Detector R&D for Collider and Underground Experiments

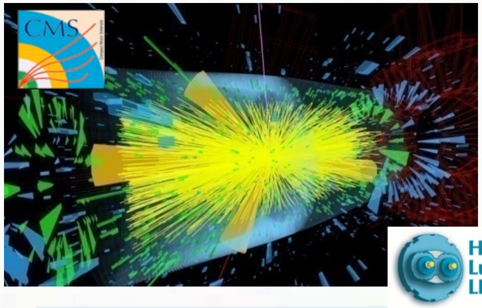
Phil Allport

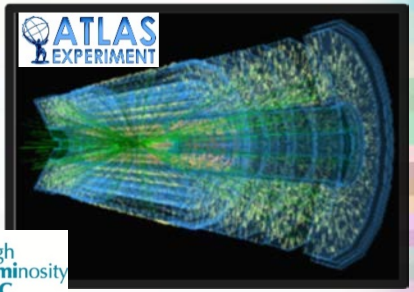
- **Introduction and Overview**
- **Experiment Areas:**
  - **Collider and Fixed Target**
    - **Hadron Collider Detectors**
    - **Lepton Collider Experiments**
    - **Lepton-hadron Colliders**
    - **Fixed Target**
  - **Accelerator and Reactor Neutrinos**
    - **Far Detector**
    - **Near Detector**
    - **Reactor**
  - **Non-accelerator and Low Energy Searches for Rare Processes**
    - **Dark Matter**
    - **Neutrino-less Double β-decay**
    - **Low Energy (includes: g-2, n-EDM, e-EDM, anti-hydrogen, …)**
  - **Astro-particle Experiments**
    - **Charged Cosmic Rays**
    - **UHE Gamma-rays**
    - **UUHE Neutrinos**
    - **Solar, Atmospheric and Supernova Neutrinos**
- **Conclusions**

School of Physics and Astronomy
UNIVERSITY OF BIRMINGHAM
ENLIGHT
ATLAS EXPERIMENT
BILPA
RD50
AIDA 2020
ECFA-DP ECFA Detector Panel
PRaVDA
Science & Technology Facilities Council

Detector R&D for Collider and Underground Experiments

Phil Allport





High Luminosity LHC

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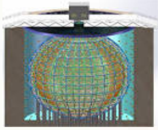
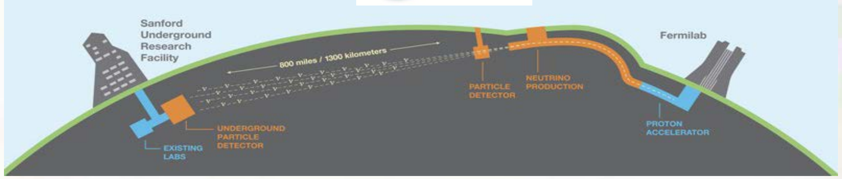
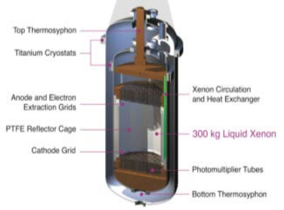
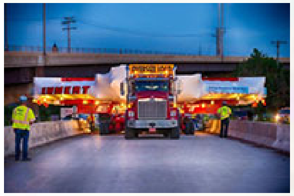
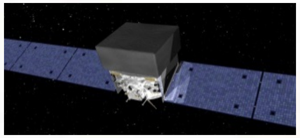
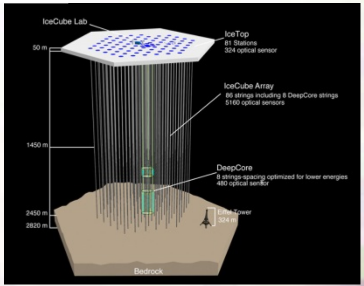










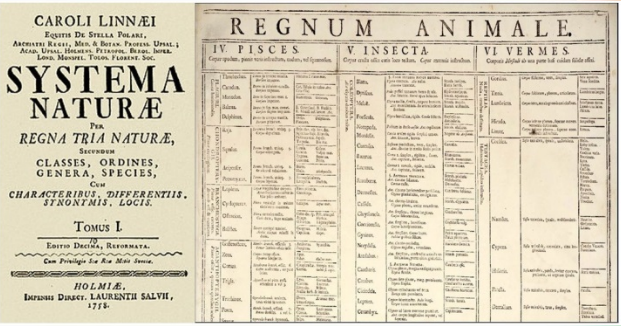


Introduction and Overview

- Too many different experiments and techniques to cover sensibly
- List of facilities is one way of grouping the different styles of experiments in our field
- Another possible attempt at a taxonomy of detectors could be by technology:

a. Pixel sensors (silicon: hybrid, monolithic)
b. Inner tracking (silicon)
c. Inner tracking and muon tracking (gas: MPGD, wires, TPC, straws and drift tubes)
d. Scintillating fibre tracking
e. Sampling calorimetry (scintillators)
f. Sampling calorimetry (liquid noble gases)
g. Sampling calorimetry (high granularity particle flow)
h. Homogenous calorimetry (crystals, plastics)
i. Fast timing detectors (semiconductor, crystal/scintillator, gas)
j. Detectors exploiting superconductivity
k. Particle Identification (Cherenkov plus efficient single photon detection)
l. Large volume liquid noble gas for track and energy reconstruction
m. Large volume liquid scintillators for timing and energy reconstruction
n. Air/Water/Ice/Rock Cherenkov and fluorescence detection (light, sound, Askaryan effect)
o. Custom microelectronics and other front-end electronics
p. Data links and optoelectronics
q. Mechanics, large-scale engineering, cooling and services
r. Trigger, data acquisition and computing

.... everything I've forgotten



CAROLI LINNÆI
Equitis De Stella Polari,
Archiatri Regii, Med. & Botan. Profess. Upsal.;
Acad. Upsal. Holmens. Petropol. Berol. Imper.
Lond. Monspel. Tolos. Florent. Soc.
SYSTEMA
NATURÆ
Per
REGNA TRIA NATURÆ,
Secundum
CLASSES, ORDINES,
GENERA, SPECIES,
Cum
CHARACTERIBUS, DIFFERENTIIS,
SYNONYMIS, LOCIS.
Tomus I.
10
Editio Decima, Reformata.
Cum Privilegio S:æ R:æ M:tis Sveciæ.
HOLMIÆ,
Impensis Direct. LAURENTII SALVII,
1758.

REGNUM ANIMALE.

IV. PISCES

V. INSECTA

VI. VERMES

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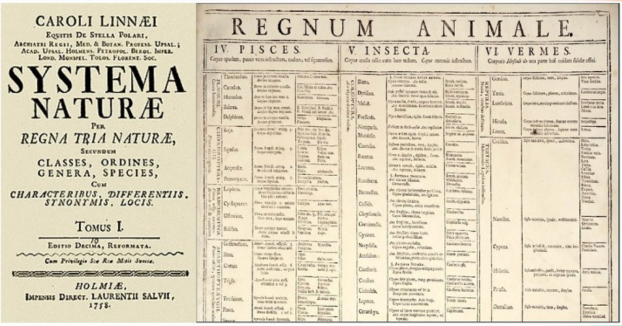
Each of these topics can easily fill a conference on its own (and many do)


CAROLI LINNÆI

SYSTEMA NATURÆ

PER REGNA TRIA NATURÆ,

SECUNDUM CLASSES, ORDINES, GENERA, SPECIES,

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TOMUS I.

HOLMIÆ,

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IV. PISCES

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1. Collider and Fixed Target

Attempt to list the key technology challenges in the context of different facilities

Technique	1.1 (hadron collider)	1.2 (lepton collider)	1.3 (lepton-hadron)	1.4 (fixed target)	Comment
1.a (Si) Vertexing (& Lumi/FP)	Rad-hard (pp) Low mass (AA) Data rate (pp)	Low mass Fine pitch Time stamp	Fine pitch Low mass	Fast R/O Fine pitch Radiation	Monolithic devices incorporate electronics. Time structure dictates on-detector R/O.
1.b Inner track (Si)	Area/cost Radiation (pp)	Low mass Area/Cost	Area/cost	Radiation	Can be few $10^{15}n_{eq}/cm^2$ radiation levels
1.c Track gas (inlc muons)	Area/cost Hit rate, aging	Volume (TPC)	Area/cost Hit rate	Hit rate	Industrialisation of gas micro-pattern detectors
1.d Sci Fibre	Radiation incl photodetectors			Efficiency	Photodetector radiation hardness
1.e Scint Calo	Radiation Granularity	Granularity EM Resolution	Granularity EM Resolution	EM Resolution	Timing for ToF or pile-up mitigation
1.f Calo L-noble	Charge collection time	EM Resolution	EM Resolution	EM Resolution Speed	Rate capabilities
1.g HG-Calo	Area/cost Resolution	Area/cost	Area/cost EM Resolution	EM Resolution	Particle Flow Analysis (EM Resolution?)
1.h Calo homogenous	Radiation Granularity	EM Resolution Granularity	EM Resolution Granularity	EM Resolution Granularity	Timing for ToF or pile-up mitigation
1.i Fast Timing (Si, gas, scintillator)	Radiation, Speed, Rate Area/cost	Time stampArea/cost	Area/cost	Speed Sensitivity	Primary vertexing. Time of Flight for lower momenta PID
1.k Particle ID RICH	Volume Area/cost	Volume Area/cost	Volume Area/cost	Volume Area/cost	Efficiency for single photo-detection
1.o FE Electronics & Interconnect	Radiation Cost/channel # Power	Channel #, Power, fine-pitch	Cost/channel #, Power	Speed/ data volumes	Prototyping costs for deep-sub-micron engineering runs
1.p Data links (incl opto-electronics)	Radiation Cost/channel # Low mass	Channel # Low mass	Channel # Low mass	Speed/ data volumes	How to exploit commercial developments?
1.q Mech, cool, services	Low mass, reliable, stable	Low mass, reliable, stable	Low mass, reliable, stable	Low mass, reliable, stable	Large-scale magnet systems
1.r TDAQ + Computing	Cost, Speed Commercial Solutions	Cost Channel #	Cost, Speed Commercial Solutions	Speed/ data volumes	Is Moore's Law safe forever?

1. Collider and Fixed Target

Aspects of some areas are the topics of dedicated international R&D programmes

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1.c Track gas	Area/cost	Volume (TPC)	Area/cost	Hit rate	Industrialisation of gas micro-

AIDA-2020: 1.1.a, 1.2.a, 1.1.b, 1.1c, 1.2c,1.1g, 1.1.i, 1.1.n, 1.2.n, 1.1.p, 1.2.p, 1.1.q, 1.2.q
CALICE: 1.2.g
Crystal Clear Collaboration: 1.1.e, 1.2.e, 1.3.e, 1.4.e, 1.2.h, 1.3.h, 1.4.h
ILC/CLIC FCAL Collaboration: 1.2.g
ILC TPC Collaboration: 1.2c
RD42: 1.1.a, 1.2.a, 1.1.i, 1.2.i
RD50: 1.1.a, 1.2.a, 1.1.b, 1.4.b, 1.1.i
RD51: 1.1.c, 1.2.c, 1.4.c, 1.2i, 1.4i, 1.2.i, 1.4.i
RD52: 1.2.e
RD53: 1.1.n, 1.2.n
Versatile Link Project: 1.1.o

Apologies to other collaborations I am not aware of particularly outside Europe

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cool, services	stable	stable	reliable, stable	reliable, stable	
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AIDA-2020: http://aida2020.web.cern.ch/activities

CALICE: https://twiki.cern.ch/twiki/bin/view/CALICE/WebHome

Crystal Clear Collaboration: https://crystalclear.web.cern.ch/crystalclear/

ILC/CLIC FCAL Collaboration: http://fcal.desy.de/

ILC TPC Collaboration: https://www.lctpc.org/

RD42 (diamond): http://rd42.web.cern.ch/rd42/*

RD50 (rad-hard silicon): https://www.cern.ch/rd50/*

RD51 (micro-pattern gas detectors): http://rd51-public.web.cern.ch/rd51-public/*

RD52 (dual readout calorimetry): http://cds.cern.ch/record/2255826/files/*

RD53 (rad-hard electronics): https://rd53.web.cern.ch/RD53/

VL Project: https://espace.cern.ch/project-Versatile-Link-Plus/SitePages/Home.aspx

** See LHCC 10/5/17 presentations at https://indico.cern.ch/event/632309/*

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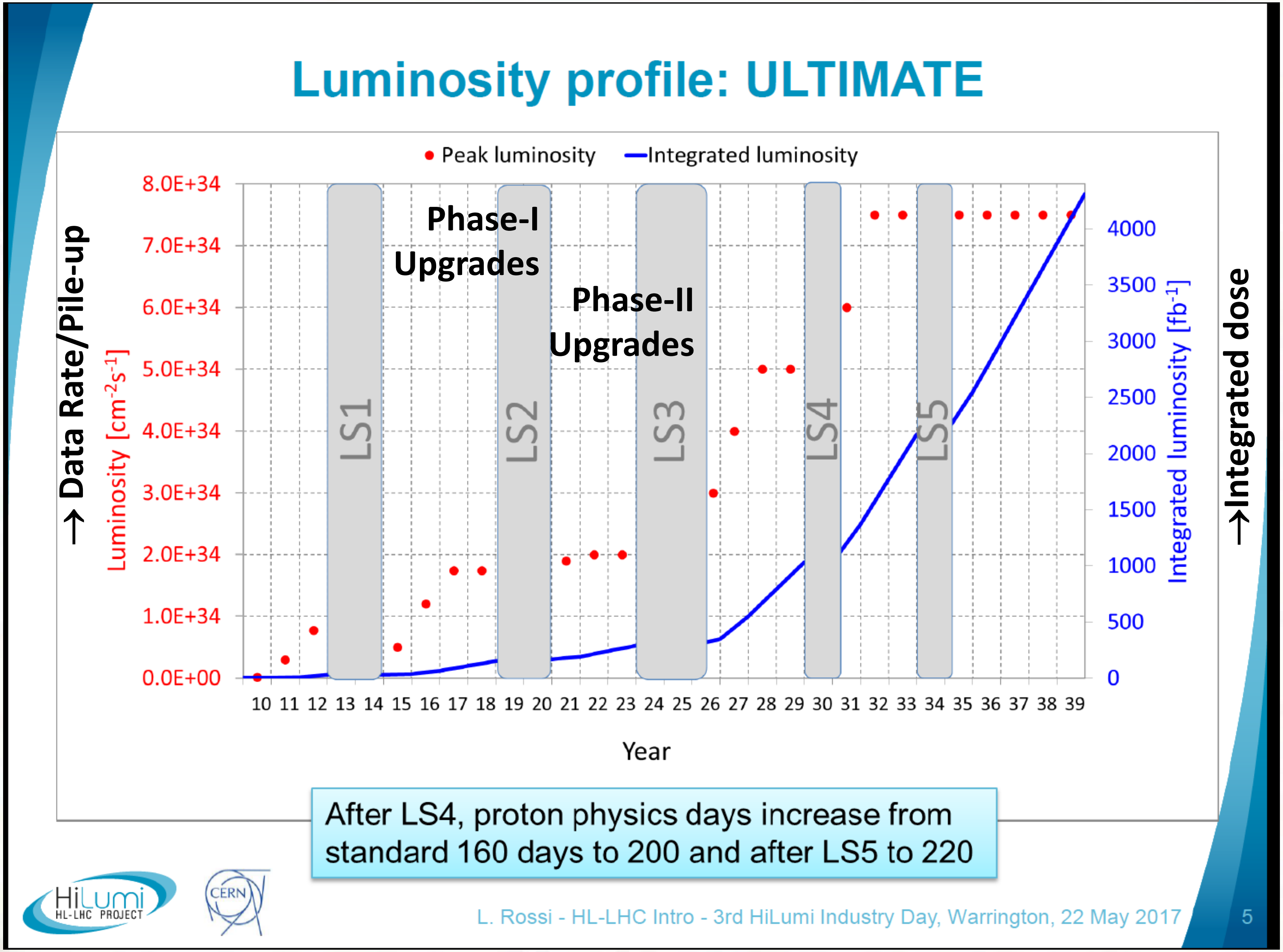
Detector Upgrades for the HL-LHC Programme



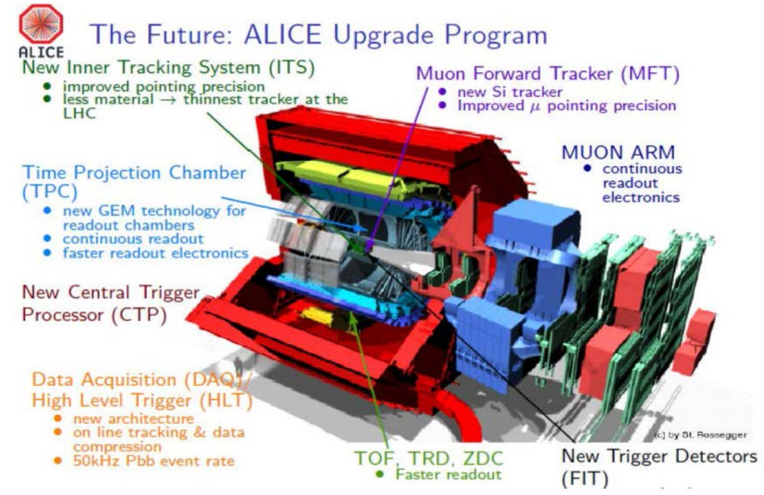
Luminosity profile: ULTIMATE

After LS4, proton physics days increase from standard 160 days to 200 and after LS5 to 220

L. Rossi - HL-LHC Intro - 3rd HiLumi Industry Day, Warrington, 22 May 2017 5

Detector Upgrades for the HL-LHC Programme

ALICE: Phase-I Upgrades



The Future: ALICE Upgrade Program

New Inner Tracking System (ITS)
- improved pointing precision
- less material → thinnest tracker at the LHC

Muon Forward Tracker (MFT)
- new Si tracker
- Improved μ pointing precision

MUON ARM
- continuous readout electronics

Time Projection Chamber (TPC)
- new GEM technology for readout chambers
- continuous readout
- faster readout electronics

New Central Trigger Processor (CTP)

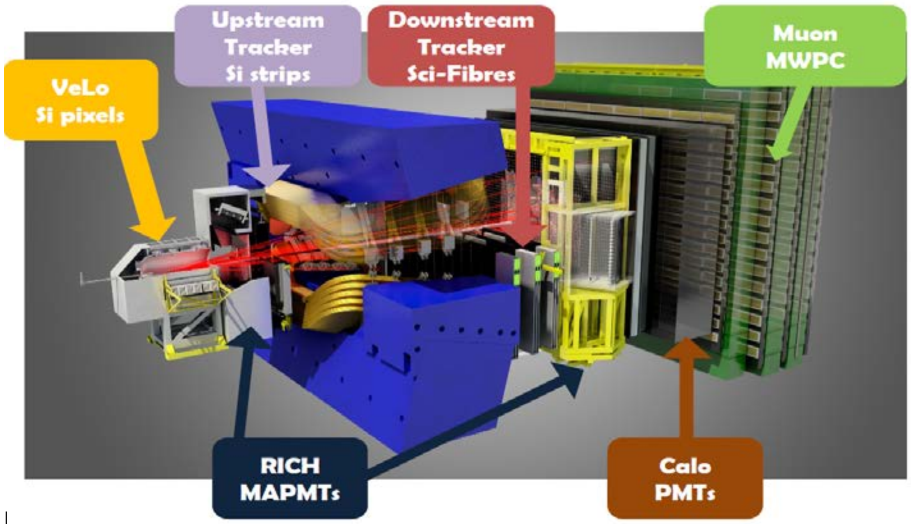
Data Acquisition (DAQ)/ High Level Trigger (HLT)
- new architecture
- on line tracking & data compression
- 50kHz Pbb event rate

TOF, TRD, ZDC
- Faster readout

New Trigger Detectors (FIT)

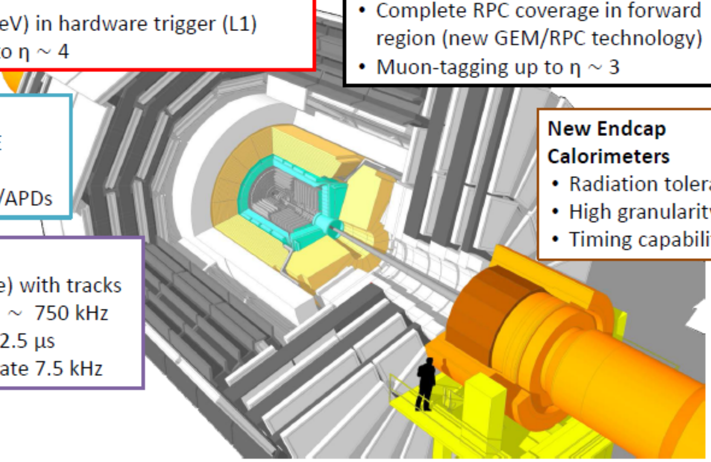
https://indico.cern.ch/category/4863/

LHCb: Phase-I Upgrades



CMS: Phase-II Upgrades

http://cds.cern.ch/record/2055167/files/LHCC-G-165.pdf?version=4



New Tracker
- Radiation tolerant - high granularity - less material
- Tracks (P_T>2GeV) in hardware trigger (L1)
- Coverage up to η ~ 4

Muons
- Replace DT and CSC FE/BE electronics
- Complete RPC coverage in forward region (new GEM/RPC technology)
- Muon-tagging up to η ~ 3

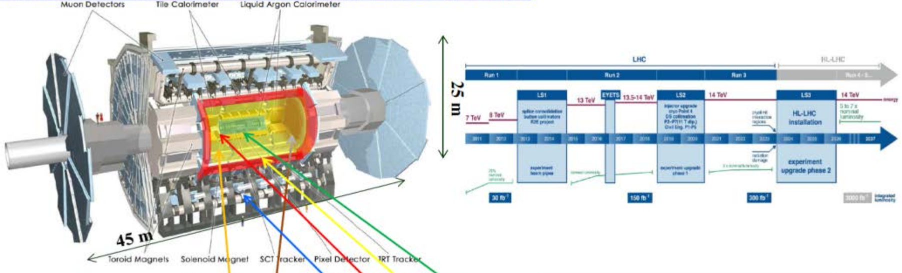
Barrel ECAL
- Replace FE/BE electronics
- Cool detector/APDs

New Endcap Calorimeters
- Radiation tolerant
- High granularity
- Timing capability

Trigger/DAQ
- L1 (hardware) with tracks and rate up ~ 750 kHz
- L1 Latency 12.5 μs
- HLT output rate 7.5 kHz

ATLAS: Phase-II Upgrades

https://cds.cern.ch/record/2055248/files/LHCC-G-166.pdf



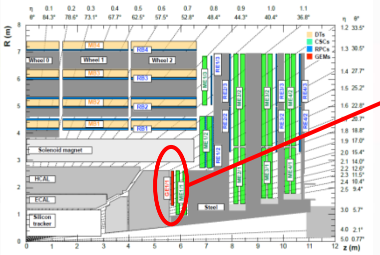
Phase-1 Upgrade	Phase-2 Upgrade
L = 2e34 (μ~60) int L = 200 fb^{-1}	L = 7.5e34 (μ~200) int L = 3000 fb^{-1}
New Muon Small Wheel (NSW) Fast Track Trigger (FTK) TDAQ Phase-1 LAr Calorimeter Electronics ATLAS Forward Protons (AFP)	All new Tracking Inner Detector (ITk-Strip/Pixel) Calorimeter Electronics Upgrade Forward Timing Detector Muon System Upgrade TDAQ Phase-2

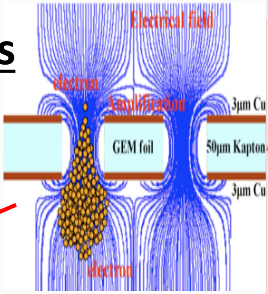
Large Area High Rate Gas Detectors ($>10^4$Hz/cm^2)

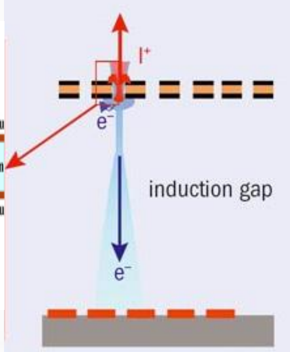
(DD-18, 19, 20, 26, 28, 29, 34)

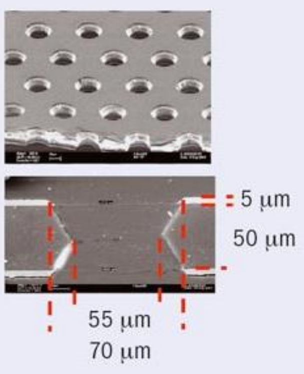
Major R&D activities on micro-pattern gaseous detectors for LHC large volume tracking (eg muon systems)

- <u>Increase rate capabilities and radiation hardness</u>
- Improved resolution (online trigger and offline analyses)
- Improved timing precision (background rejection)









Fabio Sauli
doi:10.1016/j.nima.2015

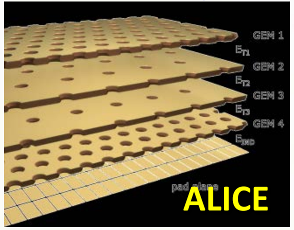
Technologies

- Straws and drift tubes
- Gas Electron Multiplier (KLOE-2, BESIII CMS, ALICE TPC R/O and current LHCb)
- MicroMegas and Thin Gap Chambers (TGCs): ATLAS "New Small Wheels"
- Resistive Plate Chambers (RPCs) - low resistivity glass for rate capability, multi-gap precision timing (ALICE/ATLAS/CMS)

Cylindrical GEM KLOE-2 and for BESIII

(Michela Greco 6/7/17)

Erika De Lucia, (6/7/17)



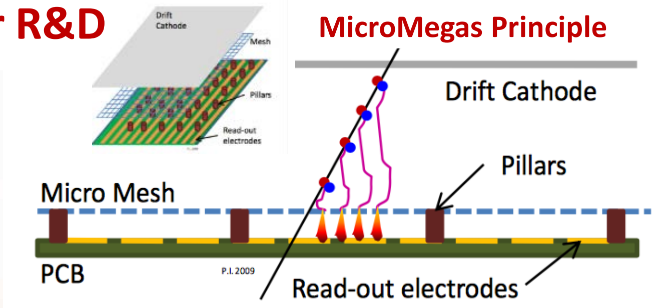
ALICE TPC Read-out
Christian Lippmann (8/7/17)

4 layer GEM stack to target Ion backflow < 1% given continuous readout at 50kHz

RD51 common micro-pattern gas detector R&D

Many challenges including the development of commercial large-scale production capabilities (ATLAS NSW Forward Muons: 2*1200m^2 and 2.4M channels)

MicroMegas Principle



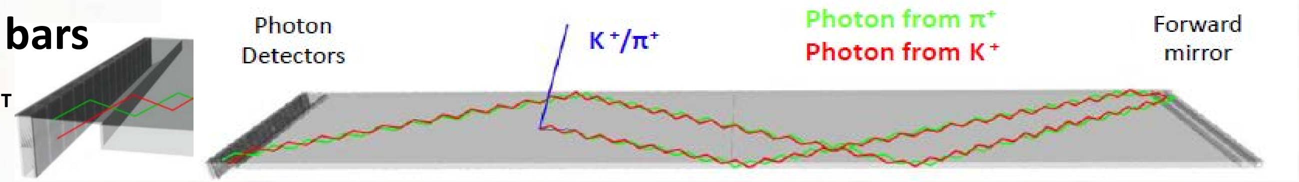
ATLAS Small Wheels

Paolo Iengo (6/7/17)

Timing Detectors (c=30cm/ns; 1/c= 33ps/cm)

https://doi.org/10.1016/j.nima.2017.02.045

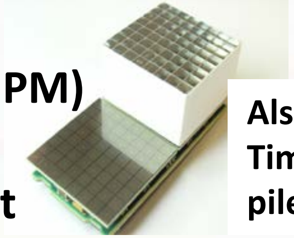
- **Many applications call for precision timing for particle ID (incl Time of Flight)**
  - ***eg* BELLE-II TOP (Time of Propagation) σ = 35ps: 2.5m x 0.45m x 2cm Quartz bars**



  - ***eg* LHCb TORCH** (Time Of internally Reflected CHerenkov light) **15ps ToF (30 pe/track)**

(DD-23, 27 38)

- **PET Scanner ToF fast scintillator and photodetector (eg LYSO+SiPM)**



Also CMS Barrel Timing Layer (30ps pile-up mitigation)

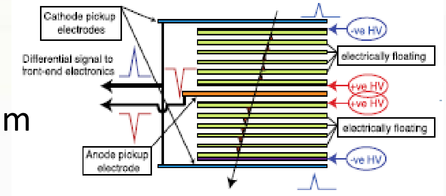
- **Also charged particle detection with quartz/scintillator plus fast photodetectors, or direct detection also possible with fast gas or semiconductor detectors**

(ATLAS AFP: <15ps James Pinfold (6/7/17))

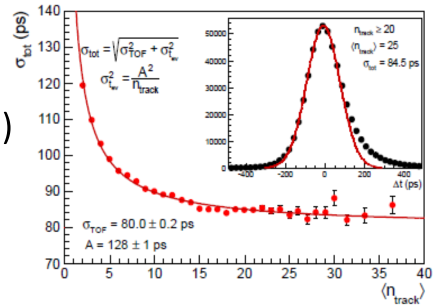
ALiCE ToF

140 m² of Multigap RPCs at 3.7 m from the IP

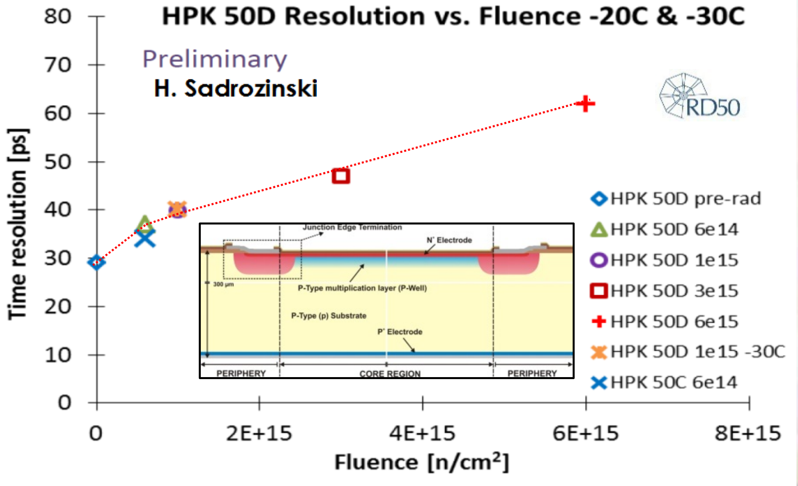
- Rate capability ~100 Hz/cm² (glass resistivity)
- **Fast readout electronics**
- Leading edge disc. with time-over-thresh correction (NINO)
- **Single particle resolution *in situ*: down to 80 ps**



2014 JINST 9 C10019



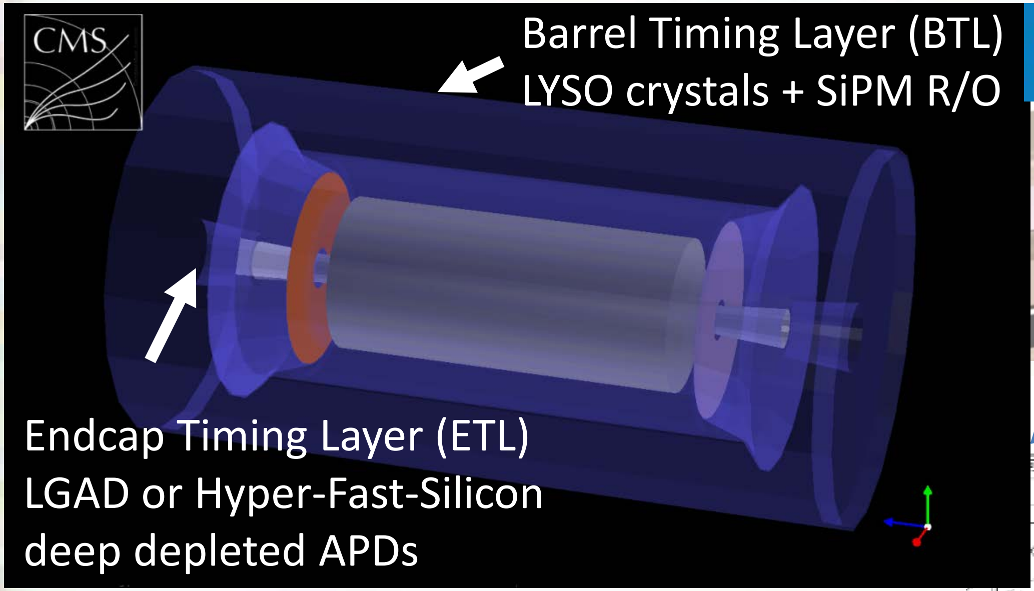
RD50, ATLAS, CMS: Low Gain Avalanche Detectors (LGAD) (need to watch radiation issues - work ongoing)



HL-LHC Timing Detectors

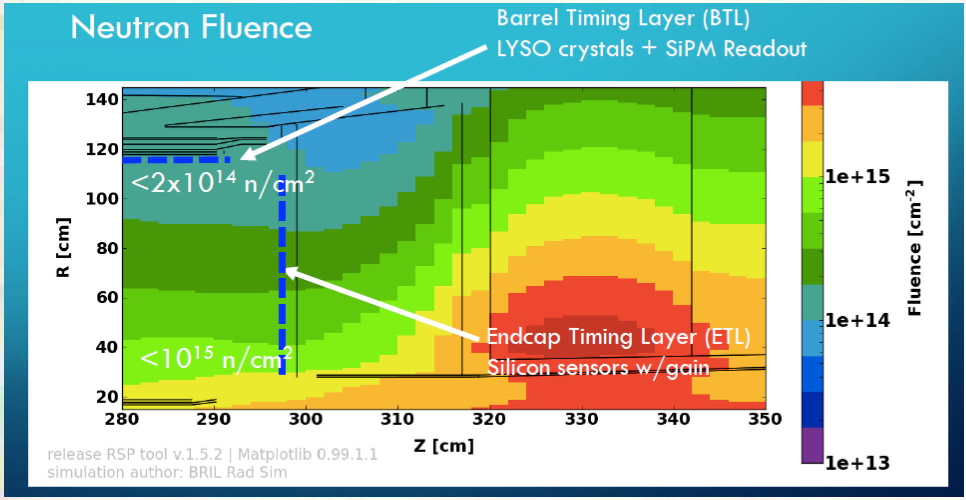
(Beamspot: σ_z ~ 9 cm; σ_t ~ 0.2ns
2017-03-16_HLLHC-TC.pdf)

See talks of Nicolo Cartiglia and Djamel Boumediene (7/7/17)

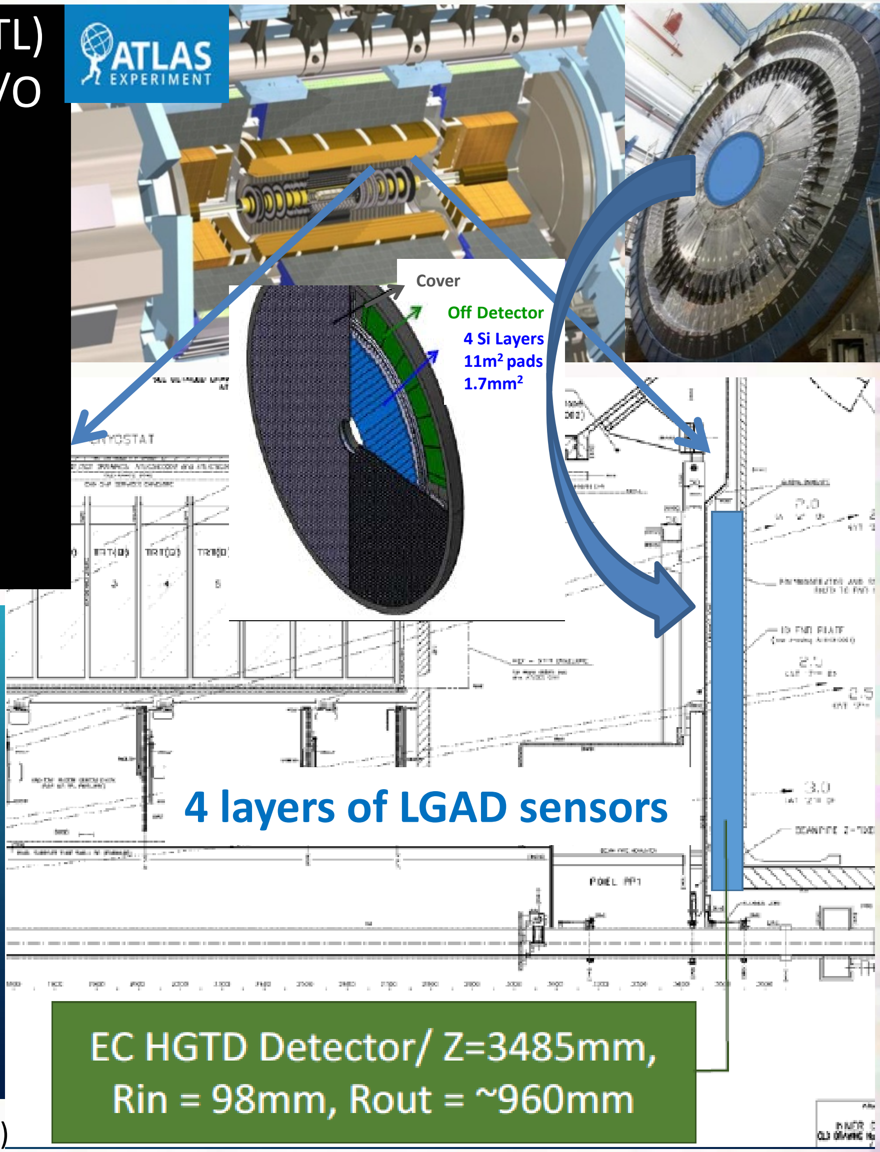


Barrel Timing Layer (BTL)
LYSO crystals + SiPM R/O

Endcap Timing Layer (ETL)
LGAD or Hyper-Fast-Silicon
deep depleted APDs



(Lectures by Christopher Tully at https://indico.cern.ch/event/633343/)



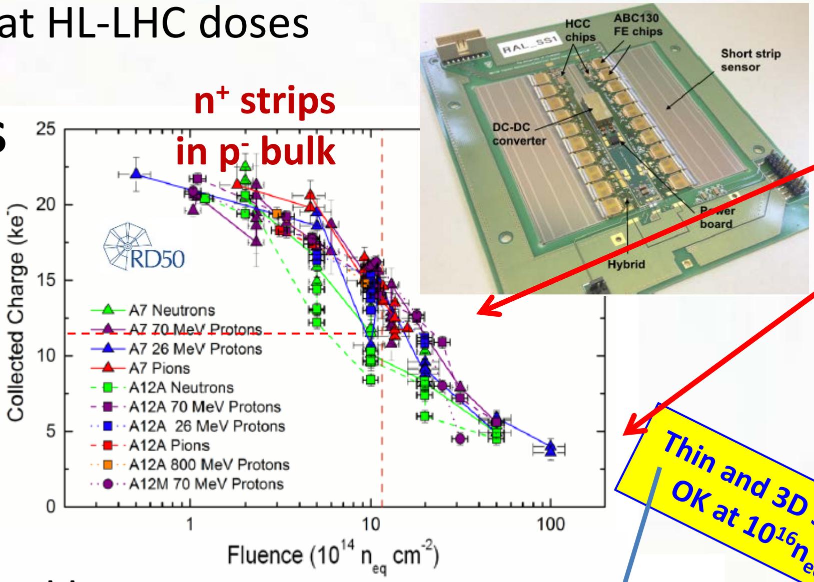
4 layers of LGAD sensors

EC HGTD Detector/ Z=3485mm,
Rin = 98mm, Rout = ~960mm

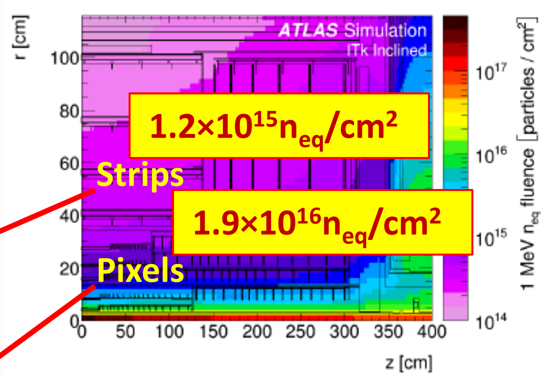
HL-LHC Radiation Hardness

- Hybrid silicon detectors (pixels strips) efficient even at HL-LHC doses

RD50
ATLAS
CMS
LHCb



n^+ strips in p^- bulk

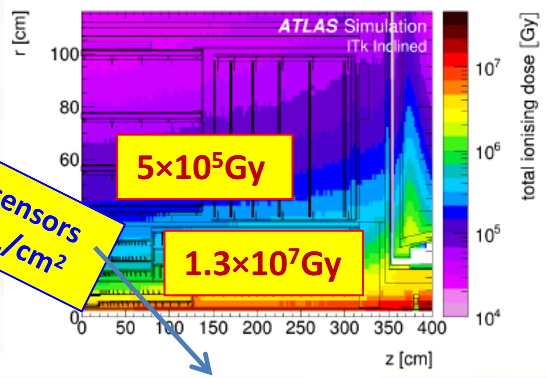


$1.2\times10^{15}n_{eq}/cm^2$ **Strips**

$1.9\times10^{16}n_{eq}/cm^2$ **Pixels**

Approved 9/6/17 CERN Research Board

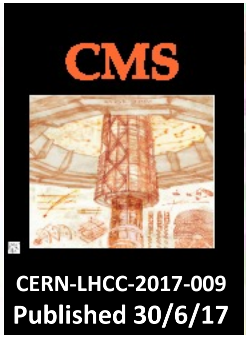
Helen Hayward (8/7/17)



5×10^5Gy

1.3×10^7Gy

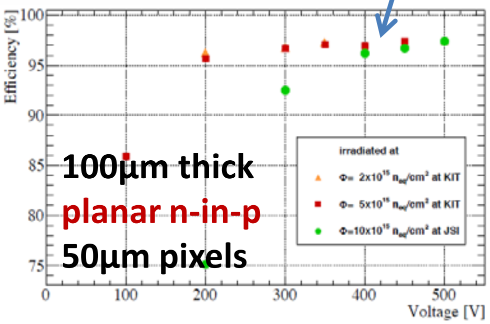
Thin and 3D sensors OK at $10^{16}n_{eq}/cm^2$



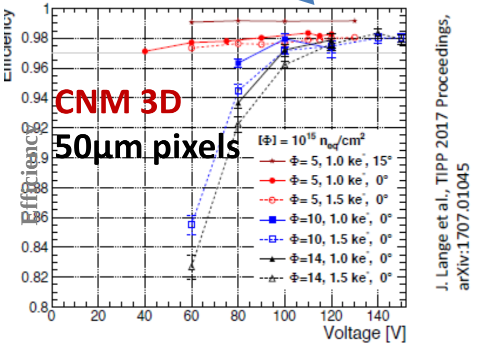
CERN-LHCC-2017-009
Published 30/6/17

Sudha Ahuja (8/7/17)

- For pixel layers: **microelectronics** (65nm CMOS - **RD53**) can start to see significant deterioration at **1Grad (=10^7Gy)** particularly in PMOS transistors with further temperature, bias and manufacturer dependence

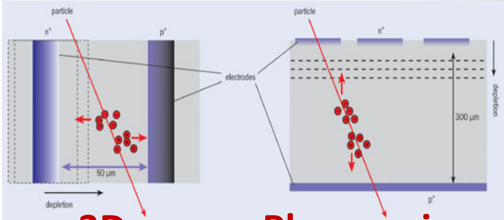


100µm thick
planar n-in-p
50µm pixels



CNM 3D
50µm pixels

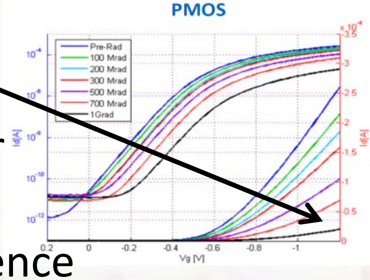
J. Lange et al., TIPP 2017 Proceedings, arXiv:1707.01045



3D
Lower V

Planar n-in-p
Simpler

(DD-15, 17)



https://indico.cern.ch/event/468486/
Federico Faccio

→ **Also need rad-hard data links with up to ~40 hits/cm² each 25ns**

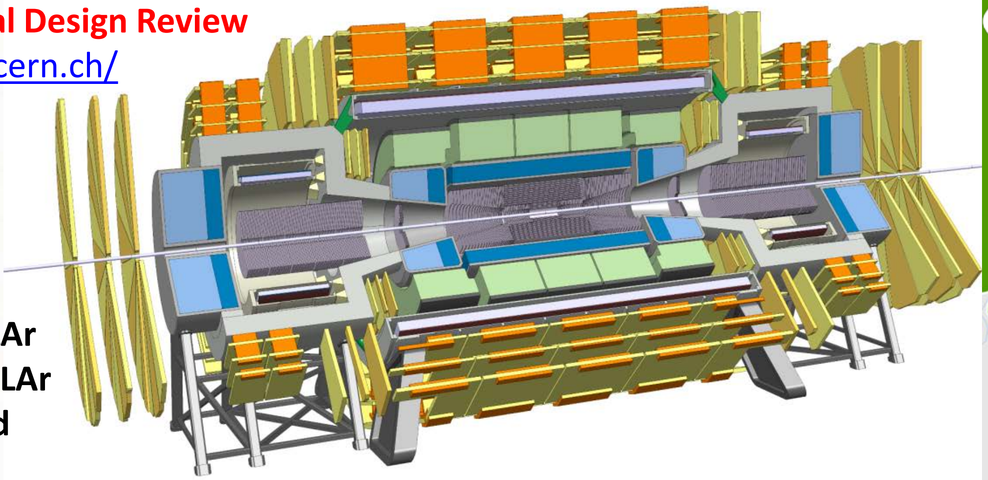
Even More Challenging: FCC-hh

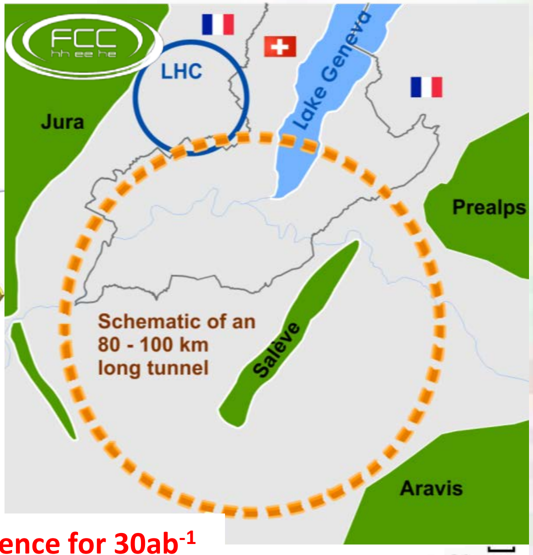
(And many other specific challenges for FCC-ee and FCC-eh)

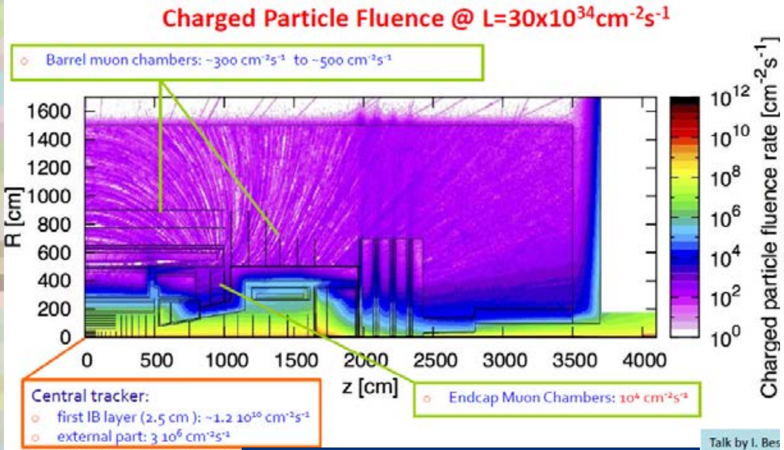
Baseline for Conceptual Design Review
https://fccw2017.web.cern.ch/

- 4T 10m solenoid
- Forward solenoids
- **Silicon** tracker
- Barrel ECAL **LAr**
- Barrel HCAL Fe/**Sci**
- Endcap HCAL/ECAL **LAr**
- Forward HCAL/ECAL **LAr**

Other options explored





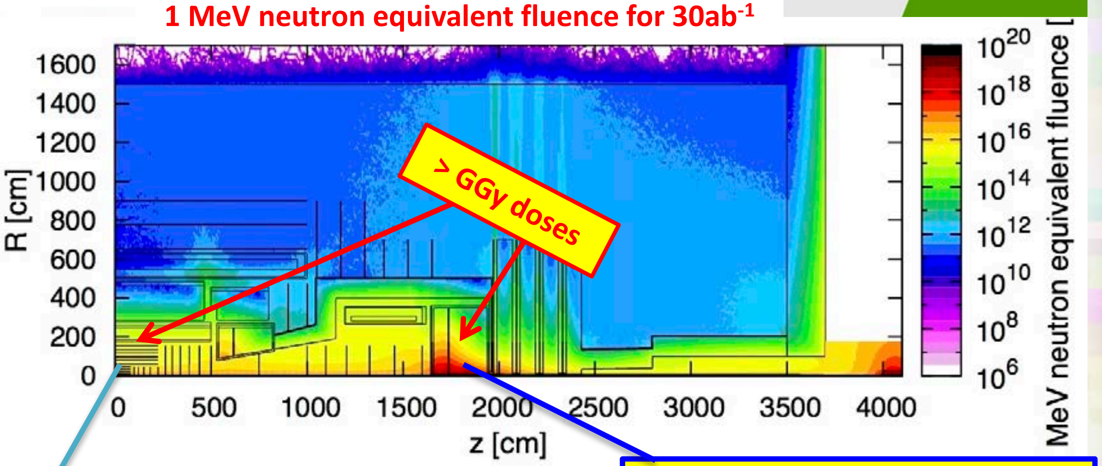

Charged Particle Fluence @ $L=30\times10^{34}cm^{-2}s^{-1}$

- Barrel muon chambers: ~300 $cm^{-2}s^{-1}$ to ~500 $cm^{-2}s^{-1}$

Central tracker:
- first IB layer (2.5 cm): ~1.2 10^{10} $cm^{-2}s^{-1}$
- external part: 3 10^{6} $cm^{-2}s^{-1}$

- Endcap Muon Chambers: 10^{4} $cm^{-2}s^{-1}$

Talk by I. Bes


1 MeV neutron equivalent fluence for $30ab^{-1}$

> GGy doses

Central tracker:
- first IB layer (2.5 cm): ~5-6 10^{17} cm^{-2}
- external part: ~5 10^{15} cm^{-2}

Forward calorimeters:
- maximum at ~5 10^{18} cm^{-2} for both the EM and the HAD-calo
- 10^{16} cm^{-2} at R=2 m

- Schedule prepared **European Strategy Update 2020**


Draft Schedule Considerations

2043

FCC Study Status and Plans
Michael Benedikt
3rd FCC Week, Berlin, 29 May 2017

ILC/CLIC Inspired Pixel Technologies

VERTEX 2016:
J Goldstein
A G Besson

(See Vertex 2016 https://indico.cern.ch/event/452781/sessions/208678/#20160930)

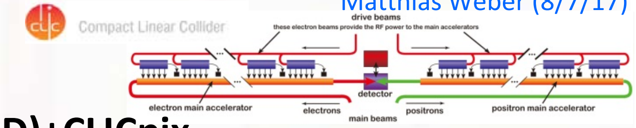
- Demands of ultra-low mass, highest resolution, low power and fast time-stamp
- A wide range of technologies with many years of development:
  - DEPFET (see also BELLE-II)
  - FinePixel CCD
  - Thin Planar sensor or HV-CMOS Hybrid (C3PD)+CLICpix
  - Monolithic CMOS
    - Vertical integration with TSVs (FNAL 3D)
    - Chronopix
    - SOi for Fine Space and Time (SOFIST)
    - Monolithic Active Pixel Sensors (MAPS)
      - MIMOSA (developments since 2000 for ILC)

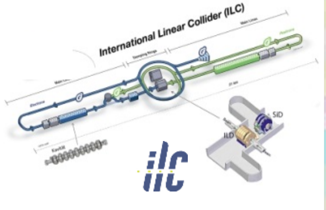
→ **STAR Heavy Flavour Tracker** (doi: 10.1016/j.phpro.2015.05.067)

→ **ALPIDE for ALICE Inner Tracker System Upgrade** (ALICE-TDR-017)

→ **Depleted MAPS (DMAPS):** **(large fill factor + deep-depletion or low fill factor = low C)**

Matthias Weber (8/7/17)

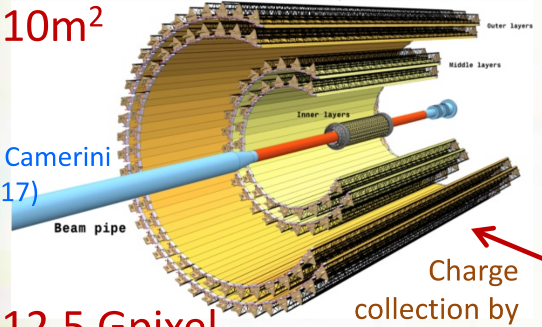




Spatial resolution: highly granular sensor:
$\sigma_{R\phi}$ ~ 3 µm (pitch ~ 20 µm)
multiple scattering : very low material budget:
O(0.1%X_0/layer)
Single bunch time resolution
→ 1st layer: ~ 5 part/cm^2/BX → few % occupancy
Power dissipation ↔ preferably gas cooling
→ <130µW/mm^2 (Power cycling, ~3% duty cycle)

SiD: Tim Barklow (8/7/17)

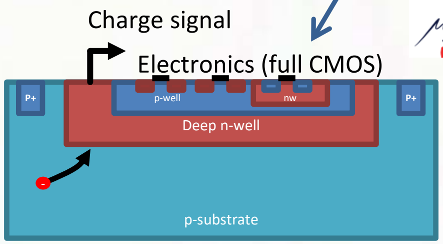
ALICE ITS (<30µs resolution)
(rad-hard to **$10^{13}n_{eq}/cm^2$**)
10m^2

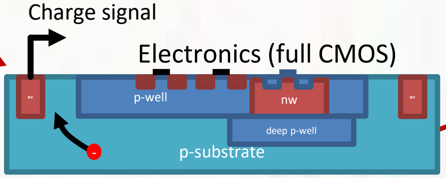


Paolo Camerini (8/7/17)

12.5 Gpixel

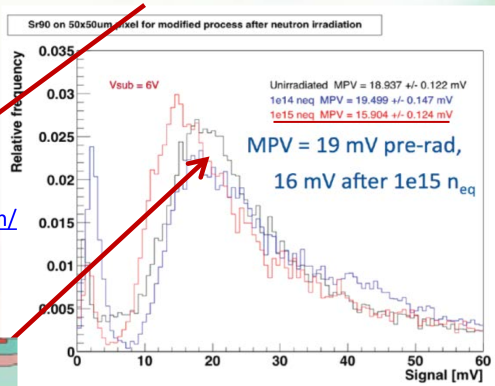
Charge collection by drift and diffusion





ATLAS

N. Wermes
https://fccw2017.web.cern.ch/



MPV = 19 mV pre-rad,
16 mV after 1e15 n_{eq}

Both DMAPS approaches Rad-hard to >$10^{15}n_{eq}/cm^2$

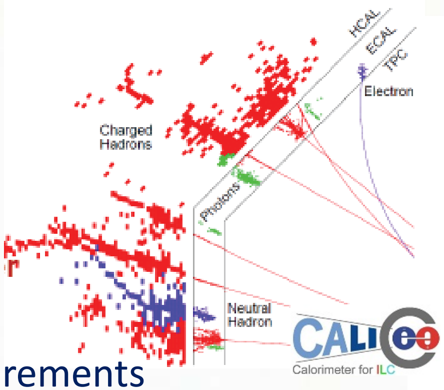
Calorimetry and Particle Flow

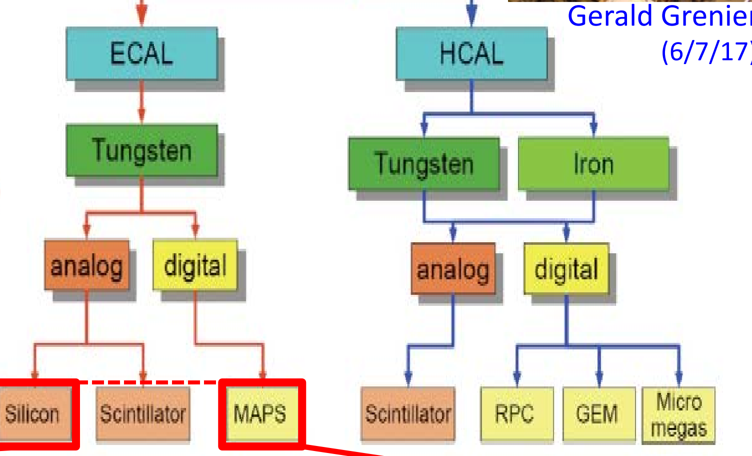
- **RD52** **D**ual **REA**d-out **M**ethod
  - FCC-ee?

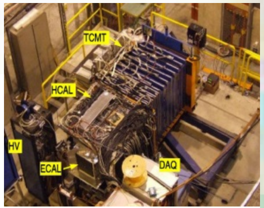
Simultaneous measurement, during shower development, of:

- **Scintillation light (dE/dx charged particles)**
- **Cherenkov light (EM part of the shower)**

- **CALICE** (Calorimeter for *ILC*)
  - Fundamental concept:
    - Particle flow
    - Associate energy deposits with charged particles
    - → Drives granularity requirements
    - Allows "tracking" of neutrals





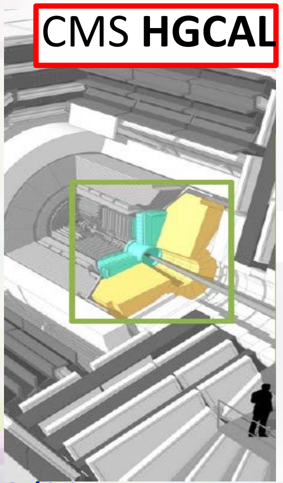


Gerald Grenier (6/7/17)

- ALICE **FoCAL**
  - Tungsten-Silicon sampling EM Calorimeter

FCC-hh?

- CMS **HGCAL**



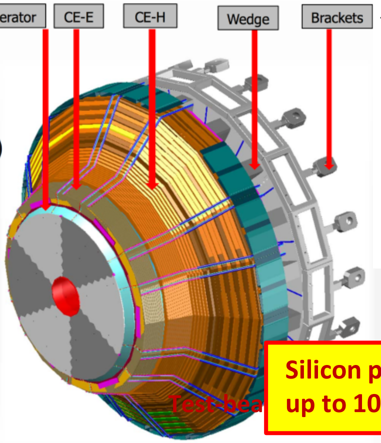
Main characteristics:

EC-E - 28 active layers, silicon sensors
EC-H - 24 active layers
8 silicon sensor
16 silicon (high η) + scint (low η)

ECAL: 25 X_0, ~1.3λ; HCAL: 8.5λ

EC-E total weight =18.5t
EC-H Absorbers material:
St.Steel, weight = 170t
Front Shielding weight = 0.8t

Total weight of Endcap = 253t



Key Parameters:

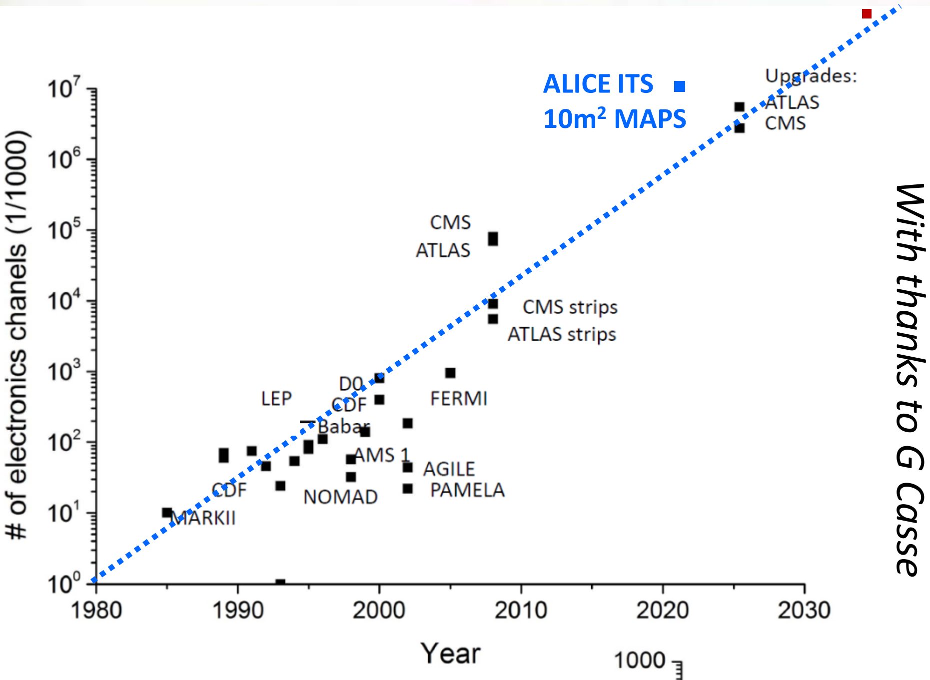
- EC covers 1.5 < η < 3.0
- Full system maintained at -30°C
- ~600m^2 of silicon sensors
- ~500m^2 of scintillators
- 6M si channels, 0.5 or 1 cm^2 cell size
- ~22000 si modules
- Power at end of HL-LHC: ~60 kW per endcap

Arnaud Steen (7/7/17)
Ivica Puljak (6/7/17)

Silicon pads to withstand doses up to 10^{16}n/cm^2 and several MGy

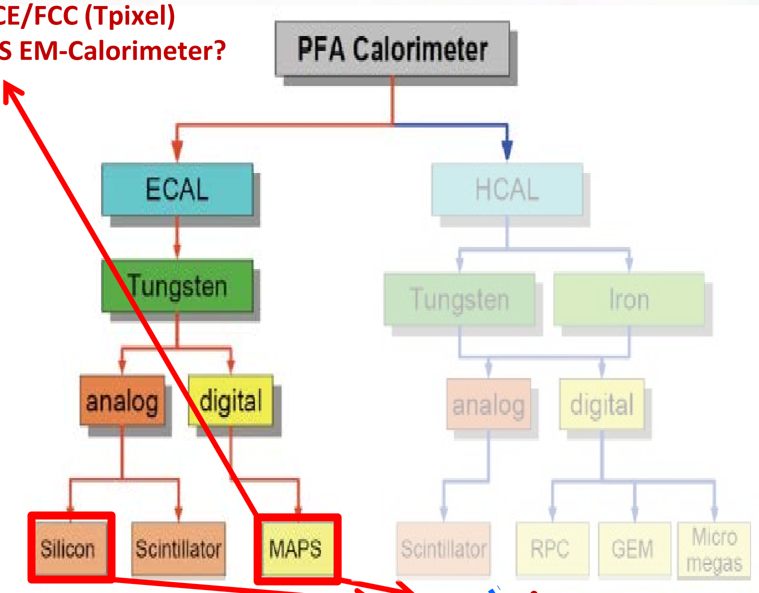
Silicon Based Detector Evolution

(See also Robert Klanner and Erik H.M. Heijne 10//7/17)

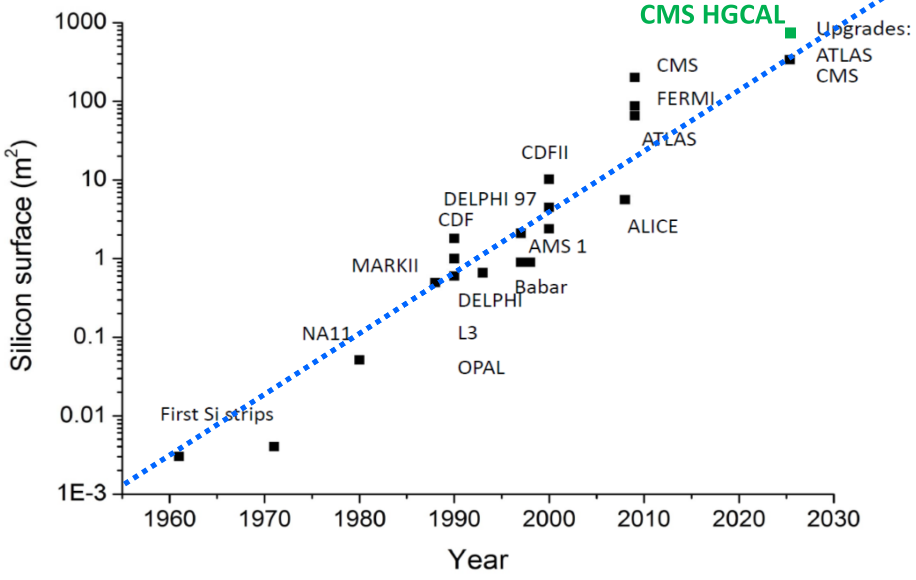


With thanks to G Casse

- CALICE/FCC (Tpixel) MAPS EM-Calorimeter?



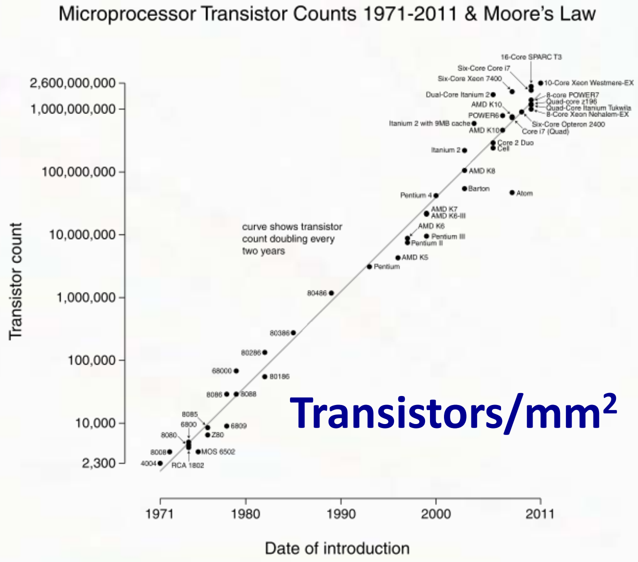
- CALICE/(FCC) SiW EM-Calorimeter



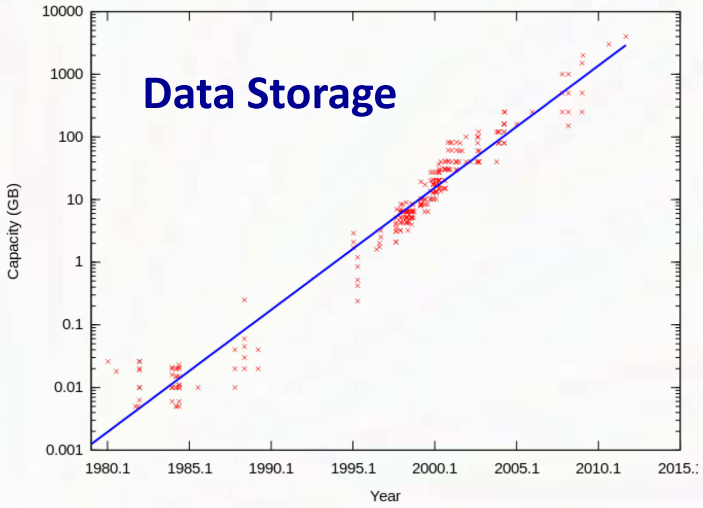
With thanks to G Casse

Need detector costs to scale with Moore's law.
For sensors, more likely with fully commercial processes such as CMOS Imaging Sensors (MAPS) as used in mobile phones, cameras etc.
(Need « \$/cm²)

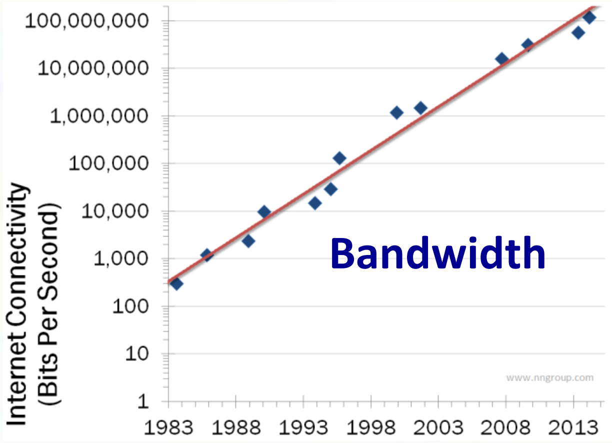
Microelectronics Evolution



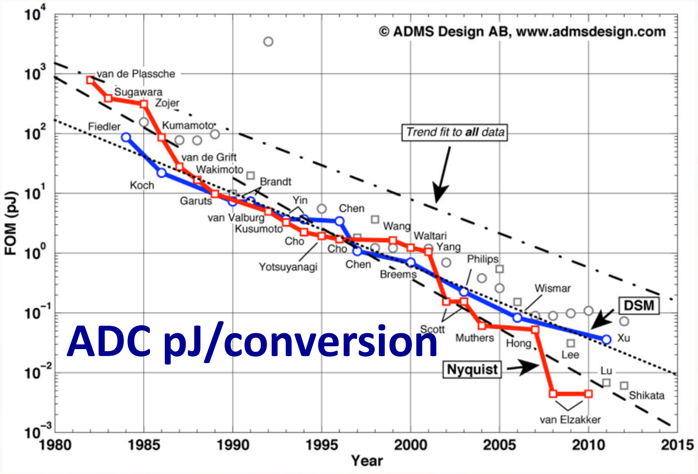
Transistors/mm²



Data Storage



Bandwidth



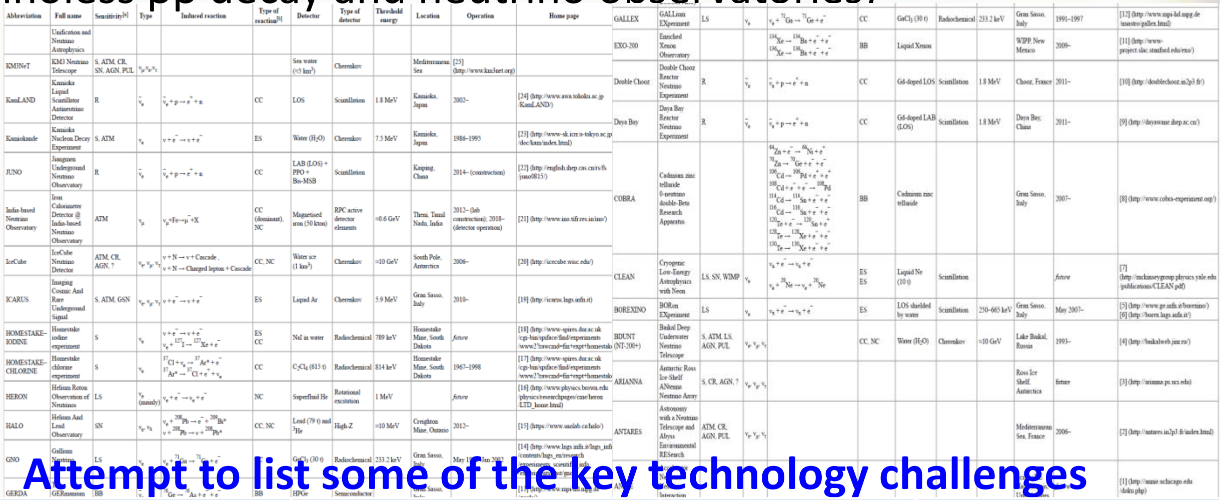
ADC pJ/conversion

With thanks to W Riegler

All these figures showed doubling times of < 2 years up to now. Some scalings will stop, but different improvements conceivable. Can still hope for major detector improvements and enhanced TDAQ plus computing capabilities. However, storage and CPU costs not expected to continue to scale this fast.

2. Accelerator and Reactor Neutrinos

https://en.wikipedia.org/wiki/List_of_neutrino_experiments gives over 50 experiments (but this list does include neutrinoless ββ decay and neutrino observatories)



Attempt to list some of the key technology challenges

	2.1 Long Baseline	2.2 Short Baseline	2.3 Reactor/source
2.c Gas detectors	Amplification	High pressure	
2.e,h Solid scintillator (sampling and homogeneous)	Photodetector costs Material costs Large scale engineering	Energy threshold Noise, Timing Granularity	Energy and spatial resolution. Low noise. Calibration. Shielding.
2.l,q Liquid scintillator and associated engineering	Photodetector sensitive area and cost, Radio-purity, Large scale engineering	Photo-detector QE Mechanics Shielding	Photo-detector QE Radio-purity, Gd doping, flux modelling
2.m,q Liquid noble gas and associated engineering	Purification Very high voltage Large scale cryogenics	In cryostat low noise CMOS, space charge, FE range	Coherent neutrino-nucleus scattering?
2.n,q Water Cherenkov and associated engineering	Photodetector timing, efficiency and costs Large scale engineering	Separation of pile-up events (same bunch), Gd-doping	Gd-doping. Radon. Shielding.
2.r DAQ & Computing	Reliability, buffering, dynamic range, data volume	Reliability, data volume	Reliability

AIDA 2020 WP8: Large scale cryogenic liquid detectors

CAUTION
WORK IN PROGRESS

2.1 & 2.2 Long Baseline Neutrino Detectors

(See plenary talk Tsuyoshi Nakaya)

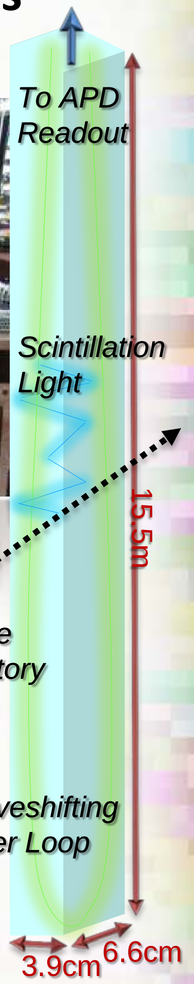
- **The issue of scale associated with current and future neutrino experiments introduces a very different set of challenges:**

Totally active, liquid scintillator, surface detector

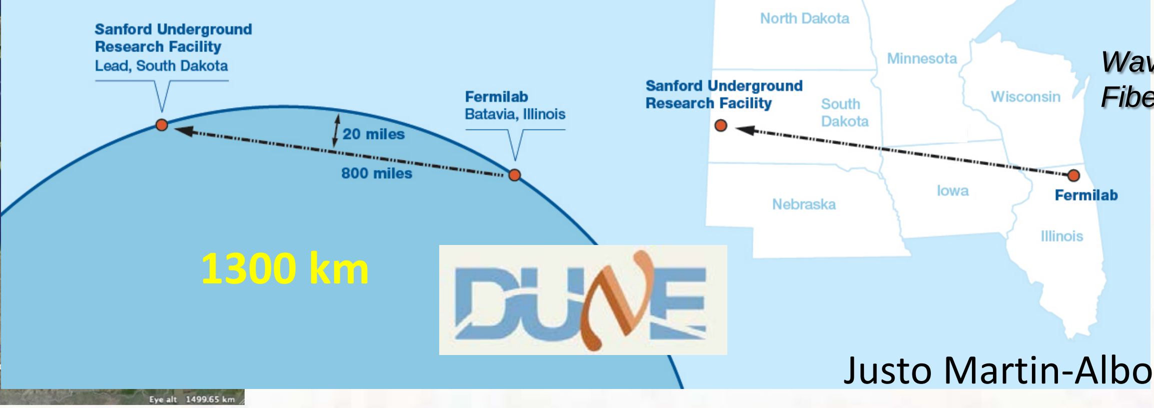
896 alternating X-Y planes 16mx16mx55m

“Largest Plastic Structure built by man”

Bruno Zamorano (6/7/17)



Deep Underground Neutrino Experiment



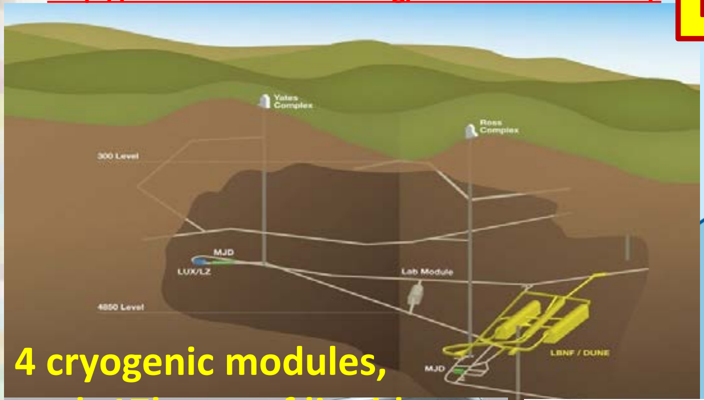
Justo Martin-Albo

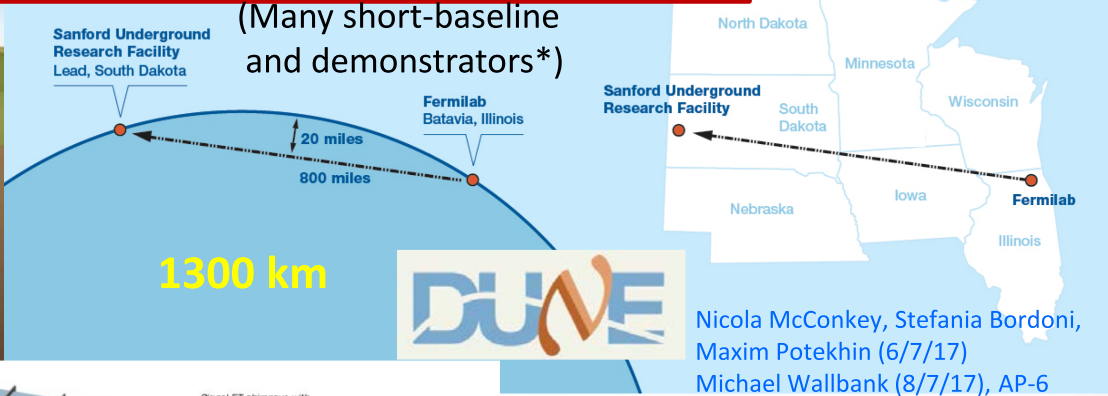
2.1 & 2.2 Long Baseline Neutrino Detectors

(*See Tsuyoshi Nakaya)

http://www.dunescience.org/neutrino-detectors/

Deep Underground Neutrino Experiment

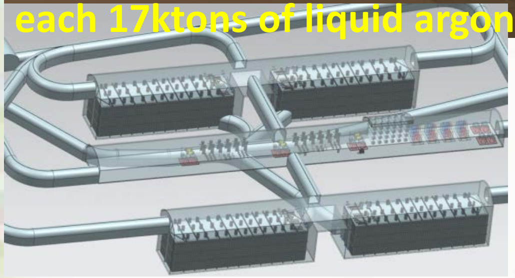




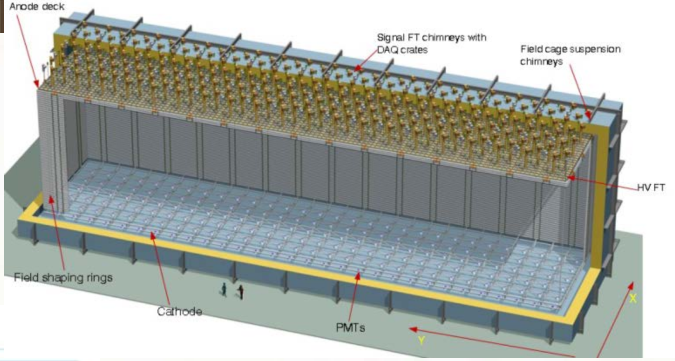
(Many short-baseline and demonstrators*)

1300 km

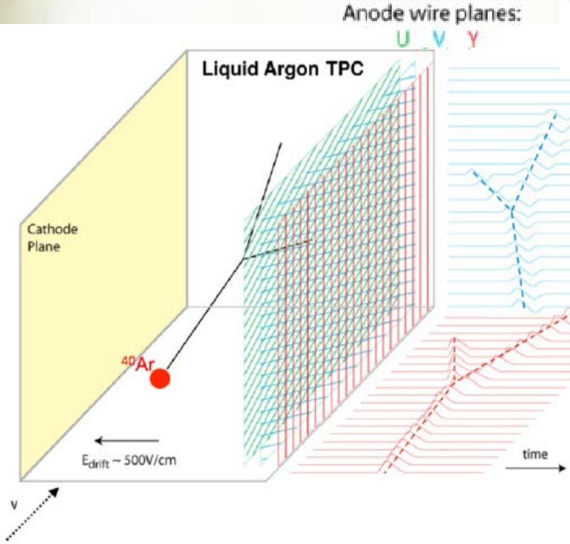
Nicola McConkey, Stefania Bordoni, Maxim Potekhin (6/7/17)
Michael Wallbank (8/7/17), AP-6



4 cryogenic modules, each 17ktons of liquid argon



- 2 technologies for far detector
  - Single phase TPC
  - Dual phase TPC
- high resolution tracking, calorimetry, PID via dE/dx



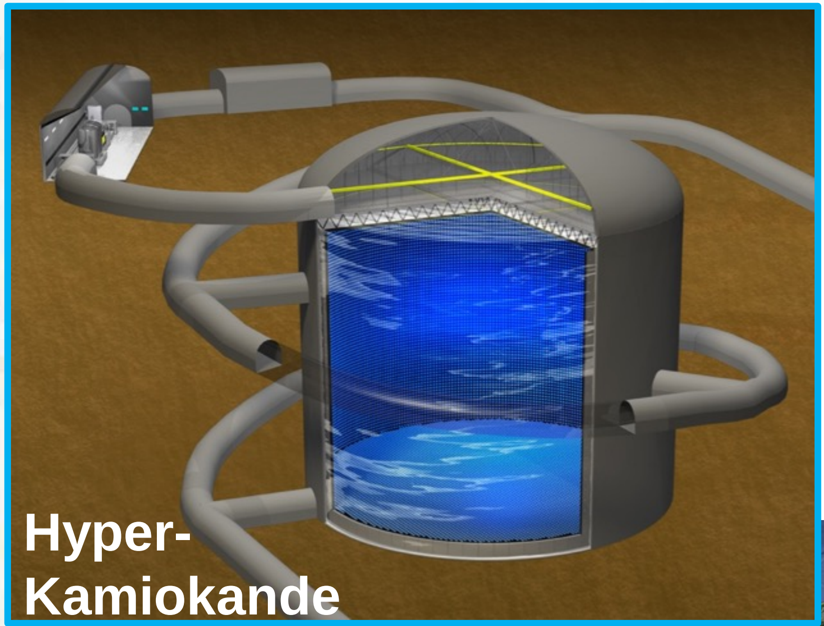
- Single phase TPC cathode planes biased to -180kV
- LAr scintillates at 128nm → drift time t_0
- Dual phase:
  - vertical drift and multiplication in gaseous phase improves signal/noise with reduced number of R/O channels
  - vertical drift over 12m requires ~600kV

→ Many challenges of scale for both detector concepts

ARIADNE: DD-37

2.1 & 2.2 Long Baseline Neutrino Detectors

(Tsuyoshi Nakaya)



Hyper-Kamiokande

- **Tank : 60 m tall × 78 m diameter**
- **260 kton ultrapure water**
  190 kton fiducial mass : 10 × Super-K
- **Innermost main volume viewed by 40,000 of new 50cm photo-sensors**
- **Improved photon sensitivity: 2×Super-K**
- **Second tank as upgrade path (6 yr later)**

Ben Richard 6/7/17

See also Mike Wilking 6/7/17

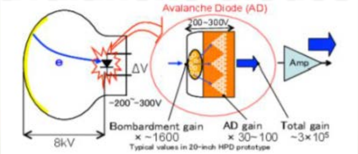
Luis Labarga 7/7/17

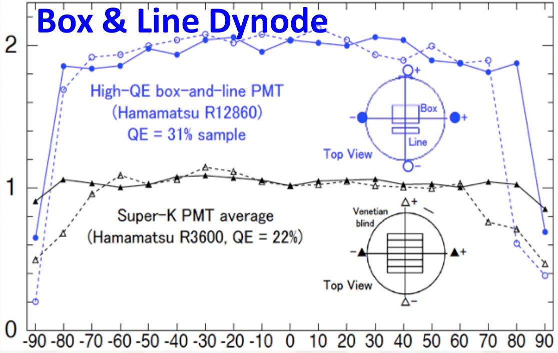
J-PARC Accelerator Complex

- **New 50 cm PMT completed**
  - **×2 single photon efficiency**
  - **×2 timing resolution**
  - **×2 hydrostatic pressure tolerance**

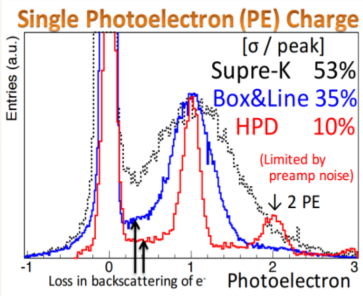
  (all w.r.t. Super-K PMT)

- **Hybrid-Photo-Detector (HPD): R&D development with avalanche diodes**

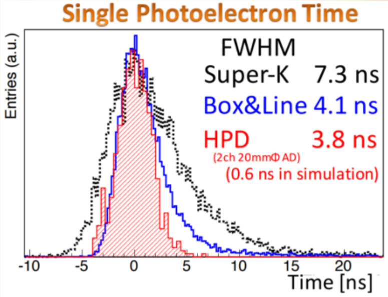




Box & Line Dynode



Single Photoelectron (PE) Charge

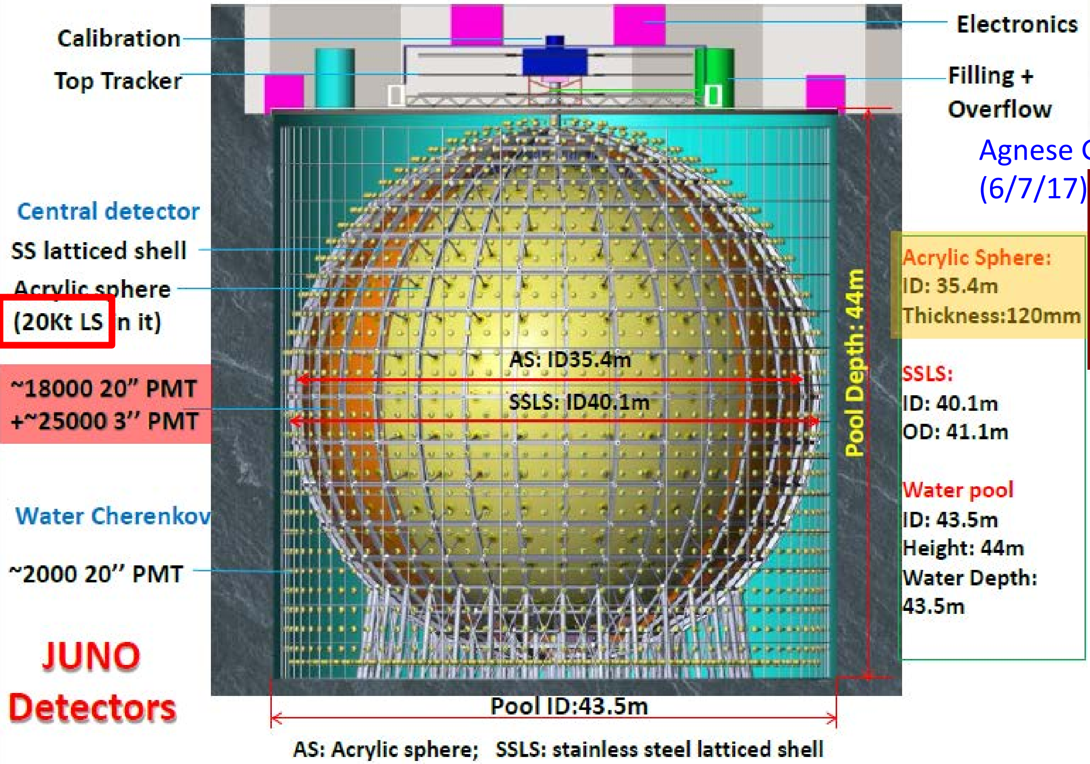


Single Photoelectron Time

2.3 Reactor Neutrino Detectors

(See plenary talk Thierry Lasserre)

Liangjian Wen TIPP, Beijing, 2017



Agnese Giaz (6/7/17)

Daya Bay Liquid Scintillator pilot plant

Linear alkyl benzene (LAB) as solvent
2,5-diphenyloxazole (PPO) as fluor
p-bis-(o-methylstyryl)-benzene (bis-MSB) as wavelength shifter

$^{14}C/^{12}C \sim 2.7 \times 10^{-18}$

^{238}U (Bi-Po 214)
$< 9.7 \times 10^{-19}$ g/g (95% CL)

^{232}Th (Bi-Po 212)
$< 1.2 \times 10^{-18}$ g/g (95% CL)

^{40}K no evidence (TBD)

$^{39}Ar << ^{85}Kr$

Technologies to achieve required radio-purity: Al_2O_3 column, distillation, gas striping, water extraction

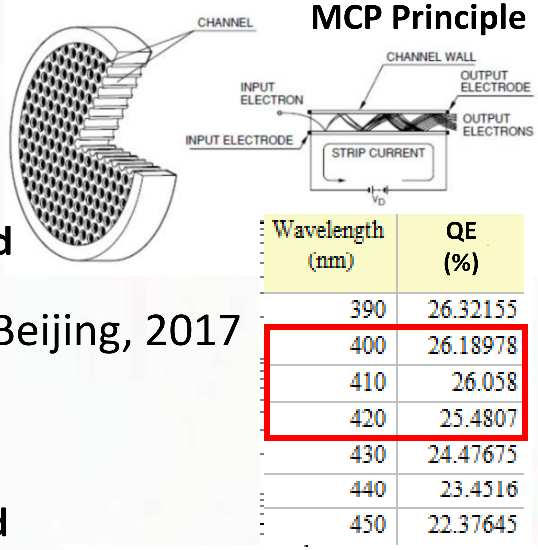
Levels achieved at Borexino: N. Rossi (Neutrino2016)

Neutrino Experiment Photodetectors

20” Micro-Channel Plate PMT for JUNO

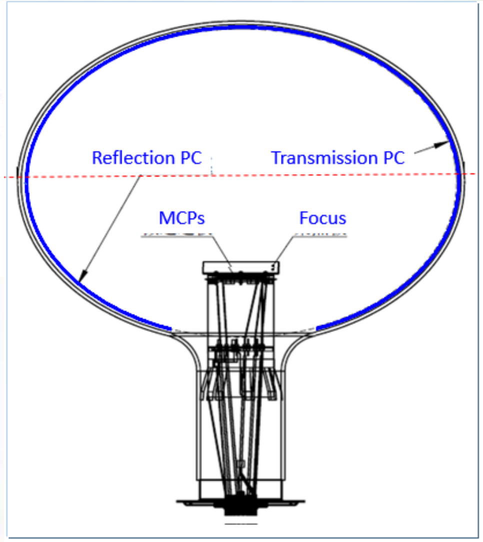
- **Higher QE: transmissive photocathode at top plus reflective photocathode at bottom**
- **Less shadowing effect**
- **Easier production: less manual operations and steps**

Liangjian Wen TIPP, Beijing, 2017



MCP Principle

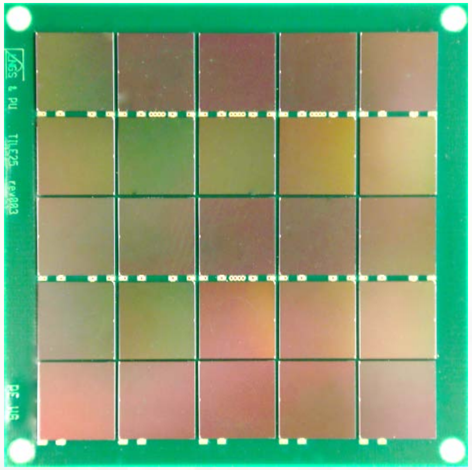
Wavelength (nm)	QE (%)
390	26.32155
400	26.18978
410	26.058
420	25.4807
430	24.47675
440	23.4516
450	22.37645



Large area (24 cm^2) single-channel, SiPM-based cryogenic (77K) photodetector with single photon sensitivity (https://arxiv.org/abs/1706.04220v2)

- **Single photon counting with signal to noise >13**
- **Dark rate lower than 4 mHz/mm^2**
- **SiPM photon detection efficiency**

(See also DD-27)



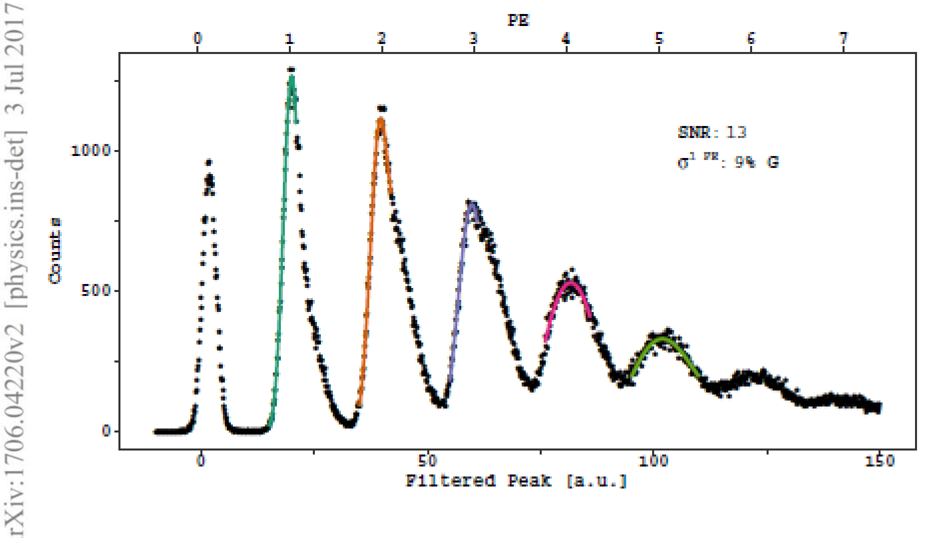


Fig. 11. Photoelectron spectrum of the full 24 cm^2 detector calculated using a matched filter. The solid lines represent a gaussian fit to the photoelectron peaks.

3. Non-accelerator and Low Energy Searches for Rare Processes

Facilities
3.1 Underground laboratories for Dark Matter searches
3.2 Underground laboratories for neutrino-less double β decay
3.3 No and low energy accelerator ultra-rare processes (eg g-2,COMET, Mu3e, edm, …)

Some Key Techniques
3.a Tracking semiconductor detectors
3.b Gaseous tracking detectors
3.d Scintillating Fibres
3.e Sampling Calorimeter
3.h Homogenous Calo
3.j Superconductor
3.l Liquid Noble gas
3.m Liquid Scintillator

Attempt to list some of the key technology challenges

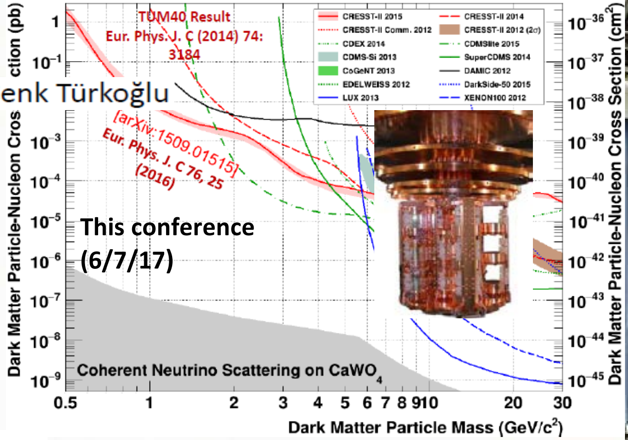
	3.1 Dark Matter	3.2 Rare neutrino	3.3 Other rare decay
3.a,b,d Tracker	Ultra-radio-purity Optical as well as electrical read-out	Radio-purity Very low material. Isotope enrichment	Thin, fine granularity. Single etch GEM foils, High rate, fast timing, complex field
3.e,h,j Calorimetry	Ultra-radio-purity, Ultra-low noise, (mK), Energy resolution	Radio-purity Ultra-low noise Energy resolution	High rate, fast timing, energy resolution at low energies, radiation
3.d Liquid noble gas	Ultra-radio-purity Ultra-low noise and high efficiency photodetectors	Radio-purity Ultra-low noise and high efficiency photodetectors	Energy resolution Background rates
3.e Liquid scintillator	Ultra-radio-purity Ultra-low noise and high efficiency photodetectors	Radio-purity Ultra-low noise and high efficiency photodetectors	Energy resolution Background rates
3.r DAQ & Computing			Event rates

⚠ CAUTION
WORK IN PROGRESS

3.1 Underground Experiments for Dark Matter

Jianglai Liu (6/7/17)

- **Huge variety of DM experiments with small and rare signals as ionisation, scintillation light, phonons or various combinations thereof.**
- **Need extreme control of background sources (radiopurity) coupled with high sensitivity and discrimination of signal from residual backgrounds.**
- **See talk of Manfred Lindner yesterday (11/7/17) for much fuller exposition**



Cenk Türkoğlu

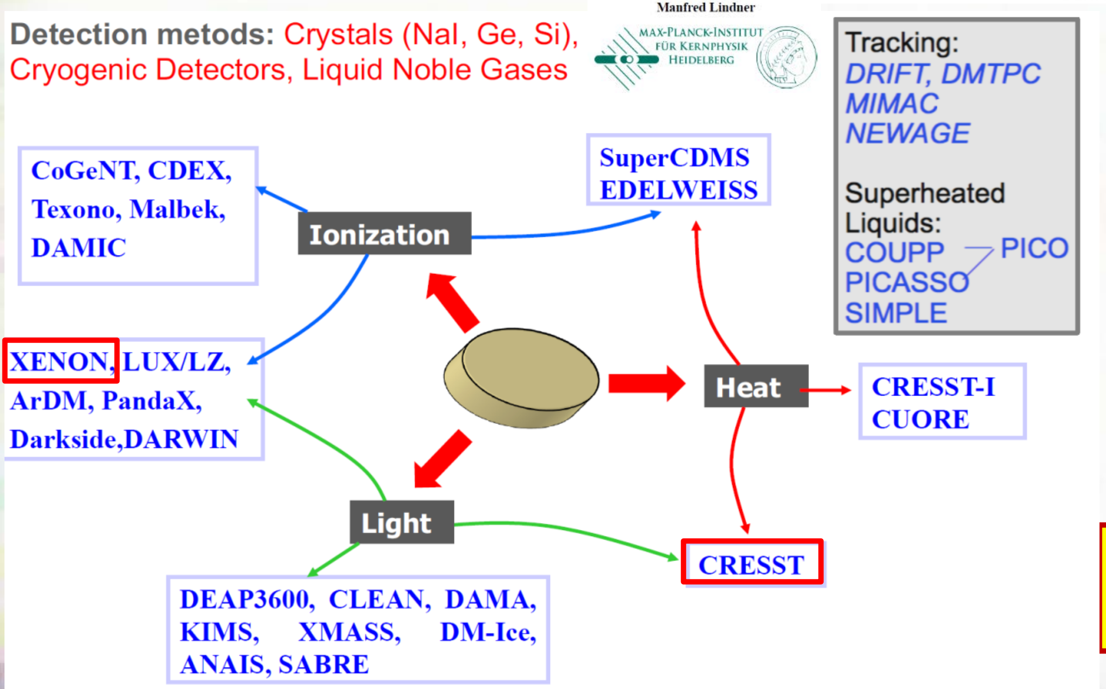
This conference (6/7/17)

CRESST $CaWO_4$ crystals (10mK)

Coherent neutrino scattering: NP-12)

largest LXe TPC ever built
cylinder: 96 × 97 cm
active LXe target: 2.0t (3.2t total)
248 PMTs (Hamamatsu R11410-21)

World leading bkg level: 0.2×10^{-3} evt/day/kg/keV



Manfred Lindner

Detection metods: Crystals (NaI, Ge, Si), Cryogenic Detectors, Liquid Noble Gases

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

CoGeNT, CDEX, Texono, Malbek, DAMIC

SuperCDMS EDELWEISS

Tracking: *DRIFT, DMTPC MIMAC NEWAGE*

Superheated Liquids: COUPP PICASSO SIMPLE PICO

Ionization

Heat

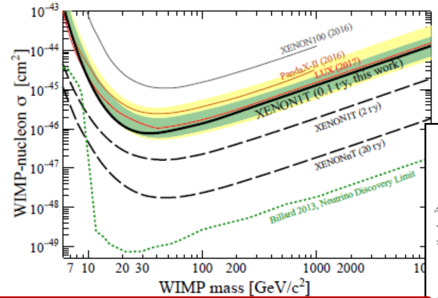
Light

XENON, LUX/LZ, ArDM, PandaX, Darkside, DARWIN

CRESST-I CUORE

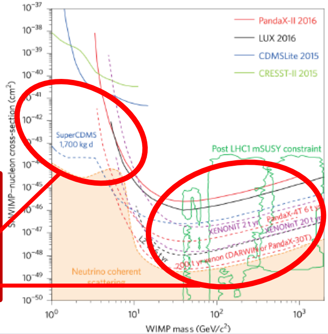
CRESST

DEAP3600, CLEAN, DAMA, KIMS, XMASS, DM-Ice, ANAIS, SABRE



Michelle Galloway (This conference 6/7/17)

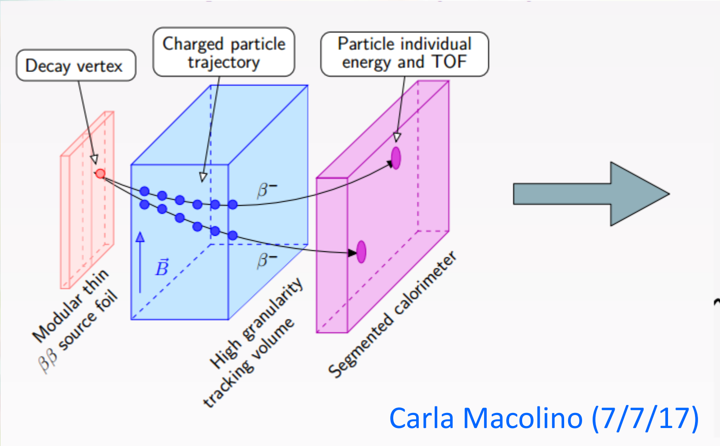
In next 5 years expect further huge progress at both low mass and high mass range



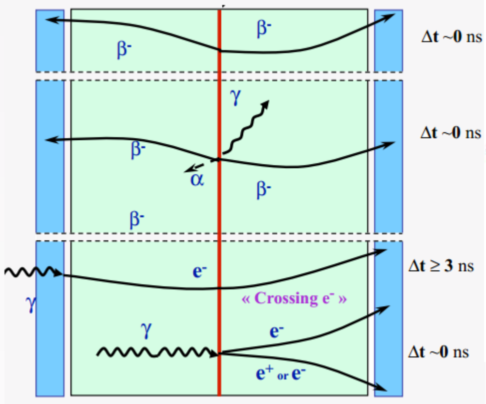
3.2 Underground Experiments for 0ν2β

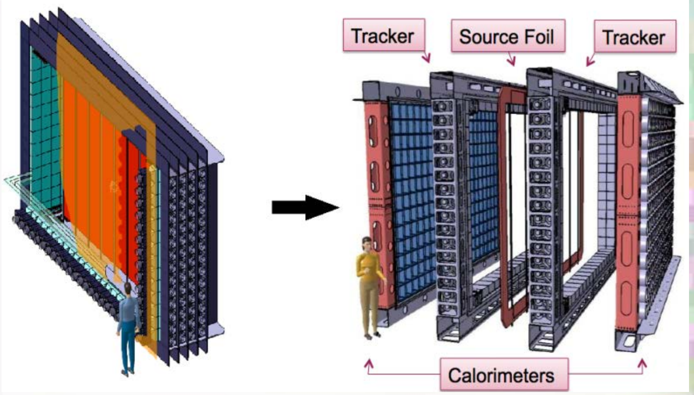
(See plenary talk Tsuyoshi Nakaya)

- **Many techniques also for neutrinoless double-beta decay involving many different techniques (SuperNEMO, EXO, CUPID, Majorana, KamLAND-Zen, NEXT, GERDA, SNO+, LEGEND, CUORE, AXEL, PANDAX, … but all with a requirement of high radio-purity, background rejection, extreme detector resolution and isotope enrichment**

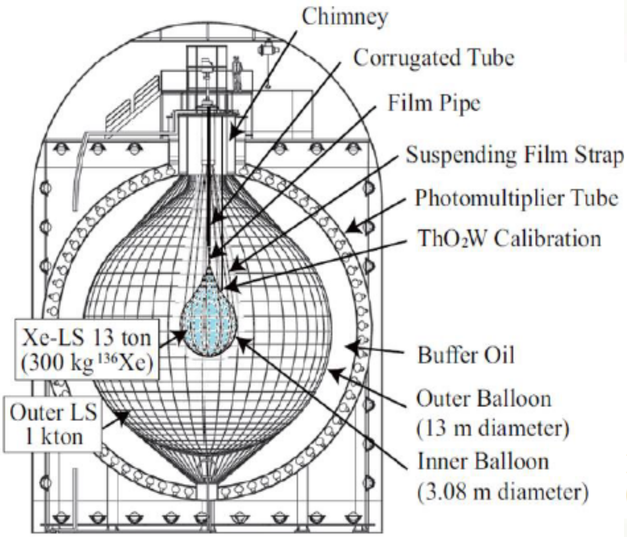


Carla Macolino (7/7/17)





- **Need better energy resolution to** CUORE **measure $T^{0\nu}_{½}$ »10^{26} yr.**
  - ➢ **GERDA, CUORE, NEXT, EXO, SNO+, CUPID, LEGEND, …**



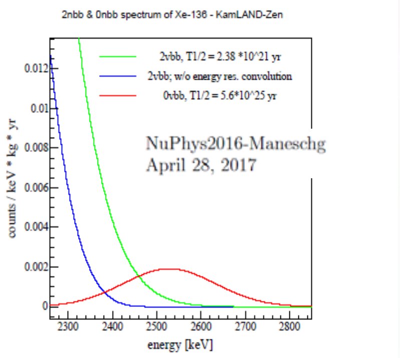
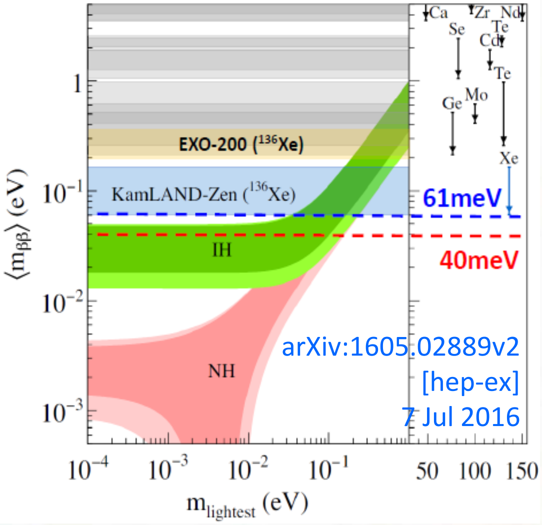


Figure 1: KamLAND-Zen: $2\nu\beta\beta$ vs. $0\nu\beta\beta$ for present $T^{0\nu}_{1/2}(^{136}\text{Xe})$.

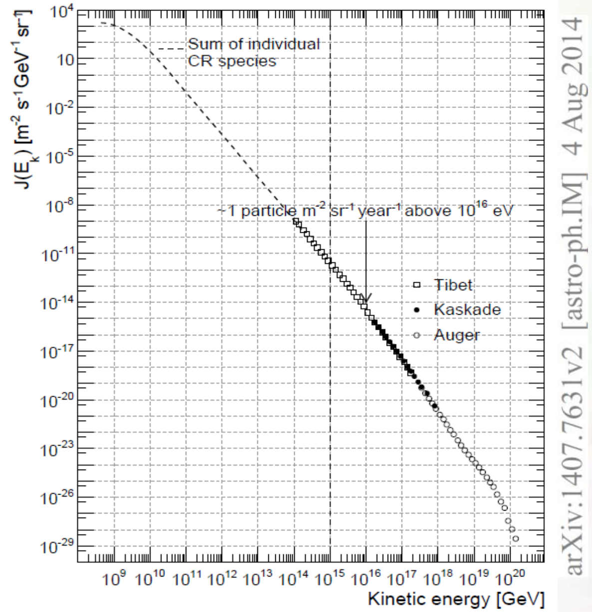


arXiv:1605.02889v2 [hep-ex] 7 Jul 2016

GERDA: Anna Julia Zsigmond
CUORE: Claudia Tomei
NEXT: Paola Ferrario
SNO+: Jack Dunge (7/7/17)
CUPID-0: Fabio Bellini

4. Astro-particle Detectors

See Plenary talks: Bruna Bertucci, Werner Hofmann, Maarten De Jong



Huge Topic (35 space based, 23 balloon and 57 ground based experiments listed at https://www.mpi-hd.mpg.de/hfm/CosmicRay/CosmicRaySites.html)

Facilities

4.1 Charged Cosmic Rays (eg Pierre Auger, …)
4.2 Ultra High Energy Gamma-rays (eg CTA, …)
4.3 Ultra and Ultra^2 High Energy Neutrinos (eg IceCube, …)
4.4 Solar, Atmospheric and Supernova Neutrinos (eg Long Baseline and Reactor experiments, SNO+, INO, …)

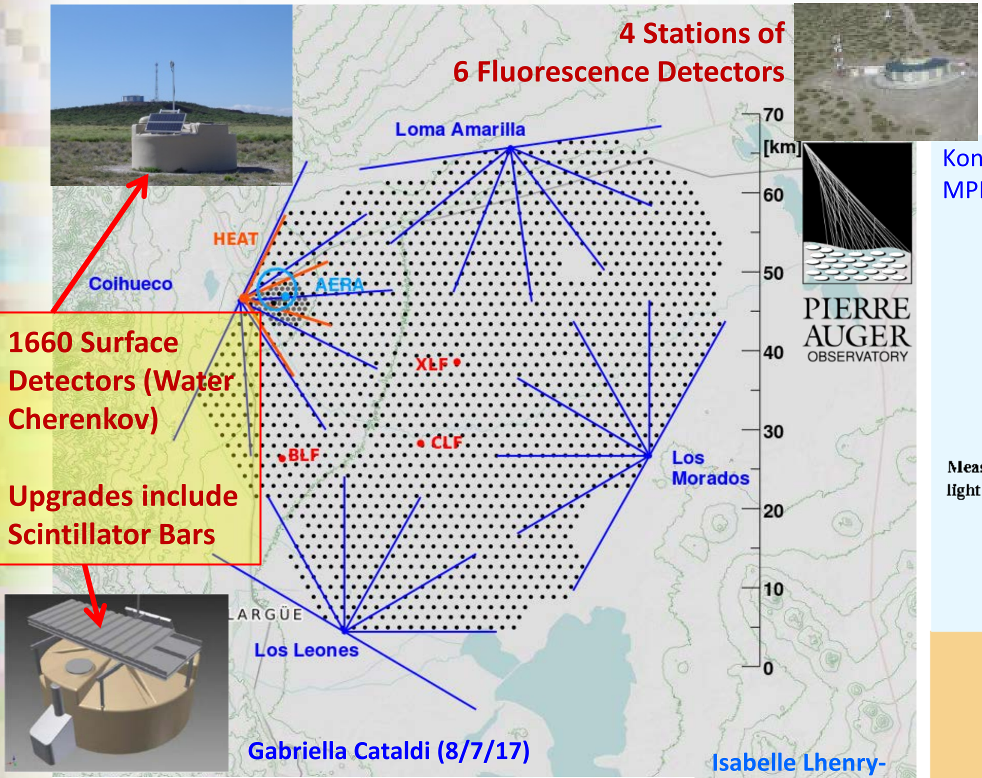
Attempt to list some of the key technology challenges

Some Key Techniques
4.a,b Tracking detectors
4.e Sampling Calorimeter
4.l Liquid Noble gas
4.m Liquid Scintillator
4.n Air/Water/Ice/rock Cherenkov and Fluorescence
4.q Large scale engineering

	Charged cosmic rays	UHE gamma rays	UHE neutrinos	Solar/At/SN neutrino
4.a,b,e Tracking Sampling/ Homogeneous Calo	Particle ID, energy angular resolution, fast timing DAQ	Cost/area for rate at higher energies		Scintillator cost RPC Technology Industrialisation
4.l,m Liquid noble gas / Scintillator	Cost/area for rate at higher energies	Cost/area for rate at higher energies	Cost/area for rate at higher energies	Radio-purity Noise, Energy resolution.
4.n Cherenkov/ scintillation Air	Backgrounds Large area cost	Photodetector cost segmentation	Hadronic background, rate	
4.n Cherenkov Water	Phototube cost, reliability	Muon veto, photodetector cost	Phototube cost Deployment	Phototube cost Dynamic range
4.n Cherenkov Ice			Phototube cost Deployment	Phototube cost Deployment
4.n Cherenkov (Rock)			Bkgnd suppression	

7/12/2017

4.1, 4.2 Detectors for Cosmic Rays and UHE Gammas



4 Stations of 6 Fluorescence Detectors

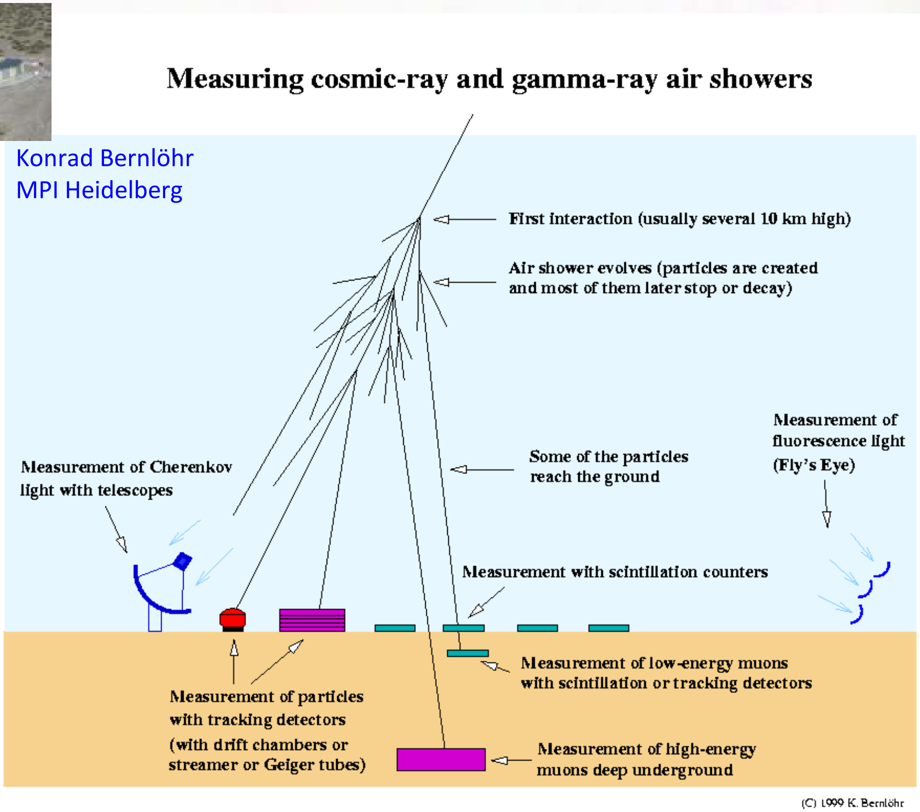
1660 Surface Detectors (Water Cherenkov)

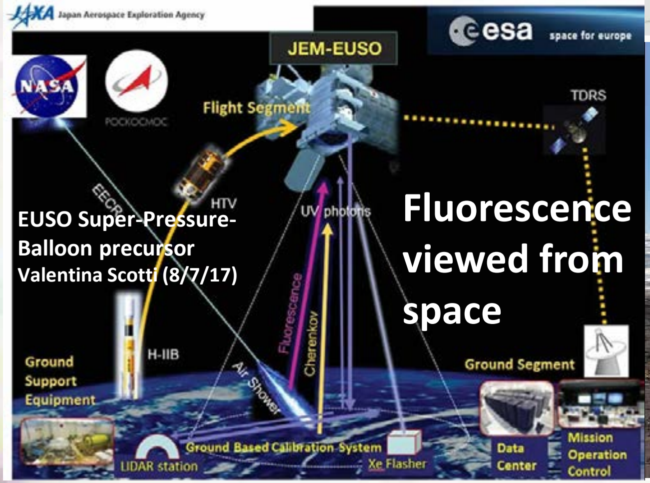
Upgrades include Scintillator Bars

Gabriella Cataldi (8/7/17)

Isabelle Lhenry-Yvon (6/7/17)

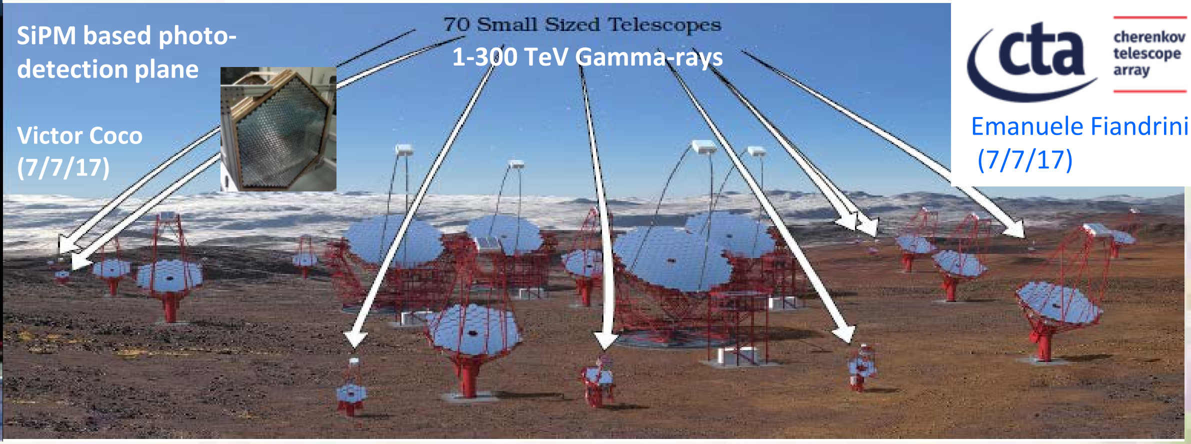
Konrad Bernlöhr
MPI Heidelberg





EUSO Super-Pressure-Balloon precursor
Valentina Scotti (8/7/17)

Fluorescence viewed from space



SiPM based photo-detection plane

Victor Coco (7/7/17)

70 Small Sized Telescopes

1-300 TeV Gamma-rays

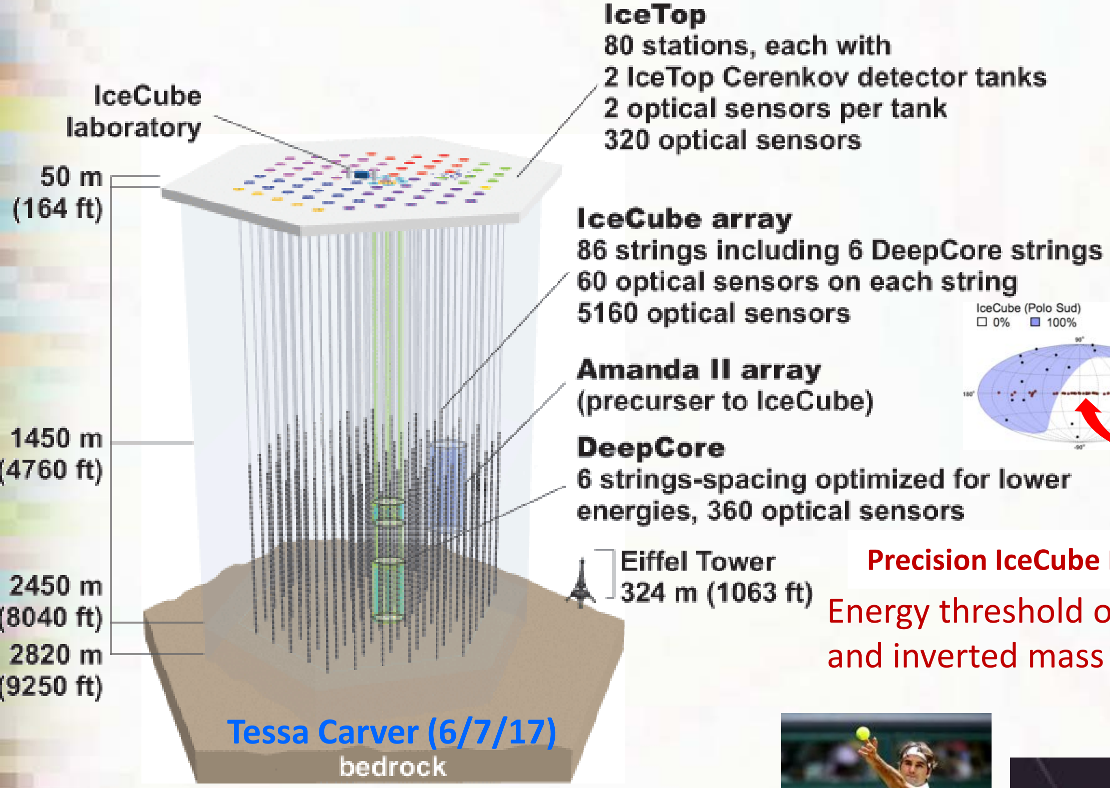
cta cherenkov telescope array

Emanuele Fiandrini (7/7/17)

4.3 High Energy Neutrinos

ANTARES: Annarita Margiotta,
KM3Net/ORCA: Liam Quinn,
MAGIC: Dariusz Gora (6/7/17),
KM3Net/ARCA: Carla Distefano (8/7/17)

Southern Hemisphere:



IceTop
80 stations, each with
2 IceTop Cerenkov detector tanks
2 optical sensors per tank
320 optical sensors

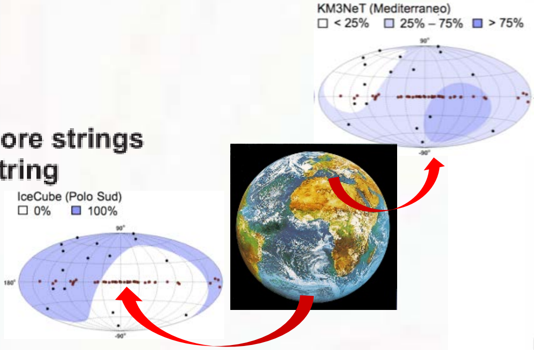
IceCube array
86 strings including 6 DeepCore strings
60 optical sensors on each string
5160 optical sensors

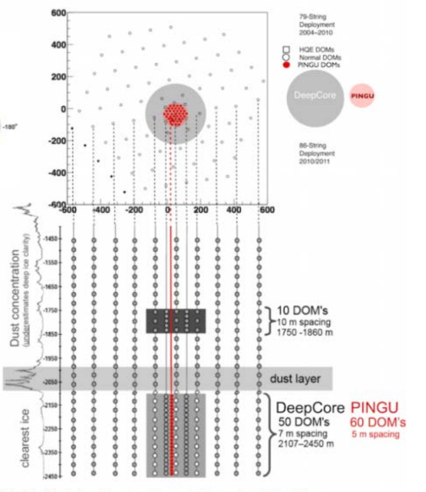
Amanda II array
(precurser to IceCube)

DeepCore
6 strings-spacing optimized for lower energies, 360 optical sensors

Tessa Carver (6/7/17)

Northern Hemisphere:
KM3NeT collaboration megaton-scale neutrino detectors 2500m depth in Mediterranean.



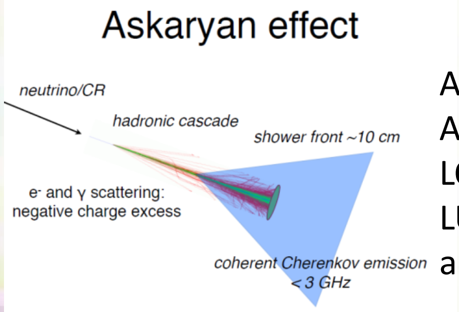


PINGU will deploy 40 new strings at the center of IceCube.

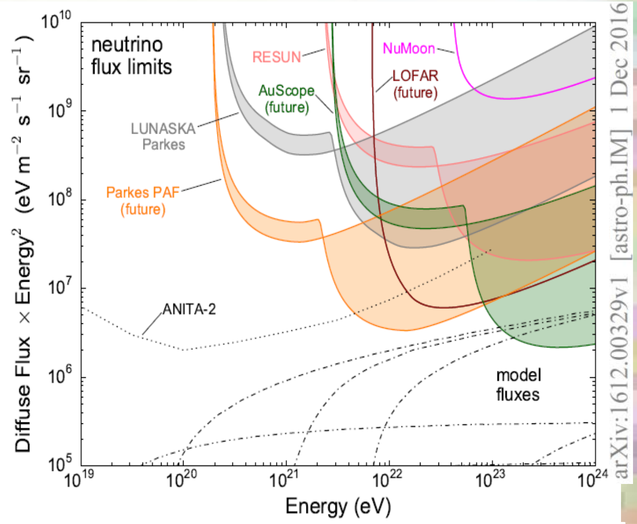
Precision IceCube Next Generation Upgrade

Energy threshold of a few GeV, able to distinguish between the normal and inverted mass hierarchy at 3σ significance with ~3.5 years of data

Surface roughness calibration for UHECR/neutrino physics with ANITA Steven Prohira (6/7/17)



ARA/ARIANNA (array in ice)
ANITA (Antarctica from balloon)
LOFAR/NuMoon/AUScope
LUNASKA Parkes (the Moon as an U^{2}HE neutrino detector)



References and Conferences

1. FCC Week (https://fccw2017.web.cern.ch/) 29/5/17
2. Technology and Instrumentation in Particle Physics, TIPP (http://tipp2017.ihep.ac.cn/) 22/5/17
3. LHCC Open Session (https://indico.cern.ch/event/632309/) 11/5/17 (Links to RD42, RD50, RD51, RD52 and RD53 along with other international R&D collaborations on slide 7)
4. AIDA 2020 Annual Meeting (https://indico.cern.ch/event/590645/) 4/4/17
5. CALICE 2017 (https://agenda.linearcollider.org/event/7454/) 22/3/17
6. Neutrino Telescopes (https://agenda.infn.it/confLogin.py?confId=11857) 13/3/17
7. IEEE NSS MIC (http://2016.nss-mic.org/) 29/10/16
8. ECFA HL-LHC Workshop (https://indico.cern.ch/event/524795/) 3/10/16
9. Vertex 2016 (https://indico.cern.ch/event/452781/overview) 25/9/16
10. Neutrino 2016 (http://neutrino2016.iopconfs.org/home) 4/7/16
11. ECFA Linear Collider Workshop (https://agenda.linearcollider.org/event/7014/) 30/5/16
12. CALOR 2016 (https://indico.cern.ch/event/472938/page/6018-calor-2016) 15/5/16
13. FCC Week (http://fccw2016.web.cern.ch/fccw2016/) 11/4/16
14. Common ATLAS CMS Electronics, ACES (https://indico.cern.ch/event/468486/) 7/3/16
15. ILC (https://www.linearcollider.org/P-D/ILC-detector-concepts)
16. CLIC (http://clicdp.web.cern.ch/)
17. LBNF (http://lbnf.fnal.gov/)

Conclusions

- Vast range of techniques and detection scales… *from microns to the Moon* (or arguably Earth/Sun/galactic centre for neutrinos/WIMPS/axions, …)
- Impossible to do justice even to the roughly 110 talks and 60 posters on detector/experimental techniques related topics at this conference
  - One exciting area of recent development is in 4D detectors (precision spatial resolution coupled with accurate timing) with many applications (such as mitigating the effects of pile-up in hadron colliders by associating tracks to vertices in both space and time)
  - Monolithic Active Pixel Sensors offer the potential of exploiting the huge commercial market in CMOS Imaging Sensors and now there are process variants which are also radiation hard
  - Large format micro-pattern gas detectors now being manufactured on industrial scales and also being produced as cylindrical structures
  - Liquid noble gas based detectors are opening up many new opportunities for precision tracking and calorimetry within huge volume detectors
  - Many experiments benefit from the steady improvements in scintillator and photodetector technologies often driven by collaboration with major industrial suppliers
- Note that typical R&D timescales are a decade from proof-of-principle to first demonstrator or small-scale implementation and a further decade to large-scale detector realisation
- In many areas, cross-experiment R&D collaborations exist which both foster cooperation and diminish duplication and help share developments costs (which can be challenging)
  - Still some gaps in R&D areas which may benefit from further such organisations
  - Great potential to link more closely with other sciences and application areas

THANK YOU