Novel Two-dimensional Materials and Devices for Biomimetic Sensing and Computing

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Building College-University Partnerships for Nanotechnology Workforce Development

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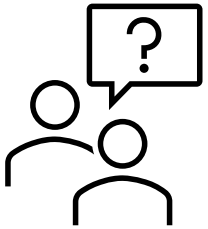

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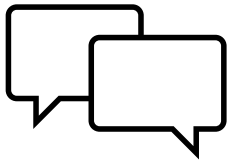

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Hosts and Presenters:

Bob Ehrmann
Managing Director
NACK Center

Ozgur Cakmak
Assistant Teaching Professor
Penn State

Saptarshi Das
Assistant Professor
Penn State

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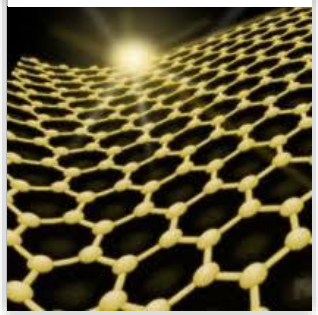
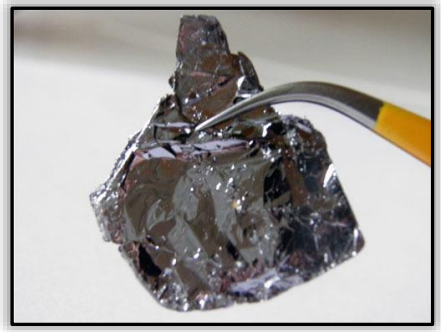
The 2D Revolution

Das. S, *et al.* ***Annual Review of Materials Research*** *45, 1-27, 2015.*

Excellent Conductor

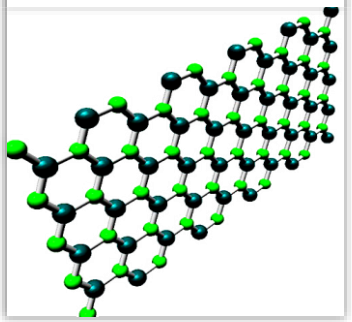
Graphene

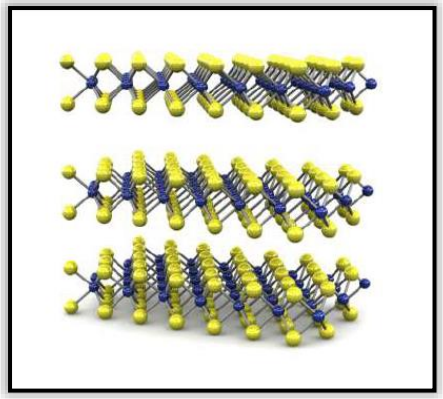




Excellent Insulator

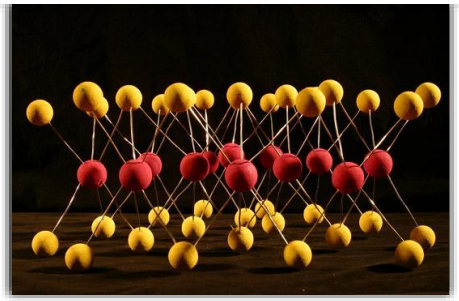
h-BN

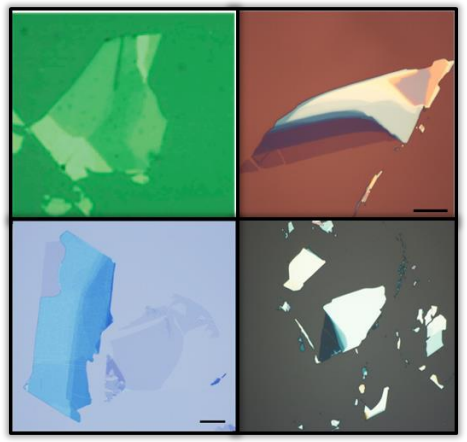




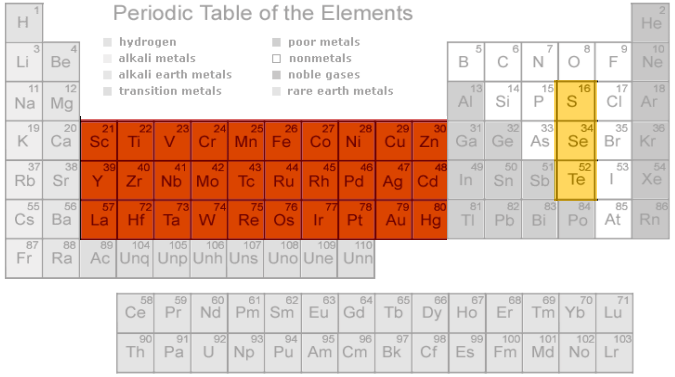
Semiconductors

Transition Metal Dichalcogenides





Periodic Table of Elements



Metals

$ScTe_2$,TaS_2

Semiconductors

WSe_2 , MoS_2

Insulators

$PtSe_2$,PdS_2

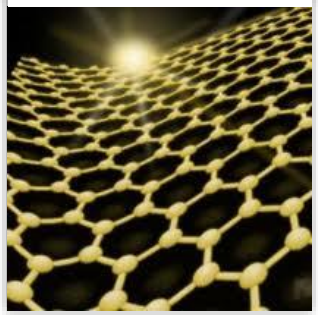
Superconductors

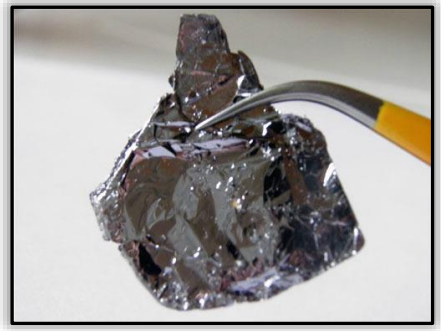
VS_2 , $NbSe_2$

Why 2D ?

Excellent Conductor

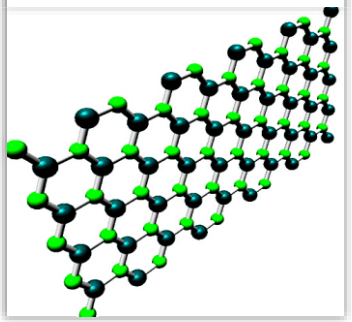
Graphene

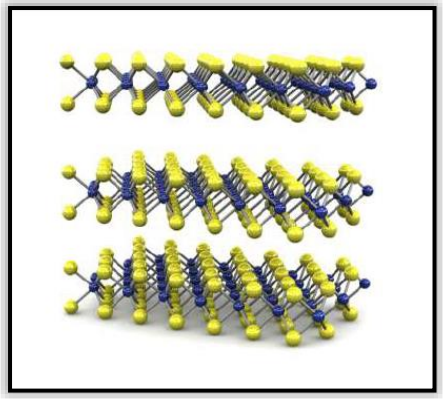




Excellent Insulator

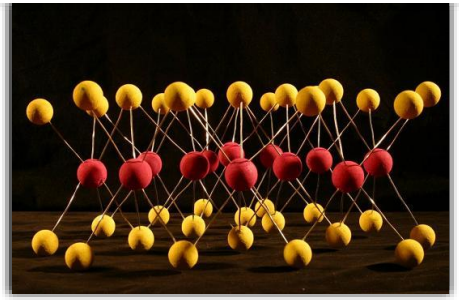
h-BN

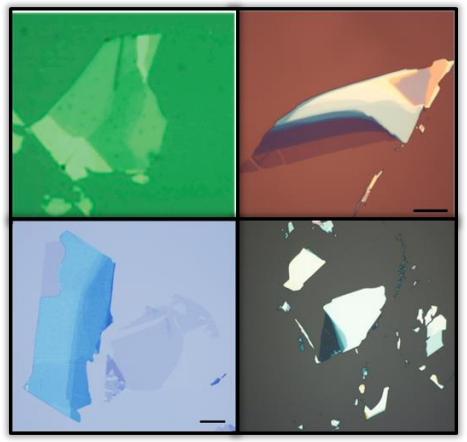


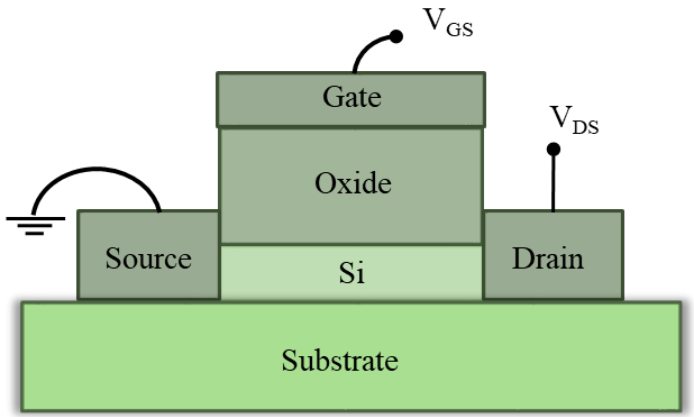


Semiconductors

Transition Metal Dichalcogenides





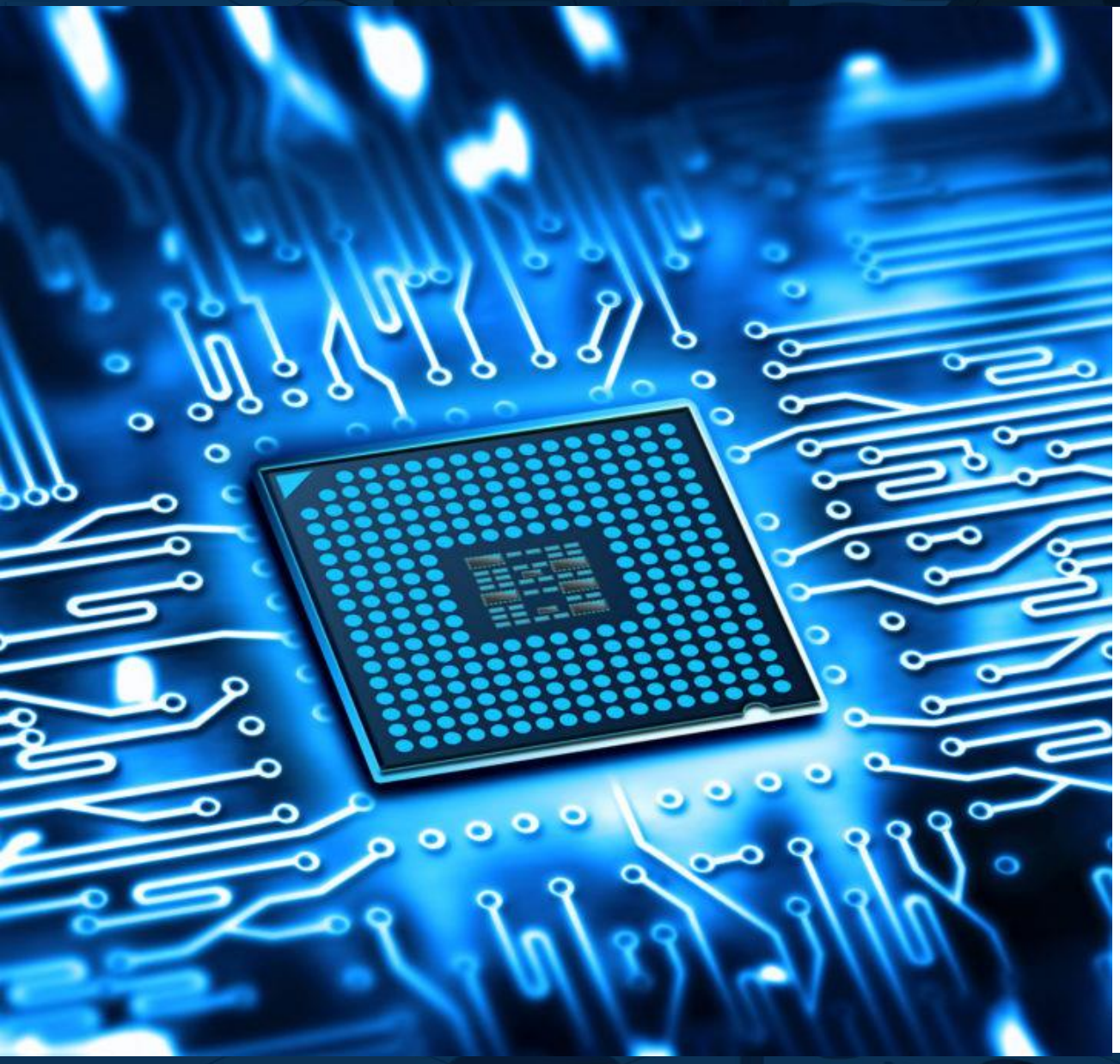


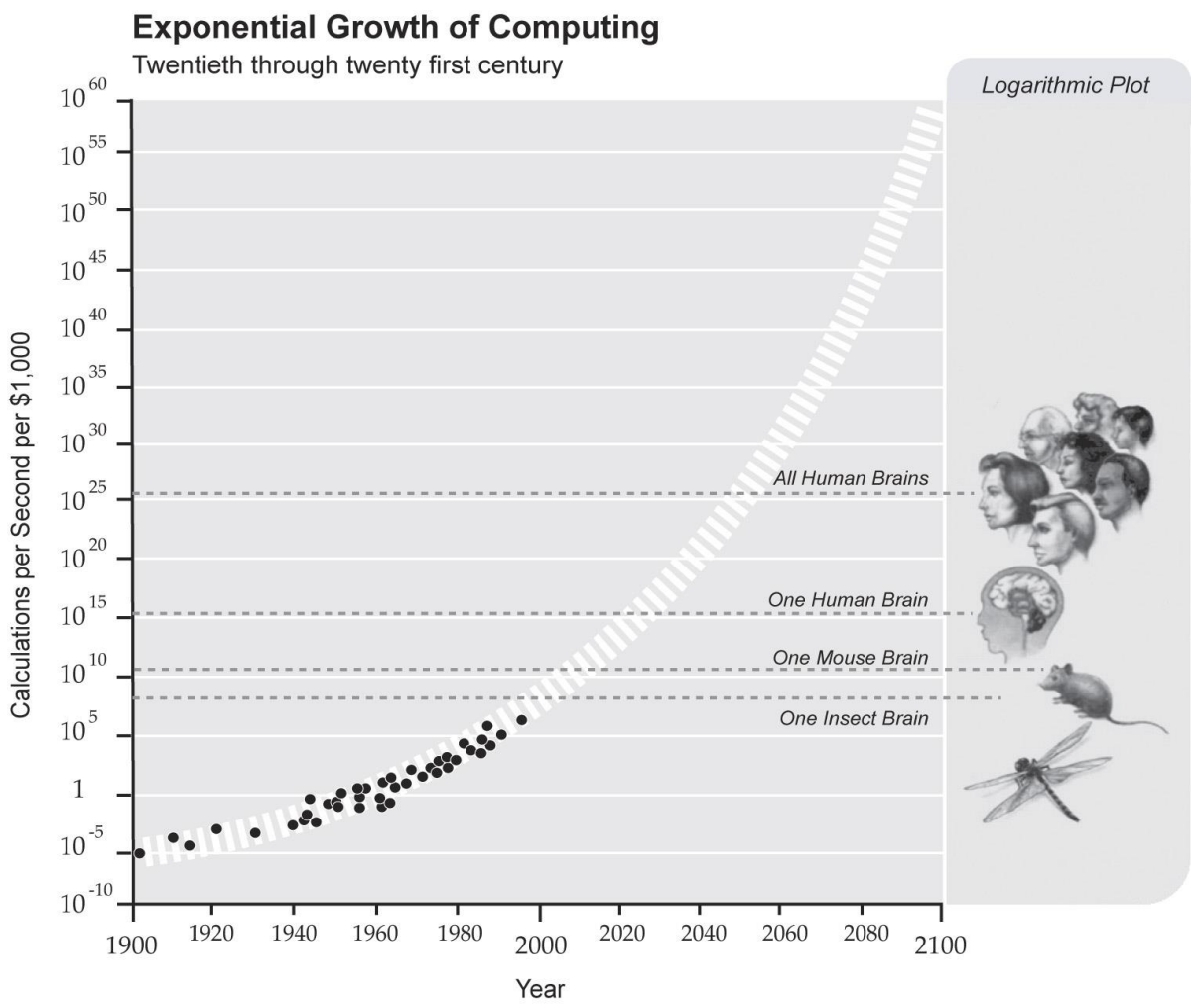
$$t_{Si} \approx 6\ nm$$

$$t_{2D} \approx 0.6\ nm$$

Smaller Transistors → More Transistors

More Transistors → Better Computing

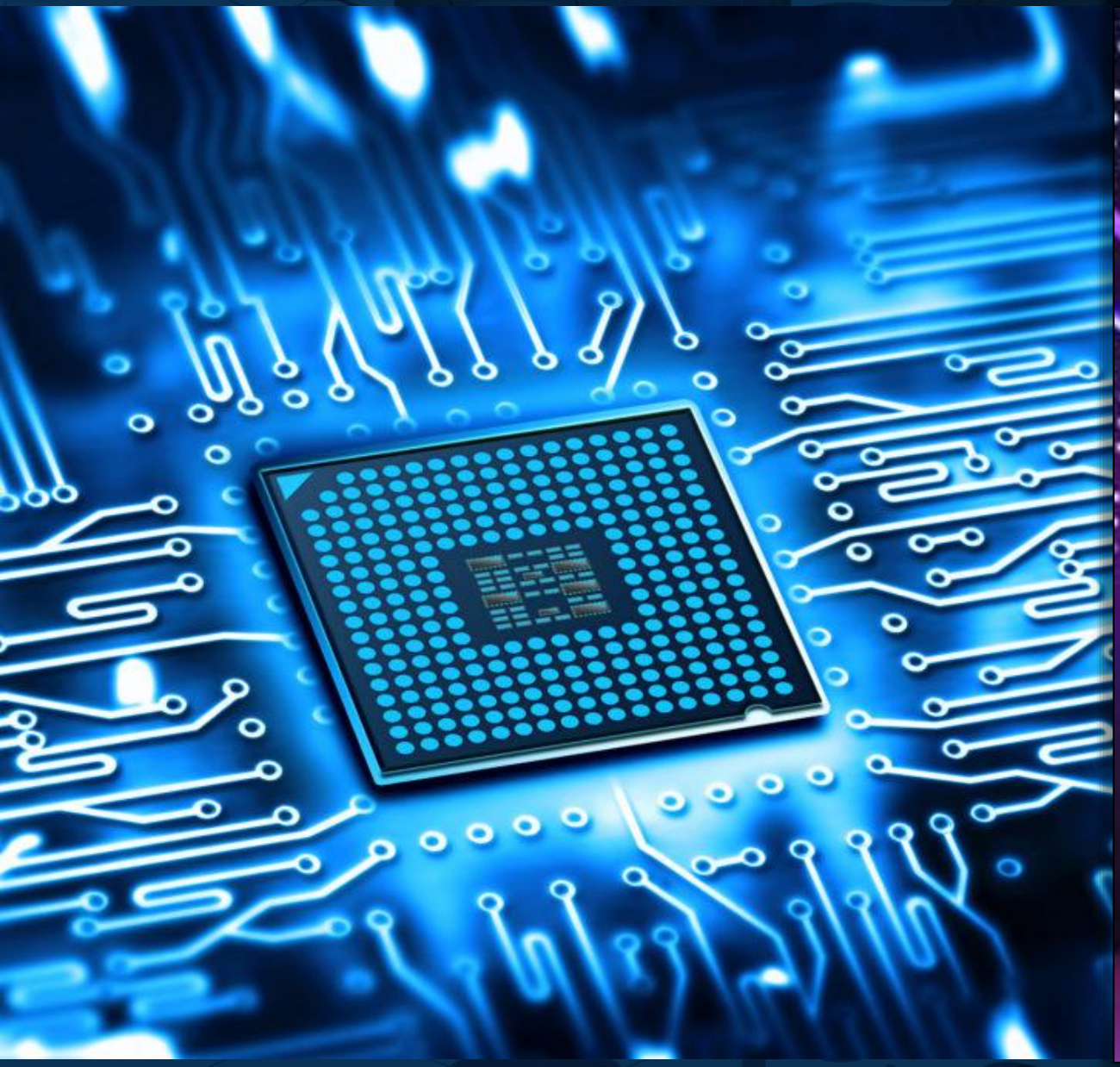




Adapted from Google Images

Supercomputers

Power: 10MW power
Size: Football field (10^9 cm^3)



Adapted from Google Images

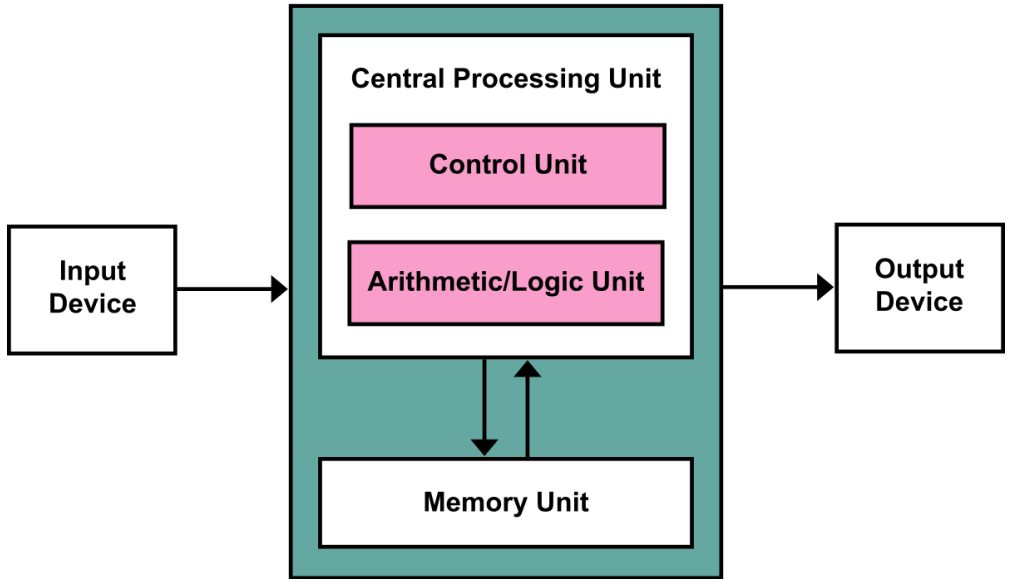
Power: 20W
Size: 10^3 cm^3

Power: 10MW power
Size: Football field (10^9 cm^3)

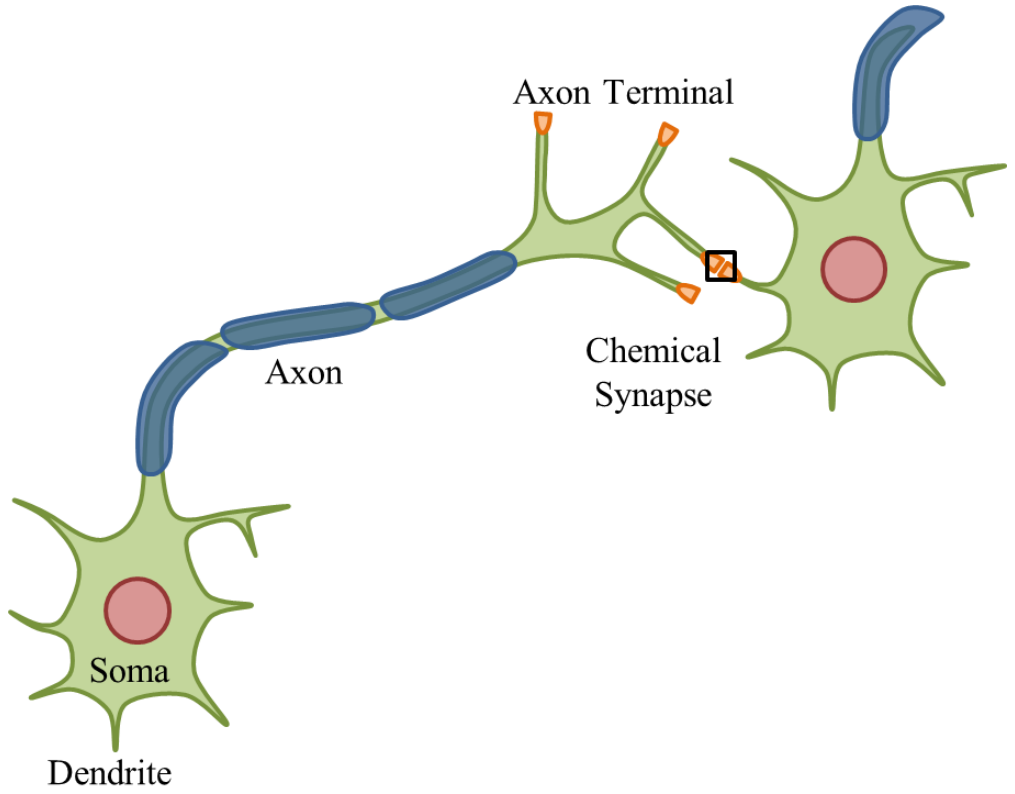
Adapted from Google Images

Biological Computing

Von Neumann Computing



Biological Computing – non Von Neumann



100 billion neurons (computation)

1000 synapses/neuron

100 trillion synapses (memory)

Biomimetic Computing

Cognitive Computing

Natural Super Sensors

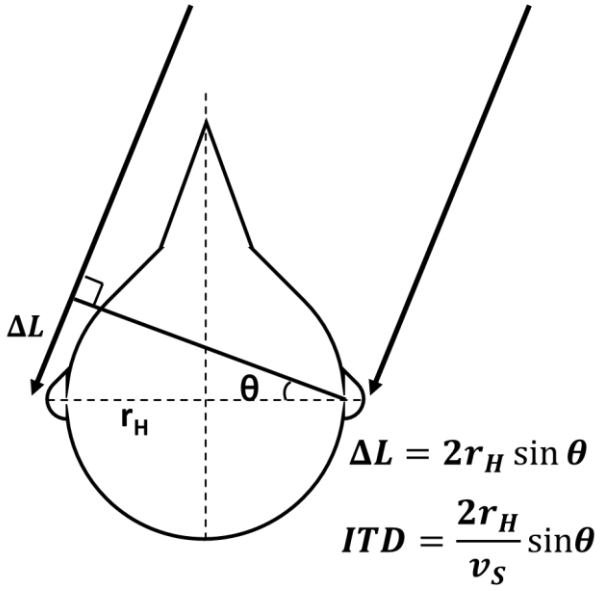
Jewel Beetle: Infrared Radiation
Bee: Earth's Magnetic Field

Sensory Computing

Barn Owl: Superior Audio Sensor

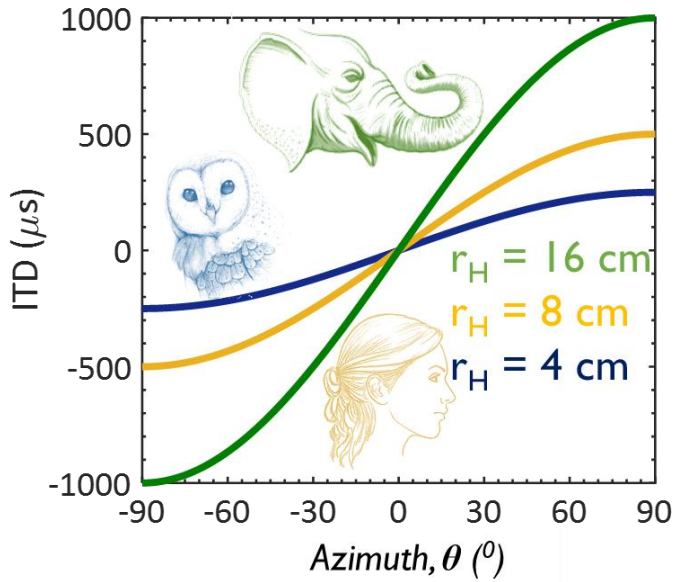
Sound localization in complete darkness with a precision of 1-3^0

Das, *et al. Nature Communications*, 2019



Path difference results in interaural time difference (ITD)

Source angle (azimuth)= ϑ
Head radius = r_H
Sound velocity = v_S

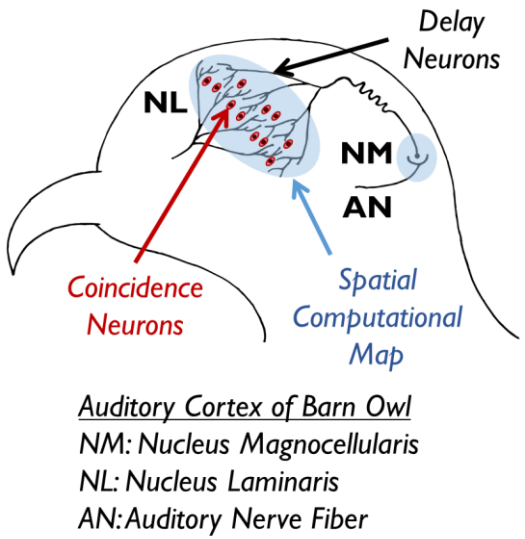


Neurons can fire only once in few ms

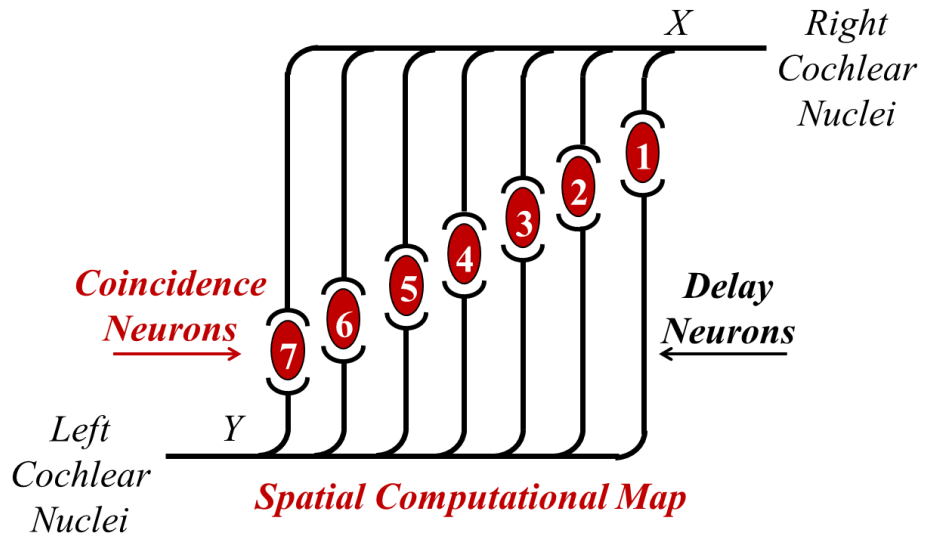
Neural Architecture transforms temporal coding into spatial coding

Barn Owl: Superior Audio Sensor

Das, *et al. Nature Communications*, 2019

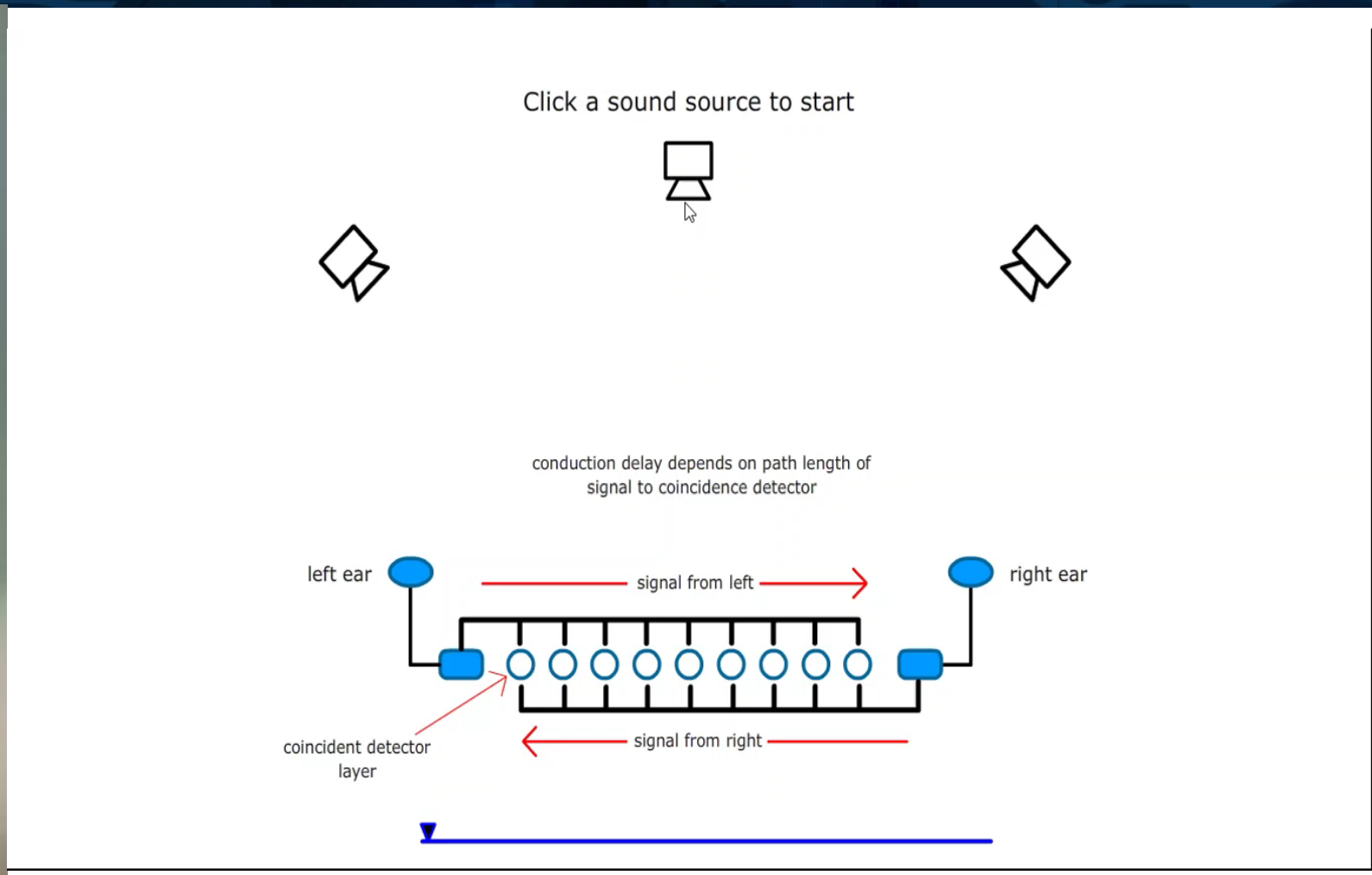


Auditory Cortex of Barn Owl
NM: Nucleus Magnocellularis
NL: Nucleus Laminaris
AN: Auditory Nerve Fiber



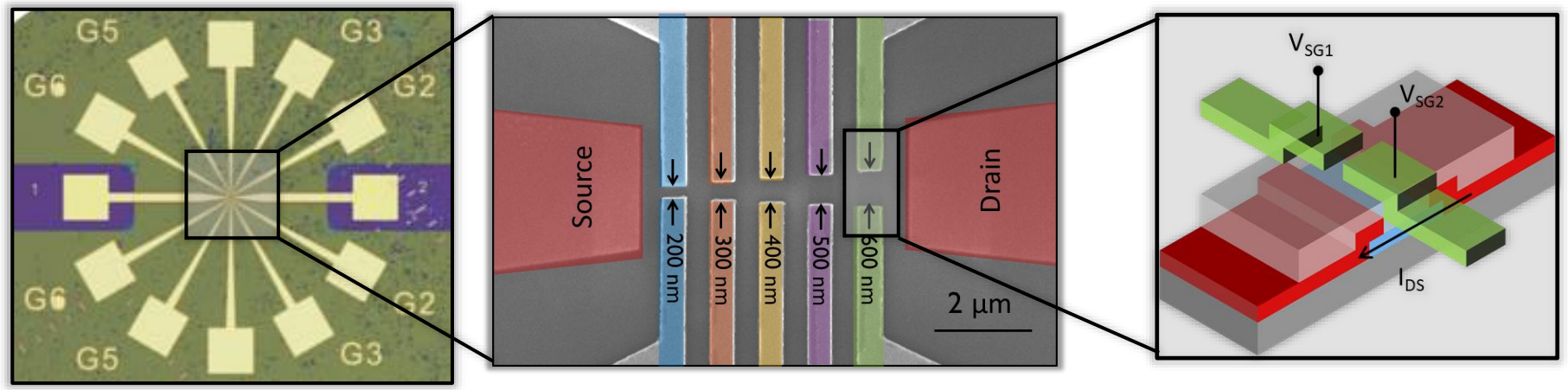
Barn Owl: Superior Audio Sensor

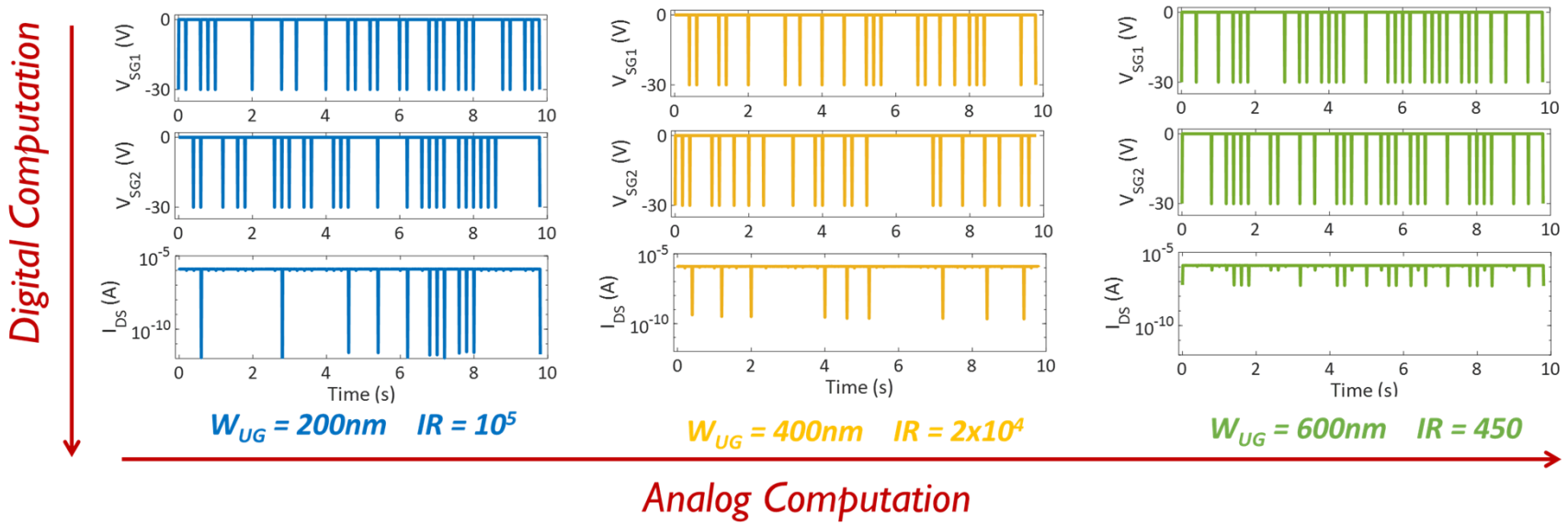
Das, *et al. Nature Communications*, 2019



Coincidence Detector and Map

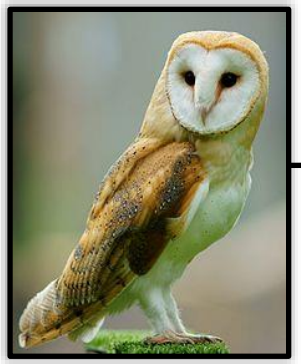
Das, *et al. Nature Communications*, 2019

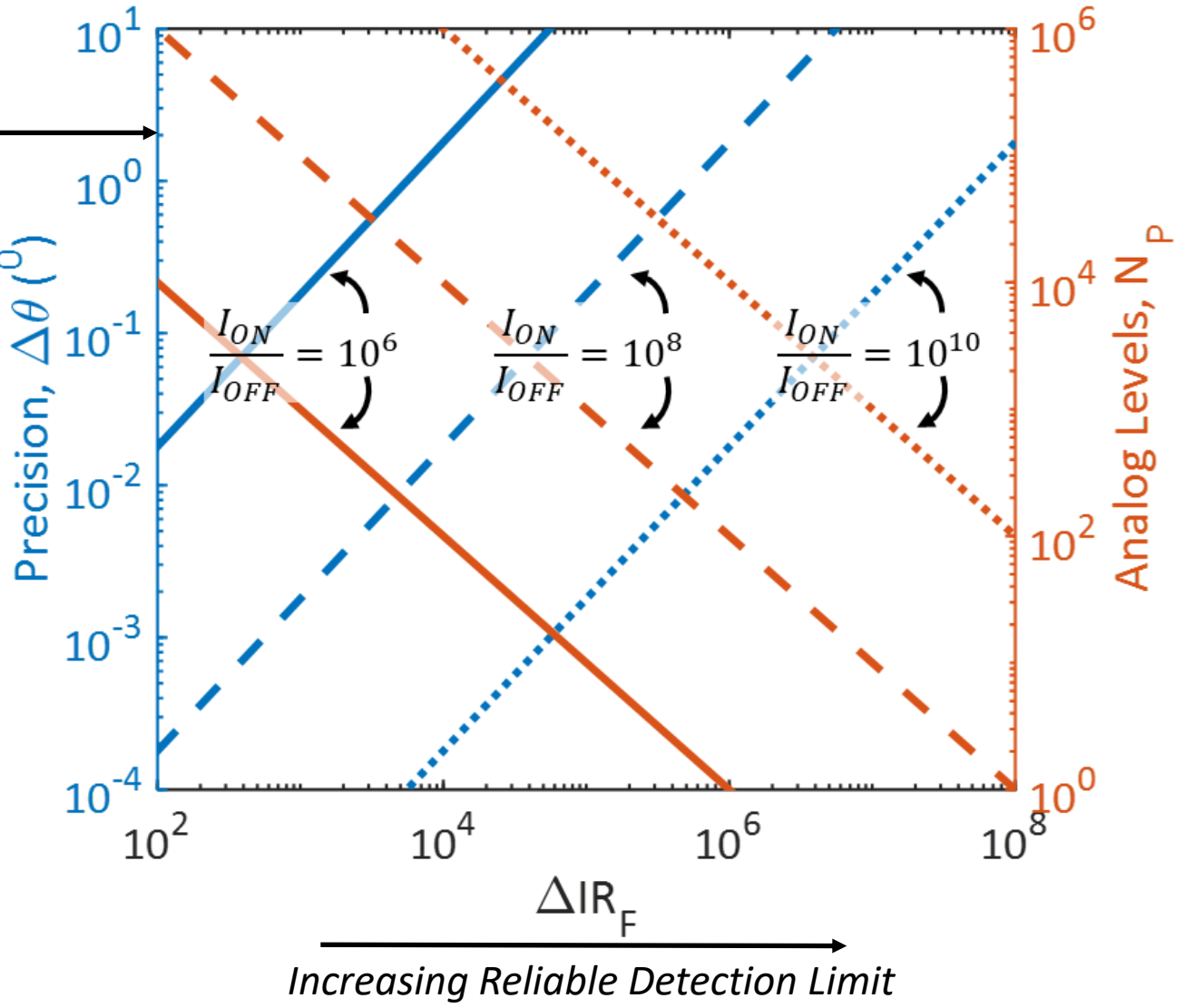




Biomimetic Navigational Sensor Supersedes Barn Owl

Das, *et al. Nature Communications*, 2019



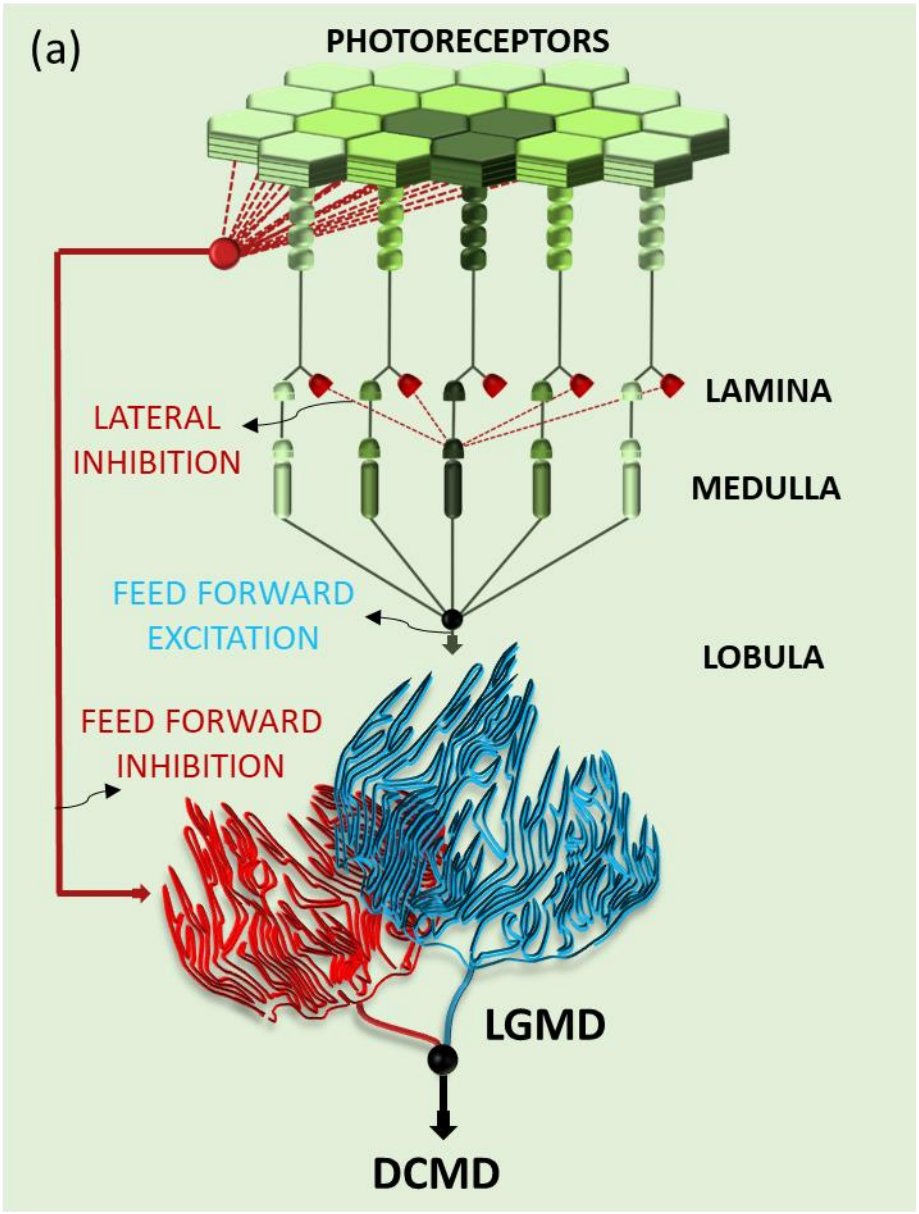


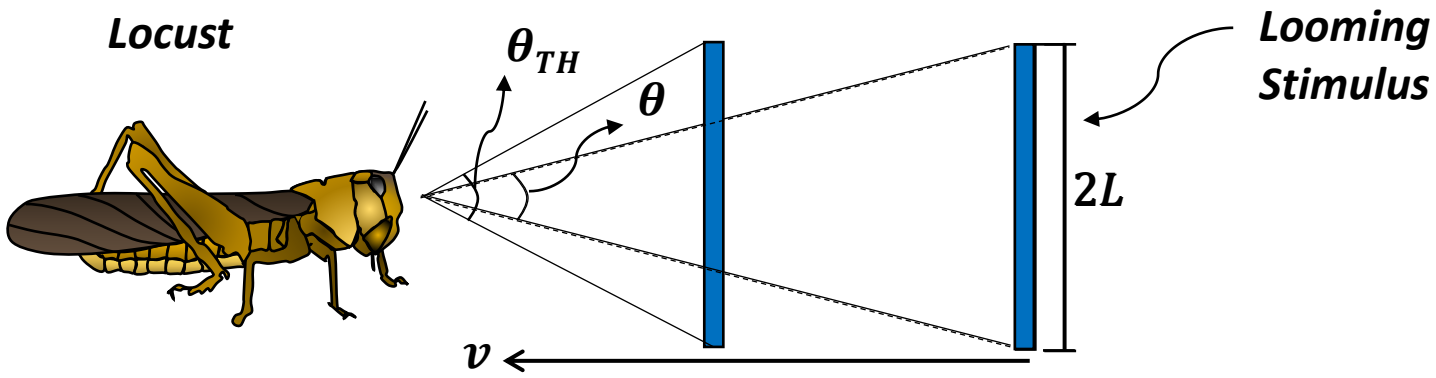
Locust: Collision Detector

Jayachandran, *et al. Nature Electronics* 2020

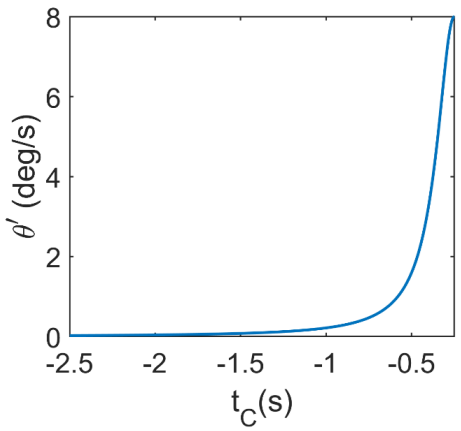
Locust: Collision Detector

LGMD Neuron
Ultra-low energy

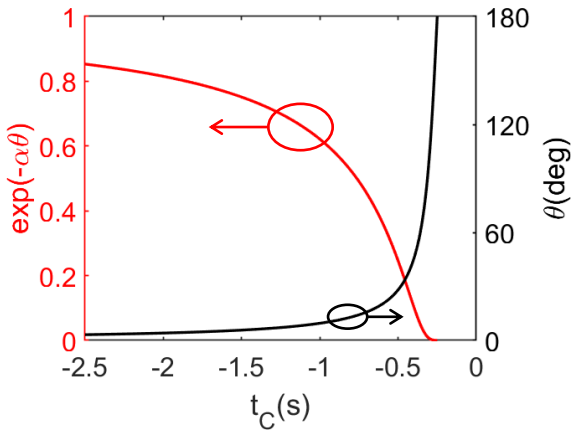




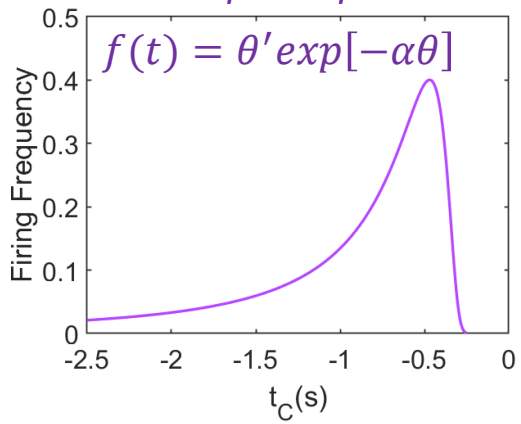
Excitatory Response



Inhibitory Response

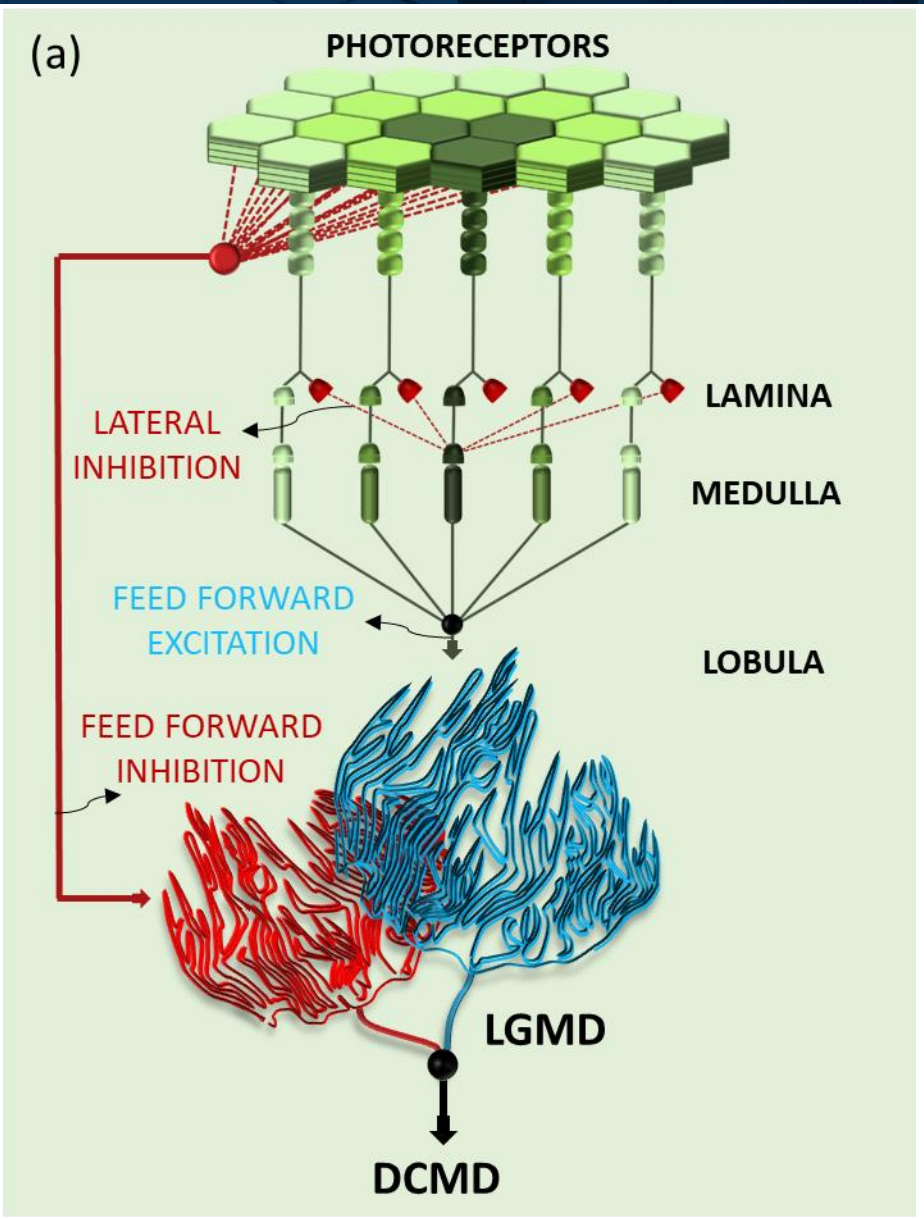


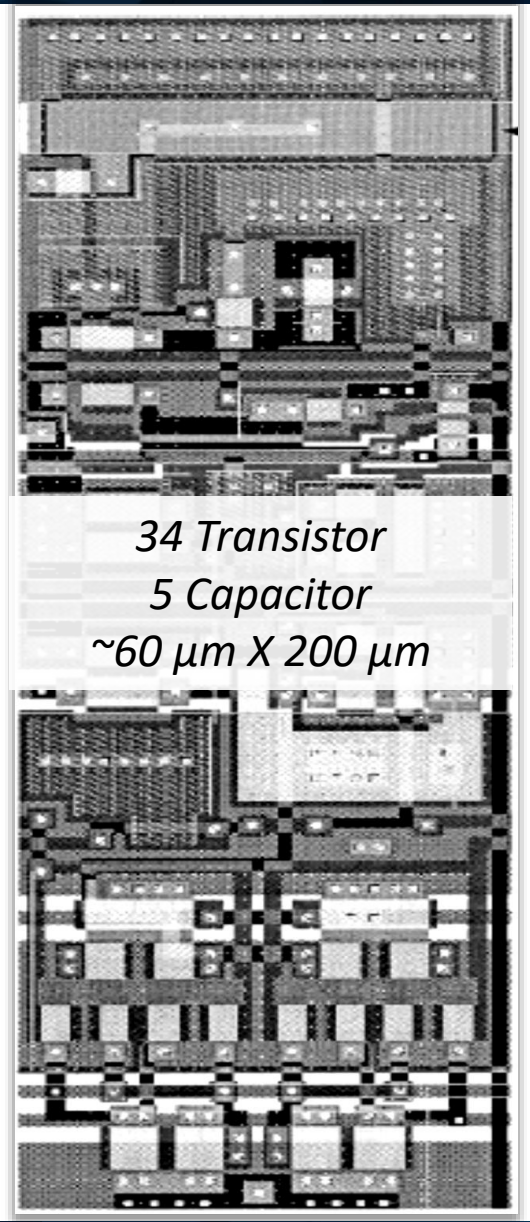
Escape Response



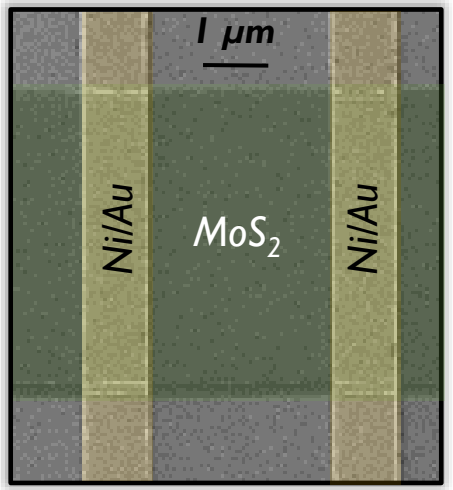
Locust: Collision Detector

LGMD Neuron
Ultra-low energy

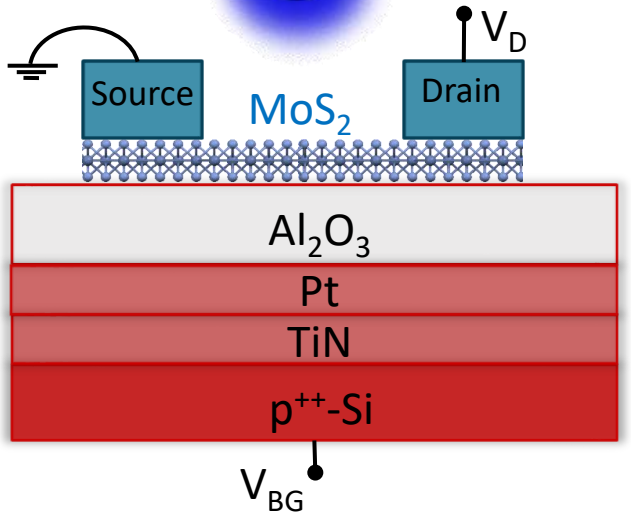




34 Transistor
5 Capacitor
~60 µm X 200 µm



The Looming Object



EXCITATORY
Monolayer MoS_2 Photodetector

INHIBITORY
Non-volatile and Programmable Memory Stack

PennState


PennState

Visual Stimulus Mimicking Approaching Object

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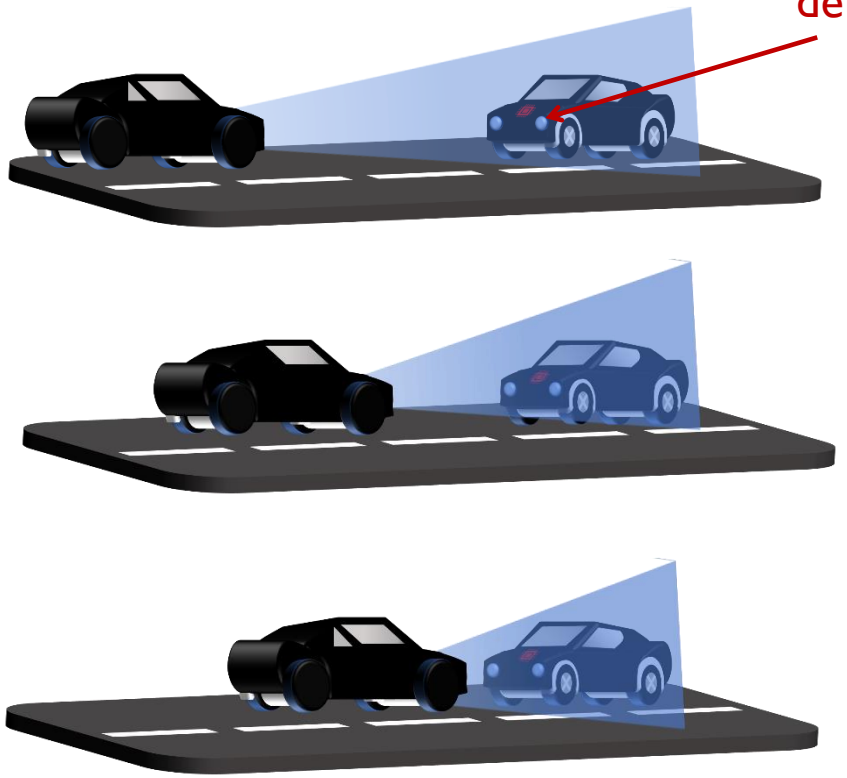
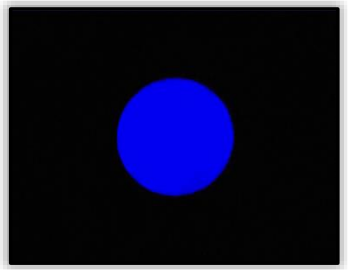
Visual Stimulus:
Headlight of approaching the Car

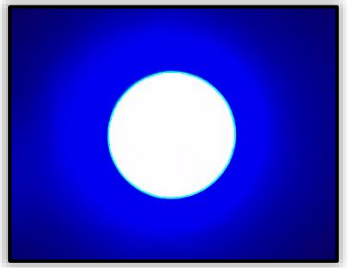


Visual stimulus experienced by the detector



Far from collision

Close to collision



At Collision

Collision Detection

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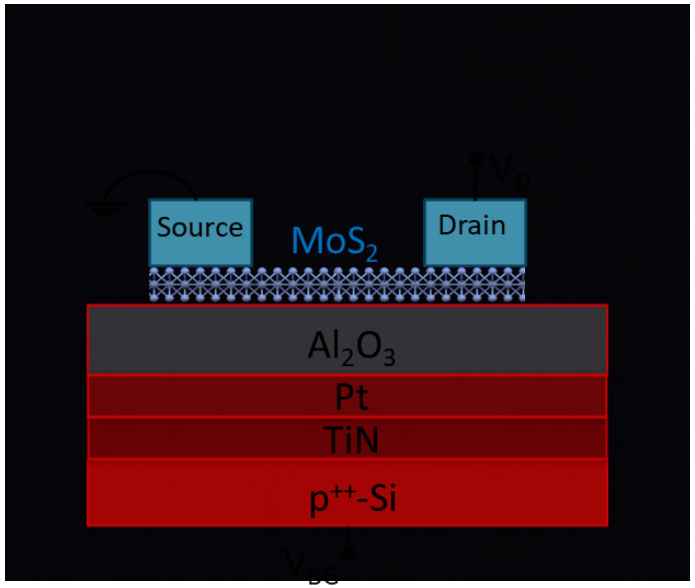

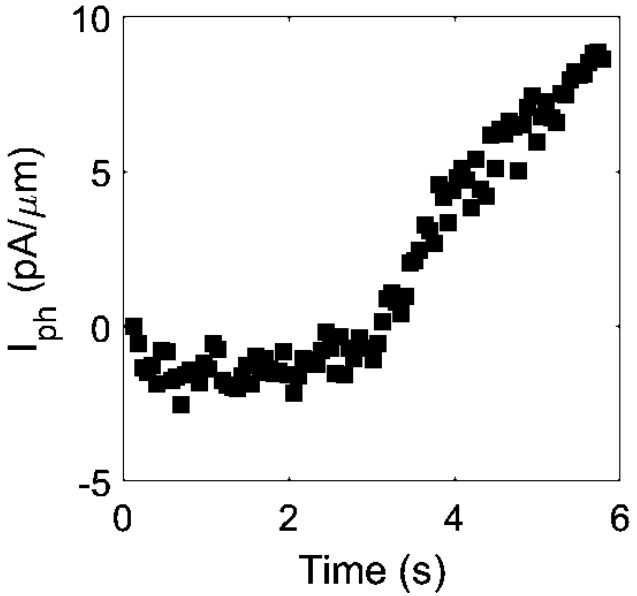

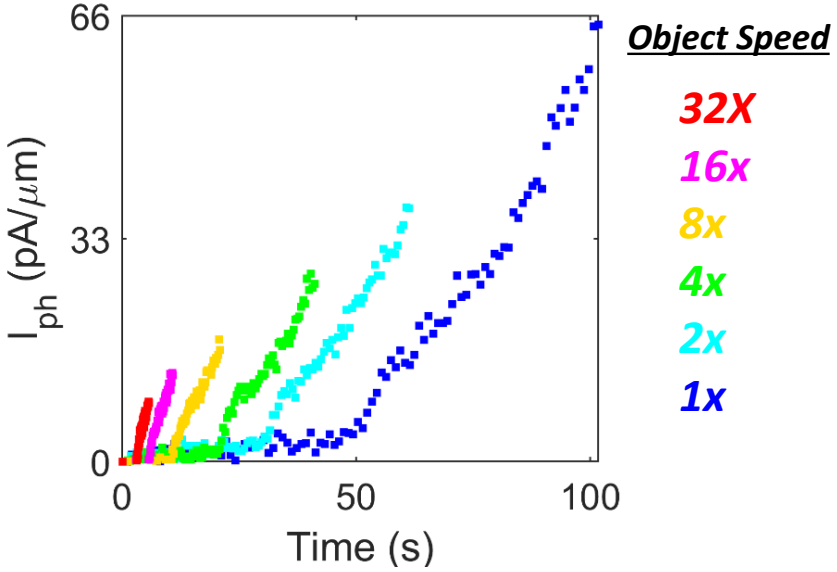

Collision Detection

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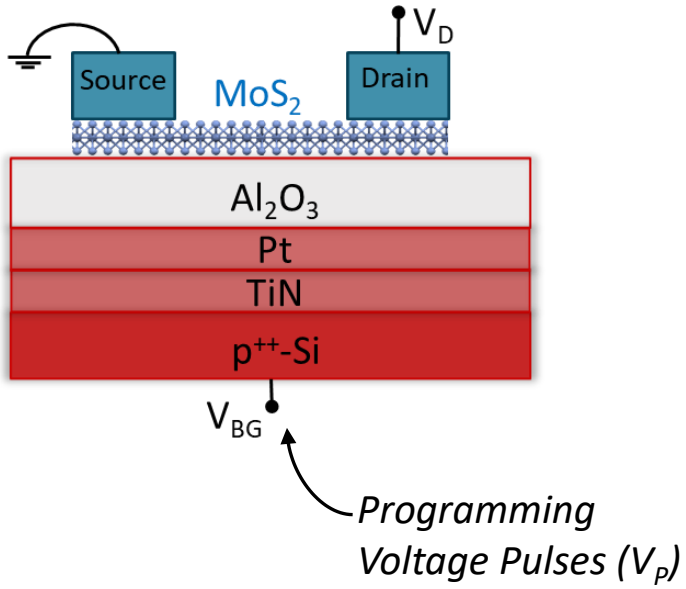

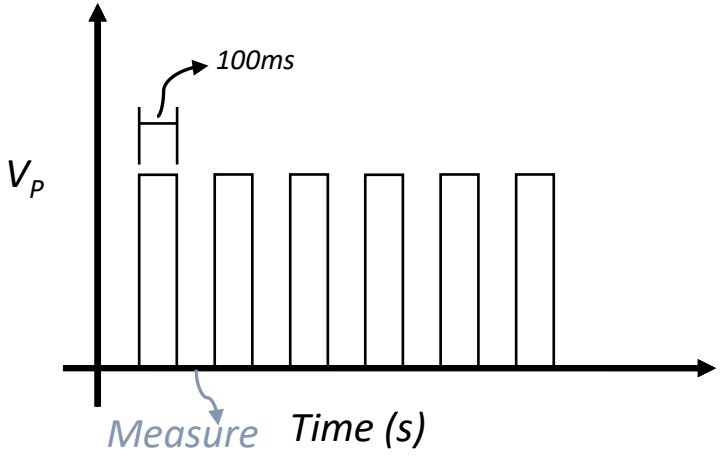

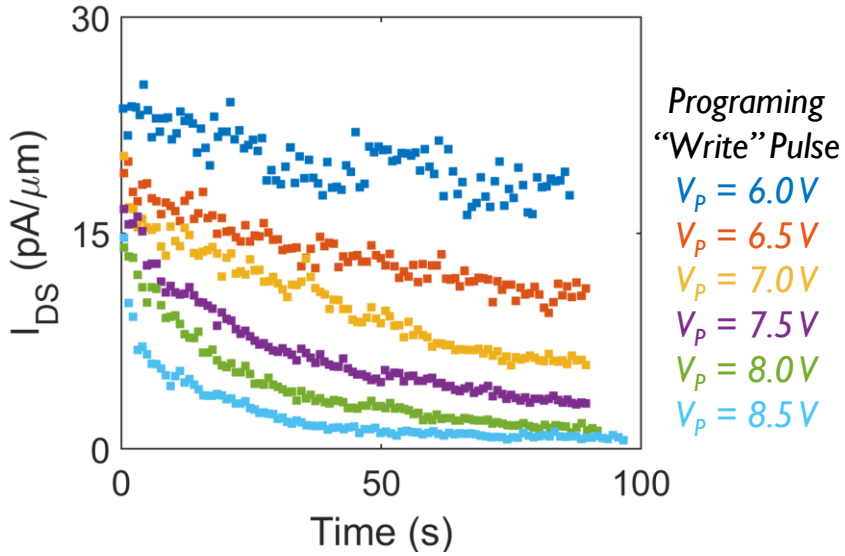

Collision Detection

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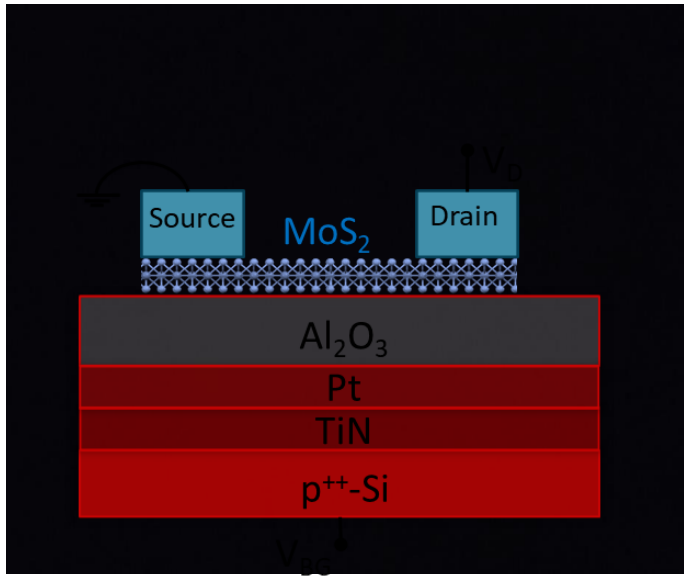
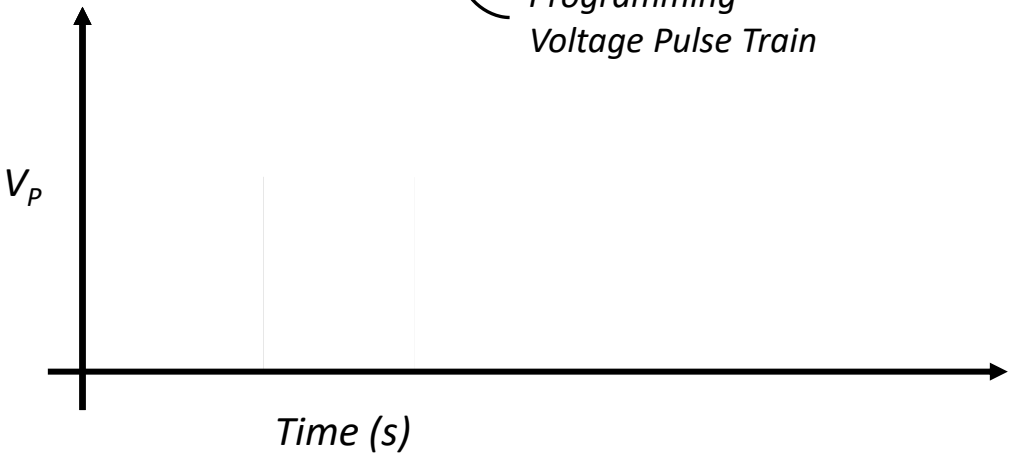


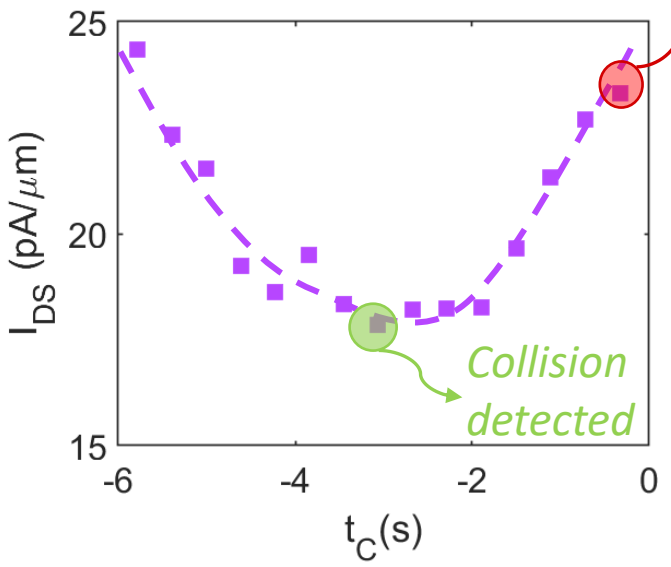
Programming Voltage Pulse Train



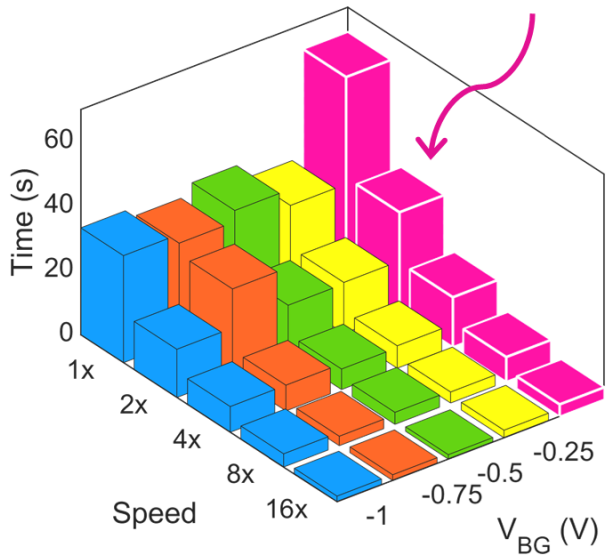
Escape Response

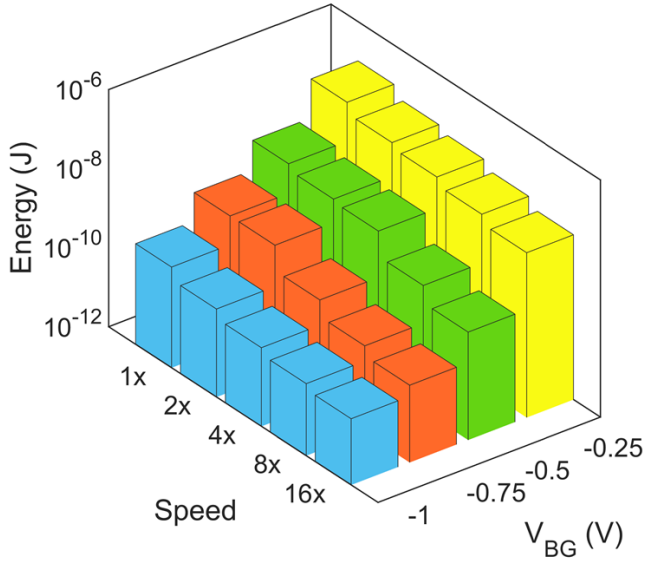
Collision Point

Collision detected



Time to collision

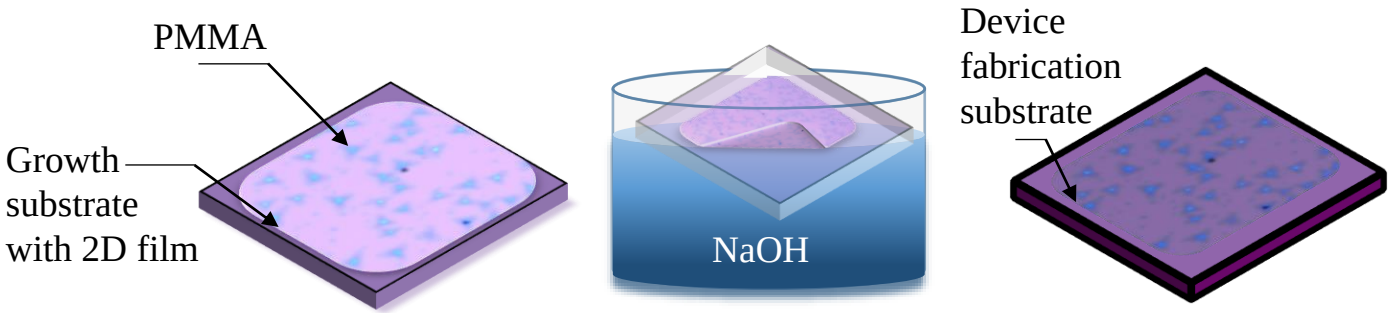


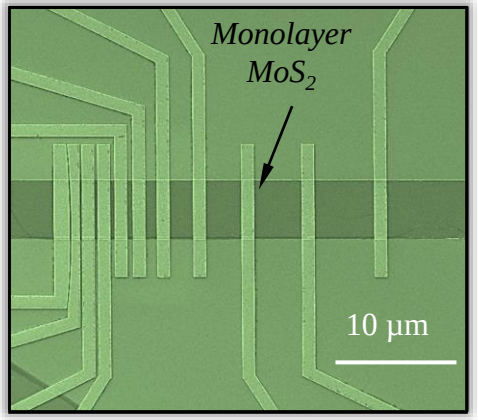


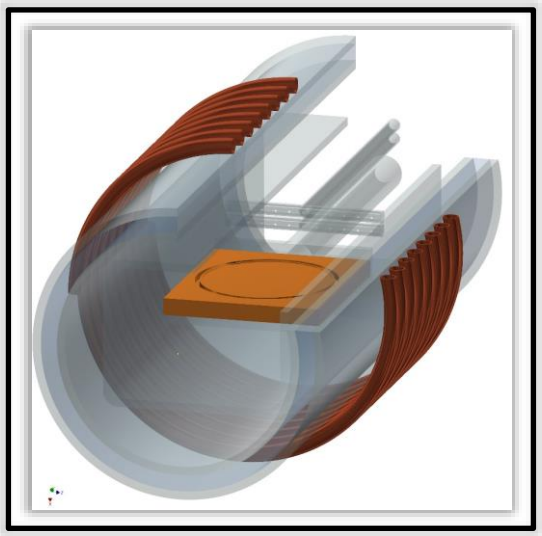
Questions?

Growth and fabrication of 2D Nanodevices

Transfer of 2D TMDs







Metal Organic Chemical Vapor Deposition (MOCVD)

Etching of 2D

Nanolithography – E-beam

Metal Deposition – E-beam

Stochastic Resonance

Constructive Role of Noise in Sensory Computation

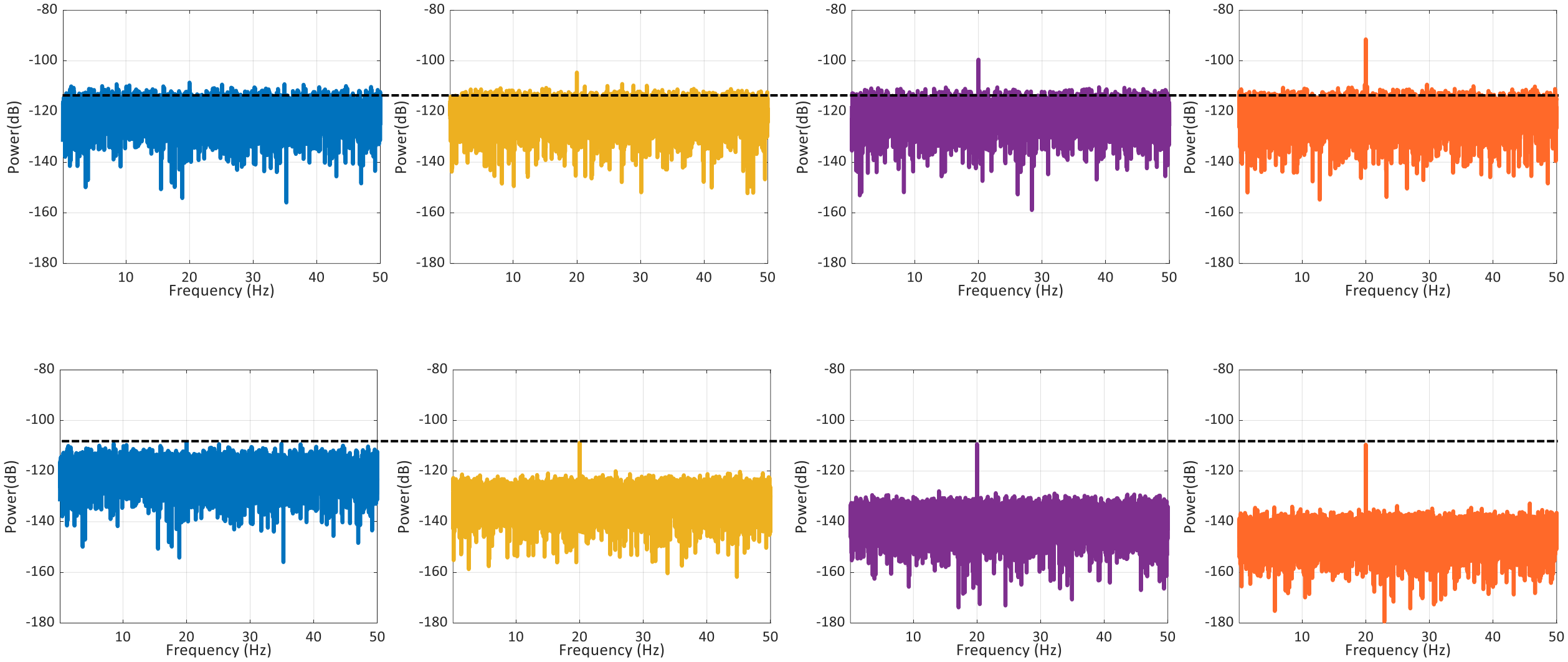
Noise is Nuisance

Noise is Nuisance

Conventional Approach

Signal to Noise Ratio (SNR)

- ✓ Increase Signal Intensity
- ✓ Reduce Noise Floor



Conventional Solid-State Sensors

Lock in Amplifier

Low Noise Amplifier

Noise Filters

- *Hardware Intensive*
- *Bulky*
- *Energy Inefficient*

Not appropriate for resource constrained IoT sensors deployed in remote and inaccessible locations with limited power supply and hardware resources

Evolutionary success of animals relies on their extraordinary sensory skills that ensure survival in resource constrained environments

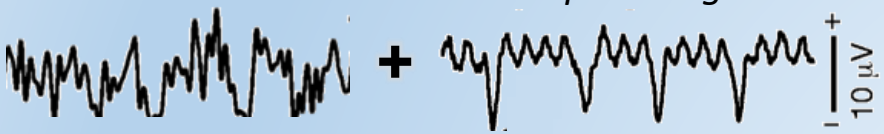
Is Noise a Nuisance ?

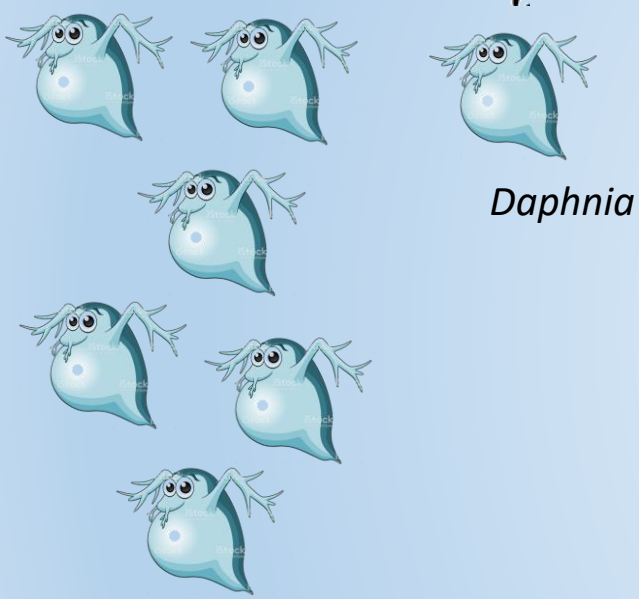
Locate Prey

Russell, *et al. Nature*, 1999

Electrical Noise

Daphnia Signal

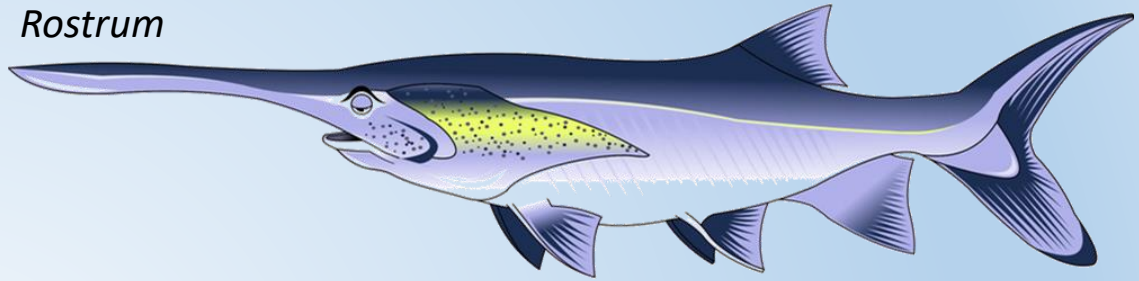


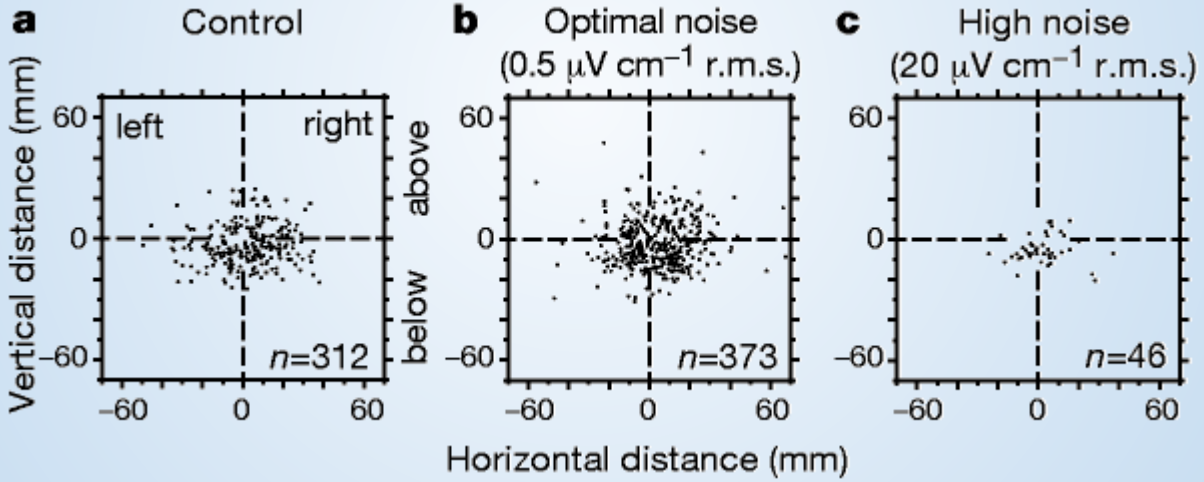


Daphnia

Electroreceptor Rostrum

Paddlefish





A noisy army betrays its outpost
Freund et al. PRL, 2001

Stochastic Resonance

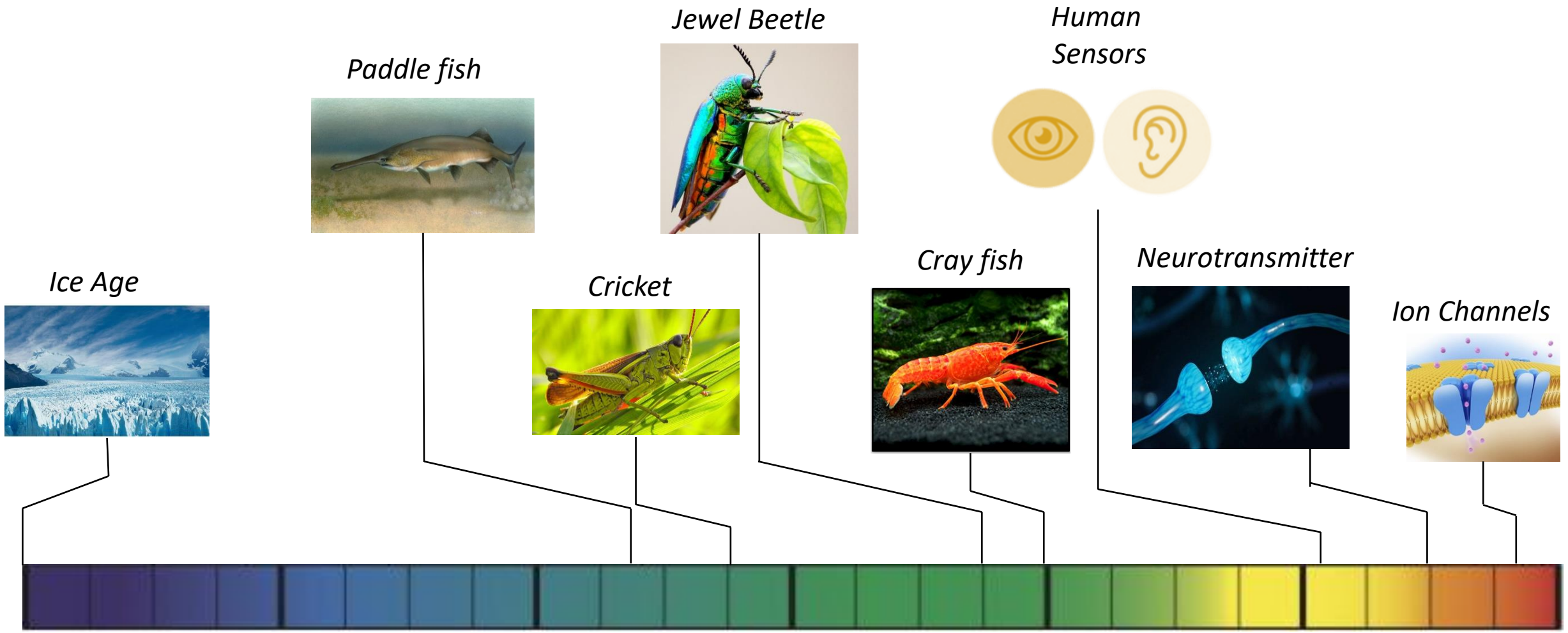
Is Noise a Nuisance ?

Escape from Predator

Douglass, *et al. Nature* 1993

Levin *et al. Nature*, 1996

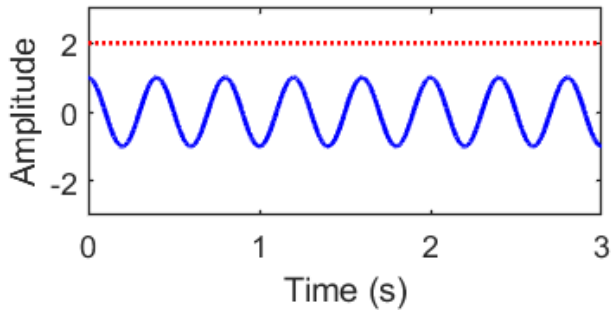
Stochastic Resonance is everywhere



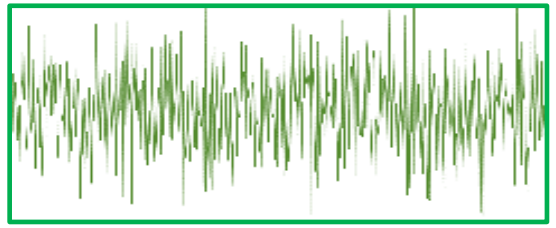
Stochastic Resonance at every scale

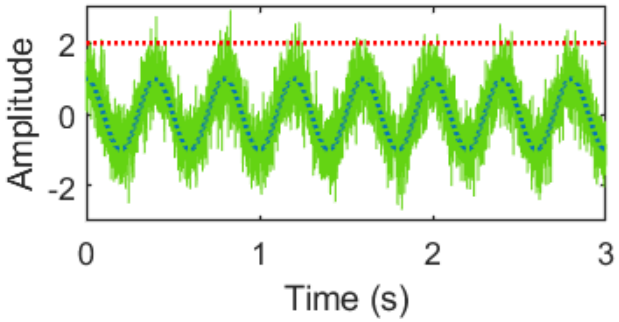
What is Stochastic Resonance

Weak Periodic Signal



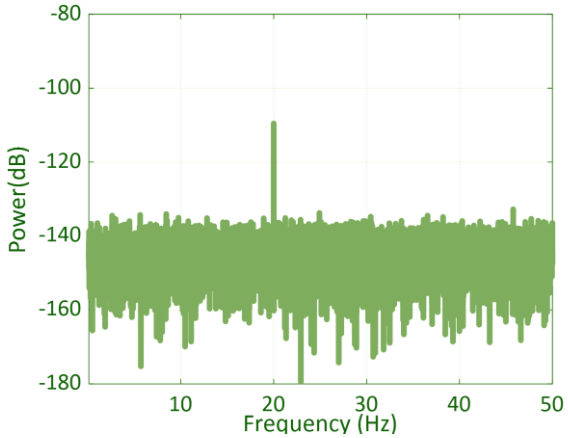
White Noise





Sensor

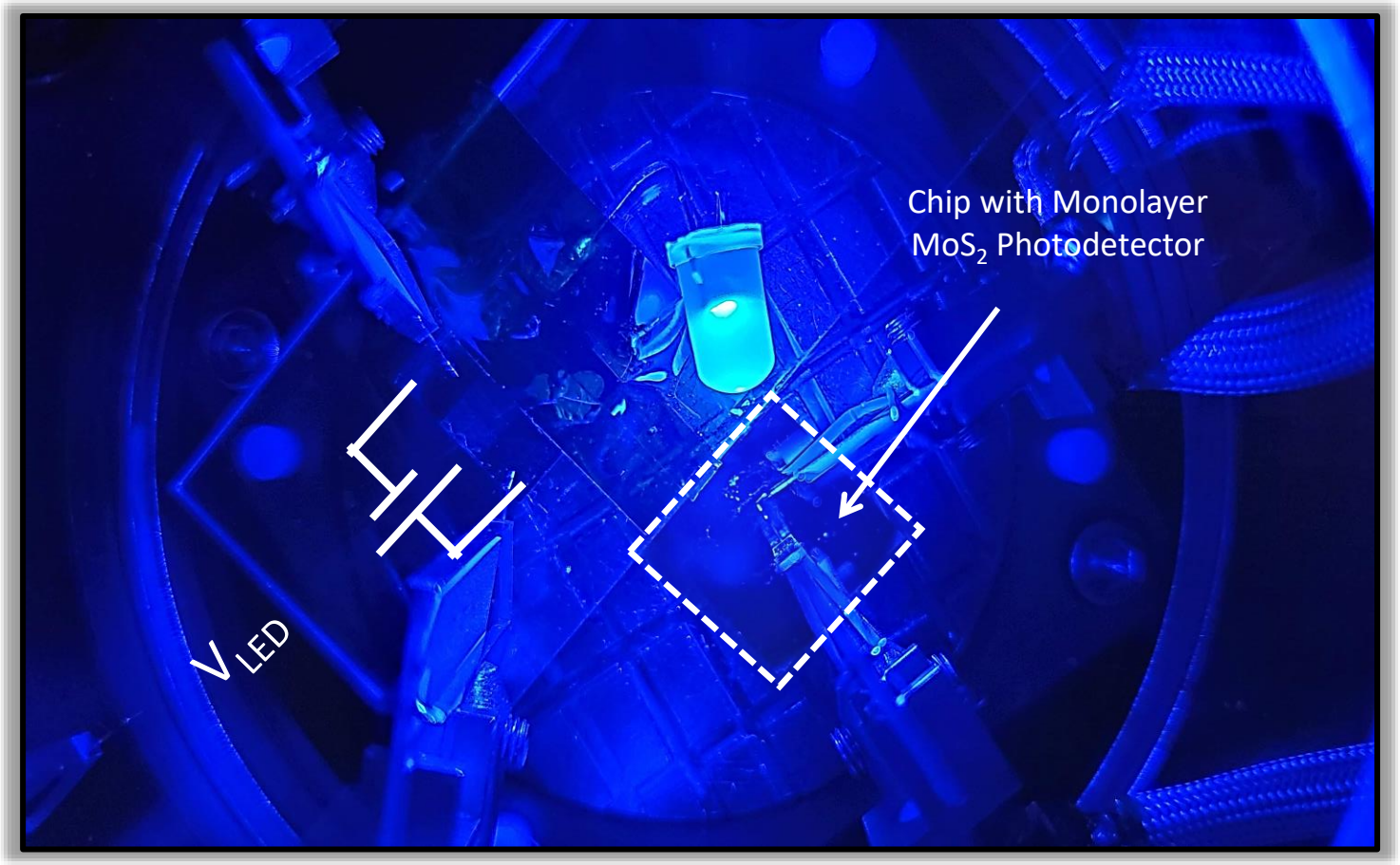
Thresholding Device



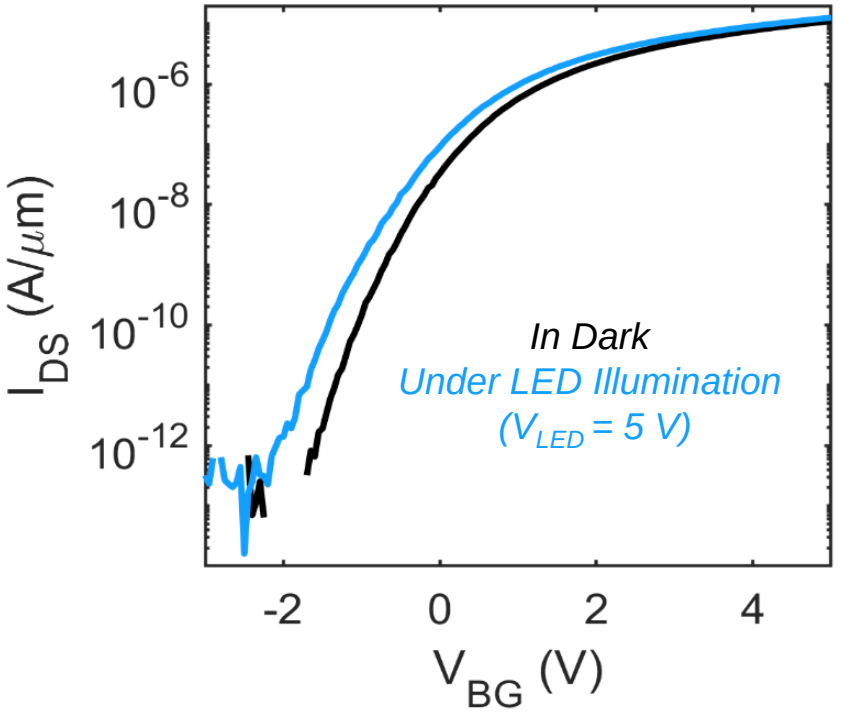
Stochastic Resonance in MoS_2 Photodetector

Dodda, *et al. Nature Communications*, 2020

Experimental Set up

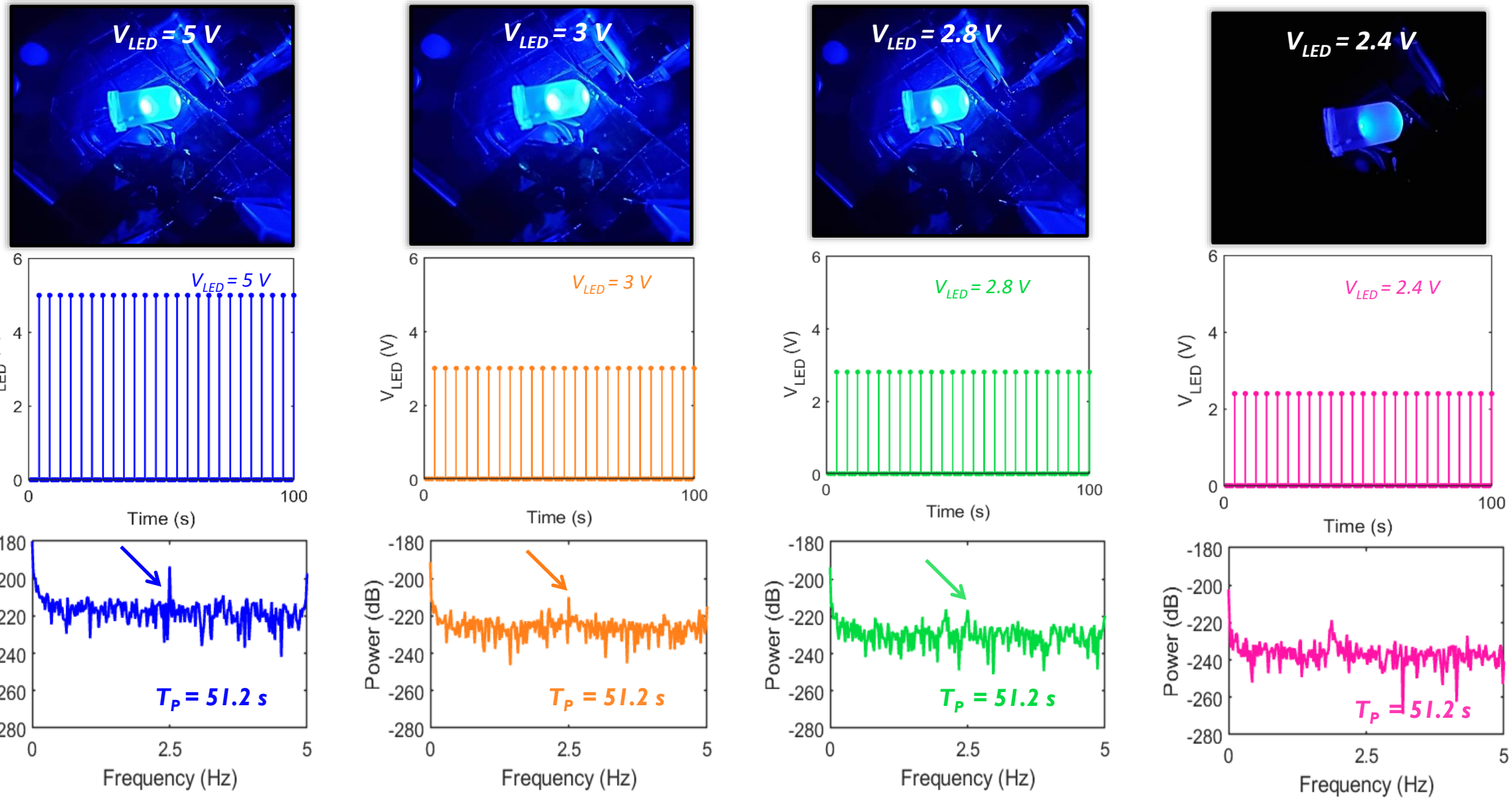


Transfer Characteristics



Limit of MoS_2 Photodetector

Dodda, *et al. Nature Communications*, 2020



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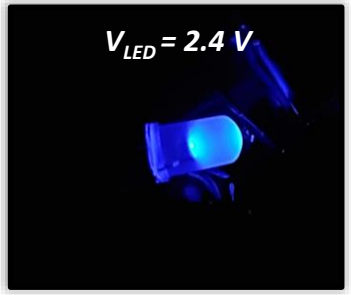
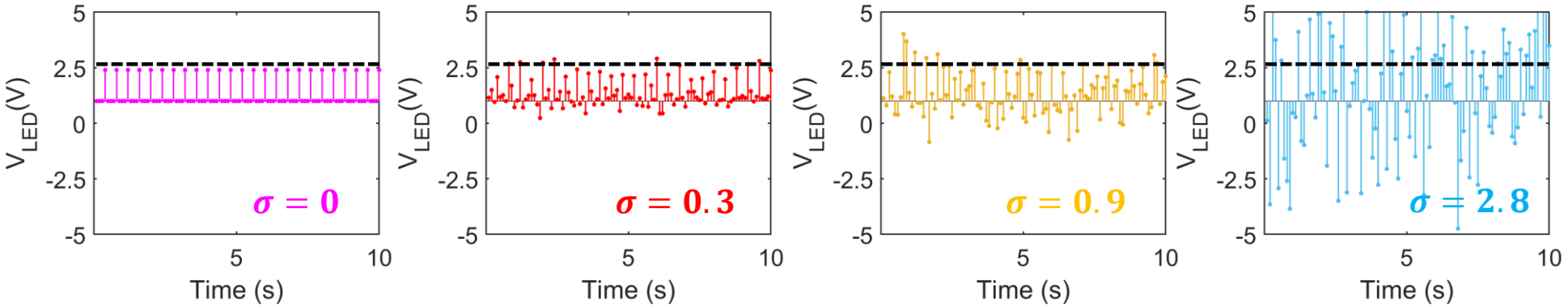
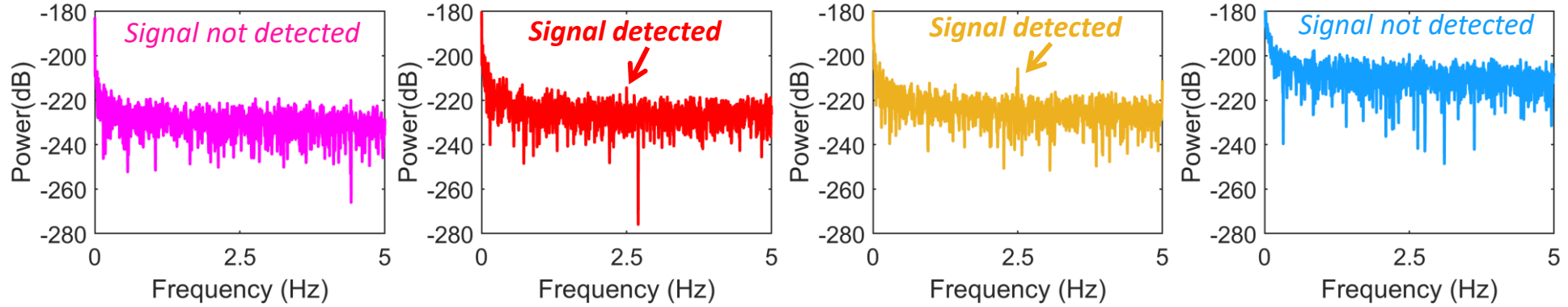
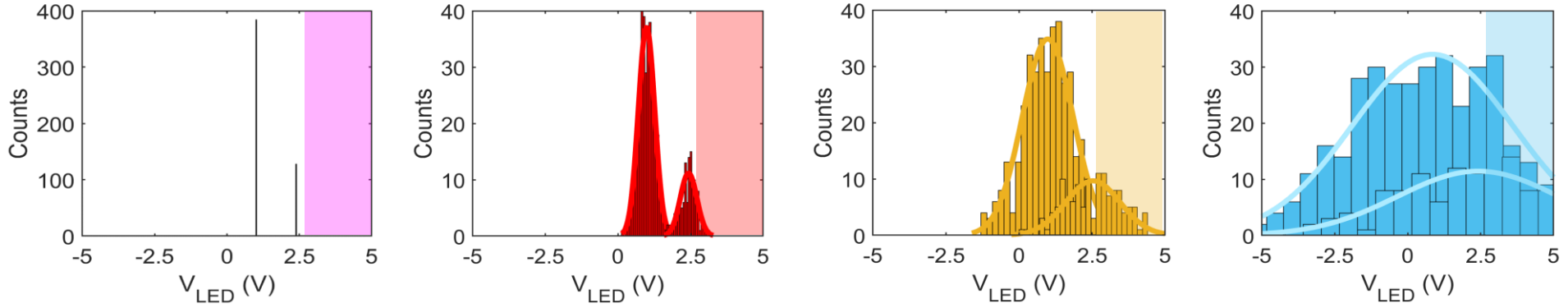
Stochastic Resonance in MoS_2 Photodetector

Dodda, *et al. Nature Communications*, 2020





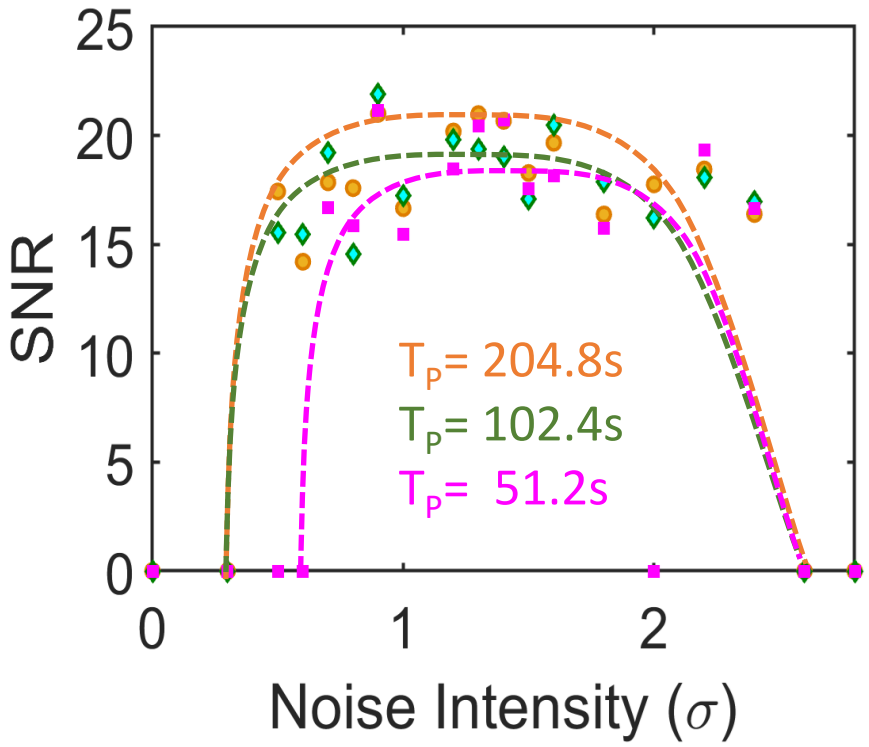


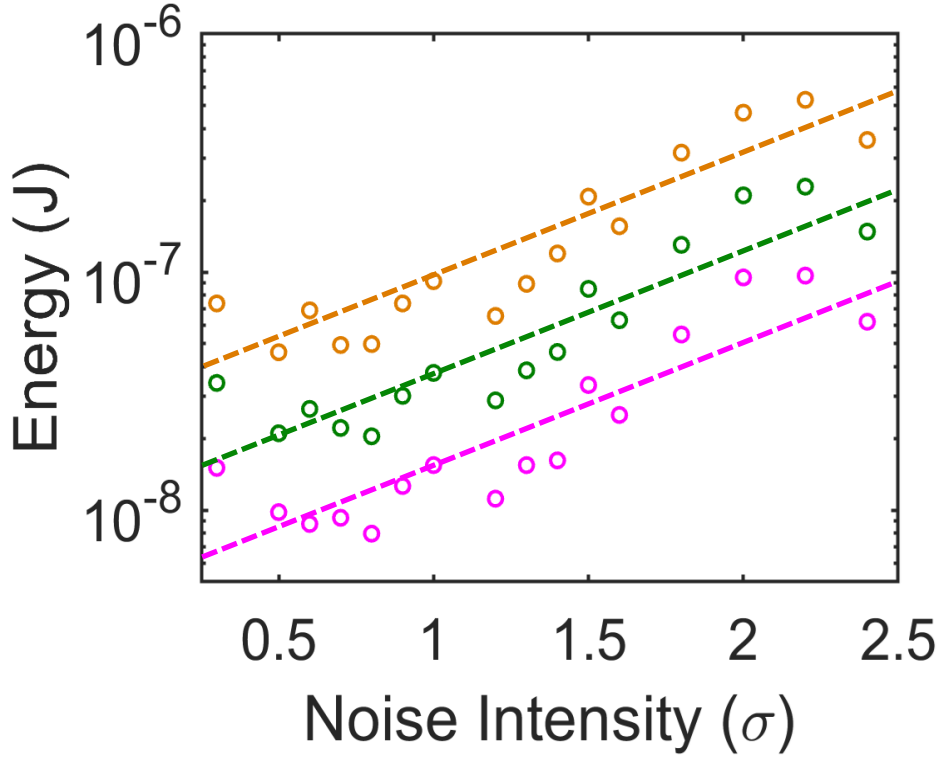


SNR and Energy Benefits

Energy Expenditure : ~ 10 nJ

Dodda, *et al. Nature Communications*, 2020





The concept of SR is generic in nature and can be extended to any other sensor including ***chemical, biological, thermal and radiation sensor***

Brain Inspired Computing and Sensing

Cognitive Computing

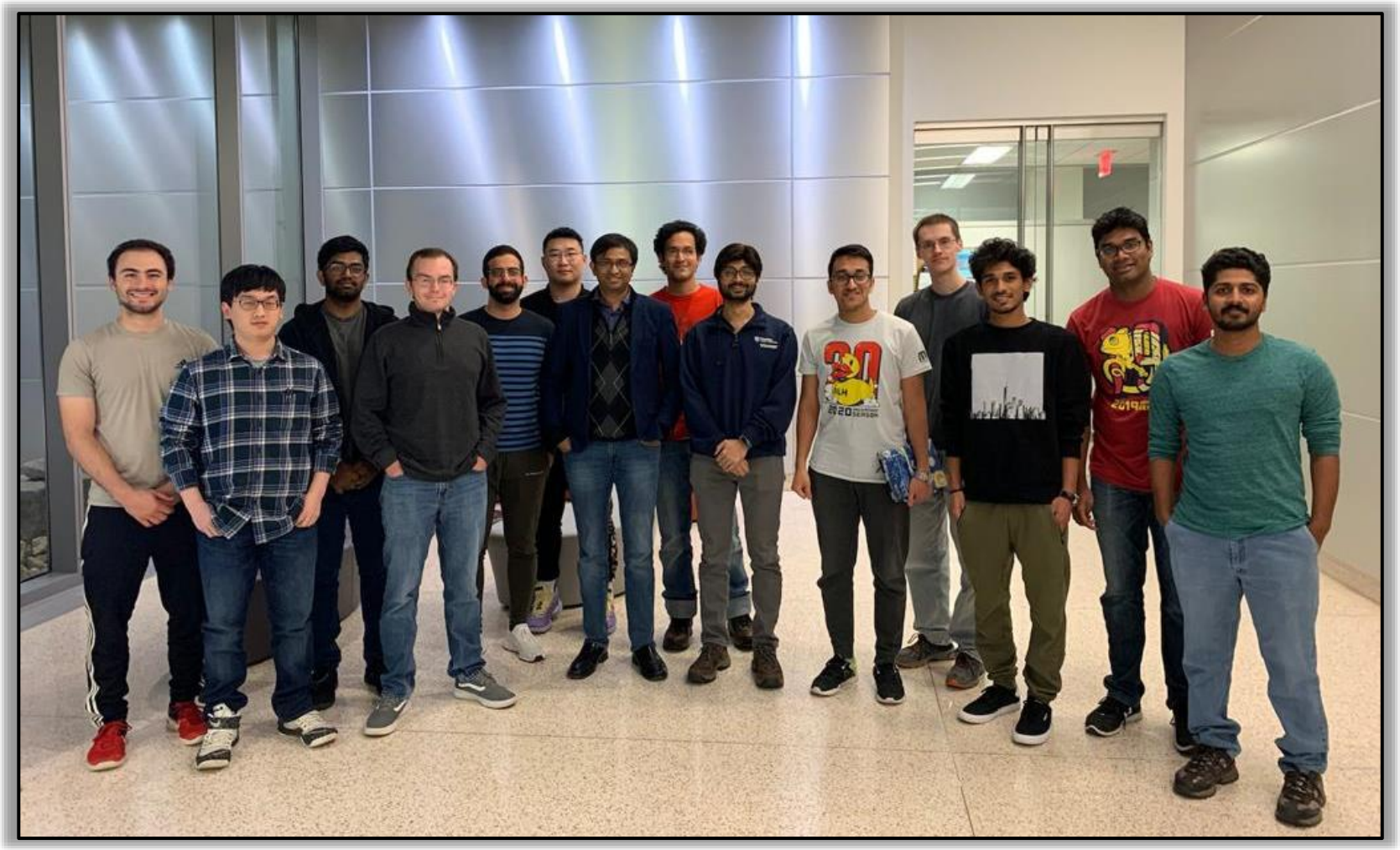
Natural Super Sensors

Jewel Beetle: Infrared Radiation
Bee: Earth's Magnetic Field

Sensory Computing

Acknowledgement

Thank You



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March 10, 2021 at 12 pm EST

Dr. Carmen Gomes

Associate Director of Virtual Reality Applications Center
Associate Professor
Iowa State University

"Future of food and agriculture from macro to nano: opportunities and challenges"

See nano4me.org or cneu.psu.edu/news for updates

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