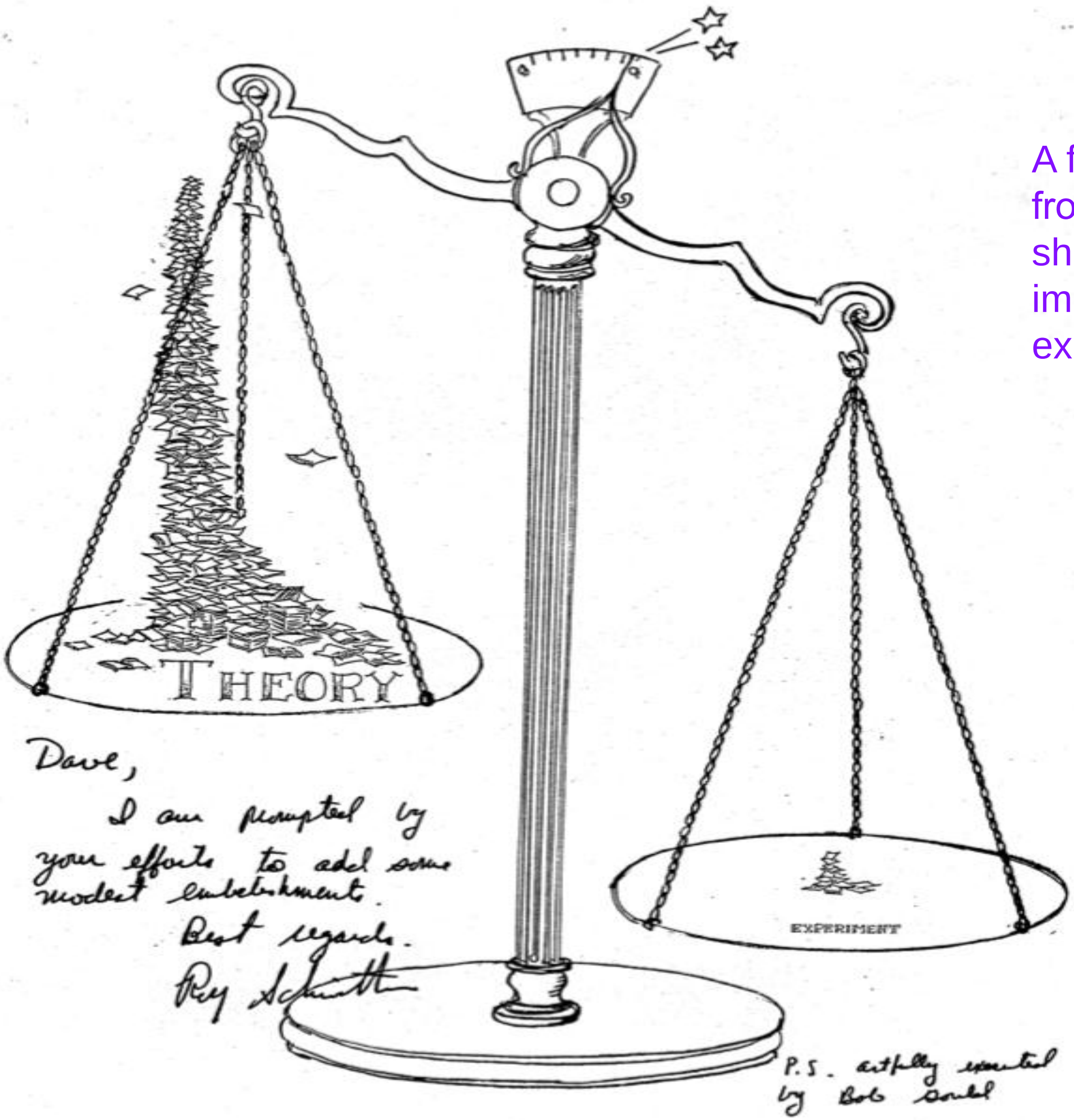
A History of Particle Detectors

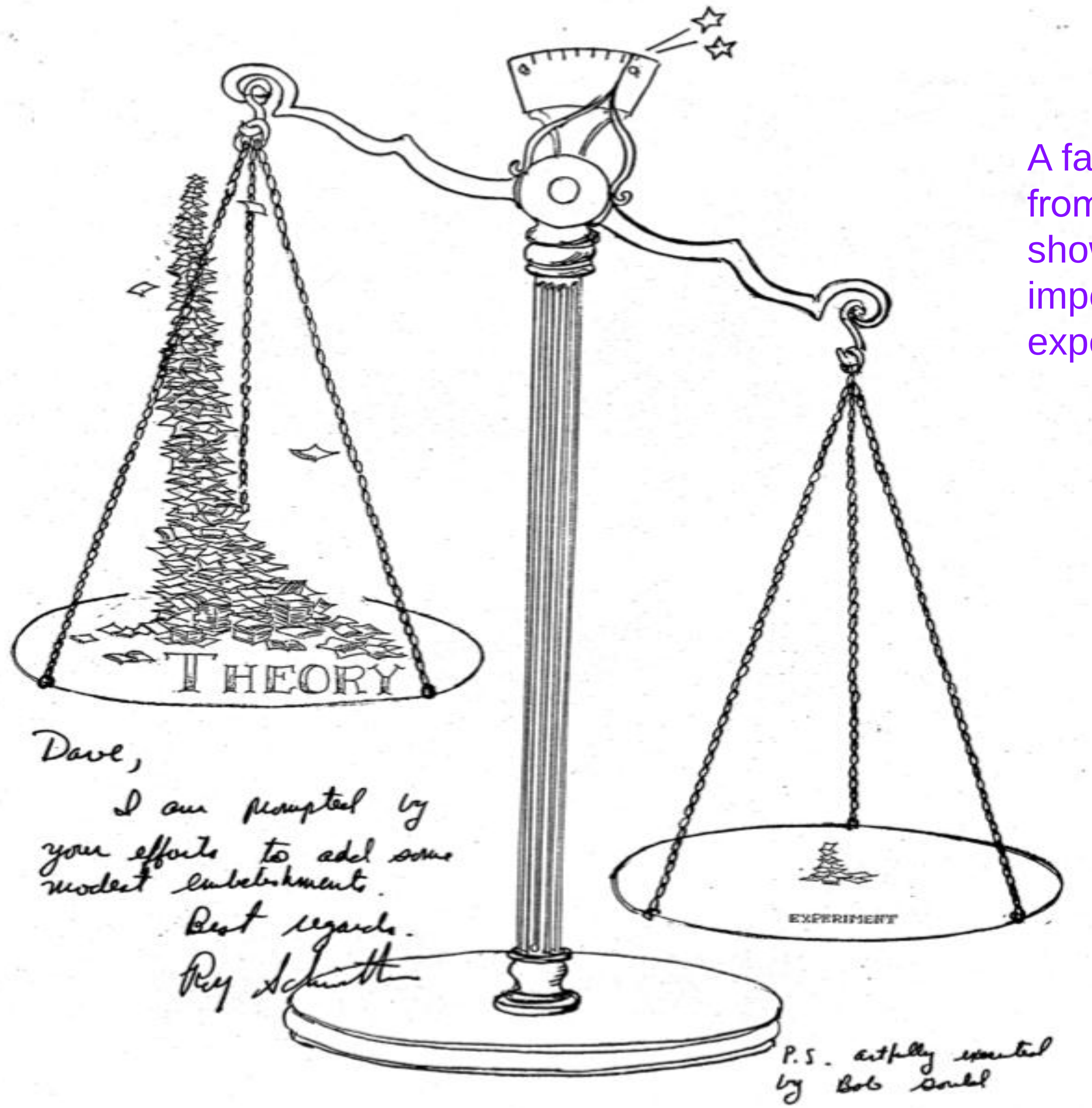
David Nygren - LBNL

EDIT School - FNAL

13 February 2012



A famous drawing from the 1970's showing the relative importance of experiment vs theory



A famous drawing from the 1970's showing the relative importance of experiment vs theory

But something else is present here...

an instrument!

History of Particle Detectors -

- Why is this stuff interesting ?
- How can I possibly use this information ?
- Is the history of particle detectors finished ?
- Where are possible avenues for progress ?

History of Particle Detectors -

- Why is this stuff interesting ?
- How can I possibly use this information ?
- Is the history of particle detectors finished ?
- Where are possible avenues for progress ?

- Will there be a quiz ? - *No!*

A biased history...

- I offer a fairly personal perspective on this fascinating story - *to indicate opportunities both found and missed* - and to look for lessons for future advances.

- A comprehensive - and necessarily superficial - review of all developments would miss this.

- Acknowledgments: Michael Hauschild, Bill Moses,...

Signals $\Rightarrow$ Physical information

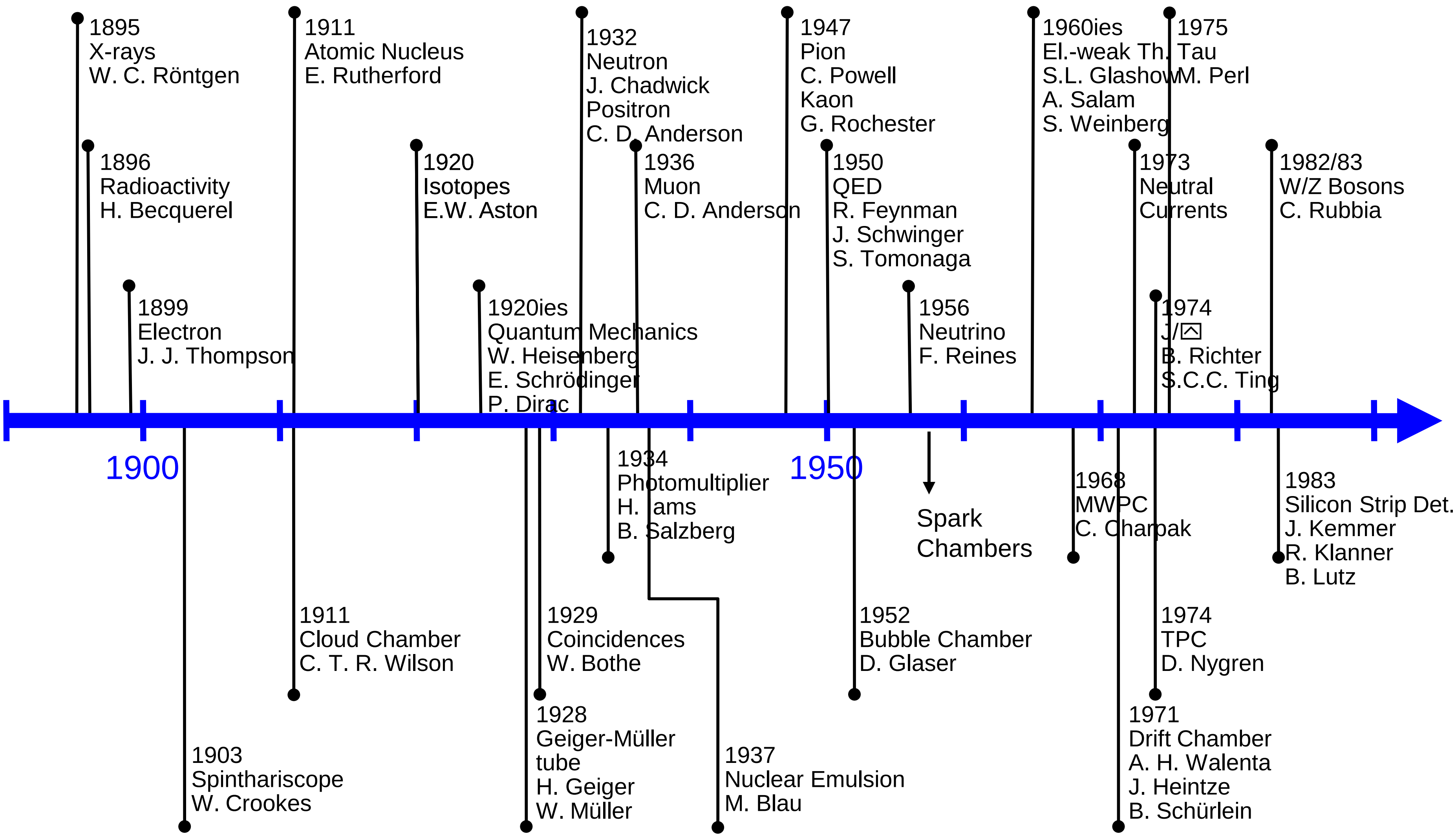
- Ionization - “free” charge
- Scintillation - “free” light
- Cherenkov radiation
- Transition radiation
- Magnetic induction
- Phonons, acoustic, heat
- ....?

- Energy
- Momentum
- Velocity
- Trajectory direction
- Particle identification
- Charge
- Patterns
- Causality
- Time

Epochs: A Century of Punctuated Equilibria

- First discoveries - "Bronze age"
  - many particles inducing visible signals
- Single particle detection - "Age of discovery"
  - large amplification achieved
- Complex event reconstruction - "Golden age"
  - tracking, energy measurements, particle ID
- Present era - *megalithic age?*
  - **huge**: data bases, systems, sophistication

Timeline of Particle Physics and Instrumentation



QuickTime™ and a
decompressor
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“Spinthariscope”

- “In 1903, while observing the apparently uniform fluorescence on a zinc sulfide screen created by the radioactive emissions (mostly alpha radiation) of a sample of radium, William Crookes spilled some of the radium sample, and, owing to its extreme rarity and cost, he was eager to find and recover it. Upon inspecting the zinc sulfide screen under a microscope, he noticed separate flashes of light created by individual alpha particle collisions with the screen. Crookes took his discovery a step further and invented a device specifically intended to view these scintillations. It consisted of a small screen coated with zinc sulfide affixed to the end of a tube, with a tiny amount of radium salt suspended a short distance from the screen and a lens on the other end of the tube for viewing the screen. Crookes named his device after the Greek word 'spintharis', meaning "a spark".”
- \- from Wikipedia

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Opera's First Tau Neutrino Event -

July 2010

arXiv:1006.1623v1

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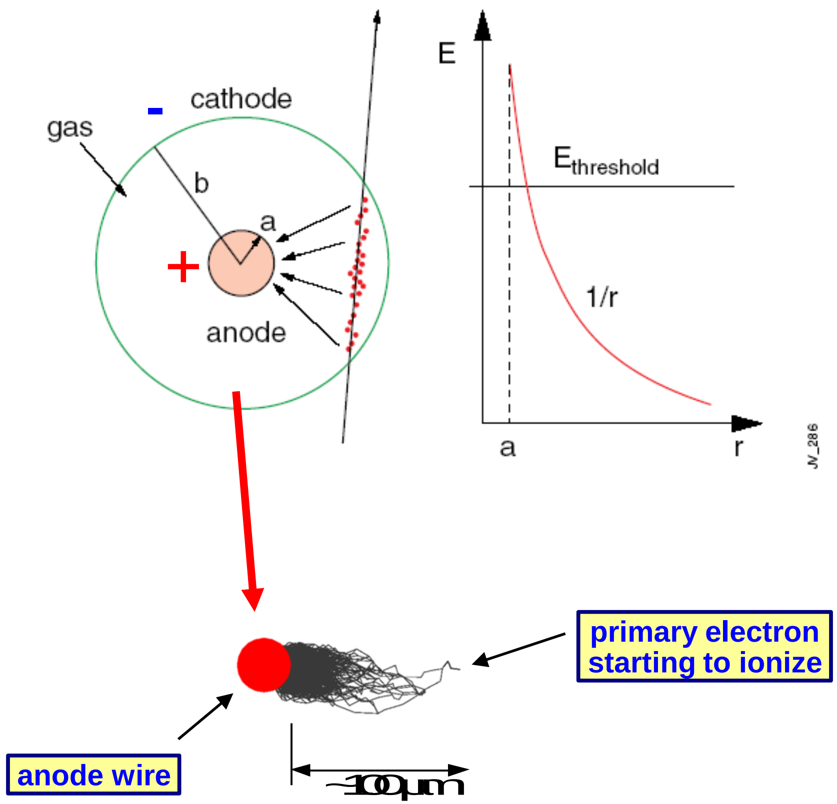
Geiger-Müller Tube

- The Geiger-Müller tube (1928 by Hans Geiger and Walther Müller)
  - Tube filled with inert gas (He, Ne, Ar) + organic vapour (alcohol)
  - Central thin wire (20 – 50 µm ⌀) , several 100 Volts between wire and tube



- **Strong increase of E-field close to the wire**
  - **electron gains more and more energy**
- **above some threshold (>10 kV/cm)**
  - **electron energy high enough to ionize other gas molecules**
  - **newly created electrons also start ionizing**
- **avalanche process: exponential increase of electrons (and ions)**
- **measurable signal on wire**
  - **discharge spreads along length of wire**
  - **proportional mode: no spreading**

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Photo Multiplier Tubes (PMT)

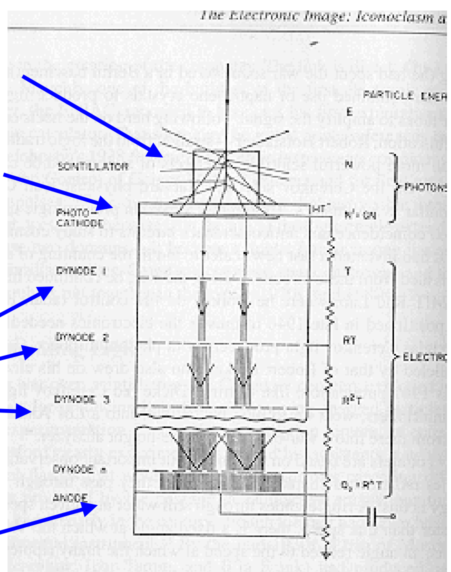
- Invented in 1934 by Harley Iams and Bernard Salzberg (RCA)
  - based on photo effect and secondary electron emission
  - sensitive to single photons, replaced human eye + belladonna at scintillator screen
  - ➜ first device had gain ~8 only, but already operated at >10 kHz
  - ➜ (human eye: up to 150 counts/minute for a limited time)
  - nowadays still in use everywhere, gain up to 10^8
  - recent developments: multi-anode (segmented) PMTs, hybrid and pure silicon PMs

plastic scintillator

photo cathode

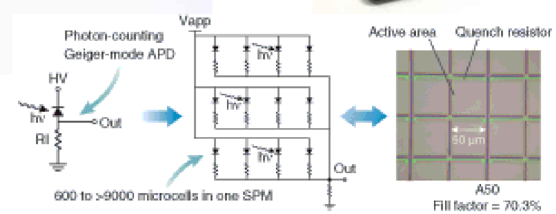
dynodes: secondary electron emission

anode



classic PMT

Silicon PM = array of avalanche photo diodes



H. Friedman, *Proc. Institute of Radio Engineers* **37** (1949)

Multi-wire common-enclosure geometries!

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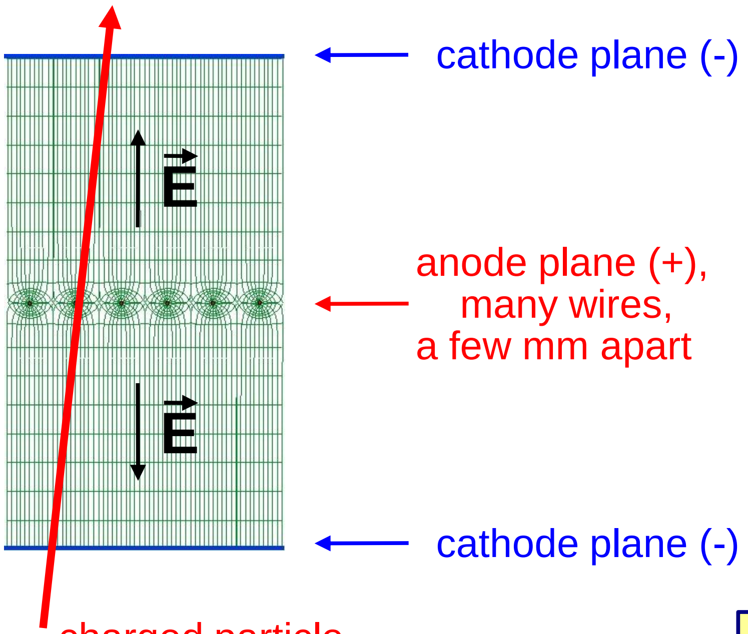
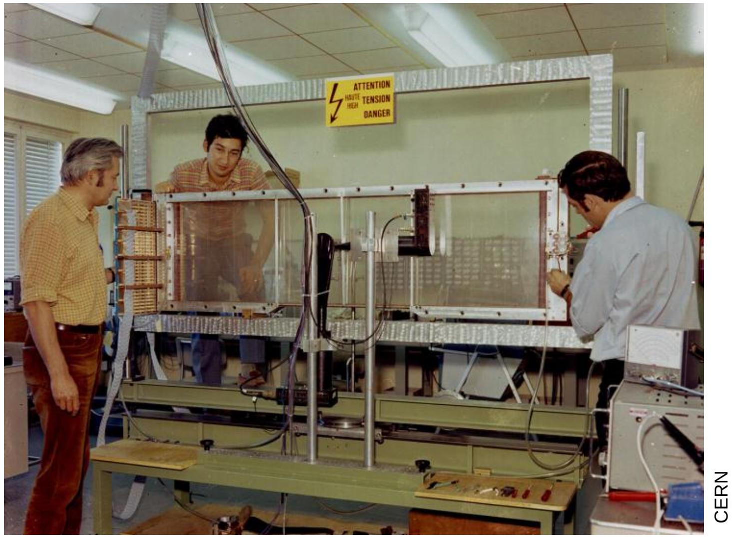
Multi Wire Proportional Chambers

Georges Charpak

- Geiger-Müller tube: Long recovery times for ions to clear
- Multi Wire Proportional Chamber (MWPC) 1968 by Georges Charpak,
- Nobel Prize 1992
  - put many wires close together with individual signal circuits
  - short distance between two parallel plates





Georges Charpak, Fabio Sauli and Jean-Claude Santiard

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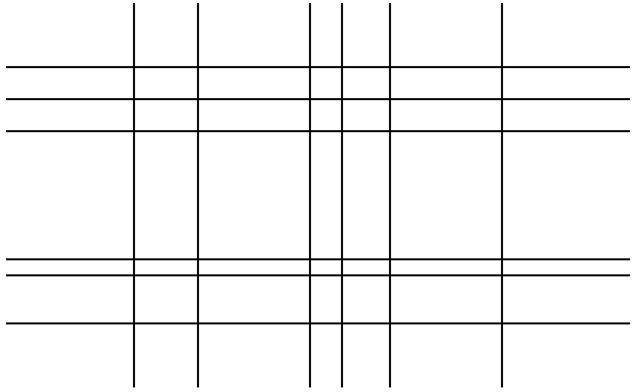
The dreaded N^2 ambiguity

- Suppose you have a detector (MWPC,...) that measures separately the x and y coordinates of tracks.
- If N tracks appear simultaneously, then you have N x coordinates, and also N y coordinates. You have N^2 possible combinations of <x,y>.



- *Which are the right ones?*

The N^2 ambiguity resolved?

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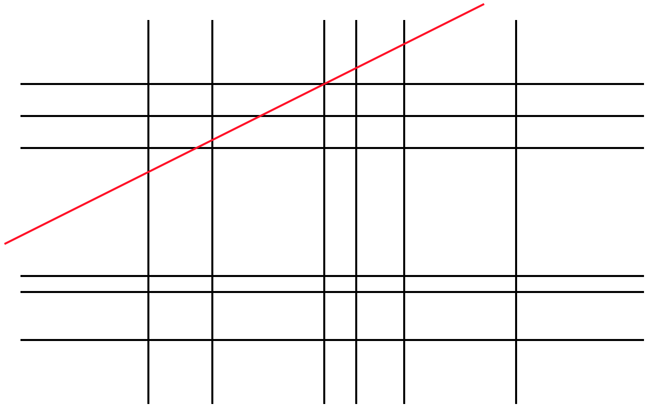

- *Which are the right ones?*
- *Unpleasant for N > ~10*
- *Anguish rises ~ N^3 ?*

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E x B ≠ 0 ⇒

Track distortion!

“Particle Detection with Drift Chambers”, Blum, Riegler, Rolandi

Wade Allison 1972 - Identification of Secondaries by Ionization Sampling -

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A rectangular box 5m long, 2m wide and 4m high, filled with argon-CO_2 at one bar pressure.

320 samples of ionization yielded 7.4% FWHM dE/dx resolution

DAQ:

Store pulse height and time whenever threshold is crossed

Origins of the TPC idea

- February 1974: **Complete frustration**, while trying to conceive a detector concept for SPEAR, an electron-positron collider at SLAC.

- Epiphany #1: if electric drift field is parallel to B,
  - then E x B distortion of tracks becomes negligible...!
- Epiphany # 2: Spark chamber tracks brighter, narrower when B-field on... !
  - Maybe diffusion transverse to fields is suppressed...?
  - $\sigma = (2DT)^{1/2}$
  - $D_m = D/(1 + (\omega\tau)^2)$ (Thompson ~1900) ω is cyclotron frequency, τ is mean collision time
  - can $\omega\tau >> 1$?

Revelation

- In argon and methane, a sharp minimum exists in the electron-atom cross-section at ~0.25 eV; this is Ramsauer-Townsend effect.
- This leads to a very large τ; hence $\omega\tau >> 1$

  Example: PEP-4 TPC B ~ 1 T
  8.5 bars Ar/CH_4 (80/20)

  D reduced by ~two orders of magnitude with B field on!

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- Quantum mechanics in action!

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Electronic Advances - 1970's

- Scene: TPC HQ (1975)
  - TPC provides superb information arriving at sectors...
  - Too many pad channels to use discrete S/H circuits!
  - How to read out the complex events foreseen at PEP?
- Idea: Let's try continuous waveform sampling - !?
  - Can we use new-fangled charge-coupled device (CCD)?
  - Linear array for delay-line applications existed (**Fairchild**)
  - Capture information at **super-high**-rate: 10 MHz
  - Digitize captured analog information <1 MHz when trigger occurs
  - When clock frequency switched, CCD device didn't work!
  - Fairchild graciously redesigned the internals to avoid "corners"
  - An enabling technology - essential to ultimate success of PEP-4.

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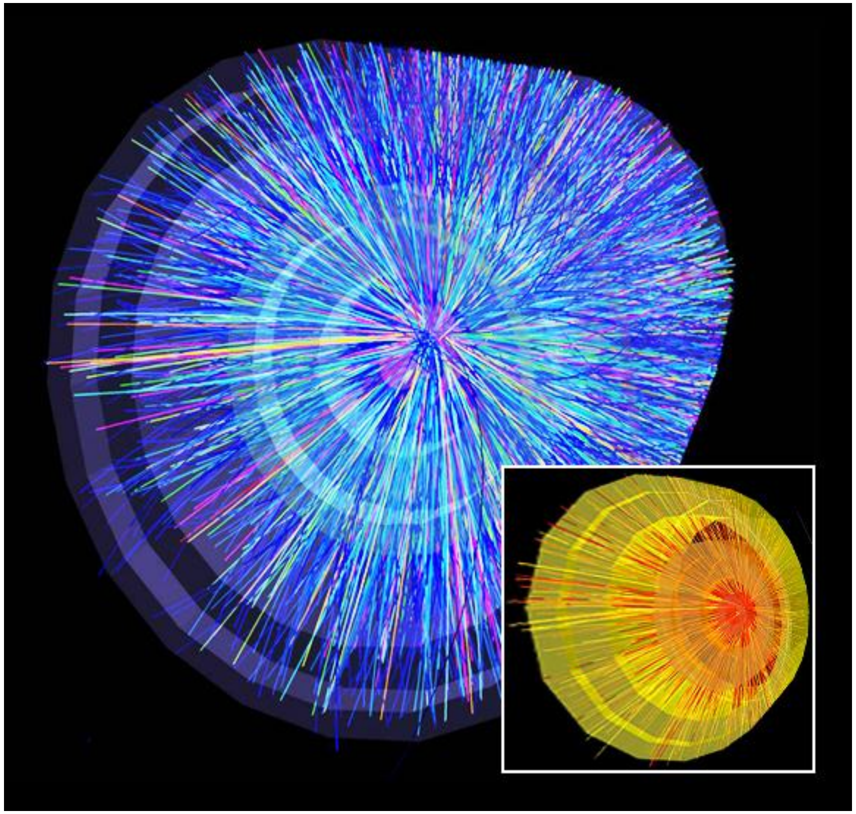
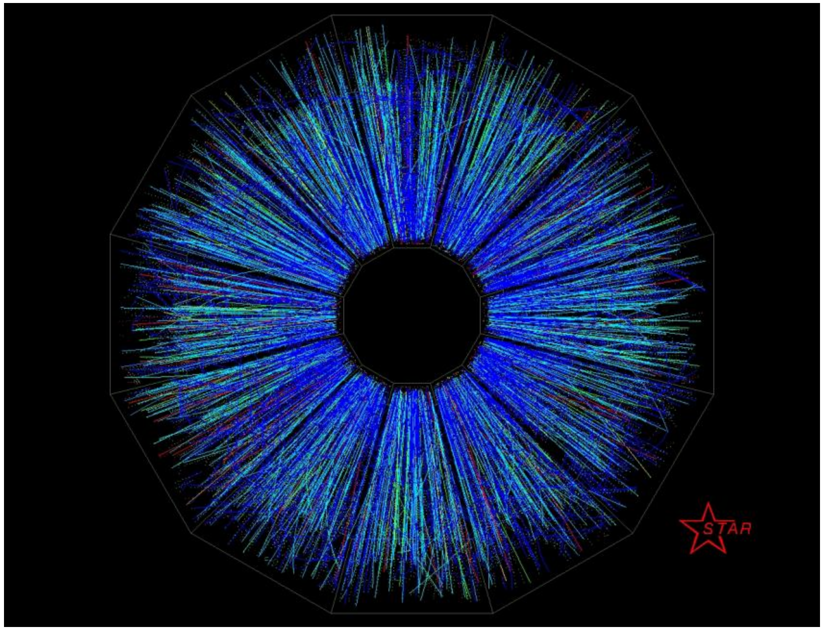
Large TPCs in action today





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IceCube at the south pole - megalith #1

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How to go from AMANDA - a centralized analog DAQ - to a DAQ based on a low-power decentralized digital network?

Wanted: 14-bit 400MHz ADC

Digital Optical Module (DOM)

86 strings completed 5000 DOMs in January 2011

~2 ns rms resolution over 1km^3 volume, 99% alive

A prime example of functional devolution (decentralization) made possible by electronic advances.

(1996): Why not use Stuart Kleinfelder's new ASIC?

Analog Transient Wave Recorder (ATWR)

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decompressor
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Stuart's Master's thesis, UCB

***

Switched-capacitors: **low power**

Three input channels

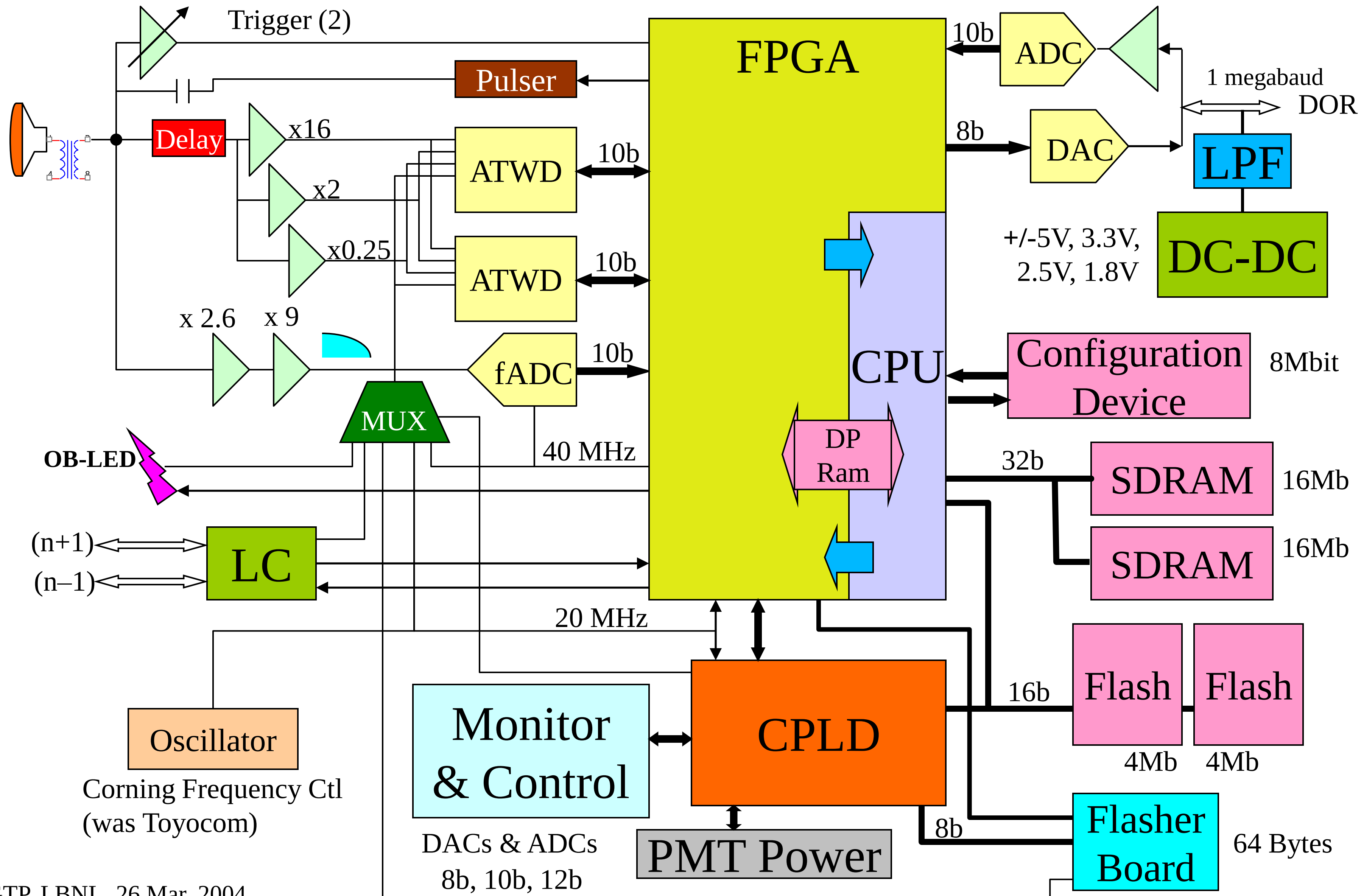
256 samples per channel

synchronous sampling: variable from 200 - 1000 MHz!

10 bit S/N, *but:* No internal ADC!

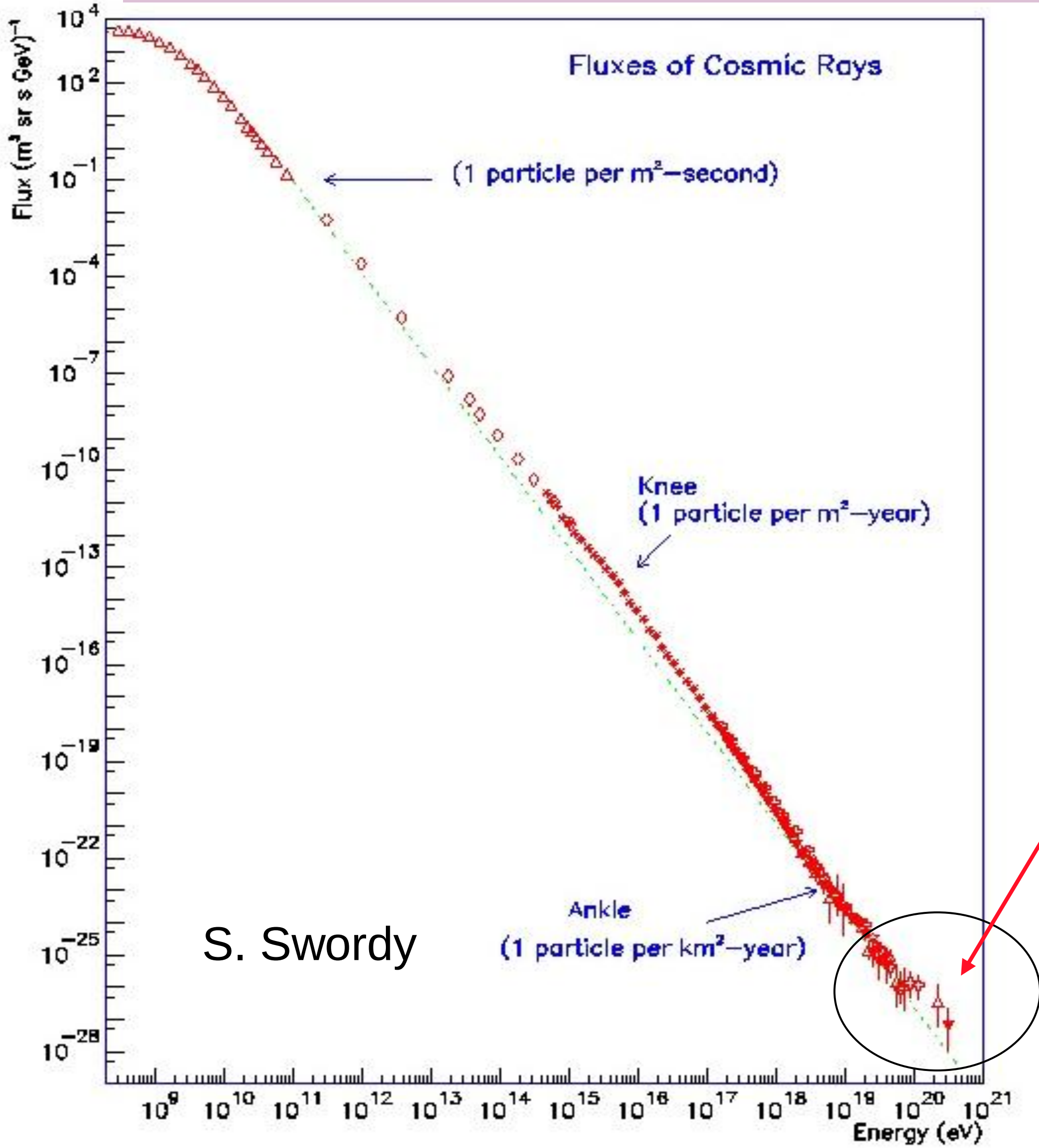
Stuart adds internal ADC - ready!

Digital Optical Module Block Diagram



GTP, LBNL, 26 Mar, 2004

Cosmic ray flux vs. Energy - megalith #2



- (nearly) uniform power-law spectrum spanning 10 orders of magnitude in E and 32 in flux!

- structures :

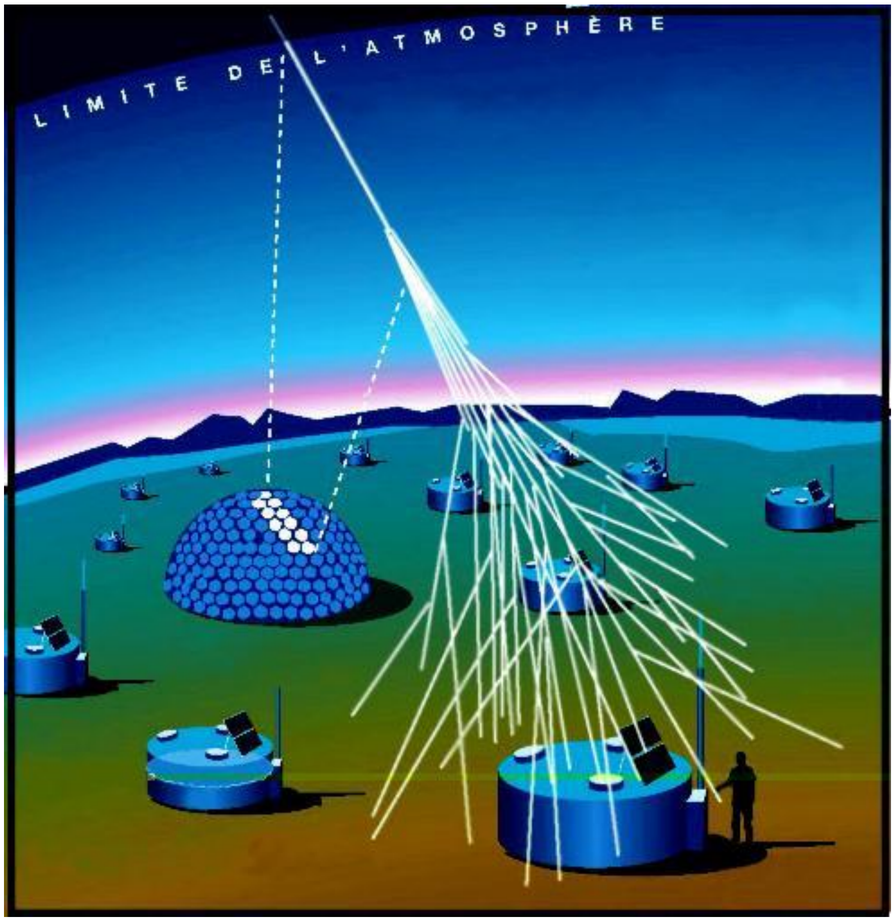
~ 3 – 5 10^{15} eV: knee
change of source? new physics?
~ 3 10^{18} eV: ankle
transition galactic – extragalatic?
change in composition?

UHECR!

- **One particle per century per km²!**
- Many interesting questions!

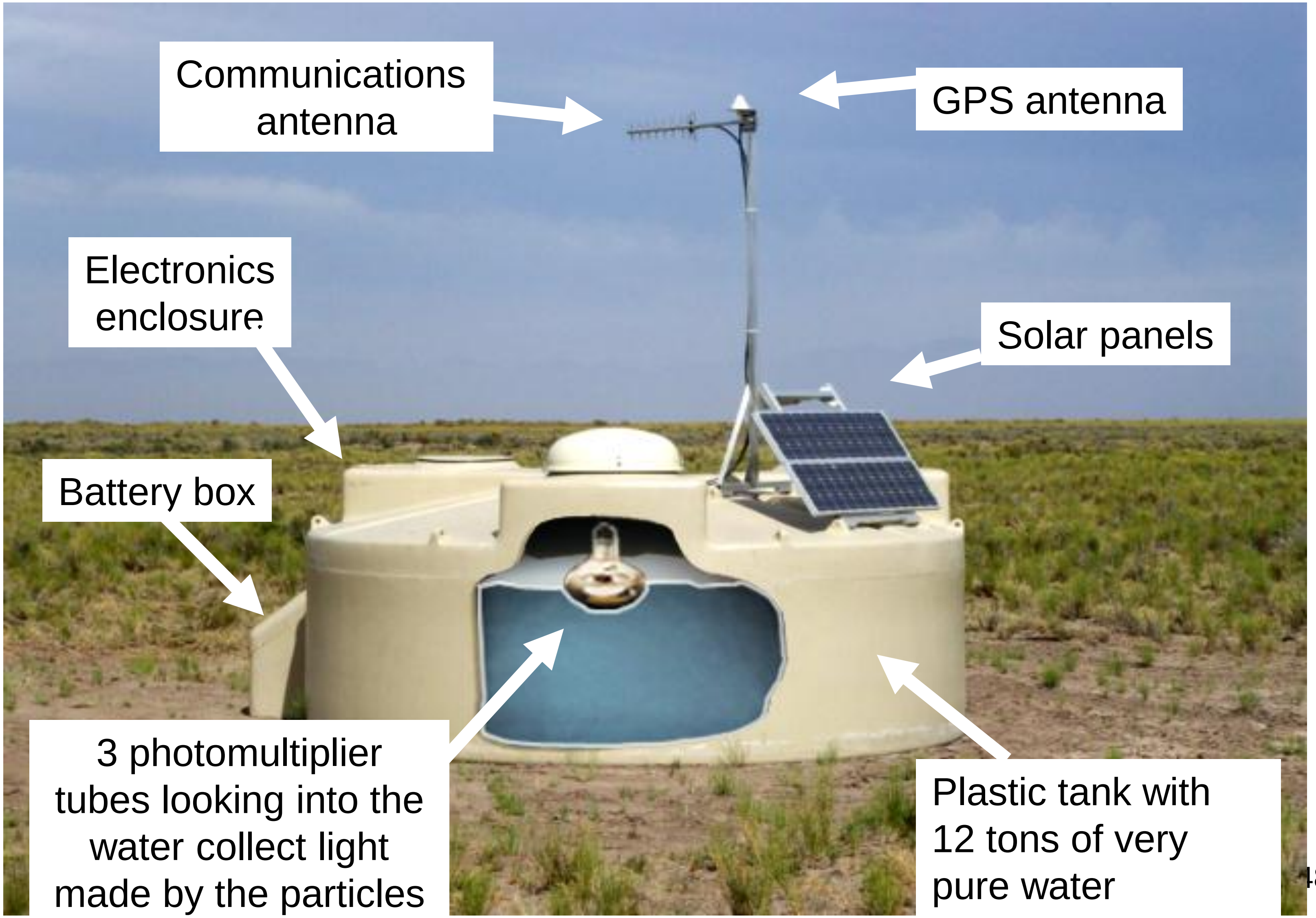
- Pierre Auger Observatory shows how **functional devolution** makes it possible to study rare processes

The Auger Observatory: Hybrid design

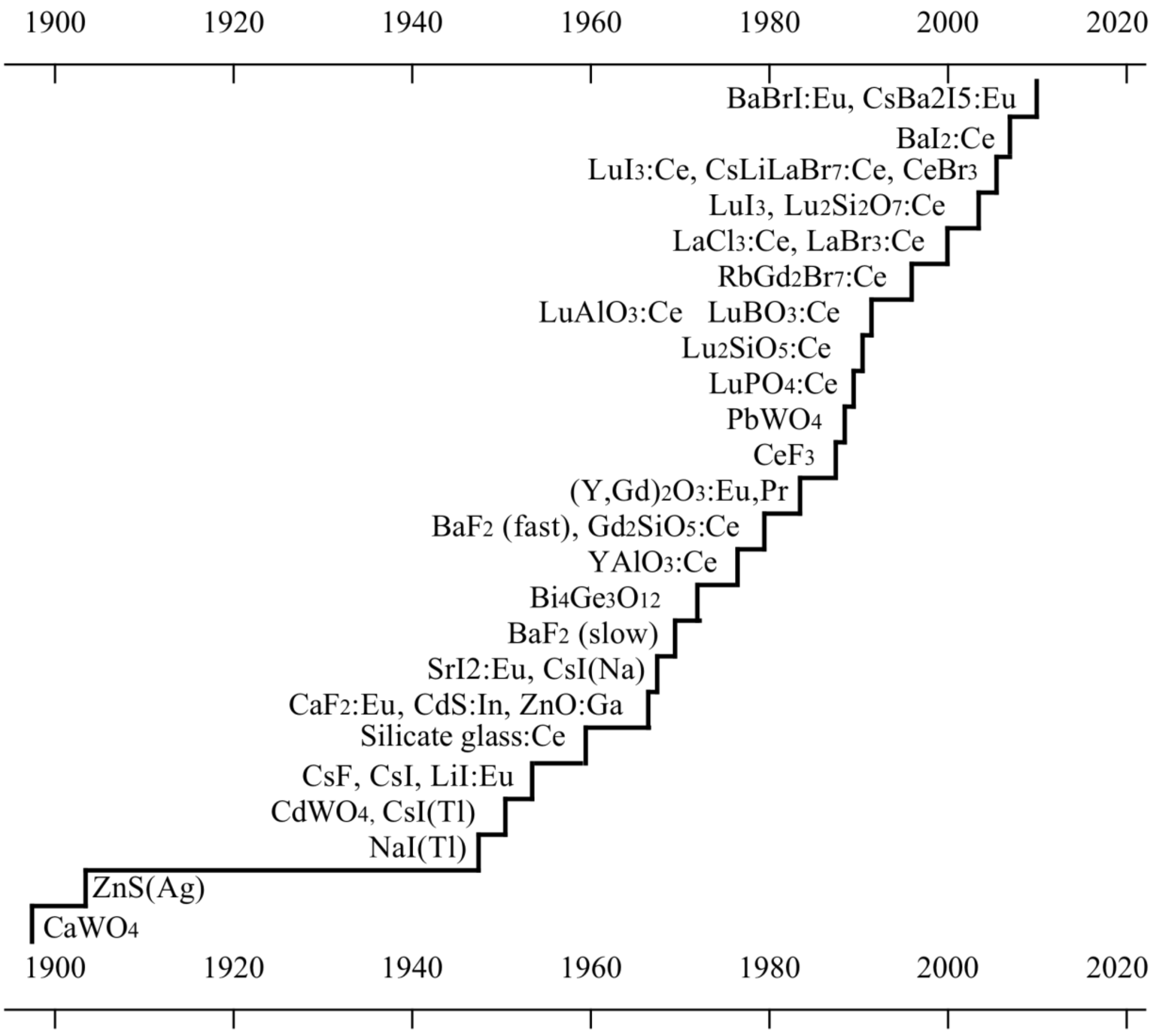


- A large surface detector array (1600 water tanks for Cherenkov light) combined with fluorescence detectors results in a unique and powerful design;
- Each tank operates as a stand-alone system for power, timing, and amplitude measurements, relayed by radio to central DAQ
- Simultaneous shower measurement allows for transfer of the nearly calorimetric energy calibration from the fluorescence detector to the event gathering power of the surface array.

Auger surface array station - devolution



History of Scintillation Materials



Hofstadter 1975 "25 Years of Scintillation Counting"

IEEE Trans Nucl Sci NS-22, 13-25, 1975

"For comparative studies of luminescence I prepared several samples of crystalline anthracene, naphthalene, a glaze of NaI(Tl), crystalline KI(Tl), NaCl(Tl), KBr(Tl), CaWO4, etc., and in the dark laid them all on a simple spectroscopic photographic plate nearby each other. Then I put the loaded plate in a thin card- board box after covering the assembly in black paper. I placed a radium source above the samples about one half a meter away and exposed the crystals for about a half hour. I then removed the source, shook off the powders or crystals and then developed and fixed the photographic plate in the usual way. To my great surprise and pleasure, the area under the former position of the NaI(Tl) powder was intensely black while that under the other samples, even under the KI(Tl), was hardly affected. At this point I suspected that I had produced something spectacularly good, but I did not yet know that the NaI (Tl) would scintillate, or produce flashes or pulses with a short decay time. Shortly afterwards I prepared a polycrystalline sample of NaI(Tl) in a 1/2" quartz test tube which was sealed off and protected the NaI(Tl) sample from air so that no deterioration could occur during experimentation or use of the crystal sample."

BGO: pay attention!

- **Marv Weber working at Raytheon on BGO:Nd laser material.**
- **At that time, Raytheon also interested in x-ray CT.**
- **Marv's best friend worked in the adjacent lab on CT.**
- **BGO placed in x-ray machine, luminescence observed.**
- **Publish paper on "Spectral and Luminescence Properties" in J. Appl. Phys. Only the final paragraph is on x-ray properties.**
- **Marv leaves Raytheon, does nothing more about BGO.**
- **Nestor & Huang at Harshaw read paper, grow BGO, measure scintillation properties, publish in IEEE TNS, …**
- **BGO dominates PET for >25 years.**

Serendipity and LSO

- **Chuck Melcher working at Schlumberger on new scintillators for well logging (fast, high-density, bright).**
- **Notices that P-47 phosphor (Y_2SiO_5:Ce) and GSO scintillator (Gd_2SiO_5:Ce) are fast and bright.**
- **Makes powders substituting Y/Gd with other trivalent atoms, as well as other metals (W, V, Ta,…) for Si.**
- **Bright signal observed in several samples.**
- **Crystals grown of brightest samples.**
- **Very good scintillation properties seen in crystalline LSO.**
- **Light output of first LSO crystals in top 10% of all LSO grown!**
- **All Siemens PET cameras sold since 2003 use LSO.**

Got Lucky on the First Sample!

Serendipity and $LaBr_3$:Ce

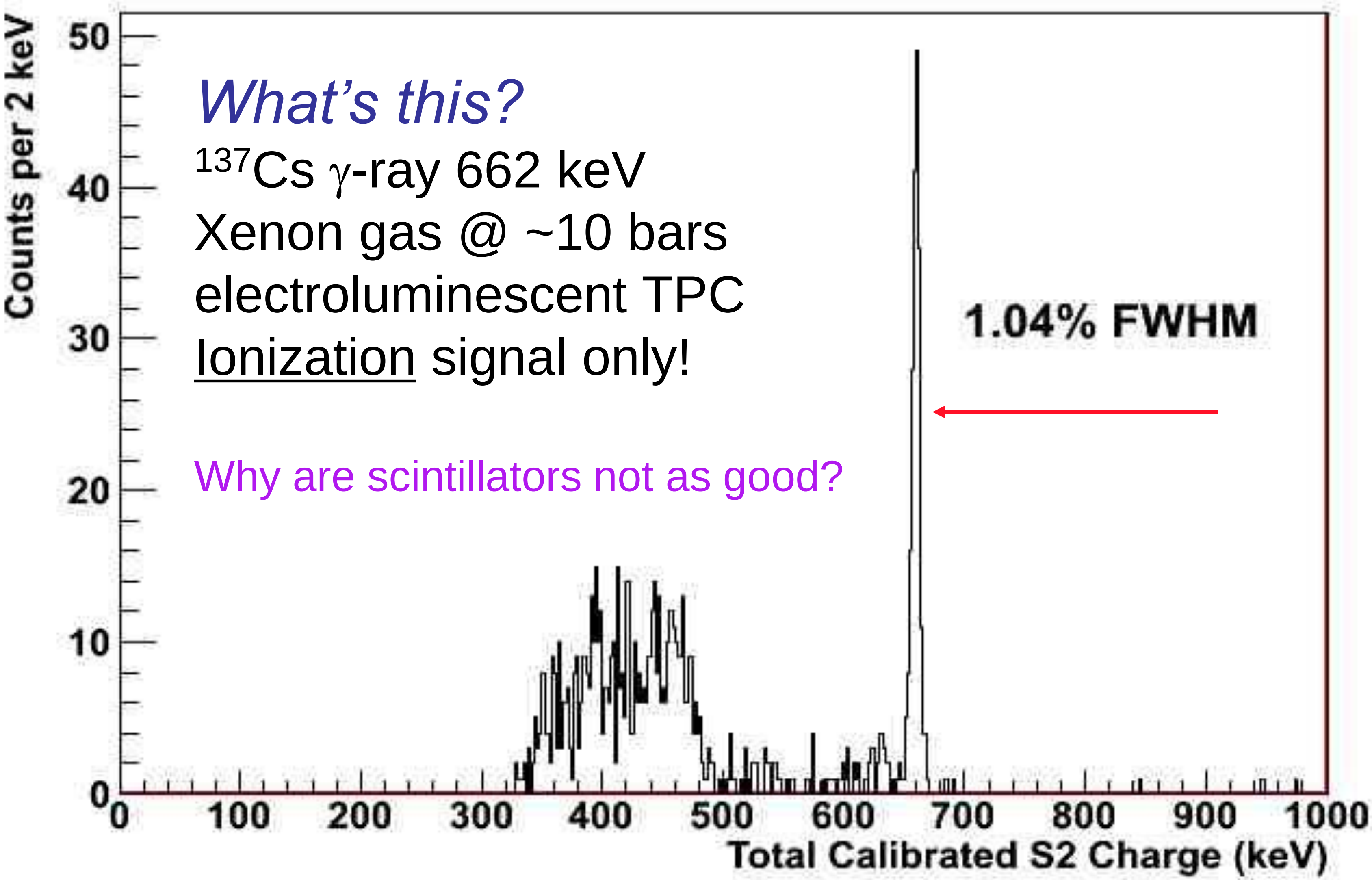
- **Derenzo & Moses working at LBNL on scintillator search.**
- **Purchase powder of $LaBr_3$ for testing.**
- **Powder is 99.9% pure.**
- **Remaining 0.1% very likely to have been Cerium.**
- **Material is hygroscopic, but Moses doesn’t realize this and doesn’t store sample properly.**
- **Sample absorbs water from atmosphere and “melts.”**
- **$LaBr_3$ sample discarded, but scintillation properties of 412 other samples are measured.**
- **$LaBr_3$:Ce discovered >10 years later by Delft group.**

Got Unlucky on the First Sample!

Top 5 Candidates vs. NaI(Tl)

Crystal	**$LaBr_3$:Ce**	**$Cs_2LiLaBr_6$:Ce**	**SrI_2:Eu**	**Ba_2CsI_5:Eu**	**BaBrI:Eu**		**NaI(Tl)**
Structure	Hexagonal	Cubic	Ortho-rhombic	Monoclinic	Ortho-rhombic		Cubic
Band Gap	6.2 eV	5.8 eV	5.4 eV	5.1 eV	5.3 eV		5.9 eV
Density	5.1	4.2	4.5	5.0	5.0		3.67
Decay time	17 ns	55 ns	1,200 ns	1,400 ns	500 ns		230 ns
Luminosity (ph/MeV)	60,000	60,000	100,000	97,000	87,000		42,000
Energy resolution @ 662KeV	2.8% (Delft)	3.0% (RMD)	3.0% (LLNL)	3.8% (LBNL)	4.3% (LBNL)		6-7%
Detection efficiency*	30%	26%	31%	36%	35%		23%

Energy resolution in xenon - rather nice!



What's this?

^{137}Cs γ-ray 662 keV

Xenon gas @ ~10 bars

electroluminescent TPC

Ionization signal only!

Why are scintillators not as good?

Xenon: Strong dependence of energy partition fluctuations on density!

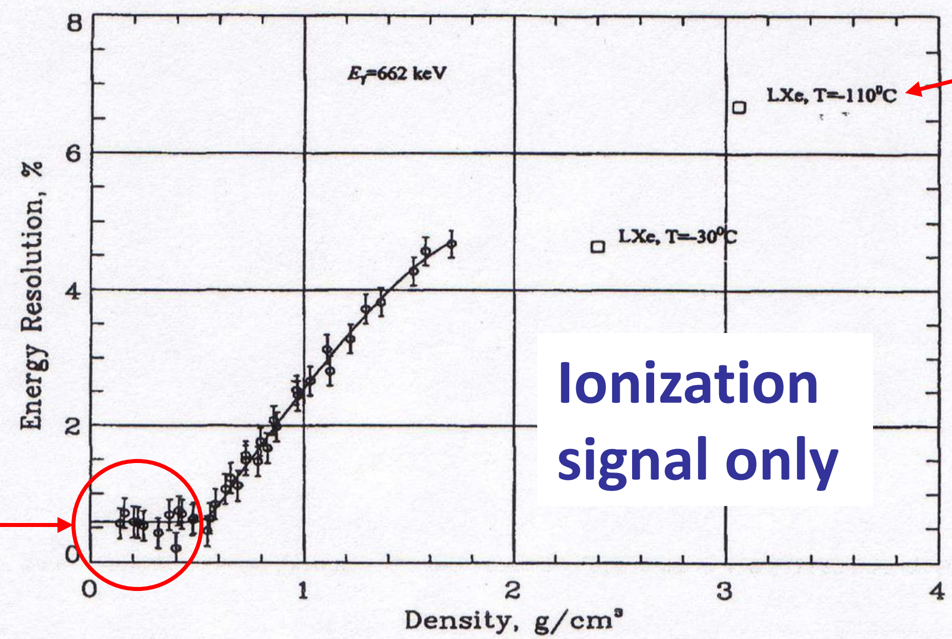


Fig. 5. Density dependencies of the intrinsic energy resolution (%FWHM) measured for 662 keV gamma-rays.

Here, the fluctuations are normal

Large fluctuations between light/charge at LXe density

⇒

DM: S2/S1 suffers!

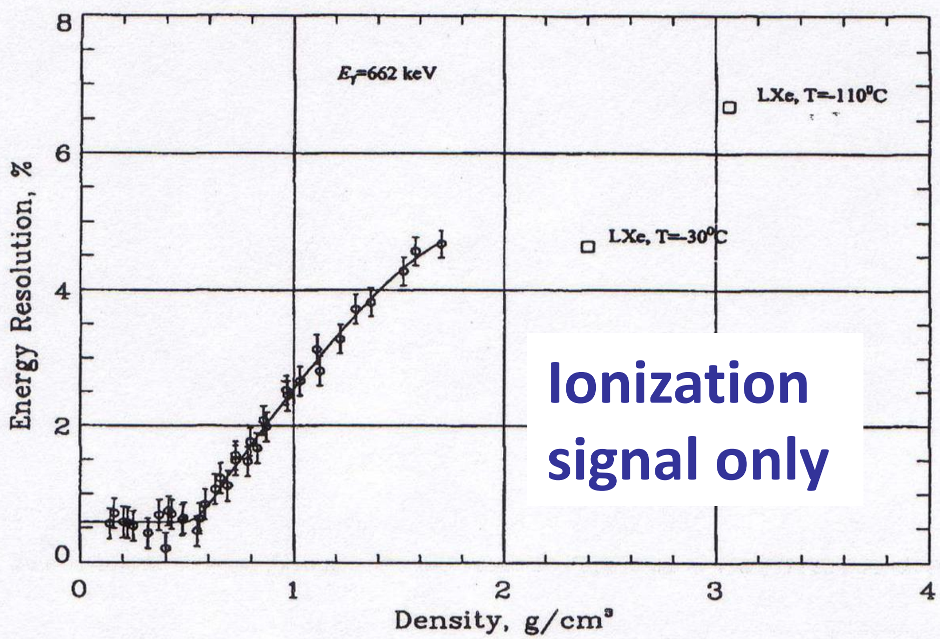
For ρ <0.55 g/cm^3, ionization energy resolution is “intrinsic”

Xenon: Strong dependence of energy partition fluctuations on density!

δ-rays display the Landau tail, making pockets of very high ionization densities; in LXe, conduction band promotes high recombination rate.

Statistics become highly non-Poisson

A. Bolotnikov, B. Ramsey / Nucl. Instr. and Meth. in Phys. Res. A 396 (1997) 360–370



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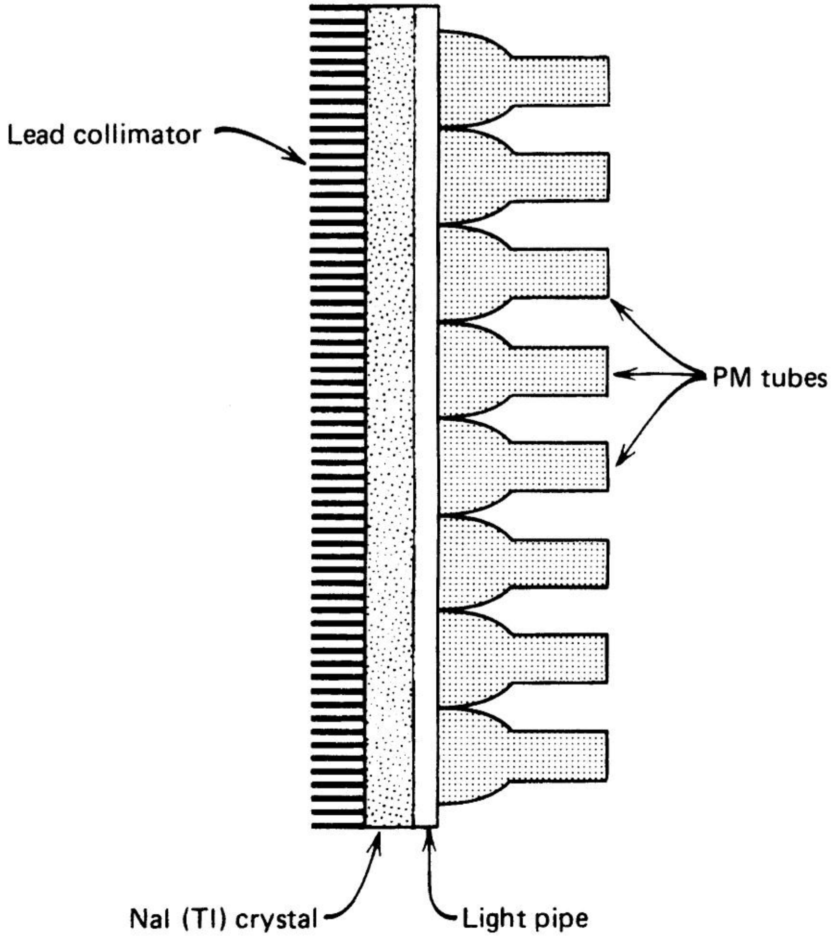
Application: Gamma Camera



Elements of a two-dimensional position-sensitive scintillation detector, commonly called a gamma camera.

Developed by Hal Anger during the 1950's at the E.O. Lawrence "Rad Lab" (now called LBNL)

This "Anger Scintillation Camera" can be found in almost every hospital in the world. Used with ^{99m}Tc for brain imaging and ^{201}Tl for heart imaging.

Another medical application

First <u>true</u> photon-counting mammography system in every-day clinical use.

Concept is based on slot-scan geometry with edge-on silicon-strips to get highest x-ray detection efficiency.

<u>Factor of >3 less dose</u>

Developed at LBNL, then commercialized by Sectra, Sweden, (now owned by Phillips). FDA approval for use in US very, very, very slow...

Bottom line - history...

- Why were some good ideas grasped so slowly?
- Easy pickings gone? - *Maybe*...
- Serendipity gone? - I don't think so!
- Where's the next great opportunity? ... your task!
- Know something beyond your computer screen!
- High-tech arena has taken the lead:
  - Semiconductor systems predominate today
  - Hybrid concepts provide new opportunities - Ingrid ...
  - Liquid state still advancing - Coupp ...
  - Cryogenic phenomena very fruitful
  - Complex megalithic systems prevail at frontiers
  - Find and befriend your exceptional rare engineer!

Perspective

- A century of curiosity-driven investigations has transformed society, as well as our field.
- From spinthariscopes, cloud, bubble, & spark chambers to ALICE, CMS, ATLAS, Auger, IceCube, xenon/argon, silicon, germanium, liquid, plastic, & inorganic scintillators, bolometric, radio wave, ..., the field of particle physics has been transformed by continuous innovation in the domain of instrumentation.

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- **Over to you!**

Thank you