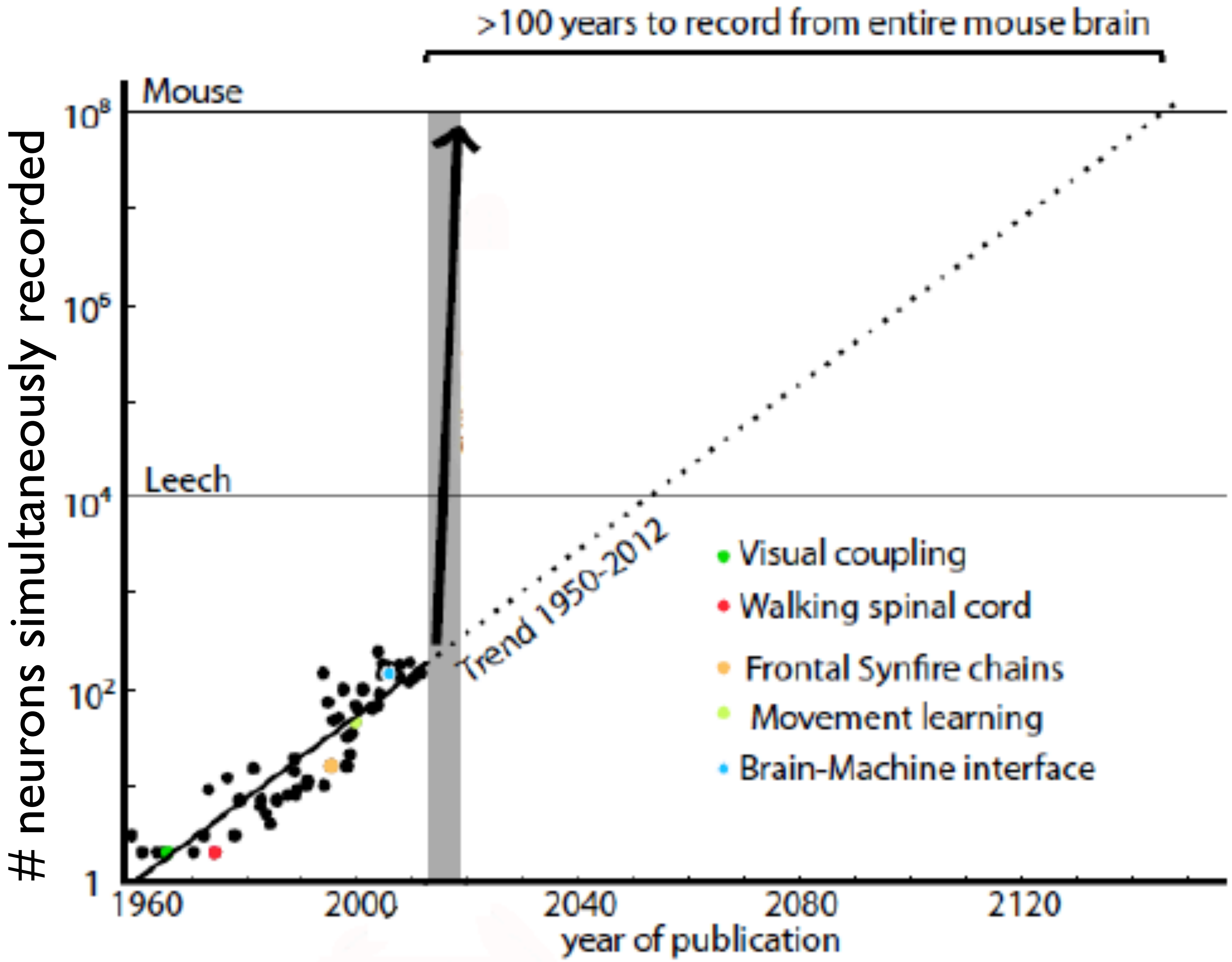
Physical Principles for Scalable Neural Recording

Adam Marblestone, PhD
MIT Media Lab
[speaking on behalf of MIT not Kernel today]

"every spike from every neuron" in a mammalian brain



<u>Mouse brain</u>:

- 100M neurons
- >100B connections
- 1-1000 Hz firing rates
- 0.5 cc volume

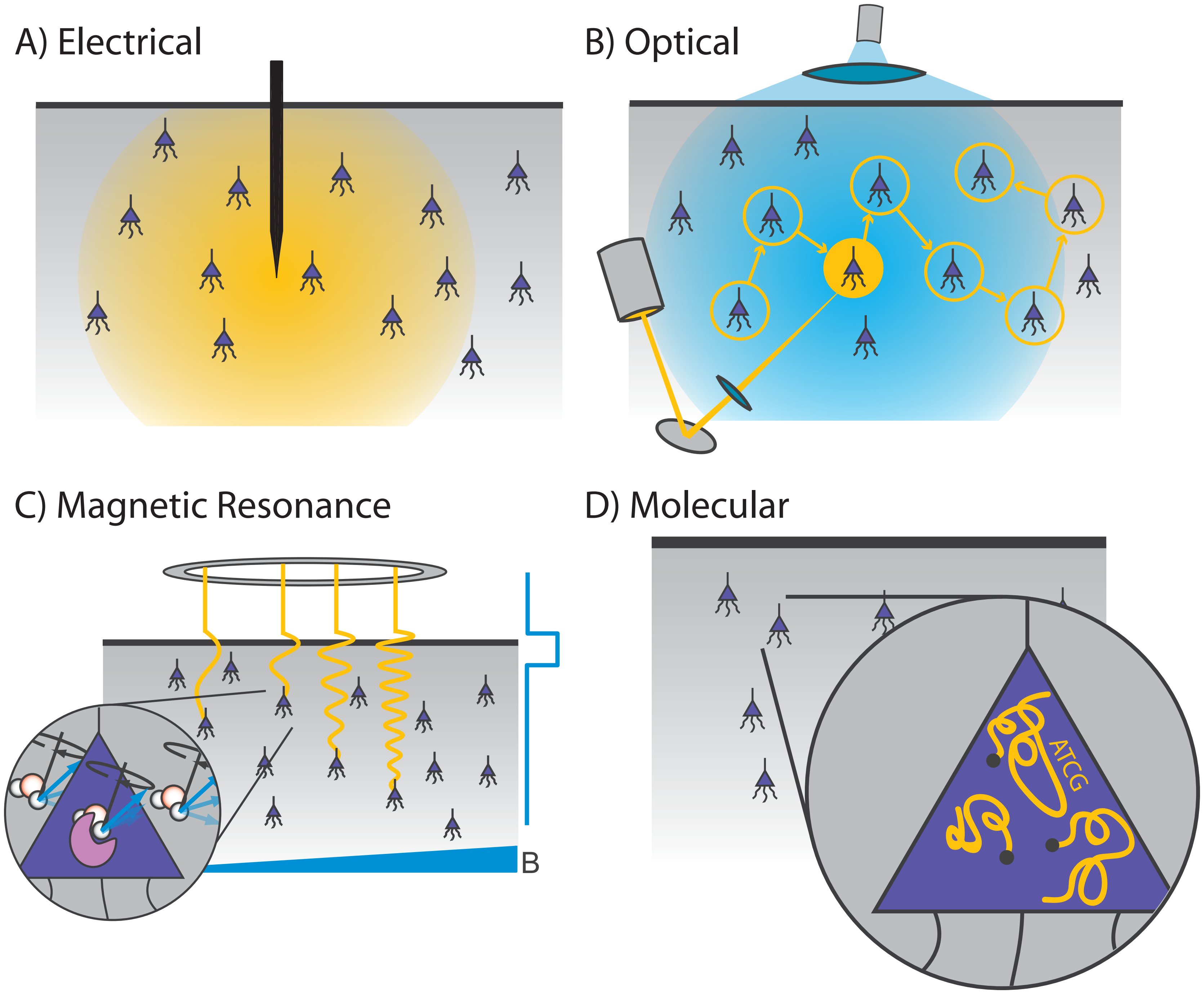
Konrad Kording 2013; Alivasatos et al 2012

Physics constraints on brain activity mapping

< 2C temperature change:

→ **< 50 mW** steady-state power dissipation

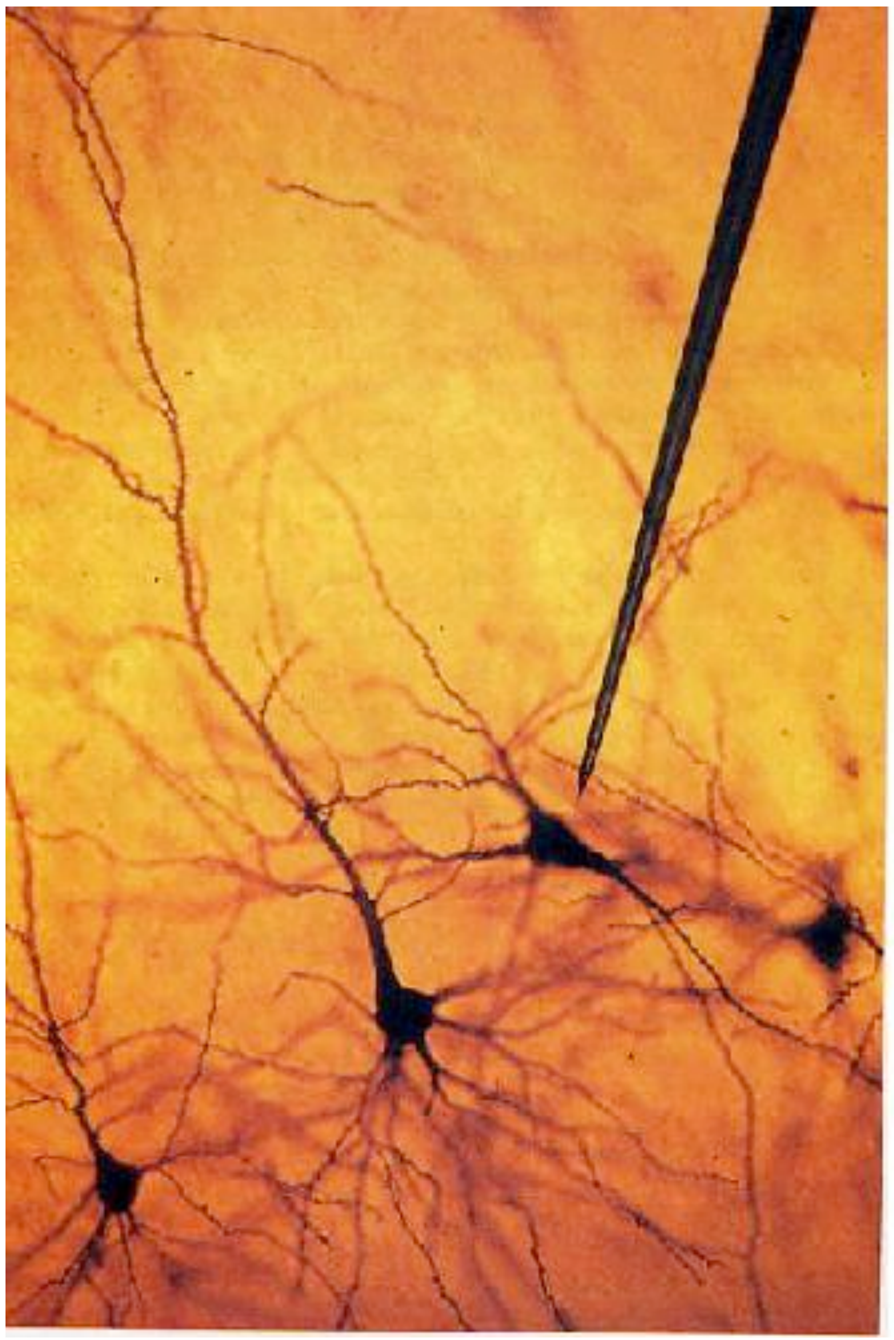
< 1% tissue volume displacement



Marblestone et al, Front. Comp. Neurosci (2013): **with >17 co-authors**

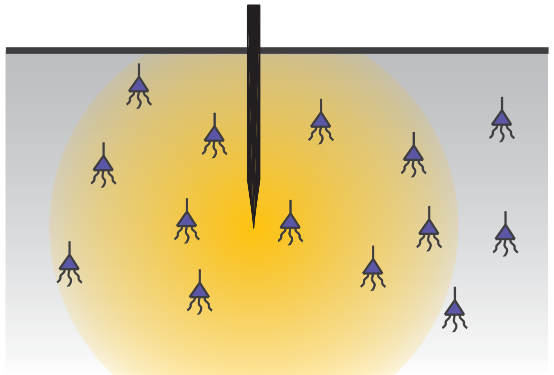
http://arxiv.org/abs/1306.5709

What's wrong with the electrode?

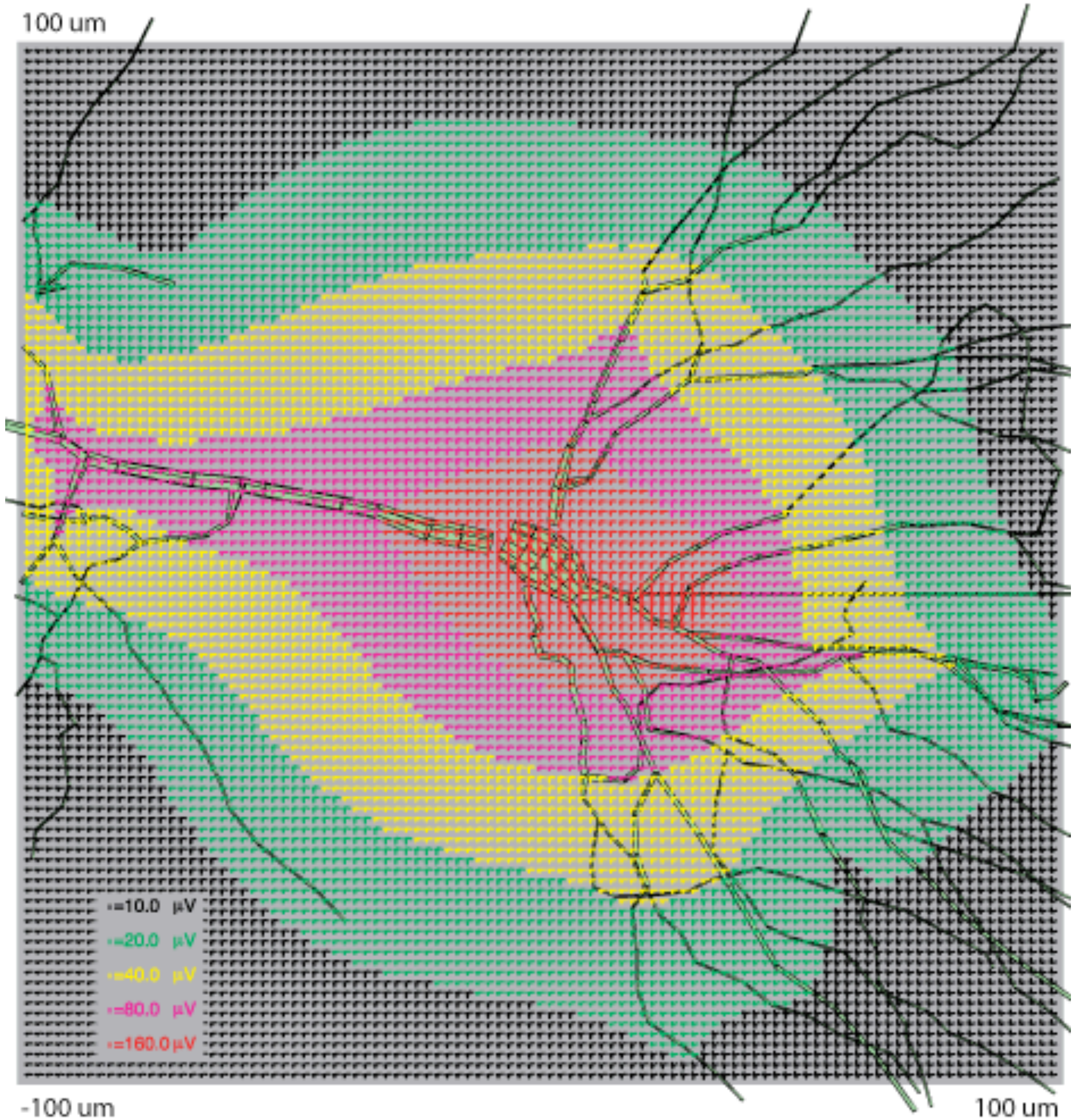


- Only a single recording site
- Hard to record from many neurons at once

How far can an electrode see?



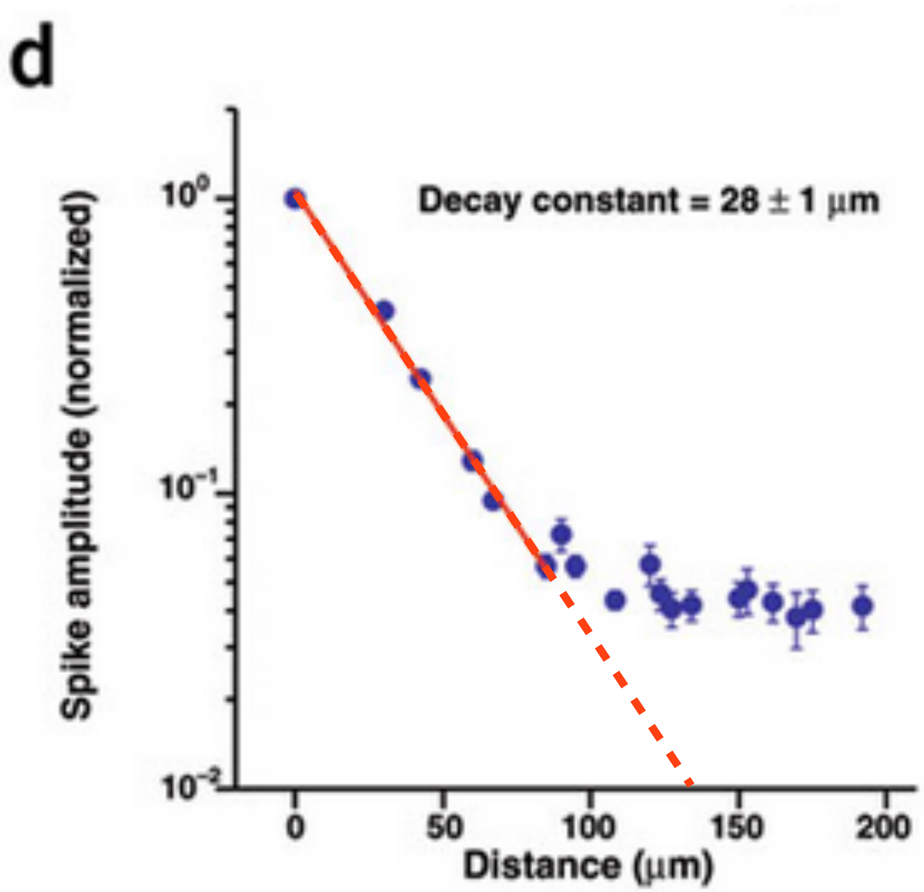
100-200 um max recording radius



Marblestone et al, Front. Comp. Neurosci (2013): **with >17 co-authors**

[Neuron/Matlab simulation based on Gold and Koch]

How far can an electrode see?



r_{max} ~ 130 um

signal size ~ 100-1000 uV

noise floor ~ 10-20 uV

SNR <100

$V_{johnson} = [4k_bTR(BW)]^{1/2}$ ~ 9 uV

amplifier noise ~ 1 uV

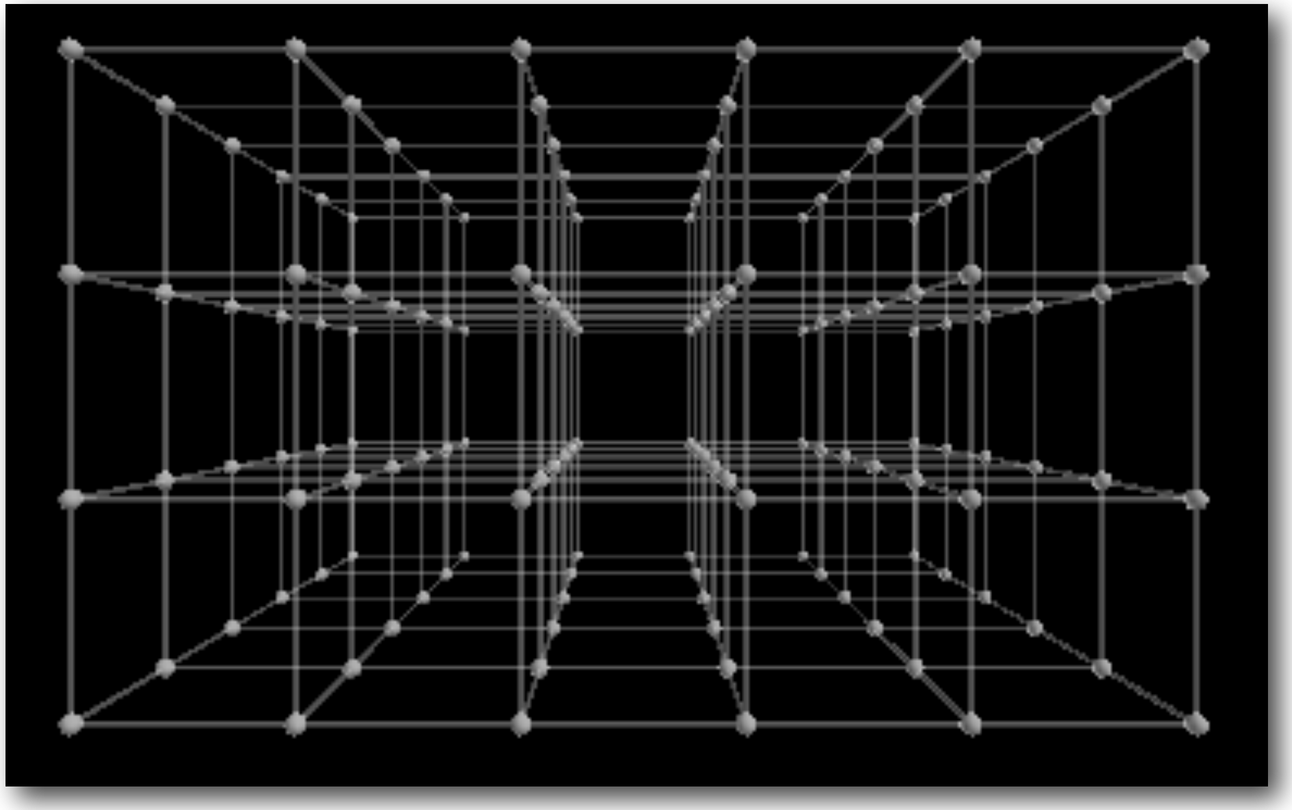
noise from other neurons

data: **Berry lab**, Princeton

Marblestone et al, Front. Comp. Neurosci (2013): **with >17 co-authors**

How far can an electrode see?

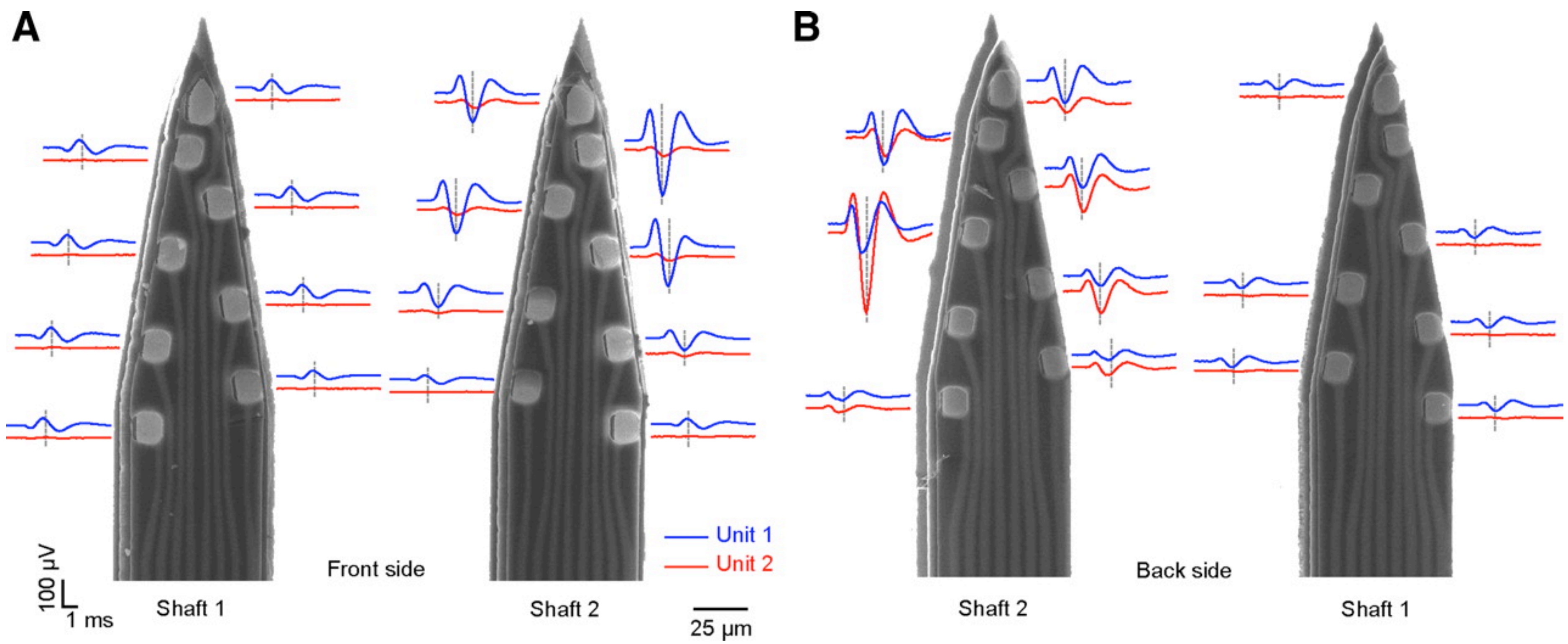
750k -7.5M electrodes for 75M mouse neurons



current spike sorting algorithms: < 10 neurons / electrode
information theory estimate: < 100 neurons / electrode
estimate from max recording radius: < 1000 neurons / electrode

Marblestone et al, Front. Comp. Neurosci (2013): **with >17 co-authors**

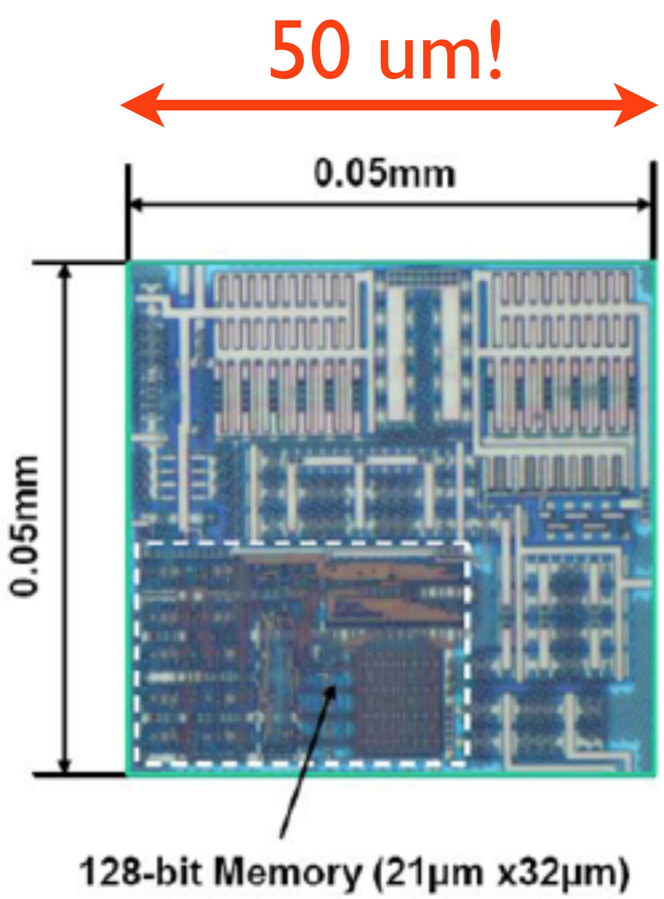
Simplest solution: many electrode pads



- Must route many electrical traces (wires) to access many neurons
- # of traces that must be routed onto same shank scales with length of probe
    - (1 mm / 20 um) = 50 traces
    - (10 cm / 20 um) = 5000 traces
    - 50 um shank width / 5000 traces = 10 nm per trace
        - Fabrication
        - Impedance

Du et al (2009)

Physics constraints on brain activity mapping



wirelessly-powered RFID chip

> 10 pJ per transmitted bit

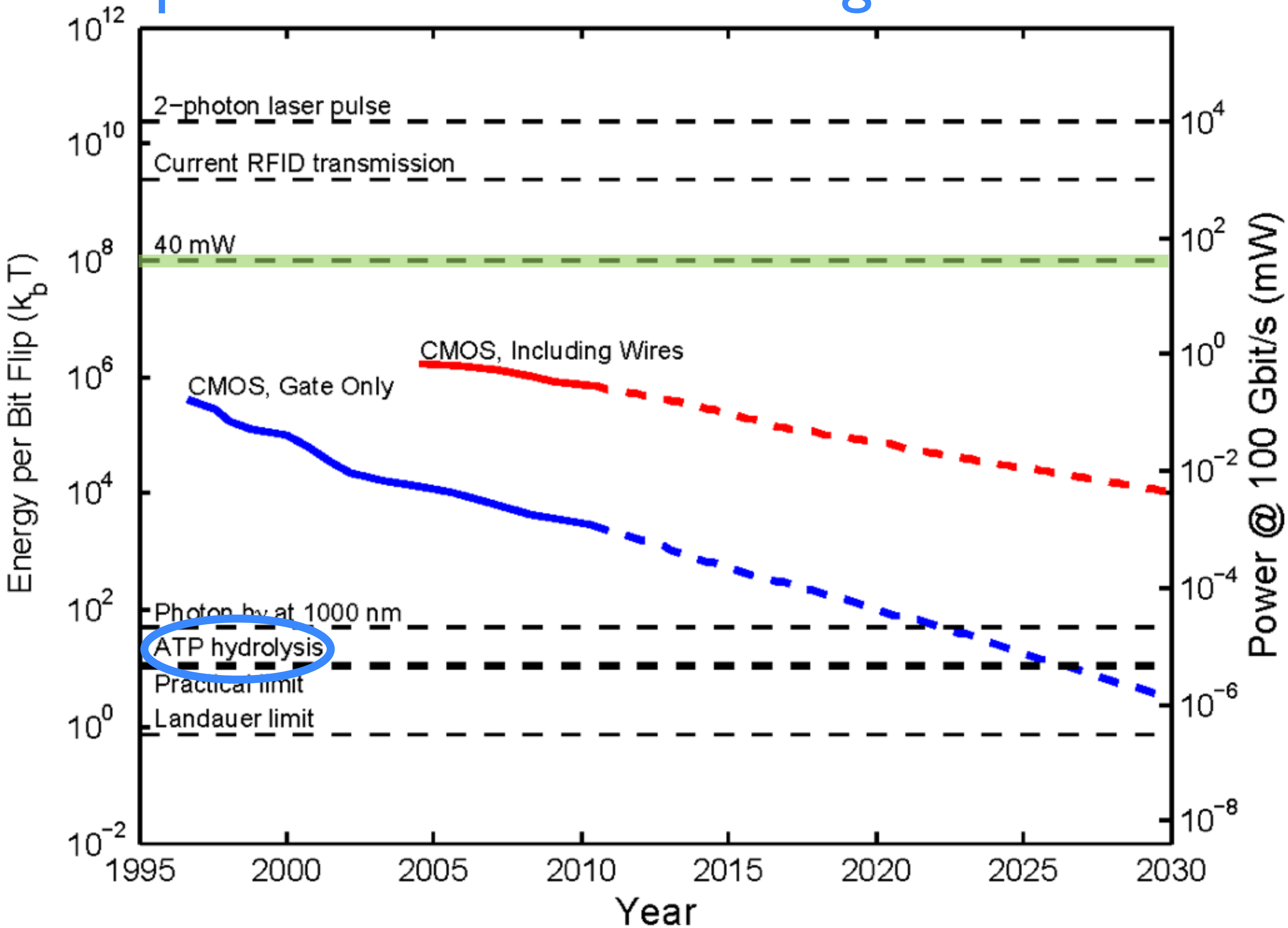
x 100 Gbit/sec = **1W**

need at **2-3 orders of magnitude** improvement
in power efficiency of electronics
to use embedded chips for whole-brain recording

Marblestone et al, Front. Comp. Neurosci (2013): **with >17 co-authors**

Physics constraints on brain activity mapping

power limits on switching elements

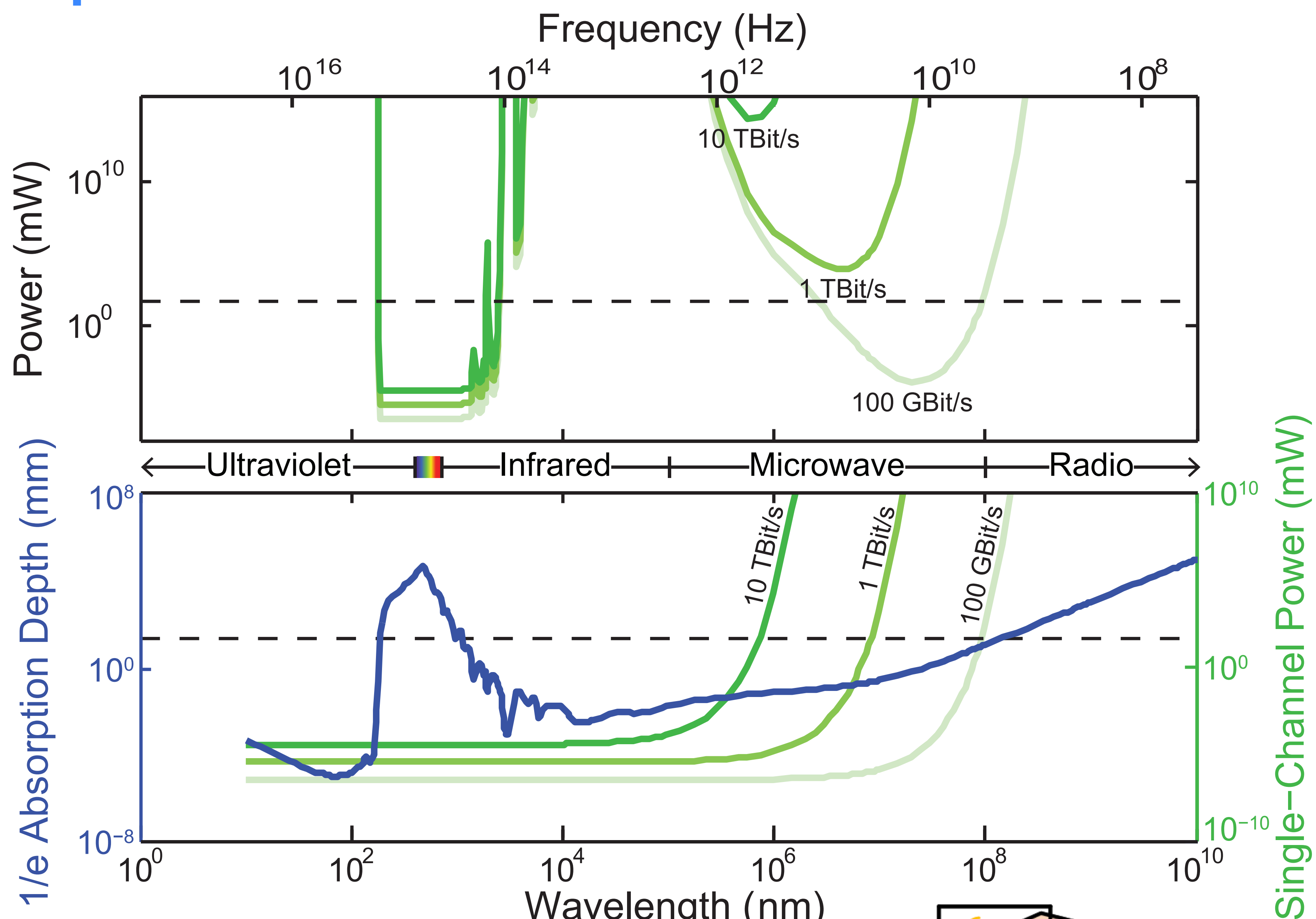


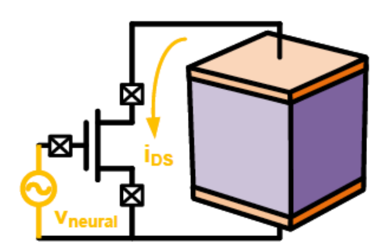
[CMOS data from Rod Tucker]

Marblestone et al, Front. Comp. Neurosci (2013): **with >17 co-authors**

Physics constraints on brain activity mapping

power limits on data transmission





Seo et al

Workarounds:

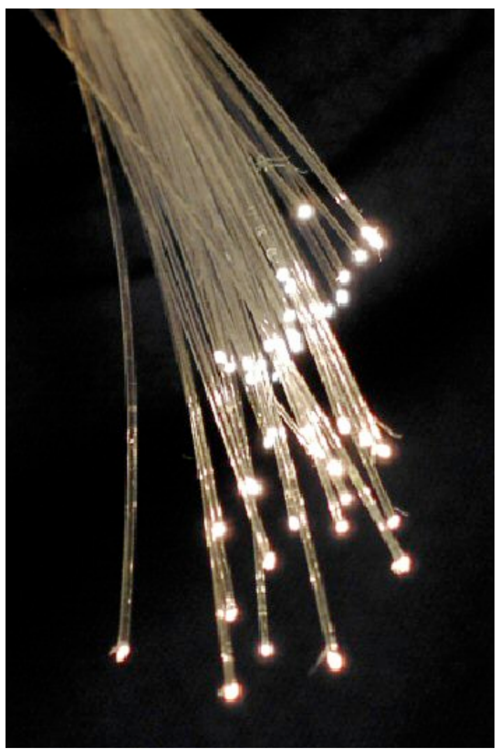
store data locally and read out slowly

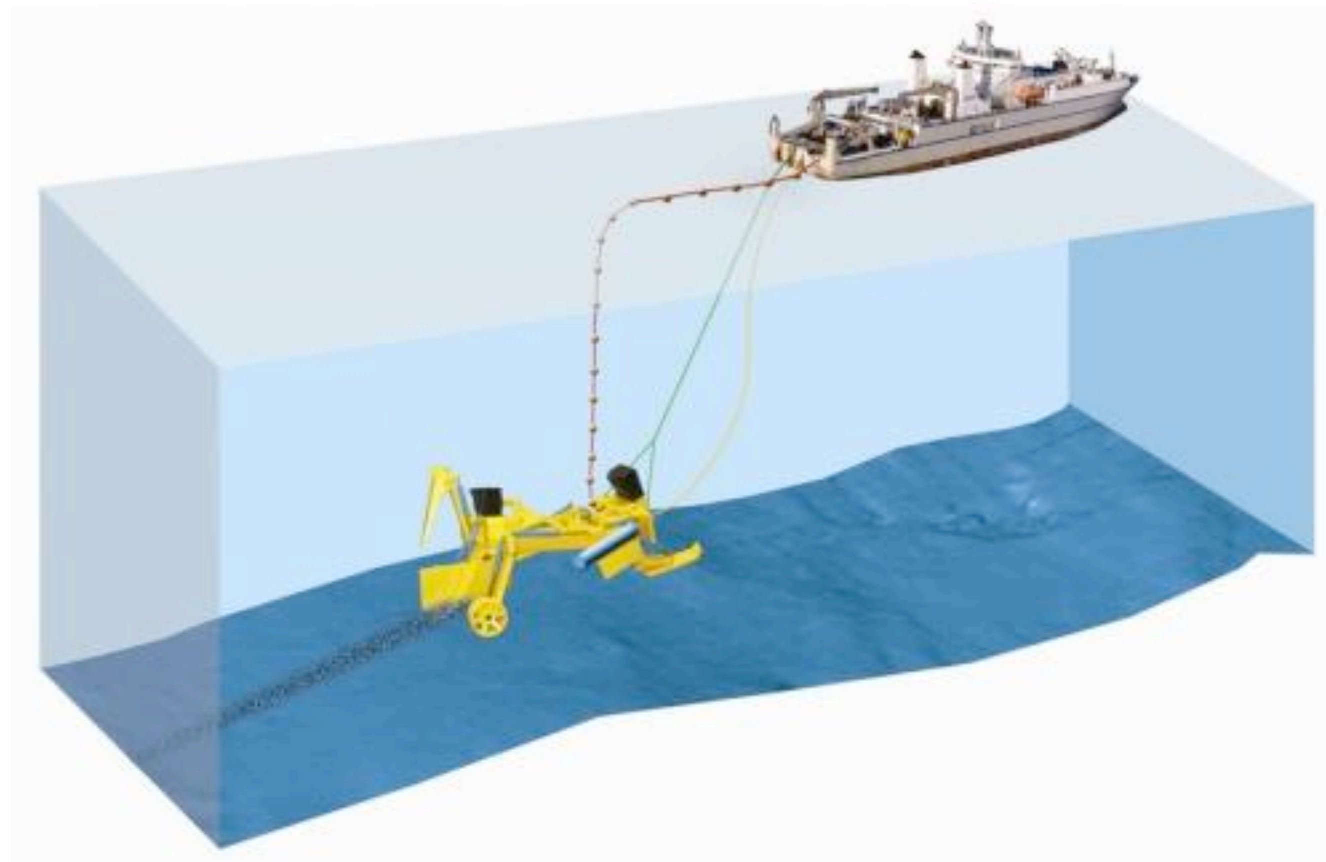
use ultrasound or infrared/visible light rather than RF / microwave transmission

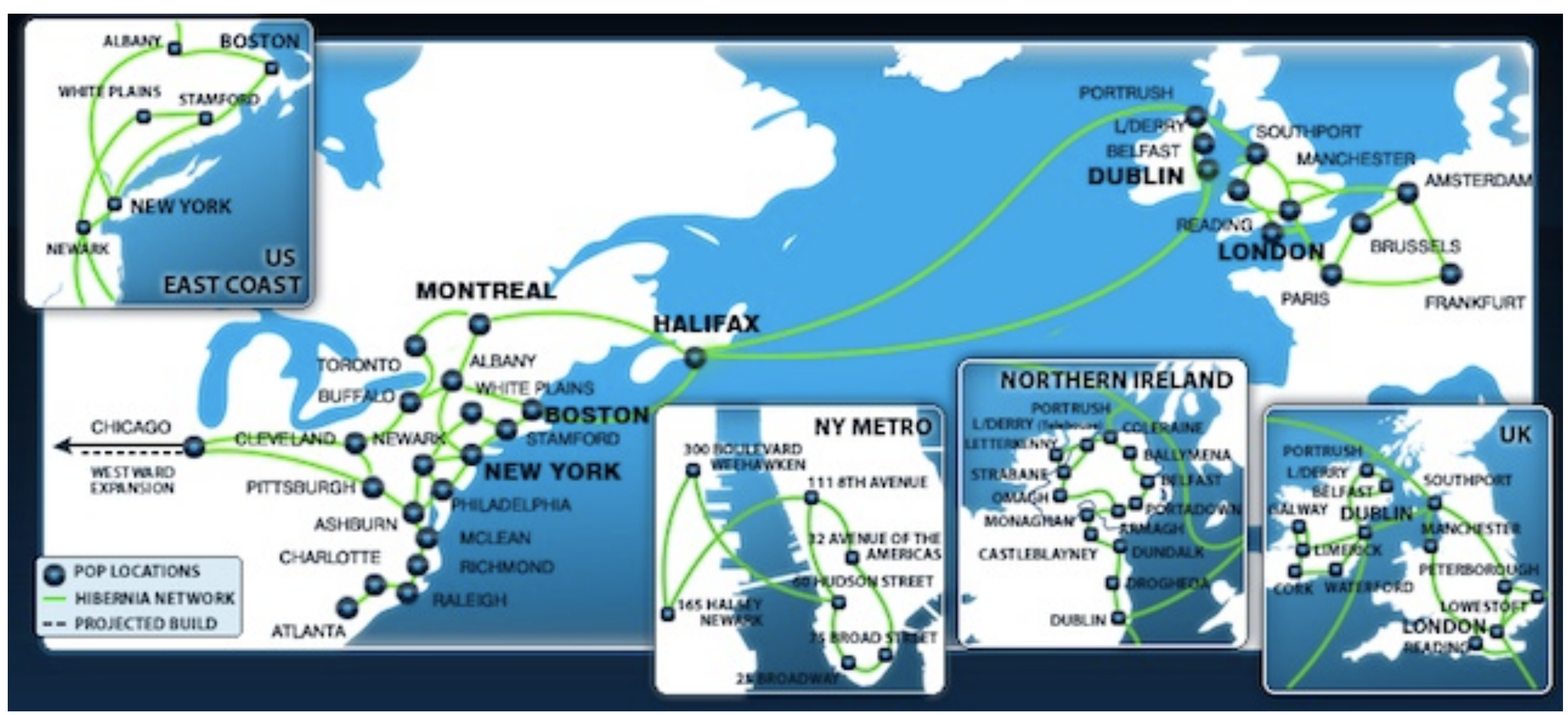
Marblestone et al, Front. Comp. Neurosci (2013): **with >17 co-authors**

What if we could **multiplex**
many signals into a single very thin
“wire” *without* separate traces?

Locating defects in long optical fibers

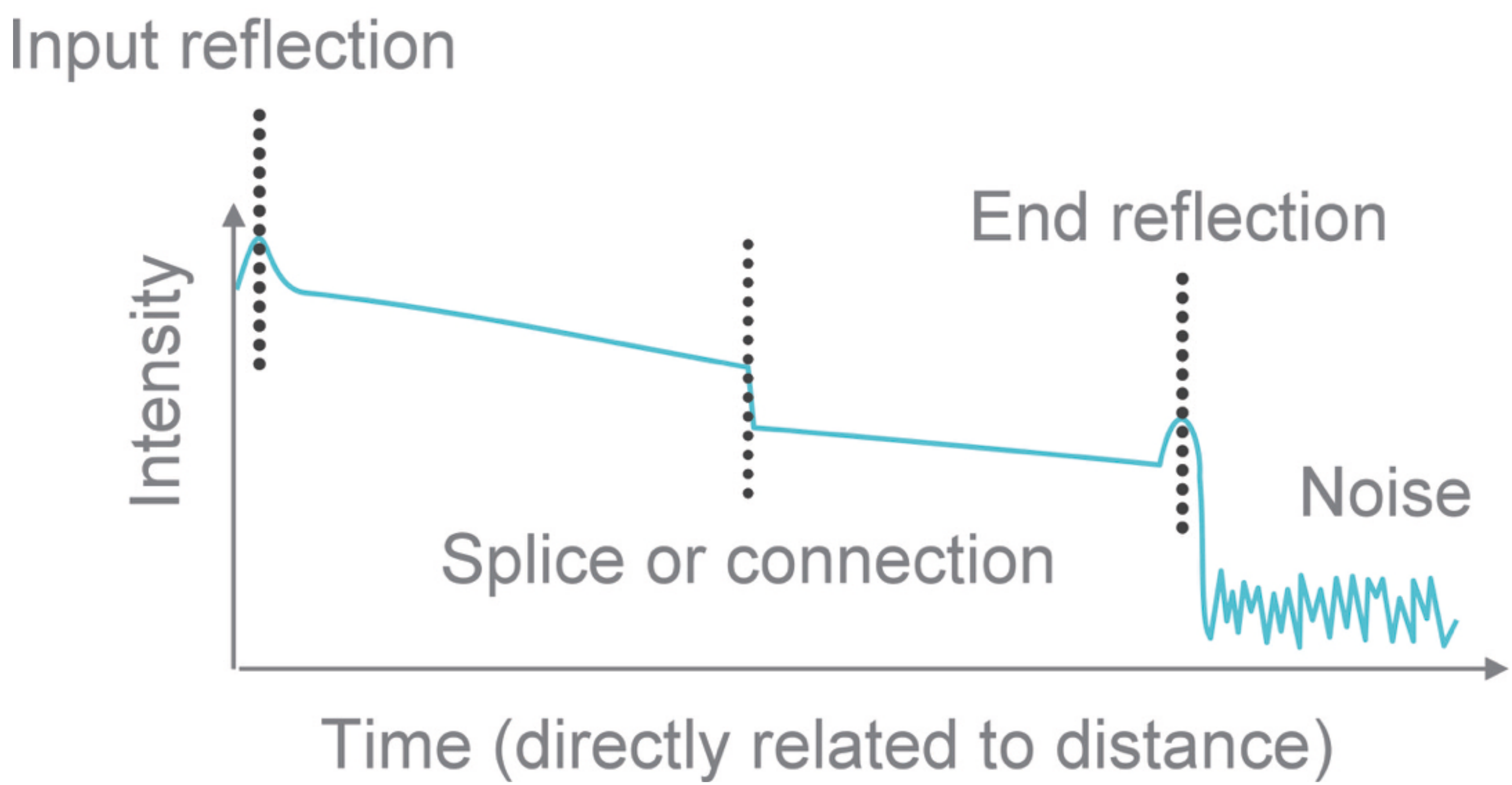






Locating defects in long optical fibers

optical reflectometry



http://www.fibercore.com/mediaLibrary/images/english/6360.jpg

Locating defects in long optical fibers

Luna's Optical Backscatter Reflectometer™ (OBR) delivers unprecedented inspection and diagnostic capabilities for the fiber optics industry. Luna's state-of-the-art OBR provides isolation of faults and problems well before final test, saving hours in rework and hard dollars in yield loss. Industry-leading 10 micron spatial resolution with zero dead-zone will pinpoint even the smallest contributors to loss: bends, crimps, bad splices, you name it —

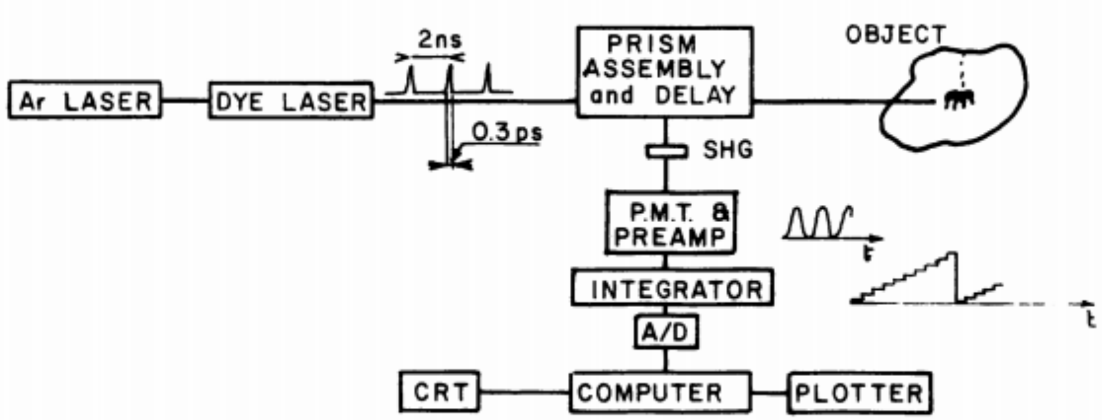


Figure 5

Instrumentation for optical TDR.

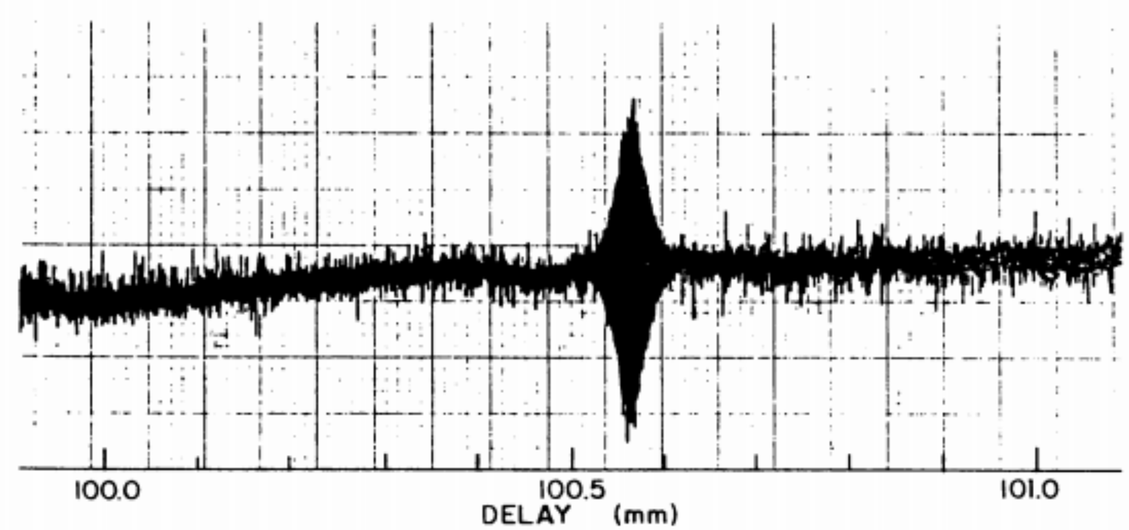
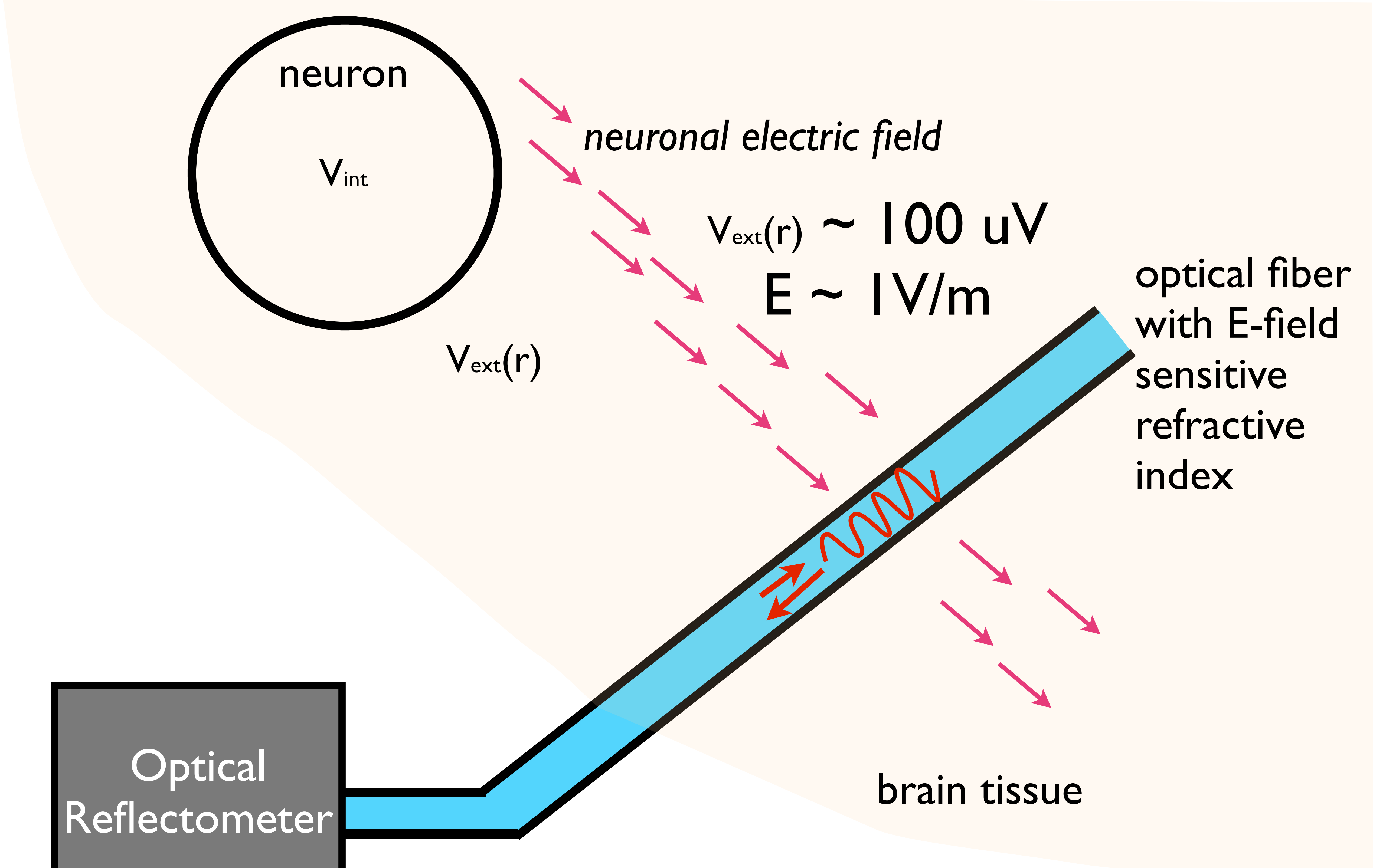


Figure 3

Localization of a weak discontinuity by TDR

Fontaine 1981



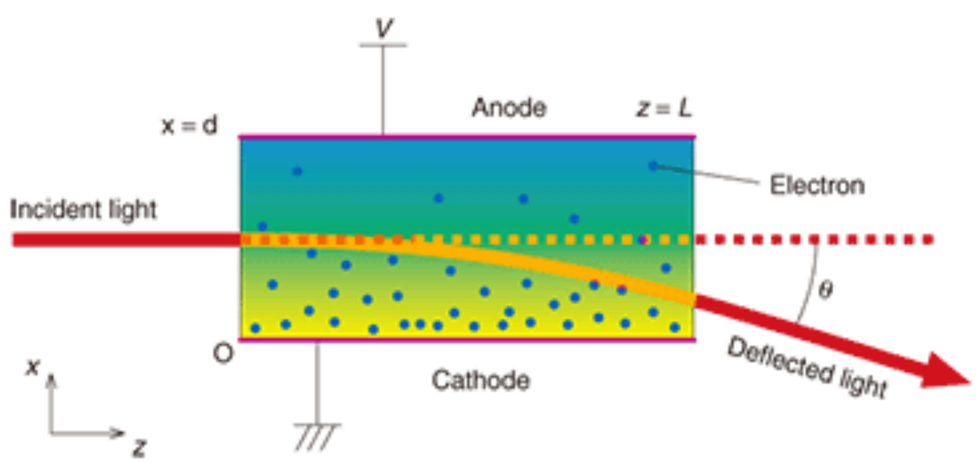
Journal of Biomedical Optics 21(5), 057003 (May 2016)

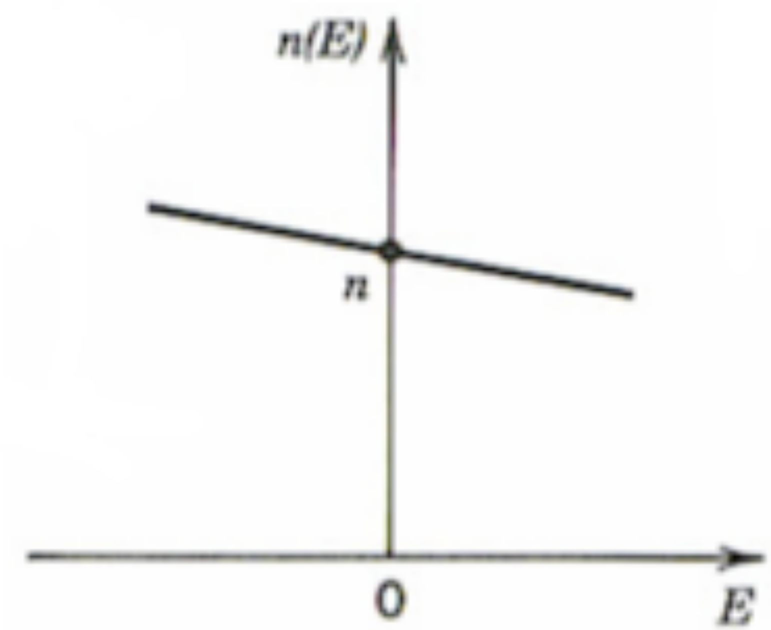
Multiplexed neural recording along a single optical fiber via optical reflectometry

Samuel G. Rodriques,[a,b,†] Adam H. Marblestone,[a,†] Jorg Scholvin,[a] Joel Dapello,[a] Deblina Sarkar,[a] Max Mankin,[c] Ruixuan Gao,[a] Lowell Wood,[d] and Edward S. Boyden[e,*]

Coupling electric field to optical reflection coefficient in fiber

Pockel's effect: change in refractive index driven by E field





https://www.ntt-review.jp/archive_html/200912/images/sf3_fig05.gif

Comparison with standard electro-optic modulators:

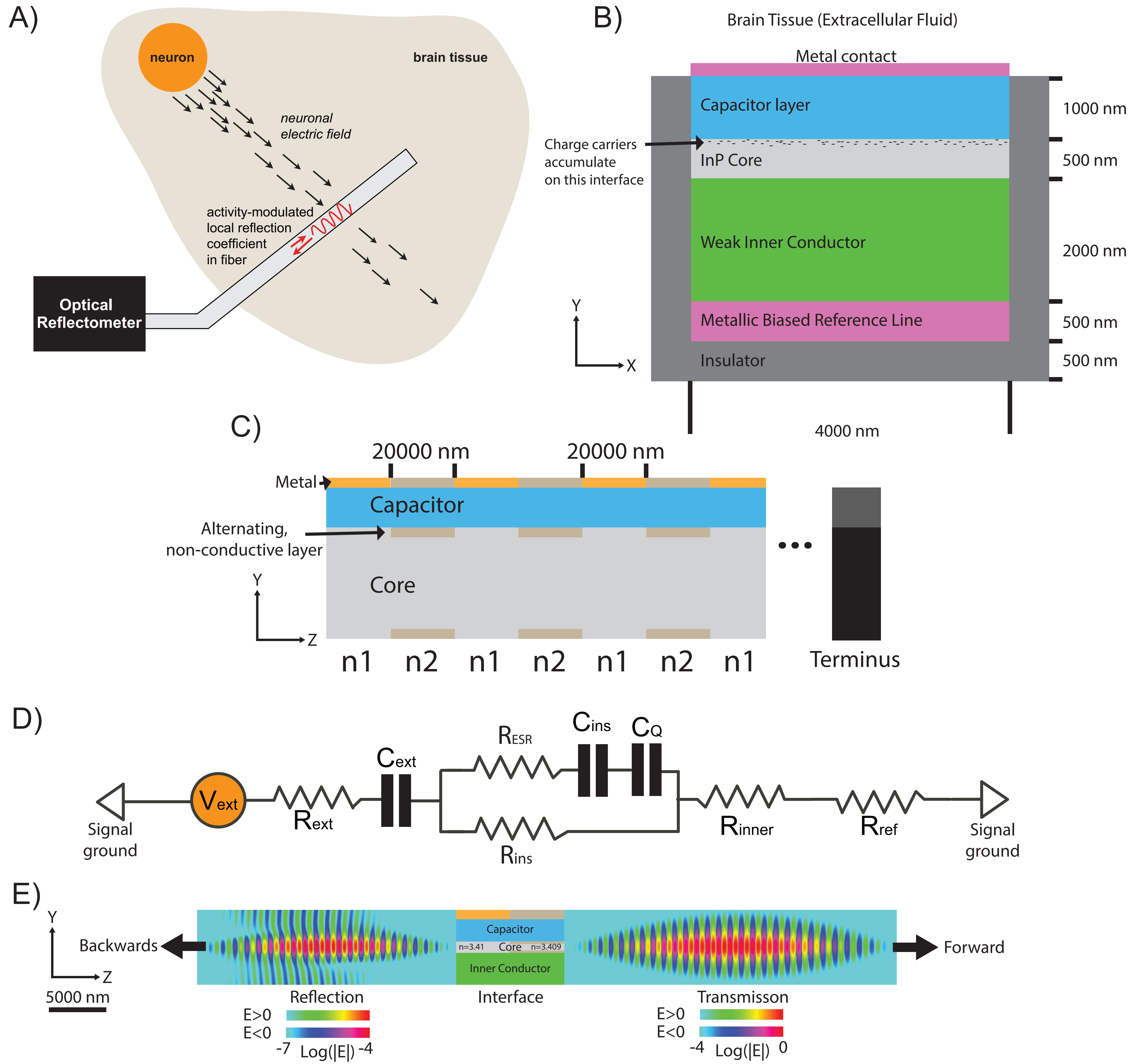
them	*us*
~5V	~5V / 10^5 = microvolts
Switch at GHz	Switch at GHz / 10^5 = kilohertz
micrometer sizes	micrometer sizes

Vol 435|19 May 2005|**doi:10.1038/nature03569** nature

LETTERS

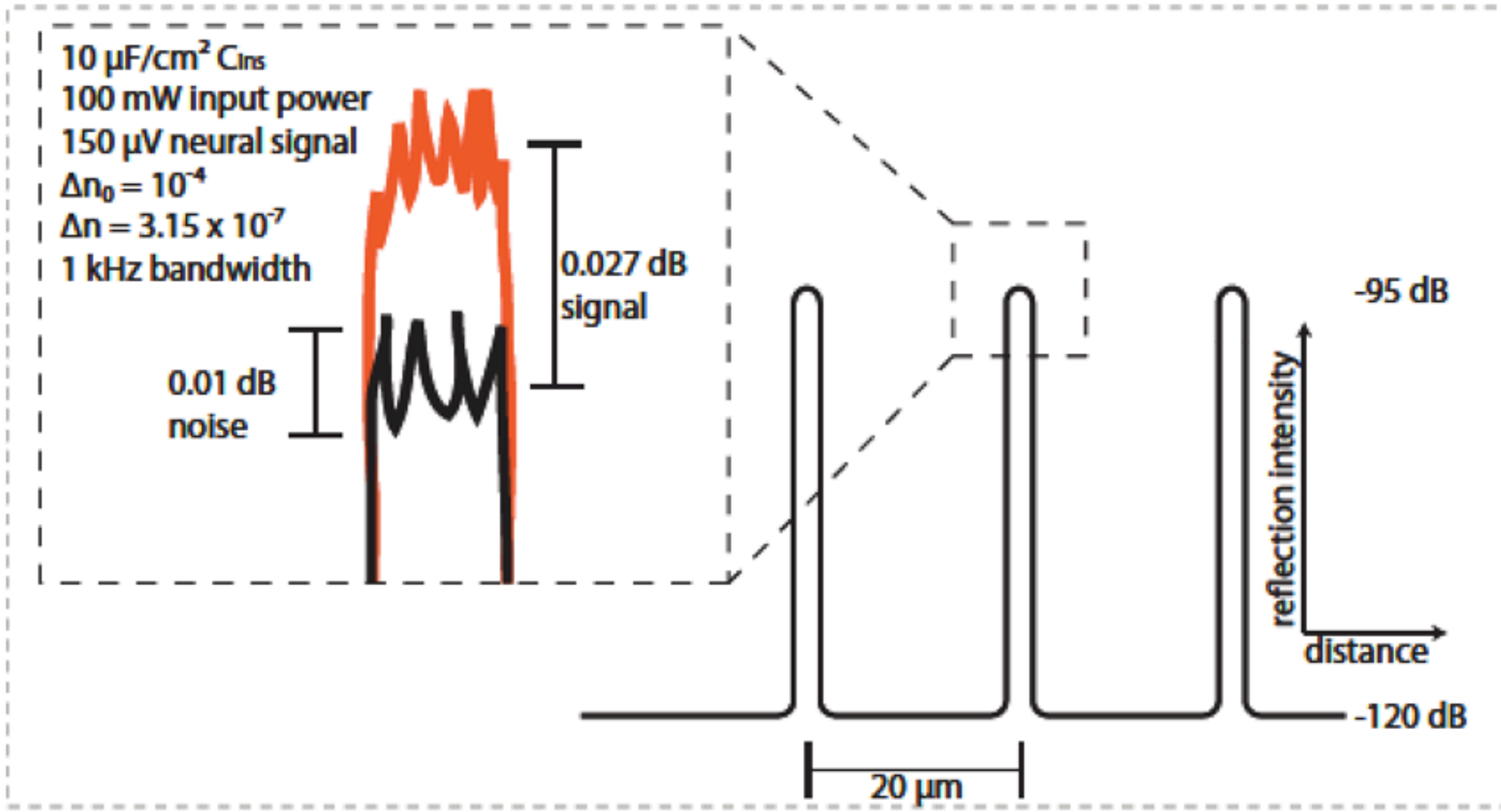
Micrometre-scale silicon electro-optic modulator

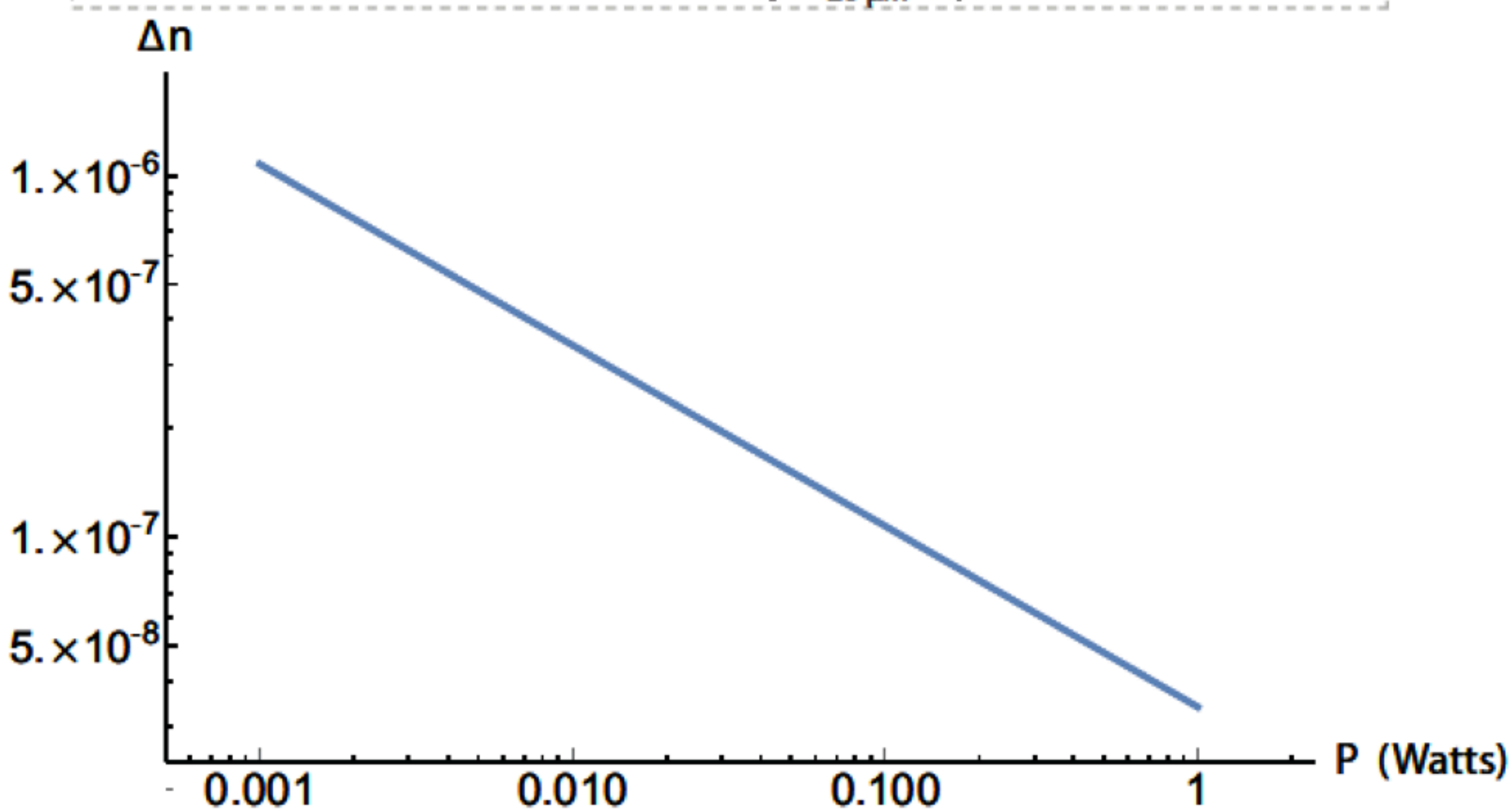
Qianfan Xu[1], Bradley Schmidt[1], Sameer Pradhan[1] & Michal Lipson[1]



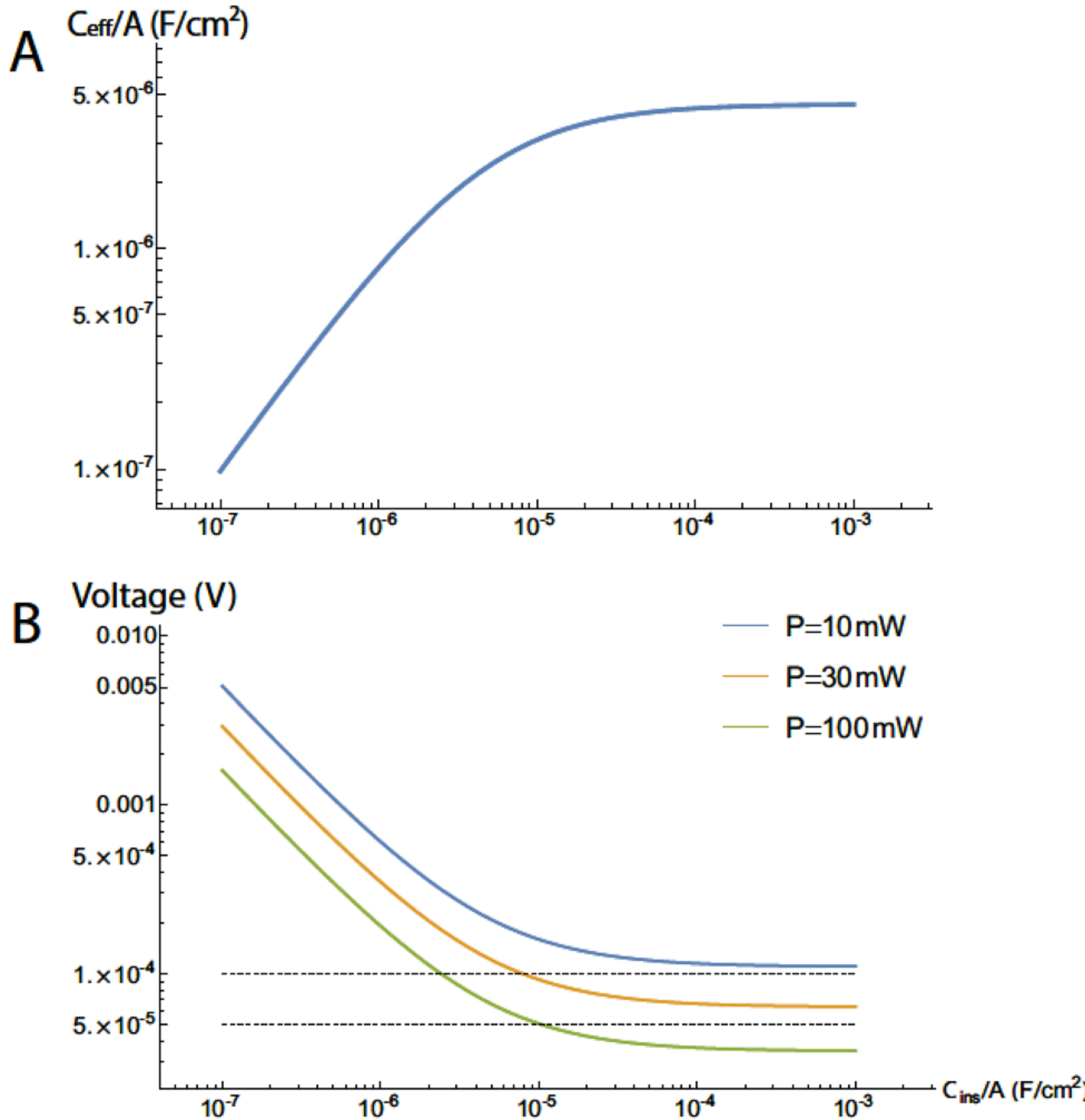
A)
neuron
brain tissue
neuronal electric field
activity-modulated local reflection coefficient in fiber
Optical Reflectometer
B)
Brain Tissue (Extracellular Fluid)
Metal contact
Capacitor layer
Charge carriers accumulate on this interface
InP Core
Weak Inner Conductor
Metallic Biased Reference Line
Insulator
1000 nm
500 nm
2000 nm
500 nm
500 nm
4000 nm
Y
X
C)
20000 nm
20000 nm
Metal
Capacitor
Alternating, non-conductive layer
Core
Y
Z
n1 n2 n1 n2 n1 n2 n1
Terminus
D)
Signal ground
V_{ext}
R_{ext}
C_{ext}
R_{ESR}
C_{ins}
C_Q
R_{ins}
R_{inner}
R_{ref}
Signal ground
E)
Y
Z
5000 nm
Backwards
Capacitor
n=3.41 Core n=3.409
Inner Conductor
Forward
Reflection
Interface
Transmisson
E>0
E<0
-7 Log(|E|) -4
E>0
E<0
-4 Log(|E|) 0

Optical shot noise in the reflected signal limits sensitivity



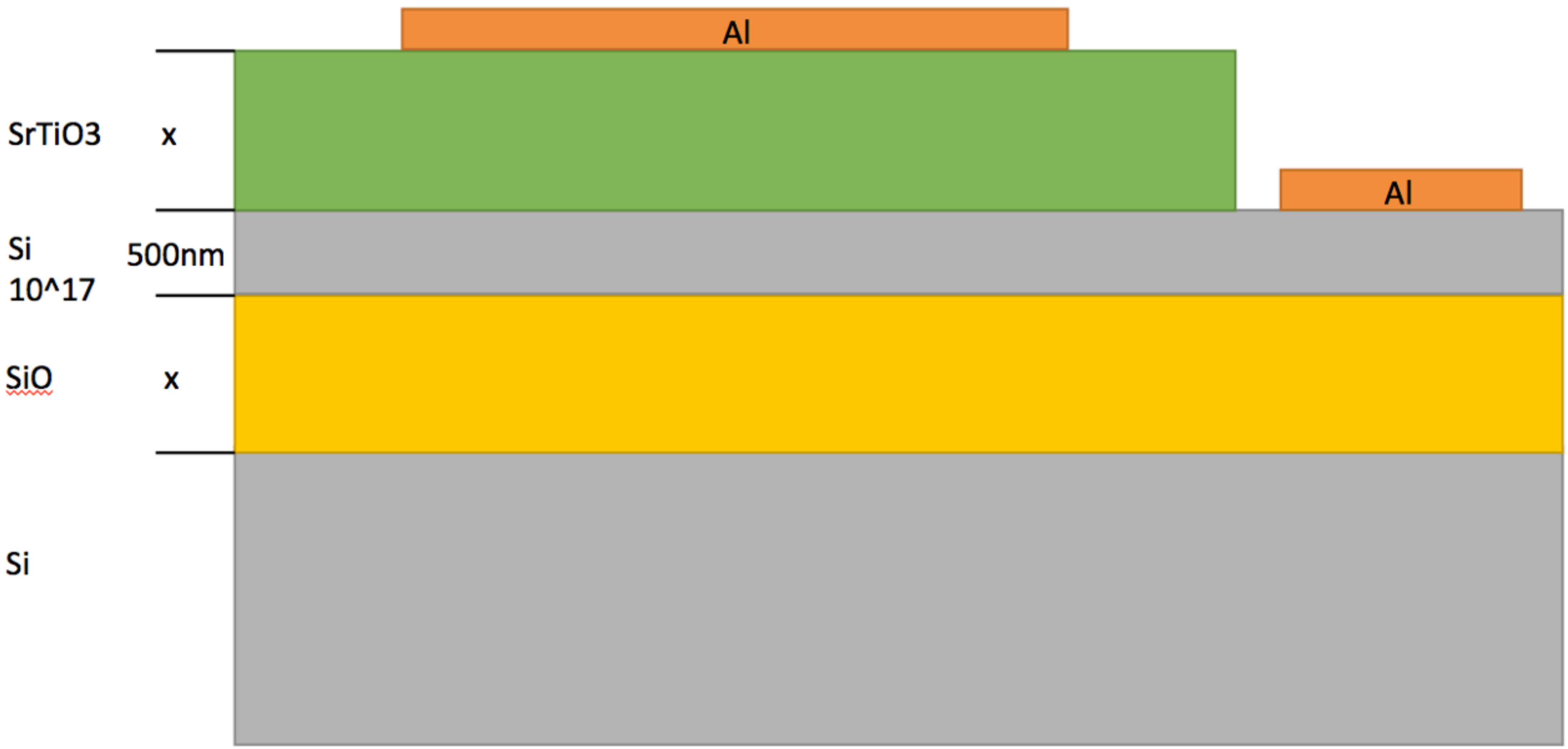


Need a very large capacitance



Minimal test system

Doping levels given in cm^{-3}
x = 500nm, 1um, 2um.



with Supratik Guha, Sam Rodriques, Deblina Sarkar, Jorg Scholvin, Ed Boyden

19 May 2016

Multiplexed neural recording along a single optical fiber via optical reflectometry

Samuel G. Rodriques; Adam H. Marblestone; Jorg Scholvin; Joel Dapello; Deblina Sarkar; Max Mankin; Ruixuan Gao; Lowell Wood; Edward S. Boyden

Author Affiliations +

J. of Biomedical Optics, 21(5), 057003 (2016). doi:10.1117/1.JBO.21.5.057003

Thank you! Please read:

HYPOTHESIS AND THEORY ARTICLE

Front. Comput. Neurosci., 21 October 2013 |
https://doi.org/10.3389/fncom.2013.00137

Physical principles for scalable neural recording

Adam H. Marblestone[1,2*†], Bradley M. Zamft[3†], Yael G. Maguire[3,4], Mikhail G. Shapiro[5], Thaddeus R. Cybulski[6], Joshua I. Glaser[6], Dario Amodei[7], P. Benjamin Stranges[3], Reza Kalhor[3], David A. Dalrymple[1,8,9], Dongjin Seo[10], Elad Alon[10], Michel M. Maharbiz[10], Jose M. Carmena[10,11], Jan M. Rabaey[10], Edward S. Boyden[9,12‡], George M. Church[1,2,3‡] and Konrad P. Kording[13,14‡]