Future Perspective: Sensors and Electronics Integration Frontier

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Instructions from the organizers:

"We encourage you to describe ways in which the physics is currently, or will be, enabled by new and creative innovations in electronic instrumentation and methods, rather than giving a historical overview …"

Nygren FEST
LBNL, May 2-3, 2014

Electron – (hole, ion) creation energy w_i

	w_i [eV]	Application:
Transition **E**dge **S**ensors (**TES**) **S**uperconducting **T**unnel **J**unctions (Bolometers, Microcalorimeters)	~ 1-2 x 10^{-3}	EM spectrum, meV – keV, eV-resolution spectrometry; precision microcalorimetry
Ge **Si** CdTe Diamond	2.9 3.6 5.2 ~13	Detectors for: x-ray, γ-ray spectrometry; Charged particle tracking, **M**onolithic **A**ctive **P**ixel **S**ensors; sampling calorimeters
Xe Kr **Ar** Ne	16 19 24 36	GeV-TeV calorimetry; Gas and liquid TPCs for detection of neutrinos, nucleon decay, ***0ββ***-decay, dark matter
NaI (+PM) **LSO** (+APD, SiPM) $PbWSO_4$ (+APD)	~ 200 ~ 100 ~ 10^5	SPECT PET GeV calorimetry

Where is prediction on detectors possible for the next ~ 20 years?

- **LHC upgrades I and II:** Increasing level 1 trigger rate from LAr calorimetry; new all-silicon tracking
- **e^+-e^- collider**
- **e-ion collider**
- **SLHC**
- **TPCs for 0ββ-decay, dark matter :** scaling up to ton size
- **LAr TPCs:** scaling up to 10-30 kton range
- **Detectors for astrophysics; photon science**

Symbiosis of "Sensors" and Microelectronics

- "composite of two species as one unit"; "obligate" – "one cannot exist without the other"

"Silicon"

- (bump/directly bonded)
  - MAPS
  - SiPMs

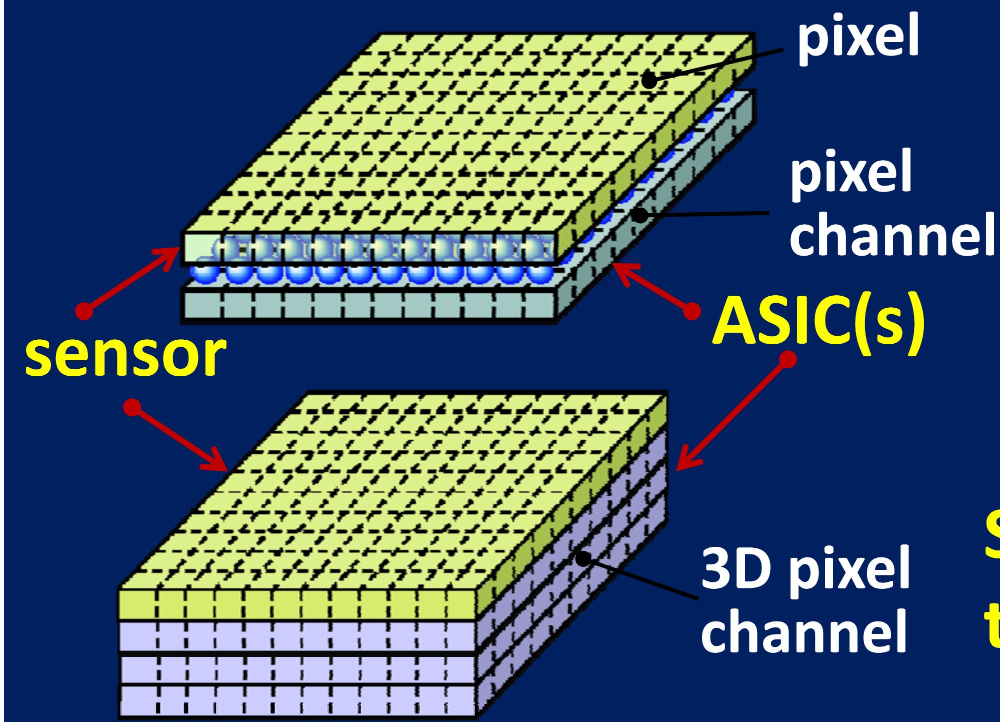
TPCs

- Gas and liquid, charge and light

"Microelectronics"

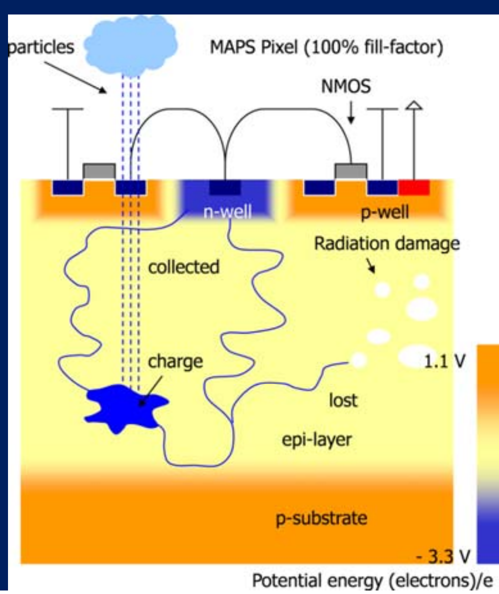
- What after CMOS?

Si “Pixel” Detectors



Sensor pixels bump-bonded to ASIC pixels

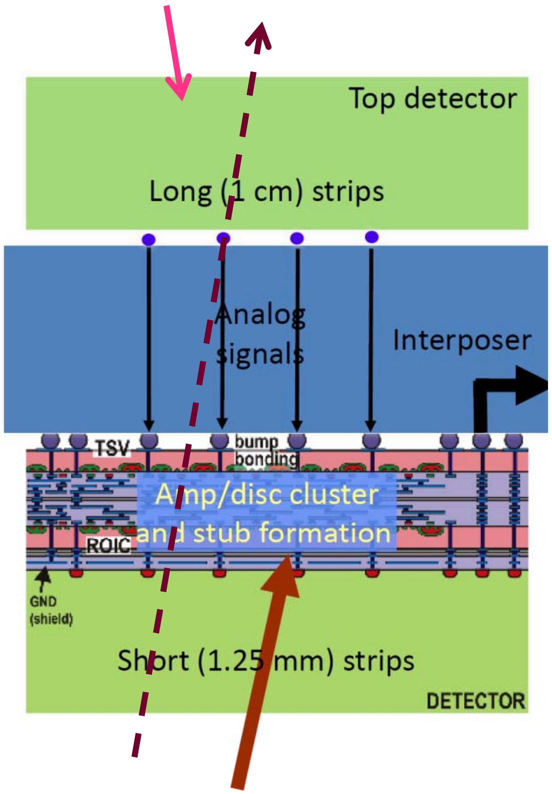
Sensor pixels fusion-bonded to (2D or 3D) ASIC pixels



Monolithic Active Pixel Sensors (MAPS)

3D Integration of Sensors and Readout ICs ("ROICs") - Goals

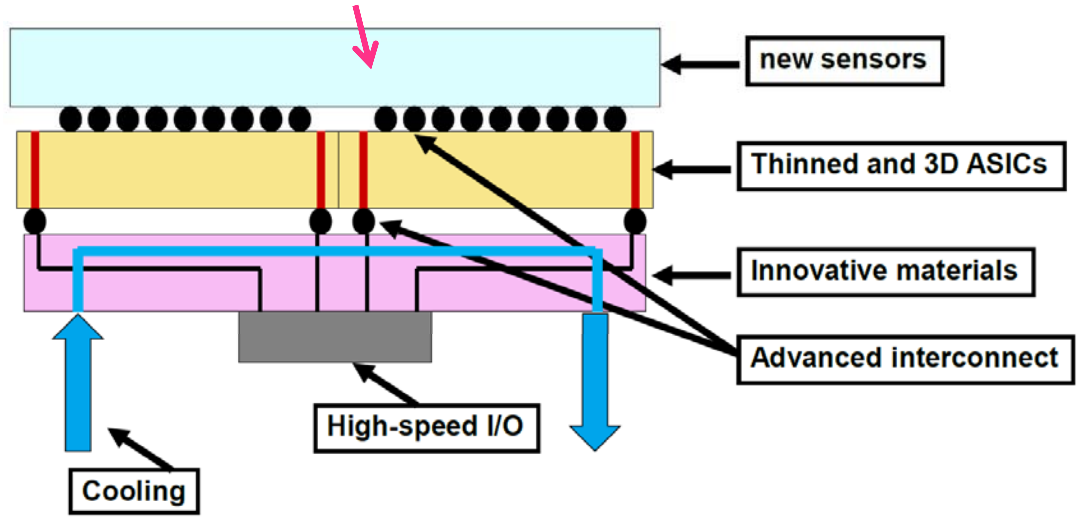
Particle Tracking (ENC~50 e rms)
Thin sensors (~50-100µm)

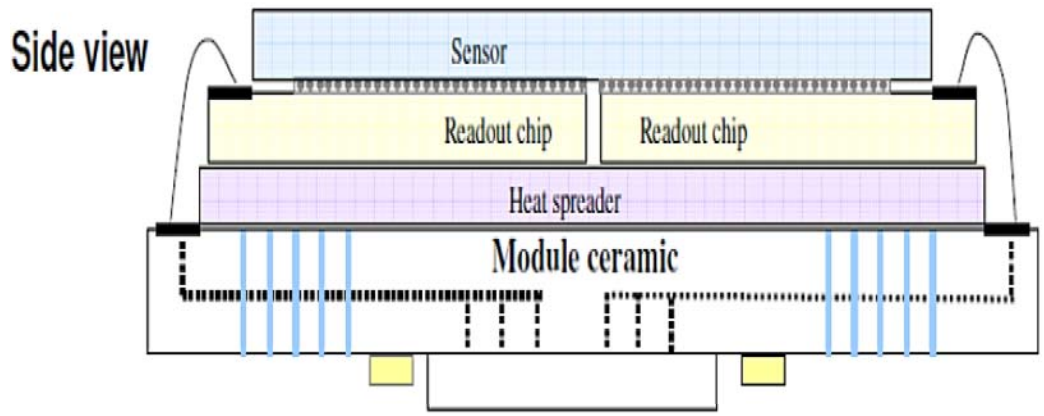


ROIC sees signals from top and bottom sensors all correlations local

From: G. Deptuch, R. Lipton

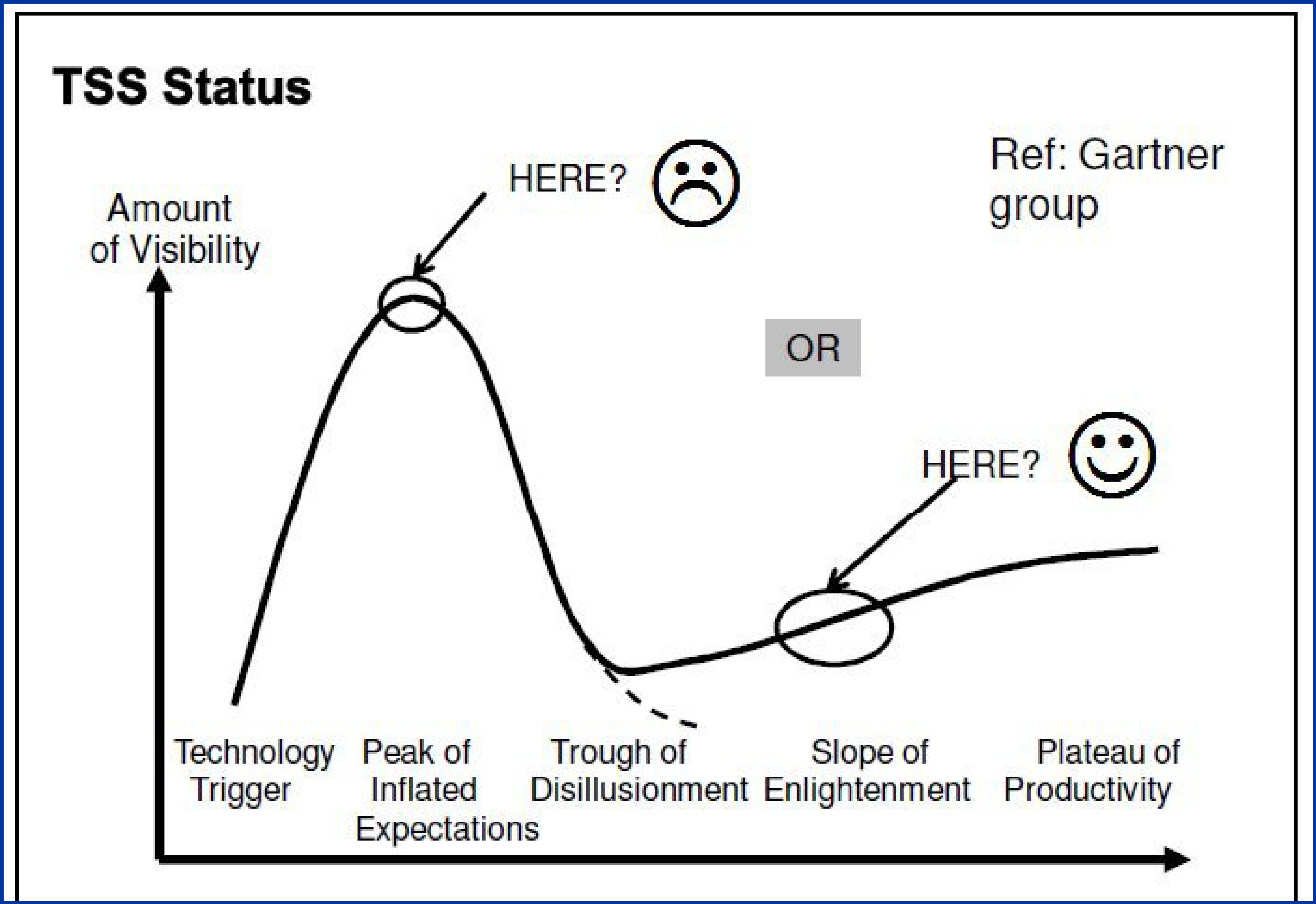
X-ray Detectors (ENC<10 e rms)
Thick sensors (300-500µm)



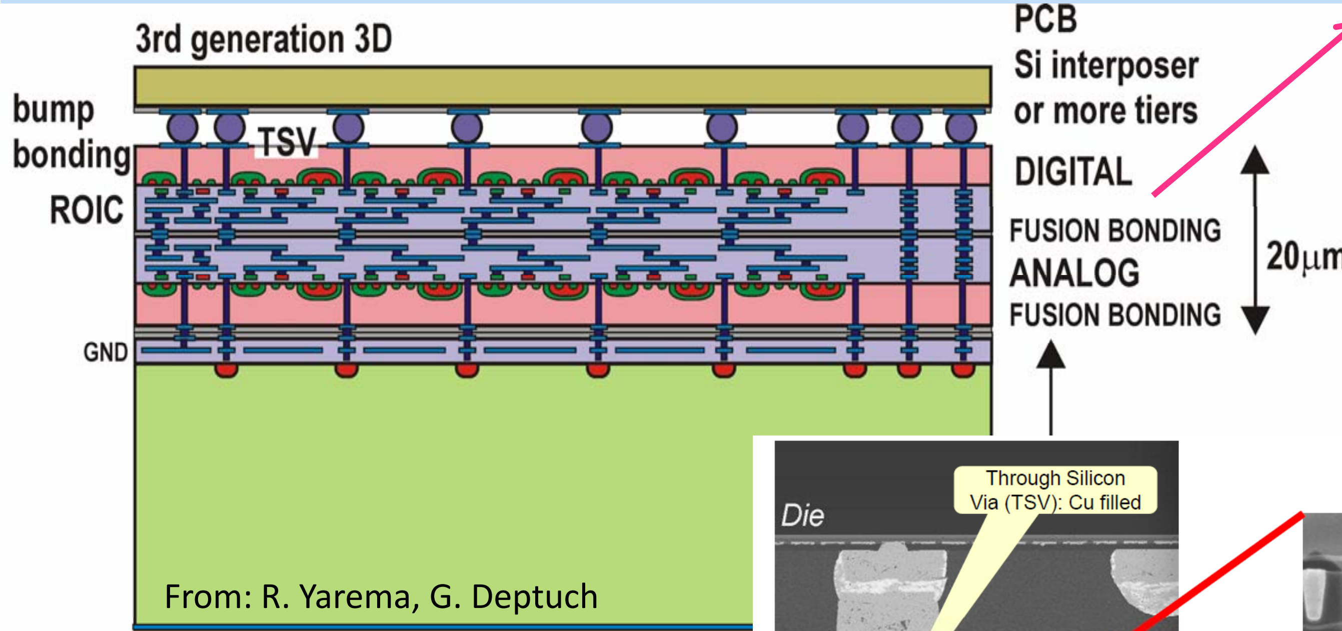


From: H. Grafsma

A more sober view ….

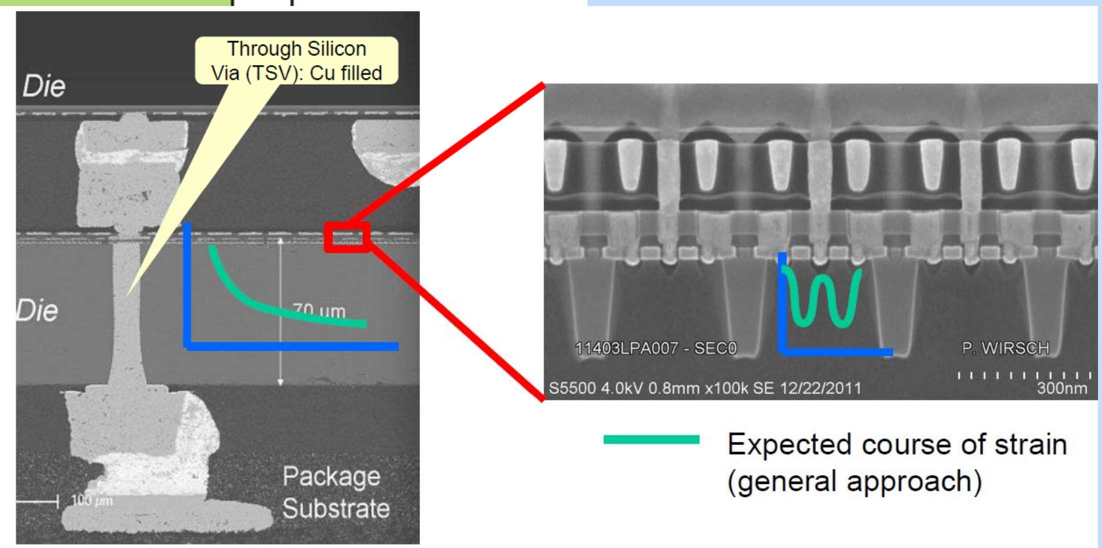


Technology Challenge → 3D or 2½D?



Bonding technology:
- Copper to copper
- Oxide to oxide fusion
- Copper to tin
- Polymer/adhesive
- Copper stud

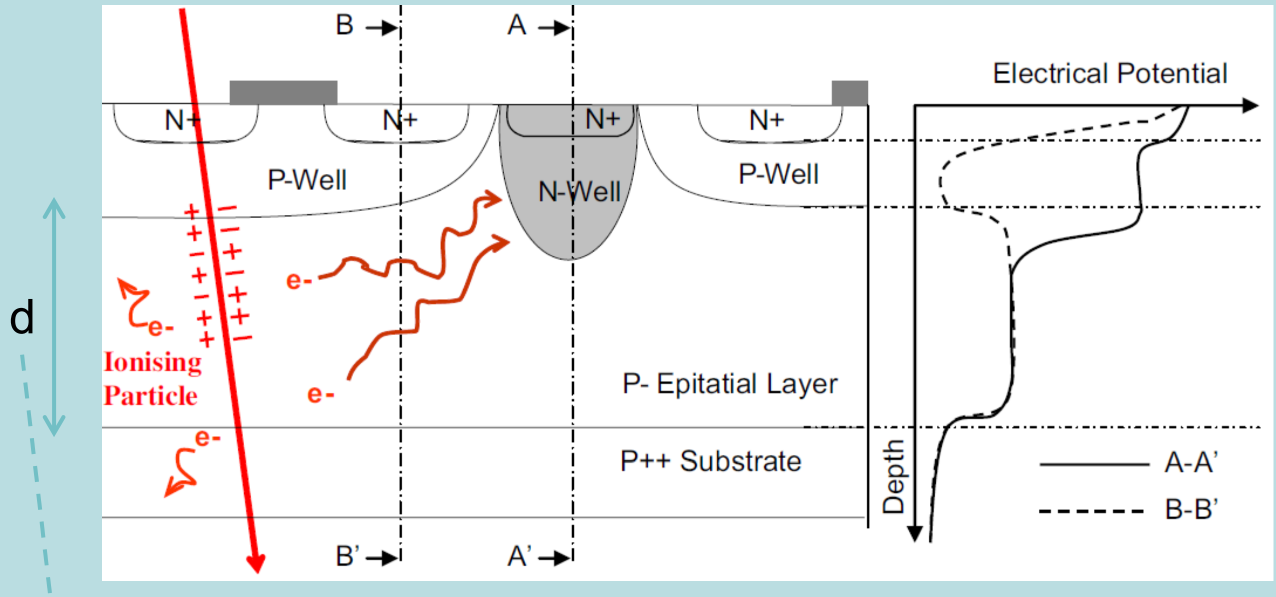
Present industry direction:
- 2½D → no *vias* in *active* silicon, only in *passive* interposers
- 3D → specialized (e.g., memories)

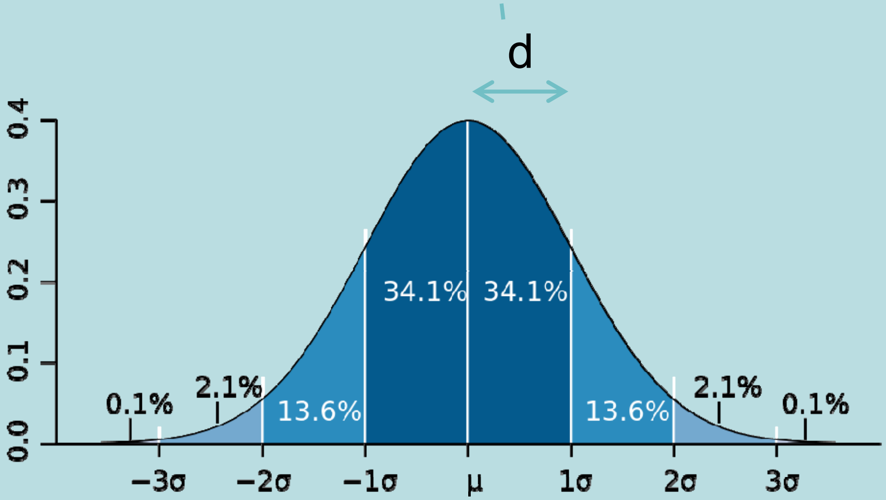


- TSV: µm-range
- Strain engineering @ MOSFETs nm-range

Fraunhofer IKTS

Charge collection in MAPS (Monolithic Active Pixel Sensors) – sensor and transistors in "standard" CMOS technology





$$\sigma = (2Dt)^{1/2}$$

$$D = \mu \frac{kT}{e}$$ Diffusion constant ("Einstein 1")

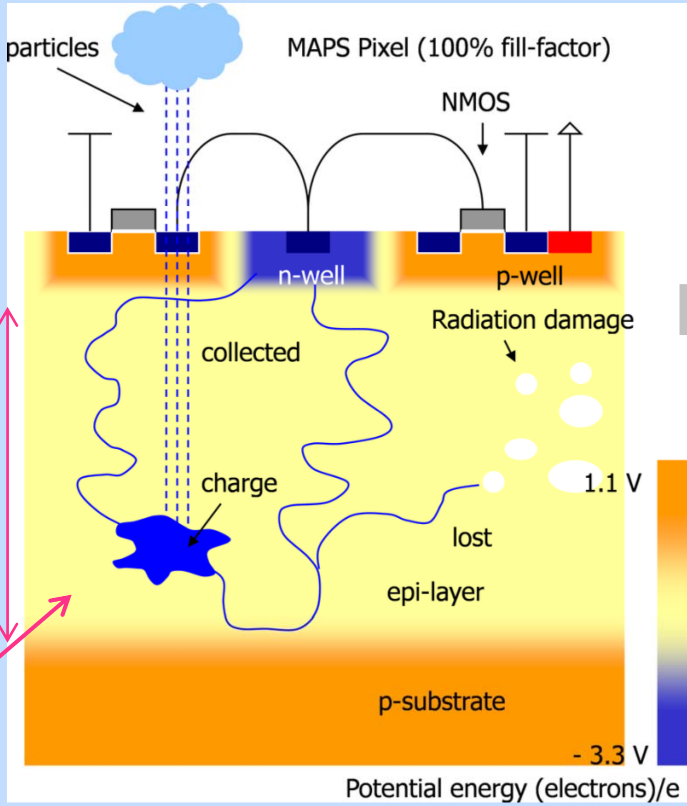
$$t = r^2 / D$$ Diffusion time *vs* ***r*** ("Einstein 2")

≈ 15ns to diffuse to 10μm;

≈135ns to 30μm in silicon.

Drift time for electrons and holes ~1/v_{drift}, ~< 10ns for 100μm

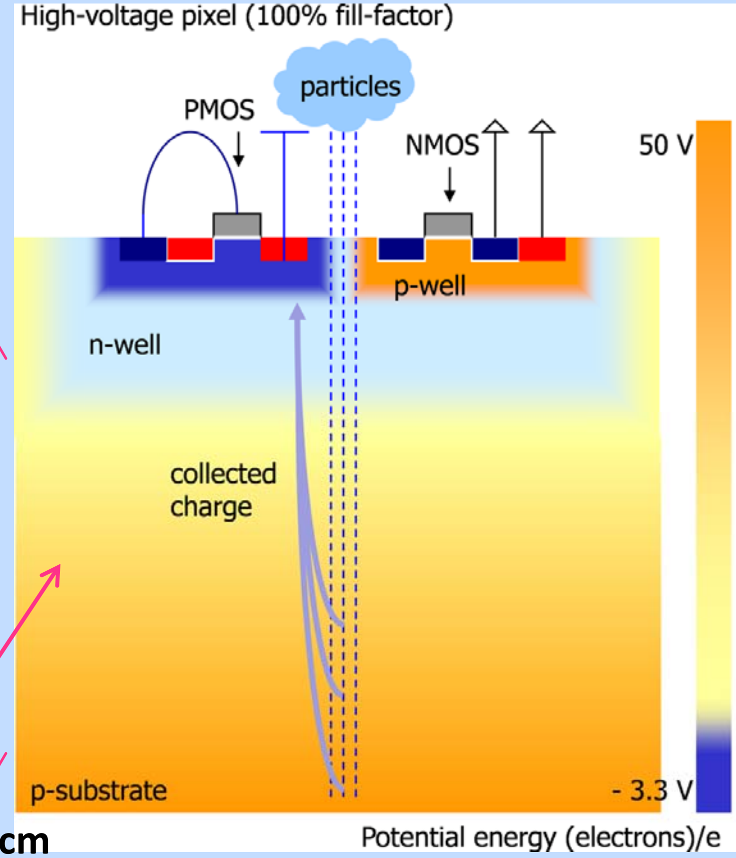
MAPS: From Charge Diffusion to Drift



10µm
~800e

20
ohm cm

25-50 µm
2-4ke



> 80 ohm cm

Challenge: How to do it in a "standard" process?

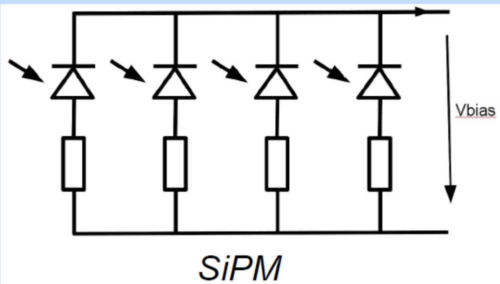
- **Better S/N**
- **Shorter charge collection time**
- **Higher radiation tolerance**

Adapted from: I. Peric

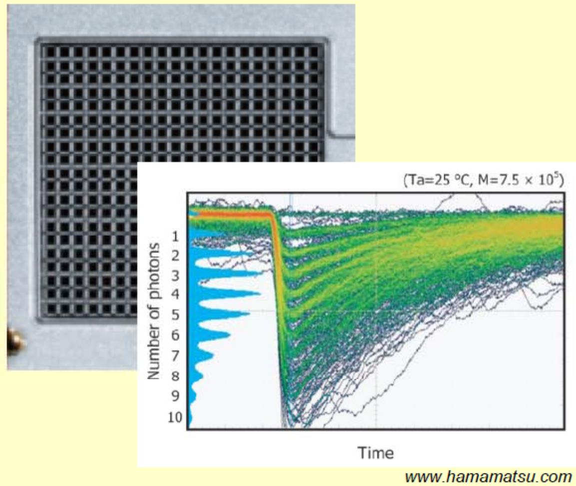
http://sus.ziti.uni-heidelberg.de/Forschung/FGDetektoren/SDA/?lang=en

Silicon Photo Multipliers (SiPMs) – Geiger-mode Avalanche Photo Diodes

Passive quenching

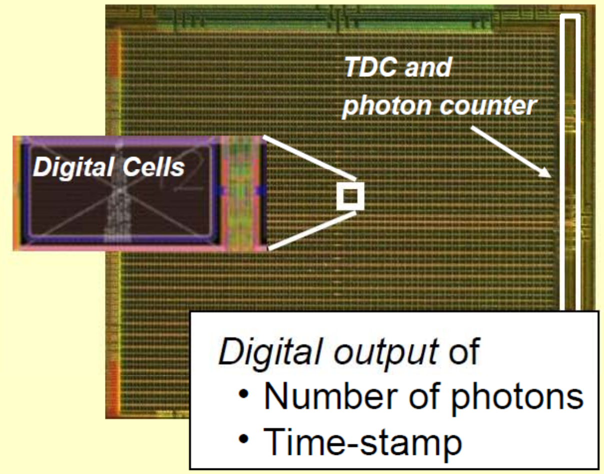


Analog SiPM

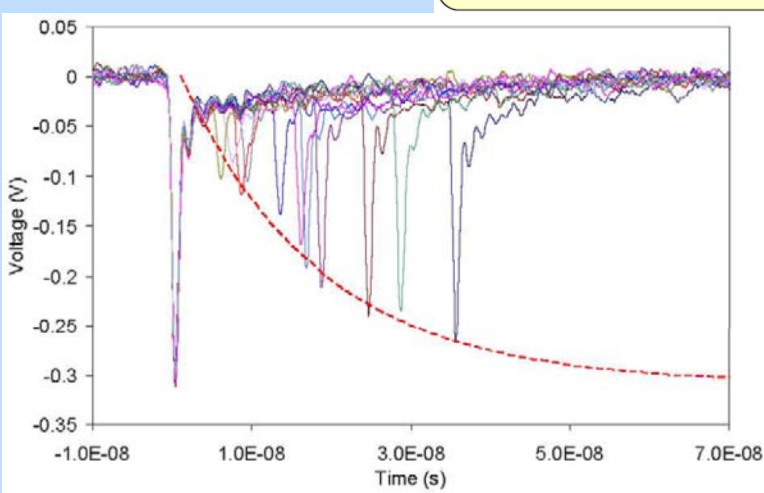


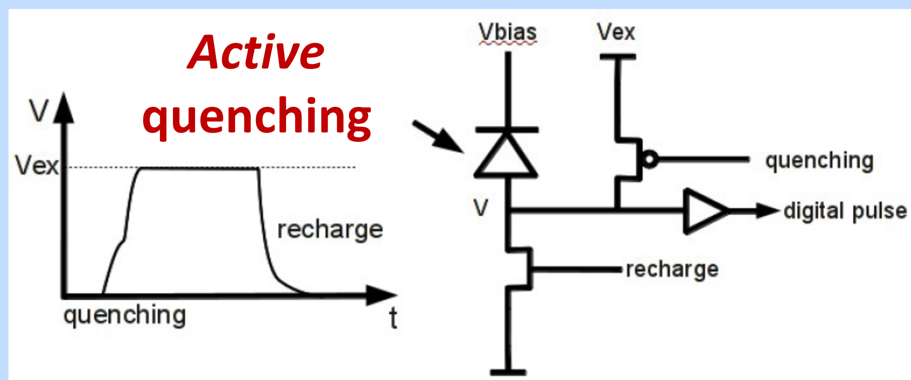
- Cells connected to common readout
- Analog sum of charge pulses
- Analog output signal

Digital SiPM



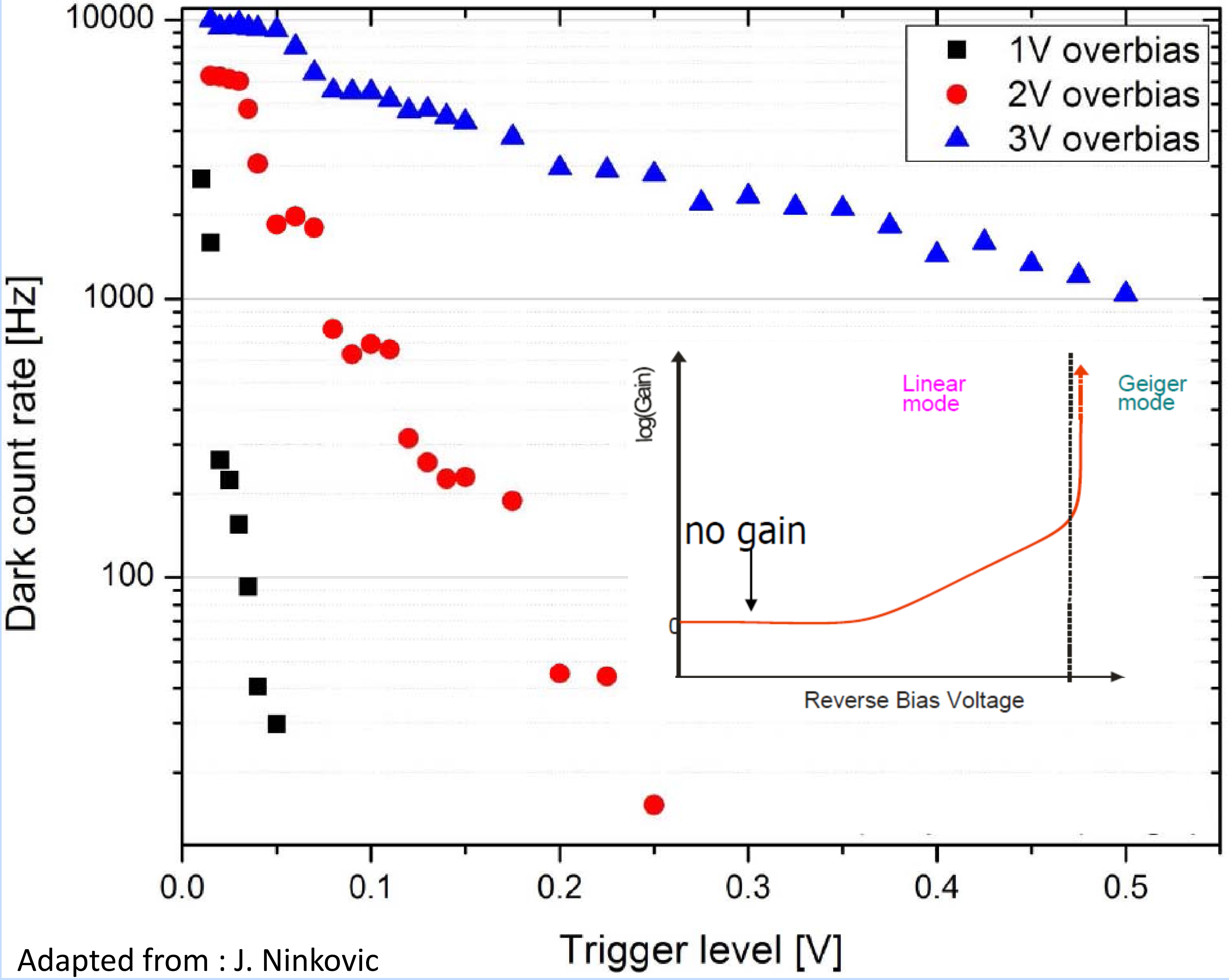
- Each diode is a digital switch
- Digital sum of detected photons
- Digital data output





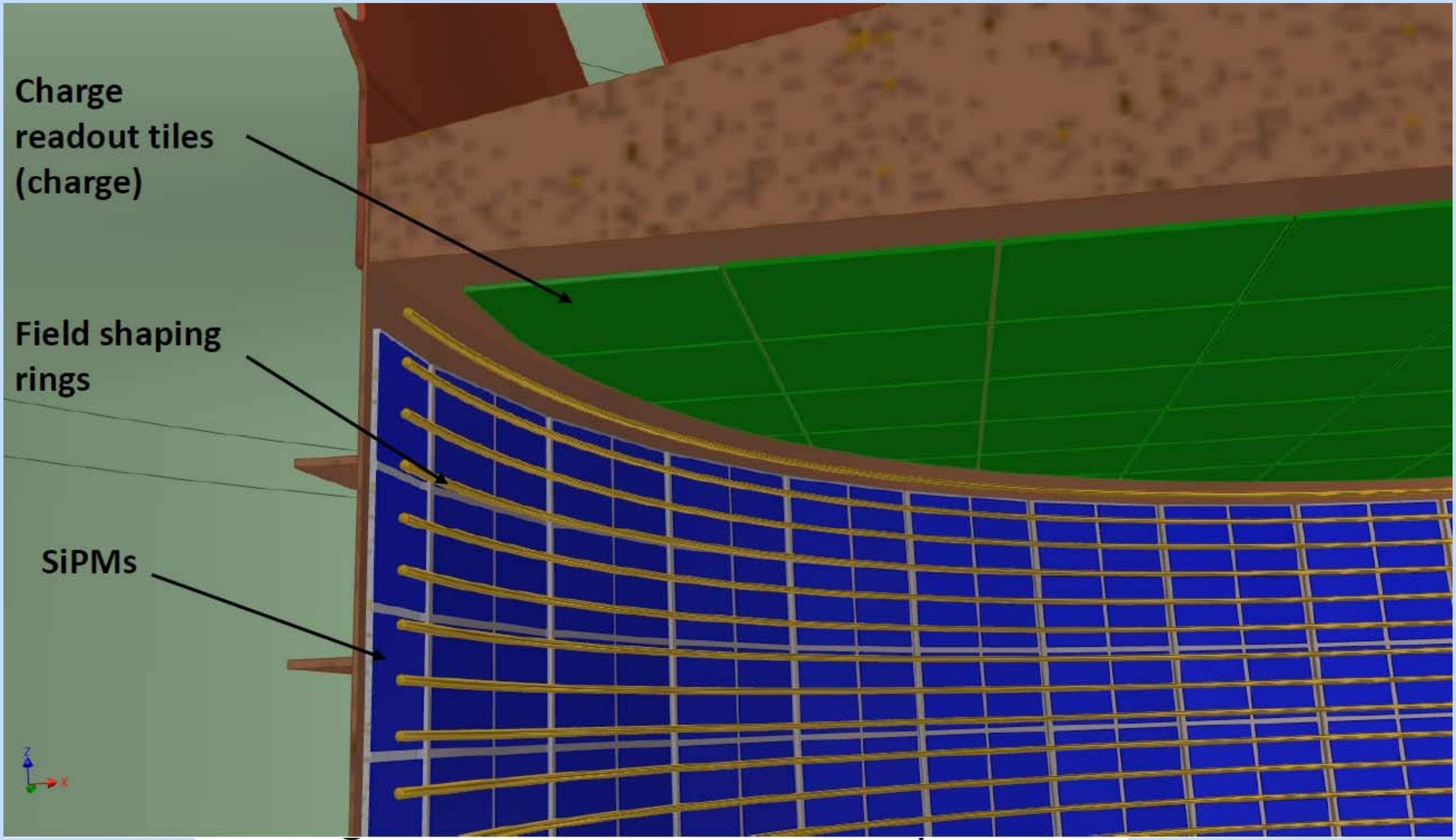
Adapted from : T. Frach et al.

SiPMs: “Dark” Noise and Optical Crosstalk → Active Quenching



Adapted from : J. Ninkovic

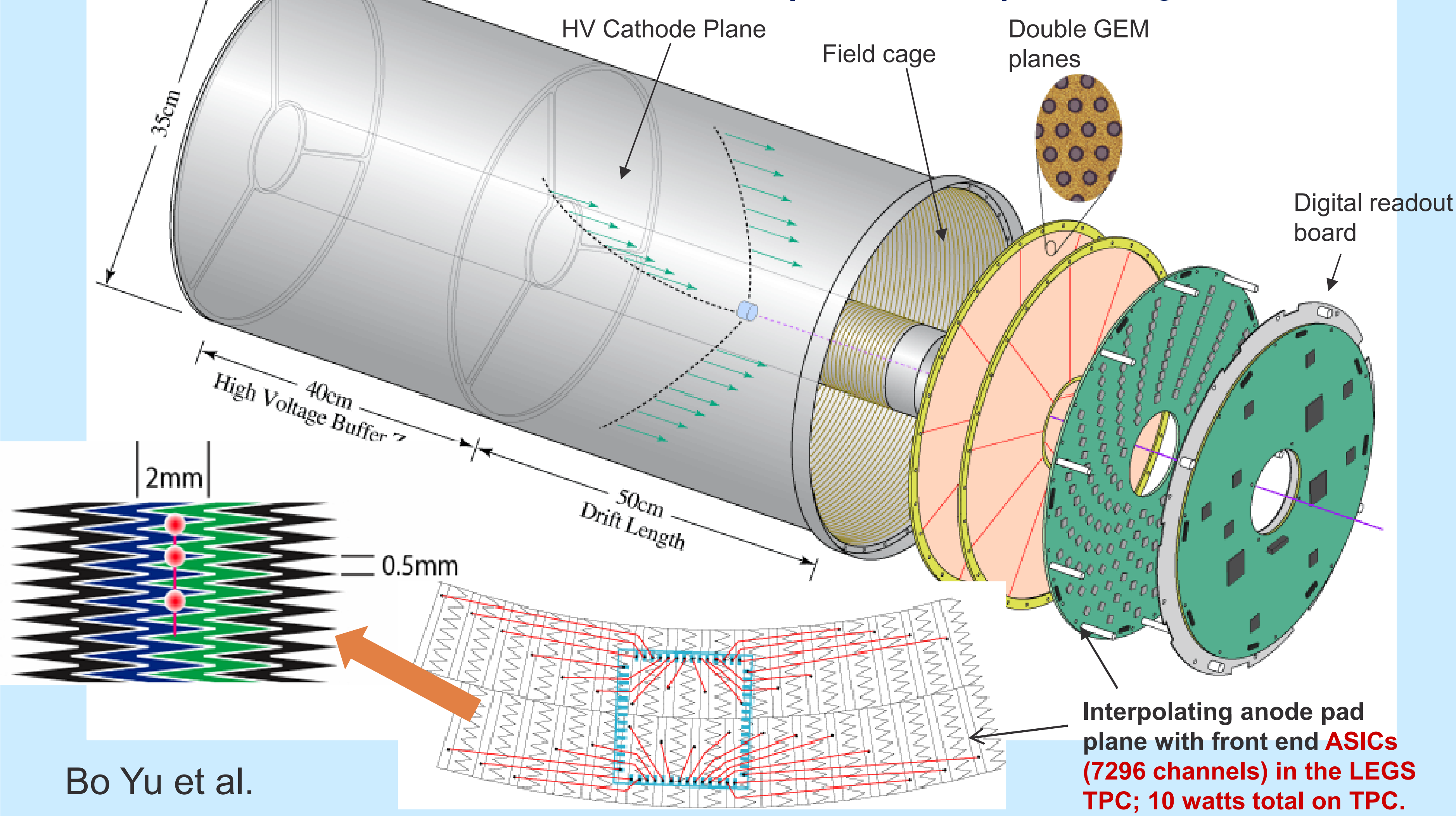
Challenge: SiPMs to cover large areas …



• Light collection on the barrel behind field shaping rings

Fine Granularity Gas TPCs:

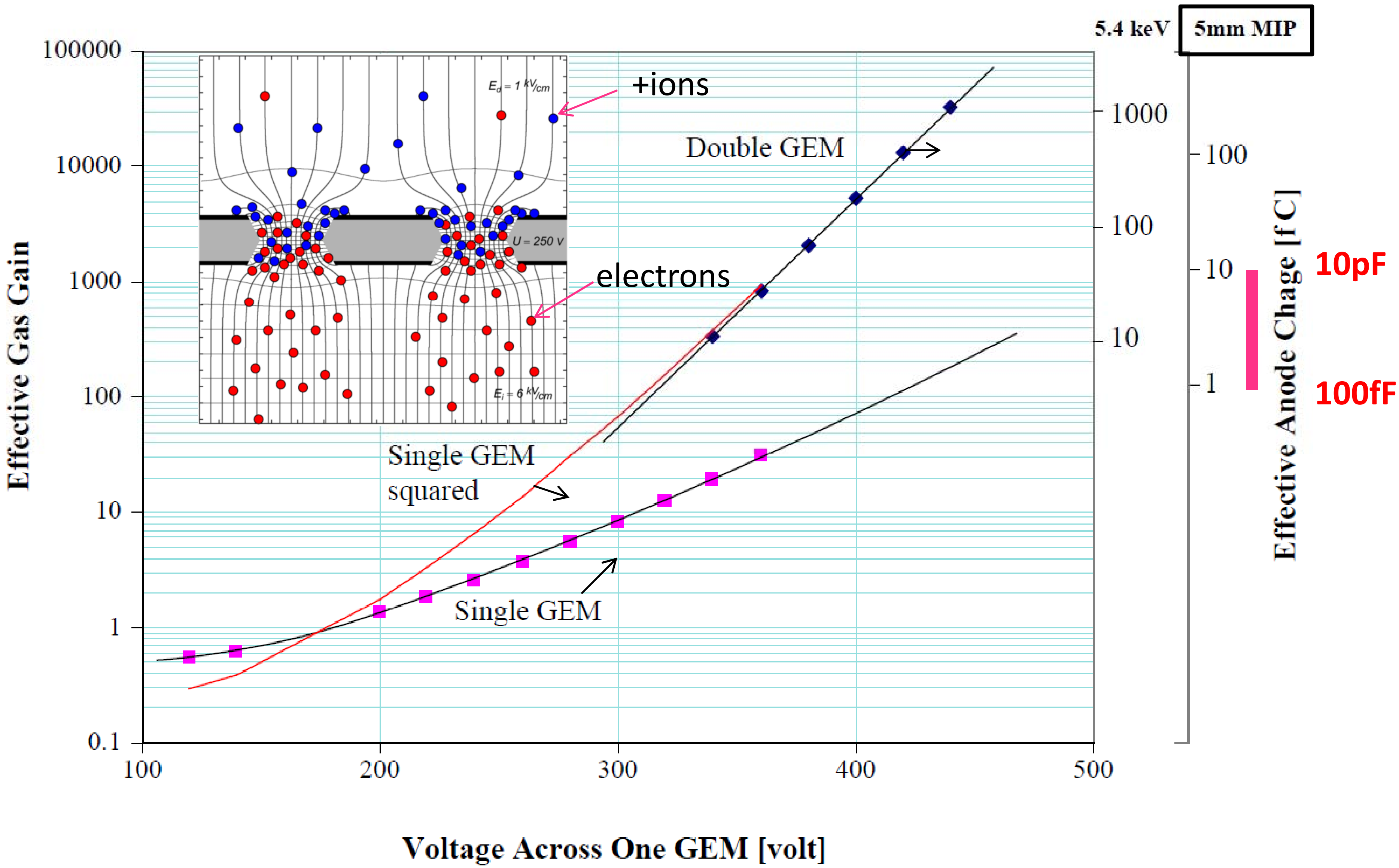
1. ***GEM*** *vs* ***Micromegas***
2. *Interpolating anode configuration -* ***chevron***
3. ***Anode-pad–ASIC board topology***
4. ***S/N, minimize capacitance, gas gain and positive ion space charge***



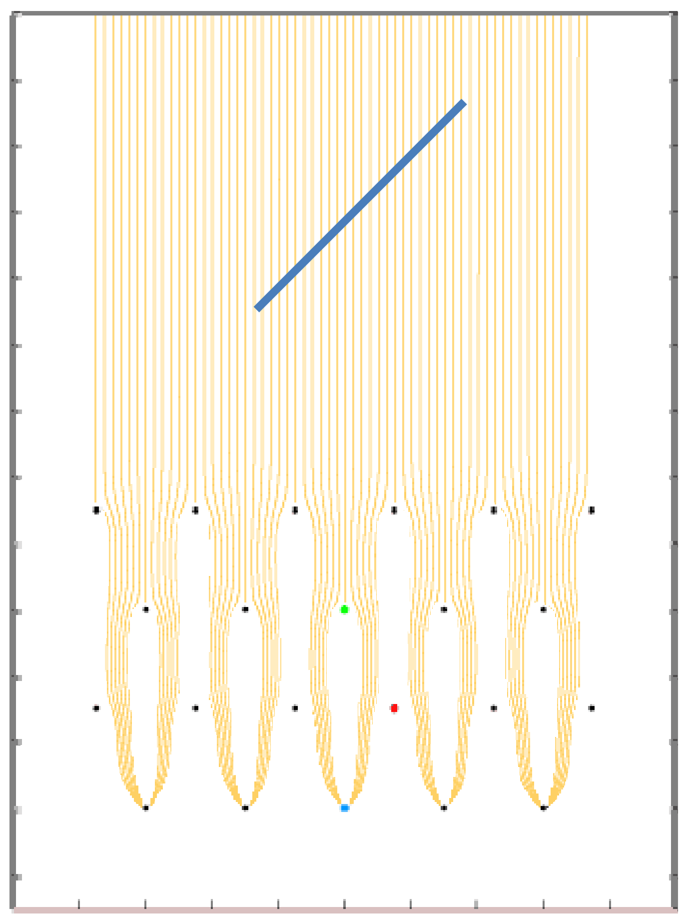
Bo Yu et al.

Effective Gas Gain of the Double GEM Detector

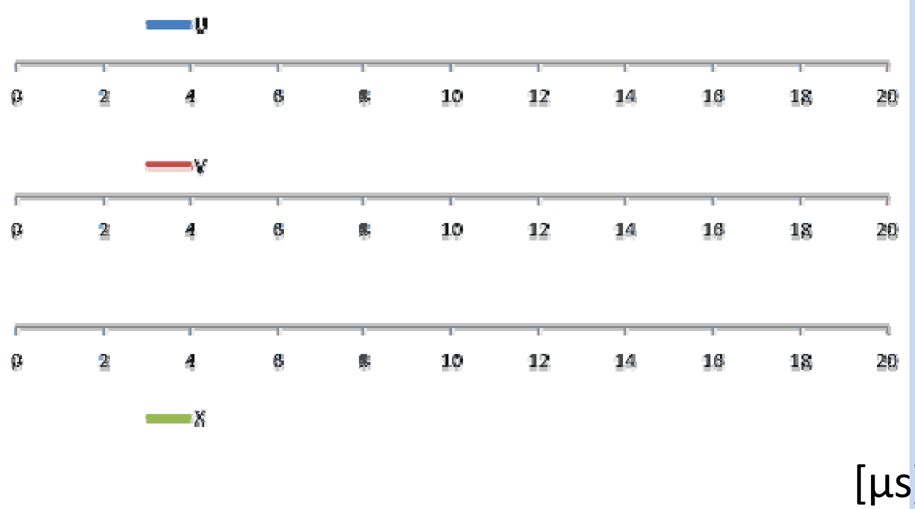
Ar+20% CO_2, 5.4 keV x-rays (~1mm^2 , 2kHz), E_d=1kV/cm, E_t=4kV/cm, E_i=5kV/cm



Signal Formation on Wire Electrodes in Noble Liquid TPCs: Induced Signals from a Track Segment



Time scale **is determined by the electron drift velocity and wire plane spacing (3 mm shown)**



LBNE style wire arrangement: 3 instrumented wire planes + 1 grid plane
Raw current waveforms convolved with a 0.5µs gaussian (~1/2 drift length) to mimic diffusion

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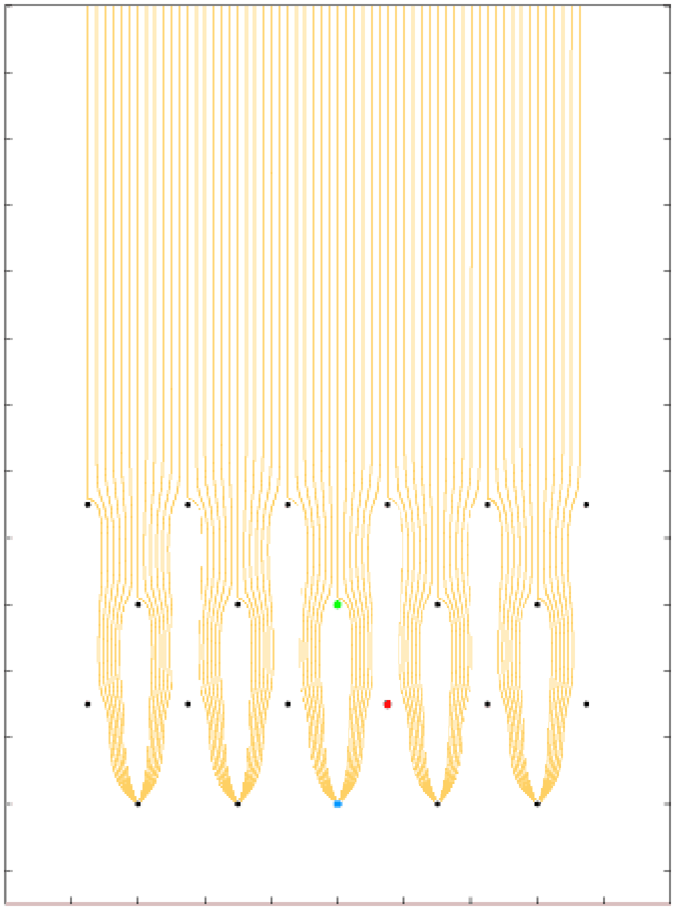

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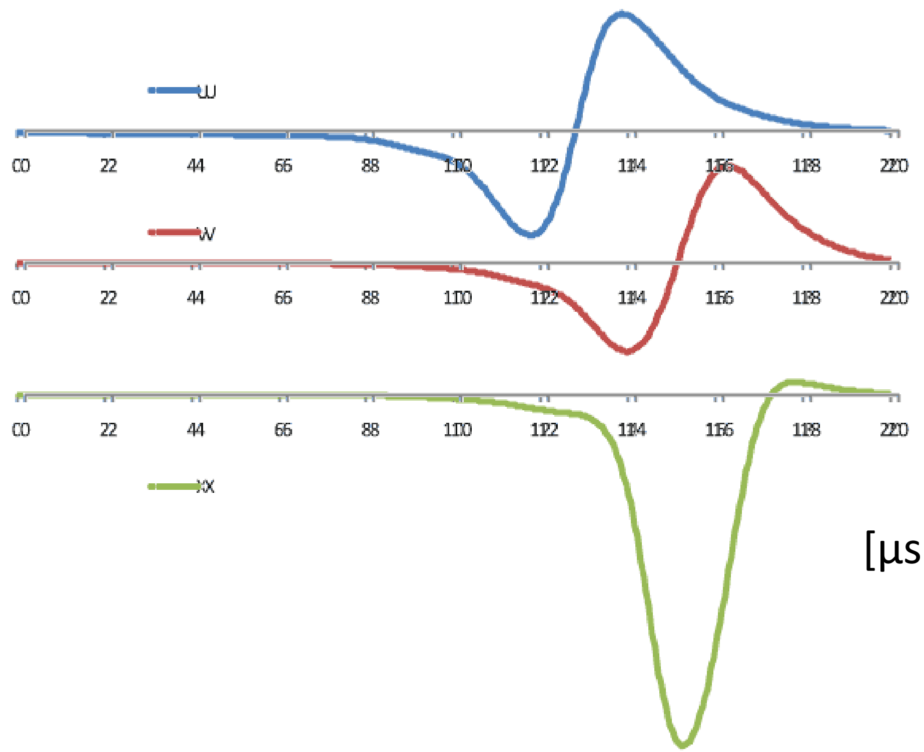
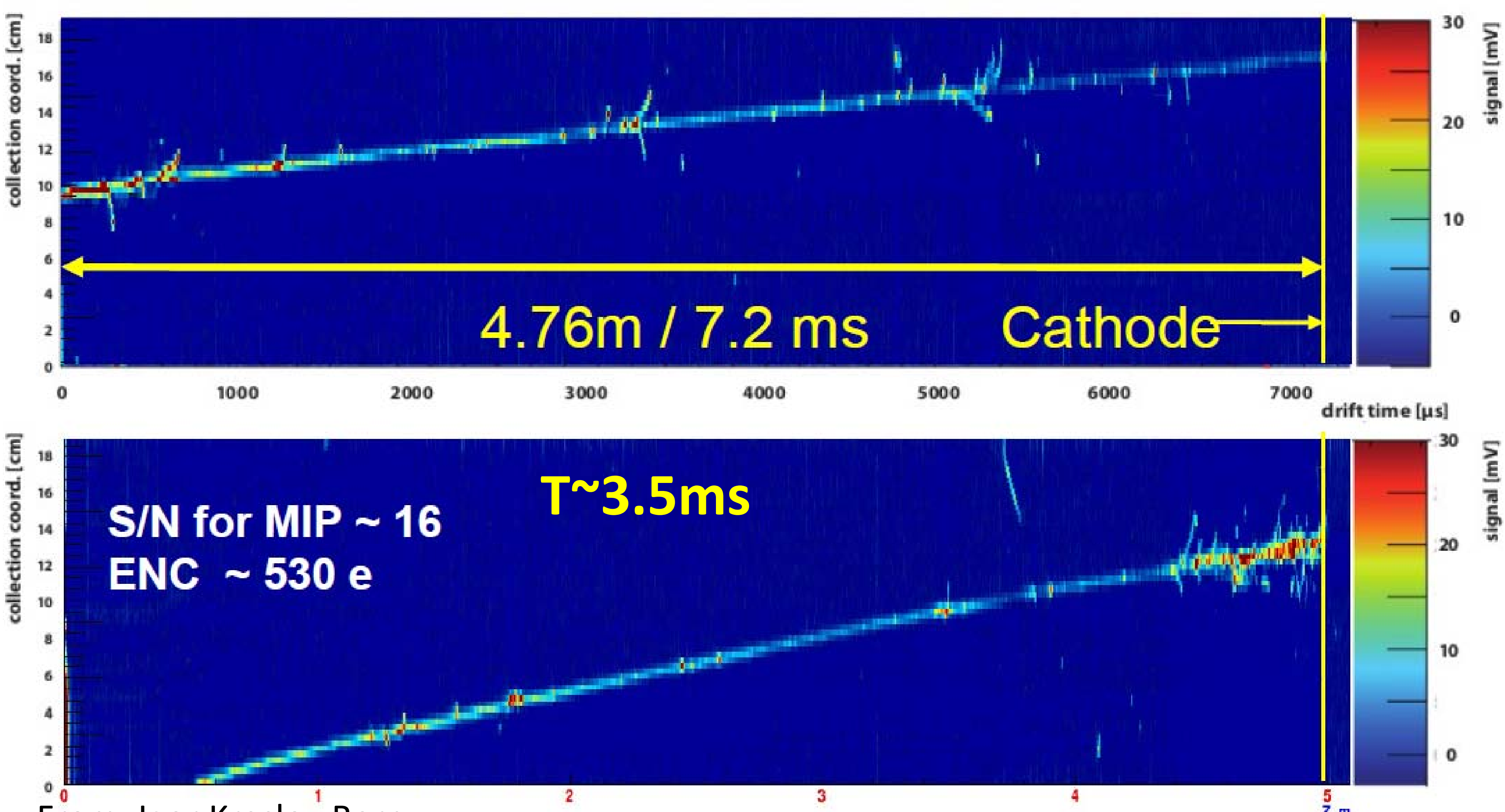


LBNE style wire arrangement: 3 instrumented wire planes + 1 grid plane
Raw current waveforms convolved with a 0.5μs gaussian (~1/2 drift length) to mimic diffusion

Testing MicroBooNE cold preamps with ARGONTUBE

~ 5 m long electrons drift in LAR: first time!

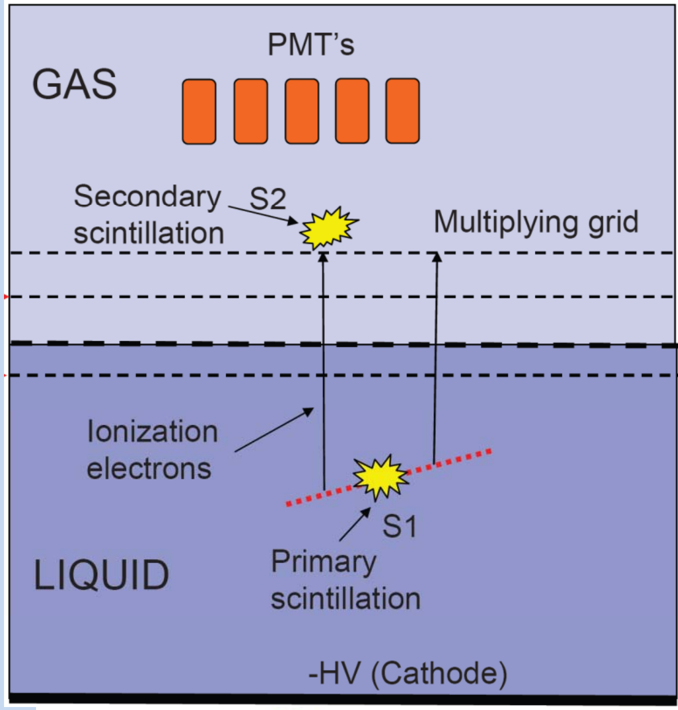
twice MicroBooNE drift lentgh, < ½ E-field



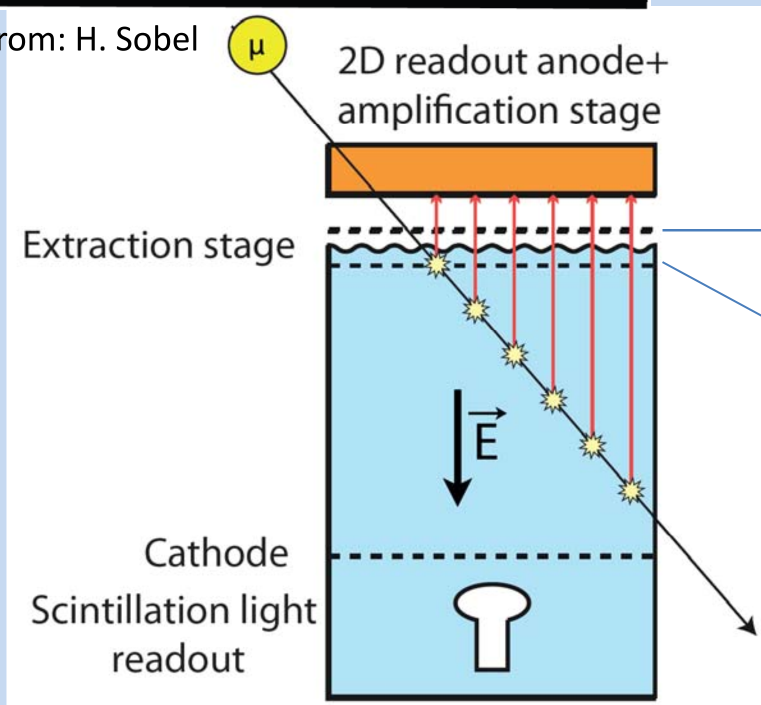
From: Igor Kreslo, Bern

Dual-Phase Noble Liquid-Gas Detectors:

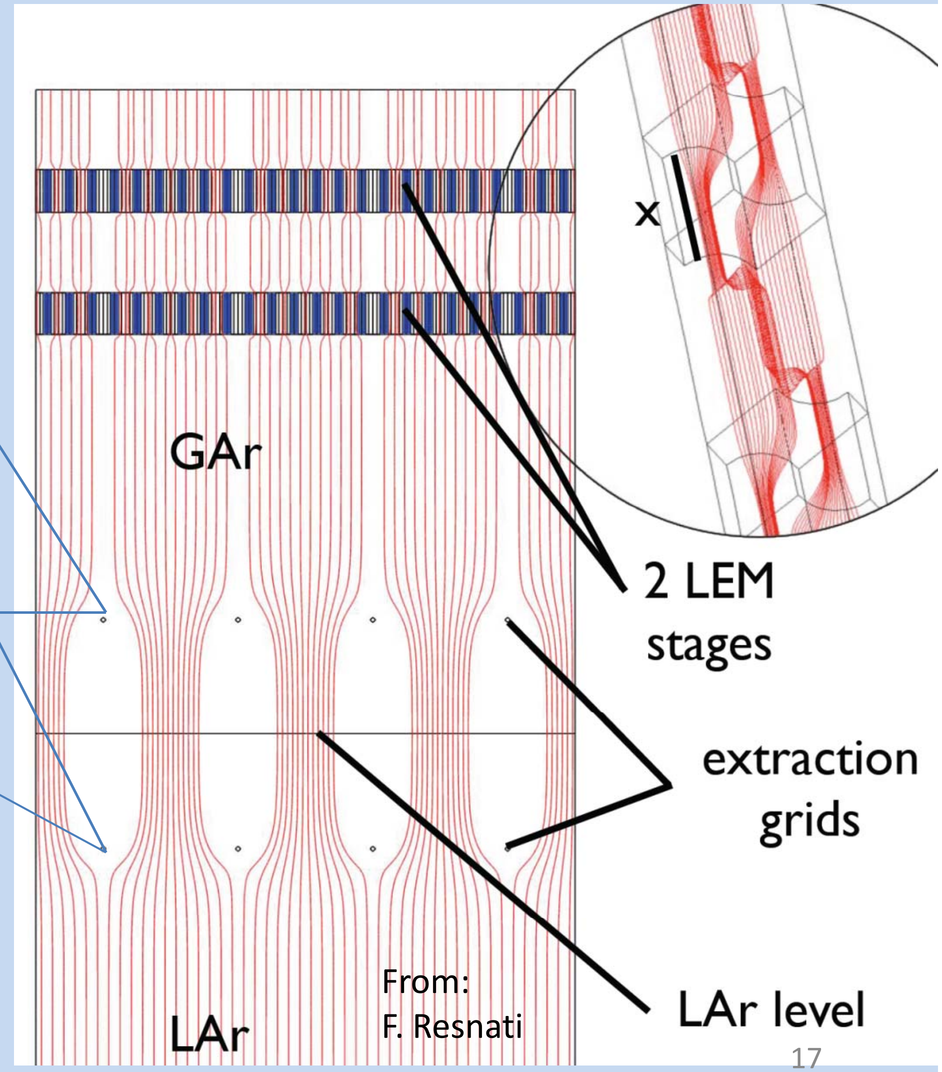
Small (multi-ton) for Dark Matter (WIMP) detection *and* Large (multi-10 kton) for neutrino studies, proton decay, neutrinos from SN



From: H. Sobel

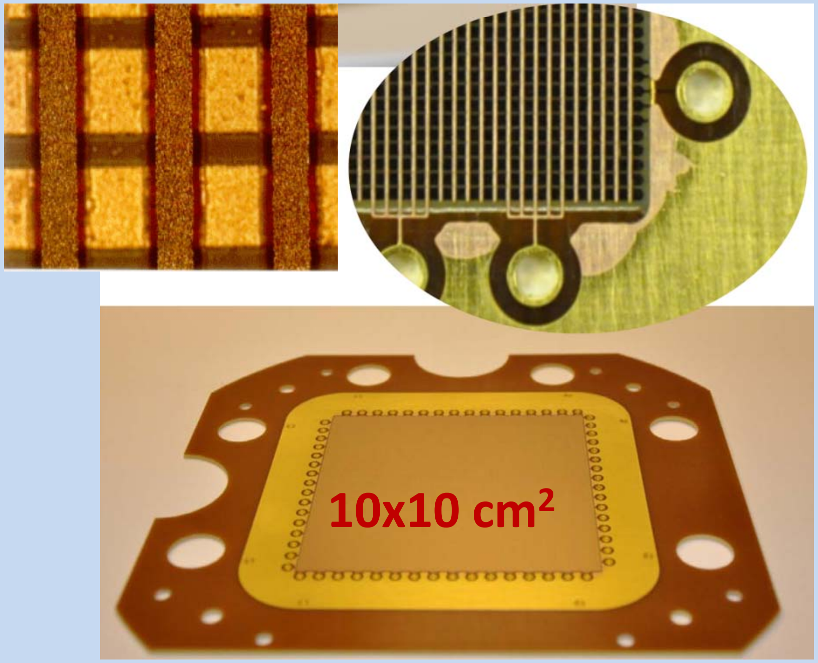


~1 cm

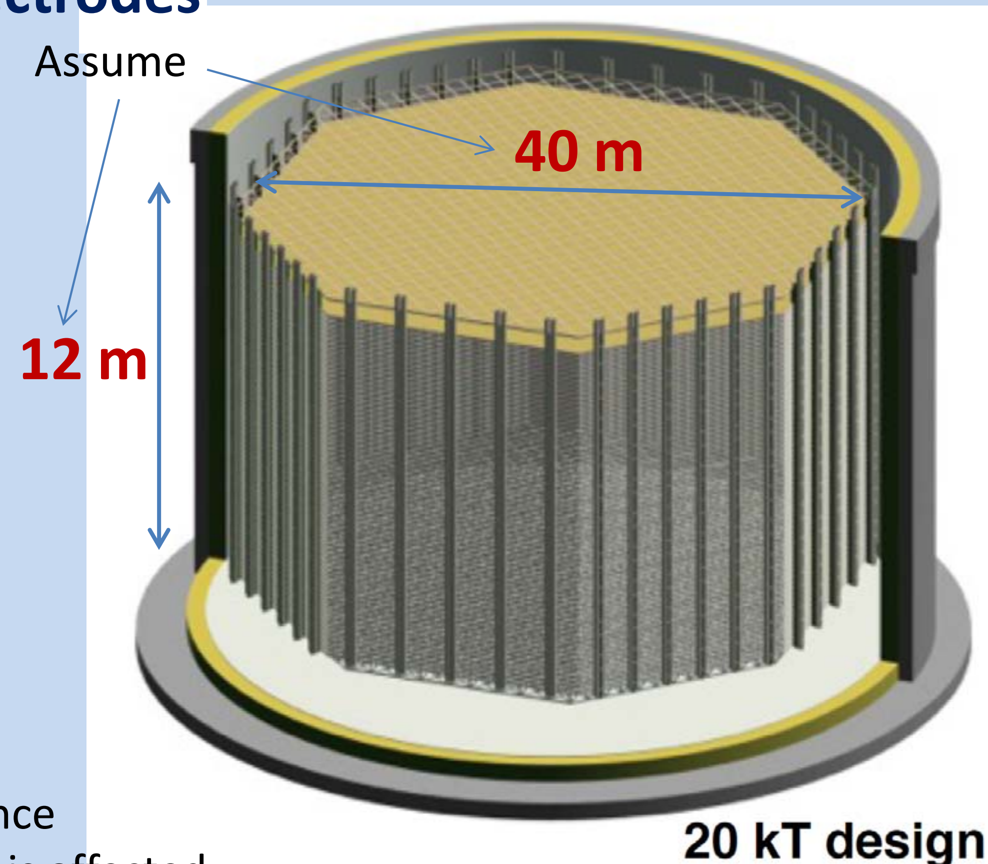


From:
F. Resnati

Large Two-Phase LAr TPCs: The Challenge of Scaling up Readout Electrodes



From: F. Resnati



- X-Y strip electrodes have a large capacitance
- above ~100-200 pF per 1 m strip, the S/N is affected
- signal channels: ≈ 400/m² → >**5x10⁵ for ~ 20 kton with 12m drift**

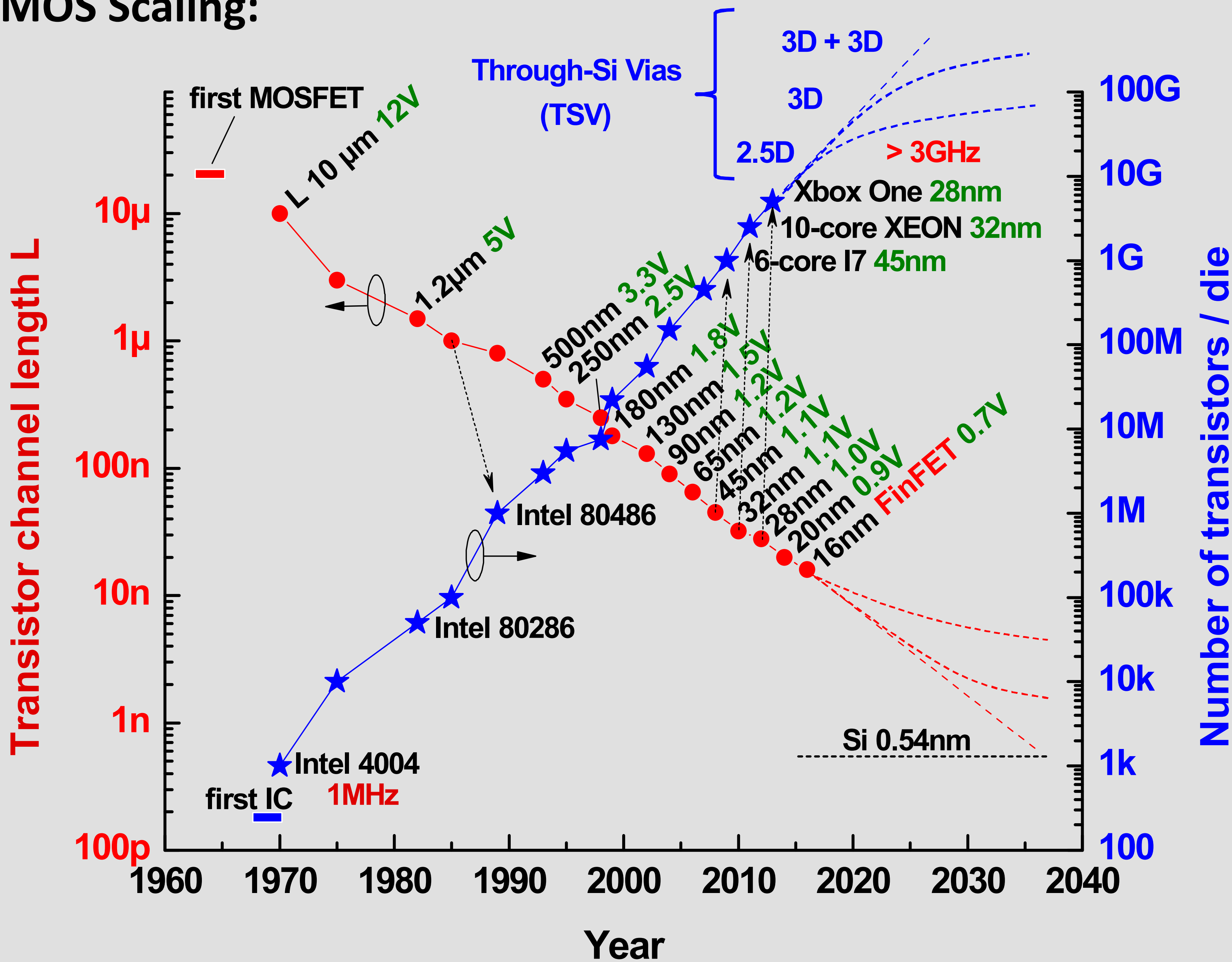
(~ 25 strips-channels/ton, nearly the same as for **LBNE** with **2.5 meter drift distance**)

- **Cold electronics with multiplexing clearly needed**

•Electron multiplication leads to loss of easy charge calibration inherent to ion chambers

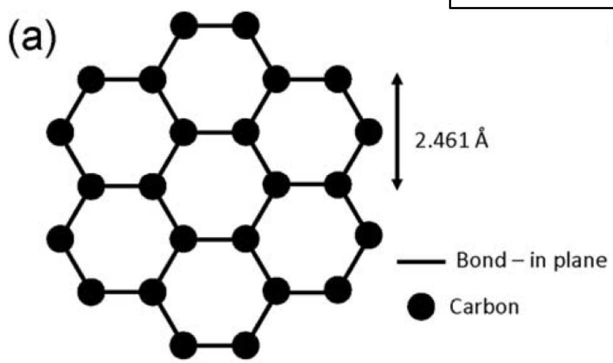
A scaled down LAGUNA concept
From: A. Rubbia, A. Ereditato
Aiming at ≥ 100 kton

CMOS Scaling:



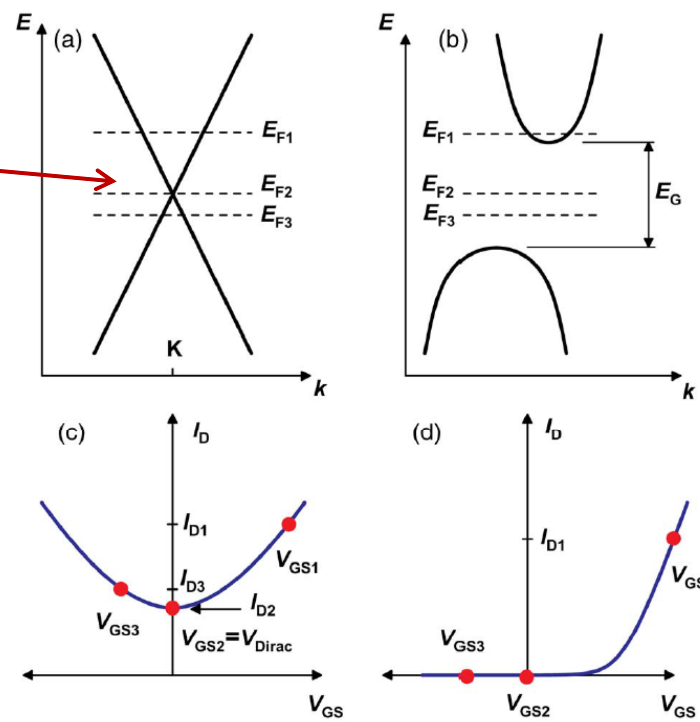
The promise of ***graphene*** …

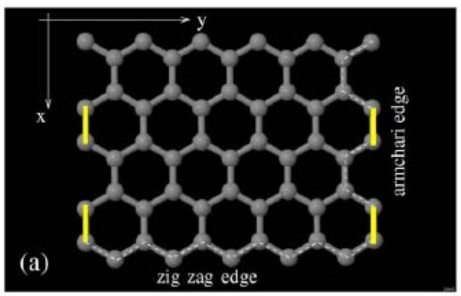
Electron mobility: >10^5 !!!



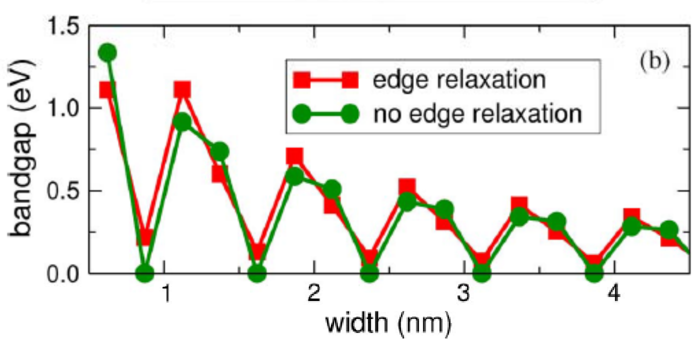
A. Hsu et al.

“Details”:
-Bandgap → 0
- contact resistance high





Bandgap is “induced” in a ribbon, but mobility drops …



From: G. Fiori, G. Iannaccone

Graphene MOSFET:
- **Not a switch**
- **RF amplifier, yes**

Si-MOSFET

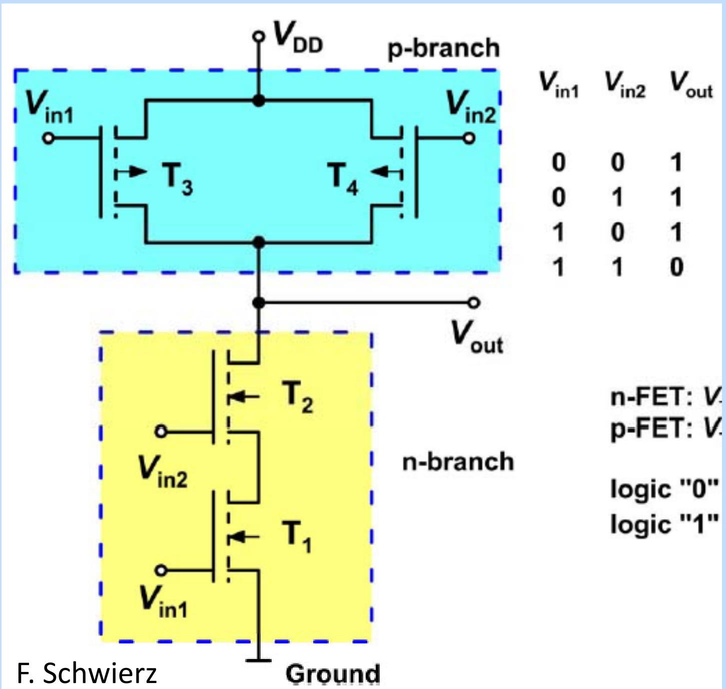
From: F. Schwierz

Graphene issue:

PROCEEDINGS OF THE IEEE | *Vol. 101, No. 7, July 2013*

Beyond CMOS?

CMOS NAND Gate:



From: F. Schwierz

<u>Any "Beyond CMOS" device should have many of the same characteristics as CMOS devices :</u>

- **power gain >1**
- **ideal signal restoration and fanout**
- **high ON/OFF current ratio ~10^{5-7}**
- **low static power dissipation**
- **compatibility with Si CMOS devices for mixed functions**

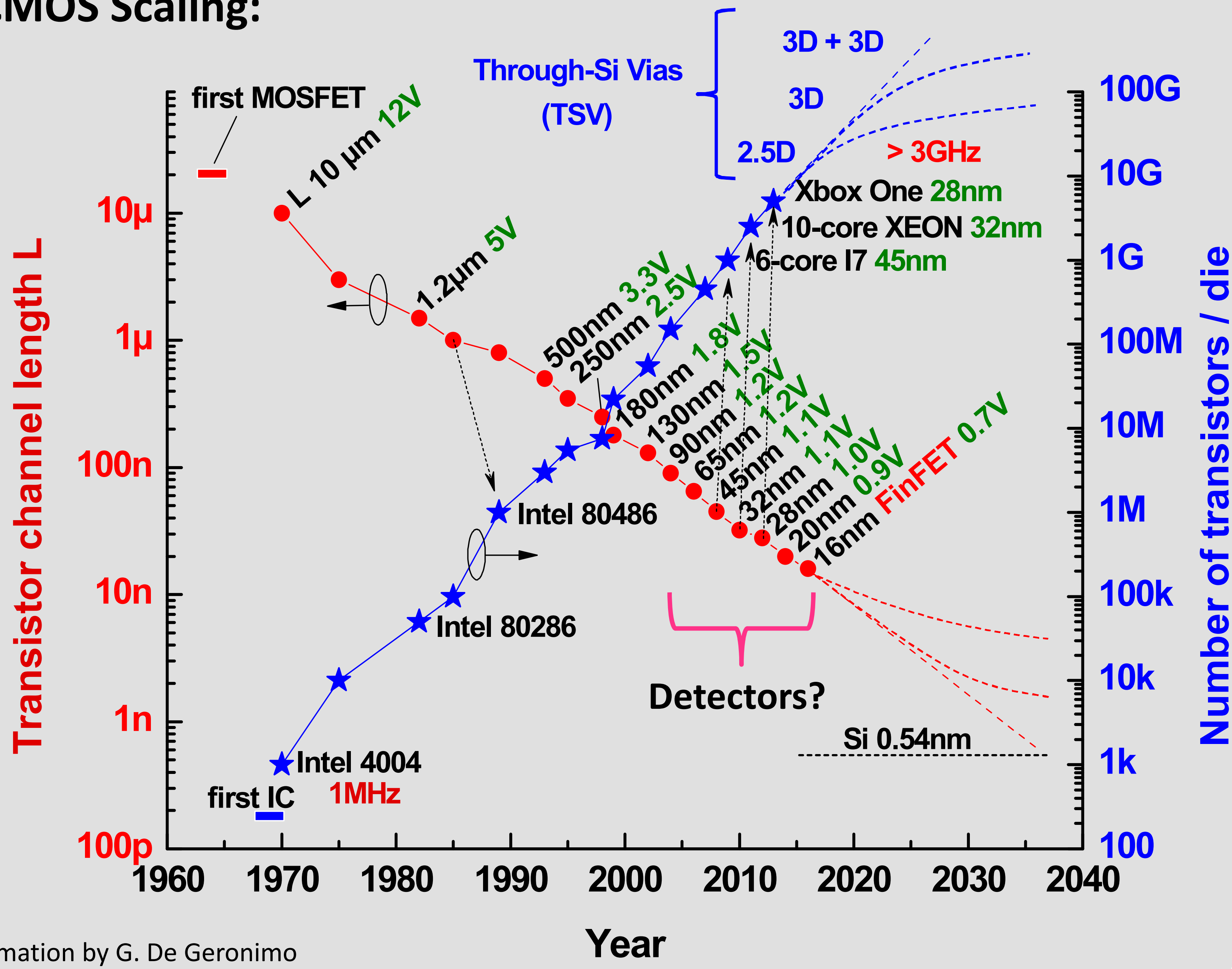
<u>Physical (computational) variables</u>:
charge, current, voltage, electric dipole,magnetic dipole, orbital state

<u>Devices considered by NRI</u>:

- **tunelling FET**
- **graphene nanoribbon FET**
- **bilayer pseudospin FET**
- **SpinFET**
- **spin transfer torque/domain wall**
- **spin majority gate**
- **spin transfer torque triad**
- **spin torque oscillator logic**
- **all spin logic device**
- **spin wave device**
- **nanomagnet logic**
- **III-V tunnel FETs**

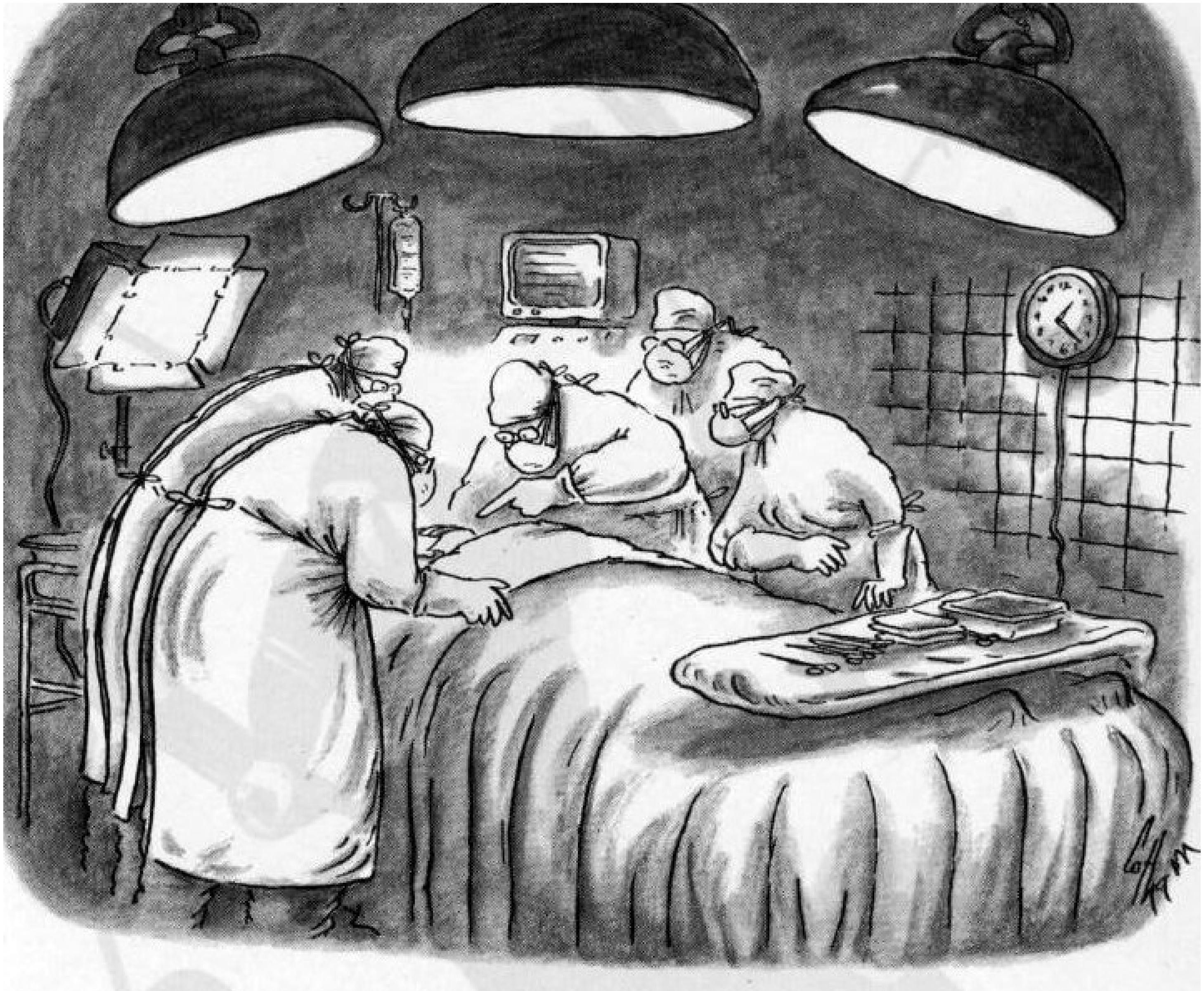
Upon analysis: Spintronic devices have longer switching delays and higher switching energies, due to inherent time of magnetization propagation …

CMOS Scaling:



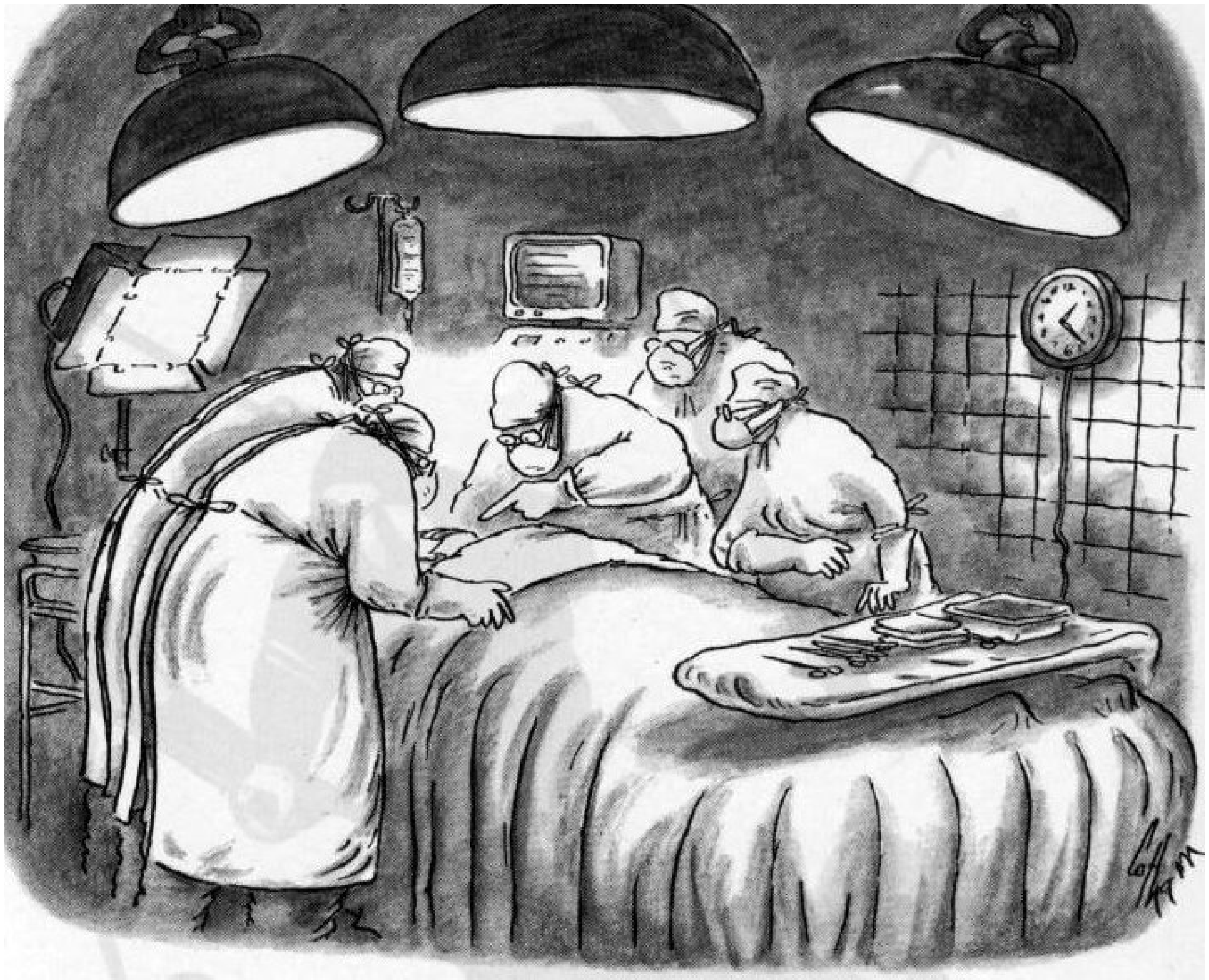
Information by G. De Geronimo

After the transistor revolution:



"What about that! His brain still uses the old vacuum tubes."

It will be some time before the cartoon reappears:



"What about that! His brain still uses those old CMOS 3D systems on chip."

Creating fertile ground for future Nygrens

The gas TPC was a unique breakthrough idea – its value has been growing due to its continuing evolution. The current and future activity on numerous gas and liquid TPCs is the best tribute to David.

To continue in David's tradition with the next generation of detector researchers, some thought will have to be devoted how to maintain a climate favorable to creation and pursuit of new ideas.

In addition to carefully planned R&D programs under tight funding conditions and the resulting oversight, the burden will be on research institutions to provide continuity and a degree of freedom. A difficult task that will require considerable vision from the future laboratory leaders …