ECFA
European Committee for Future Accelerators

ECFA Detector R&D Roadmap:

TF2 Liquid Detectors

Storytelling from Luca Scotto Lavina
(but no management role on it, just a member)

TF2: Liquid Detectors

- TF1 Gaseous Detectors https://indico.cern.ch/event/1214405/
- **TF2 Liquid Detectors https://indico.cern.ch/event/1214404/**
- TF3 Solid State Detectors https://indico.cern.ch/event/1214410/
- TF4 Photon Detectors and PID https://indico.cern.ch/event/1214407/
- TF5 Quantum and Emerging Technologies https://indico.cern.ch/event/1214411/
- TF6 Calorimetry https://indico.cern.ch/event/1213733/
- TF7 Electronics and On-detector Processing https://indico.cern.ch/event/1214423/
- TF8 Integration https://indico.cern.ch/event/1214428/
- TF9 Training https://indico.cern.ch/event/1214429/

TF2: scope and organization

Leaders:

Roxanne Guenette (University of Manchester)

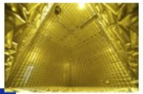
Jocelyn Monroe (Royal Holloway, University College London)

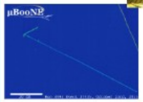
Material taken from TF2 DRD2 Community Workshop held on 20 April 2023

The Science covered

Neutrinos

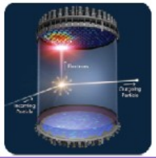
- Oscillation precision measurements (δ_{CP}, mass ordering, θ_{23} octant, sterile νs)
- Neutrino interactions (from CEvNS to DIS)
- Astro neutrinos





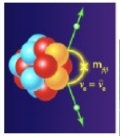
Dark Matter

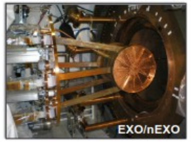
- Direct detection (WIMPs, …)



$0\nu\beta\beta$

- Search for Majorana neutrinos





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The Experiments (not exhaustive)

Neutrinos

- Current generation:
  - ✓ MicroBooNE & SBN
  - ✓ LArIAT
  - ✓ protoDUNEs
  - ✓ CAPTAIN
  - ✓ COHERENT
  - ✓ Borexino
  - ✓ SK
  - ✓ Antares
  - ✓ KM3Net
- Future generation:
  - ✓ DUNE modules 1 & 2
  - ✓ DUNE near detectors
  - ✓ DUNE modules 3 & 4
  - ✓ HK
  - ✓ Future neutrino telescopes

Dark Matter

- Current generation:
  - ✓ LUX / LZ
  - ✓ XENON 10/100/1T/nT
  - ✓ Dark Side 50/20k
  - ✓ DEAP-3600
  - ✓ Panda-X
- Future generation:
  - ✓ XLZD
  - ✓ GADMC/Argo
  - ✓ HeRALD
  - ✓ SBC

$0\nu\beta\beta$

- Current generation:
  - ✓ EXO-200
  - ✓ KamLand-Zen
  - ✓ SNO+
- Future generation:
  - ✓ nEXO
  - ✓ KL-Z+
  - ✓ Upgrades to SNO+

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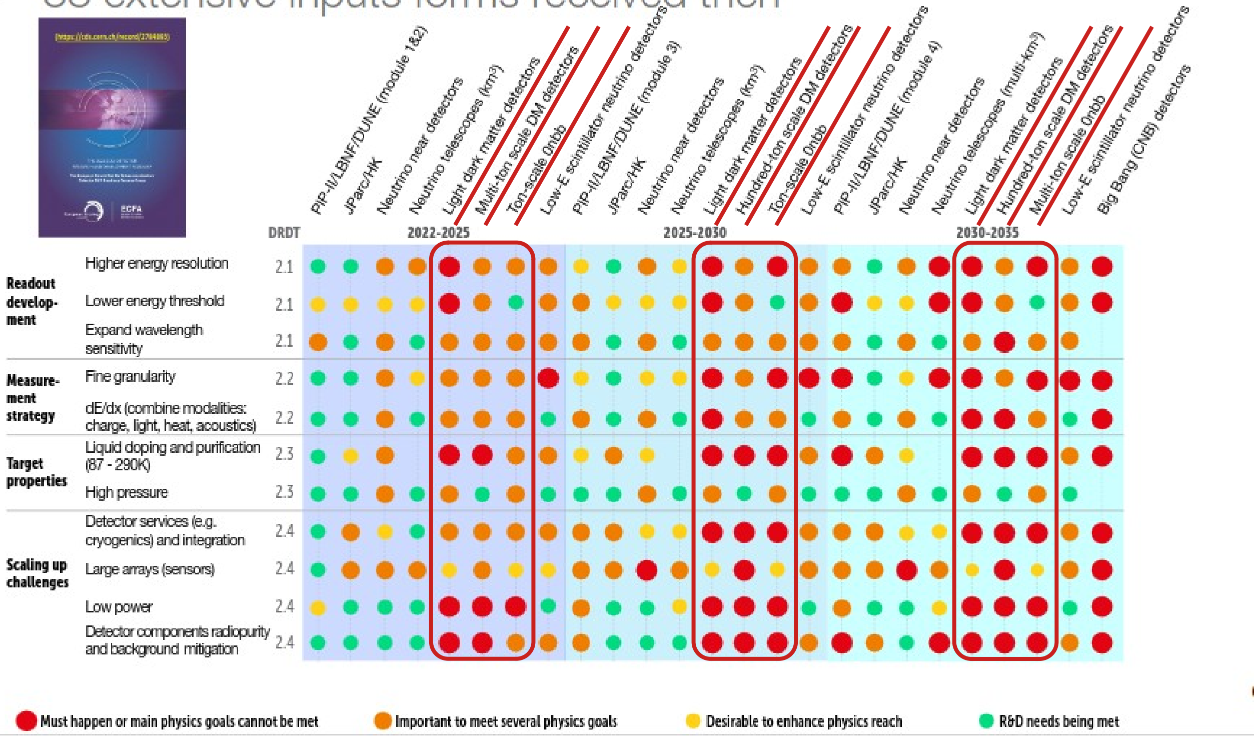
TF2: Roadmap

- TF2 Symposium was held on 9 April 2021 (link) with 6 expert talks, + ~20 breakout room discussions led by 11 early career experts, ~125 attendees (> 80% in discussions)
- 38 extensive inputs forms received then



Concerning LPNHE:

- Multi-ton scale DM detectors

Other interesting developments:

- Light dark matter detectors
- Ton-scale 0nbb

Working Packages

WP 1: Charge Readout	WP 2: Light Readout	WP 3: Target Properties	WP4: Scaling-up challenges
1.1: Pixels	2.1: Increased sensor QE	3.1: Doping & isotope loading	4.1: Radiopurity & bkg mitigation
1.2: Electroluminescence & charge amplification	2.2: WLS & increasing light collection	3.2: Purification	4.2: Detector & target procurement/production
1.3: Dual (charge + light)	2.3: Improved sensors for LS/Water	3.3: Light emission & transport	4.3 Large-area readout
1.4: Charge to light		3.4: Microphysics & characterization	4.4: Material properties
1.5: Ion detection			

Charge Readout:

- Pixels and charge+light readouts:

Jonathan Asaadi (jonathan.asaadi@uta.edu) & Elena Gramellini (elena.gramellini@manchester.ac.uk)& Roxanne Guenette (roxanne.guenette@manchester.ac.uk)

- Electroluminescence, charge multiplication & Charge-to-light readouts:

Alexander Deisting (deisting@uni-mainz.de) & Kostas Mavrokoridis (K.Mavrokoridis@liverpool.ac.uk)

Light readout:

- Increased sensor QE:

Jocelyn Monroe (Jocelyn.Monroe@rhul.ac.uk)

- Wavelength shifters and increasing light collection:

Marcin Kuzniak (mkuzniak@camk.edu.pl), Justo Martin-Albo (justo.martin-albo@ific.uv.es), Clara Cuesta (clara.cuesta@ciemat.es)

- Improved sensors for liquid scintillators and water detectors:

Mathieu Bongrand (mathieu.bongrand@in2p3.fr) & Tobias Lachenmaier (tobias.lachenmaier@uni-tuebingen.de)

Target Properties:

- Microphysics, Light emission and transport & isotope loading for Liquid Scintillators and Water Cherenkov detectors:

Stefan Schoppmann (stefan.schoppmann@uni-mainz.de) & Hans Steiger (hsteiger@uni-mainz.de)& Micheal Wurm (michael.wurm@uni-mainz.de)

- Microphysics, Light emission and transport & Doping of Noble Element detectors:

Davide Franco (dfranco@in2p3.fr) & Marie-Cecile Piro (mariecci@ualberta.ca) & Andrzej Szelc (a.szelc@ed.ac.uk) & Andrea Zani (andrea.zani@cern.ch)

Scaling-up Challenges:

- Radiopurity and background mitigation:

Roberto Santorelli (roberto.santorelli@ciemat.es) & Jim Dobson (jim.dobson@kcl.ac.uk)

- Detector & Target procurement/production & Purification:

Walter Bonivento (Walter.Bonivento@cern.ch) & Minfan Yeh (yeh@bnl.gov)

- Large-area readout:

Ines Gil-Botella (ines.gil@ciemat.es), Jose Crespo (jcrespo@ciemat.es), Giuliana Fiorillo (giuliana.fiorillo@na.infn.it)

Working Packages

WP 1: Charge Readout	WP 2: Light Readout	WP 3: Target Properties	WP4: Scaling-up challenges
1.1: Pixels	2.1: Increased sensor QE	3.1: Doping & isotope loading	4.1: Radiopurity & bkg mitigation
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1.4: Charge to light		3.4: Microphysics & characterization	4.4: Material properties
1.5: Ion detection			

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DARWIN

XeLab (IN2P3 R&D Master Project)

X-Art (ANR)

Charge Readout:

- Pixels and charge+light readouts:

Jonathan Asaadi (jonathan.asaadi@uta.edu) & Elena Gramellini (elena.gramellini@manchester.ac.uk)& Roxanne Guenette (roxanne.guenette@manchester.ac.uk)

- Electroluminescence, charge multiplication & Charge-to-light readouts:

Alexander Deisting (deisting@uni-mainz.de) & Kostas Mavrokoridis (K.Mavrokoridis@liverpool.ac.uk)

Light readout:

- Increased sensor QE:

Jocelyn Monroe (Jocelyn.Monroe@rhul.ac.uk)

- Wavelength shifters and increasing light collection:

Marcin Kuzniak (mkuzniak@camk.edu.pl), Justo Martin-Albo (justo.martin-albo@ific.uv.es), Clara Cuesta (clara.cuesta@ciemat.es)

- Improved sensors for liquid scintillators and water detectors:

Mathieu Bongrand (mathieu.bongrand@in2p3.fr) & Tobias Lachenmaier (tobias.lachenmaier@uni-tuebingen.de)

Target Properties:

- Microphysics, Light emission and transport & isotope loading for Liquid Scintillators and Water Cherenkov detectors:

Stefan Schoppmann (stefan.schoppmann@uni-mainz.de) & Hans Steiger (hsteiger@uni-mainz.de)& Micheal Wurm (michael.wurm@uni-mainz.de)

- Microphysics, Light emission and transport & Doping of Noble Element detectors:

Davide Franco (dfranco@in2p3.fr) & Marie-Cecile Piro (mariecci@ualberta.ca) & Andrzej Szelc (a.szelc@ed.ac.uk) & Andrea Zani (andrea.zani@cern.ch)

Scaling-up Challenges:

- Radiopurity and background mitigation:

Roberto Santorelli (roberto.santorelli@ciemat.es) & Jim Dobson (jim.dobson@kcl.ac.uk)

- Detector & Target procurement/production & Purification:

Walter Bonivento (Walter.Bonivento@cern.ch) & Minfan Yeh (yeh@bnl.gov)

- Large-area readout:

Ines Gil-Botella (ines.gil@ciemat.es), Jose Crespo (jcrespo@ciemat.es), Giuliana Fiorillo (giuliana.fiorillo@na.infn.it)

WP1.2 : Electroluminescence and charge amplification

Amplification stage: The structure in a detector where electrons are accelerated at to produce **electroluminescence light** (S2) and/or **charge multiplication** for the subsequent readout.

- Context: **noble liquid or dual phase time projection chambers** (TPCs)
- Task focus: Research and development (R&D) on **amplification stages**, in particular:
  - amplification stages with low energy thresholds down to single electron resolution
  - novel amplification stages, overcoming challenges of current detectors (*e.g.* maintaining uniform electrode-liquid distance)
- In summary, great interest in both generic and project specific R&D for dark matter, $0\nu\beta\beta$, and neutrino (*e.g.* CEνNS) applications:
  - DarkSide-LowMass, Darwin, LArCADe, NUXE, XLZD

- **Berkeley Lab (US)**, Yuan Mei
- **LIP-Coimbra (Portugal)**, Vitaly Chepel
- **LPNHE (France)**, Luca Scotto Lavina
- **NIKHEF (Netherlands)**, Auke Pieter Colijn
- **UC Riverside (US)**, Shawn Westerdale
- **UC San Diego (US)**, Kaixuan Ni
- **UC Santa Barbara (US)**, David Caratelli
- **University of Freiburg (Germany)**, Fabian Kuger
- **University of Mainz (Germany)**, Alexander Deisting
- **Weizman Institute of Science (Israel)**, Amos Breskin

Material taken from Alexander Deisting
TF2 DRD2 Community Workshop
held on 20 April 2023

WP1.2 : overlap with other WPs

Future large experiments:

- Development of new amplification structures, with the same (or better) performance than the current ones which:
  - allow to keep the liquid level constant between electrodes (dual phase)
  - eliminate the liquid-gas interface all together (single phase)
- Driven by the groups with interest in building the next generation of dark matter experiments. ($\rightarrow$ overlap with the "scaling up challenges" WP)

Low threshold liquid detectors:

- Development of novel amplification structures with a sub-keV threshold for the detection of energy deposits.
- Particular interest for CEνNS measurements, in combination with xenon doping of argon ($\rightarrow$ overlap with the "doping" WP)

WP1.2 : research interest and technologies

	mult.		e.lumi.		Ar	Xe
	SP	DP	SP	DP		
LIP-Coimbra	x	x	x	x	x	x
LPNHE				x		x
NIKHEF			x			x
UC Riverside			x	x	x	x
UC San Diego			x		x	x
UC Santa Barbara	x				x	
Freiburg			x			x
Mainz			x			x
Weizman	x	x	x	x	x	x

Dual-phase
Xenon
TPC

⇒ Broad mix across argon and xenon as well as between single- (SP) and dual phase (DP) applications and whether people are interested in electroluminescence or charge multiplication

- Micro structures: generic micro structures; micro structures based on industrial processes; CMOS in liquid; other custom micro/nano structures
- Micro to "macro" structures: meshes connected with vertical pillars; lithography produced micro (and slightly larger) structures; custom GEMs; MSGC like structures;
- Wires: wire grids; single-wire in the centre of cylinder shape as proportional scintillation counter; thin strip wires coated on quartz plates;
- Liquid doping: xenon doped liquid argon
- Other: bubble assisted amplification

WP1.2 : deliverable and milestones

1. Small scale amplification structure for (1.a) S2 production and (1.b) charge amplification in LAr/LXe; 2024 to 2025 and beyond → near- to mid term
   - Deliberately not tied to a certain technology to allow for a broad range of R&D, but performance driven.
2. Demonstrate the capabilities listed below for the structures developed in (1); 2025 to 2026/2027 → near- to mid term
   - Milestone 1: Single electron resolution/ sub-keV detection threshold
   - Milestone 2: ER/ NR discrimination capability
3. Show the scalability of the structure from (1) and (2); 2024 to 2029 (in parallel to (2)); → mid- to late term
   - Deliverable 1/Milestone 3: 1 m^2 demonstrator or a charge multiplication/electroluminescence structure, 2026 or later

	c. mult.[a]	e.lumi.[b]	SP	DP	M1	M2	D1/M3
Berkeley		x	x				x
LIP-Coimbra	x	x	x	x	x	x	
LPNHE		x		x		x	x
NIKHEF		x	x			x	x
UC Riverside		x	x	x	x		
UC San Diego		x	x		x	x	x
UC Santa Barbara	x		x		x		
Freiburg		x	x			x	x
Mainz		x	x			x	x
Weizman	x	x	x	x	x	x	

a: charge multiplication, b: electroluminescence

Funding requests

	funding per year		one time investment
	total FTE	E+C[a] (kEUR)	(kEUR)
M1	4.5 PhD + 3.0 PD	20	15
M2	4.5 PhD + 2.5 PD	30	
D1/M3	4.0 PhD + 2.0 PD	30	20

a : E+C: Equipment and Consumables

WP3.4 : Microphysics and characterization

High potential of noble liquids in astroparticle from eV to GeV and medical physics

- **Physics cases:**
  - Light dark matter particles
  - Solar and supernovae neutrino via coherent scattering (and ES/CC)
  - Directional signatures (dark matter and solar neutrinos via ES)
  - Neutrinoless double beta decay (liquid argon doped with enriched ^{136}Xe)
  - Time-of-flight PETs
  - Biomedical imaging

- **Microphysics and characterization: Milestones**
  - LAr/LXe nuclear recoil **quenching** and its **fluctuation** down to sub-keV region
  - LAr/LXe **ionisation response** to electron recoil/nuclear recoils vs electric field
  - Understanding **bubble nucleation** in superheated LAr/LXe
  - Understanding energy transfer and response in **Xe-doped LAr**

Material taken from Davide Franco and Marie-Cecile Piro
TF2 DRD2 Community Workshop
held on 20 April 2023

WP3.4 : contributions

- Characterization of LXe and LAr response to low energy recoils
  - Modeling of sub-keV interactions as well the angular dependence of e- recombination relative to the electric field direction in LAr and in LXe (M. Szydagis, Albany)
  - Bubble growth modeling to determinate nucleation efficiency (M.-C. Piro, UofA)
  - Mechanism of recombination and the ionization response to low-energy nuclear recoils (G. Fiorillo, Naples U.)
- Understanding single-electron background
  - Identification of causes of Single electron (SE) emissions in LAr TPC (M. Wada, AstroCeNT)
  - Identification of causes of Single electron (SE) emissions in LXe TPC (L. Scotto Lavina, LPNHE)
- Calibration sources / beams
  - Generation of 37Ar calibration source with neutron sources (M. Wada, AstroCeNT)
  - Low-energy neutron beams / neutron detectors (J. Wilson, ICJLab)
- Xe-Ar mixture
  - Cryogenic system for Xe-doped liquid Ar (M. Wada, AstroCENT)
  - Xenon doping for the production and collection of small ionization signals in liquid argon TPCs (J. Xu, LLNL)
  - Scintillation and ionization as a function of Xe concentration (D. Franco, APC - M.-C. Piro, UofA)
  - Xe-Ar phase diagram, EoS, maximum solubility of Xe (P. Stringari, ParisTech)

NEST

XeLab, phase 2

X-Art

WP3.4 : contributions

Europe

X-Art APC (France)
X-Art CTP (France)
U. Bourgogne (France)
ICPJLab (France)
Mines Paris (France)
X-Art ICB (France)
X-Art LPNHE (France)
GSSI (Italy)
INFN Torino (Italy)
INFN Cagliari (Italy)
INFN Catania (Italy)
INFN Genova (Italy)
INFN Napoli (Italy)
INFN Roma (Italy)
LNS (Italy)
Freiburg (Germany)
Mainz (Germany)
AstroCeNT (Poland)
Nikhef (Netherlands)

US

U. Albany
Duke University
Princeton U.
UCDavis
RPI
Rice U.
UC San Diego
Berkeley
UCLA
Colorado State University
UC Irvine
Lawrence Livermore National Lab.
U. California - Riverside

Brazil

Campinas U.

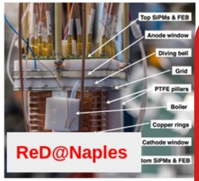
China

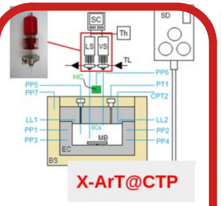
IHEP (China)

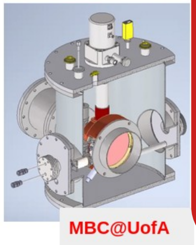
Canada

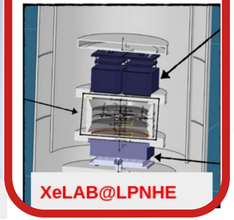
University of Alberta
University of Montreal
Carleton University

Some examples of existing or under construction setups

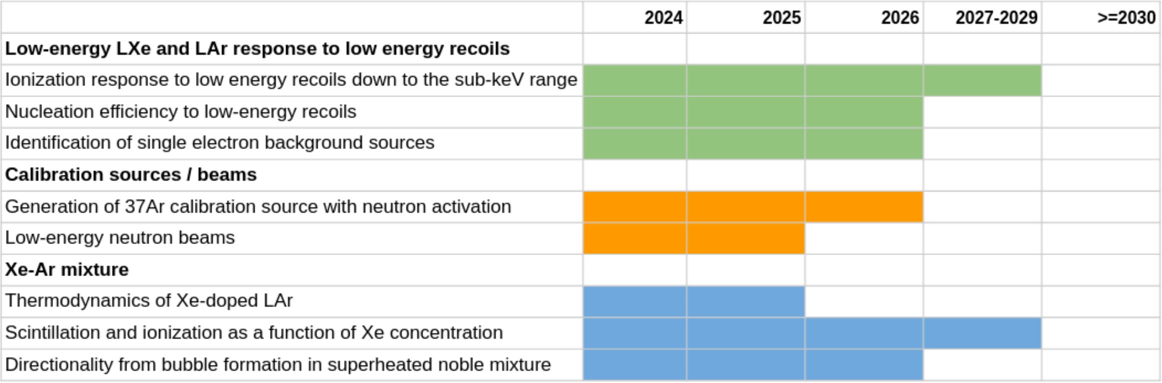








WP3.4 : deliverable and milestones



	kEuro / yr
Low-energy LXe and LAr response to low energy recoils	**615**
Ionization response to low energy recoils down to the sub-keV range	500
Nucleation efficiency to low-energy recoils	100
Identification of single electron background sources	15
Calibration sources / beams	**75**
Generation of 37Ar calibration source with neutron activation	55
Low-energy neutron beams	20
Xe-Ar mixture	**850**
Thermodynamics of Xe-doped LAr	200
Scintillation and ionization as a function of Xe concentration	450
Directionality from bubble formation in superheated noble mixture	200
Total	**1540**

Funding requests

	2024	2025	2026	2027-2029	>=2030	Total / year
Low-energy LXe and LAr response to low energy recoils						
Ionization response to low energy recoils down to the sub-keV range	8	6	7	4	4	4,8
Nucleation efficiency to low-energy recoils	4	4	4	4		4,0
Identification of single electron background sources	2,5	2	3	2		2,4
Calibration sources / beams						
Generation of 37Ar calibration source with neutron activation	1	1	1			1,0
Low-energy neutron beams	2	2				2,0
Xe-Ar mixture						
Thermodynamics of Xe-doped LAr	2,5	3,5				3,0
Scintillation and ionization as a function of Xe concentration	6	9	6	5	3	4,8
Directionality from bubble formation in superheated noble mixture	3	4	4			3,7
Total	29	31,5	25	15	7	

FTE

ECFA DRD TF2 Liquid detectors
Summary

LPNHE involved in ECFA DRD TF2 (Liquid detectors) :

- R&D on electrodes (main goal of **XeLab**) – WP1.2 (electroluminescence and charge amplification)
- R&D on single electrons background (**XeLab** phase 2) – WP3.4 (microphysics)
- R&D on xenon+argon mixture (**X-Art**) - WP3.4 (microphysics)

Expected outcomes :

- Exchange information
- Visibility
- Funding?