



Workshop on the Long Term Strategy of INFN-CSN1.  
The next 10 years of accelerator based experiments

# New Detector Technologies

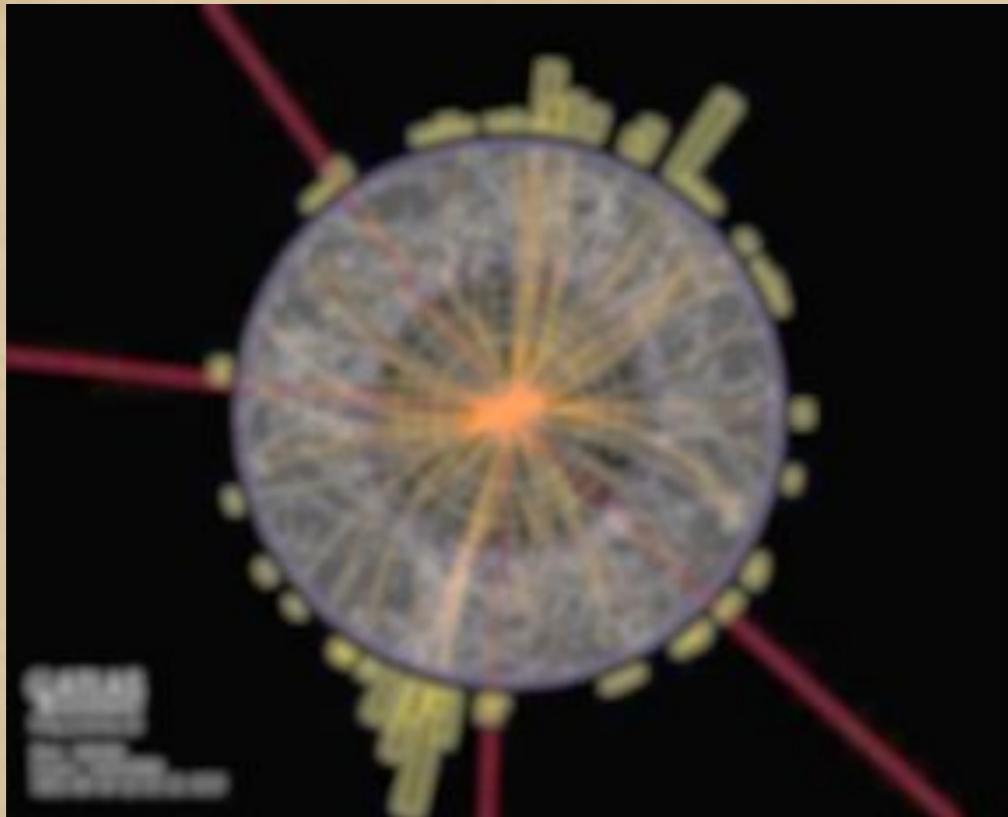


La Biodola, 22/5/2014

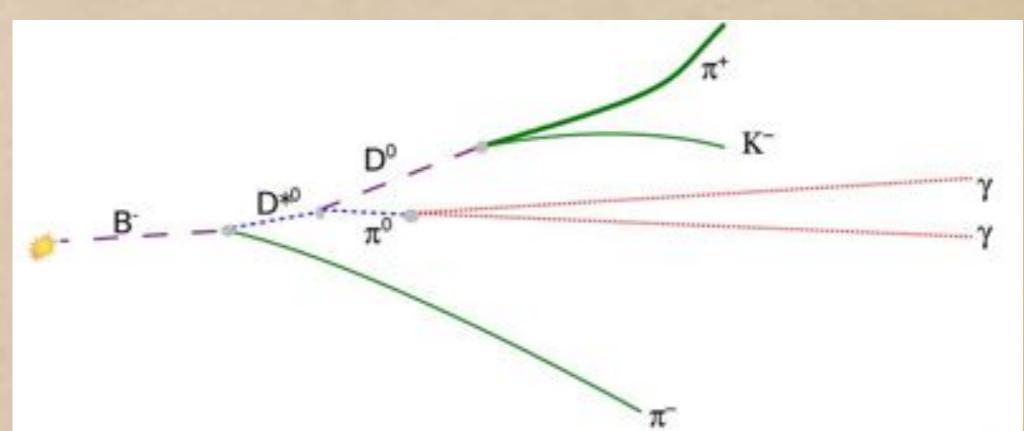
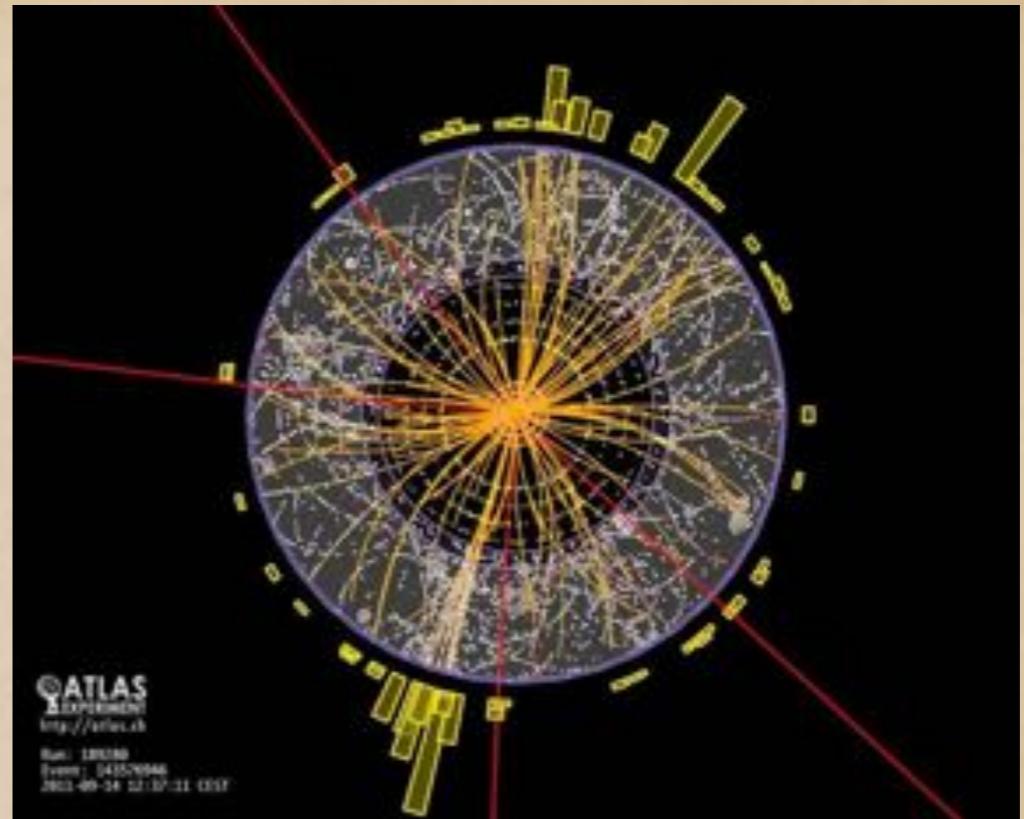
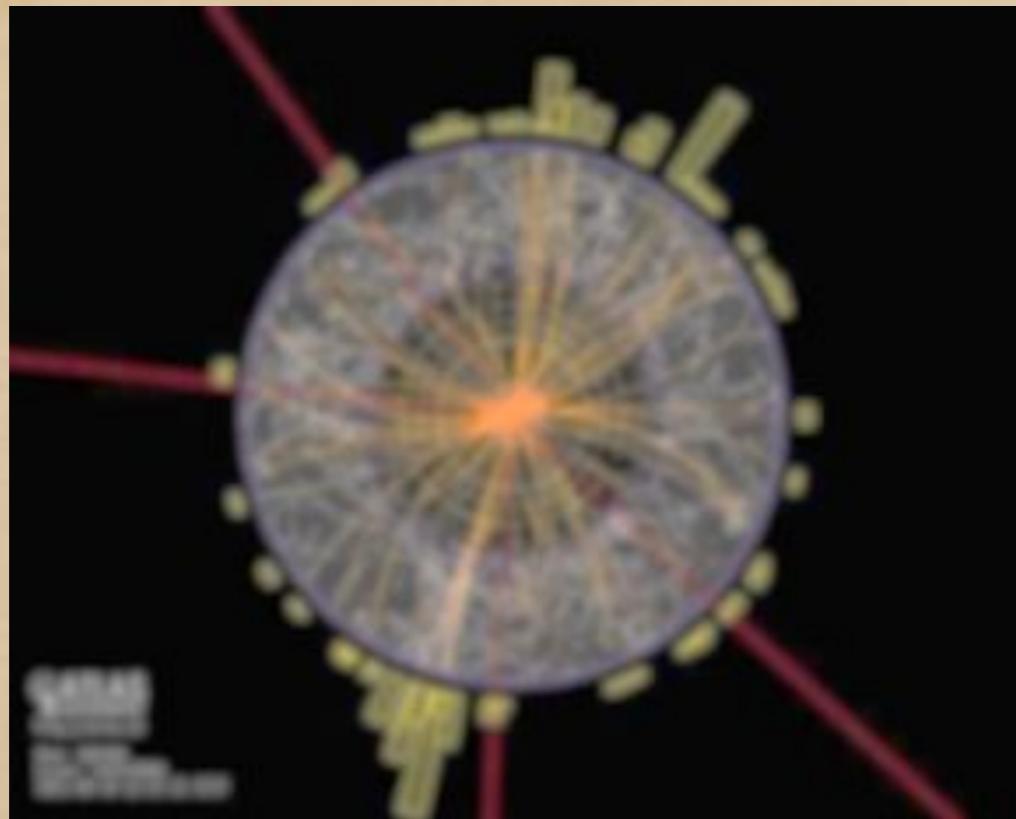
Francesco Forti

INFN and University, Pisa

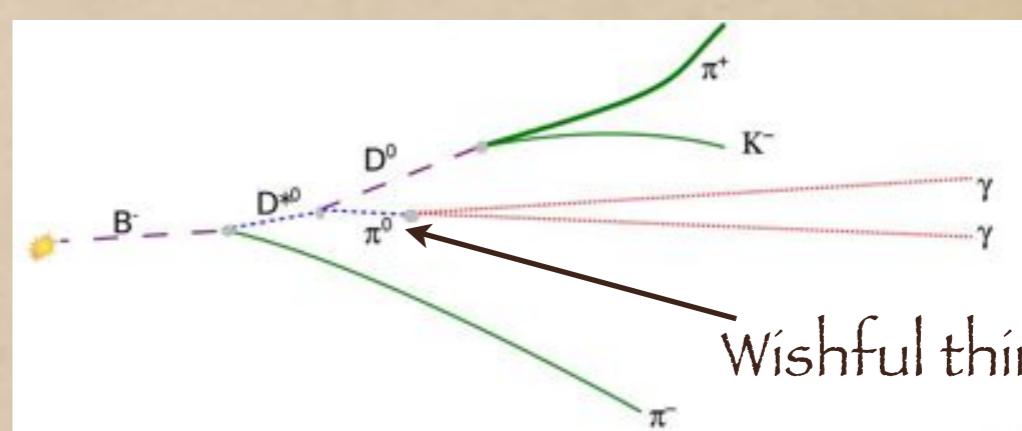
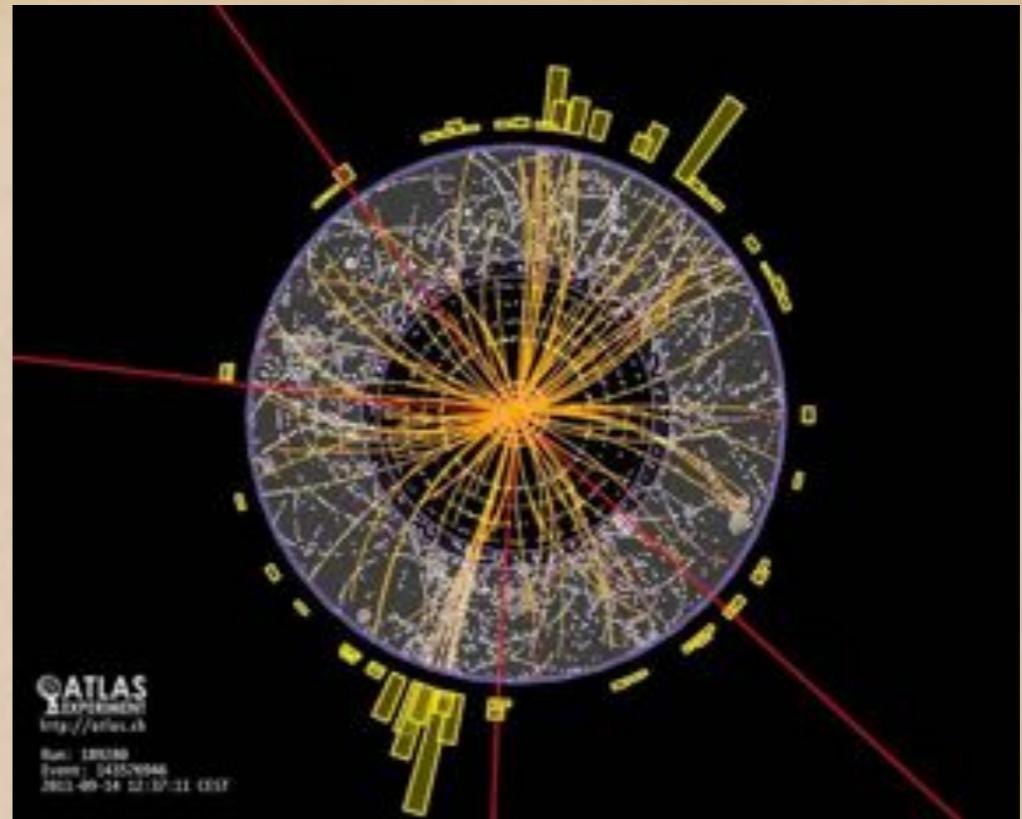
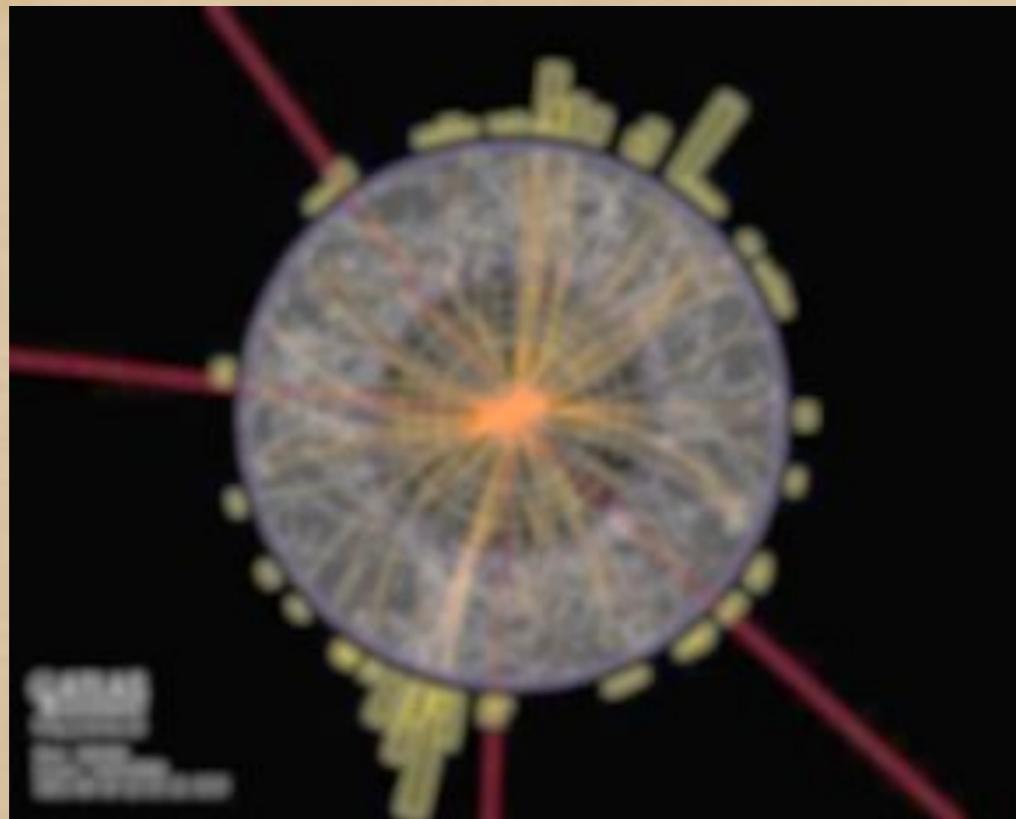




We need eyes to see



We need eyes to see



# We need eyes to see

# Frontier Detectors for Frontier Physics

Types of particles to detect

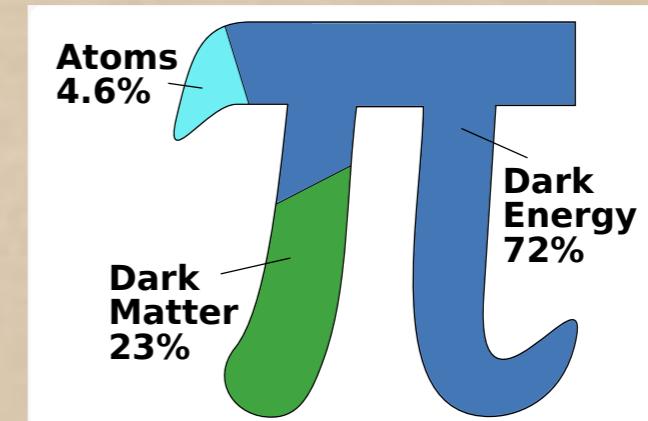
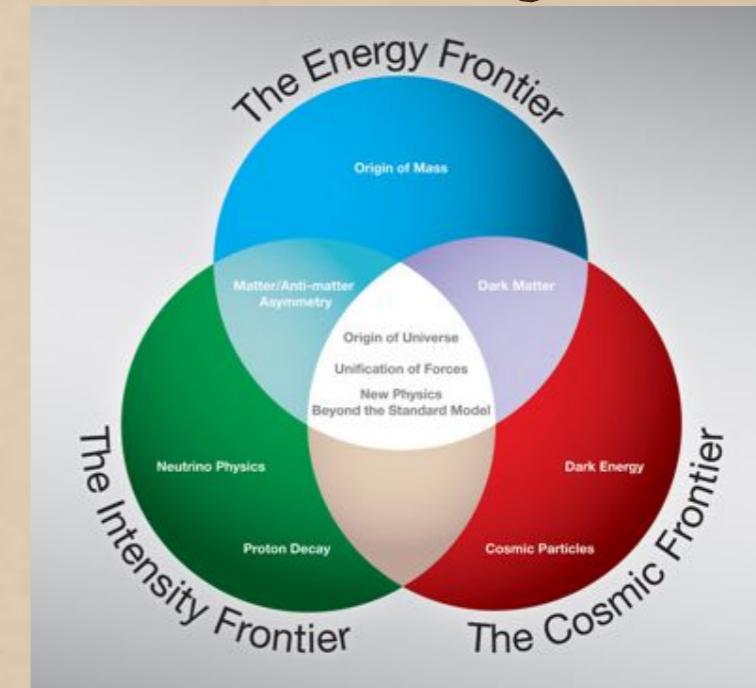
- ◆ Known knowns:  $e, \mu, \gamma, \pi, K, p, n, \dots$
- ◆ Known unknowns: DM, WIMPS, ...
- ◆ Unknown unknowns: ??????????

New detector technologies can open open new discovery horizons

New Idea  $\Rightarrow$  Research&Development  
 $\Rightarrow$  Engineering&Deployment



Technology and industry  
Applications and society

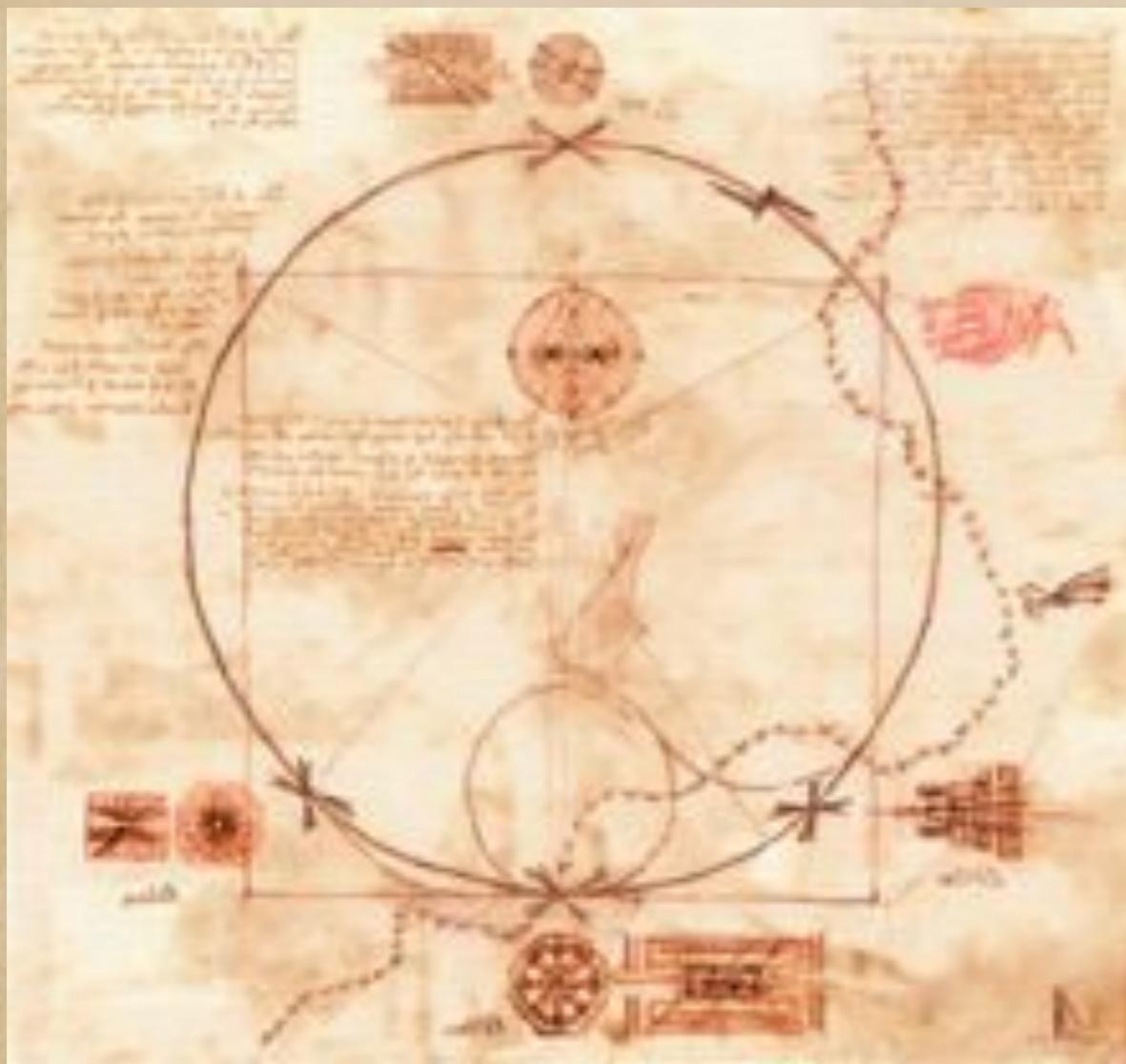


# Long R&D process

LHC ca. 1515 A.D.

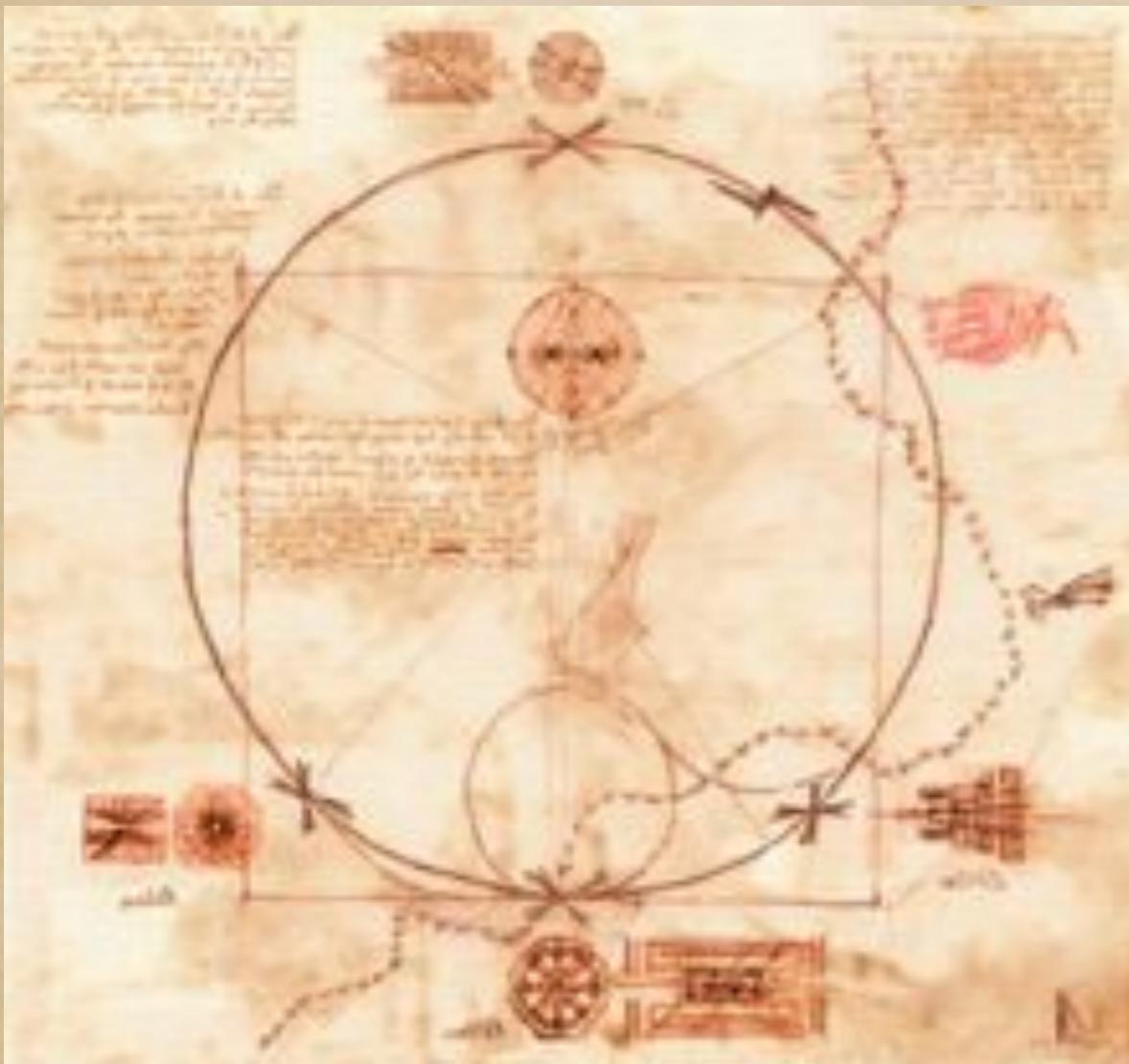
# Long R&D process

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# Long R&D process

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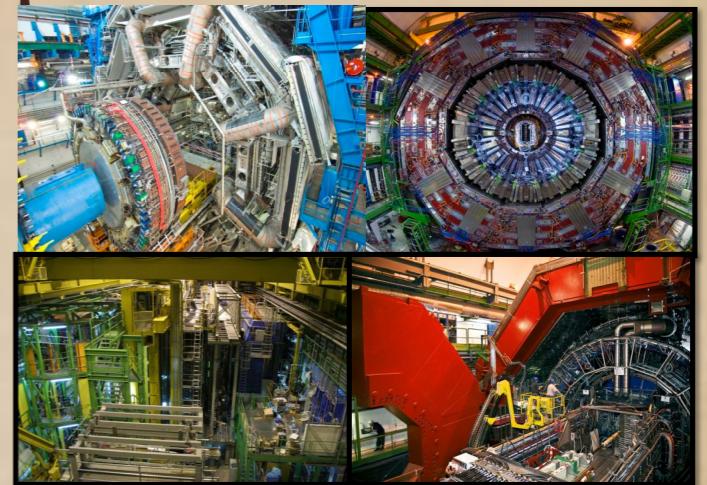


Very diverse R&D is required

# Very diverse R&D is required

## The Energy Frontier

- At LHC High Lumi, reduce granularity to less than 50um
- Develop Vertex detectors that withstand  $10^{16}$  n/cm<sup>2</sup>
- Develop trigger that can keep up with luminosity of  $10^{35}$
- At Lepton collider, obtain 4um point precision tracking
- Hadronic jet energy resolution of 30%/sqrt(E)



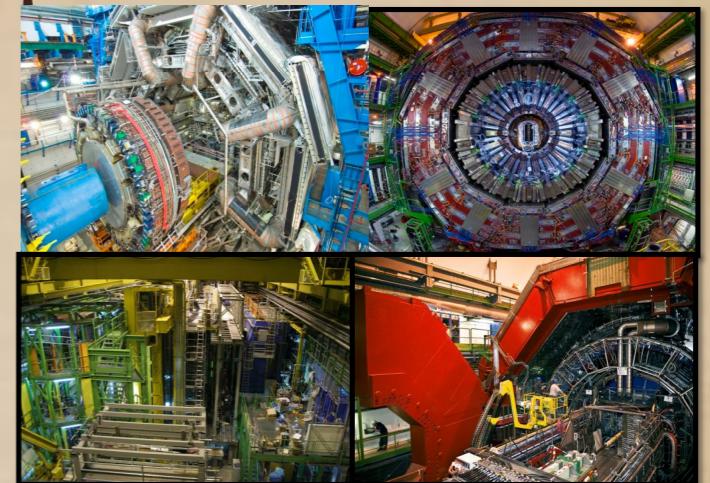
# Very diverse R&D is required

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## The Intensity Frontier

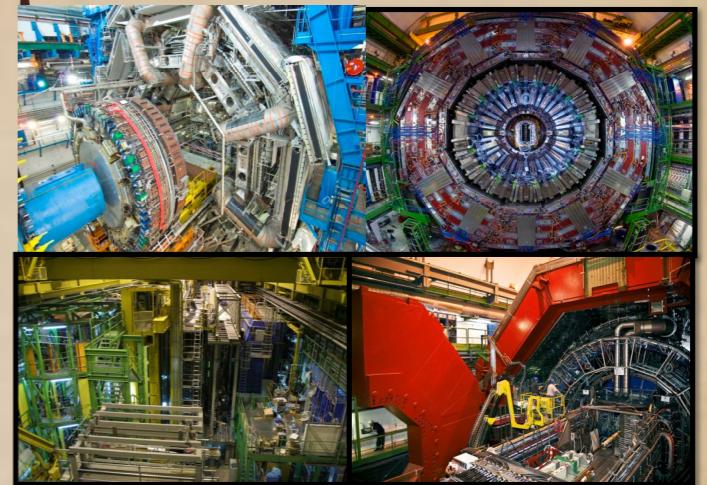
- Find a low-cost photodetector for 300kton water ( $10^5$  PMTs)
- Develop an robust and operable 20kton Argon TPC detector
- Develop ps level TOF techniques for rare decay tagging



# Very diverse R&D is required

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## The Cosmic Frontier

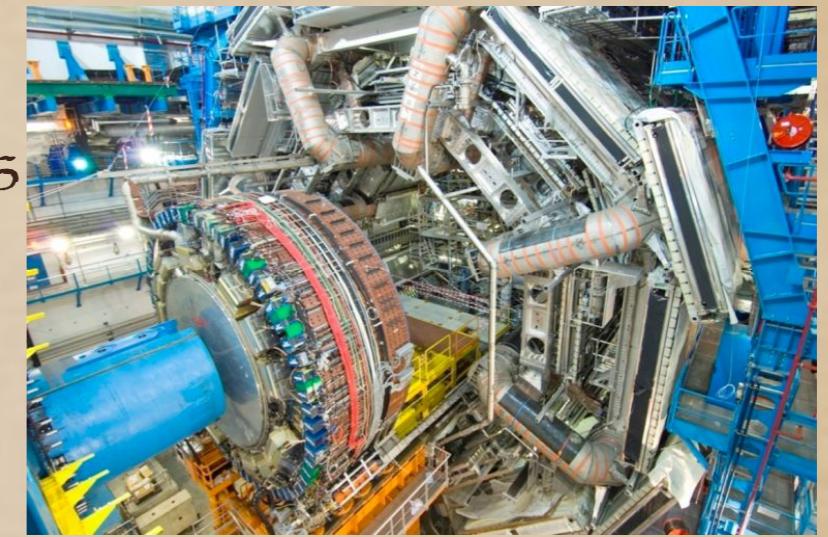
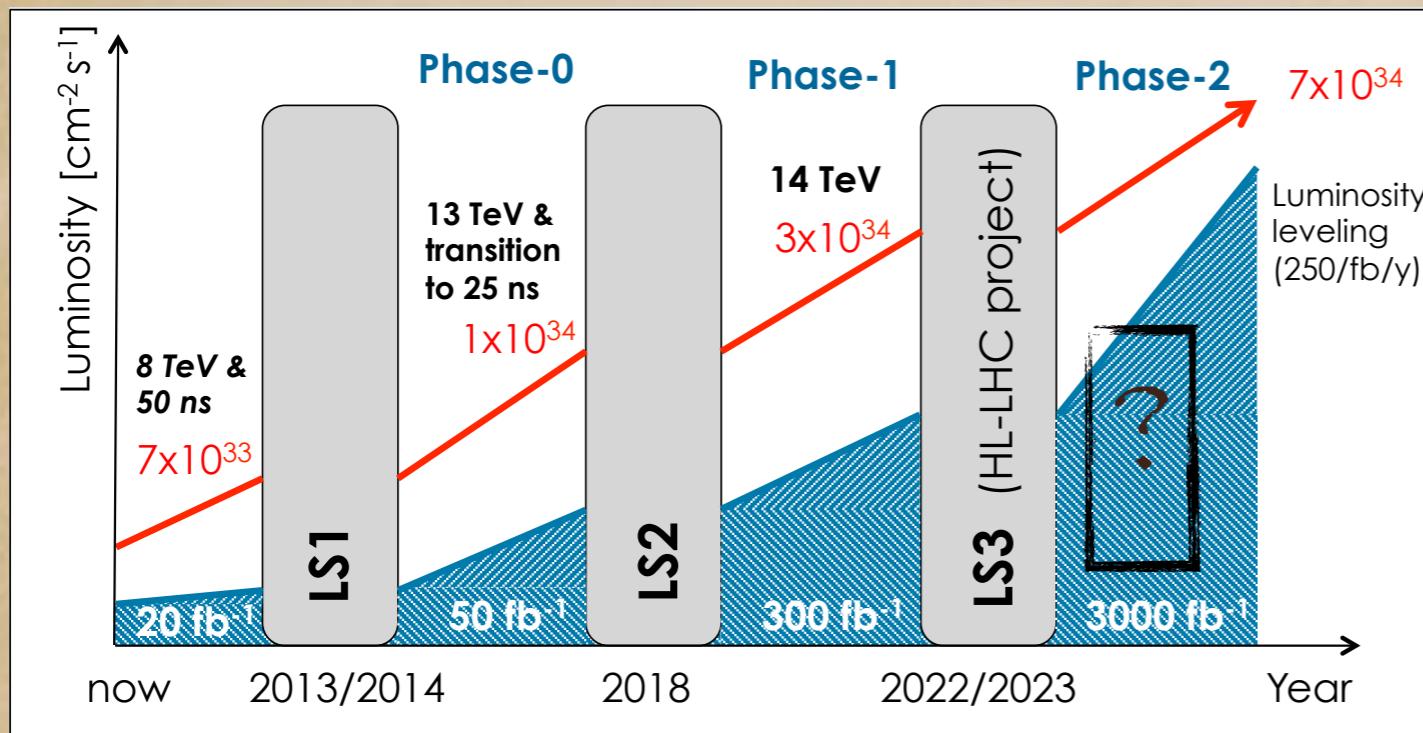
- Reduce background in DM detection to 1 nuclear recoil/ton/yr
- Develop different detection techniques for DM
- Expand the depth of observation in the galaxy to probe DE.



# The Energy Frontier

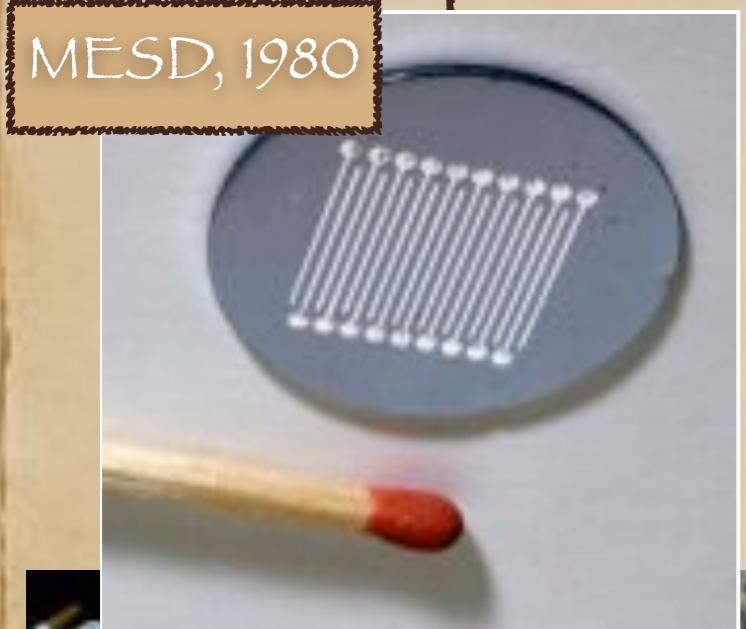
Admirable achievements

- ◆ LHC has driven in the past and is currently driving the R&D for detectors @ accelerators
- ◆ Phase-2 upgrades require significant R&D and the deployment of new detectors
- ◆ Pioneers of today will be workhorses of tomorrow !

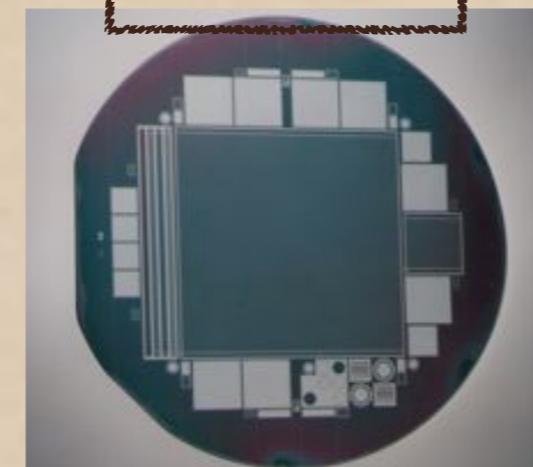


# Example: Semiconductor Strip Detectors

MESD, 1980



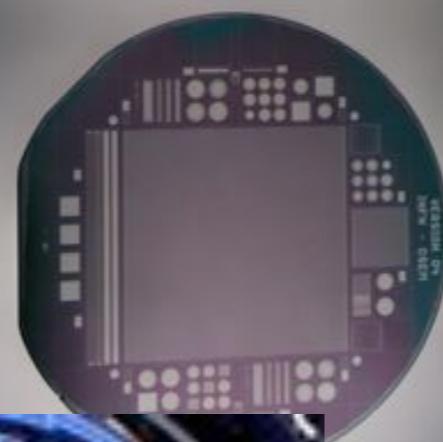
DSSD, 1986



ALEPH VDET, 1989



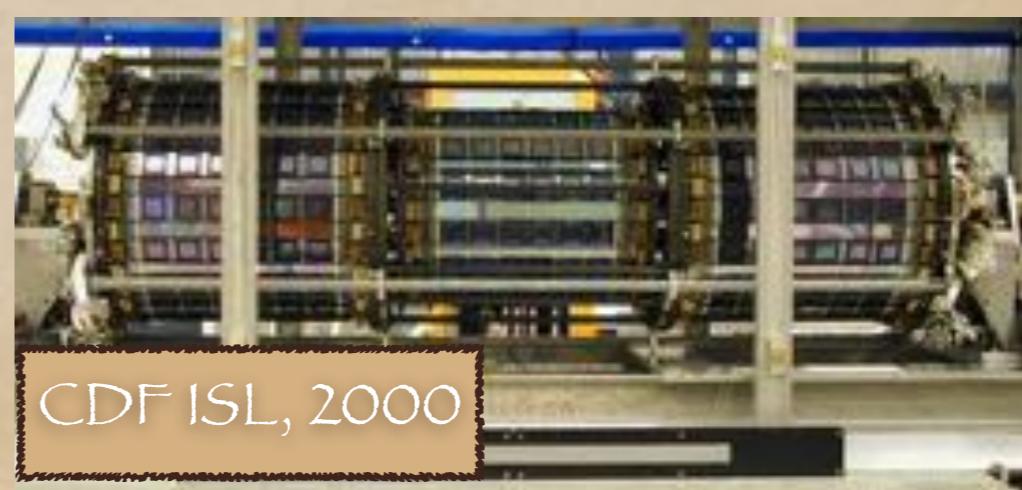
Fermi LAT, 2005



Babar SVT, 1999

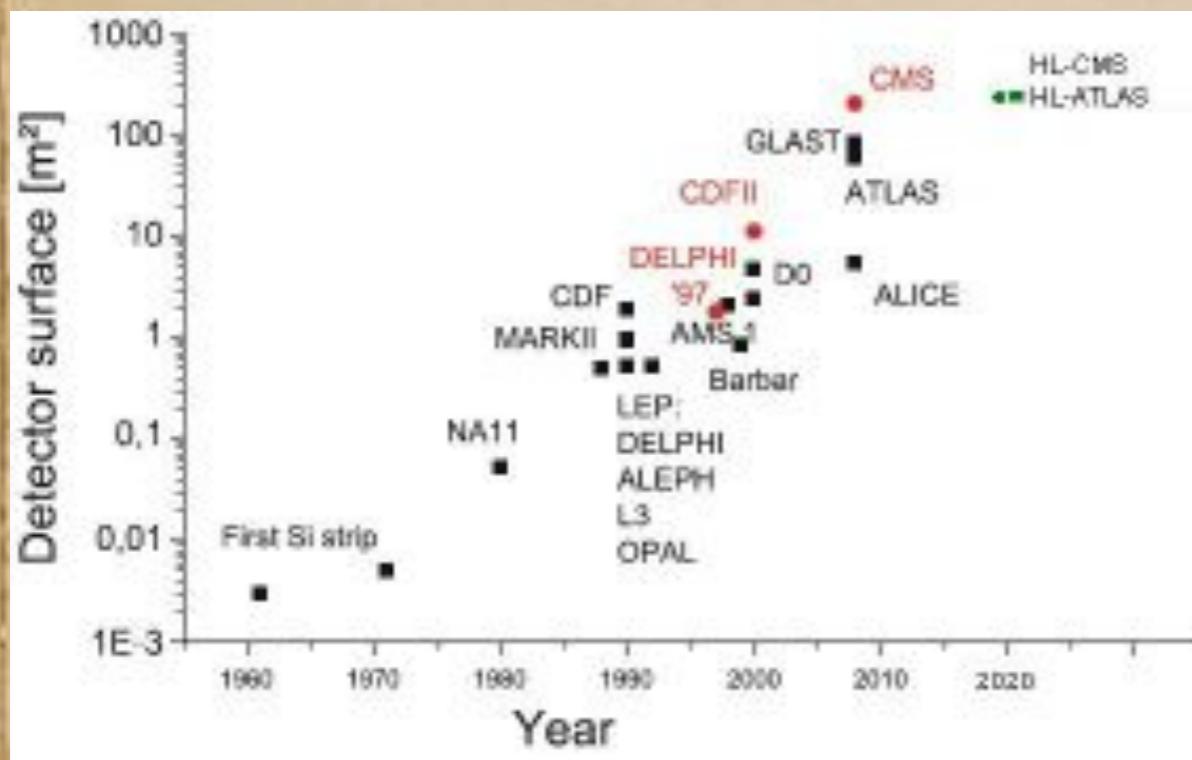
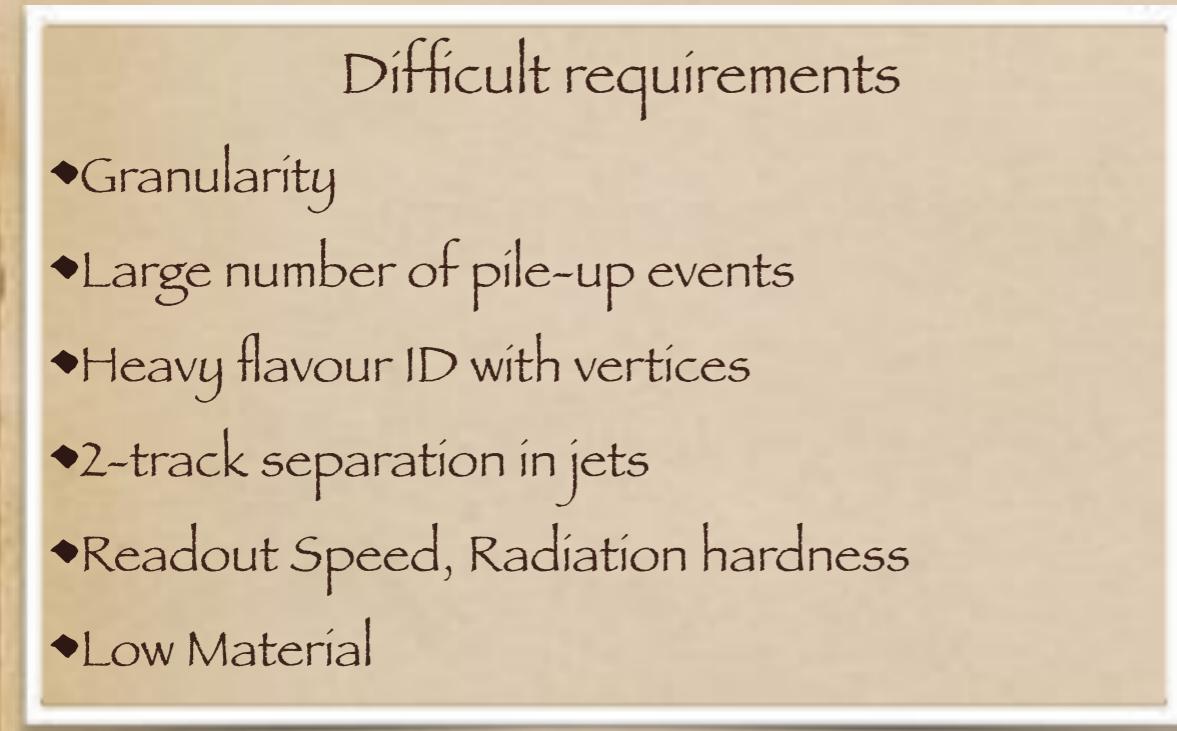


CMS Tracker, 2007

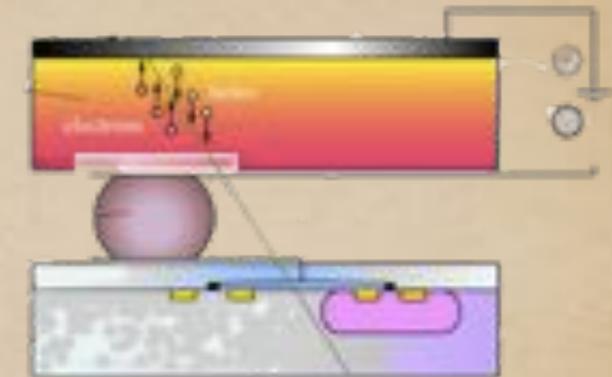
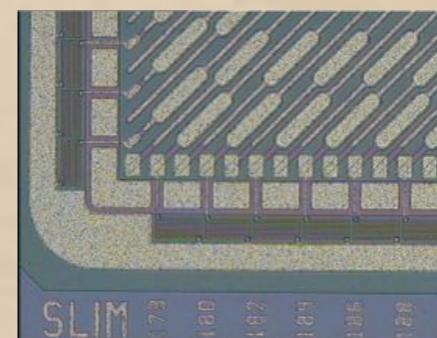


CDF ISL, 2000

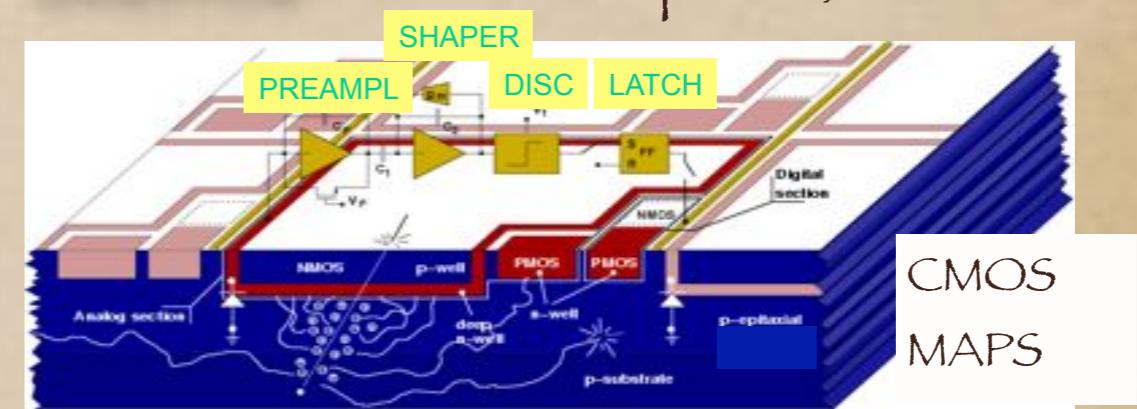
# Vertexing and Tracking



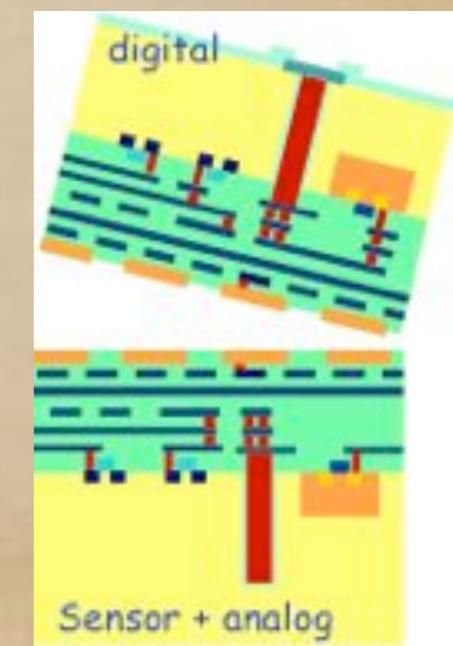
Today  
Strips and Hybrid pixels 50-100s  $\mu\text{m}$



Tomorrow Monolithic pixels, 25-50  $\mu\text{m}$

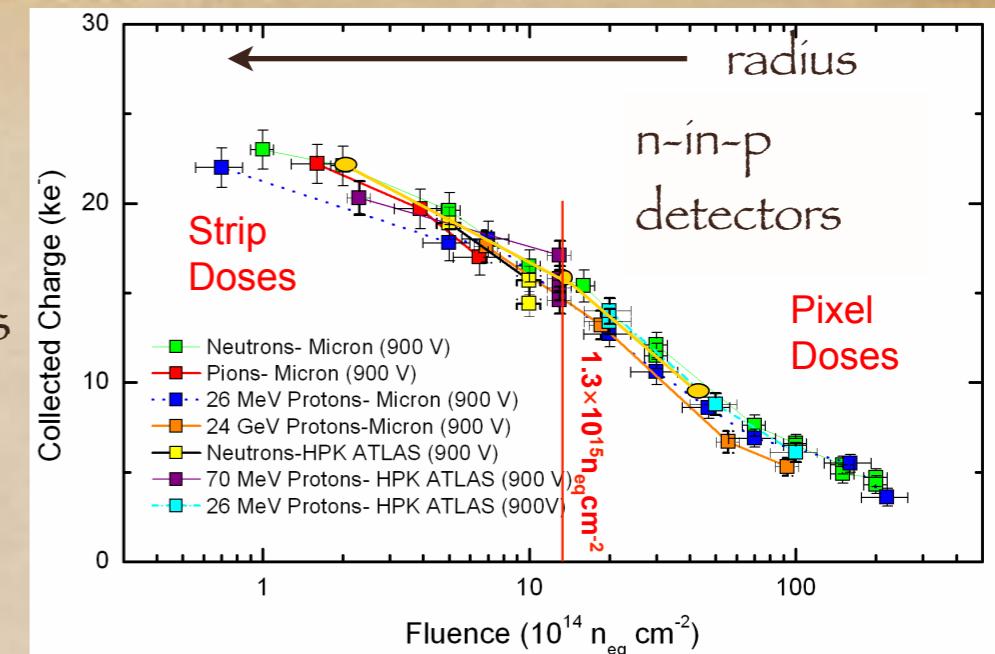


Day After Tomorrow  
3D Vertical integration  
Through silicon vias  
Micro bump bonding  
Speed, less material,  
25  $\mu\text{m}$  and less

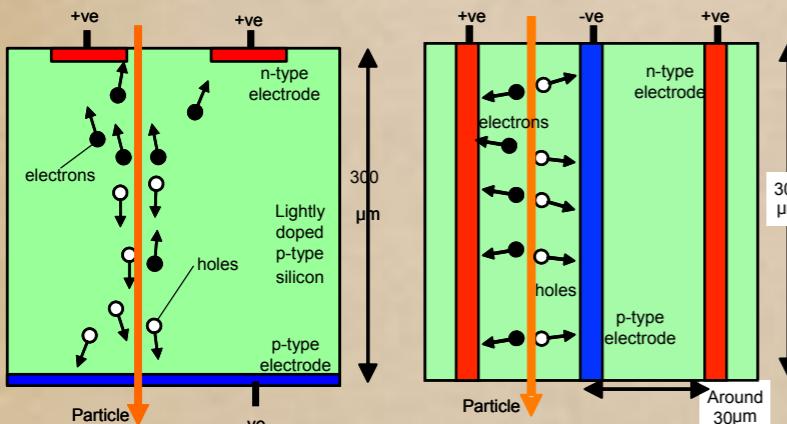


# Silicon challenges:

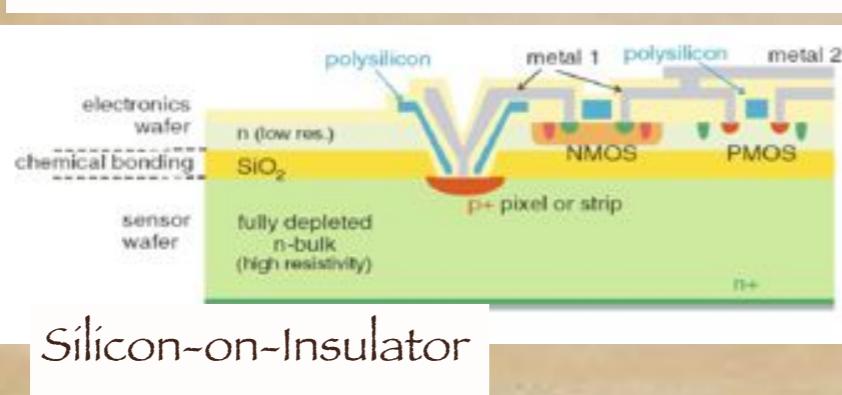
- ◆ Speed, material, granularity, rad-hardness, efficiency
- ◆ Competing requirements force to look in many directions
- ◆ Strong connection with electronics industry
- ◆ CCDs, CMOS sensors, 65nm, diamond, ...



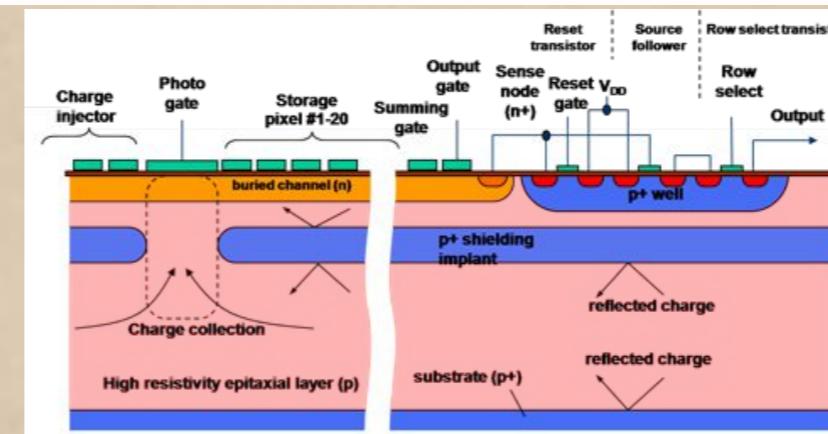
3D Detectors: improve speed and rad tolerance by lateral collection



Monolithic detectors: reduce material, pixel size, increase speed

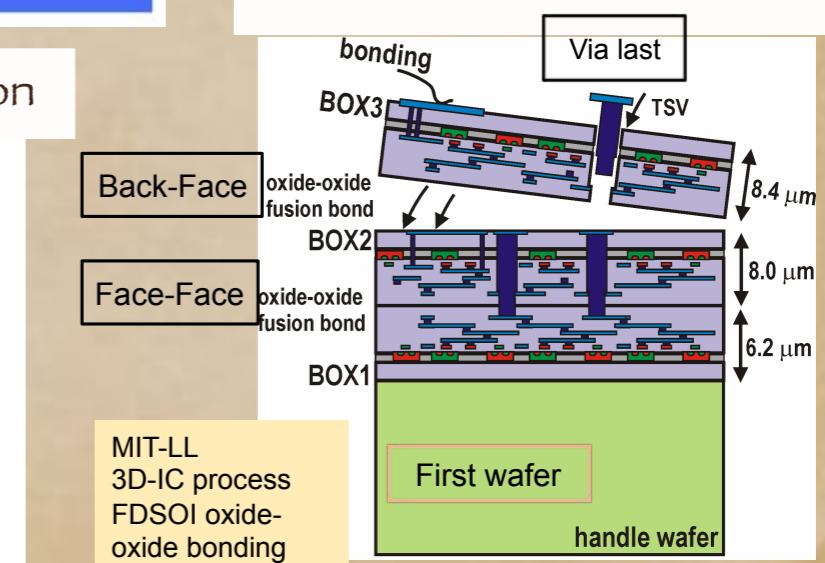


In-situ Storage Image Sensor: CCD + CMOS

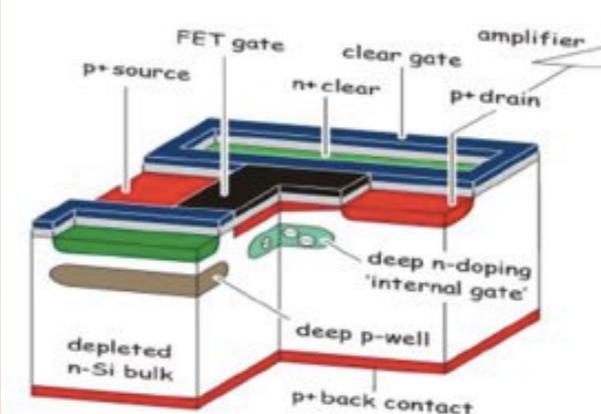


Expensive developments

Vertical Integration: a new view on interconnections

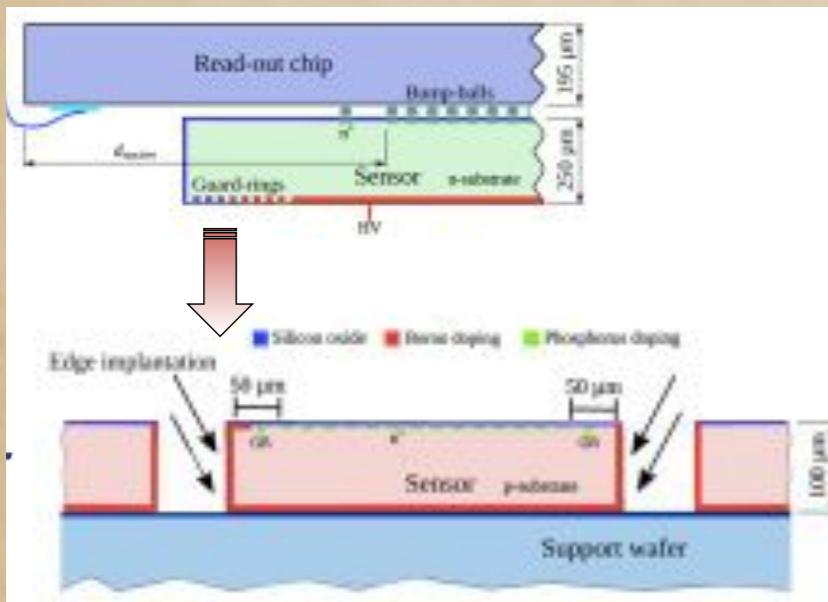


DEPFET: internal amplification



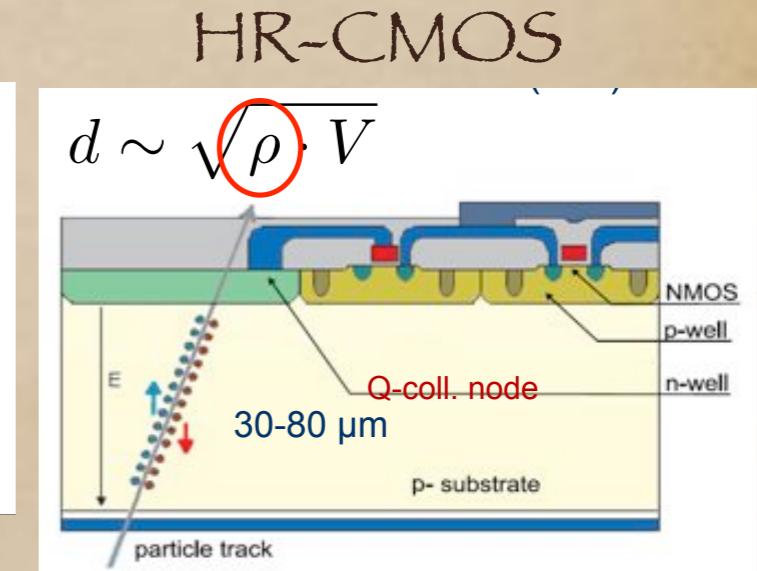
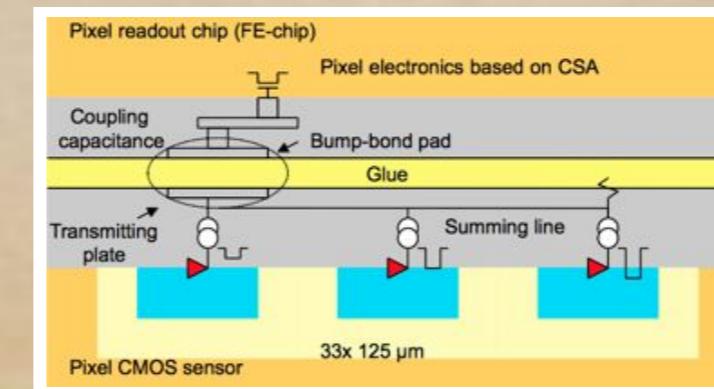
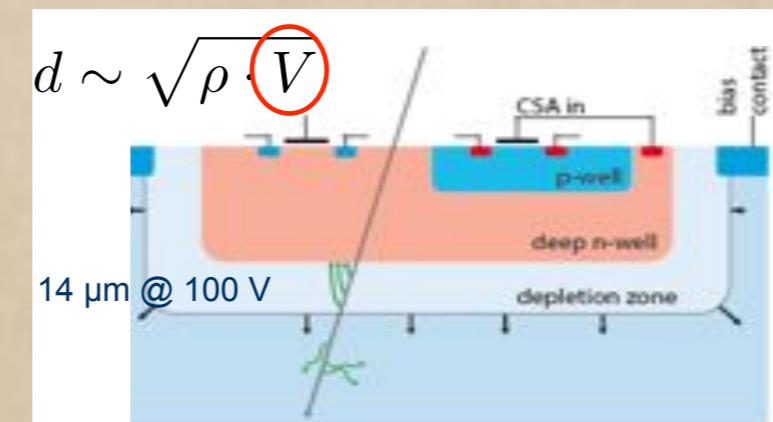
# More silicon challenges

## Active edge planar pixels

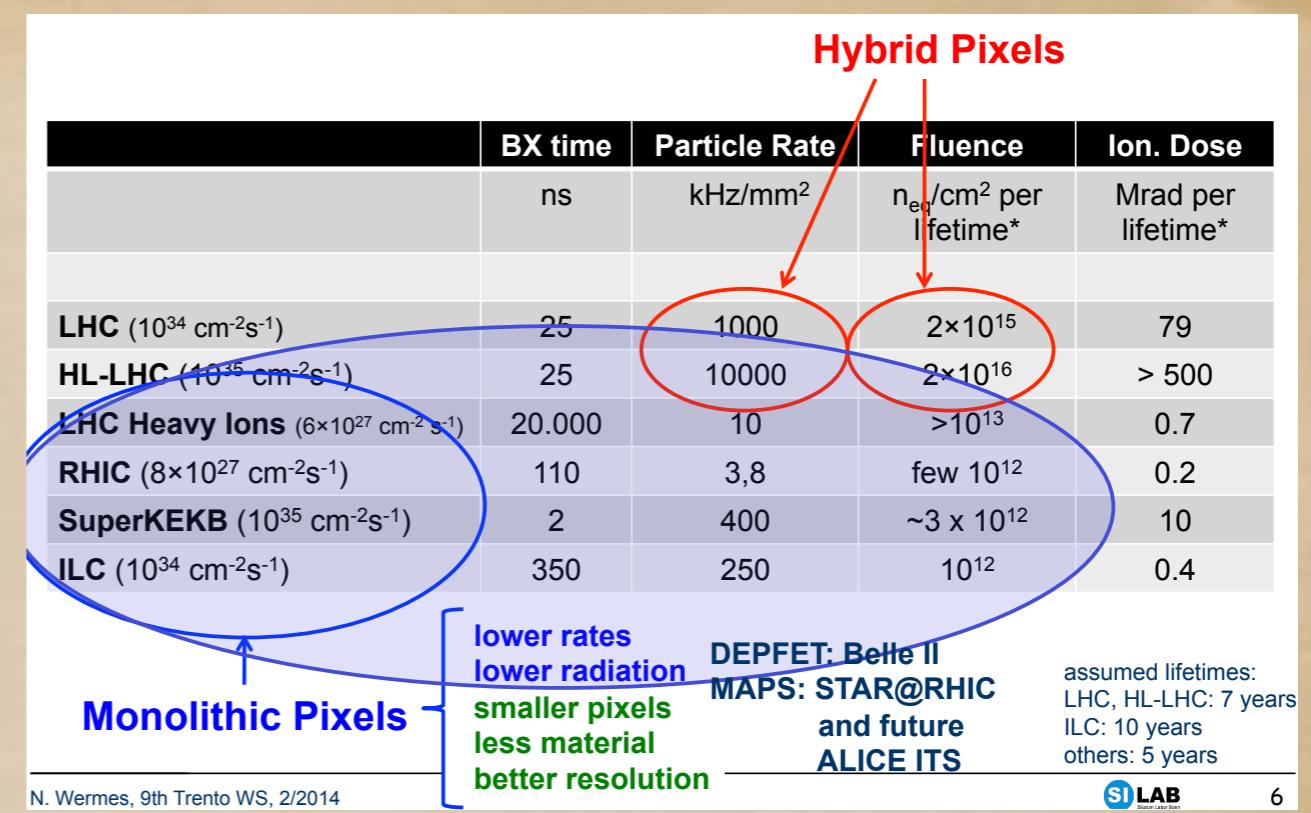


## HV/HR - CMOS

- ◆ The best of two worlds: monolithic and high signal
- ◆ Possibility of capacitive coupling
- ◆ Dedicated technology



CCPD - Capacitively coupled pixel detector

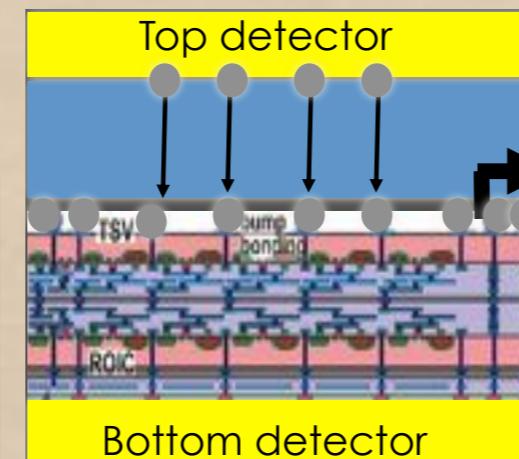
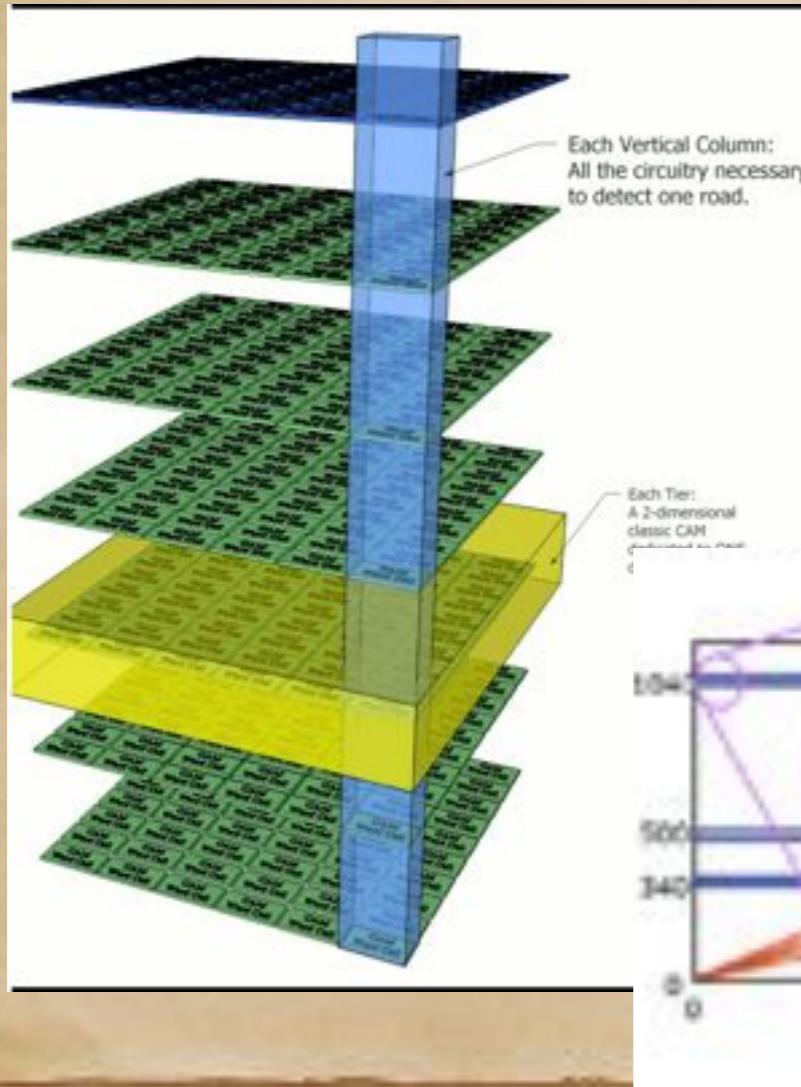


## HV-CMOS

## HR-CMOS

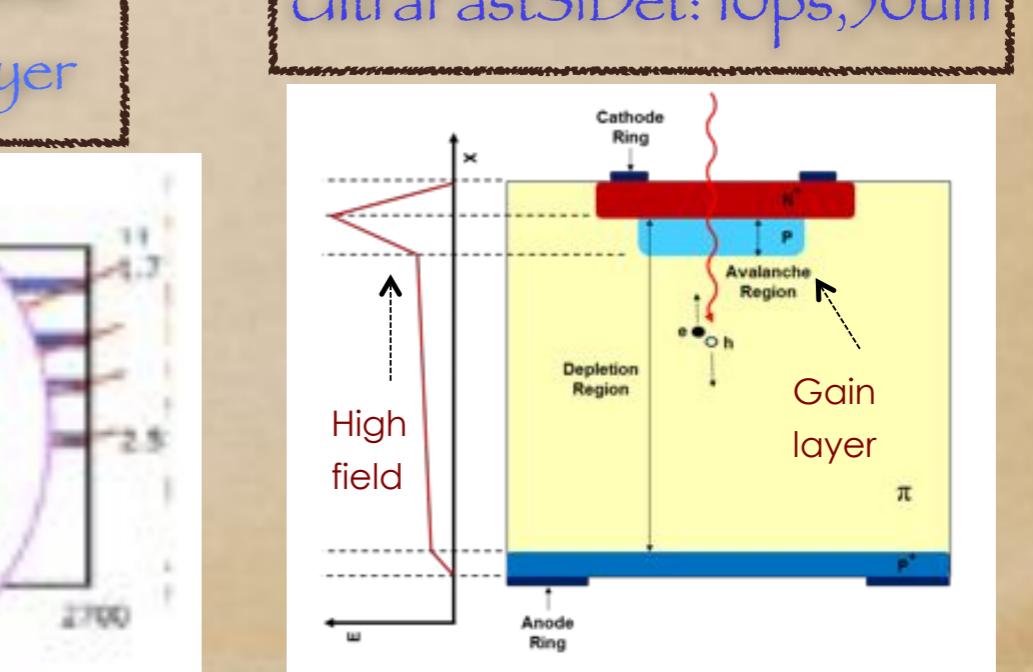
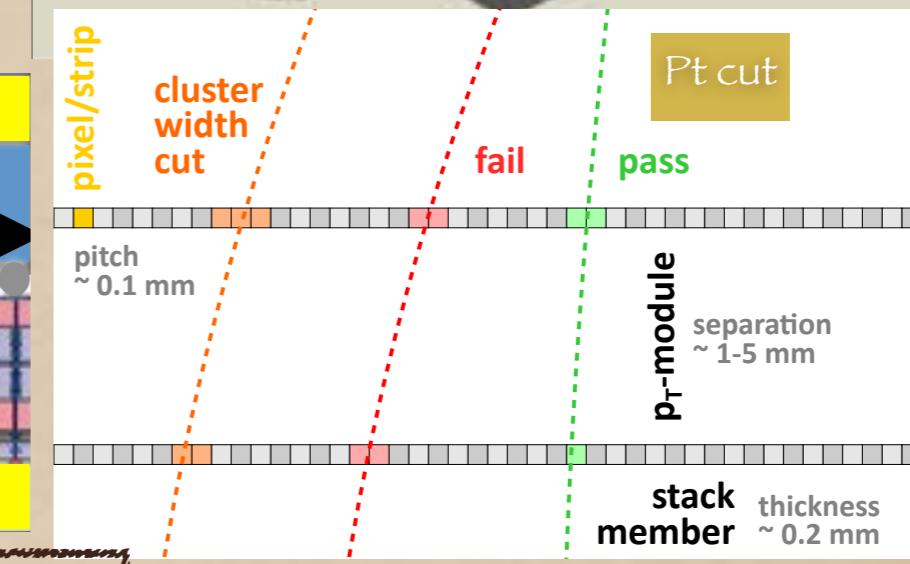
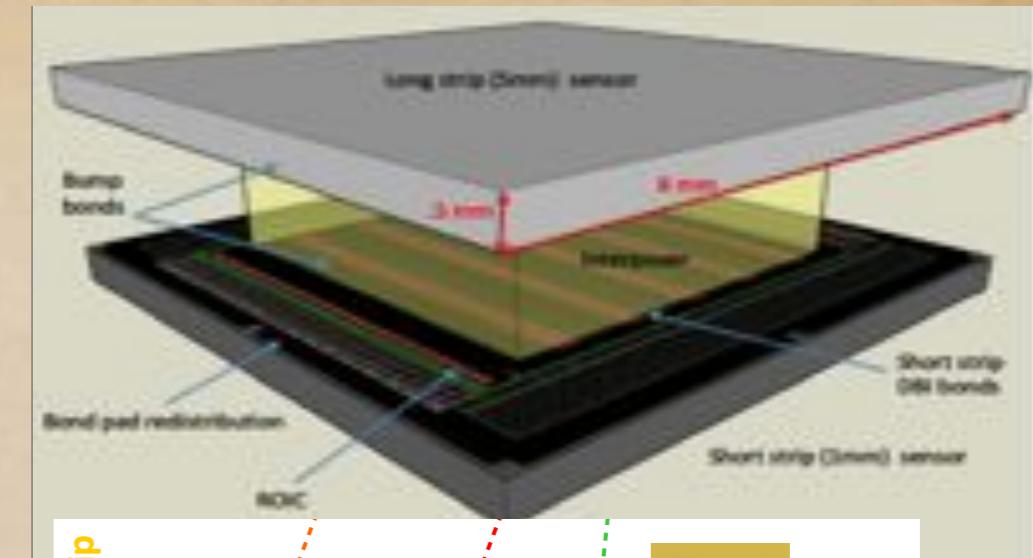
# Smart detectors

- ◆ Granularity is not enough for high rates
- ◆ LHC @  $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ : 200 events overlapping
- ◆ Build track segments or measure  $p_T$  at sensor levels and use track in LVL1-2 Trigger
- ◆ Use 3D chip technology



Content addressable memory in each layer

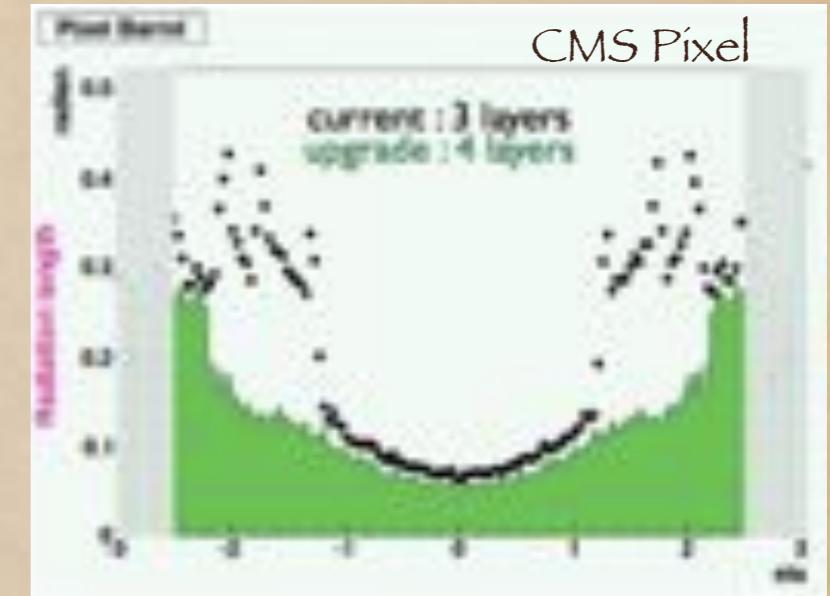
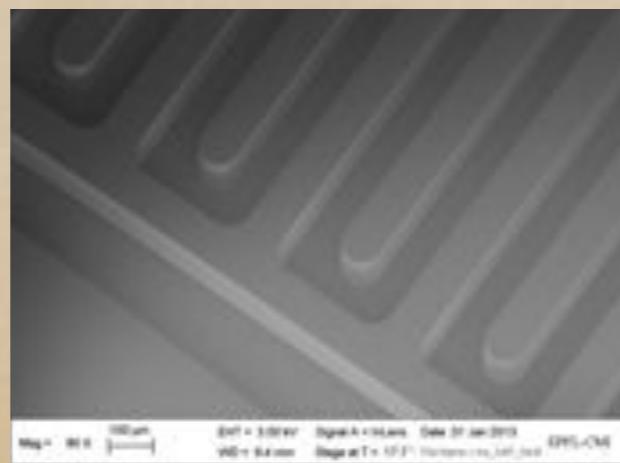
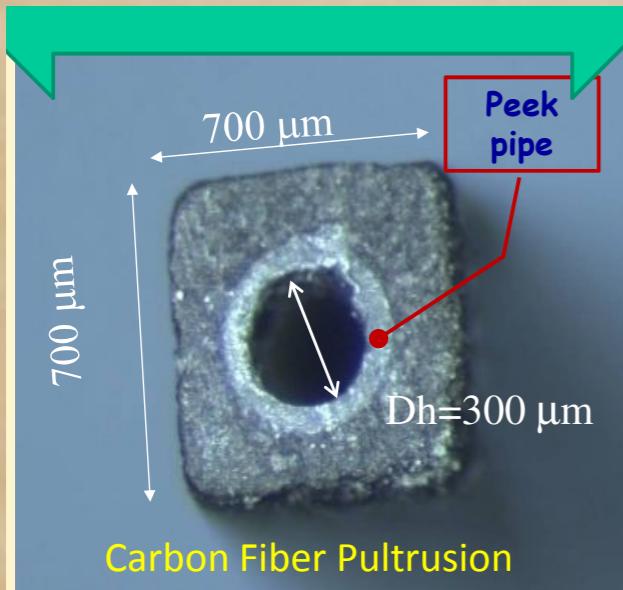
UltraFastSiDet: 10ps, 50um



# Advanced materials and powering

- ◆ Granularity, speed, local intelligence, bandwidth, complexity --> high power, many cables
- ◆ To keep radiation length under control need
  - ◆ advanced materials and integration
  - ◆ advanced powering schemes
  - ◆ heat management integrated in detector design

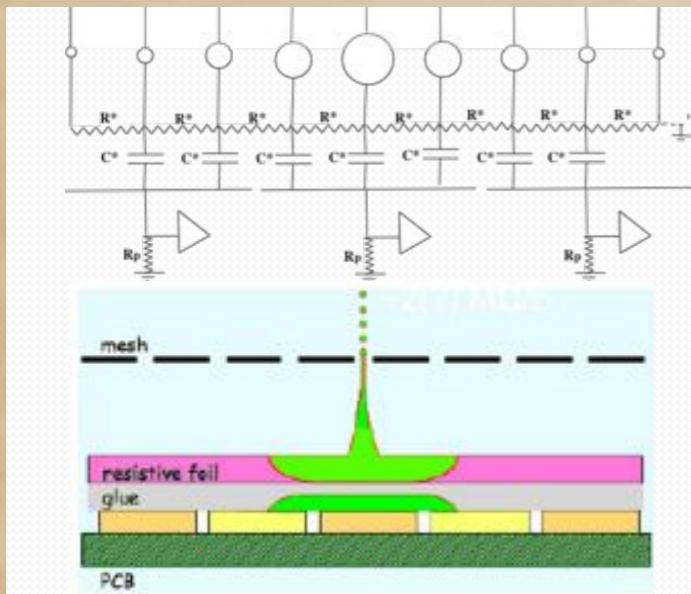
Micro channel cooling in CF and Silicon



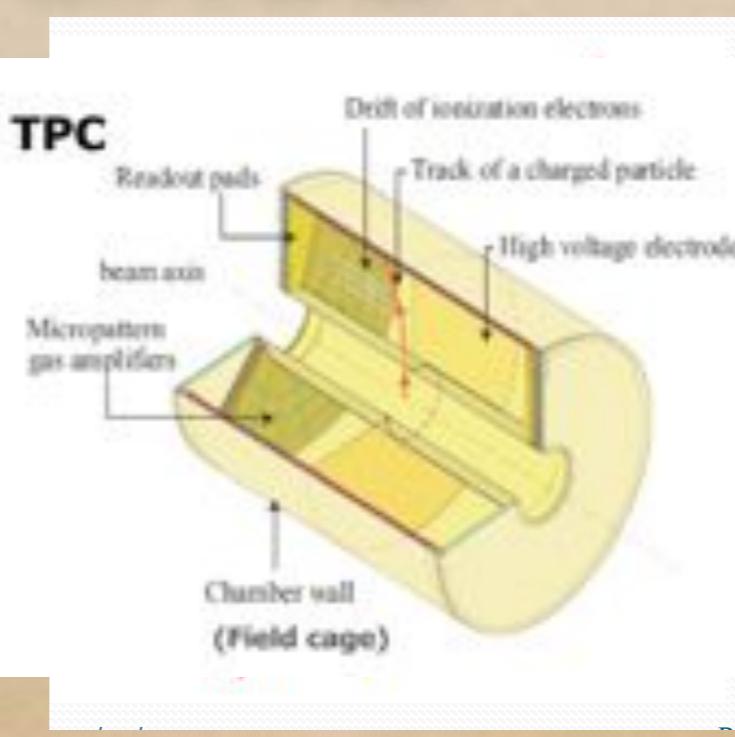
HV-MAPS on 25  $\mu\text{m}$  Kapton  
Detector thinner than a hair  
0.1%  $\chi^2 / \text{layer}$

# Gas detectors

- ◆ Workhorse: dependable, inexpensive, low mass
- ◆ Large area tracking, PID, calorimetry, muon
- ◆ Wires replaced by Micro Pattern Gas Detector, although drift chambers still going strong
- ◆ Time projection chambers - beautiful for low rate environments
- ◆ Readout with MPGC possibly with resistive division



## LCTPC for ILC



- Rate Capability
- High Gain
- Space Resolution
- Time Resolution
- Energy Resolution
- Ageing Properties
- Ion Backflow Reduction
- Photon Feedback Reduction

Benchmark process:  $e^+e^- \rightarrow HZ, Z \rightarrow \mu\mu$

### Requirements:

Momentum resolution  
 $\delta(1/p_T) < 2 \cdot 10^{-5} \text{ GeV}/c$  with vertex constraint  
 $\delta(1/p_T) < 9 \cdot 10^{-5} \text{ GeV}/c$  TPC only  
(200 points with 100  $\mu$  resolution in  $R\phi$ )

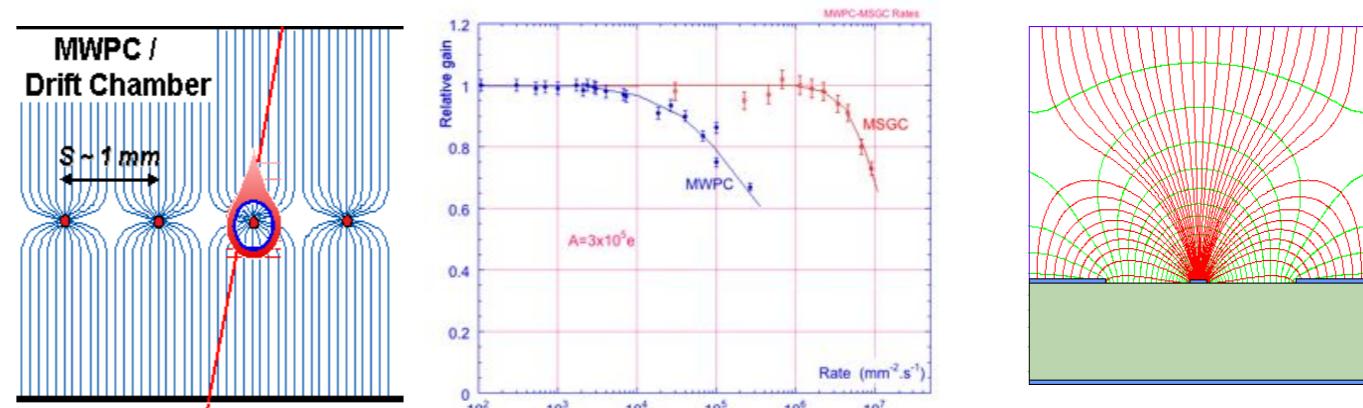
2-track separation: 2 mm in  $R\phi$  and 6 mm in  $R\theta$  in a high density background

Material budget: <5%  $X_0$  in the barrel region,  
<25%  $X_0$  in the endcap region

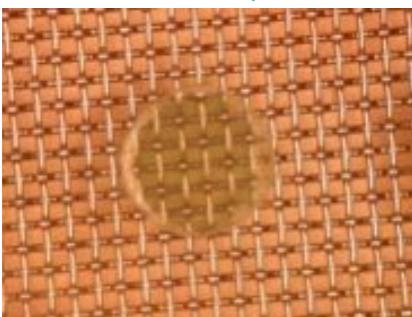
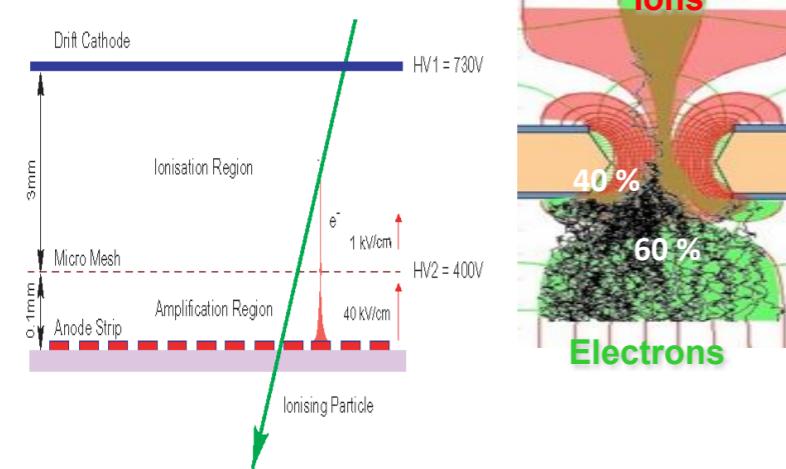
# Current Trends in Micro-Pattern Gas Detectors (Technologies)

## Semiconductor Industry technology:

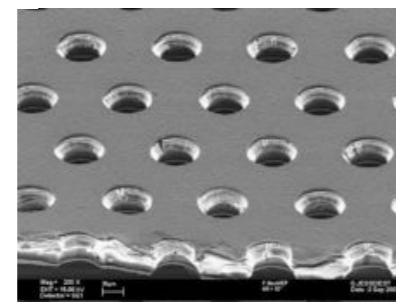
- Photolithography
- Etching
- Coating
- Doping
- Wafer postprocessing



## Gas Electron Multiplier

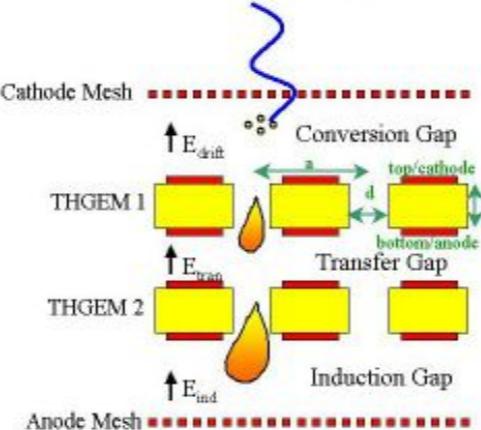


Micromegas



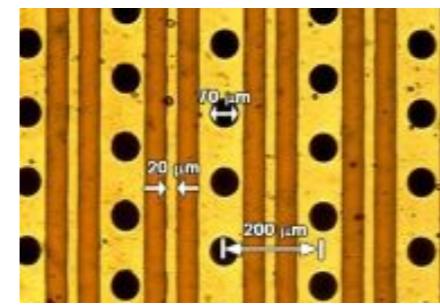
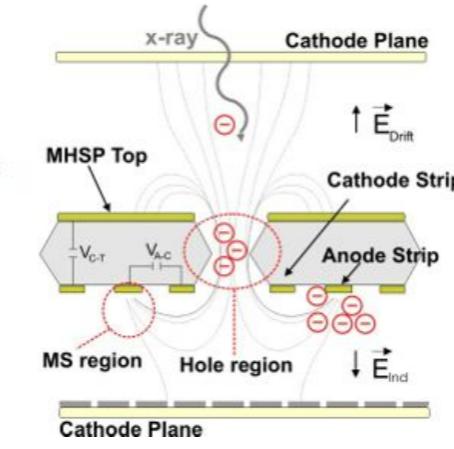
GEM

## Thick GEM

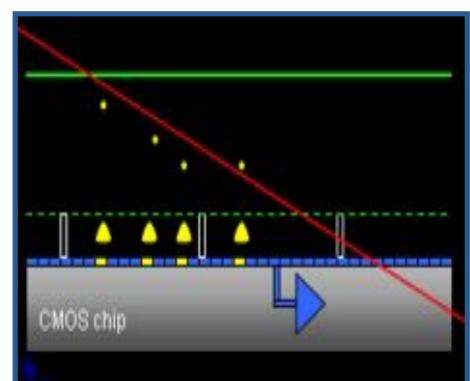


THGEM

## Microhole and strip plate GEM



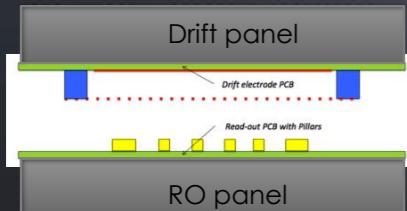
MHSP



Ingrid

# Many gaseous R&D efforts

- INDUSTRIAL PROCESS IS BEING DEFINED WITH A NUMBER OF TECHNOLOGICAL IMPROVEMENTS



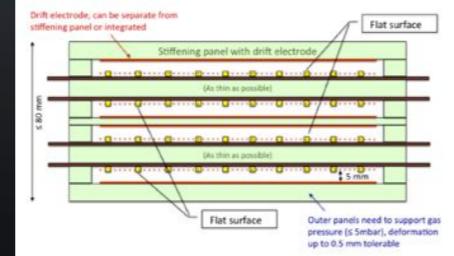
- NEW CONSTRUCTION METHOD
  - MESH MOUNTED ON THE DRIFT PANEL
  - MECHANICALLY FLOATING MESH
- INDUSTRIAL PROCESS BASED ON FEW STEPS ALREADY IN HAND TO INDUSTRIES

Giulio Aielli - IFD2014 - Trento

## Micro Megas

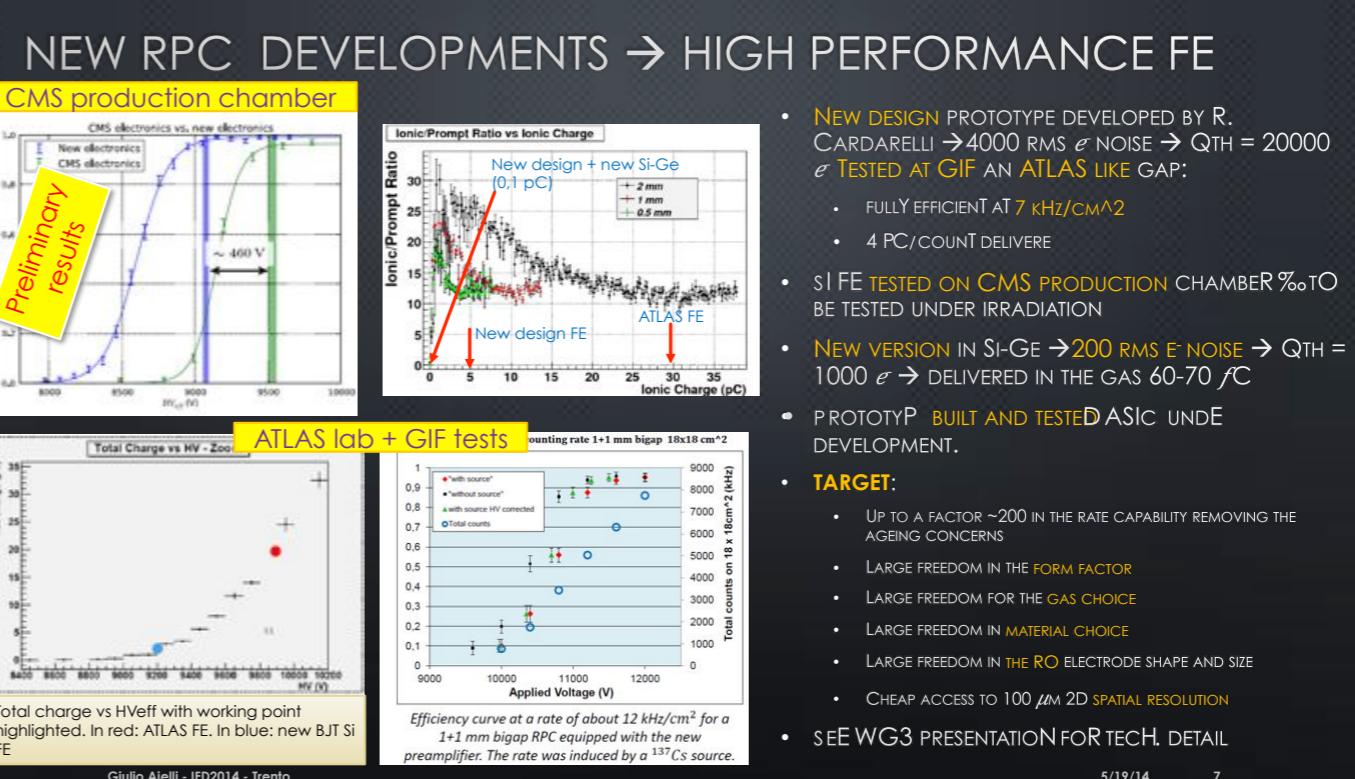
RESISTIVE FOILS PRODUCED SEPARATELY (WITH SPATTERING TECHNIQUE) AND GLUED ON THE READOUT PLANE

CHALLENGING CONSTRUCTION CONSTRAINTS: PCB ALIGNMENT AND PANEL FLATNESS VERY DEMANDING (30  $\mu\text{m}$  RMS)



5/19/14

25

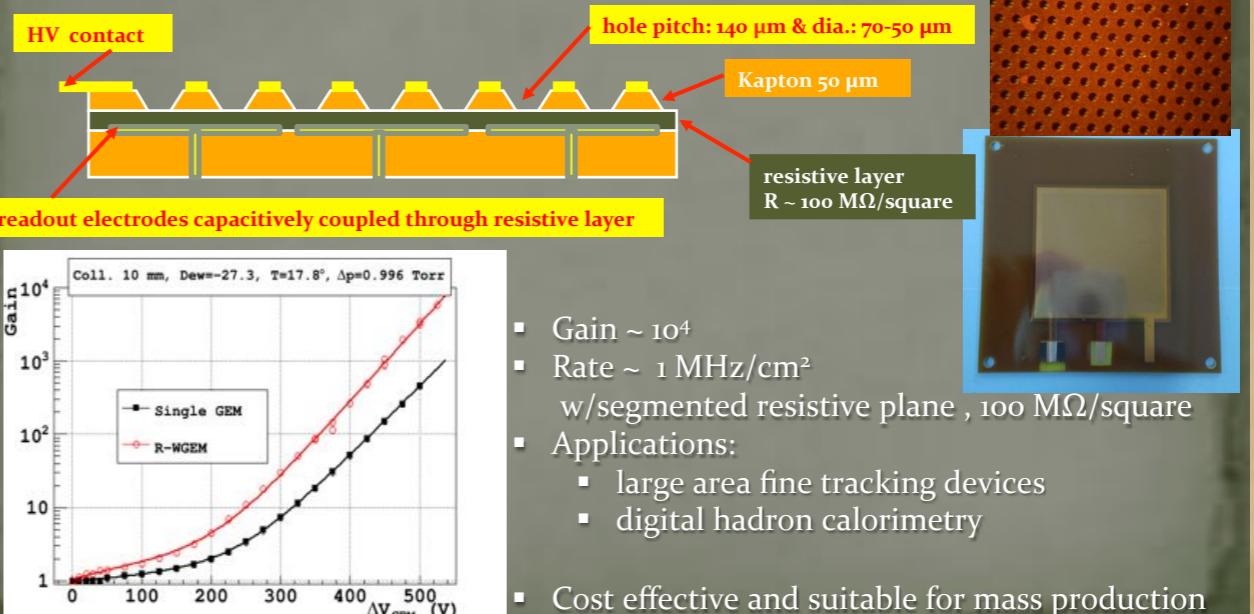


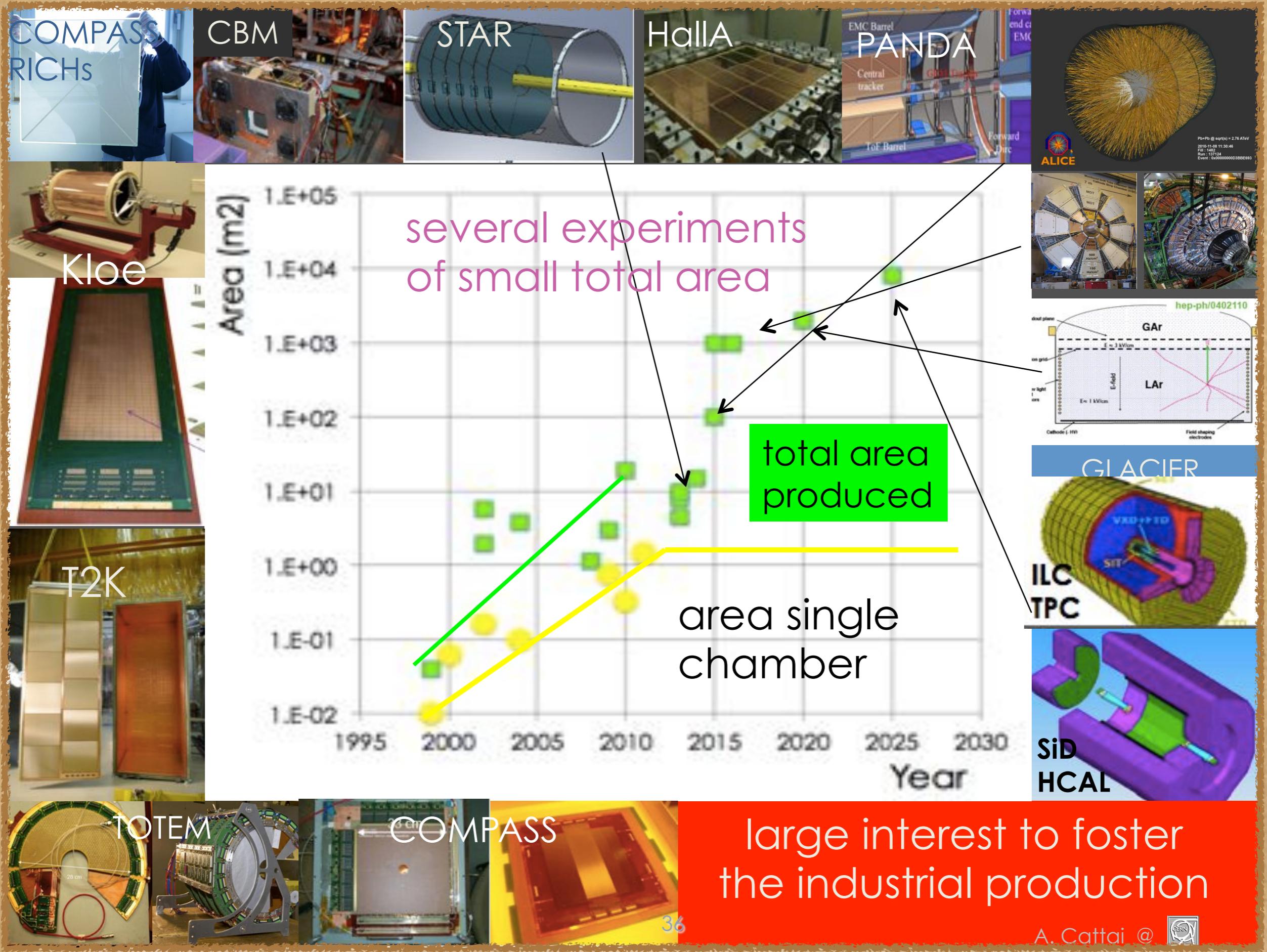
## Resistive WELL-GEM detector (G. Bencivenni-LNF-INFN)

The R-WGEM is a compact, spark-protected single amplification-stage MPGD. The amplification stage of the detector, realized with a structure similar to a GEM foil, is embedded through a resistive layer with the readout board. A cathode electrode, defining the gas conversion-drift gap, complete the detector mechanics.

The detector thickness is only 2-3 mm: diffusion and magnetic effects strongly reduced.

Rad-hard & low material budget.

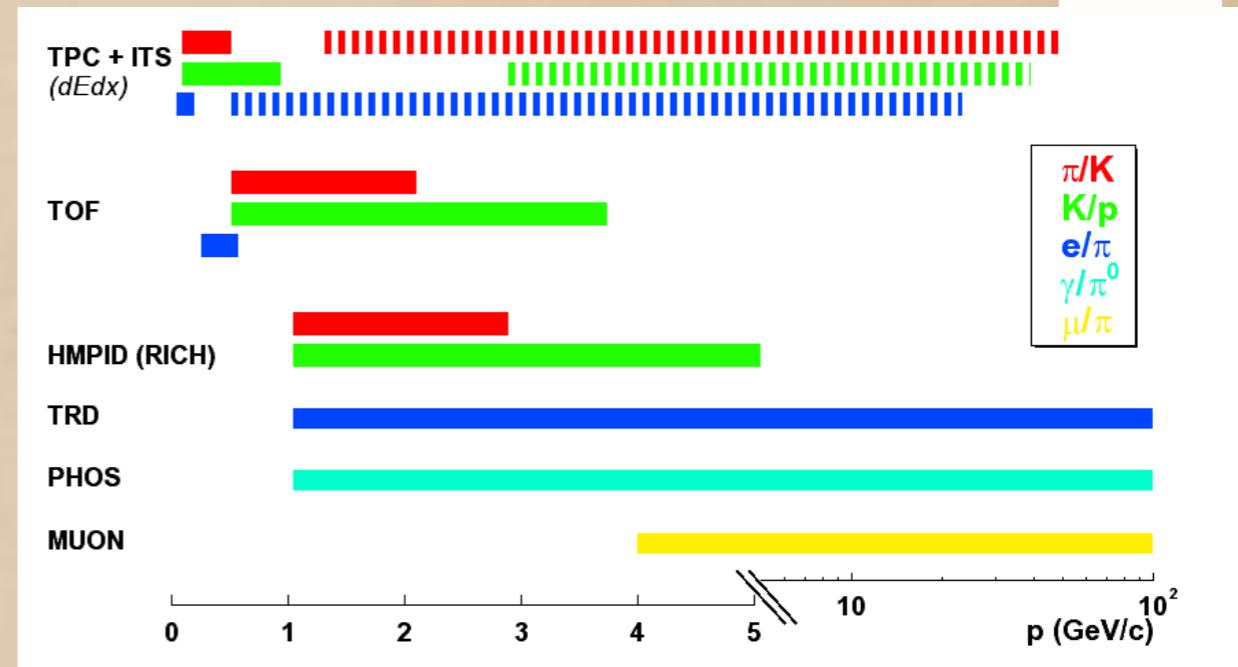




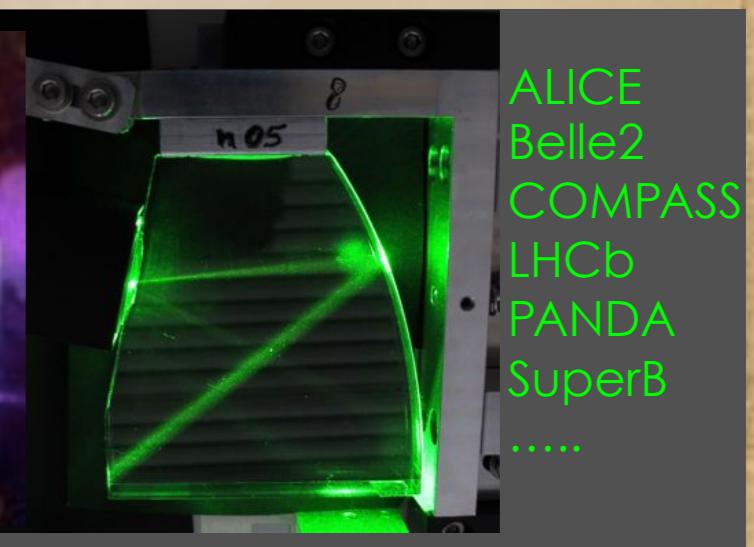
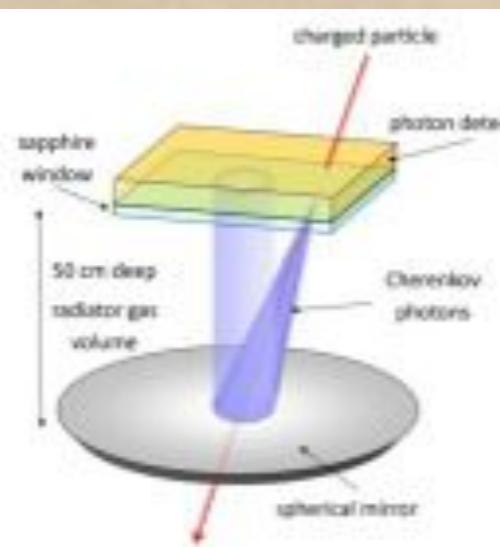
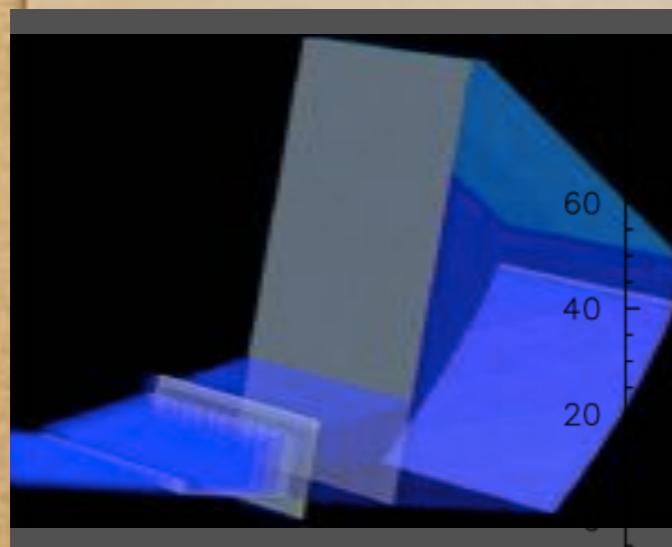
# Particle Identification

Alice

- ◆ Essential to identify decays when heavy flavour are present: everywhere
- ◆ Three legs:  $dE/dx$ , Time-of-flight, Cerenkov radiation
- ◆ Admirable workmanship in radiators and light transport: in gas, solid, liquid, aerogel, cold, warm



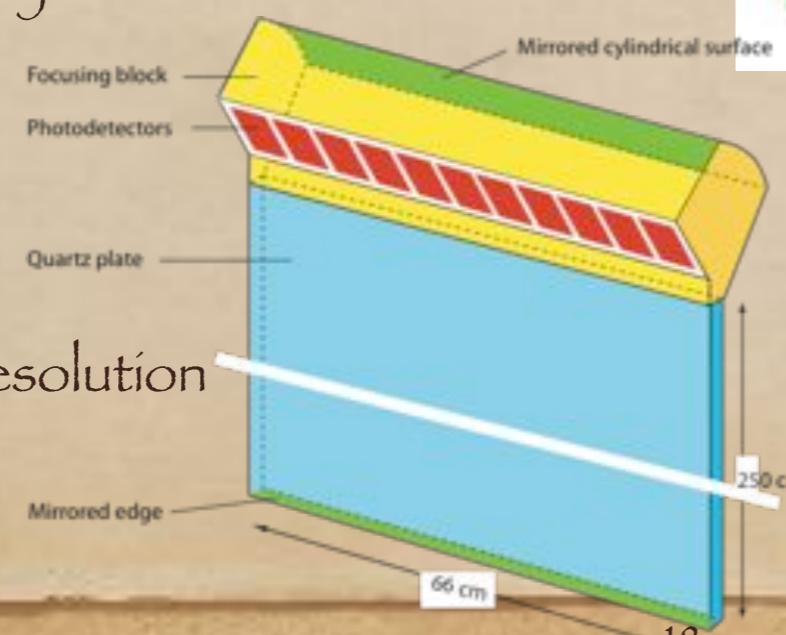
Excellent PID capabilities by combining different techniques over a large momentum range



ALICE  
Belle2  
COMPASS  
LHCb  
PANDA  
SuperB  
.....

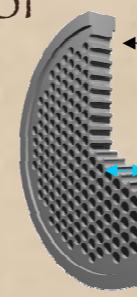
**LHC-b**

Time Of internally Reflected  
Cherenkov light  
(TORCH)  
Quartz radiator  
TOF with 15ps resolution

**Belle-II**

## 1. Time of Propagation Counter (TOP)

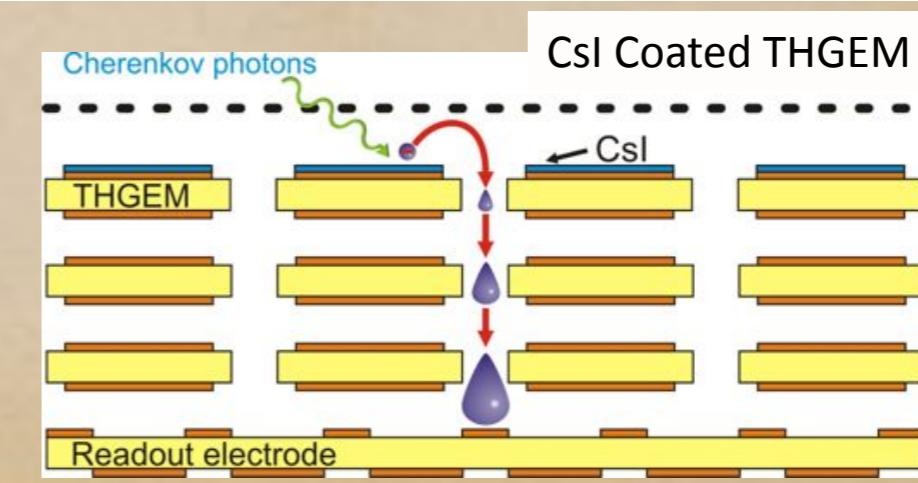
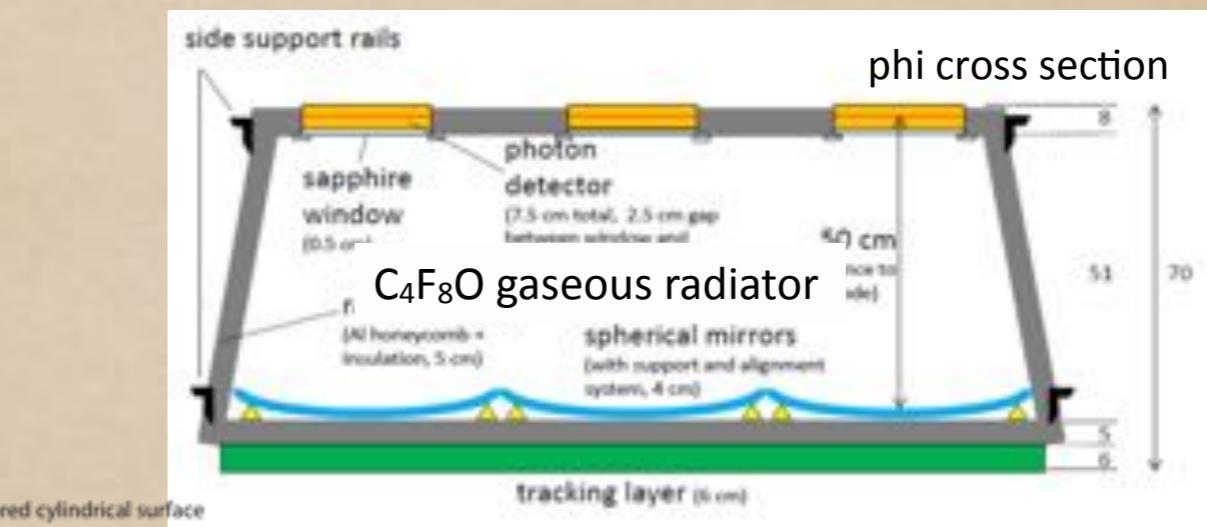
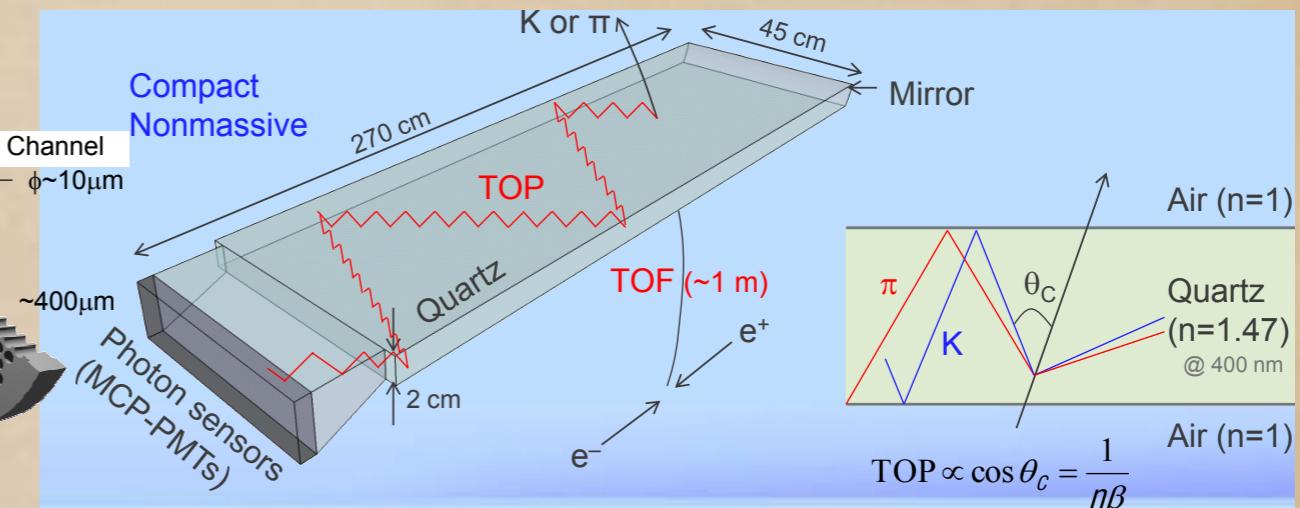
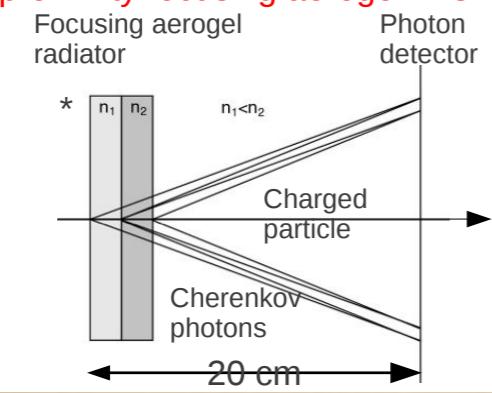
Measure both position and time of photons with MCP-PMT (40ps)



## 2. Focusing Aerogel RICH

Hybrid Avalanche Photo Diodes

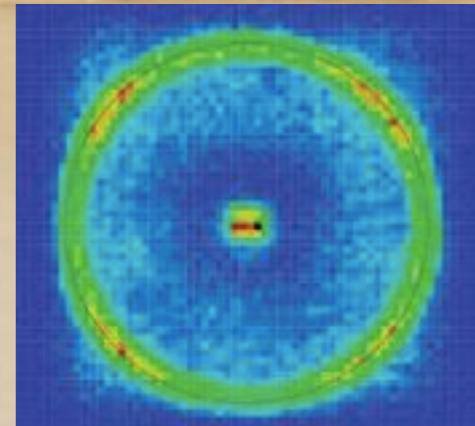
## proximity focusing aerogel RICH

**ALICE**

# Many clever techniques and geometries

# Photon detectors

## ◆ Key element PID system (and others)



High gain  $> 5 \cdot 10^5$  inside B-field

Very high time resolution  $\ll 100$  ps

Fine granularity. Long lifetime

High detection efficiency (very few  $\gamma$  !)

High rate stability (several MHz/cm<sup>2</sup>)

Technologies....cost

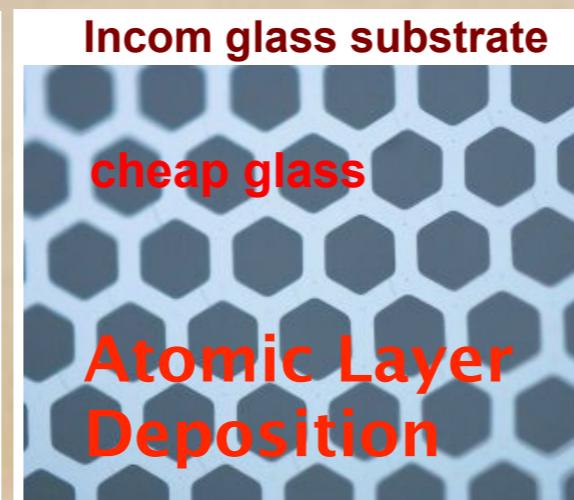
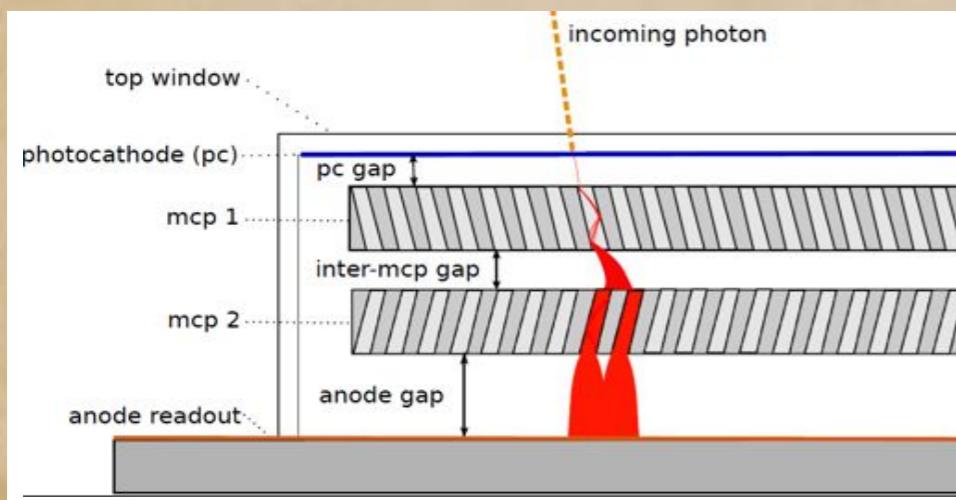
Large area: MPGD + CsI

Small area: MaPMT, MCP-PMT (\$\$\$)

R&D: Large area MCP, (d)SiPM

20 ps very hard to achieve (system)

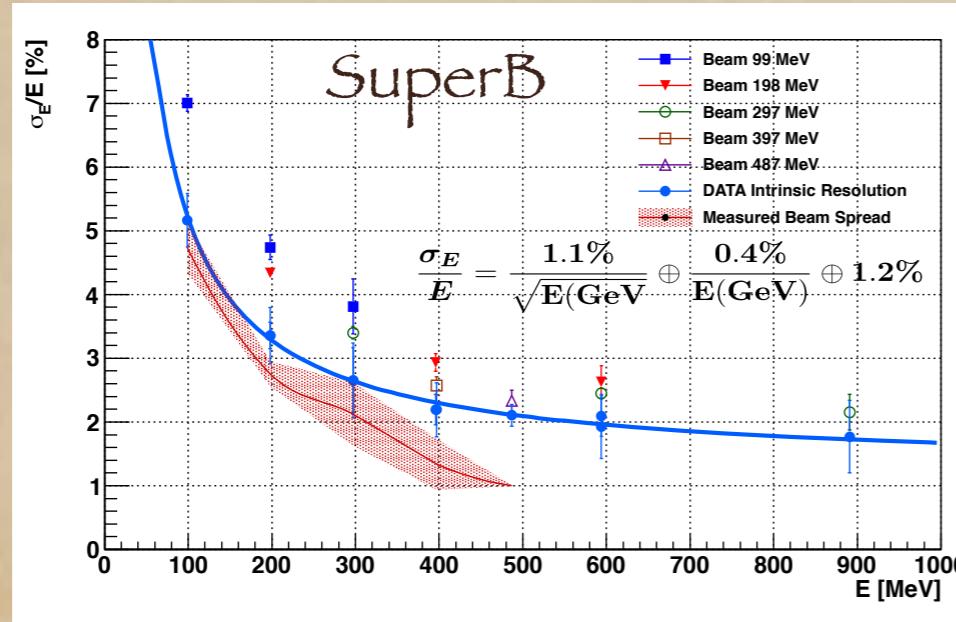
## ◆ Large Area Picosecond Photodetectors



“Cheap” 20x20 cm<sup>2</sup> tiles  
Many applications  
Time resol 15ps  
Enormous potential

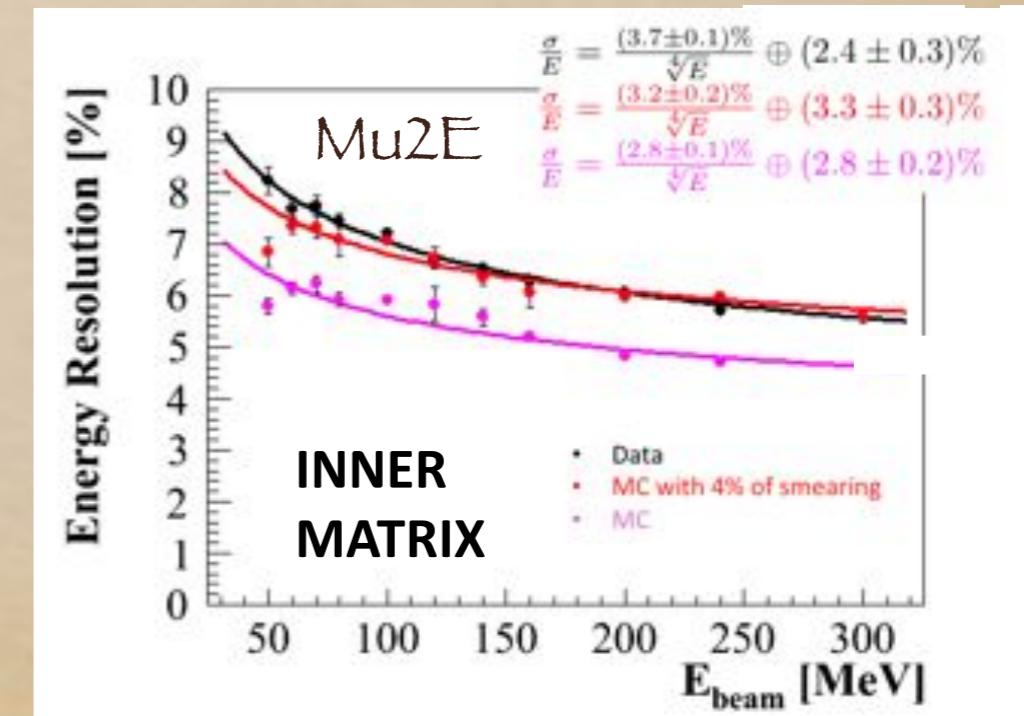
# Calorimetry

- ◆ Homeogeneous Crystals: CsI, LYSO, ...
  - ◆ Best possible resolution
  - ◆ Application to PET, homeland security ...
- ◆ Sampling:
  - ◆ Imaging: Particle Flow Algorithm
  - ◆ Dream: Dual readout
  - ◆ Sampling with Crystals shashlik
- ◆ LYSO is the expensive king of crystals: fast, high light yield, rad hard.
- ◆ Other fast (cheaper) materials: pure CsI, BaF<sub>2</sub>



Crystal	NaI(Tl)	CsI(Tl)	CsI	PWO	LYSO (Ce)
Density (g/cm <sup>3</sup> )	3.67	4.51	4.51	8.3	7.1
Melting Point (°C)	651	621	621	1123	2050
Radiation Length (cm)	2.59	1.85	1.85	0.9	1.14
Molière Radius (cm)	4.8	3.57	3.57	2.0	2.2
Hygroscopicity	yes	slight	slight	no	no
Luminescence (nm)	410	560	420/310	560/420	420
Decay Time (ns)	230	1250	35/6	30/10	45
Light Output (%)	100	165	3.6/1.1	0.3/0.08	80
d(LO)/dT (%/°C)	~0	0.3	-0.6	-1.9	-0.3
Radiation Damage	Yes	10%/krad	2%/krad	Small	Small

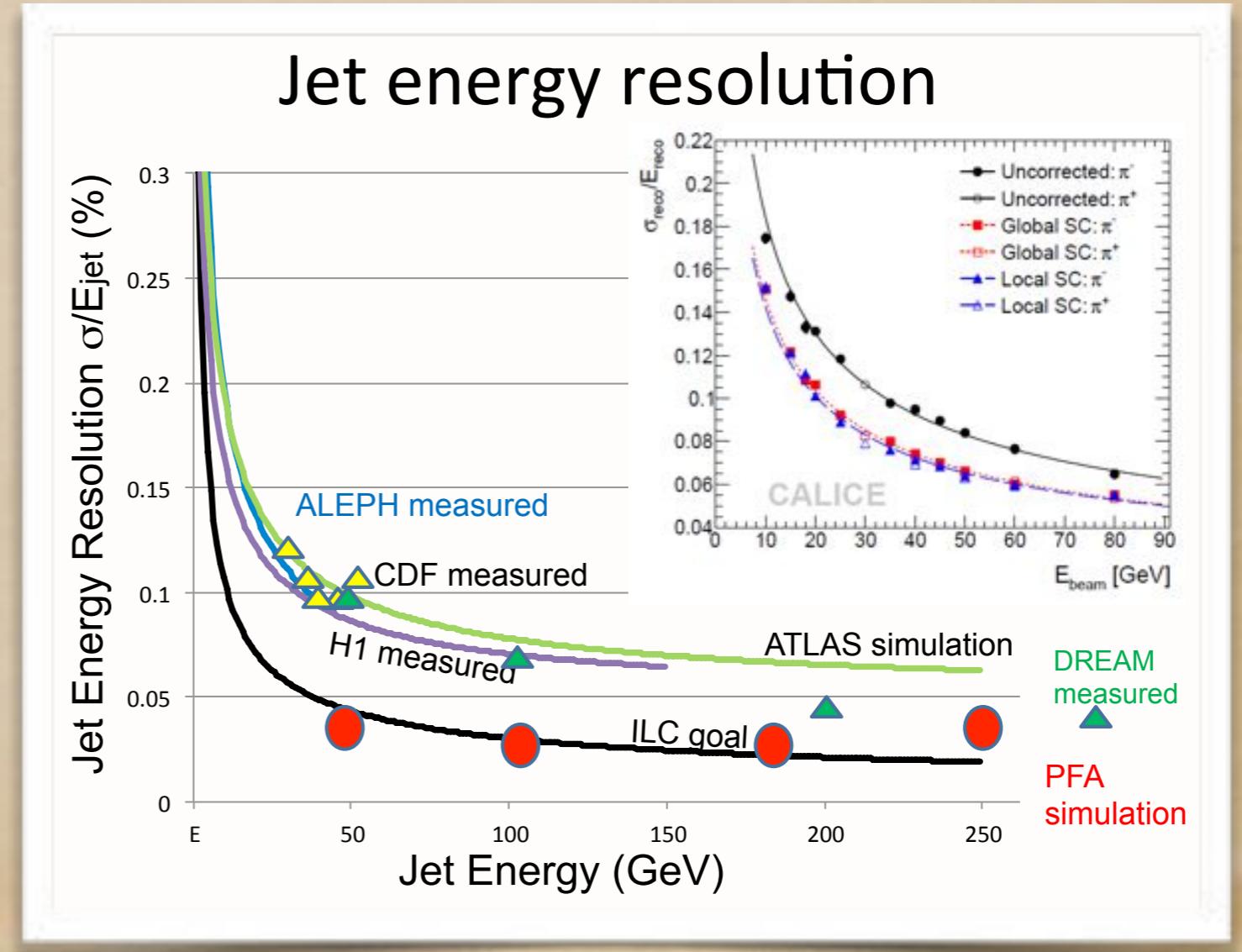
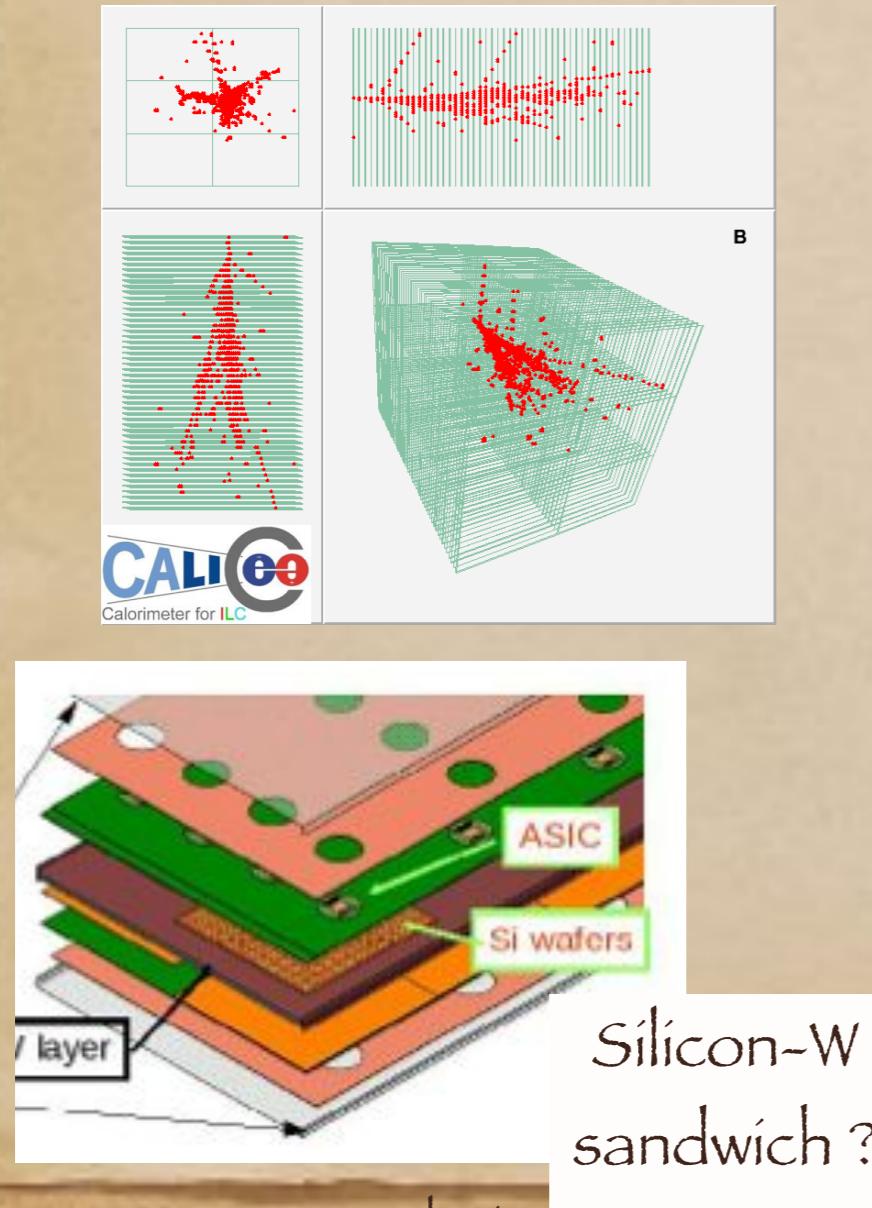
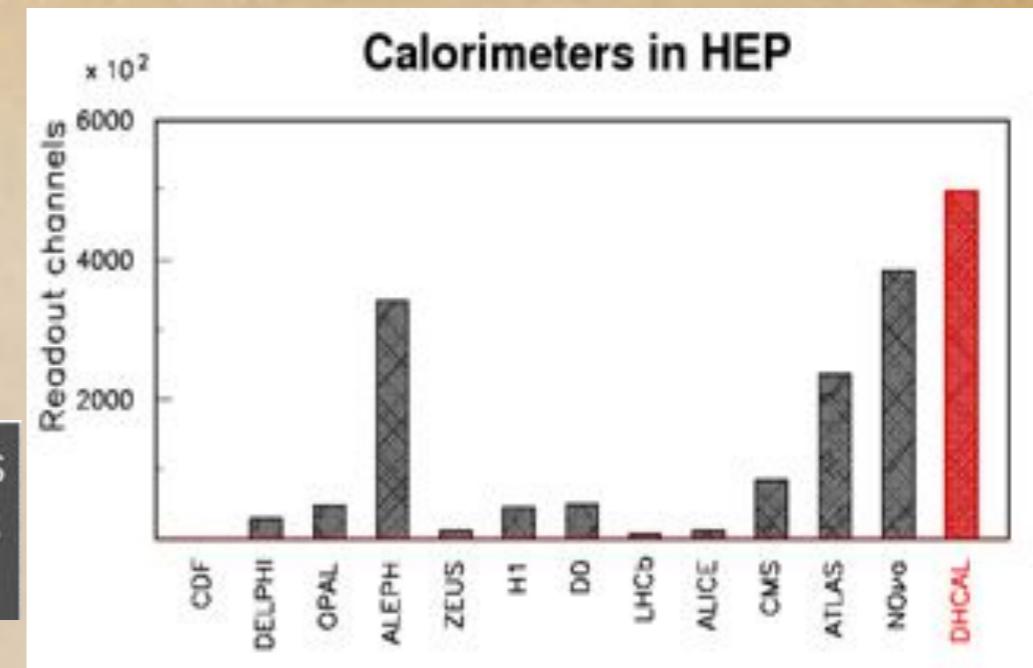
- ◆ R&D on photosensors: Avalanche Photo Diodes, Photopentodes, Silicon PhotoMultipliers,



# Imaging calorimeters

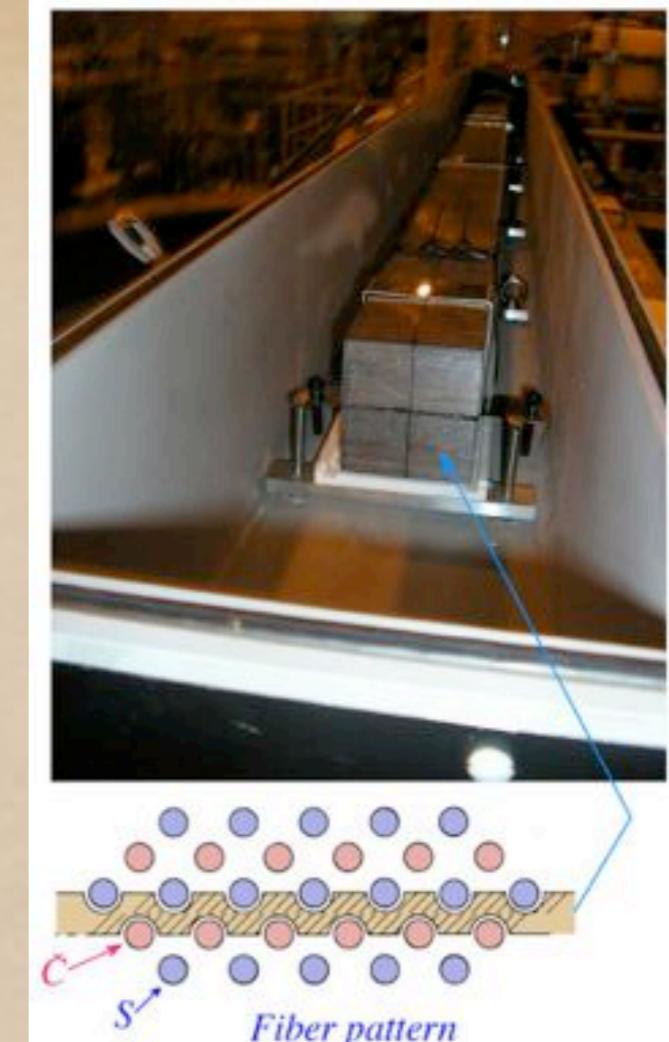
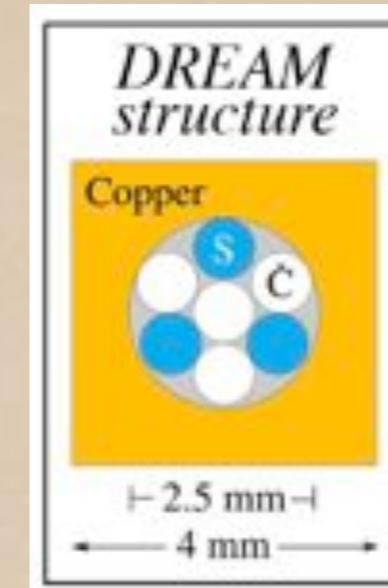
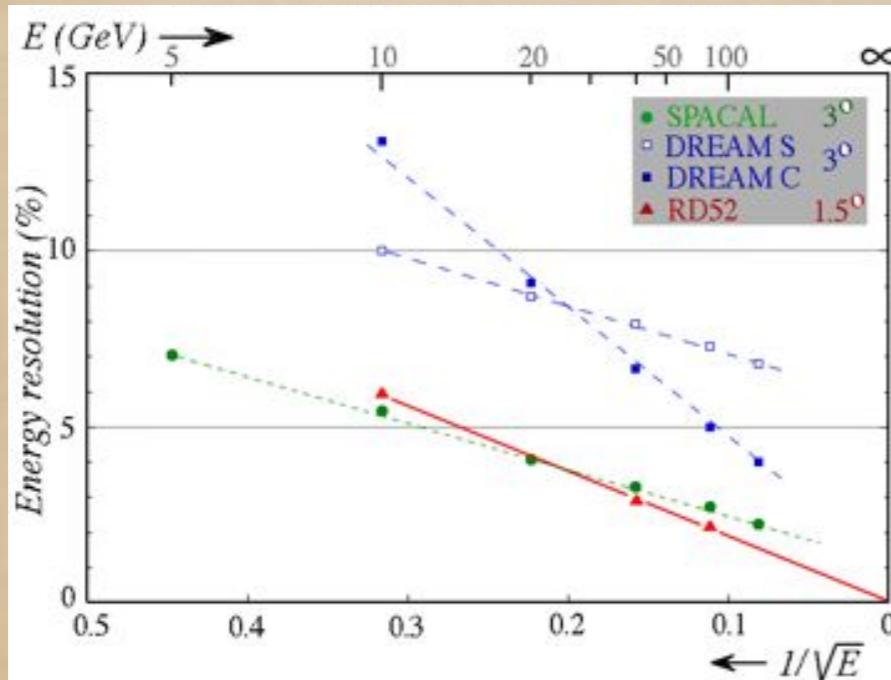
- ◆ High granularity can be expensive
- ◆ Need industrialization and engineering of sensors

ECAL $\rightarrow$ W + Si or scint.	1200-2500 m <sup>2</sup>	$10^7$ - $10^8$ chs
HCAL $\rightarrow$ Fe,W + scint.	4000-7000 m <sup>2</sup>	$10^7$ - $10^8$ chs
MPGD, RPC		



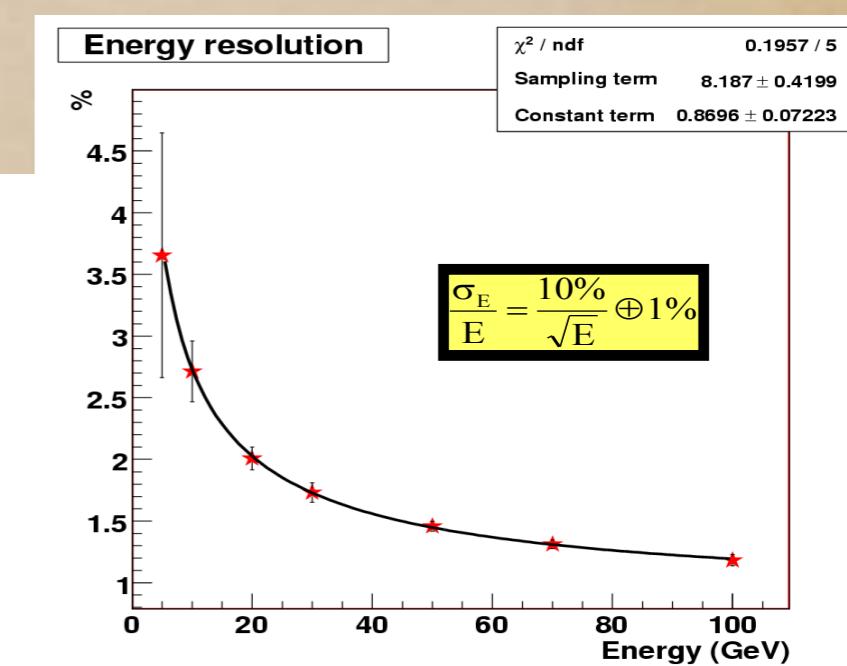
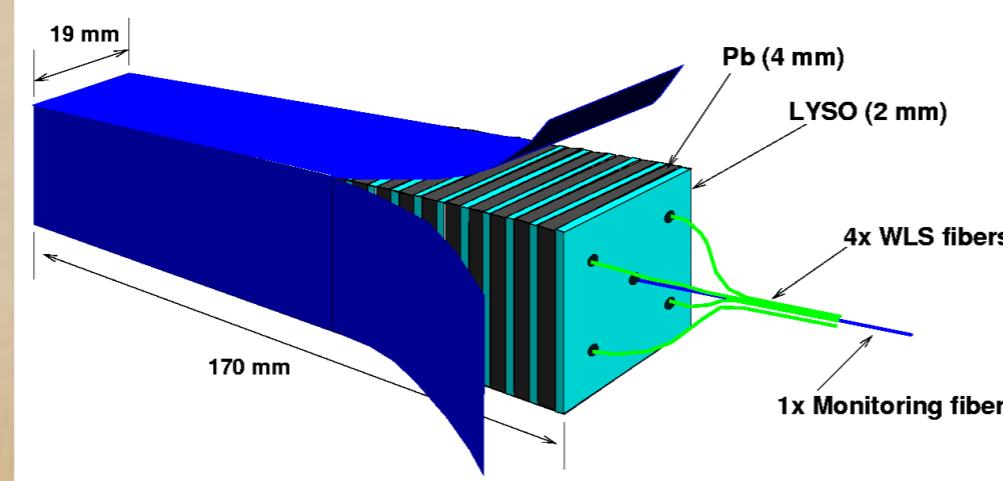
# Dual Readout Dream -> RD52

- ◆ Distinguish the scintillation and Cherenkov light in hadronic showers
- ◆ Compensate  $e/h \neq 1$  event by event
- ◆ Tried in crystals and fibers



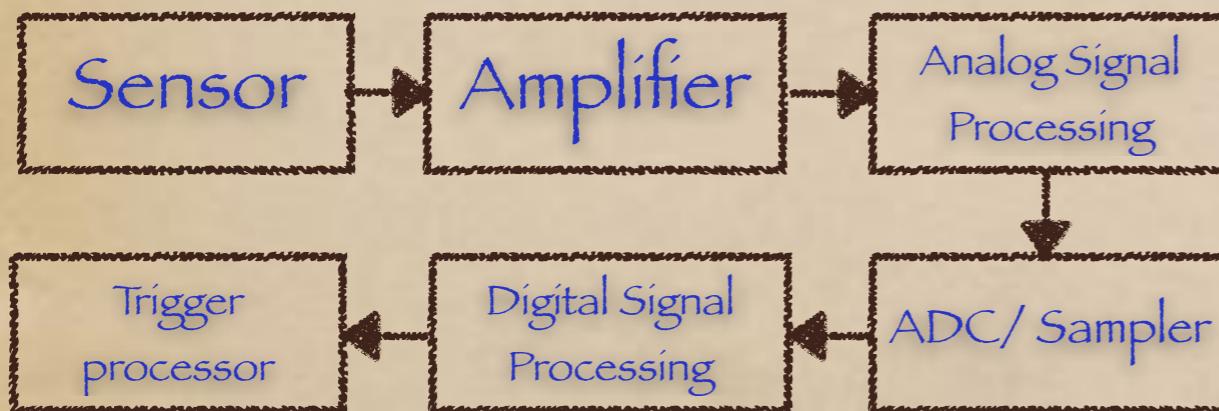
## Sampling with crystals

Optimize performance vs cost.

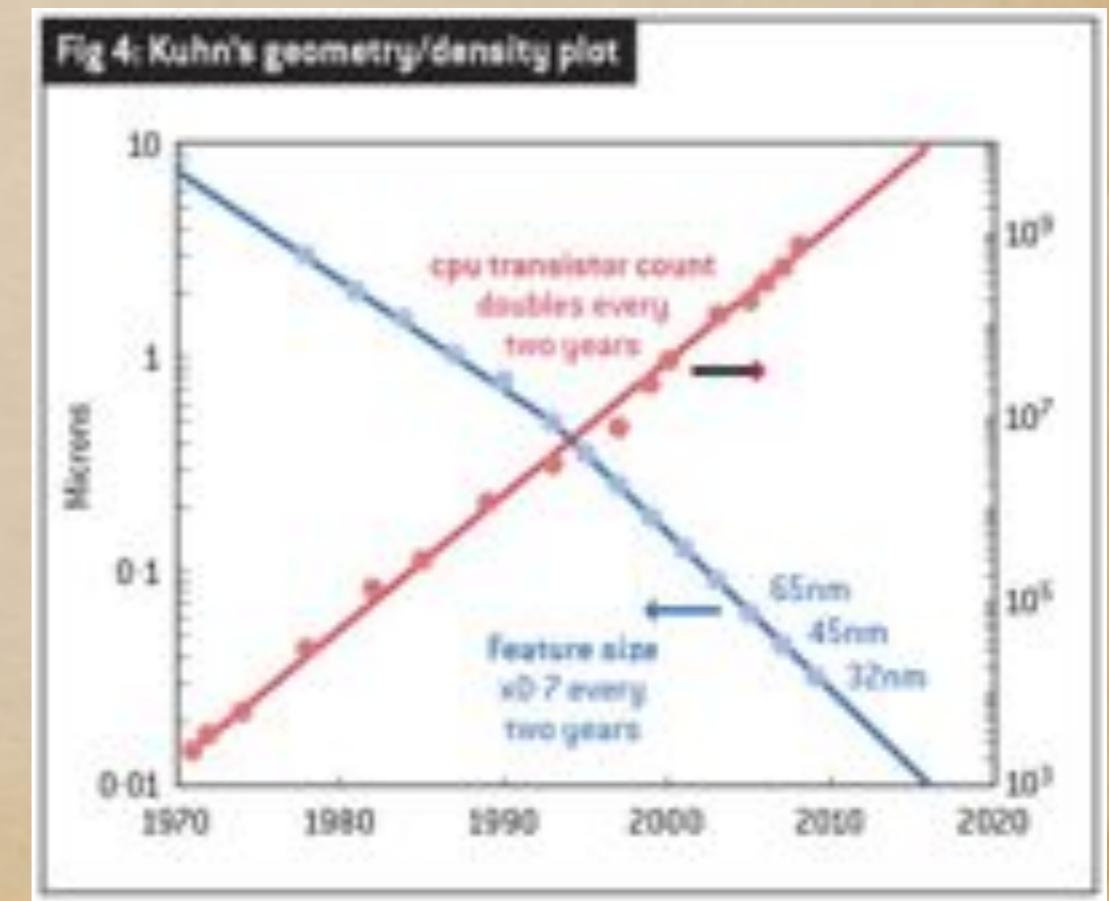


# Electronics, Trigger and DAQ

- Detectors are deaf dumb and blind without good electronics, trigger, DAQ
- Greater design complexity requires shared tools and knowledge
- HEP is still incredibly small compared to consumer electronics
- Trigger/DAQ Ingredients:
  - Fast and large FPGAs
  - Fast bus ( $\mu$ TCA ?)
  - Fast links and switches (10Gb/s)
- Following technology nodes expensive but necessary



- Simultaneous design of all elements of the readout chain
- Strong interaction and optimization
- Enormous power for information extraction

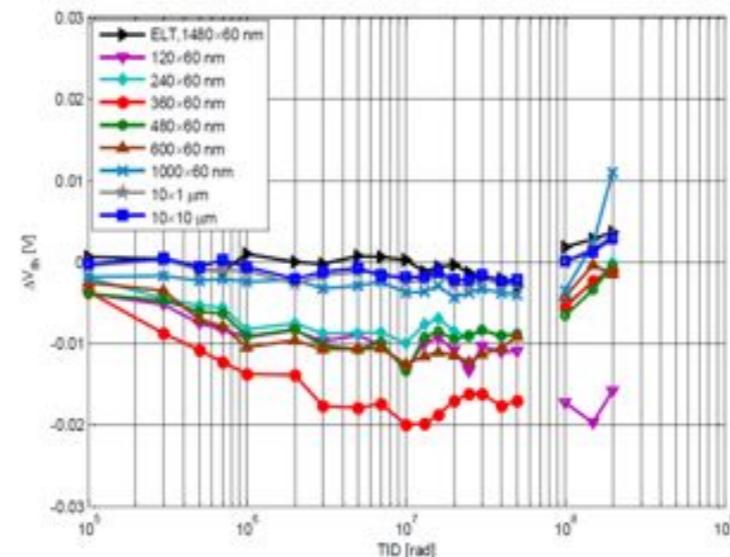


# Electronics technology node

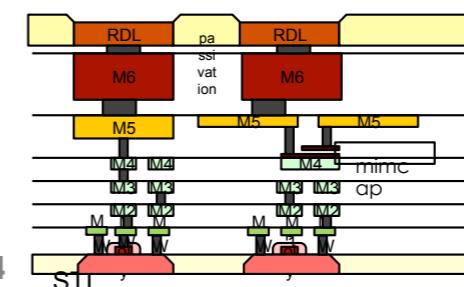
## What we gain using CMOS 65nm

5

- **Radiation Tolerance** (dose,hadrons, SEU)
  - Uses thin gate oxide
  - Verified for up to 200Mrad, better than 130nm: to be confirmed for 1GRad
- **Large amount of digital logic/ memory**
  - Vital for small pixel
  - Logic density: 250nm:~1; 130nm:~4x; **65nm:~16x**
  - Speed: 250nm~1, 130nm:~2x; 65nm:~4x
- **Low power (digital)**
  - 250nm: 1, 130nm: (1/2-1/4) ; **65nm: (1/8-1/16)**
- **Many metal(Cu) layers:**
  - Power distribution, signal distribution, pixel readout busses, etc.
- **Mature technology and stable**



- **Affordable (still...)**
  - **MPW** from foundry and Europractice;
  - Masks costs a lot: ~1 M\$ for an engineering RUN
  - Production similar as 130nm



6+1 metals  
(max to 9+1)

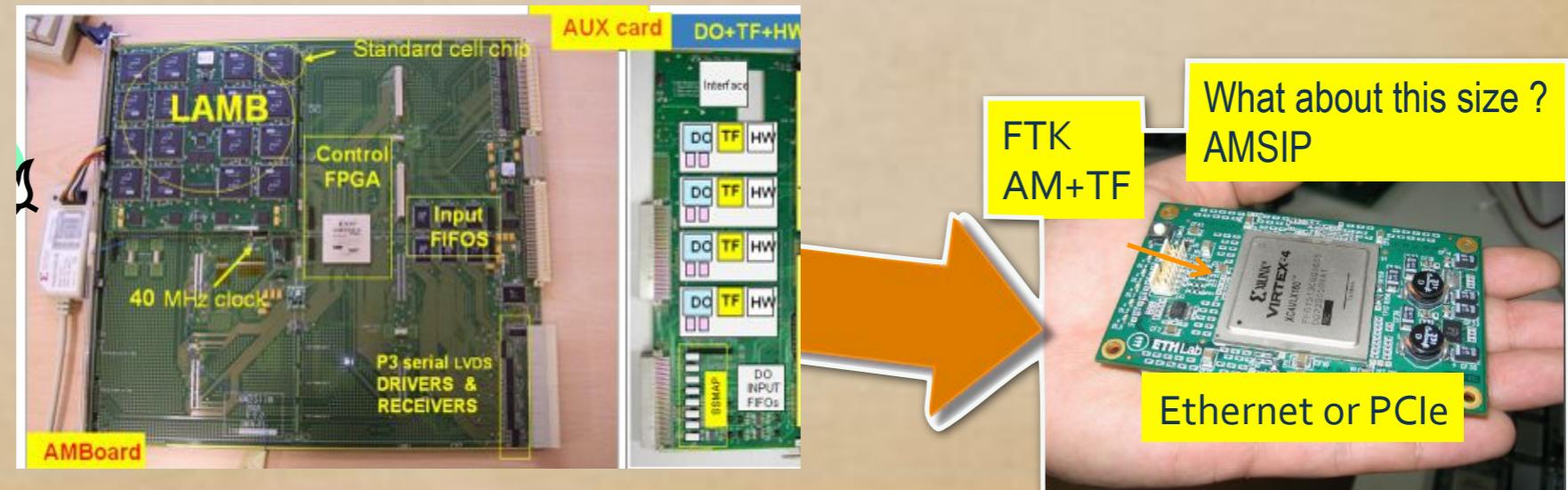
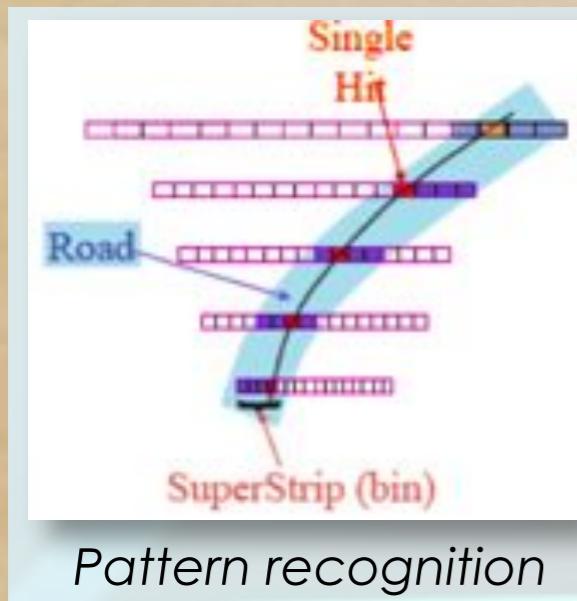
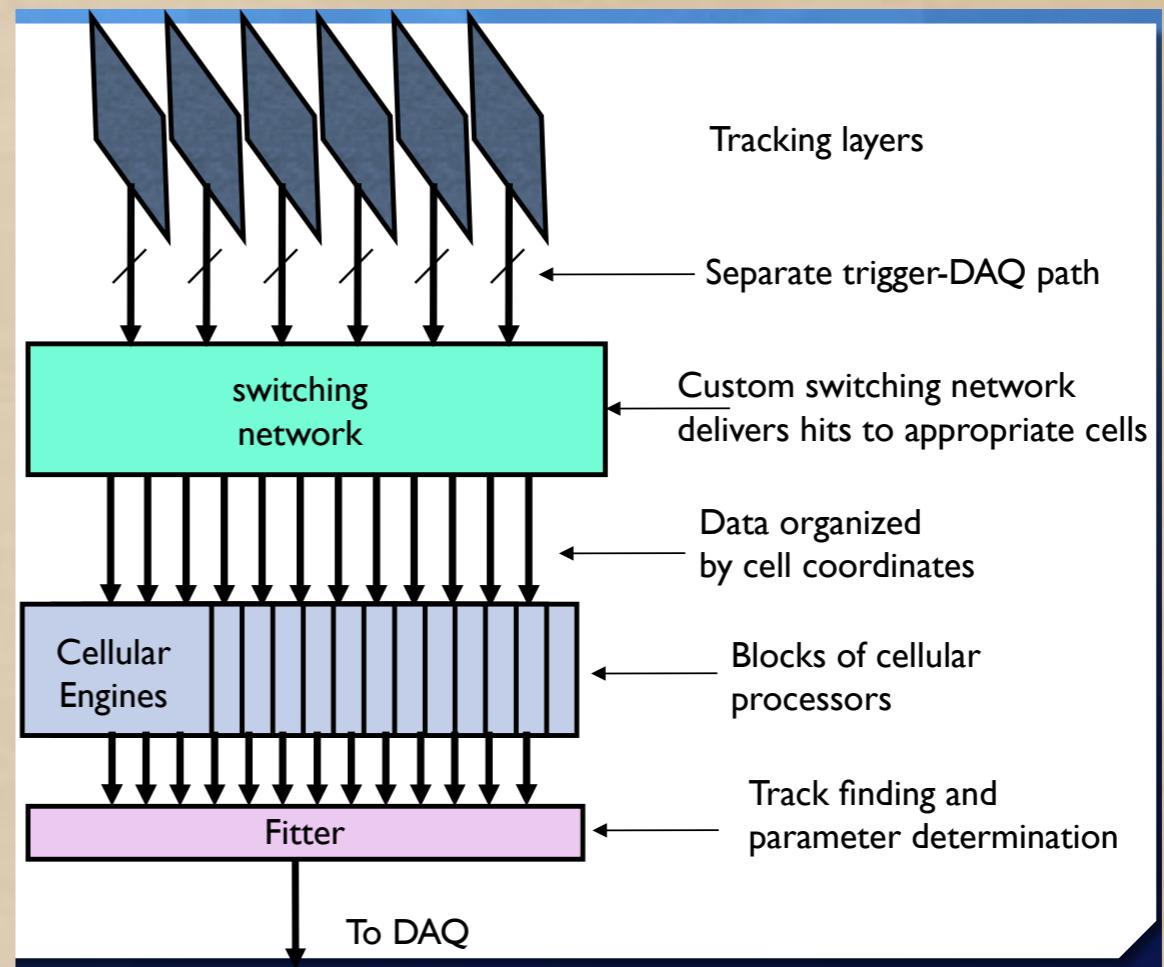
130nm up to  
7+1

12 March 2014

L.Demaria: CHIPIX65 pixel FE for HL\_LHC - INFN Future Detector Workshop 2014

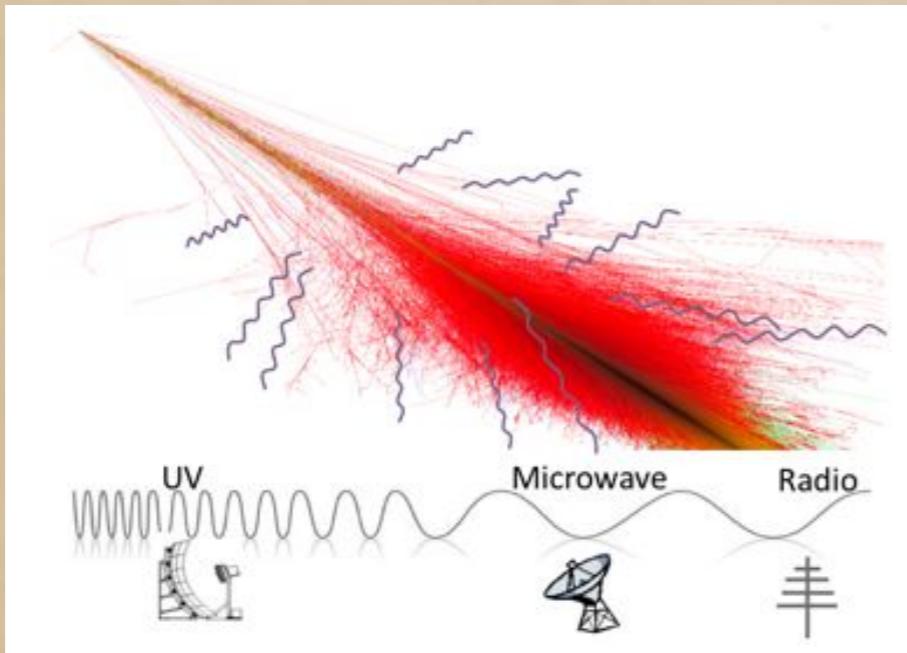
# Track triggers

- Associative memory based trigger proven in CDF, proposed in Atlas, CMS
- LHC-b proposes a vision-based FPGA implemented track trigger
- Enormous potential
  - Can change the way experiments are designed
  - Can make increased luminosity fully useful for physics



# Cosmic frontier: Dark Matter

- ◆ Dark Matter: a known unknown
- ◆ Indirect searches: detect  $\gamma$ ,  $\nu$ ,  $e, p$  generated in annihilation of unknown DM particles.
- ◆ Ground-based: large ( $\text{km}^2$ ) cosmic ray detectors.
  - ◆ Need cost effective solutions
  - ◆ Cerenkov, fluorescence
  - ◆ Radio and microwave detection of showers

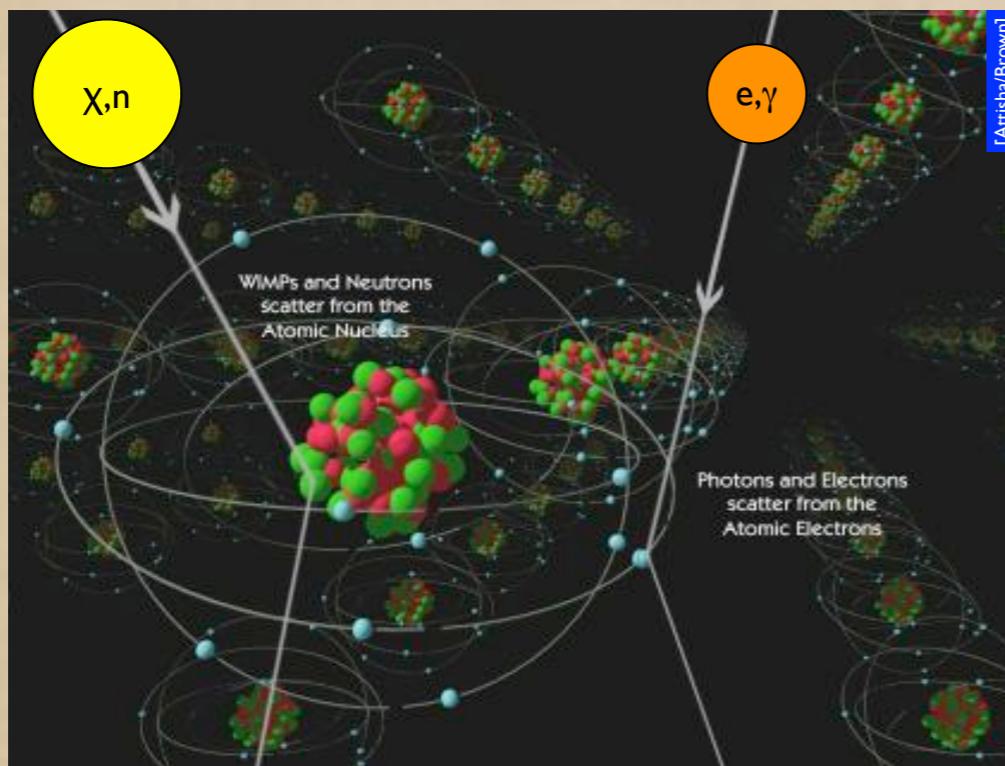


- ◆ Satellite
  - ◆ ca. 30 X0
  - ◆ few % of energy resolution
  - ◆ good angular resolution
  - ◆ high electron/proton separation
  - ◆ Tracker + calorimeter + VETO
  - ◆ LOW POWER - LOW MASS - SPACE



# Detectors for direct DM searches

WIMPS scatter off atomic nuclei:  
multiple signals.



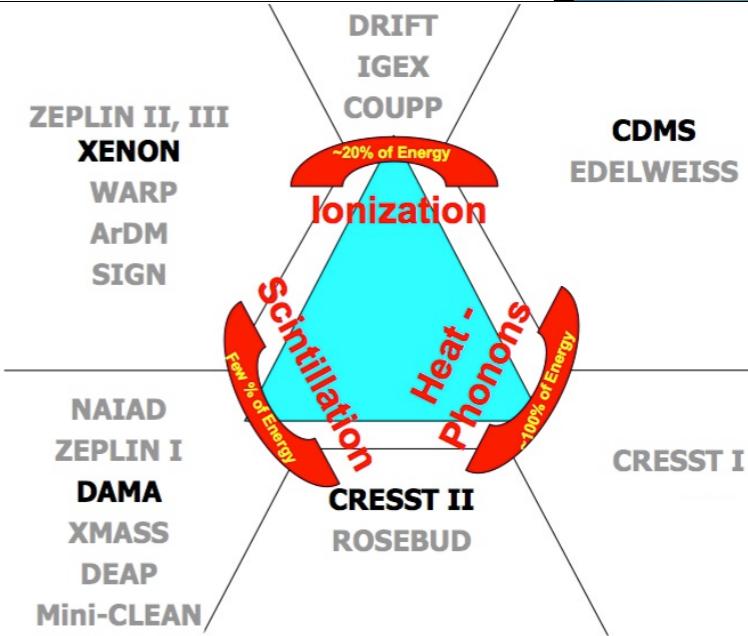
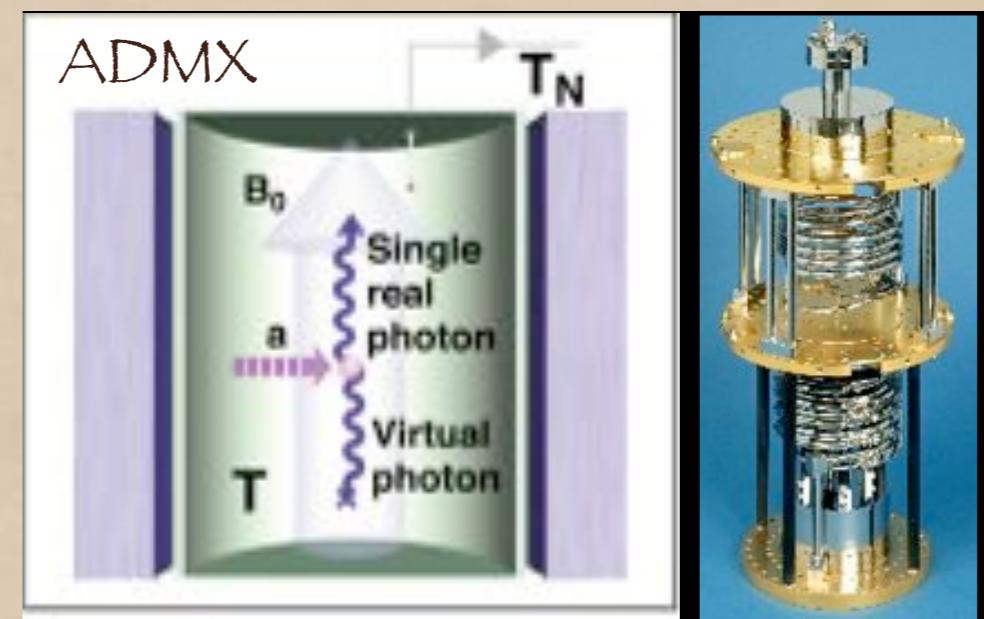
## WIMP Detectors:

Large mass. Very Pure. Background veto  
Low energy nuclear recoils ( $< 100 \text{ keV}$ ).

Low rate: 1 evt/ton/yr @  $10^{-47} \text{ cm}^2$

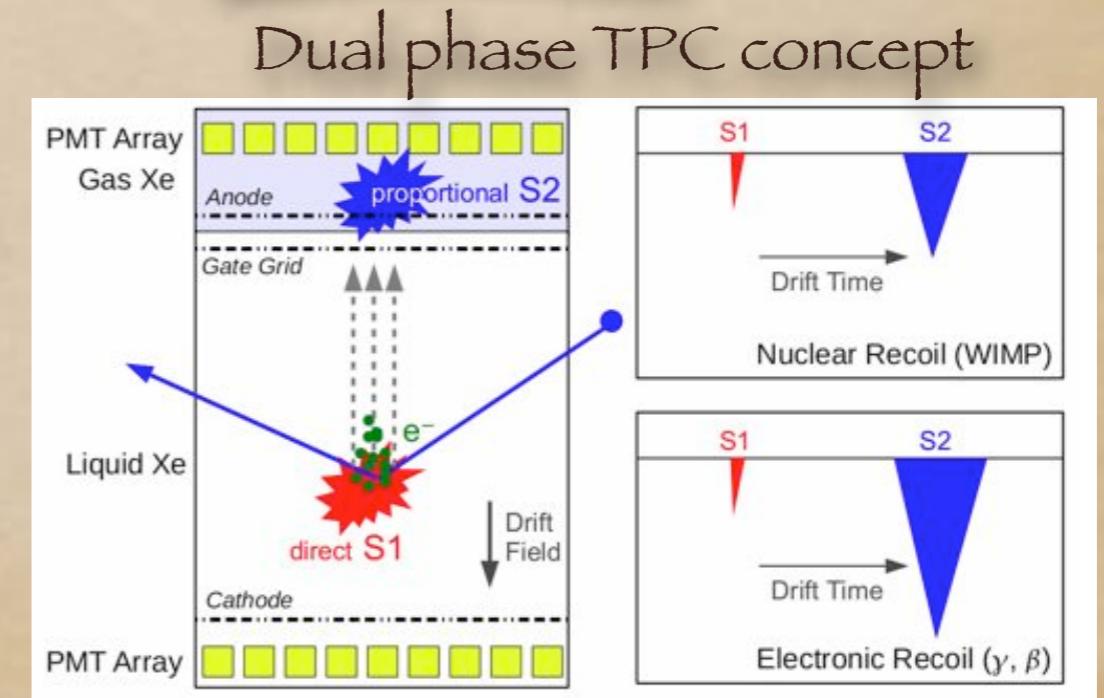
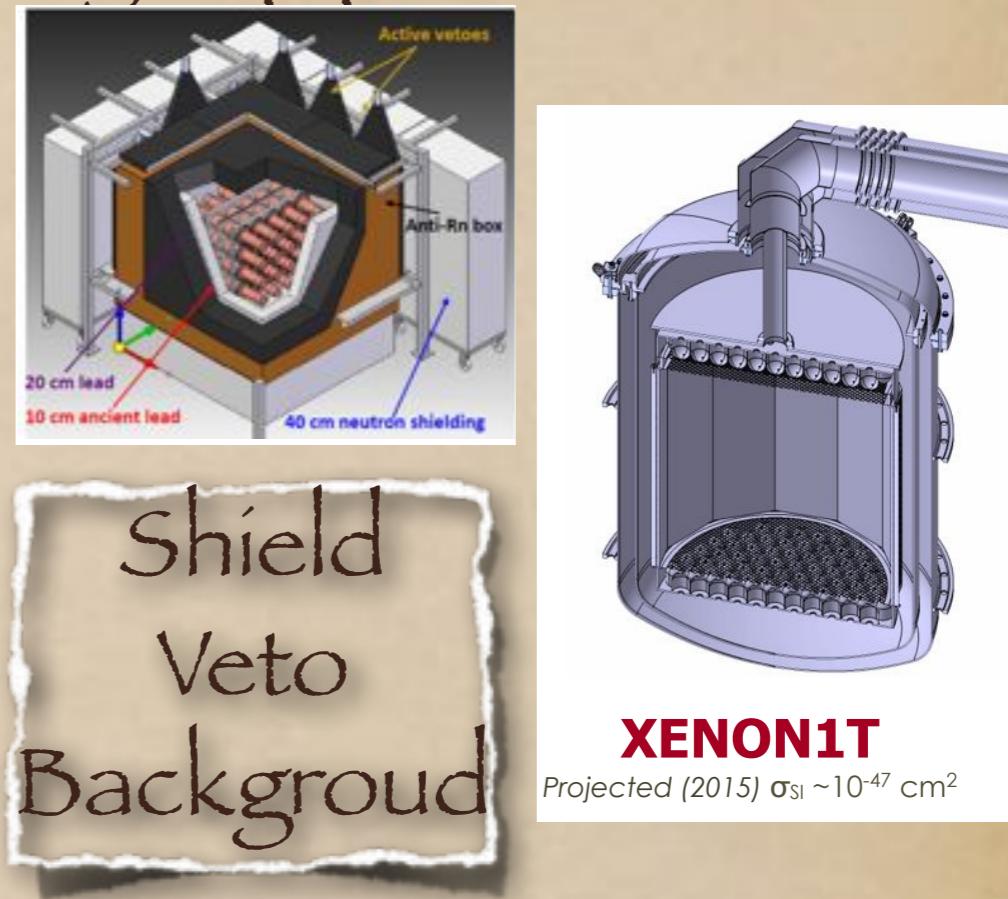
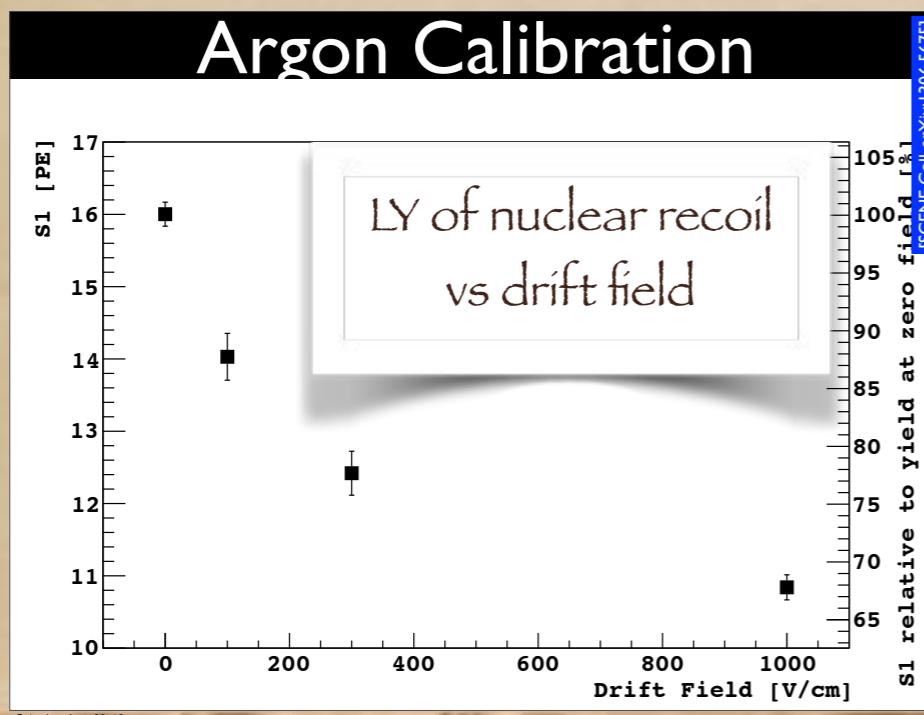
Background measurable in situ

Axions convert into microwave  
photons in an RF cavity threaded  
by a strong magnetic field. SQUIDS



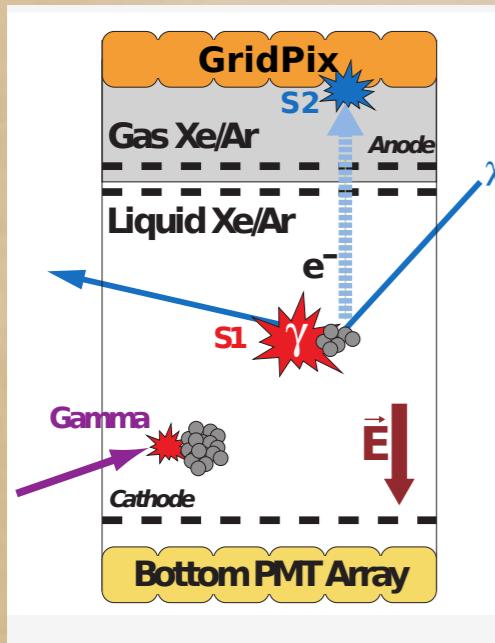
# Detector variations: many approaches

- ◆ Crystals (CsI, NaI, Ge, Si): kg
  - ◆ R&D on purity, shielding, resolution
  - ◆ DAMA/LIBRA, ANAIS plan on 250kg
- ◆ Large noble liquid-gas detectors - ton
  - ◆ Single or dual Phase TPC
  - ◆ LUX, Darkside, Xenon plan on 1000kg
  - ◆ R&D on detector response

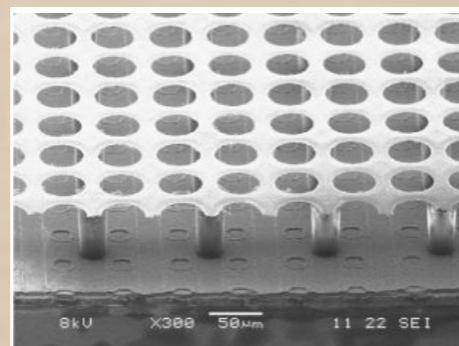


# A selection of novel detector approaches

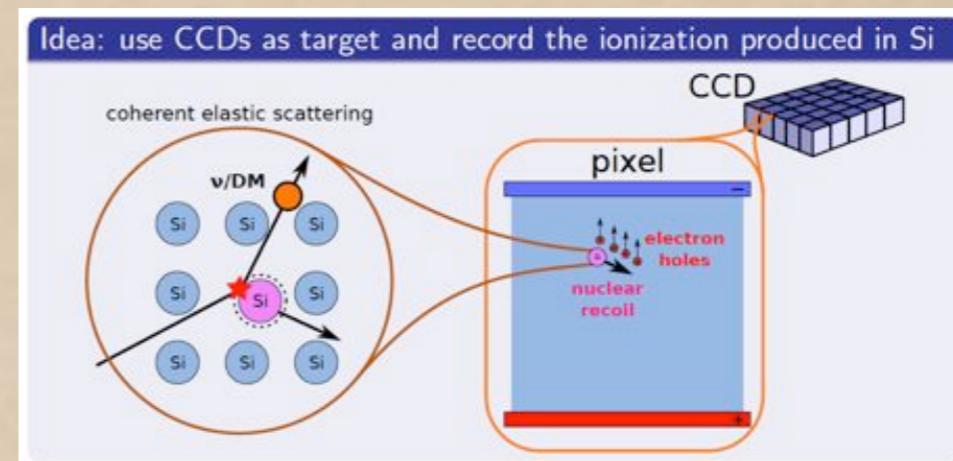
## GridPix gas readout for TPC



Better electron efficiency

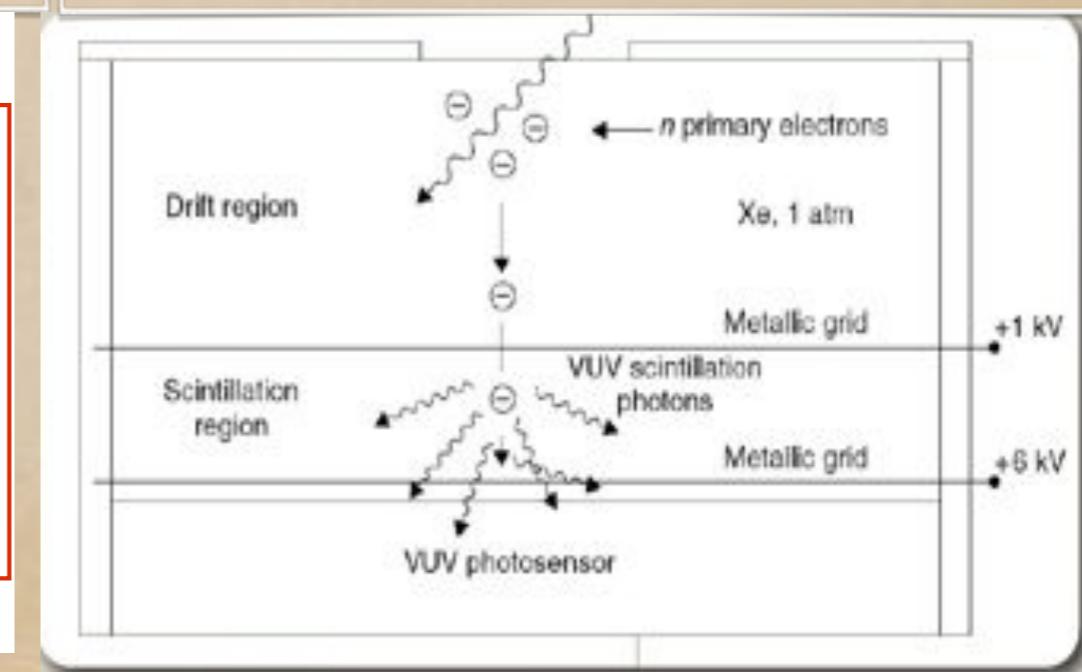
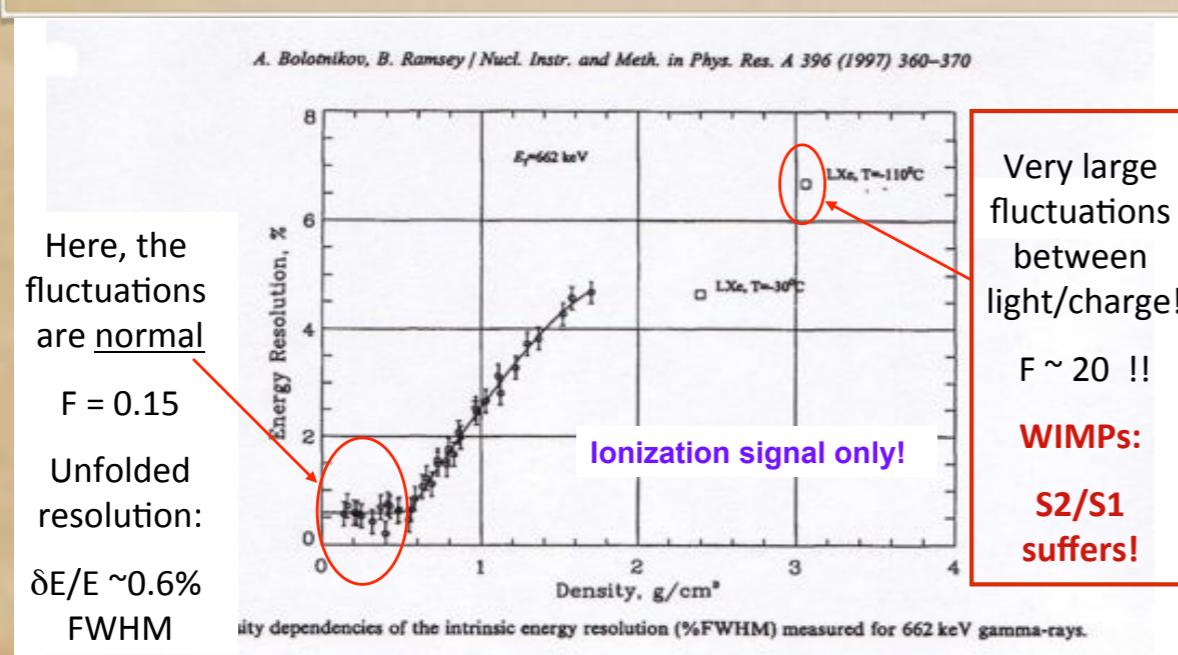


## Thick CCDs (DAMIC)



Electroluminescence: small fluctuations.  
Resolution 1% @ 662 keV  
Good for WIMP and  $\text{O}\nu\beta\beta$

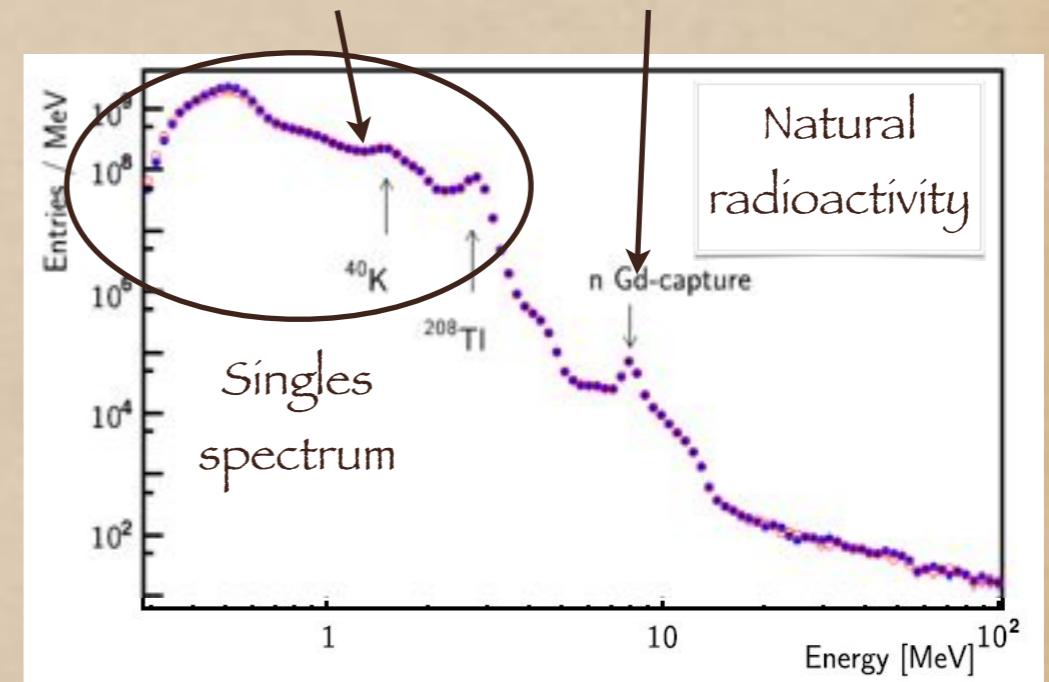
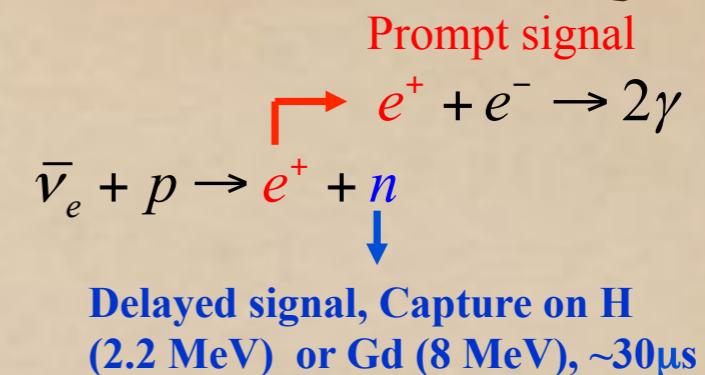
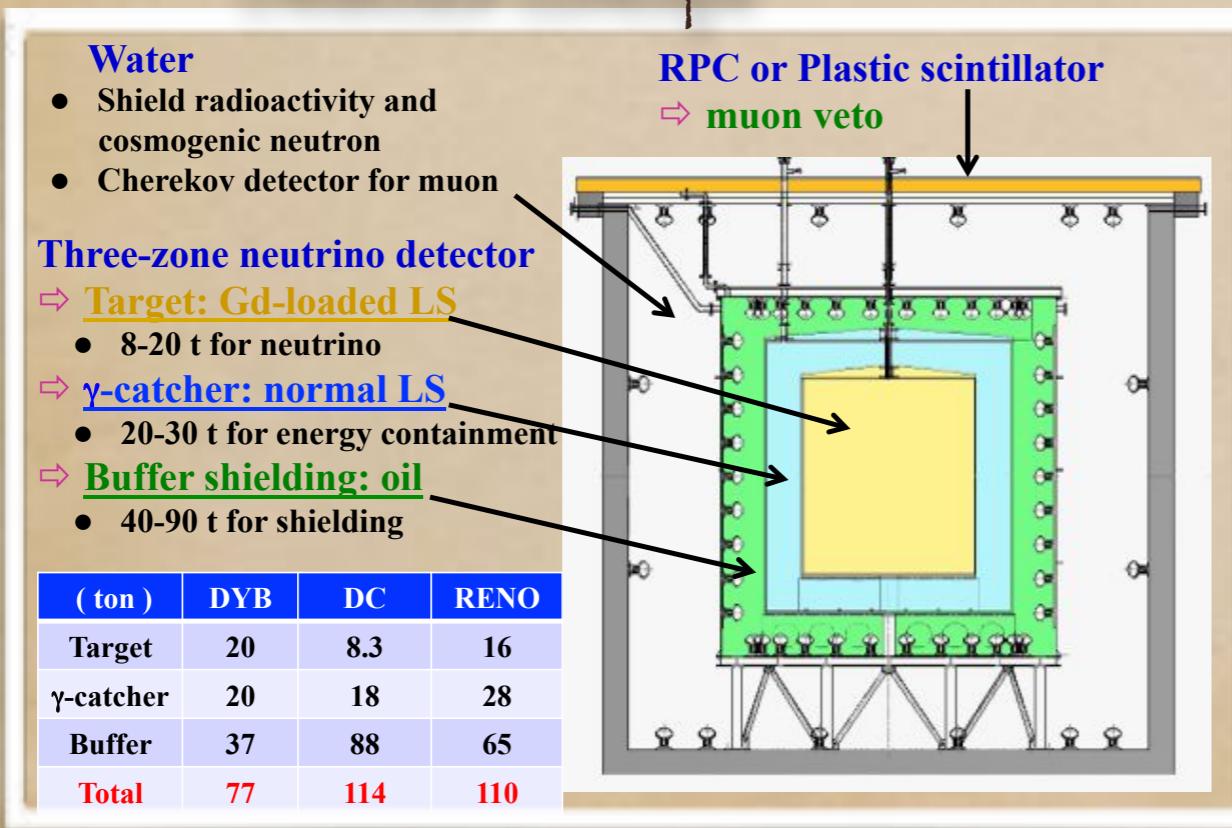
## High pressure Xenon gas TPC



# Detectors for reactor neutrinos (many)

- ◆ Inverse beta decay in water solution:  
coincidence of prompt and delayed signal
- ◆ Liquid scintillator + PMTs
- ◆ Underground for low background
- ◆ Optionally Gd-doped scintillator
- ◆ Near-far measurement to reduce sys.

Detector concept



- ◆ Challenges:
- ◆ LS: purity, Gd Loading
- ◆ PMTs: large number, stability
- ◆ Giant detectors

# Applications - blooming field

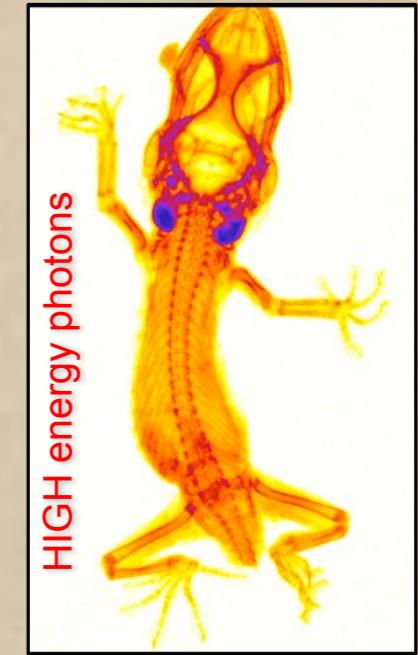
Many HEP Detector technologies applied elsewhere

PIXIRAD - INFN Spin-off

- ◆ Chromatic photon counting X-Ray imaging
- ◆ Large CdTe sensor with CMOS ASIC

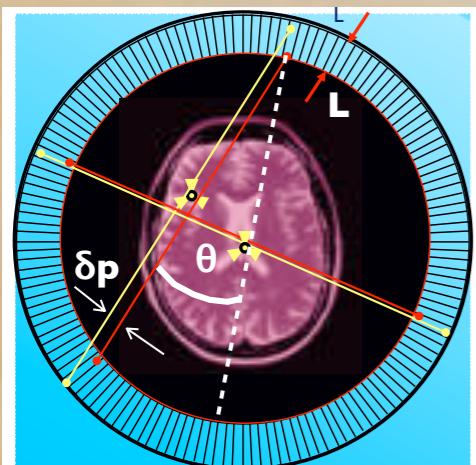


60 $\mu$ m pitch  
30 x 25 mm<sup>2</sup>



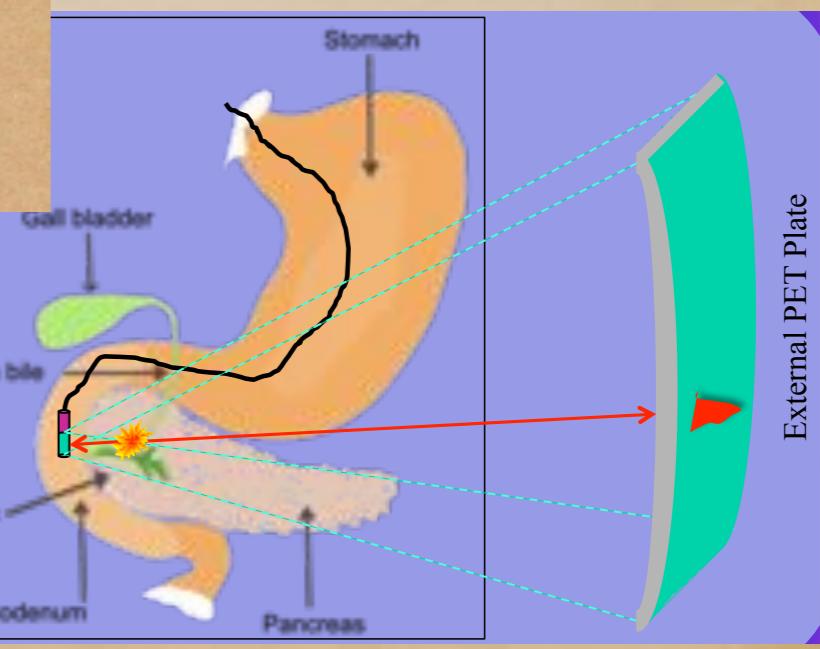
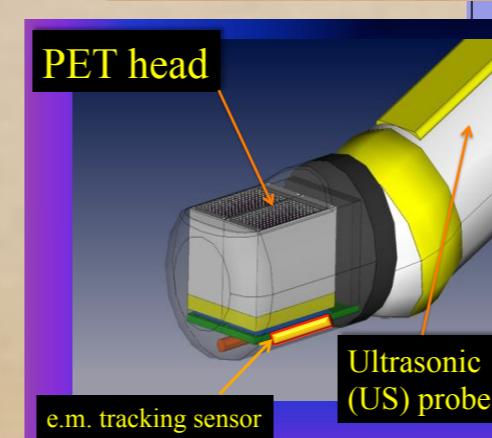
Many Improvements to PET

AXial PET: better resolution/efficiency



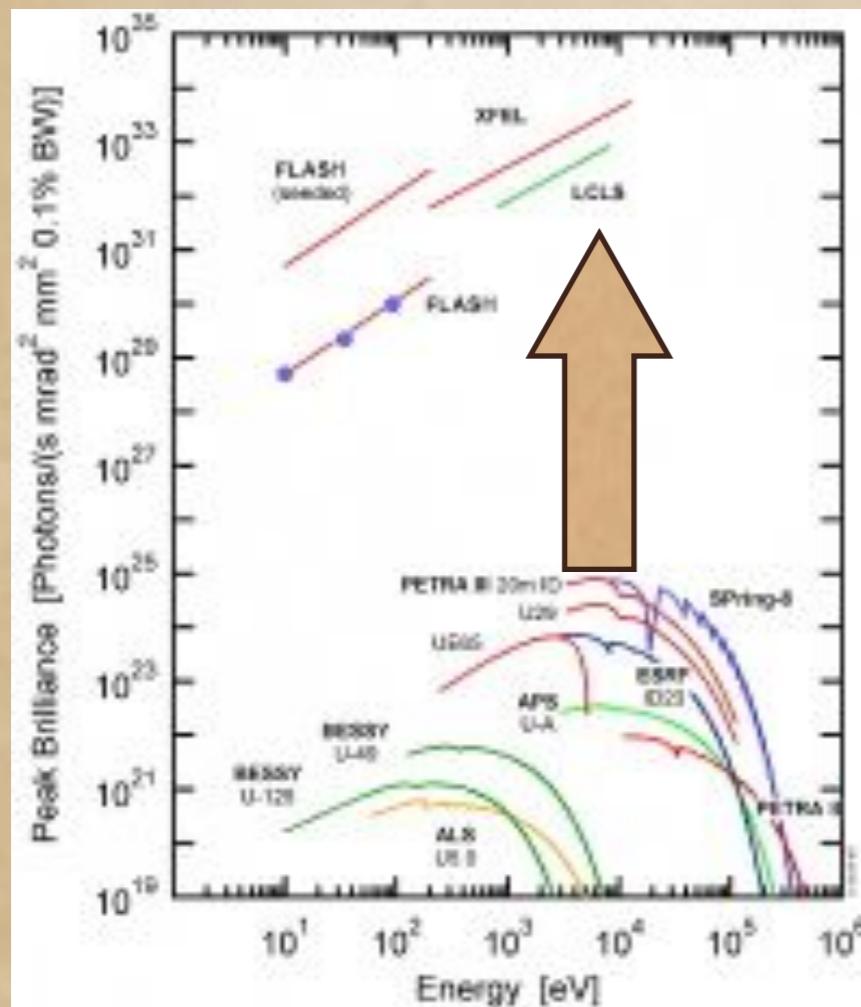
Endoscopic PET

30 $\mu$ m resolution  
multiple sensors

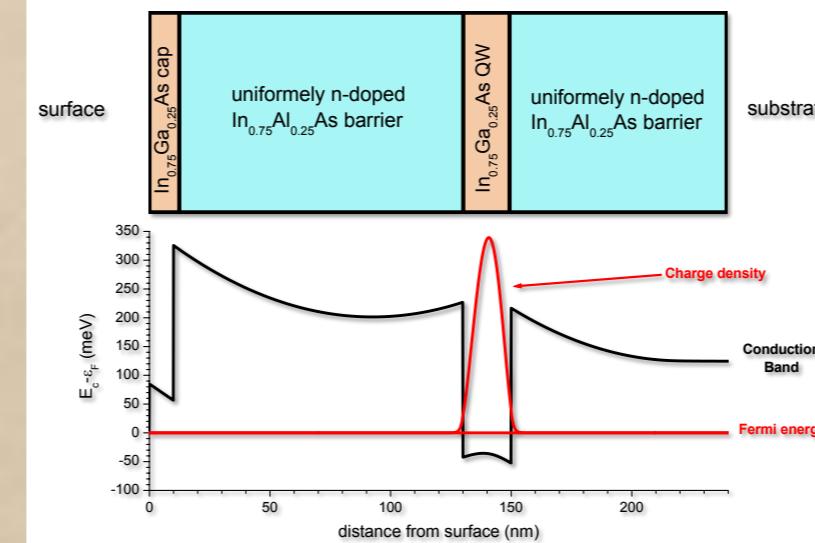


# New challenges: detectors for high brilliance FELs

- ◆ Instruments for other fields: bio, chem, material science
- ◆ Crazy range of photon energies from 0.1 eV to 10 keV
- ◆ High dynamic range ( $10^{-4}$ )
- ◆ High speed
- ◆ High bandwidth
- ◆ Radiation hardness

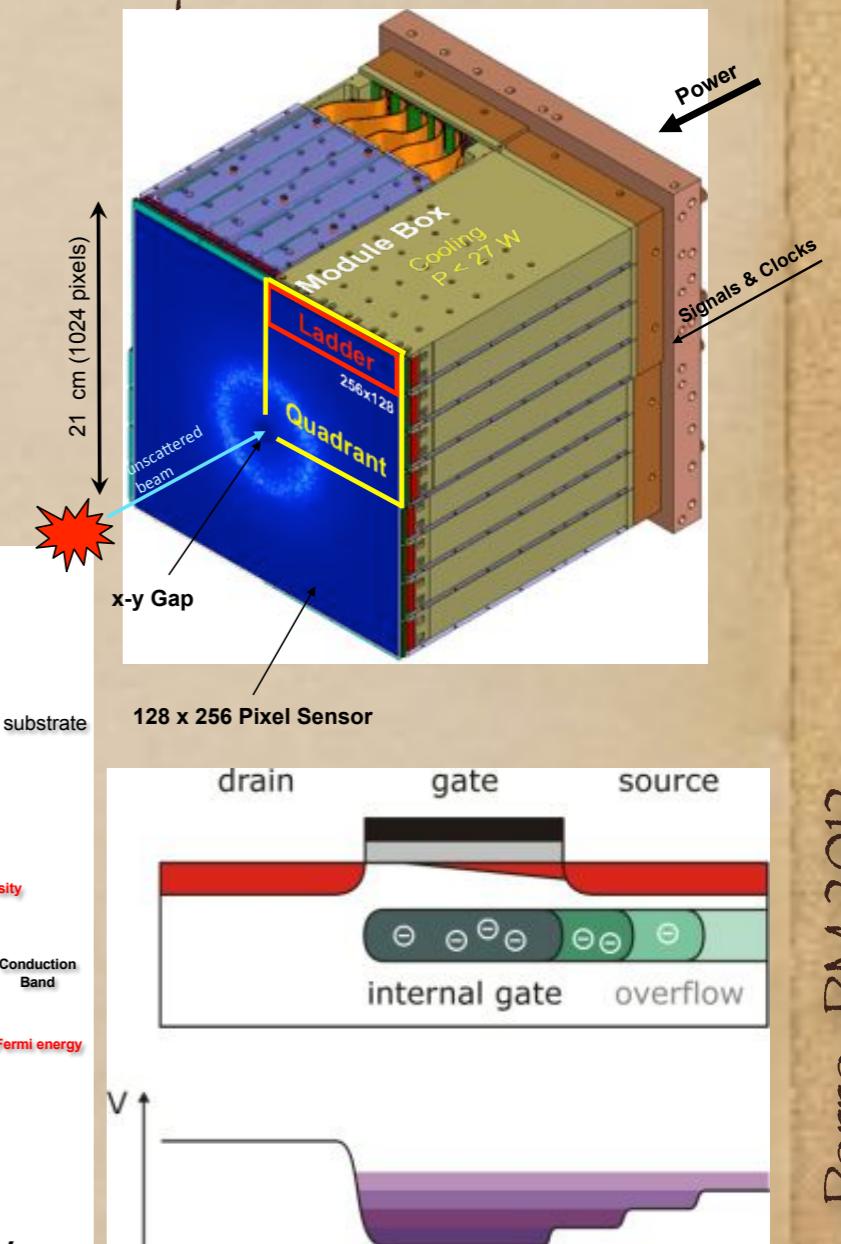


eV Photons  
Quantum Well Detector

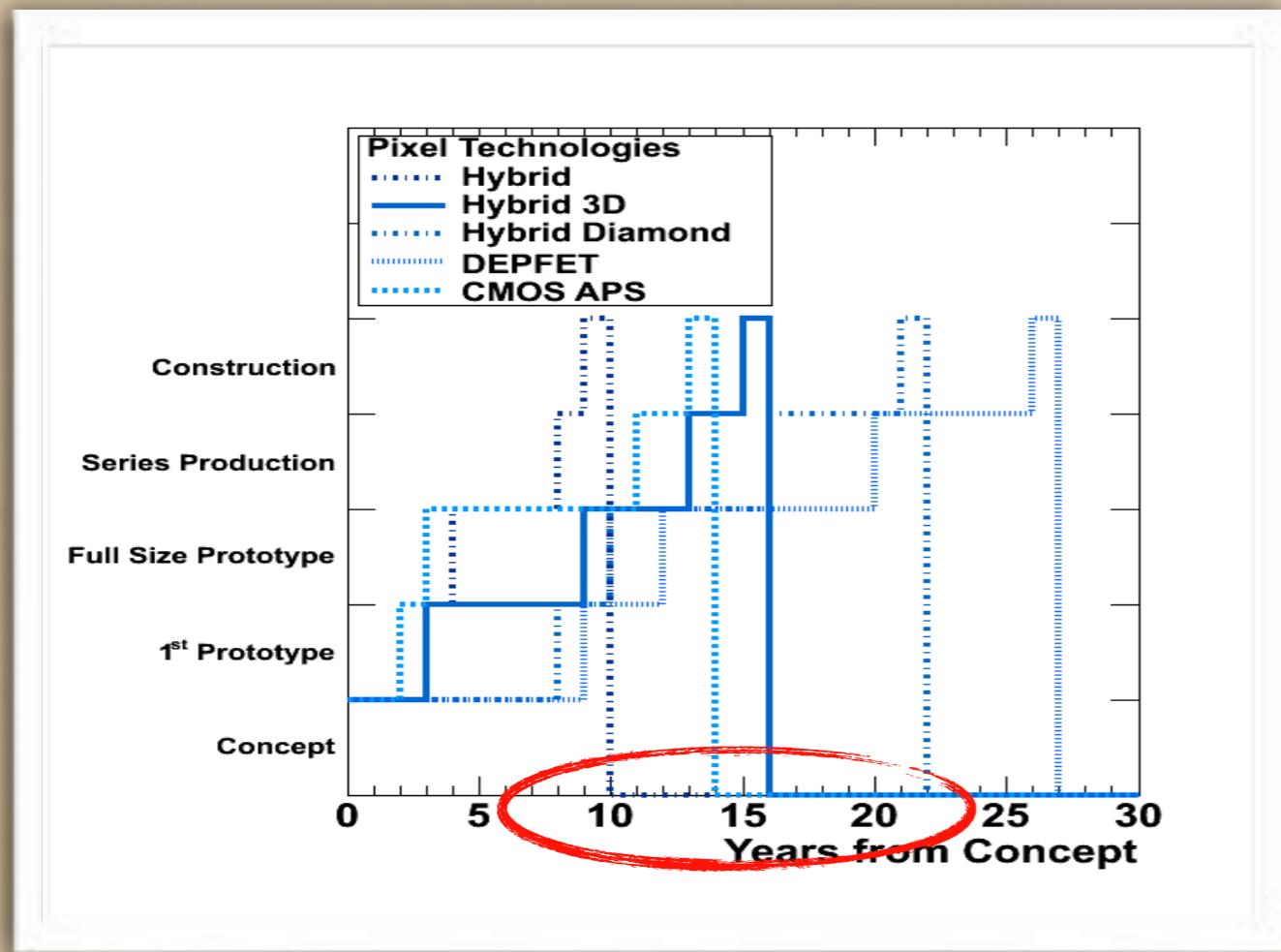


- Intrinsically fast detectors
- Charge amplification capability
- Sensitive from IR to hard x-rays
- Position encoding possible

DEPFET Sensor With Signal Compression (DSSC)



# New Detectors Development



- ◆ Long lead time: technologies require 10-15 years to mature
- ◆ Large costs: need for coordinated action
- ◆ Transition from R&D to production triggered by experiments



# Detectors are our eyes

We as a field need to maintain and develop detector expertise. Today's detector marvels are not automatically reproducible by the next generation. Three essential elements:

1. Training, organizing and stimulating participation in instrumentation schools
2. Experimenting, encouraging young experimentalists to do hands-on detector work especially in smaller, shorter scale experiments
3. Rewarding, giving proper recognition of excellence in instrumentation development in careers at universities and research institutions.

# Sources

- ◆ It is indicated the presenter at the meeting (not necessarily the original author of the work)
- ◆ 2014 Americas Workshop on Linear Colliders 2014, AWLC14:  
<http://agenda.linearcollider.org/conferenceOtherViews.py?view=standard&confId=6301>
- ◆ 2014 INFN Workshop on Future Detectors for HL-LHC, IFD14:  
<https://agenda.infn.it/conferenceOtherViews.py?view=standardshort&confId=7261>
- ◆ 2014 9th “Trento” Workshop on Advanced Silicon Radiation Detectors, TNW14:  
<http://indico.cern.ch/event/273880/>
- ◆ 2013 Lepton-Photon Symposium, LP 2013:  
<http://www-conf.slac.stanford.edu/lp13/>
- ◆ 2013 Vienna conference on instrumentation, VCI 2013:  
<http://vci.hephy.at/>
- ◆ 2012 Crakow European Strategy Meeting:  
<http://indico.cern.ch/conferenceDisplay.py?confId=175067>
- ◆ 2012 Pisa Meeting on Advanced Detectors, PM 2012:  
<http://www.pi.infn.it/pm/2012/>
- ◆ 2011 Technology and Instrumentation in Part. Phys., TIPP 2011  
<http://conferences.fnal.gov/tipp11/>
- ◆ 2010 FNAL Detector R&D Workshop:  
<https://indico.fnal.gov/conferenceDisplay.py?confId=3356>