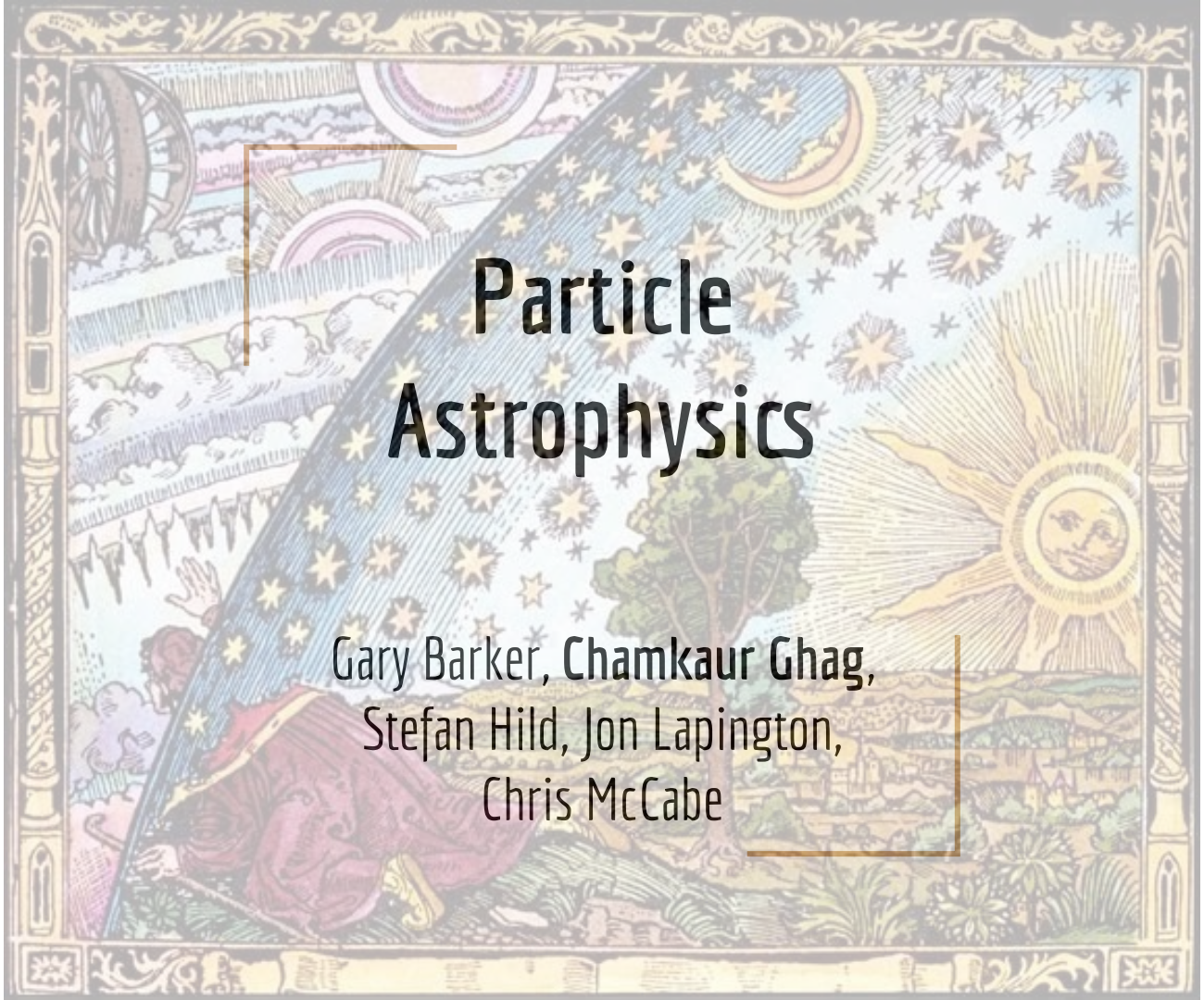


Particle Astrophysics

Gary Barker, **Chamkaur Ghag**,
Stefan Hild, Jon Lapington,
Chris McCabe

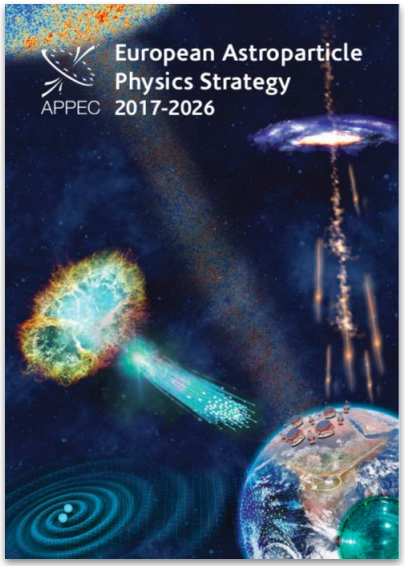
Current PA areas

- Dark Matter
- Neutrino Astronomy
- Gravitational Wave Astronomy
- Gamma Ray Astronomy
- PA Theory

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Action to be taken		*Voting Procedure*
For Approval	**EUROPEAN STRATEGY SESSION OF COUNCIL** 16th Session - 30 May 2013 **European Commission** **Berlaymont Building - Brussels**	Simple Majority of Member States represented and voting

The European Strategy for Particle Physics
Update 2013



j) A range of important non-accelerator experiments take place at the overlap of particle and astroparticle physics, such as searches for proton decay, neutrinoless double beta decay and dark matter, and the study of high-energy cosmic-rays. These experiments address fundamental questions beyond the Standard Model of particle physics. The exchange of information between CERN and ApPEC has progressed since 2006. *In the coming years, CERN should seek a closer collaboration with ApPEC on detector R&D with a view to maintaining the community capability for unique projects in this field.*

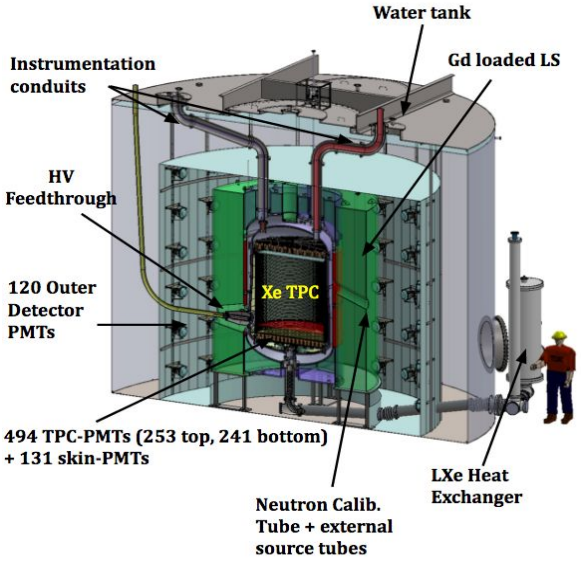
Dark Matter

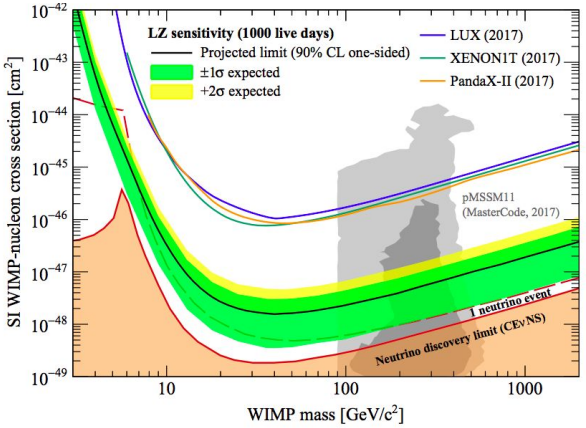
APPEC encourages the continuation of a diverse and vibrant programme (including experiments as well as detector R&D) searching for WIMPs and non-WIMP Dark Matter. With its global partners, APPEC aims to converge around 2019 on a strategy aimed at realising worldwide at least one 'ultimate' Dark Matter detector based on xenon (in the order of 50 tons) and one based on argon (in the order of 300 tons), as advocated respectively by DARWIN and Argo.

Direct Dark Matter Searches

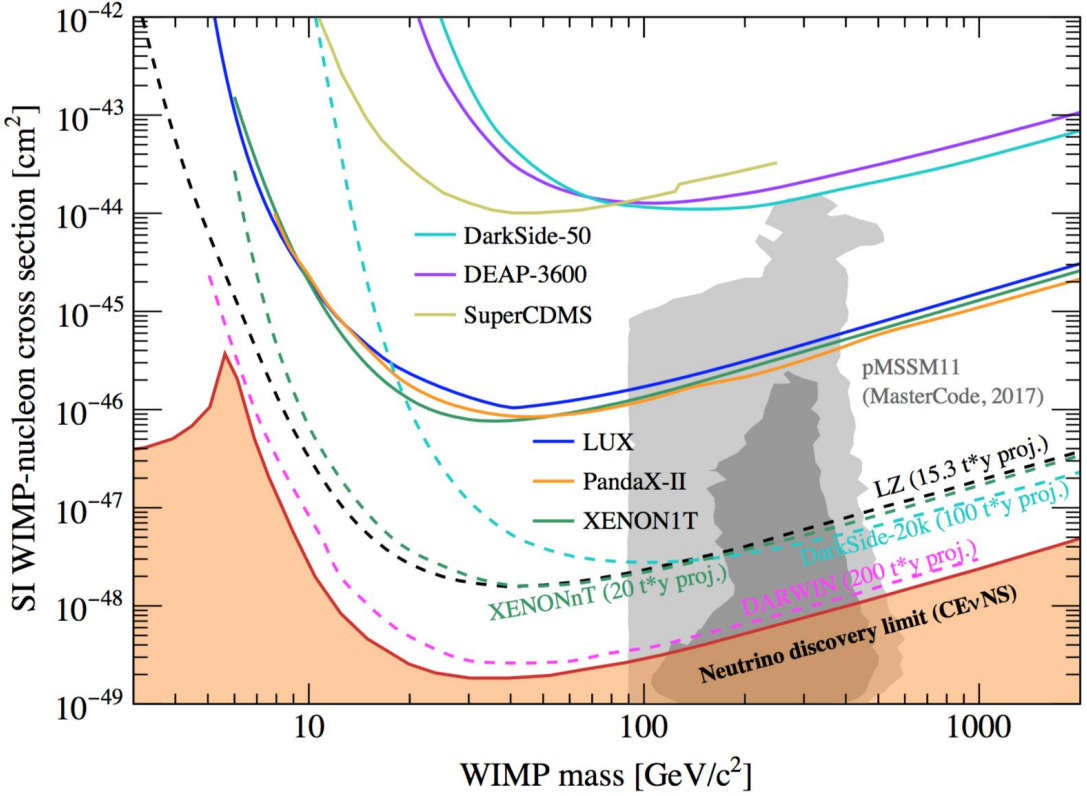
LUX-ZEPLIN (LZ)

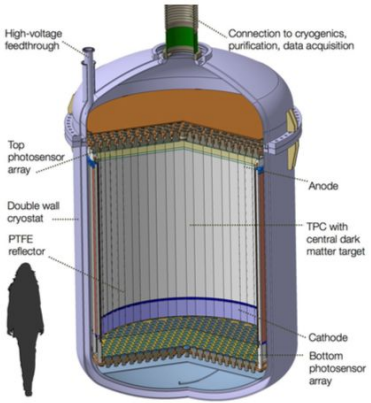
- Bristol, Edinburgh, Imperial, Liverpool, Oxford, RAL, RHUL, Sheffield, UCL
- Construction project 1/4/15 - 31/3/18
  - *Low-cost extension to 30/9/19 to better align with international project*
- UK co-lead 3/11 WP; 2/7 Exec. Board; 6/30 Technical Board; 9/39 institutes; 50/250 members; LZ Physics Co-ordinator
- Major UK Deliverables completed:
  - *PMTs delivered (⅓ of total in LZ)*
  - *UK Data Centre (1 of 2 for LZ)*
  - *Low-background assays (½ of total), background model*
  - *Titanium cryostat (delivered to SURF 14/5/18)*
- UK project 99% complete (99% baseline)
- Commissioning April 2020



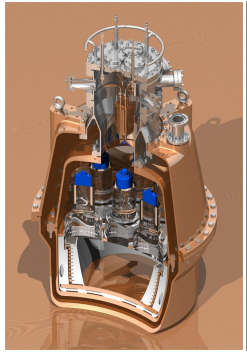
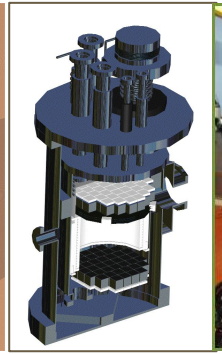
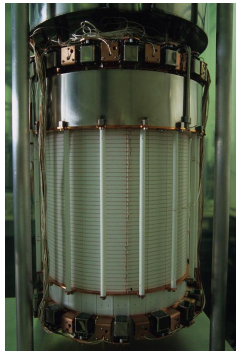
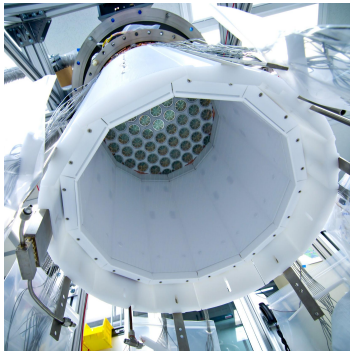


Direct Searches: The 3rd generation ('G3')



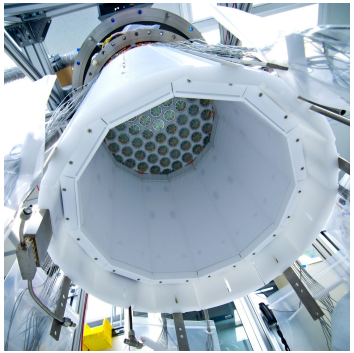


Liquid Xenon TPCs

ZEPLIN-II	XENON10	ZEPLIN-III	XENON100	LUX	PANDAX-II	XENON1T
						
31 kg (7.2 kg)	15 kg (5 kg)	12 kg (7 kg)	62 kg (34 kg)	250 kg (100 kg)	580 kg (362 kg)	2,000 kg (1,042 kg)
2007	2007	2008	2010	2013	2016	2017
6.6×10^{-43} cm^2	8.8×10^{-44} cm^2	8.1×10^{-44} cm^2	3.4×10^{-44} cm^2	3.4×10^{-46} cm^2	2.5×10^{-46} cm^2	7.7×10^{-47} cm^2

Liquid Xenon TPCs

LUX



250 kg
(100 kg)

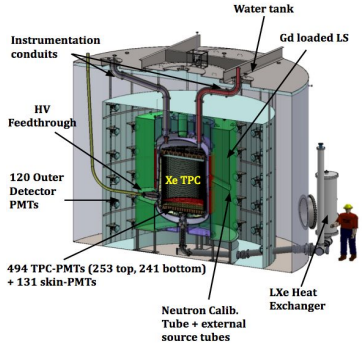
PANDAX-II

580 kg
(362 kg)

XENON1T

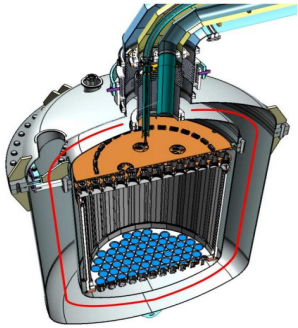
2,000 kg
(1,042 kg)

LZ



7,000 kg
(5,600 kg)

XENONnT



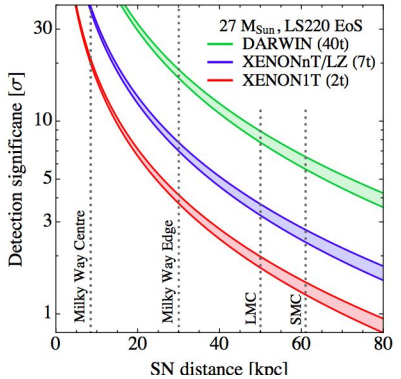
5,900 kg
(4,000 kg)

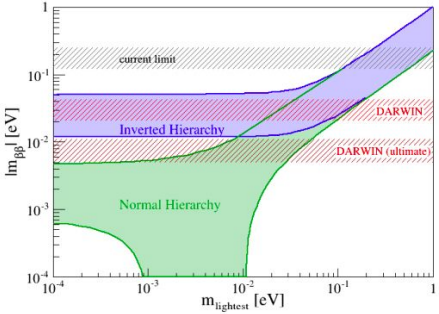
2013 — 2016 — 2017 — 2020 + 3 live years — 2020 + 5 live years

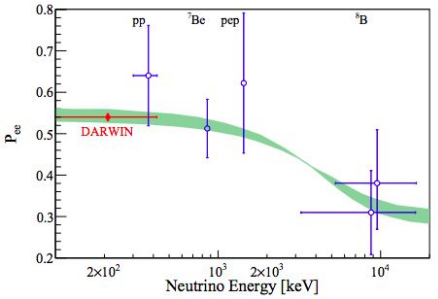
3.4×10^{-46} cm^2 — 2.5×10^{-46} cm^2 — 7.7×10^{-47} cm^2 — 1.6×10^{-48} cm^2 — 1.6×10^{-48} cm^2

‘Generation-3’ (G3)

- High stats confirmation/measurement ***or*** explore remaining ‘accessible’ WIMPs
- Size + low-background + NR + ER = Much science beyond standard WIMPs
  - *Neutrinoless double beta decay; low-energy solar neutrino flux; solar axions; galactic axion like particles: supernovae; sterile neutrinos; …*
- R&D mapped to UK expertise:
  - *engineering issues related to up-scaling*
  - *identification and mitigation of non-fiducialisable backgrounds*
  - *optical and electrical properties of materials*
  - *target doping*
  - *…*
- DMUK experiment-theory meetings & workshops:
  - *Optimise G3 R&D for non-WIMP thermal relics*
    - Single electron backgrounds (ionisation-only searches)
    - Asymmetric dark matter / FIMPs (low threshold)
    - Inelastic / magnetic dark matter (electron + nuclear recoils)
  - *Explore opportunities for high impact dark matter / dark sector models inaccessible to current/planned searches*



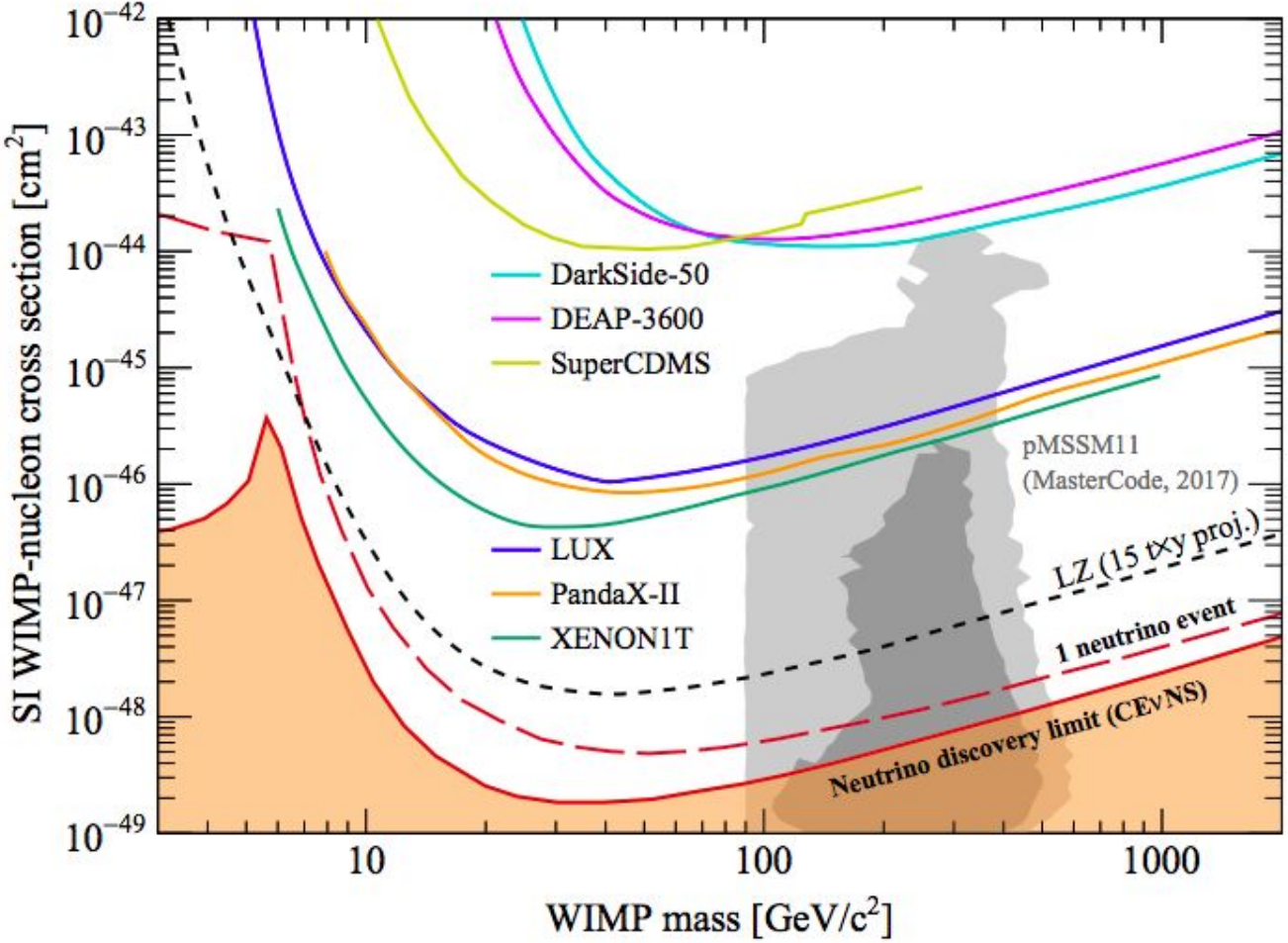




‘Generation-3’ (G3) Timescales

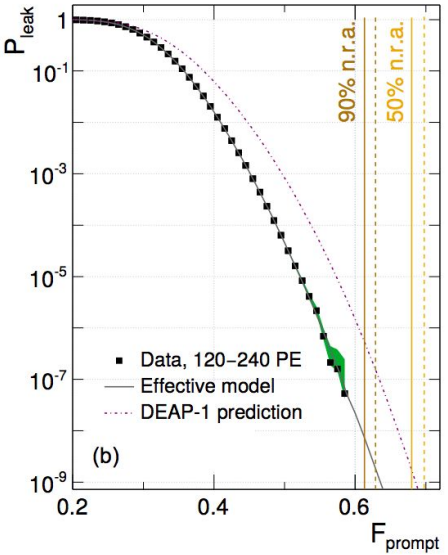
- 2019 - 2023 : G3 R&D
- 2023 - 2025 : Pre-construction phase for technical design
- 2025 - 2029 : Construction phase
- 2029 - 2034+ : Exploitation

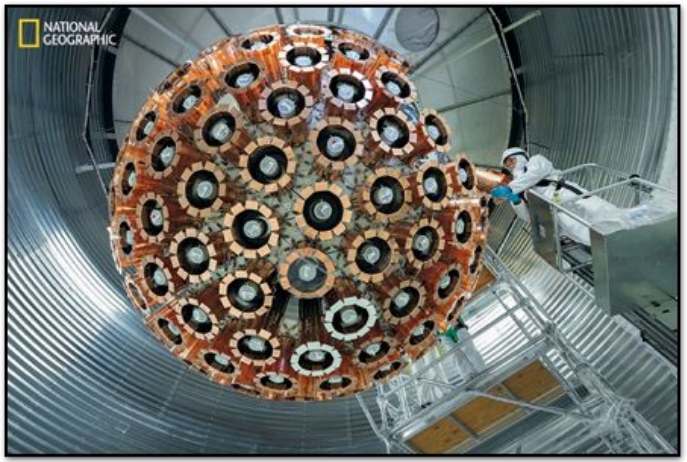
Expect similar timescales for projects deploying alternative targets for WIMPs

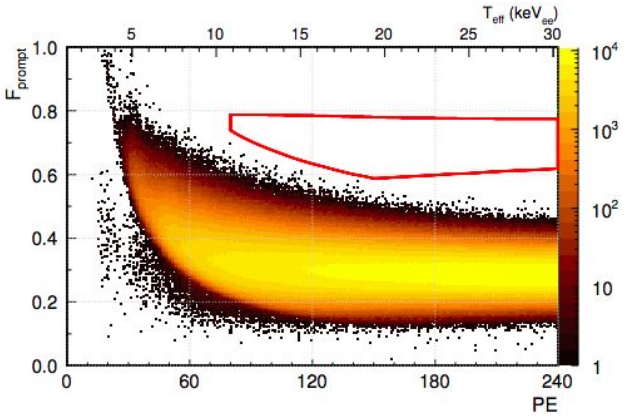

SI WIMP-nucleon cross section [cm^2]
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10
100
1000
WIMP mass [GeV/c^2]
DarkSide-50
DEAP-3600
SuperCDMS
LUX
PandaX-II
XENON1T
pMSSM11
(MasterCode, 2017)
LZ (15 t×y proj.)
1 neutrino event
Neutrino discovery limit (CEvNS)

DEAP-3600 @ SNOLab (Canada)

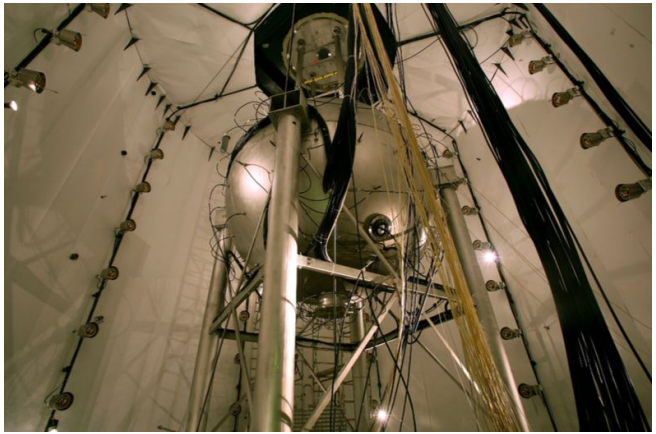
- Single phase LAr, 3.6 Ton (1 Ton fiducial)
- ‘Re-surfaced’ acrylic vessel; 255 8” PMTs
- Pulse shape discrimination (PSD) for particle ID
- *x250 difference in scintillation time constants between ER and NR*
  - *E_{th} ~ 39 keV determined by PSD (^{39}Ar β-decay, 1 Bq/kg, Q-value ~550 keV)*
  - *E_{th} better than expected; detector uniformity (calibrations - UK)*
- Data taking on going; 290 days (unblinded) in hand; blind since Jan 2018
- Plan to run till 2020



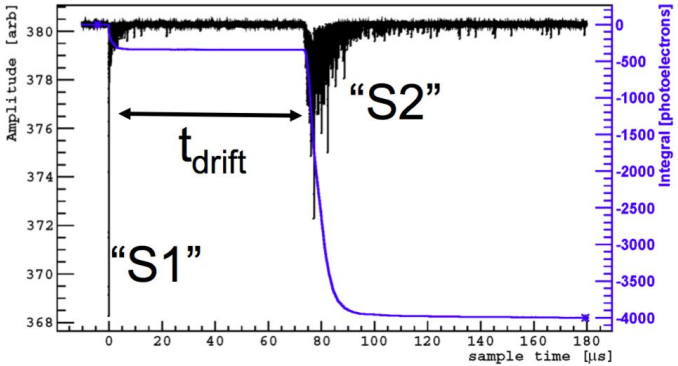


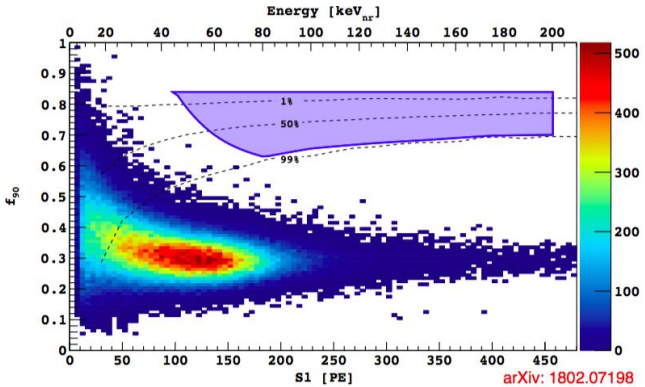


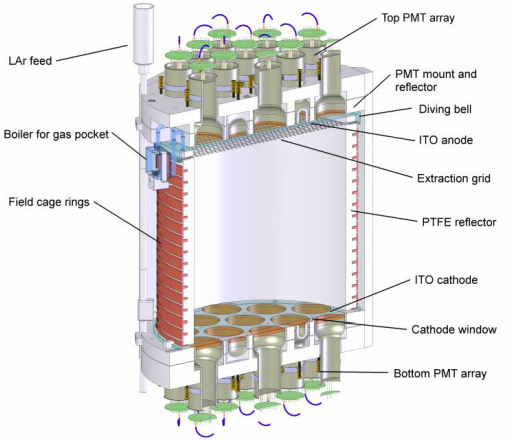
DarkSide-50 @ Gran Sasso (Italy)



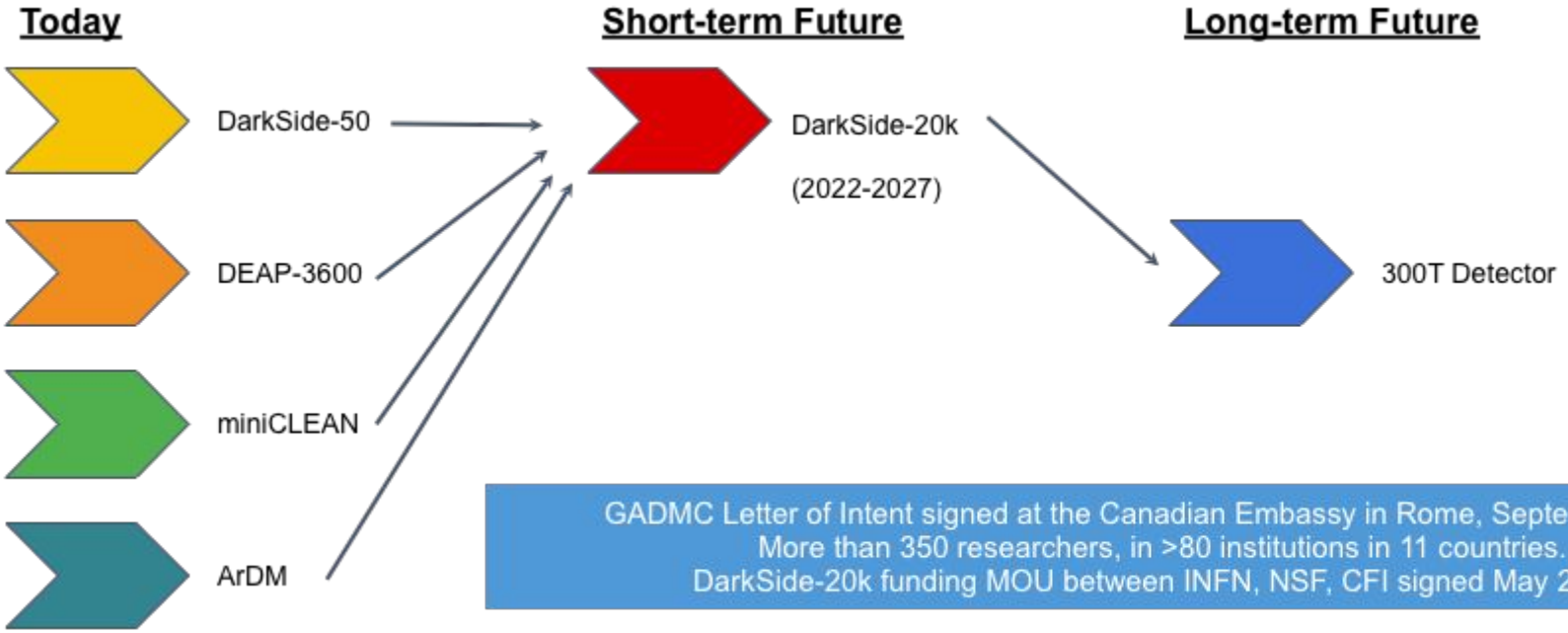
- 50 kg LAr TPC
  - *S1, S2 signals from scintillation and ionisation*
  - *TPB wavelength shifter; ITO on quartz as electrodes*
- First use of UAr (^{39}Ar depleted)
  - *New 2018 results (532 days) with UAr*
  - *Improve on 2014 results (54 days) by 5x to 1.1x10^{-44} cm^2*





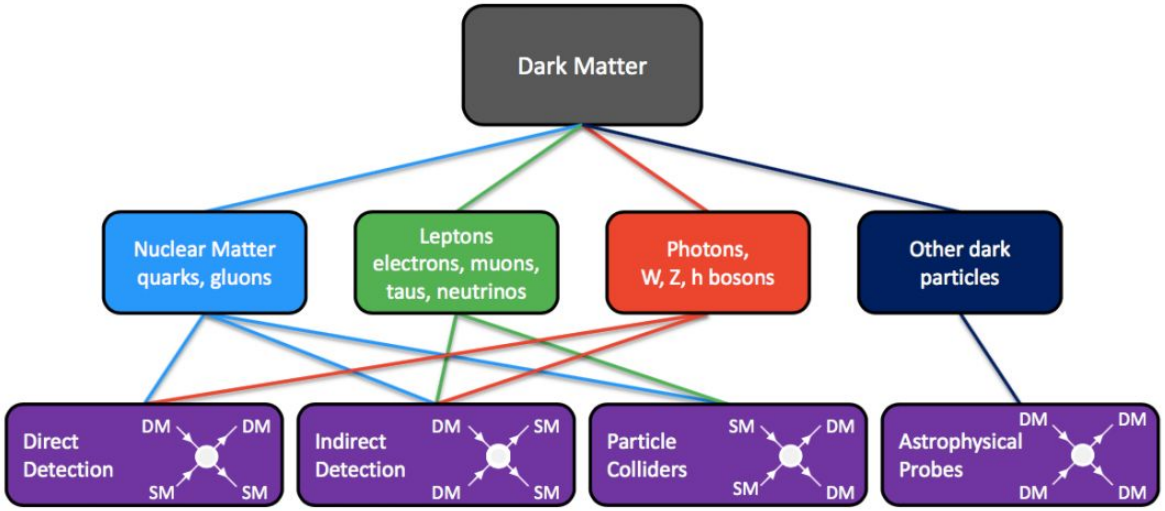


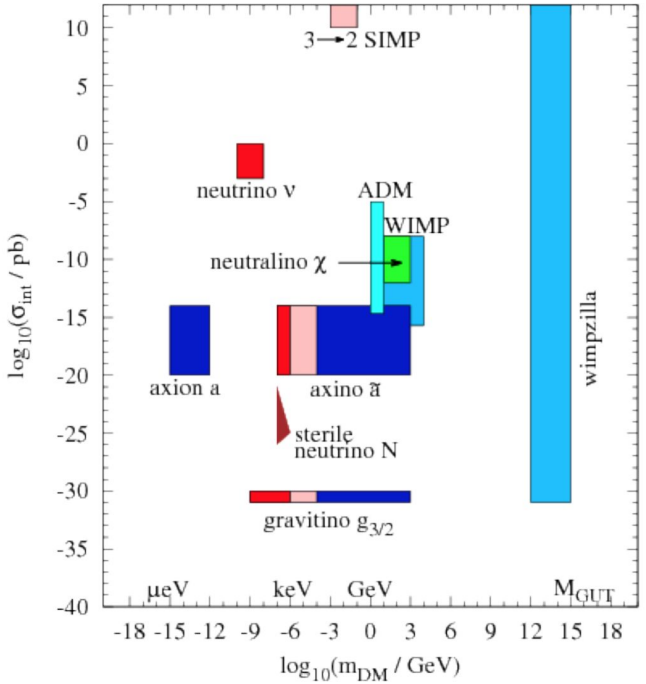
Argon



GADMC Letter of Intent signed at the Canadian Embassy in Rome, September 2017.
More than 350 researchers, in >80 institutions in 11 countries.
DarkSide-20k funding MOU between INFN, NSF, CFI signed May 2018.

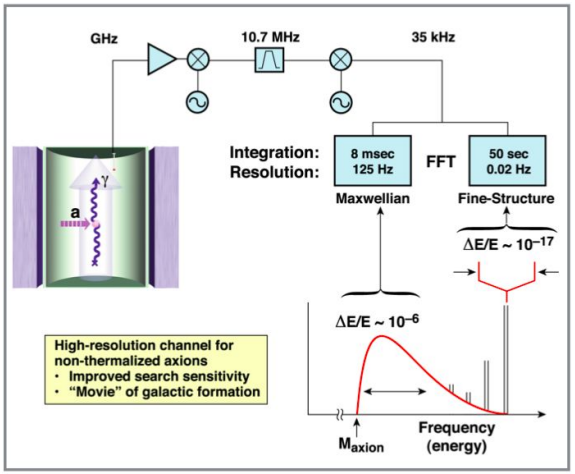
Direct Dark Matter Searches

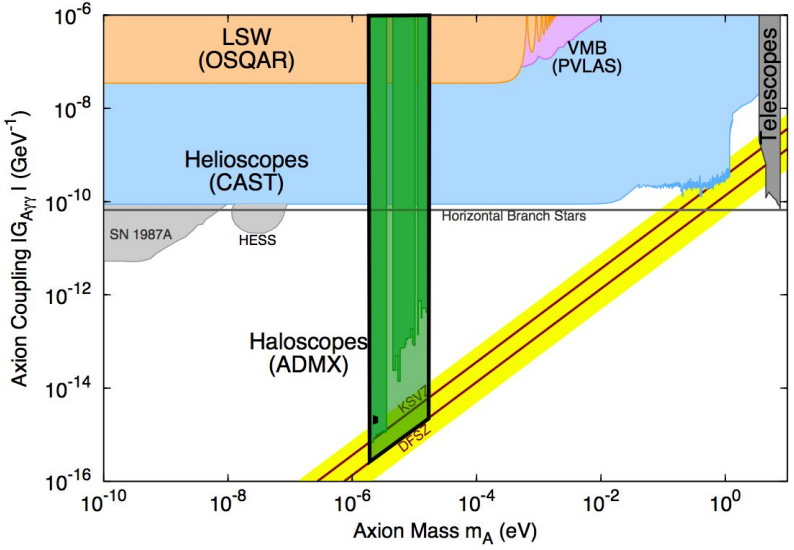




ADMX-Gen2 @ Washington (USA)

- Axions from QCD symmetry breaking mechanism
  - *Light (order 10 μeV) pseudoscalar, stable particles*
- ADMX-Gen2 is a Dark Matter axion search using a tuned electromagnetic resonator in a magnetic field
- UK groups (Lancaster, Sheffield) developing active cavity resonators to enhance ADMX range
  - *Good prospects to improves rate of axion mass coverage*





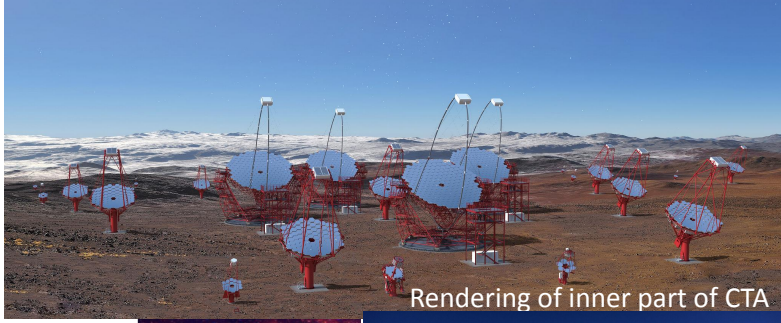
Gamma-ray Astronomy

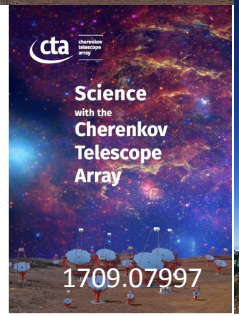
APPEC fully supports the CTA collaboration in order to secure the funding for its timely, cost-effective realisation and the subsequent long-term operation of this observatory covering both northern and southern hemispheres.

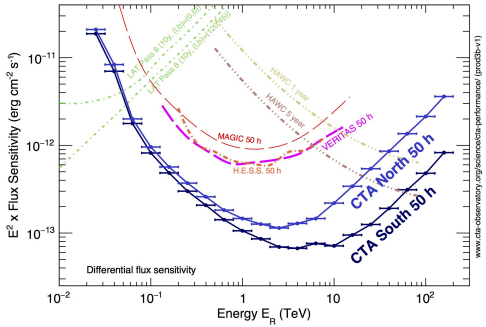
Gamma-ray Astronomy

Cherenkov Telescope Array @ La Palma and Paranal

- First open observatory in 30 GeV - 300 TeV bandpass
- 210 institutes (13 UK)
- 8 LSTs (23m), 40 MSTs (12m), 70 SSTs (4m)
- >10x sensitivity than previous experiments
- Whole sky coverage
- Site preparation at La Palma and Paranal now
- 1st production telescopes on site by 2019, ops. in 2023
- New 200+ page science case presented Sept. 2017
  - *Galactic centre, SNRs, clusters, PeVatrons, SFRs, AGN, transients, …*







Gamma-ray Astronomy - 20 year look-ahead

- CTA planned to be operational for ~30 years
  - Requirement to maintain/enhance performance throughout 2020 - 2050 timeframe
- Inevitability of technology upgrades 2025-onwards
  - Silicon photomultipliers (SiPM) already selected or proposed for all CTA telescopes
- Sensor improvements and new breakthroughs
  - SiPM improvements: lower dark noise, crosstalk and afterpulsing
  - Breakthrough photon counting technologies likely in 20 year period e.g. CMOS “Jot”
- Electronics - further miniaturisation and performance improvements
  - Electronics developments - multichannel ASICs
  - Higher channel density/faster timing → improved telescope performance
- Additions/improvements to CTA
  - UK CTA data centre – fulfils UK ambition in big data and maximises UK science return from CTA
  - Growing role of machine learning algorithms
  - Intensity interferometry – also benefitting from new sensor/electronics technologies
  - Optical follow-up telescope for CTA – strengthens UK role in multi-messenger activity

19

Gamma-ray Astronomy: PP technology overlap

Sensor technologies

- PMTs being replaced by silicon photomultipliers (SiPM)
  - SiPMs now being proposed for all CTA telescopes, even for LST upgrade
- SiPM now being applied for PP, DM, etc.
  - First major use of SiPMs for PP on CMS HCAL
  - Also Compass II, MEG II, RIKEN, nEXO, Darkside-20K

Electronics & fast computing

- Developments in fast timing/digitising multichannel ASICs
  - Already significant overlap with particle physics
- AI and machine learning in AP and PP
  - Larger telescope arrays/HL-LHC

→ Increasing amounts of data in real time

→ fast, real time data reduction algorithms

Gamma-ray Astronomy: AP-PP Linkages

- Particle astrophysics complementary to accelerator-based PP
  - Astronomy provides strong evidence for physics outside the Standard Model
  - Combination of approaches necessary to investigate: dark matter, dark energy, neutrino mass, inflation
- Increasingly powerful set of facilities to detect astroparticles
  - gamma rays, cosmic rays, gravitational waves, neutrinos, and dark matter
  - CTA will greatly enhance high energy gamma ray astronomy
- Coordination of these facilities:
  - Multi-messenger capability greater than the sum of its parts
  - Evidenced by increasing frequency of sciences successes, e.g.
    - December 2017 first multi-messenger detection of NS-NS merger
    - July 2018: first astronomical identification using a neutrino detector (IceCube)
- CTA – a dark matter discovery instrument of unprecedented sensitivity
  - a tool to study the particle and astrophysics properties of the dark matter particles

Gravitational Wave Astronomy

With its global partners and in consultation with the Gravitational Wave International Committee (GWIC), APPEC will define timelines for upgrades of existing as well as next-generation ground-based interferometers. APPEC strongly supports further actions strengthening the collaboration between gravitational-wave laboratories. It also strongly supports Europe's next-generation ground-based interferometer, the Einstein Telescope (ET) project, in developing the required technology and acquiring ESFRI status. In the field of space-based interferometry, APPEC strongly supports the European LISA proposal.

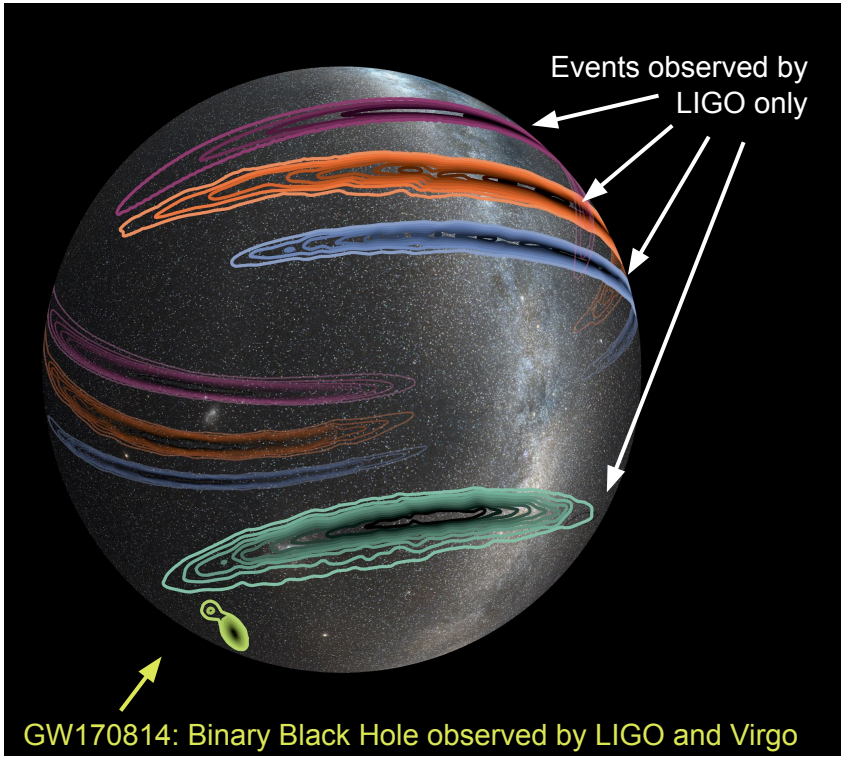
Gravitational Wave Astronomy

UK GW effort:

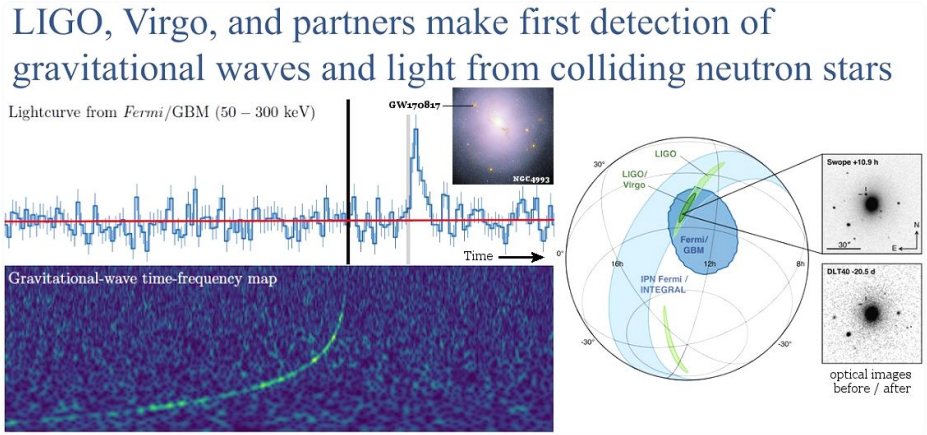
- Long leadership history in instrumentation & analysis
- Major contributions to Adv. LIGO & LISA pathfinder
  - *enabling hardware, innovations, leading searches, …*
- Faculty expansion
  - *Glasgow, Birmingham*
  - *New experimental group at Cardiff*
  - *New group created in Portsmouth*
- Restoration of ~flat total funding in BoP

Latest observation run:

- Adv. LIGO 2nd run (O2) complete (Nov ‘16 - Aug ‘17)
- Adv. Virgo joined the network in Aug 2017
- 3rd detector allows triangulation of source



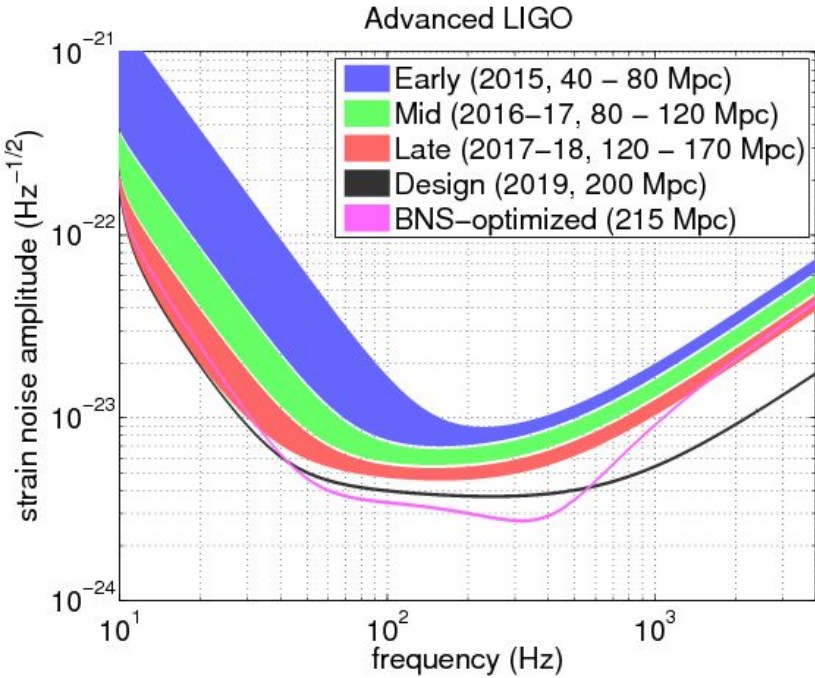
Multi-messenger Astronomy



- Nearly 500 papers (2500 astronomers) on GW170817 so far (many UK 1st author publications)
  - *Good sky localisation allowed finding optical counterpart and identification of host galaxy*
  - *Many telescopes around the globe and in space joined observation campaign*
- Observed gravitational waves from matter
- Evidence for link between binary neutron stars and some short gamma ray bursts
- Enabled observation of kilonova: observations provide evidence for the origin of heavy elements
- Constraints on speed of gravitational waves and equation of state of neutron stars
- Estimate of Hubble constant independent of distance ladder

Gravitational Wave Astronomy

- **Design sensitivity c. 2020-21**
  - Factor ~2 in sensitivity (10 in detection rates)
  - Progressing roughly on schedule
- **UK continues to contribute strongly to global GW effort**
  - Leadership of LIGO data & instrument working groups
  - Top-level management; e.g., Deputy chair of LIGO's Programme Committee (top policy body).
  - Valuable contributions to A+.
- **Well positioned to play leading role in 2.5G and 3G**



Gravitational Wave Astronomy

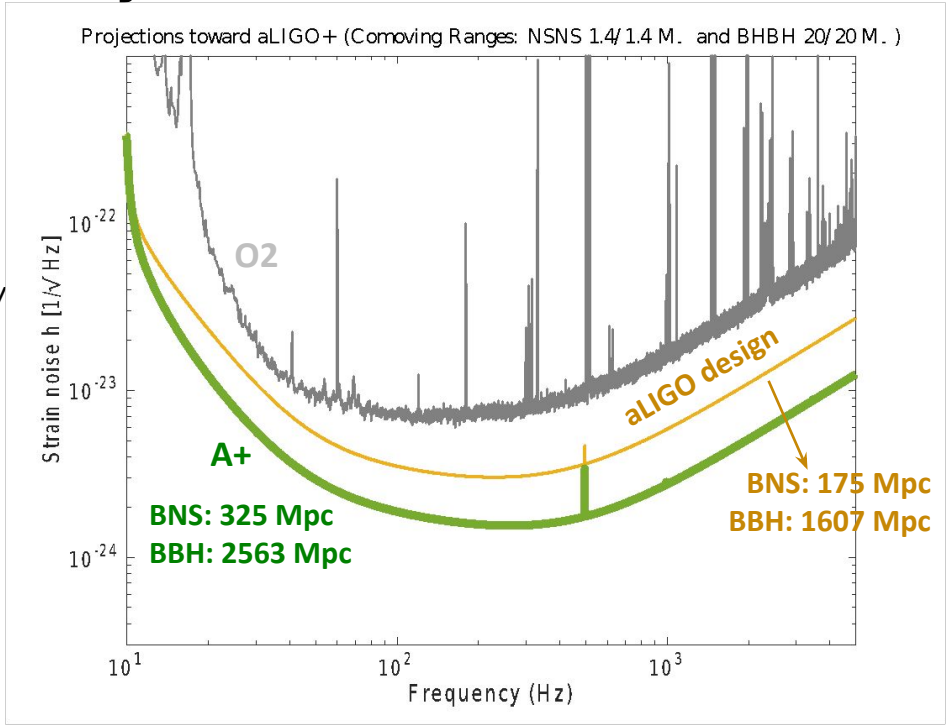
Mid-Term

LIGO A+ (2024+)

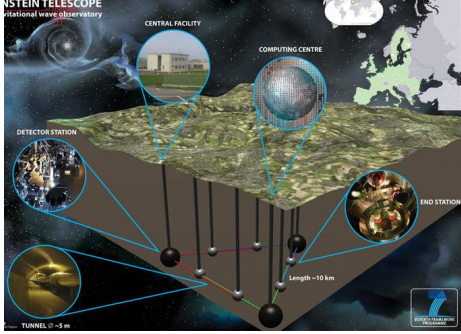
- Frequency-dependent squeezed laser light (US)
  - *1st demonstration of squeezing in km-scale GW detector at UK/German GEO detector*
- New & larger optics, upgraded suspensions (UK)
  - Improved mirror coatings & optics
  - Balanced homodyne readout

Later: LIGO-Voyager (c.2030)

- Push sensitivity to facility limits.
- Silicon optics, 2um laser, cryogenic operation.



Gravitational Wave Astronomy



Einstein Telescope (Europe)

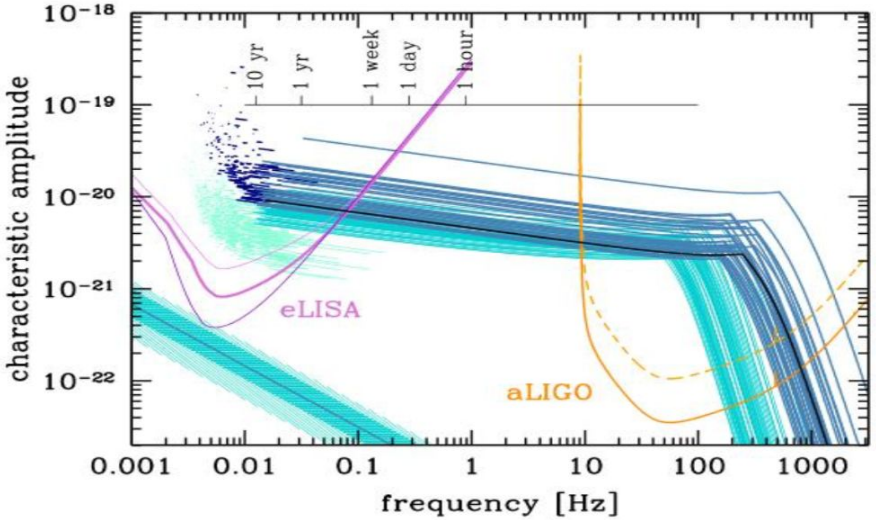
Long-term

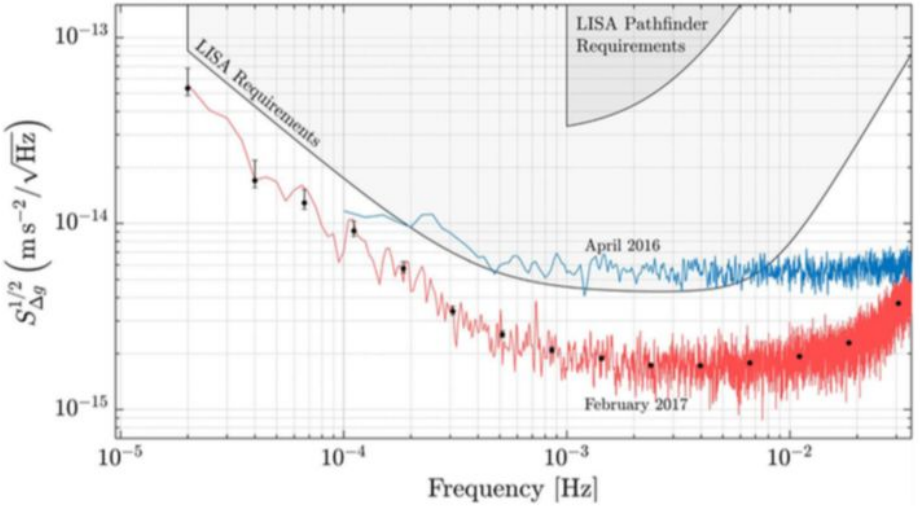
- Looking to completely new facilities for 3rd generation (2030s)
- Differing concepts in Europe (Einstein Telescope) & U.S. (Cosmic Explorer = 40 km LIGO)
- GWAC – "GW Agencies Correspondents" – informal coordination of funding agencies.
- GW International Committee: founded 3rd generation committee & science team to coordinate case
  - *includes UK scientists; draft Dec 2018*
- UK scientist chairs GWIC and another co-chairs the 3G science team

- Einstein Telescope Collaboration being formalized this summer
  - *Steering committee set up to establish collaboration roles, call for membership in fall.*
  - *Current main goal: submit to ESFRI roadmap next year. Need to define lead countries for political & financial support (1+2), cost estimates.*
- Italy & Netherlands are top contenders for the ET site.
  - *Italy has offered €5M for R&D for an ET site in Sardina, plus €10M for aVirgo upgrades.*
- Operations c.2035+ ?

LISA


LISA
Laser Interferometer Space Antenna


characteristic amplitude
frequency [Hz]
10 yr
1 yr
1 week
1 day
1 hour
eLISA
aLIGO


LISA Pathfinder Requirements
LISA Requirements
April 2016
February 2017
Frequency [Hz]

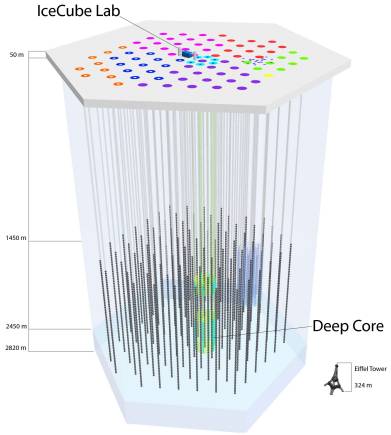
Neutrino Astronomy

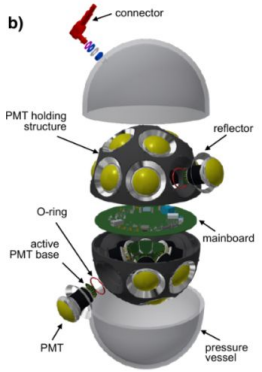
For the northern hemisphere (including Baikal GVD), APPEC strongly endorses the KM3NeT collaboration's ambitions to realise, by 2020: (i) a large-volume telescope with optimal angular resolution for high-energy neutrino astronomy; and (ii) a dedicated detector optimised for low-energy neutrinos, primarily aiming to resolve the neutrino mass hierarchy. For the southern hemisphere, APPEC looks forward to a positive decision in the US regarding IceCube-Gen2.

Neutrino Astronomy

- **IceCube** has observed astrophysical neutrinos up to 4 PeV
  - *Point sources not yet identified, flux consistent with blazar origin*

- **IceCube-Gen2** Cherenkov array @ South Pole (Manchester, Oxford, QMUL)
  - *L.E. part (PINGU): 6 Mt/26 strings each with 196 optical modules (mDOM's)*
  - *Sensitivity to ν-MH at 3 sigma after 4 years*
    - Study led by UK of existing Deep Core data and for PINGU LOI (2017)
  - *UK groups active in testbeam R&D of mDOM's*
  - *Recent NSF funding for the 7-string (Phase 1) upgrade*
  - *Momentum growing towards full the upgrade - scope for significant deliverable from UK ν-astrophysics community to PINGU (e.g. a fully instrumented string)*
- *Transient neutrino follow-up activity in the UK (e.g., Swift, Leicester)*





Neutrino Astronomy

- **ANITA-IV** & **ARA** Radio detection @ Antarctica (UCL)
    - *UCL have led the incorporation of GPUs into the online data acquisition*
    - *New ANITA-III results, world-leading flux limit at high energies (1803.02719)*
    - *New ANITA-III tau neutrino candidate event - now 2 mysterious events (1803.05088)*
    - *ANITA-IV flew in Dec. 2016, results eagerly anticipated; ANITA-V proposal with NASA*
    - *ARA: Three new stations and new phased array trigger installed in January 2018*
- Synergy with LBL neutrino future programme in technology & physics
    - *mDOM's for Hyper-K*
    - *GPU use in DAQ for DUNE*

“Building an Ambitious Portfolio”

Beyond STFC programme - what do we want to do as the PA community?

Consultation in progress - will provide input to European Strategy too. ***Possible*** projects:

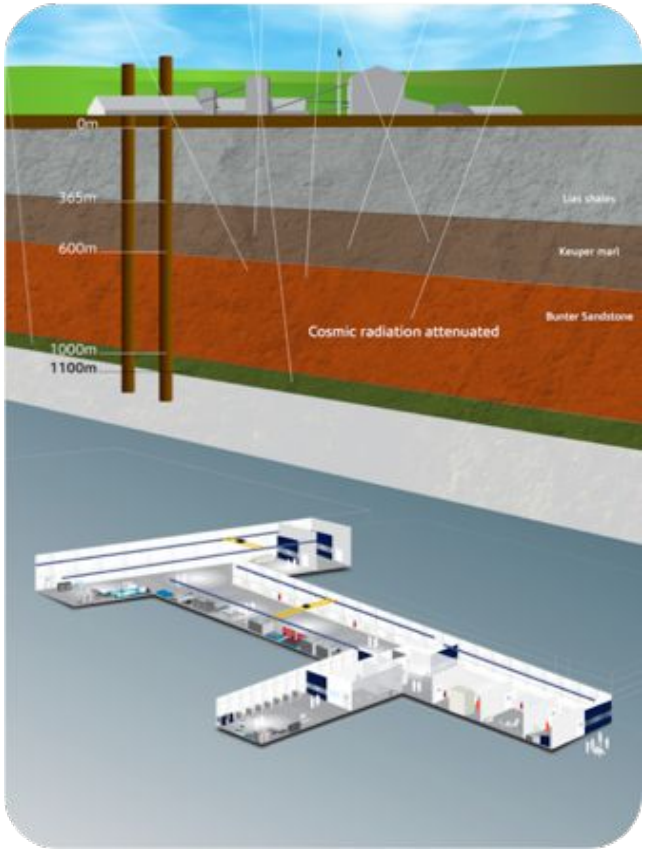
- “Large” project
  - Gravitational Waves - Einstein Telescope
- “Medium” project
  - Dark Matter - G3 LXe
- “Small” projects
  - Neutrino Astronomy - UK Antarctic Project
  - Gamma-ray astronomy - CTA (Data)

- PA/PP
  - Boulby (Low-background & cleanliness centre for DM, $0\nu\beta\beta$, GWs)
  - Ultra-light hidden sector physics (Axions, ALPS, etc; CERN Physics Beyond Colliders)

Boulby Underground Laboratory

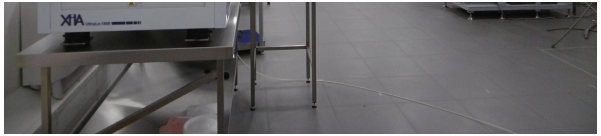
- New 4000 m^3 laboratory fully commissioned
  - *ISO 6/7 cleanroom throughout*

- Dark matter studies, neutrino physics, neutrinoless double beta decay, gravitational waves (cleanliness)
  - *Also geology/geophysics, environmental radiation, μ-tomography for deep geological surveys (incl. Carbon capture & sequestration), life in extreme environments, planetary exploration tech. R&D, …*

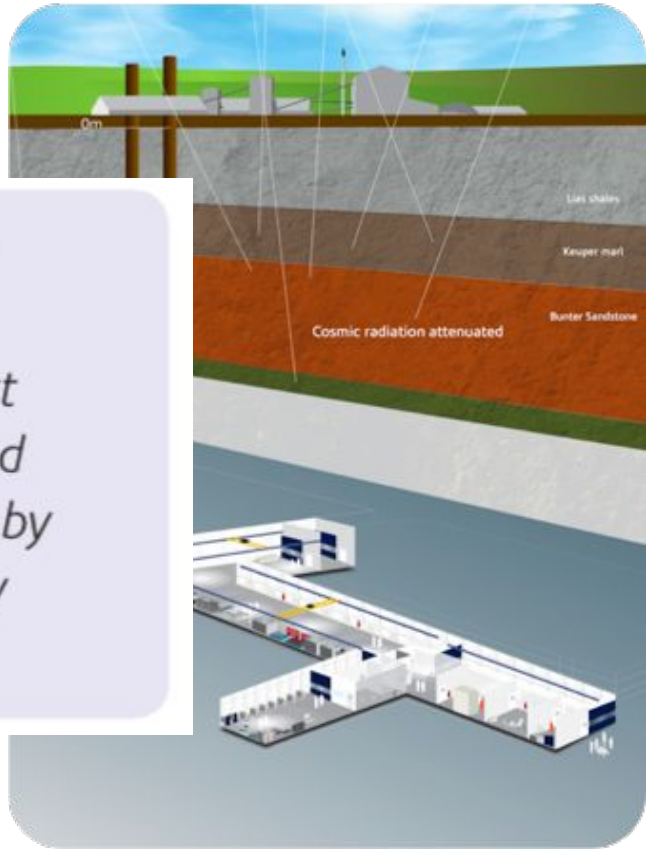


Boulby Underground Laboratory

- New 4000 m^3 laboratory fully commissioned
  - *ISO 6/7 cleanroom throughout*
- Dark matte
  decay, grav
  - *Also g*
    geolo
    envir



With a view to maintaining a good match between available capacity and planned activities, APPEC fosters continued support for and cooperation between underground laboratories – as advocated, for example, by the DULIA (Deep Underground Laboratory Integrated Activity) initiative.



Extra Slides

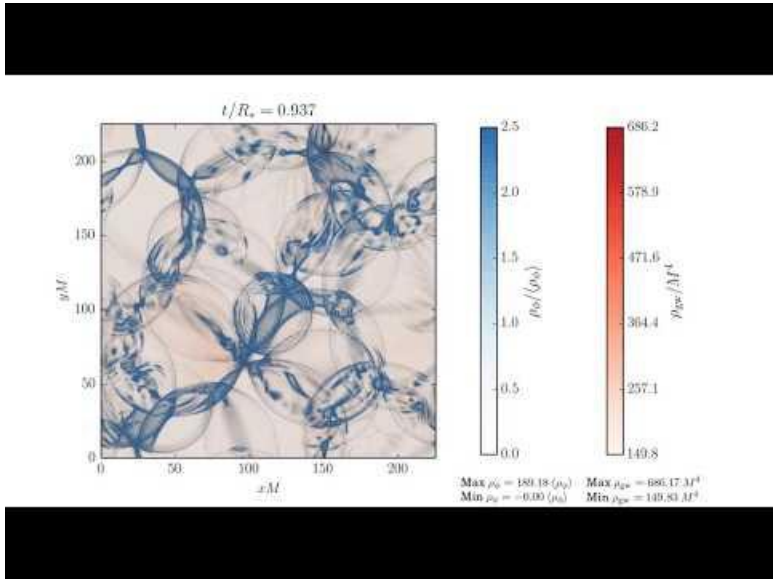
- Theory
- SuperCDMS
- CYGNUS
- QUAX
- GNOME

Theory

APPEC supports an ambitious theory programme in the field of astroparticle physics, with special attention focused on adjacent disciplines such as particle physics, astronomy and cosmology. APPEC encourages the establishment of a centre for astroparticle physics theory in one of its member countries.

Theory & Phenomenology

- Constraints on speed of GW relative to *c* ruled out large sections of parameter space of alternative theories of gravity
- GW phenomenology for alternate cosmological scenarios / gravity theories now being investigated in more detail
- Neutrinos are being included in LSS simulations, incl. N-body simulations, with interesting effects on small scales
- Incorporating Higgs in models of inflation – study of light scalars in general
- DMUK expt./theory meetings and workshops



Gravitational waves from a cosmological vacuum phase transition - scalar field energy density

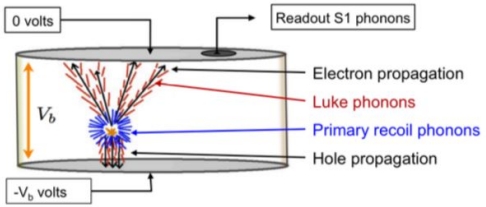
https://arxiv.org/abs/1802.05712

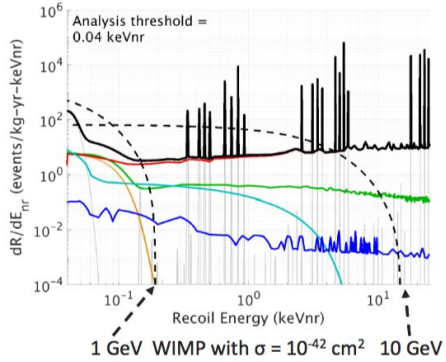
Theory & Phenomenology

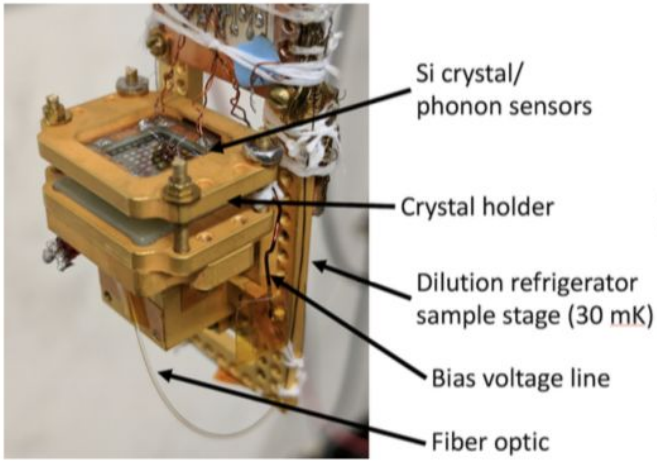
- **Improved Simplified Models for LHC Dark Matter searches:**
  - Very active field: important UK contributions (*Imperial, IPPP, KCL, Sussex)*
  - UK leading role e.g. 'Dark Matter Interpretations for Direct Detection' workshop (Aug 2016); Imperial international workshop 'Towards the next generation of simplified dark matter models' & Phys Dark Univ 16 (2017) white paper
- **Advances in direct detection:**
  - Improved theory for matching dark matter models to observable signals (*Oxford*)
  - New signals from exotic dark matter (*RHUL*)
  - Novel searches for low mass dark matter (*KCL*)
  - Direct detection as neutrino detectors (*KCL, IPPP*)
- **Axions in the sky:**
  - Axion dark matter astronomy (*Nottingham*)
  - Axion mini-clusters in micro-lensing surveys (*KCL*)
  - Novel X-ray signatures (*Oxford*)
- **GAMBIT:** Global fitting package; explore complementarity of searches (*Glasgow, Imperial*)
- **Gravitational waves:** Exotic signals from dark sectors/string theory (*Oxford, IPPP*)
- **Neutrinos:** Dark matter in high-energy neutrino signals (*Imperial, IPPP*)
- **Improved Solar Models:** transporting heat with dark matter (*Imperial*)

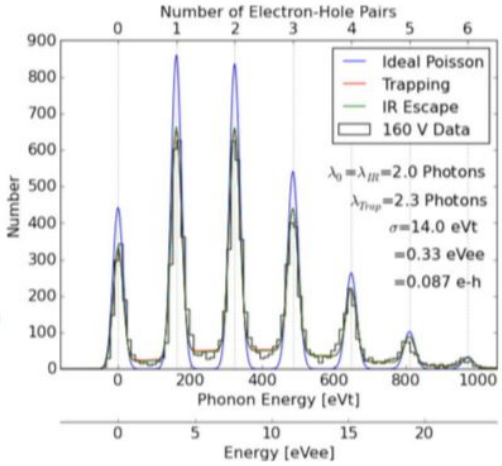
SuperCDMS @ SNOLab (Canada)

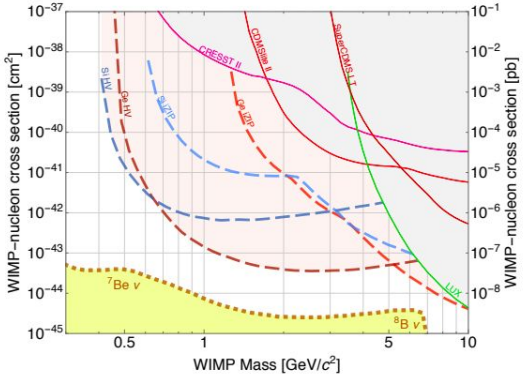
- 1.4 kg Ge and 0.6 kg Si crystals
- Targeting <10 GeV/c^2 mass range
  - *Sensitivity to sub-GeV dark matter*
- Band gap in Ge is 0.7 eV, Si is 1.1 eV
  - *Energy thresholds in tens of eV range*
- Operation at SNOLab from 2020/21



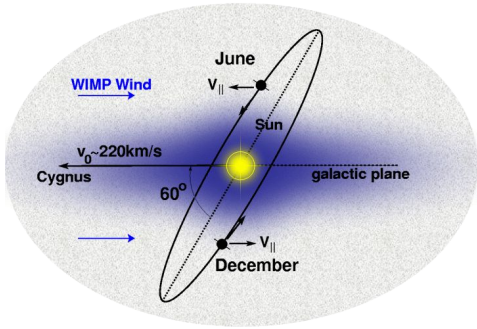




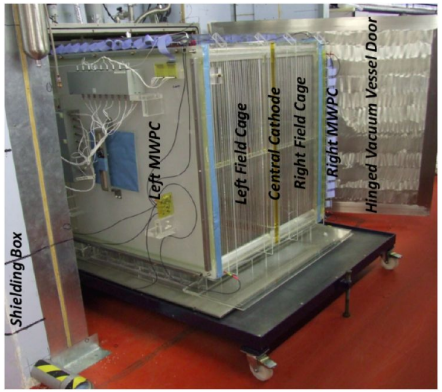


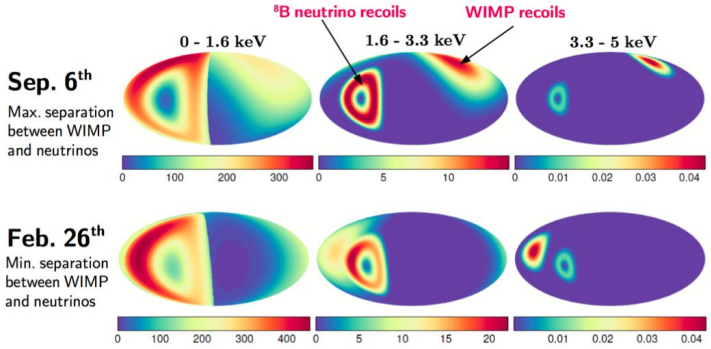


CYGNUS (Directional R&D)

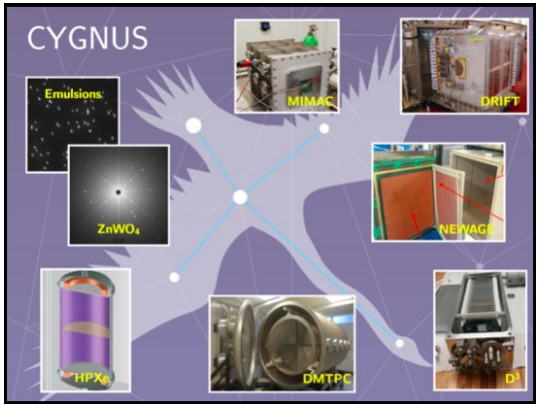


- **DRIFT**: Directionality pioneer based at Boulby
  - *DRIFT-IIe testing large area thick GEM readouts*
- **CYGNUS**: International collaboration of directionality experiments
  - *25 institutes (Australia, China, Italy, Japan, UK, US); UK spokesperson*
  - *Negative ion SF_6+He target with high demonstrated (UK)*
  - *Targeting low-mass WIMP region (~10 keV) with directionality and recoil discrimination*
  - *Distributed network of 10 m^3 (CYGNUS-10) experiments at different latitudes*
  - *New sites at Stawell (Australia), Boulby (UK), Gran Sasso (Italy) for CYGNUS-UNDER 1m^3 test*



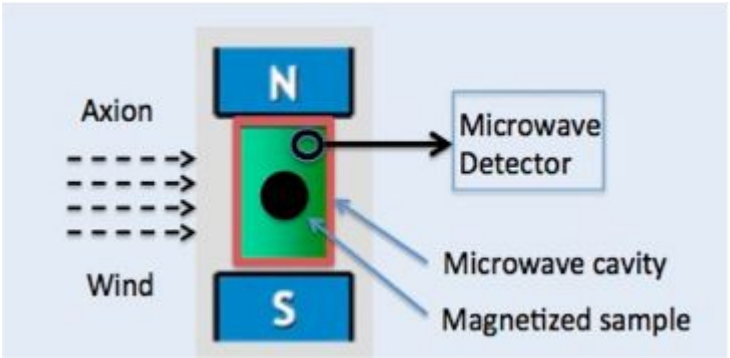


CAJ O'Hare et. al. Phys. Rev. D 92, 063518 (2015)



QUAX (QUest for Axions)

- Motion of solar system in the galaxy means an axion dark matter cloud acts as an effective RF magnetic field on electron spin via electron-axion coupling
- Field excites magnetic transition in a magnetized sample (Larmor frequency)
- Variation of magnetization is in principle measurable
- Volume of magnetized material, strong coupled in a microwave resonant cavity, will absorb energy from the axion wind and re-emit as RF power
- Must control thermal photon background
- R&D in progress (incl. UK)



Niobium Cavity

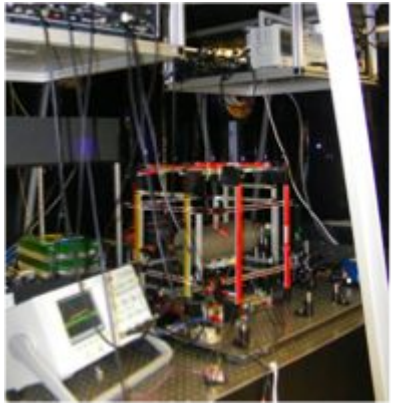
T = 300K
f_c = 13.964 GHz
Q_0 = 5.0*10^3

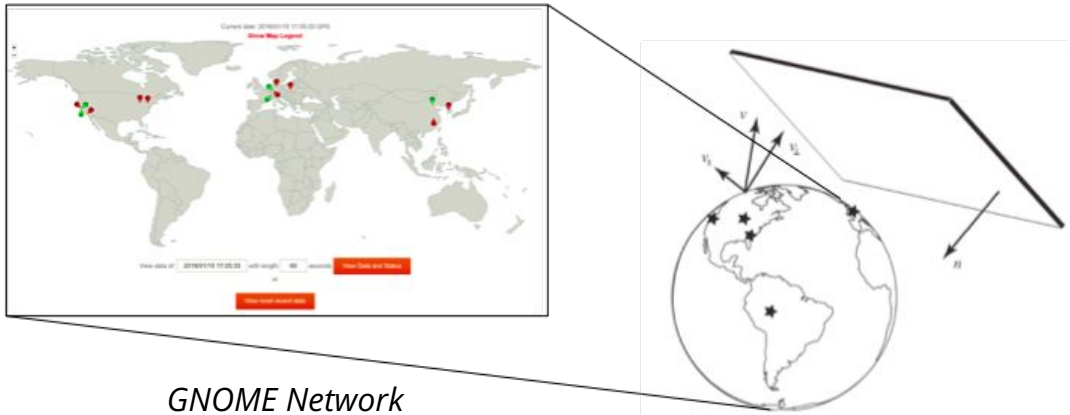
T = 4.2K
f_c = 13.960 GHz
Q_0 = 5.0*10^5

Phys. Dark Univ. ***15,*** *135 - 141 (2017)*

GNOME Network

- Optically Pumped Magnetometers (OPM): used to measure coupling between atomic spin and transient events of axion-like fields
  - *...like the crossing of domain walls*
- Coincident measurements between two or more instruments around the globe to reject false positives
- Impinging direction from triangulation if many instruments
- UK OPM (Birmingham) already operational





GNOME Network (USA+EU+China)

Axion domain wall detection