## 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

7/12/2017

School of Physics and Astronomy UNIVERSITY OF BIRMINGHAM EXCEPTION BILPA CRD50 ECFA-DEP ECFA-DEP Esclines Council

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### 7/12/2017

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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)
- I. 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

### 7/12/2017

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- Large volume liquid noble gas for track and energy reconstru-Ι.
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- n (and many do) Air/Water/Ice/Rock Cherenkov and fluorescence detection (light, sound n.
- Custom microelectronics and other front-end electronics 0.
- Data links and optoelectronics р.
- Mechanics, large-scale engineering, cooling and services q.
- Trigger, data acquisition and computing r.
  - .... everything I've forgotten

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### **Detector R&D for Collider and Underground Experiments**

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

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



### 7/12/2017

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

Technique	1.1 (hadron	1.2 (lepton	1.3 (lepton-	1.4 (fixed	Comment
	collider)	collider)	hadron)	target)	
1.a (Si) Vertexing	Rad-hard (pp) Low mass (AA)	Low mass Fine pitch	Fine pitch Low mass	Fast R/O Fine pitch	Monolithic devices incorporate electronics. Time structure dictates
(& Lumi/FP)	Data rate (pp)	Time stamp		Radiation	on-detector k/O.
1.b Inner track (Si)	Area/cost Radiation (pp)	Low mass Area/Cost	Area/cost	Radiation	Can be few 10 <sup>15</sup> n <sub>eq</sub> /cm <sup>2</sup> 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?

CAUTION WORK IN PROGRESS

### 7/12/2017

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	collider)	collider)	hadron)	target)		A OBUTION
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Vertexing	Low mass (AA)	Fine pitch	Low mass	Fine pitch	electronics. Time structure dictates	
(& Lumi/FP)	Data rate (pp)	Time stamp		Radiation	on-detector R/O.	WORK IN
1.b Inner	Area/cost	Low mass	Area/cost	Radiation	Can be few 10 <sup>15</sup> n <sub>eq</sub> /cm <sup>2</sup> radiation	PROCRESS
track (Si)	Radiation (pp)	Area/Cost			levels	I HOUHLOO
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

1.q Mech,	Low mass, reliable,	Low mass, reliable,	Low mass,	Low mass,	Large-scale magnet systems
cool, services	stable	stable	reliable, stable	reliable, stable	
1.r TDAQ +	Cost, Speed	Cost	Cost, Speed	Speed/ data	Is Moore's Law safe forever?
Computing	Commercial	Channel #	Commercial	volumes	
	Solutions		Solutions		

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Vertexing (& Lumi/FP)	Low mass (AA) Data rate (pp)	Fine pitch Time stamp	Low mass	Fine pitch Radiation	electronics. Time structure dictates on-detector R/O.	WORK IN
1.b Inner track (Si)	Area/cost Radiation (pp)	Low mass Area/Cost	Area/cost	Radiation	Can be few 10 <sup>15</sup> n <sub>eq</sub> /cm <sup>2</sup> radiation levels	PROGRESS

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: <u>http://fcal.desy.de/</u> ILC TPC Collaboration: <u>https://www.lctpc.org/</u> RD42\* (diamond): <u>http://rd42.web.cern.ch/rd42/</u> RD50\* (rad-hard silicon): https://www.cern.ch/rd50/ RD51\* (micro-pattern gas detectors): <u>http://rd51-public.web.cern.ch/rd51-public/</u> RD52\* (dual readout calorimetry): http://cds.cern.ch/record/2255826/files/ RD53 (rad-hard electronics): <u>https://rd53.web.cern.ch/RD53/</u> VL Project: <u>https://espace.cern.ch/project-Versatile-Link-Plus/SitePages/Home.aspx</u> \* See LHCC 10/5/17 presentations at https://indico.cern.ch/event/632309/ Apologies to other collaborations I am not aware of particularly outside Europe

1.r TDAQ +      Cost, Speed      Cost      Cost, Speed      Speed/ data      Is Moore's Law safe forever?        Computing      Commercial      Channel #      Commercial      volumes	cool, services	stable	stable	reliable, stable	reliable, stable	
Computing Commercial Channel # Commercial volumes	1.r TDAQ +	Cost, Speed	Cost	Cost, Speed	Speed/ data	Is Moore's Law safe forever?
	Computing	Commercial	Channel #	Commercial	volumes	
Solutions Solutions		Solutions		Solutions		

#### **Detector R&D for Collider and Underground Experiments**

## **Detector Upgrades for the HL-LHC Programme**



## **Detector Upgrades for the HL-LHC Programme**

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



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

#### New Tracker

- · Radiation tolerant high granularity less material
- Tracks (P<sub>T</sub>>2GeV) in hardware trigger (L1)

119

Coverage up to η ~ 4

#### Barrel ECAL

- Replace FE/BE electronics
- Cool detector/APDs

#### Trigger/DAQ

- · L1 (hardware) with tracks and rate up  $\sim$  750 kHz
- L1 Latency 12.5 μs
- HLT output rate 7.5 kHz

#### Muons

- Replace DT and CSC FE/BE electronics
- Complete RPC coverage in forward
- region (new GEM/RPC technology) • Muon-tagging up to  $\eta \sim 3$

#### New Endcap Calorimeters Radiation tolerant High granularity

Timing capability

#### LHCb: Phase-I Upgrades Upstream Downstream Muon Tracker Tracker MWPC Si strips Sci-Fibres VeLo **Si pixels** RICH Calo MAPMTs **PMTs**

## ATLAS: Phase-II Upgrades

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



### 7/12/2017

## Large Area High Rate Gas Detectors (>10<sup>4</sup>Hz/cm<sup>2</sup>)

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

- Increase rate capabilities and radiation hardness
- Improved resolution (online trigger and offline analyses) Improved timing precision (background rejection) **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, multigap precision timing (ALICE/ATLAS/CMS)

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<sup>2</sup> and 2.4M channels)





🔊 3µm Cu

50µm Kapton

doi:10.1016/j.nima.2015

GEM foil

Fabio Sauli



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

ALICE

Paolo lengo (6/7/17)

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

55 µm

70 µm

(Michela Greco 6/7/17)

ALICE TPC **Read-out** 

Christian Lippmann

(8/7/17)

**5** μm

50 µm

induction gap

7/12/2017

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

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



- eg LHCb TORCH (Time Of internally Reflected CHerenkov light) 15ps ToF (30 pe/track)
- PET Scanner ToF fast scintillator and photodetector (eg LYSO+SiPM)
- Also charged particle detection with quartz/scintillator plus fast

38) Also CMS Barrel

(DD-23, 27

Timing Layer (30ps pile-up mitigation)

photodetectors, or direct detection also possible with fast gas or semiconductor detectors

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

## ALICE TOF

7/12/2017

## **140 m<sup>2</sup> of Multigap RPCs** at 3.7 m from the IP

- Rate capability ~100 Hz/cm<sup>2</sup> (glass resistivity)
- Fast readout electronics
- Leading edge disc. with timeover-thresh correction (NINO)
- Single particle resolution in situ: down to 80 ps





## **HL-LHC Timing Detectors**

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

(Beamspot:  $\sigma_z \sim 9 \text{ cm}$ ;  $\sigma_t \sim 0.2 \text{ ns}$ 2017-03-16\_HLLHC-TC.pdf )



### 7/12/2017

## **HL-LHC Radiation Hardness**



## **Even More Challenging: FCC-hh**

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



## **ILC/CLIC Inspired Pixel Technologies**

### (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)



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**Detector R&D for Collider and Underground Experiments** 

VERTEX 2016: J Goldstein A G Besson

Matthias Weber (8/7/17)

 $\sigma_{R\phi} \simeq 3 \ \mu m$  (pitch  $\simeq 20 \ \mu m$ )

Single bunch time resolution

Spatial resolution: highly granular sensor:

multiple scattering : very low material budget:

Power dissipation  $\leftrightarrow$  preferably gas cooling

 $\rightarrow$  1st layer: ~ 5 part/cm<sup>2</sup>/BX  $\rightarrow$  few % occupancy

 $\rightarrow$  <130µW/mm<sup>2</sup> (Power cycling, ~3% duty cycle)

SiD: Tim Barklow (8/7/17)

Gunn Gu

O(0.1%X<sub>o</sub>/layer)

## **Calorimetry and Particle Flow**

- RD52 Dual REAd-out Method
  - FCC-ee?

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### Simultaneous measurement, during shower development, of:

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



## **Silicon Based Detector Evolution**

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



7/12/2017

## **Microelectronics Evolution**



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.

### 7/12/2017

## **2. Accelerator and Reactor Neutrinos**

# <u>https://en.wikipedia.org/wiki/List\_of\_neutrino\_experiments</u> gives over 50 experiments (but this list does include neutrinoless ββ decay and neutrino observatories)

breviation	Full name	Sensitivity	a] Type		Induced reaction	Type of reaction <sup>[b]</sup>	Detector	Type of detector	Threshold energy	Location	Operation	Home page	Abbreviation	Full name Ser	iitiviity <sup>(a)</sup> T	lype	Induced reaction	Type of reaction <sup>[1]</sup>	Detector	Type of detector	Threshold energy	Location	Operation	Home page	GALLEX	GALLium EXperiment	LS ve	$v_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$	cc	GaCl <sub>3</sub> (30 t)	Ratiochemical 233.2 keV	Gran Sasso, Italy 1991-1997	[12] (http://www.mpi-lid.mpg.de /masstro/gallex.html)
NO	Underground Nucleon decay and neutrino	S, ATM, GS RSN	N.	v, v, +	e <sup>−</sup> →v <sub>e</sub> +e <sup>−</sup>	ES	Water (440 kt H2O)	Cherenkov		Henderson Mine, Colorado	fature	[50] (http://ale.physics.sunysb.edu /uno/)		Unification and Neutrino Astrophysics	TM CR				San water			Mafaaraaa	00		EXO-200	Enriched Xenon Observatory		$\label{eq:Xe} \begin{array}{c} {}^{134}\!Xe \rightarrow {}^{134}\!Ba + e^+ + e^- \\ {}^{136}\!Xe \rightarrow {}^{136}\!Ba + e^+ + e^- \end{array}$	BB	Liquid Xenon		WIPP New Mexico 3009-	[11] (http://www- project.slac.stauford.edu/exa/)
ĸ	Tokai to Kamioka	AC	ve ve	v,+ v,+ v,+	$n \rightarrow e^{-} + p (+\pi, +X)$ $n \rightarrow \mu^{-} + p (+\pi, +X)$ $p \rightarrow e^{+} + n (+\pi, +X)$	CC (NC)	Water (H2O)	Cherenkov	200 MeV	Tokai, Japan Kamioka, Japan	2011-	[49] (http://t2k-experiment.org)	KanLAND	KARD Steinado 5, 3 Telescope SN Kamioka Liquid Scintillator Antineutrino	AGN, PUL Y	yrere A	+p→e <sup>*</sup> +n	cc i	(<5 km <sup>3</sup> ) LOS	Cherenkov	1.8 MeV	Kamioka, Japan	(22) (http://www.km3net.org) 2002-	) [24] (http://www.awa.tohoku.ac.jp /KaniLAND/)	Double Choos	Double Chooz Reactor Neumo Experiment Daya Bay	R ve	$\tilde{v}_t + p \rightarrow e^* + n$	cc	Gd-deped LO	Scintillation 18 MeV	Choor, France 2011-	[10] (http://doublechooz.in.2p3.fr/)
				ÿ,+	$p \rightarrow \mu^{+} + n (+\pi, +X)$					Modane			Kamiokande	Detector Kamioka Nucleon Decay S, J	тм у		+e - + e	ES	Water (H2O)	Chrrenkov	7.5 MeV	Kamioka, Japon	1986-1995	[23] (http://www-sk.icm.u-tokyo.ac, /doc.kam/index.html)	Deya Bey	Reactor Neurino Experiment	R	$\tilde{v}_{\mu} + p \rightarrow e^{2} + n$	cc	(LOS)	Scintillation 1.8 MeV	Daya Bay. China 2011-	[9] (http://dayasana.shep.sc.cn/)
perNEM0	SuperNEMO	BB	v.	100 <sub>S</sub>	$ie \rightarrow \frac{100}{Kr} Kr + 2 e^{-1}$ $4d \rightarrow \frac{150}{Sm} Kr + 2 e^{-1}$	BB	Tracker + calorimeter	He+Ar wire chamber, plastic scintillators	150 keV	Underground Laboratory, Fréjus Road Tunnel, France	2017-	[48] (http://nemo.in2p3.fr/nemow3/	ДN0	Jangmen Underground Neutrino Observatory	Ÿ,	i, i	+p→e <sup>+</sup> +a	cc	LAB (LOS) + PPO + Bin-MSB	Scintillation		Kaiping. China	2014- (construction)	[22] (http://mglish.ihep.cas.co.iss/fs /juno0815/)		Codmism zinc triluxide 0 constants		${}^{66}Z_{R} + e^{-} \rightarrow {}^{66}N_{1} + e^{-}$ ${}^{70}Z_{R} \rightarrow {}^{70}Ge + e^{-} + e^{-}$ ${}^{100}C_{I} \rightarrow {}^{205}P_{I} + e^{-} + e^{-}$ ${}^{100}C_{I} + e^{-} + e^{-} \rightarrow {}^{106}P_{I}$		Colours		Gene Same	
per-K	Super- Kamiokande	S, ATM, GS	iN v <sub>e</sub> v <sub>p</sub>	ve + ve + ve +	$e^{-} \rightarrow v_e^{+} e^{-}$ $n \rightarrow e^{-} + p$ $p \rightarrow e^{+} + n$	ES CC CC	Water (H2O)	Cherenkov	200 MeV	Kamioka, Japan	1996-	[46] (http://neutrino.phys.unshington.ed /~uperk/) [47] (http://www-sk.icm/ tokyo.ac.jp/sk/index_e.html)	a India-based a- Neutrino Observatory	Ison Calorimeter Detector @ ATT India-based Neutrino Observatory	1 Y	x x	+Fe→µ <sup>+</sup> +X	CC (dominant), NC	Magnetised iron (50 kton)	RPC active detector elements	::0.6 GeV	Thess, Tami Nada, Iadia	2012- (lab construction); 2018- (detector operation)	[21] (http://www.ino.tifr.res.in/ino/)	COBRA	double-Beta Research Apperatus		$^{111}Cd \rightarrow ^{111}Sn + e^{-} + e^{-}$ $^{115}Cd \rightarrow ^{115}Sn + e^{-} + e^{-}$ $^{121}Te + e^{-} \rightarrow ^{121}Sn + e^{-}$ $^{122}Te \rightarrow ^{123}Xe + e^{-} + e^{-}$	BB	telluride		Inly 2007-	[8] (http://www.cohea-experiment.or
EREO	Oscillation Search with L Detector Short baseline	R	ve	v <sub>e</sub> +	$p \rightarrow e^{+}+n$	cc	liquid organic scintillator loaded with Gd	Scintillation	≈2 MeV	Grenoble, France	2013-		lceCube	IceCube Neutrino Detector Imaging	LCR, C? V	e v <sub>µ</sub> v <sub>1</sub>	+ N → v + Cascade . + N → Charged lepton + Casca	e CC, NC	Water ice (1 km <sup>3</sup> )	Chereakov	=10 GeV	South Pole, Anterctica	2006-	[20] (http://icecube.wisc.edu/)	CLEAN	Cryogenac Law-Energy Astrophysics	LS, SN, WIMP 14	$v_k + e^- \rightarrow v_k + e^-$ $v_k + e^- \rightarrow v_k + e^-$ $v_r + {}^{23}Ne \rightarrow v_r + {}^{23}Ne^-$	ES ES	Liquid Ne (10 t)	Scatillation	fiture	[7] (http://mckanseygroup.physics.yale.e multi-mone.CTEAN.edf)
Lid	Oscillation Search with Lithium-6	R	v <sub>e</sub>	ve+	$p \rightarrow e^{+} + n$	cc	plastic and anorganic scintillator	Scintillation	=2 MeV	Mol, Belgium	2015-		ICARUS	Counic And Rare S, J Underground Signal	TM, GSN v	e * p * t * t	+e - v+e	ES	Liquid Ar	Cherenkov	5.9 MeV	Gran Sasso, Italy	2010-	[19] (http://icarus.lngs.influit)	BOREXINO	BORon EXperiment	LS ve	$v_{\mathbf{x}} + e^- \rightarrow v_{\mathbf{x}} + e^-$	ES	LOS shirlded by water	Sciatillation 250-665 k	7 Gran Sasso, Italy May 2007-	[5] (http://www.ge.infn.it/barenino/) [6] (http://boren.lags.infn.it/)
<del>(</del> 0+	SNO with liquid scintillator	S,LS,R,T, SN,LSN	ve	vx+ ve+	$e^{-} \rightarrow v_{\chi} + e^{-}$ $p \rightarrow e^{+} + n$	ES, BB	linear alkylbenzene (LAB) + PPO	Scintillation	≈lMeV	Creighton Mine, Ontario	2014-	[45] (http://www.sno.phy.queensu.c	N) HOMESTAKE- IODINE	Homestake iodine S experiment	v	4 76 37	+e -+v+e + + <sup>127</sup> I <sup>127</sup> Xe+e -	ES CC	Nal in water	Radiochemical	789 keV	Homestake Mine, South Dakota Homestake	fature	[18] (http://www-spires.dur.ac.uk /cgi-bin/spiface/find/experiments /www?rrwcmd=fin1expt1homests [17] (http://www-spires.dur.ac.uk	BDUNT ab (NT-200+)	Baikal Deep Uaderwater Neutrino Telescope	S, ATM, LS, AGN, PUL	5 N	CC, NC	Water (H2O)	Cherenkov ≈10 GeV	Lake Boskal, Runsia	[4] (http://baikalweb.jan.ra/)
0	Sudbury Neutrino Observatory	S, ATM, GS	N verver	ve +	$^{2}D \rightarrow 2p + e^{-}$ $^{2}D \rightarrow v_{x} + n + p$ $e^{-} \rightarrow v_{x} + e^{-}$	CC NC ES	Heavy water (1 kt D <sub>2</sub> O)	Cherenkov	3.5 MeV	Creighton Mine, Ontario	1999-2006	[44] (http://www.sno.phy.queensu.c	(HLORINE CHLORINE HERON	Chlorine S experiment S Heliam Roton Observation of LS	N N	- 37	$CI + v_e \rightarrow -At^* + e$ $At^* \rightarrow -3^3CI + e^* + v_e$ $+ e^- \rightarrow v_e + e^-$	NC S	C <sub>2</sub> Cl <sub>4</sub> (615 t) Superfluid He	Radiochemical Rotational excitation	814 keV 1 MeV	Mine, South Dakota	1967-1998 finare	cgi bin/spiface/find/experiments /www2nrwcmd+fin+expt+homesta [16] (http://www.physics.brown.edu /physics.brown.chupio/cme.brown. / TTD.brown.brown.	ARIANNA	Antarctic Ross Ice-Shelf ANtenna Neutrino Array	S, CR, AGN, 7	* <sub>9</sub> , v <sub>1</sub>				Ross Ice Shelf, fature Autorctica	[3] (http://arianna.ps.uci.edu)
iBooNE	SciBar (Scintillator Bar) Booster Neutrino	AC	Υµ	ν <sub>μ</sub> +	$^{12}C \rightarrow \mu^{-} + X$	CC, NC	Plastic (CH,10 ton)	Scintillation	≈100 keV	Illinois, United States	2007-2008	[43] (http://www-sciboone final.gov	HALO	Helium And Lead SN Observatory	v,	e vz	$^{+208}_{+208}P_{b \rightarrow v} - ^{+209}_{v} B_{v}^{*}$ $^{+208}_{-}P_{b \rightarrow v} + ^{208}_{v} P_{b}^{*}$	CC, NC	Lead (79 t) and <sup>2</sup> He	High-Z	=10 MeV	Creighton Mine, Ontario	2012-	[15] (https://www.saolab.ca.halo/) [14] (https://www.lags.infi.it/lags_ja	ANTARES	Astronomy with a Neutrino Telescope and Abyss Environmental	ATM, CR AGN, PCL 😽	* <sub>0</sub> , *,				Meditessmenn Sea, France 2005-	[2] (http://antares.in2p3.fs/index.htm
IGE	Soviet- American Gallium Experiment	LS	v,	v. +	$^{71}$ Ga $\rightarrow$ $^{71}$ Ge + e <sup>-</sup>	cc	GaClj	Radiochemical	233.2 keV	Baksan Valley, Russia	1990-2006	[42] (http://ewi.npl.washington.edu /SAGE/sage.html)	GERDA		m	p	tto	lis	GeClj (30 t) HPGe	Radiochemical	233.2 keV	Cran Sasso, Indy Cana Sasso,	bir in 192	contents lags_en/research increments, scientif, info en marketh on part [13] (hing: www.mpi-tai.mpg.or	AN .	RESearch Net Control (	:hr	olo	3y (	cha	allei	nges	[1] (http://manie.uchicago.edu (doku.php)
ENO	Reactor Experiment fo Neutrino	R	v.	ÿ.,+	p→e <sup>+</sup> +n	сс	Gd-doped LOS	Scintillation	1.8 MeV	South Korea	2011-								2.	1 Lo	ng	Bas	seline	:		2.	2 Sh	ort Bas	elin	e l	2.3 Re	actor/s	ource
PERA	Oscillation Project with Emulsion- tRacking	AC	v <sub>t</sub>	v <sub>t</sub> +s	nucleus $\rightarrow \tau^{-}+X$	cc	Lead Emulsion	Nuclear Emolsion	=1.0 GeV	LNGS (Italy) and CERN	2008-	[41] (http://operaweb.lngs.infn	2.c G	as de	tec	cto	ors		Ar	npli	fica	atio	n			Hi	gh p	ressure	5				
DvA	NuMI Off-Ax	s AC	v <sub>e</sub> . v <sub>µ</sub>	v <sub>e</sub> +1	nucleus $\rightarrow e^-+X$	cc	Liquid scintillator	Scintillation	≈0.1 GeV	Illinois and Minnesota,	2011-	[40] (http://www-nova.fnal.go	2.e,h	Solid	d sc	:in	tillator		Pł	noto	de	tect	or co	sts		Er	ergy	thres	nold		Energy	and sp	atial
EVOD	Cherenkov water detector NEVOD	ATM, CR	ν <sub>μ</sub>	ν <sub>μ</sub> + ν <sub>μ</sub> +	$a \rightarrow \mu^+ + p$ $p \rightarrow \mu^+ + a$	сс	Water (H <sub>2</sub> O)	Cherenkov	=2 GeV	Moscow, Russia	1993	[39] (http://www.nevod.mephi /English/index.htm)	(sam	pling	an	d			М	atei	rial	cos	sts			N	oise,	Timing	[		resolu	tion. Lo	w noise.
EMO-3	Neutrino Ettor Majorana Observatory	e BB	v.	<sup>100</sup> N	$4o \rightarrow {}^{100}Ru + 2 e^{-}$ $ie \rightarrow {}^{100}Kr + 2 e^{-}$	вв	Tracker + calorimeter	He+Ar wire chamber, plastic scintillators	150 keV	Modane Underground Laboratory; Fréjus Road Tunnel,	2003-2011	[36] (http://nemo.in2p3.fr/nem	homo	ogen	eou	ıs)			La	rge	sca	ale e	engine	eering		Gi	anu	arity			Calibra	ition. S	nielding.
EMO lescope	NEntrino Mediterranean Observatory									France Mediterranean Sea, Italy	2007-	[38] (http://www.lns.infn.i	2.l,q	Liqui	d s	cin	ntillato	r	Pł	noto	de	tect	or se	nsitive		Pł	noto-	detect	or Q	E	Photo	detect	or QE
OON	Molybdenum Observatory O Neutrinos	f LS, LSN	ve	ve +	$^{100}M_0 \rightarrow {}^{100}T_c + e^-$	cc	<sup>100</sup> Mo (1 kt) + MoF6 (gas)	Scintillation	168 keV	Washington, United Stor		ol washingtor	and a	assoc	iate	ed			ar	ea a	nd	l cos	st, Ra	dio-puri <sup>,</sup>	tv,	Μ	echa	nics			Radio-	purity,	Gd
INOS+	Upgraded electronics for MINOS Main Injector	AC, ATM	ve. v <sub>p</sub> .	v <sub>2</sub> +1	aucleus $\rightarrow \mu^- + X$	CC, NC	Solid scintillator	Scintillation			sca	ni faal go 1. http://	engir	neeri	ng				La	rge	sca	ale e	engine	eering		Sł	ieldi	ng			dopina	. flux n	nodelling
INOS	Neutrino Oscillation Search Mini Bassing	AC, ATM	ν,, νμ	v <sub>2</sub> +1	$aucleus \rightarrow \mu^+ X$	07 H	109	<u>ي: ۱</u>	a	5	-or	alge —	2.m.0	a Liai	Jid	nc	ble ga	s	Ρι	urifio	cat	ion	U	0		In	crvc	stat lo	w		Coher	" ent neu	trino-
iniBooNE	Neutrino Experiment	AC	¥., V		2020	V	JPY		Je	te	ctor	and g	and a		iate	ed			Ve	rv ł	niøl	h vo	ltage			n	oise (	MOS	snac	e	nuclei	s scatte	ring?
INERvA		11	)P		2000	lic	yuİ	d		states	2009-	[32] (http://minerva.fnal.gov/)	engir	neeri	ng				La	rge	SCa	ale c	cryoge	enics		ch	arge	, FE ra	nge		ind one o	5 Statt	
icroBooNE	The 1			2	senic		HIKe	TPC Semiconductor	few MeV	Illinois, United States Homestake Mine South	2014-	[31] (http://www- microboone.fnal.gov/) [30]	2.n.a	Wat	er (	Ch	erenko	ov 🛛	Pł	noto	de	tect	or tin	ning.		Se	para	tion of	<sup>;</sup> pile	-	Gd-dd	ping.	
INS	Low En Neutrino	cr	Y	-	$^{10}\text{In} \rightarrow ^{115}\text{Sn} + v_e + 2\gamma$	сс	In-doped LOS	Scintillation	120 keV	Dakota		[28] (http://www.phys.vt.edu/- [29] (http://tens.in2p3.fr/)	anda	assoc	iate	ed			ef	ficie	enc	v an	nd cos	sts		u	) eve	nts (sa	me		Radon	. 🚺	OAUTION
NE/DUNE	Long-Basel Neutrino Experiment / Deep									Homestake Mine (South	fature	[27] (http://lbne.fnal.gov/)	engir	neeri	ng				La	rge	SCa	ale e	engine	eering		bı	inch	), Gd-d	opin	g :	Shield	ng.	
	Underground Neutrino Experiment									Dakota)			2.r D	AO 8	Co	h	nutine		Re	liah	oilit	v. h	ufferi	ing.		Re	liabi	lity da	ta		Reliah	lity I	ROGRESS
AGUNA	Large Apparatus studying Gran	4									future	[26] (http://www.lagana-scienc							d			.,,	an d		me			,, uc				,	nountoo
-																			uv	/IIdľ	IIIC	i díl	ge, di	ata vulu	me	VC	num	e					

Detector R&D for Collider and Underground Experiments

7/12/2017

## 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:
 Single Cell



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## 2.1 & 2.2 Long Baseline Neutrino Detectors



**Detector R&D for Collider and Underground Experiments** 

7/12/2017

## 2.1 & 2.2 Long Baseline Neutrino Detectors

E box-and-line PMT

Hamamatsu R12860)

Super-K PMT average Hamamatsu R3600, QE = 22%)

OE = 31% comp

(Tsuyoshi Nakaya)



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

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- 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



### **J-PARC** Accelerator Complex





## **2.3 Reactor Neutrino Detectors**

### (See plenary talk Thierry Lasserre)



Calibration Top Tracker Central detector		Filling + Overflow Agnese G (6/7/17)	Daya Bay Liquid Scintillator pilot plant Linear alkyl benzene (L	AB) as solvent
SS latticed shell		Acrylic Sphere:	2,5-diphenyloxazole (P	PO) as fluor
Acrylic sphere		ID: 35.4m	p-bis-(o-methylstyryl)-	benzene
(20Kt LS n it)		Thickness:120mm	(bis-MSB) as waveleng	th shifter
~18000 20" PMT +~25000 3" PMT	AS: ID35.4m	SSLS: ID: 40.1m	<sup>14</sup> C/ <sup>12</sup> C ~ 2.7 x 10 <sup>-18</sup>	Technologies to achieve
1	2	OD: 41.1m	<sup>238</sup> U (Bi-Po 214)	required radio-purity:
Water Cherenkov		Water pool ID: 43.5m	< 9.7 x 10 <sup>-19</sup> g/g (95% CL)	Al <sub>2</sub> O <sub>3</sub> column,
~2000 20" PMT -		Height: 44m	<sup>232</sup> Th (Bi-Po 212)	distillation, gas striping,
2000 20 PIVIT		43.5m	< 1.2 x 10 <sup>-18</sup> g/g (95% CL)	water extraction
JUNO			<sup>40</sup> K no evidence (TBD)	Levels achieved at
Detectors	e Pool ID:43.5m		39 A m < < 851/ m	Borexino: N. Rossi
	AS: Acrylic sphere; SSLS: stainless steel latticed shell		~~AI << ~~KI	(Neutrino2016)

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Detector R&D for Collider and Underground Experiments

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## **Neutrino Experiment Photodetectors**



## 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
- 3.1 Liquid Noble gas
- 3.m Liquid Scintillator

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### Attempt to list some of the key technology challenges

	3.1 Dark Matter	3.2 Rare neutrino	<b>3.3 Other rare decay</b>
3.a,b,d Tracker	Ultra-radio-purity	Radio-purity	Thin, fine granularity.
	Optical as well as	Very low material.	Single etch GEM foils,
	electrical read-out	Isotope enrichment	High rate, fast timing,
			complex field
3.e,h,j Calorimetry	Ultra-radio-purity,	Radio-purity	High rate, fast timing,
	Ultra-low noise, (mK),	Ultra-low noise	energy resolution at
	Energy resolution	Energy resolution	low energies, radiation
3.d Liquid noble gas	Ultra-radio-purity	Radio-purity	Energy resolution
	Ultra-low noise and	Ultra-low noise and	Background rates
	high efficiency	high efficiency	
	photodetectors	photodetectors	
3.e Liquid scintillator	Ultra-radio-purity	Radio-purity	Energy resolution
	Ultra-low noise and	Ultra-low noise and	Background
	high efficiency	high efficiency	rates <b>A</b> CAUTION
	photodetectors	photodetectors	WORK IN
2 r DAO 8 Computing			Event rates PRUGRESS

3.r DAQ & Computin

## **3.1 Underground Experiments for Dark Matter**

Jianglai Liu (6/7/17)



## **3.2 Underground Experiments for 0v2β**

### (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



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## 4. Astro-particle Detectors

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

### **Facilities**

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

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



#### Some Key Techniques PRO 4.a,b Tracking detectors Sampling Calorimeter **4.**e 4.1 Liquid Noble gas Liquid Scintillator 4.m Air/Water/Ice/rock 4.n Cherenkov and Fluorescence 4.q Large scale engineering

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

### **Detector R&D for Collider and Underground Experiments**

at to list some

## 4.1, 4.2 Detectors for Cosmic Rays and UHE Gammas



**Detector R&D for Collider and Underground Experiments** 

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## **4.3 High Energy Neutrinos**

#### Southern Hemisphere:



2820 m (9250 ft)

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#### 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

Eiffel Tower 324 m (1063 ft) Precision IceCube Next Generation Upgrade

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

**Northern Hemisphere:** 

depth in Mediterranean.

KM3NeT collaboration megaton-

scale neutrino detectors 2500m

KM3NeT (Mediterraneo)

25% - 75%



Detector R&D for Collider and Underground Experiments

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

### Askaryan effect

**Tessa Carver (6/7/17)** 

bedrock



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



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



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

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## **References and Conferences**

- 1. FCC Week (<u>https://fccw2017.web.cern.ch/</u>) 29/5/17
- Technology and Instrumentation in Particle Physics, TIPP (<u>http://tipp2017.ihep.ac.cn/</u>) 22/5/17
- LHCC Open Session (<u>https://indico.cern.ch/event/632309/</u>) 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 (<u>https://indico.cern.ch/event/590645/</u>) 4/4/17
- 5. CALICE 2017 (https://agenda.linearcollider.org/event/7454/) 22/3/17
- 6. Neutrino Telescopes (<u>https://agenda.infn.it/confLogin.py?confld=11857</u>) 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 (<u>https://agenda.linearcollider.org/event/7014/</u>) 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 (<u>https://indico.cern.ch/event/468486/</u>) 7/3/16
- 15. ILC (https://www.linearcollider.org/P-D/ILC-detector-concepts)
- 16. CLIC (<u>http://clicdp.web.cern.ch/</u>)
- 17. LBNF (<u>http://lbnf.fnal.gov/</u>)

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## 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

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THANK YOU