Status and Main Challenges for Detectors for (Astronomy and) Astrophysics

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outline

Intro: incomplete overview of
physics topics and experiments

Examples (too many - will skip some)

Concluding remarks

incomplete overview

Physics topics	Experiments
Cosmic rays	AUGER, KASKADE-G , ARGO, ► LHAASO
γ-rays	Fermi, Integral, H.E.S.S., MAGIC, VERITAS, ►CTA, HAWC
X-rays	Chandra, XMM Newton, ►X-Calibur, ATHENA+
LE neutrinos	LVD, KAMLAND, BOREXINO, XMASS
HE neutrinos	NT-200, IceCube, ANTARES, ►KM3NeT, PINGU,…
[Neutrino mass	►KATRIN]
0ν2β decay	EXO, GERDA, KamLAND-Zen, ►CUORE, NEXT,SNO+,.
Dark matter	CDMS, CRESST, EDELWEISS, XENON, XMASS,…
Dark/anti matter	AMS-02, INTEGRAL, Pamela . ►EURECA
[Axions	CAST, ►ALPS-II]
Rare processes	Super-Kamkiokande, (►LAGUNA with LENA, GLACIER,
p decay, ν CPV	MEMPHYS)
[Gravitational waves	GEO-600, LIGO, E.T., LISA-pathfinder, ►eLisa]
[...] not discussed	'►' : in preparation, or projects

incomplete overview

Physics topics	**Experiments - in space**
Cosmic rays	AUGER, KASKADE-G , ARGO, ► LHAASO
γ-rays	Fermi, Integral, H.E.S.S., MAGIC, VERITAS, ►CTA, HAWC
X-rays	Chandra, XMM Newton, ►X-Calibur, ATHENA+
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[Gravitational waves	GEO-600, LIGO, E.T., LISA-pathfinder, ►eLisa]

►Specific challenges: size, weight, reliability,

Physics topics	**Experiments - underground**
Cosmic rays	AUGER, KASKADE-G , ARGO, ► LHAASO
γ-rays	Fermi, Integral, H.E.S.S., MAGIC, VERITAS, ►CTA, HAWC
X-rays	Chandra, XMM Newton, ►X-Calibur, ATHENA+
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[Neutrino mass	►KATRIN]
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Dark matter	CDMS, CRESST, EDELWEISS, XENON, XMASS,…
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p decay, ν CPV	MEMPHYS)
[Gravitational waves	GEO-600, LIGO, E.T., LISA-pathfinder, ►eLisa]

►Specific challenges: radio-purity of components, shielding of backgrounds

incomplete overview

Physics topics	Experiments - in deep-sea / ice
Cosmic rays	AUGER, KASKADE-G , ARGO, ► LHAASO
γ-rays	Fermi, Integral, H.E.S.S., MAGIC, VERITAS, ►CTA, HAWC
X-rays	Chandra, XMM Newton, ►X-Calibur, ATHENA+
LE neutrinos	LVD, KAMLAND, BOREXINO, XMASS
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[Neutrino mass	►KATRIN]
0v2β decay	EXO, GERDA, KamLAND-Zen, ►CUORE, NEXT,SNO+,.
Dark matter	CDMS, CRESST, EDELWEISS, XENON, XMASS,…
Dark/anti matter	AMS-02, INTEGRAL, Pamela . ►EURECA
[Axions	CAST, ►ALPS-II]
Rare processes p decay, ν CPV	Super-Kamkiokande, (►LAGUNA with LENA, GLACIER, MEMPHYS)
[Gravitational waves	GEO-600, LIGO, E.T., LISA-pathfinder, ►eLisa]

►Specific challenges: hostile environment (sea water, high pressure), logistics,…

another overview

Some generic detectors & specific devices

light detectors

advanced PMTs
large-area single-photon silicon-based sensors
bolometers

X-ray detectors

pixelated detectors for applications in space & balloons

particle trackers

large-area precision (silicon) trackers
very large area, low cost particle detection

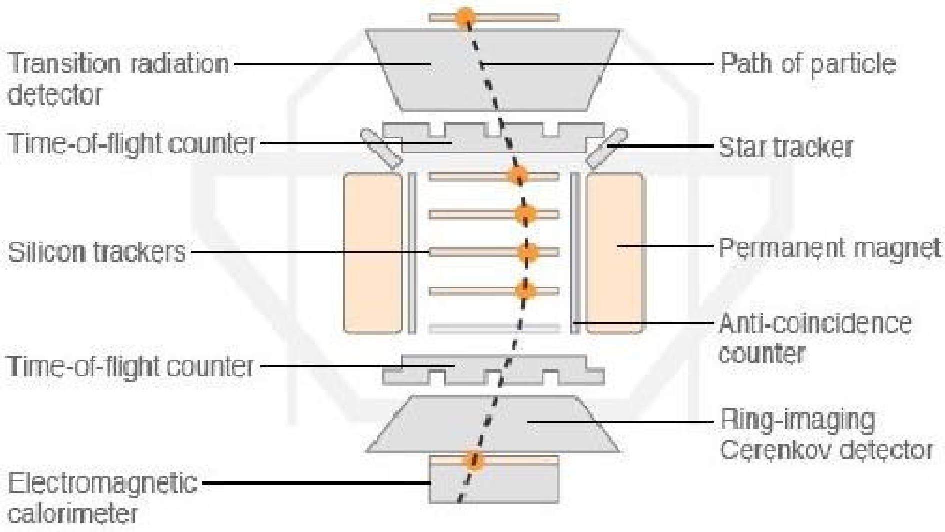
calorimeters

γ-ray / electron detection with Ge diodes enriched in Ge-76
direct dark matter detection with bolometers

combinations of all kinds including ‘particle physics detector’ in space

‘A Particle Physics Detector in Space’

THE ALPHA MAGNETIC SPECTROMETER (AMS-02) - **since May 20111 on ISS**



Source: CERN

Transition Radiation Detector determines highest-energy particle velocities

Silicon Trackers follow particle paths; how they bend reveals their charge

Permanent Magnet is core component of AMS and makes particles curve

Time-of-flight Counters determine lowest-energy particle velocities

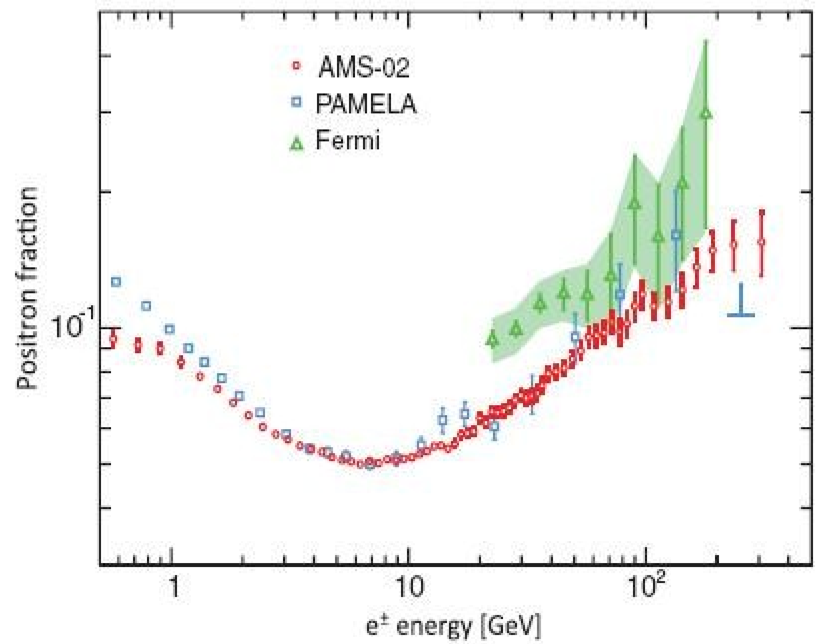
Star Trackers scan star fields to establish AMS's orientation in space

Cerenkov Detector makes accurate velocity measurements of fast particles

Electromagnetic Calorimeter measures energy of impacting particles

Anti-coincidence Counter filters signal from unwanted side particles

Excellent performance (0.5-350 GeV)



'...showing the existence of new physical phenomena.'

PRL 110 (2013) 141102

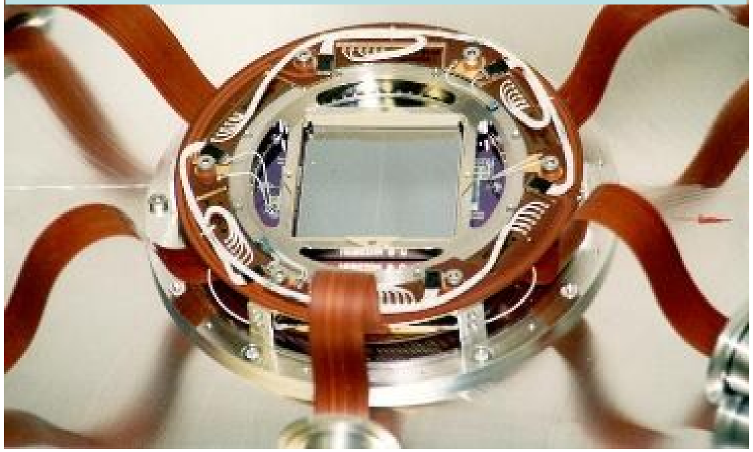
►challenges: e.g.
superconducting magnets (aband.)
huge cost increase

X-Rays, Gamma-Rays, Cosmic Rays

ESA's Eur. Photon Imaging Cameras (EPIC) in XMM Newton spacecraft 1999 - 2014

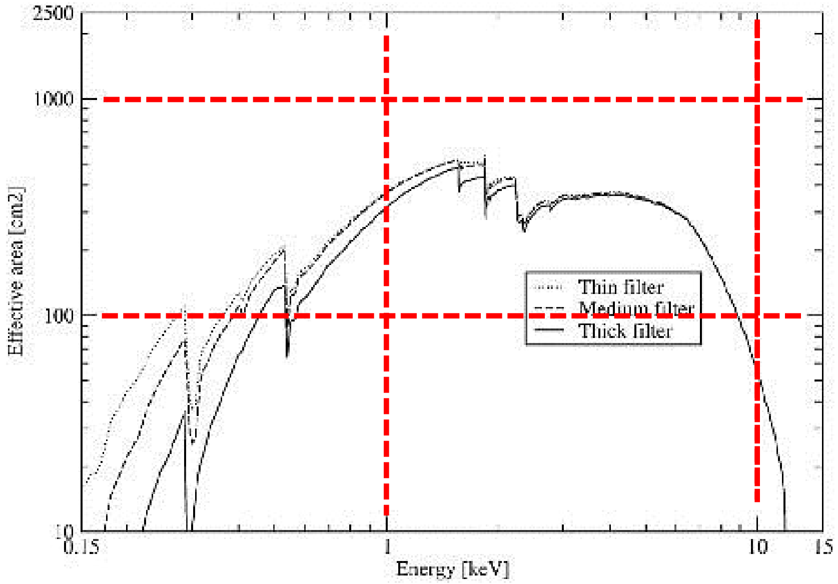
Seven 2.5x2.5 cm MOS CCDs, 40 µm pxls

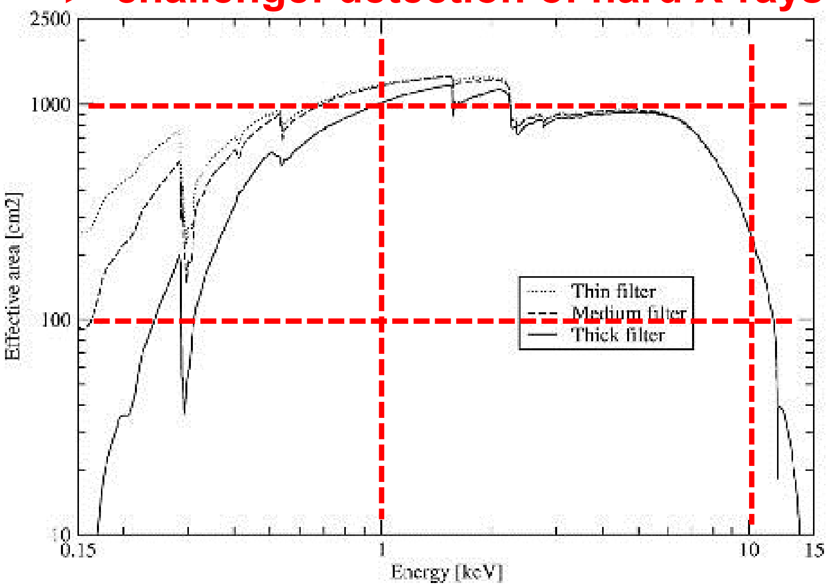
Twelve 3x1cm pn CCDs,150 µm pixels



► challenge: detection of hard X-rays

effective area – reflects QE

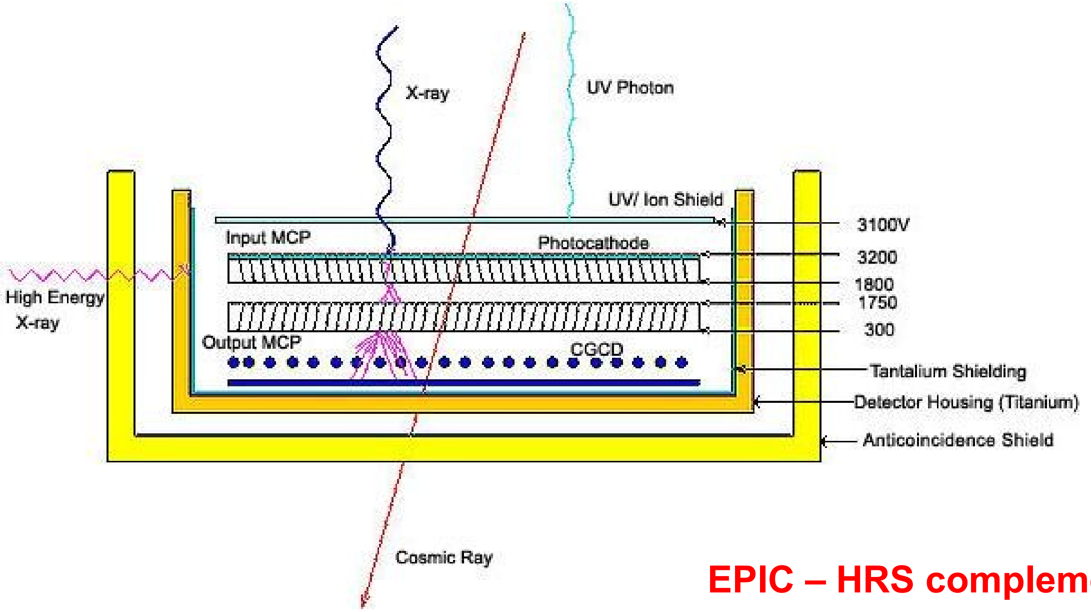




Mirror systems, e.g. SPO, not discussed!

follow-up project for late 2020s: **ATHENA+** ►www.the-athena-x-ray-observatory.eu

NASA's High Resolution Camera (HRS) in Chandra 1999 -



10x10 cm Micro Channel Plates with 69 millions PbO_2 glass tubes of 1.2 mm length and Ø10 µm;
electrons detected in CGCD wire chamber (crossed grid charge detector) .

EPIC – HRS complementary: resolution ↔ eff. area

Table 22: *Comparison of* ***XMM-Newton*** *with other X-ray satellites* 1)

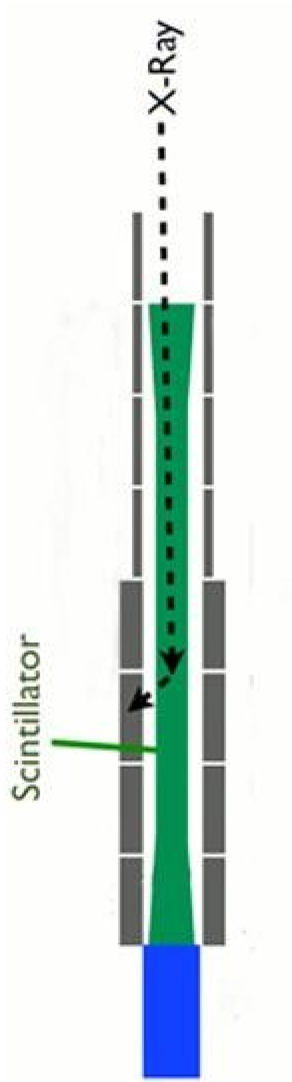
Satellite	Mirror PSF *FWHM* [″]	Mirror PSF *HEW* [″]	E range [keV]	A_e at 1 keV [cm^2]^a	Orbital target visibility [hr]
XMM-Newton	6	15	0.15 - 15	4650^b	40^c
Chandra	0.2	0.5	0.1 - 10	800	50
ROSAT	3.5	7	0.1 - 2.4	400	1.3^d
ASCA	73	174	0.5 - 10	350	0.9^d

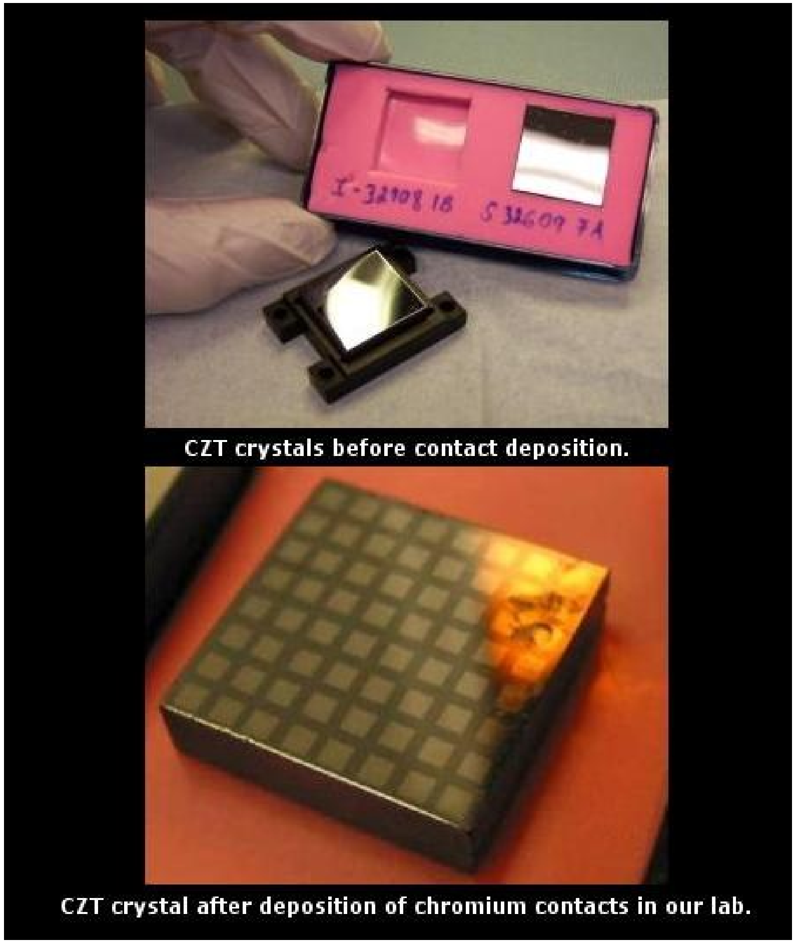
1) xmm.esac.esa.int/external/xmm_user_support/documentation/uhb_2.1/node87.html

x-ray detectors for space

R&D for hard x-ray polarimeter, 10 – 80 keV using Cd -Zn-Telluride pixel detector

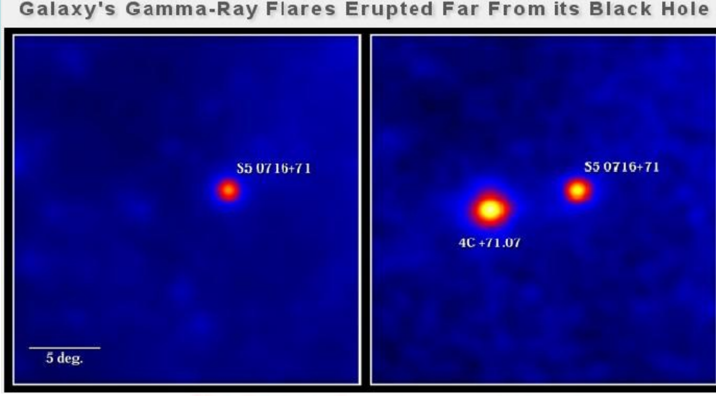
Inside X-Calibur





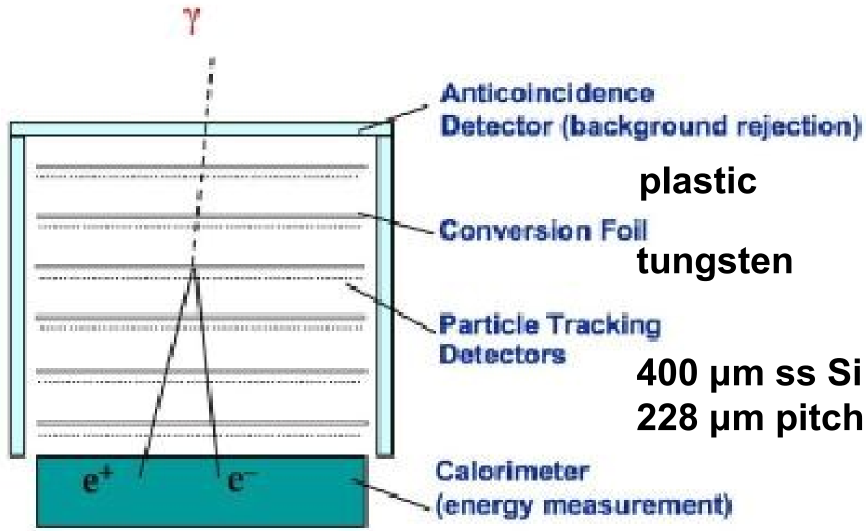
arxiv.org/abs/1101.0595
physics.wustl.edu/x-ray/

γ-ray detector for space



Fermi / LAT large area telescope
20 MeV – 300 GeV 2008 – 2018 (2013)
primary instrument on Fermi γ-ray space telescope

Principle: pair spectrometer

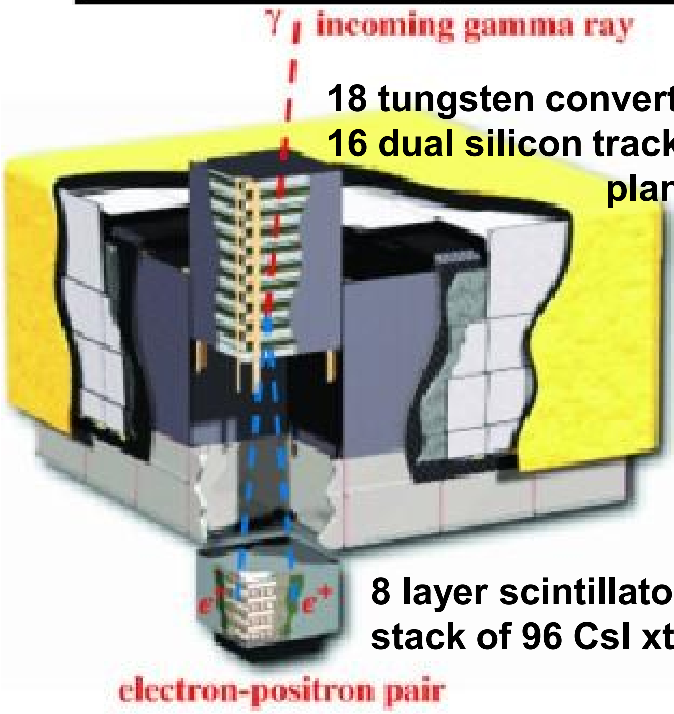


plastic

tungsten

400 µm ss Si strip det
228 µm pitch

CsI calorimeter



18 tungsten converters
16 dual silicon tracker planes

8 layer scintillator stack of 96 CsI xtals

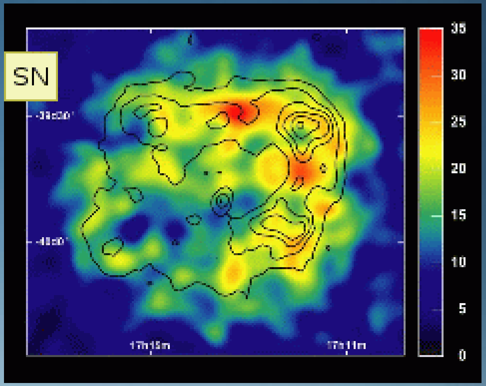
16 towers
37 x 37 x 66 cm

- ► FoV: 60% FoV
- ► PSF: 3% / 0.04% at 10 MeV / 10 GeV

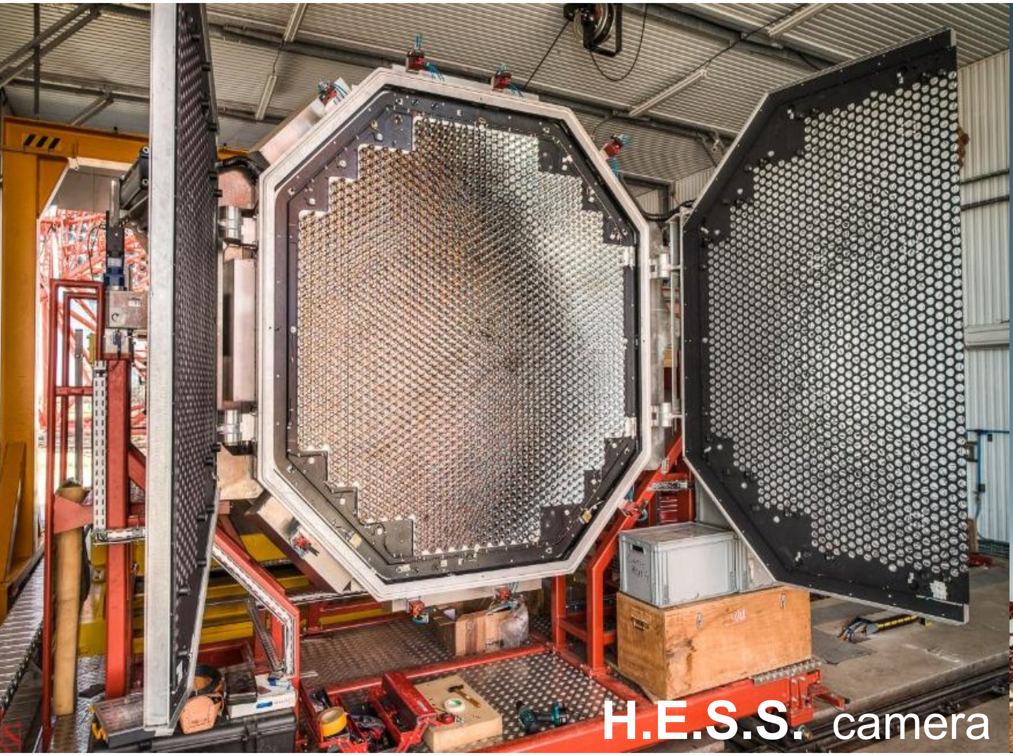
H.E.S.S. high energy stereoscopic system

γ-ray astronomy from 10s GeV to 10s TeV

H.E.S.S.	II	I
Focal length	36	15 m
FoV	3.2°	5.0° on the sky
pixel size	42	42 mm
weight	580	60 tons



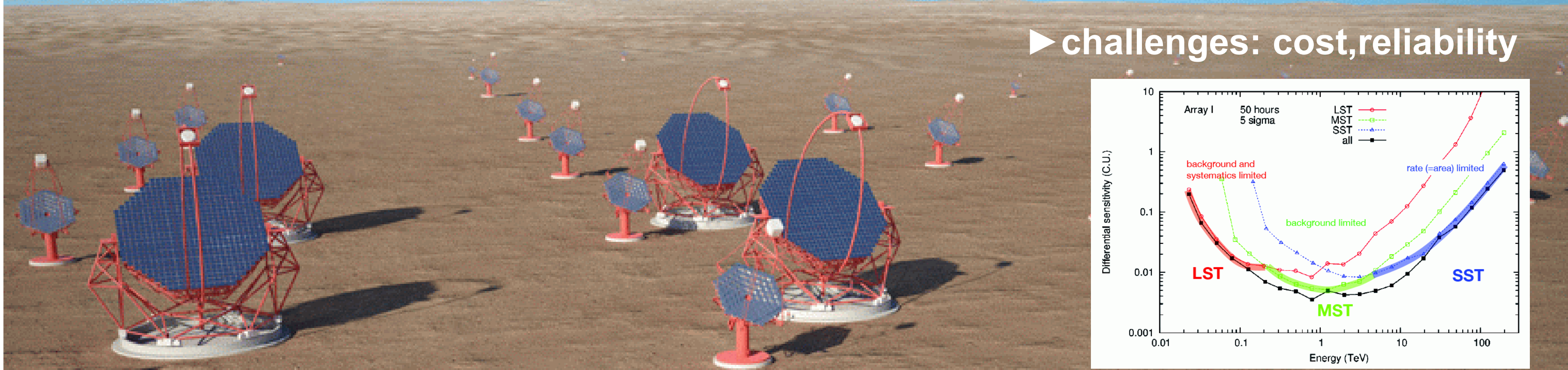
imaging atmospheric Cherenkov telescope



H.E.S.S. camera		II	I
photo sensors, # of1.25”PMT		2048	960
sensitive area	[m Ø]	2.0	1.3
signal recording	[GHz]	1	1
exposure time	[ns]	16	16
Image rec. rate	[1/s]	3600	300
power	[kW]	8	5
weight	[ton]	~3	~1
size, WxHxD	[m]	2.2x2.4x1.8	1.6x1.6x1.5

imaging atmospheric Cherenkov telescope – next generation

CTA Cherenkov Telescope Array - γ-ray observatory ; construction 2014 -

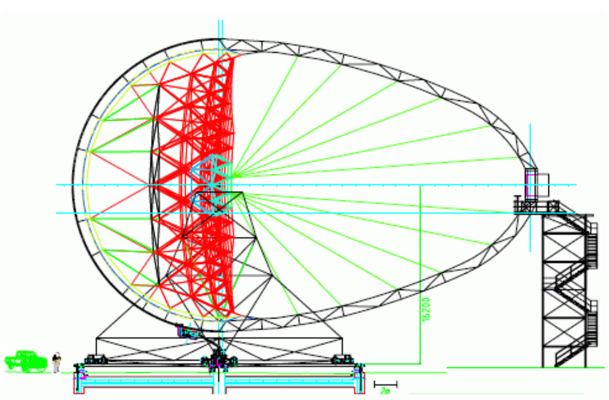


~100 (S) / 20 (N) telescopes for ●10-fold sensitivity at TeV energie ●10-fold effective energy coverage
● larger FoV ● improved angular resolution ● full sky coverage

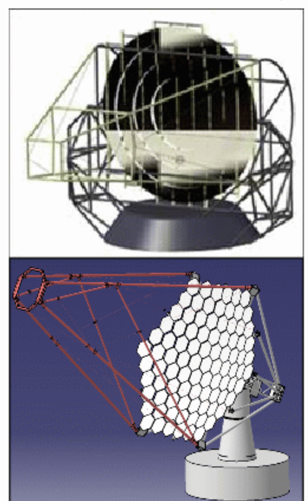
LST 4x (S) : 20 GeV - 1 TeV
>330m^2, >4.4° FoV, <0.11° pxl size

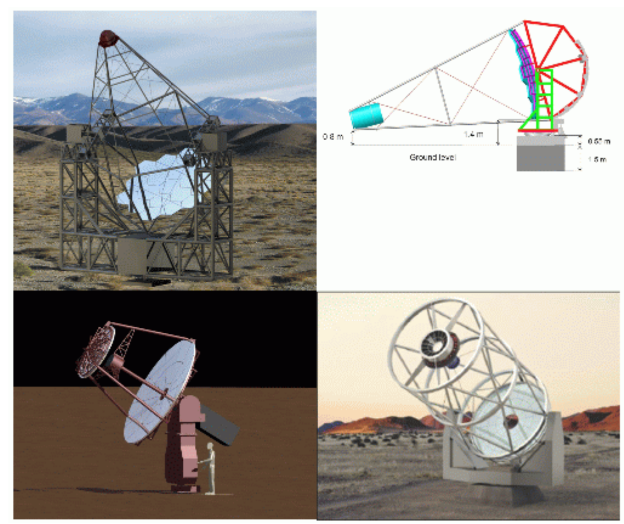
MST 25x (S) : 0.2-10 TeV
>88 m^2, >7° FoV, <0.18° pxl

SST 70x (S) : > few TeV
>5 m^2, >8° FoV, <0.25° pxl

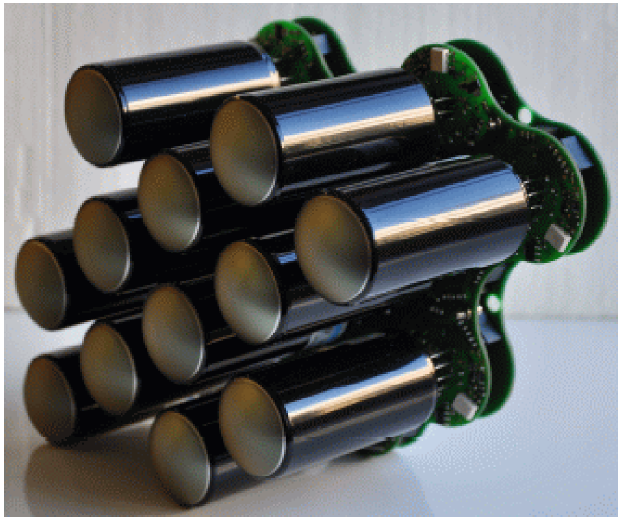


'MAGIC'-like





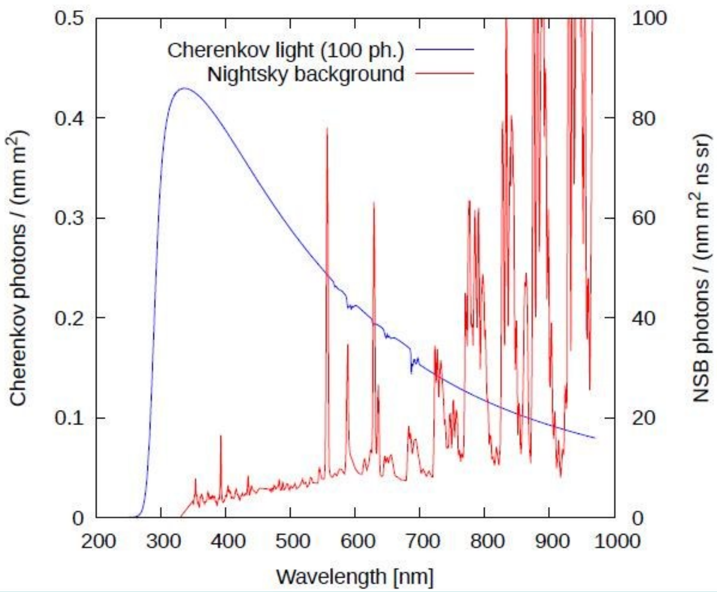
12 pixel PDP module with R11920 1.5 inch PMTs for MST



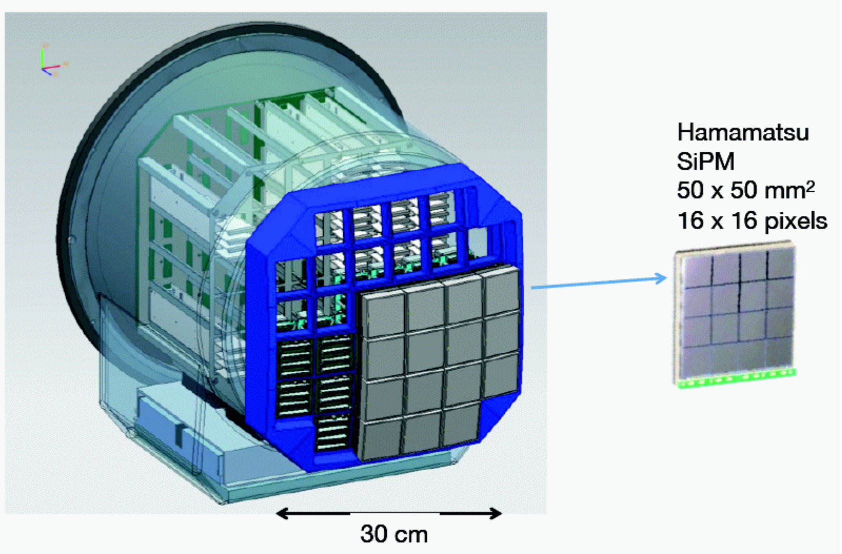
'FlashCam' – fully digital : arXiv: 1211.3684v1

separation of photon-detector-plane (PDP) with HV supply, preamps, and control logic from RO electronics (digitization, trigger boards)
► challenge: ?

performance optimized PMT: R11920-100-01
(fast time response, CC window, Super Bialkali photocathode)
► challenge: cost



Design with SiPM (up to 45% PDE)
compact, low mass
► challenges: pixel size, red (in)sensitivity, cost



imaging atmospheric Cherenkov telescope - camera options

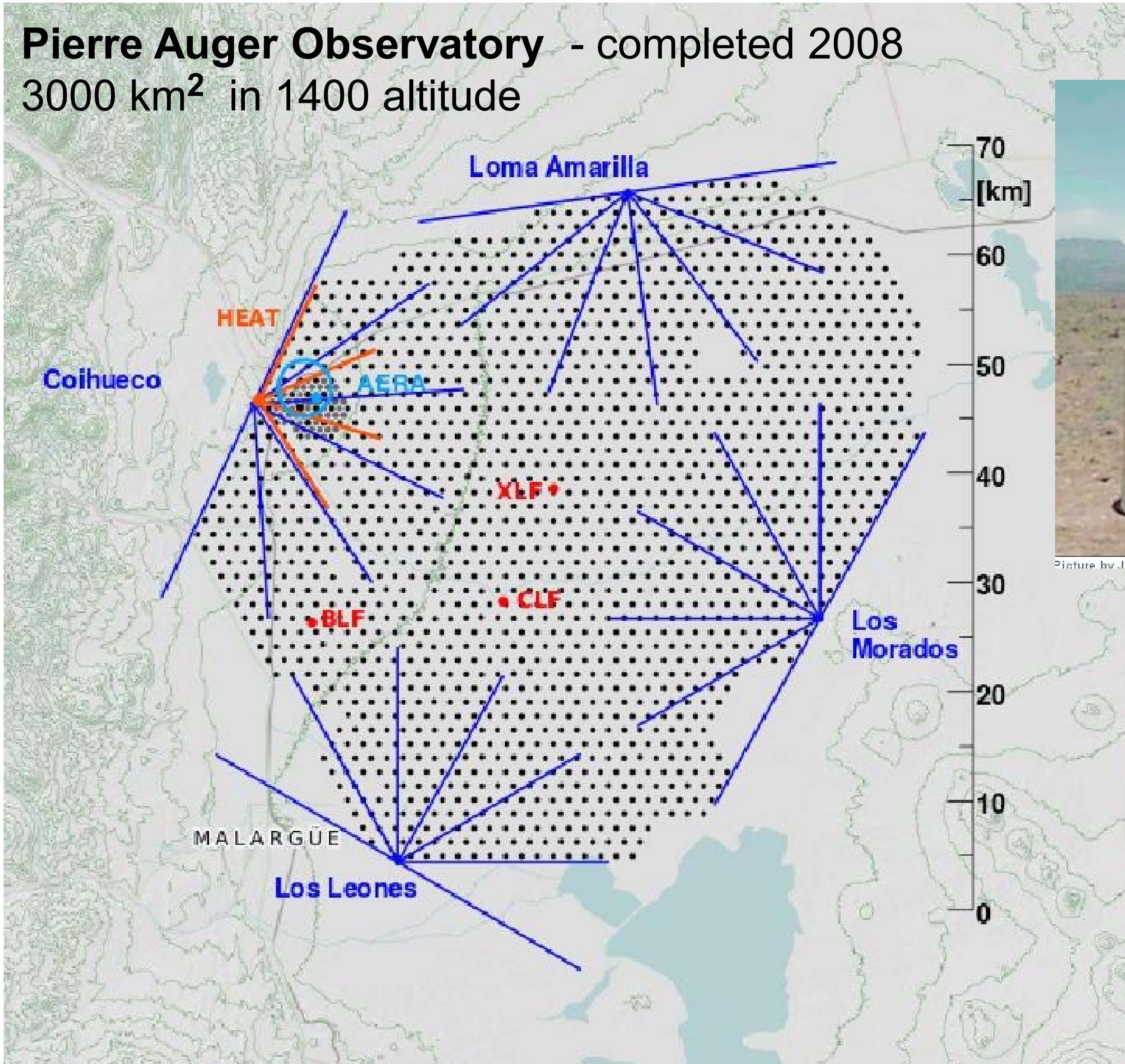
FACT taking first data on 11 October during the full moon.
Image credits: FACT/Th. Krähenbühl.

1440 pixels
4.5 deg FOV
reduced aging

►challenges:
increase of size, cost

A single G-APD, only 2.8 × 2.8 mm^2, glued to its light concentrator.

Pierre Auger Observatory - completed 2008
3000 km^2 in 1400 altitude

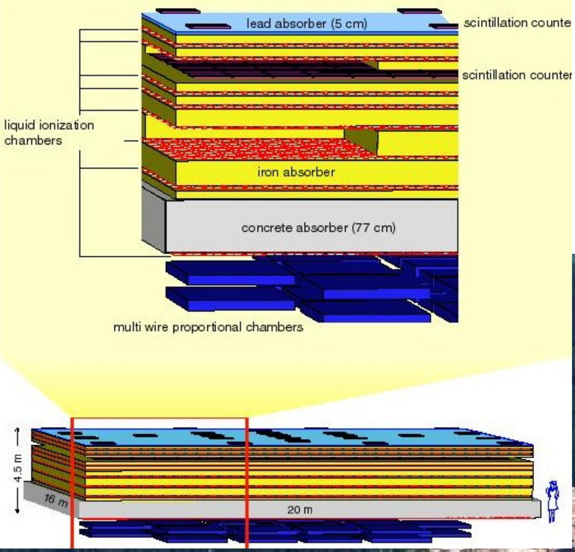


1600 water Cherenkov detectors at 1500m spacing,

4 atmospheric fluorescence detectors,

various upgrades

extensive air shower (10^{16} -10^{18} eV) experiment

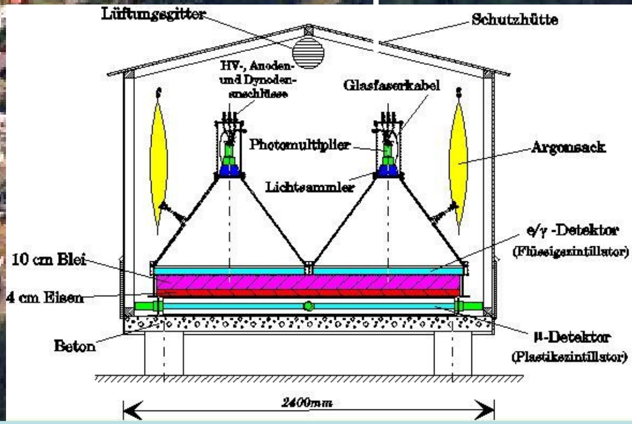


KASCADE-Grande at 110 m altitude, 1996 - 2009

200x200 m^2 scintillator array

20x16 m^2 finely segmented hadron calorimeter

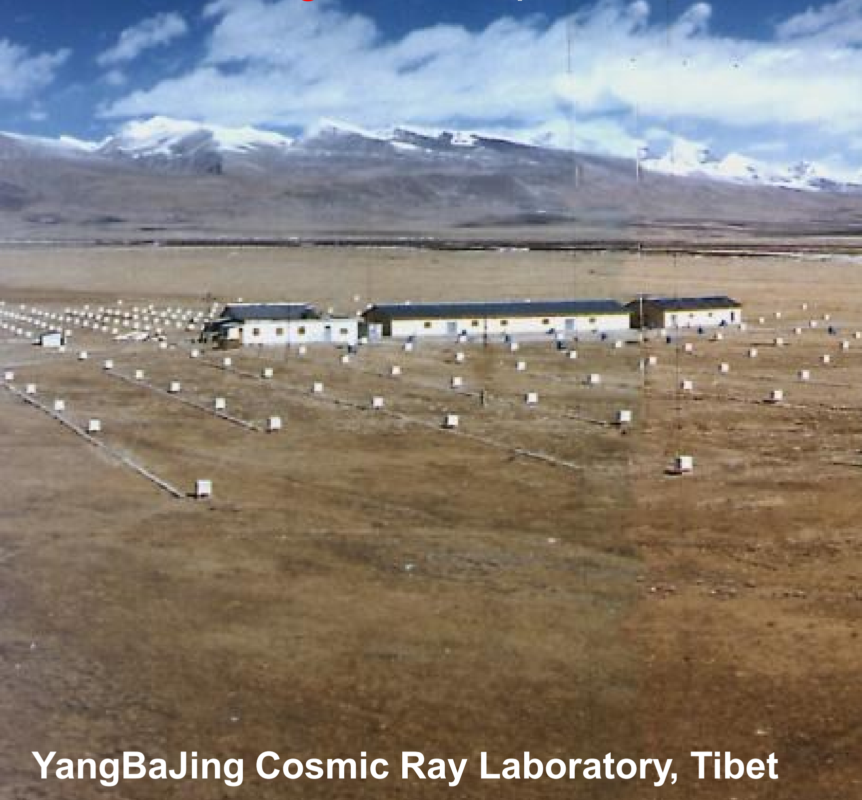
128 m^2 muon trackers with streamer tubes

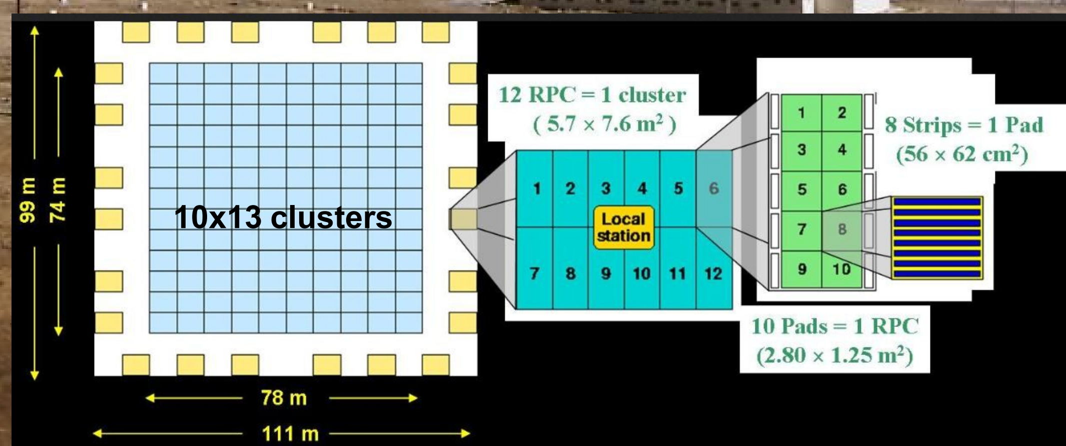


cosmic ray telescope

ARGO-YBJ experiment at 4300 m altitude, 2007 –
- γ-ray astronomy with threshold of a few 100 GeV
- cosmic ray physics in 10 – 1000 TeV range

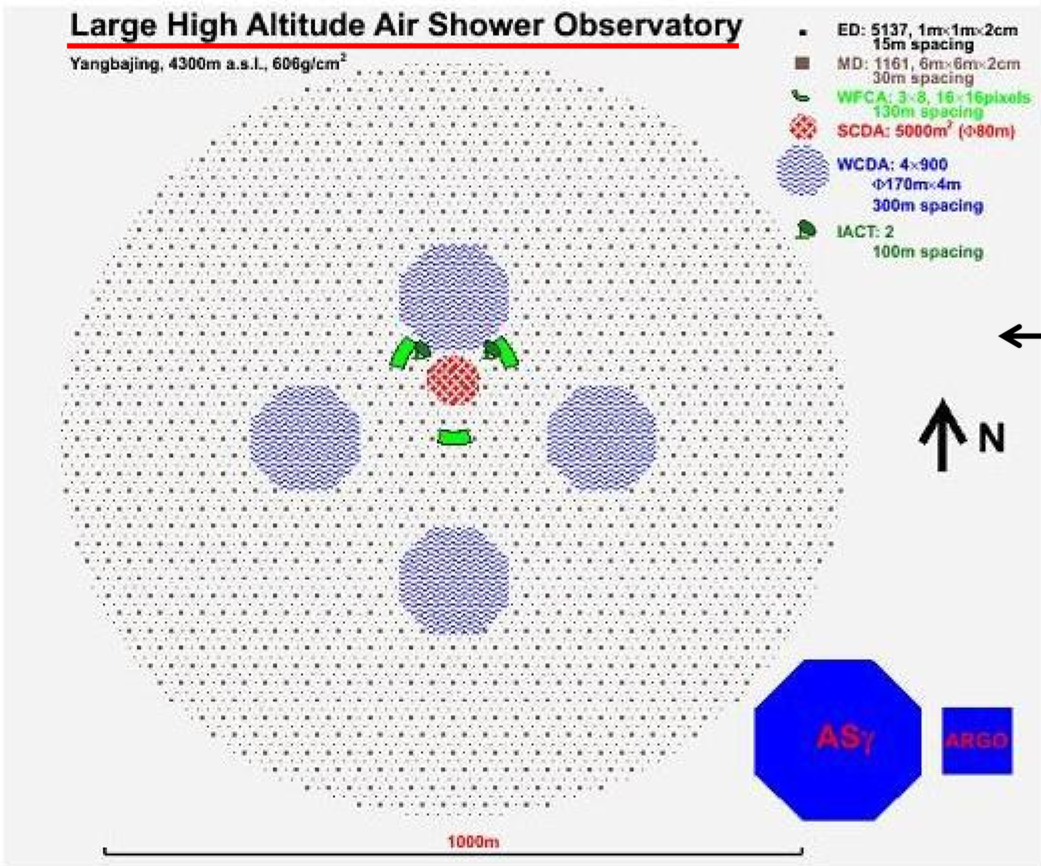
11000 m^2 array of single layer RPCs in streamer mode,
93% active area in central carpet of 5800 m^2
► challenge: cost, spatial resolution





YangBaJing Cosmic Ray Laboratory, Tibet

follow-up project **LHAASO** - http://english.ihep.cas.cn/ic/ip/LHAASO/

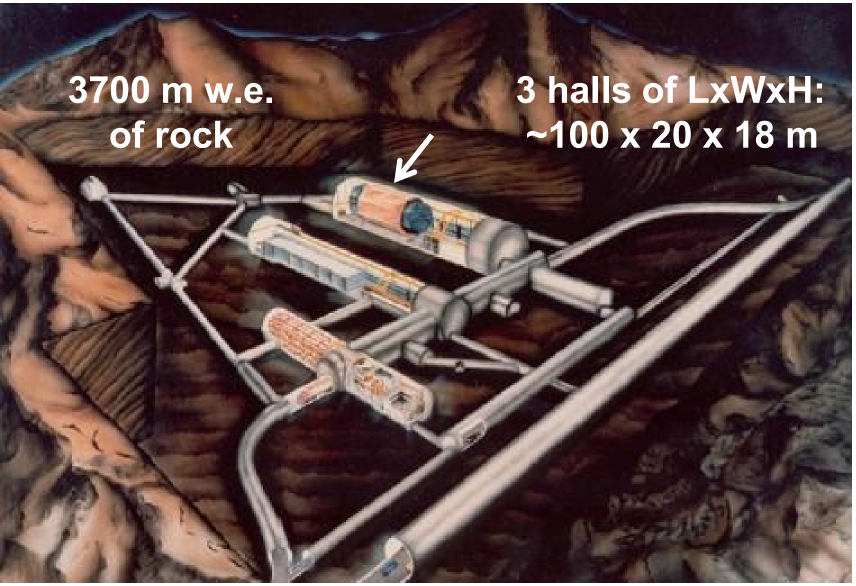


<u>3 major components</u>:

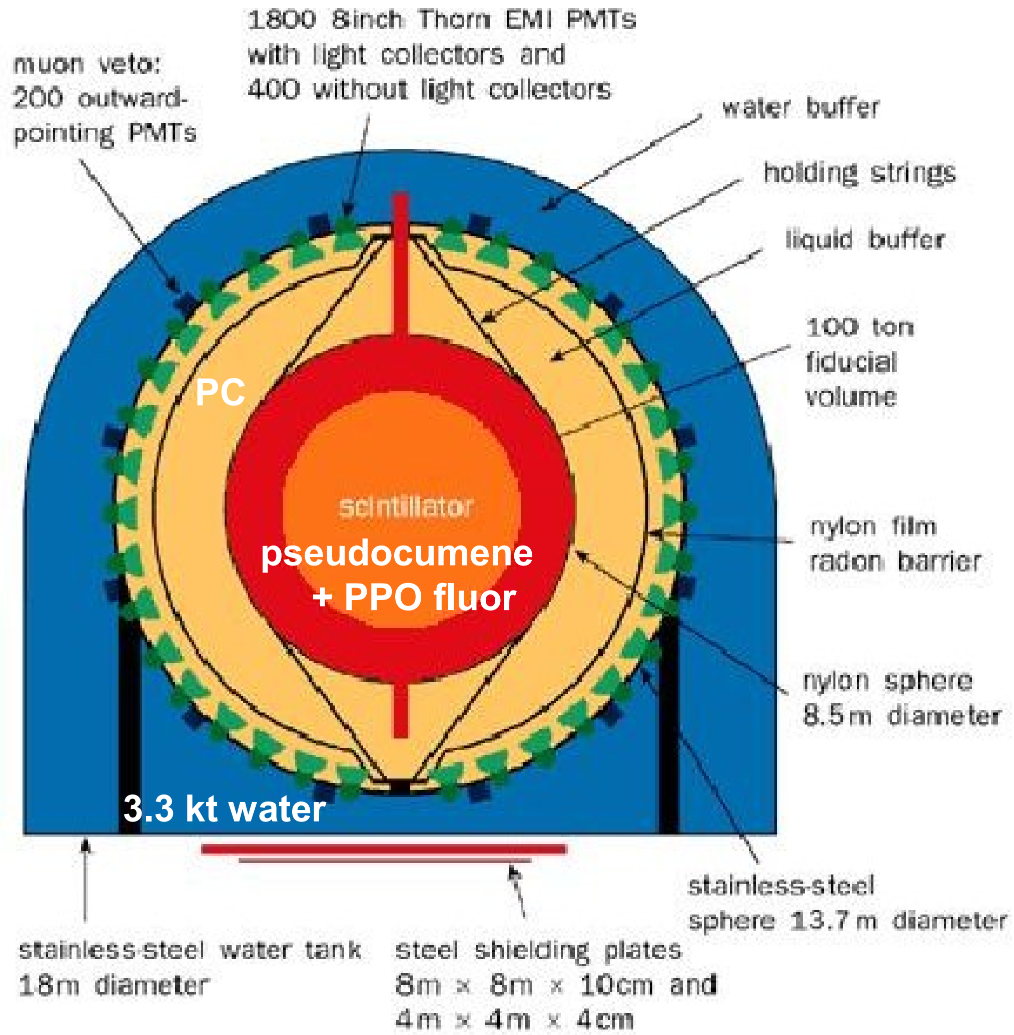
- **30 km^2 water Cherenkov array for E_γ>100 GeV**
- **1 km^2 complex array E_γ>30GeV incl. 5000 scintillators, 4800 muon detectors, ….**
- **CR detector array for >30TeV incl. 24 air fluorescence det.**

Low Energy Neutrino Experiment

BOREXINO at INFN Gran Sasso underground national laboratory (LNGS), Italy



neutrinos detected by elastic scattering on electrons

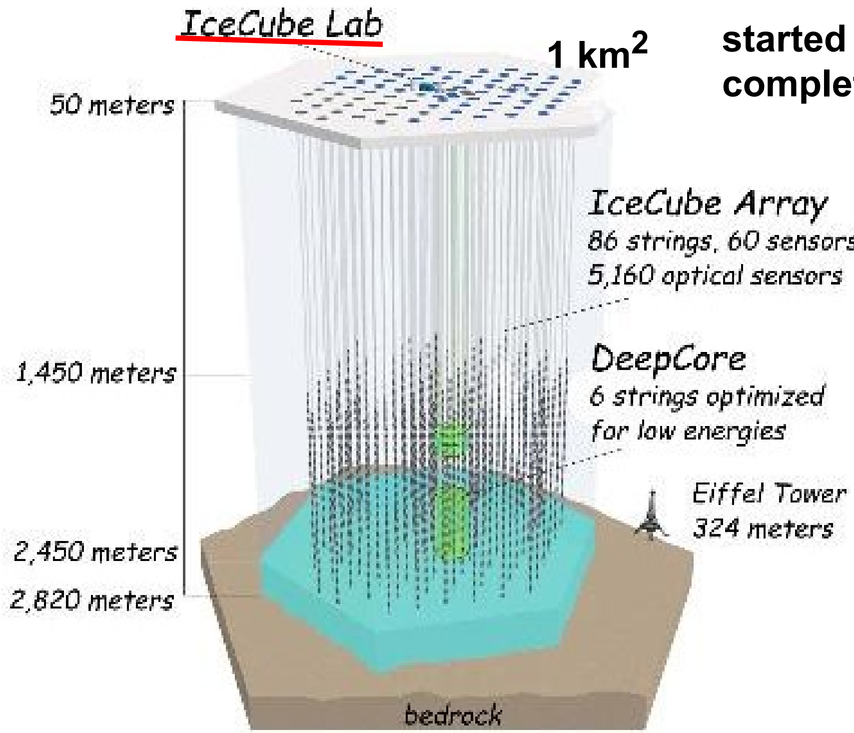


► **250 keV detection threshold**

2007 first on-line detection of Be7 solar neutrinos
2010 observation of geo-neutrinos
2011 precision meas. of Be-7 solar neutrino flux
2012 meas. of CNGS muon neutrino speed

► **challenge**
extreme radiopurity of detector
e.g. 10^{-16} g/g U-238 on ton scale

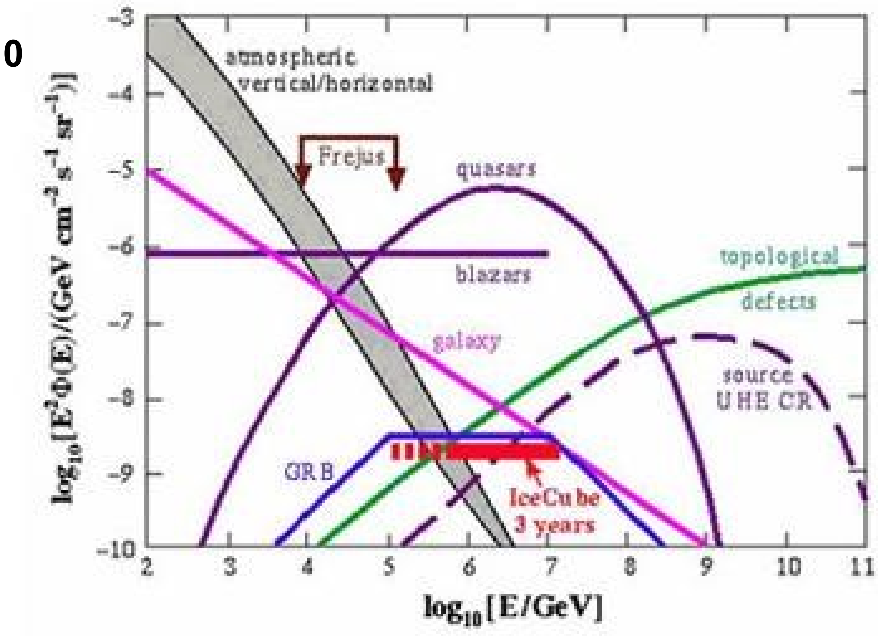
High Energy Neutrino Experiments



The IceCube neutrino observatory is designed so that 5,160 optical sensors view a cubic kilometer of clear South Polar ice.

1 km^2

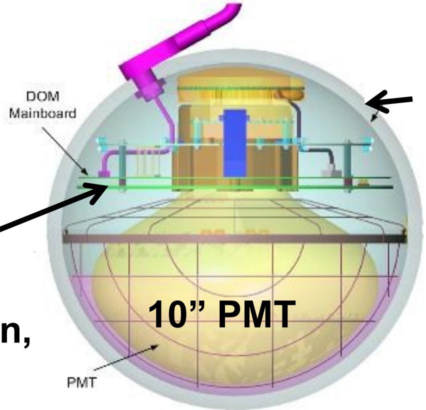
started 2004
completed 2010



Diffuse Neutrino Flux vs. Energy for various models of sources contributing to the diffuse background. The horizontal line in red indicates IceCube sensitivity after three years.

DOM 3.5 Watt
digital optical module
~5160 pcs

electronics for PMT operation & control, amplification, digitization, filtering, and calibration



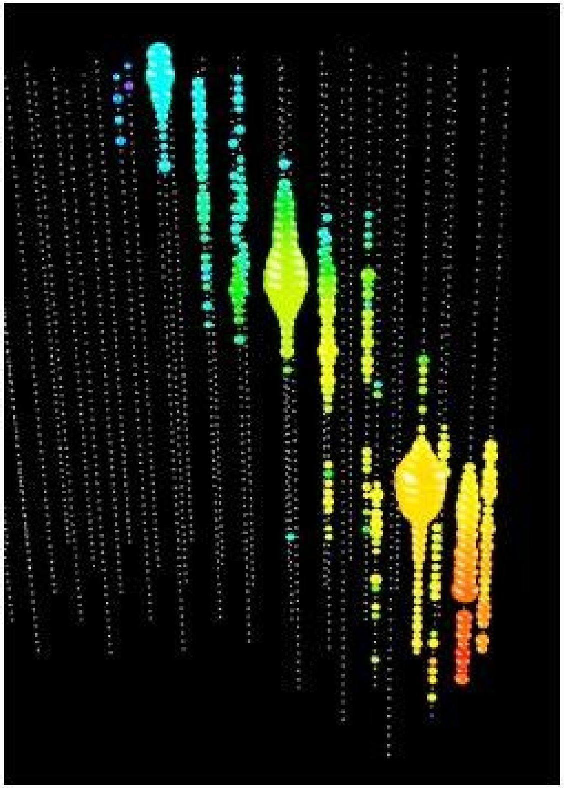
pressure-resistant glass shell

NB: QE and noise ~30% higher at -40 °C!

Also R&D on acoustic and radio detectors

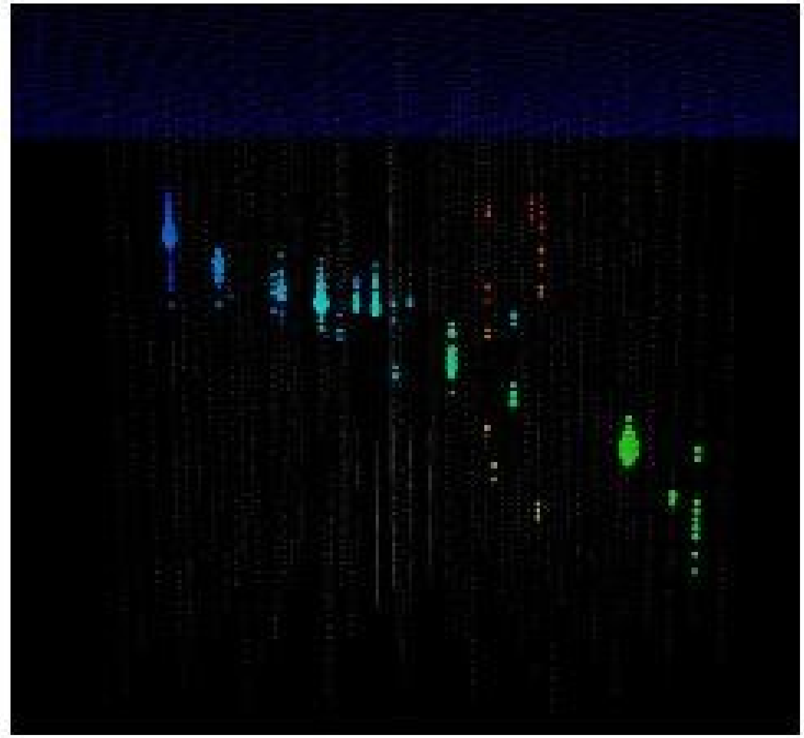
Icecube

simulated



A simulated track of a high-energy neutrino moving upward through IceCube. The circles represent DOMs, and their size represents the amount of light they detect from Cherenkov radiation. Warmer colors are earlier detections. (Click on image for best

real event

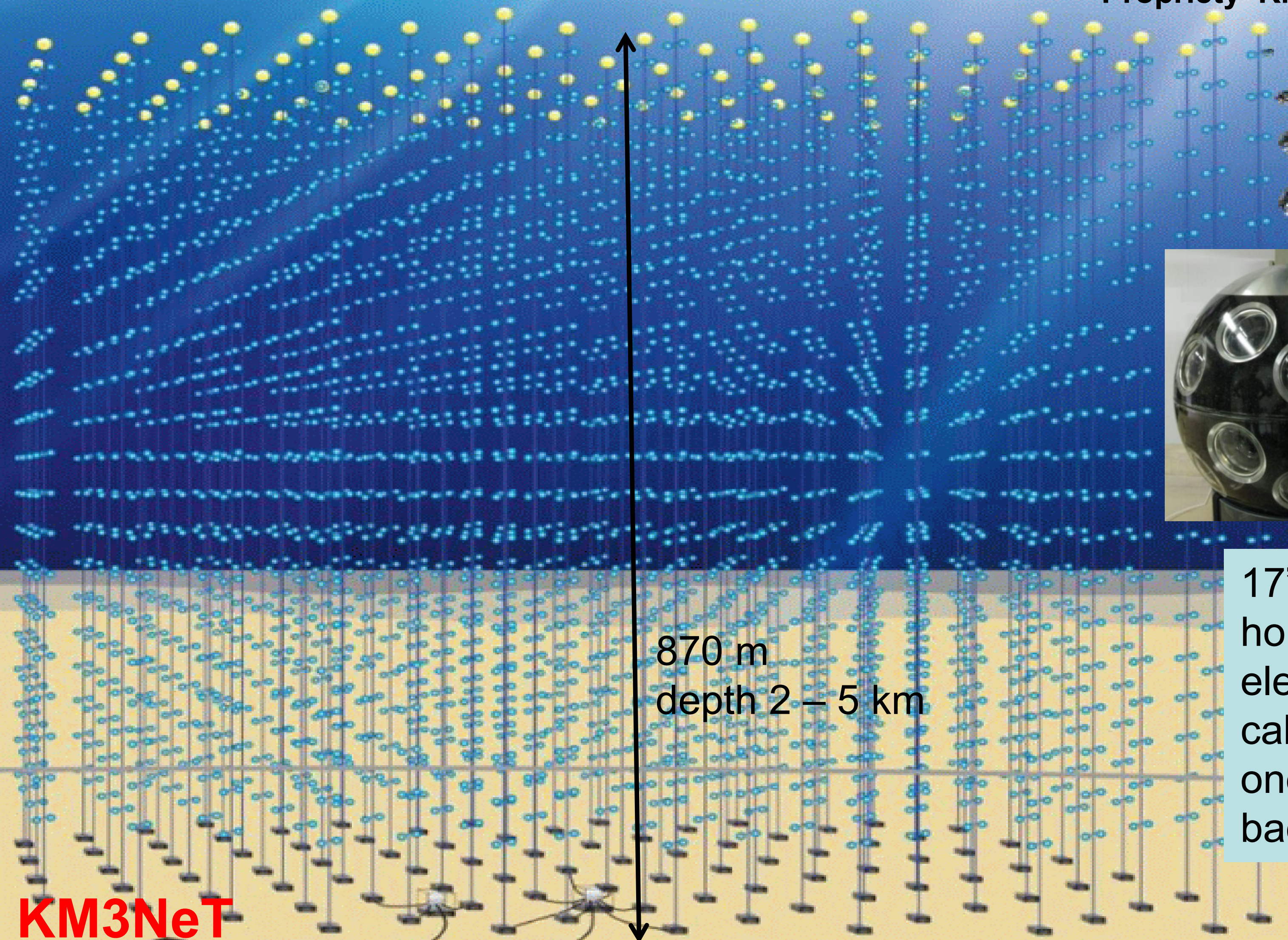


A recent IceCube event visualization seen with all 86 strings running. Photo by: L. Braun/NSF

neutrino deep-sea observatory (water Cherenkov detector)

also for earth and marine science

Propriety KM3NeT Collaboration



20 DOMs/string
1860 strings

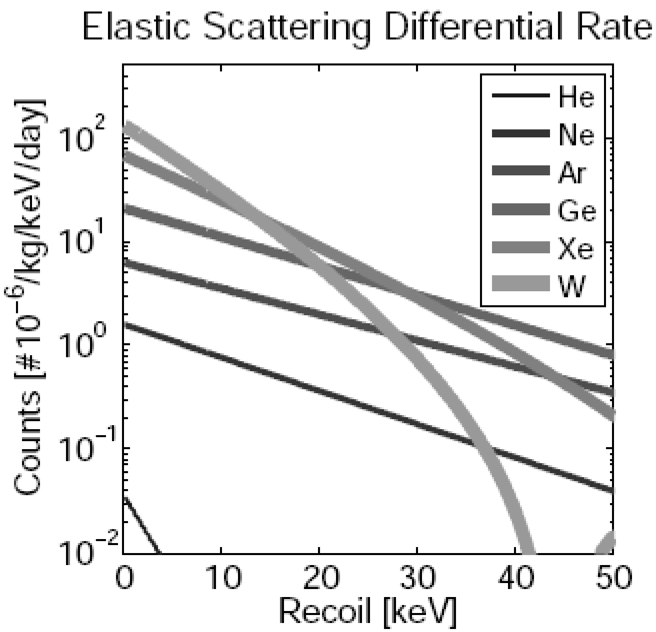
17” glass sphere housing 31 3” PMTs, electronics and calibration devices; one penetrator to back-bone cable

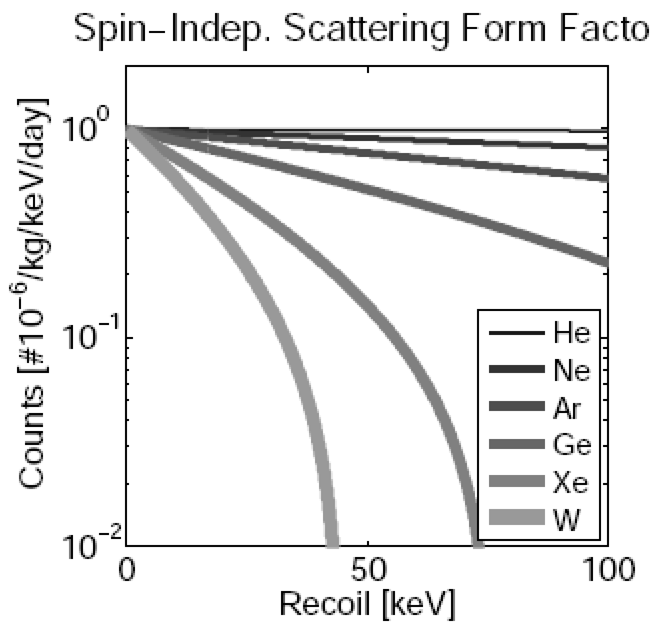
KM3NeT

multi-km^3 sized ν telescope, technology pioneered by ANTARES, under review by EC

Dark Matter Experiments

Challenges





► low detection threshold

Sensitivity S_{90}, i.e. upper limit of interaction cross section at 90% CL):

no background

$$S_{90} = \frac{2.3}{\alpha MT}$$

with background

$$S_{90} \propto \frac{N_{bkg} + 1.28\sqrt{N_{bkg}}}{\alpha MT} \longrightarrow \frac{B}{\alpha} + \frac{1.28}{\alpha}\sqrt{\frac{\beta B}{MT}}$$

► large exposure MT i.e. large mass M, low background rate N_{bkg}

T. Saab, arXiv:1203.2566v1

dark matter: direct detection by nuclear recoil

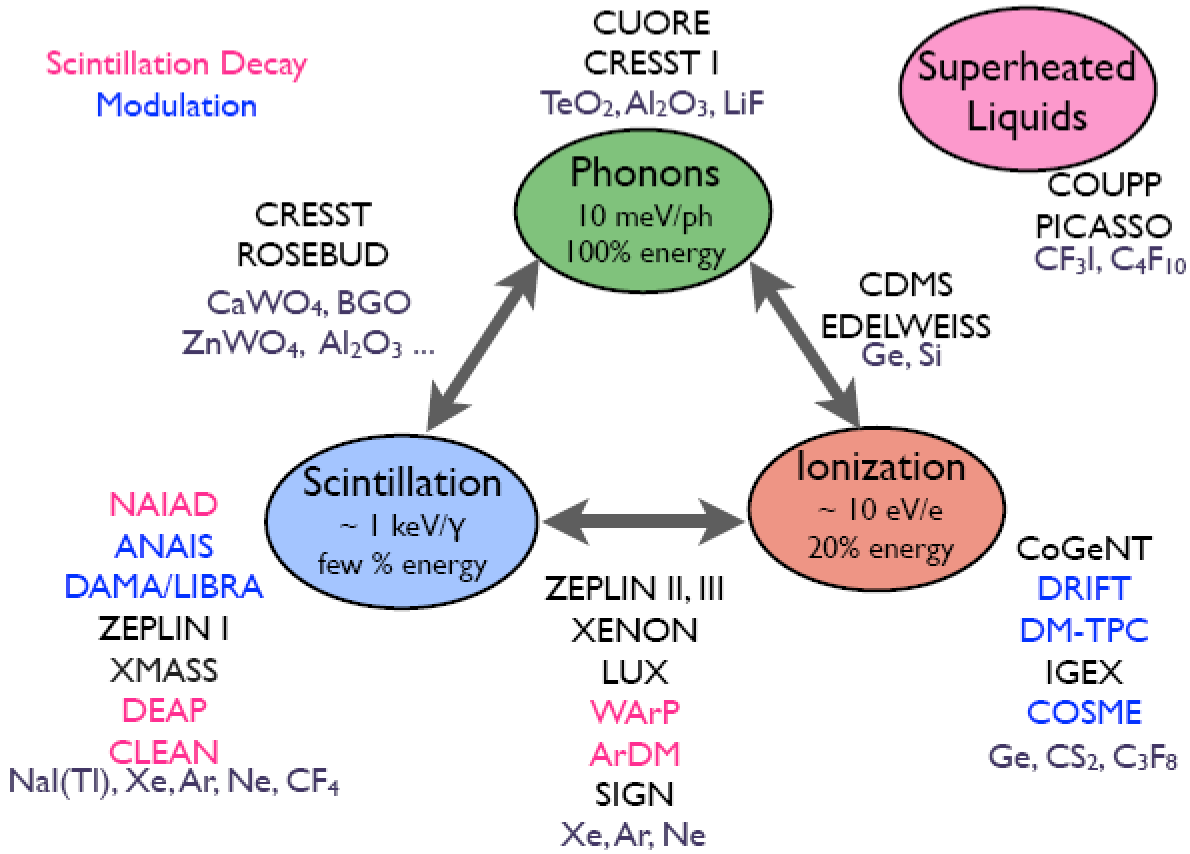
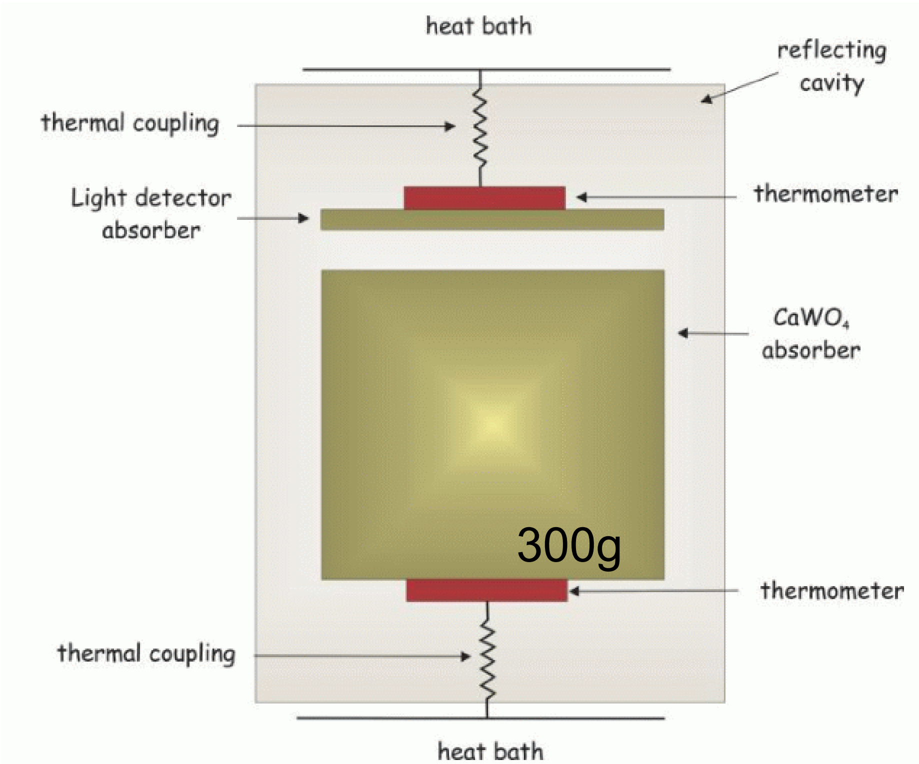


Fig. 2. The corners of the triangle correspond to common energy readout channels. Experiments are listed near the main readout channel, or between the two channels used for discrimination.

T. Saab, arXiv:1203.2566v1

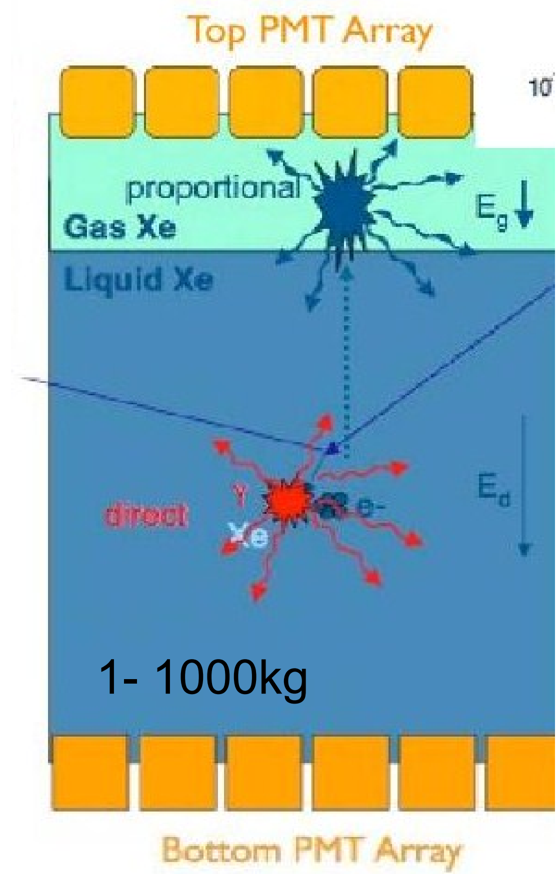
CRESST-1: bolometer + light detection

~15 mK



XENON two phase TPC

165 K



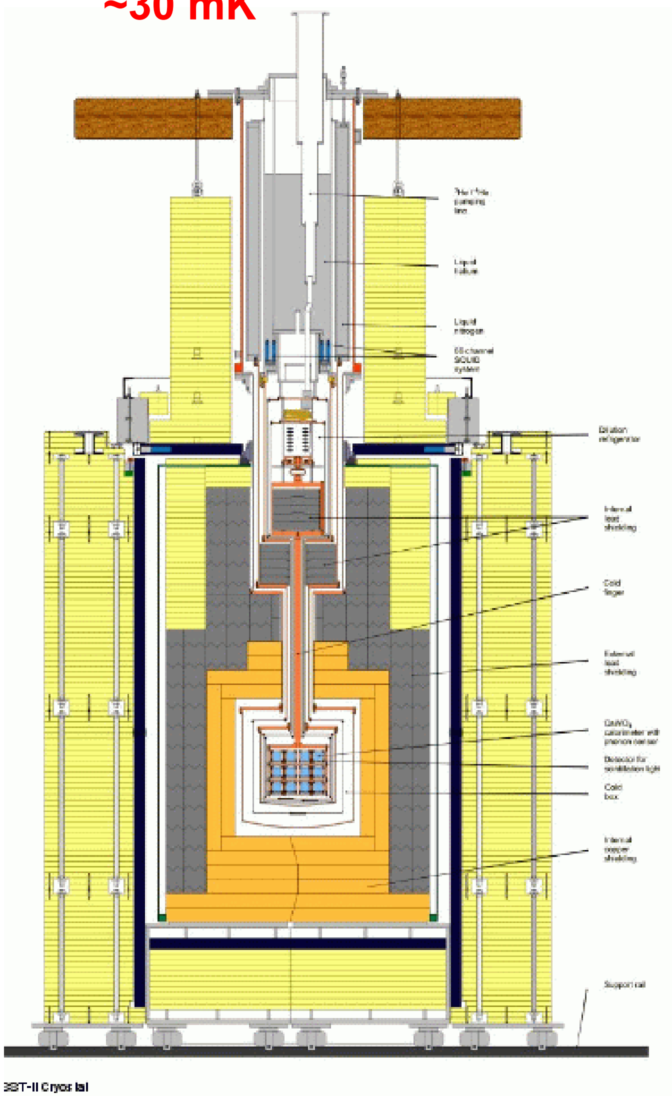
background rejection : phonons vs light

charge vs light

dark matter: direct detection by nuclear recoil

CRESST-1: bolometer + light detection

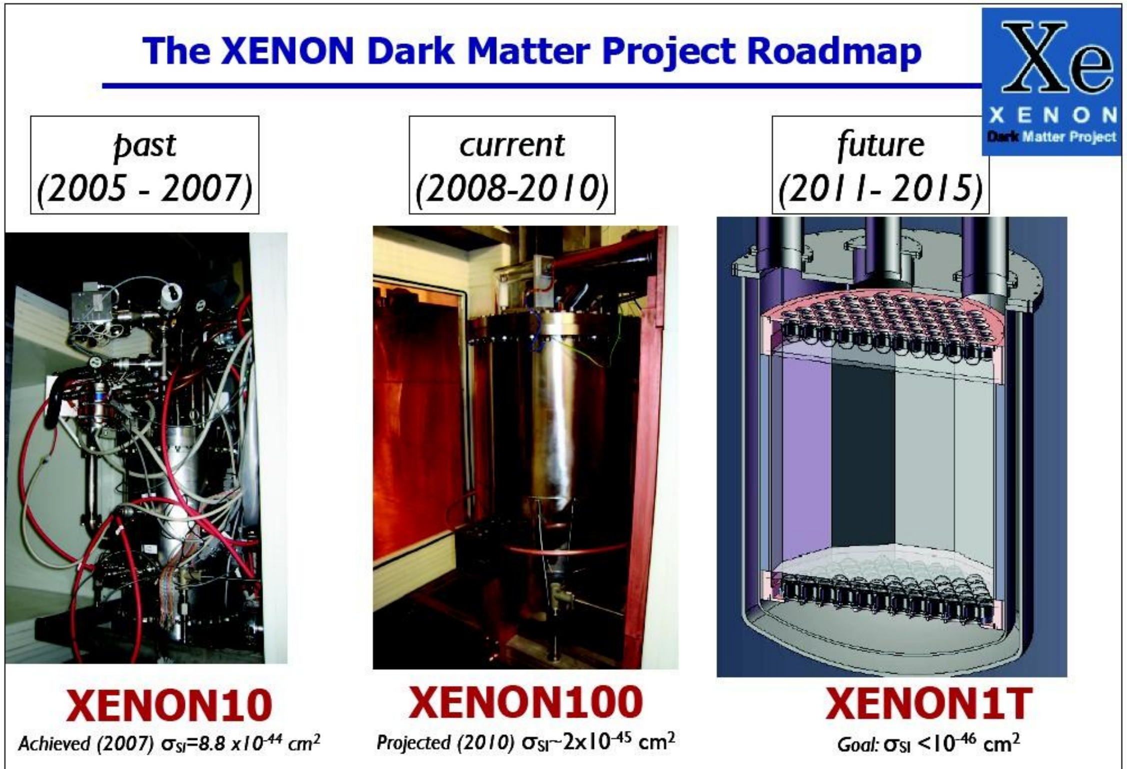
~30 mK

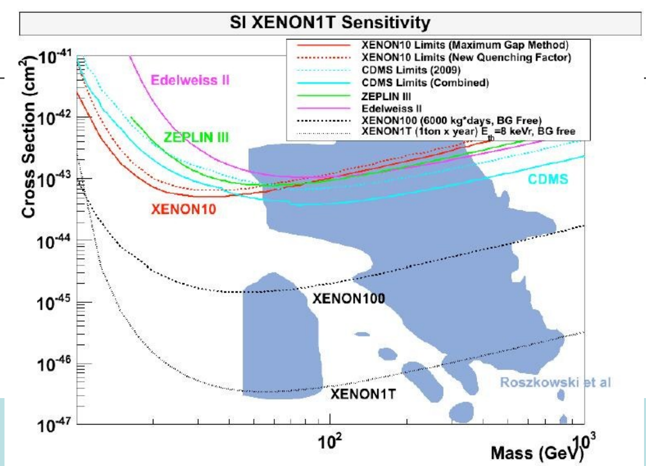


M ~ 33x 300g (►EURECA >100kg)

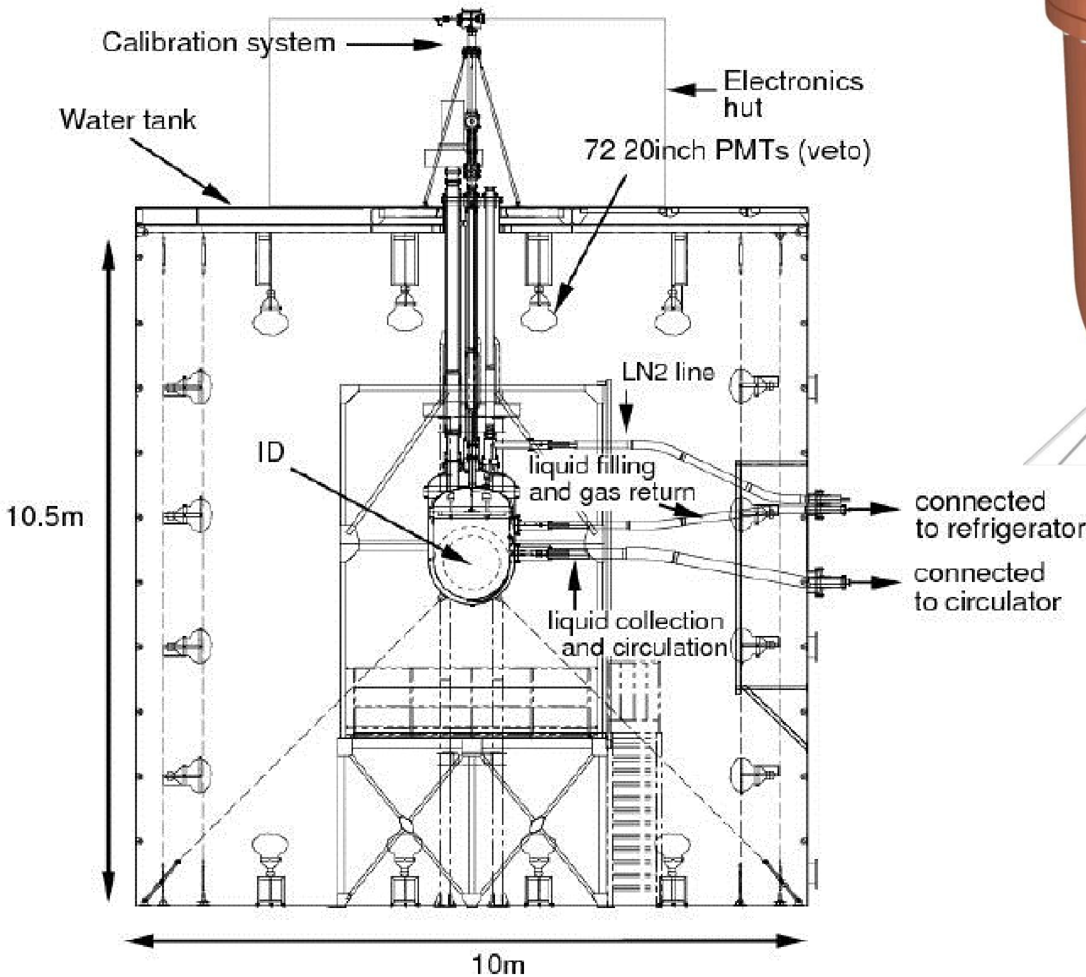
XENON two phase TPC

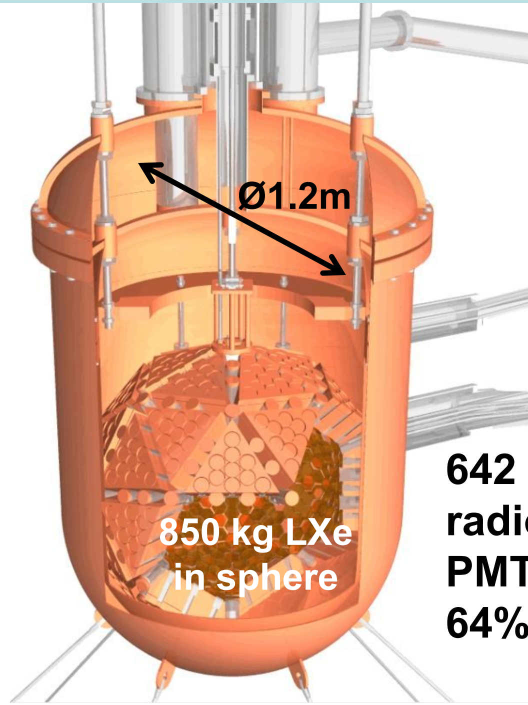
165 K



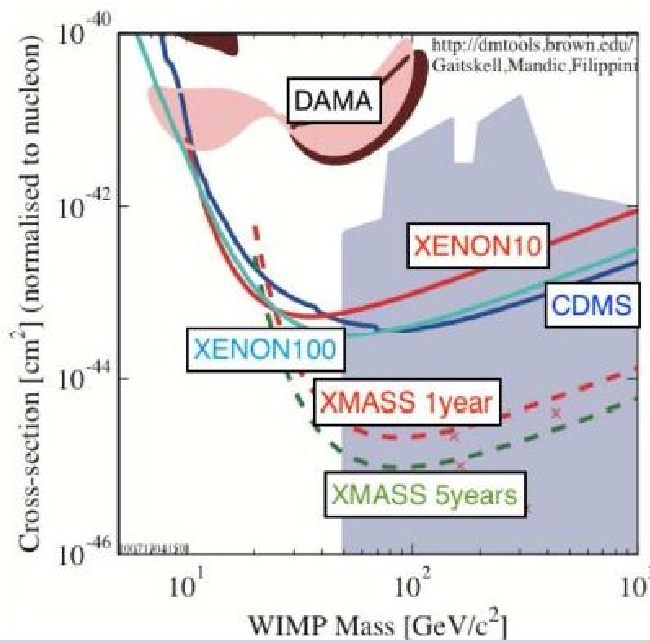


XMASS - single phase LXe (~1t)
(also solar neutrino detector)





642 ultra-low radioactivity PMTs
64% coverage



Neutrinoless Double Beta Decay

Challenges

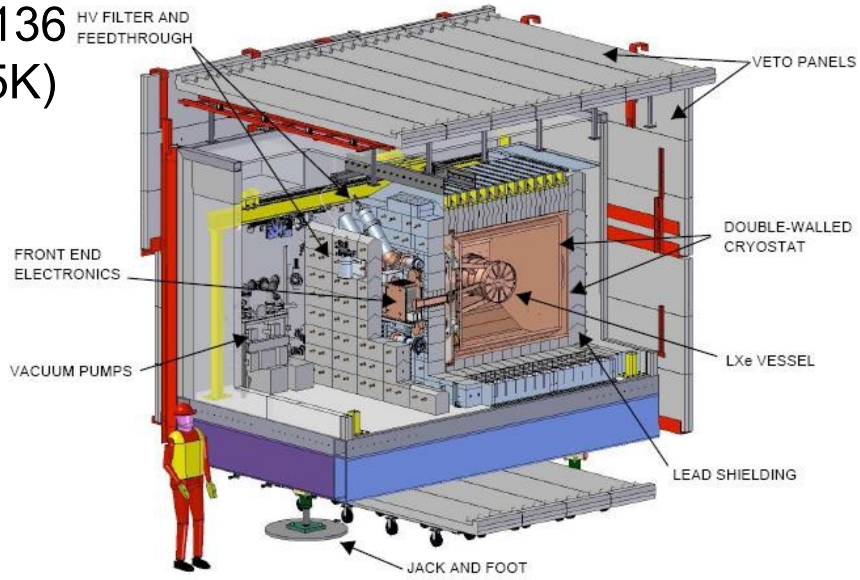
sensitivity of experiment for neutrinoless double beta decay :

$$T^{0\nu}_{1/2}(90\%CL) > \frac{\ln 2}{1.64} \frac{N_A}{A} \epsilon \cdot \eta \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

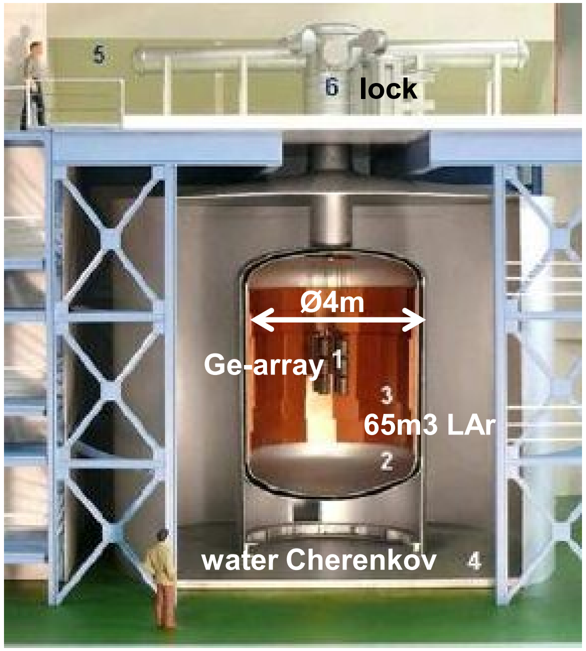
- ϵ → ~1
- η → ≤85%
- M → 300 kg (KamLAND-Zen)
- B → 10^{-3} cts/(keV·kg·yr) (EXO-200)
- ΔE → 0.2% (GERDA)

► high detection efficiency ε
high enrichment η of double beta decay isotope
large mass M
low background index B
high resolution ΔE

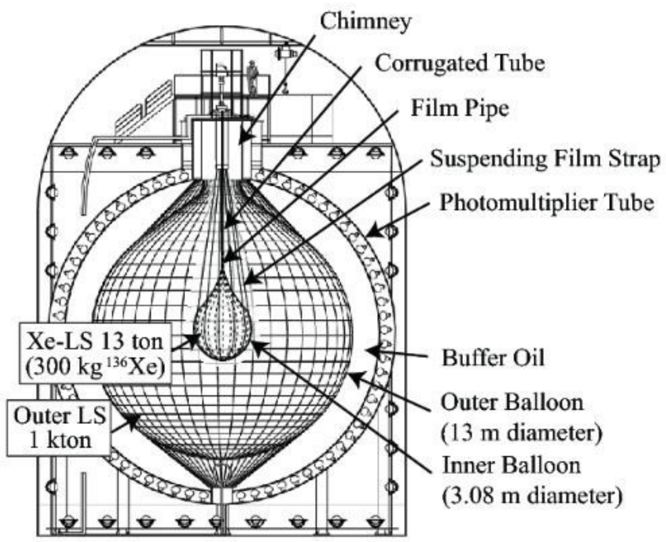
EXO-200
Xe-136
(165K)



GERDA
Ge-76
(88K)



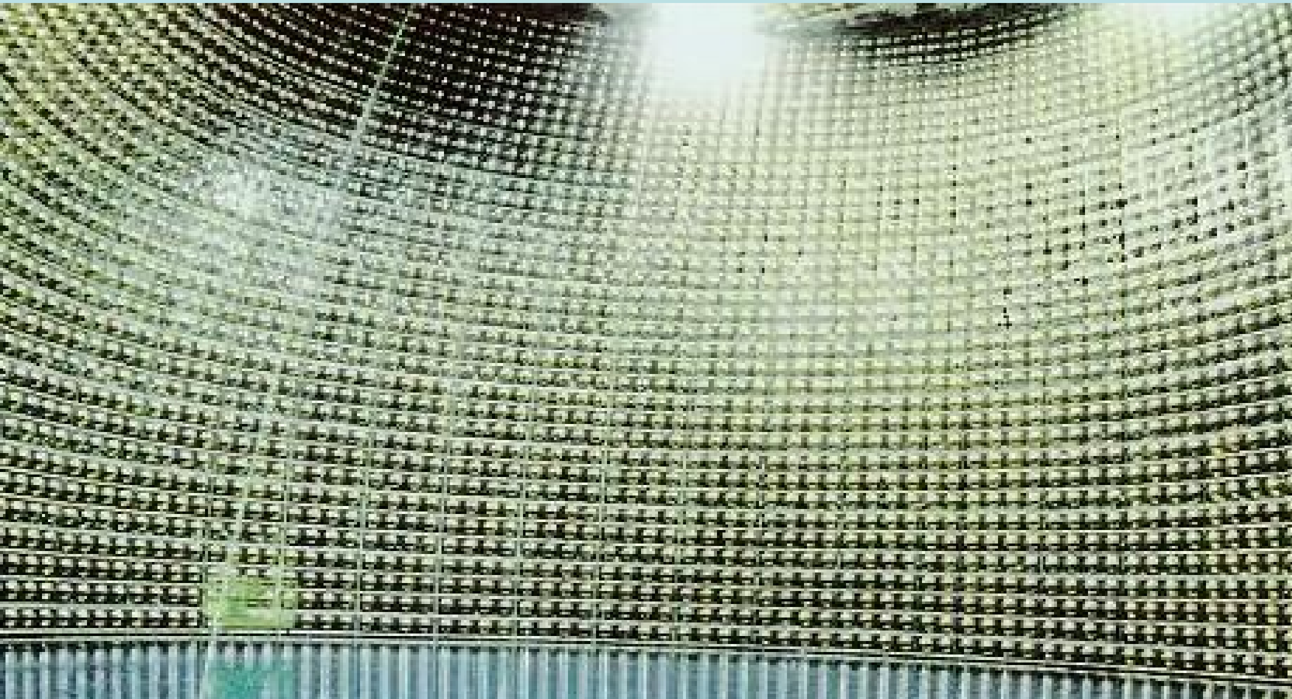
KamLAND-Zen
Xe-136
(r.t.)



	EXO	K-Zen	GERDA
detector	LXe TPC	Xe-LS	Ge-diode
source=detector	yes	no	yes
source mass (kg)	100	300	15-35
enrichment (%)	81	81	85
FWHM @ $Q_{\beta\beta}$ (%)	~5	~10	0.22

XXL Volume Detectors for Rare Processes

XXL volume detectors for rare processes



Super-Kamiokande IV Ultrapure water Cherenkov detector

1983 Kamiokande 3kt , 10^3 PMTs
'Kamioka Nucleon Decay Experiment'
1985 upgrade
1987 observation of SN1987A
1989 Super-K, 50kt, ID:10^4 20" PMTs (40% cov.), OD: 2 10^3 8" PMTs
1998 evidence for neutrino oscillations
2001 implosion of ~6600 PMTs
2006 Super-K III , all PMTs reinstalled

Hyper-K : 20-25x Super-K
LoI arXiv 1109.3262v1

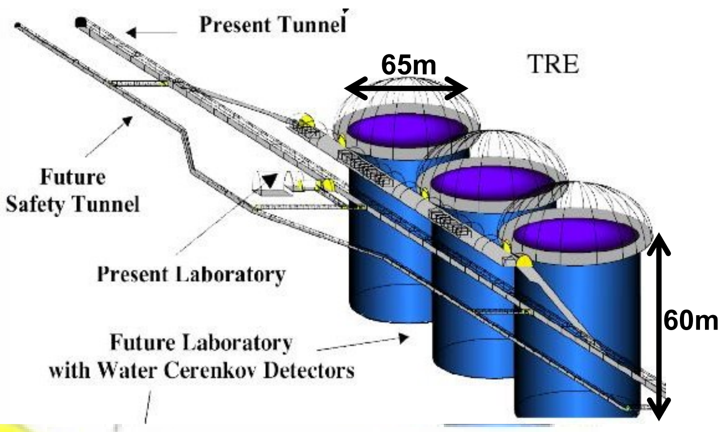
LAGUNA / LBNO project (www.laguna-science.eu)

'Large Apparatus for Grand Unification and Neutrino Astrophysics'

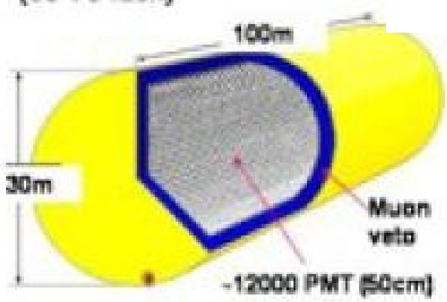
'Long-Baseline Neutrino Oscillations'

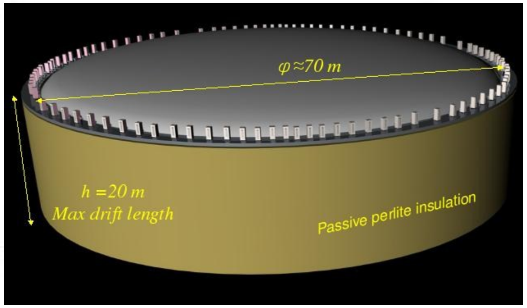
Design study by ~100 scientists from >20 institutes of 10 European countries

MEMPHYS: Water Cherenkov, (420 kton -1 Mton)

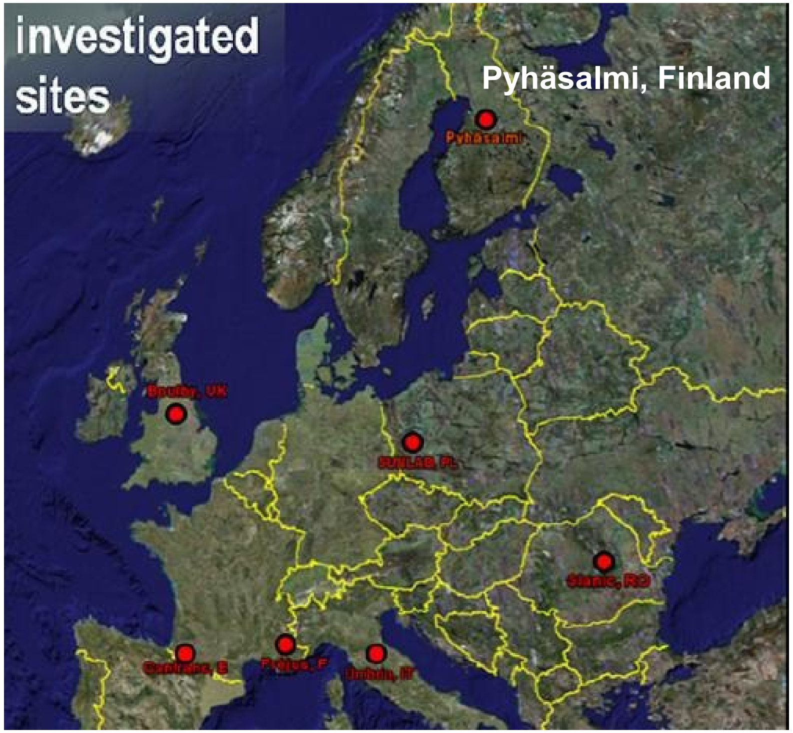


LENA: Liquid Scintillator (30-70 kton)





GLACIER: Liquid Argon (50 -100 kton)



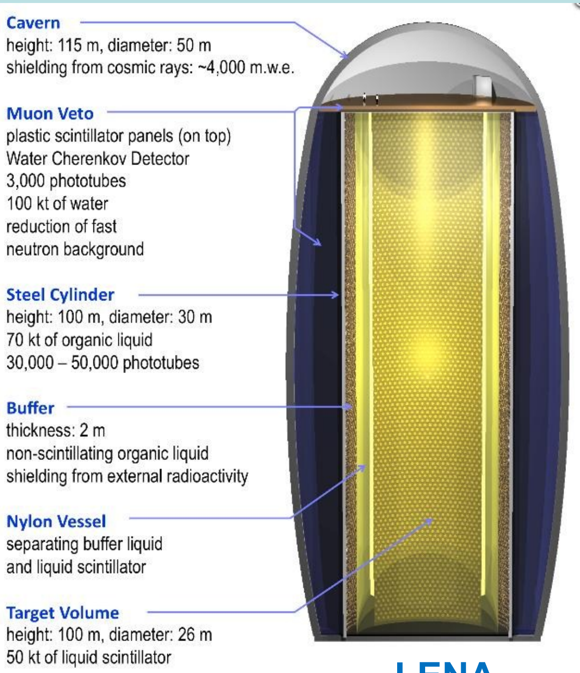
XXL volume detectors for rare processes

MEMPHYS: Mt water Cherenkov

experience with SuperK
►challenges: >10^5 photon sensors,
huge underground caverns
cost

GLACIER: 100 kt LAr TPC

R&D with ICARUS (LARTPC in US)
electronic 'LAr bubble chamber': very good energy & track resolution, particle ID
►challenges: complex detector technology,
huge number of channels, large cavity span



LENA

LENA: 50 kt liquid scintillator

mature technology demonstrated by BOREXINO and DOUBLE CHOOZ; same size and number of PMTs like SuperK
►challenges: keep purity like in BOREXINO but for 50 kt

General observation in all fields:

steady evolution from small via medium-sized to real big experiments

. e.g.:

Kamiokande → Super-K → Hyper-K

Nemo, Nestor → Antares → KM3Net

CTF → BOREXINO → LENA

HEGRA → H.E.S.S., MAGIC → CTA

Xenon10 → Xenon100 → Xenon1t

GERDA phase I → phase II → (GERDA / Majorana: 1t phase III ?)

and more

Light detection

<u>advanced PMTs - used in many experiments</u>
(e.g. Cherenkov / neutrino telescopes, DM search, large volume neutrino detectors)

► latest generation reaches 40 – 50 % quantum efficiency
► challenges

uniformity of characteristics during production
simultaneous optimization of of quantum and collection efficiency
afterpulsing
range of PMT size and types
  low temperature (77K) operation
  low radioactivity budget

<u>large-area single-photo silicon-based sensors</u>
(e.g. silicon pixel device, SiPMs = Si APD array)
► start replacing PMTs, e.g. in small- to medium-sized Cherenkov telescopes
large commercial potential, many companies active
► challenges

cost / area – still more expensive than PMTs
tailoring wavelength response (high blue / low red sensistivity)
thermal noise, cross talk between pixels
integrated readout electronics,
trigger schemes which trigger on few photons / many cm^2 area

Light detection

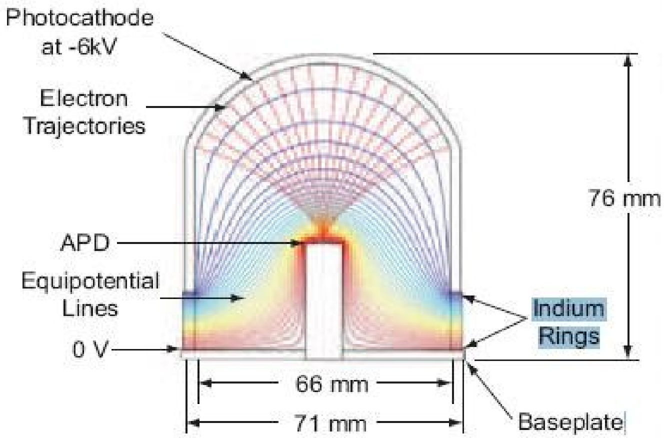
hybrids

(e.g. Quartz-photon-intensifying det. (**QUPID**), considered by Xenon, Darkside, Hyper-K)

► reaches 30% quantum efficiency, very good timing, ultra-low radioactivity device

► challenges:

not yet mature commercial product



QUPID arXiv:1103.3689v2

large-area CCD

(e.g. for optical astronomy)

- cannot comment on status and challenges

X-ray detection

pixelated X-ray detectors

e.g. for applications in space and balloons

► challenges

hard X-ray detectors with higher Z-absorbers

concluding remarks

Particle tracking

large area precision (silicon) trackers
e.g. for next generation of space experiments

very large area, low cost particle detectors
e.g. for cosmic ray air shower detectors, veto systems

►challenges

areas well above 10^4 m^2
very low cost per m^2
ideally with cm-level position information for some tracking

Calorimetry

Si-, Ge-diodes, bolometers
e.g. for searches of dark matter and neutrinoless double beta decay

►challenges

large mass / area / volume,
radiopurity
cryogenic infrastructure

the end