From Bubble Chamber to TPC: Where are we going next with detectors?

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70 YEARS OF DISCOVERY
A CENTURY OF SERVICE
U.S. DEPARTMENT OF ENERGY
BROOKHAVEN NATIONAL LABORATORY

- Where are we now?
- How did we get here? A glimpse at the history …
- What challenging developments do we see in the future?

Disclaimer :

… there is no up to date list of detectors. A new detector is being developed somewhere at this time … in many institutions …

Only a few will be mentioned in this talk ….

No, I may not mention your valuable work!

Caveat …

… about any historical account given by a participant:

"History will be kind to us …

… I intend to write it"

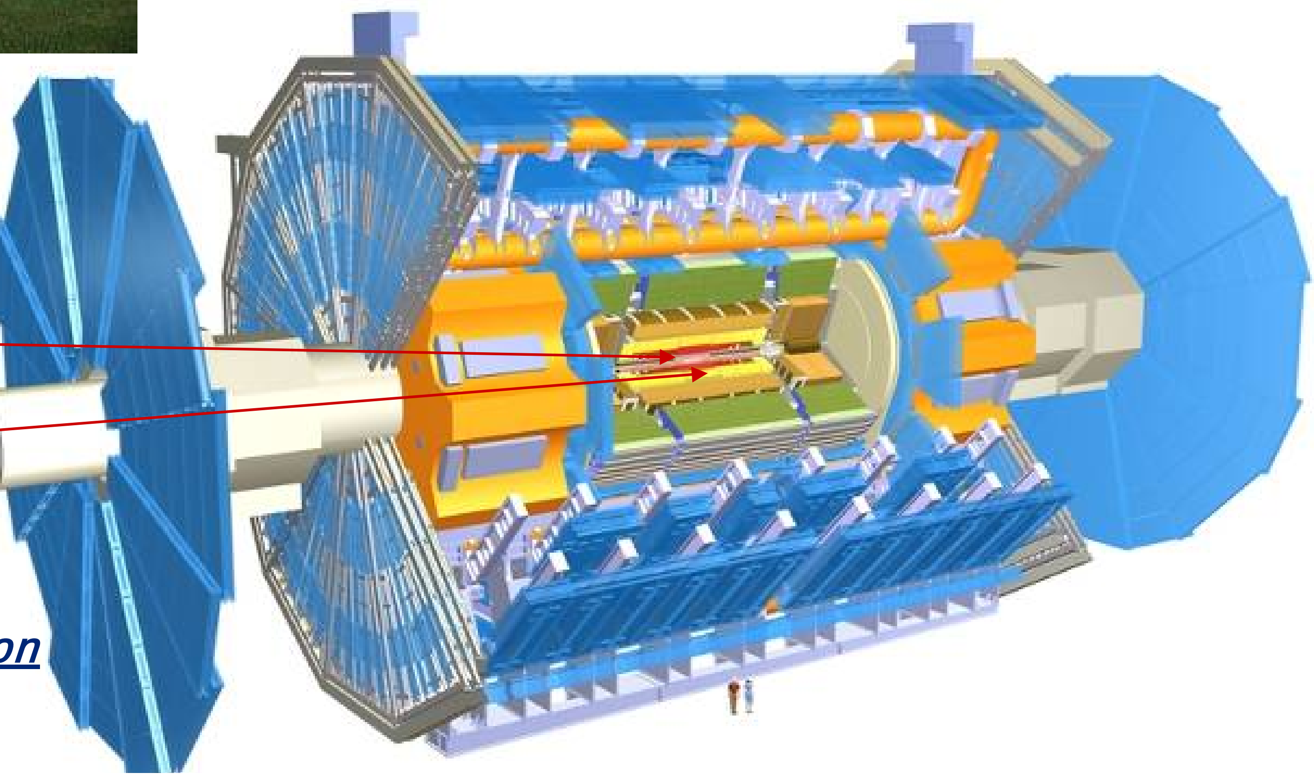
(W.C. ~1945)

ATLAS

Diameter	*25 m*
Barrel toroid length	*26 m*
End-cap end-wall chamber span	*46 m*
Overall weight	*7000 tons*
Power	***~10 megawatts !!***

~1 million detector elements and signal channels + ~100 million silicon det. pixels

LAr calorimeter, fine granularity (~180,000 channels), uniformity, stability, calibration → Highest confidence limits on Higgs

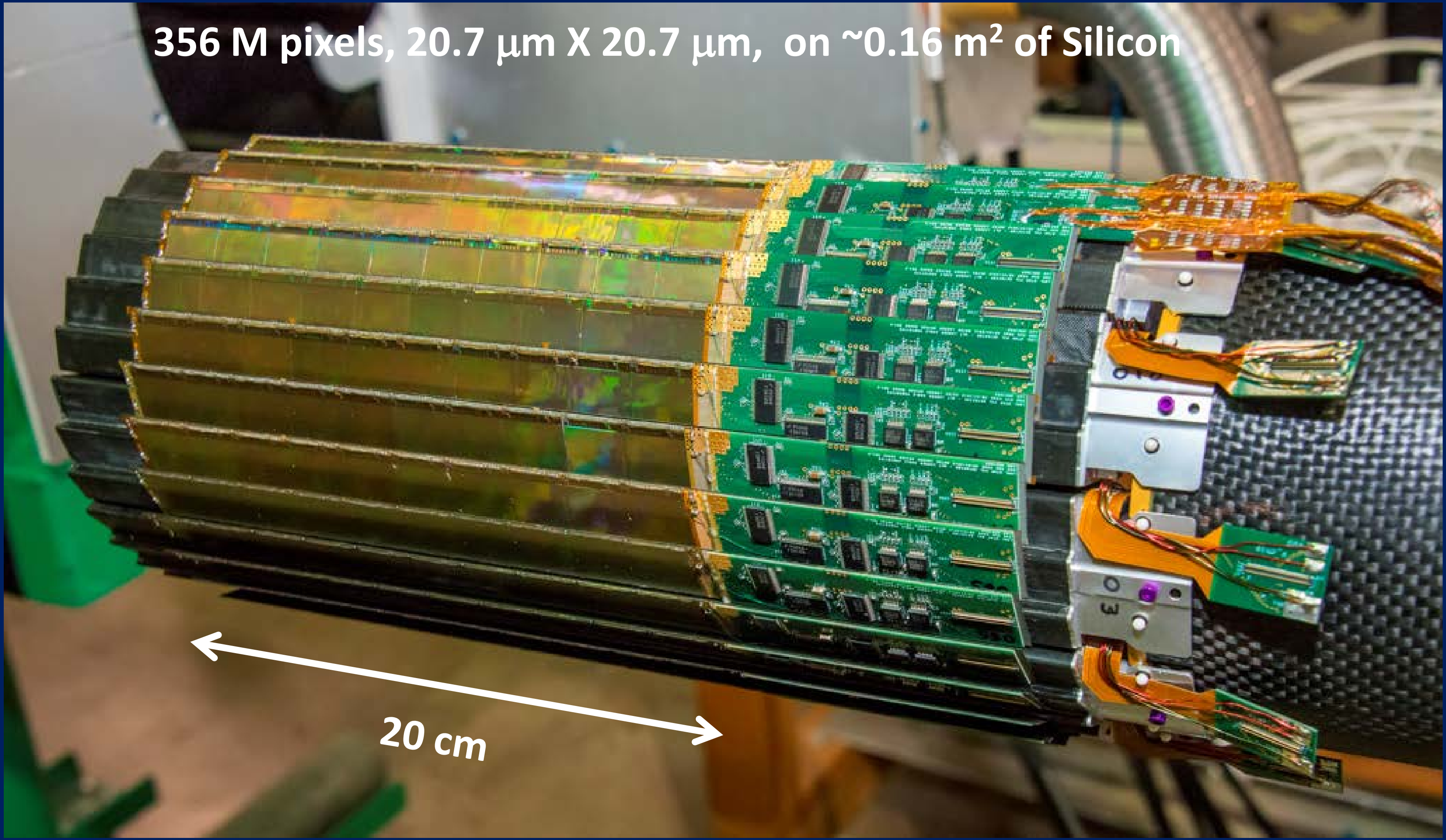


BNL has played a key role in the concept and construction of Liquid Argon (LAr) Calorimeter and Cathode Strip Chambers (CSC)

Si Vertex Detector based on MAPS – at RHIC STAR

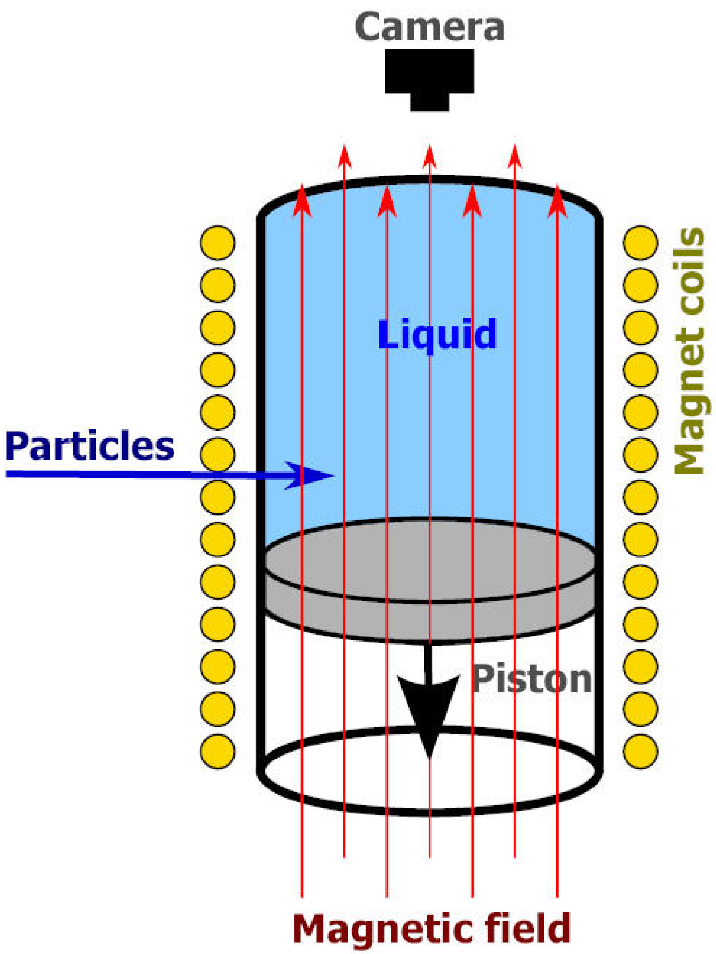
MAPS by IPHC-Strasbourg

SVT construction by LBNL and UT Austin, Tx



See: L. Greiner, FEE 2014

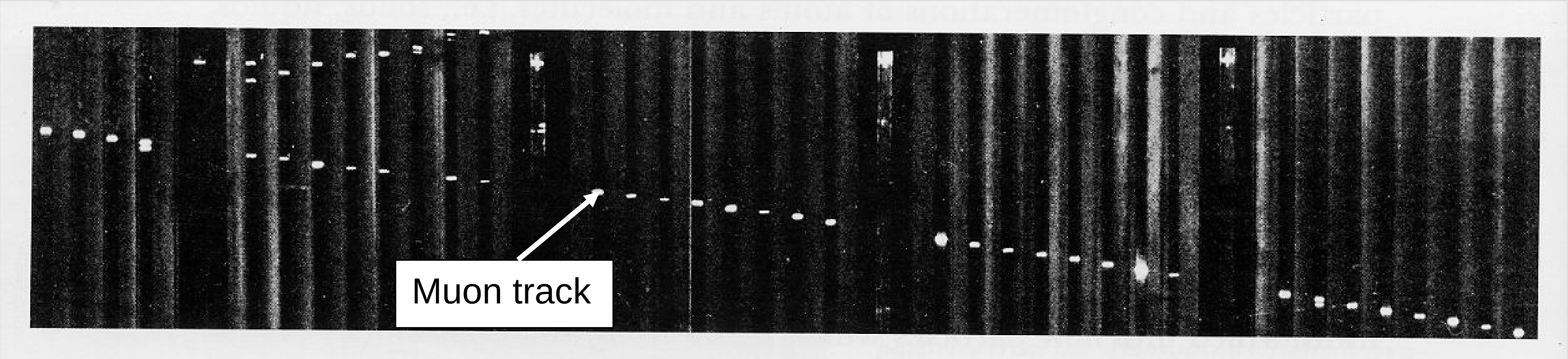
Particle Tracking-Imaging Detectors, 1947 - 1975

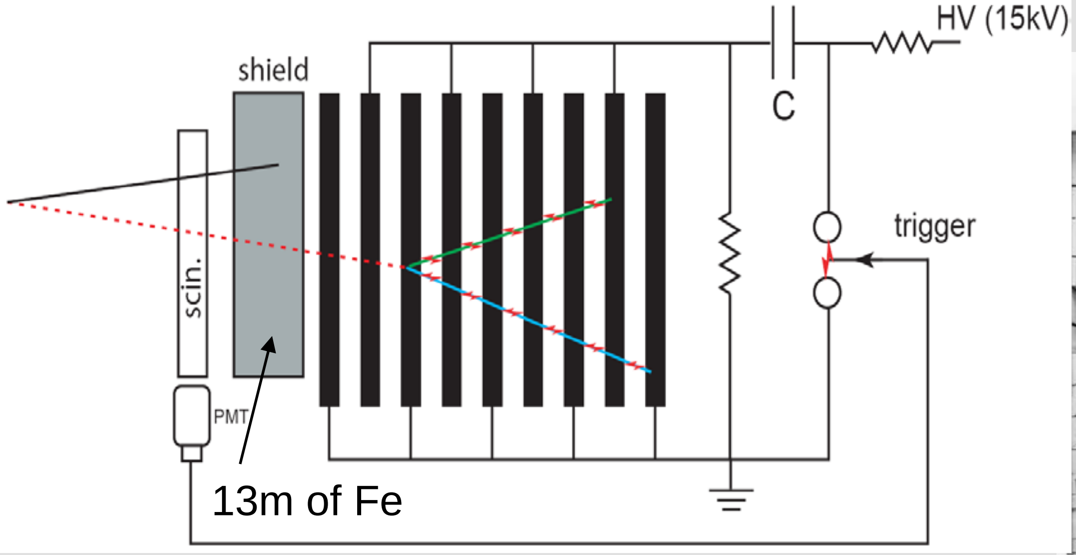


Cloud Chamber (Wilson 1911)	*Bubble Chamber (Glaser 1952)*
Super-saturated, ***super cooled vapor*** (temperature just below the boiling point):	***Super-heated liquid*** (hydrogen at temperature just above the boiling point):
- ions act as centers for ***droplet*** formation	- ***gas bubbles*** form along the particle track

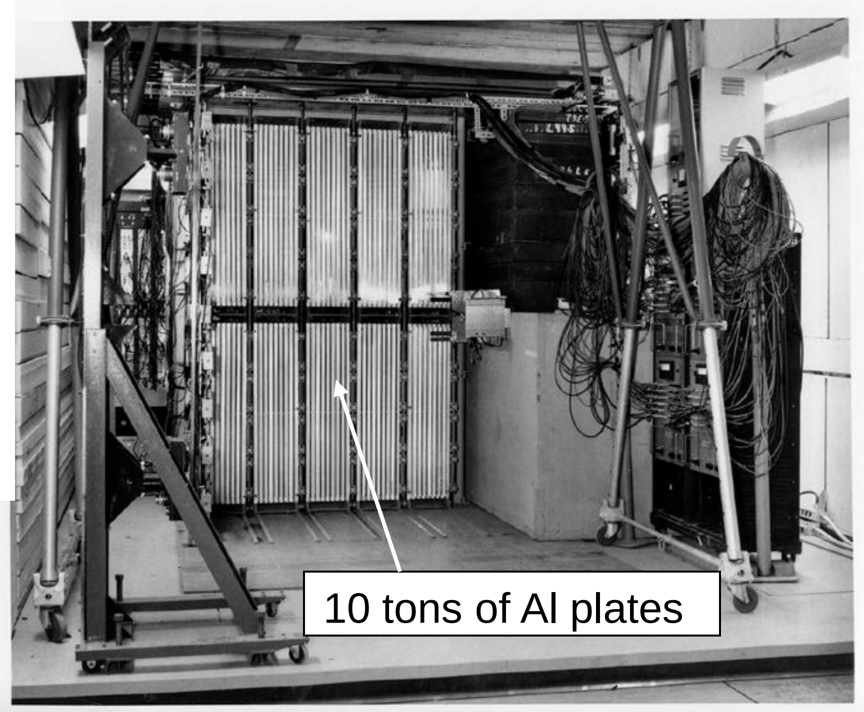
Particle disoveries → Nobel Prizes

Spark Chambers in Muon Neutrino Discovery
Lederman, Schwartz, Steinberger, 1962, Nobel Prize 1988



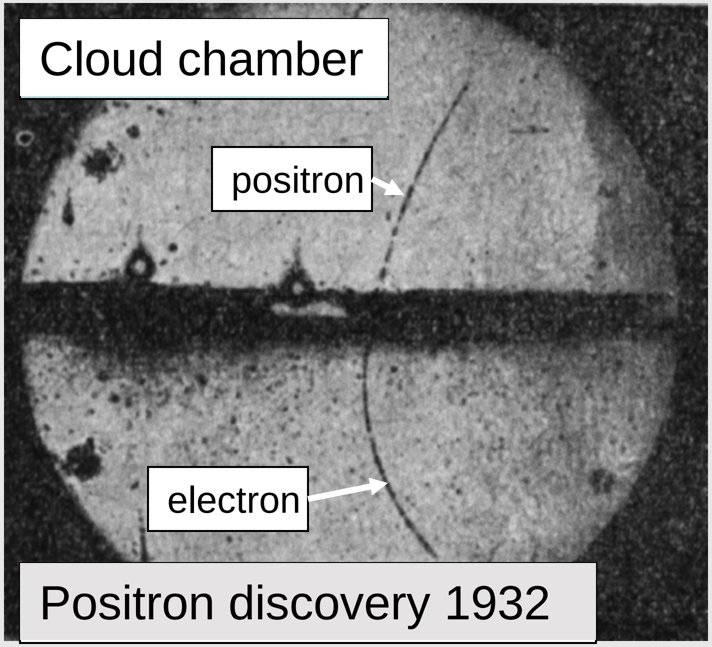


AT BNL AGS:

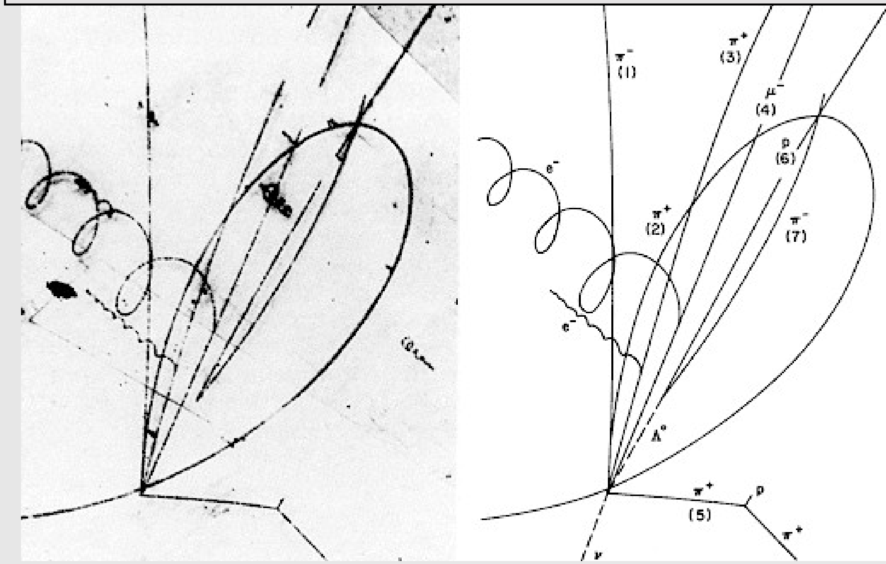


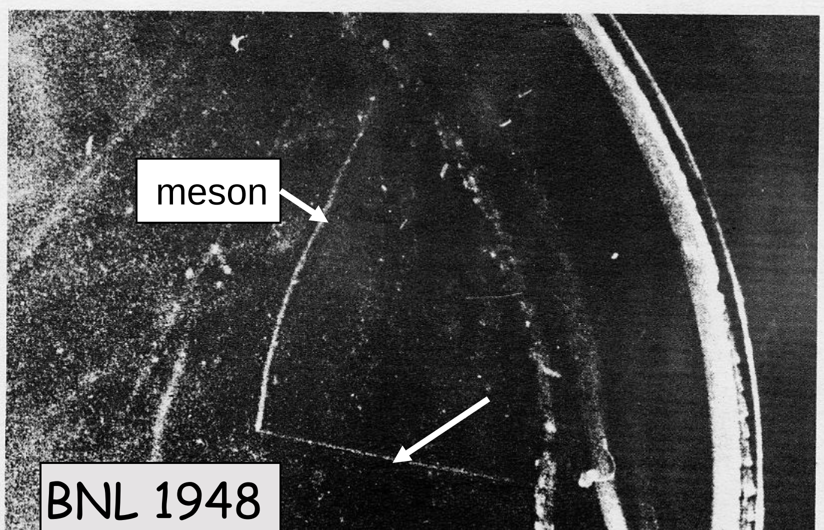
Spark Chambers also in CP Violation Experiment, Fitch and Cronin, 1964, Nobel Prize 1980

(R)evolution of Tracking Detectors Photographic to Electronic

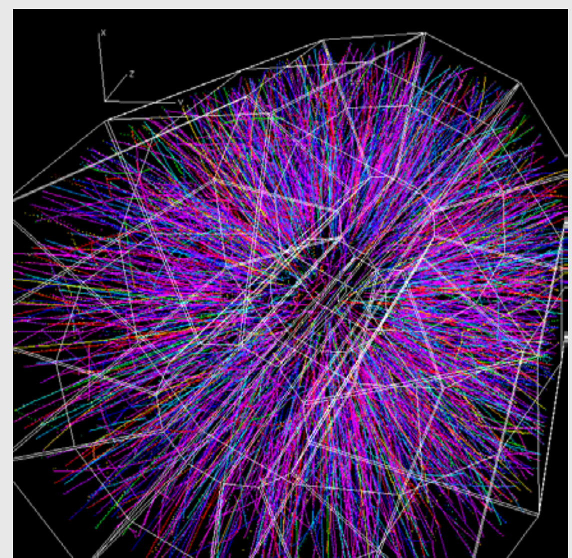


Bubble chamber: charmed baryon decay 1975



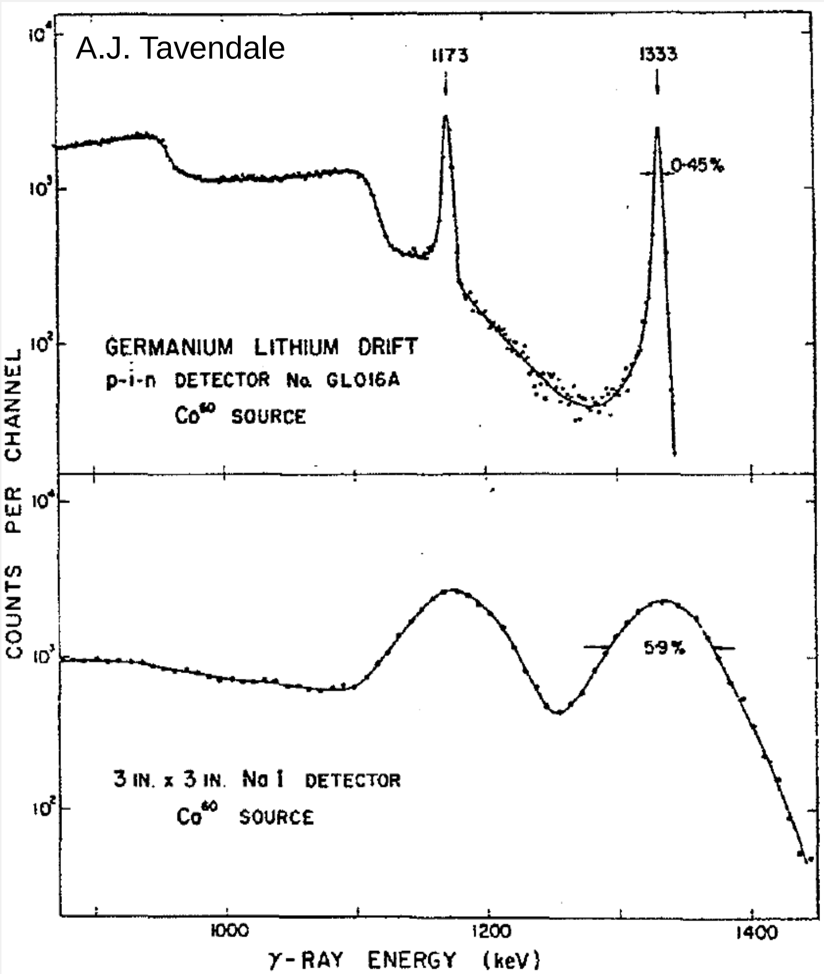


REPRODUCTION of a photograph taken in a high-pressure cloud chamber. The heavier line starting near the top is a meson being slowed down by the gas in the chamber. The thin track running to the right from the end of the meson track is an electron of high energy created when the meson disintegrated.



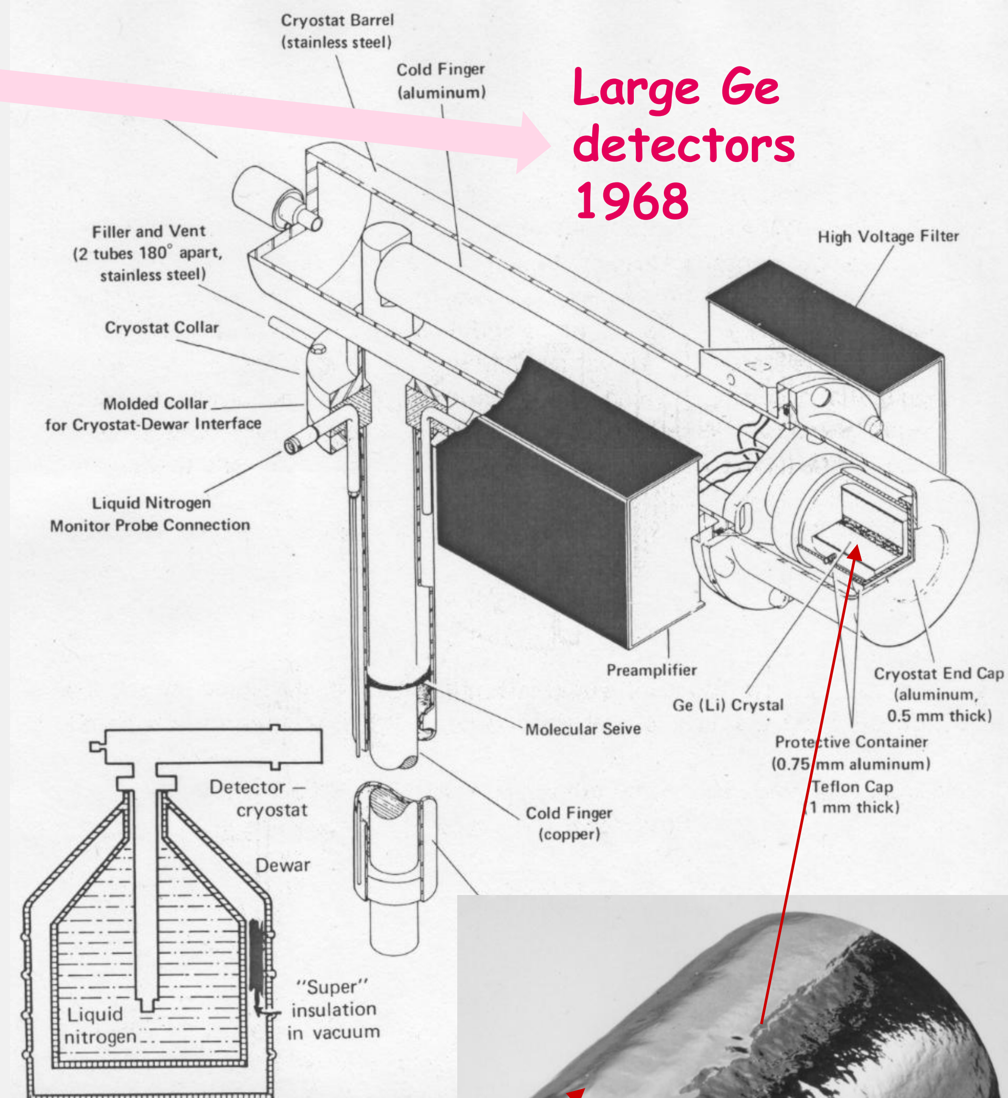
STAR TPC Au on Au 2000-

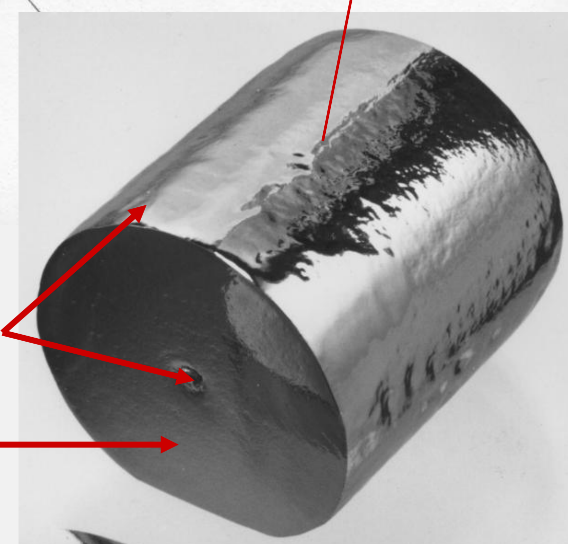
Germanium Detector Breakthrough 1963



BNL charge preamp with JFET at ~120K, 1968

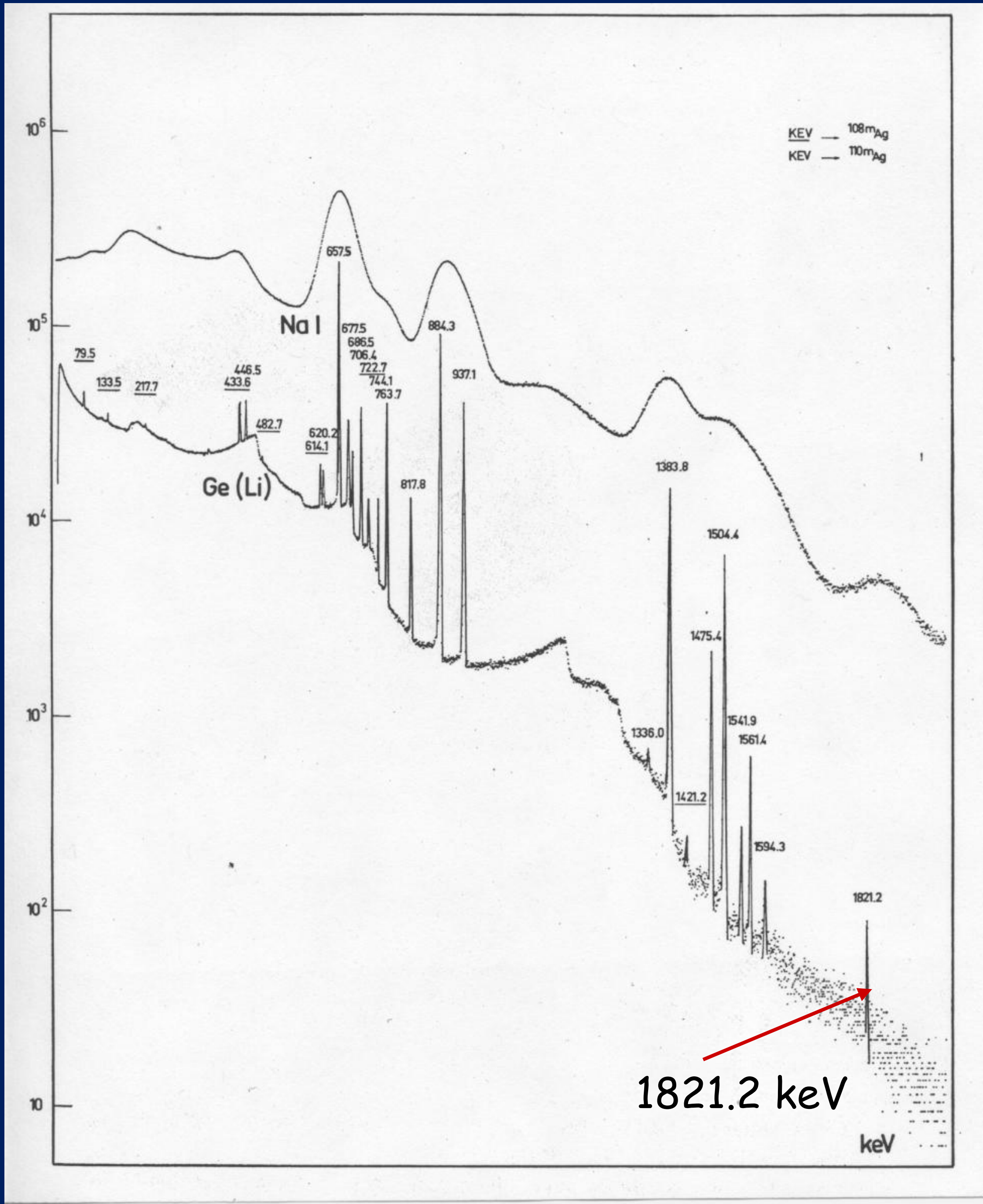
Large Ge detectors 1968





Coaxial det.contacts

Ge-crystal ~50-100 cm^3



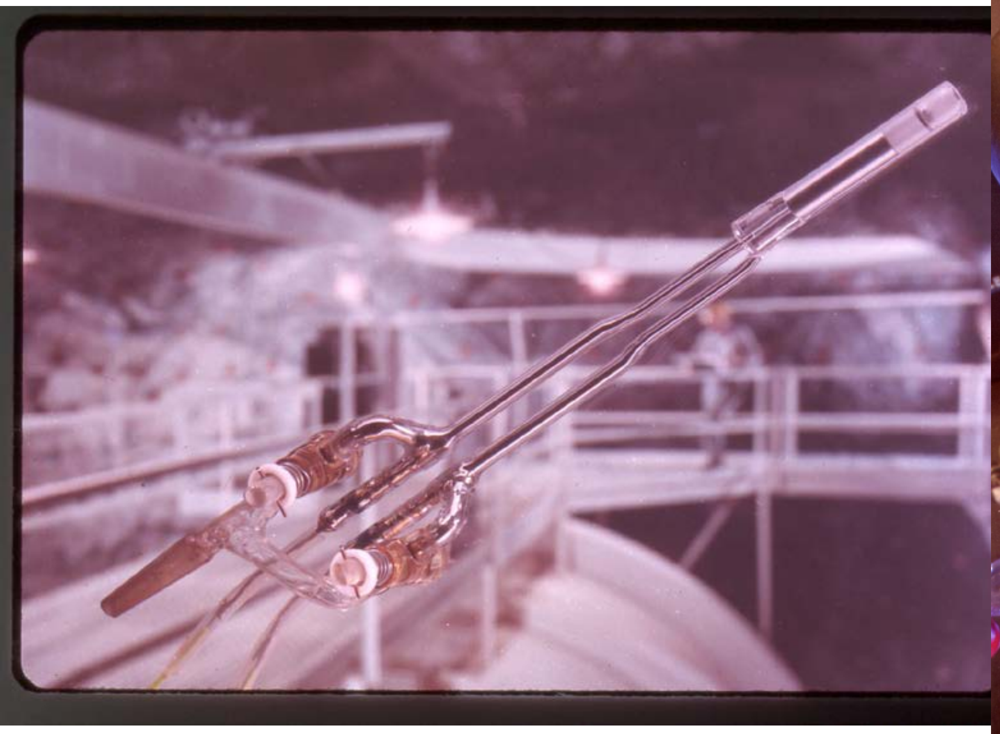
Germanium *vs* Sodium Iodide for gamma-ray spectrometry

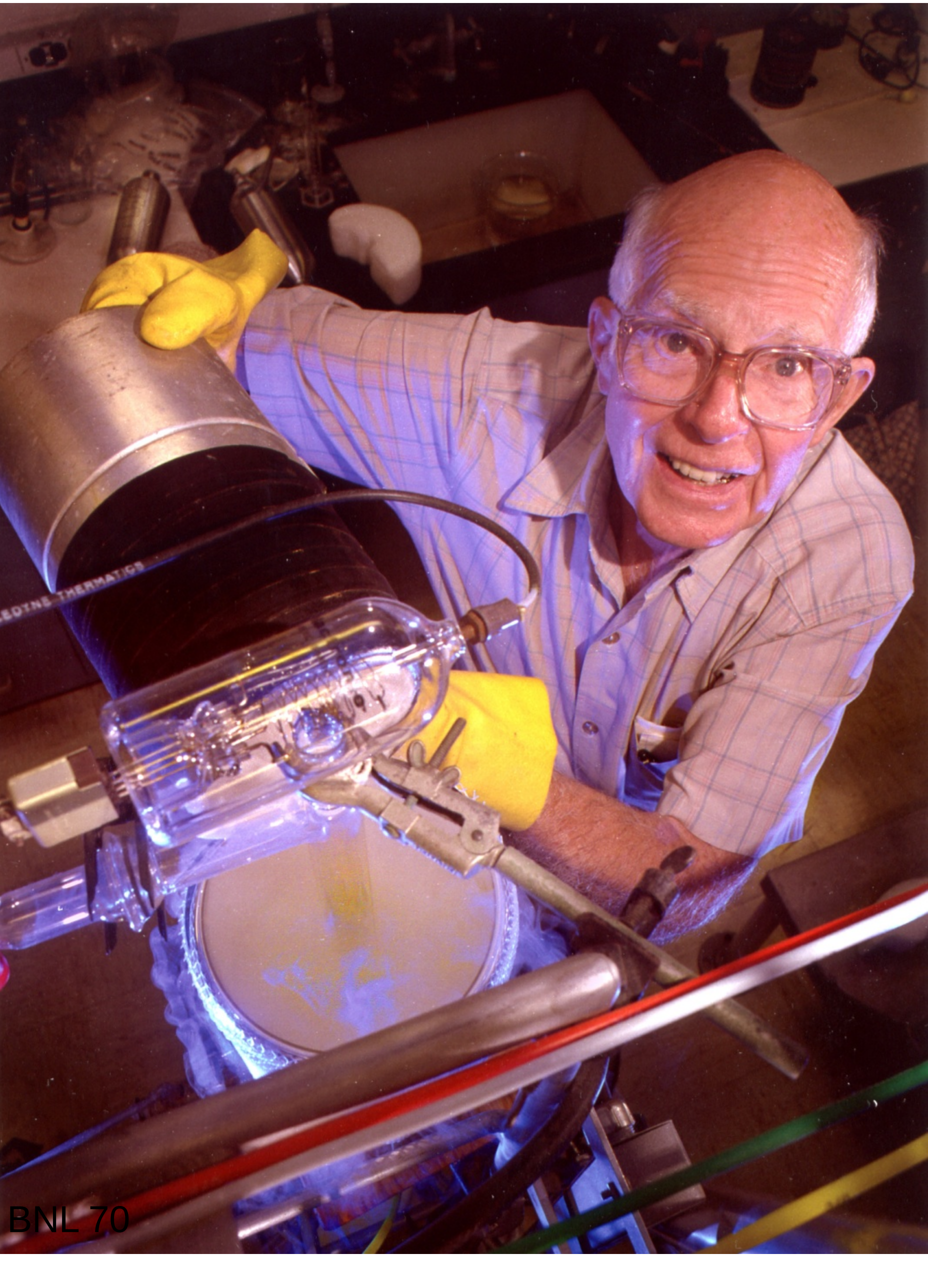
Low noise electronics (first cold JFETs) and signal processing (for gamma ray energy resolution of ~0.1%) developed for germanium detectors in ~ 1965-1970. It provided the basis for later use of these techniques in particle physics, and almost all detectors in use presently.

V. Radeka, BNL 70

Solar Neutrino Detection, Ray Davis, Nobel 2002

Gas proportional counter used to count ^{37}Ar decays by detecting 2.8 keV Auger electrons





Nanosecond charge detection to distinguish ^{37}Ar decays from background

V. Radeka, BNL 70

Select events in detector technology with long lasting impact …

- **Germanium** p-i-n detector, Tavendale (1963-4), gamma-ray and x-ray spectroscopy
- **Liquid Argon** Ionization Calorimetry (1972) → ATLAS
- **TPC , Nygren (1974), lasting impact through gas and noble liquid TPCs**
- Planar processing of **silicon detectors**, Kemmer (1980), basis for future silicon detectors
- **Silicon Drift Detector**, Gatti and Rehak (1983), p-n CCD, x-ray spectroscopy,
- Back Illuminated Fully Depleted **MOS CCD**, Holland (1988), astrophysics
- **Transition Edge Sensors**, (1940s→1990s), astrophysics (CMB, BiCEP, x-ray spectroscopy)
- **CMOS 0.25μm node (1993)**, **5nm gate oxide** →radiation resistance opens the door for integration of sensors with electronics at LHC (1990-)
- **Geiger mode avalanche photo diode, SiPM, (1960s→1990),**
- **Monolithic Active Pixel Sensors (MAPS), IPHC-Strasbourg (~2000)**
- Gas Electron Multiplier (**GEM**), Sauli (1997)
-

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 10-40 kton range**

Detectors for astrophysics; photon science; PET; neutron scattering, ...

Integration of "Chambers" and Microelectronics

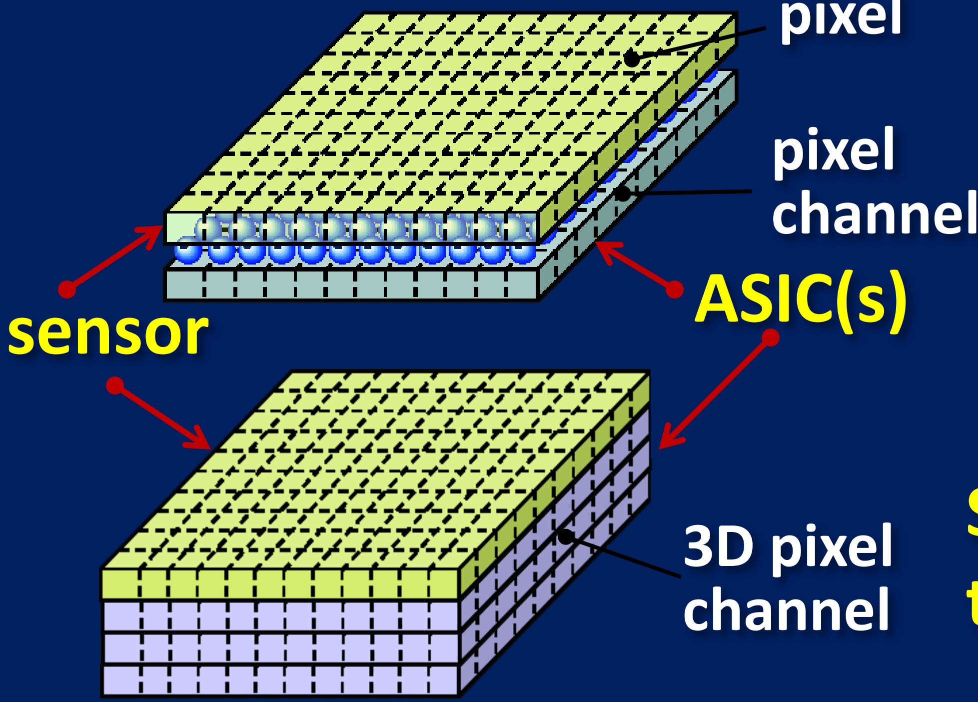
Silicon:
- **Strips/pixels** (bump/directly bonded)
- **MAPS**
- **SiPMs**

TPCs
- **Gas and noble liquid**, charge and light

"Microelectronics"

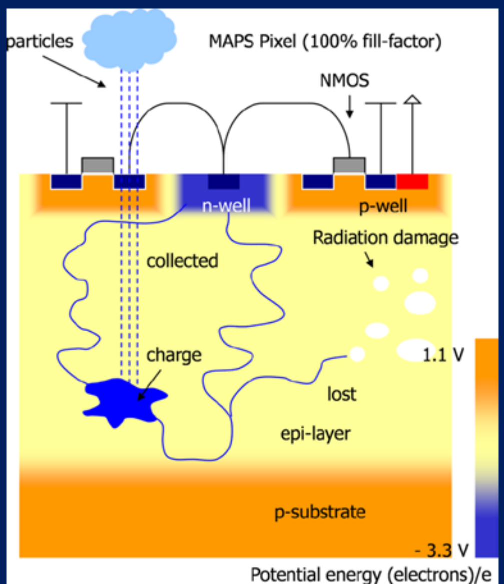
Beyond CMOS??

Si "Pixel" Detectors



Sensor pixels bump-bonded to ASIC pixels

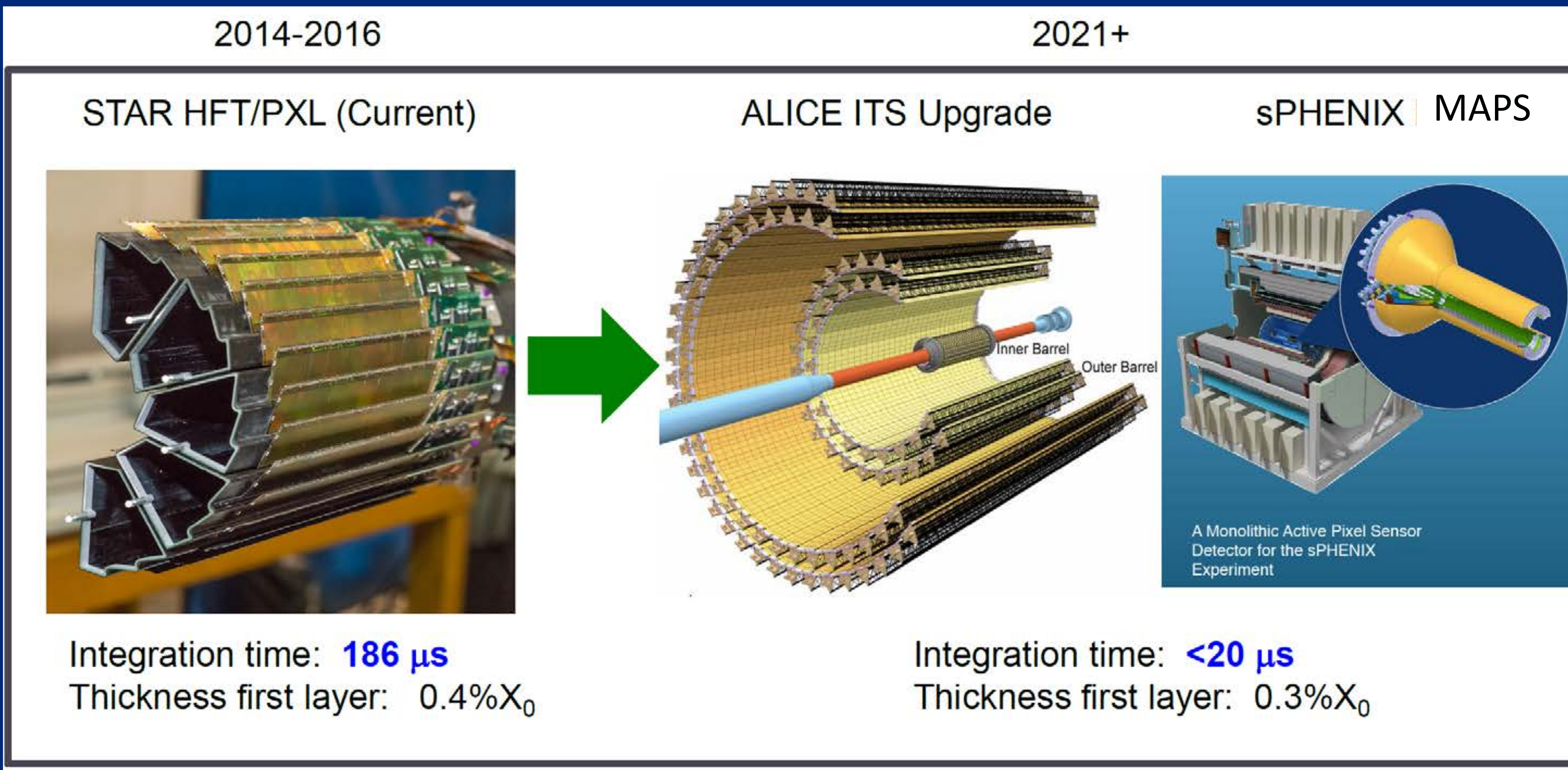
Sensor pixels fusion-bonded to (2D or 3D) ASIC pixels



Monolithic Active Pixel Sensors (MAPS): sensor and transistors in "standard" CMOS technology – new developments for ALICE and sPHENIX

Advances in MAPS

- From diffusion to drift for charge collection→ ~100ns to <10ns
- Increased epitaxial layer resistivity from ~20ohm cm to 1kohm cm
- From rolling shutter to faster readout → ~170mW/cm^2 to 5mW/cm^2

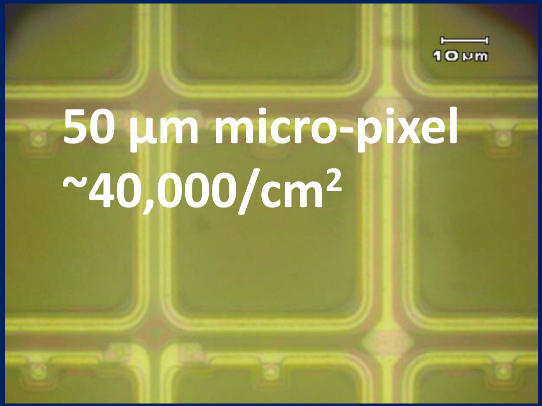


From: G. Contin, LBL

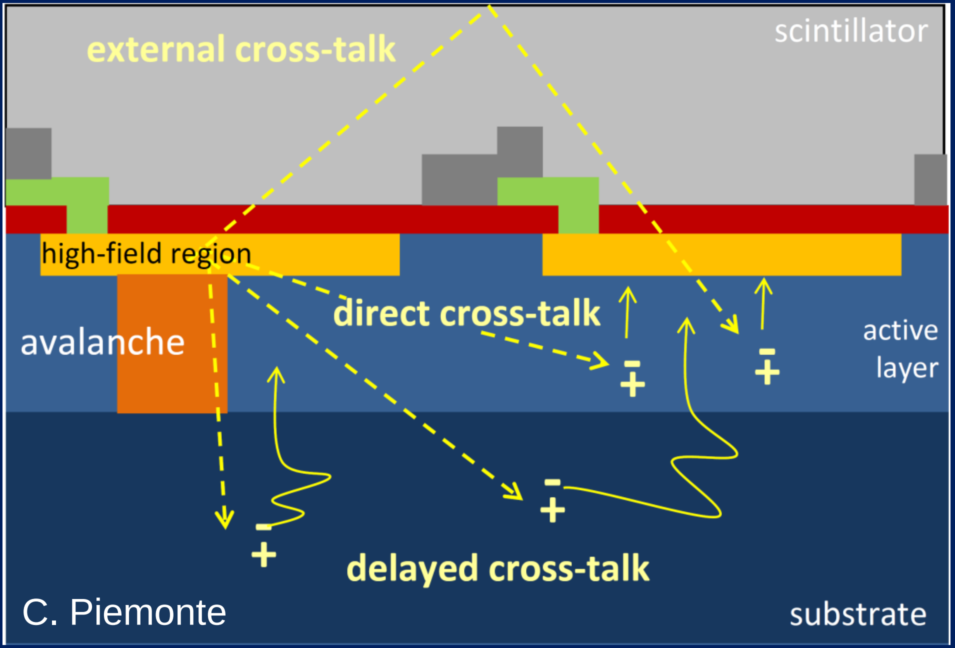
Silicon Photo Multiplier (SiPM)

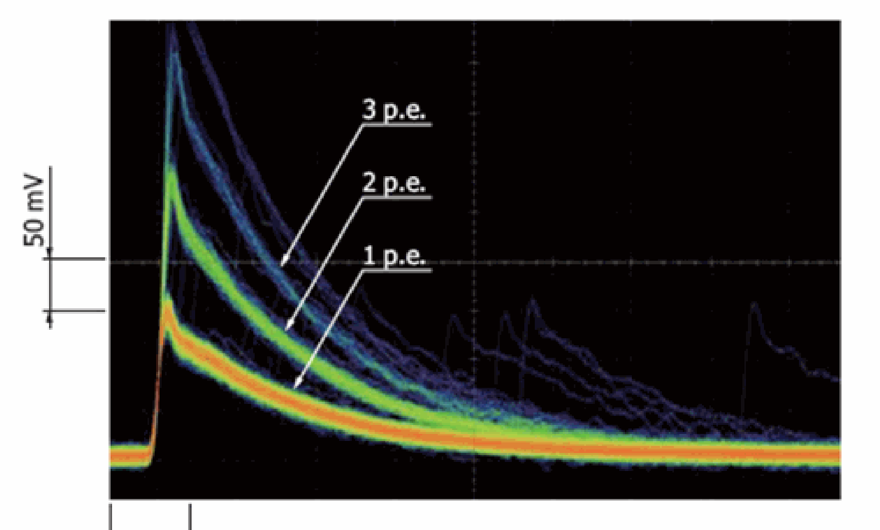
- ”Geiger-mode”: avalanche spends itself (“quenches”) by reducing the cell voltage
- Principal advantage: single electron produces ~10^6 electrons
- Principal disadvantage: single electron produces ~10^6 electrons

Large arrays



Secondary electrons α avalanche size





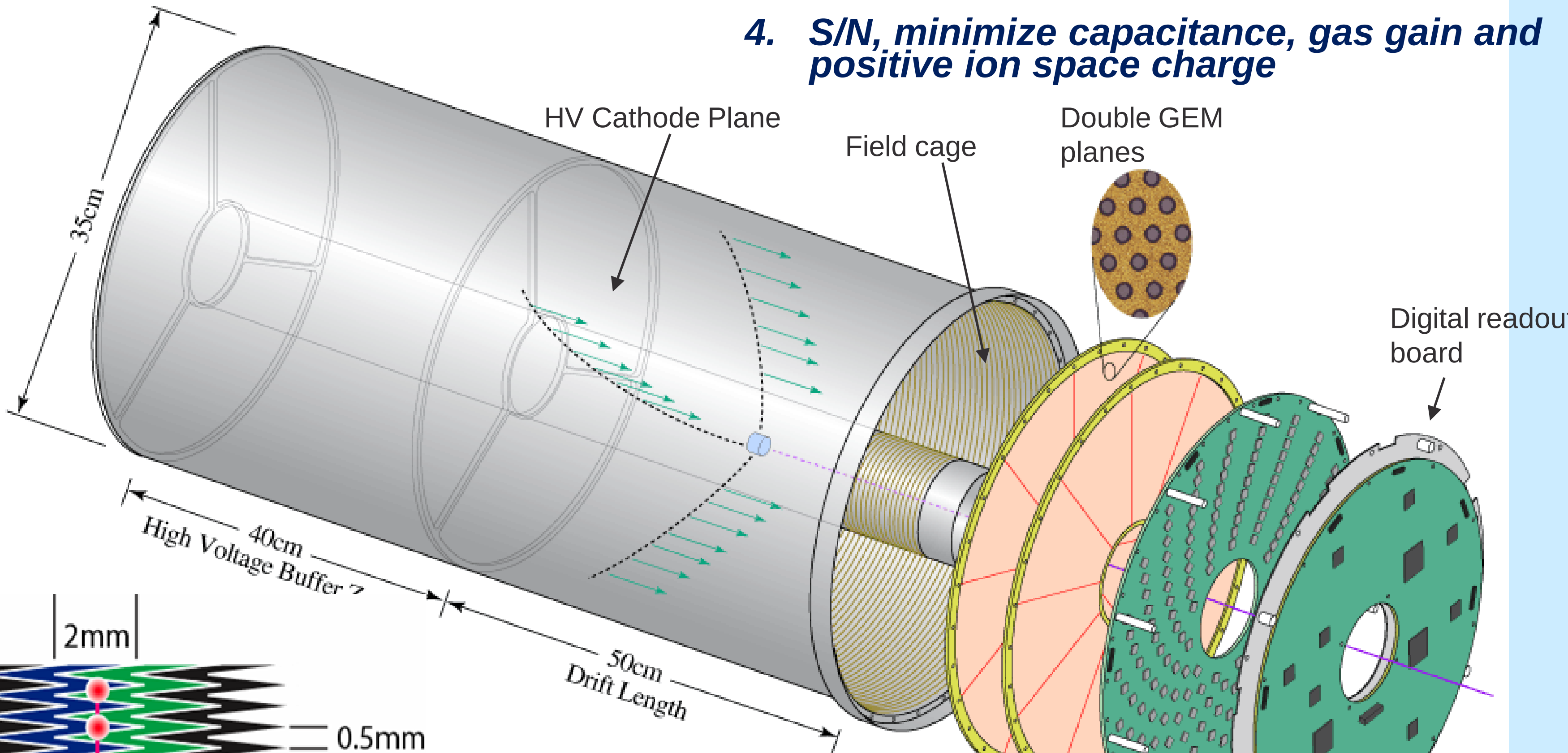
Single p.e. resolution

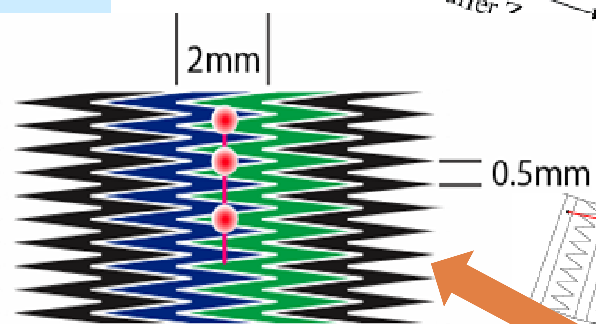
Future: Diverse applications, innovation in device design and integration with readout electronics

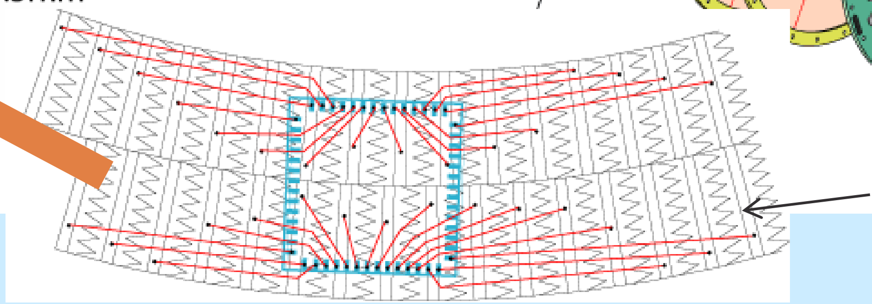
Time Projection Chambers (TPCs) with Gas or Noble Liquids "Electronic Bubble Chambers"

Fine Granularity Gas TPCs:

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







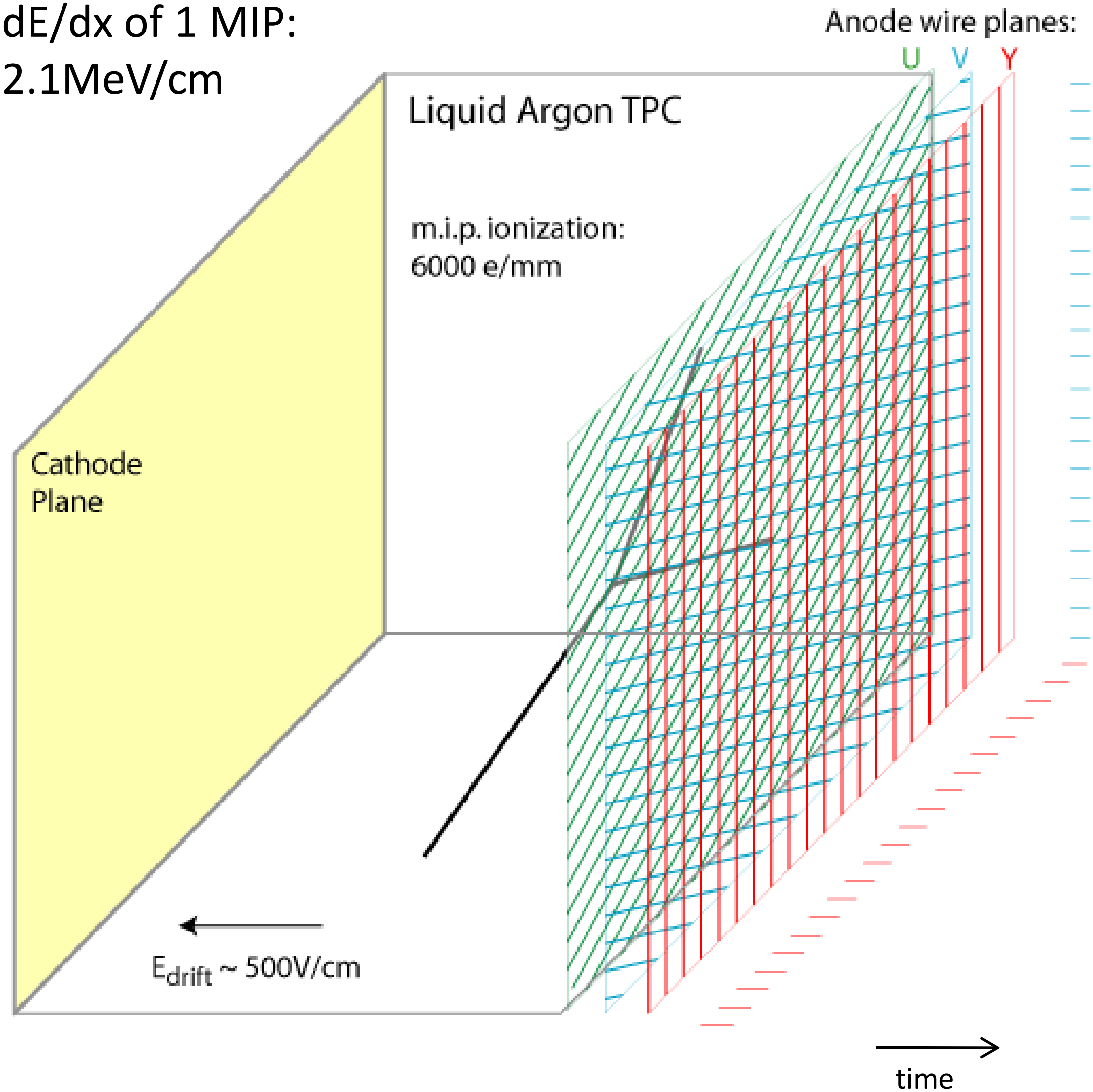
Interpolating anode pad plane with front end ASICs (7296 channels) in the LEGS TPC; 10 watts total on TPC.

Bo Yu et al. (BNL, 2002)

V. Radeka, BNL 70

LAr TPCs on Multi-kiloton scale

dE/dx of 1 MIP:
2.1MeV/cm

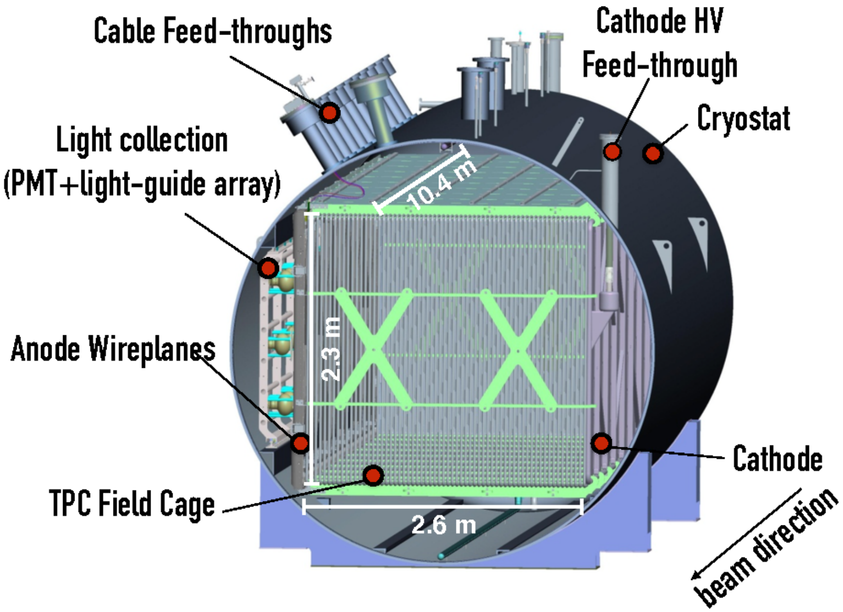


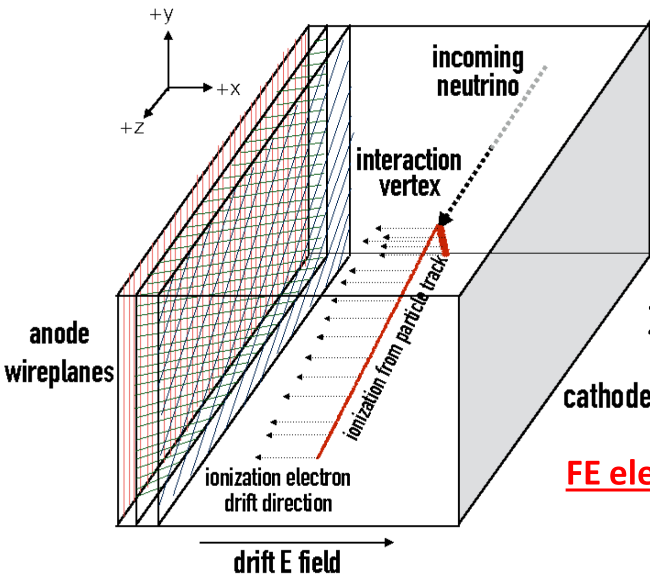
First proposed by C. Rubbia, 1977

- Sense (anode) wires (up to ~ 10m long):
  ~14-**31 kwires/kton**
- position resolution ~1mm
  - charge sensitivity
  - range ~100 fC
  - ENC < 1,000 e^-
- digital <u>multiplexing</u>
- <u>data rate: **1terrabit/s/kton**</u>

- electronics in LAr
  <u>**> 30 years**</u>

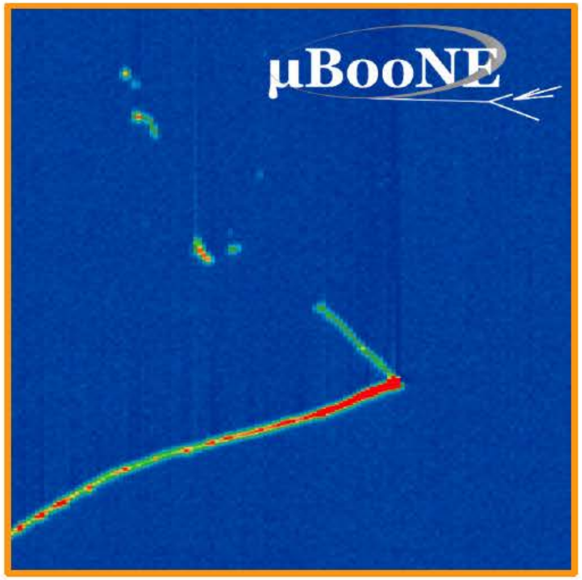
MicroBooNE LAr TPC: 62 m3 fiducial vol. (87 tons)



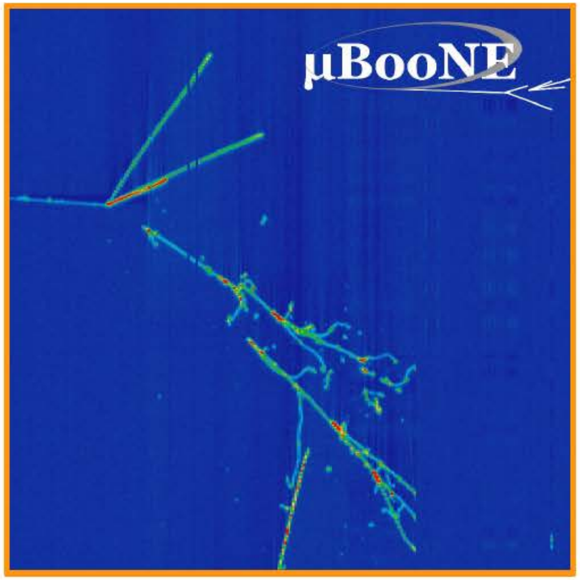


$2.5x2.5x10m^3$

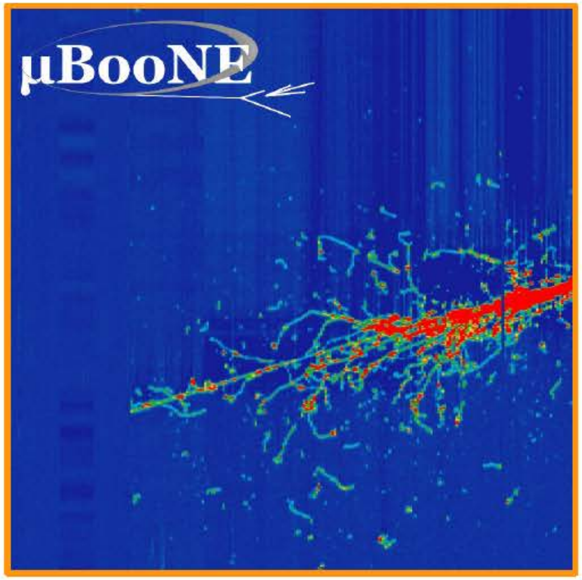
FE electronics in LAr



Michel electrons [0-55 MeV]

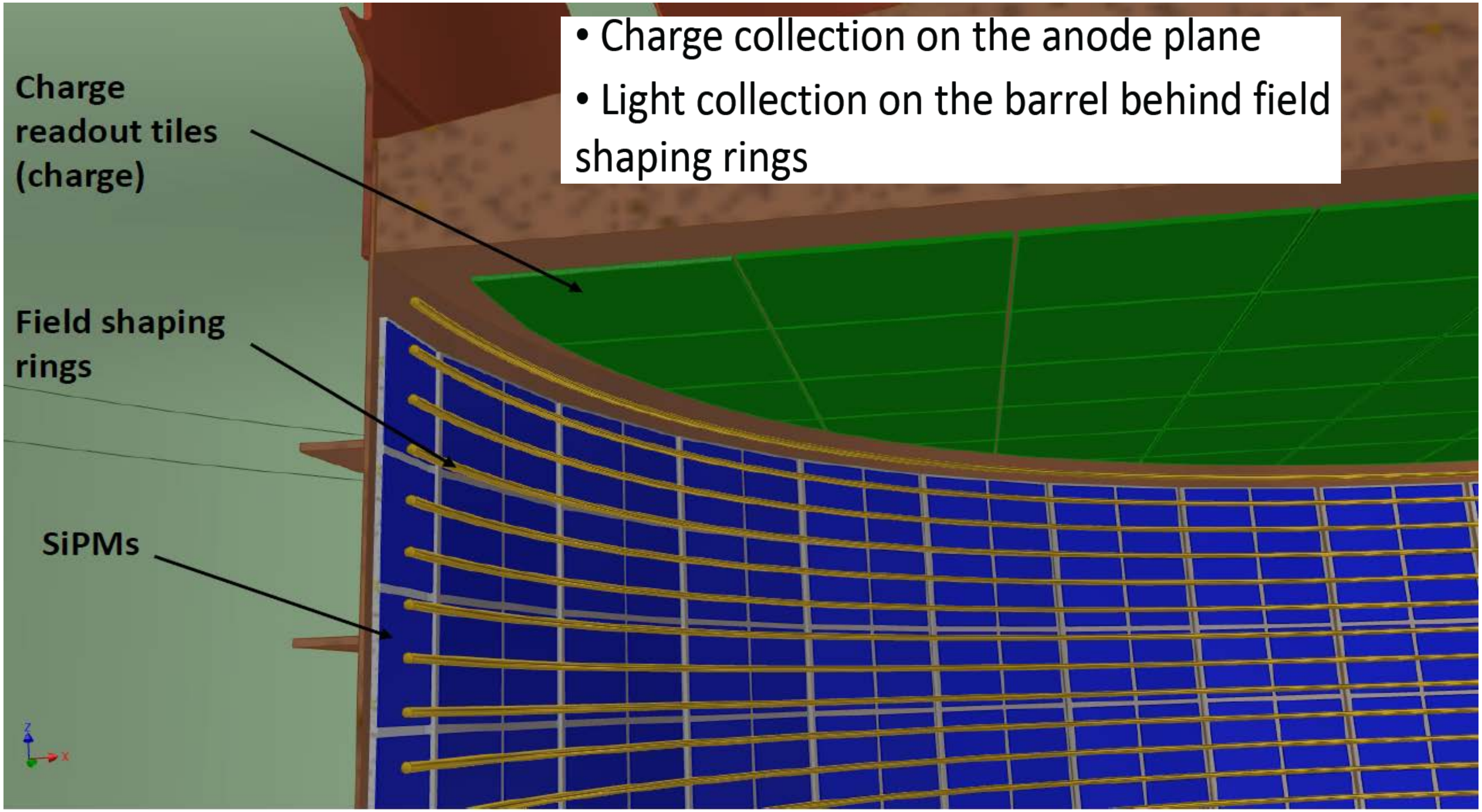


Beam π^0[tens-hundreds MeV]



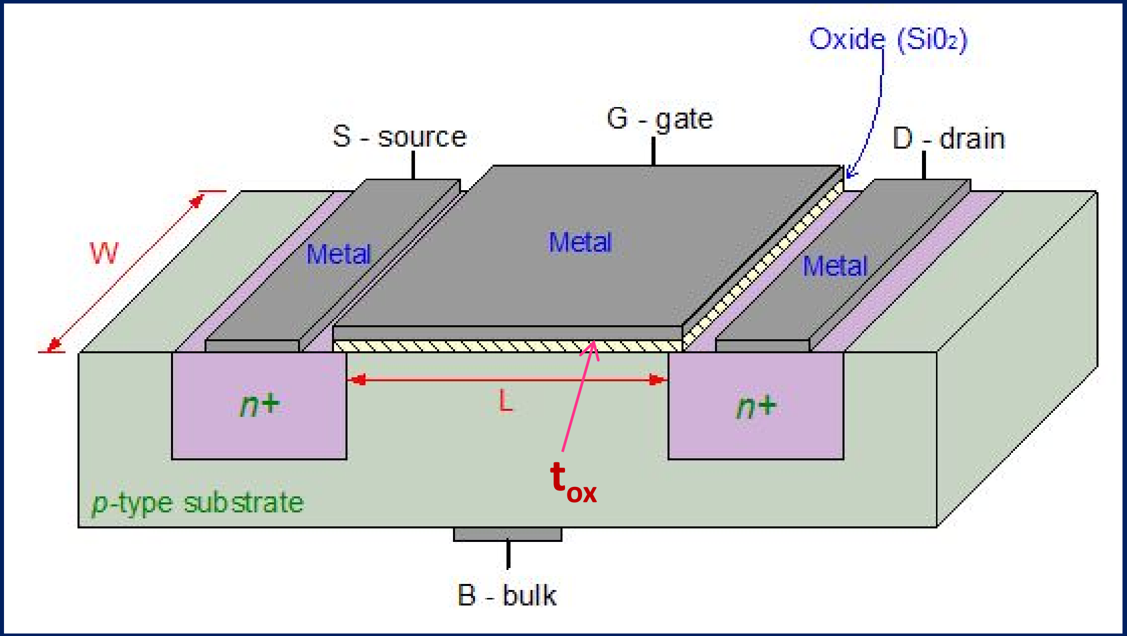
cosmic EM activity

LXe TPC with Charge and Light sensing (e.g., 0νββ decay experiment) ~2 ton scale (nEXO)



Challenge: **SiPMs to cover large areas (~5 sq. meters) in noble liquid detectors → large number of SiPMs to read out (>10^4, dark count rate ~ 10^8/s) Electronics in LXe (~160K) for both charge and light**

CMOS and Device Future



L/t_{ox}~50

W/L~0.1 - 10^6

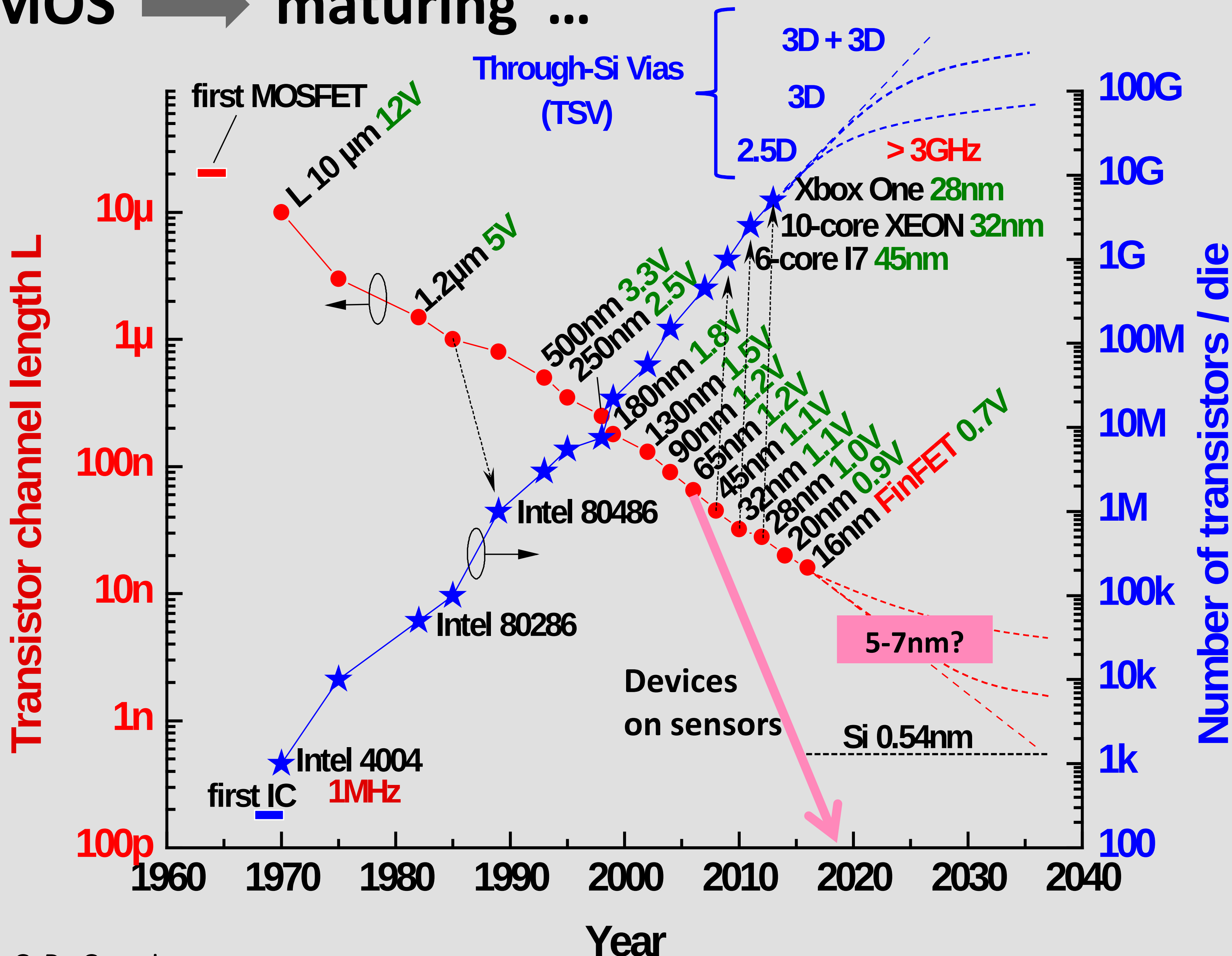
End of Moore's Scaling?

Beyond CMOS?

What after CMOS?

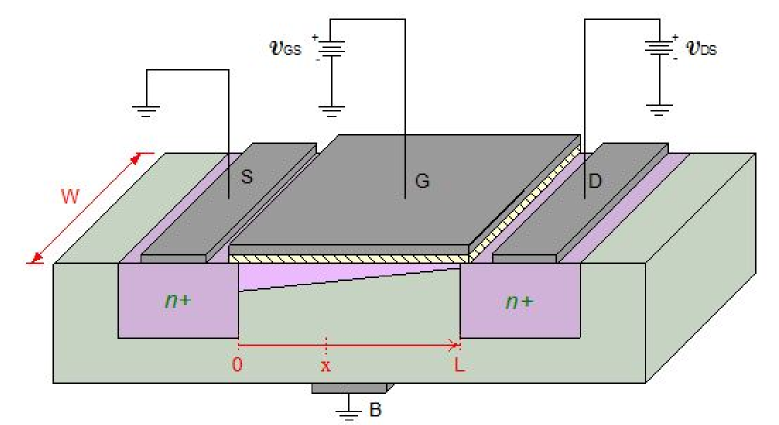
- Number of transistors/die → functionality α 1/L
- speed α 1/L
- cost/transistor α 1/L
- power dissipation/area

CMOS ➡ maturing …

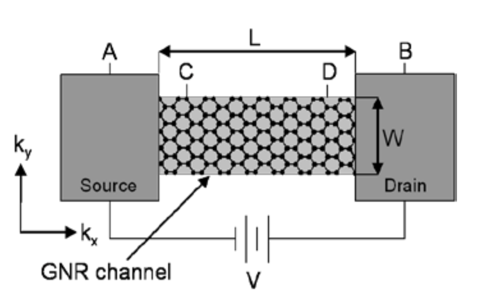


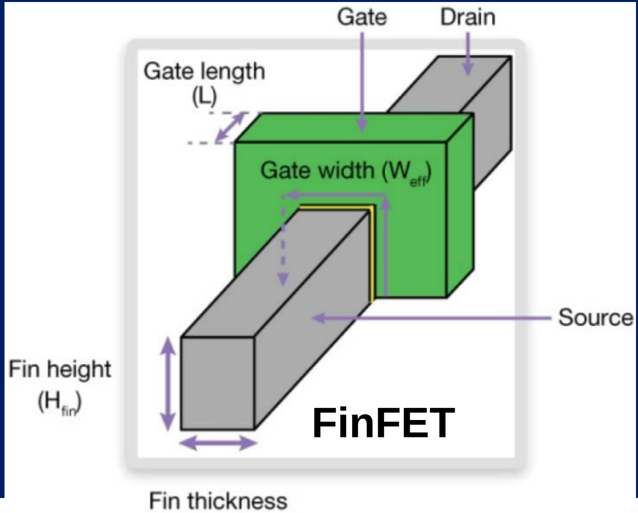
From: G. De Geronimo

Electrostatic Channel Control with Short Gate (<20nm) Goal: $I_{ON}/I_{OFF} > 10^6 \rightarrow$ Low Subthreshold Leakage

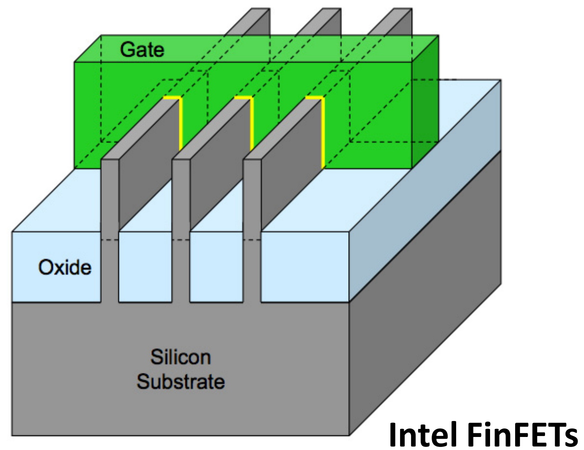


https://www.intechopen.com/books/current-trends-and-challenges-in-rfid/rf-cmos-background

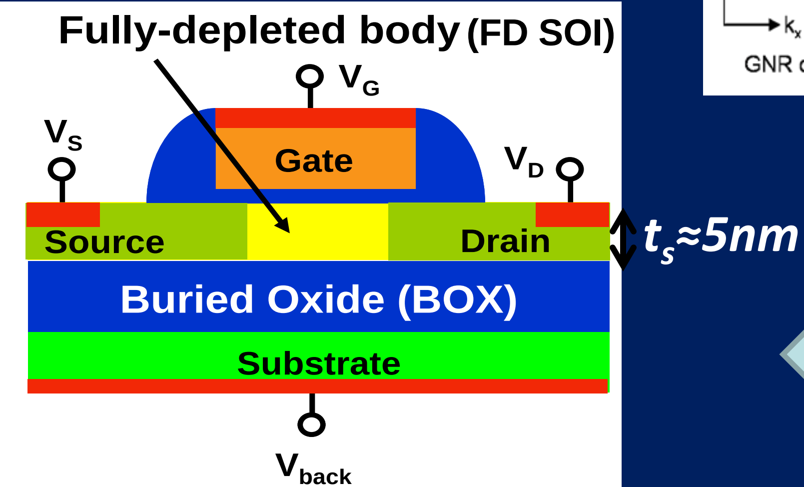




22 nm Tri-Gate Transistor



Tri-Gate transistors can have multiple fins connected together to increase total drive strength for higher performance



Adapted from: S.K. Gupta, FEE2014

Alternate Device Concepts

<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**

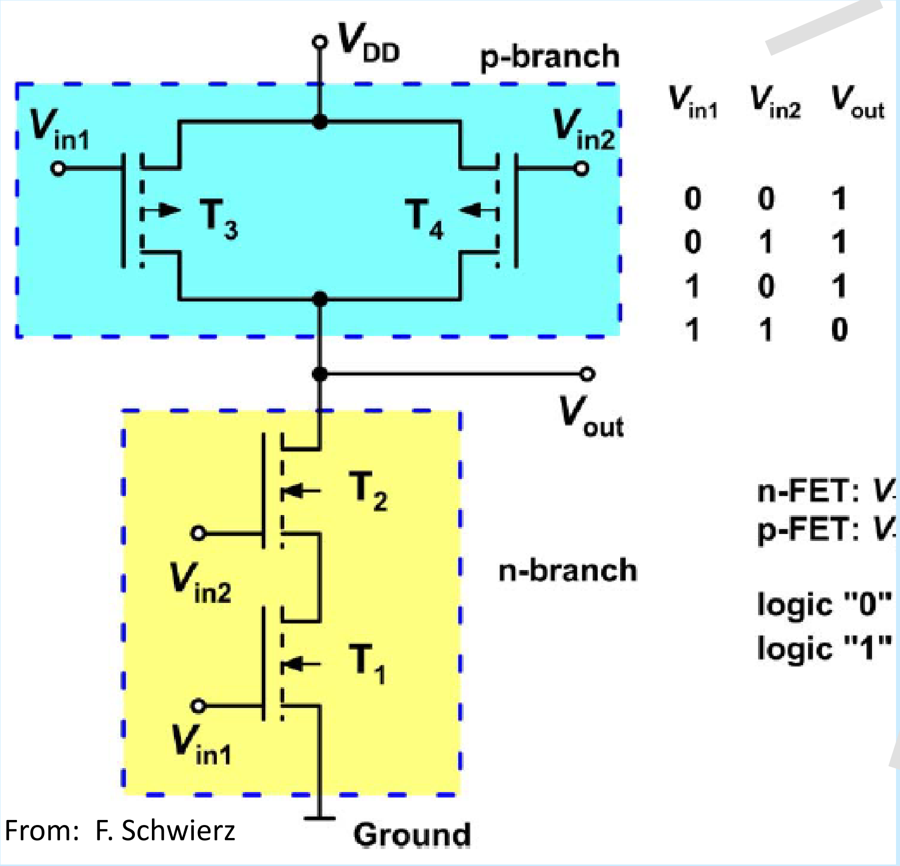
Upon analysis: *Spintronic devices have longer switching delays and higher switching energies, due to inherent time of magnetization propagation …*

<u>**Entirely new concepts (… and dreams):**</u>

- **Selfassembly of nanoscale devices (single-port devices possibly, no three-terminal devices yet)**
- **Stochastic computing: no longer deterministic logic with defective devices acceptable,**

"Beyond CMOS?" Why is it so difficult to find a "better"(smaller, faster, lower power) device?

CMOS NAND Gate:



V_{in1}	V_{in2}	V_{out}
0	0	1
0	1	1
1	0	1
1	1	0

Any "Beyond CMOS" device should have many of the same characteristics as CMOS devices :

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

The consensus : ***No new device is on the horizon with a potential to completely replace CMOS***

More likely, a gradual evolution: *New, or special functions (e.g., memories) may become possible in the nanoscale devices by new physics and such devices may be merged into CMOS circuits to enhance overall performance. Impedance matching may be necessary from the quantum resistance values (kohm) down to the 50-100ohm range. The overall logic operations and communications will still be based on CMOS.*

What to expect for electronics integrated into particle detectors?

- It will remain CMOS based (albeit with new materials) well into the mid-century.
- The channel length will level off somewhere below 10nm in semiconductor industry with expansion into 3D and new channel and gate dielectric materials.
- Science community has followed the minimum channel length with a delay in actual use of ~ 10 years. This may increase.
- The choice of technology node (e.g., 10nm vs 65nm) for high resolution detectors may depend on device parameter variations which increase with 1/L.
- Minimum noise for capacitive sensors (science applications) will require channel lengths longer than minimum feature size (for 1/f noise in particular).
- The time and effort for design of more complex ASICs has been increasing steeply with scaling: increasing functionality+growing design rules+more complex and costly design tools, more costly prototyping, extensive testing effort, unique design features for particle detectors.

•

Concluding remarks:

The future of particle detectors to be developed with advancing electronics technology is exciting.

To take full advantage (or, just to keep up) will be a challenge for research institutions and funding agencies …

… with all this you can work happily into 2050s !

Thank you!