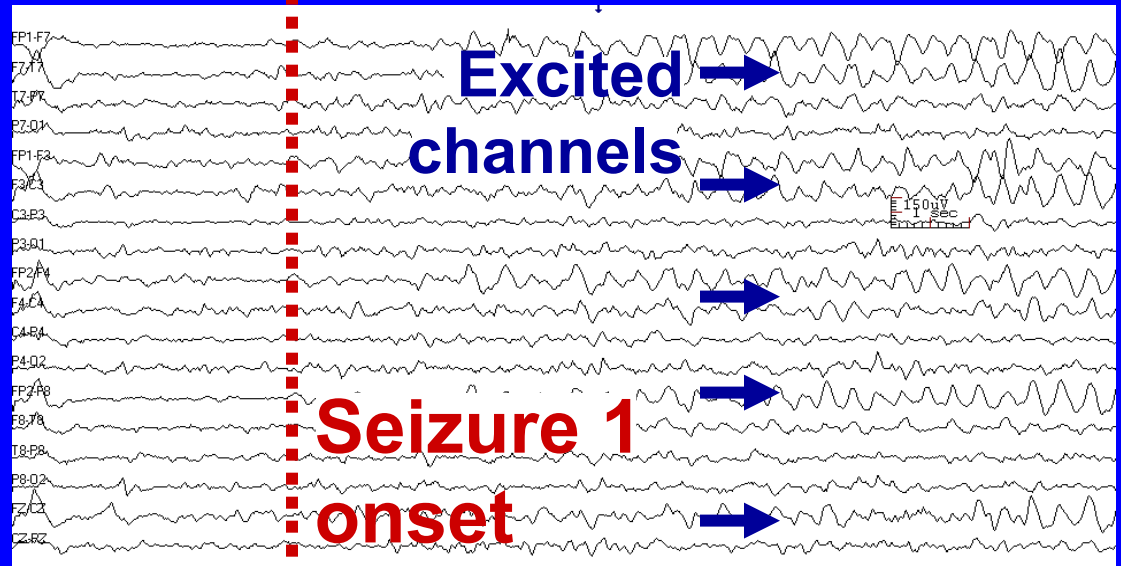
*Combine spectral  
and (patient-specific)  
spatial information  
for high specificity*



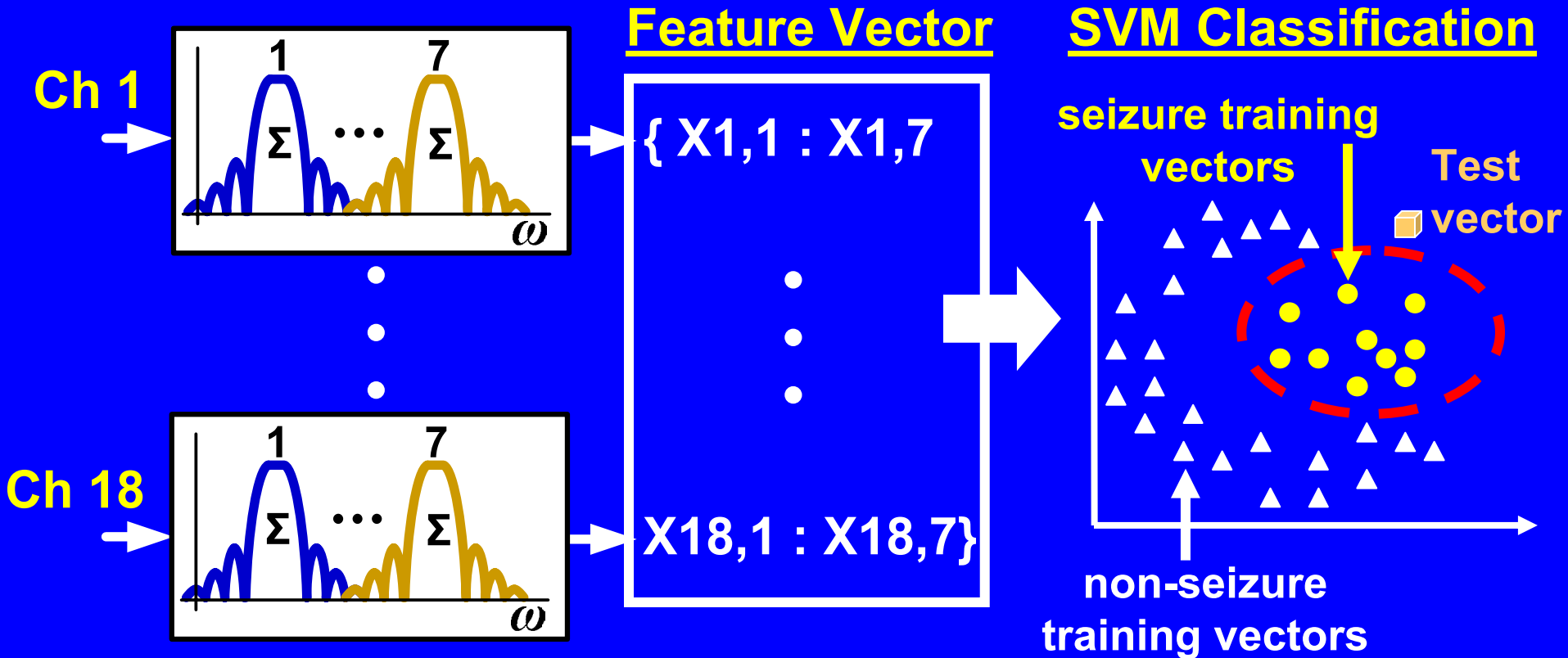
# Need for Patient-Specific Learning

Patient A:

*Algorithm must learn patient's seizure and background activity*



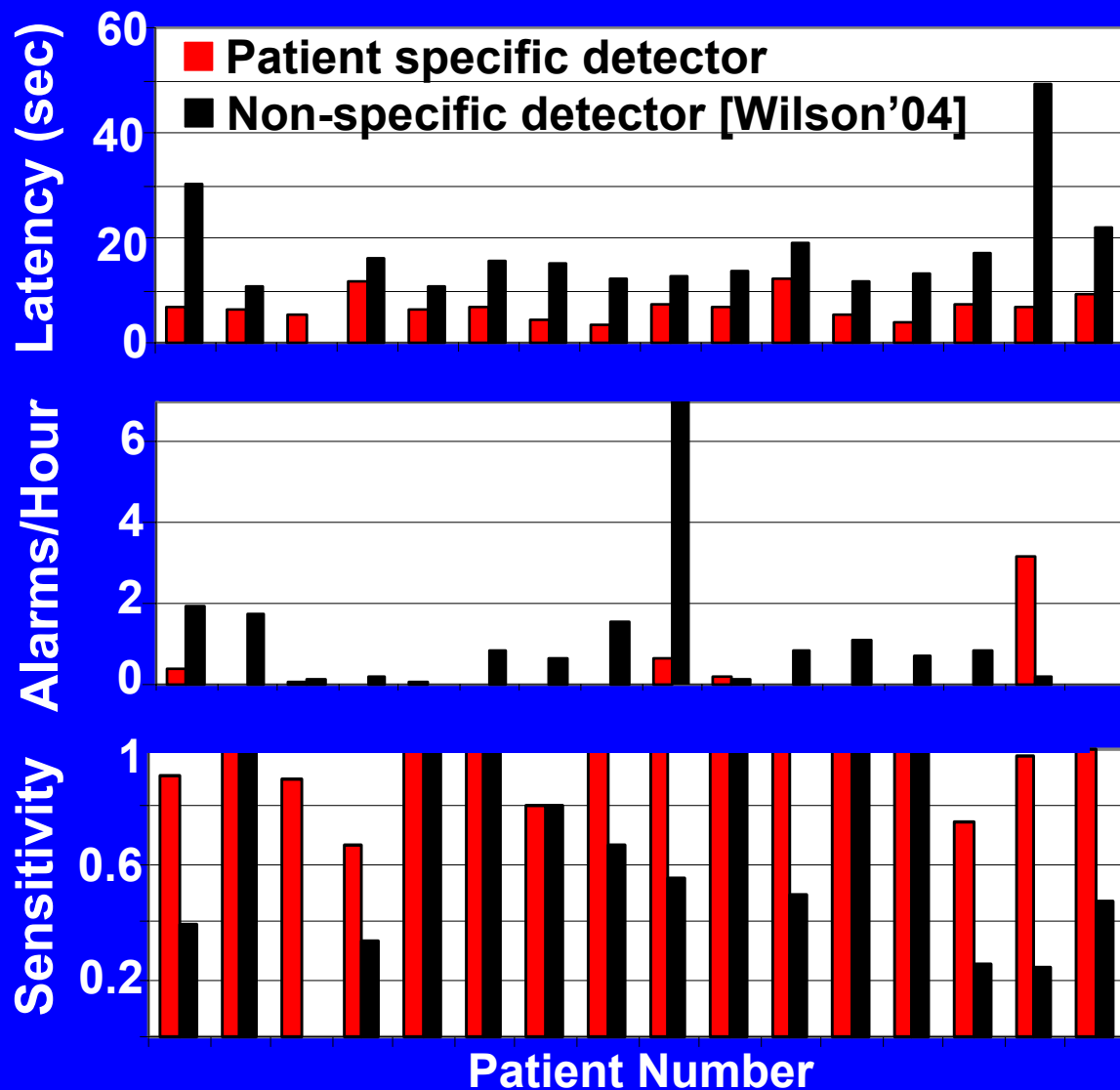
# Patient-Specific Detection Algorithm



*Support vector machine (SVM) is trained to determine optimal patient-specific decision boundary*

# Algorithm Validation

Patient test results (Boston Children's Hospital, 536 hours):



## Latency:

- Specific:  $6.77 \pm 3.0$  sec
- Non-sp.:  $30.1 \pm 15$  sec

## Specificity:

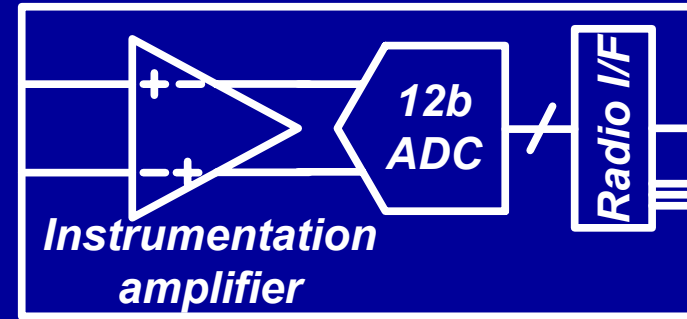
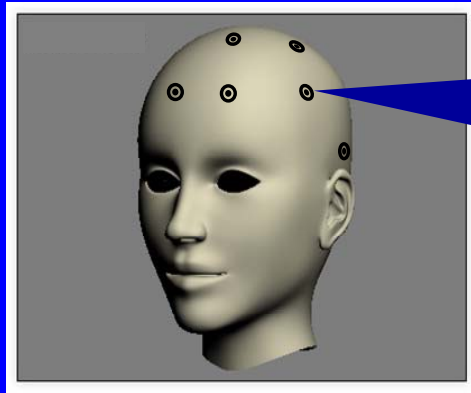
- Specific:  $0.3 \pm 0.7$  /hr
- Non-sp.:  $2.0 \pm 5.3$  /hr

## Sensitivity:

- Specific: 0.93
- Non-sp.: 0.66

[Shoeb, EMBC'07]

# System Approach- Wireless EEG



## 18 Channel recording:

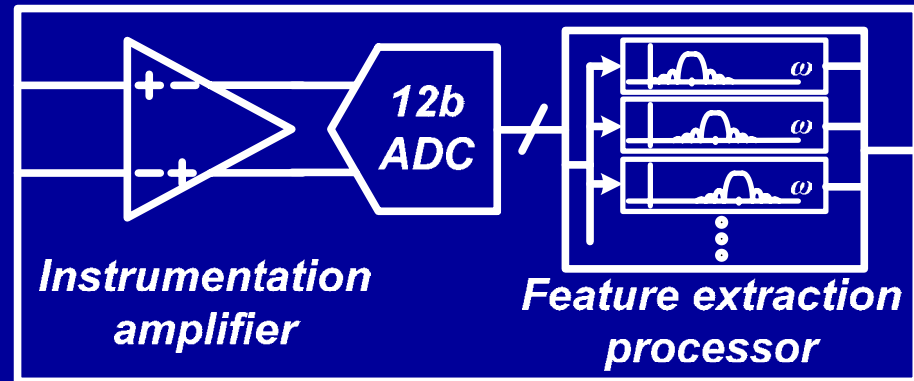
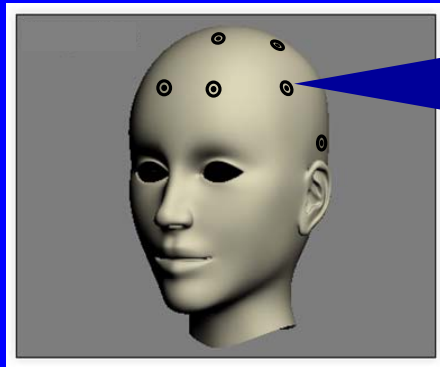
	Wireless EEG Power
Inst. amps	72 $\mu$ W
ADCs (12b, 11kS/s)	3 $\mu$ W
Radio (CC2550)	<b>1733 <math>\mu</math>W</b>
Total	1808 $\mu$ W

- **Start-up: 4.8  $\mu$ W**
- **Active: 43.2kb/s\*40nJ/b**
- **Idle-mode: 0.46 $\mu$ W**



***Recording cables are unsafe during patient convulsions,  
but for wireless EEG, radio power dominates***

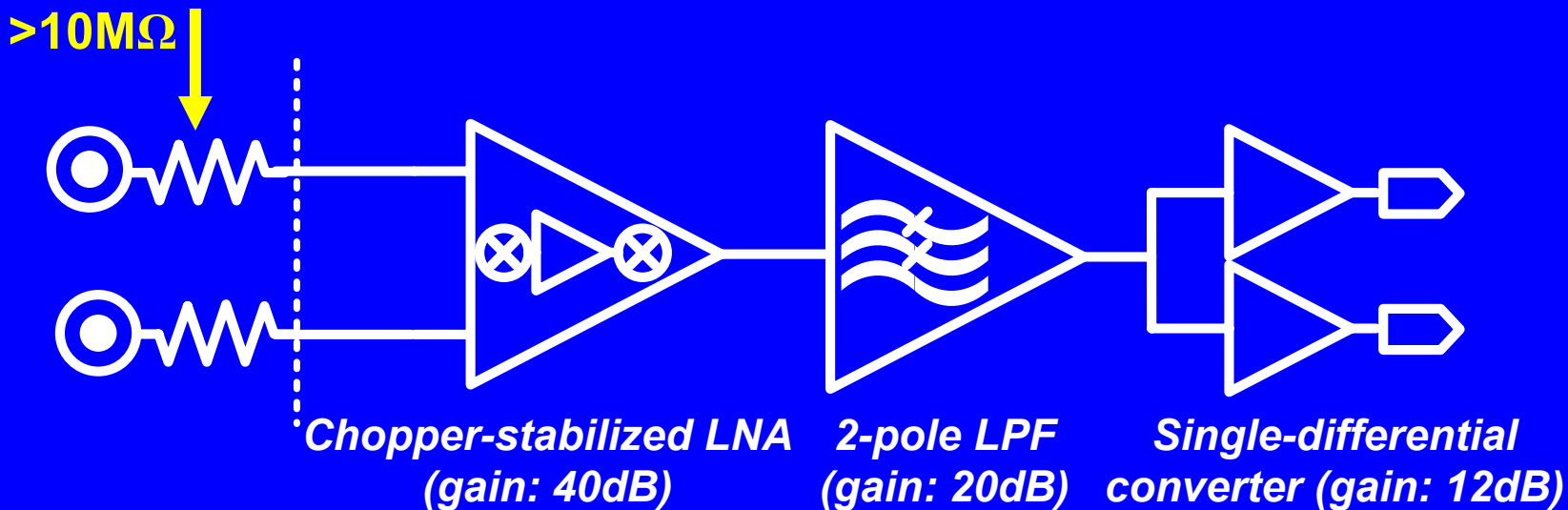
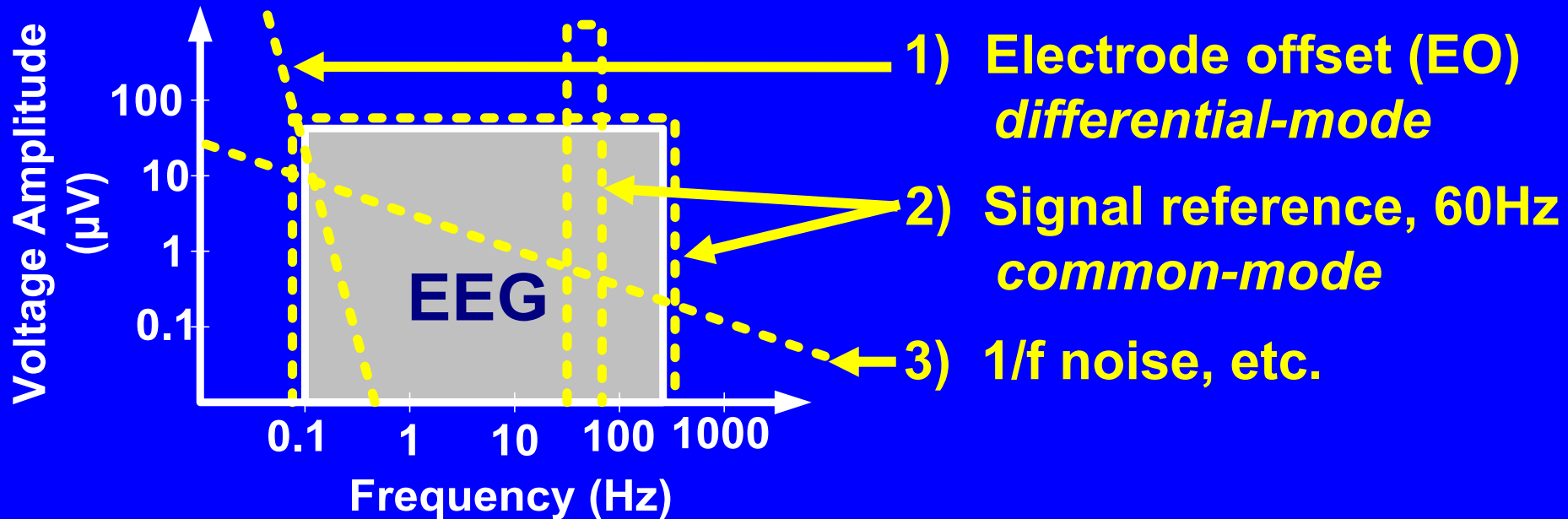
# Local Feature Vector Extraction



	Wireless EEG	Local feature extraction
Inst. amps	72 $\mu$ W	72 $\mu$ W
ADCs (12b, 11kS/s)	3 $\mu$ W	3 $\mu$ W
Digital processing	--	2.1 $\mu$ W
Radio (CC2550)	1733 $\mu$ W	43 $\mu$ W
Total	1808 $\mu$ W	120 $\mu$ W

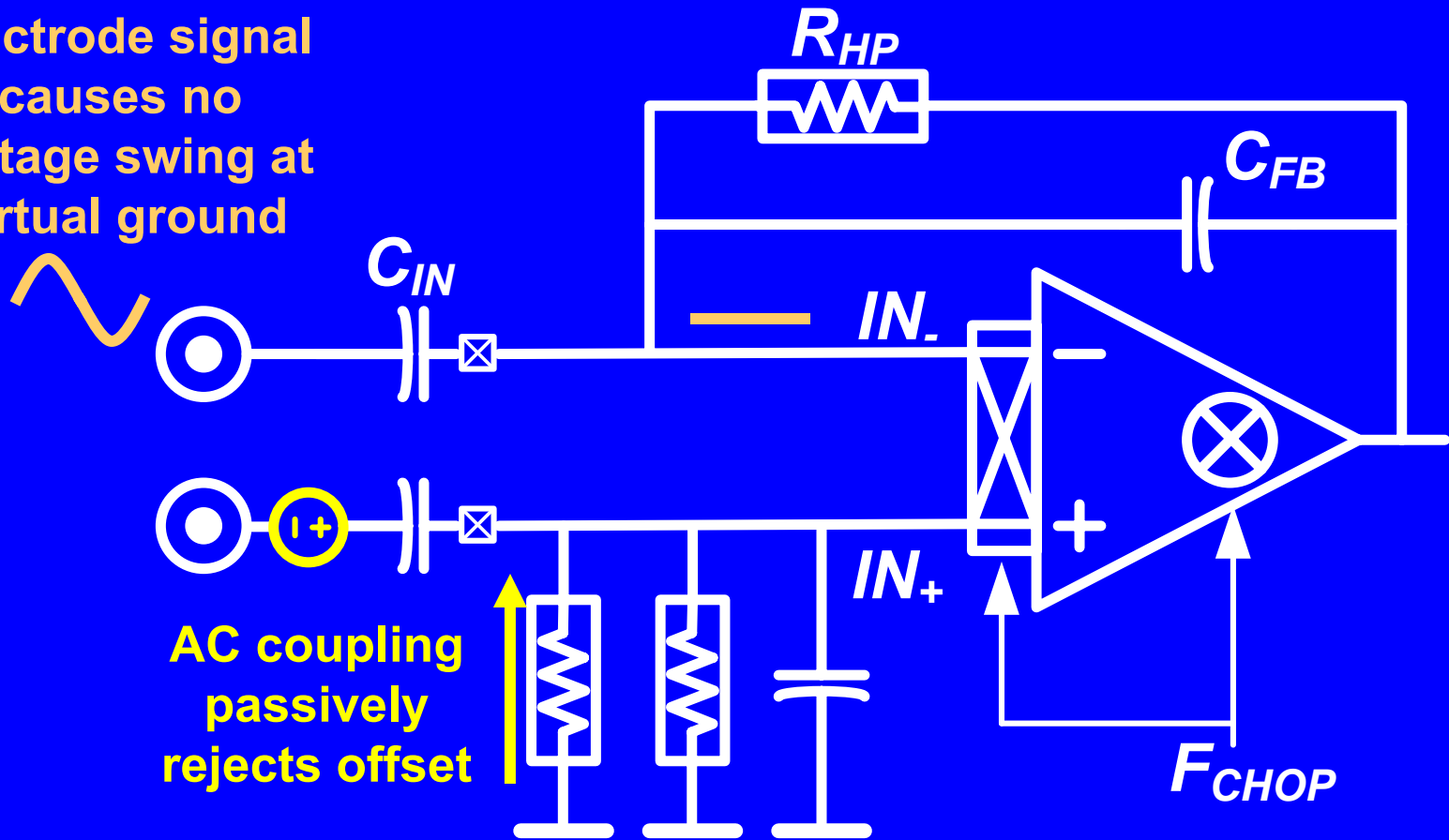
**Local feature extraction reduces data rate by 43x, total system power by 14x**

# Inst. Amp Architecture/Needs



# Chopper LNA

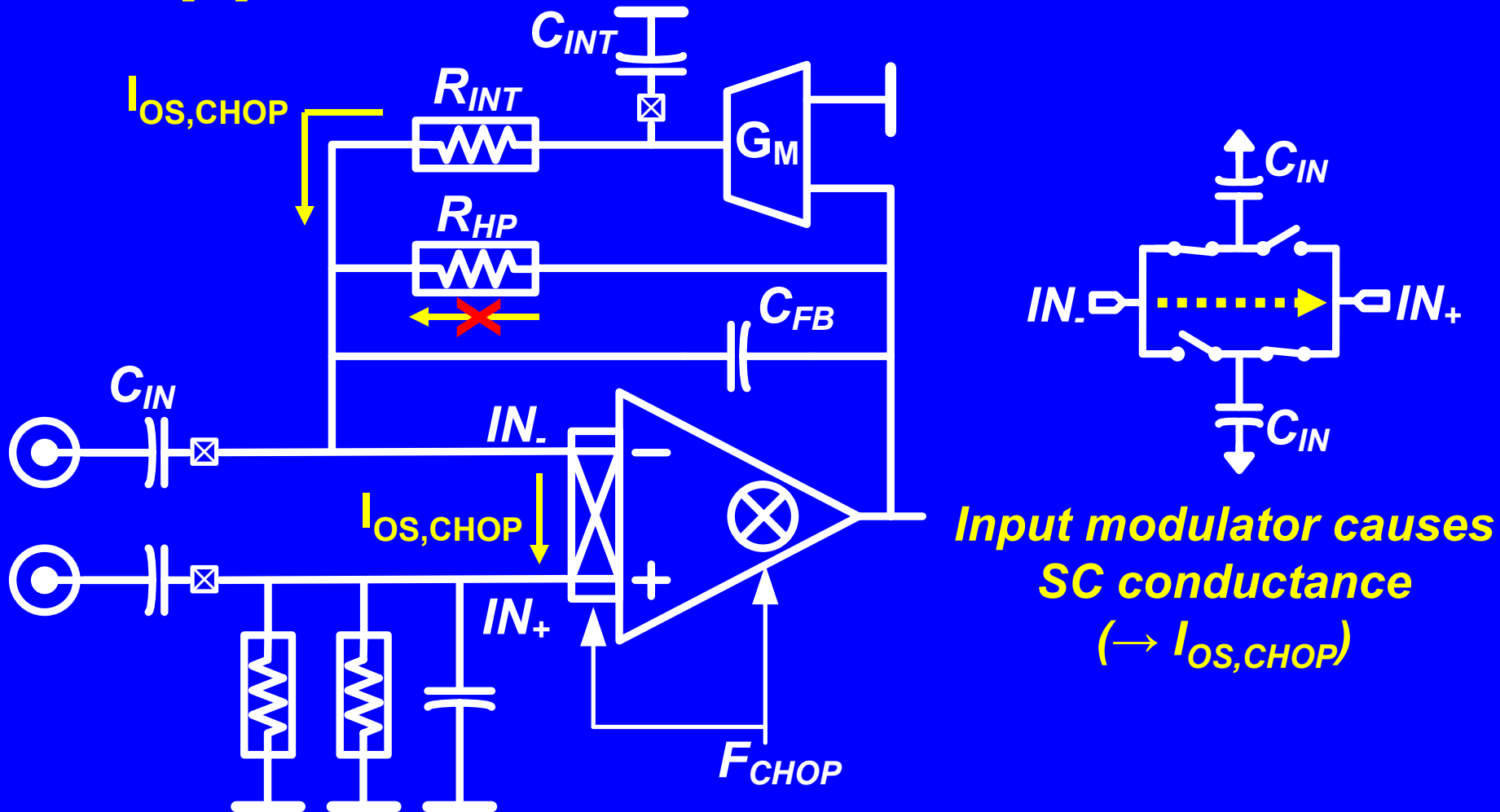
Electrode signal causes no voltage swing at virtual ground



AC coupling passively rejects offset

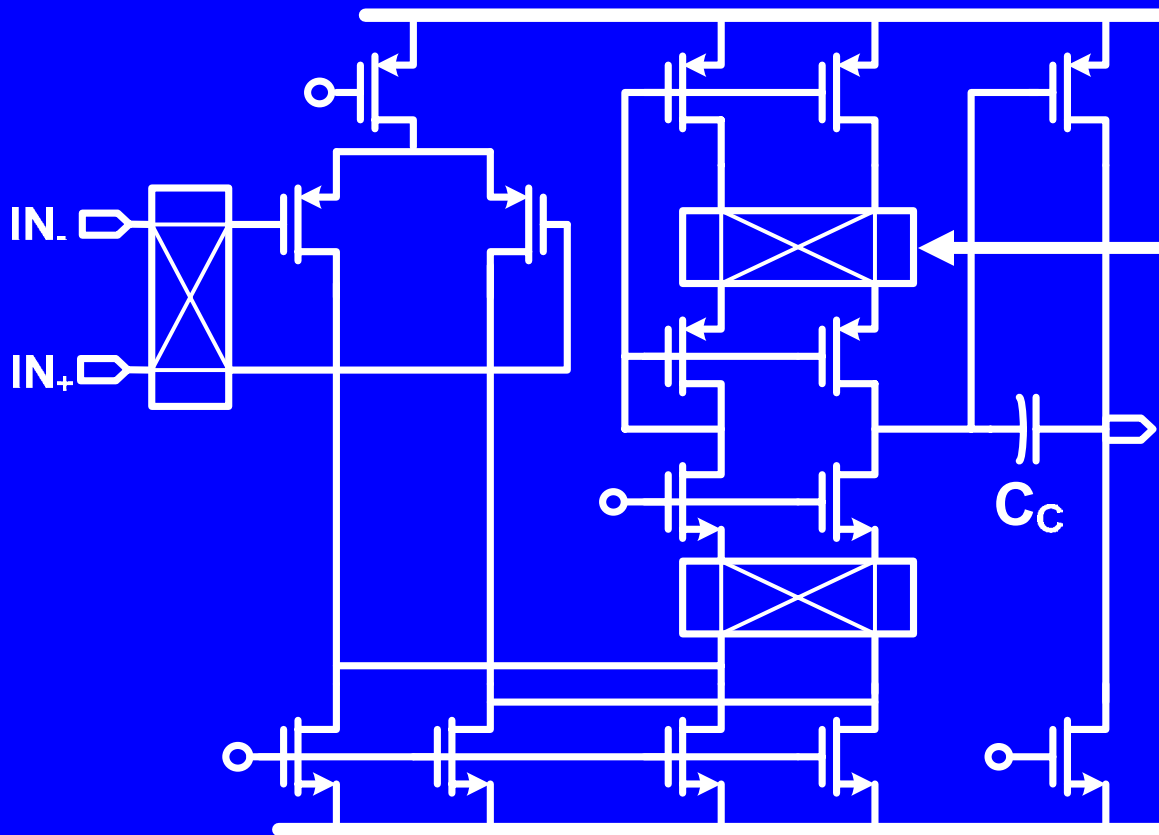
- 1) *Passive EO rejection enables low  $V_{DD}$*
- 2) *Modulator at virtual ground does not load electrodes*

# Chopper LNA



**$G_M$ -C Servo loop provides chopping offset current to avoid saturation through  $R_{HP}$**

# Chopper LNA Op-Amp



Demodulate before  
dominant-pole:  
Chopping does not  
limit BW

[Denison, ISSCC'07]

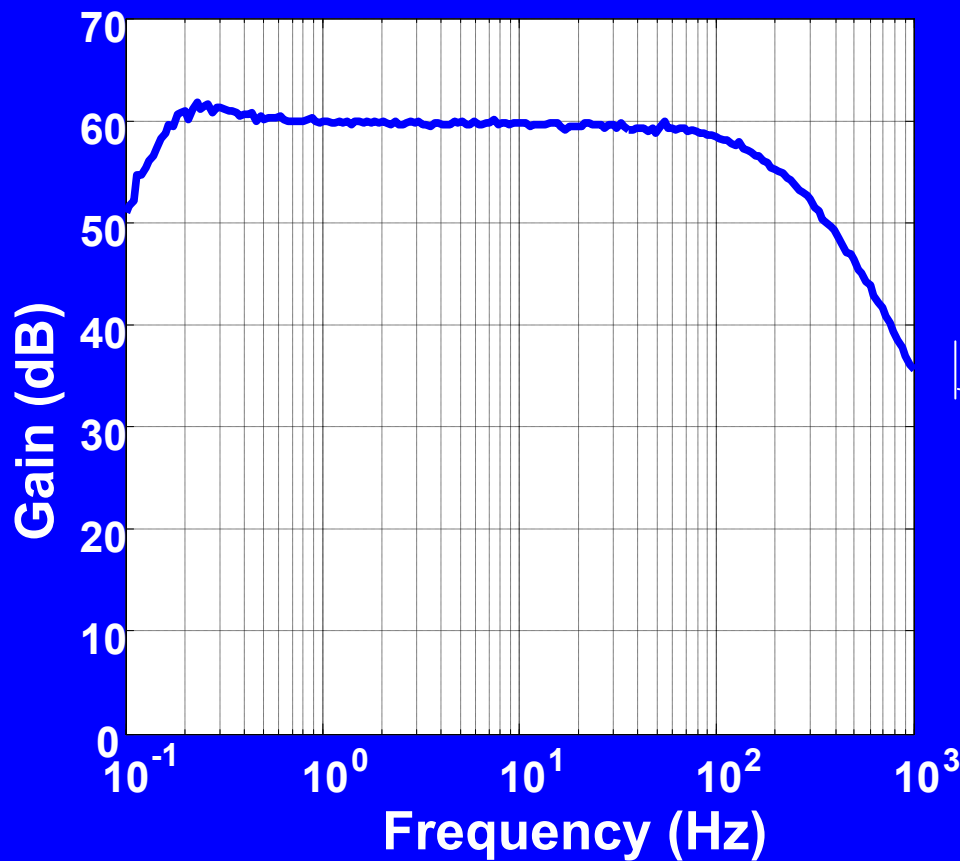
Op-amp achieves good noise-efficiency:

- 1) Low  $V_{DD}$  ( $<1V$ )  $\rightarrow$  EO rejected by AC coupling
- 2) Current of 1<sup>st</sup> diff. stage dominates  $\rightarrow$  high CL stability

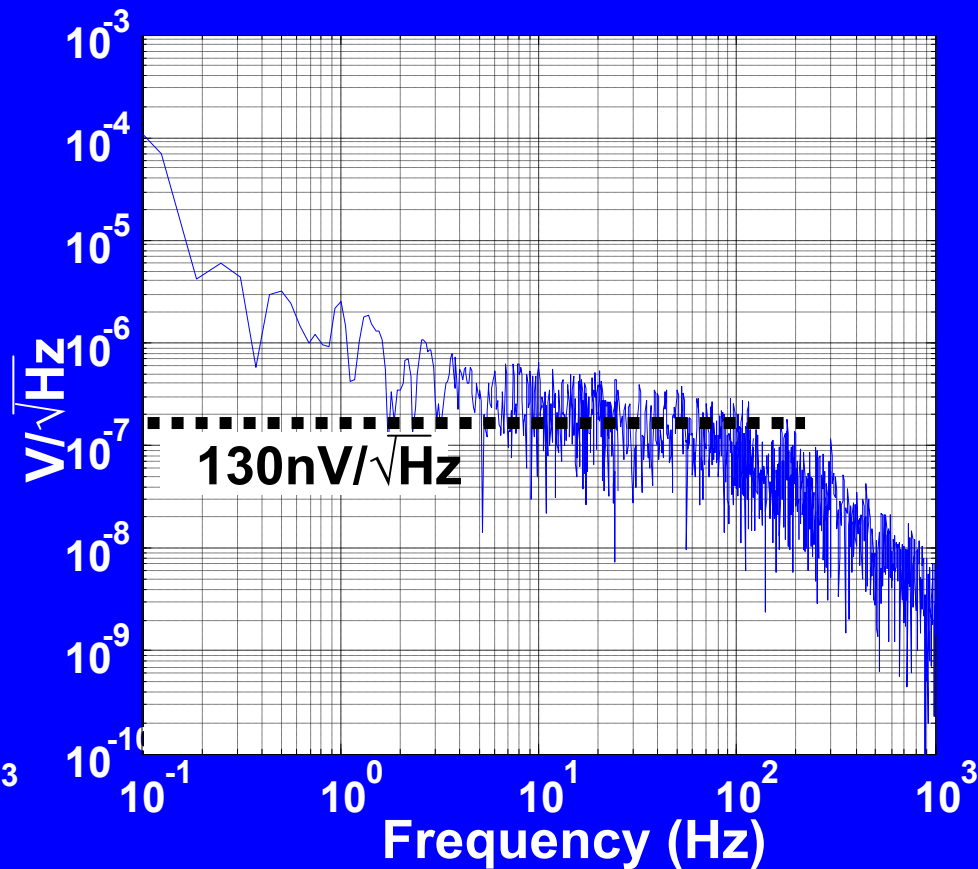
# Inst. Amp. Measurements

- LNA power:  $3.5\mu\text{W}$
- CMRR: 60dB
- $R_{IN}$ :  $700\text{M}\Omega$
- Noise:  $1.3\mu\text{V}_{\text{rms}}$  (0.5-100Hz)

## Output Response

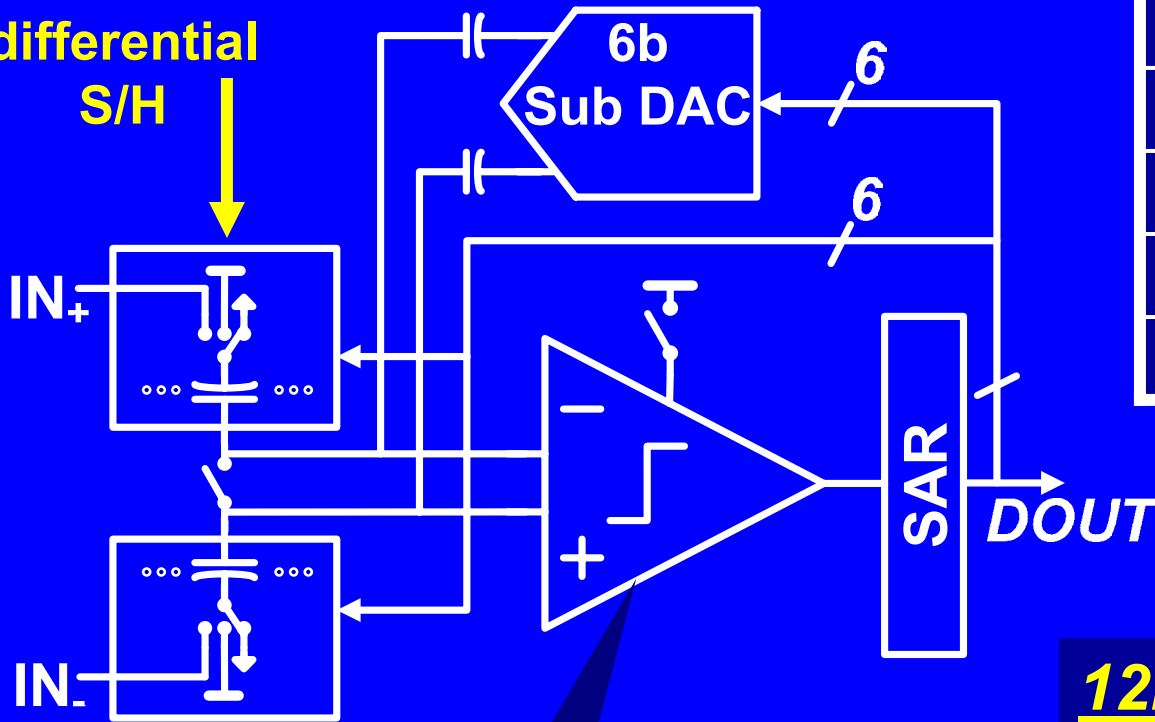


## Noise (input referred)



# 12b SAR ADC

Passive differential S/H



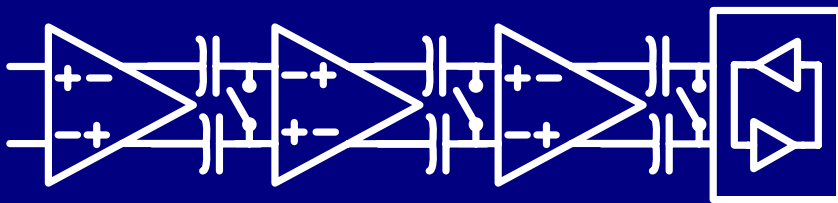
$V_{DD}$	1V
Max. Fs.	100kS/s
Energy/Conv.	250pJ
INL	0.68LSB
SNDR	65.3dB
ENOB	10.55b

[Verma, ISSCC'06]

12b SAR ADC uses

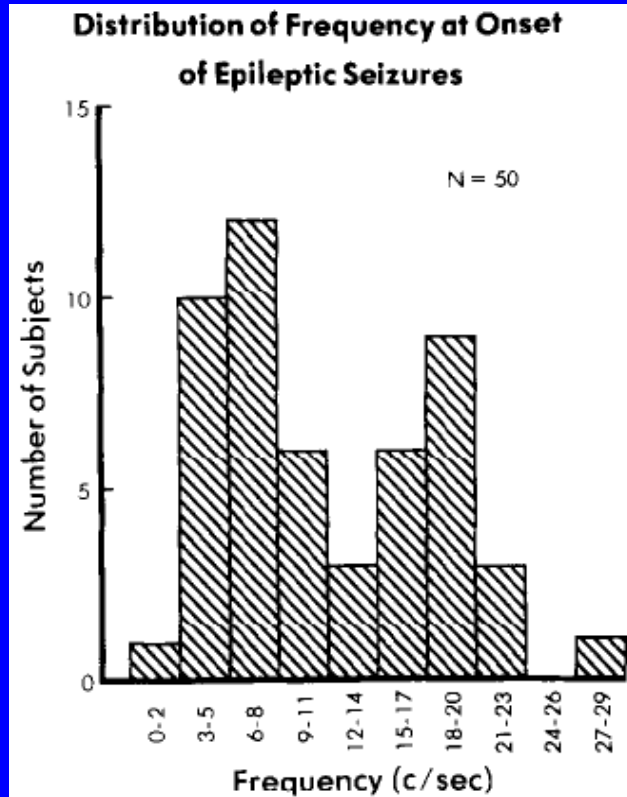
-Three stage pre-amp comparator

-Fully differential architecture

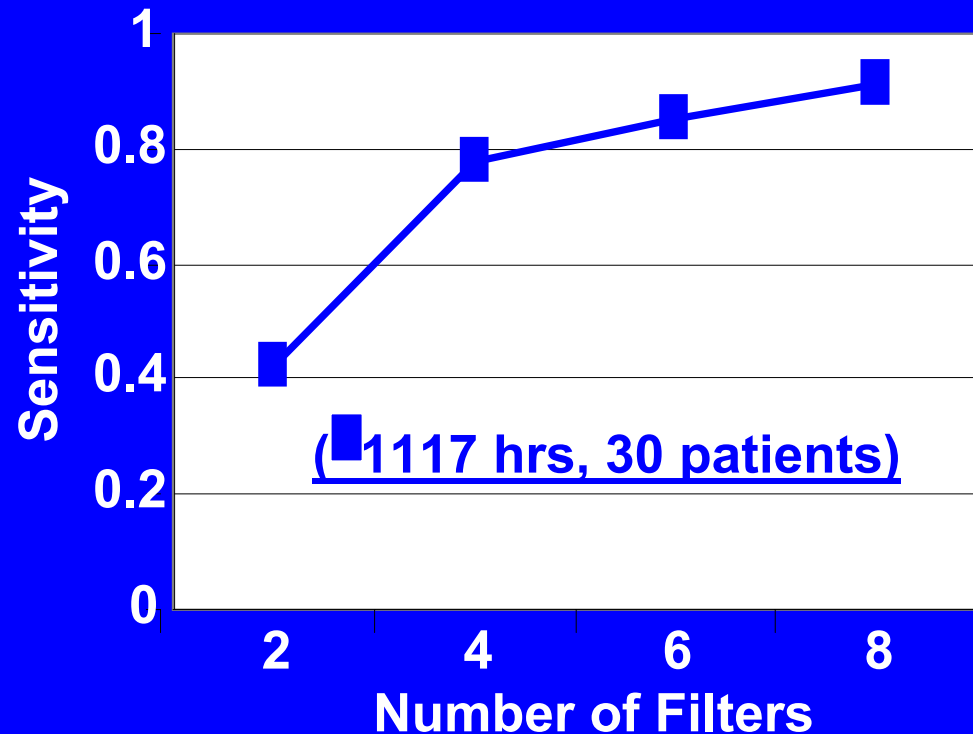
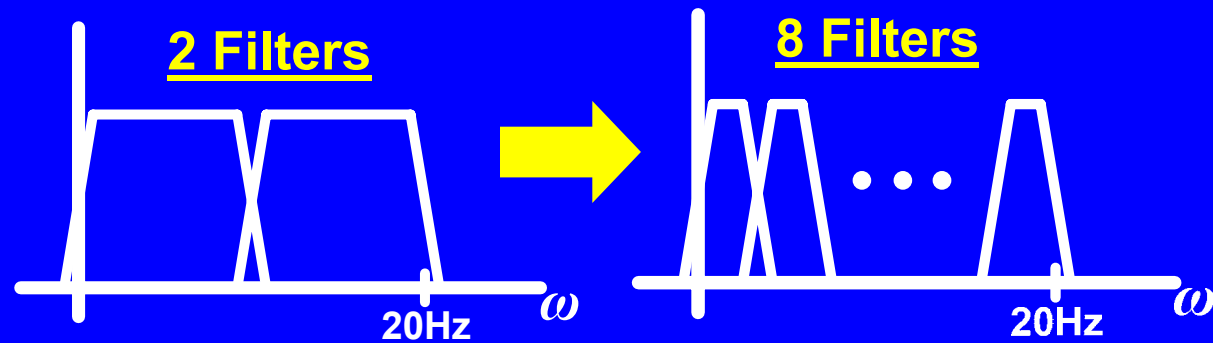


# EEG Spectral Analysis

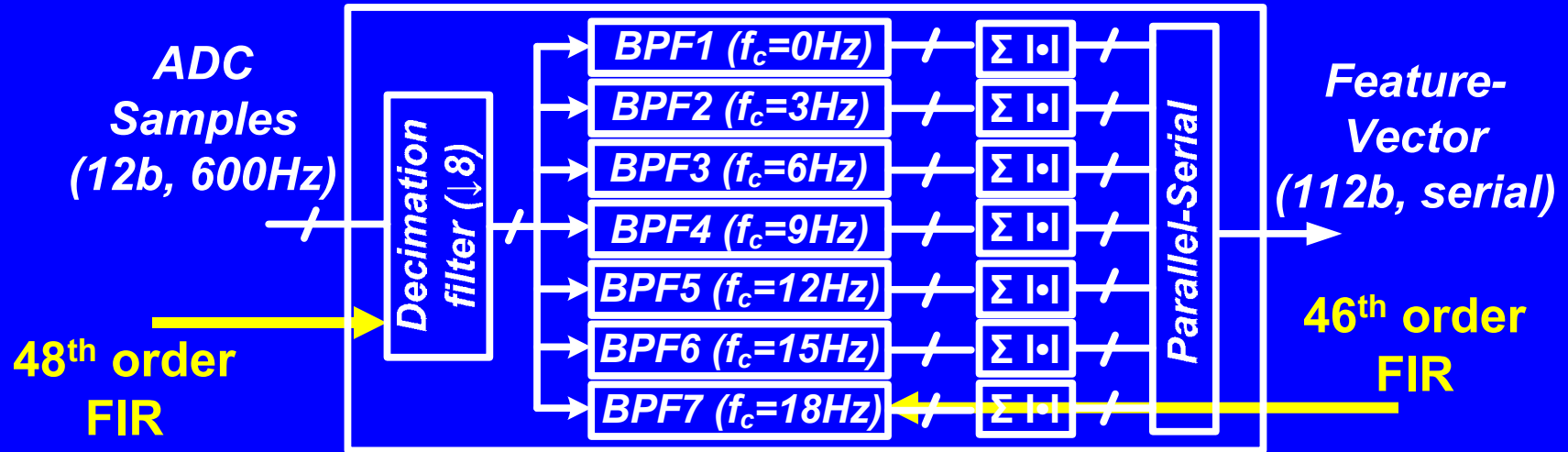
## Need for Spectral Resolution:



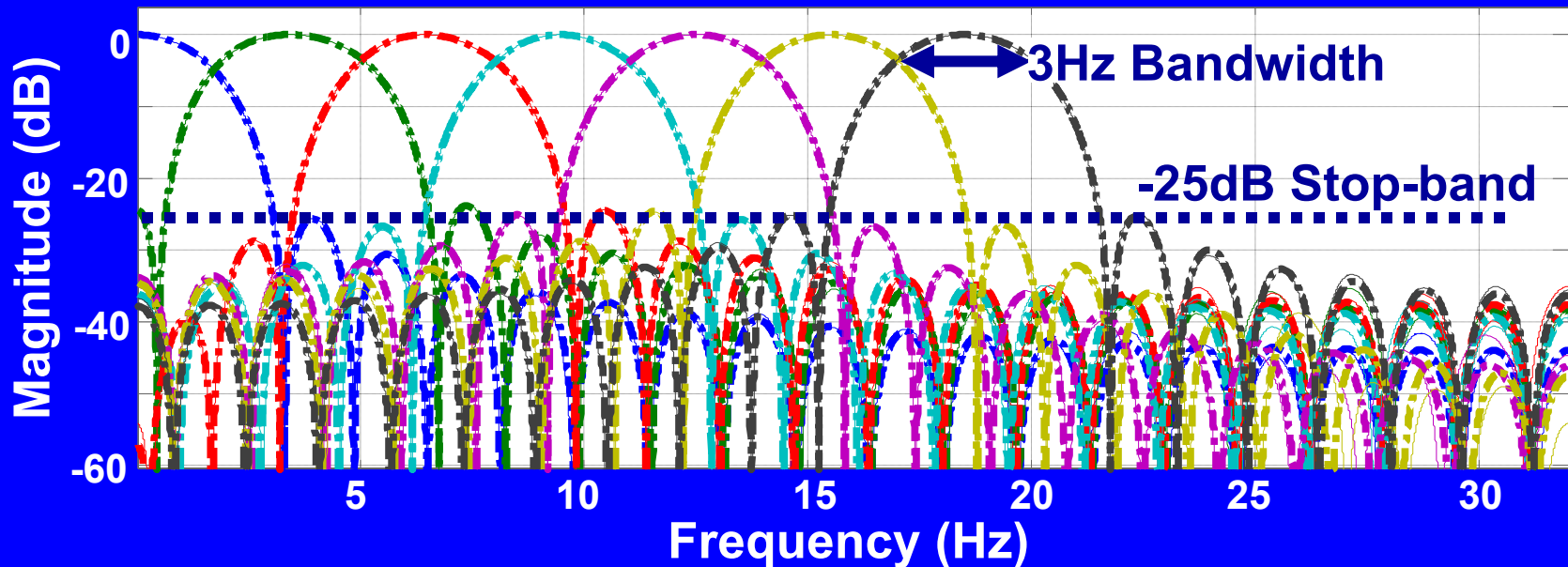
[Gotman, *EEG & Clinical Neurophys.*'81]



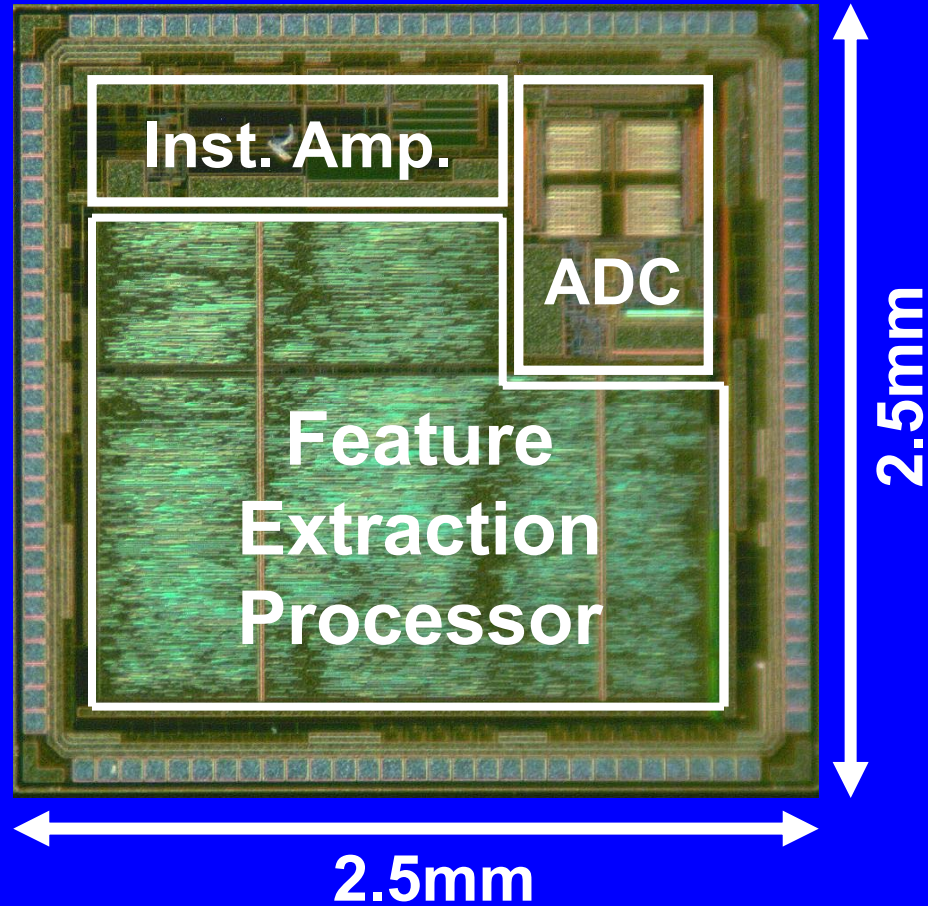
# Feature Extraction Processor



## Modulated Filter Bank:



# Seizure Detection SoC

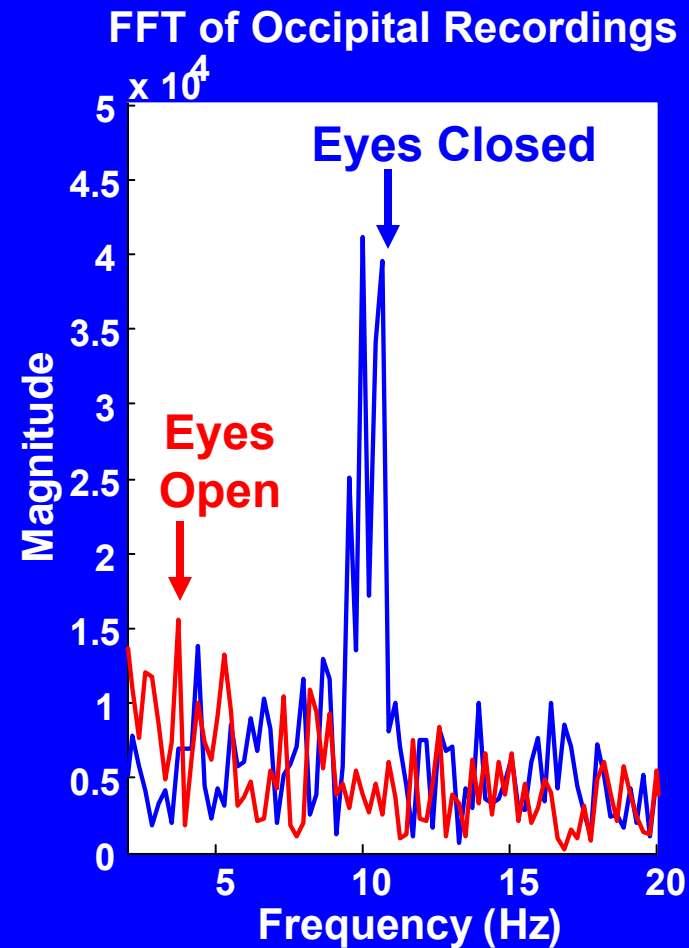
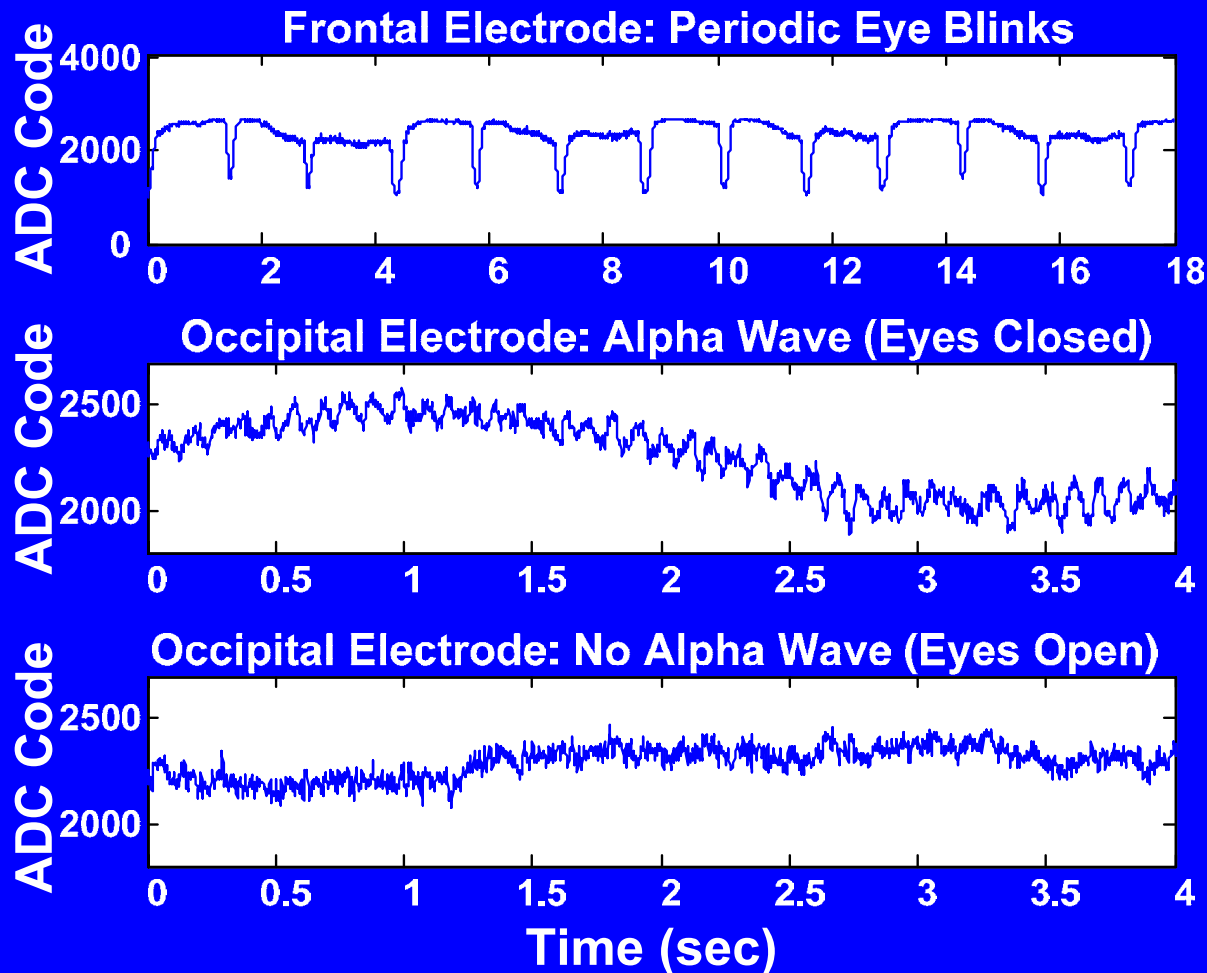


***180nm, 5M2P CMOS Prototype***

# Performance Summary

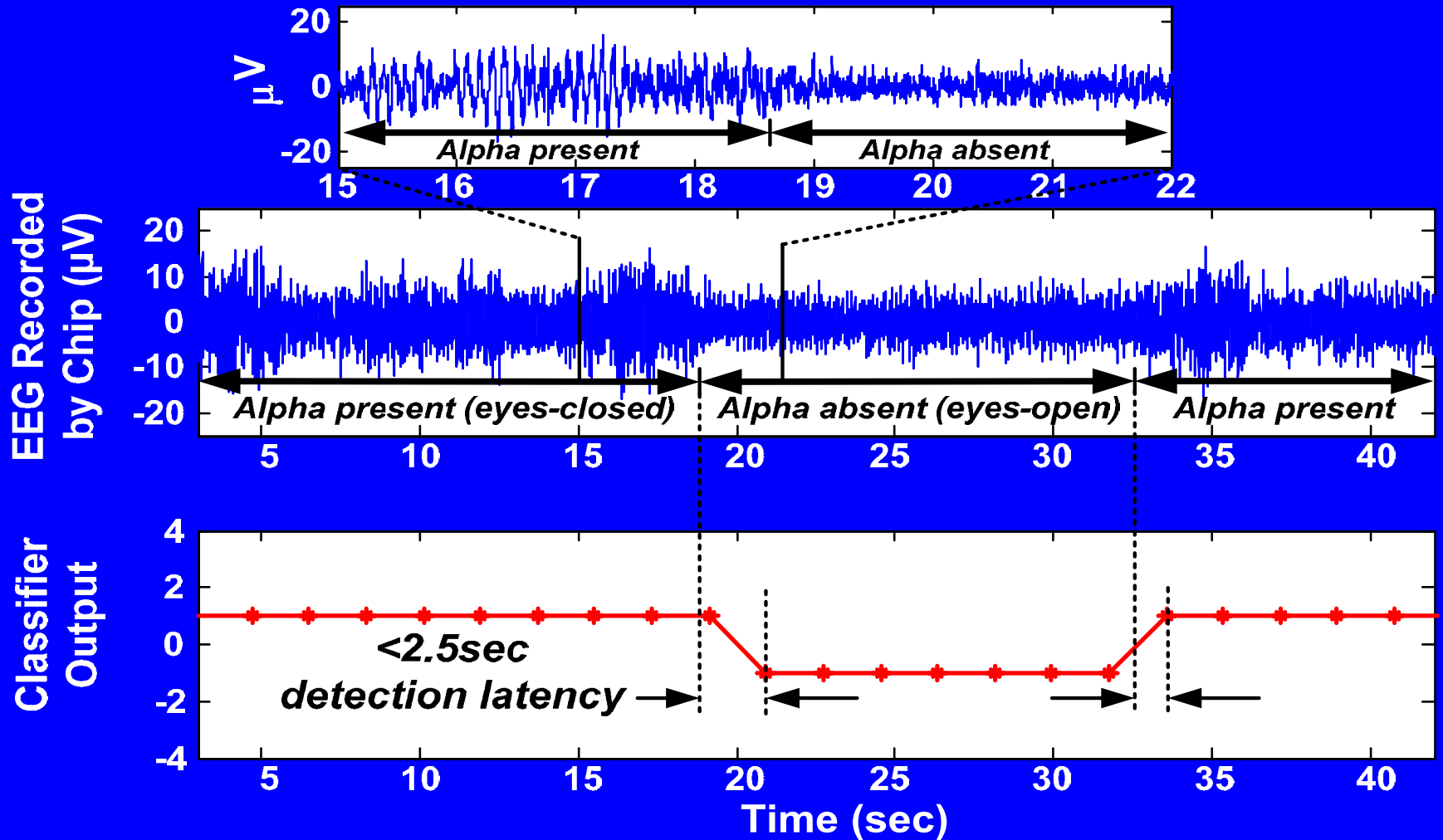
Supply voltage	1V
I-amp LNA power	3.5 $\mu$ W
I-amp input impedance	>700M $\Omega$
I-amp noise (input referred, 0.5Hz-100Hz)	1.3 $\mu$ Vrms
I-amp electrode offset tolerance	>1V
I-amp CMRR	>60dB
ADC resolution	12b
ADC energy per conversion	250pJ
ADC max. sampling rate	100kS/s
ADC INL/DNL	0.68/0.66LSB
ADC SNDR	65dB
Digital energy per feature-vector	234nJ
Feature vector computation rate	0.5Hz
<b>Total energy per feature-vector</b>	<b>9<math>\mu</math>J</b>

# EEG Recordings



**Lab recording performed by on-chip inst. amp and ADC using commercial Ag/AgCl electrodes**

# Feature Vector Classification



**System trained to detect relaxed eyes-closed (alpha) state:  $< 2.5\text{sec}$  latency observed**

# Conclusions

- **Patient-specific learning improves seizure detection**
- **General importance of spectral and spatial features can be exploited to compress EEG data**
- **Low-power EEG acquisition requires targeted rejection mechanisms in instrumentation amp**

**Acknowledgements: Funding by Intel Foundation Ph.D Fellowship Program and MIT CICS. IC fabrication by NSC**