Recent Developments in Detector Technology

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Introduction

- ✱ Discoveries are limited by detector advances
  - – Must keep pace with moving scientific frontiers, and accelerators
  - – Detectors can rejuvenate accelerator programs

- ✱ Large challenges posed by future scientific opportunities
  - sLHC
  - ILC
  - Super B
  - Neutrinos
  - Dark Matter
  - Astro

  } many common challenges

- ✱ Many advances in promising technologies
  - – Impossible to do justice - apologies for biases and omissions

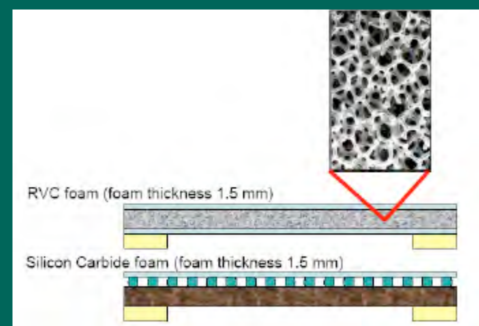
Challenges

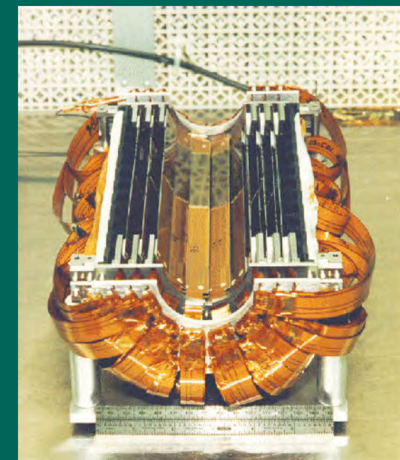
* Precision - energy, momentum, time, space
* Speed/Occupancy
* Radiation Hardness/Background Rejection
* Power/Cooling
* Cost

* Progress presented in several recent major conferences
  - IEEE Nuclear Science Symposium, Dresden, October, 2008
  - TIPP09, Tsukuba, March, 2009
  - 11th Pisa Meeting, May, 2009

Enabling Advances

- ✱ Segmentation
  - 10-300 μm Si pixels, Si Cal, MPGDs
- ✱ Speed & Power
  - Faster electronics, lower noise
- ✱ Integration
  - Microelectronics, mechanics
- ✱ Materials
  - Sensor, rad hard, robust, thin
- ✱ Radiation immunity
  - Understanding, design, annealing

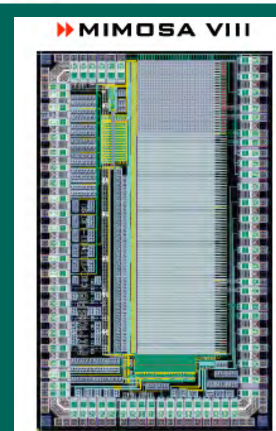


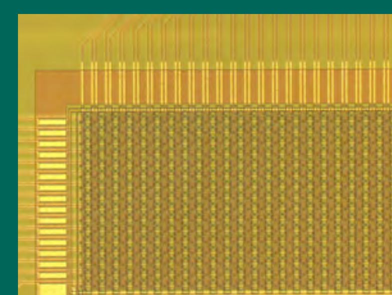


307 Mpixel SLD vxd3

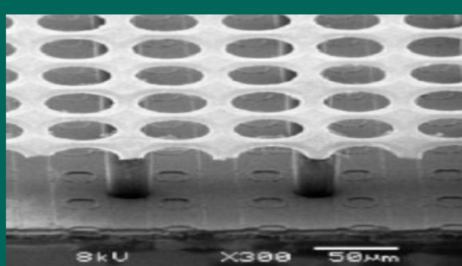
⇩

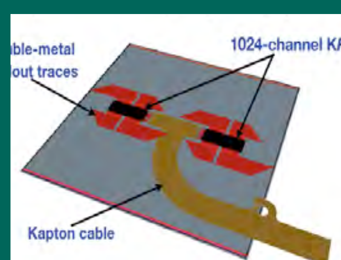
LC - Maintain segmentation with increased speed





16x128 DEPFET-Matrix



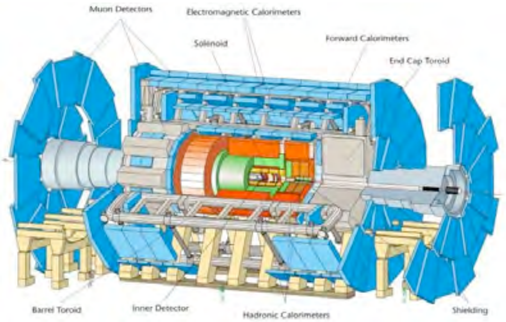


The Enterprise

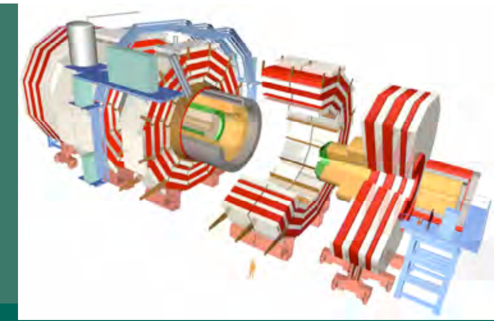
- Applications
  - Colliders
    - Vertex
    - Tracker
    - Calorimeter
    - PID, incl. muon
  - Dark Matter Detectors
  - Neutrinos
  - Ground-based Particle Astro
  - Space

- Core Technologies
  - Silicon
  - Gas
  - Crystals
  - Liquids
  - Readout, Electronics
  - Services, Power, Cooling, Support, Materials
  - Metrology
  - Trigger, DAQ

} Parallel Advances



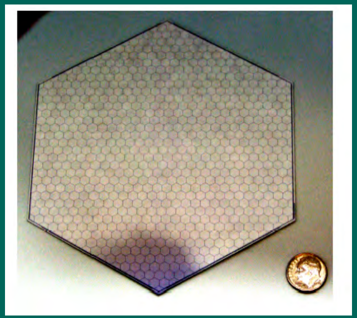
ATLAS and CMS

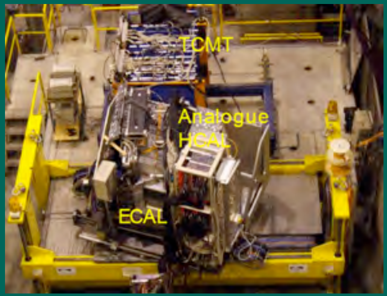


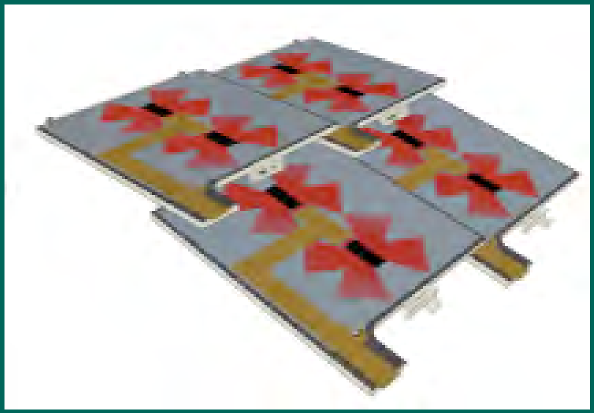
- Successful Construction & Commissioning established critical lessons for future
- Upgrades for increased LHC luminosity
  - 10^{35} for sLHC at end of decade (shutdown ~2017)
- Inner trackers
  - Complete replacement (even for lower luminosity due to accumulated radiation)
  - Radiation damage limits
  - Increased rate (eg. ATLAS TRT)
  - Improved granularity - for pattern recognition
- Other systems will need some upgrades, esp. electronics

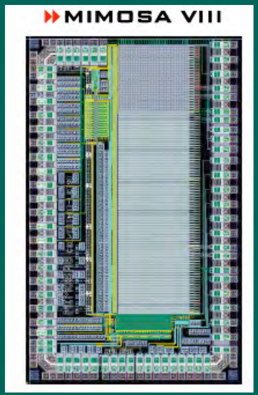
Linear Collider Detectors

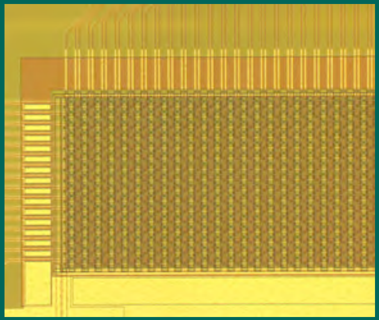
- Goals - exceptional precision and time stamping
  - Bunch train is ~3000 bunches over 1 msec (ILC)
- Vertex detectors
  - < 4 μm precision w/ ~20 μm pixels
- Trackers
  - $\sigma(1/p)$ ~ *few* $\times 10^{-5}$
- Calorimeter
  - 3-4% $\sigma(E_{jet})/E_{jet}$ for E_{jet} > 100 GeV

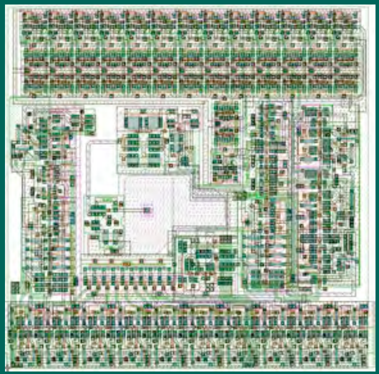










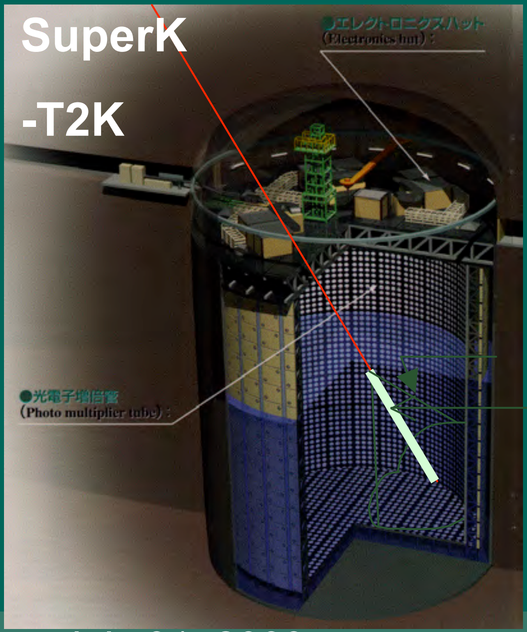


Heavy Flavor Experiments

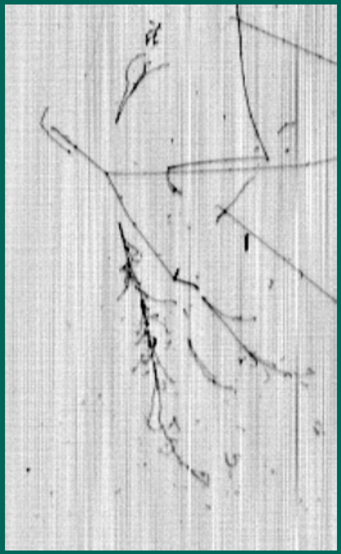
- LHC-b
  - Radiation - rad-hard vertex locator
- Super B
  - Reduce scattering in tracker - thinner
  - Endcap crystals - radiation
  - Endcap PID
- NA62 ($K^+ \rightarrow \pi^+ \nu \bar{\nu}$)
  - giga-tracker
  - RICH
- MEG ($\mu \rightarrow e \gamma$)
  - Liquid Xe Calorimeter
    - purity, cal response, calibration

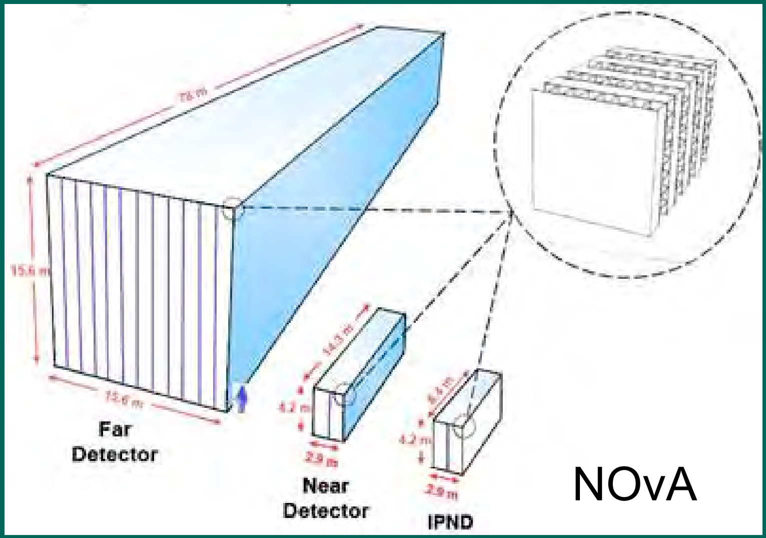
Neutrinos

- Current and recent advances
  - MPPC (SiPMs) at T2K
  - NOvA (~15 kton seg. Liquid Scintillator)
- Future (toward the ~MegaTon detector)
  - Large liquid argon TPC - tracking
  - New PMTs (low cost) - H_2O Cherenkov



Cherenkov
Charged particle





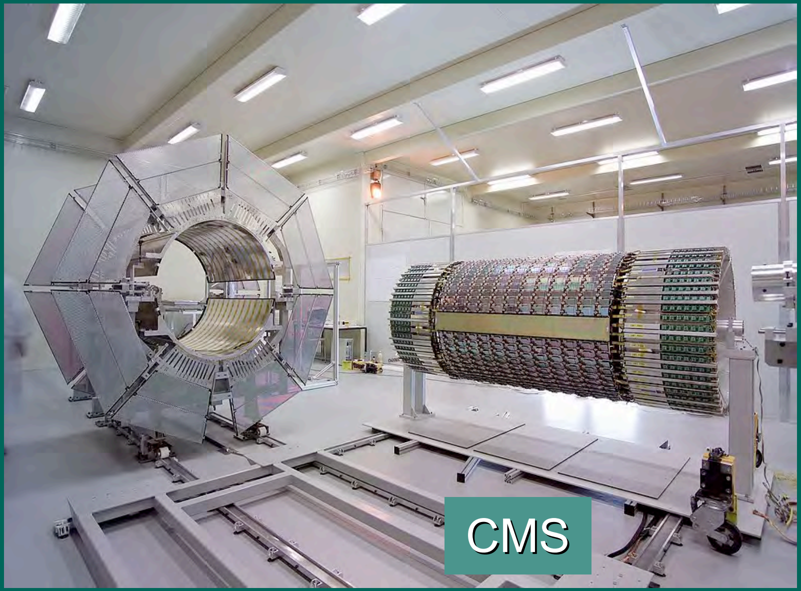
Direct Dark Matter Detection

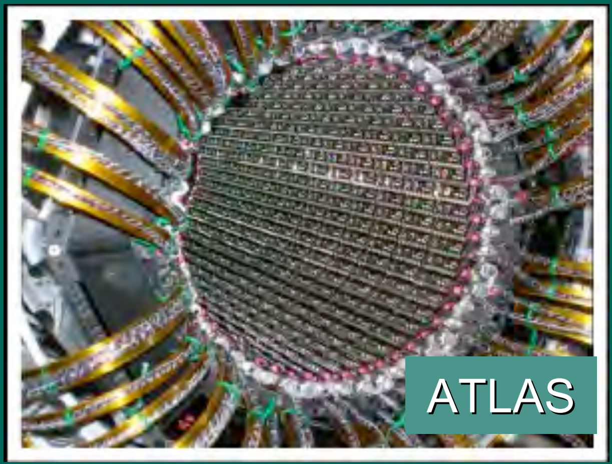
- large mass
- low energy threshold (a few keV)
- background suppression
  - deep underground
  - passive shield
  - low intrinsic radioactivity
  - gamma background discrimination

- Signatures
  - Ionization
  - Scintillation
  - Phonons

Silicon

- Construction/commission experience of LHC and Fermi
- Future challenges
  - Increased rate and radiation at sLHC
  - Increase precision for ILC and B factories
  - Specialize applications, such as NA62 Gigatracker

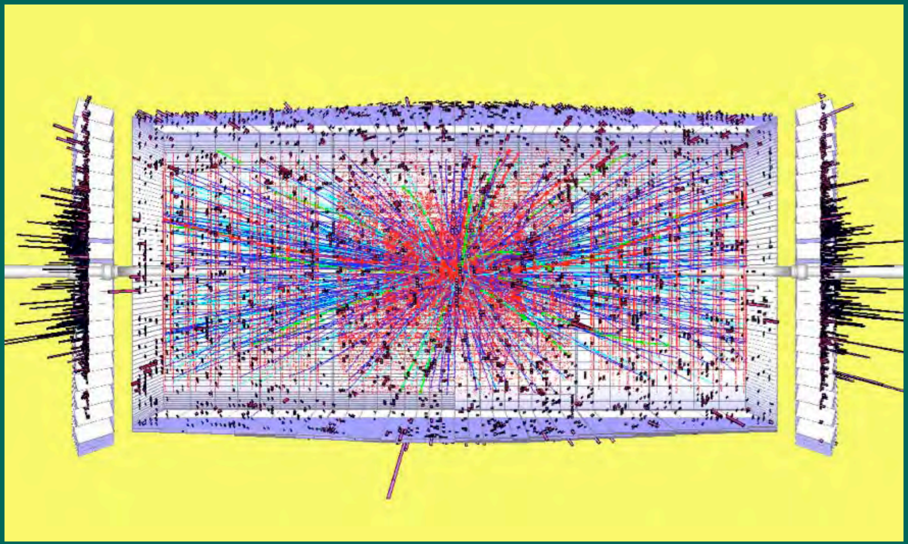




sLHC Tracking

- Intense Radiation Levels
  - 10^{16} /cm^2 @ 5 cm (~400 MRad)
  - 10^{15} /cm^2 @ 20 cm (~40 MRad)
  - 2×10^{14} /cm^2 @ 50 cm (~10 MR)

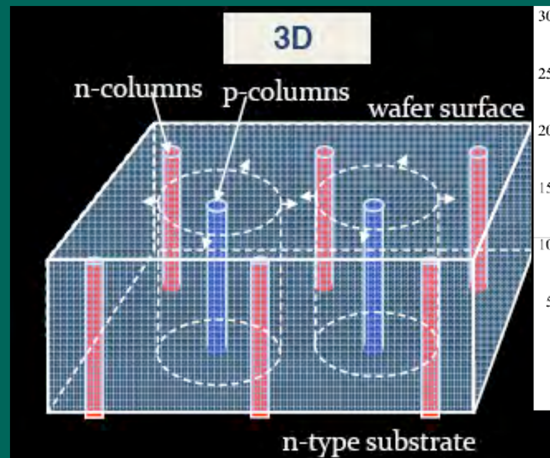
  (dictates technology for tracker)
- R > 20 cm
  - Silicon Strips (> 60 cm)
  - Pixels (20 - 60 cm)
- R< 20 cm
  - New technologies

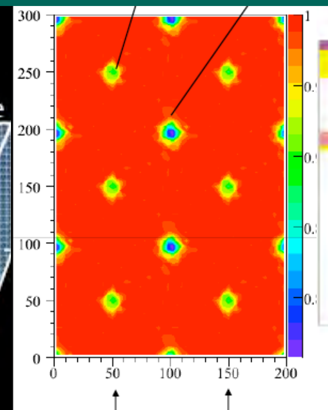


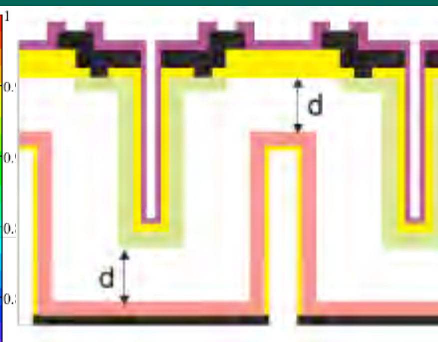
- 300-400 events/crossing
- ~ 10000 particles in $|\eta| \leq 3.2$
- mostly low p_T tracks

sLHC Inner Tracking (R<20cm)

✱ ATLAS Candidates:
- Planar
- 3D-silicon
- Diamond
- GOSSIP (Gas Pixel)



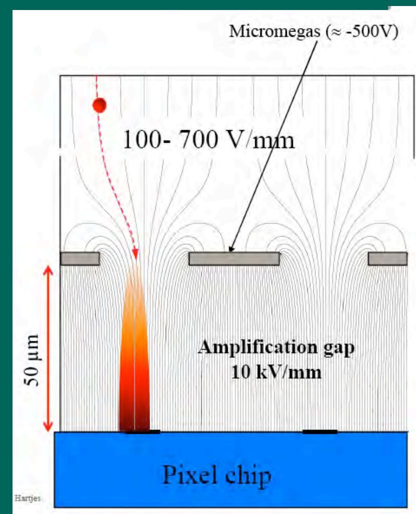


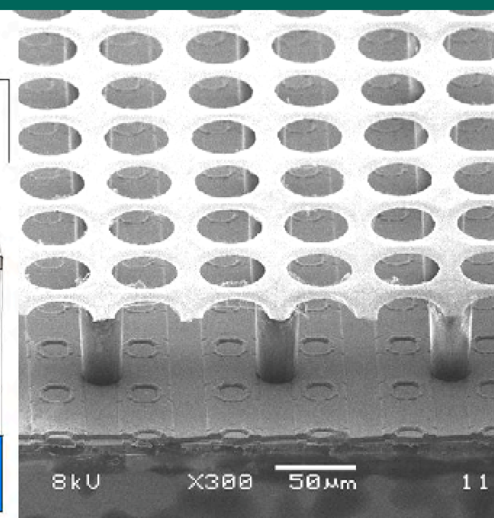


3D- Double Type Columns

technology	Planar silicon	3D silicon	Diamond	Gossip
possible pos resolution (um)	< 10	< 10 ?	~ 14 (polycryst)	~20
resolution for inclined tracks	reasonable	reasonable	reasonable	mediocre
charge collection time (ns)	< 6	20 - 35	2	20 - 80
mass including cooling	pretty high	pretty high	medium	low
life time in SLHC (3000 fb-1)	20 - 50%?	~ 50%	~ 50%	> 100% poss
production technology	well known	difficult	difficult	much R&D
bias voltage control	easy	easy	easy	critical
ease of operation	reasonable	reasonable	relaxed	critical
cooling	critical	less critical	relaxed	relaxed
additional services	NO	NO	NO	HV + gas
additional DAQ channels	NO	NO	NO	probably
track efficiency	100%	>95%?	98-100%	98%
costs	75 - 300 €/cm2	150 - 300 €/cm2	~ 1000 €/cm2 ?	20-30 €/cm2
size of coll. (ATLAS institutes)	>10	10	6	2
approved R&D?	yes	yes	Yes	near submit

ATLAS F. Hartjes





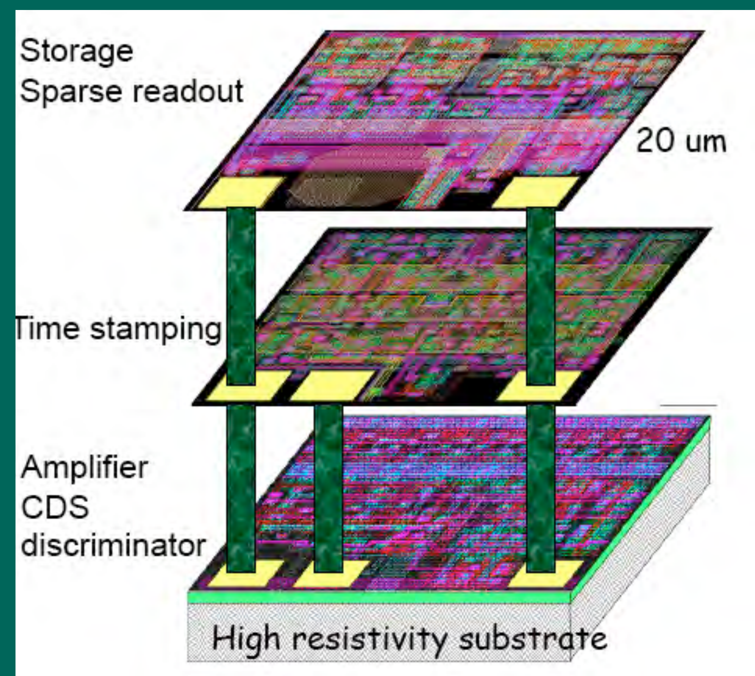
GOSSIP

Silicon for Linear Collider
vertex sensors

- ✱ **Excellent spacepoint precision (** < 4 microns **)**
- ✱ **Superb impact parameter resolution (** 5µm ⊕ 10µm/(p $\sin^{3/2}\theta$) **)**
- ✱ **Transparency** (~0.1% X_0 per layer **)**
- ✱ **Track reconstruction (** find tracks in VXD alone **)**
- ✱ **Sensitive to minimal bunch crossings (** <150 = 45 µsec for ILC)
- ✱ **EMI immunity**
- ✱ **Power Constraint** (< 100 Watts)

<u>Concepts under Development</u>

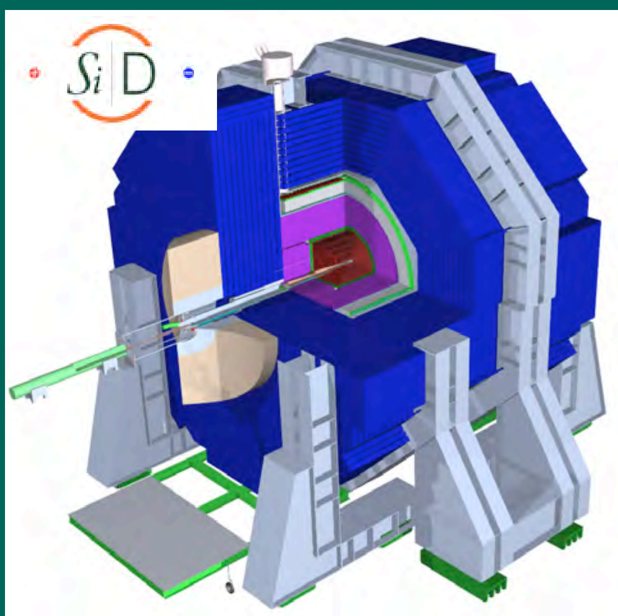
- ✱ **Charge-Coupled Devices (CCDs)**
  - **Build on 307Mpx of SLD ⇒ Column Parallel CCDs, FPCCD (slow!)**
- ✱ **Monolithic Active Pixels – CMOS**
  - **MAPs, FAPs, Chronopixels, 3D-SOI**
- ✱ **DEpleted P-channel Field Effect Transistor (DEPFET)**
- ✱ **Silicon on Insulator (SoI)**
- ✱ **Image Sensor with In-Situ Storage (ISIS)**
- ✱ **HAPS (Hybrid Pixel Sensors)**

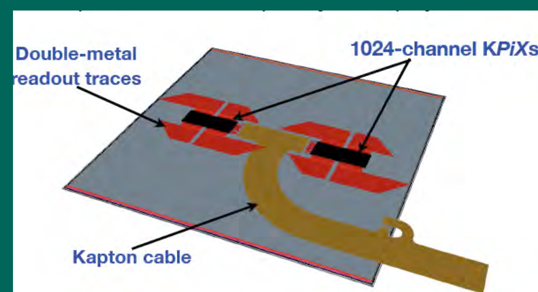


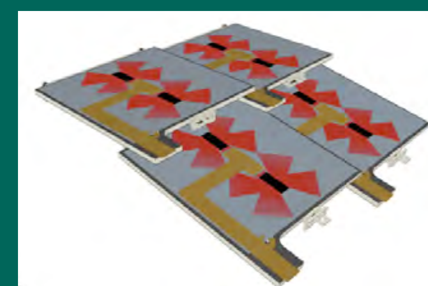
3D concept - Yarema

Silicon for Linear Collider
tracker

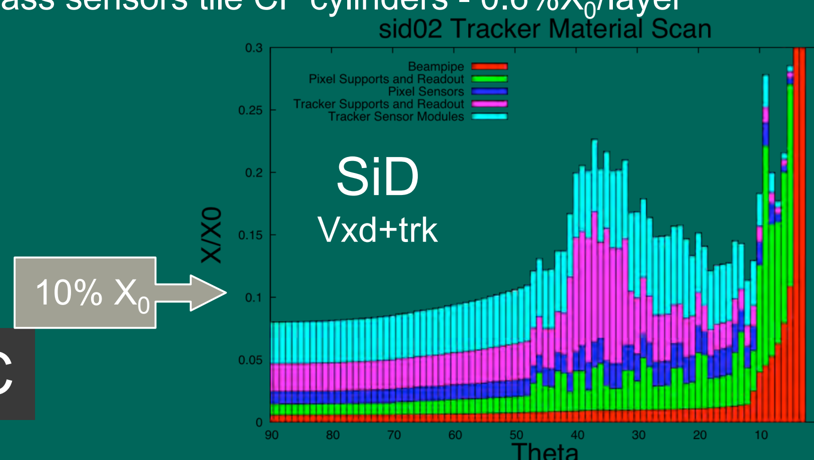
- ✱ Superb resolution allows small tracking volume
  - – <1% σ_p/p at 100 GeV
- ✱ Fast - robust to backgrounds
- ✱ Requires very low mass support (passive cooling)







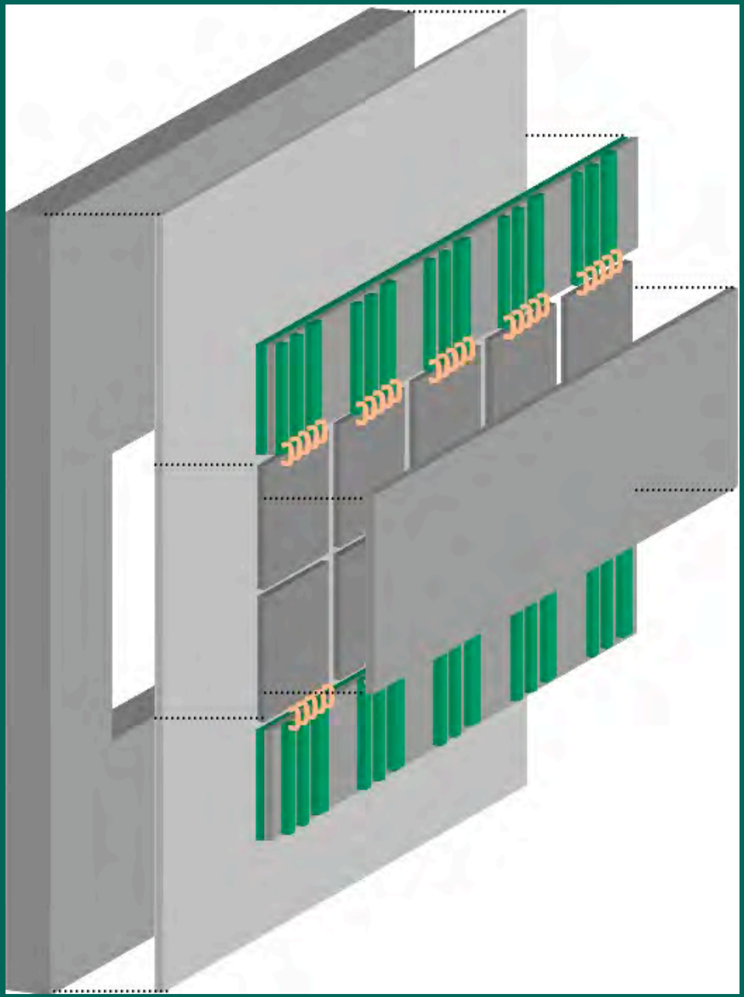
Modular low mass sensors tile CF cylinders - 0.6%X_0/layer



ALSO - SiLC - Silicon envelope for TPC

NA62 Gigatracker

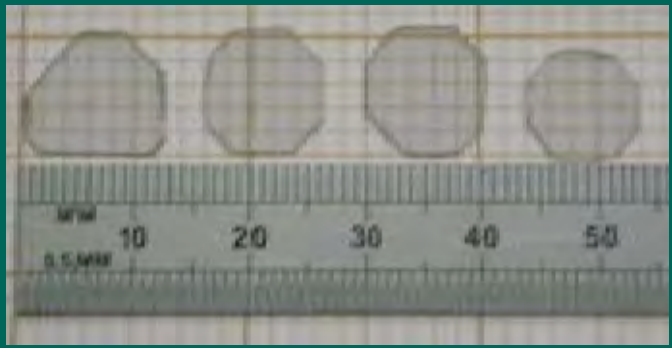
- Three silicon pixel sensors
  - Precise direction & timing
  - ~ GHz rate
  - 1.5 MHz/mm^2 maximum
  - In vacuum
- Two readout options
  - Constant Fraction Discriminator (CFD) with complex pixel circuitry
  - Time Over Threshold (TOT) with simple, low power pixel circuitry
- Prototypes of analog for both options in CMOS 0.13 μm passed tests

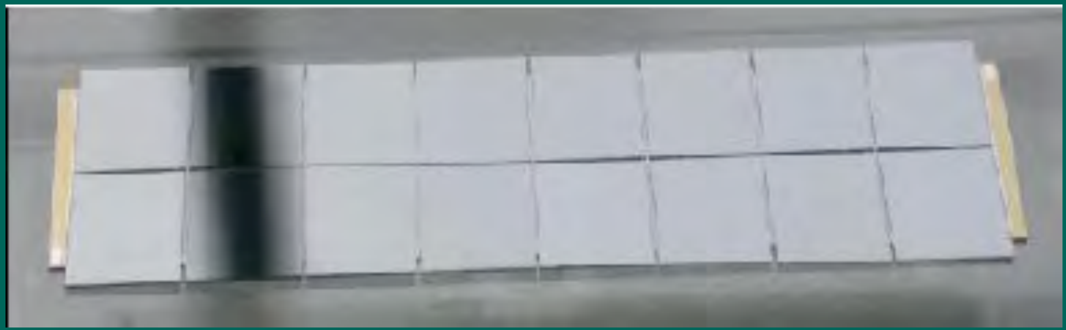


Diamond

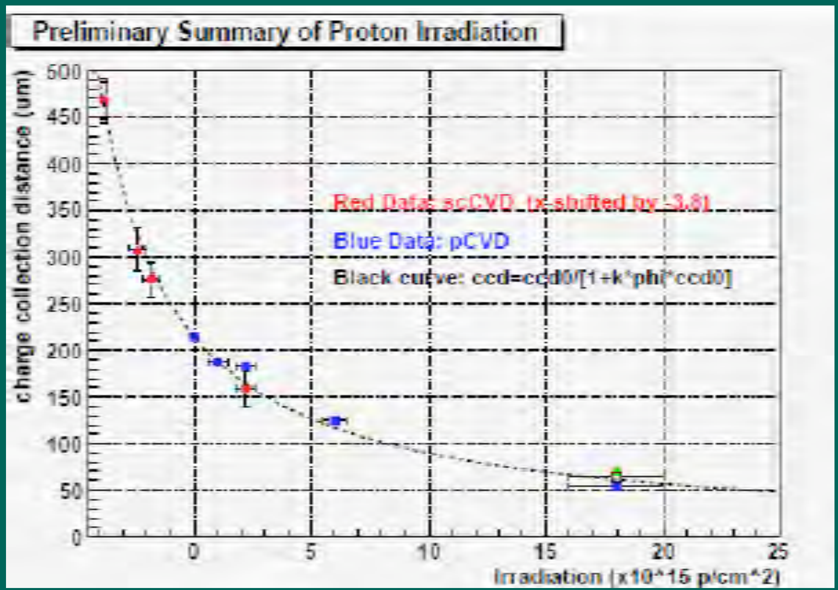
- Advantages over silicon
  - Larger bandgap
  - Smaller dielectric constant
- Single Crystal (> 12 cm, 2 cm thick) polycrystalline (few cm^2)
- Experience as radiation monitors
- Candidate for LHC inner tracking

Polycrystalline



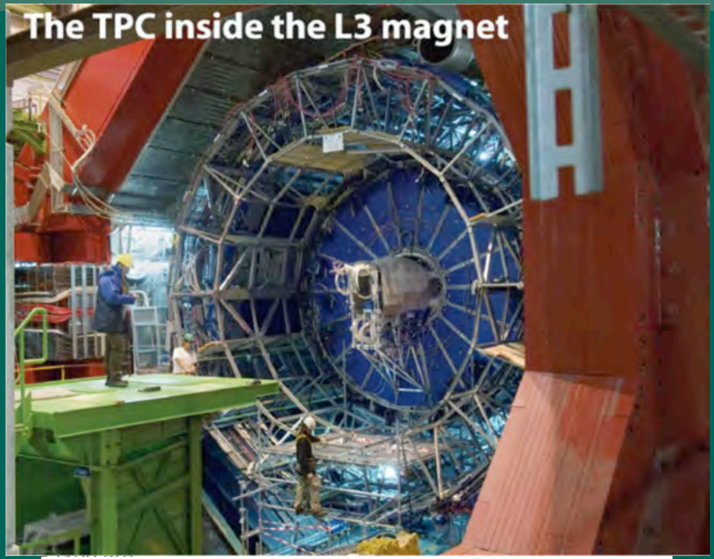


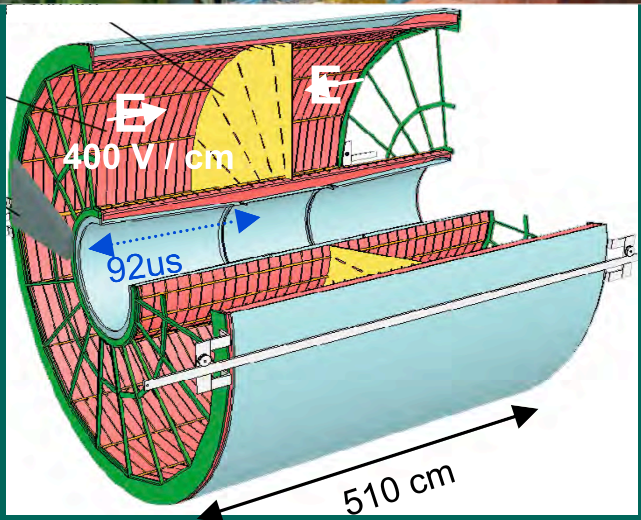
16 chip ATLAS Module of single crystal

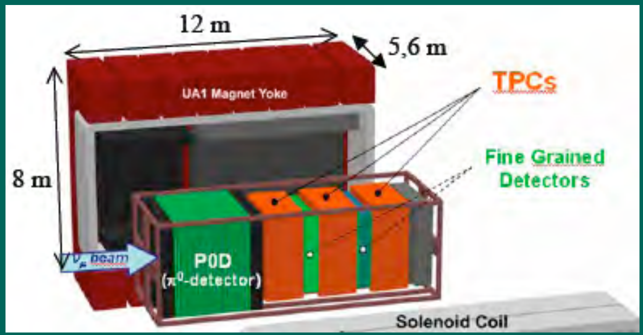


Gas Detectors

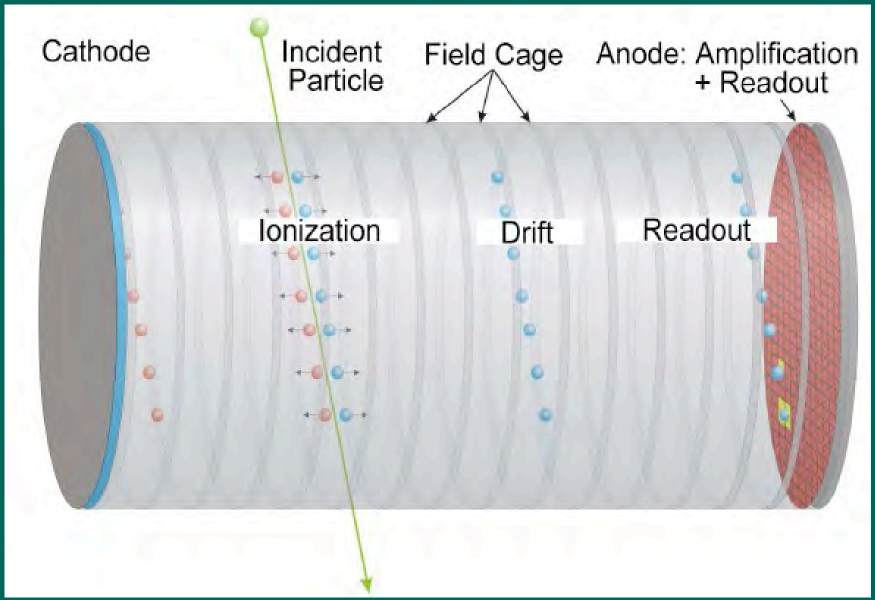
- ALICE TPC
  - Largest - 2466 mm Rout,
    2 x 2500 mm drift
- Micro Pattern Gas Detectors (MPGDs)
  - GEMs
  - MicroMegas
  - Timepix(CMOS)/Ingrid
- T2K Near Detector
  - Largest TPC equipped with MPGDs



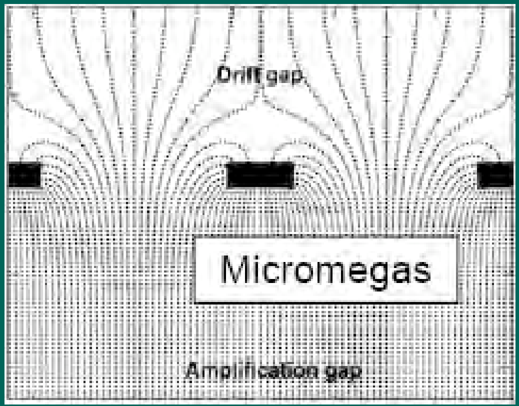




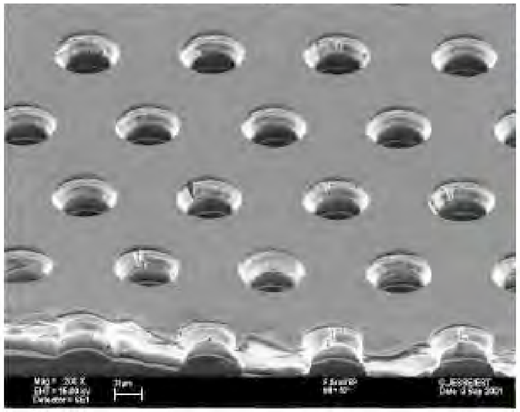
Linear Collider TPC w/MGPDs

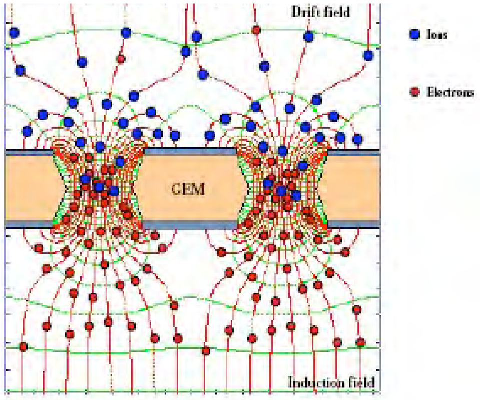


MicroPatternGasDetector
MPGD
not limited by **E** x **B** effects



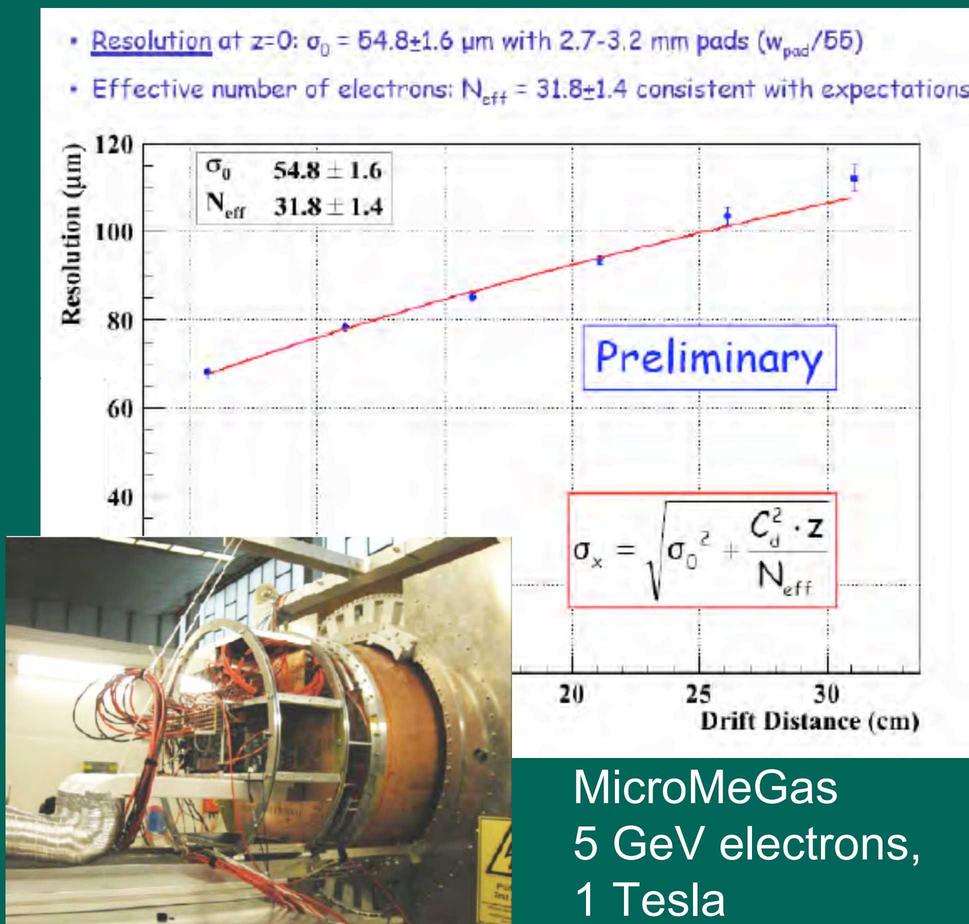
Gas Electron Multiplier GEM



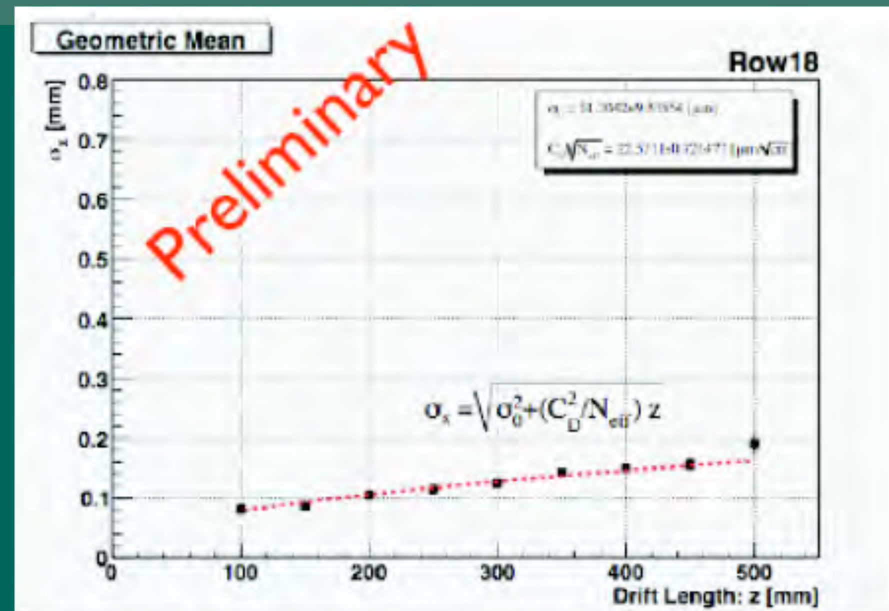


Linear Collider TPC

✱ DESY Beam Test



MicroMeGas
5 GeV electrons,
1 Tesla



B=1T

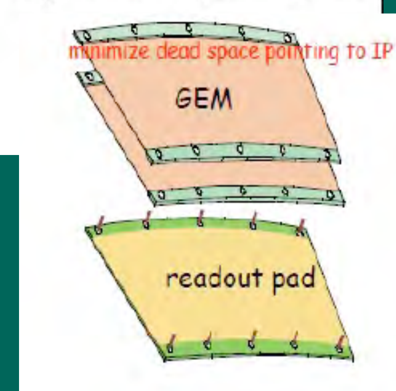
$$\begin{cases} C_D = 101.6 \pm 0.4 [\mu/\sqrt{cm}] \\ \frac{C_D}{\sqrt{N_{eff}}} = 22.6 \pm 0.7 [\mu m/\sqrt{cm}] \end{cases}$$

$\longrightarrow N_{eff} \sim 20 \pm 1$

Garfield

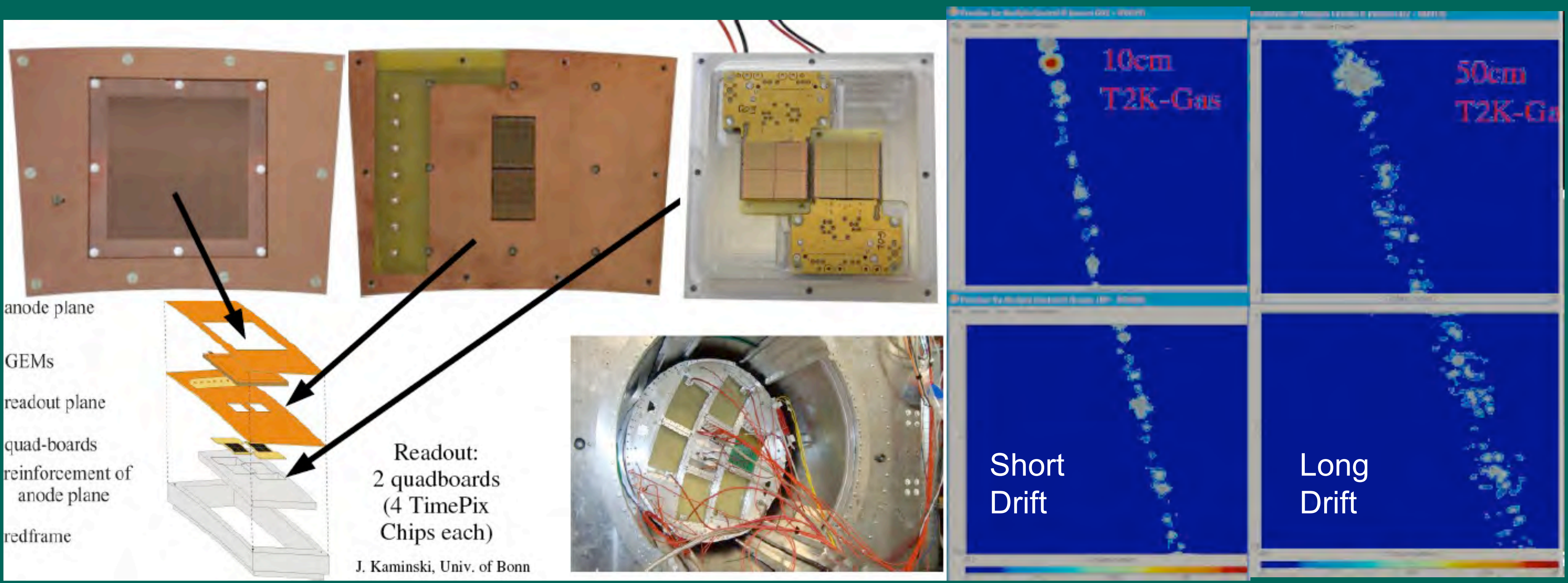
$C_D = 95.4 [\mu m / \sqrt{cm}]$

Double GEMs



Linear Collider TPC

* Triple GEM structure with Timepix readout



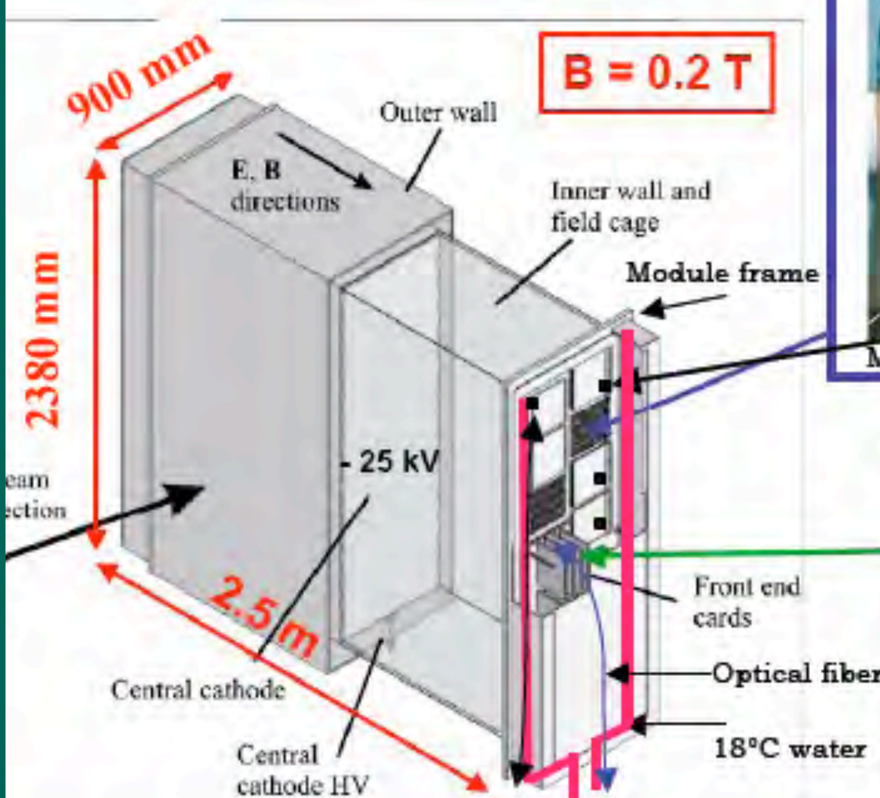
J. Kaminiski, Univ. of Bonn

T2K TPCs

the largest TPCs equipped with MPGDs

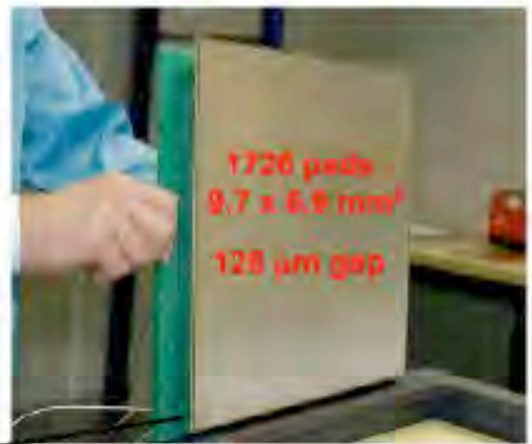
A. Delbart

T2K deploys 3 TPCs for the near detector



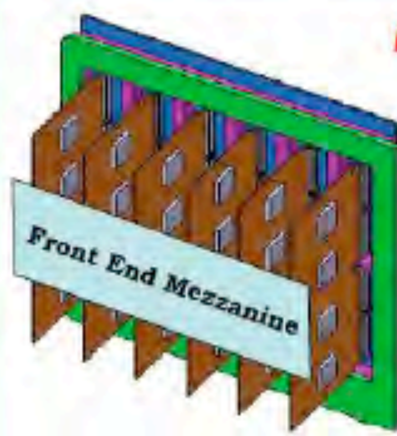
72 modules for ~9 m² active area
~120k electronic channels

36 x 34 cm² « Bulk » MicroMegas



12 modules per Readout plane

Total of 72 modules



FEE based on the ASIC AFTER

6 FECs + 1 FEM per module

Total of
1728 ASICs
432 FECs
72 FEMs

With On-detector FEE cooling mechanicals

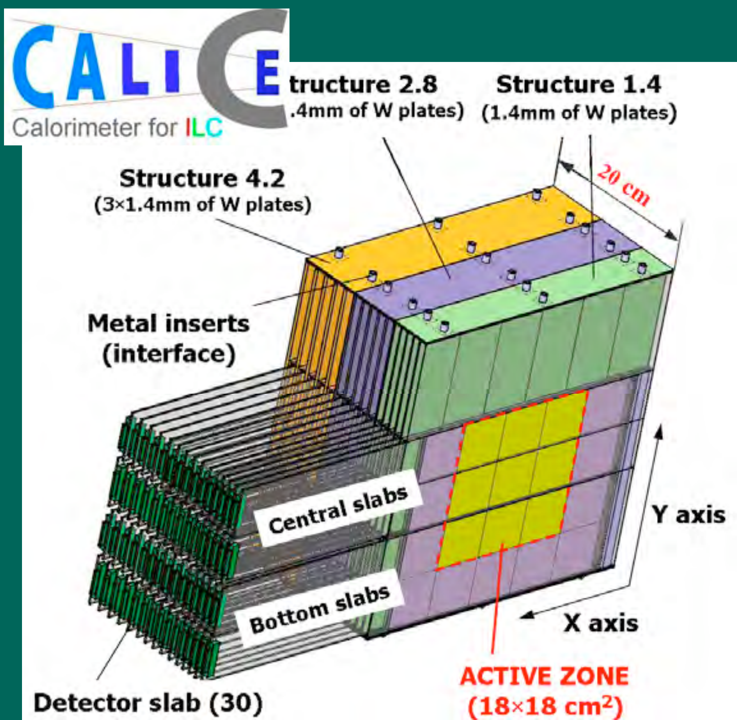
Calorimetry

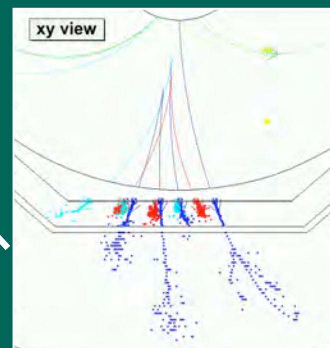
* Electromagnetic Calorimetry
  - Silicon-Tungsten
  - Scintillator strips
  - Crystals
  - Liquid Xe (MEG)
* Hadron Calorimetry
  - Particle Flow
  - Dual Readout

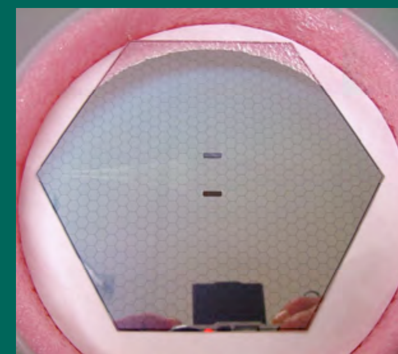
Electromagnetic Calorimetry

Silicon-Tungsten for Linear Collider

✱ High granularity needed for Particle Flow Analysis

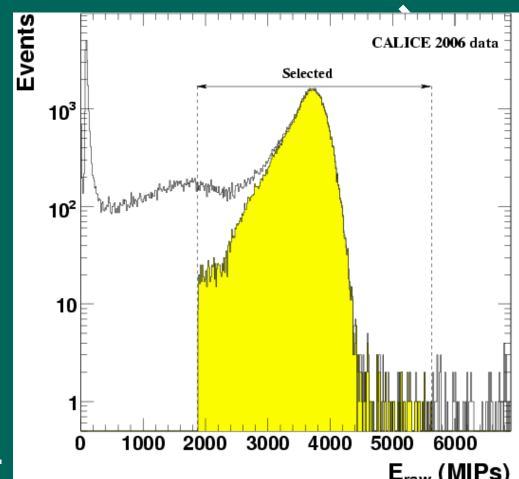


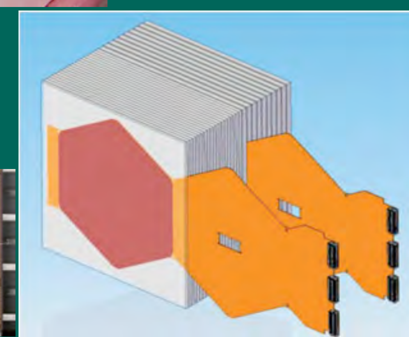




1024

13mm² pixels handled by KPiX





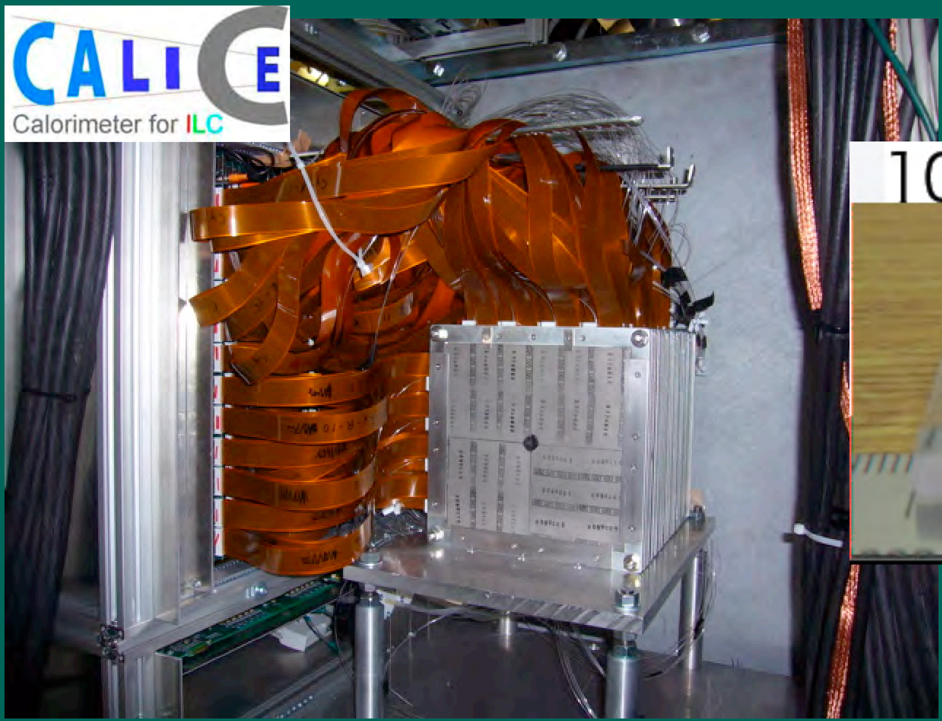
Test Beam Program	2006 - DESY/CERN 2007 - CERN 2008 - FNAL	⇨ building Technolog. Prototype

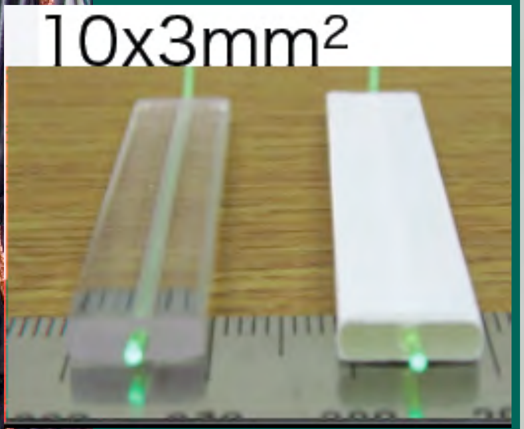
Working toward stack with 13mm² Pixels & MAPS version

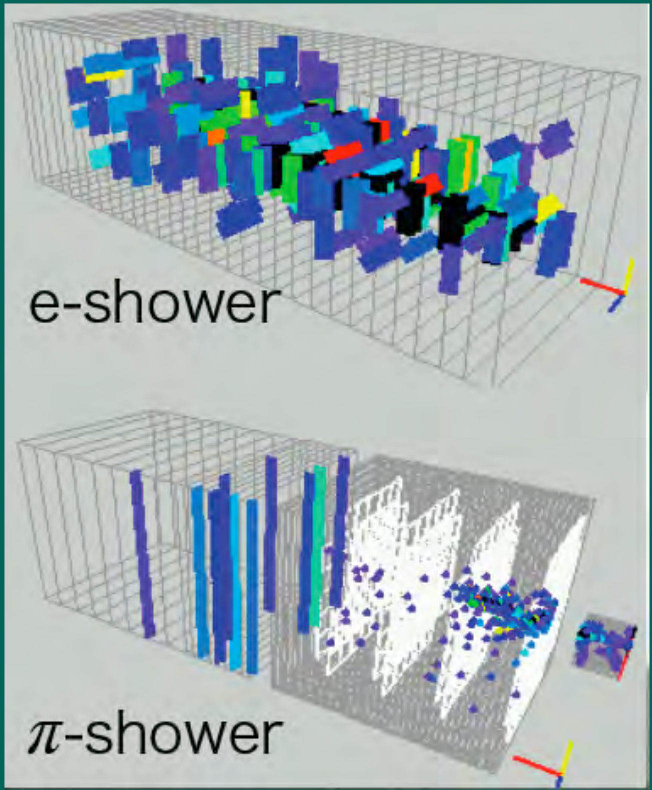
Electromagnetic Calorimetry

Scintillator Strips w/ MPPC* for Linear Collider

- 3-5 mm strips for high granularity needed for Particle Flow
- Tested at DESY & Fermilab







* Multi-Pixel Photon Counters

Electromagnetic Calorimetry

Crystals

Crystal Calorimeters in HEP

Date	75-85	80-00	80-00	80-00	90-10	94-10	94-10	95-20
Experiment	C. Ball	L3	CLEO II	C. Barrel	KTeV	*BaBar*	BELLE	CMS
Accelerator	SPEAR	LEP	CESR	LEAR	FNAL	SLAC	KEK	CERN
Crystal Type	NaI(Tl)	BGO	CsI(Tl)	CsI(Tl)	CsI	CsI(Tl)	CsI(Tl)	$PbWO_4$
B-Field (T)	-	0.5	1.5	1.5	-	1.5	1.0	4.0
r_{inner} (m)	0.254	0.55	1.0	0.27	-	1.0	1.25	1.29
Number of Crystals	672	11,400	7,800	1,400	3,300	6,580	8,800	76,000
Crystal Depth (X_0)	16	22	16	16	27	16 to 17.5	16.2	25
Crystal Volume (m^3)	1	1.5	7	1	2	5.9	9.5	11
Light Output (p.e./MeV)	350	1,400	5,000	2,000	40	5,000	5,000	2
Photosensor	PMT	Si PD	Si PD	WS[a]+Si PD	PMT	Si PD	Si PD	APD[a]
Gain of Photosensor	Large	1	1	1	4,000	1	1	50
σ_N/Channel (MeV)	0.05	0.8	0.5	0.2	small	0.15	0.2	40
Dynamic Range	10^4	10^5	10^4	10^4	10^4	10^4	10^4	10^5

Future crystal calorimeters in HEP:

PWO for PANDA at GSI

LYSO for a Super B Factory, Mu2e and CMS Endcap Upgrade

PbF_2, BGO, PWO for HHCAL

R. Zhu

11/18/2008 ILC Workshop 2008, Ren-yuan Zhu, Caltech 3

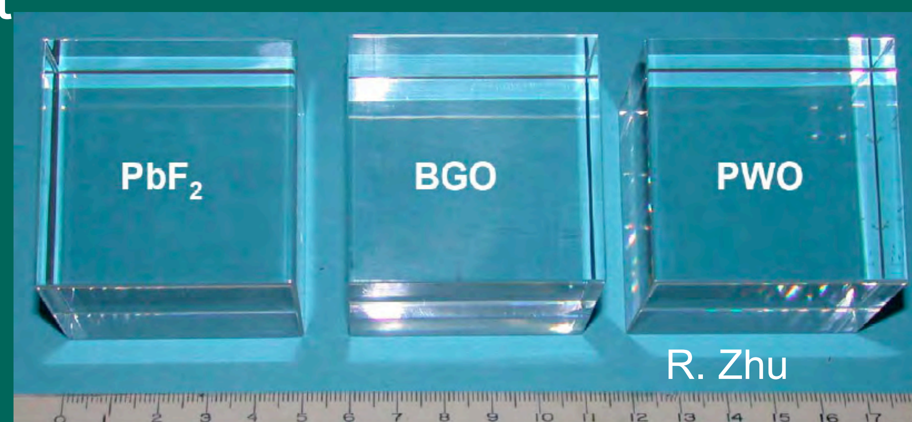
Electromagnetic Calorimetry

Crystals

- Rad Hard for SuperB, Mu2e, CMS Endcap upgrade
  - LYSO favored
  - Large light, low noise

($Lu_{2(1-x)}Y_{2x}SiO_5$: Ce - Cerium doped Lutetium Yttrium Orthosilicate)

- Recent Application - Homogenous <u>HCAL</u> -dual readout
  - For large volume, cost-effective UV transparent material crucial.
  - Three candidates evaluated.
  - Initial investigation favors scintillating PbF_2.



Electromagnetic Calorimetry

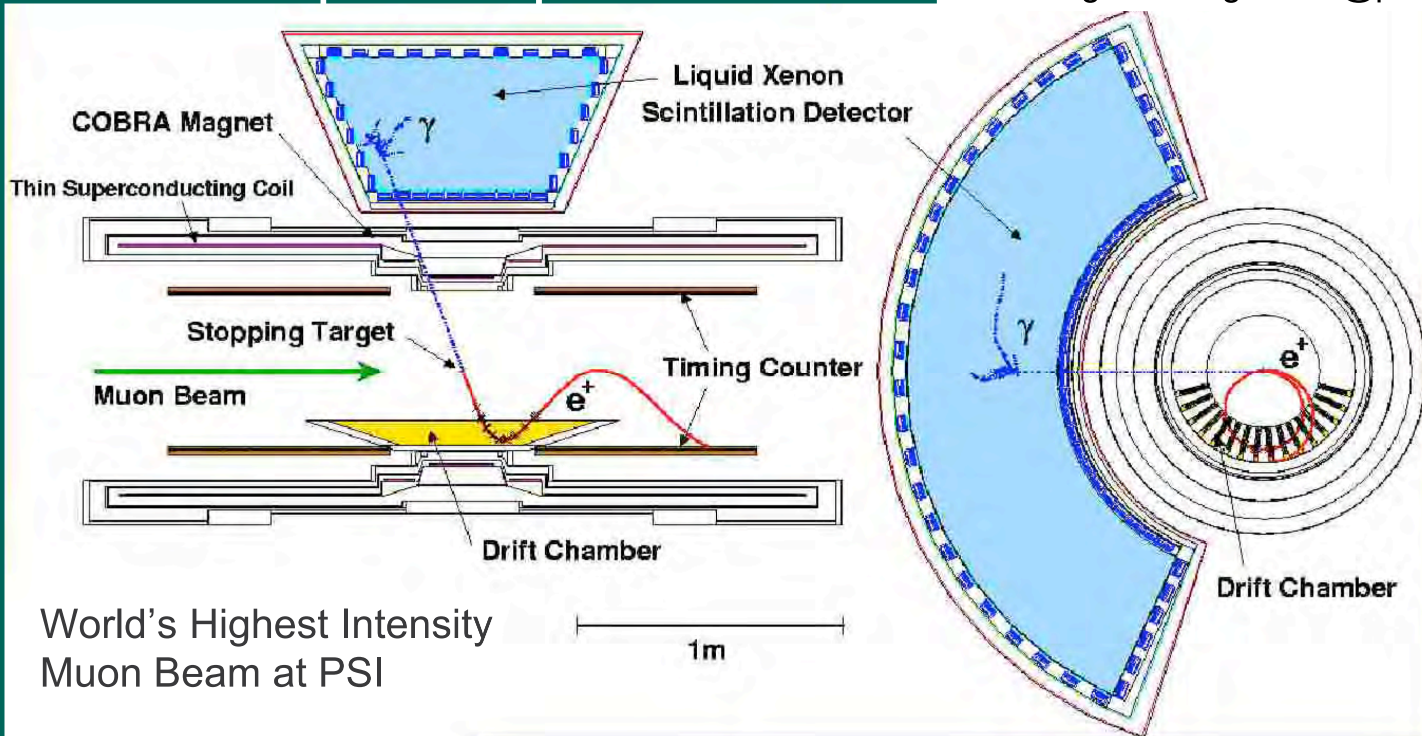
Liquid Xenon - MEG

- 800 liters of LXe
  - 846 PMTs
- Nearing start of new run with improved performance

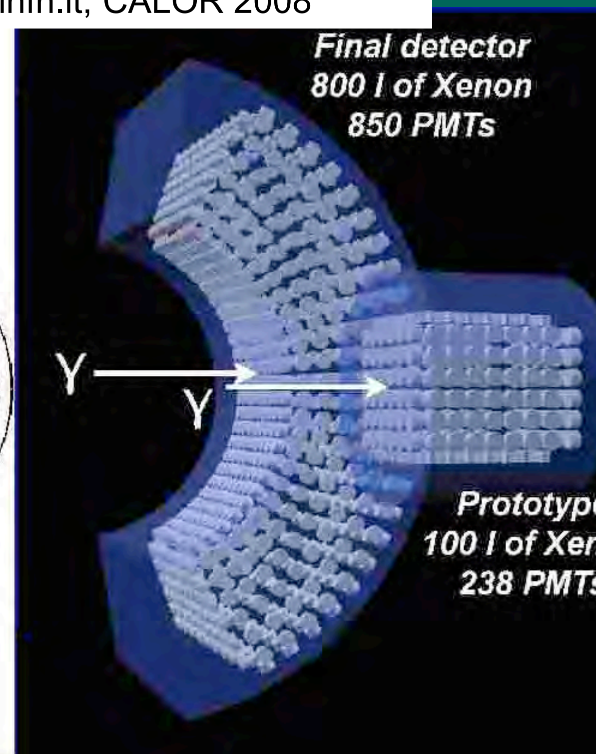
Table 1. Summary of liquid xenon detector resolution

Measurement	Resolution (FWHM)
γ Energy (on 55 MeV)	4.8
γ Position (mm)	15.0
γ Time (nanosecond)	0.15

giovanni.gallucci@pi.infn.it, CALOR 2008



World's Highest Intensity
Muon Beam at PSI



Hadronic Calorimetry

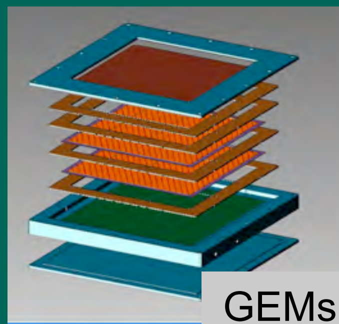
Particle Flow for Linear Collider

* Particle Flow demands high granularity
* Intense test beam program

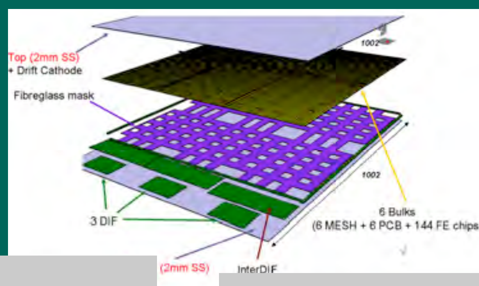
Calorimeter for ILC

DIGITAL

Small RPC calorimeter in the
Fermilab test beam
Fully containing Hcal under construction



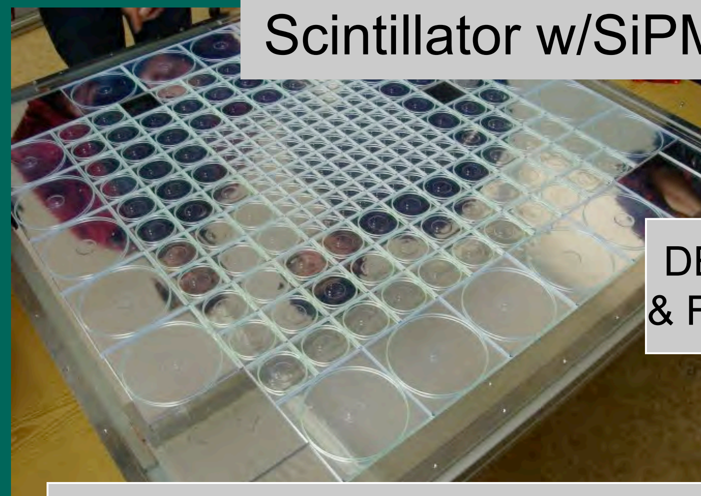
GEMs



MicroMeGas

ANALOG

Scintillator w/SiPM



DESY, CERN,
& Fermilab tests

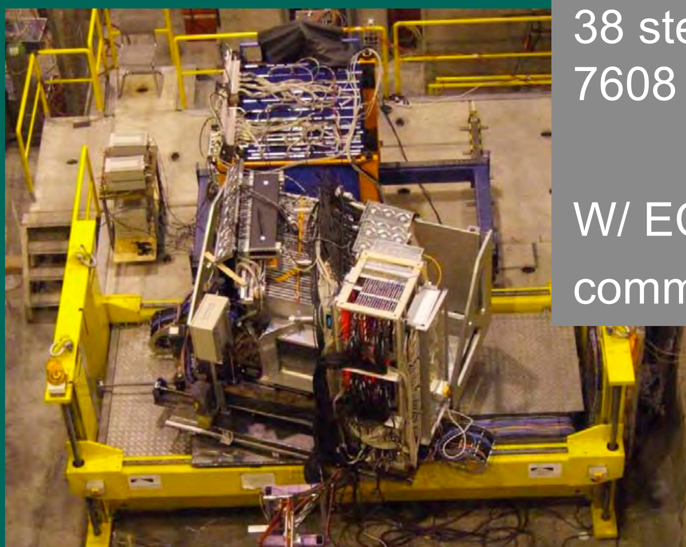
One of 38 layers
of the prototype

CALICE Scintillator Tests

Particle Flow for Linear Collider

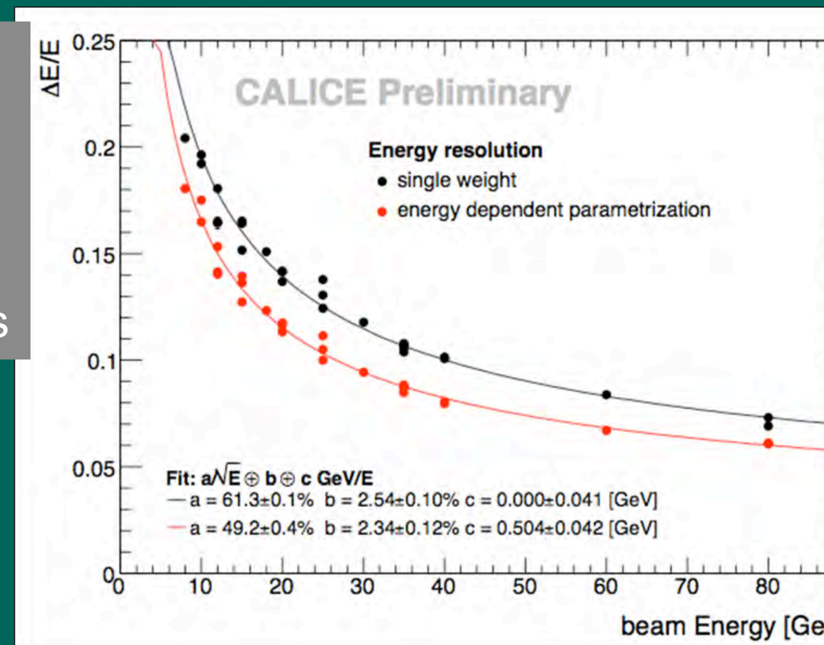
Calorimeter for ILC

- ✱ CERN 2006-07, FNAL 2008-09



38 steel layers (2cm), 4.5λ
7608 tiles with SiPMs

W/ ECAL and TCMT
common readout electronics



- ✱ CALICE's conclusions:
  - The SiPM technology has proven to be robust and stable
  - The calibration is well under control
  - The performance is as expected and understood
  - Strong support for predicted PFLOW performance

CALICE Digital HCAL Tests

Particle Flow for Linear Collider

✱ Small glass RPC module tested in Fermilab beam

20 x 20 cm^2 RPCs (based on two different designs)
1 x 1 cm^2 readout pads
Up to 10 chambers → 2560 readout channels
Complete readout chain as for larger system
Detailed tests with cosmic rays & in Fermilab beam
(μ, 120 GeV p, 1 – 16 GeV π^+, e^+)

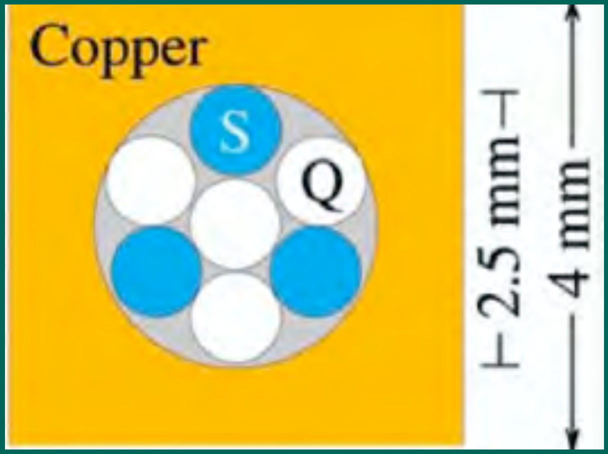
✱ $1m^3$ prototype under construction

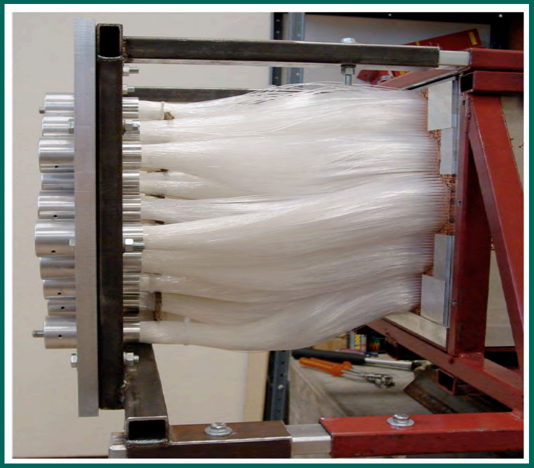
Cosmic ray tests for each chamber
Fermilab test beam with μ, $\pi^\pm$, $e^\pm$
hadronic shower MC model comparison
analog HCAL (CALICE) comparison
Construction completed in CY 2009
Data analysis in 2010/2011

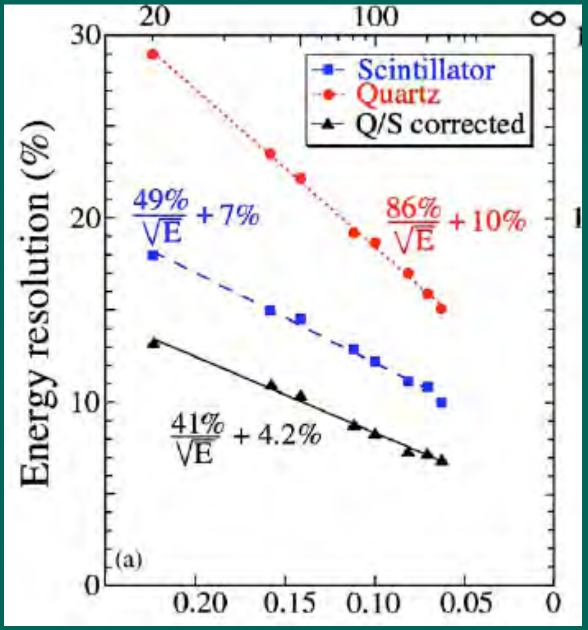
Hadronic Calorimetry

Dual Readout

- Fluctuations in hadronic shower
  - Nuclear binding energy losses & π^0 energy variations
- Measure separately the EM shower component
  - DREAM Collaboration measured in HE calorimeter
  - Correct for EM fraction event by event (Q/S method)
- What resolution with combined signals?
  - DREAM leakage limited



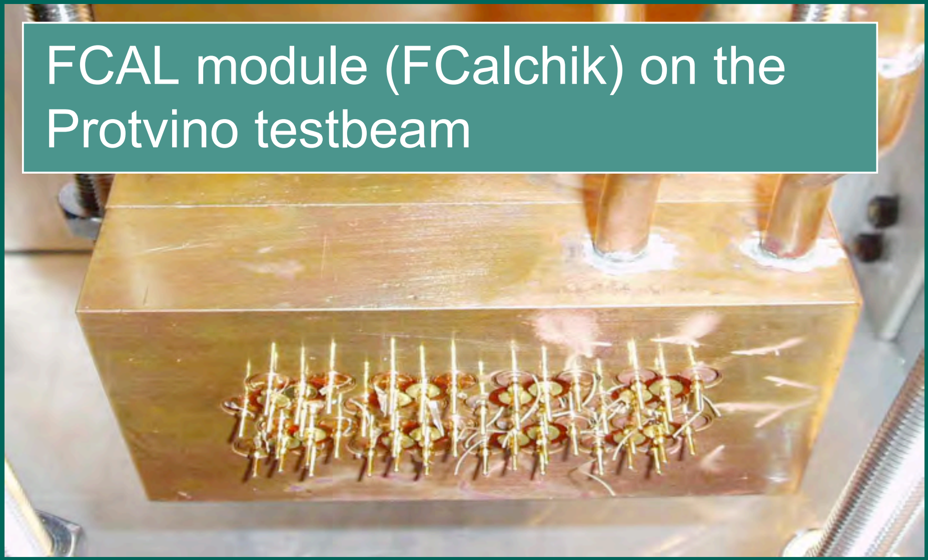


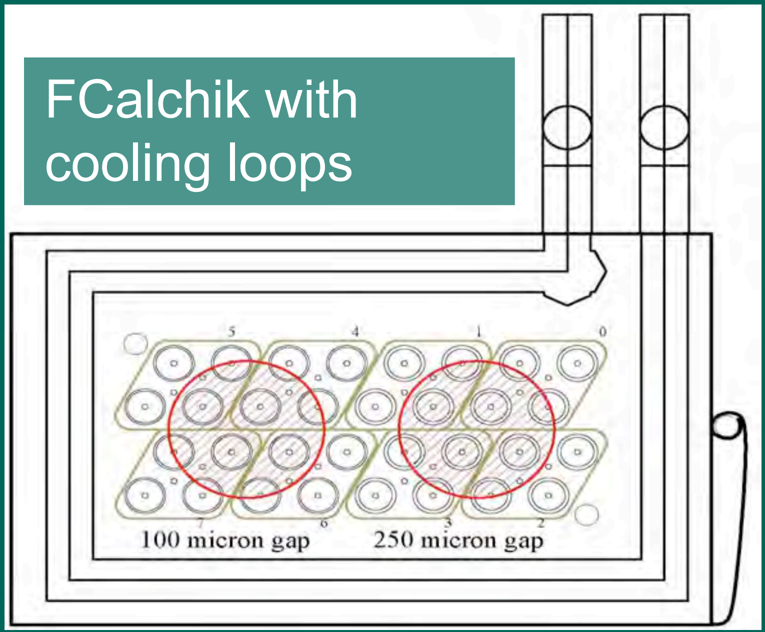


sLHC Calorimetry

Confronting the Radiation Challenge

- ATLAS Forward Calorimeter
  - LAr boiling, inter-electrode ion build-up, HV resistor voltage drop
  - Two possible solutions
    - Warm calorimeter in front of current FCAL
    - New FCAL - smaller gaps and increased cooling


FCAL module (FCalchik) on the Protvino testbeam

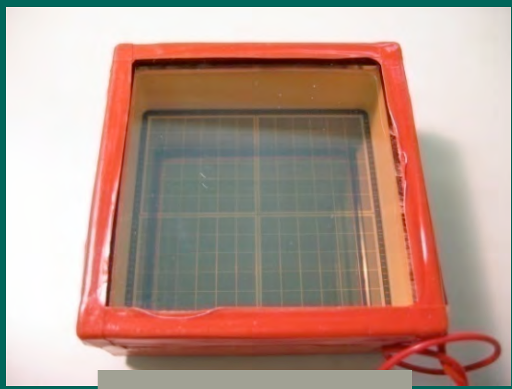


FCalchik with cooling loops

Particle ID

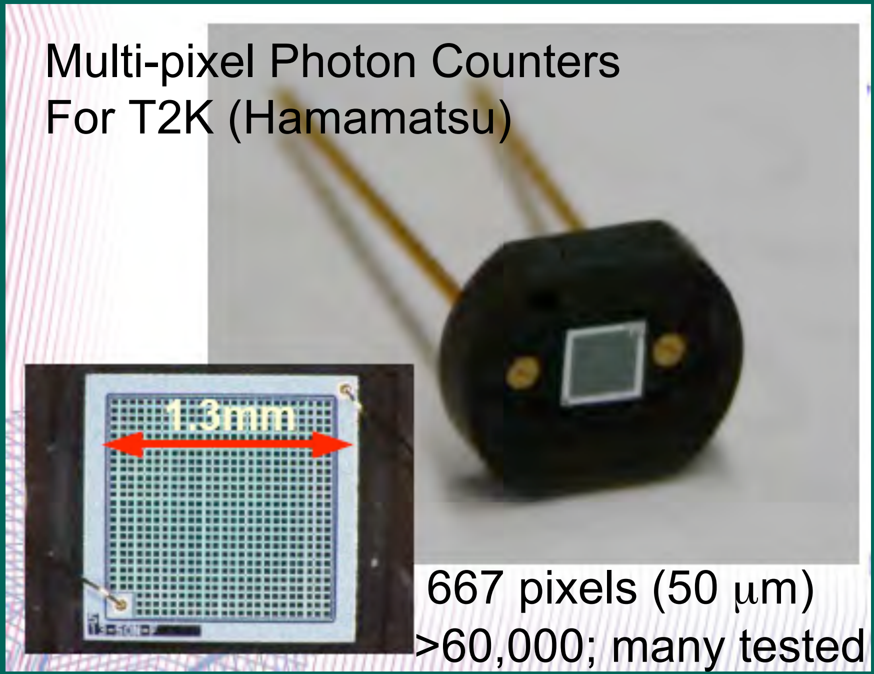
- ✱ Crucial role in many experiments
  - BaBar, Belle, LHC-b
- ✱ Future Needs
  - Belle II, INFN SuperB, NA62
- ✱ Key Technologies
  - Radiators
    - Quartz (fused Silica) - polishing
    - Silica aerogel - improved transmission, mulit-index tiling
  - Photodetectors
    - Hybrid PD
    - MCP-PMT
    - MPPC

Novosibirsk Aerogel


144ch HAPD

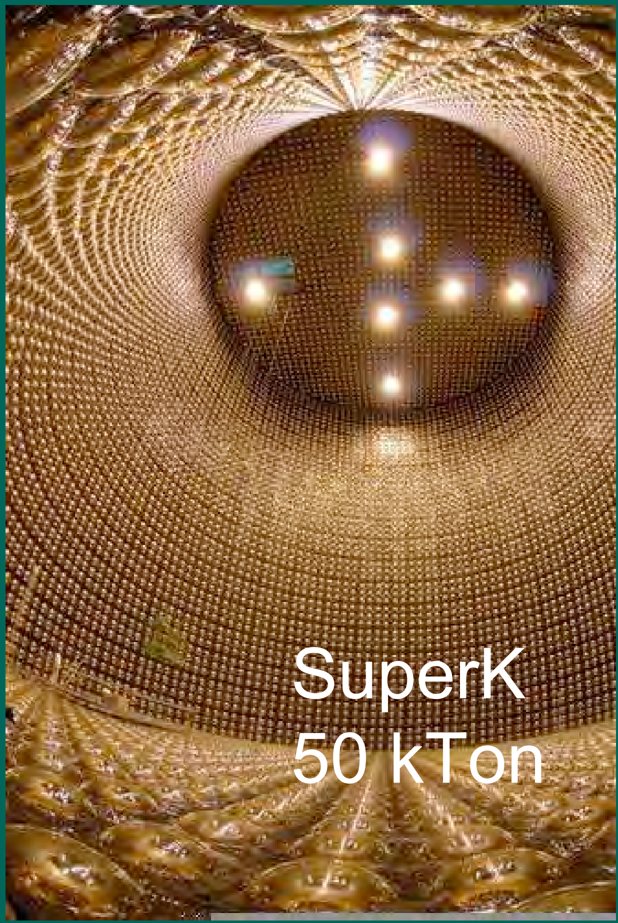
MPPCs, SiPMs

- Single photon sensitive devices built from an avalanche photodiode (APD) array on common Silicon substrate.
- Many attractive properties
  - Extremely compact
  - B-field immune
  - Good timing
  - Gain and QE competitive with PMT
- Many investigations



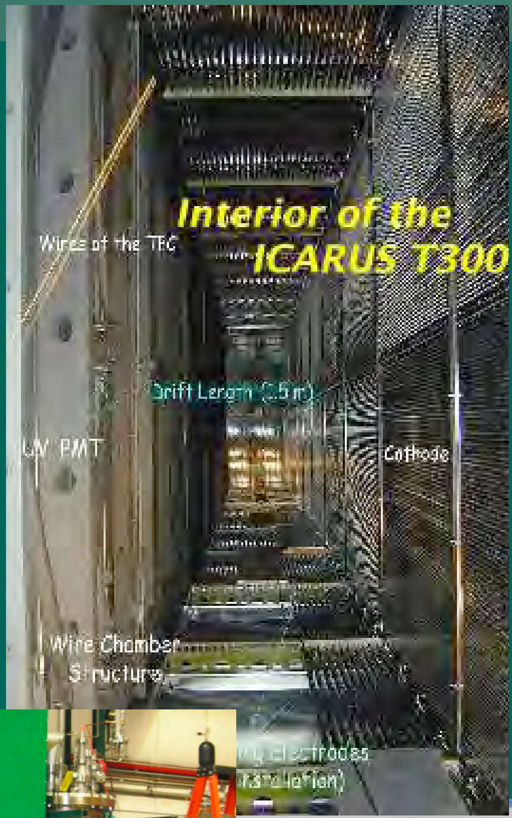
Megaton Detectors for Neutrinos

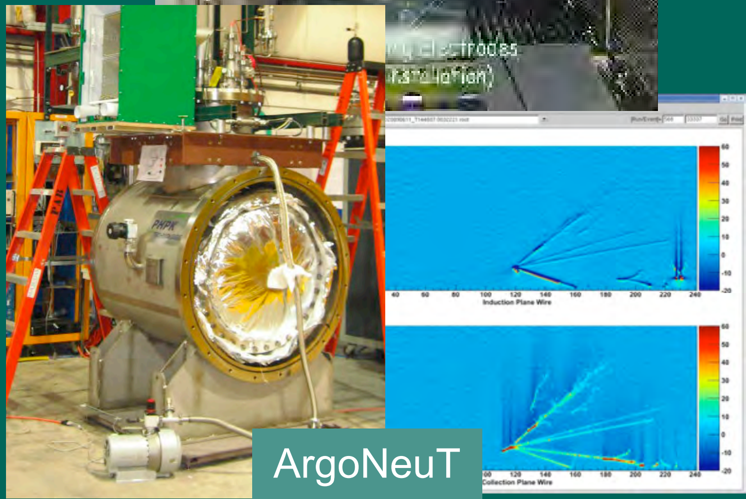
- SuperK proves performance of water Cherenkov
- Future goal - 1 MTon
- Challenges
  - Costs
  - PMTs (increased QE)
  - Readout Electronics
  - New photosensors
  - Harden against accident
- T2K develops MPPC (SiPM)



Liquid Ar TPC for Neutrinos

- ICARUS demonstrated potential
- Promising candidate for future massive experiments
  - Low threshold
- Goal - scale up to ~100kTon
- Challenges
  - Purification
  - Cold, low noise electronics, signal mplex
  - Vessel - design, materials, insulation
  - Siting
  - Costs
- ArgoNeuT - 175 liters in NuMI beam

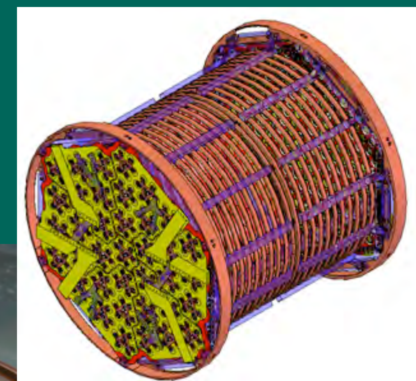


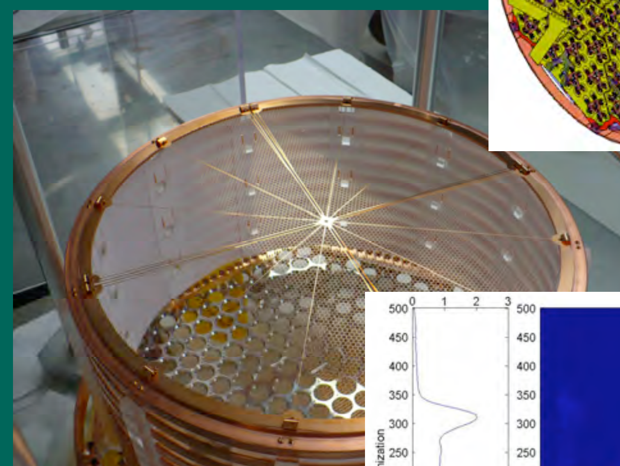


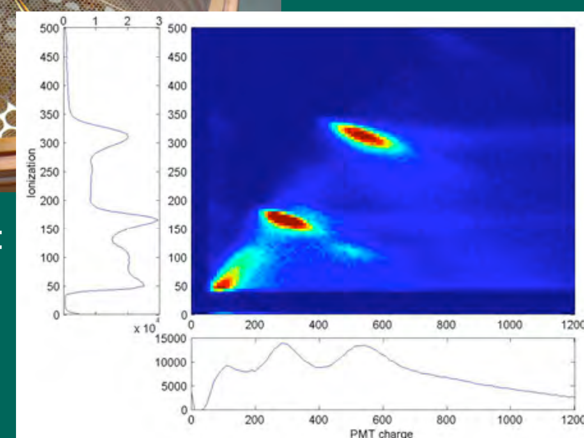
Neutrinoless Double Beta Decay

- Several 100-200 kg detectors being developed
  - Challenge to minimize backgrounds
  - CUORE
    - 203 kg ^{130}Te
    - 988 TeO_2 bolometers
    - Follows 11 kg ^{130}Te CUORICINO
  - EXO-200
    - 200 Kg ^{136}Xe
    - Measure ionization and scintillation plus Ba tag
  - Majorana
    - Goal: 120 kg of ^{76}Ge

EXO-200
LXe Field Cage
& Readout Planes



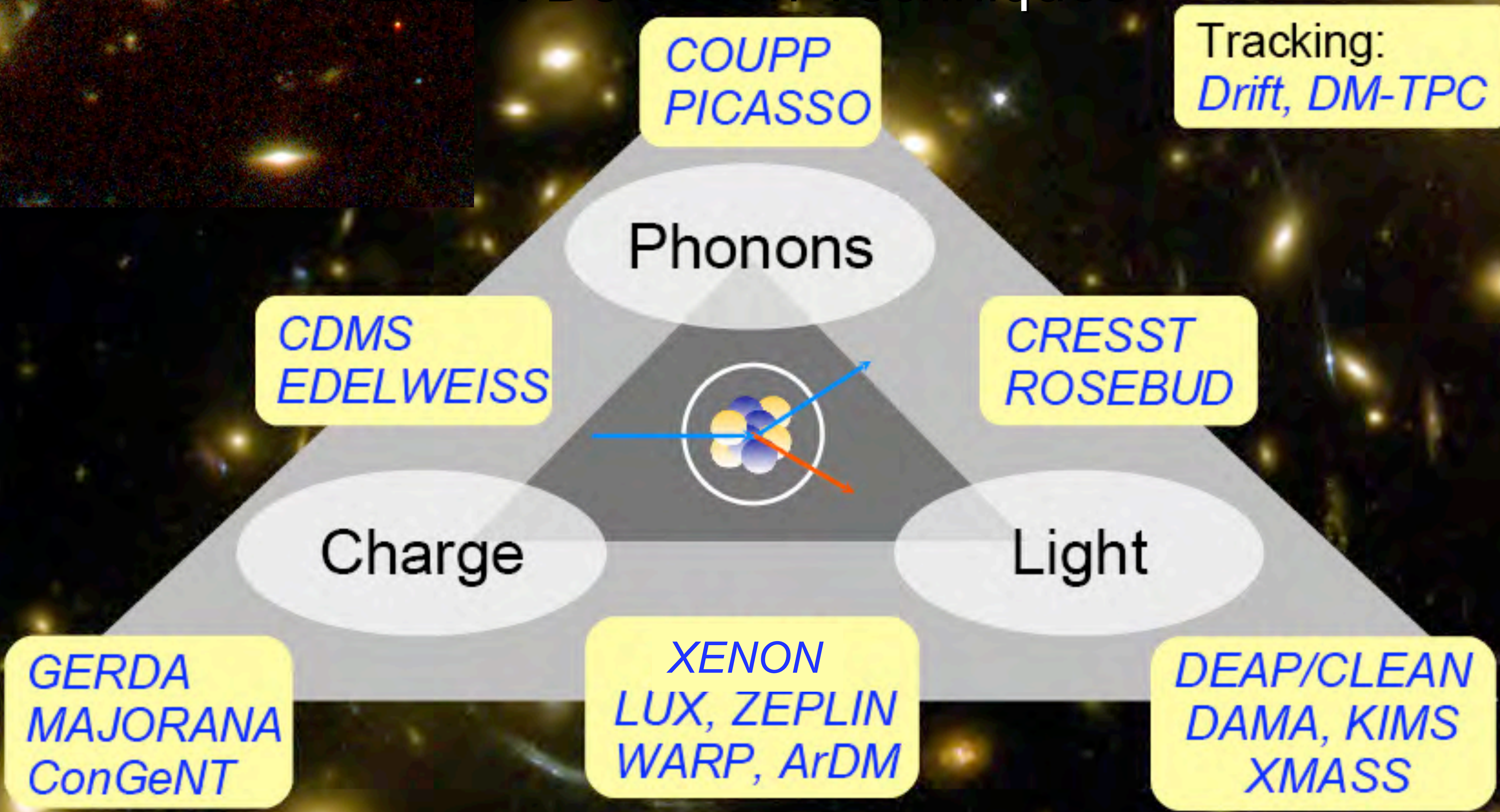




R&D -Ionization & Scintillation:
$\sigma(E)/E$ = 3.0% @ 570 keV
or 1.4% @ $Q_{\beta\beta}$

Will add Ba tagging

Dark Matter
Direct Detection Techniques

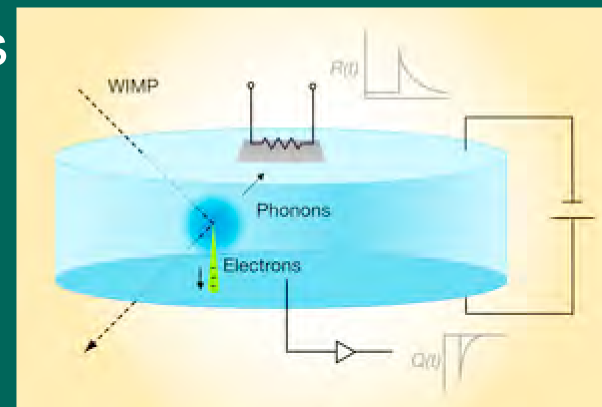


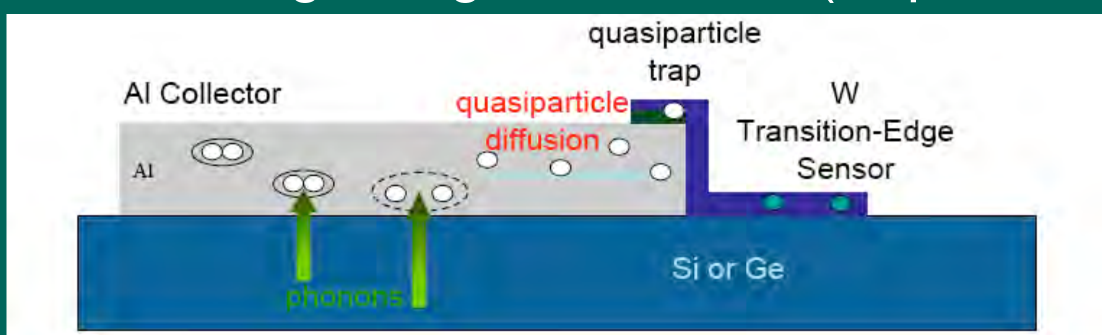
M. Schumann

Bolometers for DM Detection

mK detectors

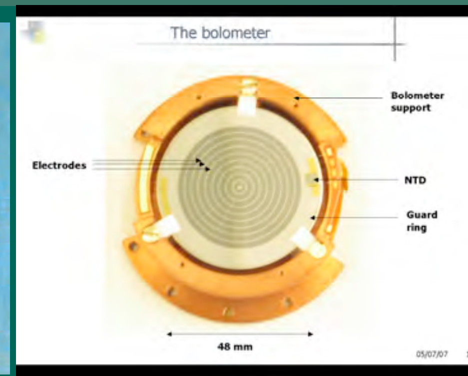
- CDMS
  - Phonon/Charge detection with ZIP detectors
    - Electric field pulls charge to sensitive amplifier
    - Phonons break Cooper pairs in thin superconducting Al layer, heating transition-edge sensor & causing change in resistance.
    - Readout elements highly segmented, and relative timing of ionization and phonon signals provide good event localization.
  - Operated 5 kg in Soudan
  - Planning 25 kg in SNOLAB (SuperCDMS)





Bolometers, cont.

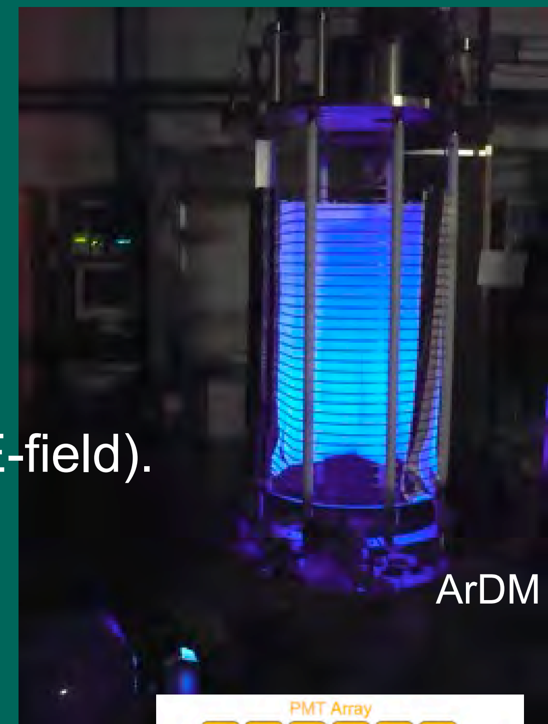
- ✱ EDELWEISS
  - – Ge/NTD
  - – Ge/NbSi
  - – Ge/Interdigit
    - 30 kg operating
- ✱ CRESST-II
  - – ~ 300 g $CaWO_4$ crystal
    - Gran Sasso
- ✱ ROSEBUD
  - – BGO
  - – LiF (n-mon)
  - – Sapphire

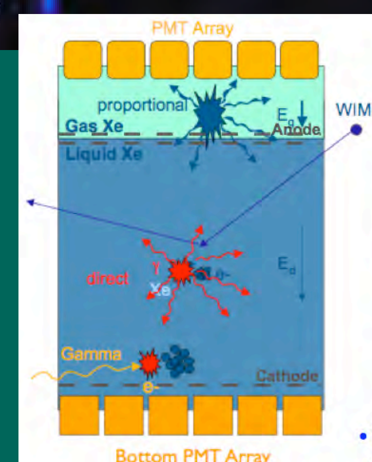


Noble Liquid Dark Matter Detectors

- ✱ Many Attractive Features
  - – Low cost, easy to obtain, dense target material.
  - – Easily purified due to freeze out of contaminants at cryogenic temperatures.
  - – Very small electron attachment probability.
  - – Large electron mobility (Large drift velocity for small E-field).
  - – High scintillation efficiency.
  - – Possibility for large, homogenous detectors.
  - – Current scale ~ 100 kg
- ✱ Problem - ^{39}Ar, ^{85}Kr.

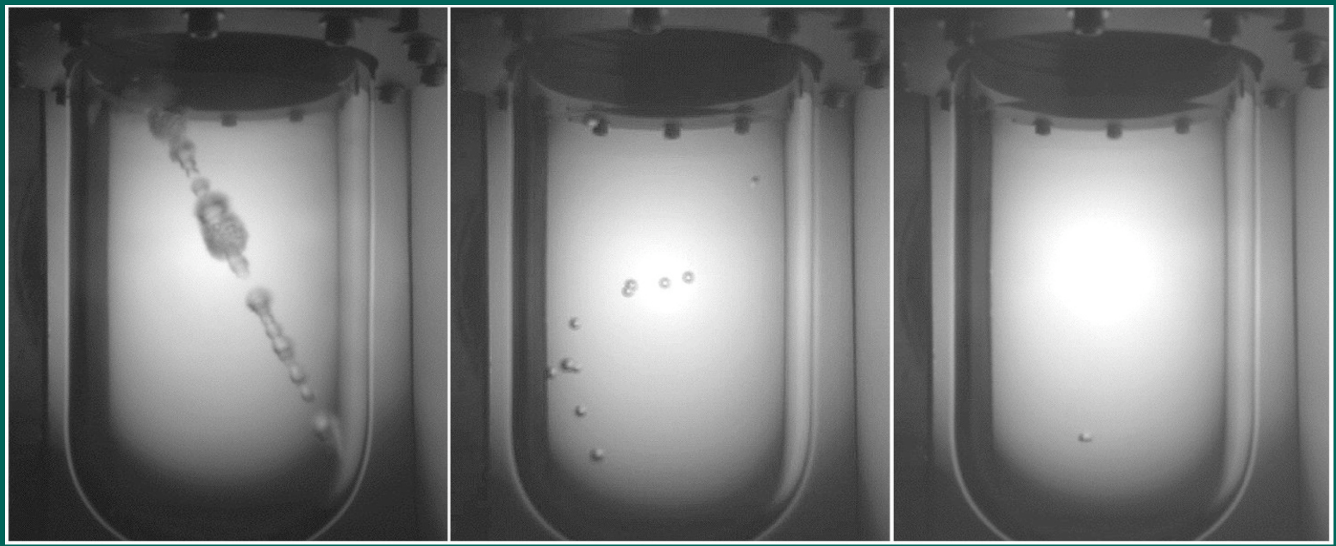
- ✱ Single Phase - XMASS, CLEAN/DEAP
- ✱ Two Phase - XENON, LUX, ZEPLIN II/III, WARP, ArDM
  - – Scintillation-to-ionization ratio





Warm Liquid Dark Matter Detector

- COUPP
  - Room Temp Bubble Chamber, CF_3I, 2 kg tested



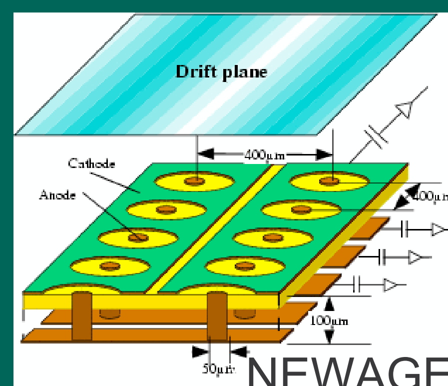
A CCD camera takes pictures at 50 Hz. Chamber triggers on appearance of bubble in the frame.

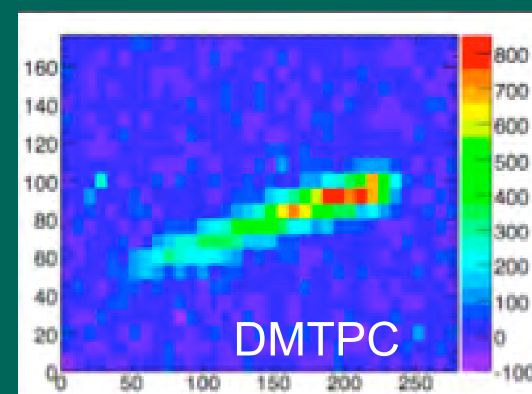
Single bubble DM signature.

  - New 20 and 60 kg chambers will go underground in 2010

Directional Dark Matter Detectors

- Low pressure TPCs favored
  - CS_2 - spin-dependent interactions
  - CF_4 and ^3He - spin-independent interactions
- Wire chamber readout
  - DRIFT-II
  - Two 1m^3 (CS_2) modules underground
- MPGDs
  - NEWAGE, MIMAC
- CCD and PMT readout
  - DMTPC (CF_4)

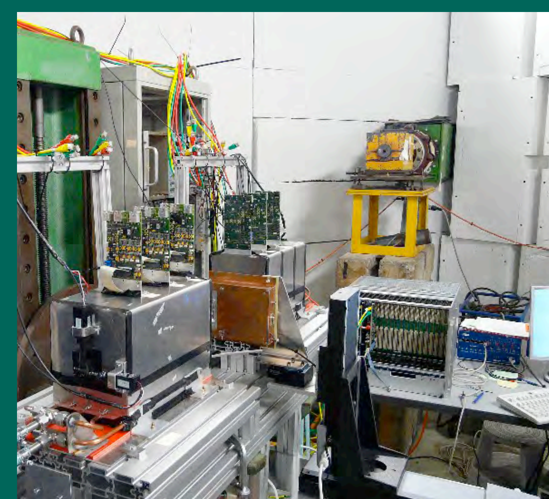




Test Beams

- ✱ Needed for detector development
  as well as in many other phases of HEP experiment
  eg. prototype testing, calibrations, etc.
- ✱ Laboratory support of test beams very important





Conclusion

- Discoveries in HEP vitally depend on advances in detector technology
- Challenges are huge
  - speed, granularity, radiation, exotic materials, etc.
- Many efforts confronting these challenges
- Critical that the efforts are well funded
- Technology will continue to advance, with important emerging capabilities critical to future discoveries

  - with timescales dependent on the level of financial support

■ ■ Don't forget the test beams

Acknowledgements

* E. Aprile, M. Breidenbach, A. Bevan, K. Dehmelt, M Demarteau, B. Fleming, G. Gratta, D. Hitlin, J. Jaros, G. Rakness, J. Repond, F. Sefkow, A. Seiden, D. Strom, F. Taylor, J. Timmermans, D. Wark, A. White